

Minimum Bias, MPI and DPS, and Diffractive and Exclusive measurements at CMS



Dipanwita Dutta



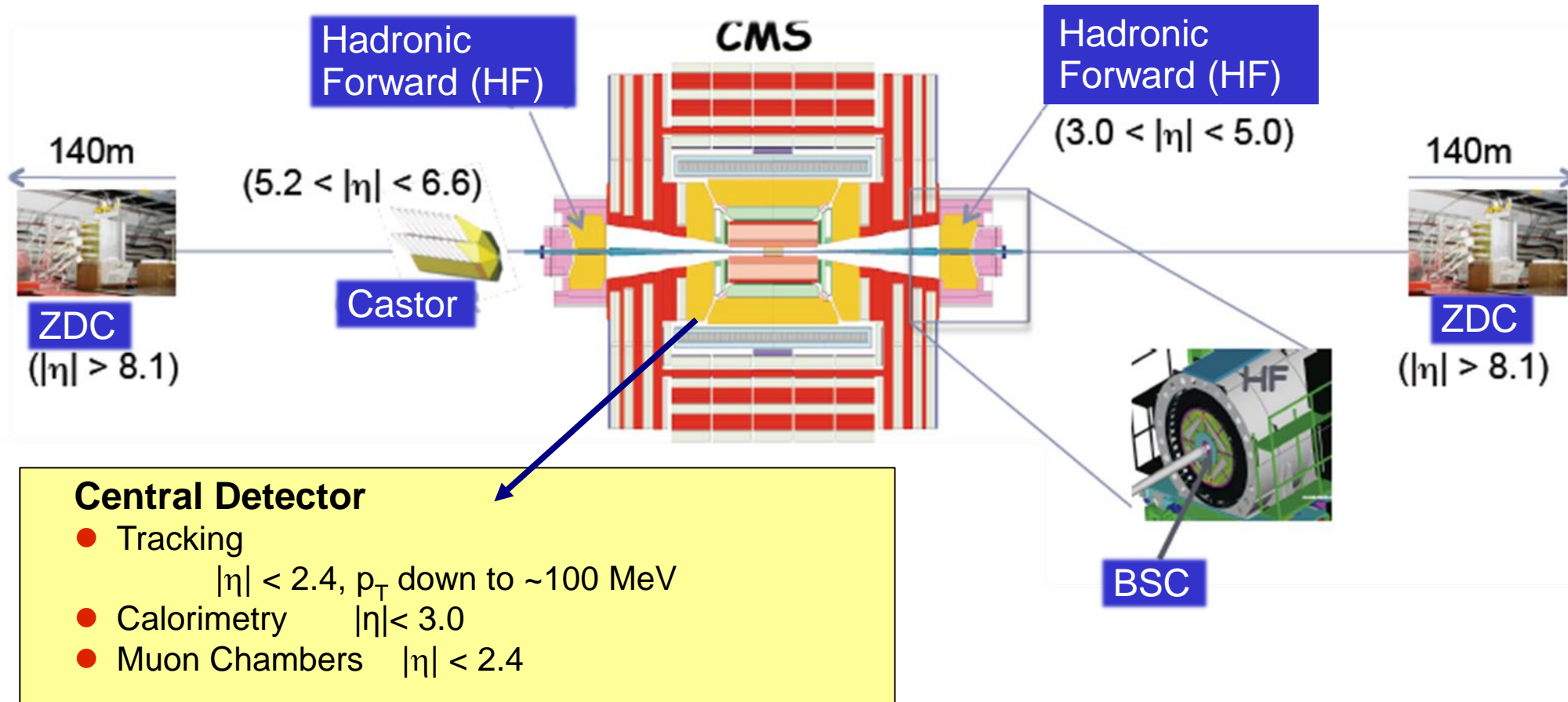
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On behalf of the CMS Collaboration



ICHEP, 2014
Valencia, Spain,
2nd -9th July, 2014



Forward detectors:

- HF, hadron forward calorimeter (11m from IP)
- BSC, beam scintillator counters (in front of HF)
- CASTOR calorimeter (one side only)

- $3 < |\eta| < 5$
- $3.2 < |\eta| < 4.7$
- $-6.6 < \eta < -5.2$

Not used in these analysis {

- FSC (Forward Shower Counters)
- ZDC (zero degree calorimeter)

$6 < |\eta| < 8$
 $|\eta| > 8.1$

● Forward Detectors in CMS (also TOTEM)

● Diffractive Physics

- Single and double diffractive cross sections at $\sqrt{s} = 7$ TeV [CMS PAS FSQ-12-005]
- Pseudorapidity distribution of charged particles at $\sqrt{s} = 8$ TeV [arXiv:1405.0722] **First CMS-TOTEM paper ever!**

● Exclusive production

- Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$, $\gamma\gamma \rightarrow e^+e^-$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV [JHEP 01 (2012) 052, JHEP 11 (2012) 080]
- Study of exclusive two-photon production of W^+W^- in pp collisions at $\sqrt{s} = 7$ TeV [JHEP 07 (2013) 116]

● MPI/UE/DPS

- Jet and underlying event properties as a function of charged-particle multiplicity in proton-proton collisions at $\sqrt{s}=7$ TeV [Eur. Phys. J C73 (2013) 2674]
- Study of double parton scattering using $W+2$ jet events in proton-proton collisions at $\sqrt{s}=7$ TeV [JHEP 03 (2014) 032]

● Summary

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

Diffraction cross-sections

Total, Inelastic, elastic, Diffractive cross-sections

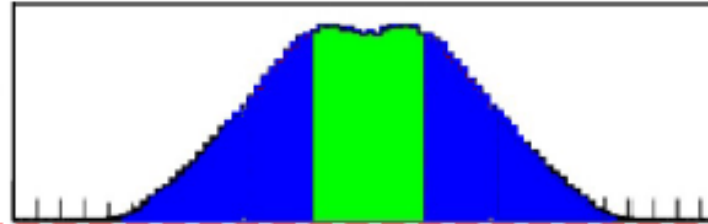
- Hadrons are extended composite objects: Even at asymptotically large c.m. energies, **~40% of hadronic interactions are not "point-like"**:

pQCD

- Perturbative parton-parton collisions

~60%

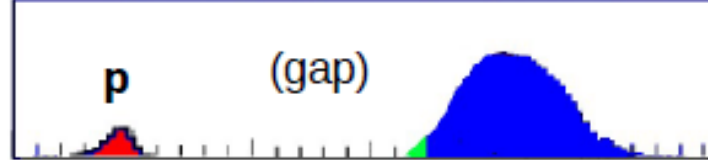
Non diff. inelastic



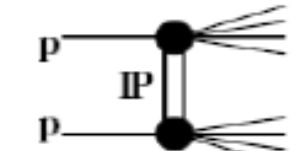
- Diffractive, elastic

~40%

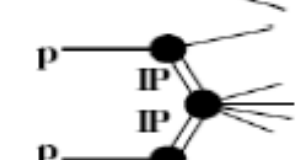
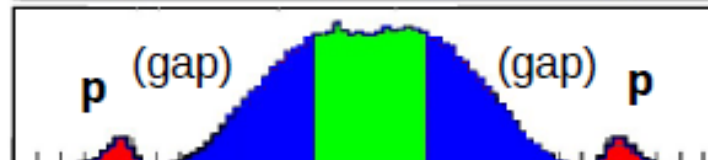
Single diff.



Double diff.



Central diff.



Elastic scatt.



-15 -10 -5 0 5 10 15

Regge-Gribov

- 1 or 2 protons "intact" + 1 or 2 rapidity gaps:
- No colour flux.
- Colourless exchange with vacuum $J^{PC}=0^{++}$ quantum-numbers: |Pomeron = 2-gluons in colour-singlet state.

- pQCD (~60 mb) + elastic (~25 mb) + diffractive (~15mb) ~ 100 mb at the LHC.

Slide from D. d'Enterria

Motivation:

- Diffractive cross-section estimated by models based on Regge theory
- Difference between model prediction pre-LHC to LHC era
- Valuable input to improve models

Measurement

- Inclusive Diffractive cross-section based on Large Rapidity Gap (LRG) tagging
- Single and double diffractive contributions separated with CASTOR tag ($-6.6 < \eta < -5.2$)

Sample

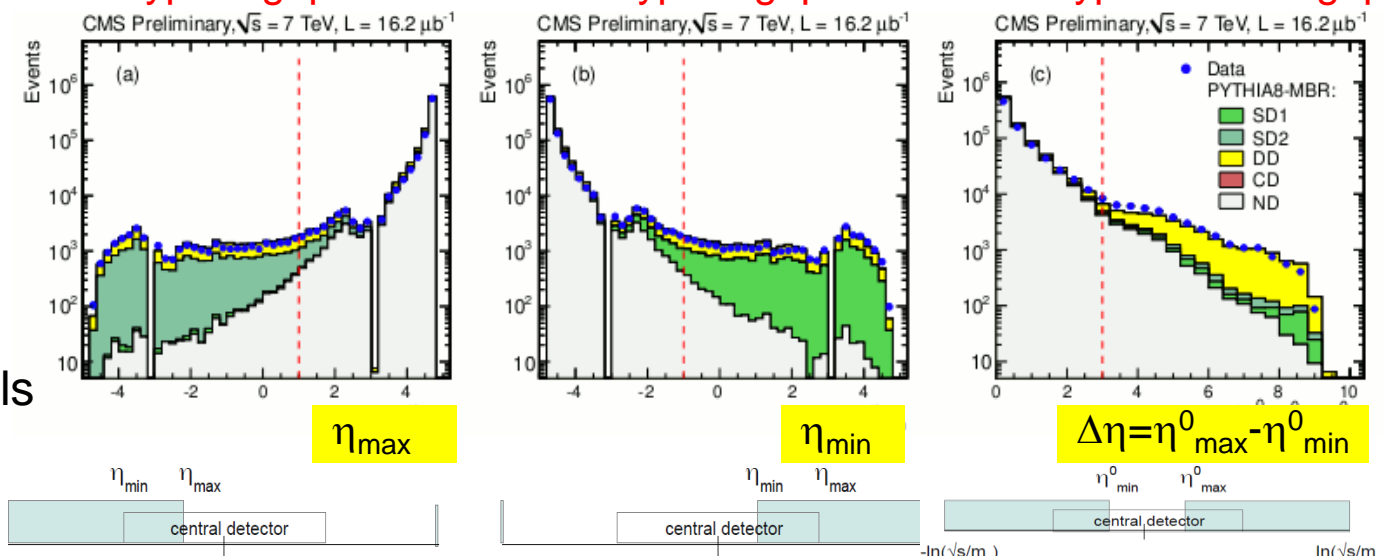
data of 2010 at $\sqrt{s} = 7$ TeV

Monte Carlo model compared

- PYTHIA8-MBR(*), diffraction with Minimum Bias Rockfeller model
- PYTHIA8-4C, diffraction with Schuler & Sjostrand model from PYTHIA6, Tune 4C - additional scaling of SD and DD downwards by 10% and 12%.

* MBR (Minimum-Bias Rockfeller) – implemented in Pythia8.165. Regge-based model with renormalized flux, developed for and successfully tested at CDF. Hadronization model tuned to describe diffractive masses at lower energies.

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



- η_{\max} (η_{\min}) are the maximum and minimum η of the Particle Flow (PF) candidate reconstructed in central detector
- $\Delta\eta^0 = \eta_{\max}^0 - \eta_{\min}^0$, η_{\max}^0 (η_{\min}^0) are the reconstructed PF closest to $\eta=0$ in +(-) side

Separation of SD/DD events with CASTOR

- SD2 with an $\eta_{\min} > -1$ selection

Detector level ξ distribution

$$\xi = \frac{\sum(E^i + p_z^i)}{\sqrt{s}} \sim \frac{M_X^2}{s}$$

Cross-sections:

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

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

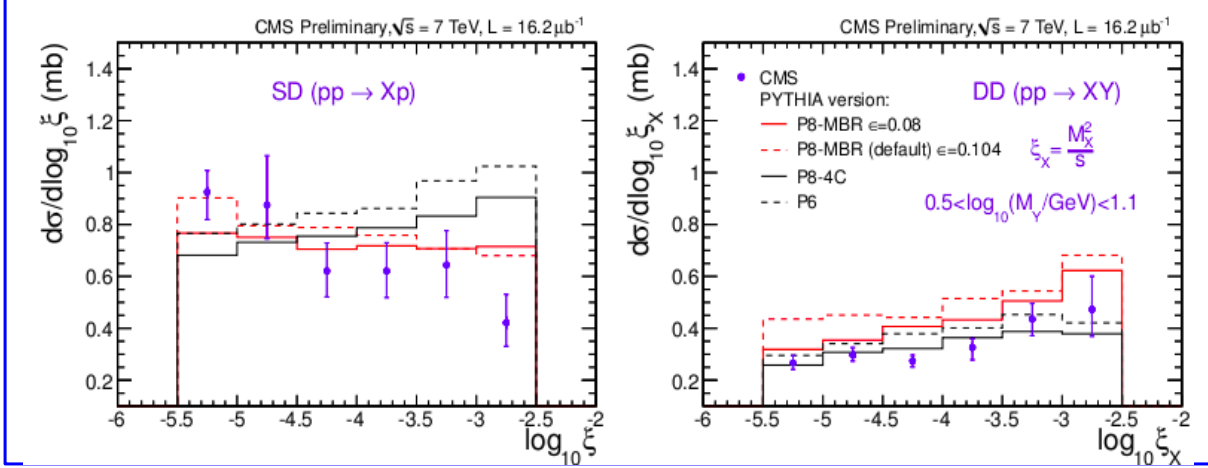
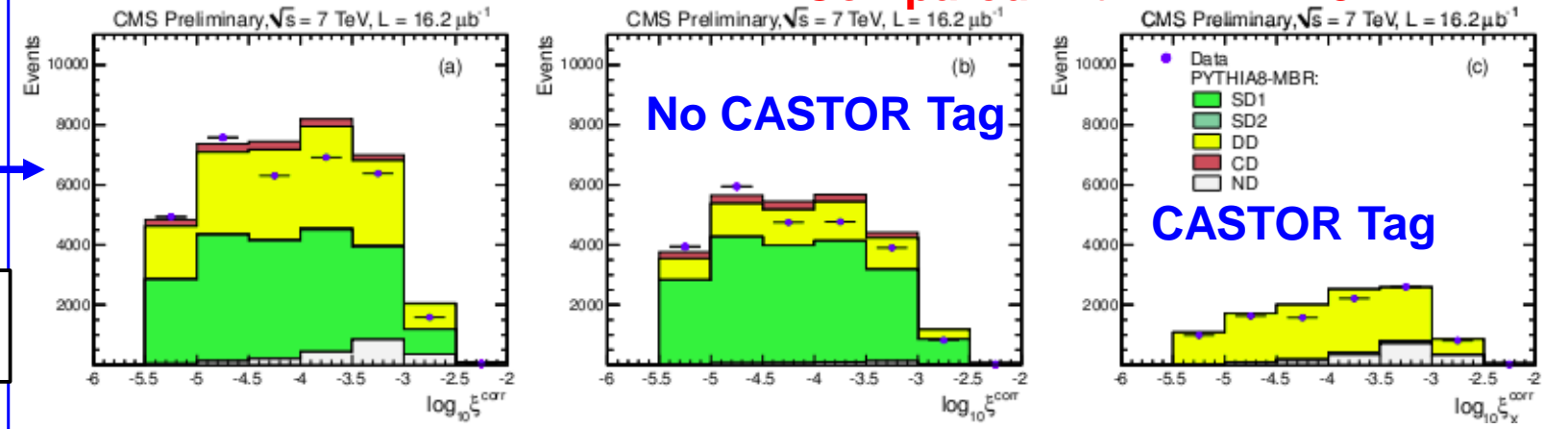
Compared to theoretical models:

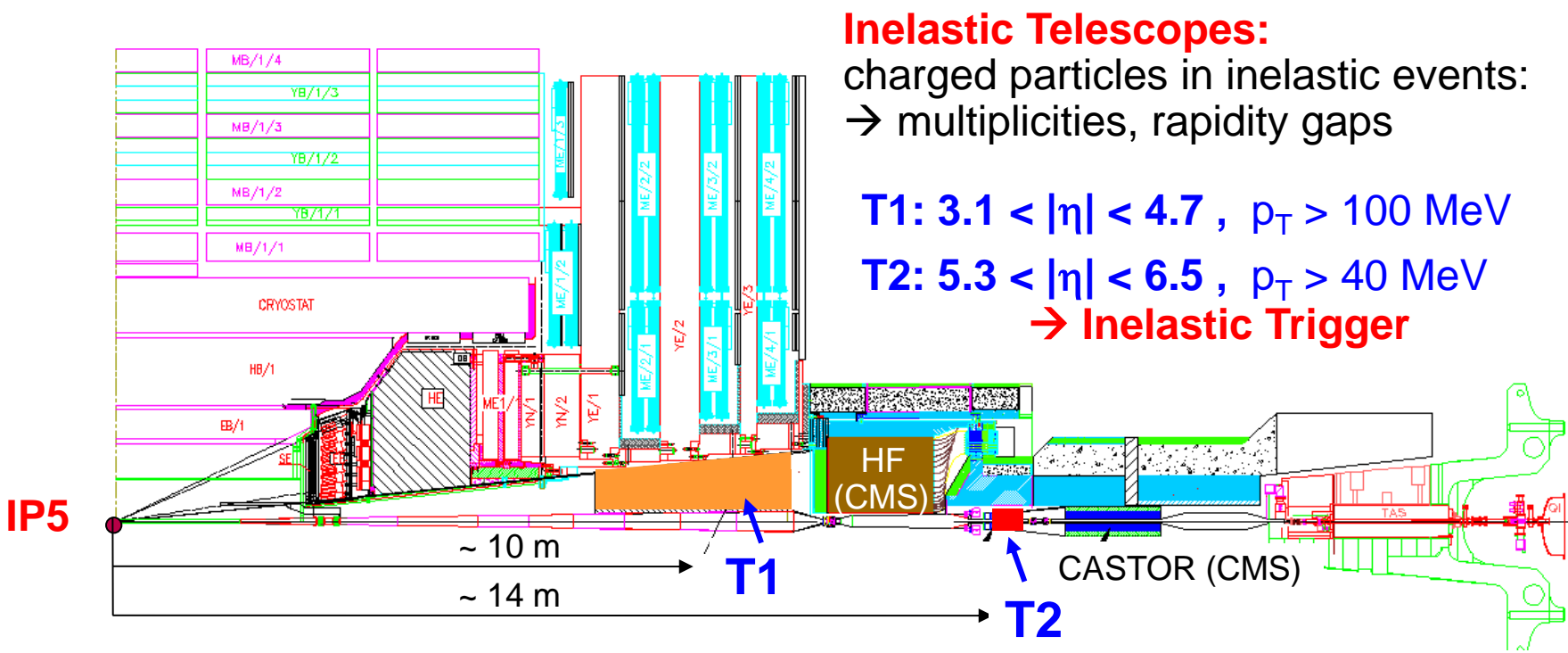
PYTHIA8 MBR shown for two values of the Pomeron trajectory ($\alpha(t) = 1 + \epsilon + \alpha' t$), $\epsilon = 0.08$ and $\epsilon = 0.104$. Both describe the measured SD cross section well. The DD data favour the smaller value of ϵ .

$$\sigma_{vis}^{SD} = 4.27 \pm 0.04 \text{ (stat.) } {}^{+0.65}_{-0.58} \text{ (syst.) mb for } -5.5 < \log_{10} \xi < -2.5$$

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

Compared with PYTHIA 8 MBR





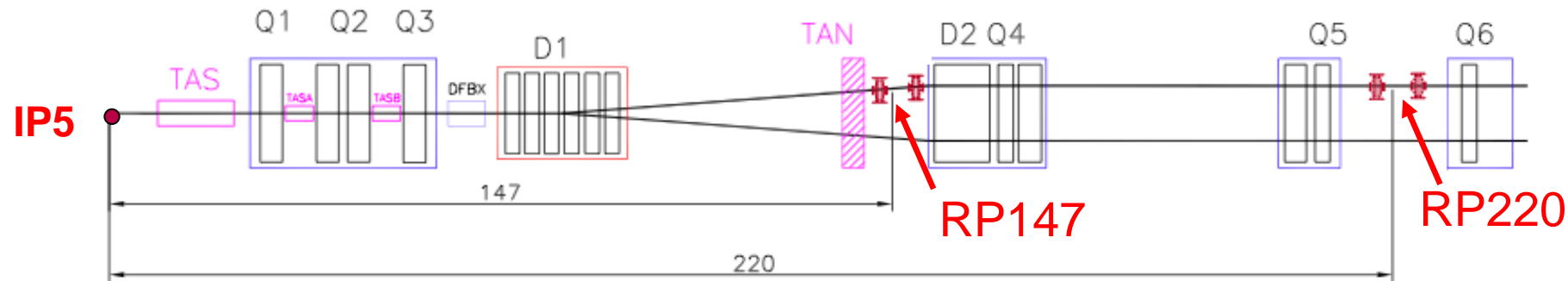
Inelastic Telescopes:
 charged particles in inelastic events:
 → multiplicities, rapidity gaps

T1: $3.1 < |\eta| < 4.7$, $p_T > 100$ MeV

T2: $5.3 < |\eta| < 6.5$, $p_T > 40$ MeV

→ **Inelastic Trigger**

Roman Pots: elastic & diffractive protons close to outgoing beams → **Proton Trigger**



Motivation:

- Particle production by semi (hard) multi-parton interaction, need phenomenological model
- Measured experimental distributions are valuable input to tune models and event generators

Sample

★ CMS+TOTEM 2012 low pileup run $\sqrt{s} = 8$ TeV

Selection:

minimum bias trigger provided by TOTEM T2 telescopes

3 experimental topologies:

Inclusive sample: at least one primary candidate in T2

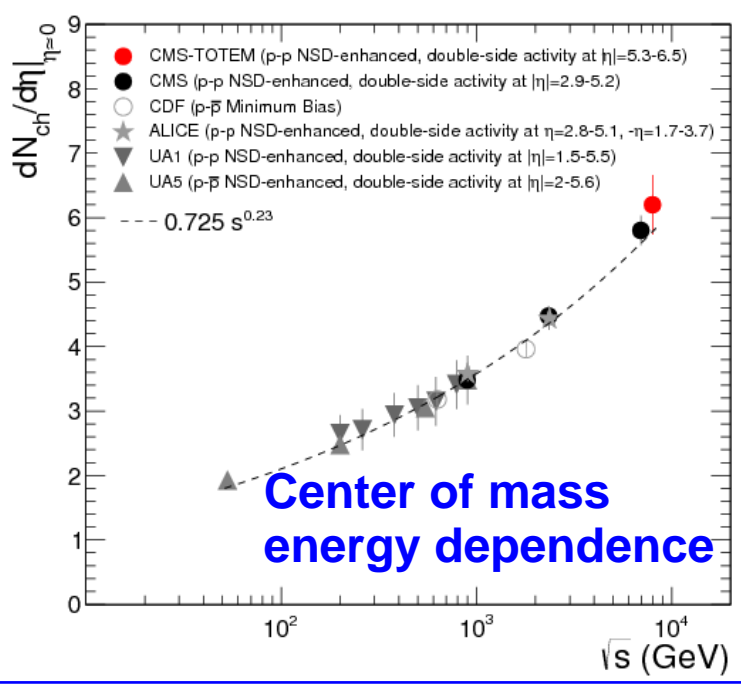
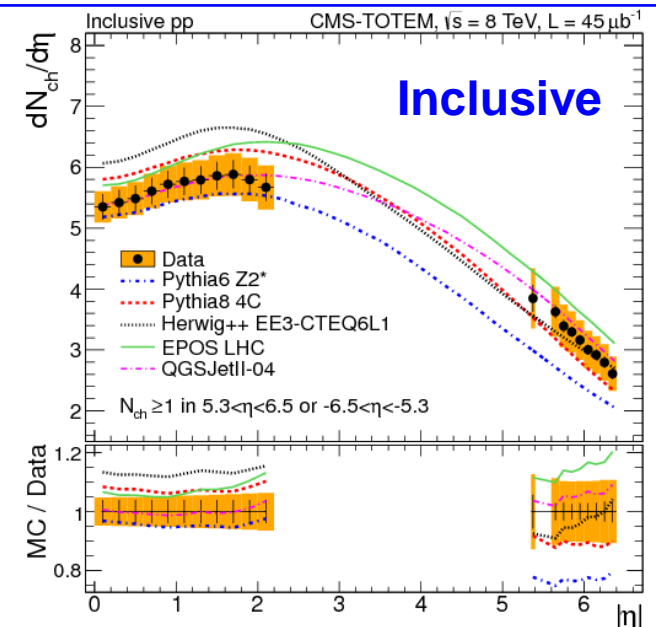
Non single diffractive (NSD) sample: at least one primary candidate in T2, in both z-directions

Single diffractive (SD) sample: at least one primary candidate in T2, in only one z-direction

● **Span largest pseudorapidity ever measured in LHC**

● **No MC could describe $dN_{ch}/d\eta$ of all topologies in the whole rapidity region**

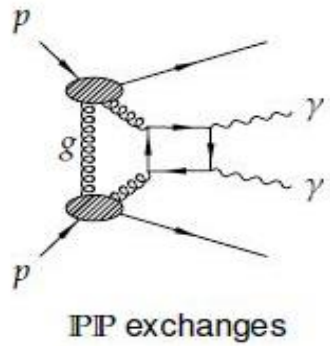
● **Particle production at mid rapidities follow a power-law centre-of mass energy dependence s^ϵ .**



Exclusive Production

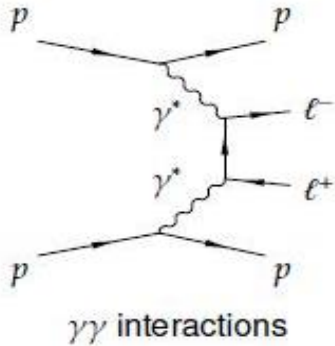
Exclusive: intact protons in the final states, **Semi exclusive:** proton dissociation p^*

Reaction $pp \rightarrow p(*)Xp(*)$ where $X=e^+e^-, \mu^+\mu^-, \gamma\gamma, W^+W^-$



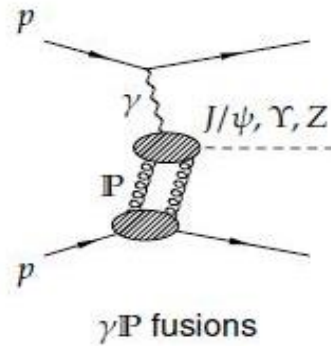
PP exchanges

χ_c, χ_b , Dijet, $\pi^+\pi^-$



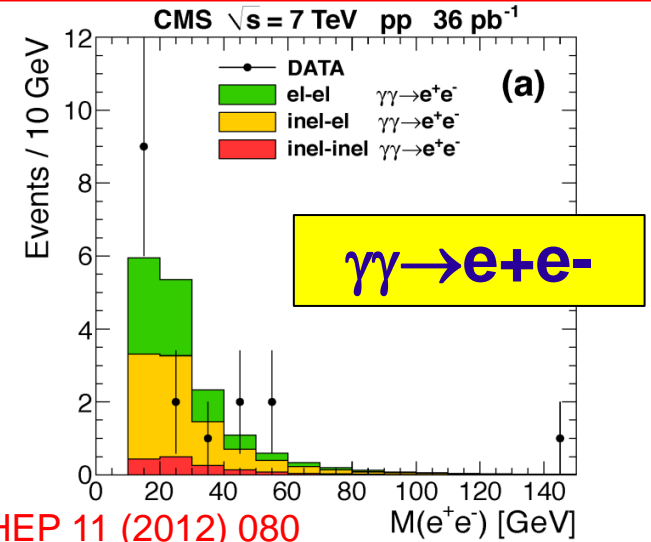
$\gamma\gamma$ interactions

$\mu^+\mu^-, e^+e^-, W^+W^-$

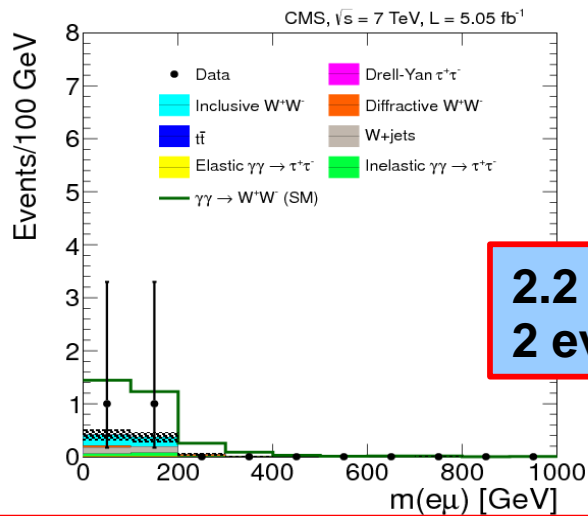


γP fusions

$J/\psi, \Upsilon$



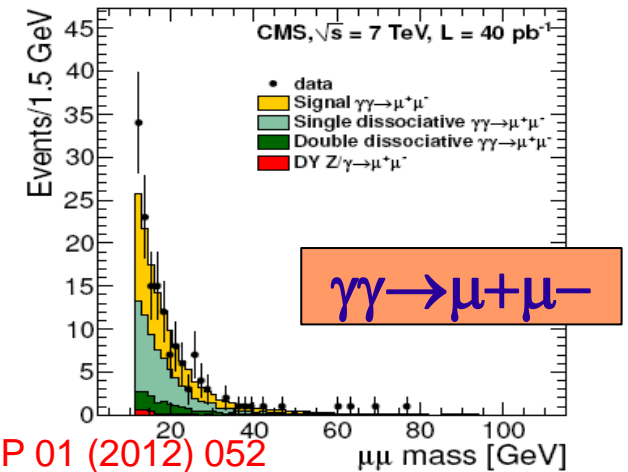
- W^+W^- : study of exclusive processes at high mass and constraint of anomalous couplings



Signal: 2.2 ± 0.4 evt
Bkg: 0.84 ± 0.15 evt

2.2 events expected
2 events found

JHEP 07 (2013) 116



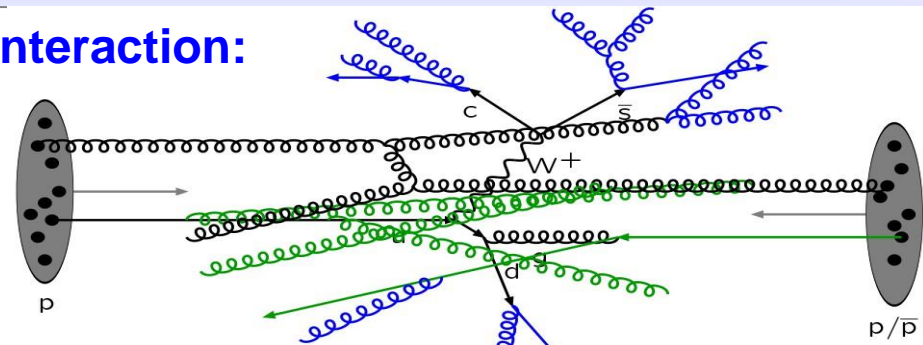
- l^+l^- : comparison to precision QED predictions, integrated luminosity normalisation

Underlying Event/MPI/DPS

Underlying Event – all besides products of hard interaction:

Components of UE:

- Initial and final state radiations (ISR & FSR)
- Beam-beam remnants (BR)
- **Multiple parton interactions (MPI)**



Tobjoern Sjostrand, April 2005

- Understanding of the Underlying Event data is crucial
- The energy dependence of the UE data is not well described by the current tunes

Event divided into two subsets:

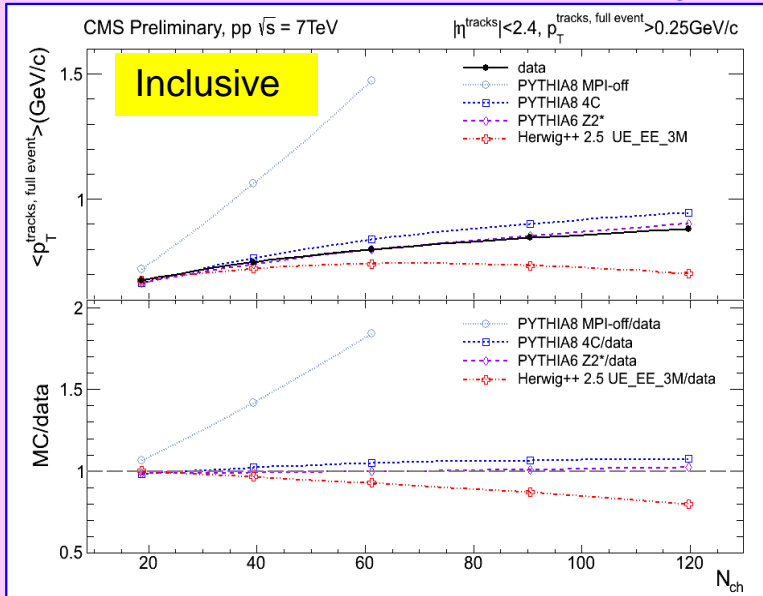
- (i) Jet induced contribution
- (ii) UE

Measurement divided into subspaces of charged particle multiplicity

MC Models:

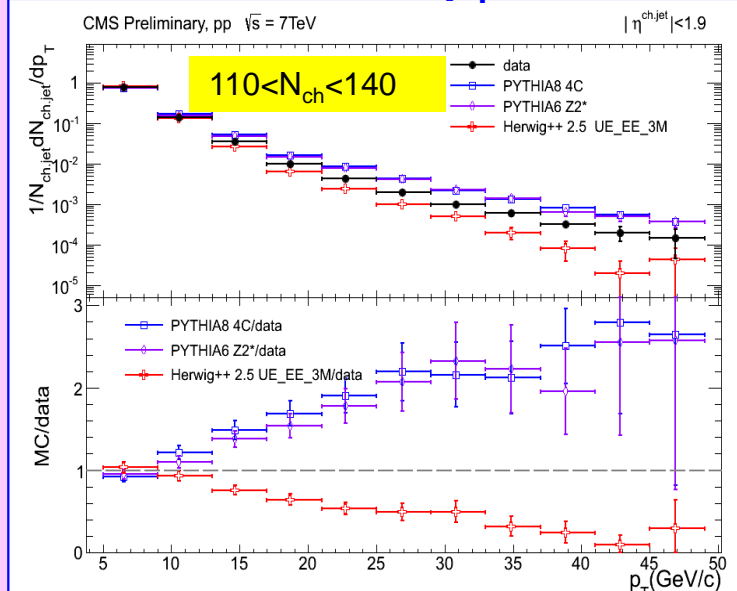
- Pythia 6 Z2*
- Pythia 8 4C
- Herwig++ 2.5
- Pythia 8 MPI-off

Jet < p_T > distribution with N_{ch}



• PYTHIA nicely follows at all multiplicities, **MC without MPI fails**

Jet rates with p_T



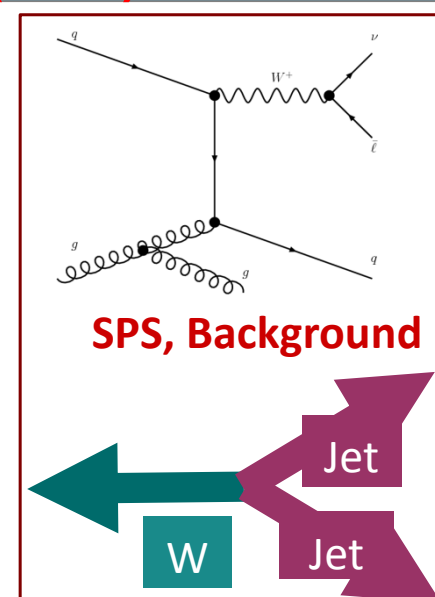
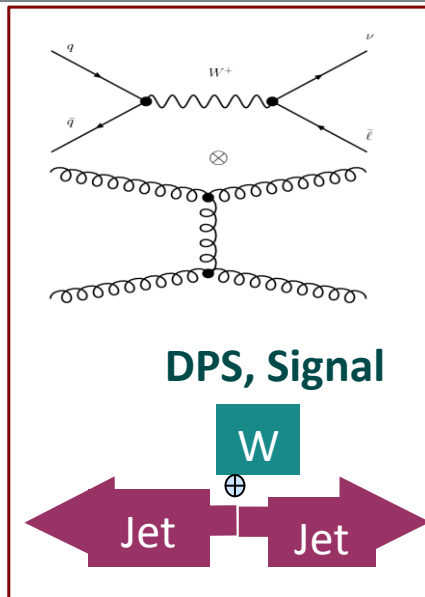
• Not well described by any model for **increasing multiplicities**

Motivation:

- DPS becomes more important as the collider energy grows, and probe smaller x ($\sim 2p_T/\sqrt{s}$) where there is a larger density of partons,
- Reveals information about correlations between partons in the proton
- Background to new physics searches

Signal: W from 1st hard parton-parton interaction, two jets from second one.

Background: $W + 2$ jets from single parton scattering (SPS)



σ_{eff} = the effective transverse area of hard partonic interaction

DPS Variables used :

- $\Delta^{rel} p_T$ = relative p_T balance between two jets
- ΔS = azimuthal angle between W boson and dijet

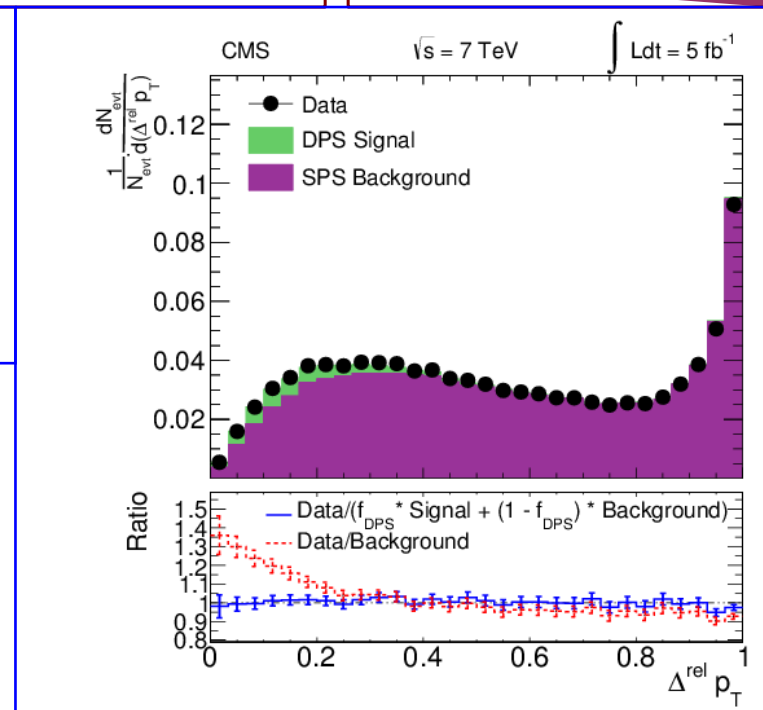
f_{DPS} = ratio of number of DPS event to SPS event

Extracted f_{DPS} with a DPS +SPS template fit to distributions of ΔS and $\Delta^{rel} p_T$:

$$f_{DPS} = 0.055 \pm 0.002(stat.) \pm 0.014(syst.)$$

$$\sigma_{eff} = 20.7 \pm 0.8(stat.) \pm 6.6(syst.)mb$$

Value comparable to Tevatron and ATLAS results



Diffractive and Exclusive production:

- **Inclusive single and double diffractive cross-sections at $\sqrt{s}=7$ TeV**
Separation of SD and DD cross-sections
- **Charged particle pseudorapidity distribution for $|\eta| < 2.4$ and $5.3 < |\eta| < 6.4$**
Span the largest pseudorapidity interval ever explored in LHC
- **The observed cross-sections are in agreement with the theoretical QED predictions for exclusive $\gamma\gamma \rightarrow l^+l^-$ production**

Underlying Events, MPI and DPS:

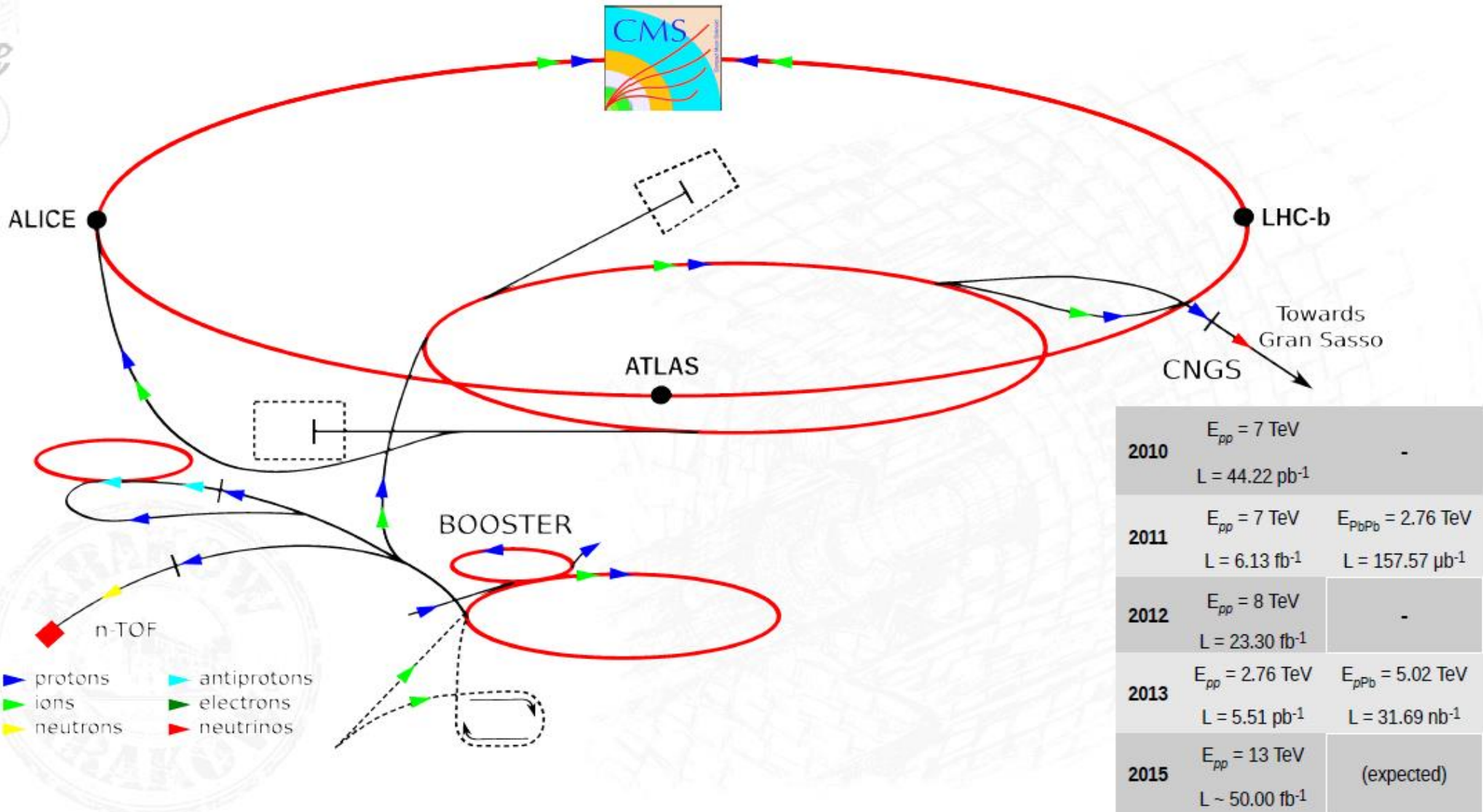
- **UE vs particle multiplicity**
MPI is an important part of underlying event modelling
- **DPS via W+2 jet**
 σ_{eff} effective transverse area of hard partonic interactions in collisions measured comparable to ATLAS and Tevatron results

Thanks for your kind attention!

Back up

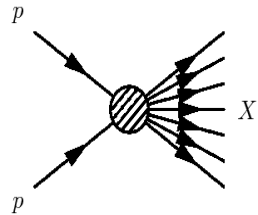
Back up

Large Hadron Collider



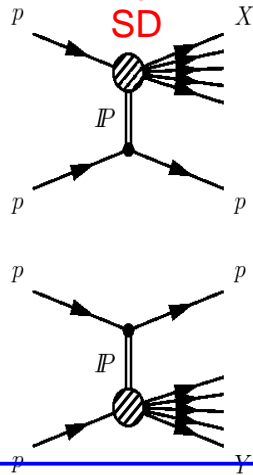
Back up

non-diffractive
ND



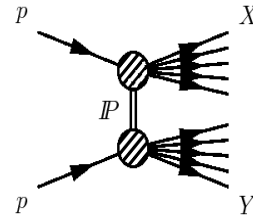
(a)

single-
SD



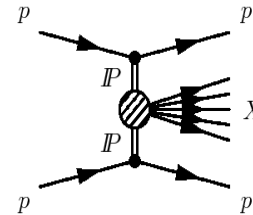
(b)

double-
DD



(c)

central-diffractive
CD



(d)

Diffraction Physics

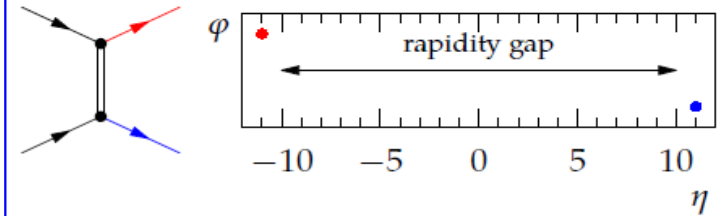
➤ Soft diffraction

➤ Hard diffraction

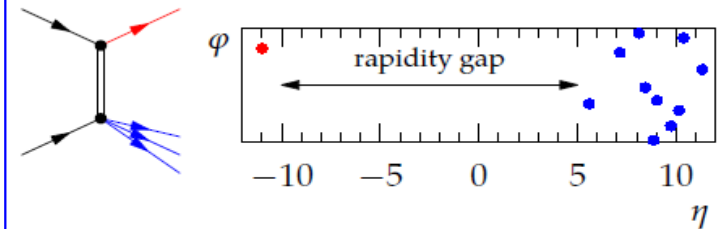
➤ If X=anything,
measure fundamental quantities of soft QCD

➤ If X includes jets, W's, Z's
Hard processes, calculable by pQCD

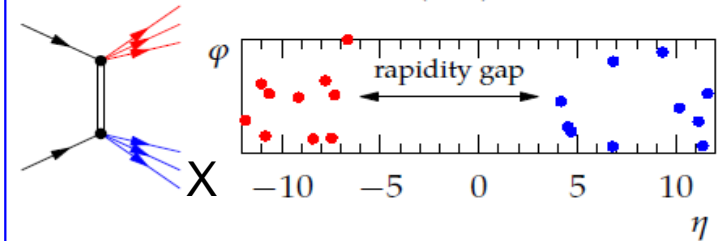
Elastic Scattering (ES), ≈ 25 mb



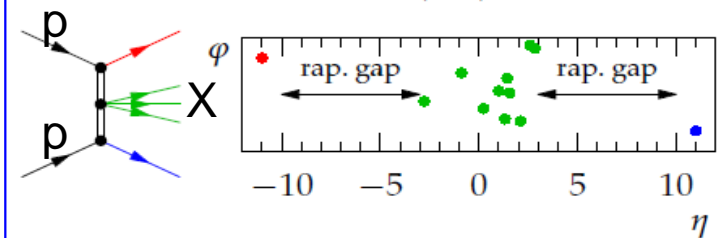
Single Diffraction (SD), ≈ 10 mb



Double Diffraction (DD), ≈ 5 mb



Central Diffraction (CD), ≈ 1 mb



Back up

Diffractive x-sections

$$\begin{aligned}\frac{d^2\sigma_{SD}}{dt d\Delta y} &= \frac{1}{N_{\text{gap}}(s)} \left[\frac{\beta^2(t)}{16\pi} e^{2[\alpha(t)-1]\Delta y} \right] \cdot \left\{ \kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right\}, \\ \frac{d^3\sigma_{DD}}{dt d\Delta y dy_0} &= \frac{1}{N_{\text{gap}}(s)} \left[\frac{\kappa \beta^2(0)}{16\pi} e^{2[\alpha(t)-1]\Delta y} \right] \cdot \left\{ \kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right\}, \\ \frac{d^4\sigma_{DPE}}{dt_1 dt_2 d\Delta y dy_c} &= \frac{1}{N_{\text{gap}}(s)} \left[\prod_i \left[\frac{\beta^2(t_i)}{16\pi} e^{2[\alpha(t_i)-1]\Delta y_i} \right] \right] \cdot \kappa \left\{ \kappa \beta^2(0) \left(\frac{s'}{s_0} \right)^\epsilon \right\}\end{aligned}$$

$$\beta^2(t) = \beta^2(0) F^2(t)$$

$$F^2(t) = \left[\frac{4m_p^2 - 2.8t}{4m_p^2 - t} \left(\frac{1}{1 - \frac{t}{0.71}} \right)^2 \right]^2 \approx a_1 e^{b_1 t} + a_2 e^{b_2 t}$$

$\alpha_1=0.9, \alpha_2=0.1, b_1=4.6 \text{ GeV}^{-2}, b_2=0.6 \text{ GeV}^{-2}, s'=s e^{-\Delta y}, \kappa=0.17,$
 $\kappa\beta^2(0)=\sigma_0, s_0=1 \text{ GeV}^2, \sigma_0=2.82 \text{ mb or } 7.25 \text{ GeV}^{-2}$

Inclusive measurement, SD+ DD

Forward rapidity gap $\Delta\eta^F = \max(4.7-\eta_{\max}, 4.7+\eta_{\min})$

Sample

16.2 μb^{-1} low pileup data at $\sqrt{s} = 7$ TeV

Selection

Same inclusive selection

No Large Rapidity Gap requirement

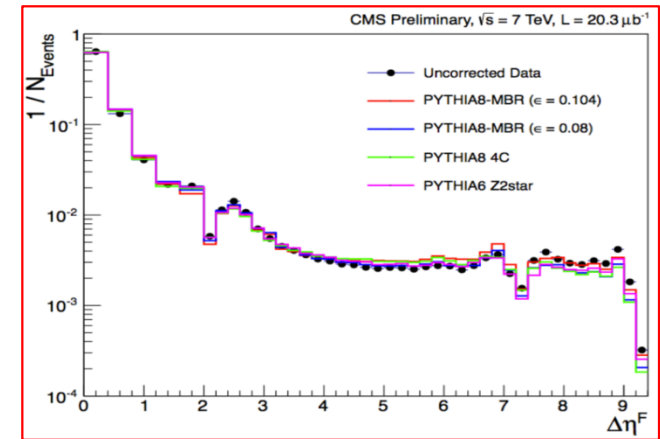
Monte Carlo

PYTHIA8-MBR, diffraction with Minimum Bias Rockfeller model

PYTHIA8-4C, diffraction with Schuler & Sjostrand model from PYTHIA6

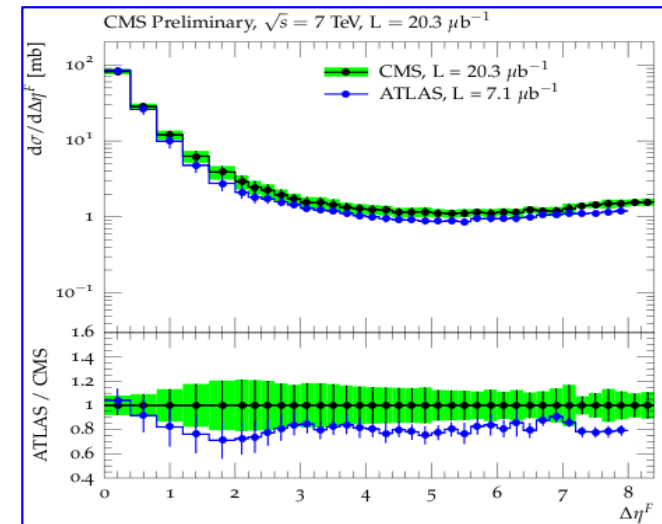
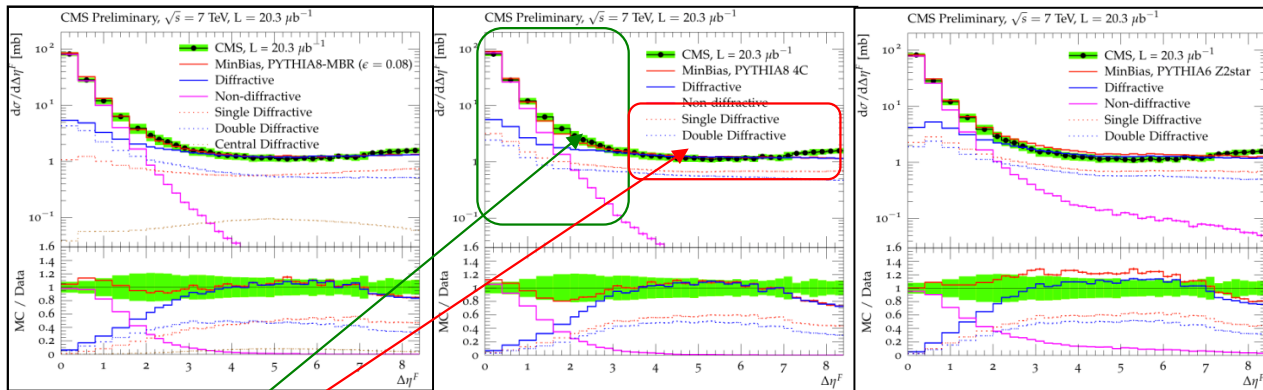
PYTHIA6-Z2*

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



Comparison with ATLAS

(EPJ C72 (2012) 1926)



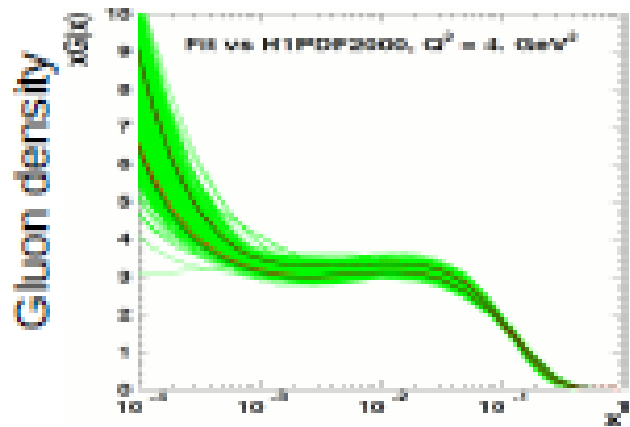
At low $\Delta\eta^F$ Exponentially suppressed, ND contribution is dominant

At large $\Delta\eta^F$ Diffractive plateau ~ 1 mb/ unit of gap size

- CMS & ATLAS: Agreement within uncertainties
- CMS result extends ATLAS measurement by 0.4 unit of gap size

Low-x dynamics

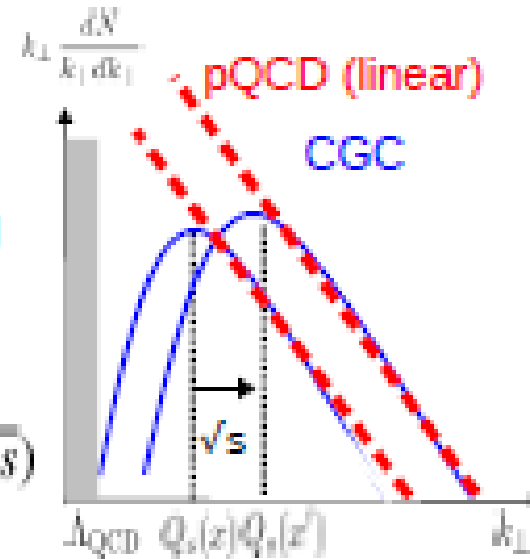
- Gluons start to **overlap** at "saturation scale"



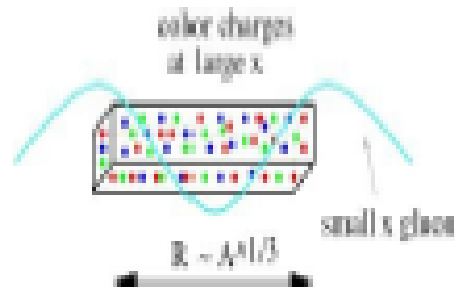
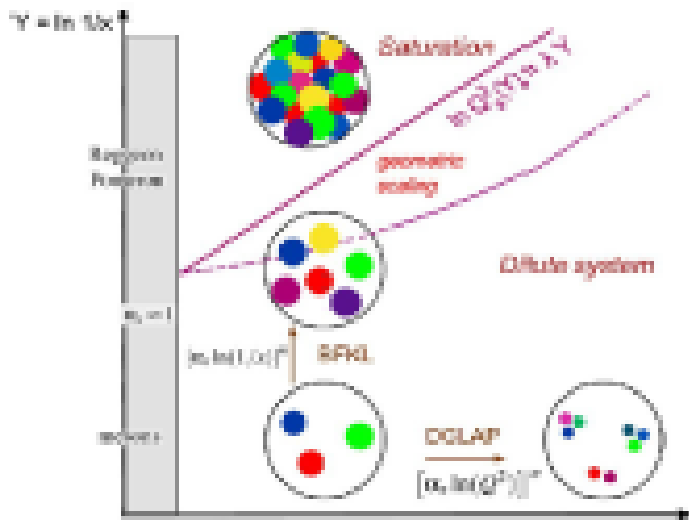
$$Q_s^2 \sim \alpha_s \frac{x G_A(x, Q_s^2)}{\pi R_A^2}$$

- Asymptotic pQCD g-g x-section peaks at $p_T \sim Q_s(\sqrt{s}) \sim 1-4 \text{ GeV}$

$$Q_{\text{sat}}^2 \propto \log(1/x) \propto \log(\sqrt{s})$$



- Hadrons ~ "Color Glass Condensate" below Q_s
- Saturation effects enhanced in nuclei:



Large # of partons per transverse area

$$Q_s^2 \sim A^{1/3} \sim 6$$

PYTHIA6(version 6.426) with Tune Z2*
PYTHIA8(version 8.153) with Tune 4C

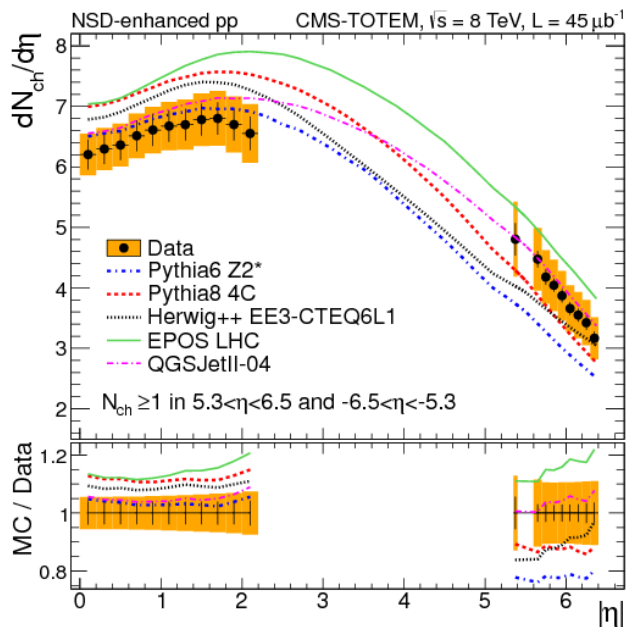
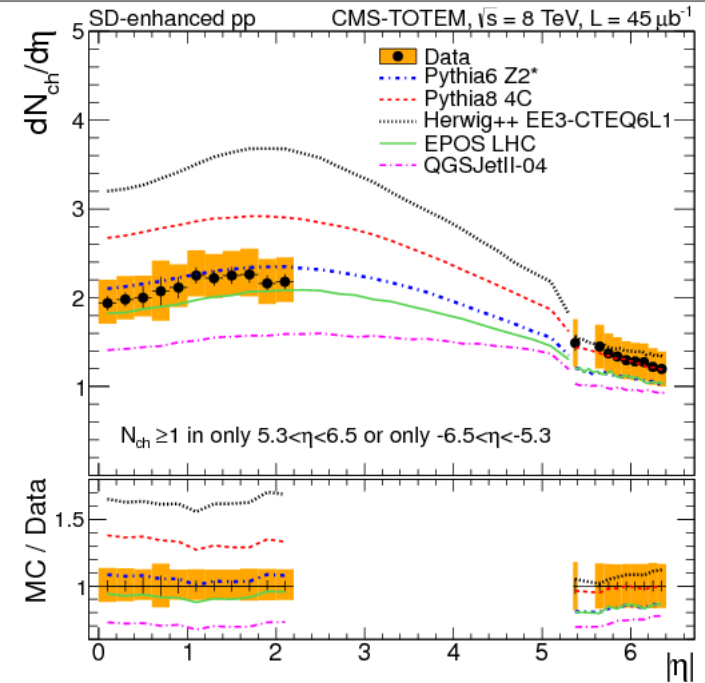
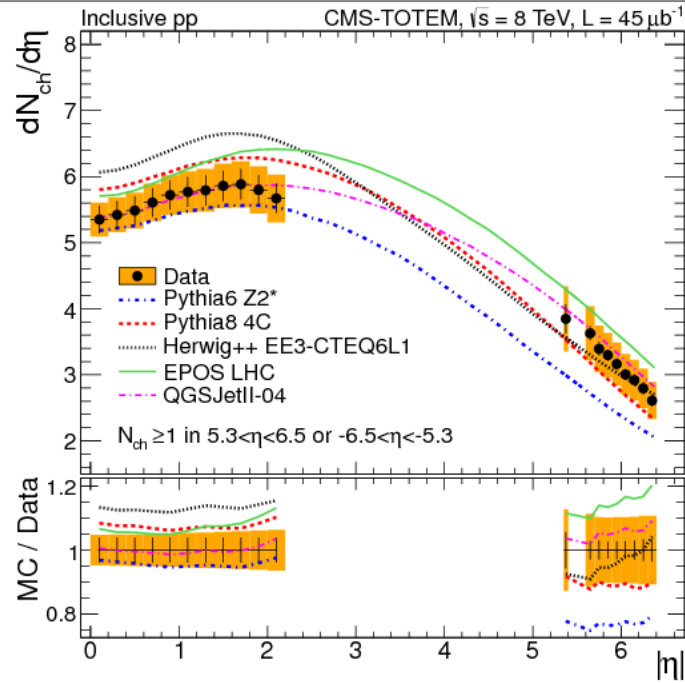
- providing different description of non-diffractive components
- Both use new model where multiple partonic interactions are interleaved with parton showering
- Z2* derived from Z1 tune updated to CTEQ6L PDF
- Parton showers in PYTHIA are modelled according to DGLAP and hadronisation with Lund String model
- Diffractive cross-section by Schuler-Sjostrand model
- Pythia6 and Pythia8 use different model for particle production for different M_x region, Pythia8 use perturbative pomeron-parton scattering $M_x > 10$ GeV

HERWIG++(version 2.5.0) with tune UE-EE-3C

- Use same matrix element as PYTHIA
- Parton shower development with DGLAP
- Z2* derived from Z1 tune updated to CTEQ6L
- Angular ordered parton shower
- Cluster fragmentation for hadronisation
- Diffractive cross-section use diffractive parton distribution function

EPOS LHC Tune (version 1.99) and QGSJetII04:

- Used in Cosmic ray studies
- Soft and hard parton dynamics
- Soft component, exchange virtual quasi particle state: Gribov-Reggeon field theory, with multi-pomeron exchange, accounting for UE
- Hard processes included via “cut (hard) Pomerons” \approx LO pQCD with DGLAP
- Tuned to variety of LHC data

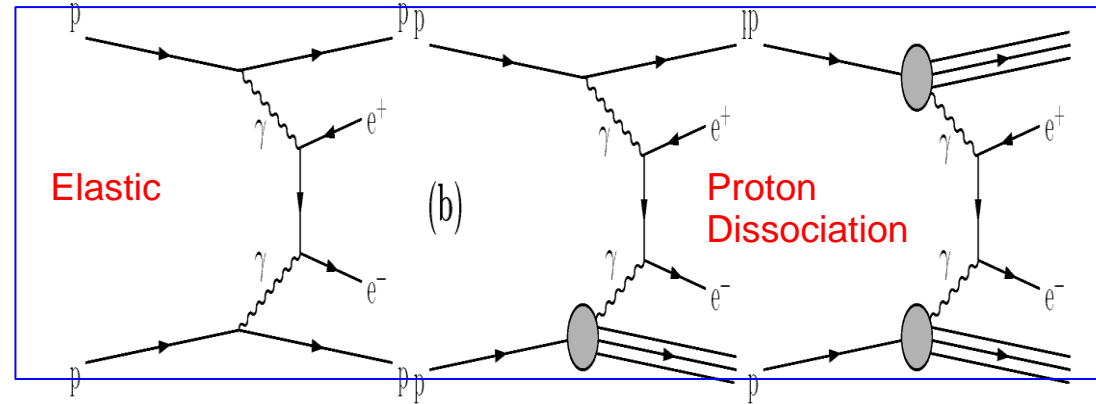


Sample

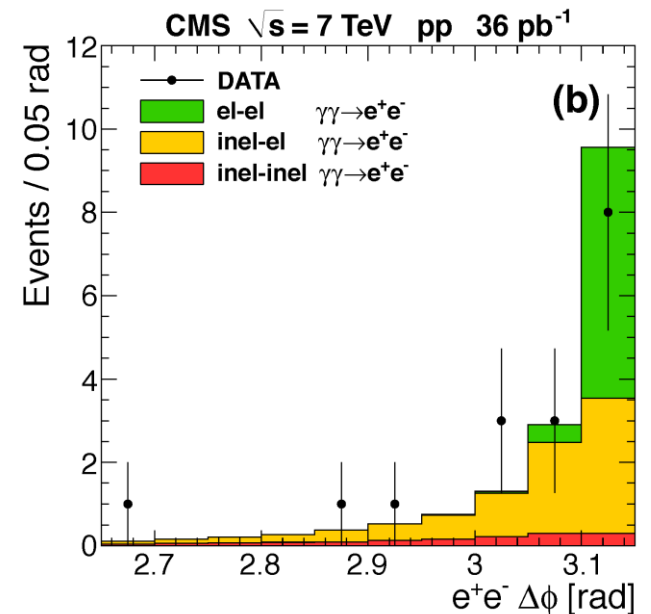
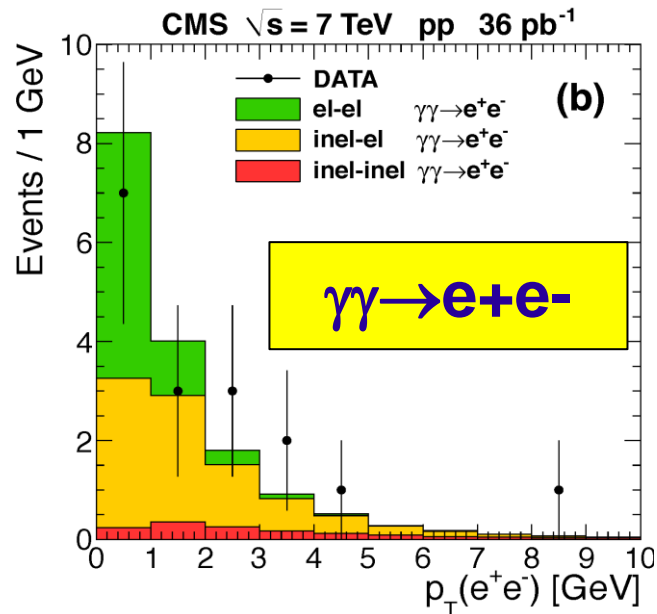
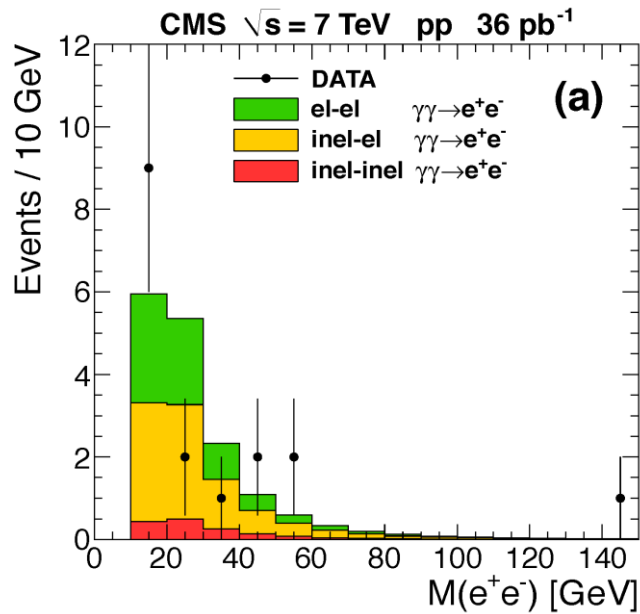
36 pb⁻¹ of 2010 data at 7 TeV

Selection

- ★ $E_T(e) > 5.5$ GeV and $|\eta(e)| < 2.5$;
- ★ No additional tracks in the Tracker;
- ★ No additional activity above noise threshold in the calorimeters.



MC : LPAIR includes both elastic and proton dissociation

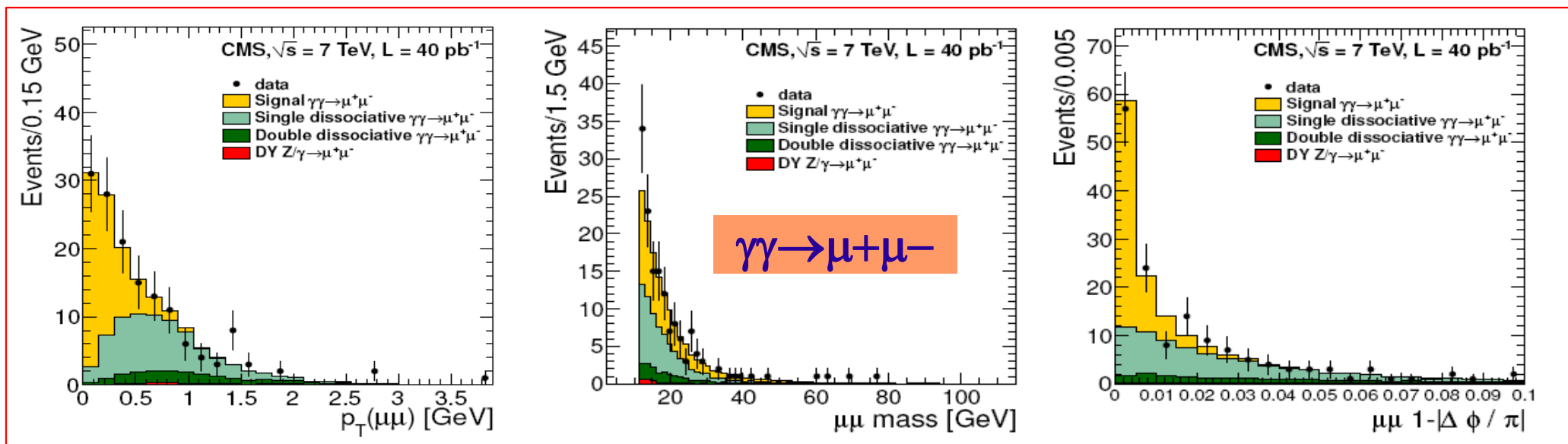
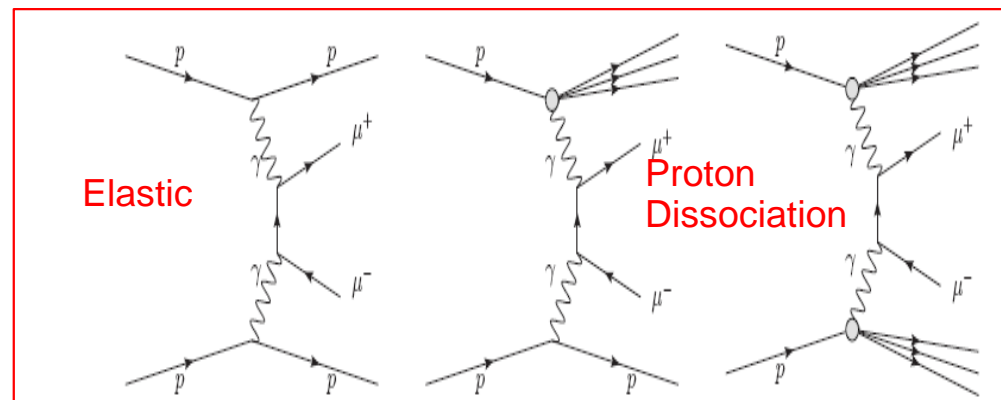


- Pair- p_T very small (peak at ~ 200 MeV/c). Electrons \sim back to back.
- 17 (semi) exclusive events observed in 36 pb⁻¹, Good agreement between LPAIR and data

Exclusive dimuons observed in $m_{\mu^+\mu^-} \sim 11 - 80$ GeV (above Y peak):

Sample: 40 pb⁻¹ of 2010 data at 7 TeV

- ★ Vertex with 2μ and no track within 2 mm
- ★ $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.1$
- ★ Exclusivity cuts: $1 - |\Delta\phi/\pi| < 0.1$ and $|\Delta p_T| < 1.0$ GeV



- Pair- p_T very small (peak at ~ 50 MeV/c). Muons are \sim back to back.
- Good agreement with LPAIR ; $\sigma(pp \rightarrow p \mu^+\mu^- p) = 3.38^{+0.58}_{-0.55}(\text{stat}) \pm 0.16(\text{sys}) \pm 0.14(\text{lumi})$ pb

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

FSQ-12-010 , JHEP 07 (2013) 116

Sample

5.05 μb^{-1} 2011 data at $\sqrt{s} = 7$ TeV

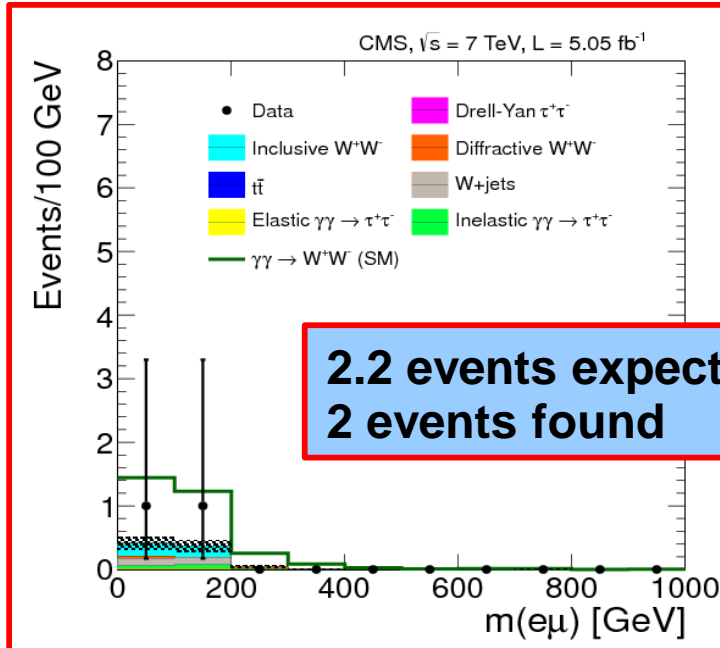
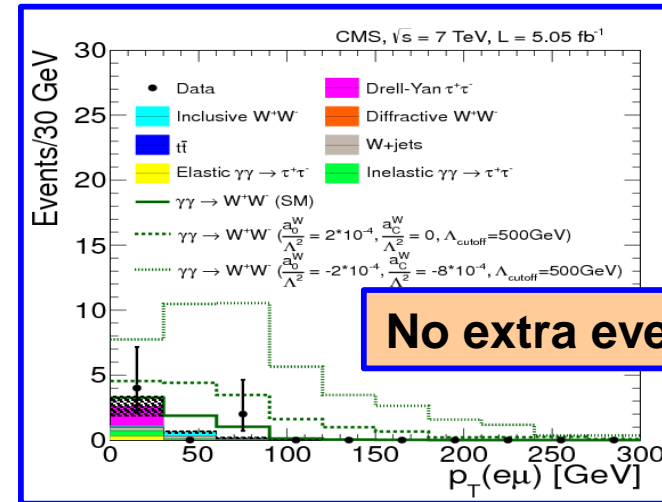
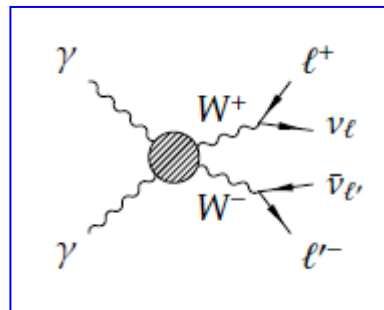
SM signal region:

- $p_T(l) > 15$ GeV and $|\eta(l)| < 2.4$;
- $m(l^+l^-) > 20$ GeV and $p_T(l^+l^-) > 30$ GeV
- $\Delta p_T < 1$ GeV, $\Delta\phi > 0.9\pi$
- No extra tracks associated to the dilepton vertex

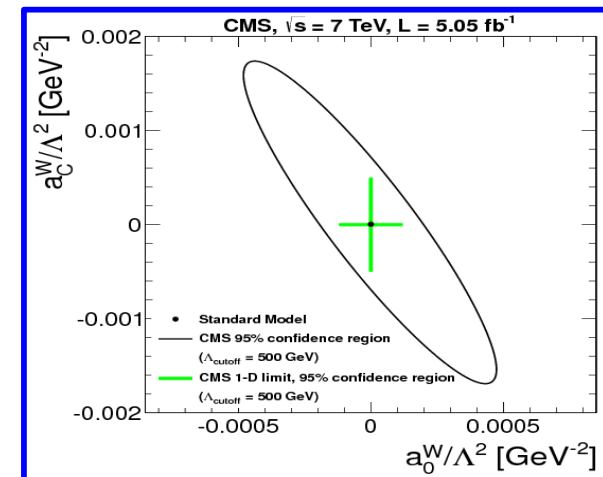
aQGCs search:

- $p_T(\mu^\pm e^\mp) > 100$ GeV
- no extra tracks associated to the dilepton vertex

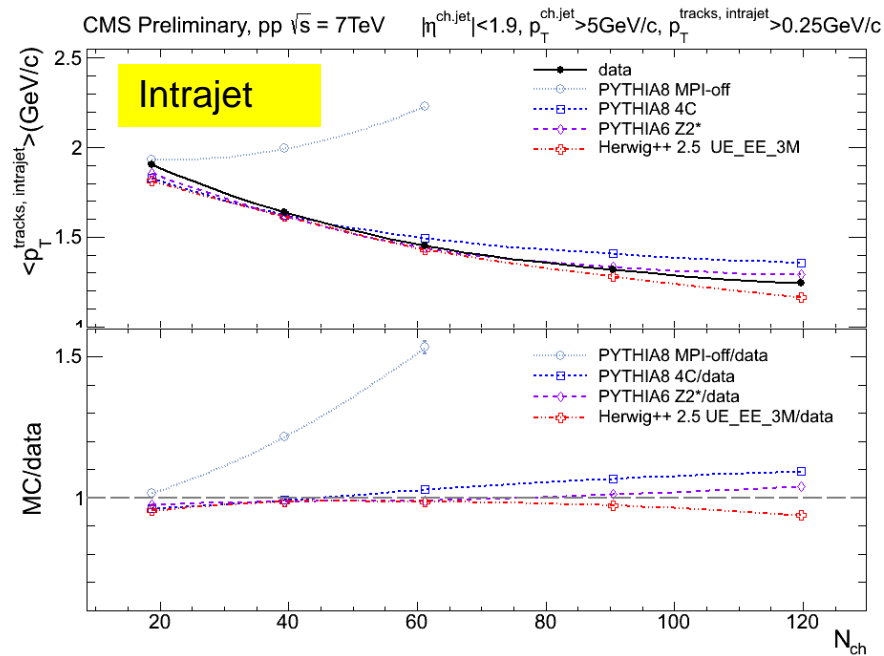
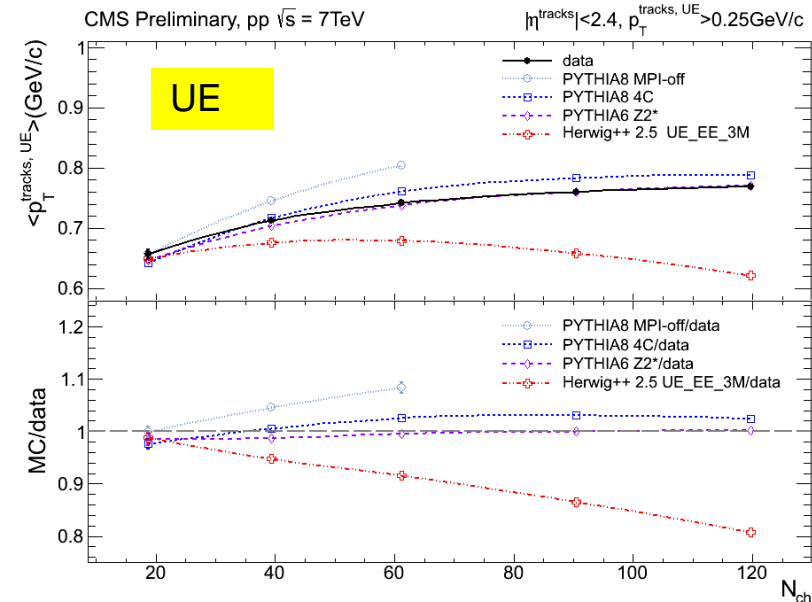
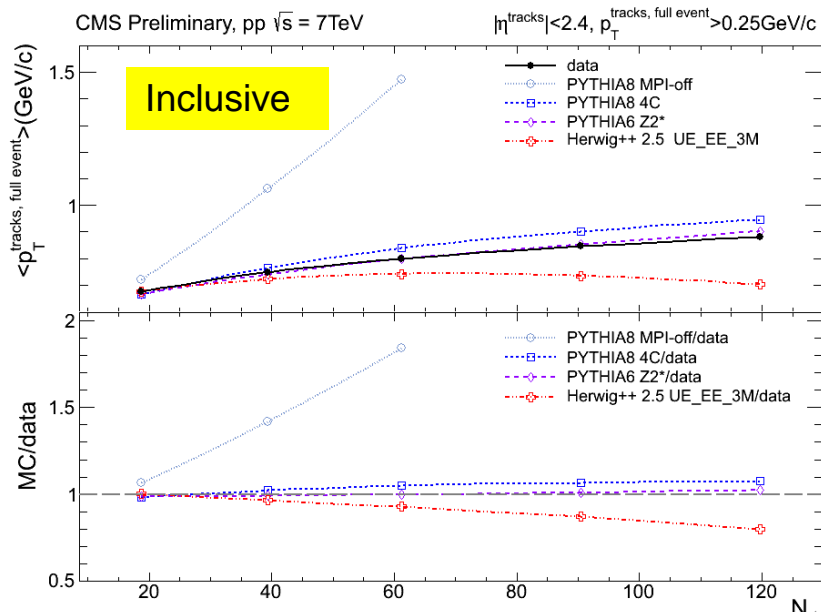
Signal: 2.2 ± 0.4 evt
Bkg: 0.84 ± 0.15 evt

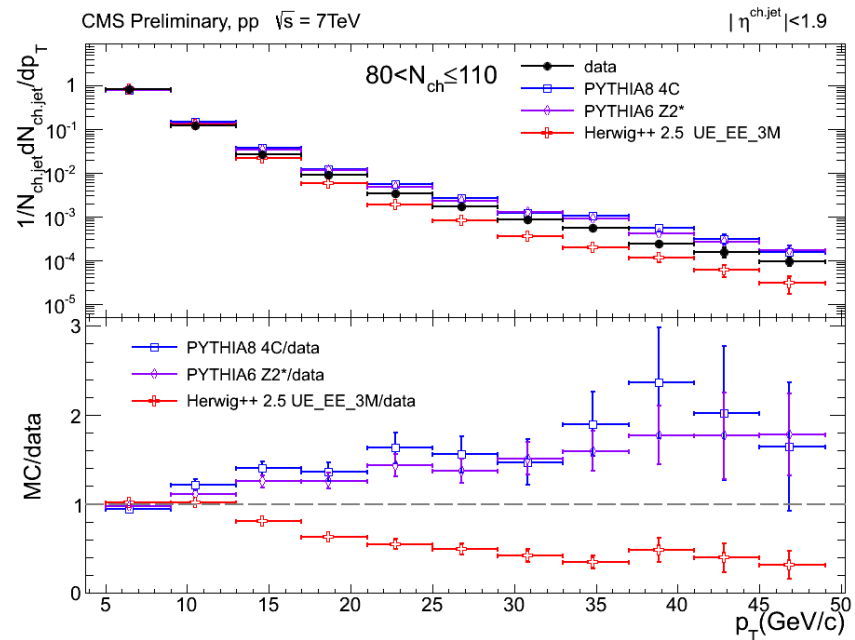
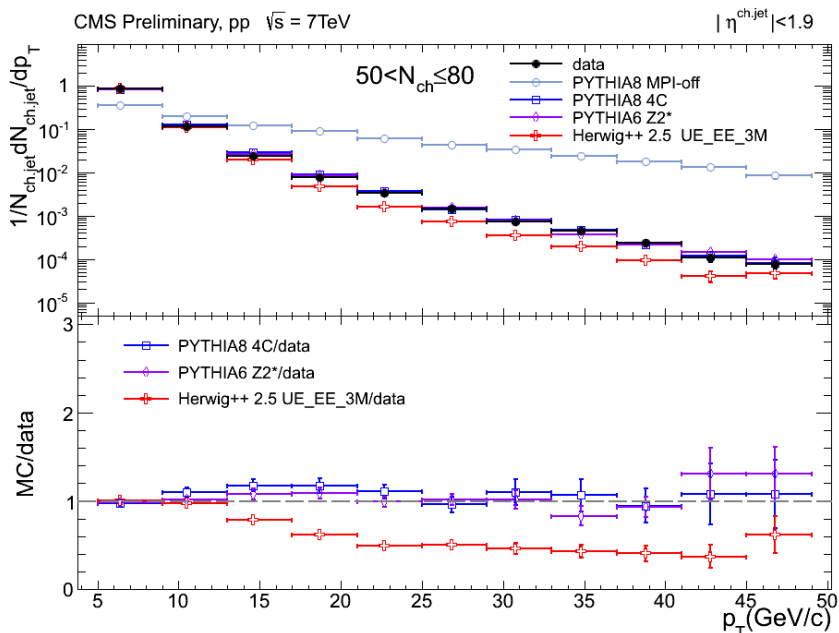
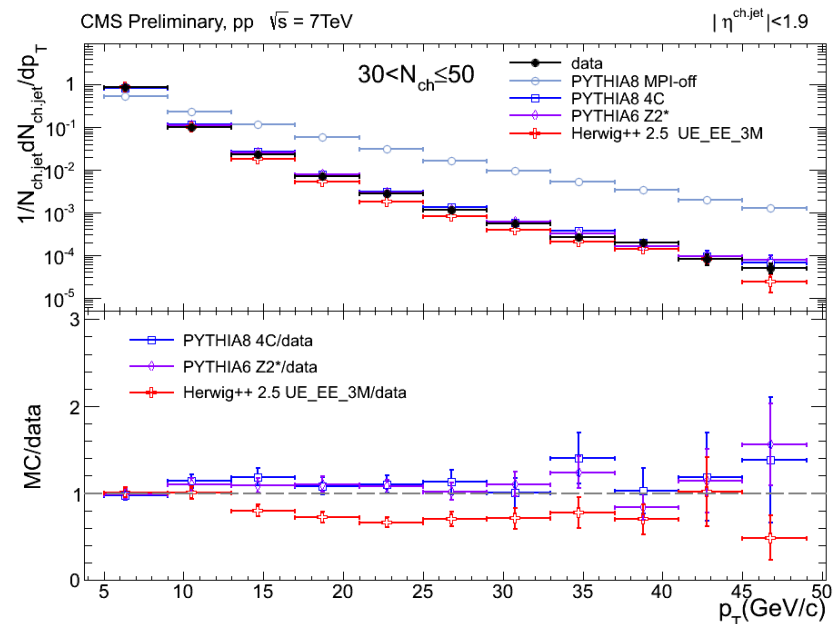
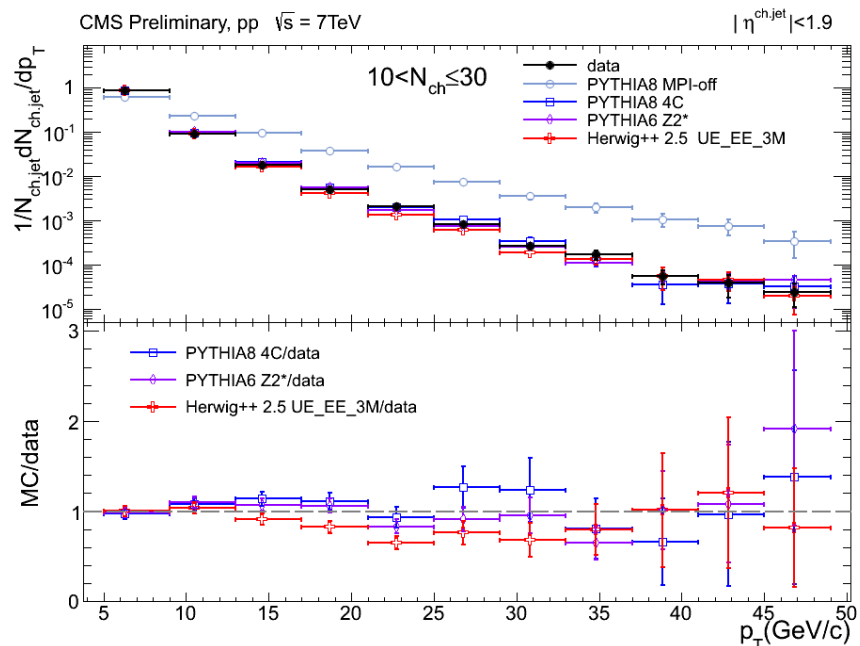


AQGC limits: two orders of magnitude more stringent than the limits of LEP & Tevatron



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





W selection:

- Exactly one μ
- with $p_T > 35$ GeV, $|\eta| < 2.1$
- Required to be isolated and to pass tight ID criteria
- particle flow Missing Transverse Energy, MET (with type1 correction) > 30 GeV
- transverse mass of (μ and MET) > 50 GeV

Jet selection:

- Anti k_T PF jet with $R=0.5$
- $p_T > 20$ GeV/c, $|\eta| < 2.0$
- Exactly two jets

f_{DPS}	=	$0.076 \pm 0.013(\text{stat.}) \pm 0.018(\text{syst.})$	(ATLAS)
f_{DPS}	=	$0.055 \pm 0.002(\text{stat.}) \pm 0.014(\text{syst.})$	(CMS)
σ_{eff}	=	$15 \pm 3(\text{stat}) + 5/-3(\text{syst})$ mb	(ATLAS)
σ_{eff}	=	$20.7 \pm 0.8(\text{stat}) \pm 6.6(\text{syst})$ mb	(CMS)

σ_{eff} effective transvers area of hard partonic int.

$$\sigma_{\text{eff}} = \sigma_A / \sigma_{A+B}^{\text{DPS}}, \quad \sigma_{\text{eff}} = \frac{R}{f_{DPS}} \cdot \sigma'_{2j}$$

$$R = N'_{W+0j} / N'_{W+2j}; \quad f_{DPS} = N^{\text{DPS}}_{W+2j} / N'_{W+2j}$$

Extracted f_{DPS} with a DPS +SPS template fit to distributions of ΔS and $\Delta^{\text{rel}} p_T$:

$f_{DPS} = 0.055 \pm 0.002(\text{stat.}) \pm 0.014(\text{syst.})$
 $\sigma_{\text{eff}} = 20.7 \pm 0.8(\text{stat.}) \pm 6.6(\text{syst.}) \text{mb}$
 Value comparable to Tevatron and ATLAS results

