On the discrepancy between ATLAS and TOTEM total cross sections

Seminar 26th June at PNPI

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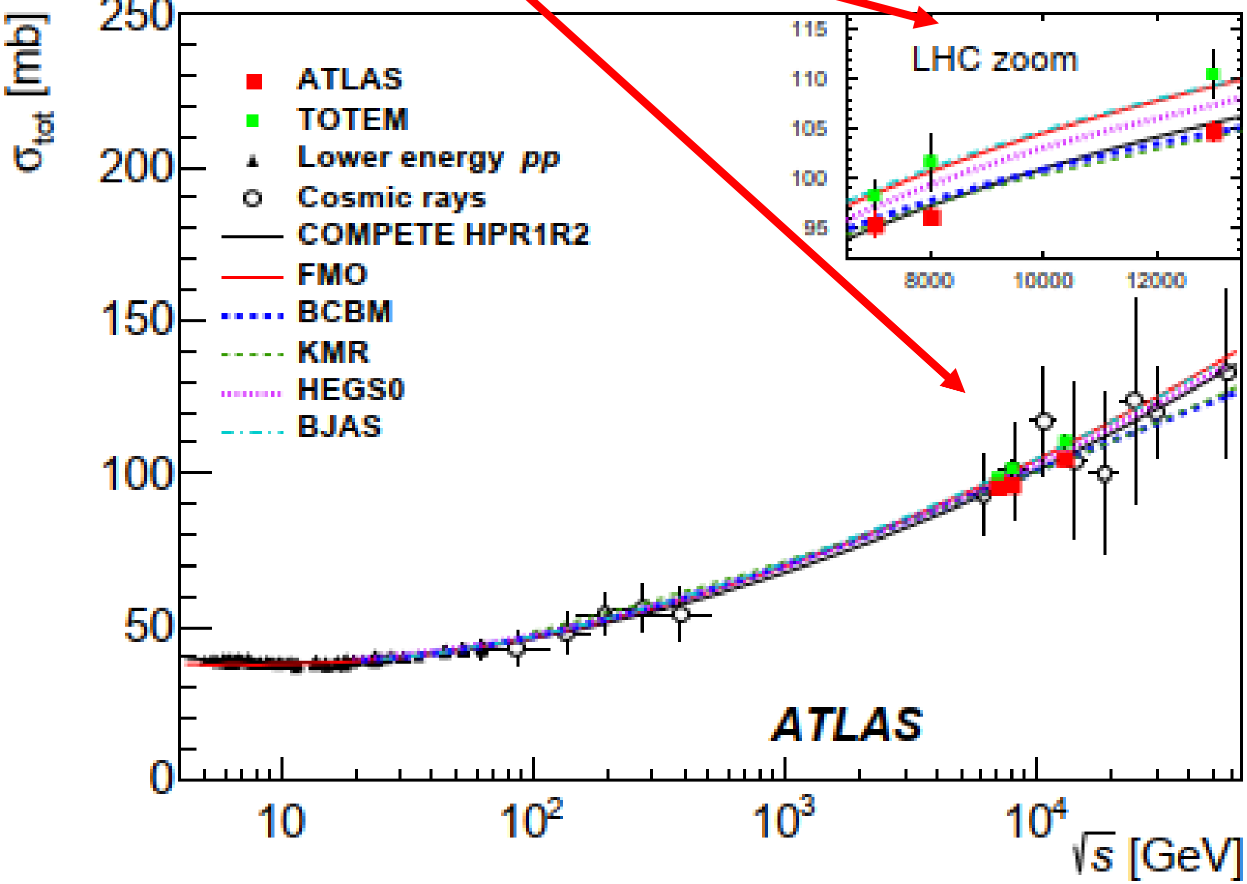
University of Bologna
and CERN
June 2025

The topic of today



Chi2 for the hypothesis of no difference between the ATLAS and TOTEM measurement of σ_{tot}

$\sqrt{s}$ TeV	Chi2	p-value
7	0.87	0.35
8	3.42	0.06
13	2.73	0.10

2.2 σ effect at 13 TeV

Outline:

- **From elastic scattering to total cross section**
- The discrepancy is basically a normalization problem and what are the methods used to normalize the data
- The TOTEM approach to the discrepancy
- Our approach- the main thrust of the seminar
- Our method
- Our results
- Compare with other constraints at the LHC
- Conclusion

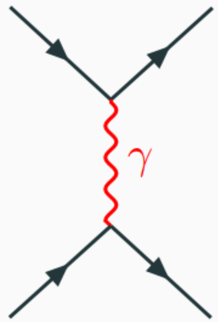
Both the ATLAS and the TOTEM experiment are measuring σ_{tot} via measurements of the elastic differential cross section $d\sigma_{el}/dt$.

Elastic scattering – the most simple process possible

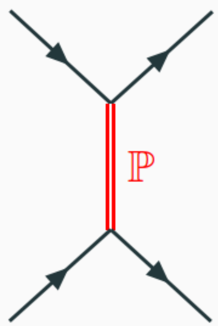
- Energy and momentum conservation
- two degrees of freedom: φ,θ
- φ uniform
- $t \approx -p^2\theta^2 = -p_t^2$
- small $|t|$-large distance, large $|t|$–small distance

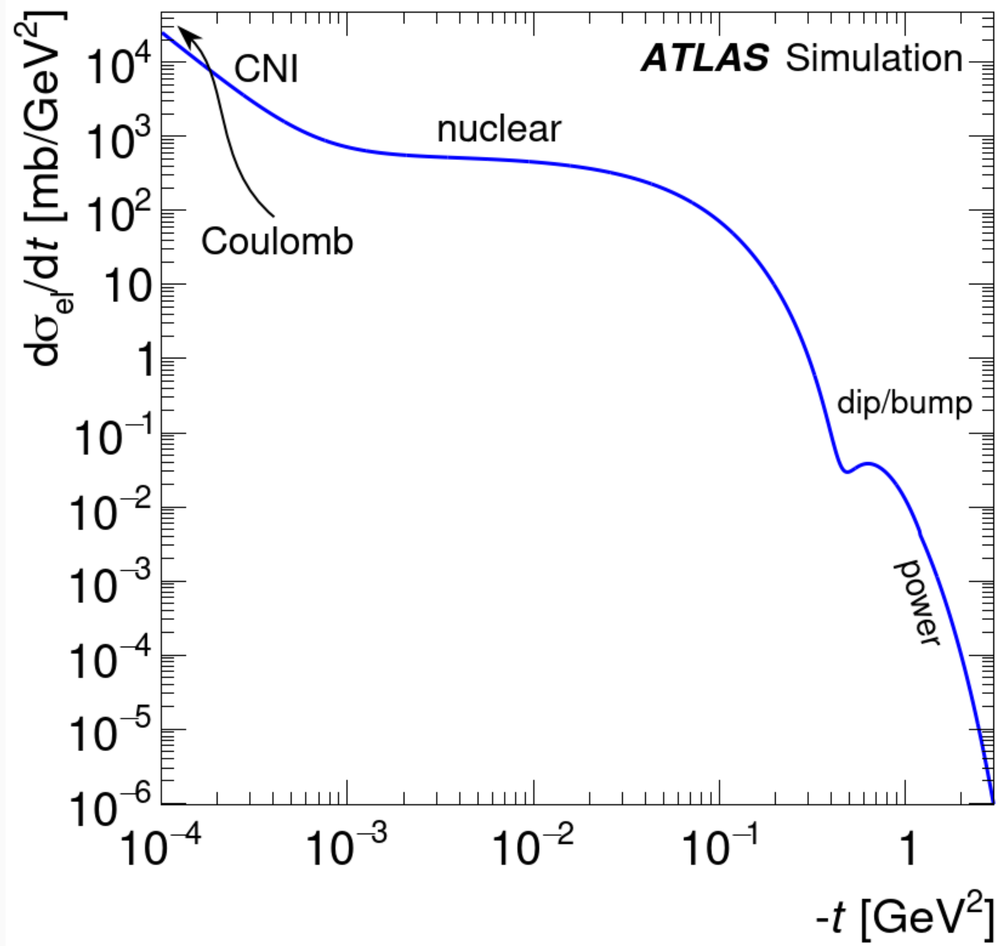
The nuclear(strong) part relevant for σ_{tot}

Coulomb (electromagnetic)



Nuclear (strong)





How to get to from $d\sigma_{el}/dt$ to σ_{tot} ?

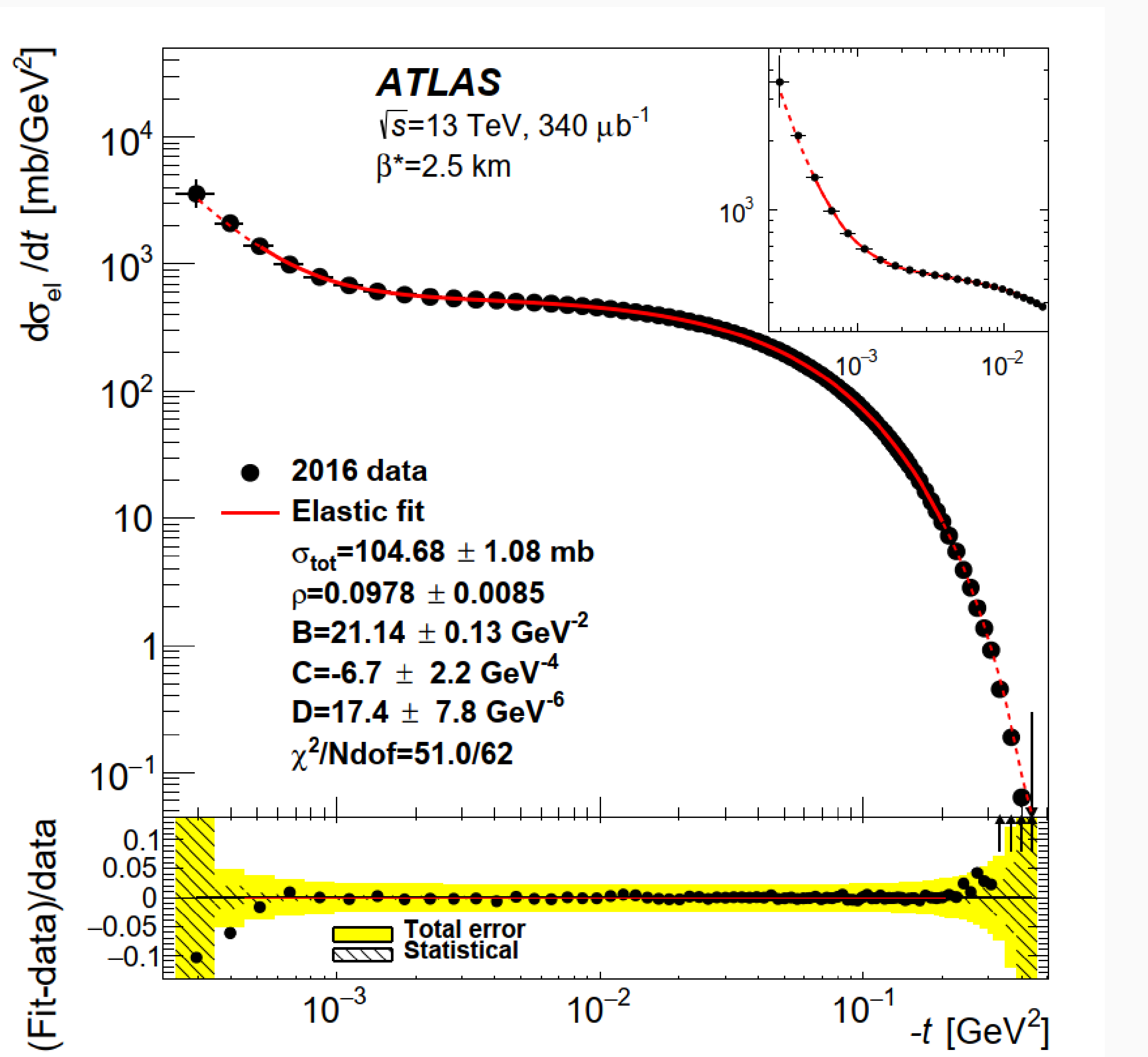
Use the optical theorem

$$\sigma_{\text{tot}} = 4\pi \,\text{Im}\, f_{\text{el}}(t=0)$$

..and use simple t-dependence $f_{el} \sim \exp(-B\,|t|/2)$
and define $\rho = \text{Re}\, f_{el}/\text{Im}\, f_{el}|_{t=0}$

$$\frac{d\sigma_{\text{el}}}{dt} = \sigma_{\text{tot}}^2 \frac{1+\rho^2}{16\pi} \exp\left(-B|t|\right)$$

Example from ATLAS 13 TeV



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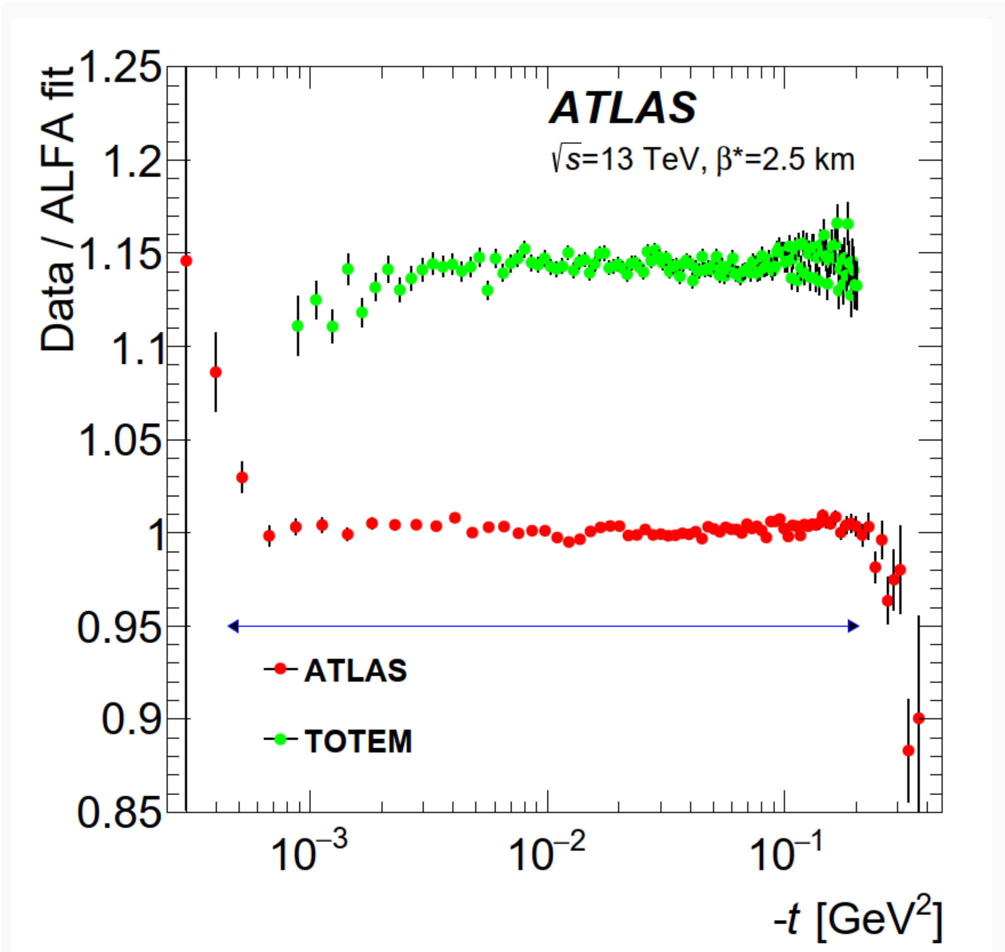
Here the difference between ATLAS and TOTEM is illustrated in a clear way



Both experiments measure basically the same shape of $d\sigma_{el}/dt$ but have 12-13 % in normalization difference

What normalization method are used?

There are three methods in use

$$\frac{d\sigma_{el}}{dt} = \sigma_{tot}^2 \frac{1+\rho^2}{16\pi} \exp\left(-B|t|\right)$$

1. Luminosity dependent

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \frac{1}{L} \frac{dN_{el}}{dt}\bigg|_{t\to 0}$$

2. Luminosity independent

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{1}{N_{el}+N_{inel}} \frac{dN_{el}}{dt}\bigg|_{t\to 0}$$

3. Coulomb normalization

The luminosity is a free parameter in the fit and if there is data at sufficient small-t the luminosity can be constrained by the well-known coulomb interaction

ATLAS uses the luminosity-dependent method at all three energies (7,8 and 13 TeV)

TOTEM uses luminosity-in dependent method at all three energies (7,8 and 13 TeV)

In addition TOTEM uses at 7 TeV luminosity-dependent “borrowing”the CMS luminosity measurement (4%) and at 13 TeV TOTEM also use Coulomb normalization

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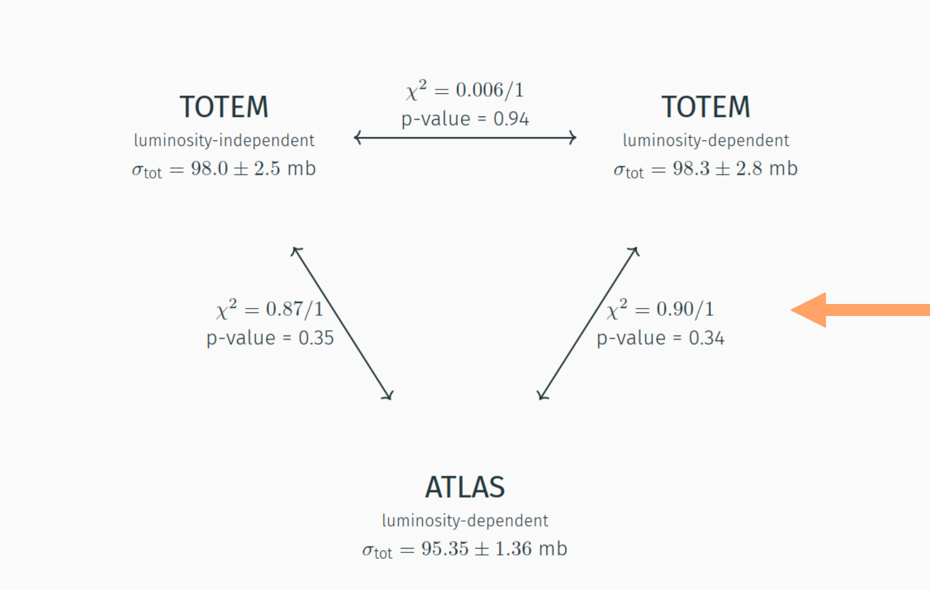
Before discussing the main message of this seminar let me summarize the opinion of TOTEM representatives as it appears during conference and during discussions …

Two main arguments

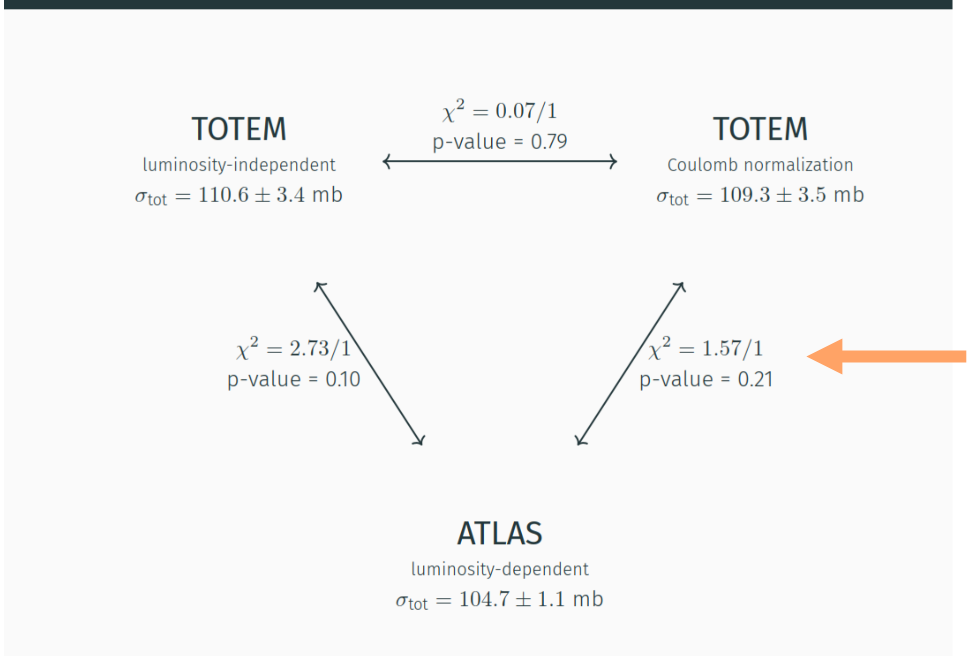
- TOTEM has performed measurements with different normalization methods- the different measurements are in perfect agreement

- ATLAS luminosity measurement is wrong- "It is probably due to the fact that the conditions for luminosity calibration is very different from the conditions for data taking.
The number of colliding bunches are different, the spot-sizes at the Interaction Point are different, the bunch intensity are different"..

ATLAS vs TOTEM @ 7 TeV



ATLAS vs TOTEM @ 13 TeV



"TOTEM" argument 1:

TOTEM has performed measurements with different methods-
- they are in perfect agreement

It is true that the two TOTEM measurement are in perfect agreement

However it is also true that the TOTEM luminosity dependent measurement and the Coulomb normalized measurement agree reasonable well with he ATLAS measurement.

Thus the TOTEM luminosity in-dependent measurement can not be validated by the TOTEM luminosity dependent or by the Coulomb normalization measurement at a level corresponding to the size of the disagreement with ATLAS

"TOTEM" argument 2:

- ATLAS luminosity measurement is wrong- "It is probably due the fact that the conditions for luminosity calibration is very different from the conditions for data taking.
The number of colliding bunches are different, the spot-sizes at the Interaction Point are different, the bunch intensity are different"..

Of course the ATLAS luminosity measurement could be wrong.
An experimentalist is never 100% convinced that what he/she is doing is correct.

Argument against is this

- ATLAS has measured all the standard model cross section with high precision and using the luminosity dependent method and also in those cases there are large difference between calibration conditions and data taking conditions (this fact is never mentioned in the discussions)

- I am not aware of any discrepancy with cross section measurements from CMS for all those standard model processes

Table 5: Main parameters for high-$\beta^\star$ runs, vdM scans and high-luminosity runs [6].

Parameters	2016 high-$\beta^\star$ runs	2016 vdM scan	High-luminosity runs
Number of colliding bunches	4–5	32	2208
Average pile-up parameter μ	0.002–0.006	0.5	41
Instantaneous luminosity (10^{27} cm^{-2} s^{-1})	$\sim$ 1.4–4	$2.6 \cdot 10^3$	$13 \cdot 10^6$
$\beta^\star$ (m)	2500	19	0.4

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Extraction of low-mass diffractive cross section from the discrepancy between ATLAS and TOTEM total cross sections

Per Grafström[1] and Rafał Staszewski[2]

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[2] *The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland*

February 20, 2025

Abstract

At the LHC, two experiments – ATLAS and TOTEM – measure the total proton–proton cross section. Unfortunately, a significant discrepancy, persisting at different collision energies, is observed between the values reported by the two groups. This paper considers the hypothesis that this tension is predominantly driven by the assumption about the low-mass diffraction used in one of the measurement methods. It is shown that in such a case it is possible to extract the low-mass diffraction cross section from measurements of ATLAS and TOTEM. The results are compared with other data-driven estimates, showing better agreement than the original assumption.

arXiv:2502.13618v1 [hep-ph] 19 Feb 2025

We have taken a different approach

We assume that all measurements done by
TOTEM and ATLAS are correct....

...acceptance, efficiency, background, luminosity and so forth i.e. all relevant experimental parameters are correctly determined in both experiments.

How is this possible???

To understand this we have to look more in detail on the two main methods used for normalization

Luminosity dependent

ATLAS

$$\sigma_{\rm tot}^2 = \frac{16\pi}{1+\rho^2}\frac{1}{L}\frac{dN_{\rm el}}{dt}\bigg|_{t\to 0}$$

Requires dedicated luminosity measurement

Luminosity independent

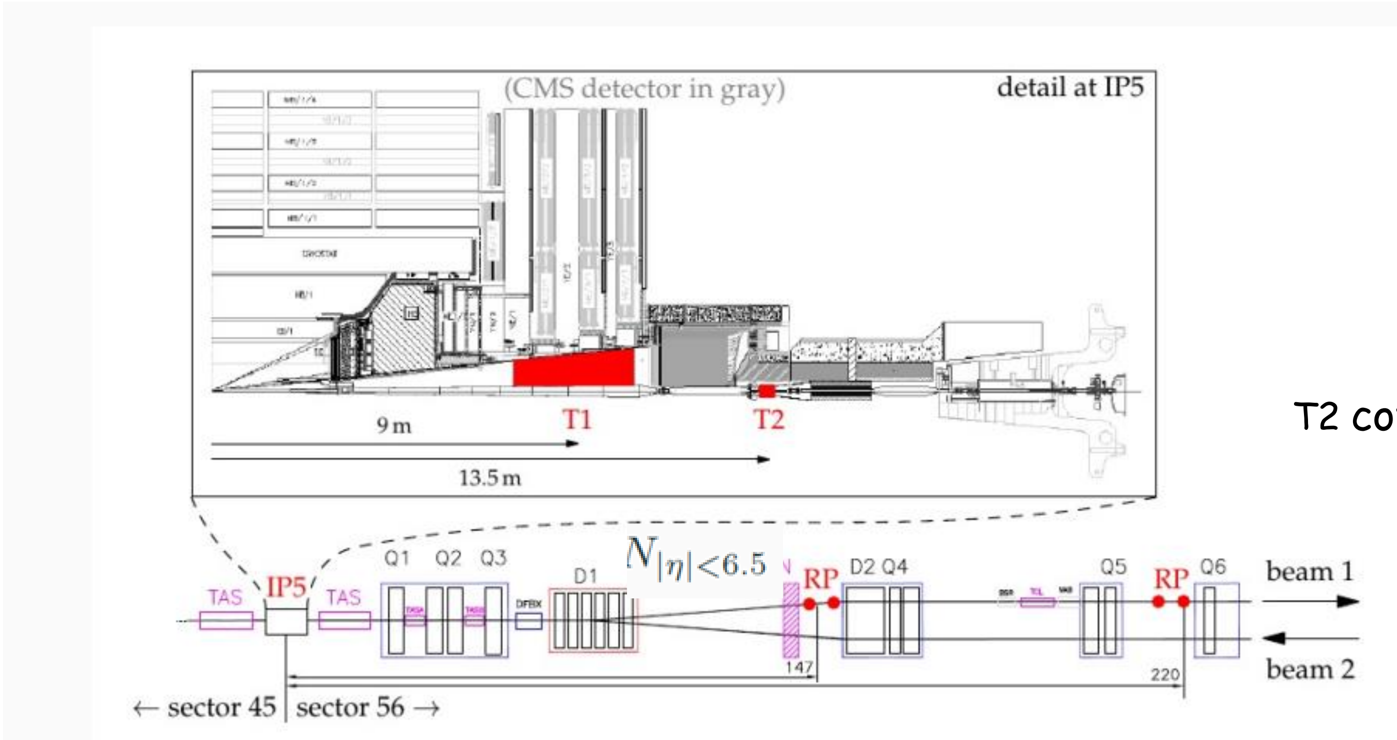
TOTEM

$$\sigma_{\rm tot} = \frac{16\pi}{1+\rho^2}\frac{1}{N_{\rm el}+N_{\rm inel}}\frac{dN_{\rm el}}{dt}\bigg|_{t\to 0}$$

Requires to know the full inelastic event rate and for this you need a correction for the not measured low-mass diffraction
(see next slide)

Assuming that all measurements are correct the only possibility to explain the difference in σ_{tot} between the two experiments is **to question the theoretical input used by TOTEM to correct for the not measured low-mass diffraction**

How does TOTEM correct for the non-measured low-mass diffraction?



T2 cover $N_{|\eta|<6.5}$

TOTEM estimates what escapes detection in T2 using MC-estimates

$$N_{\text{inel.}} = (1+\epsilon)N_{|\eta|<6.5}$$

Luminosity-independent becomes instead MC-dependent!

Diffractive dissociation….

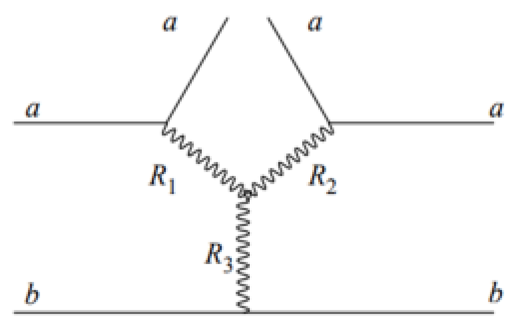
In general: Non-perturbative nature……obviously difficult

Low-mass: M_x<3-4 GeV

Good-Walker formalism often used- the proton is treated as a superposition of several diffractive eigenstates

High mass: M_x >3-4 GeV

triple-pomeron coupling



TOTEM uses the M-C program QGSJET to correct

Sergey Ostapchenko

The framework is Gribov's reggeons approach and a two-component diffraction treatment

$$N_{\mathrm{inel.}} = (1+\epsilon) N_{|\eta|<6.5}$$

$$\sigma_{\mathrm{tot}} = \frac{16\pi}{1+\rho^2} \frac{1}{N_{\mathrm{el}} + N_{\mathrm{inel}}} \left. \frac{\mathrm{d}N_{\mathrm{el}}}{\mathrm{d}t} \right|_{t\to 0}$$

$\sqrt{s}$	7	8	13
$\epsilon[\%]$	4.2	4.8	7.1

$$\delta\epsilon = \epsilon/2$$

Our approach:

- Find what assumption TOTEM has to make to get the same result as ATLAS (or more strictly) the same result as the model-independent approach.

- Check to what extent the outcome is compatible with other data available

Our input data-summary of all data available

Model-dependent data

Table 1: Summary of model-dependent measurements.

	σ_{tot}^{md} [mb]	σ_{inel}^{md} [mb]
TOTEM 7 TeV [9]	98.0 ± 2.5	72.9 ± 1.5
TOTEM 8 TeV [10]	101.7 ± 2.9	74.7 ± 1.7
TOTEM 13 TeV [11]	110.6 ± 3.4	79.5 ± 1.8

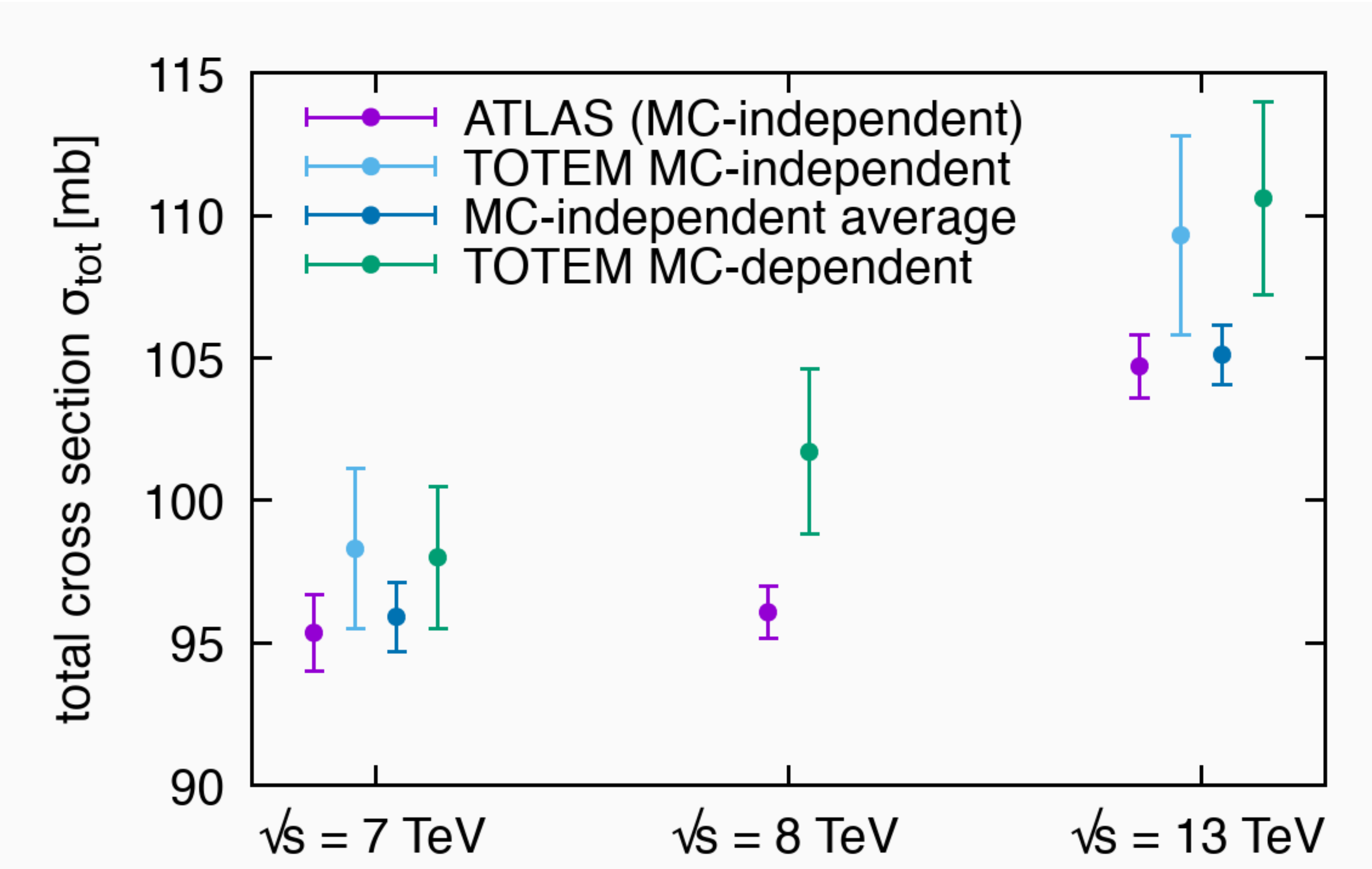
Model-independent data

Table 2: Summary of model-independent measurements.

		σ_{tot}^{mi} [mb]	σ_{inel}^{mi} [mb]	R^{mi}	B^{mi} [GeV^{-2}]
7 TeV	ATLAS [4]	95.35 ± 1.36	71.34 ± 0.82	0.253 ± 0.005	19.73 ± 0.3
	TOTEM[a] [7]	98.3 ± 2.8	73.5 ± 1.9	0.253 ± 0.005	19.73 ± 0.3
	Average	95.9 ± 1.2	71.68 ± 0.75	0.253 ± 0.004	19.73 ± 0.2
8 TeV	ATLAS [5]	96.07 ± 0.92	71.73 ± 0.71	0.252 ± 0.004	19.74 ± 0.24
13 TeV	ATLAS [6]	104.7 ± 1.1	77.41 ± 1.09	0.257 ± 0.012	21.14 ± 0.13
	TOTEM[b] [12]	109.3 ± 3.5	–	–	–
	Average	105.1 ± 1.0	–	–	–

[a] luminosity-dependent method
[b] Coulomb normalisation

Summary of all data in graphic form



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Our method

Defining: $\varepsilon = \varepsilon_0 + \varepsilon'$

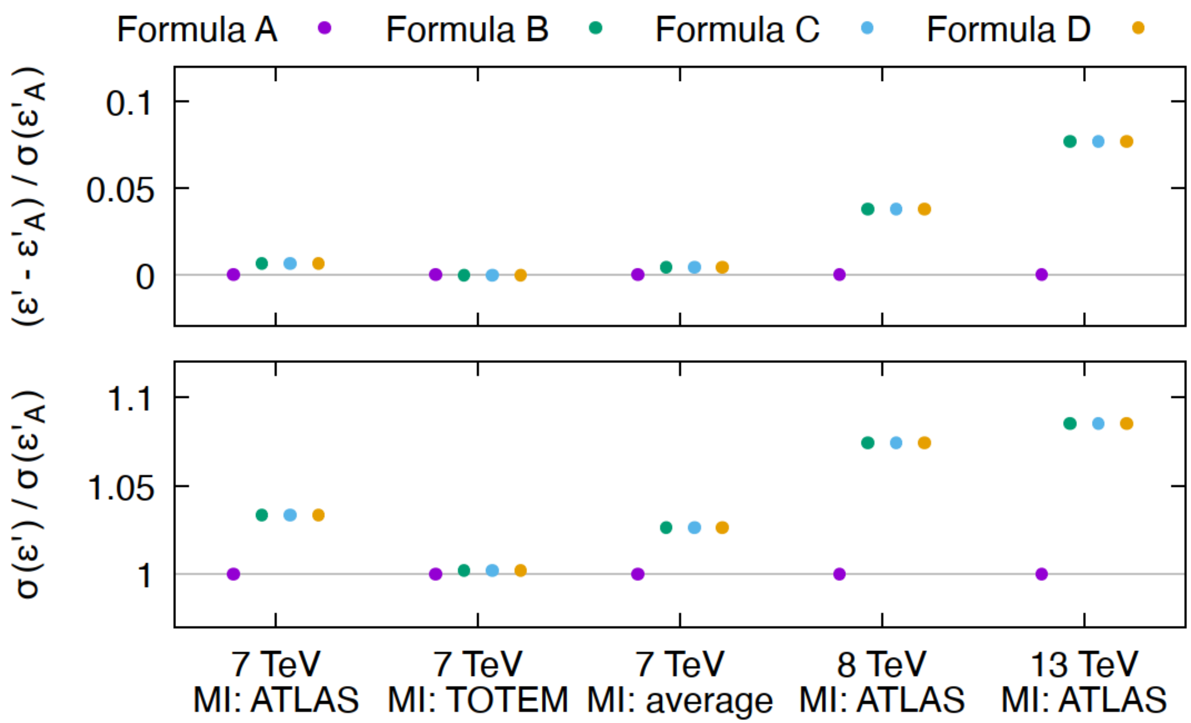
ε_0= correction used by TOTEM
ε' = correction to ε_0
ε = correction giving the same result as ATLAS

Different approaches to calculate ε'

Approach	Input	Formula for ϵ'
A	$\underline{\sigma_{\text{tot}}^{\text{md}}}, \sigma_{\text{tot}}^{\text{mi}}, \sigma_{\text{inel}}^{\text{mi}}$	$\dfrac{\sigma_{\text{tot}}^{\text{md}} - \sigma_{\text{tot}}^{\text{mi}}}{\sigma_{\text{inel}}^{\text{mi}}}$
B	$\underline{\sigma_{\text{tot}}^{\text{md}}}, \sigma_{\text{tot}}^{\text{mi}}, \sigma_{\text{inel}}^{\text{md}}$	$\dfrac{\sigma_{\text{tot}}^{\text{md}}\left(\sigma_{\text{tot}}^{\text{md}} - \sigma_{\text{tot}}^{\text{mi}}\right)}{\sigma_{\text{inel}}^{\text{md}}\sigma_{\text{tot}}^{\text{mi}}}$
C	$\underline{\sigma_{\text{tot}}^{\text{md}}}, R^{\text{mi}}, \sigma_{\text{inel}}^{\text{md}}$	$\dfrac{\sigma_{\text{tot}}^{\text{md}}}{\sigma_{\text{inel}}^{\text{mi}}} - \dfrac{1}{1 - R^{\text{mi}}}$
D	$\underline{\sigma_{\text{tot}}^{\text{md}}}, \sigma_{\text{tot}}^{\text{mi}}, B^{\text{mi}}$	$\left(\dfrac{\sigma_{\text{tot}}^{\text{md}}}{\sigma_{\text{tot}}^{\text{mi}}} - 1\right) / \left(1 - \dfrac{\sigma_{\text{tot}}^{\text{mi}}(\rho^2 + 1)}{16\pi B^{\text{mi}}}\right)$

Different approaches with different inputs and different error propagation

Comparison of approaches



The results using the TOTEM Coulomb normalization is not shown because the available data only allow for formula B to be applied

Good agreement between methods – both central value and uncertainty

We choose method B-the only one that can be applied to all different data sets including the TOTEM Coulomb normalization

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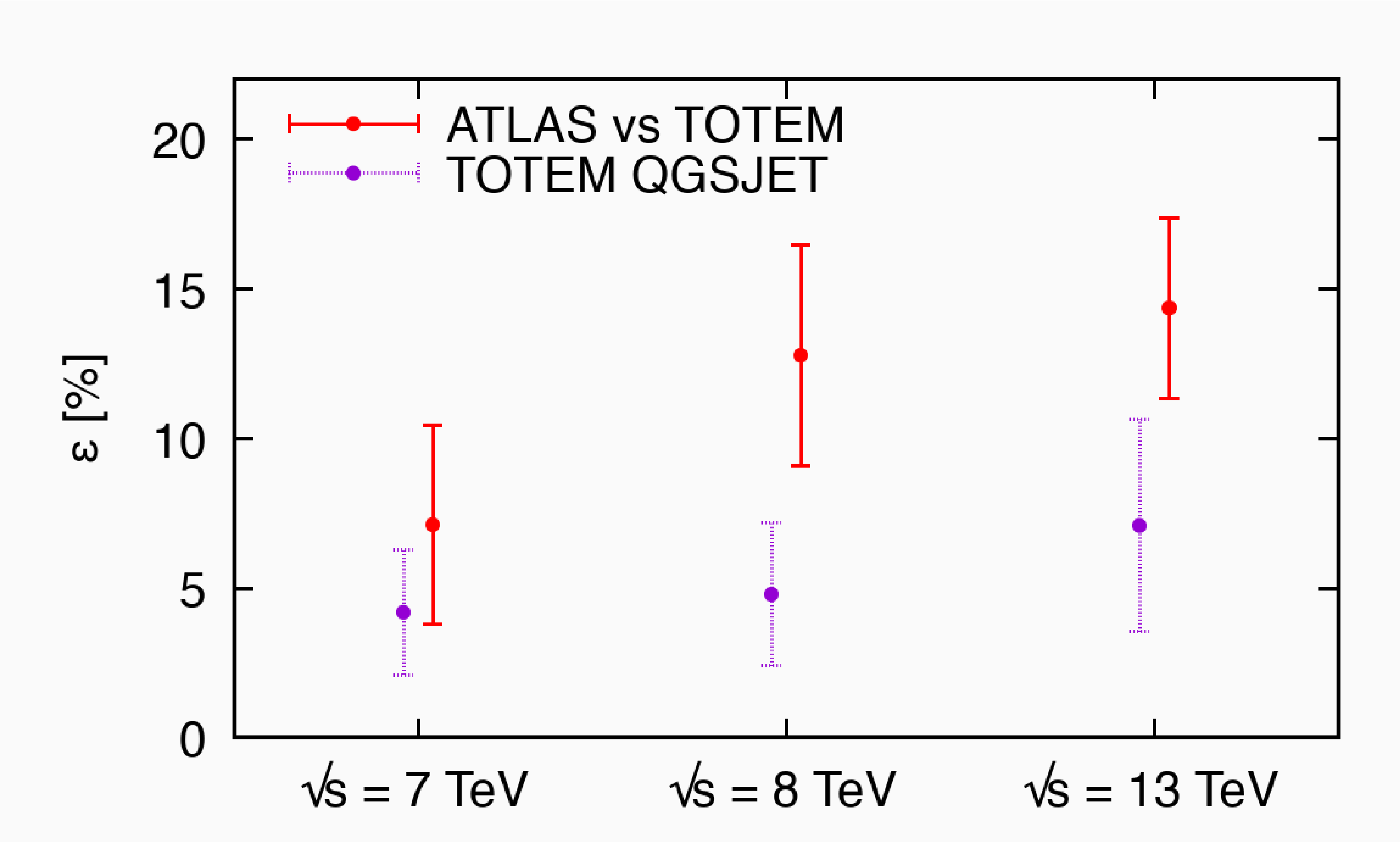
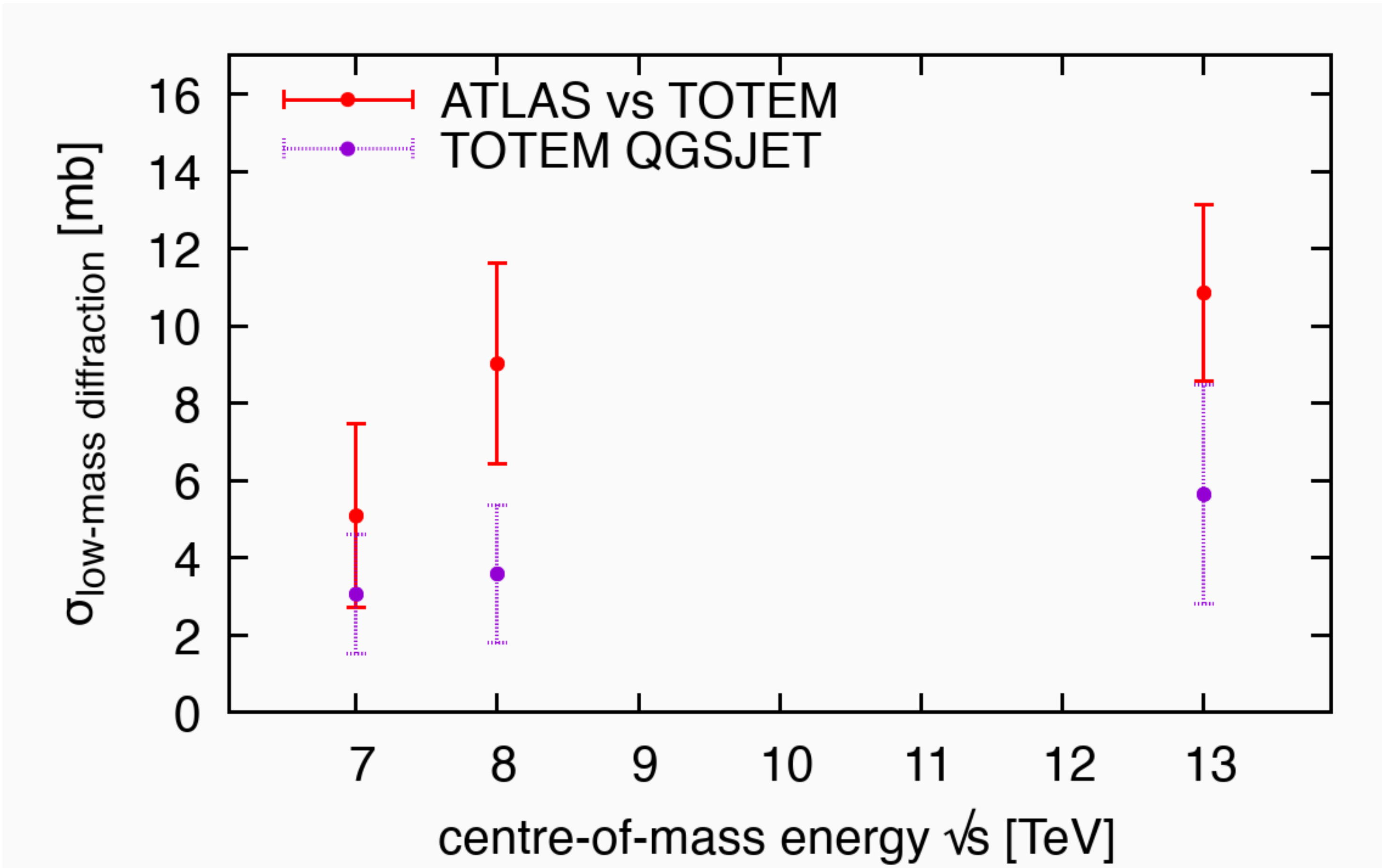
Numerical results-the correction ε



At 7 and 13 TeV the values represent the average between the ATLAS and TOTEM model-independent measurement.
At 8 TeV the only model-independent measurement available is the one of ATLAS

Numerical result-low-mass diffraction cross-section



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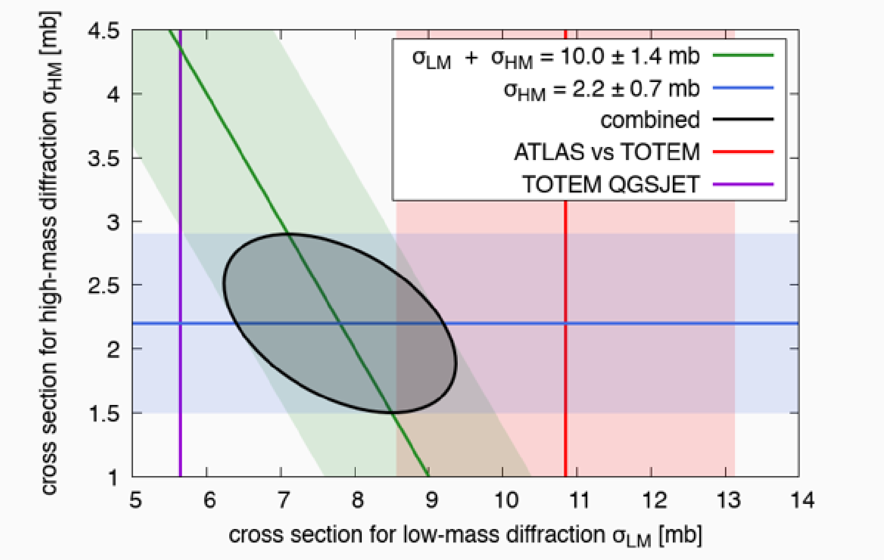
Compare our result ("totem vs atlas") with other LHC measurements

No direct measurements of low mass diffraction available at LHC but some constraints can be derived !

1. Constraint at 13 TeV

- ATLAS and CMS has measured the fiducial inelastic cross section for M_x>13 GeV-good agreement average 68 mb
- The total Inelastic cross section is measured to be 78 mb
- CMS measured 2.2 mb in the mass region 13 GeV >M_x> 4.1 GeV

Putting the low/high mass border at 4.1 GeV and call the region between 4.1 GeV and 13 GeV high mass region and calculating the uncertainties correctly the argument can be illustrated in a plot



- First two bullets gives the green area
- third bullet give the blue area
- the ellipse represents the constraint

Our result (ATLAS vs TOTEM) (red area) has an overlap with the ellipse

QGSJET lies outside
(but with the arbitrary uncertainty of 50% it would also fall inside the ellips)

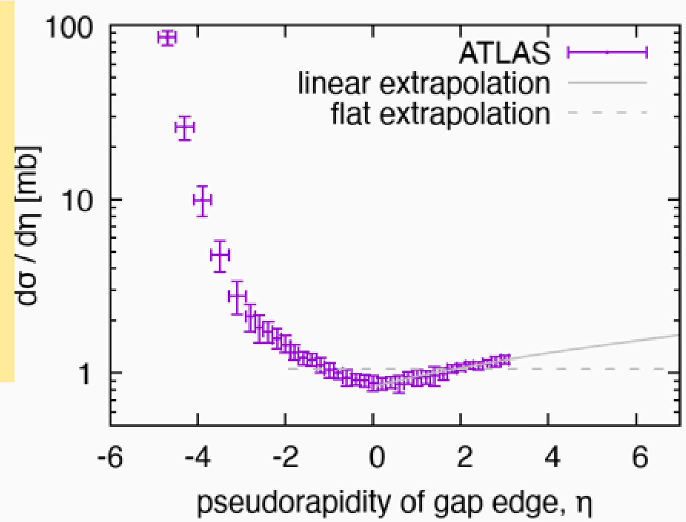
2. Constraint at 7 TeV

The same starting point as at 13 TeV

- ATLAS , CMS and ALICE has measured the fiducial inelastic cross section for M_x>15.7 GeV-good agreement- average 60 mb
- The total inelastic cross section is measured to be 71 mb
- but NO measurement in the 15.7 GeV >M_x> 3-4 GeV region

Instead we have a gap size distribution from an ATLAS measurement at 7 TeV .
By extrapolating to the TOTEM limit of η=6.5 we can estimate the high-mass cross section up to M_x=15.7.

Putting it all together
we get a cross section
for low-mass diffraction
of **5.9+-3.0 mb**.
(the uncertainty also include
the different extrapolations
seen in the figure)



Eur. Phys. J. C (2012) 72:1926
DOI 10.1140/epjc/s10052-012-1926-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Rapidity gap cross sections measured with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration*

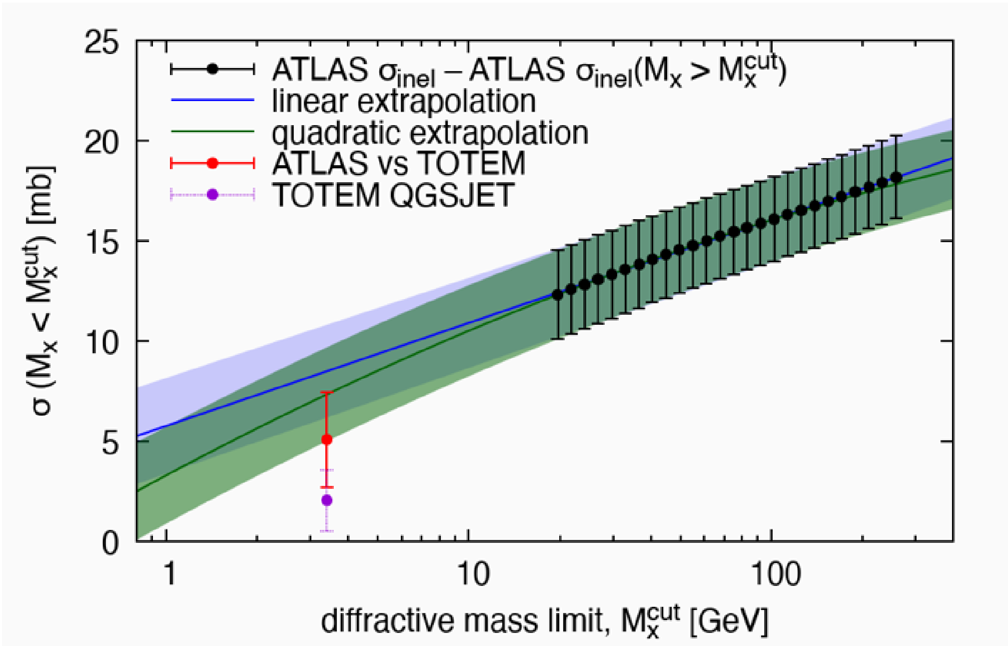
CERN, 1211 Geneva 23, Switzerland

(we will compare later)

3. Constraint at 7 TeV-a different method.

The ATLAS paper from previous slide also provides a distribution of the inelastic cross section excluding diffractive events with a given mass cut. Using the total inelastic cross section of 71 mb one gets the plot below.

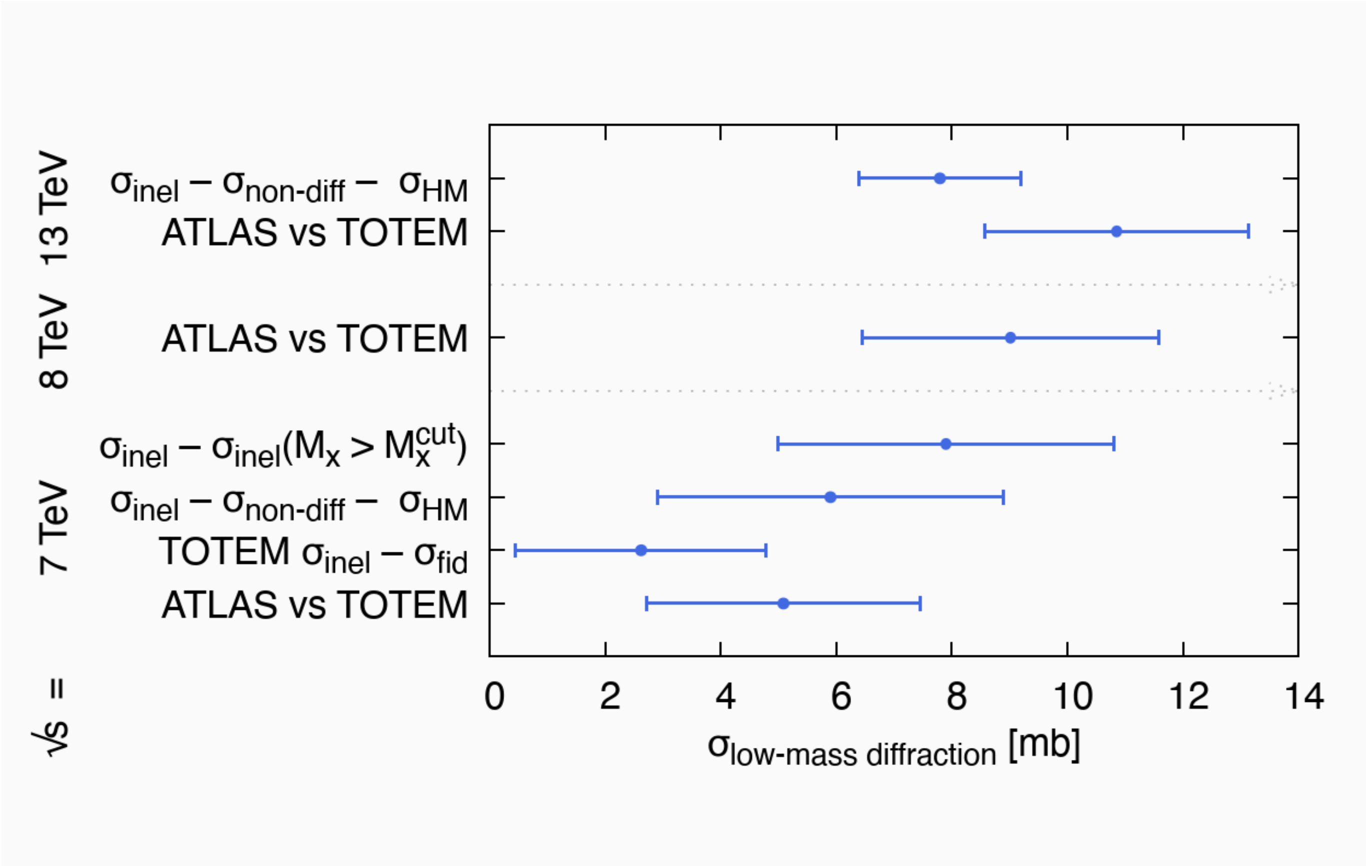
Using both extrapolations indicated one gets:
Low-mass diffraction = **7.9+- 2.9 mb**



4. Constraint at 7 TeV from TOTEM

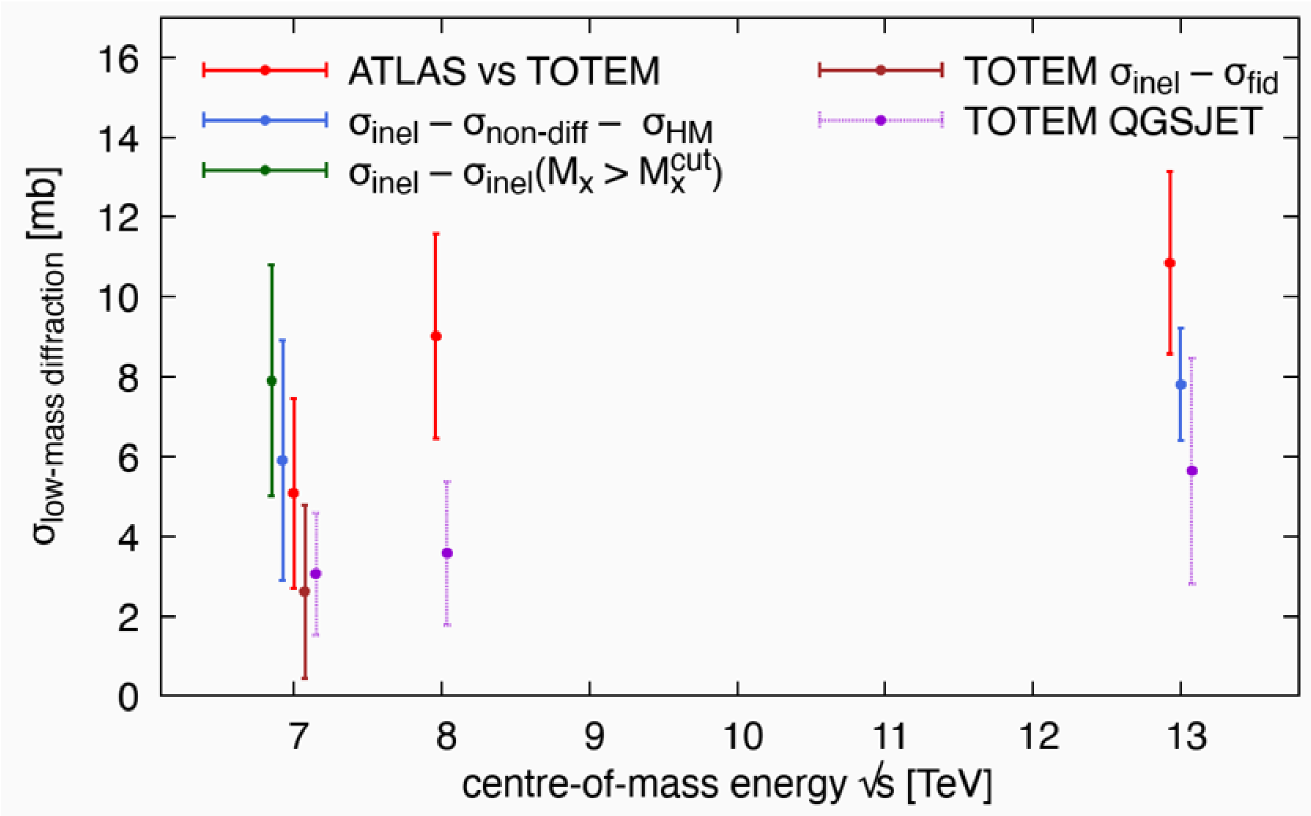
- From EPL 101(2013) 2,21003
- TOTEM obtain the total inelastic cross section as the total cross section minus the elastic cross section (luminosity dependent method)
- TOTEM measure the fiducial inelastic cross section using theT2 detector
- Results: Low-mass diffraction 2.62+-2.17 mb (95% CL limit 6.31 mb)

Summary of data driven results



Our measurement (" ATLAS vs TOTEM") in good agreement with all other measurements

Comparison with TOTEM QGSJET assumption



QGSJET below all other estimates except at 7 TeV

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Conclusion or Summary

- Long standing tension between ATLAS and TOTEM in measurements of the total cross section
- Effectively a tension between ATLAS luminosity-dependent method and the TOTEM model dependent method
- Exploiting the hypothesis that the problem is related to the TOTEM assumption about low-mass diffraction which leads to data-driven cross section for low-mass diffraction
- Compare the found low-mass diffraction cross sections with other data driven estimates.
- Result in better agreement with those other data-driven estimates than the TOTEM assumptions
- Quite possible that the discrepancy between TOTEM and ATLAS has its main origin in the assumption about low-mass diffraction

Back up