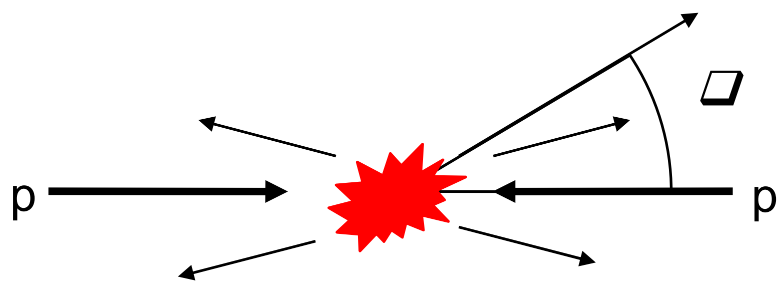
Forward Physics at CMS

Samim Erhan

UCLA/CERN

For the CMS Forward Physics Analysis Group

Overview

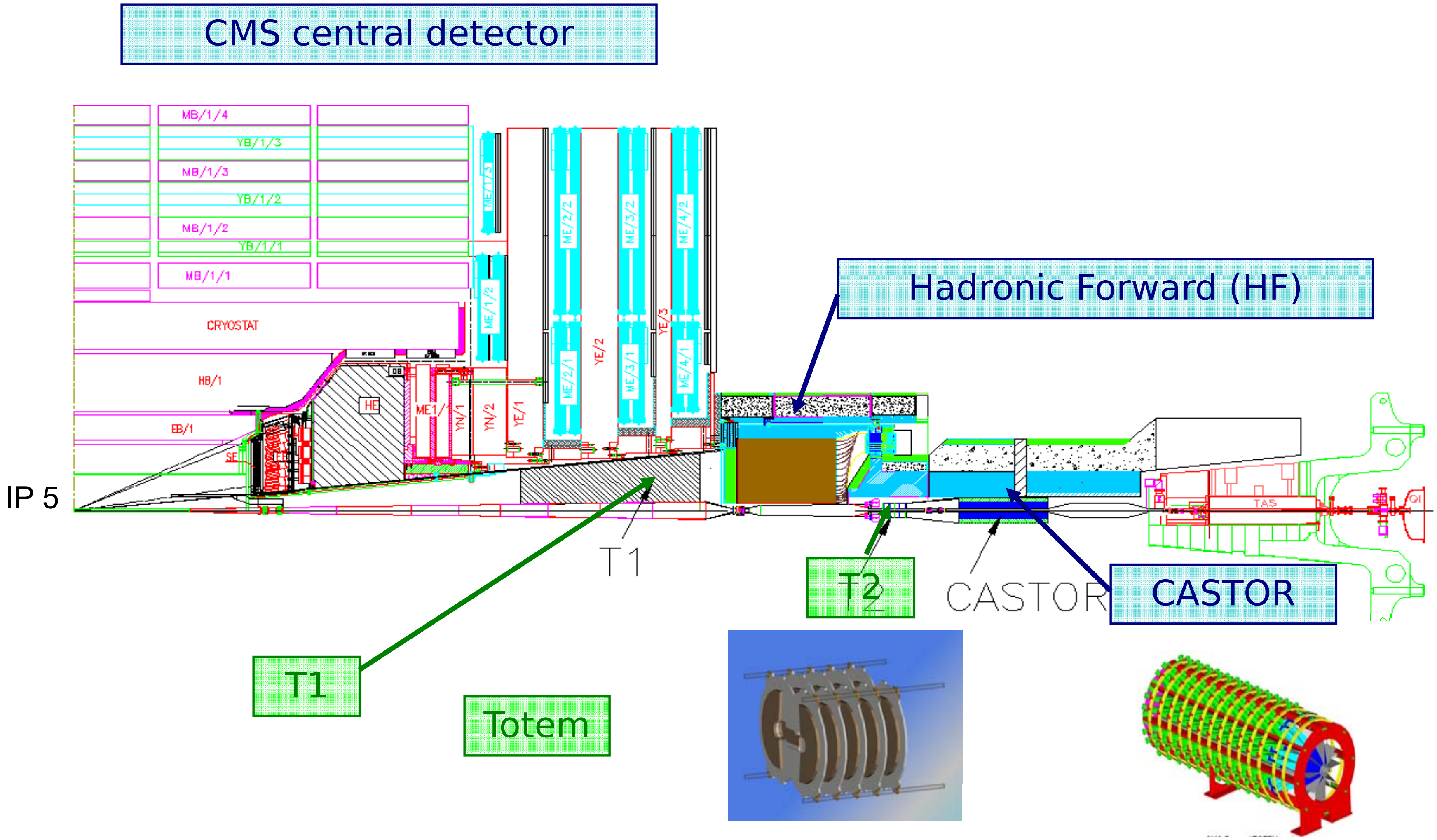


Experimental Definition:

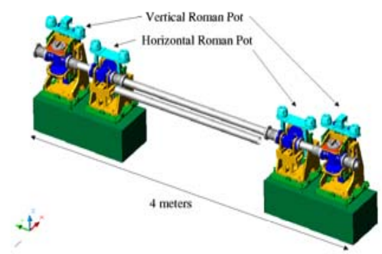
All processes in which particles are produced at small polar angles (i.e. large rapidities

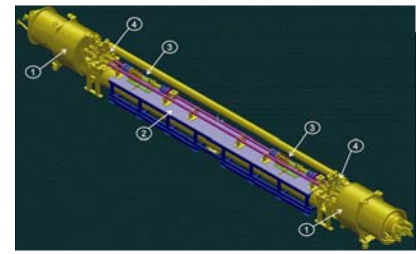
- Explore hard diffraction in the new kinematic regime of 14 TeV
  - Rapidity Gap Physics
- Study if energy and particle flow
- Measure rapidity gap survival probability on single diffraction and DPE topology events
- Study of jet - gap -jet events
- Study of forward jets and forward Drell-Yan
- Study of gamma-gamma and gamma-proton ineractions.

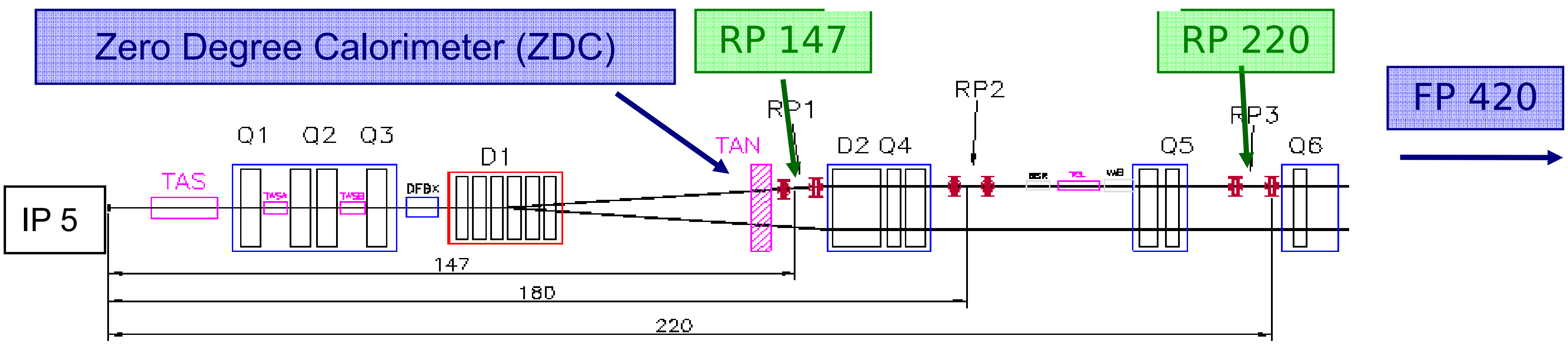
Forward Detectors of CMS



Forward Detectors II







CMS

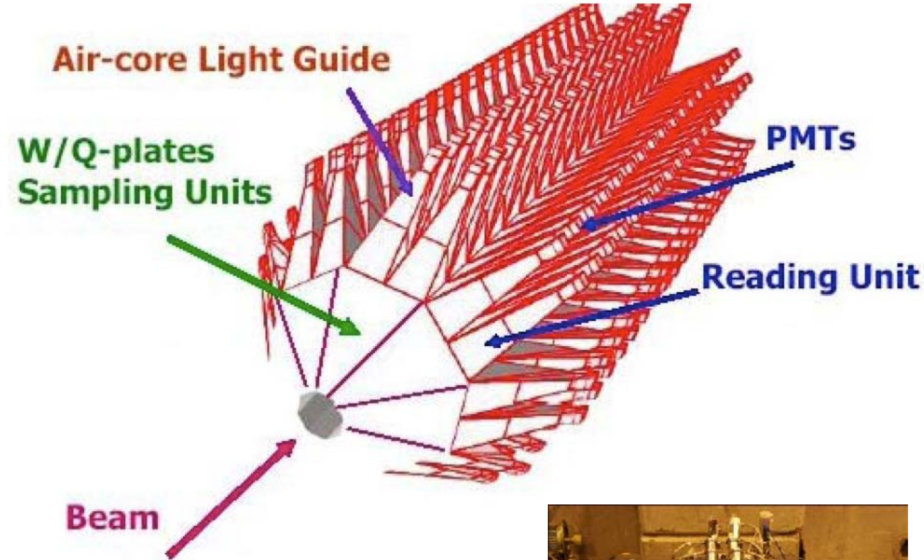
TOTEM

CASTOR

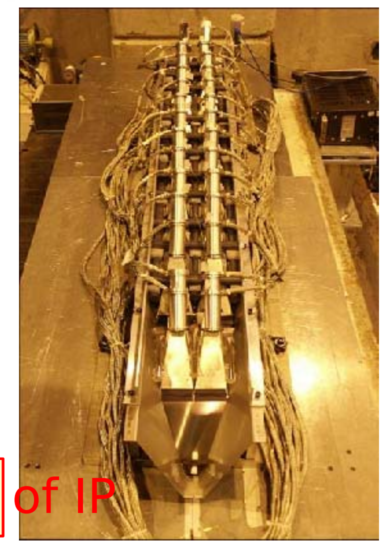
- electromagnetic and hadronic sections
- extends the coverage to $5.2 < \eta < 6.6$

→ enhances the hermiticity of CMS!

- 16 seg. in φ, 14 seg in z
  no segmentation in η

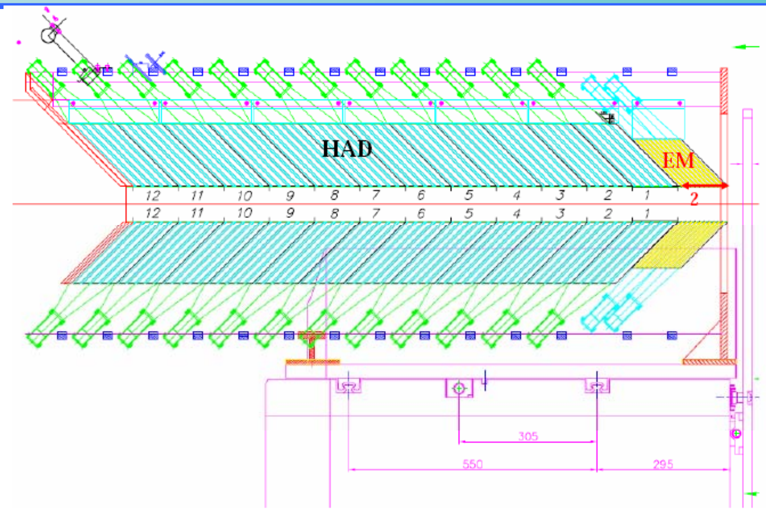


- 14.37 m from the interaction point
- octogonal cylinder with inner radius 3.7cm, outer radius 14cm and total depth 10.5 λ_I
- W absorber & quartz plates sandwich, with 45° inclination with respect to the beam axis
- signal collection through Čerenkov photons transmitted to PMTs through aircore lightguides



Currently funding available only for CASTOR on one side of IP

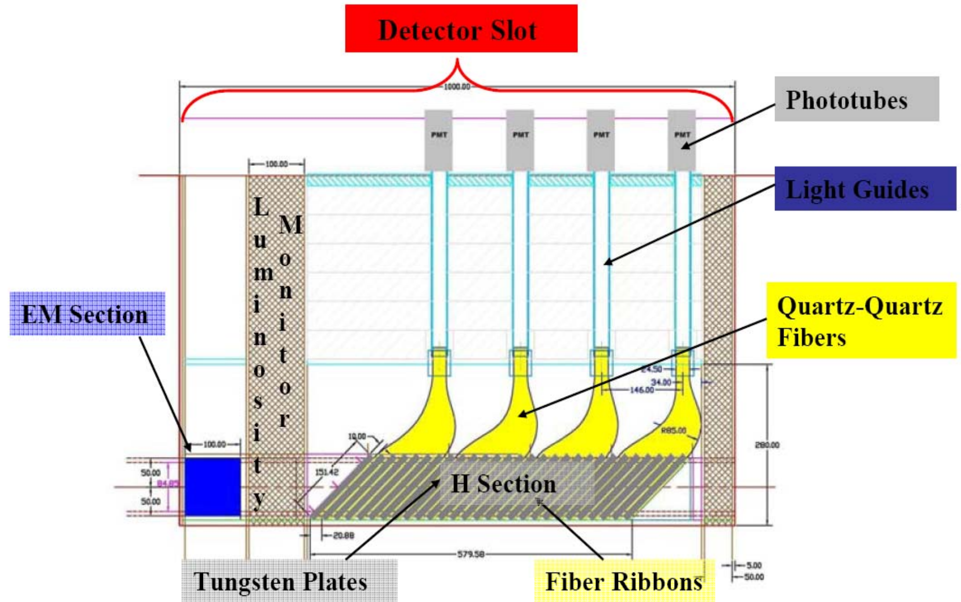
CASTOR specifications

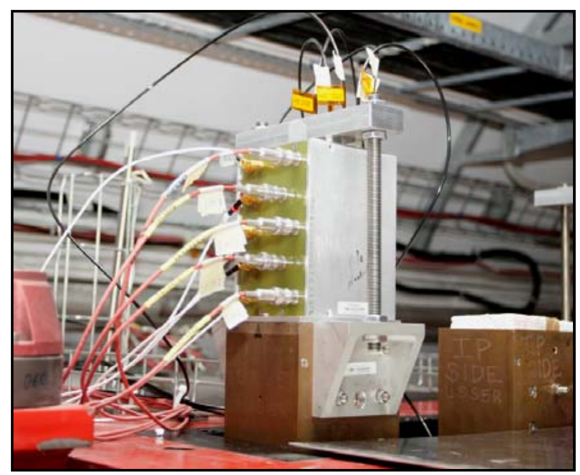


	Electromagnetic section	Hadronic section
Absorber:	5 mm thick tungsten plates	10 mm thick tungsten plates
Active material	2 mm thick fused silica plates	4 mm fused silica plates
Reading unit	5 tungsten-quartz sandwiches	5 tungsten-quartz sandwiches
Total radiation, interaction lenght	2 readout units 20.12 X_0	2+12 readout units 10.3 λ_I

Zero Degree Callorimeter (ZDC)

- 140 m from interaction point in TAN absorber
- Thungsten/quartz Čerenkov calorimeter with separate e.m. (19 X_0) and had.(5.6 λ_I) sections
- em: 5-fold horizontal seg. in z
- had: 4-fold seg. in *z*
- Acceptance for neutrals (γ, π^0, n) from $\eta > 8.1$
  (100% for $\eta > 8.4$)

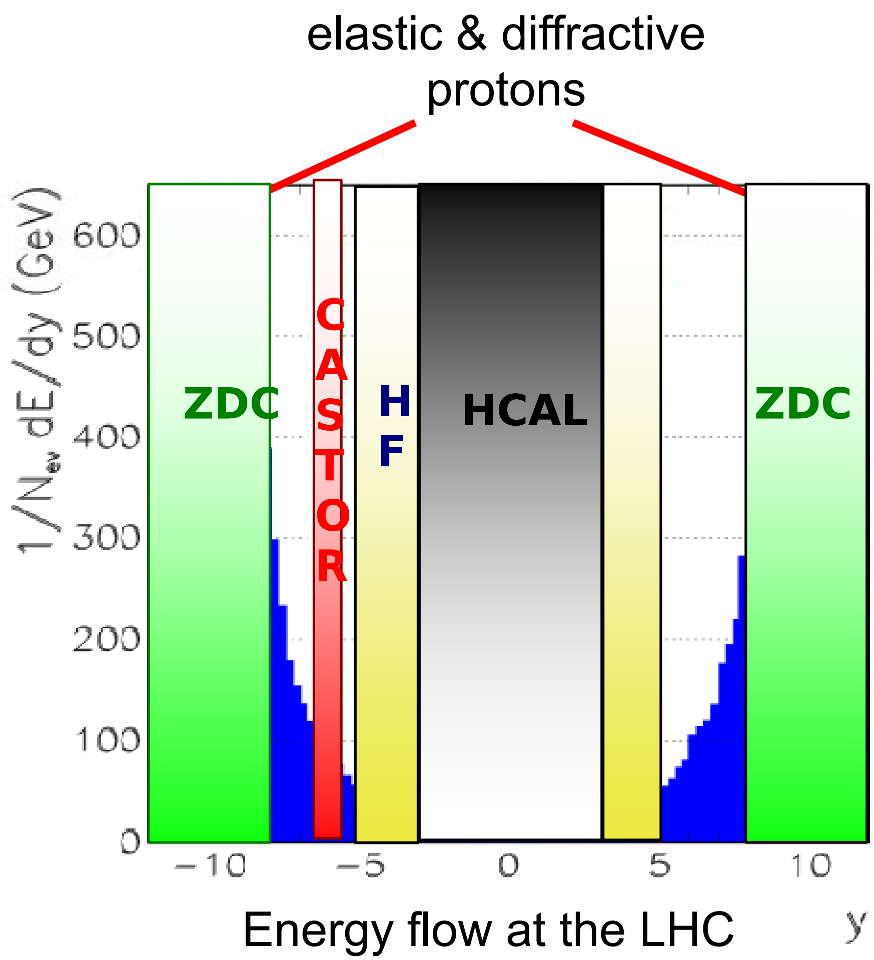




Rapidity Coverage at CMS

HCAL+HF+CASTOR+ZDC

largest calorimetric η coverage ever!



Maximum Rapidity y at LHC:

$$y_{max} = \ln \frac{\sqrt{s}}{m} \approx 11.5$$

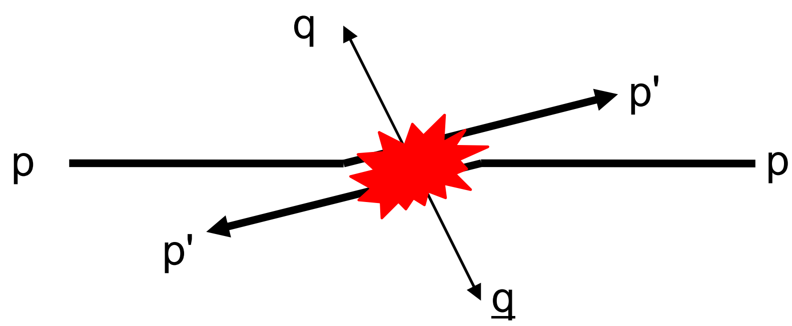
- most energy is deposited between:

  $8 < |y| < 9$

- main CMS calorimeters:

  $|\eta| < 5$

GAP Physics



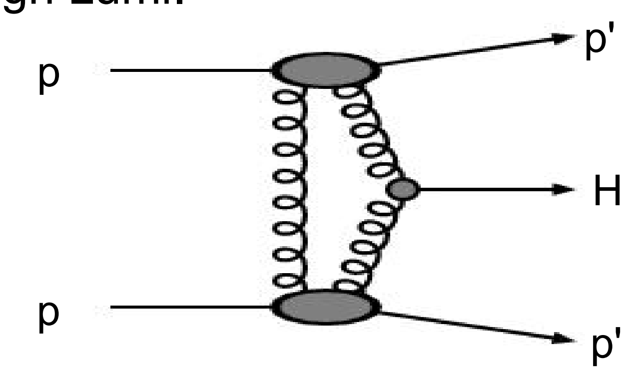
- One or both protons survive intact hard interaction that yields jets, heavy quarks,…
  - Intact proton(s) emerge with most of the beam momentum.
  - Gap between intact proton(s) and the rest of the system
- diffraction (including soft diffraction) makes up 25% of σ_{tot}!

❼ tool to study (pertubative) QCD and the structure of hadrons

❼ measure diffractive jet, W, Z, heavy quark production and rapidity gap survival

Requires single intraction bunch crossings, i.e. no pileup.

Special case: CEP is highly constrained, possible even high Lumi.



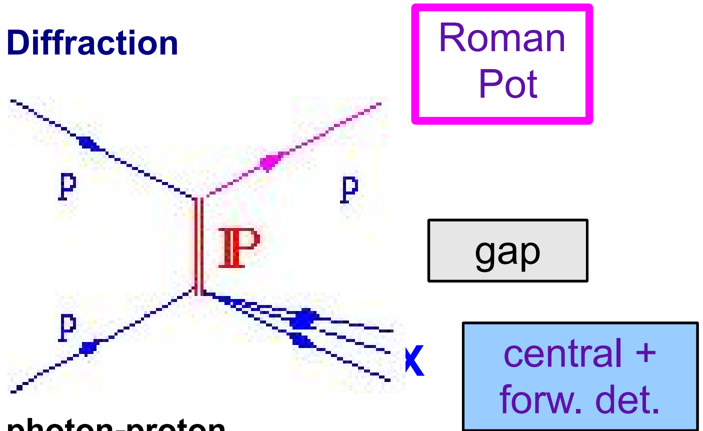
Diffractive Higgs production

pp -> p H p

❼ particularly clean channel for the study (or discovery) of the Higgs boson

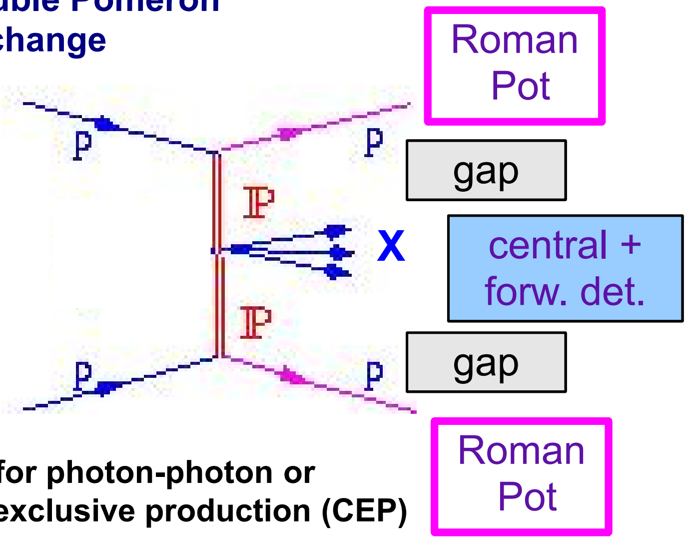
Experimental Signatures

Single Diffraction



Similar for photon-proton

Double Pomeron Exchange



Similar for photon-photon or central exclusive production (CEP)

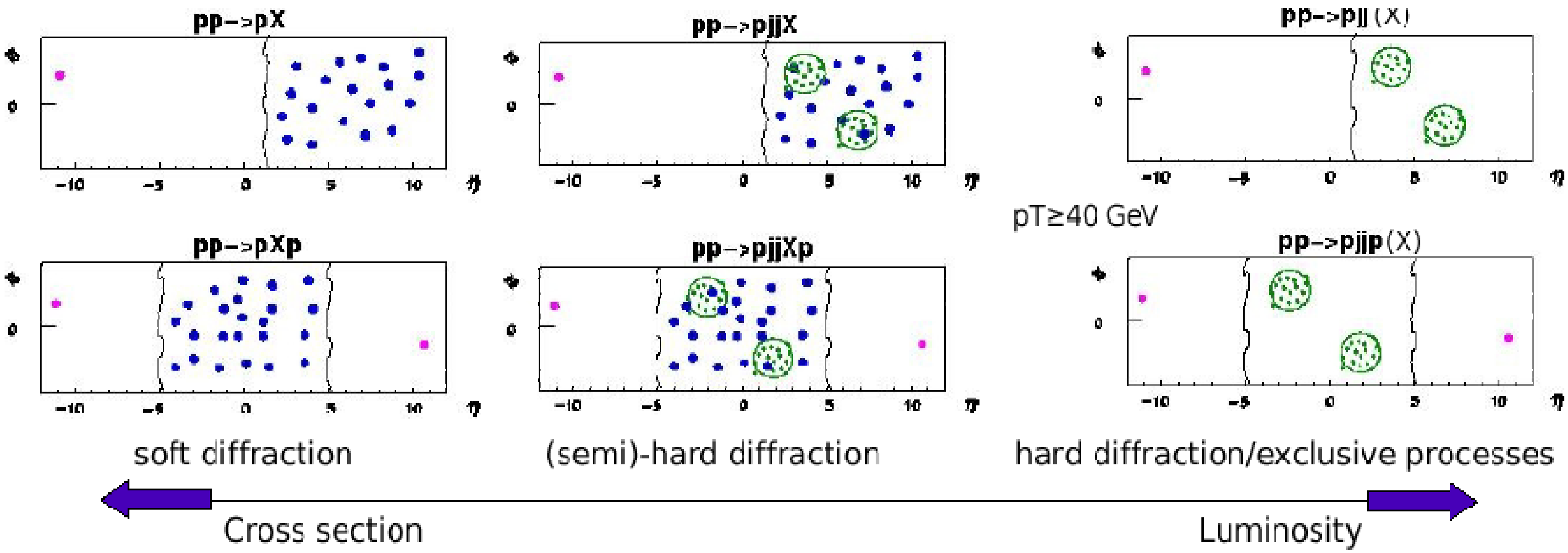
Experimental observables:

- *large rapidity gaps*
- *tag in TOTEM RP and/or FP420:* $\xi_1 \xi_2 s = M^2$
- *reconstruction with central & forward detectors:* $\xi_{1,2} = \frac{1}{\sqrt{s}} \sum_{\text{particles}} E_T e^{\pm\eta}$

Topics of soft and hard diffraction:

- *Dependencies on ξ, t and Mx as fundamental quantities of non-pert. QCD*
- *Gap survival dynamics, multi-gap events*
- *Hard diffraction: production of jets, W; J/ψ ; b; t hard photons, diffr.PDF's*
- *Double Pomeron exchange events as a gluon factory*
- *Central exclusive Higgs production*
- *SUSY & other (low mass) exotics & exclusive processes*
- *Proton light cone studies (e.g. pp → 3jets + p)*

Running Scenarios



Much better with proton tagger(s)

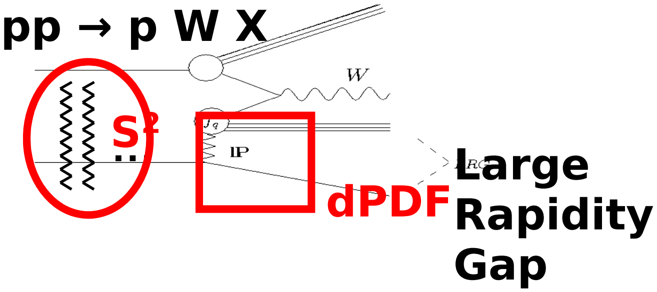
Possible with gap selection

Requires proton tagger(s)

Single diffractive W production

Details in: Antonio Vilela Pereira's talk

pp → p W X



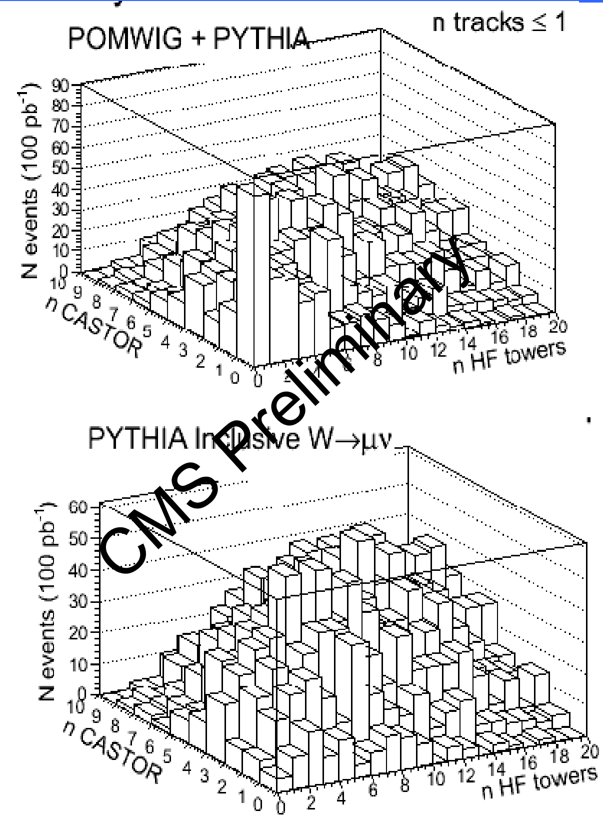
Motivation:

•pp → p W X, W μυ sensitive to quark component of dPDFs

•Probe Rapidity Gap Survival Probability (S^2) – connection to multiple partonic interactions and soft rescattering effects

Selection:

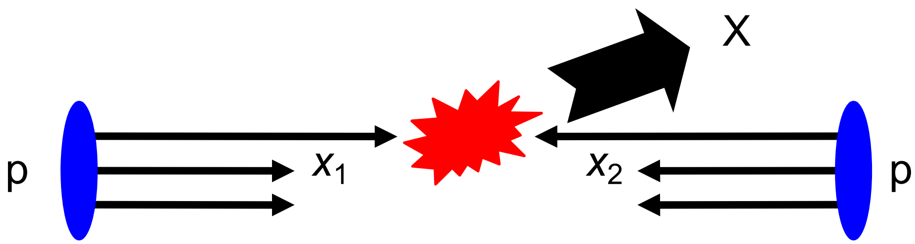
- Rap gap based selection - Require absence of activity in the forward calorimeters (HF 3< |η| < 5, Castor 5.2 < |η| < 6.6) of CMS
  - use single intraction bunch crossings. I.e. no pile-up
- Standard W trigger and reconstruction



- For rap gap survival factor of S^2 = 5%

  O(100) evts/100pb^{-1} in the [n(Castor), n (HF)] = [0,0] bin
- Much better rejection of non-diffractive background with CASTOR veto (**S/B ≈ 20**)
- Signal enhancement by ~30% due to diffractive dissociatio

Forward hard scattering

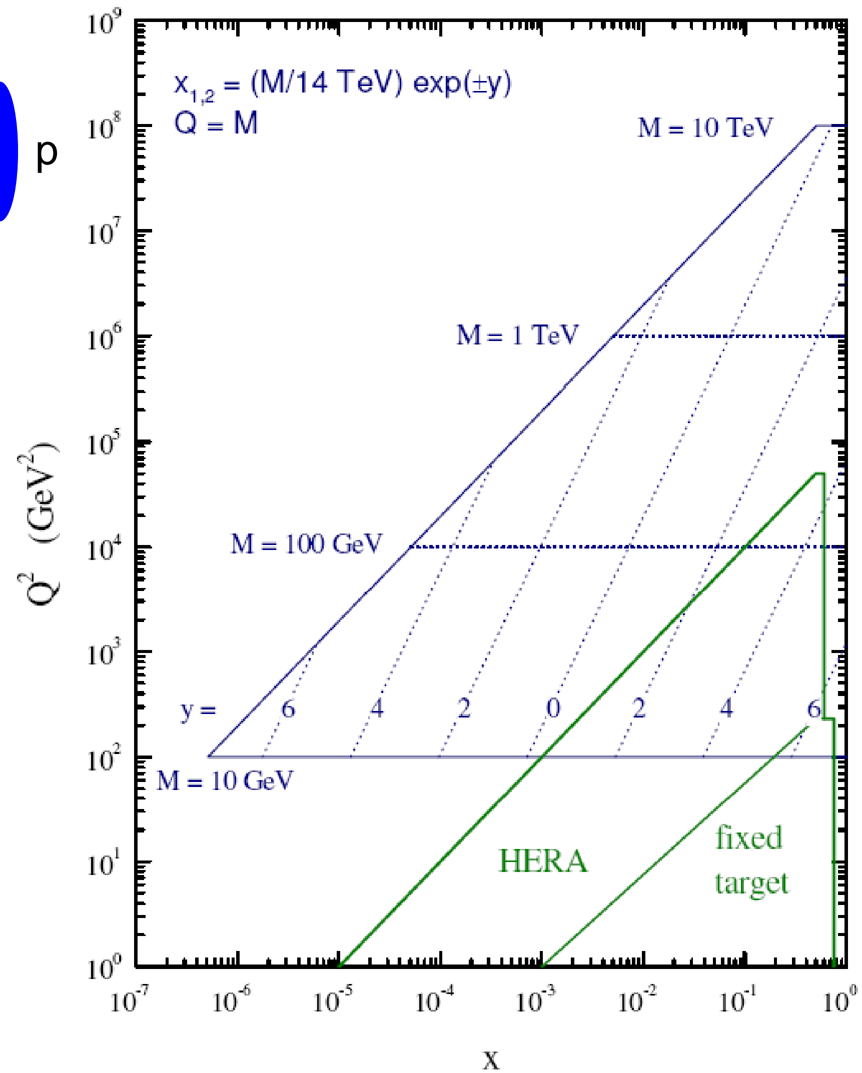


- X can be jets, Drell-Yan pairs, prompt photons, heavy quark pairs, ...
- X goes forward if $x_2 \ll x_1$ → access to low-x_{Bjorken} proton structure:

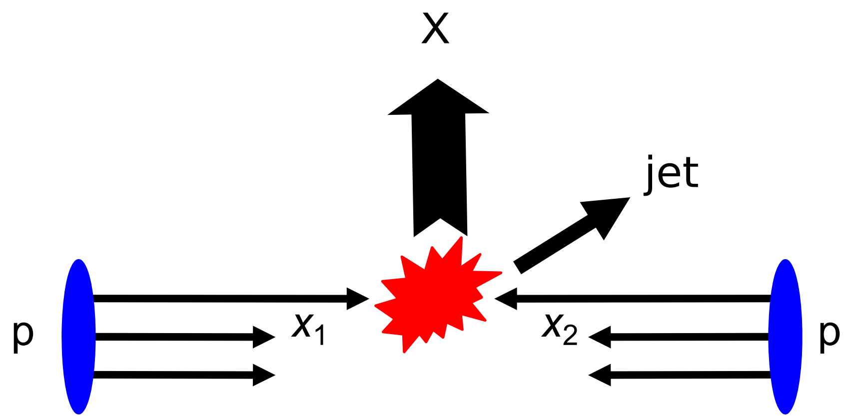
$$x_{Bj} = \frac{Q}{\sqrt{s}} e^{-\eta}, \qquad Q = p_T, M, \ldots$$

❼ at LHC (for $Q \gtrsim 10$ GeV and $\eta = 6$): $x_{\mathrm{Bjorken}} \gtrsim 10^{-6}$

❼ x_{Bjorken} decreases approx. by factor 10 for each 2 units in rapidity



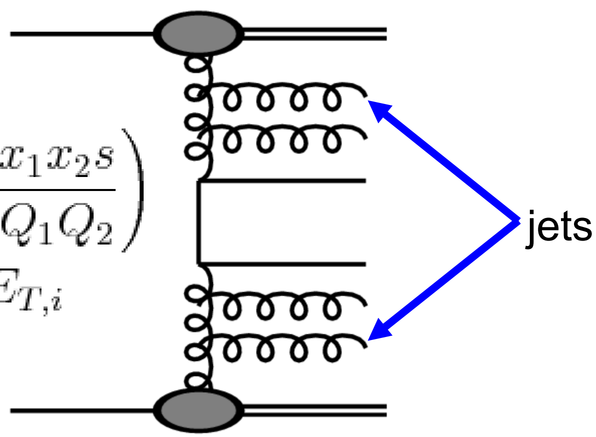
Forward Jets from QCD evolution



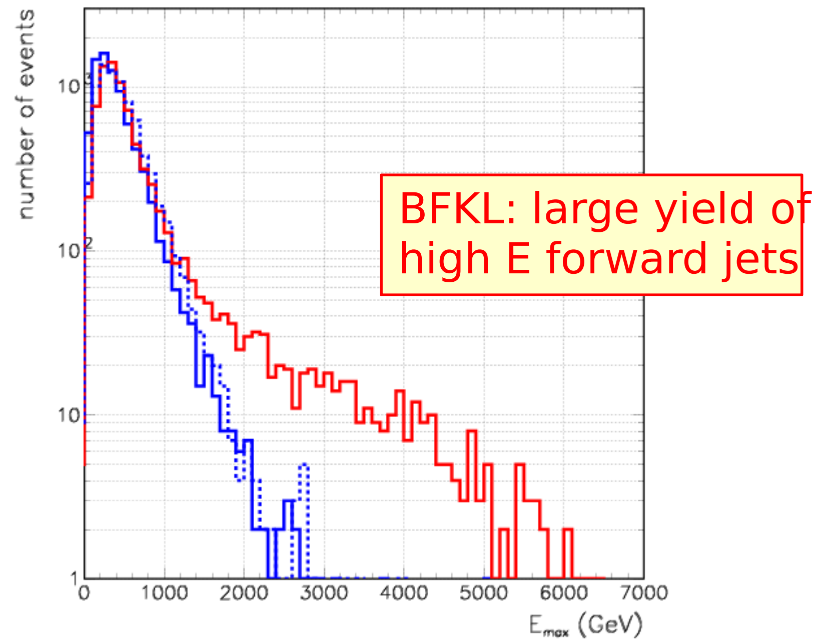
$x_2 \simeq x_1 \rightarrow$ X can be (di-)jets in CMS detector

$$\Delta y = \log\left(\frac{x_1 x_2 s}{Q_1 Q_2}\right)$$

$$Q_i \approx E_{T,i}$$



PYTHIA jets central dijet with p_T > 60 GeV, $|\eta|$ < 3



"Jet energy" in CASTOR

Also possible:
jet-gap-jet events or
Mueller-Navelet jets

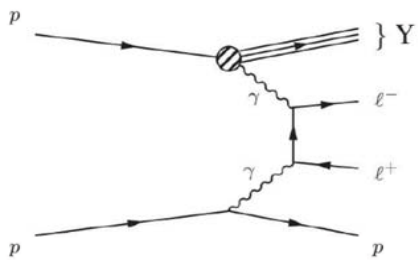
Exclusive di-lepton production

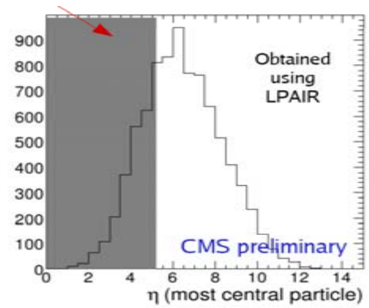
Nearly pure QED process

- Absolute luminosity measurement with precision of **4%** is feasible
- Calibration/alignment of proton taggers

Selection

- exclusivity condition in central detector + veto on CASTOR & ZDC activity
- p dissociative background can be reduced with CMS fwd calorimeters

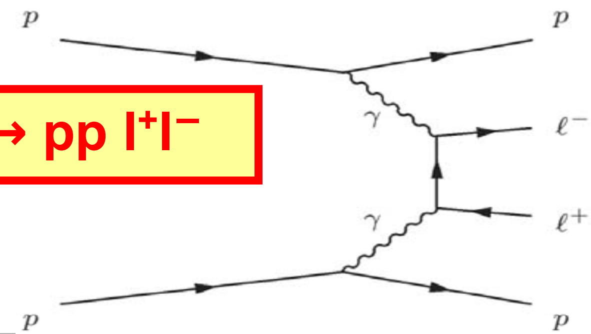


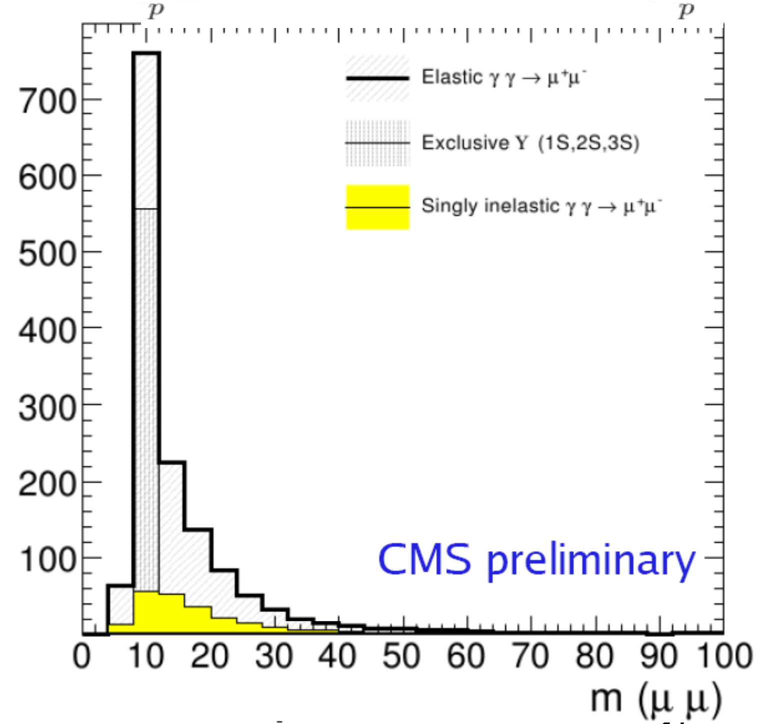


~700 μμ events in 100 pb^{-1} single interaction bunch crossings.
Dominant background from p dissociative events (~200)

Details in: Jonathan Hollar's talk

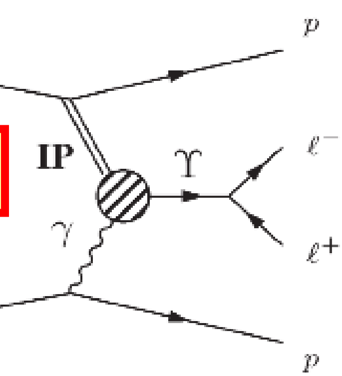
pp → pp l^+l^-

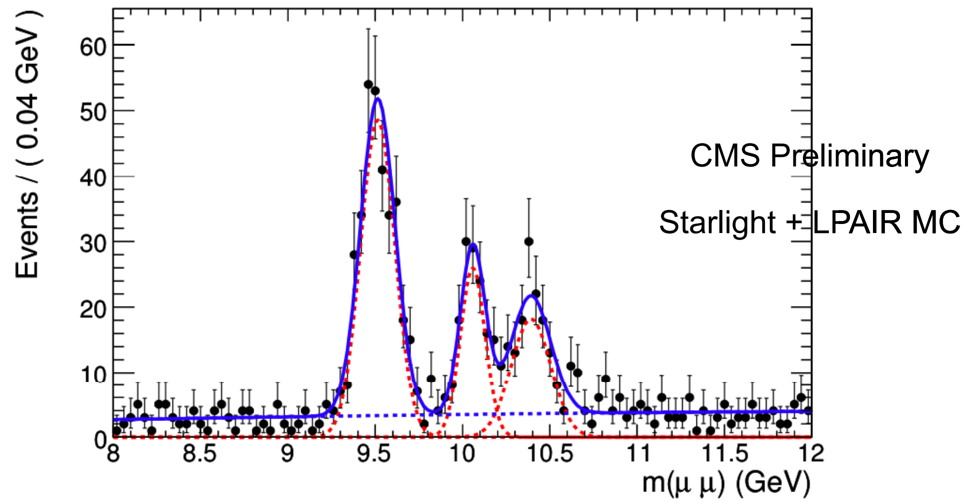




$\gamma p \rightarrow \Upsilon p \rightarrow l^+l^- p$

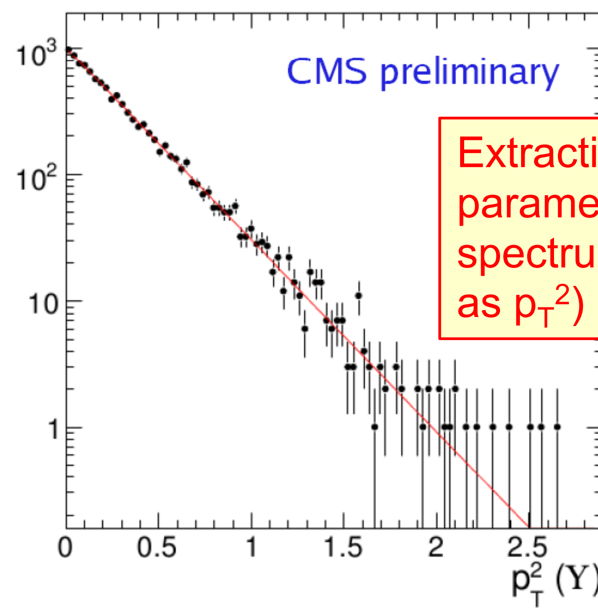
$pp \rightarrow pp\Upsilon,\ \Upsilon \rightarrow \mu\mu$





- Photoproduction process: cross-section sensitive to Generalized P Distributions (GPD's),
  - Measured at HERA, mean CM energy at LHC is ~1 order of magnitude higher
- Identical selection as two-photon sample
  - Fit $m(\mu^+\mu^-)$ spectrum to separate from two-photon production

No sensitivity in e^+e^- due to trigger thresholds/reconstruction efficiency

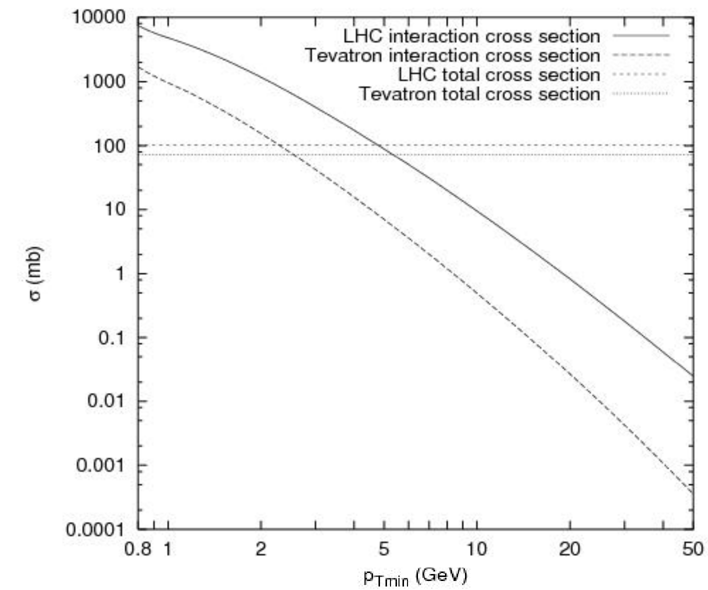


Extraction of slope parameter *b* from *t* spectrum (approx. as p_T^2)

Multiple Interactions

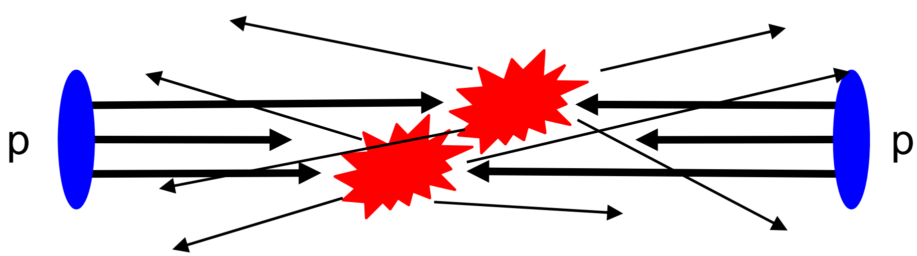
Basic partonic cross section

$$\sigma_{hard}(p^2_{\perp min}) = \int_{p^2_{\perp min}} \frac{d\sigma(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$



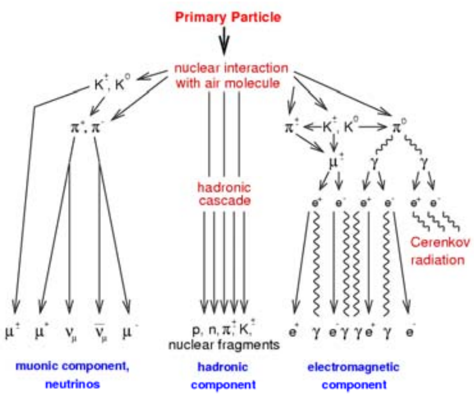
- diverges faster than $1/p^4_{\perp min}$ as $p_{\perp min} \to 0$
- eventually exceeds σ_{tot}(even for $p_{\perp min} > \Lambda_{QCD}$).

Consequence: Multiple parton interactions per event

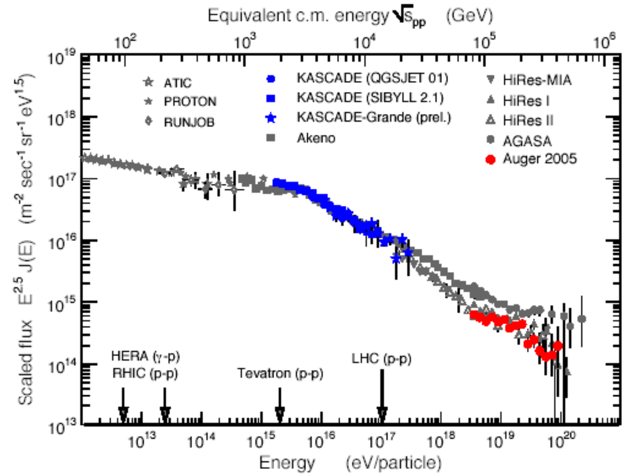


- higher particle multiplicity (additional energy offset in jet profiles)
- long distance correlations in rapidity (need to cover forward region!)
- additional hard interactions may fake a discovery signal !
  (e.g. pp → W H X with H → b$\underline{\text{b}}$ vs. pp → W b$\underline{\text{b}}$ X)

Hadronic Shower Models for Cosmic Ray Data Analyses



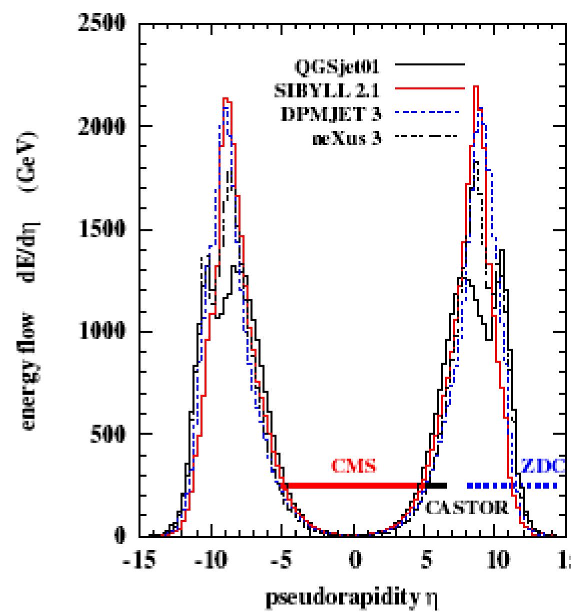
Dynamics of the high energy particle spectrum is crucial for the understanding of cosmic ray data. But models differ significantly !



Statistics for 100 PeV in fixed target frame is too low for reliable analysis
($O(10^{-4})$ particles per m^2 per year).

High momenta are needed
→ only available in the forward region

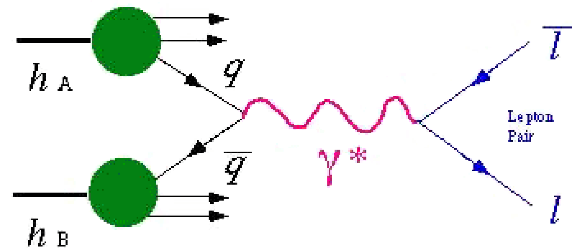
→ measurement of energy (HF, CASTOR, ZDC) and particle flow (T1, T2) in the forward regions will help to tune the models and the generators.



Small – x and Saturation

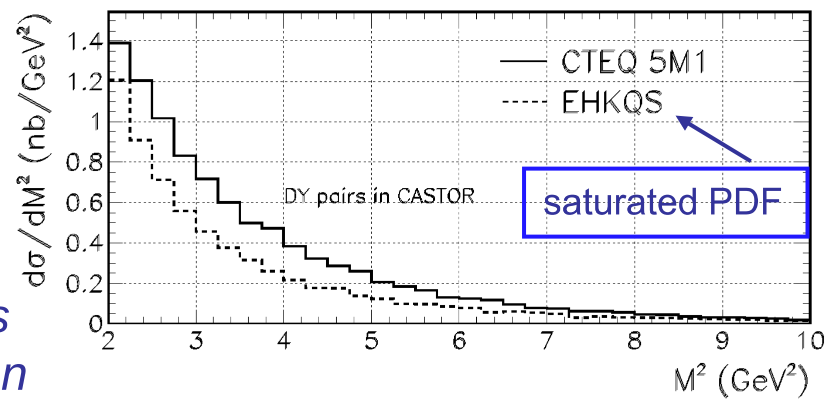
Forward Drell-Yan in CASTOR (5.3<η<6.6):

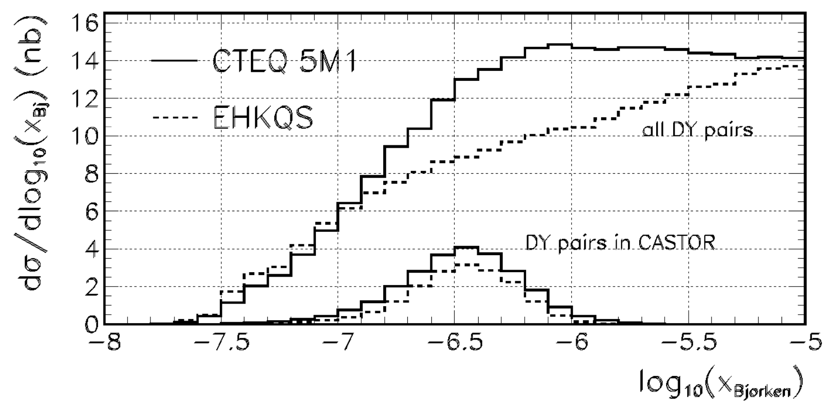
→ probes the pdf down to $x_1 \approx 10^{-7}$ when a large enough mass M is produced



→ Drell-Yan pairs are suppressed by about 30 % when using a a saturated pdf like EHKQS

Angle measurement of the electrons with T2 will give valuable information





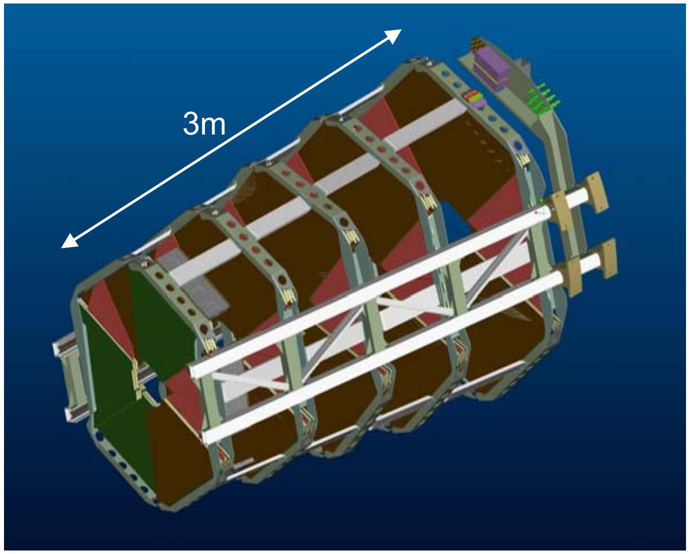
Synergy between CMS & Totem

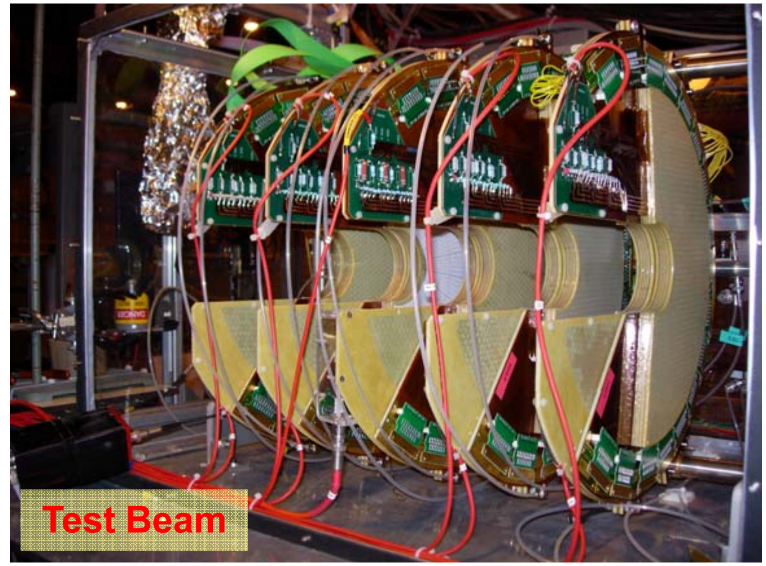
- TOTEM is an approved experiment to measure σ_{tot} and σ_{el} at the LHC, located at the same intersection region of CMS.
  - Expression of wish of CMS + TOTEM to carry out a joint physics program:

    "Prospects of diffraction and forward physics at the LHC"

    CERN LHCC 2006-039 G124, CMS note 2007-02, TOTEM note 06-5
- Possibility to read both detectors through common DAQ
  - Use of proton tags in Event selection and/or offline analysis
  - Provide tracking information (low lumi) in front of HF (T1) and CASTOR (T2)
- Possibility to trigger CMS with Totem proton tag
  - Lower L1 thresholds when combined with proton tags

TOTEM T1 & T2 tracking detectors



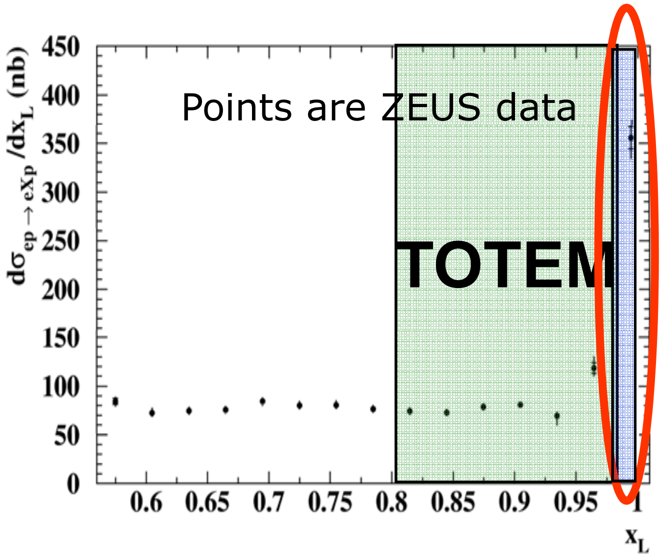


- **Cathode Strip Chambers (CSC)**
- Mounted in front of Hadron Forward calorimeter of CMS
- $3.1 < |\eta| < 4.7$
- 5 planes with 3 coordinates/plane
- 6 trapezoidal CSC detectors/plane
- Resolution $\sigma \sim 0.8\text{mm}$

- **Gas Electron Multiplier (GEM)**
- Mounted in front of CASTOR
- $5.3 < |\eta| < 6.5$
- 10 planes formed by 20 GEM semi-circular modules
- Radial position from strips, η,ϕ from pads
- Resolution σ_{strip}~70μm

FP420 Acceptance

At nominal LHC optics, β^*=0.5m

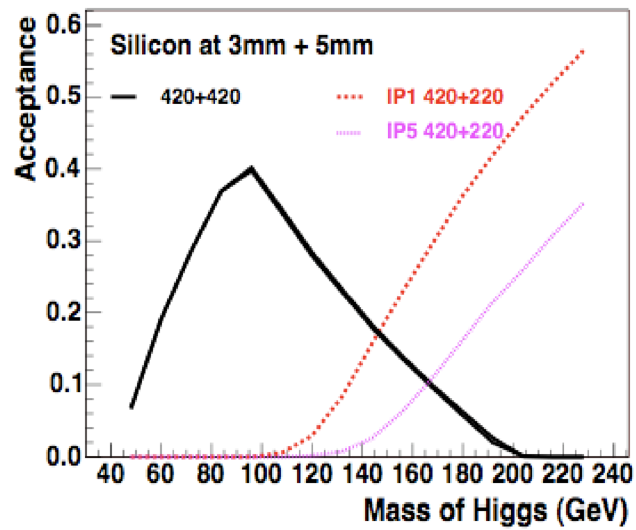


diffractive peak

FP420

$x_L = P'/P_{beam} = 1-\xi$

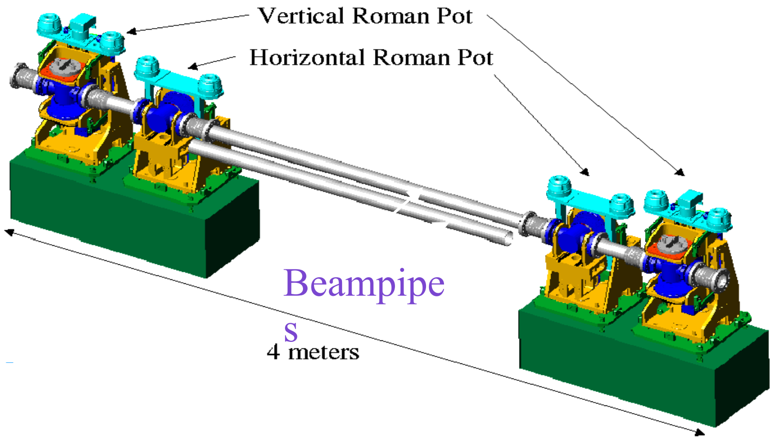
$m^2 = \xi_1 \xi_2 s$

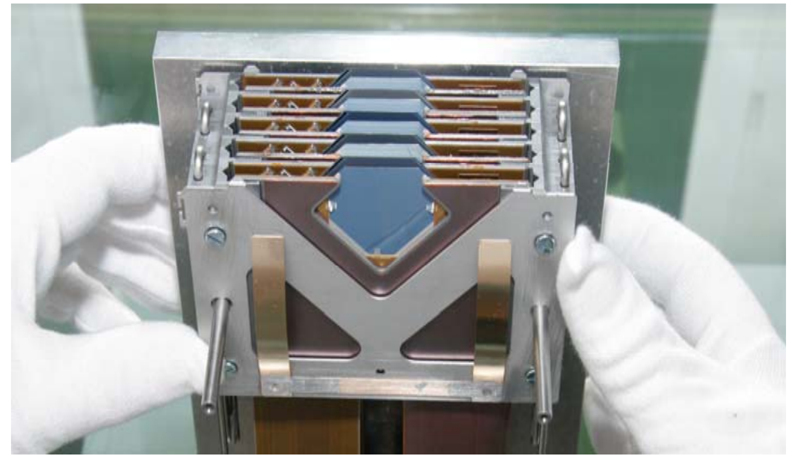


Note: Totem RP's optimized for special optics runs at high β^*
β^* is measure for transverse beam size at vertex
TOTEM coverage in ξ improves with increasing β^*

Good acceptance for Higgs masses 60 - 160 GeV

Proton taggers @ 220m and 420m from IP



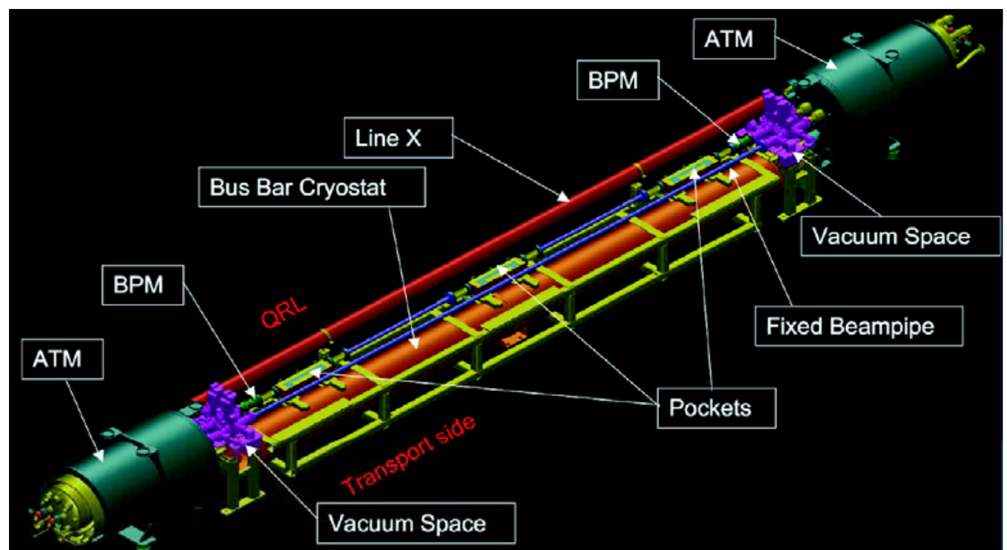


TOTEM uses Roman pot technique to approach the beam with their Si detectors

FP420, because of location in cryogenic region of LHC, uses movable beampipe

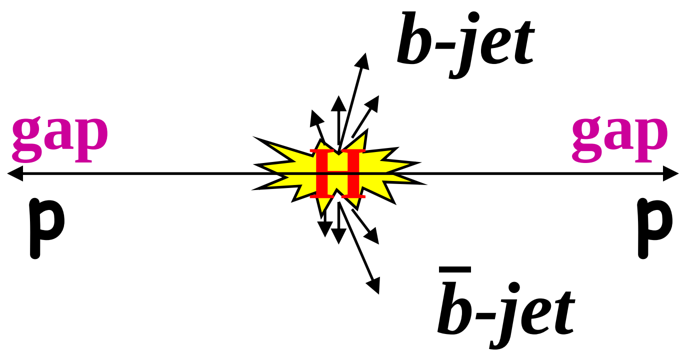
Extremly rad hard novel Si technology: 3-d Silicon

Cherenkov timing detectors with $\sigma_t \sim 10$ ps to filter out events with protons from pile-up



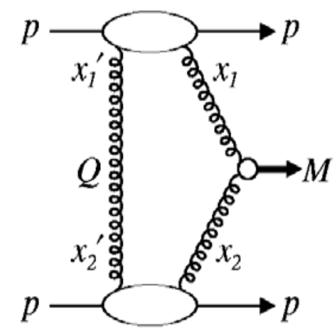
Central Exclusive Higgs Production

pp→ p H p



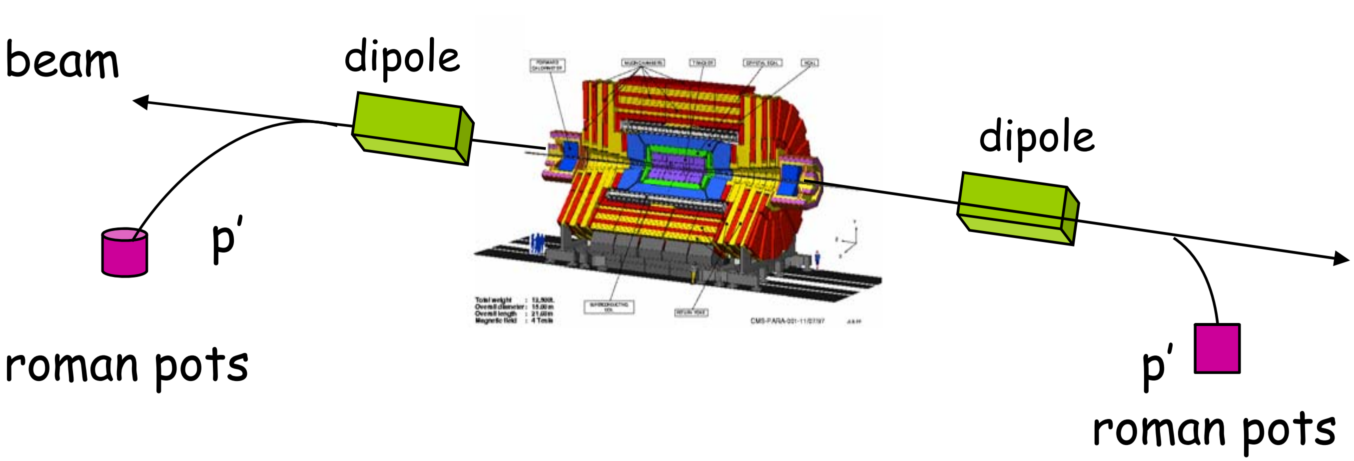
$$M_H^2 = (p+\bar{p}-p'-\bar{p}')^2$$

ΔM = O(1.0 - 2.0) GeV



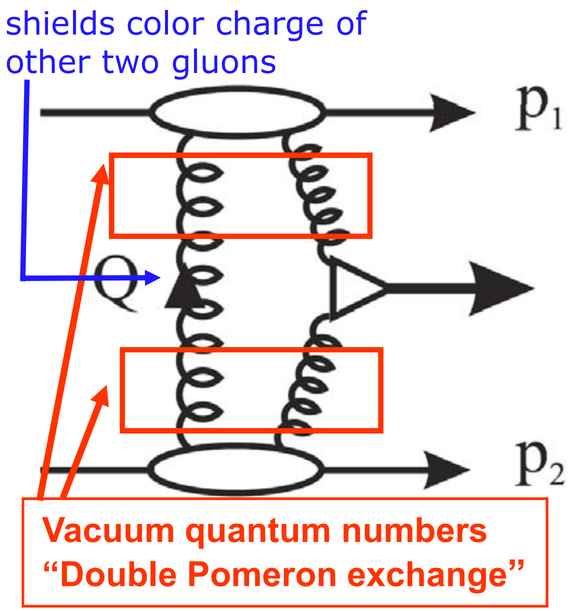
2-10 fb (SM)
~10-100 fb (MSSM)

E.g. V. Khoze et al
ADR et al.
M. Boonekamp et al.
B. Cox et al.
V. Petrov et al…
Brodsky et al.



Added value:
way to get an
information on the
spin of the Higgs

Central exclusive production pp →pXp: Discovery channel for MSSM Higgs



Selection rules: central system is $J^{PC} = 0^{++}$ (to good approx)

Excellent mass resolution (~GeV) from the protons, independent of decay products of the central system

For light (~120 GeV) Higgs:
Proton tagging improves S/B for SM Higgs dramatically
CEP may be the discovery channel in certain regions in MSSM

CP quantum numbers and CP violation in Higgs sector directly measurable from azimuthal asymmetry of the protons

In addition: Rich QCD program

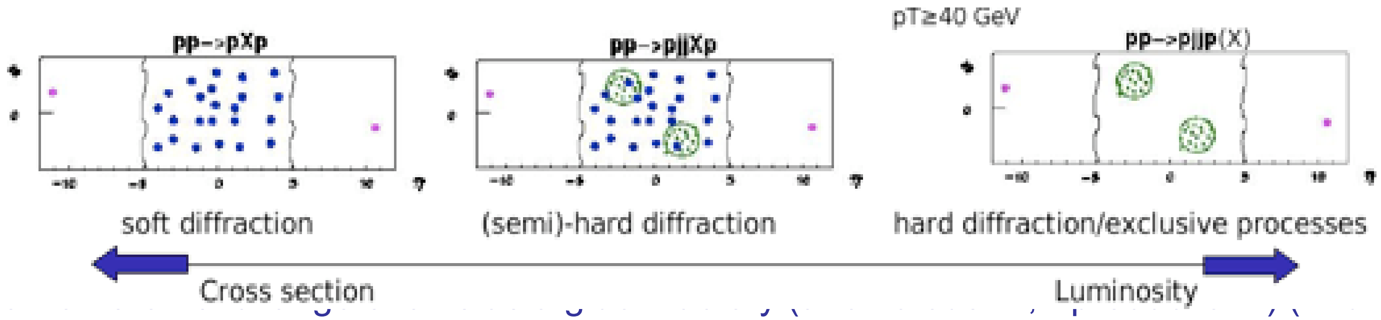
Looking at the proton in QCD through a lens that filters out everything but the vacuum quantum numbers: measure diff PDFs, learn about parton correlations via GPDs, quantify soft multiple scattering effects via diff factorization breaking, ...

In addition: Rich program of gamma-gamma mediated processes

p in $\gamma\gamma$ processes have lower ξ values than diffractively scattered ones, hence FP420 indispensable

Physics Program

- General: the physics program starts when TWO arms are avaialble
- QCD and Diffraction $\Rightarrow$ Accessible from 10^{32} onwards

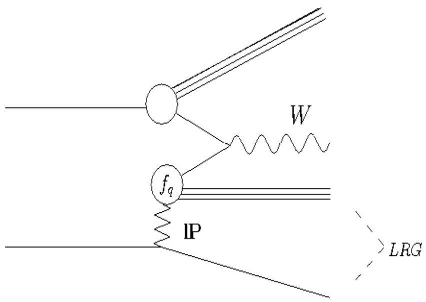


  - Dif
  - Do
- Exclusive production of new mass states $\Rightarrow$ accessible from 10^{33} onwards
  - Exclusive Higgs production in bb, WW and $\tau\tau$ final states (~ 10-30 fb^{-1})
  - Exclusive nMSSM higgs $\rightarrow$ aa (~ 100 fb^{-1})
  - CP properties of the MSSM Higgs (~ 30 fb^{-1})
  - CP violation in the Higgs sector (> 100 fb^{-1})
  - Radion production (~ 30 fb^{-1}), split supersymmetry (> 100 fb^{-1})
- Two-photon photon-proton interactions $\Rightarrow$ accessible from 10^{33} onwards
  - SUSY slepton and chargino (~ 100 fb^{-1})
  - Anomalous couplings (~ 10 fb^{-1})

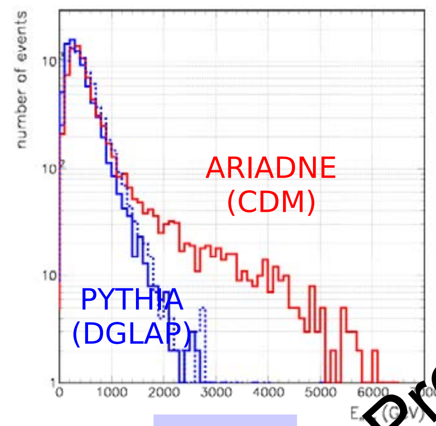
Summary

- *CMS forward detector components provide the possibility for a rich program for forward physics. Negotiations to include FP420 into the CMS experiment in progress.*
- *Comprising different physics topics for special low, standard and highest luminosity optics the forward and diffractive physics program spans the full lifetime of the LHC.*
- *In Diffraction:*
  - *<u>low luminosity:</u> standard measurements exploring traditional observables and processes in the new kinematic regime.*
  - *<u>nominal luminosity:</u> unprecedented statistics for processes presently studied at the TeVatron at lower center of mass energies.*
  - *<u>highest luminosity:</u> enabling the discovery of a Higgs Boson with a mass close to the exclusion limit constituting a special challenge for the central LHC experiments.*
- *Forward detector components make it possible to study underlying event structure and multi-parton interactions, representing a crucial input for all precision measurements. They open the window to a new region in the area of small-x, giving insight to parton evolution and saturation effects.*

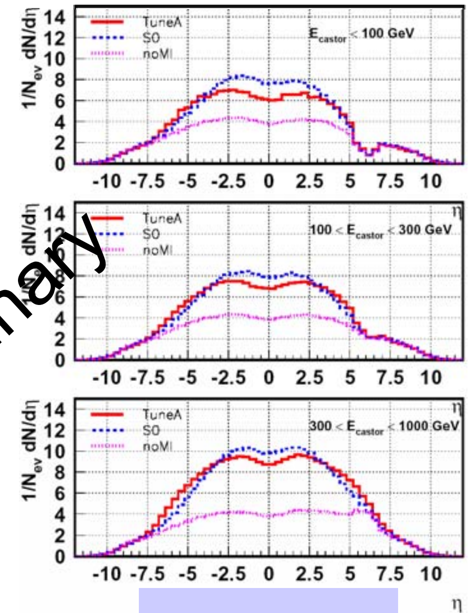
CMS Forward Physics Program



Diffractive W production

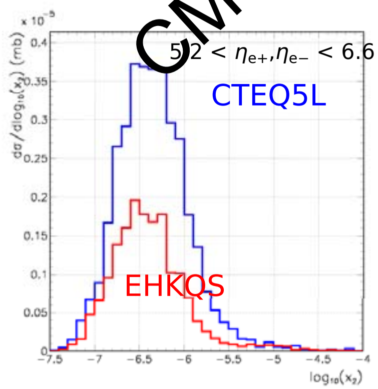


BFKL

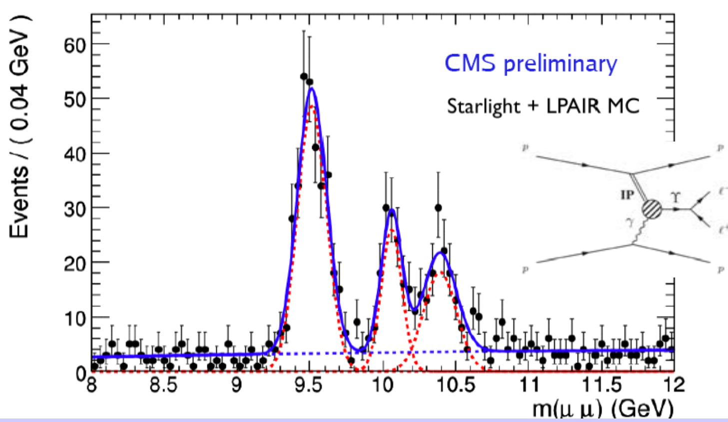


Underliying
Event &
Multiple Int

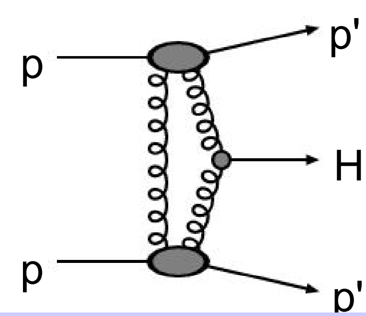
CMS Preliminary



Saturation

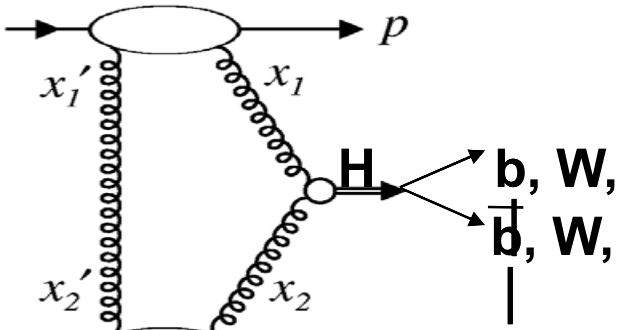


Exclusive dilepton and Upsilon production



Diffractive and VBF Higgs

Discovery potential of CEP of Higgs

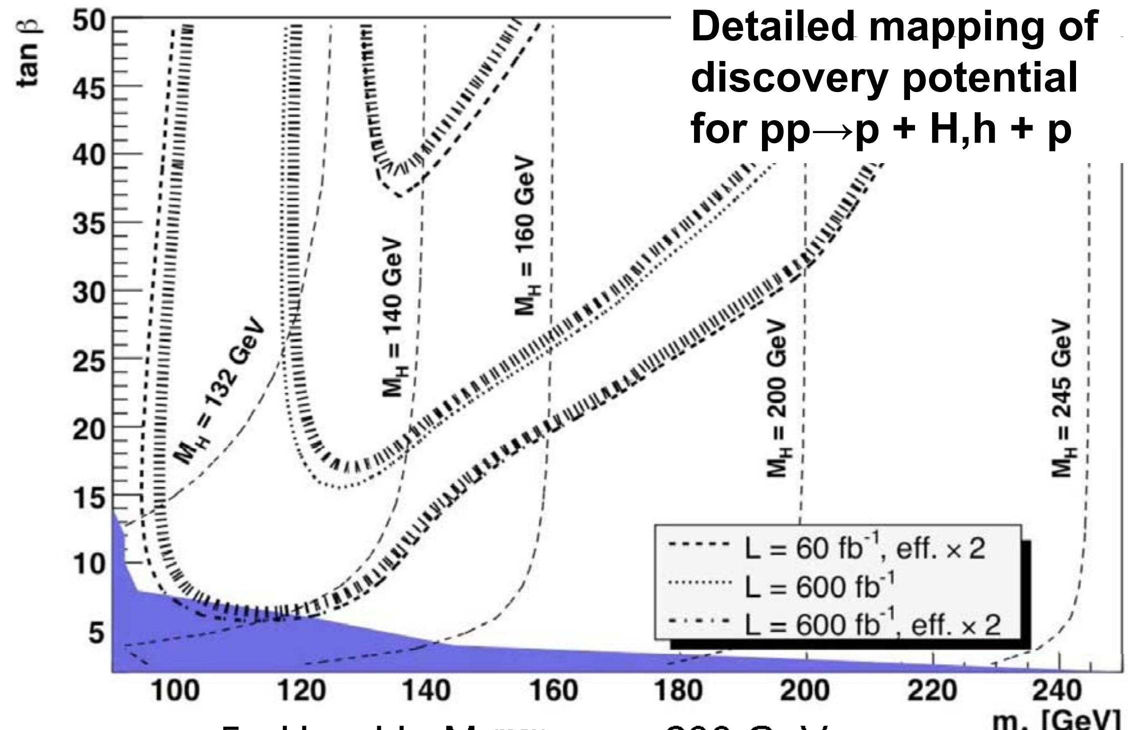


CEP may be the discovery channel for MSSM Higgs:

Heavy Higgs states decouple from gauge bosons, hence preferred search channels at LHC not available

But large enhancement of couplings to bb, ττ at high tanβ

Detailed mapping of discovery potential for pp→p + H,h + p



5σ H → bb, M_h^{max}, μ = +200 GeV

CEP Higgs may also open door to discovery of an **NMSSM Higgs** in channel

$h \rightarrow aa \rightarrow 4\tau$,

which would be unique at the LHC