The 20th Nordic Particle Physics Meeting
Spåtind, Norway, 3 - 7 January 2008


Munch Museum Oslo

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

Durham University

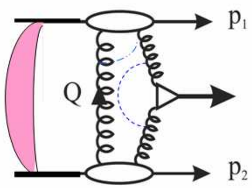
V.A. Khoze (IPPP, Durham)

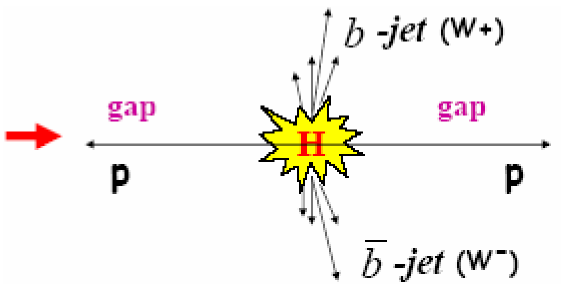
IP³

"…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 aim: to overview the (very) forward physics programme at the LHC and
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





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. Prospects for CED Higgs production.

5. 'Exotics'

6. The 'standard candle' processes (*experimental checks* ***).***

7. Luminometry revisited.

8. Conclusion

9. Ten commandments of Physics with Forward Protons at the LHC

10. FP420 R&D project

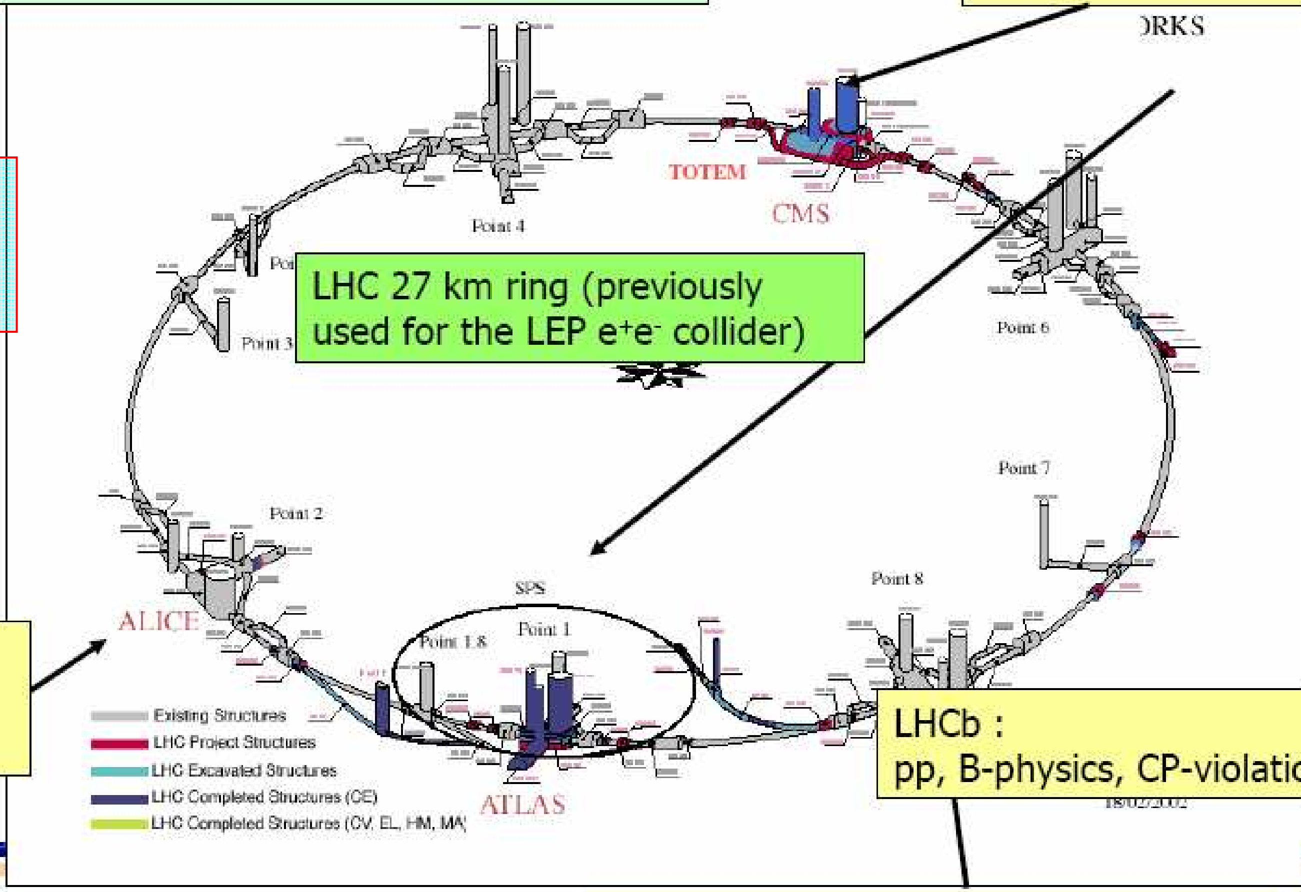
LHC basics

- pp $\sqrt{s}$ = 14 TeV x7 Tevatron
  L_{design} = 10^{34} cm^{-2} s^{-1} (after 2010) x100 Tevatron
  $L_{initial}$ < few x 10^{33} cm^{-2} s^{-1} (before)
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

(O.Buchmuller)

ATLAS and CMS : general purpose

LHC will run for many years: upgrade plans are already well advanced (R.Brenner)

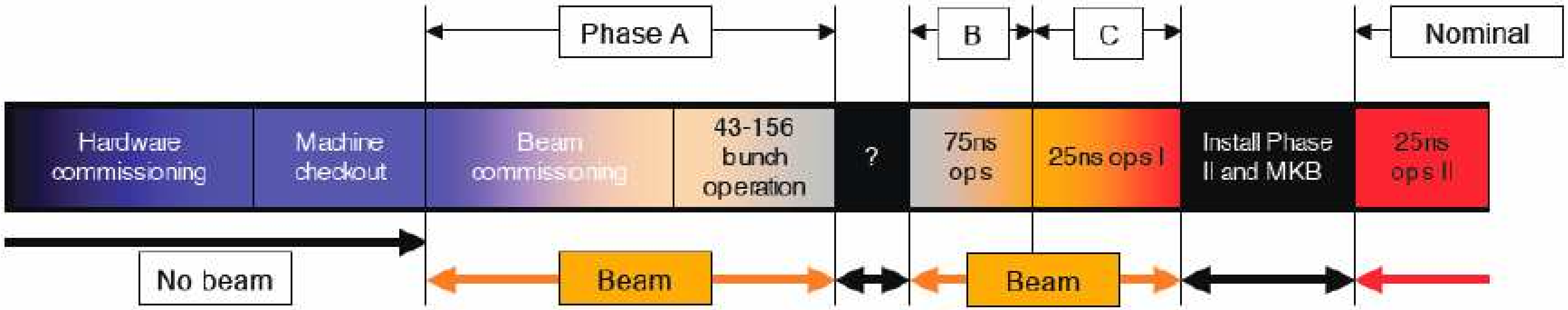


LHC 27 km ring (previously used for the LEP e^+e^- collider)

(J. Rak)

ALICE : ion-ion, p-ion

LHCb : pp, B-physics, CP-violation



Parameter	Phase A	Phase B	Phase C	Nominal
k / no. bunches	43-156	936	2808	2808
Bunch spacing (ns)	2021-566	75	25	25
N (10^{11} protons)	0.4-0.9	0.4-0.9	0.5	1.15
Crossing angle (μrad)	0	250	280	280
$\sqrt{(\beta^*/\beta^*_{nom})}$	2	$\sqrt{2}$	1	1
σ^* (μm, IR1&5)	32	22	16	16
L ($cm^{-2}s^{-1}$)	6×10^{30}-10^{32}	10^{32}-10^{33}	$(1-2)\times10^{33}$	10^{34}
Year (?)	2008	2009	2009-2010	> 2010

LHC is a discovery machine

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

▶ *High -pt signatures in the central region*

(O. Buchmuller)

But…

- Main physics 'goes Forward'

The LHC is a very challenging machine!

- Difficult background conditions.
- The precision measurements are limited by systematics (luminosity goal of $\delta L \leq 5\%$)

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 , …

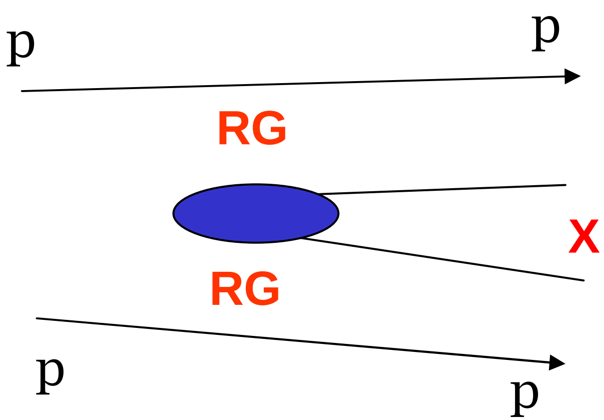
ILC chartered territory

Is there a way out?

YES → Forward Proton Tagging

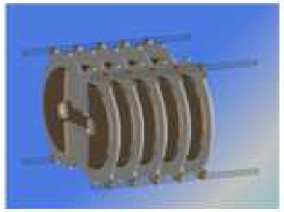
Rapidity Gaps ⇨ Hadron Free Zones

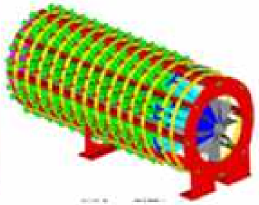
matching Δ Mx ~ δM (Missing Mass)

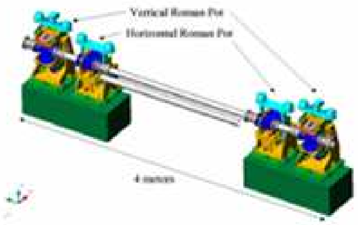


Forward detectors at LHC

TOTEM -T2	CASTOR	ZDC/FwdCal	TOTEM-RP	FP420



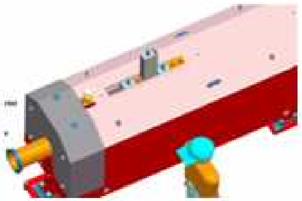


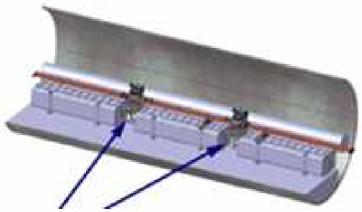


IP5

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

IP1

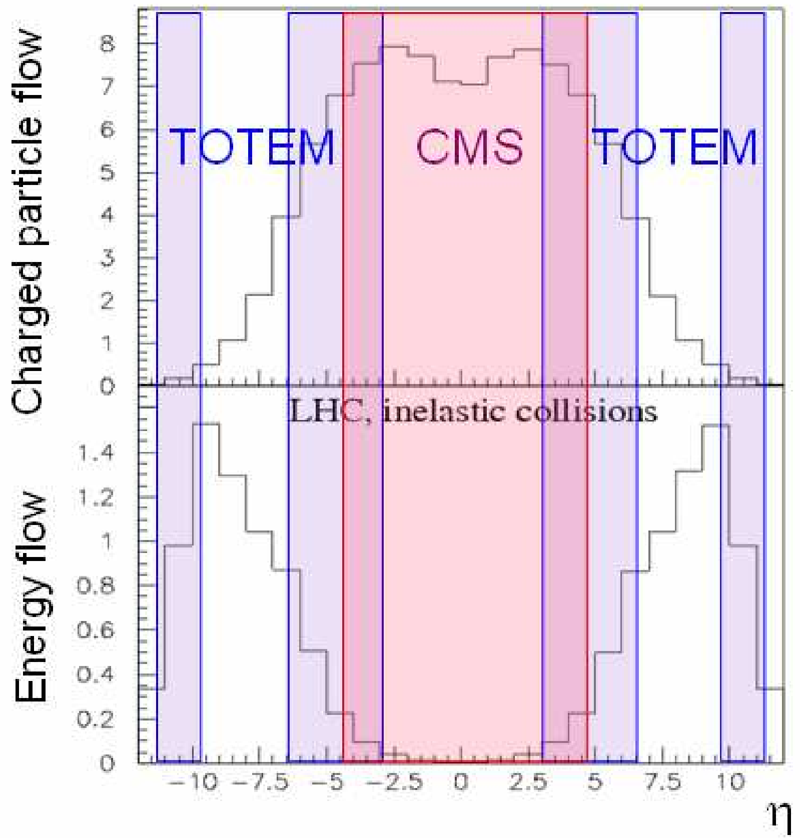


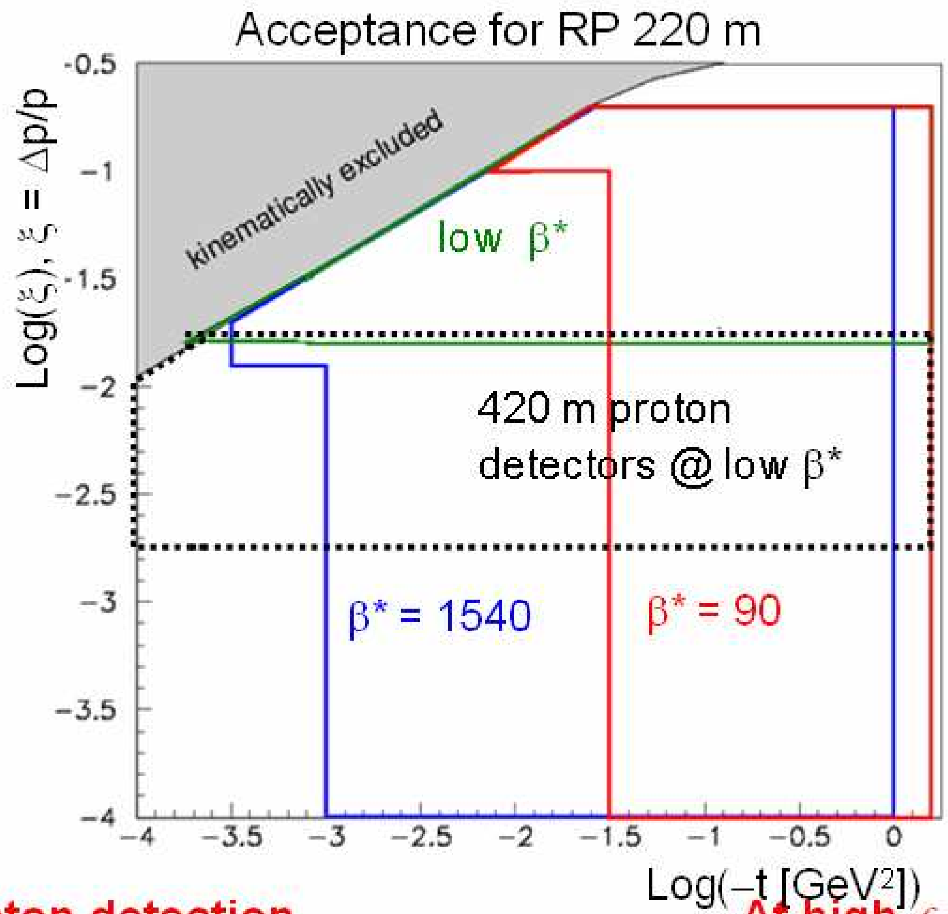


LUCID	ZDC	ALFA/RP220	FP420

CMS/TOTEM combined acceptance

Unique coverage makes a wide range of physics studies possible – from diffraction & proton low-x dynamics to production of SM/MSSM Higgs





At high $\mathcal{L}$

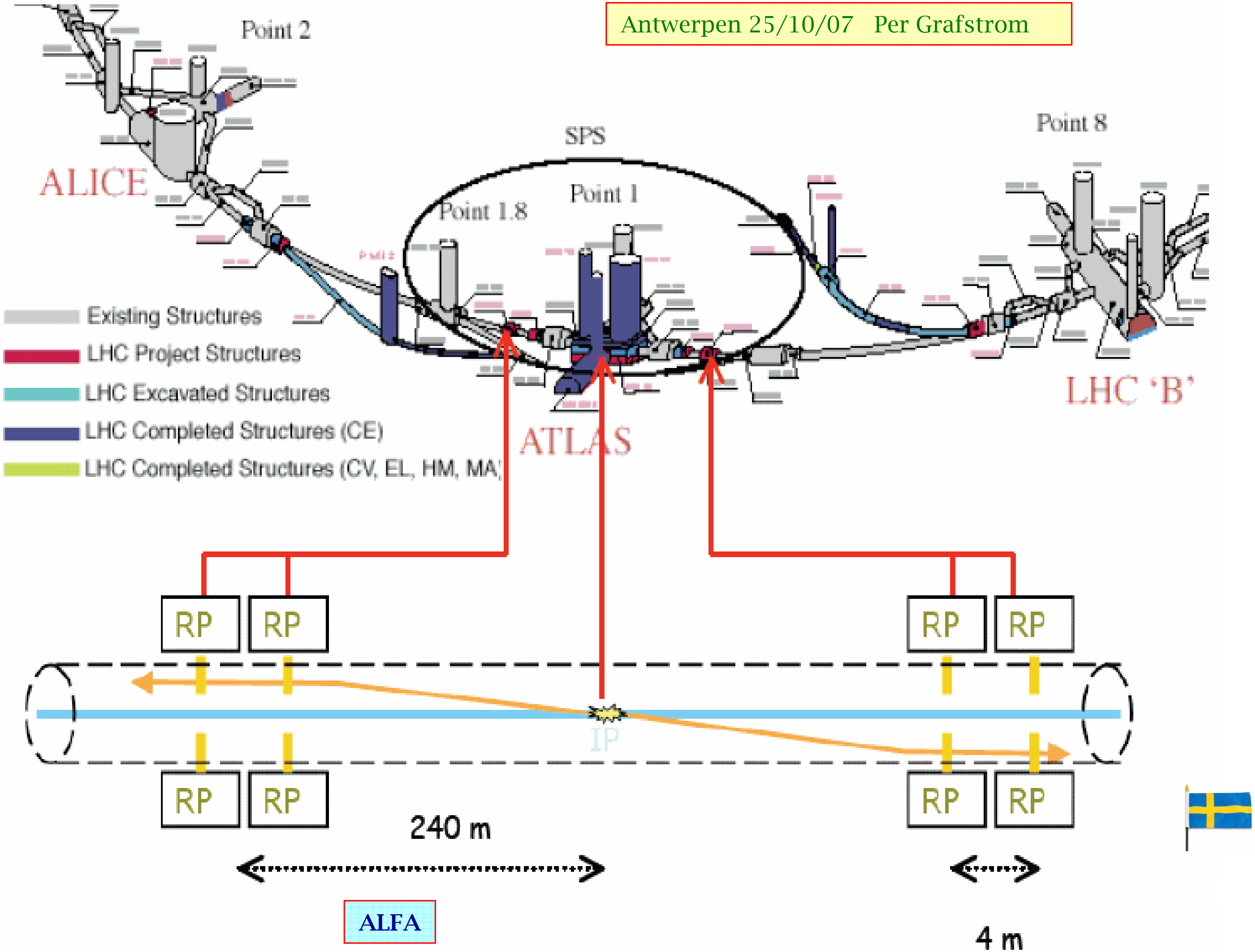
Wide coverage in pseudorapidity & proton detection

proton detectors @420 m enlarge acceptance to $\xi \sim 2 \cdot 10^{-3}$

Helsinki Group (Orava et al)

K. Österberg

Antwerpen 25/10/07 Per Grafstrom



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

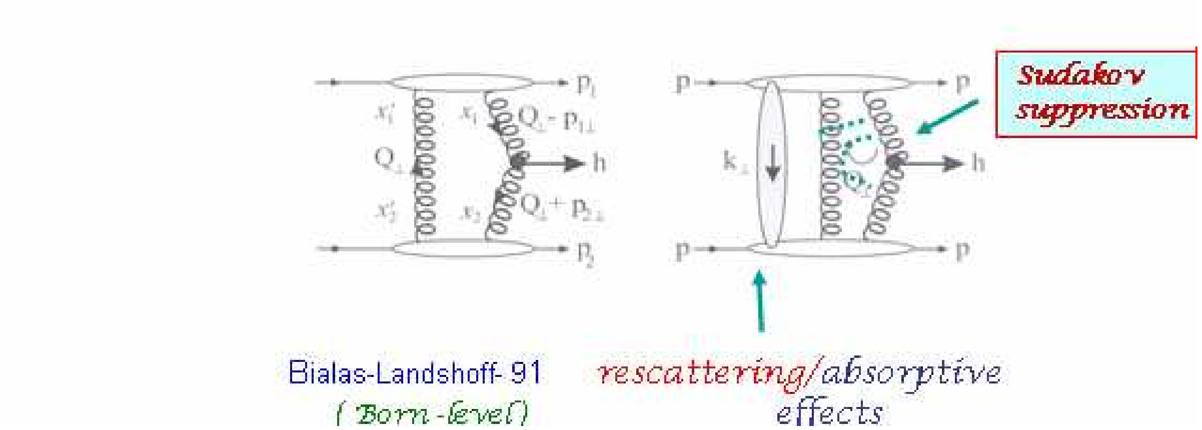
✳ Higgs is only a part of the broad EW, BSM and diffractive program@LHC

wealth of QCD studies, glue-glue collider, photon-hadron, photon-photon interactions…

The basic ingredients of the KMR approach
(Khoze-Martin-Ryskin 1997-2007)

Interplay between the soft and hard dynamics

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



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 

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

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 $W = S^2 T^2$

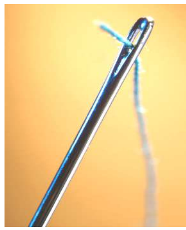
Colour charges of the 'digluon dipole' are screened only at $r_d \geq 1/(Q_t)_{ch}$

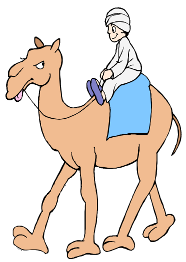
GAP Keepers (Survival Factors) , protecting RG against:

- 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 it to your (grand) children ?

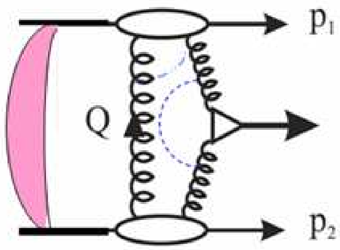
Forcing two (inflatable) camels to go through the eye of a needle





P → **H** ← **P**

KMR technology (implemented in ExHume MC)



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

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

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

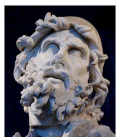
$$< Q_t >_{SP} \simeq M / 2 * \exp(-1/\bar{\alpha}_s) \approx 2 GeV \gg \Lambda_{QCD},$$

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

Tg + anom .dim. → *IR filter*

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

new CDF results



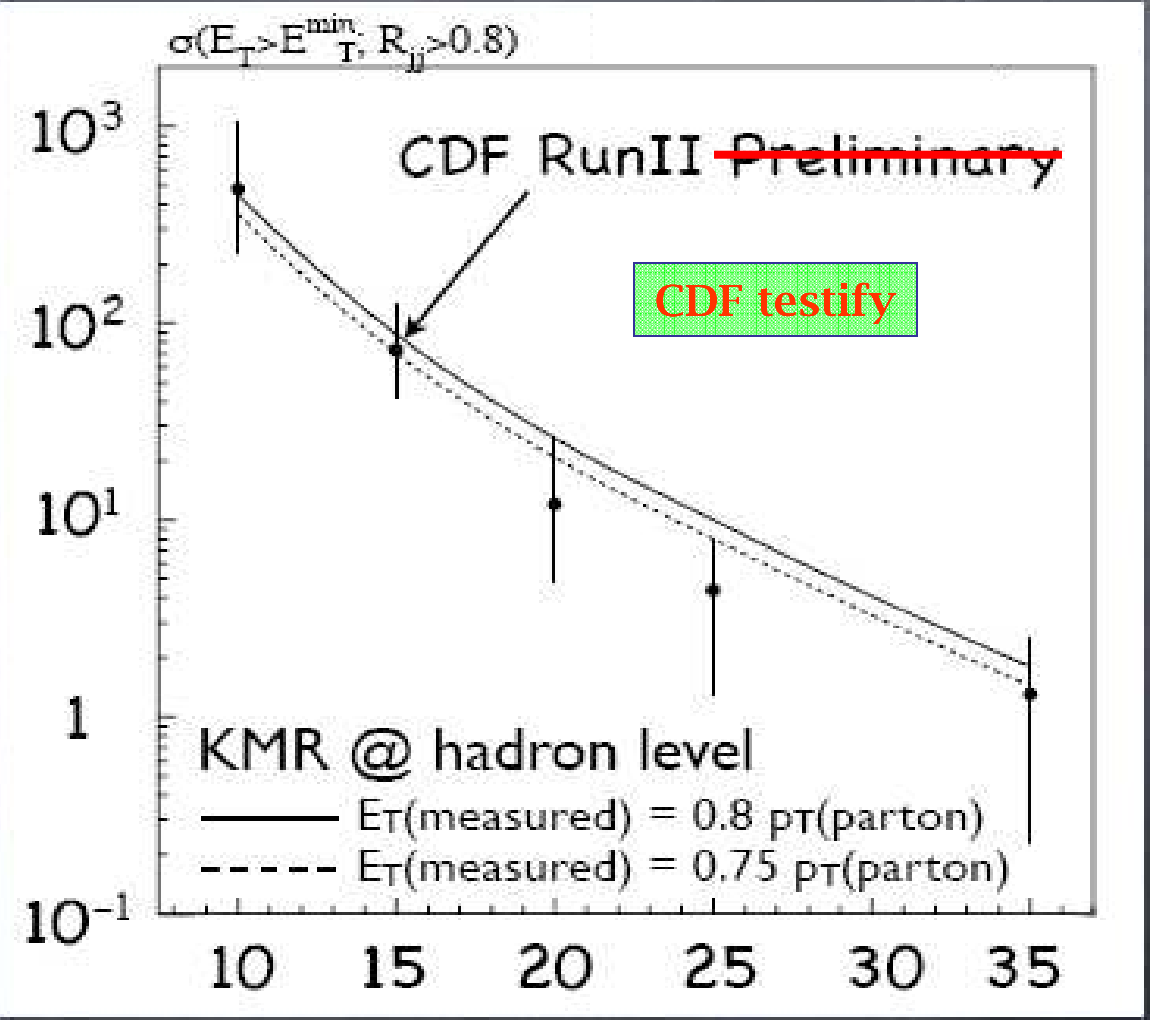
not so long ago: between Scylla and Charibdis:
orders of magnitude differences in the theoretical predictions are now a history

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

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



Koji Terashi

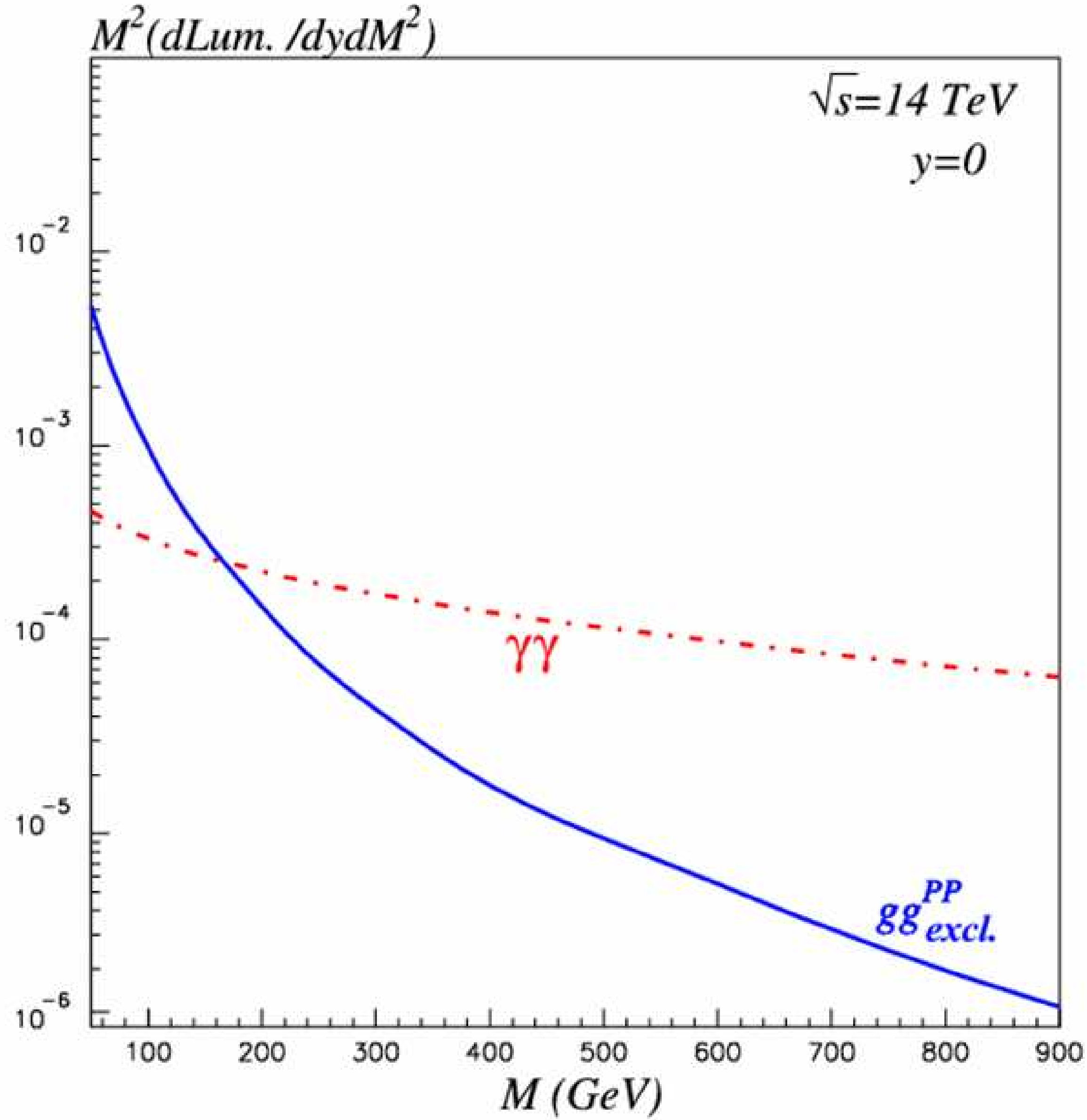
photon-photon production mechanism

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

$$\sigma(PP \to SMH) \approx 3\,fb$$

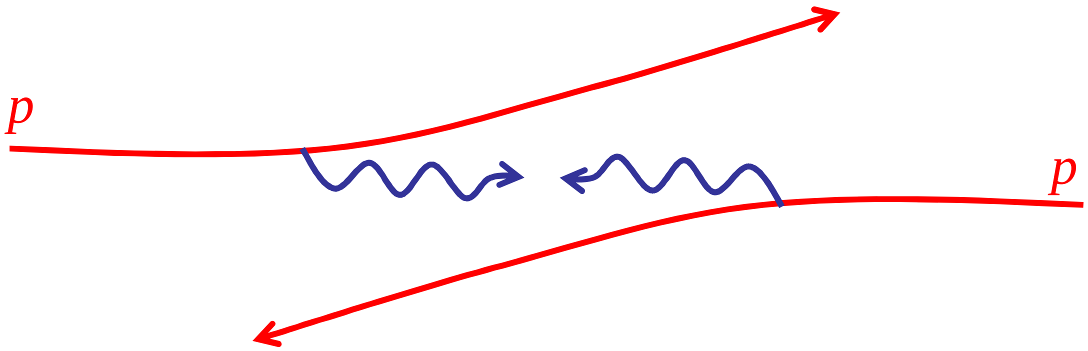
$$\alpha_S{}^2/8 \to \alpha^2$$

QCD ‘radiation damage’ in action



LHC as a High Energy γγ Collider

K. Piotrzkowski, Phys. Rev. **D63** (2001) 071502(R)
KMR-02

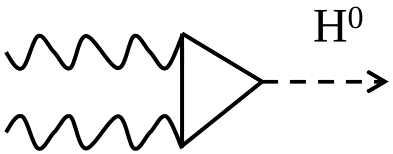


Highlights:

- **γγ CM energy *W* up to/beyond 1 TeV (and under control)**
- **Large photon flux *F* therefore significant γγ luminosity**
- **Complementary (and clean) physics to *pp* interactions, eg studies of** *exclusive* **production of heavy particles might be possible ➡ opens new field of studying very high energy γγ (and γp) physics**

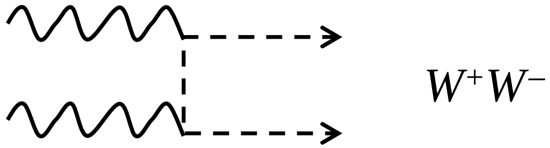
Very rich Physics Menu

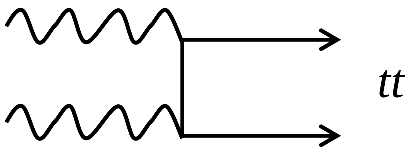
$\gamma\gamma$ Physics Menu - Highlights



$\sigma \sim 10$ pb (at $W=M_H=200$ GeV)

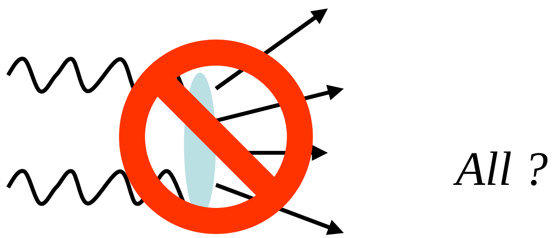
$\sigma \sim 80$ pb





$\sigma \sim 1$ pb

+ SUSY processes

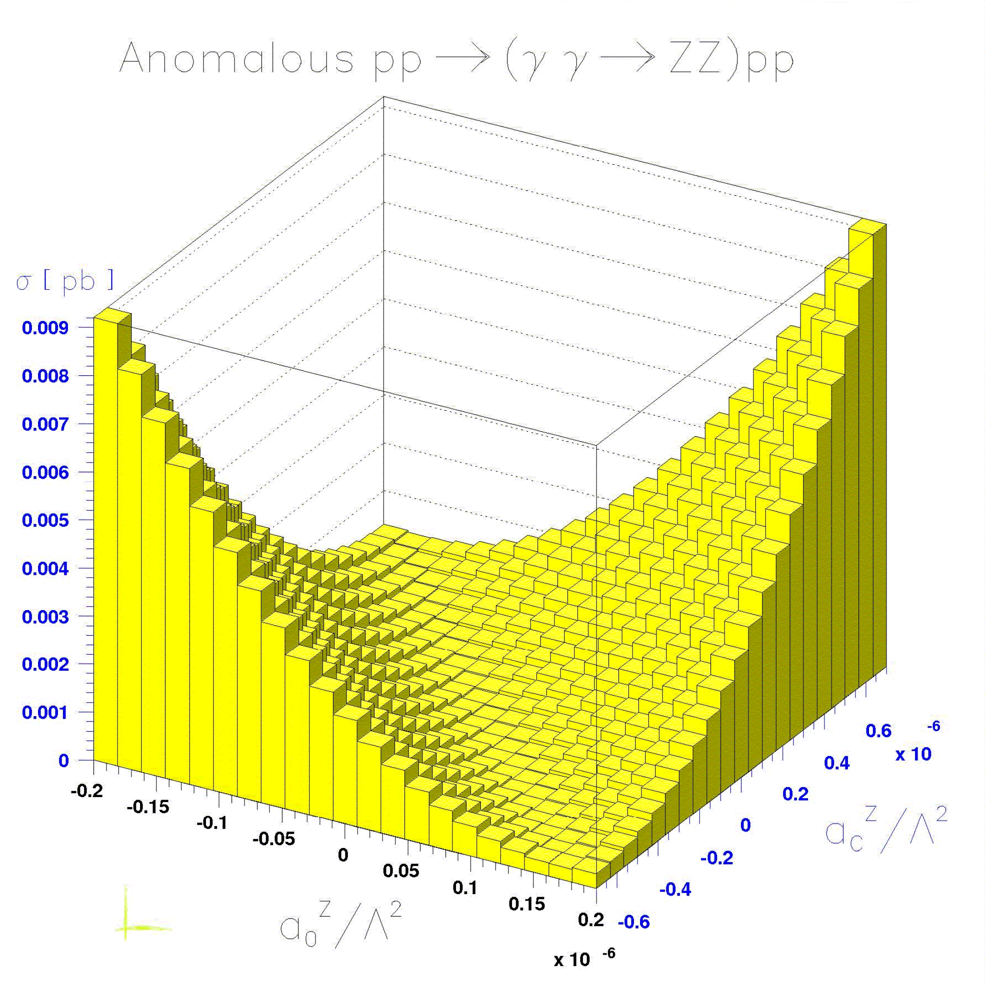


$\sigma \sim 100$–500 nb

K. Piotrzkowski
Université Catholique de Louvain

K.Piotrzkowski et al.,
UCLouvain

Anomalous $\gamma\gamma \rightarrow$ZZ quartic couplings



- In SM $\gamma\gamma \rightarrow ZZ$ quantum effect

  for $\int L_{pp}\,dt$=30fb^{-1} $\Rightarrow$ about 5 SM Z pairs will be produced

- our limits estimations (more 10 000 $\times$):

$$-0.2{\cdot}10^{-6}\ \mathrm{GeV}^{-2} < a_0^{\mathrm{Z}}/\Lambda^2 < 0.2{\cdot}10^{-6}\ \mathrm{GeV}^{-2}$$

$$-0.7{\cdot}10^{-6}\ \mathrm{GeV}^{-2} < a_c^{\mathrm{Z}}/\Lambda^2 < 0.7{\cdot}10^{-6}\ \mathrm{GeV}^{-2}$$

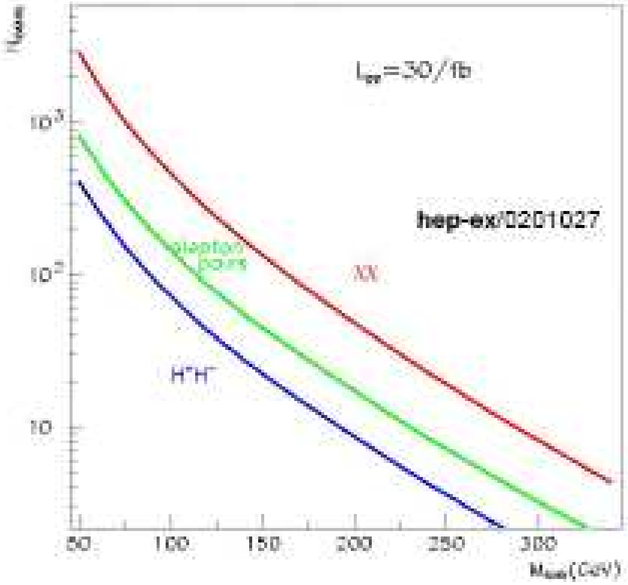
Non-CEP physics using forward detectors

Diffractive Physics:

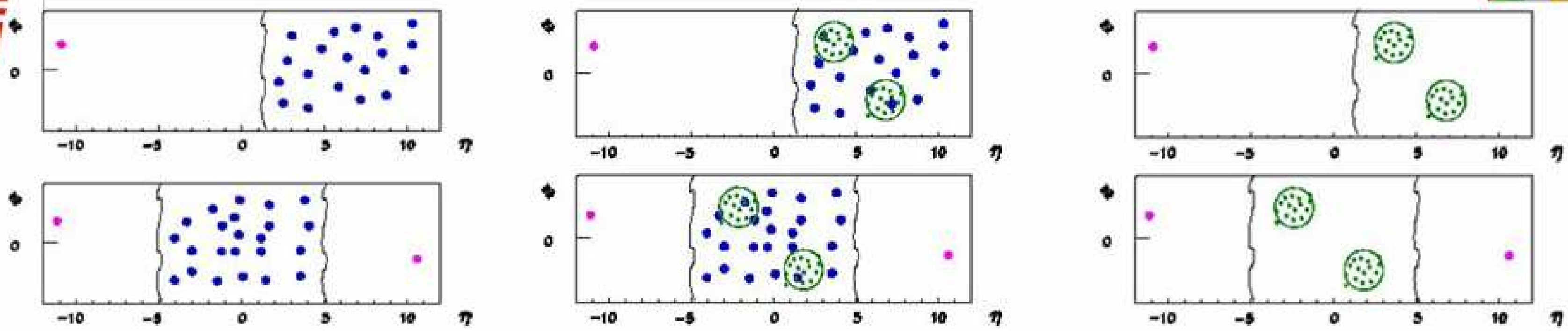
Measure single diffractive and double pomeron exchange events;
1) Diffractive jet transverse momentum distributions.
2) Low x partons through diffractive PDFs.
3) Gap survival probabilities.

Photon-Photon physics:

1) Measurement of anomalous quartic couplings; $\gamma\gamma\mathbf{WW}$ and $\gamma\gamma\mathbf{ZZ}$.
2) lepton pair production.
3) slepton and chargino pair production.
4) $\gamma\mathbf{p}$ interactions for HERA-type physics.



Running scenario



pp->pX
pp->pXp

pp->pjjX
pp->pjjXp

pp->pjj
pp->pjjp
(bosons, heavy quarks, Higgs...)

soft diffraction (semi)-hard diffraction hard diffraction

cross section ⟵ ⟶ luminosity

σ	mb	μb	nb	
β* (m)	1540	90	2	0.5
$\mathcal{L}$ (cm^{-2} s^{-1})	10^{28}	10^{30}	10^{32}	10^{34}
	TOTEM runs		Standard runs	

Accessible physics depends on: luminosity
β* (i.e. proton acceptance)

"The World's Most Wanted"

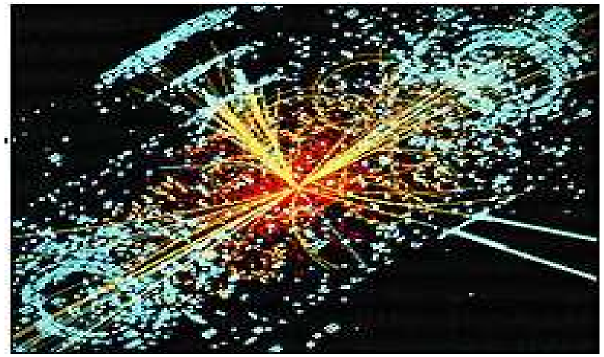
Fugitives

Higgs boson

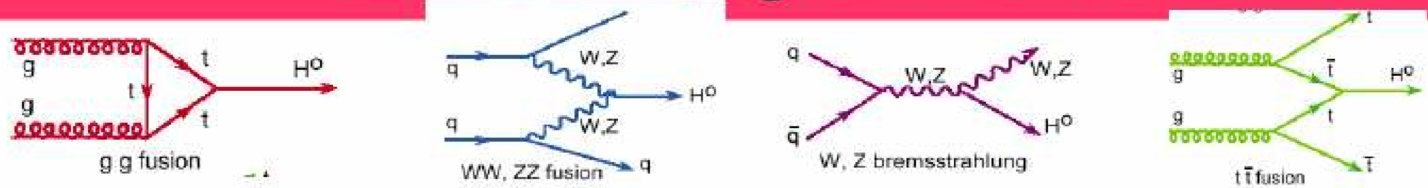
Nowhere to Run! Nowhere to Hide!

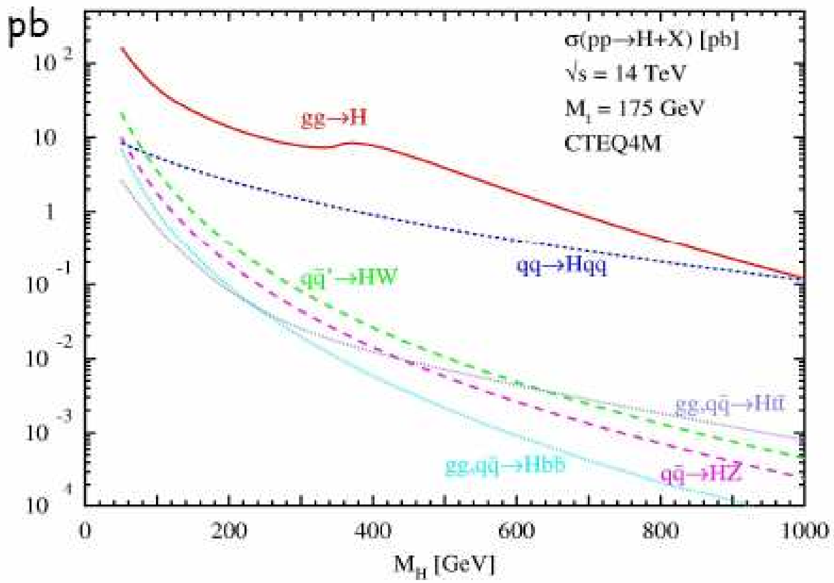
REWARD

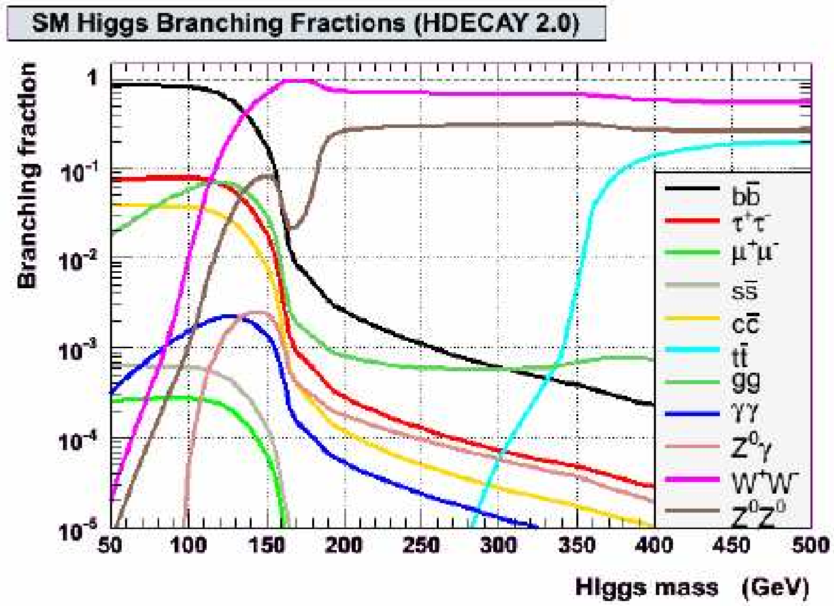
2.5 billion



LHC Higgs in one slide







m_H < 130 GeV : H □ bb, ττ dominate

□ best search channels at LHC: qqH → qqττ, ttH→ lbbX, H →γγ

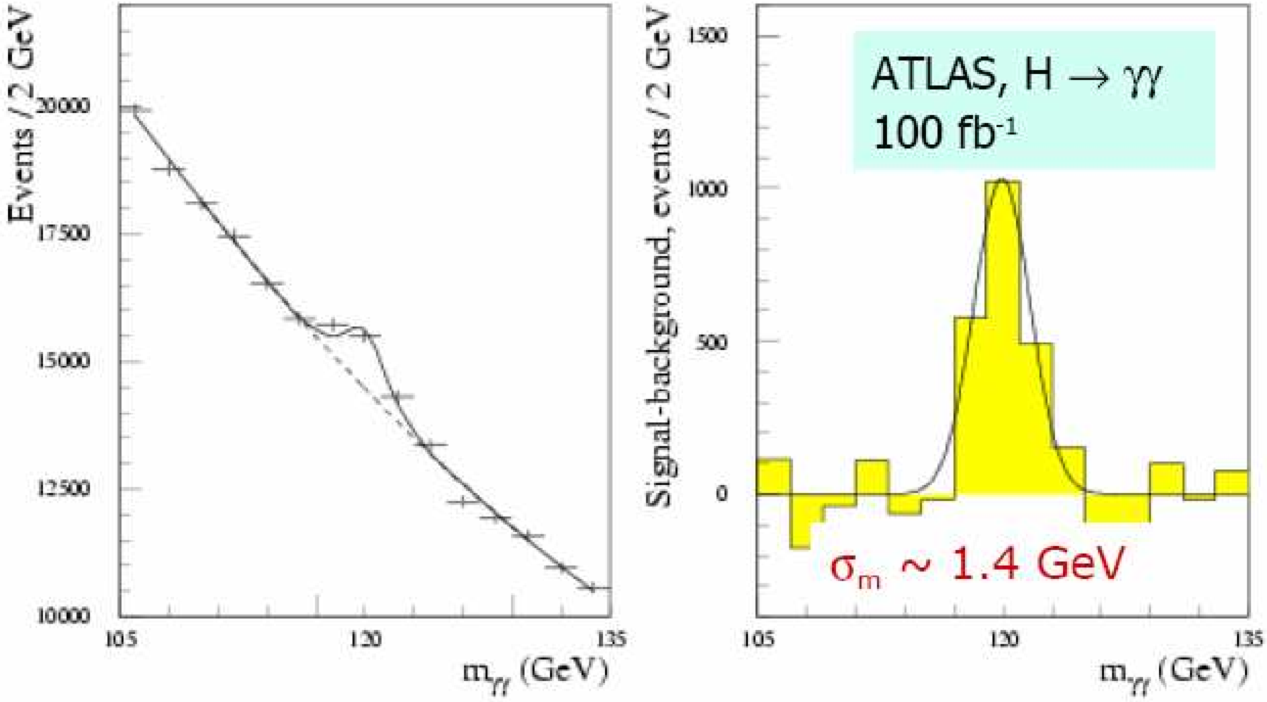
m_H > 130 GeV : H → WW$^{(*)}$, ZZ$^{(*)}$ dominate

□ best search channels at LHC: H → ZZ$^{(*)}$ → 4l (gold-plated), H → WW$^{(*)}$ □ lν lν

Especially in the region m_H<130 GeV, excellent detector performance needed:

b-tag, lγ E-resolution, γ/j separation, E_T^{miss} resolution, forward jet tag, etc.

□ Higgs searches used as benchmarks for ATLAS and CMS detector design



It will need a perfectly understood detector in terms of photon identification, calorimetr tracking, ….

BG dominated by irreducible components

2010 ?

Current consensus on the LHC Higgs search prospects

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

m_H (SM) <144 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. ☺

(Tord Ekelof)

- 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*

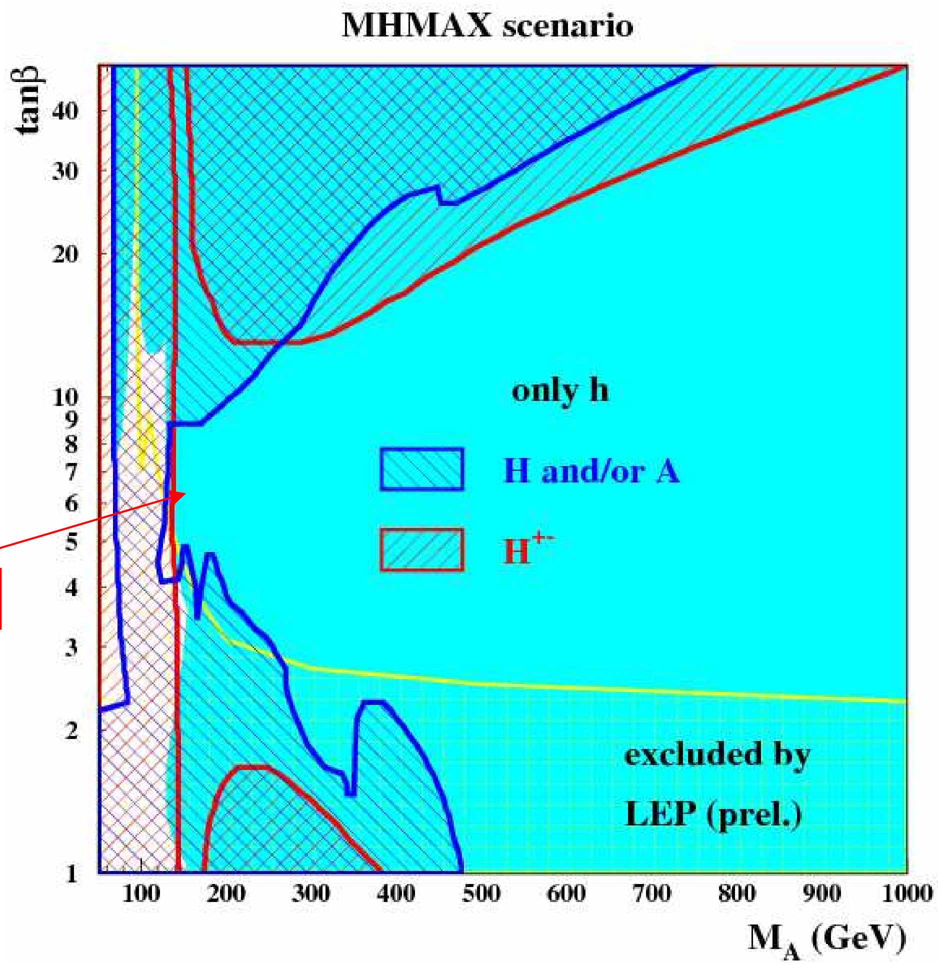
 we ♥ and need ILC

How do we know what we have found?

Experimental questions

- Is it a Higgs boson?
- What are its mass, spin and $\mathcal{CP}$ properties?
- What are its couplings to fermions and gauge bosons? Are they really proportional to the masses of the particles?
- What are its self-couplings?
- Are its properties compatible with the SM, the MSSM, the NMSSM, . . . ?
- Are there indications that there are more than one Higgs bosons?
- Are there indications for other new states that influence Higgs physics?

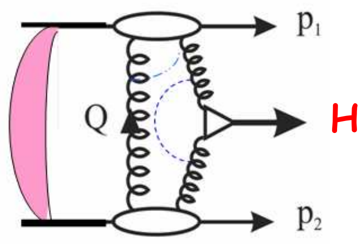
D.Kcira, **arXiv:0710.1957** [hep-ex]



The 'LHC wedge'

Fig. 6. Overall discovery potential for Higgs boson in the M_h^{max} scenario with 300 fb^{-1} as calculated with simulated data for the ATLAS detector.

The main advantages of CED Higgs production



- Prospects for high accuracy 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.)
- Recent MSSM studies (HKRSTW-07, CLP-07) ➔ very promising results.
- 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 !

Experimental Advantages

– Measure the Higgs mass via the missing mass technique
Mass measurements do not involve Higgs decay products
Cleanness of the events in the central detectors.

Experimental Challenges

– Tagging the leading protons
– Selection of exclusive events & backgrounds, PU -events
– Triggering at L1 in the LHC experiments.
– bb-mode requires special attention.

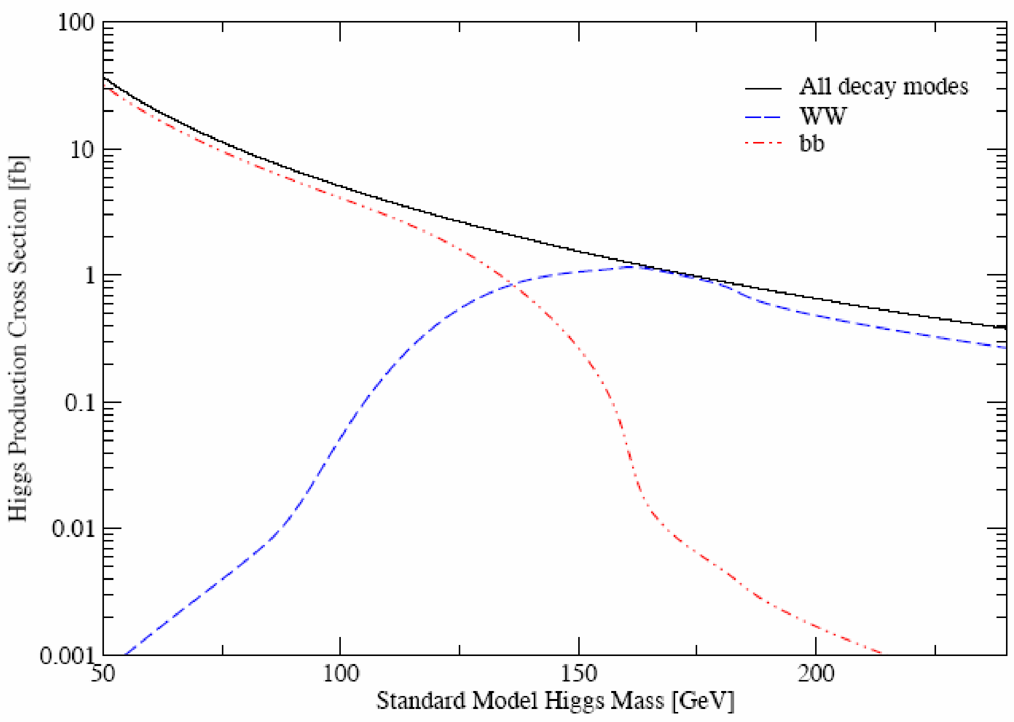
Uncertainties in the theory

(Unusually& uncomfortably) large higher-order effects,
model dependence of predictions *(soft hadronic physics is involved after all)*

There is still a lot to learn from the Tevatron/Hera diffractive data (KKMRS- friendly so far).

SM Higgs

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

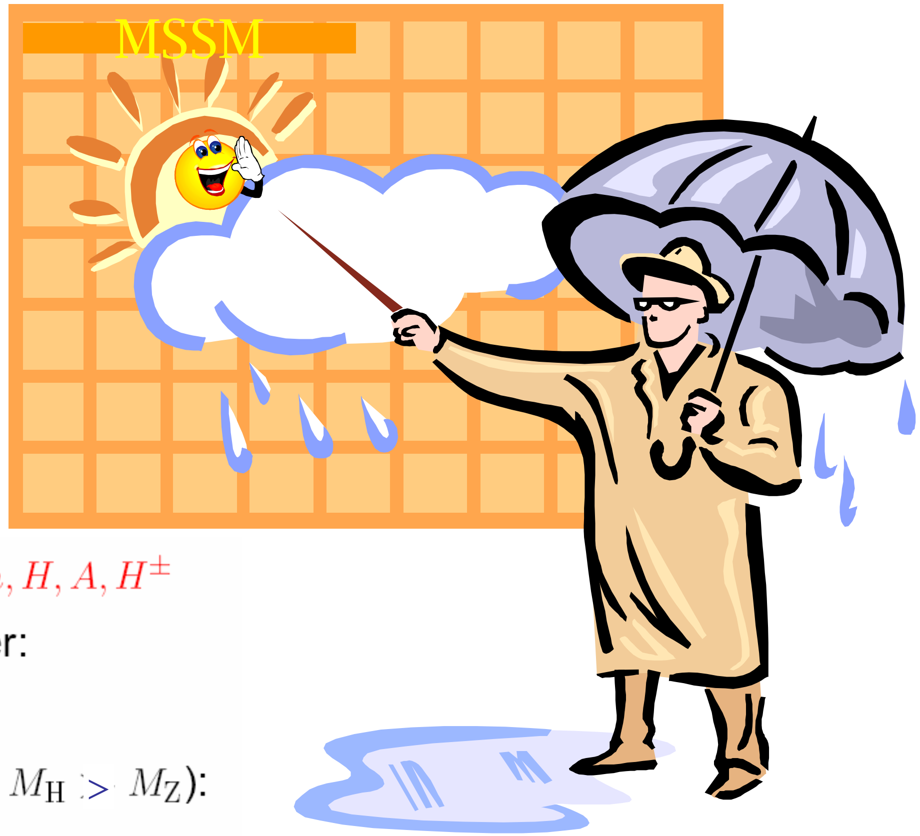


Cox, de Roeck, Khoze, Pierzchala, Ryskin, Stirling, Nasteva, Tasevsky without 'clever hardware':

for H(SM)→bb at 60fb-1 only
a handful of events due to
severe exp. cuts and low efficiencies,
though **S/B~1**

but **H->WW** mode at M>135 GeV

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



- Higgs sector of the MSSM: physical states $h, H, A, H^{\pm}$

  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

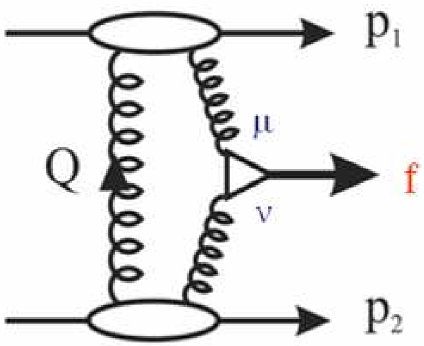
The backgrounds to the diffractive H bb mode are manageable but should be studied very thoroughly !

for Higgs searches in the forward proton mode QCD 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 $(\vec{Q}_t)$ angular integration at $p_{t,i} = 0$ ➔ $-\delta^{(2)}_{\mu\nu} Q_t^2 / 2$

KMR-01

(J. Pumplin 1995)

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 ➔ $\dfrac{(2p_{1,t}p_{2,t})^2}{Q_t^4}$

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

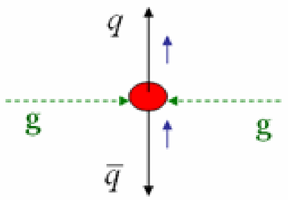
(+ - ; + -) J_z=2, **HCA** (S .Parke, T.Taylor (1986))

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

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)

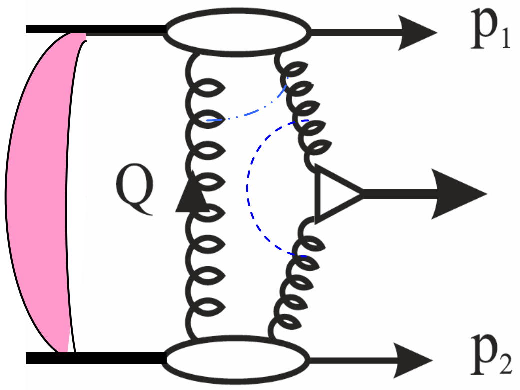
- LO **HCA** vanishes in the Jz=0 case (*valid only for the Born amplitude*)

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)

The MSSM and more *exotic* scenarios

$$pp \longrightarrow p + \phi + p$$



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

- an *'Invisible' Higgs* (BKMR-04)

- *NMSSM* (J. Gunion, J.Forshaw et al.)

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

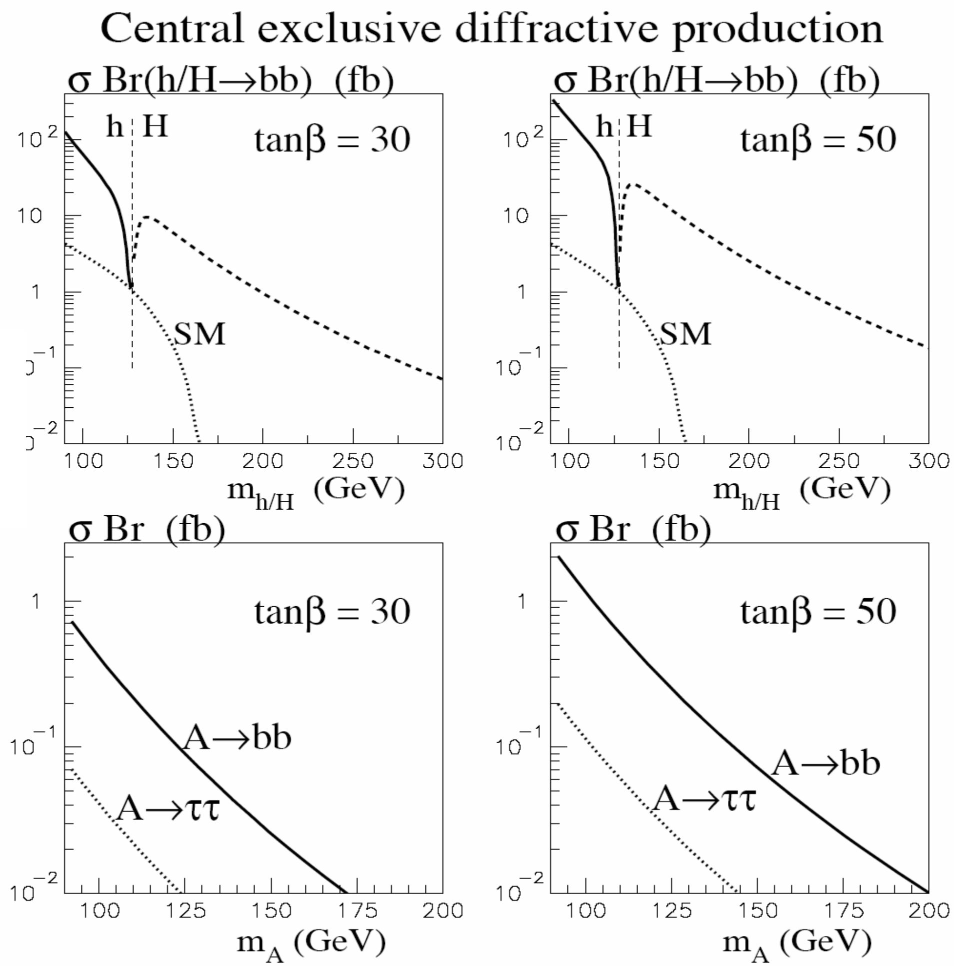
$\gamma\gamma, WW^\star, ZZ^\star$ suppressed

$gg \to \phi$ enhanced

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

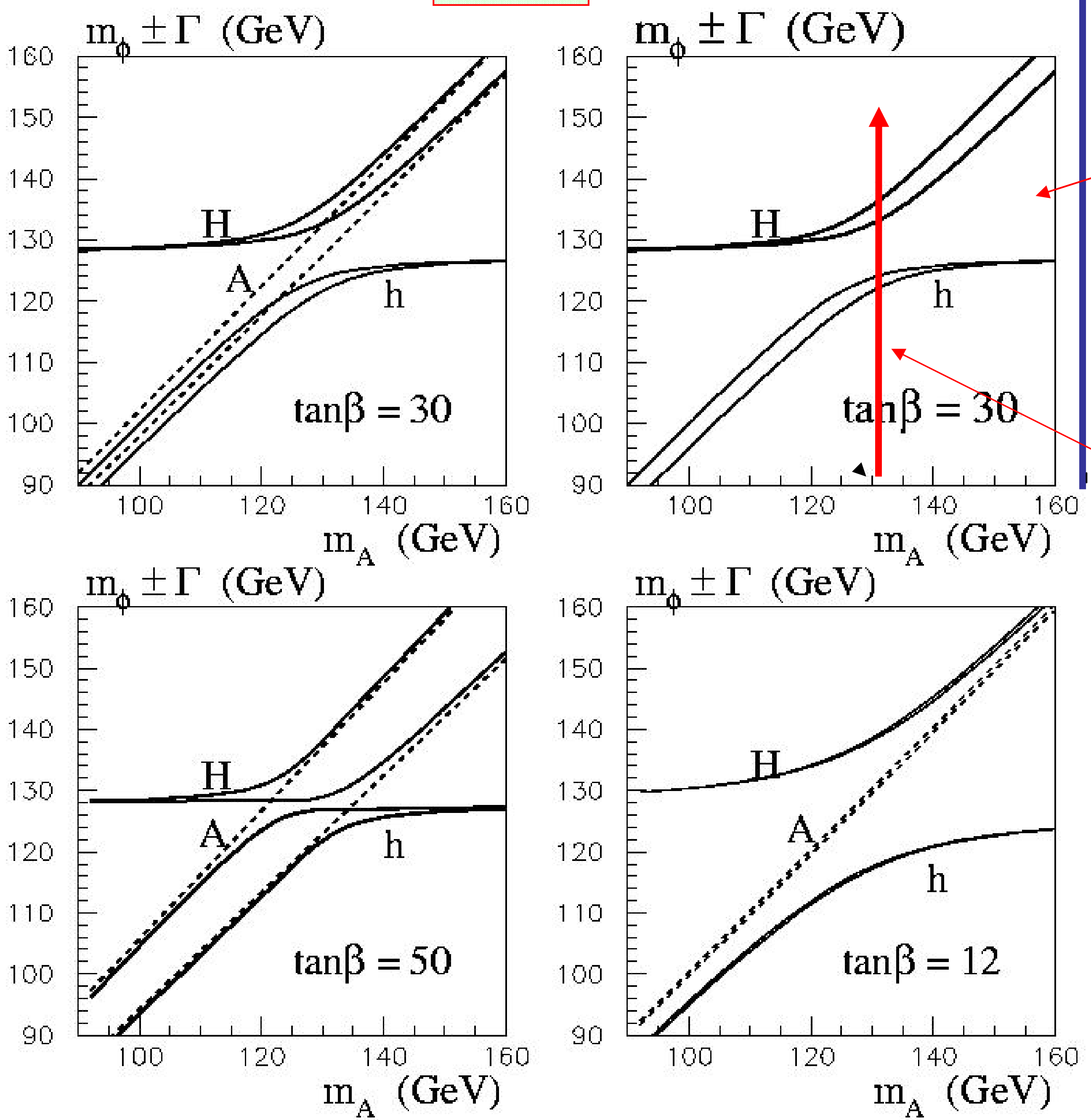
CEDP 'filters out' pseudoscalar production, leaving pure H sample for study

KKMR-04



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

KKMR-04



decoupling regime

$m_A \sim m_H \geq 150$ GeV,

$\tan\beta > 10$;

h = SM

intense coupling:

$m_h \sim m_A \sim m_H$

$\gamma\gamma$,WW.. coupl suppressed

with CEDP:

- **h,H** may be clearly distinguishable outside 130+-5 GeV range,
- **h,H** widths are quite different

Studying the MSSM Higgs Sector by Forward Proton Tagging at the LHC

arXiv:0708.3052 [hep-ph]

Based on collaboration with S.Heinemeyer, M.Ryskin, W.J.Stirling, M.Tasevsky & G. Weiglein

Higgs sector of the MSSM: physical states $h, H, A, H^{\pm}$

Described by two parameters at lowest order: M_{A}, $\tan\beta \equiv \frac{v_2}{v_1}$

Dominant decay mode of a light SM-like Higgs: $h \to b\bar{b}$

However: $h \to b\bar{b}$ is difficult to access in Higgs searches at the LHC ($t\bar{t}h$, $h \to b\bar{b}$, ...)

Knowledge of $hb\bar{b}$ coupling is important for determining any Higgs-boson coupling at the LHC

[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]

Precise information on the couplings, spin, $\mathcal{CP}$ properties, etc. of a Higgs candidate will be crucial for

– determining the nature of the detected particle

– experimentally verifying the Higgs mechanism

Extended Higgs sectors: "typical" features

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

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

Four integrated luminosity scenarios

(assuming that the overlap (PU) backgrounds scan be completely removed)

- **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.

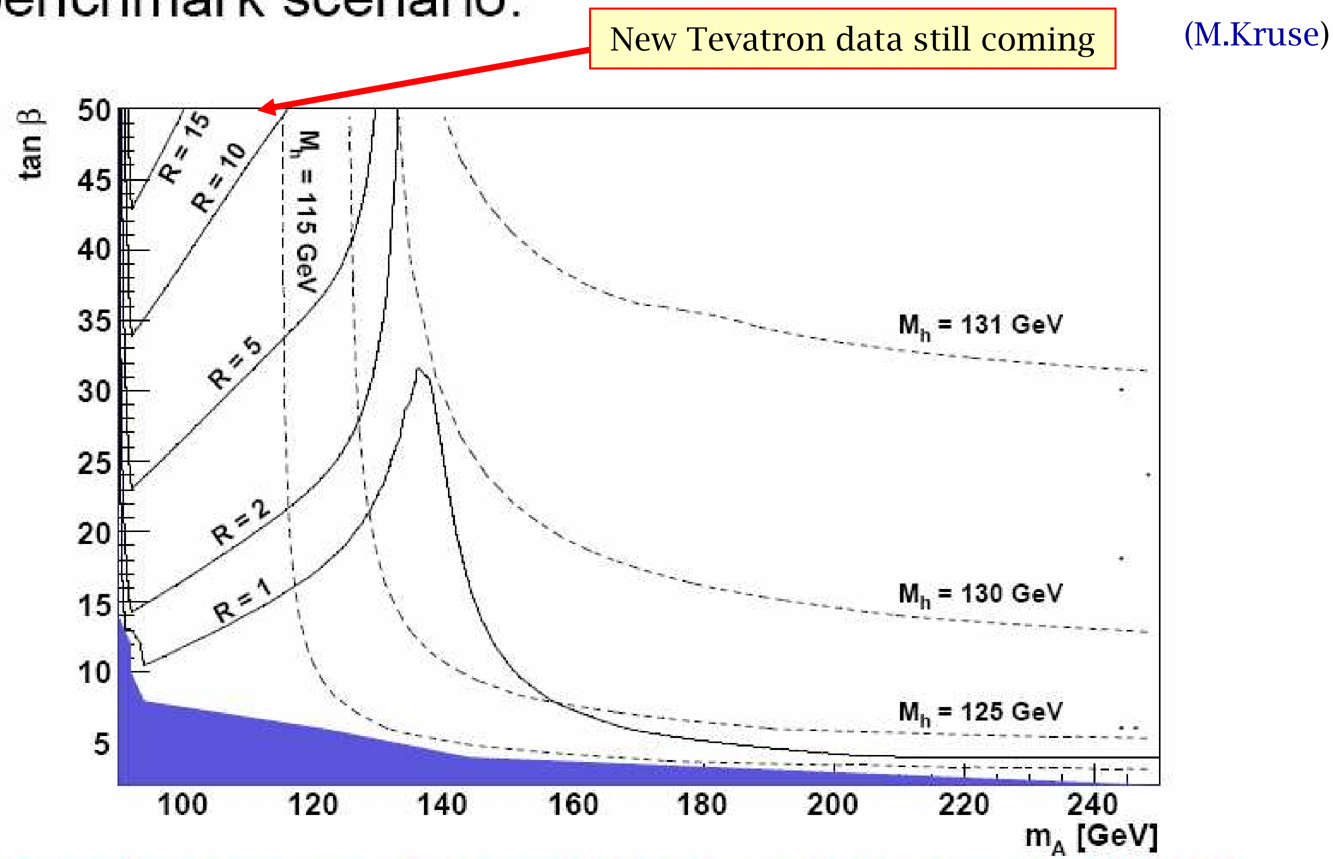
3. L = 600fb^{-1}: 300 (ATLAS) + 300 (CMS) : 3 yrs with L=10^{34}cm^{-2}s^{-1}

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

we have to be open-minded about the theoretical uncertainties

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

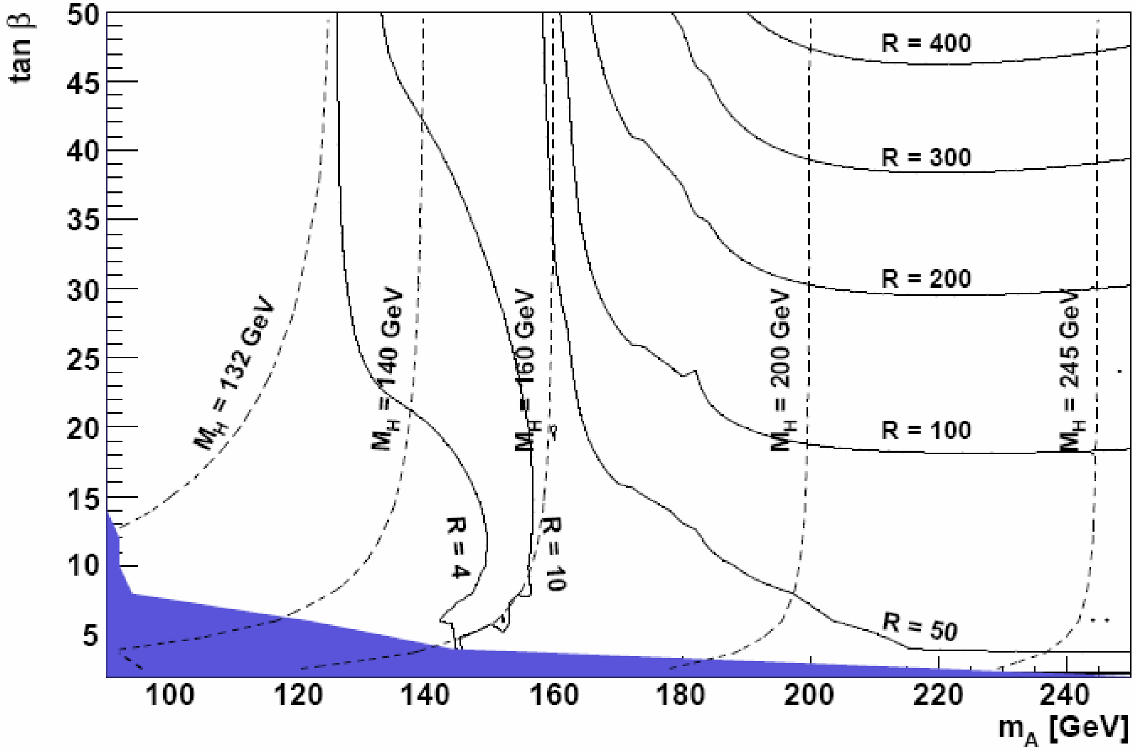
m_h^{max} benchmark scenario:



⇒ 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

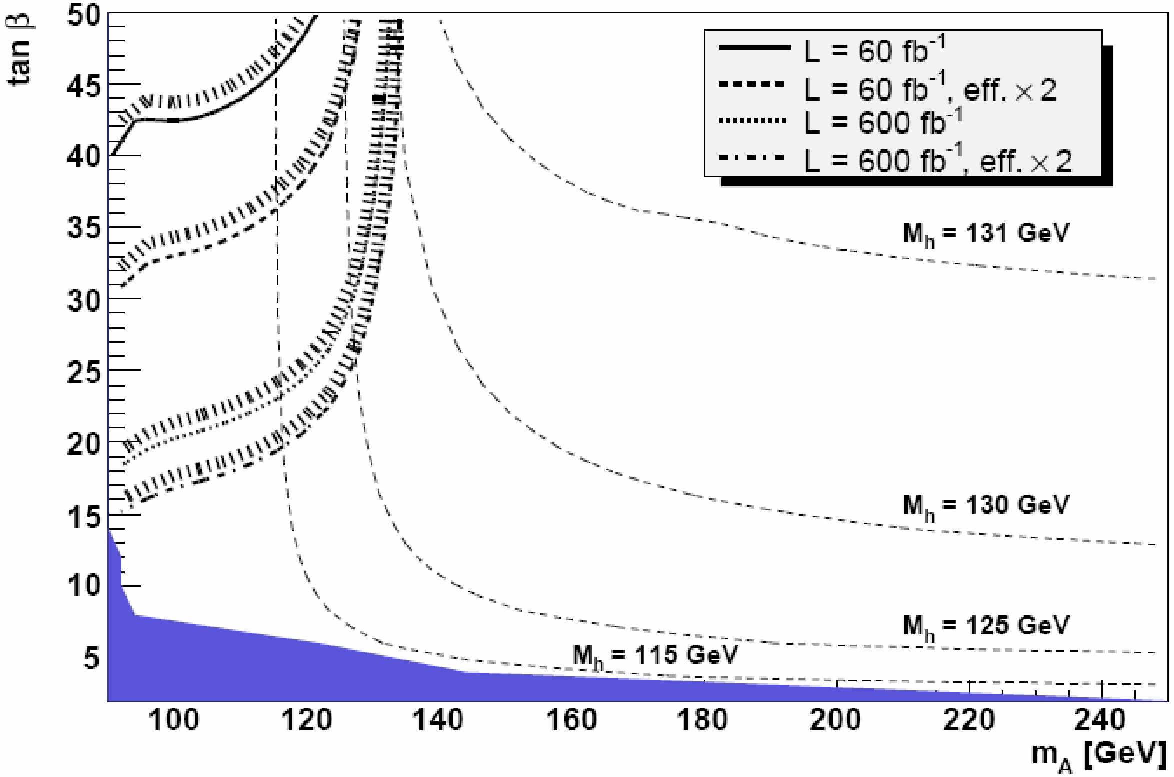
m_h^{max} benchmark scenario:



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

5σ *discovery contours for CED production of the light MSSM Higgs boson in the $h \to b\bar{b}$ channel*

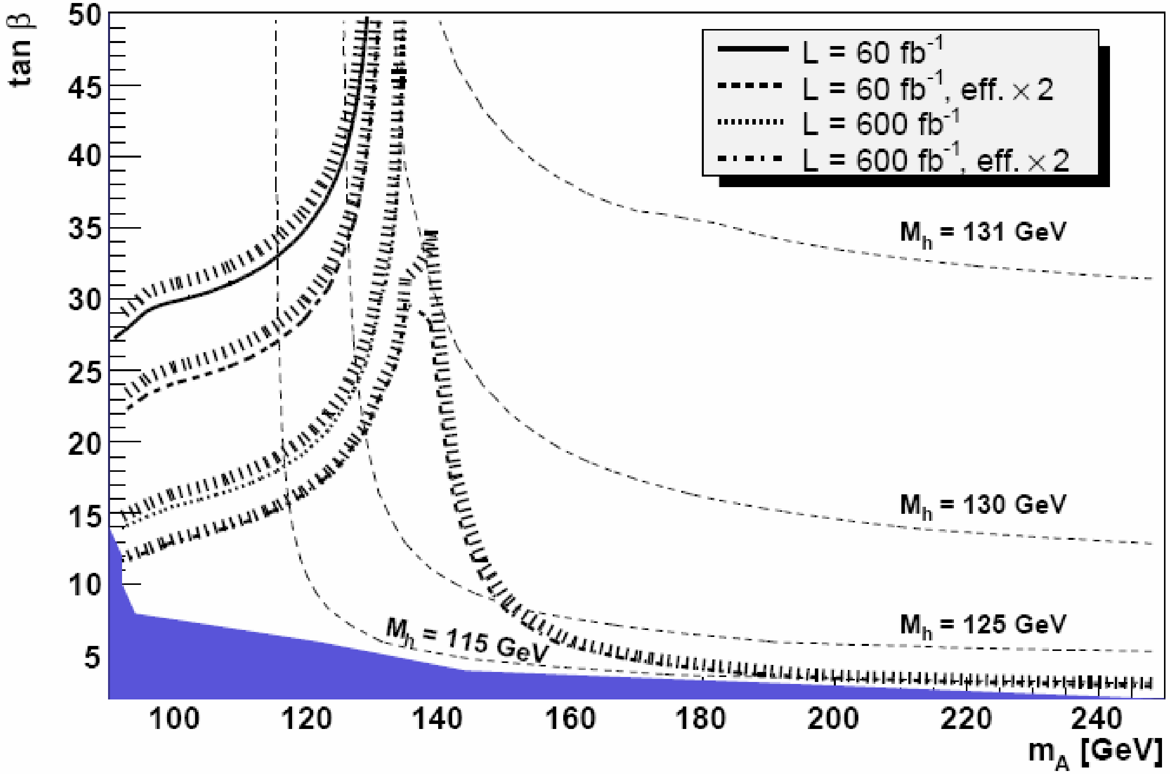
m_h^{max} benchmark scenario:



⇒ Discovery possible in region of rel. small M_A and large $\tan\beta$

3σ *contours for CED production of the light MSSM Higgs boson in the* $h \to b\bar{b}$ *channel*

$m_h^{\max}$ benchmark scenario:

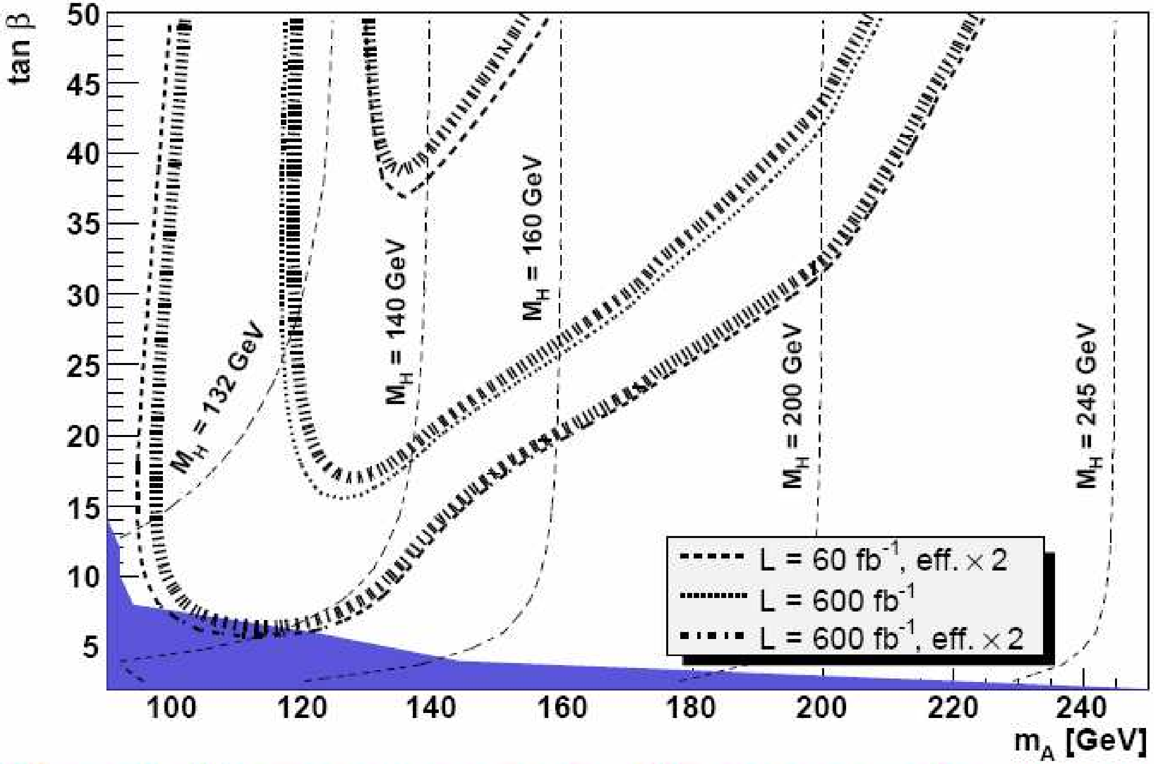


$\Rightarrow$ Almost complete coverage with $600\ \mathrm{fb}^{-1} \times 2$

$\Rightarrow$ CED channel may yield crucial information on $hb\bar{b}$ coupling

5σ *discovery contours for CED production of the heavy $\mathcal{CP}$-even MSSM Higgs, $H \to b\bar{b}$ channel*

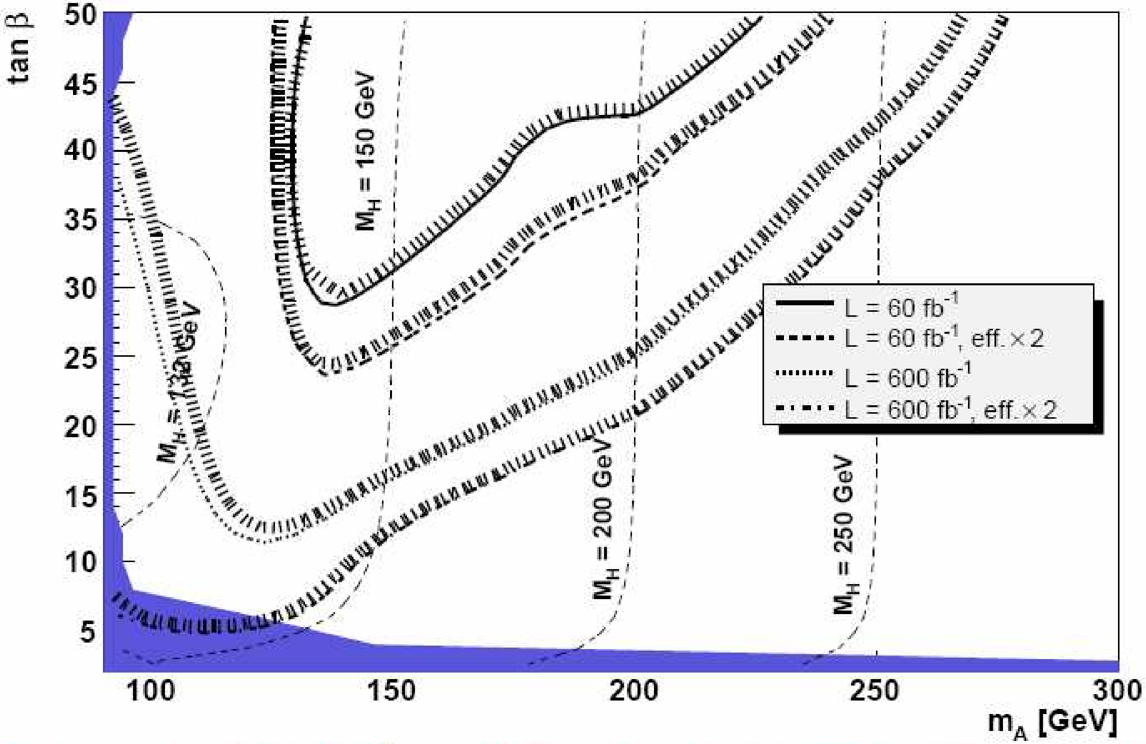
$m_{\mathrm{h}}^{\mathrm{max}}$ benchmark scenario:



$\Rightarrow$ Significant discovery reach, discovery of a 140 GeV Higgs for all values of $\tan\beta$ with $600\ \mathrm{fb}^{-1} \times 2$

5σ *discovery contours for CED production of heavy $\mathcal{CP}$-even Higgs,* $H \to b\bar{b}$, $\mu = -500$ GeV

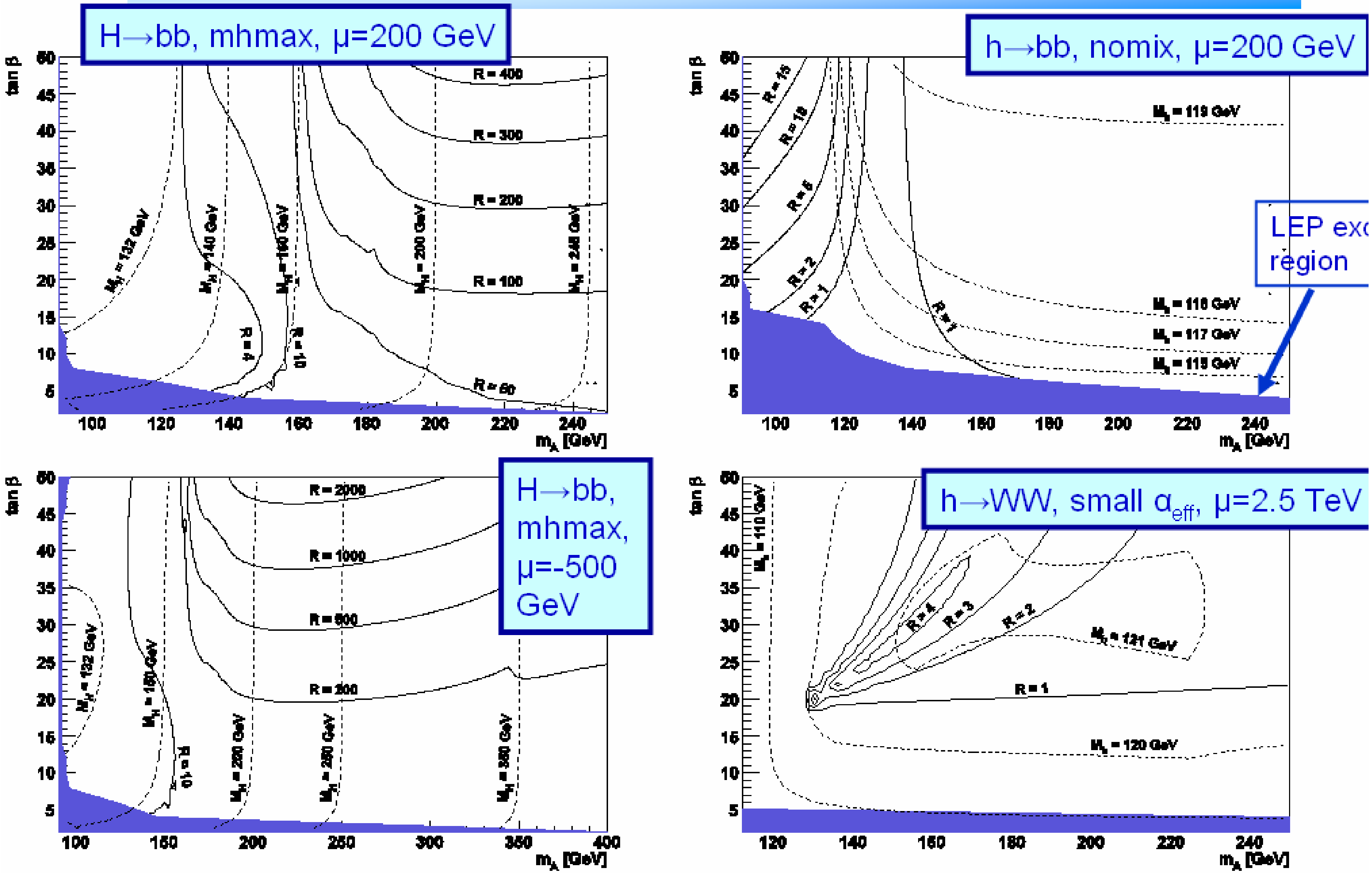
m_h^{max} benchmark scenario, $\mu = -500$ GeV:



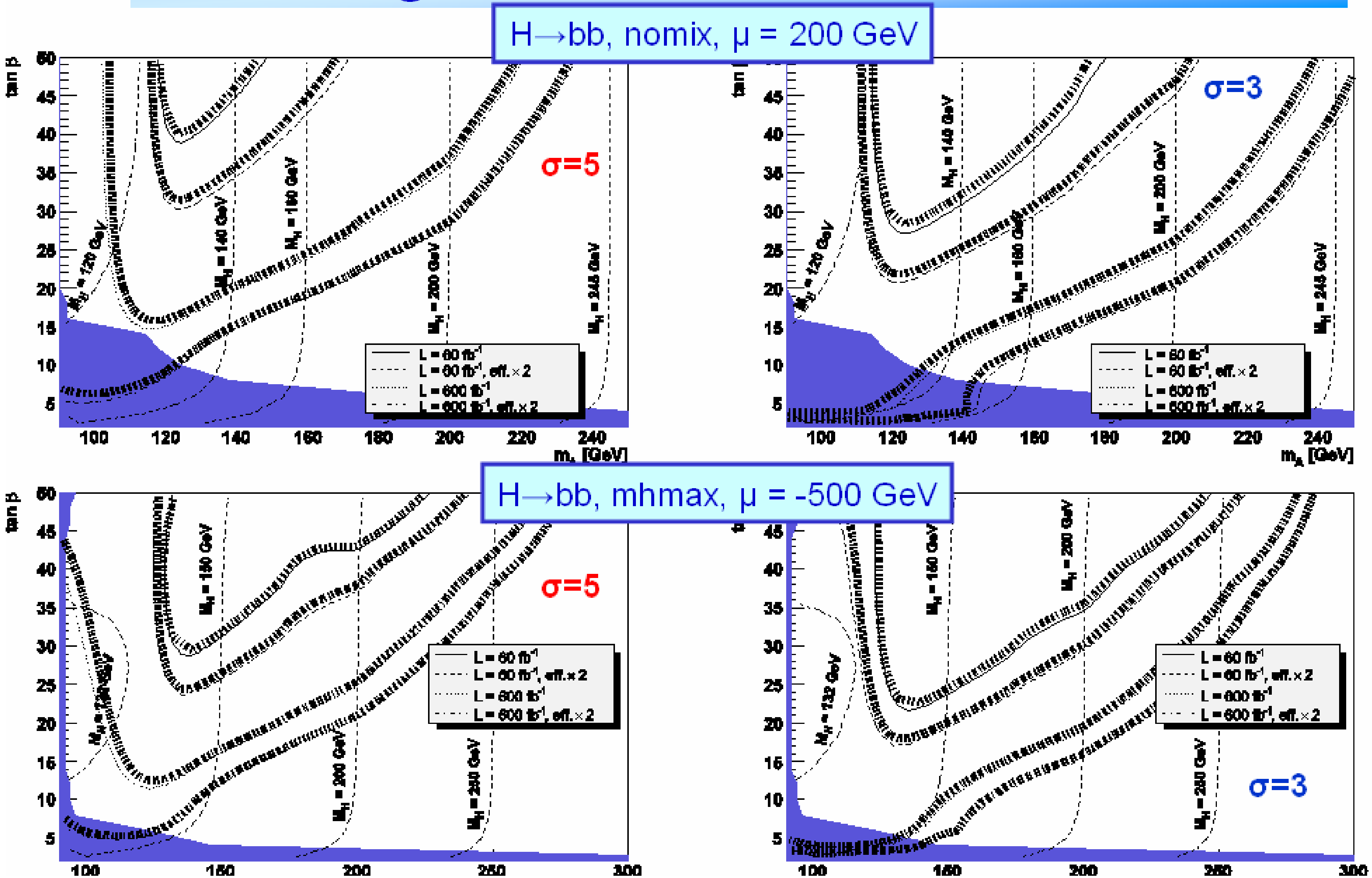
⇒ Large $\tan\beta$, $600\ \text{fb}^{-1} \times 2$: 5σ reach beyond $M_H \approx 250$ GeV

⇒ Access to $Hb\bar{b}$ coupling even for rel. heavy Higgs

R=MSSM[M,tanβ] / SM[M]



Stat. significance for H→bb: from 5 to 3



CED Higgs production at the LHC

$J_Z = 0$, $\mathcal{CP}$-even selection rule

$\Rightarrow$ Strong suppression of QCD background

Information about quantum numbers of produced state

Reconstruct mass of produced state from proton momenta

$\Rightarrow$ Excellent mass resolution possible, independently of decay mode of produced state

Access to main Higgs decay modes: $H \to b\bar{b}, WW, \tau^+\tau^-$

$\Rightarrow$ Information about bottom Yukawa coupling

$\Rightarrow$ CED Higgs production could provide crucial information on SM-like Higgs and heavy states of extended Higgs sector

MSSM: possibility to measure total Higgs width (high $\tan\beta$) and to distinguish between nearly degenerate Higgs states

[*J. Ellis, J.-S. Lee, A. Pilaftsis '05*] [KKMR '04]

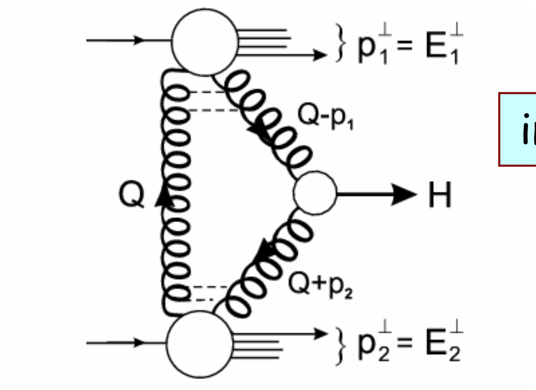
Hunting the CP-odd boson, A

✳(LO) selection rule – an attractive feature of the CEDP processes, but……

☹ *the flip side to this coin:*
strong (factor of ~ 10^2)suppression of the CED production of the A boson.

✳A way out : to allow incoming protons to dissociate (E-flow E_T>10-20 GeV) KKMR-04

pp→ p + X +H/A +Y +p (CDD)



in LO azim. angular dependence: $\cos^2\phi$ (H), $\sin^2\phi$ (A), bkgd- flat

A testing ground for CP-violation studies in the CDD processes (KMR-04)

☹ challenges: bb mode – bkgd conditions ττ-mode- small (QED)bkgd, but low Br

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

MA= 120 GeV,
tanβ =40, a factor
of ~10 enhancement

B. E. Cox, F. K. Loebinger, A. D. Pilkington (**arXiv:0709.3035** [hep-ph])

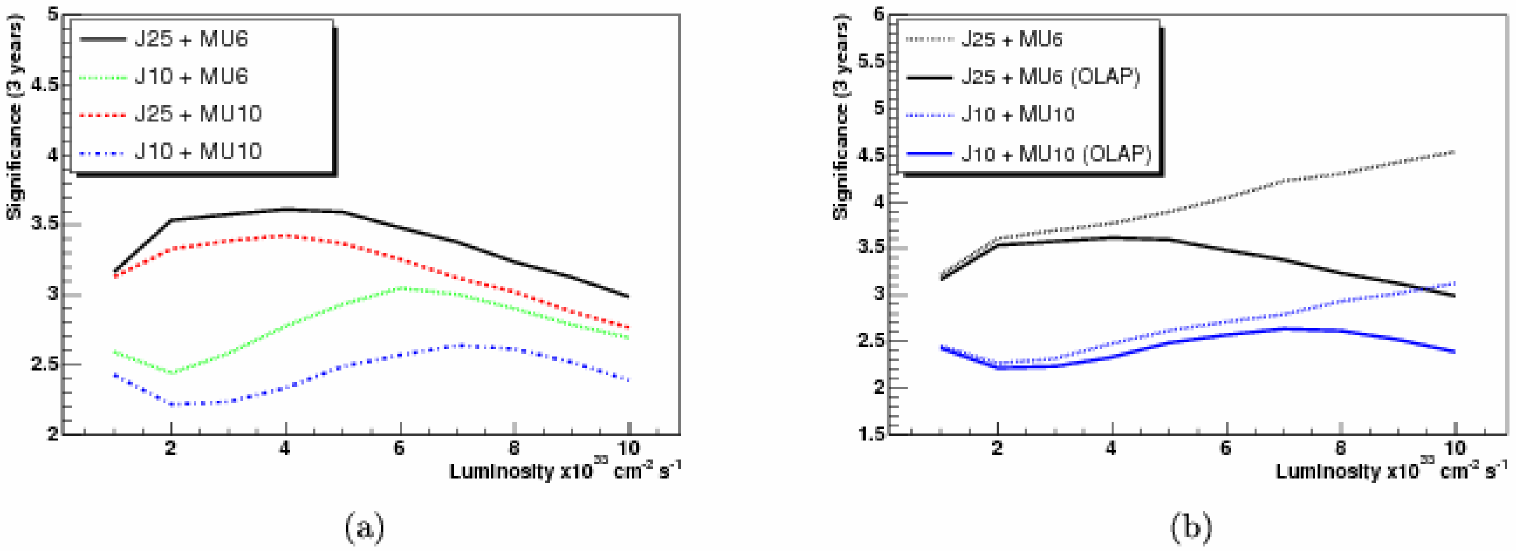


Figure 15: Figure (a) shows the significance of the measurement of the 120 GeV MSSM Higgs Boson for the model described in the text, using the combined muon, rapidity gap and jet rate triggers for the analysis with both protons detected at 420m. Figure (b) shows the effect of completely removing the overlap background on two of the trigger strategies.

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

'CPX' scenario
(σ in fb)

KMR-04

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

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

CP even

CP odd active at non-zero t

A is practically uPDF - independent

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

➔ an 'Invisible ' Higgs

BKMR-04

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

(one of the 'LHC headaches')

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

strong requirements :

- triggering directly on L1 on the proton taggers

- low luminosity : $L = 10^{32}$ -10^{33} cm -2 sec-1 (pile-up problem) ,

- forward calorimeters (…ZDC) (QED radiation , soft DDD),

- veto from (T1, T2, CASTOR)- background reduction, improving the trigger budget)

  ➪ *there is a (good) chance to observe such an invisible object, which, otherwise, may have to await a ILC*

➔ searches for extra dimensions – diphoton production (KMR-02)

Stable gluinos

- May bind into gluinonium or decay into distinctive final state (R-hadrons).
- Gluinonium decay to gluons is at too low a rate.
- Stable gluinos, e.g. as in split SUSY, pair-produced with a "large" cross-section.

New (super) heavy objects (KMR-02)

- R-hadrons look like slow muons good for triggering

Peter Bussey, Tim Coughlin, Andy Pilkington, Jeff Forshaw
JHEP 0611:027,2006.

Observation of R-hadrons and mass measurement with ~1% accuracy

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.

More experimental results to come (CDF: exclusive J/ψ, ϒ, Z..)

- Exclusive high-Et dijets
  (CDF: Run I, Run II) data up to (Et)min>35 GeV (submitted to PRD) NEW!

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

(KKMR-01, a quantitative description of the results, both in normalization and the shape of the distribution)

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

- Preliminary CDF results on exclusive charmonium CEDP.

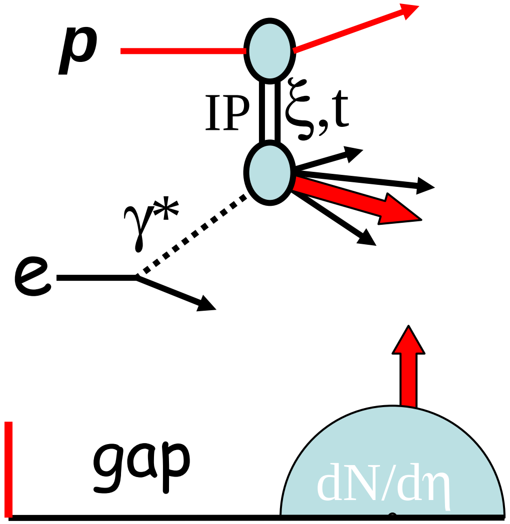
- Energy dependence of the RG survival (D0, CDF).

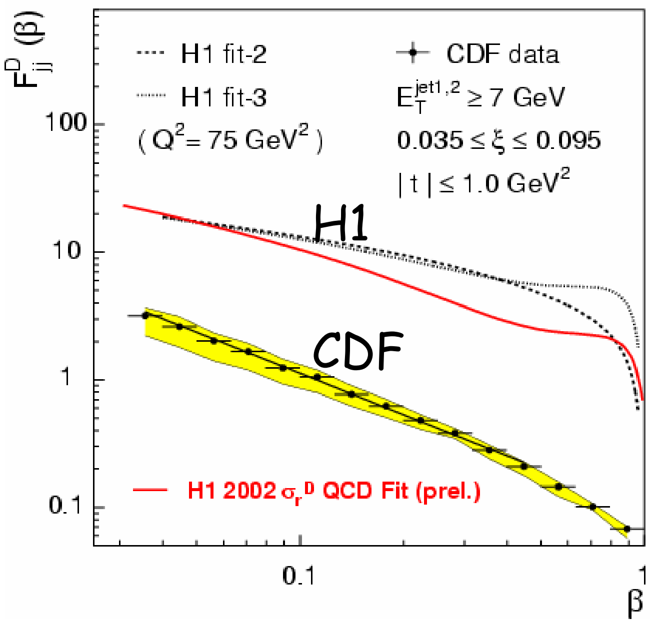
- Central Diffractive Production of γγ (….ππ,ηη) (accepted by PRL) NEW!
  (in line with the KMRS calculations)

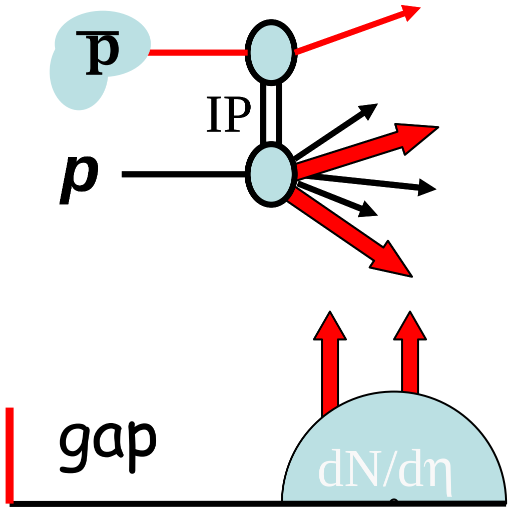
- Leading neutrons at HERA NEW!

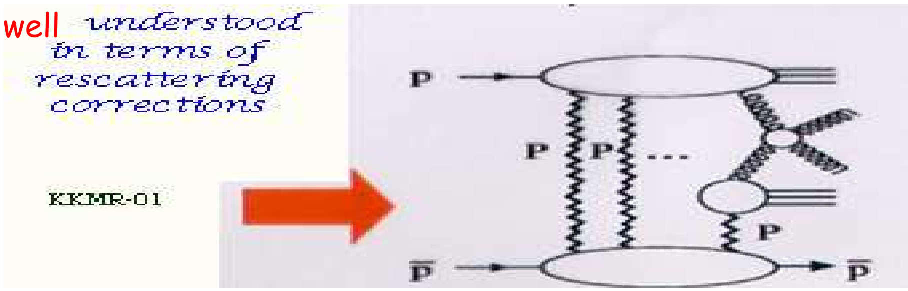
LET THE DATA TALK !

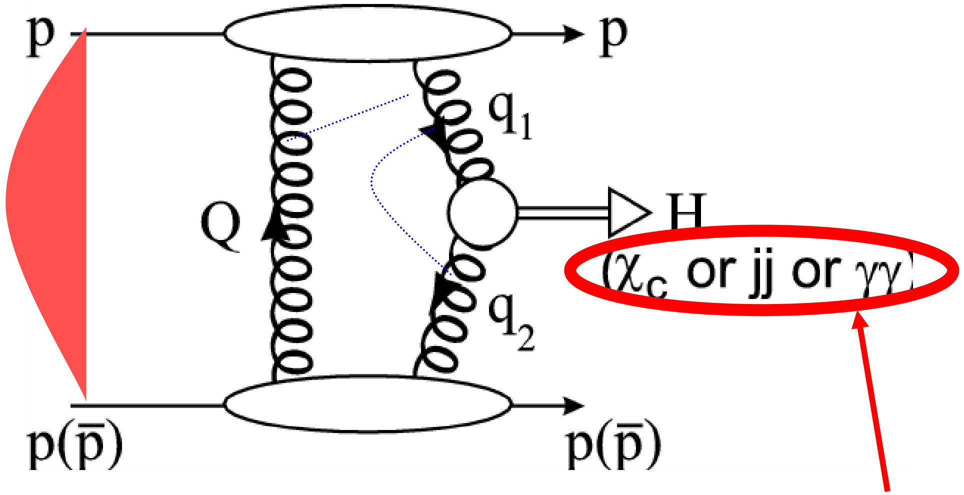
Tevatron vs HERA: Factorization Breakdown











"standard candles"

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

pre-dictions, KMRS

$pp \rightarrow p + \chi + p$ high rate, but low scale (uncertainties in the estimates)

$pp \rightarrow p + jj + p$ rate rather high, but exclusive events should be separated

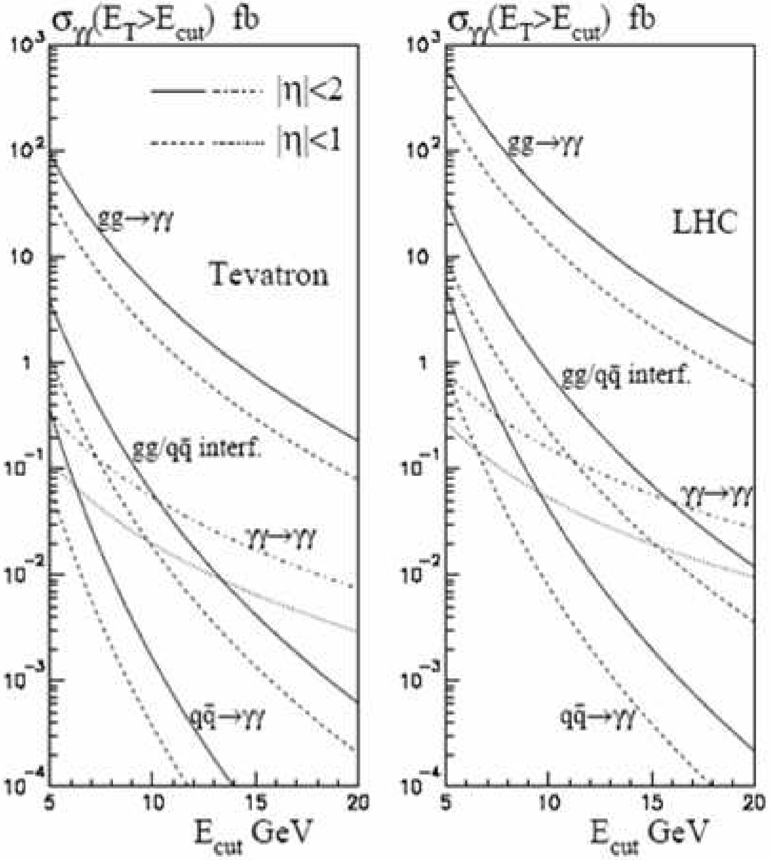
$pp \rightarrow p + \gamma\gamma + p$ low rate, but cleaner signal

Experimental results are encouraging

Information from Tevatron!

Study of central exclusive processes

V. Khoze et al., hep-ph/0409037



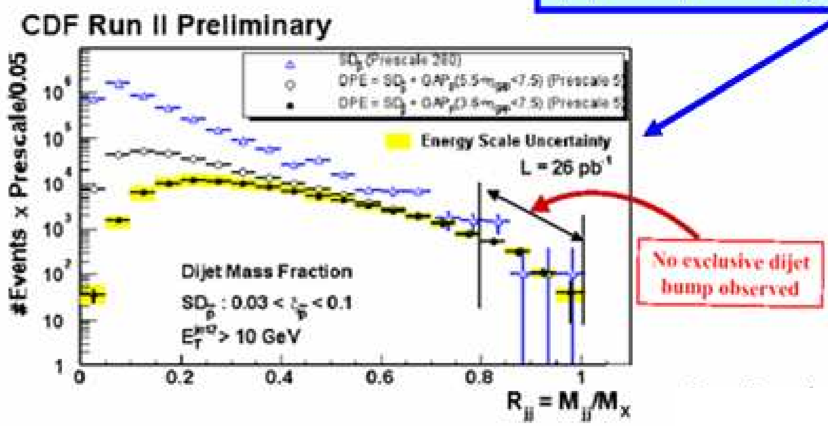
pp $\to$p + $\gamma\gamma$ +p

V. Khoze et al., hep-ph/0403218

	Tevatron $\sqrt{s}=2$ TeV		LHC $\sqrt{s}=14$ TeV	
	χ_c	χ_b	χ_c	χ_b
$d\sigma_{excl}/dy\|_{y=0}$	130	0.2	340	0.6
σ_{excl}	650	0.5	3000	4
$d\sigma_{incl}/dy\|_{y=0}$	13	0.06	30	0.2
σ_{incl}	70	0.3	200	2

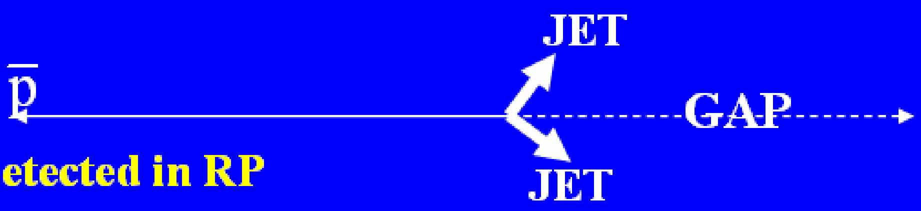
pp $\to$p + χ_c +p

pp $\to$p + dijets+p

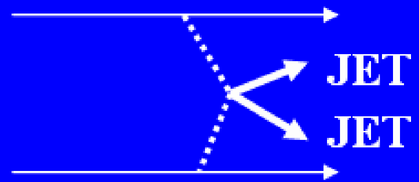


pre-dictions

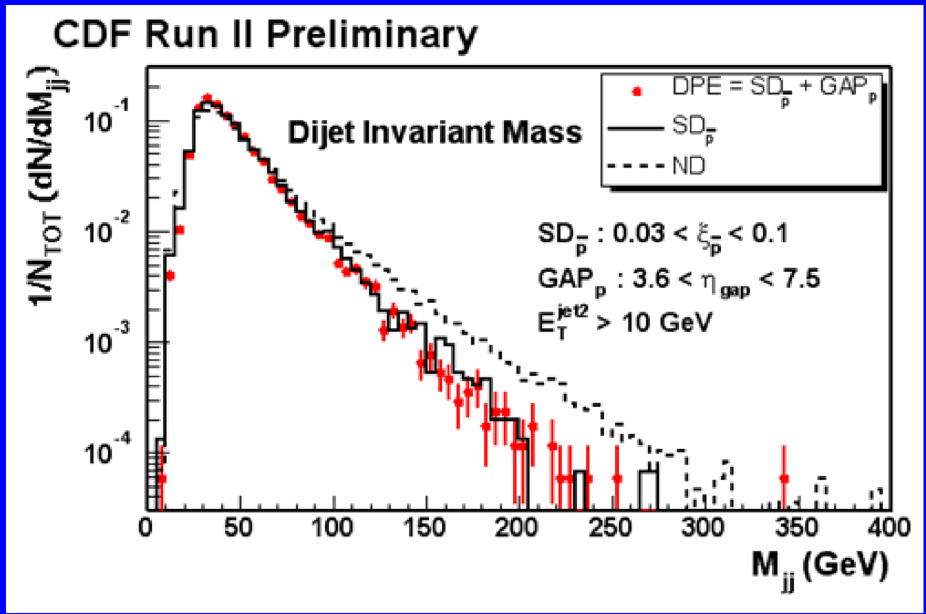
Double Pomeron Exchange Di-Jets in CDF

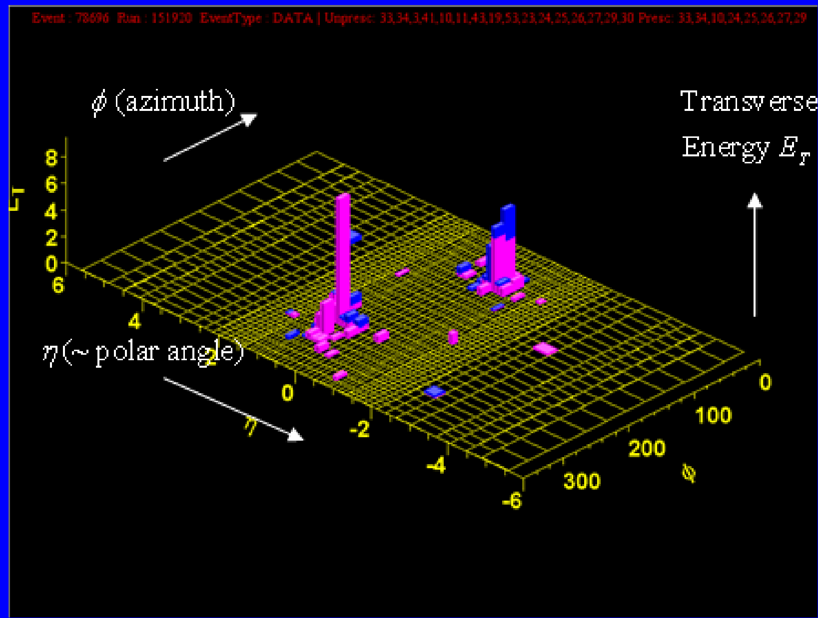


(p not seen)



Detected in RP





Jet <ET> spectra ~ same in SD and DPE

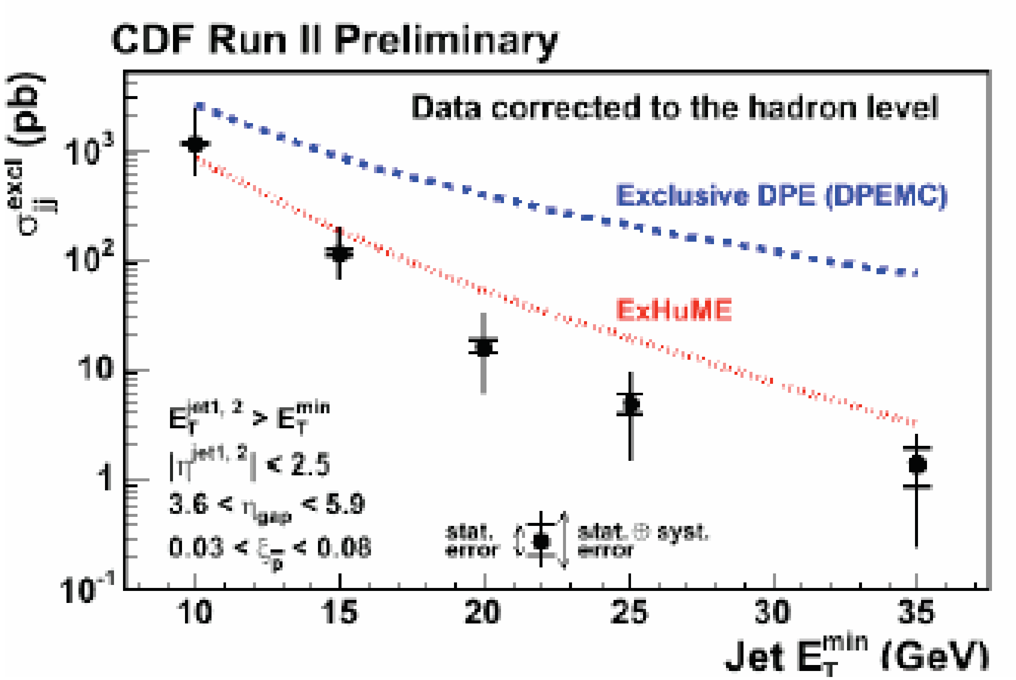
"Almost" exclusive di-jet,
Two jets and nothing else

$$\frac{M_{JJ}}{M_{CEN}} > 0.8$$

No pile-up essential; low-L
(at LHC if both p detected, some PU allowed)

QCD Mediated Dijet Production

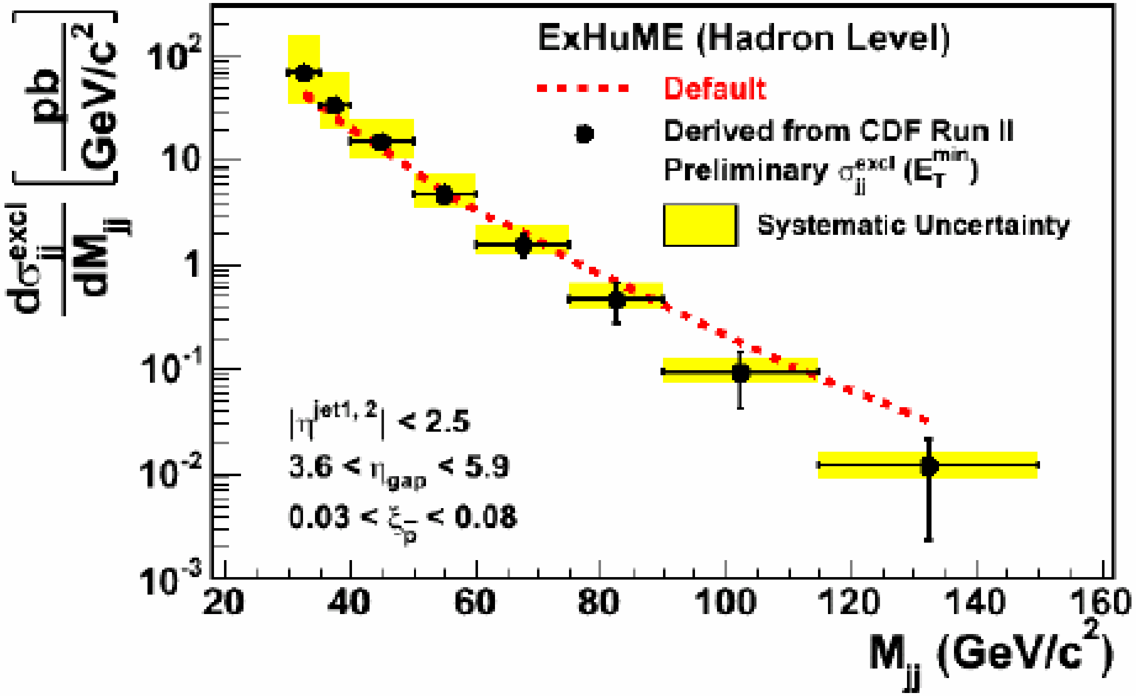
Congratulations to CDF !
….a lot of new exciting plots to come…



ExHuMe (KMR-based)

JJ_{excl} : cross section predictions

ExHuME Hadron-Level Differential Exclusive Dijet Cross Section vs Dijet Mass
(dotted/red): Default ExHuME prediction
(points): Derived from CDF Run II Preliminary excl. dijet cross sections



Statistical and systematic errors are propagated from measured cross section uncertainties using ExHuME M_{jj} distribution shapes.

Central Exclusive 2-Photon Production

Cleanest test of p+H+p theory

MGA et al. (2001) hep-ex/0511057

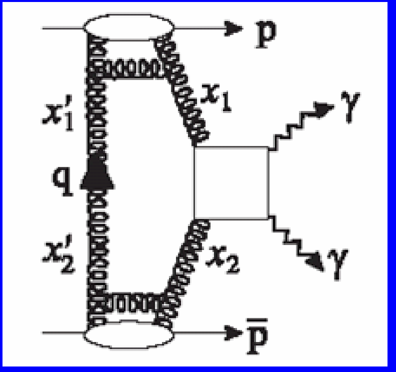
Khoze, Martin and Ryskin, hep-ph/0111078, Eur.Phys.J. C23: 311 (2002)
KMR+Stirling hep-ph/0409037

QCD diagram identical to pHp

$M(\gamma\gamma) \sim 10 - 20$ GeV

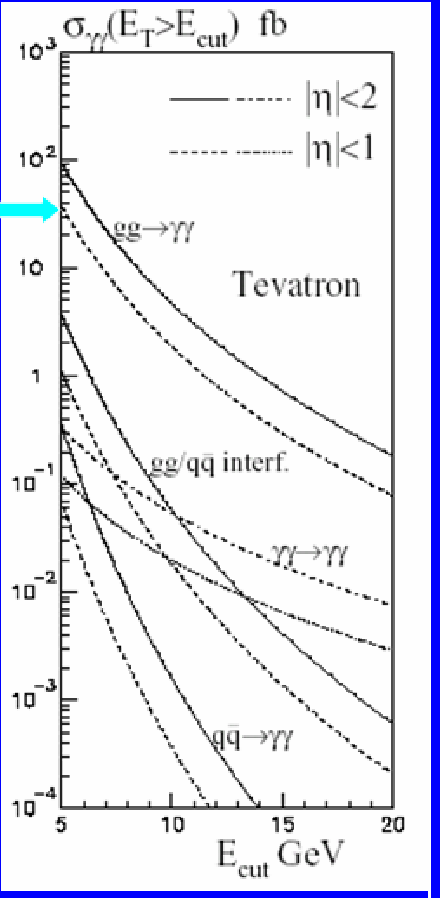
x_1, x_2 similar, Q^2 lower

top $\rightarrow$ u,c (mainly)



Tevatron

38 fb



~ 40 events per fb^{-1} with $p_T(\gamma) > 5$ GeV/c & $|\eta| < 1.0$

Claim factor ~ 4 uncertainty

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

Conclusion: We have observed:

3 candidates for exclusive $(\gamma\gamma + \pi^0\pi^0 + \eta\eta)$ production

May be mixture

$B/G = 0.09 \pm 0.04;\ \ P(\geq 3) = 1.7\times 10^{-4} \equiv 3.7\sigma$

$\sigma(\gamma\gamma) < 410$ fb (95% c.l.)

A, B favor $\gamma\gamma$ and C favors $\pi^0\pi^0$

If 2 of the 3 candidates are $\gamma\gamma$ events we obtain a cross section: $\sigma(2\text{ events}) = (90^{+120}_{-30} \pm 16)$ fb

cf

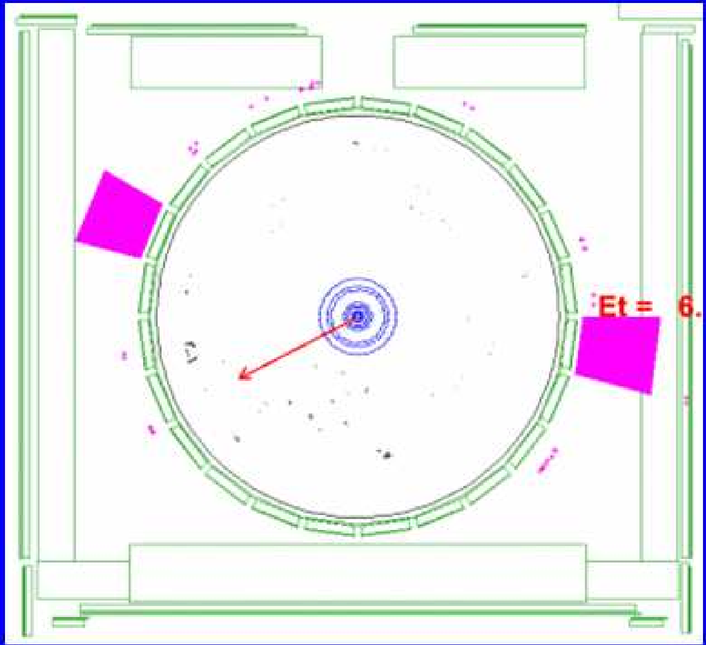
Durham Group Khoze, Martin, Ryskin & Stirling
hep-ph/0507040 Eur.Phys.J C38 (2005) 475 :
38 fb with factor ~ 3 uncertainty

Existence of exclusive $\gamma\gamma$ implies that exclusive H must exist (if H exists)

Agreement with Durham group suggests H cross section at LHC in reach

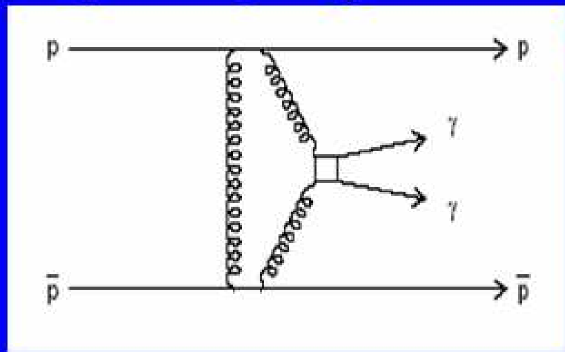
2 $(+1\,\pi^0\pi^0)$ events were like this:

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

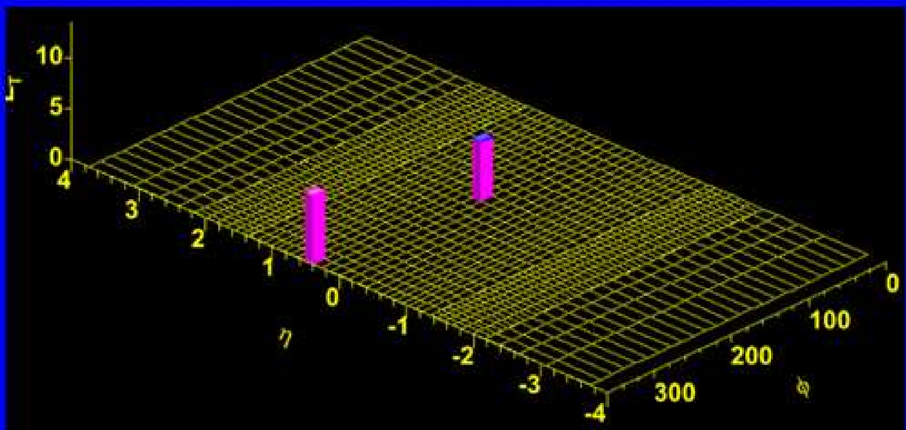


$$\boxed{\begin{array}{l}\Delta\phi > 175^0; \quad \Delta p_T\ \text{small} \\ M(\gamma(\gamma = 10 - 12\,\mathrm{GeV}\end{array}}$$

QCD +QED process



$gg \to \gamma\gamma$



$$\sigma(2\ \text{events}) = (90^{+120}_{-30} \pm 16)\ \text{fb}$$

KMR : 38/fb (x4/4)

ExHuME Monte Carlo

Durham Gp, James Monk & Andy Pilkington

$$\boxed{\text{Note}: \sigma_{MEAS} \approx 2\times 10^{-12}\,\sigma_{INEL}\,!}$$

arXiv:0707.2374 submitted to PRL

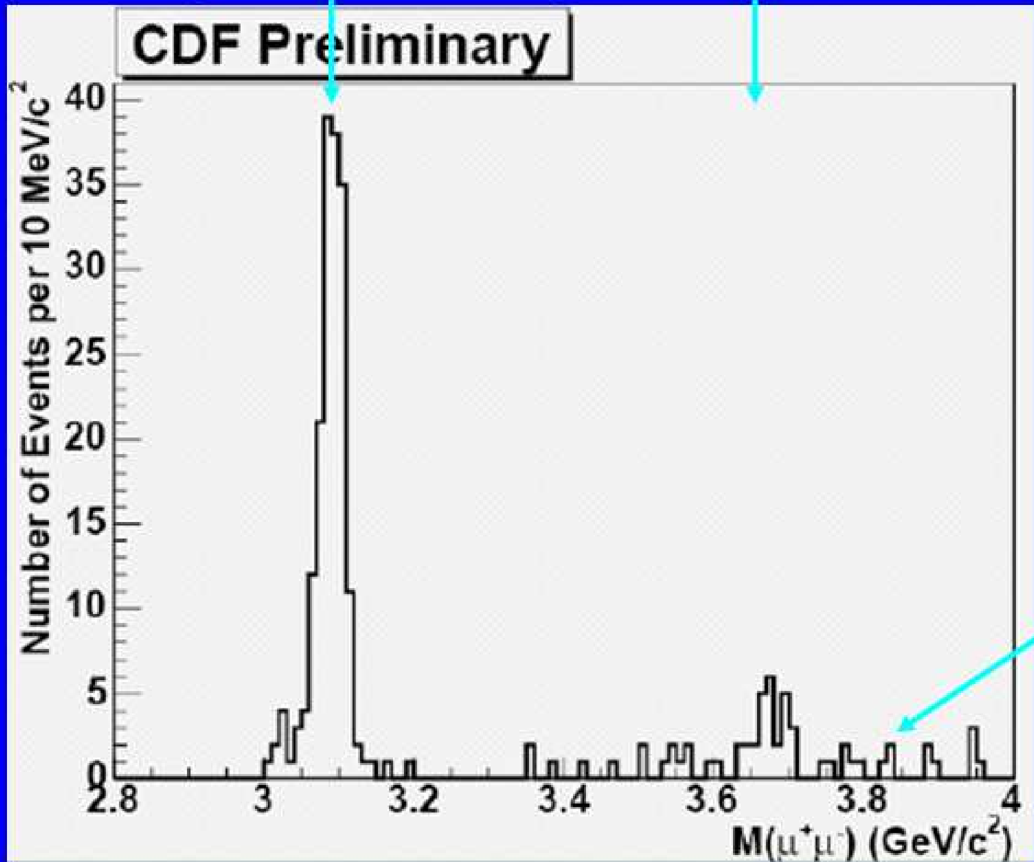
Exclusive $\mu^+ \mu^-$ candidates (Low mass)

Photoproduction
(1st time in hadron-hadron)

$J/\psi, \psi'$

Khoze,Martin,Ryskin
Eur.Phys.J C24 (2002) 459

ψ(1S)(3097) ψ(2S)(3686)

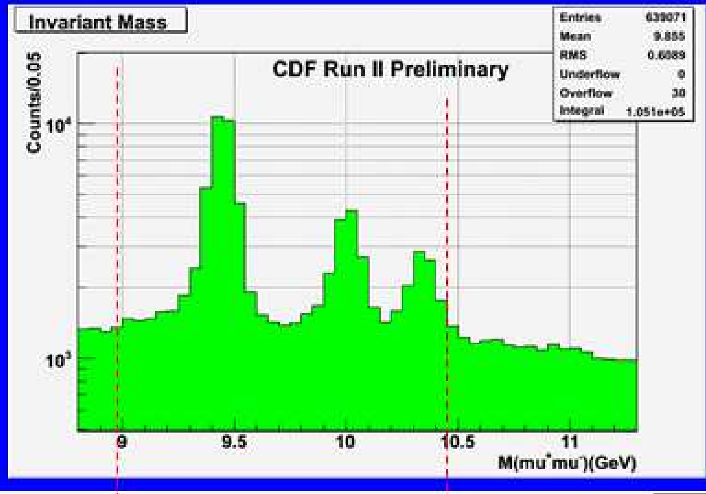


Continuum
$\gamma\gamma \to \mu^+ \mu^-$

Acceptance rising strongly through mass range
Calculations of acceptance, and possible background
from $\chi_c \to J/\psi + \gamma$ underway.

Invariant Mass Distribution - Upsilon Region

All (inclusive)
in sample in Y region



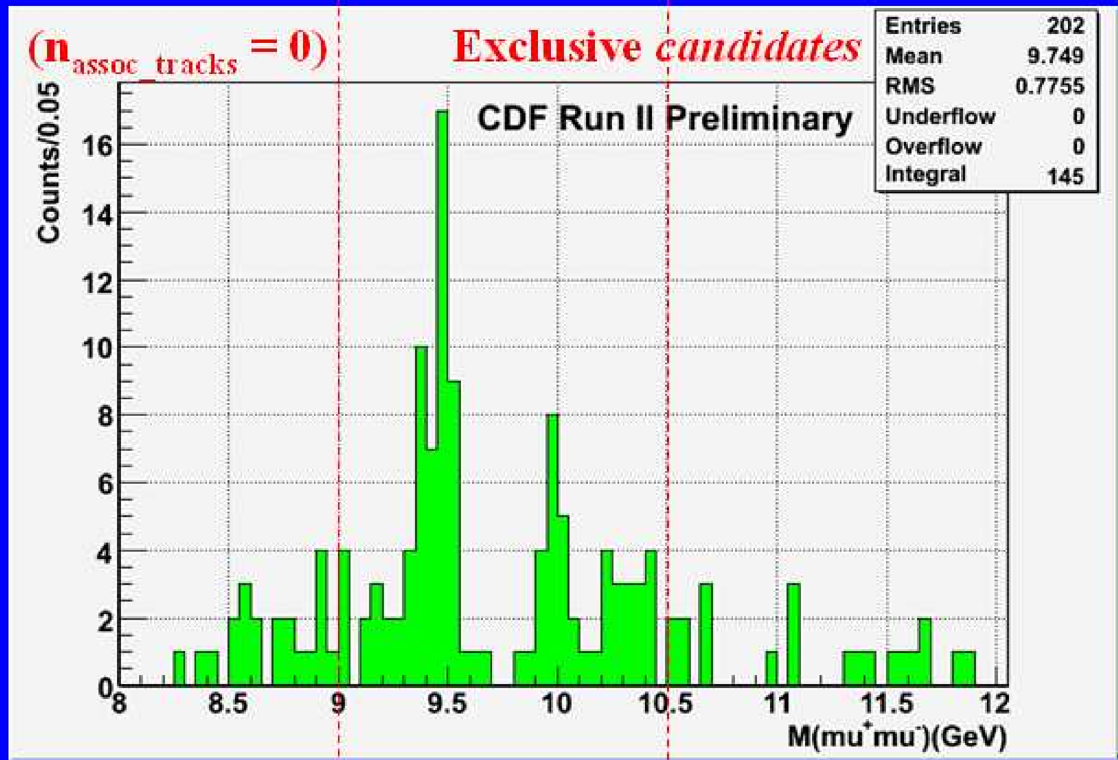
Branching ratios for μ+μ- channels:

Y(1s)[9.46 GeV] : 2.5%

Y(2s)[10.02 GeV] : 1.3%

Y(3s)[10.36 GeV] : 1.8%

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



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

Value of CDF Central Exclusive Program for p+H+p at LHC

1) Exclusive $\gamma\gamma$ **(if confirmed ... more data being analysed)** implies that exclusive Higgs must happen (if H exists) at ~ KMR level. Cross section > 10x higher at LHC, but still difficult.

2) $\gamma\gamma \rightarrow e^+e^-, \mu^+\mu^-$. Luminosity calibration will be very hard, but p-calibration of p-spectrometers will work as long as have trigger in good kinematic region (high M, forward).

3) Photoproduction of Y,Y',Y'' : cross section higher than continuum and good p-calibration tool (pile-up allowed).

4) Can exclusive χ_b states be measured (Y+ γ) as another calibration of p+H+p cross section? Low-L, no pile-up, $\mu^+\mu^-\gamma$

5) Evidence for exclusive di-jets, with suggestion of depletion of exclusive b-bbar dijets as expected.

Luminosity measurements-why?

- Cross sections for "Standard " processes
  - t-tbar production
  - W/Z production
  - ....

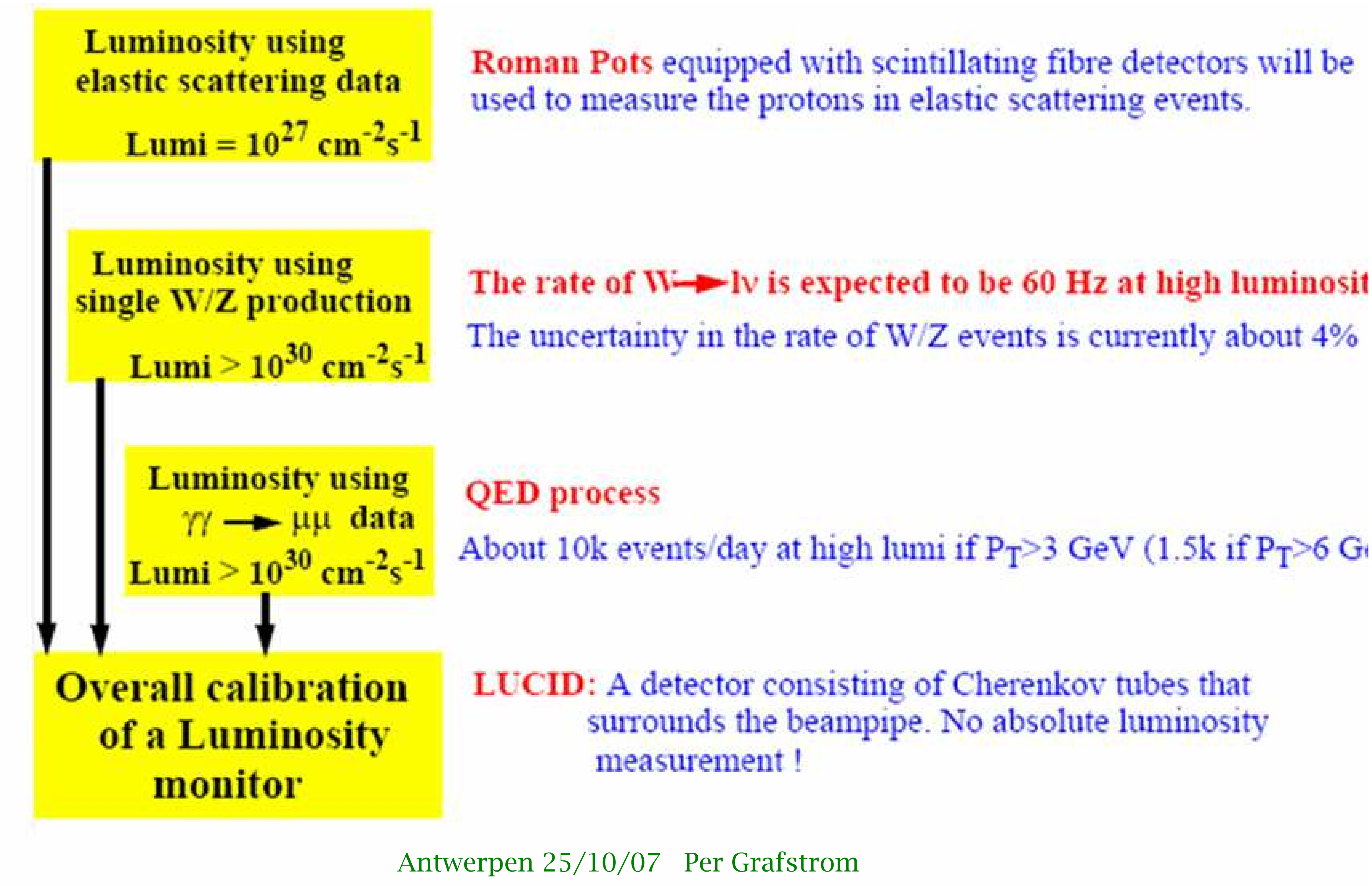
Theoretically known to better than 10% ......will improve in the future

- New physics manifesting in deviation of $\sigma \times$ BR relative the Standard Model predictions

- Important precision measurements
  - Higgs production $\sigma \times$ BR
  - tanβ measurement for MSSM Higgs
  - ....

Luminosity Monitoring processes

Orava + KMR, Eur.Phys.J.C19:313,2001.



Elastic scattering as a handle on luminosity

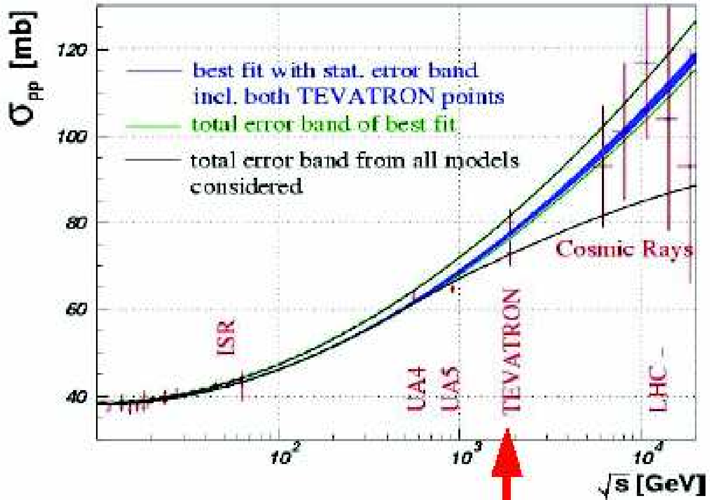
- optical theorem: forward elastic rate + total inelastic rate (TOTEM)
  - →needs large $|\eta|$ coverage to get a good measurement of the inelastic rate- otherwise rely on MC in unmeasured regions
  - →Combine machine luminosity with optical theorem
- luminosity from Coulomb Scattering

ATLAS pursuing all options

Total PP cross section, elastic scattering

Helsinki Group

- σ_{tot} predictions for LHC vary by $^{+10}_{-20}$ %.



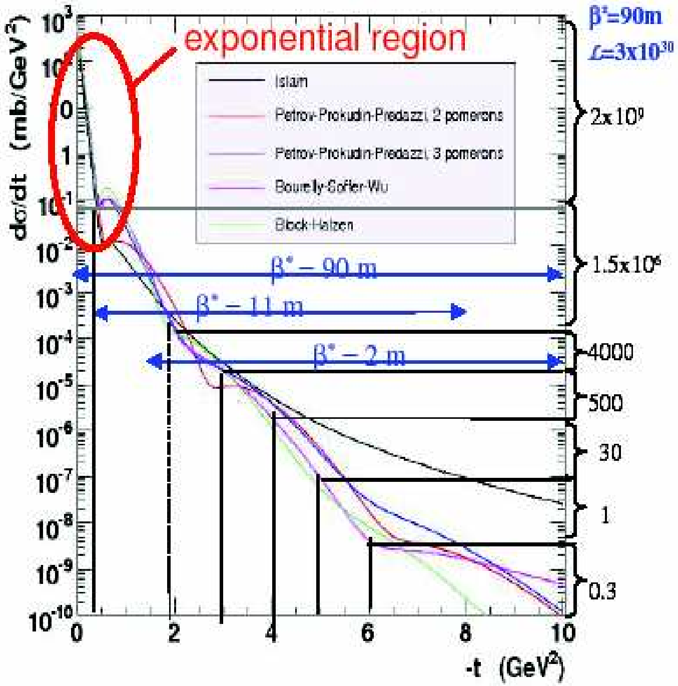
E710/811–CDF 2.6σ disagreement

Durham-07, 90mb @LHC

- TOTEM goal: ~1% precision (for β* = 1500m)

- Luminosity measurement via optical theorem:

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN/dt)|_{t=0}}{N_{el}+N_{inel}}$$



β* = 90m optics needed (acceptance at low |t|)

~5% precision with β=90m at start

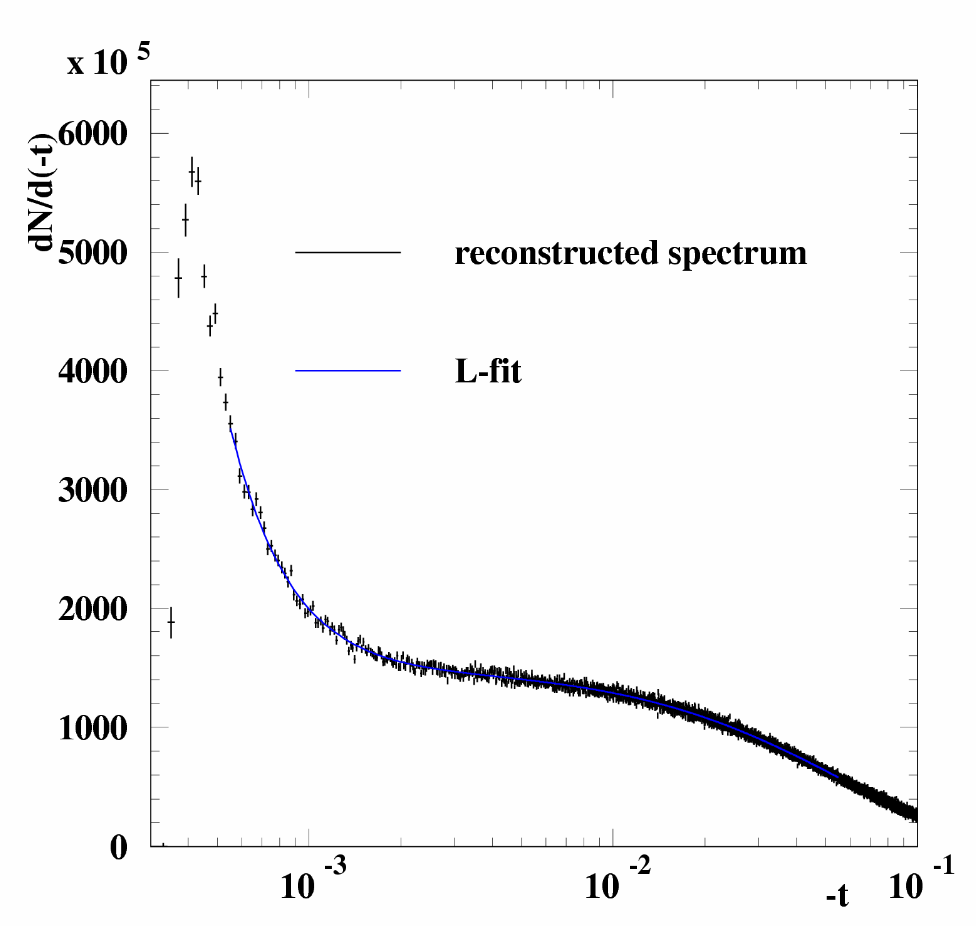
ATLAS: 2625 β optics, access to smaller |t|, CNI region →access to ρ as well

L from a fit to the t-spectrum

Per Grafstrom (UK Forum-07)

$$\frac{dN}{dt} = L\pi\left|F_C + F_N\right|^2$$

$$= L\left(\frac{4\pi\alpha^2(\hbar c)^2}{|t|^2} - \frac{\alpha\rho\sigma_{tot}e^{-B|t|/2}}{|t|} + \frac{\sigma_{tot}^2(1+\rho^2)e^{-B|t|}}{16\pi(\hbar c)^2}\right)$$



Simulating 10 M events,
running 100 hrs
fit range 0.00055-0.055

	input	fit	error	correlation
L	8.10 10^{26}	8.151 10^{26}	1.77 %	
σ_{tot}	101.5 mb	101.14 mb	0.9%	-99%
B	18 Gev^{-2}	17.93 Gev^{-2}	0.3%	57%
ρ	0.15	0.143	4.3%	89%

large stat.correlation between L and other parameters

Summary - Coulomb

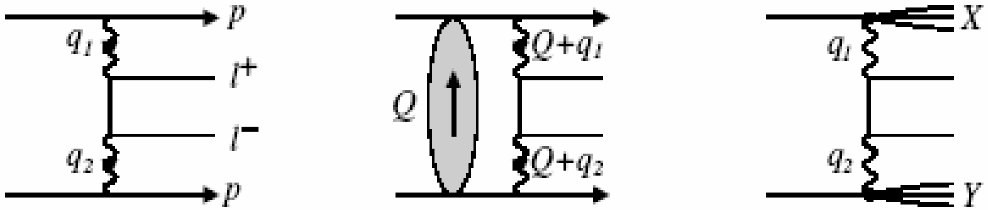
- Getting the Luminosity through Coulomb normalization will be extremely challenging due to the small angles and the required closeness to the beam.
- Main challenge is not in the detectors but rather in the required beam properties
- Will the optics properties of the beam be know to the required precision?
- Will it be possible to decrease the emittance as much as we need?
- Will the beam halo allow approaches in the mm range?

No definite answers before LHC start up

- UA4 achieved a precision using this method at the level of 2-3 %
but at the LHC it will be harder .....

- QED process (a) production σ precisely known.

event generator LPAIR based on ME by Vermaseren



(a) (b) (c)

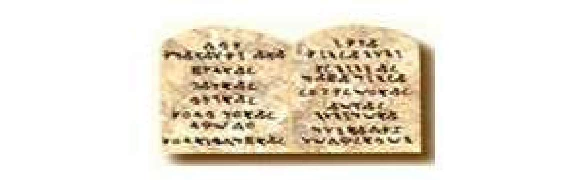
- Hadronic corrections [(b) (c)] small. Can suppress with experimental cuts and subtract by fitting final state kinematics.

V. A. Khoze et al Eur. Phys. J **C19**, *313-322 (2001)*

- Production rate considerable,

e.g. $\sigma_{(P_T>2\ \mathrm{GeV})} = 0.129\ \mathrm{nb} \pm 0.234\ \mathrm{pb}.$

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.

of Forward Physics at LHC

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

2. Thou slalt not make unto **thee** any **graven image, thou shalt not** bow down **thyself** to them **.**

3.Thou shalt treat the existing diffractive experimental data in ways that show great consideration and respect.

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 not exceed the trigger thresholds and
the L1 saturation limit. Otherwise **thy** god shall surely punish **thee** for **thy** arrogance.

9. Thou shalt not annoy machine people.

10. Thou shalt not delay, the LHC start-up is approaching

FP-420

FP420

CERN-LHCC-2005-025
LHCC-I-015
FP420 : An R&D Proposal to Investigate the Feasibility of Installing Proton Tagging Detectors in the 420m Region at LHC

FP420 R&D Collaboration

- Spokespersons : Brian Cox (Manchester, ATLAS) and Albert DeRoeck (CERN,CMS)
- Technical Co-ordinator : Cinzia DaVia (Manchester)

Collaboration : FNAL, The University of Manchester, University of Eastern Piedmont, Novara and INFN-Turin, The Cockcroft Institute, University of Antwerpen, University of Texas at Arlington, The University of Glasgow, University of Calabria and INFN-Cosenza, CERN, Lawrence Livermore National Laboratory, University of Turin and INFN-Turin, University of Lund, Rutherford Appleton Laboratory, Molecular Biology Consortium, Institute for Particle Physics Phenomenology, Durham University, DESY, Helsinki Institute of Physics and University of Helsinki, UC Louvain, University of Hawaii, LAL Orsay, University of Alberta, Stony Brook University, Boston University, University of Nebraska, Institute of Physics, Academy of Sciences of the Czech Republic, Brookhaven National Laboratory, University College London, Cambridge University

R&D report being completed

Note: FP420 is a common study with ATLAS, CMS and non-associated members
At the end ATLAS and/or CMS will have to decide to extent with FP420

Forward Physics upgardes at the LHC

• FP420 is currently an R&D collaboration between ATLAS, CMS and non-affiliated groups.

• In addition, there is a strong, complementary program to upgrade the 220m region which adds value to 420m program

• Aim is to submit proposal for a sub-detector upgrade for 420m and 220m upgrades

• If accepted by ATLAS and / or CMS, this would lead to TDR from experiments early 2008

• If funding is secured, cryostats (built by TS-MME) and baseline detectors could be ready for installation in Autumn 2008.

• However, more likely goal is autumn 2010

• 220m and 420m tagging detectors have the potential to add significantly to the discovery reach of ATLAS and CMS for modest cost, particularly in certain regions of MSSM parameter space

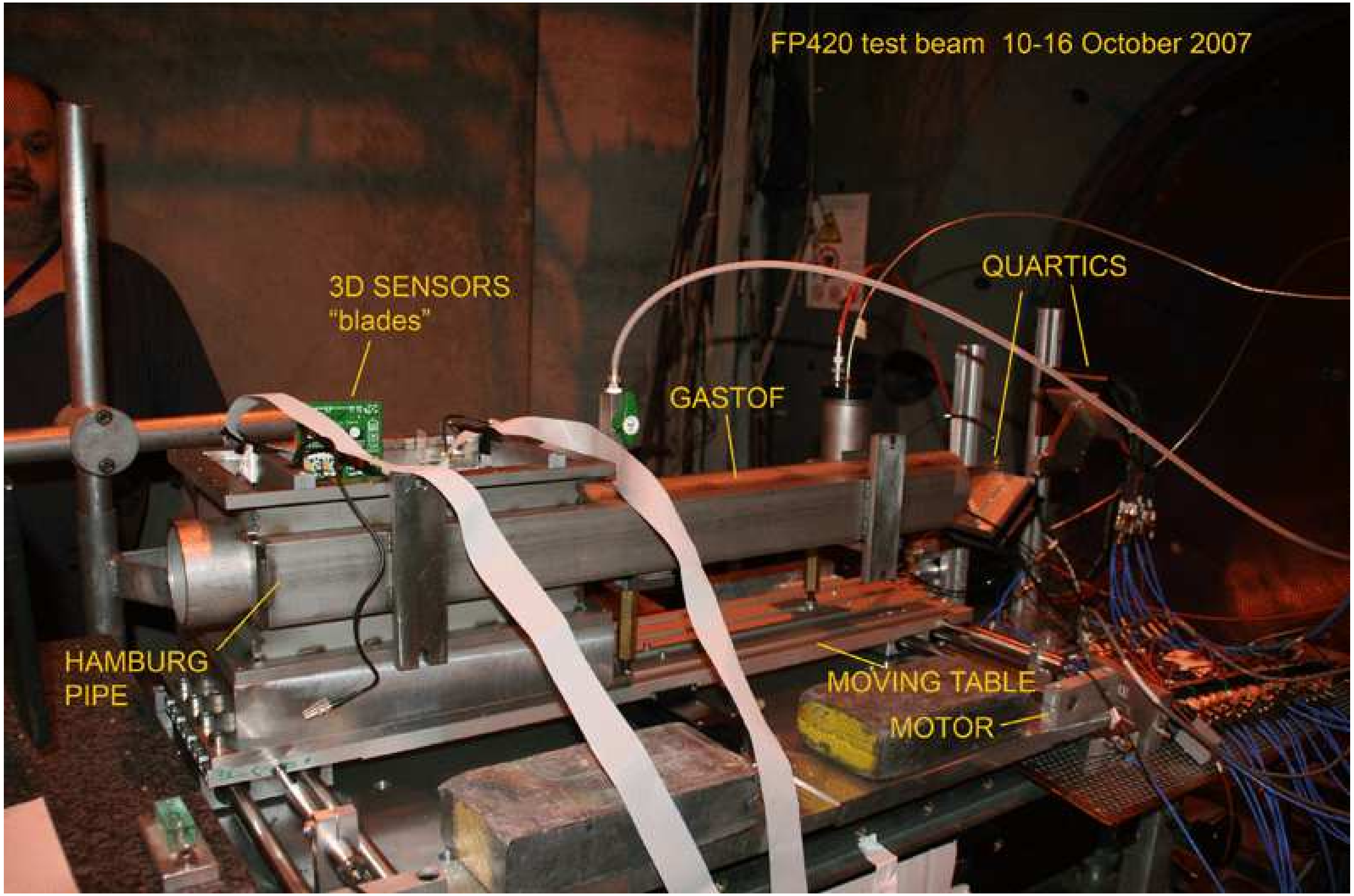
• There is a rich QCD and electroweak physics program in parallel with discovery physics

The FP420 R&D project is an international collaboration with members from 29 institutes from 10 countries.

The aim is to assess the feasiblity of installing proton tagging detectors at 420m from th interaction points of the ATLAS and / or CMS experiments at the LHC.

Latest News 16 October 2007

A full FP420 module, with moving Hamburg pipe, 3D Silicon, GASTOF and QUARTIC producing data in test beam at CERN.



The LHC is coming!

FP420, It is now or never

BACKUP