

Jan Kašpar

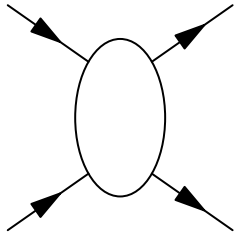


ISMD2017, Tlaxcala, Mexico
15 September, 2017

- selected processes:

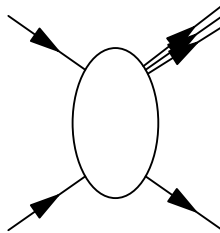
Elastic scattering

$$p + p \rightarrow p + p$$



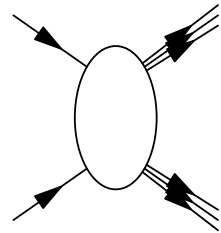
Single diffraction

$$p + p \rightarrow p + X$$



Double diffraction

$$p + p \rightarrow X + Y$$



+ σ_{tot} , σ_{el} , σ_{inel}

- common characteristics

- exchange of colourless objects (Pomerons) \Rightarrow *large rapidity gaps*
- very *forward particles in final state*
- often surviving *forward proton*

\Rightarrow dedicated instrumentation needed

(used in the papers discussed below)

- ALICE

- V0: $|\eta|_{\max} = 3.7$ (right), **5.1** (left)
- Forward Multiplicity Detector (FMD): $|\eta|_{\max} = 3.4$ (right), **5.1** (left)

- ATLAS

- Minimum-bias trigger scintillators (MBTS): $|\eta|_{\max} = 3.9$
- ALFA: *proton tagging* with Roman Pots at 240 m from IP

- CMS

- Hadron Forward calorimeter (HF): $|\eta|_{\max} = 5.2$
- CASTOR calorimeter, single side: $|\eta|_{\max} = 6.6$

- LHCb

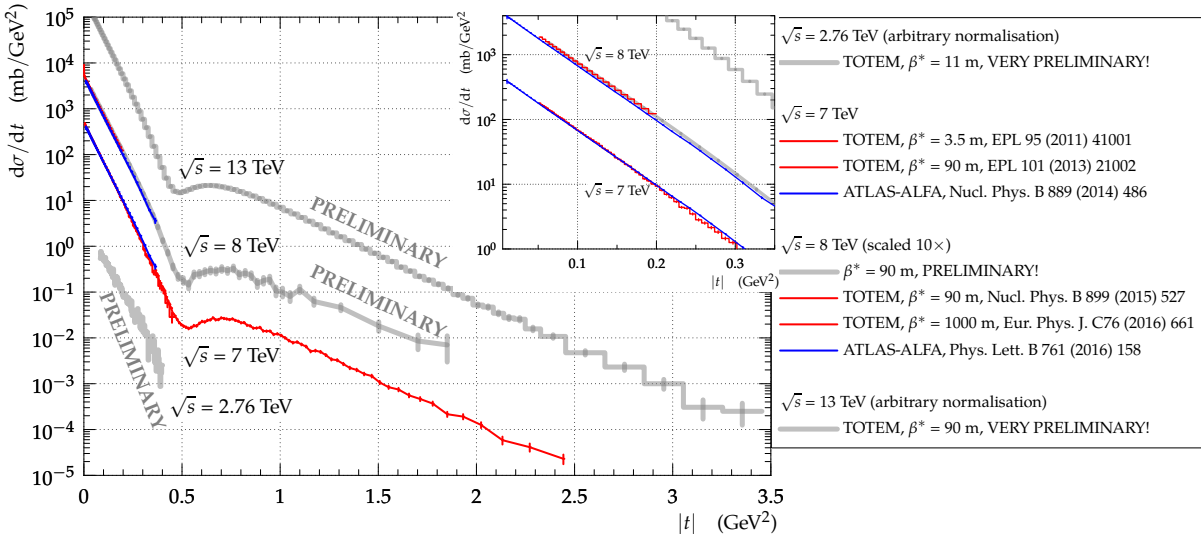
- single side, $2 < \eta < 4.5$

- TOTEM

- T2: $|\eta|_{\max} = 4.7$, T2: $|\eta|_{\max} = 6.5$
- *proton tagging* with Roman Pots at 200 and 220 m from IP

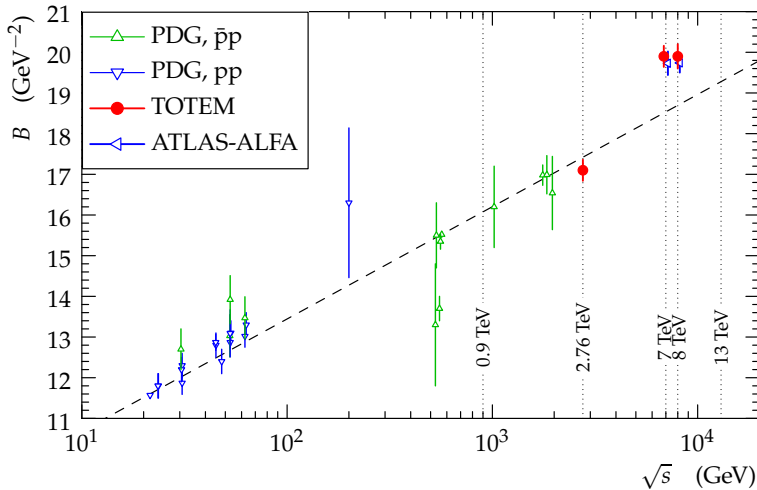
$t = -p^2\theta^2$: four-momentum transfer sq.

(uncertainties shown: only statistical)



- different $|t|$ probe different physics regimes - from lowest to highest $|t|$:
 - Coulomb interference
 - diffractive cone: Pomeron exchange
 - dip-bump: interference of amplitude components
 - transition to pQCD

- at low $|t|$: $d\sigma/dt \approx A \exp(-B|t|)$



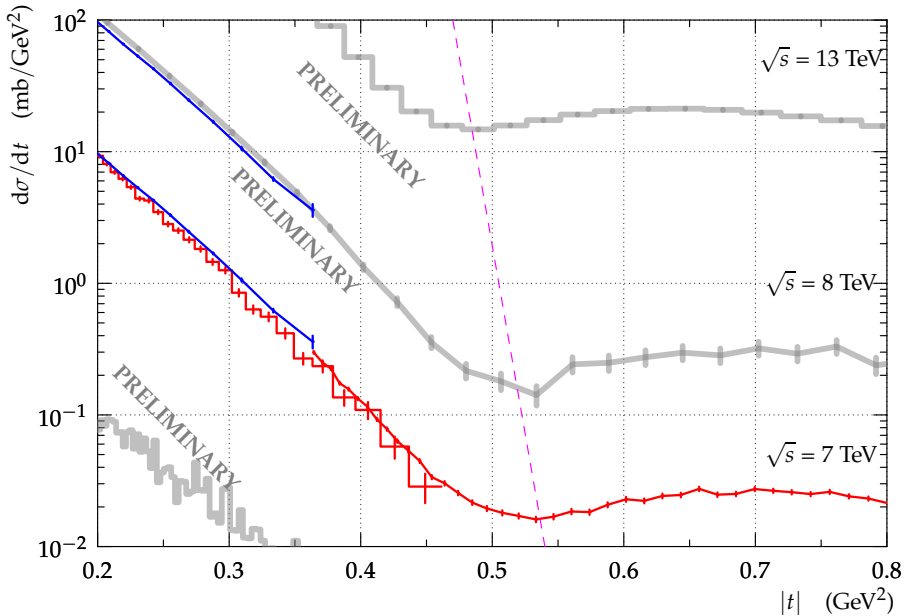
- up to $\sqrt{s} \approx 3$ TeV: linear in $\ln s$; agrees with simple Regge model:

$$d\sigma/dt \propto s^{2(\alpha(t)-1)}, \quad \alpha(t) = \alpha_0 + \alpha' t \quad \Rightarrow \quad B = B_0 + 2\alpha' \ln s$$

- 7 and 8 TeV

- o measurements compatible between TOTEM and ATLAS-ALFA
- o significantly above the linear extrapolation (dashed line)
- o change of regime around 3 TeV ? \Rightarrow 13 TeV point available soon

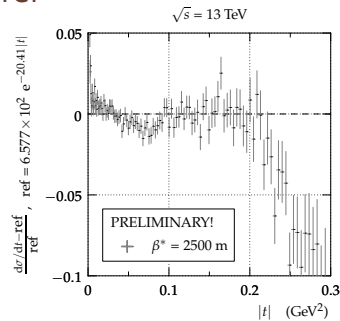
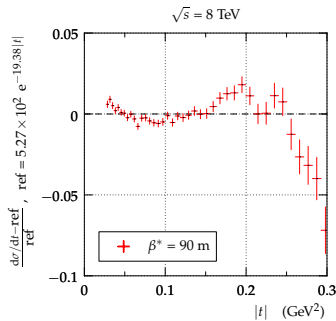
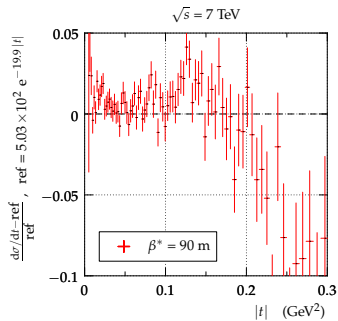
- forward code shrinks with increasing energy: dip moves to lower $|t|$



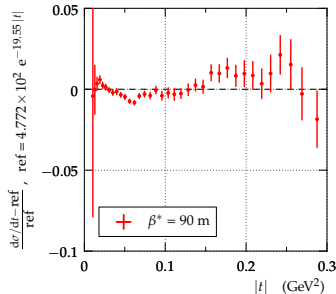
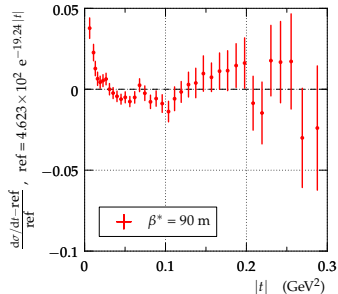
(the same legend as on slide 4)

- deviations from the leading exponential behaviour: $\frac{d\sigma/dt - \text{ref}}{\text{ref}}$

TOTEM



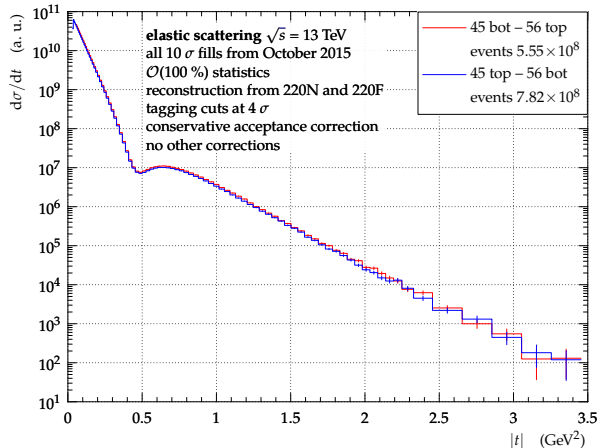
ATLAS-ALFA



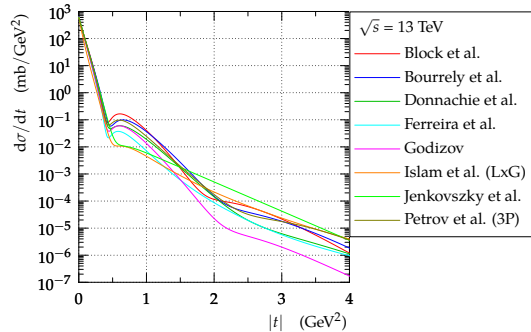
(stat. unc. only)

- $|t| \lesssim 0.2 \text{ GeV}^2$: similar pattern at all energies and from both experiments
- $|t| \gtrsim 0.2 \text{ GeV}^2$: often rapid change of behaviour (faster decrease)

- TOTEM, $\sqrt{s} = 13$ TeV: very preliminary, but already very strong results



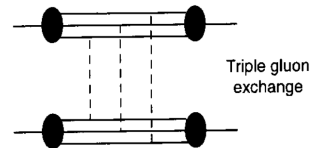
model predictions:



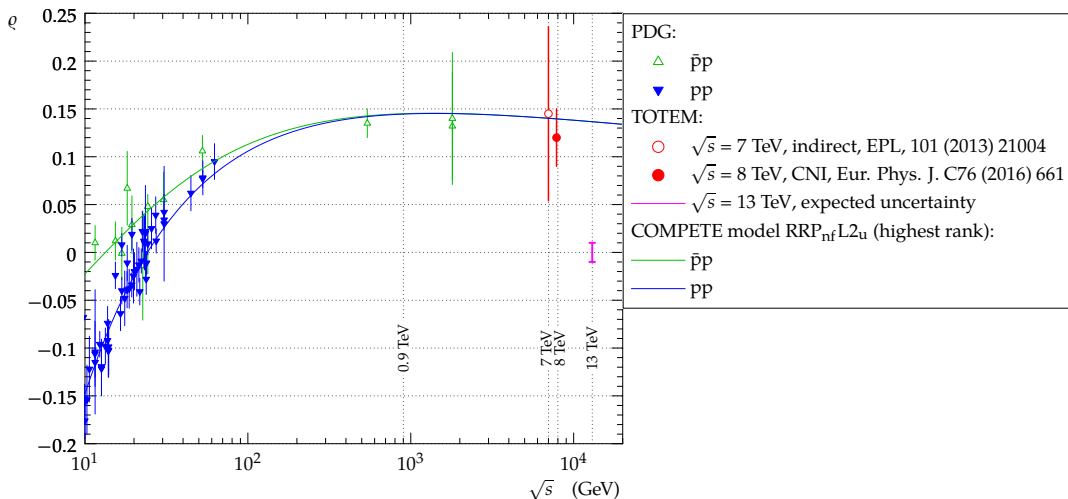
oscillations in almost each model

- *high- $|t|$: no structures!*

- rules out many models
- rules out physics mechanism: “optical” models
- physics interpretation: transition between diffraction and pQCD? \Rightarrow e.g. Donnachie-Landshoff \Rightarrow



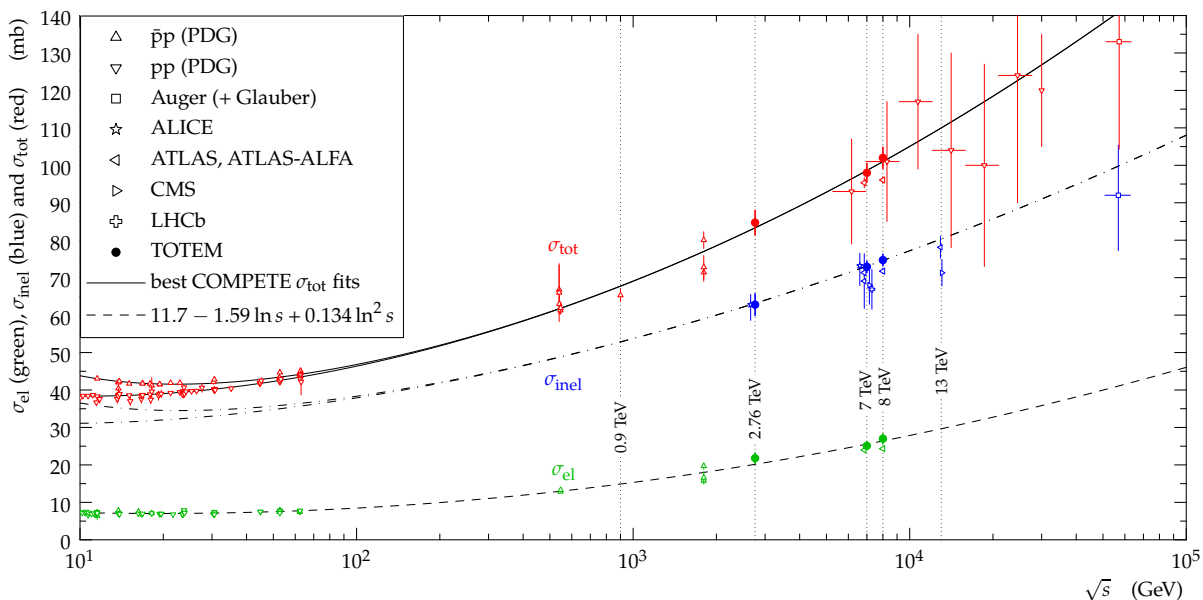
- at $|t| \sim \mathcal{O}(10^{-4} \text{ GeV}^2)$: interference between Coulomb and hadronic amplitude
 - Coulomb phase known (QED) \Rightarrow sensitivity to phase of hadronic amp. \mathcal{A}^N
 - parameter $\rho = \Re \mathcal{A}^N / \Im \mathcal{A}^N|_{t=0}$
 - via dispersion relations: prediction of $d\sigma_{\text{tot}}(s)/ds$
 - sensitivity to presence of Odderon
- ATLAS-ALFA: 8 TeV results expected soon, method demonstrated in PhD thesis by S. H. Stark (<http://cds.cern.ch/record/2283206>)



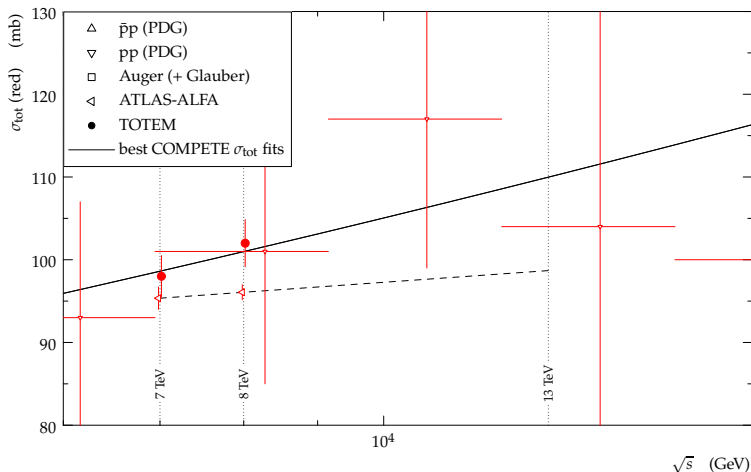
- Odderon = crossing-odd partner of Pomeron; 3 gluon JPC = 1^{--} state
 - studied within Regge theory (Lukaszuk, Nicolescu), QCD (Vacca, Braun, Dosch), lattice calculations (Luscher, Morningstar), BFKL-like (Bartels)
- at LHC, other signatures of Odderon (currently) not accessible
 - spin dependence
 - differences in pp and p \bar{p} scattering (e.g. dip)
 - LHC would need to decelerate protons to e.g. UA4 energy
 - effects at large $|t|$: preliminary $\beta^* = 90$ m data suggest domination by a pQCD-like contribution
- effect of Odderon on ρ (e.g. Nicolescu, Gauron)
 - prediction for pp: faster decrease of ρ with \sqrt{s}
 - expected effect $|\Delta\rho| \approx 0.04$
- TOTEM: analysis advanced, expected uncertainty $\sigma(\Delta\rho) \approx 0.01$
 - chance for significant sensitivity
- ATLAS-ALFA: a priory similar sensitivity

Total, inelastic and elastic cross-sections

(list of references in backup)



- new results soon at 13 TeV from TOTEM (and ATLAS-ALFA)
- measurements at 0.9 TeV foreseen for 2018
- s-dependence: in general compatible with $\ln^2 s$ at high energies



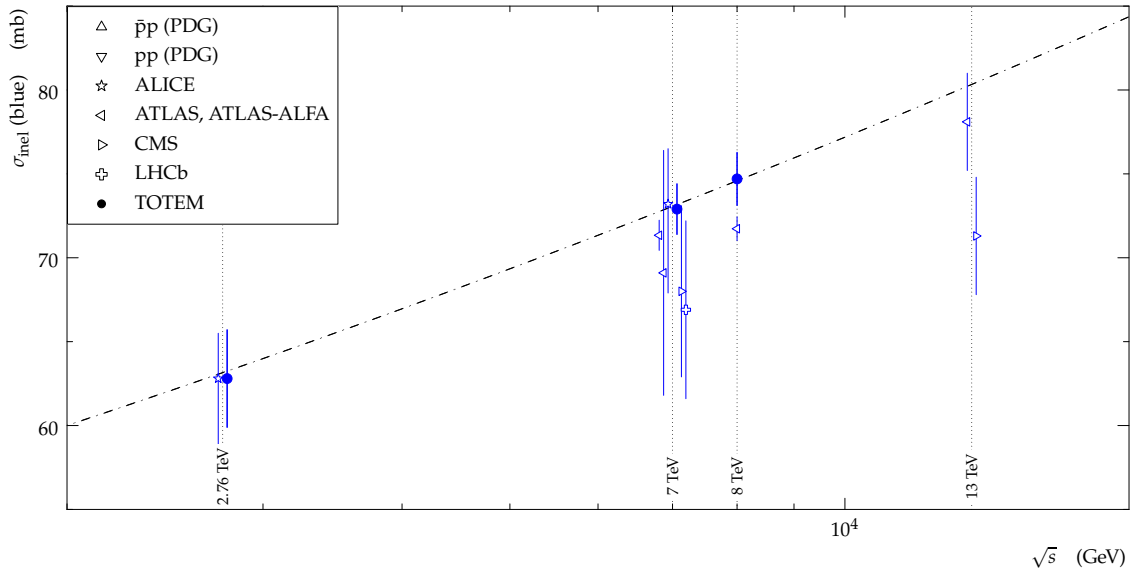
- determined via Optical Theorem:

$$\sigma_{\text{tot}} \propto \Im \mathcal{A}^{\text{el}}(t = 0)$$

- TOTEM vs. ATLAS-ALFA**

- o 7 TeV: compatible
- o 8 TeV: discrepancy $\approx 2 \sigma$
 - elastic slopes similar (see slide 5) \Rightarrow difference comes from normalisation (luminosity)
- o quite different extrapolation from 7 and 8 to 13 TeV ($\Delta\sigma_{\text{tot}} \approx 10 \text{ mb}$)
 - \Rightarrow 13 TeV measurement available soon

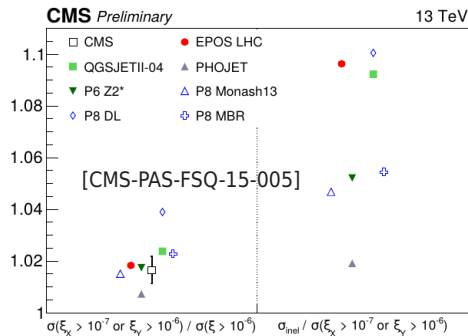
Inelastic cross-sections : Details



- **observation: variety of results**

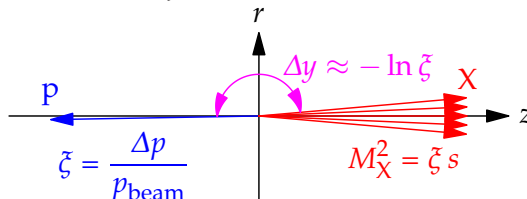
- often: ALICE and TOTEM on the line, others (significantly) below
- different methods \Rightarrow different systematics (see next slide)

- ALICE, ATLAS, CMS and LHCb
 - count minimum-bias events + experimental corrections
 - using MC: correct for invisible cross-section (very forward) ↓
 - sizeable
 - model dependent
 - e.g. CMS: “democratic” over several MC
 - e.g. ATLAS: MCs selected and tuned with data



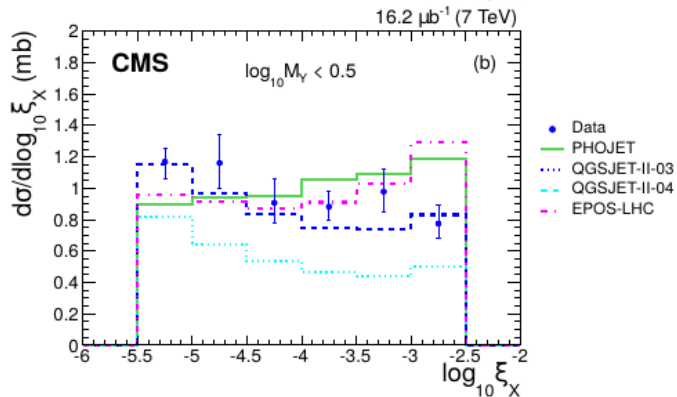
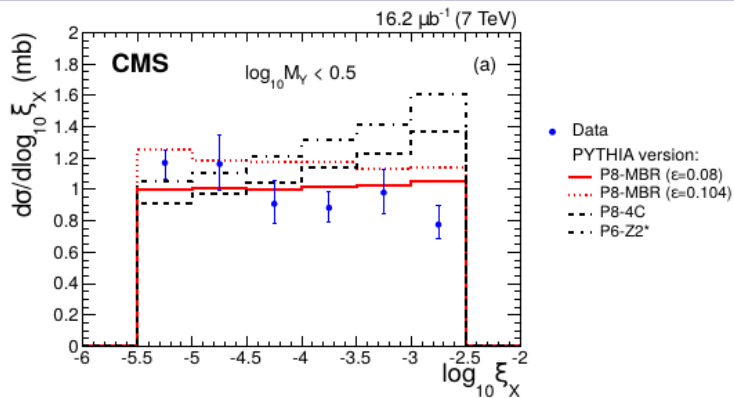
- ATLAS-ALFA, TOTEM (+CMS): from elastic rate and luminosity
 - $d\sigma_{el}/dt = 1/\mathcal{L} dN_{el}/dt \Rightarrow \sigma_{el}$
 - $\sigma_{tot} \propto \Im \mathcal{A}_{el}(t=0)$, $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$
- TOTEM: “luminosity independent” using inelastic rate from T2
 - correction of N_{inel} for very forward diffraction: not as large as for others
 - $\sigma_{tot} \propto \frac{dN_{el}/dt(t=0)}{N_{el} + N_{inel}}$
- TOTEM at 7 TeV: 3 methods used, all results consistent \Rightarrow confidence

- ALICE, $\sqrt{s} = 2.76, 7$ and 8 TeV [EPJ C73 (2013) 2456]
 - count single-sided events
 - proton not tagged, only integrated cross-section
- CMS: $\sqrt{s} = 7$ TeV [arXiv:1503.08689, CMS-PAS-FSQ-12-005]
 - events with rapidity gap on one side (detector edge to $\eta = 1$)
 - proton not tagged \Rightarrow proton t not determined
 - cross-section as function of ξ



- TOTEM, $\sqrt{s} = 7$ TeV, preliminary
 - events with proton tag and rapidity gap
 - 3 (4) bins of ξ
 - cross-section as function of proton t
- TOTEM + CMS, $\sqrt{s} = 8$ TeV, in development
 - inelastic event classification: ND, SD, DD

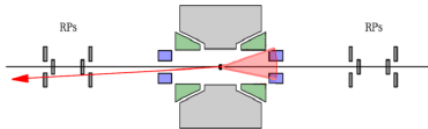
Single diffraction : CMS



Low mass

$$M_{\text{diff}} = 3.4 - 8 \text{ GeV}$$

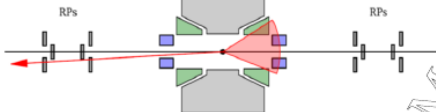
T2 T1 T1 T2



Medium mass

$$M_{\text{diff}} = 8 - 350 \text{ GeV}$$

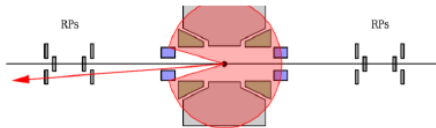
T2 T1 T1 T2



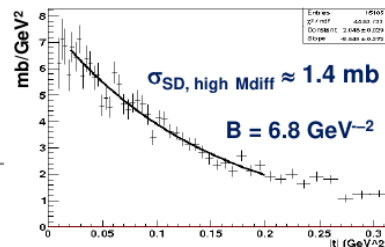
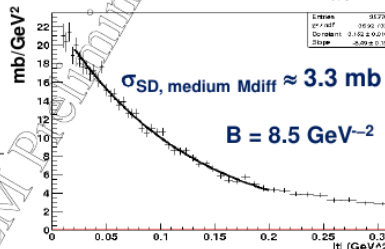
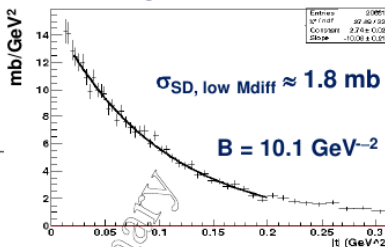
High mass

$$M_{\text{diff}} = 0.35 - 1.1 \text{ TeV}$$

T2 T1 T1 T2



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



Corrections included:

- Trigger efficiency
- Proton acceptance & reconstruction efficiency
- Background subtraction
- Extrapolation to $t = 0$

Missing corrections:

- Class migration
- ξ resolution & beam divergence effects

Estimated uncertainties:

$$B \sim 15\% ; \sigma \sim 20\%$$

TOTEM preliminary:

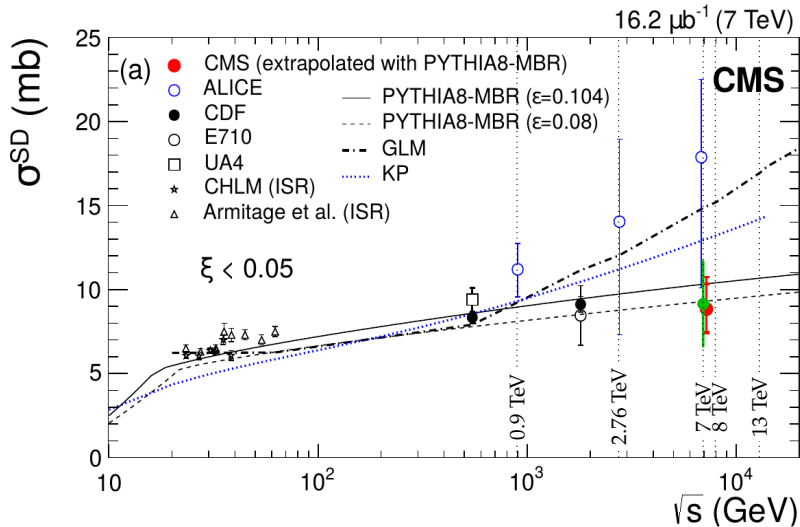
$$\sigma_{\text{SD}} = 6.5 \pm 1.3 \text{ mb}$$

$$3.4 \text{ GeV} < M_{\text{diff}} < 1.1 \text{ TeV}$$

Analysis of very high mass SD events ongoing

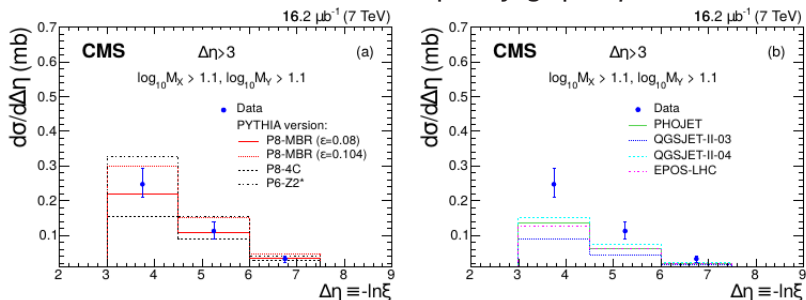
courtesy of H. Saarikko

- original plot from [arXiv:1503.08689], ALICE data [EPJ C73 (2013) 2456]

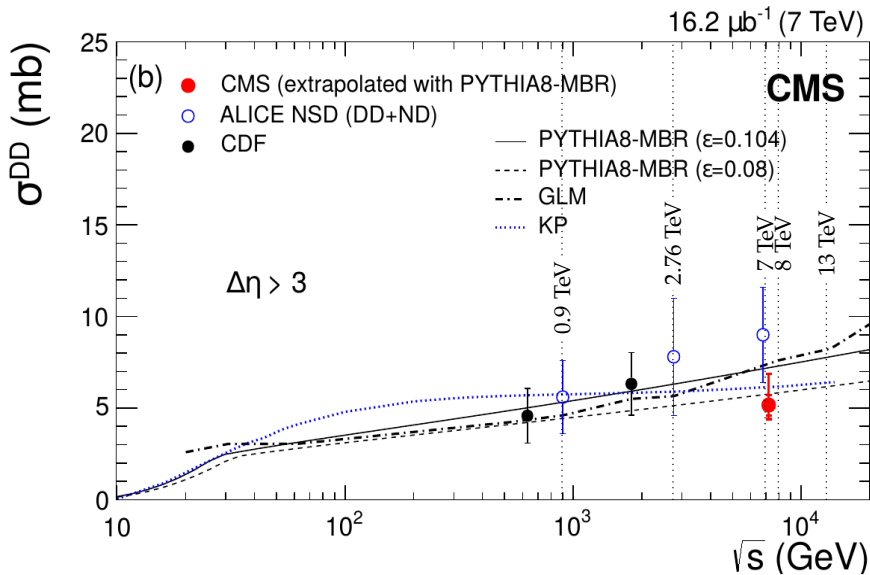


- green: compilation from TOTEM data, $\sqrt{s} = 7 \text{ TeV}$, $\xi \lesssim 0.022$
 - previous slide, $3.4 < M_X < 1100 \text{ GeV}$: $(6.5 \pm 1.3) \text{ mb}$
 - [EPL 101 (2013) 21003], $M_X < 3.4 \text{ GeV}$ (SD dominated): $(2.62 \pm 2.17) \text{ mb}$
 - $\sigma_{\text{SD}} \approx (9.1 \pm 2.9) \text{ mb}$

- ALICE, $\sqrt{s} = 2.76, 7$ and 8 TeV [EPJ C73 (2013) 2456]
 - count events with central rapidity gap $\Delta\eta > 3$
 - only integrated cross-section
- CMS: $\sqrt{s} = 7$ TeV [arXiv:1503.08689, CMS-PAS-FSQ-12-005]
 - events with central rapidity gap $\Delta\eta > 3$
 - cross-section as function of central rapidity gap $\Delta\eta$



- TOTEM, $\sqrt{s} = 7$ TeV, [PRL 111 (2013) 262001]
 - narrow fiducial region where background reasonable ($3.4 < M_{X\bar{Y}} < 8$ GeV)
 - no attempt made to extrapolate to full phase space
- TOTEM + CMS, $\sqrt{s} = 8$ TeV, in development
 - inelastic event classification: ND, SD, DD

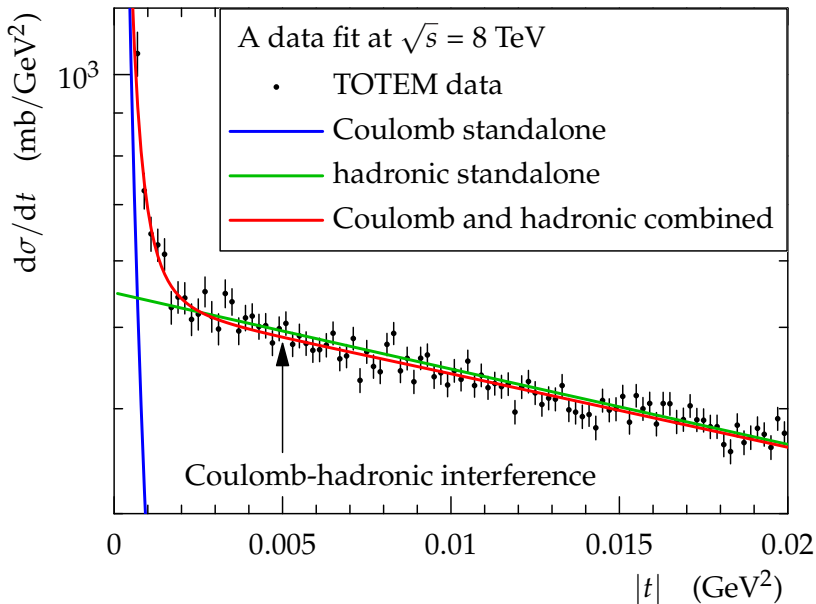


- elastic scattering
 - measurements by ATLAS-ALFA and TOTEM
 - s -dependence of forward slope: acceleration at $\sqrt{s} \approx 3$ TeV ?
 - non-exponentiality at low $|t|$: similar at different energies and from both experiments
 - Coulomb-nuclear interference at very low $|t|$: sensitivity to Odderon contribution
- total, elastic and inelastic cross-section
 - measurements by ALICE, ATLAS, CMS, LHCb and TOTEM
 - s -dependence generally compatible with $\ln^2 s$ growth
 - non-negligible differences in σ_{inel} - can be related to MC corrections
- single diffraction
 - differential measurements by CMS (ξ) and TOTEM (t)
 - integral measurements by ALICE, CMS and TOTEM
- double diffraction
 - differential measurement ($\Delta\eta$) by CMS
 - integral measurements by ALICE, CMS (and TOTEM in limited ph. space)

Backup

- PDG data: K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)
- Auger: P. Abreu et al. (Pierre Auger Collaboration), Phys. Rev. Lett. 109, 062002 (2012)
- ALICE: Eur. Phys. J. C73 no. 6, (2013) 2456
- ATLAS
 - 7 TeV: Nature Commun. 2 (2011) 463
 - 13 TeV: Phys. Rev. Lett. 117, 182002
- ATLAS-ALFA
 - 7 TeV: Nucl. Phys. B889 (2014) 486-548
 - 8 TeV: Phys. Lett. B 761 (2016) 158-178
- CMS
 - 7 TeV: CMS-PAS-FWD-11-001
 - 13 TeV: CMS-PAS-FSQ-15-005
- LHCb
 - 7 TeV: JHEP 02 (2015) 129
- TOTEM
 - 2.76 TeV: publication in preparation
 - 7 TeV: Europhys. Lett. 101 (2013) 21004
 - 8 TeV: Phys. Rev. Lett. 111 no. 1, (2013) 012001

- 8 TeV data with $\beta^* = 1000$ m optics
 - RPs very close to the beam: $\approx 3 \sigma_{\text{beam}}$
 - $|t|_{\text{min}} \approx 6 \cdot 10^{-4} \text{ GeV}^2$



- *inelastic cross-section*: event counting with T2 (and T1)
 - 95 % of inelastic events have at least 1 track in the T2 region
 - only one significant MC correction: contribution from low mass diffraction

- 3 methods to determine *total cross-section*

elastic observables only:

$$\sigma_{\text{tot}}^2 = \frac{16\pi}{1+q^2} \frac{1}{\mathcal{L}} \left. \frac{dN_{\text{el}}}{dt} \right|_0$$

σ_{tot}

q-independent:

$$\sigma_{\text{tot}} = \frac{1}{\mathcal{L}} (N_{\text{el}} + N_{\text{inel}})$$

luminosity-independent:

$$\sigma_{\text{tot}} = \frac{16\pi}{1+q^2} \frac{dN_{\text{el}}/dt|_0}{N_{\text{el}} + N_{\text{inel}}}$$