elastic and diffractive forward proton measurements with ATLAS

using ALFA detector

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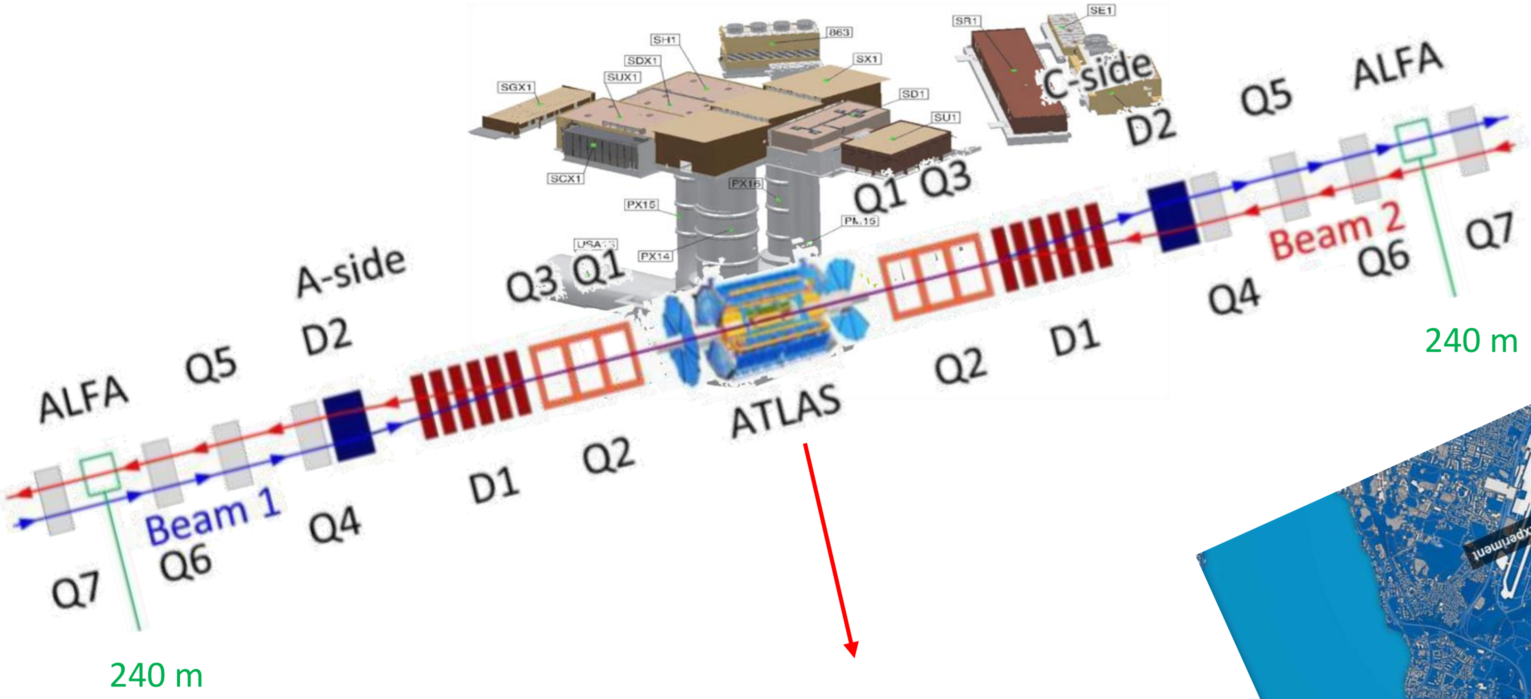
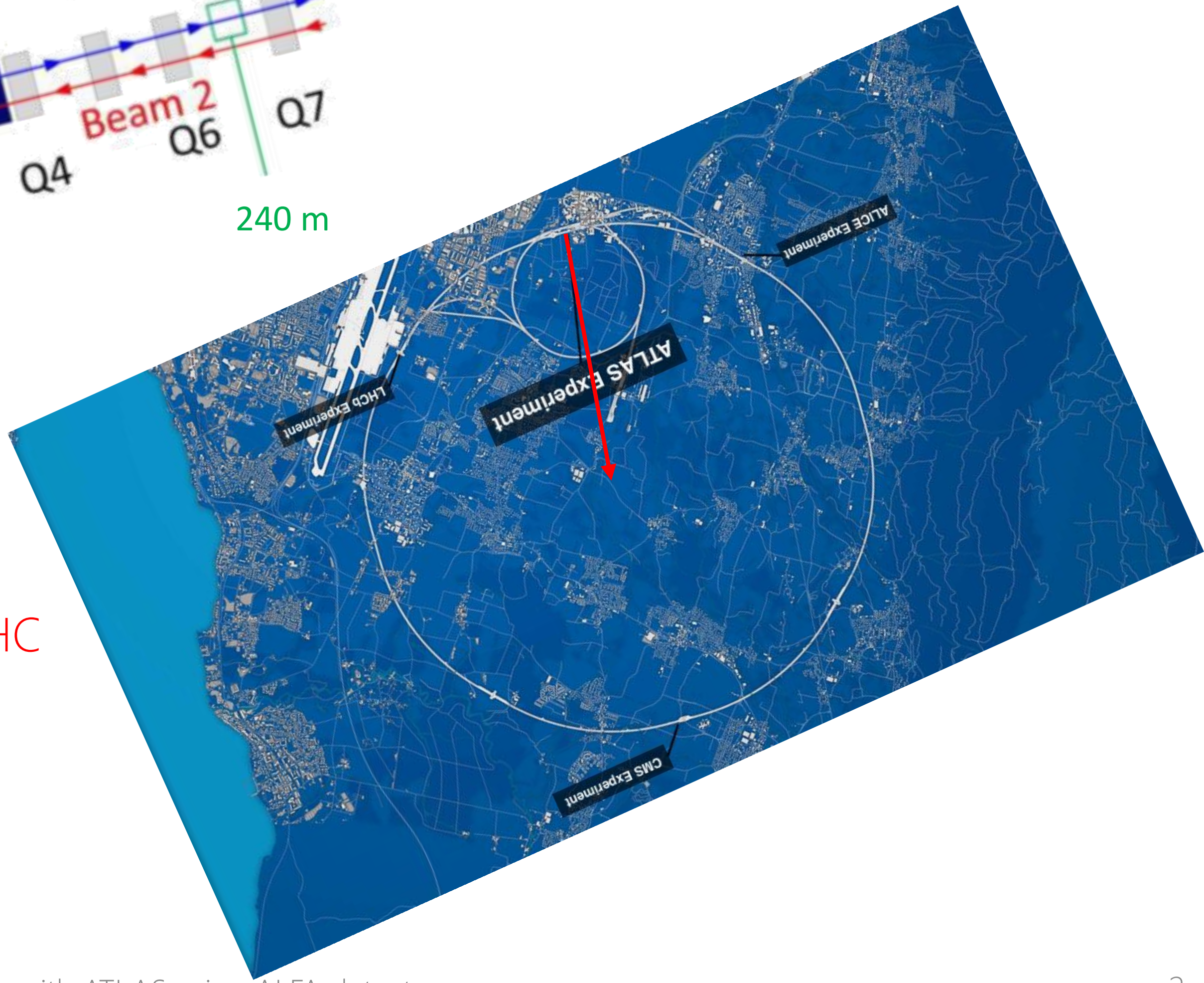
ALFA – forward detector

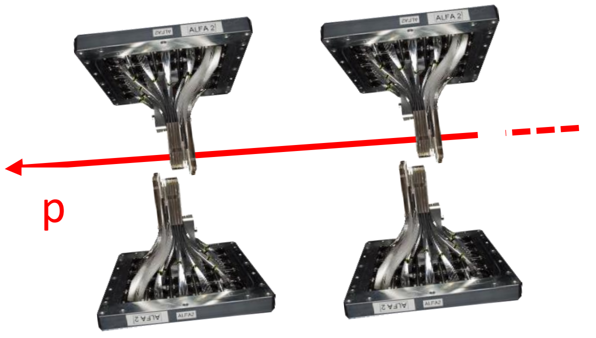


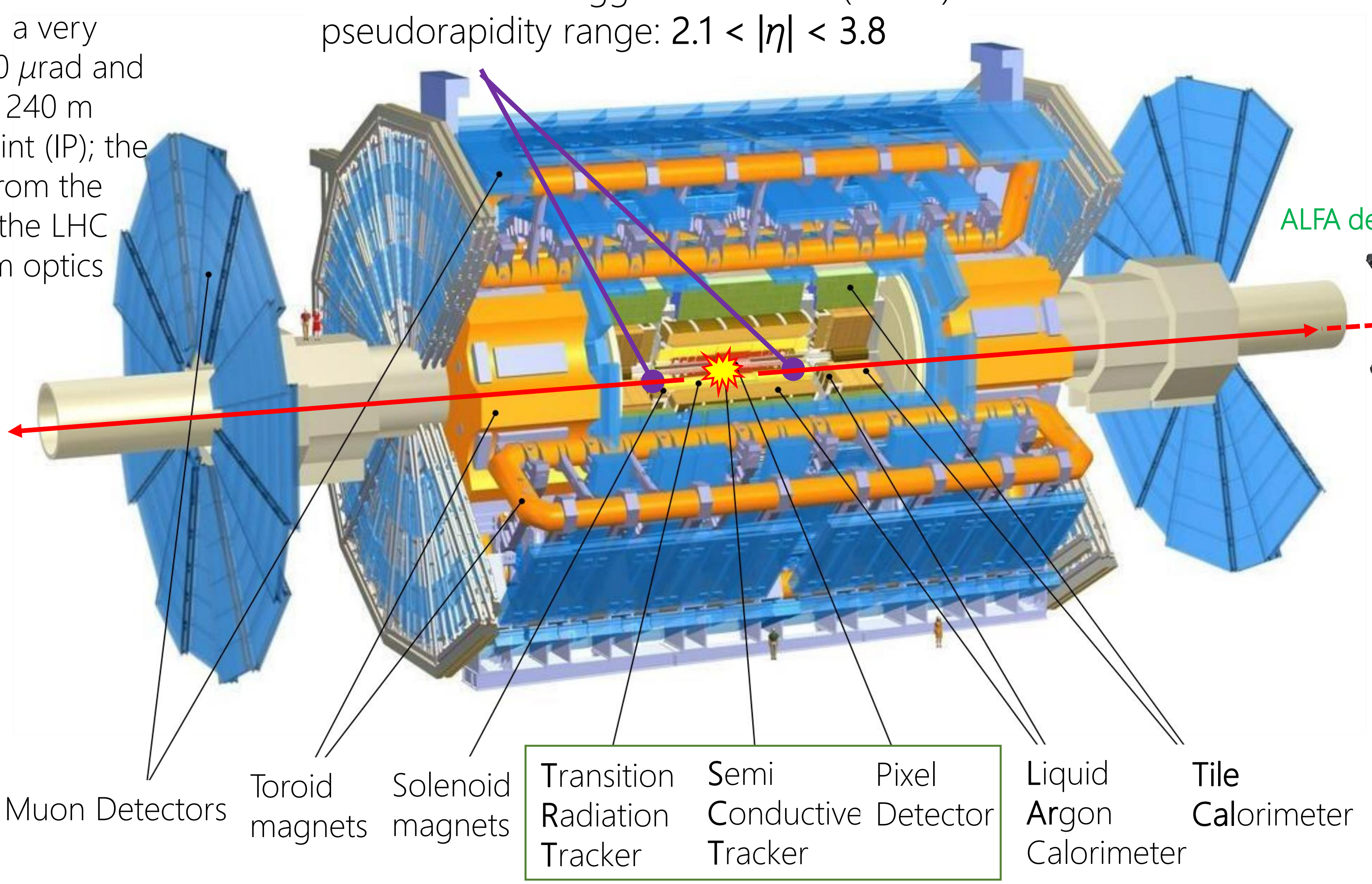
to the center of the LHC



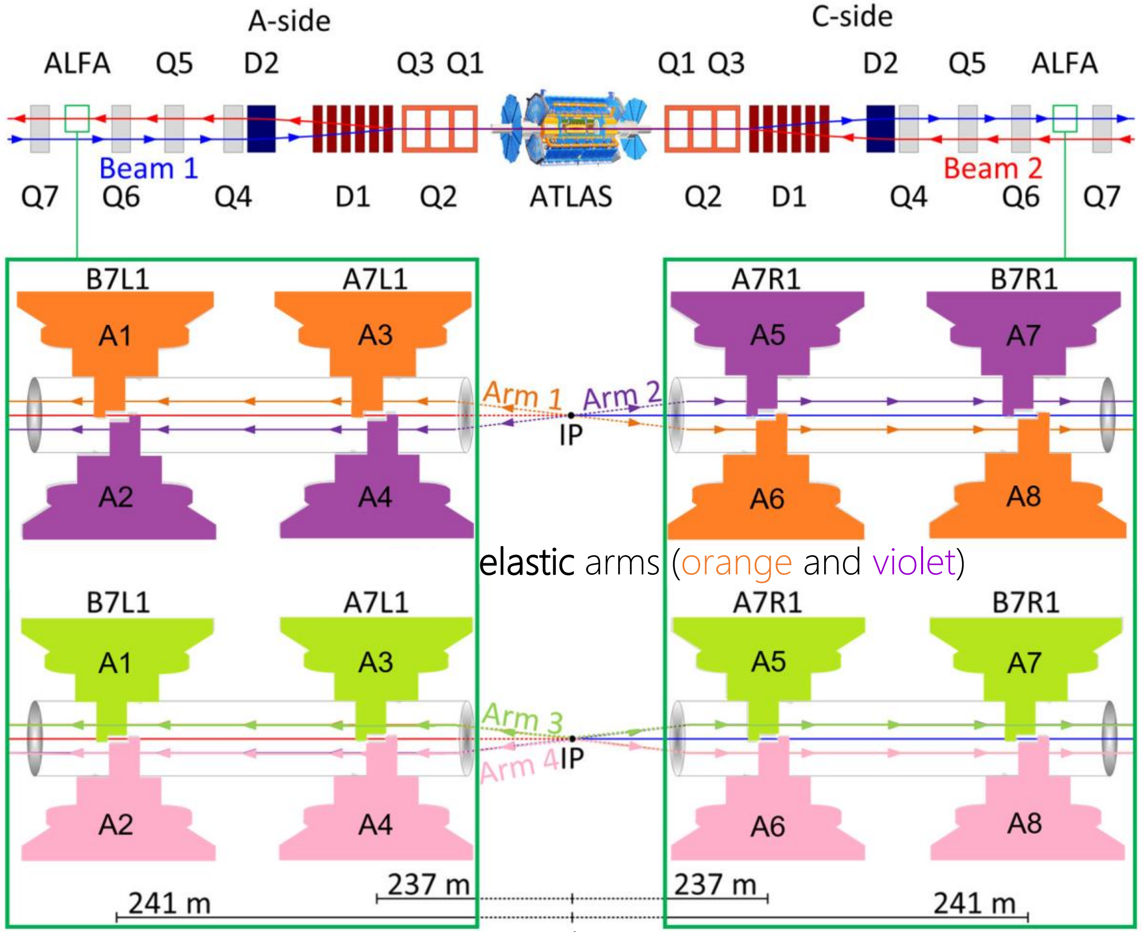
experimental setup

protons p is scattered through a very small angle of typically 10 - 100 μrad and is measured by ALFA detector 240 m from the ATLAS Interaction Point (IP); the detector was placed 7.5 mm from the beam in the dedicated run of the LHC with the special high β^{*} = 90 m optics





ALFA detector

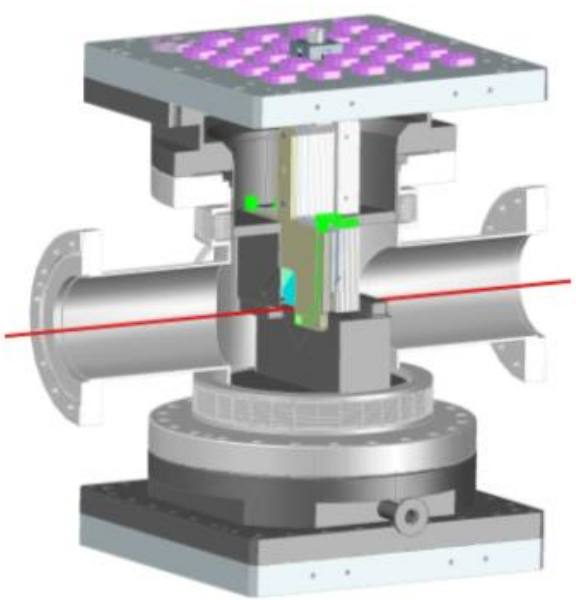


elastic arms (orange and violet)

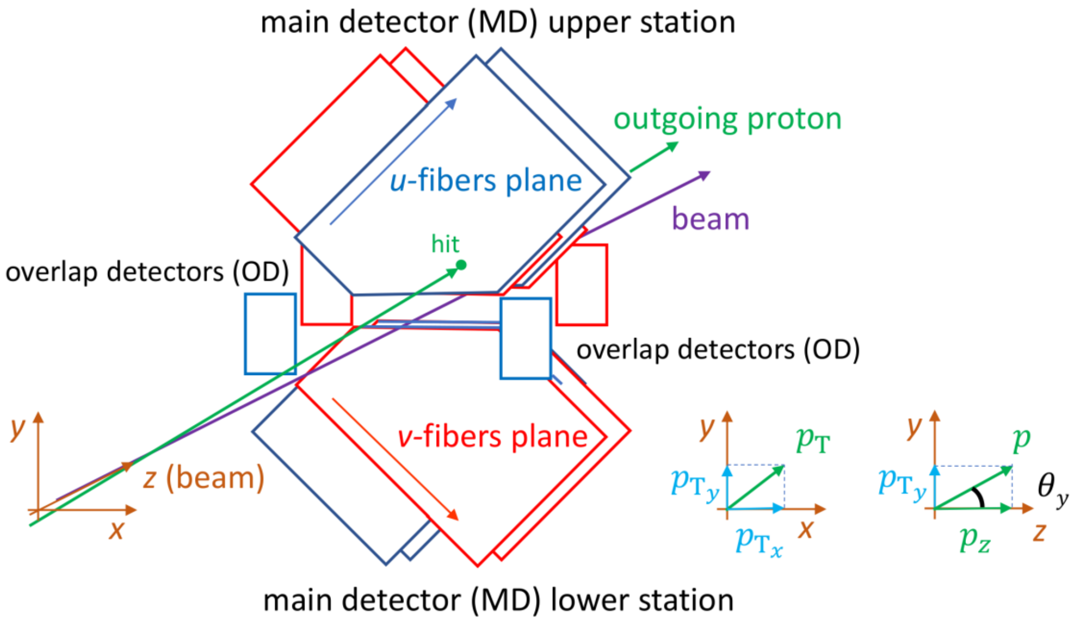
anti-elastic arms (green and pink)

each of arms consists of 2 **armlets**, each with 2 detectors

arm $_{ijkl}$ = Ai+Aj+Ak+Al



ALFA detector (left in Roman Pot)

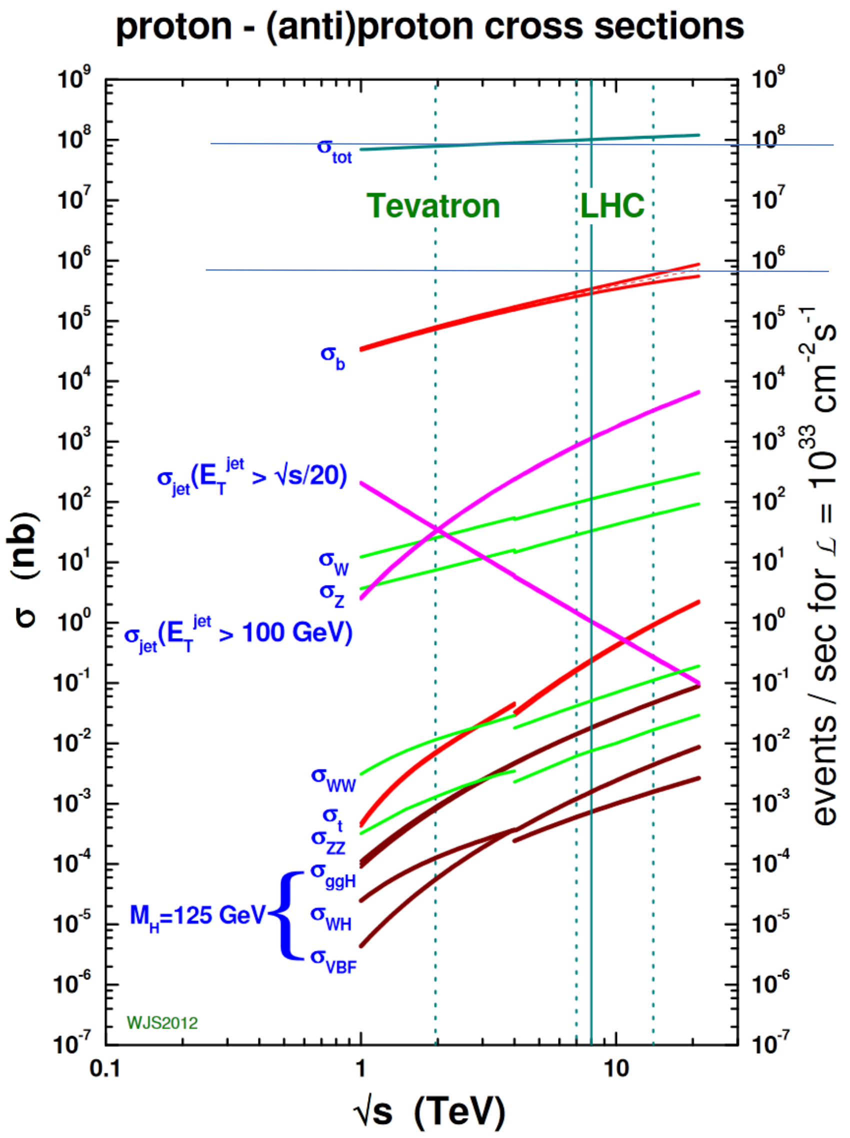


total cross section σ_{tot} of proton-proton interaction at $\sqrt{s}$ = 13 TeV

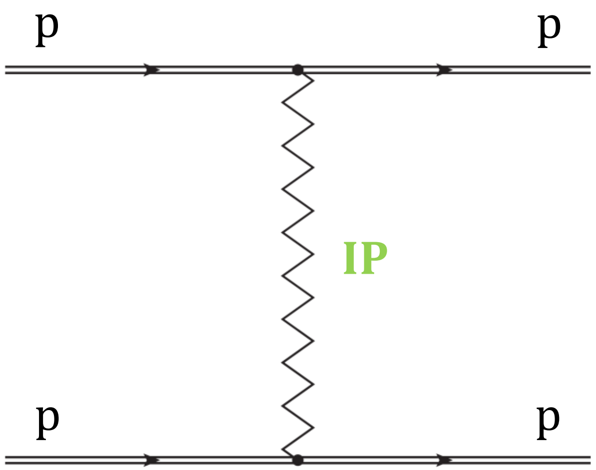
arXiv:2207.12246 [hep-ex], accepted for publication in EPJC

total cross section σ_{tot} of proton-proton interaction

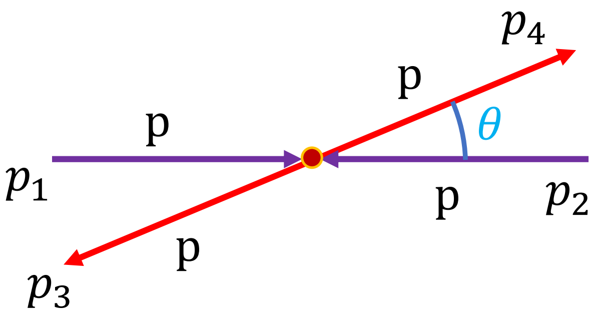
- σ_{tot} of p-p interaction is a fundamental quantity giving the upper bound on probability (cross section) of any process in p-p collisions
- σ_{tot} is not calculable in the framework of perturbative QCD; Regge model is used in HEP generators to describe kinematic area where perturbative QCD cannot be applied



measurement of σ_{el} – simplest process and kinematics



IP – pomeron



Mandelstam variables, invariants

$s = (p_1 + p_2)^2$

$t = (p_1 - p_4)^2 \cong -(p_0\theta)^2, |\vec{p_1}| = |\vec{p_2}| = |\vec{p_4}| = p_0$

σ_{tot} and σ_{el}

direct (ρ-independent; see below) measurement of $\sigma_{tot} = N_{tot}/L$, where N_{tot} is total number of events with interaction, L is luminosity, is nontrivial; (due to the limited acceptance, model dependence)

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

$\sigma_{inel} = \sigma_{inel\ diffractive} (\sigma_{SD} + \sigma_{DD} + \dots) + \sigma_{non\ diffractive}$

traditional way (ISR) of σ_{tot} measurement – via elastic cross section measurement and the use of optical theorem

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

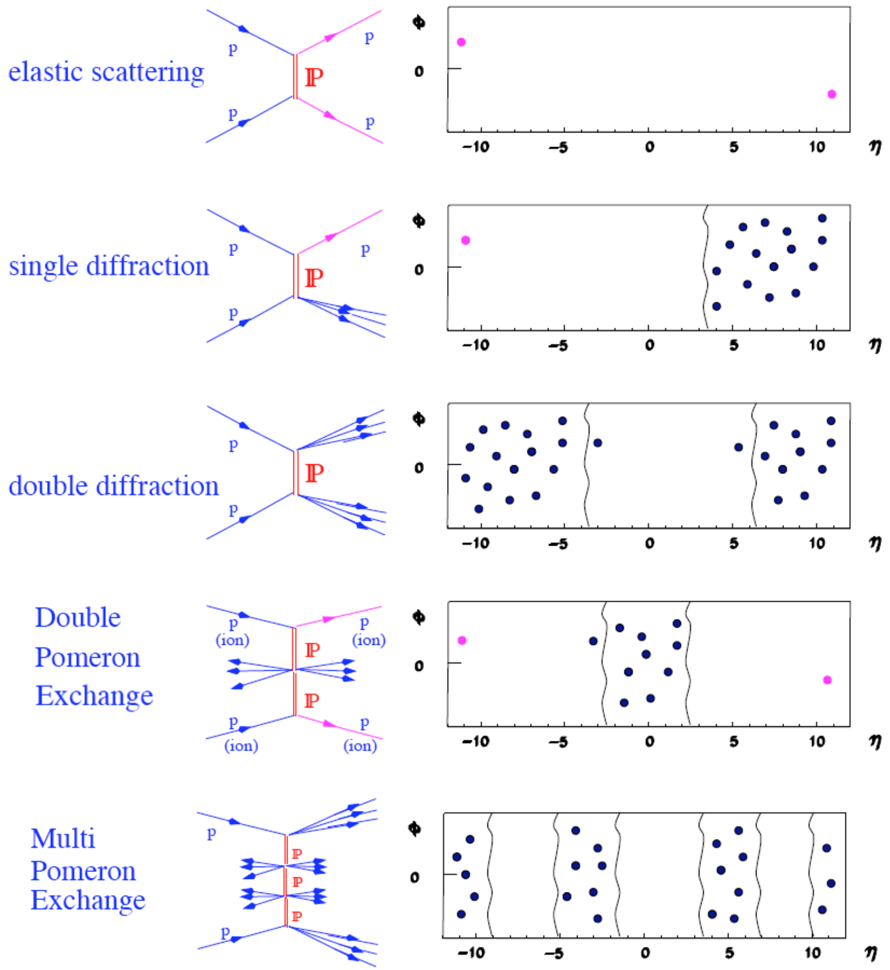
where f_{el} is elastic amplitude

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\frac{1}{L}\left(\frac{dN_{el}}{dt}\right)_{t=0} \qquad \rho = \left.\frac{\mathrm{Re}[f_{el}(t)]}{\mathrm{Im}[f_{el}(t)]}\right|_{t\to 0}$$

luminosity dependent measurement, N_X - number of events of X∈(el, tot, inel, ...) type

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

luminosity independent measurement



elastic events are the subset of diffractive events; diffractive like pattern was actually observed in elastic collisions

differential elastic cross section – fit (illustration)

Coulomb **N**uclear **I**nterference **(CNI)** region

ATLAS ALFA method

$$\frac{d\sigma_{el}}{dt} = \frac{1}{16\pi}\left|f_N(t) + f_C(t)e^{i\alpha\phi(t)}\right|^2$$

coulomb amplitude

$$f_C(t) = -8\pi\alpha\hbar c\frac{G^2(t)}{|t|}$$

nuclear amplitude

$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c}e^{\frac{-B|t|}{2}}$$

phase

$$\phi(t) = -\ln\frac{B|t|}{2} - \phi_C$$

proton form factor

$$G(t) = \left(\frac{\Lambda}{\Lambda + |t|}\right)^2$$

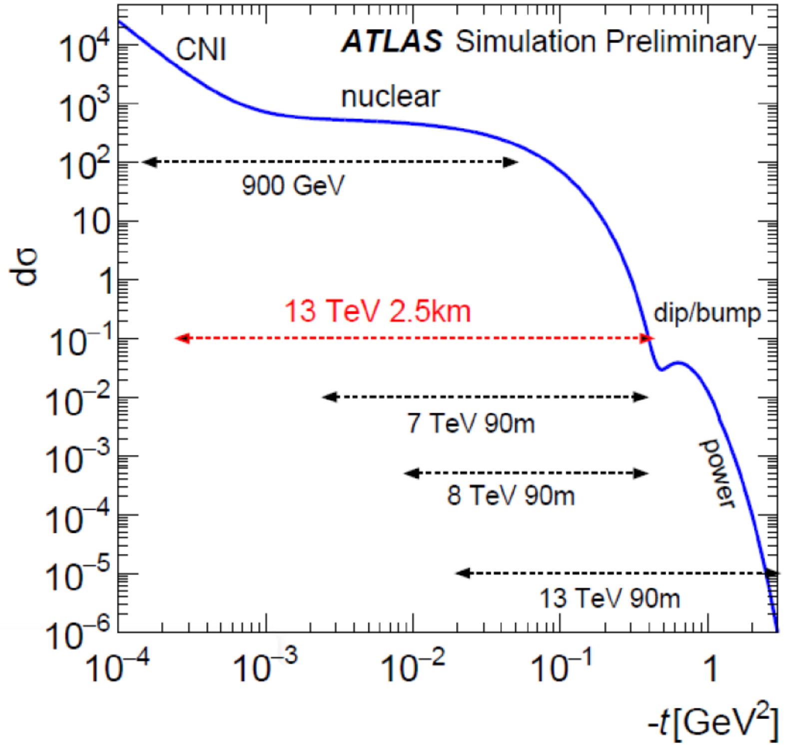
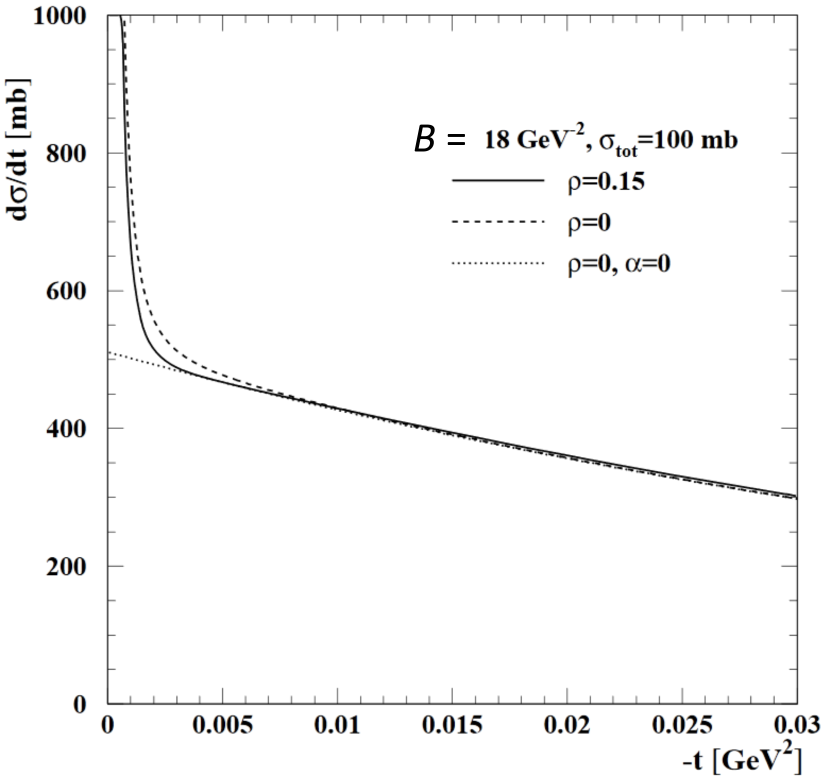


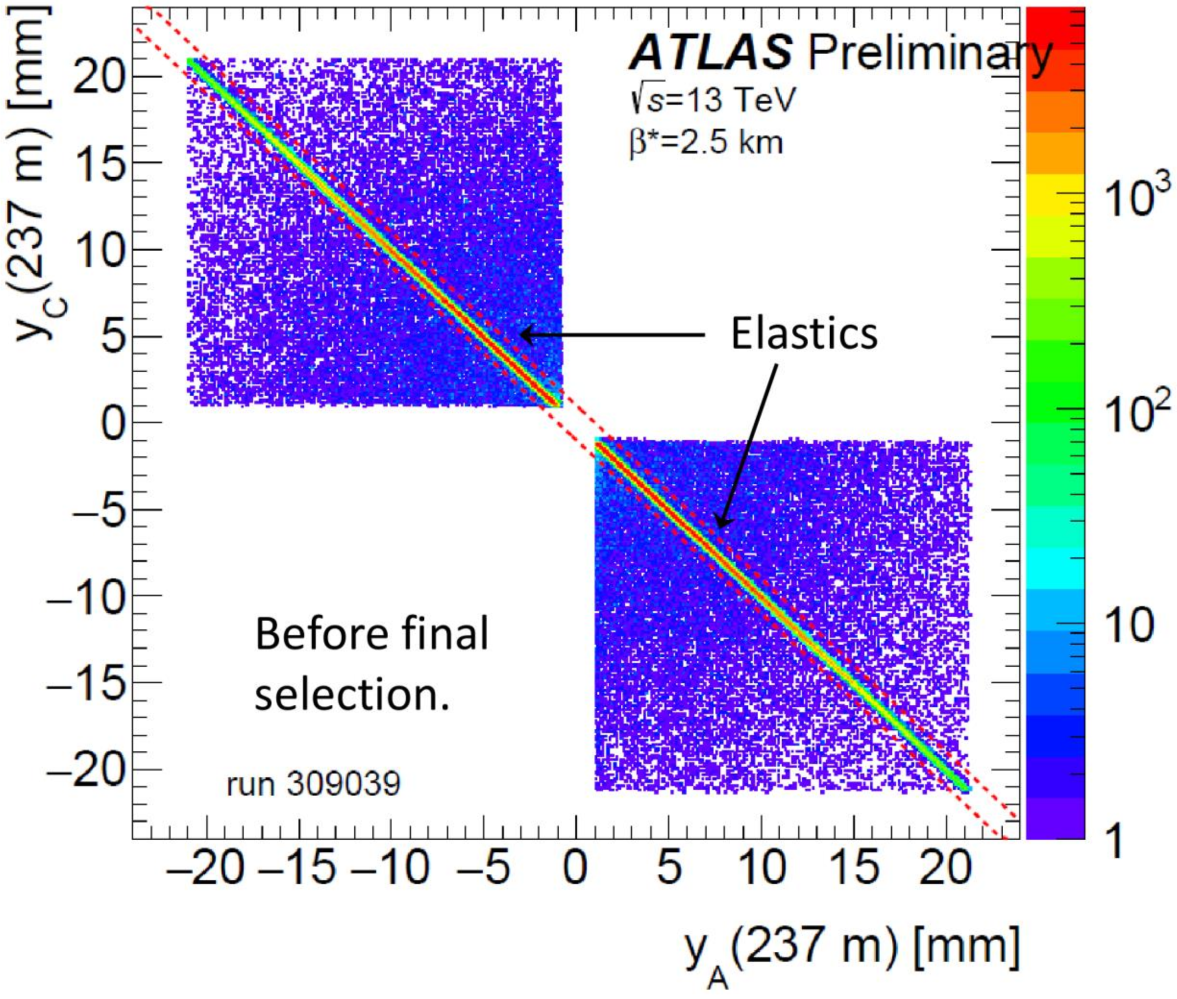
illustration - Pythia 8 – values:

ρ	0.14
Λ	0.71 GeV^2
ϕ_C	0.577

for an illustration, from ATLAS ALFA TDR, CERN/LHCC 2008-04



data – selection of elastic events

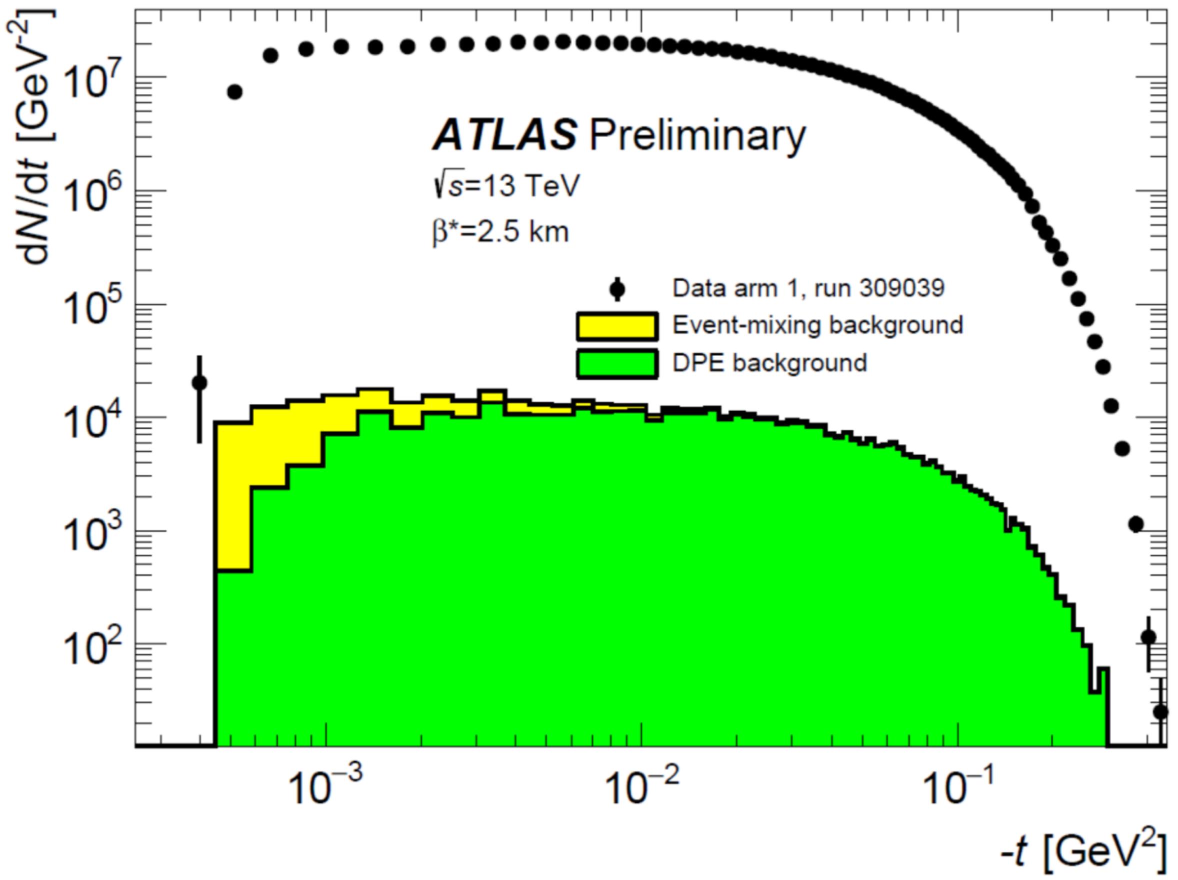


elastic scattering data were taken in 2016 at energy $\sqrt{s}$=13 TeV with β^* = 2.5 km and
Roman Pot insertion to 3.5σ recording 6.8 M events for integrated luminosity 340 nb^{-1}

the selection of elastic events is based on a pre-selection of data-quality and geometrical acceptance cuts

the final selection exploits the back-to-back topology of elastic events

data – background



two sources of background are considered:

1. accidental halo+halo and halo+single diffraction coincidences
2. Double-Pomeron exchange (DPE)

accidental coincidence are determined from single-side templates, DPE from simulation

both backgrounds are normalized to control regions in the data

the irreducible background fraction is very small: 0.75‰, with a relative uncertainty of 10-15%

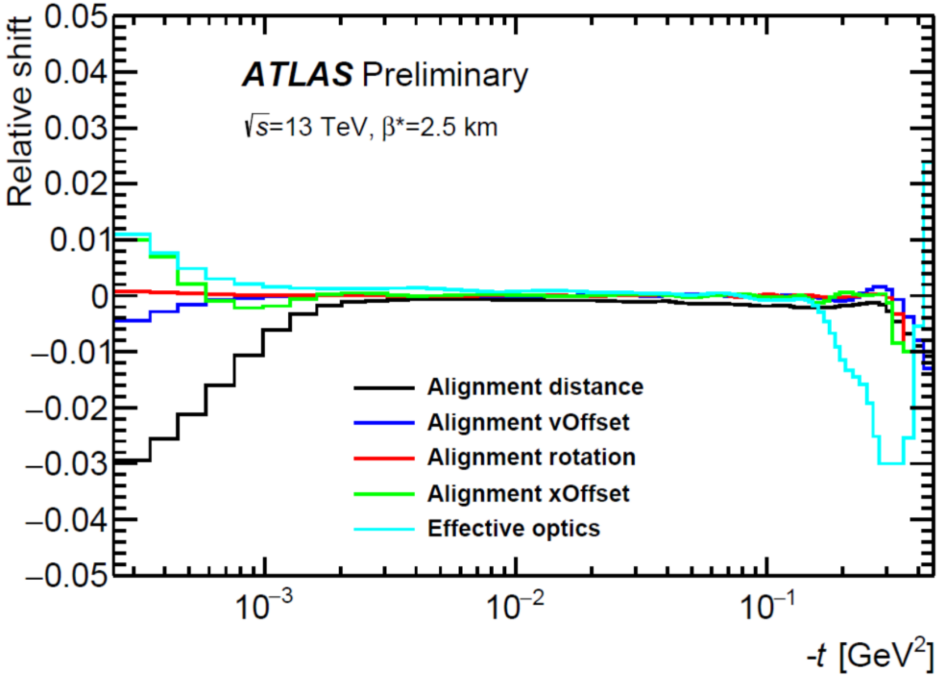
systematic uncertainties for $d\sigma_{el}/dt$

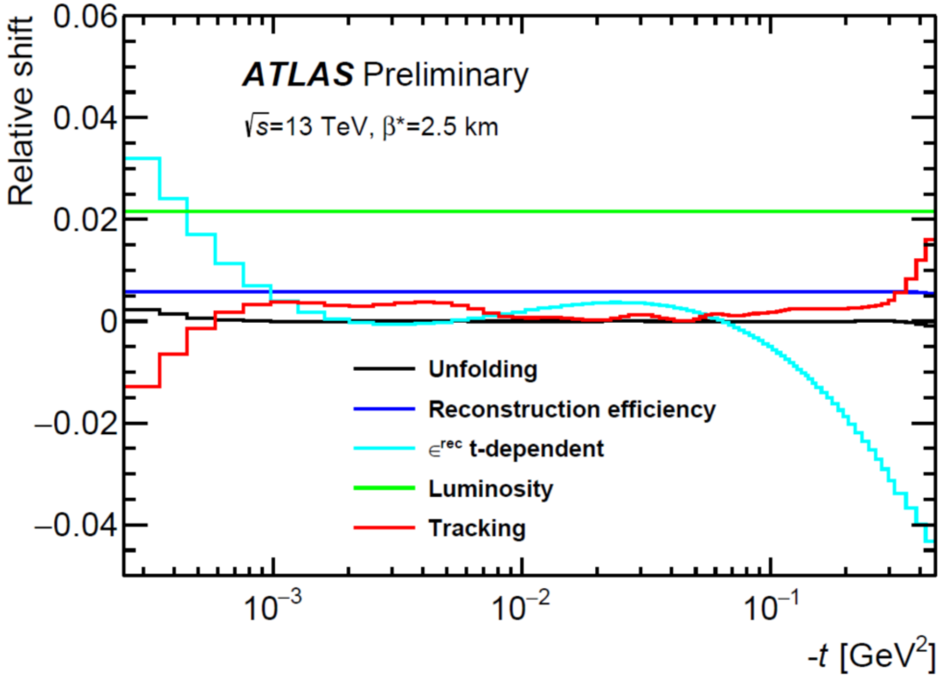
$$\frac{d\sigma}{dt_i} = \frac{1}{\Delta t_i} \times \frac{\mathcal{M}^{-1}[N_i - B_i]}{A_i \times \epsilon^{\text{reco}} \times \epsilon^{\text{trig}} \times \epsilon^{\text{DAQ}} \times L_{\text{int}}}$$

A_i – acceptance in i-th bin, $\mathcal{M}^{-1}$– unfolding

ϵ^X – efficiency in X; N_i, B_i – number of signal, background events

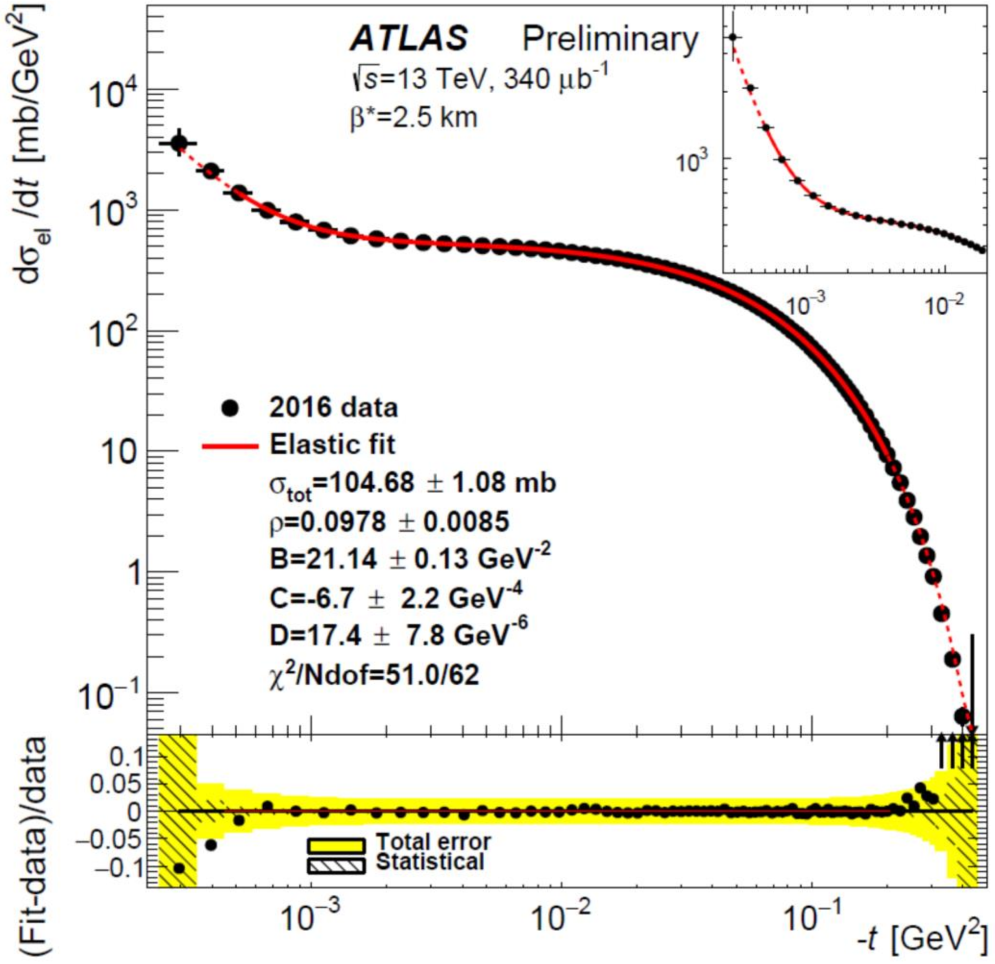
experimental systematic uncertainties calculated as function of t





main uncertainties: alignment, luminosity, reconstruction efficiency

differential elastic cross section – results



$t \in [2.5 \cdot 10^{-4}, 4.6 \cdot 10^{-1}]$ GeV²

physics parameters are extracted from a profile fit
to the cross section including experimental systematic uncertainties

fit function – nuclear part depends on considered models (next slide)

$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c} e^{\frac{-B|t|}{2}}$$

$$\phi(t) = -\ln\frac{B|t|}{2} - \phi_C$$

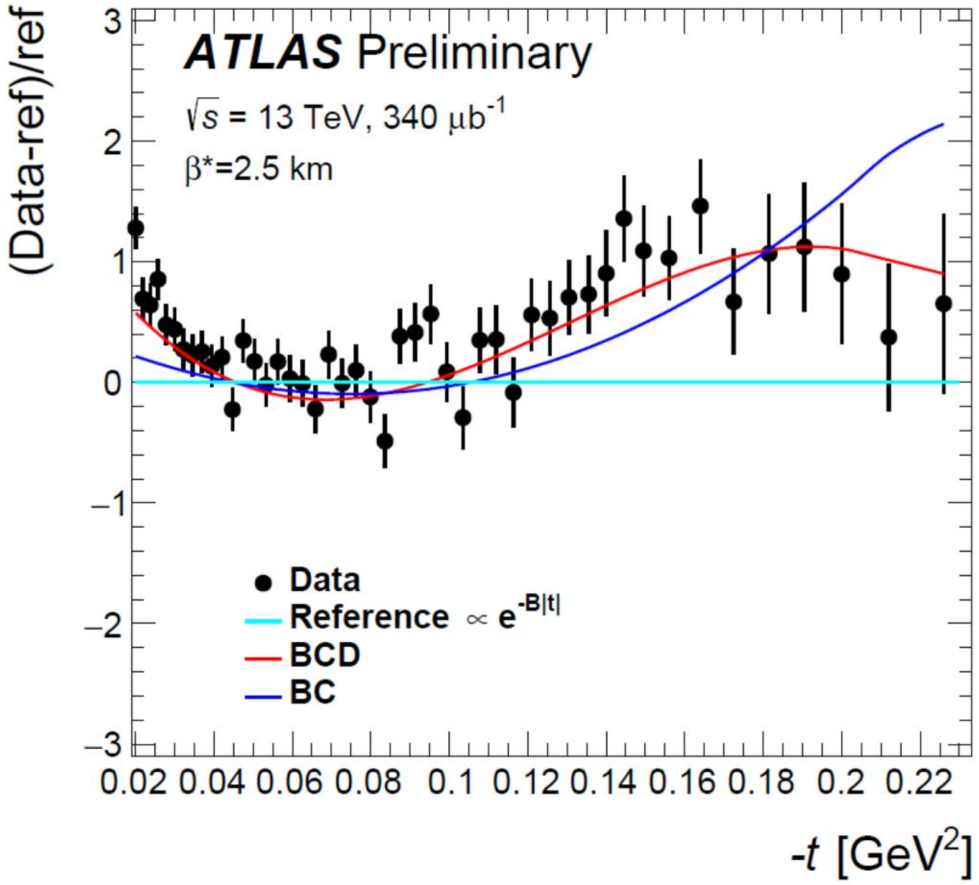
$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c} e^{\frac{-B|t| - Ct^2 - D|t|^3}{2}}$$

$$\phi(t) = -\left(\gamma_E + \ln\frac{B|t|}{2} + \ln\left(1 + \frac{8}{B\Lambda}\right)\right) + \frac{4|t|}{\Lambda} \cdot \ln\frac{\Lambda}{4|t|} - \frac{2|t|}{\Lambda}$$

σ_{tot}	105 mb
B	21.13 GeV^{-2}
C	−6.5 GeV^{-4}
D	17.4 GeV^{-6}
ρ	0.096
Λ	0.71 GeV^2
ϕ_C	0.577

the main uncertainties are related to the luminosity and to the alignment;
for ρ also theoretical uncertainties are important

theoretical (model) uncertainties



$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c} e^{\frac{-B|t|-Ct^2-D|t|^3}{2}}$$

	σ_{tot}[mb]	ρ	B[GeV^{-2}]	C[GeV^{-4}]	D[GeV^{-6}]
Central value	104.68	0.0978	21.14	−6.7	17.4
Statistical error	0.22	0.0043	0.07	1.1	3.8
Experimental error	1.06	0.0073	0.11	1.9	6.8
Theoretical error	0.12	0.0064	0.01	0.04	0.15
Total error	1.09	0.0106	0.13	2.3	7.8

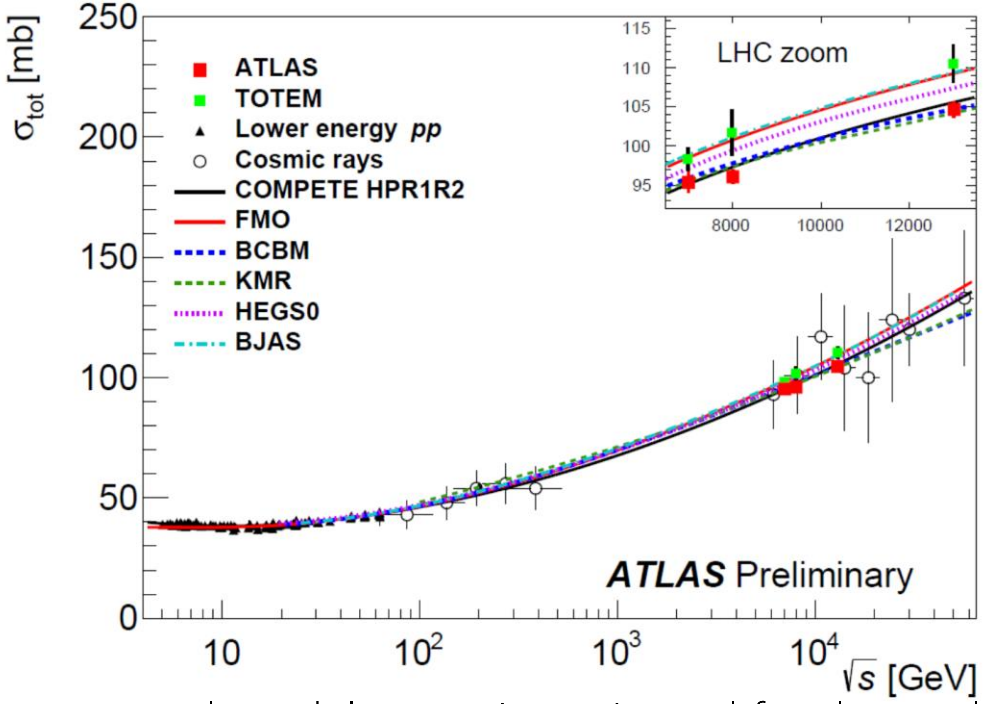
theoretical uncertainties:

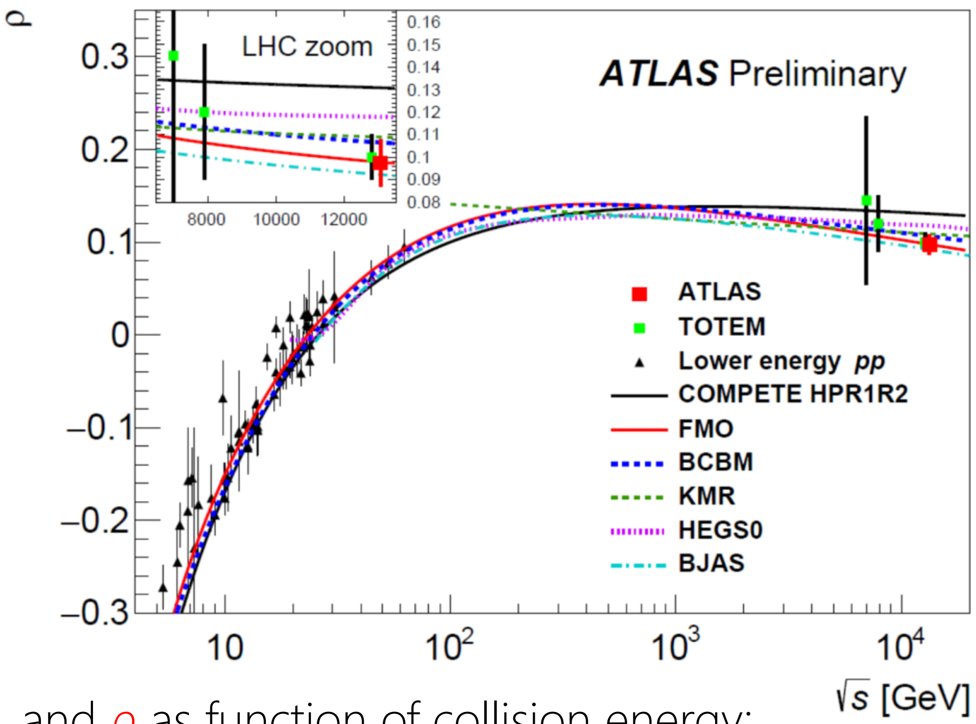
- parametrization of the strong amplitude
- Coulomb phase
- proton form factor
- nuclear phase important for ρ

stability:

- time dependence
- fit range
- different t-reconstruction methods
- difference between arms

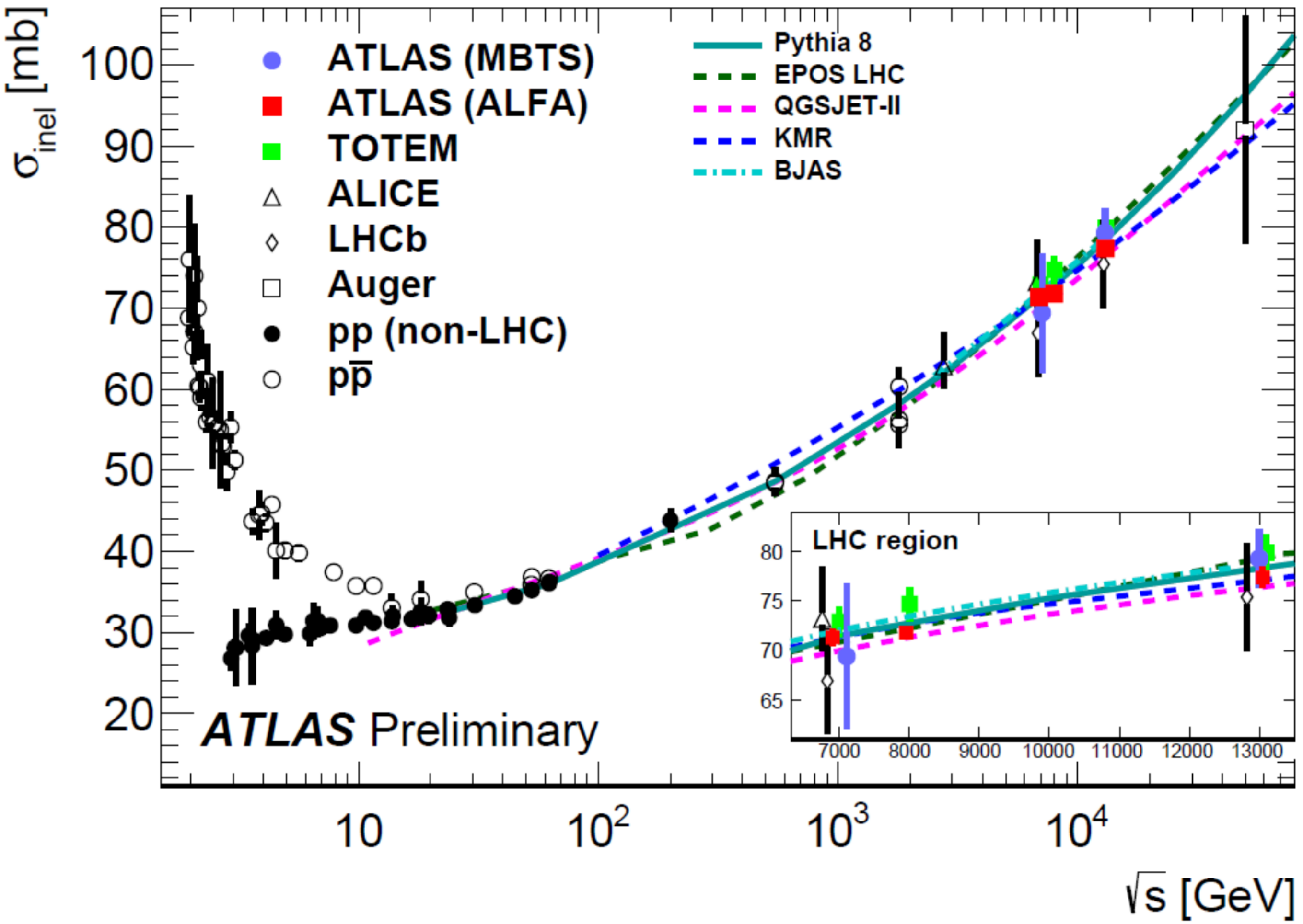
behavior of σ_{tot} and ρ as function of collision energy





- several models were investigated for the evolution of σ_{tot} and ρ as function of collision energy; σ_{tot} and ρ connected via dispersion relations
- the canonical evolution model, COMPETE, is disfavored as it predicts the value of $\rho \approx 0.13$
- the model with an Odderon and tuned to TOTEM data is not in a good agreement with corresponding ATLAS σ_{tot} result
- the damped amplitude model is in the best agreement with ATLAS data
- ALFA and TOTEM difference in σ_{tot} about 2.2 σ (similar trend seen at 7 and 8 TeV)

elastic and inelastic cross sections at $\sqrt{s}$ = 13 TeV



after the differential elastic cross section over the full phase space is got (by integrating the nuclear part of the theoretical prediction we get

$$\sigma_{el}^{extr} = 27.27 \pm 1.10\ (\text{exp.}) \pm 0.30\ (\text{th.})\ \text{mb}$$

then, since we get

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

we get

$$\sigma_{inel} = 77.41 \pm 1.07\ (\text{exp.}) \pm 0.18\ (\text{th.})\ \text{mb}$$

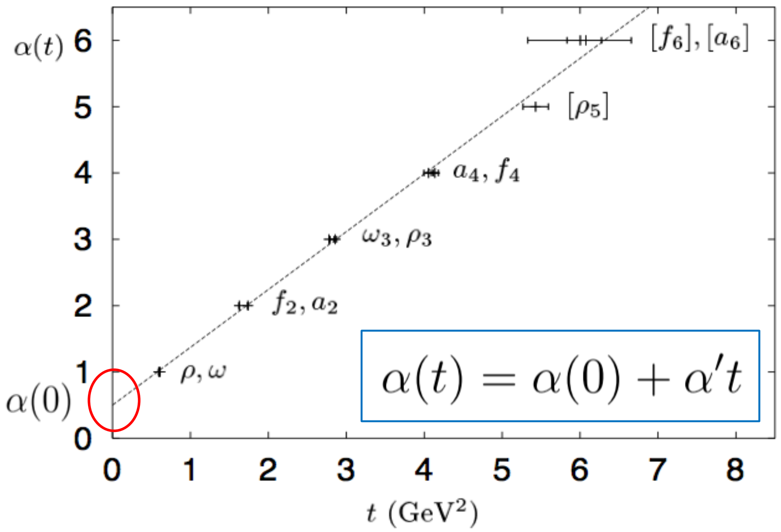
evolution of B; σ_{el}/σ_{tot} ratio

using optical theorem and Regge theory we can write

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

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

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

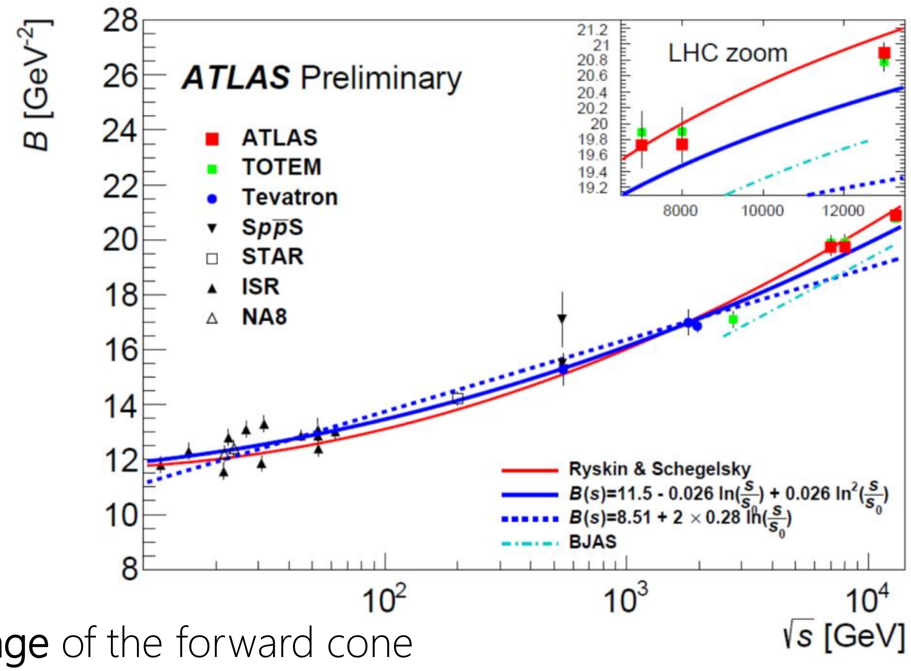


then:

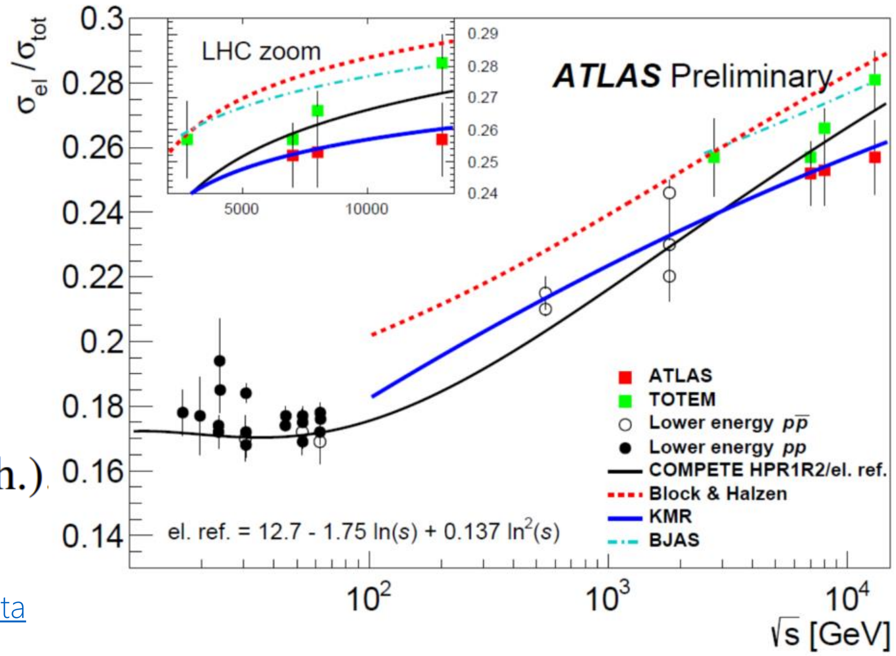
$$\frac{\sigma_{\mathrm{el}}}{\sigma_{\mathrm{tot}}} \approx s^{\alpha(0)-1}/(B_0 + \alpha' \ln s^2)$$

measurement at $\sqrt{s} = 13$ TeV gives:

$$\frac{\sigma_{\mathrm{el}}}{\sigma_{\mathrm{tot}}} = 0.257 \pm 0.008\ (\mathrm{exp.}) \pm 0.009\ (\mathrm{th.})$$



shrinkage of the forward cone

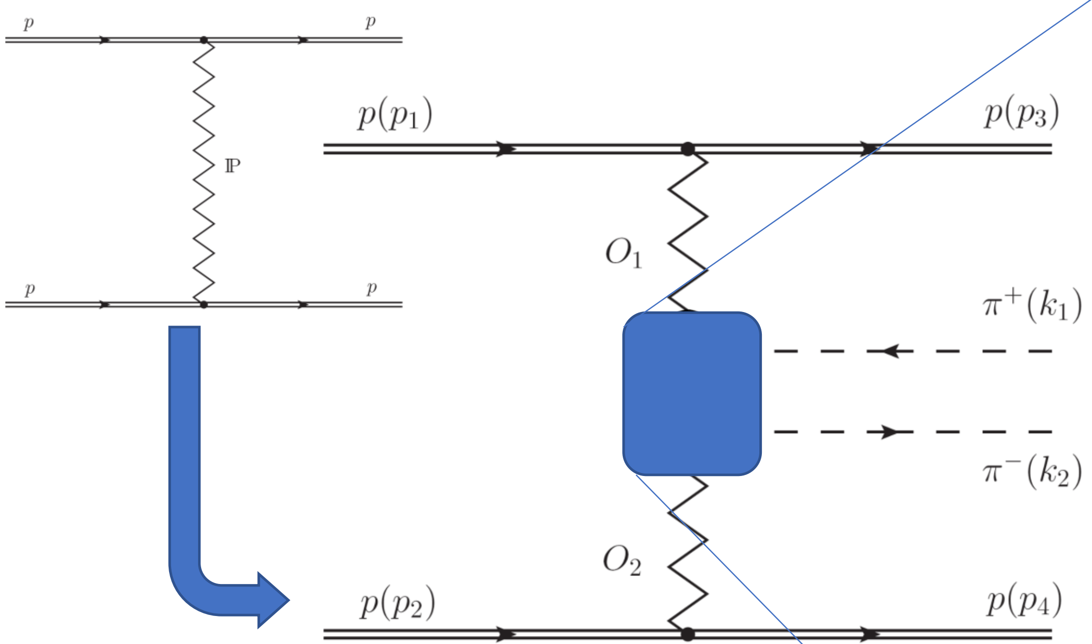


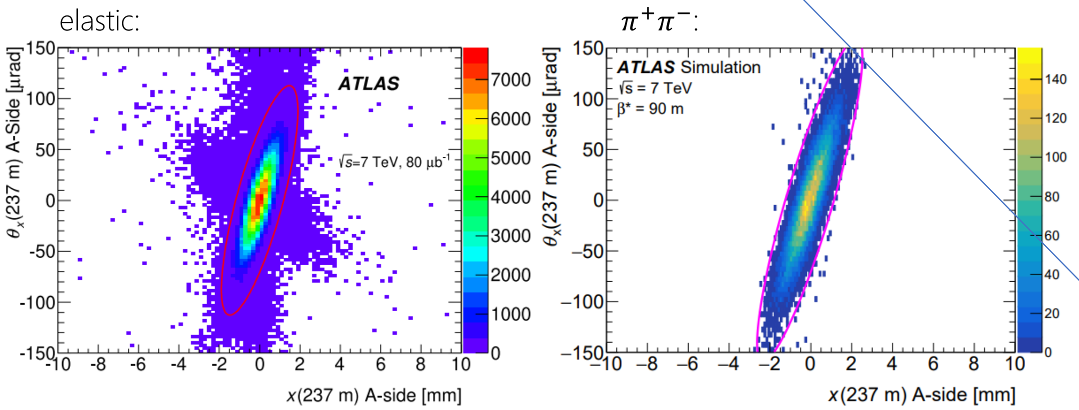
for some recent discussion see e.g. Soft Pomeron in light of the LHC correlated data

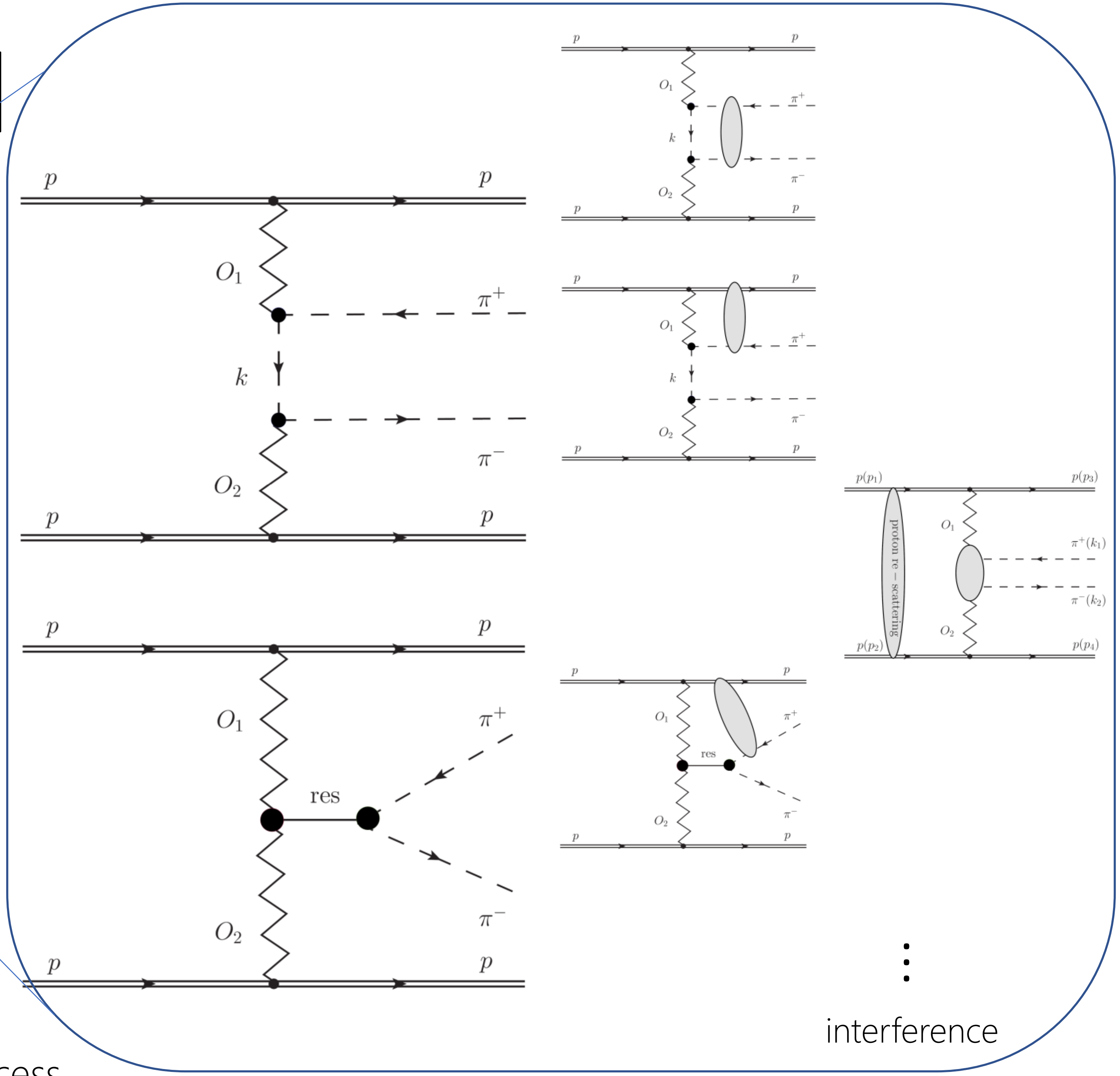
exclusive pion pair production at $\sqrt{s}$ = 7 TeV

arXiv:2212.00664 [hep-ex], accepted for publication in EPJC

exclusive pion pair $\pi^+\pi^-$ production







very similar, very small t and ξ → non-perturbative process

data selection and cut flow

- data samples, the same as for ATLAS Collaboration, *Measurement of the total cross section from elastic scattering in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector*, Nucl. Phys. B 889 (2014) 486, arXiv: 1408.5778 [hep-ex]
- the present analysis used also the same proton reconstruction criteria – bunch group, data quality, selections on the reconstructed track and geometrical deflection, beam-screen and edge conditions (see Table 2) – together with the detector alignment

Selection
Bunch selection
Lumi blocks selection
Trigger configuration
Pions:
number of tracks
primary vertex
ID track quality
MBTS veto
Protons:
ALFA track quality
ALFA *uv*-condition
ALFA clean track
ALFA geometry condition
Full system momentum balance in p_x and p_y
Fiducial region

fiducial region:

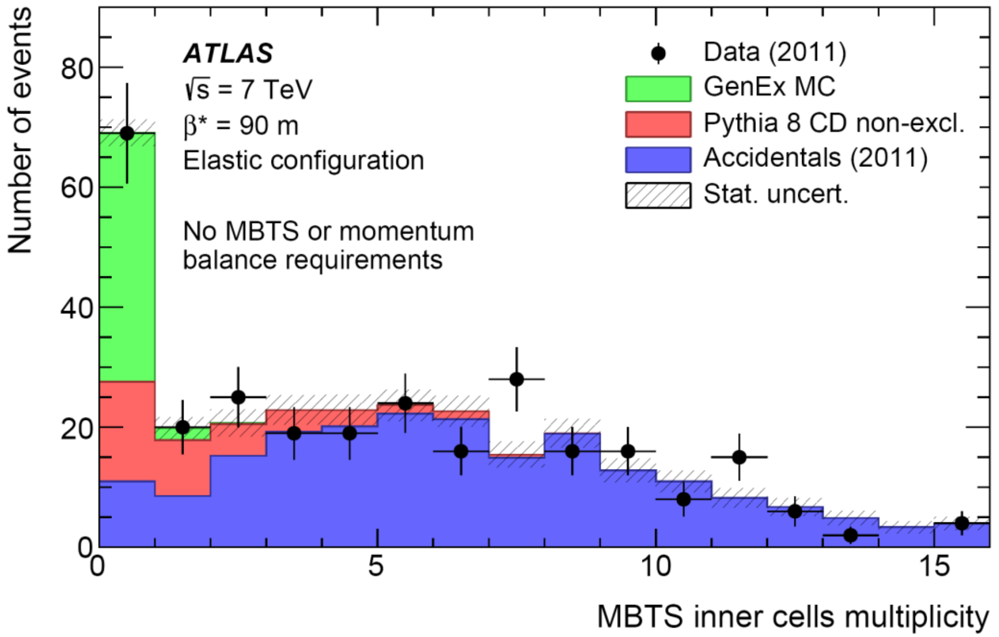
$$|\eta(\pi)| < 2.5,\ p_{\mathrm{T}}(\pi) > 0.1\ \mathrm{GeV},\ 2m_\pi < m_{\pi\pi} < 2.0\ \mathrm{GeV}$$

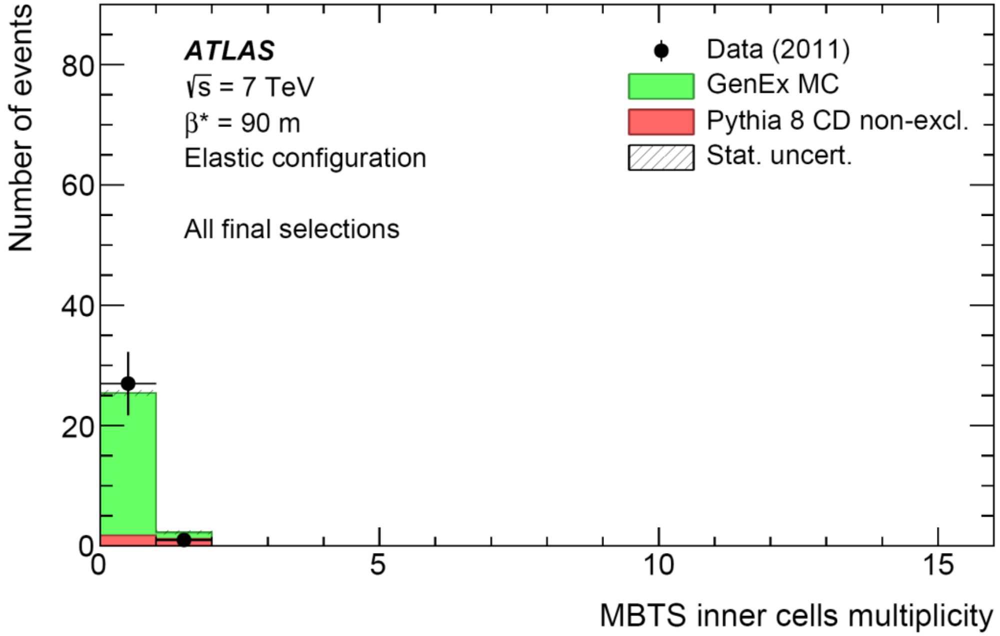
$$\mathrm{armlet}_{ij}^{\mathrm{low\_cut}} < p_{\mathrm{y}}(\mathrm{A}) < \mathrm{armlet}_{ij}^{\mathrm{up\_cut}} \quad \text{and} \quad \mathrm{armlet}_{kl}^{\mathrm{low\_cut}} < p_{\mathrm{y}}(\mathrm{C}) < \mathrm{armlet}_{kl}^{\mathrm{up\_cut}}$$

$$ijkl \in \{1368, 2457, 1357, 2468\}$$

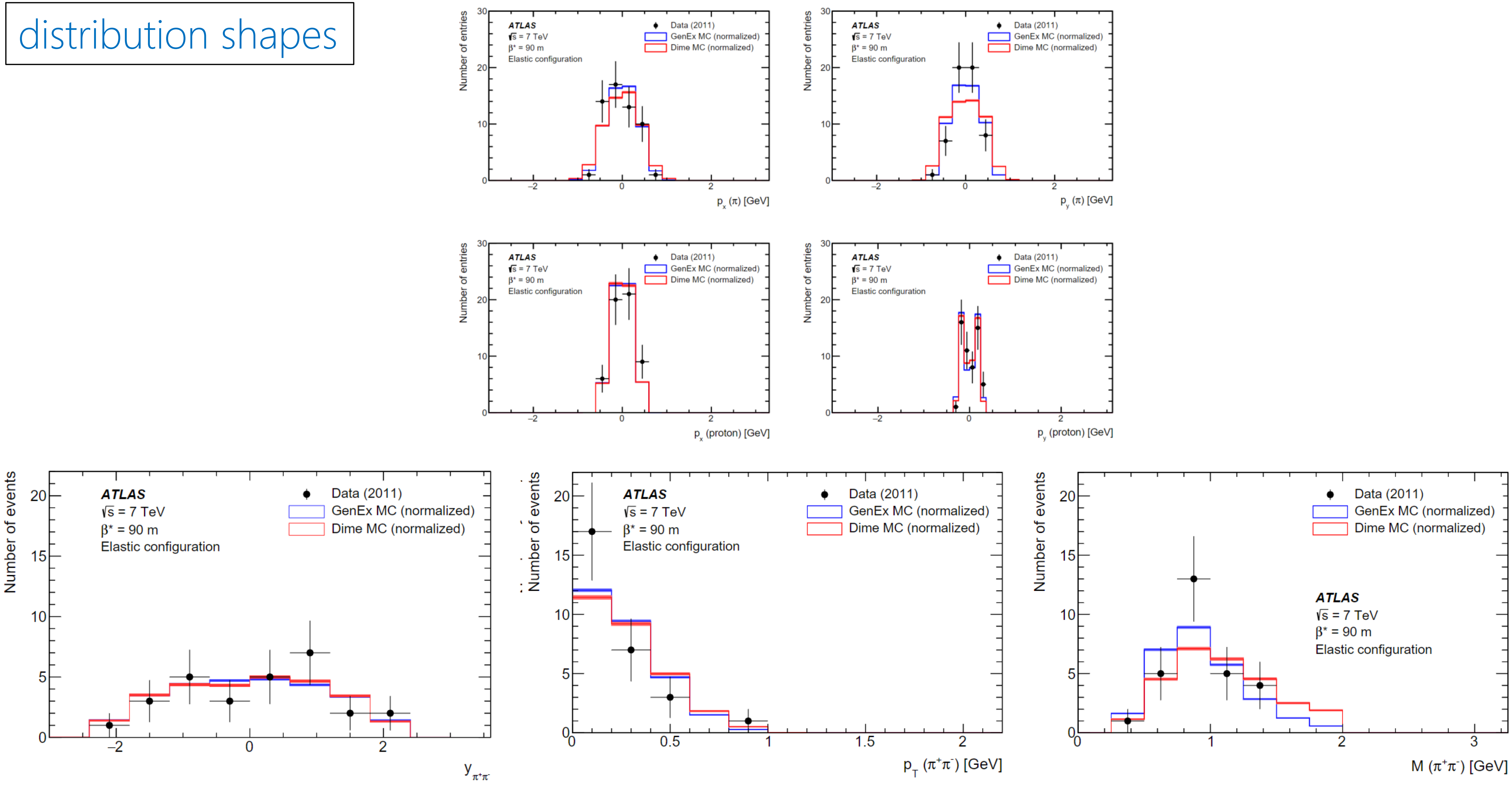
Selection	Configuration	
	elastic	anti-elastic
Recorded ATLAS events	6 620 953	
Data quality and trigger preselections	1 106 855	397 683
ID selection (pion pair)	1 520	1 115
ALFA track selection (incl. clean track and *uv*-condition)	486	11
MBTS veto	136	5
ALFA geometry condition	96	5
Full system momentum balance in *x* and *y*	30	3
Fiducial region	28	3
(arm 0 + arm 1) **Total selected**	(18+10) **28**	(2+1) **3**

Generators and background estimation





distribution shapes



systematic uncertainties and results

Source of uncertainty	Uncertainty [%] elastic	Uncertainty [%] anti-elastic
Trigger efficiency ϵ_{trig}	±0.1	±0.3
Background determination	±3.5	±3.5
Signal and background corrections:		
Beam energy	±0.1	±0.1
ID material	+4.8	+4.1
Veto on MBTS signal	±1.3	±2.0
ALFA single-track selection	±0.9	±0.9
ALFA reconstruction efficiency	±0.9	±0.8
ALFA geometry selection	±0.5	±0.5
Optics	±1.1	±1.0
Overall systematic uncertainty	$^{+6.4}_{-4.2}$	$^{+6.0}_{-4.4}$
Statistical uncertainty	±21.2	±61.6
Theoretical modelling	±2.8	±8.0
Luminosity	±1.2	±1.2

$$\sigma_{\pi^+\pi^-}^{\text{vis, conf}} = \frac{1}{L} \times \left[\left(N_0^{\text{conf}} - B_0^{\text{conf}} \right) \times C_0^{\text{conf}} + \left(N_1^{\text{conf}} - B_1^{\text{conf}} \right) \times C_1^{\text{conf}} \right] \times \frac{1}{\epsilon_{\text{trig}}^{\text{conf}} \cdot \epsilon_{\text{DAQ}}}$$

the meaning of parameters is similar to the case of the total cross section measurement except of the correction factor C^{conf}_i, which covers *uv*-condition and single track selection

	Exclusive $\pi^+\pi^-$ cross-section [μb]
Elastic configuration	
Measurement	4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) ± 0.1 (lumi) ± 0.1 (model)
GenEx × 0.22 (absorptive correction)	1.5
Dime	1.6
Anti-elastic configuration	
measurement	9 ± 6 (stat) $^{+1}_{-1}$ (syst) ± 1 (lumi) ± 1 (model)
GenEx × 0.22 (absorptive correction)	2
Dime	3

the results may be compared with cross-sections provided by MC generators using the same fiducial region definition but due to the lack of statistics no conclusion can be made

conclusion

A. total cross section via optical theorem

- $$\begin{aligned}\sigma_{\text{tot}}(pp \to X) &= 104.68 \pm 1.08\ (\text{exp.}) \pm 0.12\ (\text{th.})\ \text{mb},\\ \rho &= 0.0978 \pm 0.0085\ (\text{exp.}) \pm 0.0064\ (\text{th.}),\\ B &= 21.14 \pm 0.13\ \text{GeV}^{-2},\\ C &= -6.7 \pm 2.2\ \text{GeV}^{-4},\\ D &= 17.4 \pm 7.8\ \text{GeV}^{-6}.\end{aligned}$$

- the low value of ρ and our measurement of σ_{tot} are in tension with the standard evolution models like COMPETE
- measurements of σ_{tot} are systematically lower than the results from TOTEM (5.9 mb, 2.2 σ at 13 TeV); the difference is mostly in the normalization

B. visible exclusive pion pair production, $pp \to pp\pi^+\pi$

- $\sigma^{\text{visible}}_{\text{elastic}}(pp \to pp\pi^+\pi) = 4.8 \pm 1.0\ (\text{stat})\ ^{+0.3}_{-0.2}\ (\text{syst}) \pm 0.1\ (\text{lumi}) \pm 0.1\ (\text{model})$
- $\sigma^{\text{visible}}_{\text{anti-elastic}}(pp \to pp\pi^+\pi) = 9 \pm 6\ (\text{stat})\ ^{+1}_{-1}\ (\text{syst}) \pm 1\ (\text{lumi}) \pm 1\ (\text{model})$
- the first observation at the LHC with the forward proton, ALFA detector based, tag…

for (some/other) related additional experimental and theoretical considerations see the talk of Rafal Staszewski

ALFA detector: for (some) experimental details see the talk of Peter Bussey backup

models

Model	global χ^2/Ndof	ALFA partial χ^2/Ndof	TOTEM partial χ^2/Ndof	LHC data included in model tuning
COMPETE HPR1R2	1.42	3.00	3.50	A 7; T 7, 8
FMO	1.61	9.50	0.13	T 7, 8, 13
BCBM	1.03	0.81	2.04	all
KMR		0.85	2.29	A 7, 8; T 7, 8, 13
HEGS		8.10	0.83	A 7; T 7, 8
BJAS		11.90	0.29	A 7; T 7, 8, 13

the best agreement with ALFA data observed for the BCBM model (damped amplitude) and the KMR model

main messages:

1. "standard" evolution model like COMPETE is not able to describe simultaneously σ_{tot} and ρ
2. new effects in the evolution are observed, if these are induced by the Odderon or a flatter energy evolution of σ_{tot} will need to be studied further
3. the situation complicated by the σ_{tot} discrepancy between ALFA and TOTEM

models II

COMPETE Collaboration, J. R. Cudell et al., *Benchmarks for the Forward Observables at RHIC, the Tevatron Run II and the LHC*, Phys. Rev. Lett. 89 (2002) 201801, arXiv: hep-ph/0206172 [hep-ph]

M. M. Block and R. N. Cahn, *Forward Hadronic pp and $p\bar{p}$ Elastic Scattering Amplitudes: Analysis of Existing Data and Extrapolations to Collider Energies*, Phys. Lett. B 120 (1983) 224

C. Bourrely and A. Martin, *Theoretical predictions for pp and p anti-p elastic scattering in the TeV energy domain*,
CERN - ECFA Workshop on Feasibility of Hadron Colliders in the LEP Tunnel, 1984, url:
https://cds.cern.ch/record/153114

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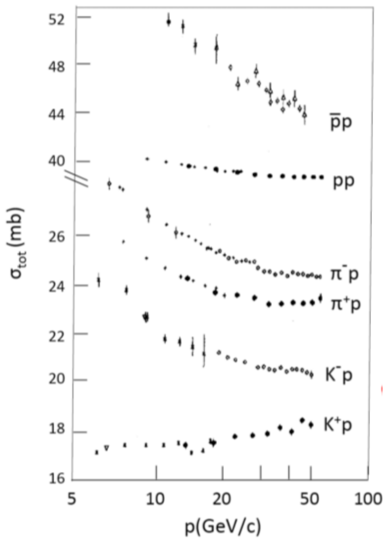
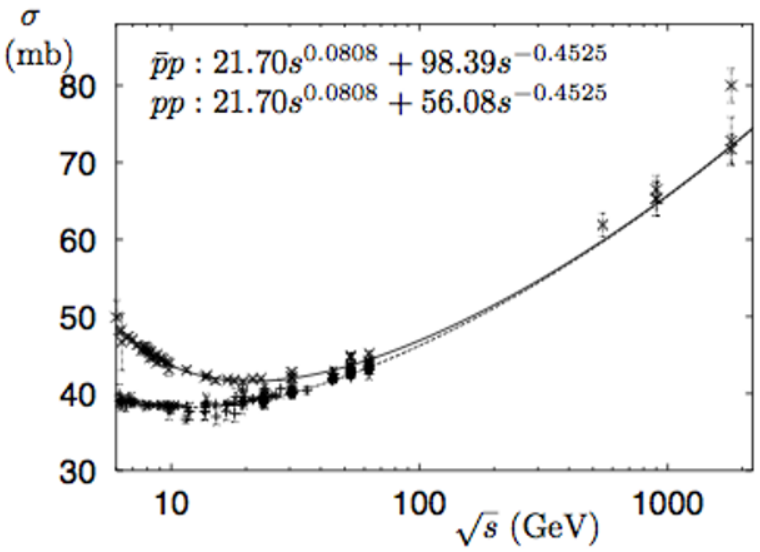
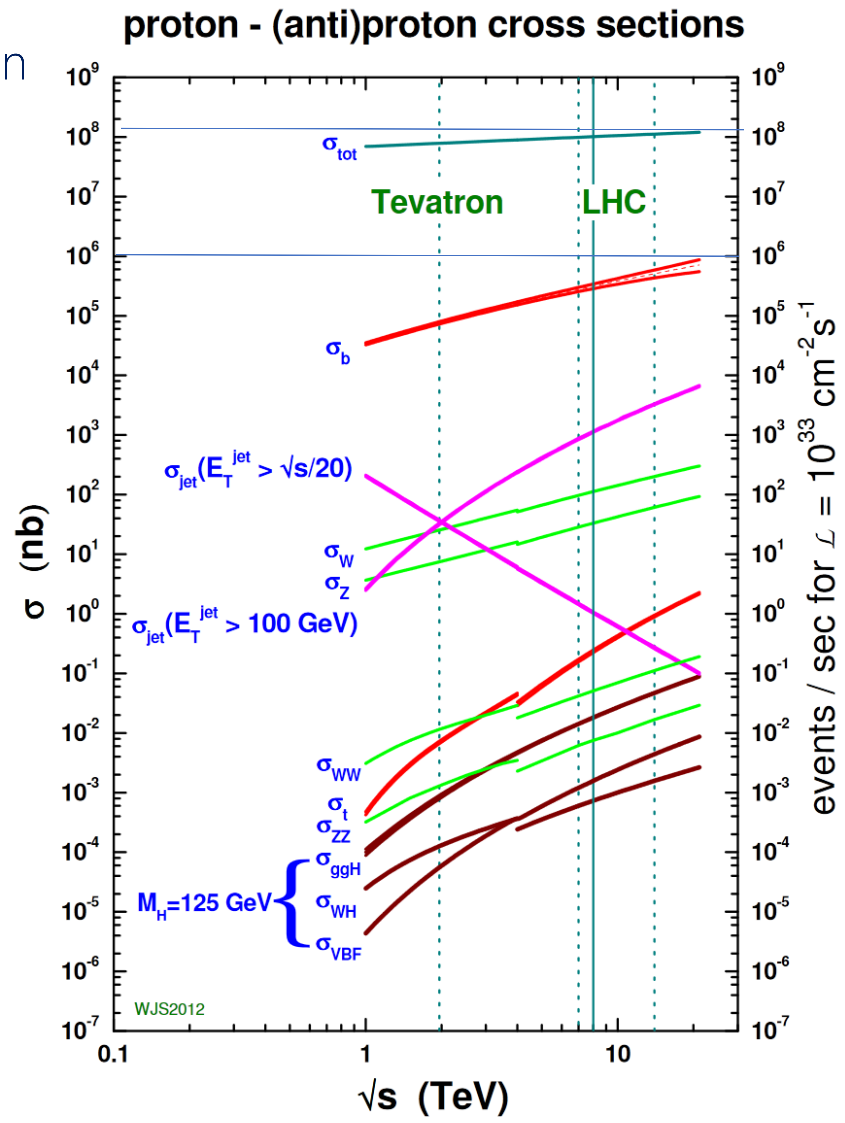
total cross section σ_{tot} of proton-proton interaction

σ_{tot} of p-p interaction is a fundamental quantity giving the upper bound on probability (cross section) of any process in p-p collisions

- 1973 – Intersection Storage Rings (ISR): **rising of σ_{tot} value**



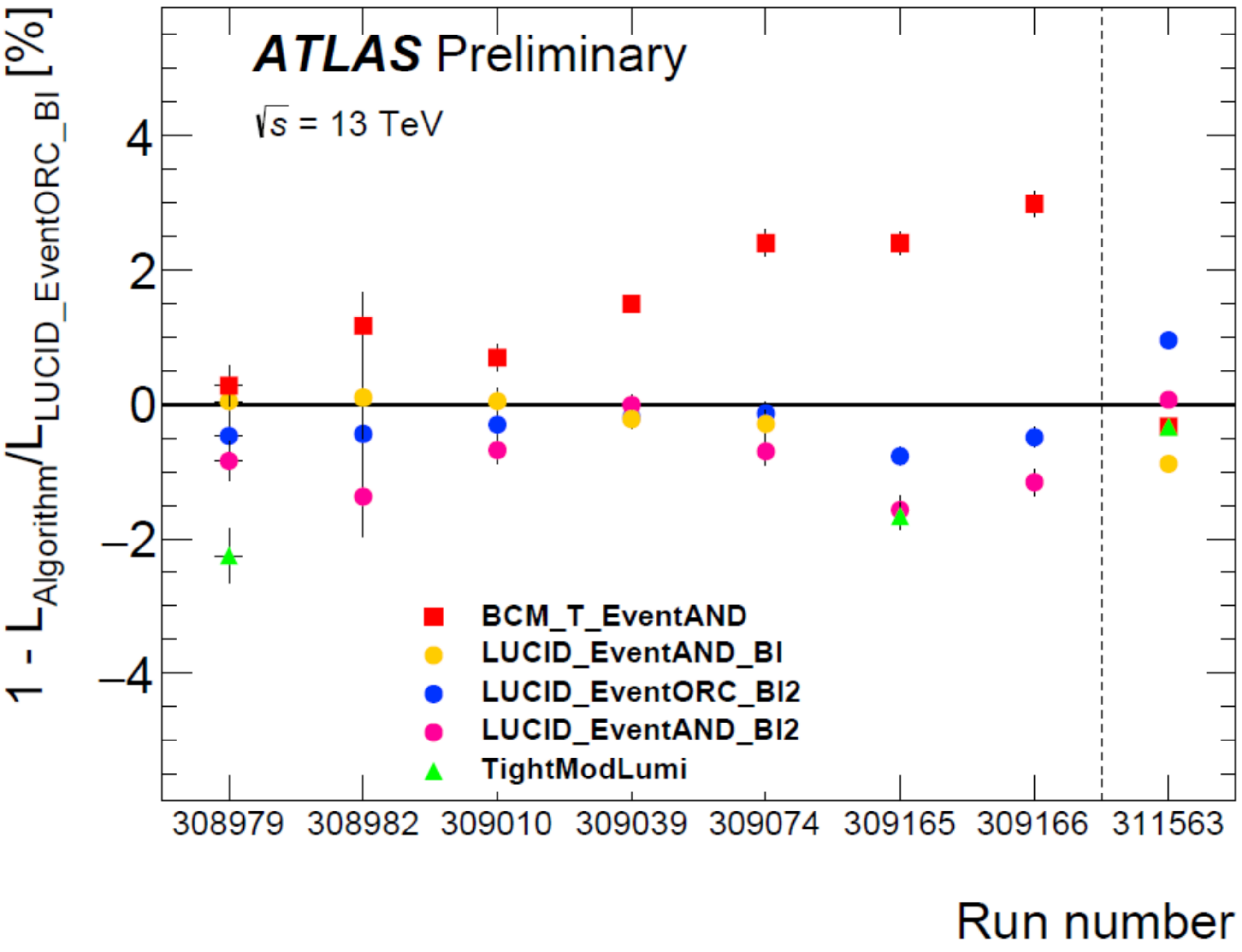




measurement of σ_{tot} at LHC energies – TOTEM and ALFA

at higher energies (57 TeV) – cosmic showers, Auger experiment

luminosity



a dedicated analysis of the luminosity for this special low-μ run was performed

the main uncertainty is derived from the stability of different algorithms with respect to the nominal algorithm from ATLAS detector LUCID

- calibration transfer, long-term stability and background uncertainty: 1.85%
- vdM calibration uncertainty: 1.1%
- total uncertainty: 2.15%

$$L_{\text{int}} = 339.9 \pm 0.1\ (\text{stat.}) \pm 7.3\ (\text{syst.})\ \mu\text{b}^{-1}$$