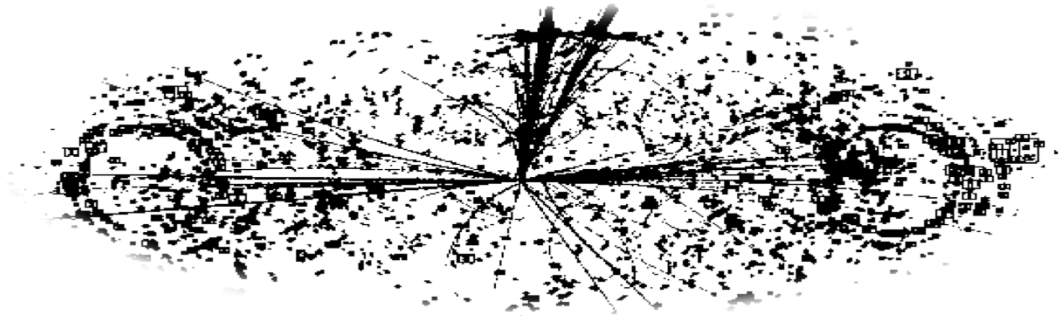


Diffraction
and
Forward Physics

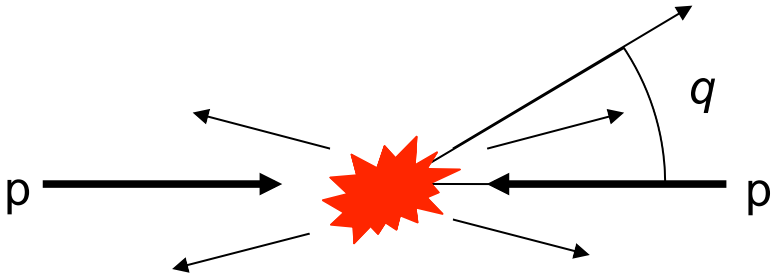
Mohsen Khakzad
School of Particles and Accelerators (IPM)

7-11 Oct. 2013

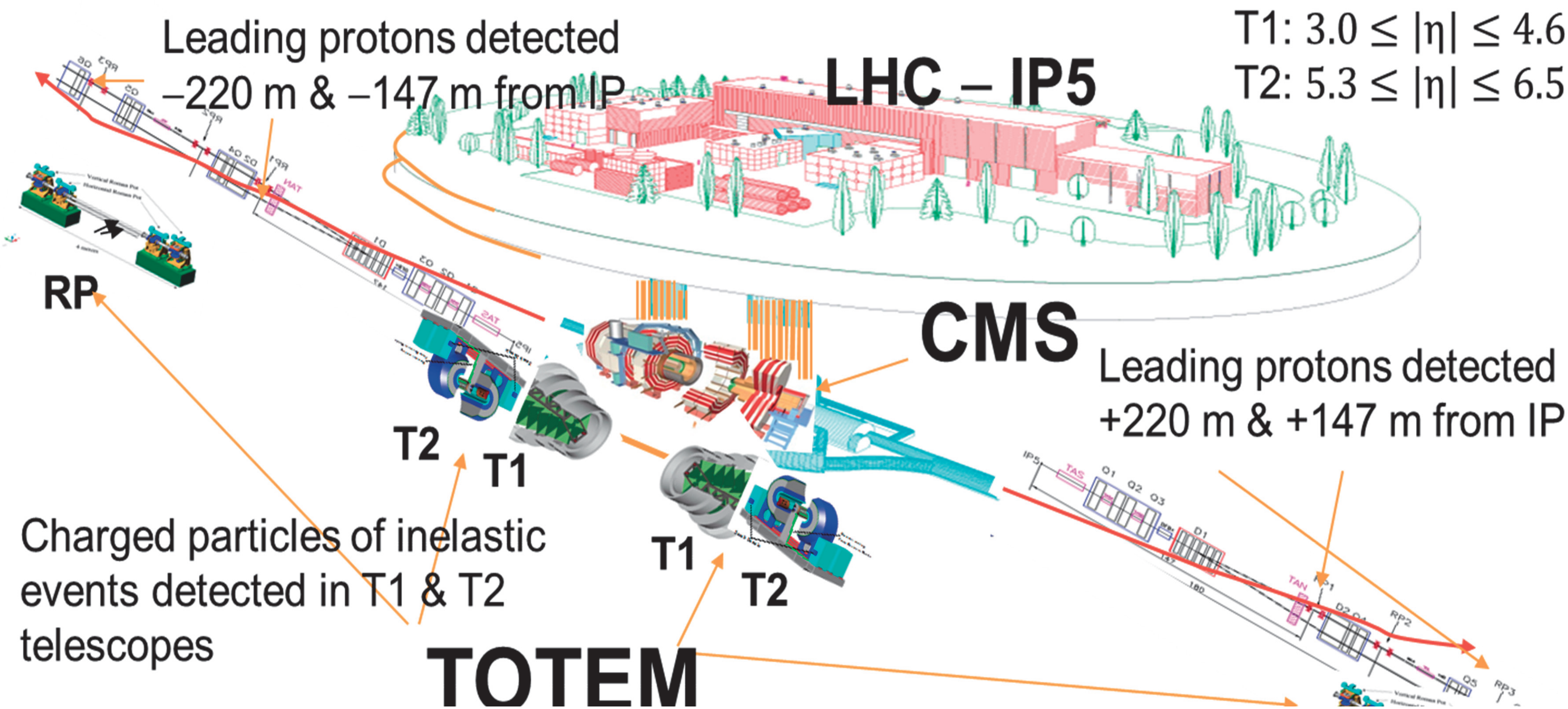
On behalf of the CMS Collaboration

Outline

- Introduction
- Forward Detectors
- Forward Physics
  - Diffraction
  - Exclusive Processes
- Future Projects
- Final Remarks

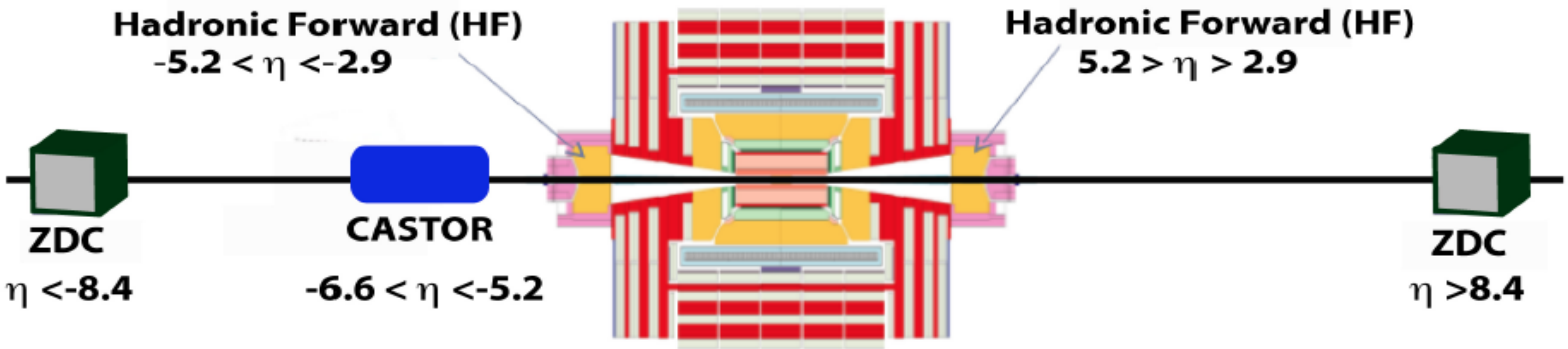


The Compact Muon Solenoid (CMS) Detector



- Leading protons: RP's at ±147m, ±220m and ±420m
- Rap gaps & Fwd particle flows: T1 & T2 spectrometers
- Fwd energy flows: Castor & ZDC
- Veto counters at: ±60m & ±140m?

Forward Detectors



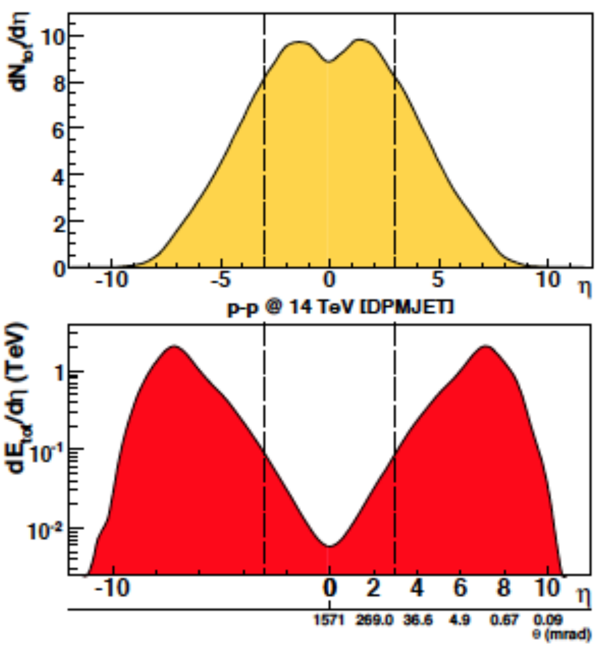
- **HF**
  - rapidity coverage: $2.9 < |\eta| < 5.2$
  - at 11.2 m from IP
  - steel absorbers and embedded radiation -hard quartz fibers for fast collection of Cherenkov light
  - segmentation in η et ϕ: 0.175×0.175
- **CASTOR**
  - rapidity coverage: $-6.6 < \eta < -5.2$
  - at 14.3 m from IP
  - alternate tungsten absorbers and quartz plates
  - segmentation in ϕ: 16 sectors
  - 14 modules (2EM+12HAD)
- **ZDC**
  - rapidity coverage: $|\eta| > 8.4$
  - at 140 m from IP
  - tungsten/quartz Cherenkov calorimeter with separated EM and HAD sections
  - detection of neutrals (γ, π^0, n)

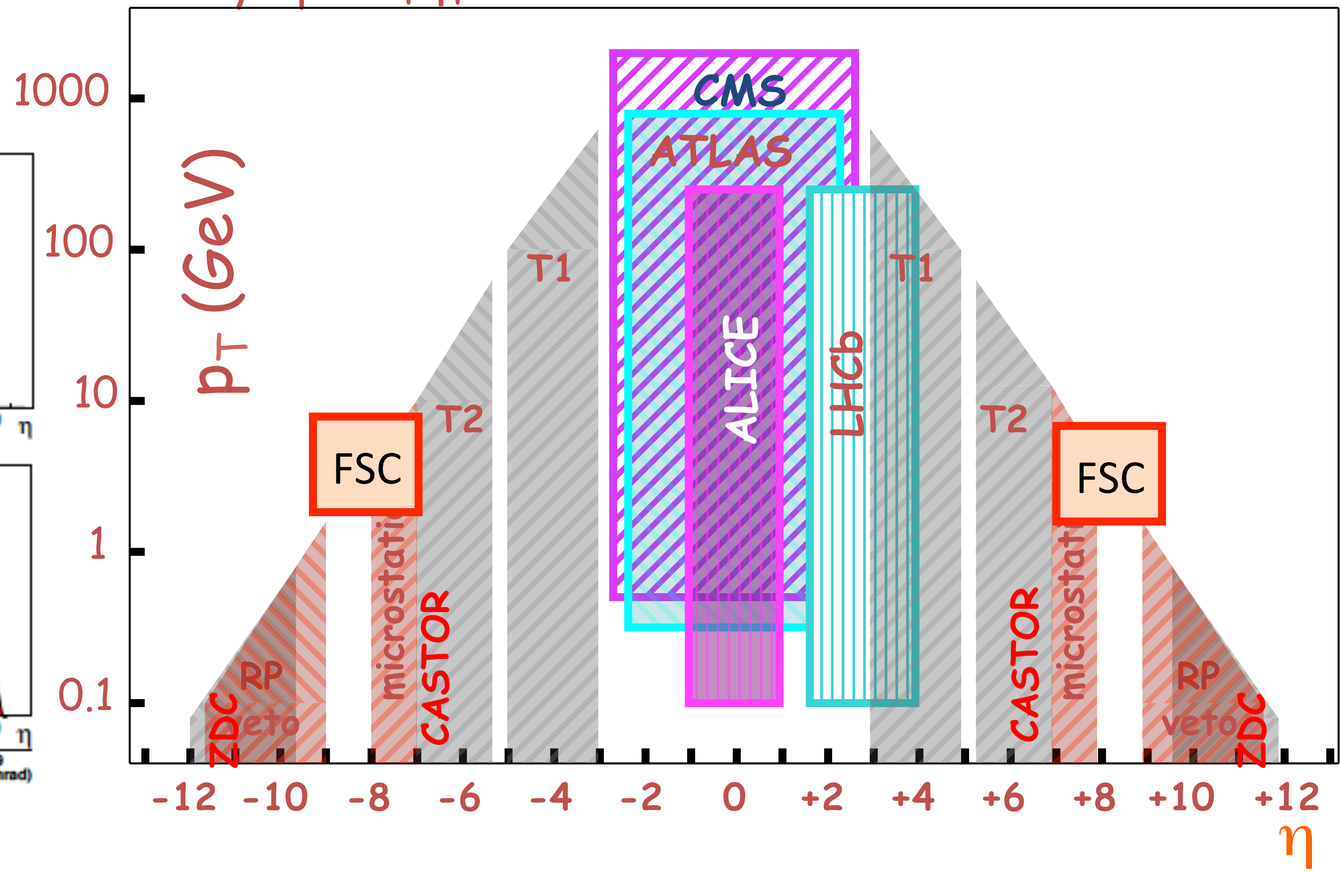
- FSC
  - Covers gap after CASTOR
  - Scintillator at: 59 85, 114 m from IP5

LHC Experimens: p_T - η coverage

CMS fwd calorimetry up to |η| ≈ 5 + Castor + ZDC

$p_T^{max} \sim \sqrt{s}\exp(-\eta)$





The eta distributions for the total hadron multiplicity and energy in p-p At 14 TeV

+ fp420m

Total pp Cross-Section

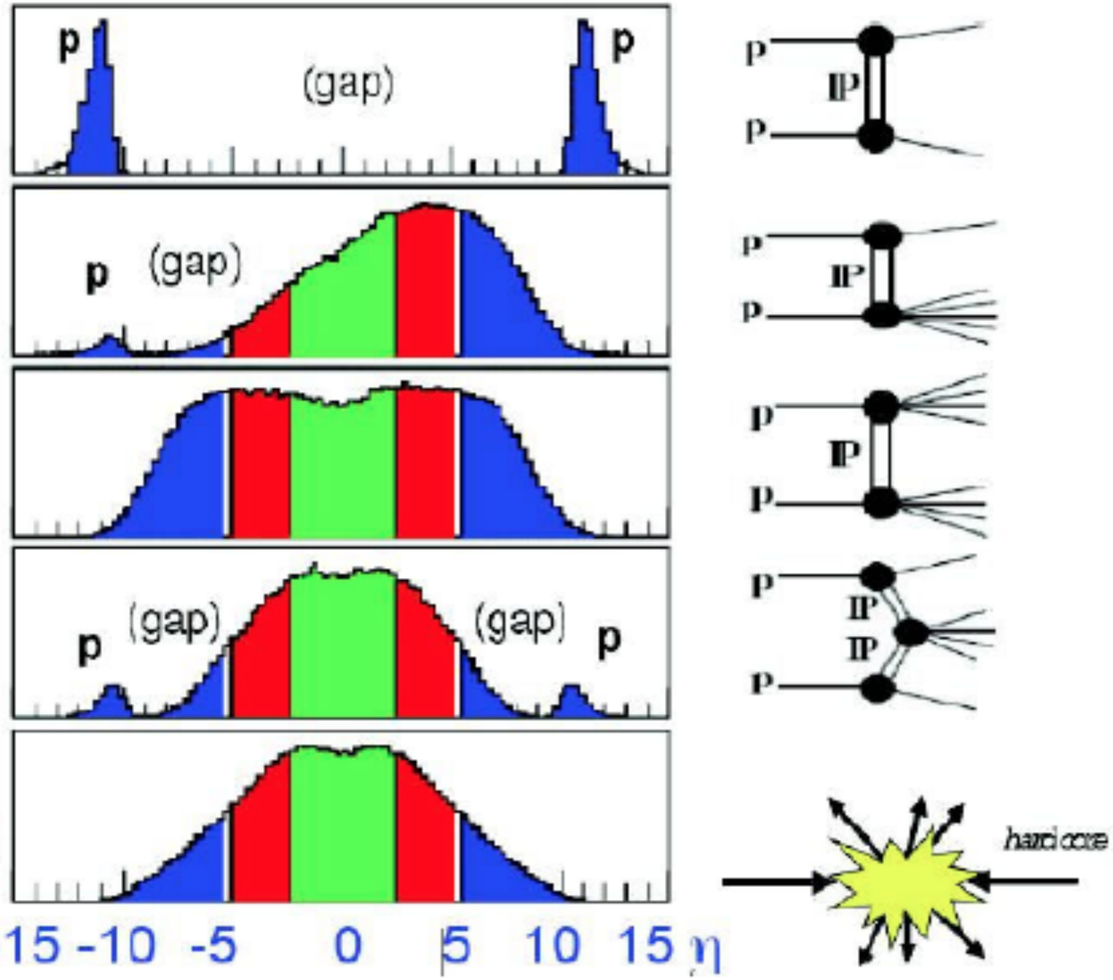
Elastic Scattering
~25% of σ_{tot}

Single Diffraction
~10% of σ_{tot}

Double Diffraction
~3% of σ_{tot}

Central Diffractive
~1% of σ_{tot}

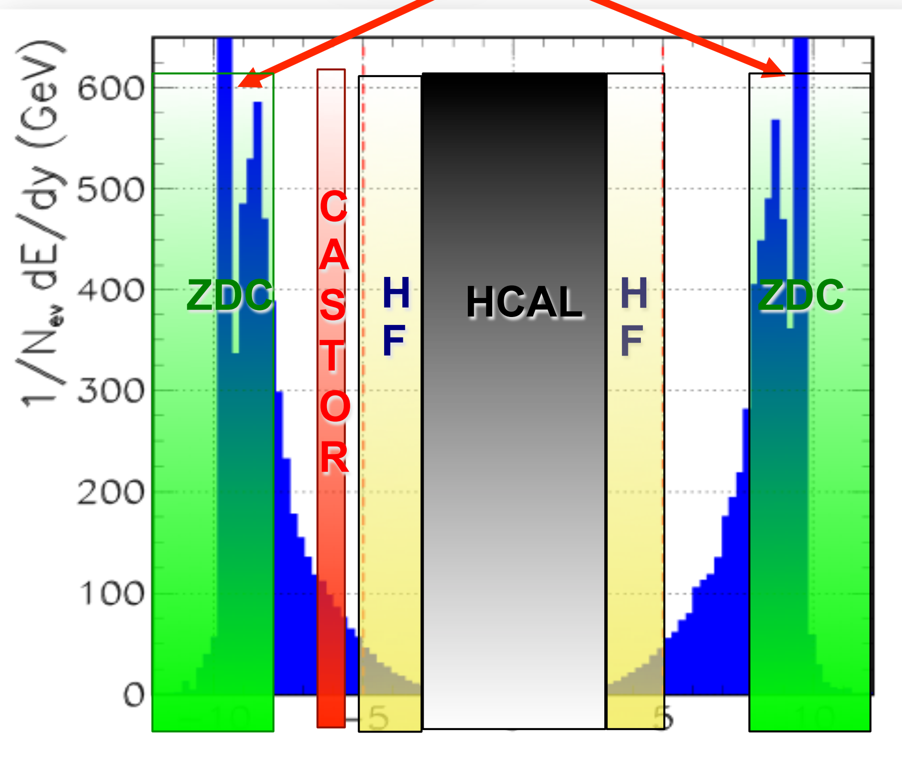
Inelastic (non-Diffractive)
~60% of σ_{tot}



$\eta = -\log(\tan\theta/2)$; θ = polar angle

Rapidity Coverage at CMS

elastic & diffractive protons



Energy flow at the LHC

$$y = \frac{1}{2} \cdot \ln \frac{(E+p_z)}{(E-p_z)}$$

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:

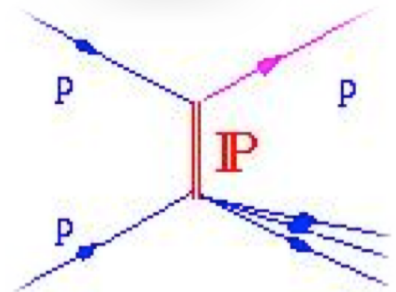
  $|\eta| < 5$

Two experimental definitions of diffractive events:

- Tagging outgoing proton escaping close to the beam
  - ✓ Requires special detectors which are placed close to the beam
- Request large rapidity gap in the forward calorimeter

Experimental Signatures

Single Diffraction



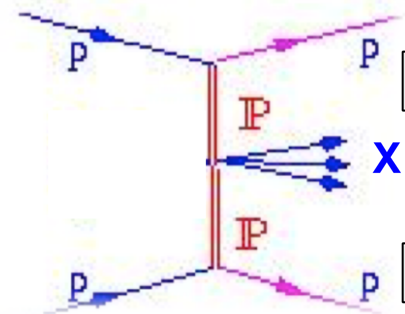
Roman Pot

gap

X central + forw. det.

Similar for photon-proton

Double Pomeron Exchange



Roman Pot

gap

X central + forw. det.

gap

Roman Pot

Similar for photon-photon or exclusive production (CEP)

central

Experimental observables:

- large rapidity gaps   (ξ : Proton fractional energy loss)
- tag in TOTEM RP and/or FP420: $\xi_1 \xi_2 s = M^2$
- reconstruction with central & forward detectors:

$$\xi_{1,2} = \frac{1}{\sqrt{s}} \sum_{\text{particles}} E_T e^{\pm\eta}$$

$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$

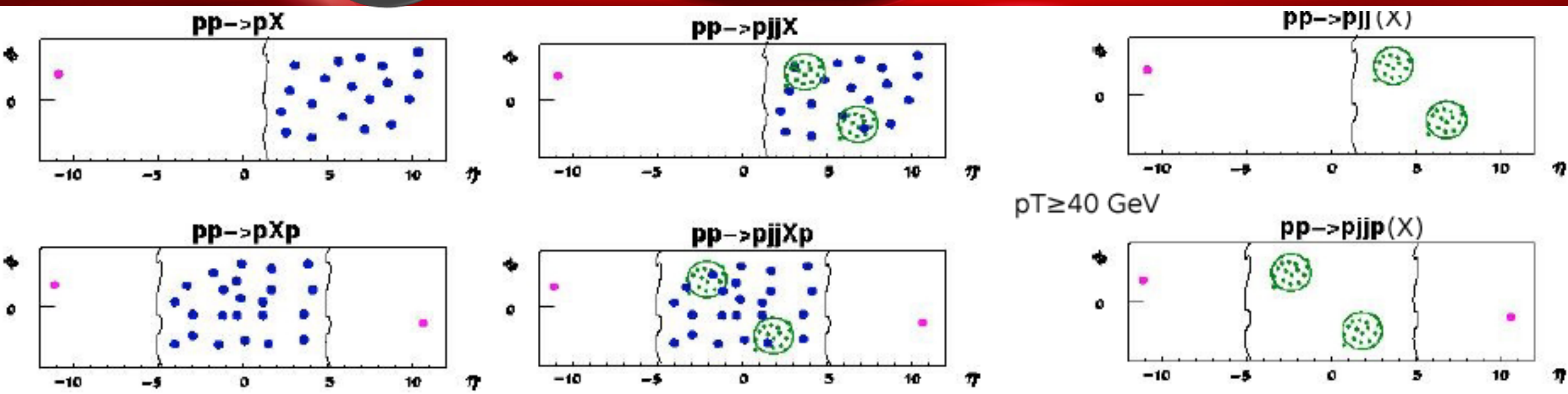
Topics of soft and hard diffraction:

- Dependencies on ξ, t and M_x as fundamental quantities of non-pe
- 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

CMS + TOTEM (RP) Tags in combined runs (current) vs FP420 (a proposed detector system)

Different LHC Run Options:

Complementary Physics Scenarios at the LHC



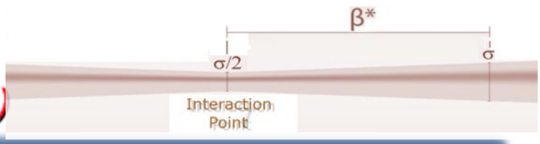
soft diffraction — (semi)-hard diffraction — hard diffraction/exclusive processes

← Cross section — Luminosity →

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

The accessible physics depends on : luminosity

β (different proton acceptance)*

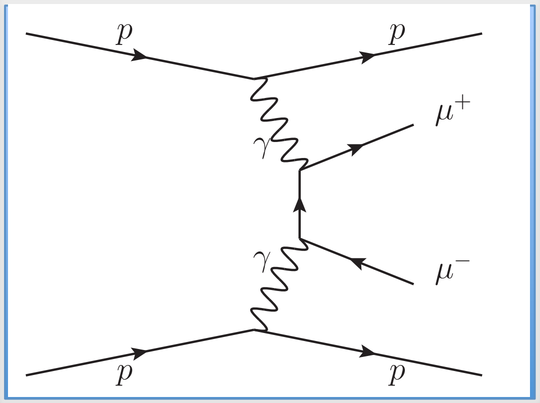
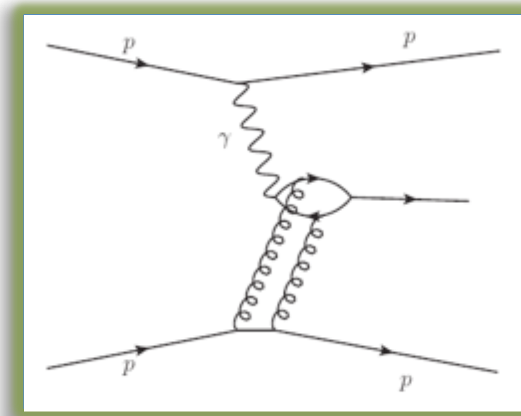
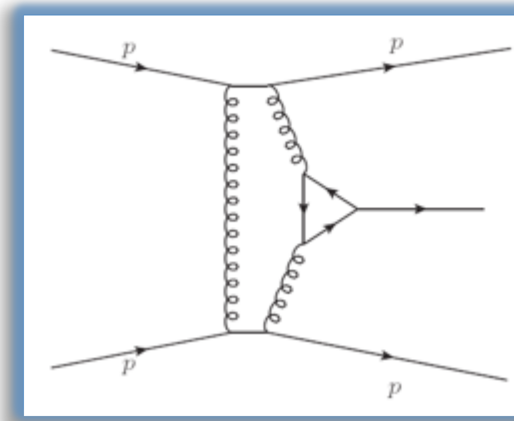


In the experiments, the beam will be "squeezed" as much as possible, to increase the number of collisions, so at a distance of beta before the focus point, the beam is also twice as wide.

Exclusive Process

Physics Motivation

Exclusive production: **processes where the protons remain intact after the interaction and escape undetected along the beamline.**

Exclusive Two-Photon	Elastic Photo-Production	CEP
		
$\mu^+\mu^-$, $e^+ e^-$, W^+W^-,	ρ, J/ψ, Υ, Z, …	χ_c , χ_b , $\pi^+\pi^-$, Dijet , gg, …

- ✓ **QED lepton pair production is of interest for the integrated luminosity normalization**

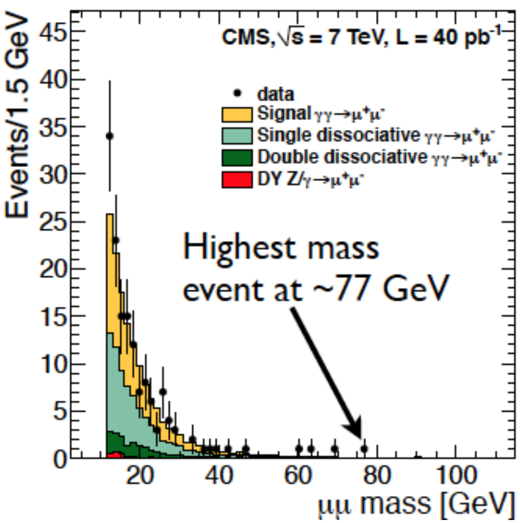
- ✓ **At higher luminosity, probe new physics with search of exclusive massive vector particles**

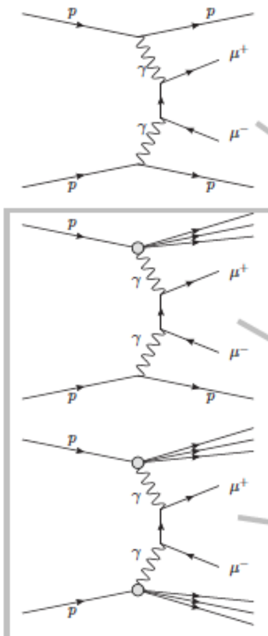
- ✓ **test of low-x physics**
- ✓ **Related to the gluon-gluon correlations**

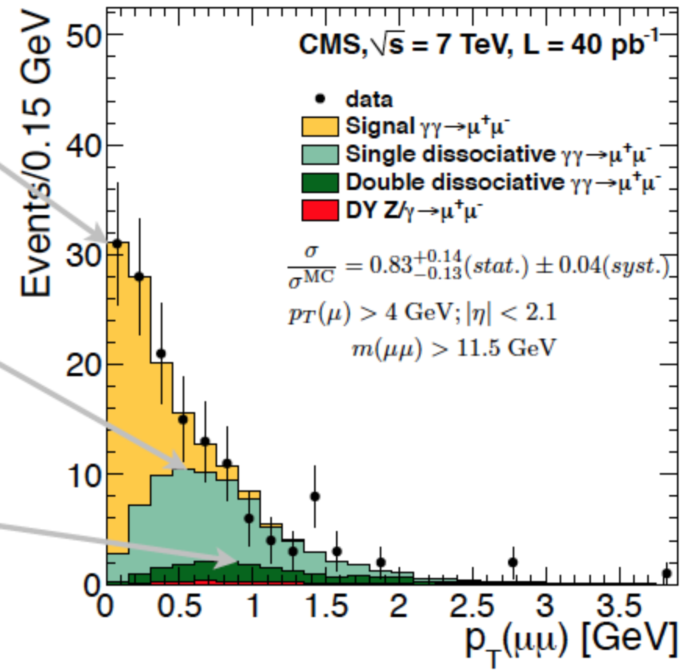
Exclusive γγ → μμ Production

JHEP 01 (2012) 052

- Measurement restricted to well controlled kinematic region ($p_T(\mu) > 4$ GeV, $|\eta| < 2.1$, $m(\mu\mu) > 11.5$), rejecting Υ photo-production
- Exclusivity condition requires a primary vertex with exactly 2 muons and no other track within 2 mm
- Signal extracted with a binned maximum likelihood fit to the $p_T(\mu\mu)$ distribution





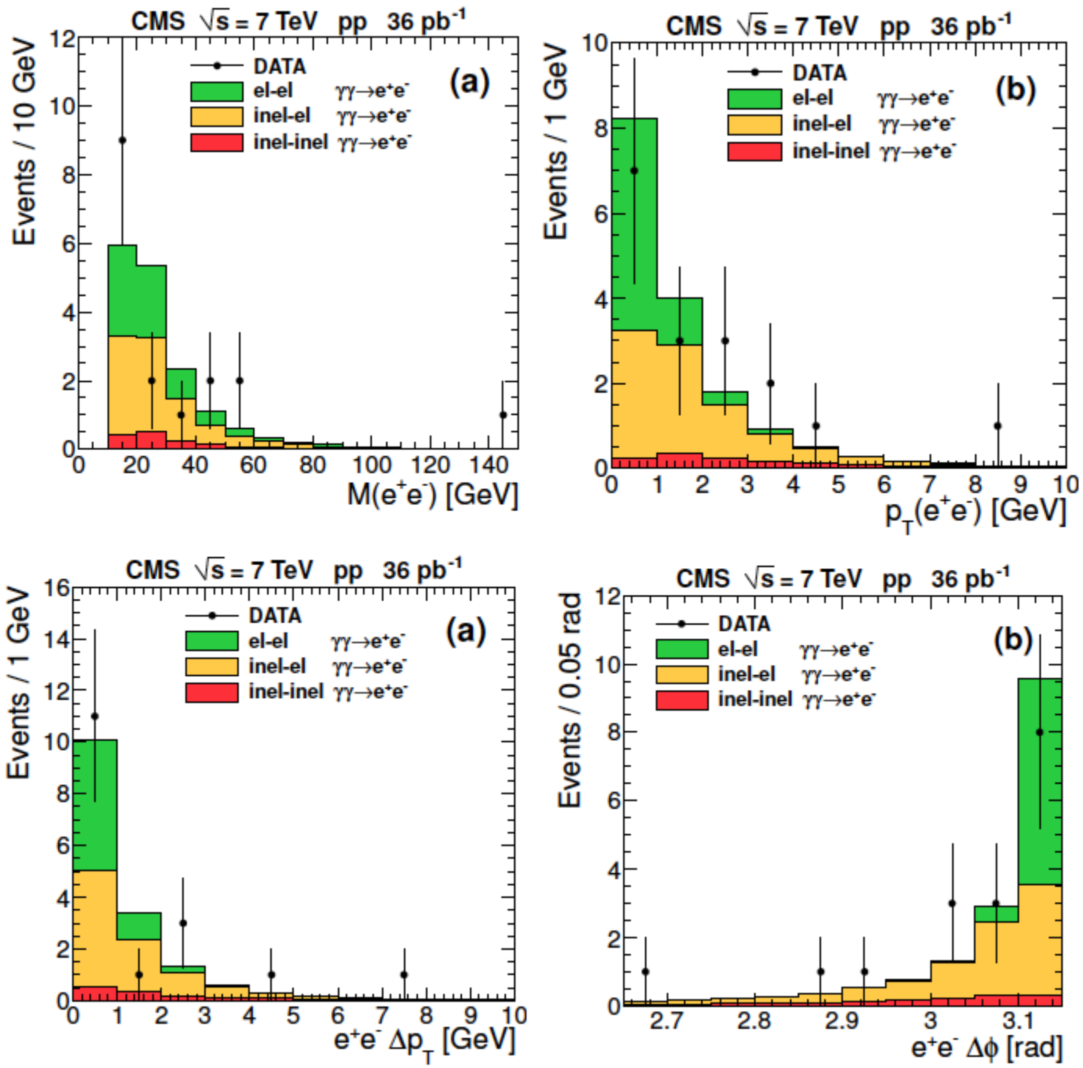


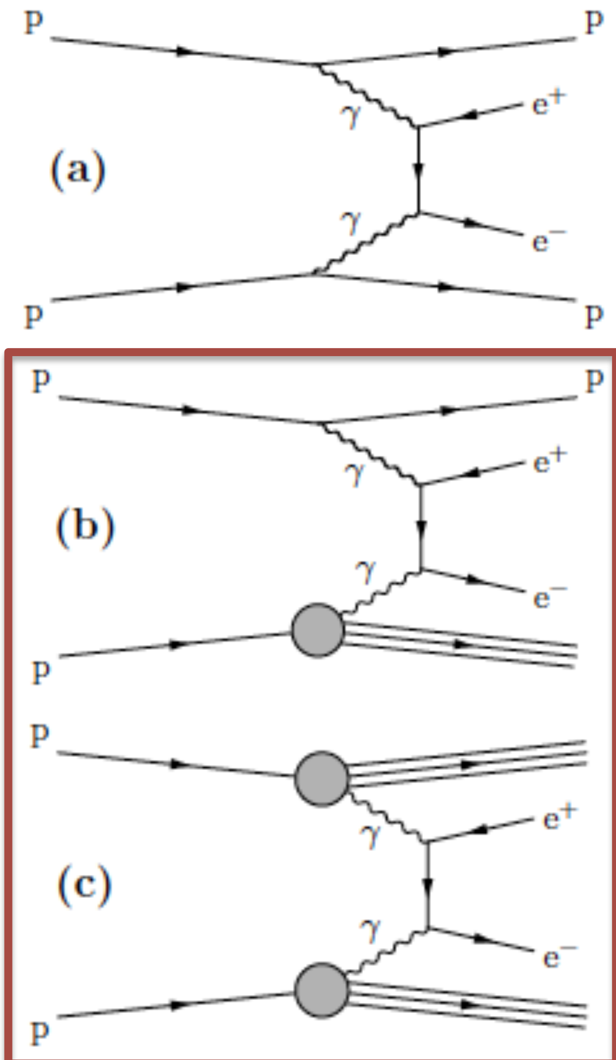
$$\sigma\,(p+\mu\mu+p) = 3.38^{+0.58}_{-0.55}(stat.) \pm 0.16(syst.) \pm 0.14(lum.)\text{pb}$$

- Largest systematics from track veto efficiency (data driven - pile-up sensitive)
- Good agreement between data and LPAIR MC (signal and proton dissociation)
- Potential to become competitive luminosity monitor at the LHC

Exclusive $\gamma\gamma \rightarrow e^+e^-$ Production

JHEP 11 (2012) 080





Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production

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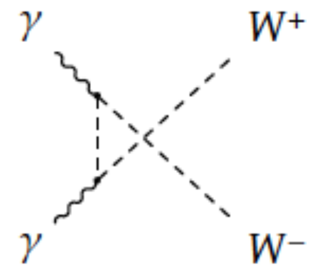
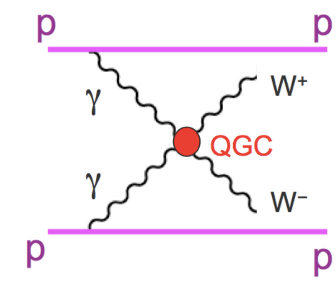
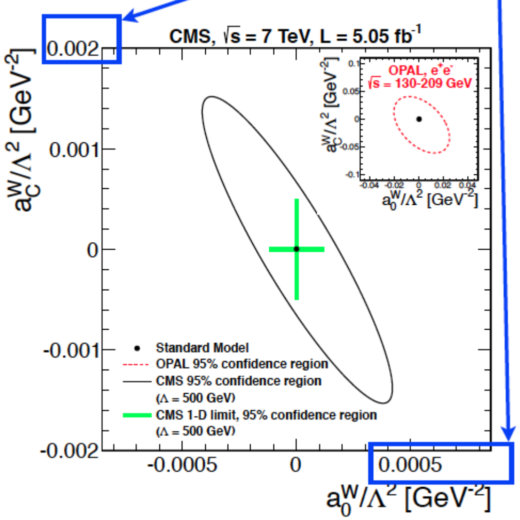
- Production of two photon of WW pairs is sensitive to Anomalous Quartic Gauge Couples (AQGC).
- CMS has the most stringent World limits on Quartic gauge couplings and it is ~100 times stronger than LEP results.

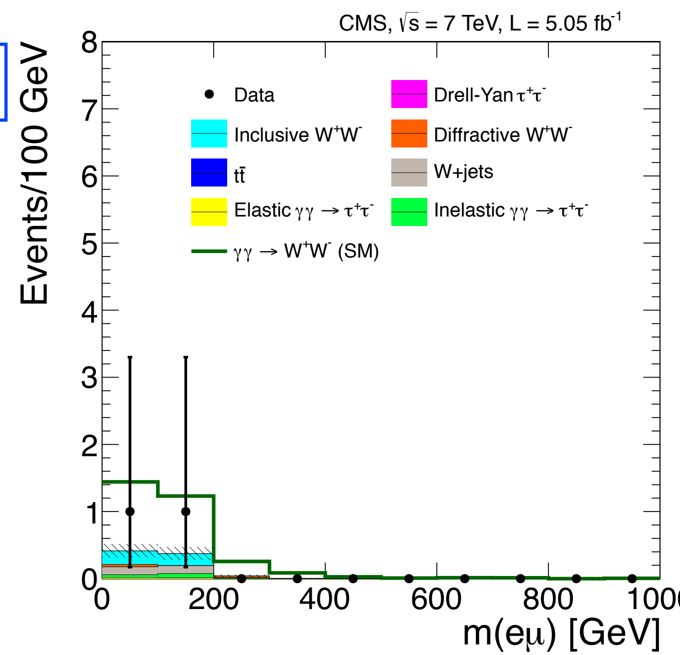


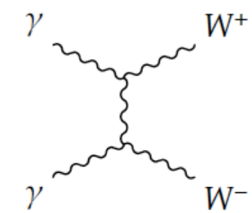


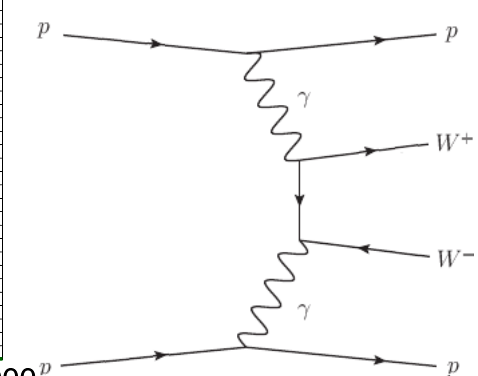
AQGC would increase yields at high pT(pair) and No extra event found.

Two orders of magnitude improvements over LEP reach.









$$\sigma(pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.2^{+3.3}_{-2.0}\ \text{fb},$$

Diffractive Dijet

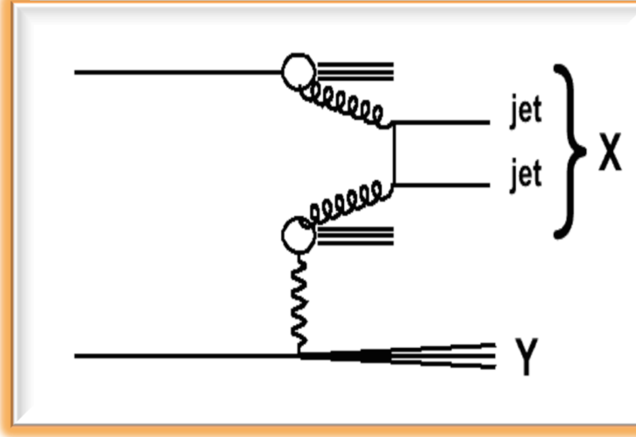
Diffractive Di-jet

Phys. Rev. D 87 (2013)

- Diffractive Dijet studied in pp, ep at CERN, HERA, Fermilab

- DPDFs were measured at HERA in diffractive DIS and used to describe different diffractive in ep collisions.

- In hadron-hadron collisions hard diffraction is suppressed wrt HERA predictions. The suppression factor, called rapidity gap survival probability, is ~10% on average. The suppression depends on x (fractional parton momentum) changing from 0.05 to 0.3 with decreasing x.



- Systems X and Y separated by fixed η=4.9 cut

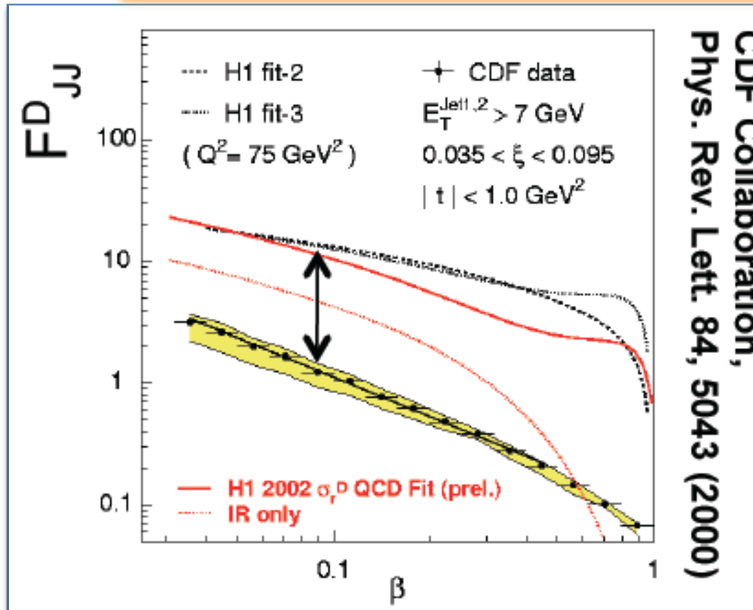
  X includes all particles with η < 4.9

  Y includes all particles with η > 4.9

(ξ : Proton fractional energy loss)

$$\xi = M_X^2 / s$$

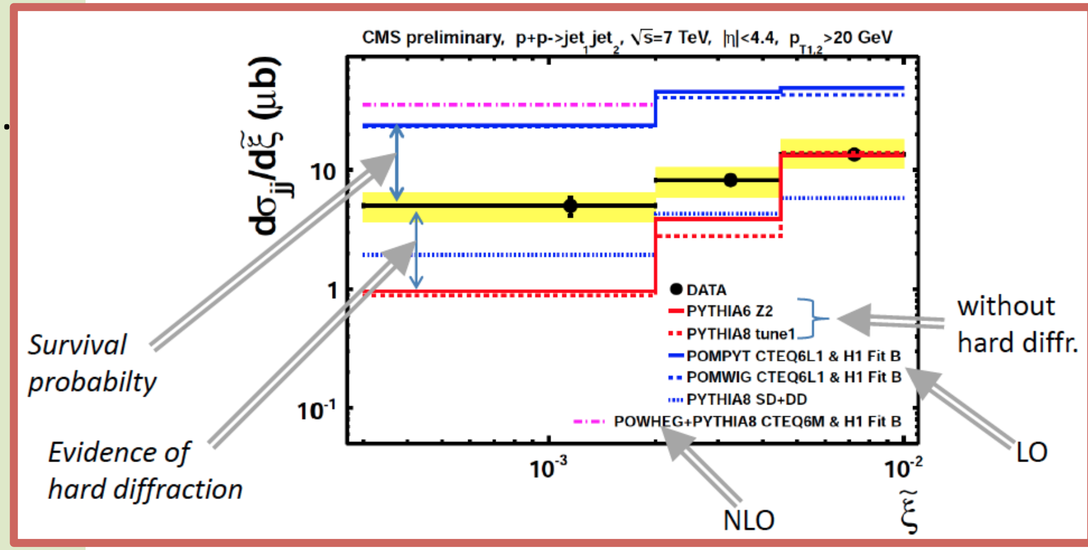
$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$



Diffractive Di-jet

Phys. Rev. D 87 (2013)

- Dijet cross section as a function of ξ for events with both jets P_T>20 GeV in $|\eta|$ <4.4 range.
- The first bin is dominated by diffraction.
- Diffractive models based on diffractive pdfs from HERA (POMPYT, POMWIG) overestimate the measured cross section (gap survival probability).



The suppression factor (data/theory):

0.21±0.07 (data / LO MC)

0.14±0.05 (data / NLO)

Estimate of the rapidity gap survival probability after correction for the proton dissociation:
(0.12±0.05 @ LO, 0.08±0.04 @ NLO)

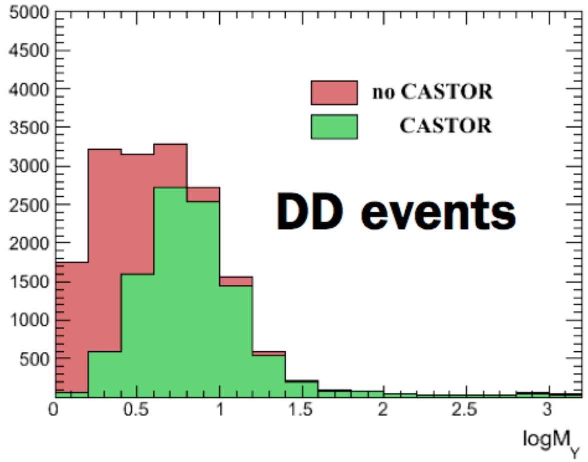
- This is an upper limit of the gap survival probability because the measured cross section includes a contribution from double diffraction.

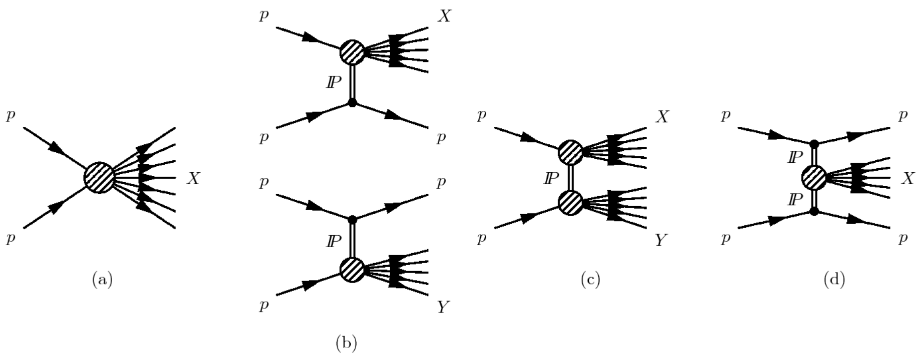
Soft Diffraction

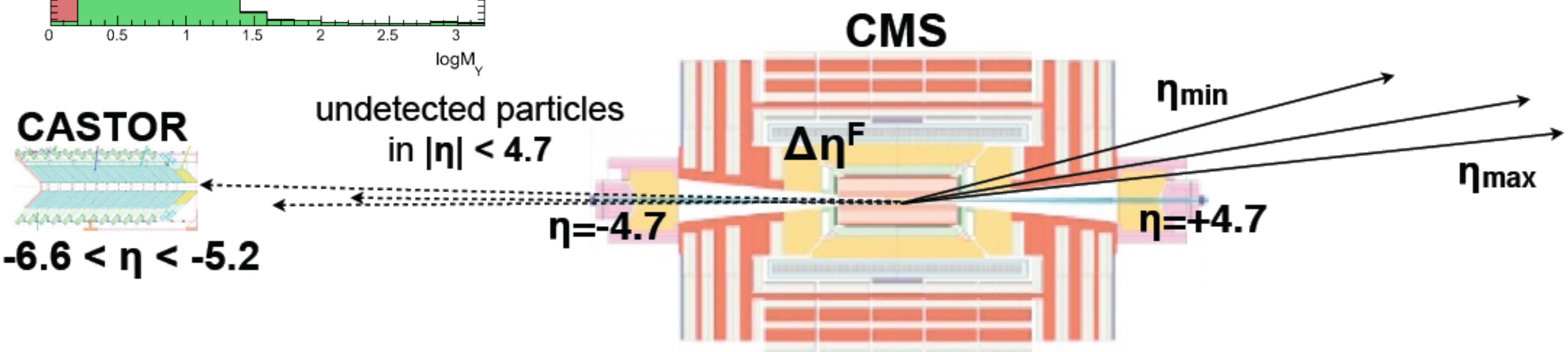
Soft diffractive cross sections

PAS FSQ-12-005

- First CMS measurement of inclusive diffractive cross sections.
- Using Large Rapidity Gap (LRG) signatures.
- SD and DD separated with CASTOR -6.6 < η < -5.2





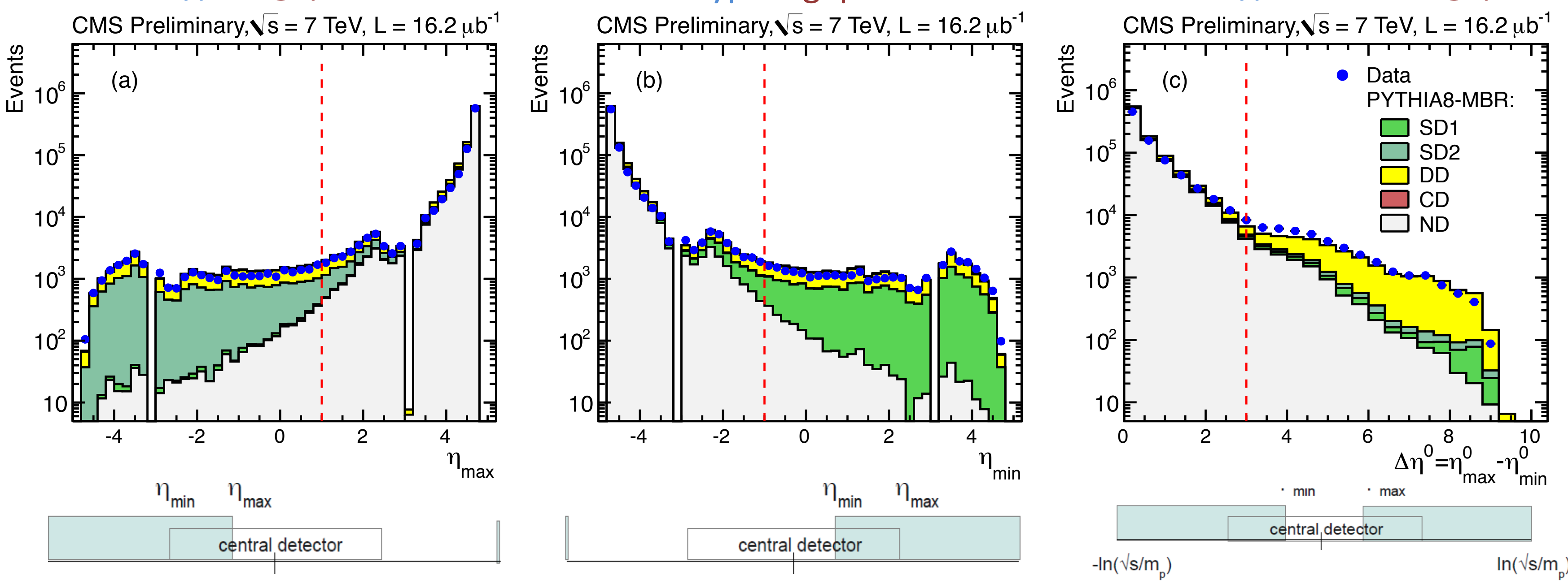


Soft diffractive cross sections

PAS FSQ-12-005

Experimental Topologies of diffractive events with LRG

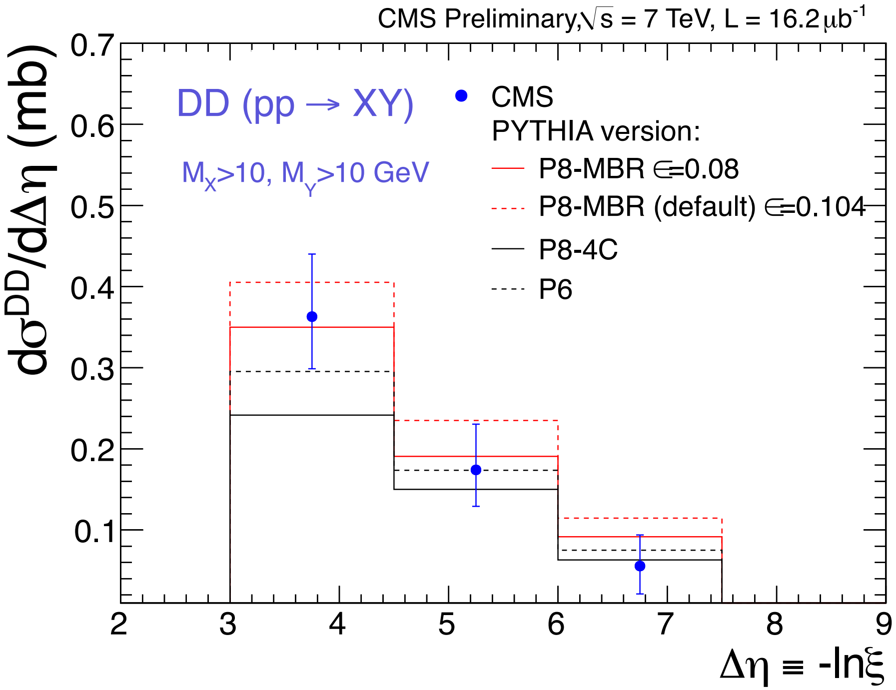
SD1 type – gap on +side | SD2 type – gap on -side | DD type – central gap



η_{max} (η_{min}): highest (lowest) η of the particle reconstructed in the central detector

η^0_{max} (η^0_{min}): closest-to-zero positive (negative) η of the central detector $\Delta\eta^0=\eta^0_{max}-\eta^0_{min}$

Soft diffractive cross sections



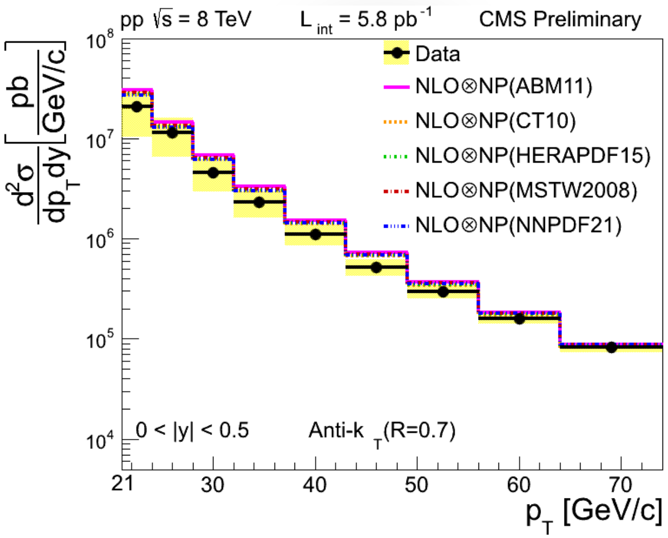
$$\sigma_{vis}^{DD} = 0.93 \pm 0.01(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})\text{ mb for } \Delta\eta > 3,\ M_X > 10\text{ GeV and } M_Y > 10\text{ GeV}$$

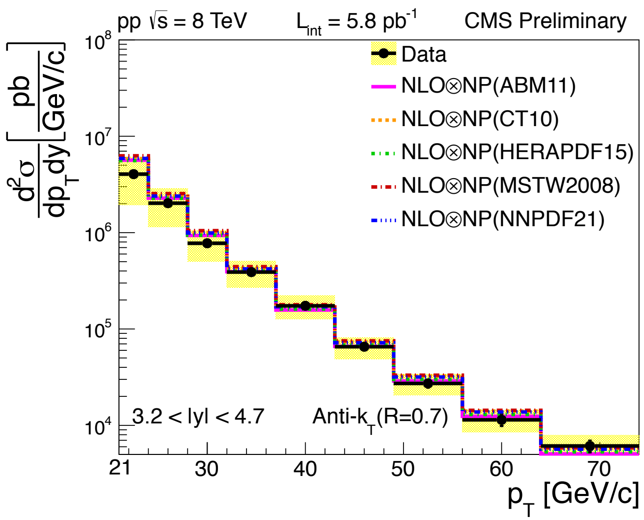
- PYTHIA8-MBR, PYTHIA 6/8 are in agreement with data.
- The dominant source of uncertainties:
  Energy scale of HF (Hadron Forward), hadronization and diffraction model.

Low p_T at Jet

Low p_T Jet

PAS FSQ-12-031



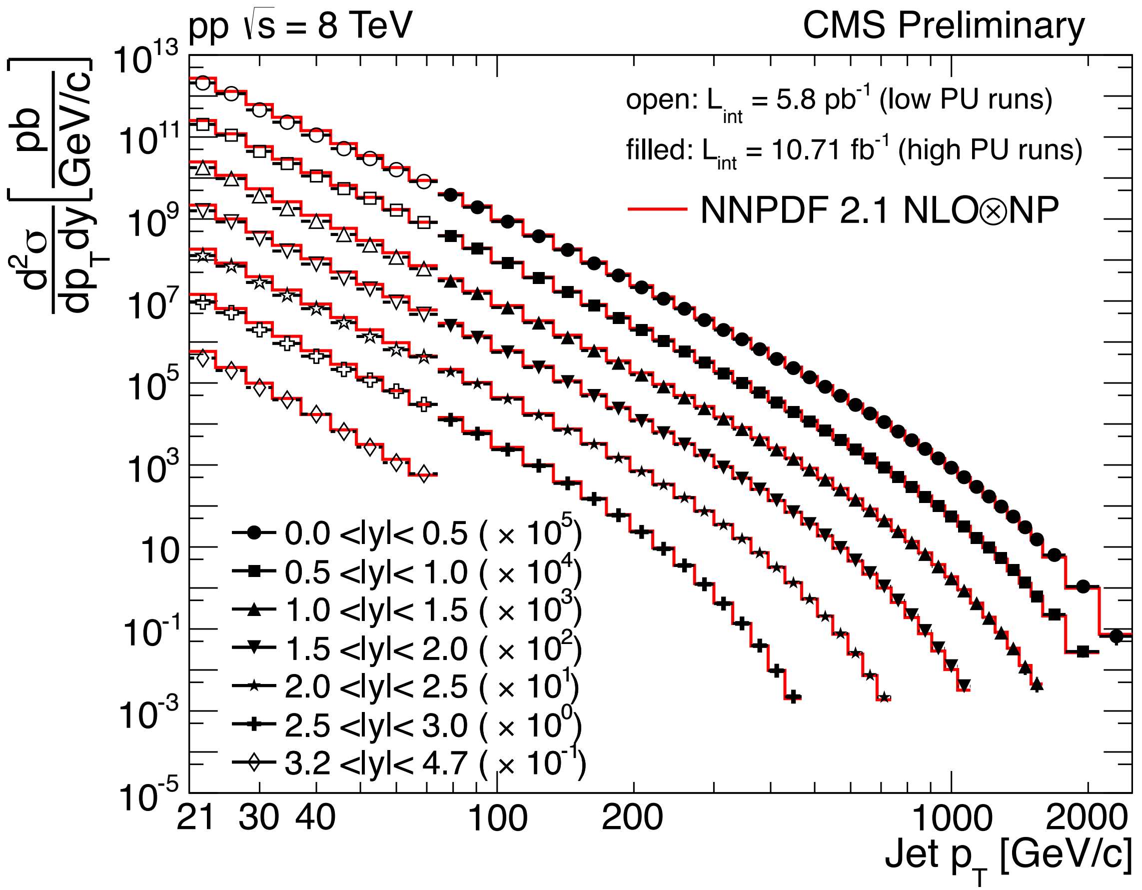


- Forward jets measured at the collision energy of 8 TeV (even smaller *x*).
- New measurement (8/2013): CMS-PAS-FSQ-12-031 based on 2012 data, 5.8 pb^{-1}
- Dedicated low pile-up run (4 interactions / bunch crossing), requirement on one “good” primary vertex in the event.
- Inclusive jet spectrum up to forward rapidities $|\eta|<4.7$.
- Low p_t: 21 GeV < p_t < 75 GeV (even smaller *x*) in bins of *y*.
- Zero bias trigger (> 2 tracks in Pixels).
- PF jets reconstructed with anti-k_t algorithm, R=0.7

Low p_T Jet

PAS FSQ-12-031

- Combined jet spectrum with NLO predictions at 8 TeV.
- Cross-section: 15 order of magnitude!

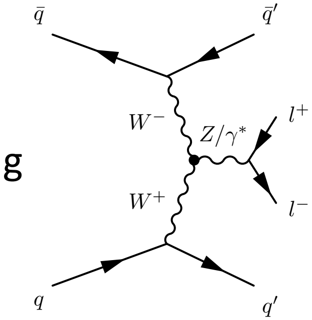


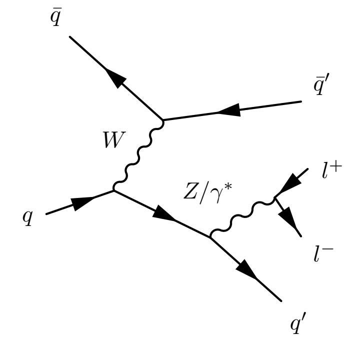
VBF-Z + Jets

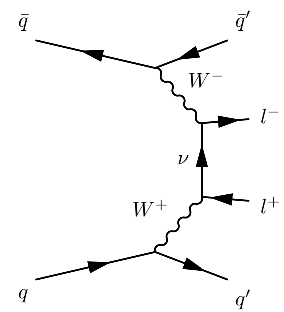
The first observation EWK/VBF Z+Jets at the LHC

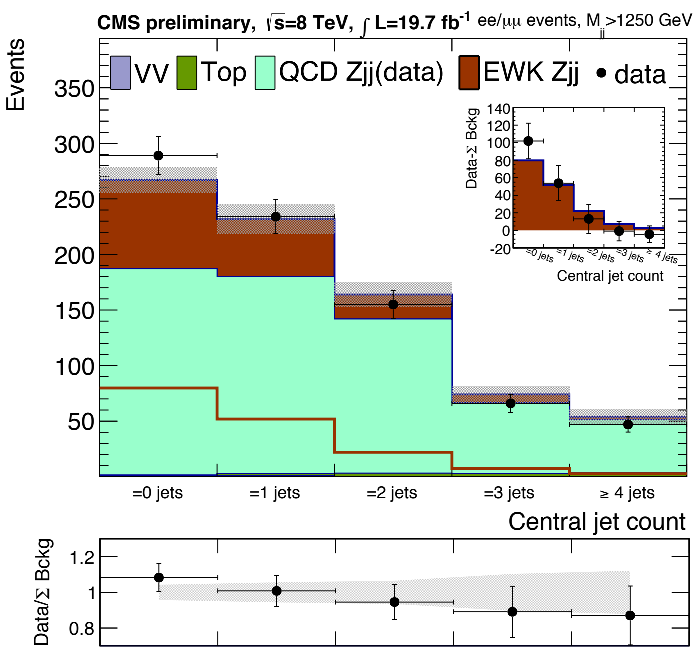
PAS FSQ-12-035

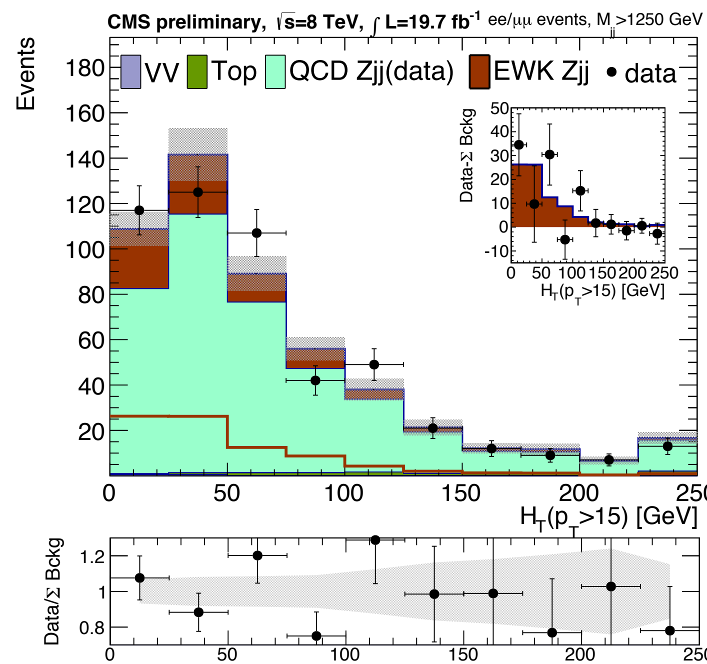
- A new, 8 TeV VBF Z production
  - Improves and extends earlier analysis it to higher energy/statistics
  - Strong destructive interference between the VBF diagram (top) and bremsstrahlung (middle) & multiperipheral (down) production
  - Cross section is suppressed by x5 compared to the VBF contribution alone
- Important testing ground for understanding of the VBF Higgs production





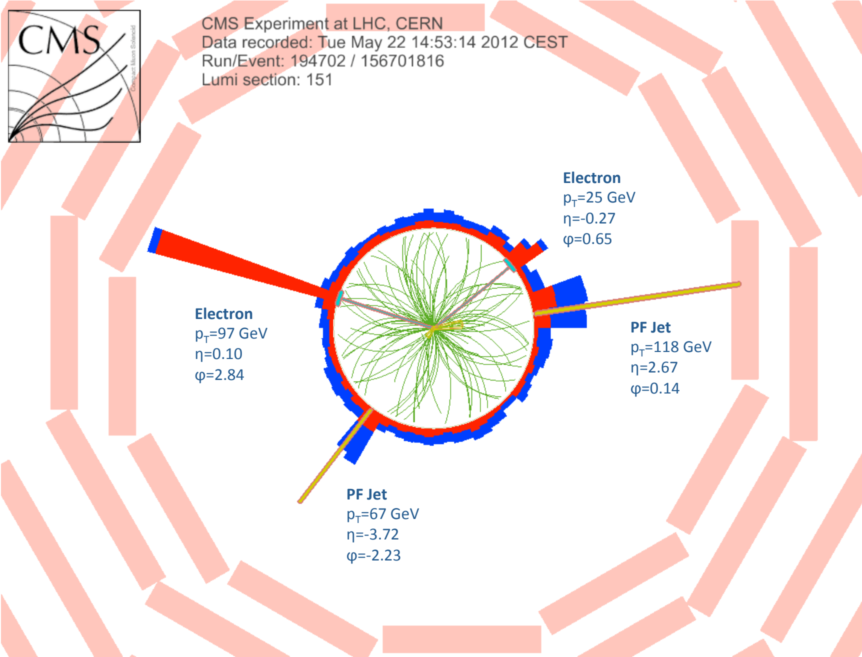


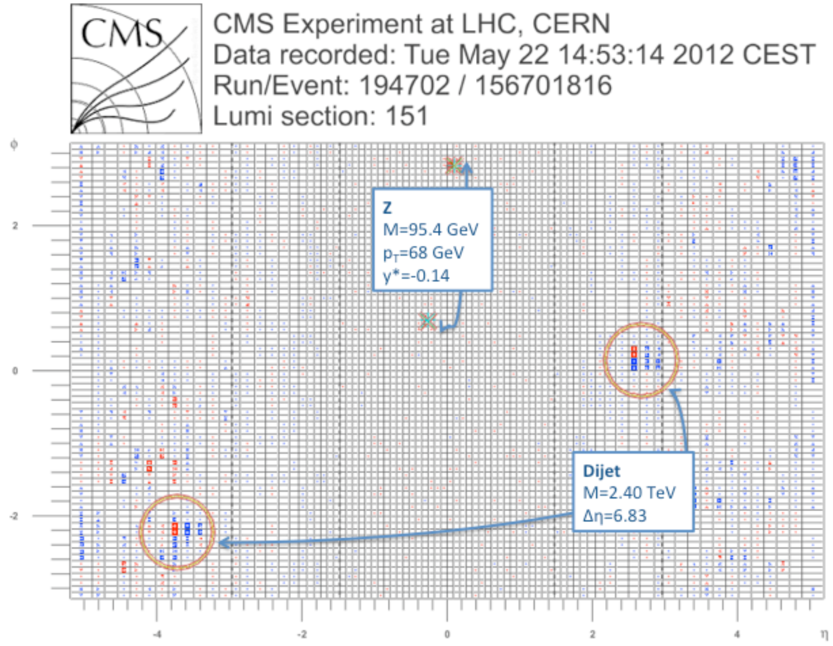




VBF-Z Jets

PAS FSQ-12-035



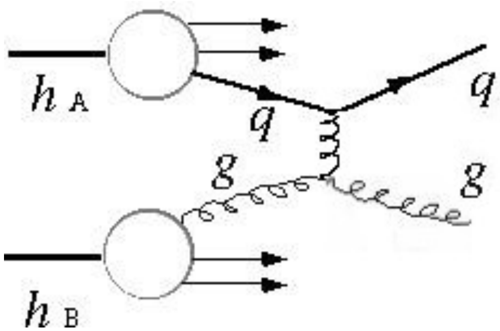


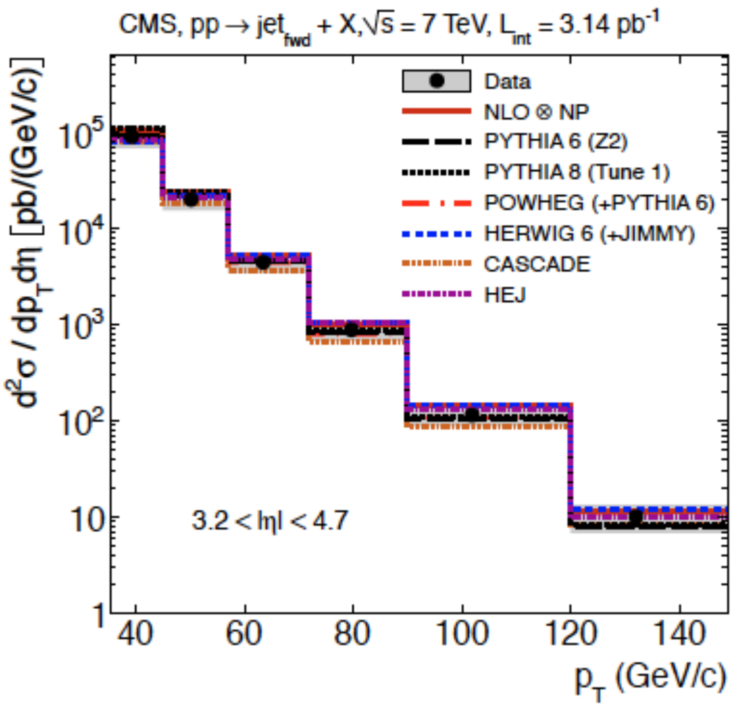
Forward Jets

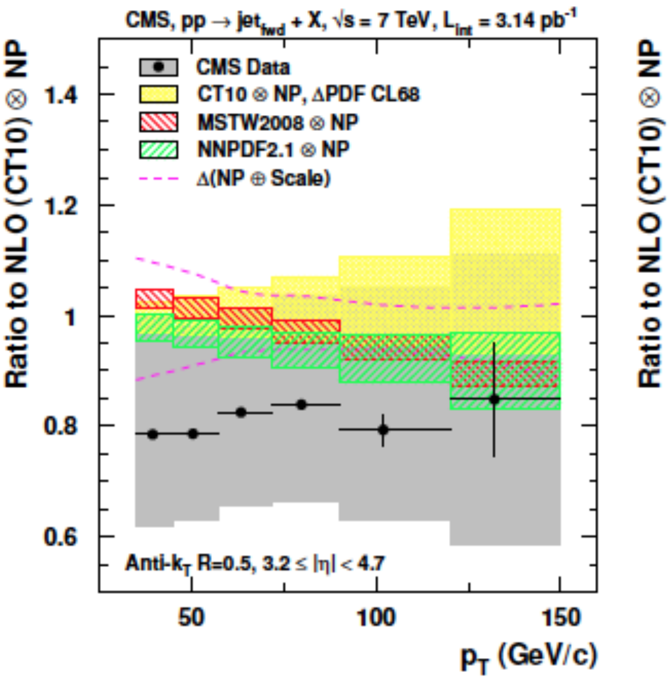
CMS: Forward Jets at 3 < |η| < 5

JHEP 1206 (2012) 036

- **Forward Jets:** E_T (30-140 GeV) at low x
  - Jets in HF (3<|η|<5)
- **Spectrum:** reproduced by NLO



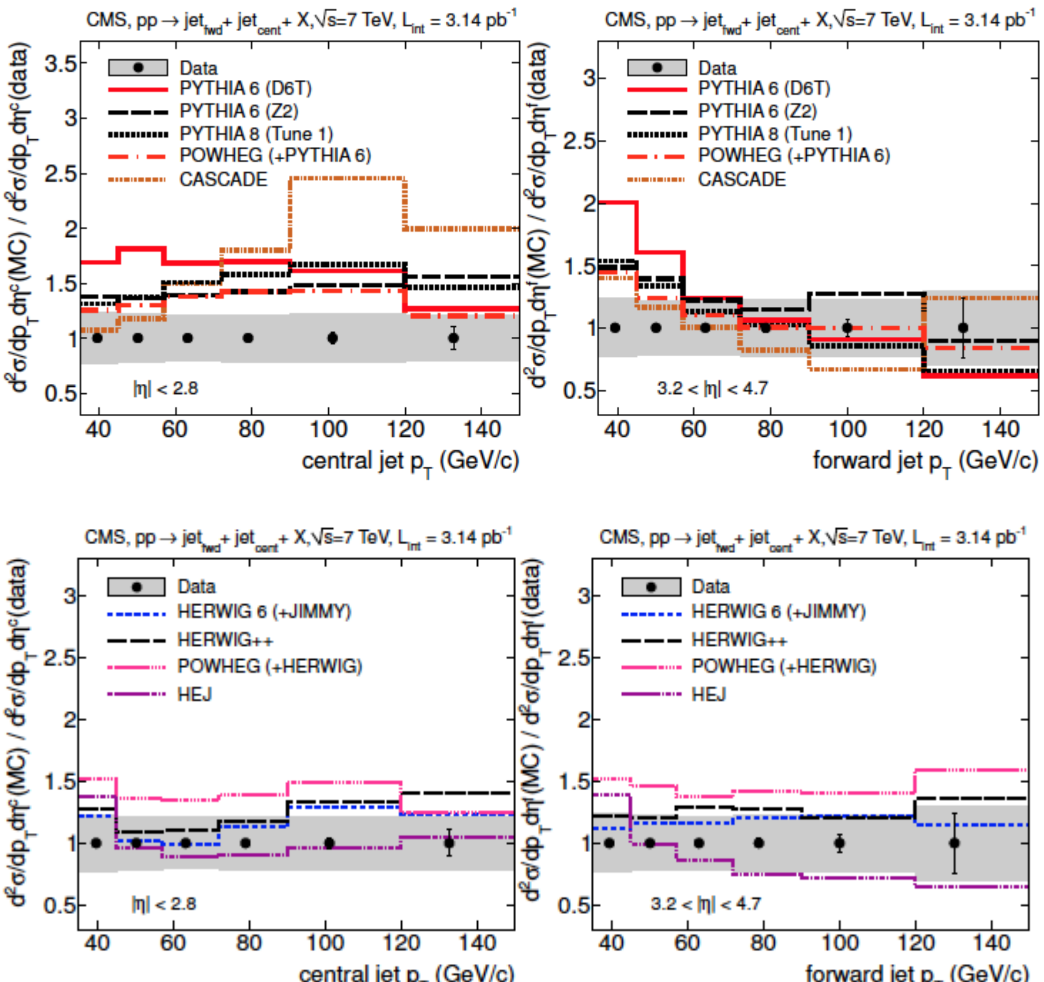




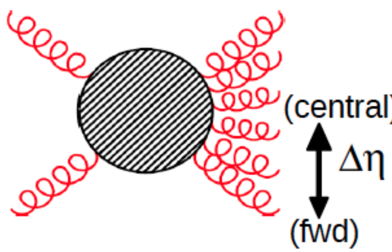
CMS: Forward-central Di-jets

JHEP 1206 (2012) 036

Mueller-Navalet dijet decorrelations result → New: FSQ-12-002



- **Forward central Jets:**
  - With Large separation probe BFKL dynamics
- **Ratio (Theory / data):**
  - For fwd and central jets p_T spectra



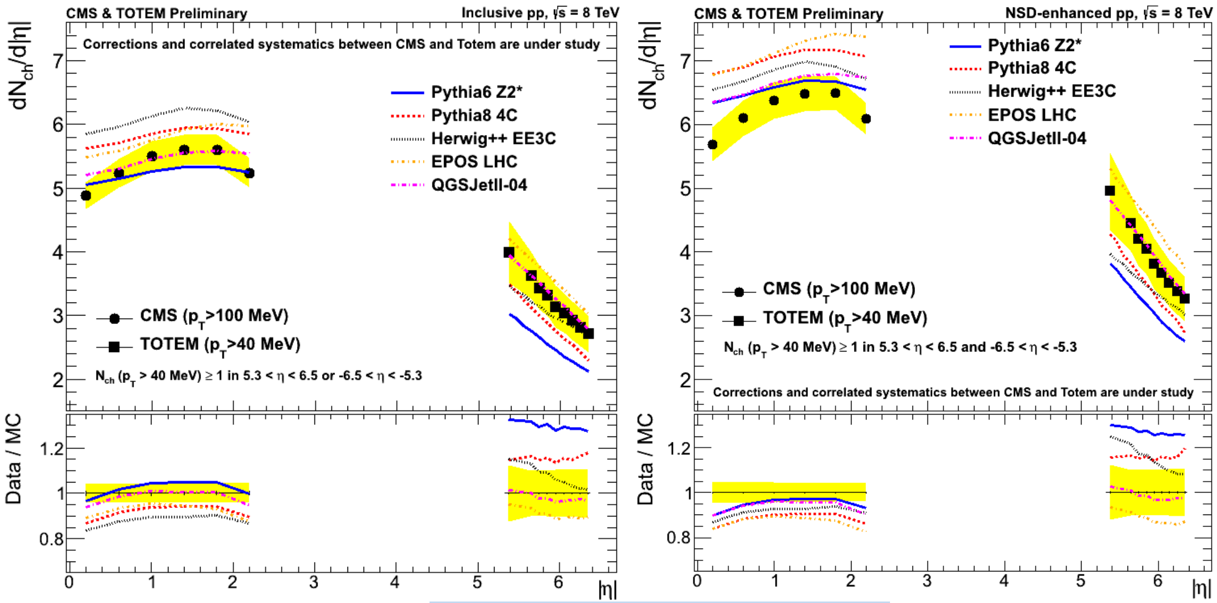
- PYTHIA & NLO overpredict jet spectra specially at low p_T
- HERWIG & models w/ wide-angle radiation (HEJ) show better agreement, but CASCADE (DGLAP+ BFKL) also overshoots.

dN/dη (CMS + TOTM)

Central and forward dN / dη
(Combined CMS and TOTEM)

$dN_{ch}/d\eta$: mean number of charged particles per event and per unit of η:

- probes hadronisation ➔ constrains phenomenological models used in MC generators
- "Non-Single diffractive enhanced": primary tracks in both T2 hemispheres
- "Single diffractive enhanced": primary tracks in only one T2 hemispheres
- Study of the "soft" and "hard" scatterings



PAS FSQ-12-026

- CMS (tracker) & TOTEM (T2) analysis on same events triggered by T2
- Same CMS-TOTEM event selection (at least a primary track candidate in T2)
- $dN_{ch}/d\eta$ for inelastic events with at least one primary charged particle.

CMS:

$p_T > 100$ MeV: $|\eta| < 2.4$

TOTEM:

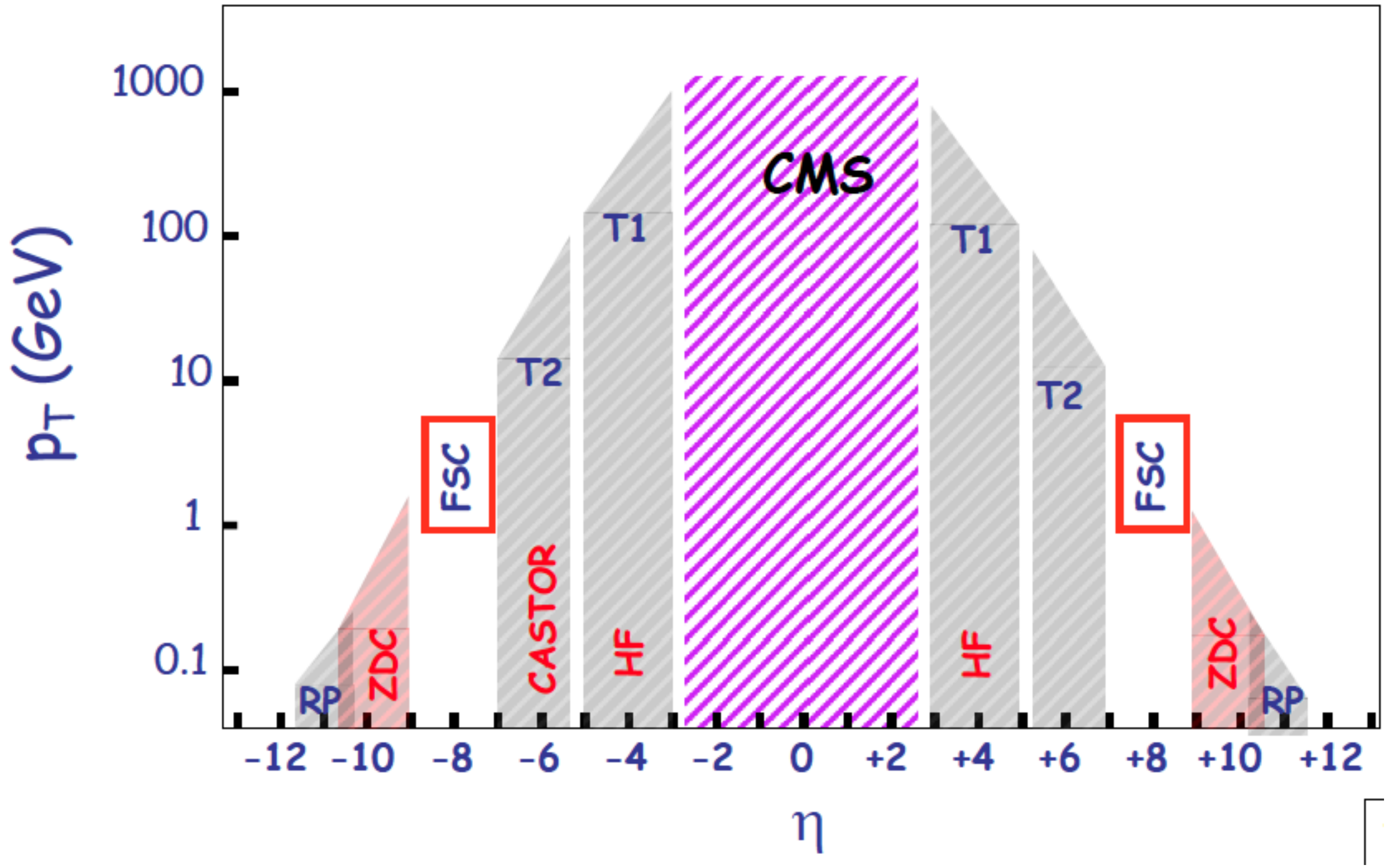
$p_T > 40$ MeV: $5.3 < |\eta| < 6.5$

Physics with FSC

Forward Scintillator Shower(FSC) extending CMS η-coverage

- CMS, as most collider detectors, has excellent hermeticity at low η
- In the forward direction the CMS coverage is extended with different additional detectors: HF + Castor + ZDC (+ TOTEM)
- There may be gaps in the coverage of the forward region (high η)
- The Forward Shower Counters (FSC) system is made of scintillators installed near the LHC beam pipe at 59, 85 and 114 m from IP5, on both sides of CMS
- These counters detect showers produced by very forward hadrons hitting the beam pipe and surrounding materials.

Towards Full Acceptance



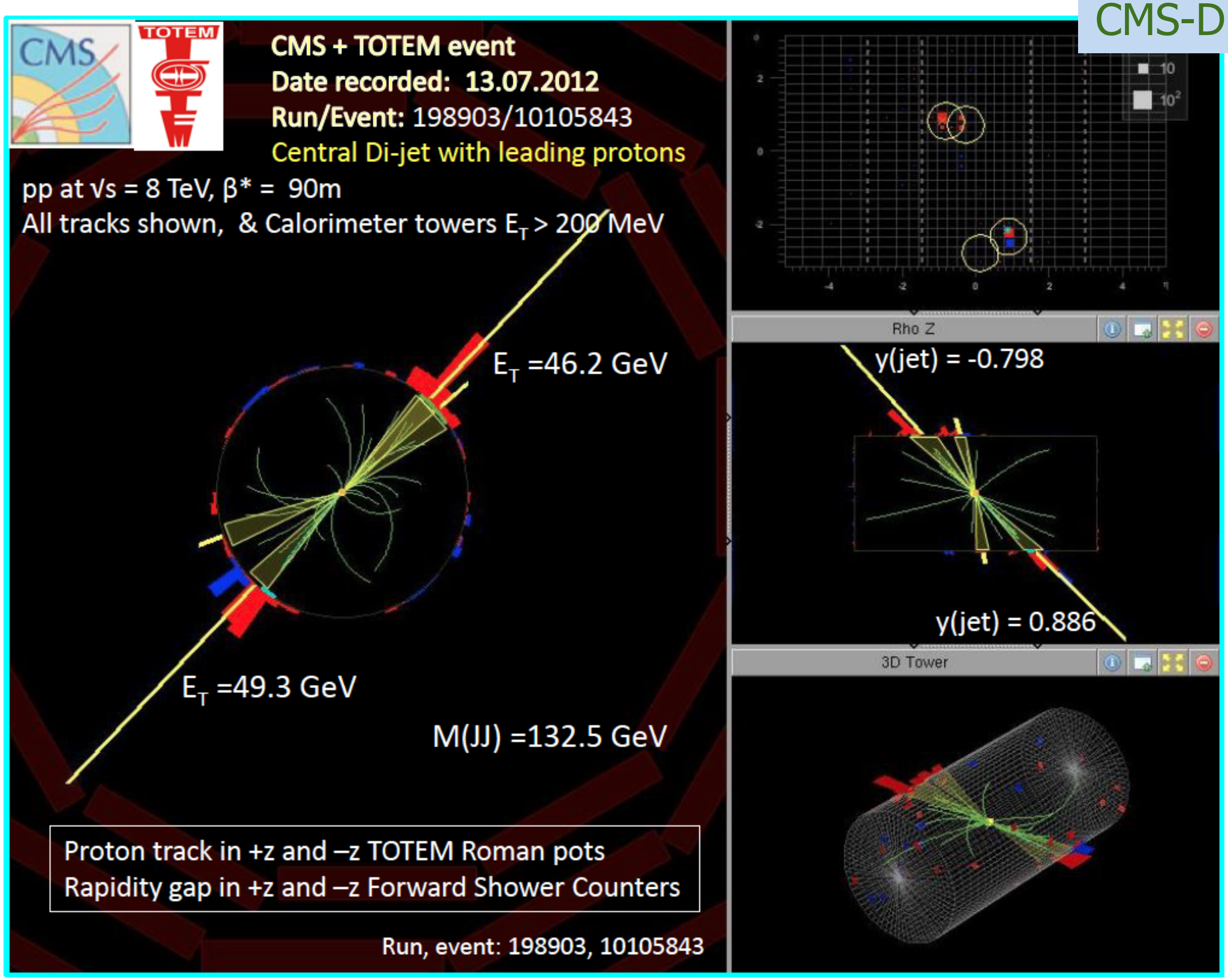
- **FSC covers a gap in eta between the forward calorimeters (HF, CASTOR) and the very forward (ZDC, TOTEM RP)**

FSC Tasks

- **Physics**, mainly diffractive
  - Detecting rapidity gaps in diffractive events
  - Measure low mass diffraction and double pomeron exchange
  - Heavy Ion runs
- **Beam monitoring**
  - Beam halo of incoming and outgoing beams
  - Comparison with forward flux simulations (MARS, Fluka)
  - VdM scans

Central Dijet events candidate with two leading protons

CMS-DP 2013/004



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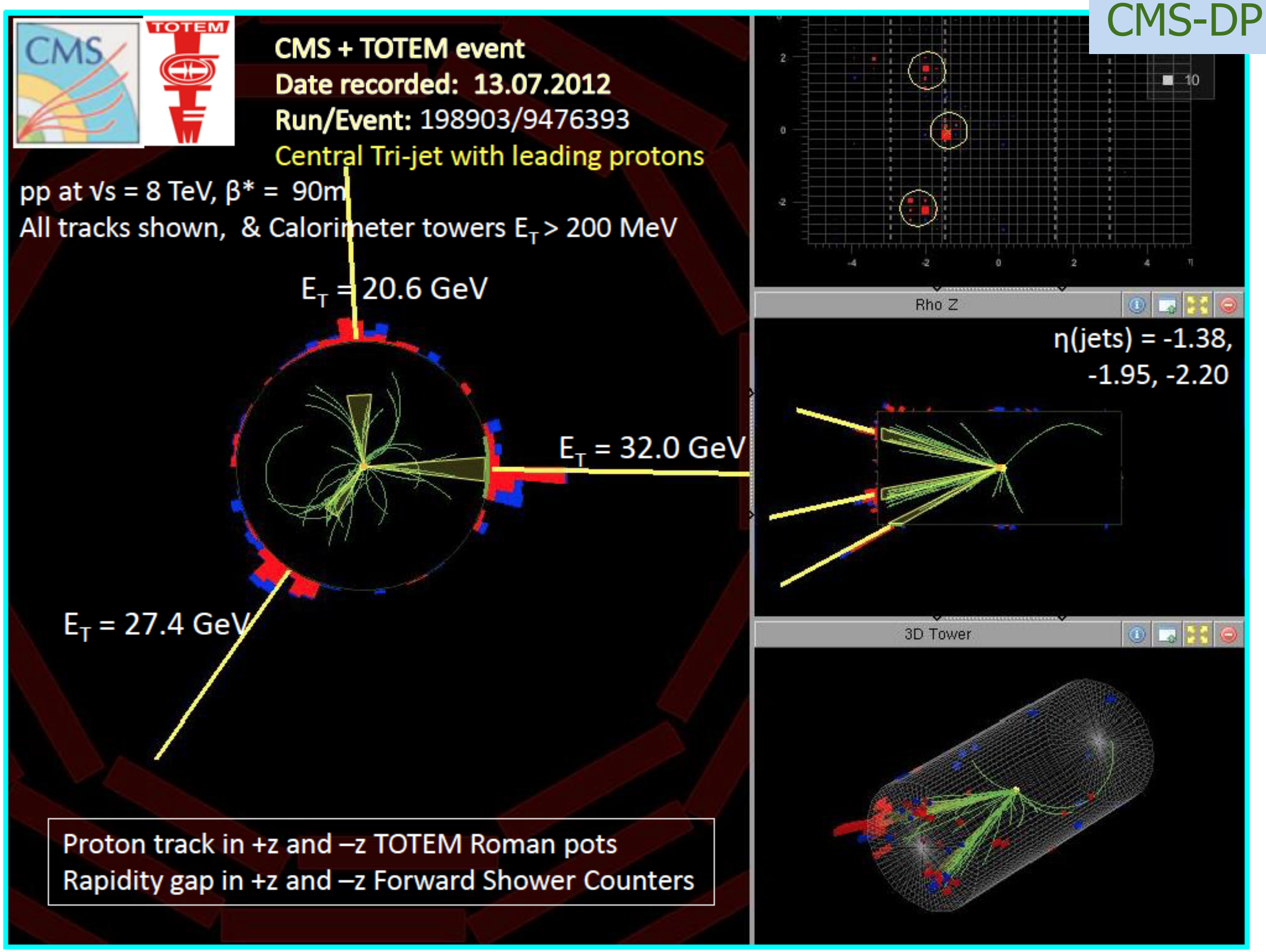
Central Dijet events candidate with three jets with 2 leading protons

CMS-DP 2013/004



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Future Project

PPS: a CMS – TOTEM: forward detector

CMS and TOTEM have decided to work together toward a plan of common data taking. This collaboration is outlined as follow:

Phase I (after LS1): low luminosity running.

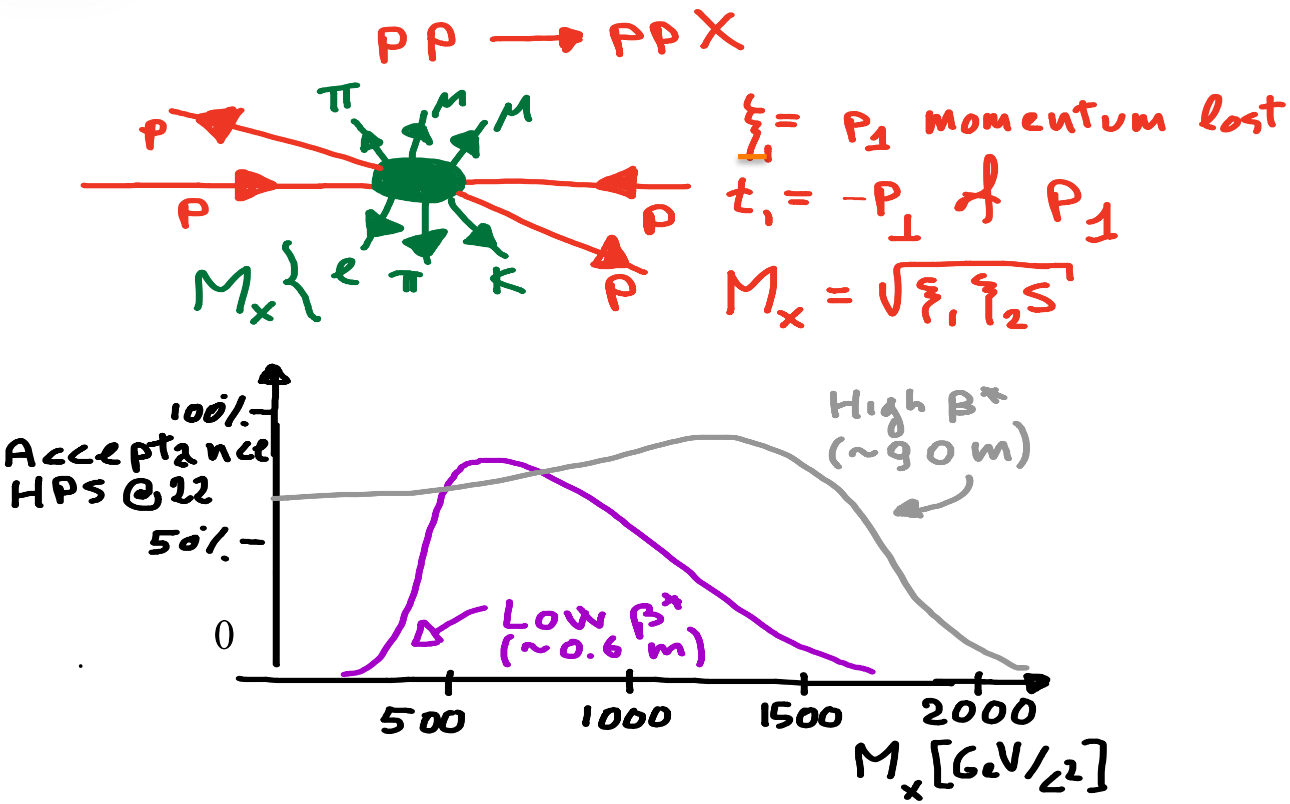
1. common data-taking using the TOTEM hardware in the forward region
2. Use one cylindrical RP for impedance/detector studies
3. Develop the Movable Beam Pipe

Phase II (after LS1+ 1-2 years): high luminosity running.

1. Replace the TOTEM silicon strips with rad-hard pixel detector
2. Use timing detector

PPS = Precision Proton Spectrometer

Central Exclusive Production



- Low Mass: FP420 is a detector that can be used to study physics topics including Higgs central exclusive production as a rich QCD and electroweak program.

PPS Physics Reach

PPS is the sole detector that can measure Central Exclusive Production processes, both at low and high mass.

PPS @ 220 meter:

Low β* (~ 0.6 meter)

High mass states ($M_x > 300$ GeV),

high & small cross section processes (standard luminosity optics)

High β* (~ 90 meter)

Full mass range ($M_x < 2000$ GeV),

Large cross section processes (1-3 day of dedicated optics)

PPS @ 420 meter:

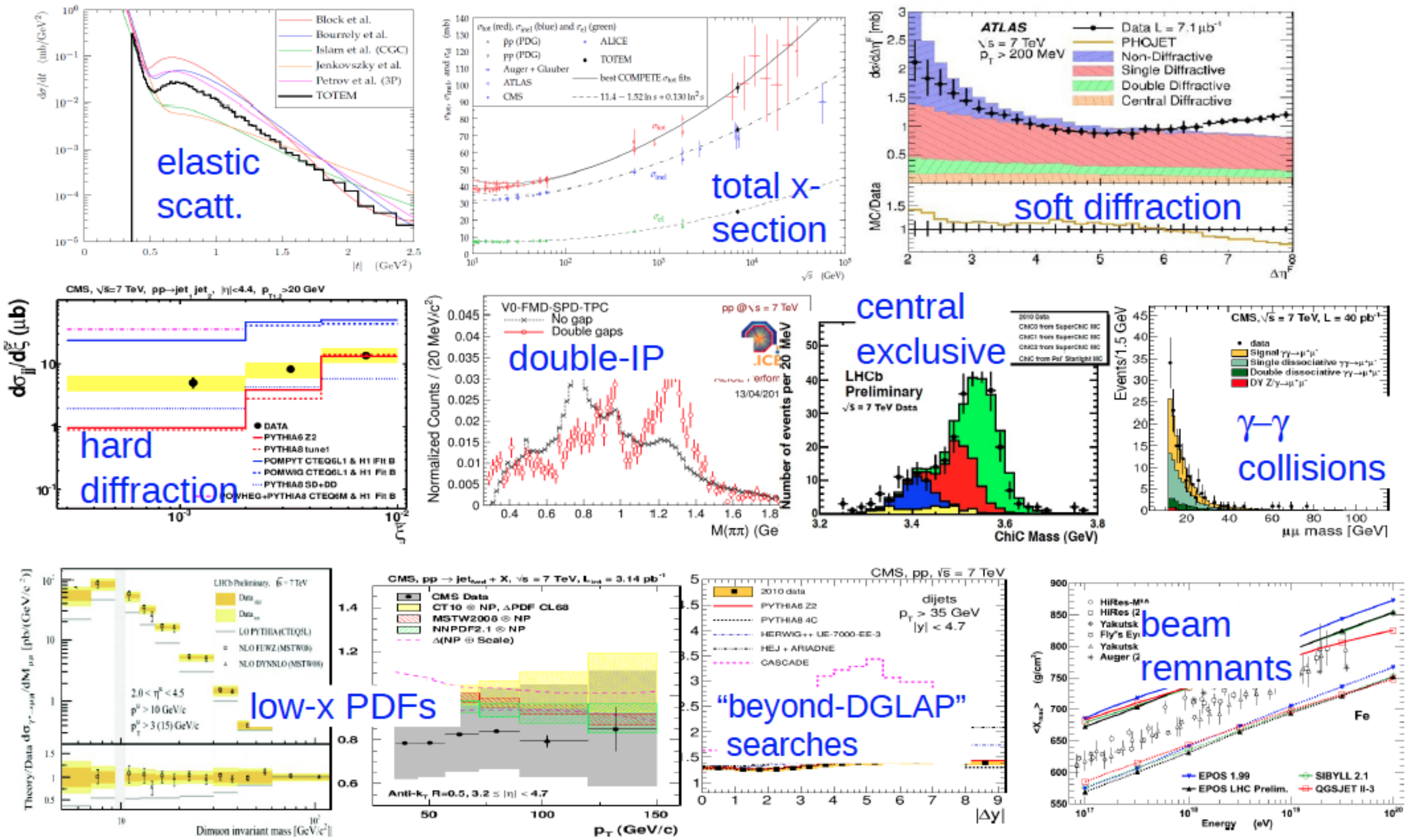
Low β* (~ 0.6 meter)

Low mass states, large & small cross section processes

(standard luminosity optics)

Conclusions
(from: D. d'Enterria)

- The LHC is providing a wealth of new forward data open to study !



- Exciting experimental/theoretical QCD physics for the years to come!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

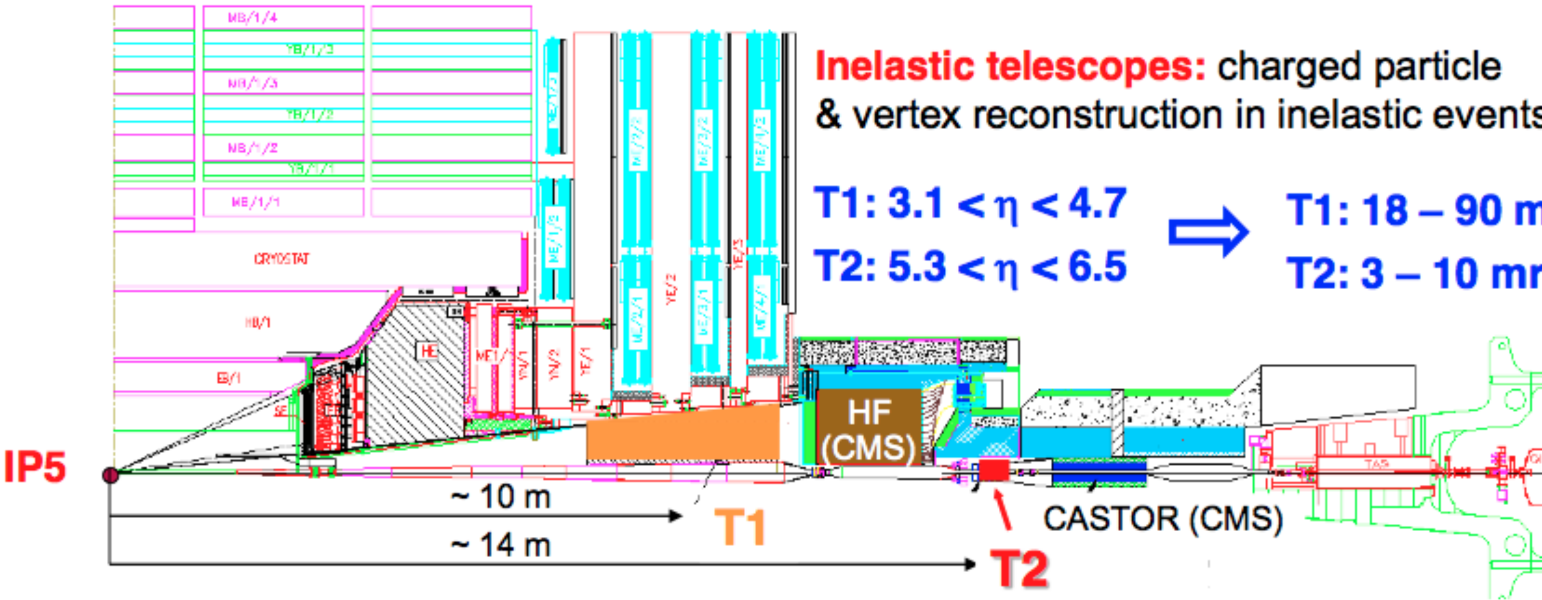
Backup

The TOTEM Detector

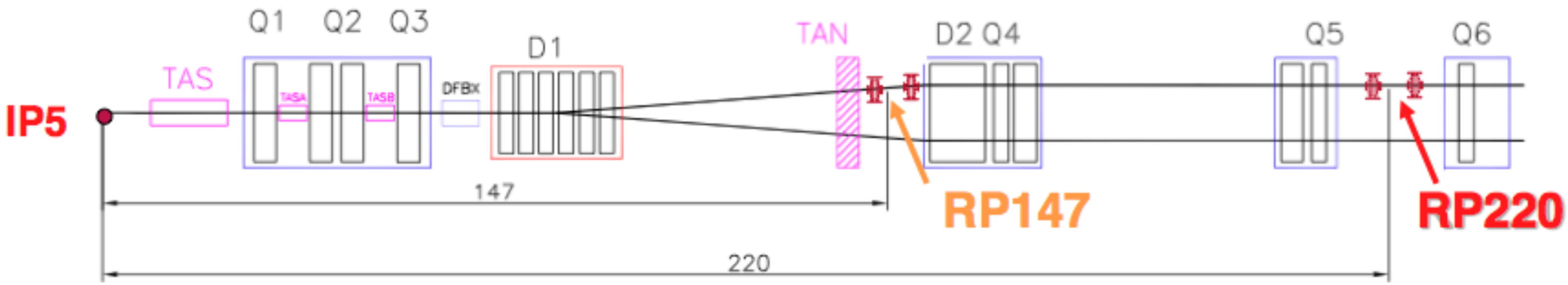
Inelastic telescopes: charged particle & vertex reconstruction in inelastic events

T1: 3.1 < η < 4.7 ⇨ **T1: 18 – 90 mrad**

T2: 5.3 < η < 6.5 **T2: 3 – 10 mrad**



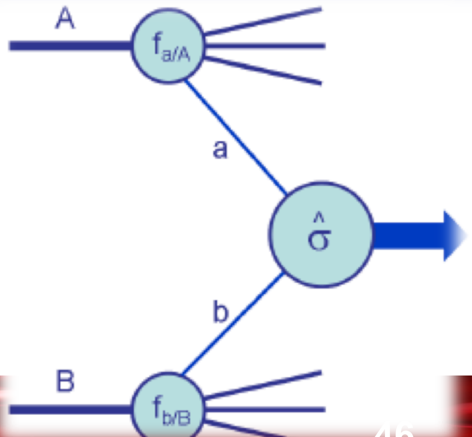
Roman Pots: measure elastic & diffractive protons close to outgoing beam



Diffraction ? A way to probe the proton

- Protons are not elementary particles: made of **partons**.
  $\Rightarrow$ **P**arton **D**istribution **F**unctions (**PDF**s) essential to relate theory to experiment at the LHC (and Tevatron, HERA, ...).
- $f_{a/A}(x, Q^2)$ gives *number density* of partons a in hadron A with momentum fraction x at a hard scale $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$.

$$\sigma_{AB} = \sum_{a,b=q,g} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a/A}(x_a, Q^2)\, f_{b/B}(x_b, Q^2)\, \hat{\sigma}_{ab}$$



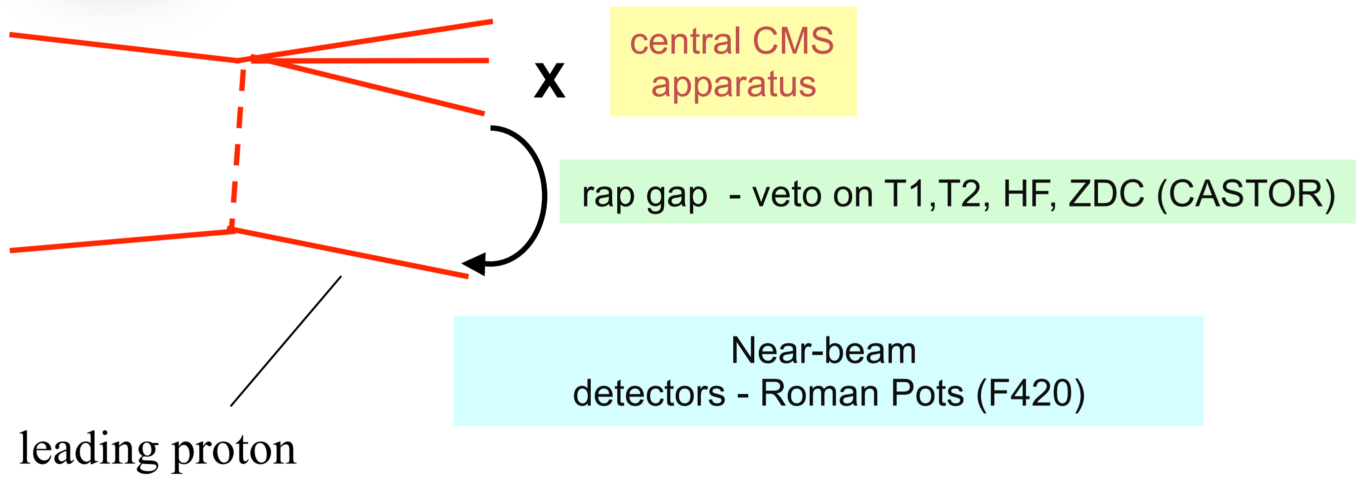
Experimental Issues in selecting diffractive events at the LHC

1. Trigger is a major limiting factor for selecting diffractive events

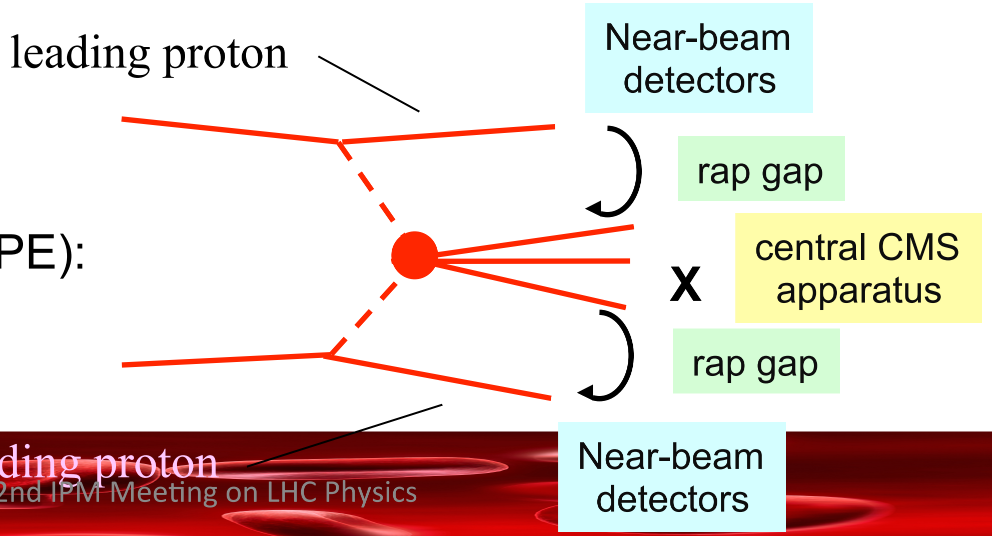
2. Background from non-diffractive events that mimic diffractive events because of protons from pile-up events

Diffractive Physics with CMS, TOTEM, and the Forward Detectors

Single diffraction (SD):



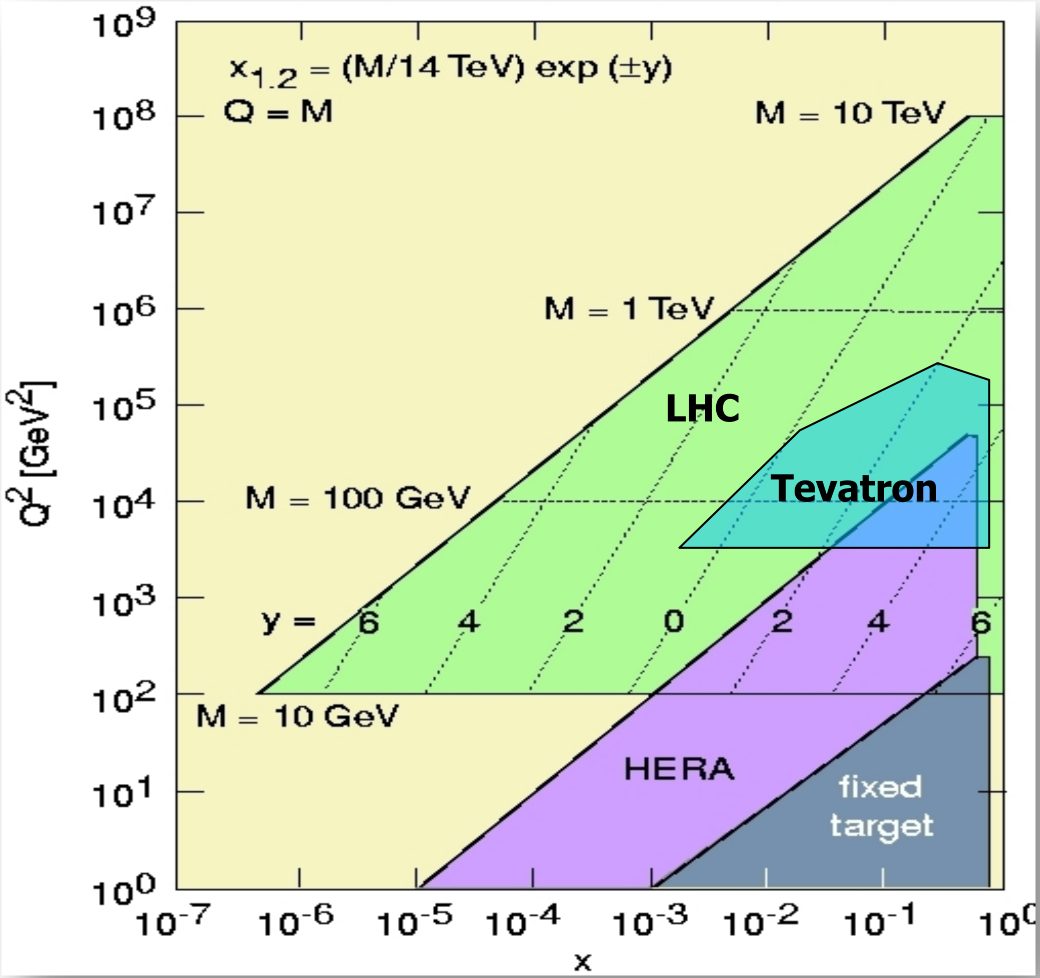
Double Pomeron exchange (DPE):



From the Tevatron to the LHC

- LHC will probe forward rapidities y ~ 5, Q^2 ~ 100 GeV and x down to ~10^{-5}
- Some of the available processes:

Inclusive single diffraction (SD) and double "pomeron" exchange (DPE)	pp→pX pp→pXp
production of dijets, vector bosons and heavy quarks	pp→pjjX pp→p*W*(*Z*) pp→pq$\bar{q}$
Central exclusive production	pp →p*H*p with *H* (120GeV)→ b$\bar{b}$
High energy photon interactions	pp→pWX pp→(pγp)→p*WHX*



Based on Stirling's Eur. Phys. J. C 14, 133 (2000)

Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production

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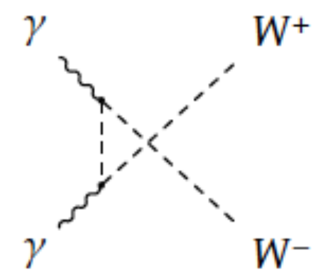
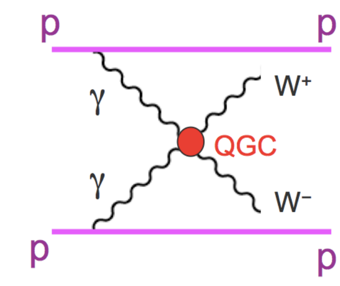
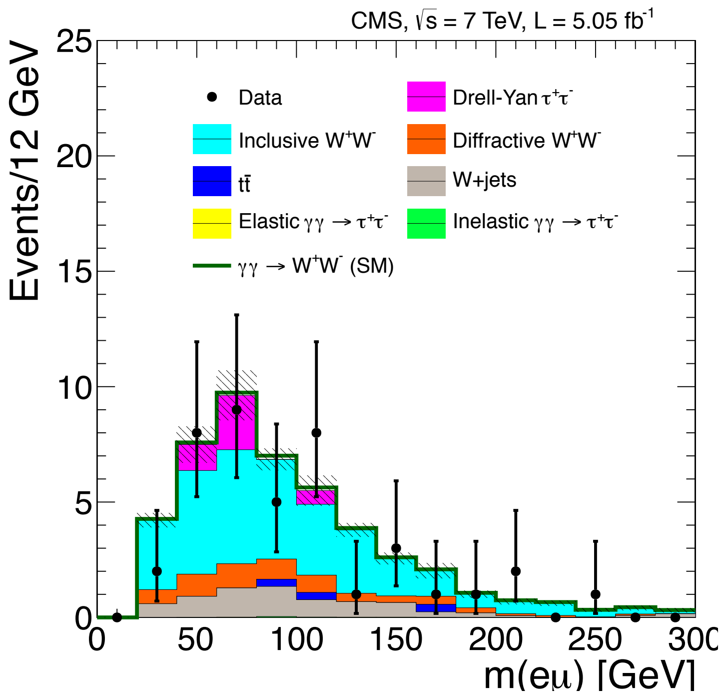
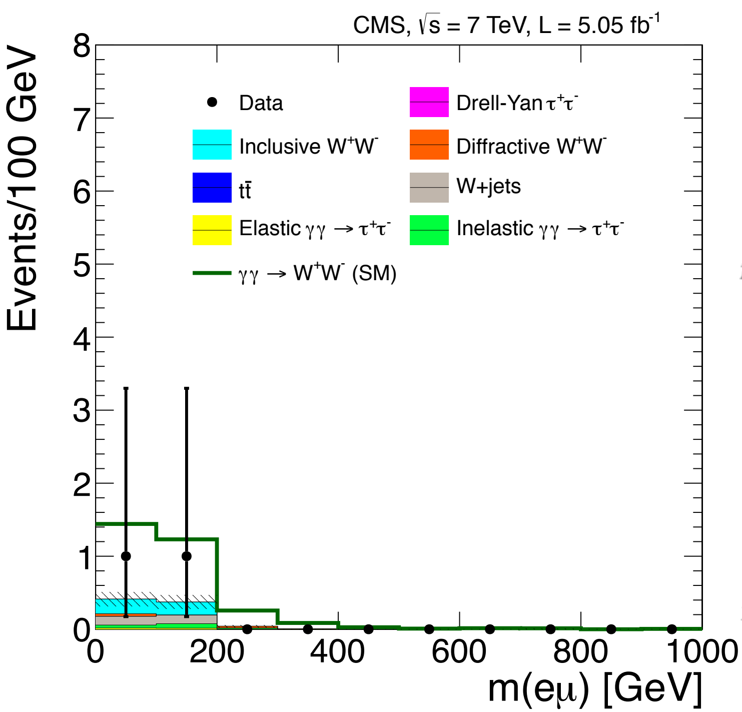
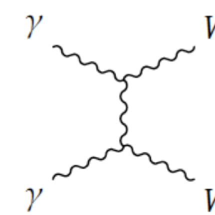
- Production of two photon of WW pairs is sensitive to Anomalous Quartic Gauge Couples (AQGC).
- CMS has the most stringent World limits on Quartic gauge couplings and it is ~100 times stronger than LEP results.

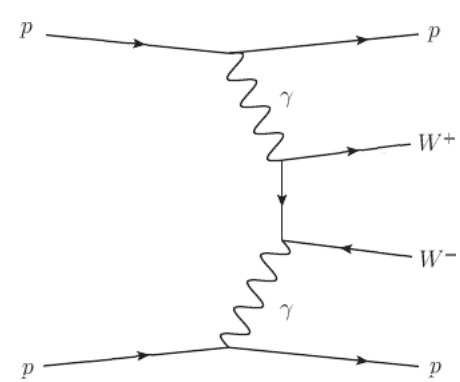












$$\sigma(pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.2^{+3.3}_{-2.0}\,\text{fb},$$

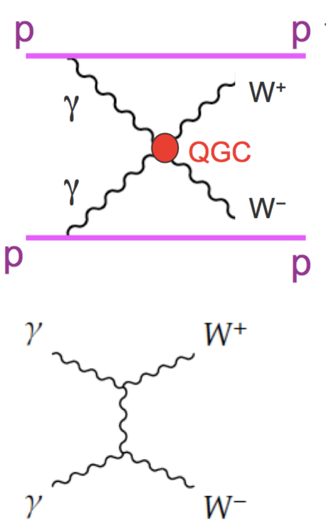
Quartic gauge coupling

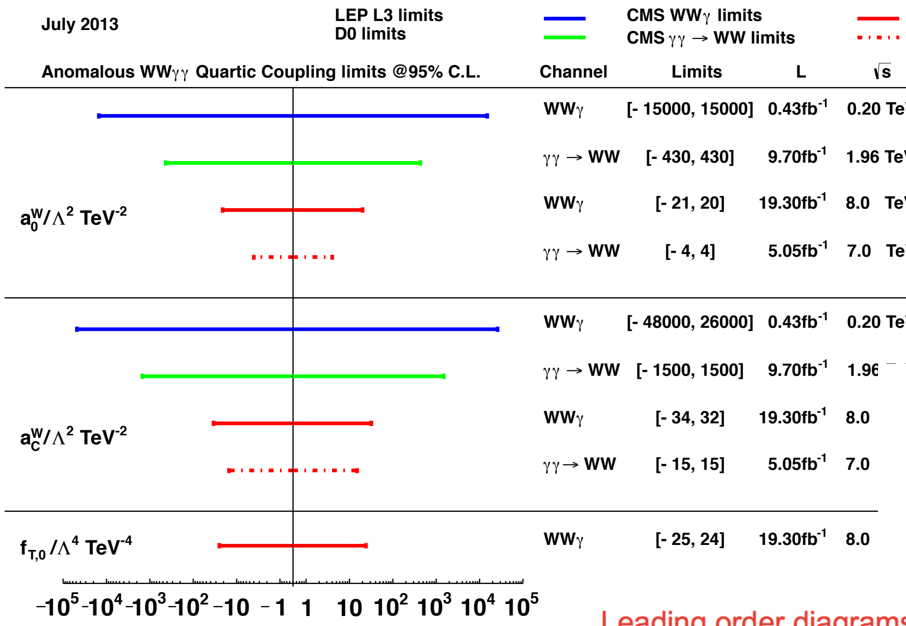
From Tiziano

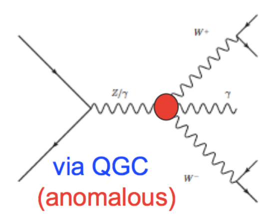
- CMS has the most stringent World limits on Quartic gauge couplings

Red is CMS limits range

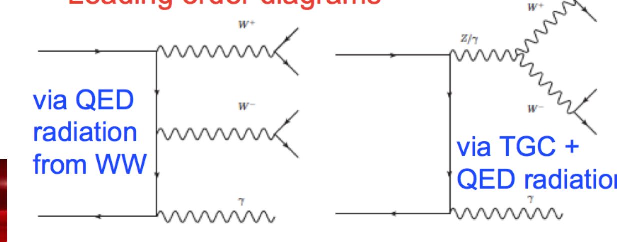
$\gamma\gamma \rightarrow$ WW





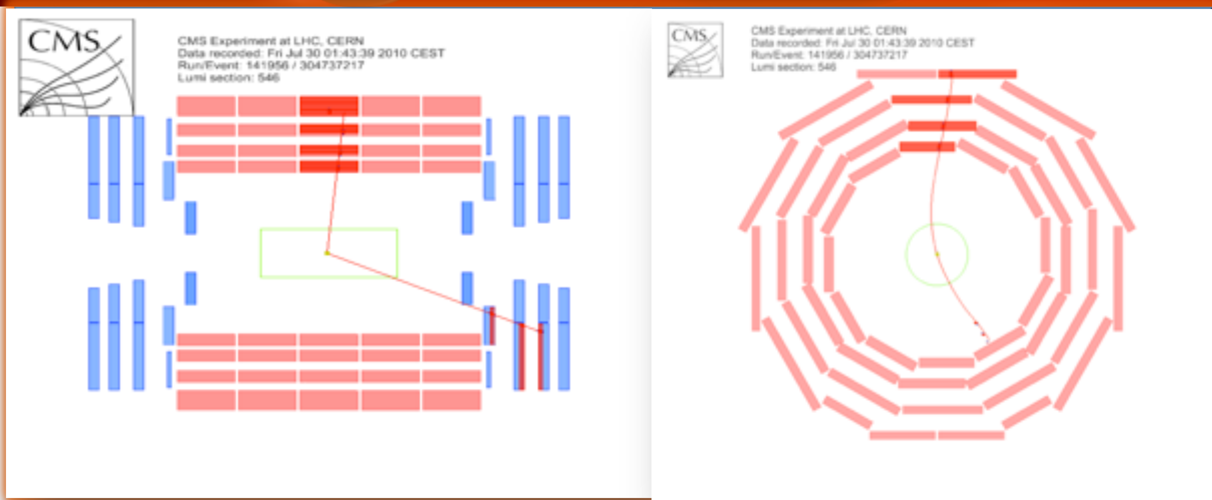


Leading order diagrams

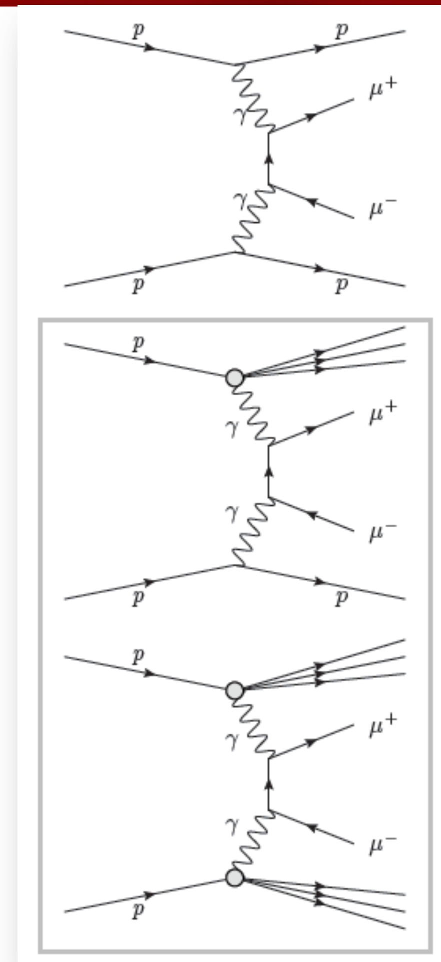


WWγ prod

Exclusivity Conditions



$$m = 20.51 \pm 0.2\ \text{GeV}$$
$$\frac{\Delta\phi}{\pi} = 0.98$$
$$\Delta p_T = 0.48$$



- impose exclusivity using tracking for dimuon and W^+W^-
- The e^+e^- and gamma-gamma analyses using the calorimeter
- 2010, each event of this process was accompanied by extra “PileUp” events within the same bunch crossing: **~ 2-3 pileup interactions**

CMS FSC Team

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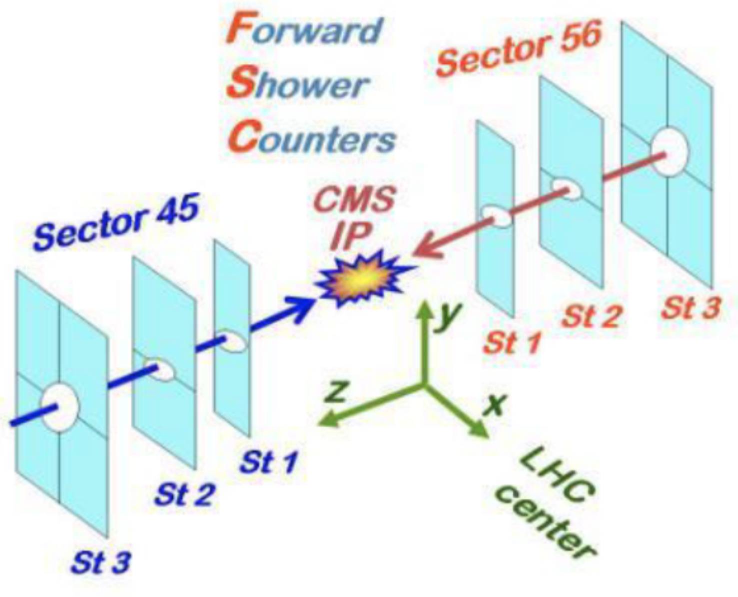
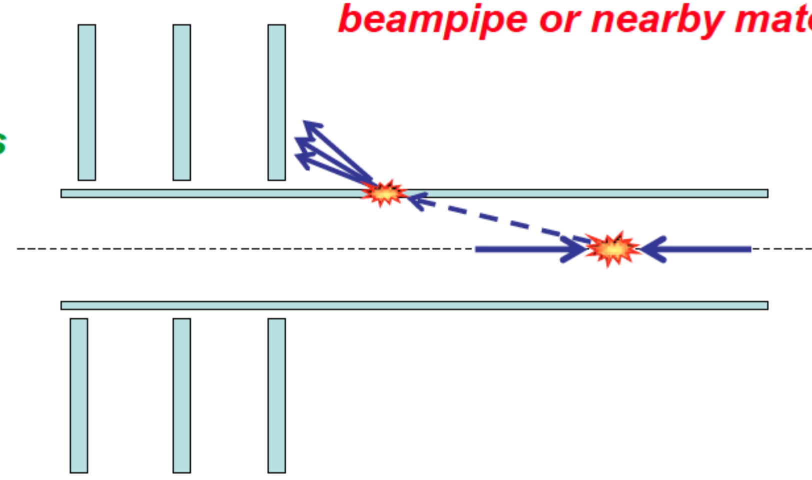


FSC Setup

- Scintillator paddles
  ~25cm x 25cm wide
  with one PMT each,
- 8 per side, symmetric to IP5
- See showers produced by particles from collisions in beampipe or nearby material

Forward Shower Counters cover a rapidity region:

$\sim 6 < |\eta| < 8$



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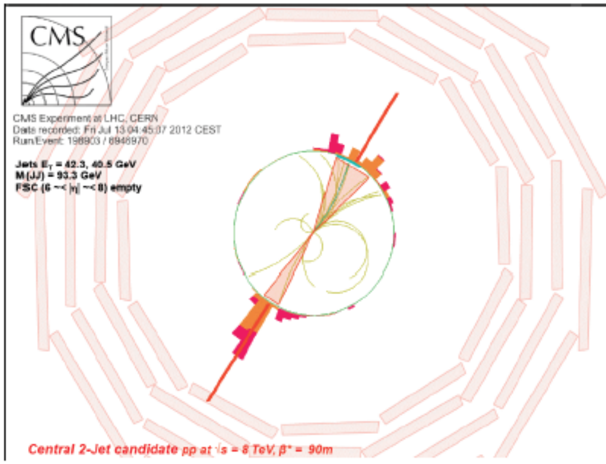
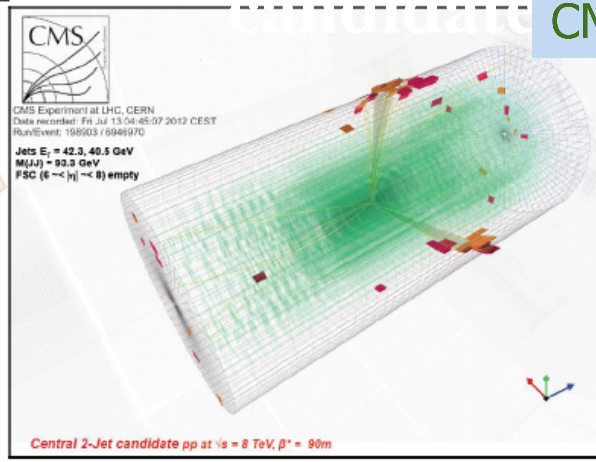
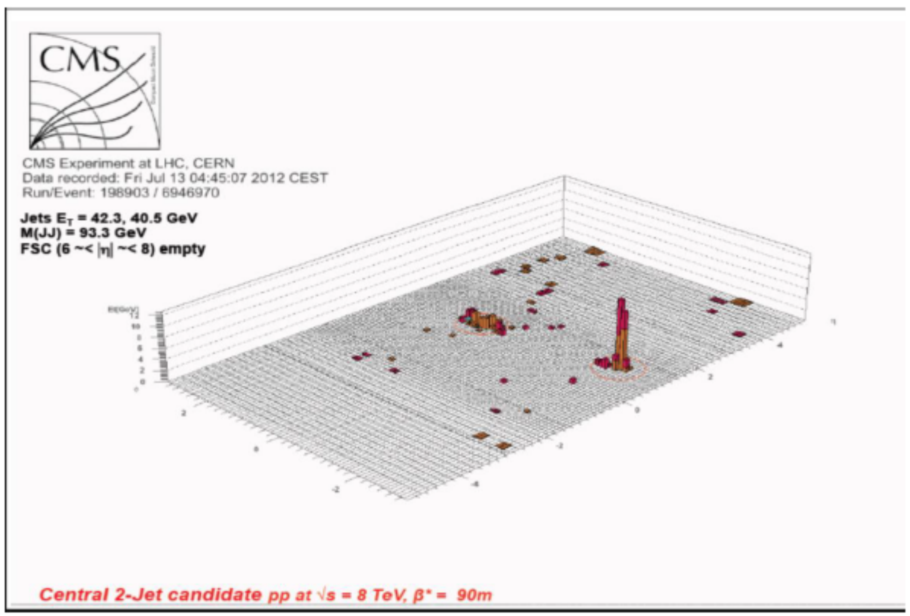
Central High-p_T jet production: Low PU at $\sqrt{8}$ TeV: 2-jet candidate

CMS-DP 2013/006

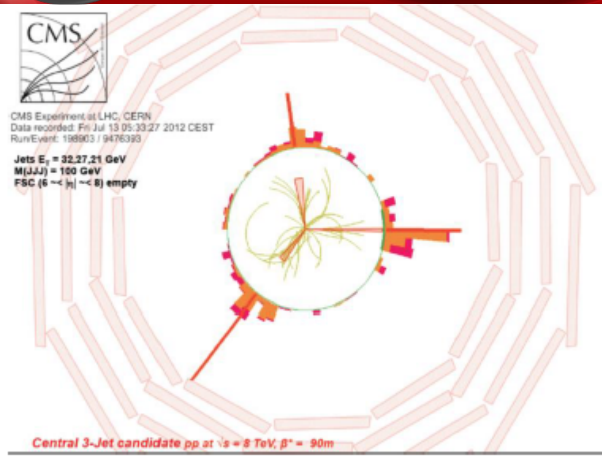


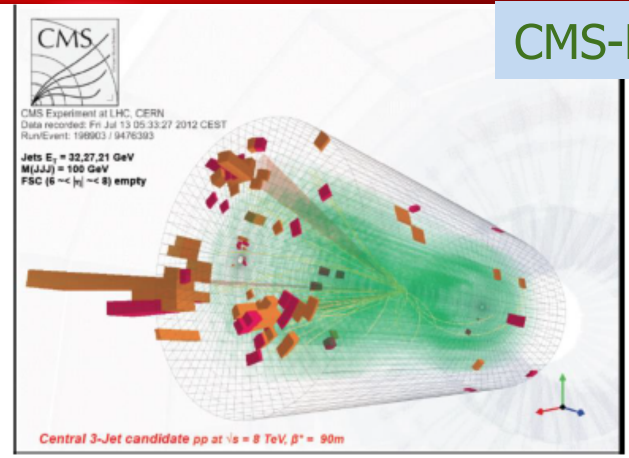


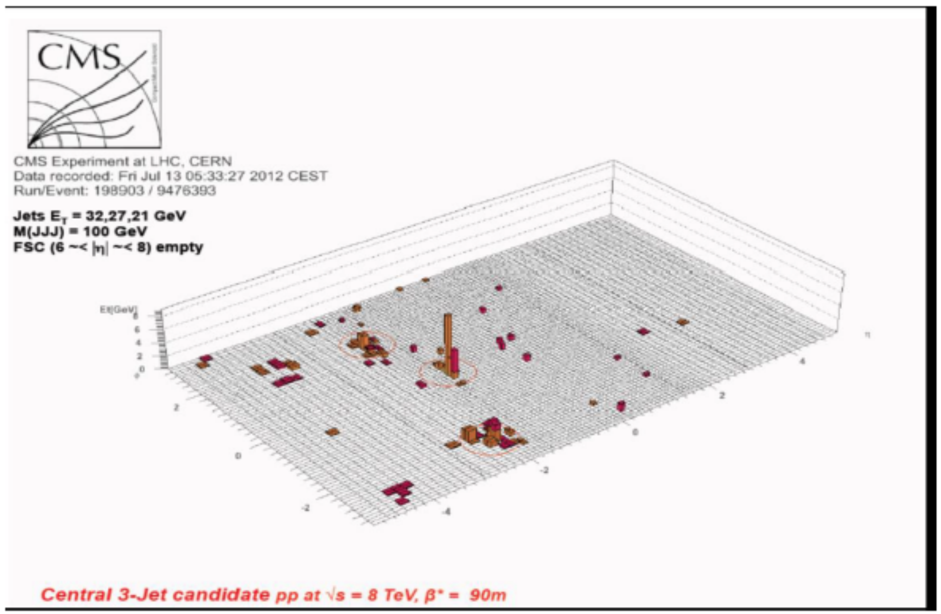


Central High-p_T jet production: Low PU at $\sqrt{8}$ TeV: 3-jet candidate

CMS-DP 2013/006



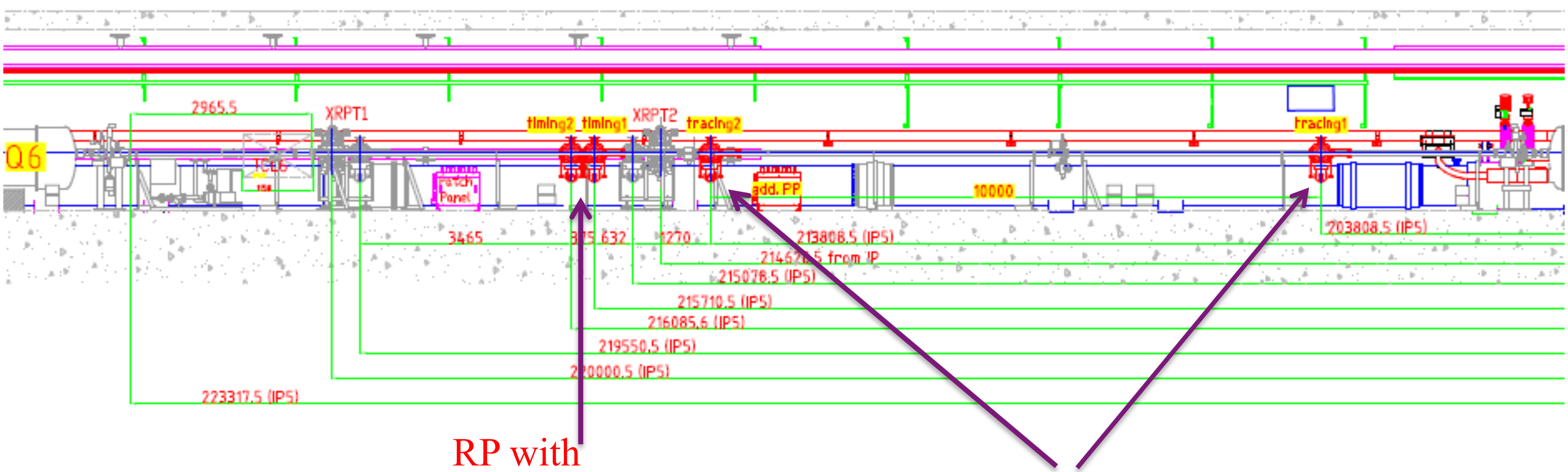




Phase II layout of the PPS-Totem project

Two Roman-Pots for tracking, 10 meters apart, instrumented with upgraded rad-hard pixel.

Timing detector in RPs and MBP (depending on what we learn)



RP with
timing detector

Rad-hard Si-pixel detectors