University of Warsaw

FACULTY OF PHYSICS WARSAW UNIVERSITY

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Faculty of Physics
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Forward proton tagging at the LHC as a tool to study New Physics

Durham University

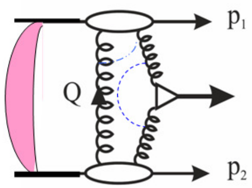
V.A. Khoze (IPPP, Durham)

"…The mechanic, who wishes to do his work well, must first sharpen his tools …"
—Chapter15, **'The Analects'** attributed to Confucius, translated by James Legge. (from X. Zu at DIS05)

(Based on works of K(KMR)S Durham group)

main aims:

- to overview the (very) forward physics programme at the LHC,
- to show that the Central Exclusive Diffractive Processes may provide an exceptionally clean environment to study QCD and to search for and to identify the nature of, New Physics at the LHC,
- to attract new members to the Exclusive Forward Club



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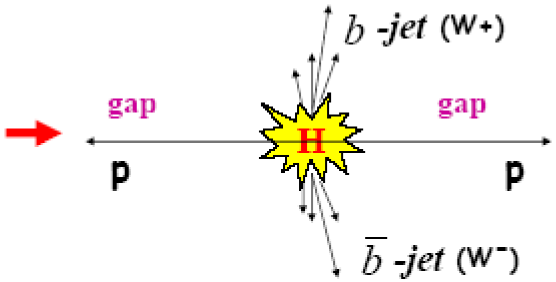


PLAN

1. **Introduction** (looking forward to forward physics at the LHC).

2. **LHC** (in the forward proton mode) as a **gluonic** Aladdin's lamp.

3. **Basic elements of KMR approach** (only a taste) .

4. ***The 'standard candle' processes.***

5. **Prospects for CED Higgs production.**

6. ***'Exotics'***

7. **Conclusion.**

8. **Ten commandments of Physics with Forward Protons at the LHC.**

9. **FP420 project**

CMS & ATLAS were designed and optimised to look *beyond the SM*

➔ *High -pt signatures in the central region*

The LHC is a discovery machine !

with a bit of personal flavour

But…

The LHC is a very challenging machine!

• Main physics **'goes Forward'**

•Difficult background conditions, pattern recognition, Pile Up...

• The precision measurements are limited by systematics (luminosity goal of $\delta L \leq 5\%$, machine ~10%)

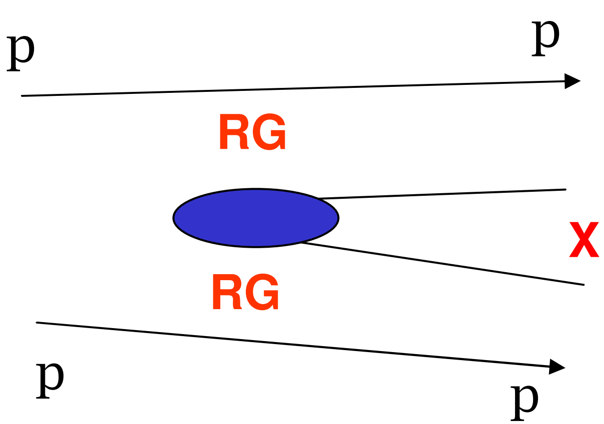
The LHC is not a precision machine (yet) !

Lack of :

•Threshold scanning , resolution of nearly degenerate states (e.g. MSSM Higgs sector)
•Quantum number analysing

•Handle on CP-violating effects in the Higgs sector
•Photon – photon reactions , …

ILC/CLIC chartered territory



Is there a way out?

YES → Forward Proton Tagging

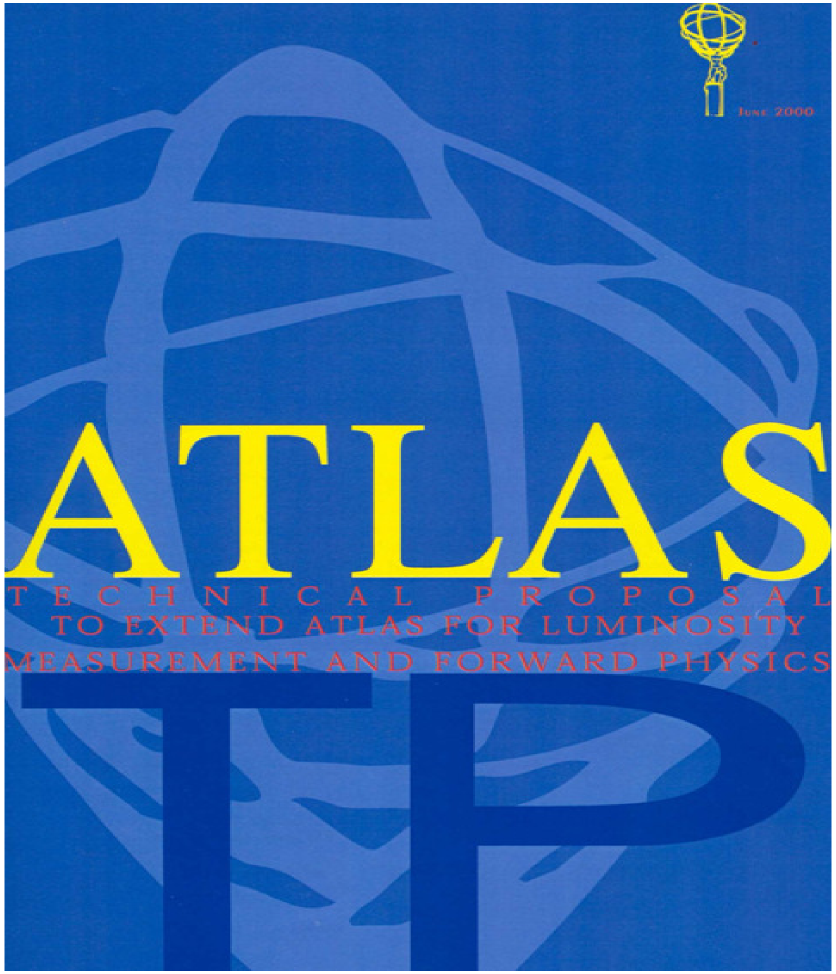
Rapidity Gaps ⇨ Hadron Free Zones

matching Δ Mx ~ δM (Missing Mass)

A BIT OF HISTORY

Full Acceptance Detector – J. Bjorken **(1991)**

FELIX LOI **(1997)**
TOTEM LOI **(1997)**
TOTEM TDR **(2004)**



June 2000

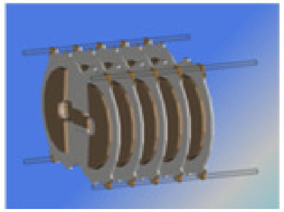
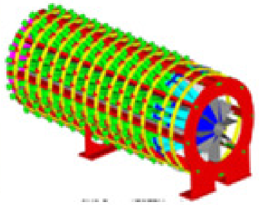
Proposal to Extend
ATLAS
for Luminosity Measurement
and Forward Physics

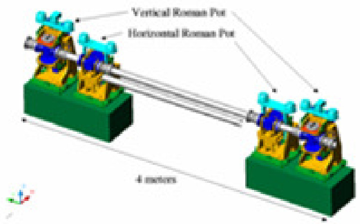
H. Ahola[1], M. Battaglia[2], O. Bouianov[3,4], M. Bouianov[2,3], G. Forconi[4], E. Heijne[5], J. Heino[4], V. Khoze[6], A. Kiiskinen[4,7], K. Kurvinen[4], L. Lahtinen[4], J.W. Lamsa[8], E. Lippmaa[9], T. Meinander[1], V. Nomokonov[4], A. Numminen[4], R. Orava[2,4], K. Piotrzkowski[10], M. White[4], M. Ryynänen[1], L. Salmi[4,7], J. Subbi[9], K. Tammi,[4], S. Tapprogge[4], T. Taylor[5]

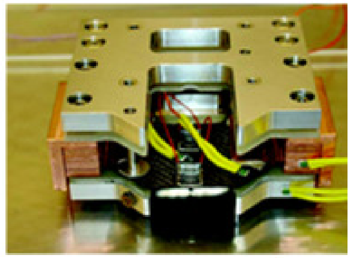
1 Technical Research Center of Finland, VTT Automation, Espoo, Finland
2 Physics Department, University of Helsinki, Finland
3 Espoo-Vantaa Institute of Technology, Finland
4 Helsinki Institute of Physics, Helsinki, Finland
5 CERN, Geneva, Switzerland
6 University of Durham, U.K.
7 Academy of Finland, Helsinki, Finland
8 Iowa State University, Ames, U.S.A.
9 KBFI, Tallinn, Estonia
10 Department of High Energy Physics, H.Niewodniczanski Institute of Nuclear Physics, Krakow, Poland

Forward detectors at LHC

TOTEM -T2 | **CASTOR** | **ZDC/FwdCal** | **TOTEM-RP** | **FP420**

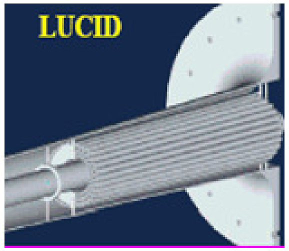


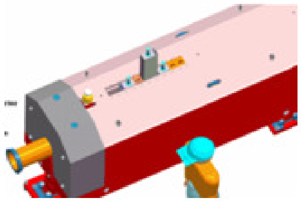
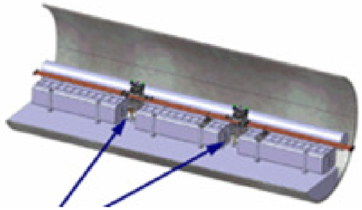
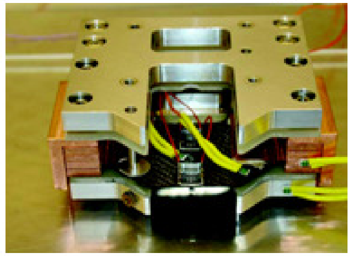


IP5

14 m | **16 m** | **140 m** | **147m - 220 m** | **420 m**

IP1



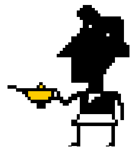




LUCID | **ZDC** | **ALFA/RP220** | **FP420**

Forward Proton Taggers as a gluonic Aladdin's Lamp

(Old and New Physics menu)

- **Higgs Hunting** (the LHC *'core business'*)



- Photon-Photon, Photon - Hadron Physics.
- **'Threshold Scan':** 'Light' SUSY ...
- Various aspects of Diffractive Physics (*soft & hard*).

- High intensity **Gluon Factory** (underrated gluons)
  QCD test reactions, dijet P-luminosity monitor

- Luminometry
- Searches for new heavy gluophilic states
  and many other goodies…

FPT

✳ Would provide a unique additional tool to complement the conventional strategies at the LHC and ILC.

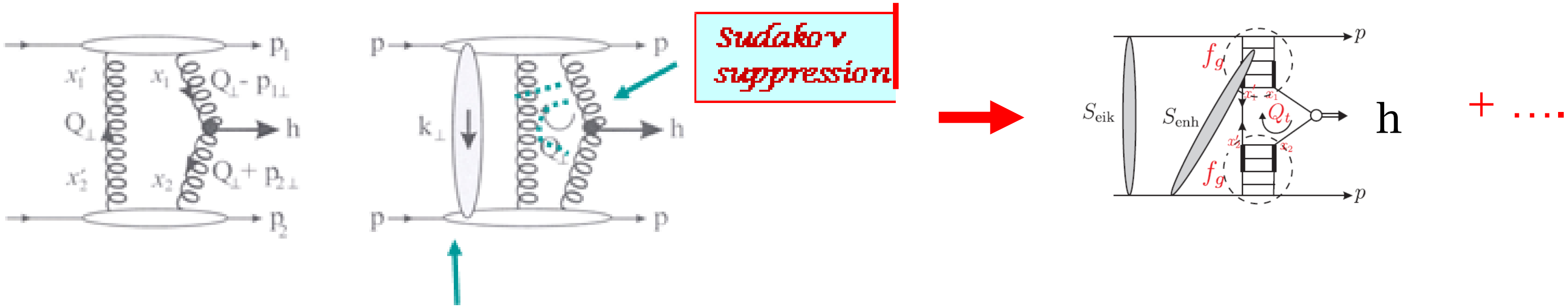
FPT ▶ will open up an additional rich physics menu ILC@LHC

✳ Higgs is only a part of the broad EW, BSM and diffractive program@LHC
wealth of QCD studies, glue-glue collider, photon-hadron, photon-photon interactions…

The basic ingredients of the KMR approach
(Khoze-Martin-Ryskin 1997-2009)

Interplay between the soft and hard dynamics

RG signature for Higgs hunting (Dokshitzer, Khoze, Troyan, 1987). Developed and promoted by Bjorken (1992-93)



Bialas-Landshoff- 91
(Born-level)

rescattering/absorptive effects

Further development (KKMR-01, BBKM-06, GLMM, KMR)

Main requirements:
- inelastically scattered protons remain intact
- active gluons do not radiate in the course of evolution up to the scale M
- $\langle Q_t \rangle \gg \Lambda_{QCD}$ in order to go by pQCD book

$\sigma(CDPE) \sim 10^{-4} * \sigma$ (incl)

High price to pay for such a clean environment:

σ (CEDP) ~ 10^{-4} σ(inclus.)

Rapidity Gaps should survive **hostile** hadronic *radiation damages* and *'partonic pile-up'*

symbolically $W = S^2\, T^2$

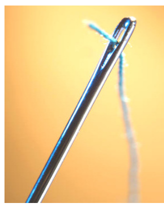
Colour charges of the 'digluon dipole' are screened only at $r_d \geq 1/(Q_t)_{ch}$

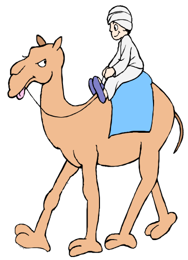
GAP Keepers (Survival Factors) , protecting RG against:

- the debris of QCD radiation with $1/Q_t \geq \lambda \geq 1/M$ **(T)**
- soft rescattering effects (necessitated by unitariy) **(S)**

How would you explain this to your (grand) children ?

Forcing two camels to go through the eye of a needle

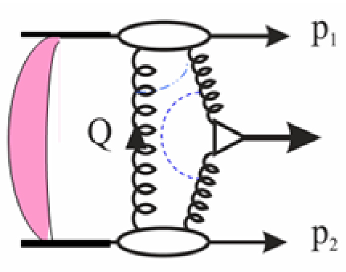




P → **H** ← **P**

KMR technology (implemented in ExHume MC)

(Khoze-Martin-Ryskin 1997-2009)



$$\sigma_{pp}(M^2,\ldots) = L_{eff}(M^2,y) * \sigma_{hard}(M^2,\ldots)$$

$$\frac{\partial^2 L_{eff}}{\partial y \partial M^2} M^2 = S^2 * L(M^2)$$

σ(CDPE) ~ 10^{-4} σ (incl)

focus on $\sigma^{bgd}_{hard}(M^2,\ldots)$

$L_{eff}(M^2,y)$ → the same for Signal and Bgds

$$L_{eff} \sim \frac{\hat{S}^2}{b^2} \left| N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right|^2$$

contain Sudakov factor T_g which exponentially suppresses infrared Q_t region → pQCD

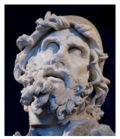
$$< Q_t >_{SP} \simeq M / 2 * \exp(-1/\bar{\alpha}_s) \approx 2 GeV \gg \Lambda_{QCD},$$

$$\bar{\alpha}_S = (N_c/\pi) * \alpha_s(M) * C_\gamma$$

T_g + anom .dim. → *IR filter*

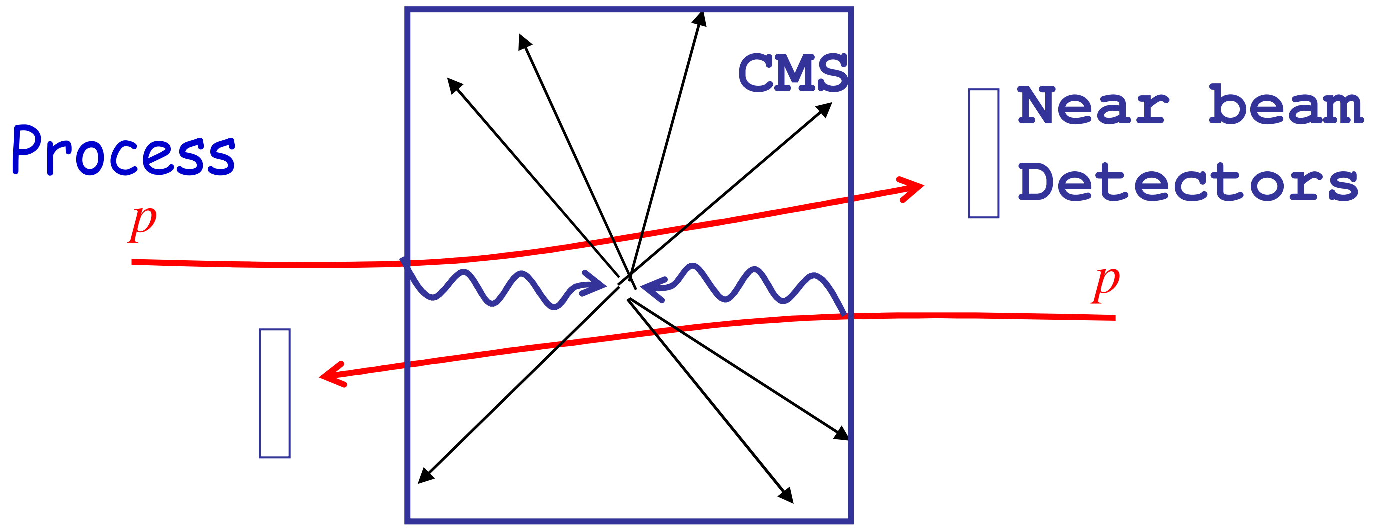
S^2 is the prob. that the rapidity gaps survive population by secondary hadrons → soft physics

New CDF results (dijets, $\gamma\gamma$, χ_c)



not so long ago: between Scylla and Charibdis:
orders of magnitude differences in the theoretical predictions are now a history

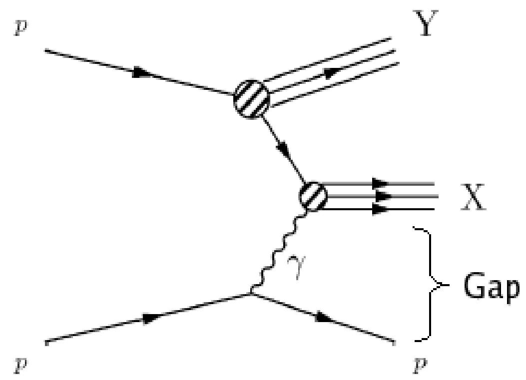
LHC as a High Energy γγ Collider



Extensive Program

- γ γ→ μμ, ee QED processes
- γ γ→ QCD (jets..)
- γ γ→ WW anomalous couplings
- γ γ→ squark, top… pairs
- γ γ→ BSM Higgs
- γ γ→ Charginos
- …

…and γp



photon-proton collider @ LHC

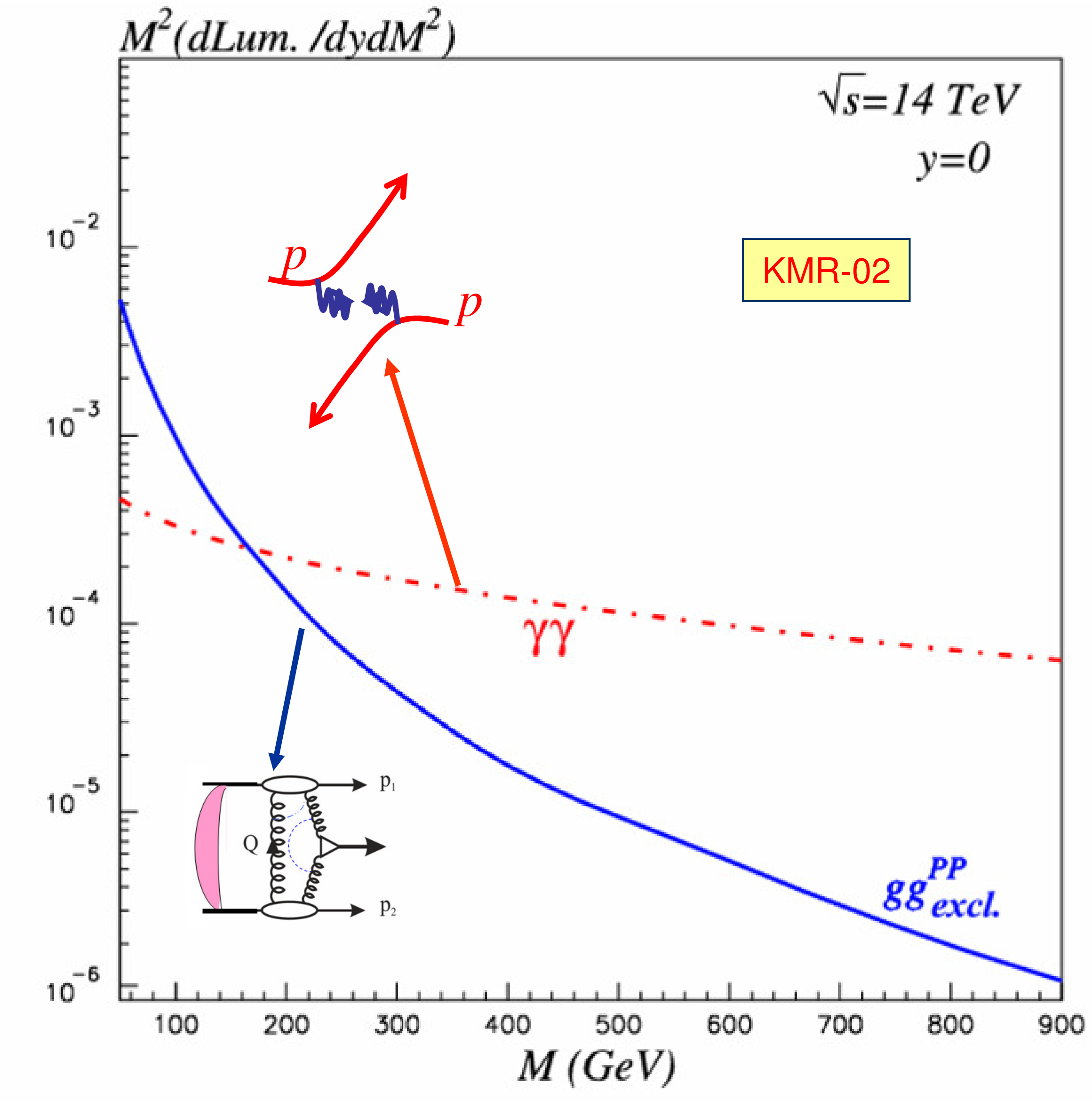
LHC as a High Energy $\gamma\gamma$ Collider

$$\sigma(\gamma\gamma \to SMH) \approx 0.1 fb$$

$$\sigma(PP -> SMH) \approx 3 fb$$

$$\alpha_S{}^2/8 \to \alpha^2$$

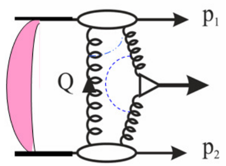
QCD 'radiation damage' in action

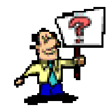


How reliable are the calculations ?

Are they well tested experimentally ?

- How well we understand/model soft physics ?
- How well we understand hard diffraction ?
- Is 'hard-soft factorization' justified ?

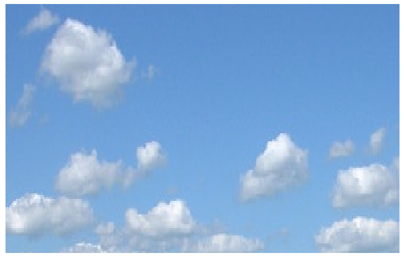




✵ What else could/should be done in order to improve the accuracy of the calculations ?

So far the Tevatron diffractive data have been Durham-friendly)

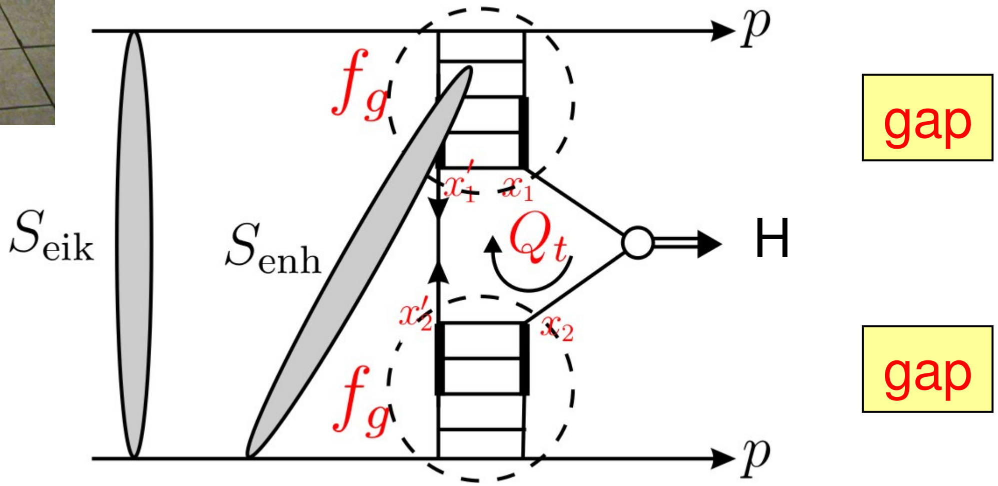
clouds on the horizon ?



or

?

"soft" scattering can easily destroy the gaps



soft-hard factoriz^n

eikonal rescatt: between protons ← conserved

enhanced rescatt: involving intermediate partons ← broken

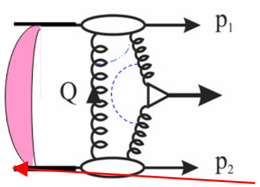
Subject of hot discussions : S^2

Far more theoretical papers than the expected number of the CED produced Higgs events

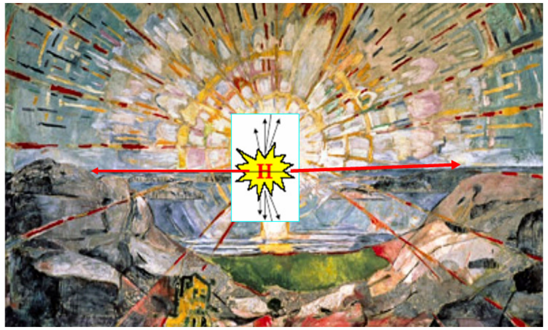
'Well, it is a possible supposition.'
'You think so, too ?'
'I did not say a probable one'

Survival of the Survival Factor

- Importance for the Forward Physics Studies at the LHC
- Serve as a **litmus paper** indicator of the level of our knowledge (theory & experiment) on diffractive physics at high energies



Account for the absorption effects -necessitated by unitarity



S^2 -a crucial ingredient of the calculations of the rate of the Central Excl. Diffractive processes +…..

Prospects of New Physics studies in the Forward Proton mode.

Qualitatively new stage

- orders of magnitude differences in theoretical expectations – are a history
- new (encouraging) CED Tevatron results available, more results to come
- we are discussing now the differences on the level of a factor of (3-5)

Comparing apples with apples.


Apples are not all alike; above some different types of apples.

S^2 are not all alike.

Dependence on the nature of the basic process, kinematical configuration, cuts….. pt- dependence in the realistic matrix elements

(compare for instance, S^2 (H) to S^2 (A))

$< S^2 >$ - effect. quantity, character. prob. that rapidity gaps survive population by secondary hadrons → soft diffraction physics (model dependence)

for reference. purp. KMR

$$< S^2 >_{th} = 0.02(KMR)$$

σ(pp → p + H + p) ~ 3 fb at LHC for SM 120 GeV Higgs
(factor ~ 3 uncertainty after 'sanity checks')

Impl. in **ExHume MC** with default $< S^2 >$(Exh)≈0.03 , **KMR**- b-space integration with **exact** ME

Symbolically

$$< S^2 > = < S^2 >_{GW} * < S^2 >_{enh}$$

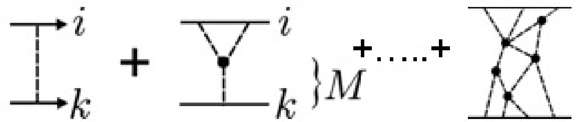
$< S^2 >_{enh}$ -multi-Pomeron interact. for High Mass diffr.

$< S^2 >^{eik}$ el everybody's ~ happy
(KMR, GLM, FHSW, Petrov, MC(LL), BH, GGPS, Luna….)

$< S^2 >^{eik}_{2,3ch}$ (KMR- 2-3 ch, GLM- 2ch)

(conceptually ~similar)

known for quite a while,… KPT-86….KKMR-01
interest boosted by BBKM-06

Ω_{ik} =


(GW= elast. + low mass diffr. dissoc.)

Selection Criteria for the Models of Soft Diffraction

- We have to be **open-eyed** when the soft physics is involved.
  Theoretical models contain various assumptions and parameters.

- Available data on soft diffraction at high energies are still fragmentary,
  especially concerning the (low mass) diffractive dissociation.

A viable model should:

- incorporate the inelastic diffraction :SD, DD
  (for instance 2-3 channel eikonal of KMR or GLM(M))

- describe all the existing experimental data on elastic scattering and SD ,DD and **CED**
  at the Tevatron energies and below (KMR; GLM(M))

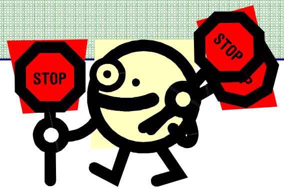
- be able to explain the existing CDF data on the HERA-Tevatron factorization breaking
  and on the CED production of the di-jets, di-photons, χ, J/ψ, Υ.., lead. neutr. at HERA

- provide testable **pre-dictions** or at least **post-dictions** for the Tevatron and HERA

So far **KMR** model has passed these tests.

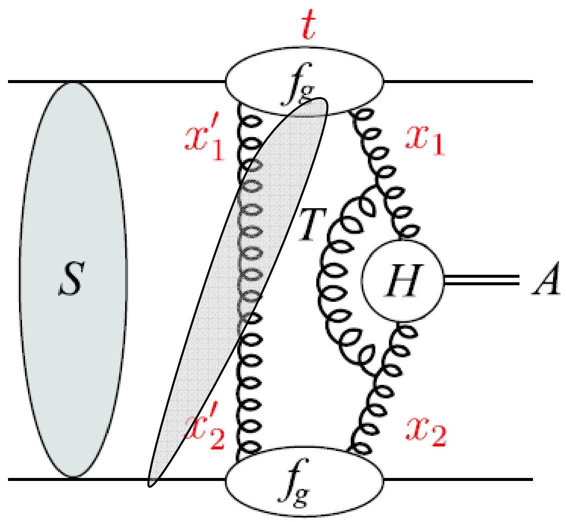
Only a large enough data set would impose the restriction order on the theoretical models and to create a confidence in the determination of S^2.

Program of Early LHC measurements (KMR)



LET THE DATA TALK !

Are the early LHC runs,
without proton taggers,
able to check estimates
for pp → p+A+p ?



gap

gap

KMR: 0802.0177

Possible checks of:

Divide et Impera

(i) survival factor S^2:	W+gaps, Z+gaps
(ii) generalised gluon f_g :	$\gamma p \to \Upsilon p$
(iii) Sudakov factor T :	3 central jets

(iv) **soft-hard factorisation**
(enhanced absorptive corr^n)

$$\frac{\#(\text{A+gap})\ \text{evts}}{\#(\text{inclusive A})\ \text{evts}}$$

with A = W, dijet, ϒ…

CURRENT EXPERIMENTAL CHECKS

☺ Up to now the diffractive production data are consistent with K(KMR)S results
Still more work to be done to constrain the uncertainties.

- Exclusive high-Et dijets
  CDF: data up to (Et)min>35 GeV (PRD-2008)

• 'Factorization breaking' between the effective diffractive structure functions measured at the Tevatron and HERA.

•The ratio of high Et dijets in production with one and two rapidity gaps

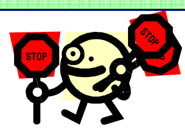
•CDF results on exclusive charmonium CEDP, (CDF, submitted to PRL)

•Energy dependence of the RG survival (D0, CDF).

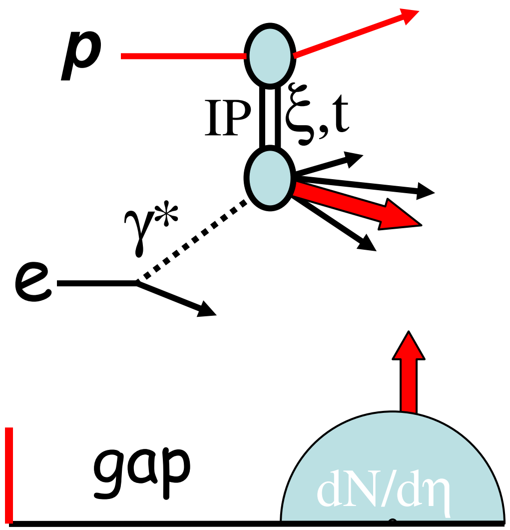
- Central Diffractive Production of $\gamma\gamma$ (….$\pi\pi$,$\eta\eta$) (**CDF**, PRL-07)
  (in line with the KMRS calculations) (3 candidates & 2 more candidates in the new data)
- Leading neutrons at HERA

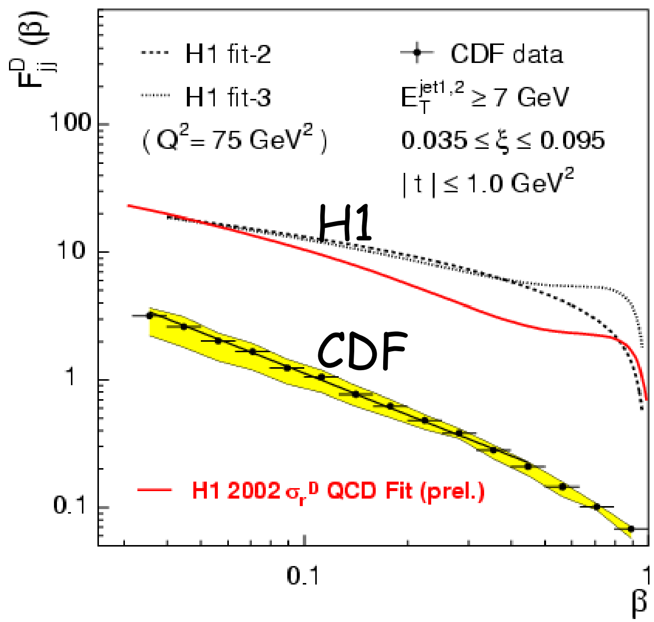
LET THE DATA TALK !

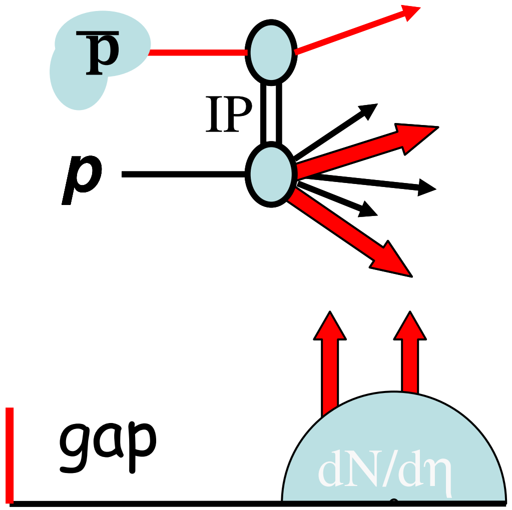
Only a large data set would allow to impose a restriction order on the theoretical models

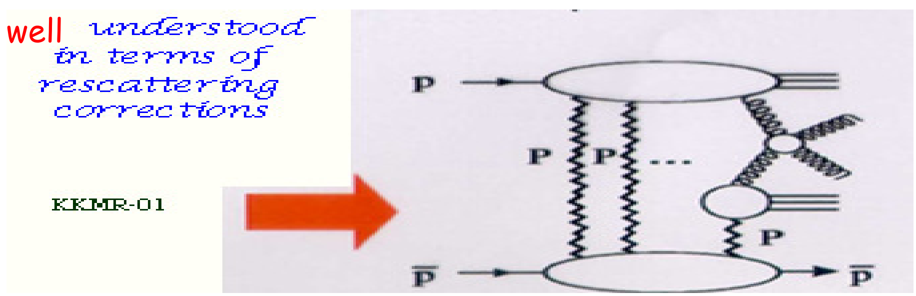


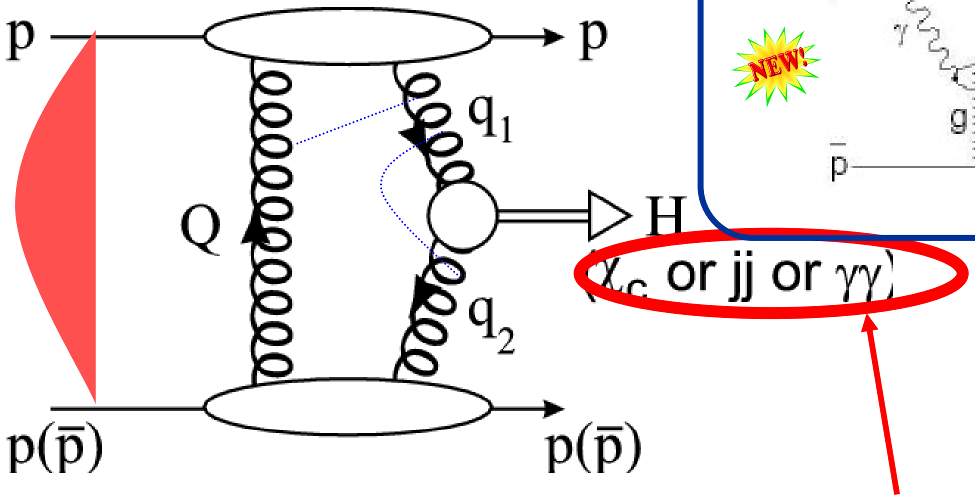
Tevatron vs HERA: Factorization Breakdown

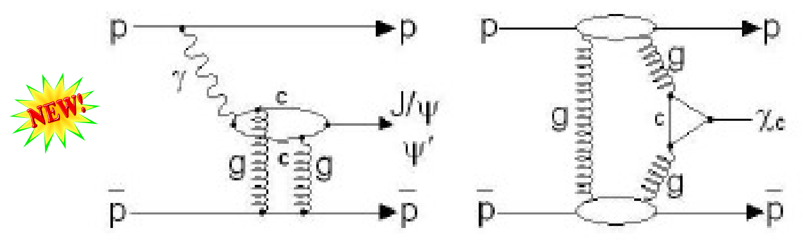












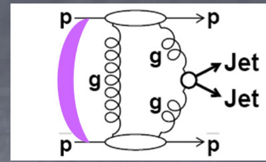
"standard candles"

"Standard Candles"
at Tevatron to test exclusive prod. mechanism

pre-dictions, KMRS

- $pp \to p + \chi + p$ high rate, but low scale (uncertainties in the estimates)
- $pp \to p + jj + p$ rate rather high, but exclusive events should be separated
- $pp \to p + \gamma\gamma + p$ low rate, but cleaner signal

Experimental results are encouraging!



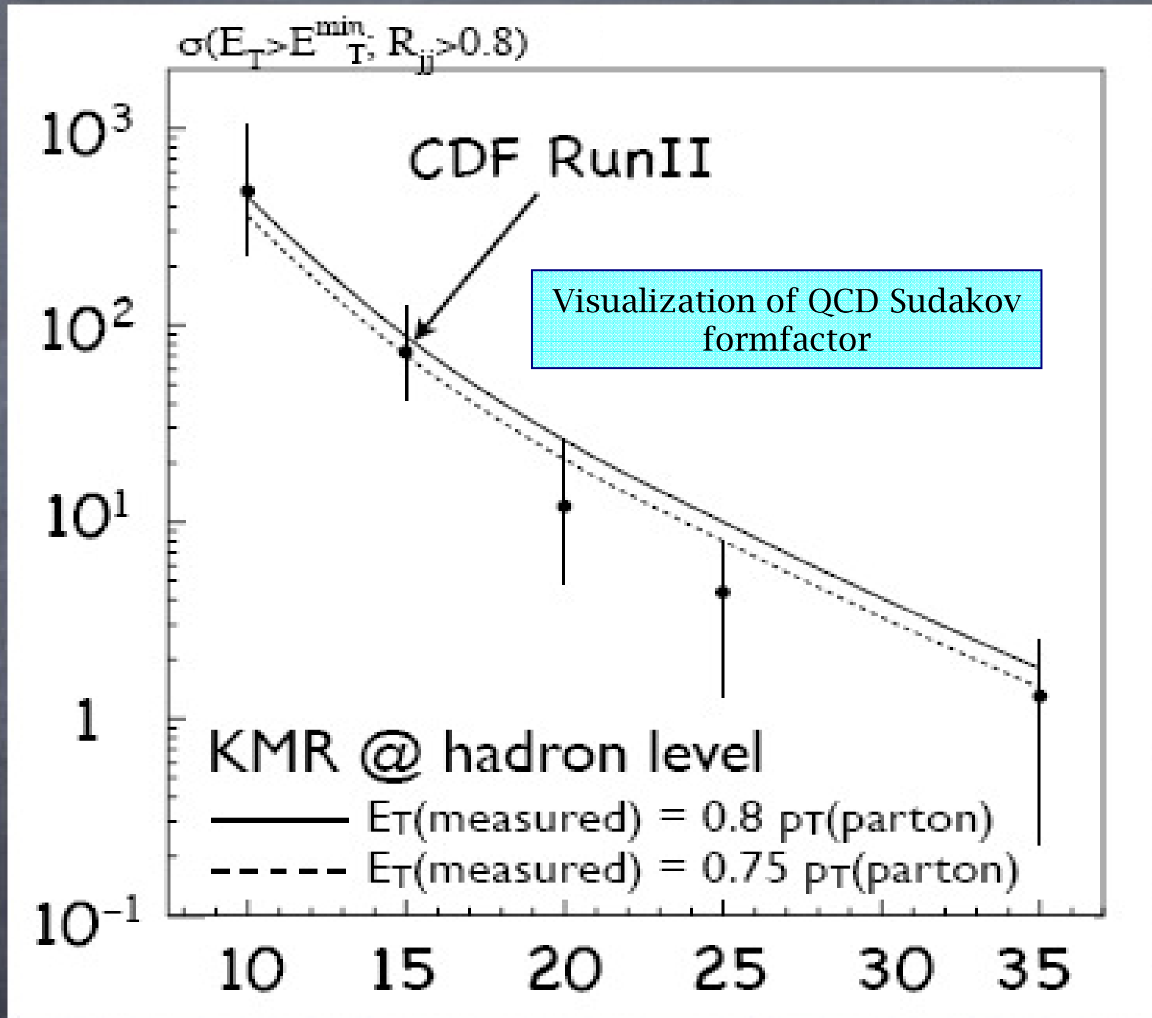
Comparison with KMR

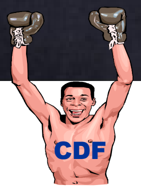
More direct comparison with KMR calculations including hadronization effects preferred

CDF out-of-cone energy measurement (cone R=0.7) :
- 20–25% at E_T^{jet}=10–20 GeV
- 10–15% at E_T^{jet}=25–35 GeV

Koji Terashi

Good agreement with data found by rescaling parton p_T to hadron jet E_T



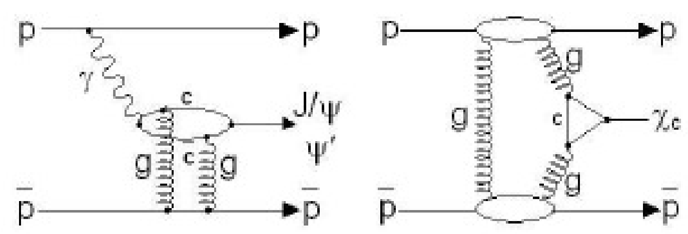


A killing blow to the wide range of theoretical models.

CDF
PRD-2008

Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

CDF Collaboration, arXiv:0902.1271 [hep-ex] (PRL-09)



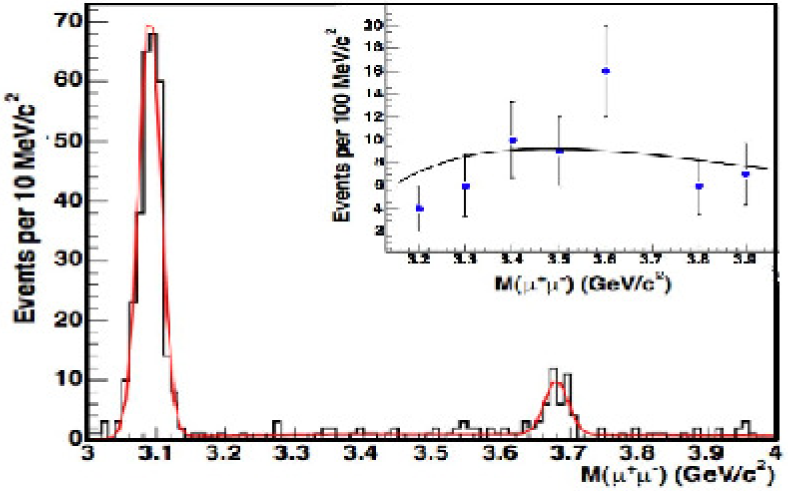


FIG. 2: Mass $M_{\mu\mu}$ distribution of 402 exclusive events, with no EM shower, (histogram) together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the J/ψ and excluding $3.65 < M_{\mu\mu} < 3.75$ GeV/c^2 ($\psi(2S)$) with the fit to the QED spectrum times acceptance (statistical uncertainties only).

TABLE I: Numbers of events fitted to classes $J/\psi, \psi(2S)$, QED and χ_{c0}. Backgrounds are given as percentages of the fit events, and efficiencies are to be applied to the events without background. The stated branching fraction $\mathcal{B}$ for the χ_{c0} is the product of the $\chi_{c0} \to J/\psi + \gamma$ and $J/\psi \to \mu^+\mu^-$ branching fractions [11]. The cross sections include a 6% luminosity uncertainty.

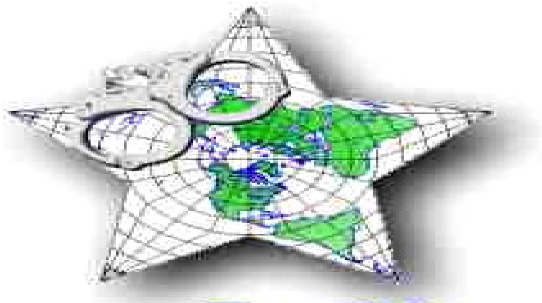
Class	J/ψ	$\psi(2S)$	$\gamma\gamma \to \mu^+\mu^-$	$\chi_{c0}(1P)$
Acceptances:				
Detector(%)	18.8±2.0	54±3	41.8±1.5	19±2
Efficiencies:				
μ-quality(%)	33.4±1.7	45±6	41.8±2.3	33±2
Photon(%)	-	-	-	83±4
Events(fit)	286±17	39±7	77±10	65±8
Backgrounds:				
Dissoc.(%)	9±2	9±2	8±2	11±2
Non-excl.(%)	3±3	3±3	9±5	3±3
χ_{c0}(%)	4.0±1.6	-	-	-
Events(corr.)	243±21	34±7	65±10	56±8
$\mathcal{B}.\sigma_{FKR}$(pb)	28.4±4.5	1.02±0.26	2.7±0.5	8.0±1.3
$\mathcal{B} \to \mu^+\mu^-$(%)	5.93±0.06	0.75±0.08	-	0.076 ±0.007
$\frac{d\sigma}{dy}\|_{y=0}$(nb)	3.92±0.62	0.53±0.14	-	76±14

KMRS -2004: **130 nb** → 90 nb (PDG-2008)

PST-09, 1++ ?

(role of higher spin states, NLO-effects, DD…. need further detailed studies)

ππ/KK mode as a spin-parity analyzer



Fugitive

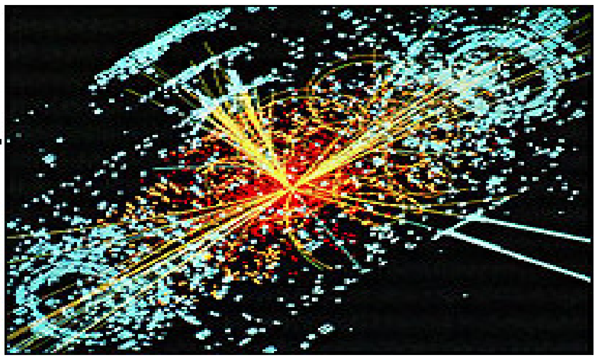
"The World's Most Wanted"

Higgs boson

Nowhere to Run ! Nowhere to Hide !

REWARD

? *billions*



Current consensus on the LHC Higgs search prospects

•SM Higgs : detection is in principle guaranteed for any mass. 

mH (SM) <160 GeV @95% CL

•In the MSSM h-boson most probably cannot escape detection, and in large areas of parameter space other Higgses can be found.

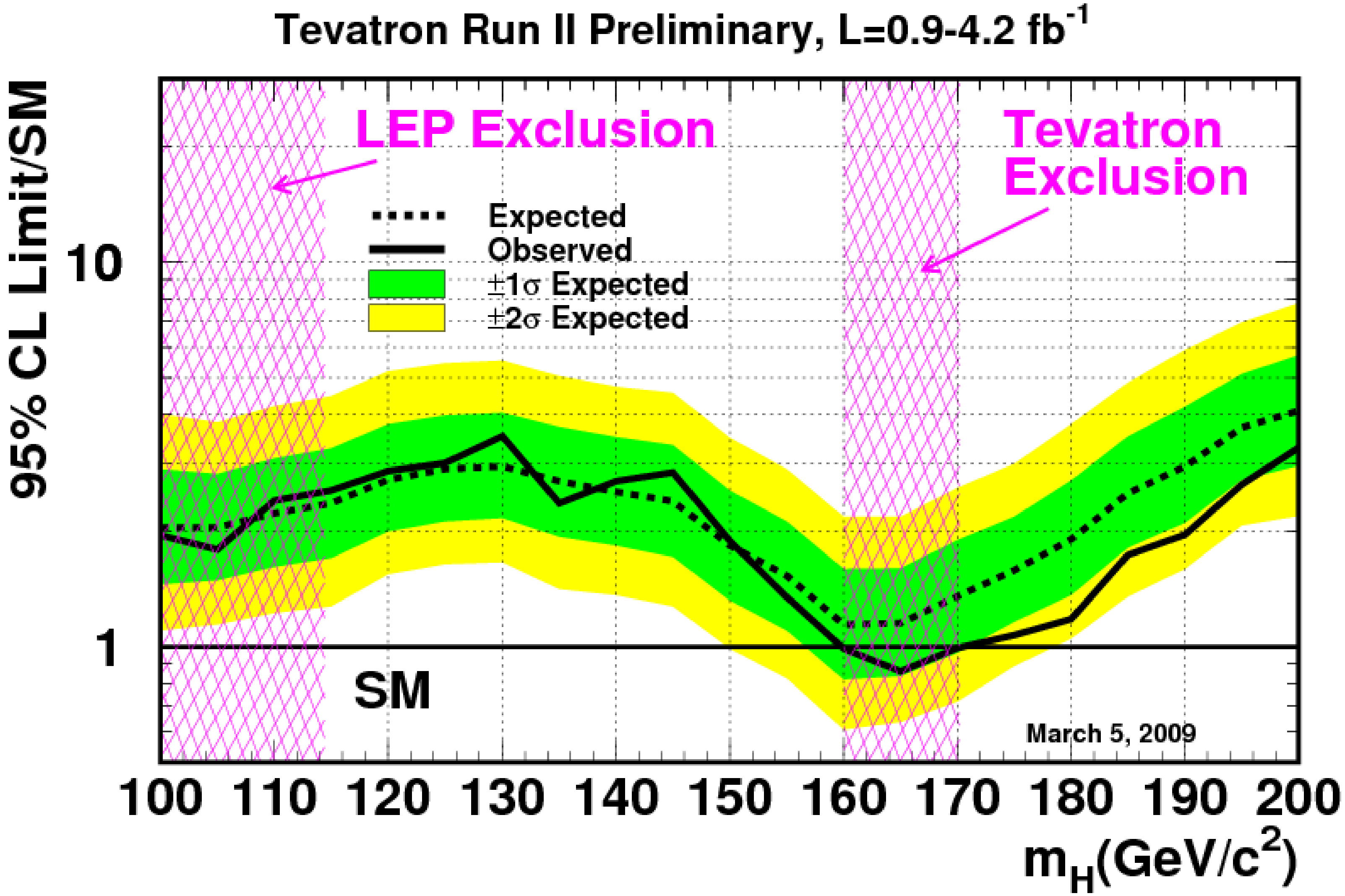
•But there are still *troublesome* areas of the parameter space:
intense coupling regime of MSSM, MSSM with CP-violation…

•More surprises may arise in other SUSY non-minimal extensions: NMSSM……

'Just' a discovery will not be sufficient!

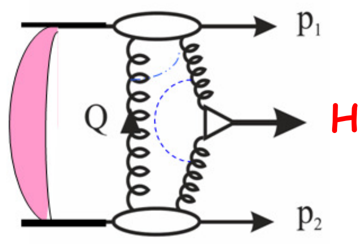
• After discovery stage (Higgs Identification):

✳ The ambitious program of precise measurements of the Higgs mass, width, couplings, and, especially of the quantum numbers and CP properties would require an interplay with a *ILC* .



Tevatron Run II Preliminary, L=0.9-4.2 fb-1
95% CL Limit/SM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM
March 5, 2009
10
1
100
110
120
130
140
150
160
170
180
190
200
mH(GeV/c2)

The main advantages of CED Higgs production



- Prospects for high accuracy (~1%) mass measurements (irrespectively of the decay mode).

- Quantum number filter/analyser.
  (0++ dominance ;C,P-even)

- H ->bb opens up (Hbb- coupl.)

  (gg)CED ⊗→ bb in LO ; NLO,NNLO, b- mass effects – controllable.

- For some areas of the MSSM param. space CEDP may become *a* **discovery channel !**
- **H →WW*/WW - an added value** (less challenging experimentally + small bgds., better PU cond.)

- A handle on the overlap backgrounds- Fast Timing Detectors (10 ps timing or better).

- New leverage –proton momentum correlations (probes of QCD dynamics , CP- violation effects…)

  ✳ LHC : 'after discovery stage', Higgs **ID**……

  How do we know what we've found?

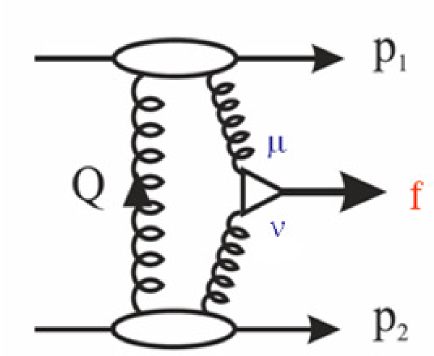
  mass, spin, couplings to fermions and Gauge Bosons, invisible modes…
  → for all these purposes the CEDP will be particularly handy !

for Higgs searches in the forward proton mode the QCD bb backgrounds are suppressed by Jz=0 selection rule and by colour, spin and mass resolution (ΔM/M) -factors.

There must be a god !

The origin of Jz=0 selection rule

KMR-2000



$$M_{\mu\nu}(gg^{PP}) \sim (p_{t,1} - Q_t)_\mu (p_{t,2} + Q_t)_\nu$$

after $(\vec{Q}_t)$ angular integration at $p_{t,i} = 0$ ➔ $-\delta^{(2)}_{\mu\nu} Q_t^2 / 2$

in terms of helicity amplitudes . $1/2\{(++;f) + (--;f)\}$ ➔ Jz=0, P-even state

at non-zero $p_{t,i}$ - an admixture of Jz=2 ➔ $\frac{(2p_{1,t}p_{2,t})^2}{Q_t^4}$

in terms of the **MHV rules** the only nonzero amplitudes gg→qq (S .Parke, T.Taylor (1986))

(+ - ; + -) J_z=2, **HCA**

(-+ : -+ /+-) (very fashionable nowadays)

some regions of the MSSM parameter space are especially *proton tagging friendly*
(at large tan β and M ≤ 250 , $S/B \geq 20$)

KKMR-04

HKRSTW, 0.7083052[hep-ph]   B. Cox, F.Loebinger, A.Pilkington-07

Myths

For the $b\bar{b}$ channel bgds are well known and incorporated in the MCs:

Exclusive **LO** - $b\bar{b}$ production (mass-suppressed) + gg misident+ soft & hard PP collisions.

Reality

The background calculations are still in progress :
(uncomfortably & unusually large high-order QCD and b-quark mass effects).

About a dozen various sources (studied by Durham group)

❶ admixture of |Jz|=2 production.
❷ NLO radiative contributions (hard blob and screened gluons)

❸ NNLO one-loop box diagram (mass- unsuppressed, cut-non-reconstructible)
❹ 'Central inelastic' backgrounds (soft and hard Pomerons)

Not fully in MCs (❶–❹)

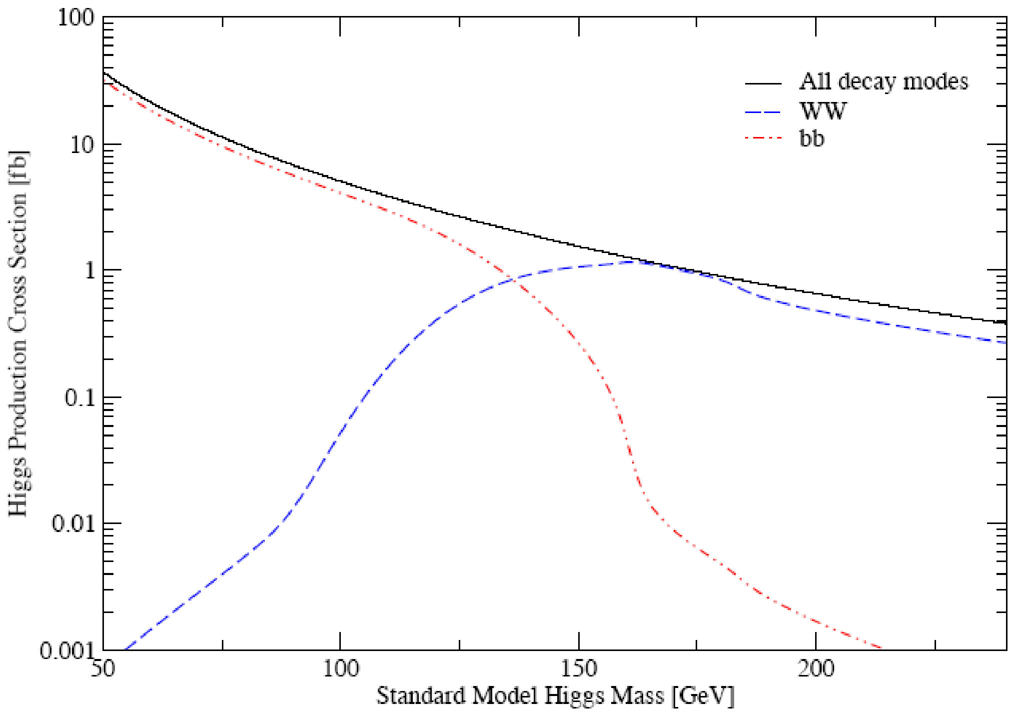
❺ b-quark mass effects in dijet events 

(Shuvaev+KMR-08)

……….

SM Higgs

WW decay channel: require at least one W to decay leptonically (trigger). Rate is large enough….

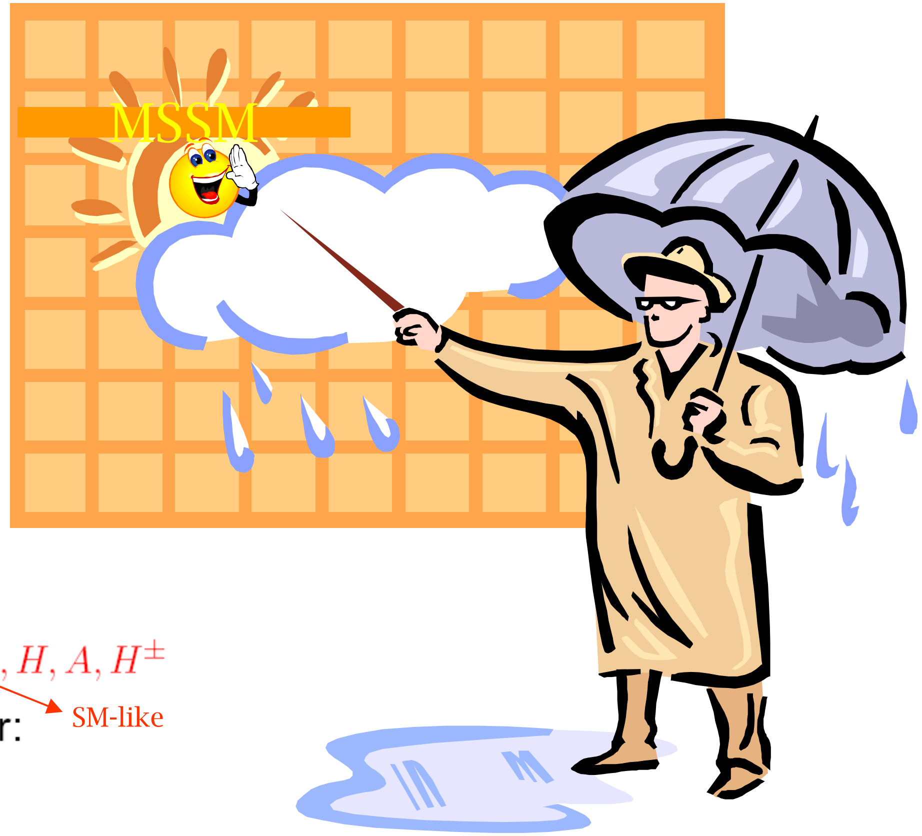


Cox, de Roeck, Khoze, Pierzchala, Ryskin, Stirling, Nasteva, Tasevsky-04

without 'clever hardware':
for H(SM)→bb at 60fb-1 only
a handful of events due to
severe exp. cuts and low efficiencies,
though **S/B~1** .

H->WW mode at M>135 GeV; **ττ-** mode.

enhanced trigger strategy & improved timing detectors (FP420, TDR)



Situation in the MSSM is **very different** from the SM

- Higgs sector of the MSSM: physical states $h, H, A, H^{\pm}$ (h → SM-like)

  Described by two parameters at lowest order:
  M_A, $\tan\beta \equiv v_2/v_1$

- Search for heavy MSSM Higgs bosons ($M_A, M_H > M_Z$):
  Decouple from gauge bosons
  ⇒ no HVV coupling
  ⇒ no Higgs production in weak boson fusion
  ⇒ no decay $H \to ZZ \to 4\mu$

  Large enhancement of coupling to $b\bar{b}$ (and $\tau^+\tau^-$) in region of high $\tan\beta$

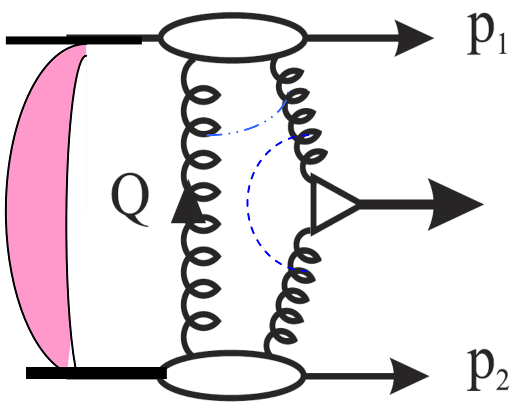
Conventionally due to overwhelming QCD backgrounds, the direct measurement of Hbb is hopeless

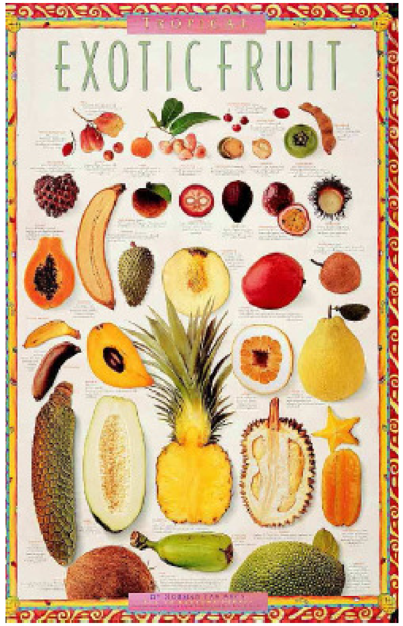
The backgrounds to the diffractive H bb mode are manageable!

The MSSM and more '*exotic*' scenarios

$$pp \to p + \phi + p$$

If the coupling of the Higgs-like object to gluons is large, double proton tagging becomes very attractive





- *The intense coupling regime of the MSSM* (E.Boos et al, 02-03)
- CP-violating MSSM Higgs physics (B.Cox et al . 03, KMR-03, J. Ellis et al. -05)
- CEP of the MSSM Higgs bosons- HKRSTW-2008.
- Triplet Higgs bosons (CHHKP-2009)
- Fourth Generation Higgs
- NMSSM (J. Gunion, et al.)
- *Invisible' Higgs* (BKMR-04)

> - There is no *experimental preference* for a Standard Model (SM) Higgs boson.
> - *Any Higgs boson is exotic!*

Extended Higgs sectors: “typical” features

Search for heavy MSSM Higgs bosons ($M_{\mathrm{A}}, M_{\mathrm{H}} \gg M_{\mathrm{Z}}$):

Decouple from gauge bosons

$\Rightarrow$ no HVV coupling

$\Rightarrow$ no Higgs production in weak boson fusion

$\Rightarrow$ no decay $H \to ZZ \to 4\mu$

Large enhancement of coupling to $b\bar{b}$, $\tau^+\tau^-$ for high $\tan\beta$

$\Rightarrow$ Decays into $b\bar{b}$ and $\tau^+\tau^-$ play a crucial role

“Typical” features of models with an extended Higgs sector:

- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons

The MSSM can be very proton tagging- friendly

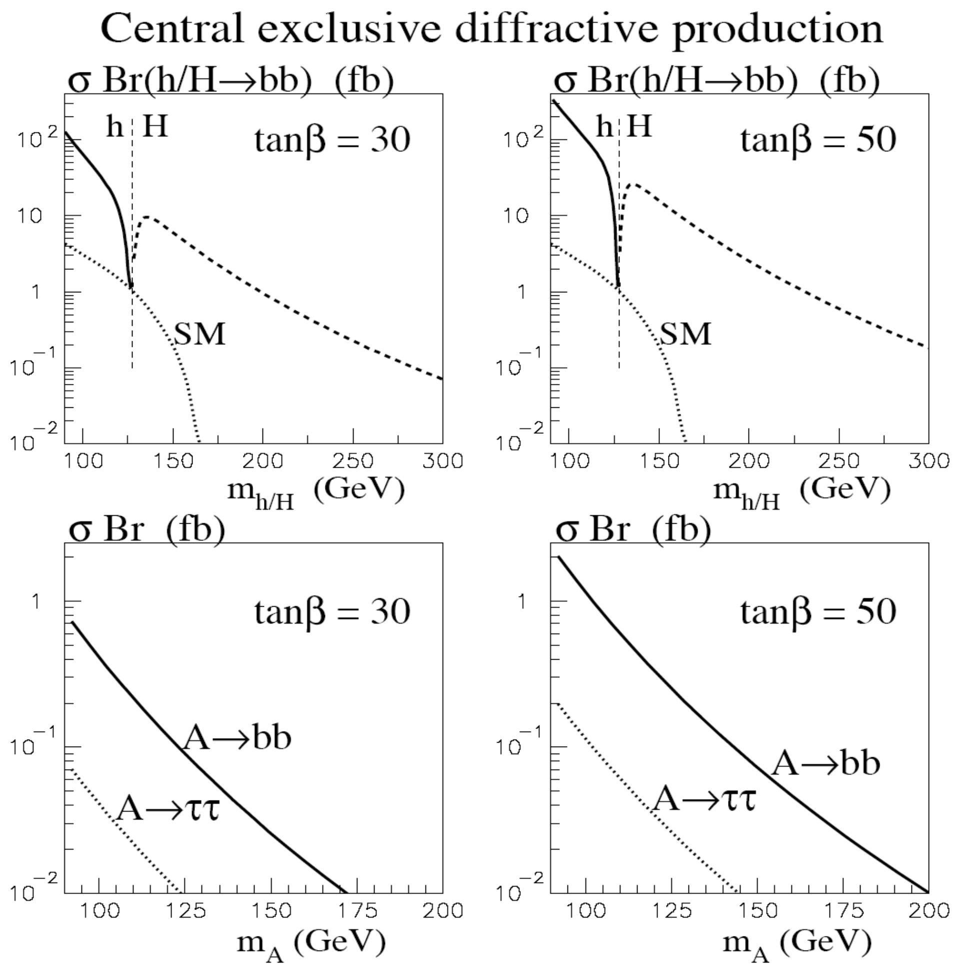
The **intense coupling regime** is where the masses of the 3 neutral Higgs bosons are close to each other and tan β is large

$\gamma\gamma, WW^{\star}, ZZ^{\star}$ suppressed

$gg \rightarrow \phi$ enhanced

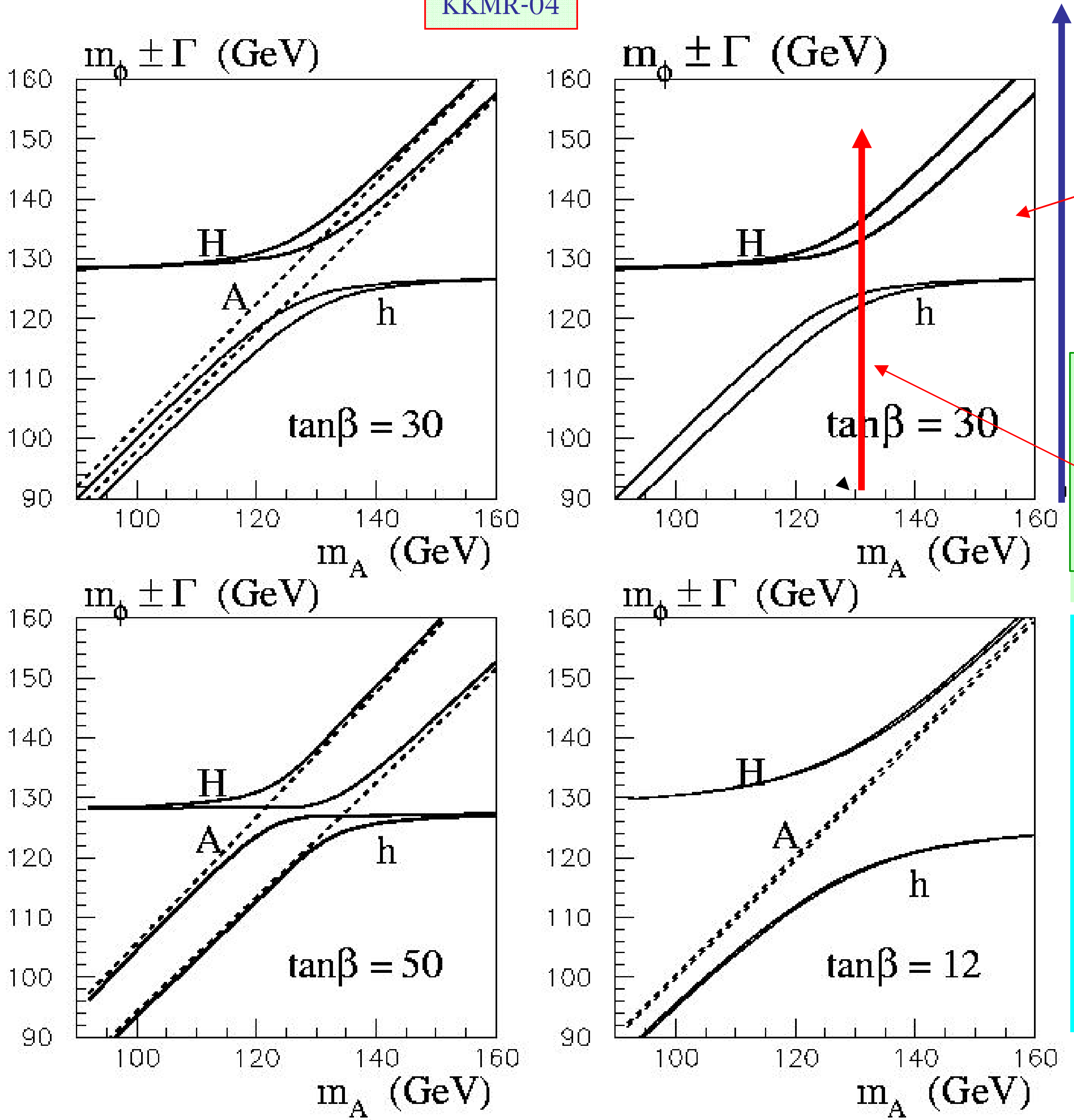
0^{++} selection rule suppresses A production:

CEDP 'filters out' pseudoscalar production, leaving pure H sample for study KKMR-04



Well- known difficult region for conventional channels, tagged proton channel may be the **discovery channel** , and is certainly a powerful **spin/parity filter**

KKMR-04



decoupling regime

$m_A \sim m_H \geq$ 150GeV,

tanβ >10;

h = SM

intense coupling regime:

$m_h \sim m_A \sim m_H$

γγ,WW.. couplings suppressed

with CEDP:

- **h,H** may be clearly distinguishable outside130+-5 GeV range,
- **h,H** widths are quite different

Four integrated luminosity scenarios

HKRSTW, arXiv:0708.3052 [hep-ph]

(**bb**, WW, ττ- modes studied)

1. L = 60fb^{-1}: 30 (ATLAS) + 30 (CMS): 3 yrs with L=10^{33}cm^{-2}s^{-1}

2. L = 60fb^{-1}, effx2: as 1, but assuming doubled exper.(theor.) eff.

3. L = 600fb^{-1}: 300 (ATLAS) + 300 (CMS) : 3 yrs with L=10^{34}cm^{-2}s^{-1}

4. L = 600fb^{-1},effx2: as 3, but assuming doubled exper.(theor.) eff.

upmost !

We have to be open-minded about the theoretical uncertainties.

Should be constrained by the early LHC measurements (KMR-08)

NEW DEVELOPMENT

- Current Tevatron limits implemented.

- CDM scenarios analysed

Compliant with the **C**old **D**ark **M**atter and **EW** bounds
(EHHOW-07)

- bb backgrounds revisited
- Neutral Higgs in the triplet model
- 4 Generation scenarios

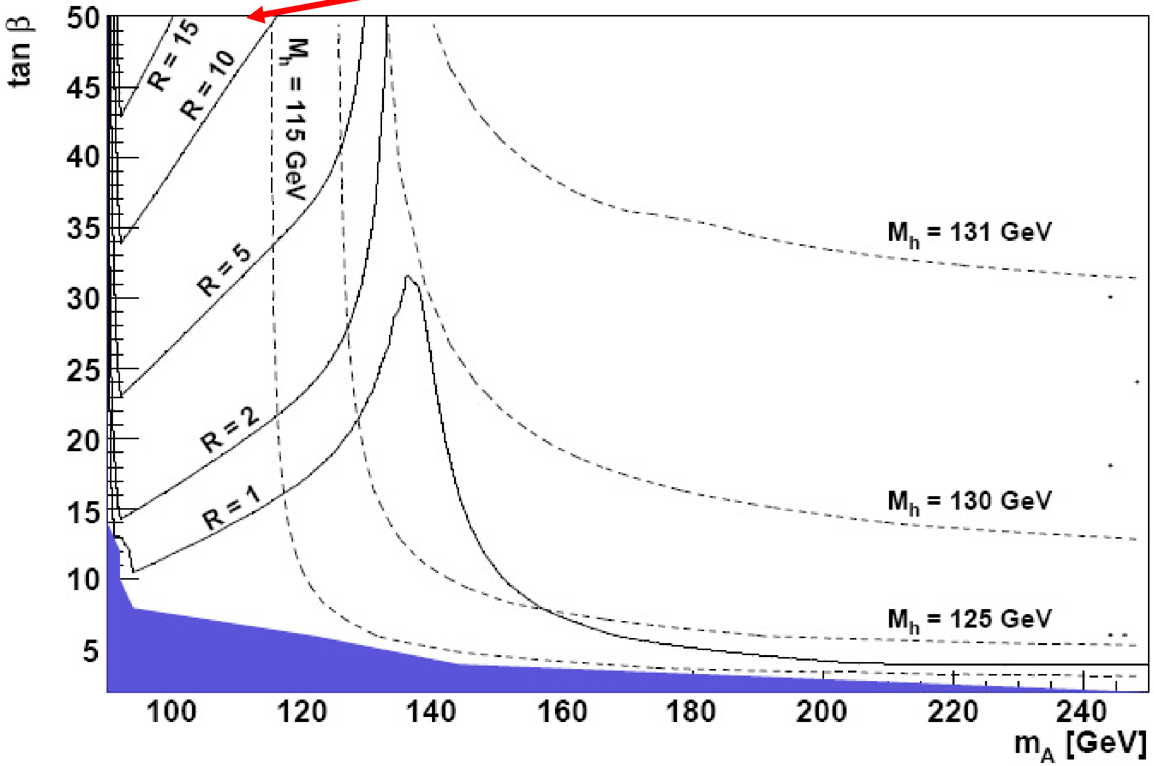
- **Still to come**
- $\tau\tau$ -mode, in particular, trigger strategy

Charged Higgs bosons in MSSM and triplet models

Ratio of signal rate for the light MSSM Higgs boson over the SM rate in the $h \to b\bar{b}$ channel

m_h^{max} benchmark scenario:

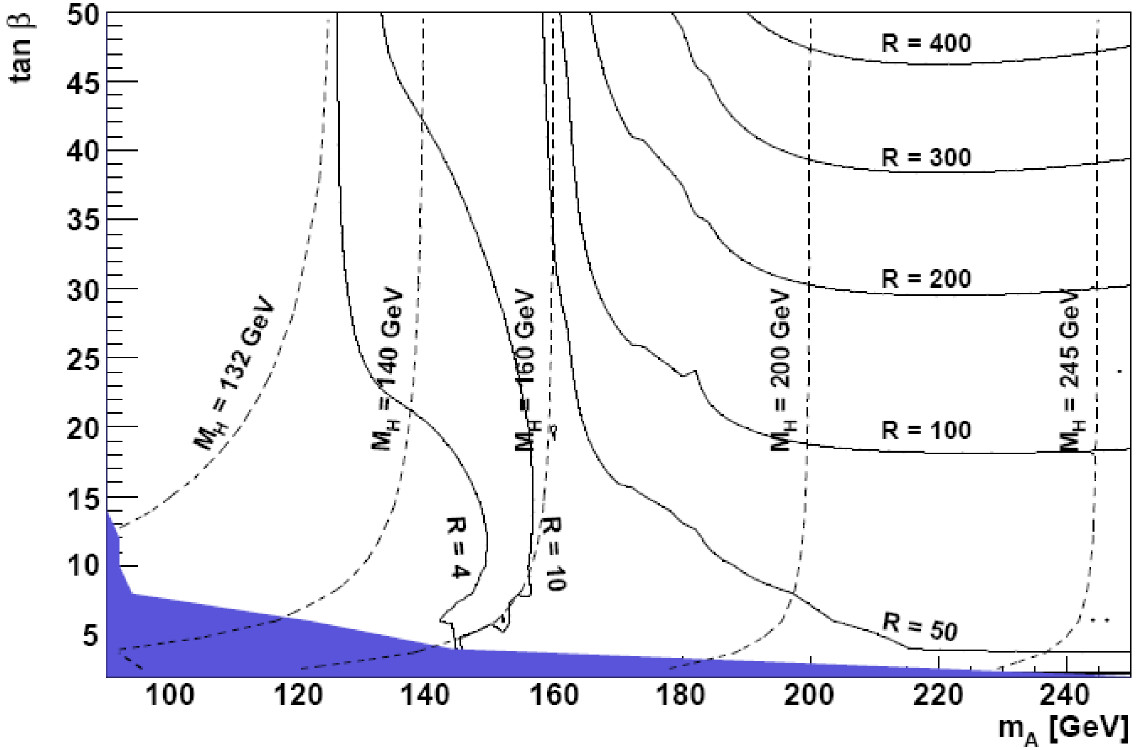
New Tevatron data still pouring



$\Rightarrow$ Large enhancement possible for relatively small M_A and large $\tan\beta$

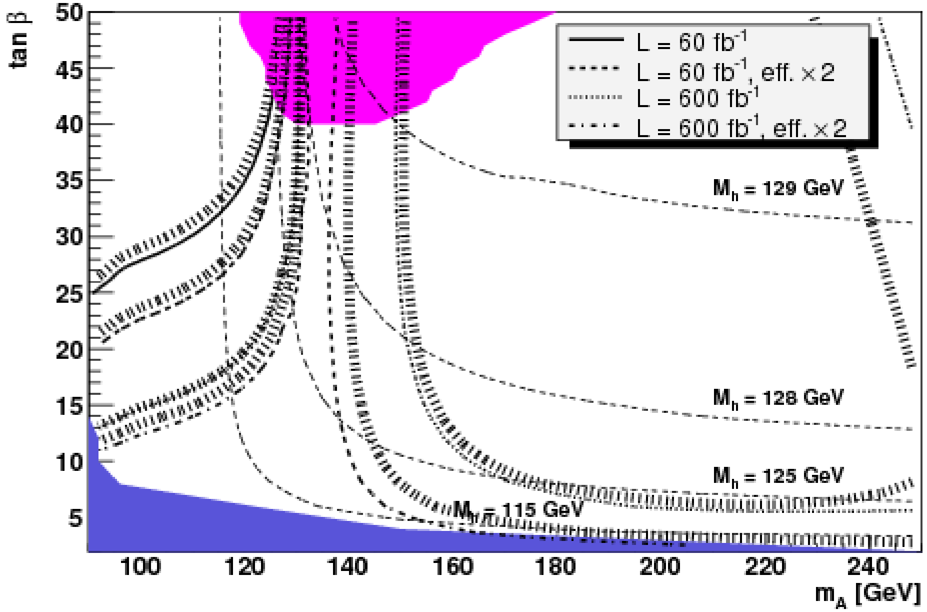
Ratio of signal rate for the heavy $\mathcal{CP}$-even MSSM Higgs boson over the SM rate, $H \to b\bar{b}$ channel

$m_{\rm h}^{\rm max}$ benchmark scenario:



⇒ Huge enhancement compared to SM case, up to factor 400

HKRTW-08



- Tevatron limits shown.
- Updated theory calculations
- New bb-backgrounds

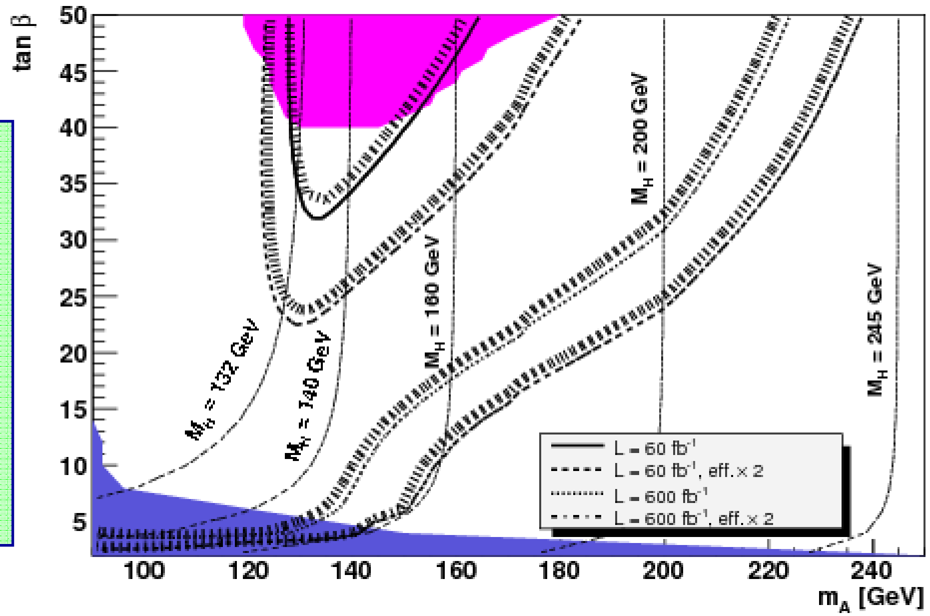
Mhmax benchmark scenario
Improved theory & background

3σ countours

- “600x 2” scenario covers nearly the whole allowed region for the light Higgs.

For large tan β heavy Higgs reach goes beyond 235 GeV.

- For the H-boson the area reachable in the “60”-scenario is to large extent ruled out by the Tevatron data.



HKRTW-08

CDM benchmarks

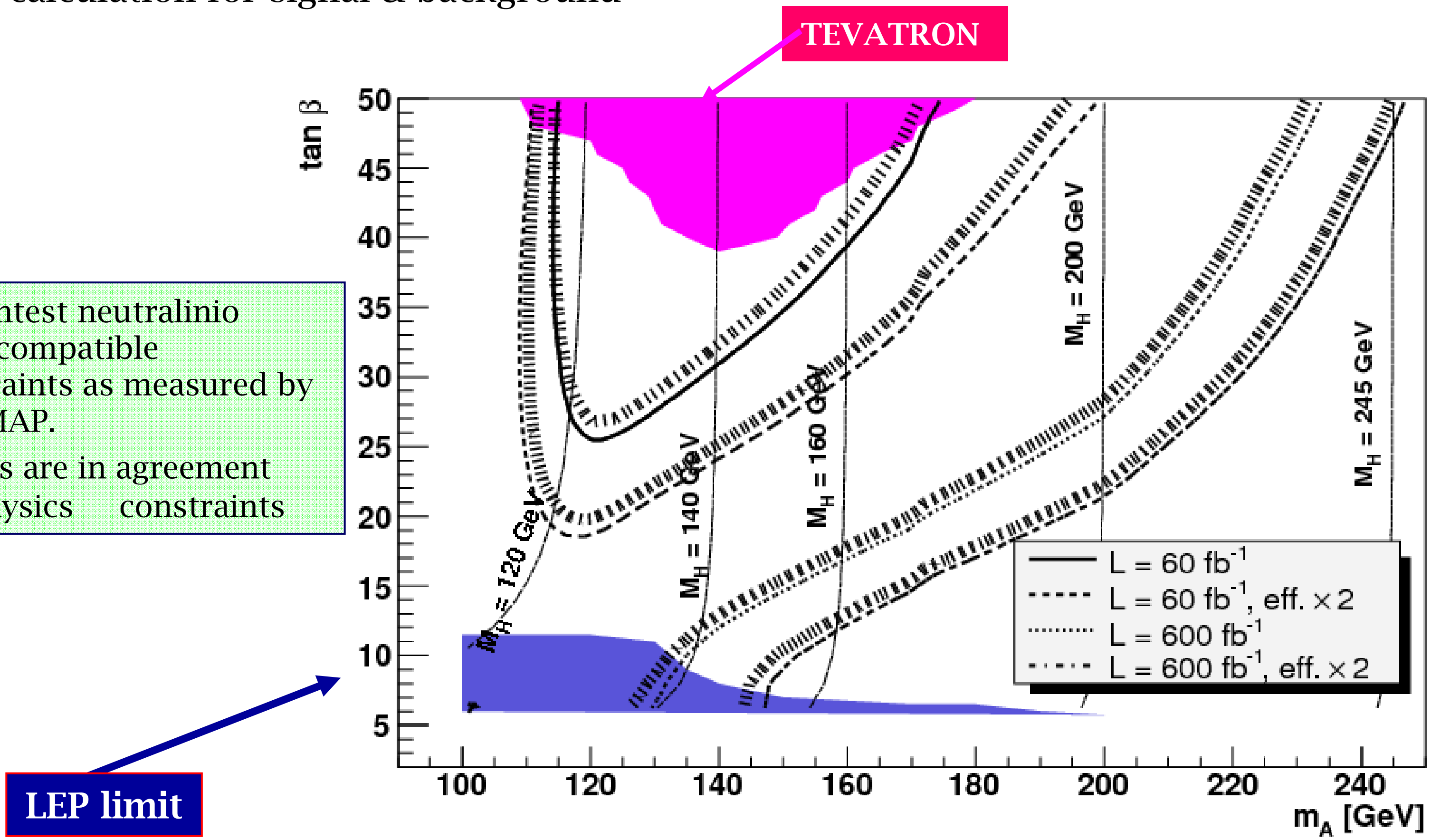
3σ contours
P3- NUHM scenario

•Updated theory calculation for signal & background

$H \to b\bar{b}$

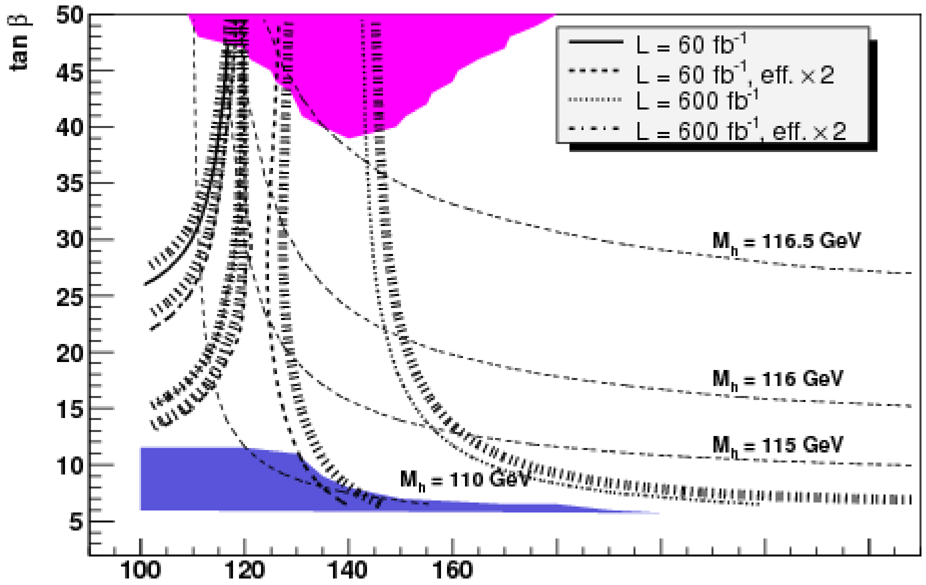
Abundance of the lightest neutralinio in the early universe compatible with the CDM constraints as measured by WMAP.

The $M_A - \tan\beta$ planes are in agreement with the EW and B-physics constraints



HKRTW-08

CDM P3 scenario
3 σ contours



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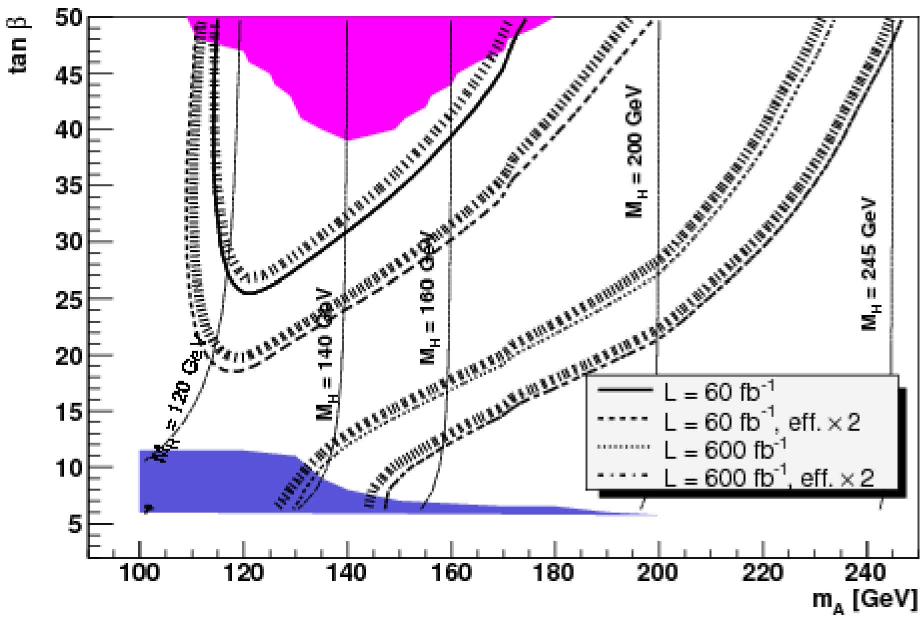
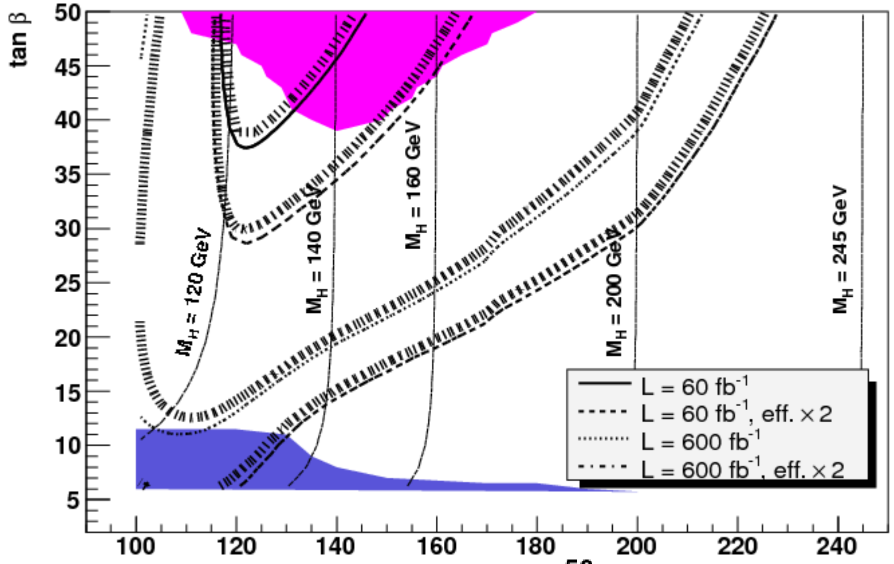
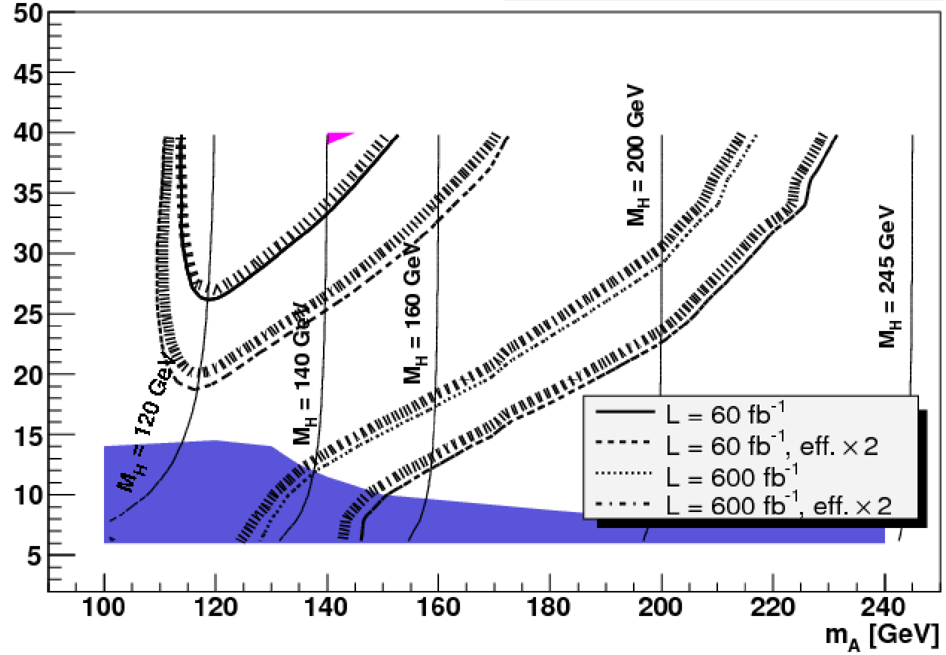


$H \to b\bar{b}$



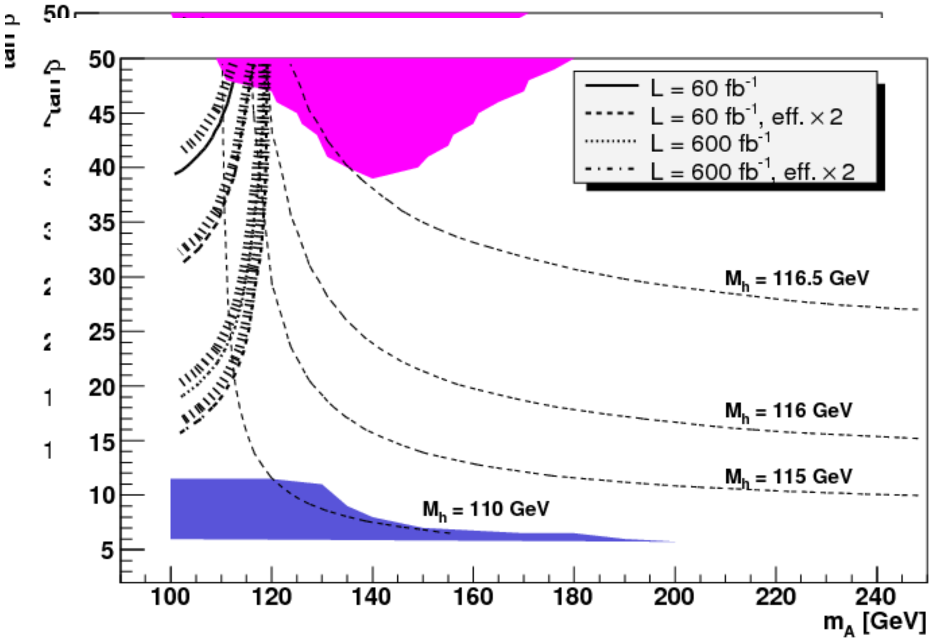
5σ -discovery,
P3- NUHM scenario

3σ -contours,
P4- NUHM scenario

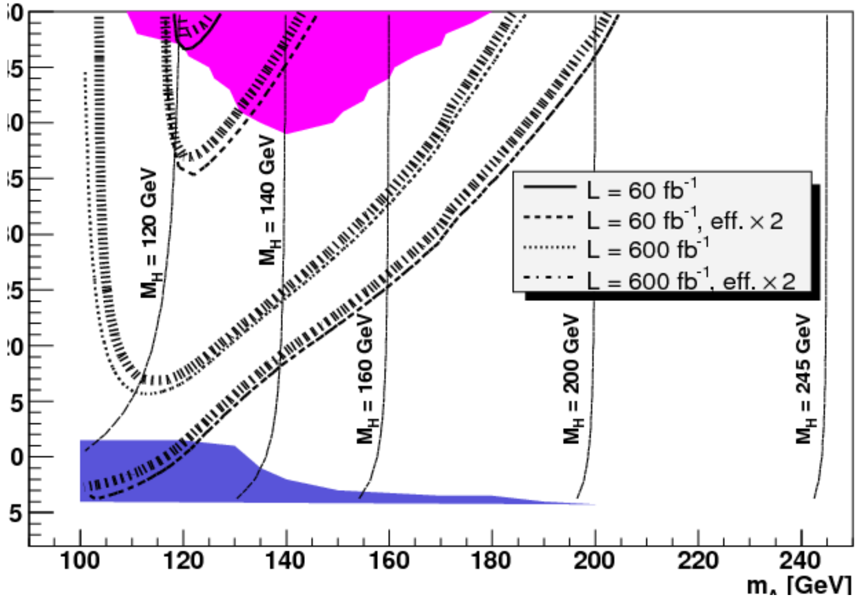


3σ -contours,
P3- NUHM scenario

$$h \to \tau^+\tau^-$$



$$H \to \tau^+\tau^-$$



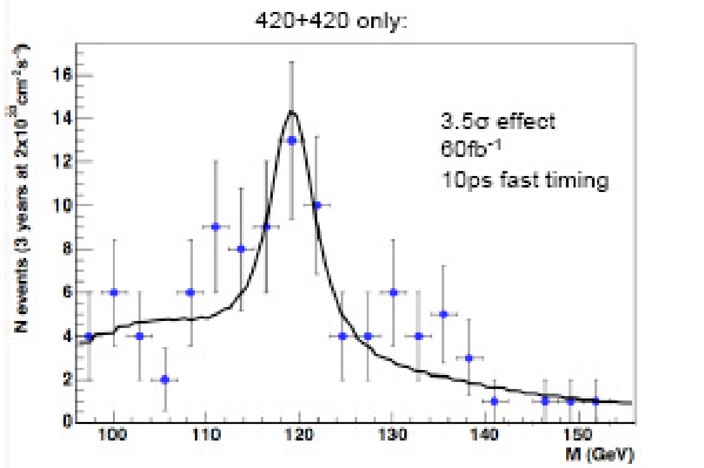
h→bb in the MSSM

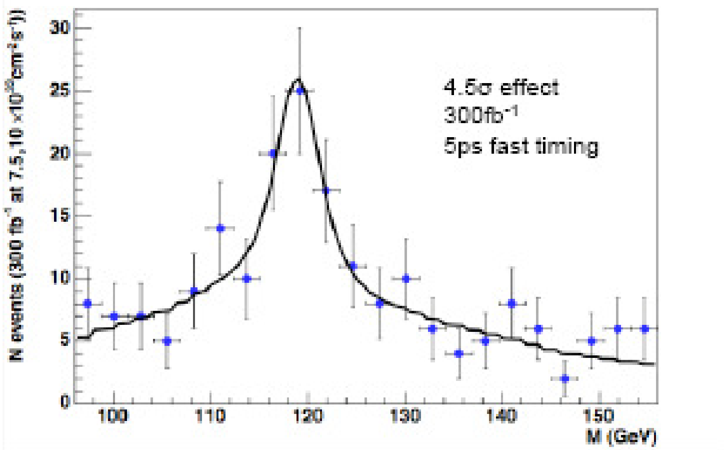
Simulation : A.Pilkington

- MSSM Higgs sector has 2 neutral scalars (h,H).
- Pseudo-scalar (A) can't be produced in CEP due to spin selection rule.
- CEP of bb suppressed by m_b^2/M^2.

- MSSM h→bb studied by Cox. et.al. (JHEP 0710:090,2007) for one parameter point, m_A=120GeV and tanβ=40, resulting in m_h=119.5GeV.

- Experimental efficiencies determined using ATLAS resolutions in TDR.
- Trigger strategy:
  - 40GeV jet + 6GeV muon.
  - 40GeV jet + proton tagged at 220m.
  - 40GeV jets, rate prescaled to 25 (10) kHz (note, recent estimates show rate can be reduced to 12.5 (5) kHz, with same results).





HKRSTW (arXiv: 0708.3052[hep-p])

Conclusions

- Detailed analysis of prospects for CED production of $\mathcal{CP}$-even MSSM Higgs bosons, $pp \to p \oplus h, H \oplus p$
- Light MSSM Higgs boson, $h \to b\bar{b}$ channel: almost complete coverage of M_A–$\tan\beta$ plane (and case of light SM Higgs) at the 3σ level with $600\ \mathrm{fb}^{-1} \times 2$

  $\Rightarrow$ CED channel may yield crucial information on bottom Yukawa coupling and $\mathcal{CP}$ properties
- Heavy $\mathcal{CP}$-even Higgs boson, $H \to b\bar{b}$ channel: discovery of a $140\ \mathrm{GeV}$ Higgs for all values of $\tan\beta$ with $600\ \mathrm{fb}^{-1} \times 2$

  In high $\tan\beta$ region: discovery reach beyond $M_H \approx 200\ \mathrm{GeV}$ also for lower luminosities
- 'Semi-exclusive' production of A looks challenging

$\Rightarrow$ Interesting physics potential for probing MSSM Higgs sector; further experimental + theoretical efforts desirable

Studying the MSSM Higgs Sector by Forward Proton Tagging at the LHC, Georg Weiglein, EPS07, Manchester, 07/2007 – p.18

Other BSM Scenarios

❧ *'Invisible' Higgs* B(KMR)-04

several extensions of the SM: fourth generation,
some SUSY scenarios,
large extra dimensions,…

(one of the 'LHC headaches')

the potential advantages of the CEDP – a sharp peak in the MM spectrum, mass determination, quantum numbers

strong requirements :

- triggering directly on L1 on the proton tigers
  or rapidity gap triggers (forward calorimeters,.., ZDC)

❧ *Implications of fourth generation* (current status: e.g. G.Kribs et.al, arXiv:0706.3718)

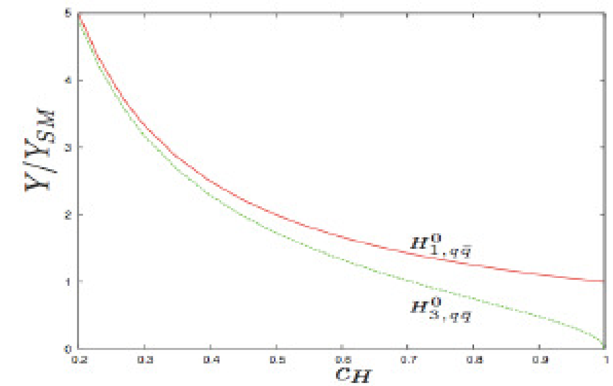
For CEP → enhanced $H \to bb$ rate (~ 5 times), while WBF is suppressed.

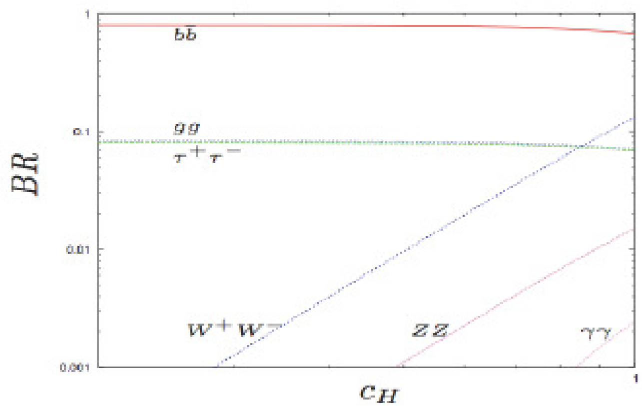
M. Chaichian, P.Hoyer, K.Huitu, VAK, A.Pilkington, JHEP (to be published)

Higgs bosons in a triplet model

- Extend SM by addition of higher representations of Higgs sector in addition to the doublet.
  - One real and one complex triplet chosen ala Georgi and Machacek.

- 4 neutral scalar Higgs' bosons, charged and doubly charged Higgs also.
- Enhancement of Higgs-fermion-antifermion coupling by $1/c_H^2$ where c_H is a doublet-triplet mixing parameter.
- Large enhancement in CEP production cross section for $c_H < 1$ (top-loop).
- LEP constraints on Higgs mass weaker as coupling to weak bosons reduced by c_H^2.
- Tevatron will be able to access c_H=0.2 in tau-tau decay channel in near future.





An additional bonus: doubly charged Higgs in photon-photon collisions → factor of 16 enhancement

Simulation by A. Pilkington

The University of Manchester

CEP Triplet Higgs (II)

$\sigma_{H\to b\bar{b}}$ (fb)	$m_H = 120$ GeV	$m_H = 150$ GeV
$c_H = 0.2$	113.5	55.2
$c_H = 0.5$	18.0	7.4
$c_H = 0.8$	6.6	1.5

Forward detector information

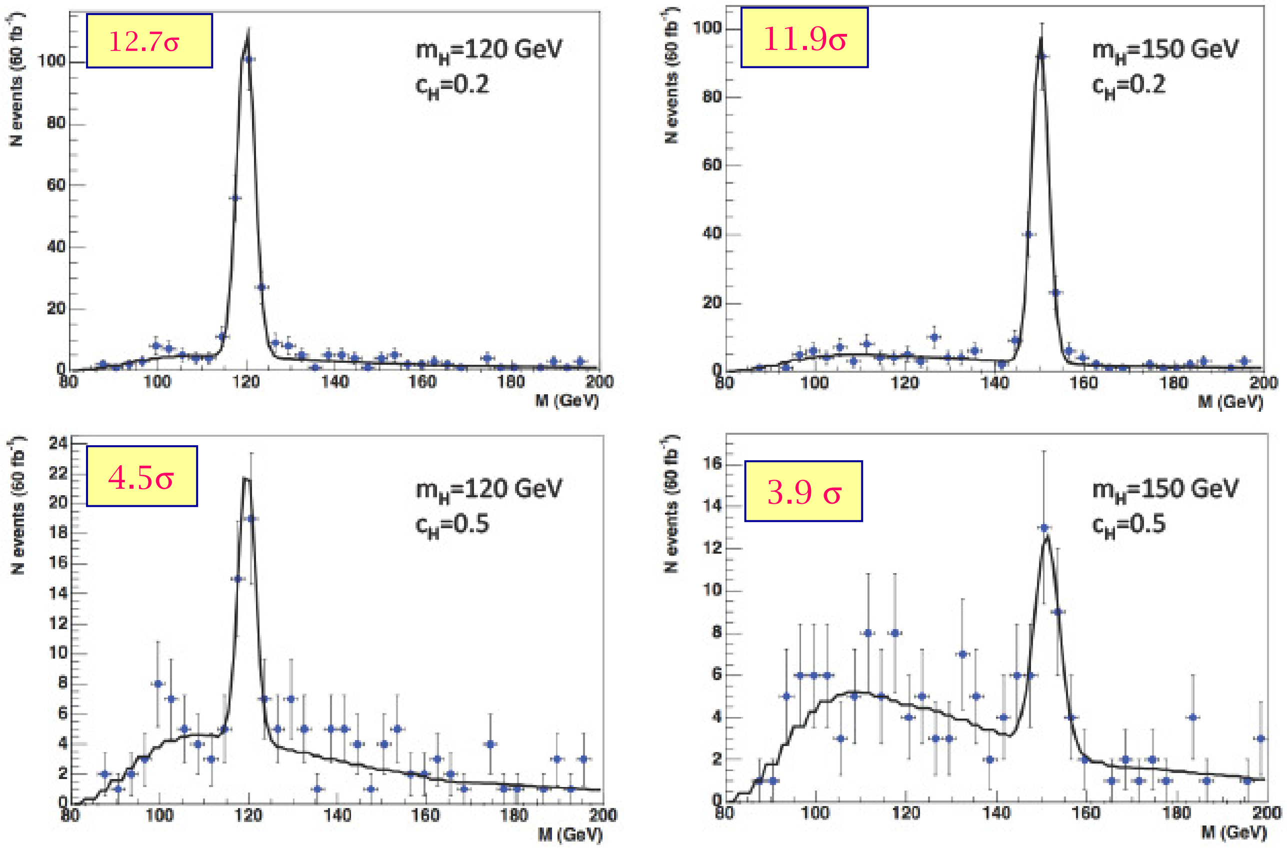
- Level 1 (L1): Information from detectors at 220m from IP is available.
- Level 2 (L2): Full forward proton tagging information available.

Jet L1 triggers for CEP

- Use final state muon if final state has b-jets. (10% efficient for triplet signal if muon p_T>6GeV).
- 1 jet (E_T>40GeV) and 1 proton tagged at 220m. Rate<1kHz up to L~$2x10^{33}cm^{-2}s^{-1}$. Could allow fixed rate trigger of 5 kHz or 10 kHz up to higher luminosities.
- 2 jets at L1 with high rate. Reduced at L2 by full proton tagging information. Rejection ~20000 (140) for L=10^{33} (10^{34}) $cm^{-2}s^{-1}$.

Simulation by A. Pilkington

Results: Triplet Higgs production



Expected mass distributions given 60 fb-1 of data.

Simplest example of the BSM Higgs physics

Beyond the 3SM generation at the LHC era

4-5 September 2008

http://indico.cern.ch/conferenceDisplay.py?confId=33285

Enhancement of $\Gamma(H\rightarrow gg)$ ➔

at 220 GeV:
CED ($H\rightarrow WW/ZZ$) rate – factor of **~9;**
at 120 GeV
CED ($H\rightarrow bb$) rate – factor of **~5.**

$B(H\rightarrow\gamma\gamma)$ is suppressed

$H\rightarrow ZZ$ – especially beneficial at M= 200-250 GeV

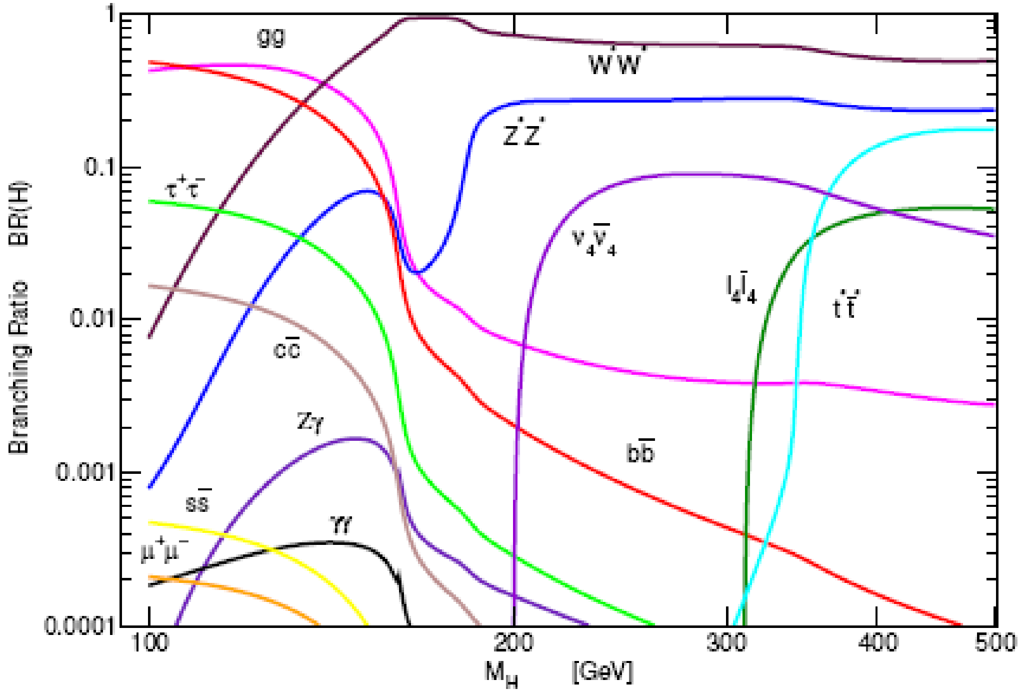


Figure 1. Branching ratio of the Higgs with fourth–generation effects in the parameter point (b).

G.D. Kribs et al. / Nuclear Physics B (Proc. Suppl.) 177–178 (2008) 241–245

for the light Higgs below 200 GeV

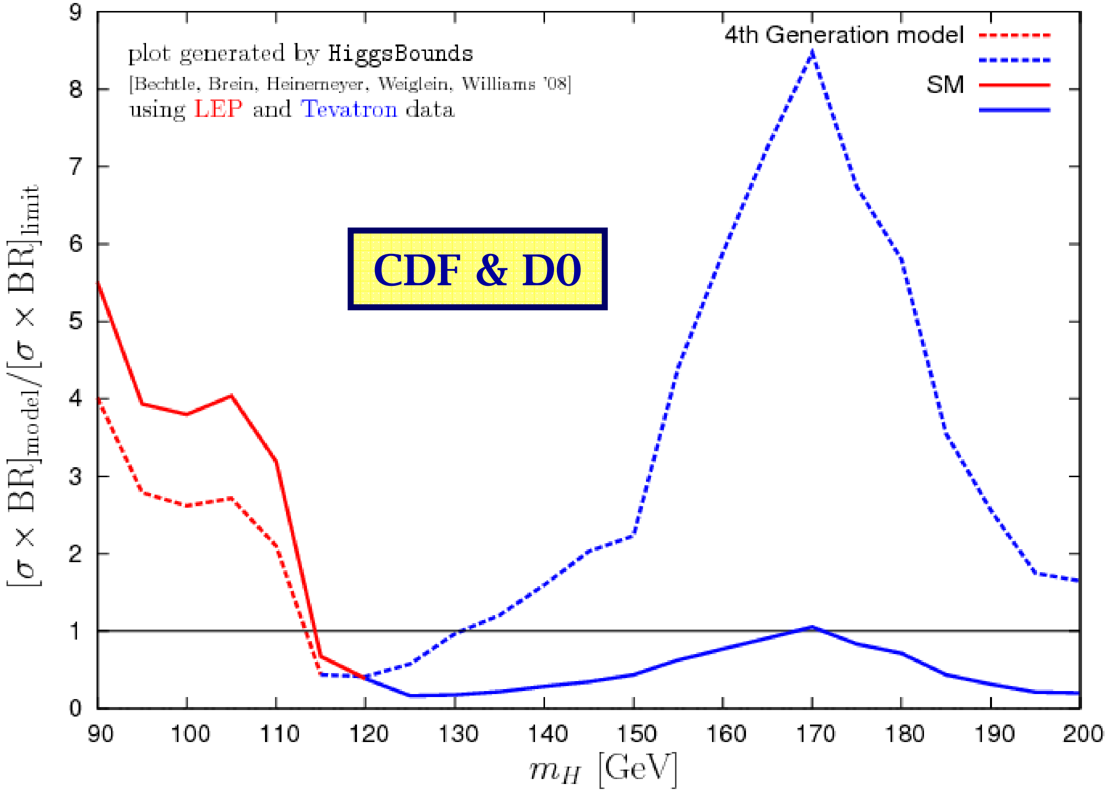
$$\sigma_{gg}\mathrm{BR}(ZZ)\Big|_{\mathrm{G4}} \simeq (5\cdots 8)\ \sigma_{gg}\mathrm{BR}(ZZ)\Big|_{\mathrm{SM}}$$

$$\sigma_{gg}\mathrm{BR}(f\overline{f})\Big|_{\mathrm{G4}} \simeq 5\ \sigma_{gg}\mathrm{BR}(f\overline{f})\Big|_{\mathrm{SM}}$$

B(H→γγ) is suppressed

Tevatron data rule out a Higgs in a 4-generation scenario below 210 GeV apart from the low mas window at 115-130 GeV

L (fb^{-1})	σ
60	3.7
60*2	5.2
600	11.1
600*2	15.7



At 60 fb-1 : for M=120 GeV , ~25 bb ev; for M=220 GeV, ~ 50 WW ev; favourable bgs

Central Exclusive Higgs Production and the NMSSM

Jack Gunion

5th Manchester Forward Physics Workshop, December 9, 2007

- The Next to Minimal Supersymmetric Model (NMSSM) maintains all the attractive features of the MSSM while avoiding all its problems.

- If low fine-tuning is imposed for an acceptable SUSY model, we should expect:

  – a h_1 with $m_{h_1} \sim 100~\mathrm{GeV}$ and SM-like couplings to SM particles but with primary decays $h_1 \to a_1 a_1$ with $m_{a_1} < 2m_b$, where the a_1 is mainly singlet.

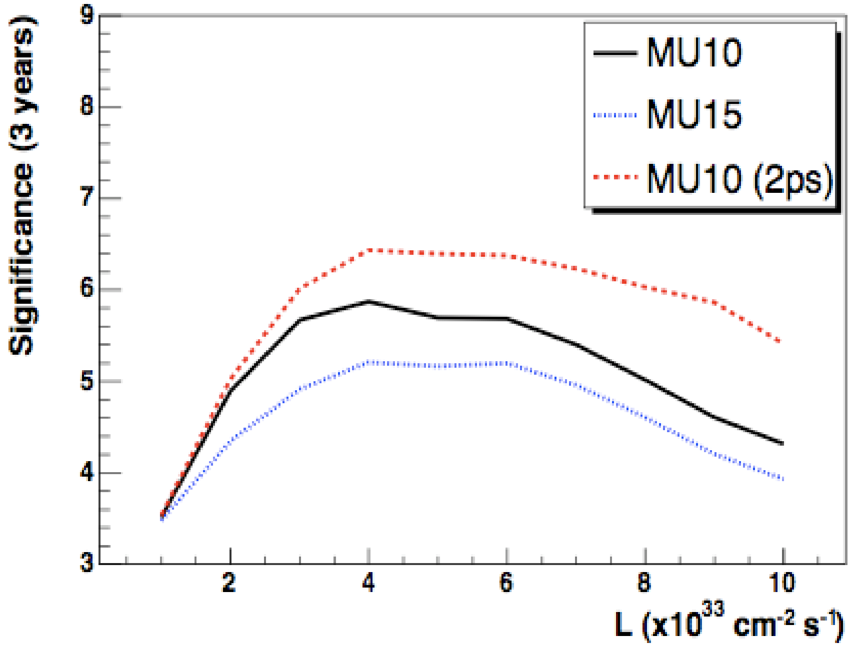
  Higgs detection will be quite challenging at a hadron collider.

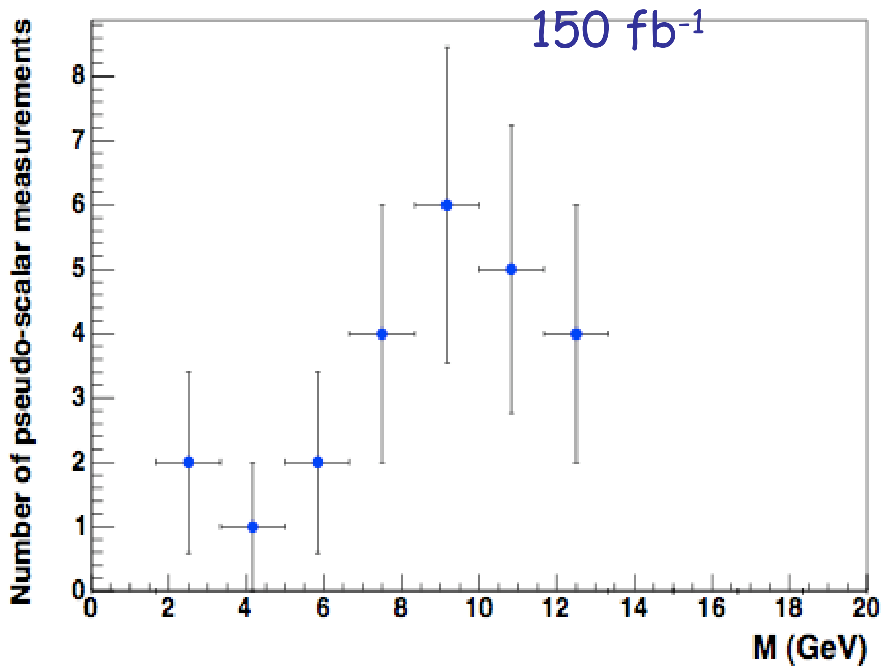
- CEP could be the discovery channel for NMSSM Higgs

(J.R. Forshaw, J.F. Gunion, L. Hodgkinson, A. Papaefstathiou, A.D. Pilkington, arXiv:0712.3510)

h→aa→ττττ

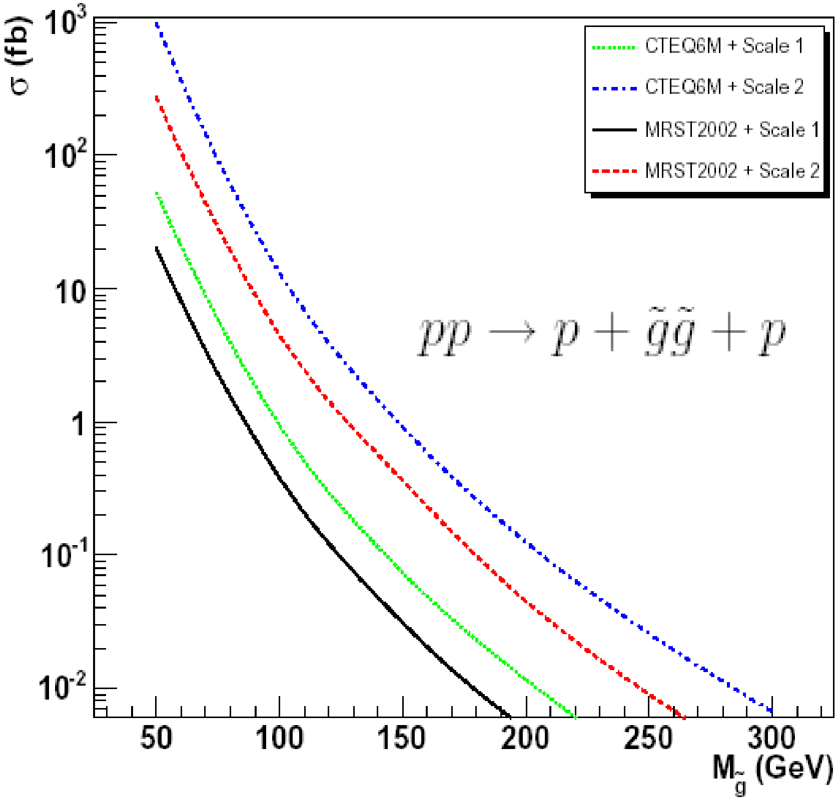
Low mass higgs in NMSSM: If $m_a < m_B$ difficult (impossible) at standard LHC
J. Gunion: FP420 may be the only way to see it at the LHC





Long Lived gluinos at the LHC

P. Bussey et al
hep-ph/0607264



$m_{\tilde{g}}$ (GeV)	$\sigma_{m_{\tilde{g}}}$ (GeV)	$\frac{\sigma_{m_{\tilde{g}}}}{\sqrt{N-1}}$ (GeV)	N
200	2.31	0.19	145
250	2.97	0.50	35.0
300	3.50	1.10	10.2
320	3.61	1.54	6.5
350	3.87	2.45	3.5

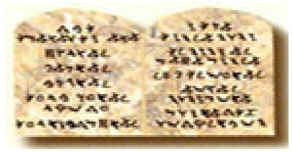
Gluino mass resolution with 300 fb^{-1}
using forward detectors and muon system

The event numbers includes acceptance
in the FP420 detectors and central
detector, trigger…

R-hadrons look like slow muons good for triggering

Measure the gluino mass with a precision (much) better than 1%

CONCLUSION



God Loves Forward Protons

- Forward Proton Tagging would significantly extend the physics reach of the ATLAS and CMS detectors by giving access to a wide range of exciting new physics channels.
- FPT has the potential to make measurements which are unique at LHC and challenging even at a ILC.
- For certain BSM scenarios the FPT may be the Higgs **discovery channel.**
- FPT offers a sensitive probe of the CP structure of the Higgs sector.

1. Thou shalt not worship any other god but the *First Principles*, and even if **thou likest it not,** go by **thy** (QCD) *Book.*

2. Thou slalt not make unto **thee** any **graven image,**

thou shalt not bow down **thyself** to them.

3.Thou shalt not ignore existing diffractive data.

(a 'restriction order' on the theoretical fantasies)

4. Thou shalt draw **thy** daily guidance from the **standard candle processes** for testing **thy** theoretical models.

5. Thou shalt remember the **speed of light** to keep it **holy.** (trigger latency)

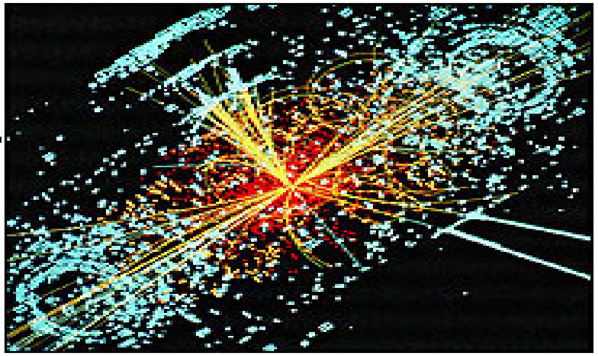
6.Thou shalt not dishonour backgrounds and **shalt** study them with great care.

7.Thou shalt not forget about the pile-up (an invention of **Satan**).

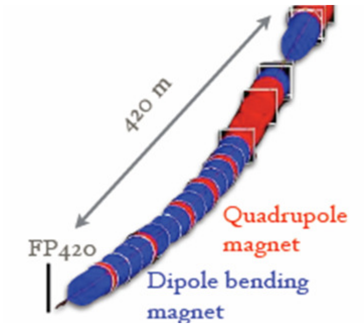
8. Though shalt achieve the best possible fast-timing resolution.

9. Thou shalt not annoy machine people.

10. Thou shalt not delay, the start of the LHC experimental programme is **approaching.**



FP420



Alberta, Antwerp, UT Arlington, Brookhaven,
CERN, Cockroft, UC Davis, Durham, Fermilab,
Glasgow, Helsinki, Lawrence Livermore,
UCL London, Louvain, Kraków, Madison/Wisc,
Manchester, ITEP Moscow, Prague,
Rio de Janeiro, Rockefeller, Saclay, Santander,
Stanford U, Torino, Yale.

January 4, 2009

The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC

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FP420 R&D Collaboration

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†Now at Rice University

There has been huge progress over the past few years…

- ATLAS has LOI
- CMS in refereeing phase

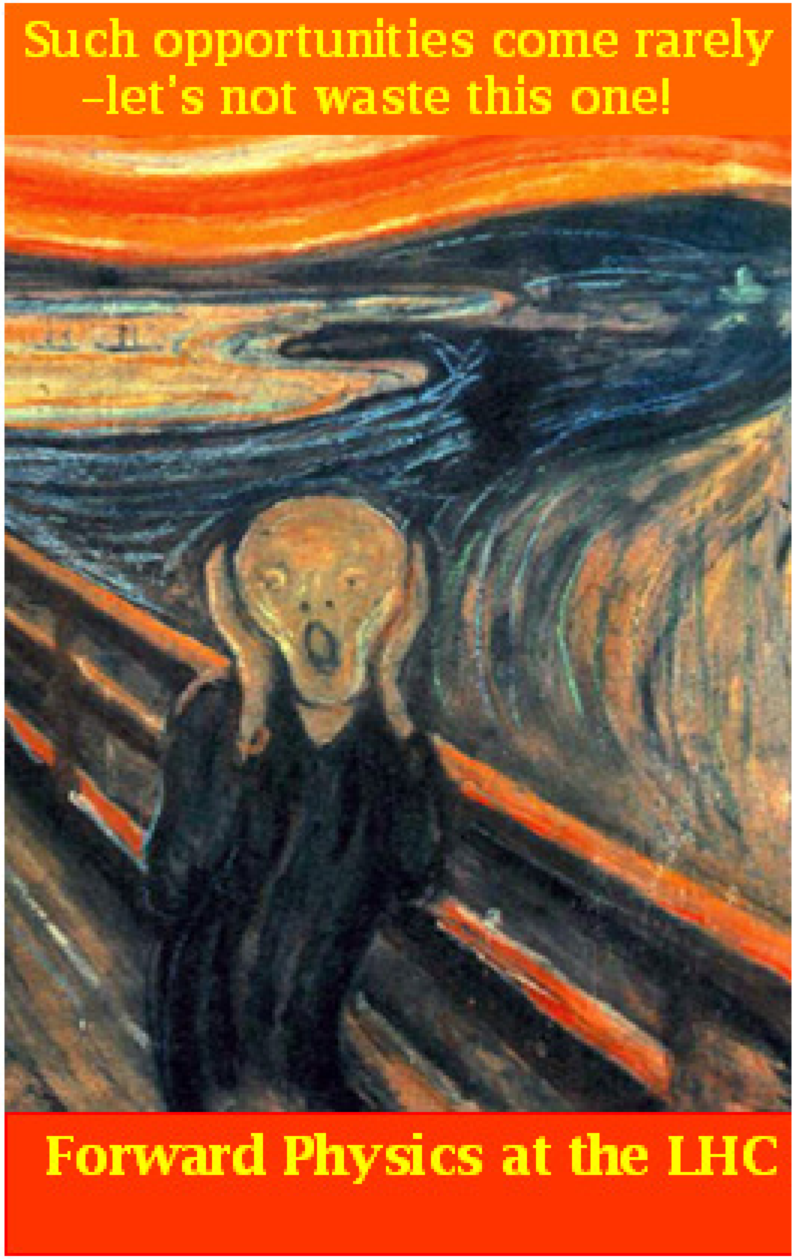
?

- Decisions – spring 2009
- Installation – 2011-2013

- 175 page report
- 96 authors
- 29 institutions

FP420 - Summary

- Near beam detectors at 420m will extend the physics potential of the central detector CMS.
  - Main physics aim pp $\rightarrow$ p+ X + p
    - Higgs, in particular (N)MSSM, New physics, Exotic physics
    - QCD/diffractive studies
      - dijets, WW, 2 photon production measurements etc.
    - Photon induced interactions
      - Significant sensitivity to new physics
  - Data taking at 10^{34} $cm^{-2}s^{-1}$ seems feasible
- ATLAS: FP420 part of the 'forward detector package'
- CMS: project being evaluated by internal referees
- FP420 is an excellent 'extension' of the CMS/ATLAS baseline detector. First DPE events in FP420 in 2010?


Such opportunities come rarely
-let's not waste this one!
Forward Physics at the LHC

Backup

σ(tot) , σ(el) , σ(SD)

- Bread and butter of TOTEM and ALFA measurements
- Importance for various LHC studies (e.g. notorious Pile-Up)
- Low mass SD (DD)- one of the major current limitations on the models (still not sufficient exp. Information)

KMR-07: relatively low (about 20% below the ‘standard’ central value) value of σ(tot) at the LHC
(S.Sapeta and K. Golec-Biernat-05)

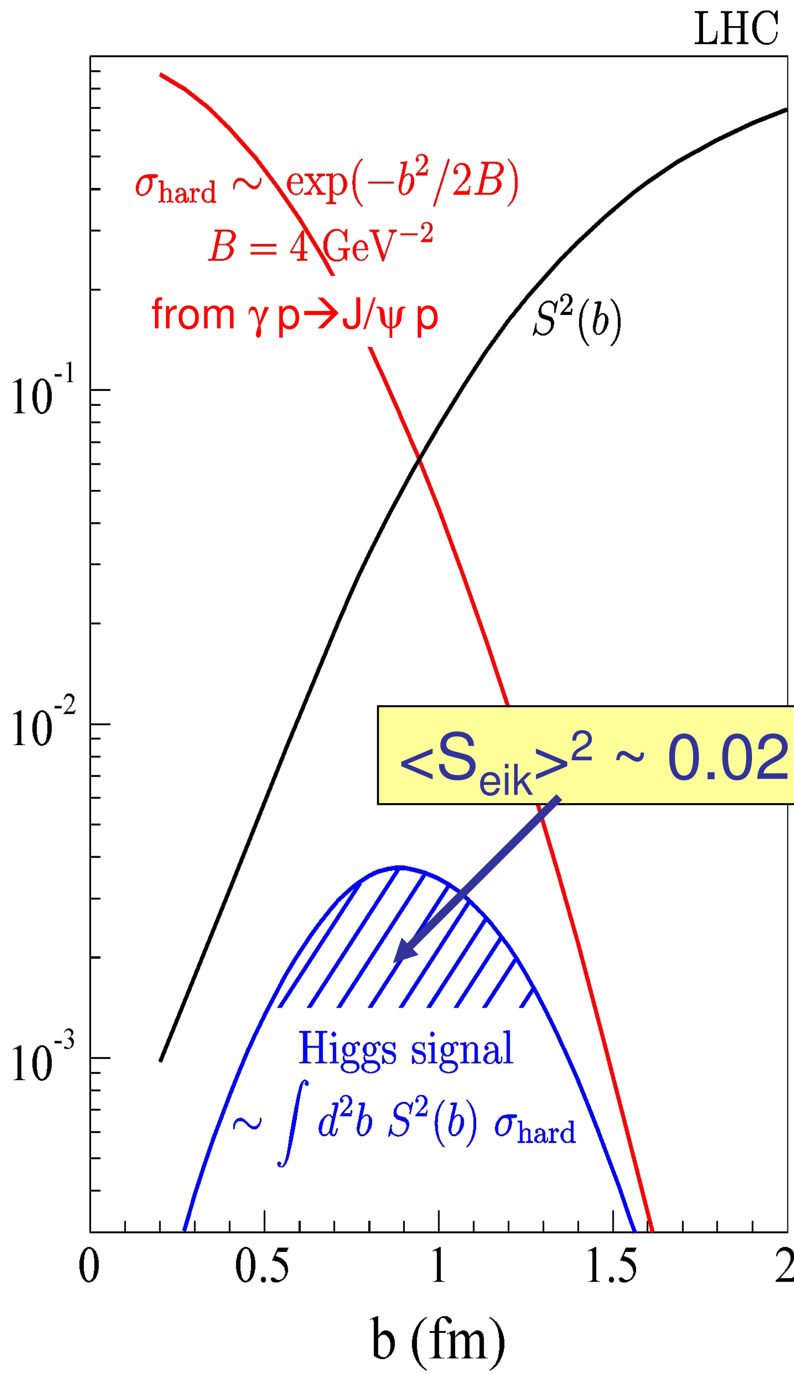
, **σ(tot) ≈90 mb** …cosmic rays, (early) LHC tests – coming soon

inescapable consequence of the absorptive corrections caused by the higher-mass excitations

GLM (arXiv; 0805.0418): σ(tot) =110.5 mb, σ(el) =25.3 mb

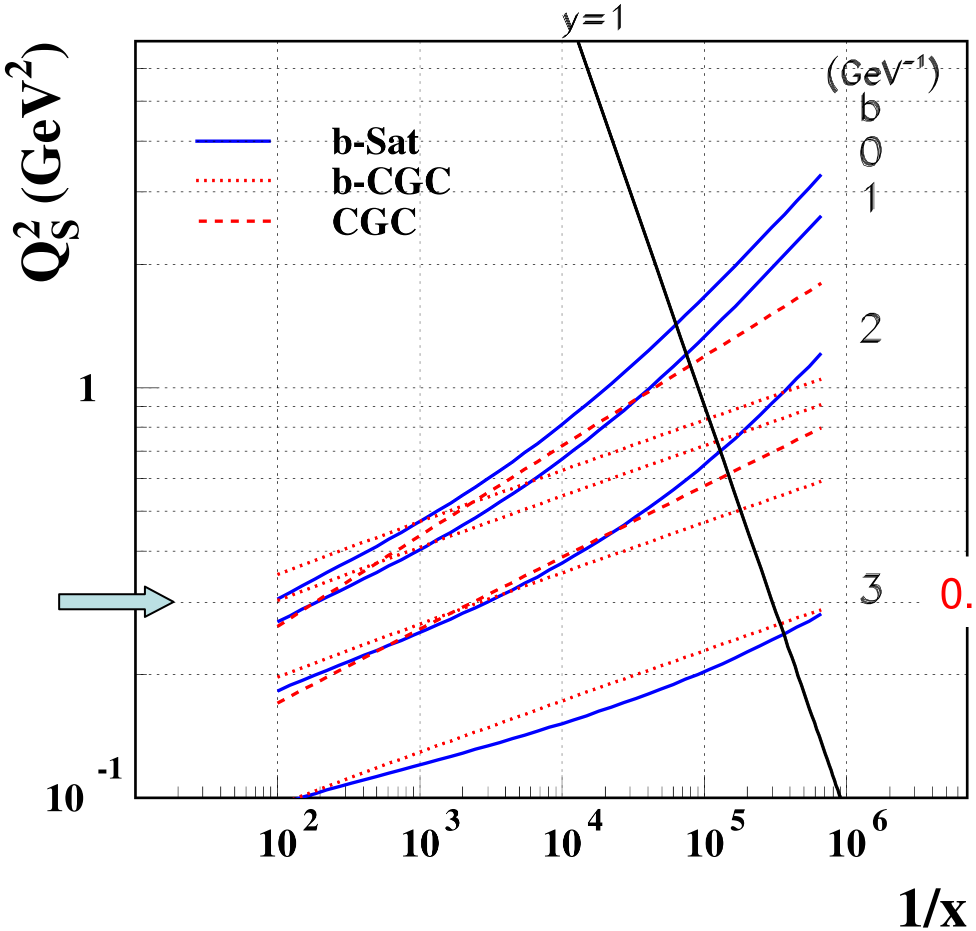
(GLM)M (arXiv; 0805.2799): σ(tot) = 92,1 mb, σ(el) =20.9 mb

KMR (2007) σ(tot) =90.5 mb, σ(el) =20.8 mb



<S_{eik}>^{2} ~ 0.02

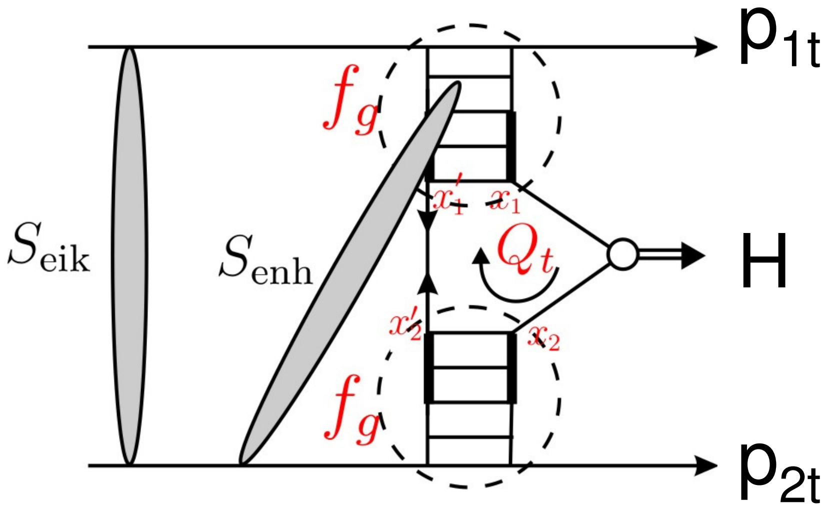
<S_{enh}>^{2} = ??



0.6 fm

Watt, Kowalski

Survival prob. for pp → p+H+p



$<S^2_{eik}> \sim 0.02$ consensus
$<S^2_{enh}> \sim 0.01 - 1$ controversy

KMR 2008 →
$<S^2>_{tot}=<S^2_{eik}S^2_{enh}> \sim 0.015$ ($B=4\ GeV^{-2}$)

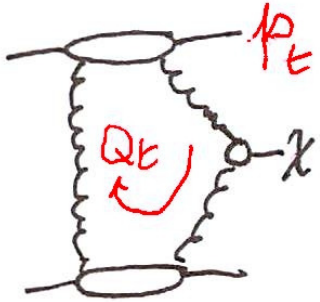
However enh. abs. changes p_t behaviour from exp form, so

$<S^2>_{tot}<p^2_t>^2 =$

0.0015	LHC	KMR 2000 (no S_{enh})
0.0030	Tevatron	
0.0010	LHC	KMR 2008 (with S_{enh})
0.0025	Tevatron	

see arXiv:0812.2413

Exclusive $\bar{p}p \to \bar{p} + \chi_c + p$



CDF: $\chi_c \to J/\psi\,\gamma \to \mu^+\mu^-\gamma$ (0.06 for $J/\psi \to \mu^+\mu^-$)

$$\left.\frac{d\sigma_\chi}{dy}\right|_{y=0} = 76 \pm 14 \text{ nb}$$

B. fractions:	0^{++}	0.013		~30 nb
	1^{++}	0.36	$\sim \langle p_t^2\rangle/M^2$	"
	2^{++}	0.20	$\sim \langle p_t^2\rangle^3/Q_t^4$	"

even tho' $\frac{\chi_0}{\chi_1} \sim \frac{\chi_0}{\chi_2} \sim 10\text{-}40$

The KMRS pred^n is reduced by $S^2_{enh} \sim 1/3$ and by 1.45 due to a revised $\Gamma_{tot}(\chi_c(0))$

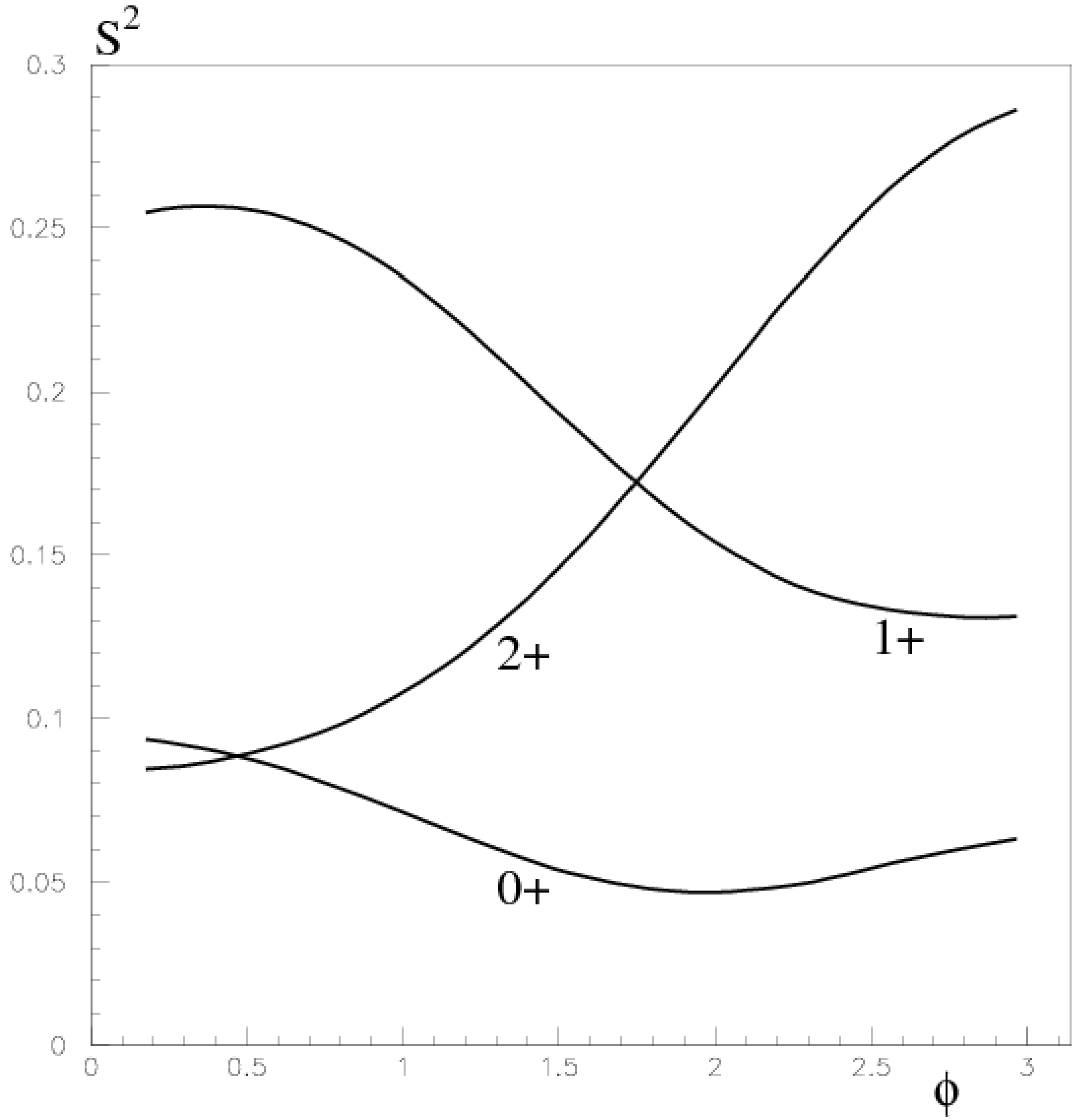
KMRS: only order-mag. pred$^{\underline{ns}}$
(light M_X, non-pQCD effects)

Better decay channels $\chi_c \to \pi\pi$ or $K\bar{K}$

B. fractions	0^{++}	~1%
	1^{++}	forbidden
	2^{++}	suppressed

χ_b ?

S^2 for the Tevatron energies



$\langle S^2 \rangle$= 0.065 (0++); 0.16 (1++); 0.17(2++)

Probing CP violation in the Higgs Sector

Azimuthal asymmetry in tagged protons provides direct evidence for CP violation in Higgs sector

$$A = \frac{\sigma(\varphi < \pi) - \sigma(\varphi > \pi)}{\sigma(\varphi < \pi) + \sigma(\varphi > \pi)}$$

$M(H_1)$ GeV	cuts	30	40	50
$\sigma(H_1)\mathrm{Br}(\tau\tau)$	a, b	1.9	0.6	0.3
$\sigma^{\mathrm{QED}}(\tau\tau)$	a, b	0.2	0.1	0.04
$A_{\tau\tau}$	b	0.2	0.1	0.05

(b) $p_i^{\perp} > 300$ MeV for the forward outgoing protons

'CPX' scenario
(σ in fb)

KMR-04

$$\mathcal{M} = g_S \cdot (e_1^{\perp} \cdot e_2^{\perp}) - g_P \cdot \varepsilon^{\mu\nu\alpha\beta} e_{1\mu} e_{2\nu} p_{1\alpha} p_{2\beta} / (p_1 \cdot p_2)$$

CP even

CP odd active at non-zero t

A is practically uPDF - independent

(Similar results in tri-mixing scenaio (J.Ellis et al))

Exclusive $\mu^+\mu^-$ Candidates (High Mass)

Invariant Mass - Upsilon Region

$$\Delta\phi > 120^0,\ p_T(\mu^+ + \mu^-) < 7\ \mathrm{GeV/c}$$

Branching ratios for μ+μ- channels:

Υ(1s)[9.46 GeV] : 2.5%

Υ(2s)[10.02 GeV] : 1.3%

Υ(3s)[10.36 GeV] : 1.8%

Clearly visible peaks Υ(1s) and Υ(2s), perhaps Υ(3S) too.
+ continuum