Total, elastic and inelastic pp scattering

(a selection of results and methods)

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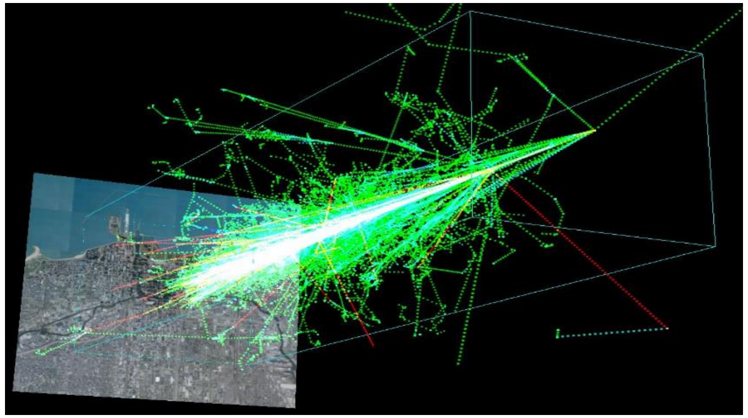
23 May 2017

Introduction



This talk is a mini-review on (mostly LHC) results on pp σ_{tot}, σ_{el}, $\sigma_{inelastic}$ and CEP measurements.
Emphasis is given to different measurement methods, promising channels.

Soft-QCD: why measure it? A non-comphrensive list:

1. No model manages to describe all data available:

- PQCD approach cannot be used in this context (low momentum transfer). Some of the models are still based on Regge theory, others uses optical or eikonal approaches. QCD-inspired models are trying to connect the concepts of Pomeron and proton opacity to the QCD description in terms of quarks and gluons
- Still much to clarify on low-mass spectroscopy (i.e. glueball existence)

2. If you are just interested in BSM Physics, let's consider the $\gamma\gamma \rightarrow \gamma\gamma$ or AQGC($\gamma\gamma \rightarrow WW$) searches:

One of the largest systematic in high pile-up runs can be introduced by the request of vertex/track isolation or Rap/Gap requirement. Non perfect knowledge/modeling of the soft events make uncertainty of the selection efficiency larger.

3. If you are a Cosmic Rays physicist:

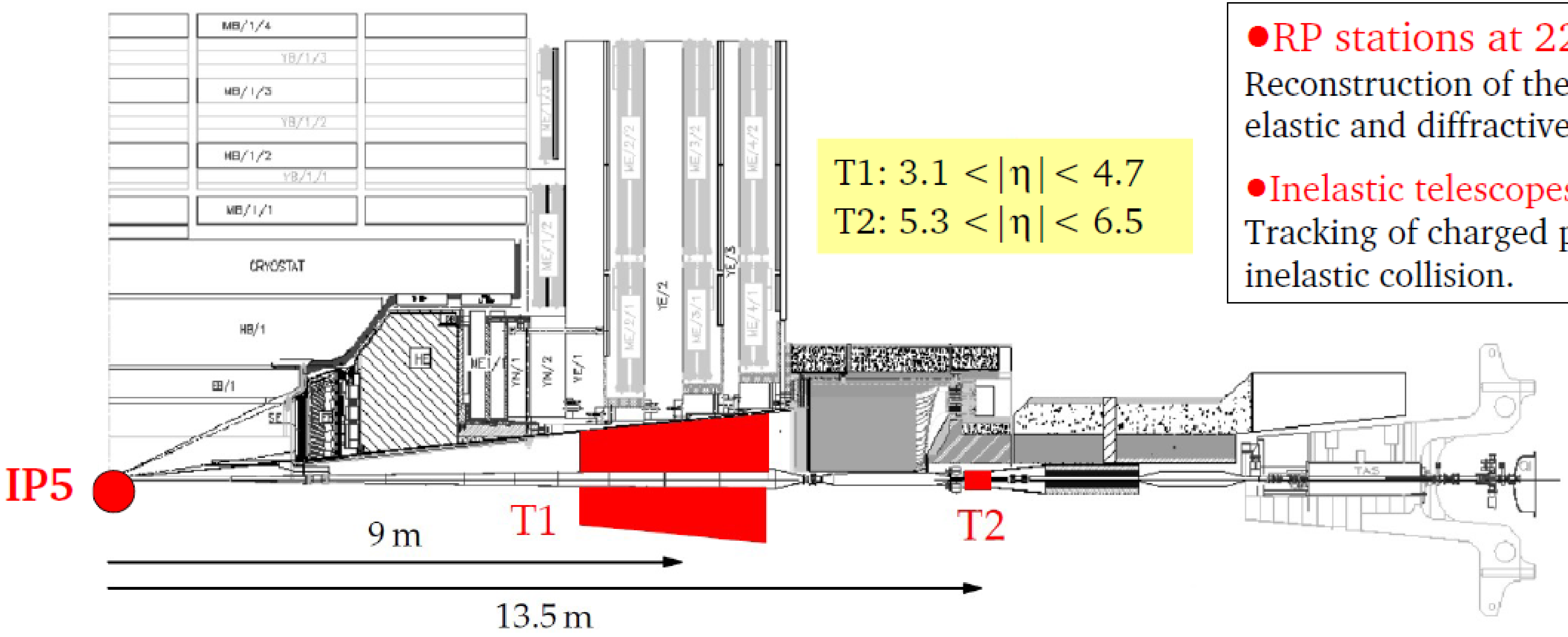
The accurate estimation of the CR primary nature and energy at ground depends on the availability of a reliable description of the hadronic interaction (σ,multiplicities, Eflow...). Moreover proton interaction cross sections (with p,He..) is needed to evaluate the effect of the interactions in the intergalactic medium of the CR.

Overview on pp inelastic scattering measurements

(EPL, 101 (2013) 21003)

σ_{inel} by TOTEM at 7 TeV

- Luminosity dependent inelastic cross section obtained triggering with T2: 5.3<|η|<6.5, M>3.4 GeV



- RP stations at 220m: Reconstruction of the proton from elastic and diffractive interaction.
- Inelastic telescopes T1,T2: Tracking of charged particles from inelastic collision.

(EPL, 101 (2013) 21003)

σ_{inel} by TOTEM at 7 TeV

- Luminosity dependent inelastic cross section obtained triggering with T2: **5.3<|η|<6.5, M>3.4 GeV**

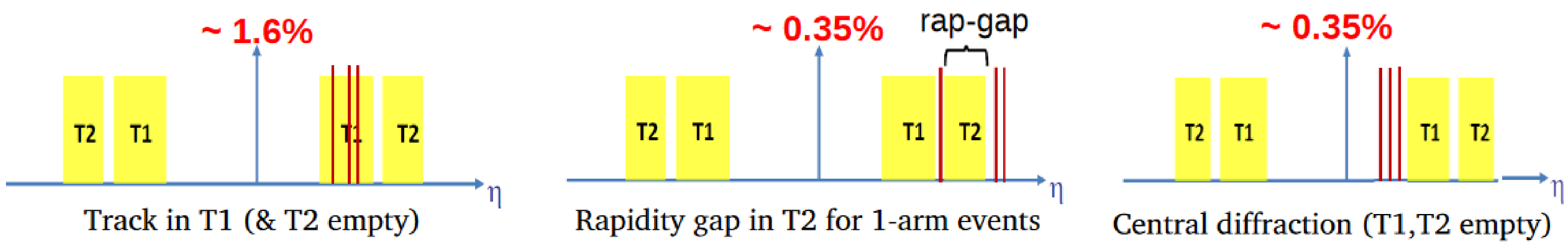
- Cross section for events with at least a stable particle in the T2 acceptance:

$\sigma_{Inel,T2\ vis}$ (mb): 69.7 ± 0.1stat ± 0.7syst ± 2.8lumi

- Cross section for events with at least a stable particle with |η|<6.5:

$\sigma_{Inel,|\eta|<6.5}$ (mb): 70.5 ± 0.1stat ± 0.8syst ± 2.8lumi

Correction sizes:

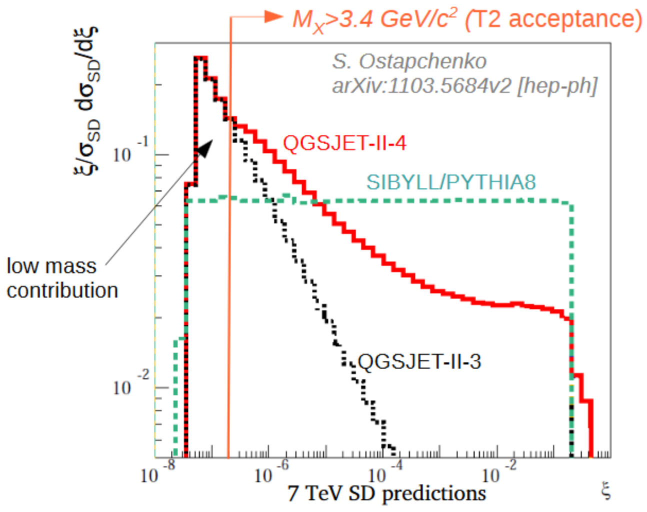


- Correction for events having particles only at |η|>6.5: 4.2% ± 2.1% (syst):

σ_{inel} (mb): 73.74 ± 0.09stat ± 1.74syst ± 2.95lumi

N.B.:

- same analysis published at 8 TeV $\sigma_{inel} = (74.7 \pm 1.7)$ mb. and completed at 2.76 TeV
- Valuable for low-M generator tuning (QGSJETII-04 compatible with $\sigma_{inel,RP}$-$\sigma_{inel,VIS}$)



σ_{inel} by TOTEM and ALFA at 7 TeV (via optical theorem)

Method based on optical theorem : $$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)} \frac{1}{\mathcal{L}} \left(\frac{dN_{el}}{dt}\right)_{t=0}$$

- Mesurement of the elastic rate with RP detectors. σ_{inel} is then computed by difference.
- Needs knowledge of the L and ρ (more on this later)

Importance of the method : *possibility to bound the low mass diffraction cross section (with small model dependence):*

ALFA(ATLAS)

$$\sigma_{\rm inel} = 71.34\ \pm 0.36\ ({\rm stat.}) \pm 0.83\ ({\rm syst.})\ {\rm mb}$$

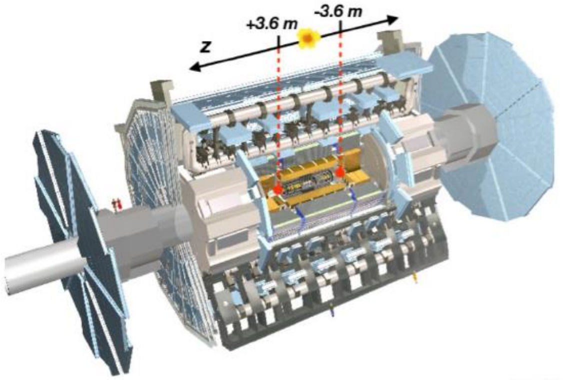
TOTEM

Cross-section [mb]	Value	Statistical	Systematic rate	Systematic lumi	$\Rightarrow$ Full
$\sigma_{inel,T2vis}$	69.73	± 0.08	± 0.72	± 2.79	$\Rightarrow \pm 2.88$
$\sigma_{inel,\|\eta\|<6.5}$	70.53	± 0.08	± 0.77	± 2.82	$\Rightarrow \pm 2.93$
σ_{inel}	73.74	± 0.09	± 1.74	± 2.95	$\Rightarrow \pm 3.43$
σ_{inel} [9]	73.15				± 1.26
$\sigma_{inel,\|\eta\|>6.5}$	2.62				± 2.17

Comment on cross section values and methods

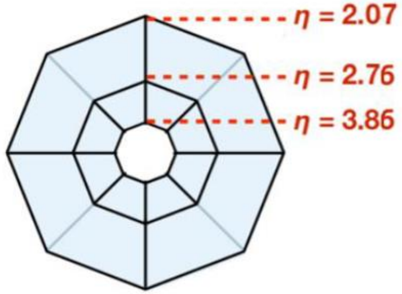
- To get σ_{tot} ALFA used pure exponential in dN_{el}/dt and fits with Coulomb. But it has more detailed luminosity determination.
- At 7 TeV, TOTEM used three methods that agreed. At 8 TeV for the 1 km measurement, TOTEM takes non-pure exponentiality into account, removes effect of Coulomb by fit (in a t-region with sensitivity) and simultaneously extracts ρ.

σ_{inel} by ATLAS at 13 TeV



Fiducial cross section measurement:

- Triggered with MSTB scintillator counter $2.07 < |\eta| < 3.86$ (μ=0.23%)



$$\sigma^{fid}_{inel}(\xi > 10^{-6}) = \frac{N - N_{BG}}{\epsilon_{trig} \times \mathcal{L}} \times \frac{1 - f_{\xi<10^{-6}}}{\epsilon_{sel}}$$ (50% eff at M=13 GeV)

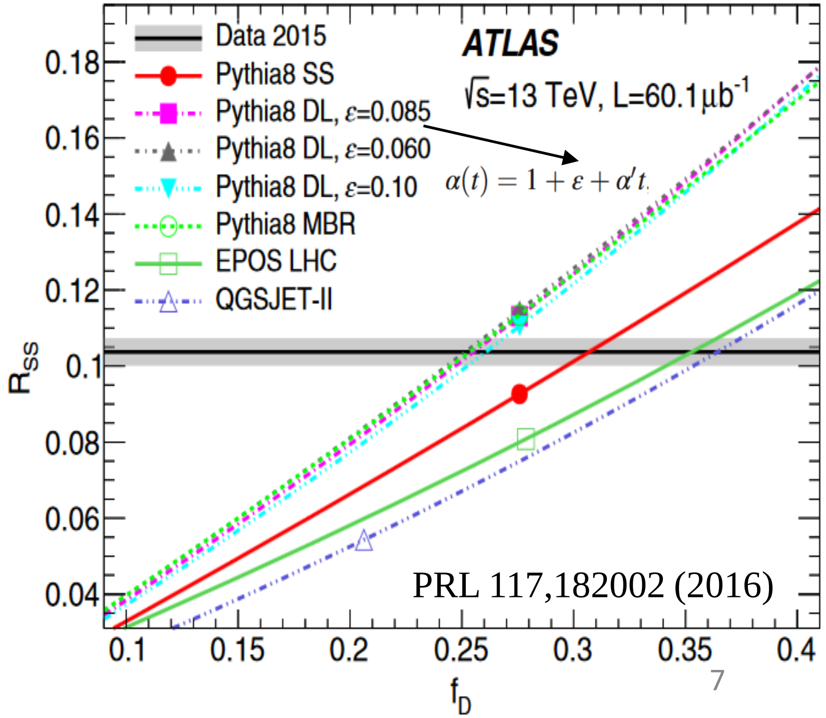
- In each MC the SD and DD cross section are varied such that f_D reproduces the value of R_{ss} measured in the data

$$f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{inel}$$

$$R_{ss} = \frac{\text{number of Single side events}}{\text{number of Inclusive events}}$$

Tuned PYTHIA8 DL model with ε= 0.085 (which best describes the MSTB multiplicities) is chosen as the nominal MC model for the measurement correction $f_{\xi<10^{-6}}$ corrections, and only the DL and MBR models are considered for systematic uncertainties related to the MC corrections

$$\sigma^{fid}_{inel} = 68.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum})\ \text{mb}$$



σ_{inel} by ATLAS at 13 TeV

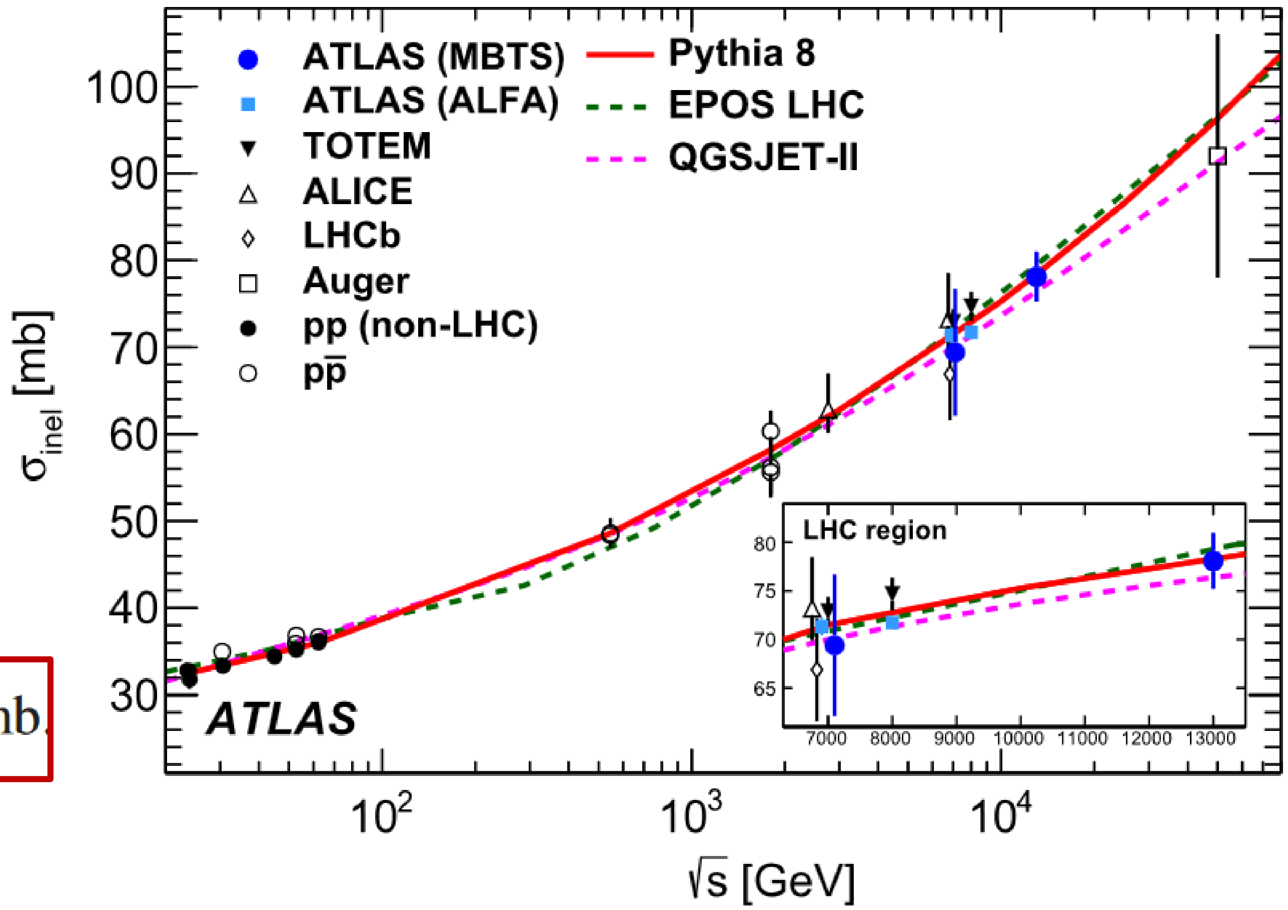
Extrapolation to inclusive inelastic cross section:

$$\sigma_{inel} = \sigma_{inel}^{fid} + \sigma^{7\ TeV}(\xi < 5 \times 10^{-6}) \times \frac{\sigma^{MC}(\xi < 10^{-6})}{\sigma^{7\ TeV,MC}(\xi < 5 \times 10^{-6})}.$$

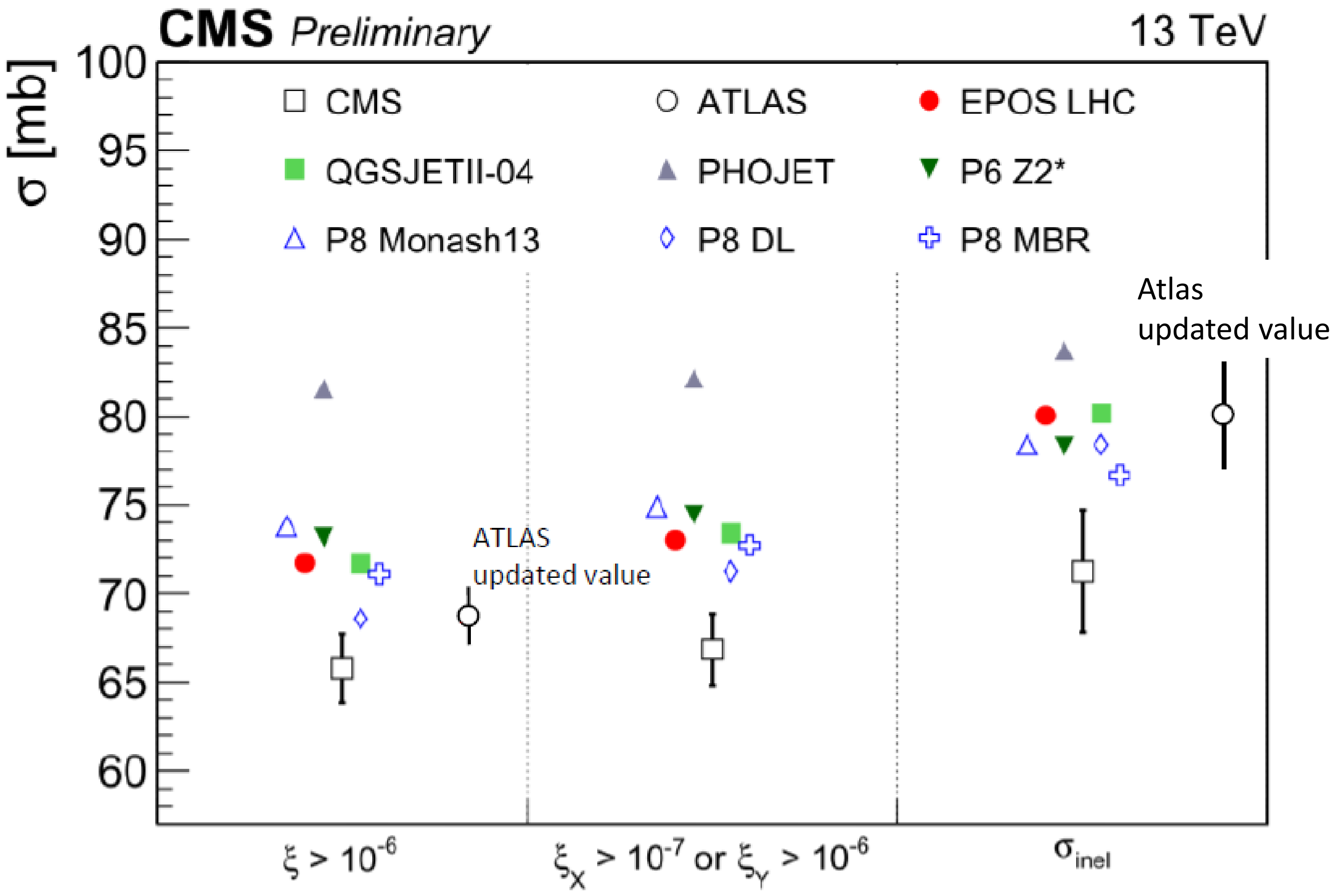
Where: $\sigma^{7\ TeV}(\xi < 5 \times 10^{-6})$ =
Total cross section by ALFA – Cross section MBST with $\xi > 5 \cdot 10^{-6}$

$$\sigma_{inel} = 78.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum}) \pm 2.6(\text{extrap})\ \text{mb}.$$

PRL 117,182002 (2016)



σ_{inel} by CMS at 13 TeV



Trigger with calorimetry (CASTOR & HF), μ<0.4

($M_X > 4.1$ GeV and $M_Y > 13$ GeV):

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

(average used for the extrapolation. Max var/2 as error)

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

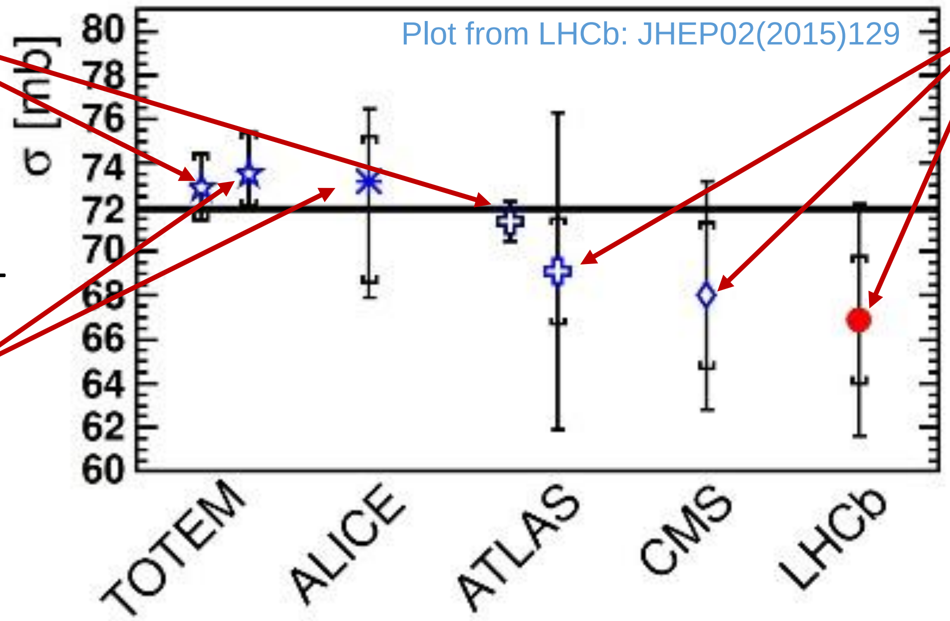
$$\sigma_{\text{inel}} = 71.26 \pm 0.06\ (\text{stat.}) \pm 0.47\ (\text{sys.}) \pm 2.09\ (\text{lum.}) \pm 2.72\ (\text{ext.})\ \text{mb}$$

COMPILATION of σ_{inel} @ 7 TeV

From elastic pp scattering using optical theorem

Visible inelastic rate + extrapolation using multi-Pomeron models for low mass diffraction

σ_{inel} measurements @ $\sqrt{s}$ = 7 TeV:



Visible inelastic rate + extrapolation using "average" of several MCs (not necessarily with good low M_{diff} model)

Experiment	Acceptance η range	"Visible" ξ range	M_X range (GeV/c²)	Reference
ALICE	$-3.7 < \eta < 5.1$	$\xi > 5 \cdot 10^{-6}$	$M_X > 7$	EPJ C73 (2013), 2456
ATLAS	$2.09 < \lvert\eta\rvert < 3.84$	$\xi > 5 \cdot 10^{-6}$	$M_X > 15.7$	Nat. Commun. 2 (2011), 463
CMS	$3 < \lvert\eta\rvert < 5$	$\xi > 5 \cdot 10^{-6}$	$M_X > 15.7$	Phys. Lett. B 722 (2013), 5
LHCb	$2 < \eta < 4.5$	$\xi > \sim 1.5 \cdot 10^{-6}$ (n)	$M_X > \sim 8.6$ (n)	arXiv: 1412.2500 (2014)
TOTEM	$3.1 < \lvert\eta\rvert < 6.5$	$\xi > 2.4 \cdot 10^{-7}$	$M_X > 3.4$	EPL 101 (2013), 21003

- Shouldn't we try to measure low M_{diff} using very forward shower counters ?
- Shouldn't cosmic ray shower MCs with multi-Pomeron exchange be used for extrapolation ?

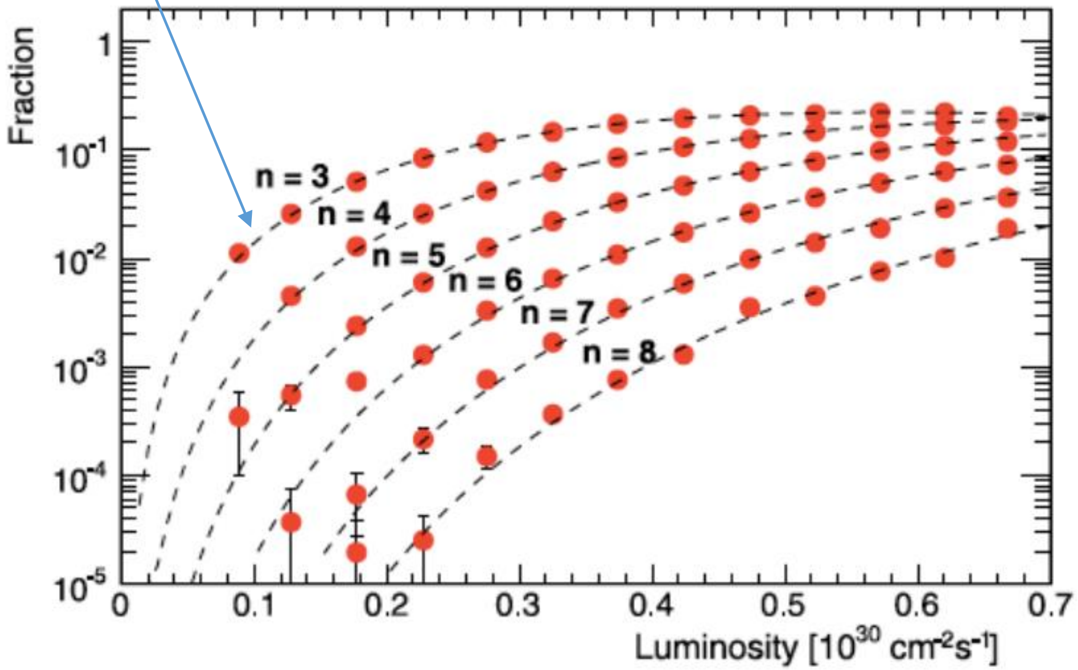
CMS PAS FWD-11-001

σ_{inel} by CMS with the vertex-count method

$$P(n_{pileup}) = \frac{(L_{inst} * \sigma)^{n_{pileup}}}{n_{pileup}!} e^{-(L_{inst} * \sigma)}$$

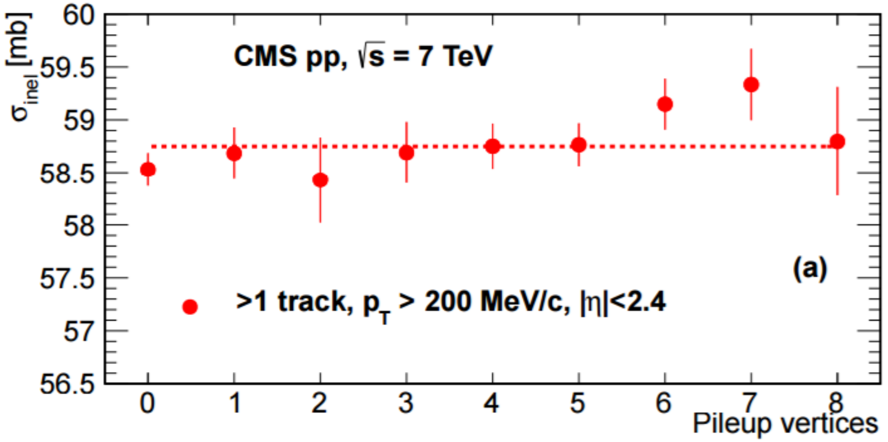
Idea: use the measured probability of having n (0 to 8) inelastic pp interactions each producing a vertex for different luminosities to evaluate σ_{inel} from fit.

Fraction of pp events with n pile up vertices



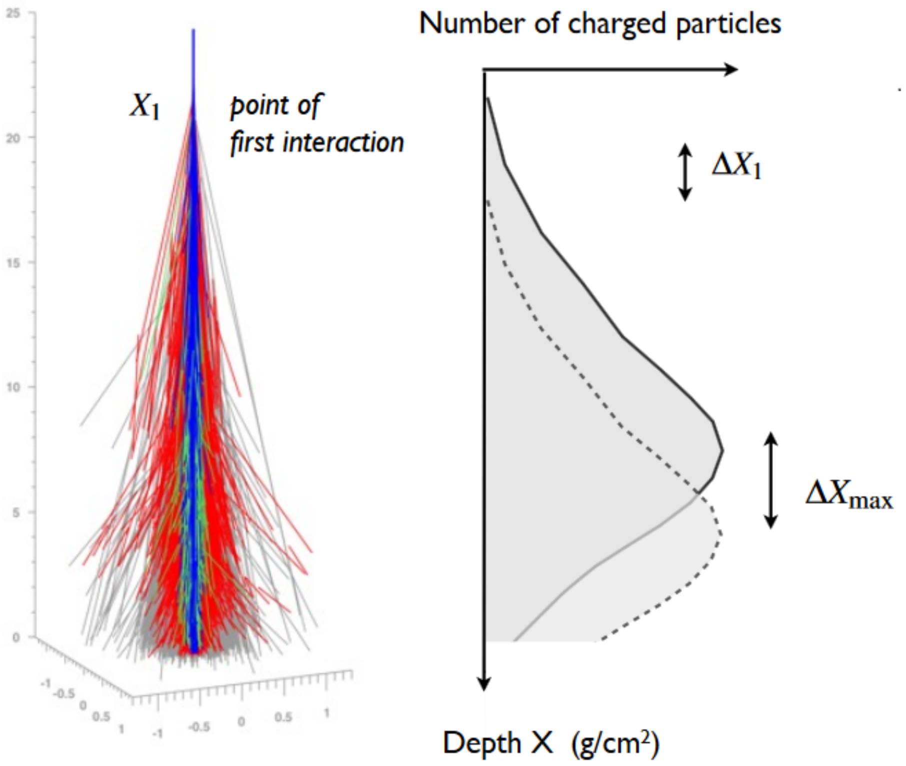
Fit the probability of having 0 to 8 pile-up events as a function of luminosity with a Poisson curve. 9 values of $\sigma_{visible}$ obtained.

- High pt muon trigger (vertex not counted).
- Apart from the L uncertainty, needs vertex reco performance well under control (merging, fake, low multiplicity ε..)



σ_{inel} by AUGER at 57±7 TeV

Phys. Rev. Lett. 109, 062002



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\mathrm{RMS}(X_1) = \lambda_{int}$$

$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

$$\sigma_{pp}^{inel} = [92 \pm 7(\mathrm{stat}) \, ^{+9}_{-11}(\mathrm{sys}) \pm 7(\mathrm{Glauber})] \ \mathrm{mb}$$

- The cross section is obtained by studying the shower longitudinal profile and in particular the X_{MAX} distribution
- First p-A cross section is obtained by analysing only the most deeply penetrating events having larger X_{MAX} (sample enriched in protons). The lack of knowledge of the helium component is the largest source of systematic uncertainty.
- Then pp cross section is extracted from the Glauber model.
- Systematic error due to: primary cosmic-ray mass composition, hadronic interaction models, simulation settings, Glauber theory.

Overview on pp elastic scattering measurements

Disclaimer: great effort by theorists to improve the models based on the LHC data.

arXiv.org > full text search (last 10 years)

Search for (Help | Advanced search)

Pomeron AND LHC | All articles | Go!

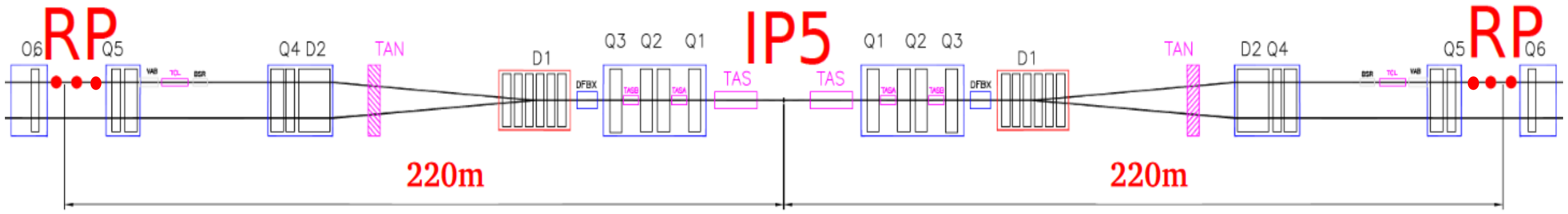
arXiv.org Full Text Search Results

Displaying hits 1 to 10 of 200. Reorder by score.

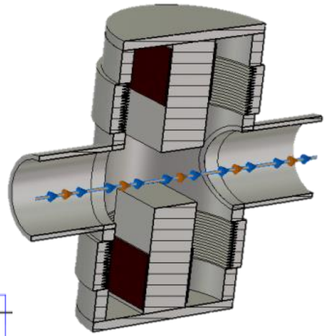
Only few works mentioned here.... sorry if I miss other relevant contributions...

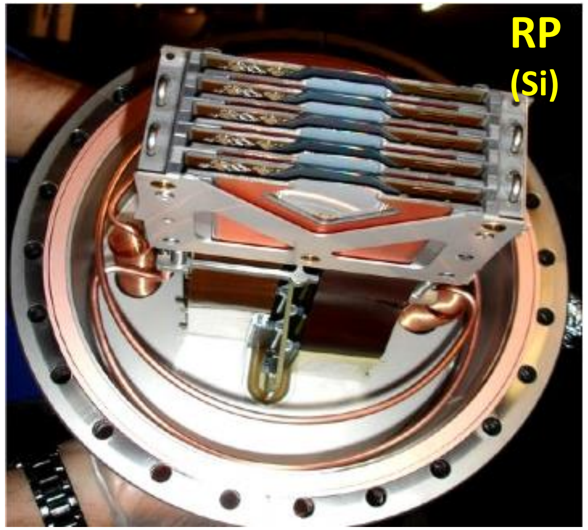
Elastic pp scattering: tagging

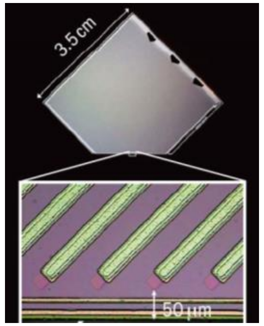
TOTEM: 2 standard vertical RP + 1 rotated (enhance multi-tracking), silicon detectors



Sketch of a (vertical) silicon strip RP

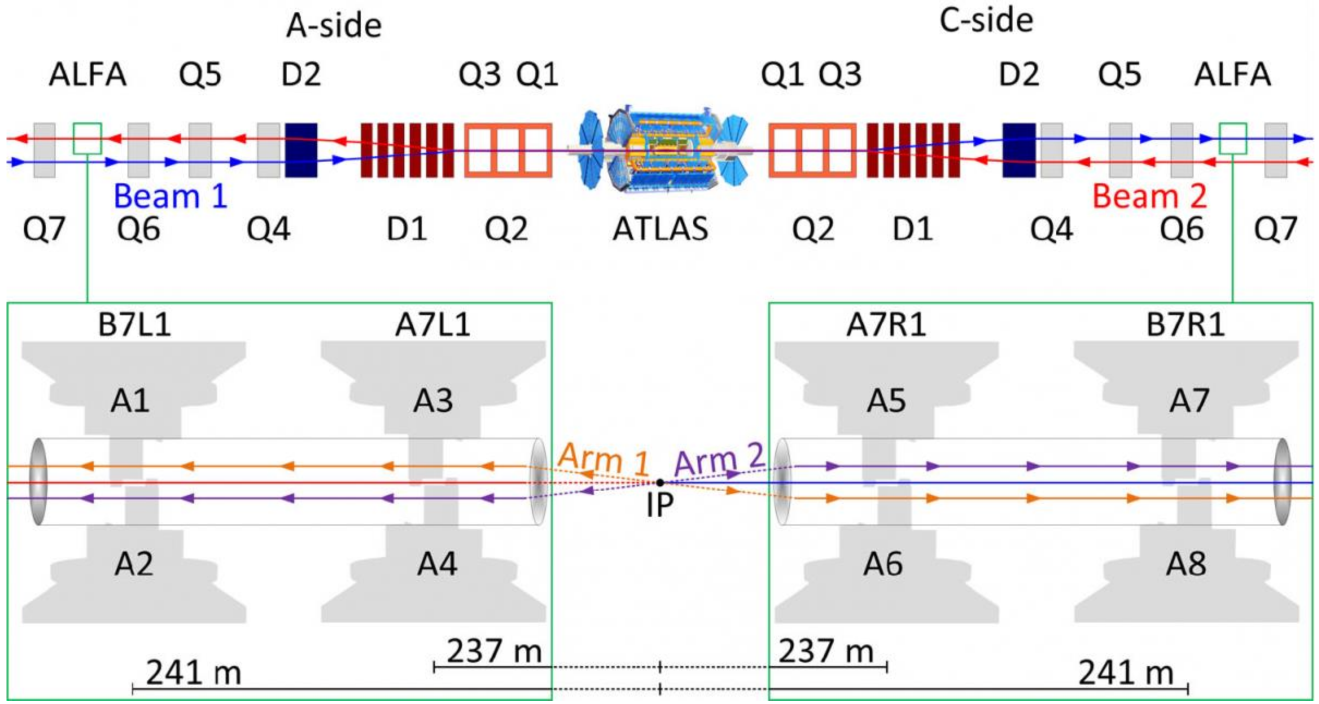


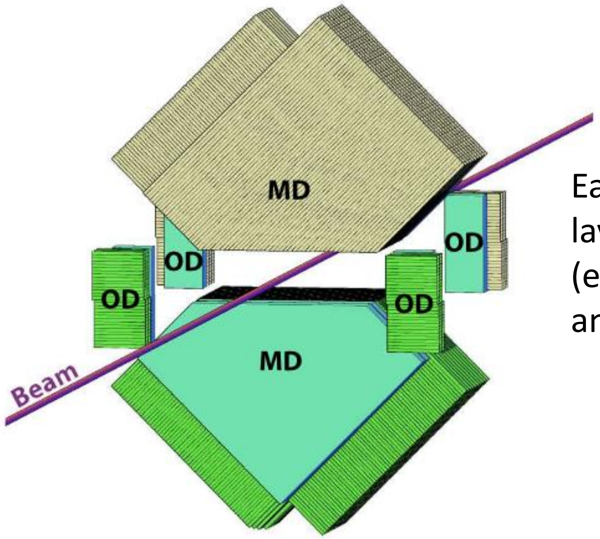




RP are equipped with 10 planes of edgless Si-strip detectors (50 μm ineff. at the edge). 5 planes/projection, 66 μm pitch

ALFA: 2 standard vertical RP / side, scintillating fibers





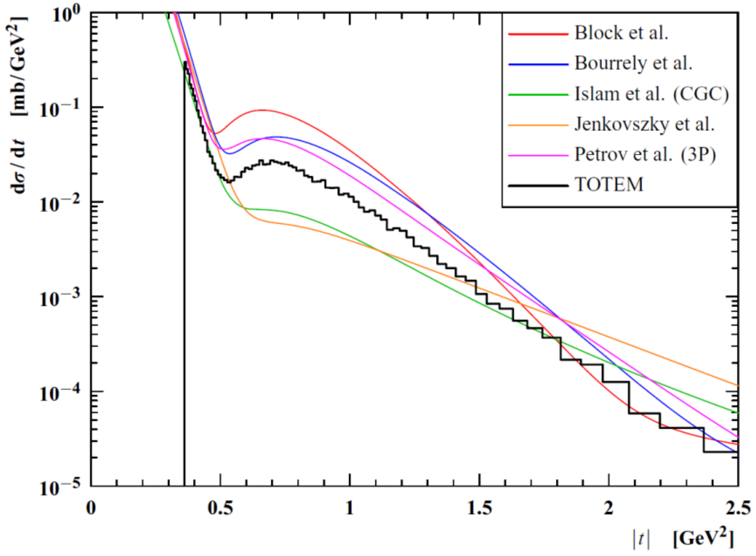
Each station consists of 10 layers of scintillating fibers (each u or v projection, 'MD') and overlap detector 'OD'

Elastic scattering highlights:

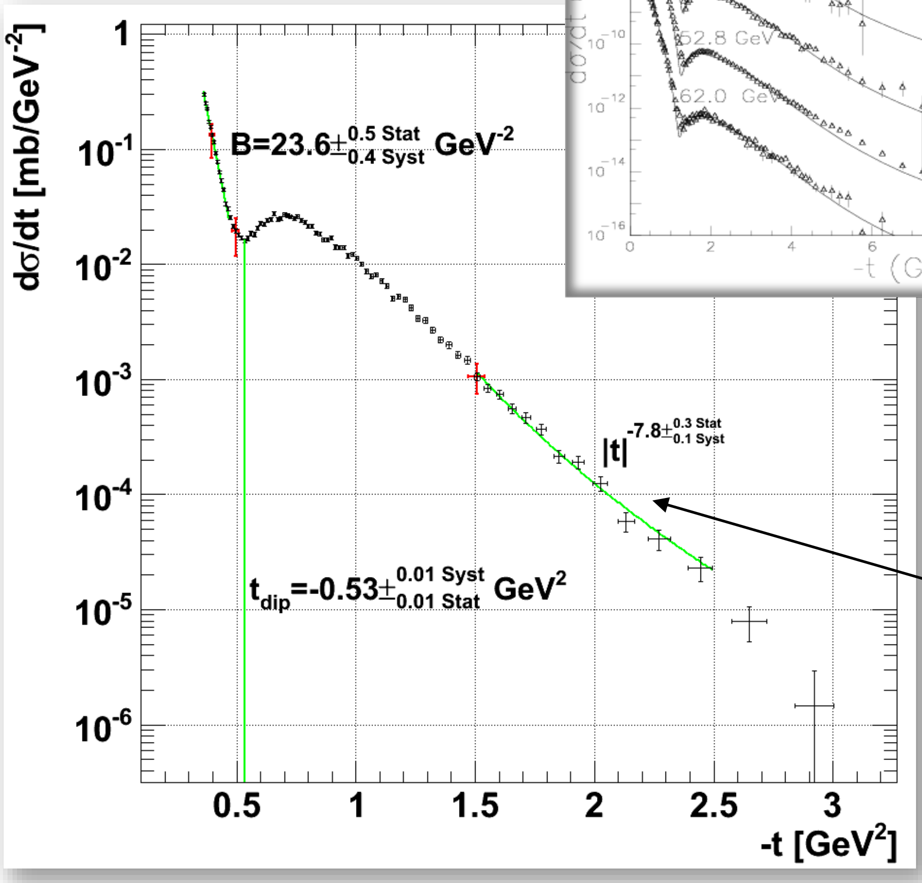
High-t distribution at 7 TeV, high discriminative power and pQCD compatibility.

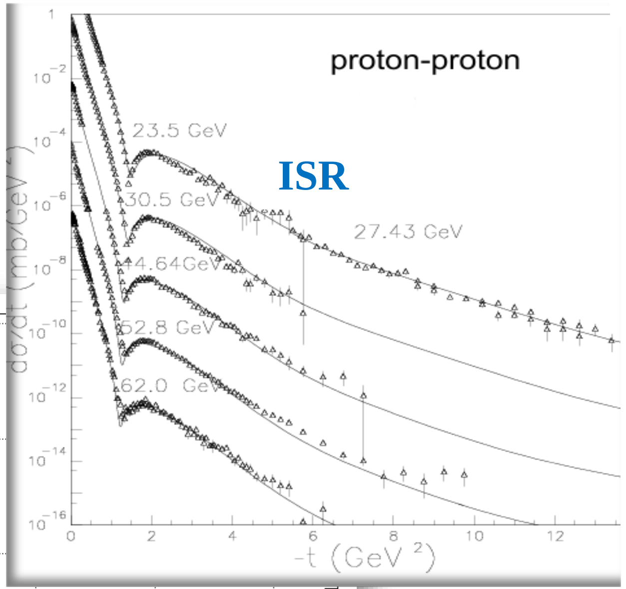
Published in EPL **95** (2011) 41001:

- |t| range spans from 0.36 to 2.5 GeV^2
- Below |t| = 0.47 GeV^2 exponential $e^{-B|t|}$ behavior
- Dip moves to lower |t|, proton becomes "larger"
- 1.5 - 2.5 GeV^2 power low behavior $|t|^{-n}$

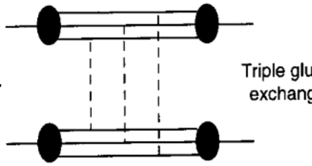


The measured dσ/dt compared with predictions of several models:
No models predicted the value of the differential cross section beyond the first cone!





"Perturbative QCD" behavior



A. Donnachie and P. V. Landshoff, Z. Phys. C 2 (1979) 55.

Elastic scattering highlights:

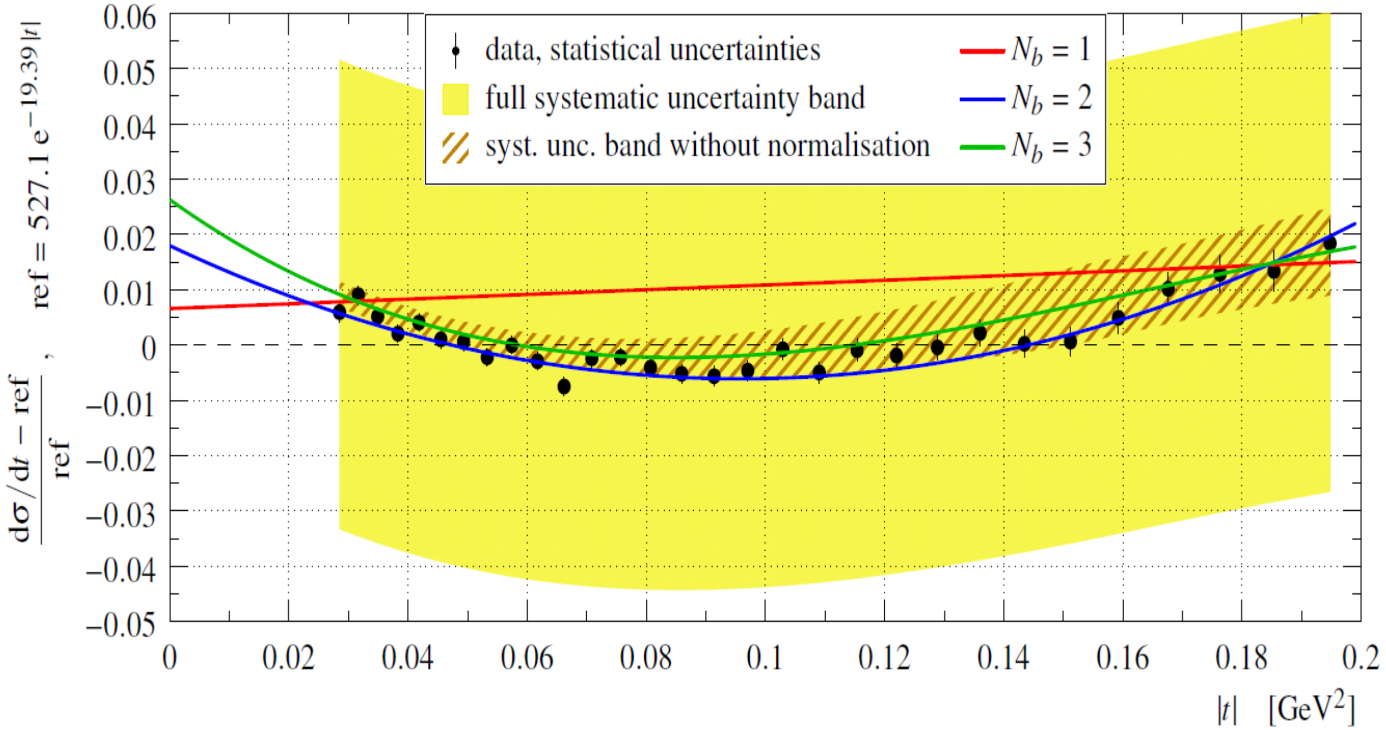
First evidence of non-exponentiality of the hadronic distribution at 8 TeV.

Read more:
- Eur. Phys. J. C76 (2016) 661
- Nucl. Phys. B 899 (2015) 527-546

$\sigma_{tot\ (Nb=1)}$ [mb]	σ_{el} [mb]	σ_{inel} [mb]
101.7 ± 2.9	27.1 ± 1.4	74.7 ± 1.7

N_b	σ_{tot} [mb]
2	101.5 ± 2.1
3	101.9 ± 2.1

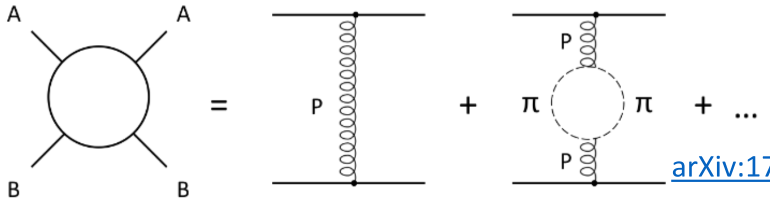
$$|A^N| = a \cdot \exp(b_1 t) \Rightarrow |A^N| = a \cdot \exp(b_1 t + b_2 t^2 + b_3 t^3)$$



➢ ***Rich Phenomenology:***

*According to A.D. Martin, et al.,*J. Phys. G: Nucl. Part. Phys. 42 (2015) 025003
non-exp data are well fitted if all these ingredients are used:

➢ ***Non-linear Pom. trajectory (due to π-loop)***
➢ ***Non-exp Pom.-nucleon coupling***
➢ ***MultiPomeron (2-channel eik. expansion)***

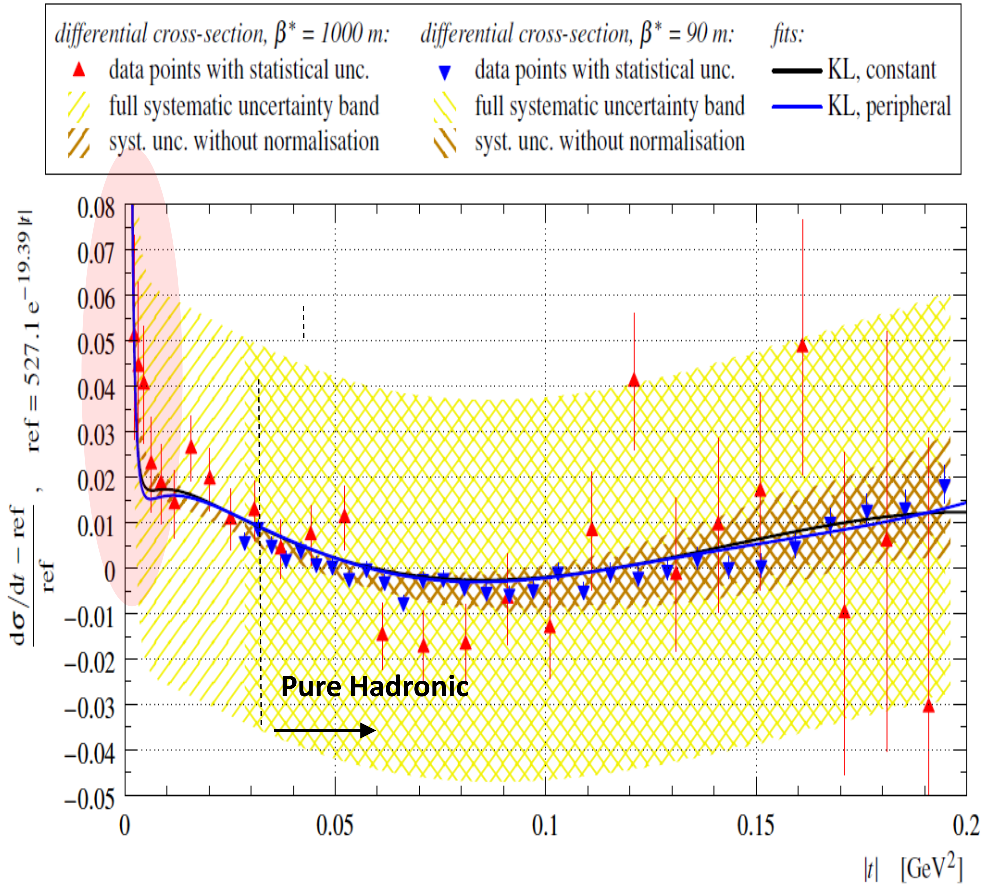


arXiv:1705.04880

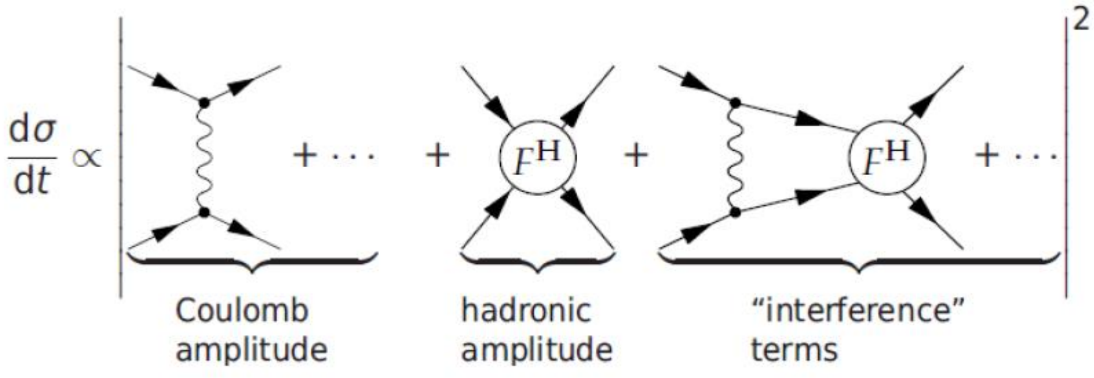
See also: D.A. Fagundes et al., IJMPA 31 (2016) 1645022

Elastic scattering highlights:

Study on Coulomb-Hadronic interference region at 8 TeV



- **At small enough t the pp scattering is also affected by the Coulomb interaction:**



- **Hadronic amplitude and Interference formula are phenomenological!**
  - **We found however that exponential hadronic module is disfavored for different hypothesis of phase and interference formula.**
  - **SWY formula (exponential hadronic and constant phase is ruled out!)**

SWY:

$$\frac{d\sigma^{C+N}}{dt} = \frac{\pi(\hbar c)^2}{sp^2}\left|\frac{\alpha s}{t}\mathcal{F}^2 e^{i\alpha\Phi(t)} + \mathcal{A}^N\right|^2$$

$$\Phi(t) = -\left(\log\frac{b_1|t|}{2} + \gamma\right), \quad \arg\mathcal{A}^N \approx \text{const}$$

Elastic scattering highlights: ρ parameter

- Thanks to the study of the Coulomb-Hadronic interference we can:
  - Quantify and remove the effect of the electromagnetic interaction for a better determination of the hadronic one and its better extrapolation to t=0:

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

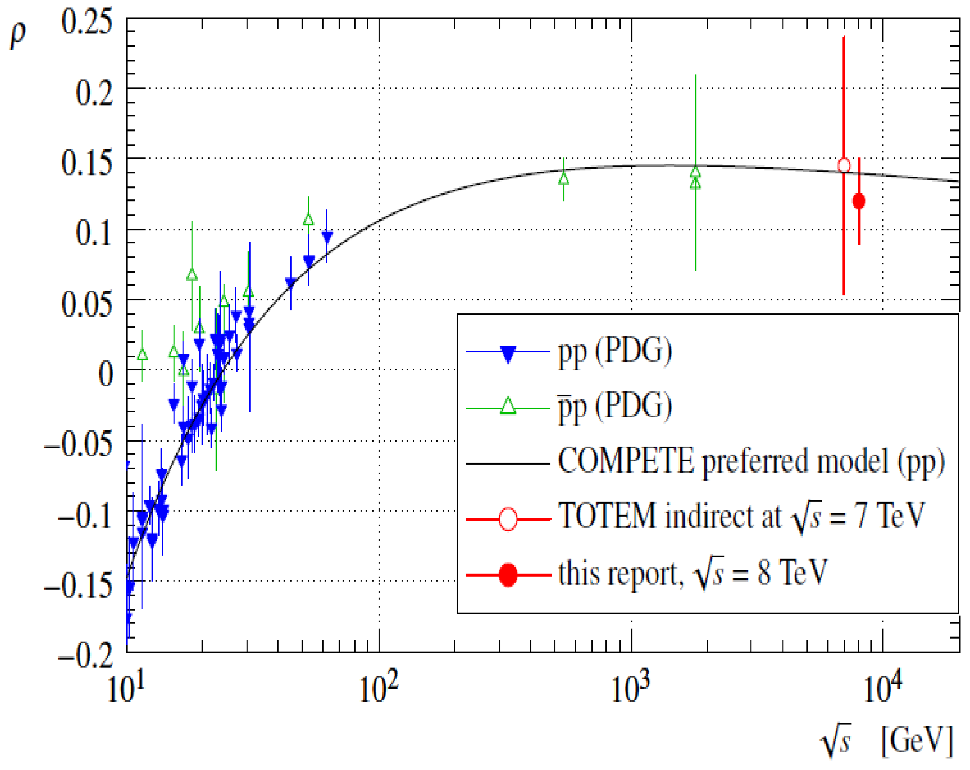
σ_{TOT}=102.9±2.3 mb (centr. phase)

Luminosity-independent determination of σ_{TOT} is consistent with the previously published by TOTEM (PRL 111, 012001) but this time no external parameter has been used

  - Make the first determination of ρ at the LHC :

$$\rho = \frac{\mathrm{Re}\,F^H}{\mathrm{Im}\,F^H}\bigg|_{t=0} = 0.12 \pm 0.03$$

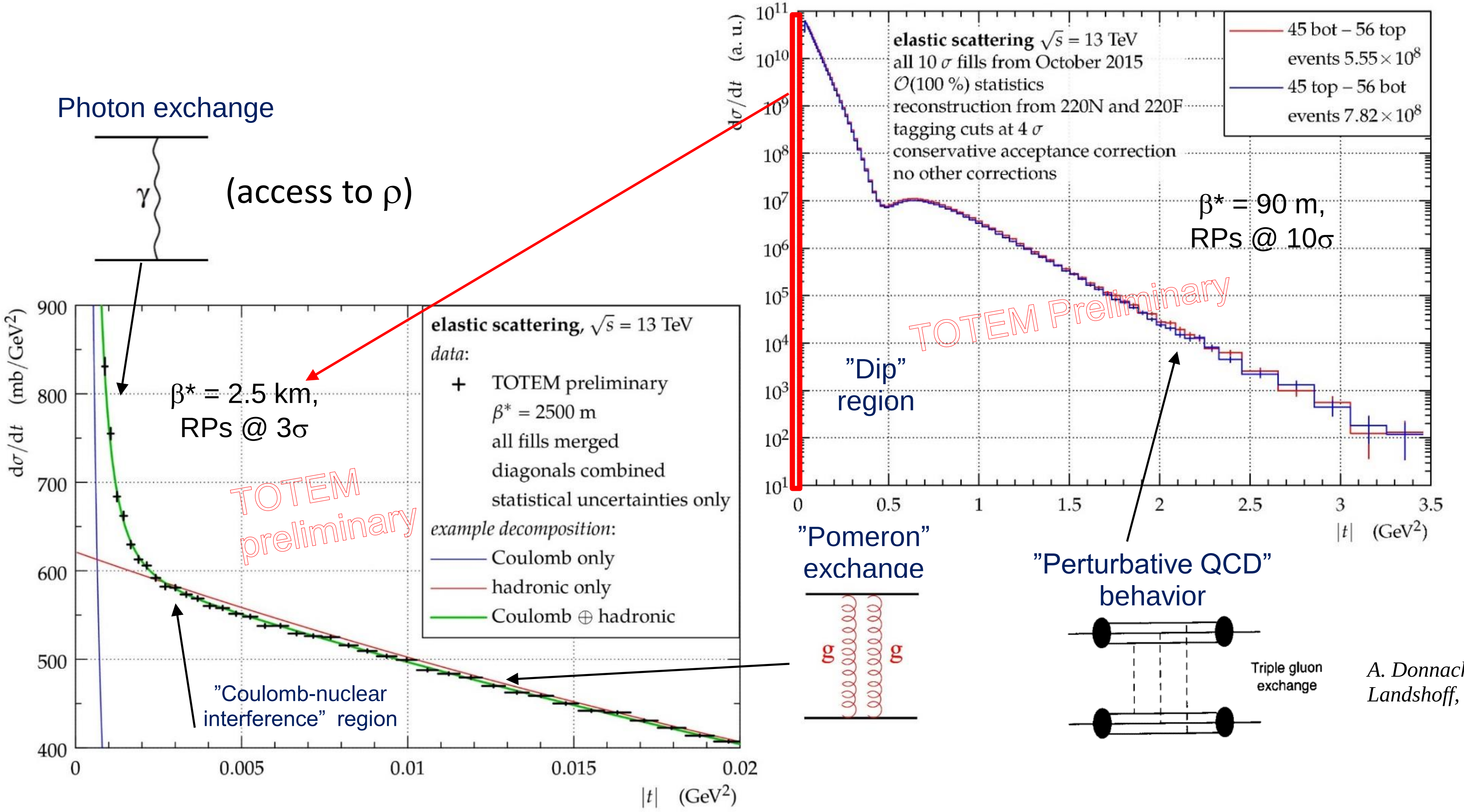
[Eur. Phys. J. C76 (2016) 661]



- *The precise knowledge of this parameter is needed by theory: discovery of a 3-gluon ($J^{PC}=1^{--}$) state as mediator contributing to the elastic interaction: ρ measured at LHC can be sensitive to the Odderon Eur.Phys.J.C49:581-592, 2007 (together with the pp-pp̄ difference in the dip region)*
- *Run-2 data will be crucial to reduce the experimental error.*

Elastic scattering highlights: results at 13 TeV

Analyses well advanced with β*=2.5 km and β*=90m.

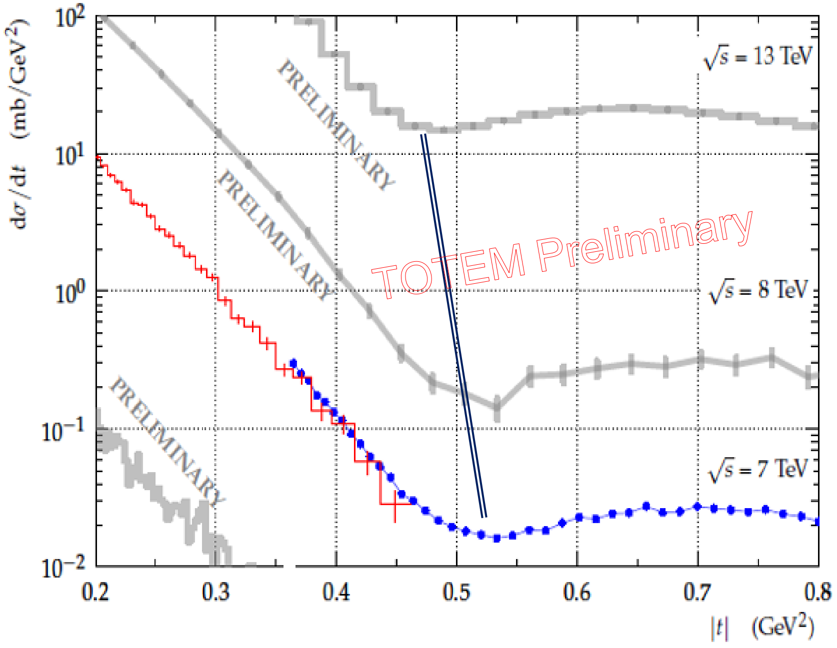


A. Donnachie and P. V. Landshoff, Z. Phys. C 2 (1979) 55.

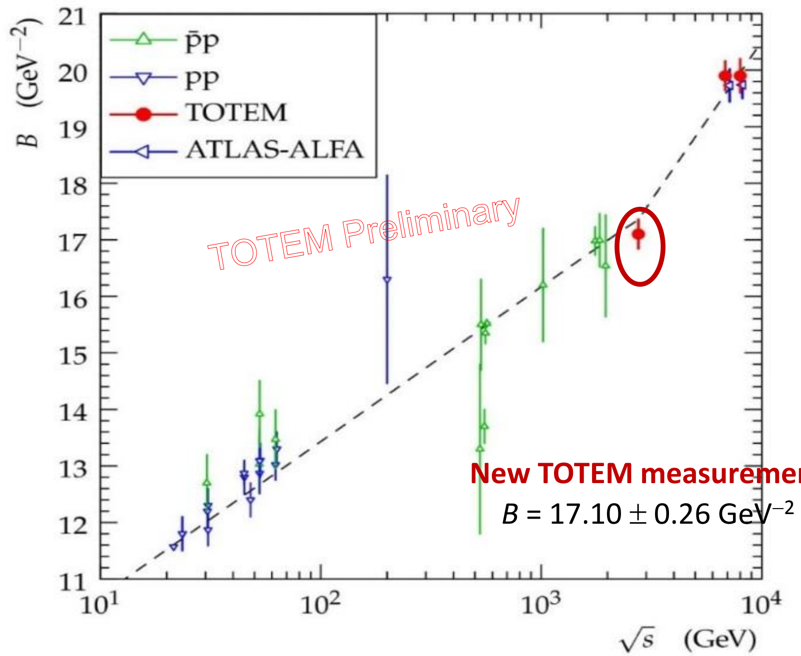
Elastic scattering highlights: results at 13 TeV

Non exponentiality of the elastic scattering t-distribution and energy dependence

|t|-value of dip position decreases with increasing $\sqrt{s}$



Diffractive slope parameter $B = \frac{d}{dt} ln(\frac{d\sigma}{dt}|_{t=0})$ increase with $\sqrt{s}$



New TOTEM measurement @ √s = 2.76 TeV:
$B = 17.10 \pm 0.26$ GeV^{-2} ($d\sigma_{el}/dt \propto e^{-B|t|}$)

B ∝ ln√s → ln²√s +.. @ LHC? Interpretation?

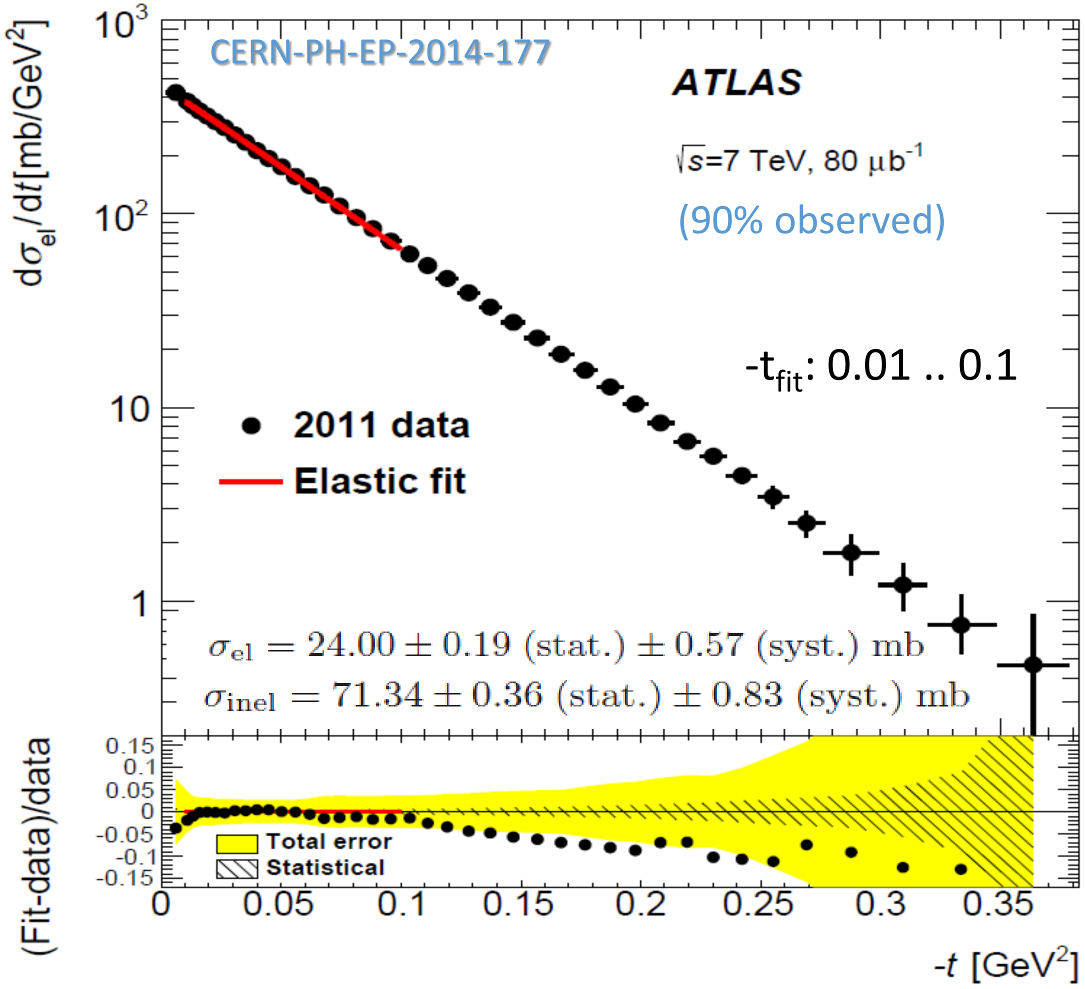
(because of) the TOTEM measurement it is necessary the introduction of terms accounting also for higher order Regge diagram (cuts), multipomeron
PHYSICAL REVIEW D 85, 094024 (2012):

$$B_{el} = B_0 + b_1 \ln(s/s_0) + b_2 \ln^2(s/s_0).$$

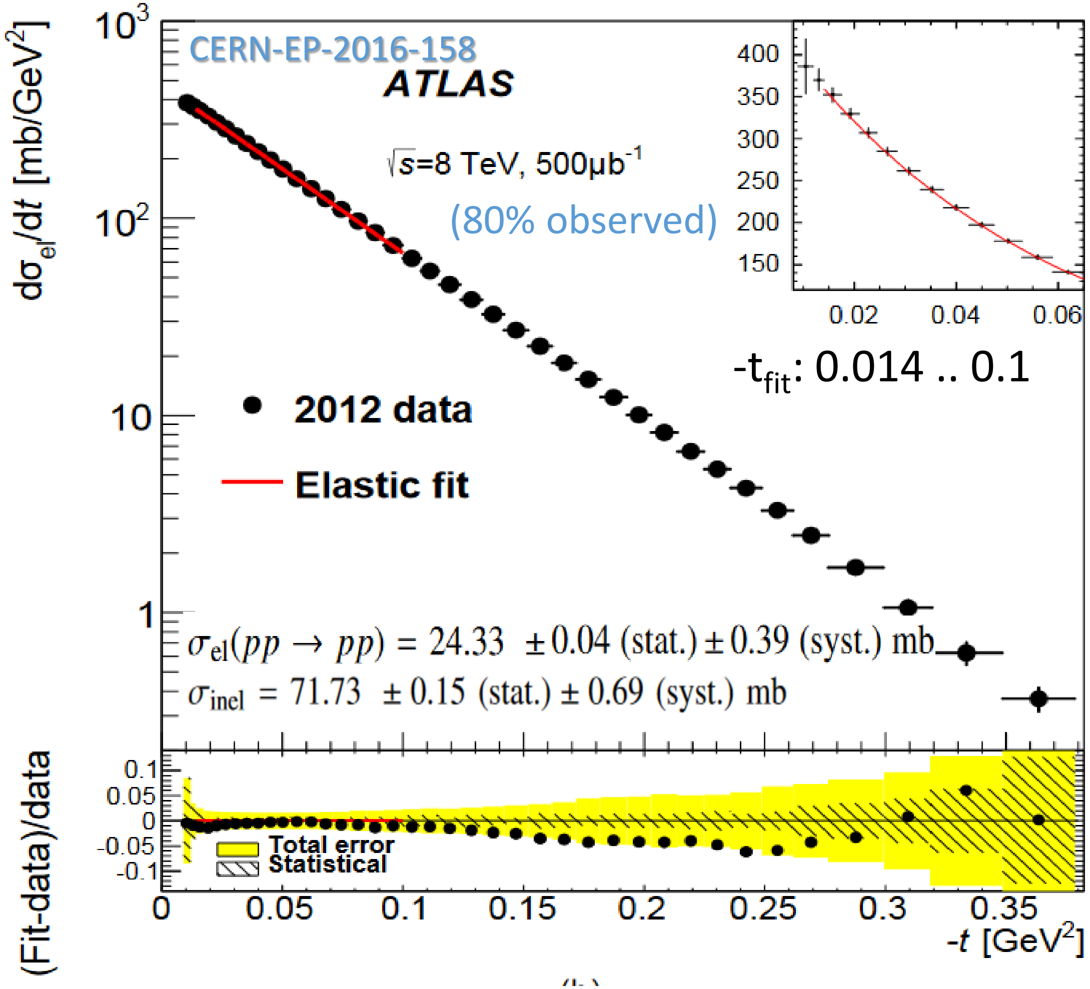
Larger impact from contribution of multi-Pomeron (soft+hard) single pole exchanges:
A. Donnachie, P.V. Landshoff arXiv1112.2485, PRD 85 (2012) 094024

Elastic scattering highlights: results by ALFA (7 and 8 TeV)

Pure exponential, Lumi dependent: $$\frac{d\sigma_{el}}{dt} = \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} \exp(-B|t|)$$ $$\sigma^2_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{d\sigma_{el}}{dt}\right|_{t\to 0}$$



$$\sigma_{tot}(pp \to X) = 95.35 \pm 0.38\ (\text{stat.}) \pm 1.25\ (\text{exp.}) \pm 0.37\ (\text{extr.})\ \text{mb}$$



$$\sigma_{tot} = 96.07 \pm 0.18\ (\text{stat.}) \pm 0.85\ (\text{exp.}) \pm 0.31\ (\text{extr.})\ \text{mb}\,,$$
$$B = 19.74 \pm 0.05\ (\text{stat.}) \pm 0.16\ (\text{exp.}) \pm 0.15\ (\text{extr.})\ \text{GeV}^{-2}$$

SUMMARY of Total, elastic and inelastic cross section at the LHC

σ_{tot}, σ_{inel}, σ_{el} vs $\sqrt{s}$

New TOTEM @ $\sqrt{s}$ = 2.76 TeV
(ρ = 0.145):

σ_{tot} = 84.7 ± 3.3 mb

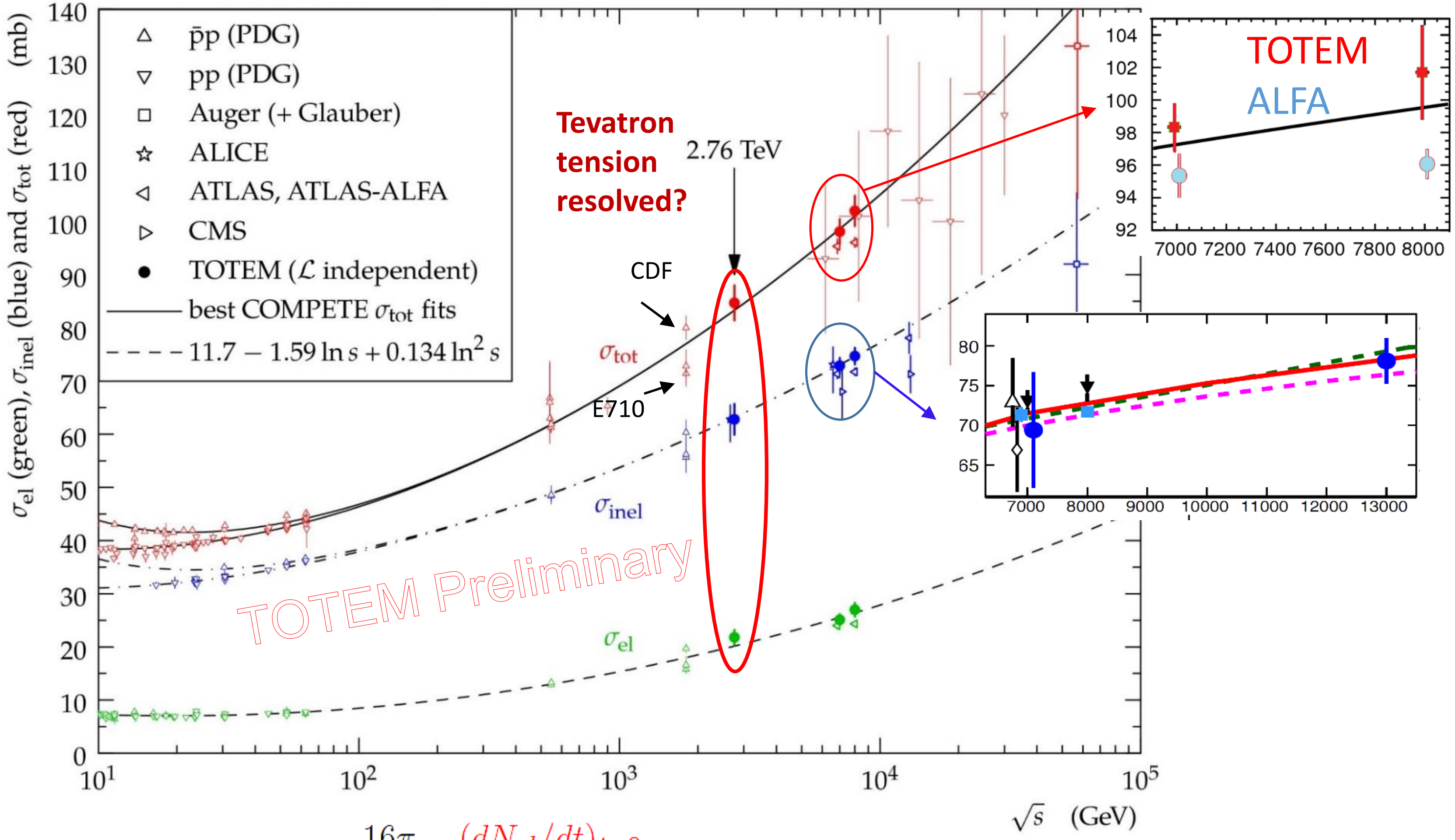
σ_{inel} = 62.8 ± 2.9 mb

σ_{el} = 21.8 ± 1.4 mb

ALICE @ $\sqrt{s}$ = 2.76 TeV:

$\sigma_{inel} = 62.8^{+2.4}_{-4.0} \pm 1.2$ mb

ALICE coll., EPJC 73 (2013) 2456

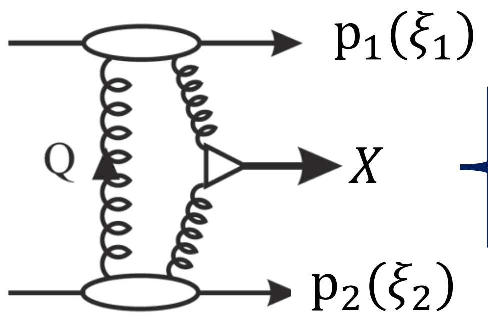


(TOTEM reported with the luminosity independent method: $\sigma_{tot} = \frac{16\pi}{(1+\rho^2)} \frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$)

... TOTEM 13 TeV analysis well advanced, results expected soon

Central diffraction: opportunities

Central diffraction: opportunities

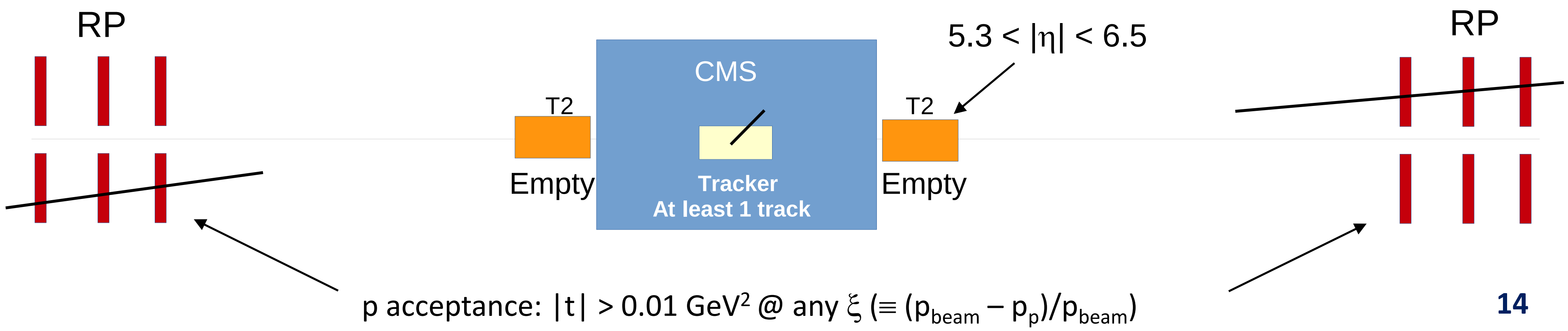


$$\begin{cases} M_X{}^2 = \xi_1\xi_2 s \\ y_X = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right) \end{cases}$$

selection rules for system X:
$J^{PC} = 0^{++}, 2^{++}, \ldots$ (PP, gg)
$J^{PC} = 1^{--}$ (γP)

At $x \sim 10^{-3} - 10^{-4}$ gluon overwhelms $\Rightarrow$ CEP@LHC ideal for glueball production since @ LHC: CEP with $M_X \sim 1 - 4$ GeV produced very purely from gg

Low mass CEP trigger: double arm RP & T2 Veto & at least 1 track in CMS tracker, $\mathcal{L} = 0.4\ \mathrm{pb}^{-1}$

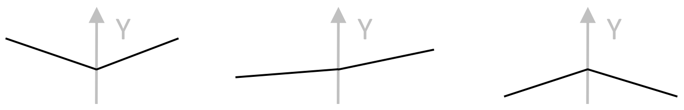


Lattice QCD: $0^{++}(2^{++})$ glueball candidates: f_0 (f_2) resonances in 1.3 -1.8 GeV(> 2 GeV) mass range.

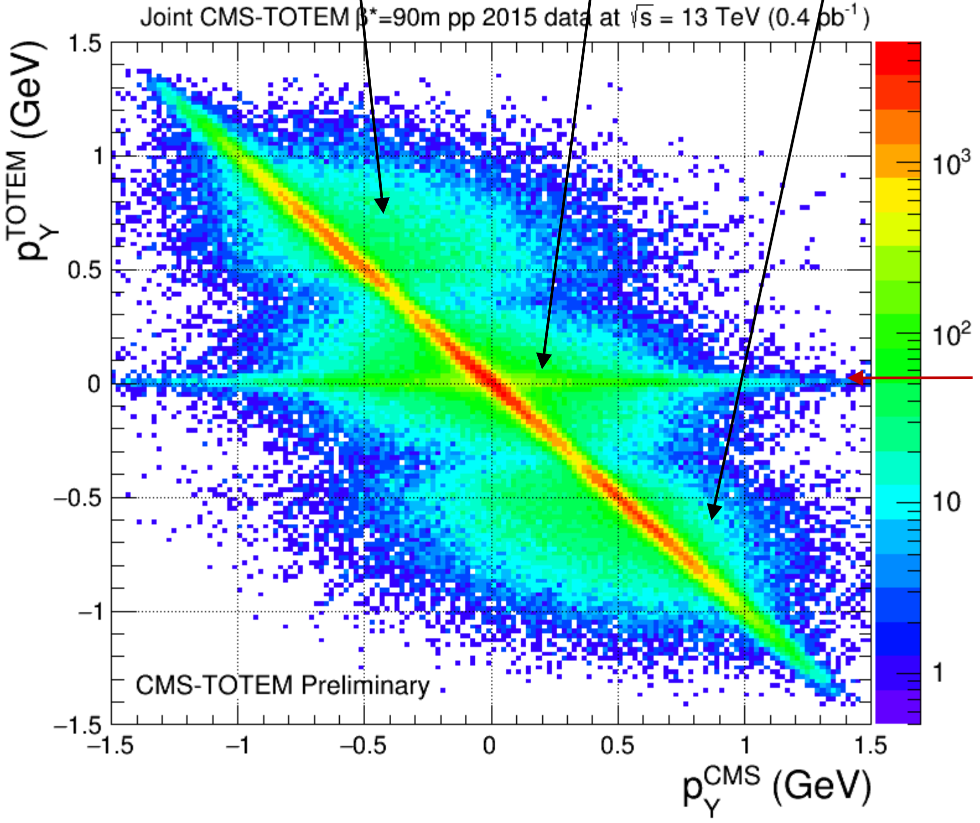
→ This is a region full of hadronic resonances, extreme care is needed in the interpretation of the data (quarkonium mixing). Competitive channel with respect to $J/\psi \rightarrow \gamma f_0$ and B (Eur. Phys. J. A (2013) 49:58)?

Performance plots pp → p + $\pi^+\pi^-$ + p candidates

Different proton configurations

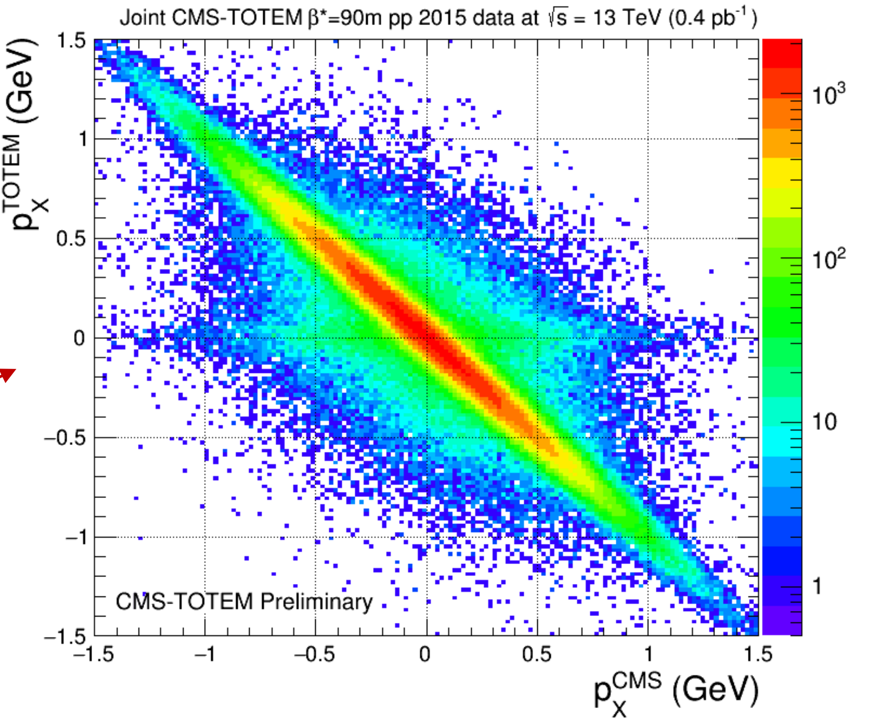


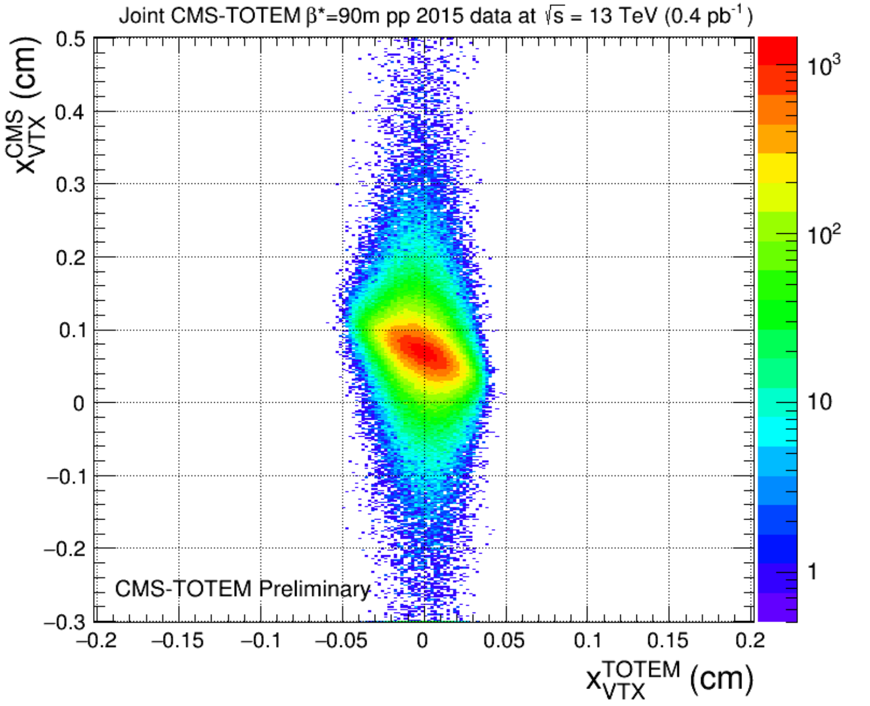
top-top   diagonal   bottom-bottom



Transverse momentum sum of proton vs transverse momentum sum of charged particles in tracker

elastic pileup ($p_{x,y} \sim 0$)





We proved on the data that the exclusivity condition obtained from the proton is necessary to enhance the resonant spectrum (despite the T2 veto)
→ CMS-TOTEM data are unique. Critical points: charged channels only, dE/dx.

Conclusions and perspectives (σ_{el})

- σ_{el}: high precision TOTEM/ALFA measurements:
  - ➢ constraint on the rising of the total cross section at the LHC.
    - σ_{tot} should include also $\ln^2 s$ terms, to be confirmed at 13 TeV, single pole pomeron not enough
    - fast increase of B(s)
  - ➢ Impact of non exponentiality on the models (virtual pion loop, multiple pomeron, ...)? Is there other observable as a cross check to reduce the number of possible interpretations?
  - ➢ TOTEM precision measurement of ρ and the Odderon: do we agree on the LHC discovery potential of the Odderon (model independence)?
  - ➢ Large impact on the models due to the high t behaviour t^{-8}? Most of the pre-LHC models ruled out. Can theorist learn something fundamental on the model which failed or it is just a wrong tuning of the parameters?

Conclusions and perspectives (σ_{inel})

- σ_{inel}: many LHC measurements, precious information already after Run1.

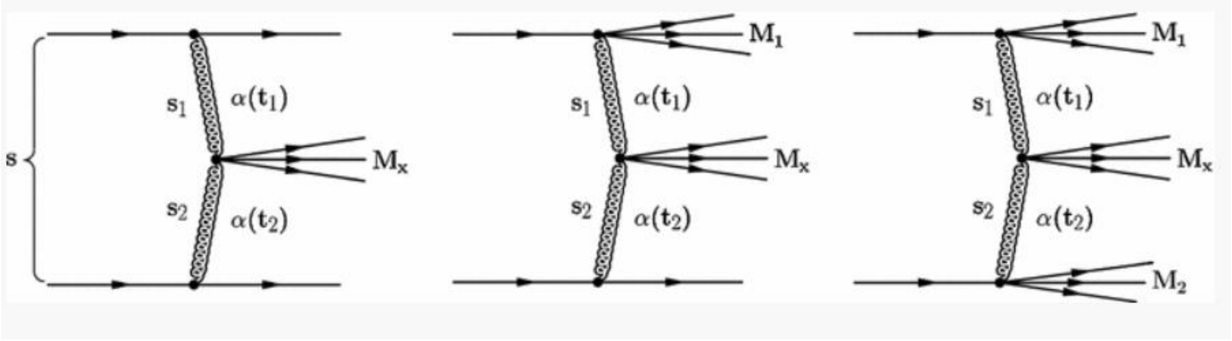
  - Clear pattern of extrapolation dependence according to the MC: multipomeron-reggeon vs averaged. Possibility to uniform the results and shrink the LHC predictions?

  - Still LHC can give 'for free' other unique opportunities to exploit. Example in IP5: inclusive trigger (FSC,ZDC+TOTEM/HF) will dramaticaly reduce the uncertanty in the classification of the interactions (analysis proved but unpublished) and on the rapidity gap probability.

  - In particular, we still have to measure the N*-> pX resonances which can be a serious background for missing mass studies with proton tagging (RP+ FSC or ZDC).

... And in general:

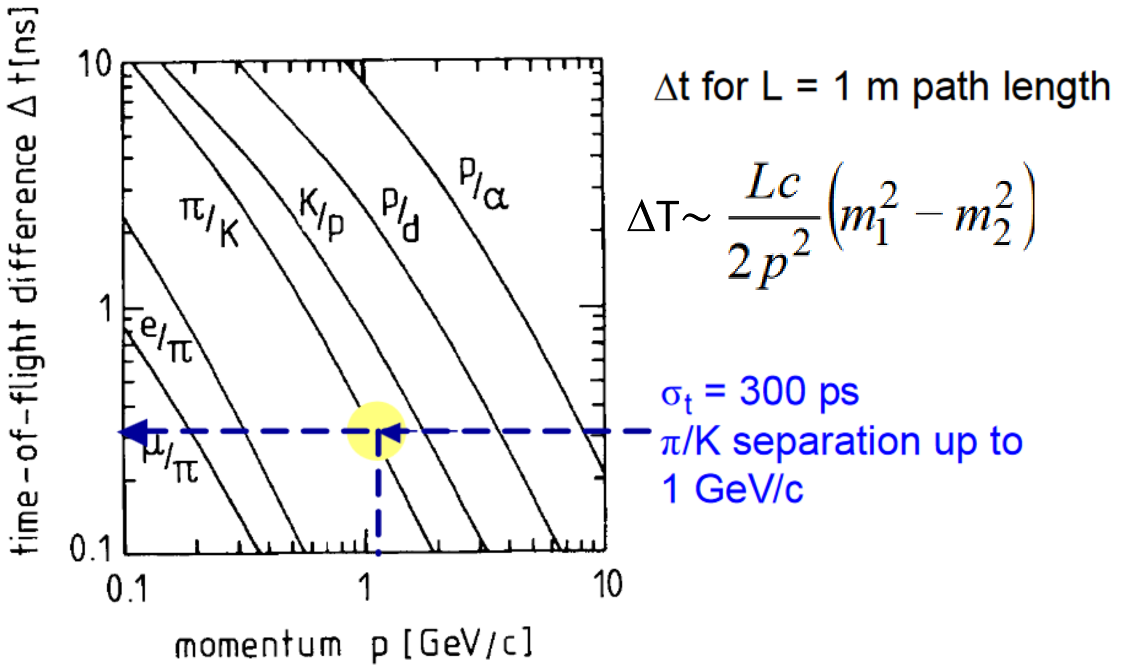
Fiore, R., Jenkovszky, L. & Schicker, R. Eur. Phys. J. C (2016) 76: 38



Conclusions and perspectives (3)

- **CEP:** perfect gluon-enriched environment to study resonance production at low mass (exclusivity). Effort done to improve the algorithms for this soft physics studies. We are working to understand if the final states we measure are sensitive to probe eventual glueaball candidates. Problems: limited dE/dx, neutral channel lost.

  - Future runs could profit from timing detectors to measure CEP at $\mu \sim 1$.
  - Moreover in the (unfortunately far) future the probable MIP timing capability of central CMS detector could also improve dE/dx (time 0 would be provided by the protons!).



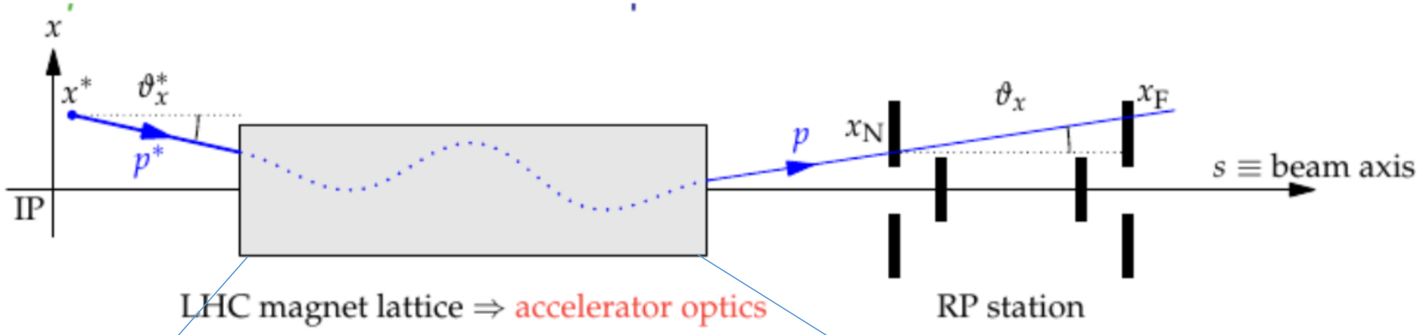
THANK YOU

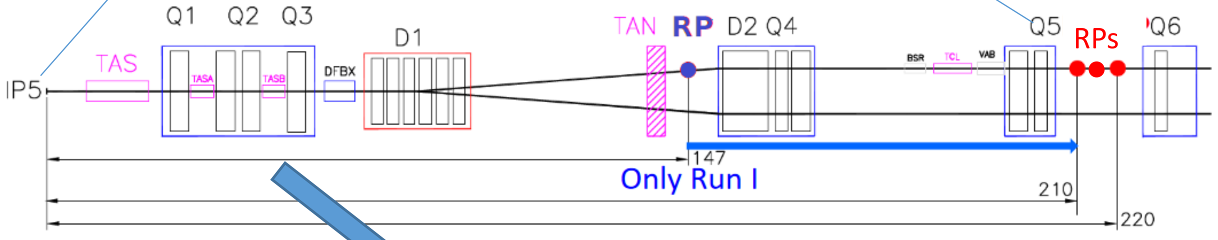
Total, elastic and inelastic pp scattering

(a selection of results and methods)

Mirko Berretti
Helsinki University and Helsinki Institute of Physics

Proton reconstruction at LHC: general aspects





Machine imperfections alter the optics:

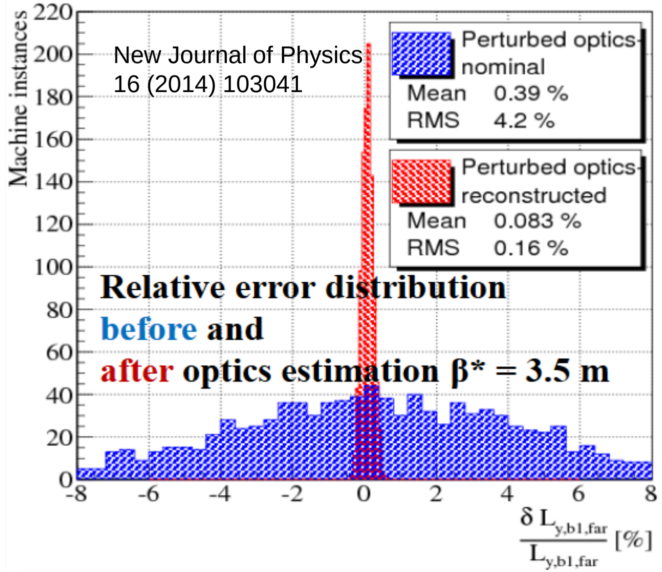
- **Strength conversion error, σ(B)/B ≈ 10^{-3}**
- **Beam momentum offset, σ(p)/p ≈ 10^{-3}**
- Magnet rotations, σ(ϕ) ≈ 1 mrad
- Magnetic field harmonics, σ(B)/B ≈ 10^{-4}
- Power converter errors, σ(I)/I ≈ 10^{-4}
- Magnet positions Δx, Δy ≈ 100 μm

$$t(v_x, L_x, L_y, ..., p) = -p^2 \cdot (\Theta_x^{*2} + \Theta_y^{*2})$$

- Proton kinematics at the RP is determined by optics and proton kinenematics at IP.
- Need to solve the following equation (matrix element are x dependent):

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \xi \end{pmatrix}_{RP} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ v'_x & L'_x & m_{23} & m_{24} & D'_x \\ m_{31} & m_{32} & v_y & L_y & D_y \\ m_{41} & m_{42} & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \xi^* \end{pmatrix} \text{IP}$$

- Precise measurements needs the control (determination) of the optics parameter on the data: *Novel method developed by TOTEM (based on kinematics at RP for elastic candidates)*



Total pp cross-section: methods & results

Excellent agreement between 7 TeV σ measurements:

$$\sigma_{tot}^2 = \frac{16\pi}{(1+\rho^2)}\frac{1}{\mathcal{L}}\left(\frac{dN_{el}}{dt}\right)_{t=0}$$

based on elastic scattering ⇒ low mass diffraction independent

σ_{total} = 98.3 mb ± 2.0 mb
EPL 96 (2011) 21002

σ_{total} = 98.6 mb ± 2.3 mb
EPL 101 (2013) 21002

testing validity of optical theorem at ~3.5 % level

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$$

optical theorem & ρ independent

σ_{total} = 99.1 mb ± 4.3 mb
EPL 101 (2013) 21004

$$\sigma_{tot} = \frac{16\pi}{(1+\rho^2)}\frac{(dN_{el}/dt)_{t=0}}{(N_{el}+N_{inel})}$$

$\mathcal{L}$ independent

σ_{total} = 98.1 mb ± 2.4 mb
EPL 101 (2013) 21004

7 TeV

σ_{total} = 101.7 mb ± 2.9 mb
PRL 111(2013) 012001

8 TeV

compatible

Combining 8 TeV β* = 90 m & 1 km data: Improved extrapolation of hadronic amplitude to t = 0 (Coulomb interference measured) & simultaneous ρ determination

σ_{total} = 102.9 mb ± 2.3 mb (central hadronic phase)

σ_{total} = 103.0 mb ± 2.3 mb (peripheral hadronic phase)

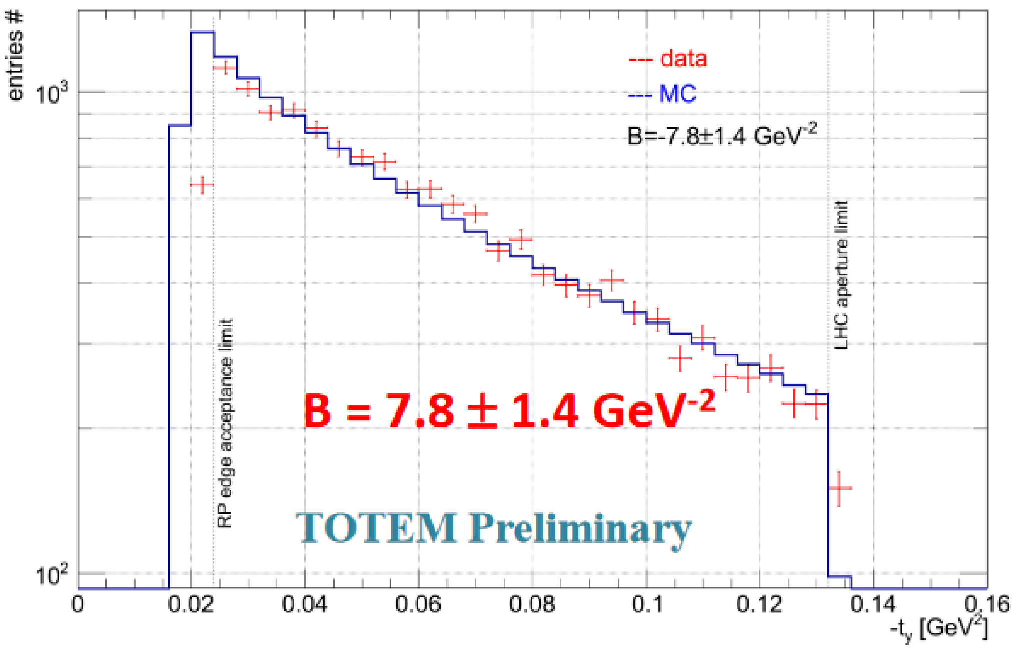
CERN-PH-EP-2015-235, accepted by EPJC

8 TeV

Central Diffraction TOTEM alone

Available data $\sqrt{s}$ = 7 TeV and β^* = 90 m optics:

- Trigger selection: 2 × RP
- Nearly complete ξ - acceptance
- Background: elastic, beam-halo + inelastic
  - Elastic: anti-elastic cuts, e.g. forbidden topologies (top-top, bottom-bottom)
  - Beam-halo: $|y| > 11 \times \sigma_{beam}$ → halo is negligible



σ_{CD} estimation:

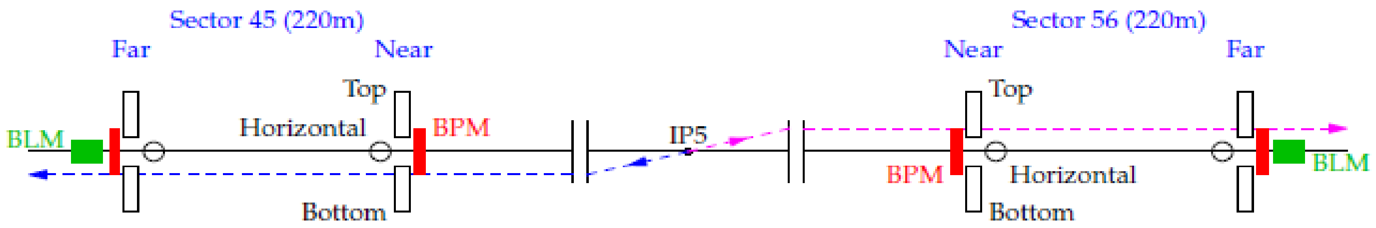
$$\frac{d^2\sigma_{CD}}{dt_1 dt_2} = C(\Delta\varphi_{1,2}) e^{-Bt_1} e^{-Bt_2}$$

$$\sigma_{CD} = \int_{-\infty}^{0} dt_1 \int_{-\infty}^{0} dt_2 \frac{d^2\sigma_{CD}}{dt_1 dt_2} \approx 1\,\text{mb}$$

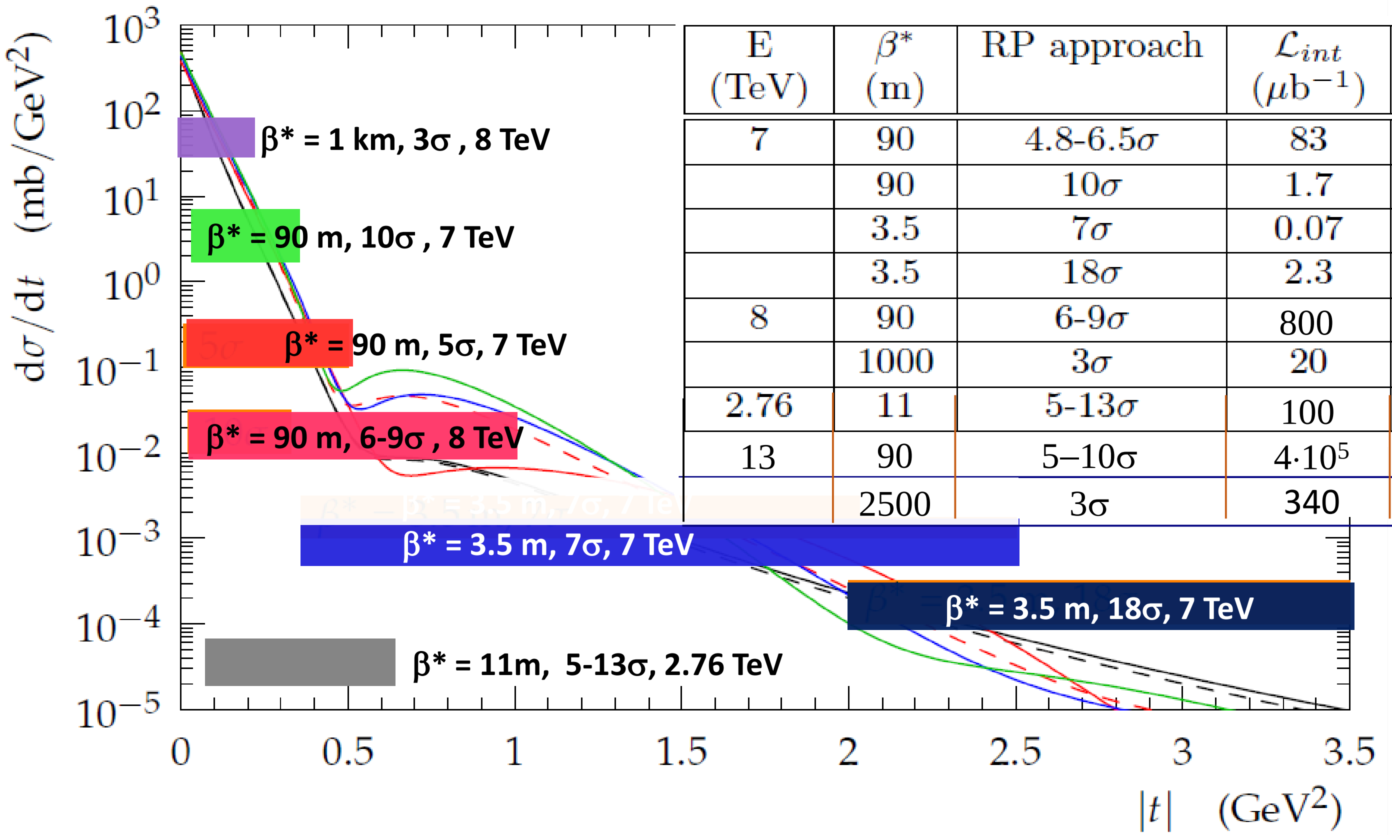
Single arm CD event rate in RP

integrated ξ, acceptance corrected

Elastic pp scattering: LHC data sets



TOTEM data sets at different conditions to measure over as wide |t|-range as possible:



E (TeV)	β^* (m)	RP approach	$\mathcal{L}_{int}$ (μb^{-1})	t range (GeV^2)	Elastic events	
7	90	4.8-6.5σ	83	$7 \cdot 10^{-3}$ - 0.5	1M	√
	90	10σ	1.7	0.02 - 0.4	14k	√
	3.5	7σ	0.07	0.36 - 3	66k	√
	3.5	18σ	2.3	2 - 3.5	10k	
8	90	6-9σ	800	0.01 - 1	7M	√
	1000	3σ	20	$6 \cdot 10^{-4}$ - 0.2	0.4M	√
2.76	11	5-13σ	100	0.05-0.6	45k	O
13	90	5–10σ	$4 \cdot 10^5$	0.01 – 3.5	~ 1400M	O
	2500	3σ	340	8 10^{-4} - 1.0	7.4 M	O

√ **Data published**
O Analysis finished
O Analysis on-going

ATLAS-ALFA data sets:
similar as TOTEM for the β*=90m (7,8,13 TeV), β*= 1Km (8 TeV) and β*= 2.5 km (13 TeV) runs.

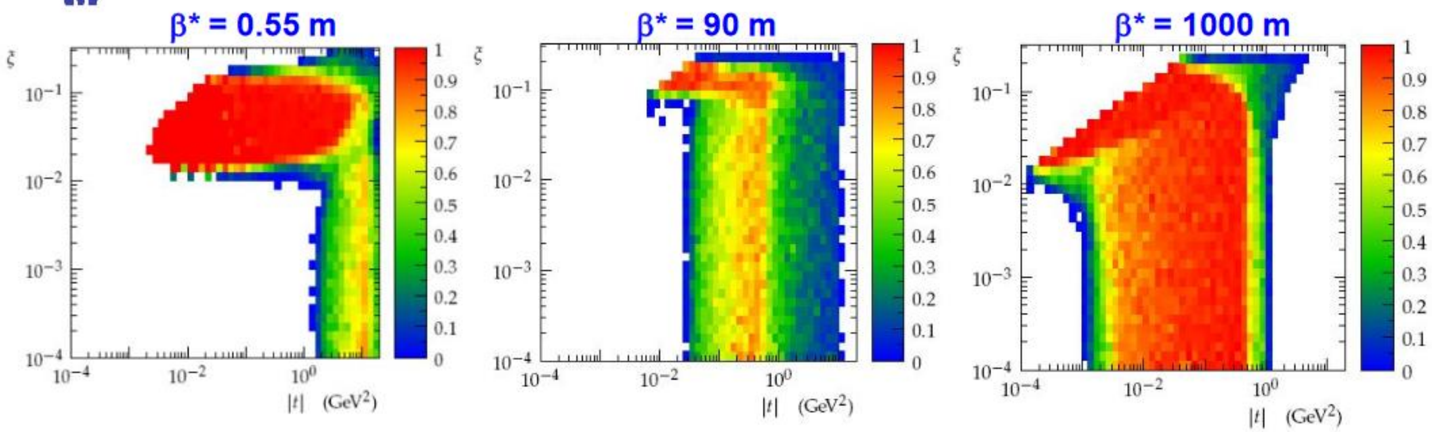
Table 1.3: Summary of the machine parameters for the different running conditions.

Conditions	β^* [m]	N [10^{11} p]	N_b	μ (pileup)	L [$cm^{-2}s^{-1}$]	L_{int} [24h]	Physics
LOW	≥ 1000 19	0.7 0.1	2 40	0.004 0.01	10^{27} $5 \cdot 10^{28}$	0.1/nb 4.8/nb	σ_{tot}; Coulumb region Lhcf Run; Multiplicity; Energy flow; Inelastic cross section
MEDIUM	19	0.7	40	0.4	$2 \cdot 10^{30}$	0.17/pb	High cross section diffraction
	90	0.7	156–700	0.1	10^{30}–10^{31}	0.2–1/pb	σ_{tot}; low mass diffraction; Hard diffraction
	90	1.5	700	0.6	$5 \cdot 10^{31}$	4.4/pb	Glueball searches; CEP
HIGH	0.5 0.5	1.15 1.15	2800 2800	30	10^{34}	1/fb	LHCb programme Exclusive dijets, anomalous coupling

TOTEM

LHC Optics & proton acceptance

$t \approx -p^2\,\Theta^{*\,2}$: four-momentum transfer squared; $\xi = \Delta p/p$: fractional momentum loss



$> 10^{33}\ cm^{-2}\ s^{-1}$ ← $\mathcal{L} \propto \frac{1}{\beta^*}$ → $\sim 10^{27}\ cm^{-2}\ s^{-1}$

Diffraction:
$\xi > \sim 0.01$, low cross-section processes (hard diffraction)
Elastic scattering: large |t|

Diffraction: all ξ if $|t| > \sim 10^{-2}$ GeV^2, soft & semi-hard diffraction
Elastic scattering: low to mid |t|
Total Cross-Section

Elastic scattering: very low |t|, Coulomb-Nuclear Interference
Total Cross-Section

8

Auger determination of the "muon problem"

PRL117,192001 (2016)

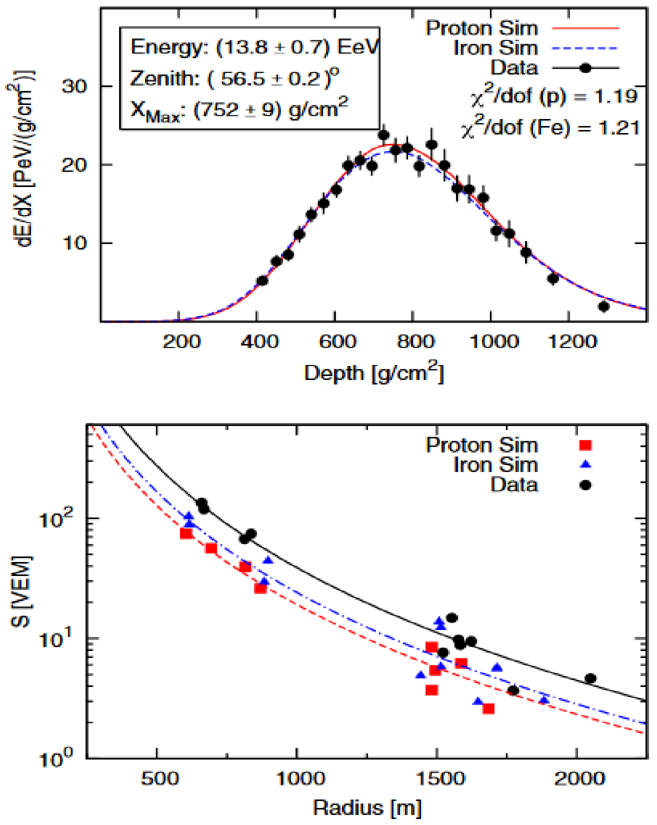
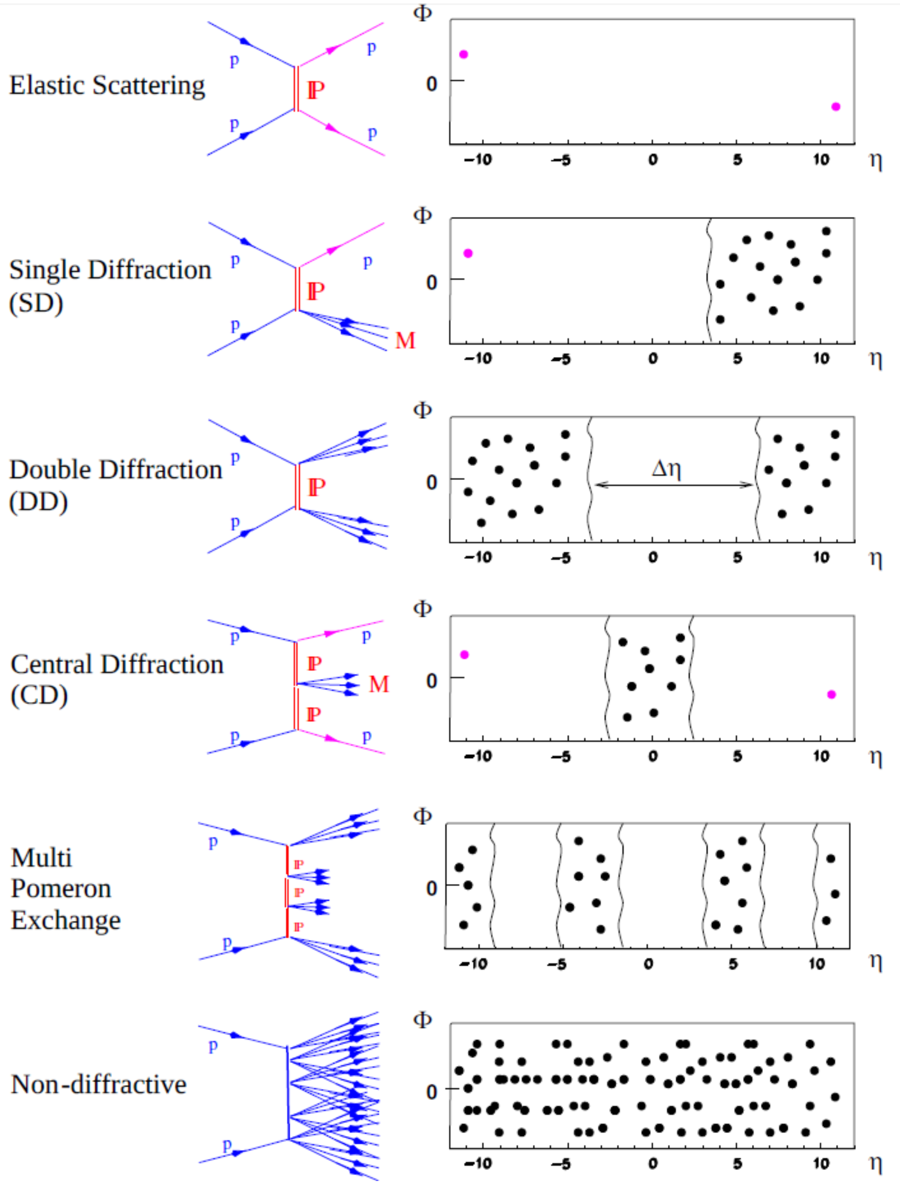


FIG. 1. Top: The measured longitudinal profile of an illustrative air shower with its matching simulated showers, using QGSJet-II-04 for proton (red solid) and iron (blue dashed) primaries. Bottom: The observed and simulated ground signals for the same event (p: red squares, dashed-line, Fe: blue triangles, dot-dash line) in units of vertical equivalent muons; curves are the lateral distribution function (LDF) fit to the signal.



ALICE strategy

For this study the M_X distributions in PYTHIA6 and PHOJET were modified so as to use the distributions from model [7] (Fig. 4), which includes in the calculation of the SD cross section all eight terms contributing to the diagram of Fig. 3. Their relative contributions are determined from a fit to lower-energy data. The predictions of this model for the total, elastic, and diffractive cross sections at LHC energies can be found in [18] and they are confirmed by measurements [19–21]. The modification of PYTHIA6 and PHOJET consists in reproducing the model M_X distribution, by applying weights to the generated events. Numerical values of the diffractive-mass distributions from this model, at the three centre-of-mass energies relevant to this publication, can be found in [22].

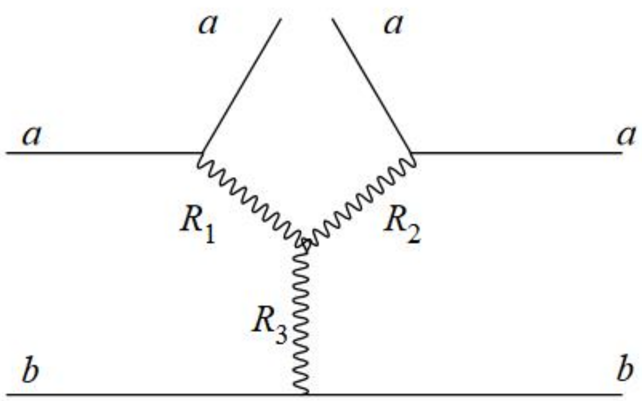


Fig. 3: Triple-Reggeon Feynman diagram occurring in the calculation of the amplitude for single diffraction, corresponding to the dissociation of hadron b in the interaction with hadron a. (See Ref. [1]). Each of the Reggeon legs can be a Pomeron or a secondary Reggeon (e.g. f-trajectories), resulting in eight different combinations of Pomerons and Reggeons. In the text, we use the notation $(R_1R_2)R_3$ for the configuration shown in this figure.

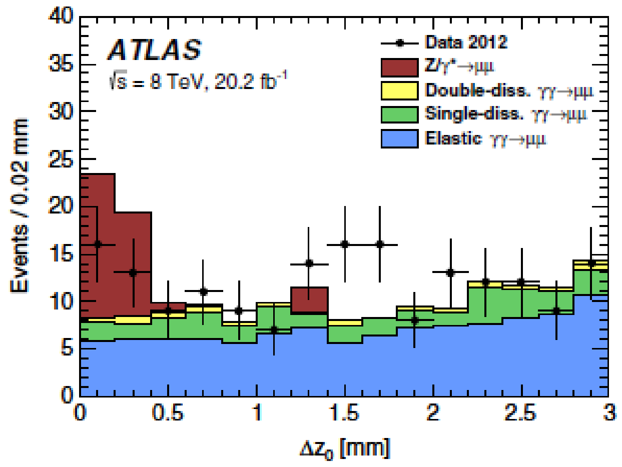


FIG. 5. Absolute Δz_0 of the extra track to the lepton vertex in the region defined by acoplanarity < 0.0015. The exclusivity requirement was changed to select exactly one extra track within 3 mm. The exclusive predictions are scaled by a factor of 0.70.

background normalization factor. The zero-track and one-track normalization factors are consistent at the level of 10%, which is taken to be a measure of the accuracy of the pileup simulation in predicting signal efficiency.

The value of $f_{\rm EL}$ with the additional $\pm 10\%$ relative systematic uncertainty for signal efficiency added in quadrature with the previous systematic uncertainty

$$f_{\rm EL} = 0.76 \pm 0.04(\text{stat}) \pm 0.10(\text{sys}) \qquad (6)$$

is consistent with the value of $0.791 \pm 0.041(\text{stat}) \pm 0.026(\text{sys}) \pm 0.013(\text{theory})$ obtained in an earlier analysis using data from pp collisions at $\sqrt{s} = 7$ TeV [65]. This value is also consistent with the theoretical estimate of $f_{\rm EL} \sim 0.73$–0.75, related to the proton size effects in the probed region of dimuon mass [66].

Comment on cross section values and methods ALFA/TOTEM

- Elastic slope in good agreement
- ALFA uses only one method, ignores non-pure exponentiality and fits with Coulomb. But it has more detailed luminosity determination.
- At 7 TeV, TOTEM used three methods that agreed. At 8 TeV for the 1 km measurement, TOTEM takes non-pure exponentiality into account, removes effect of Coulomb by fit (in a t-region with sensitivity) and simultaneously extracts ρ.

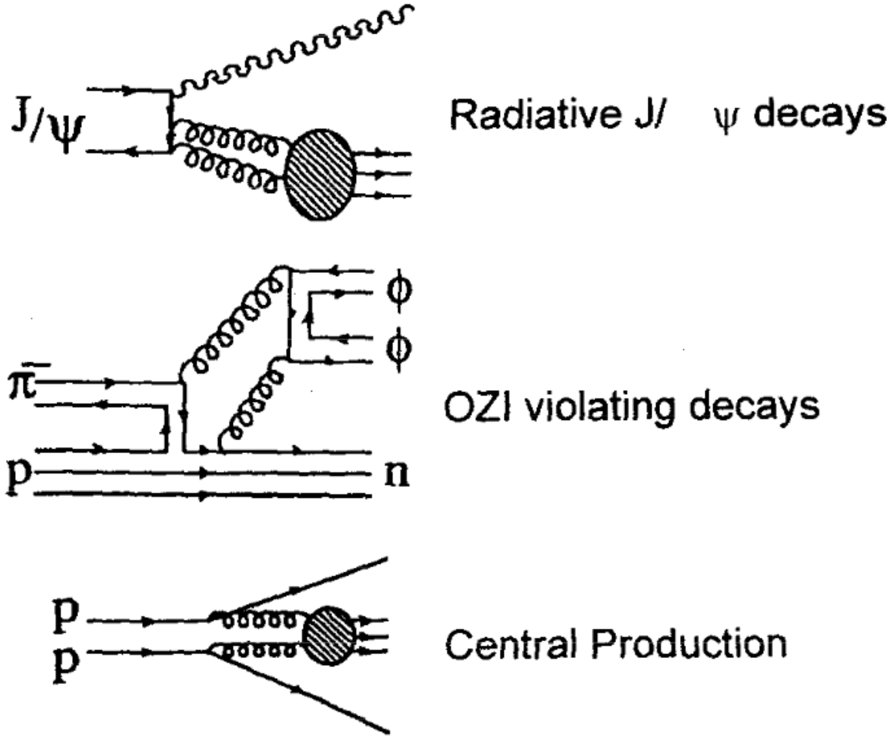
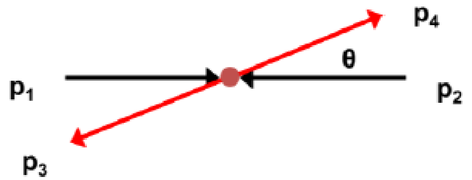
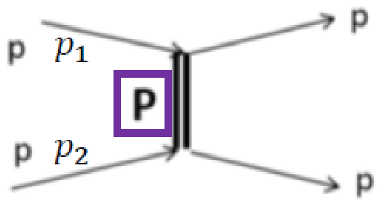


Figure 1. Gluon rich production reactions.

rising σ_{tot}, Regge model, pomeron

- using optical theorem and Regge theory we can write for a process



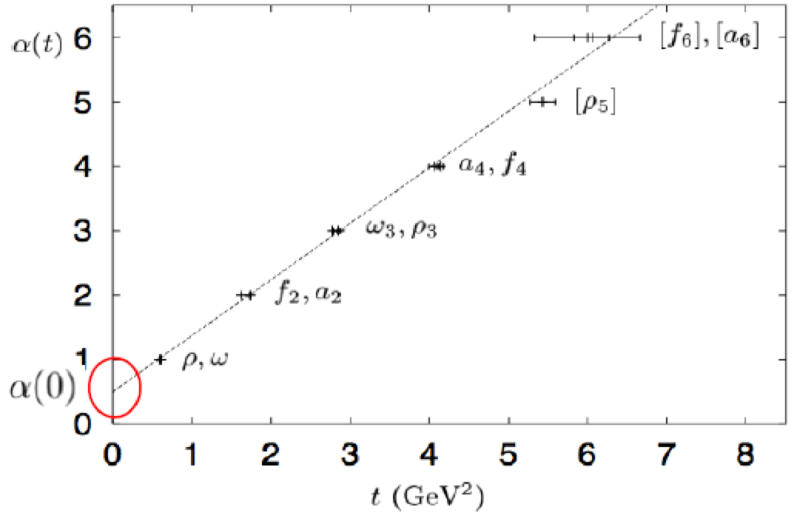


$$\sigma_{tot} \approx s^{\alpha(0)-1} \qquad s = (p_1 + p_2)^2$$

$$\frac{d\sigma_{el}}{dt} \approx s^{2(\alpha(0)-1)} e^{-B|t|} \qquad B = B_0 + 2\alpha' \ln s$$

where $\alpha(0)$ is so-called intercept of a Regge trajectory

$$\alpha(t) = \alpha(0) + \alpha' t \qquad t = (p_1 - p_2)^2 \underset{\text{elastic}}{\cong} -(p_0\theta)^2, \ |p_1| = |p_2| = p_0$$



- if $\alpha(0) > 1$, σ_{tot} will rise with rise of s
- trajectory with $\alpha(0) > 1$ has only one "particle" – pomeron **P**
- σ_{tot} is not calculable in the framework of the perturbative QCD; Regge model is used in HEP generators to describe kinematic area where the QCD cannot be applied