Diffractive results from CMS and TOTEM experiments at LHC

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on behalf of

CMS & TOTEM collaborations, LHC, CERN

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Motivation

- Forward physics:

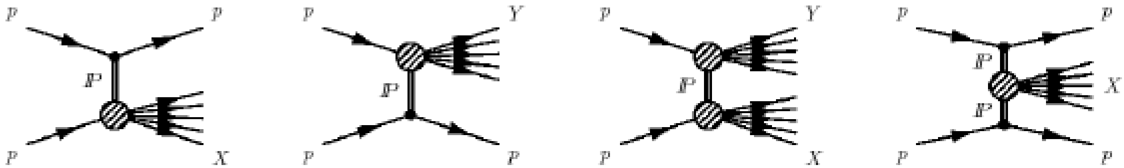
  (i) addresses strong interaction dynamics at the interface of hard and soft scatterings.

  (ii) provides the tool to study different components of particle production.

- Diffractive processes : colourless exchange with vacuum quantum numbers

  → characterized by large rapidity gap in the final state,

  → and absence of multiple parton interactions.



- LHC results on diffractive processes are crucial inputs for understanding strong interaction at low-x, underlying events, soft QCD at high CM energies.

- Hard processes in hadron collisions are necessarily embedded in soft ones!

  ➔ study of diffractive processes helps in understanding the hadron collision in a more complete way → helps in tuning Monte Carlo event generators.

Test of models for hadronic interactions

- Measurements in CMS and TOTEM experiment performed for

(i) pp collisions at $\sqrt{s}$ = 900 GeV, 7, 8 & 13 TeV

(for 13 TeV additionally in region $3.15 < |\eta| < 6.6$)

(ii) pPb: 5 TeV,

(iii) PbPb: 2.76 TeV

- Observables compared with variety of models available with different tunes

(i) Pythia with (a) Monash 2013, (b) CUETP8M(S)1, (c) MBR model for diffraction

(ii) HERWIG with UE-EE-4C

(iii) EPOS-LHC (includes collectivity/hydrodynamics) and QGSJETII.04

Gribov-Regge multiple scattering + string fragmentation

(iii) Airshower: SIBYLL (for exclusive muon pair production)

Total cross section and its components

$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$ where $\sigma_{inel} = \sigma_{diff} (\sigma_{SD} + \sigma_{DD} + ..) + \sigma_{non\text{-}diff}$

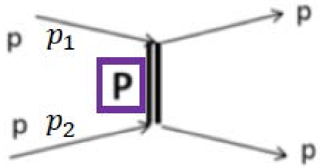
Cross section measurements

- Total cross section for p-p collision is a fundamental quantity .
  → estimation is important for understanding the scattering behaviour at high energies ➔ unitarity of the cross section.
  → cannot be calculated from perturbative QCD

$$\sigma_{\text{tot}} \approx s^{\alpha(0)-1}$$

➔ rise of σ_{tot} for $\alpha(0) > 1$

- Using optical theorem and Regge theory total cross section can be measured independent of luminosity.



$\sigma_{tot} = 4\pi\, \text{Im}[f_{el}(t=0)]$ where f_{el} : elastic amplitude

$$\frac{d\sigma_{\text{el}}}{dt} \approx s^{2(\alpha(0)-1)} e^{-B|t|}$$

$s = (p_1 + p_2)^2$
$t = (p_1 - p_2)^2 = -(p_0\, \vartheta)^2$

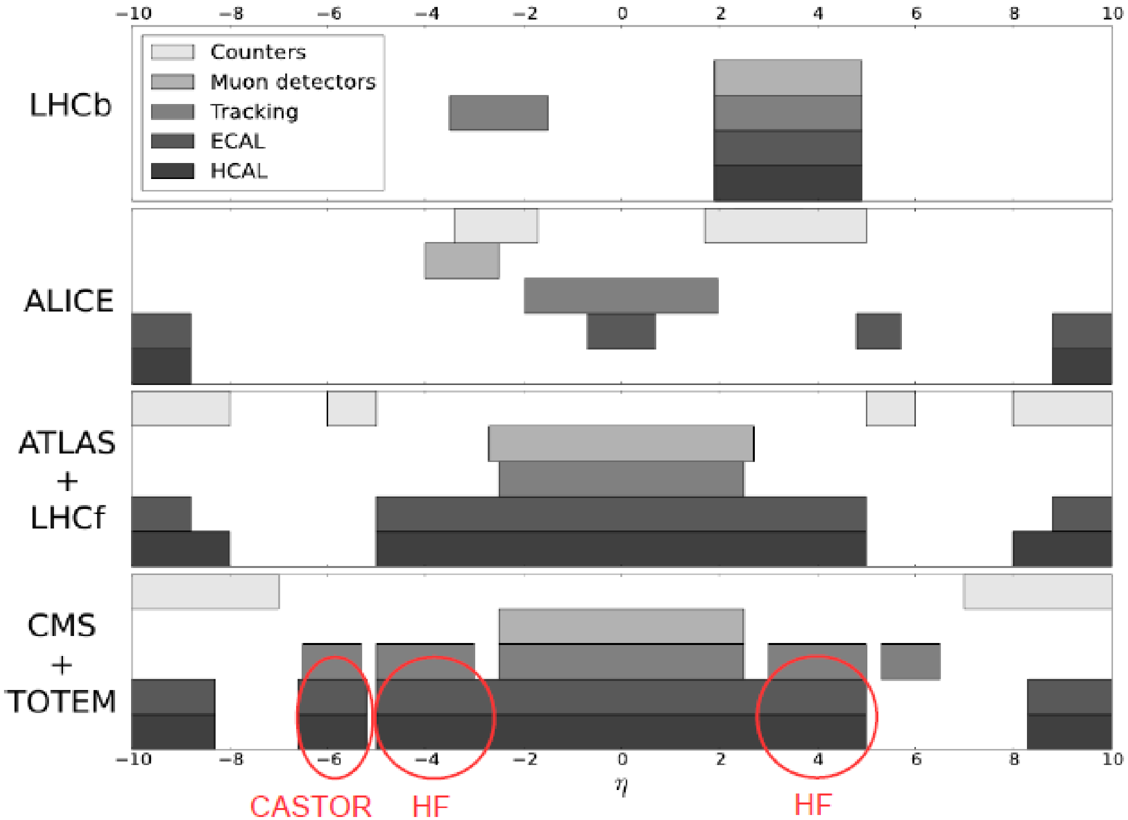
➔ small angle measurement

- **Soft, inclusive inelastic events: both diffractive and non-diffractive**

Measurements of different components depend on beam optics, proton acceptance, ..

Measurements in forward region

Courtesy: C. Baus



- At high energy about 40% of total cross section is due to diffractive processes
- Forward region of CMS experiment is well equipped with HF, Castor + TOTEM

Lorentz-invariant fractional momentum loss of proton $\xi > 10^{-6}$

X, Y system of particles around the pair with the largest rapidity gap

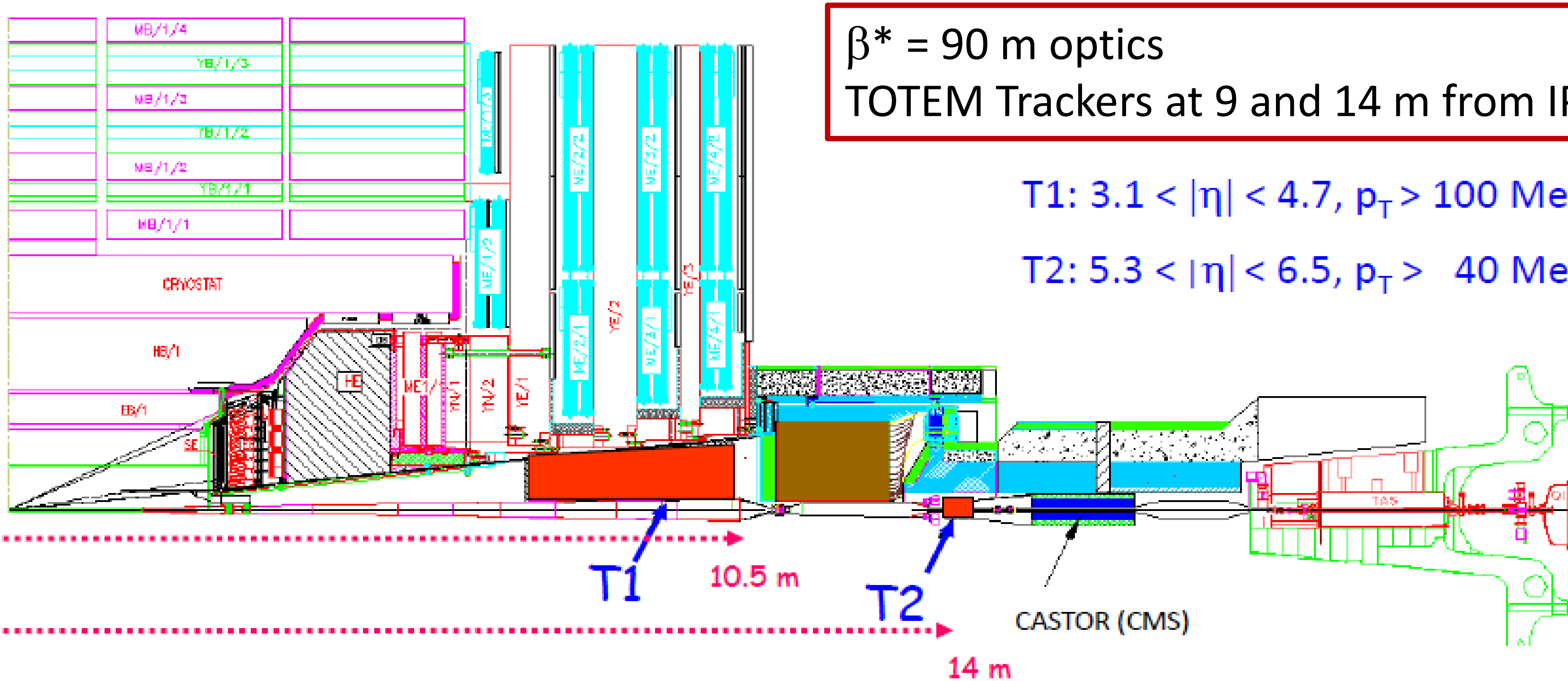
$$\xi_X = M_X^2/s, \quad \xi_Y = M_Y^2/s,$$
$$\xi = \max(\xi_X, \xi_Y).$$

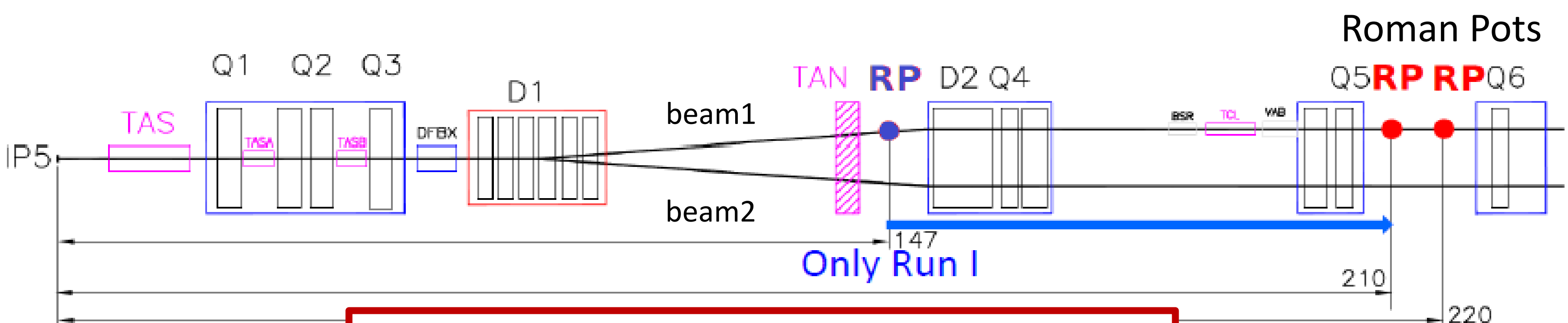
Layout for TOTEM experiment at Run II

β^* = 90 m optics
TOTEM Trackers at 9 and 14 m from IP

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

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





Measure scattered proton at low angle ~ μrad

Main goals of TOTEM experiment

Measurement of total cross section

$$\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \left.\frac{d\sigma_{EL}}{dt}\right|_{t=0}$$

$$\frac{d\sigma_{EL}}{dt} = \frac{1}{L} \bullet \frac{dN_{EL}}{dt}$$

$$\sigma_{TOT} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{\left.\frac{dN_{EL}}{dt}\right|_{t=0}}{N_{EL} + N_{INEL}}$$

Using luminosity from CMS

Luminosity independent

ρ = ratio of real to imaginary part of elastic amplitude

ρ parameter determined from COMPETE fit

Ref.: J.R. Cudell et.al., PRL 89: 201801 (2002)

N_{INEL}: using TOTEM detectors integrated in CMS (T1, T2)

N_{EL}: using TOTEM detectors integrated in LHC (Roman Pots)

Main analyses:

- Forward multiplicity
- Diffractive physics (soft & hard diffraction, jets)
- Total & elastic cross sections

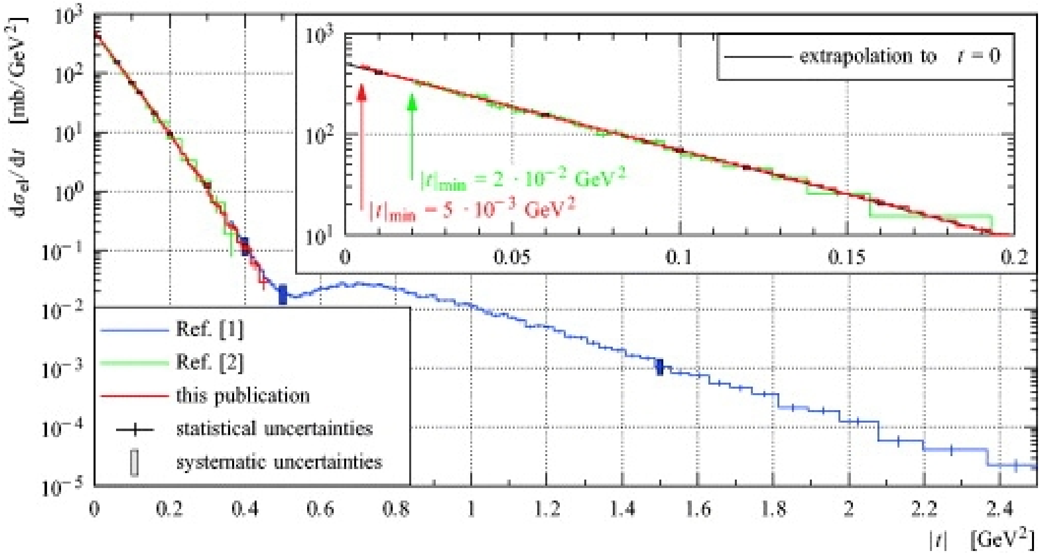
TOTEM (stand alone)

TOTEM&CMS at low / highβ*, special runs

TOTEM&CMS at low β* and high luminosity

Differential elastic cross section in TOTEM at √s = 7 TeV

2013 EPL 101 21002



t-slope of elastic amplitude determines the value of interaction radius.

→ Can be transformed to the representation of impact parameter to study interaction behaviour at high energies.

- Very small *t*: interference of nuclear & coulomb interactions → access to phase of the nuclear amplitude; $\rho \equiv \frac{\Re \mathcal{A}^N}{\Im \mathcal{A}^N}\Big|_{t=0}$

- Small |*t*| : cross section decreases exponentially → dσ/d*t* ~ *A* exp(-B|*t*|) .

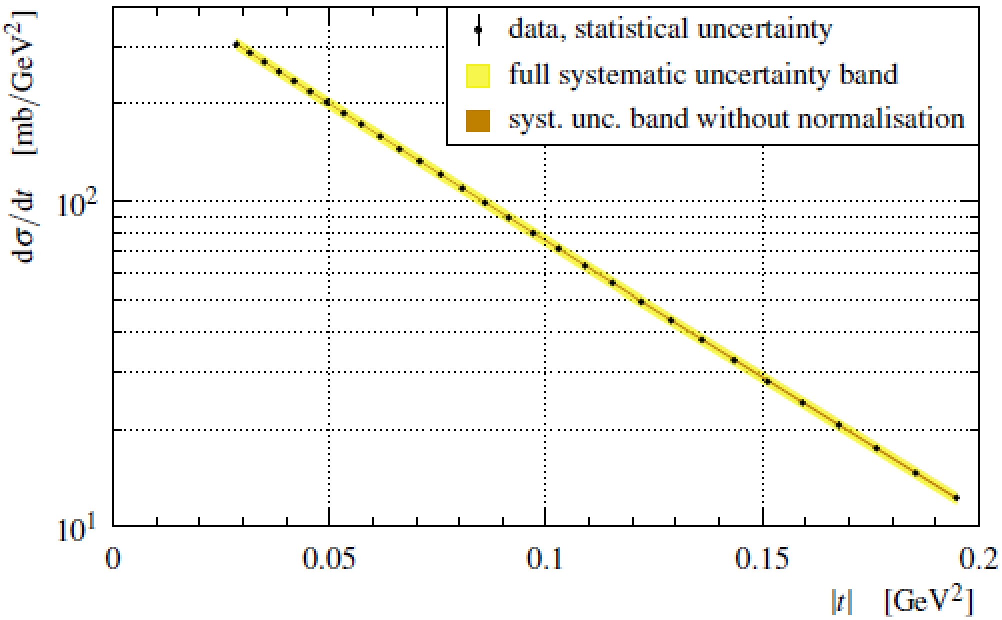
→ nuclear slope parameter *B* increases with energy ➔ shrinking forward cone

- Large |*t*|: diffractive minimum → position depends on energy

- Very large |*t*| : distribution follows power law

Elastic cross section at low $|t|$ by TOTEM at $\sqrt{s}$ = 8 TeV

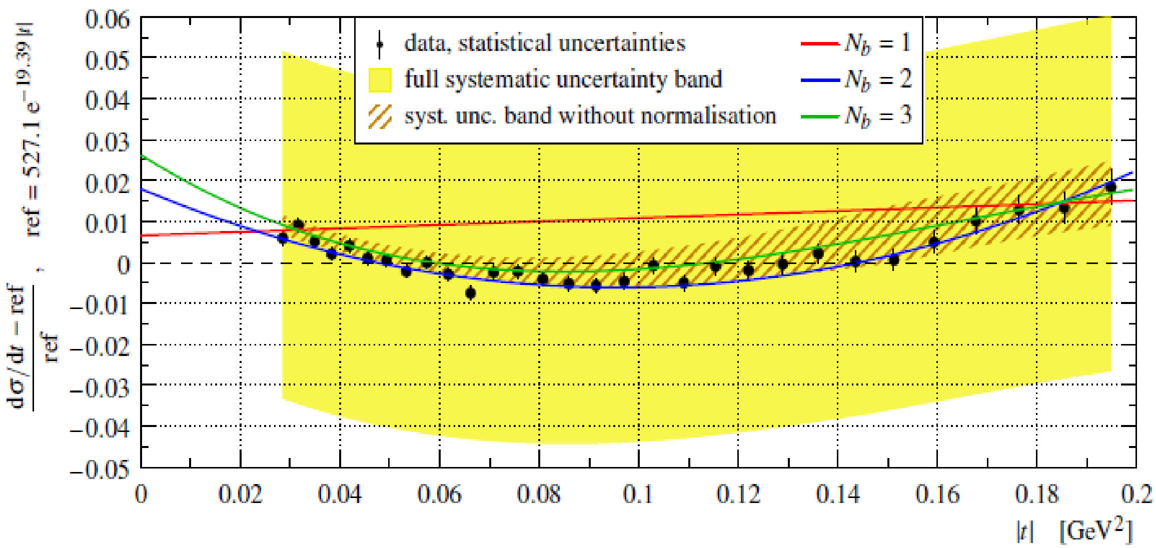
arXiv: 1503.08111
Nucl. Phys. B 899 (2015) 527



$$\sigma_{\rm tot}^2 = \frac{16\pi\,(\hbar c)^2}{1+\rho^2}\left.\frac{d\sigma_{\rm el}}{dt}\right|_{t=0}$$

$$\frac{d\sigma}{dt}(t) = \left.\frac{d\sigma}{dt}\right|_{t=0} \exp\left(\sum_{i=1}^{N_b} b_i\, t^i\right)$$

N_b : degree of the polynomial
→ parametrises nature of the interaction between 2 protons



For $|t|$ =[0.027, 0.2] GeV^2 purely exponential increase of elastic cross section ruled out at > 7 σ level,

Measurement of elastic and total cross section in TOTEM experiment at √s = 8 TeV

Eur. Phys. J.C76 (2016) 661

- Luminosity ~ 1/ β^*
- β^* = 90 m for elastic scattering
- Elastic pp scattering Coulomb-Nuclear interference region for high β^* (1KM)

➔ Use special beam optics and novel collimation method.

σ_{tot} = 101.5 ± 2.1 mb & 102.9 ± 2.3 mb (using 2 methods)

σ_{el} = 27.1 ± 1.4 mb, σ_{inel} = 74.7 ± 1.7 mb,

- First measurement at LHC of ρ parameter via Coulomb-Nuclear interface

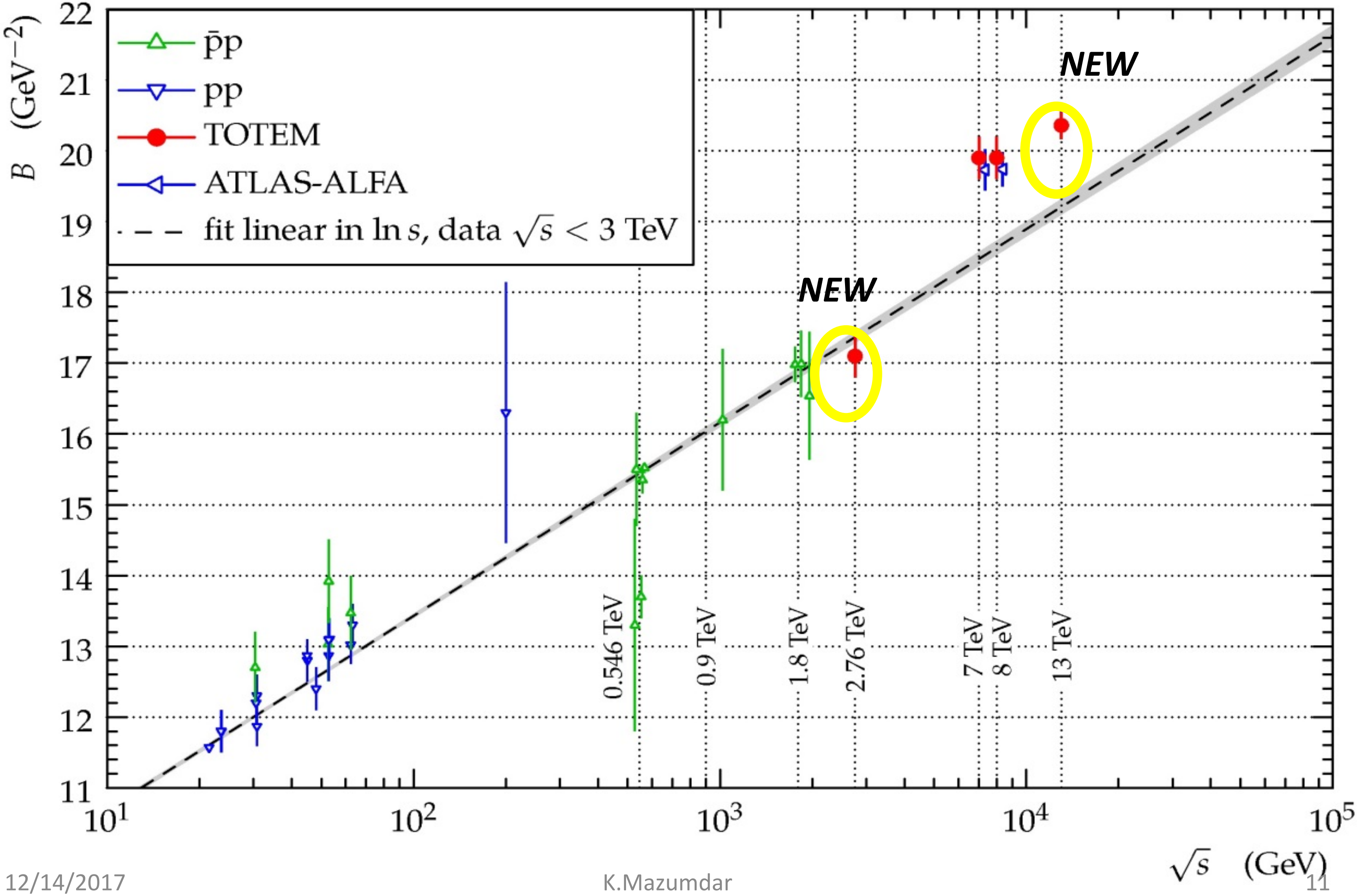
ρ = 0.12 ± 0.03 @ 8 TeV

- Measurement of cross section in CNI region at √s = 13 TeV with β^* =2.5 KM
- $|t|_{min}$ ~ $8*10^{-4}$ GeV^{-2}

Measurement of diffractive slope parameter *B*

At 13 TeV $B = (20.36 \pm 0.19)\ GeV^{-2}$

CERN-EP-2017-321



Inelastic cross section by CMS at √s = 13 TeV

CMS PAS FSQ-15-005

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s).$$

$$\sigma_{inel}(s) = \sigma_{sd}(s) + \sigma_{dd}(s) + \sigma_{cd}(s) + \sigma_{nd}(s).$$

- Estimation of total cross section also required for modeling pile up.

Measured cross section within fiducial is to be extrapolated to the full domain of phase-space. → dependence on model introduced.

- Precise calibration of luminosity needed for a reliable determination.
  $N = \sigma \mathscr{L} \varepsilon / A$

CMS measurement in $-6.6 < \eta < -3.0$ and $+3.0 < \eta < +5.2$, using HF + CASTOR

$$\sigma(\xi_X > 10^{-7} \text{ or } \xi_Y > 10^{-6}) = 66.85 \pm 0.06\,(\text{stat.}) \pm 0.44\,(\text{sys.}) \pm 1.96\,(\text{lum.})\text{ mb.}$$

$M_X > 4.1$, $M_Y > 13$ GeV

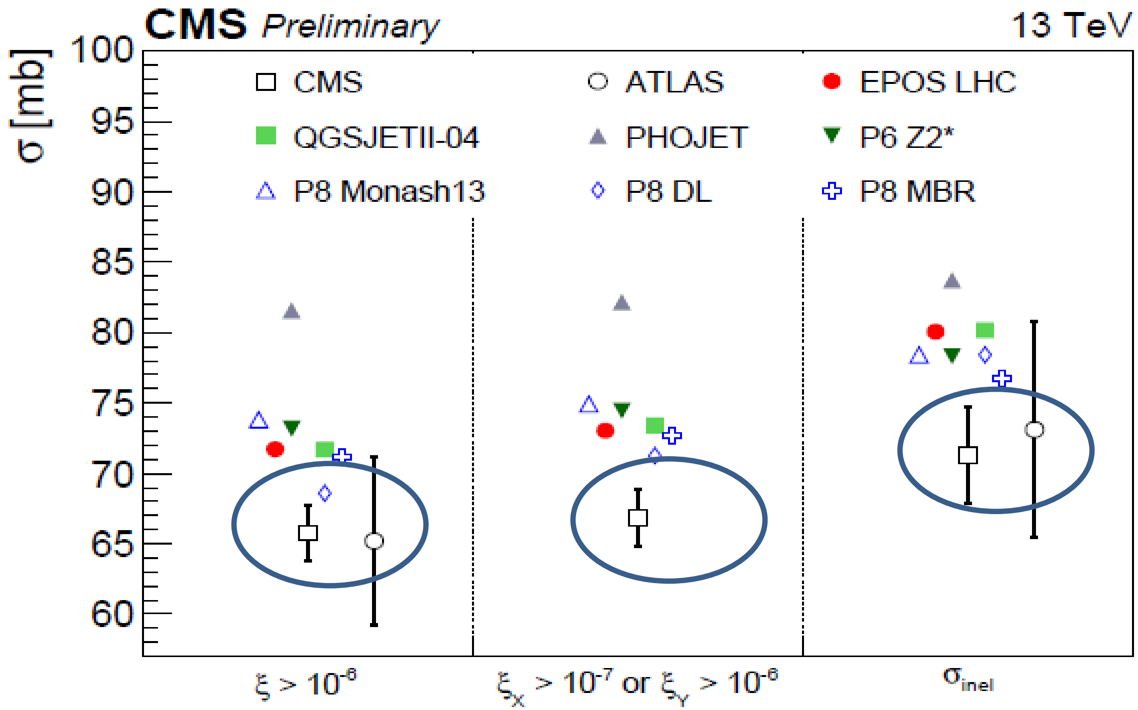
Extrapolation to whole phase space →

$$\sigma_{\text{inel}} = 71.26 \pm 0.06\,(\text{stat.}) \pm 0.47\,(\text{sys.}) \pm 2.09\,(\text{lum.}) \pm 2.72\,(\text{ext.})\text{ mb,}$$

matches well with measurement by ATLAS

Predictions compared to measurement

CMS PAS FSQ-15-005



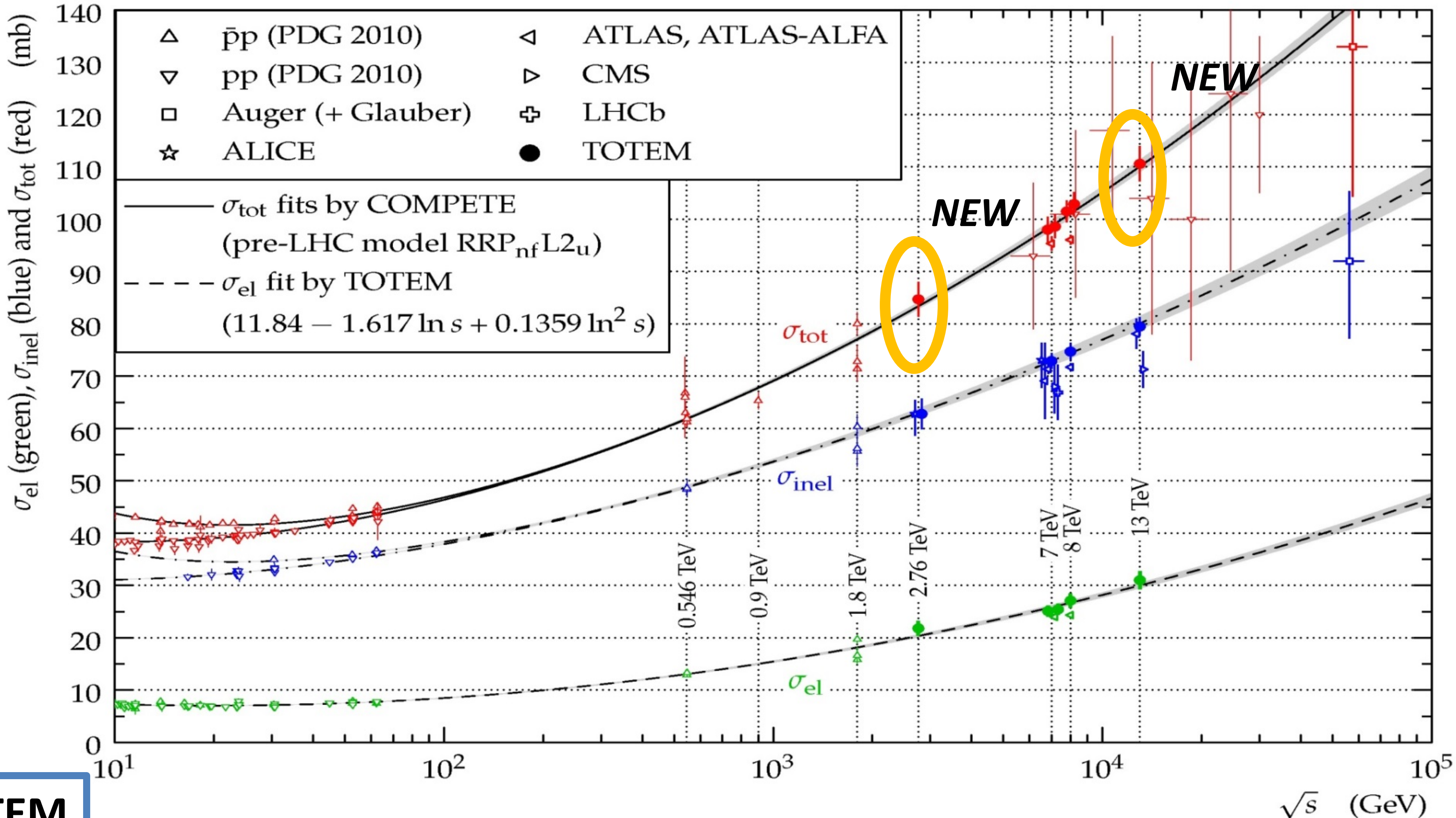
Measurements lower than predictions!

Phase-space extrapolation factor

Model	Extrapolation factor
EPOS LHC	1.096
QGSJETII	1.092
PHOJET	1.019
PYTHIA6 Z2*	1.052
PYTHIA8 Monash	1.047
PYTHIA8 DL	1.101
PYTHIA8 MBR	1.054
Average	1.066

Total, inelastic and elastic cross sections at LHC

CERN-EP-2017-321



TOTEM

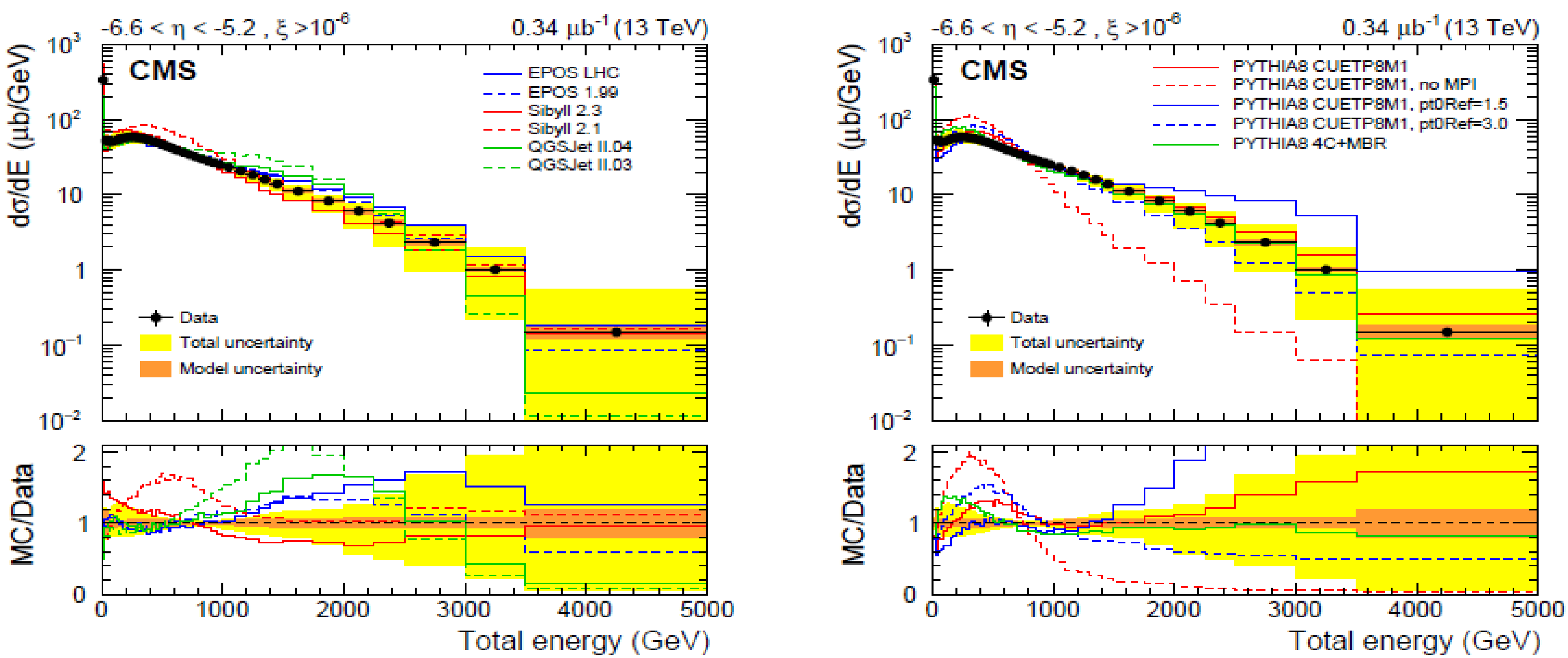
$\sqrt{s}$=2.76 TeV: σ_{tot} = 84.7 ± 3.3 mb, σ_{inel} = 62.8 ± 2.9 mb and σ_{el} = 21.8 ± 1.4 mb.
$\sqrt{s}$=13 TeV: σ_{tot} = 110.6 ± 3.4 mb, σ_{inel} = 79.5 ± 1.8 mb and σ_{el} = 31.0 ± 1.7 mb.
Value of ρ parameter @ 13 TeV coming up soon using β^* =2.5 km data

Energy spectrum at √s = 13 TeV in CMS forward region

CMS Paper FSQ-16-002
arXiv: 1701.08695,
JHEP 08 (2017) 046

- Models for hadronic interactions depends on parameters affecting multiplicity, elasticity, baryon production
  ➔ interesting structures below 1 TeV
- Amount of energy transported into hadronic and electromagnetic energy affects the muon production → can be tested in extensive air showers.

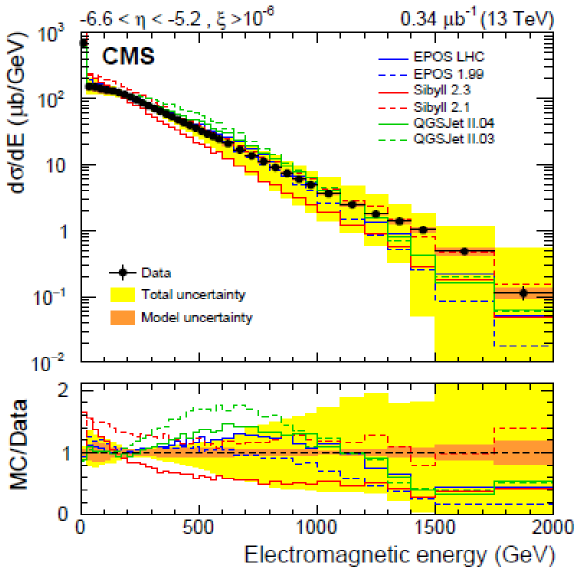
- Energy spectrum in forward direction: benchmark for UE, MPI tunings

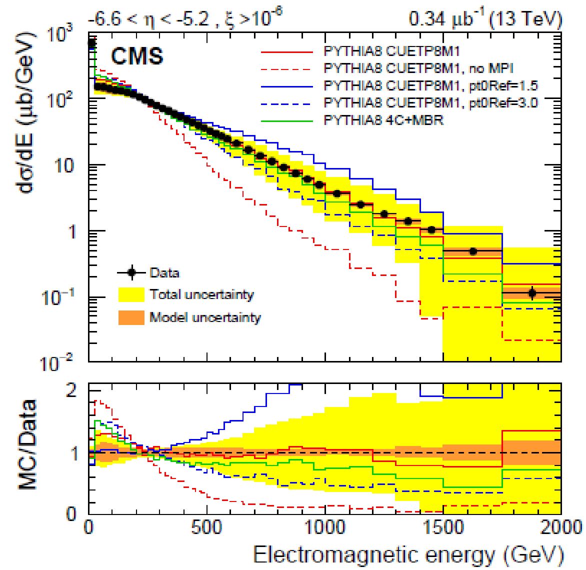


13 TeV data compared to air-shower models & Pythia tunes

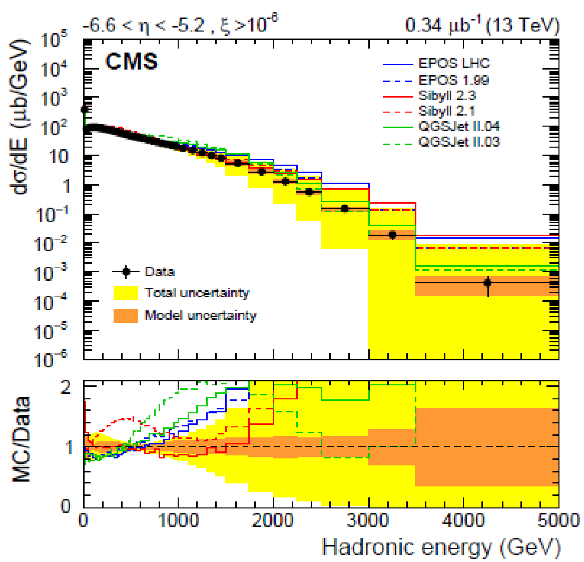
CMS Paper FSQ-16-002
arXiv: 1701.08695
JHEP 08 (2017) 046

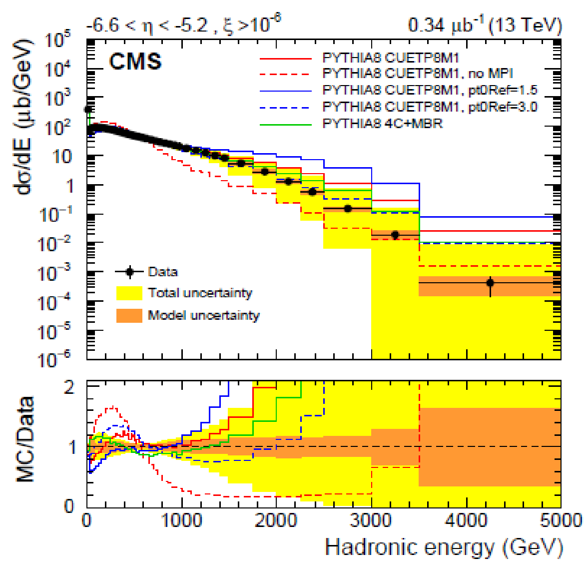
EM energy:





Hadronic energy





Pseudo-rapidity spectra in CMS at √s =13 TeV

CMS PAS FSQ-15-008

- Zero-bias trigger → Both beams pass at IP
- Event categories: vertex based or HF (3 <|η| < 5) tower selection

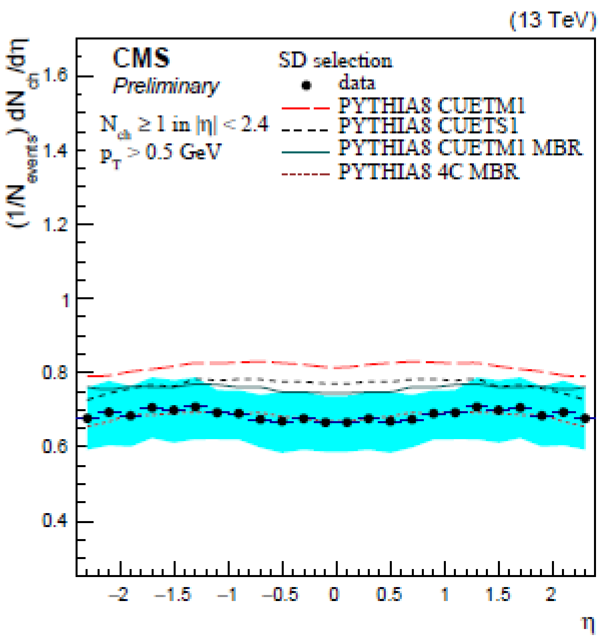
i) inclusive → exactly one good reconstructed vertex with >= 2 tracks, no p_T cut

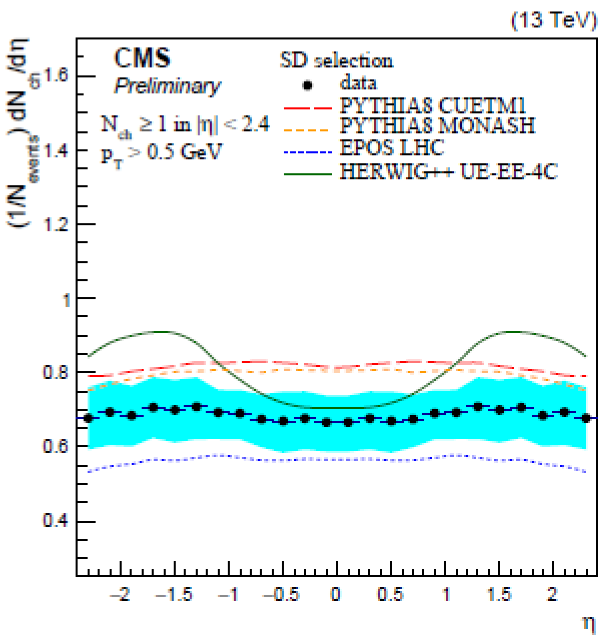
(ii) inelastic enhanced: ≥ 1 particle in either HF with with E > 5 GeV

(iii) non-single diffractive (NSD) enhanced : ≥ 1 particle in each of both HF

(iv) single diffractive (SD) enhanced : ≥ 1 particle in one HF , veto on the other HF

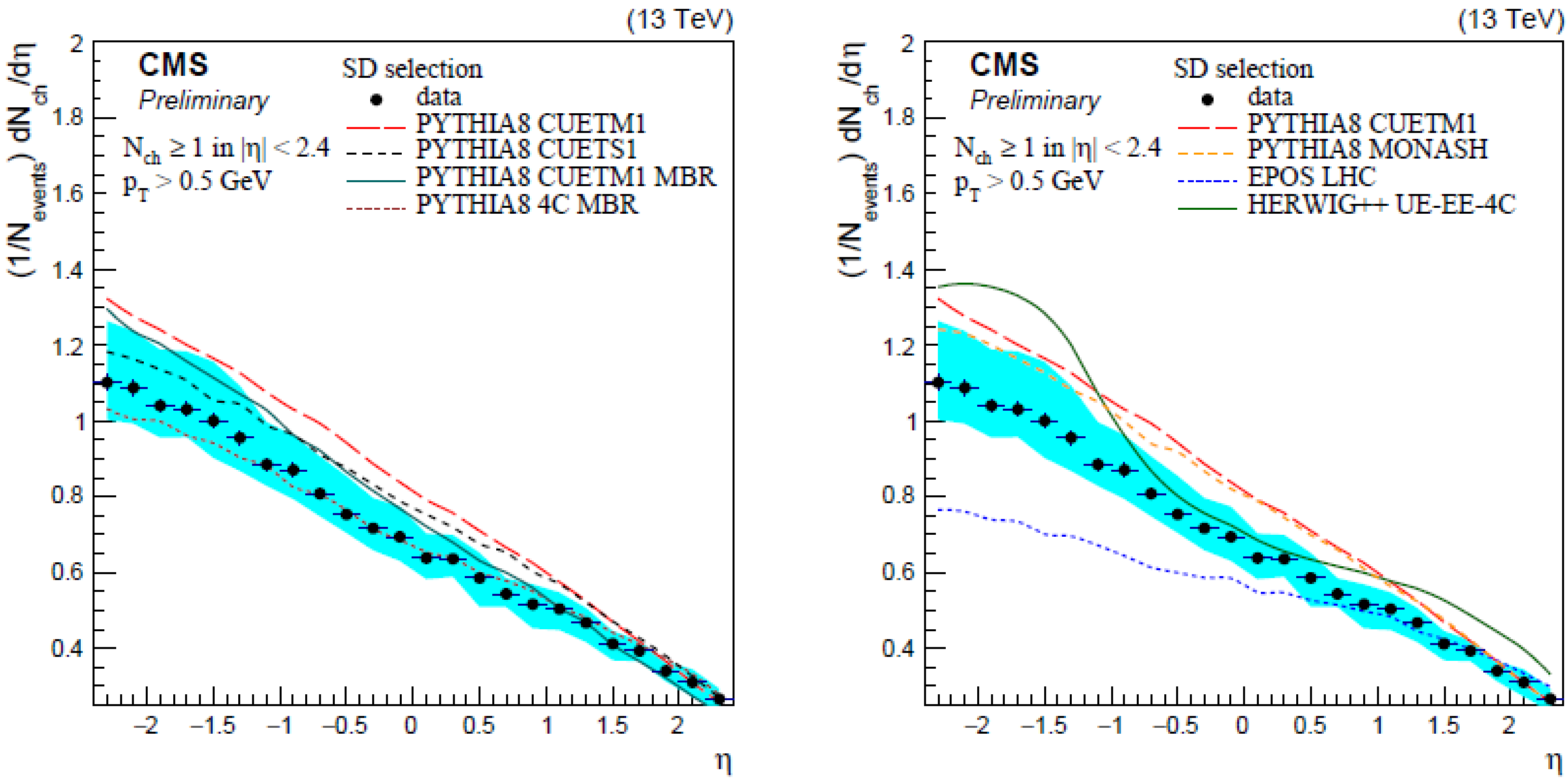
Charged particle density
In central region:
SD enhanced events





One sided SD enhanced in CMS

CMS PAS FSQ-15-008



- Pythia8+MONASH (4C MBR) gives better estimates in all categories
- HERWIG does not match well with data

Summary

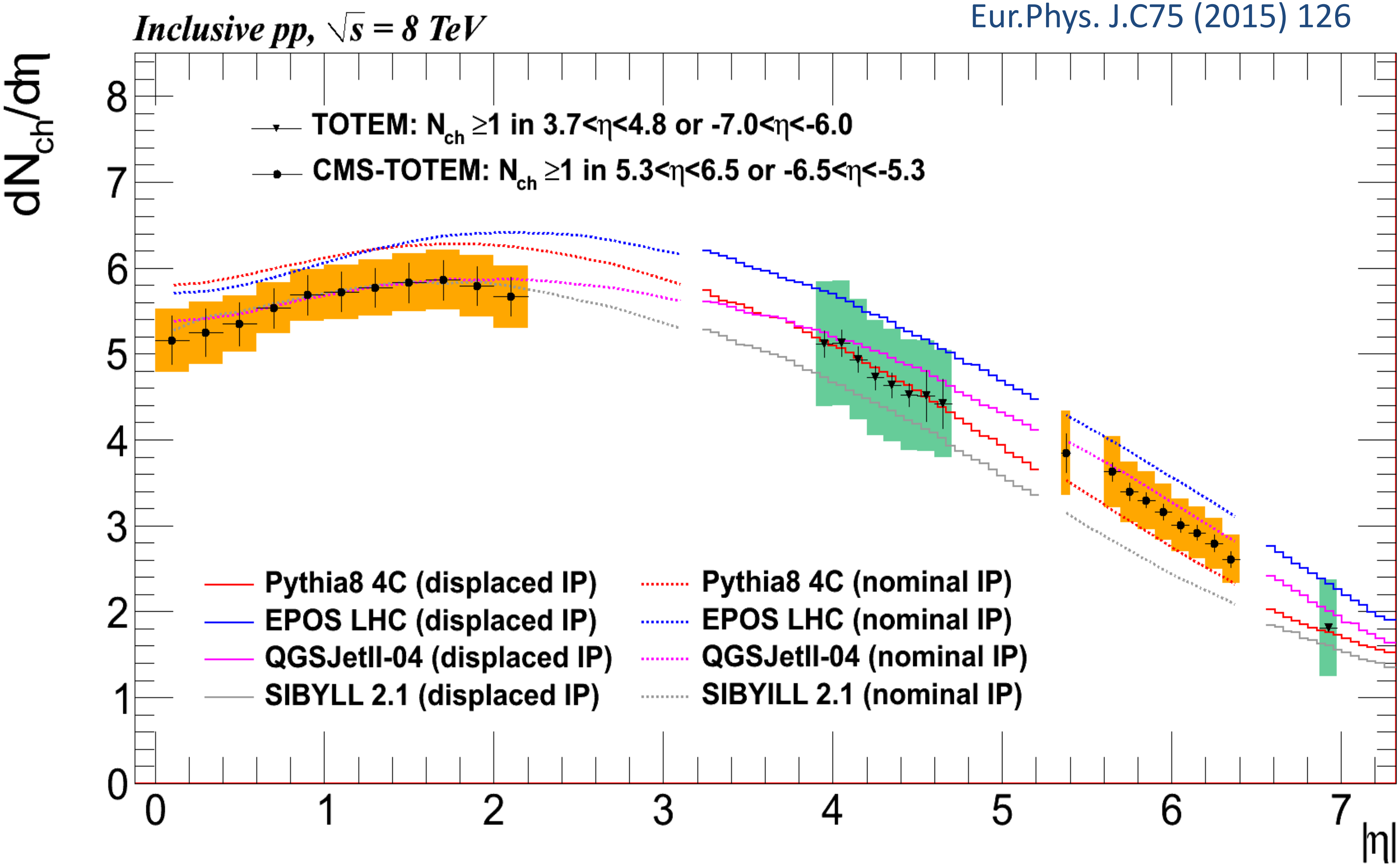
- Presented selected results highlighting on diffractive and very forward (low-x) physics being done in CMS and TOTEM experiments at different centre-of-mass energies.
- CMS, CASTOR and TOTEM T1, T2 telescopes, along with forward shower counters allows data collection with larger span of pseudo-rapidity gaps leading to access for lower diffractive masses.
- Several interesting analyses are in progress.
- Stay tuned.

Thank you!

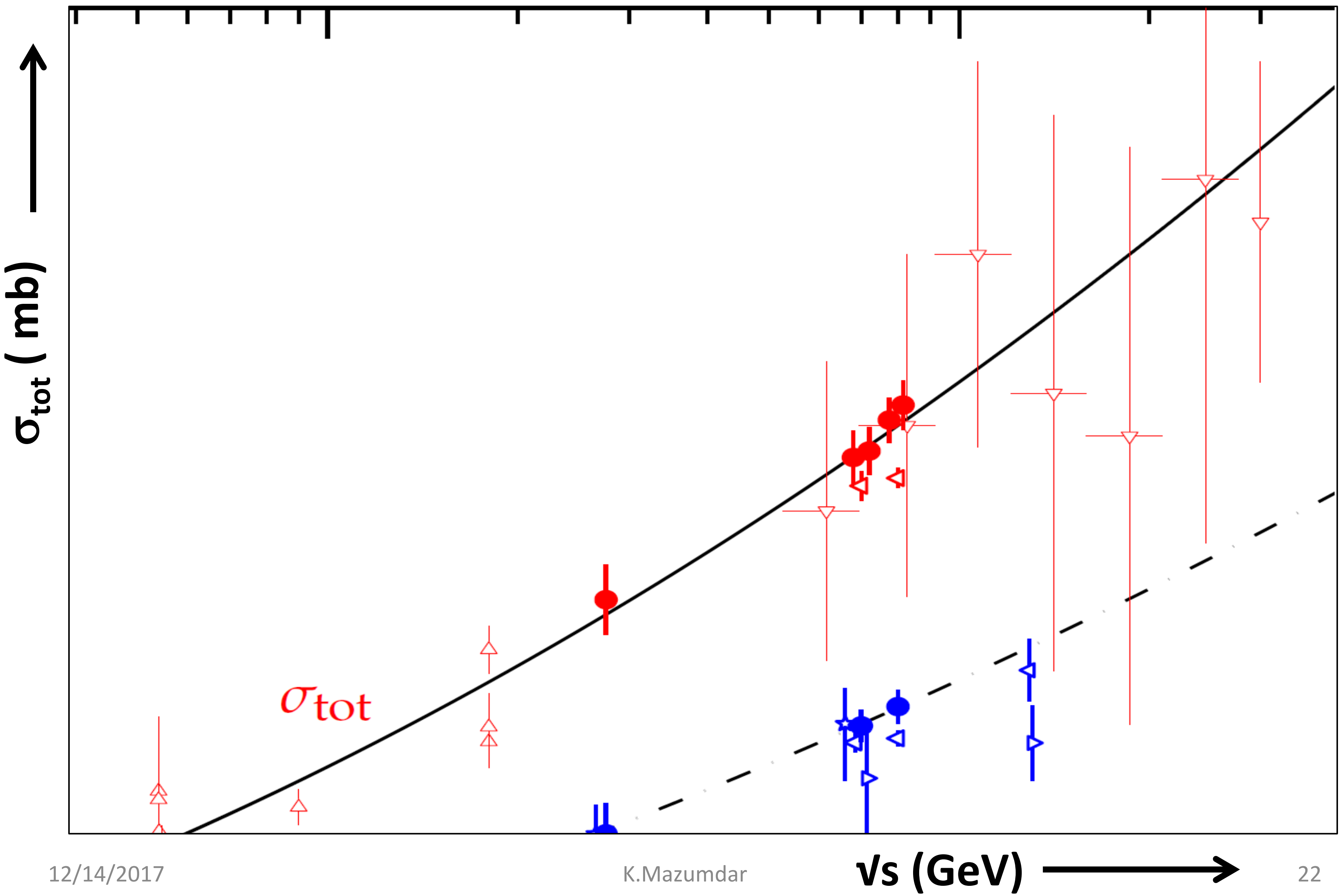
backup

Pseudo-rapidity spectrum at 8 TeV

Eur.Phys. J.C74 (2014) 2053
Eur.Phys. J.C75 (2015) 126

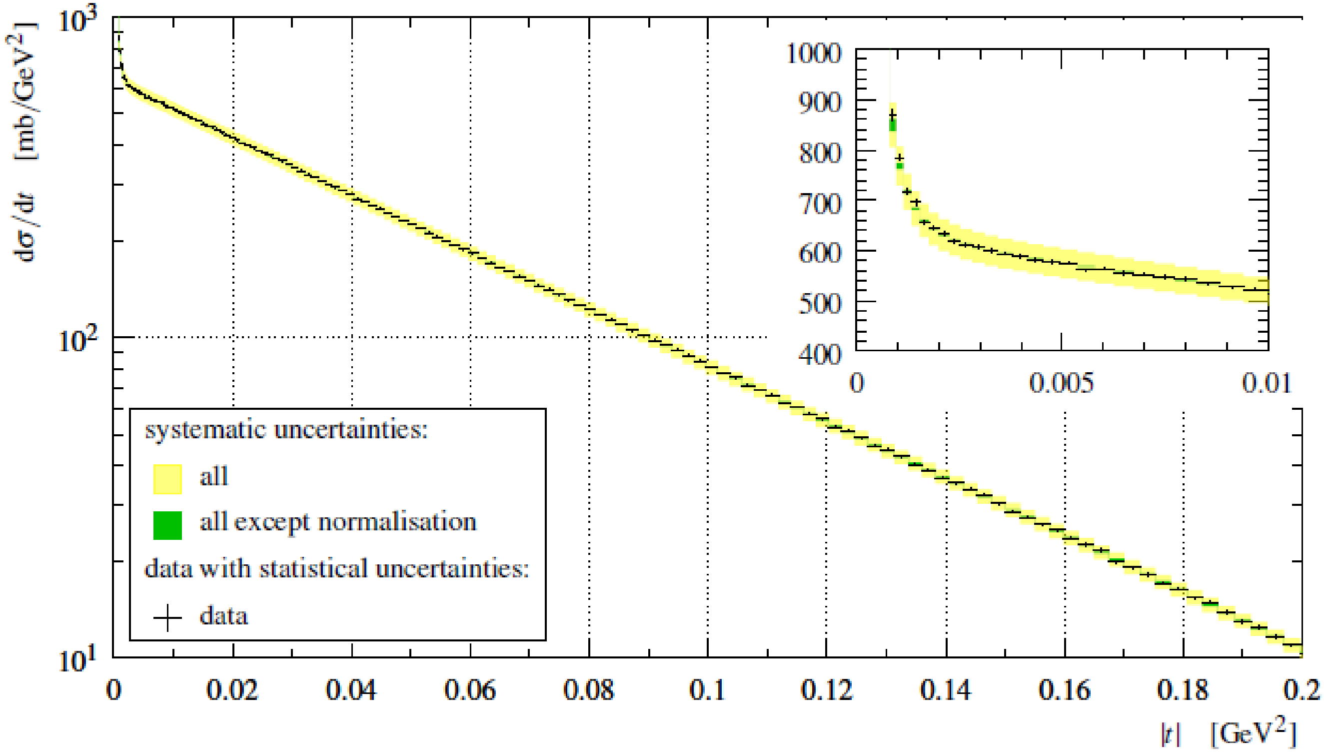


Total cross section measurements, zoomed in LHC region

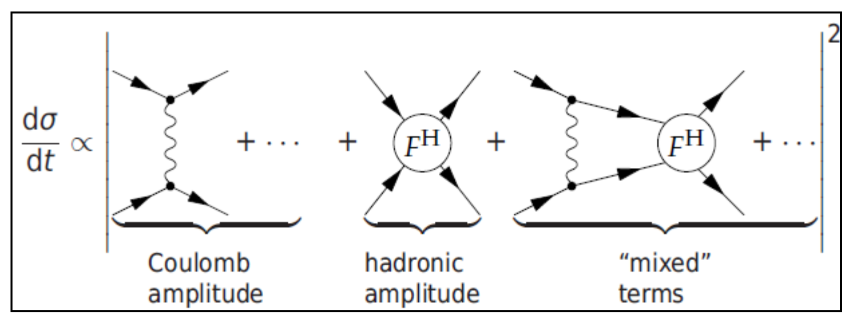


Elastic scattering in coulomb-nuclear interference region

- at low $|t|$: effects due to CNI visible



Observed cross section modelled as



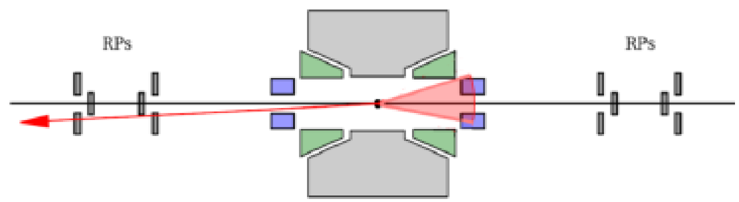
Soft single diffraction t-spectra at 7 TeV

Different beam optics for TOTEM

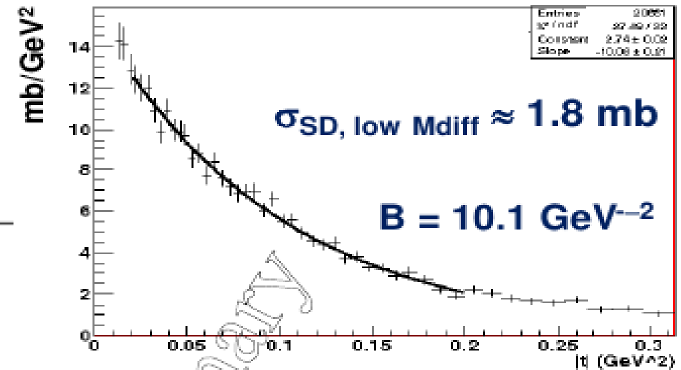
Proton + gap + X

Low mass

M_{diff} = 3.4 - 8 GeV

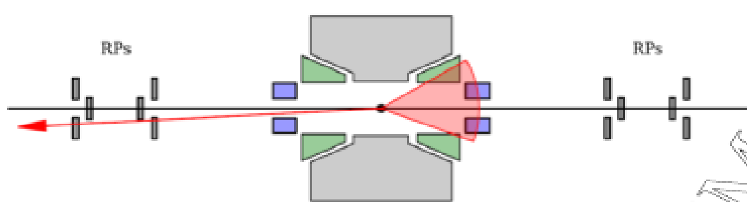


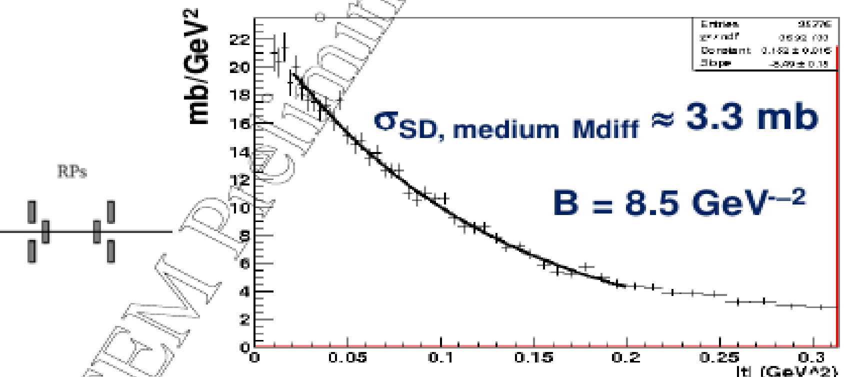
$d\sigma/dt \sim A \cdot e^{-Bt}$



Medium mass

M_{diff} = 8 - 350 GeV

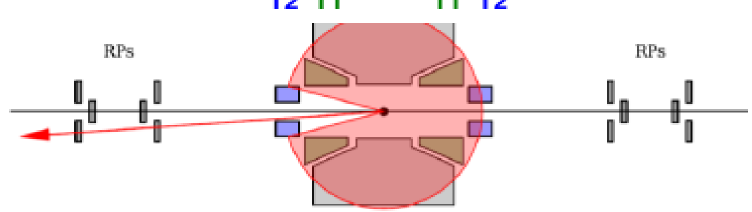


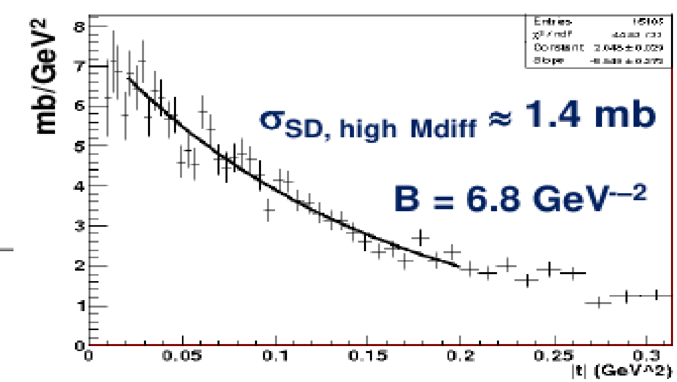


Uncertainty estimated on slope B ~ 15 %

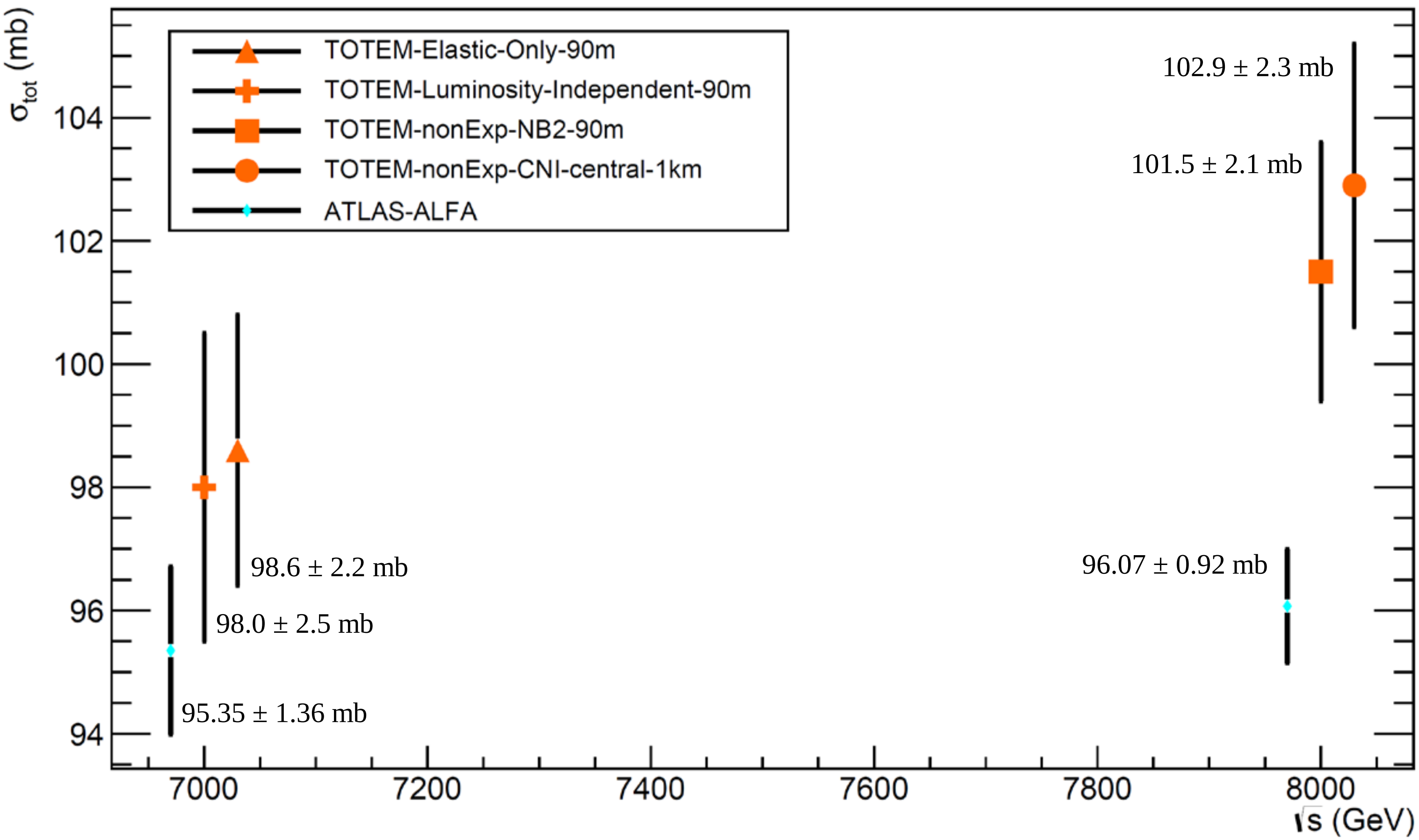
High mass

M_{diff} = 0.35 - 1.1 TeV





Summary of total cross section measurements at 7 & 8 TeV



- σ_{tot} measurements from TOTEM using different methods (using lumi-independent formula) do not match with those of ATLAS-ALFA (using lumi dependent formula), at least at 8 TeV.

Uncertainties in measurements

	Total		Electromagnetic		Hadronic	
	300 GeV	3000 GeV	300 GeV	1200 GeV	300 GeV	2000 GeV
Energy Scale	$^{+17\%}_{-14\%}$	$^{+94\%}_{-77\%}$	$^{+5.9\%}_{-2.1\%}$	$^{+93\%}_{-65\%}$	$^{+11\%}_{-10\%}$	$^{+169\%}_{-80\%}$
Unfolding	±5.8%	±6.4%	±5.2%	±4.1%	±6.9%	±17%
Event selection	±0.5%	<0.01%	±0.14%	<0.01%	±0.06%	<0.01%
Luminosity	±2.6%					
Statistical	±1.2%	±4.3%	±1.5%	±5.9%	±1.0%	±4.2%

FSQ-16-002

Systematic effect	Inclusive	Inelastic	NSD	SD
Model Dependence	1%	1%	0.5%	7%
HF event selection	N.A.	1%	7%	18%
Pile Up dependence	1%	1%	1%	4%
Tracking reconstruction	5%			
TOTAL	5.2%	5.3%	8.7%	20%

FSQ-15-008

Hadron Level definition

At least one stable particle in $|\eta| < 2.4$ with $p_T > 0.5$ GeV

$$Acceptance = \frac{N_{\text{matched charged particles}}(\eta_{gen})}{N_{\text{all charged particles}}(\eta_{gen})}$$

$$Background = \frac{N_{\text{unmatched tracks}}(\eta_{reco})}{N_{\text{all tracks}}(\eta_{reco})}$$

$$= 1 - \frac{N_{\text{matched tracks}}(\eta_{reco})}{N_{\text{all tracks}}(\eta_{reco})}$$

$$Purity = \frac{N_{\text{matched tracks}}(\eta_{reco})\ \eta_{reco}\&\eta_{gen} \ \epsilon \text{ same bin}}{N_{\text{matched tracks}}(\eta_{reco})}$$

$$Stability = \frac{N_{\text{matched charged particles}}(\eta_{gen})\ \eta_{reco}\&\eta_{gen} \ \epsilon \text{ same bin}}{N_{\text{matched charged particles}}(\eta_{gen})}$$

Matching gen-reco:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.05$$

Correction Factors

FSQ-15-008

$$C = \frac{N^{\text{HF sel}}_{\text{evt MC}}}{N^{\text{particle sel}}_{\text{evt MC}}} \frac{N^{\text{particle sel}}_{\text{ch MC}}(\Delta\eta)}{N^{\text{HF sel}}_{\text{track MC}}(\Delta\eta)}$$

$N^{\text{HF sel}}_{\text{evt MC}}$, $N^{\text{particle sel}}_{\text{evt MC}}$: **numbers of selected events** in the Monte Carlo by the selection at **detector level** and stable **particle level**

$N^{\text{HF sel}}_{\text{track MC}}(\Delta\eta)$, $N^{\text{particle sel}}_{\text{ch MC}}(\Delta\eta)$: **numbers of tracks** in a given η bin in the Monte Carlo at **detector level** and **number of stable charged particles** in a given η bin at **particle level**

$$\frac{1}{N_{evt}} \frac{dN_{ch}}{d\eta} = C \times \frac{1}{N^{HF sel}_{evt\ data}} \times \frac{N^{HF sel}_{track\ data}(\Delta\eta)}{\Delta\eta}$$

$\Delta\eta$ the bin width

$N^{HF sel}_{evt\ data}$ number of selected events in data

$N^{HF sel}_{track\ data}(\Delta\eta)$ number of tracks in a given η bin

Correction factor
Take average of 2 MCs