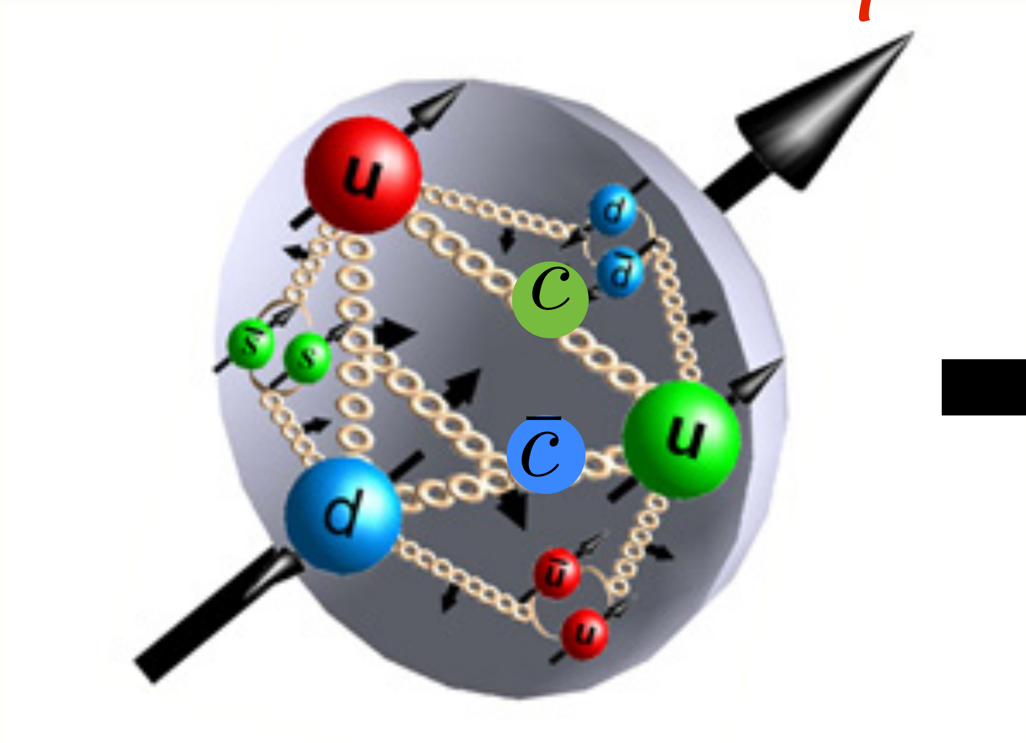
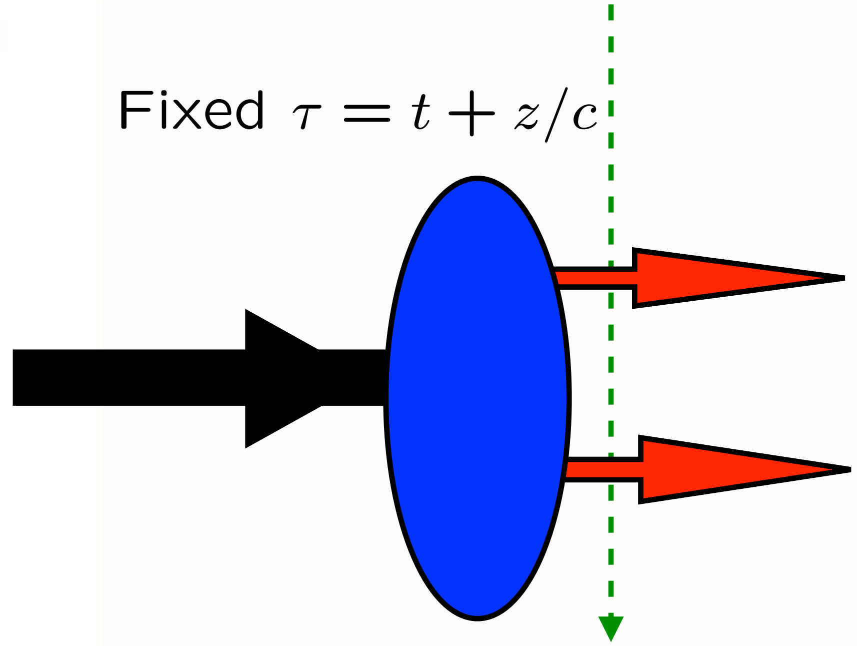
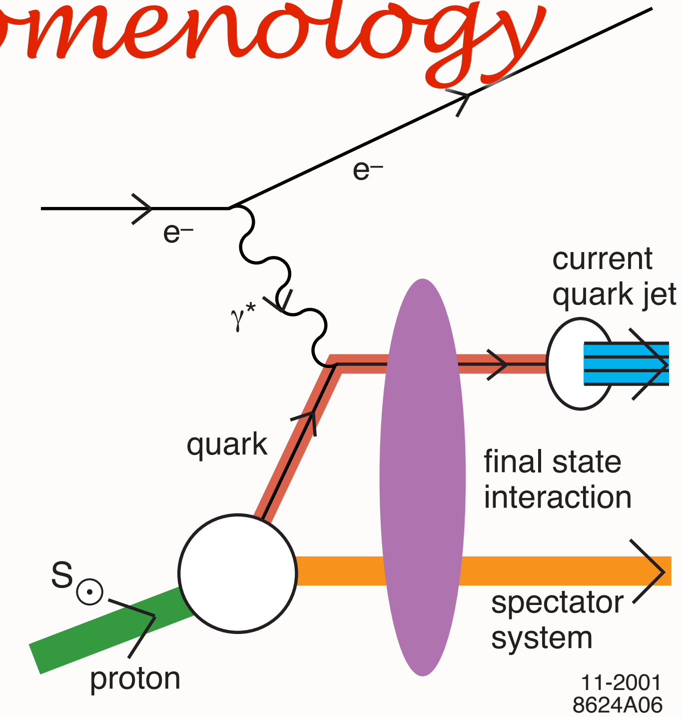
Hadrons, AdS/QCD Duality, and the Physics of the Vacuum

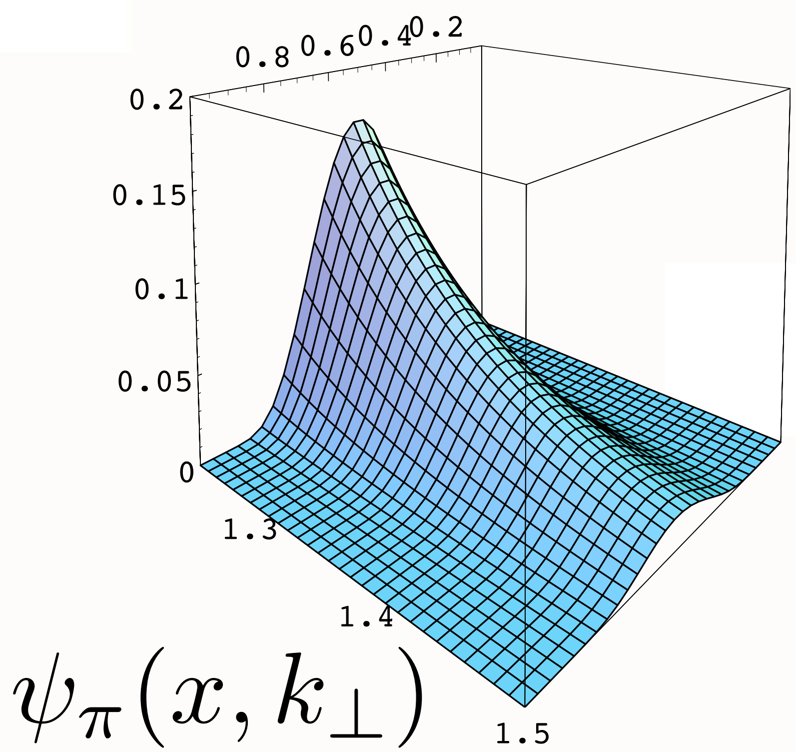
University of Warsaw Workshop, July 3-6, 2012

Hot Topics in QCD Phenomenology









Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Hot Topics in QCD

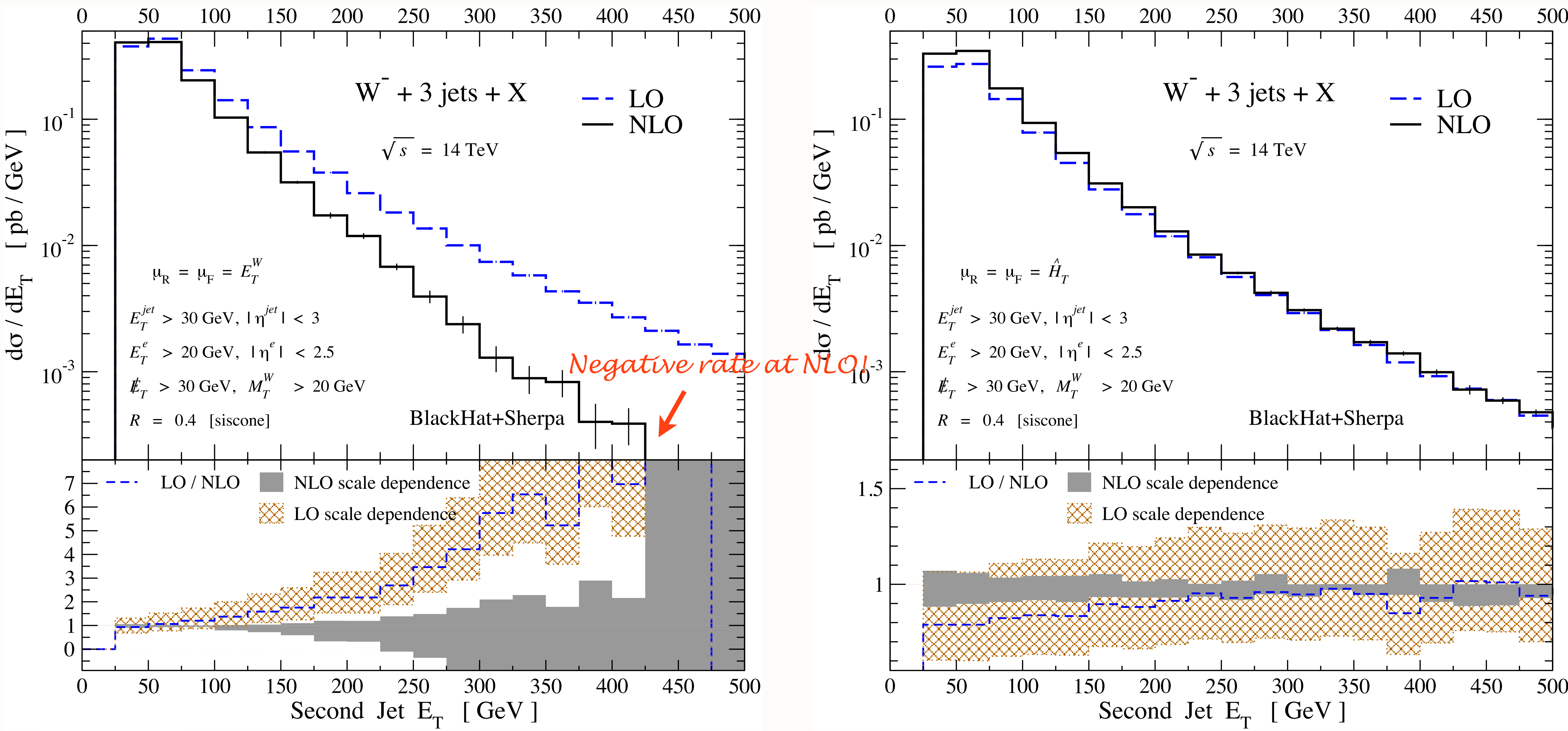
- *Intrinsic Heavy Quarks*
- *Breakdown of pQCD Leading-Twist Factorization*
- *Top/anti-Top asymmetry*
- *Non-universal antishadowing*
- *Demise of QCD Vacuum Condensates*
- *Elimination of the QCD Renormalization Scale Ambiguity*
- *AdS/QCD and Light-Front Holography*

Crucial to Understand QCD to High Precision to Illuminate New Physics

Next-to-Leading Order QCD Predictions for W + 3-Jet Distributions at Hadron Colliders

Black Hat

$$\mu_R = \mu_F = E_T^W \qquad\qquad \mu_R = \mu_F = \hat{H}_T$$



C. F. Berger, Z. Bern, L. J. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, H. Ita, D. A. Kosower, and D. Maître

Goals

- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$ at all scales
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Relate renormalization schemes without ambiguity
- Maximize sensitivity to new physics at the colliders

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

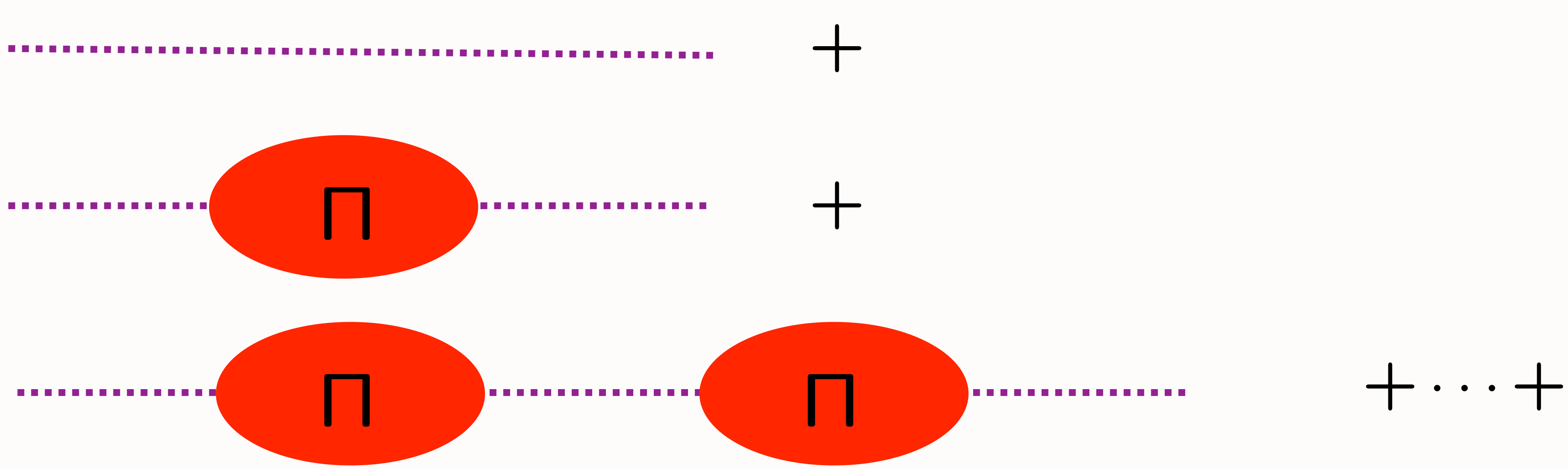
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell-Mann--Low Effective Charge

QED Effective Charge

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

All-orders lepton-loop corrections to dressed photon propagator



$$\alpha(t) = \frac{\alpha(t_0)}{1-\Pi(t,t_0)} \qquad \Pi(t,t_0) = \frac{\Pi(t)-\Pi(t_0)}{1-\Pi(t_0)}$$

Initial **scale t_0 is arbitrary -- Variation gives RGE Equations**
Physical renormalization scale t not arbitrary!

Relation between scales of the Gell-Mann--Low and $\overline{\text{MS}}$ schemes

$$\log \frac{\mu_0^2}{m_\ell^2} = 6 \int_0^1 x(1-x) \log \frac{m_\ell^2 + Q_0^2 x(1-x)}{m_\ell^2}$$

$$\log \frac{\mu_0^2}{m_\ell^2} = \log \frac{Q_0^2}{m_\ell^2} - 5/3$$

$$\boxed{\mu_0^2 = Q_0^2 \; e^{-5/3}} \quad \text{when } Q_0^2 >> m_\ell^2$$

D. S. Hwang, sjb

M. Binger

Can use $\overline{\text{MS}}$ scheme in QED; answers are scheme independent
Analytic extension: coupling is complex for timelike argument

Electron-Electron Scattering in QED

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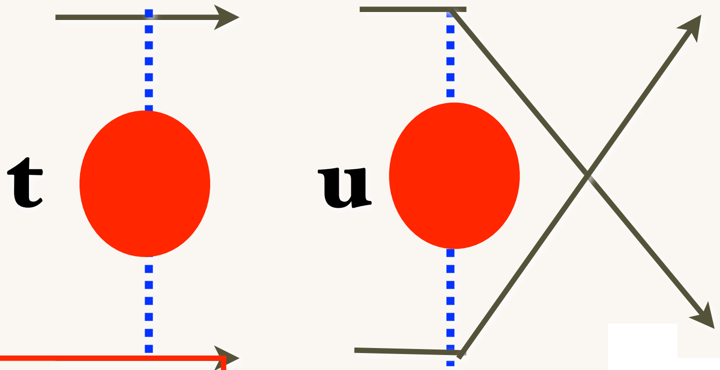


- **Two separate physical scales: t, u = photon virtuality**
- **Gauge Invariant. Dressed photon propagator**
- **Sums all vacuum polarization, non-zero beta terms into running coupling. This is the purpose of the running coupling!**
- **If one chooses a different initial scale, one must sum an infinite number of graphs -- but always recover same result!**
- **Number of active leptons correctly set**
- **Analytic: reproduces correct behavior at lepton mass thresholds**
- **No renormalization scale ambiguity!**

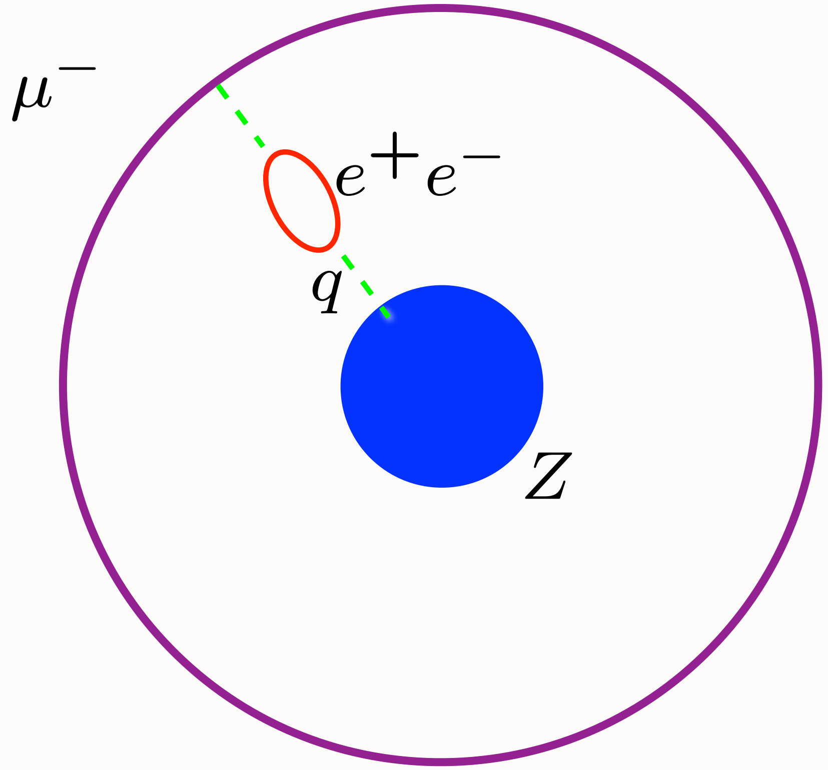
Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb Phys.Rev.D28:228,1983

- **"Principle of Maximum Conformality"** **Di Giustino, Wu, sjb**
- **All terms associated with nonzero beta function summed into running coupling**
- **Standard procedure in QED**
- **Resulting series identical to conformal series**
- **Renormalon n! growth of PQCD coefficients from beta function eliminated!**
- *Scheme Independent* **!!!**
- **In general, BLM/PMC scales depend on all invariants**
- **Single Effective PMC scale at NLO**

Another Example in QED: Muonic Atoms



$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

$$\mu_R^2 \equiv q^2$$

$$\alpha_{QED}(q^2) = \frac{\alpha_{QED}(0)}{1-\Pi(q^2)}$$

Scale is unique: Tested to ppm

Gyulassy: Higher Order VP verified to 0.1% precision in μ Pb

QCD Observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda_{QCD}^2}{Q^2}) + F(\frac{\Lambda_{QCD}^2}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Scale-Free Conformal Series

Running Coupling Effects

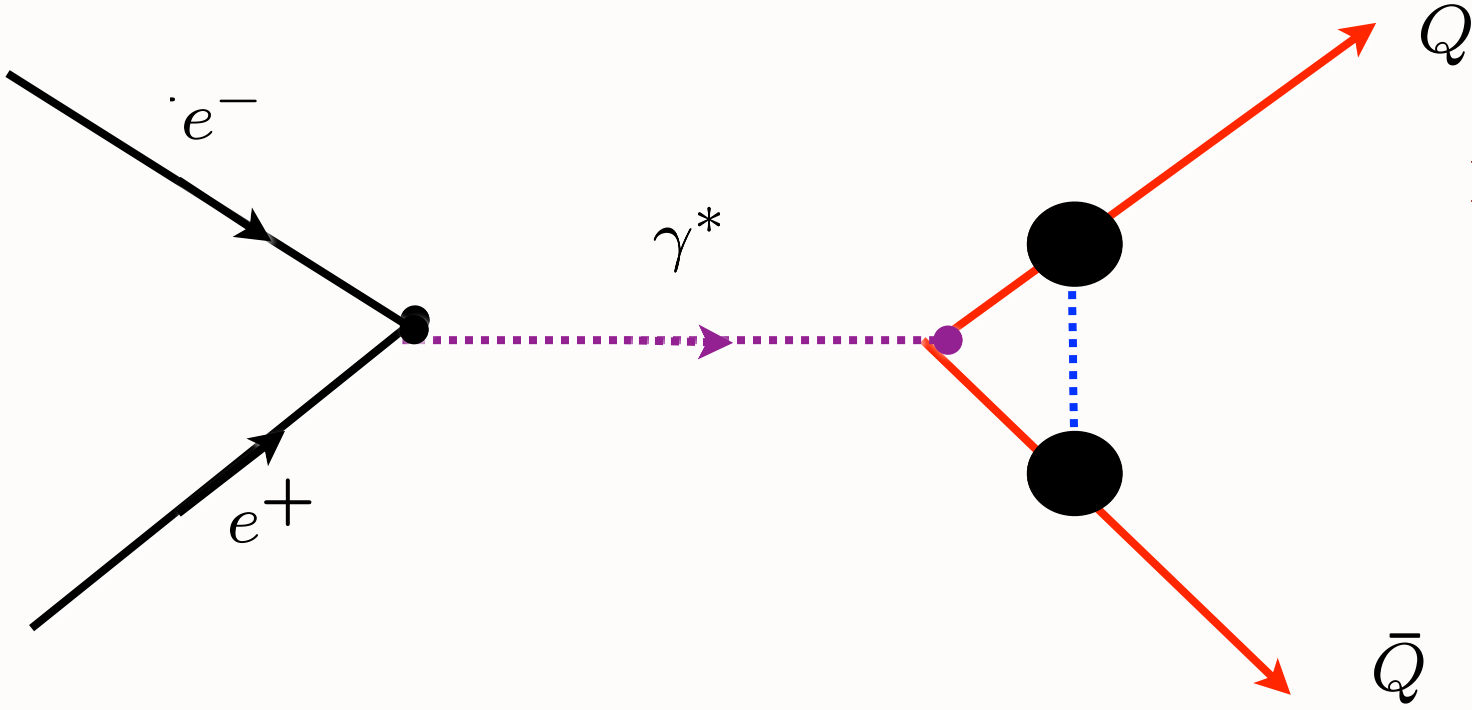
Higher Twist from Hadron Dynamics

Intrinsic Heavy Quarks

Light by Light Loops

BLM/PMC: Absorb β-terms into running coupling

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda_{QCD}^2}{Q^2}) + F(\frac{\Lambda_{QCD}^2}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$



Hoang, Kuhn, Teubner, sjb

$$F_1 + F_2 = [1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}] \times [1 + \frac{\pi\alpha_s(sv^2)}{4v}]$$

Angular distributions of massive quarks close to threshold.

Example of Multiple BLM Scales

Need QCD coupling at small scales at low relative velocity v

Need to set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

Choose renormalization scheme; e.g. $\alpha_s^R(\mu_R^{\rm init})$

↓

Choose μ_R^{init}; *arbitrary initial renormalization scale*

↓

Identify $\{\beta_i^R\}$ *− terms using* n_f *− terms*

through the PMC − BLM correspondence principle

↓

Shift scale of α_s *to* $\mu_R^{\rm PMC}$ *to eliminate* $\{\beta_i^R\}$ *− terms*

↓

Conformal Series

Result is independent of $\mu_R^{\rm init}$ *and scheme at fixed order*

Principle of Maximum Conformality

PMC/BLM

No renormalization scale ambiguity

Result is independent of Renormalization scheme and initial scale

Apply to Evolution kernels, hard subprocesses

Eliminates unnecessary systematic uncertainty

Xing-Gang Wu
Leonardo di Giustino, SJB

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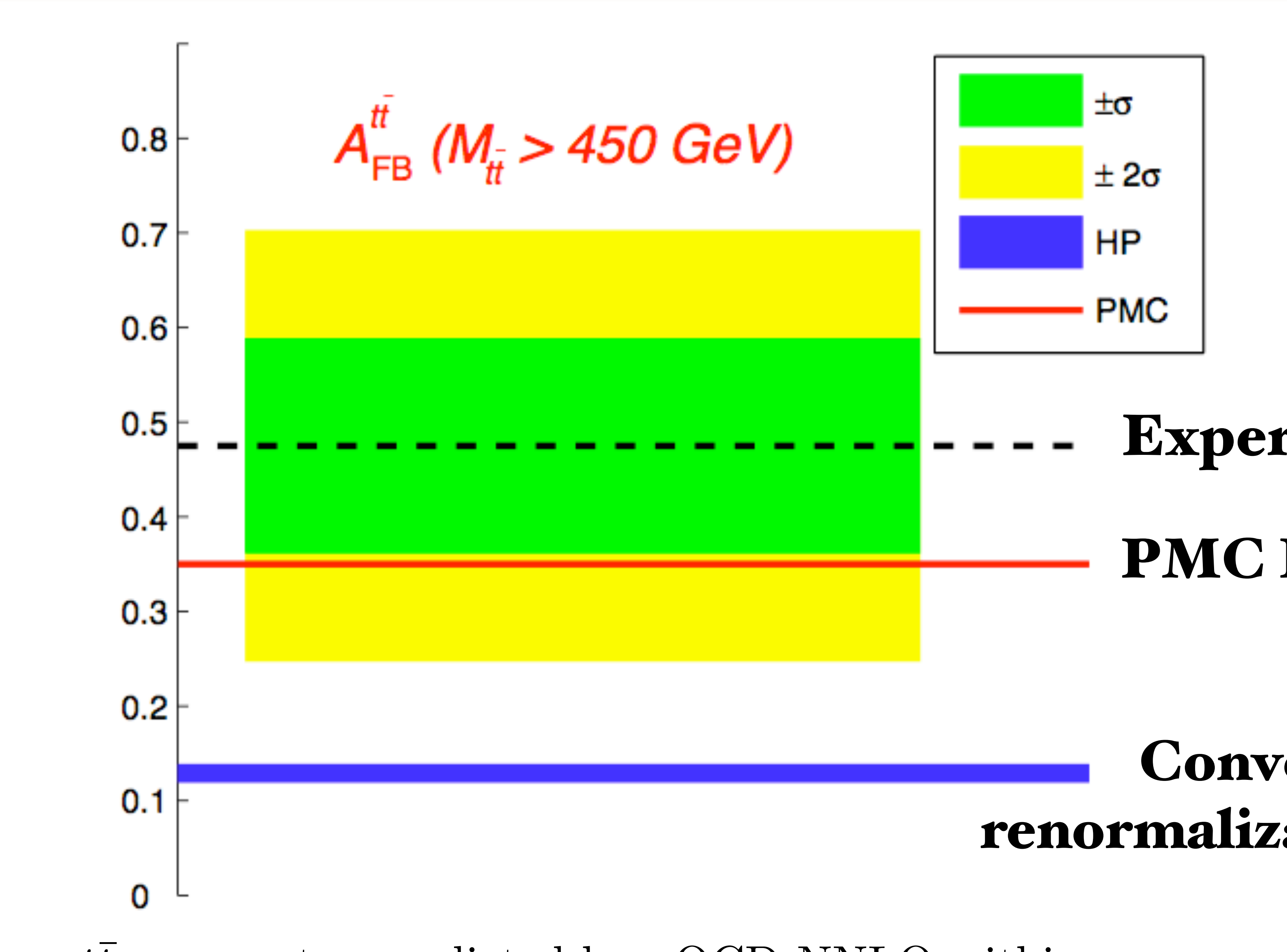

Experimental asymmetry

PMC Prediction

Conventional: guess renormalization scale and range

$t\bar{t}$ asymmetry predicted by pQCD NNLO within
1 σ of CDF/D0 measurements using PMC/BLM scale setting

The Renormalization Scale Problem

- No renormalization scale ambiguity in QED
- Gell Mann-Low QED Coupling defined from physical observable
- Sums all Vacuum Polarization Contributions
- Recover conformal series
- Renormalization Scale in QED scheme: Identical to Photon Virtuality
- Analytic: Reproduces lepton-pair thresholds -- number of active leptons set
- Examples: muonic atoms, g-2, Lamb Shift
- Time-like and Space-like QED Coupling related by analyticity
- Uses Dressed Skeleton Expansion
- Results are scheme independent!
- *Predictions for physical observables cannot be scheme dependent*

Define QCD Coupling from Observables

Grunberg

Effective Charges: analytic at quark mass thresholds, finite at small momenta

$$R_{e^+e^-\to X}(s) \equiv 3\Sigma_q e_q^2 \; [1 + \frac{\alpha_R(s)}{\pi}]$$

$$\Gamma(\tau \to X e\nu)(m_\tau^2) \equiv \Gamma_0(\tau \to u\bar{d}e\nu) \times [1 + \frac{\alpha_\tau(m_\tau^2)}{\pi}]$$

Commensurate scale relations:
Relate observable to observable at commensurate scales

H.Lu, Rathsman, sjb

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Conformal Template
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q^{\,2} \left[1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

$$\sqrt{s^*} \simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)

No renormalization scale ambiguity!

Both observables go through new quark thresholds at commensurate scales!

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8} C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32} C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12} C_A - \frac{7}{8} C_F - \frac{1}{3} f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32} C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.$$

Eliminate MSbar, Find Amazing Simplification

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
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$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi} \right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi} \right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze, Sjb

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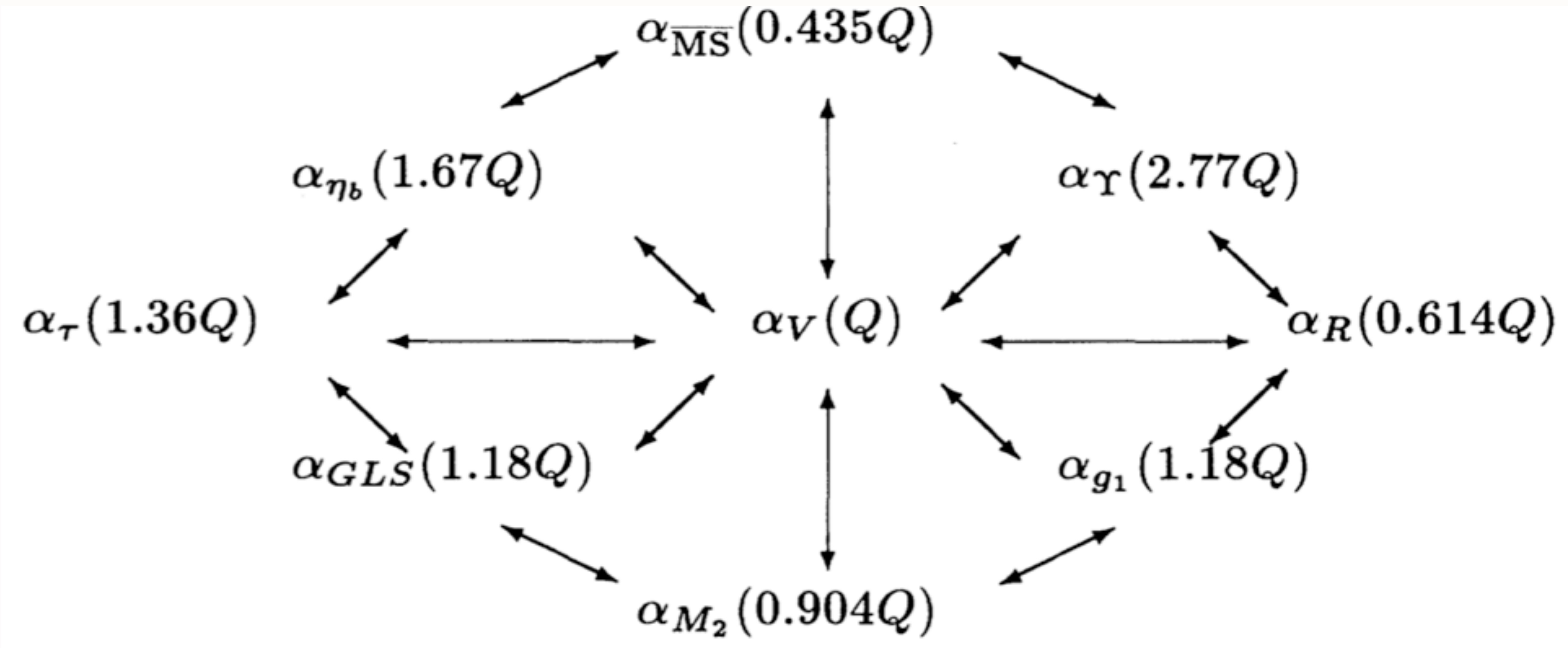
$$\frac{\alpha_\tau(M_\tau)}{\pi} = \frac{\alpha_R(Q^*)}{\pi},$$

$$Q^* = M_\tau \exp\left[-\frac{19}{24} - \frac{169}{128}\frac{\alpha_R(M_\tau)}{\pi}\right]$$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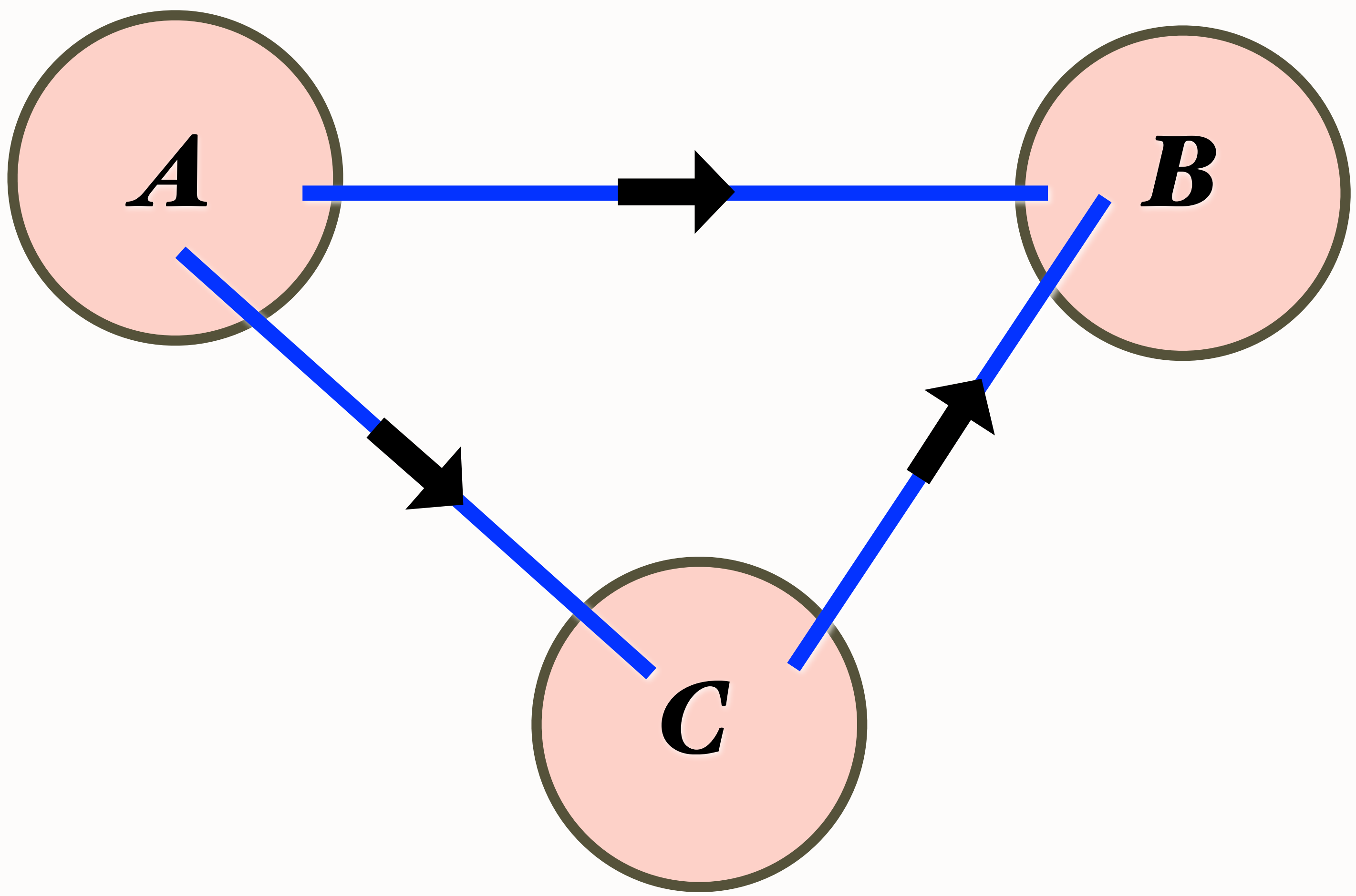
$\alpha_{GLS}(1.18Q)$
$\alpha_{g_1}(1.18Q)$
$\alpha_{M_2}(0.904Q)$

Transitivity Property of Renormalization Group

Relation of observables must be independent of intermediate scheme



A → C   C → B   identical to   A → B

Violated by PMS!

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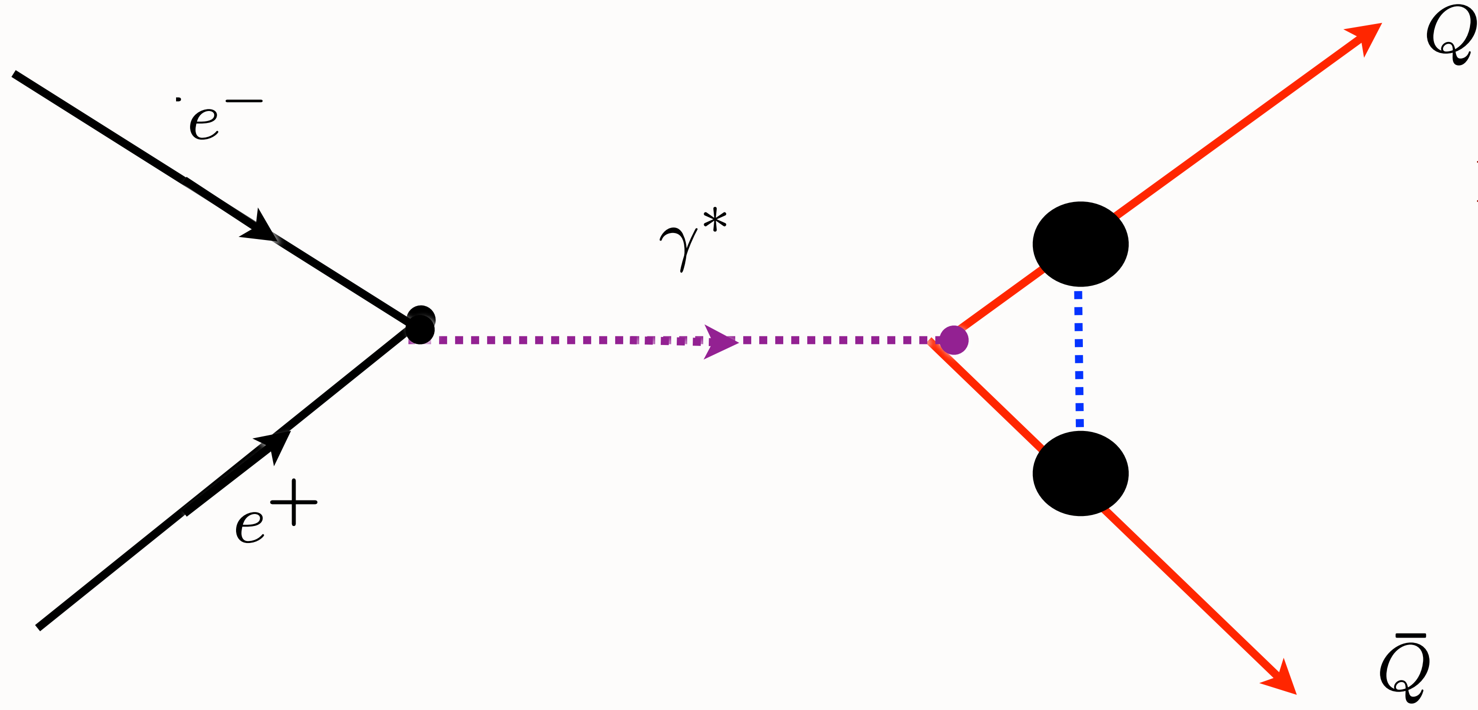

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Angular distributions of massive quarks close to threshold.

Example of Multiple BLM Scales

Need QCD coupling at small scales at low relative velocity v

Myths concerning scale setting

- Renormalization scale “unphysical”: No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess with an arbitrary range
- Factorization scale should be taken equal to renormalization scale

$$\mu_F = \mu_R$$

Guessing the scale: Wrong in QED. Scheme dependent!

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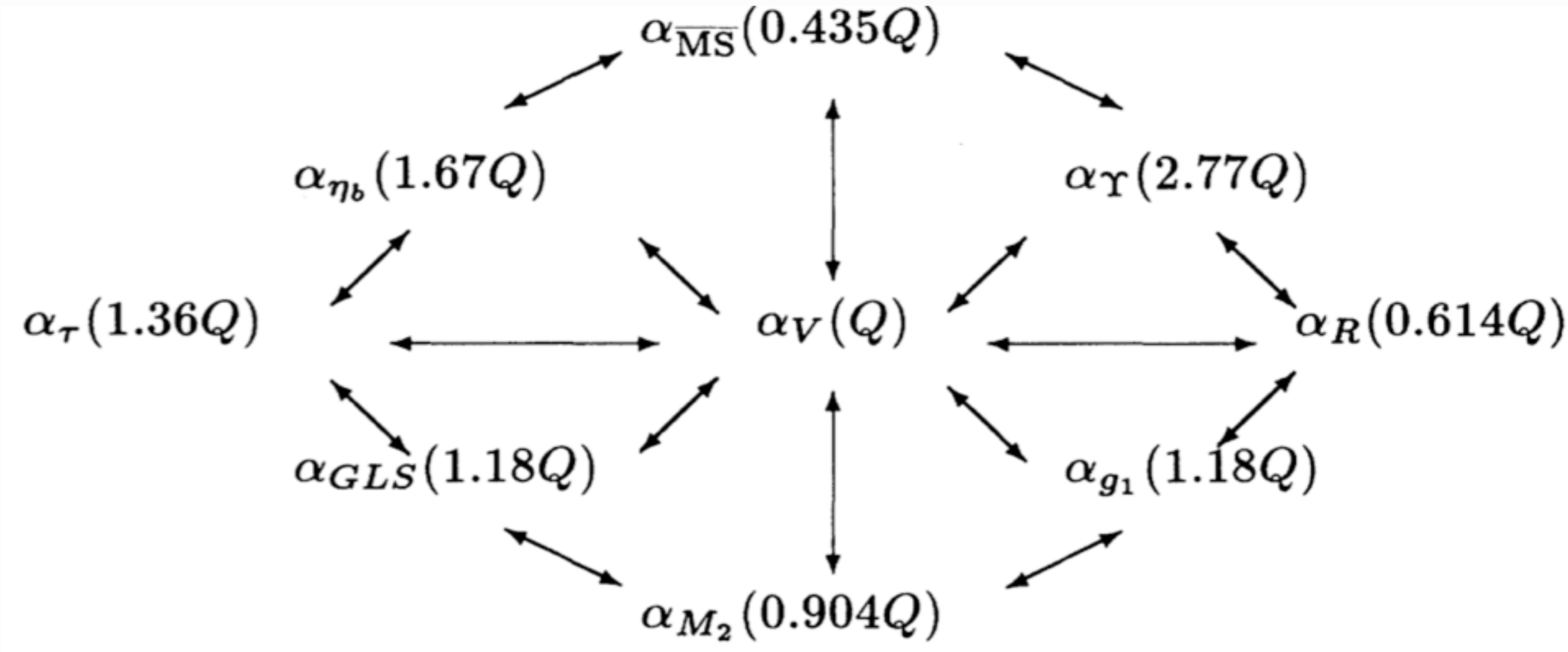
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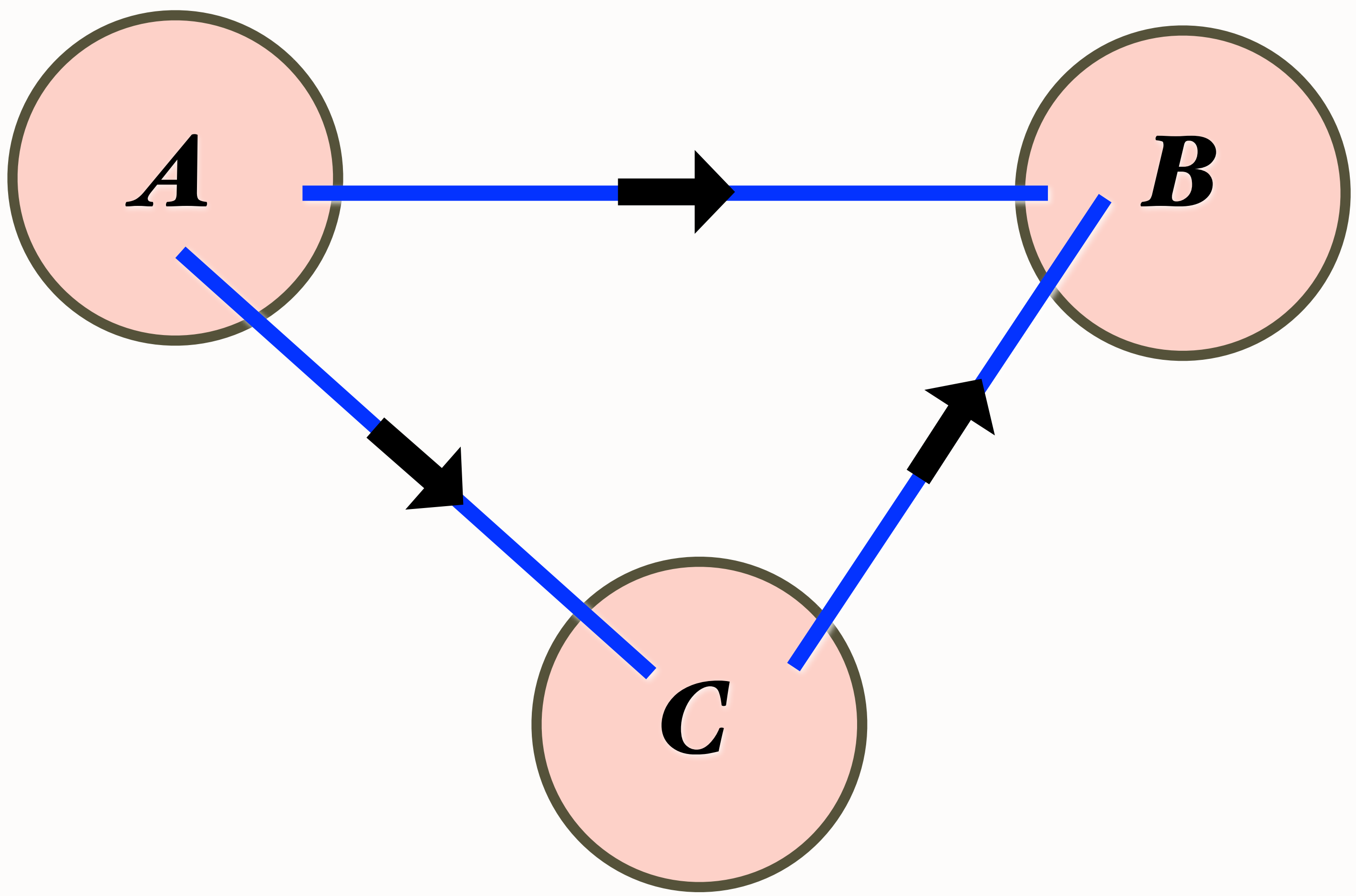

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Crucial to Understand QCD to High Precision to Illuminate New Physics

Each element of flash photograph illuminated at same LF time

$$\tau = t + z/c$$

Evolve in LF time

$$P^- = i \frac{d}{d\tau}$$

Eigenstate -- independent of τ

Measurements never at fixed time t

HELEN BRADLEY - PHOTOGRAPHY

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

$$L^{QCD} \to H_{LF}^{QCD}$$

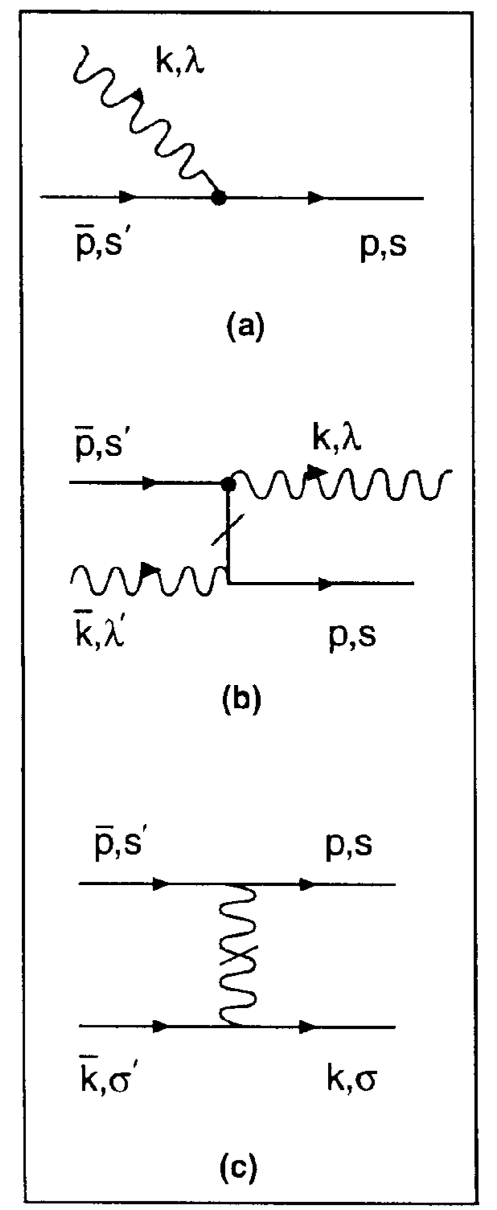
$$H_{LF}^{QCD} = \sum_i [\frac{m^2 + k_\perp^2}{x}]_i + H_{LF}^{int}$$

H_{LF}^{int}: Matrix in Fock Space

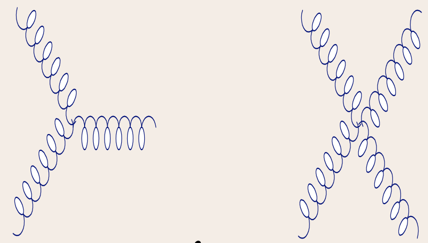
$$H_{LF}^{QCD} |\Psi_h> = \mathcal{M}_h^2 |\Psi_h>$$

$$|p, S_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



LFWFs: Off-shell in P- and invariant mass



H_{LF}^{int}

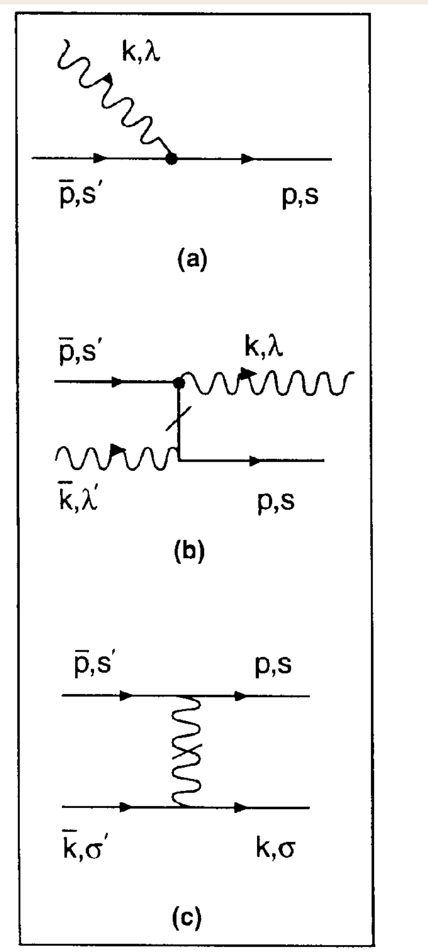
Light-Front QCD

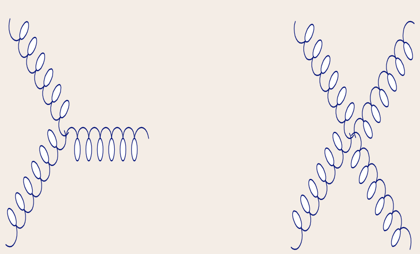
Heisenberg Matrix Formulation

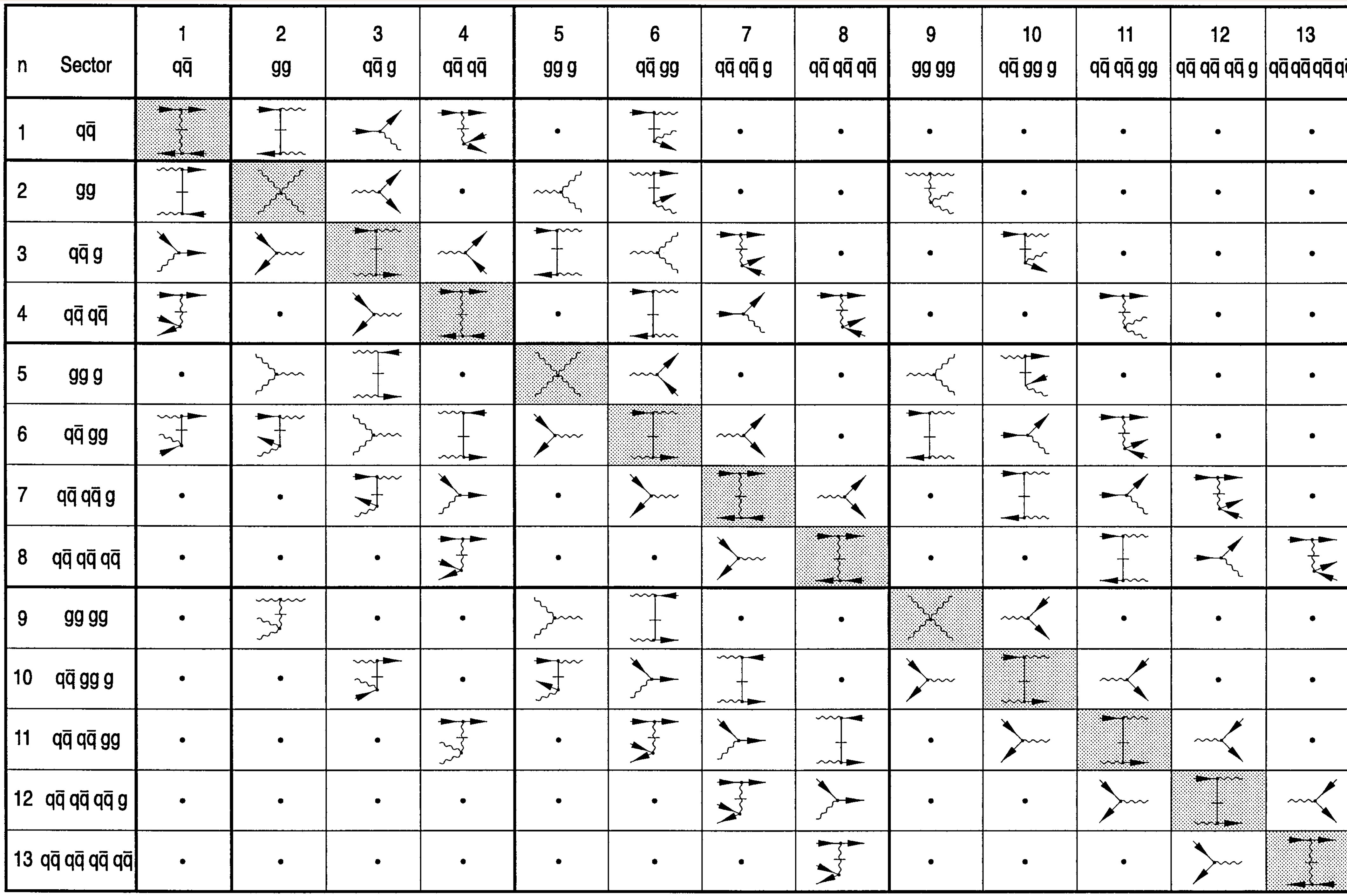
$$H^{QCD}_{LC} |\Psi_h\rangle = \mathcal{M}^2_h \; |\Psi_h\rangle$$

DLCQ

Discretized Light-Cone Quantization







Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

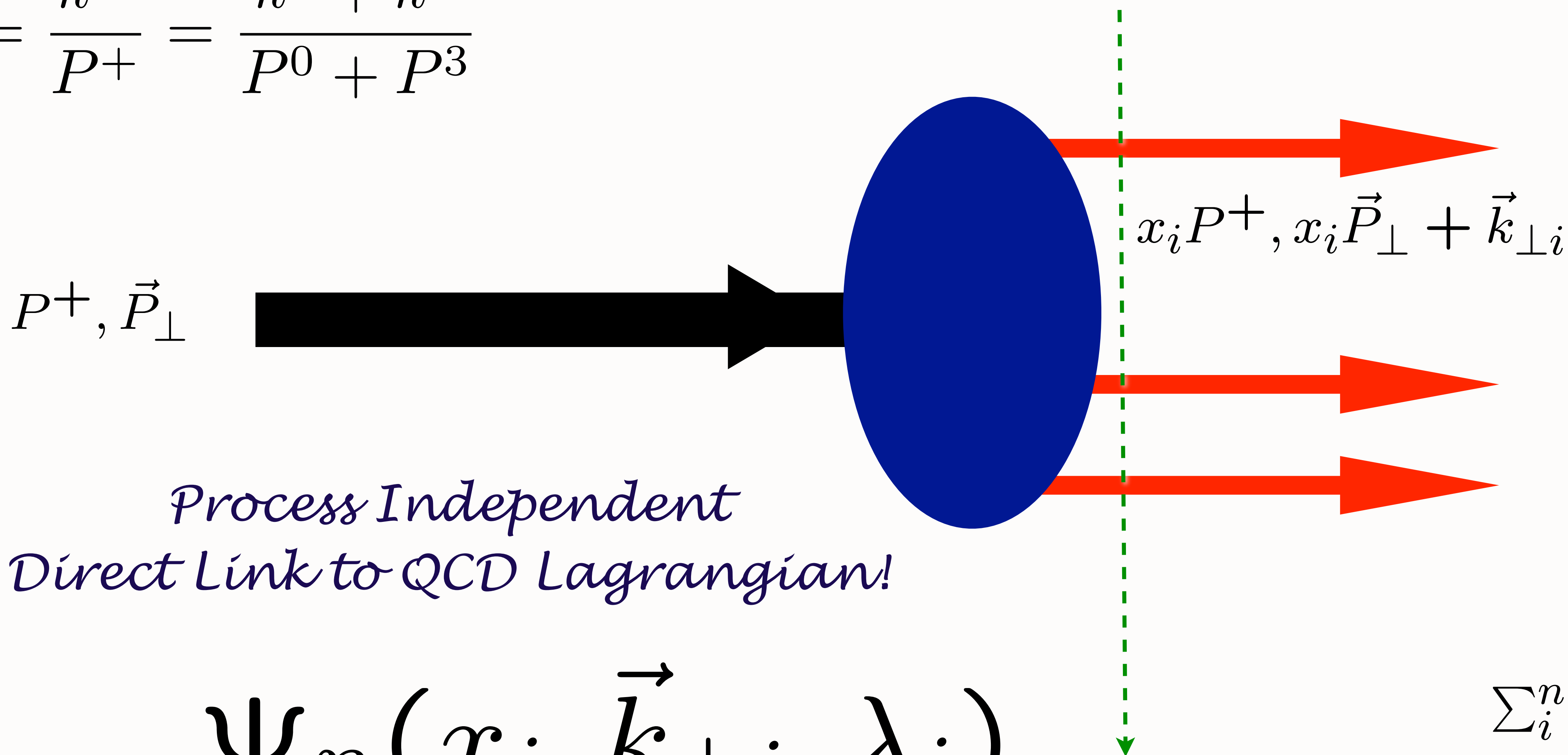
Pauli, Hornbostel & sjb

e.g. solve QCD(1+1): arbitrary color, flavor, quark mass

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory. Eigenstates of QCD Light-Front Hamiltonian

Fixed $\tau = t + z/c$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



Process Independent
Direct Link to QCD Lagrangian!

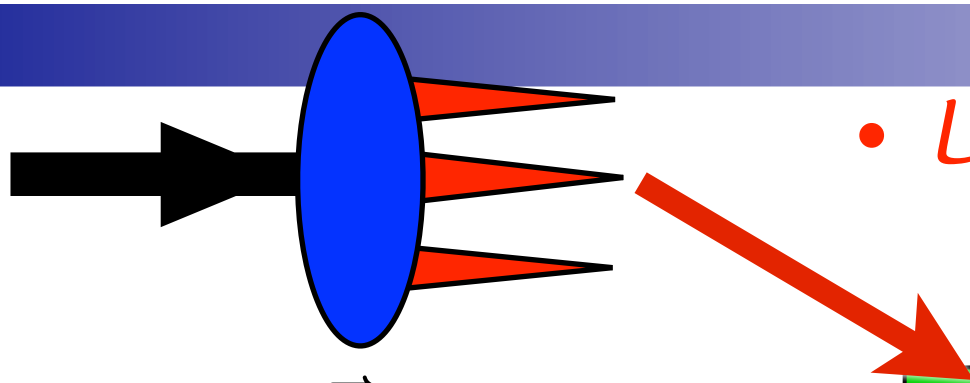
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

• Light Front Wavefunctions:



Lorce

$\xi = 0$

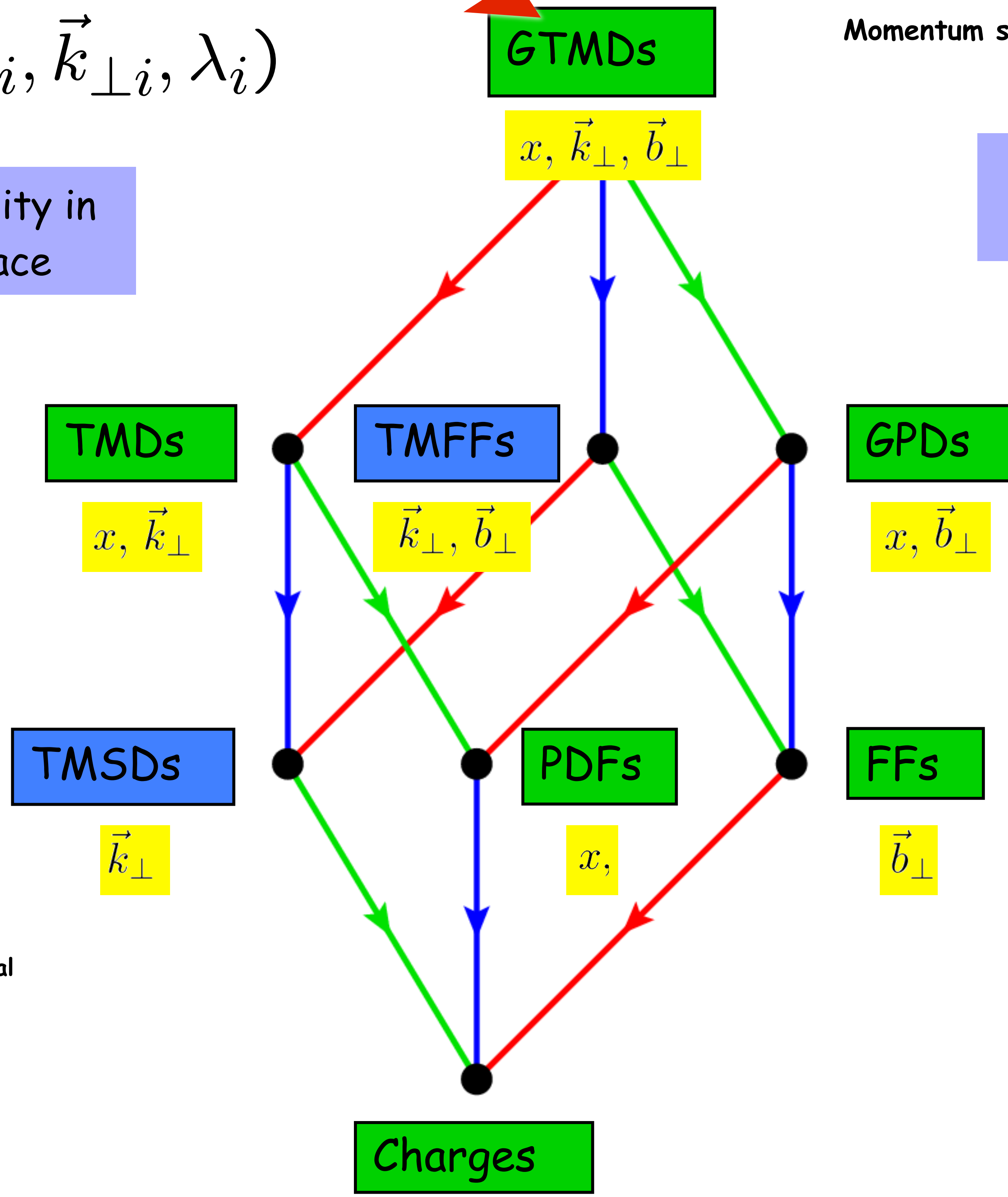
$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

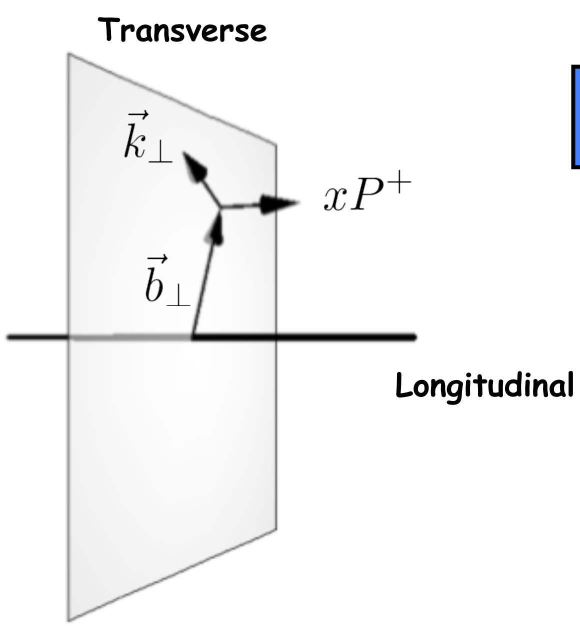
Transverse density in momentum space

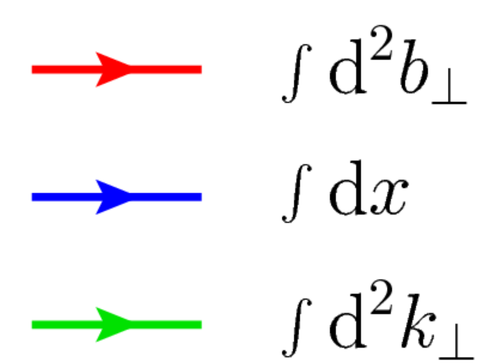
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in position space







Angular Momentum on the Light-Front

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

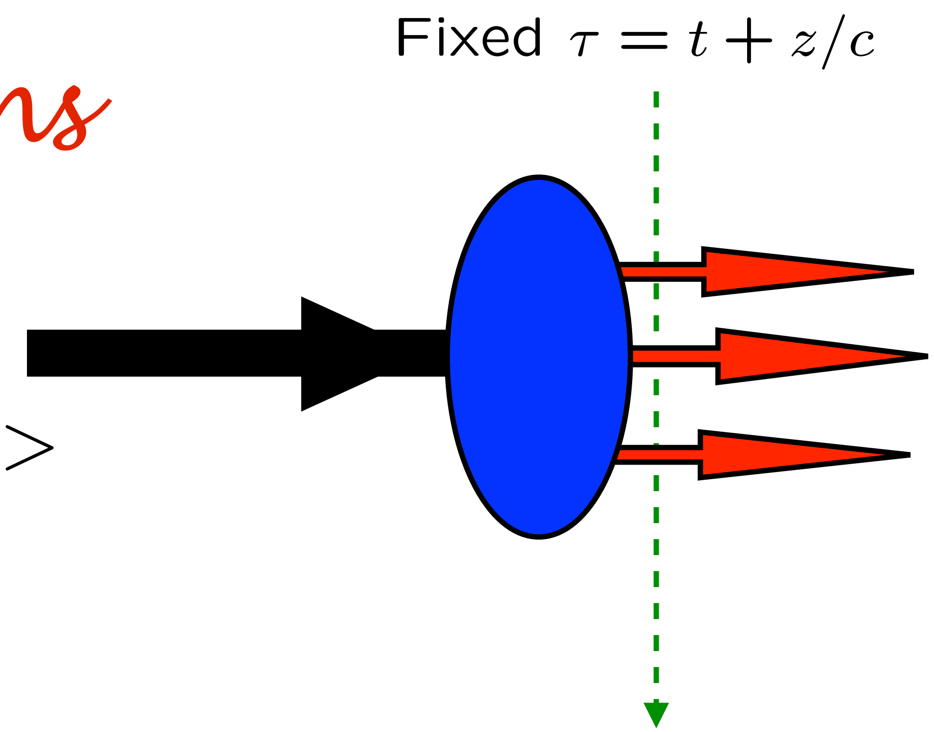
Conserved in each LF Fock state

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

Light-Front Wavefunctions



$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

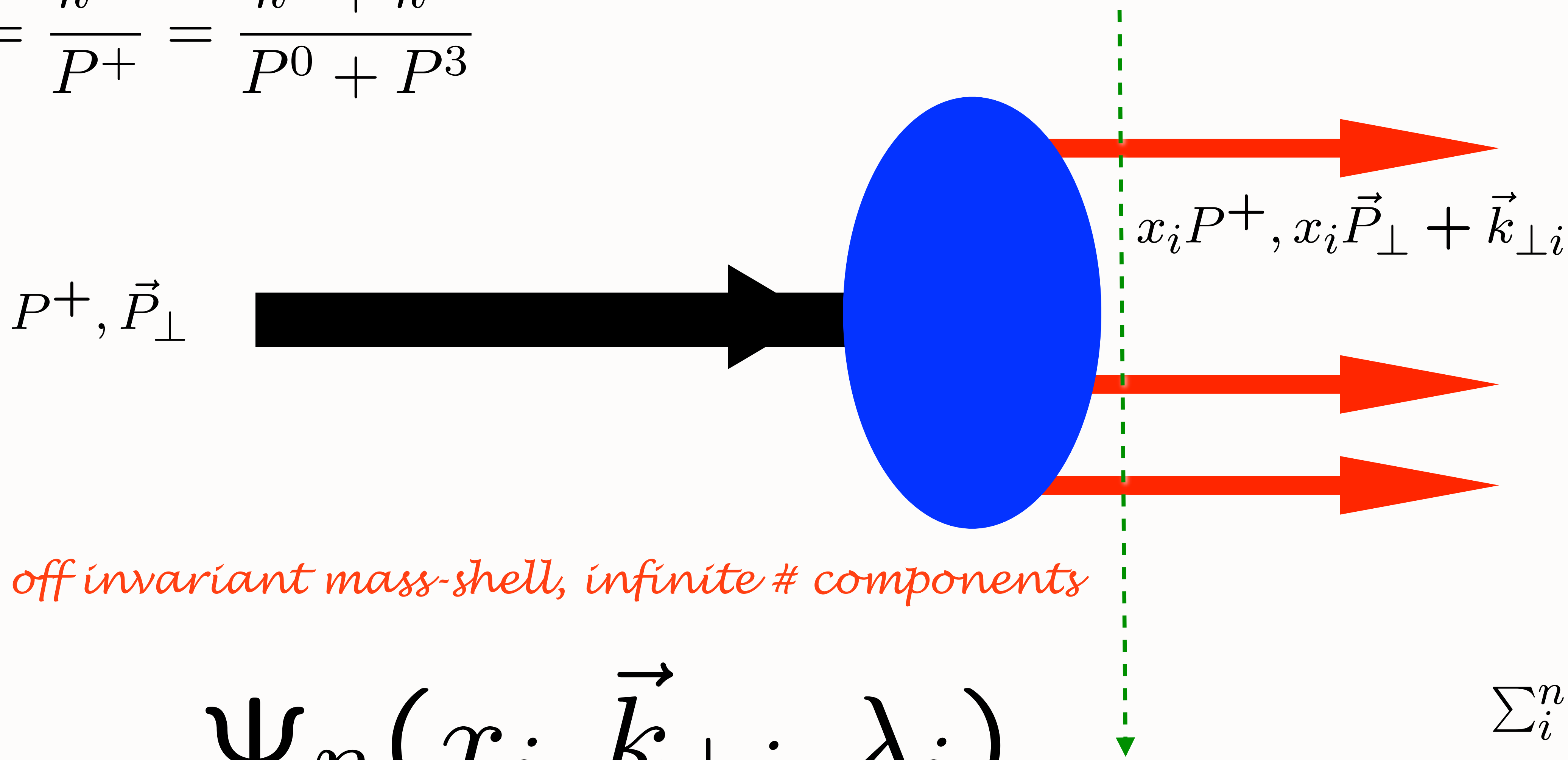
$$|p, S_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

- **Eigenfunctions of the exact QCD LF Hamiltonian**
- **Boost invariant! Independent of P^+, $P_\perp$**
- **Compute all observables intrinsic to hadron from LFWFs**
- **Form factors, structure functions, GPDs, transverse momentum distributions**
- **DGLAP and ERBL Evolution Built In**
- **No renormalization scale ambiguity: "Principle of Maximal Conformality"**
- **LF Vacuum Trivial: In-Hadron Condensates -- Eliminate 10^{45} discrepancy with cosmological constant**
- **Pseudo-T-odd observables from Lensing**
- **Angular Momentum Sum Rule for each Fock state**

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Fixed $\tau = t + z/c$



LFWFs: off invariant mass-shell, infinite # components

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

Eigensolutions of the LF Hamiltonian:

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) | n; \vec{k}_{\perp_i}, \lambda_i >$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

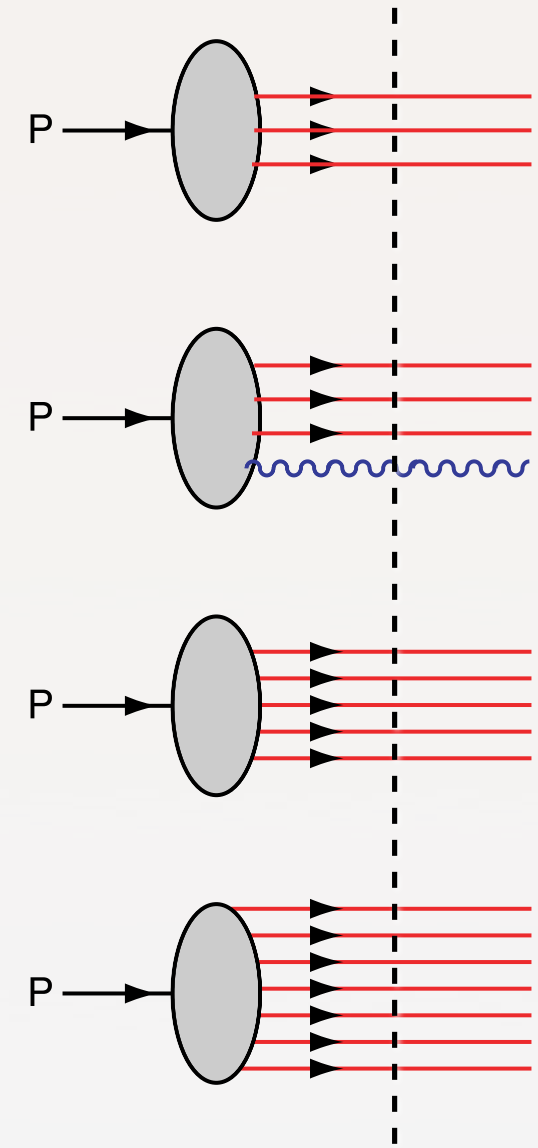
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \; \sum_i^n x_i = 1, \; \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Fixed LF time
Coupled. infinite set

Intrinsic heavy quarks
s(x), c(x), b(x) at high x !

$\bar{s}(x) \neq s(x)$
$\bar{u}(x) \neq \bar{d}(x)$

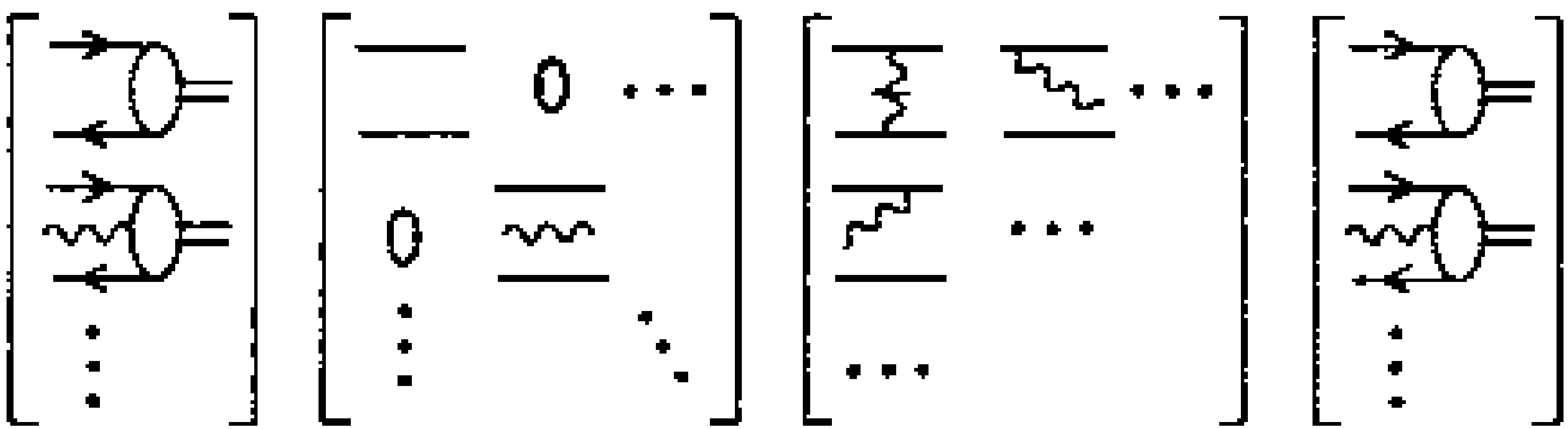
Nuclei: Hidden Color

Mueller: gluonic Fock states >> BFKL

LIGHT-FRONT SCHRODINGER EQUATION

Direct connection to QCD Lagrangian

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^{\,2} + m_i^2}{x_i} \right) \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\, V \,|q\bar{q}\rangle & \langle q\bar{q}|\, V \,|q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\, V \,|q\bar{q}\rangle & \langle q\bar{q}g|\, V \,|q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix}$$



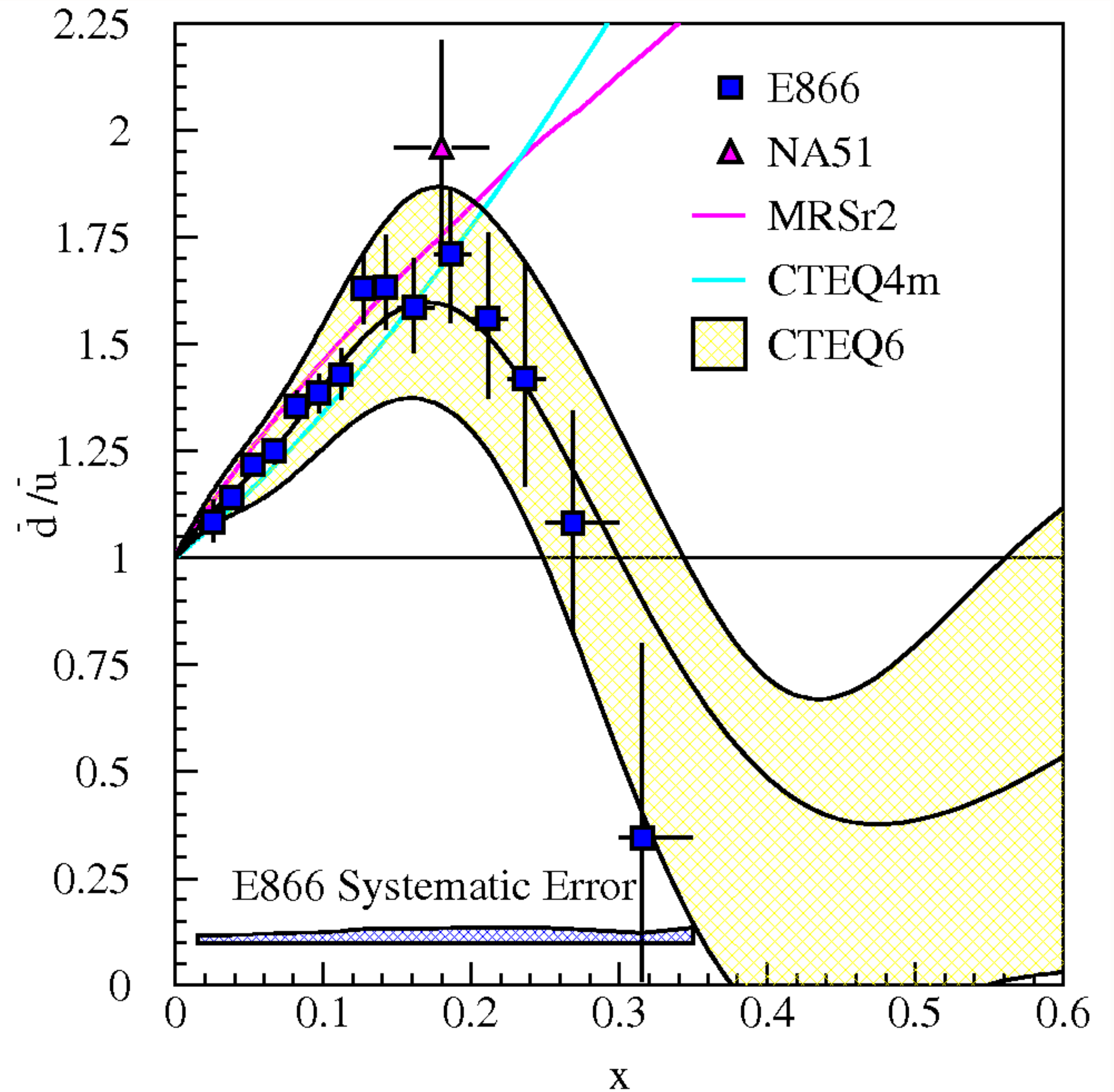
$A^+ = 0$

G.P. Lepage, sjb

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \le x \le 0.35$$

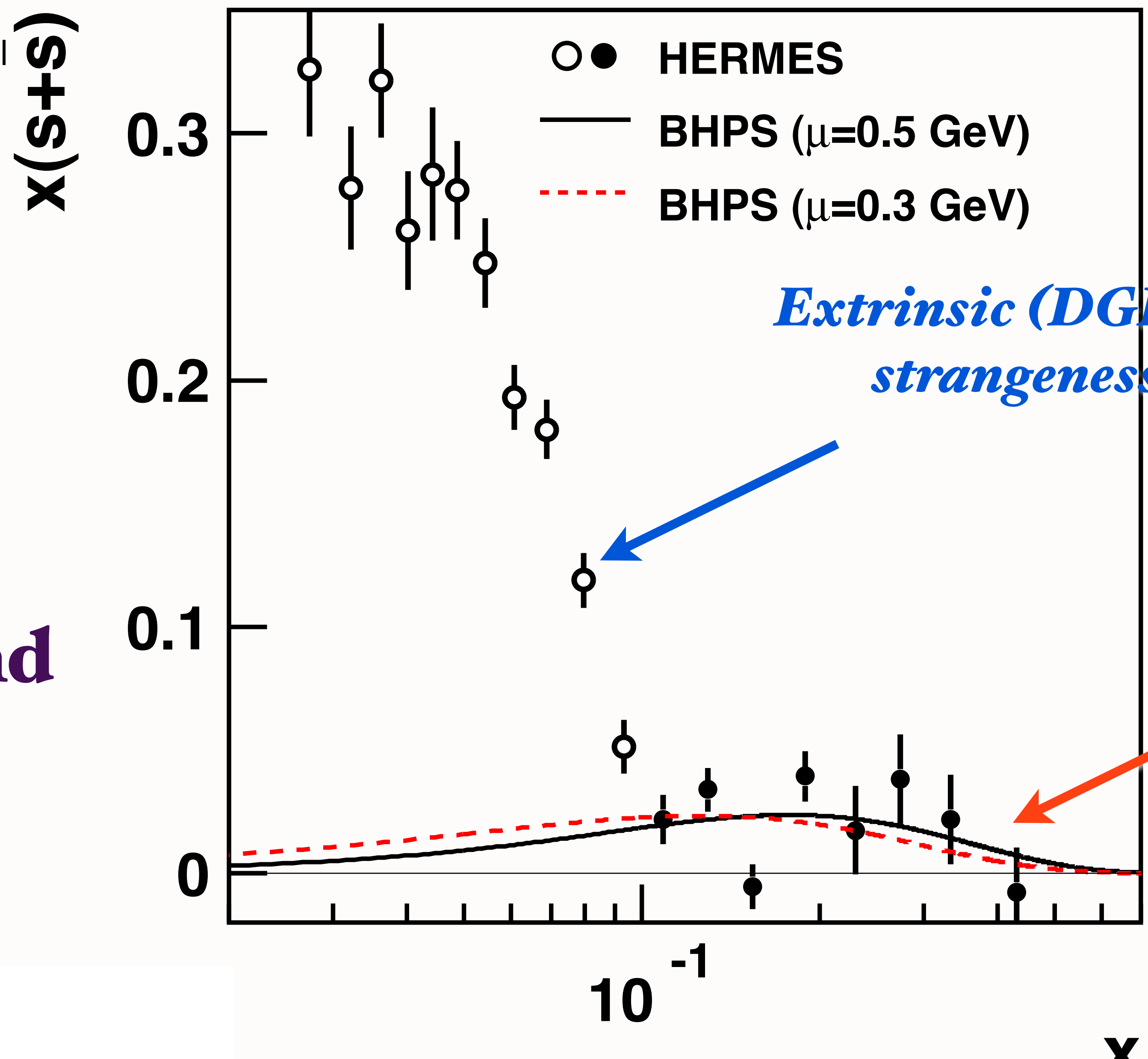
- E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$



Intrinsic glue, sea, heavy quarks

HERMES: Two components to s(x,Q²)!



Extrinsic (DGLAP) strangeness!

Intrinsic strangeness!

W. C. Chang and J.-C. Peng

arXiv:1105.2381

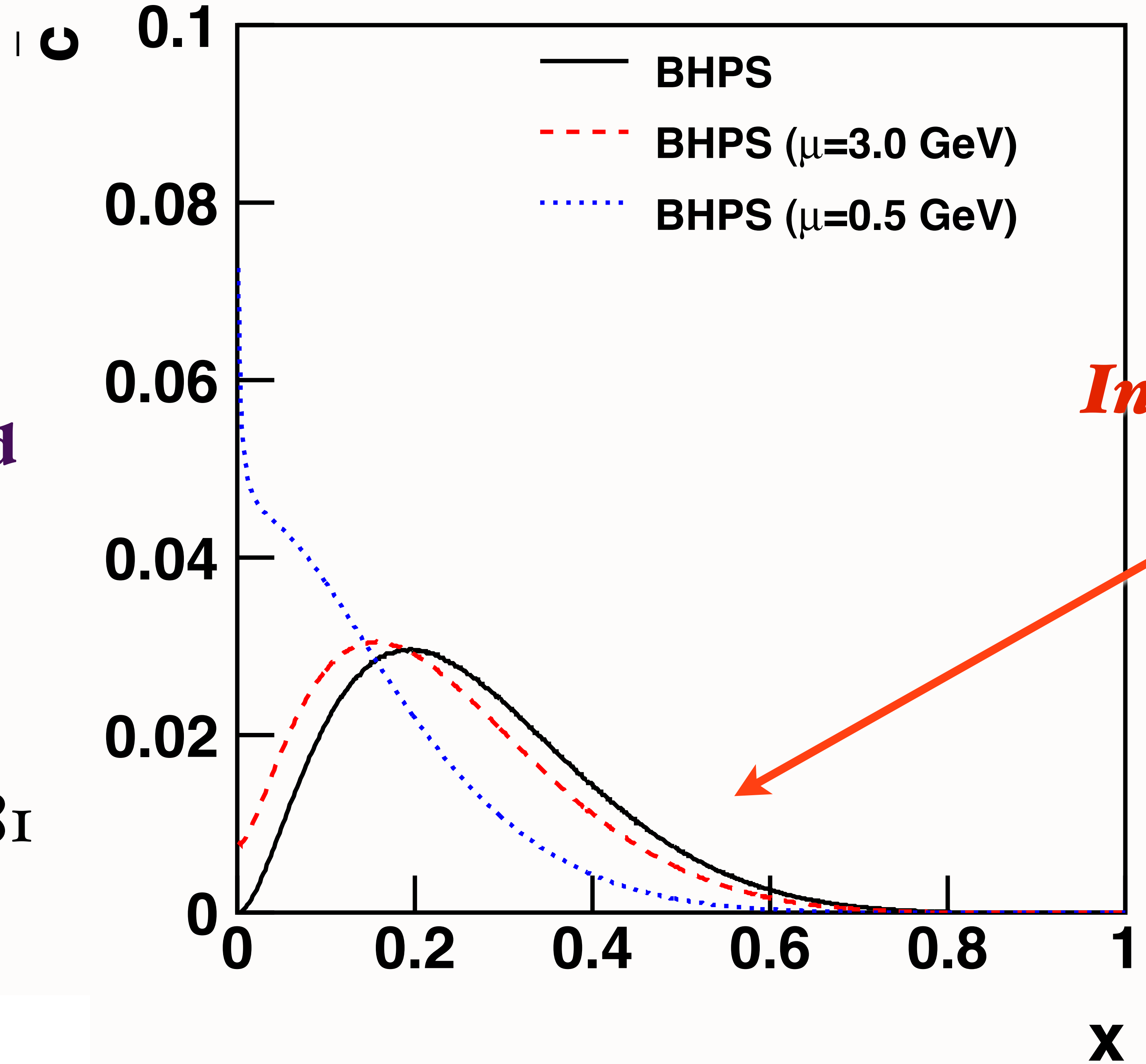
Consistent with intrinsic charm data

QCD: $\frac{1}{M_Q^2}$ scaling

Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

$$s(x,Q^2) = s(x,Q^2)_{\text{extrinsic}} + s(x,Q^2)_{\text{intrinsic}}$$

QCD ($1/m_Q^2$) scaling: predict IC



Intrinsic Charm

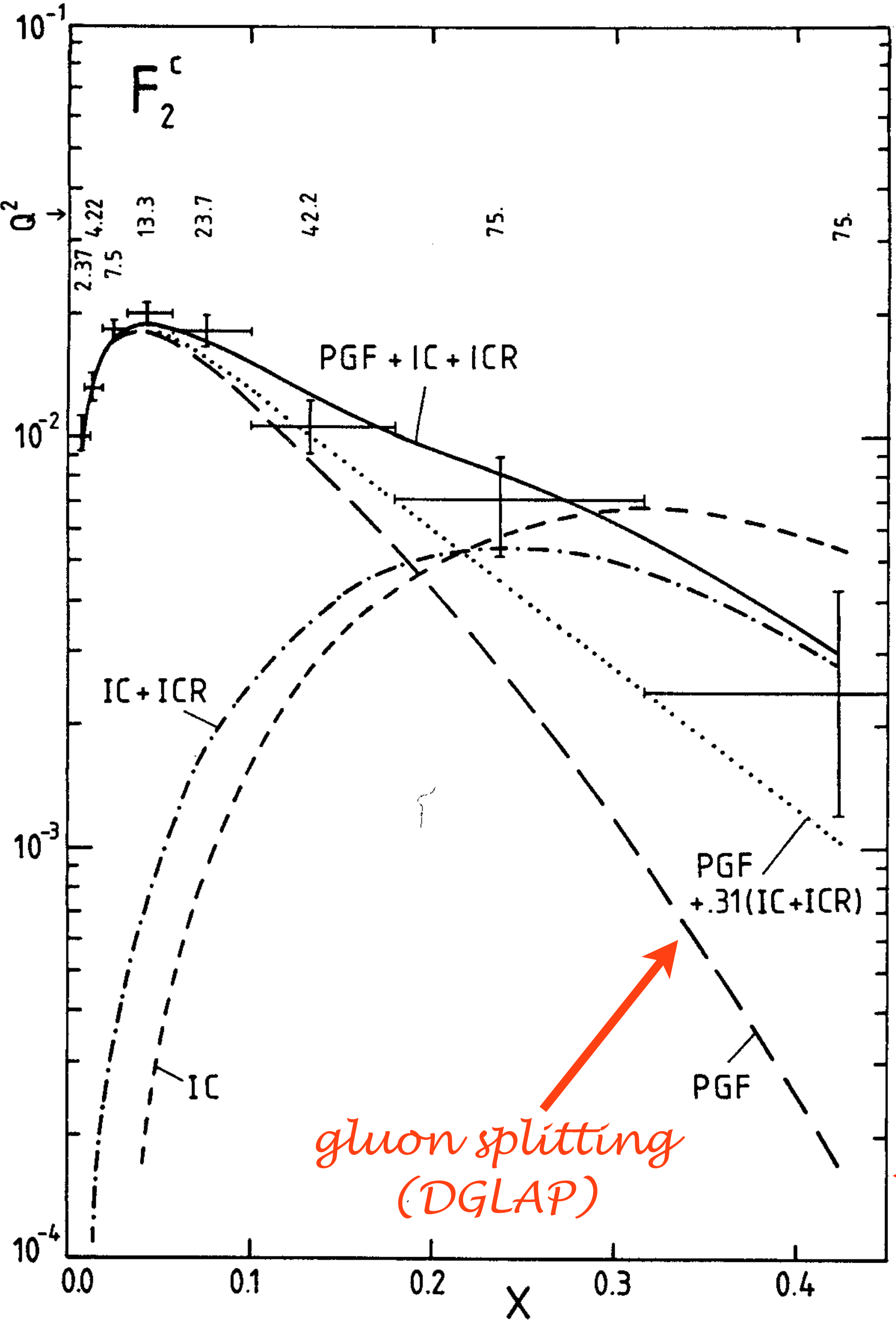
W. C. Chang and J.-C. Peng

arXiv:1105.2381

Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 75$ GeV^2 using $\mu = 3.0$ GeV, and $\mu = 0.5$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.

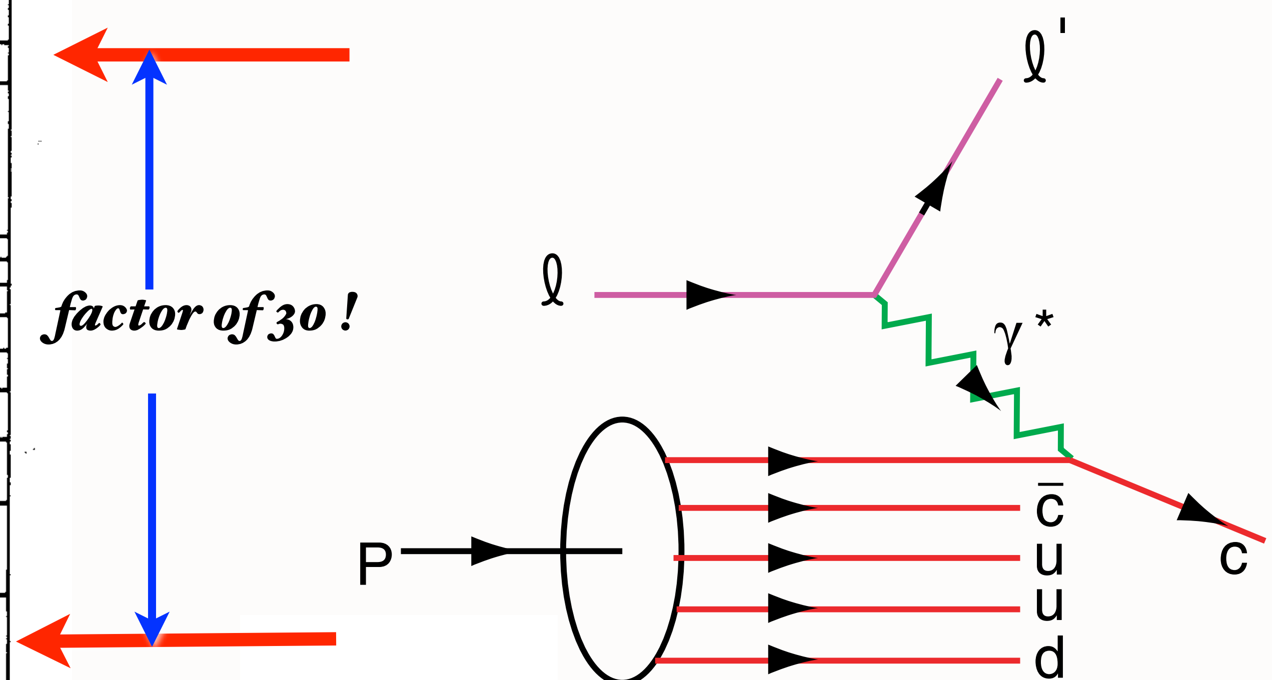
Consistent with EMC

Measurement of Charm Structure Function



J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm



DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

Do heavy quarks exist in the proton at high x?

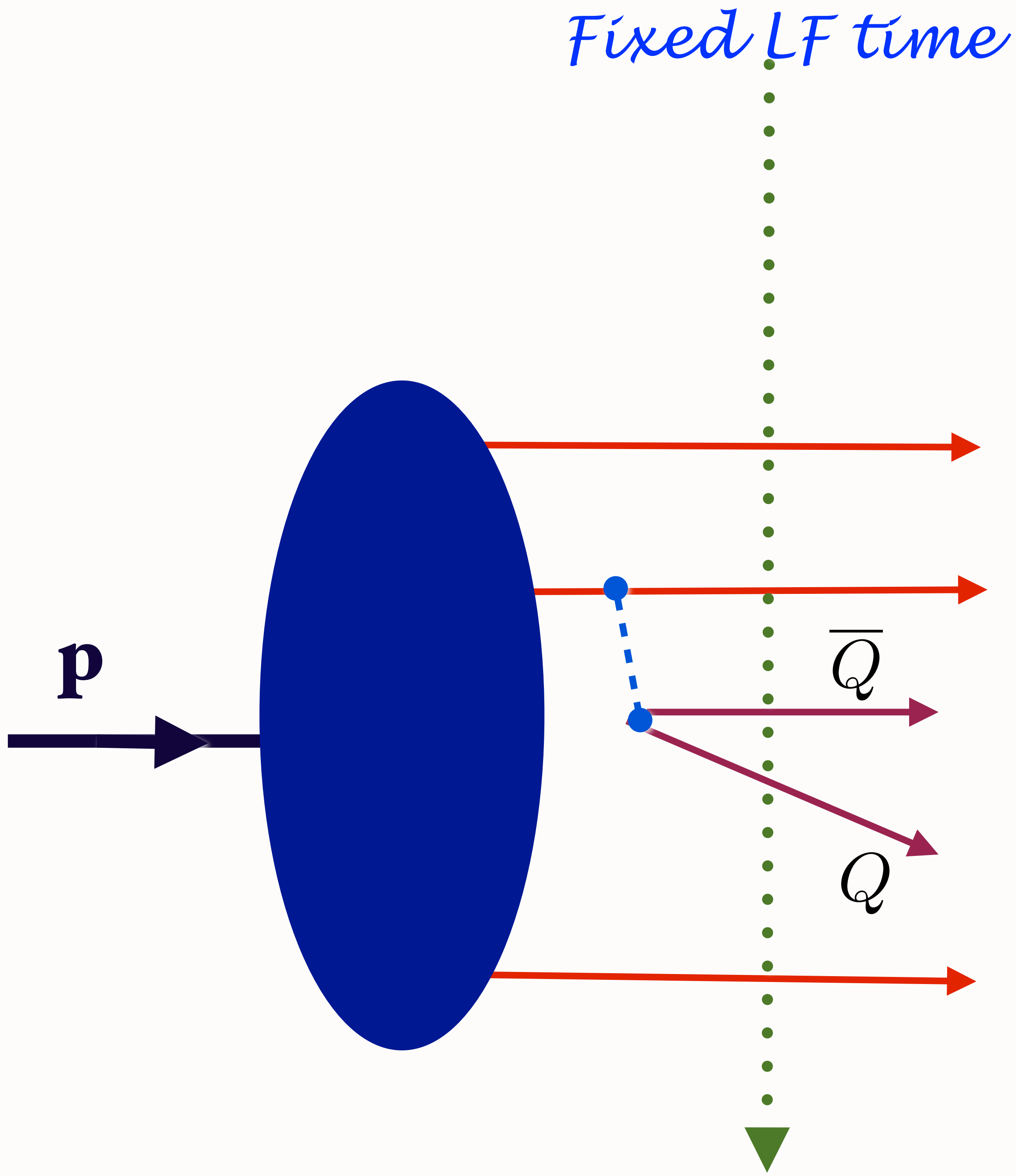
Conventional wisdom: impossible!

Heavy quarks generated only at low x via DGLAP evolution from gluon splitting

$$s(x, \mu_F^2) = c(x, \mu_F^2) = b(x, \mu_F^2) \equiv 0$$

$$\text{at starting scale } \mu_F^2$$

Conventional wisdom is wrong even in QED!



Proton's 5-quark Fock State from gluon splitting

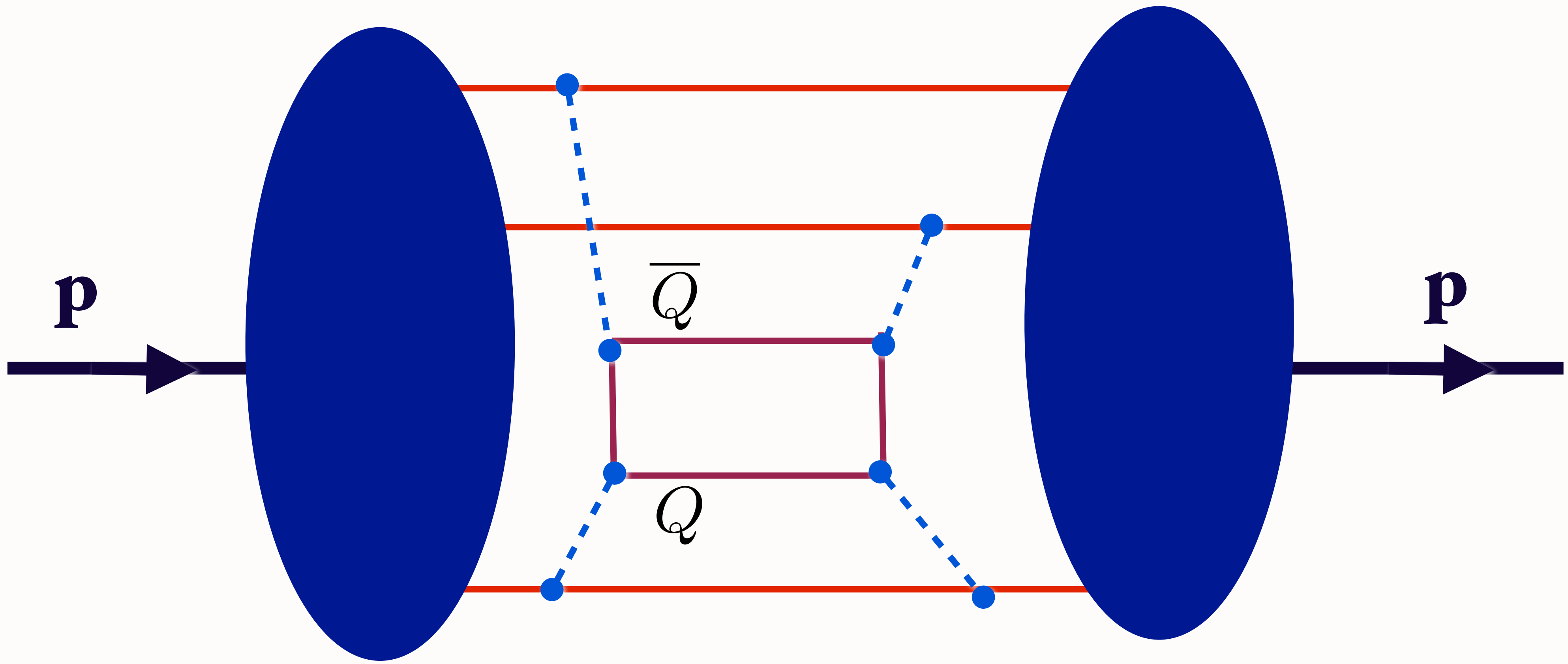
"Extrinsic" Heavy Quarks

$$s(x, Q^2)_{\text{extrinsic}} \sim (1-x)g(x,Q^2) \sim (1-x)^5$$

Proton Self Energy from gluon-gluon scattering

QCD predicts Intrinsic Heavy Quarks!

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

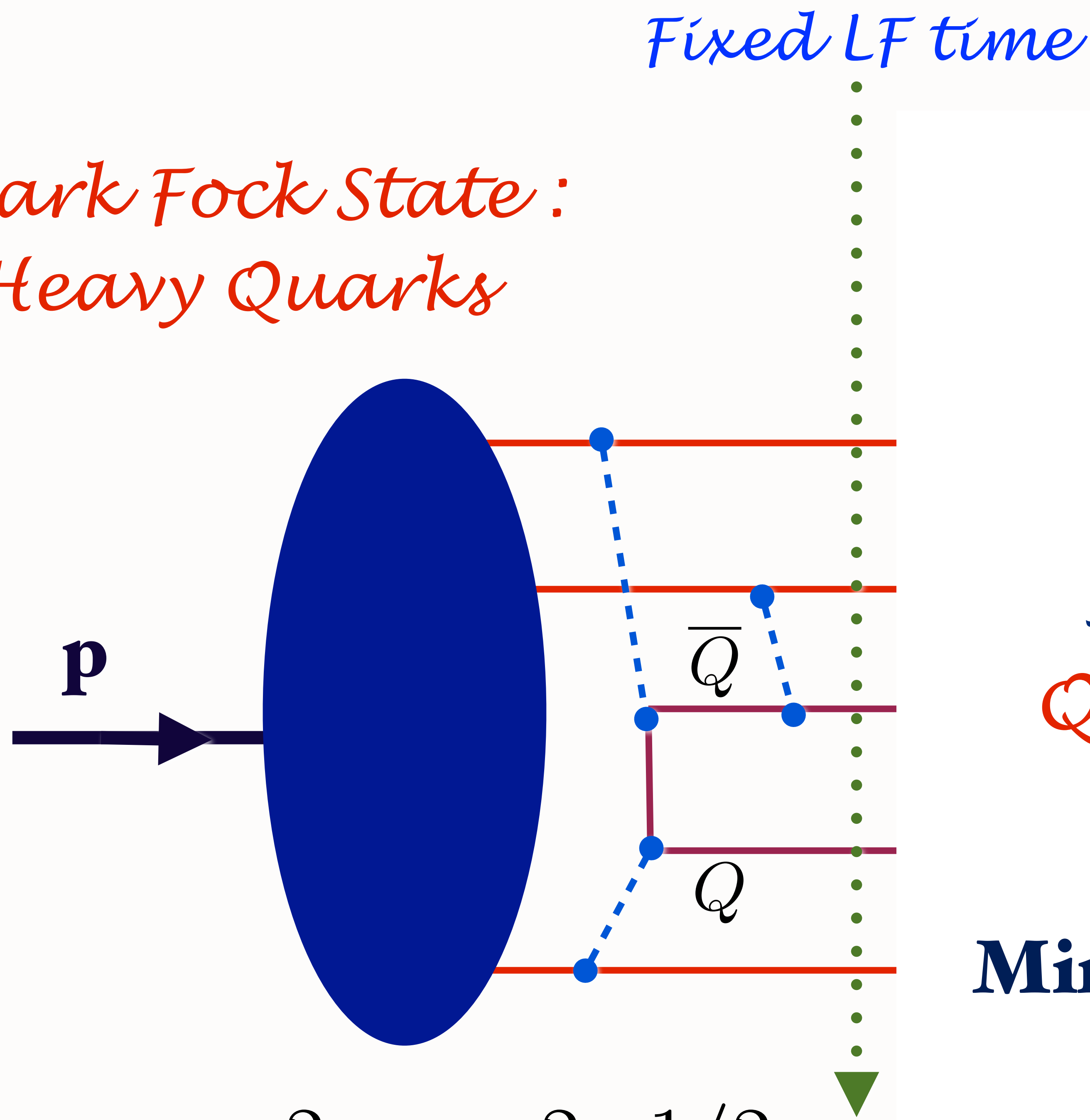
$$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

$$(g-2)_\mu \propto \frac{\alpha^3}{\pi^3} \log \frac{m_\mu^2}{m_e^2}$$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

from light-by-light scattering

Proton 5-quark Fock State : Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

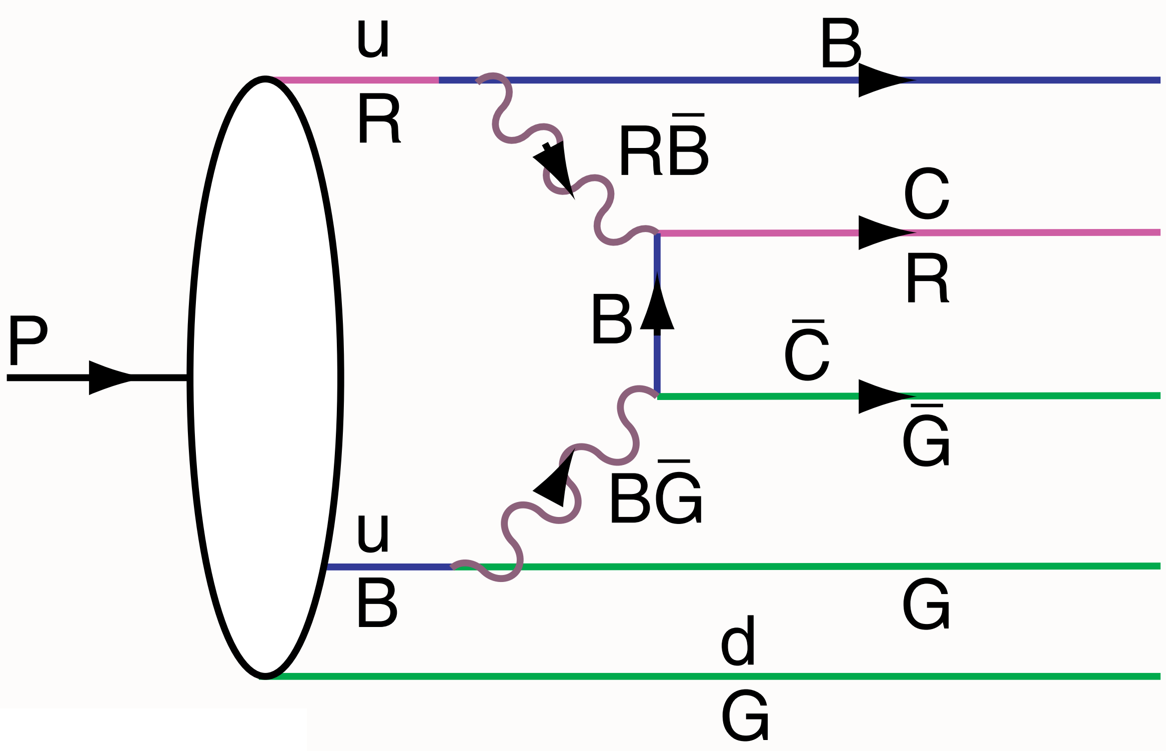
Minimal off-shellness

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$ $\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov

BHPS: Hoyer, Peterson, Sakai, sjb



$|uudcc>$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^->$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

cc in Color Octet

$$\widehat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

Distribution peaks at equal rapidity (velocity)

Therefore heavy particles carry the largest momentum fractions

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

High x charm! *JLab: Charm at Threshold*

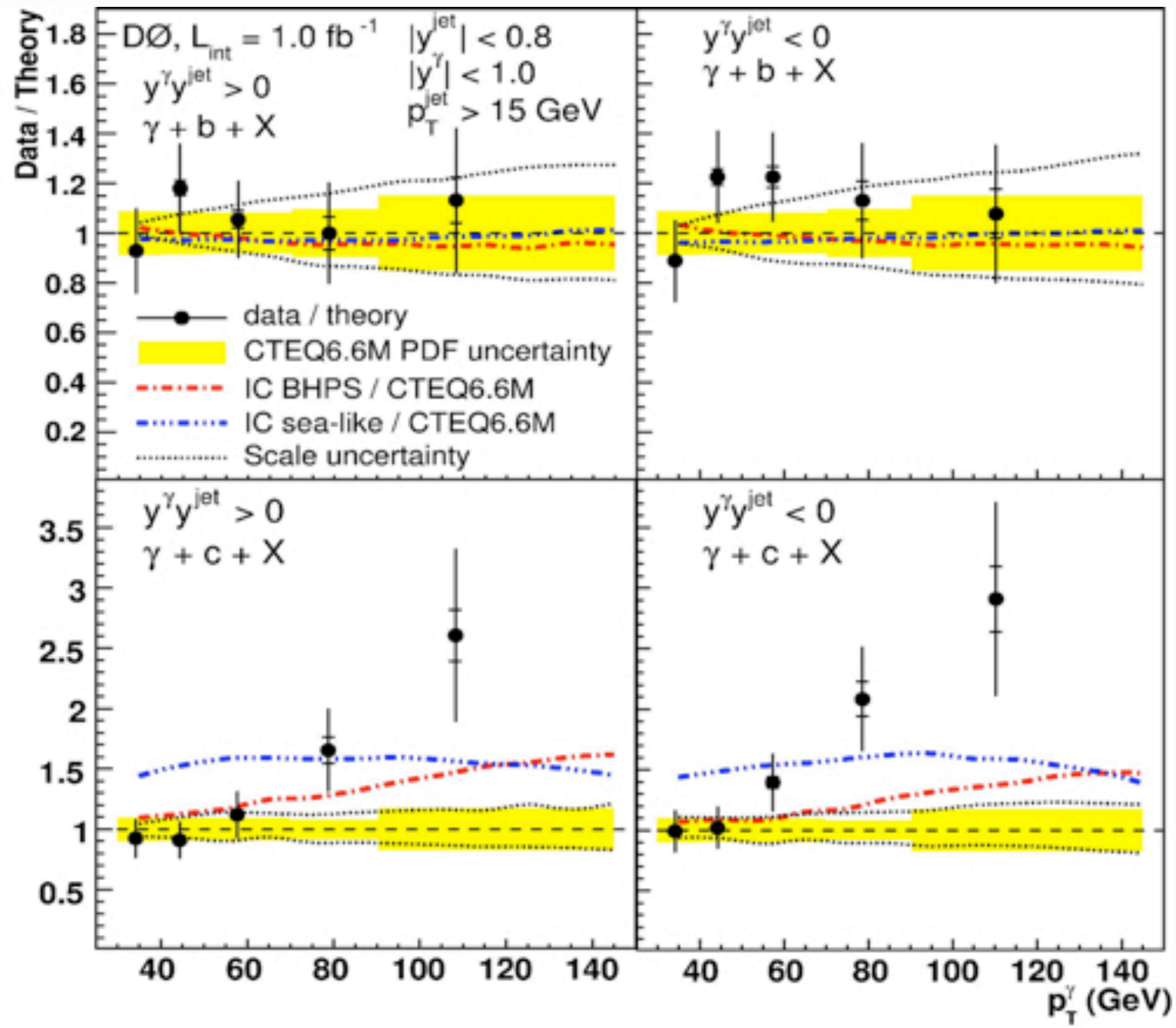
Action Principle: Minimum KE, maximal potential

PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

DO

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

$$p\bar{p} \to \gamma + Q + X$$

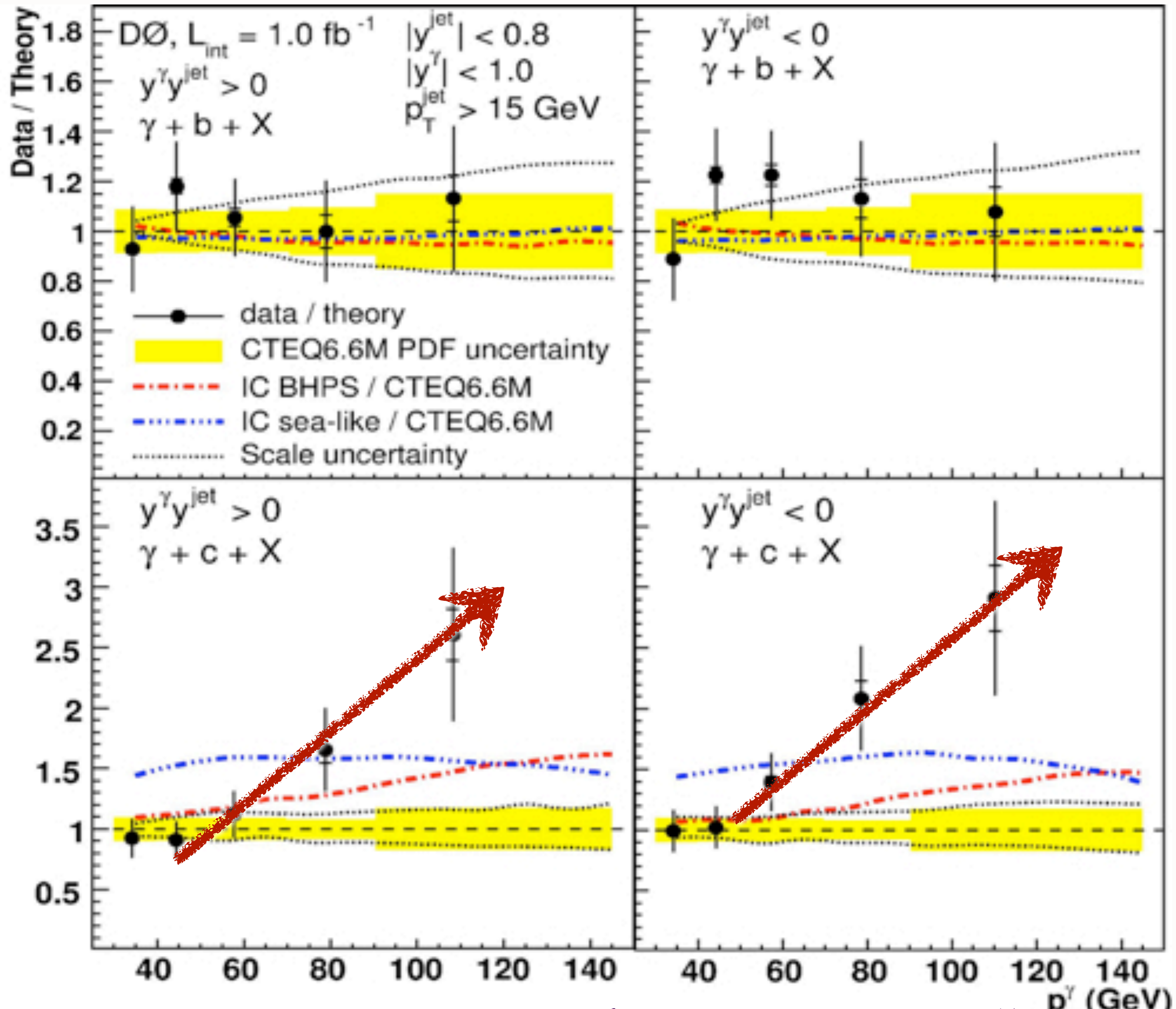


$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio is insensitive to gluon PDF, scales

DØ **Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV**

$$p\bar{p} \to \gamma + Q + X$$



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio is insensitive to gluon PDF, scales

$$gc \to \gamma c$$

Signal for significant intrinsic charm at x > 0.1 ?

Two Components (separate evolution):

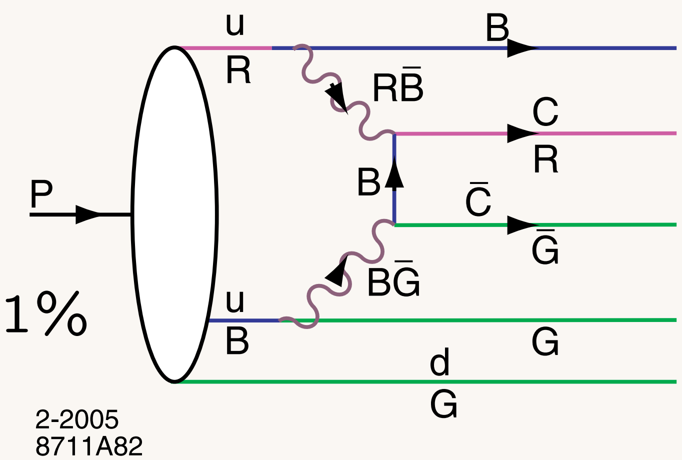
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

(Need to evolve IC with nonzero quark mass)

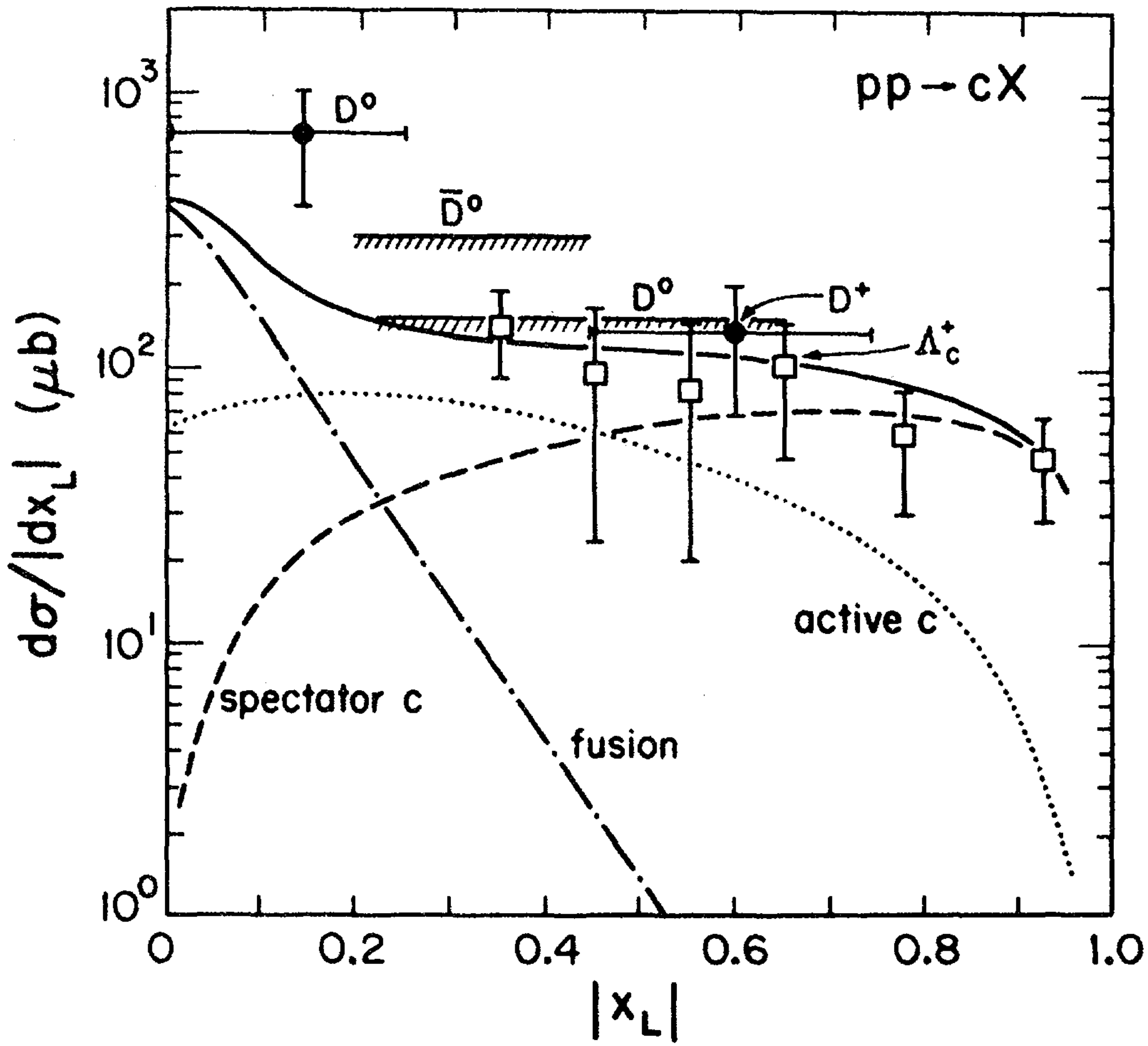
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States

- ***Rigorous*** prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$



- ***Large Effect at high x and at threshold!***
- Greatly increases kinematics of colliders such as Higgs production (**Kopeliovich, Schmidt, Soffer, Goldhaber, sjb**)
- Severely underestimated in conventional parameterizations of heavy quark distributions (**Except CTEQ**)
- Important corrections to penguin contributions to B-meson weak decays (**Gardner, sjb**)
- Slow evolution compared to extrinsic quarks from gluon splitting!
- Many empirical tests at JLAB 12, COMPASS



Barger, Halzen, Keung

More evidence for charm at large x

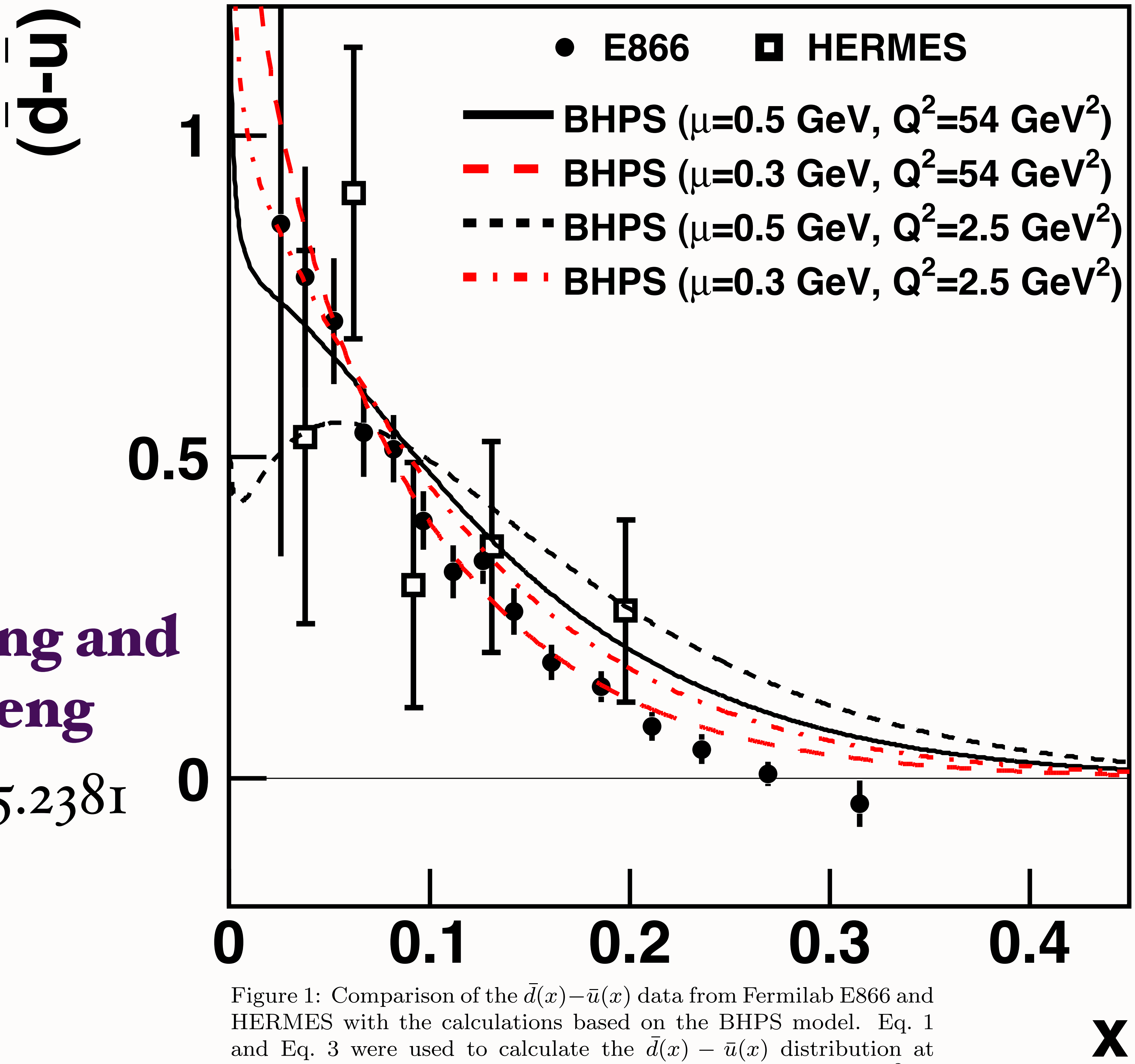
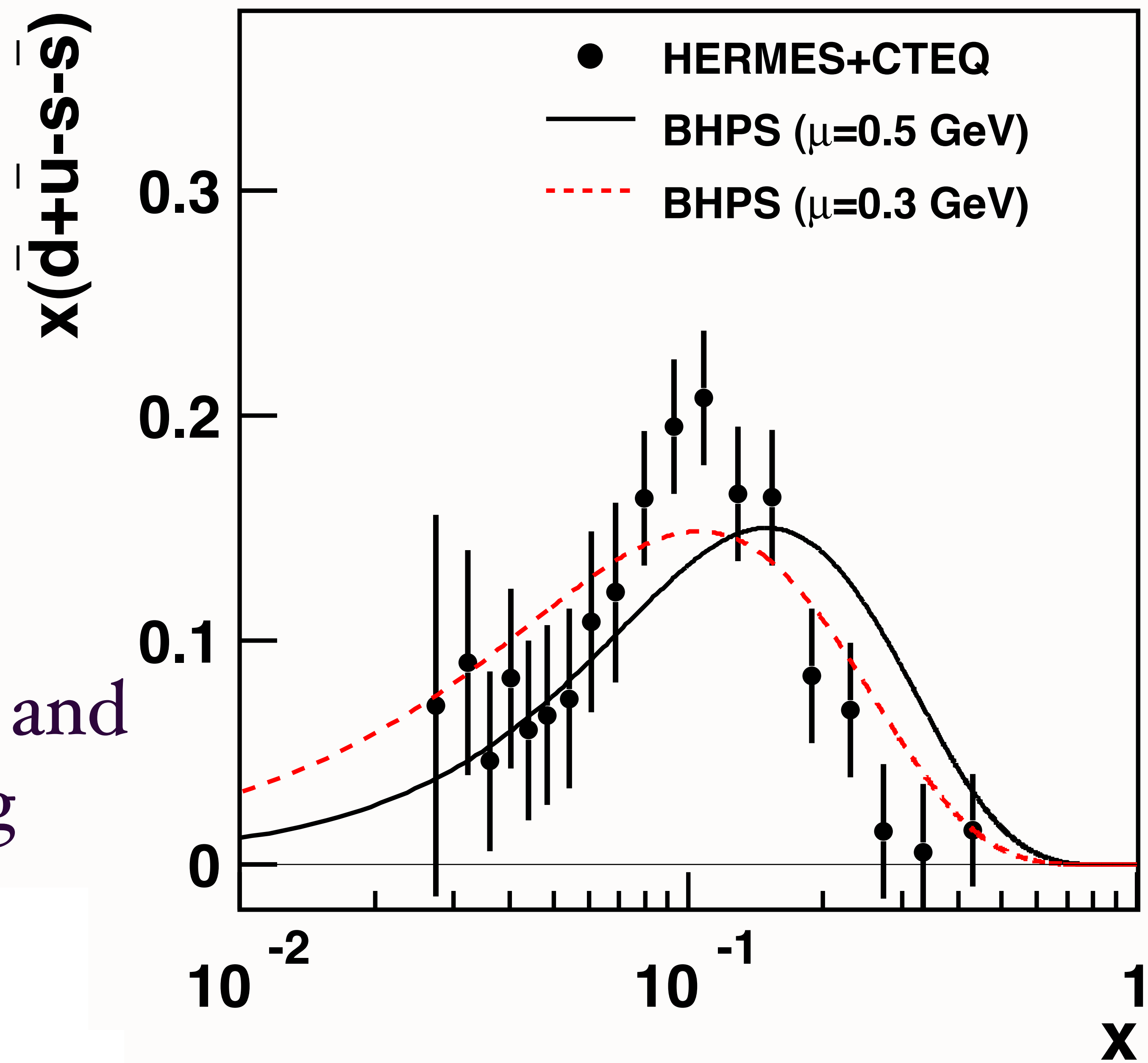


Figure 1: Comparison of the $\bar{d}(x)-\bar{u}(x)$ data from Fermilab E866 and HERMES with the calculations based on the BHPS model. Eq. 1 and Eq. 3 were used to calculate the $\bar{d}(x)-\bar{u}(x)$ distribution at the initial scale. The distribution was then evolved to the Q^2 of the experiments and shown as various curves. Two different initial scales, $\mu = 0.5$ and 0.3 GeV, were used for the E866 calculations in order to illustrate the dependence on the choice of the initial scale.

W. C. Chang and J.-C. Peng

arXiv:1105.2381

$$x[\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x)]$$



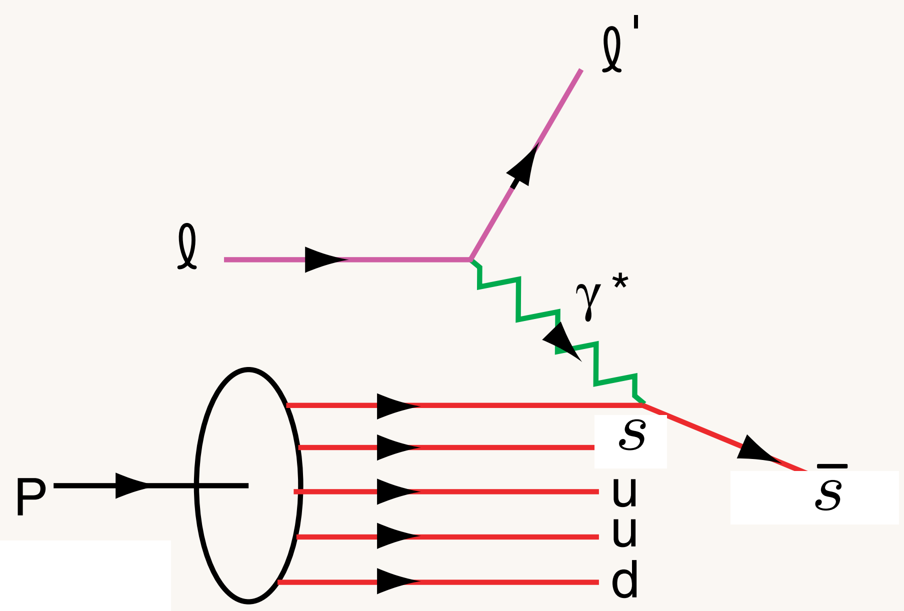
W. C. Chang and J.-C. Peng

Comparison of the $x(\bar{d}(x)+\bar{u}(x)-s(x)-\bar{s}(x))$ data with the calculations based on the BHPS model. The values of $x(s(x)+\bar{s}(x))$ are from the HERMES experiment [6], and those of $x(\bar{d}(x)+\bar{u}(x))$ are obtained from the PDF set CTEQ6.6 [11]. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalization of the calculations are adjusted to fit the data.

Measure strangeness distribution in Semi-Inclusive DIS at JLab

$$\text{Is } s(x) = \bar{s}(x)?$$

- **Non-symmetric strange and antistrange sea?**
- **Non-perturbative physics; e.g** $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- **Crucial for interpreting NuTeV anomaly**



Tag quark flavor in semi-inclusive DIS $ep \to e' K^+ X$

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

CERN NA3

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

ISR

- High x_F $pp \to \Lambda_b X$

Intrinsic Bottom!
Zichichi, Cifarelli, et al.

- High x_F $pp \to \Xi(ccd)X$ (SELEX)

FermiLab

IC Structure Function: Critical Measurement for EIC

Many interesting spin, charge asymmetry, spectator effects

Excitation of Intrinsic Heavy Quarks in Proton

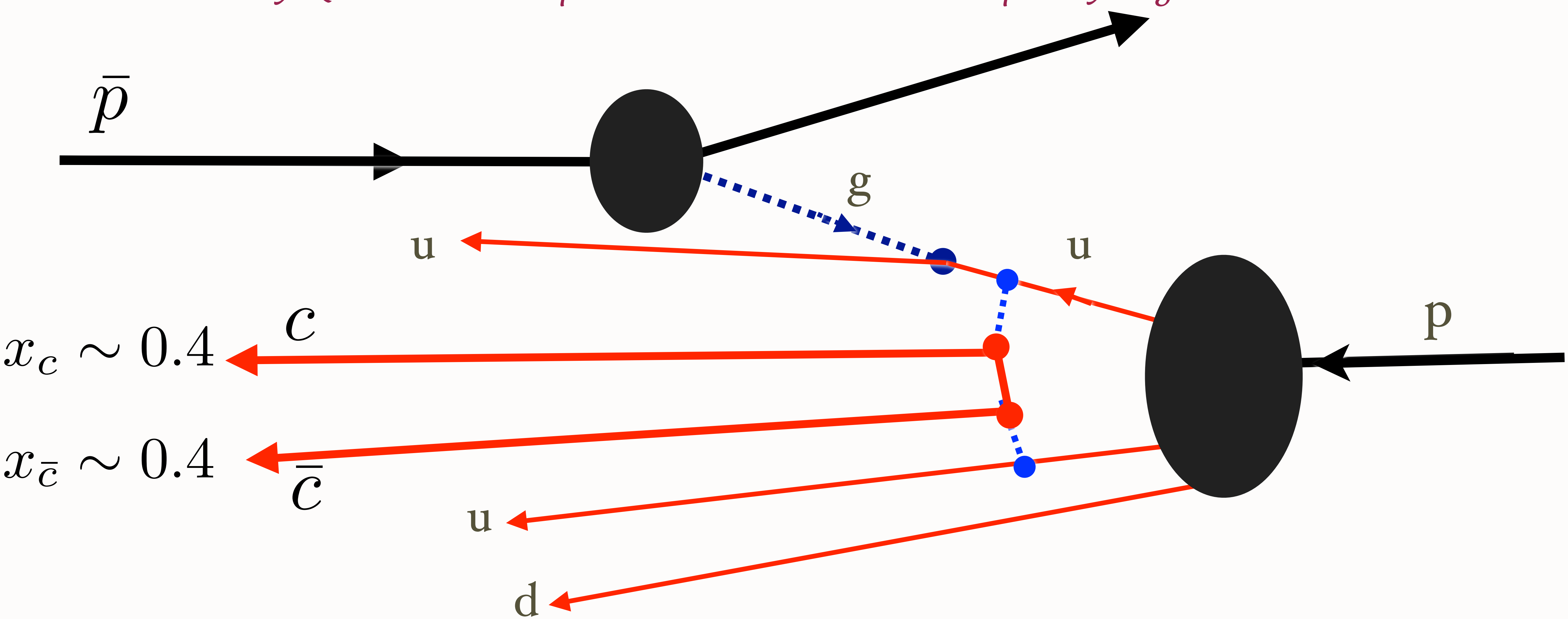
Amplitude maximal at small invariant mass, equal rapidity

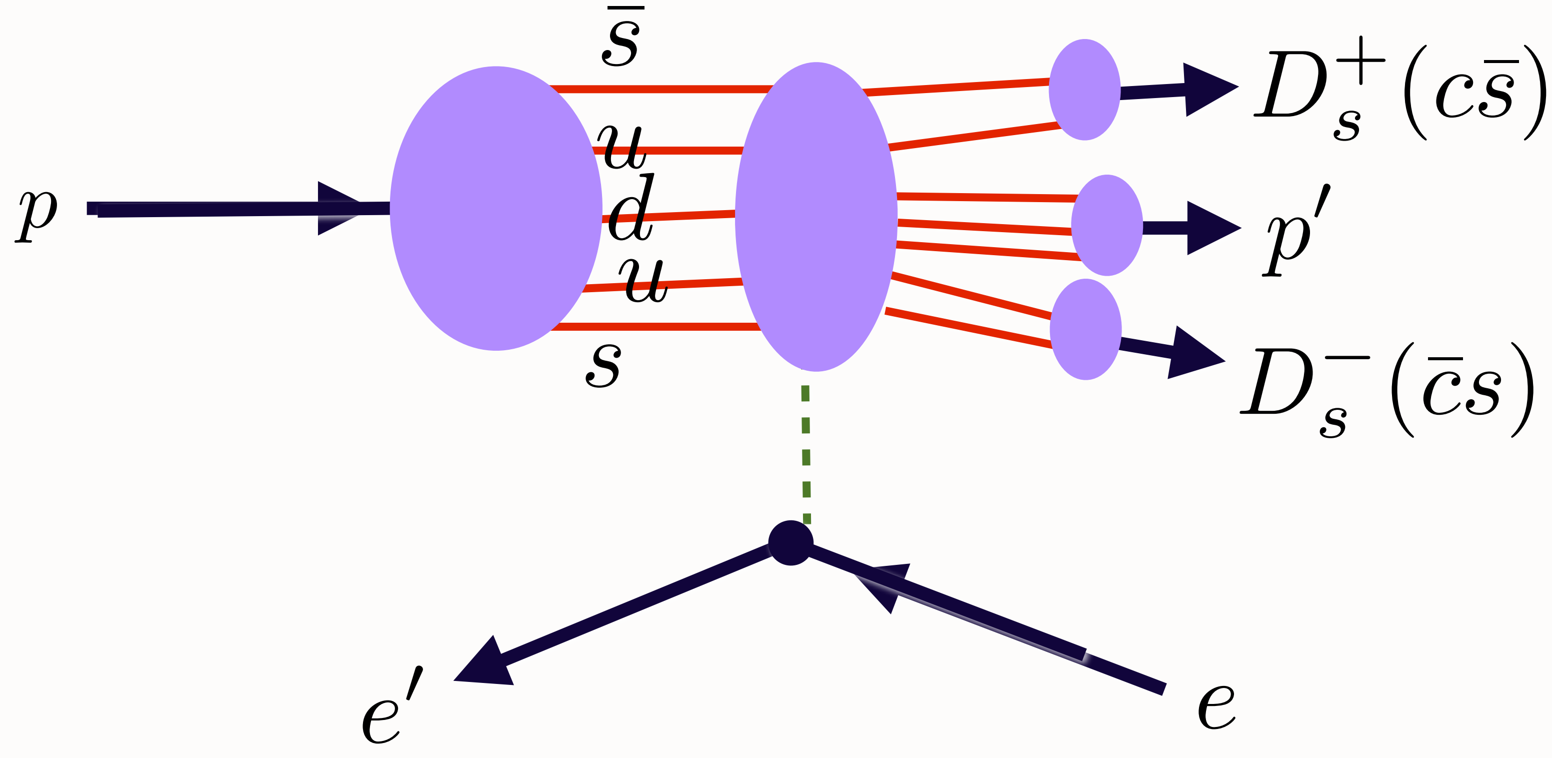
$$x_i \sim \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

$$\frac{d\sigma}{dy_{J/\psi}}(\bar{p}p \to J/\psi X)$$

J-P Lansberg, sjb

Heavy Quarkonium produced in **TARGET** *rapidity region*



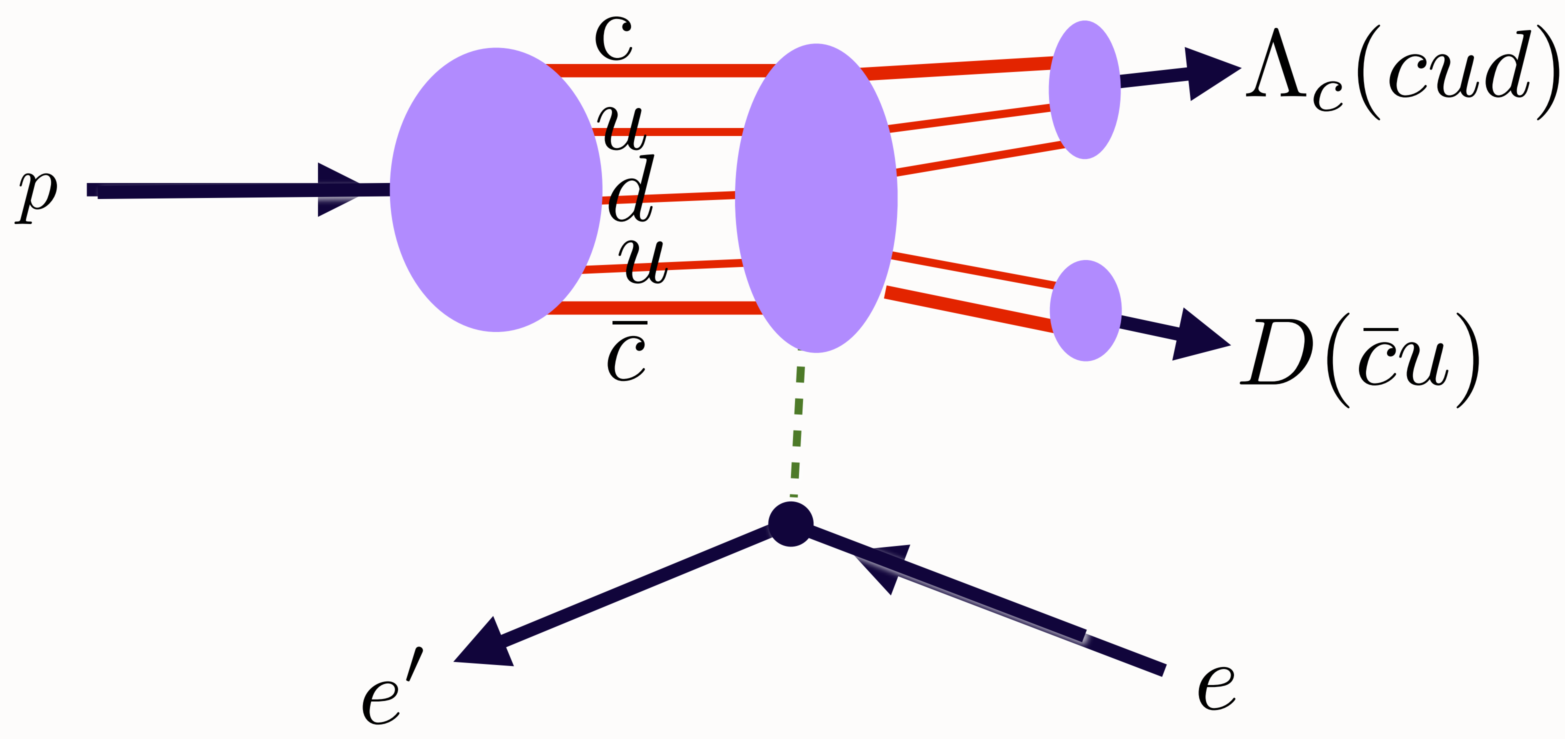


Look for $D_s^-(\bar{c}s)$ vs. $D_s^+(c\bar{s})$ asymmetry

Reflects s vs. $\bar{s}$ asymmetry in proton $|uuds\bar{s}>$ Fock LF state.

Asymmetry natural from $|K^+\Lambda>$ excitation **Ma, sjb**

Assumes symmetric charm and anti-charm distributions

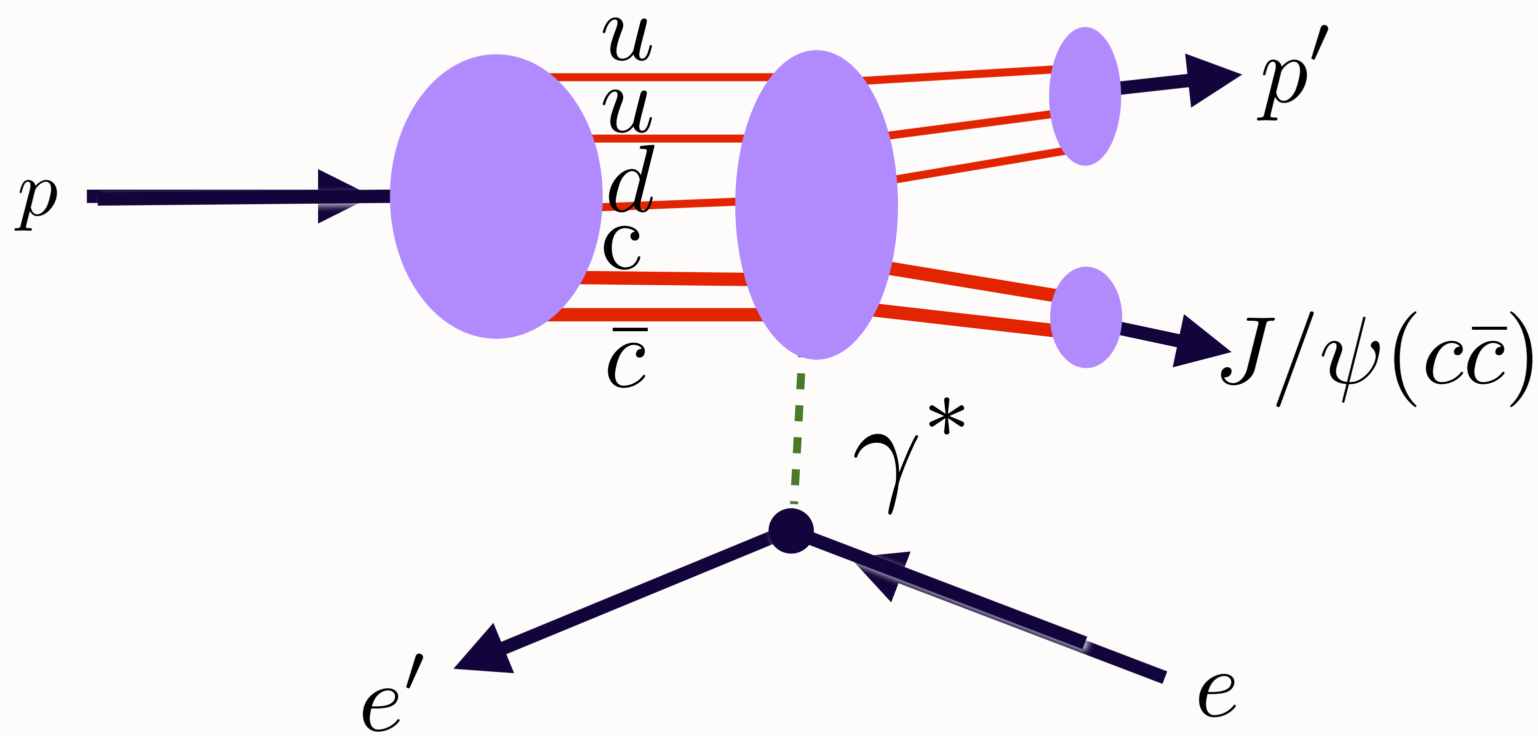


EIC Experiment

Dissociate proton to high x_F heavy-quark pair

$$\gamma^* p \to \Lambda_c(cdd) + D(\bar{c}u), \gamma^* p \to \Lambda_b(bud) B^+(\bar{b}u)$$

Test intrinsic charm, bottom

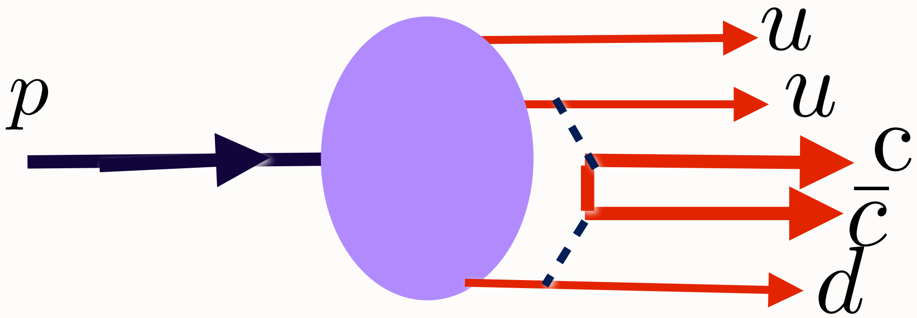


Lansberg, sjb

Dissociate proton to high x_F Quarkonium:

$$\gamma^* p \to J/\psi + p'$$

$$\gamma^* p \to \Upsilon + p'$$



But possibly disfavored since

$$|p> \simeq |(uud)_{8_C}(c\bar{c})_{8C} >$$

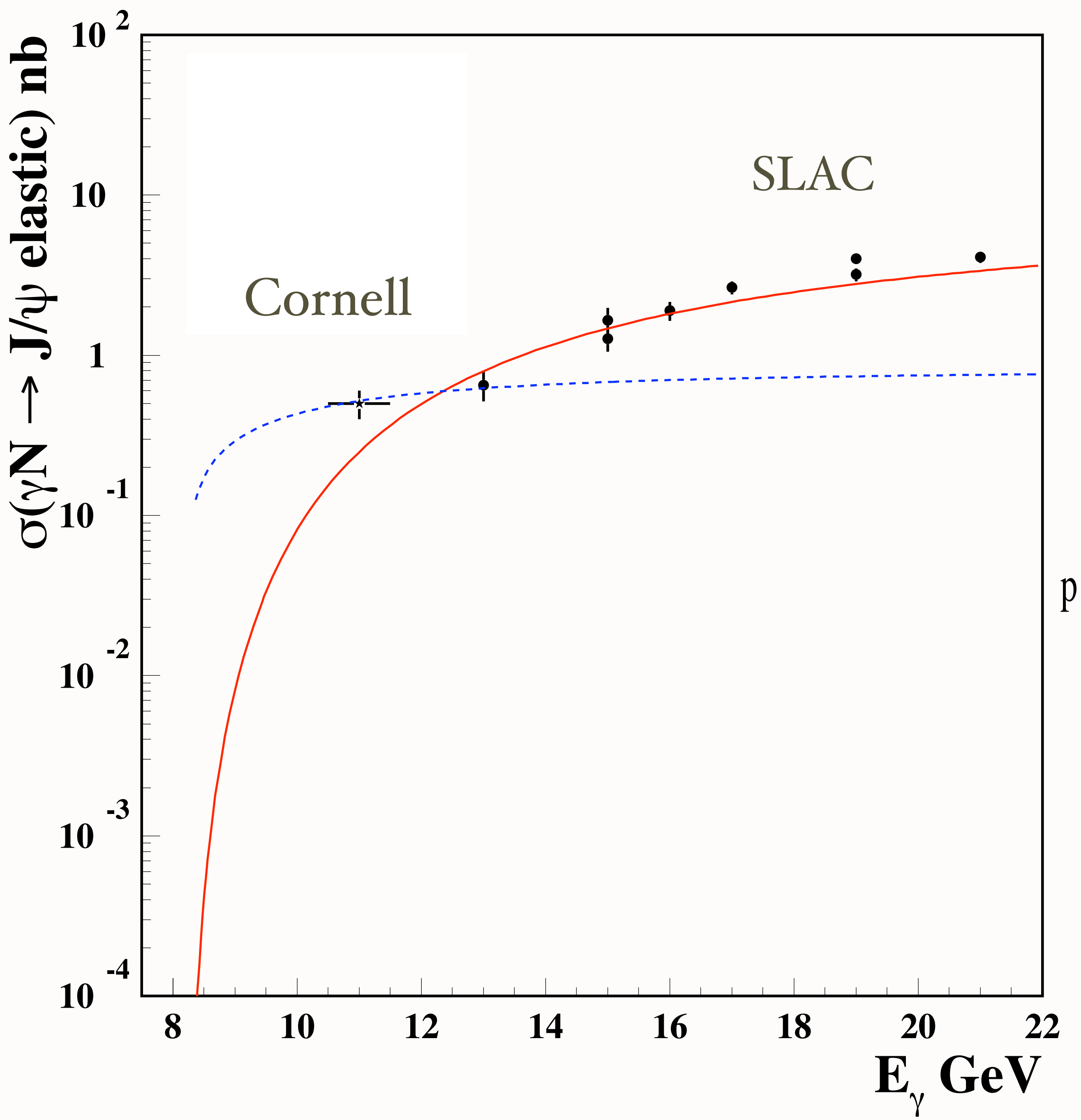
Collins, Ellis, Gunion,Mueller, sjb

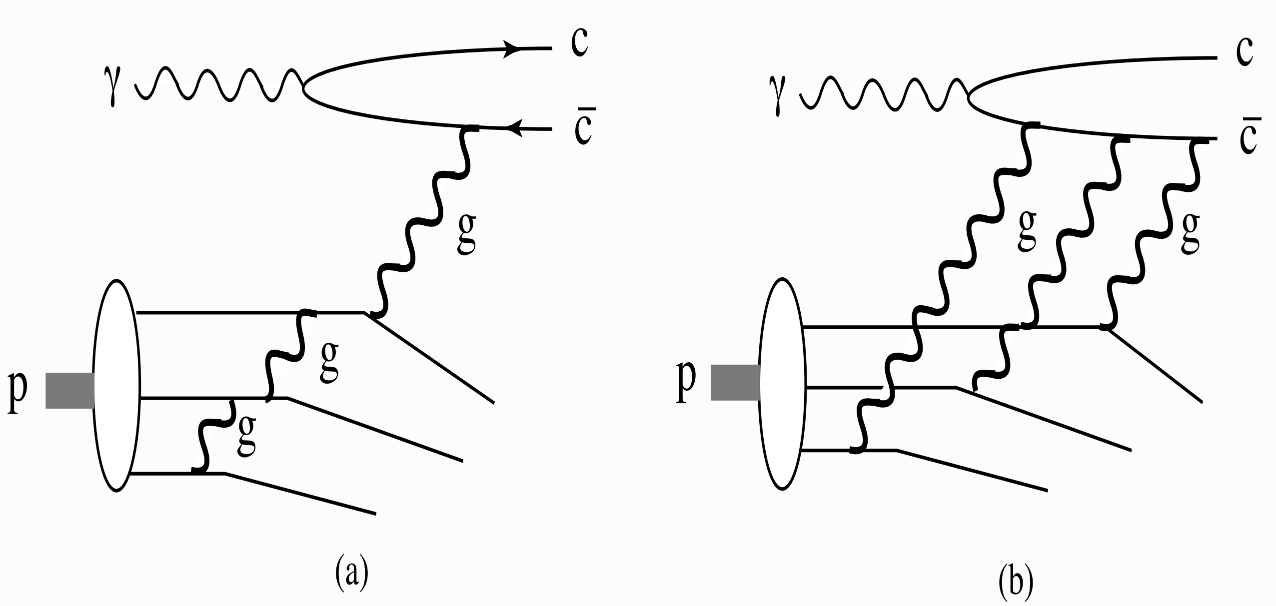
M. Polyakov et al.

Test intrinsic charm, bottom

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb



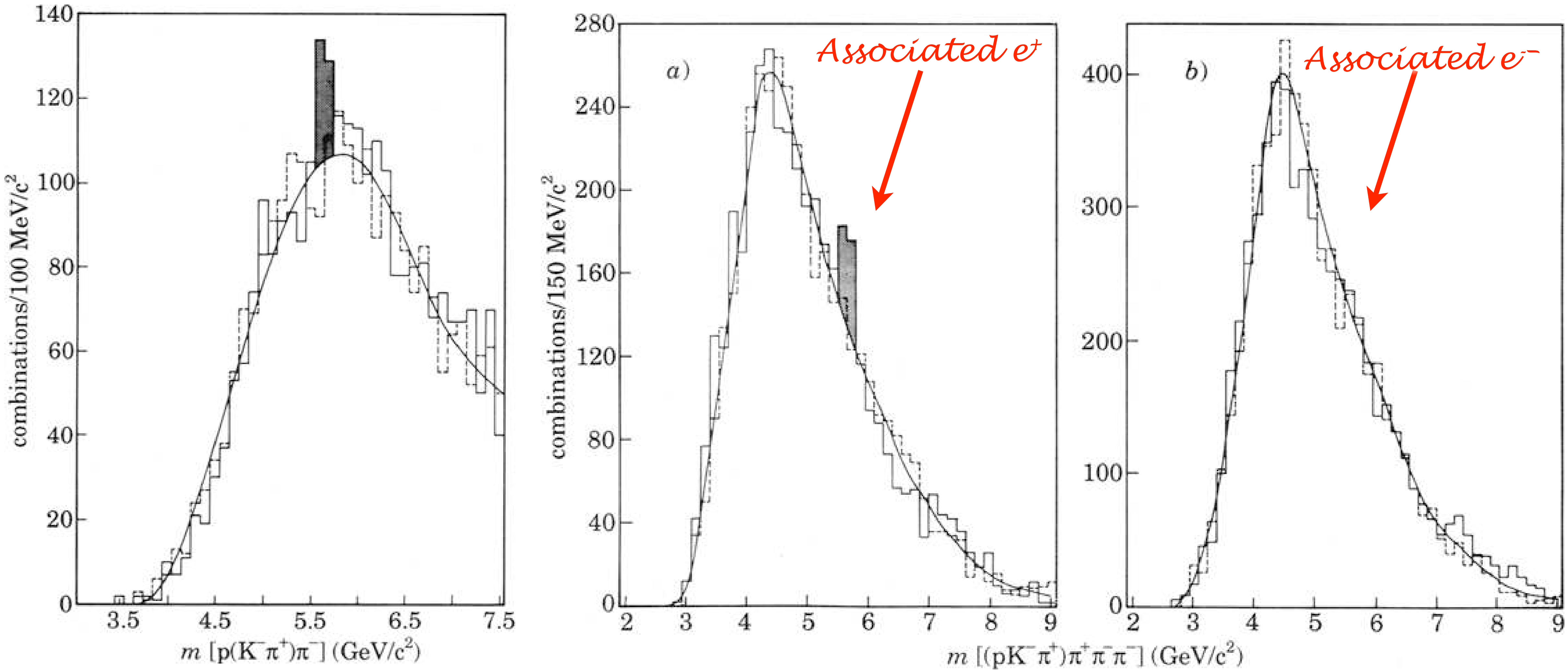


Leading twist contribution

Dominant near threshold

$pp \to \Lambda_b(bud)B(\bar{b}q)X$ at large x_F

CERN-ISR R422 (Split Field Magnet), 1988/1991



$\Lambda_b^0 \to pD^0\pi^-$

$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$

Il Nuovo Cimento 104, 1787

First Evidence for Intrinsic Bottom!

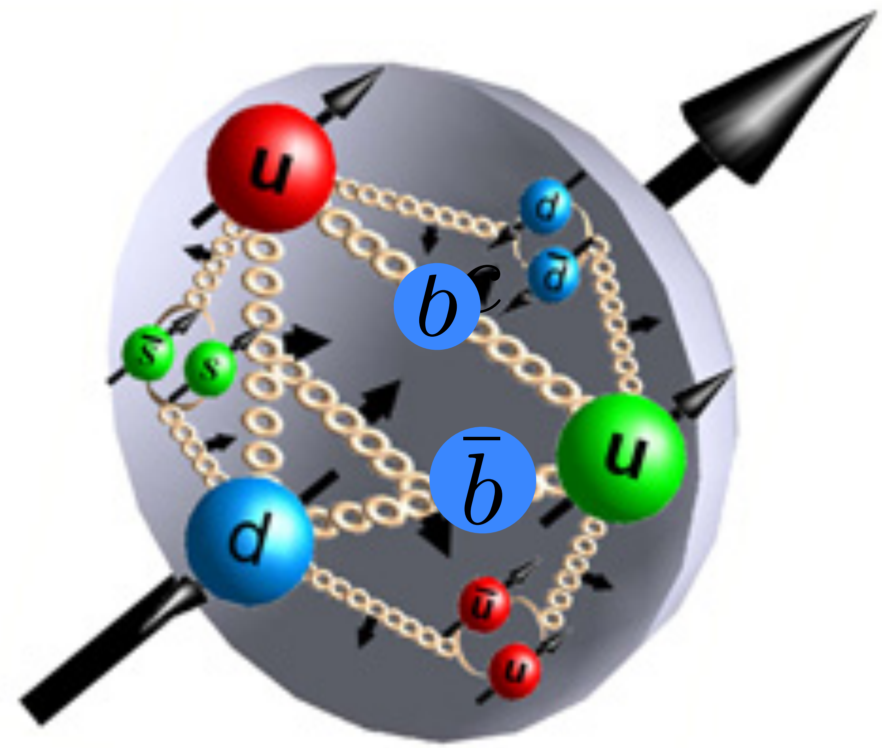
27 May 1991

CM-P00063074

THE Λ_b^o BEAUTY BARYON PRODUCTION IN PROTON-PROTON INTERACTIONS AT $\sqrt{s}$=62 GeV: A SECOND OBSERVATION

G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli, F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti, G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

CERN, Geneva, Switzerland
Dipartimento di Fisica dell'Università, Bologna, Italy
Dipartimento di Fisica dell'Università, Cosenza, Italy
Istituto di Fisica dell'Università, Palermo, Italy
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto Nazionale di Fisica Nucleare, LNF, Frascati, Italy

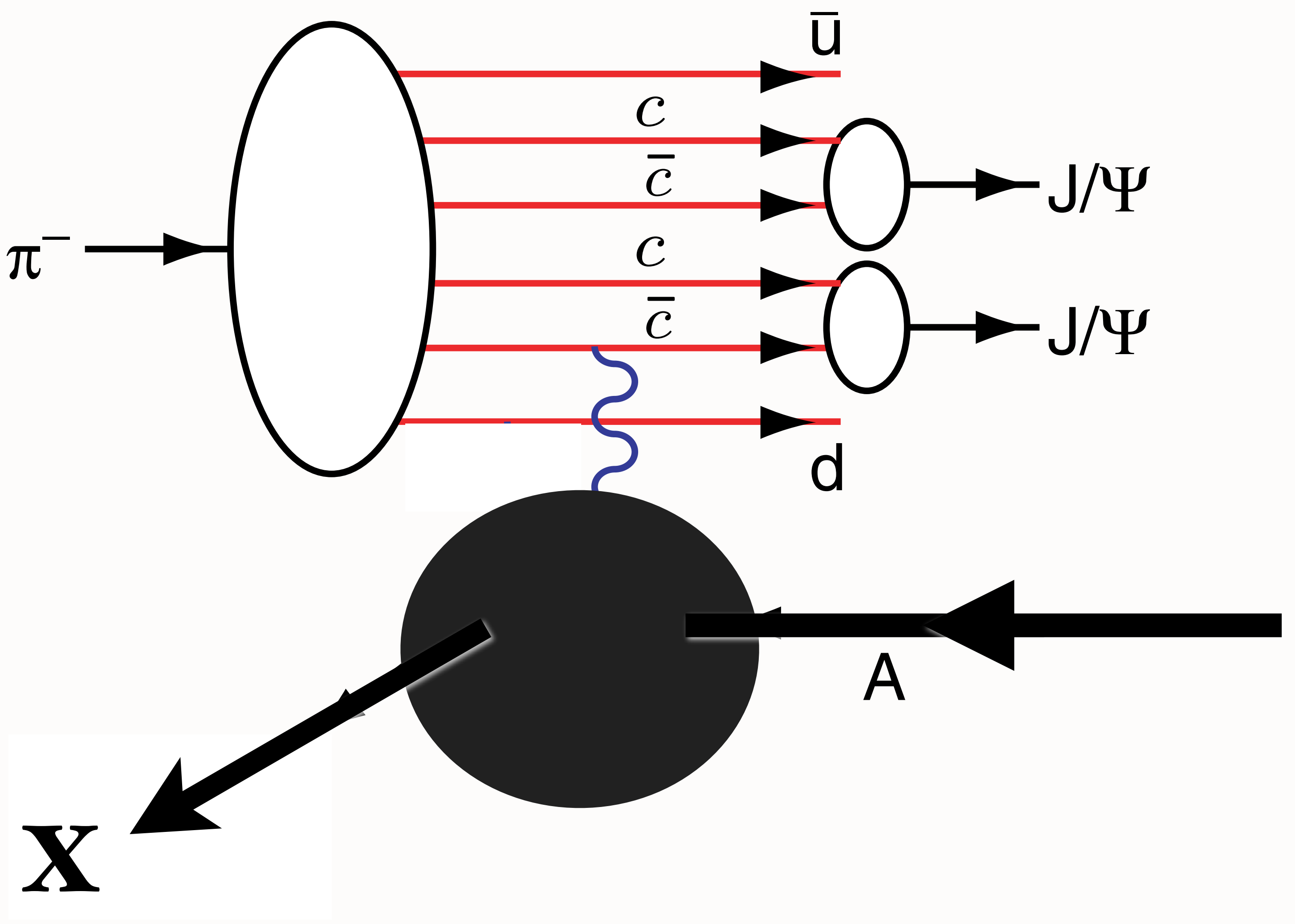


Abstract

Another decay mode of the Λ_b^o (open-beauty baryon) state has been observed: $\Lambda_b^o \rightarrow \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \rightarrow pD^o\pi^-$, are reported. These results confirm our previous findings on Λ_b^o production at the ISR. The mass value (5.6 GeV/c^2) is found to be in good agreement with theoretical predictions. The production mechanism is found to be "leading".

First Evidence for Intrinsic Bottom!

Production of Two Charmonia at High x_F



Excludes PYTHIA 'color drag' model

All events have $x^F_{\psi\psi} > 0.4$!

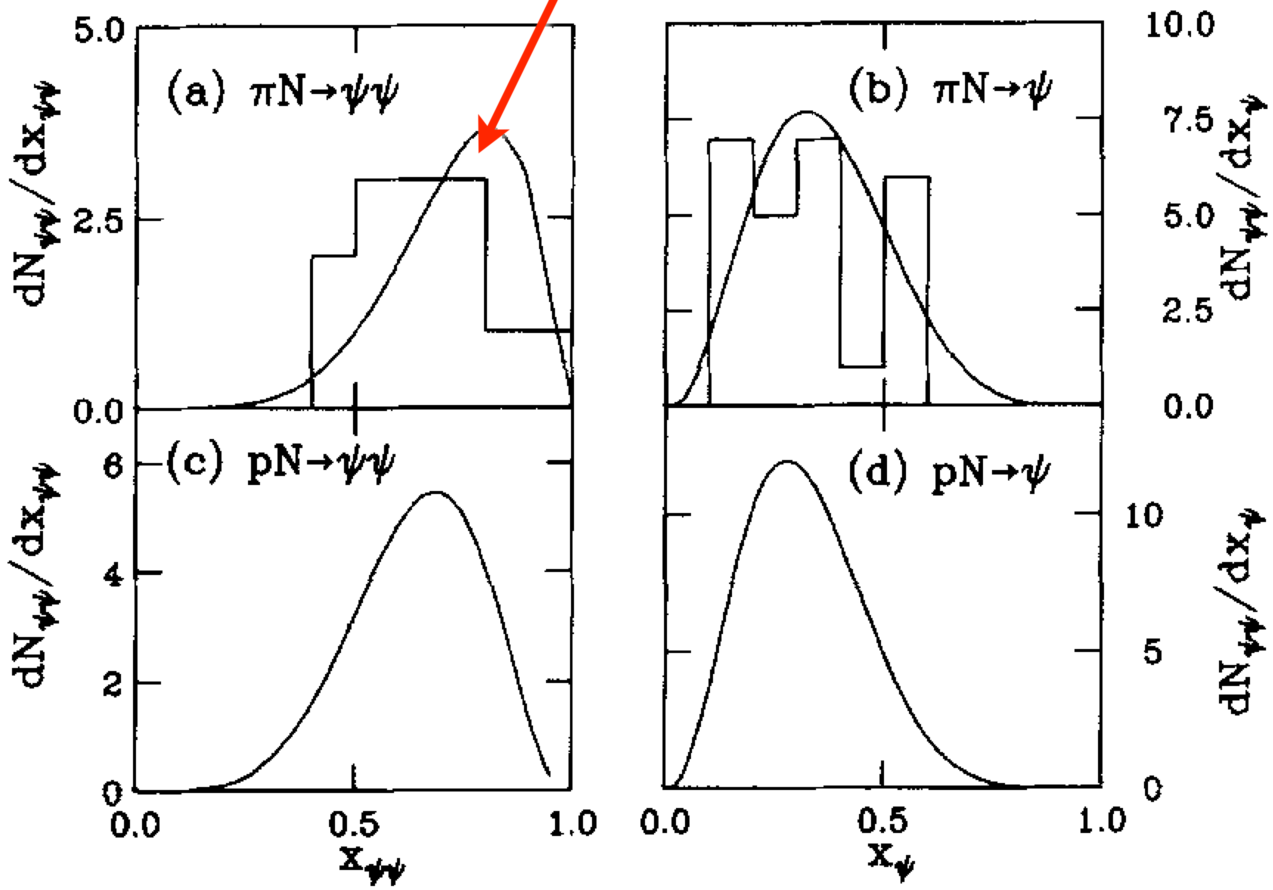


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

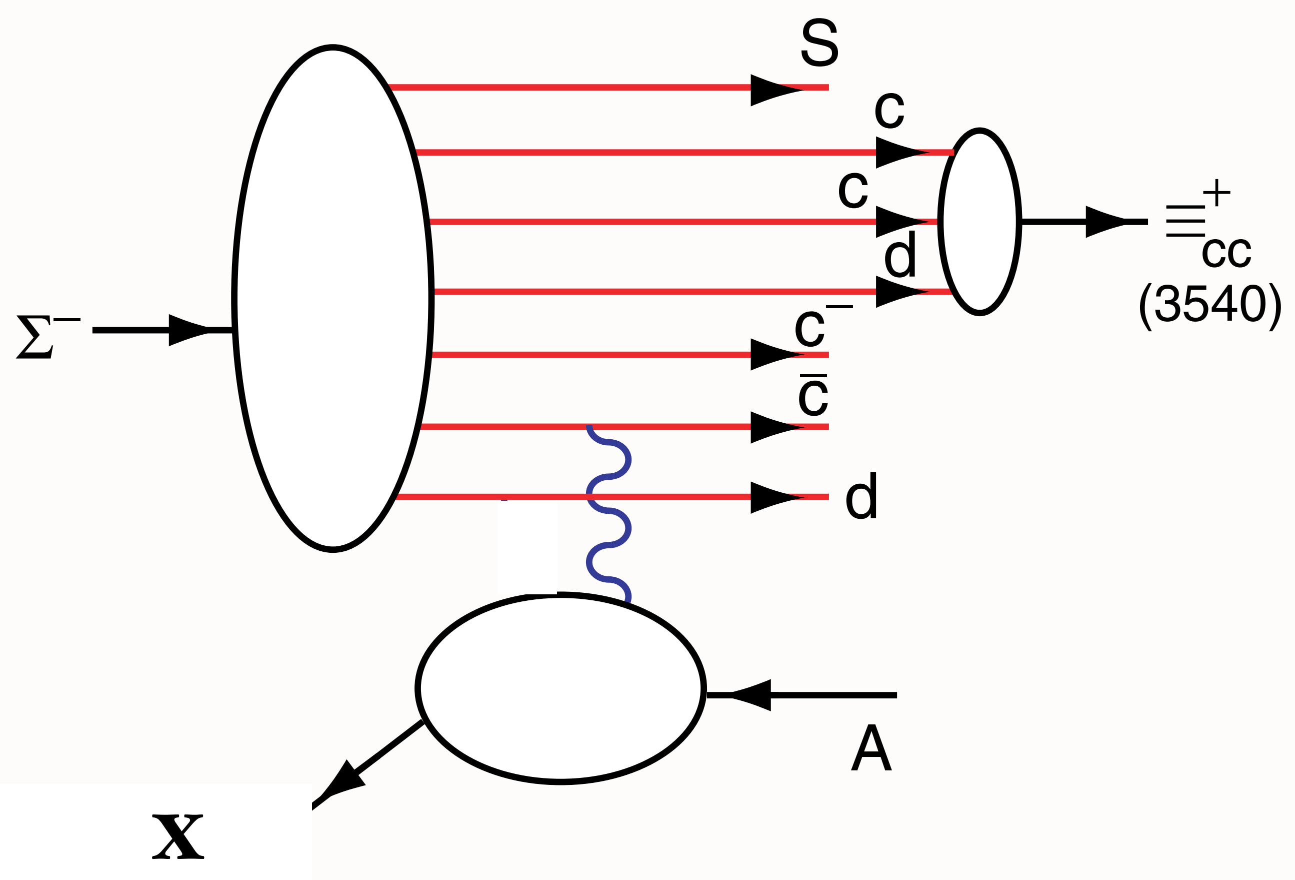
NA3 Data

$$\pi A \to J/\psi J/\psi X$$

R, Vogt, sjb

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

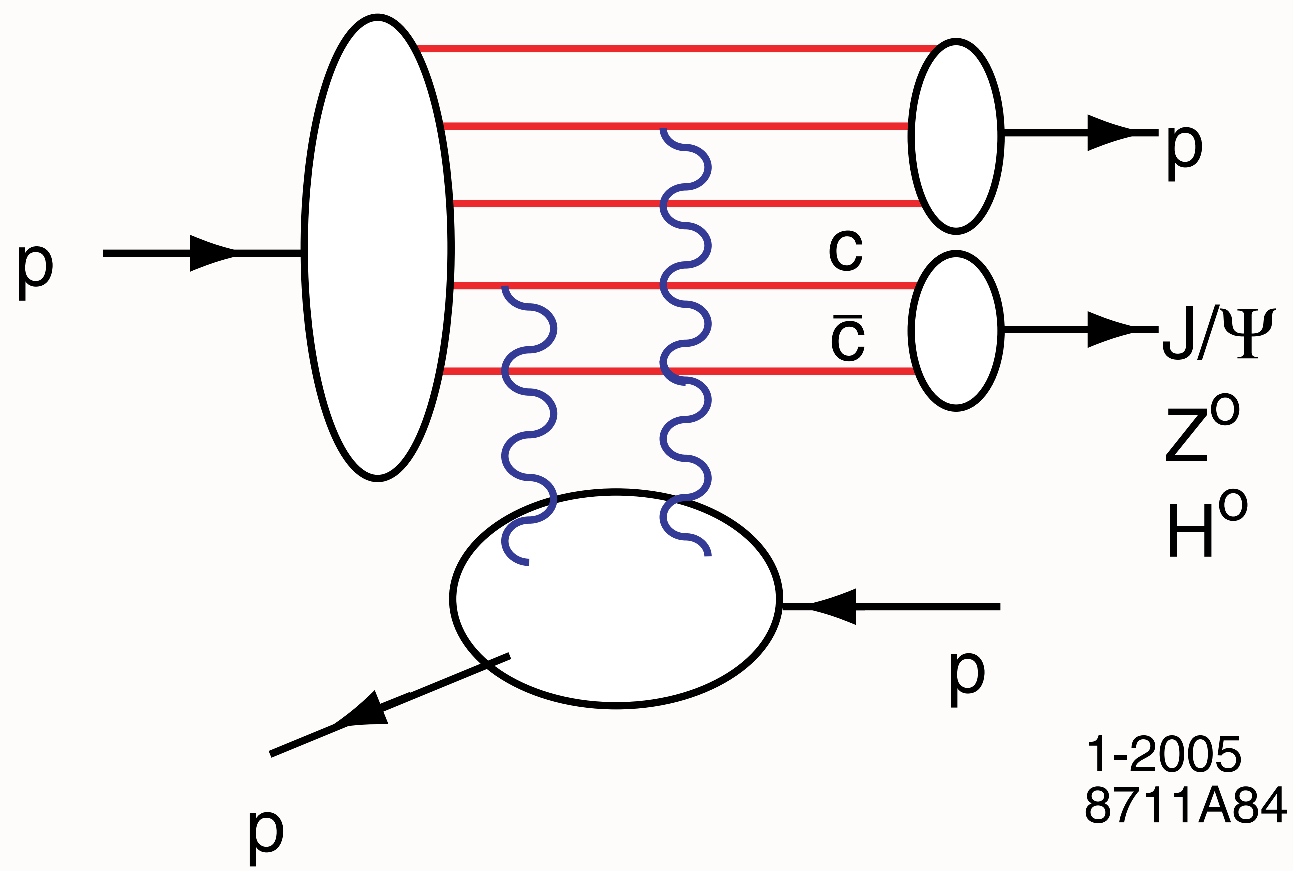
$$\frac{dP_{\mathrm{ic}}}{\prod_{i=1}^n dx_i d^2 k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\,\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$



Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$p\,p \to J/\psi\; p\; p$$

$$x_{J/\psi} = x_c + x_c$$

Exclusive Diffractive High-X_F Higgs Production

Kopeliovitch, Schmidt, Soffer, sjb

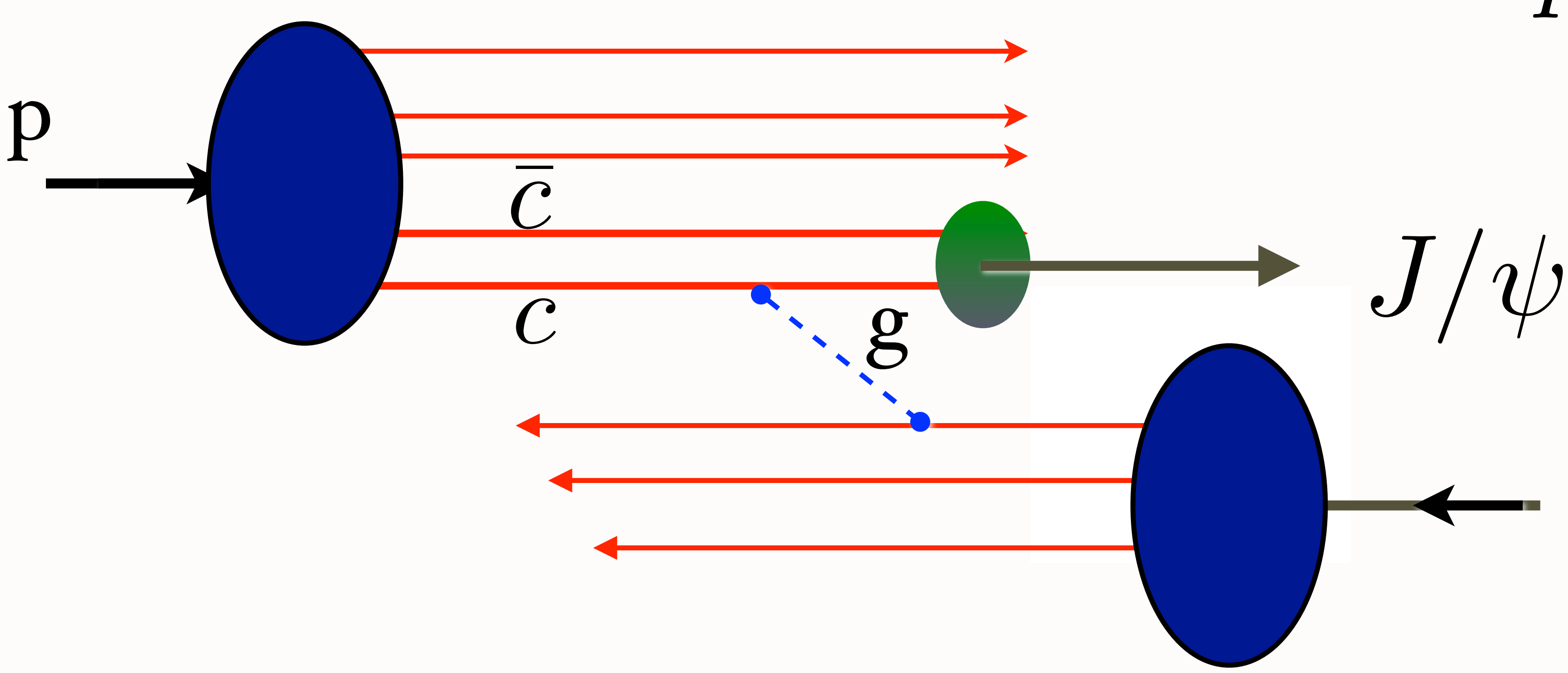
Intrinsic *cc* pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

Intrinsic Charm Mechanism for Inclusive High-X_F Quarkonium Production

$$pp \to J/\psi X$$



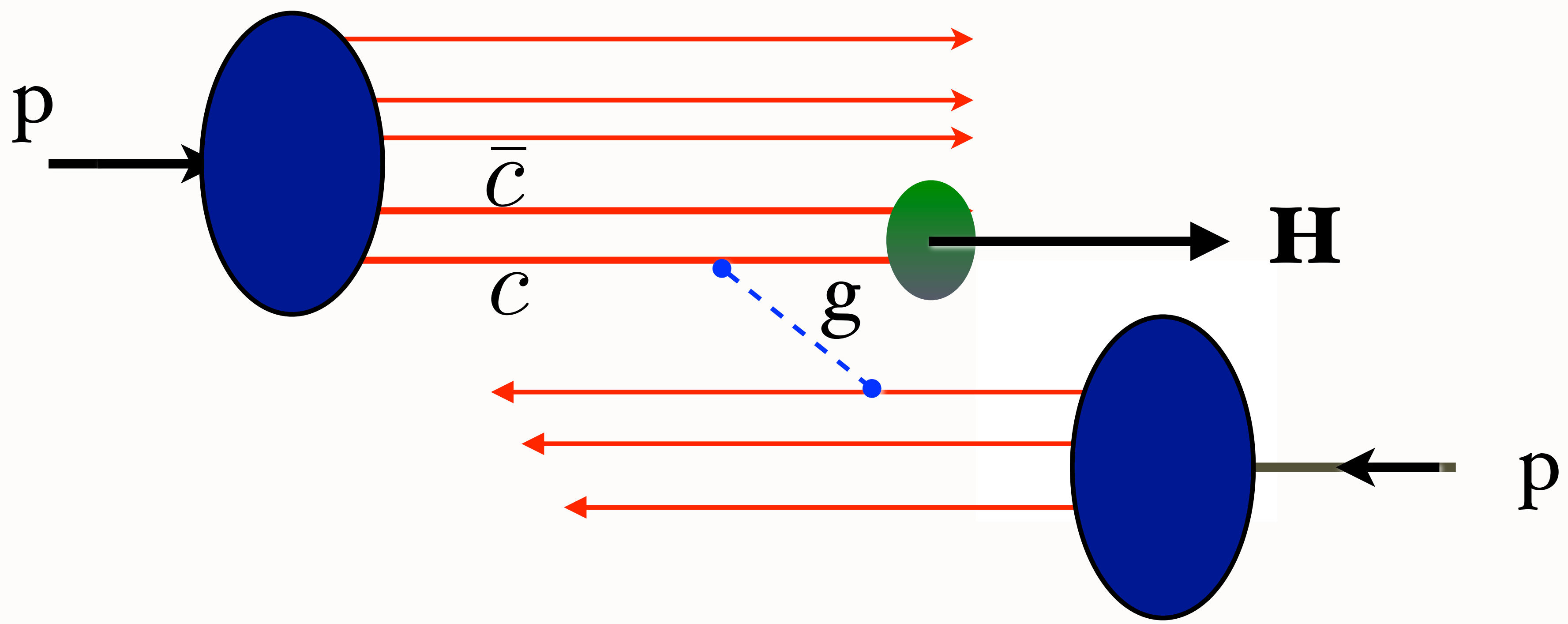
Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

Quarkonia can have 80% of Proton Momentum!

Color-octet IC interacts at front surface of nucleus

IC can explains large excess of quarkonia at large x_F, A-dependence

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to HX$$

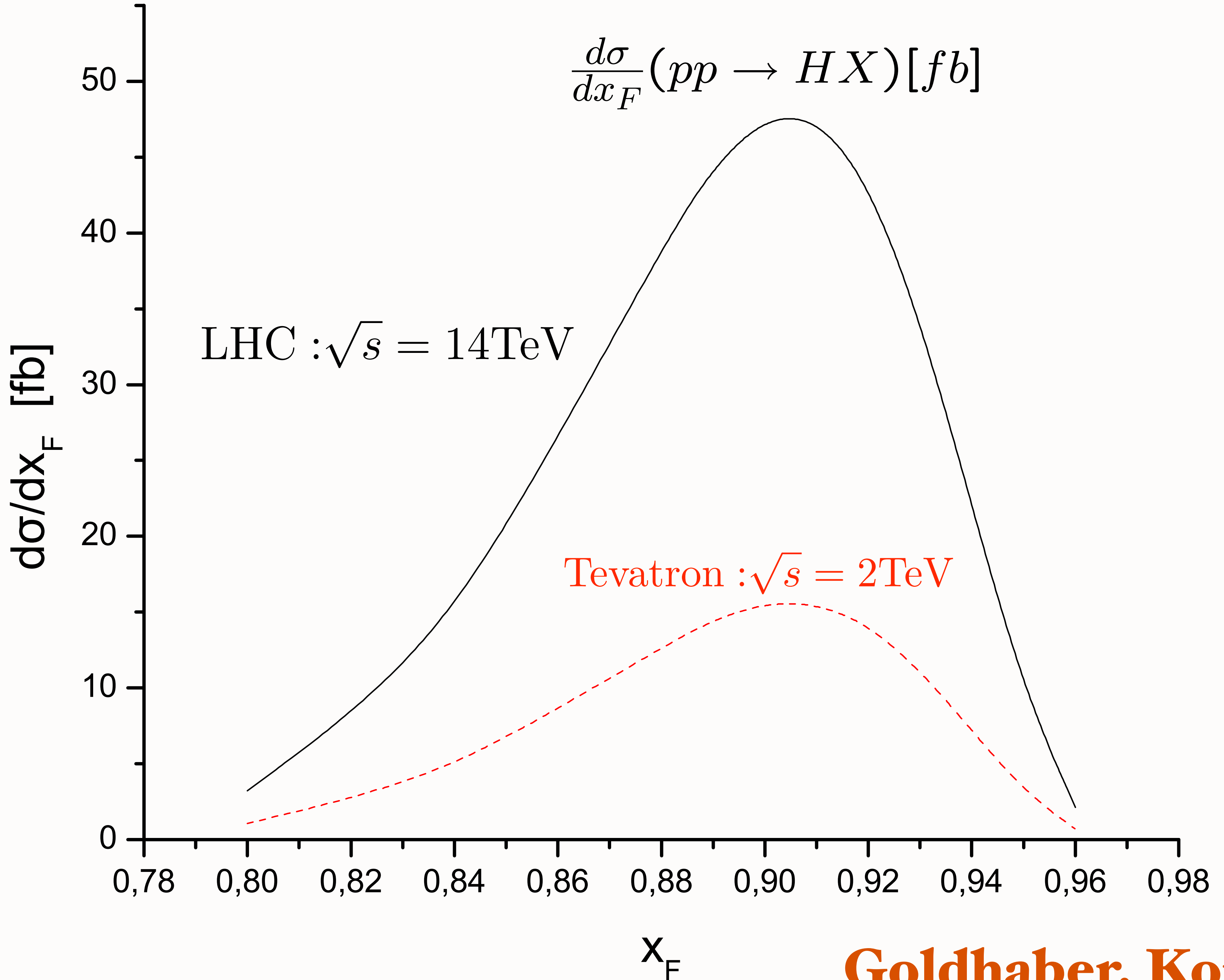
Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

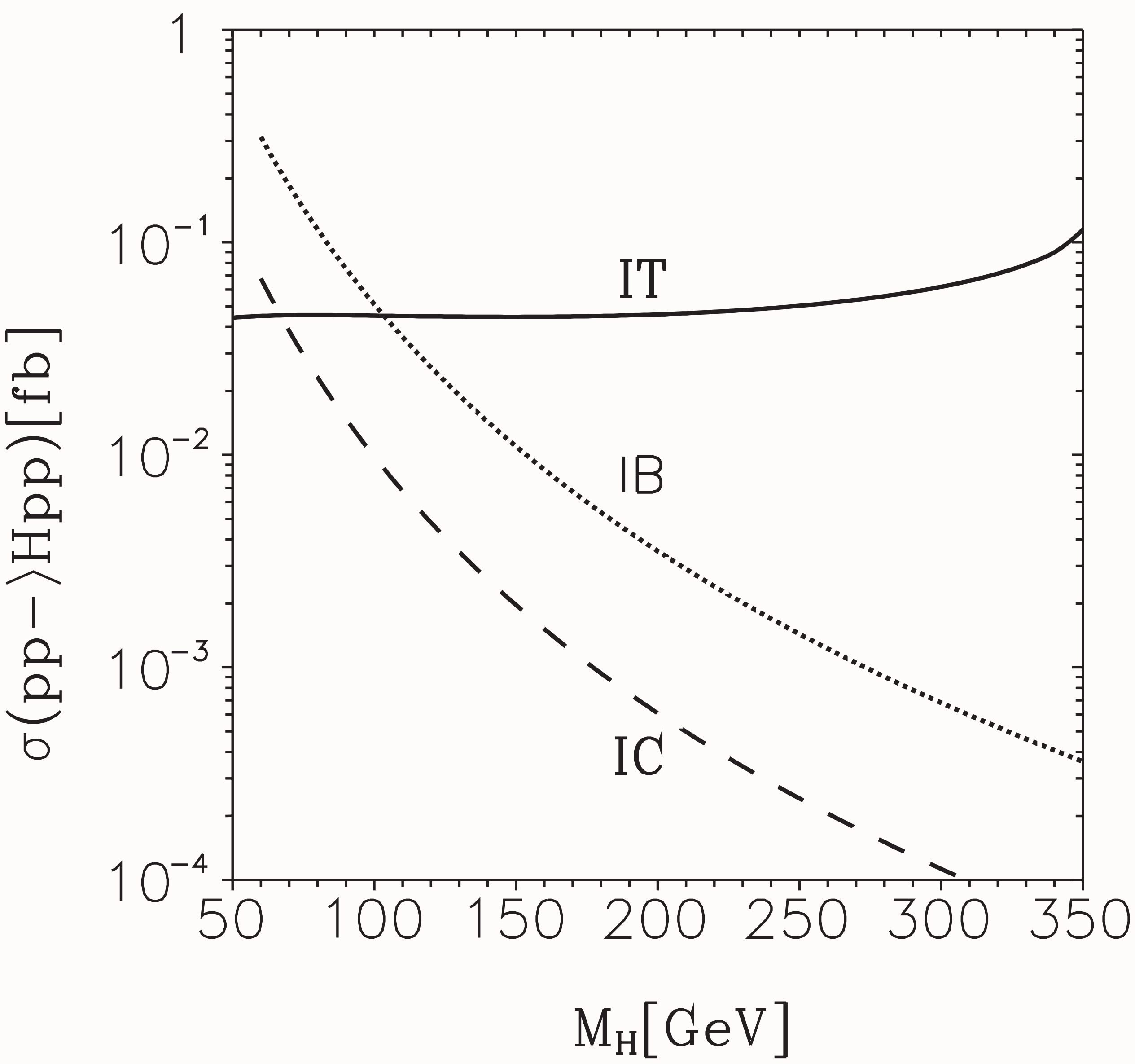
Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Intrinsic Bottom Contribution to Inclusive Higgs Production



Goldhaber, Kopeliovich, Schmidt, sjb

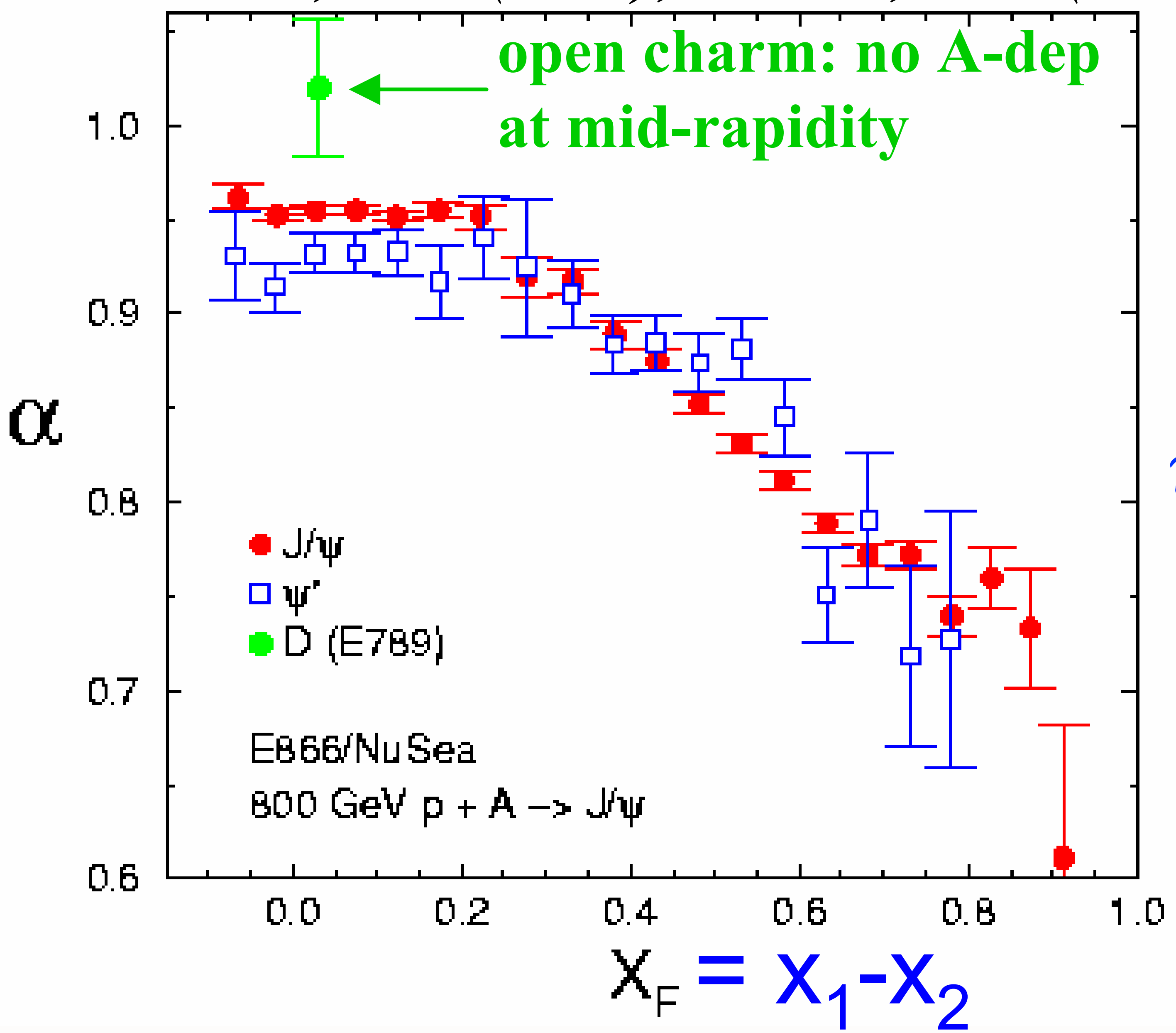


The cross section of the reaction $pp \to Hp + p$ as a function of the Higgs mass. Contributions of IC (dashed line), IB (dotted line), and IT (solid line).

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

M. Leitch



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization

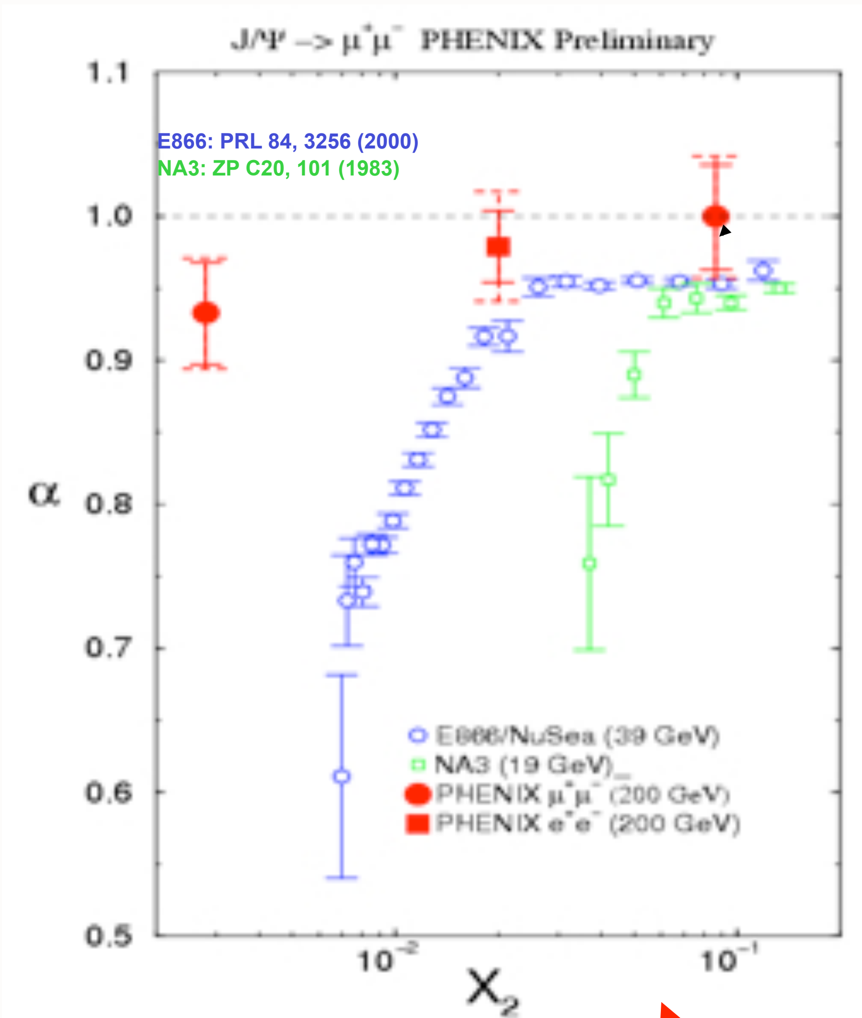
Violation of factorization in charm hadroproduction.
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.
Published in Phys.Lett.B246:217-220,1990

IC Explains large excess of quarkonia at large x_F, A-dependence

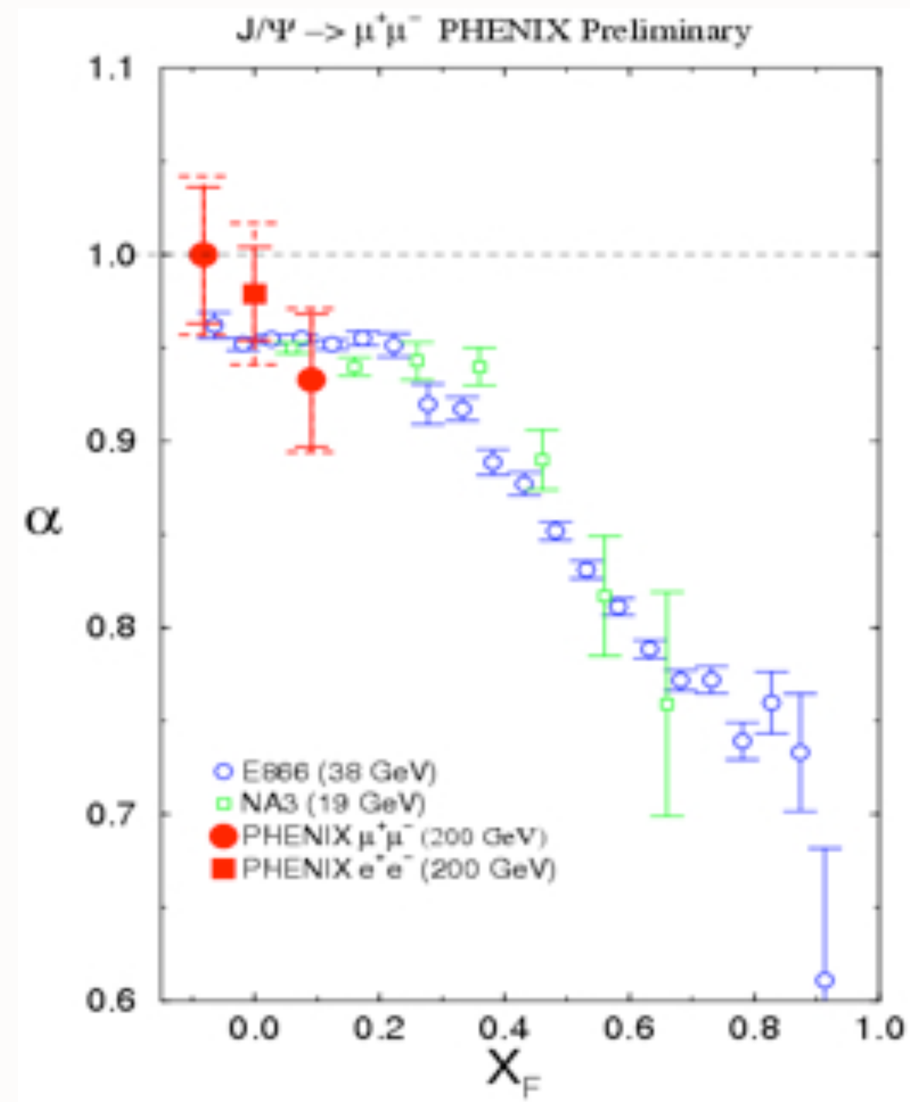
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001



Huge "absorption" effect

Violates PQCD factorization!

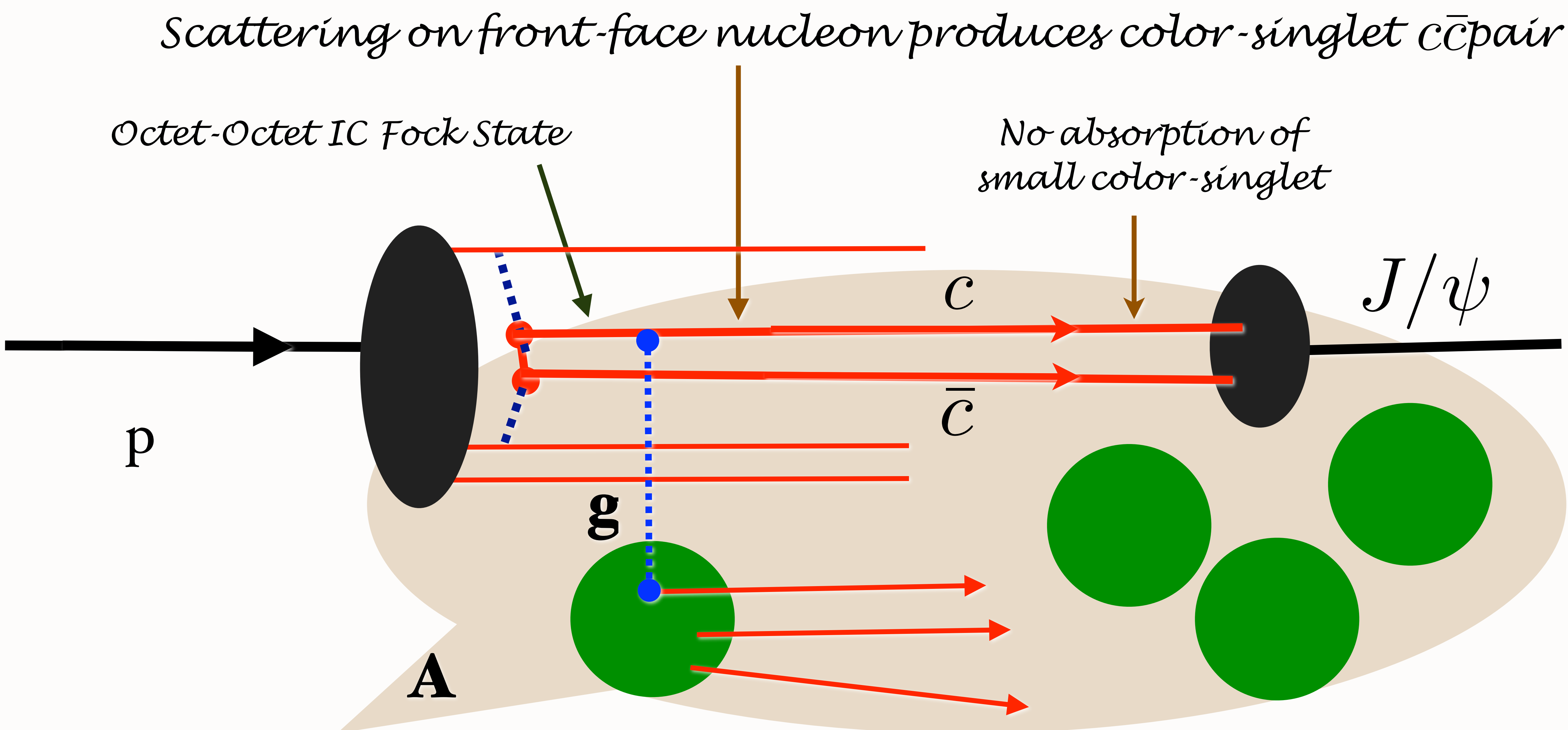
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Hoyer, Sukhatme, Vanttinen

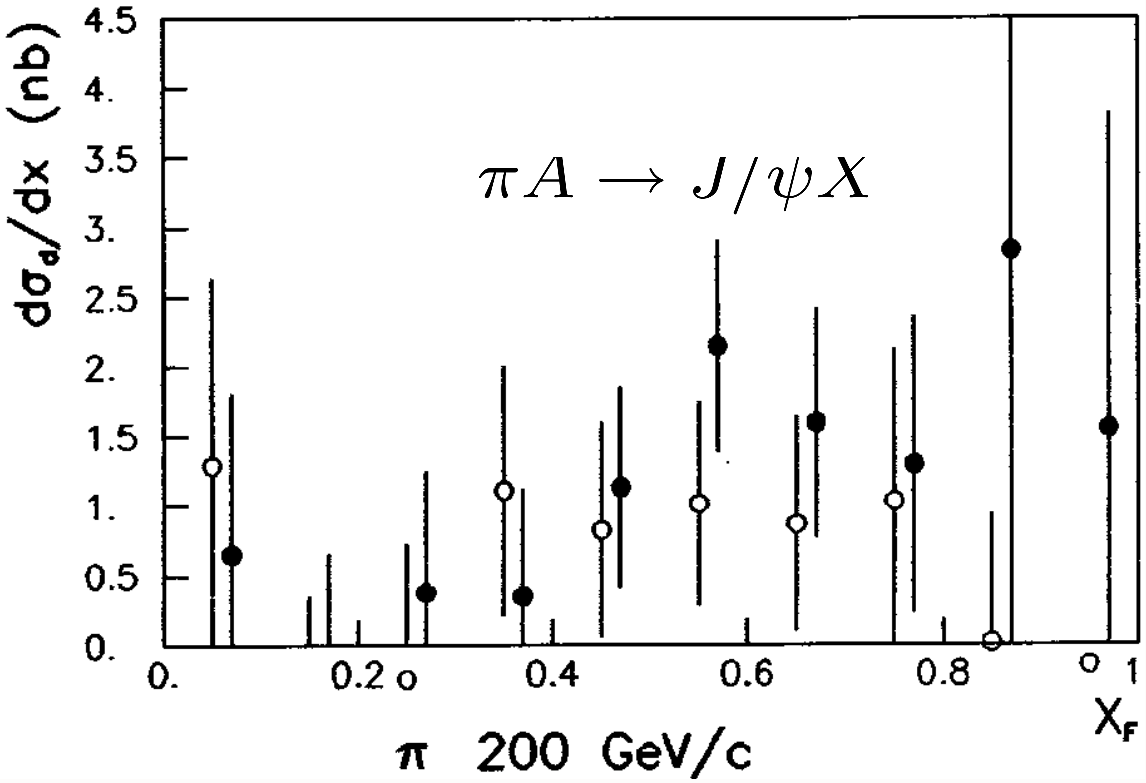
Violates PQCD Factorization: $A^\alpha(x_F)$ not $A^\alpha(x_2)$

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Goldhaber, Soffer, sjb

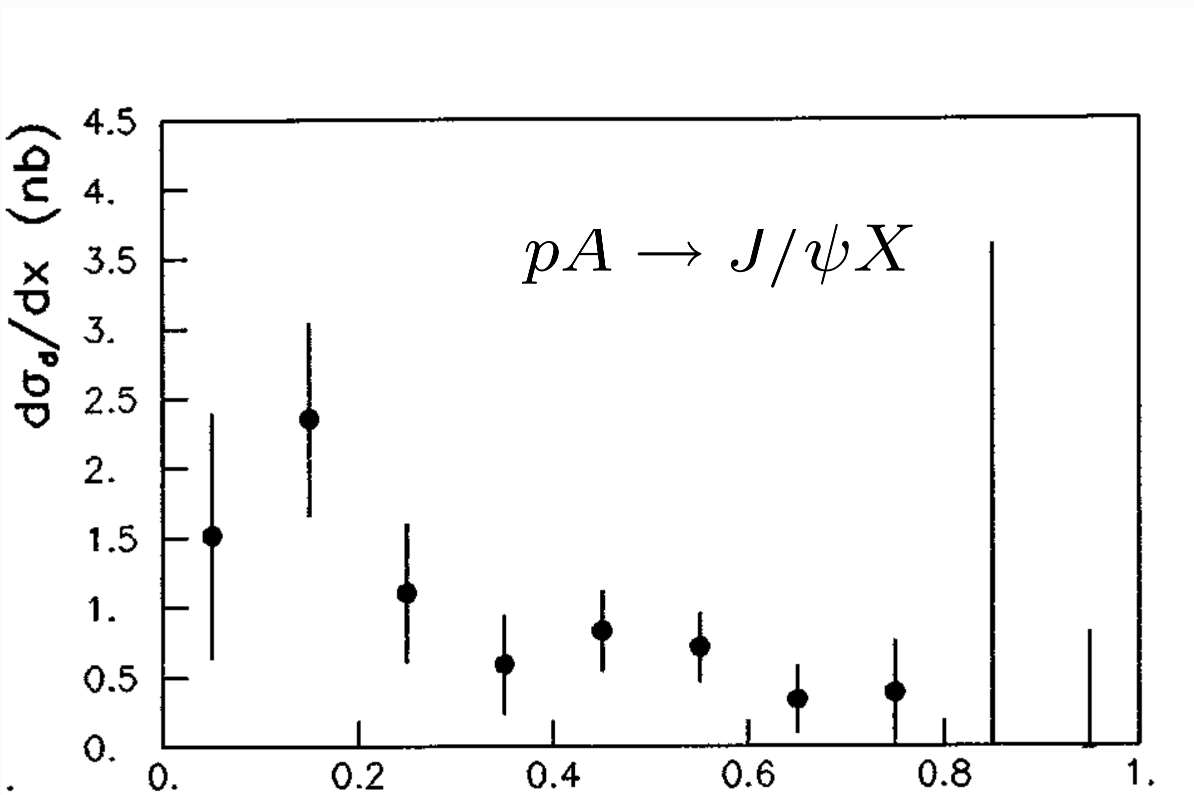


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$



J. Badier et al, NA3

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_2}{dx_F}$$



p 200 GeV/c

$A^{2/3}$ component

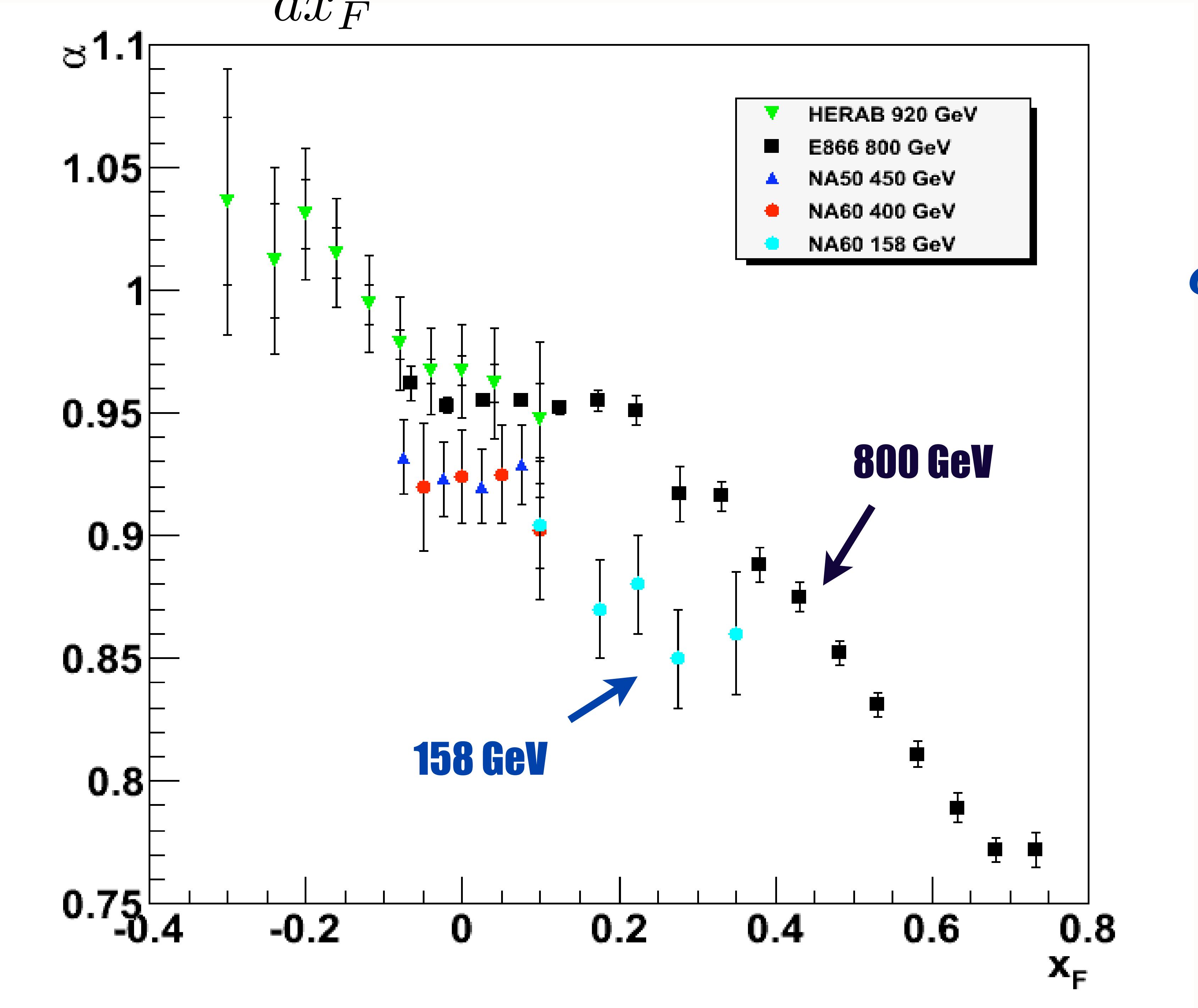
High x_F:

Consistent with color -octet intrinsic charm

Excess beyond conventional gluon-splitting PQCD subprocesses

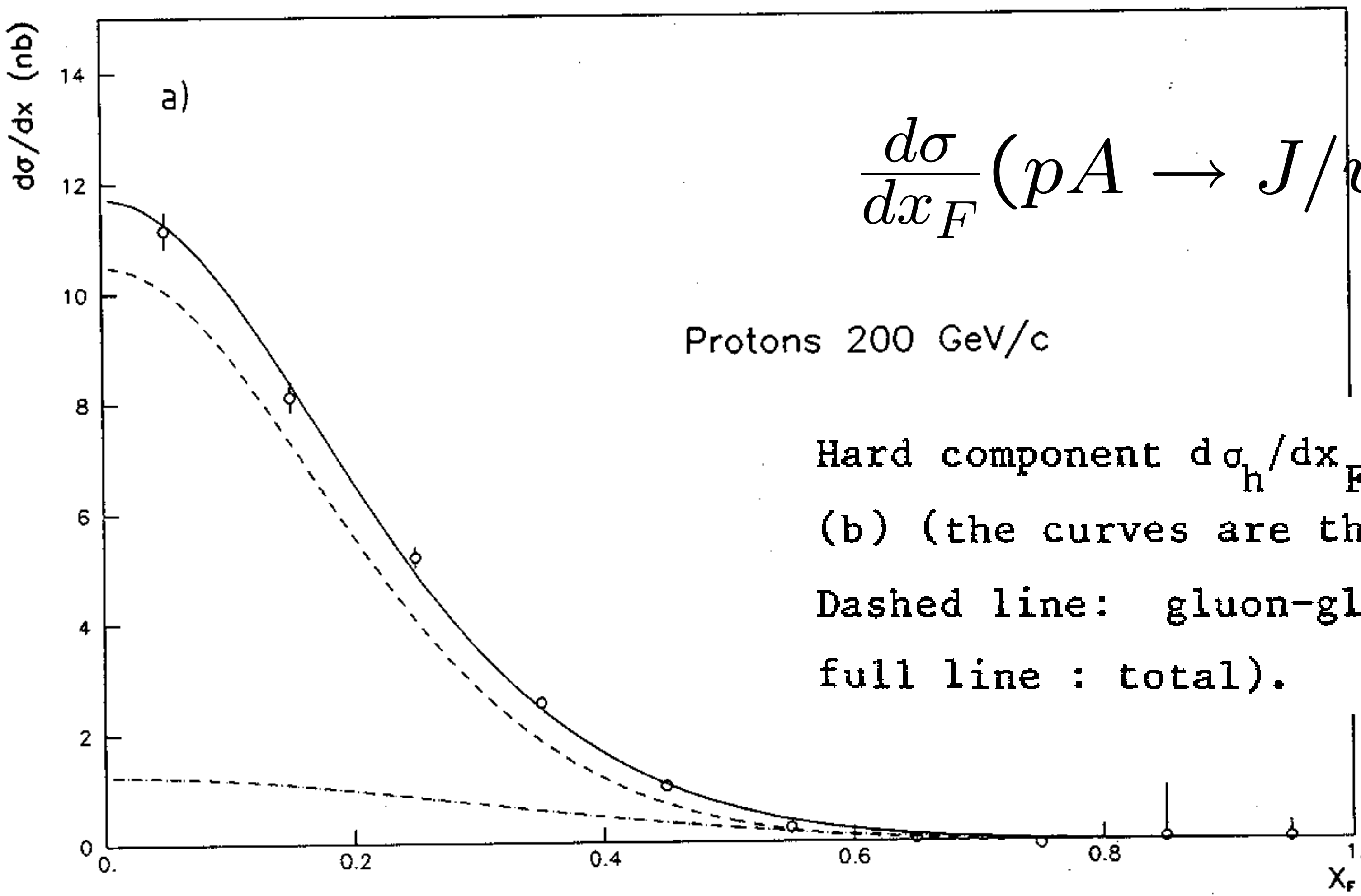
NA60 pA data @ 158GeV

$$\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) \propto A^{\alpha}$$

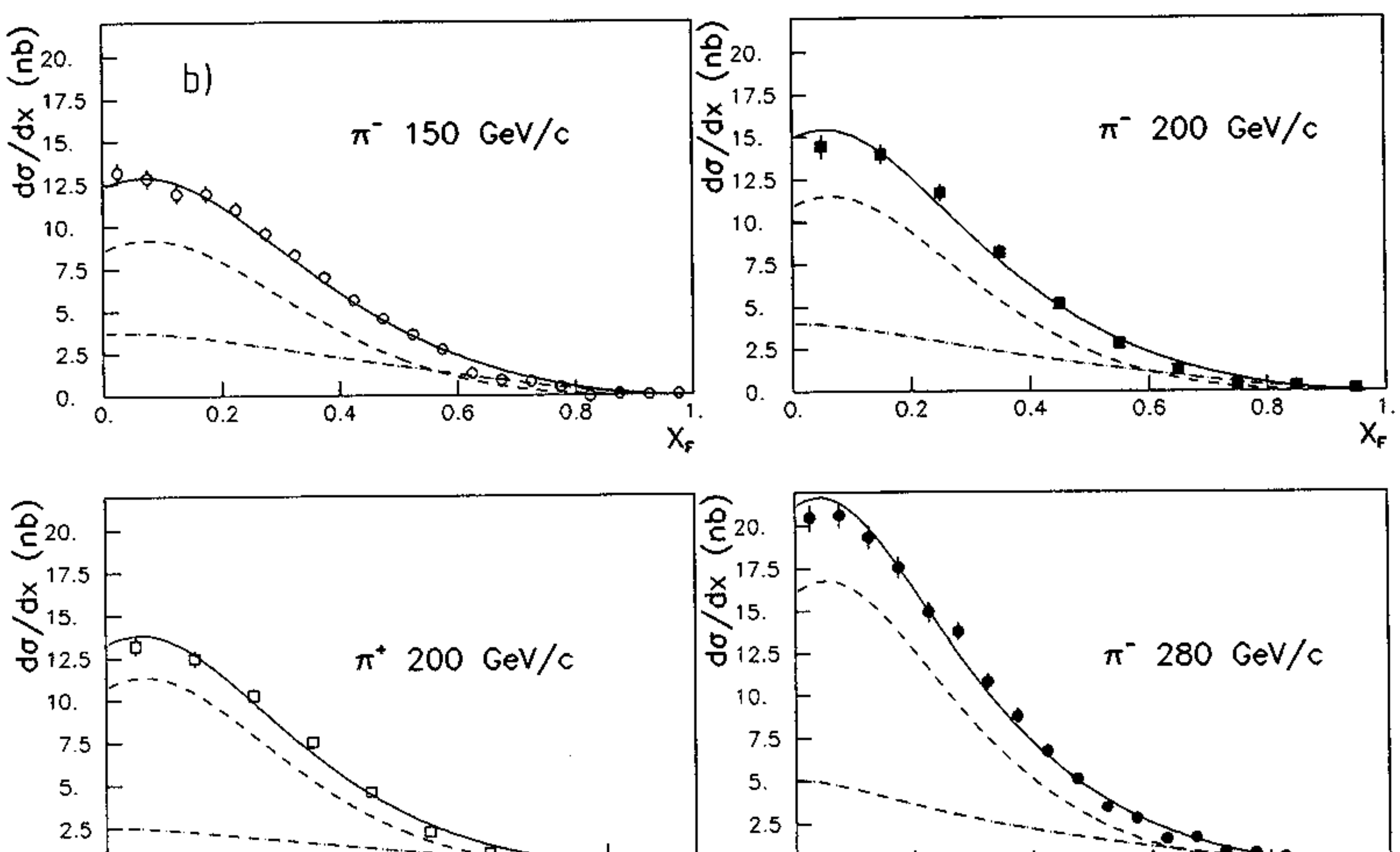


Clear dependence on x_F and beam energy

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F}$$



Hard component $d\sigma_h/dx_F$ for incident protons (a) and pions (b) (the curves are the result of the fit described in the text. Dashed line: gluon-gluon fusion; dash-dotted line : $q\bar{q}$ fusion; full line : total).



A^1 component consistent with sum of gg and $\bar{q}q$ fusion

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

Color Opaqueness

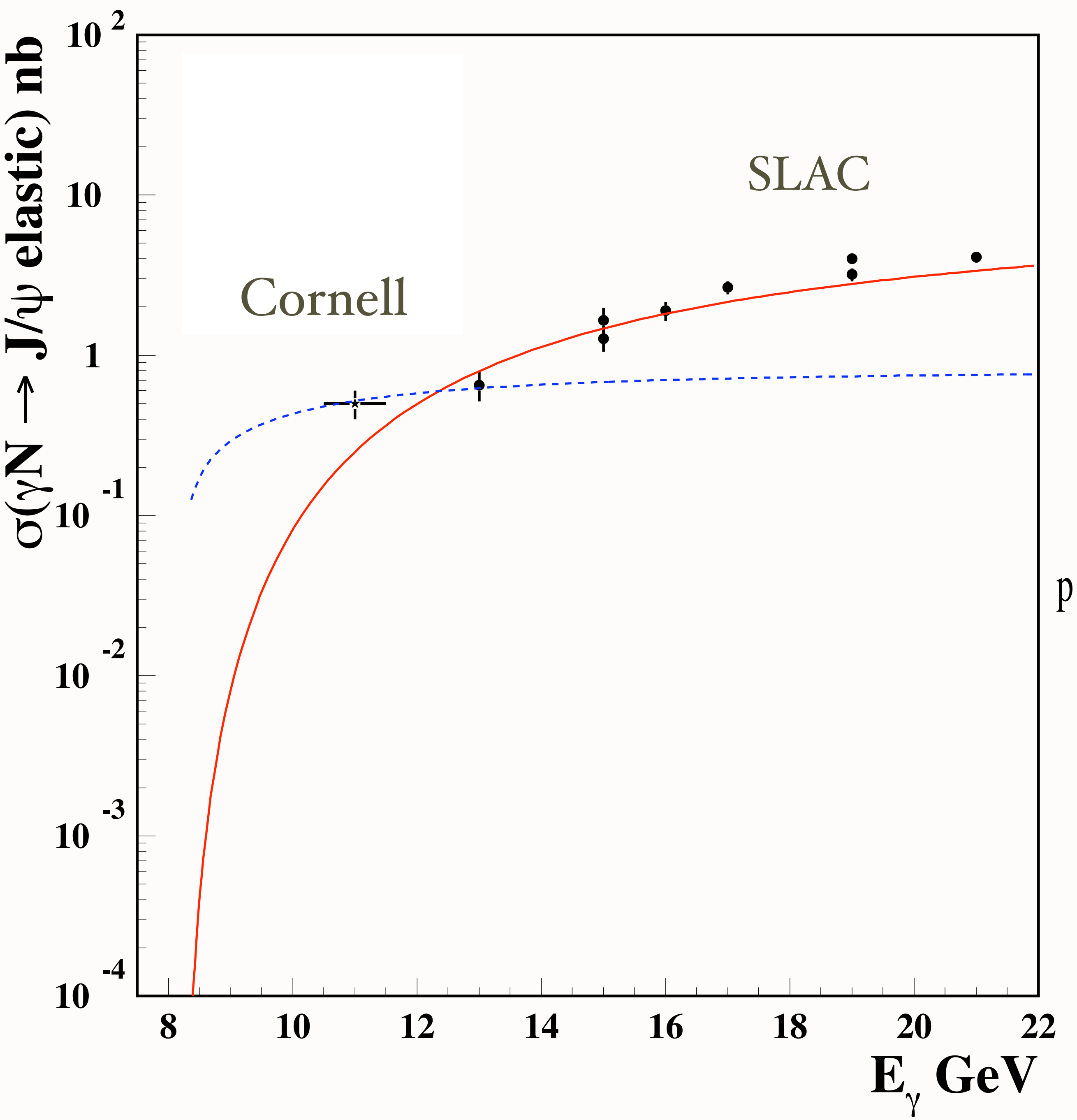
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

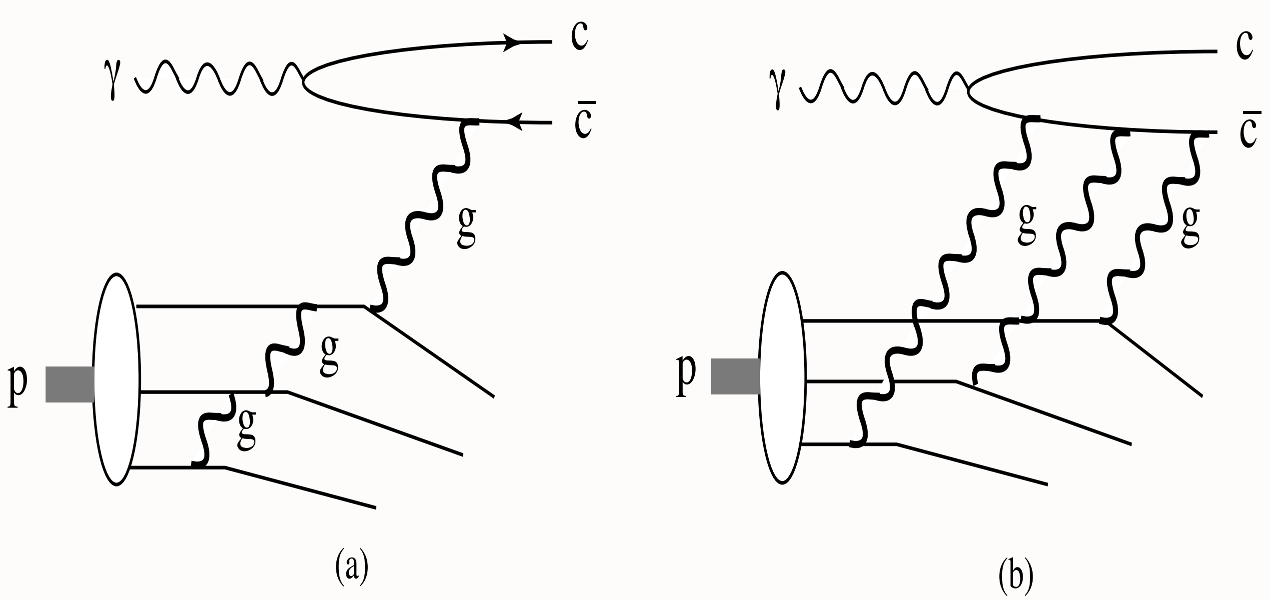
- IC leads to new effects in B decay (Gardner, SJB)

Higgs production at x_F = 0.8

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb





Leading twist contribution

Dominant near threshold

Why is IQ Important for Flavor Physics?

- New perspective on fundamental nonperturbative hadron structure
- Charm structure function at high x
- Dominates high x_F charm and charmonium production
- Hadroproduction of new heavy quark states such as ccu, ccd, bcc, bbb, at high x_F
- Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay *Gardner, sjb*
- $J/\psi \to \rho\pi$ puzzle explained *Karliner , sjb*
- Novel Nuclear Effects from color structure of IC, Heavy Ion Collisions
- New mechanisms for high x_F Higgs hadroproduction
- Dynamics of b production: LHCb

New Multi-lepton Signals

- Fixed target program at LHC: produce bbb states

- *7 TeV proton beam collisions on a proton or nuclear target -- Extract beam with Crystals -*
- *Minimal effects on the collider*
- *Equivalent to Ecm = 115 GeV*
- *Nuclear and Polarized Targets*
- *Nuclear Beams: Produce QGP in Rest Frame of Target Nucleus*
- *Study Dynamics at extreme rapidities:* $X_F = -1$
- *Secondary Beams -- Even B and D*
- *Diffraction on Nucleons and Nucleus*
- *Cosmic Ray Simulations*

AFTER @ LHC

A Compelling Idea for QCD:

Utilize the High-Energy LHC proton and nuclear beams in a fixed-target mode

AFTER @ LHC

A Fixed-Target ExpeRiment

A new hadron physics laboratory for studying and testing QCD

- Both p and Pb LHC beams can be extracted without disturbing the other experiments
- Extracting a few per cent of the beam $\rightarrow 5 \times 10^8$ protons per sec
- This allows for high luminosity pp, pA and PbA collisions at $\sqrt{s} = 115$ GeV and $\sqrt{s_{NN}} = 72$ GeV
- **Example**: precision quarkonium studies taking advantage of
  - high luminosity (reach in y, P_T, small BR channels)
  - target versatility (CNM effects, strongly limited at colliders)
  - modern detection techniques (e.g. γ detection with high multiplicity)
- This would likely prepare the ground for $g(x, Q^2)$ extraction
- A wealth of possible measurements:
  DY, Open b/c, jet correlation, UPC... (not mentioning secondary beams)
- Planned LHC long shutdown (< 2020 ?) could be used to install the extraction system
- Very good complementarity with electron-ion programs

Fixed Target Physics with the LHC Beams

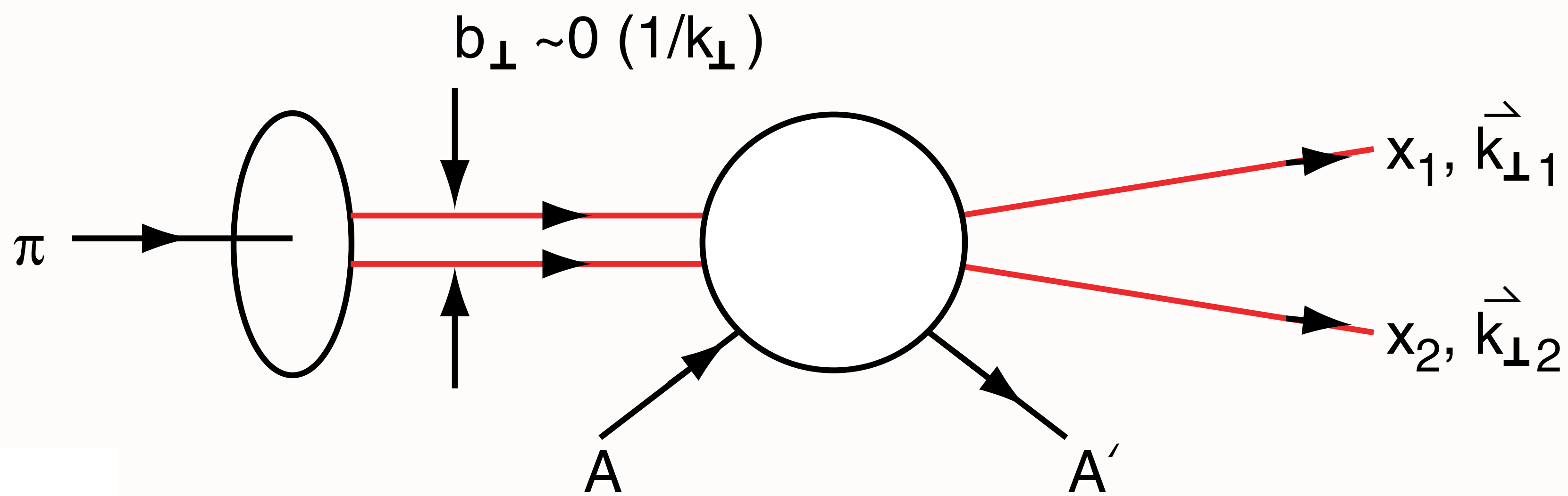
- 7 TeV proton beam, nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations!
- Single-Spin Asymmetries, Transversity Studies, A_N
- High-x_F Dynamics
- High-x_F Heavy Quark Phenomena
- Production of ccq to ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System
- Anti-Shadowing: Flavor Specific?

Nuclear Collisions with AFTER

- Nucleus-Nucleus and Proton-Nucleus Scattering in Lab Frame Look at Target Fragmentation Region $x_F=-1$
- What happens to Target Nucleus when QGP is formed?
- Ridge at extreme rapidity
- What are the critical parameters for the onset of QGP
- Light-Front Description: Frame-Independent
- Use Fool's ISR Frame -- No Lorentz Contraction of LFWF
- Energy Loss Studies, LPM, Non-Abelian
- Quarkonium Production, Polarization
- Open charm, bottom

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



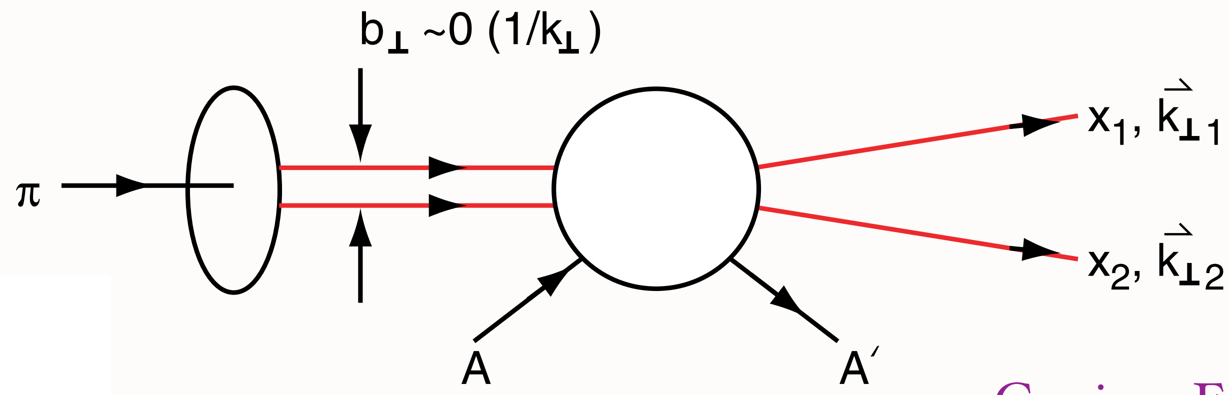
$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

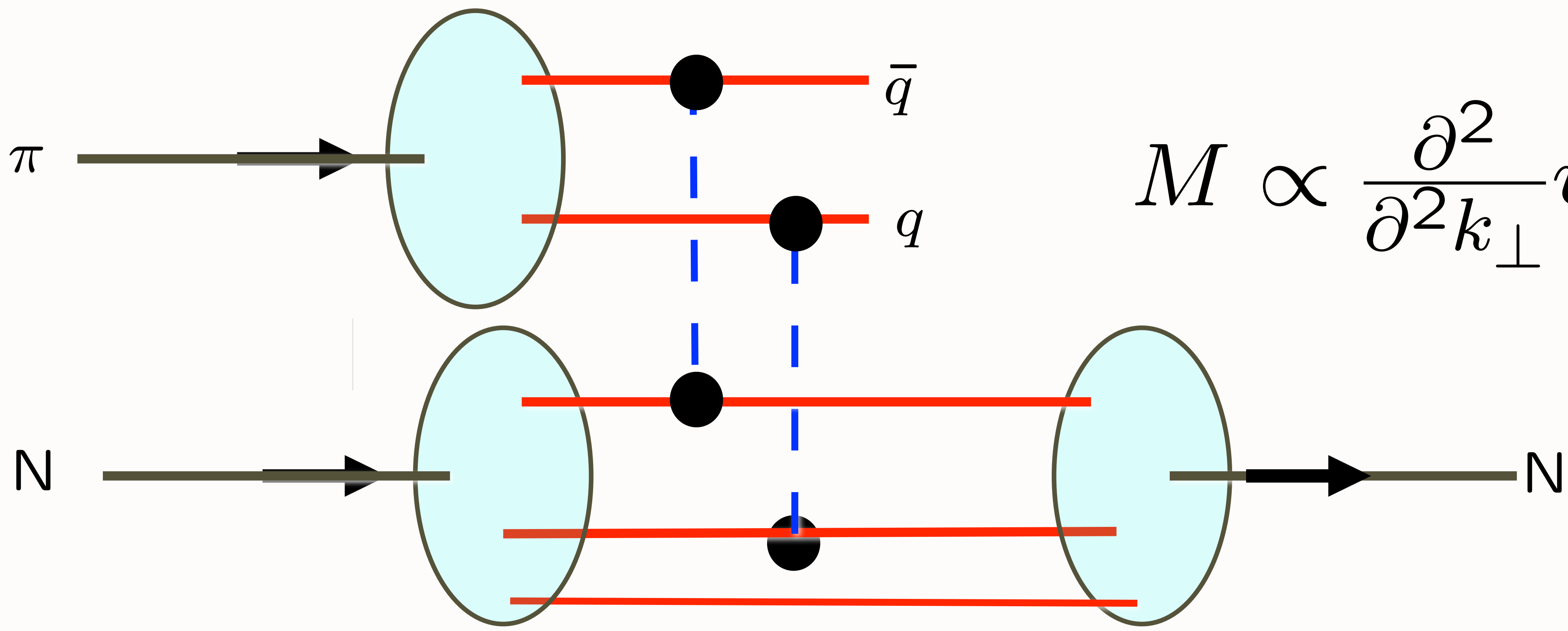
Nucleus left Intact!

E791 FNAL Diffractive DiJet



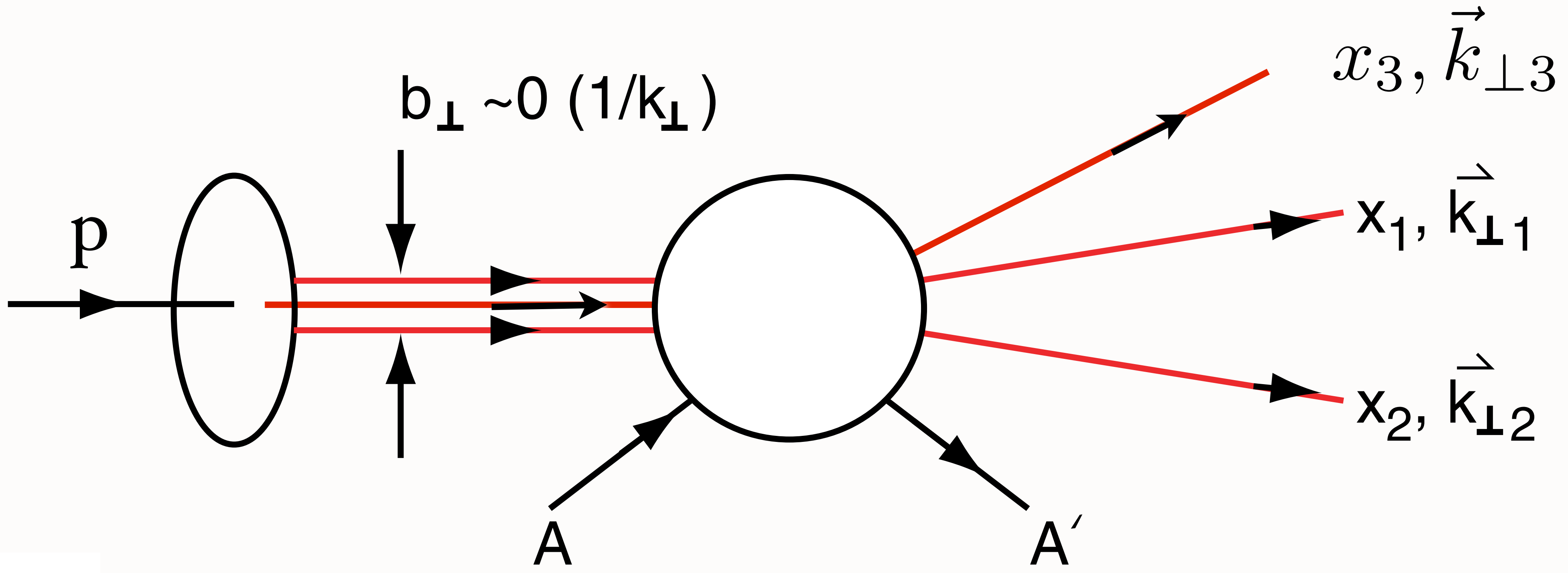
Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

Two-gluon exchange measures the second derivative of the pion light-front wavefunction



$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

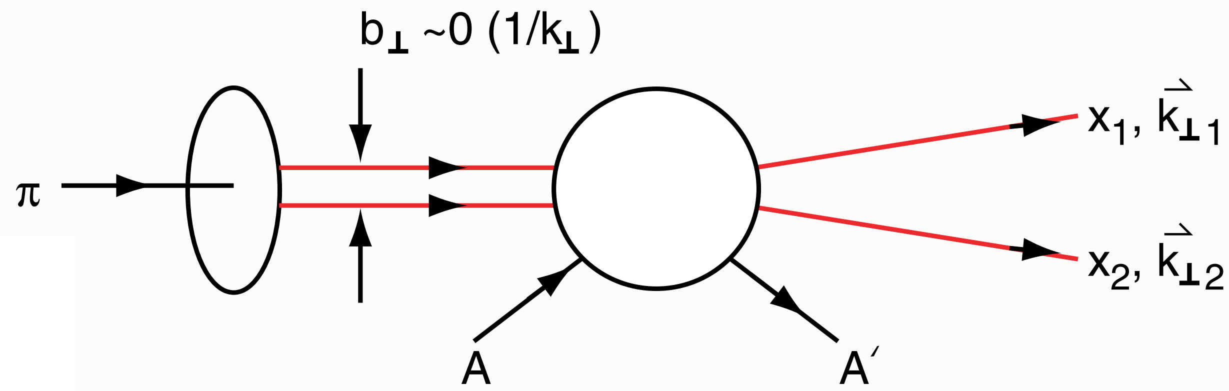
Diffractive Dissociation of Proton into Three Quark Jets



Measure Light-Front Wavefunction of Proton

Minimal momentum transfer to nucleus
Nucleus left Intact!

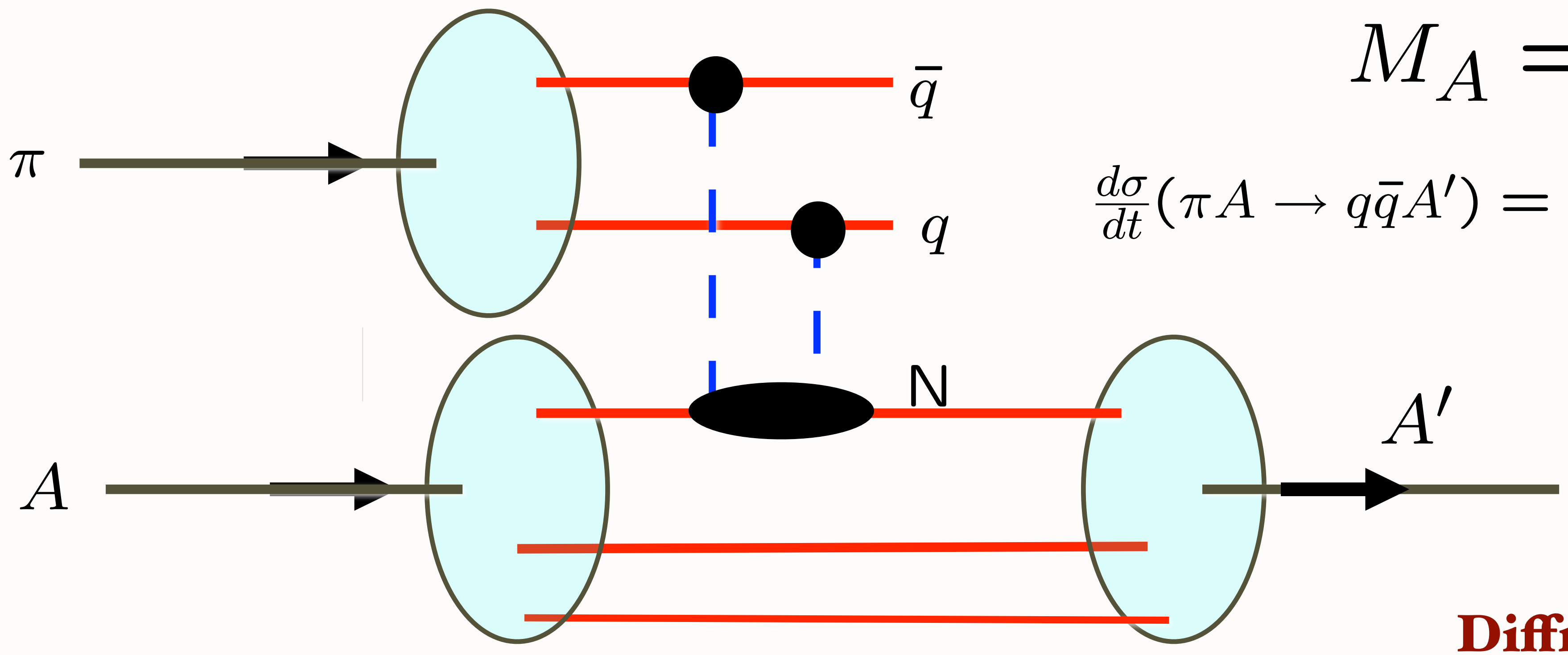
Key Ingredients in E791 Experiment



Brodsky Mueller
Frankfurt Miller Strikman

Small color-dipole moment pion not absorbed; interacts with each nucleon coherently

QCD COLOR Transparency



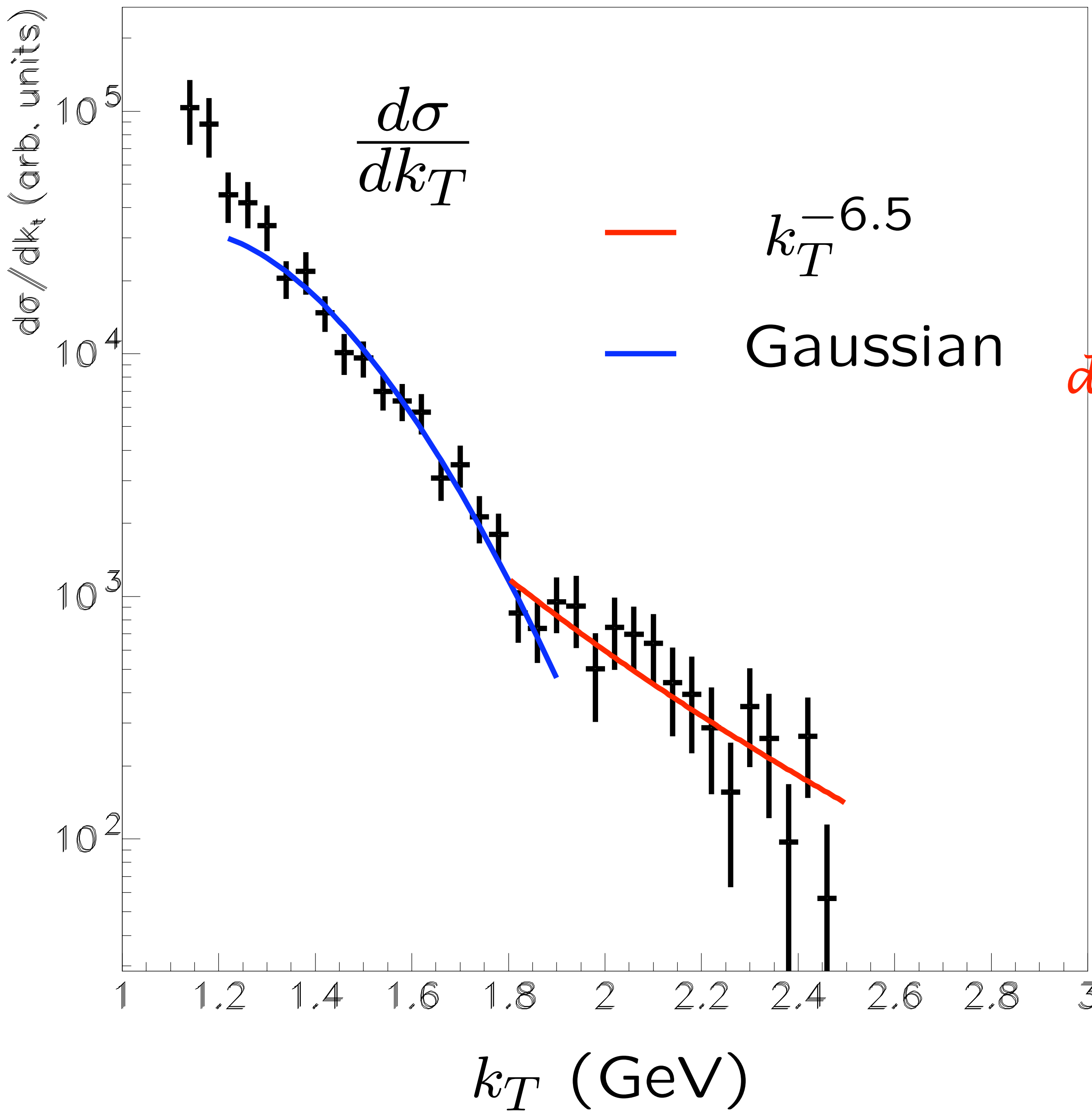
$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F_A^2(t)$$

Target left intact

Diffraction, Rapidity gap

E791 Diffractive Di-Jet transverse momentum distribution

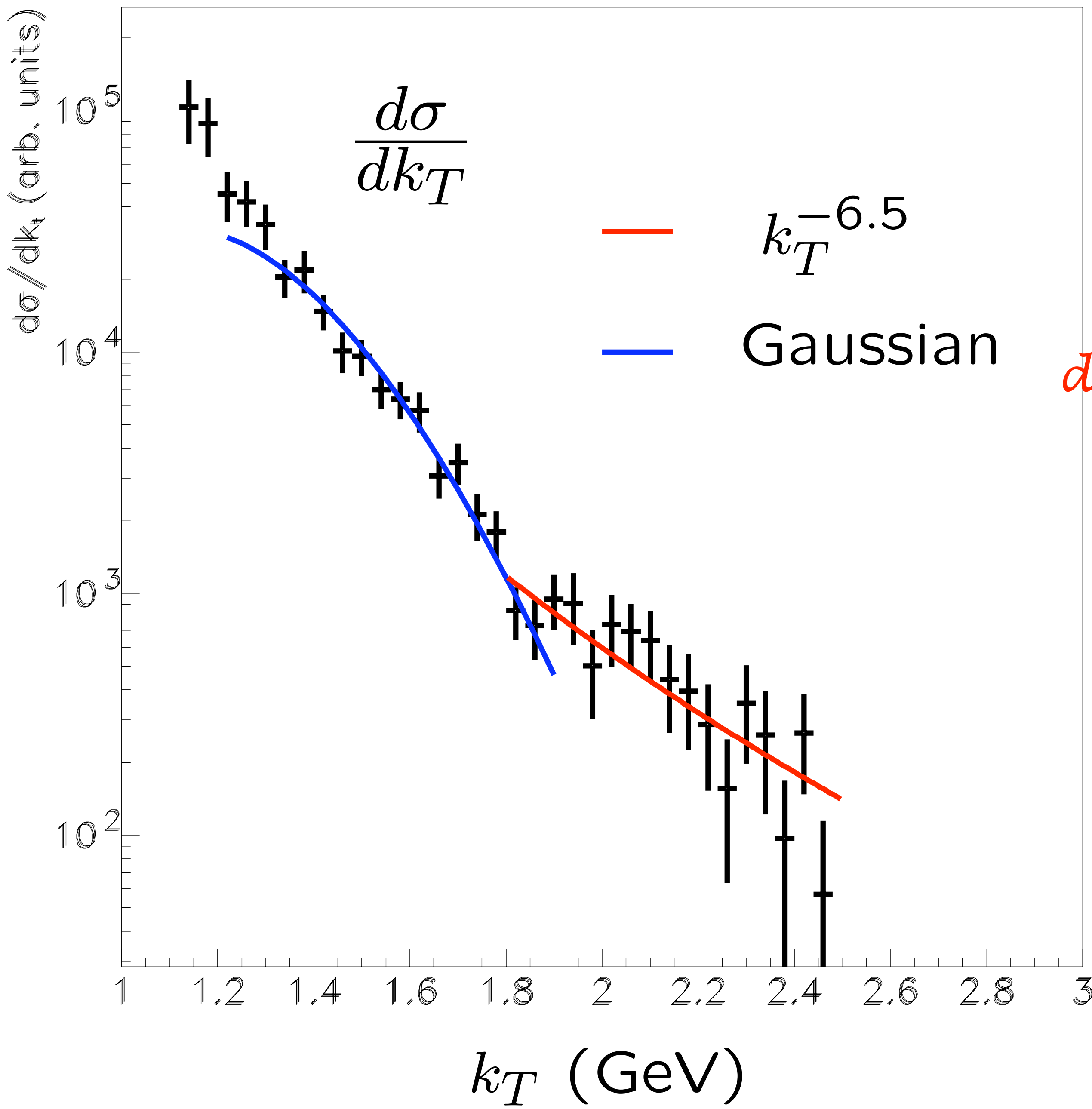


Two Components

High Transverse momentum dependence consistent with PQCD, ERBL Evolution $k_T^{-6.5}$

Gaussian component similar to AdS/CFT HO LFWF

E791 Diffractive Di-Jet transverse momentum distribution



Two Components

High Transverse momentum dependence consistent with PQCD, ERBL Evolution $k_T^{-6.5}$

Gaussian component similar to AdS/CFT HO LFWF

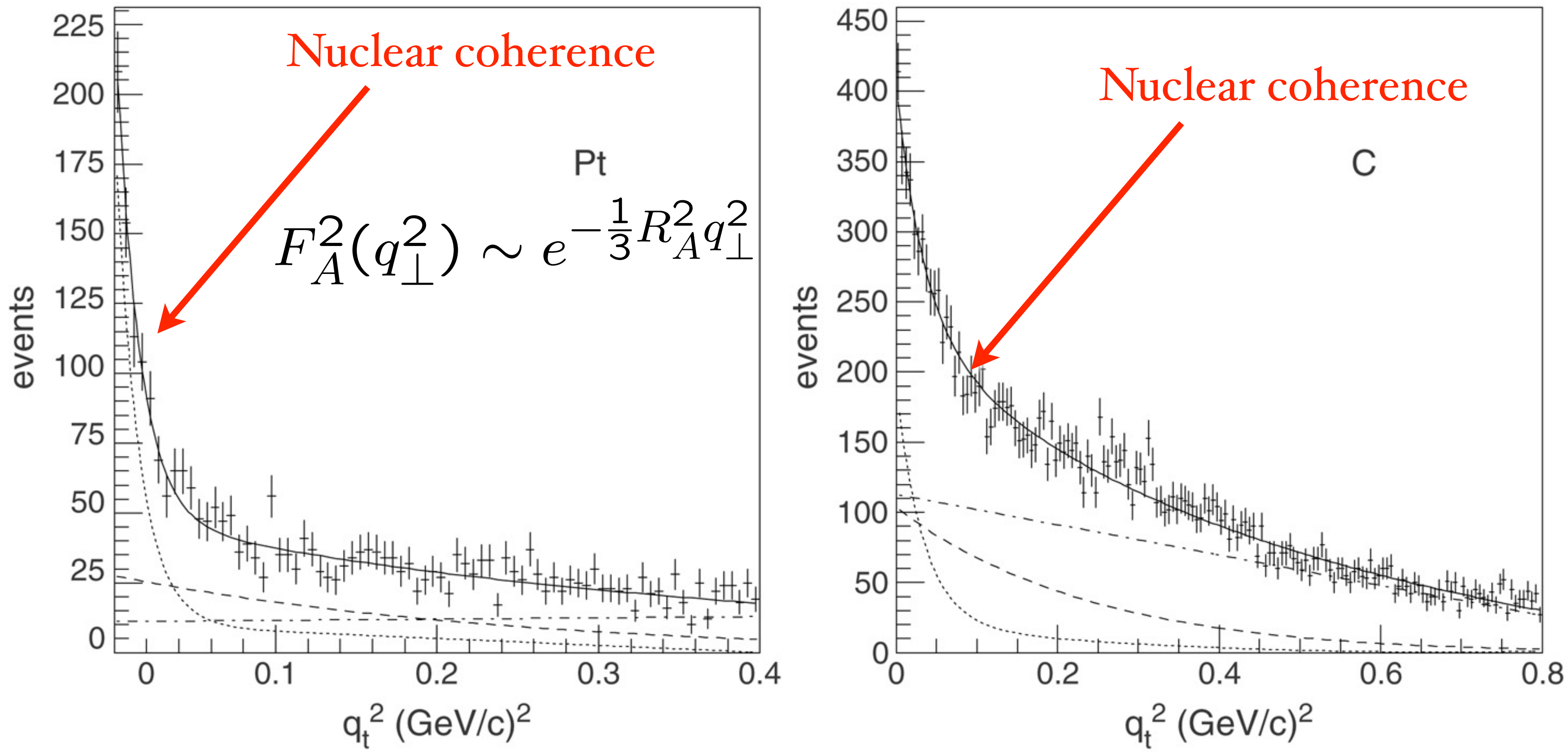
- Fully coherent interactions between pion and nucleons.

- Emerging Di-Jets do not interact with nucleus.

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0$$

$$\sigma \propto A^{4/3}$$



Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	1.64 +0.06 -0.12	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

Ashery E791

α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

Color Transparency

Bertsch, Gunion, Goldhaber, sjb

A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

$\pi^- N \to \mu^+ \mu^- X$ at 80 GeV/c

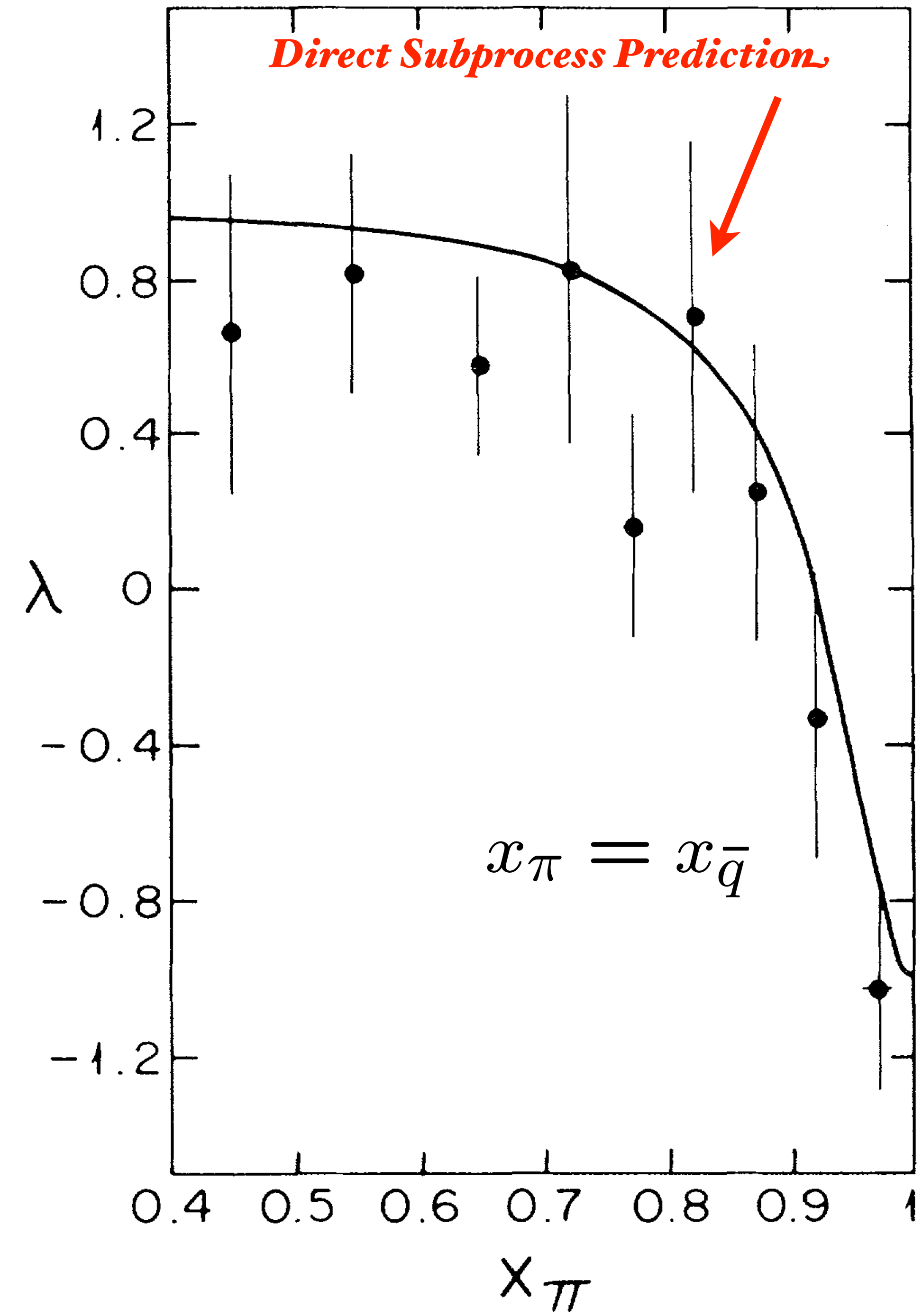
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi.$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

$$\langle k_T^2 \rangle = 0.62 \pm 0.16 \ \text{GeV}^2/c^2$$

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F



Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Example of a higher-twist direct subprocess

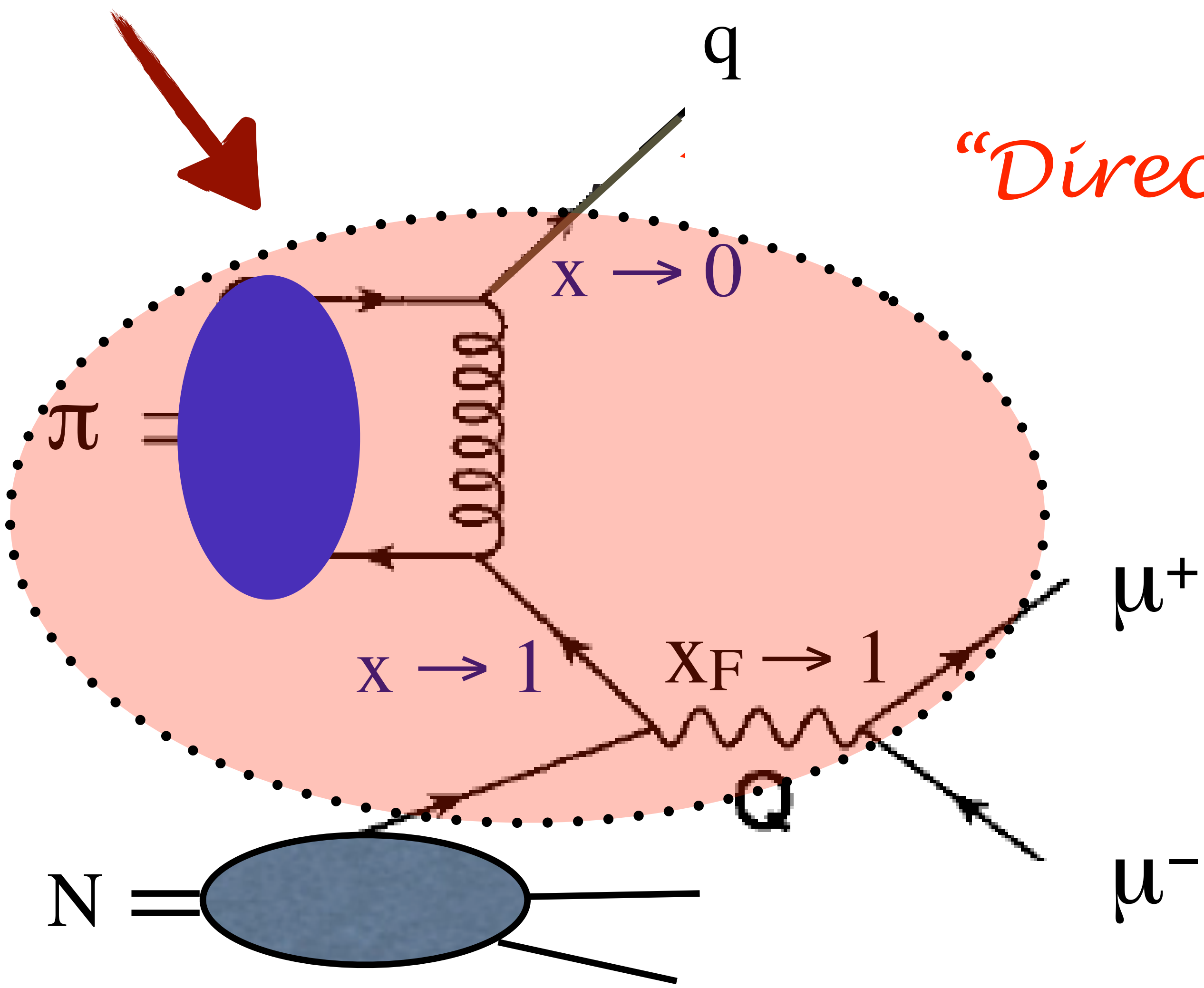
Many Tests at AFTER

$\pi N \to \mu^+ \mu^- X$ at high x_F

In the limit where $(1-x_F)Q^2$ is fixed as $Q^2 \to \infty$

Distribution amplitude from AdS/CFT

Entire pion wf contributes to hard process



"Direct" Subprocess

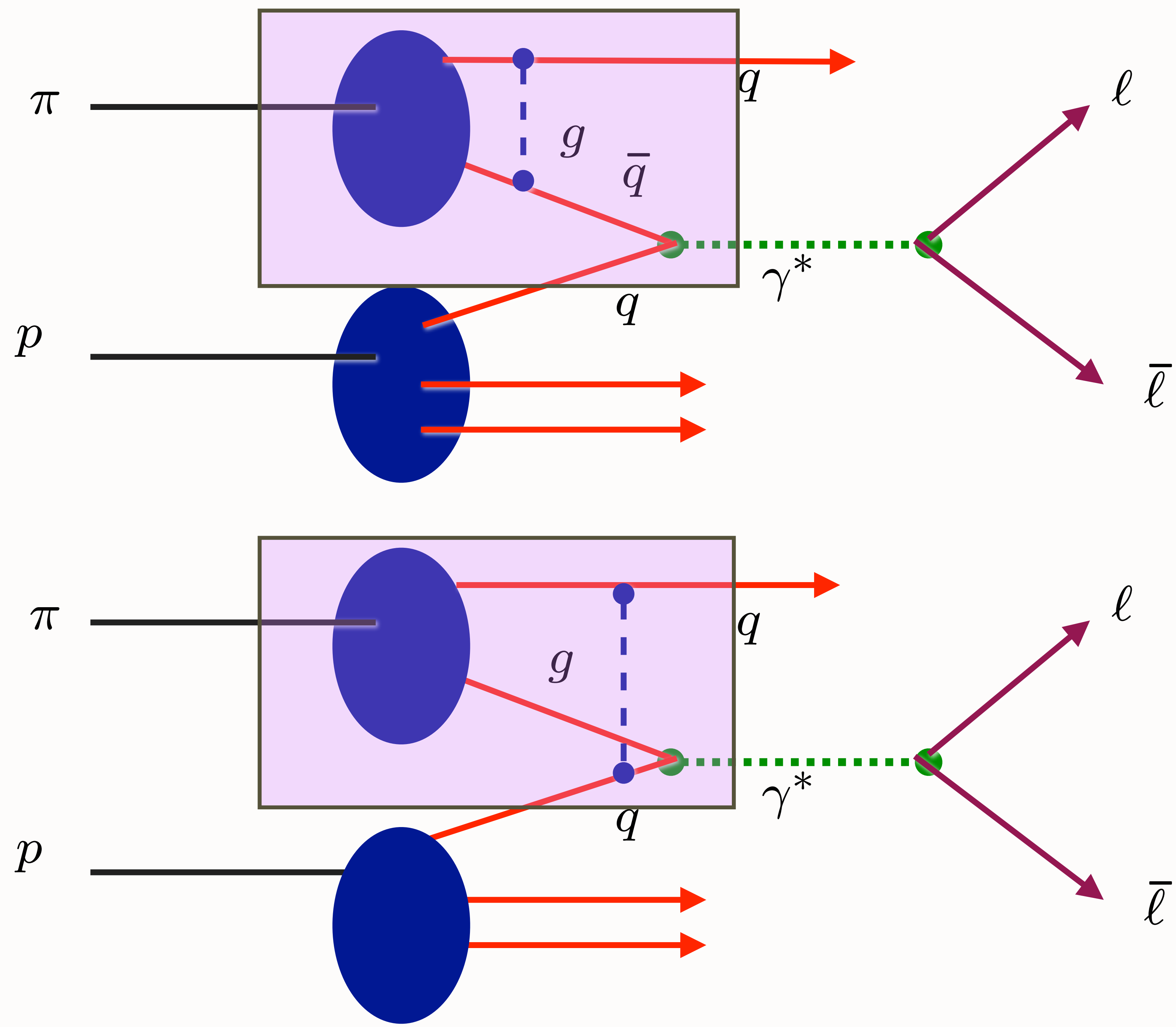
Virtual photon is longitudinally polarized

Similar higher twist terms in jet hadronization at large z

Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

Berger, Lepage, sjb



$$\pi q \to \gamma^* q$$

Initial State Interaction

Pion appears directly in subprocess at large x_F

All of the pion's momentum is transferred to the lepton pair

Lepton Pair is produced longitudinally polarized

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; \vec{k}_{\perp_i}, \lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

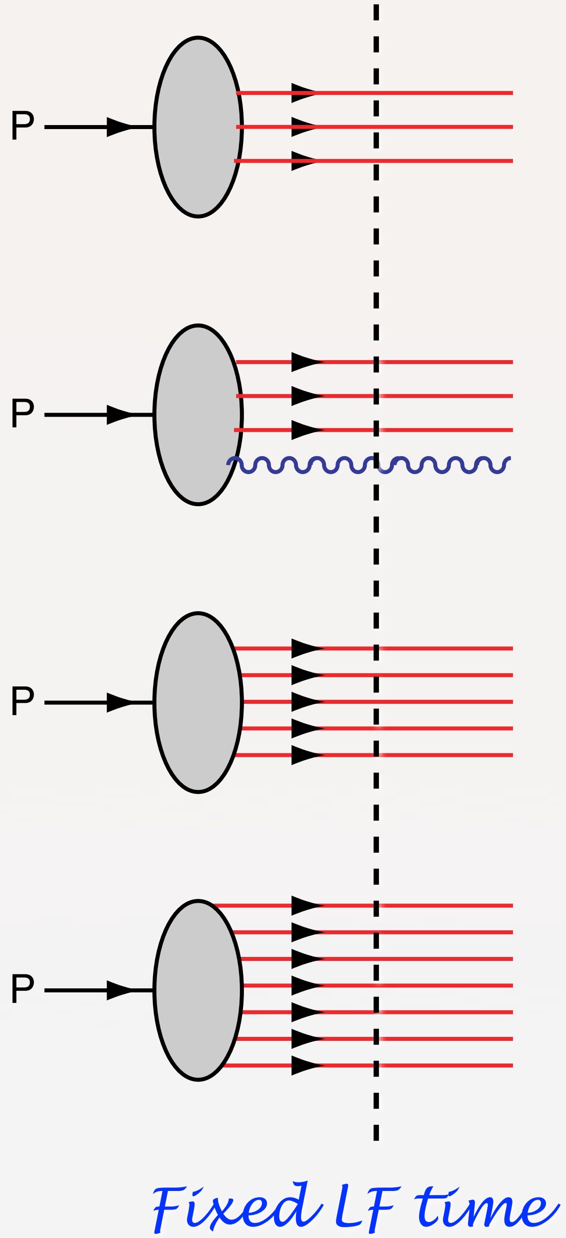
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Intrinsic heavy quarks
c(x), b(x) at high x !

$\bar{s}(x) \neq s(x)$
$\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states BFKL Pomeron

Hidden Color

Bjorken, Kogut, Soper; Blankenbecler, Gunion, sjb;
Blankenbecler, Schmidt

Crucial Test of Leading -Twist QCD: Scaling at fixed x_T

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^{n_{\rm eff}}}$$

$$x_T = \frac{2p_T}{\sqrt{s}}$$

Parton model: $n_{eff} = 4$

As fundamental as Bjorken scaling in DIS

scaling law: $n_{eff} = 2\, n_{active} - 4$

Dimensional analysis

Scattering amplitude $1\ 2 \cdots \to \ldots n$ has dimension

$$\mathcal{M} \sim [\mathrm{length}]^{n-4}$$

Consequence

In a conformal theory (no intrinsic scale), scaling of inclusive particle production

$$E\,\frac{d\sigma}{d^3p}(A\ B\ \to C\ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta^{\mathrm{cm}})}{p_\perp^{2n_{\mathrm{active}}-4}}$$

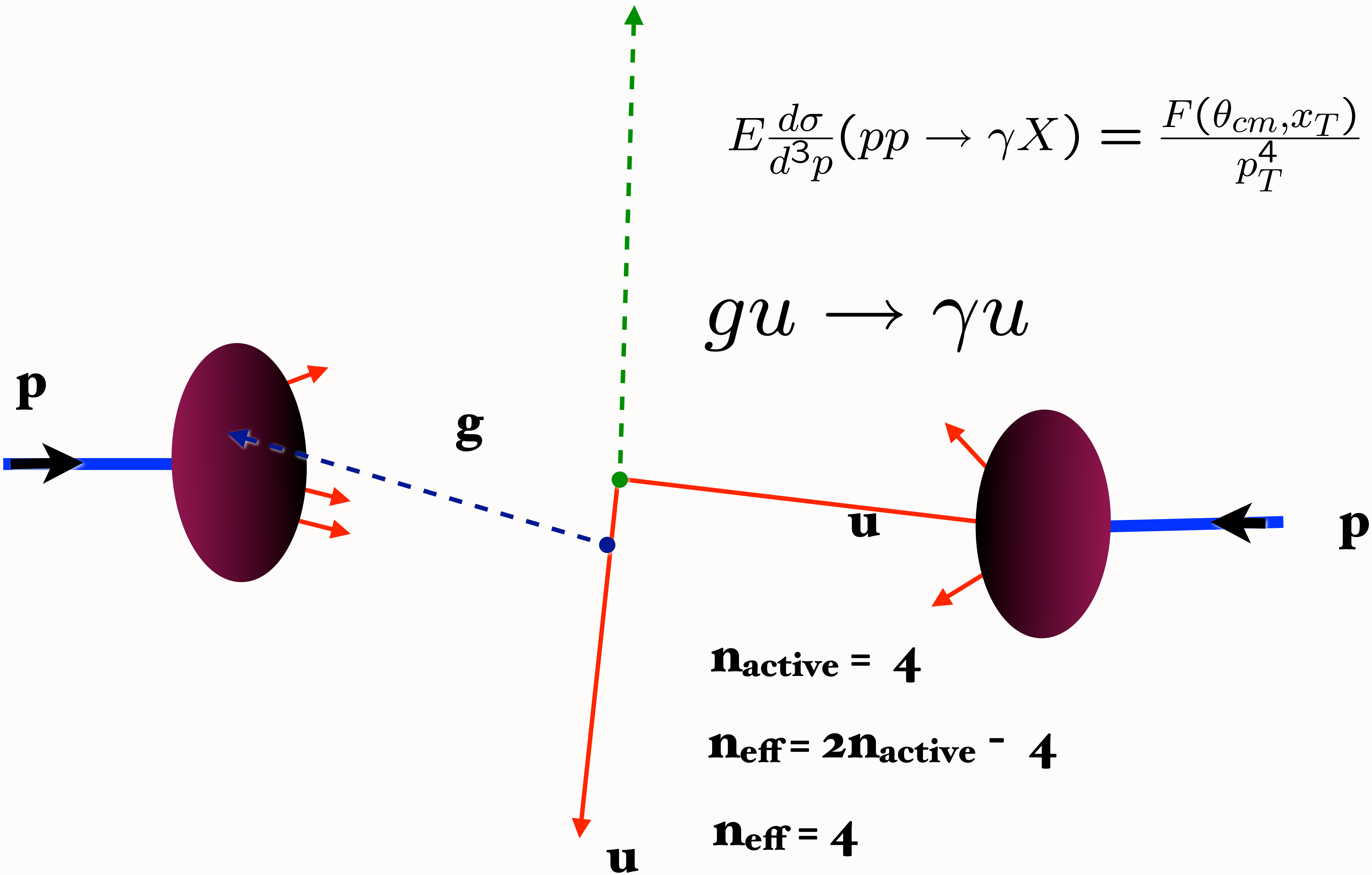
where n_{active} is the number of fields participating to the hard process

$x_\perp = 2p_\perp/\sqrt{s}$ and ϑ^{cm}: ratios of invariants

$$n_{active} = 4 \to n_{eff} = 4$$

$$pp \to \gamma X$$

$$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$$



$$gu \to \gamma u$$

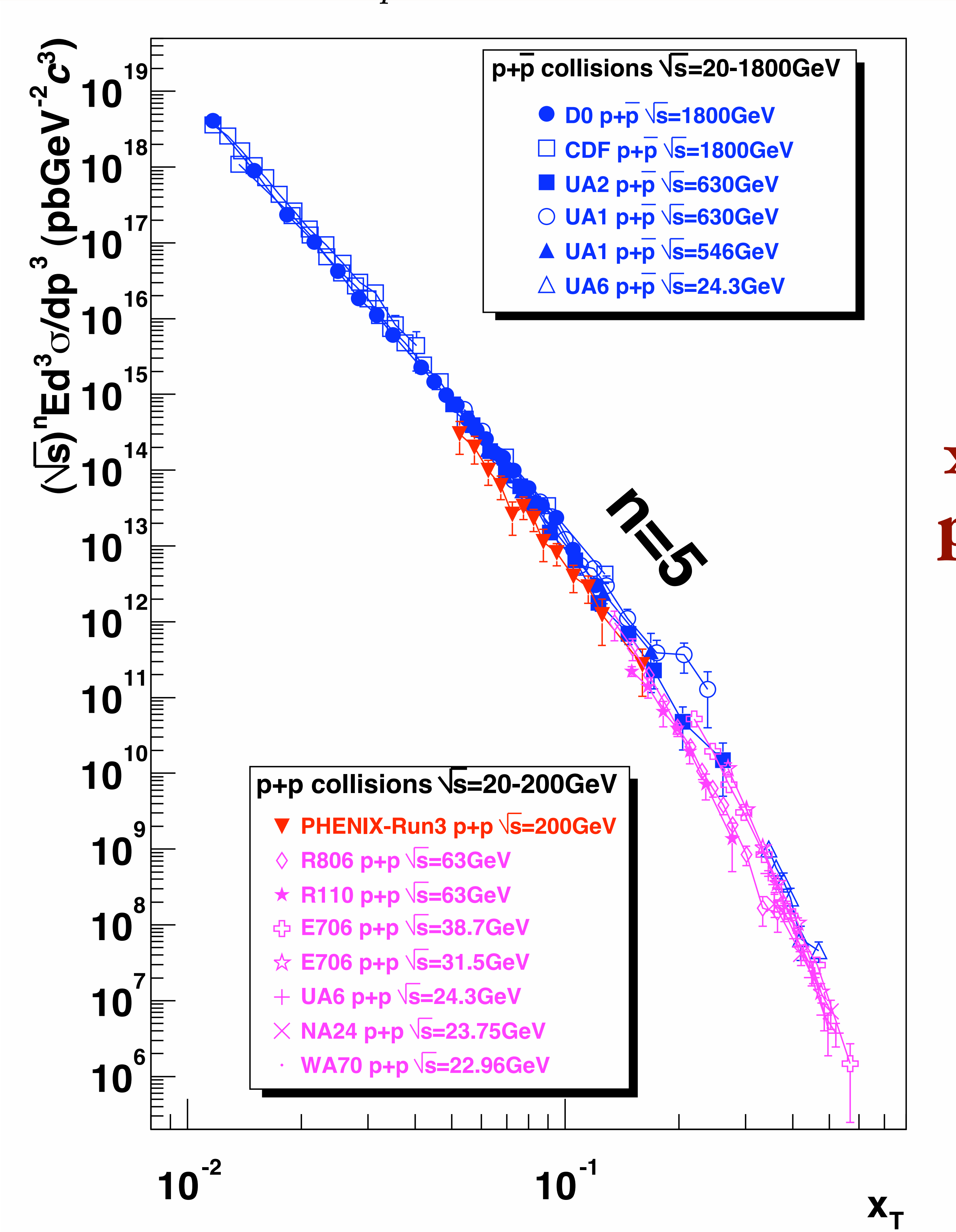
$n_{active} = 4$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 4$

$$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X) \text{ at fixed } x_T$$

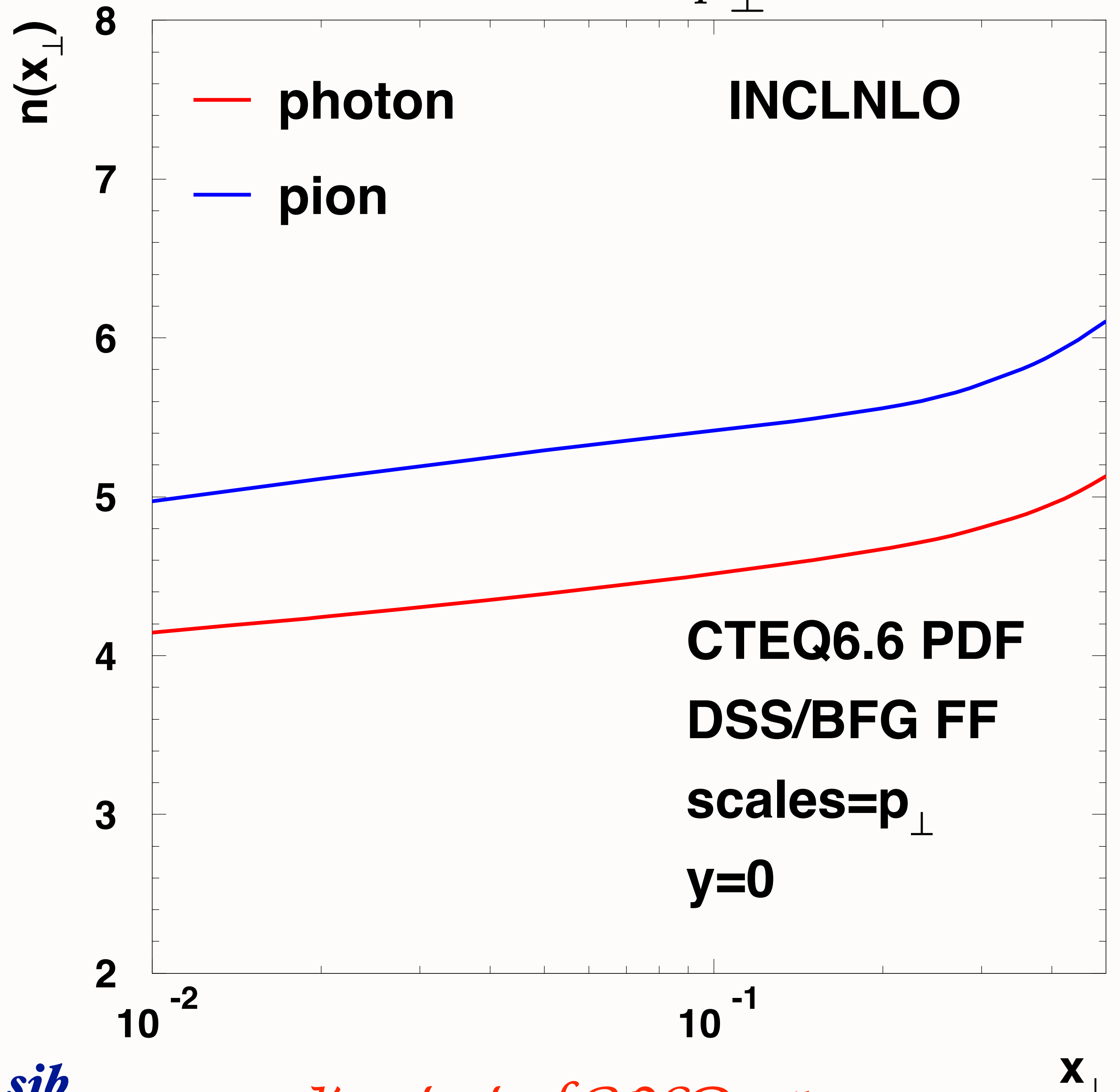
Tannenbaum



x_T-scaling of direct photon production: consistent with PQCD

QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$



$$pp \to \pi X$$

$$pp \to \gamma X$$

$$5 < p_\perp < 20\ GeV$$

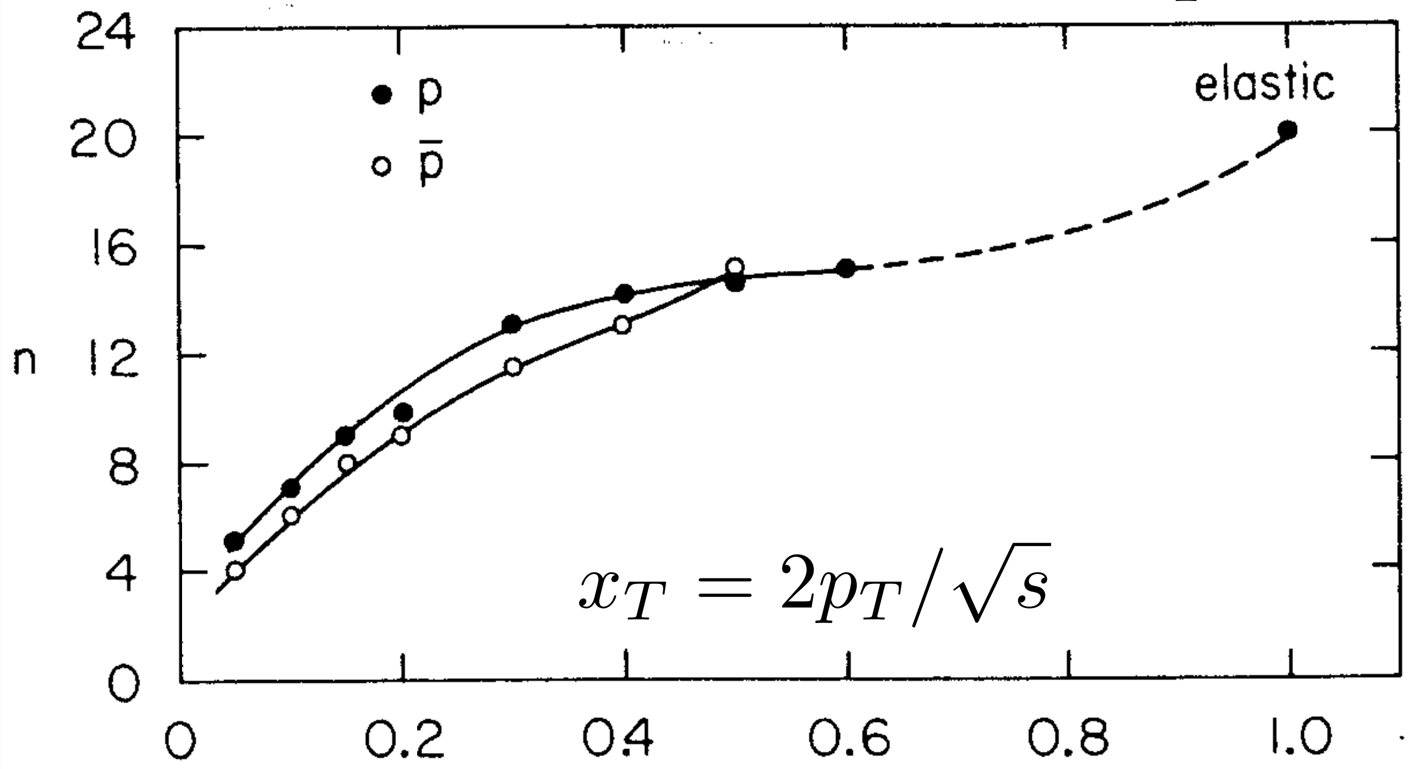
$$70\ GeV < \sqrt{s} < 4\ TeV$$

Arleo, Hwang, Sickles, sjb

Pirner, Raufeisen, sjb

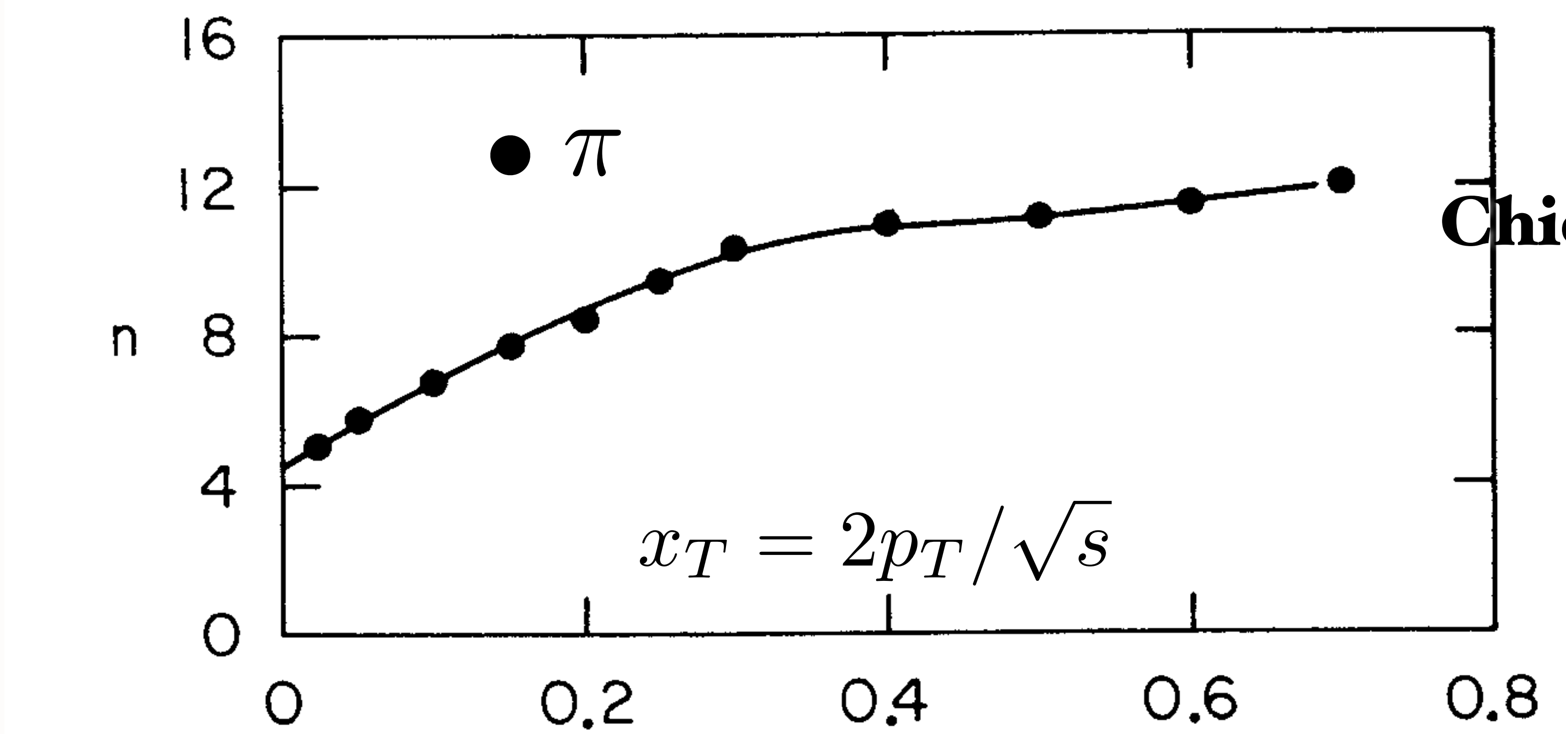
Key test of PQCD: power-law fall-off at fixed x_T

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm} = \pi/2)}{p_T^n}$$



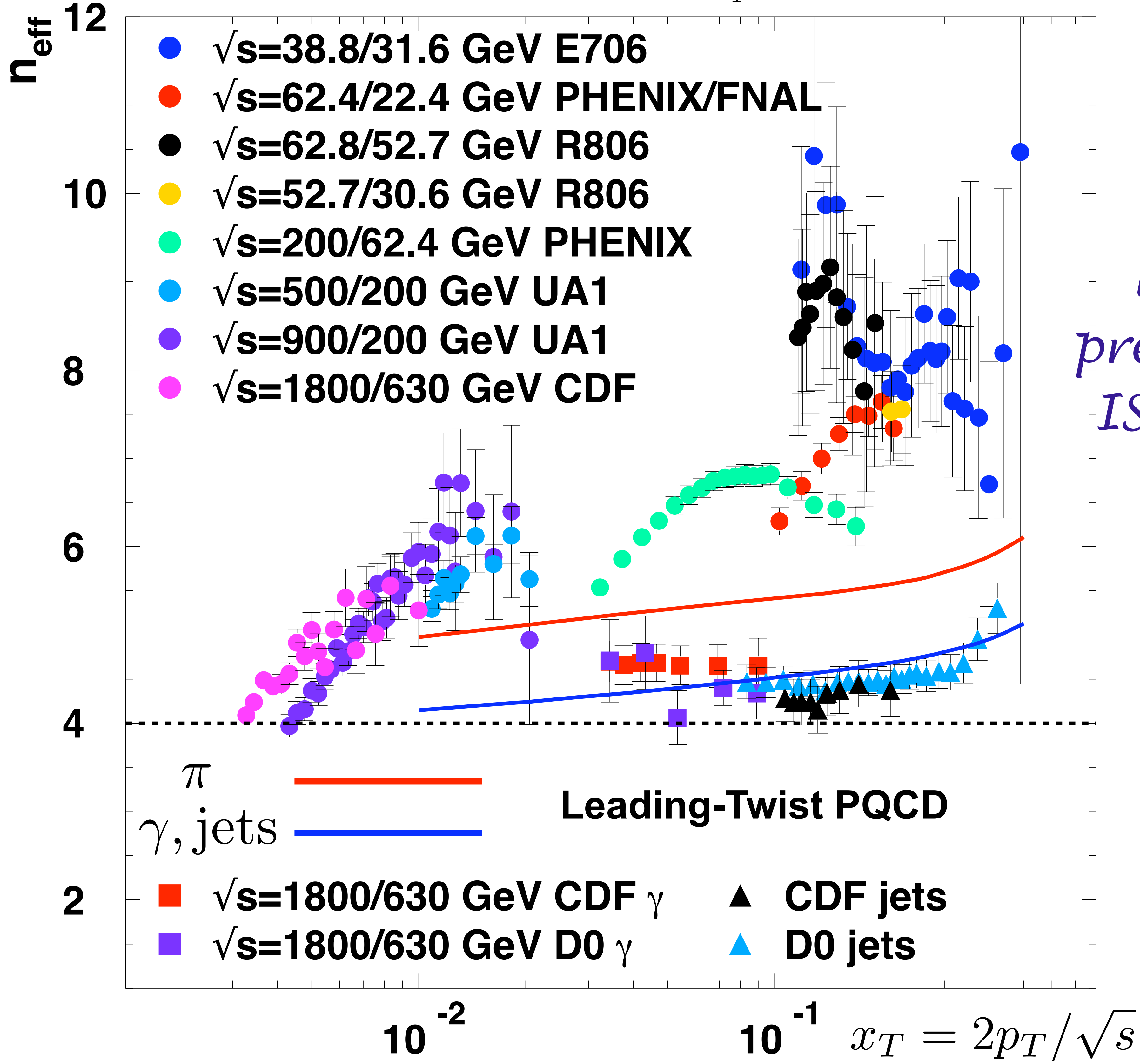
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974



Chicago-Princeton FNA

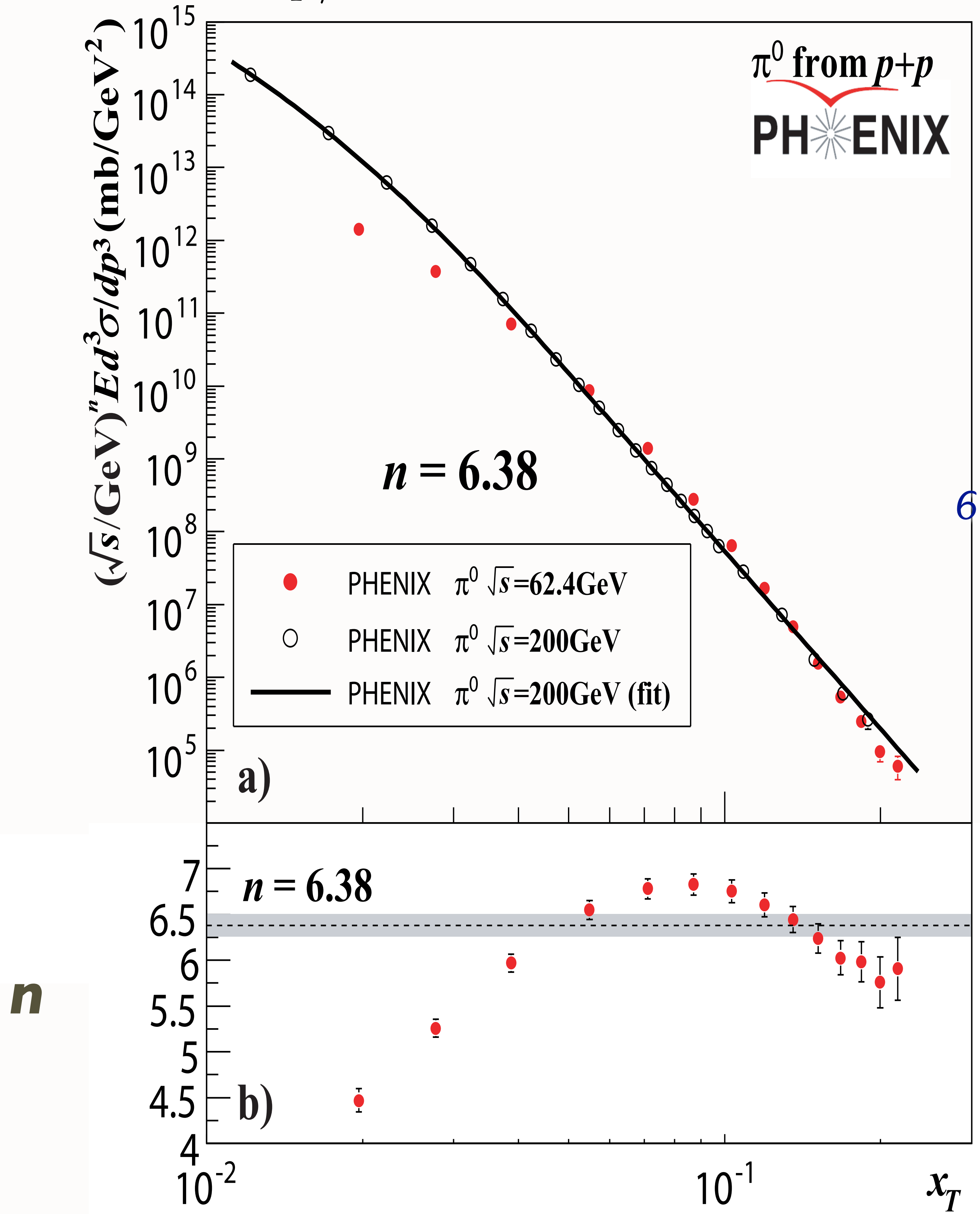
$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{\rm eff}}}$$



Leading-twist prediction fails at ISR, FNAL, RHIC, CDF!

Arleo, Hwang, Sickles, sjb

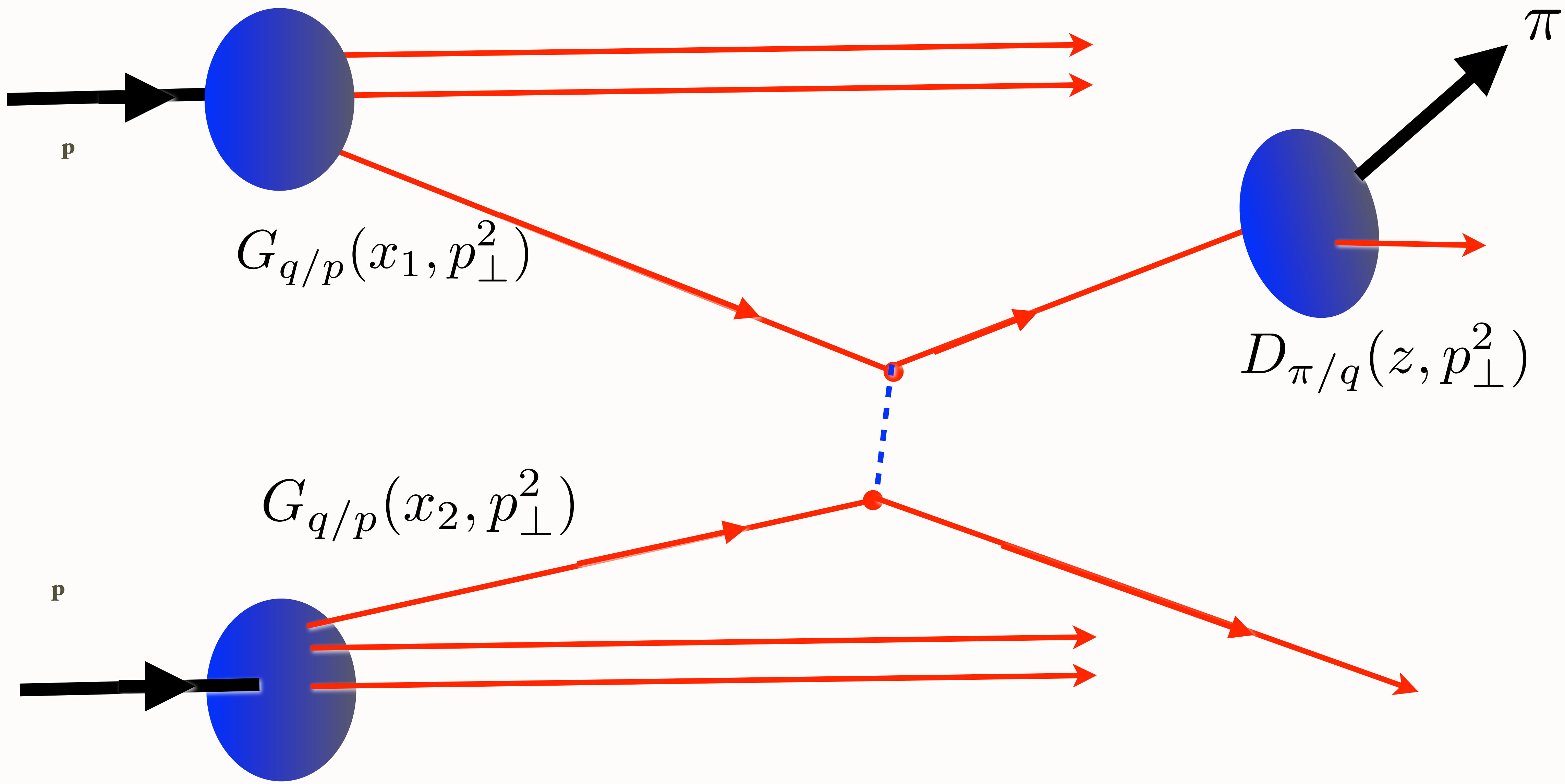
$$[\sqrt{s}]^n \frac{d\sigma}{d^3p/E}(pp \to \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}}$$



M. J. Tannenbaum

PHENIX
62.4 and 200 GeV data

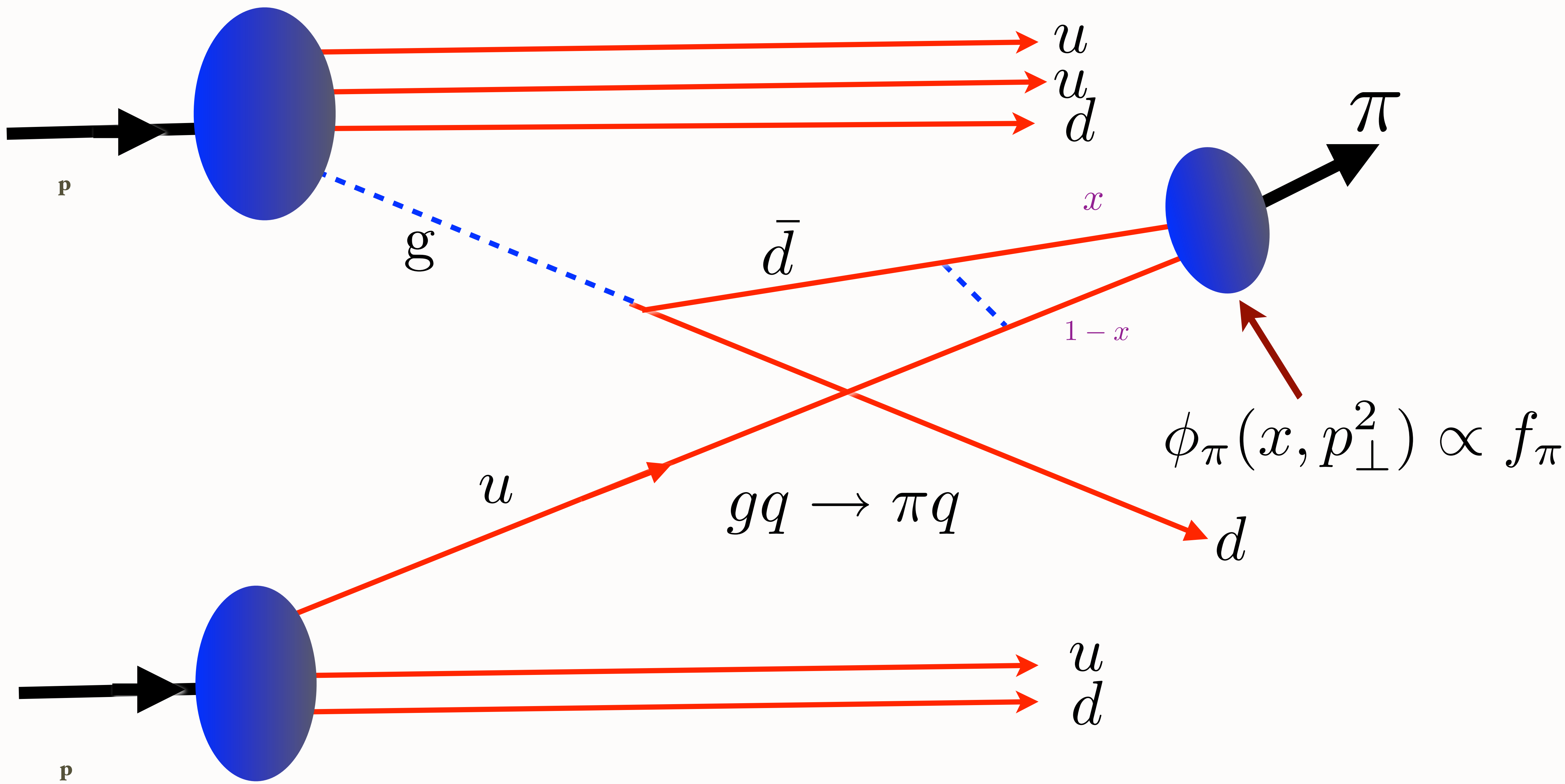
Leading-Twist Contribution to Hadron Production



Parton model and Conformal Scaling:

$$\frac{d\sigma}{d^3p/E} = \alpha_s^2 \frac{F(x_\perp, y)}{p_\perp^4}$$

Direct Higher-Twist Contribution to Hadron Production



$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

2-component toy-model

$$\sigma^{\rm model}(pp \to \pi\ \mathrm{X}) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

$$\begin{aligned} n_{\rm eff}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\rm model}}{\partial \ln p_\perp} + n^{\rm NLO}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\rm NLO}(x_\perp, p_\perp) \end{aligned}$$

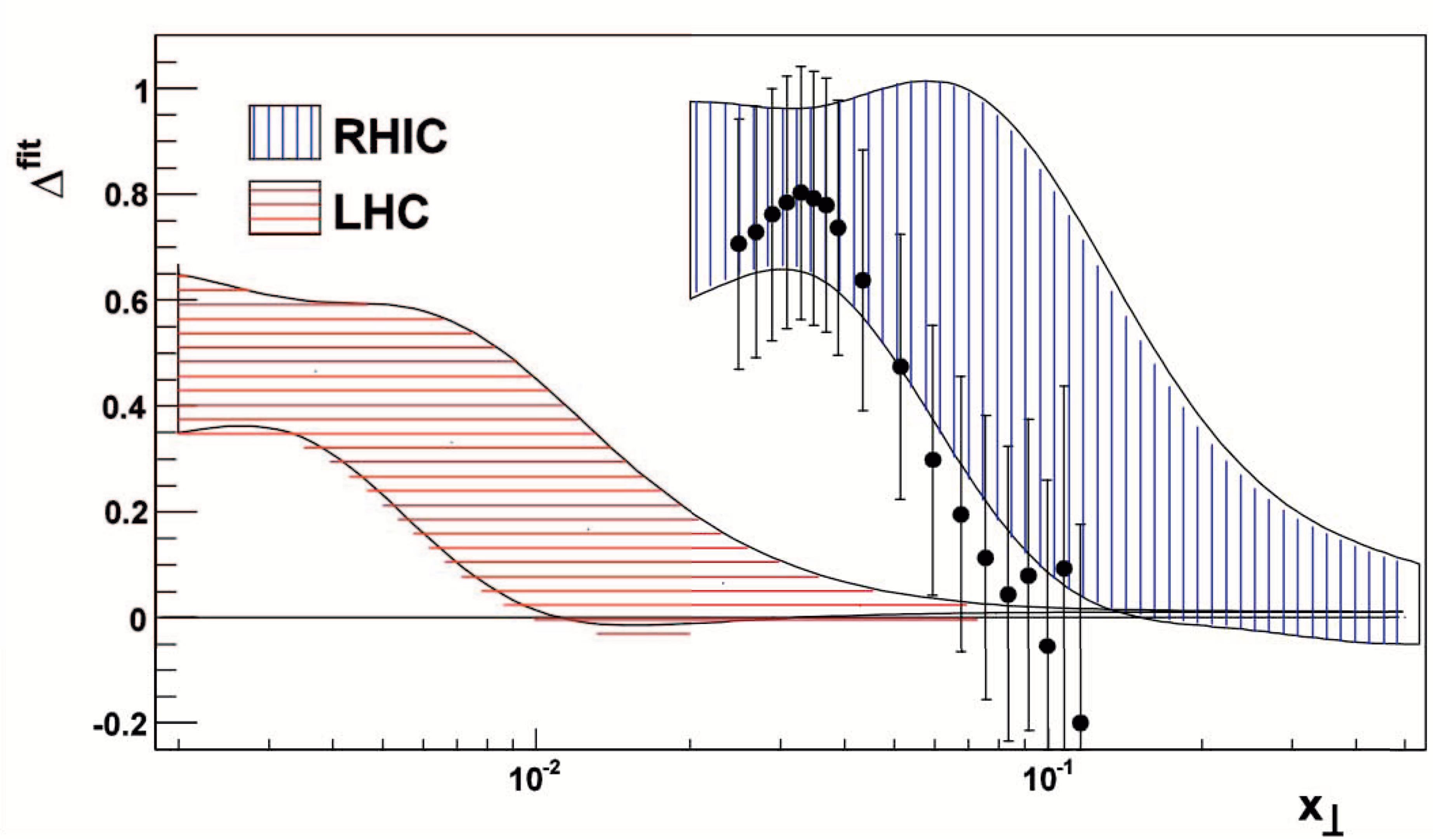
Arleo, Hwang, Sickles, sjb

RHIC/LHC predictions

PHENIX results

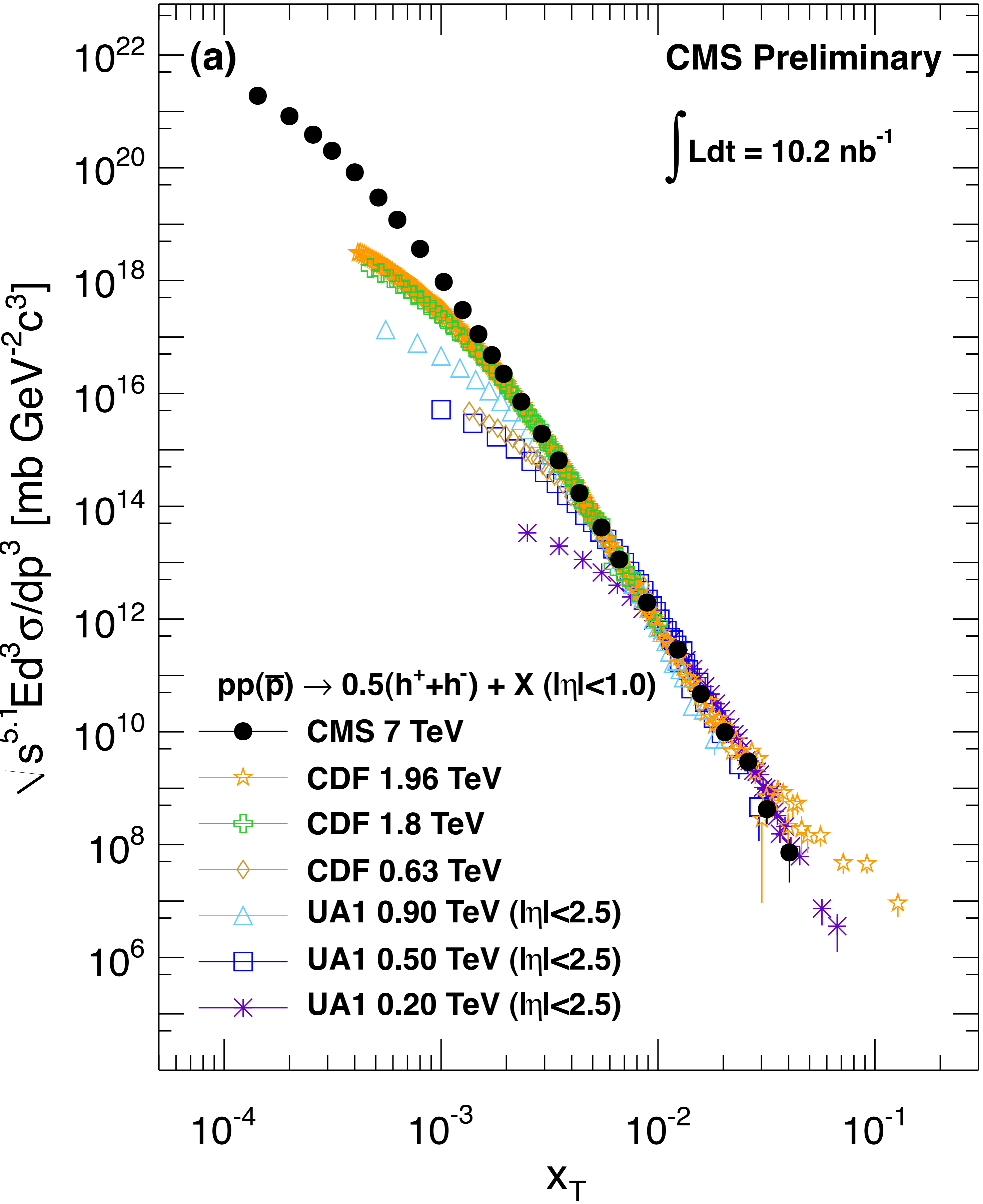
Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

[A. Bezilevsky, APS Meeting]



- Magnitude of Δ and its $x_\perp$-dependence consistent with predictions

Arleo,Hwang, Sickles, sjb



Jet-triggered charged particle transverse momentum spectra in pp collisions at 7 TeV

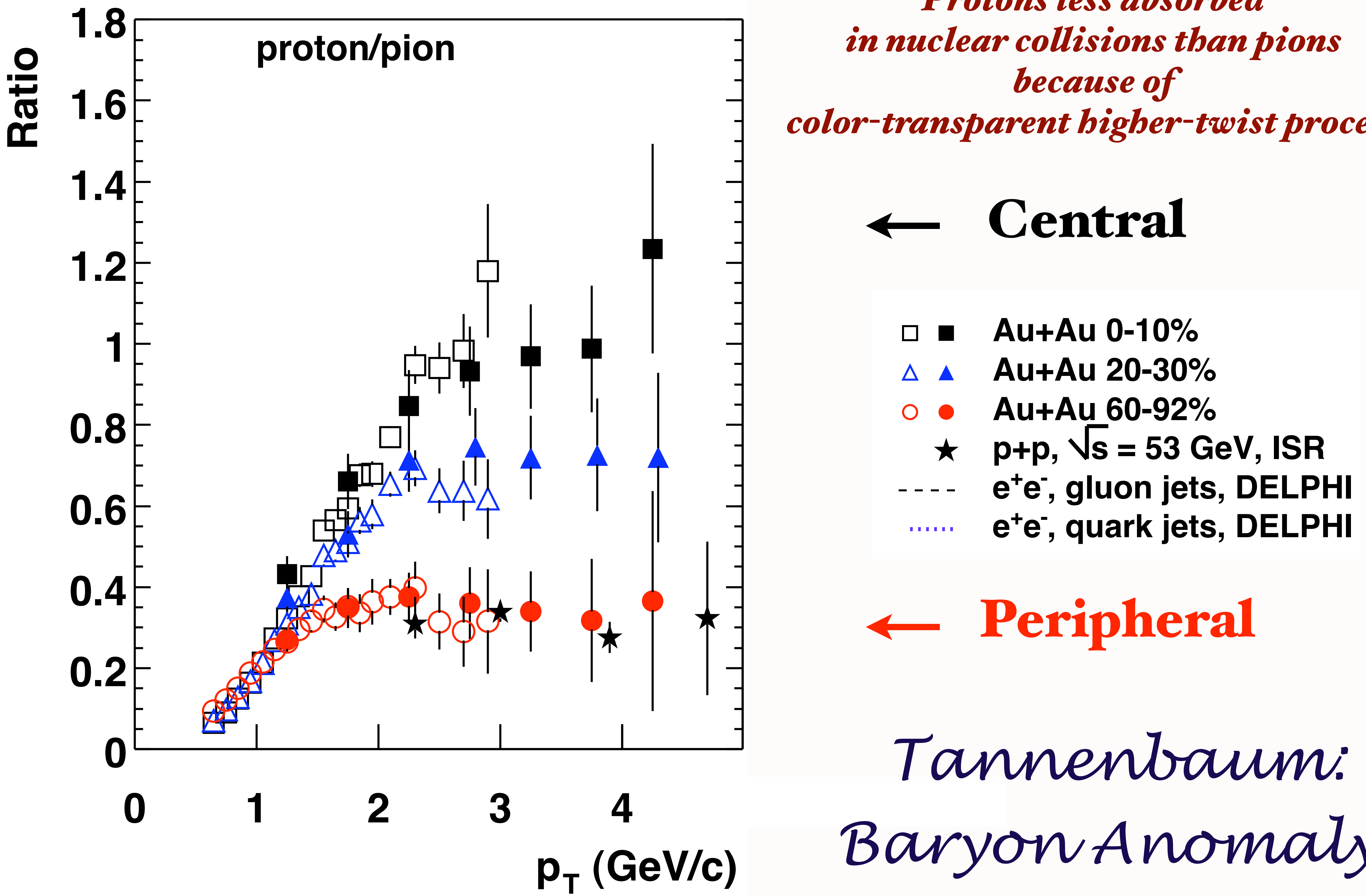
The CMS Collaboration

x_T scaling fails at the LHC

Inclusive invariant cross sections, scaled by $\sqrt{s}^{5.1}$

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett*. **91**, 172301 (2003).

Particle ratio changes with centrality!



Protons less absorbed in nuclear collisions than pions because of color-transparent higher-twist process

← **Central**

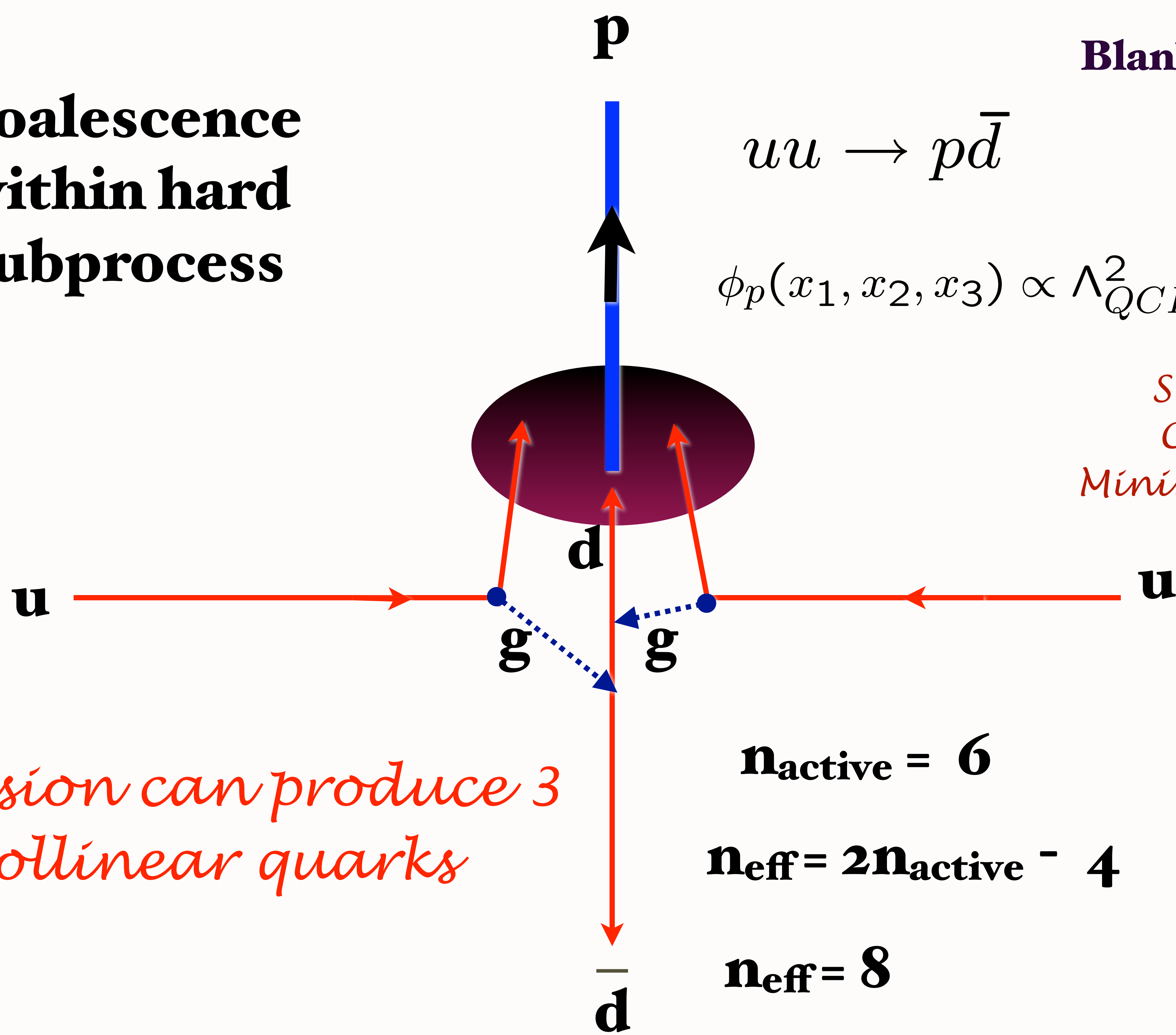
← **Peripheral**

Tannenbaum:

Baryon Anomaly:

Baryon can be made directly within hard subprocess

Coalescence within hard subprocess



$$uu \longrightarrow p\bar{d}$$

$$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$$

Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Sickles, Sjb

Small color-singlet
Color Transparent
Minimal same-side energy

Collision can produce 3 collinear quarks

$\mathbf{n_{active} = 6}$

$\mathbf{n_{eff} = 2n_{active} - 4}$

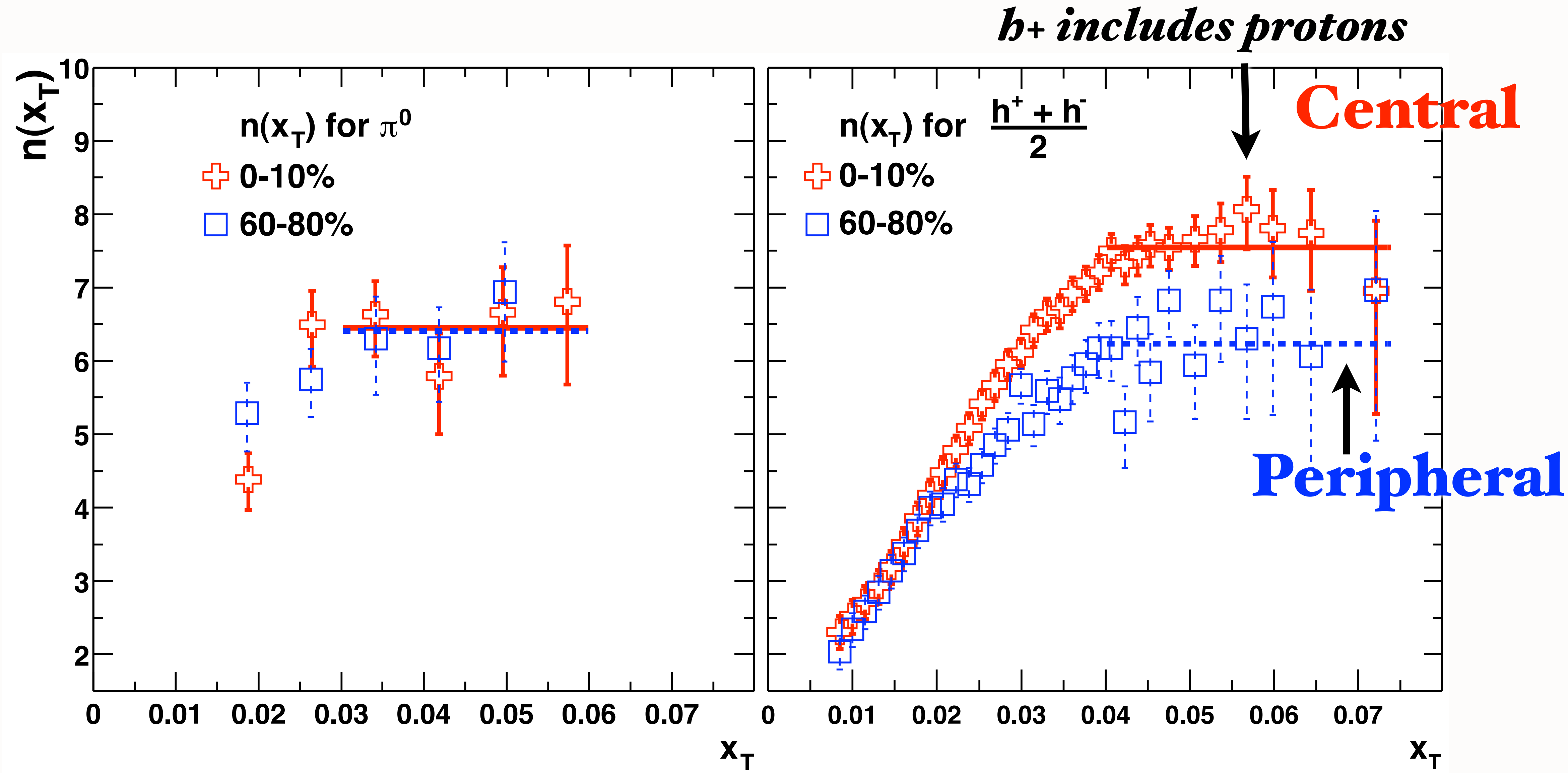
$\mathbf{n_{eff} = 8}$

$$qq \longrightarrow B\bar{q}$$

Arleo, Hwang, Sickles, sjb

Power-law exponent $n(x_T)$ for π^0 and h spectra in central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV

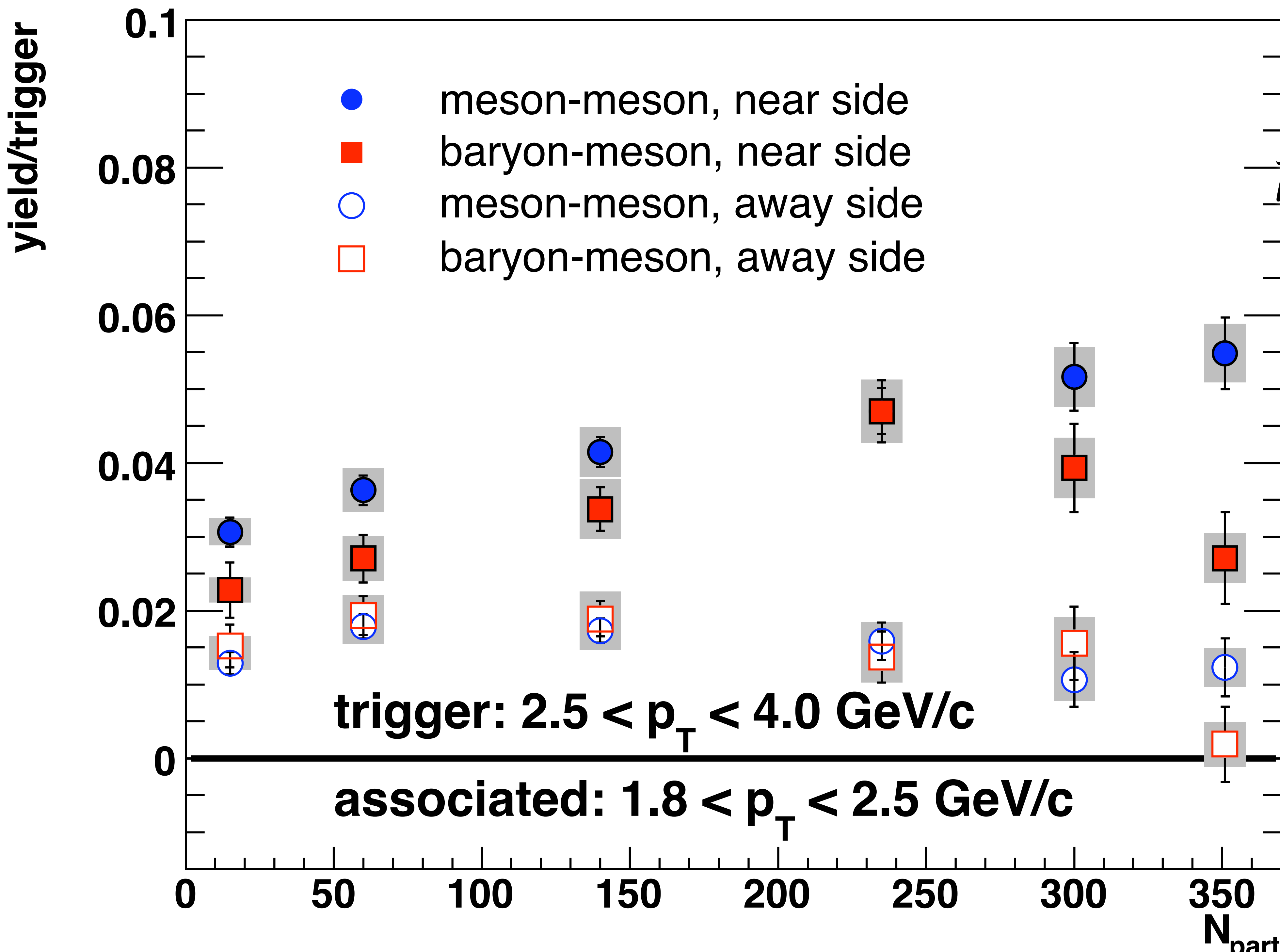
S. S. Adler, *et al.*, PHENIX Collaboration, *Phys. Rev.* C **69**, 034910 (2004) [nucl-ex/0308006].



Proton power changes with centrality !

Proton production dominated by
color-transparent direct high n_{eff} subprocesses

Anne Sickles



proton trigger: # same-side particles decreases with centrality

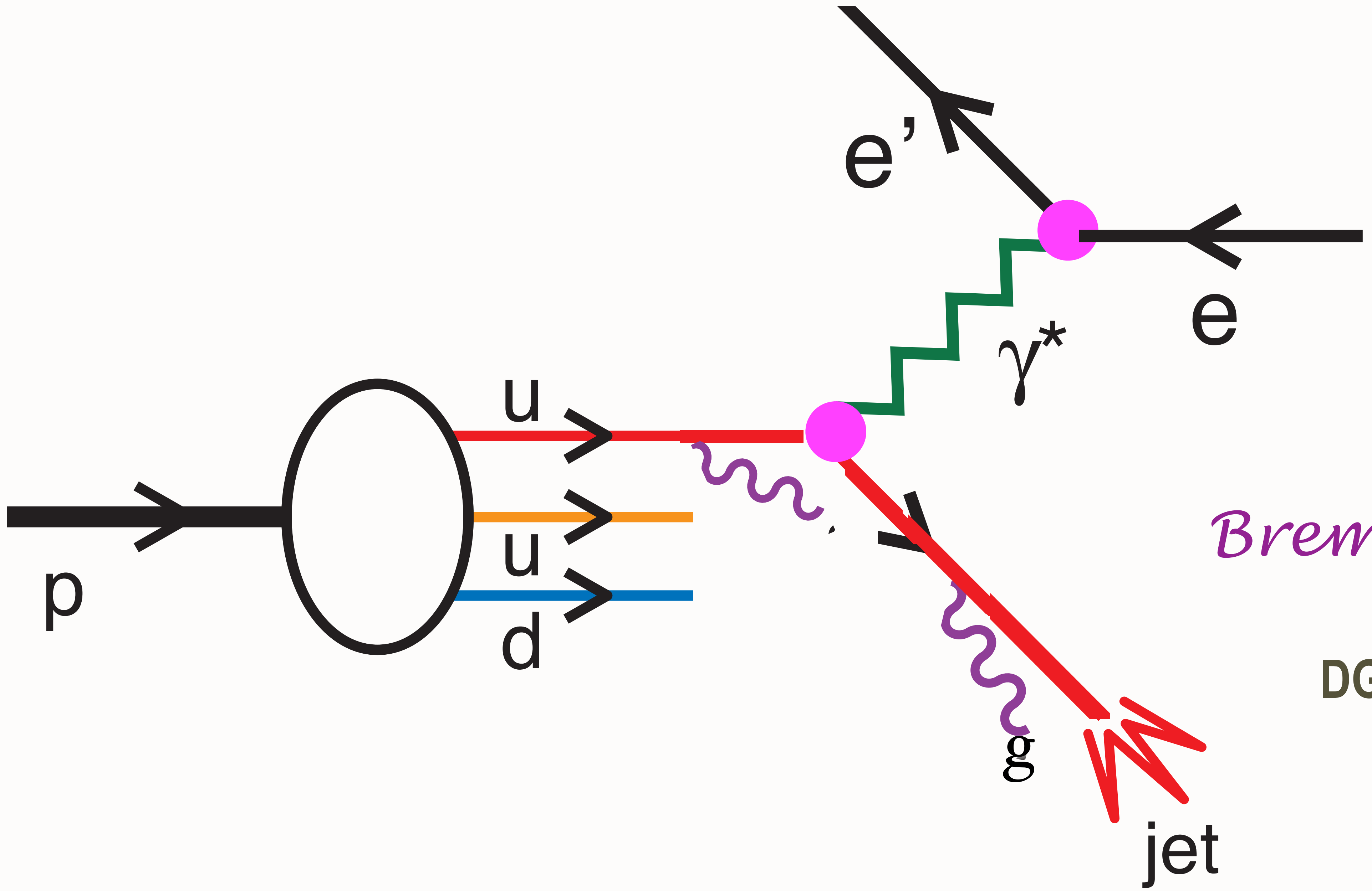
Proton production more dominated by color-transparent direct high-n_{eff} subprocesses

Evidence for Direct, Higher-Twist Subprocesses

- **Explains anomalous power behavior at fixed x_T**
- **Protons more likely to come from direct higher-twist subprocess than pions**
- **Protons less absorbed than pions in central nuclear collisions because of color transparency**
- **Predicts increasing proton to pion ratio in central collisions** *Baryon Anomaly Explained*
- **Proton power n_{eff} increases with centrality since leading twist contribution absorbed**
- **Fewer same-side hadrons for proton trigger at high centrality**
- **Exclusive-inclusive connection at $x_T = 1$**

Arleo, Hwang, Sickles, sjb

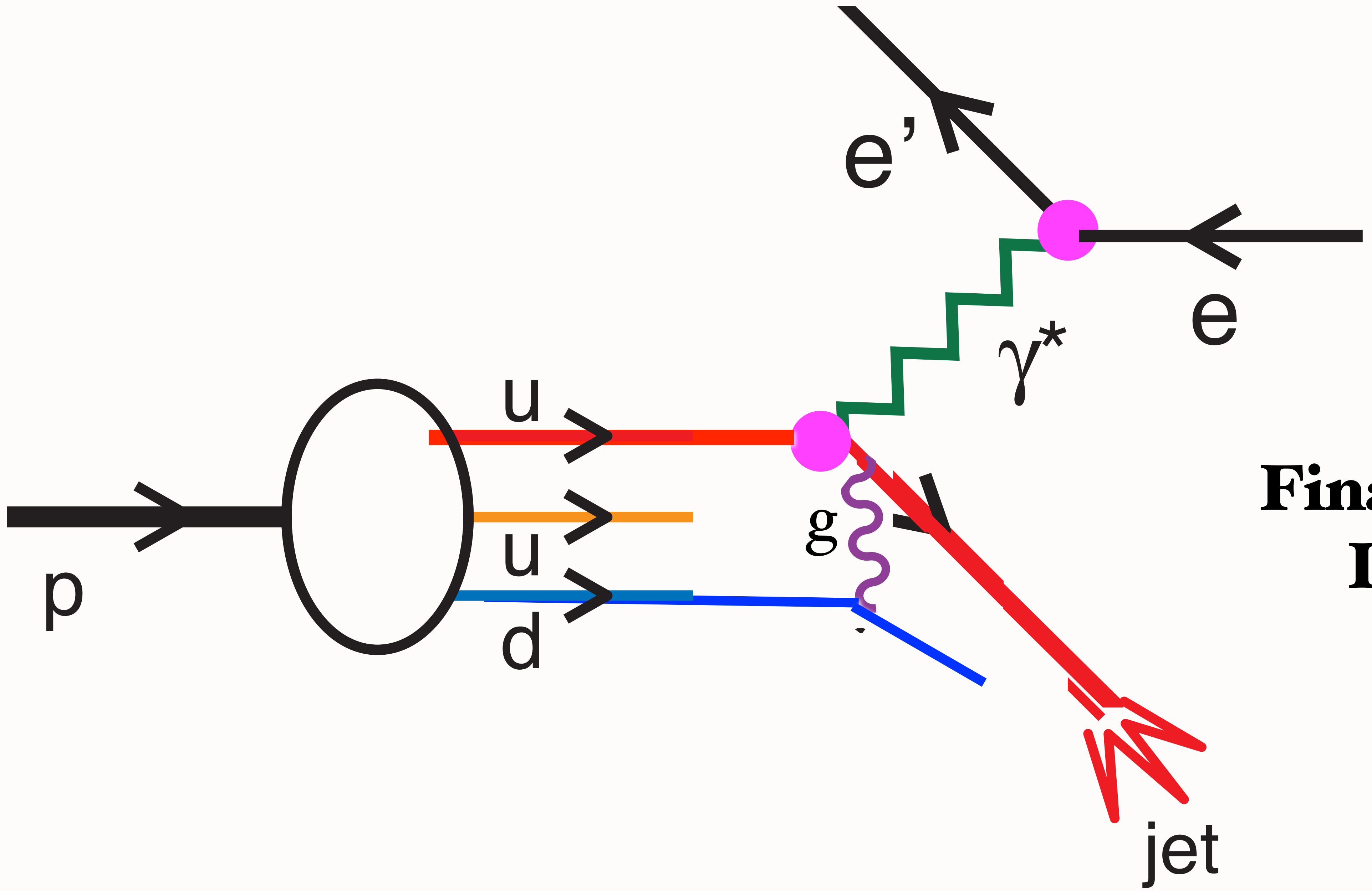
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:
Final-state interactions of struck quark can be neglected

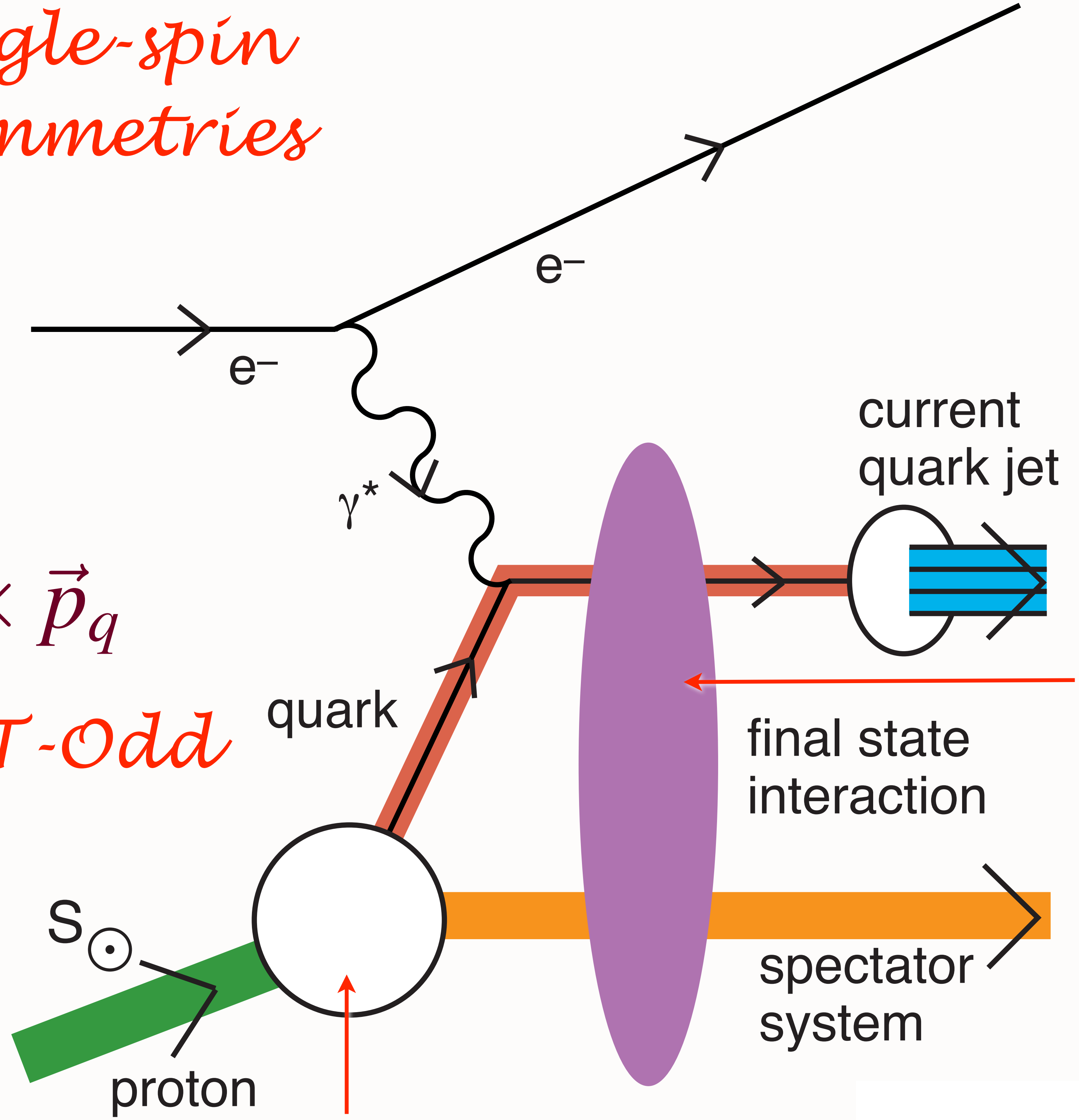
Single-spin asymmetries

Leading Twist Sivers Effect

Dae Sung Hwang, Ivan Schmidt, sjb

$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

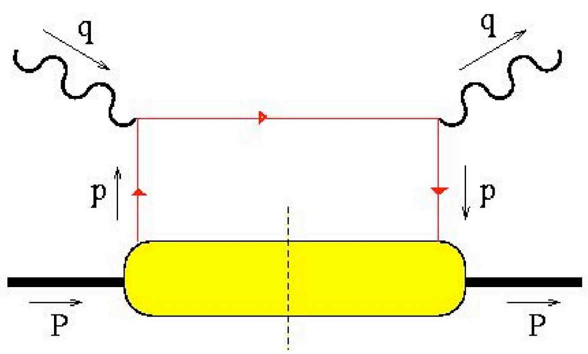
Pseudo- T-Odd



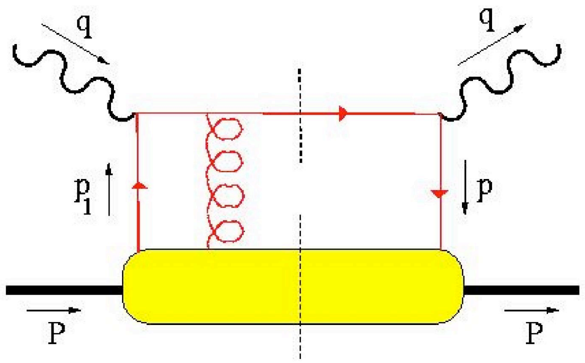
QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

Leading-Twist Rescattering Violates pQCD Factorization!



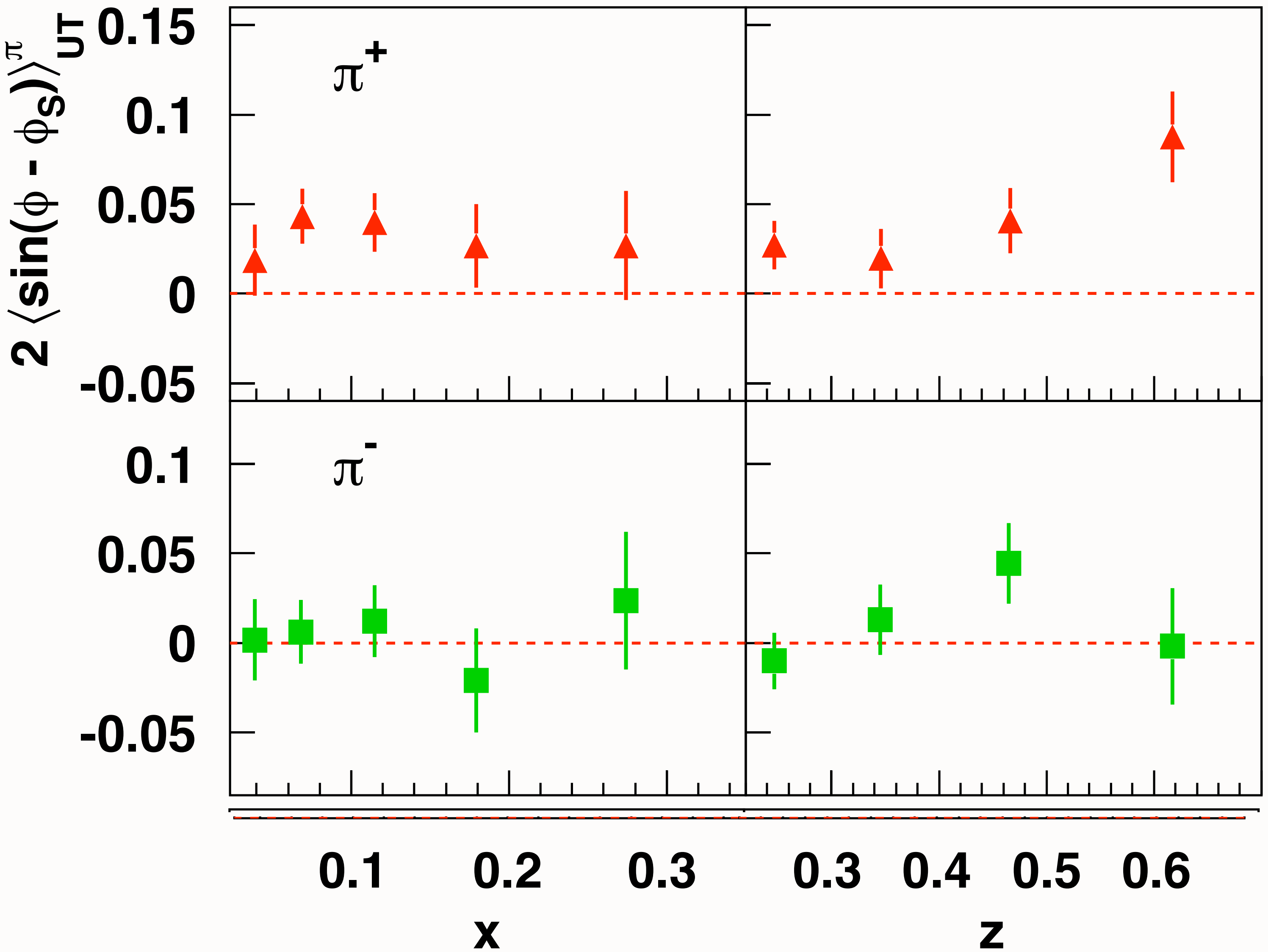
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

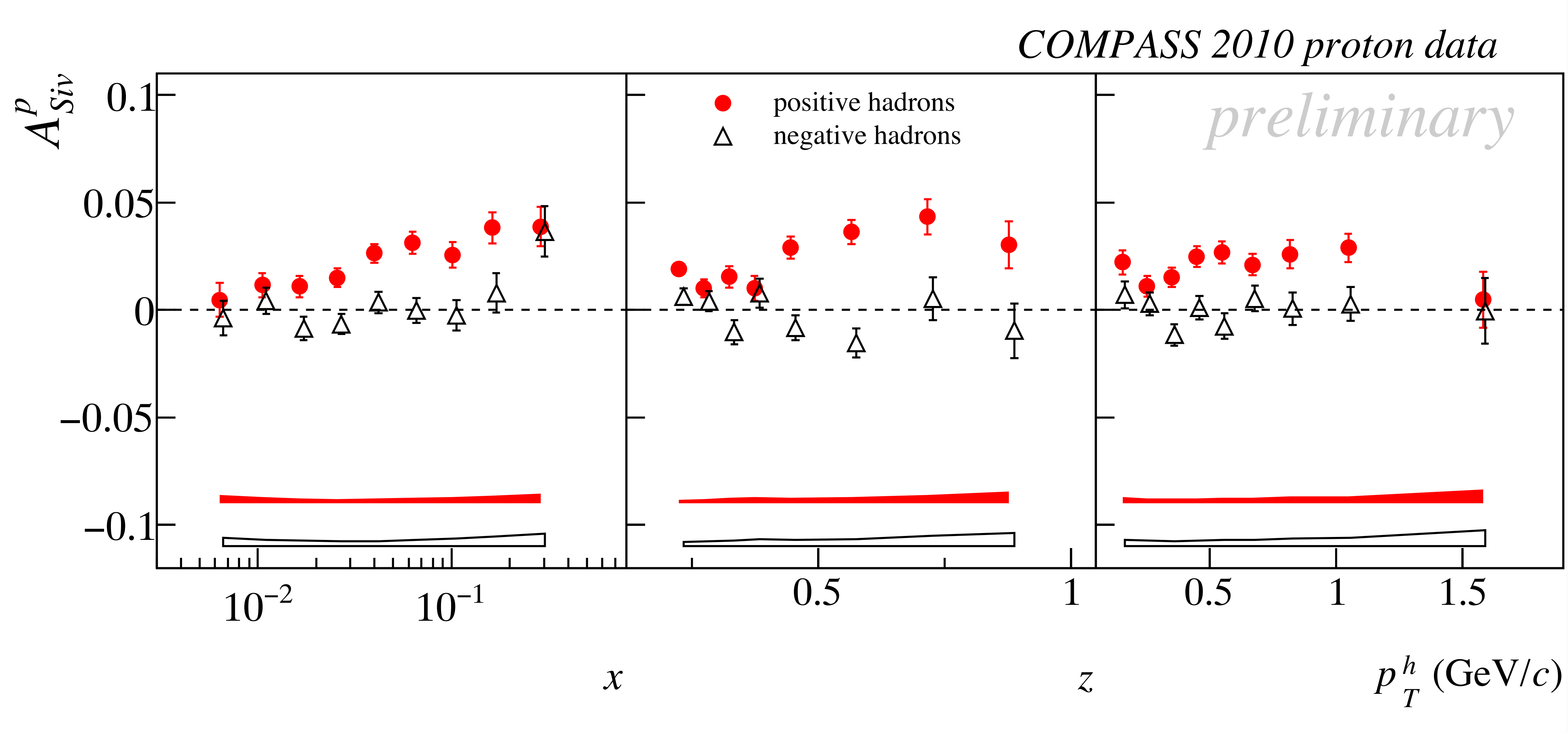
Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for π^+...
  Consistent with zero for π^-...

Gamberg: Hermes data compatible with BHS model

Schmidt, Lu:
Asymmetry ratios should follow quark contributions to anomalous moment

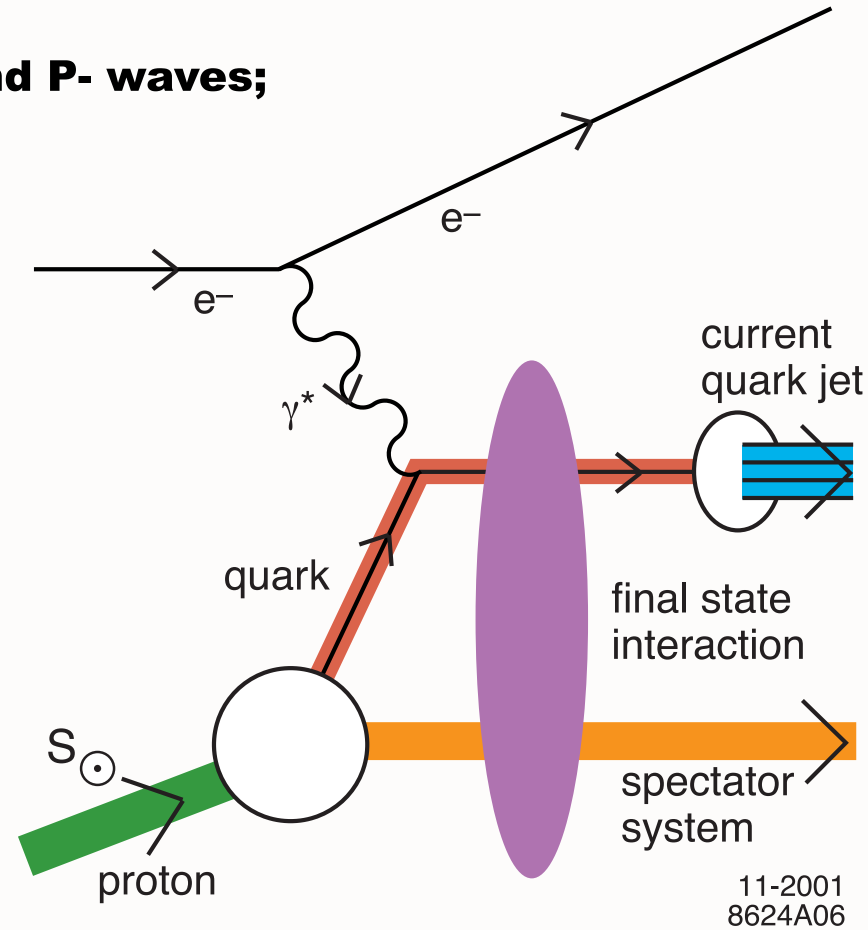

COMPASS 2010 proton data
A^p_{Siv}
0.1
0.05
0
−0.05
−0.1
positive hadrons
negative hadrons
preliminary
10^{-2}
10^{-1}
0.5
1
0.5
1
1.5
x
z
p^h_T (GeV/c)

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

Hwang, Schmidt, sjb
Collins

- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves;**
- **Wilson line effect -- gauge independent**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$



Pasquini, Xiao, Yuan, sjb
Mulders, Boer   Qiu, Sterman

Recent COMPASS data on deuteron: small Sivers effect

- The anomalous magnetic moment, the Sivers function, and the generalized parton distribution E can all be connected to matrix elements involving the orbital angular momentum of the nucleon's constituents.
- The SSA can be generated by either a quark or gluon mechanism, and the isospin structure of the two mechanisms is distinct. The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentum carried by gluons in the nucleon, is small.
- Studies of the SSA in ϕ or K^+K^- production, via $\gamma^* g \to s\bar{s} \to \phi + X$ or $\gamma^* g \to s\bar{s} \to K^+K^- + X$ should provide additional constraints on the gluon mechanism.

Gardner, sjb

PHYSICAL REVIEW D **75**, 073008 (2007)

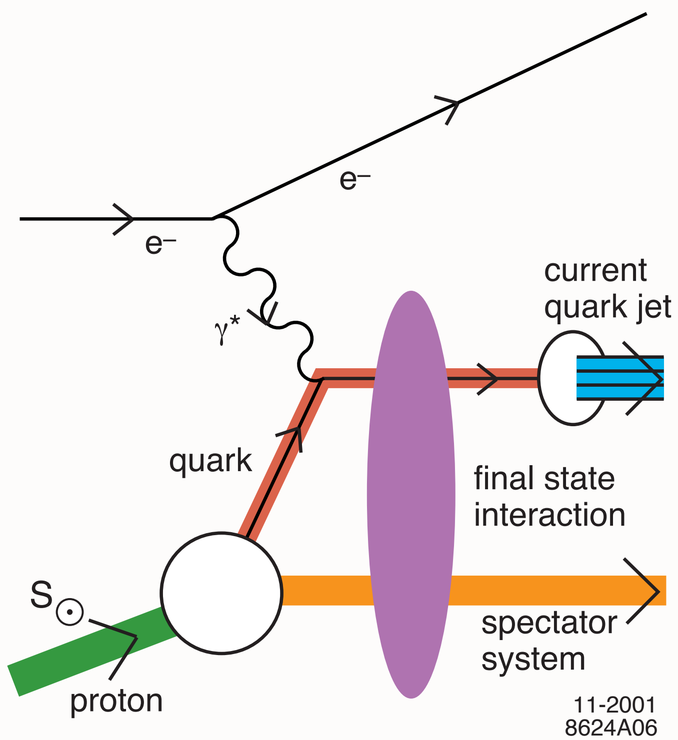
Connection between the Sivers function and the anomalous magnetic moment

Zhun Lu* and Ivan Schmidt†

Departamento de Física, Universidad Técnica Federico, Santa María, Casilla 110-V, Valparaíso, Chile
and Center of Subatomic Physics, Valparaíso, Chile

(Received 8 January 2007; revised manuscript received 14 February 2007; published 9 April 2007)

The same light-front wave functions of the proton are involved in both the anomalous magnetic moment of the nucleon and the Sivers function. Using the diquark model, we derive a simple relation between the anomalous magnetic moment and the Sivers function, which should hold in general with good approximation. This relation can be used to provide constraints on the Sivers single spin asymmetries from the data on anomalous magnetic moments. Moreover, the relation can be viewed as a direct connection between the quark orbital angular momentum and the Sivers function.



$$\kappa_p = (2)(2/3)\kappa_{u/p} + (-1/3)\kappa_{d/p},$$

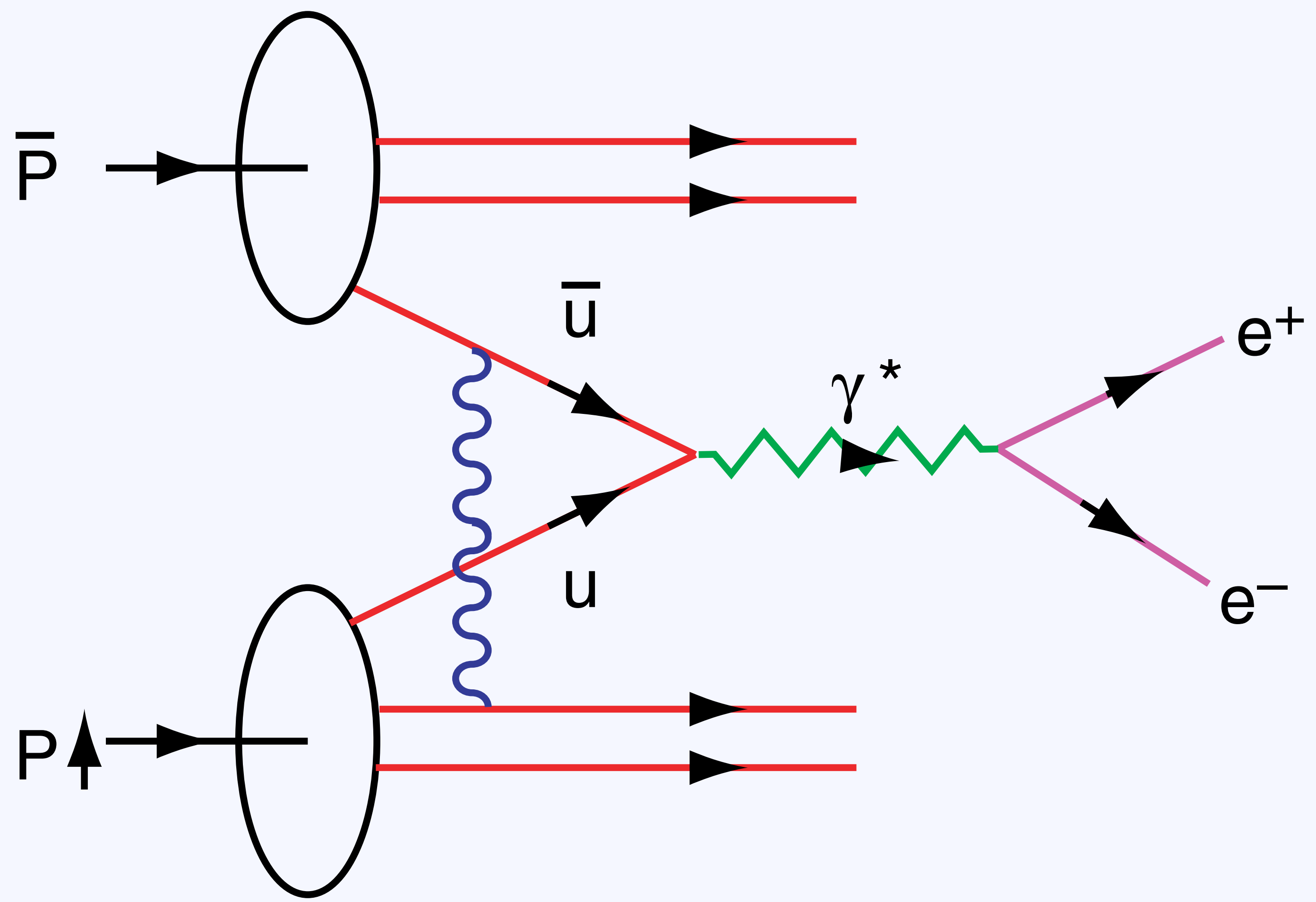
$$\kappa_n = (2)(-1/3)\kappa_{u/p} + (2/3)\kappa_{d/p}.$$

$$\frac{A_{UT}^{\rm Siv}(\pi^+)}{A_{UT}^{\rm Siv}(\pi^-)} \approx \frac{2e_u^2 f_{1T}^{\perp u} D_1^{\pi^+/u}}{e_d^2 f_{1T}^{\perp d} D_1^{\pi^-/d}} \approx \frac{2e_u^2 \kappa_u}{e_d^2 \kappa_d} = -3.3.$$

$$\frac{A_{UT}^{\rm Siv}(\pi^0)}{A_{UT}^{\rm Siv}(\pi^-)} \approx \frac{2e_u^2 f_{1T}^{\perp u} D_1^{\pi^0/u} + e_d^2 f_{1T}^{\perp d} D_1^{\pi^0/d}}{e_d^2 f_{1T}^{\perp d} D_1^{\pi^-/d}} \approx \frac{2e_u^2 \kappa_u + e_d^2 \kappa_d}{2e_d^2 \kappa_d} = -1.15,$$

$$\frac{A_{UT}^{\rm Siv}(K^+)}{A_{UT}^{\rm Siv}(K^0)} \approx \frac{2e_u^2 f_{1T}^{\perp u} D_1^{K^+/u}}{e_d^2 f_{1T}^{\perp d} D_1^{K^0/d}} \approx \frac{4e_u^2 \kappa_u}{e_d^2 \kappa_d} = -6.6.$$

Predict Opposite Sign SSA in DY !



Collins

Hwang
Schmidt
sjb

Single Spin Asymmetry In the Drell Yan Process
$\vec{S}_p \cdot \vec{\overline{p}} \times \vec{q}_{\gamma^*}$
Quarks Interact in the Initial State
Interference of Coulomb Phases for *S* and *P* states
Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.
Opposite Sign to DIS! No Factorization

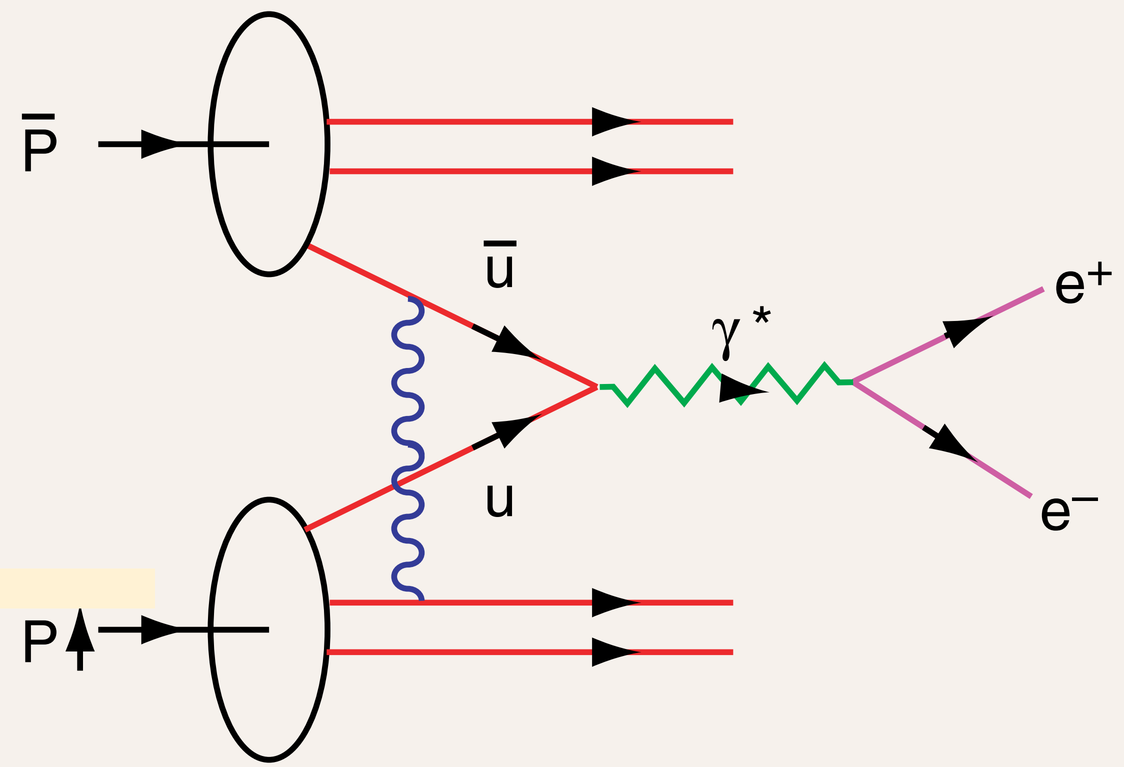
Key QCD Experiment

Collins;
Hwang, Schmidt.
sjb

Measure single-spin asymmetry A_N in Drell-Yan reactions

Leading-twist Bjorken-scaling A_N from S, P-wave initial-state gluonic interactions

Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!



$$\bar{p}p_{\uparrow} \to \ell^+\ell^- X$$

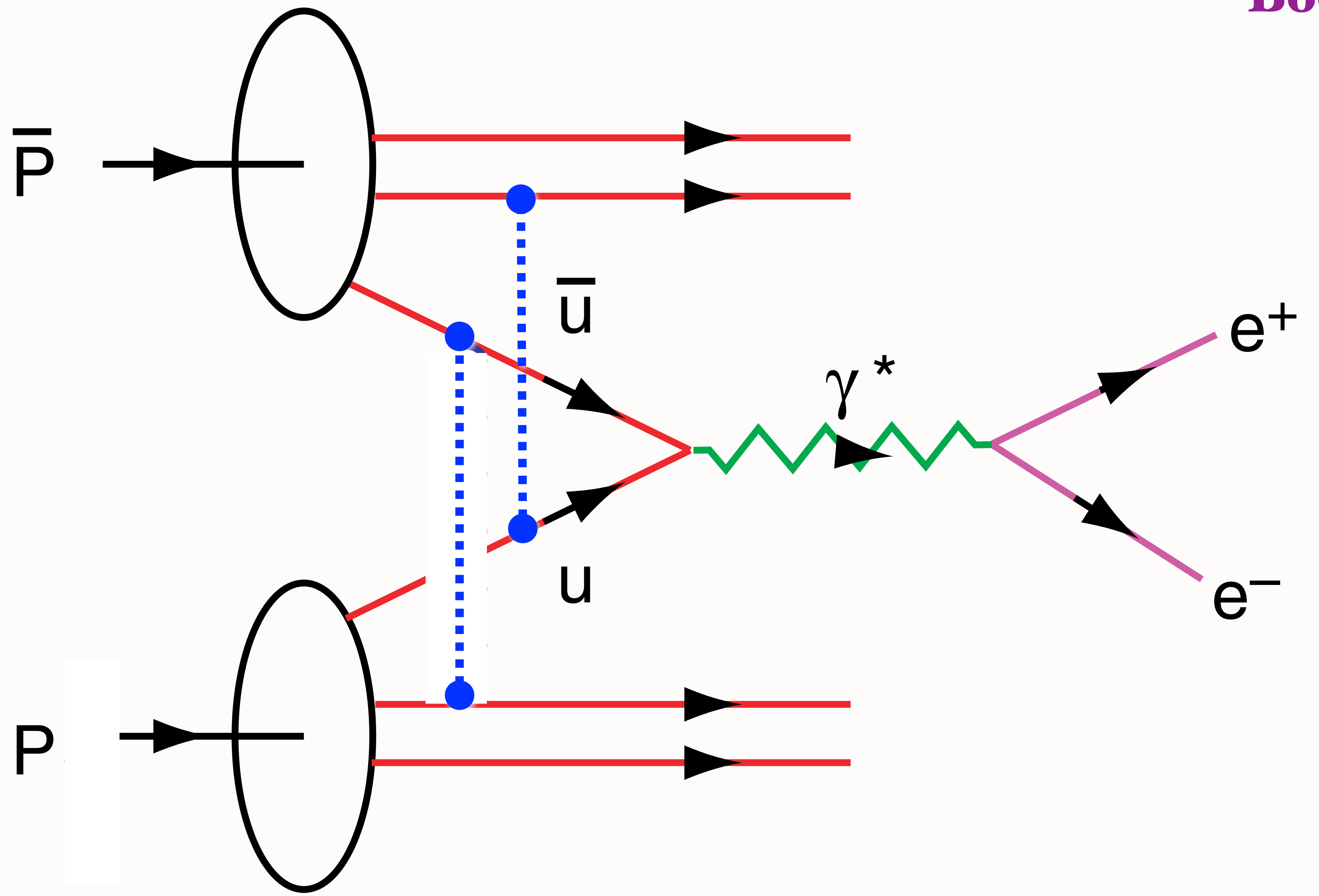
$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

Recent COMPASS data on deuteron: small Sivers effect

- The anomalous magnetic moment, the Sivers function, and the generalized parton distribution E can all be connected to matrix elements involving the orbital angular momentum of the nucleon's constituents.
- The SSA can be generated by either a quark or gluon mechanism, and the isospin structure of the two mechanisms is distinct. The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentum carried by gluons in the nucleon, is small.
- Studies of the SSA in ϕ or K^+K^- production, via $\gamma^* g \to s\bar{s} \to \phi + X$ or $\gamma^* g \to s\bar{s} \to K^+K^- + X$ should provide additional constraints on the gluon mechanism.

Gardner, sjb

Boer, Hwang, sjb



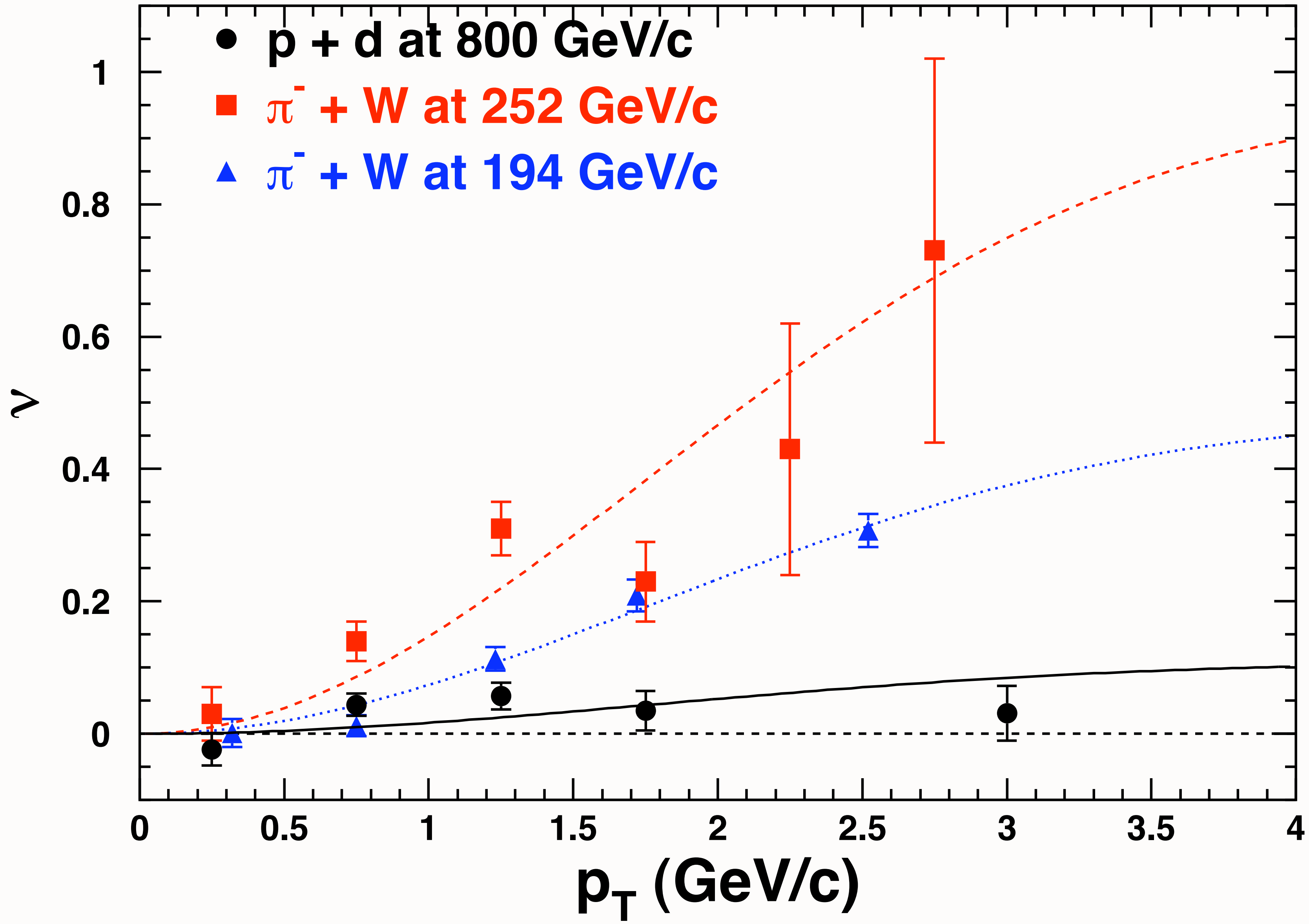
DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_{\perp}^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_{\perp}^2)$$

Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)



Huge Effect in $\pi W \to \mu^+ \mu^- X$

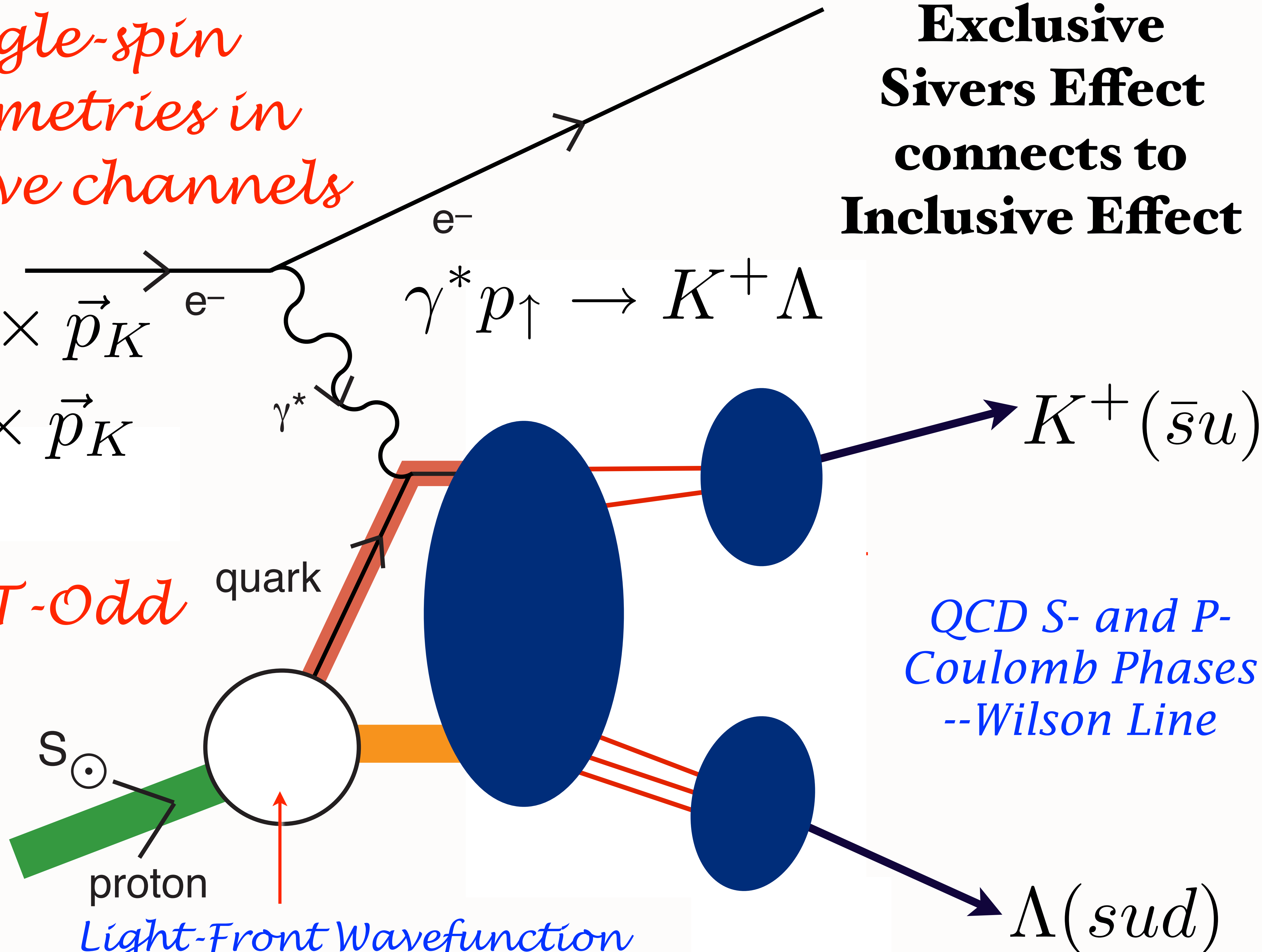
Negligible Effect $pd \to \mu^+ \mu^- X$

Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Single-spin asymmetries in exclusive channels

$$i\vec{S}_\Lambda \cdot \vec{q} \times \vec{p}_K$$
$$i\vec{S}_p \cdot \vec{q} \times \vec{p}_K$$

Exclusive Sivers Effect connects to Inclusive Effect



Pseudo- T-Odd

QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

Double Initial-State Interactions generate anomalous $\cos 2\phi$

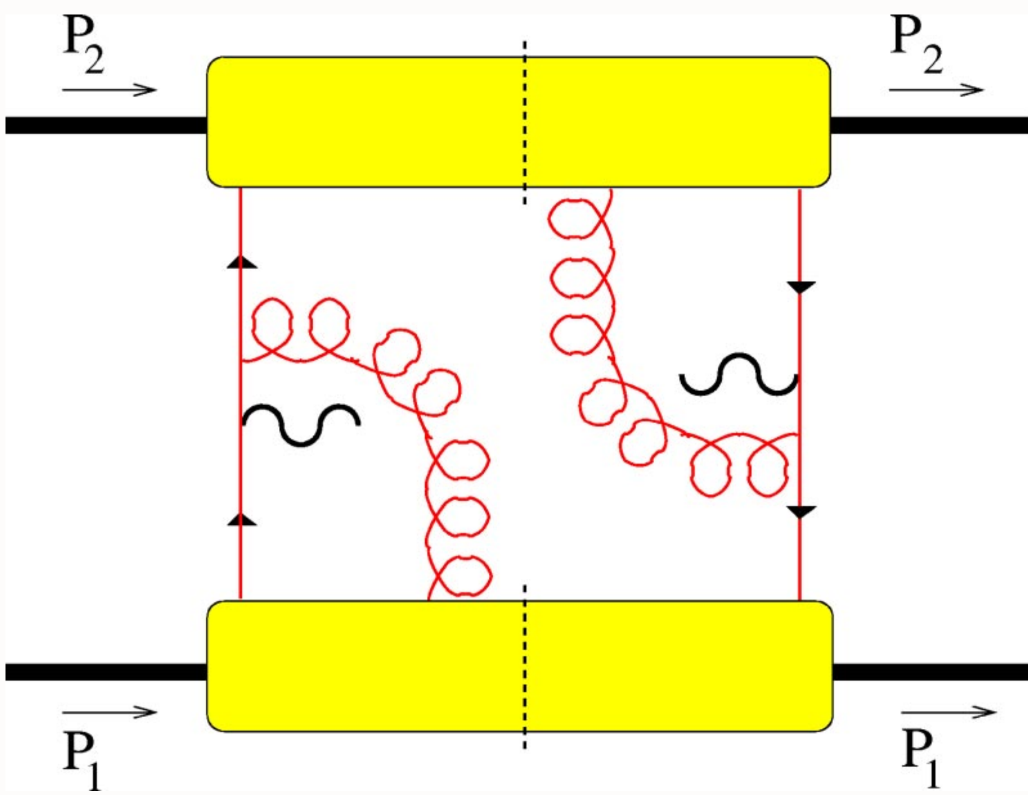
Boer, Hwang, sjb

Drell-Yan planar correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

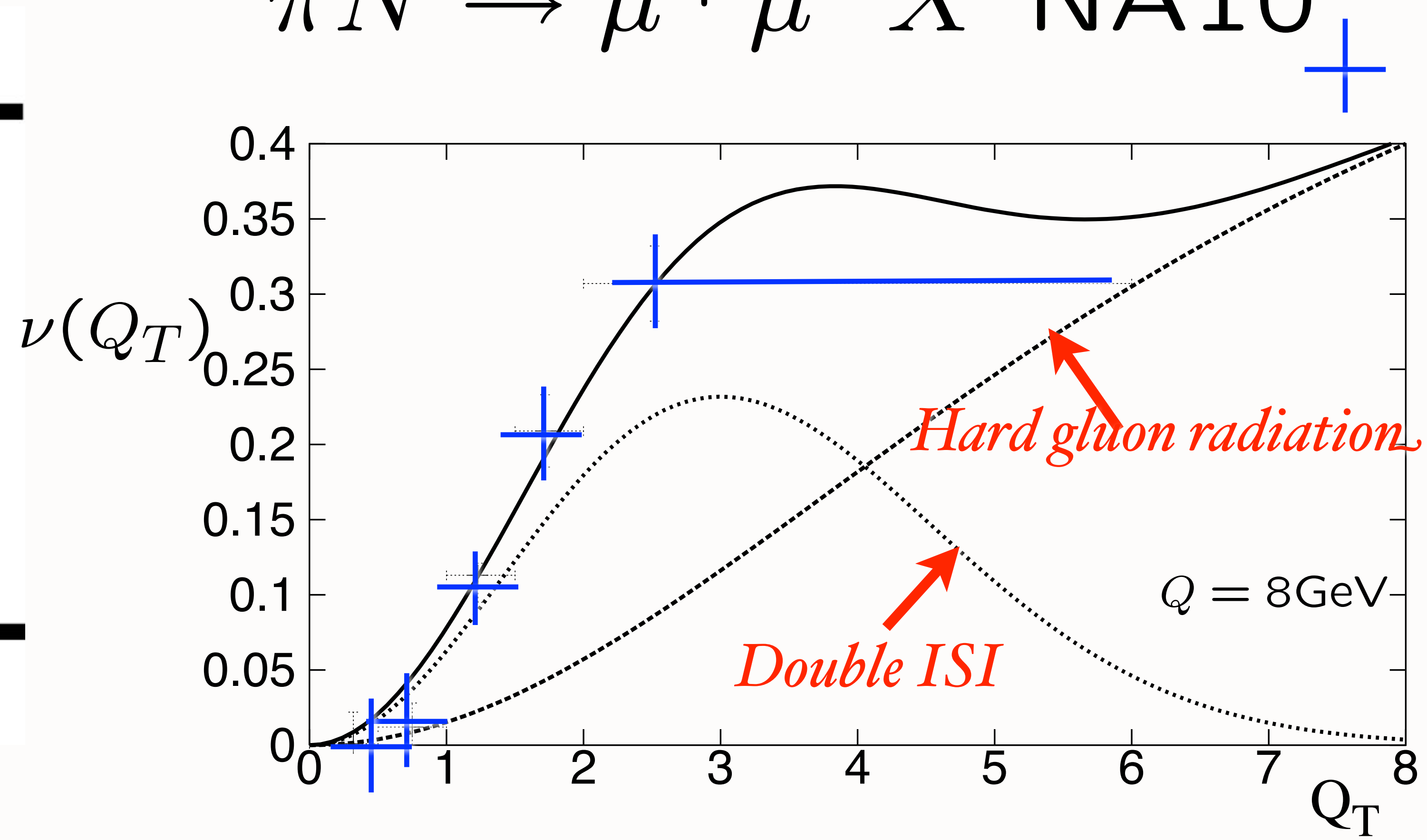
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^\perp(\pi)\, h_1^\perp(N)$$



Violates Lam-Tung relation!

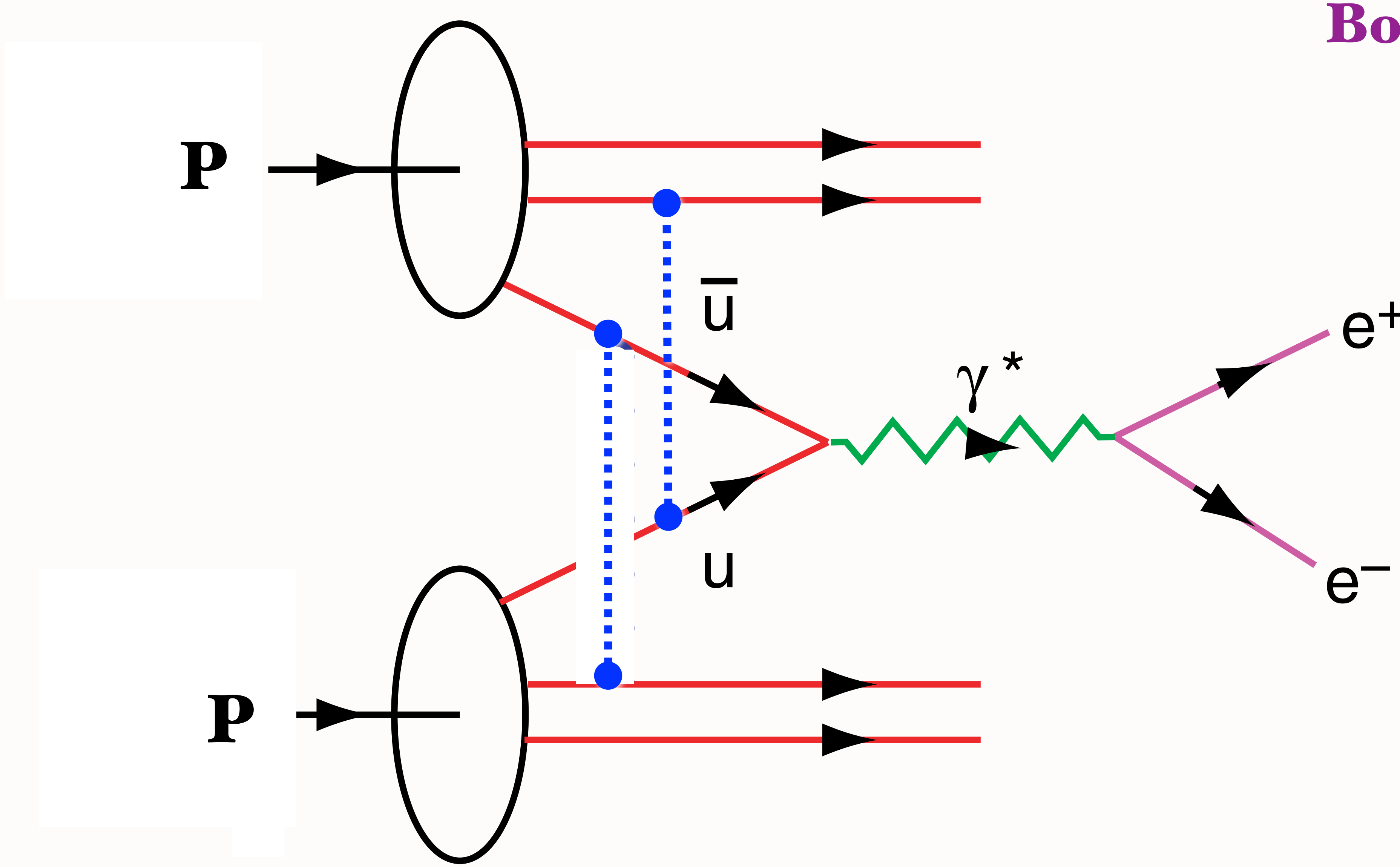
$\pi N \to \mu^+\mu^- X$ NA10



Model: Boer,

LHC Experiment

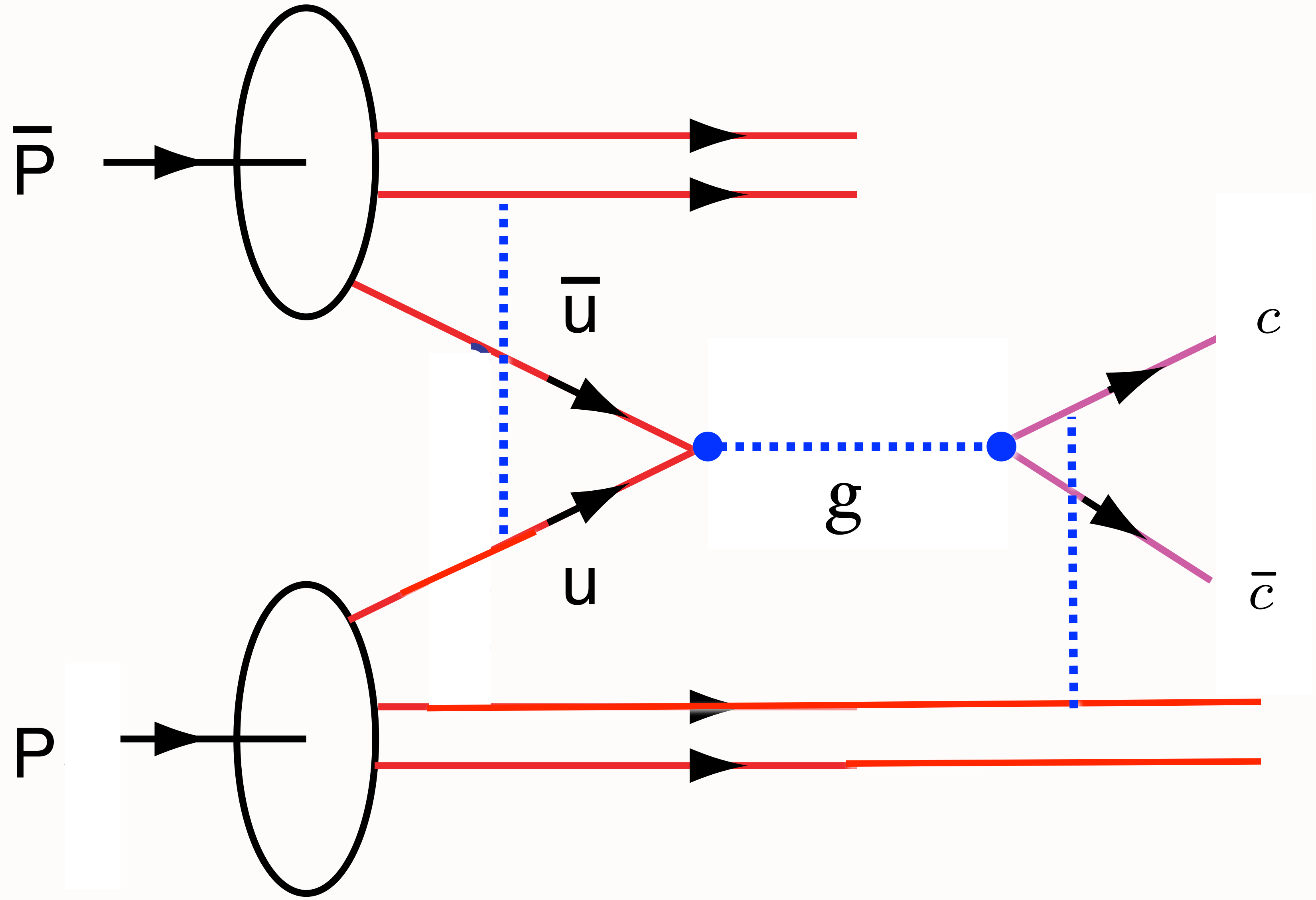
Boer, Hwang, sjb



DY $\cos 2\phi$ **correlation at leading twist from double ISI**

Product of Boer - Mulders Functions

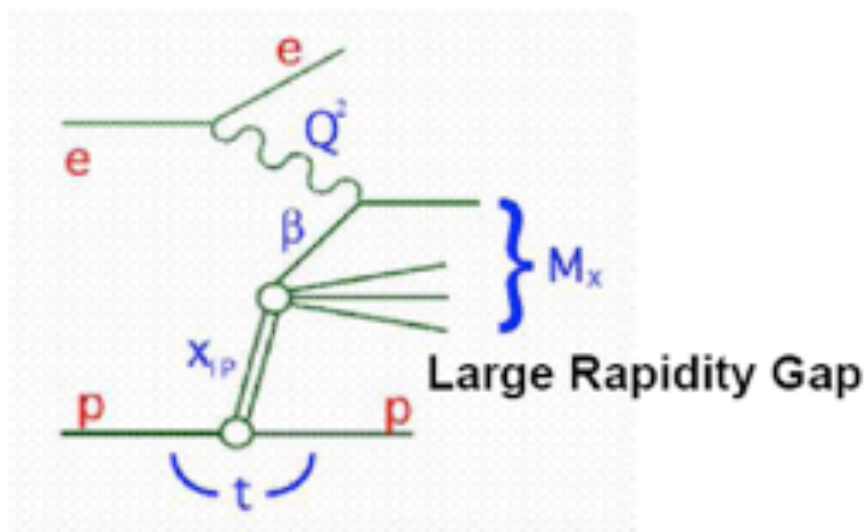
$$h_1^{\perp}(x_1, \boldsymbol{p}_{\perp}^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_{\perp}^2)$$



Problem for factorization when both ISI and FSI occur!

de Roeck

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

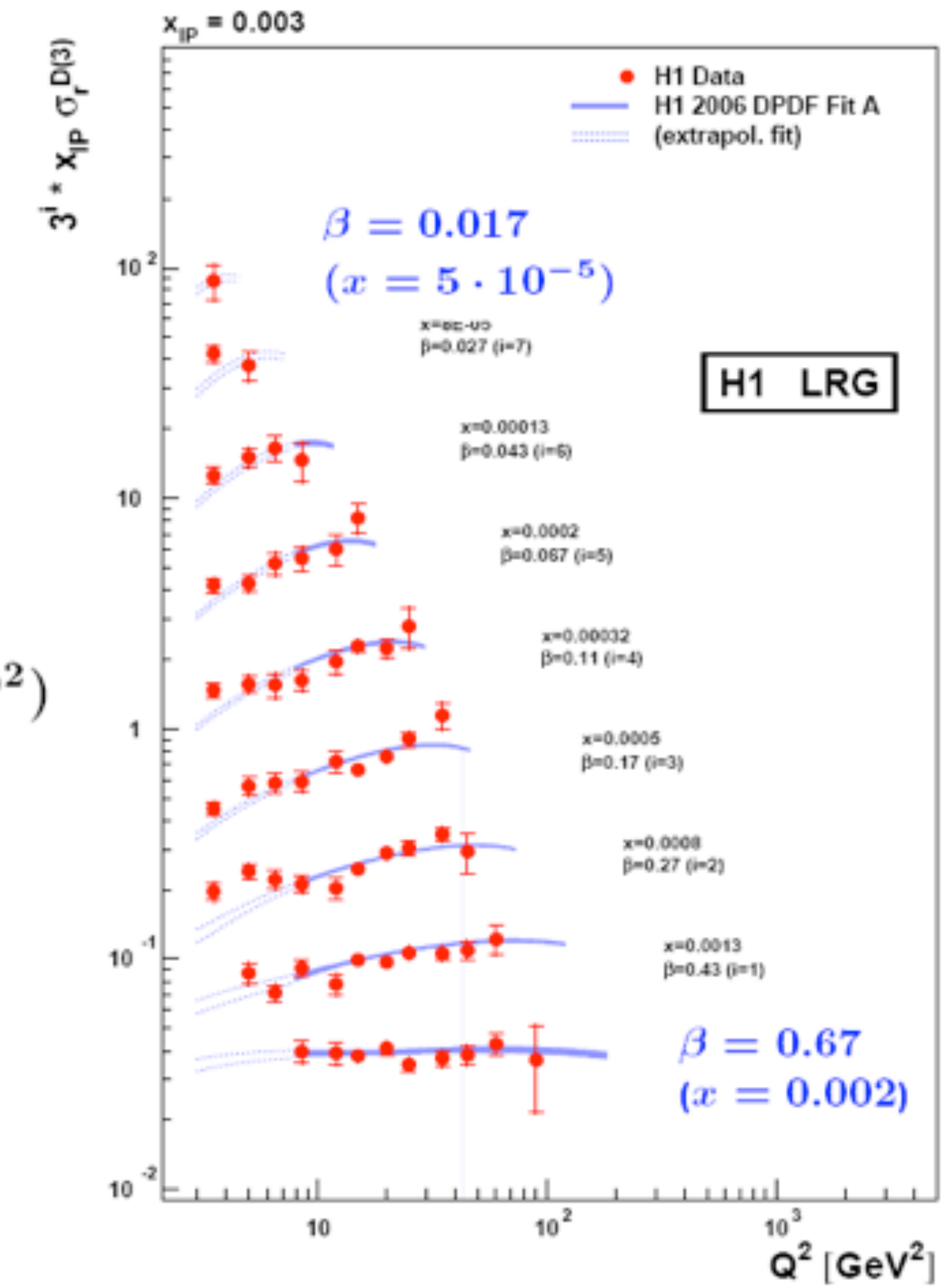
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

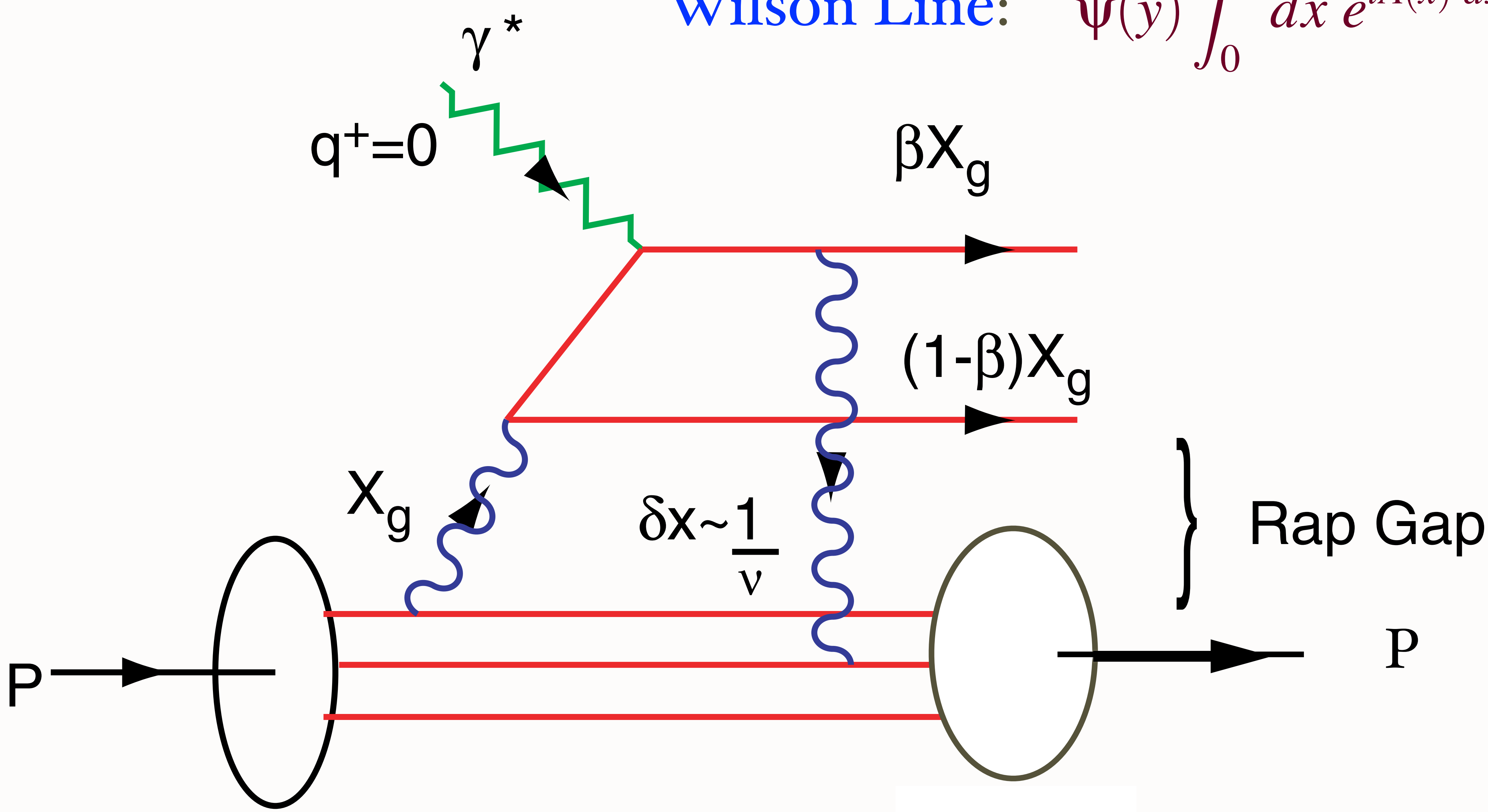
Precise measurements *sys 5%, stat 5–20%*



Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$

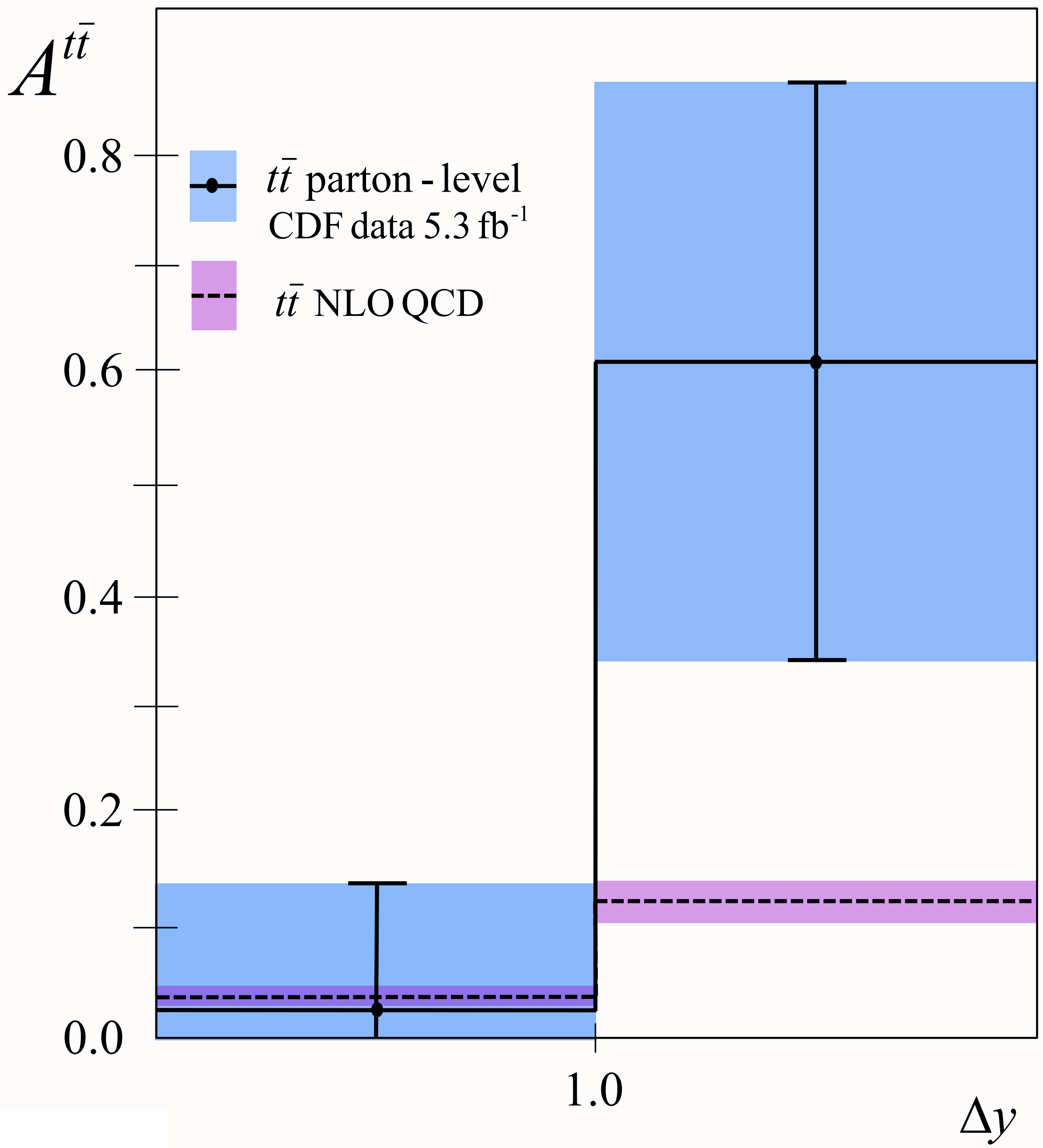


Reproduces lab-frame color dipole approach

Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!

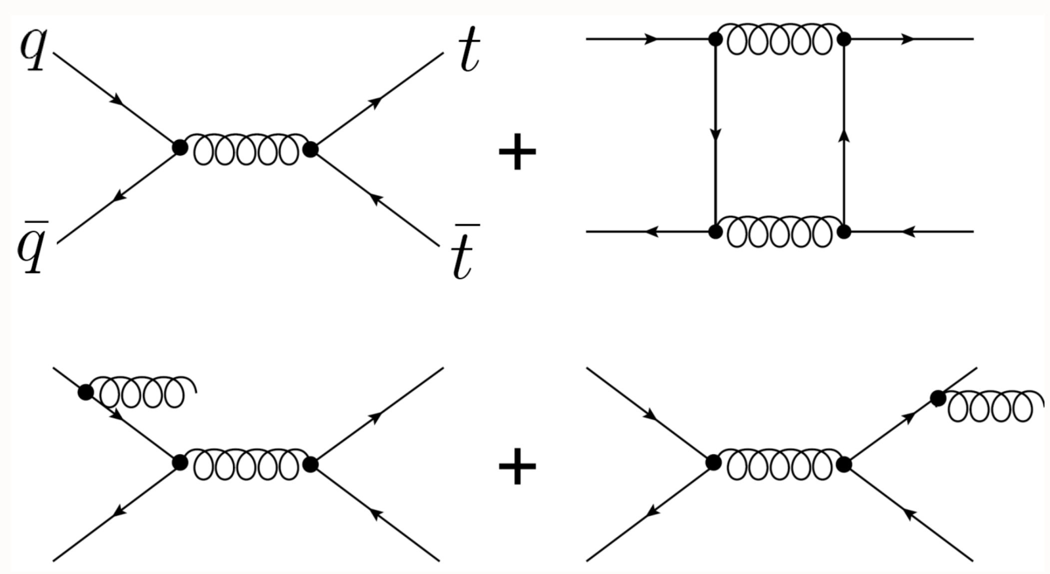
  Not square of LFWFs
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon



Heavy Quark Asymmetries

$$A^{\mathrm{t\bar{t}}}(\Delta y_i) = \frac{N(\Delta y_i) - N(-\Delta y_i)}{N(\Delta y_i) + N(-\Delta y_i)}$$

Asymmetries in Δy are identical to those in the t production angle in the $t\bar{t}$ rest frame. We find a parton-level asymmetry of $A^{\mathrm{t\bar{t}}} = 0.158 \pm 0.075$ (stat+sys), which is somewhat higher than, but not inconsistent with, the NLO QCD expectation of 0.058 ± 0.009.

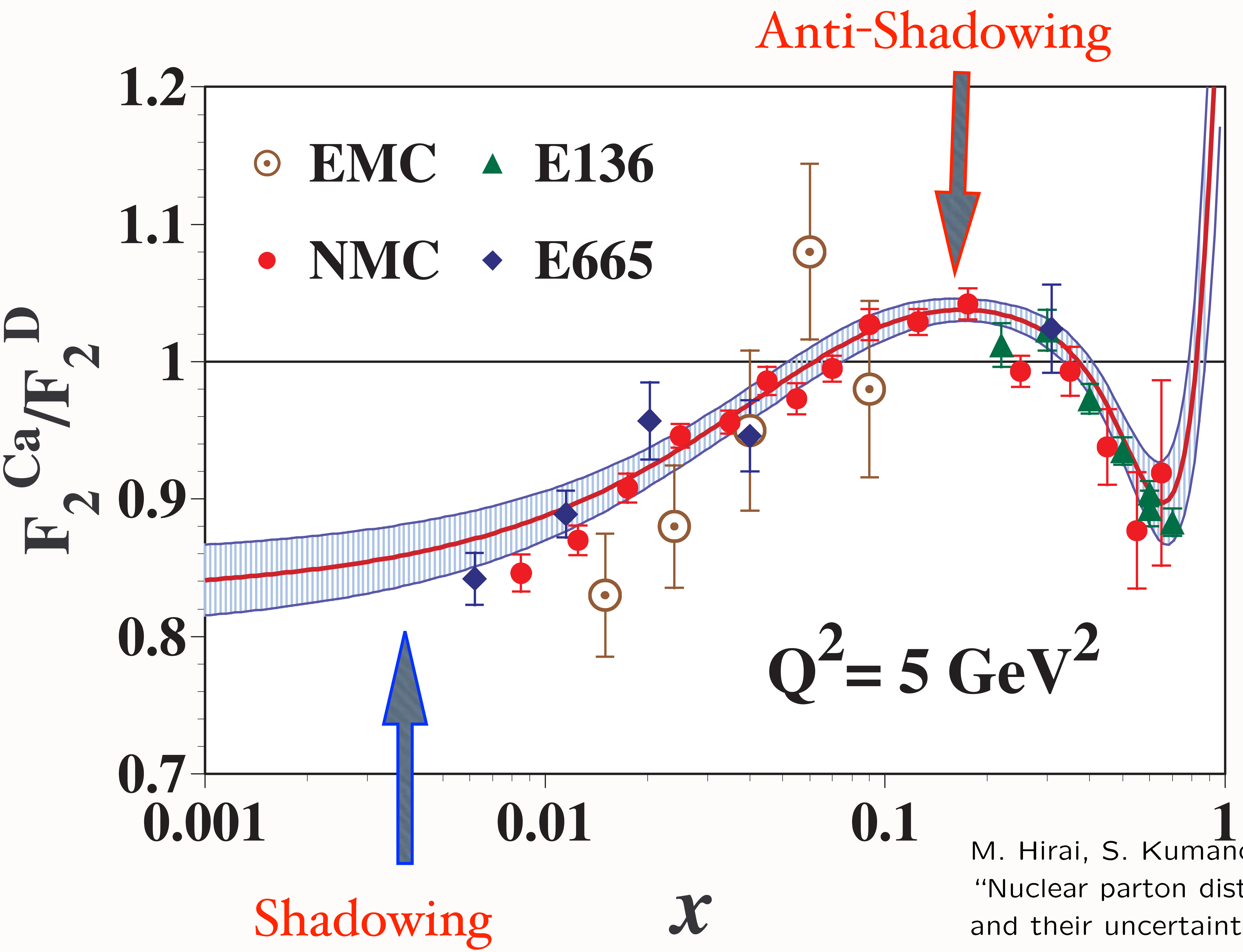


Parton level asymmetries at small and large Δy compared to SM prediction of MCFM. The shaded bands represent the total uncertainty in each bin. The negative going uncertainty for $\Delta y < 1.0$ is suppressed.

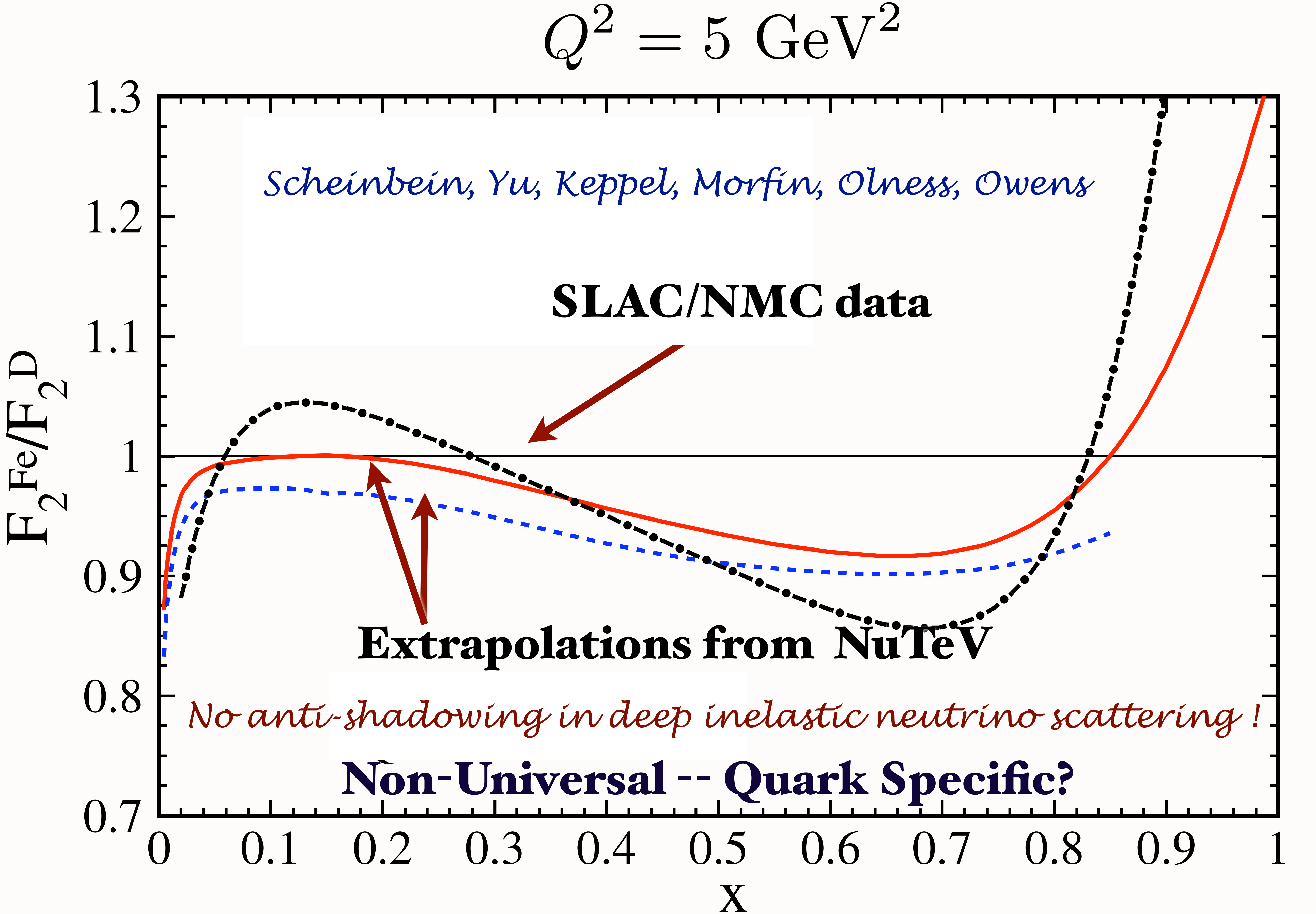
Fermilab-Pub-10-525-E

Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production

CDF Collaboration

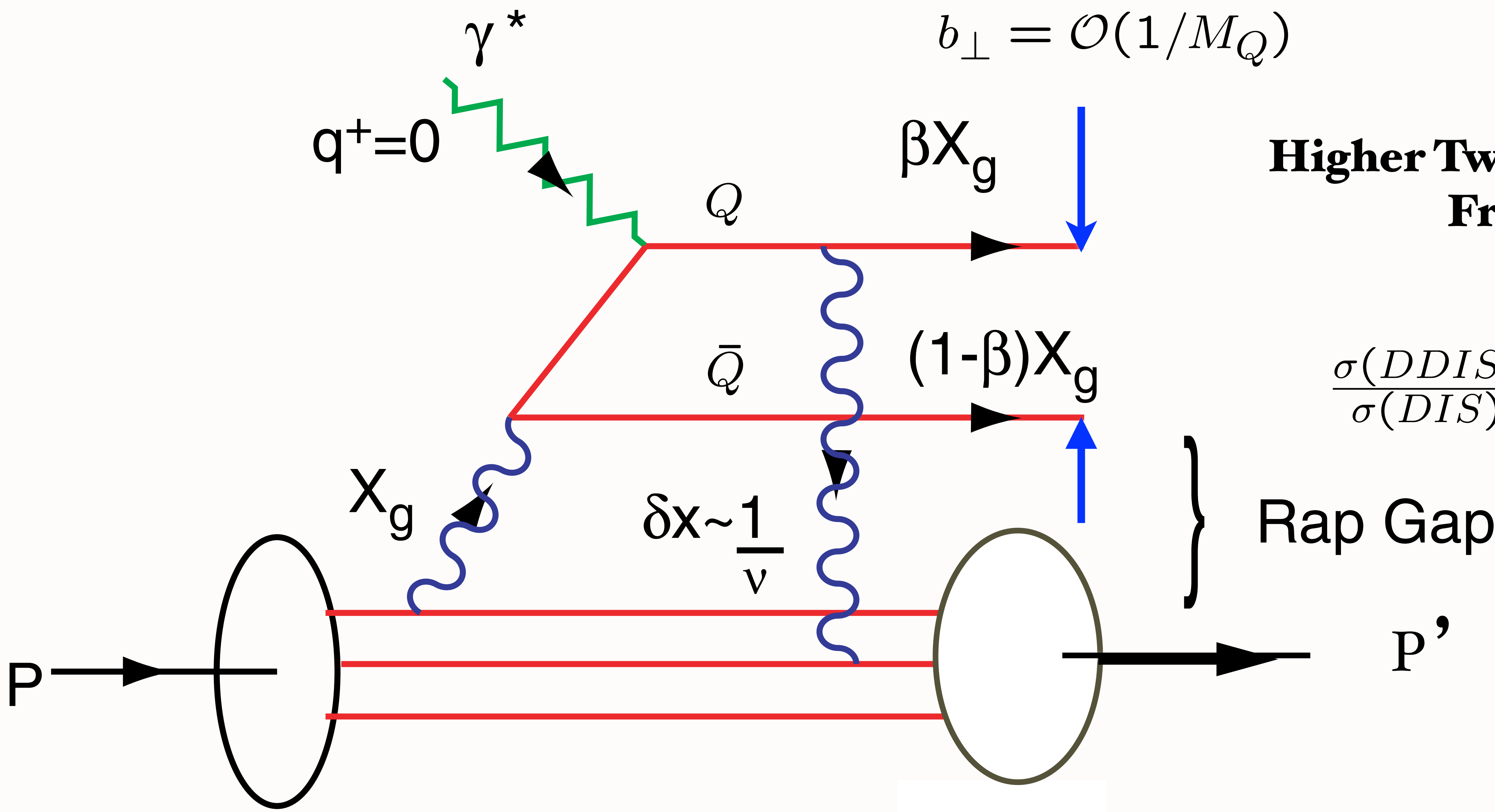


M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].



$Q^2 = 5\ \mathrm{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
Non-Universal -- Quark Specific?
F_2^{Fe}/F_2^{D}
x
1.3
1.2
1.1
1
0.9
0.8
0.7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Predict: Reduced DDIS/DIS for Heavy Quarks



Higher Twist Diffraction Fraction

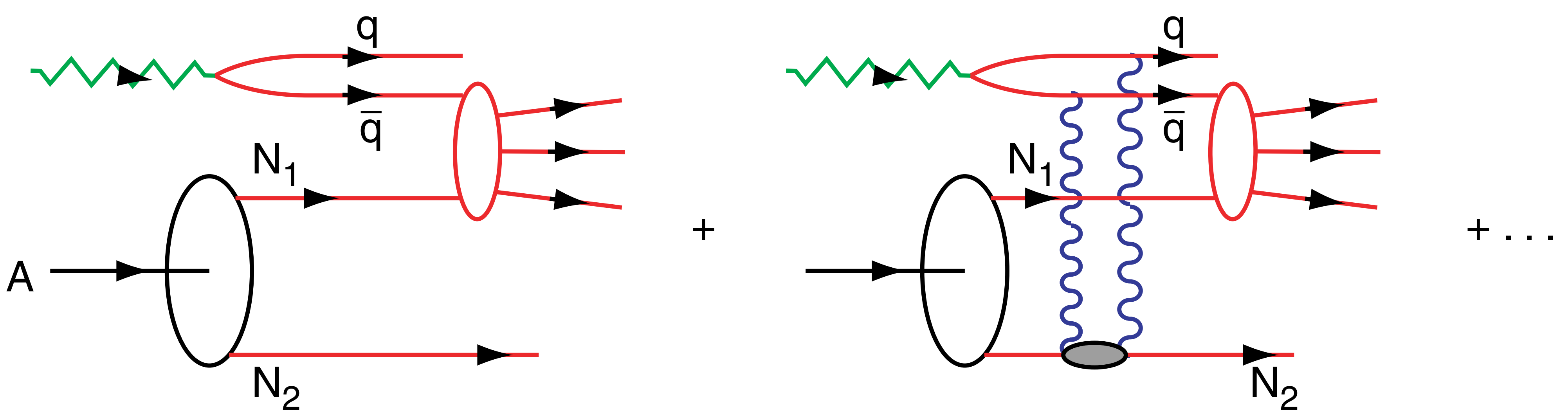
$$\frac{\sigma(DDIS)}{\sigma(DIS)} \simeq \frac{\Lambda^2_{QCD}}{M_Q^2}$$

Kopeliovitch, Schmidt, sjb

Reproduces lab-frame color dipole approach

Stodolsky
Pumplin, sjb
Gribov

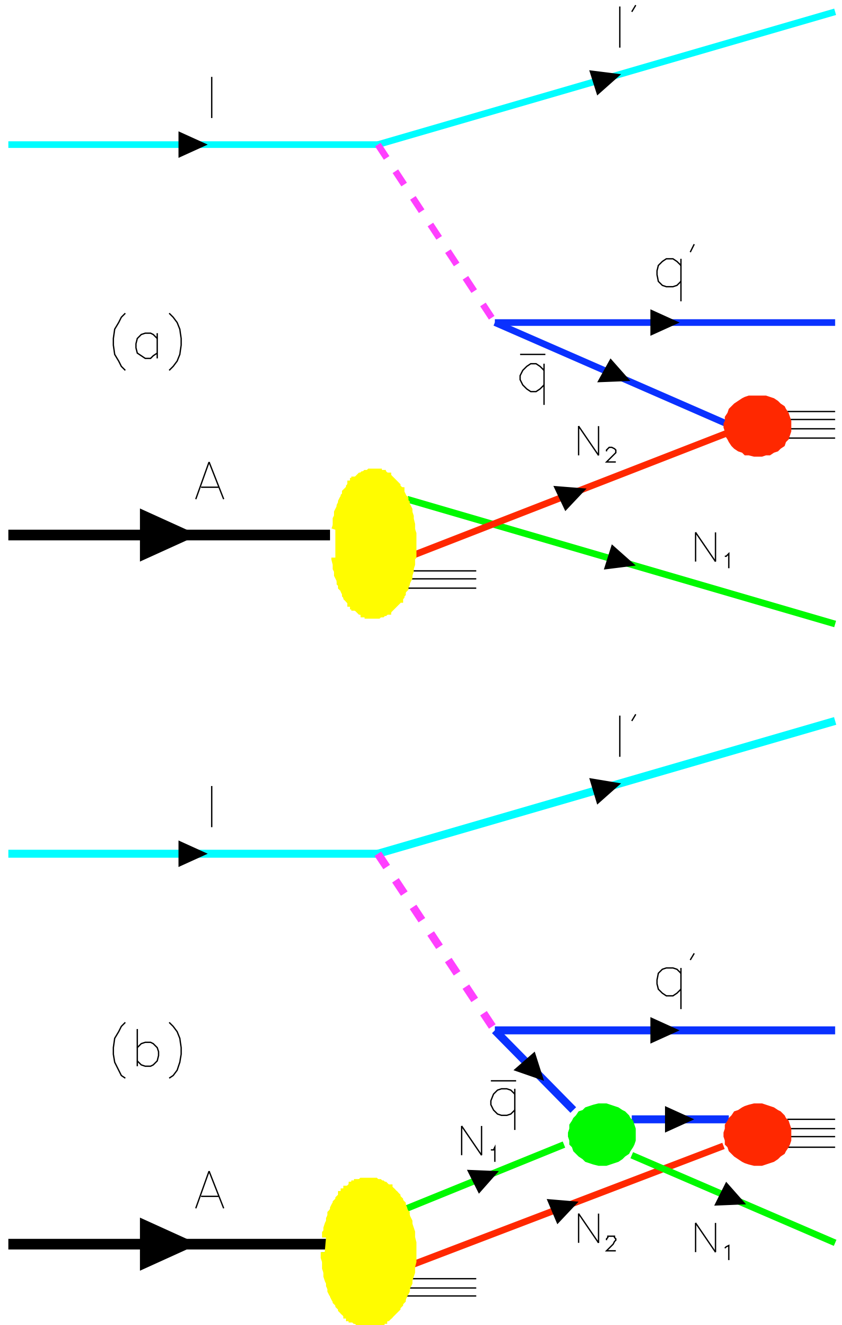
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



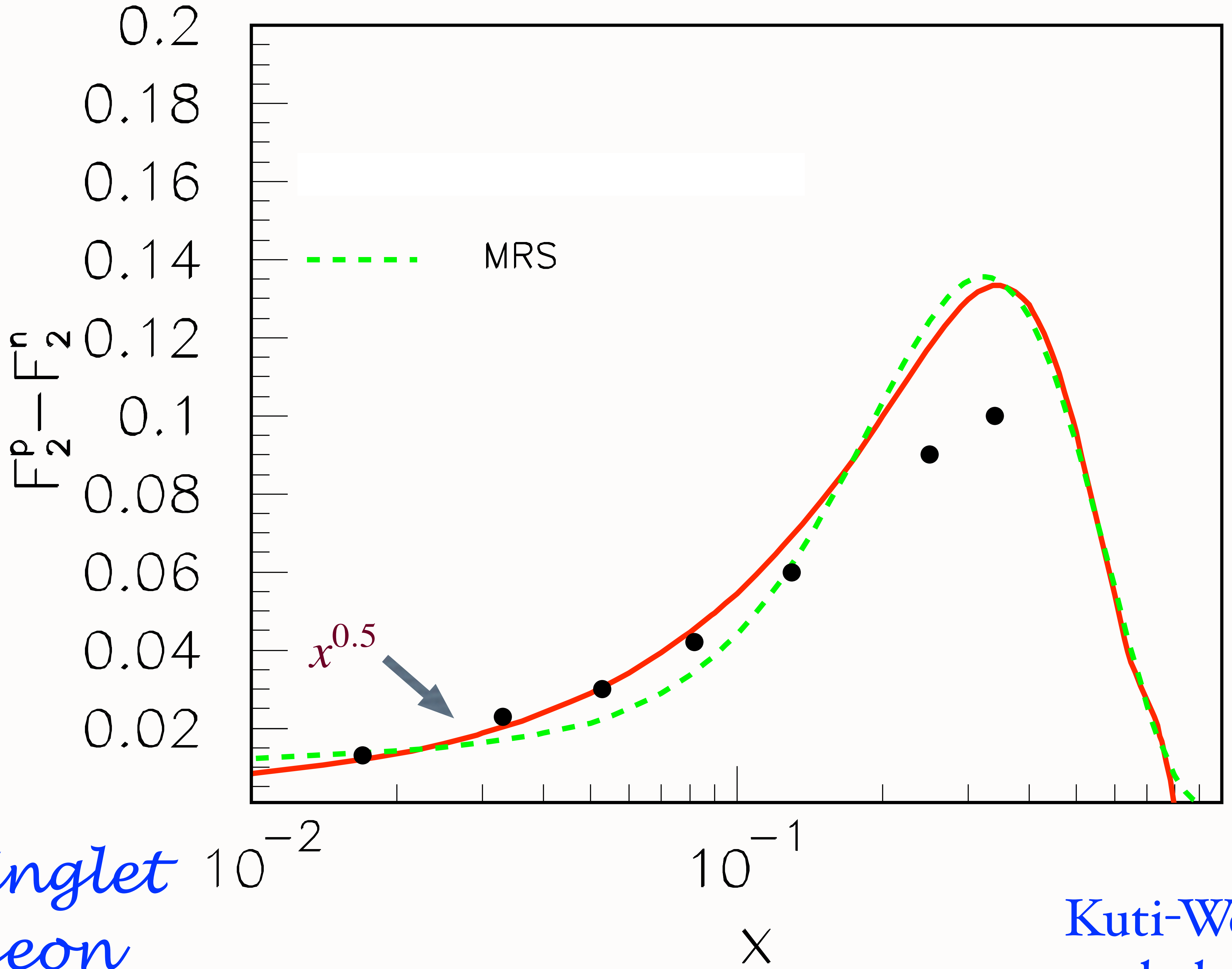
The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Observed HERA DDIS produces nuclear shadowing



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

Depends on quark flavor!

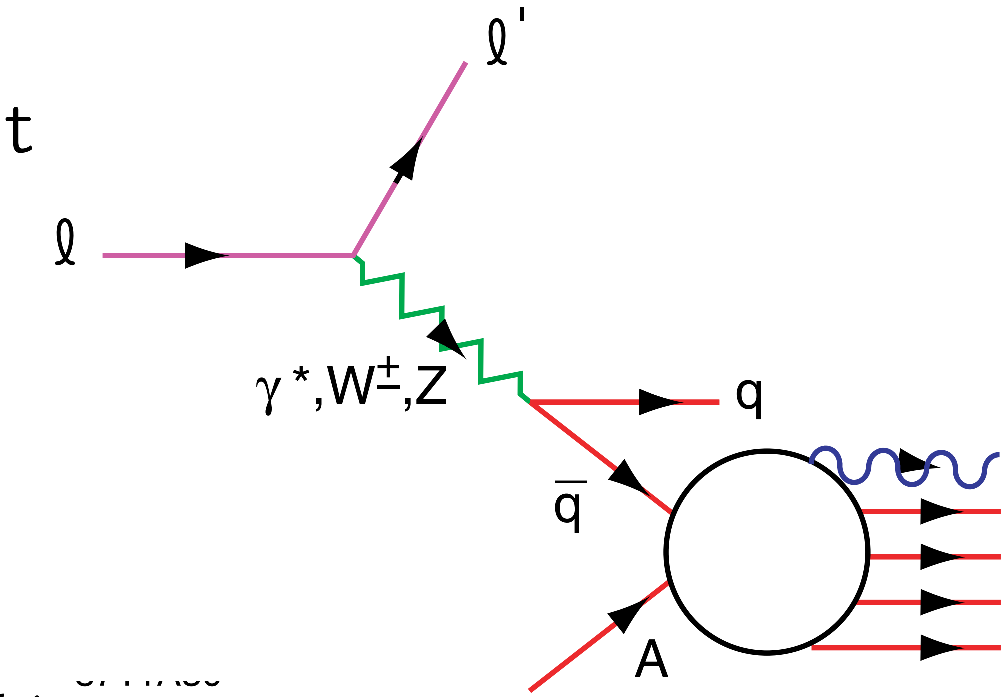
Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

Critical test: Tagged Drell-Yan

Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$



Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$

Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

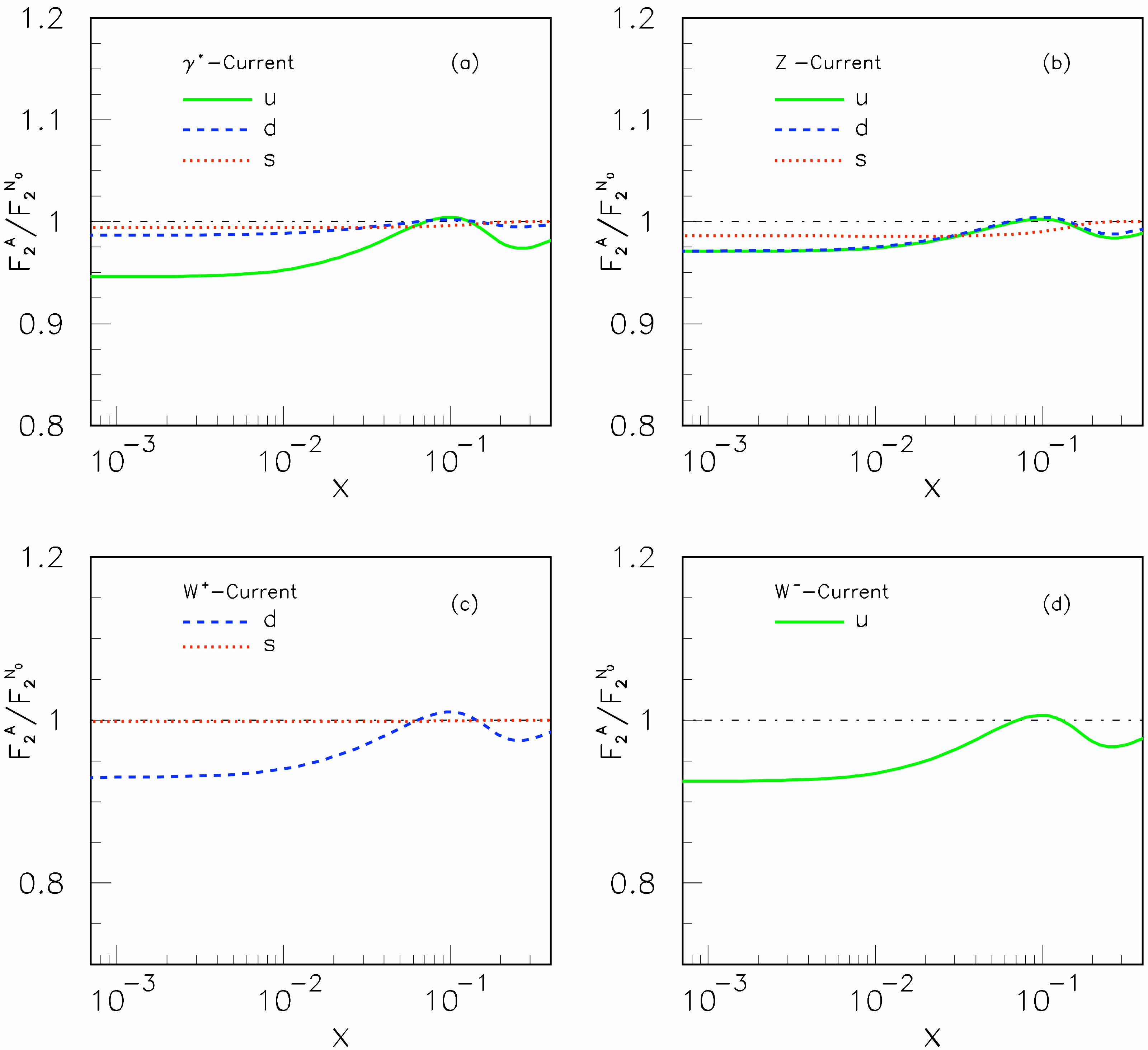
Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb

Shadowing and Antishadowing of DIS Structure Functions

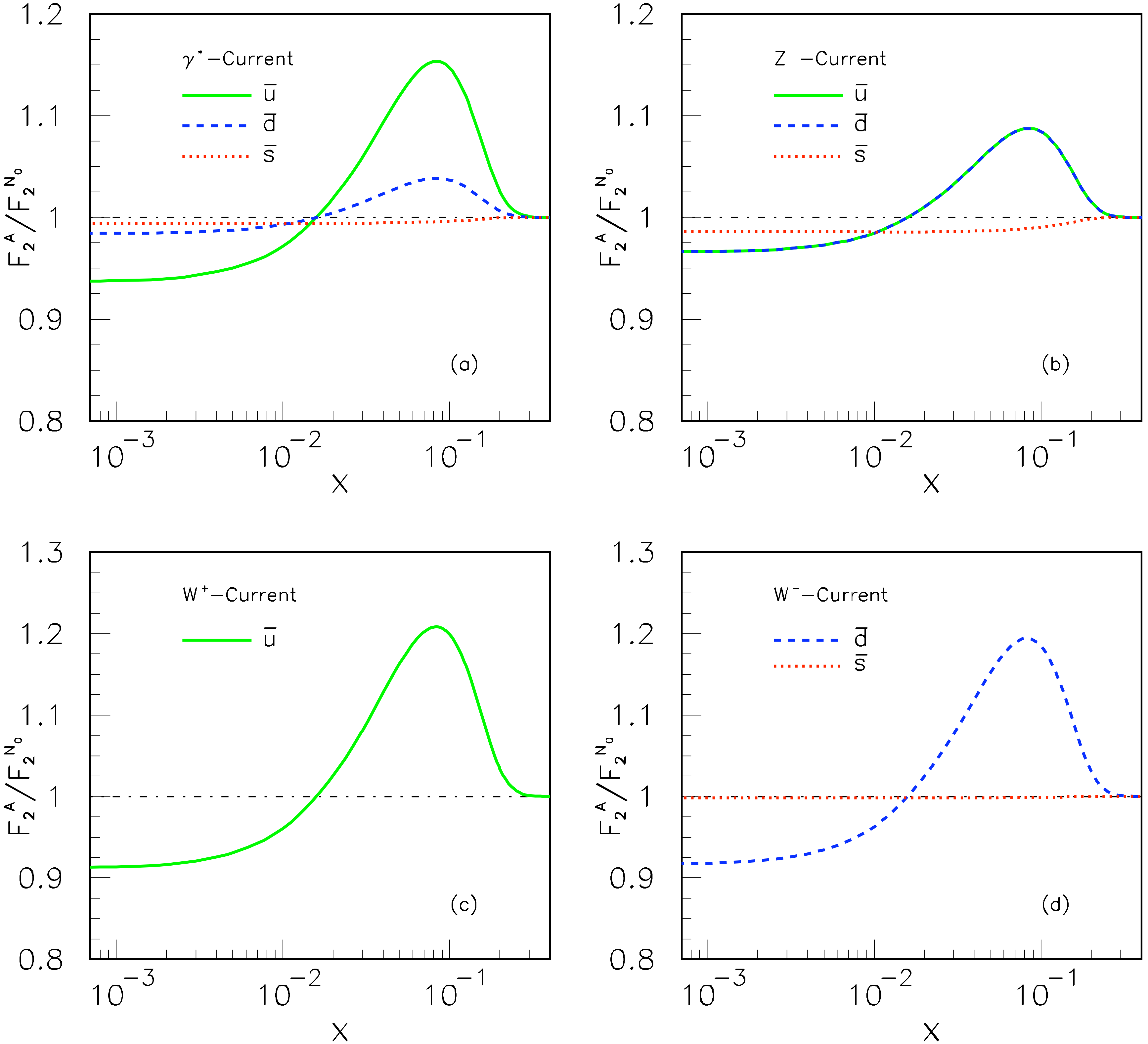


S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Modifies NuTeV extraction of

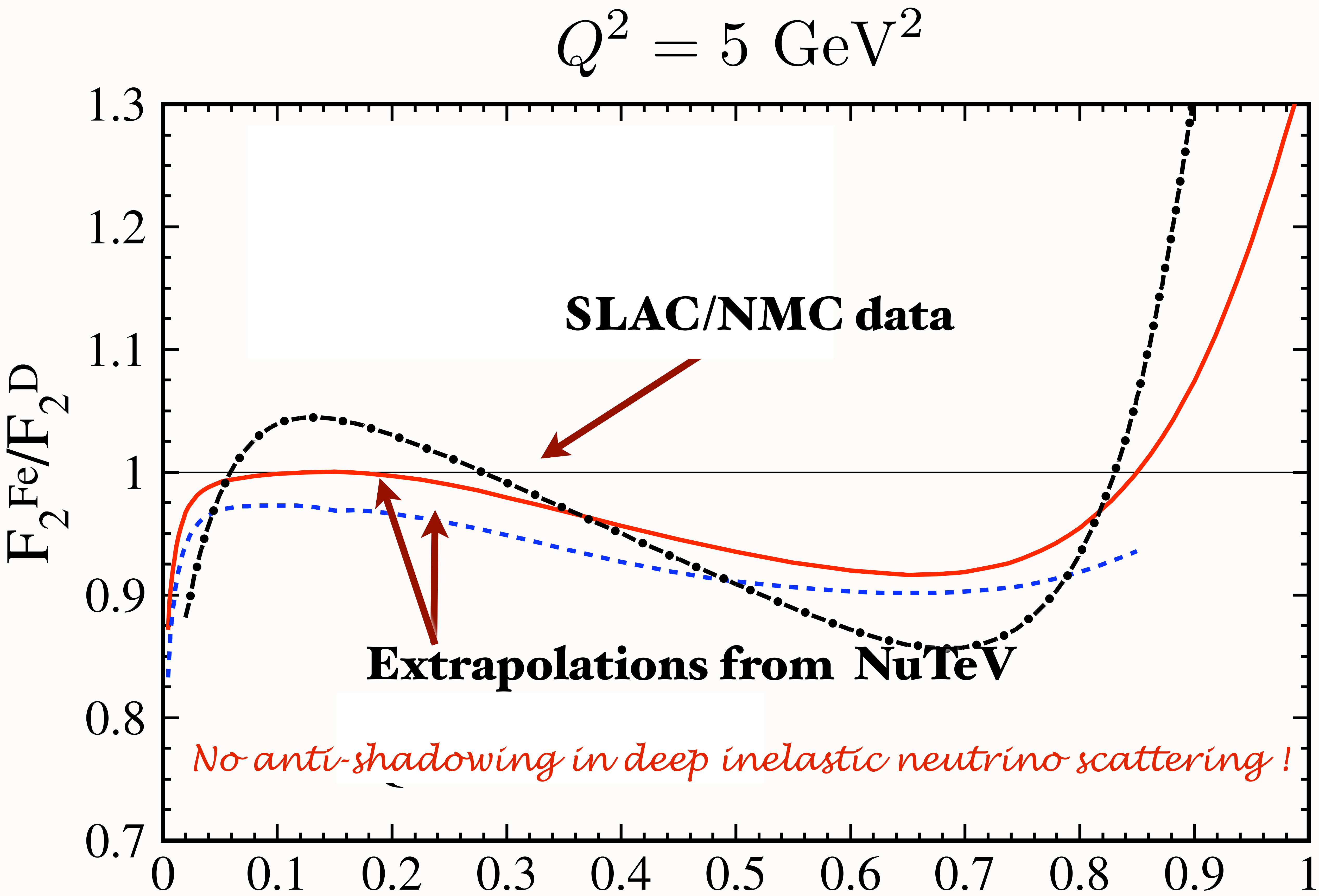
$$\sin^2 \theta_W$$

Test in flavor-tagged lepton-nucleus collisions



Schmidt, Yang; sjb

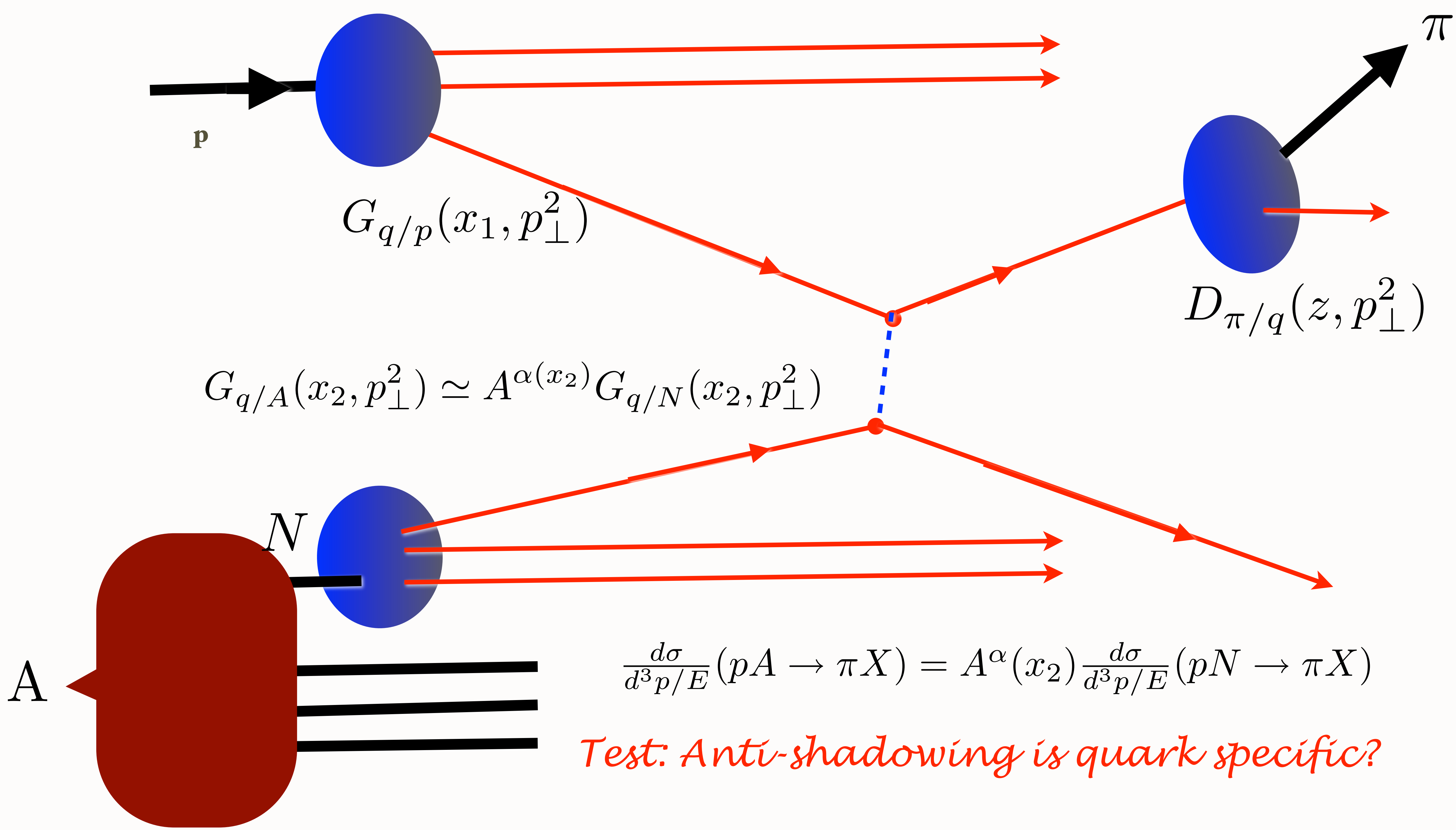
Nuclear Antishadowing not universal !



Scheinbein, Yu, Keppel, Morfin, Olness, Owens

LHC p-A Collisions

Leading-Twist Contribution to Hadron Production on Nuclei



$$\frac{d\sigma}{d^3p/E}(pA \to \pi X) = A^{\alpha}(x_2) \frac{d\sigma}{d^3p/E}(pN \to \pi X)$$

Test: Anti-shadowing is quark specific?

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

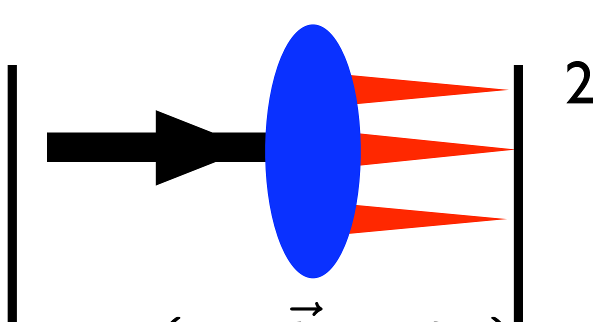
Hwang, Schmidt, sjb,

Mulders, Boer

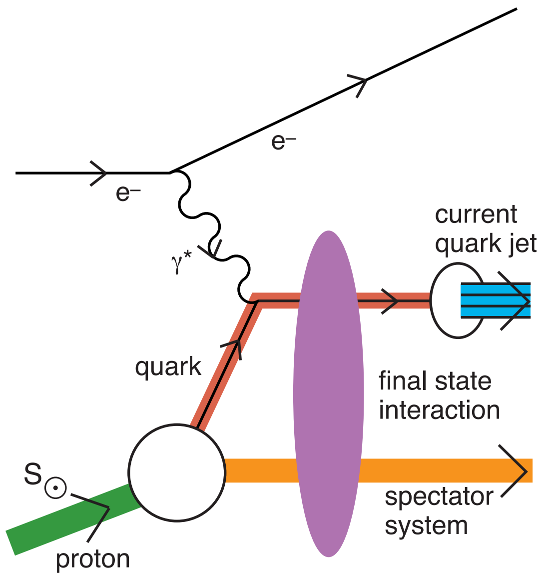
Qiu, Sterman

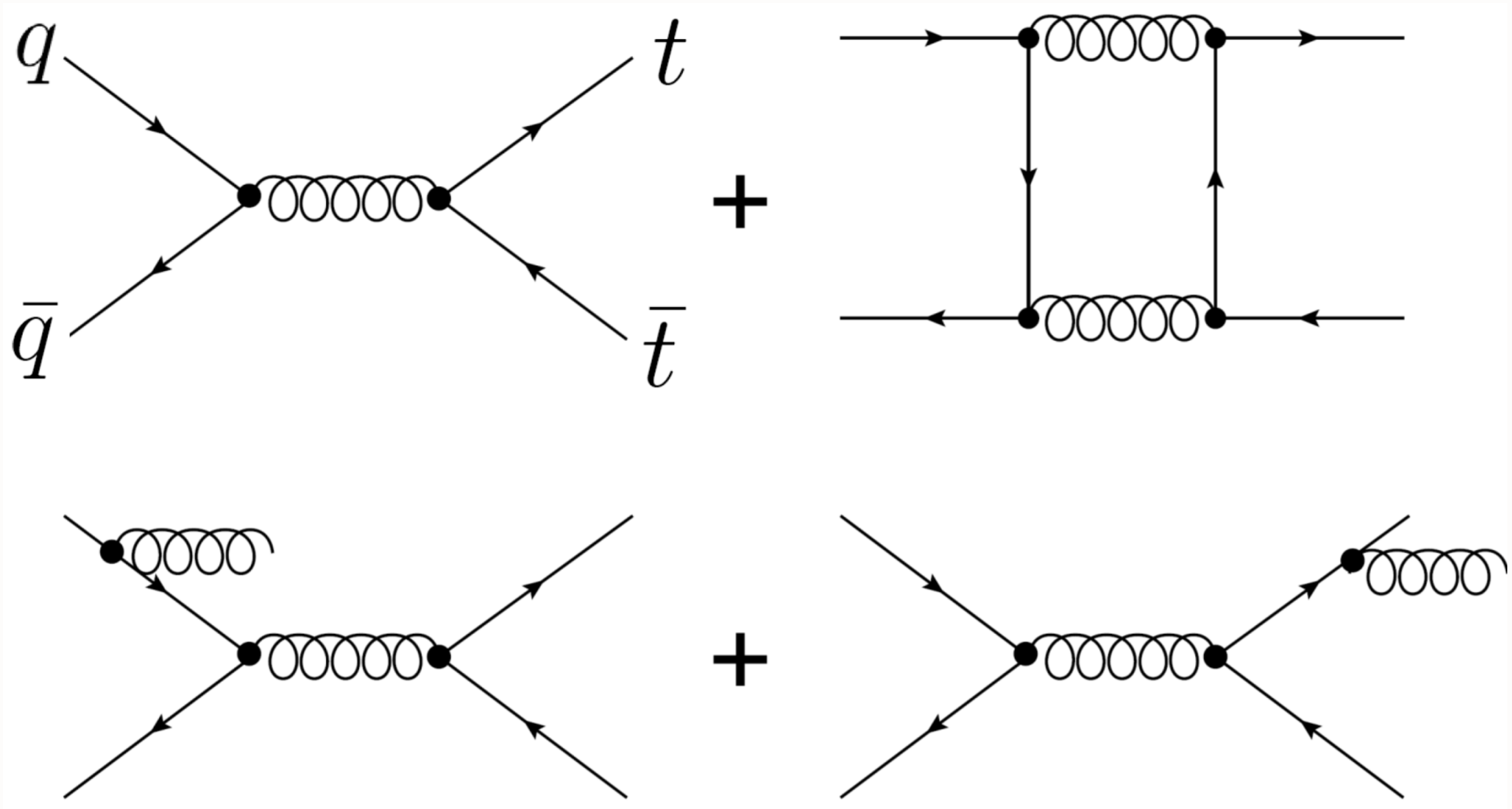
Collins, Qiu

Pasquini, Xiao, Yuan, sjb



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



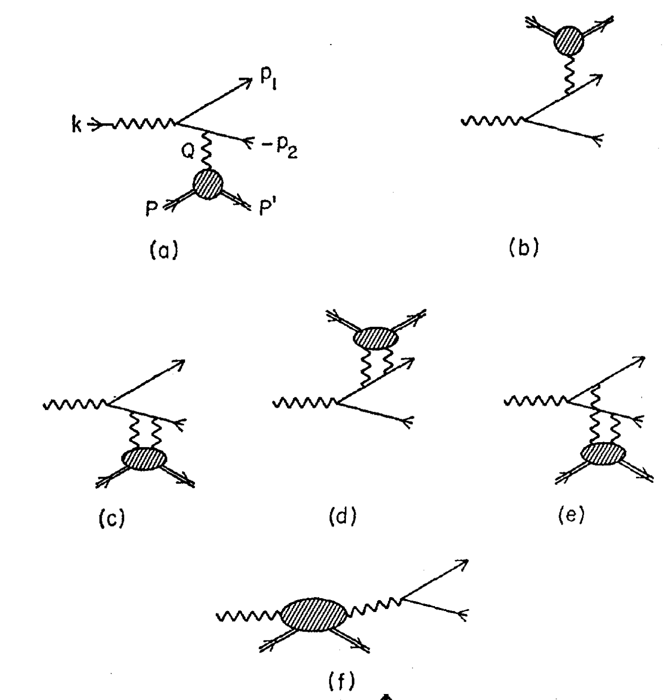


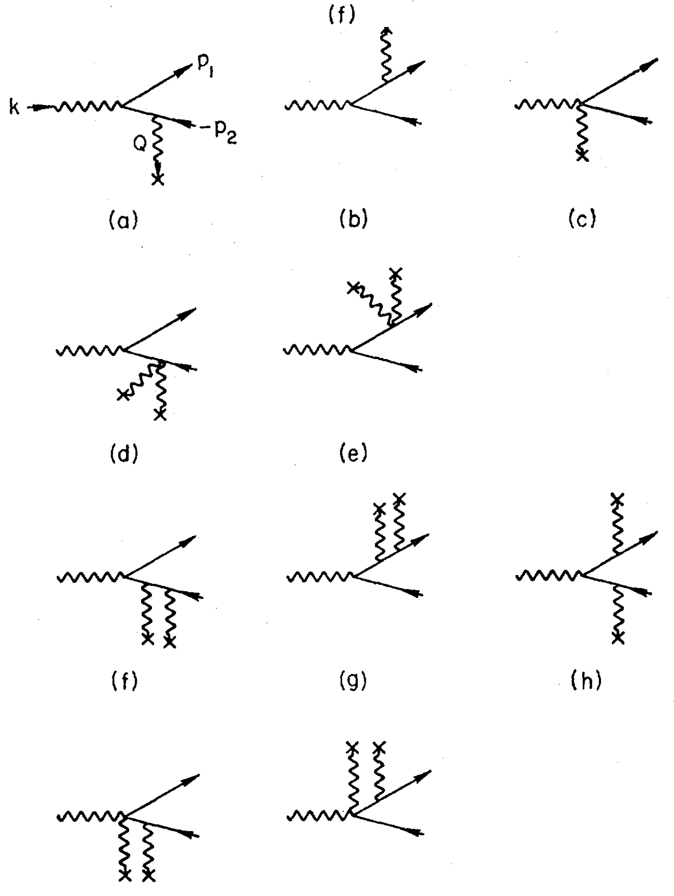
Conventional pQCD approach

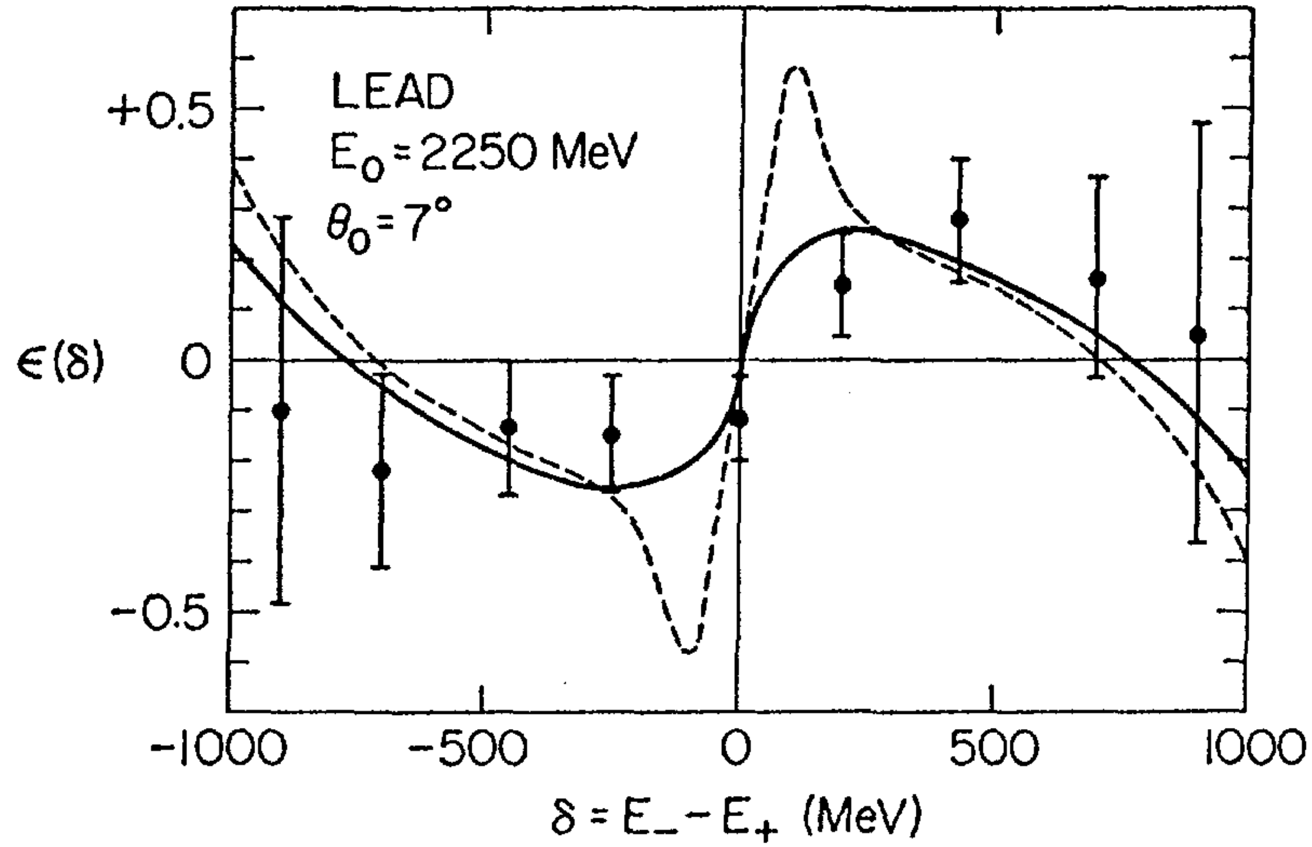
Second Born Corrections to Wide-Angle High-Energy Electron Pair Production and Bremsstrahlung*

J. Gillespie and sjb

PR 173 1011 (1968)







[4] J. G. Asbury, W. K. Bertram, U. Becker, P. Joos, M. Rohde, A. J. S. Smith, S. Friedlander, C. L. Jordan, and S. C. C. Ting, Phys. Rev. **161**, 1344 (1967), and references therein.

$$\mathcal{R} \equiv \frac{d\sigma_{\text{int}}}{d\sigma_{\text{Born}}} = \tfrac{1}{4} Z\alpha\pi |\mathbf{Q}| \times \left[\frac{(E_2-E_1)Q^2+2E_2 k\cdot p_2-2E_1 k\cdot p_1}{E_1E_2Q^2+(k\cdot p_1)(k\cdot p_2)}\right]+O(Z\alpha)^3$$

(spin zero, point nucleus). (4.9)

QCD Analysis of heavy quark asymmetries

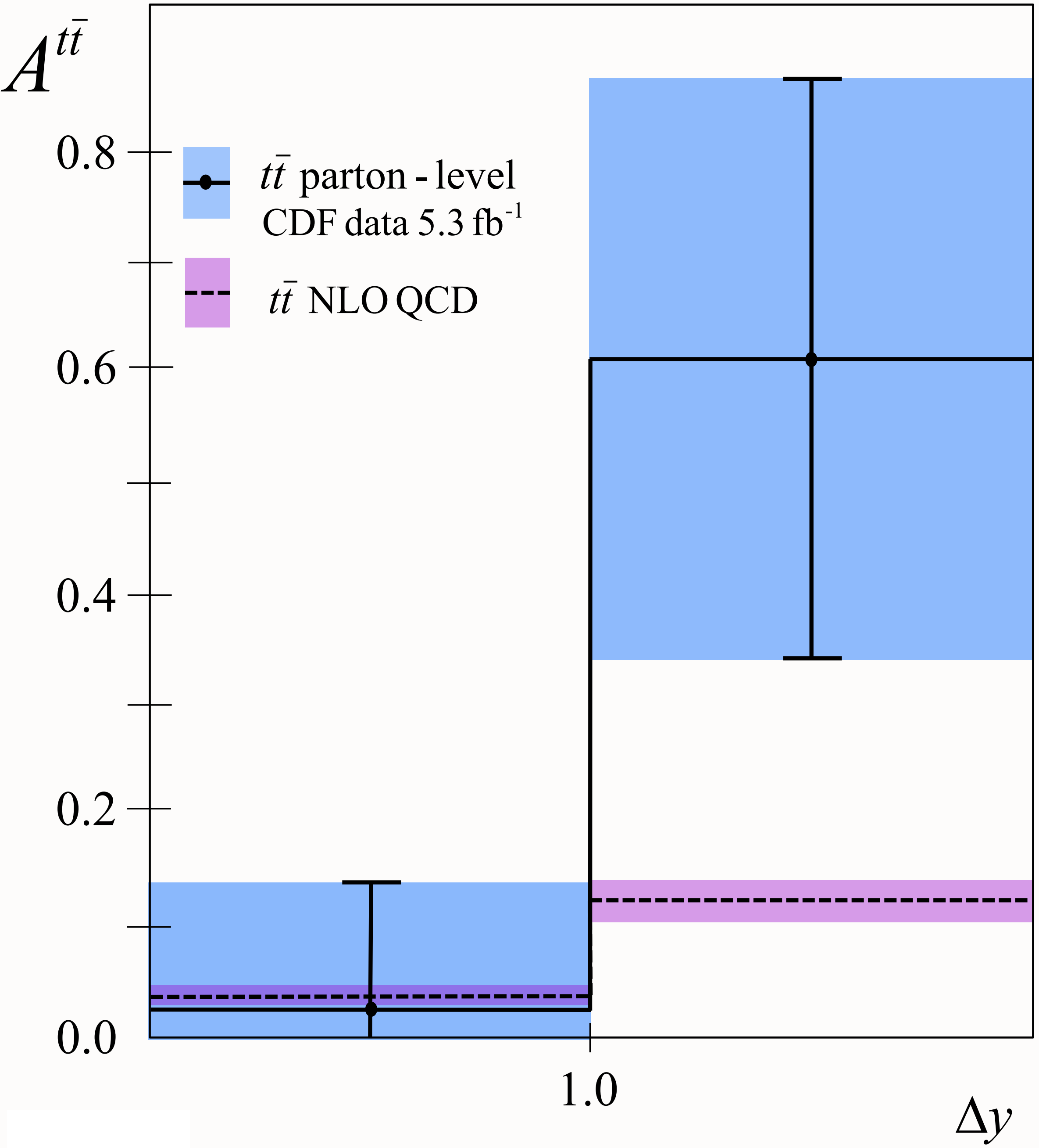
B. von Harling, Y. Zhao, sjb

- **Include Radiation Diagrams**
- **FSI similar to Sivers Effect**

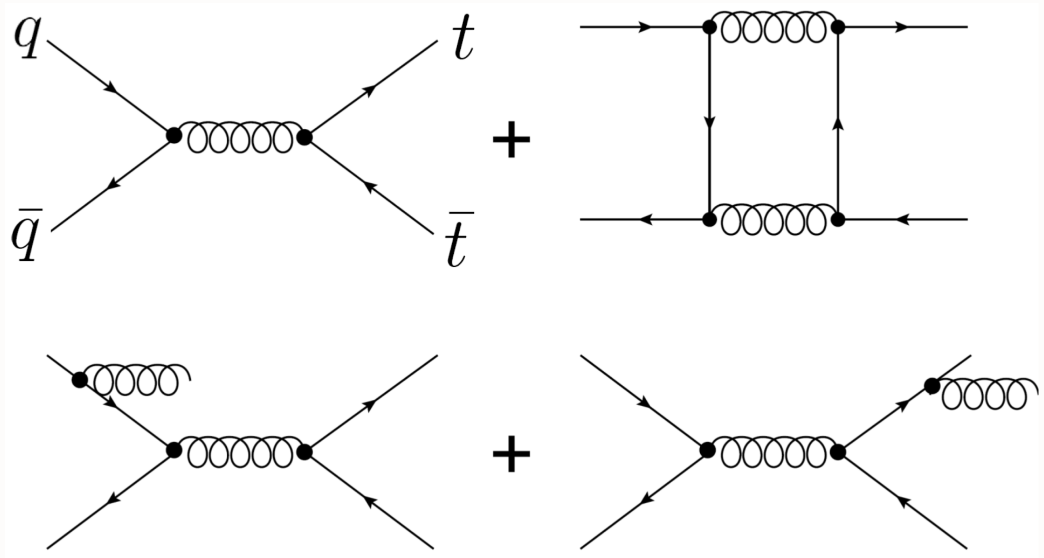
$$\pi Z\alpha \rightarrow \pi C_F \alpha_s$$

- **Renormalization scale relatively soft**

Large $t\bar{t}$ asymmetries seen at CDF



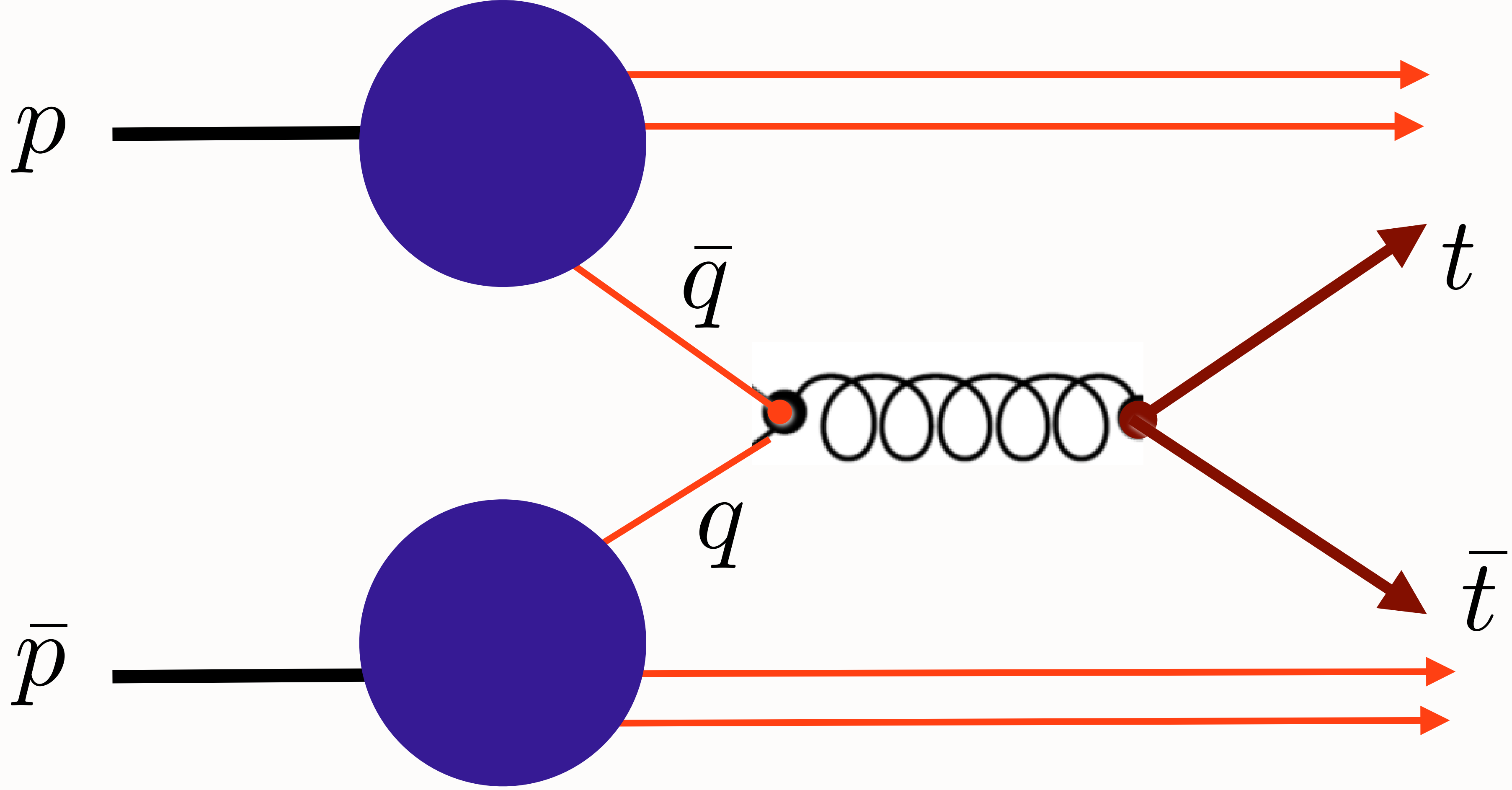
$$A^{t\bar{t}}(\Delta y_i) = \frac{N(\Delta y_i) - N(-\Delta y_i)}{N(\Delta y_i) + N(-\Delta y_i)}$$



Fermilab-Pub-10-525-E

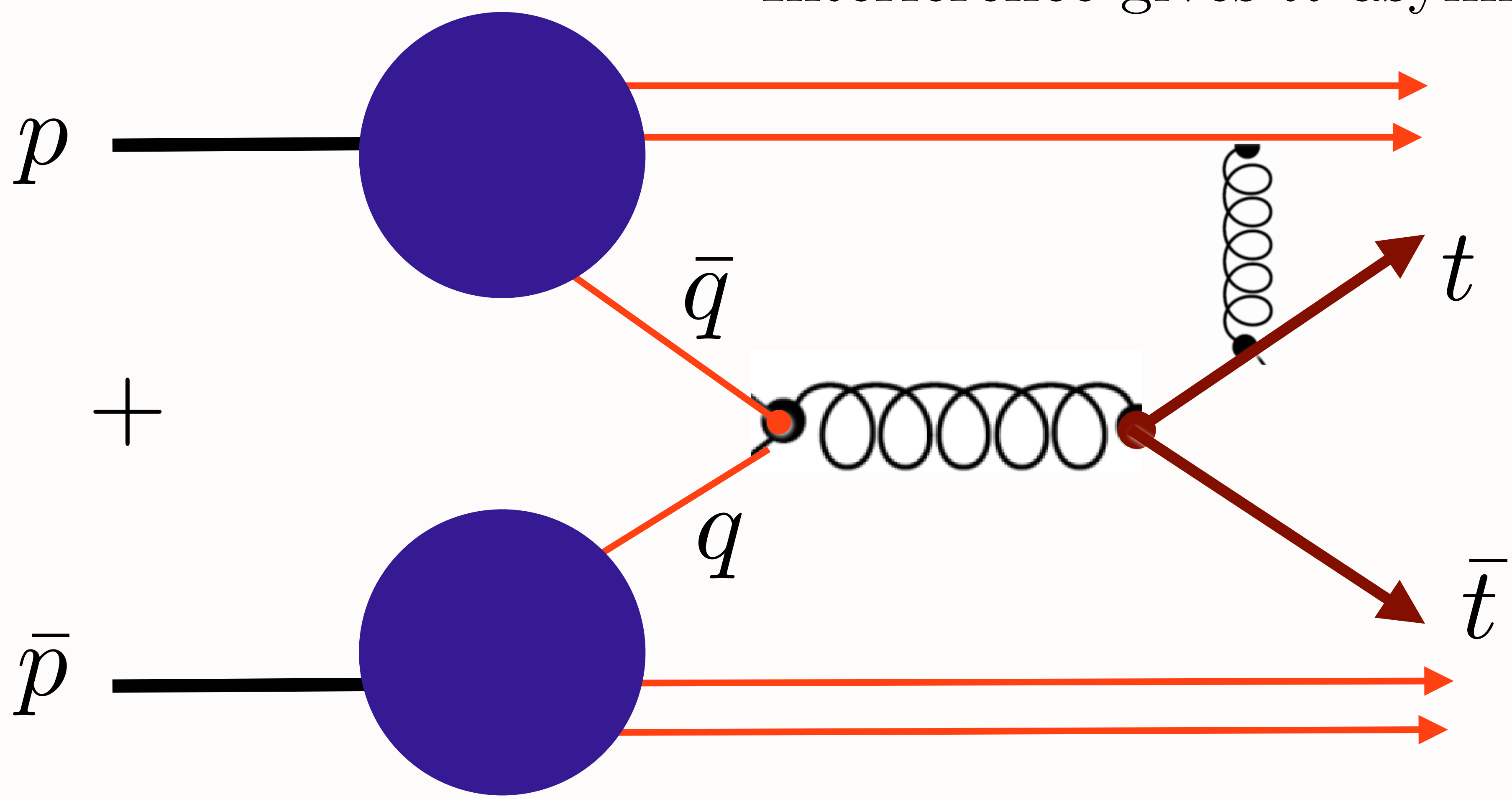
Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production

CDF Collaboration



Interference gives $t\bar{t}$ asymmetry

$+$



$+\cdots$

QCD Analysis of heavy quark asymmetries

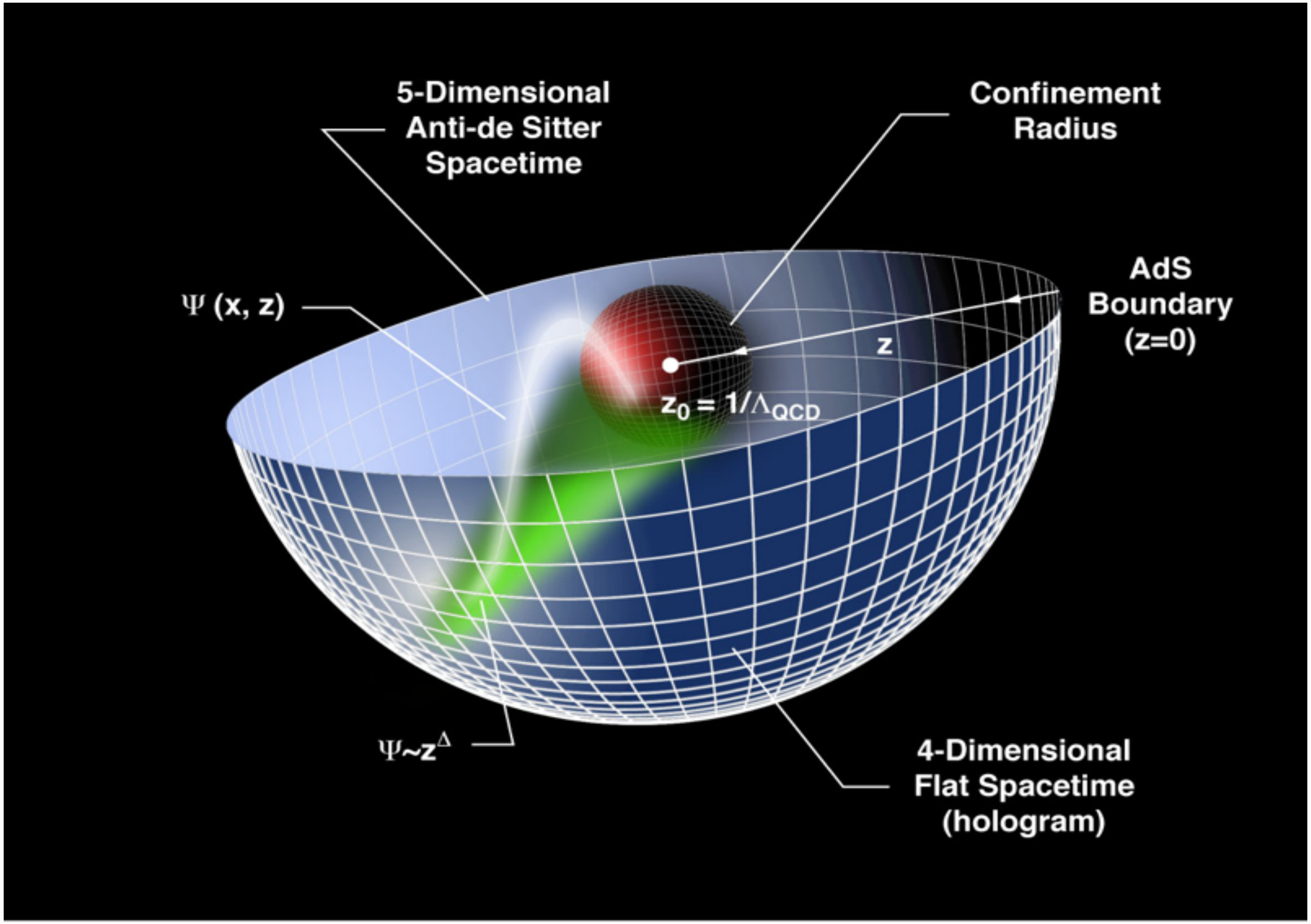
B. von Harling, Y. Zhao, sjb

- **Rescattering Corrections analogous to QED**

$$\pi Z\alpha \longrightarrow \pi C_F \alpha_s$$

- **Include Radiation Diagrams**
- **Top Decay truncates gluon radiation**
- **FSI similar to Sivers Effect**
- **Renormalization scale relatively soft**

Applications of AdS/CFT to QCD



Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

Soft-Wall Model

$$S = \int d^4x \, dz \, \sqrt{g} \, e^{\varphi(z)} \mathcal{L}, \qquad \varphi(z) = \pm \kappa^2 z^2$$

Retain conformal AdS metrics but introduce smooth cutoff which depends on the profile of a dilaton background field

Karch, Katz, Son and Stephanov (2006)]

- Equation of motion for scalar field $\mathcal{L} = \frac{1}{2}\left(g^{\ell m}\partial_\ell \Phi \partial_m \Phi - \mu^2 \Phi^2\right)$

$$\left[z^2\partial_z^2 - \left(3 \mp 2\kappa^2 z^2\right) z \, \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2\right] \Phi(z) = 0$$

with $(\mu R)^2 \geq -4$.

- LH holography requires 'plus dilaton' $\varphi = +\kappa^2 z^2$. Lowest possible state $(\mu R)^2 = -4$

$$\mathcal{M}^2 = 0, \quad \Phi(z) \sim z^2 e^{-\kappa^2 z^2}, \quad \langle r^2 \rangle \sim \frac{1}{\kappa^2}$$

A chiral symmetric bound state of two massless quarks with scaling dimension 2:

Massless pion

- de Teramond, sjb

$$e^{\Phi(z)} = e^{+\kappa^2 z^2}$$

Positive-sign dilaton

AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:

$$\left[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z) \right] \phi(z) = \mathcal{M}^2 \phi(z)$$

$$U(z) = \kappa^4 z^2 + 2\kappa^2 (L+S-1)$$

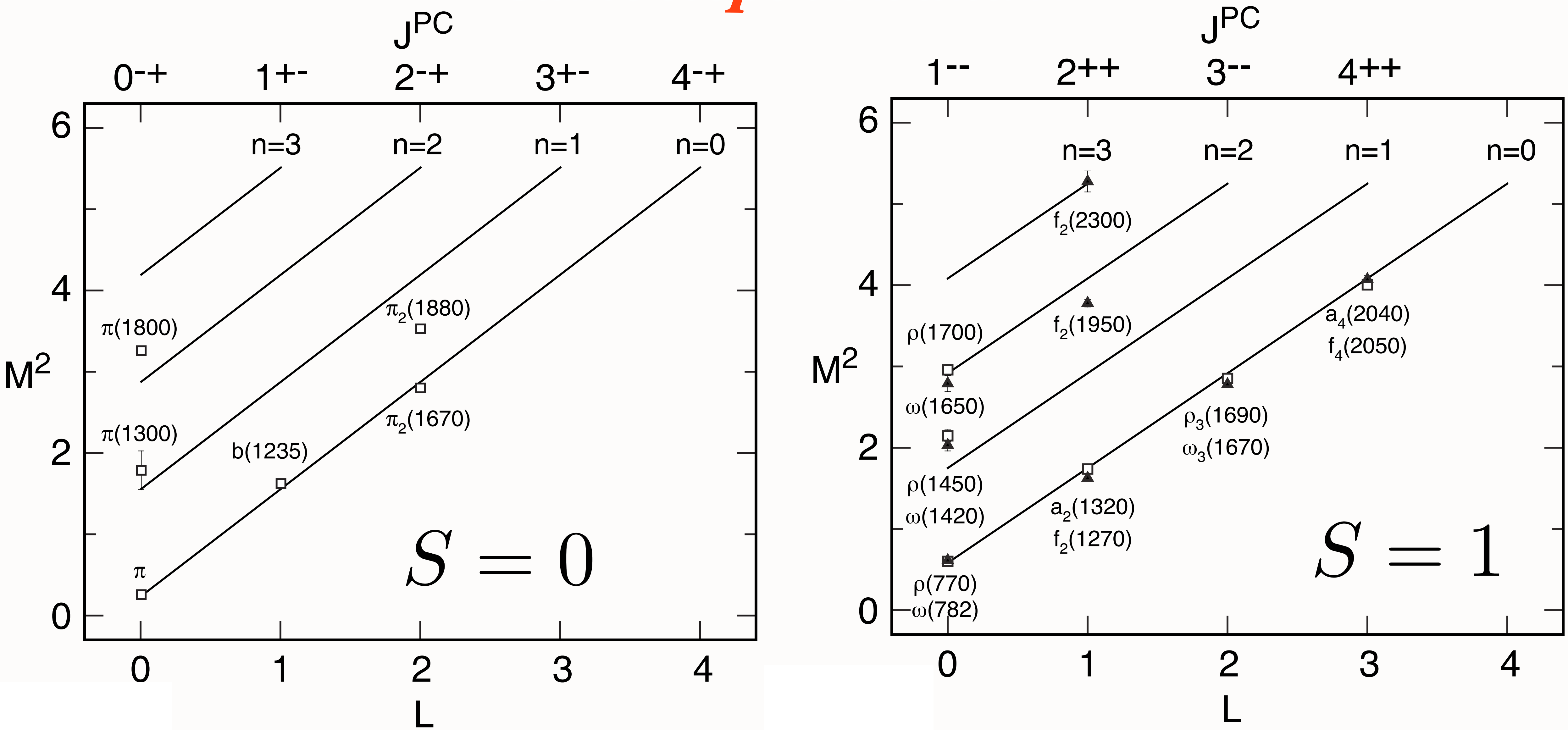
Derived from variation of Action Dilaton-Modified AdS_5

Bosonic Modes and Meson Spectrum

$$\mathcal{M}^2 = 4\kappa^2(n + J/2 + L/2) \to 4\kappa^2(n + L + S/2)$$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

Same slope in n and L



Regge trajectories for the π ($\kappa = 0.6$ GeV) and the $I = 1$ ρ-meson and $I = 0$ ω-meson families ($\kappa = 0.54$ GeV)

Quark separation increases with L

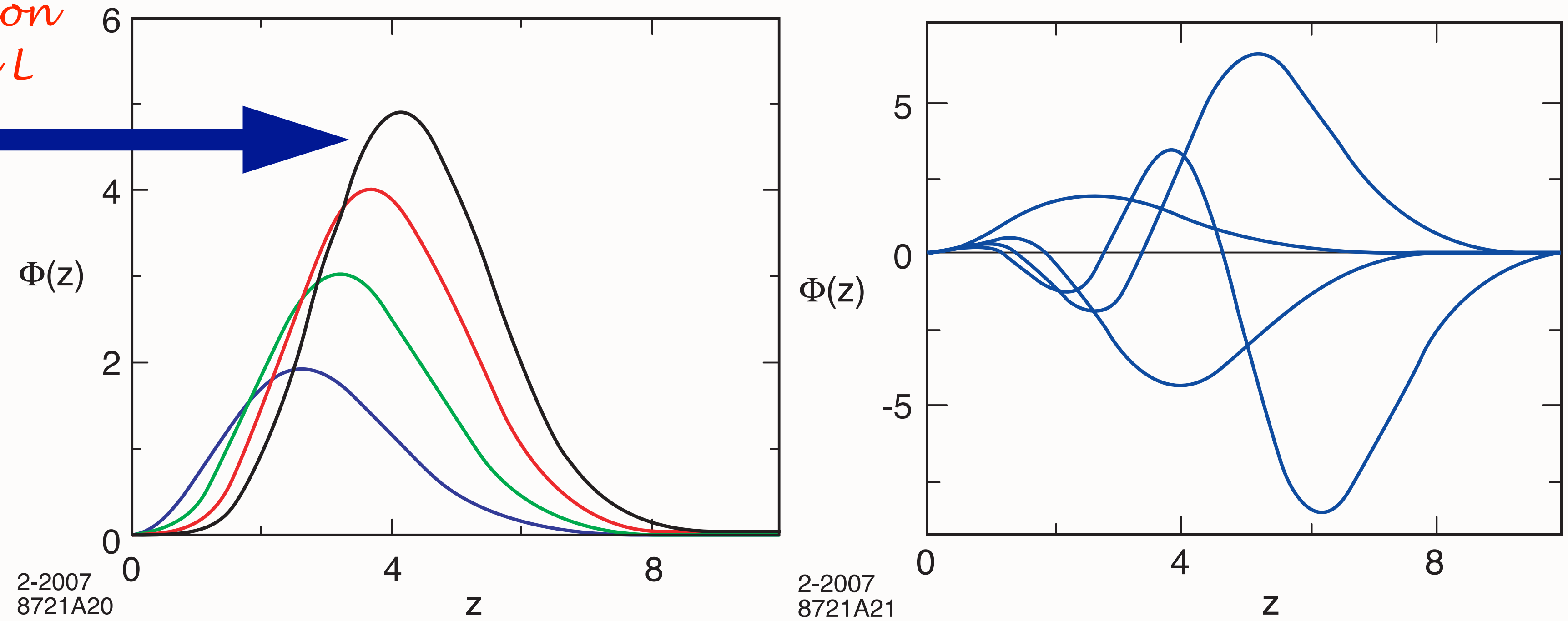
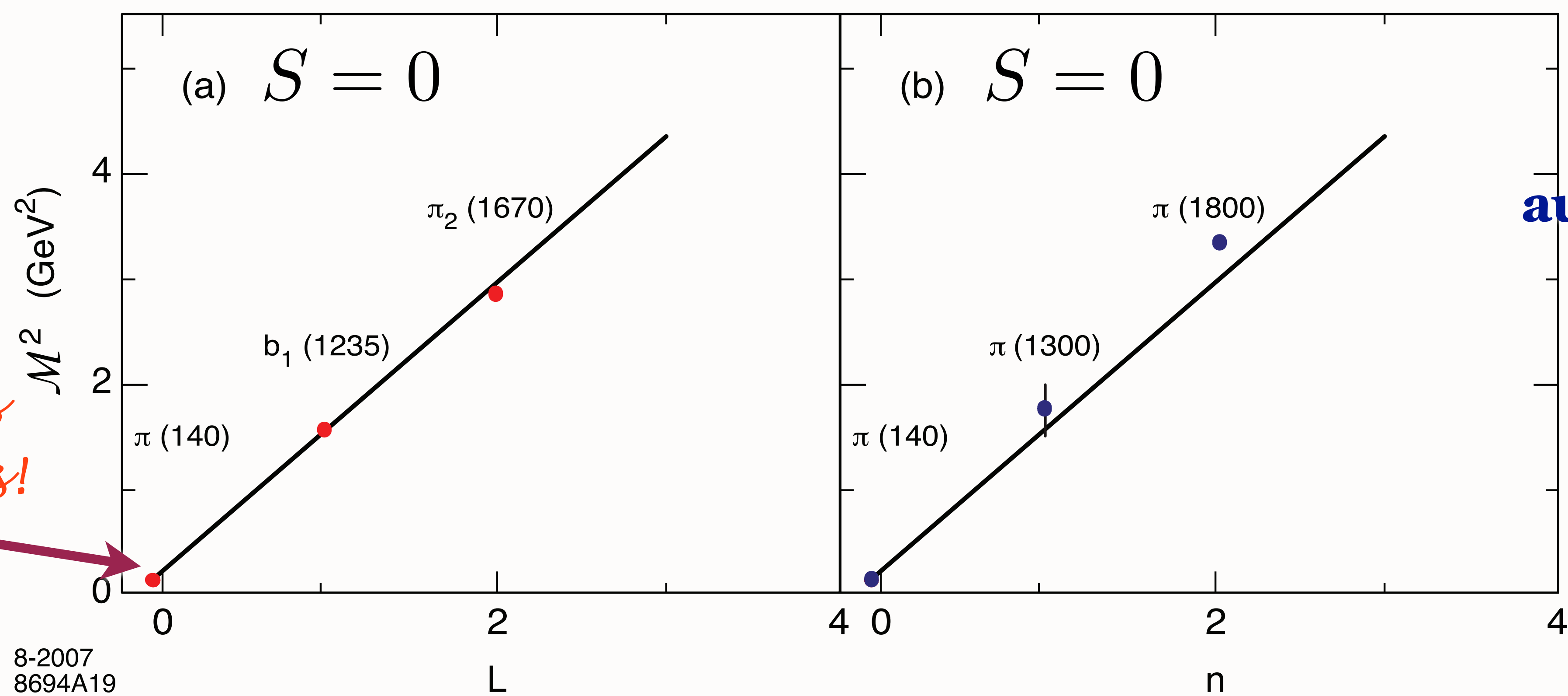


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Pion mass automatically zero!

$$m_q = 0$$



Pion has zero mass!

Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

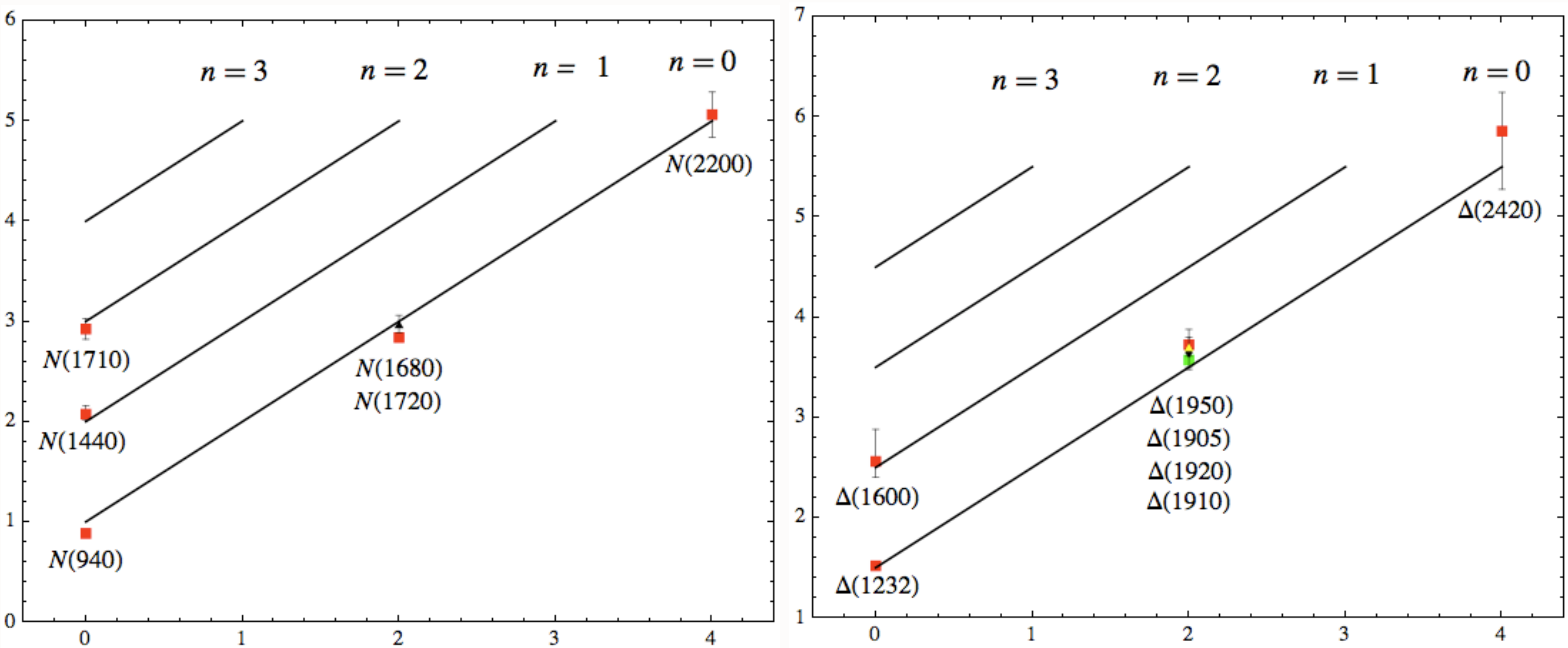
- **Δ spectrum identical to Forkel and Klempt, Phys. Lett. B 679, 77 (2009)**

$4\kappa^2$ for $\Delta n = 1$

$4\kappa^2$ for $\Delta L = 1$

$2\kappa^2$ for $\Delta S = 1$

$\mathcal{M}^2$



L

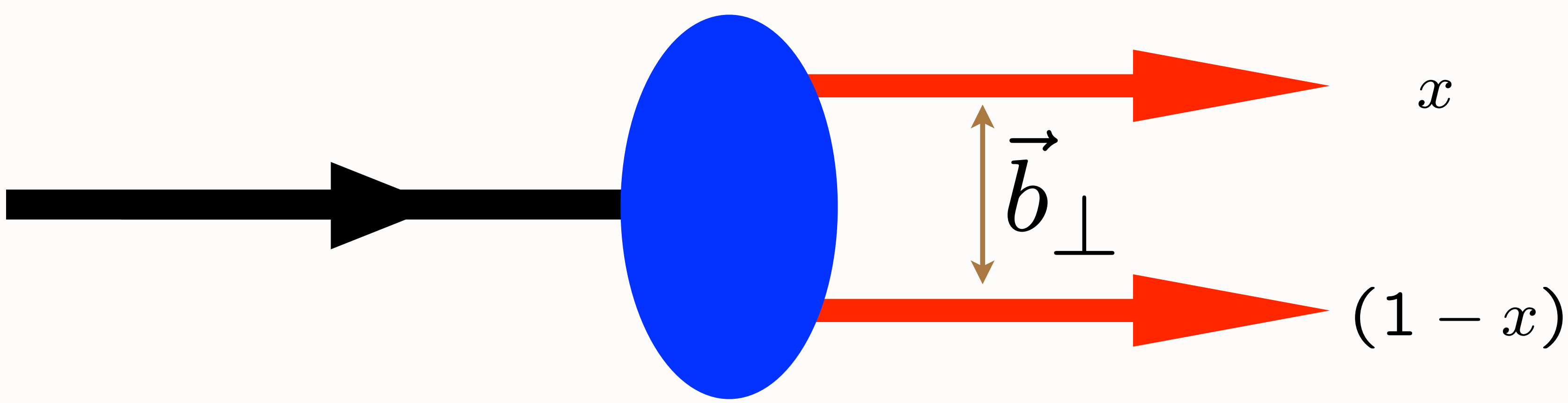
Parent and daughter **56** Regge trajectories for the N and Δ baryon families for $\kappa = 0.5$ GeV

LF(3+1) AdS$_5$

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2} \longleftrightarrow z$$

$\psi(x, \vec{b}_\perp)$



$$\psi(x,\zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

Light-Front Holography: Unique mapping derived from equality of LF and AdS formula for current matrix elements

$$H_{QED}$$

QED atoms: positronium and muonium

$$(H_0 + H_{int}) \ |\Psi >= E \ |\Psi >$$

Coupled Fock states

$$[-\frac{\Delta^2}{2m_{\rm red}} + V_{\rm eff}(\vec{S}, \vec{r})] \ \psi(\vec{r}) = E \ \psi(\vec{r})$$

Effective two-particle equation

Includes Lamb Shift, quantum corrections

$$[-\frac{1}{2m_{\rm red}}\frac{d^2}{dr^2} + \frac{1}{2m_{\rm red}}\frac{\ell(\ell+1)}{r^2} + V_{\rm eff}(r, S, \ell)] \ \psi(r) = E \ \psi(r)$$

Spherical Basis r, θ, ϕ

$$V_{eff} \to V_C(r) = -\frac{\alpha}{r}$$

Coulomb potential

Bohr Spectrum

Semiclassical first approximation to QED

$$H^{LF}_{QCD}$$

QCD Meson Spectrum

$$(H^0_{LF} + H^I_{LF})|\Psi>= M^2|\Psi>$$

Coupled Fock states

$$[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\text{eff}}]\ \psi_{LF}(x, \vec{k}_\perp) = M^2\ \psi_{LF}(x, \vec{k}_\perp)$$

Effective two-particle equation

$$\zeta^2 = x(1-x)b^2_\perp$$

$$[-\frac{d^2}{d\zeta^2} + \frac{-1+4L^2}{\zeta^2} + U(\zeta, S, L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

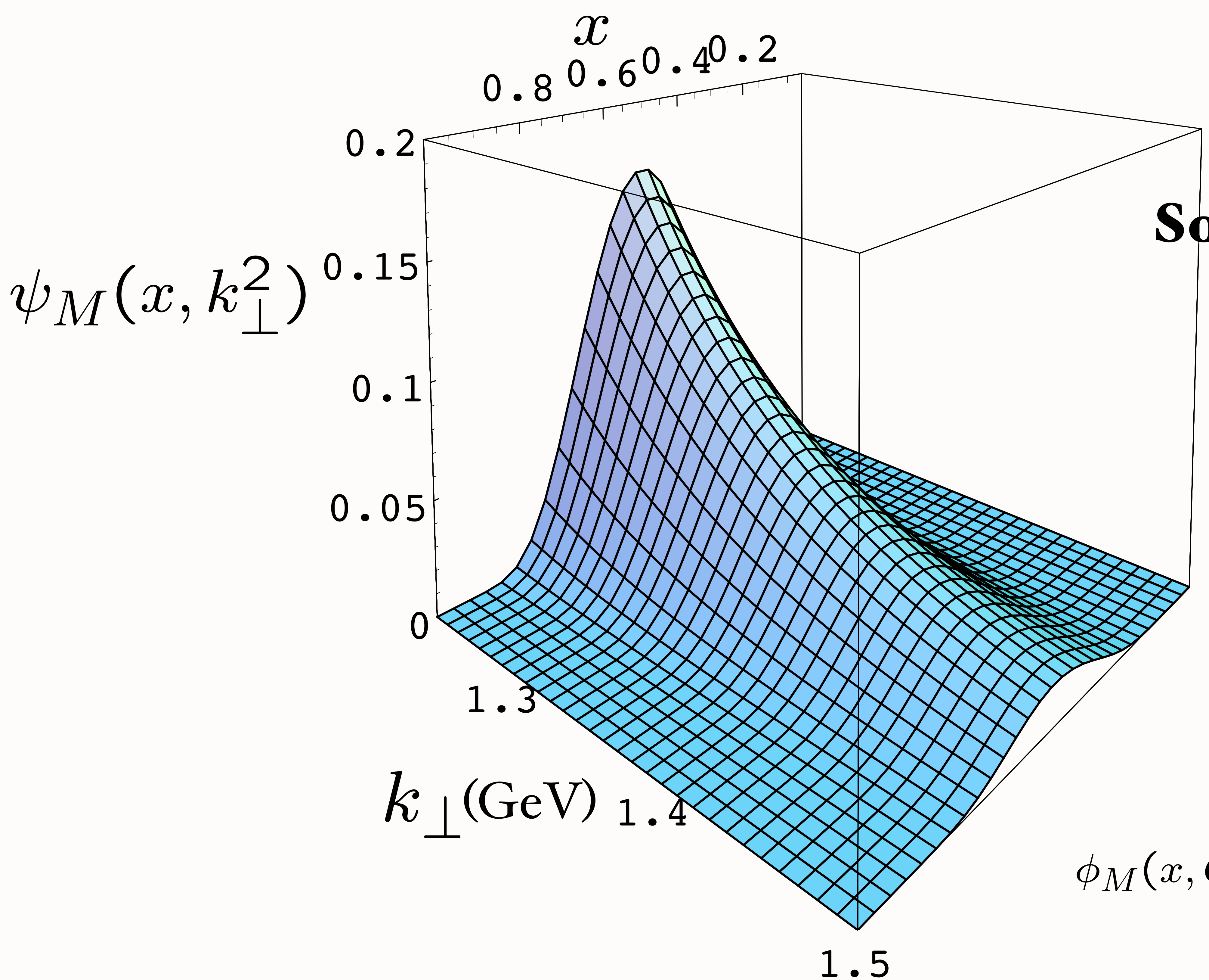
Azimuthal Basis ζ, ϕ

$$U(\zeta, S, L) = \kappa^2\zeta^2 + \kappa^2(L + S - 1/2)$$

Confining AdS/QCD potential

Semiclassical first approximation to QCD

Prediction from AdS/CFT: Meson LFWF



Soft Wall Model

de Teramond, sjb

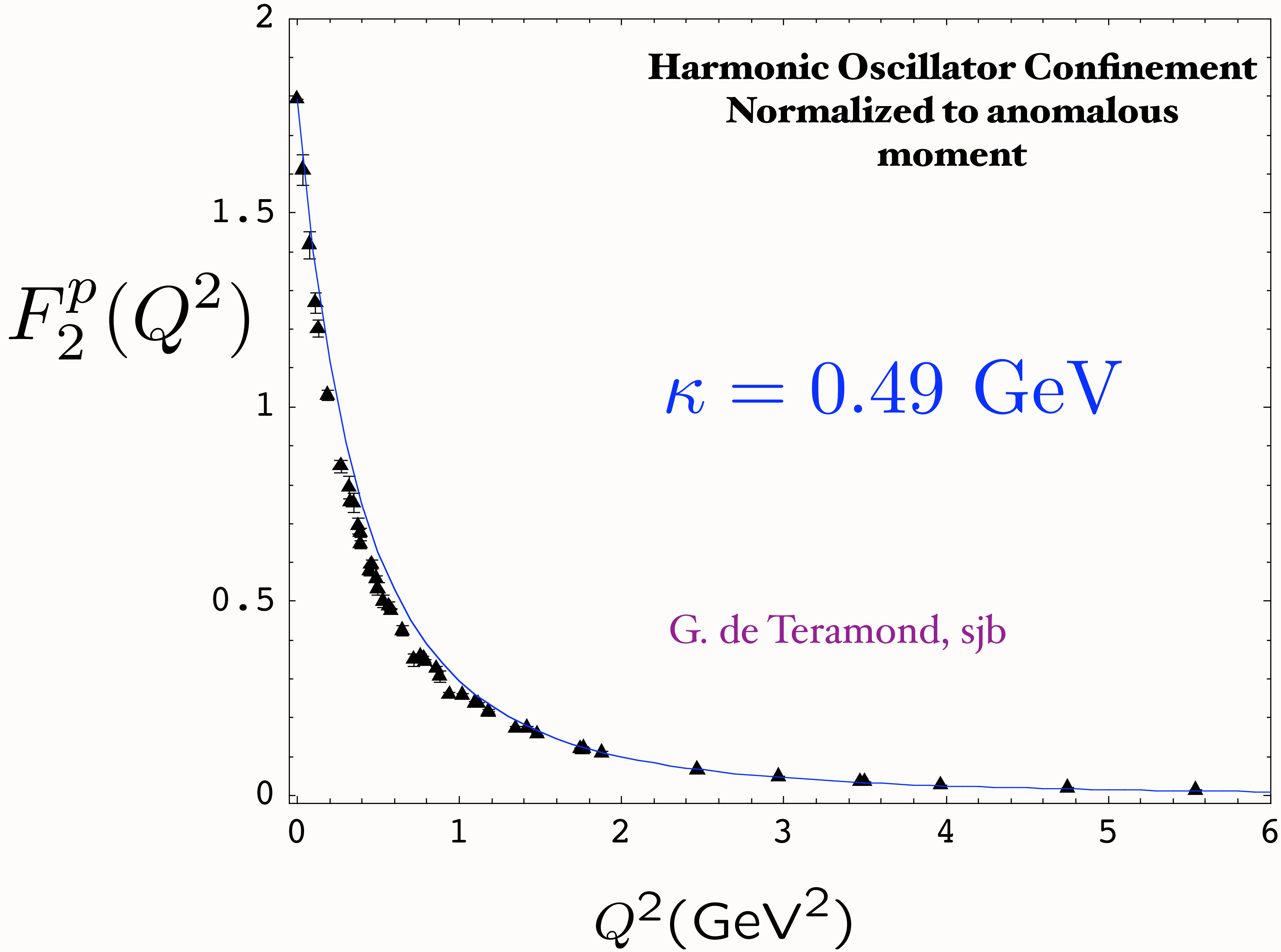
$$\phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

Increases PQCD prediction for $F_\pi(Q^2)$ by 16/9

Spacelike Pauli Form Factor

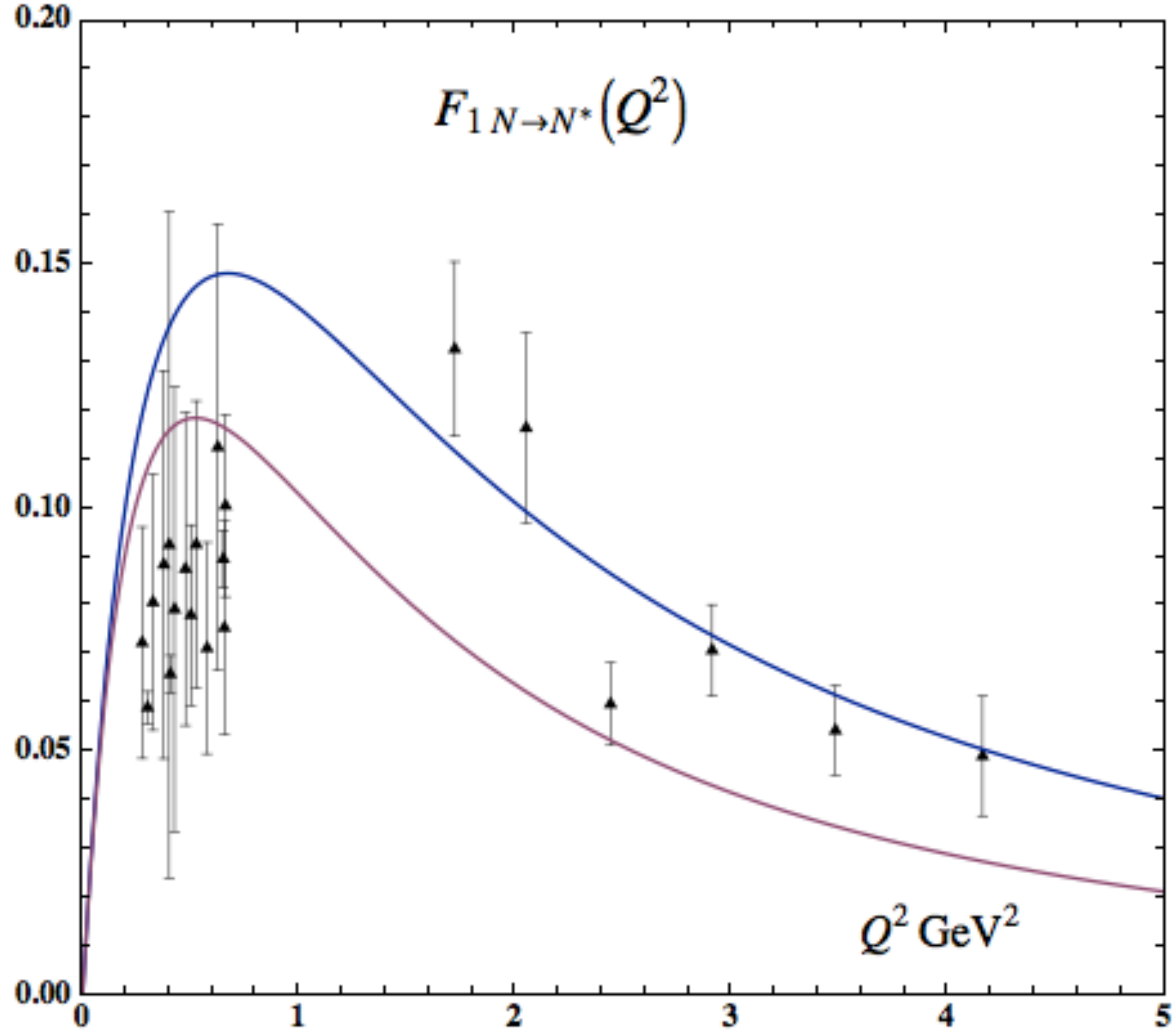
Preliminary

From overlap of $L = 1$ and $L = 0$ LFWFs



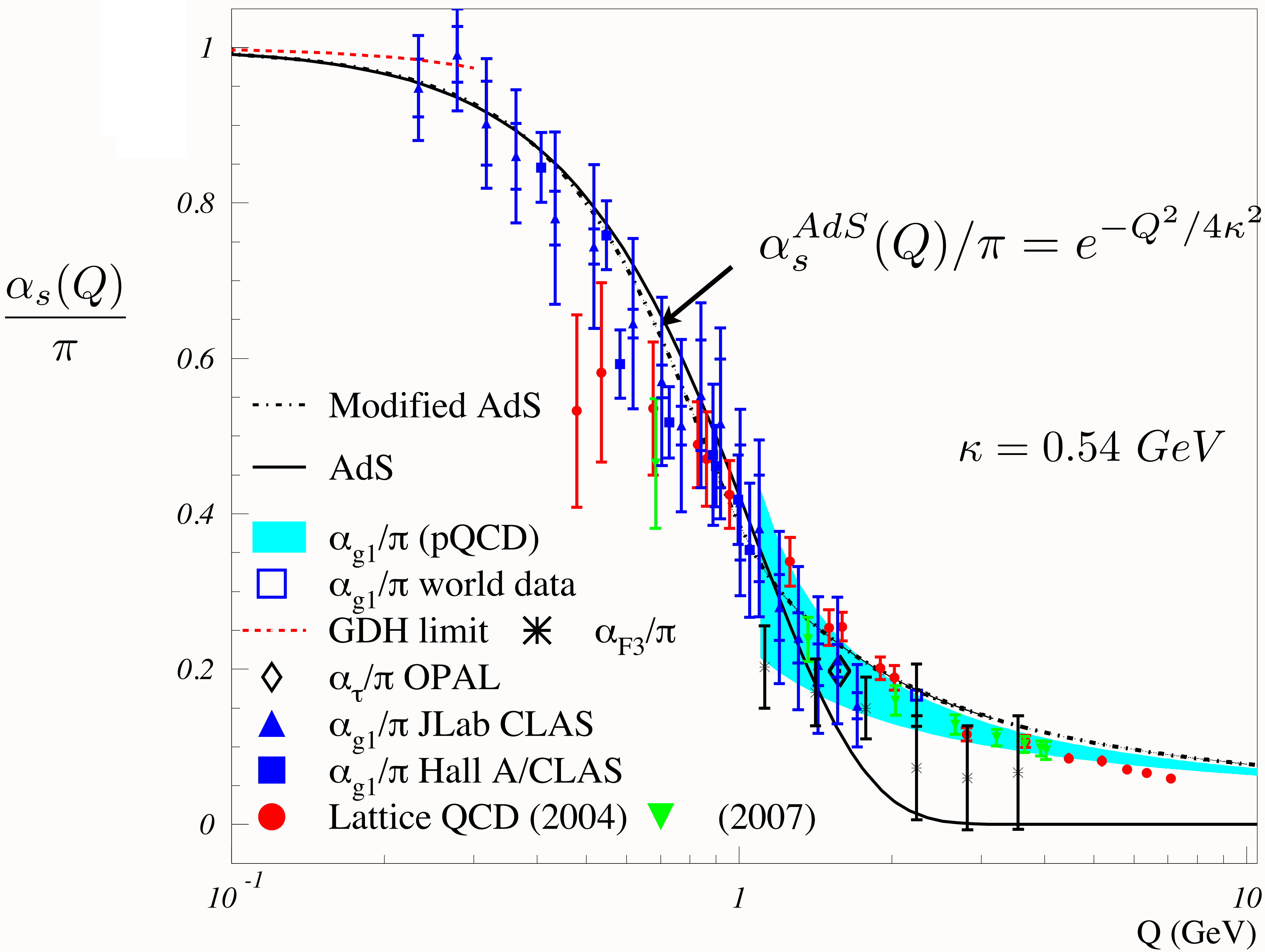
$$F_{1\,N\to N^*}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_\rho^2}}{\left(1+\frac{Q^2}{M_\rho^2}\right)\left(1+\frac{Q^2}{M_{\rho'}^2}\right)\left(1+\frac{Q^2}{M_{\rho''}^2}\right)}$$

Nucleon Transition Form Factor



Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



Deur, de Teramond, sjb

Applications of Nonperturbative Running Coupling from AdS/QCD

- Sivers Effect in SIDIS, Drell-Yan
- Double Boer-Mulders Effect in DY
- Diffractive DIS
- Heavy Quark Production at Threshold

All involve gluon exchange at small momentum transfer

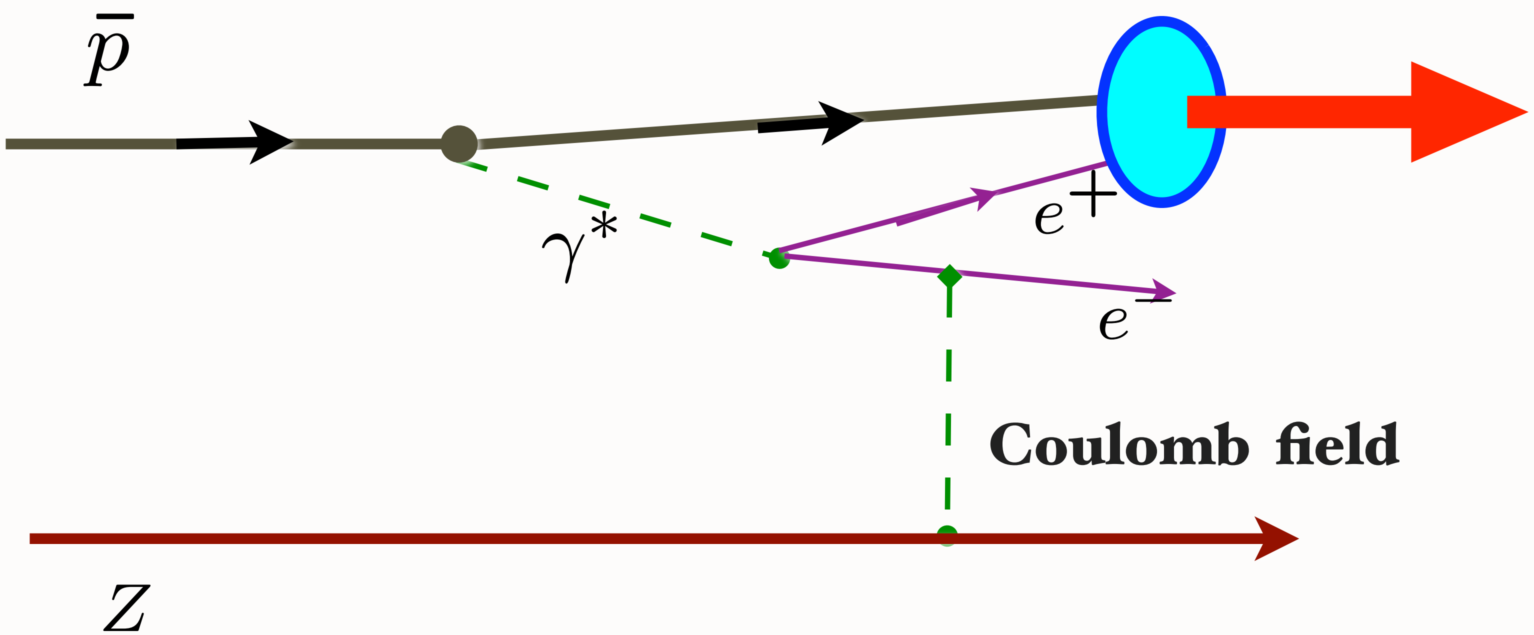
Features of Soft-Wall AdS/QCD

- Single-variable frame-independent radial Schrodinger equation
- Massless pion (m_q =0)
- Regge Trajectories: universal slope in n and L
- Valid for all integer J & S.
- Dimensional Counting Rules for Hard Exclusive Processes
- Phenomenology: Space-like and Time-like Form Factors
- LF Holography: LFWFs; broad distribution amplitude
- No large Nc limit required
- Add quark masses to LF kinetic energy
- Systematically improvable -- diagonalize H_{LF} on AdS basis

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



$\bar{H}(\bar{p}e^+)$

$$b_\perp \leq \frac{1}{m_{red}\alpha}$$

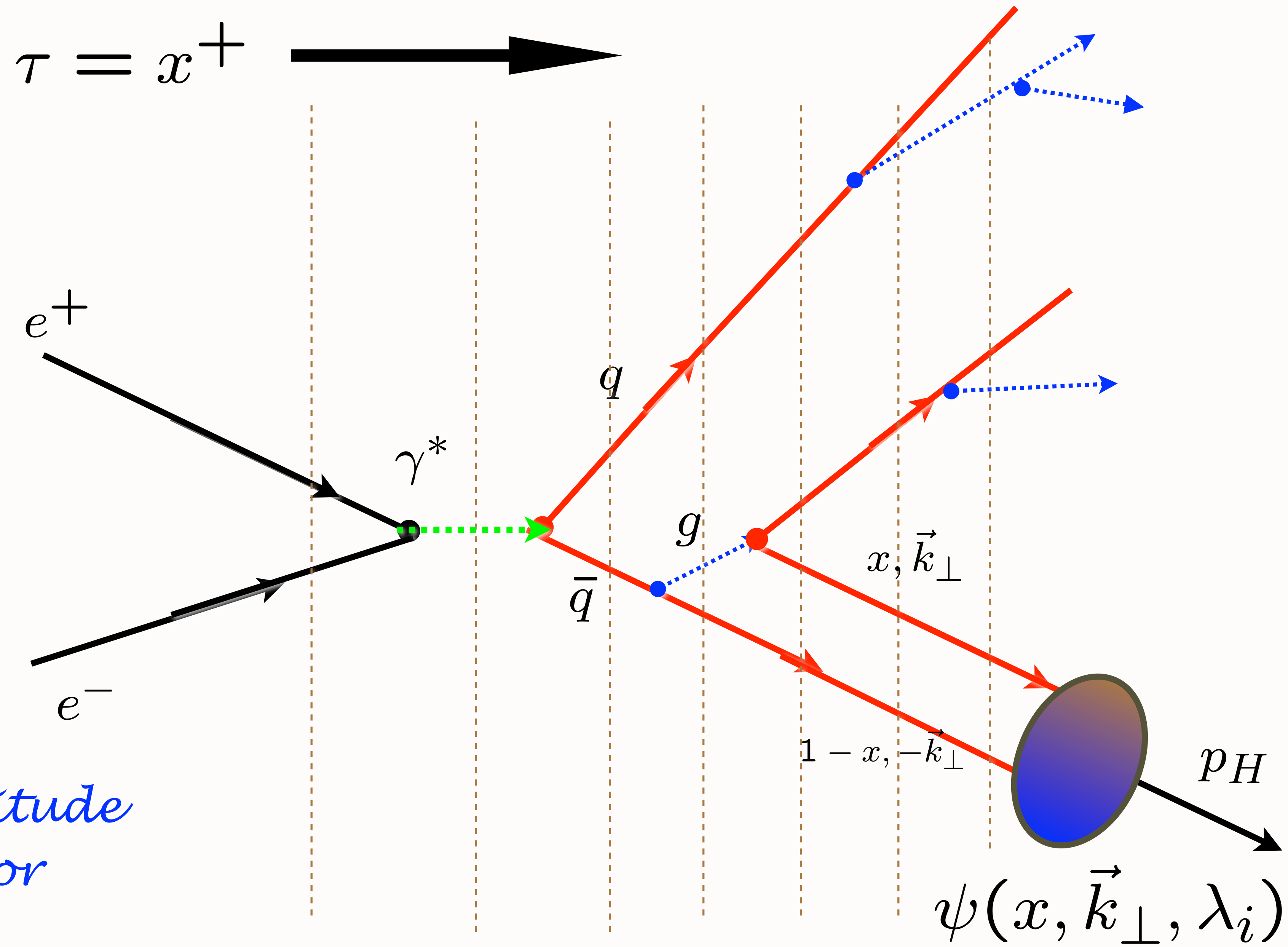
$$y_{\bar{p}} \simeq y_{e^+}$$

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

"Hadronization" at the Amplitude Level

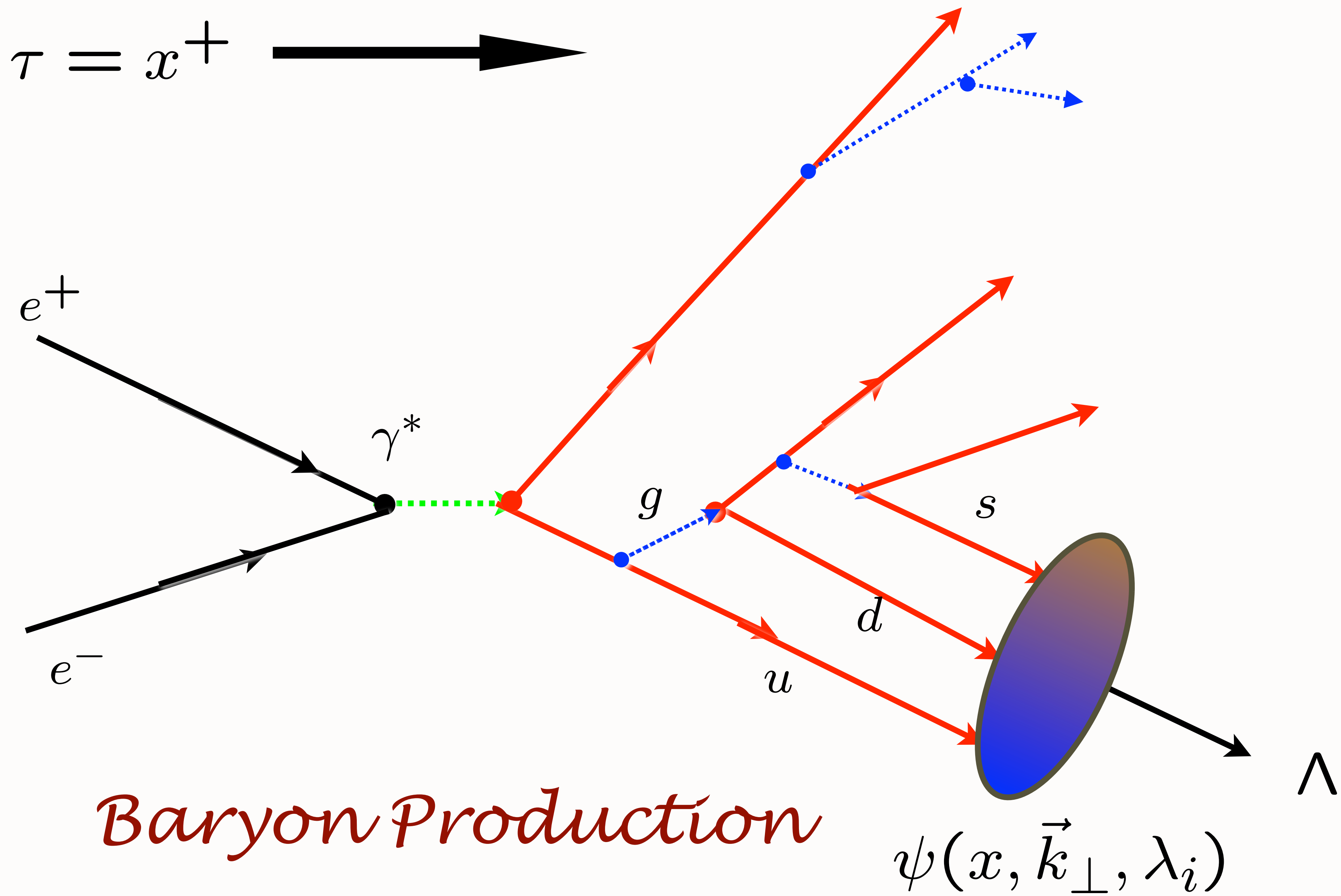
Hadronization at the Amplitude Level



Event amplitude generator

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

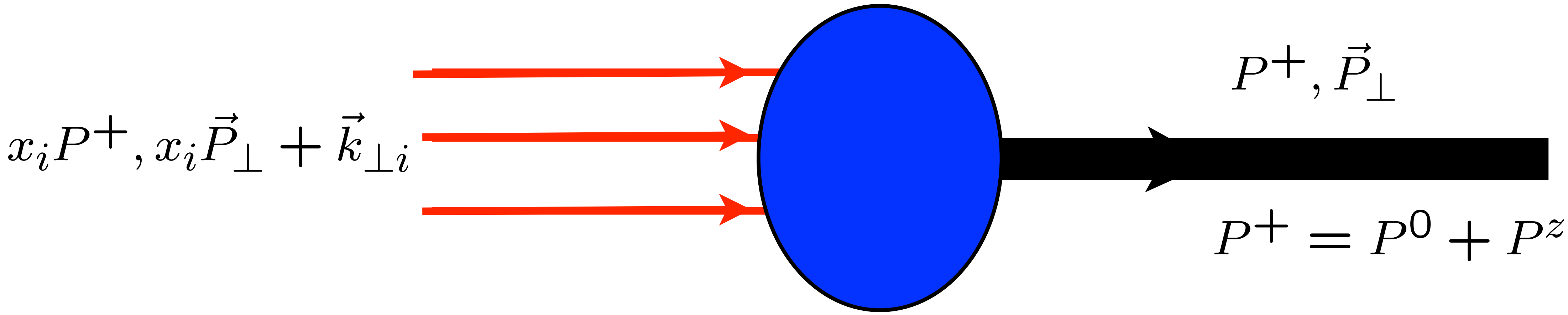
Hadronization at the Amplitude Level



Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Features of LF T-Matrix Formalism
"Event Amplitude Generator"

- Same principle as antihydrogen production: off-shell coalescence
- coalescence to hadron favored at equal rapidity, small transverse momenta
- leading heavy hadron production: D and B mesons produced at large z
- hadron helicity conservation if hadron LFWF has $L^z = 0$
- Baryon AdS/QCD LFWF has aligned and anti-aligned quark spin



"One of the gravest puzzles of theoretical physics"

DARK ENERGY AND THE COSMOLOGICAL CONSTANT PARADOX

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$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

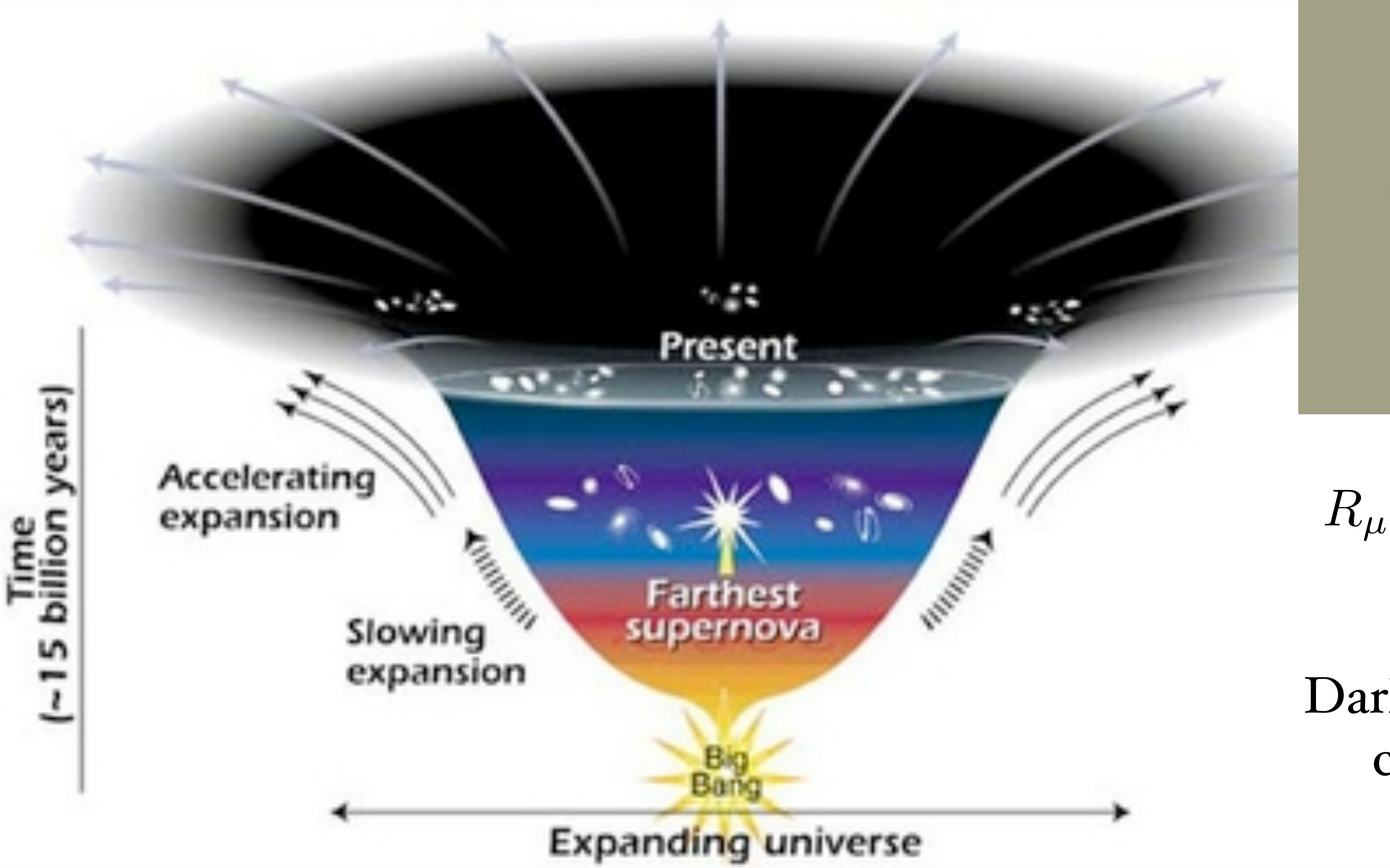
$$\Omega_\Lambda = 0.76(expt)$$

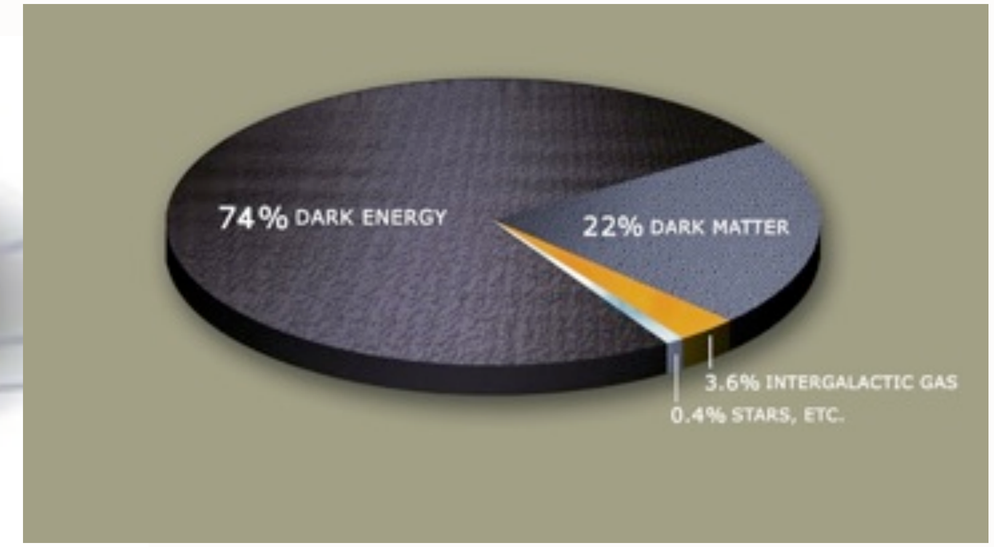
$$(\Omega_\Lambda)_{QCD} \propto < 0|q\bar{q}|0 >^4$$

QCD Problem Solved if quark and gluon condensates reside within hadrons, not vacuum!

R. Shrock, sjb Proc.Nat.Acad.Sci. 108 (2011) 45-50 "Condensates in Quantum Chromodynamics and the Cosmological Constant"

C. Roberts, R. Shrock, P. Tandy, sjb Phys.Rev. C82 (2010) 022201 "New Perspectives on the Quark Condensate"





$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = (8\pi G_N) T_{\mu\nu}$$

↑

Dark energy/cosmological constant causes accelerating expansion

$$\frac{1}{a}\frac{d^2}{dt^2} a = \Lambda/3 = (8\pi) G_N \rho_\Lambda/3$$

If the vacuum energy ρ is due to QCD condensates

$$\rho_\Lambda^{\rm QCD} \simeq M_{\rm QCD}^4 \simeq 10^{45} \rho_\Lambda^{\rm obs}\,!$$

$$\Omega_\Lambda = \frac{\rho_\Lambda^{\rm obs}}{\rho_c} \simeq 0.76 \qquad \rho_c = \frac{3H_0^2}{8\pi G_N}$$

Gell-Mann Oakes Renner Formula in QCD

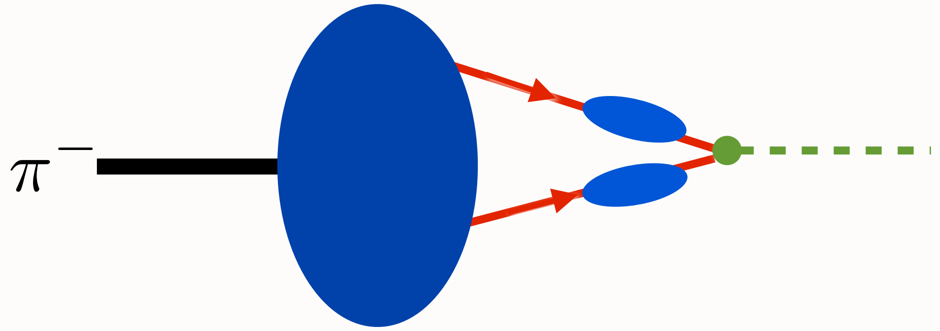
$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi^2} < 0|\bar{q}q|0 >$$

current algebra: effective pion field

$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi} < 0|i\bar{q}\gamma_5 q|\pi >$$

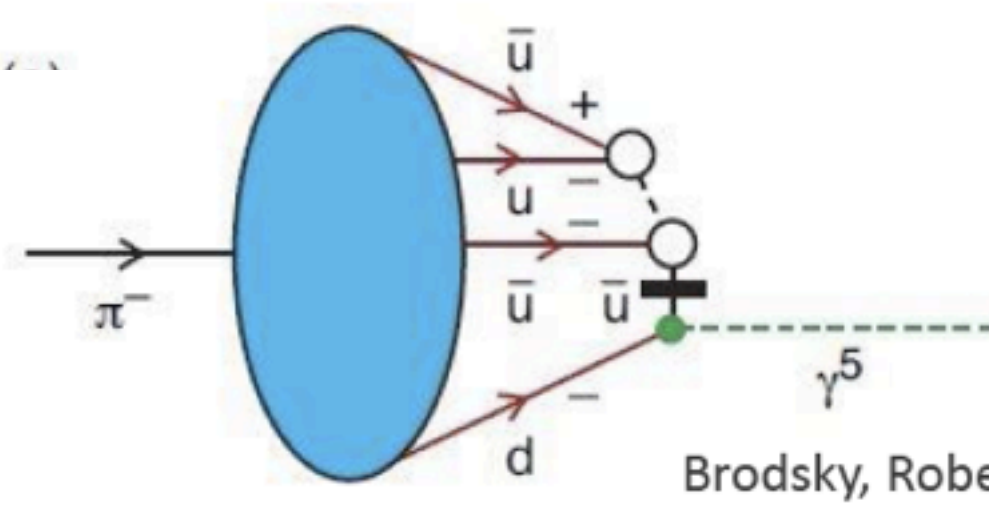
QCD: composite pion Bethe-Salpeter Eq.

vacuum condensate actually is an "in-hadron condensate"



$< 0|\bar{q}\gamma_5 q|\pi >$

Maris, Roberts, Tandy



Paradigm shift: In-Hadron Condensates

Brodsky, Roberts, Shrock, Tandy, Phys. Rev. C**82** (Rapid Comm.) (2010) 022201
Brodsky and Shrock, arXiv:0905.1151 [hep-th], to appear in PNAS

- **Resolution**
  - Whereas it might sometimes be convenient in computational truncation schemes to imagine otherwise, "condensates" do not exist as spacetime-independent mass-scales that fill all spacetime.
  - *So-called* vacuum condensates can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wavefunctions.
  - No qualitative difference between f_π and ρ_π

Chiral limit

$$\kappa_\pi(0;\zeta) = -<\bar{q}q>_\zeta^0$$

PHYSICAL REVIEW C **82**, 022201(R) (2010)

New perspectives on the quark condensate

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(Received 25 May 2010; published 18 August 2010)

We show that the chiral-limit vacuum quark condensate is qualitatively equivalent to the pseudoscalar meson leptonic decay constant in the sense that they are both obtained as the chiral-limit value of well-defined gauge-invariant hadron-to-vacuum transition amplitudes that possess a spectral representation in terms of the current-quark mass. Thus, whereas it might sometimes be convenient to imagine otherwise, neither is essentially a constant mass-scale that fills all spacetime. This means, in particular, that the quark condensate can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wave functions.

Light-Front vacuum: trivial, causal, frame-independent

Summary on QCD `Condensates'

- Condensates do not exist as space-time-independent phenomena
- Property of hadron wavefunctions: Bethe-Salpeter or Light-Front: "In-Hadron Condensates"
- Find: $$\frac{< 0|\bar{q}q|0 >}{f_\pi} \to - < 0|i\bar{q}\gamma_5 q|\pi >= \rho_\pi$$

$$< 0|\bar{q}i\gamma_5 q|\pi > \text{ similar to } < 0|\bar{q}\gamma^\mu\gamma_5 q|\pi >$$

- Zero contribution to cosmological constant! Included in hadron mass
- ρ_π survives for small m_q -- enhanced running mass from gluon loops / multiparton Fock states
- Light-Front Vacuum: Causal, trivial, no normal ordering needed

Fixed Target Physics with the LHC Beams

- 7 TeV proton beam, nuclear beams
- Full Range of Nuclear and Polarized Targets
- Cosmic Ray simulations!
- Single-Spin Asymmetries, Transversity Studies, A_N
- High-x_F Dynamics at Forward and Backward Rapidities
- High-x_F Nuclear Anomalies
- Production of ccc to bbb baryons
- Quark-Gluon Plasma in Nuclear Rest System--No Ellipse in LF

More Outstanding QCD Problems

- Single inclusive high-p_T hadrons -- wrong scaling !
- Quark Interchange dominance in hadron scattering reactions
- Quarkonium nuclear target dependence
- The Same-Side Ridge at CMS
- How to Find the Odderon?
- Signals of Hidden Color in the Deuteron
- Quark-Gluon Phase of Heavy Ion Collisions
- Quark-Gluon Phase in the Target Frame
- The Top/anti-Top Asymmetry
- Color Transparency and Opaqueness
- ...

Studies of QCD just beginning
IHEP, GSI, LHeC, AFTER

QCD Myths

- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- Infrared Slavery
- Nuclei are composites of nucleons only
- Real part of DVCS arbitrary
- heavy quarks only from gluon splitting

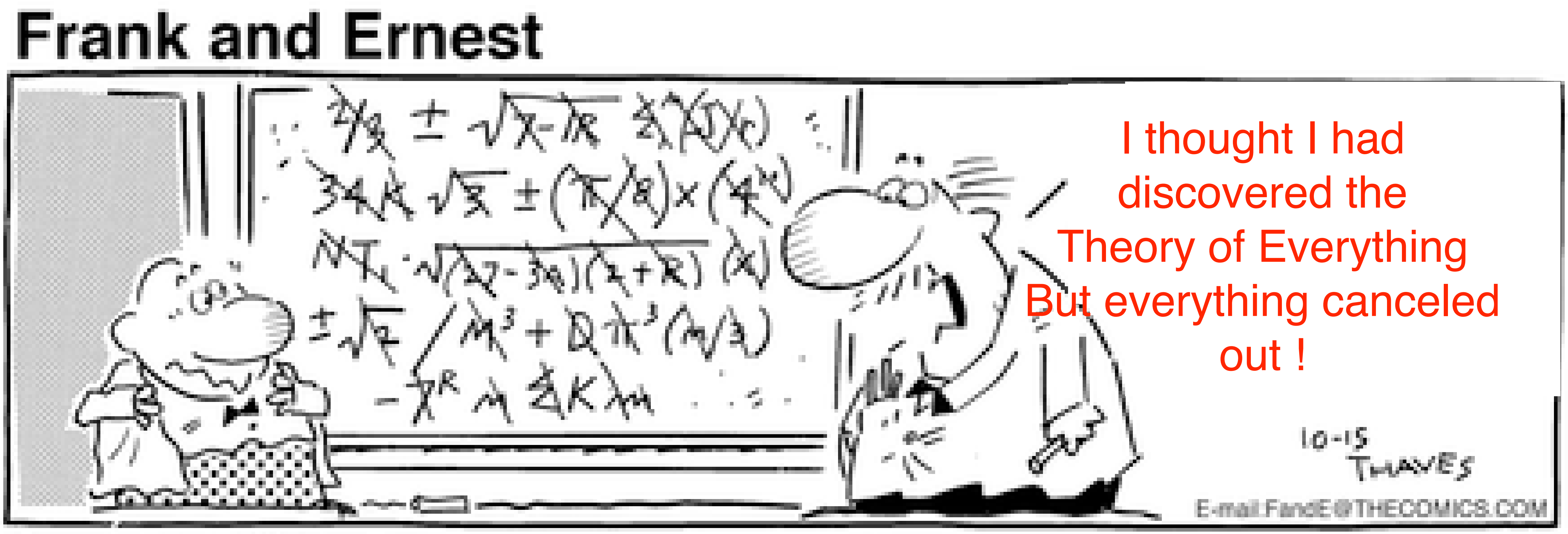
Hot Topics in QCD Phenomenology

- The nonperturbative origin of strange, charm and bottom quarks in the nucleon at large light-cone momenta
- The breakdown of pQCD factorization theorems due to the lensing effects of initial- and final-state interaction
- Important corrections to pQCD scaling for inclusive reactions due to processes in which hadrons are created at high transverse momentum directly in the hard processes and their relation to the baryon anomaly in high-centrality heavy-ion collisions
- The nonuniversality of quark distributions in nuclei;
- light-front holography -- a relativistic, color-confining, first approximation to QCD based on AdS/QCD and its correspondence to light-front quantization
- The principle of maximum conformality -- a method which determines the renormalization scale and gives scheme-independent predictions -- the elimination of the renormalization scale ambiguity using the PMC has important consequences for top quark production a colliders
- The replacement of quark and gluon vacuum condensates by "in-hadron condensates", and how this resolves the conflict between the QCD vacuum and the cosmological constant

SCIENCE VOL 265 15 SEPTEMBER 1995

A Theory of Everything Takes Place

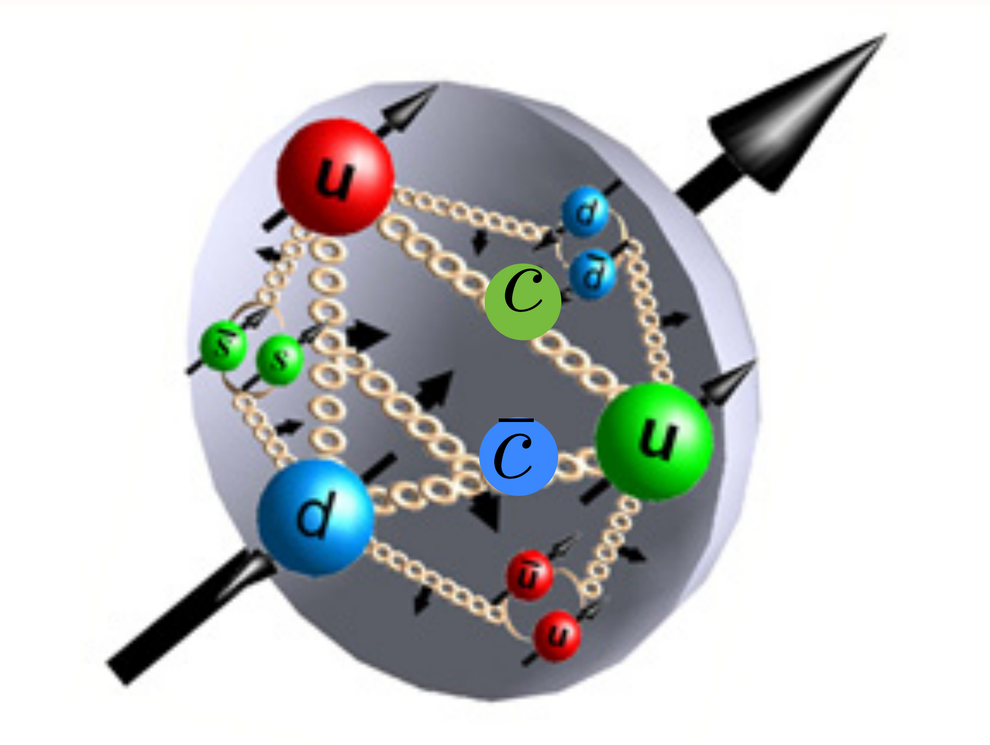
String theorists have broken an impasse and may be on their way to converting this mathematical structure -- physicists' best hope for unifying gravity and quantum theory -- into a single coherent theory.

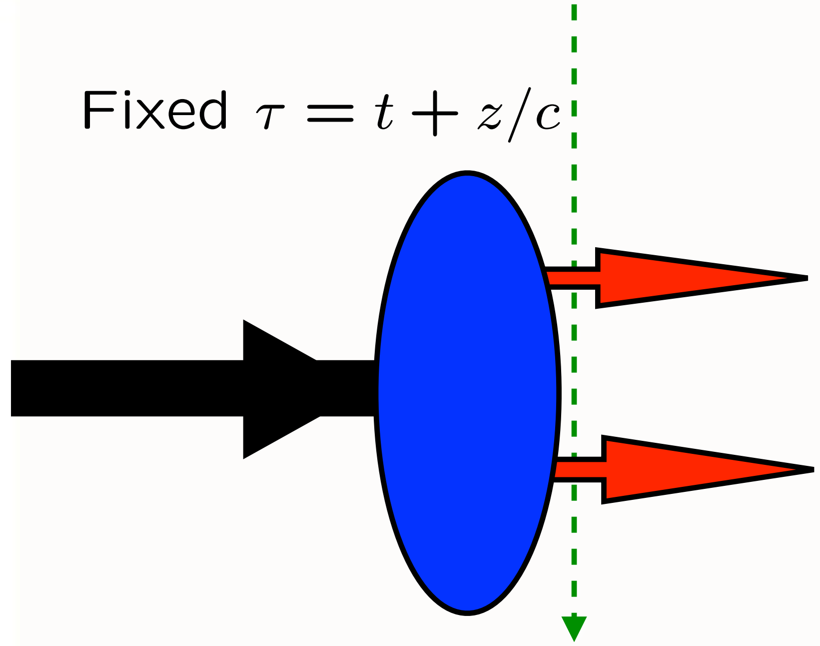


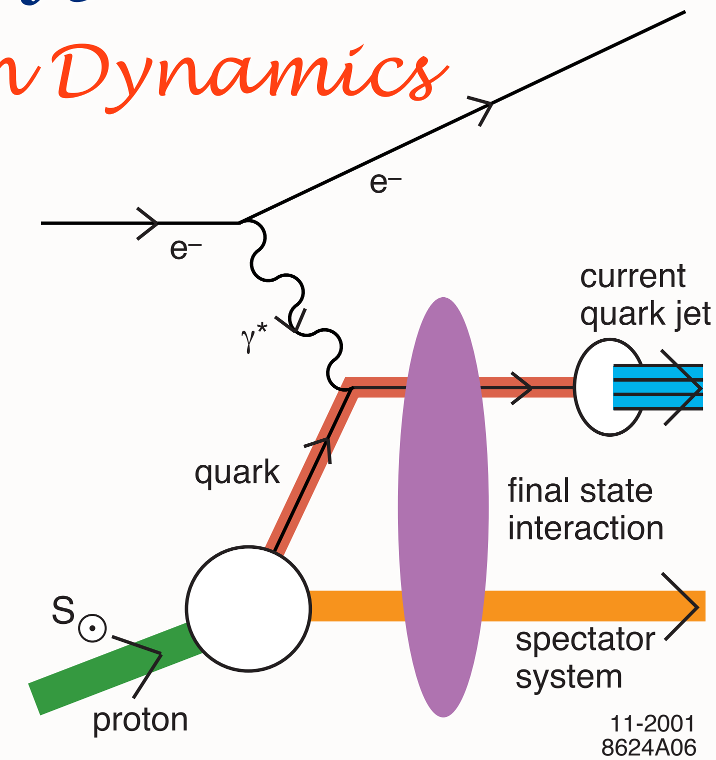
Hadrons, AdS/QCD Duality, and the Physics of the Vacuum

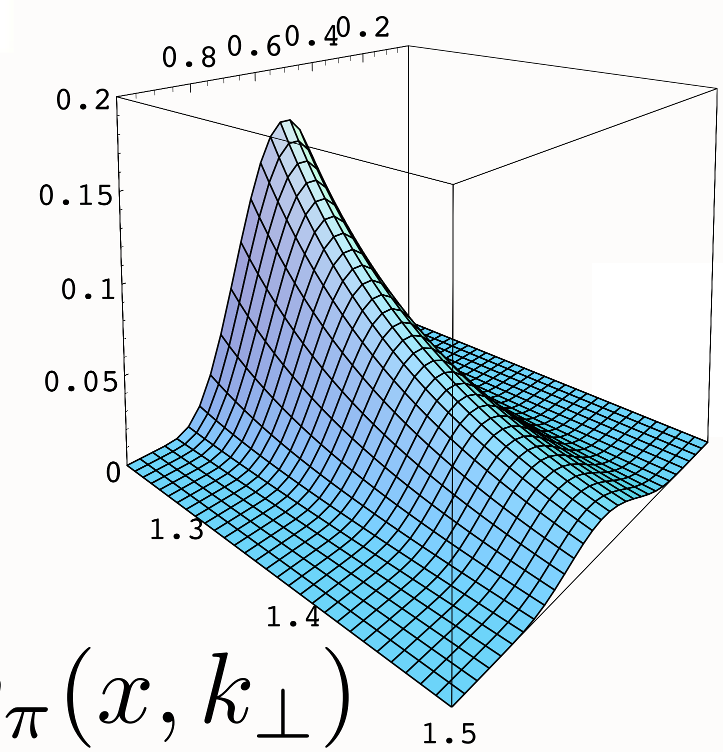
University of Warsaw Workshop, July 3-6, 2012

Novel Features of Hadron Dynamics









$\psi_\pi(x, k_\perp)$

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY