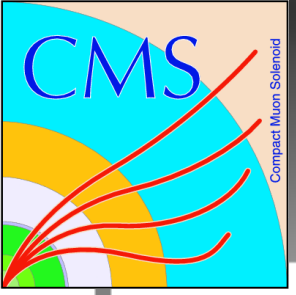



# Diffractive and Forward Physics at CMS

E.Kuznetsova (KIT)

*Heidelberg, School on Diffractive and Electromagnetic Processes, September 2013*

# INTRODUCTION

**Diffraction**

- soft diffraction
  - large contribution to total cross-section
  - Pomeron structure
- hard diffraction
  - gap survival probability

**Exclusive production ($\gamma\gamma$)**

- possible lumi measurements
- WW production – anomalous quartic couplings

**Forward QCD (non-diffractive)**

- small-x (forward jets)
- MPI/UE (energy flow)

**=> understanding of LHC events**

- underlying events
- crucial in high pile-up environment

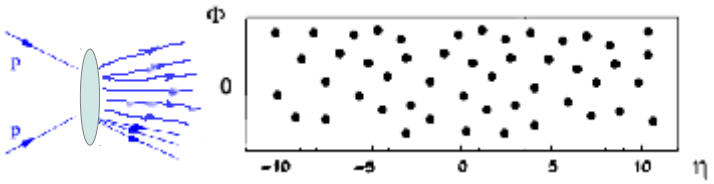
=> MC tunes, PU corrections

**=> input for cosmic ray physics (air shower)**

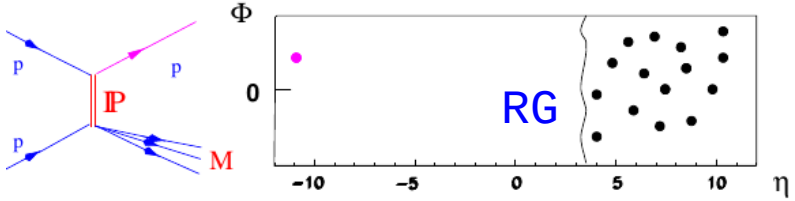
**==> no way to overview all results!..**

# INTRODUCTION

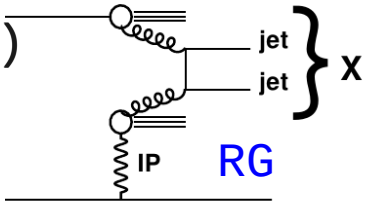
## Inelastic pp collisions:

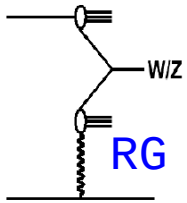



### Single Diffraction

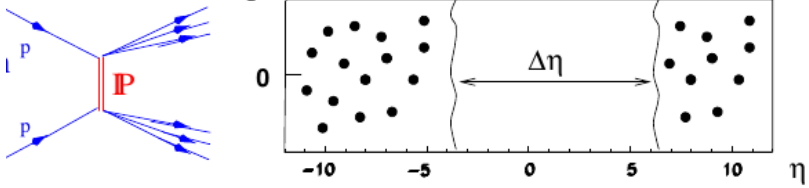



(semi-) hard

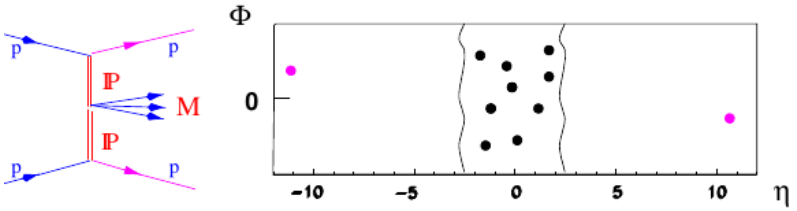


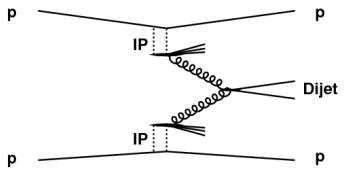

### Double Diffraction



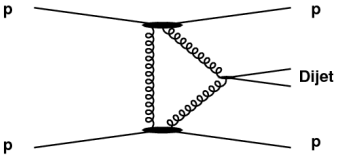

### Central Diffraction (DPE)



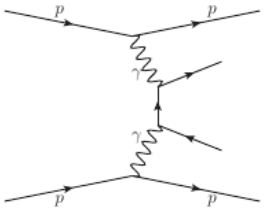

**inclusive**




**exclusive**




… similar topology – **central exclusive QED processes** (γγ interaction)




… γ-Pomeron... not covered here

# Introduction

## Diffraction

- large contribution to total inelastic x-section

| 7 TeV | SD | DD | CD | SD+DD+CD |
|---|---|---|---|---|
| PYTHIA6 | 19% | 13% | - | 32% |
| PHOJET | 14% | 5% | 2% | 21% |

SD $\frac{d\sigma}{dM_X^2} \propto \frac{1}{M_X^2}$

DD $\frac{d\sigma}{dM_X^2 dM_Y^2} \propto \frac{1}{M_X^2 M_Y^2}$

- topology:
  - rapidity gap(s)+ diffractively produced system (CMS)
  - proton tagging (TOTEM)
  - proton tagging + diffractively produced system (CMS+TOTEM)

- mass of diffractive system (e.g. SD): $\xi = M_x^2/s$
  - measurement from diffractive products

Momentum and energy conservation:
E(Pomeron) + E(proton 1) = E(X)
$p_z$(Pomeron) + $p_z$(proton 1) = $p_z$(X)

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

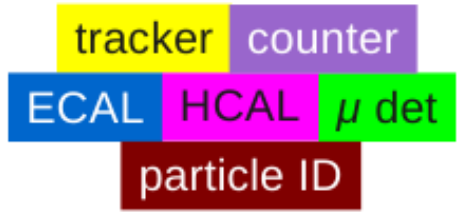
  - direct proton momentum loss measurements(TOTEM, CMS+TOTEM)

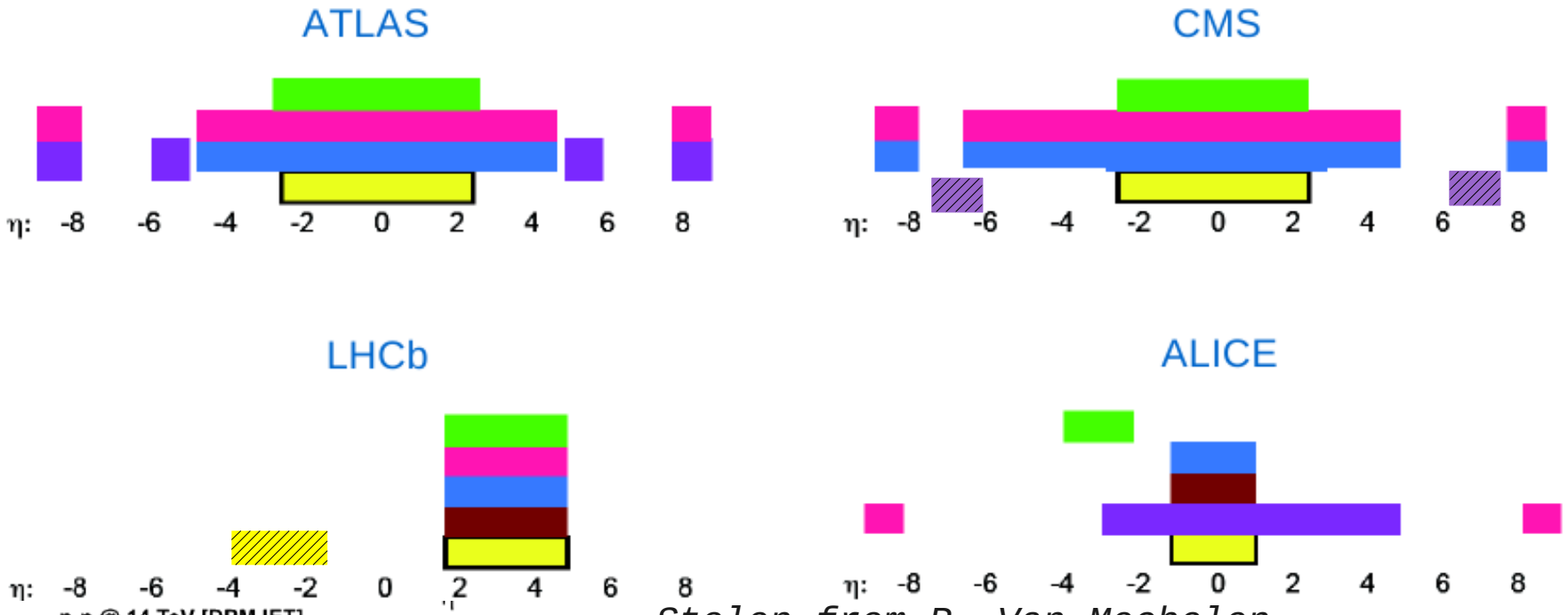
=> we need large acceptance! (and TOTEM :)

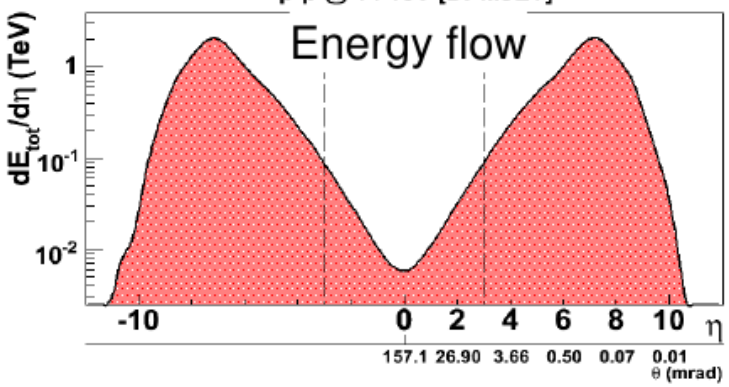
...and low “noise”

# Acceptance

## Acceptance of LHC experiments



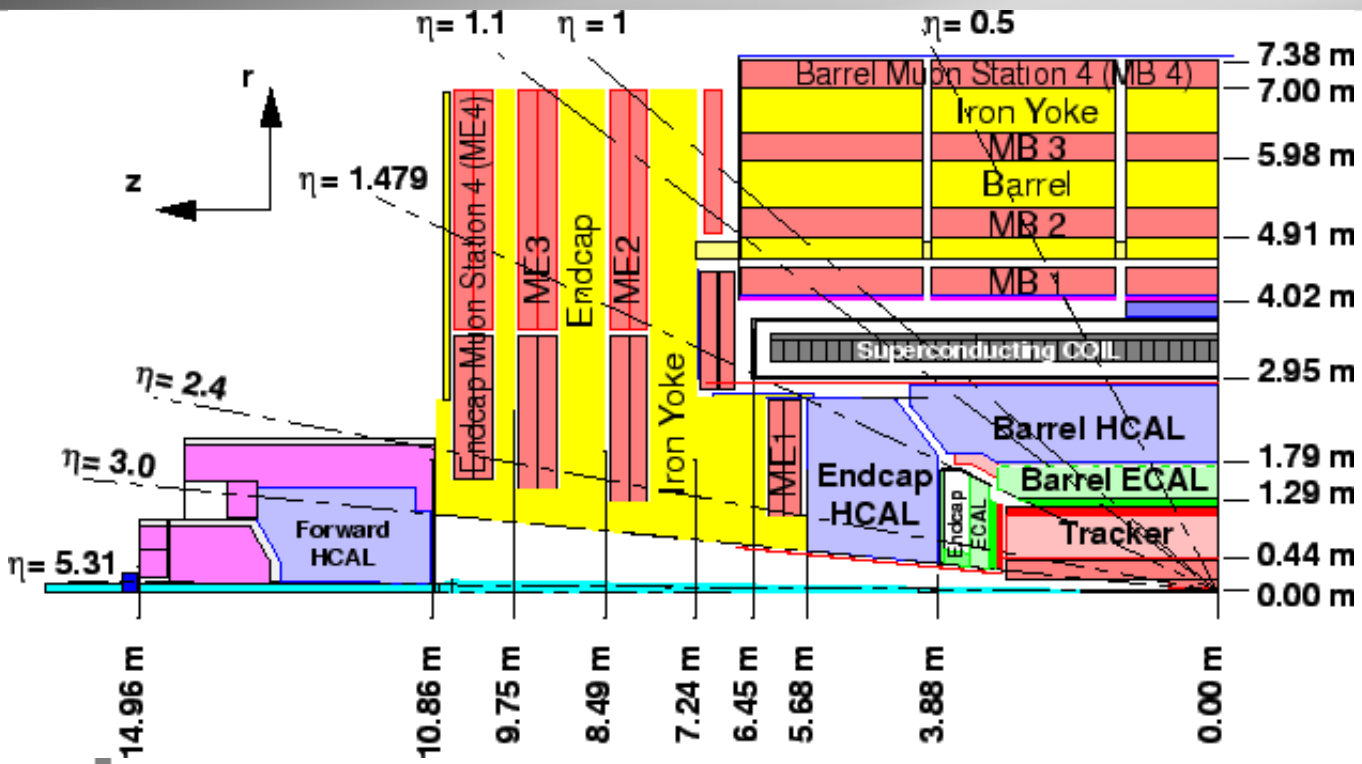

*Stolen from P. Van Mechelen*

*Talk at INT Workshop Perturbative and Non-Perturbative Aspects of QCD at Collider Energies, Seattle, 2010*

***introduced later***

*Stolen from D. d'Enterria (2008)*

# CMS central detector




## Muons

(CSC+DT+RPC)
$|\eta|<2.4$

## Tracker

(Pixel+SiStrip)
$|\eta|<2.4$; $P_t>100$ MeV

***Calorimetry + tracking***
**Particle Flow Objects**

## ECAL

PbWO4: $|\eta|<3$

## HCAL

central: scint.+brass : $|\eta|<3$
$\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$

**HF**: steel+quartz : $2.9<|\eta|<5.2$
$\Delta\eta \times \Delta\varphi \sim 0.175 \times 175$

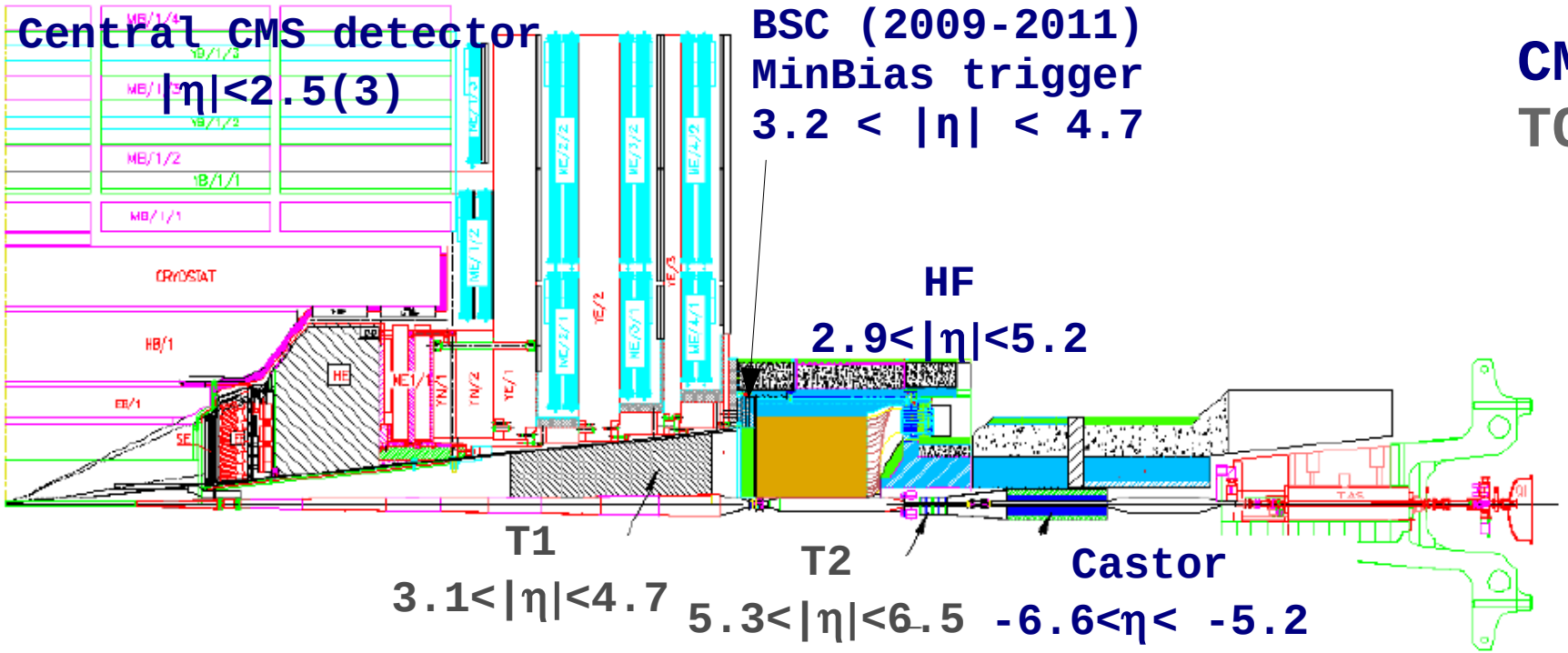
# FORWARD INSTRUMENTATION @ P5

Central CMS detector
|η|<2.5(3)

BSC (2009-2011)
MinBias trigger
3.2 < |η| < 4.7

CMS
TOTEM

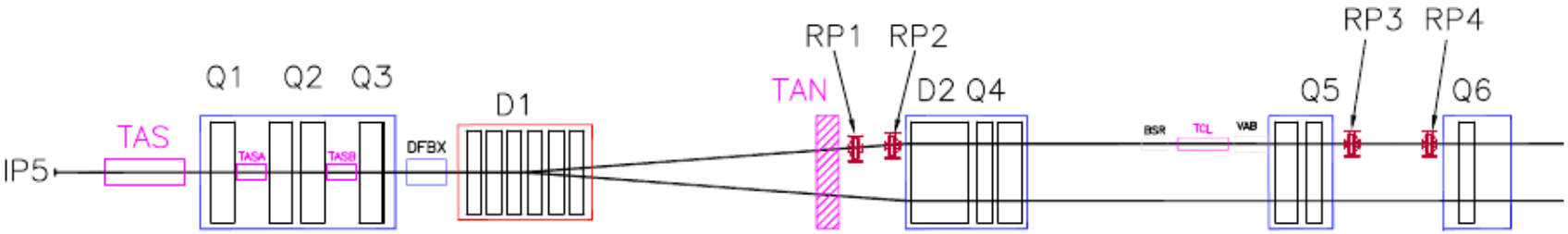
HF
2.9<|η|<5.2




T1
3.1<|η|<4.7

T2
5.3<|η|<6.5

Castor
-6.6<η< -5.2

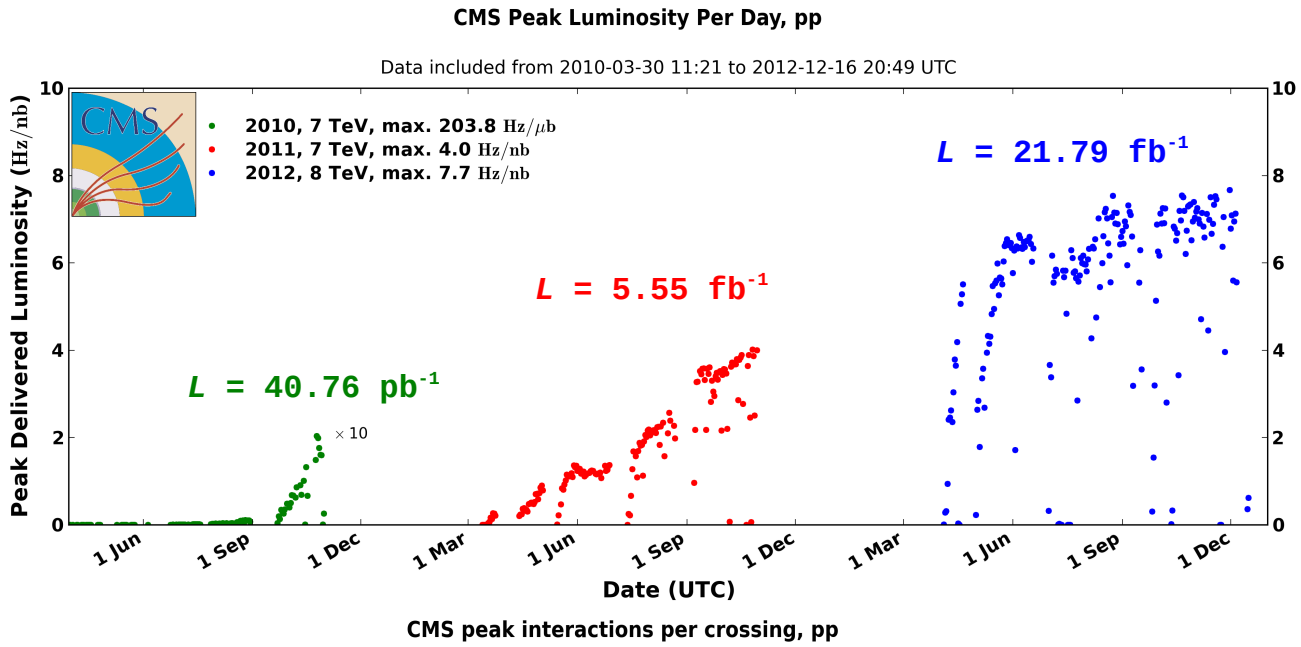


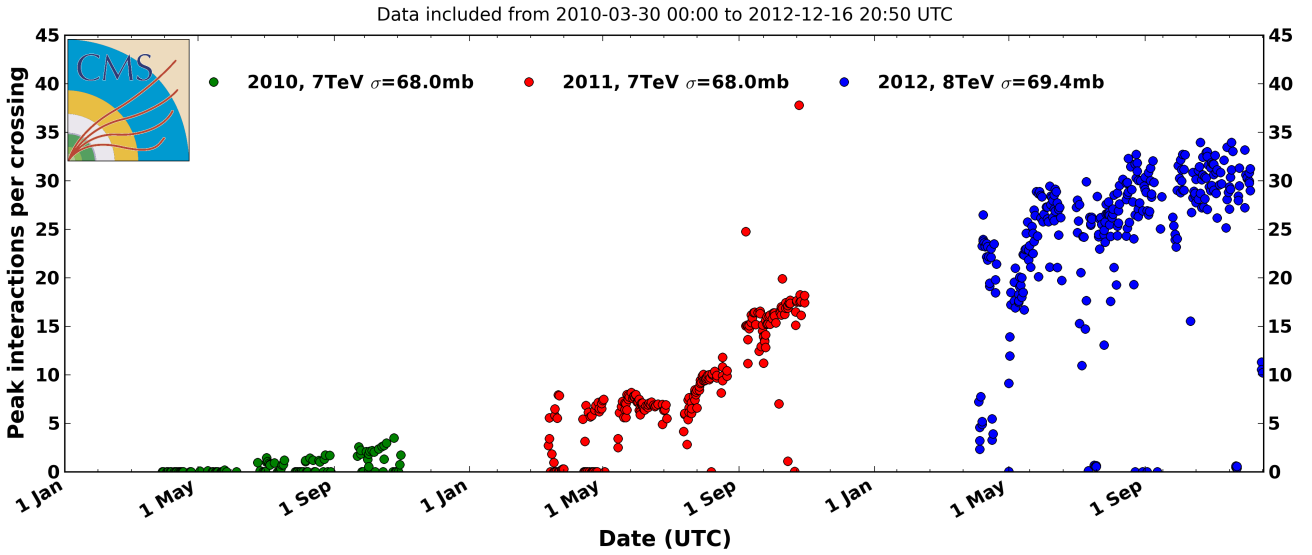

...59..85..114m
FSC (>2011)
~6<|η|<~8
η=f(ϕ)

RP@147m
...140m
ZDC(neutral)
8.2<|η|

RP@220m

# DATA – lumi vs pile-up




**"Pile-Up" = price for luminosity!**

**Still OK for most of analyses (good primary vertex resolution), but not for diffraction and forward physics:(**

**(but not a problem for large x-sec processes :)**

**...and exclusive γγ analyses with leptonic final states survive!**

**=>**
**Most of the results low pile-up data 2010, however....**

# Total inelastic cross section

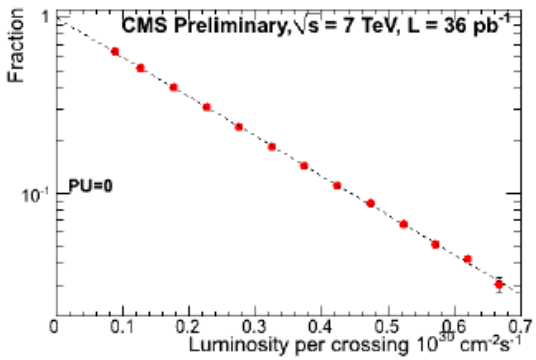
PLB 722 (2013) 5, http://arxiv.org/abs/arXiv:1210.67181206 (2012) 036 (PAS-FWD-11-001)

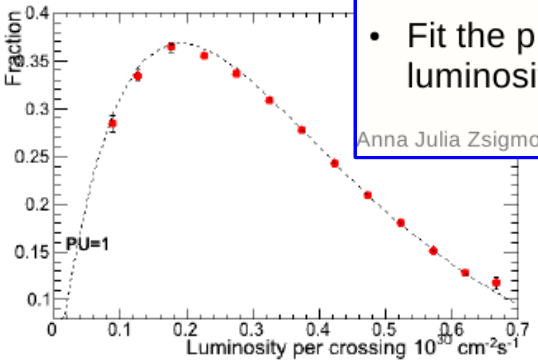
- If we count the number of pile-up events as a function of the instantaneous luminosity, we can measure the pp cross section:

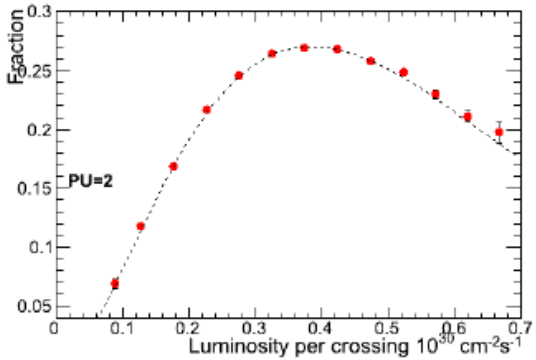
$$P(n) = \frac{(L \cdot \sigma)^n}{n!} e^{-L \cdot \sigma}$$

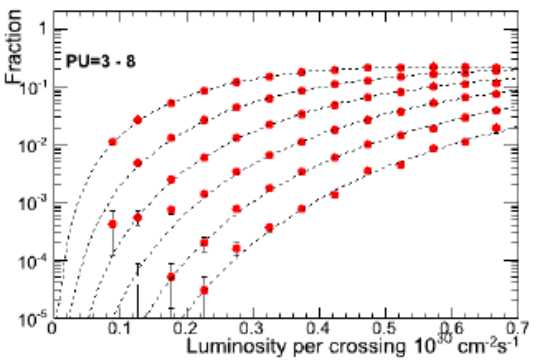
- Acquire the bunch crossing using a primary event:
  - the bunch crossing is recorded because there was an event that fired the trigger. We don't use this primary event, we only use it to record the bunch crossing.
- Count the number of pile-up events:
  - for any given bunch crossing, we count the number of vertices in the event.
- Correct the number of visible vertices for various effects:
  - vertex merging, vertex splitting, real secondary vertices…
- Fit the probability of having n = 0, … 8 pile-up events as a function of luminosity: using a Poisson fit, we obtain 9 values of $\sigma_{visible}$





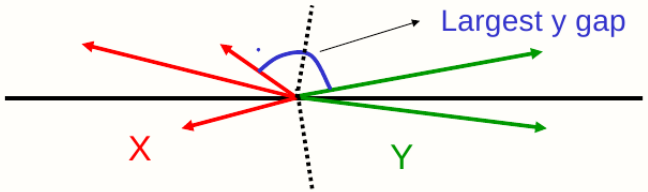




**+ x-check with HF @ PU < 0.11**

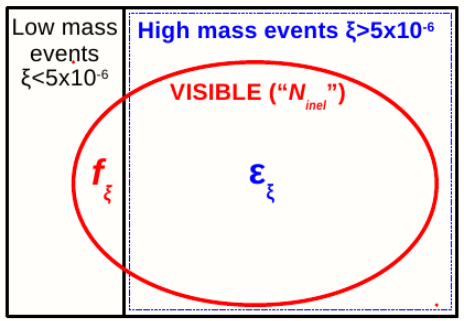
# Total inelastic cross section

PLB 722 (2013) 5, http://arxiv.org/abs/arXiv:1210.67181206 (2012) 036 (PAS-FWD-11-001, QCD-11-002)

**Selection:** any event with at least one HF hit > 5GeV




- $\xi = M_X^2/s$ where $M_X > M_Y$ the invariant mass of the system
- In case of single diffractive events, ξ is the fractional momentum loss of the scattered proton




- $f_\xi$: fraction of visible events that are low mass (contamination)
- $\varepsilon_\xi$: fraction of high mass events that are visible (efficiency)

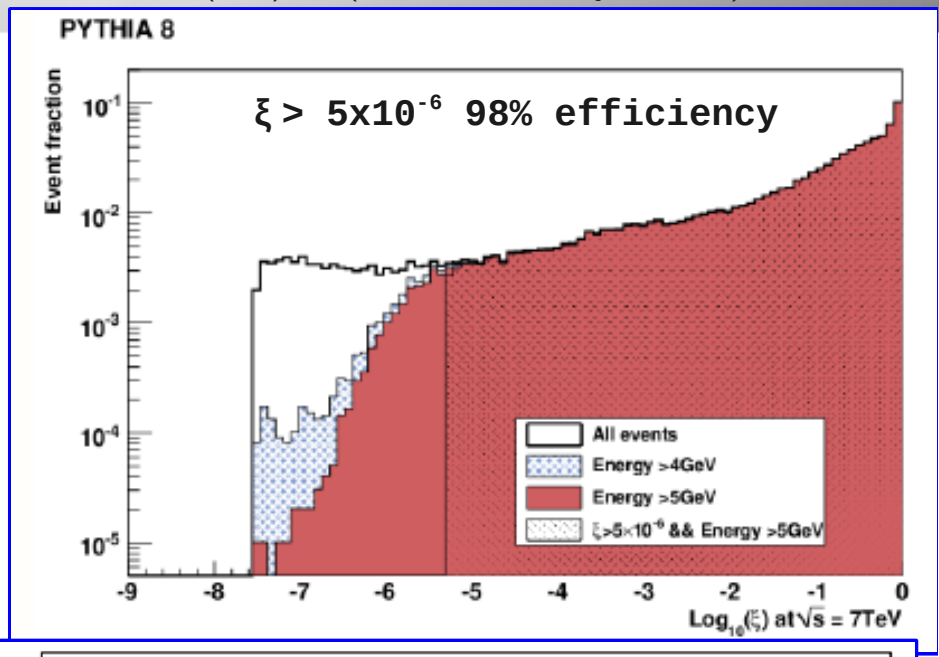
$$\sigma_{\text{inel}}(\xi > 5\times10^{-6}) = \frac{N_{\text{inel}}(1-f_\xi)F_{\text{pileup}}}{\mathcal{L}\epsilon_\xi}$$

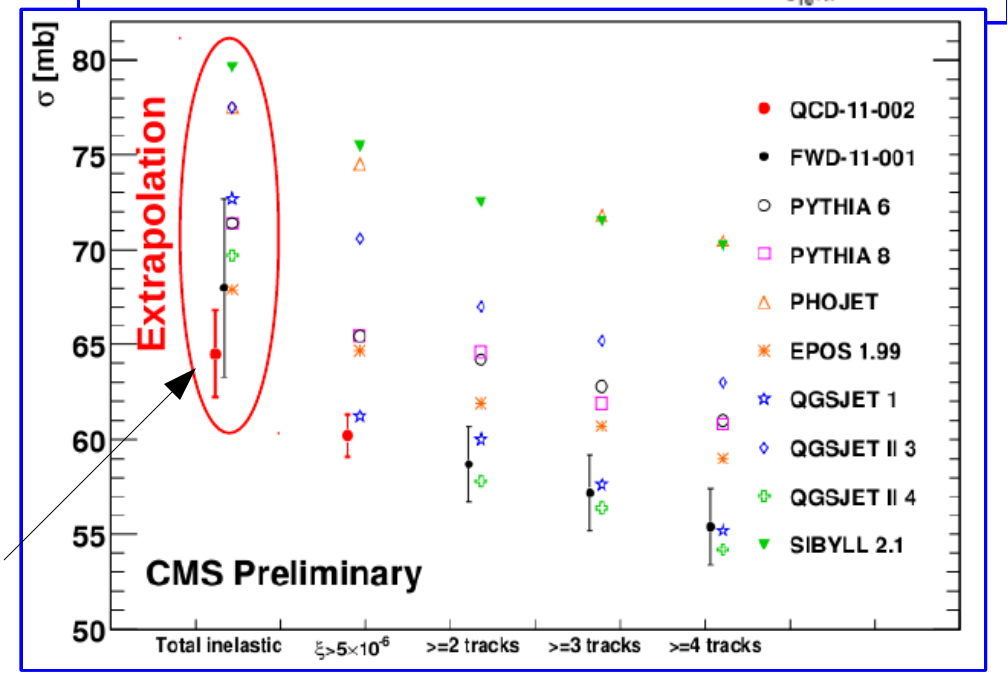
Pile-up correction

Luminosity

$\sigma_{\text{inel}}$ = 64.5 ± 0.2 (stat.) ± 1.1 (syst.) ± 2.6 (lumi.) ± 1.5 (extr.) mb

$\sigma_{\text{inel}}$ = 68 ± 2.0 (syst.) ± 2.4 (lumi.) ± 4 (extr.) mb




*Track: |η|<2.4; Pt>200MeV/c*

# Soft diffractive x-section

CMS PAS FSQ-12-005

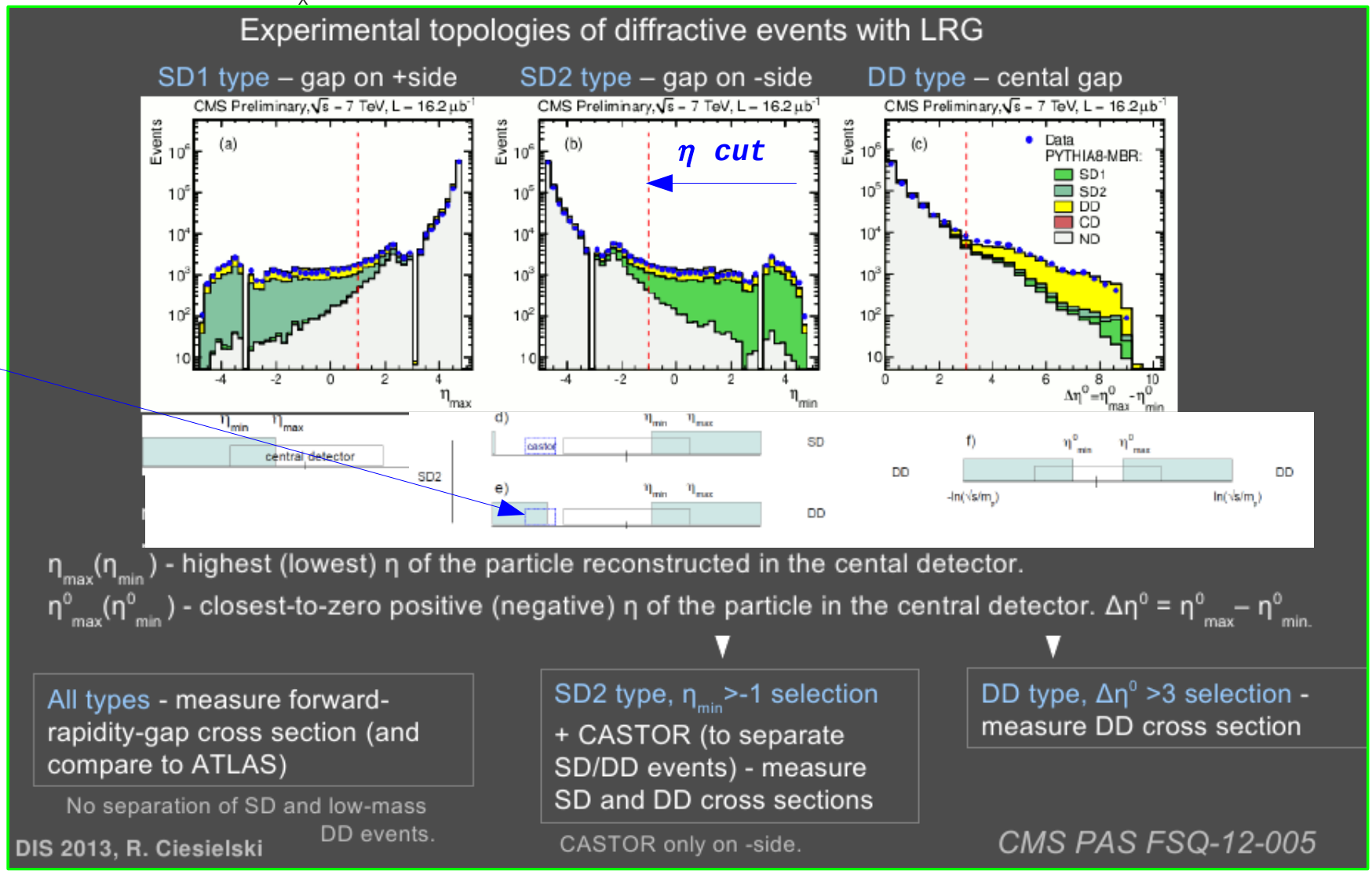
**Data:** Low-PU (~0.14) 2010 data at $\sqrt{s}$= 7 TeV

**Selection:** MinBias with BSC (~total inelastic sample) + LRG topology

At least 2 particle candidates in the BSC acceptance $|\eta|<4.7$

No vertex requirement ($M_X$<100 GeV)

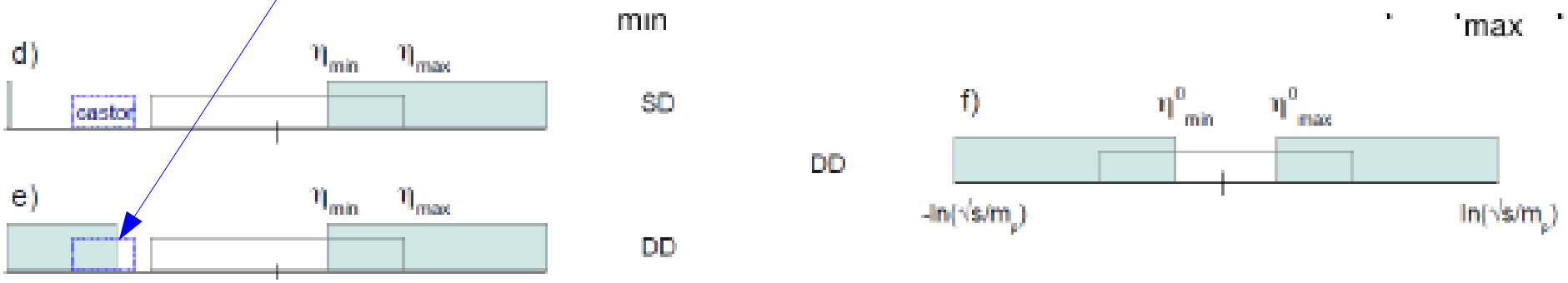
***CASTOR tag any signal E >1.48 GeV***



# Soft diffractive x-section

CMS PAS FSQ-12-005

***CASTOR tag***
***any signal***
***E >1.48 GeV***



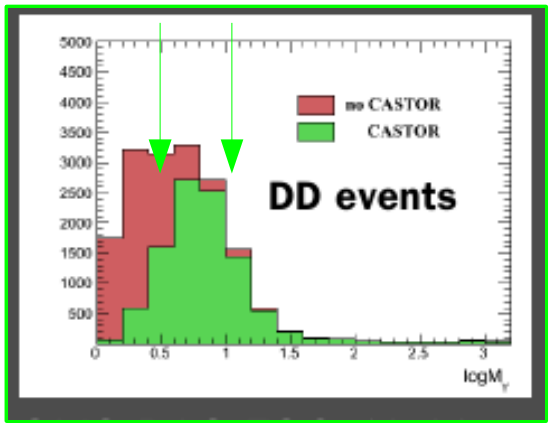
# Soft diffractive x-section

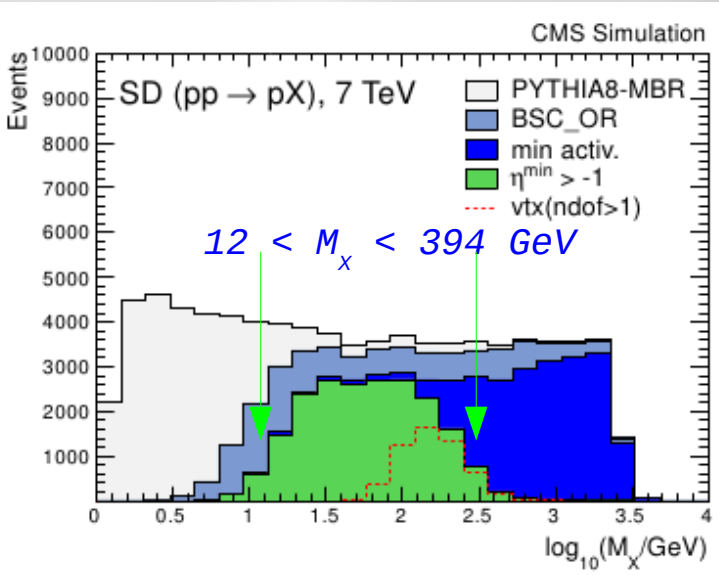
CMS PAS FSQ-12-005

**MC (gen. level): η cut (SD)**

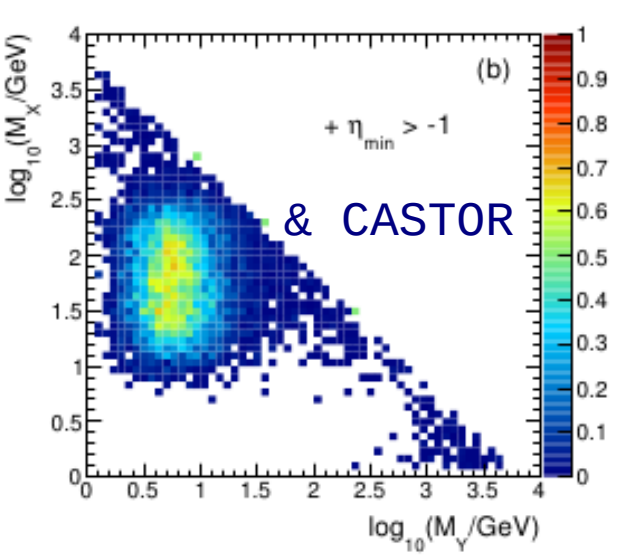
**CASTOR tag (DD)**

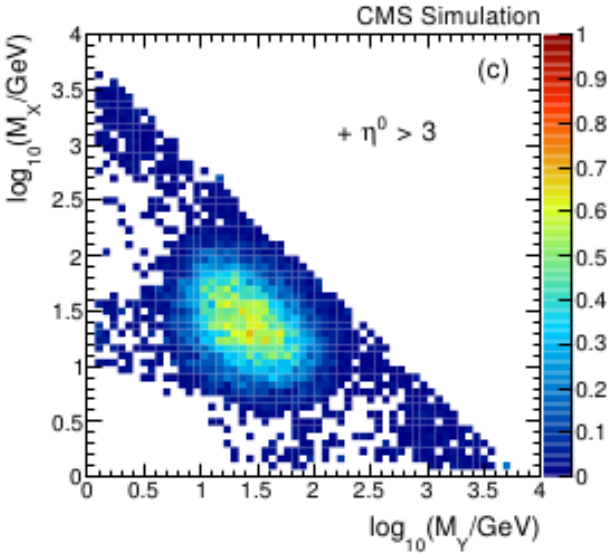
*3.2 < $M_Y$ < 12 GeV*




**DD MC (gen. Level); selection efficiency**




**$\xi = M_x^2/s$** ← $\xi = \frac{\sum(E^i + p_z^i)}{\sqrt{s}}$ ,

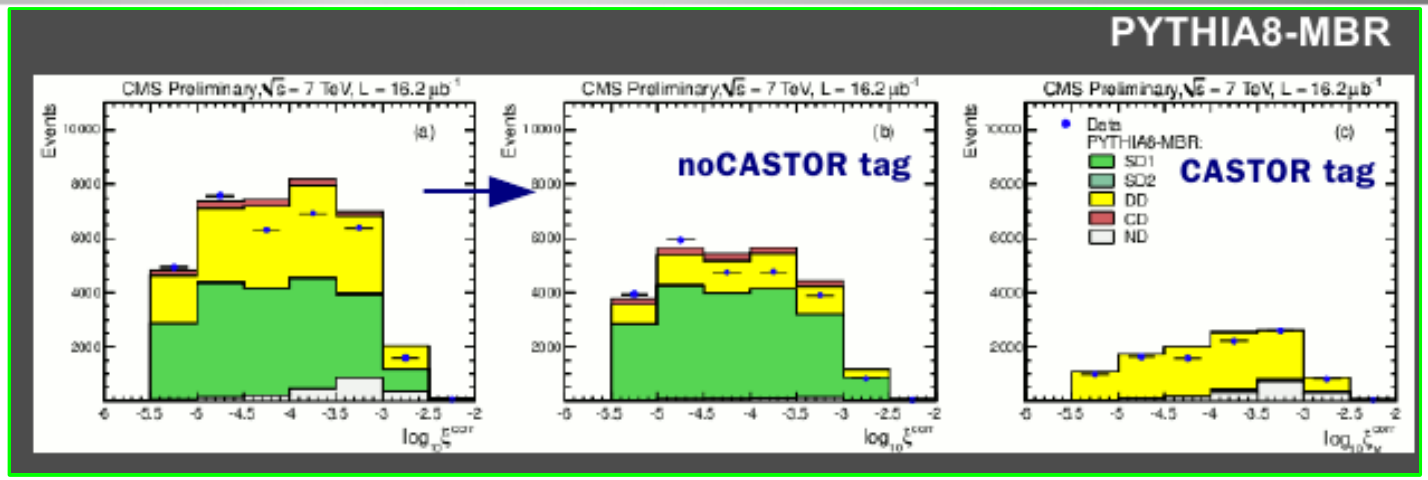
**=>** **ξ needs to be corrected for undetected particles**

**(a MC based ξ dependent correction)**

# Soft diffractive x-section

CMS PAS FSQ-12-005

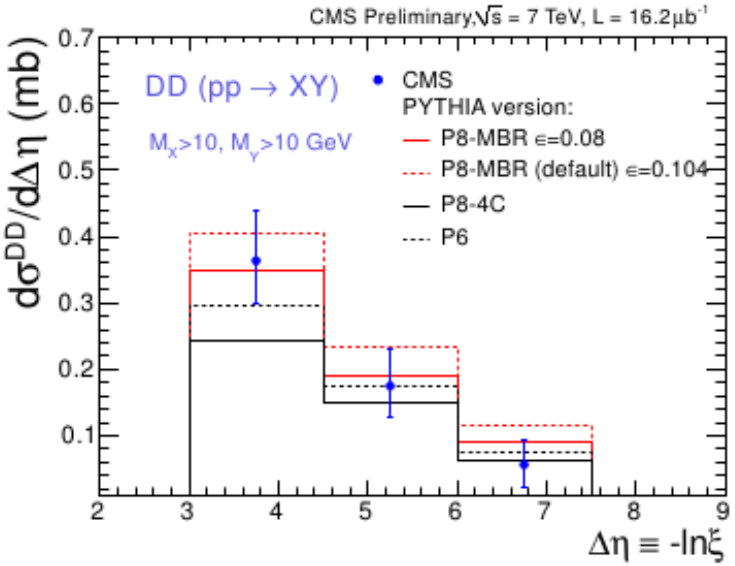
## Detector-level distribution ξ:

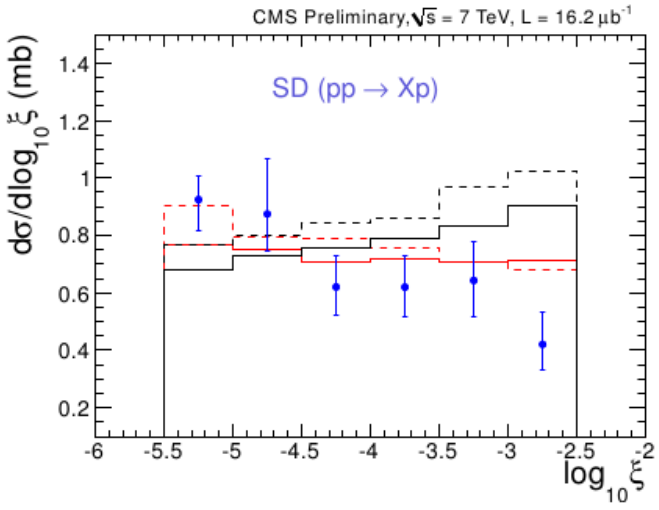


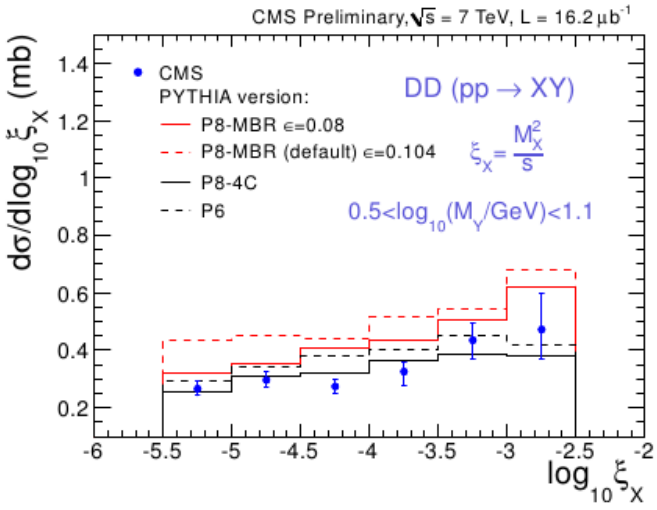

## Cross-section:

$$\frac{d\sigma^{SD}}{d\log_{10}\xi} = \frac{N^{data}_{noCASTOR} - (N_{DD} + N_{CD} + N_{ND})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi)_{bin}}$$

$$\frac{d\sigma^{DD}}{d\log_{10}\xi_X} = \frac{N^{data}_{CASTOR} - (N_{ND} + N_{SD} + N_{CD})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi_X)_{bin}}$$




$$\frac{d\sigma^{DD}}{d\Delta\eta} = \frac{N^{data} - (N_{ND} + N_{SD} + N_{CD})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta\eta)_{bin}}$$

# … or RG cross-section

CMS PAS FSQ-12-005

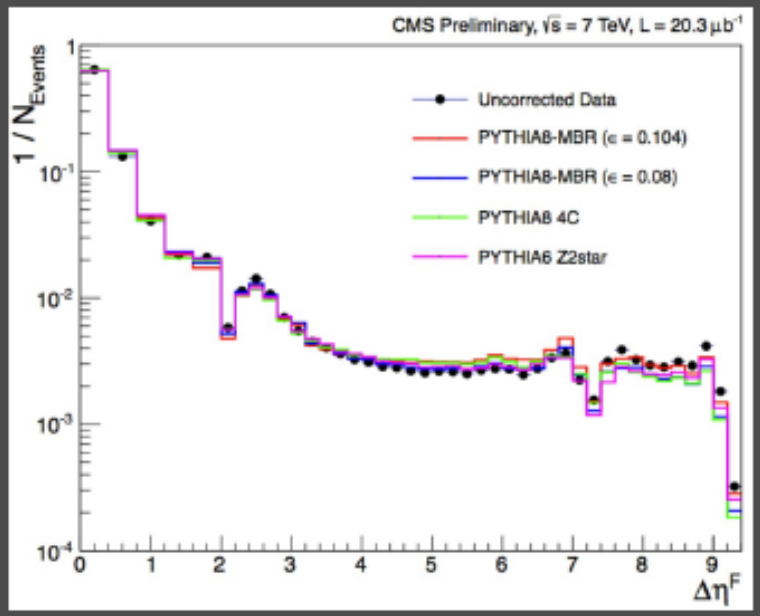
$$\frac{d\sigma(\Delta\eta^F)}{d\Delta\eta^F} = \frac{A(\Delta\eta^F)}{\Delta\eta_{bin\,width}} \frac{N(\Delta\eta^F) - N_{BG}(\Delta\eta^F)}{\varepsilon(\Delta\eta^F) \times \mathcal{L}}$$

N – number of Minimum-Bias events.

$N_{BG}$ – number of background events (beam-gas, estimated from unpaired bunches, < 1%).

A – correction factor for the migrations between bins.

ε - trigger efficiency,



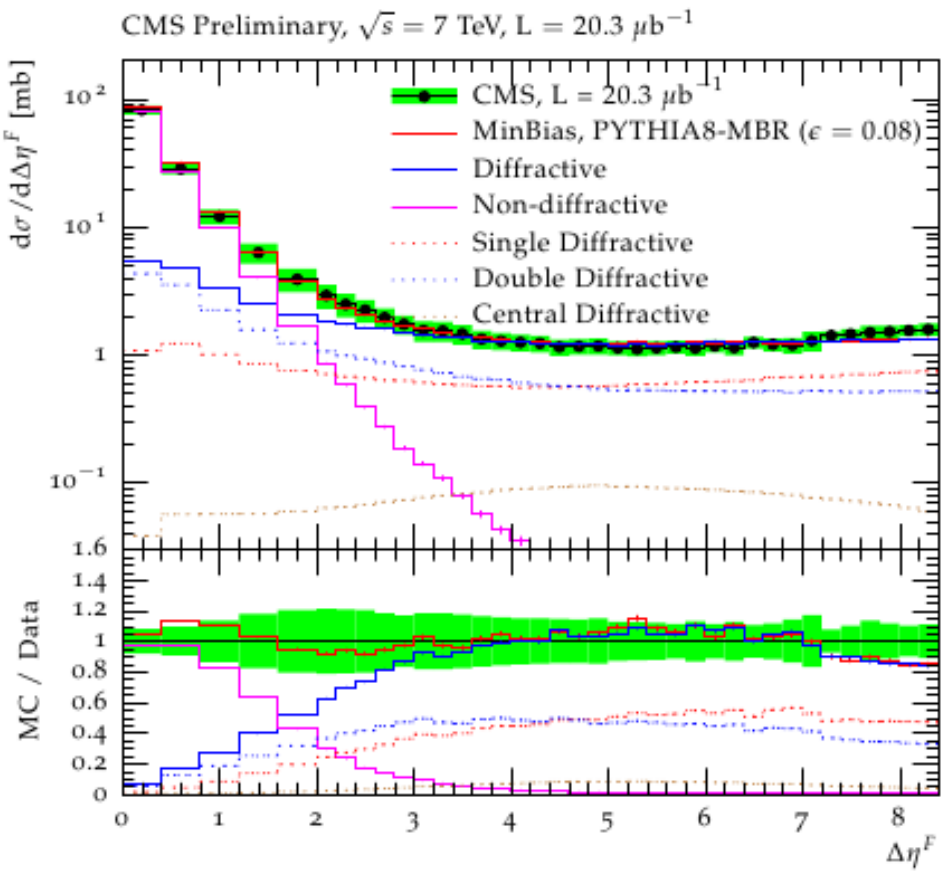

Detector-level $\Delta\eta^F$ distribution.

## Inclusive SD+DD

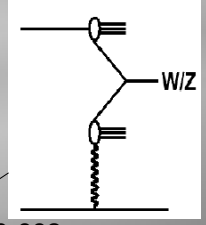
**Forward rapidity gap $\Delta\eta_F$**

**largest of the two empty regions**
**-from the edges of acceptance (η = ±4.7)**
**-to the nearest particle candidate**

$\Delta\eta^F = \mathrm{Max}(4.7-\eta_{max}, 4.7+\eta_{min})$



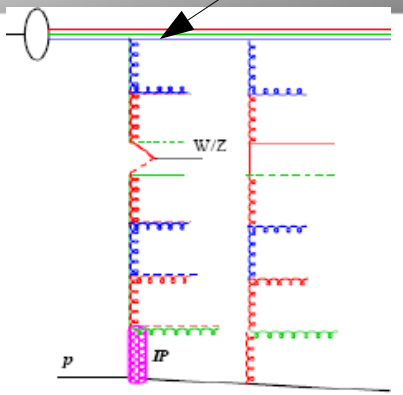
# HARD DIFFRACTION – W/Z




Eur. Phys. J. C72 (2012), FWD-10-008

## Event selection:

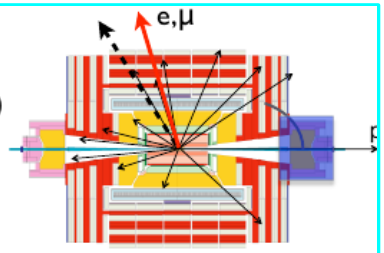
-leptonic final states (e, μ ) - 10-17 and 9-15 GeV
-single vertex (PU influence)
-tracker+ECAL or MuonDet; |η|<2.5 & Pt>25GeV
-W->lν or Z/γ*->ll selection; l: |η|<1.4
<1% BG




...

+MPI

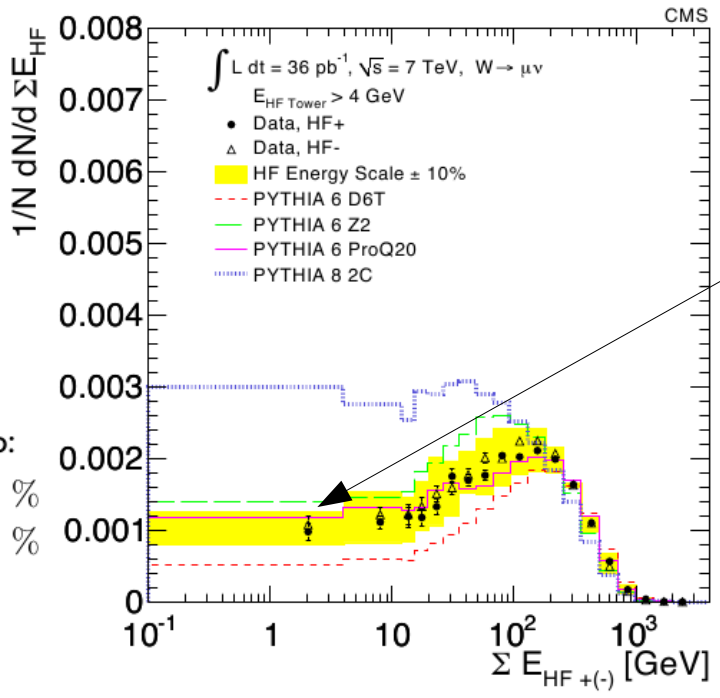
## W/Z events with an η-gap




Diffractive component in W/Z data set

Events with low energy deposits at the forward calorimeters

Monte Carlo generators cannot describe the data (extensive studies on overall energy flow and correlations)




Fraction of W/Z events with a forward gap:

W→lν: $1.46 \pm 0.09(\text{stat.}) \pm 0.38(\text{syst.})$ %

Z→ll: $1.60 \pm 0.25(\text{stat.}) \pm 0.42(\text{syst.})$ %

CMS FWD-10-008

*Eur. Phys. J. C (2012) 72:1839*

**Forward RG events: E(HF)<thr=4GeV**

# HARD DIFFRACTION – W/Z

Eur. Phys. J. C72 (2012), FWD-10-008

## Diffractive events:

**forward RG**

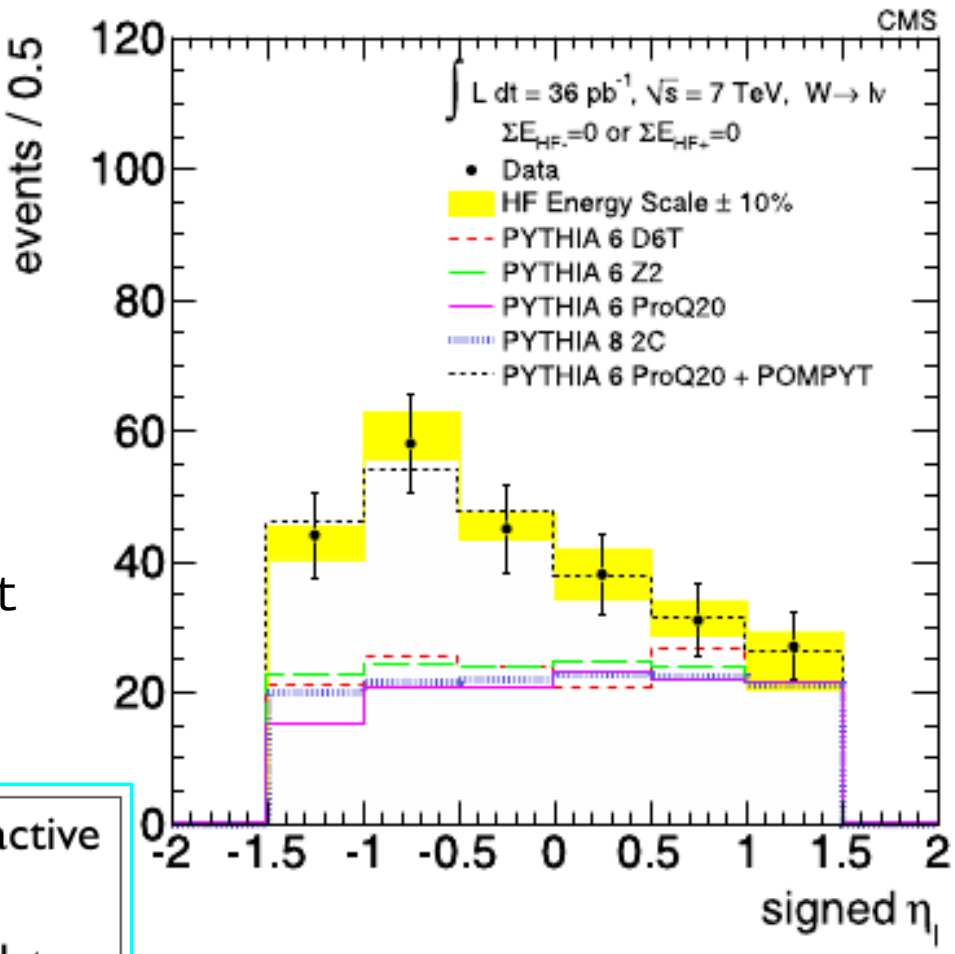
at least one HF: E<4 GeV

Look at **signed** $\eta_{lepton}$

<0 <=> opposite to RG

**=>**

- asymmetry of ~20%
- the best fit gives ~50% diffractive component




Flat for non-diffractive, asymmetric for diffractive events

Evidence of diffractive W production in the data

Fit for PYTHIA (ND) + POMPYT (SD):

$$f_{SD} = 50.0 \pm 9.3(\text{stat.}) \pm 5.2(\text{syst.})\ \%$$

(η-gap sample)

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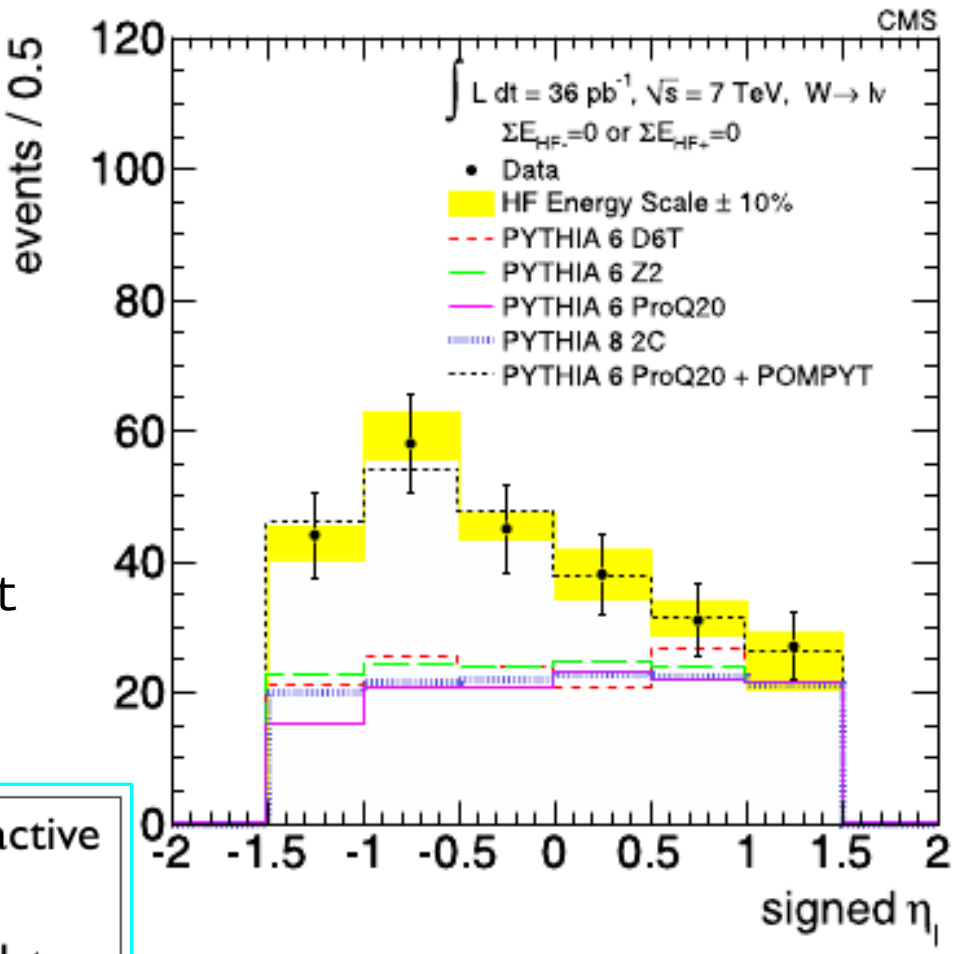


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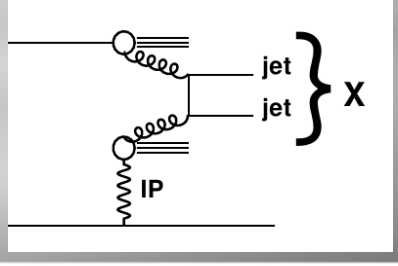
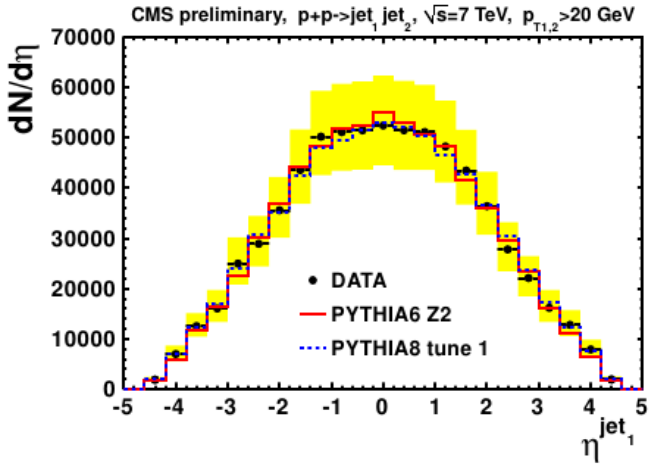
# HARD DIFFRACTION - DIJETS

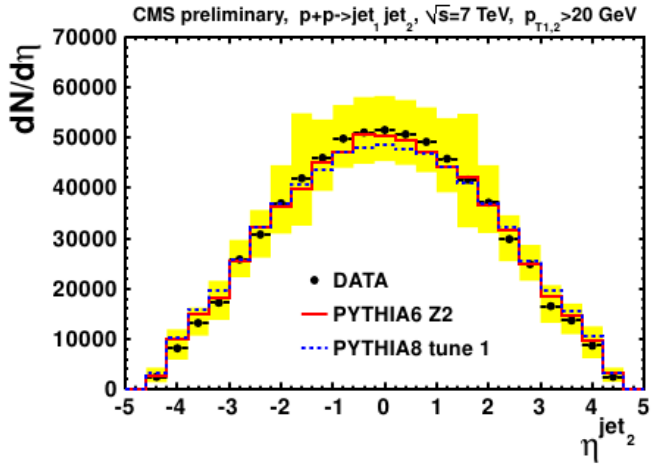



PRD 87 (2013) 012006 http://arxiv.org/abs/arXiv:1209.1805 ; FWD-10-004

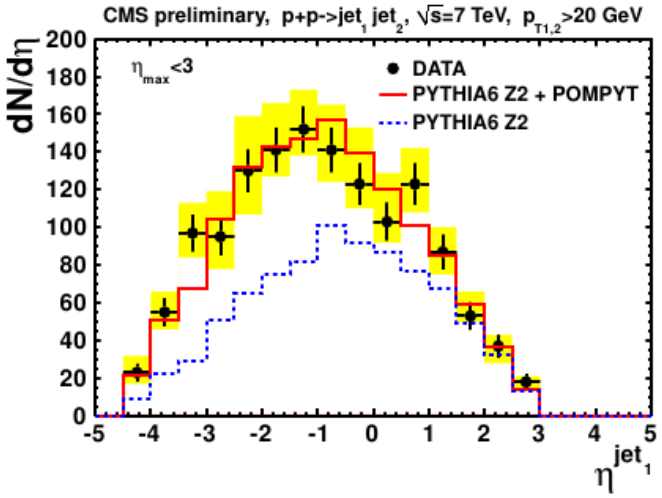
## Low PU data; Event selection:

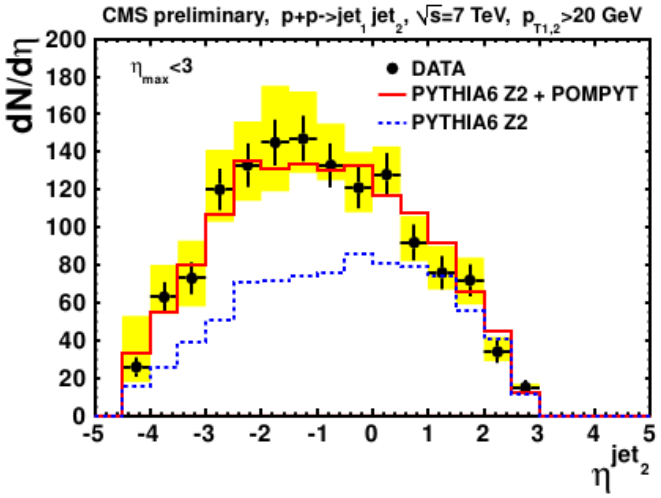
-Trigger: >=1jet: Pt>6GeV (10k-1M events)
-good vertex && no beam BG
- >= 2PFjets: E>0.2 (4) Gev (central and HF jets), Pt>20GeV, |η|<4.4




**+ LRG: most forward jet in the event to satisfy $\eta_{max} < 3$ (or most backward $\eta_{min} > -3$).**




HF | central

η=4.9 η=3

# HARD DIFFRACTION - DIJETS

PRD 87 (2013) 012006 http://arxiv.org/abs/arXiv:1209.1805 ; FWD-10-004

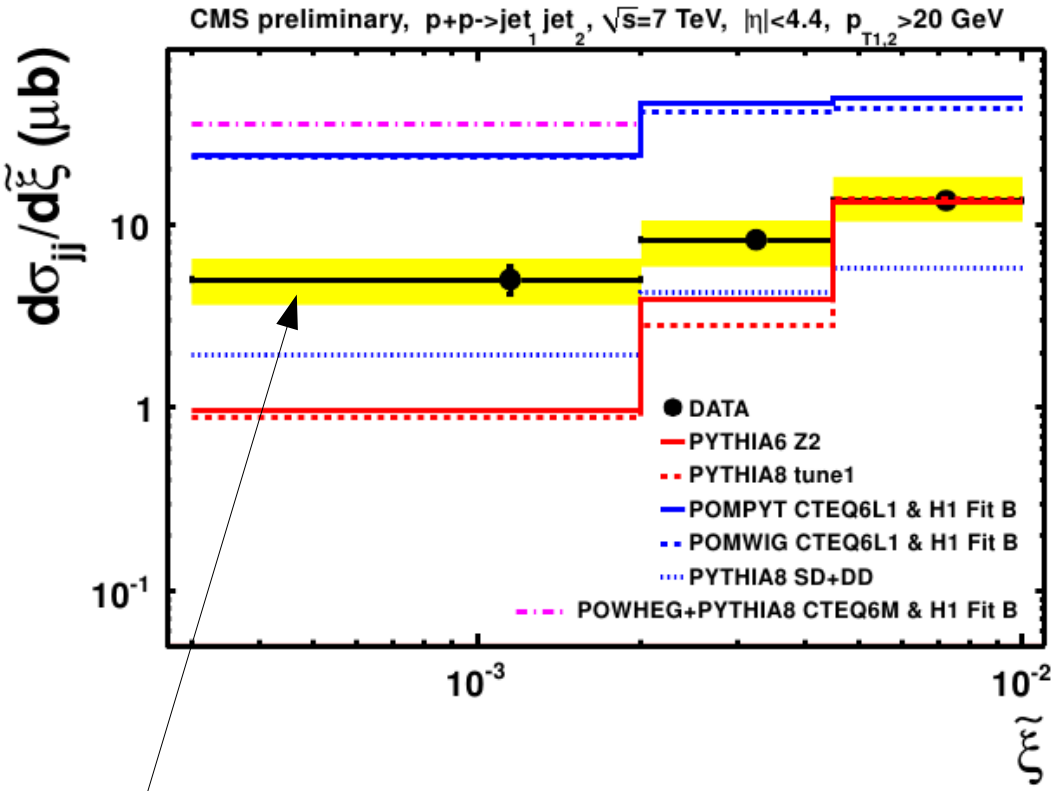
$$\tilde{\xi}^{\pm} = C \frac{\sum (E \pm p_z)}{\sqrt{s}}$$

C-detector effect corrections ~1.45

**Cross-section- data vs MC:**

$$\frac{d\sigma_{jj}}{d\tilde{\xi}} = \frac{N^i_{jj}}{L \cdot \epsilon \cdot A^i \cdot \Delta\tilde{\xi}^i}$$

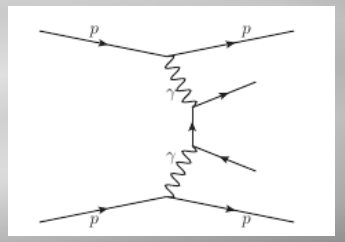
-PYTHIA 6, 8tune1 : non-diffractive
-POMPYT, POMWIG : SD with HERA dPDF and tune
-PYTHIA8 : SD+DD with HERA dPDF
-POWHEG : NLO




**Data/MC(no S) – estimates for RG survival probability**

**0.21 ± 0.07 from POMPYT and POMWIG**
**0.14 ± 0.05 from POWHEG**

# Exclusive γγ → μμ



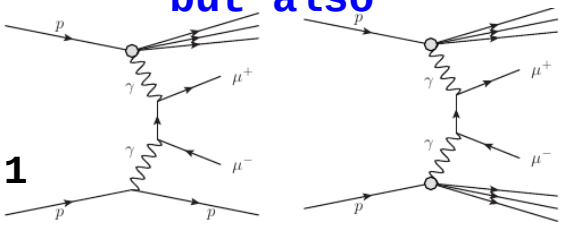
JHEP 01 (2012) 052 http://arxiv.org/abs/arXiv:1111.5536; FWD-10-005

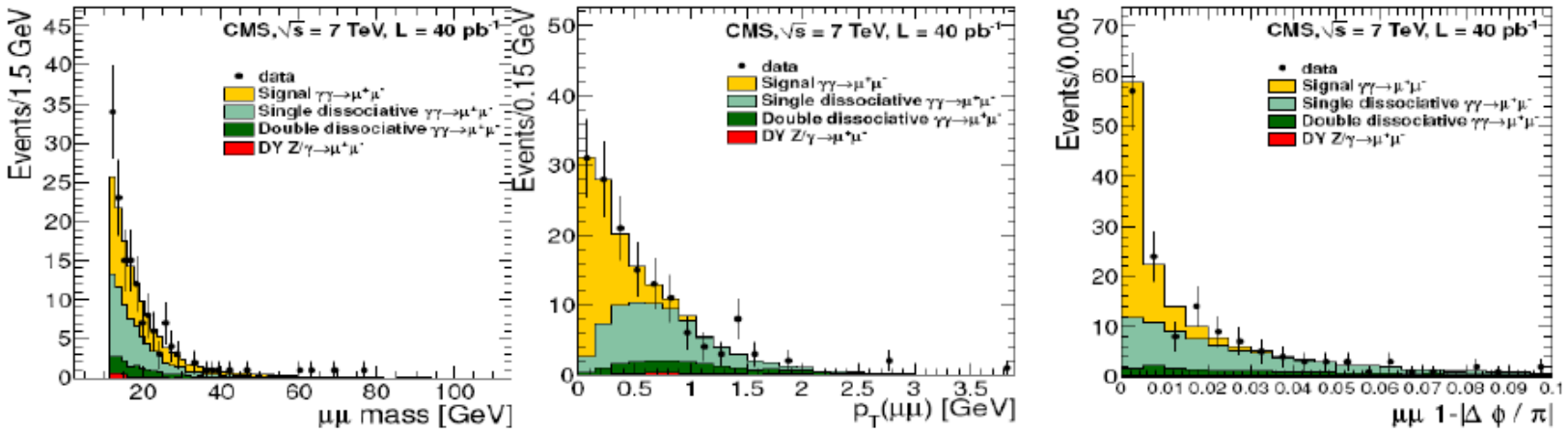
**Data:** Sample: 40 pb$^{-1}$ of 2010 data at 7 TeV, any PU

**Event selection:**

- trigger: 2 μ Pt>3GeV
- 2 "tight" μ of opposite charge; pT > 4 GeV and |η| < 2.1
- primary vertex with 2 μ and no other track within 2 mm
- cosmic-ray rejection and m(μμ) > 11.5 GeV to reject Υ photoproduction

**but also**






- Pair-$p_T$ very small (peak at ~50 MeV/c). Muons are ~back to back.
- Agreement with LPAIR (QED): pp → γ γ → μμ

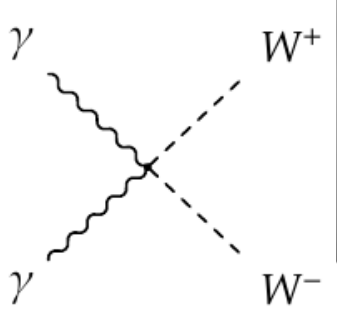


**+ signal selection** $(1 - |\Delta\phi(\mu^+\mu^-)/\pi| < 0.1)$ $(|\Delta p_T(\mu^+\mu^-)| < 1.0\ \text{GeV})$ **+ maximal LH fit**

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

# Exclusive γγ → WW

JHEP 1307 (2013) 116 http://arxiv.org/abs/arXiv:1305.5596

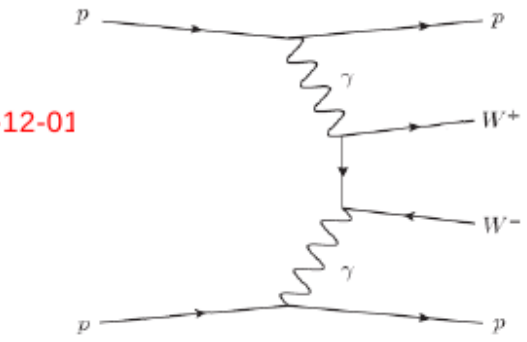



**Data:**
**5.05 fb$^{-1}$ of 2011 data at 7 TeV, any PU**

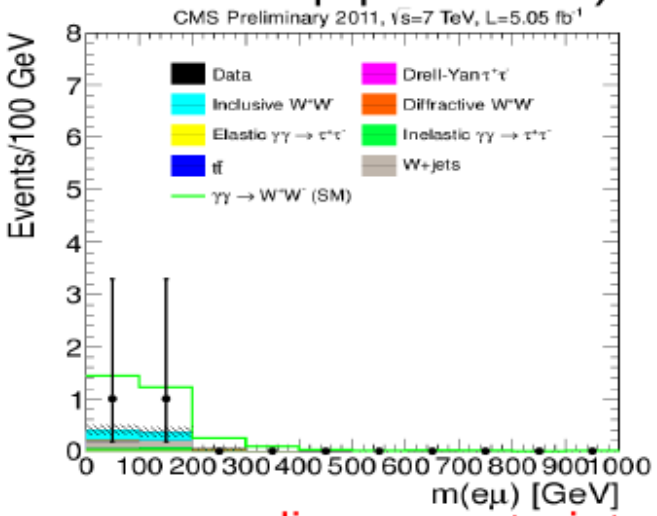
**Motivation :**
**Anomalous quartic coupling (different from SM)**

- Exclusive opposite-sign μ-e events (2 seen in 5.0 fb$^{-1}$ p-p at 7 TeV):

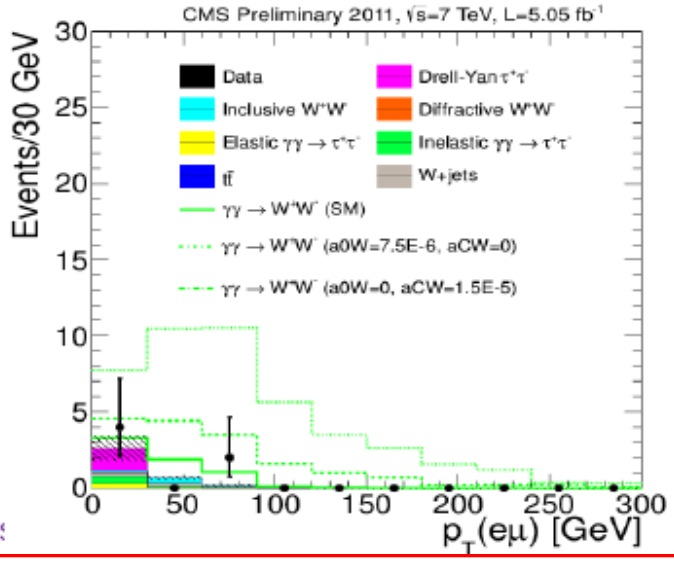
CMS PAS-FSQ-12-01

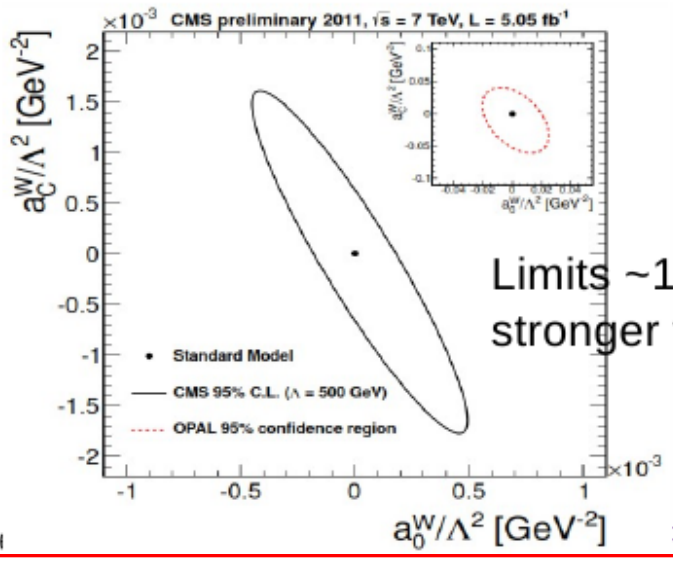



$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}) = 2.1^{+3.1}_{-1.9}\ \text{fb}$$




- No high-$p_T$ evts: strong anomal. quartic gauge couplings constraints:



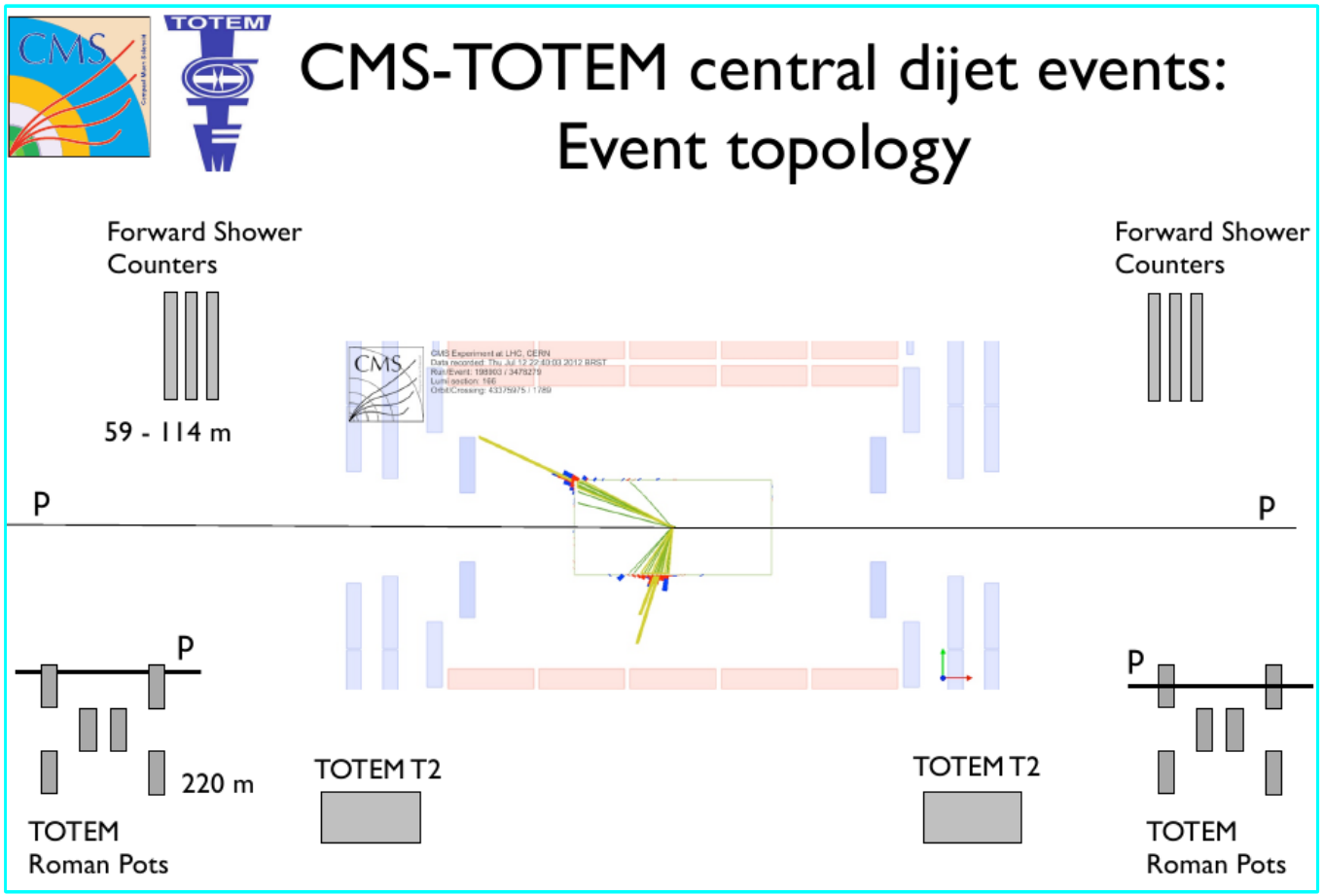




Limits ~100 times stronger than LEP

# What if we knew about proton(s)?!

## Common CMS-TOTEM run with Roman Pots (July 12)

- Low PileUp required (90 m optics)
- Trigger exchange (CMS  TOTEM):
  - CMS: DoubleJet20,...  TOTEM: RP&, MinBias T2
- CMS additional: FSC readout




...what if we could work with PU?..... :)

# ...more public CMS results...

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

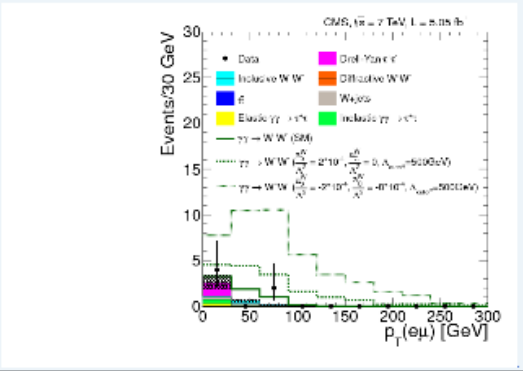


## CMS Forward and Small-x QCD Physics Results

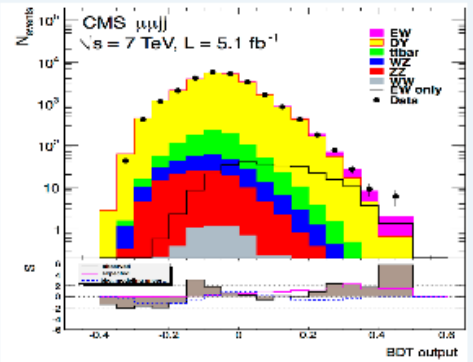


### Recent highlights:

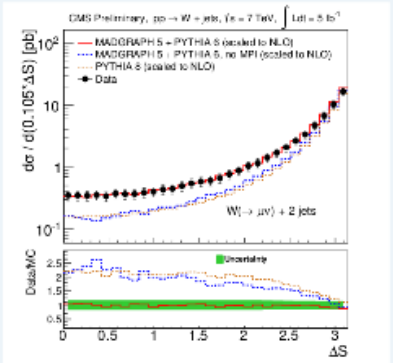
Study of gammagamma->WW (pp at 7 TeV):



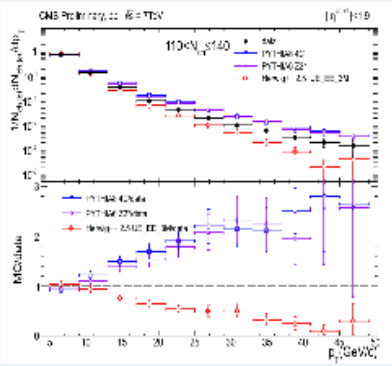

Electroweak Z + forward-backward jets production (pp at 7 TeV):



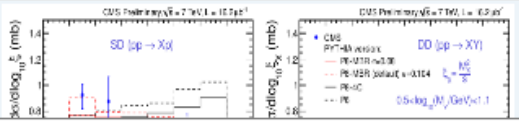

Double parton scattering in W+jets (pp at 7 TeV):



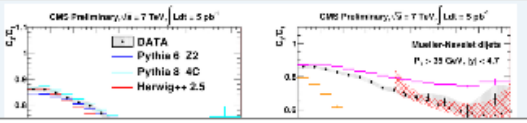

Properties of jets and UE as a function of charged-particle multiplicity (pp at 7 TeV)



Single & double diffraction cross sections (pp at 7 TeV):

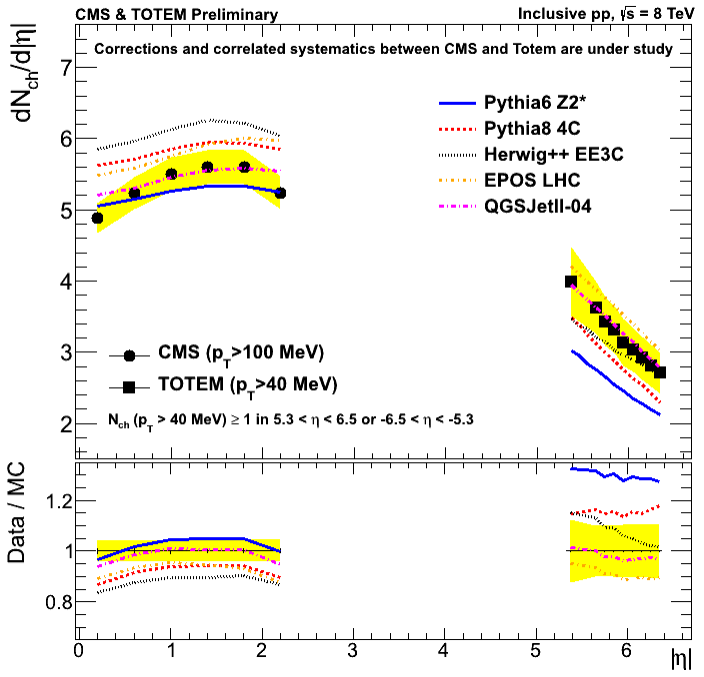



Mueller-Navelet dijet azimuthal decorrelations (pp at 7 TeV):



# one more slide :)

- a lot of results at $E_{cm}$ up to 8 TeV
- a lot of analyses ongoing
- and there are Heavy Ion data too...
- we started to work with TOTEM!




- looking forward to 2015 :)

# backup

# FORWARD ENERGY FLOW - HF

JHEP 1206 (2012) 036

**Energy flow** $\frac{1}{N}\frac{dE}{d\eta}$ **in 3.2 < |η| < 4.9 :**

**Minimum Bias events:**

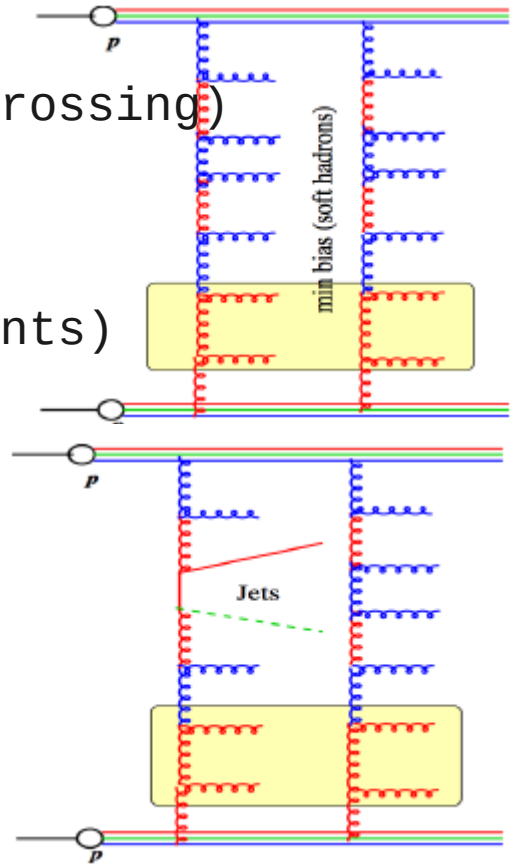
-BSC AND(3.9 < |η| < 4.9) && BPTX (bunch crossing)
-good vertex && no beam BG
-suppressed SD (<5% according MC)
-correction to hadron level
- ~200ub-1 for 0.9 and 7 TeV ( 9-4 M events)

**Subsample of dijet events:**

-central jets |η|<2.5 & pt>8 pt>20 GeV,
azimuthal angle correlation
-~10k evts

**Uncertainty:**

-mainly HF energy scale and model (dijets)
-10-14 % MinBias; 13-22 % dijets



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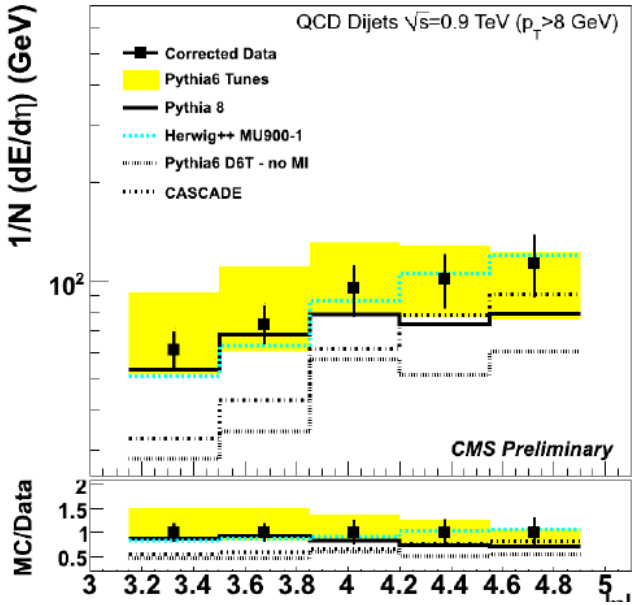
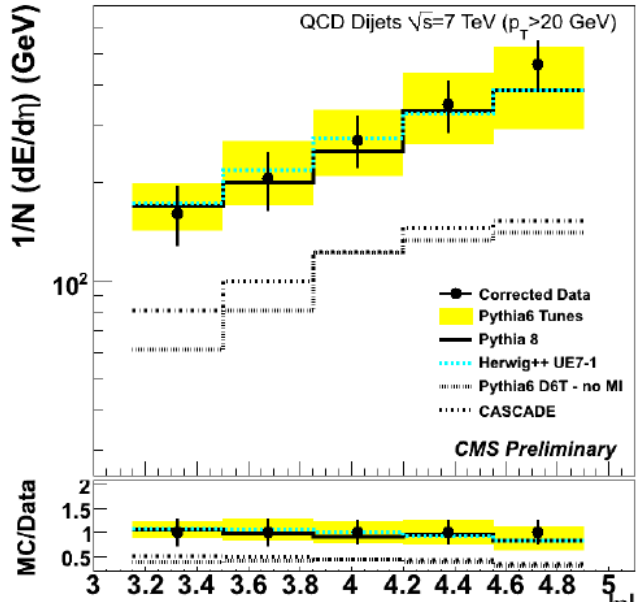
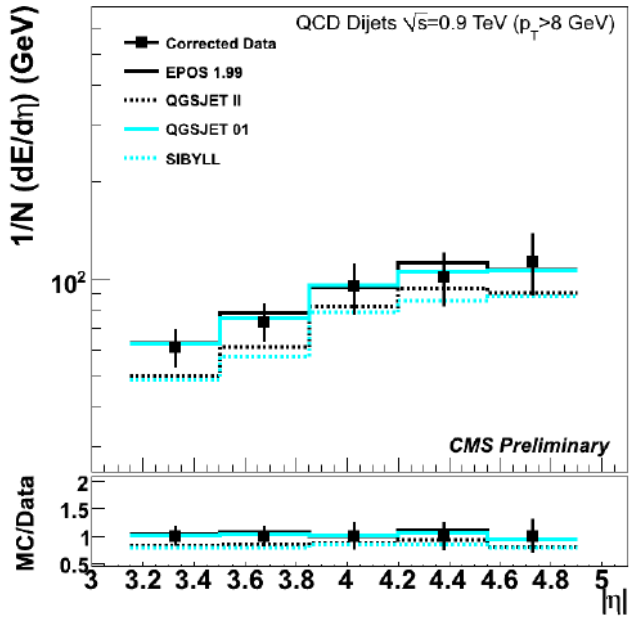
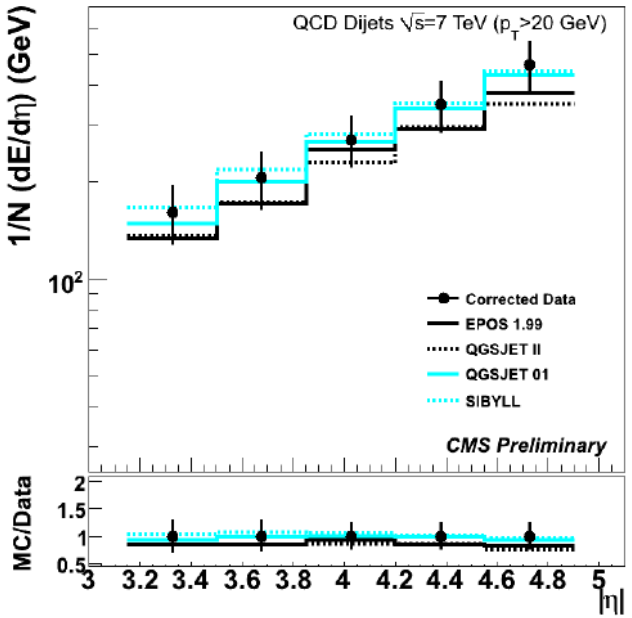
JHEP 1206 (2012) 036



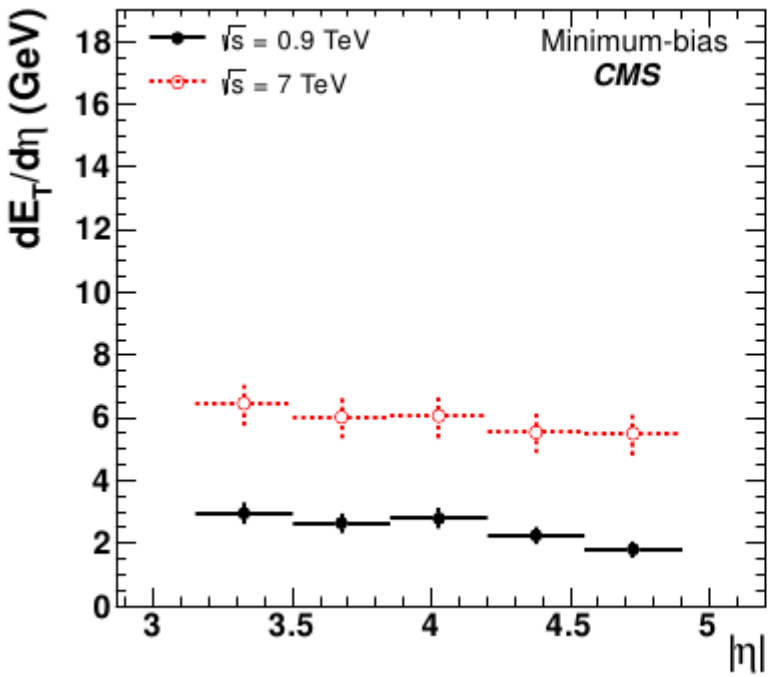



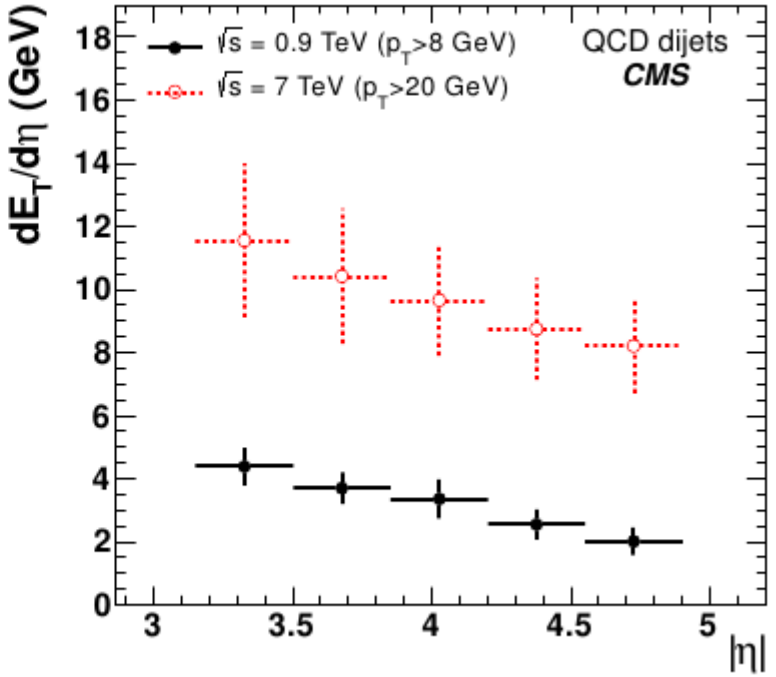



# FORWARD ENERGY FLOW - HF

JHEP 1206 (2012) 036




**Significant contribution of MPI**
**Larger energy flow for dijets**
**Center-of-mass energy dependence (MC and data)**
**Large variation with different tunes**
**Good description with cosmic ray MC**
**More activity in the hard jet direction**

# FORWARD ENERGY FLOW - CASTOR

PAS-FWD-11-003

## Energy flow: hard-to-inclusive ratio in $-6.6 < \eta < -5.2$ :

## Minimum Bias events:

- BSC AND ($3.9 < |\eta| < 4.9$) && BPTX (bunch crossing)
- HF- & HF+ & CASTOR tower (3.2 $\lambda$int)
- good vertex && no beam BG
- suppressed SD
- correction to hadron level
- (120-300)ub-1 for 0.9, 2.76 and 7 TeV (5-10 M events)

## Subsample of hard events:

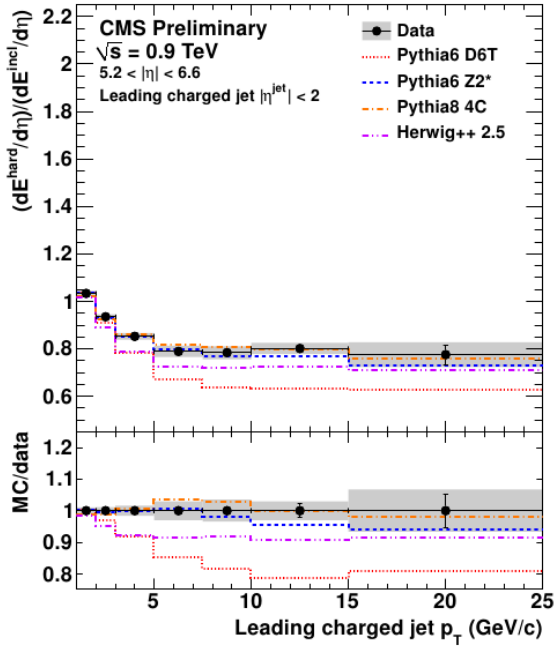
- track-jets $|\eta|<2$ & pt>1 GeV, polar angle correlation
- correction for track-jet - CASTOR energy correlations

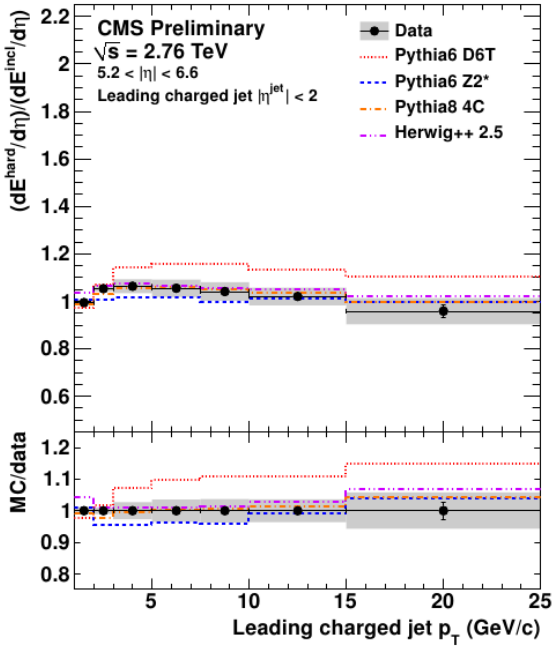
## Uncertainty:

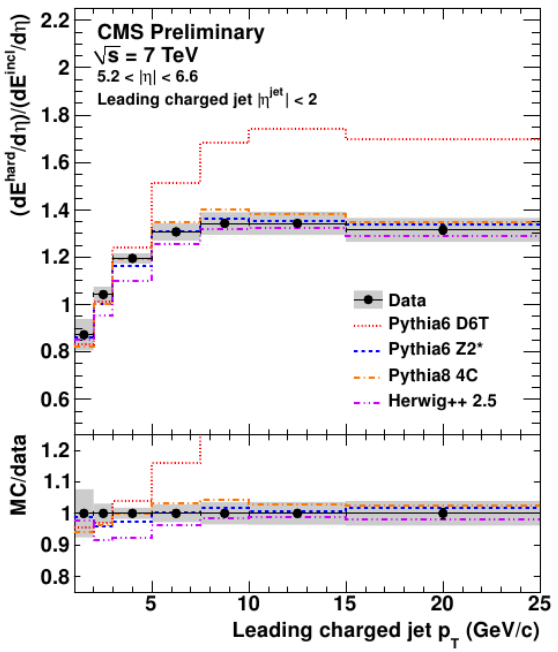
- mainly CASTOR (alignment, non-compensation,....)

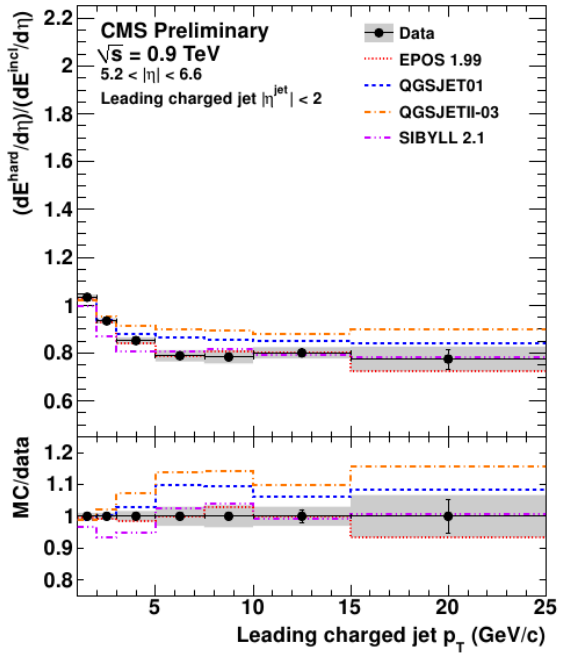
# FORWARD ENERGY FLOW - CASTOR

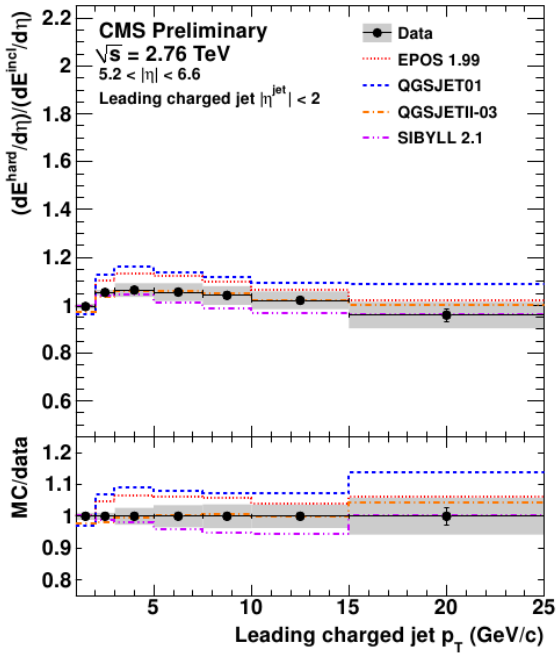
PAS-FWD-11-003

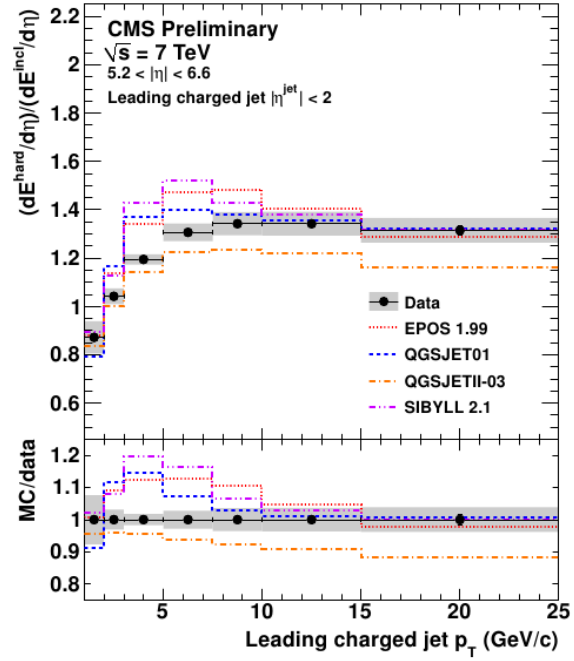


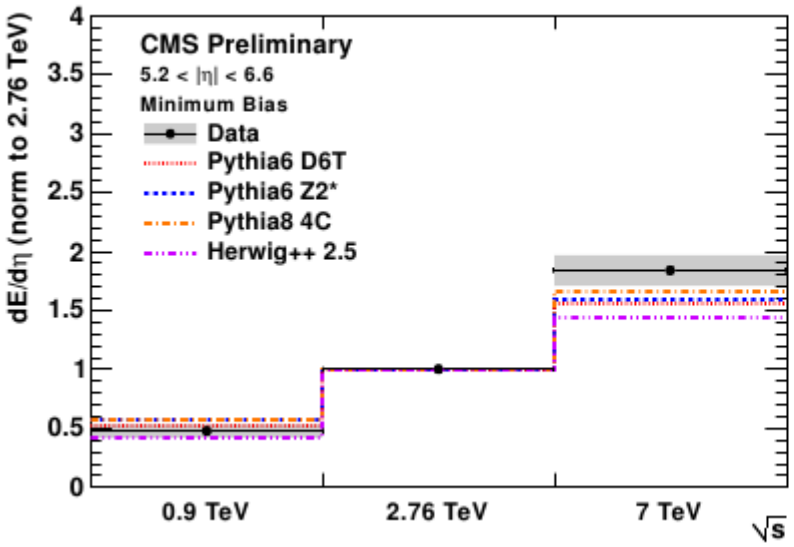



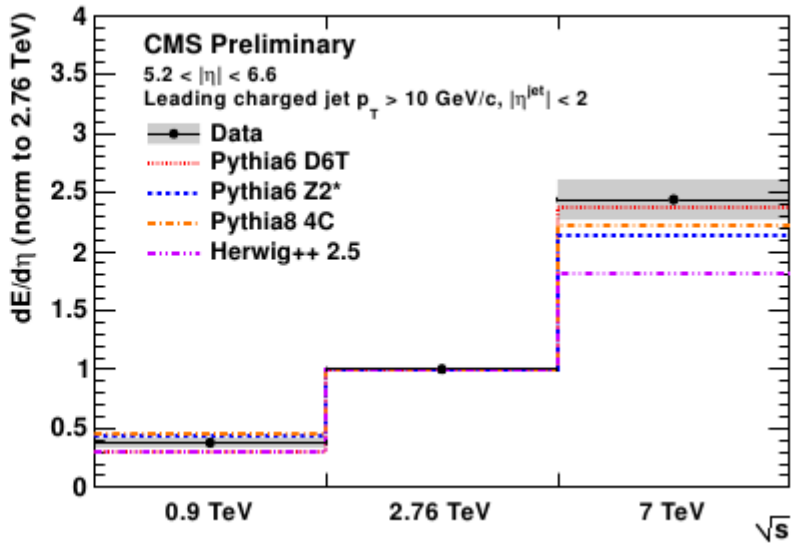



# FORWARD ENERGY FLOW - CASTOR

PAS-FWD-11-003




**Relative measurements**
**Complimentary to UE studies with a jet in the central region**
**Typical UE behaviour (7TeV)**
**Center-of-mass energy dependence (MC and data)**
**Better description with cosmic ray MC**

# backup

## Exclusive/diffractive cross sections