Central Exclusive Processes at the Tevatron and LHC

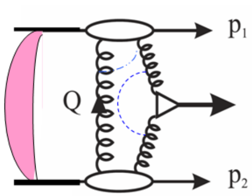
V.A. Khoze (IPPP, Durham)

"...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 extended 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 SM & to search for and to identify the nature of, New Physics at the LHC;
- to discuss the new Exclusive results at the Tevatron;
- to attract new members to the Exclusive Forward Club.



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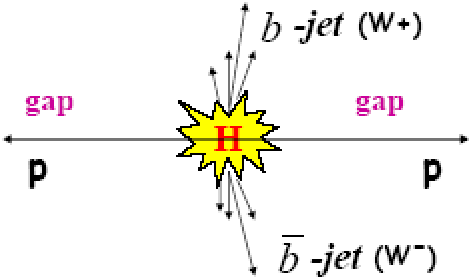
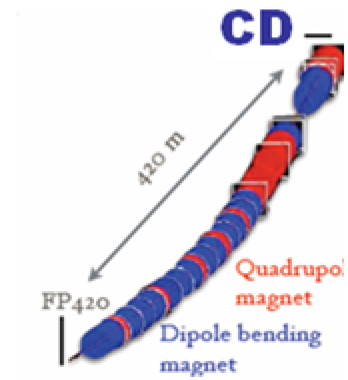


PLAN



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* ***(experimental checks at the Tevatron).***

5. Prospects for CED Higgs production.

6. *Other* BSM *scenarios, 'Exotics'.*

7. Conclusion.

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

The LHC is a discovery machine !

➔ *High -pt signatures in the central region*

But…

with a bit of personal flavour

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 δL ≤5% , machine ~10-15%, progress with the W/Z(MSTW))

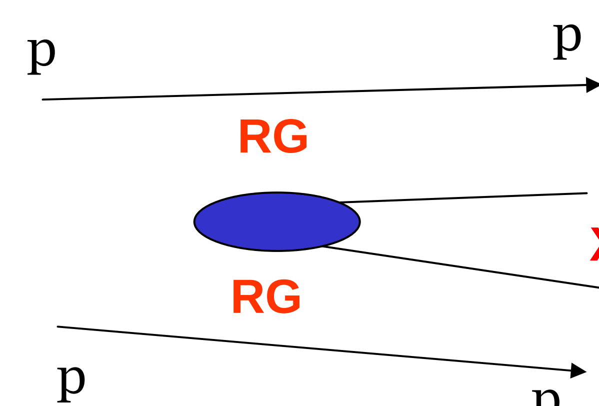
Lack of :

The LHC is not a precision machine (yet) !

•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)

Forward detectors at LHC

FAD -bj

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.

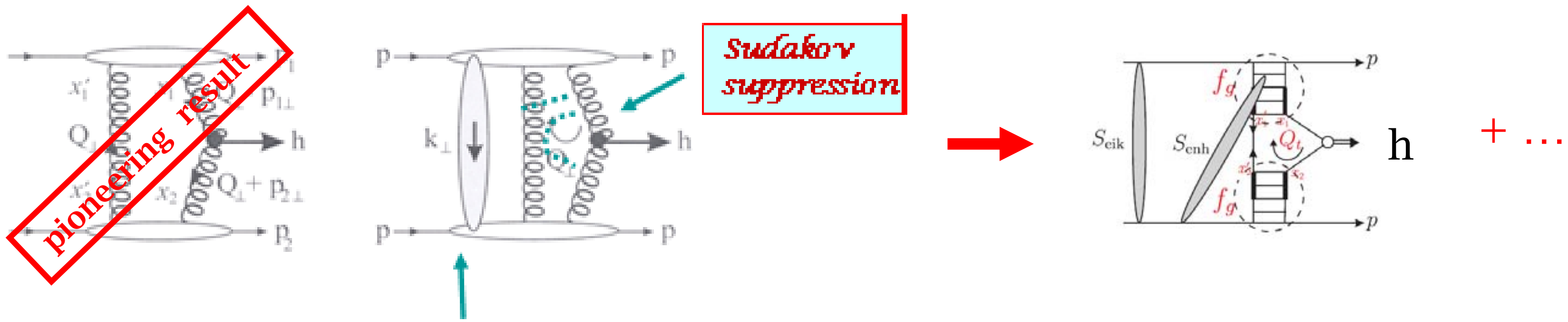
FPT ▶ will open up an additional rich physics menu ILC@LHC

✳ 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 Durham approach
(Khoze-Martin-Ryskin-Stirling 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, GLMM08-09, KMR07-09)

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

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

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 $W = \mathbf{S^2\ T^2}$

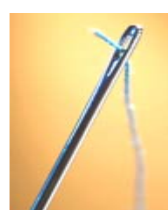
Colour charges of the 'digluon dipole' are screened only at $r_d \geq 1/(Q_t)_{ch}$

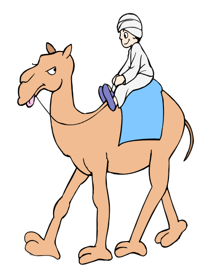
GAP Keepers (Survival Factors) , protecting RG against:

- 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

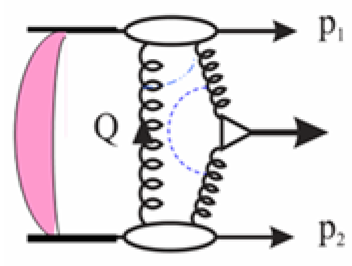




P → **H** ← **P**

KMR technology (implemented in ExHume MC)

(Khoze-Martin-Ryskin 1997-2009)



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

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

σ(CDPE) ~ 10^{-4} σ (incl)

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

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

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

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

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

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

Tg + 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 $\gamma\gamma$ Collider

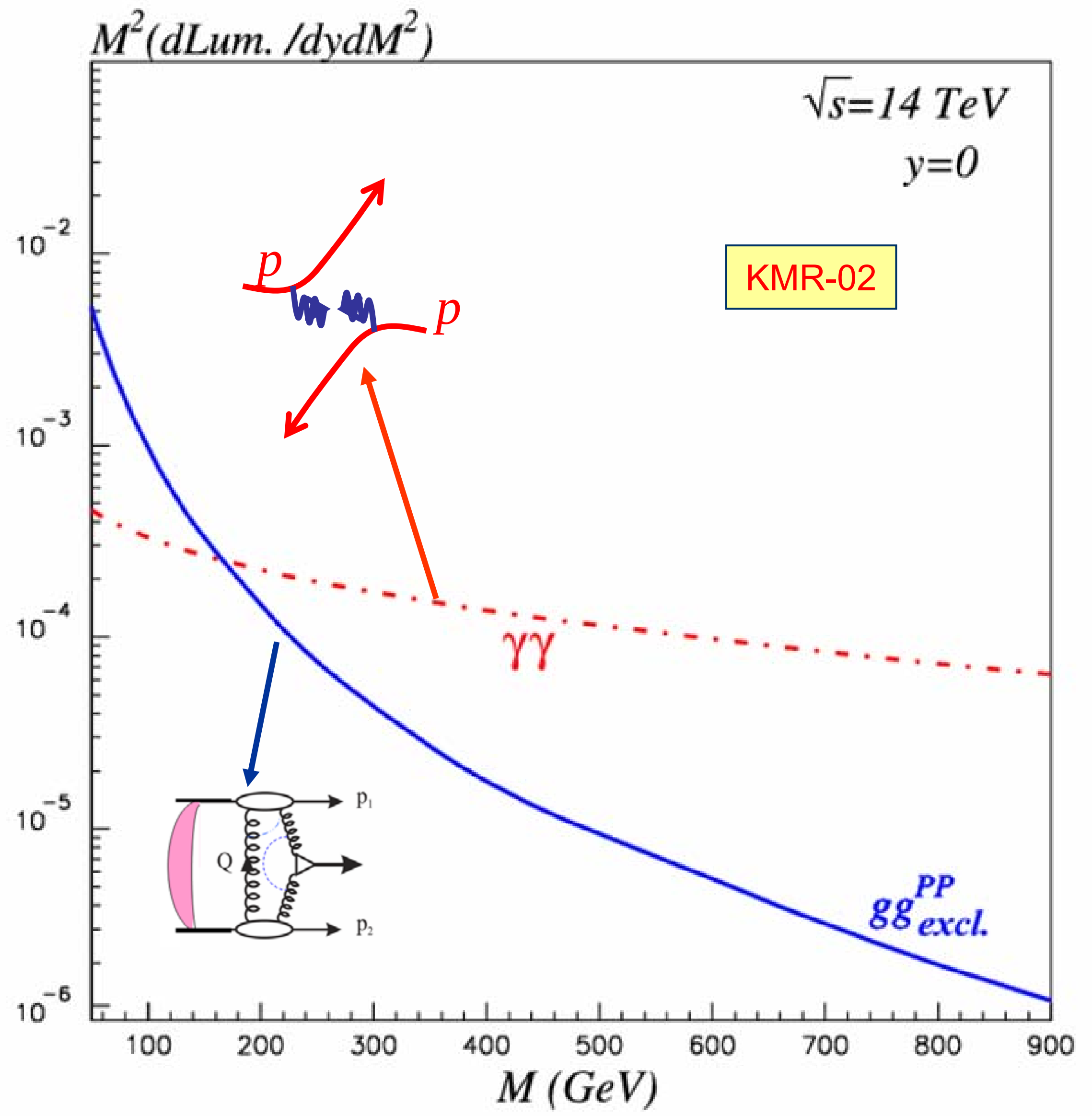
$$\sigma(\gamma\gamma \rightarrow SMH) \approx 0.1 fb$$

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

$$\alpha_S^2/8 \rightarrow \alpha^2$$

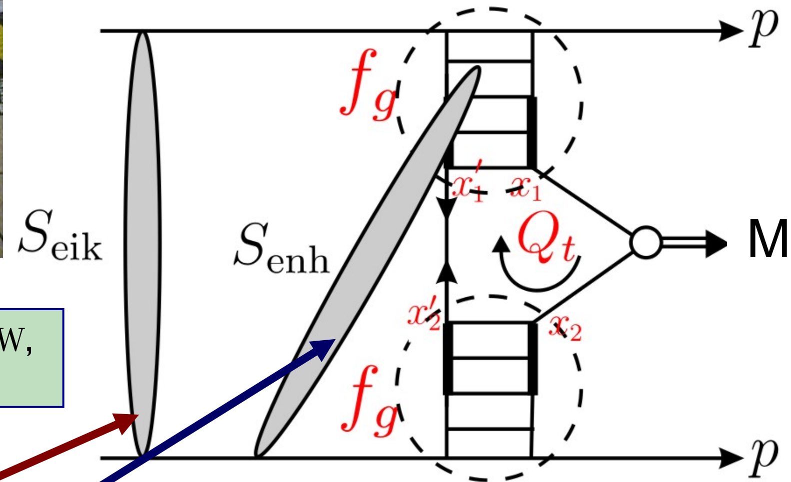
QCD 'radiation damage' in action

QCD Sudakov Formfactor



“soft” scattering can easily destroy the gaps

S² ➔ absorption effects -necessitated by unitarity



gap

gap

Everybody’s happy (KMR, GLM, FHSW, Petrov et al, BH, GGPS, Luna…MCs)

eikonal rescatt: between protons

enhanced rescatt: involving intermediate partons

soft-hard factoriz^{n} conserved

broken

Subject of hot discussions nowadays : S²enh

Selection Criteria for the Models of Soft Diffraction

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

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

with a bit of personal flavour

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. neutrons at HERA

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

So far Durham 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.

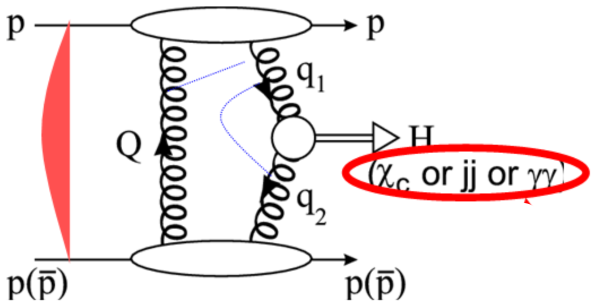
Tevatron data & program of Early LHC measurements (KMR)

LET THE DATA TALK !

Standard Candle Processes

'BETTER TO LIGHT A CANDLE THAN TO RANT AGAINST DARKNESS'

(Confucius)



The process p-p→$\gamma\gamma$/ χ_c/ χ_b/ j-j are standard candles for the exclusive Higgs

孔夫子

孔丘 Kong Qiu

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 (PRD-2008)
  CDF: data up to $(Et)_{min}>35$ GeV

- 'Factorization breaking' between the effective diffractive structure functions measured at the Tevatron and HERA. **CDF**

- The ratio of high Et dijets in production with one and two rapidity gaps. **CDF**

- **CDF** results on exclusive charmonium CEP, (**CDF**, PRL-09)

- 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 & ? more candidates in the new data)

- Leading neutrons at HERA

(Cannot detect p/pbar, down beam pipe, but BSC → η = 7.4 empty)

* $p+\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$
* $p+\bar{p} \rightarrow p+\chi_c+\bar{p}$
$p+\bar{p} \rightarrow p+\chi_b+\bar{p}$
* $p+\bar{p} \rightarrow p+JJ+\bar{p}$

Cleanest (no S.I.) but smallest σ
KMR: 38 pb in our box). 2+1 candidates

Clean, big σ: $\frac{d\sigma}{dy}(y=0) \sim 100\,\text{nb}$ (KMRS)

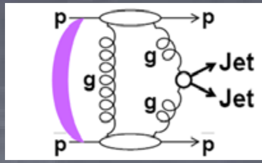
but M(c) small (non-pert) & hadron

More perturbative, smaller theory uncertainty
But σ ~ 1/500$^{\text{th}}$ χc. Also BR's not known!
See next slide.

Big cross section, but least well defined (jets!)
and largest background. ~ 100 pb for M(JJ) > 30 GeV

Our 3 measurements are all in good agreement (factor "few") with the Durham group predictions.

Comparison with KMR



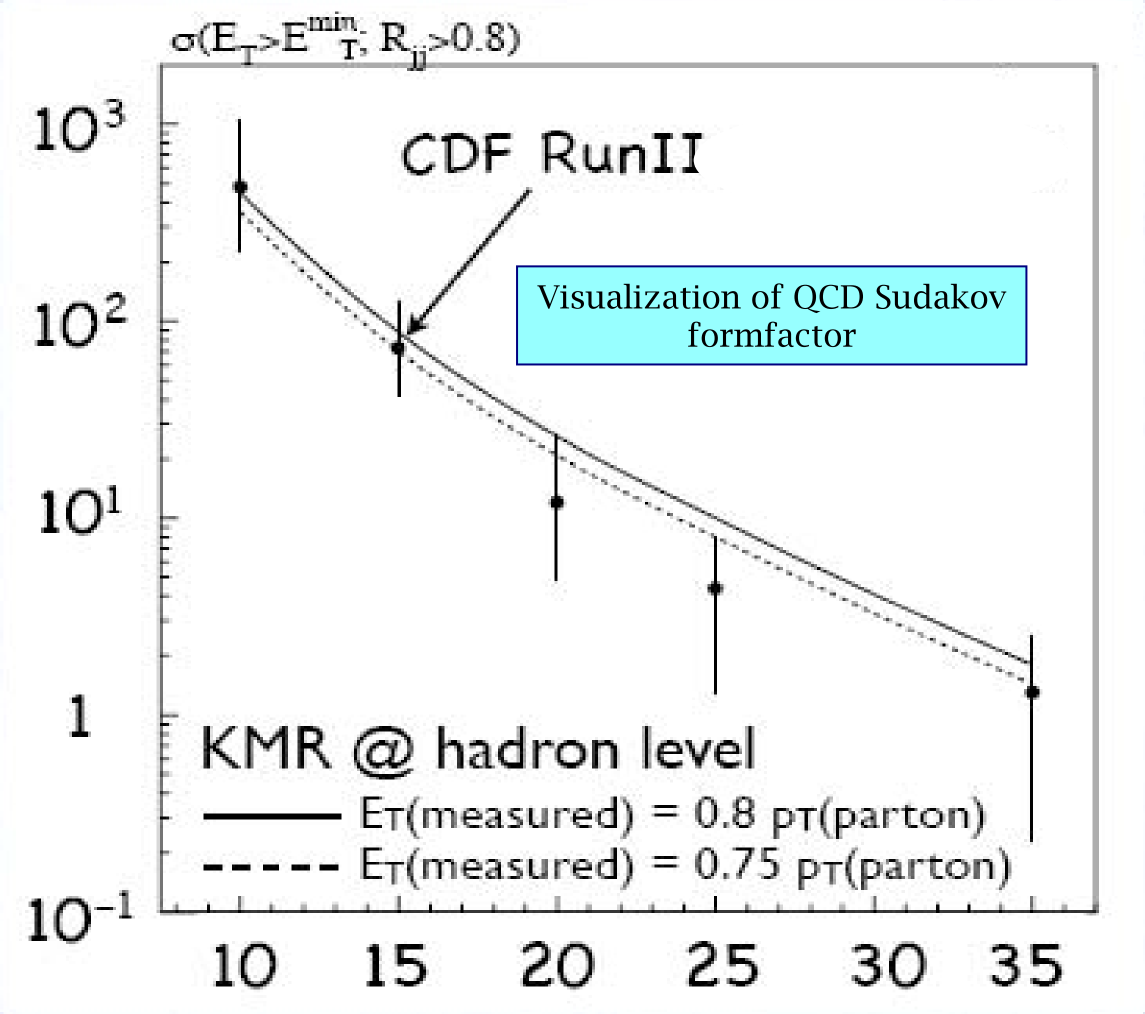
More direct comparison with KMR calculations including hadronization effects preferred

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

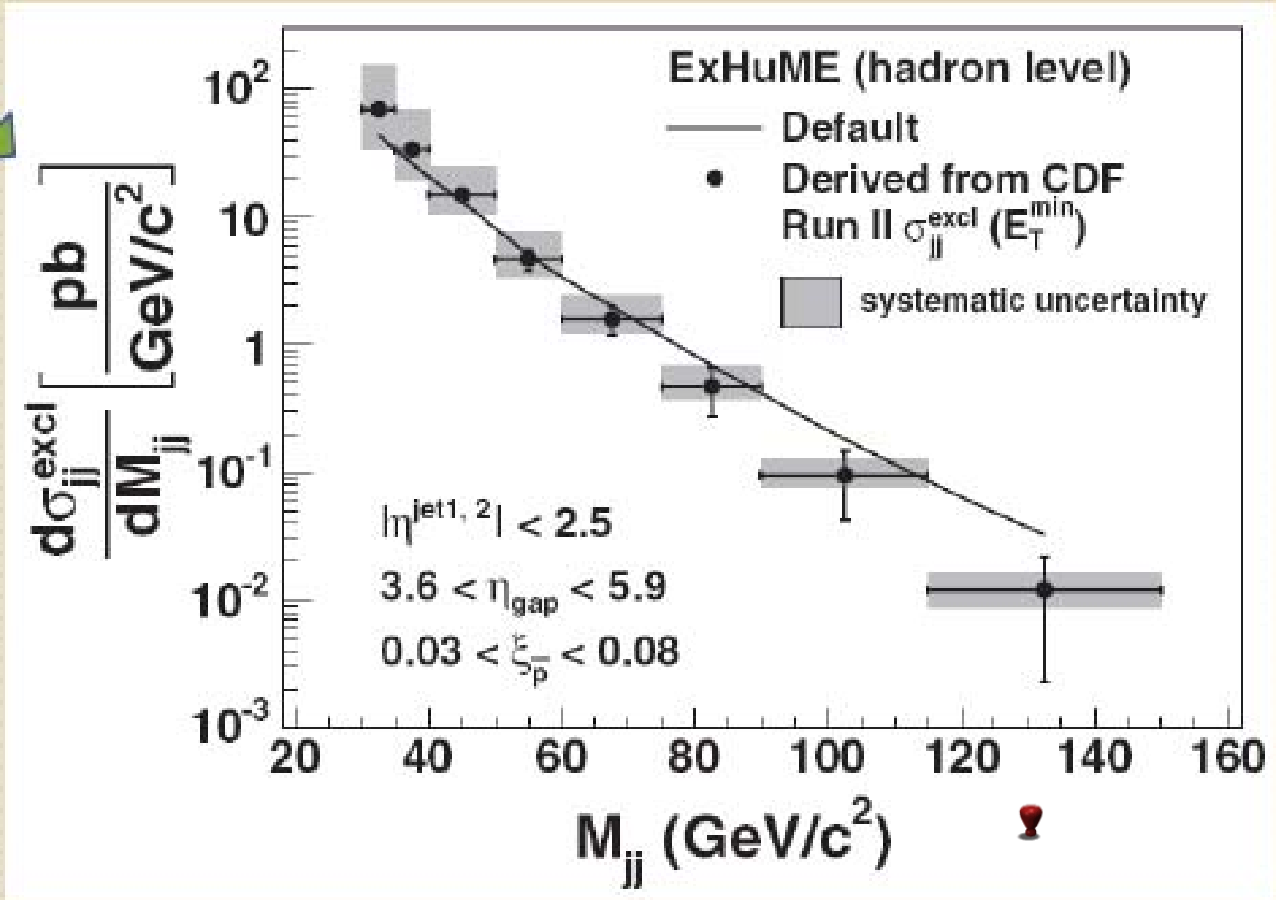


A killing blow to the wide range of theoretical models.

CDF PRD-2008

(Jim)

derived from CDF excl. dijet x-sections using ExHuME



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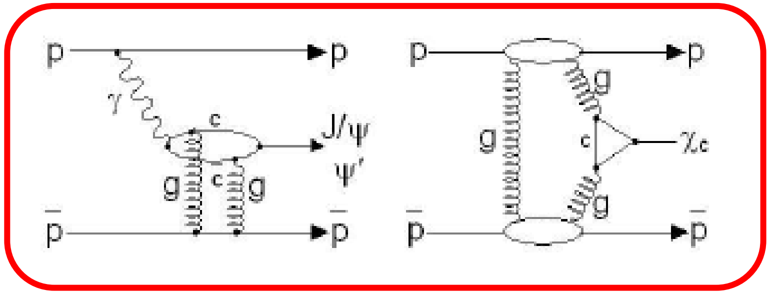
Excl. Cross Section vs Dijet Mass

Stat. and syst. errors are propagated from measured cross section uncertainties using M_{jj} distribution shapes of ExHuME generated data.

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]



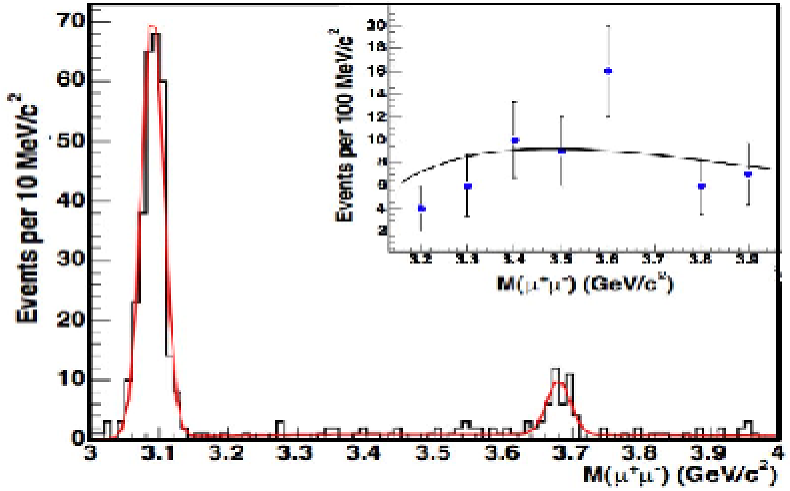


FIG. 2: Mass $M_{\mu\mu}$ distribution of 402 exclusive events, with no EM shower, (histogram) together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the J/ψ and excluding $3.65 < M_{\mu\mu} < 3.75$ 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** → **80 nb** (PDG-2008)

ππ/KK mode as a spin-parity analyzer

Prospects of χ(b)-spectroscopy , FSC@CMS

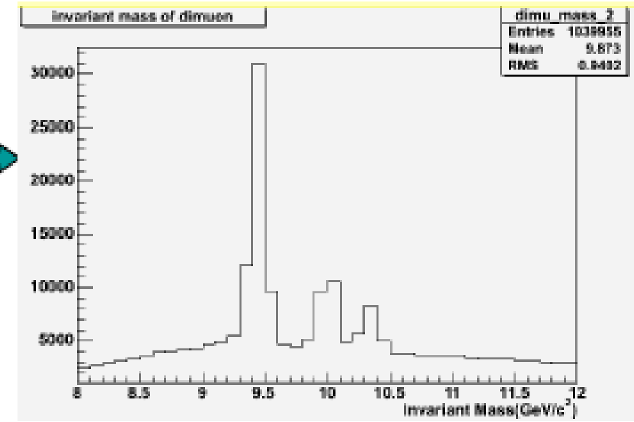
Dimuons: Upsilon Region

Trigger: $\mu+\mu-$
$|\eta|<0.6$, $pT(\mu) > 4$ GeV/c

Search for/measurement of photoproduction of Υ(1S),Υ(2S),Υ(3S) (not before seen in hadron-hadron)

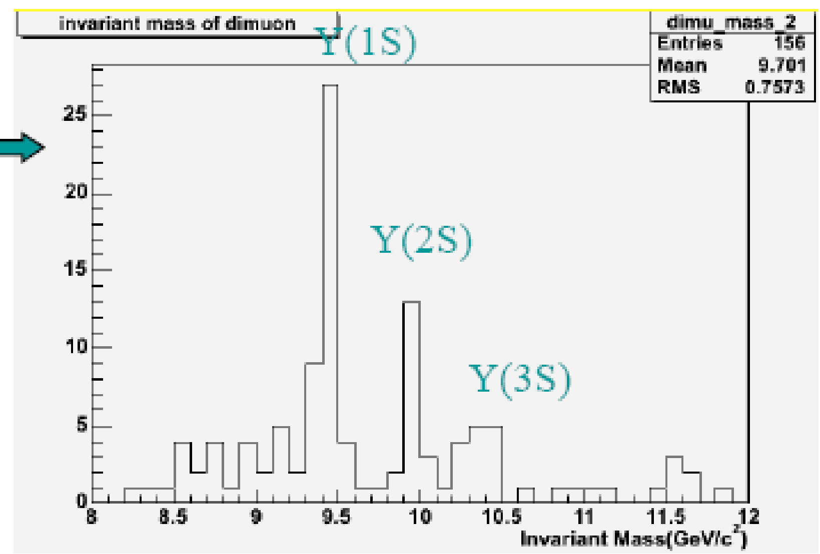
Inclusive

CDF Run II Preliminary



Invariant Mass
0 associated tracks
$pT(\mu\mu) < 1.5$ GeV/c

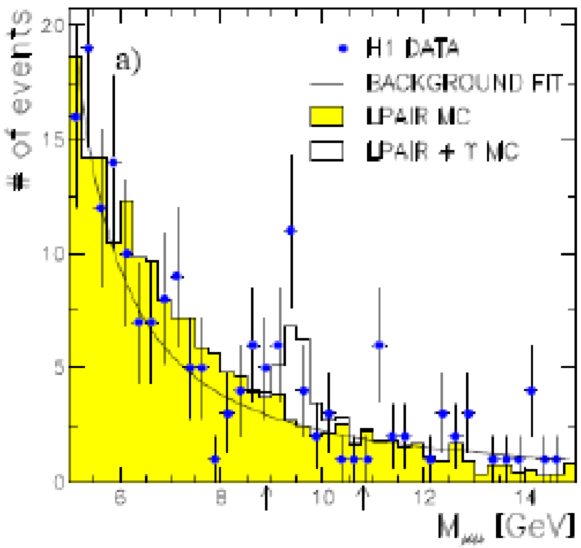
CDF Run II Preliminary



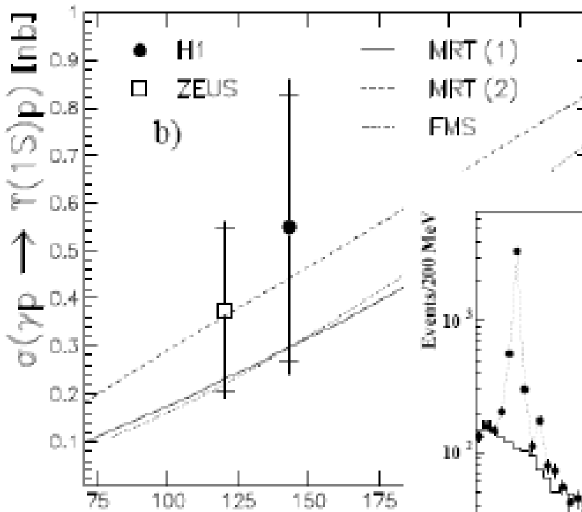
Status:
analysis in progress.
QED continuum check
Υ : cf HERA (we resolve states)
Can we see $\chi_b \to \Upsilon + \gamma$?

HERA: e + p

H1

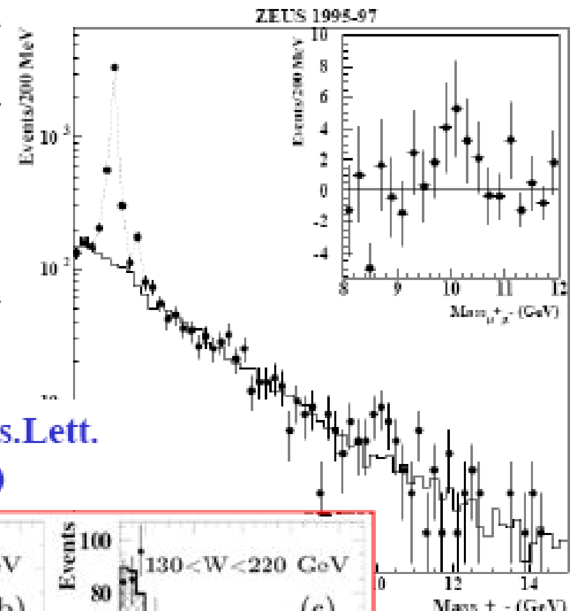


Phys.Lett.B483:23-35 (2000)



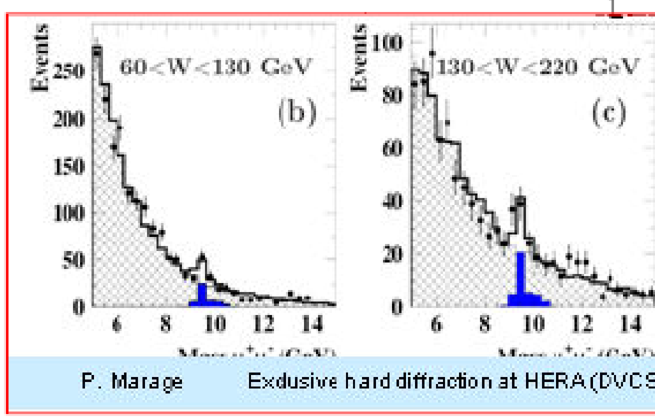
J.Breitweg et al.,Phys.Lett.
B437: 432-444 (1998)

ZEUS



Y(1),Y(2),Y(3) signals in CDF cleaner than at HERA!
Better mass resolution,
less γγ→μμ background.
BUT χ_b → Y+γ background absent at HERA!

Just saw
in Marage talk



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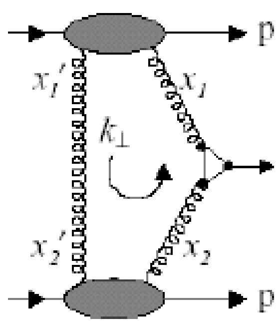
PRL 99, 242002 (2007) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2007

Search for Exclusive $\gamma\gamma$ Production in Hadron-Hadron Collisions

Khoze, Martin and Ryskin, Eur.Phys.J. C23: 311 (2002) ; KMR+Stirling hep-ph/040903?

Claim factor ~ 3 uncertainty ; Correlated to p+H+p



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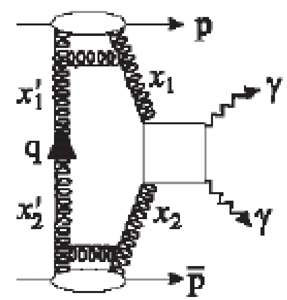
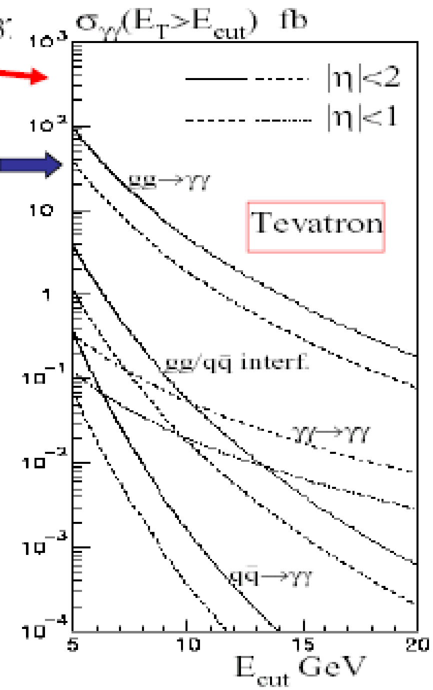
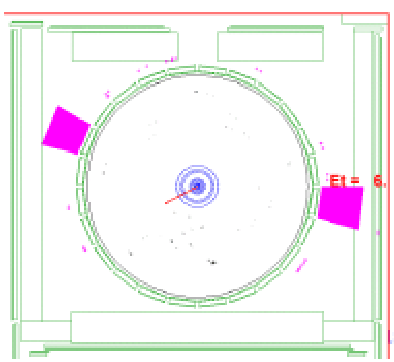


36 fb



$\gamma\gamma \to \gamma\gamma$ & $q\bar{q} \to \gamma\gamma$ much smaller



$E_T(\gamma) > 5\,\mathrm{GeV}; |\eta(\gamma)| < 1.0$

3 candidates, 2 golden, 1 ? $\pi^0\pi^0$?

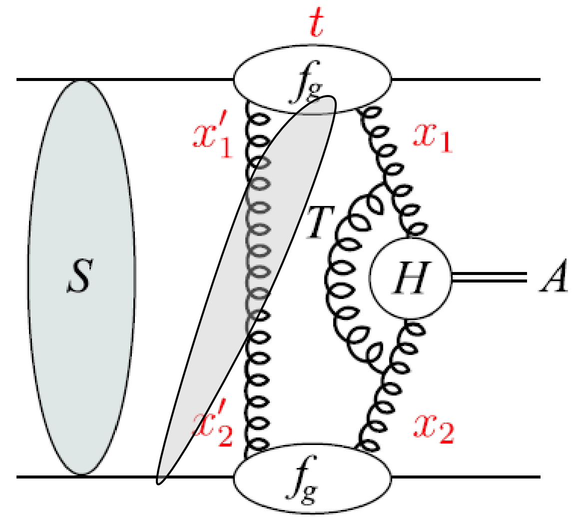
36 fb → 0.8 events

$\text{Note}: \sigma_{MEAS} \approx 2\times10^{-12}\,\sigma_{INEL}$!

New data, Lower threshold, possible "observation"

sive production in CDF: M > 8 GeV

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 : $\gamma p \rightarrow \Upsilon p$

(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 consensus on the LHC Higgs search prospects

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

mH (SM) <150 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……

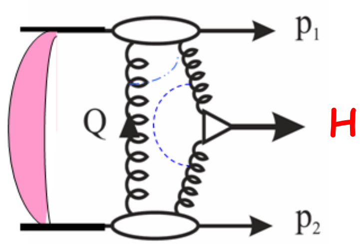
'Just' a discovery will not be sufficient!

• After discovery stage (Higgs Identification):

SPIN-PARITY

✱ 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* .

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 Yukawa coupl.)
  (gg)$_{CED}$ $\not\to$ bb in LO ; NLO,NNLO, b- mass effects – controllable.

- For some BSM scenarios CEP may become *a* discovery channel !
- H →WW* (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?

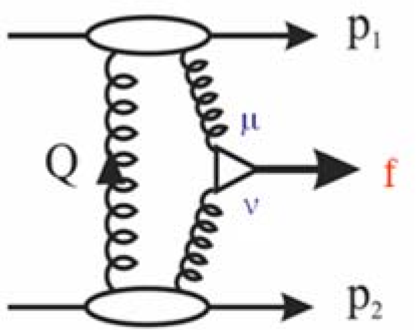
mass, spin, couplings to fermions and Gauge Bosons, invisible modes…
→ for all these purposes the CEP will be particularly useful !

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 ($\Delta M/M$) –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 $(\bar{Q}_t)$ 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)

in terms of the **MHV rules** the only nonzero amplitudes

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

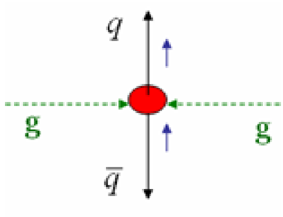
(-+ ; -+ /+-)

(S .Parke, T.Taylor (1986))

an advantageous property of the $gg^{PP} \to q\bar{q}$ large angle amplitudes

- all HNCA (Jz=0, Jz=2, all orders in α_s) are suppressed by m_q / E_T
- all HC gg^{PP} ampts ((Jz=0, Jz=2, all orders) are prop. $\cos\theta$ → vanish at 90°

(z)



rotational invariance around q-direction (Jz=2, PP-case only)

$$60^\circ < \theta < 120^\circ \to |\eta_1 - \eta_2| < 1.1$$

(acceptance of CD and suppression of t-channel singularities in background processes)

- LO HCA vanishes in the Jz=0 case (*valid only for the Born amplitude*)

Jz=0 suppression is *removed* by the presence of an additional (*real/ virtual*) gluon
But the contributions are still very small (KMRS -06)

MHV results for gg(Jz=0)→qq +ng, mg amplitudes (QCD backgrounds, jet calibration…)
cut-nonreconstructible contributions (KRS 06)

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

KKMR-04

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

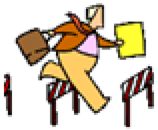
Myths

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 the extended Durham group)

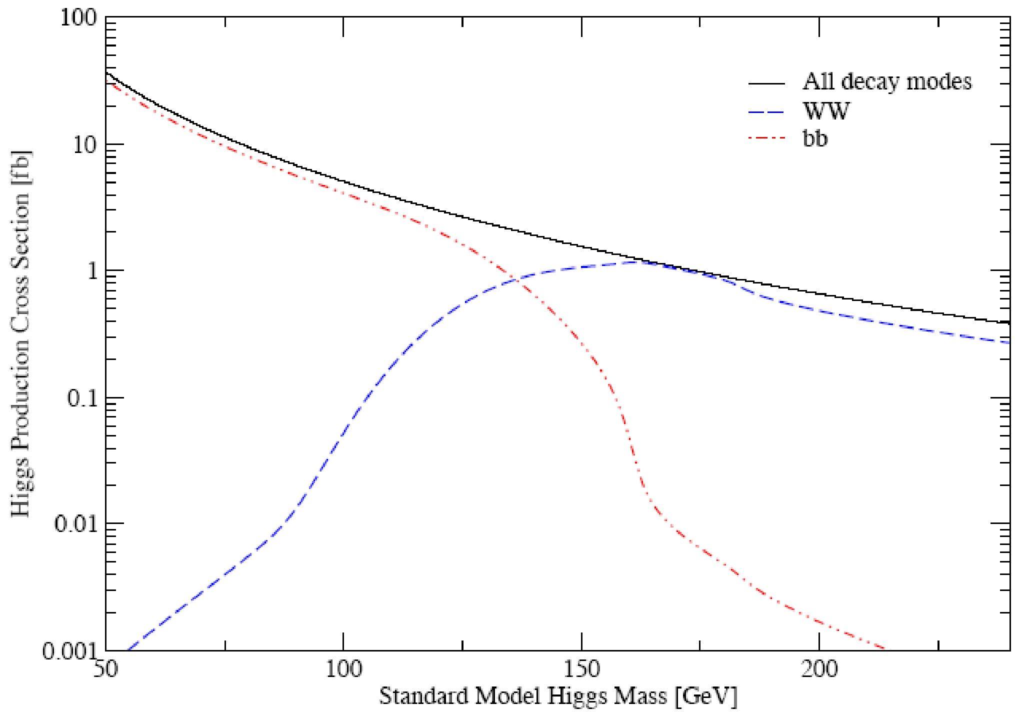
❶ admixture of |Jz|=2 production.
❷ NLO radiative contributions (hard blob and screened gluons)

❸ NNLO one-loop box diagram (mass- unsuppressed, cut-non-reconstructible)
❹ 'Central inelastic' backgrounds (soft and hard Pomerons)
❺ b-quark mass effects in dijet events (Shuvaev+KMR-08)
❻ radiation off screening gluon (KMR-09)
……….

Not fully in MCs yet

SM Higgs

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

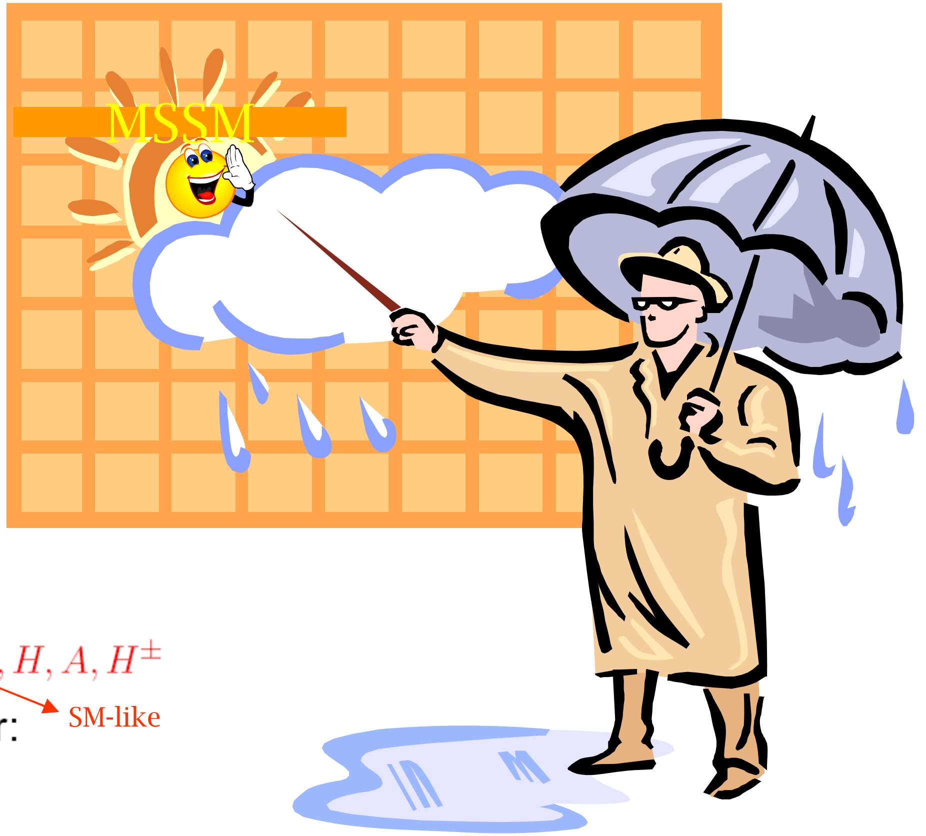


Cox, de Roeck, Khoze, Pierzchala, Ryskin, Stirling, Nasteva, Tasevsky -04

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 $h, H, A, H^{\pm}$

  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
  $\Rightarrow$ no HVV coupling
  $\Rightarrow$ no Higgs production in weak boson fusion
  $\Rightarrow$ no decay $H \to ZZ \to 4\mu$

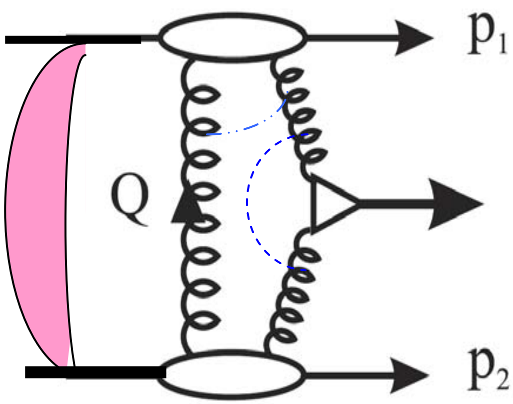
  Large enhancement of coupling to $b\bar{b}$ (and $\tau^+\tau^-$) in region of high $\tan\beta$

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

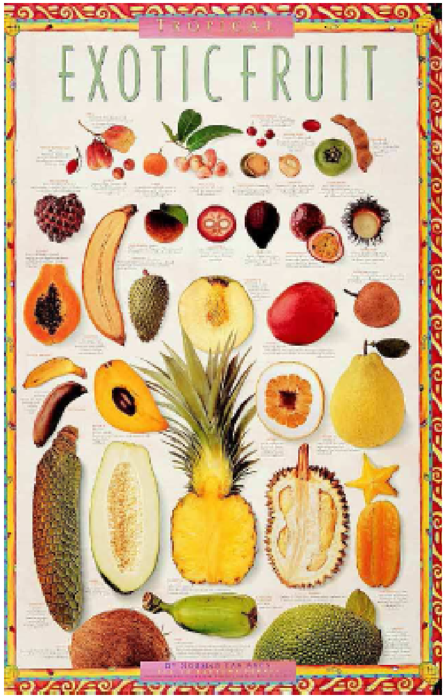
The backgrounds to the diffractive H bb mode are manageable!

The MSSM and more '*exotic*' scenarios

$$pp \rightarrow p + \phi + p$$



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)

Potentially of great importance for electroweak baryogenesis

•Triplet Higgs bosons (CHHKP-2009)

•Fourth Generation Higgs

- NMSSM (J. Gunion, et al.)

- *Invisible' Higgs* (BKMR-04)

There is NO experimental preference for a SM Higgs. Any Higgs-like boson is very welcome !

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

$M_A \sim 130$GeV, tanβ ≥20

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

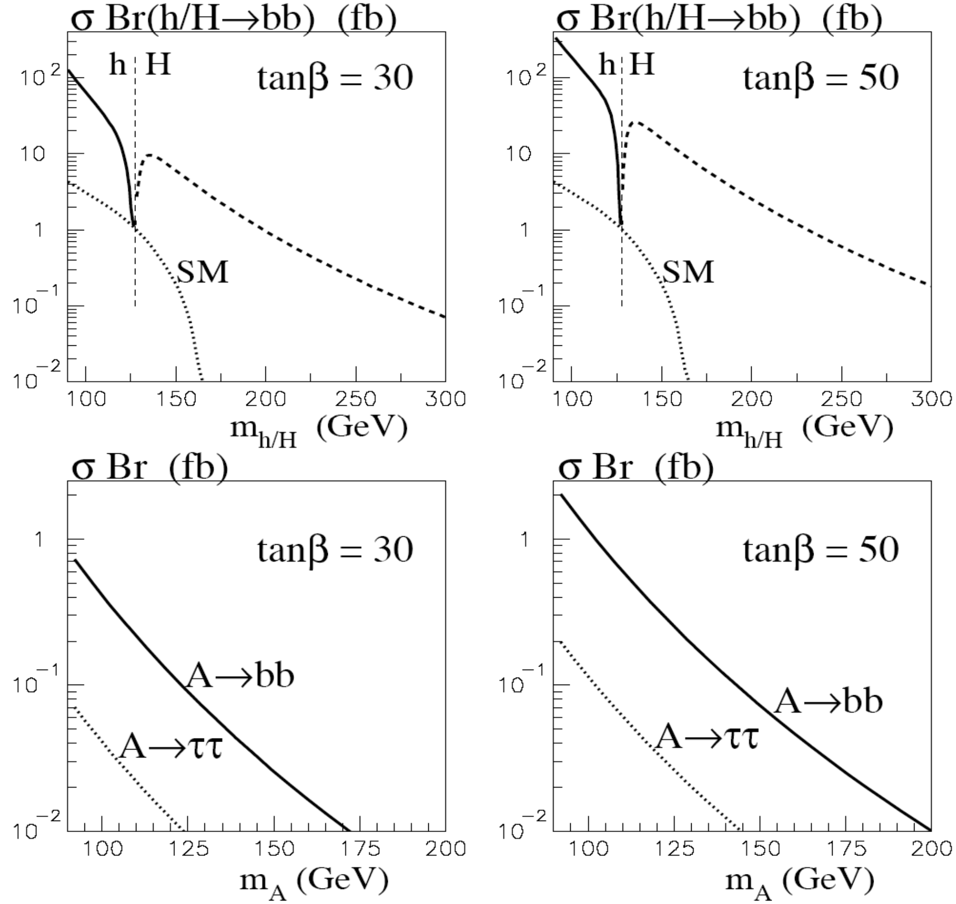
$gg \rightarrow \phi$ enhanced

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

CEP 'filters out' pseudoscalar production, leaving pure H sample for study

KKMR-04

Central exclusive diffractive production



A challenging region for conventional channels, tagged proton channel allows accurate mass measurement and is certainly a powerful **spin/parity filter**

Higgs spin-parity determination

Higgs coupling structure determination?

[T. Plehn, D. Rainwater, D. Zeppenfeld '01]
⇒ explore $HV_\mu V^\mu$ coupling ($V = W, Z$)
⇒ works well for $M_H = 160$ GeV (where $H \to WW$ is maximal)

Problem in MSSM:*

$$g_{hVV} = g_{HVV}^{\mathrm{SM}} \times \sin(\beta - \alpha)$$
$$g_{HVV} = g_{HVV}^{\mathrm{SM}} \times \cos(\beta - \alpha)$$
$$g_{AVV} = 0 \qquad \text{at tree-level}$$

$M_H \approx M_A \gtrsim 150$ GeV $\Rightarrow \beta - \alpha \to \pi/2$
$M_H \approx M_A \gtrsim 150$ GeV $\Rightarrow h$ has substantial VV coupling
$M_H \approx M_A \lesssim 130$ GeV $\Rightarrow H$ has substantial VV coupling

In the MSSM: $M_h \lesssim 130$ GeV

⇒ no heavy Higgs with substantial coupling to VV in the MSSM
⇒ method cannot be applied

* α diagonalizes the neutral $\mathcal{CP}$-even Higgs sector

Higgs coupling structure determination?

[C. Ruwiedel, M. Schumacher, N. Wermes '07]

$\Rightarrow$ explore $HW_\mu W^\mu$ coupling via $WW \to H \to \tau^+\tau^-$

$\Rightarrow$ $2\,\sigma$ effect for $M_H = 120$ GeV

Problem in MSSM:

$$g_{hVV} = g_{HVV}^{\text{SM}} \times \sin(\beta - \alpha)$$
$$g_{HVV} = g_{HVV}^{\text{SM}} \times \cos(\beta - \alpha)$$
$$g_{AVV} = 0 \qquad \text{at tree-level}$$

$M_H \approx M_A \gtrsim 150$ GeV $\Rightarrow$ h has substantial VV coupling
but no (sufficient) $h \to \tau^+\tau^-$ enhancement

$M_H \approx M_A \lesssim 130$ GeV $\Rightarrow$ H has substantial VV coupling
but no (sufficient) $H \to \tau^+\tau^-$ enhancement

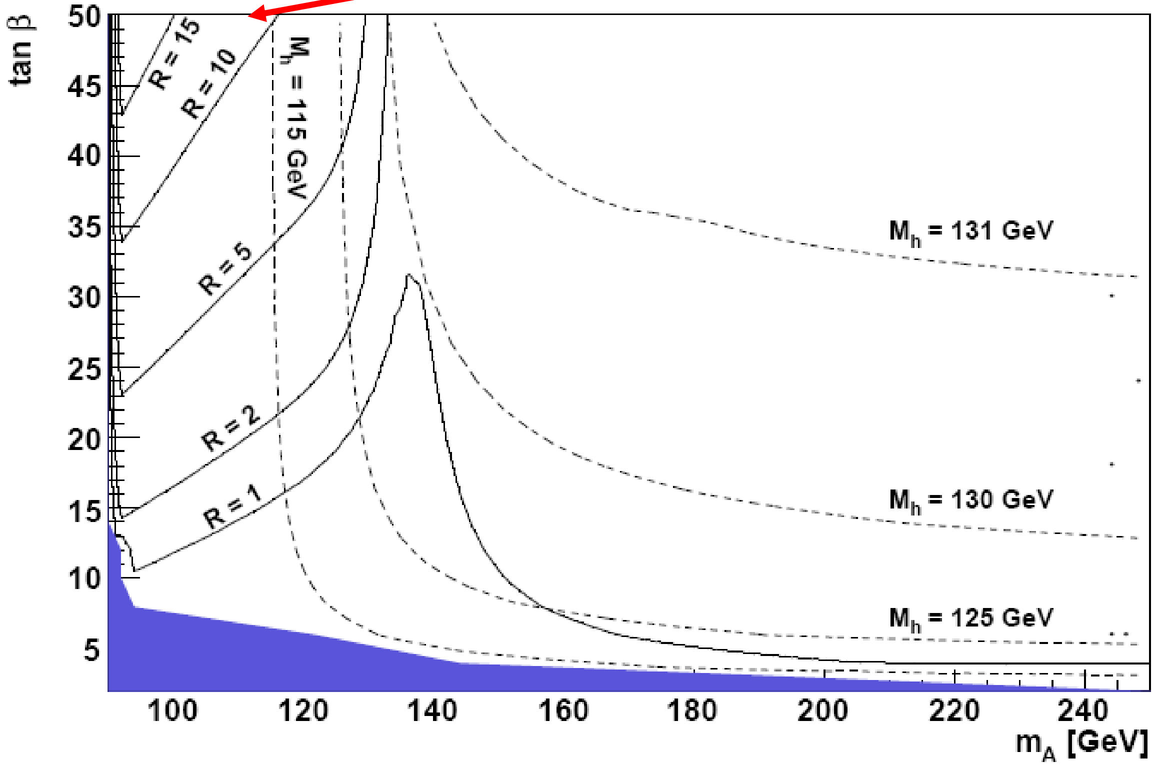
$\Rightarrow$ no improvement with respect to SM analysis

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

HKRSTW-07

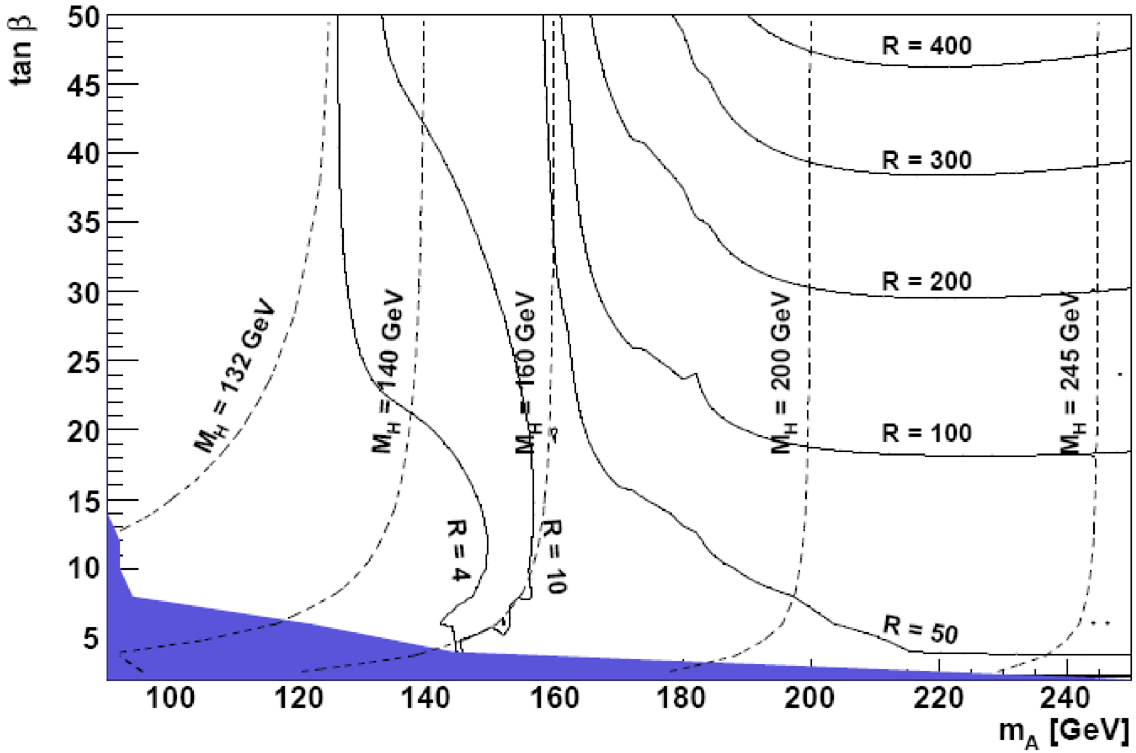


⇒ Large enhancement possible for relatively small M_A and large $\tan\beta$

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:

HKRSTW-07



$\Rightarrow$ Huge enhancement compared to SM case, up to factor 400

(S.Heinemeyer, VAK, M.Ryskin, W.J.Stirling, M.Tasevsky and G.Weiglein 07-08)

Some details ($\phi = h^{\text{MSSM}}, H^{\text{MSSM}}, H^{\text{4th gen}}$):

1. Proton detection: in Forward Proton Taggers at 220 m, 420 m

2. Higgs decay: (here only) $\phi \to b\bar{b}$
   two high p_T b jets, measured in ATLAS or CMS

3. Trigger to keep signal (2):
   "cocktail" of triggers: 220, high p_T jets, high p_T leptons, . . .

4. Identification of signal: (1) and (2) have to match in mass

5. Cross section calculation: $\sigma_{\text{SM}} \times \frac{\Gamma(gg\to\phi)_{\text{NP}}}{\Gamma(gg\to H)_{\text{SM}}}$

6. Decay calculation: $\text{BR}_{\text{NP}}(\phi \to b\bar{b})$ $\Rightarrow$ FeynHiggs (MSSM: incl. Δ_b dep.)
   advantage over SM: possibly enhanced decay rates

7. Backgrounds and pile-up:
   taken into account according to recent analyses/
   best available estimates

$\Rightarrow$ 5 σ discovery contours, 3 σ significance bounds

(**bb**, WW, $\tau\tau$- modes studied)

Four luminosity assumptions:

$60\ \ \mathrm{fb}^{-1}$:

$\mathcal{L} = 2 \times 30\ \ \mathrm{fb}^{-1}$: three years of low-luminosity running

$60\ \ \mathrm{fb}^{-1}$ eff $\times$ 2:

as "60", but assuming an improvement in signal efficiency etc.

effectively: signal rates doubled

$600\ \ \mathrm{fb}^{-1}$:

$\mathcal{L} = 2 \times 300\ \ \mathrm{fb}^{-1}$: three years of high-luminosity running

$600\ \ \mathrm{fb}^{-1}$ eff $\times$ 2:

as "600", but assuming an improvement in signal efficiency etc.

effectively: signal rates doubled

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

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

NEW DEVELOPMENT

Update with respect to 2007 analysis:

– Update of background estimates: NLO for $gg \to b\bar{b}$

– Update of LEP and Tevatron exclusion bounds

$\Rightarrow$ HiggsBounds [B. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams '08]

– Update of σ and BR calculation

$\Rightarrow$ FeynHiggs [T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '98 - '09]

(small changes in Δ_b, $gg \to h$ improved)

MSSM scenarios:

– "normal" benchmarks: m_h^{max}, no-mixing ($\mu = +200$ GeV)

– CDM benchmarks: M_A-$\tan\beta$ planes in agreement with CDM

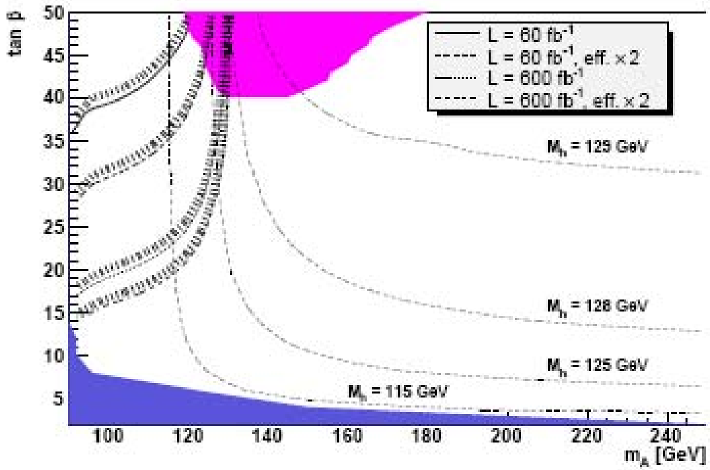
[J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07]

Compliant with the **C**old **D**ark **M**atter and **EW** bounds

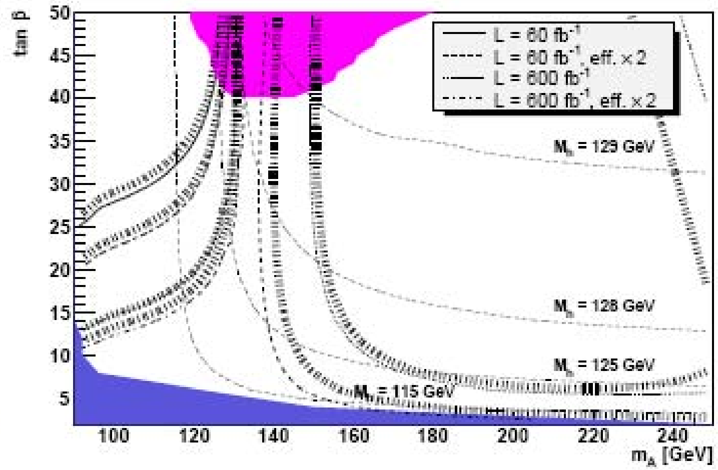
$\boxed{H \to b\bar{b}}$

Results for h in the $m_h^{\max}$ scenario:

5σ discovery



3σ evidence



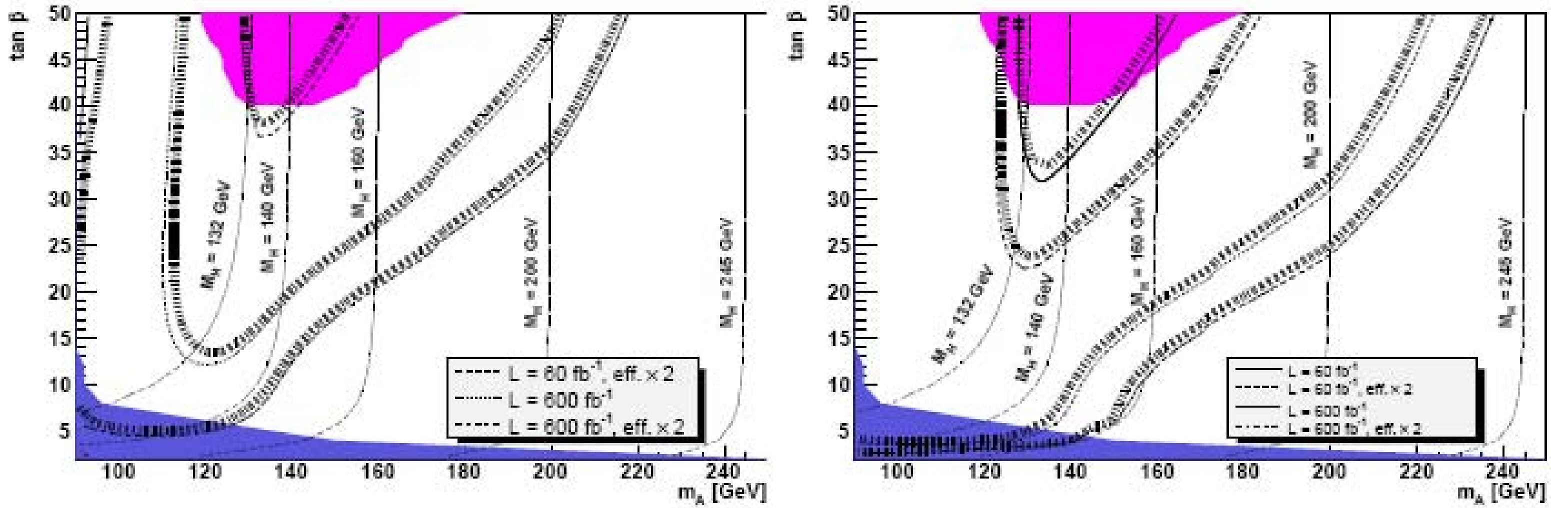
pink: Tevatron exclusion bounds
blue: LEP exclusion bounds

$\Rightarrow$ large parts can be covered at 3σ!

$H \to b\bar{b}$

Results for H in the $m_h^{\max}$ scenario:

5 σ discovery 3 σ evidence



pink: Tevatron exclusion bounds

blue: LEP exclusion bounds

⇒ large discovery regions, but no "LHC wedge" coverage

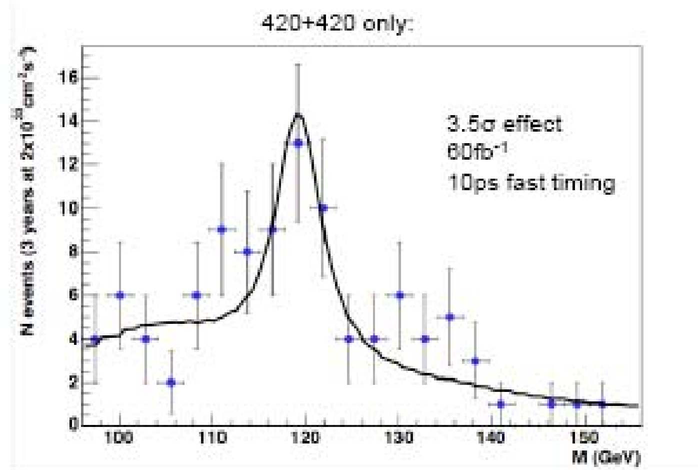
h→bb in the MSSM

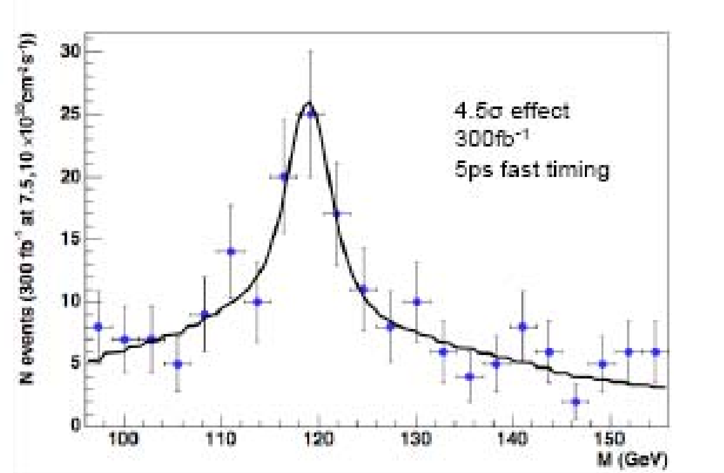
Simulation : A.Pilkington

- 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).



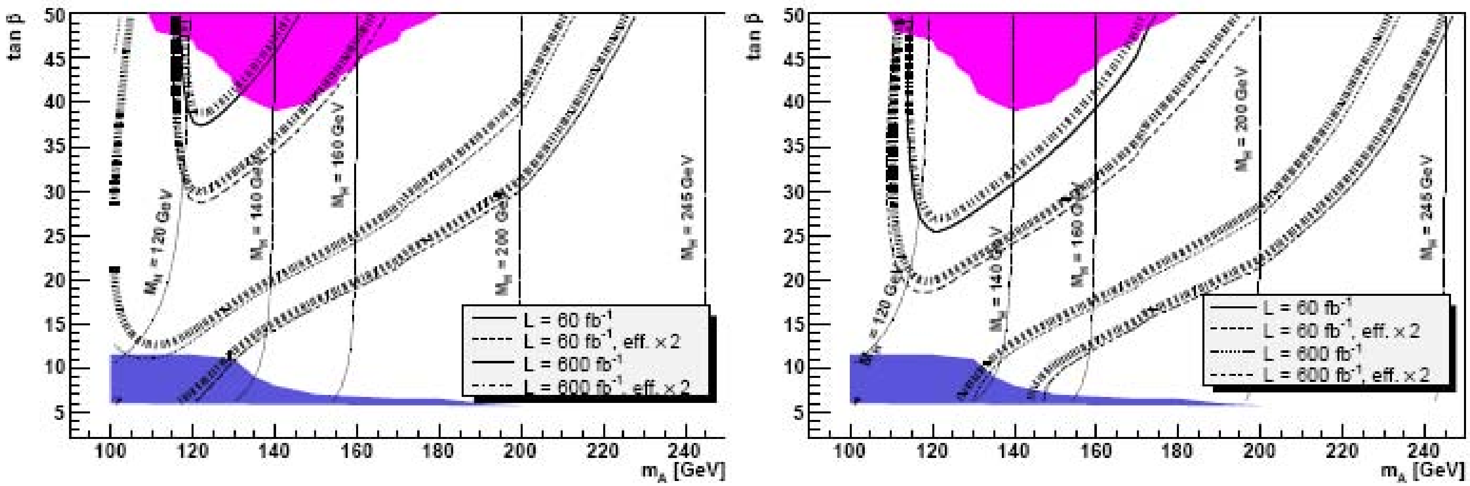


$H \to b\bar{b}$

CDM benchmarks

Results for H in the CDM scenario (#3):

5 σ discovery | 3 σ evidence



pink: Tevatron exclusion bounds
blue: LEP exclusion bounds

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

The MA − tanβ planes are in agreement with the EW and B-physics constraints

$\Rightarrow$ large discovery regions, but no "LHC wedge" coverage (slightly better than in $m_h^{\max}$)

HKRSTW (arXiv: 0708.3052[hep-p])

MSSM
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 $600\ \text{fb}^{-1} \times 2$

  $\Rightarrow$ 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 $140\ \text{GeV}$ Higgs for all values of $\tan\beta$ with $600\ \text{fb}^{-1} \times 2$

  In high $\tan\beta$ region: discovery reach beyond $M_H \approx 200\ \text{GeV}$ 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

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

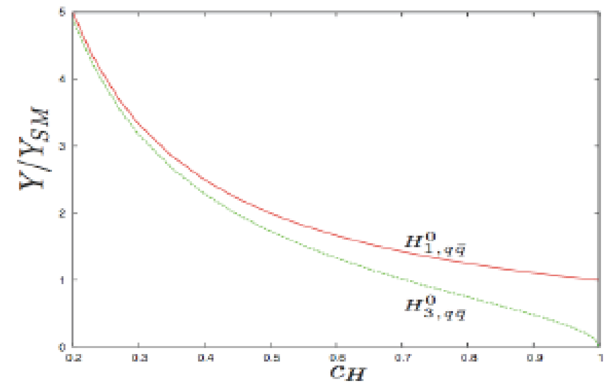
"Typical" features of models with an extended Higgs sector:

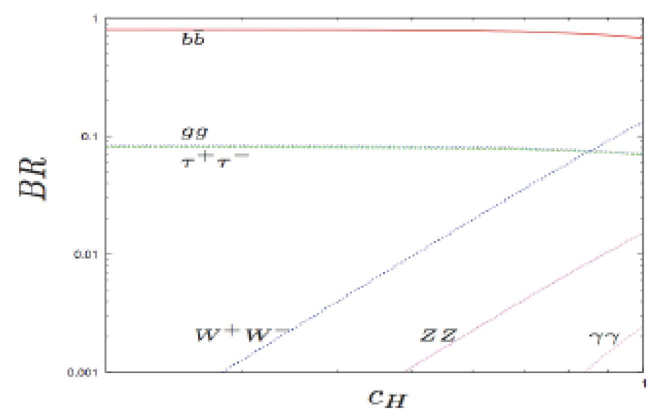
- A light Higgs with SM-like properties, couples with about SM-strength to gauge bosons
- Heavy Higgs states that decouple from the gauge bosons

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.

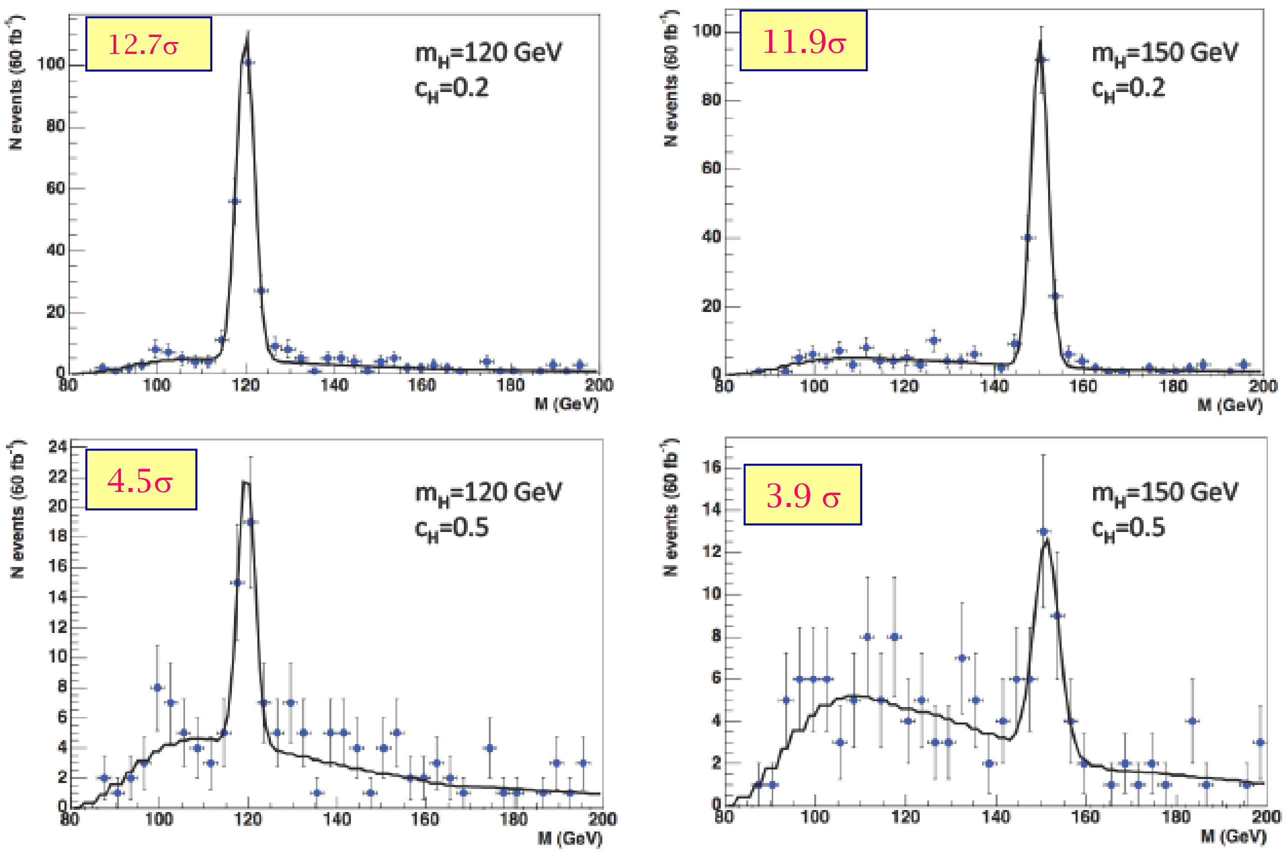




An additional bonus: doubly charged Higgs in photon-photon collisions → factor of 16 enhancement

M. Chaichian, P.Hoyer, K.Huitu, VAK, A.Pilkington, JHEP-09

Results: Triplet Higgs production



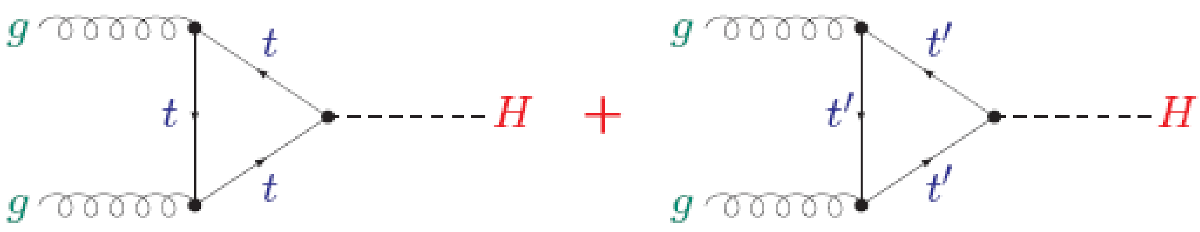
Expected mass distributions given 60 fb-1 of data.

3. 4th generation model

Assume the SM with a 4th generation of heavy fermions

Relevant changes:

1. additional contribution to $gg \to H$:



$\Rightarrow$ factor of ~ 9 in Higgs production cross section

2. $\Rightarrow$ factor of ~ 9 in $\Gamma(H \to gg)$

   $\Rightarrow$ reduced $\mathrm{BR}(H \to b\bar{b})$, $\mathrm{BR}(H \to \tau^+\tau^-)$

B(H→γγ) is suppressed

Evaluation of SM quantities with FeynHiggs
subsequent application of reduction and enhancement factors

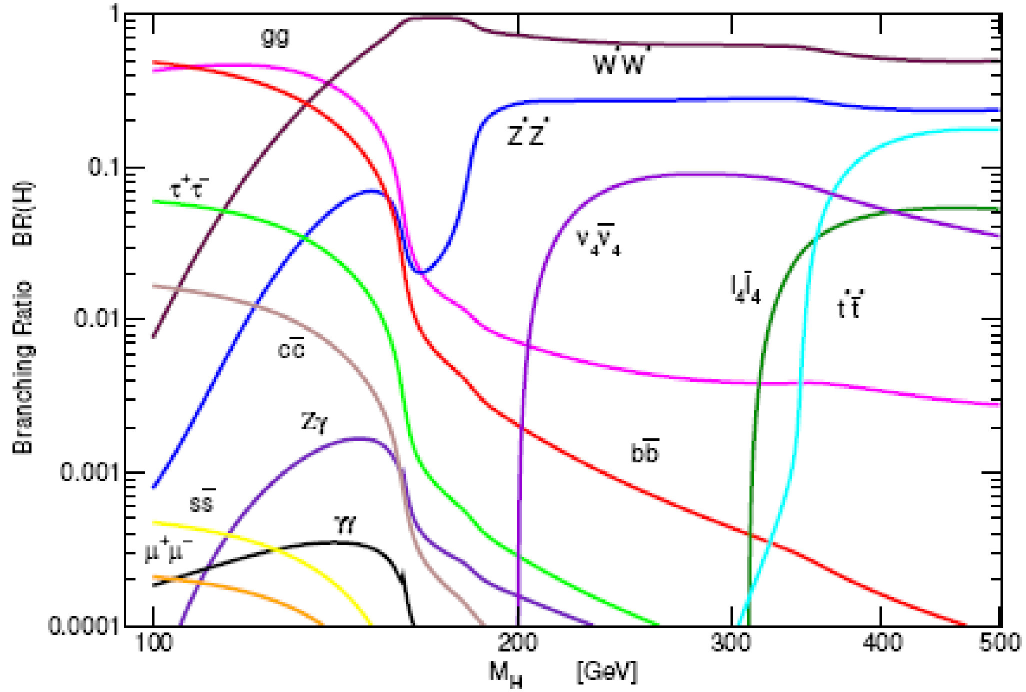


Figure 1. Branching ratio of the Higgs with fourth–generation effects in the parameter point

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

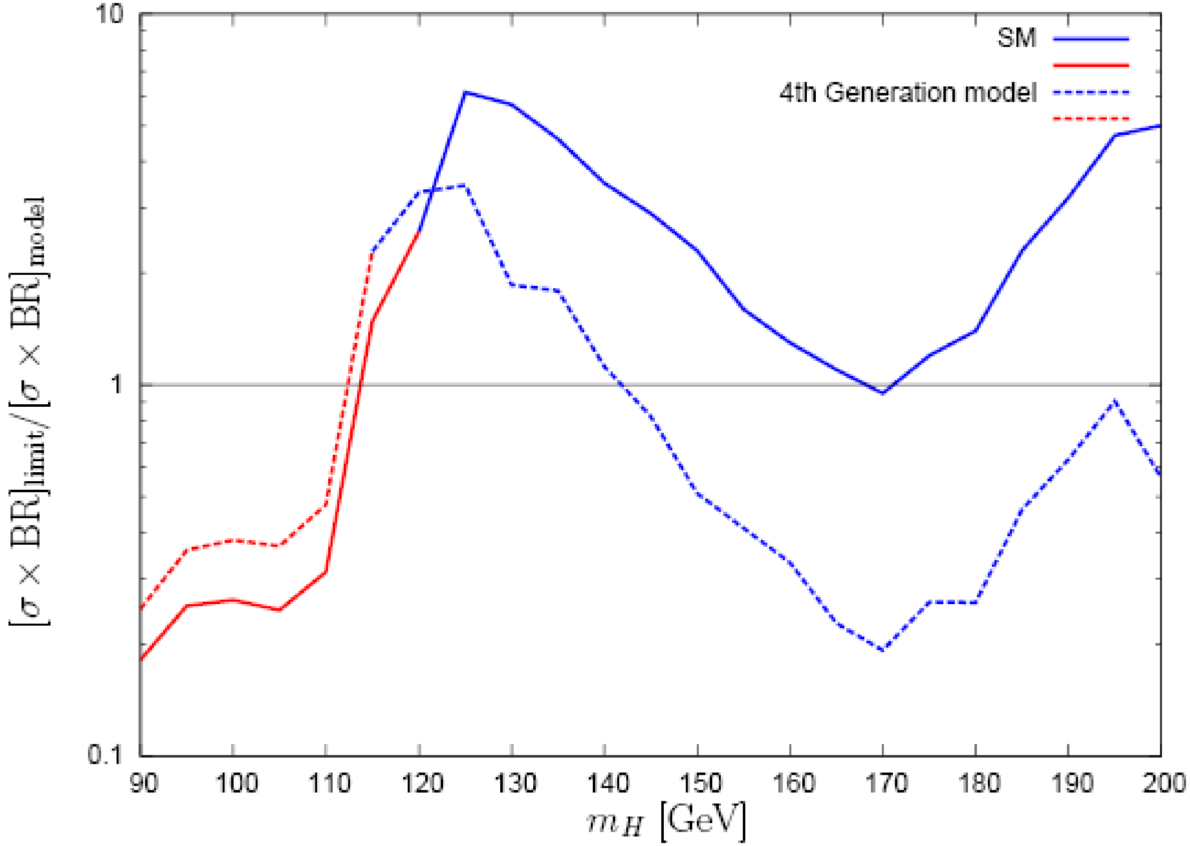
at 220 GeV:
CED (H→WW/ZZ) rate – factor of **~9;**
at 120 GeV
CED (H→bb) rate – factor of **~5.**

H→ZZ – especially beneficial at M= 200-250 GeV

Tevatron limits for 4th generation model

[P. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams '08]

CDF & D0



$\Rightarrow$ only 112 GeV $\lesssim M_H \lesssim$ 143 GeV, $M_H \gtrsim$ 220 GeV still allowed

$\Rightarrow$ will be tested very soon by the Tevatron

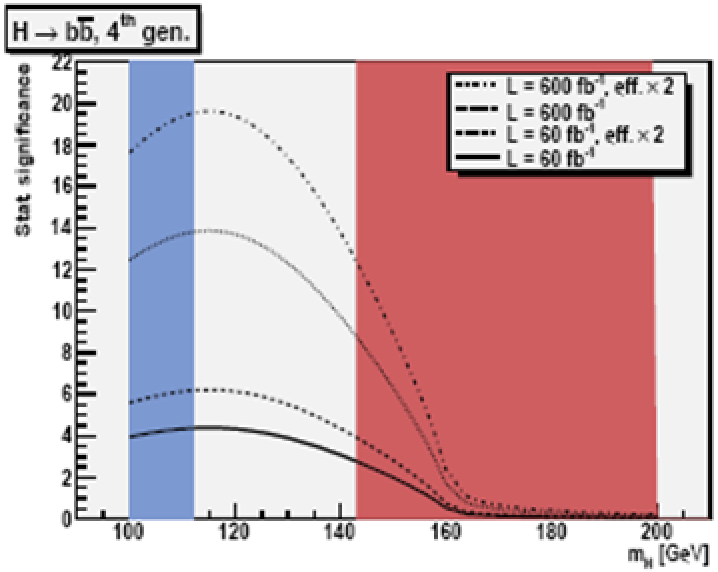


Figure 4: Significances reachable in the SM4 in the $H \to b\bar{b}$ (left) and $H \to \tau^+\tau^-$ (right) channel for effective luminosities of "60 fb^{-1}", "60 fb^{-1} eff$\times$2", "600 fb^{-1}" and "600 fb^{-1} eff$\times$2". The regions excluded by LEP appear as blue/light grey for low values of $M_{H^{SM4}}$ and excluded by the Tevatron as red/dark grey for larger values of $M_{H^{SM4}}$.

⇒ good prospects even with relatively low luminosity

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

New approach to study heavy quarkonia and new charmonium-like states

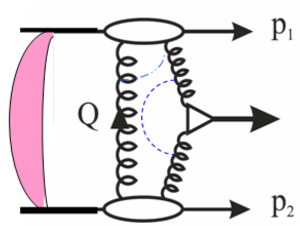
(work together with L. Harland-Lang, M.Ryskin and W.J. Stirling)

Issues addressed:

- New **SUPERCHIC** MC for all $c\bar{c}$ **P** -states.
- Absorption effects for **CEP** of the $0^+, 1^+, 2^+, 0^-$ $c\bar{c}$ - states revisited
- Proton angular correlations for different $0^+, 1^+, 2^+, 0^-$ $c\bar{c}$ -states.
- Expectations for the CEP of the $0^+, 1^+, 2^+, 0^-$ $b\bar{b}$ -states.

As compared to the previous K(KMR)S studies:

- More comprehensive calculation of the absorption effects using the new KMR-07/08 model for soft diffraction (including the enhanced screening).
- New calculational routine for implementing polarization structure in the b-space.
- New experimental/theoretical results for the parameters of heavy quarkonia, in particular $\Gamma(\chi \to gg)$.



χ_c, χ_b

Why an interest to the CEP of χ_c, χ_b ?

- Testing ground for the formalism of CEP used to evaluate the New Physics signals (e.g. 'Diffractive Higgs')
- Open issues in Quarkonium Spectroscopy, such as χ_b quantum numbers. New way to address Quarkonium Physics (numerous new exotic charmonium like states).
- New Encouraging CDF results on CEP of the χ_c .

Heavy Quarkonia

Traditional testing ground for various aspects of QCD

- NRQCD, QCDME, Lattice QCD, QCD sum rules, potential models
- Large NLO..... PT corrections.
- P-states- sensitivity to the derivatives of the wave function, relativistic effects....
- Nature of the new states around 4 GeV; X, Y, Z, other applications of the CEP...

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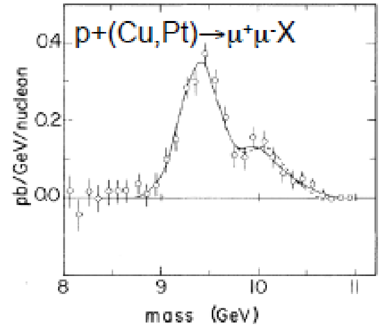
Bottomonium history started 30 years ago
(PRL 39, 242 (1977) and PRL 39,1240 (1977))

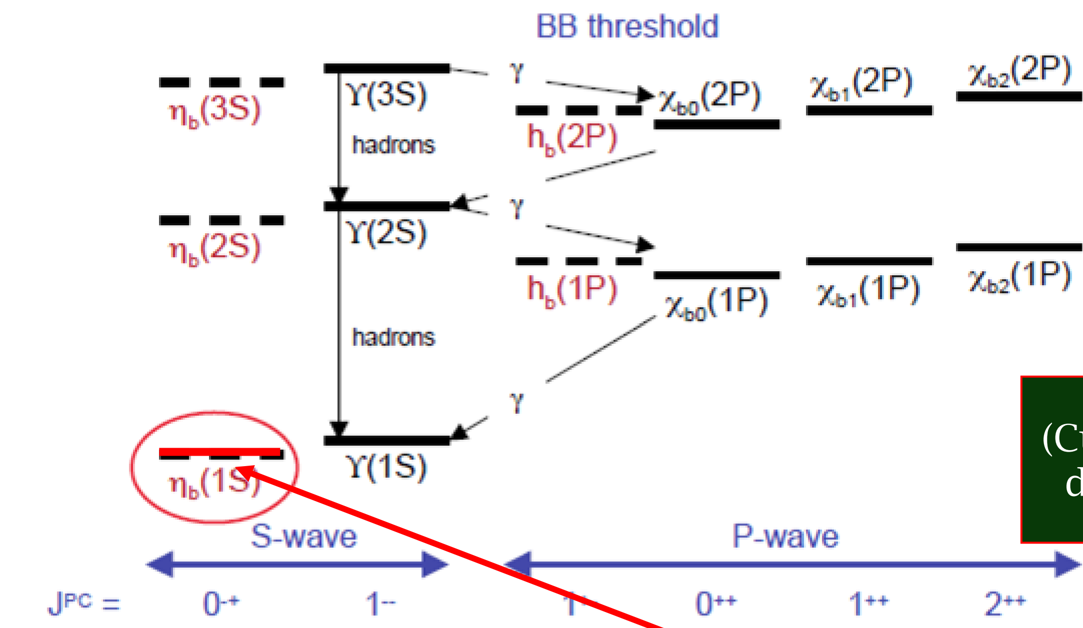


M(Υ)=9.40±0.013
M(Υ')=10.00±0.04
M(Υ'')=10.43±0.12

FNAL, E288

30 years later….

(spins- still unconfirmed)



Υ(nS) confirmed and χ_{bJ}(1,2P) states observed

Below $B\bar{B}$, several states not yet observed: 3 S-wave (η_b), 2 P-wave (h_b), D-wave,etc…

(Currently no complete theoretical description of onium properties.)

(BABAR (2008))

(Still puzzles)

The heaviest and most compact quark-antiquark bound state in nature

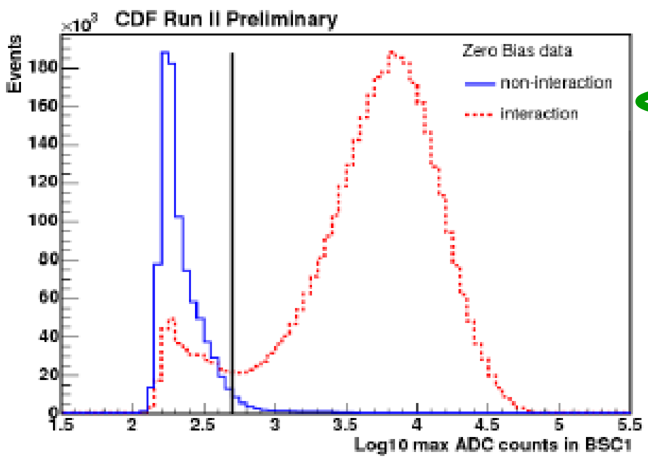
BSC very important as rap gap detectors.
All LHC experiments should have them!

FORWARD PHYSICS WITH RAPIDITY GAPS AT THE LHC

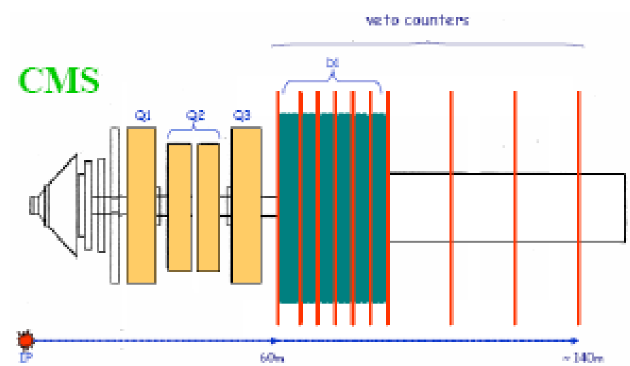
arXiv:0811.0120

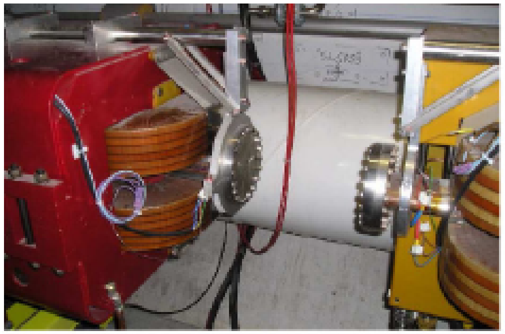
Michael Albrow[1], Albert De Roeck[2], Valery Khoze[3], Jerry Lämsä[4,5], E. Norbeck[6],
Y. Onel[6], Risto Orava[5], and M.G. Ryskin[7]
Sunday, November 09, 2008

JINST in press



Warm accessible vacuum pipe (circular – elliptical)
Do not see primary particles, but showers in pipe ++
Simple scintillator paddles: **Gap detectors in no P-U events**





Take 0-bias events (Essential!)
{1} = prob no interaction
{2} = prob >= 1 interaction
Take hottest PMT of 8 BSC1
Plot log max ADC for {1} and {2}
Separates empty / not empty
Repeat for all detectors

CENTRAL DIFFRACTION AT THE LHCb

LHCb IS IDEAL FOR DETECTING AND ANALYSING LOW MASS CENTRAL DIFFRACTIVE PRODUCTION OF EXCLUSIVE $\pi^+\pi^-/K^+K^-$ STATES IN:

$$pp \rightarrow p + M + p$$

glueballs, hybrids, heavy quarkonia: χ_c, χ_b

$\pi^+\pi^-/K^+K^-$ STATES AS SPIN-PARITY ANALYZERs.

HOW TO FACILITATE THIS?

Jerry W. Lämsä and Risto Orava arXiv:0907.3847

Jerry W. Lämsä and Risto Orava arXiv:0907.3847

THE PROPOSED LHCb FSC LAY-OUT

ADD FSCs AT **20 – 100 METERS** ON BOTH SIDES OF IP8 – THE FSCs DETECT SHOWERS FROM THE VERY FORWARD PARTICLES.

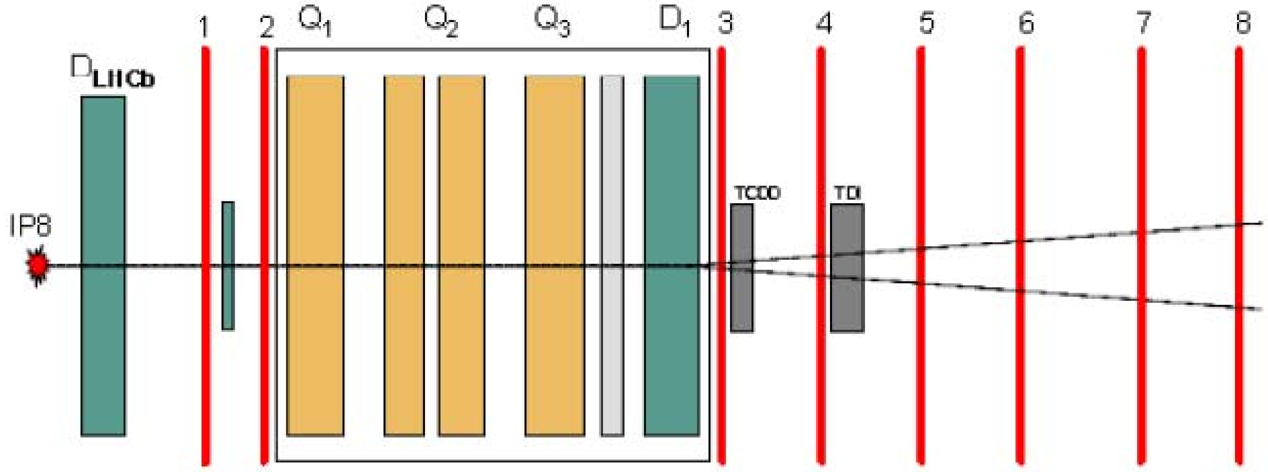
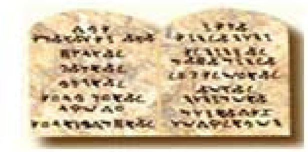


Figure 1. *The layout of LHCb detectors at the LHC Interaction Point (IP8). The proposed Forward Shower Counters (FSCs) are shown as vertical lines (1 to 8). The locations of the dipole (D) and quadrupole (Q) magnet elements are shown as green (dark) and yellow (light) boxes.*

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 sometimes 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.

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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arXiv:0806.0302v2 [hep-ex] 2 Jan 2009

There has been huge progress over the past few years…

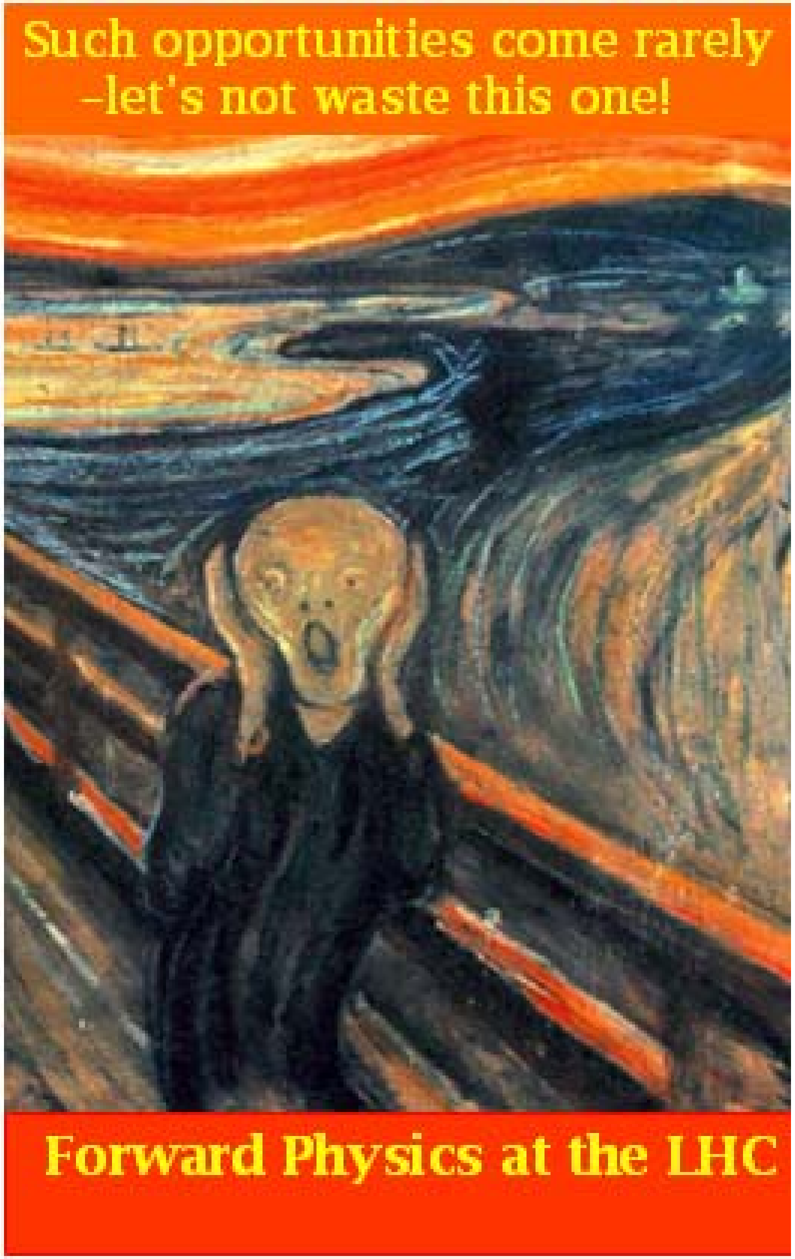
- ATLAS has LOI
- CMS/ATLAS in refereeing phase

?

- Decisions
- Installation – 2011-2013 **maybe**

- 175 page report
- 96 authors
- 29 institutions

Central Exclusive Physics case is led by the UK


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

Thank You

BACKUP

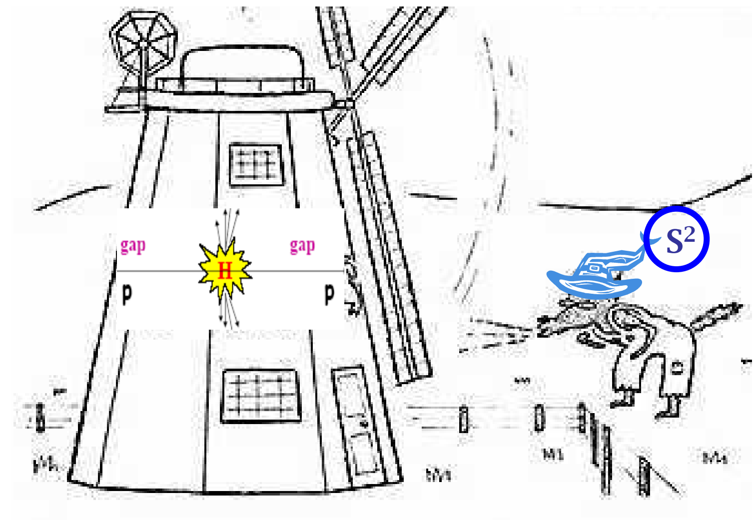
Far more theoretical papers than the expected number of the CED produced Higgs events

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

Who's Afraid of the Big, Bad Wolf?

- S^2 does not affect the signal-to-background ratio- for all irreducible backgrounds (signal evidence is much less affected).

  Overlap background ☛ psec (not lifetime of theor. pred^{ns}, but **FTD** resol^{n})



- Main reduction of the signal (factor of ~50) comes from the experimental requirements (cuts and efficiencies...) which are currently known mainly for the inclusive environment. Further progress with hard/soft -ware for the **CEP** processes can be expected.
  More experimental work needed. 

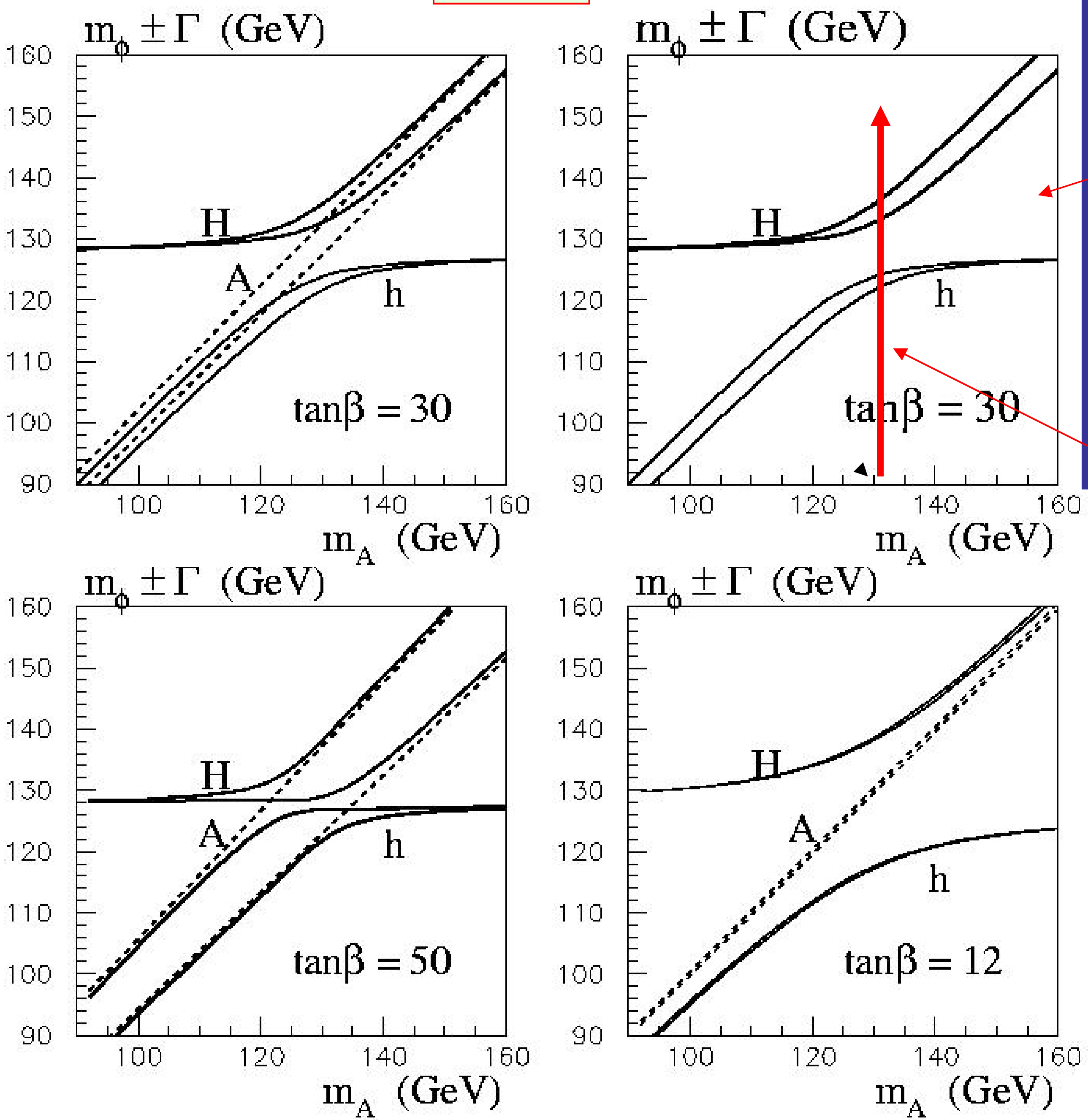
- Experimentally we have not seen (at least so far) any evidence in favour of large enhanced absorption (KKMR, KMR- 2001-2009).

- Durham selection of the UPDF is quite conservative.
  Due to the $(f_g)^4$ behaviour- rise up to a factor of 3 (Cox et al, KMR).
  New studies (including NLO effects) are underway.

- We should be careful with relaying on the NLO corrections (e.g. BBKM-06).
  Could be misleading when large parameters are involved.
  (textbook example: non-relativistic Coulomb corrections)

Up to two orders of magnitude rise in the popular BSM Higgs models.

KKMR-04



decoupling regime
$m_A \sim m_H \geq 150$GeV,
$\tan\beta > 10$;
h = SM

intense coupling regime:
$m_h \sim m_A \sim m_H$
$\gamma\gamma$,WW.. couplings suppressed

with CEDP:
•h,H may be clearly distinguishable outside130+-5 GeV range,
•h,H widths are quite different

‘ Invisible ‘ Higgs B(KMR)-04

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

(one of the ‘LHC headaches’)

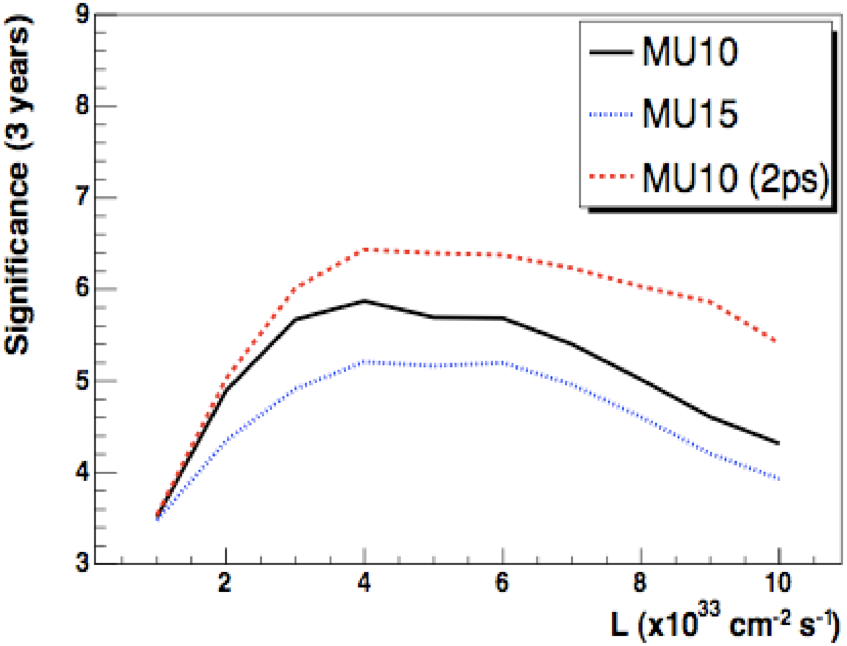
the potential advantages of the CEDP – a sharp peak in the MM spectrum, mass determination, quantum numbers

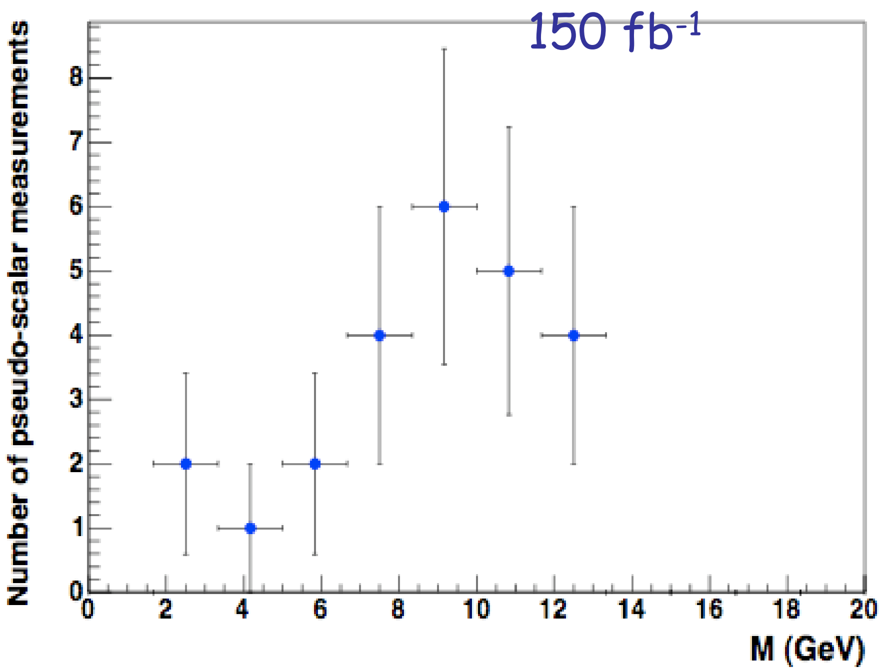
strong requirements :

triggering 

$h \rightarrow aa \rightarrow \tau\tau\tau\tau$

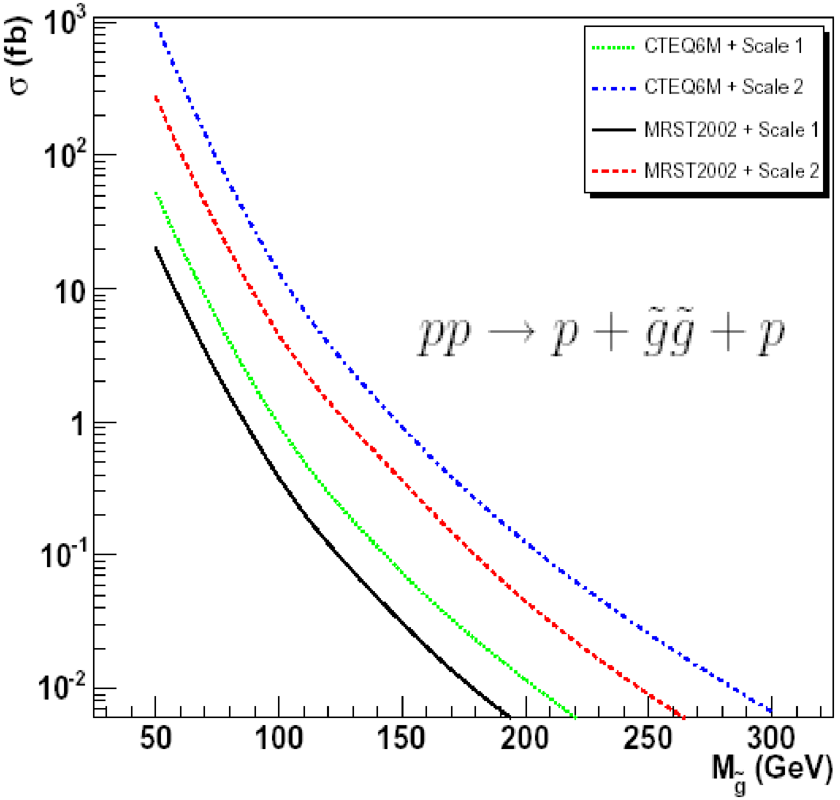
Low mass higgs in NMSSM: If $m_a < m_B$ difficult (impossible) at standard LHC
J. Gunion: FP420 may be the only way to see it at the LHC





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

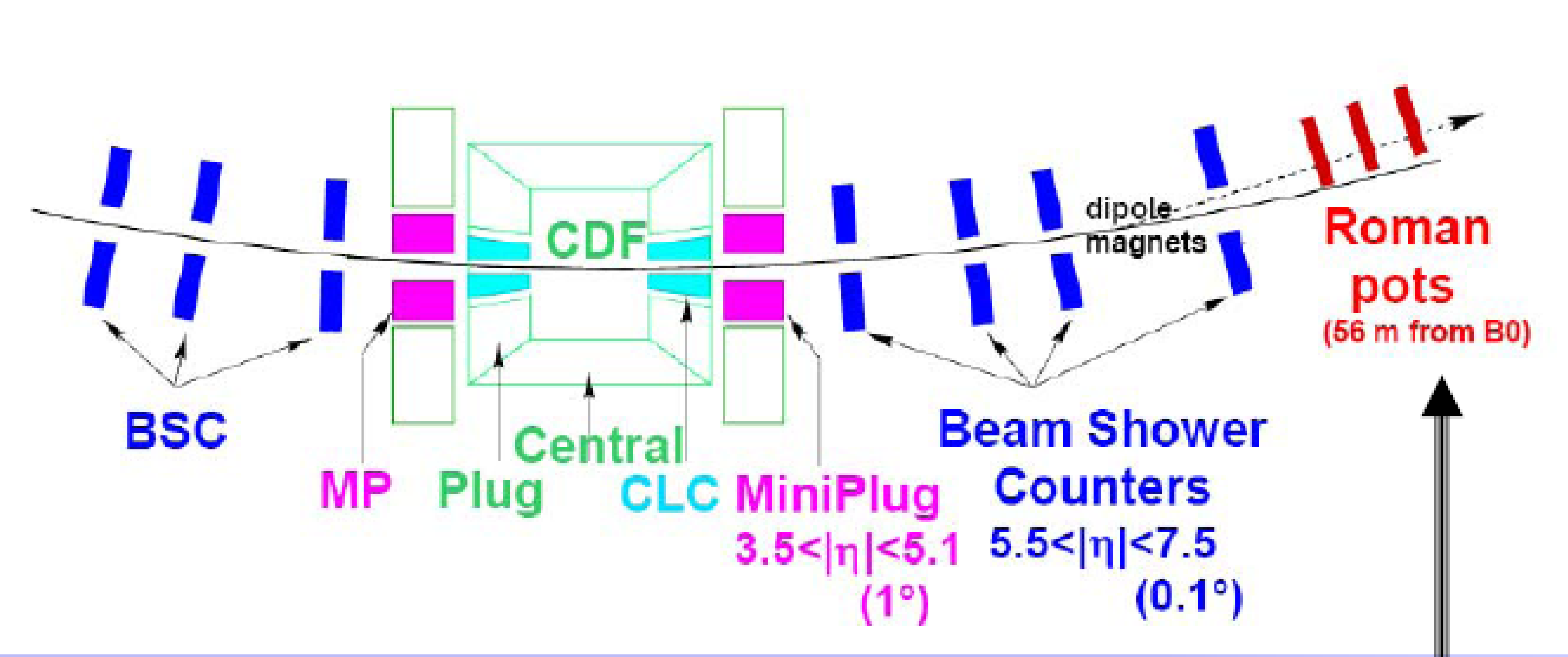
Gluino mass resolution with 300 fb^{-1} using forward detectors and muon system

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%

The CDF II detectors



RPS acceptance ~80% for $0.03 < \xi < 0.1$ and $|t| < 0.1$