Forward physics at the LHC: QCD, electro-weak & Higgs

QCD-School Les Houches

March 25th-Apr. 4th, 2008

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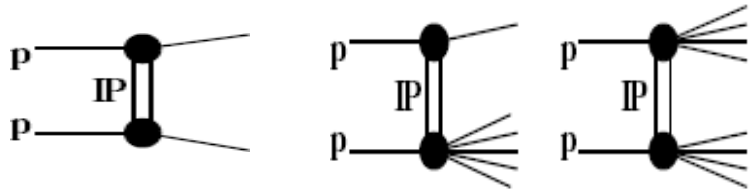
CERN

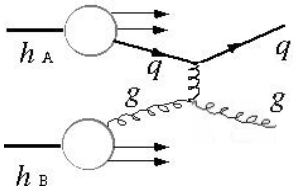
LHC forward physics: why ?

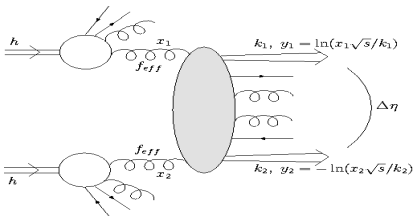
- Many interesting (mostly color-singlet exchange) scatt. processes at the LHC are characterized by forward particle production:

QCD:
- elastic/diffractive interactions:



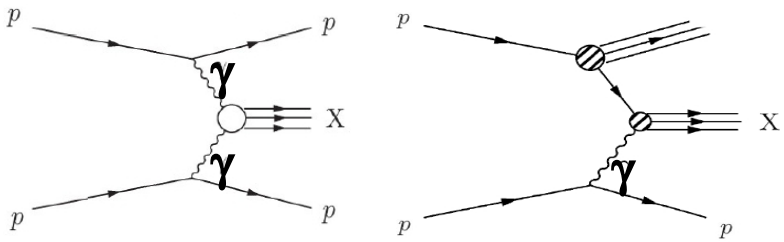
- low-x:





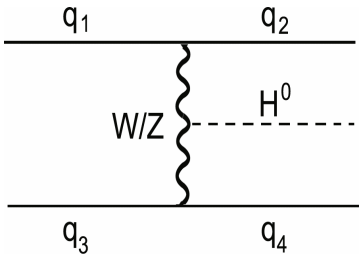
- cosmic-rays MCs

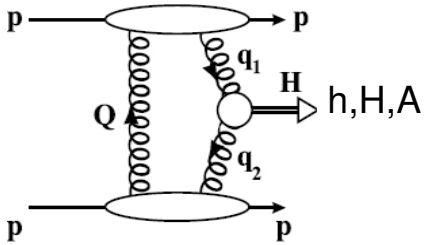
EWK: two-photon, photon-proton colls.



Higgs: VBF, central exclusive,

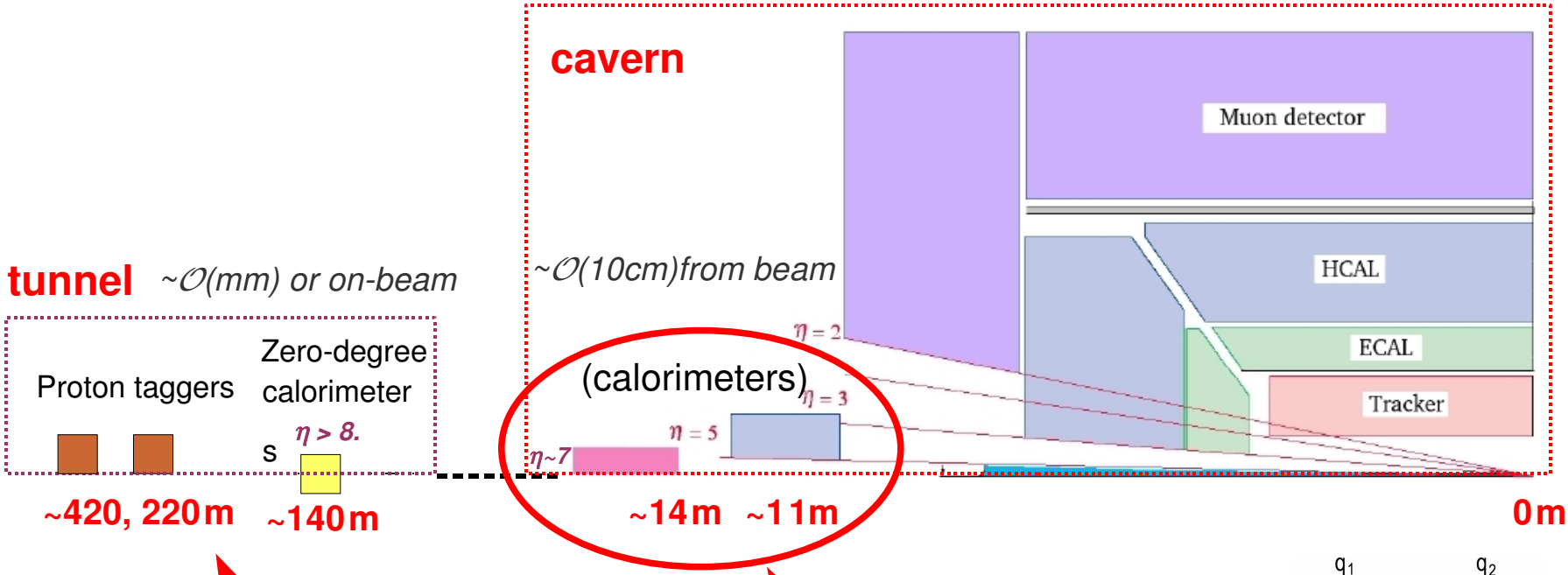
MSSM Higgs, ...



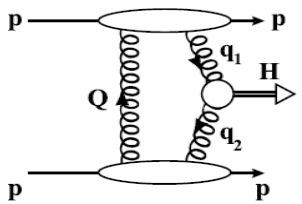


LHC forward detectors: where ?

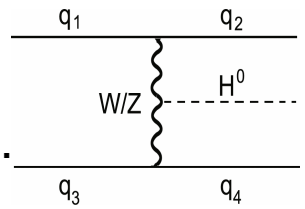
- Near-beam detectors (CMS/ATLAS): $|\eta| = \ln \tan(\theta/2) > 3$



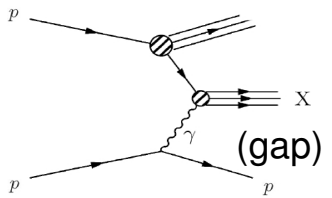
1) p,n tagging devices



2) Direct particle measurements: fwd. jets, ..



3) Hadron "vetoing" devices: rapidity gaps



Lectures – Programme

1st

0. Introduction
1. Forward **detectors** at the LHC
2. **QCD** physics with forward detectors:
   - Diffractive/Elastic scattering.
   - UHE cosmic-rays MCs.

2nd

   - **Low-x QCD**

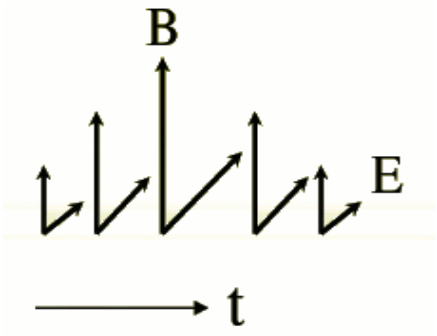
3th

3. **EW** physics with forward detectors:
   - photon-photon, photon-proton collisions
4. **Higgs** physics with forward detectors
   - VBF Higgs, central-exclusive Higgs, ...

EWK (γ-γ,γ-p) physics

The LHC as a photon collider

- Electromagnetic field of a relativistic charged particle:

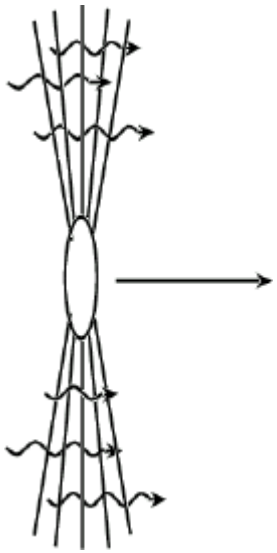


An observer at a perpendicular distance b from the trajectory sees:

(i) $|E| \simeq |B|$ (ii) $(E \perp B)$ (iii) $\Delta t \sim b/\gamma$

- Fermi [1924, hep-th/0205086]: The effect of the fields is equivalent to a flux of of photons with a continuous energy spectrum.

  pulse width $b/\gamma \leftrightarrow$ the spectrum contains photons with $\omega < \gamma/b$



- Weizsäcker, Williams [1935]: Quantum-mechanical derivation

  Equivalent photon spectrum $n(\omega)$ calculable through Fourier transform.

Equivalent γ spectrum & luminosities

- Spectrum of photons with fractional energy $x = E_\gamma/E_{beam}$ & virtuality Q^2 :

$$x\frac{dn_\gamma}{dxdQ^2} = \frac{\alpha Z^2}{\pi}(1 - x + 1/2x^2)\frac{Q^2 - Q^2_{min}}{Q^4}$$

Q^2_{min} constrained by *x*, projectile mass.

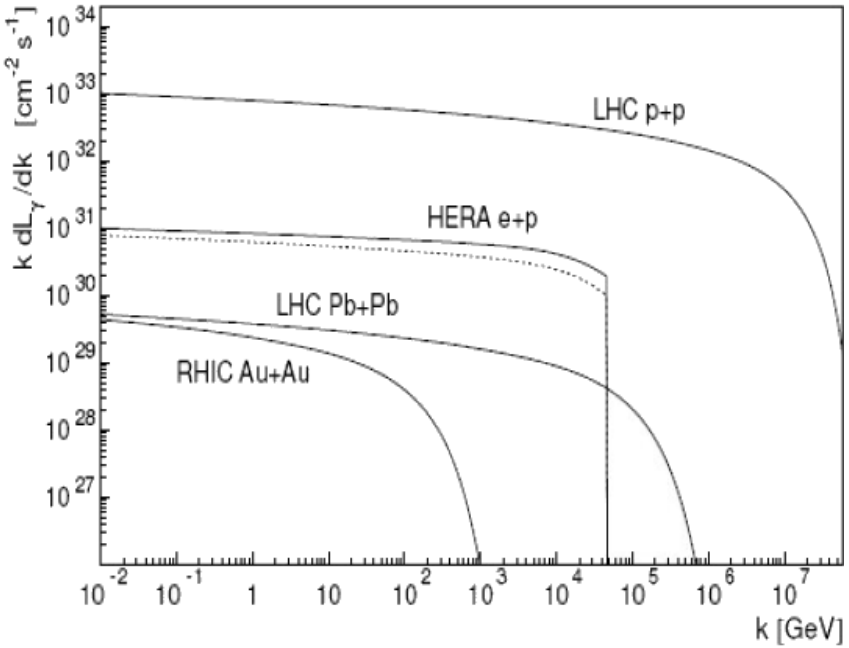
Q^2_{max} given by form factor for hadron beams: $Q^2_{max} = (1/R)^2$.

- Equivalent photon luminosity:

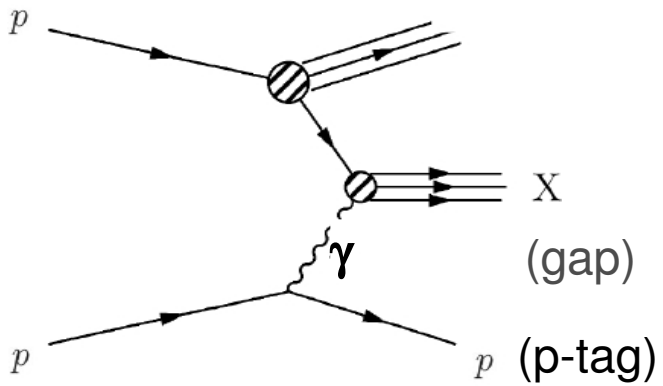
  - integrating over all virtualities

  - accounting for collider luminosity

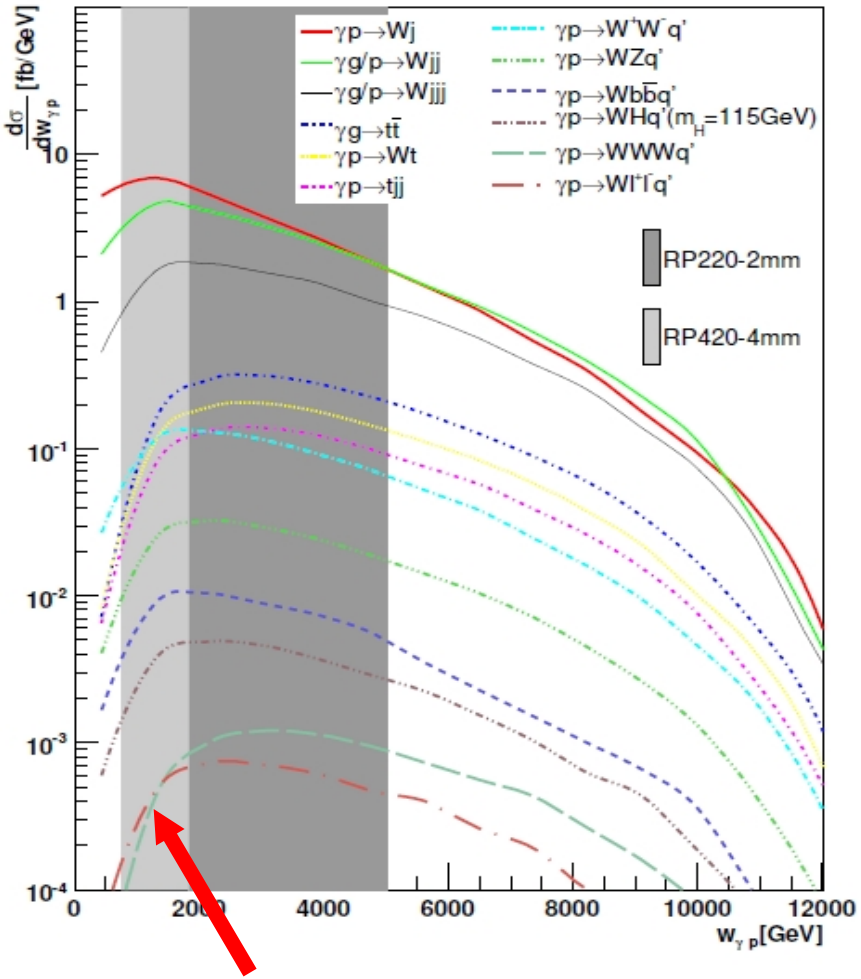
  (energy in rest frame of the target)



γ-proton interactions at the LHC



[UC Louvain CMS group]



- Significant cross-sections up to few TeV !
- Cleaner, better S/B (than parton-parton)

measurements of:

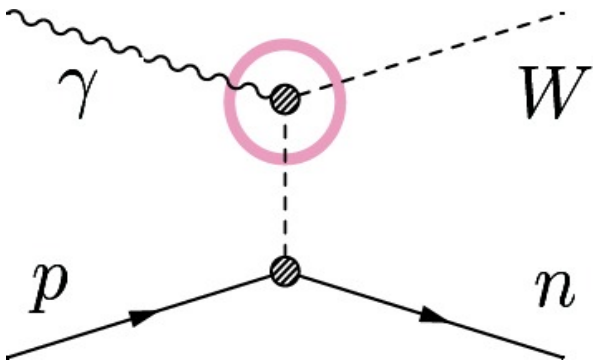
- Top physics (e.g. $|V_{tb}|$ via Wt channel)
- Associated W-H production: $\mathcal{O}$(20fb)
- (Anomalous) single top production: $\mathcal{O}$(100fb)
- (Anomalous) triple gauge boson couplings

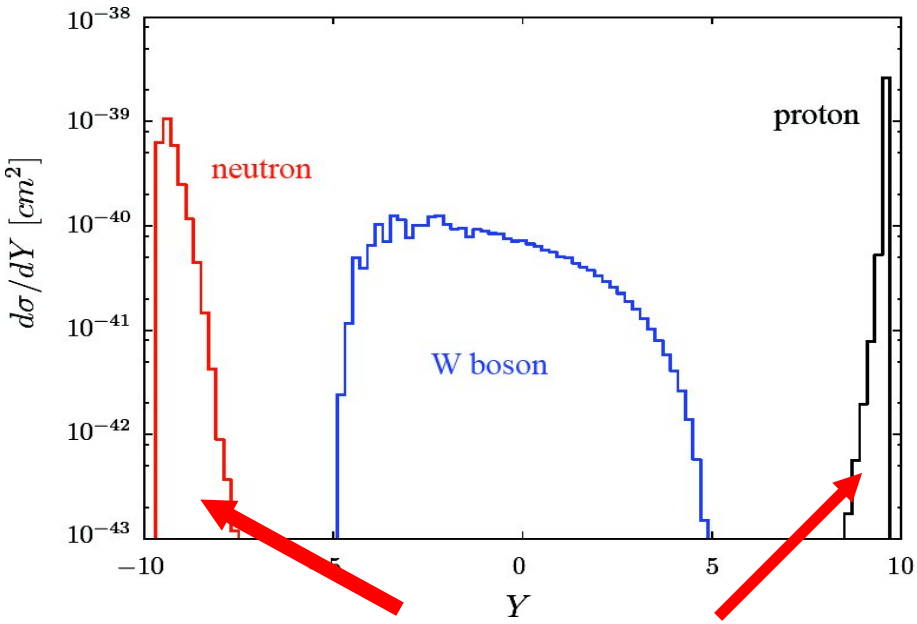
- 220 & 420 m proton detectors essential for γ-processes tagging.

γ p → W : triple gauge couplings

[U.Dreyer, ECT*-UPC'07]

- W photoproduction allows one to probe triple (anomalous ?) gauge coupling vertex WWγ :





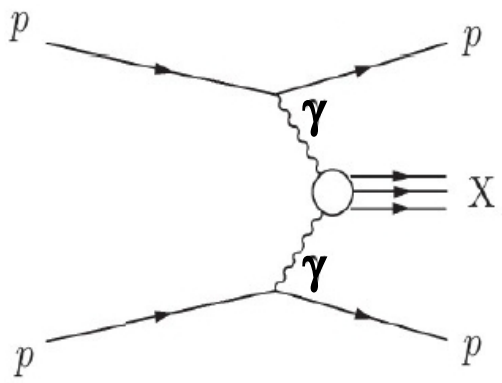
~50 evts./100 pb^{-1} in p-p 14 TeV

Leading neutron,proton tagging in ZDC / RPs

[Also quartic couplings: γγ→WW,ZZ (see later)]

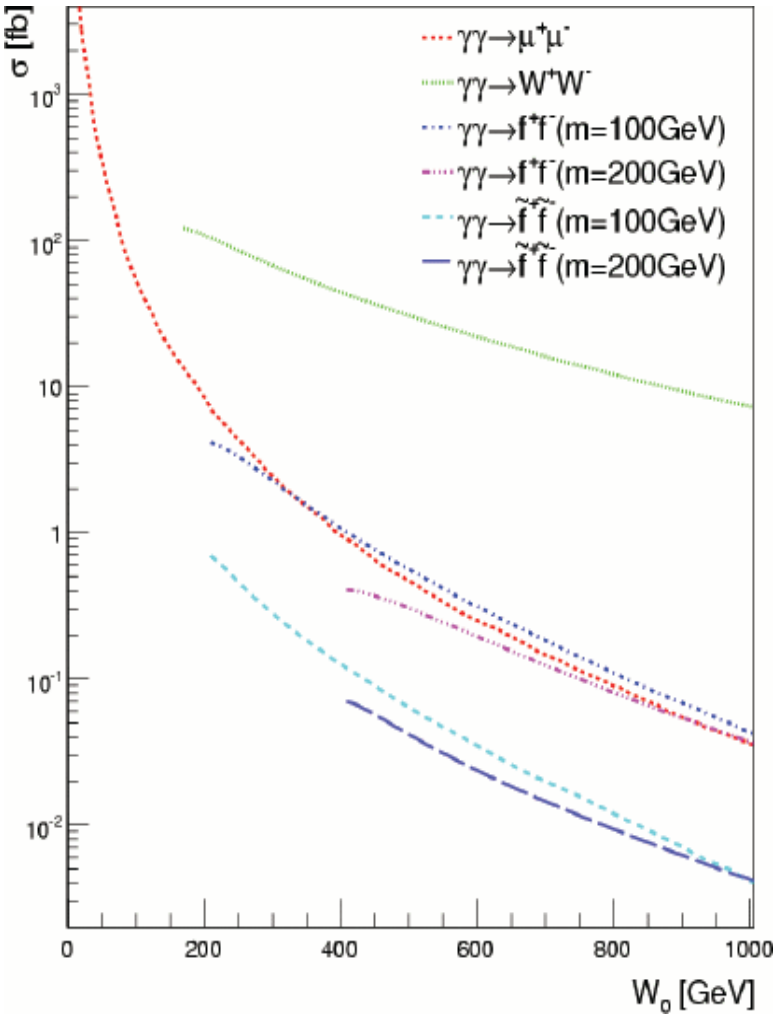
γγ interactions at the LHC

[UC Louvain CMS group]



(p-tag)

(p-tag)

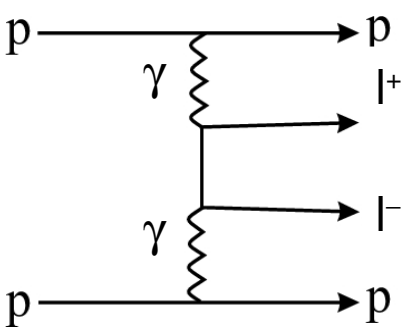


- Photon-photon physics up to 1 TeV !
- Very clean processes: central *X*, fwd. p's
- Accessible measurements:

- Luminosity via QED: $\gamma\gamma \to \ell^+\ell^-$ (large σ!)
- (Anomal.) quartic gauge-couplings: $\gamma\gamma \to WW$
- SUSY pair production: $\gamma\gamma \to \tilde{\chi}\tilde{\chi}, \tilde{\ell}^+\tilde{\ell}^-$

$\gamma\,\gamma \rightarrow$ dileptons: LHC luminosity

- Exclusive $\ell^+\ell^-$ (e^+e^-,$\mu^+\mu^-$) production

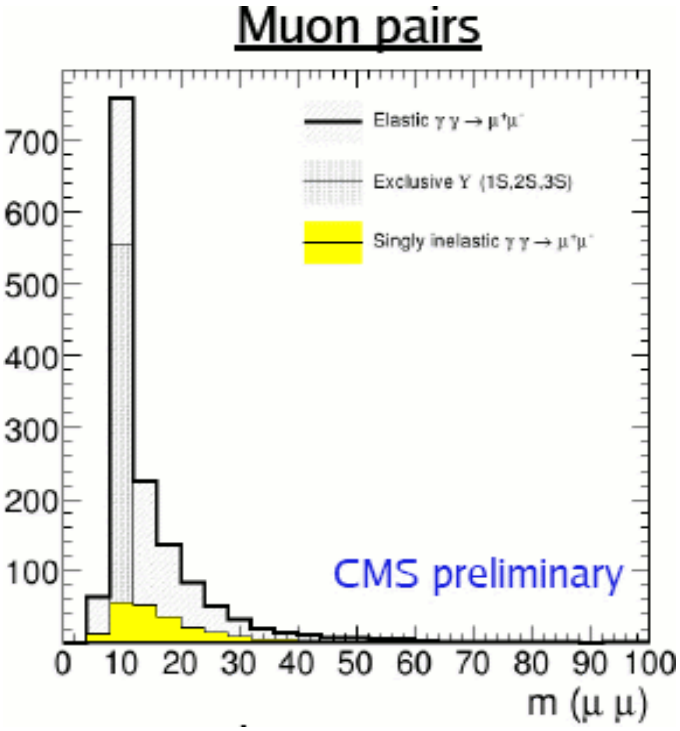


(fwd. proton in RPs)

(e^+e^- in T2/CASTOR)

($\mu^+\mu^-$ in muon-chambers)

(fwd. proton in RPs)



QED process: x-section known precisely

$\sigma_{\mu\mu}(p^{\mu}_{T}>2.5\ \text{GeV/c}) = 75\ \text{pb}$ (LPAIR)

- ~700 evts./100 pb^{-1} in CMS

(plus Υ photoproduction)

- Interests:

  - absolute p-p luminosity within ~3% (stat.)

  - Cross-calibration of fwd. proton taggers (FP420,TOTEM).

γ γ → WW: quartic gauge couplings

[UC Louvain CMS group]

- Probe quartic (anomalous ?) gauge coupling vertex WWγγ :

$$L_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu}F^{\mu\nu} W^{+\alpha} W^-_{\alpha}$$

Commonly used Lagrangian
for anomalous quartic vector boson couplings
which conserves C, P as well as local $U(1)_{em}$

$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_{\beta} + W^{-\alpha}W^+_{\beta})$$

investigating $\gamma\gamma \to W^+W^- \to \mu^+\mu^-\bar{\nu}_\mu\nu_\mu$ effective cross sections (σ_{acc}) are:

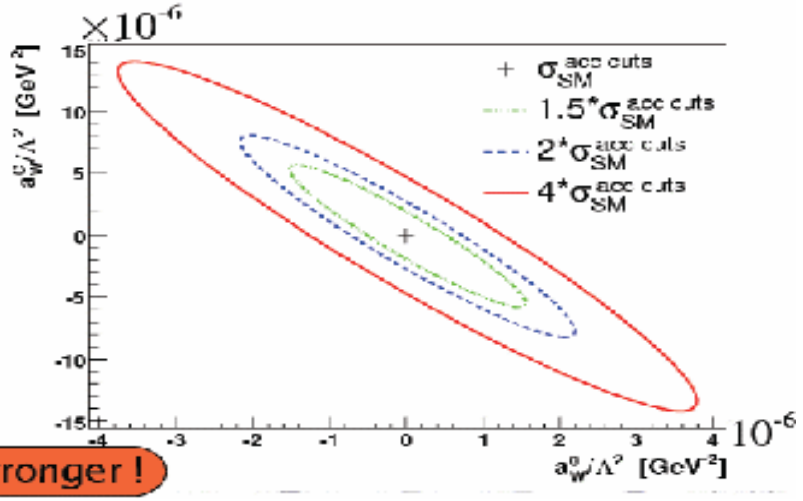
SM here background	pt(μ)>3 GeV	pt(μ)>10 GeV
σ_{acc}	0.76 fb	0.72 fb
σ_{acc} (with RP)	0.66 fb	0.62 fb

no other background than SM γγ→WW
for 30 fb^{-1} expected 22.8 (18.6) events

while current OPAL limits are:

$$-0.020 \text{ GeV} < a_0^W < 0.020 \text{ GeV}$$

$$-0.052 \text{ GeV} < a_C^W < 0.037 \text{ GeV}$$



we expect limits to be ~ 10 000 times stronger !

Higgs (VBF tagging)

SM Higgs: production modes at the LHC

- Gluon fusion:

  $gg \rightarrow H$

  dominant,

  large QCD backgrounds

- Vector-Boson-Fusion:

  $qq \rightarrow qq\ H$

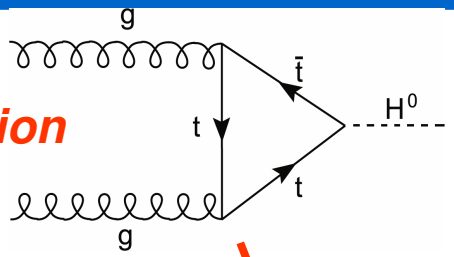
  ~20% of σ_H

  distinct final state (fwd. jets)

- Associated:

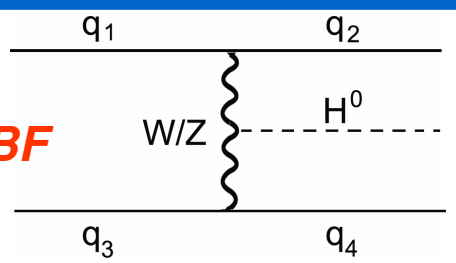
  ttH, WH, ZH

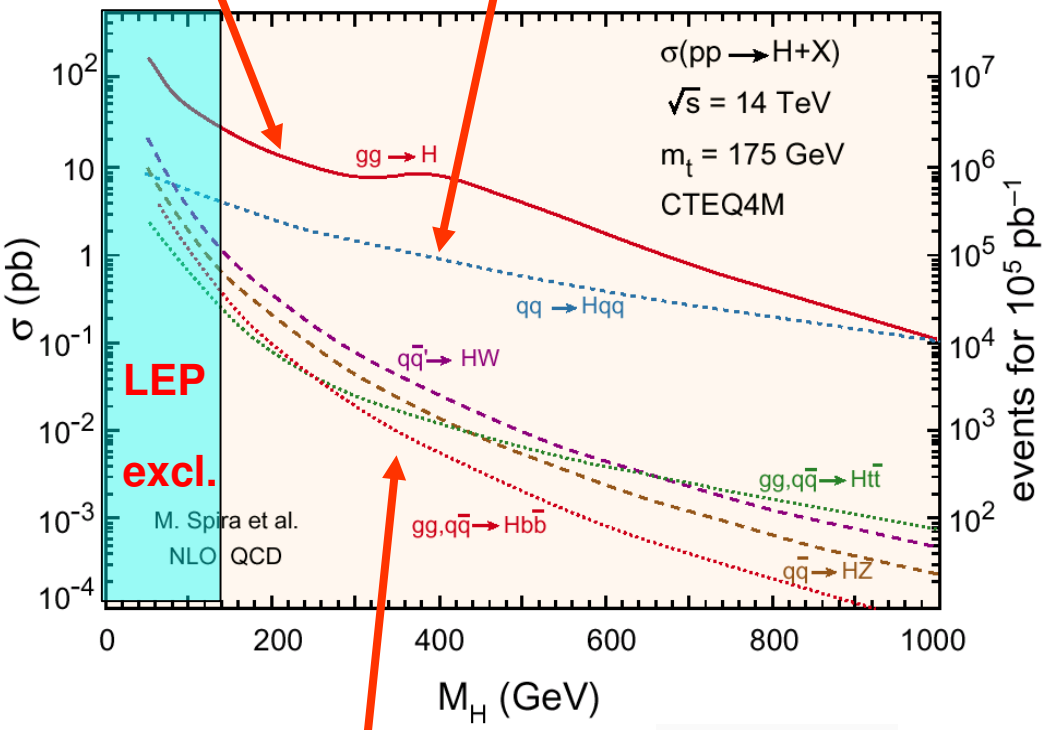
  small cross-sections



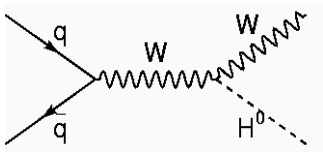
gg fusion

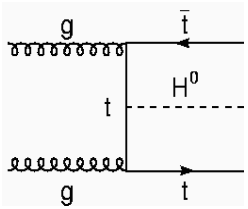
VBF





associated





SM Higgs: decay modes

- M_H<135 GeV:

Dominant BR: bbar

Huge QCD bckgd !

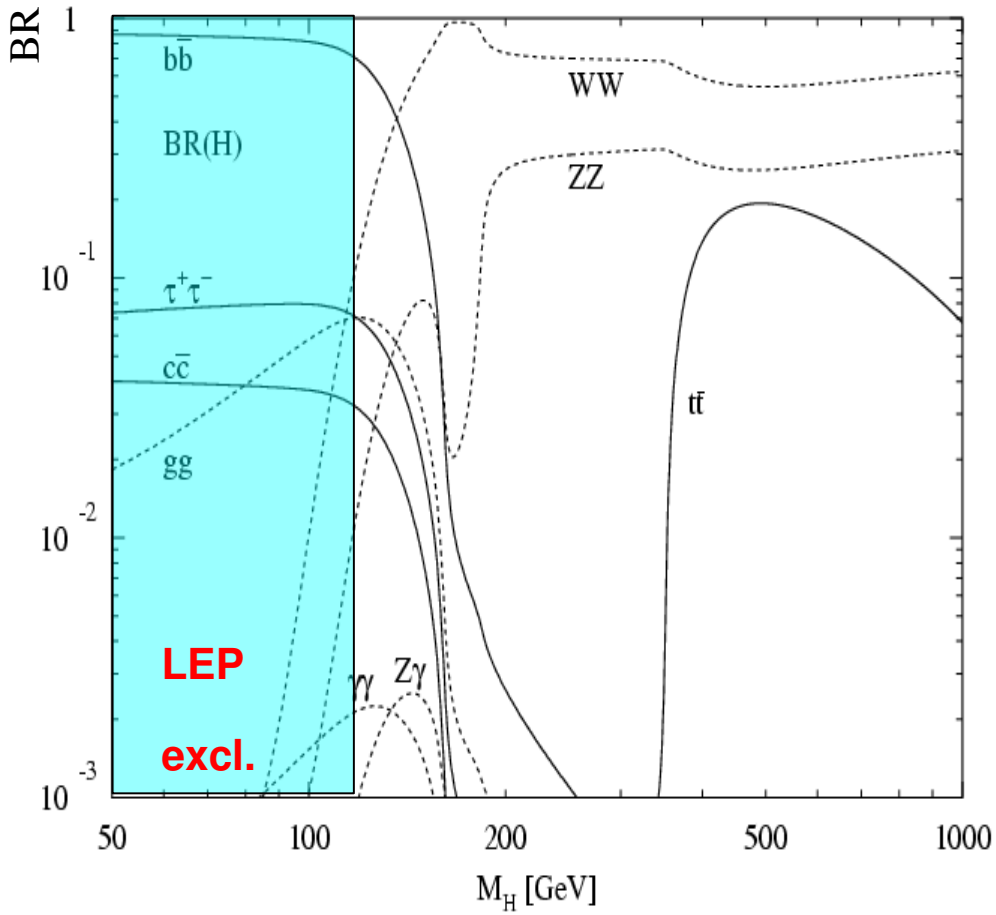
Very difficult at the LHC

Discovery channels: $\gamma\gamma$ $\tau^+\tau^-$

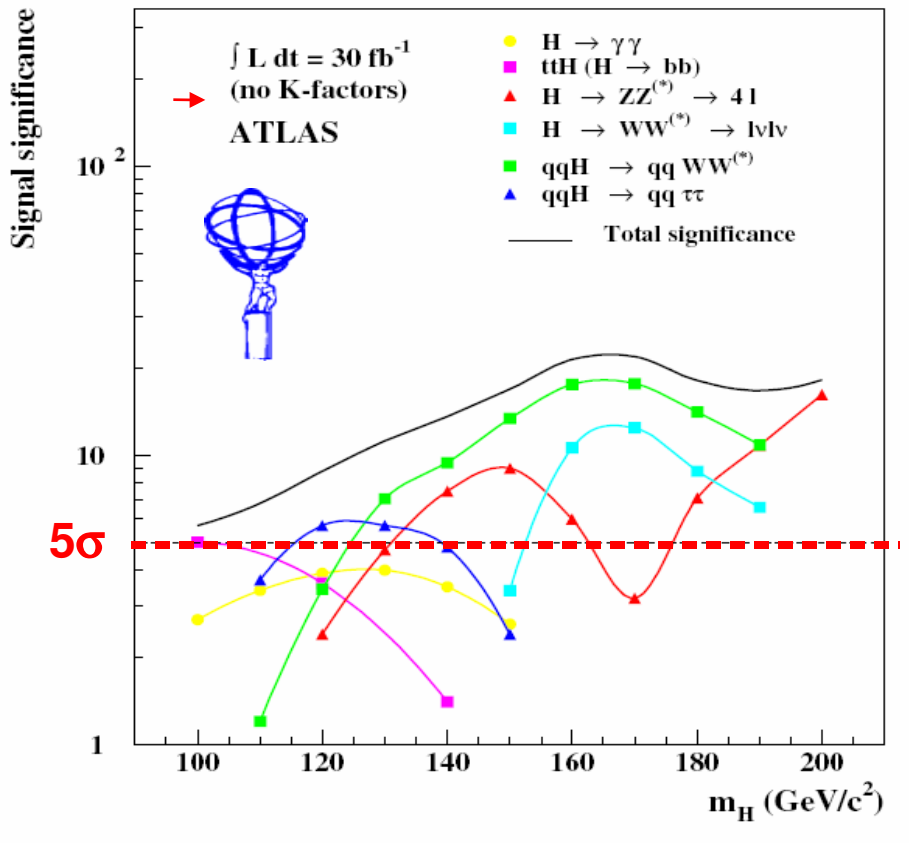
- M_H>135 GeV:

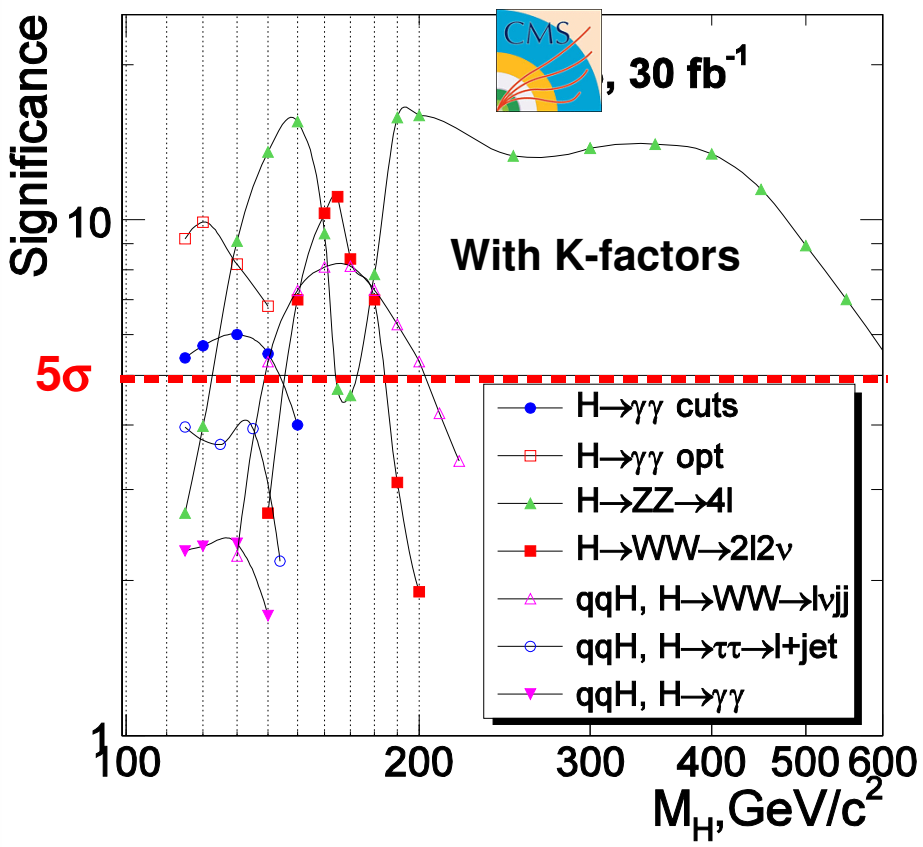
Dominant BR: $WW^{(*)}$,$ZZ^{(*)}$

(relatively easy discovery via leptonic W,Z decays)



SM Higgs: signal significance (30 fb^{-1})





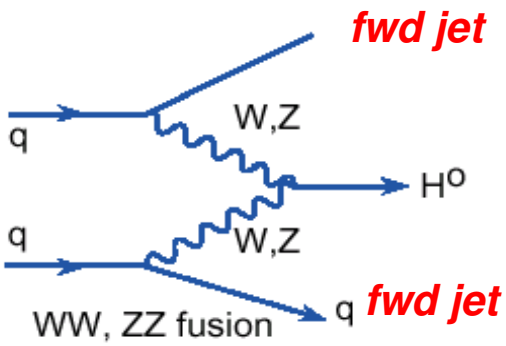
- LHC: ~1 fb^{-1} in 2009(?), increasing to 100 fb^{-1}/year at design luminosity.

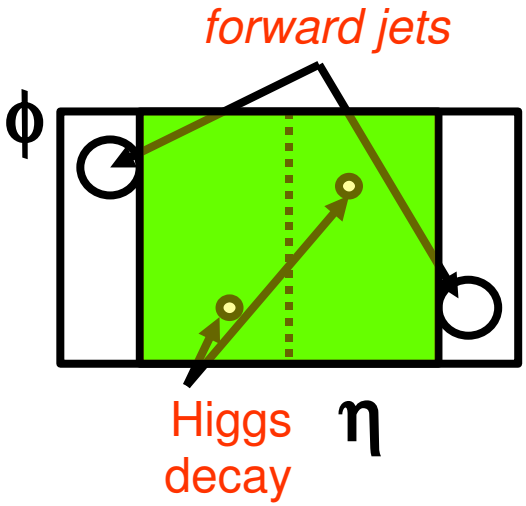
Vector-Boson-Fusion Higgs (I)

- qq→qqH distinct signature:

  2 jets (p_T~20-60 GeV)

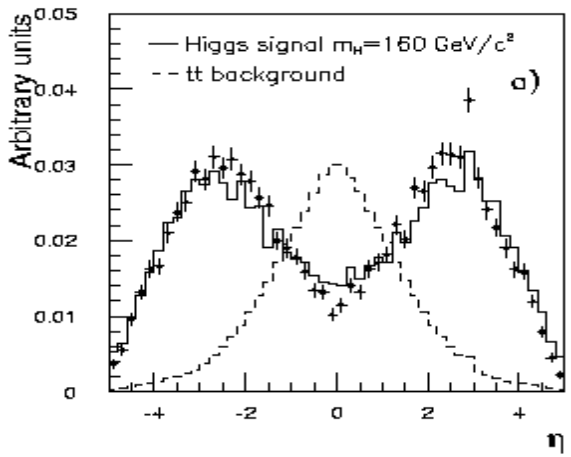
  w/ large $\Delta\eta$~5 separation





- Fwd. jets allow for good rejection of QCD backgrounds:

H→ WW(→l±jj ν) vs. ttbar, WW

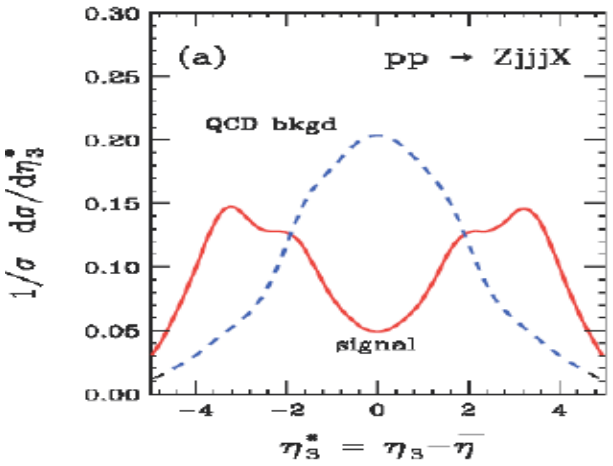


bckgd. jets

at central

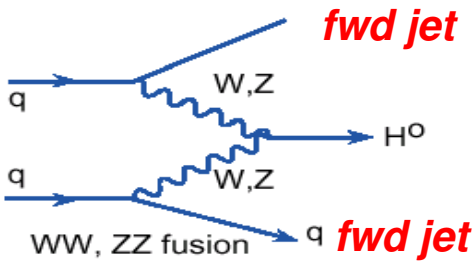
rapidities

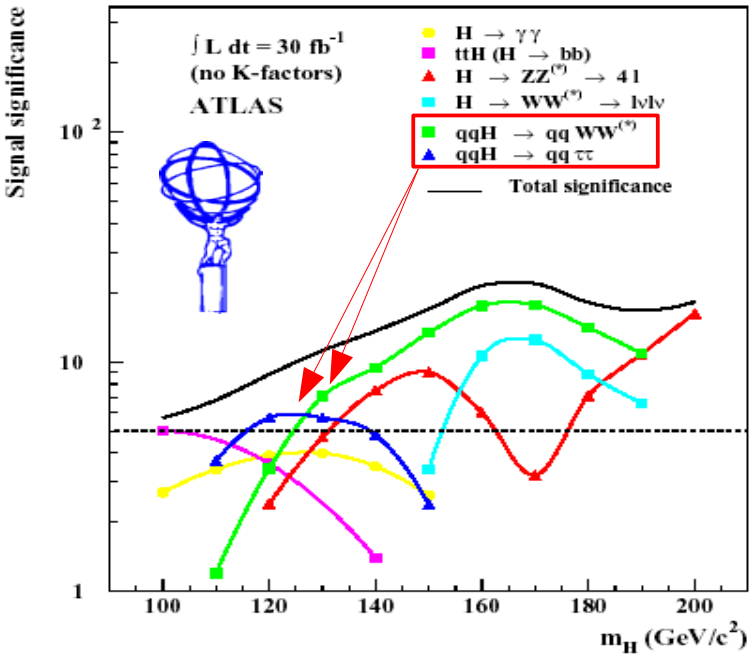
H→ ττ vs. Z+nj, W+nj, ttbar

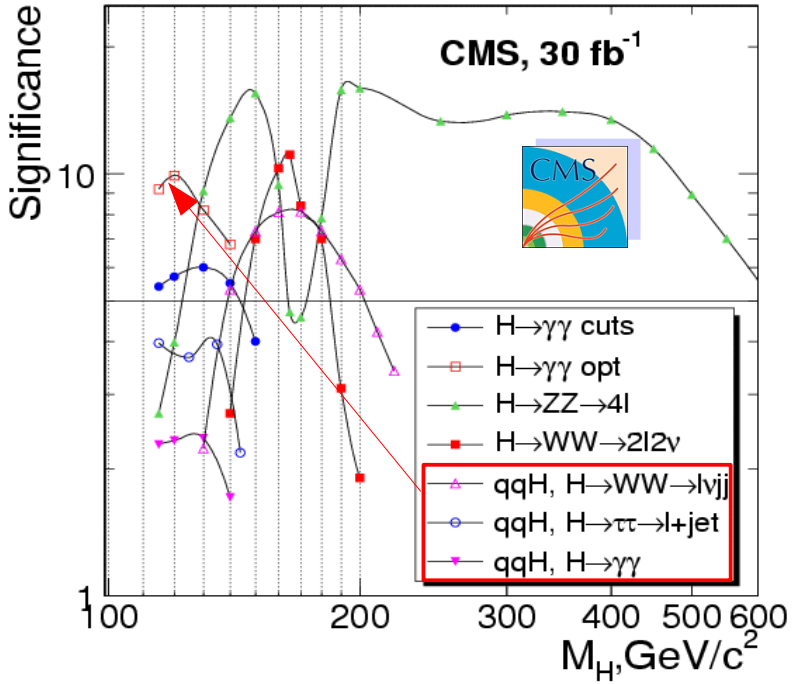


Vector-Boson-Fusion Higgs (II)

- VBF ($qq \to qqH$) with Higgs decay in $\tau\tau$,WW channels shows good discovery potential:







- [Note: All this also applies for VBF MSSM-Higgs & for VB-scatt.: WW→WW, ...]

Pseudo-rapidity of VBF quarks

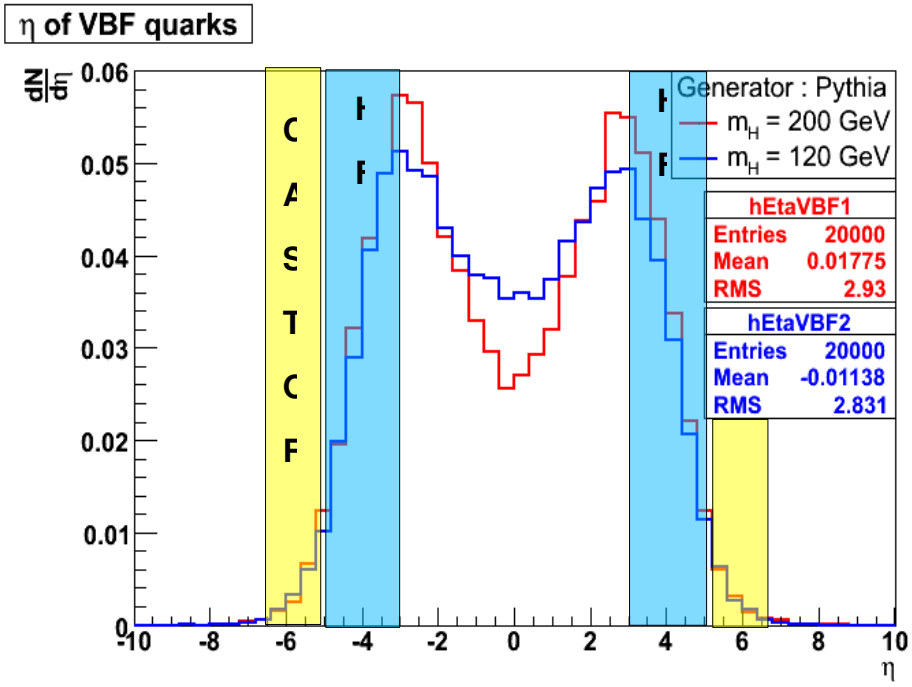
- VBF quarks peaked at

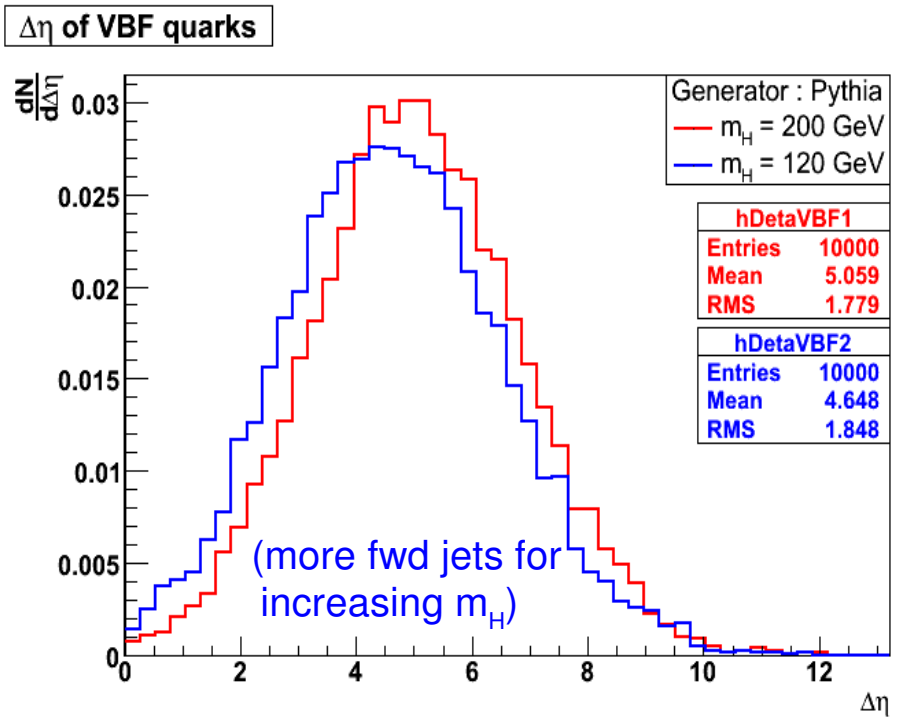
  $|\eta| \sim 3, \quad \eta_1 \times \eta_2 < 0$

- Average rapidity separation:

  $\Delta\eta \sim 4.7$ (m_H=120 GeV)

  $\Delta\eta \sim 5.1$ (m_H=200 GeV)





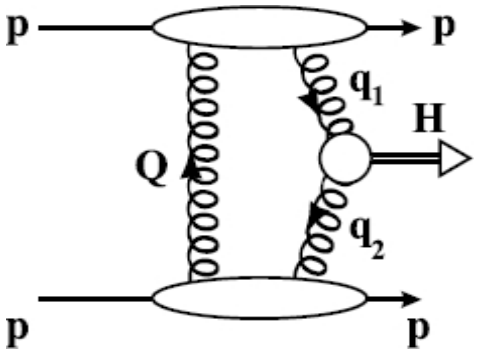
- CMS: CASTOR+HF fwd. jet acceptance to $3. < |\eta| < 6.$ (+15% extra VBF tagging efficiency)

Higgs (central exclusive)

Central exclusive Higgs: motivation

[FP420 R&D report]

- Central exclusive Higgs production: $pp \rightarrow p\,H\,p$



(leading proton)

H decay in central det.

(leading proton)

σ_H = 3-10 fb (SM), x10(0) in MSSM

- Excellent physics motivations !

  - Quantum numbers: central system is approx. $J^{PC} = 0^{++}$ (selection rule)
  - Excellent mass resolution: from protons, indep. of central decay products.
  - Enhanced S/B: Reduced QCD background. $H \rightarrow$ bbar channel accessible !
  - CP violation in Higgs sector: directly measurable from protons φ asymmetry
  - Discovery channel (bbar, $\tau^+\tau^-$) in certain regions in MSSM

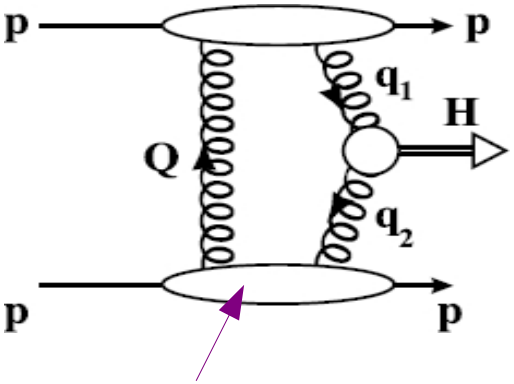
Central exclusive Higgs: SM x-section

KMR = Khoze-Martin-Ryskin

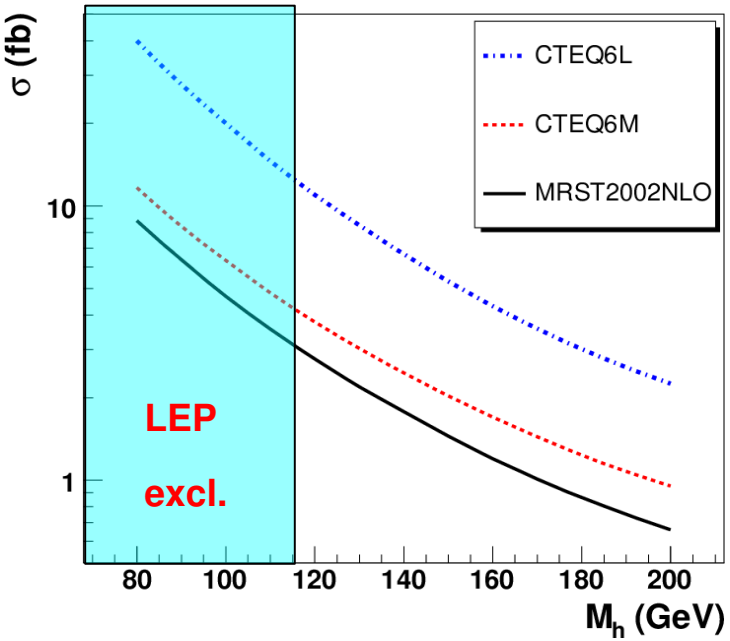
- Central exclusive Higgs calculable via pQCD:

$\sigma_{pp\to pHp} = \text{uPDF} \otimes \sigma_{gg\to H} \otimes S^2_{\text{gap-survival}}$

σ_H = 3-10 fb (SM)



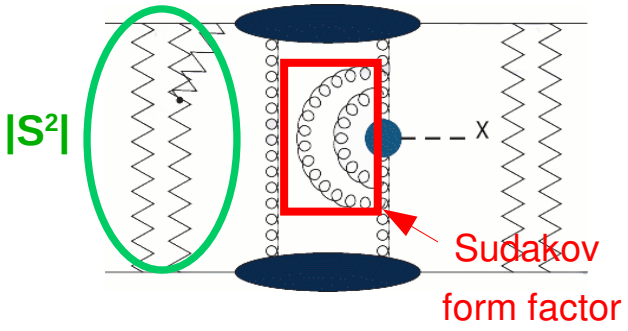
(uPDFs: standard PDFs taken)



- Two extra ingredients:

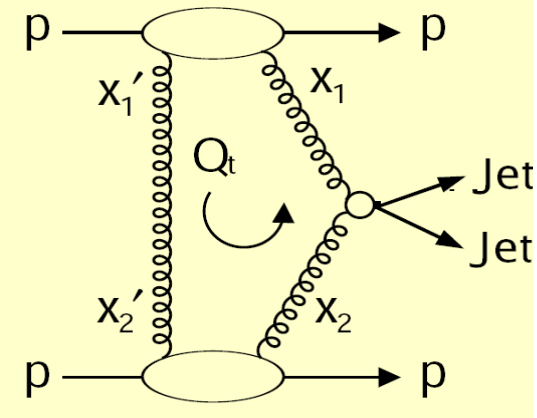
(i) gap survival $|S^2|$: probability to fill rap-gap with hadrons (rescattering corrs.)

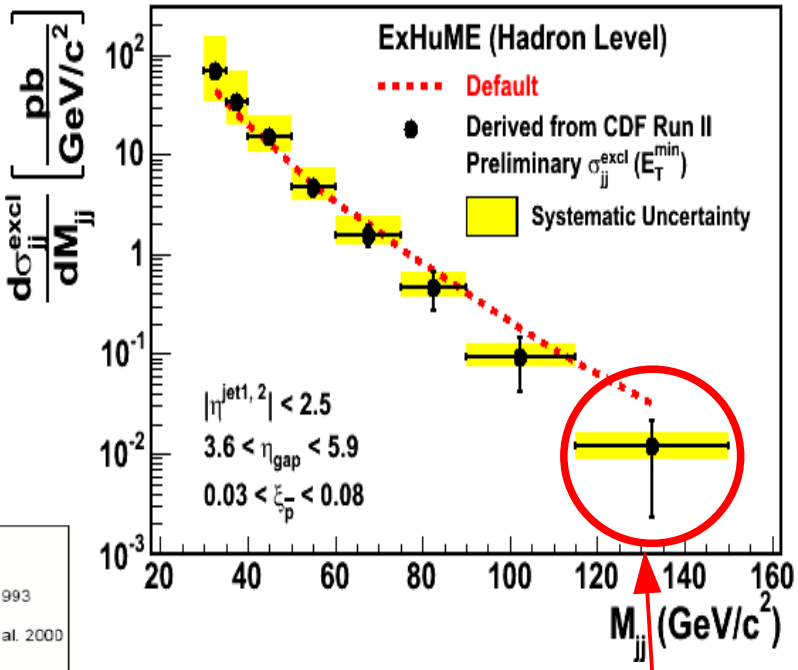
(ii) Sudakov form-factor: large, $S \sim \log^2(M_{gg}^2)$, virtual corrs.



Central exclusive Higgs: x-section "validation"

- Exclusive dijets (CDF) have same type of diagrams as for Higgs: validation of KMR model & npQCD ingredients (ExHuME MC):

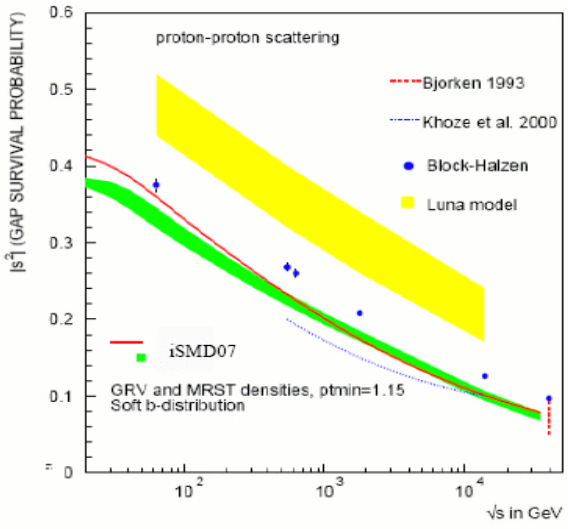




Note M_{jj}~130 GeV !

- In particular:

  $|S^2|$~0.03



MSSM Higgs'

- MSSM: Minimal Supersymmetric SM extension

  2 Higgs doublets ⇒ 8 degrees of freedom (5 physical states):

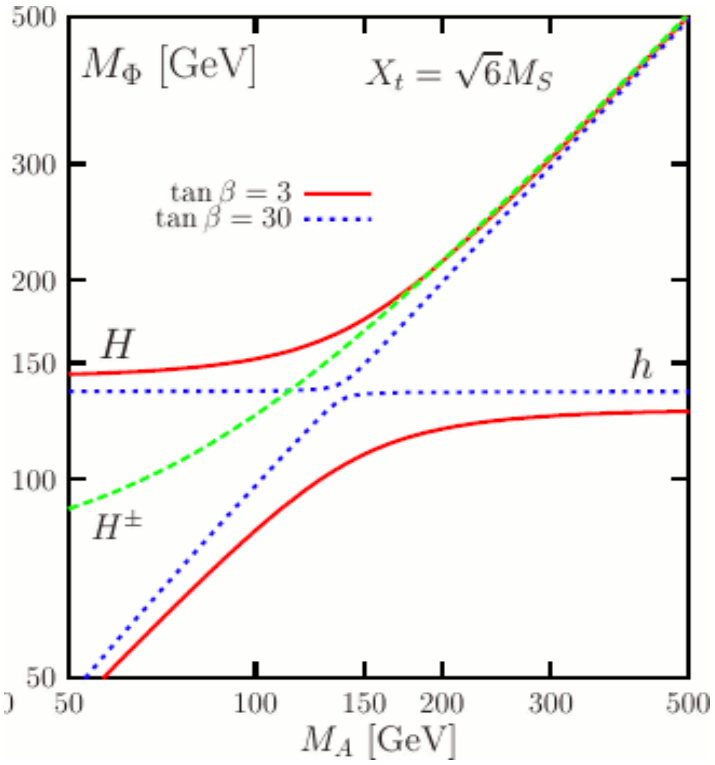
  CP-even : h,H CP-odd: A Charged: H^+,H^-

- MSSM parameter space:

  M_A, tanβ ≡ vev_2/vev_1

  At high M_A, heavy H's degenerate in mass &

  h saturates at M_h~130 GeV



- Couplings to SM particles modified:

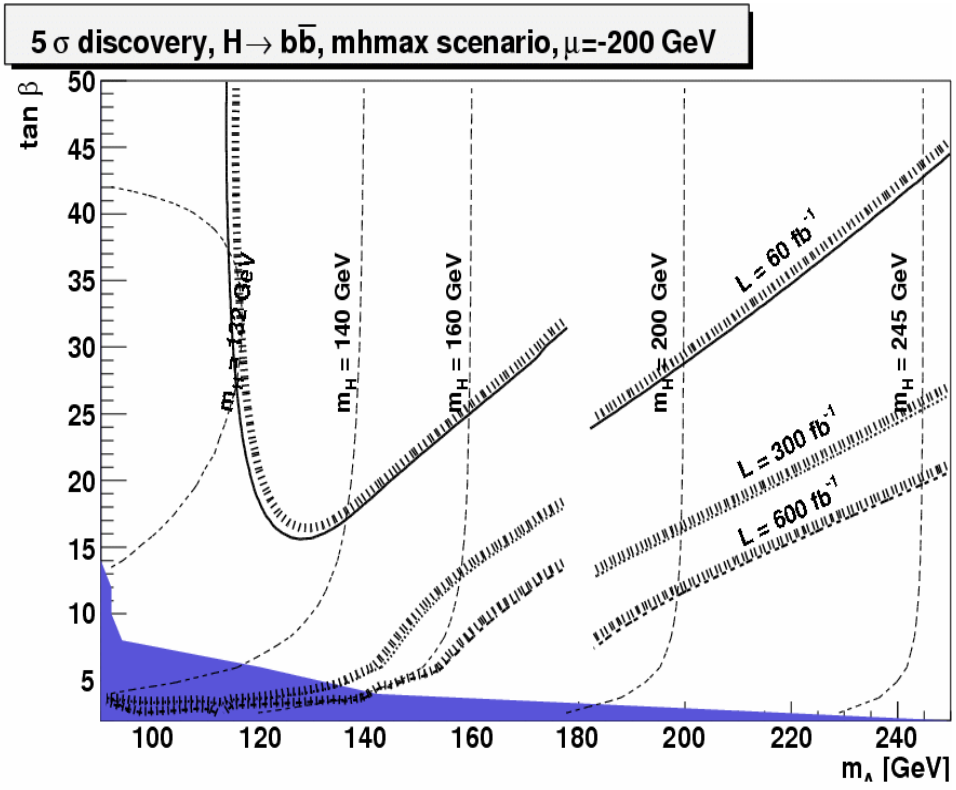
  Decay into 3d generation fermions (b,τ)

  enhanced at high tanβ: challenging discovery in “normal” bosonic modes !

MSSM Higgs': Central exclusive

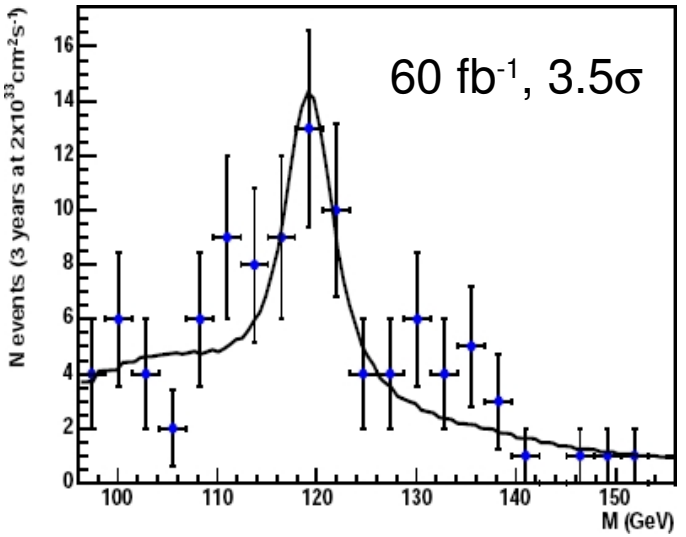
[FP420 R&D report]

- MSSM Higgs(es): tagged proton channel is discovery channel (bbar and $\tau^+\tau^-$ decays !) in wide m_A-tanβ range:



[Heinemann et al.arXiv:0708.3052]

Higgs line-shape in bbar channel !

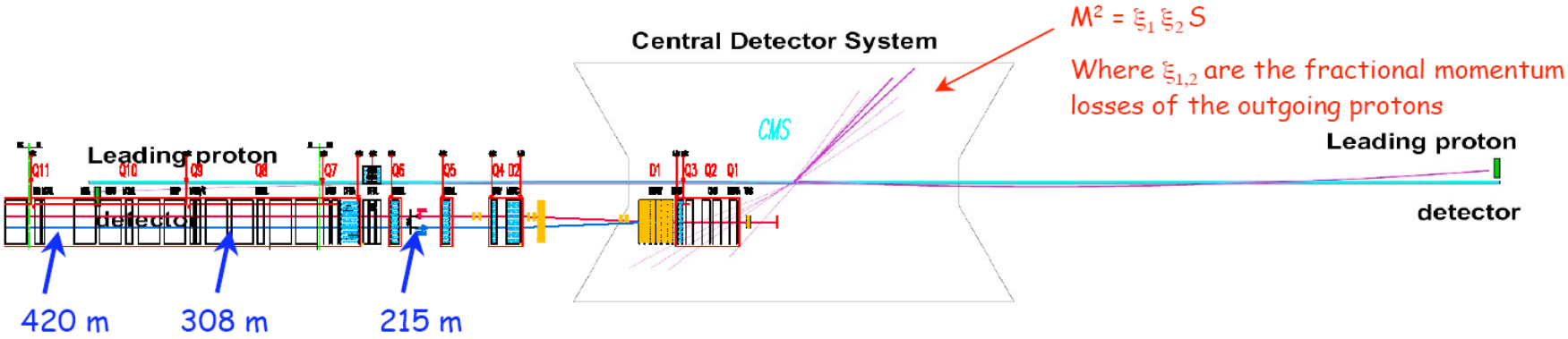


[Cox/Loebinger/Pilkington JHEP 0710:090,2007]

Central exclusive Higgs: FP-420 project

[FP420 R&D report]

- For $m_H < 200$ GeV, proton tagging acceptance needed at ±420 m
- FP420 R&D project (ATLAS/CMS):

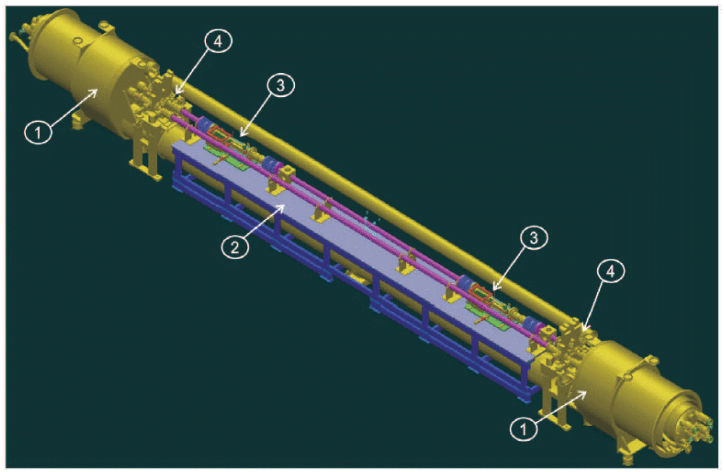


- Novel technologies:

(i) Moving beampipe in cold LHC area

(ii) Very fast (τ ~10 ps) Cerenkov detectors:

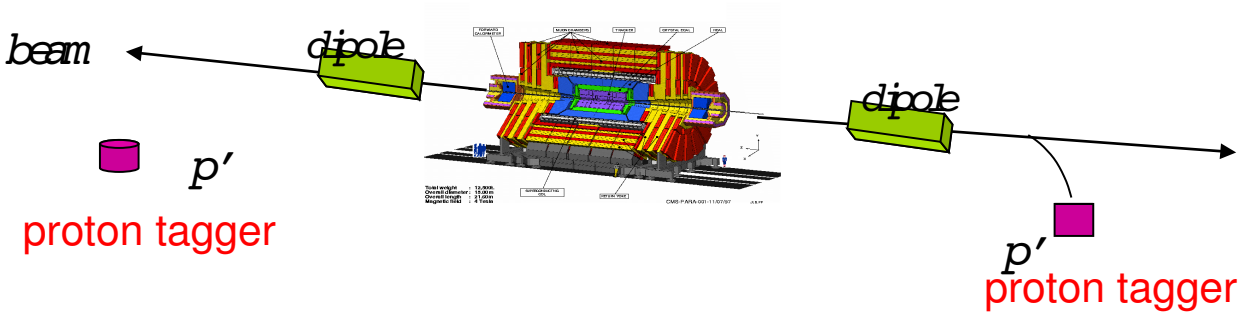
GASTOF (gas), Quartic (Quartz)



Precise leading protons time-difference to isolate pp → p H p vertex in high luminosity (~25 p-p colls.) conditions

Central exclusive Higgs: LHC optics

- Scattered protons survive interaction & lose only a small fraction ξ of their initial longitudinal momentum (a few 100 μrads):

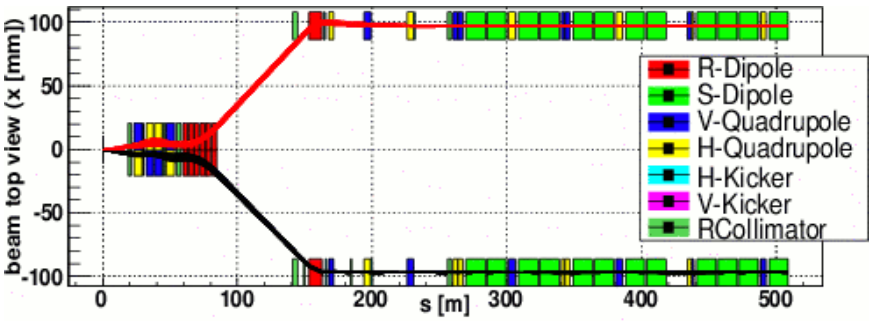


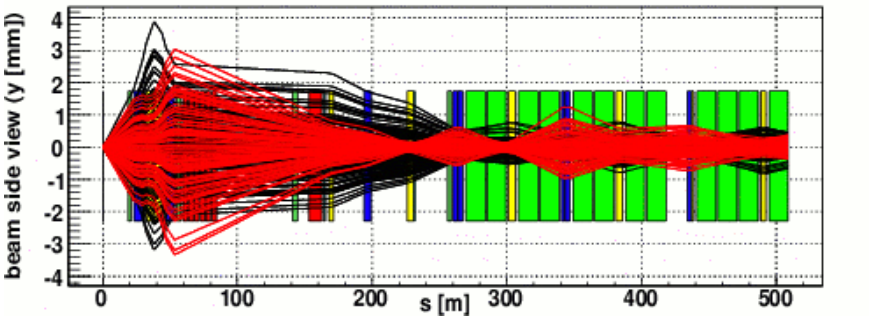
$\xi_1 \xi_2 s = M^2$

For $\sqrt{s}$=14TeV, M_X=120 GeV:

proton fractional momentum loss:

$\xi \approx 0.009 \approx 1\%$



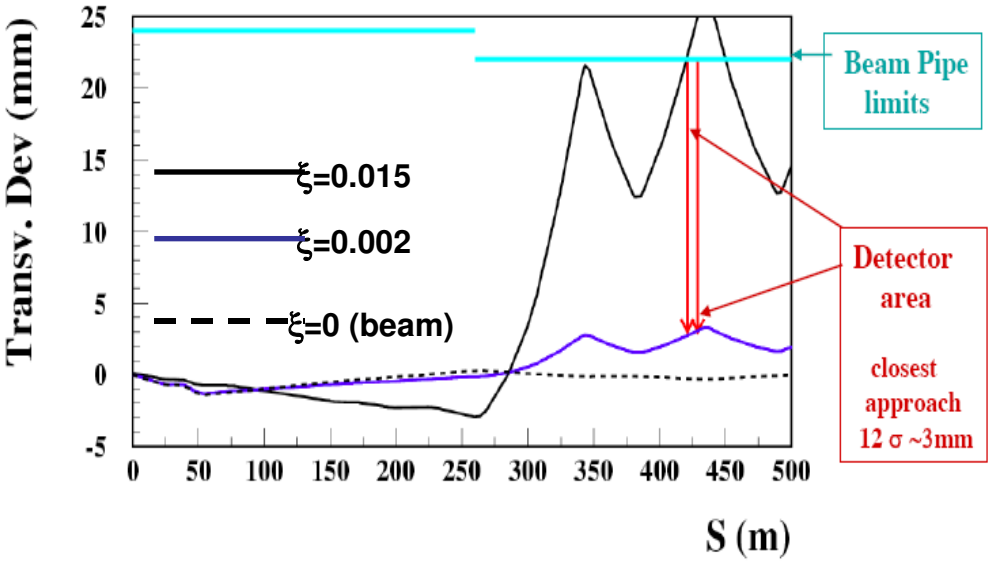


- LHC beam magnets deflect leading protons by a few mm after ~420 m:

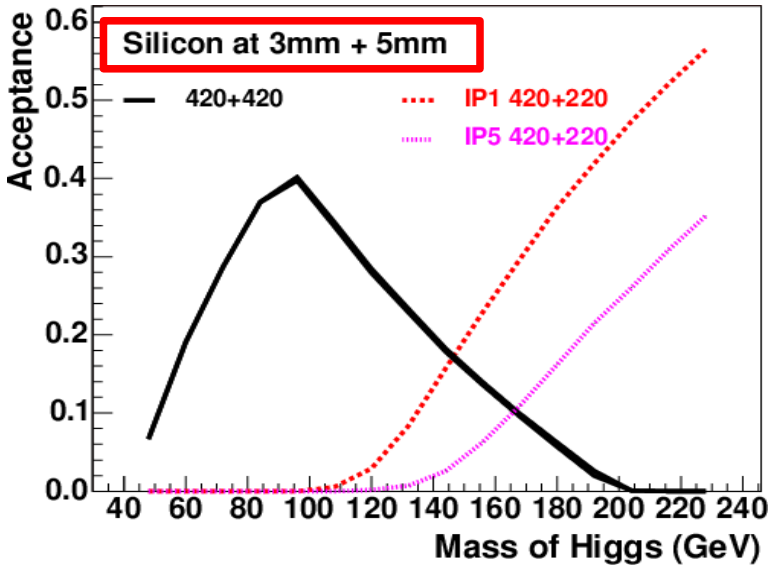
  Detection needed inside beam pipe.

FP420(+220m): central exclusive acceptance

- Scattered proton inside beam trajectory: transverse distance at 220m & 420m



- Acceptance of FP420+220m versus CEP Higgs mass:



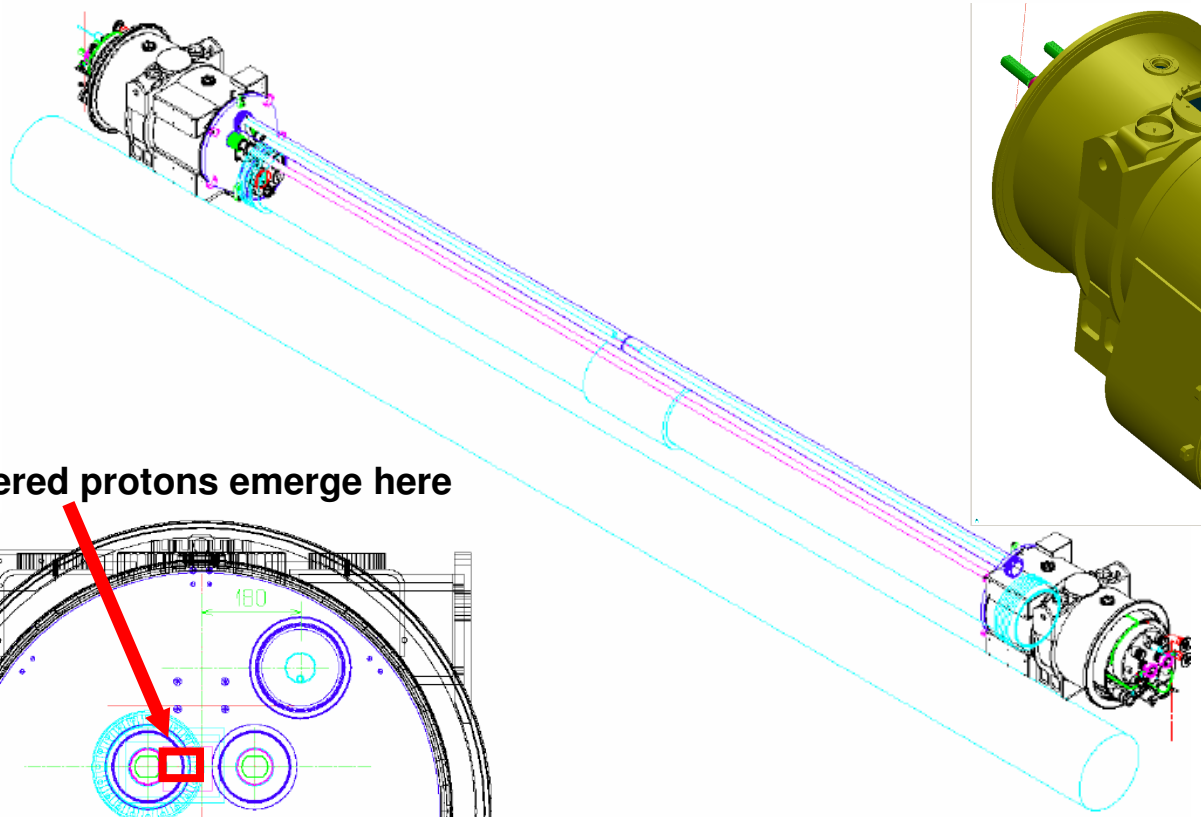
Nominal LHC beam optics:

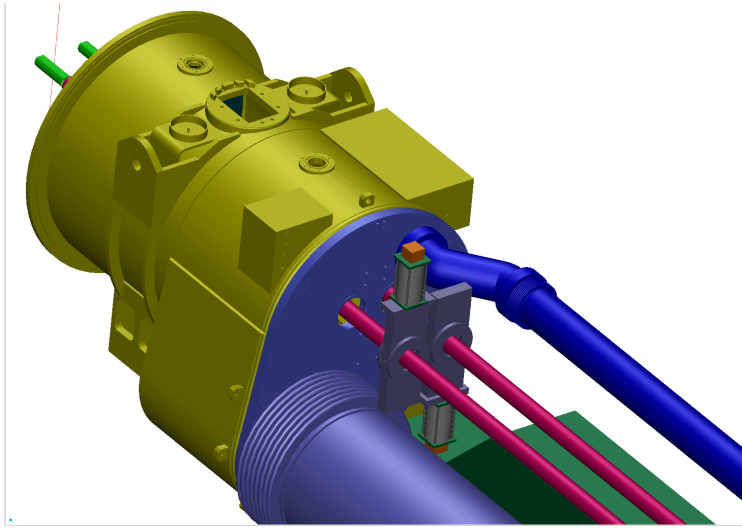
Low b* (0.5m): Lumi = 10^{33}-10^{34}cm^{-2}s^{-1}

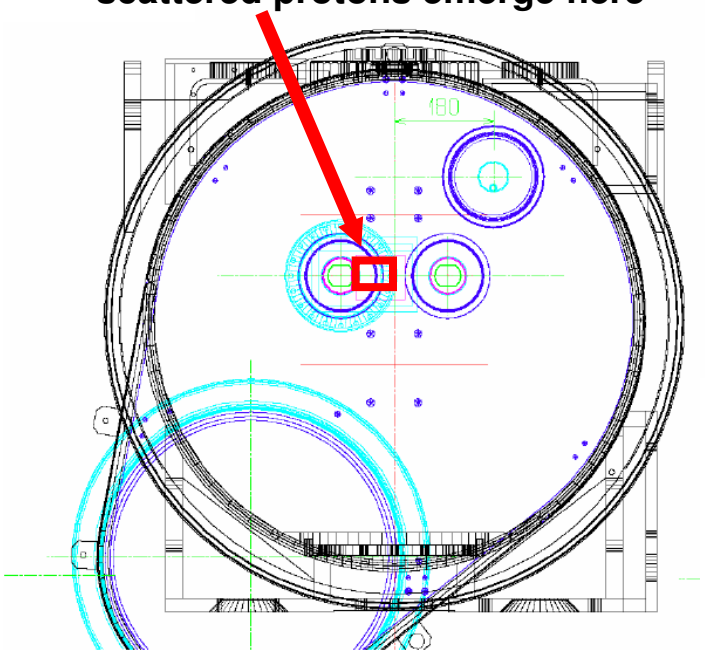
- Detectors @220m ($0.02 < \xi < 0.2$): acceptance for m_H>150 GeV, but ξ resolution inferior
- Detectors @420m ($0.002 < \xi < 0.02$): superior ξ (i.e. in Higgs mass) resolution, but cannot be used in L1 trigger (too far away)

FP420: new connection cryostat

[FP420 R&D report]

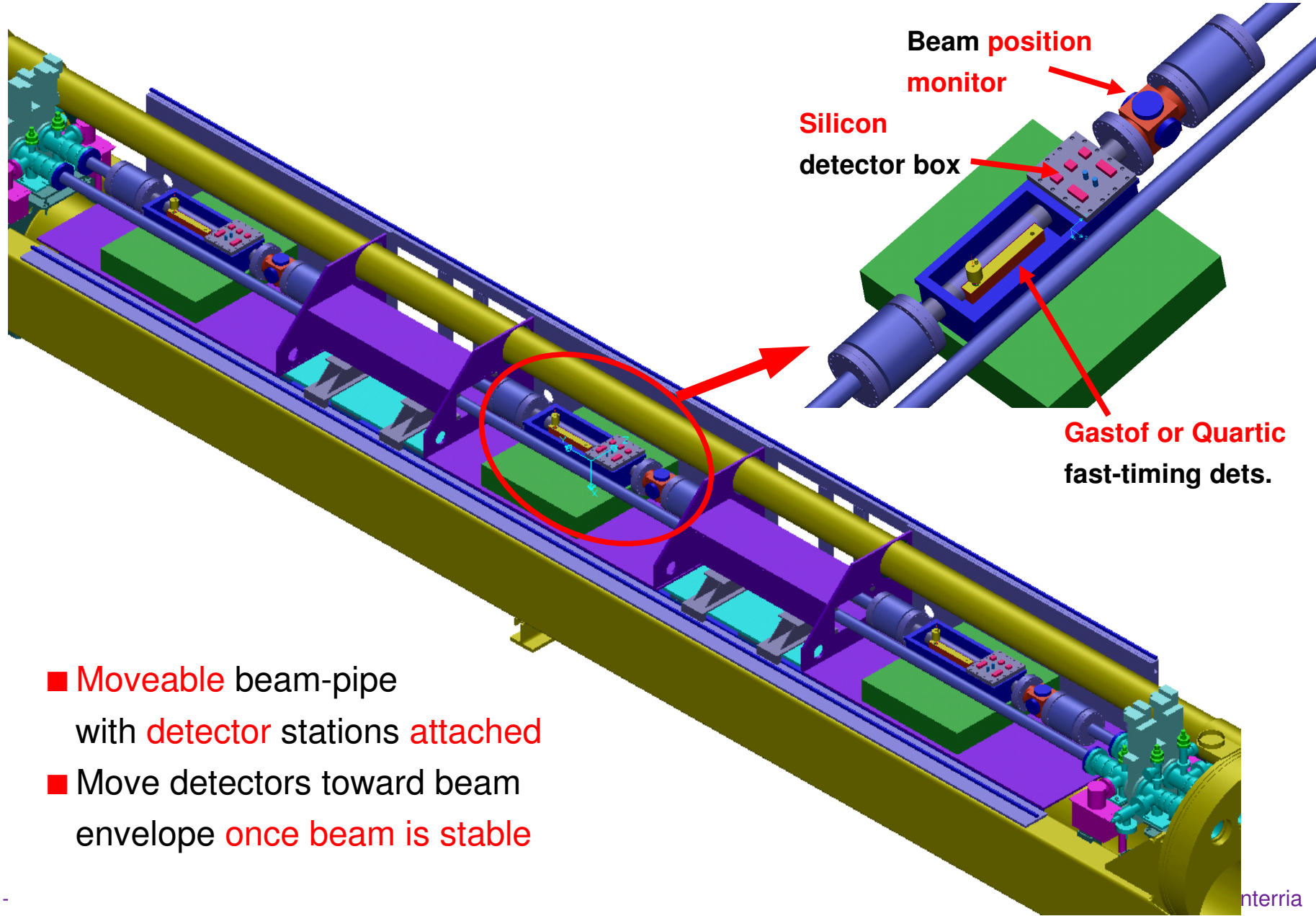






- 420m from the IP in the cold section of the LHC.
- New connection cryostat needed:
  Modify LHC Arc Termination Modules for cold-to-warm transition such that detectors can be operated at ~ room temperature

FP420: new “Hamburg” beam-pipe



- Moveable beam-pipe with detector stations attached
- Move detectors toward beam envelope once beam is stable

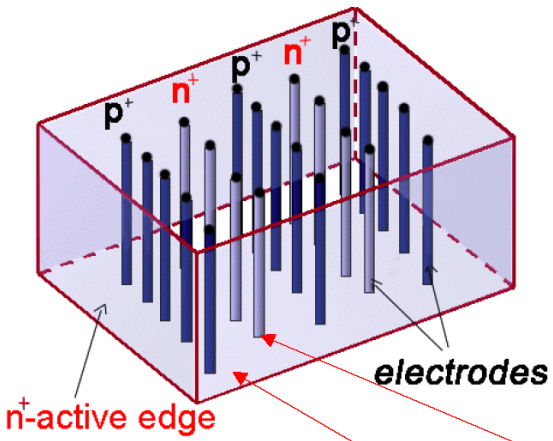
FP-420: proton Si-detectors

- 3D edgeless Silicon detectors:

  Edgeless, i.e. distance to beam envelope can be minimized.

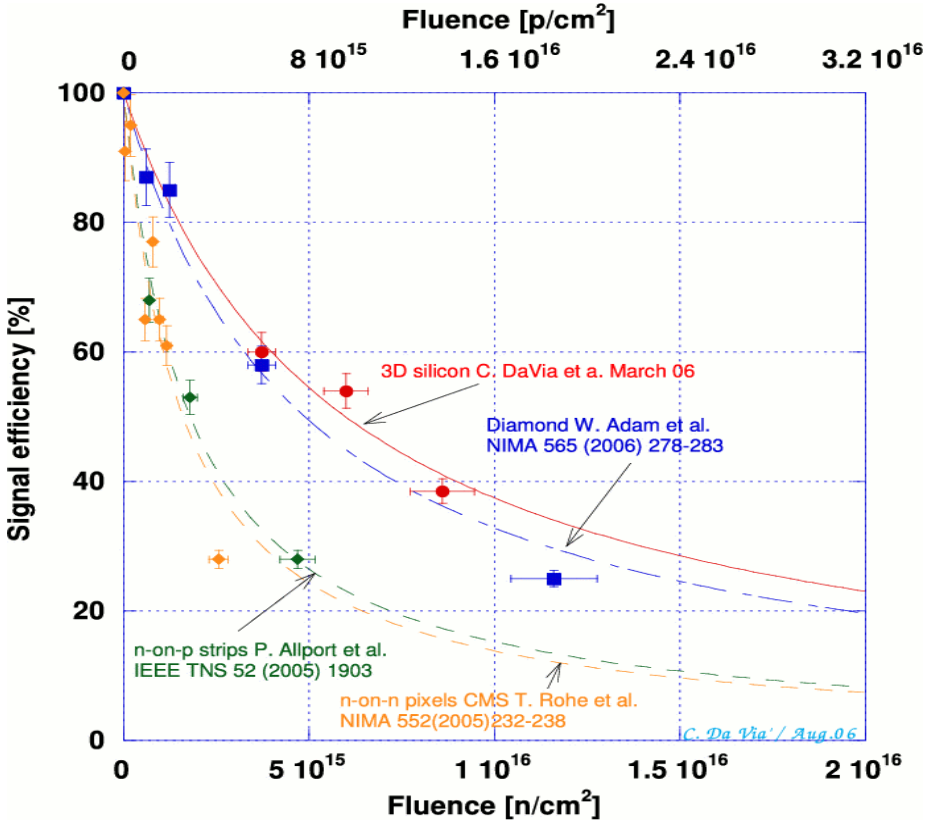
  Radiation hard, can withstand 5 years at 10^{35} cm^{-2} s^{-1}

  Use ATLAS pixel chip (rad hard) for readout



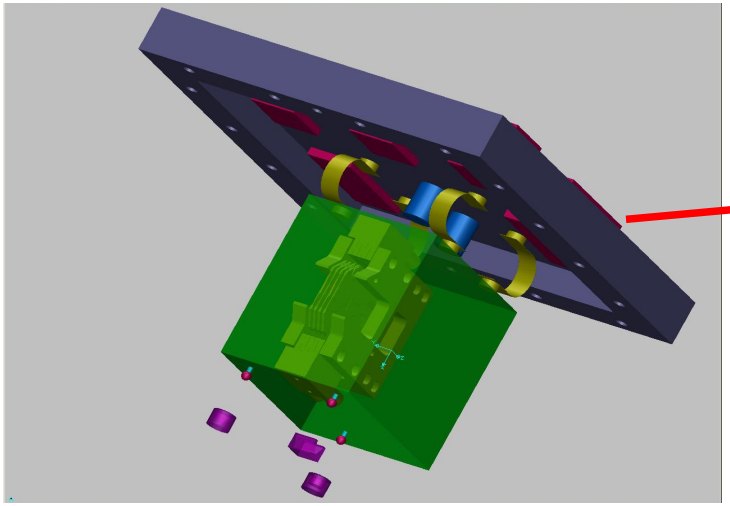
Active edges: the edge is itself an electrode, so dead volume at the edge < 5 μ.

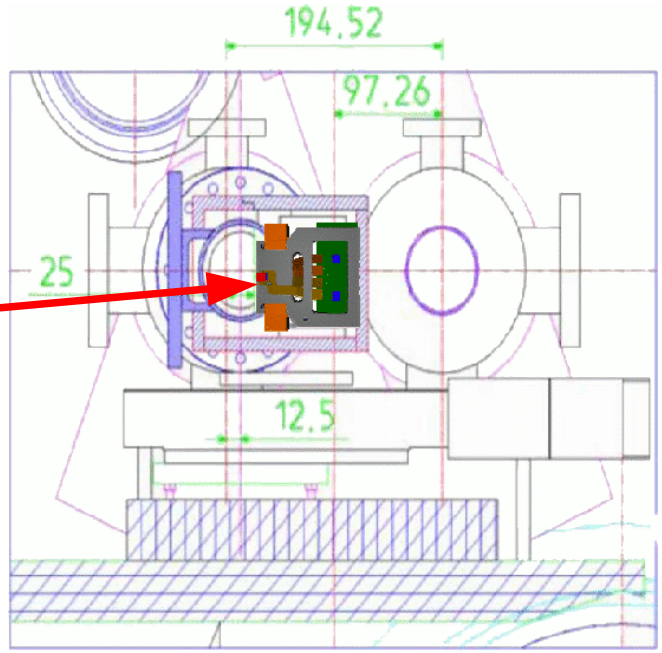
Electrodes are processed inside the detector bulk instead of being implanted on the wafer's surface.



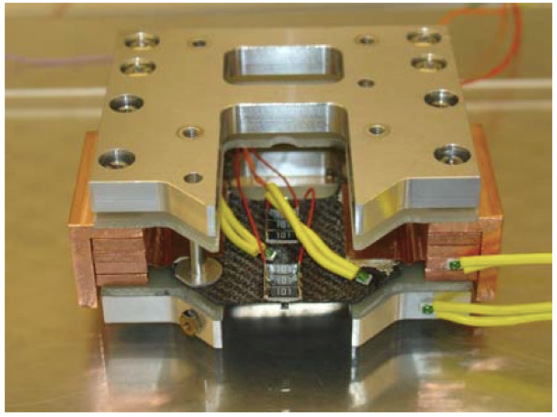
FP-420: proton Si-detectors

- A complete tracking station (+lid)





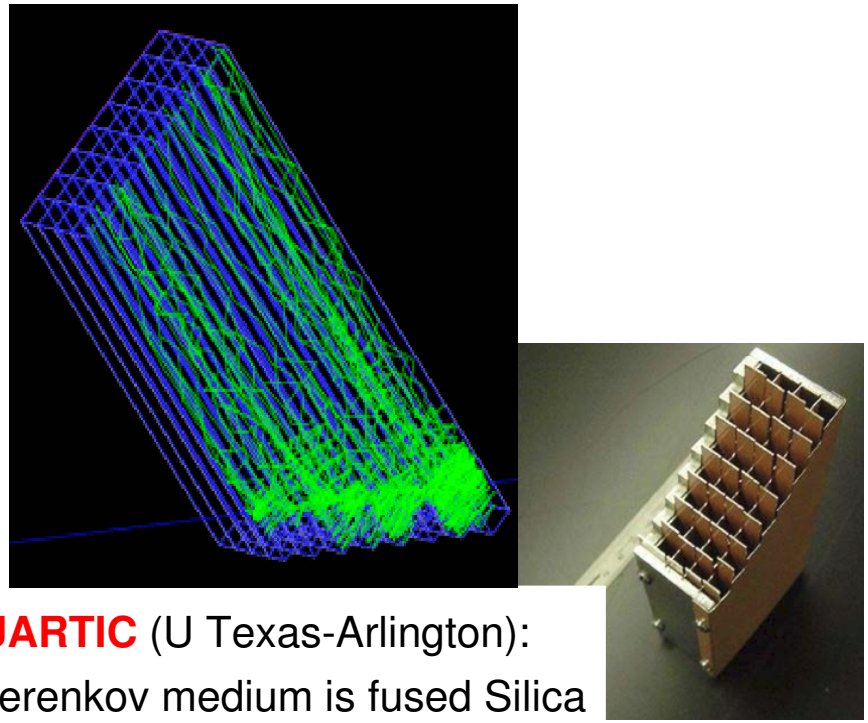
- 3 detector stations with 8 layers each



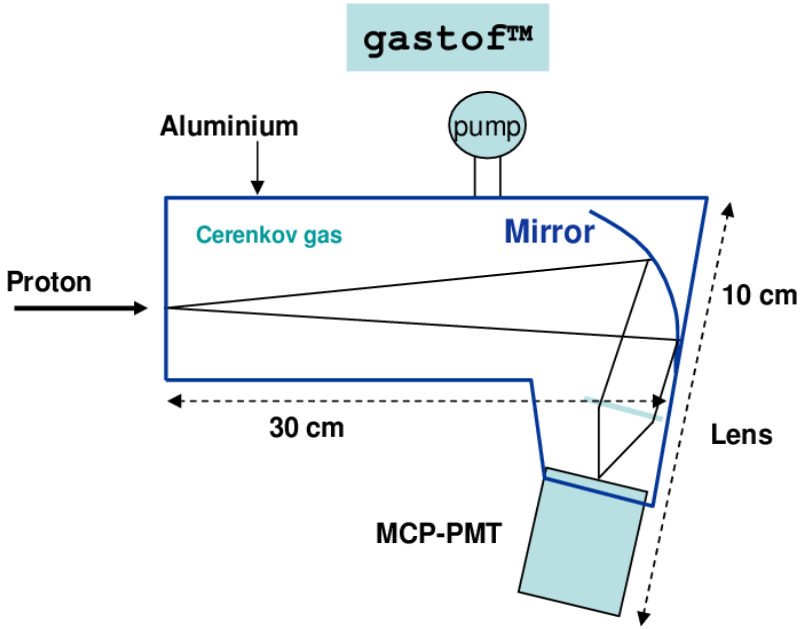
- Tracking performances:
  - Detection efficiency: ~80-86%
  - Angular resolution: 0.9 μrad

FP-420: fast-timing detectors

- Fast-timing detectors needed to identify CEP vertex out of other pile-up events.
- Micro channel plate photo-multiplier tubes (MCP-PMT) employed in Cherenkov-light based TOF detector with resolution of ~10ps.
- Expected z-vertex resolution of better than 3mm.
- Two technologies: Quartz- or gas-based Cherenkov.



QUARTIC (U Texas-Arlington):
Cherenkov medium is fused Silica

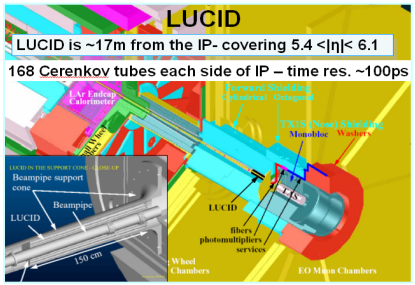


GASTOF (UC Louvain)
Cherenkov medium is a gas

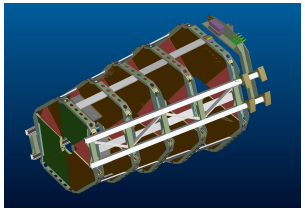
Summary: forward instrumentation @ LHC

ATLAS

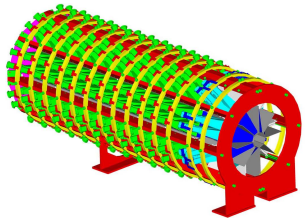
LUCID



TOTEM T1



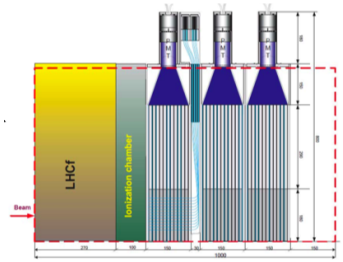
CMS CASTOR



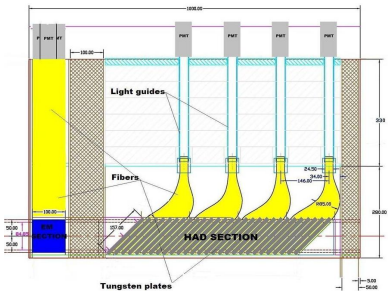
TOTEM T2

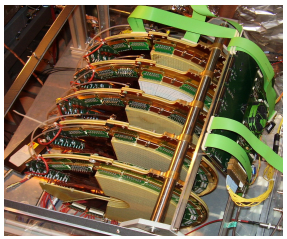
ATLAS ALFA

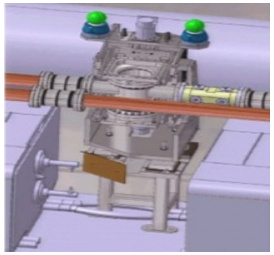
ATLAS ZDCs



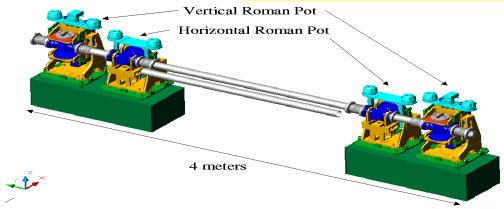
CMS ZDCs

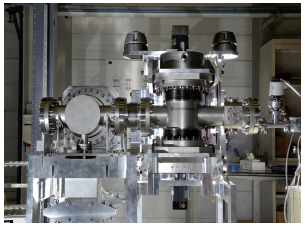




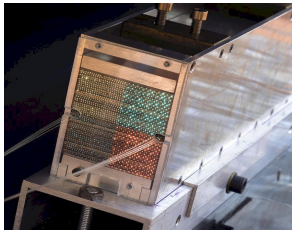


TOTEM RPs

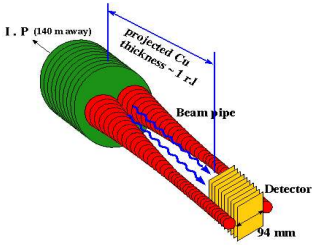




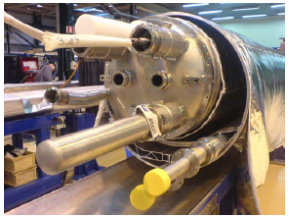
ALICE ZDCs



LHCf

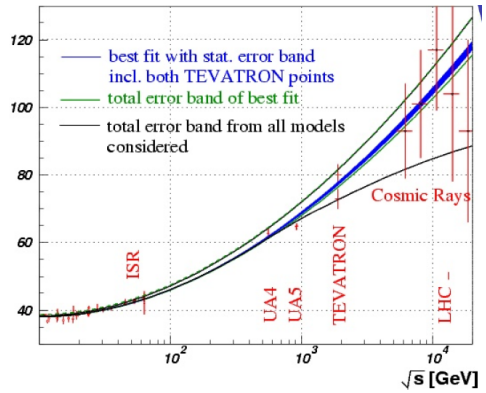


FP420

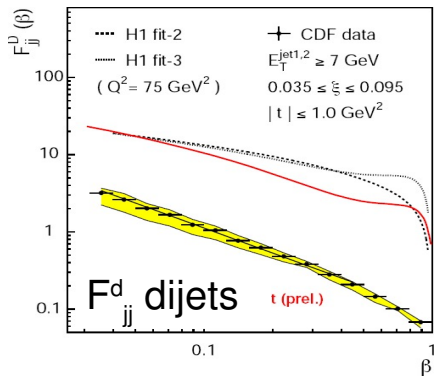


Summary: forward physics @ LHC

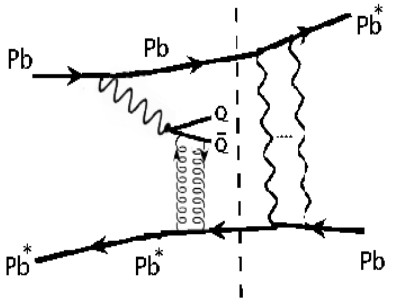
p-p σ_{tot}, elastic scatt.



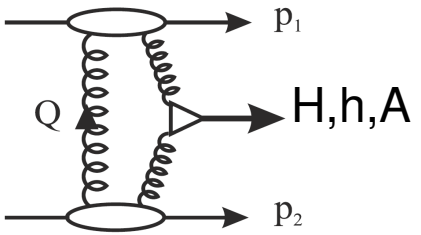
hard diffraction



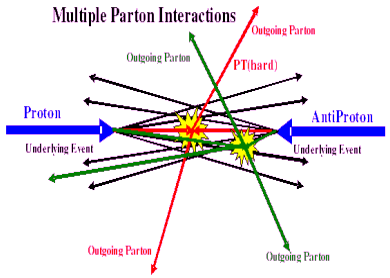
VM photoprod.



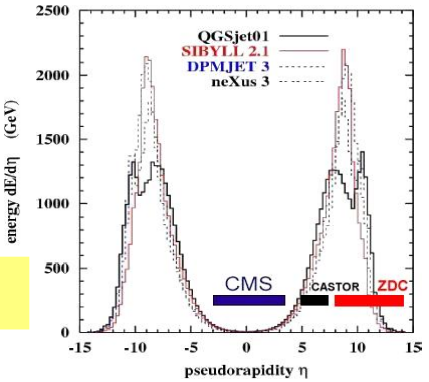
(B)SM Higgs



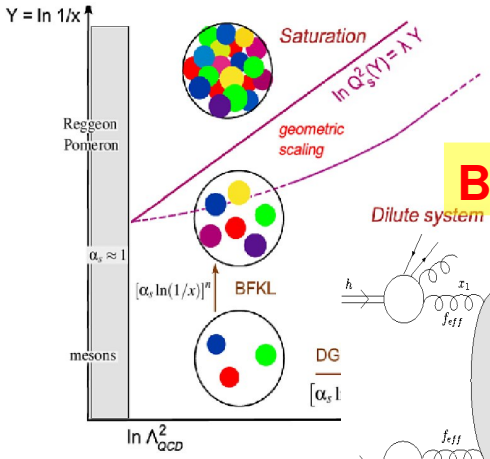
MB/UE/MPI



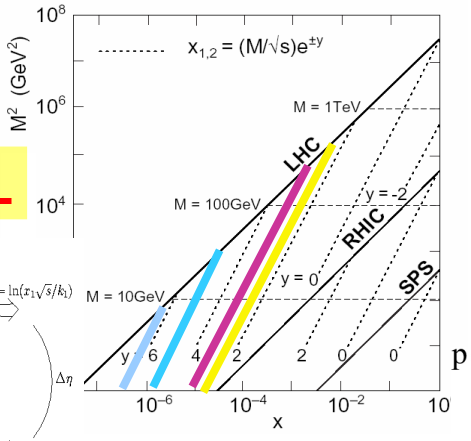
UHE cosmic-rays



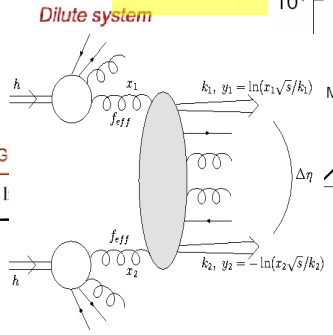
gluon saturation, CGC



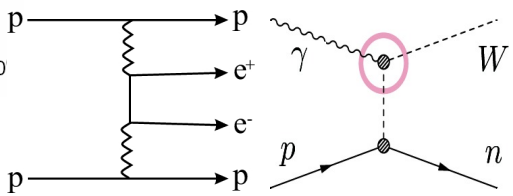
low-x PDFs



BFKL



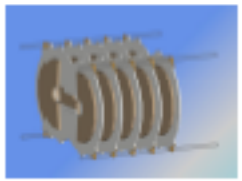
E-W (γ-γ,γ-W,...)

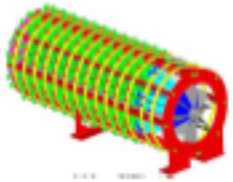


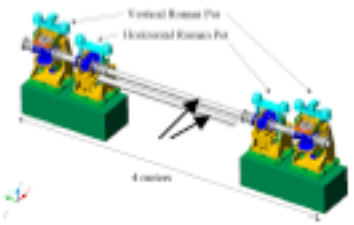
Backup slides

Summary: forward instrumentation @ LHC

IP5







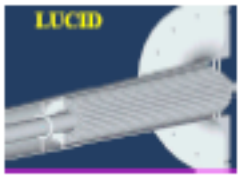
TOTEM-T2 14m

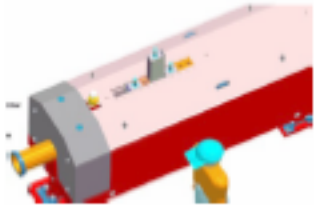
CASTOR 16m LUCID

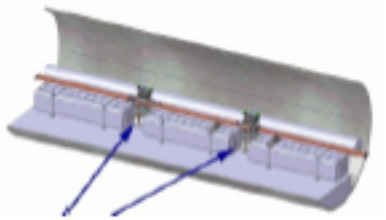
ZDC/FwdCal 140m ZDC

TOTEM-RP 147-(180)-220m ALFA/FP220

FP420 420m FP420







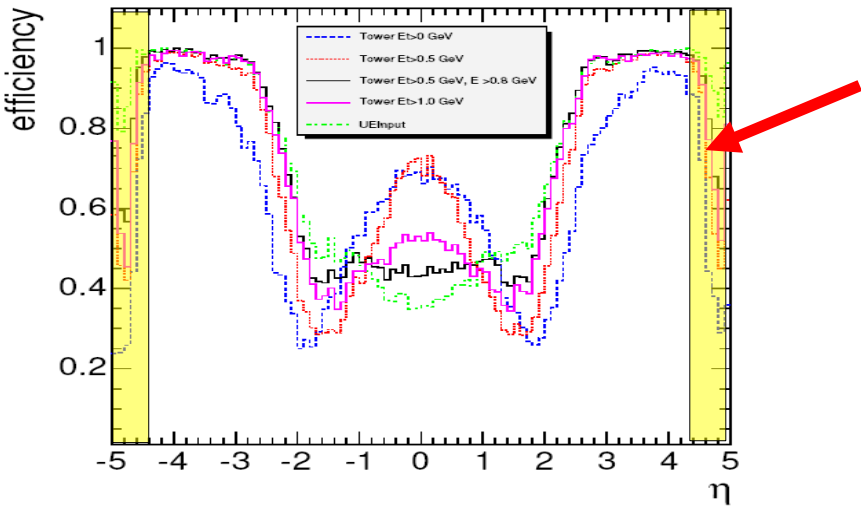
IP1

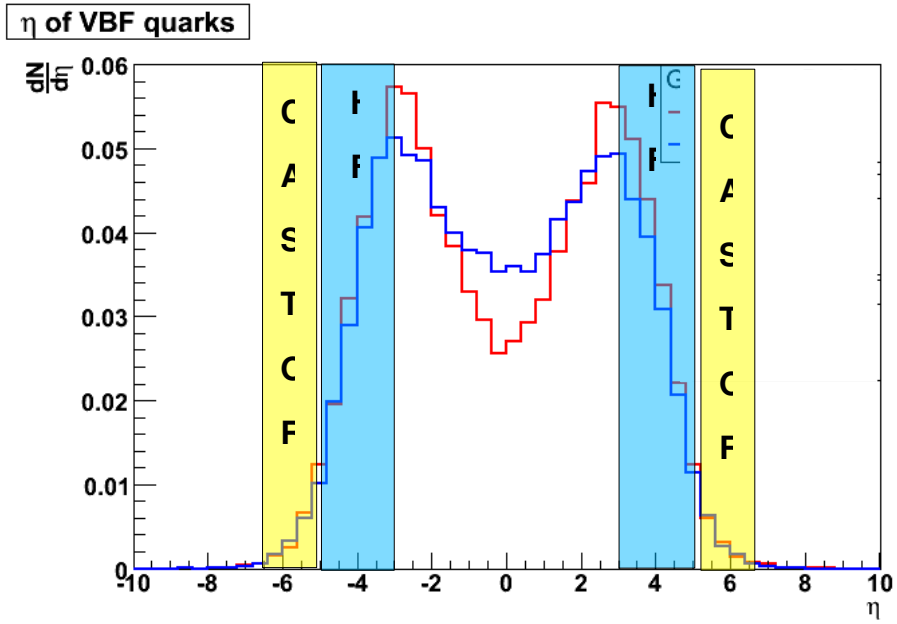
possible upgrade RP220 with Si detectors

possible addition

VBF tagging in CMS (HF+CASTOR)

- CASTOR+HF extends effective jet acceptance to 3.<|η|< 6.:





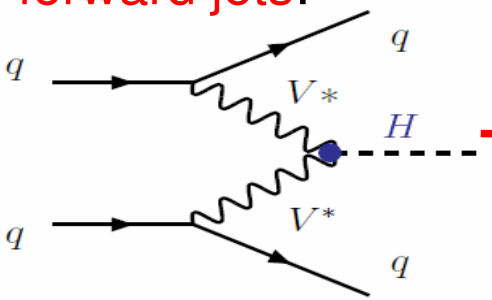
Vector-Boson-Fusion Higgs tagging

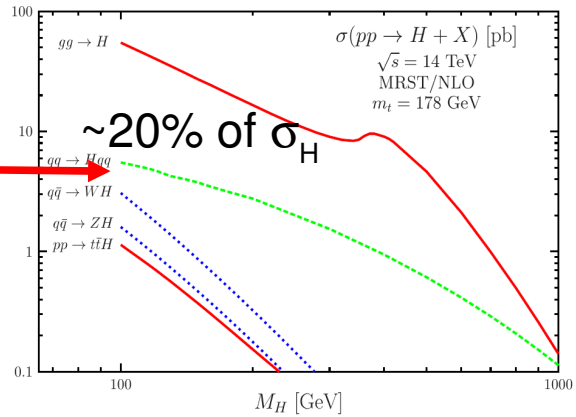
[DdE/LeMenedeu, BWS'07]

- qq→ qqH accompanied by forward jets:

  2 jets (p_T~20-60 GeV)

  w/ large $\Delta\eta$~5 separation

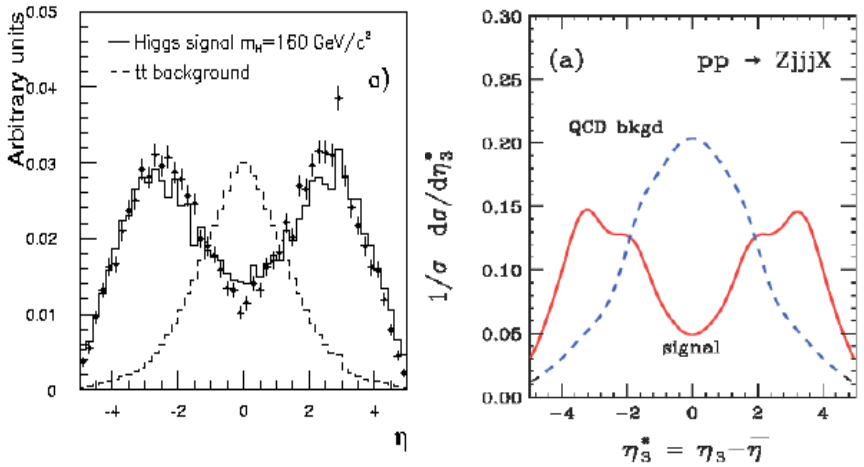




- Good QCD background rejection :

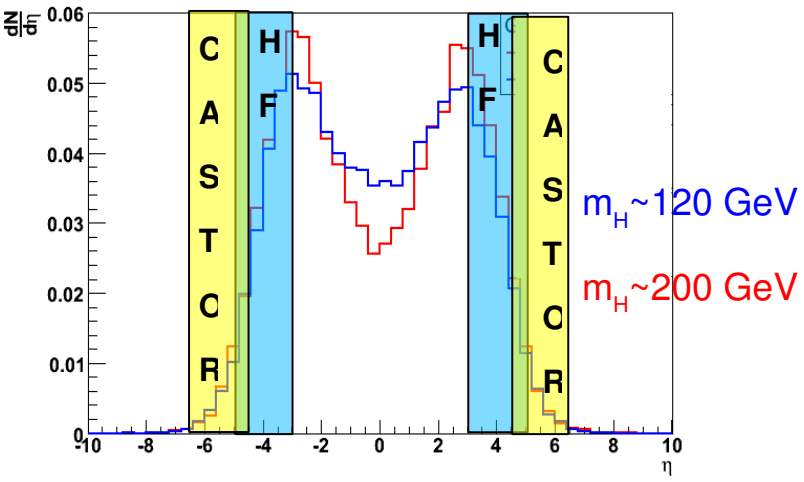
  H→WW(→l±jj ν) vs. ttbar,WW

  H→ττ vs. Z+nj, W+nj, ttbar



background jets at central rapidities

Combined HF+CASTOR extends (~15%) VBF jet tagging efficiency:



$\gamma\gamma \rightarrow$ SUSY pairs

[Cf. Séverine Ovyn & UCL CMS group]

- Production x-sections defined only by mass, charge & spin !
- Very clean signature: 2 (and only 2) opposite charged leptons & MET

Three post-WMAP mSugra benchmark points checked:

- LM1: light LSP, light sleptons & charginos, tan(β)=10
- LM2: medium LSP, heavy sleptons&charginos, tan(β)=30
- LM6: heavy LSP, medium right sleptons, tan(β)=10

m [GeV]	LM1	LM2	LM6
$\tilde{\chi}_1^0$	97	141	162
$\tilde{l}_R^+$	118	229	175
$\tilde{l}_L^+$	184	301	283
$\tilde{\tau}_1^+$	109	155	168
$\tilde{\tau}_2^+$	188	313	285
$\tilde{\chi}_1^+$	180	265	303
H^+	386	448	592

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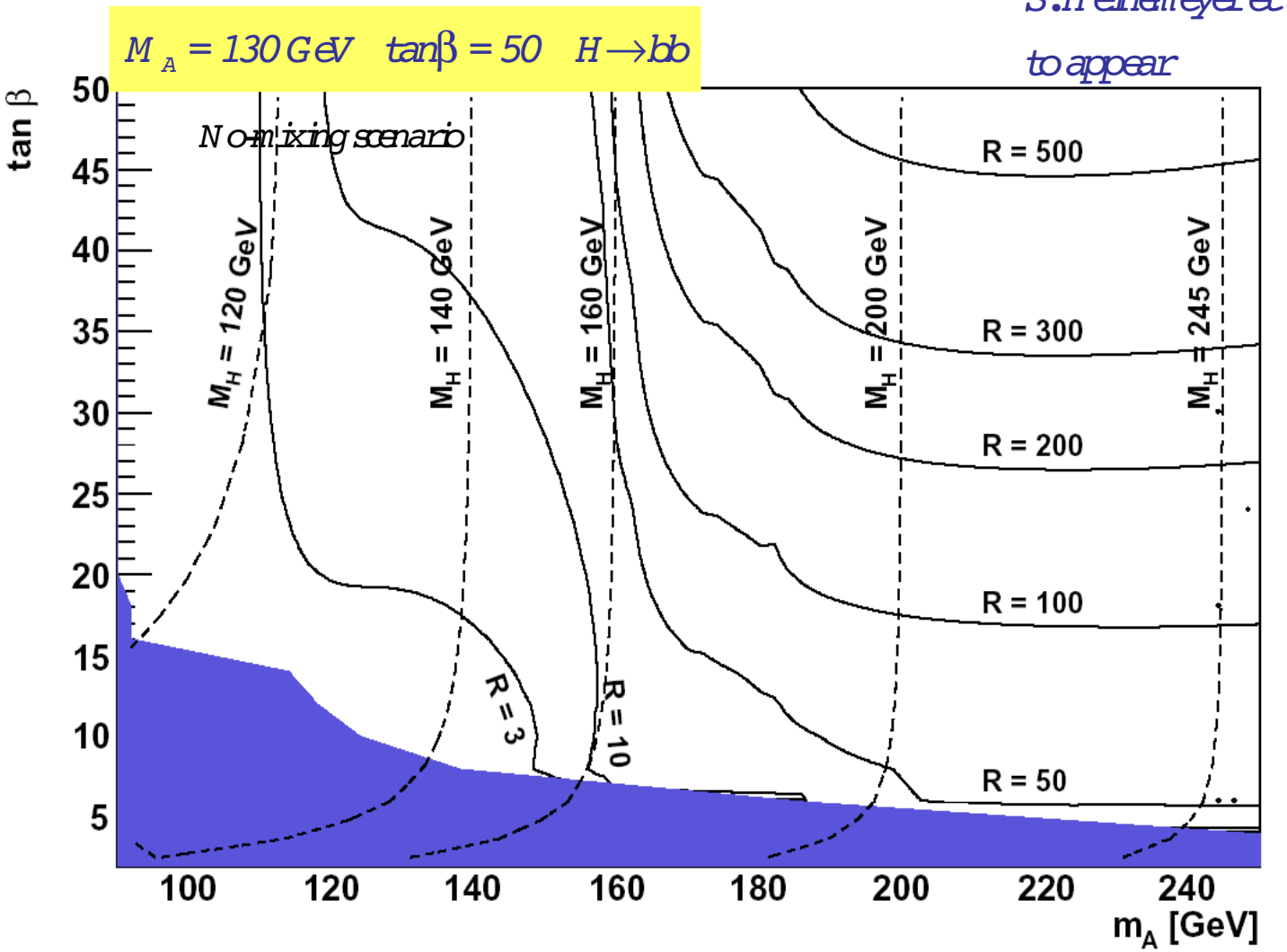
Central exclusive MSSM Higgs

S. Heinemeyer et al. to appear

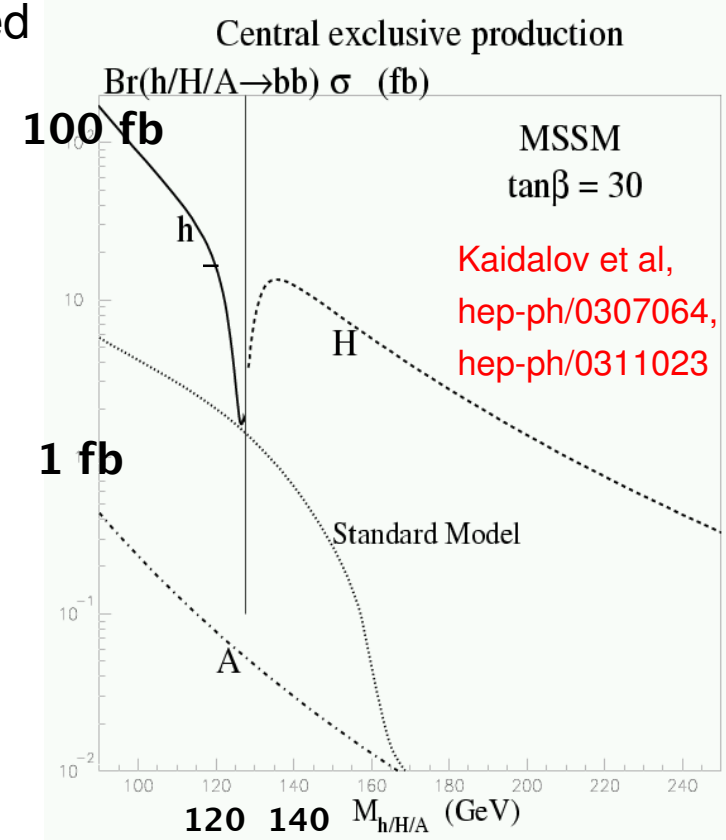


Contours of ratio of signal events in the MSSM over the SM

Central exclusive MSSM Higgs

- Intense-coupling regime of the MSSM:
  $M_h \sim M_A \sim M_H \sim O(100\text{GeV})$:
  coupling to $\gamma\gamma$, WW*, ZZ* strongly suppressed
  8 discovery very challenging at the LHC

→ **CEP as discovery channel**



Cross section of two scalar (0+) Higgs bosons enhanced compared to SM Higgs

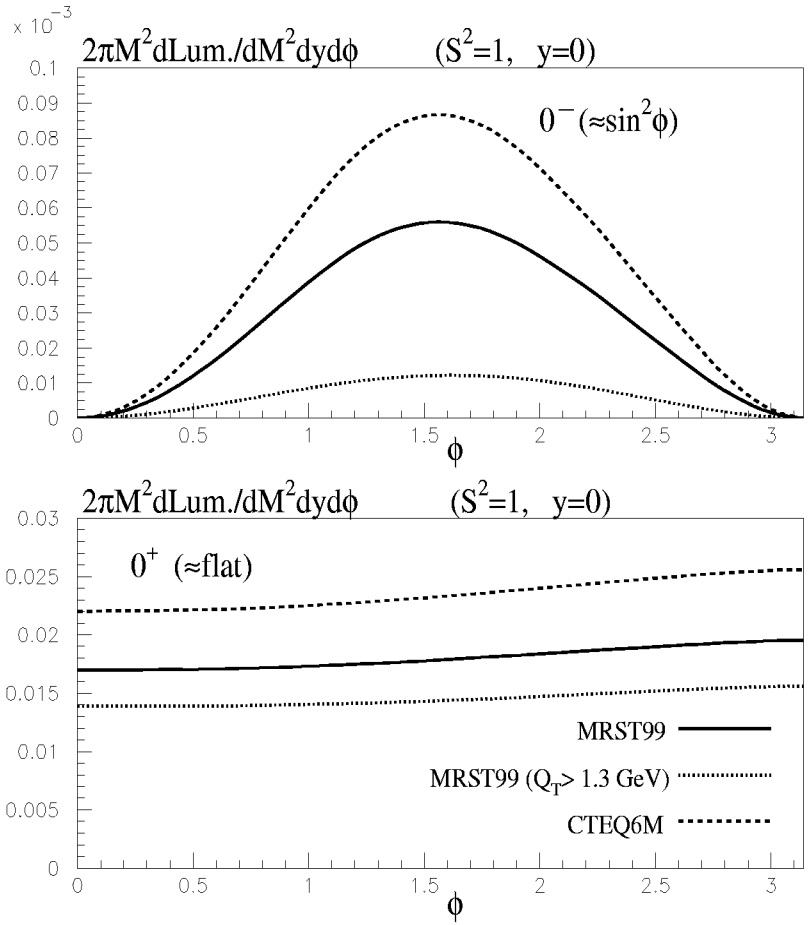
Production of pseudo-scalar (O-) Higgs suppressed because of J_Z selection rule

Superior missing mass resolution from tagged protons allows to separate h, H

Spin-partity of Higgs can be determined from the azimuthal angles between the two taggedprotons (J_Z rule only approx)

Higgs spin-parity

- Azimuthal angle between outgoing protons sensitive to Higgs spin-parity: $J^P=0^+$ vs $J^P=0^-$ (recall J_Z selection rule only approximate)



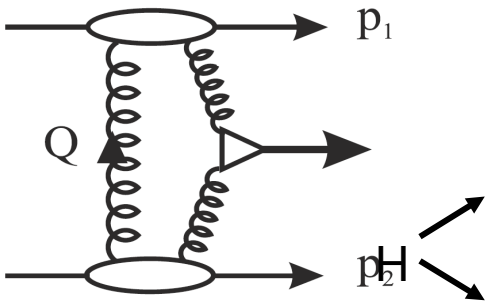
0^-

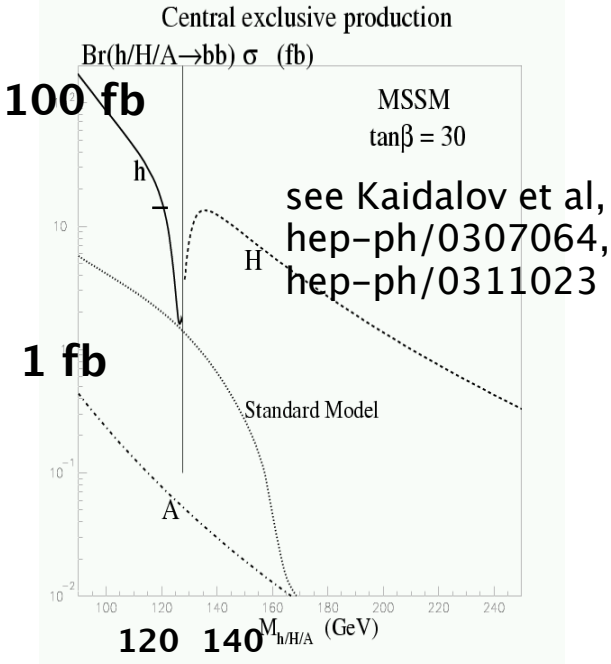
0^+

Kaidalov et al., hep-ph/0307064

Central exclusive SM Higgs

- Central exclusive Higgs production: $pp \rightarrow p\,H\,p$





Generator studies with detector cuts

b jets : M_H = 120 GeV; = 2 fb (uncertainty factor ~ 2.5)

M_H = 140 GeV; = 0.7 fb

M_H = 120 GeV: S/B=11 signal/O(10) in 30 fb^{-1} w/ detector cuts

Note: This H decay channel is impossible in non-CEP production !

WW^* : M_H = 120 GeV; L = 0.4 fb

M_H = 140 GeV; L = 1 fb

M_H = 140 GeV : S/B=8 signal / O(3) in 30 fb^{-1} with detector cuts

Note: Use semi-leptonic decays for measurement

Central exclusive MSSM Higgs'es

- Intense coupling regime: similar masses of the 3 neutral Higgs bosons and tanβ is large

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

$gg \to \phi$ enhanced

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

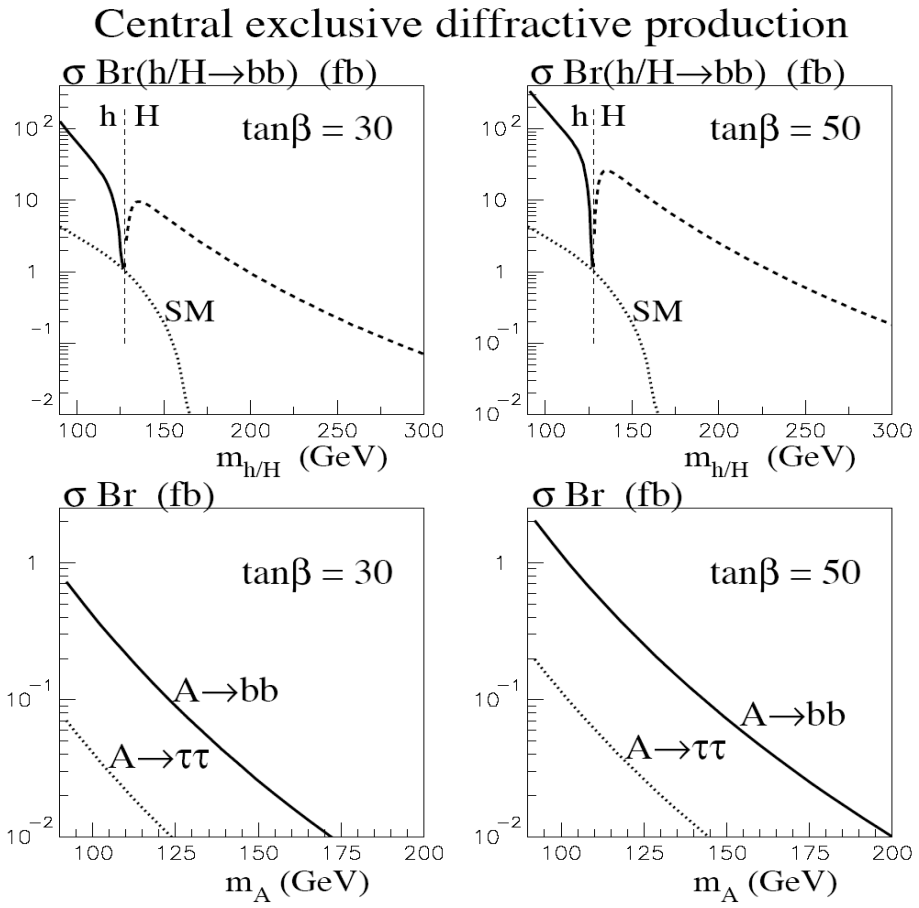
CEDP 'filters out' pseudo-scalar production, leaving pure H sample for study

m_A = 130 GeV, tan β = 50

m_h = 124 GeV : S/B = 70 / (3-10) in 30 fb^{-1}

m_H = 135 GeV : S/B = 125 / (2-5) in 30 fb^{-1}

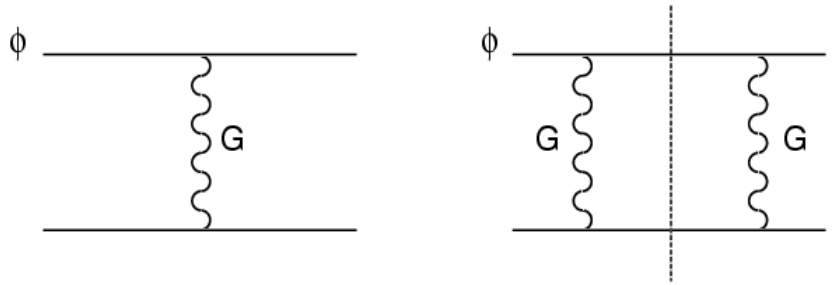
m_A = 130 GeV : S/B =3 / (2-5) in 30 fb^{-1}

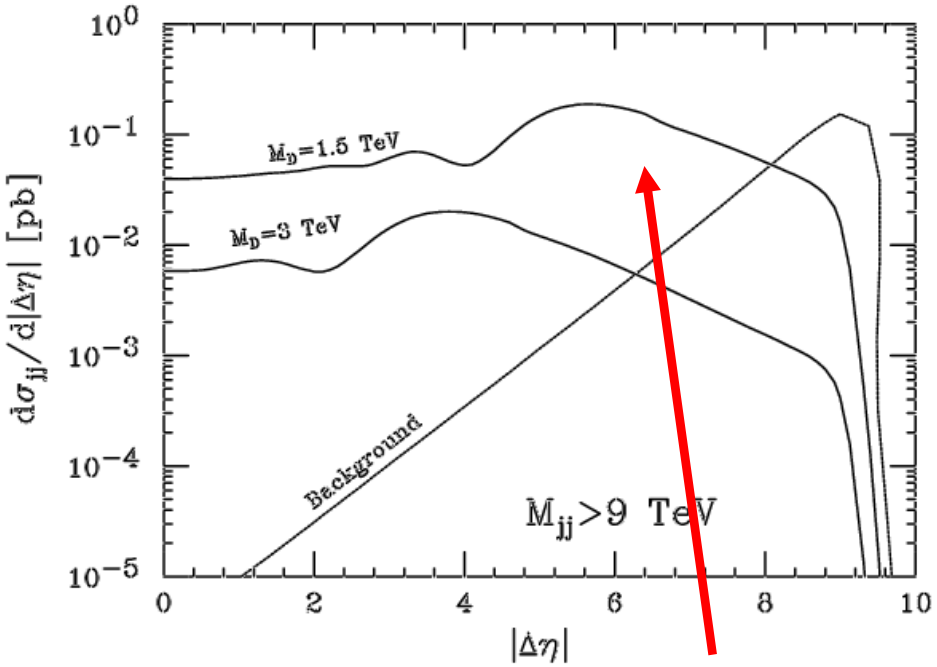


- Tagged proton channel may well be the discovery channel, and is certainly a powerful spin/parity filter

other BSM signals ... Transplanckian effects

Once you pass the Planck scale $\sqrt{s} >> M_D$…





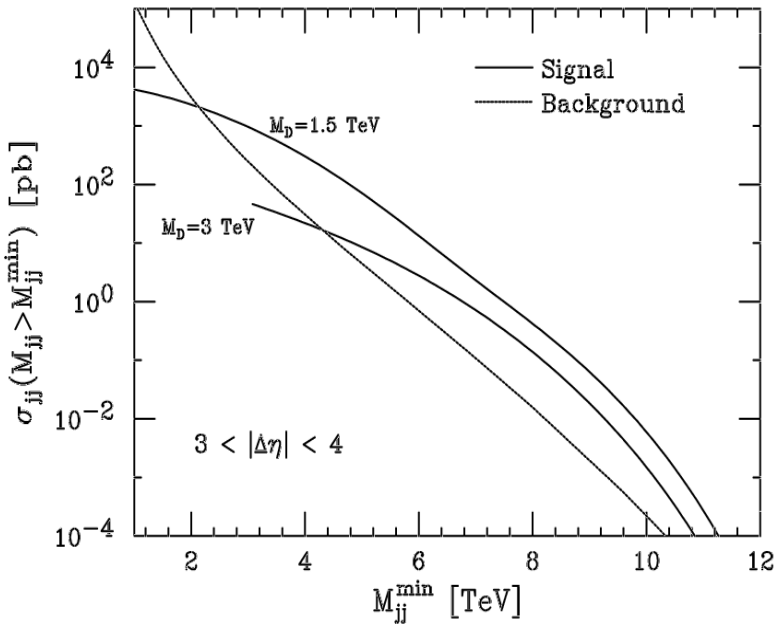
Large rapidity separation of 2 jets

Processes with small momentum transfer e.g. :

Elastic transplanckian colls.:

Study gravity propagation in ED's

Signal: dijets with large Δy, M_{jj}

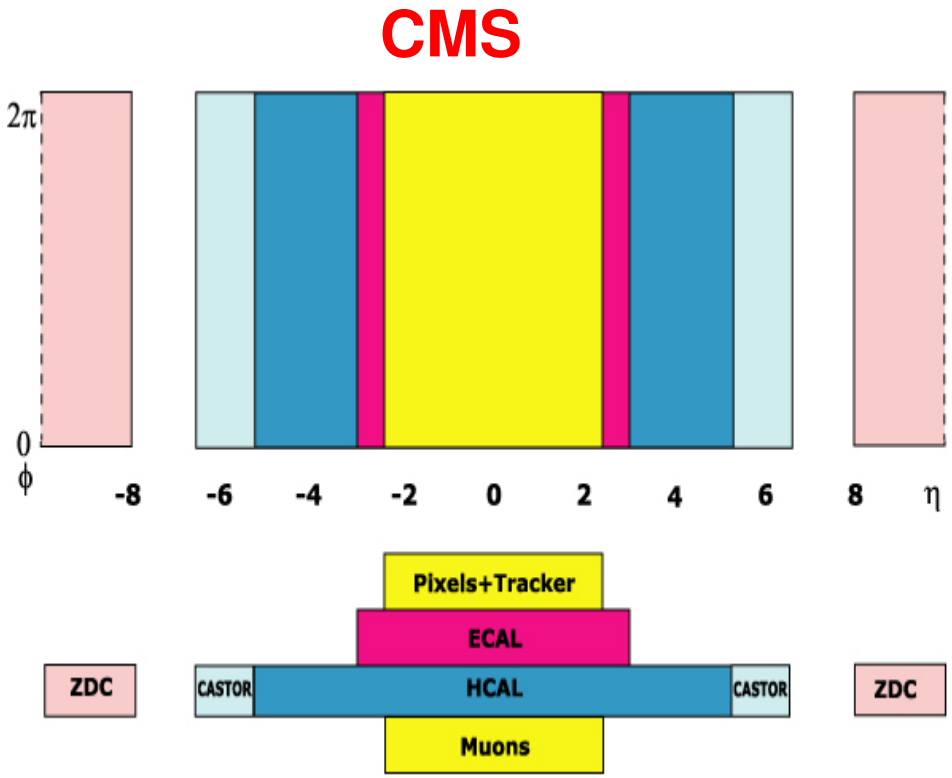


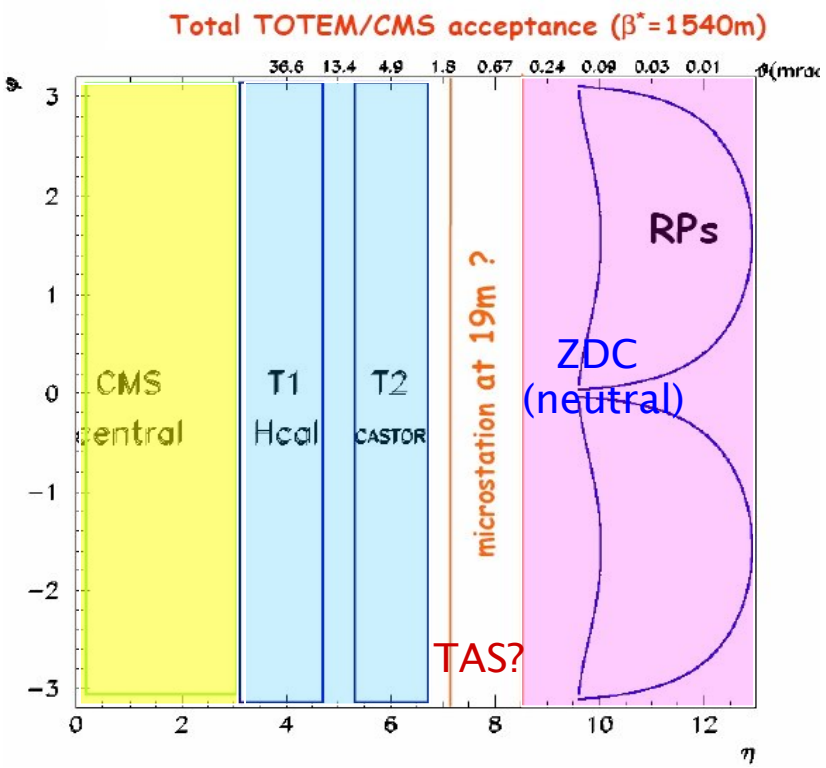
Giudice, Rattazzi, Wells, NPB 630 (2002)293

CMS+TOTEM forward detectors

- CMS (central, CASTOR, ZDC)+TOTEM:

  largest acceptance ever at a collider





EW & Higgs forward measurements

1. EW: Two-photon interactions:
   - Absolute luminosity via: pp → γγ → p $\ell^+\ell^-$ p
   - Triple/Quartic gauge boson couplings via: pp → γp → pnW, γγ →WW,ZZ
   - SUSY pair production: γγ → kk,

3. EW: γ–proton interactions:
   - AbsA

5. Higgs
   - Vector-Boson-Fusion SM Higgs tagging
   - Central exclusive (SM, MSSM) Higgs