Parton Distribution Functions and the LHC

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- introduction: parton distribution functions
- the MSTW* project
- implications for LHC physics

*with Alan Martin, Robert Thorne, Graeme Watt

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deep inelastic scattering and parton distributions

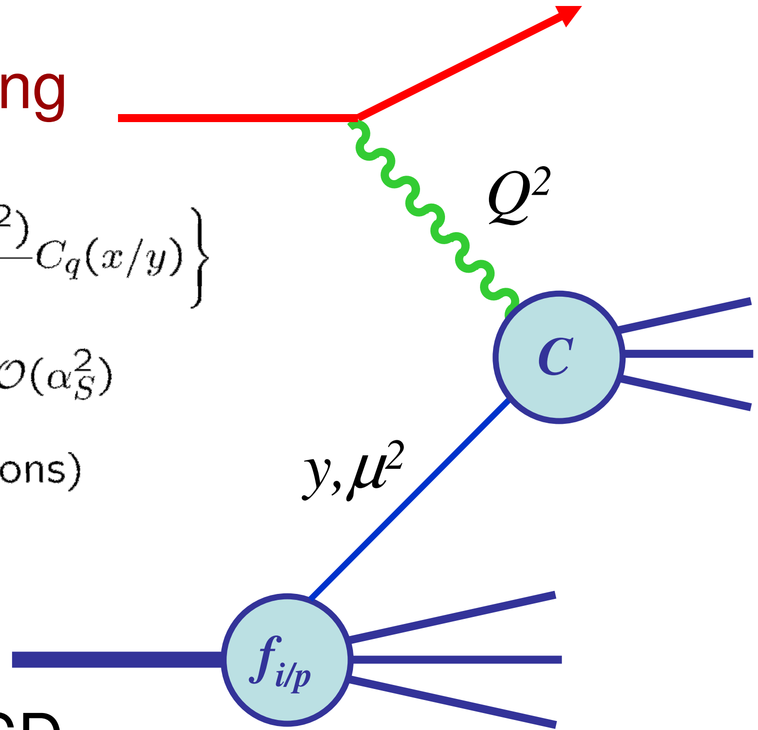
parton distribution functions

$$f_{i/A}(x, Q^2)$$

- introduced by Feynman (1969) in the *parton model*, to explain Bjorken scaling in deep inelastic scattering data; interpretation as probability distributions

- according to the QCD *factorisation theorem* for inclusive hard scattering processes, universal distributions containing long-distance structure of hadrons; related to parton model distributions at leading order, but with logarithmic scaling violations

- key ingredients for Tevatron and LHC phenomenology for example, in Deep Inelastic Scattering



$$\begin{aligned}\frac{1}{x}F_2^{lp}(x,Q^2) &= x\sum_q e_q^2 \int_x^1 \frac{dy}{y} q(y,Q^2)\left\{\delta(1-\frac{x}{y}) + \frac{\alpha_s(Q^2)}{2\pi}C_q(x/y)\right\} \\ &+ x\sum_q e_q^2 \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y} g(y,Q^2)C_g(x/y) + \mathcal{O}(\alpha_S^2) \\ &+ \mathcal{O}(1/Q^2) \quad \text{(higher twist, mass corrections)}\end{aligned}$$

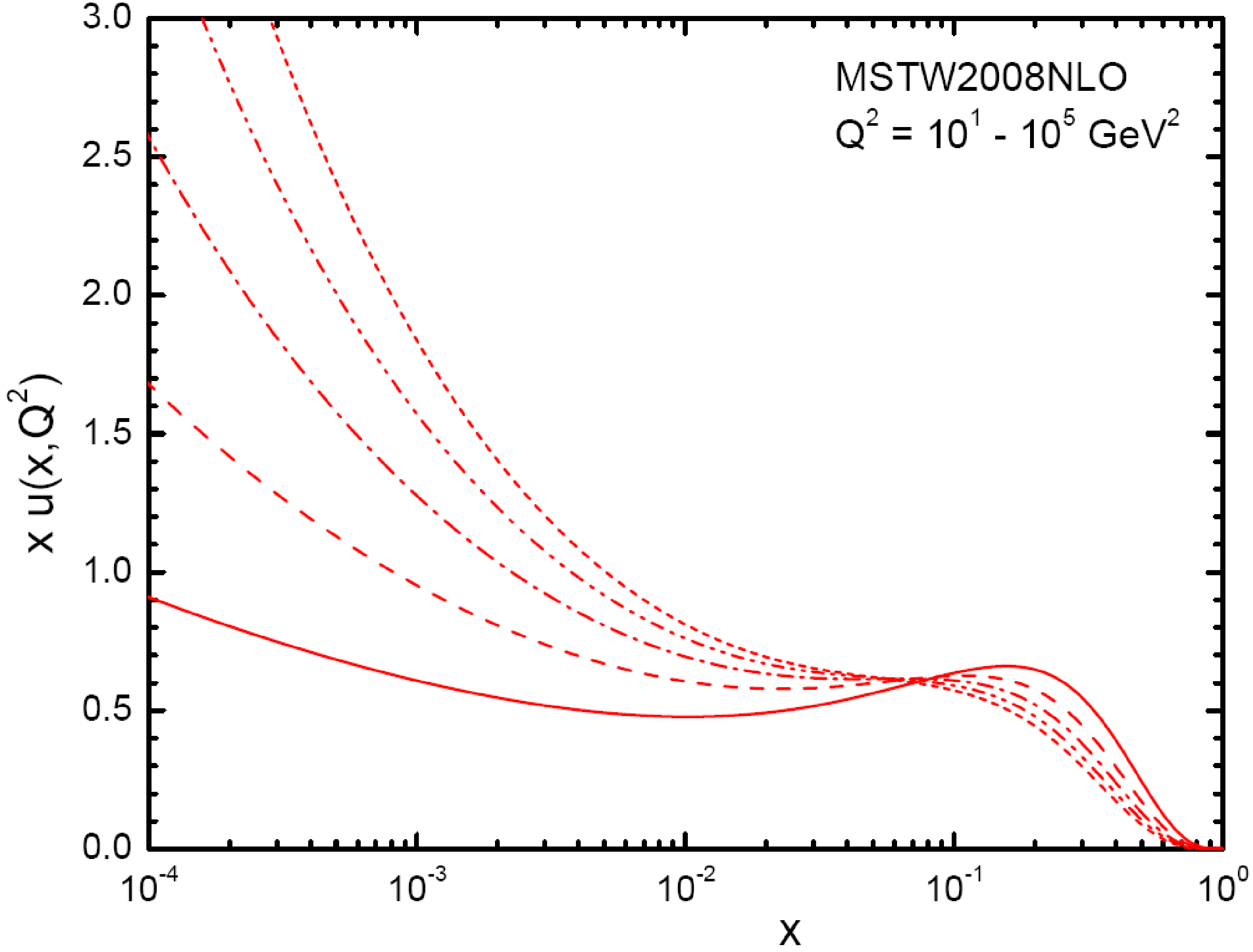
where the scale dependence of the parton distributions is calculable in QCD perturbation theory

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(x,\mu^2) = \frac{\alpha_S(\mu^2)}{2\pi}\sum_j \int_x^1 \frac{dy}{y} f_j(y,\mu^2) P_{ij}(x/y, \alpha_S(\mu^2))$$

Dokshitzer
Gribov
Lipatov
Altarelli
Parisi

… and $f_i(x,\mu_0^2)$ determined from

- lattice QCD
- fits to data


MSTW2008NLO
$Q^2 = 10^1 - 10^5\ GeV^2$
x u(x,Q²)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
x

beyond leading order in pQCD:

$$P(x,\alpha_S) \;=\; \underbrace{P^{(0)}(x)}_{\text{1972-77}} + \left(\frac{\alpha_S}{2\pi}\right) \underbrace{P^{(1)}(x)}_{\text{1977-80}} + \left(\frac{\alpha_S}{2\pi}\right)^2 \underbrace{P^{(2)}(x)}_{\text{2004}} + \ldots$$

the 2004 calculation of the complete set of $P^{(2)}$ splitting functions by Moch, Vermaseren and Vogt completes the calculational tools for a consistent NNLO (massless) pQCD treatment of lepton-hadron and hadron-hadron collider hard-scattering cross sections

Note:

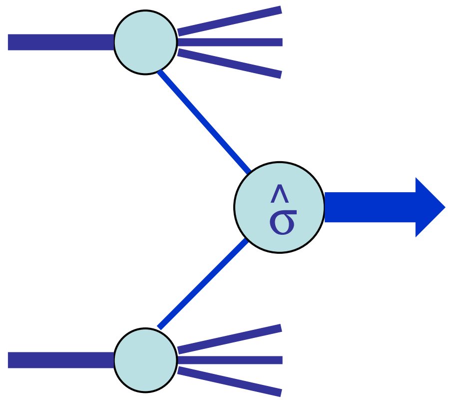
- f_i^{LO} , f_i^{NLO} and f_i^{NNLO} are different quantities!
- beyond LO, they depend on the factorisation prescription (e.g. $\overline{\text{MS}}$)

and in hadron-hadron collisions

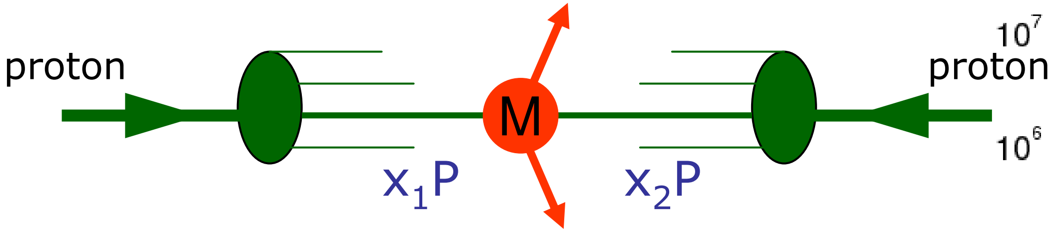
$$\sigma^{pp\to X+\ldots} = \sum_{ij}\int_0^1 dx_1 dx_2 f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) \times \hat{\sigma}_{ij\to X+\ldots}\left(x_1, x_2, \{p_i^\mu\}, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

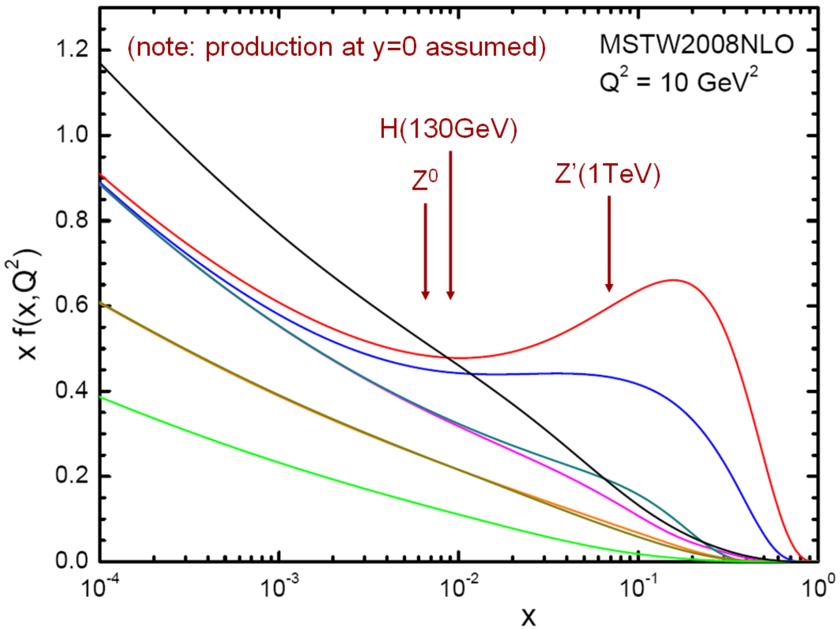
Collins
Soper
Sterman
…

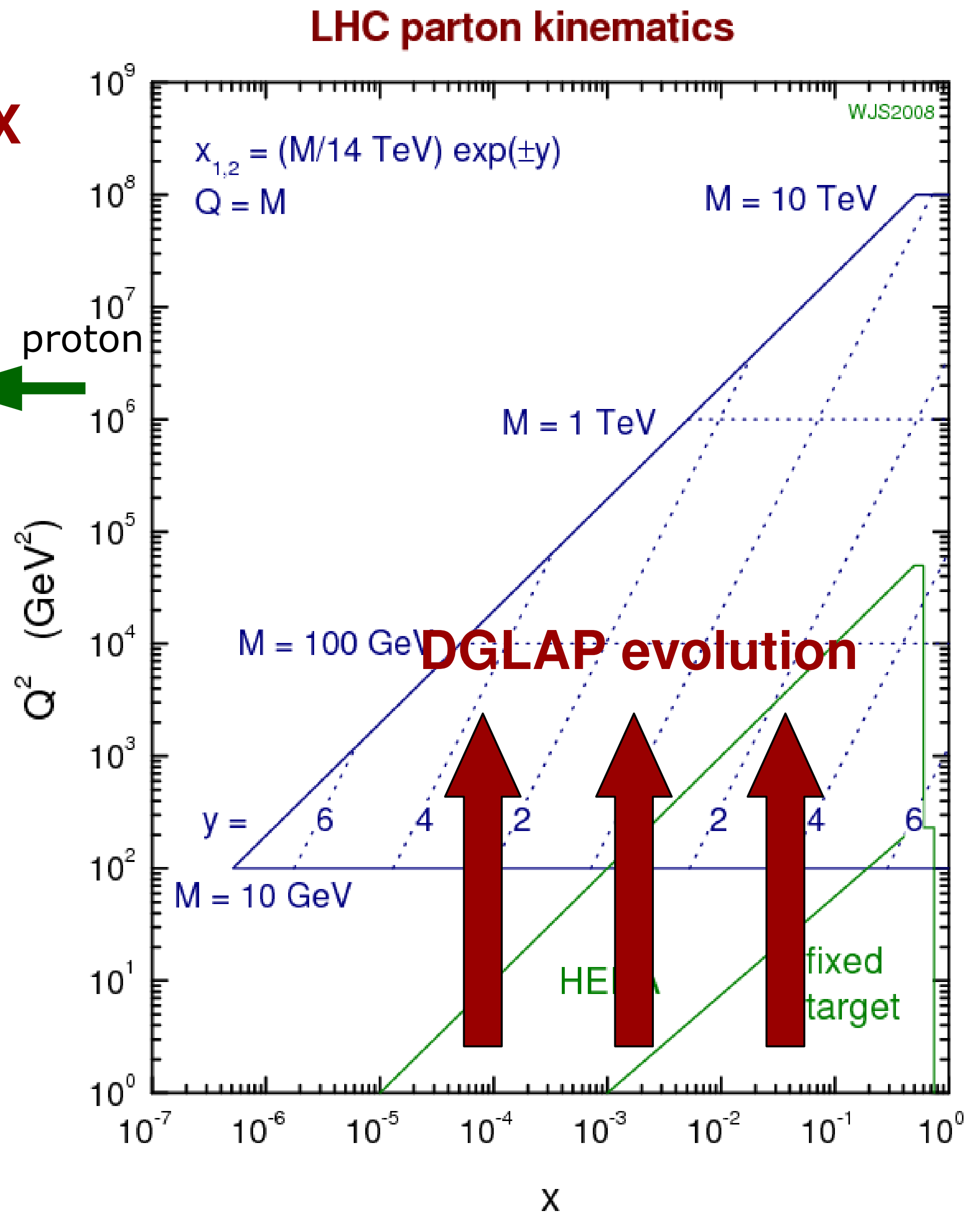
where Q is the 'hard scale' (e.g. = M_X), usually μ_F , $\mu_R = cQ$, and $\hat{\sigma}$ is known to fixed order in pQCD (sometimes with additional resummed large log corrections, QED corrections, ….)



momentum fractions x_1 and x_2
determined by mass and rapidity of **X**



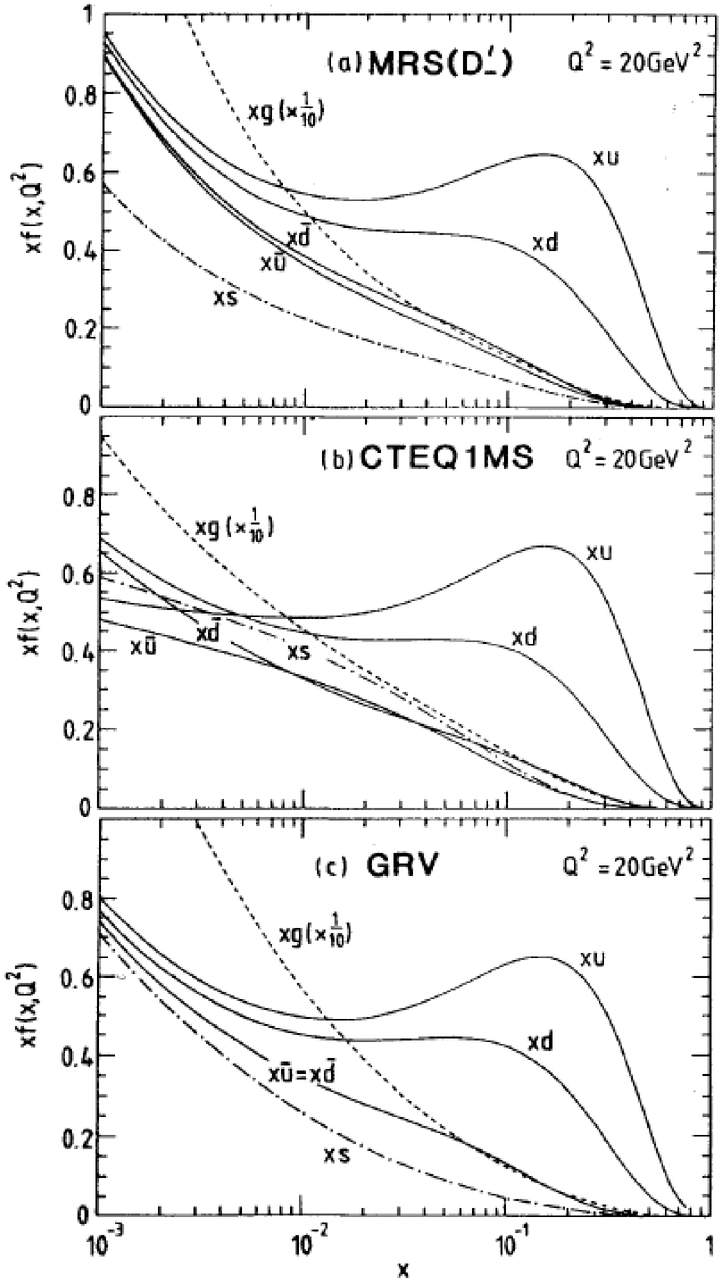




pdfs in 1993

	μ-DIS	ν-DIS	Prompt γ	D-Yan	W, Z
MRS '88	EMC + ..	CDHSW	AFS($+J/\psi$)	–	–
DFLM '88	(EMC + ..)	CHARM + ..	–	E288 + ..	–
ABFOW '89	BCDMS	–	WA70	–	–
HMRS '90	EMC BCDMS NMC(n/p)	CDHSW	WA70	E605	–
MT '90	EMC BCDMS	CDHSW	–	E288 E605	–
KMRS '90 (sets B_0,B_-)	BCDMS NMC(n/p)	CDHSW	WA70	E605	–
MRS (Apr '92) (sets D_0,D_-)	BCDMS NMC(p,n)†	CDHSW CCFR†	WA70	E605	(UA2, CDF
MRS (Nov '92) (sets D'_0,D'_-)	BCDMS NMC(p,n)	CCFR	WA70	E605	(UA2, CDF)
CTEQ ('93)	BCDMS NMC(p,n)	CCFR	WA70 E706,UA6	E605	

MRS, DIS93, Durham

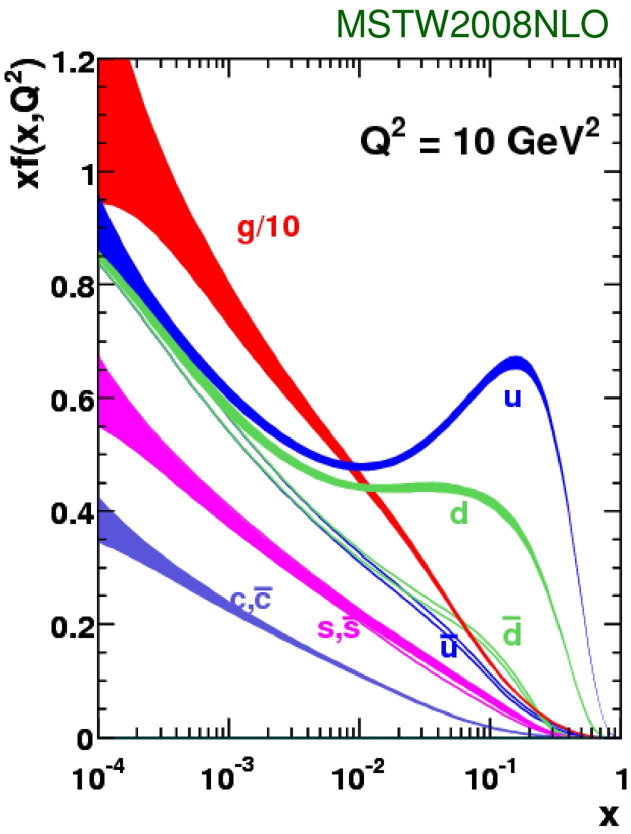


pdfs in 2009

Data set	$N_{\rm pts.}$
H1 MB 99 e^+p NC	8
H1 MB 97 e^+p NC	64
H1 low Q^2 96–97 e^+p NC	80
H1 high Q^2 98–99 e^-p NC	126
H1 high Q^2 99–00 e^+p NC	147
ZEUS SVX 95 e^+p NC	30
ZEUS 96–97 e^+p NC	144
ZEUS 98–99 e^-p NC	92
ZEUS 99–00 e^+p NC	90
H1 99–00 e^+p CC	28
ZEUS 99–00 e^+p CC	30
H1/ZEUS $e^\pm p$ $F_2^{\rm charm}$	83
H1 99–00 e^+p incl. jets	24
ZEUS 96–97 e^+p incl. jets	30
ZEUS 98–00 $e^\pm p$ incl. jets	30
DØ II $p\bar{p}$ incl. jets	110
CDF II $p\bar{p}$ incl. jets	76
CDF II $W \to l\nu$ asym.	22
DØ II $W \to l\nu$ asym.	10
DØ II Z rap.	28
CDF II Z rap.	29

Data set	$N_{\rm pts.}$
BCDMS μp F_2	163
BCDMS μd F_2	151
NMC μp F_2	123
NMC μd F_2	123
NMC $\mu n/\mu p$	148
E665 μp F_2	53
E665 μd F_2	53
SLAC ep F_2	37
SLAC ed F_2	38
NMC/BCDMS/SLAC F_L	31
E866/NuSea pp DY	184
E866/NuSea pd/pp DY	15
NuTeV νN F_2	53
CHORUS νN F_2	42
NuTeV νN xF_3	45
CHORUS νN xF_3	33
CCFR $\nu N \to \mu\mu X$	86
NuTeV $\nu N \to \mu\mu X$	84
All data sets	**2743**

- Red = New w.r.t. MRST 2006 fit.



how pdfs are obtained

- choose a factorisation scheme (e.g. MSbar), an order in perturbation theory (LO, NLO, NNLO) and a ‘starting scale’ Q_0 where pQCD applies (e.g. 1-2 GeV)
- parametrise the quark and gluon distributions at Q_0, e.g.

$$f_i(x, Q_0^2) = A_i x^{a_i}[1 + b_i\sqrt{x} + c_i x](1 - x)^{d_i}$$

- solve DGLAP equations to obtain the pdfs at any x and scale $Q > Q_0$; fit data for parameters $\{A_i, a_i, \ldots \alpha_S\}$
- approximate the exact solutions (e.g. interpolation grids, expansions in polynomials etc) for ease of use; thus the output ‘global fits’ are available ‘off the shelf”, e.g.

```
SUBROUTINE PDF(X,Q,U,UBAR,D,DBAR,…,BBAR,GLU)
```

input | output

the pdf industry

- many groups now extracting pdfs from 'global' data analyses (MSTW, CTEQ, NNPDF, HERAPDF, ABKM, GJR, …)

- broad agreement, but differences due to
  - choice of data sets (including cuts and corrections)
  - treatment of data errors
  - treatment of heavy quarks (s,c,b)
  - order of perturbation theory
  - parameterisation at Q_0
  - theoretical assumptions (if any) about:
    - flavour symmetries
    - $x \rightarrow 0,1$ behaviour
    - …

DIS
Drell-Yan
Tevatron jets
Tevatron W,Z
other

recent global fits

ABKM (Alekhin, Blumlein, Klein, Moch): global (DIS + DY) NNLO fits in FFNS, BMSN-VFNS [arXiv:0908.2766]

CTEQ (Nadolsky et al): global LO, NLO VFNS fit [arXiv:0802.0007]

GJR (Jimenez-Delgado, Reya): global (DIS + DY) NLO, NNLO FFNS, VFNS fits [arXiv:0909.1711]

HERAPDF (H1+ZEUS): NLO VFNS fit to DIS data [arXiv:0906.1108]

MSTW (Martin, Stirling, Thorne, Watt): global LO, NLO and NNLO VFNS fits [arXiv:0901.0002]

NNPDF (Ball et al): NLO VFNS fit to DIS data using neural net technology to avoid parameterisation dependence [arXiv:0906.1958]

+ older fits

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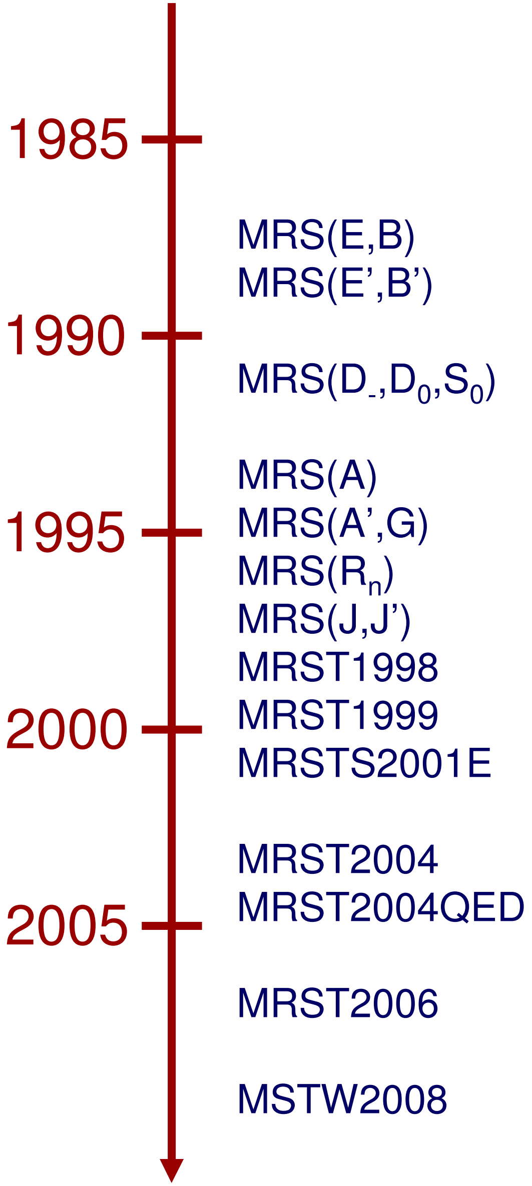
MSTW*

*Alan Martin, WJS, Robert Thorne, Graeme Watt

arXiv:0901.0002 [hep-ph], arXiv:0905.3531 [hep-ph]

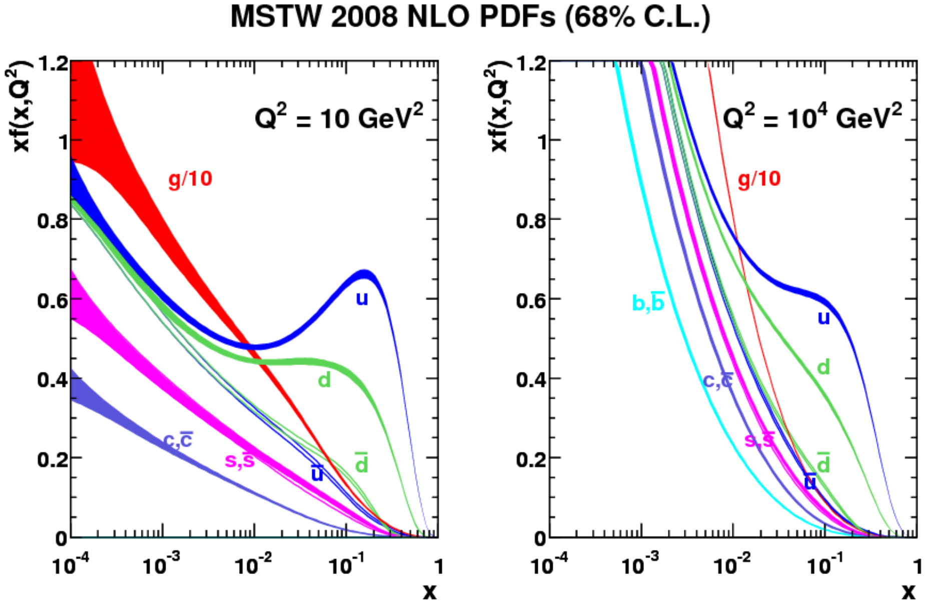
the MRS/MRST/MSTW project



- since 1987 (with Alan Martin, Dick Roberts, Robert Thorne, Graeme Watt), to produce 'state-of-the-art' pdfs
- combine experimental data with theoretical formalism to perform 'global fits' to data to extract the pdfs in user-friendly form for the particle physics community
- currently widely used at HERA and the Fermilab Tevatron, and in physics simulations for the LHC
- currently, the only available NNLO pdf sets with rigorous treatment of heavy quark flavours

MSTW 2008

- supersedes MRST sets
- new data (see next slide)
- new theory/infrastructure



  - δf_i from new dynamic tolerance method: 68%cl (1σ) and 90%cl (*cf.* MRST) sets available
  - new definition of α_S (no more Λ_{QCD})
  - new GM-VFNS for c, b (see Martin et al., arXiv:0706.0459)
  - new fitting codes: FEWZ, VRAP, fastNLO
  - new grids: denser, broader coverage
  - slightly extended parametrisation at Q_0^2 :34-4=30 free parameters including α_S

code, text and figures available at:
`http://projects.hepforge.org/mstwpdf/`

data sets used in fit

Data set	$N_{\mathrm{pts.}}$
H1 MB 99 e^+p NC	8
H1 MB 97 e^+p NC	64
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H1 high Q^2 98–99 e^-p NC	126
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E665 μd F_2	53
SLAC ep F_2	37
SLAC ed F_2	38
NMC/BCDMS/SLAC F_L	31
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NuTeV νN F_2	53
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All data sets	**2743**

- Red = New w.r.t. MRST 2006 fit.

values of χ^2/N_{pts} for the data sets included in the MSTW2008 global fits

Data set	LO	NLO	NNLO
BCDMS μp F_2 [32]	165 / 153	182 / 163	170 / 163
BCDMS μd F_2 [102]	162 / 142	190 / 151	188 / 151
NMC μp F_2 [33]	137 / 115	121 / 123	115 / 123
NMC μd F_2 [33]	120 / 115	102 / 123	93 / 123
NMC $\mu n/\mu p$ [103]	131 / 137	130 / 148	135 / 148
E665 μp F_2 [104]	59 / 53	57 / 53	63 / 53
E665 μd F_2 [104]	49 / 53	53 / 53	63 / 53
SLAC ep F_2 [105, 106]	24 / 18	30 / 37	31 / 37
SLAC ed F_2 [105, 106]	12 / 18	30 / 38	26 / 38
NMC/BCDMS/SLAC F_L [32–34]	28 / 24	38 / 31	32 / 31
E866/NuSea pp DY [107]	239 / 184	228 / 184	237 / 184
E866/NuSea pd/pp DY [108]	14 / 15	14 / 15	14 / 15
NuTeV νN F_2 [37]	49 / 49	49 / 53	46 / 53
CHORUS νN F_2 [38]	21 / 37	26 / 42	29 / 42
NuTeV νN xF_3 [37]	62 / 45	40 / 45	34 / 45
CHORUS νN xF_3 [38]	44 / 33	31 / 33	26 / 33
CCFR $\nu N \to \mu\mu X$ [39]	63 / 86	66 / 86	69 / 86
NuTeV $\nu N \to \mu\mu X$ [39]	44 / 40	39 / 40	45 / 40
H1 MB 99 e^+p NC [31]	9 / 8	9 / 8	7 / 8
H1 MB 97 e^+p NC [109]	46 / 64	42 / 64	51 / 64
H1 low Q^2 96–97 e^+p NC [109]	54 / 80	44 / 80	45 / 80
H1 high Q^2 98–99 e^-p NC [110]	134 / 126	122 / 126	124 / 126
H1 high Q^2 99–00 e^+p NC [35]	153 / 147	131 / 147	133 / 147
ZEUS SVX 95 e^+p NC [111]	35 / 30	35 / 30	35 / 30
ZEUS 96–97 e^+p NC [112]	118 / 144	86 / 144	86 / 144
ZEUS 98–99 e^-p NC [113]	61 / 92	54 / 92	54 / 92
ZEUS 99–00 e^+p NC [114]	75 / 90	63 / 90	65 / 90
H1 99–00 e^+p CC [35]	28 / 28	29 / 28	29 / 28
ZEUS 99–00 e^+p CC [36]	36 / 30	38 / 30	37 / 30
H1/ZEUS ep $F_2^{\rm charm}$ [41–47]	110 / 83	107 / 83	95 / 83
H1 99–00 e^+p incl. jets [59]	109 / 24	19 / 24	—
ZEUS 96–97 e^+p incl. jets [57]	88 / 30	30 / 30	—
ZEUS 98–00 $e^\pm p$ incl. jets [58]	102 / 30	17 / 30	—
DØ II $p\bar{p}$ incl. jets [56]	193 / 110	114 / 110	123 / 110
CDF II $p\bar{p}$ incl. jets [54]	143 / 76	56 / 76	54 / 76
CDF II $W \to \ell\nu$ asym. [48]	50 / 22	29 / 22	30 / 22
DØ II $W \to \ell\nu$ asym. [49]	23 / 10	25 / 10	25 / 10
DØ II Z rap. [53]	25 / 28	19 / 28	17 / 28
CDF II Z rap. [52]	52 / 29	49 / 29	50 / 29
All data sets	**3066 / 2598**	**2543 / 2699**	**2480 / 2615**

MSTW input parametrisation

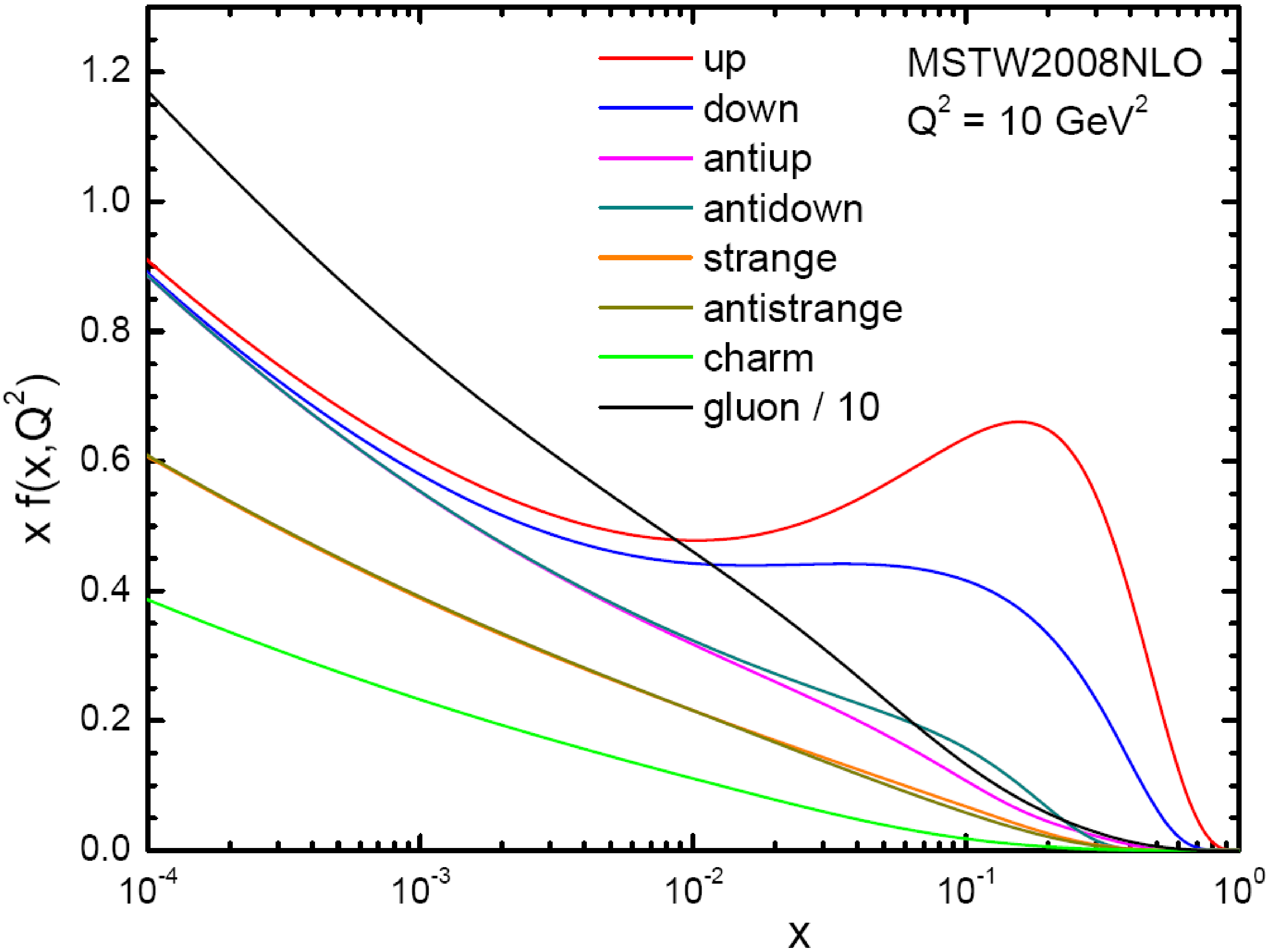
At input scale $Q_0^2 = 1\ \mathrm{GeV}^2$:

$$
\begin{aligned}
xu_v &= A_u\, x^{\eta_1} (1-x)^{\eta_2} (1 + \epsilon_u \sqrt{x} + \gamma_u\, x) \\
xd_v &= A_d\, x^{\eta_3} (1-x)^{\eta_4} (1 + \epsilon_d \sqrt{x} + \gamma_d\, x) \\
xS &= A_S\, x^{\delta_S} (1-x)^{\eta_S} (1 + \epsilon_S \sqrt{x} + \gamma_S\, x) \\
x\bar{d} - x\bar{u} &= A_\Delta\, x^{\eta_\Delta} (1-x)^{\eta_S + 2} (1 + \gamma_\Delta\, x + \delta_\Delta\, x^2) \\
xg &= A_g\, x^{\delta_g} (1-x)^{\eta_g} (1 + \epsilon_g \sqrt{x} + \gamma_g\, x) + A_{g'}\, x^{\delta_{g'}} (1-x)^{\eta_{g'}} \\
xs + x\bar{s} &= A_+\, x^{\delta_S} (1-x)^{\eta_+} (1 + \epsilon_S \sqrt{x} + \gamma_S\, x) \\
xs - x\bar{s} &= A_-\, x^{\delta_-} (1-x)^{\eta_-} (1 - x/x_0)
\end{aligned}
$$

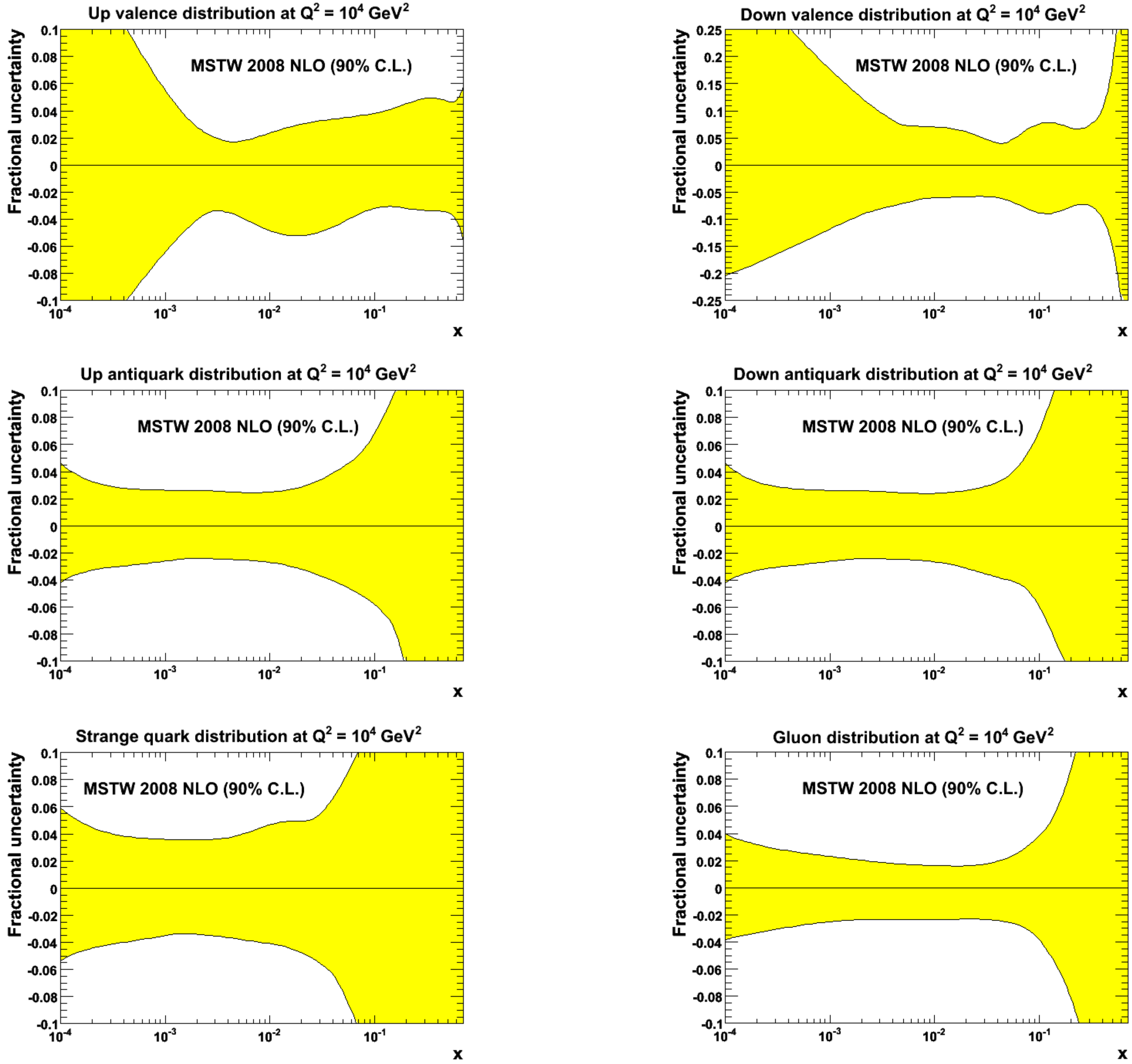
Note: 20 parameters allowed to go free for eigenvector PDF sets, *cf.* 15 for MRST sets

which data sets determine which partons?

Process	Subprocess	Partons	x range
$\ell^{\pm}\,\{p,n\} \to \ell^{\pm}\,X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^{\pm}\,n/p \to \ell^{\pm}\,X$	$\gamma^*\,d/u \to d/u$	d/u	$x \gtrsim 0.01$
$pp \to \mu^+\mu^-\,X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \to \mu^+\mu^-\,X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})\,N \to \mu^-(\mu^+)\,X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu\,N \to \mu^-\mu^+\,X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu}\,N \to \mu^+\mu^-\,X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^{\pm}\,p \to e^{\pm}\,X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+\,p \to \bar{\nu}\,X$	$W^+\,\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
$e^{\pm} p \to e^{\pm}\,c\bar{c}\,X$	$\gamma^* c \to c,\ \gamma^* g \to c\bar{c}$	$c,\ g$	$0.0001 \lesssim x \lesssim 0.01$
$e^{\pm} p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \to (W^{\pm} \to \ell^{\pm}\nu)\,X$	$ud \to W, \bar{u}\bar{d} \to W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \to (Z \to \ell^+\ell^-)\,X$	$uu, dd \to Z$	d	$x \gtrsim 0.05$

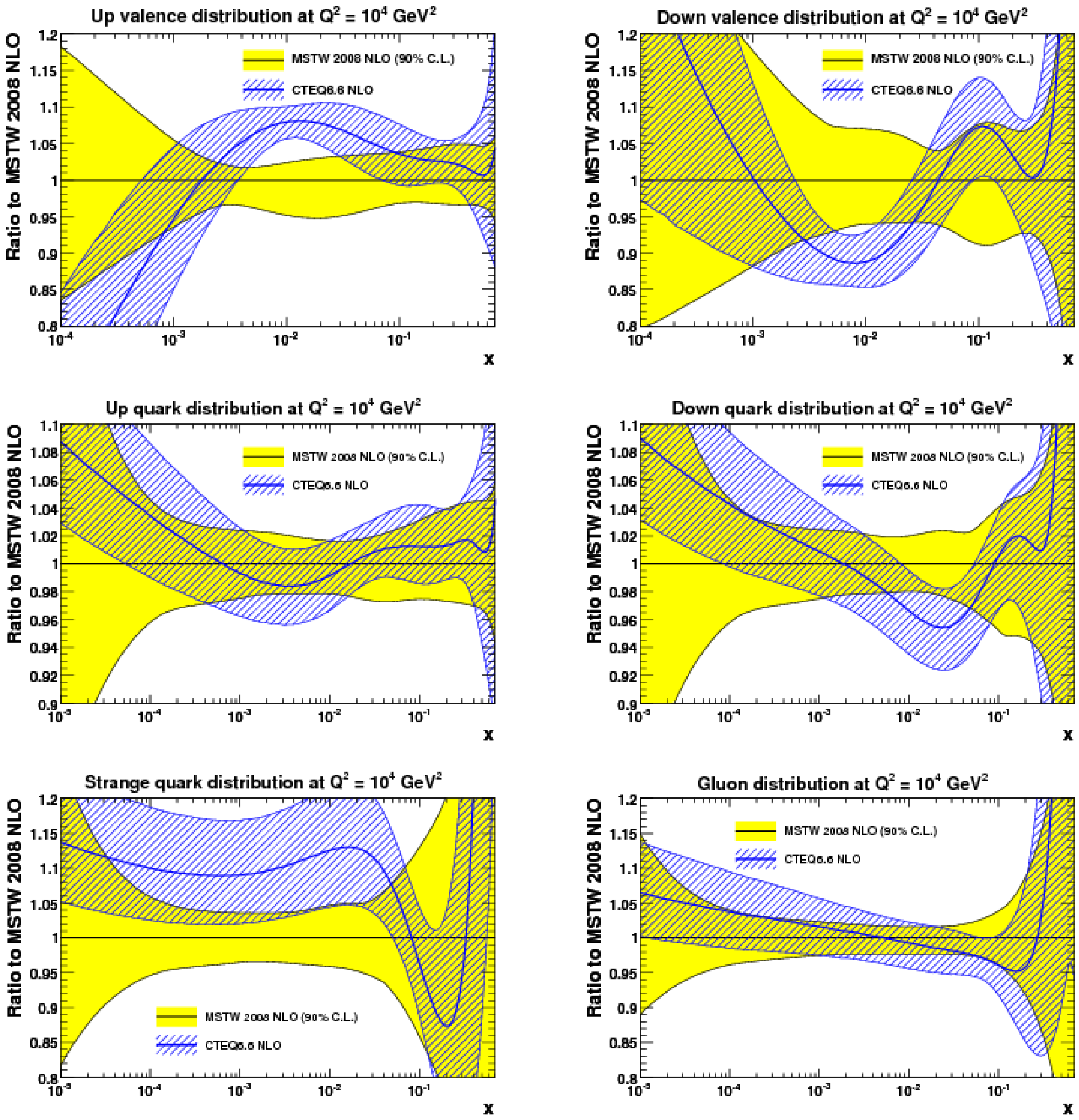


up
down
antiup
antidown
strange
antistrange
charm
gluon / 10
MSTW2008NLO
Q^2 = 10 GeV^2
x f(x,Q^2)
x
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}



Up valence distribution at Q^2 = 10^4 GeV^2
MSTW 2008 NLO (90% C.L.)
Fractional uncertainty
x
Down valence distribution at Q^2 = 10^4 GeV^2
MSTW 2008 NLO (90% C.L.)
Fractional uncertainty
x
Up antiquark distribution at Q^2 = 10^4 GeV^2
MSTW 2008 NLO (90% C.L.)
Fractional uncertainty
x
Down antiquark distribution at Q^2 = 10^4 GeV^2
MSTW 2008 NLO (90% C.L.)
Fractional uncertainty
x
Strange quark distribution at Q^2 = 10^4 GeV^2
MSTW 2008 NLO (90% C.L.)
Fractional uncertainty
x
Gluon distribution at Q^2 = 10^4 GeV^2
MSTW 2008 NLO (90% C.L.)
Fractional uncertainty
x

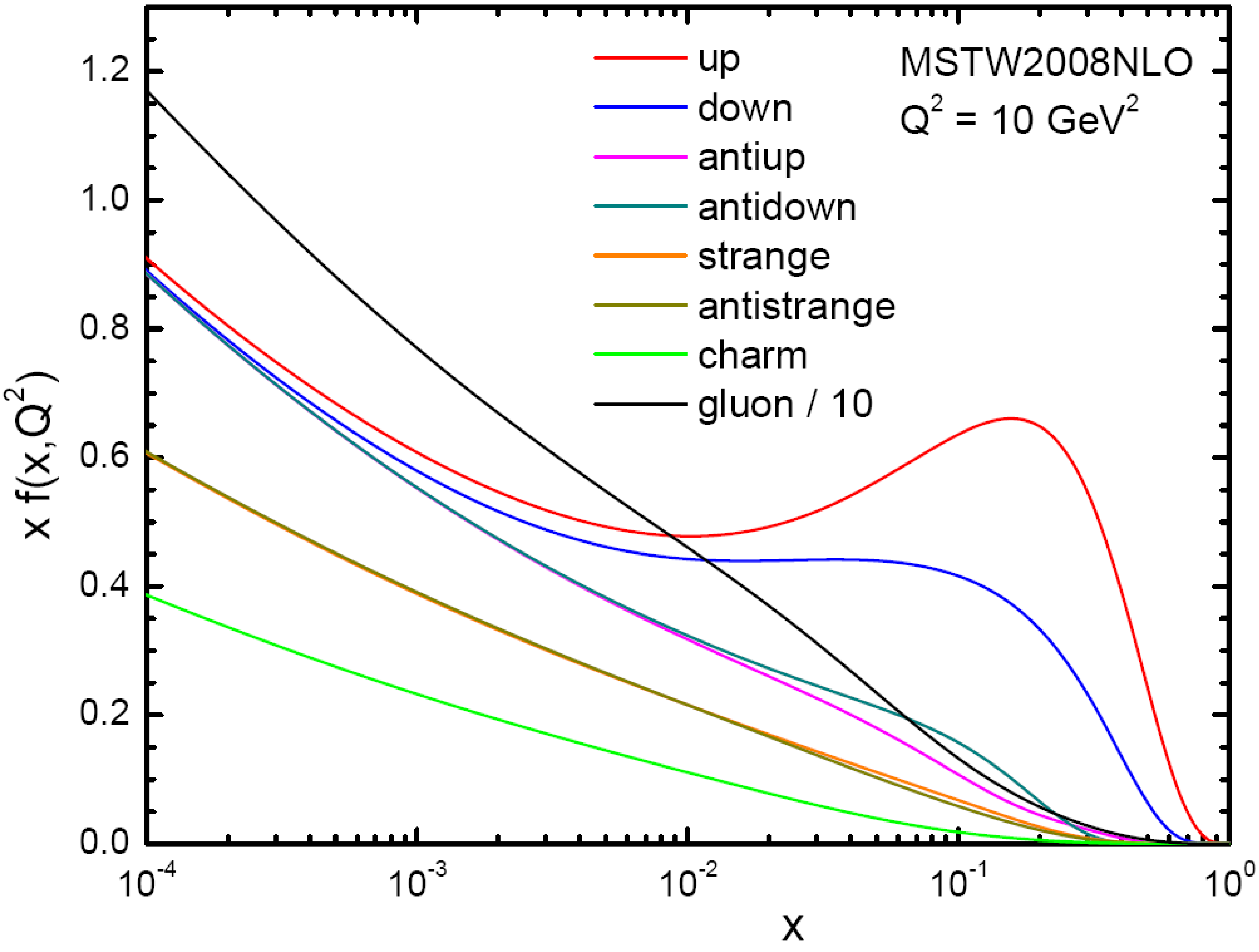
MSTW2008(NLO) vs. CTEQ6.6



Note:

CTEQ error bands comparable with MSTW 90%cl set (different definition of tolerance)

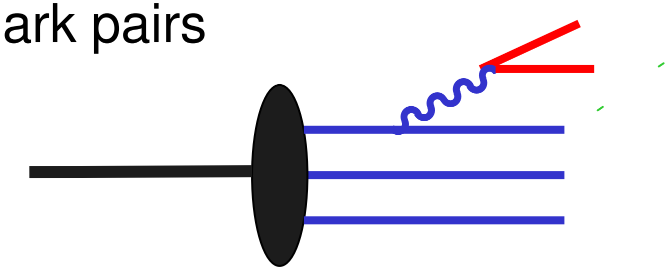
CTEQ light quarks and gluons slightly larger at small x because of imposition of positivity on gluon at Q_0^2



up
down
antiup
antidown
strange
antistrange
charm
gluon / 10
MSTW2008NLO
$Q^2 = 10\ \mathrm{GeV}^2$
x f(x,Q²)
x
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

the asymmetric sea

- the sea presumably arises when 'primordial' valence quarks emit gluons which in turn split into quark-antiquark pairs, with suppressed splitting into heavier quark pairs

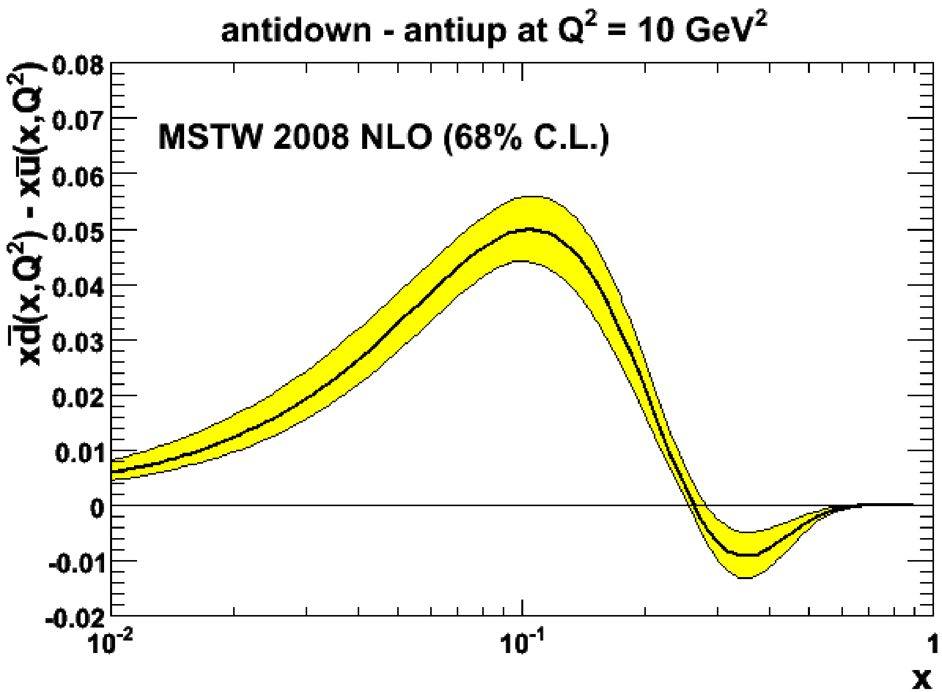


- so we naively expect

$$\bar{u} \approx \bar{d} > \bar{s} > \bar{c} > \ldots$$

- but why such a big d-u asymmetry? Meson cloud, Pauli exclusion, …?

The ratio of Drell-Yan cross sections for $pp, pn \to \mu^+\mu^- + X$ provides a measure of the difference between the *u* and *d* sea quark distributions



strange

earliest pdf fits had SU(3) symmetry: $s(x,Q_0^2) = \bar{s}(x,Q_0^2) = \bar{u}(x,Q_0^2) = \bar{d}(x,Q_0^2)$

later relaxed to include (constant) strange suppression (cf. fragmentation):

$$s(x,Q_0^2) = \bar{s}(x,Q_0^2) = \frac{\kappa}{2}\left[\bar{u}(x,Q_0^2) + \bar{d}(x,Q_0^2)\right]$$

with $\kappa = 0.4 - 0.5$

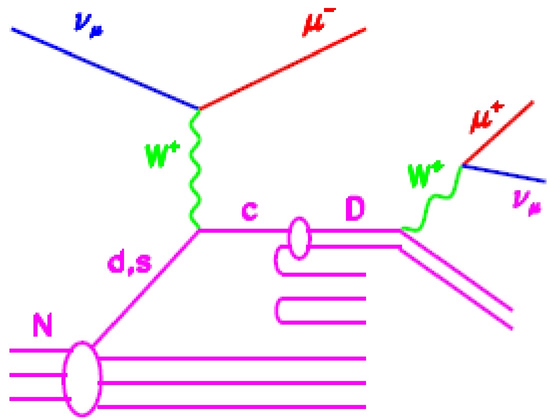
nowadays, dimuon production in νN DIS (CCFR, NuTeV) allows 'direct' determination:

$$\frac{d\sigma}{dxdy}\left(\nu_\mu(\bar{\nu}_\mu)N \rightarrow \mu^+\mu^- X\right) = B_c\,\mathcal{N}\mathcal{A}\,\frac{d\sigma}{dxdy}\left(\nu_\mu s(\bar{\nu}_\mu \bar{s}) \rightarrow c\mu^-(\bar{c}\mu^+)X\right)$$

in the range $0.01 < x < 0.4$

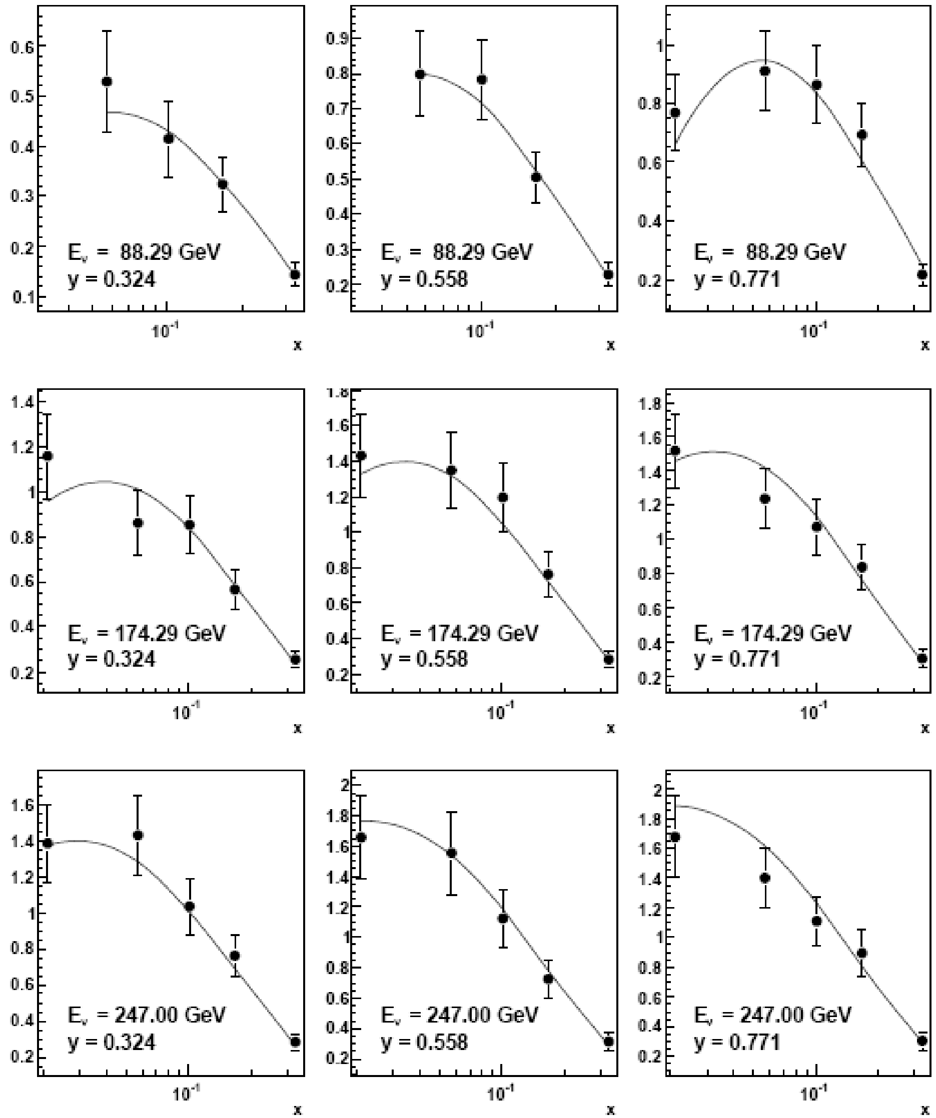
data seem to prefer $s(x,Q_0^2) - \bar{s}(x,Q_0^2) \neq 0$

theoretical explanation?!

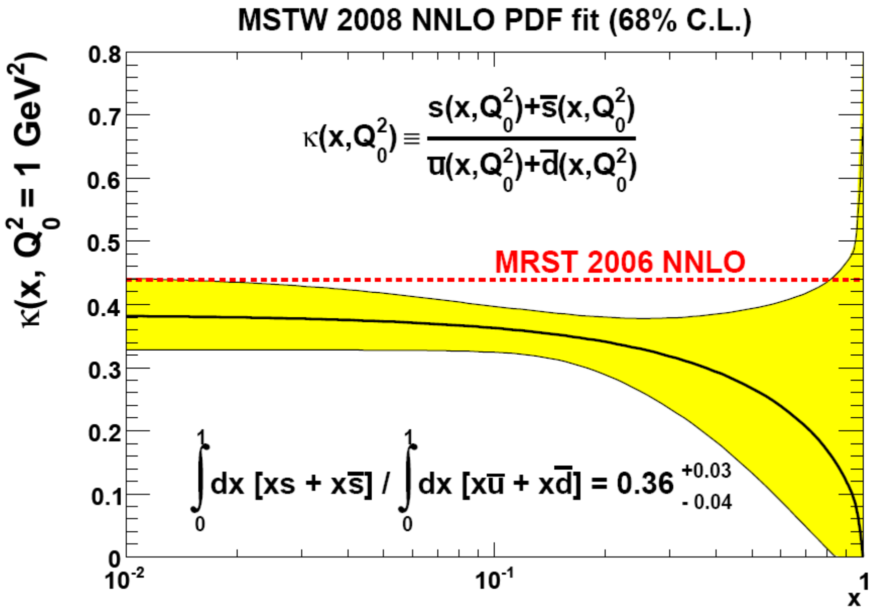


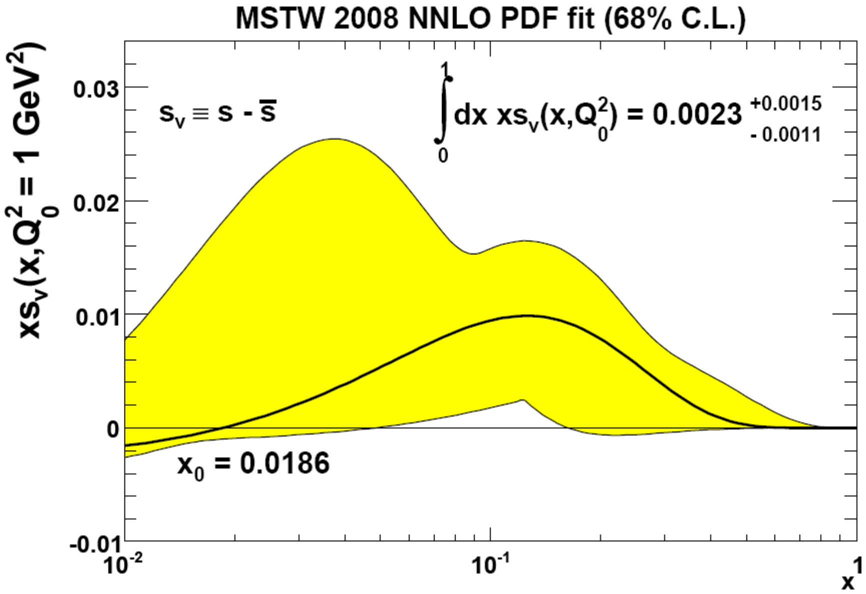
NuTeV $\frac{100\pi}{G_F^2 M_N E_\nu} \frac{d\sigma}{dxdy}(\nu_\mu N \rightarrow \mu^+\mu^- X)$ in GeV^{-2}

MSTW 2008 NNLO PDF fit, χ^2 = 13 for 21 DOF



MSTW


MSTW 2008 NNLO PDF fit (68% C.L.)
$\kappa(x,Q_0^2) \equiv \frac{s(x,Q_0^2)+\bar{s}(x,Q_0^2)}{\bar{u}(x,Q_0^2)+\bar{d}(x,Q_0^2)}$
MRST 2006 NNLO
$\int_0^1 dx\,[xs + x\bar{s}] \,/\, \int_0^1 dx\,[x\bar{u} + x\bar{d}] = 0.36^{+0.03}_{-0.04}$
$\kappa(x,\ Q_0^2 = 1\ \mathrm{GeV}^2)$
x


MSTW 2008 NNLO PDF fit (68% C.L.)
$s_V \equiv s - \bar{s}$
$\int_0^1 dx\, xs_V(x,Q_0^2) = 0.0023^{+0.0015}_{-0.0011}$
$x_0 = 0.0186$
$xs_V(x,Q_0^2 = 1\ \mathrm{GeV}^2)$
x

MSTW

charm, bottom

considered sufficiently massive to allow pQCD treatment: $g \rightarrow Q\overline{Q}$

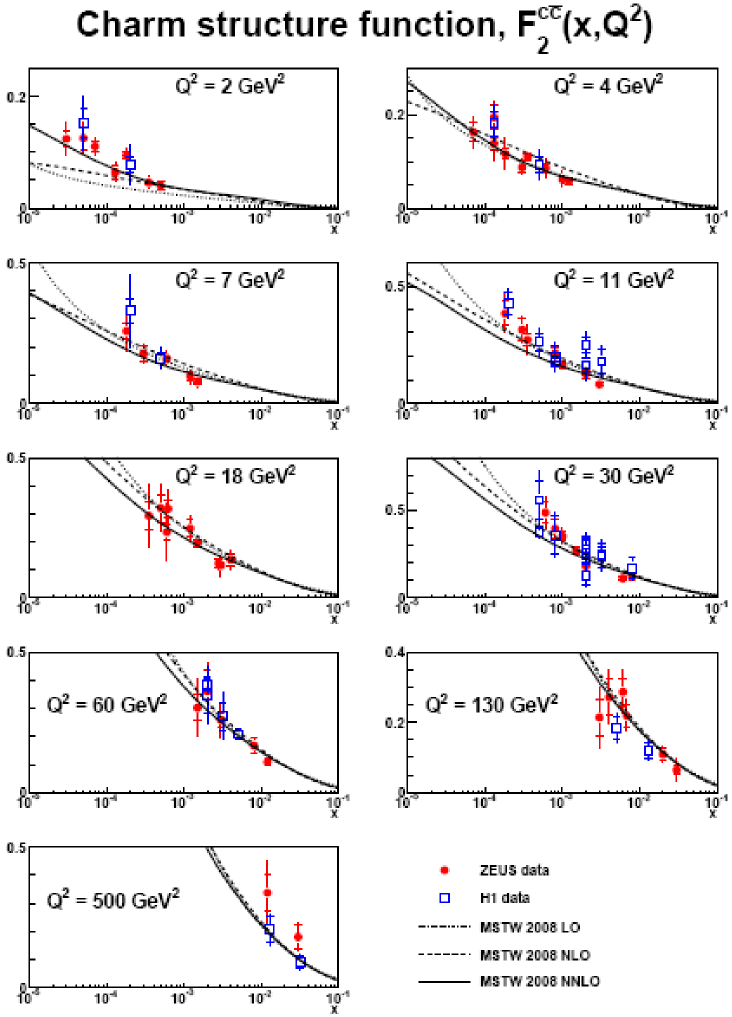
distinguish two regimes:
(i) $Q^2 \sim m_H^2$ include full m_H dependence to get correct threshold behaviour
(ii) $Q^2 \gg m_H^2$ treat as ~massless partons to resum $\alpha_S^n \log^n(Q^2/m_H^2)$ via DGLAP

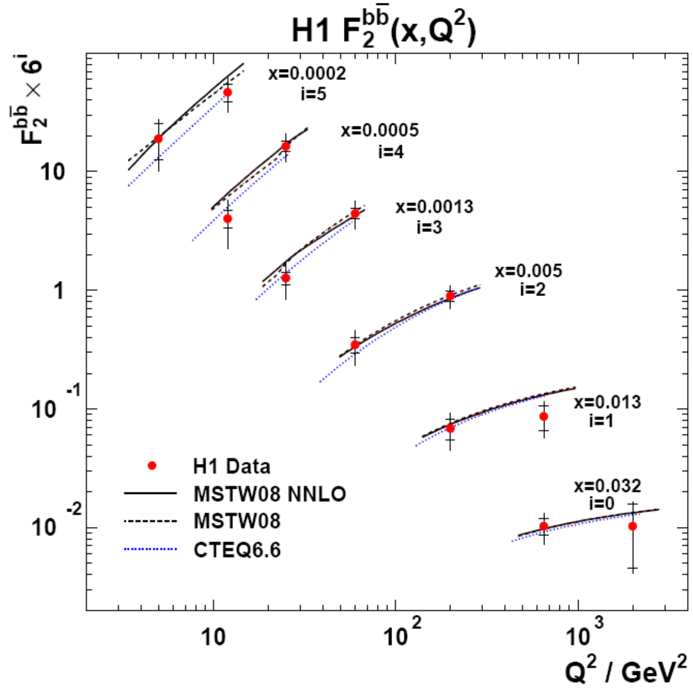
FFNS: OK for (i) only **ZM-VFNS:** OK for (ii) only

consistent **GM**(=general mass)-**VFNS** now available (e.g. ACOT(χ), Roberts-Thorne) which interpolates smoothly between the two regimes

Note: definition of these is tricky and non-unique (ambiguity in assignment of $O(m_H^2/Q^2)$ contributions), and the implementation of improved treatment (e.g. in going from MRST2006 to MSTW 2008) can have a big effect on light partons

charm and bottom structure functions



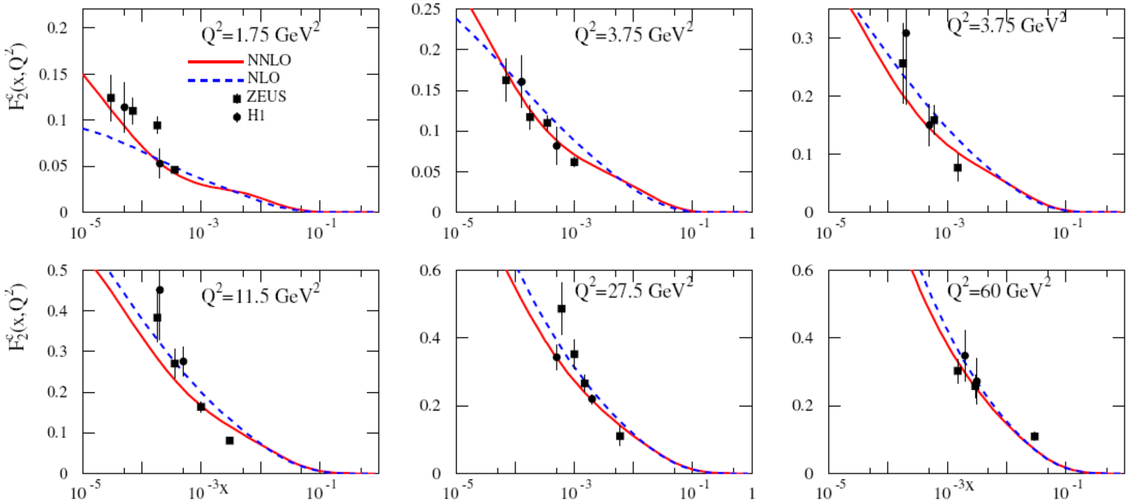


- MSTW 2008 uses *fixed* values of m_c = 1.4 GeV and m_b = 4.75 GeV in a GM-VFNS
- can study the sensitivity of the fit to these values

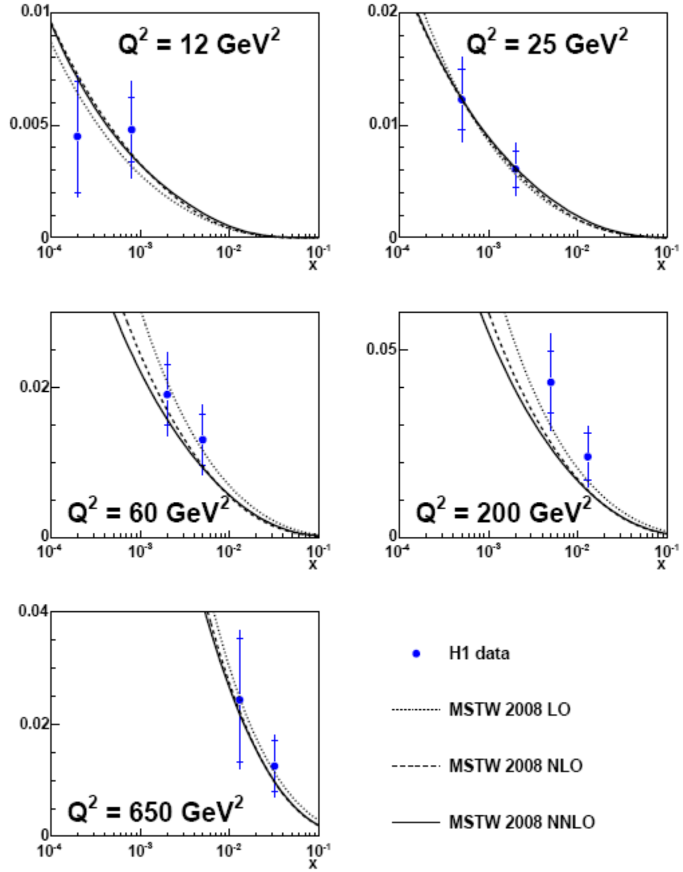
charm and bottom structure functions

MSTW 2008

F_2^{cc}



F_2^{bb}



MSTW 2008 uses *fixed* values of m_c = 1.4 GeV and m_b = 4.75 GeV in a GM-VFNS --- can study the sensitivity of the fit to these values

dependence on m_c at NLO in 2008 fits (preliminary)

m_c (GeV)	χ^2_{global} 2699 pts	$\chi^2_{F_2^c}$ 83 pts	$\alpha_s(M_Z^2)$
1.1	2730	264	0.1181
1.2	2626	188	0.1187
1.3	2563	134	0.1194
1.4	2543	107	0.1202
1.5	2545	97	0.1208
1.6	2574	104	0.1214
1.7	2627	129	0.1221

- correlation between m_c and α_S
- for low m_c overshoot low Q^2 medium x data badly
- preferred value (1.4 GeV) towards lower end of pole mass determination
- (asymmetric) uncertainty from global fit of order ± 0.15 GeV

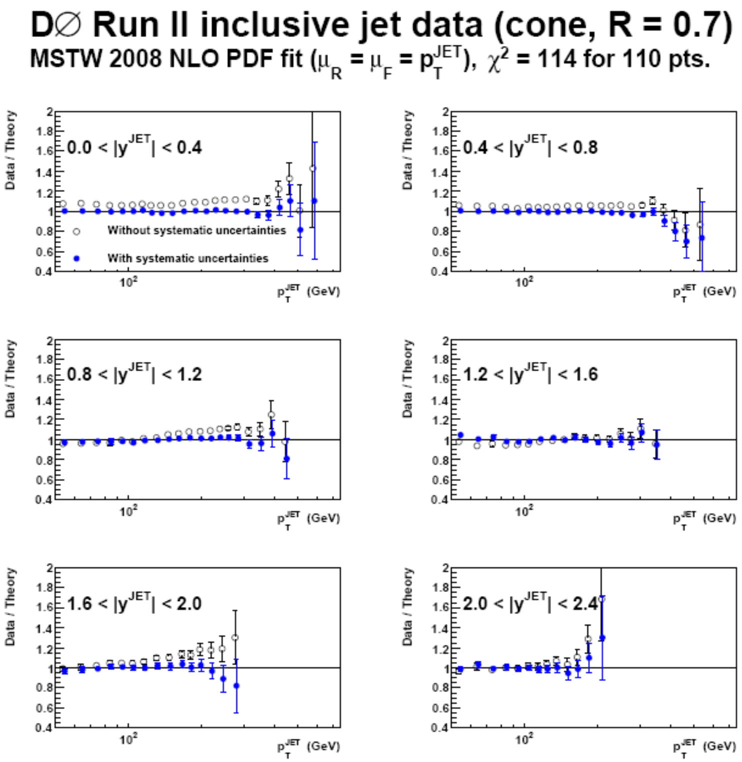
- in contrast, only weak sensitivity to m_b

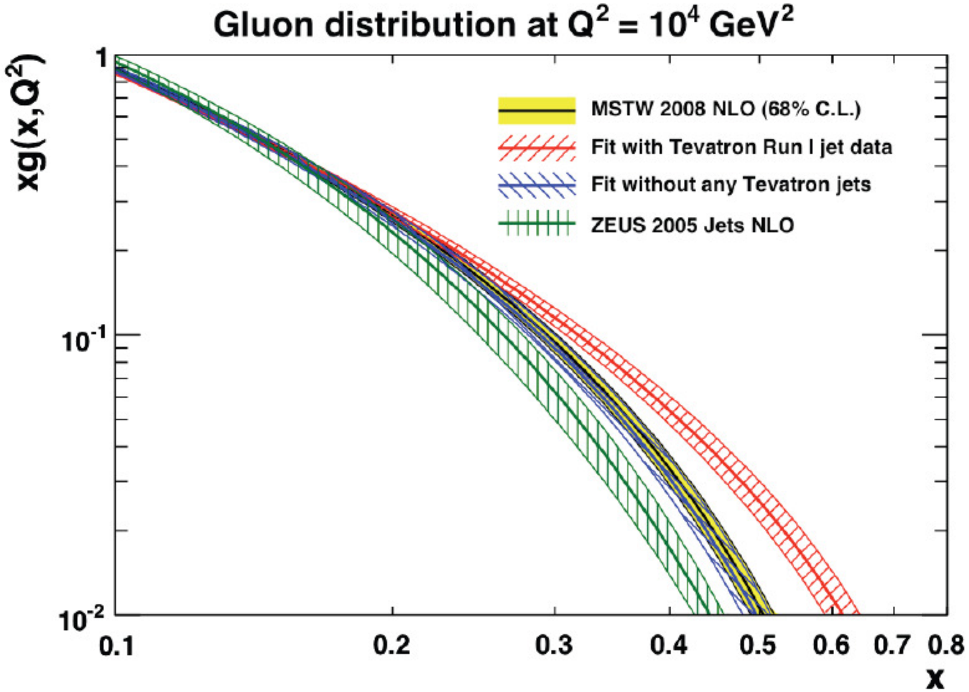
impact of Tevatron jet data on fits

- a distinguishing feature of pdf sets is whether they use (MRST/MSTW, CTEQ,…) or do not use (H1, ZEUS, Alekhin, NNPDF,…) Tevatron jet data in the fit: the impact is on the *high-x gluon*

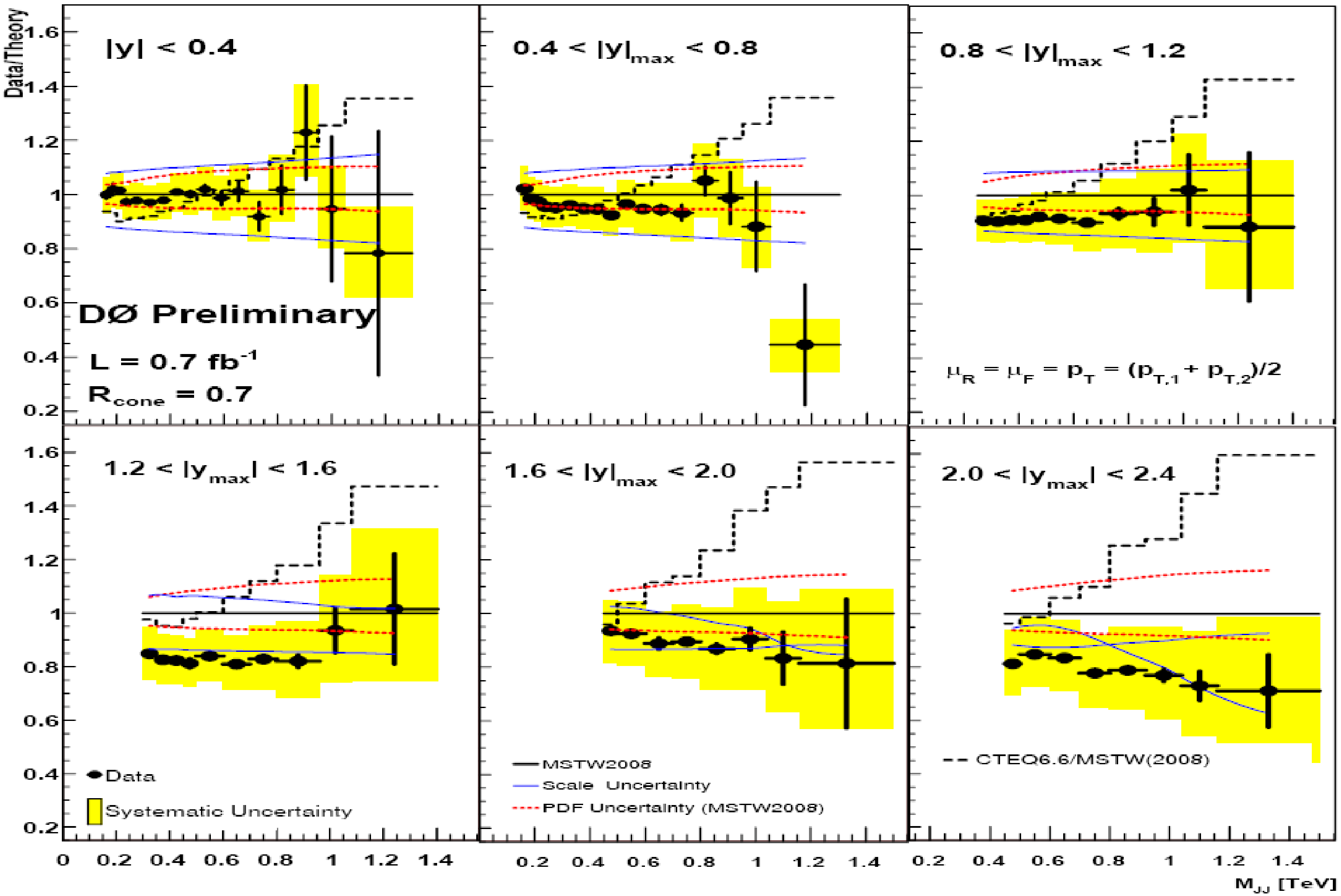
  (Note: Run II data requires slightly softer gluon than Run I data)

- the (still) missing ingredient is the full NNLO pQCD correction to the cross section, but not expected to have much impact in practice





dijet mass distribution from D0



a note on α_S

- world average value (PDG 2008):

$$\alpha_S^{\overline{MS},NNLO}(M_Z^2) = 0.1176 \pm 0.002$$

- MSTW global fit value (minimum χ^2):

$$\alpha_S^{\overline{MS},NNLO}(M_Z^2) = 0.1171$$

- the pdf error sets are generated with α_S fixed at its 'best fit' value, therefore variation of (e.g. jets, top, etc at LHC) cross sections with α_S is not explicitly included in the 'pdf error'

Note: $\alpha_S^{\overline{MS},NLO}(M_Z^2) = 0.1202$

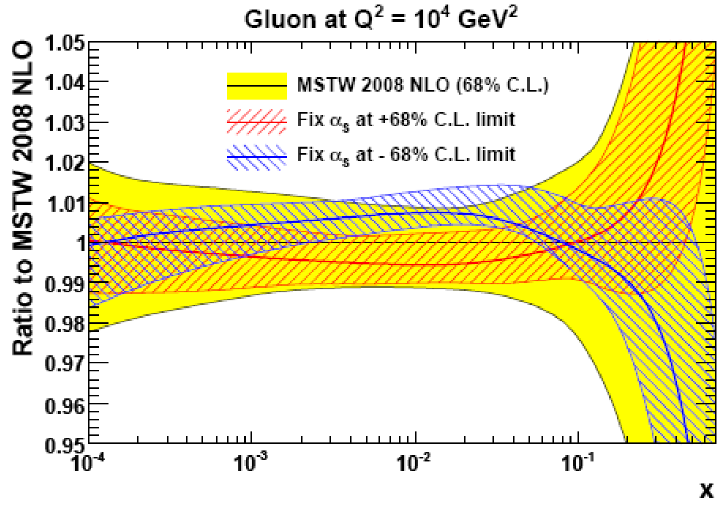
MSTW variable-α_S sets*

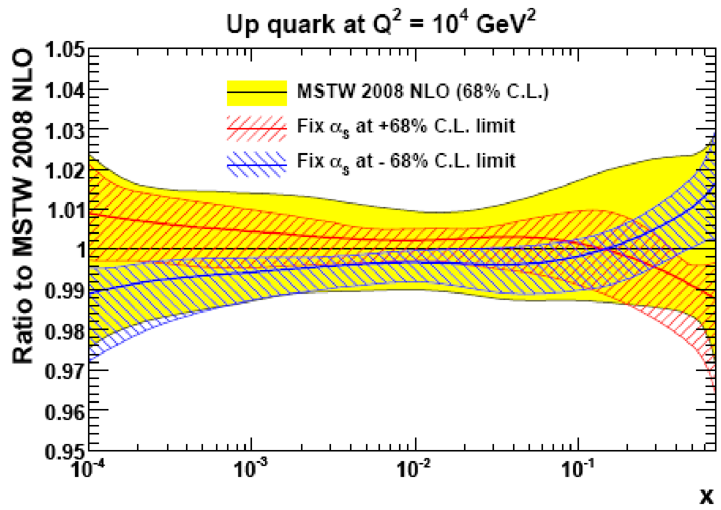
- allow α_S to vary in global fit

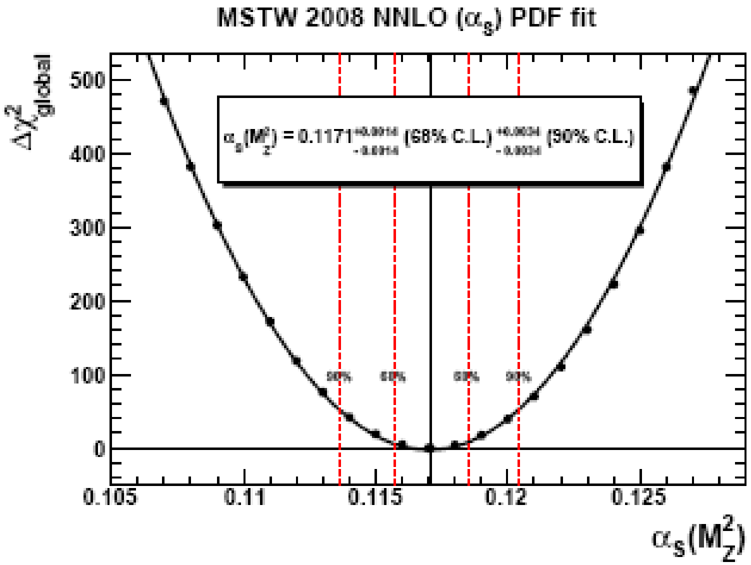
$$\alpha_S^{\overline{MS},NNLO}(M_Z^2) = 0.1171^{+0.0014}_{-0.0014}$$

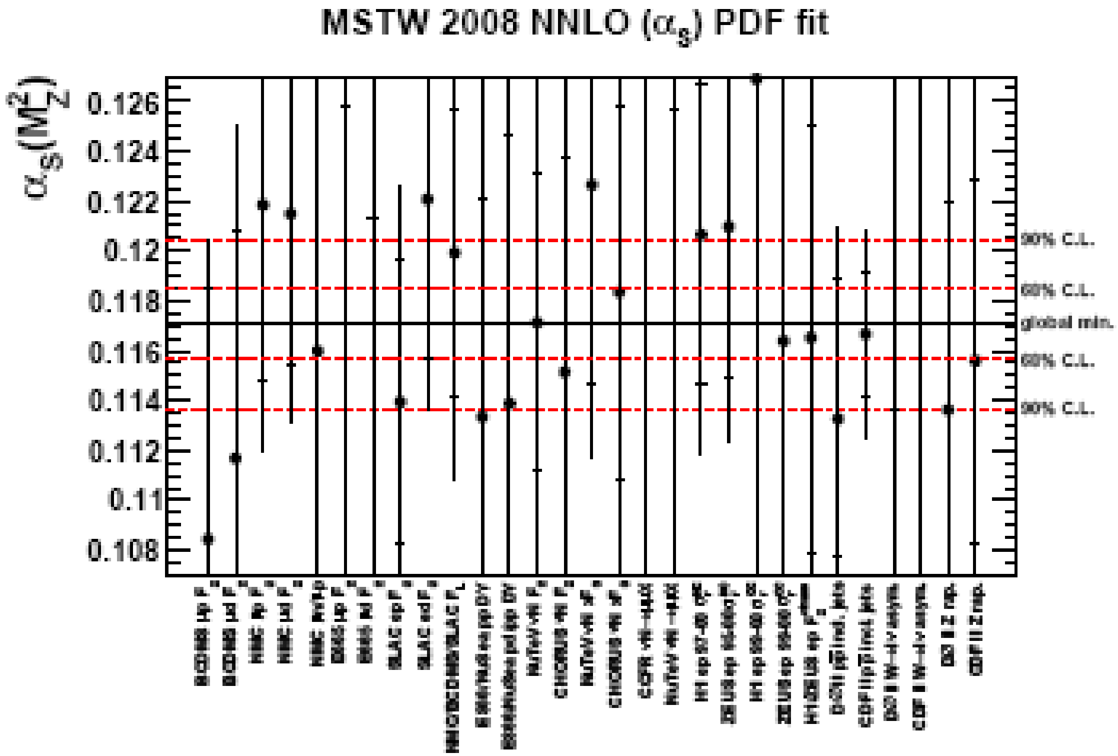
- for fixed $\alpha_S \pm \delta\alpha_S$, produce sets with 'pdf errors', as before
- note gluon – α_S anticorrelation at small x and quark – α_S anticorrelation at large x
- use resulting sets to quantify combined 'pdf + α_S' error on observables

* arXiv:0905.3531 [hep-ph]

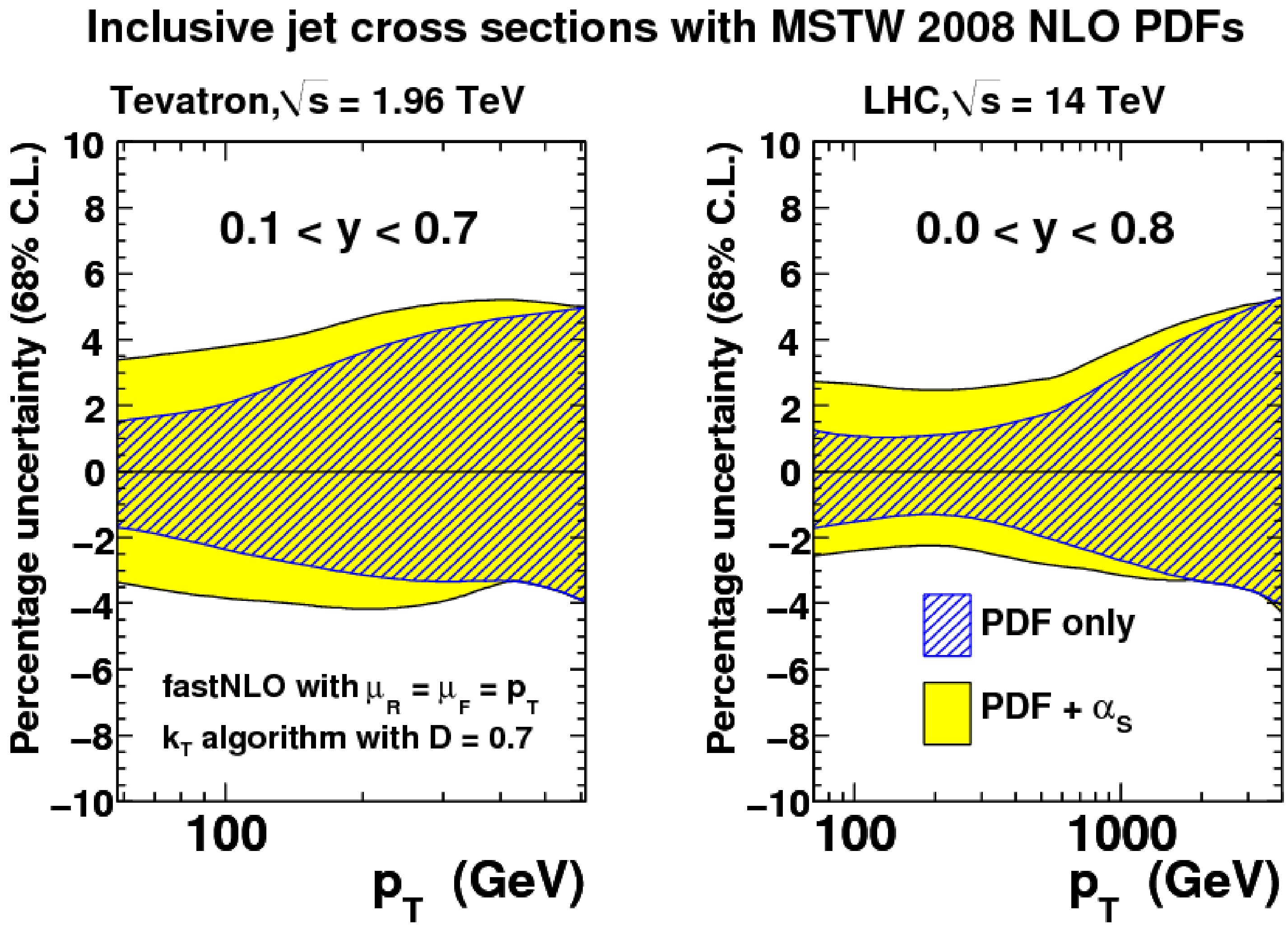


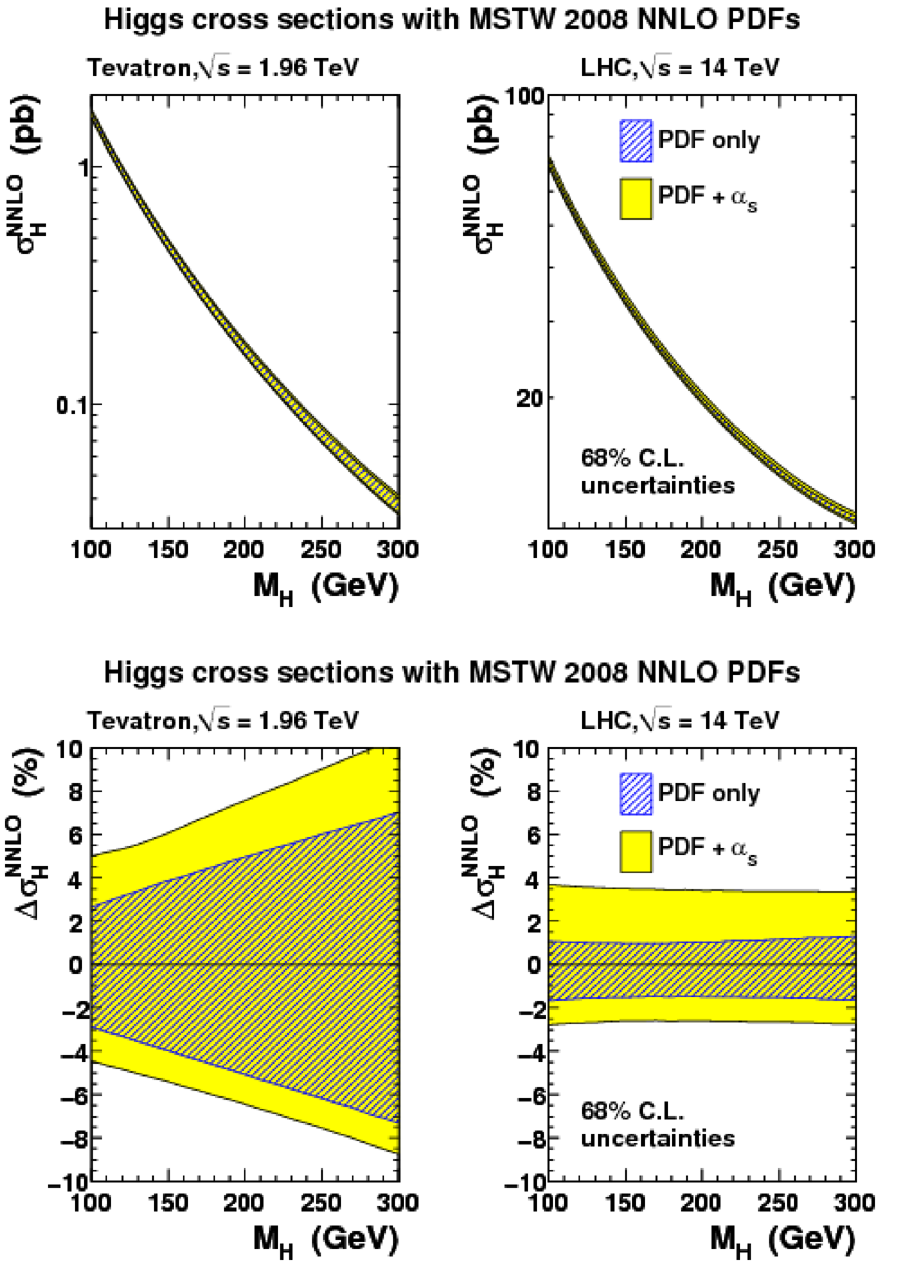



MSTW 2008 NNLO (α_S) PDF fit
$\Delta\chi^2_{global}$
$\alpha_S(M_Z^2)$
90%
68%
68%
90%


MSTW 2008 NNLO (α_S) PDF fit
$\alpha_S(M_Z^2)$
90% C.L.
68% C.L.
global min.
68% C.L.
90% C.L.

pdf, α_S uncertainties in jet cross sections





Note: still dominated by scale variation uncertainty - see earlier

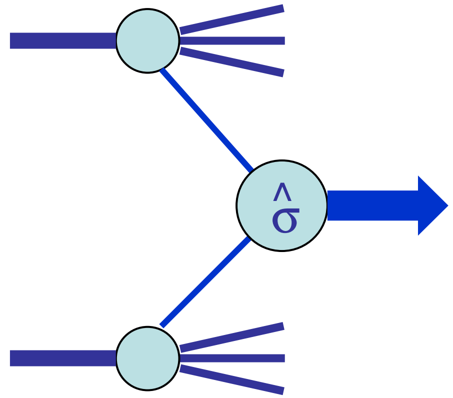
3

pdfs at LHC:

— impact on precision phenomenology

— can we constrain pdfs further?

the QCD **factorization theorem** for hard-scattering (short-distance) inclusive processes



$$\sigma_X = \sum_{a,b} \int_0^1 \mathbf{dx_1 dx_2 \, f_a(x_1, \mu_F^2) \, f_b(x_2, \mu_F^2)}$$

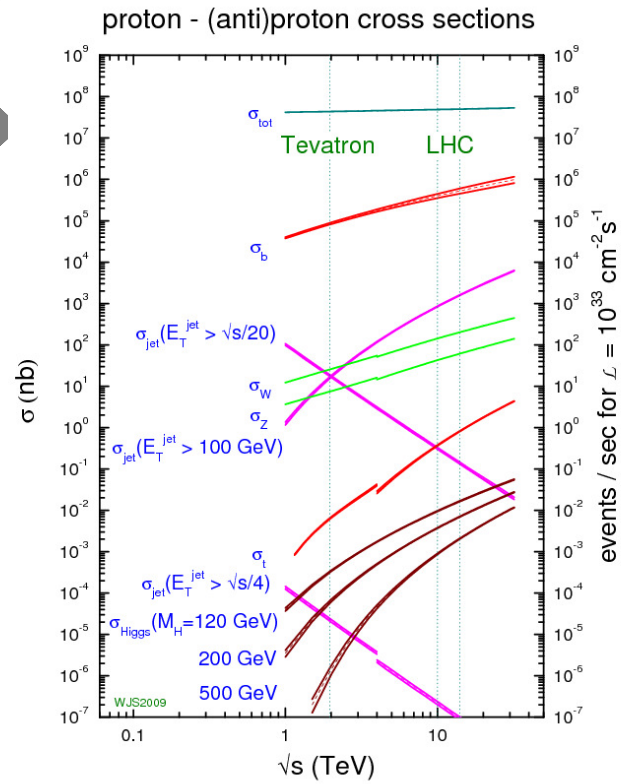
$$\times \;\; \hat{\sigma}_{ab\to X}\left(\mathbf{x_1, x_2, \{p_i^\mu\}}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{\mathbf{Q^2}}{\mu_R^2}, \frac{\mathbf{Q^2}}{\mu_F^2}\right)$$

where X=W, Z, H, high-E_T jets, SUSY sparticles, black hole, …, and Q is the 'hard scale' (e.g. = M_X), usually $\mu_F = \mu_R = Q$, and $\hat{\sigma}$ is known …

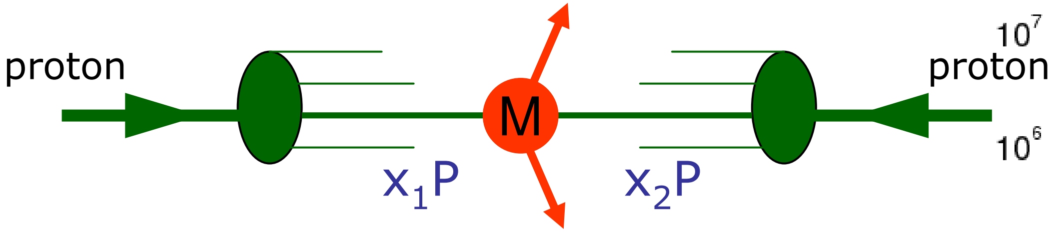
- to some fixed order in pQCD (and EW), e.g. high-E_T jets

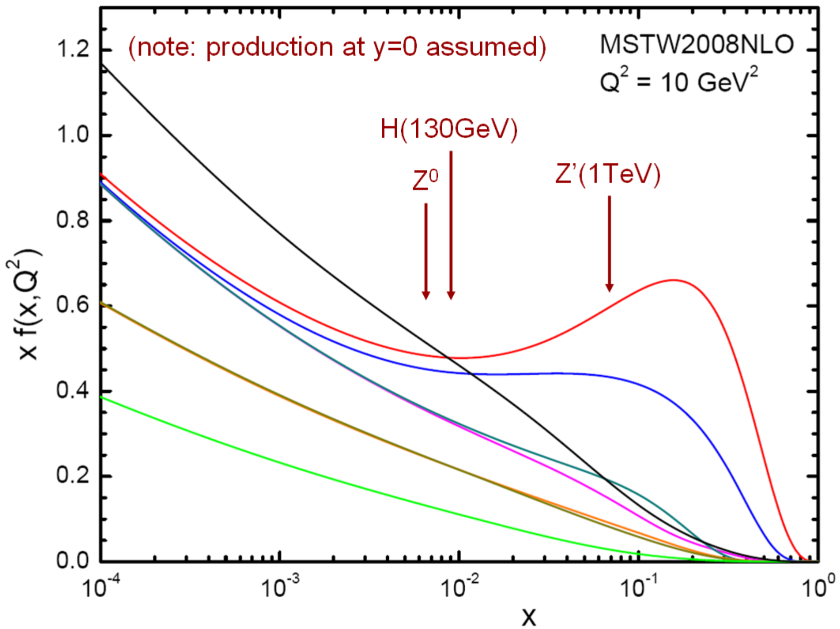
$$\hat{\sigma} = A\alpha_S^2 + B\alpha_s^3$$

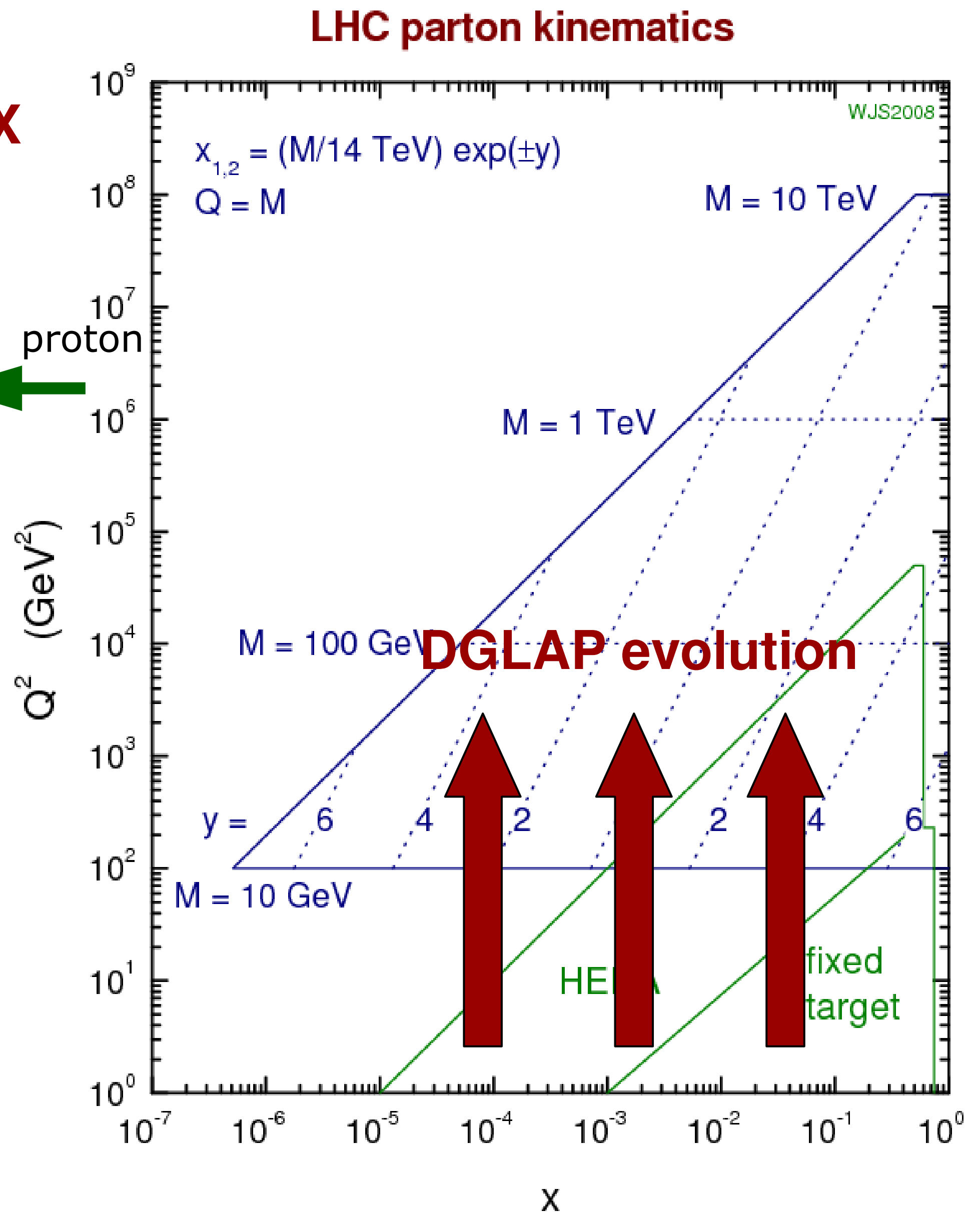
- or 'improved' by some leading logarithm approximation (LL, NLL, …) to all orders via resummation



momentum fractions x_1 and x_2 determined by mass and rapidity of **X**







pdfs at LHC – the issues

- high precision cross section predictions require accurate knowledge of pdfs: $\delta\sigma_{th} = \delta\sigma_{pdf} + \ldots$
  → improved signal and background predictions
  → easier to spot new physics

- 'standard candle' processes (e.g. σ_Z) to
  - check formalism (factorisation, DGLAP, …)
  - measure machine luminosity?

- learning more about pdfs from LHC measurements. e.g.
  - high-E_T jets → gluon?
  - W^+, W^-, Z^0 → quarks?
  - forward Drell-Yan → small x?
  - …

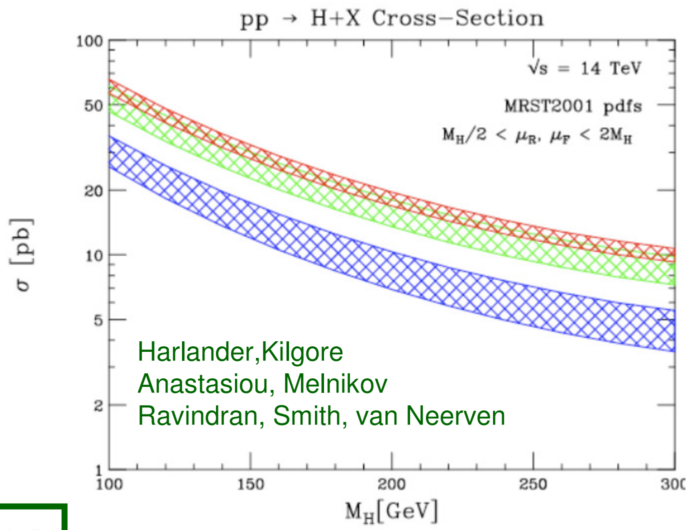
how important is pdf precision?

- Example 1: $\sigma(M_H=120\ \text{GeV})$ @ LHC

$\delta\sigma_{pdf} \approx \pm 2\%$, $\delta\sigma_{ptNNL0} \approx \pm 10\%$

$\delta\sigma_{ptNNLL} \approx \pm 8\%$

$\rightarrow \quad \delta\sigma_{theory} \approx \pm 10\%$

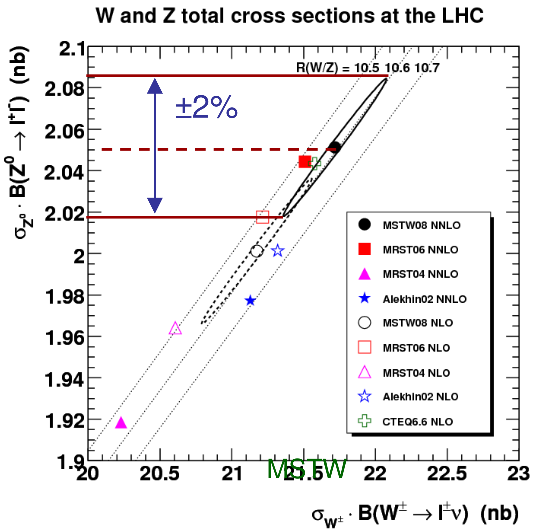


see de Florian,Grazzini arXiv:0901.2427 [hep-ph]

- Example 2: $\sigma(Z^0)$ @ LHC

$\delta\sigma_{pdf} \approx \pm 2\%$, $\delta\sigma_{ptNNL0} \approx \pm 2\%$

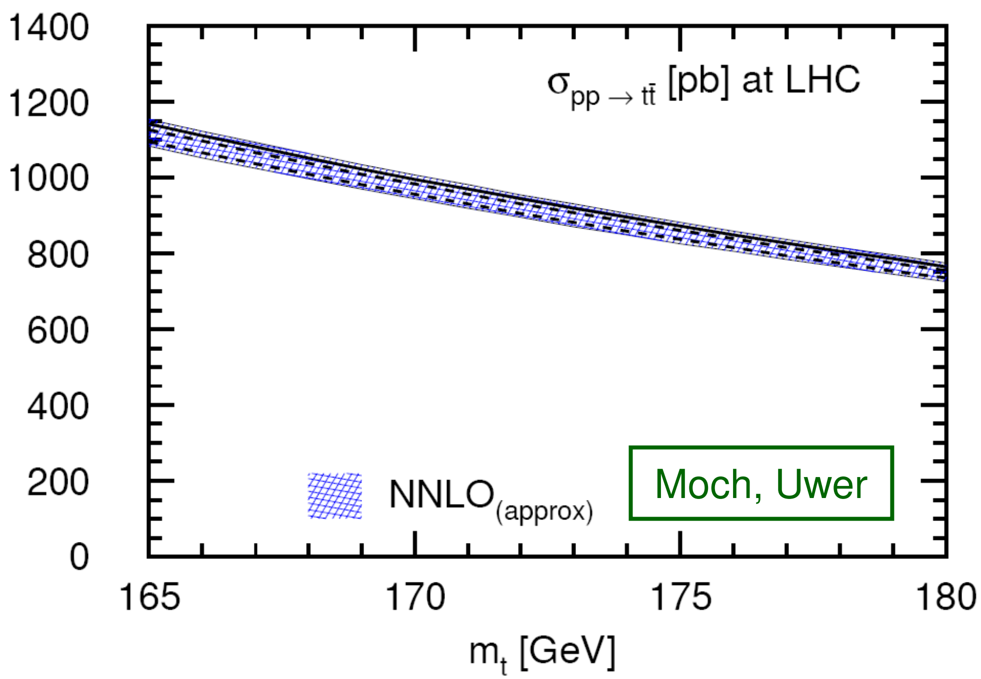
$\rightarrow \quad \delta\sigma_{theory} \approx \pm 3\%$



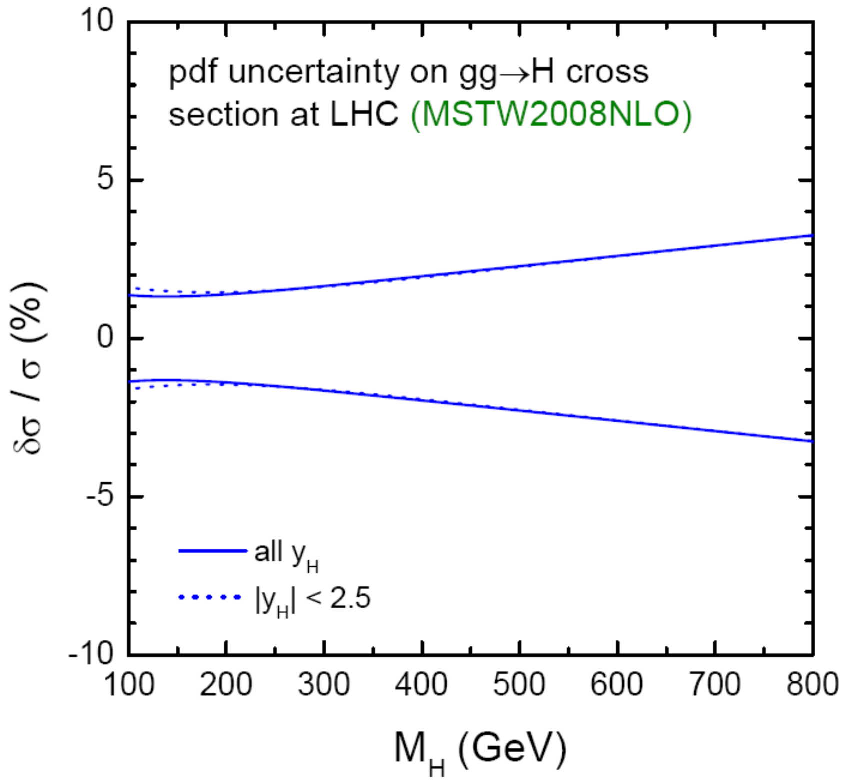
- Example 3: $\sigma(tt)$ @ LHC

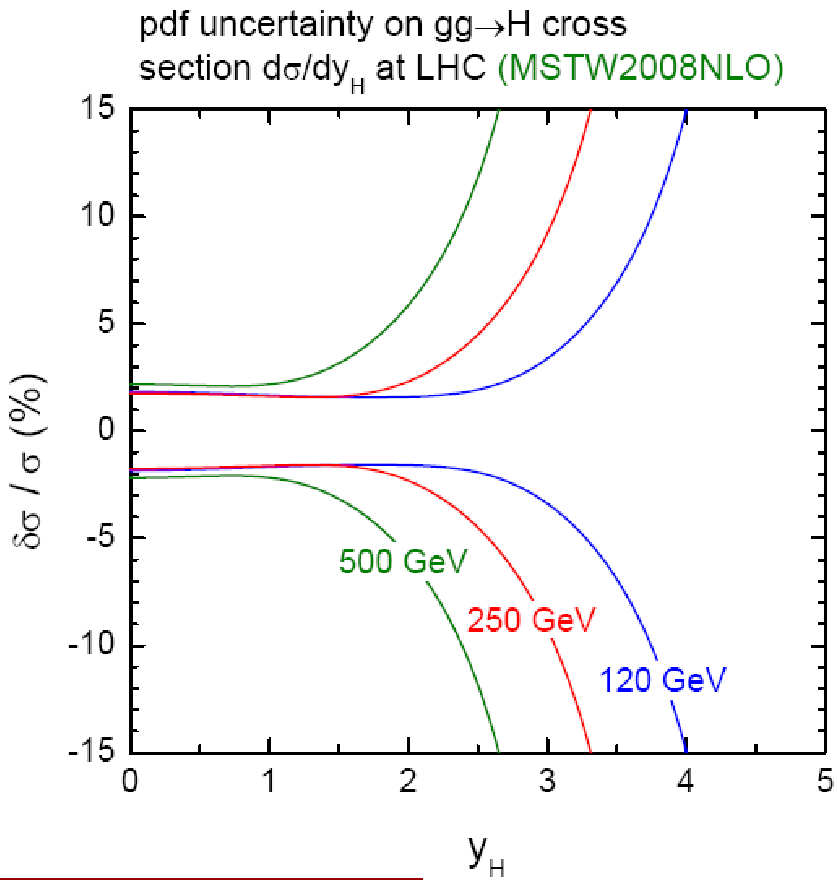
  $\delta\sigma_{pdf} \approx \pm 2\%$, $\delta\sigma_{ptNNL0approx} \approx \pm 3\%$

$\rightarrow$ $\delta\sigma_{theory} \approx \pm 4\%$



pdf uncertainty on σ(gg→H)

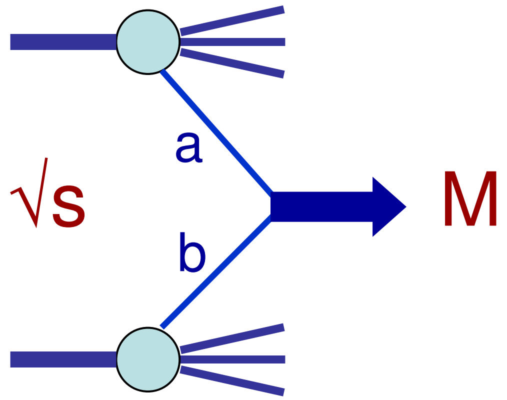




→ typically ± 2-3% pdf uncertainty, except near edges of phase space

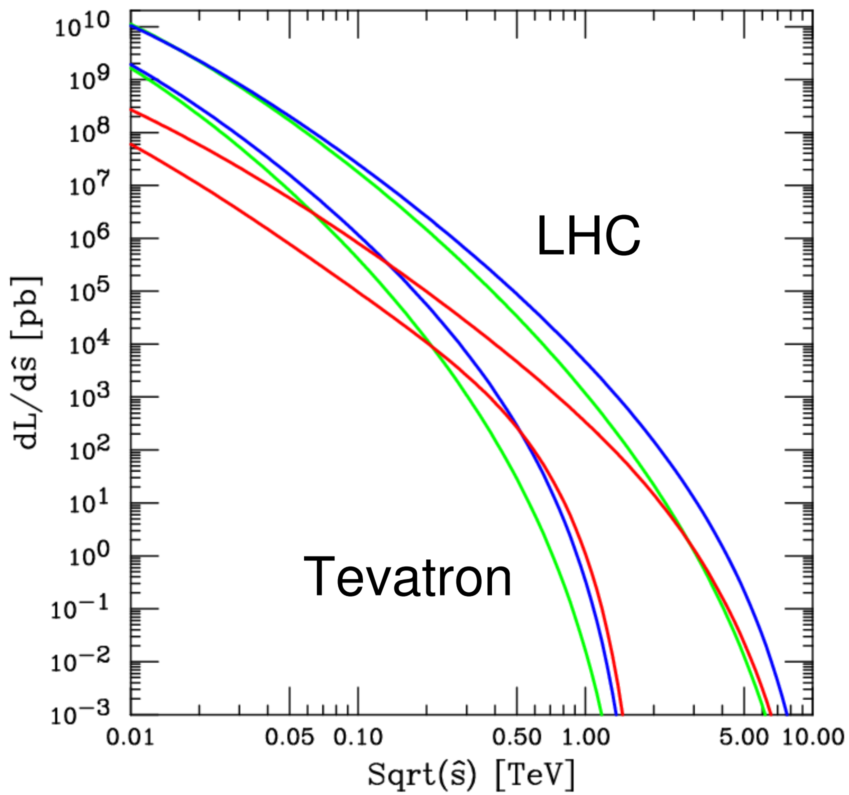
parton luminosity functions

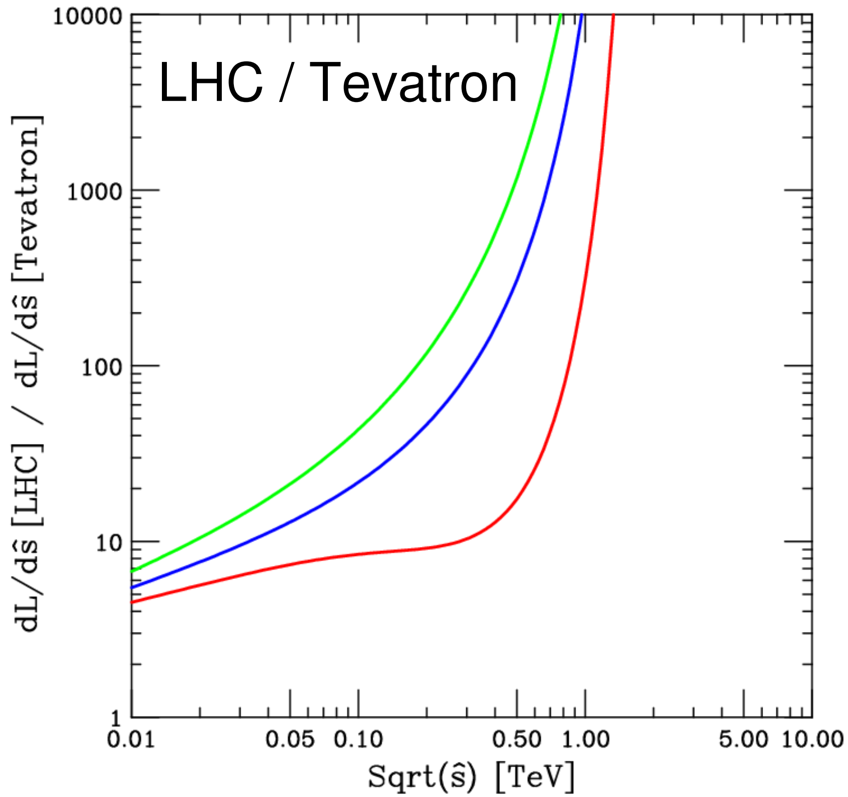
- a quick and easy way to assess the mass and collider energy dependence of production cross sections



$$
\begin{aligned}
\hat{\sigma}_{ab\to X} &= C_X \delta(\hat{s} - M^2) \\
\sigma_X &= \int_0^1 dx_a dx_b \, f_a(x_a, M^2) f_b(x_b, M^2) \, C_X \, \delta(x_a x_b - \tau) \\
&\equiv C_X \left[\frac{1}{s} \frac{\partial \mathcal{L}_{ab}}{\partial \tau} \right] \qquad\qquad (\tau = M^2/s) \\
\frac{\partial \mathcal{L}_{ab}}{\partial \tau} &= \int_0^1 dx_a dx_b \, f_a(x_a, M^2) f_b(x_b, M^2) \, \delta(x_a x_b - \tau)
\end{aligned}
$$

- i.e. all the mass and energy dependence is contained in the X-independent parton luminosity function in [ ]
- useful combinations are $ab = gg, \sum_q q\bar{q}, \ldots$
- and also useful for assessing the uncertainty on cross sections due to uncertainties in the pdfs





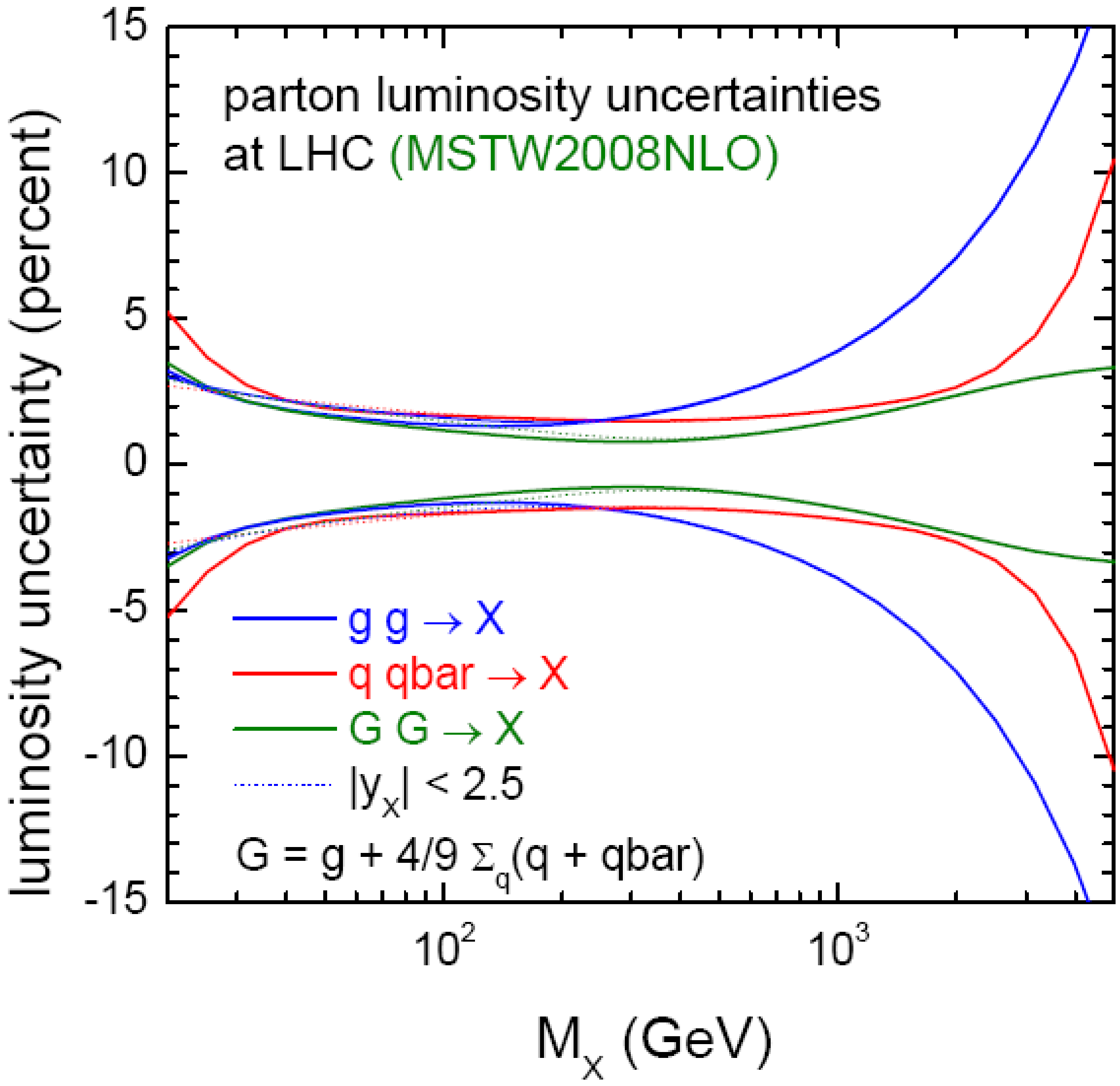
(green) $= \; gg$

(blue) $= \sum_i (gq_i + g\bar{q}_i + q_i g + \bar{q}_i g)$

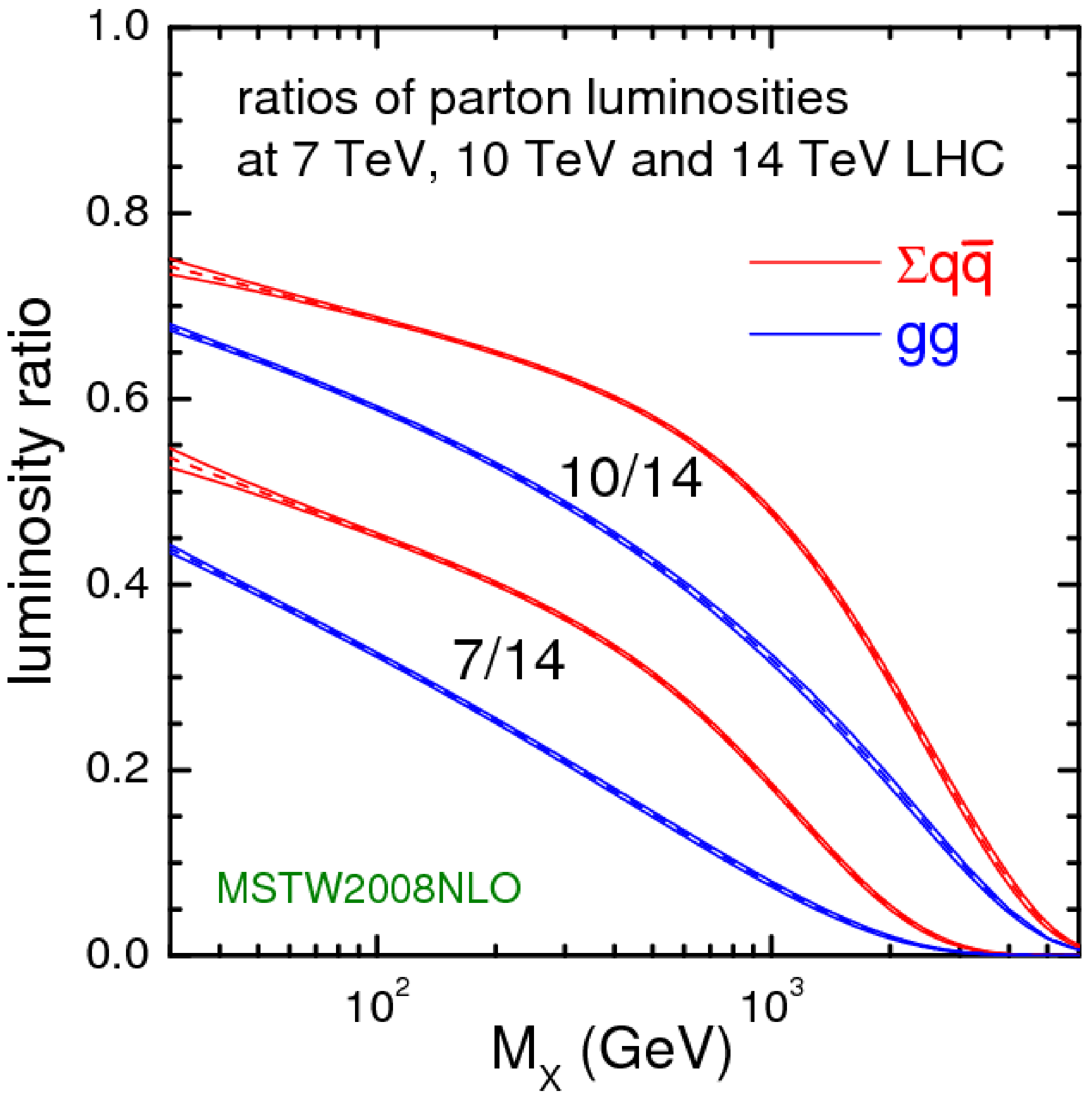
(red) $= \sum_i (q_i\bar{q}_i + \bar{q}_i q_i)$

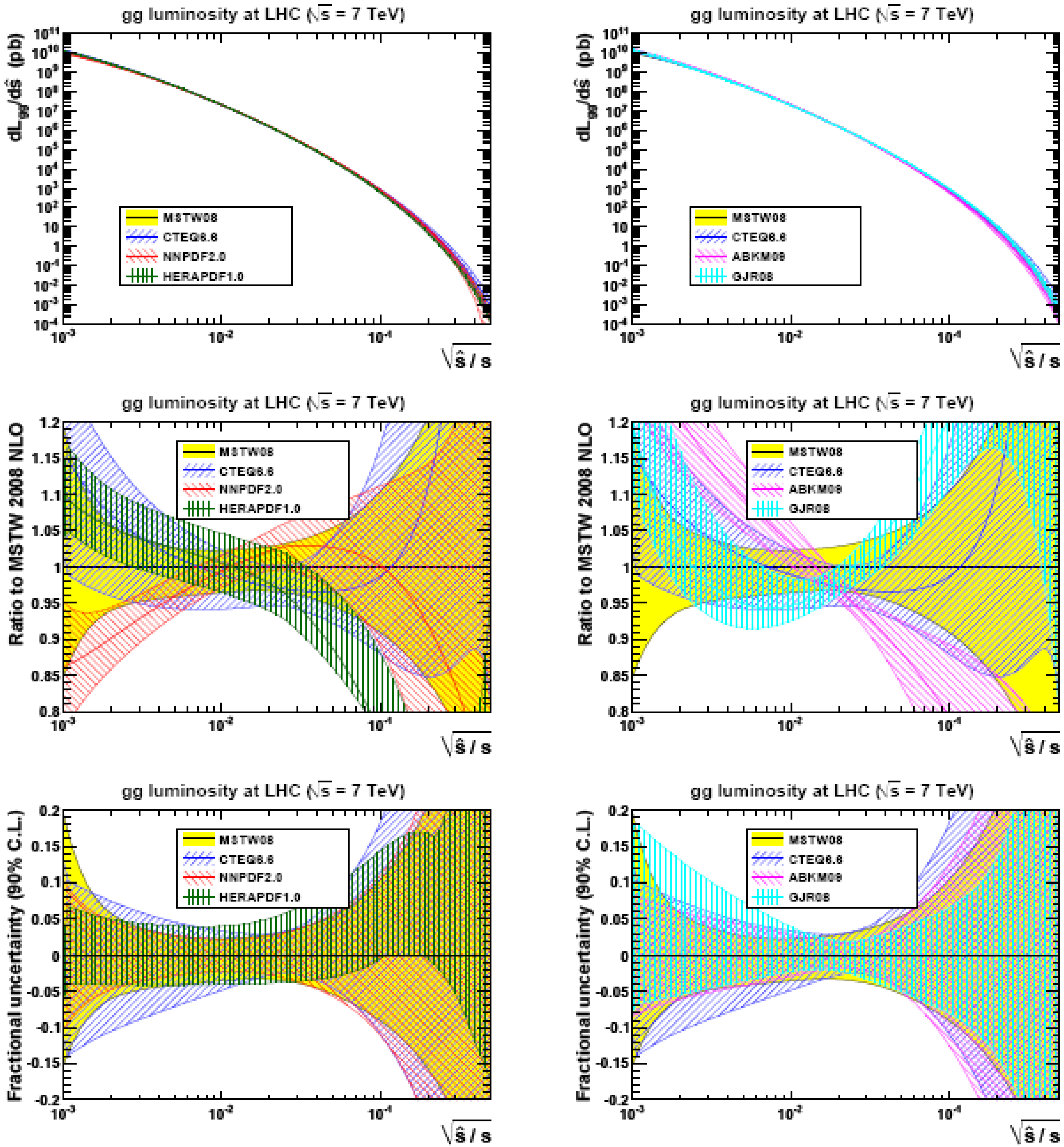
Huston, Campbell, S (2007)

parton luminosity (68%cl) uncertainties at LHC



LHC at 7 and 10 TeV





comparison of gg luminosities at LHC (7 TeV) with 90%cl pdf uncertainty bands

pdfs at LHC – the issues

- high precision cross section predictions require accurate knowledge of pdfs: $\delta\sigma_{th} = \delta\sigma_{pdf} + \ldots$
  → improved signal and background predictions
  → easier to spot new physics

- 'standard candle' processes (e.g. σ_Z) to
  – check formalism (factorisation, DGLAP, …)
  – measure machine luminosity?

- learning more about pdfs from LHC measurements. e.g.
  – high-E_T jets → gluon?
  – W^+,W^-,Z^0 → quarks?
  – forward DY → small x?
  – …

standard candles: $\sigma(W,Z)$ @ LHC

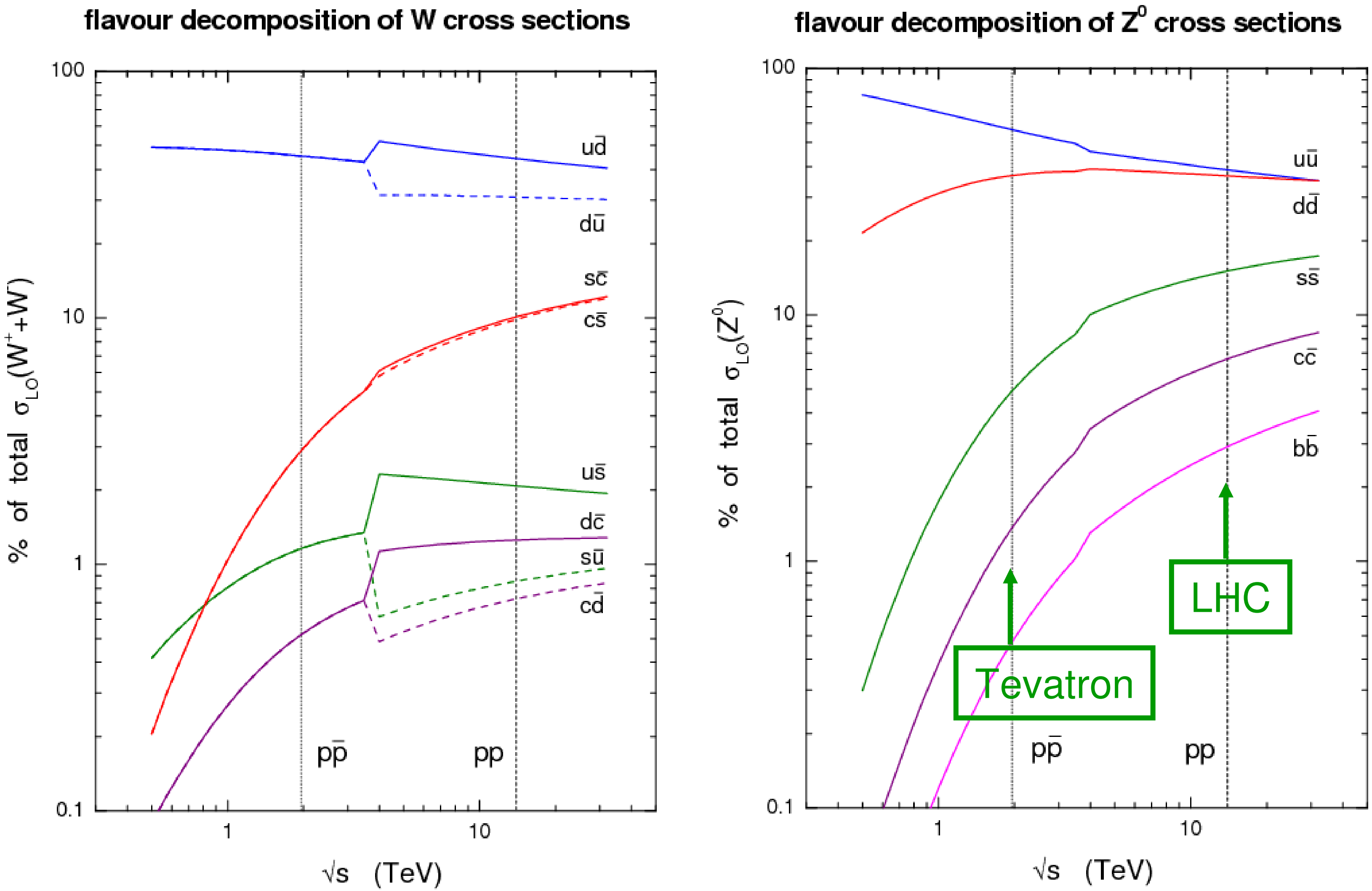
- cross sections (total and rapidity distributions) known to NNLO pQCD and NLO EW; perturbation series seems to be converging quickly

- EW parameters well measured at LEP

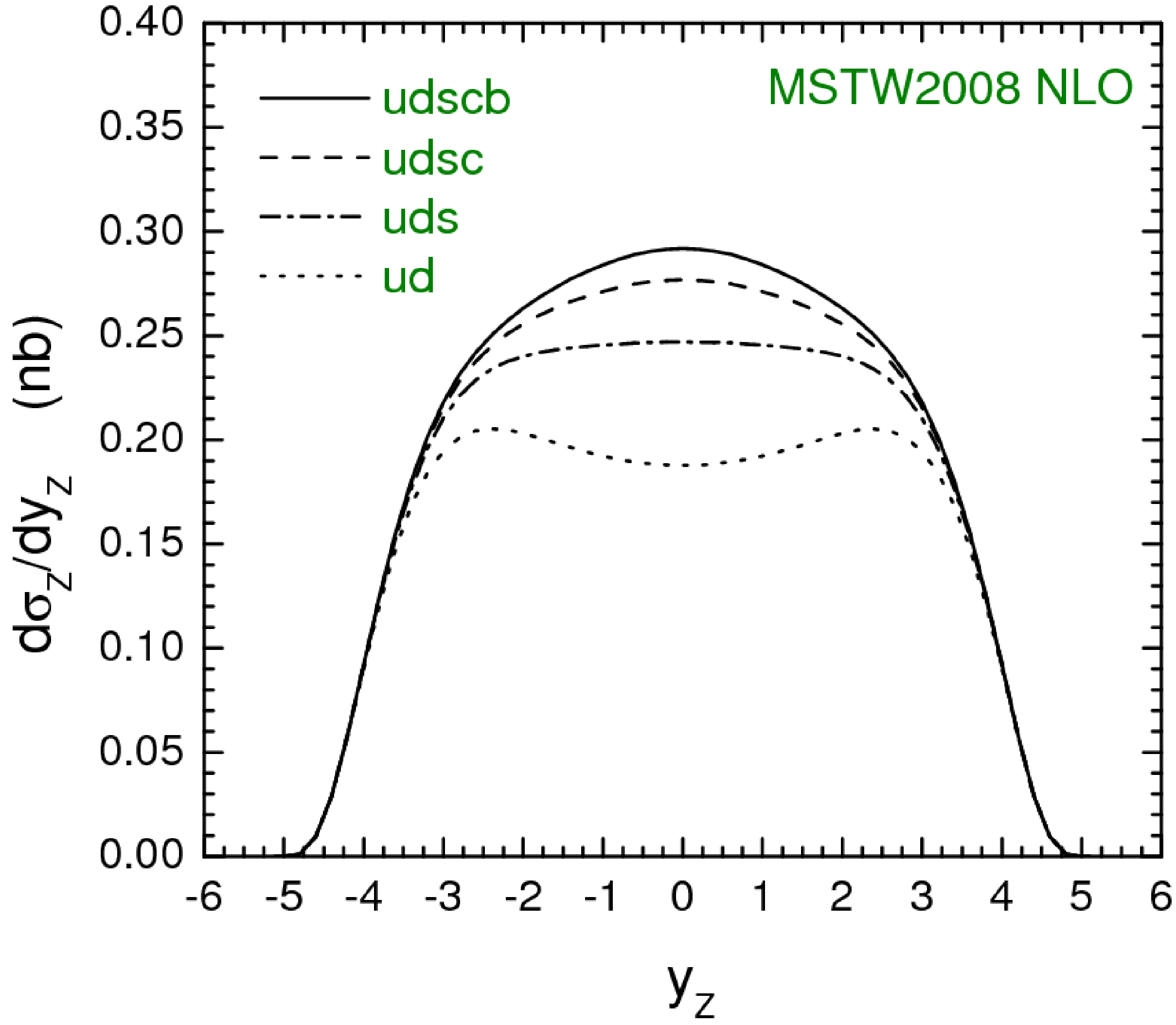
- samples pdfs where they are well measured (in x) in DIS

- … although the mix of quark flavours is different: F_2 and $\sigma(W,Z)$ probe *different* combinations of u,d,s,c,b → sea quark distributions important

- precise measurement of cross section *ratios* at LHC (e.g. $\sigma(W^+)/\sigma(W^-)$, $\sigma(W)/\sigma(Z)$) will allow these subtle effects to be explored further



at LHC, ~30% of W and Z total cross sections involves s,c,b quarks



MSTW2008 NLO
udscb
udsc
uds
ud
$d\sigma_Z/dy_Z$ (nb)
y_Z
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6

Tevatron, $\sqrt{s} = 1.96$ TeV	$B_{l\nu} \cdot \sigma_W$ (nb)	$B_{l^+l^-} \cdot \sigma_Z$ (nb)	R_{WZ}
MSTW 2008 LO	$1.963^{+0.025}_{-0.028}$ $\left(^{+1.2\%}_{-1.4\%}\right)$	$0.1788^{+0.0023}_{-0.0025}$ $\left(^{+1.3\%}_{-1.4\%}\right)$	$10.98^{+0.02}_{-0.03}$ $\left(^{+0.2\%}_{-0.3\%}\right)$
MSTW 2008 NLO	$2.659^{+0.057}_{-0.045}$ $\left(^{+2.1\%}_{-1.7\%}\right)$	$0.2426^{+0.0054}_{-0.0043}$ $\left(^{+2.2\%}_{-1.8\%}\right)$	$10.96^{+0.03}_{-0.02}$ $\left(^{+0.3\%}_{-0.2\%}\right)$
MSTW 2008 NNLO	$2.747^{+0.049}_{-0.042}$ $\left(^{+1.8\%}_{-1.5\%}\right)$	$0.2507^{+0.0048}_{-0.0041}$ $\left(^{+1.9\%}_{-1.6\%}\right)$	$10.96^{+0.03}_{-0.03}$ $\left(^{+0.2\%}_{-0.2\%}\right)$

LHC, $\sqrt{s} = 10$ TeV	$B_{l\nu} \cdot \sigma_W$ (nb)	$B_{l^+l^-} \cdot \sigma_Z$ (nb)	R_{WZ}
MSTW 2008 LO	$12.57^{+0.13}_{-0.19}$ $\left(^{+1.1\%}_{-1.5\%}\right)$	$1.163^{+0.011}_{-0.017}$ $\left(^{+1.0\%}_{-1.5\%}\right)$	$10.81^{+0.02}_{-0.02}$ $\left(^{+0.2\%}_{-0.2\%}\right)$
MSTW 2008 NLO	$14.92^{+0.31}_{-0.24}$ $\left(^{+2.1\%}_{-1.6\%}\right)$	$1.390^{+0.029}_{-0.022}$ $\left(^{+2.1\%}_{-1.5\%}\right)$	$10.73^{+0.02}_{-0.02}$ $\left(^{+0.2\%}_{-0.2\%}\right)$
MSTW 2008 NNLO	$15.35^{+0.26}_{-0.25}$ $\left(^{+1.7\%}_{-1.6\%}\right)$	$1.429^{+0.024}_{-0.022}$ $\left(^{+1.7\%}_{-1.6\%}\right)$	$10.74^{+0.02}_{-0.02}$ $\left(^{+0.2\%}_{-0.2\%}\right)$

LHC, $\sqrt{s} = 14$ TeV	$B_{l\nu} \cdot \sigma_W$ (nb)	$B_{l^+l^-} \cdot \sigma_Z$ (nb)	R_{WZ}
MSTW 2008 LO	$18.51^{+0.22}_{-0.32}$ $\left(^{+1.2\%}_{-1.7\%}\right)$	$1.736^{+0.019}_{-0.028}$ $\left(^{+1.1\%}_{-1.6\%}\right)$	$10.66^{+0.02}_{-0.02}$ $\left(^{+0.2\%}_{-0.2\%}\right)$
MSTW 2008 NLO	$21.17^{+0.42}_{-0.36}$ $\left(^{+2.0\%}_{-1.7\%}\right)$	$2.001^{+0.040}_{-0.032}$ $\left(^{+2.0\%}_{-1.6\%}\right)$	$10.58^{+0.02}_{-0.02}$ $\left(^{+0.2\%}_{-0.2\%}\right)$
MSTW 2008 NNLO	$21.72^{+0.36}_{-0.36}$ $\left(^{+1.7\%}_{-1.7\%}\right)$	$2.051^{+0.035}_{-0.033}$ $\left(^{+1.7\%}_{-1.6\%}\right)$	$10.59^{+0.02}_{-0.03}$ $\left(^{+0.2\%}_{-0.3\%}\right)$

Note: at NNLO, factorisation and renormalisation scale variation M/2 → 2M gives an additional ± 2% change in the LHC cross sections

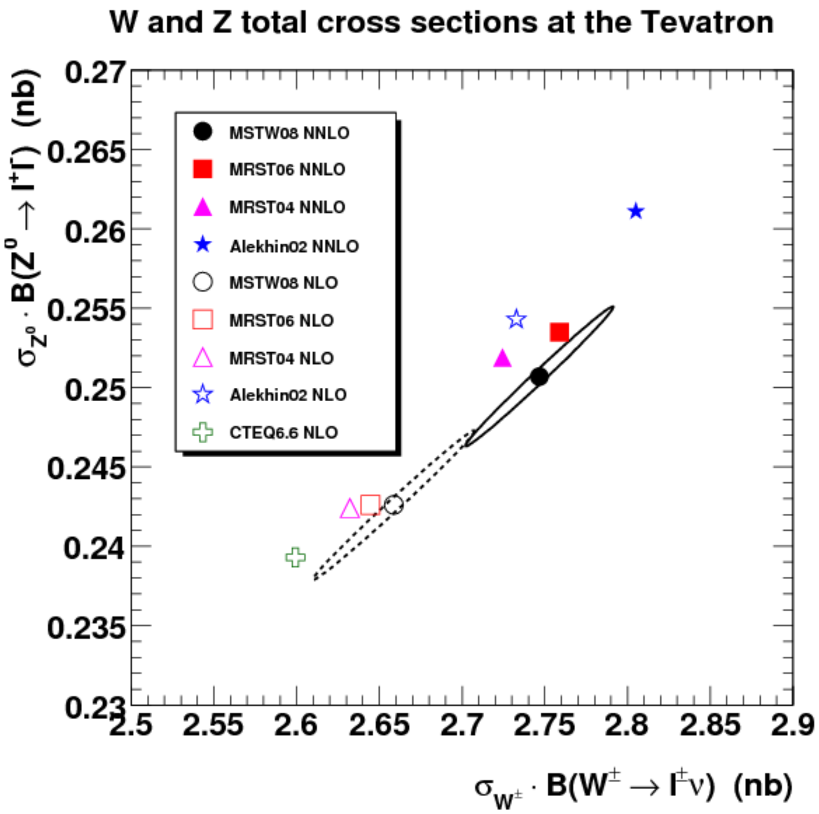
predictions for σ(W,Z) @ LHC (Tevatron)

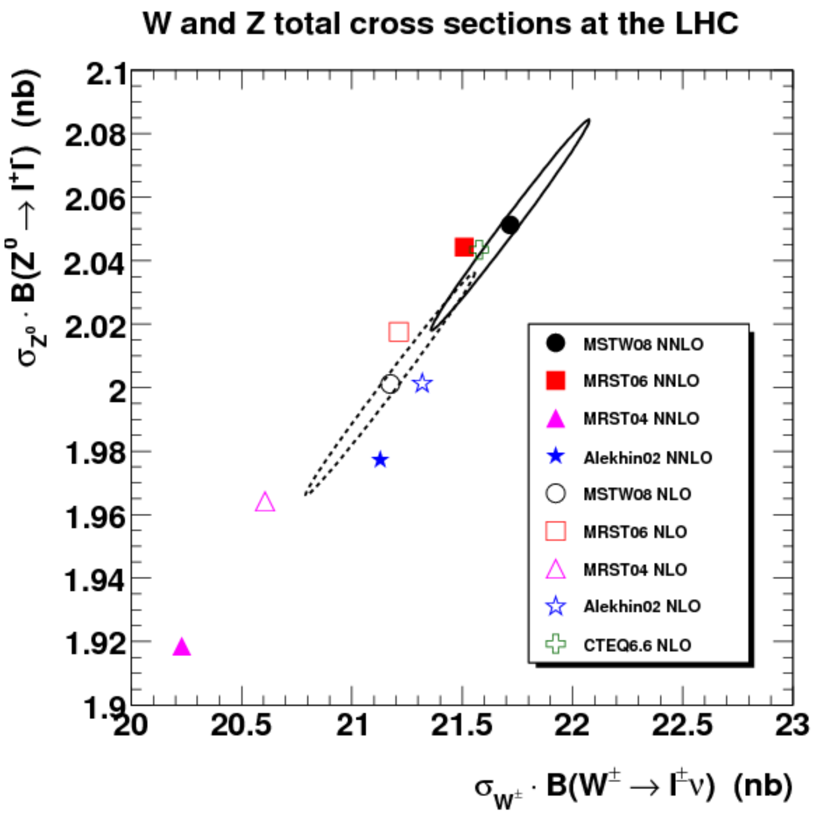
	$B_{l\upsilon} . \sigma_W$ (nb)	$B_{ll} . \sigma_Z$ (nb)
MSTW 2008 NLO	21.17 (2.659)	2.001 (0.2426)
MSTW 2008 NNLO	21.72 (2.747)	2.051 (0.2507)

MRST 2006 NLO	21.21 (2.645)	2.018 (0.2426)
MRST 2006 NNLO	21.51 (2.759)	2.044 (0.2535)
MRST 2004 NLO	20.61 (2.632)	1.964 (0.2424)
MRST 2004 NNLO	20.23 (2.724)	1.917 (0.2519)
CTEQ6.6 NLO	21.58 (2.599)	2.043 (0.2393)
Alekhin 2002 NLO	21.32 (2.733)	2.001 (0.2543)
Alekhin 2002 NNLO	21.13 (2.805)	1.977 (0.2611)

MSTW

predictions for σ(W,Z) @ Tevatron, LHC





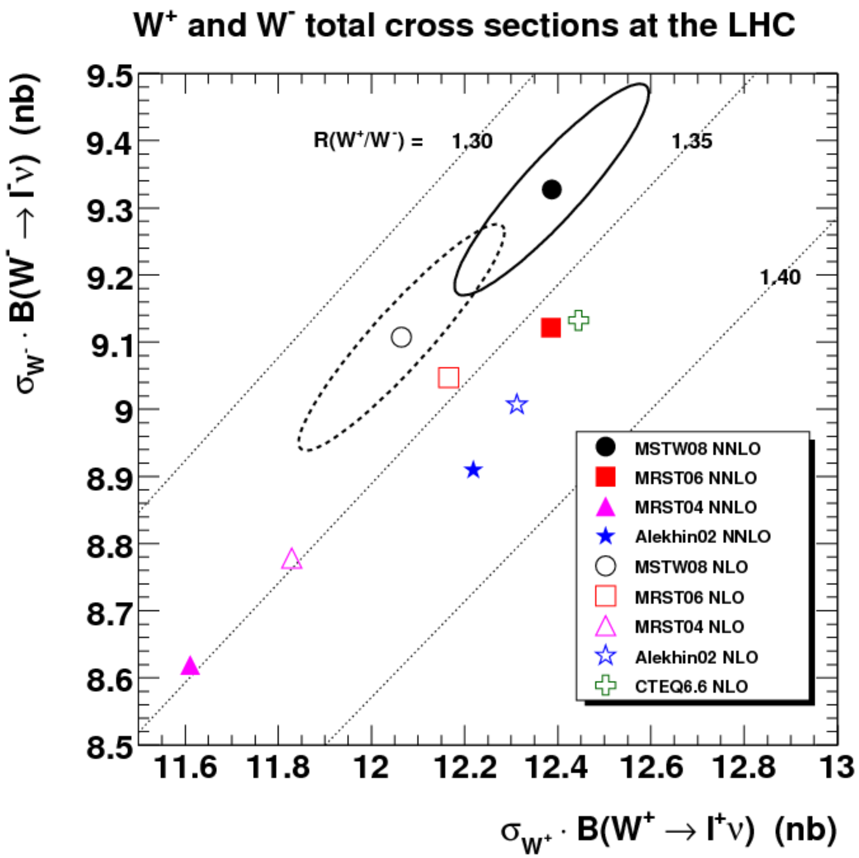
- MRST/MSTW NNLO: 2008 ~ 2006 > 2004 mainly due to changes in treatment of *charm*
- CTEQ: 6.6 ~ 6.5 > 6.1 due to changes in treatment of *s,c,b*
- NLO: CTEQ6.6 2% higher than MSTW 2008 at LHC, because of slight differences in quark (u,d,s,c) pdfs, difference within quoted uncertainty

$$R_{\pm} = \sigma(W^+ \rightarrow l^+ \nu) \,/\, \sigma(W^- \rightarrow l^- \nu)$$

$$R_{\pm} \approx \frac{u(x_1)\bar{d}(x_2) + c(x_1)\bar{s}(x_2) + (1 \leftrightarrow 2)}{d(x_1)\bar{u}(x_2) + s(x_1)\bar{c}(x_2) + (1 \leftrightarrow 2)}$$

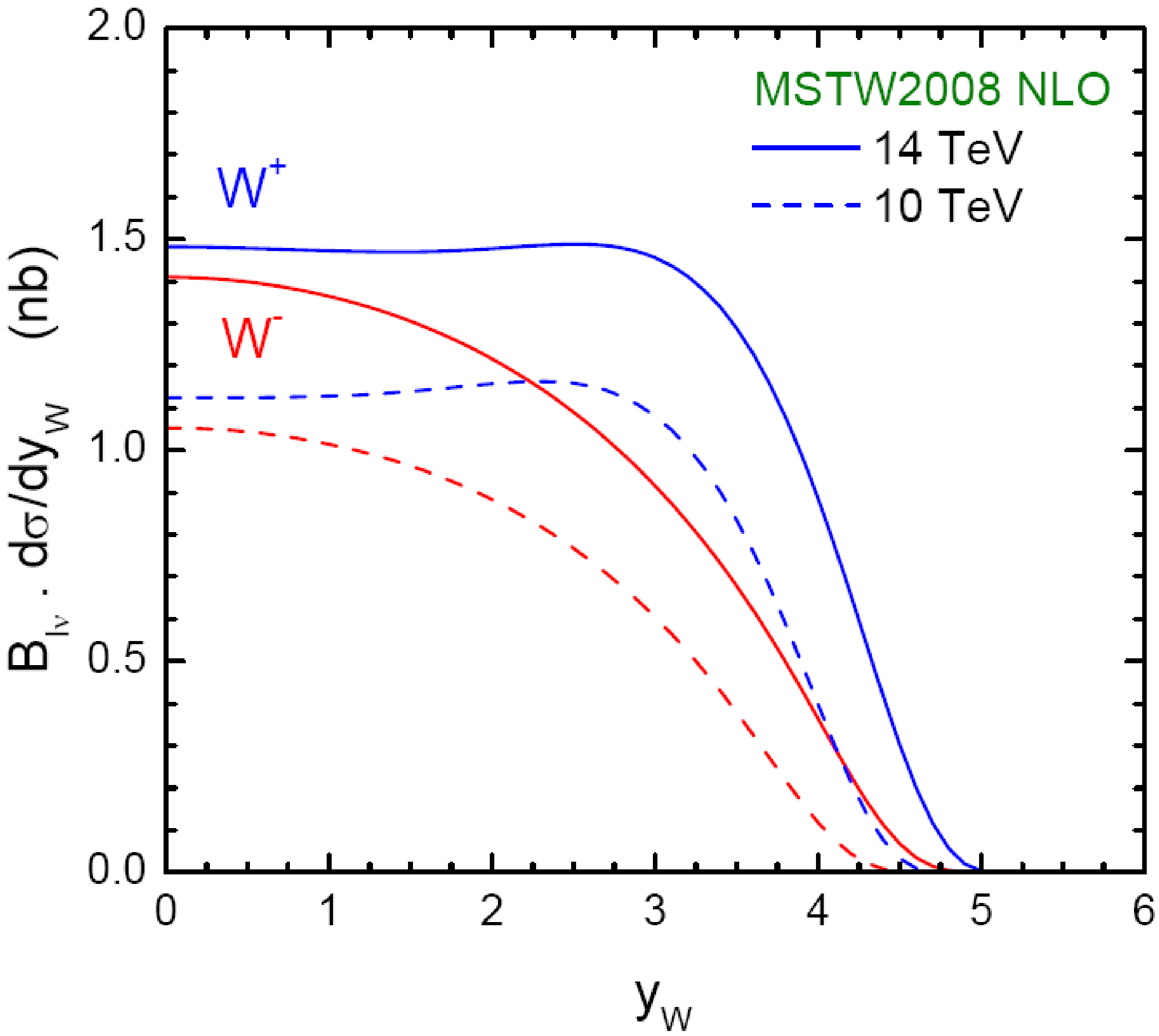
$\delta\sigma_{th} \approx \delta\sigma_{pdf} \approx \pm 1\%,$

$\delta\sigma_{expt} \approx$???



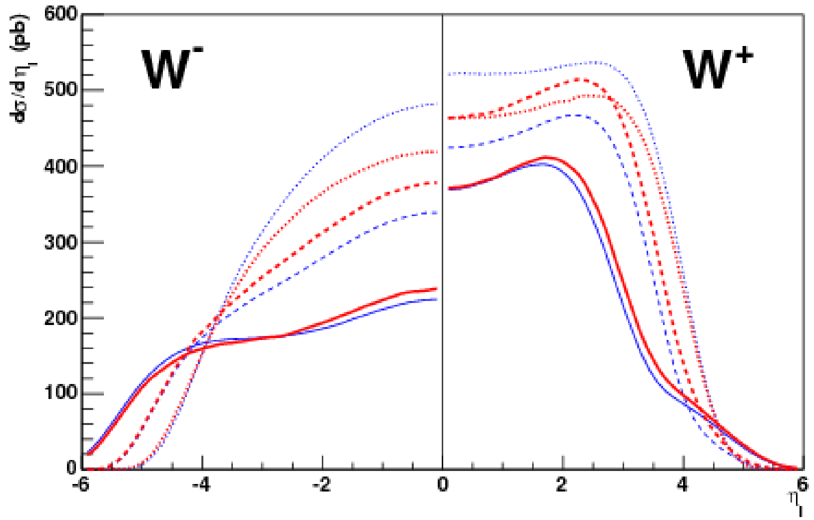
LHC, $\sqrt{s} = 10$ TeV	$B_{l\nu} \cdot \sigma_{W^+}$ (nb)	$B_{l\nu} \cdot \sigma_{W^-}$ (nb)	$R_{\pm}$
MSTW 2008 LO	$7.35^{+0.08}_{-0.12}$ $\binom{+1.1\%}{-1.6\%}$	$5.22^{+0.06}_{-0.09}$ $\binom{+1.1\%}{-1.7\%}$	$1.408^{+0.015}_{-0.012}$ $\binom{+1.0\%}{-0.8\%}$
MSTW 2008 NLO	$8.62^{+0.18}_{-0.14}$ $\binom{+2.1\%}{-1.7\%}$	$6.30^{+0.14}_{-0.11}$ $\binom{+2.2\%}{-1.7\%}$	$1.367^{+0.012}_{-0.010}$ $\binom{+0.9\%}{-0.7\%}$
MSTW 2008 NNLO	$8.88^{+0.15}_{-0.15}$ $\binom{+1.7\%}{-1.6\%}$	$6.47^{+0.11}_{-0.11}$ $\binom{+1.7\%}{-1.6\%}$	$1.373^{+0.012}_{-0.010}$ $\binom{+0.8\%}{-0.7\%}$

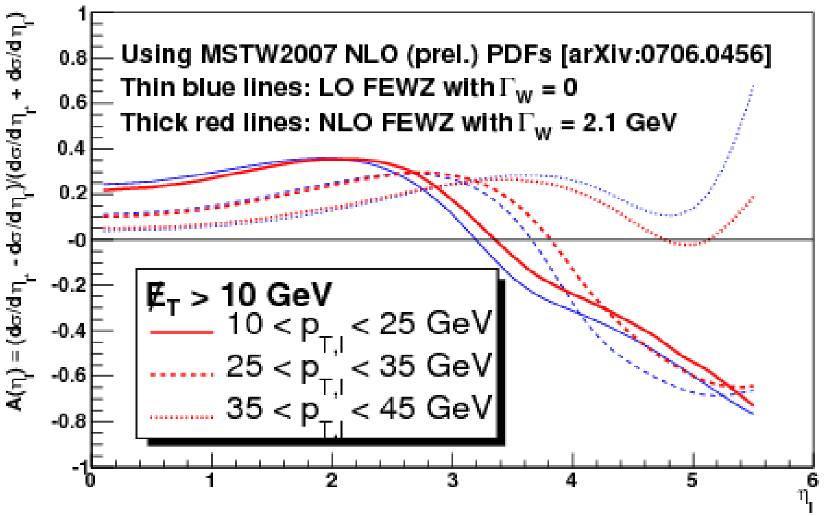
LHC, $\sqrt{s} = 14$ TeV	$B_{l\nu} \cdot \sigma_{W^+}$ (nb)	$B_{l\nu} \cdot \sigma_{W^-}$ (nb)	$R_{\pm}$
MSTW 2008 LO	$10.69^{+0.14}_{-0.19}$ $\binom{+1.3\%}{-1.8\%}$	$7.83^{+0.10}_{-0.14}$ $\binom{+1.2\%}{-1.8\%}$	$1.366^{+0.013}_{-0.010}$ $\binom{+0.9\%}{-0.8\%}$
MSTW 2008 NLO	$12.06^{+0.24}_{-0.21}$ $\binom{+2.0\%}{-1.8\%}$	$9.11^{+0.19}_{-0.16}$ $\binom{+1.2\%}{-1.6\%}$	$1.325^{+0.011}_{-0.009}$ $\binom{+0.8\%}{-0.7\%}$
MSTW 2008 NNLO	$12.39^{+0.22}_{-0.21}$ $\binom{+1.8\%}{-1.7\%}$	$9.33^{+0.16}_{-0.16}$ $\binom{+1.7\%}{-1.7\%}$	$1.328^{+0.011}_{-0.009}$ $\binom{+0.8\%}{-0.7\%}$

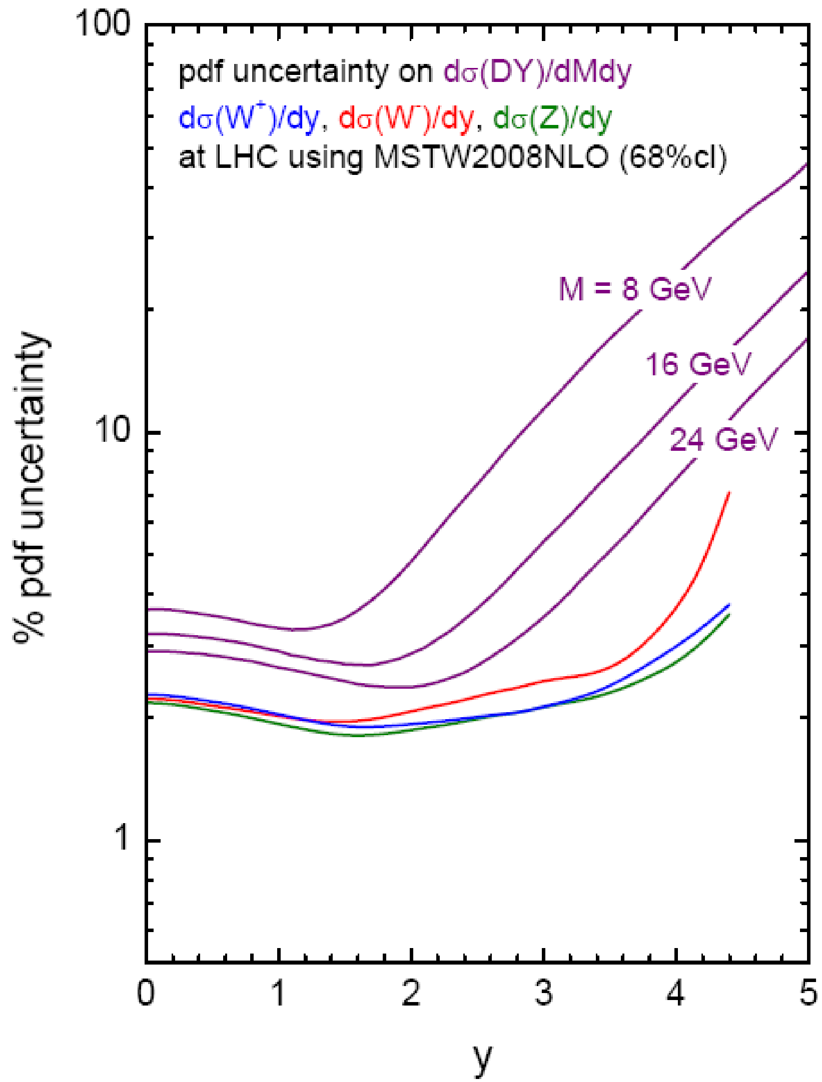


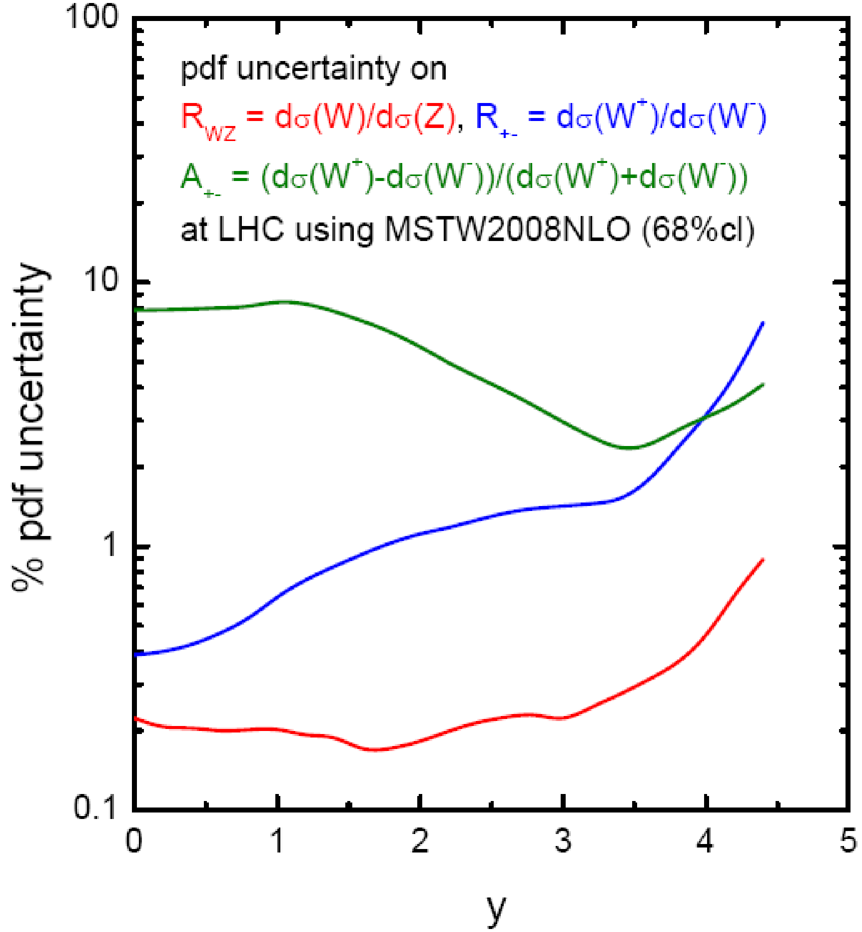
MSTW2008 NLO
14 TeV
10 TeV
W^+
W^-
$B_{l\nu} \cdot d\sigma/dy_W$ (nb)
y_W
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6

$W \rightarrow l\,\nu_l$ charge asymmetry at LHC






pdf uncertainty on dσ(DY)/dMdy
dσ(W+)/dy, dσ(W-)/dy, dσ(Z)/dy
at LHC using MSTW2008NLO (68%cl)
M = 8 GeV
16 GeV
24 GeV
% pdf uncertainty
y
100
10
1
0
1
2
3
4
5


pdf uncertainty on
R_WZ = dσ(W)/dσ(Z), R+- = dσ(W+)/dσ(W-)
A+- = (dσ(W+)-dσ(W-))/(dσ(W+)+dσ(W-))
at LHC using MSTW2008NLO (68%cl)
% pdf uncertainty
y
100
10
1
0.1
0
1
2
3
4
5

using the W^{+-} charge asymmetry at the LHC

- at the Tevatron $\sigma(W^+) = \sigma(W^-)$, whereas at LHC $\sigma(W^+) \sim 1.3\sigma(W^-)$

- can use this asymmetry to calibrate backgrounds to new physics, since typically $\sigma_{NP}(X \to W^+ + \ldots) = \sigma_{NP}(X \to W^- + \ldots)$

- example:

$$gg \to t\bar{t} \to W^+W^-b\bar{b} \to W^\pm(\to l^\pm + \nu) + 4\text{jets}$$

in this case

$$\sigma_{\text{signal}}(W^+ + 4\text{jets}) = \sigma_{\text{signal}}(W^- + 4\text{jets})$$

whereas…

$$\sigma_{\text{QCDbkgd}}(W^+ + 4\text{jets}) \neq \sigma_{\text{QCDbkgd}}(W^- + 4\text{jets})$$

which can in principle help distinguish signal and background

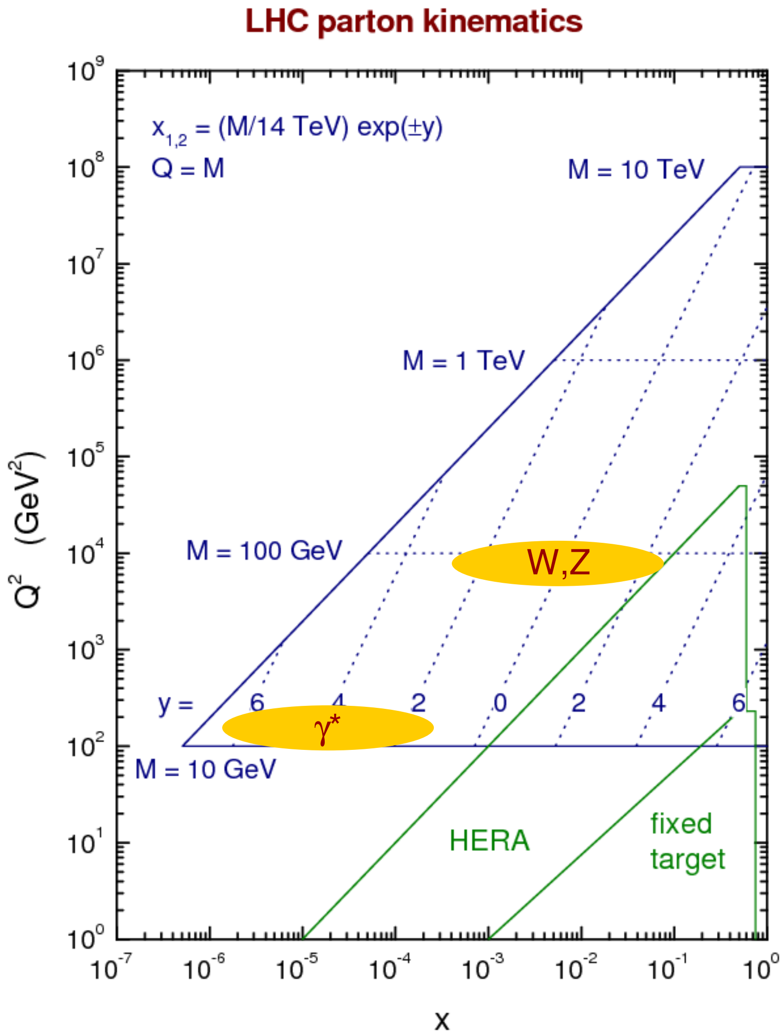
pdfs at LHC – the issues

- high precision cross section predictions require accurate knowledge of pdfs: $\delta\sigma_{th} = \delta\sigma_{pdf} + \ldots$
  $\rightarrow$ improved signal and background predictions
  $\rightarrow$ easier to spot new physics
- 'standard candle' processes (e.g. σ_Z) to
  - check formalism (factorisation, DGLAP, …)
  - measure machine luminosity?
- learning more about pdfs from LHC measurements. e.g.
  - high-E_T jets $\rightarrow$ gluon?
  - $W^+,W^-,Z^0 \rightarrow$ quarks?
  - forward DY $\rightarrow$ small x?
  - …

impact of LHC measurements on pdfs

- the standard candles: central $\sigma(W,Z,tt,jets)$ as a probe and test of pdfs in the $x \sim 10^{-2\pm1}$, $Q^2 \sim 10^{4\text{-}6}$ GeV^2 range where most New Physics is expected (H, SUSY, ….)

- forward production of (relatively) low-mass states (e.g. γ^*,dijets,…) to access partons at $x<<1$ (and $x\sim1$)



LHCb

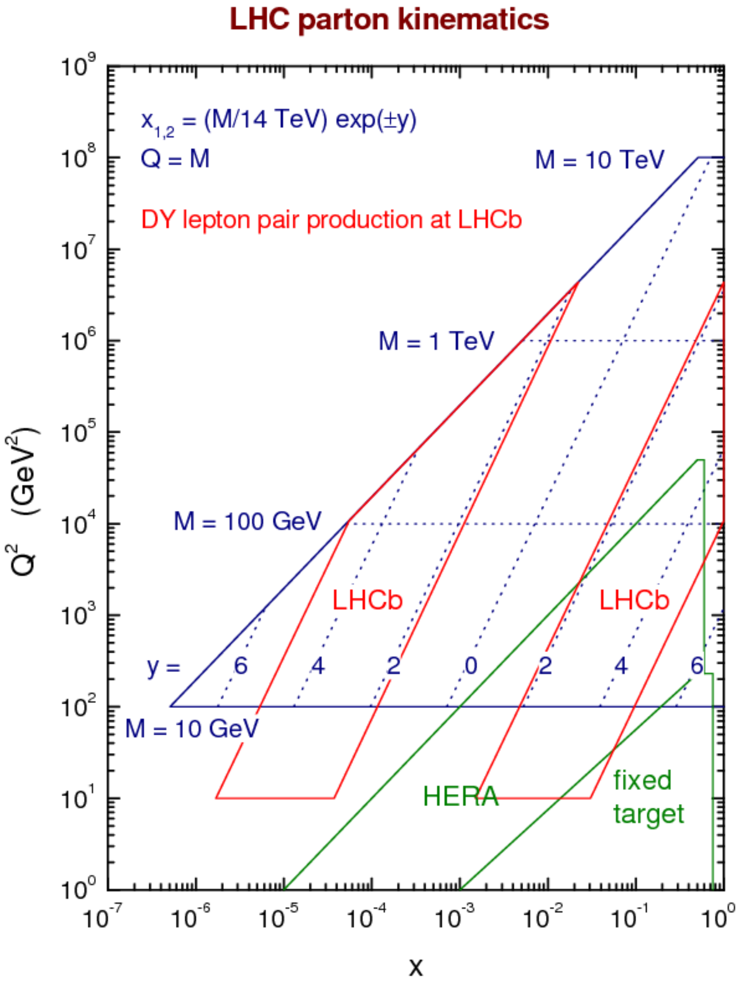
Unique features

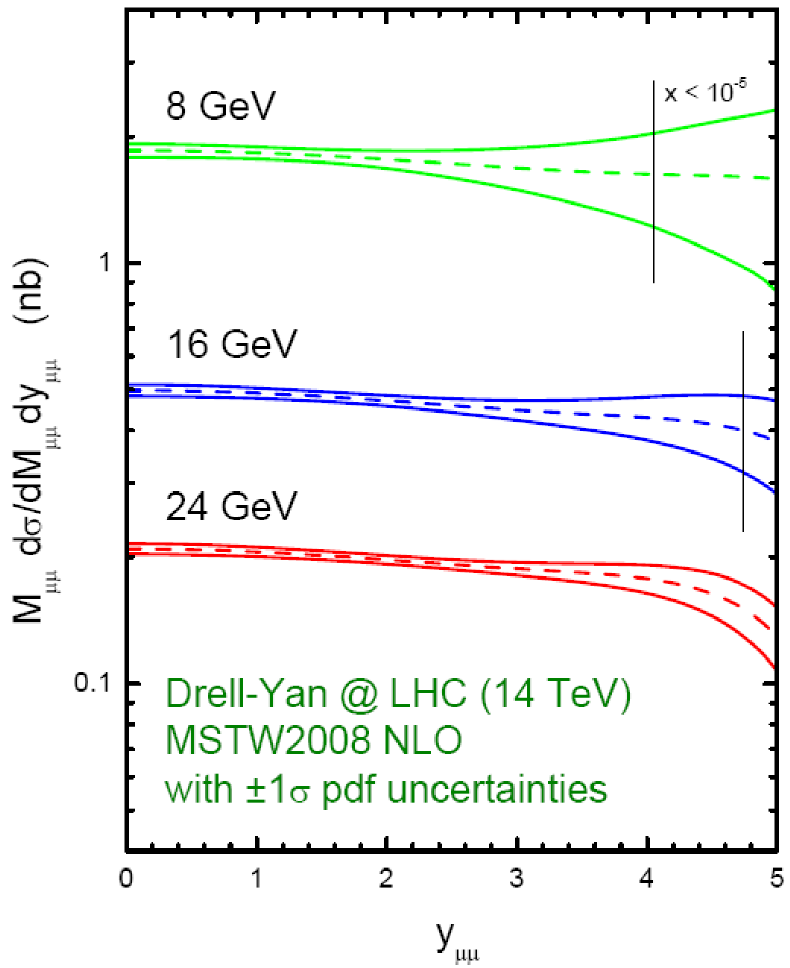
- pseudo-rapidity range 1.9 - 4.9
  - 1.9 - 2.5 complementary to ATLAS/CMS
  - $>$ 2.5 unique to LHCb
- beam defocused at LHCb: 1 year of running = 2 fb^{-1}
- trigger on low momentum muons: $p > 8$ GeV, $p_T > 1$ GeV

→ access to unique range of (x,Q^2)

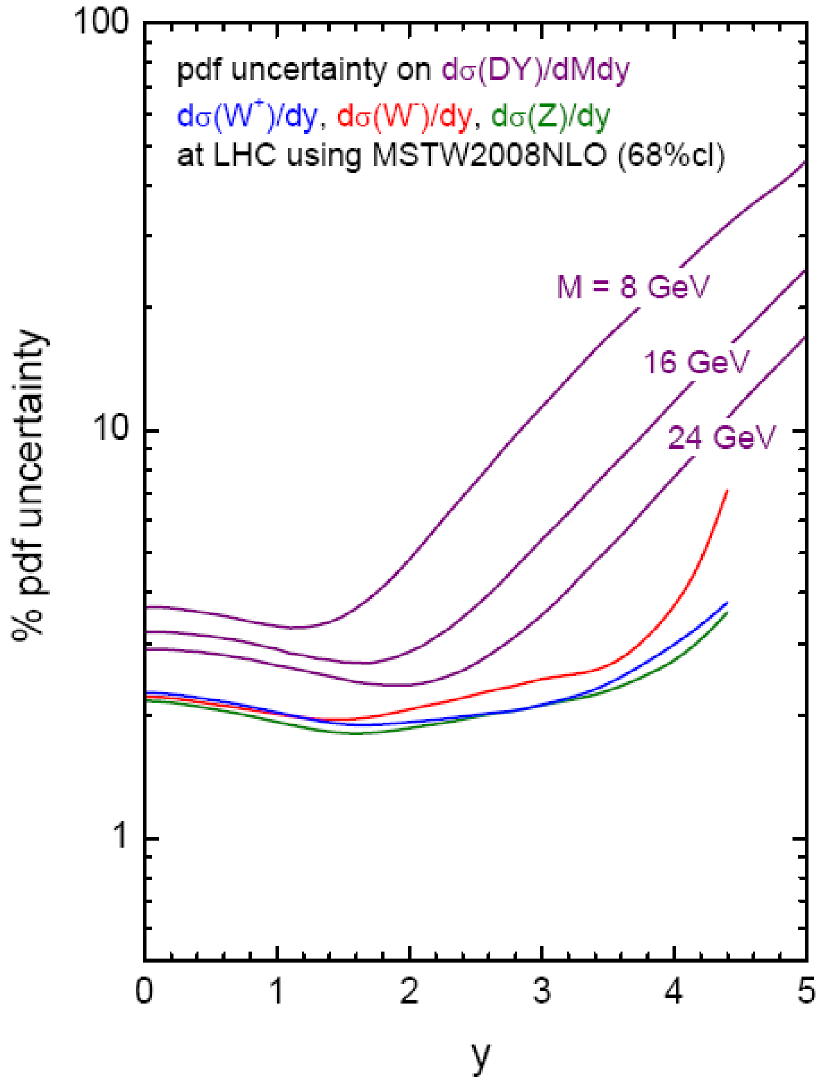
LHCb

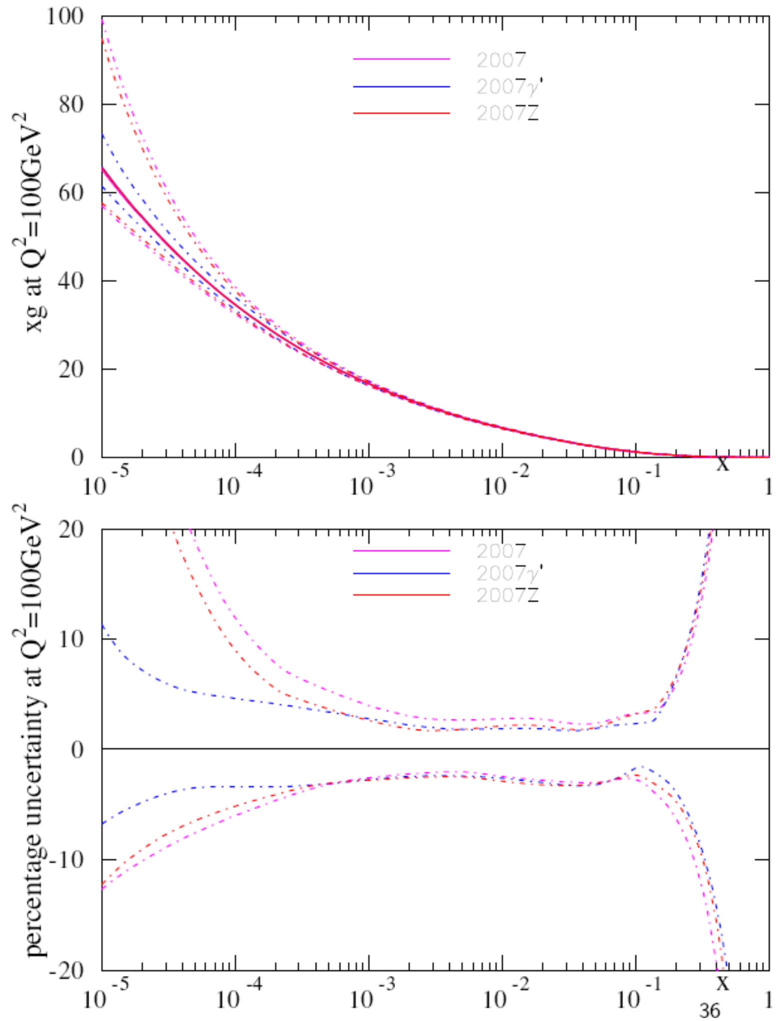
$\rightarrow$ detect forward, low p_T muons from $q\bar{q} \rightarrow \mu^+\mu^-$





Impact of 1 fb^{-1} LHCb data for forward Z and γ^* (M = 14 GeV) production on the gluon distribution uncertainty





summary

- precision phenomenology at high-energy colliders such as the LHC requires an accurate knowledge of the distribution functions of partons in hadrons

- determining pdfs from global fits to data is now a major industry… the MSTW collaboration has released its latest (2008) LO, NLO, NNLO sets

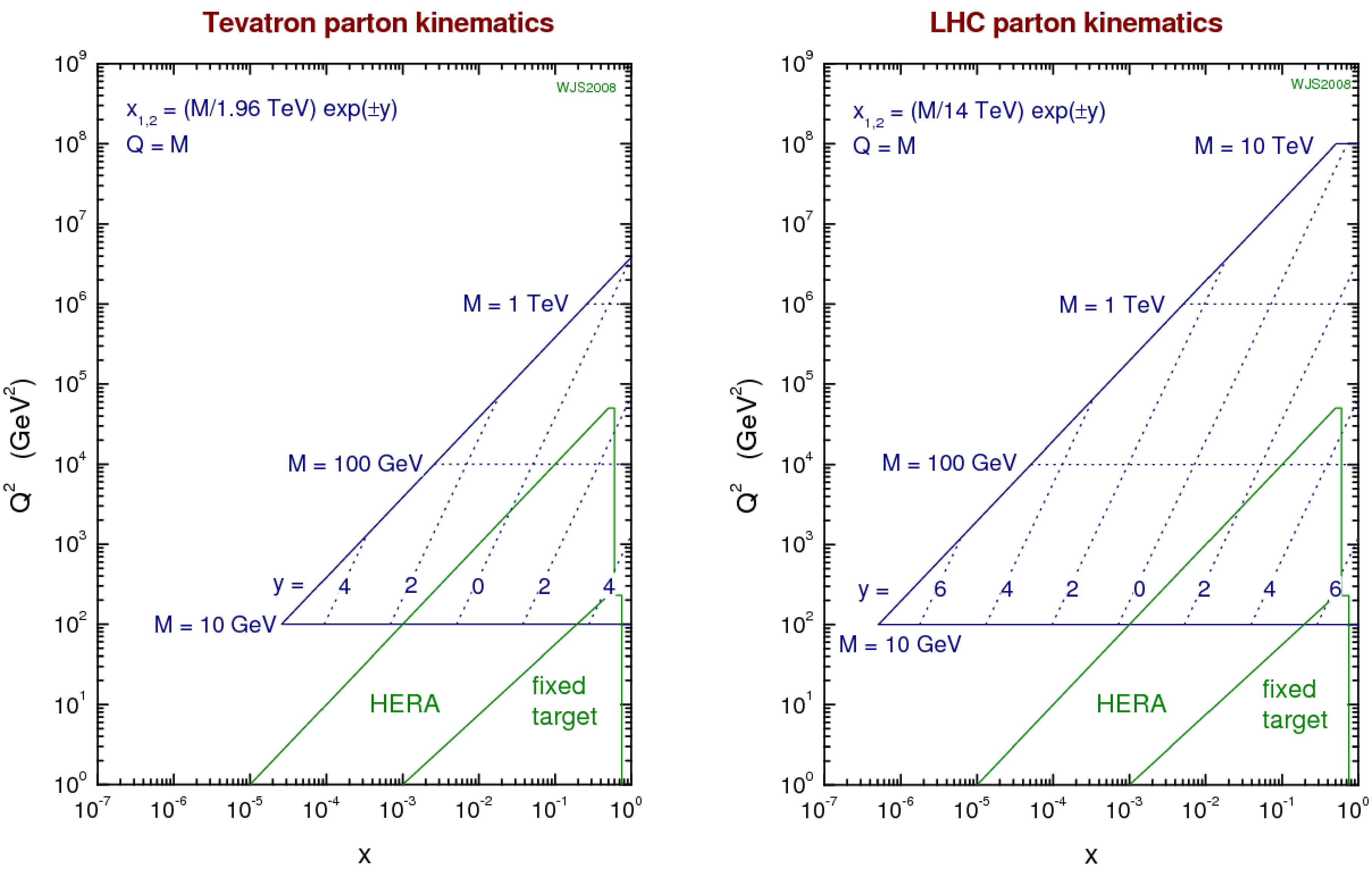
- pdf uncertainty for ‘new physics’ cross sections not expected to be too important (few % level), apart from at very high mass

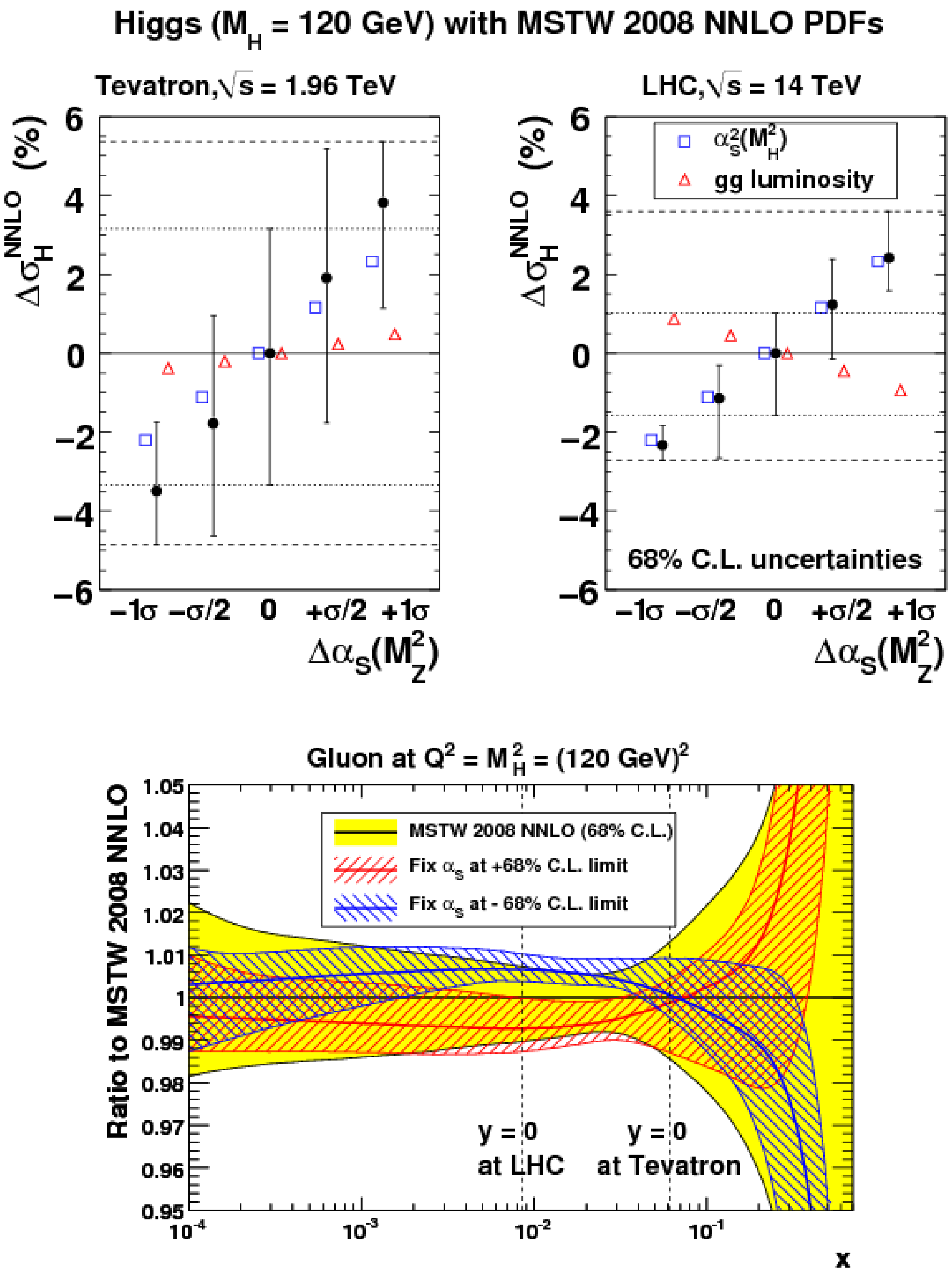
- ongoing high-precision studies of standard candle cross sections and ratios (→ new PDF4LHC benchmarking initiative)

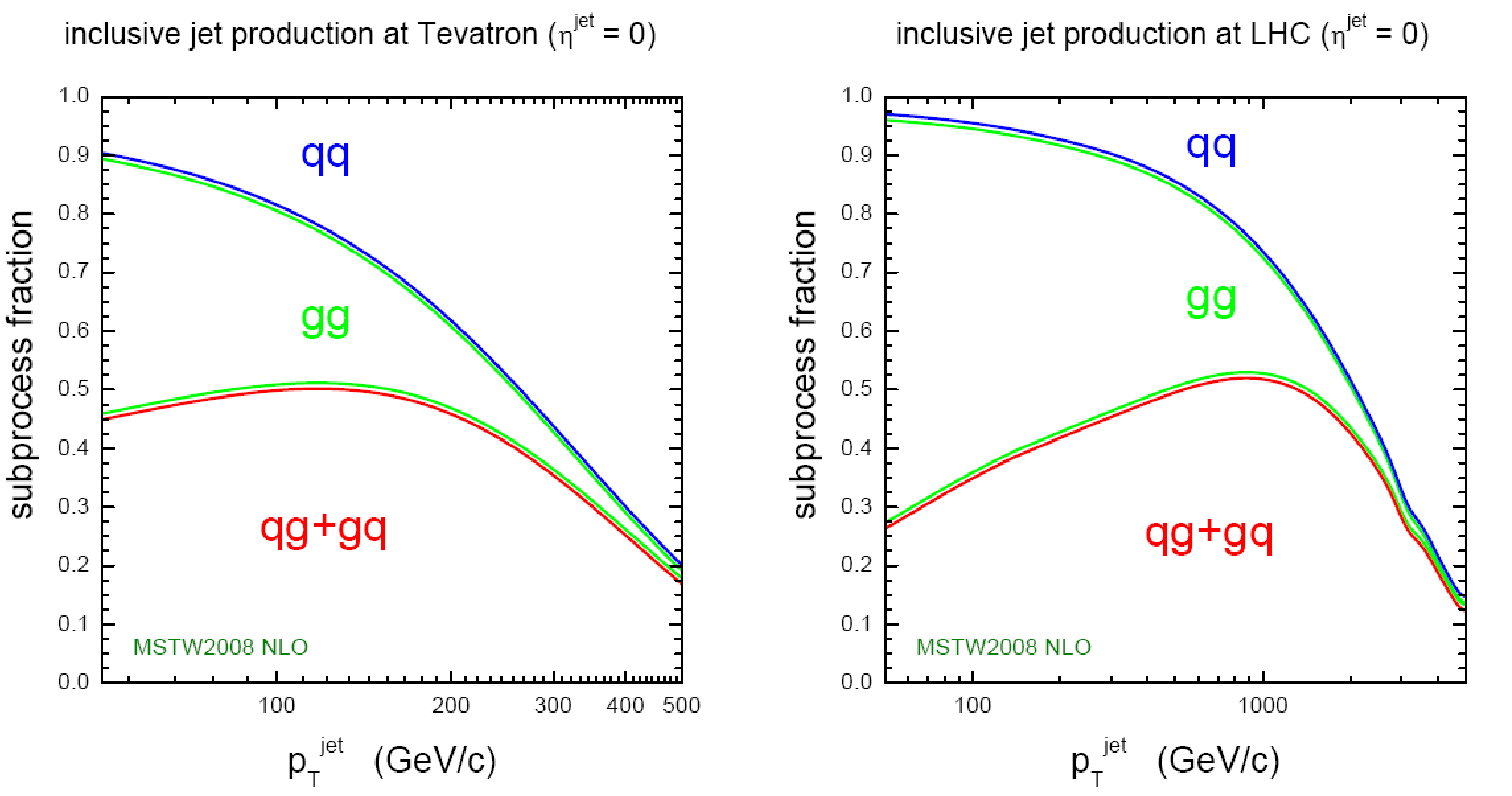
- potential of LHCb to probe very small *x* via low-mass Drell-Yan

- 7 TeV LHC is already interesting!

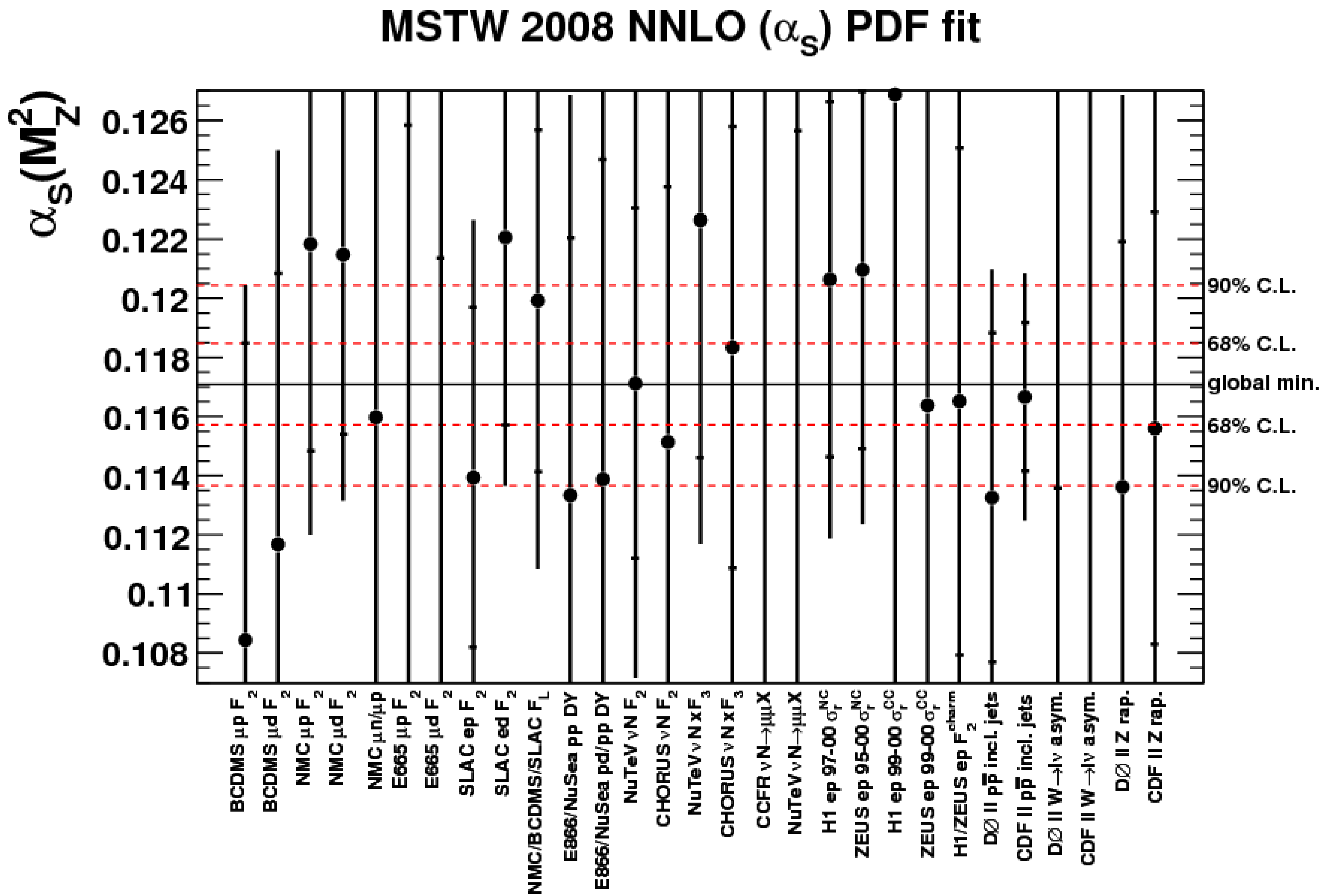
extra slides


Tevatron parton kinematics
$x_{1,2}$ = (M/1.96 TeV) exp(±y)
Q = M
WJS2008
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 4 2 0 2 4
HERA
fixed target
Q^2 (GeV^2)
x
LHC parton kinematics
$x_{1,2}$ = (M/14 TeV) exp(±y)
Q = M
WJS2008
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = 6 4 2 0 2 4 6
HERA
fixed target
Q^2 (GeV^2)
x

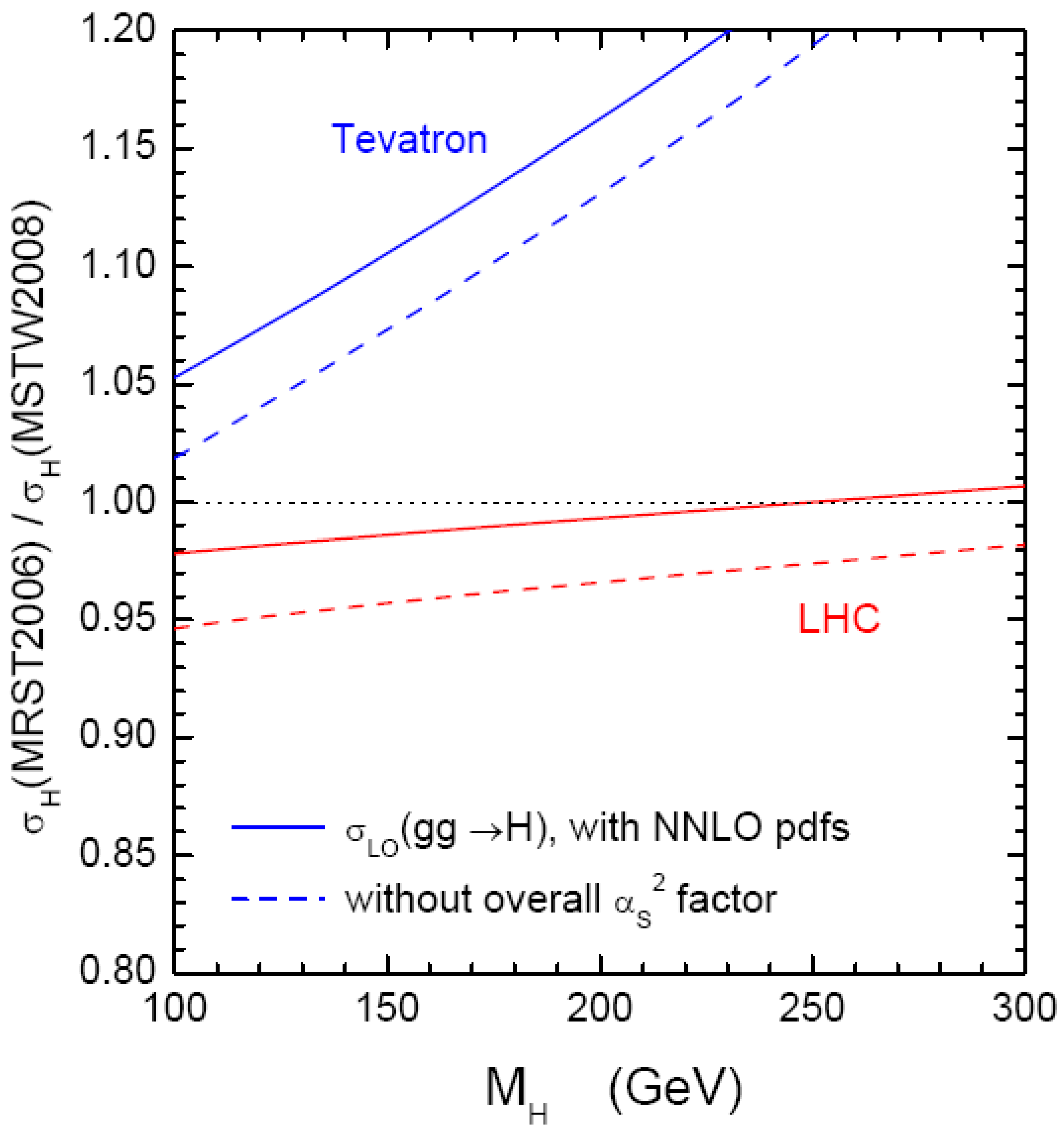

Higgs (M_H = 120 GeV) with MSTW 2008 NNLO PDFs
Tevatron, $\sqrt{s}$ = 1.96 TeV
LHC, $\sqrt{s}$ = 14 TeV
$\Delta\sigma_H^{NNLO}$ (%)
$\alpha_S^2(M_H^2)$
gg luminosity
68% C.L. uncertainties
−1σ −σ/2 0 +σ/2 +1σ
$\Delta\alpha_S(M_Z^2)$
Gluon at $Q^2 = M_H^2 = (120\text{ GeV})^2$
Ratio to MSTW 2008 NNLO
MSTW 2008 NNLO (68% C.L.)
Fix α_S at +68% C.L. limit
Fix α_S at - 68% C.L. limit
y = 0
at LHC
y = 0
at Tevatron
x



inclusive jet production at Tevatron (η^{jet} = 0)
subprocess fraction
qq
gg
qg+gq
MSTW2008 NLO
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
100
200
300
400
500
p_T^{jet} (GeV/c)
inclusive jet production at LHC (η^{jet} = 0)
subprocess fraction
qq
gg
qg+gq
MSTW2008 NLO
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
100
1000
p_T^{jet} (GeV/c)



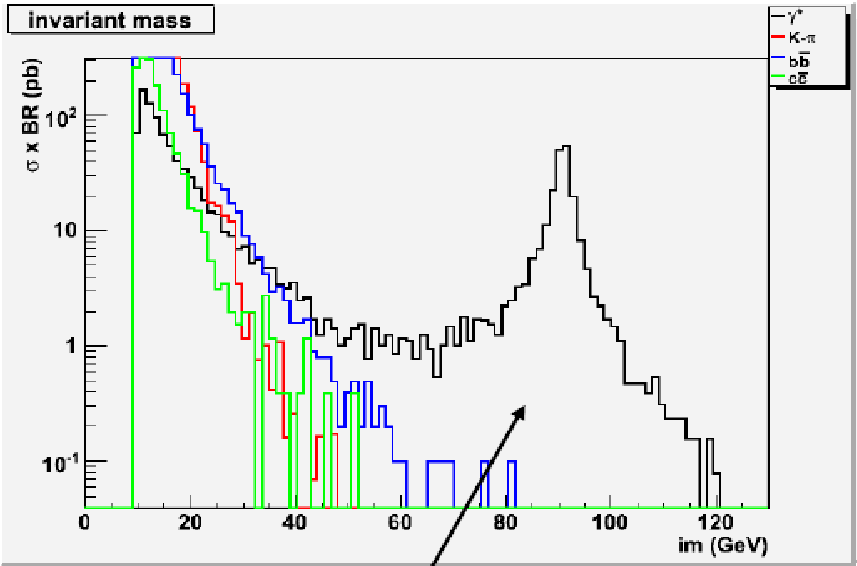
MSTW 2008 NNLO (α_S) PDF fit
$\alpha_S(M_Z^2)$
0.126
0.124
0.122
0.12
0.118
0.116
0.114
0.112
0.11
0.108
90% C.L.
68% C.L.
global min.
68% C.L.
90% C.L.
BCDMS μp F_2
BCDMS μd F_2
NMC μp F_2
NMC μd F_2
NMC μn/μp
E665 μp F_2
E665 μd F_2
SLAC ep F_2
SLAC ed F_2
NMC/BCDMS/SLAC F_L
E866/NuSea pp DY
E866/NuSea pd/pp DY
NuTeV νN F_2
CHORUS νN F_2
NuTeV νN xF_3
CHORUS νN xF_3
CCFR νN→μμX
NuTeV νN→μμX
H1 ep 97-00 σ_r^{NC}
ZEUS ep 95-00 σ_r^{NC}
H1 ep 99-00 σ_r^{CC}
ZEUS ep 99-00 σ_r^{CC}
H1/ZEUS ep F_2^{charm}
DØ II $p\bar{p}$ incl. jets
CDF II $p\bar{p}$ incl. jets
DØ II W→lν asym.
CDF II W→lν asym.
DØ II Z rap.
CDF II Z rap.

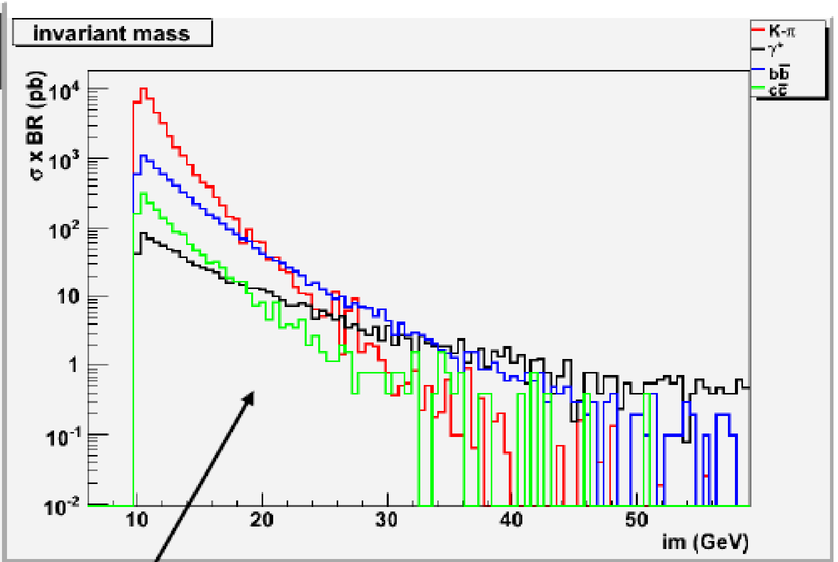


1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
100
150
200
250
300
Tevatron
LHC
$\sigma_{LO}(gg \to H)$, with NNLO pdfs
without overall α_S^2 factor
σ_H(MRST2006) / σ_H(MSTW2008)
M_H (GeV)

γ^*->$\mu\mu$ selection

- 4-vector Pythia + LHCb acceptance

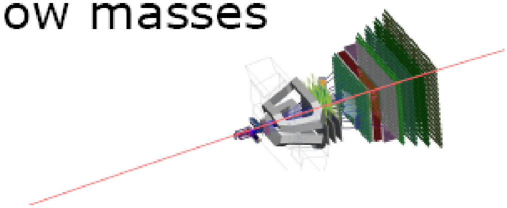




Dominant at Z but large backgrounds at low masses

8th April 2008

Ronan McNulty et al, at DIS08



using the W^{+-} charge asymmetry at the LHC

- at the Tevatron $\sigma(W^+) = \sigma(W^-)$, whereas at LHC $\sigma(W^+) \sim 1.3\sigma(W^-)$

- can use this asymmetry to calibrate backgrounds to new physics, since typically $\sigma_{NP}(X \longrightarrow W^+ + \ldots) = \sigma_{NP}(X \longrightarrow W^- + \ldots)$

- example:

$$gg \to t\bar{t} \to W^+W^-b\bar{b} \to W^\pm(\to l^\pm + \nu) + 4\text{jets}$$

in this case

$$\sigma_{\text{signal}}(W^+ + 4\text{jets}) = \sigma_{\text{signal}}(W^- + 4\text{jets})$$

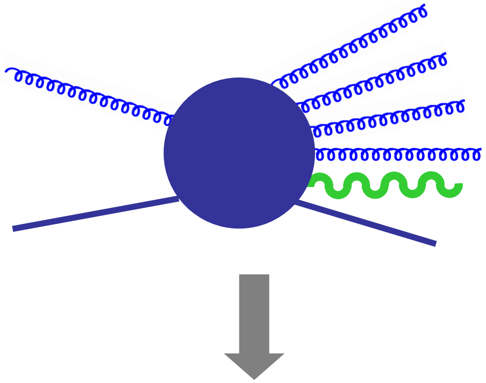
whereas…

$$\sigma_{\text{QCDbkgd}}(W^+ + 4\text{jets}) \neq \sigma_{\text{QCDbkgd}}(W^- + 4\text{jets})$$

which can in principle help distinguish signal and background

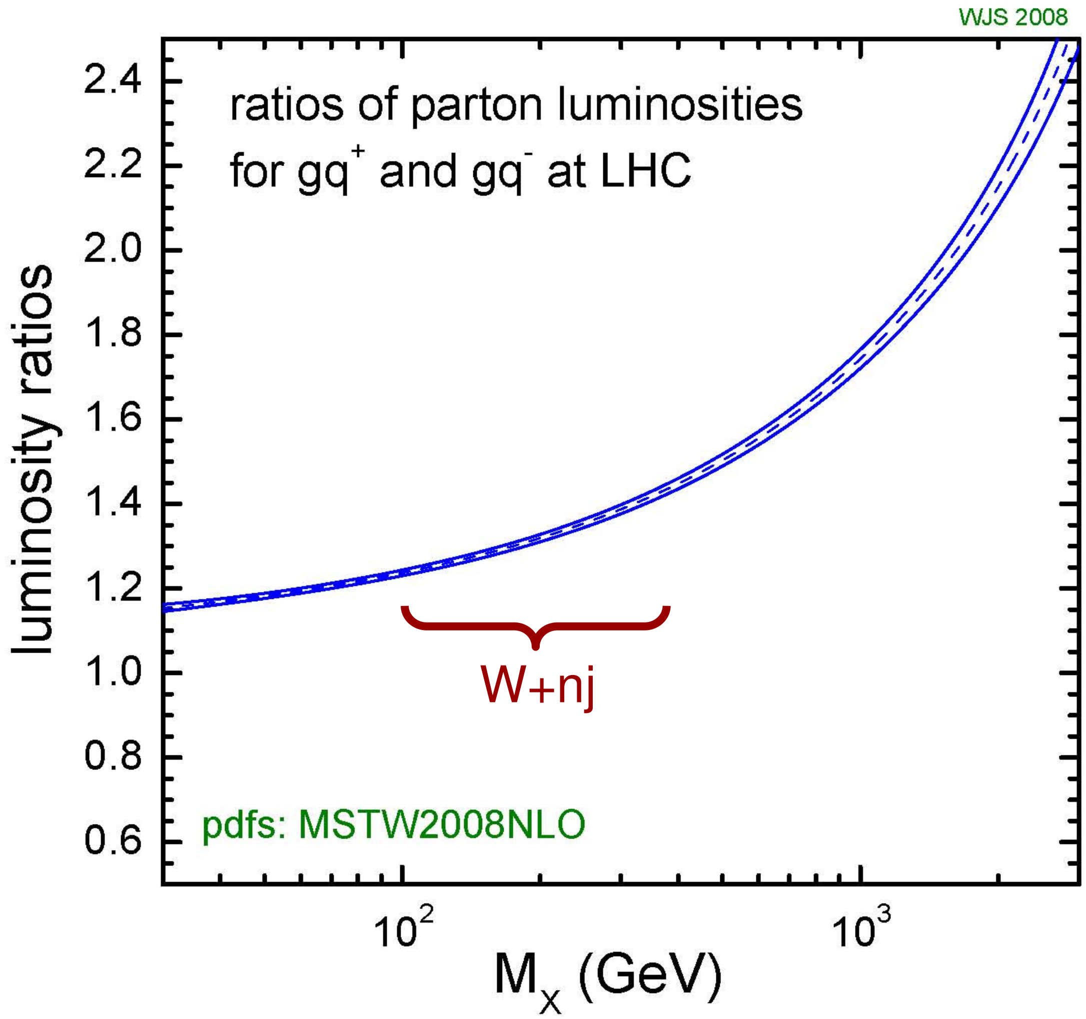
W^{+-} + n jets @ LHC

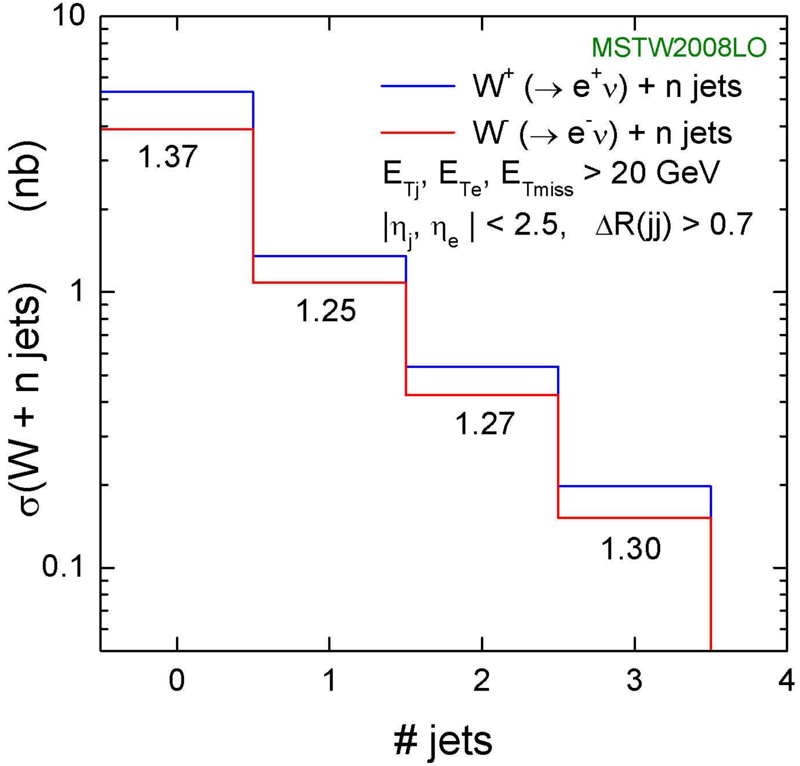
for $n_{jet} > 1$ dominant subprocess is:

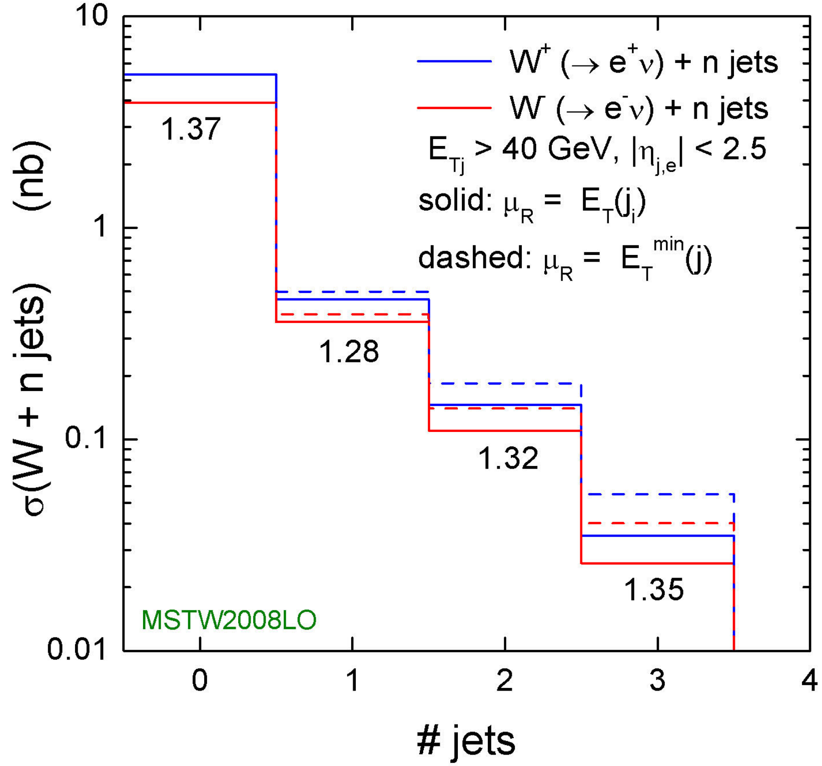


$$g + q^{+} \;\to\; W^{+} + q^{-} + ng$$
$$g + q^{-} \;\to\; W^{-} + q^{+} + ng$$

	%qq	%qg	%gg
W+0j	100	0	0
W+1j	75	25	0
W+2j	18	75	7
W+3j	18	72	10

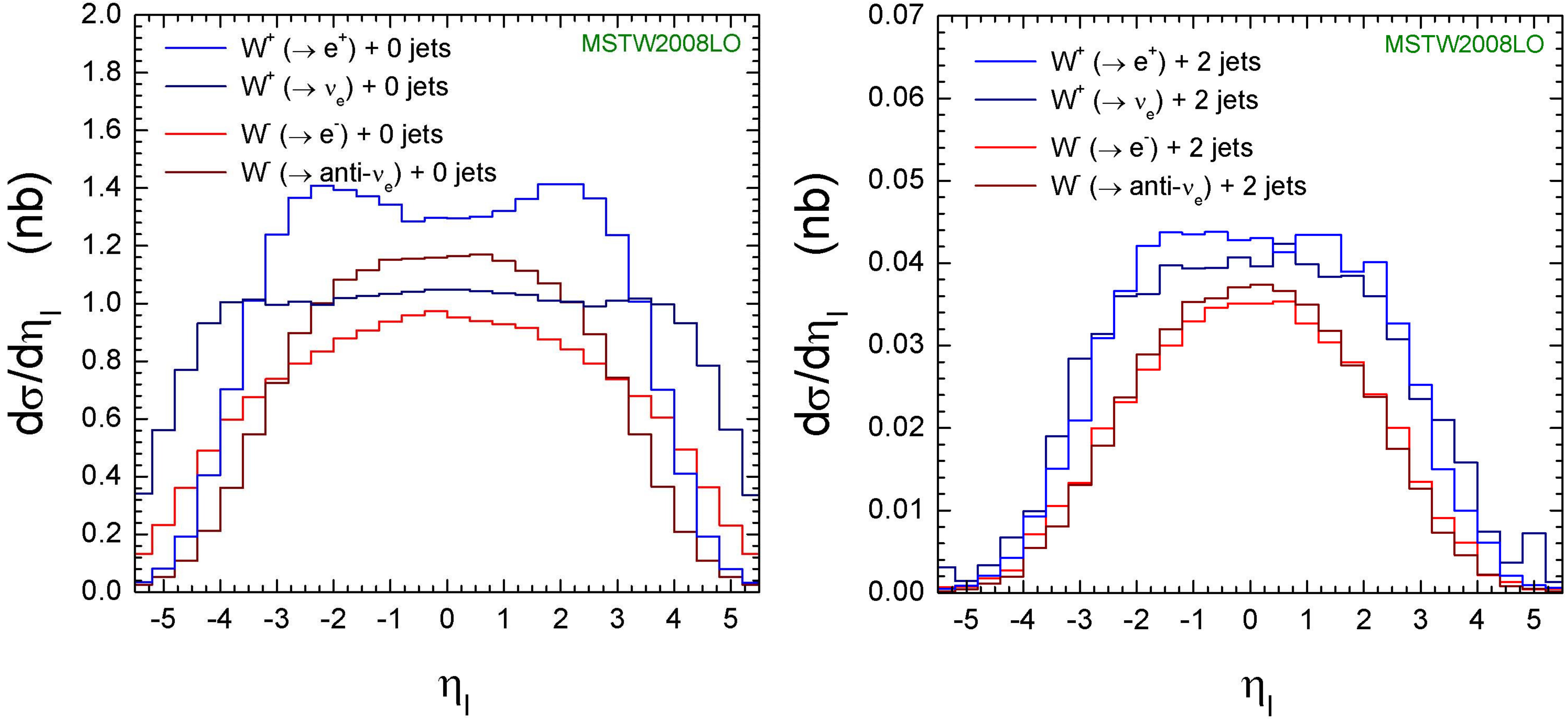




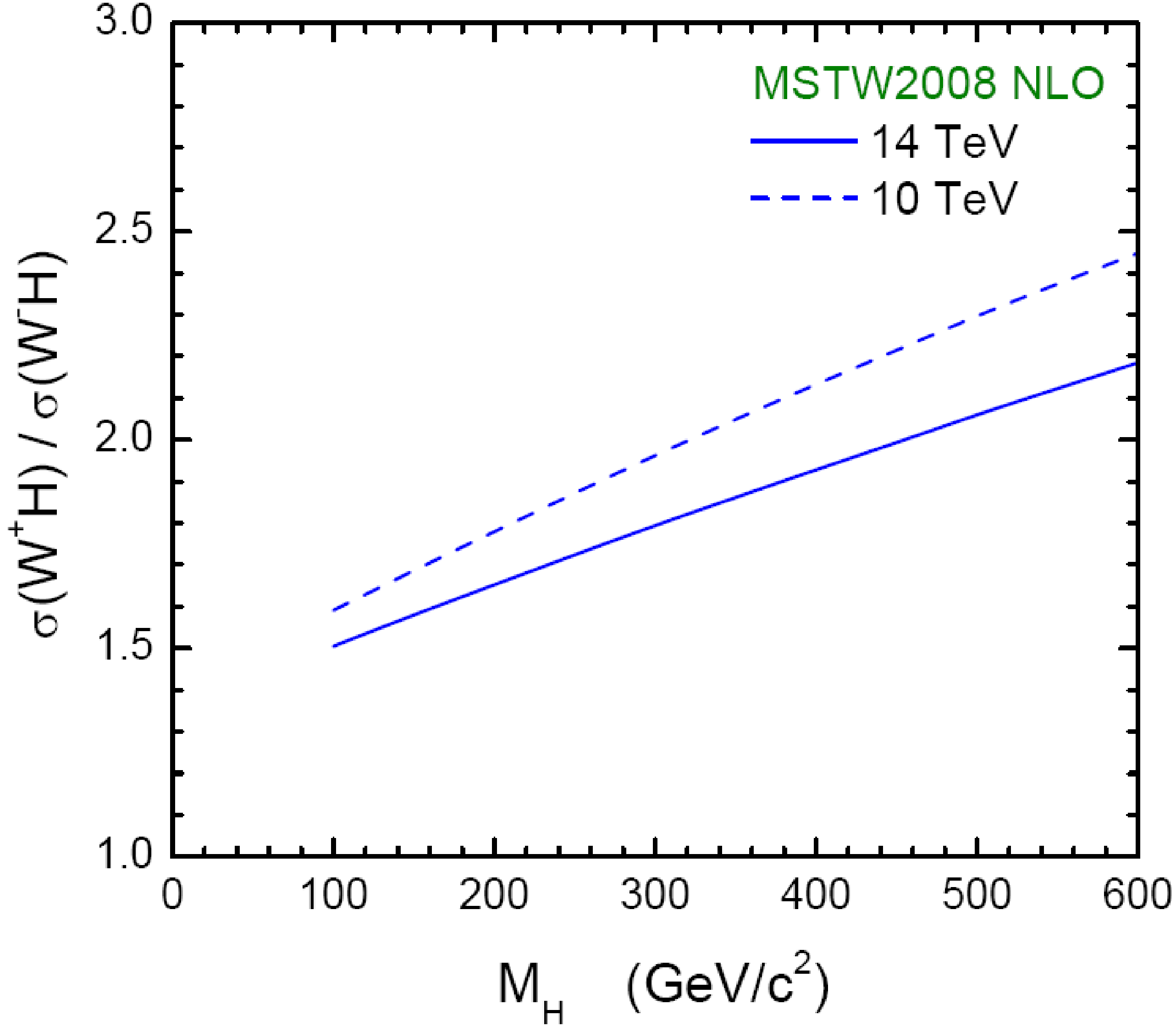


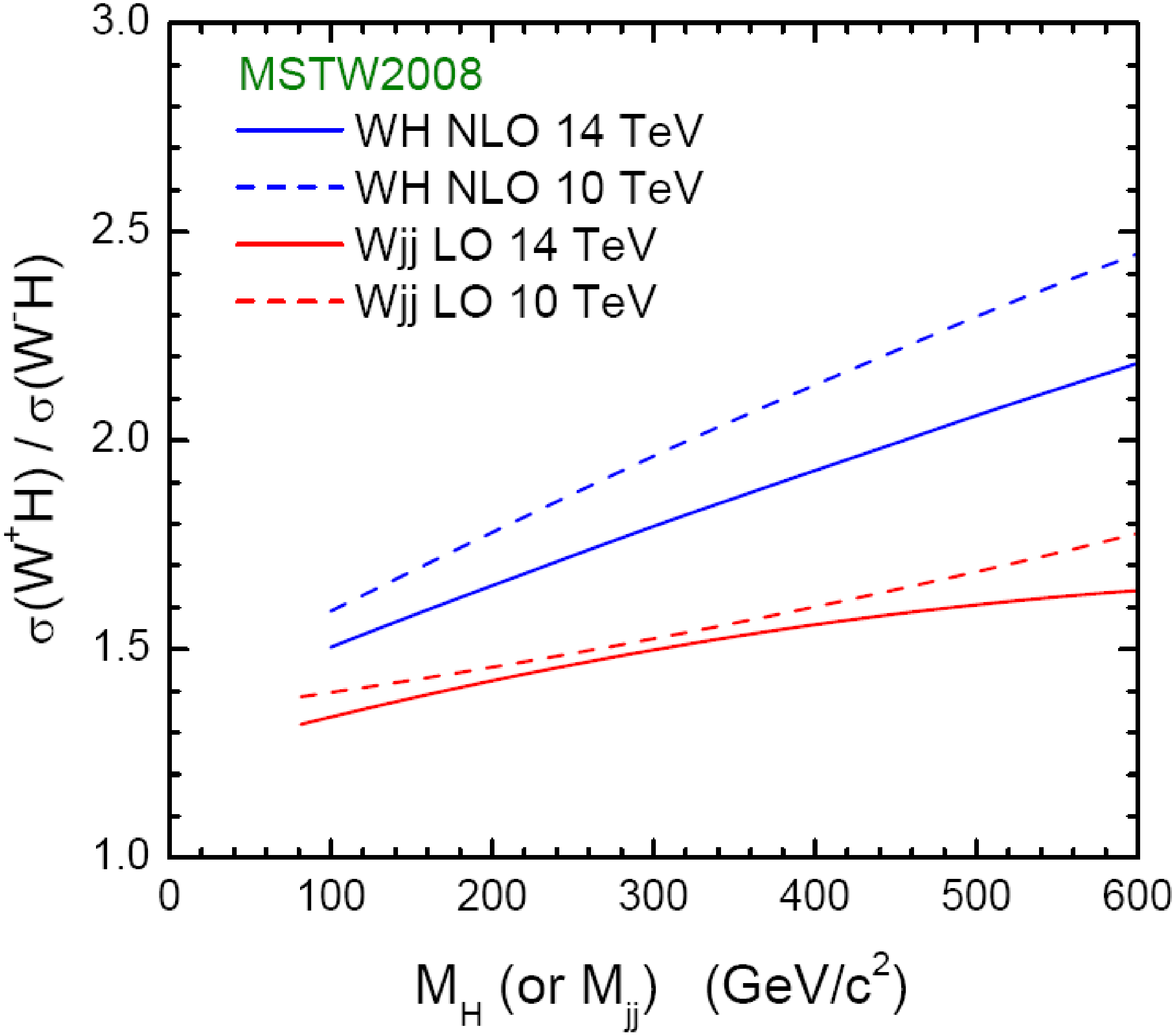
W^+/W^- ratio:

- very sensitive to u/d pdf ratio
- varies with y_W
- depends slightly on n_{jet} and E_{Tj}(min)
- fairly independent of scale choice etc

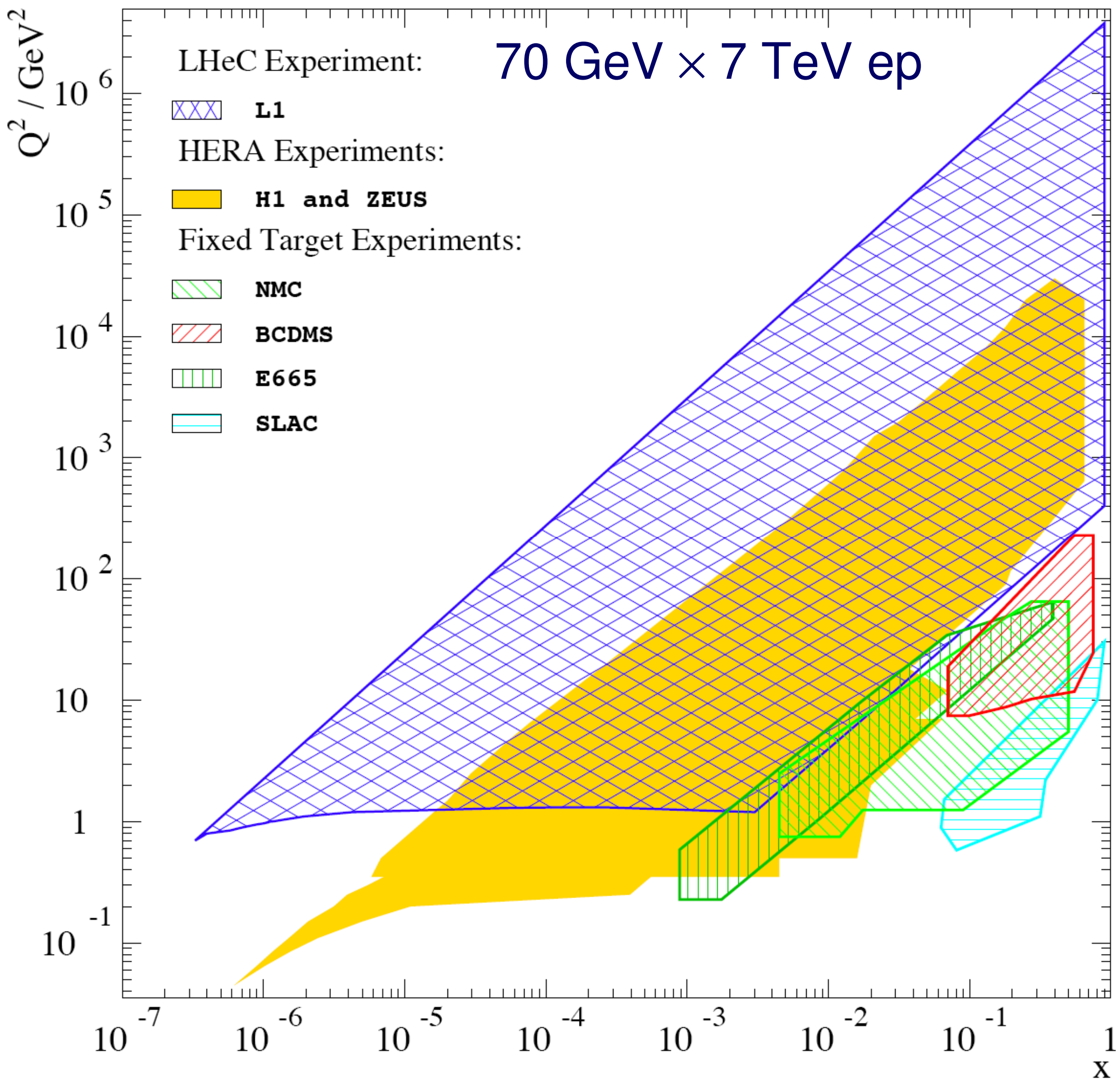


MSTW2008LO
W+ (→ e+) + 0 jets
W+ (→ νe) + 0 jets
W- (→ e-) + 0 jets
W- (→ anti-νe) + 0 jets
dσ/dηl (nb)
ηl
MSTW2008LO
W+ (→ e+) + 2 jets
W+ (→ νe) + 2 jets
W- (→ e-) + 2 jets
W- (→ anti-νe) + 2 jets
dσ/dηl (nb)
ηl


MSTW2008 NLO
14 TeV
10 TeV
3.0
2.5
2.0
1.5
1.0
0
100
200
300
400
500
600
$\sigma(W^+H) / \sigma(W^-H)$
M_H (GeV/c^2)

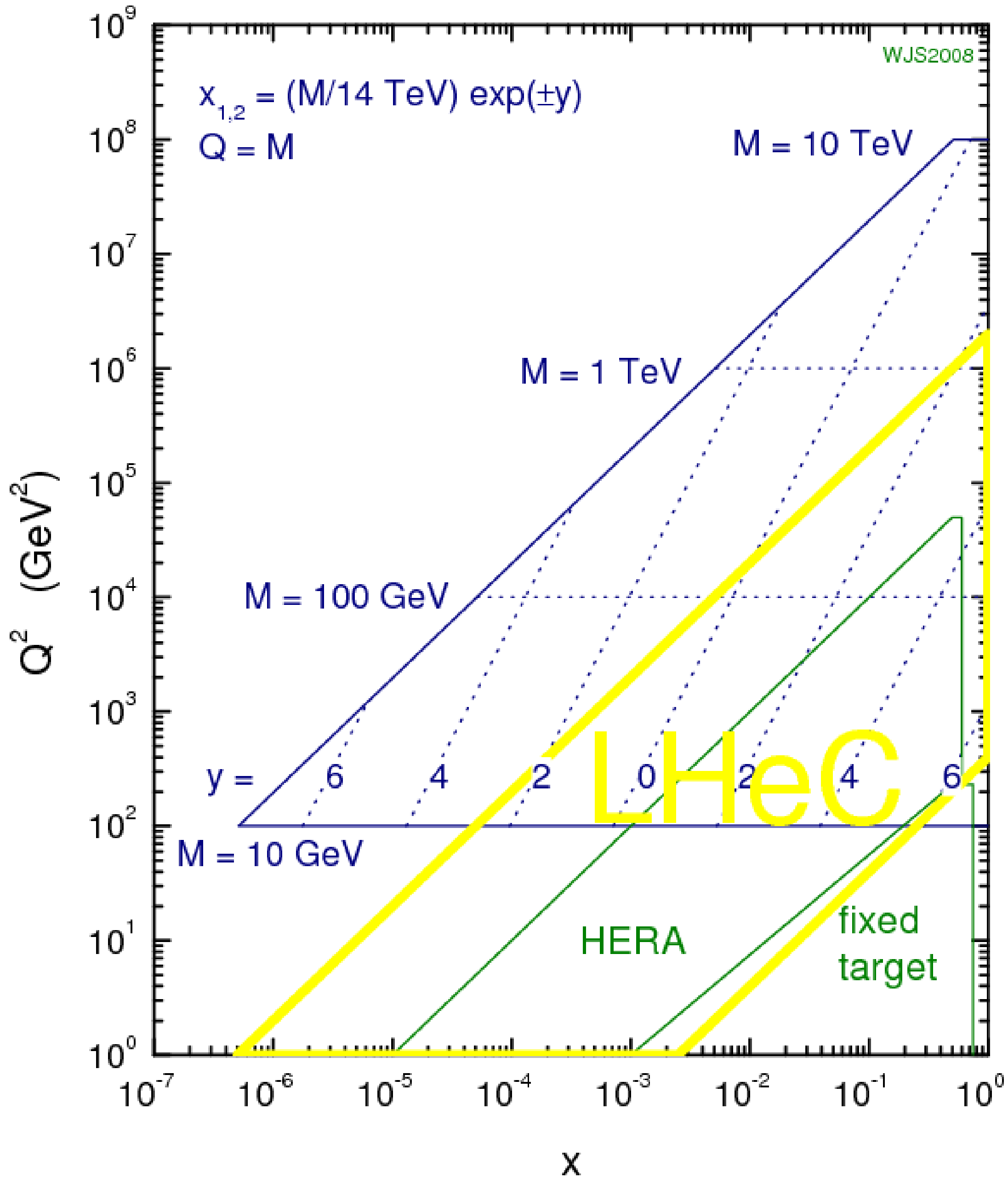


MSTW2008
WH NLO 14 TeV
WH NLO 10 TeV
Wjj LO 14 TeV
Wjj LO 10 TeV
$\sigma(W^+H) / \sigma(W^-H)$
M_H (or M_{jj}) (GeV/c^2)
3.0
2.5
2.0
1.5
1.0
0
100
200
300
400
500
600

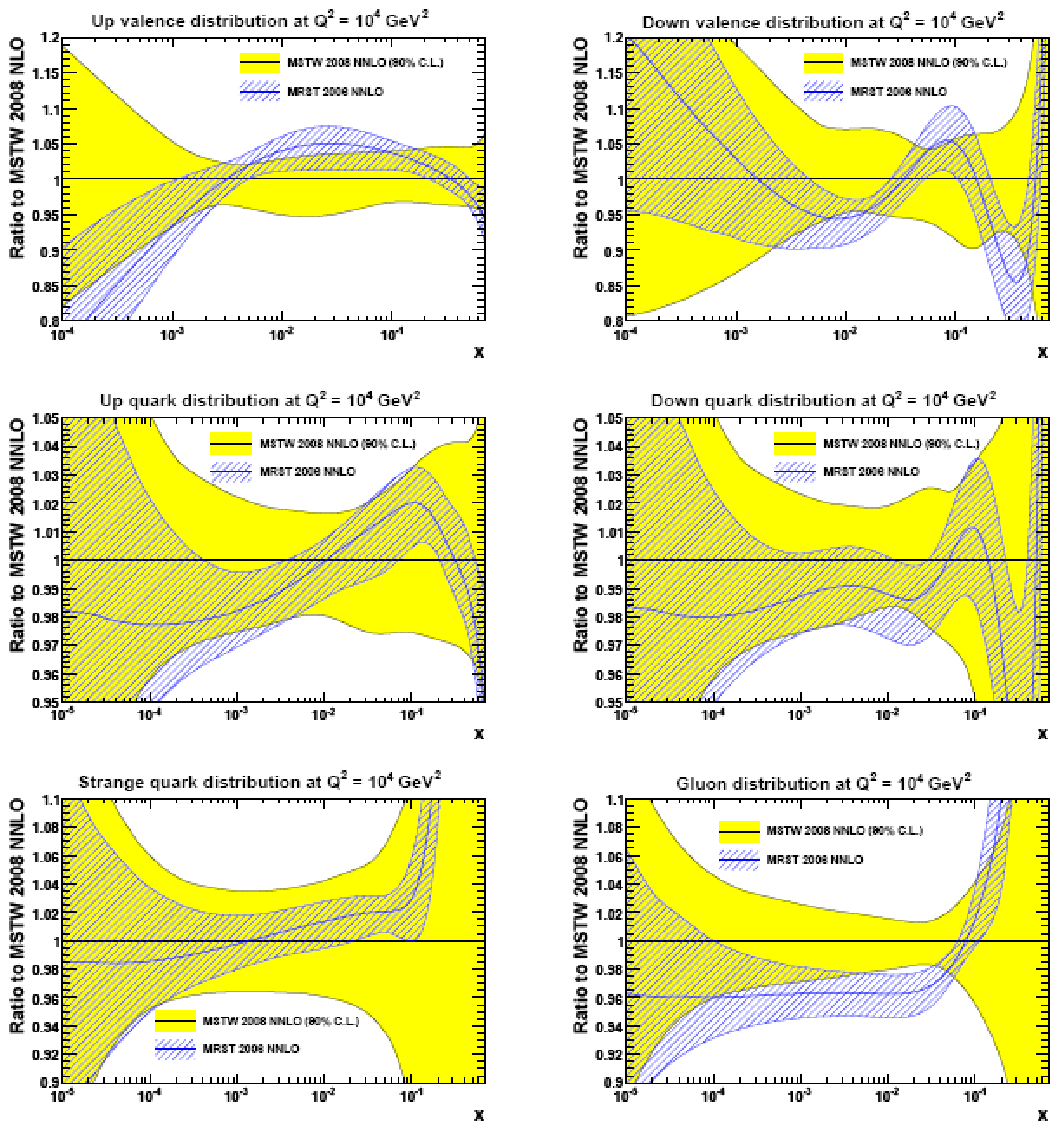


70 GeV × 7 TeV ep
LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
Q^2 / GeV^2
x

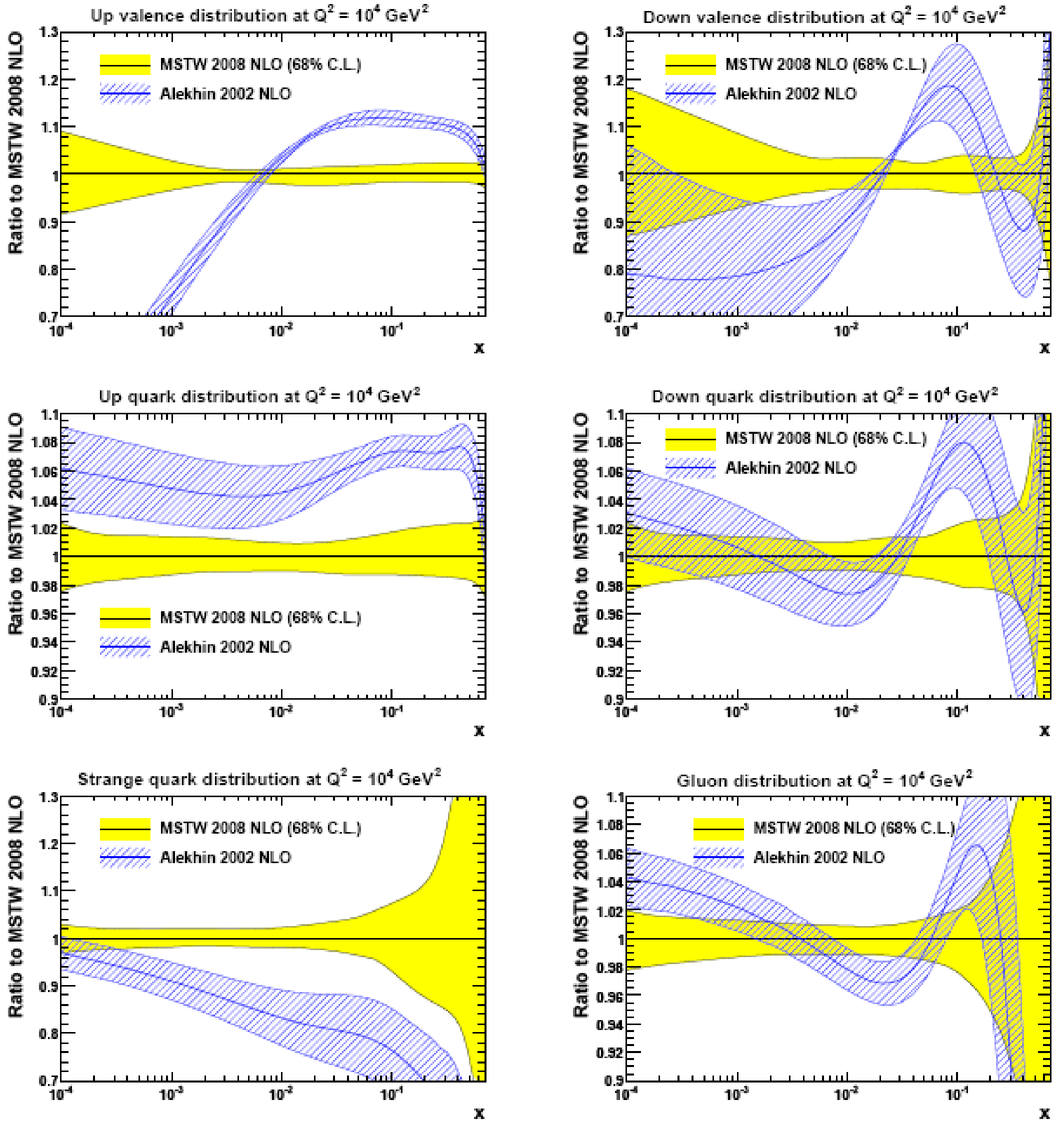
LHC parton kinematics



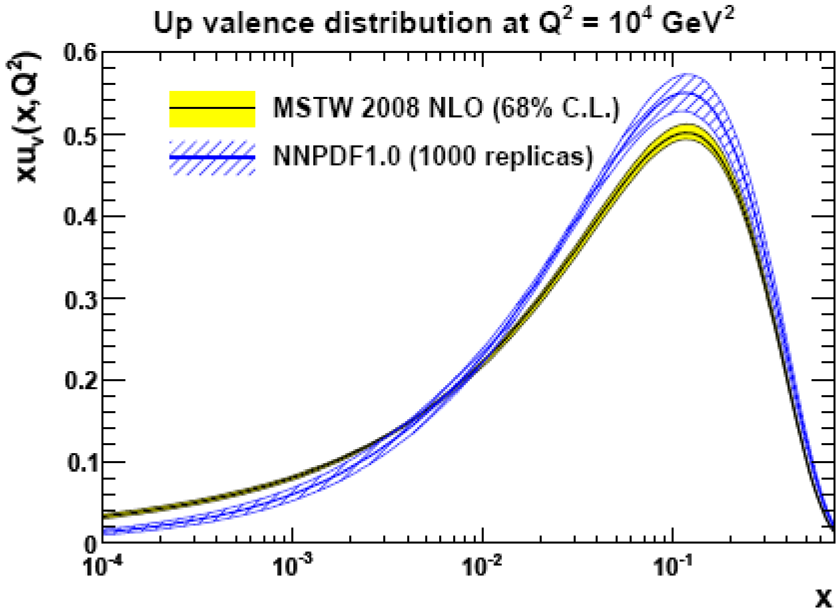
MSTW2008 *vs* MRST2006

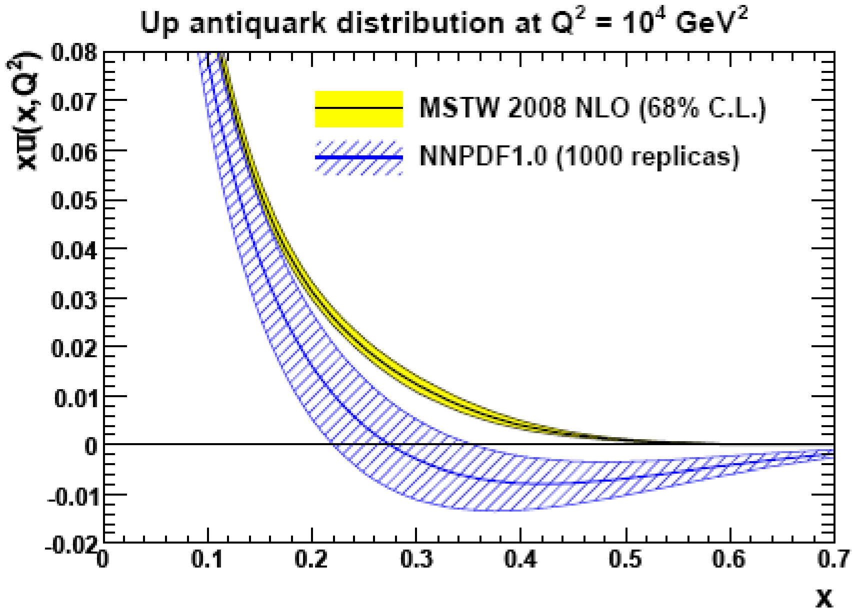


MSTW2008 *vs* Alekhin2002

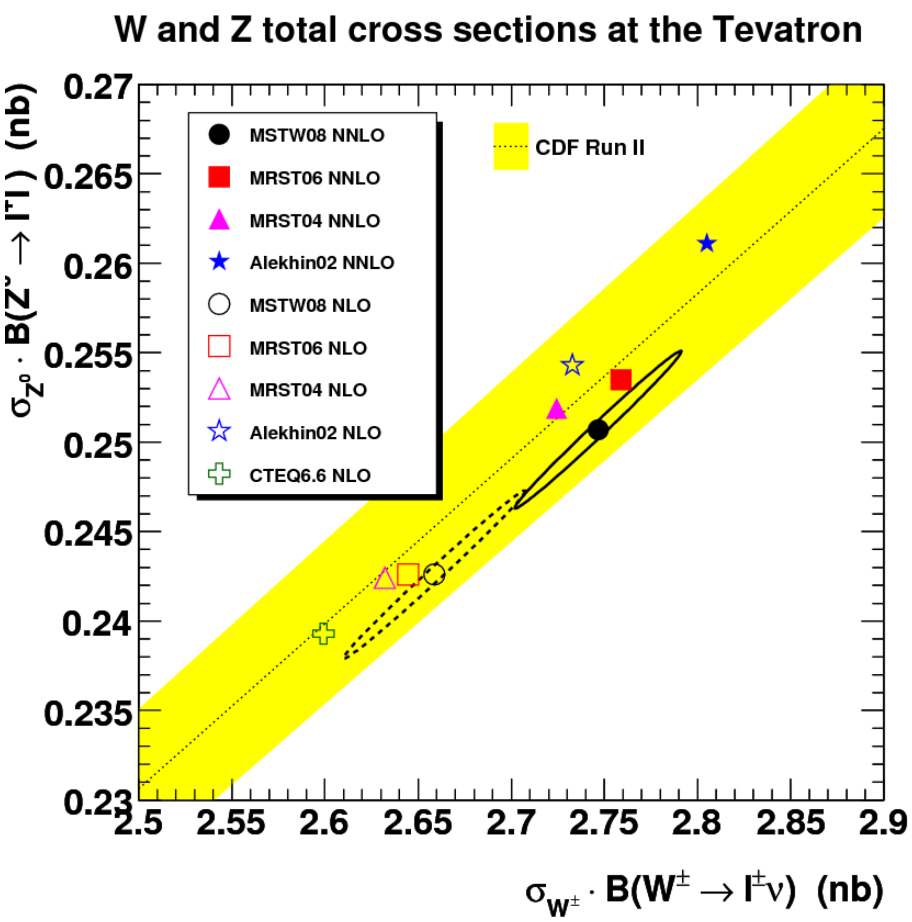


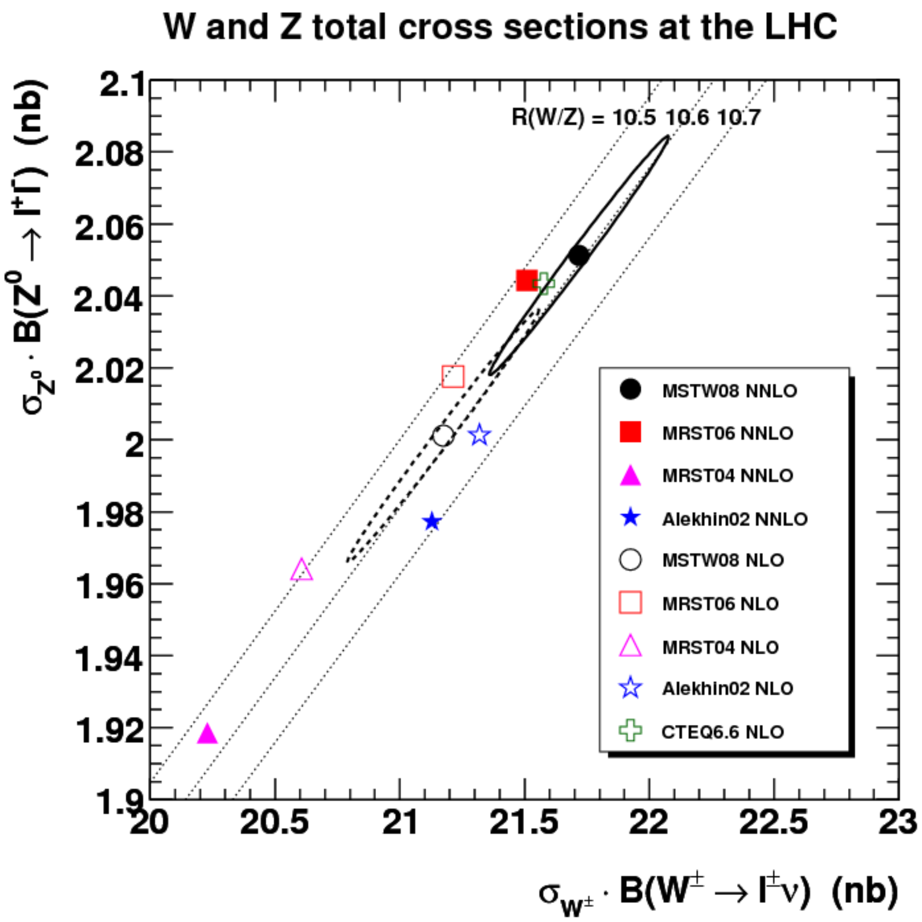
MSTW2008 *vs* NNPDF1.0





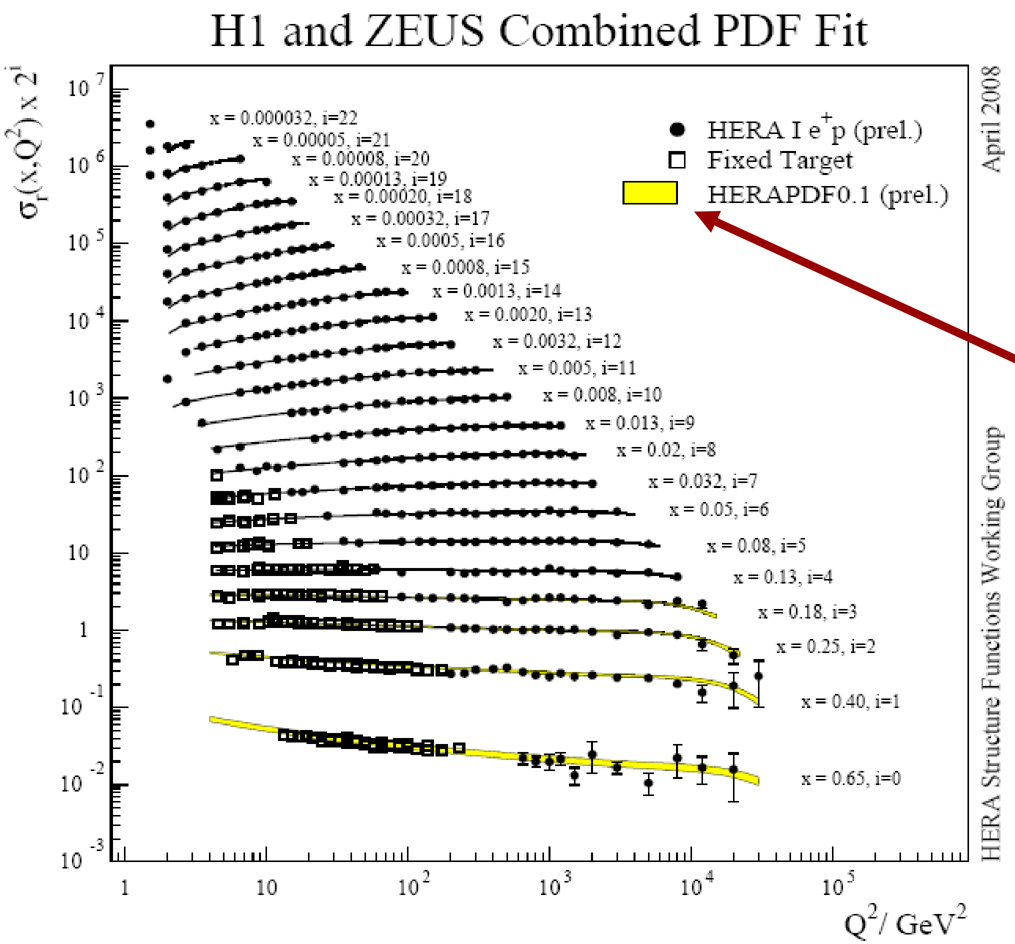
R(W/Z)=σ(W)/σ(Z) @ Tevatron & LHC





CDF 2007: R = 10.84 ± 0.15 (stat) ± 0.14 (sys)

scaling violations measured at HERA



NLO DGLAP fit

pdf uncertainties

$$\Delta\chi^2_{\text{global}} \equiv \chi^2_{\text{global}} - \chi^2_{\text{min}} = \sum_{i,j=1}^{n} H_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

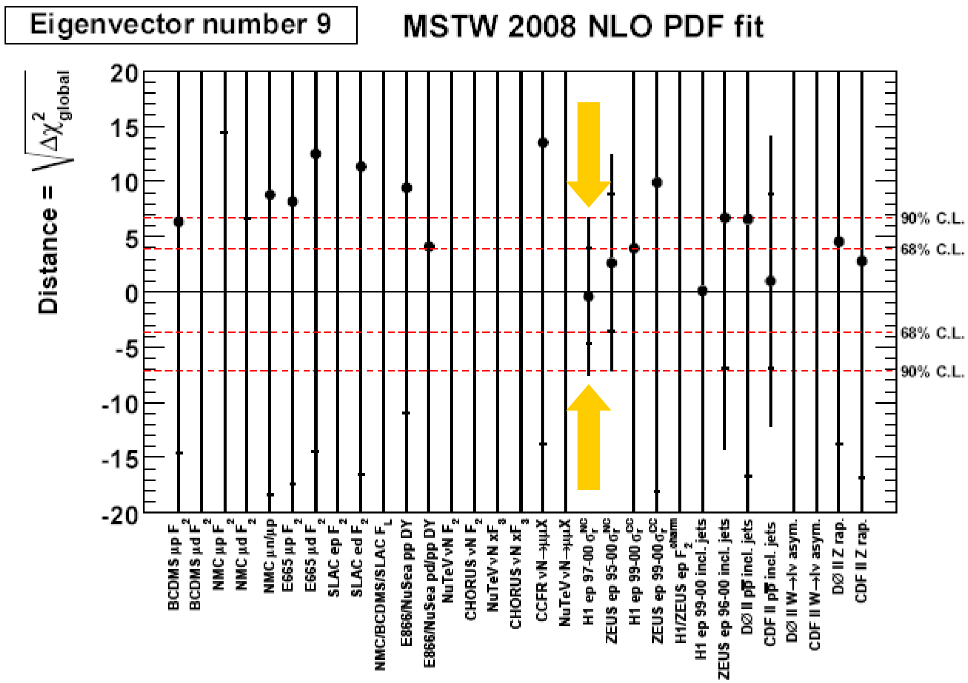
$$\vec{a} - \vec{a}^0 = \sum_{k=1,n} z_k \vec{e}_k \text{ where } (H^{-1})\cdot\vec{e}_k = \lambda_k \vec{e}_k,\ \vec{e}_k\cdot\vec{e}_l = \lambda_k \delta_{kl}$$

$$\text{then} \quad \Delta\chi^2_{\text{global}} = \sum_{k=1,n} z_k^2 \le T^2 \quad (T = \text{tolerance})$$

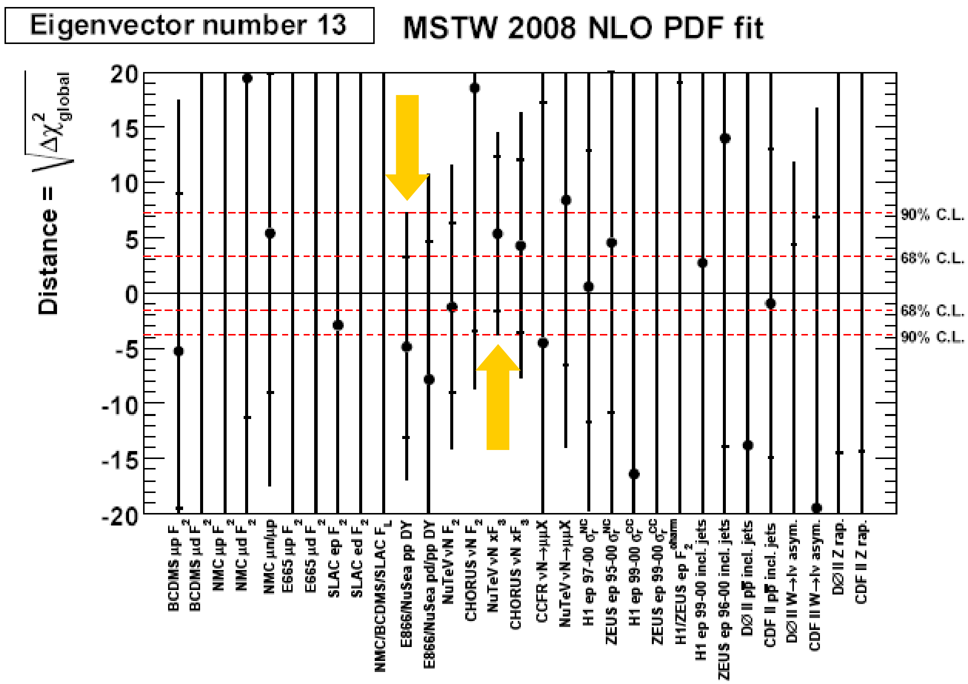
this defines a set of n 'error' pdfs, spanning the allowed variation in the parameters, as determined by T:

$$\vec{a}(S_k^{\pm}) = \vec{a}^0 \pm T\vec{e}_k$$

rather than using a fixed value of T (*cf.* MRST, CTEQ), we determine the 'dynamic' tolerance for each eigenvector from the condition that all data sets should be described within their 68% or 90% or … confidence limit

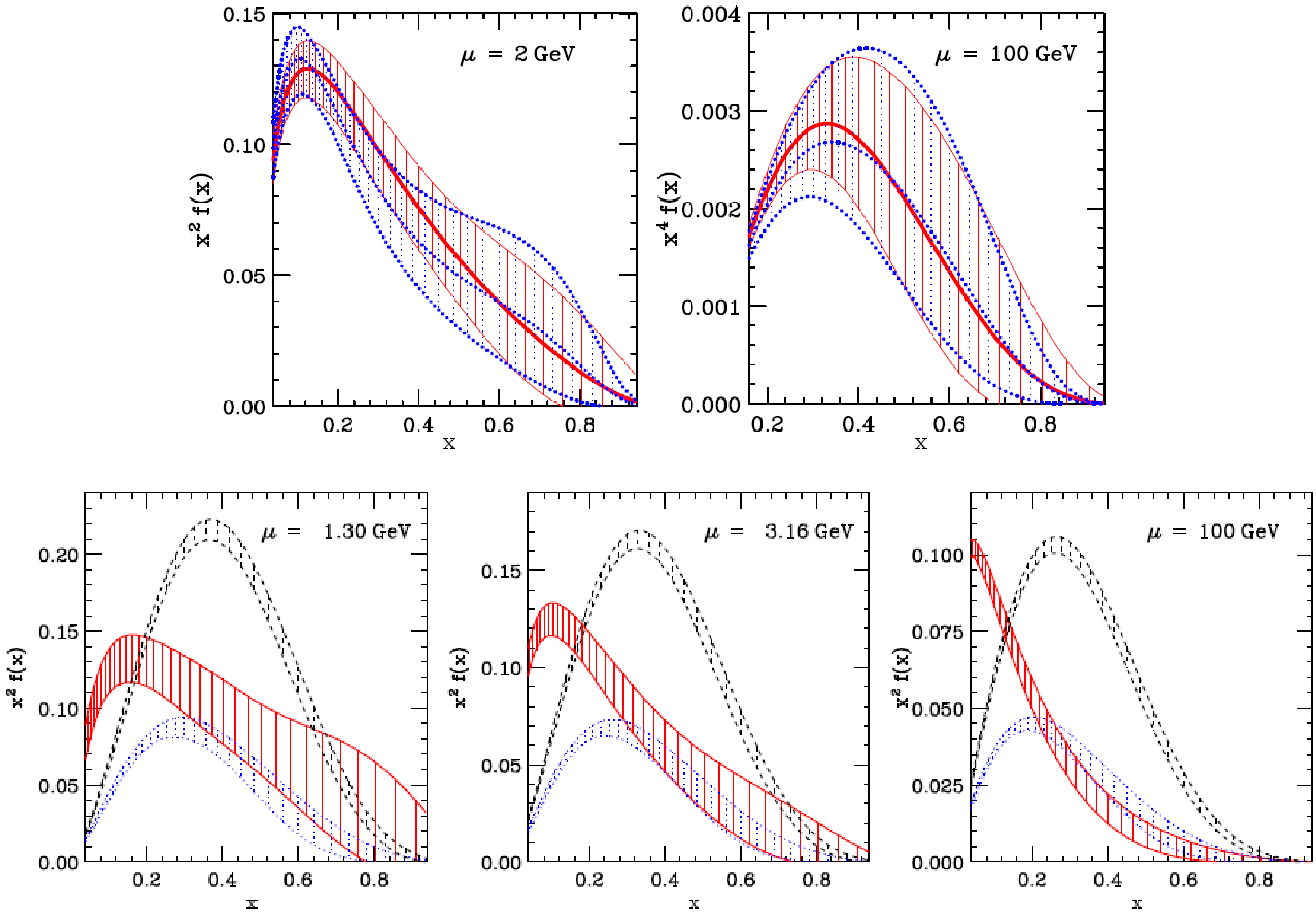


Eigenvector number 9
MSTW 2008 NLO PDF fit
Distance = $\sqrt{\Delta\chi^2_{global}}$
90% C.L.
68% C.L.
68% C.L.
90% C.L.
BCDMS μp F_2
BCDMS μd F_2
NMC μp F_2
NMC μd F_2
NMC μn/μp
E665 μp F_2
E665 μd F_2
SLAC ep F_2
SLAC ed F_2
NMC/BCDMS/SLAC F_L
E866/NuSea pp DY
E866/NuSea pd/pp DY
NuTeV νN F_2
CHORUS νN F_2
NuTeV νN xF_3
CHORUS νN xF_3
CCFR νN→μμX
NuTeV νN→μμX
H1 ep 97-00 σ_r^{NC}
ZEUS ep 95-00 σ_r^{NC}
H1 ep 99-00 σ_r^{CC}
ZEUS ep 99-00 σ_r^{CC}
H1/ZEUS ep F_2^{charm}
H1 ep 99-00 incl. jets
ZEUS ep 96-00 incl. jets
DØ II p$\bar{p}$ incl. jets
CDF II p$\bar{p}$ incl. jets
DØ II W→lν asym.
CDF II W→lν asym.
DØ II Z rap.
CDF II Z rap.

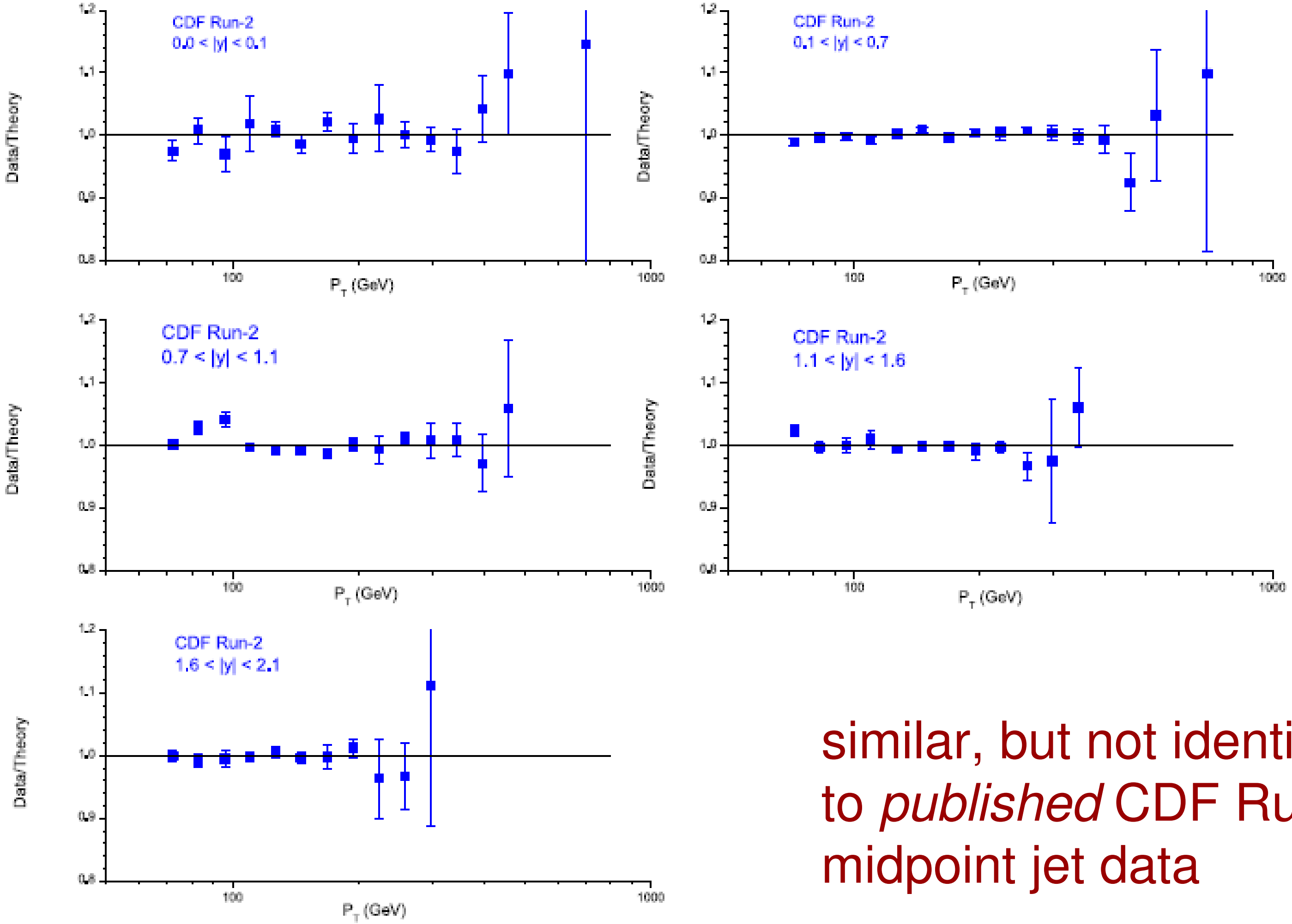


Eigenvector number 13
MSTW 2008 NLO PDF fit
Distance = $\sqrt{\Delta\chi^2_{global}}$
90% C.L.
68% C.L.
68% C.L.
90% C.L.
BCDMS μp F_2
BCDMS μd F_2
NMC μp F_2
NMC μd F_2
NMC μn/μp
E665 μp F_2
E665 μd F_2
SLAC ep F_2
SLAC ed F_2
NMC/BCDMS/SLAC F_L
E866/NuSea pp DY
E866/NuSea pd/pp DY
NuTeV νN F_2
CHORUS νN F_2
NuTeV νN xF_3
CHORUS νN xF_3
CCFR νN→μμX
NuTeV νN→μμX
H1 ep 97-00 σ_r^{NC}
ZEUS ep 95-00 σ_r^{NC}
H1 ep 99-00 σ_r^{CC}
ZEUS ep 99-00 σ_r^{CC}
H1/ZEUS ep F_2^{charm}
H1 ep 99-00 incl. jets
ZEUS ep 96-00 incl. jets
DØ II p$\bar{p}$ incl. jets
CDF II p$\bar{p}$ incl. jets
DØ II W→lν asym.
CDF II W→lν asym.
DØ II Z rap.
CDF II Z rap.

Pumplin et al., arXiv:0904.2424 [hep-ph]

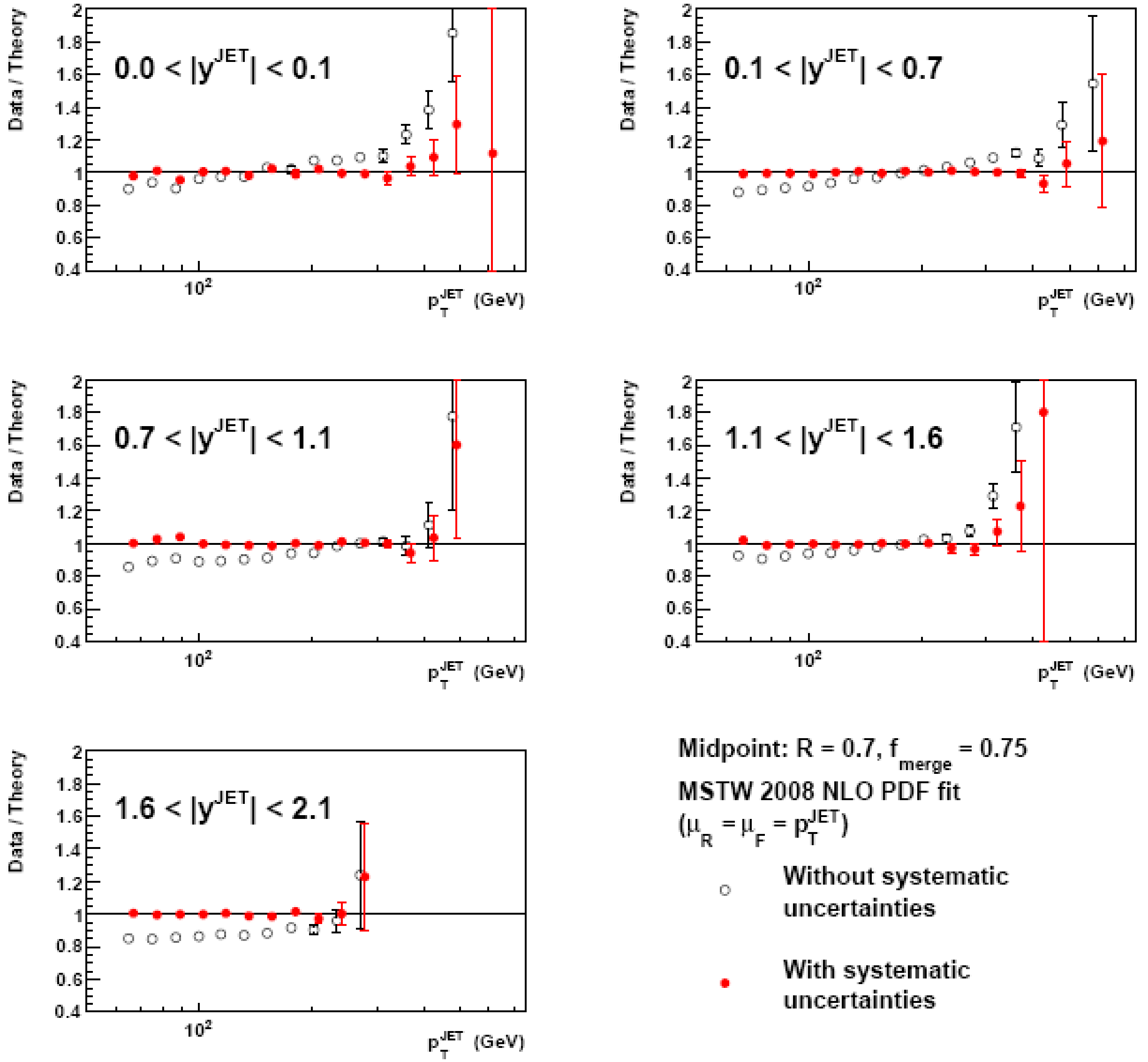


Pumplin et al., arXiv:0904.2424 [hep-ph]



similar, but not identical, to *published* CDF Run-2 midpoint jet data

CDF Run II inclusive jet data, χ^2 = 119 for 72 pts.



A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, arXiv:0901.0002 [hep-ph]

CDFI [179] (33 pts.)	DØI [176] (90 pts.)	CDFII [54] (76 pts.)	DØII [56] (110 pts.)	$\Delta\chi^2_{\text{non-jet}}$ (2513 pts.)	$\alpha_S(M_Z^2)$
53	119	64	117	0	0.1197
51	**48**	132	180	9	0.1214
56	110	**56**	**114**	2	0.1202
53	**85**	**68**	**117**	1	0.1204

Table 8: χ^2 values for Tevatron data on inclusive jet production from various global fits. The large bold values indicate the data sets explicitly included in each fit. The "MSTW 2008" fit includes only the Run II data. We also indicate the increase in the χ^2 for all data sets other than Tevatron inclusive jets when these data are added to the fit. Finally, the value of $\alpha_S(M_Z^2)$ is given for each fit. All fits are carried out at NLO with a scale choice of $\mu_R = \mu_F = p_T$.

A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, arXiv:0901.0002 [hep-ph] (revised)