ATLAS EXPERIMENT

News from the strong interaction and its most difficult aspect

Why measure the pp cross section and its related challenges

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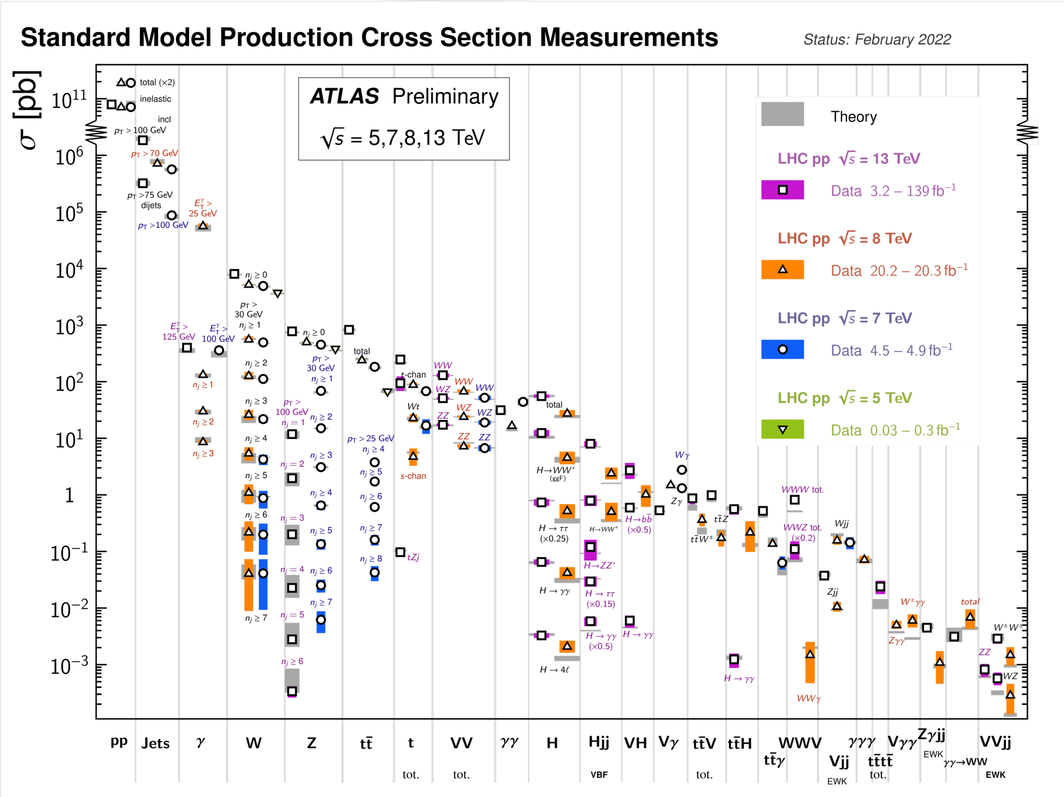
A bit of context…

Typical measurements at LHC

- ➢ SM processes (EW, QCD)
- ➢ New physics (SUSY, Exotics, DM,…)



→All these processes account for **~60% of the total pp cross section**…**what about the rest?**

- ➢ Low p_T diffractive processes (el. scattering, single/double diffractive dissociation)
- ➢ Very forward processes → need specialized detectors!

Why is forward physics important?

- ✓ Cross section not-calculable from pQCD → **experimental approach needed!**
- ✓ Crucial for **Monte Carlo simulations** especially at high pile-up
- ✓ We can have predictive power for high energy scales → cosmic ray physics and **FCC**!

Measuring σ_{TOT} and ρ

At ATLAS, we can measure σ_{TOT} via elastic scattering

Optical theorem $\sigma_{tot} = 4\pi Im[f_{el}(t \to 0)]$

$$\sigma^2_{tot} = \frac{16\pi(\hbar c)^2}{1+\rho^2} \left.\frac{d\sigma_{el}}{dt}\right|_{t\to 0} \quad \text{and} \quad \rho = \left.\frac{Re[f_{el}(t)]}{Im[f_{el}(t)]}\right|_{t\to 0}$$

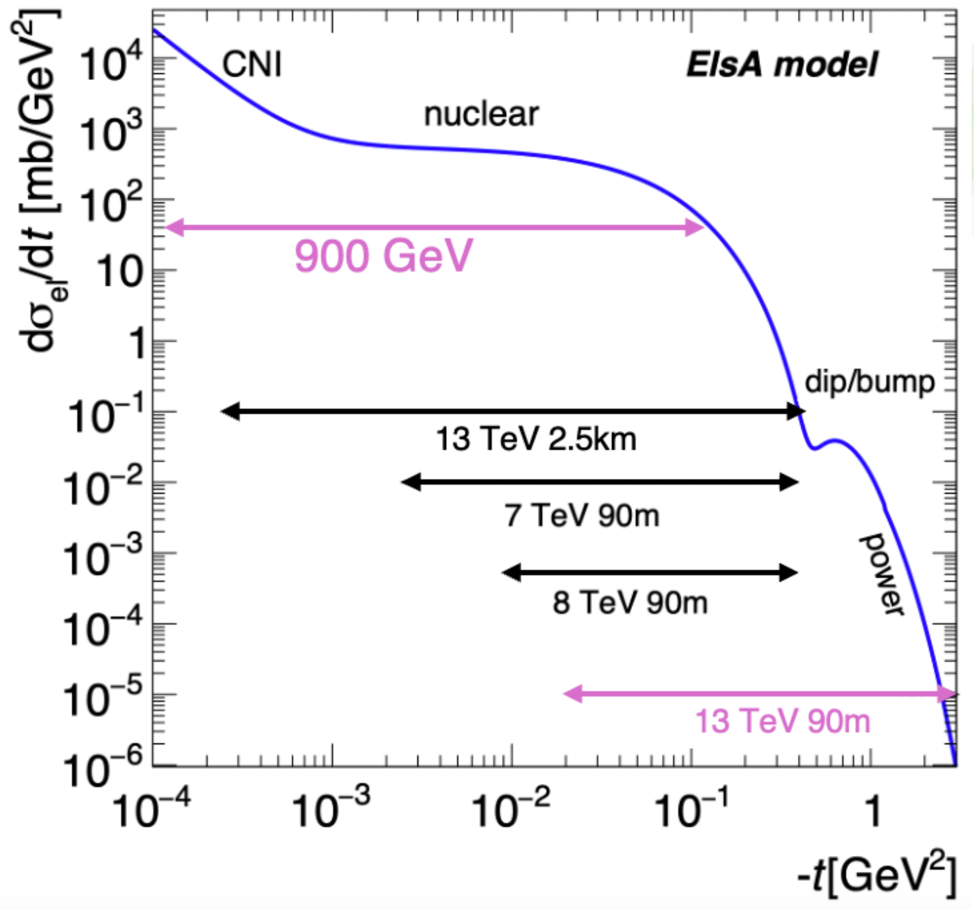
→ Measure the differential elastic cross section → get ρ and σ_{TOT}

→ Different beam conditions and $\sqrt{s}$ values allow to investigate different regions of the σ_{el} spectrum

Who performs these measurements?

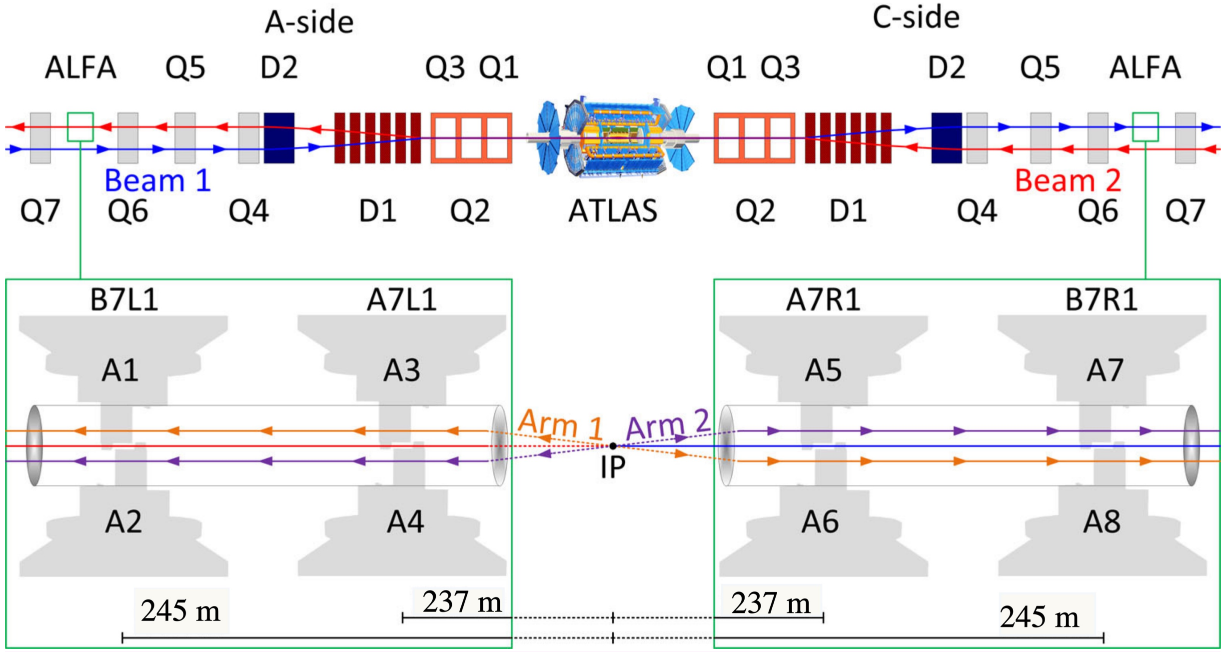
ALFA → designed to measure small-angle proton scattering

LUCID + Inner Detector → provide luminosity to normalize σ_{el}



Already 3 measurements published and 2 more are ongoing!

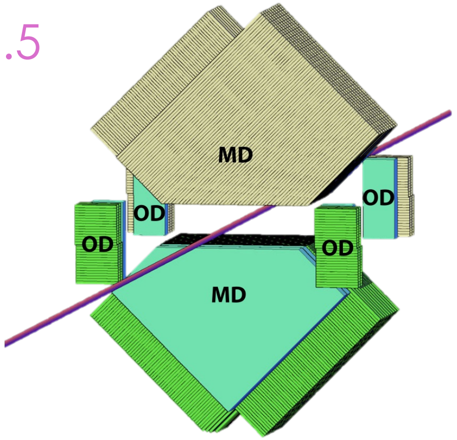
ALFA



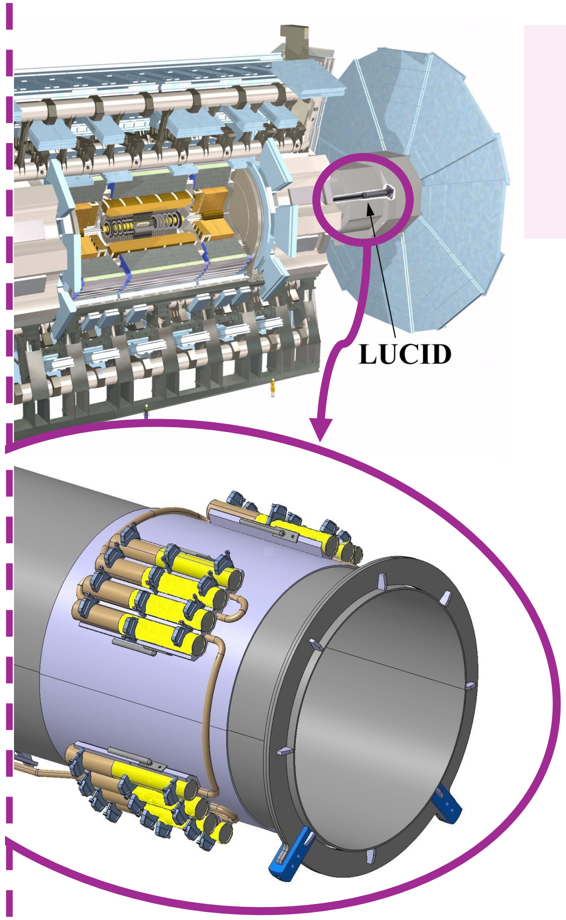
Two tracking stations in vertical Roman Pots

→ detection of protons at $|\eta| > 8.5$

layers of staggered scintillating fibers



LUCID



16 PMTs for each side of ATLAS (A and C) at 17m from IP

- Measure Cherenkov light produced on PMT quartz window
- Gain monitoring system with ^{207}Bi

measured

machine parameters, known

$$\mathscr{L} = \frac{\mu_{vis} n_b f_r}{\sigma_{vis}}$$

from vdM scans

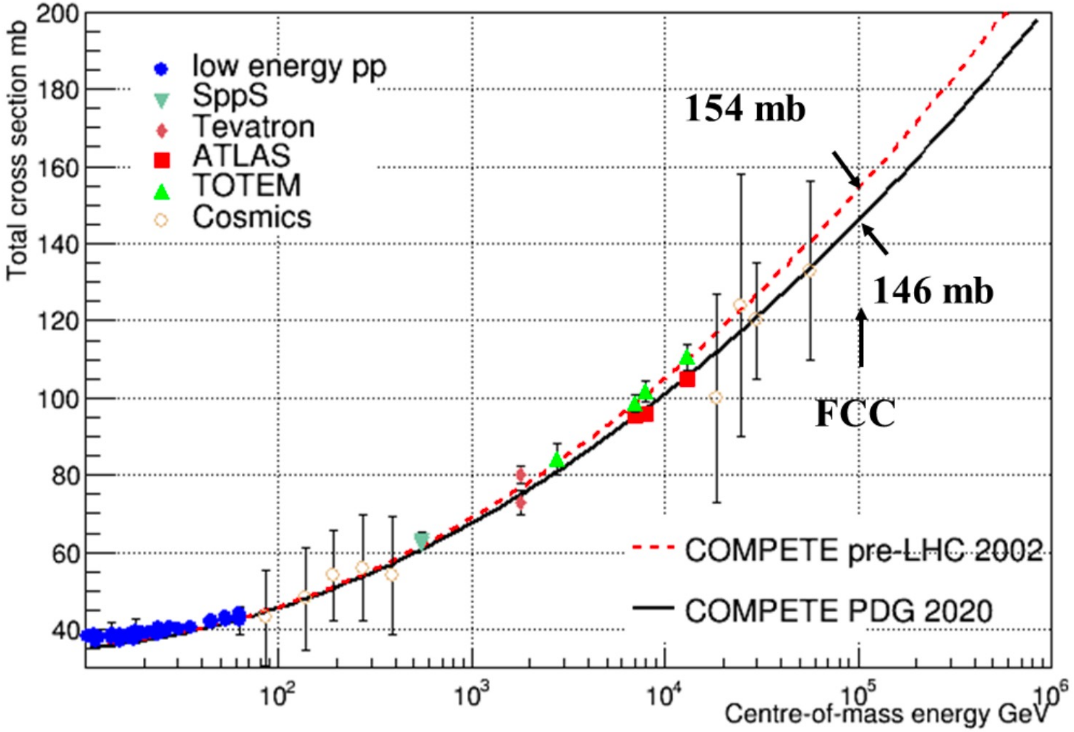
Single PMTs act as independent detectors or be combined in **global algorithms**

The total cross-section for FCC

- σ_{tot} cannot grow faster than $ln^2(s)$ (Froissart-Martin bound)

- ρ at a given energy becomes sensitive to the energy evolution of σ_{tot} beyond that energy (given dispersion relations)

→ **We can be sensitive to σ_{tot} at the FCC expected $\sqrt{s}$!**



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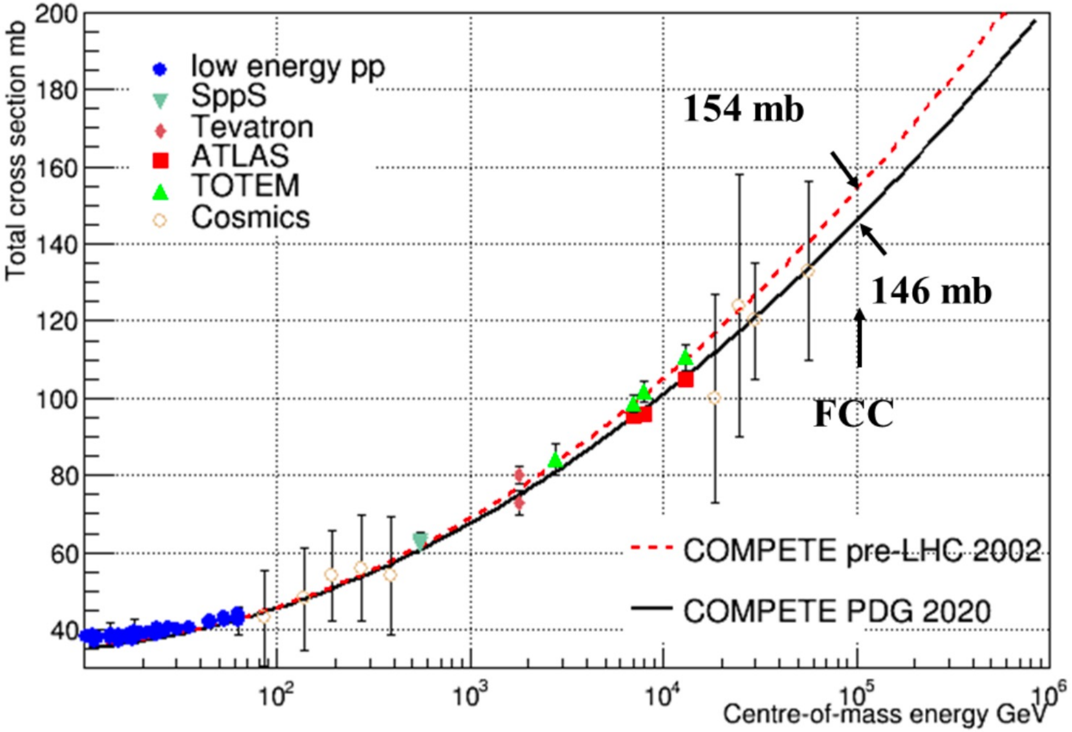

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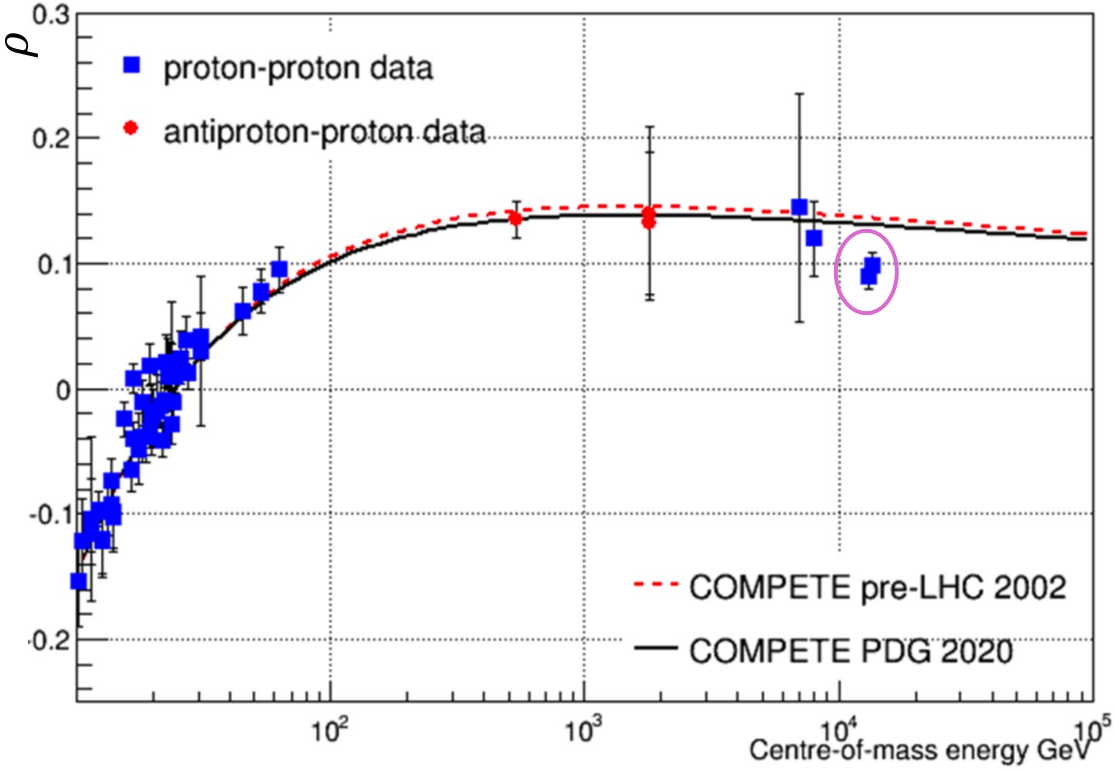

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BUT

Two recent **measurements of ρ** (by TOTEM and ATLAS) **do not agree with predictions** from dispersion relation using the $ln^2(s)$ parametrisations

→ We need to understand what is the cause of this ~3σ (!) discrepancy

Understanding the discrepancy: 900 GeV ATLAS/ALFA runs

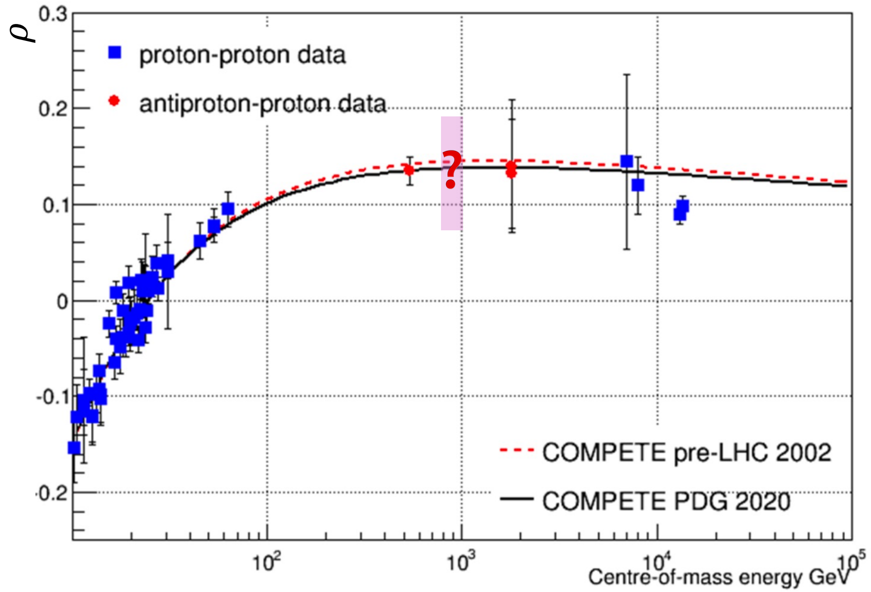
1) σ_{tot} grows slower than predictions at energies beyond LHC
2) Possible existence of the Odderon ($CP = - -$ state of 3 gluons)

→ Considering these two scenarios σ_{tot} at FCC energies will lie in the range 130 -155 mb

How can we discern between these two cases?

An interesting measurement can be performed by ALFA at $\sqrt{s} = 900$ GeV

See Ref. 3



If the explanation is 1) → no influence on the ρ value at $\sqrt{s} = 900$ GeV and data would then agree with prediction

If the explanation is 2) → it could affect ρ at this energy and the ρ measurement will be at tension wrt prediction

The smallest possible uncertainty on ρ and σ_{tot} is needed
→ A major – often *the* major – contribution to the systematic uncertainty has been the luminosity uncertainty

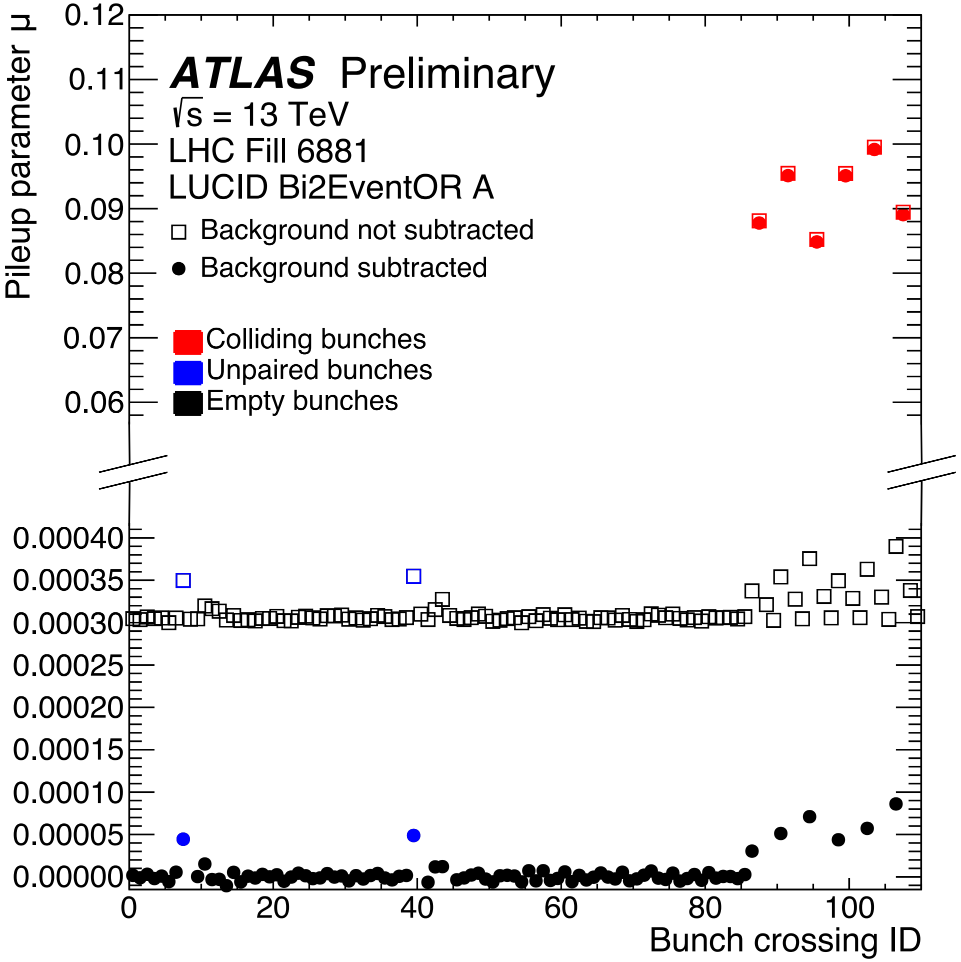
Luminosity measurement in ALFA runs

14 runs at low-luminosity and high-β* (100m vs ~25cm in usual physics runs) done in 2018 at $\sqrt{s} = 900$ GeV

Approach to luminosity measurement in ALFA runs

1. Measure the background-subtracted absolute luminosity (or μ), with various LUCID algorithms, calibrated in vdM scans

2. Compare different detectors and algorithms to account for:
   - Background subtraction uncertainty
   - Stability and algorithms compatibility



$$\mu = \mu_{vis}\sigma_{tot}/\sigma_{vis}$$

Background subtraction

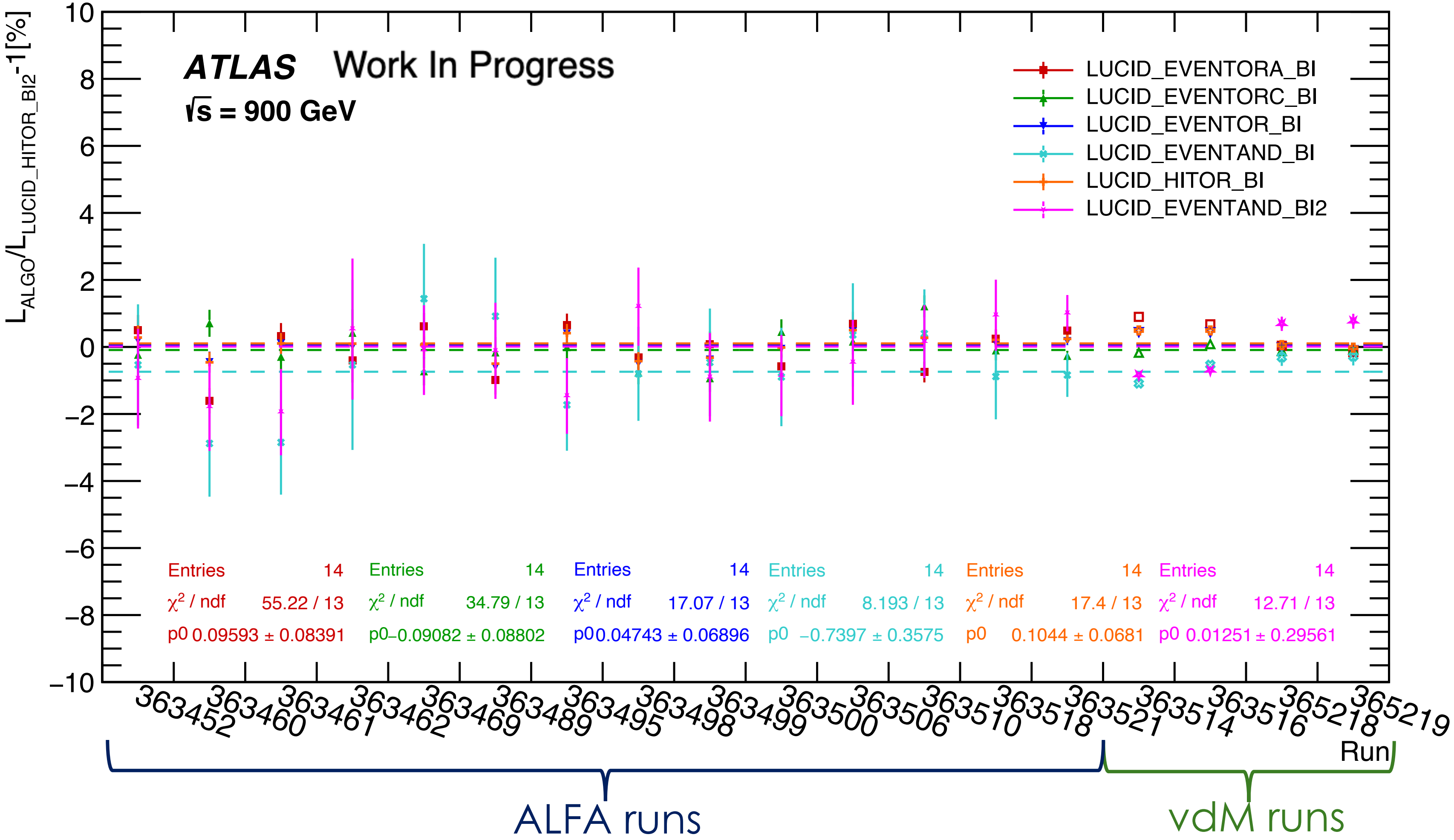
- Constant rate from ^{207}Bi activity
- Afterglow from nuclear de-excitation after collisions

+ Single-beam (beam-gas) interactions

⇨ To be carefully evaluated using unpaired (non-colliding, filled) bunches

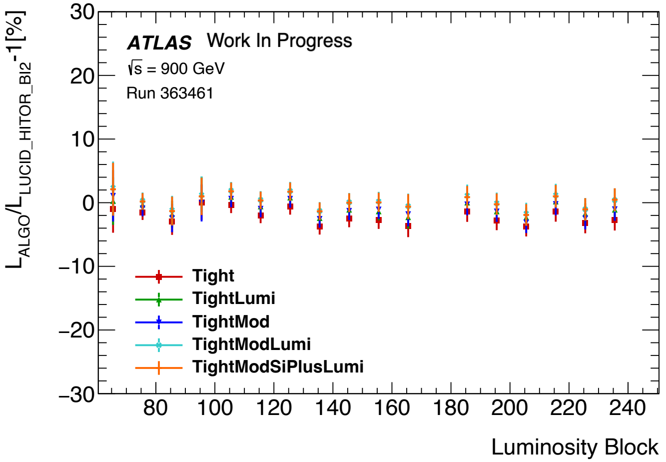
Luminosity measurement at 900 GeV

- ➢ Ad-hoc van der Meer scans were needed to provide absolute luminosity calibration → very challenging analysis
- ➢ Accurate evaluation of background, whose magnitude can compete with signal



- ➢ Relative algorithms stability is compared → input on the systematic uncertainty

- ➢ Track Counting luminosity data also considered



Luminosity measurement at 900 GeV

Difficult evaluation of the single-beam background due to the low-luminosity and different beam currents in the filled colliding vs unpaired bunches

Many methods have been tested and developed

- Observe the data looking for clear indications of beam-gas bkg
- Use the nominally empty bunches and compare them with the unpaired ones
- Use the LUCID AND algorithm: a logic AND between the two sides of LUCID allows to cut down on background and obtain a background free algorithm

RESULTS (WORK IN PROGRESS!)

Integrated luminosity and its statistical uncertainty $\mathscr{L} = 1437.58 \pm 0.65_{stat}\,\mu b^{-1}$

Systematic uncertainty →

Source	Sys. Uncertainty (%)
Stability (LUCID EVENTAND BI)	1.50
vdM Calibration	1.85
Beam Gas	0.74
TOTAL	2.49

WORK IN PROGRESS!

Conclusion

- σ_{tot} is a pivotal parameter for hadron colliders
- There are open questions regarding σ_{tot} evolution, which can result from new physics

ATLAS and ALFA have an ongoing **measurement at $\sqrt{s} = 900$ GeV** in order to constrain σ_{tot} and ρ evolution → their measurement aims to **discern between two alternative explanations of the disagreement of the ρ measurement** of TOTEM and ATLAS at 13 TeV wrt the expected evolution

The luminosity uncertainty could be the determining factor of this measurement's discriminating power → precise estimate required

- ➢ **Very challenging beam-conditions affect the luminosity uncertainty evaluation** → in-depth beam gas study was required and the use of less-used LUCID algorithms
- ➢ Currently the **luminosity measurement is waiting for approval** and the final uncertainty is expected to be of the order of 2.5% total luminosity uncertainty

STAY TUNED! ☺

REFERENCES

1. Marcel Froissart. Asymptotic behavior and subtractions in the mandelstam representation. Phys. Rev., 123:1053–1057, 1961.
2. Andre Martin. Extension of the axiomatic analyticity domain of scattering amplitudes by unitarity-i. Il Nuovo Cimento A (1965-1970), 42(4):930–953, 1966.
3. P. Grafstrom, The total cross section for proton-proton interactions at the FCC, arXiv:2306.15449v1 [hep-ph] 27 Jun 2023
4. ATLAS Collaboration,Luminosity determination in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector at the LHC,(2022), arXiv: 2212.09379
5. ATLAS Collaboration, Measurement of the total cross section from elastic scattering in $p\,p$ collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, Nucl. Phys. B 889 (2014) 486
6. ATLAS Collaboration, Measurement of the total cross section from elastic scattering in $p\,p$ collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector, Phys. Lett. B 761 (2016) 158
7. ATLAS Collaboration, Measurement of the total cross section and ρ-parameter from elastic scattering in $p\,p$ collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, Eur. Phys. J. C 83 (2023) 441

BACKUP

More about dispersion relations

Dispersion relations are based upon the Kramers-Kronig theorem.

Let $\chi(\omega) = \chi_1(\omega) + i\,\chi_2(\omega)$ be a complex analytic function of the complex variable ω where $\chi_1(\omega)$ and $\chi_2(\omega)$ are real

Then:

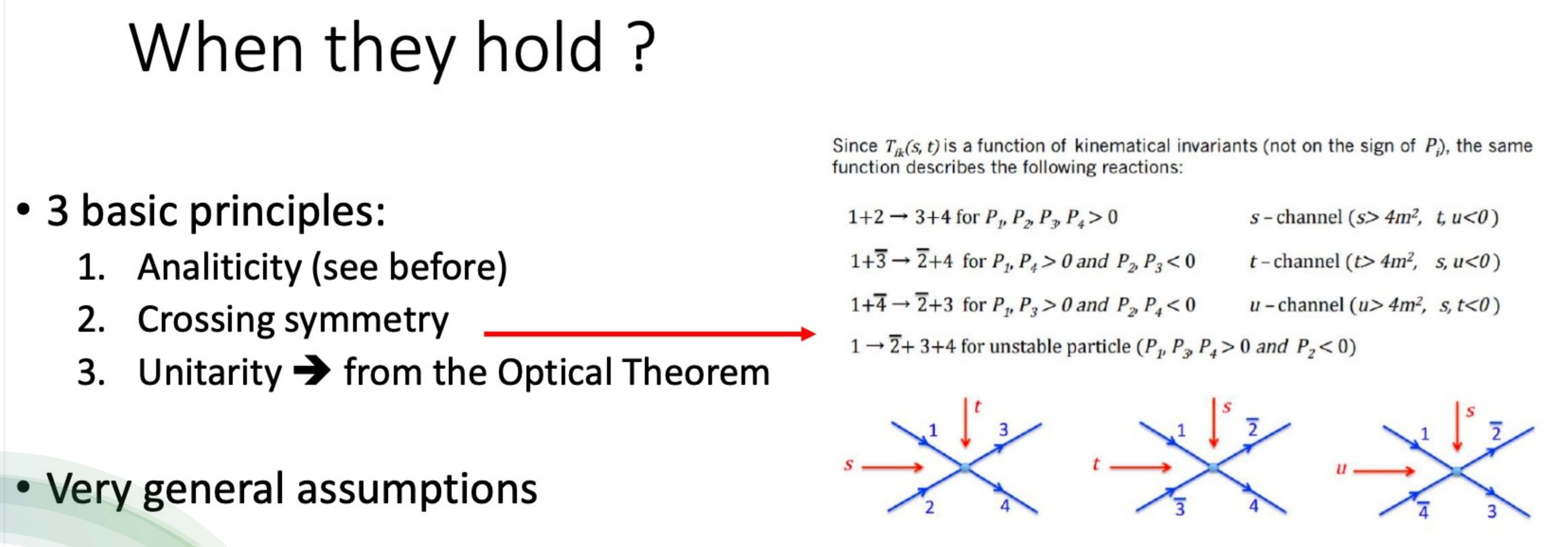
$$\chi_1(\omega) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} \frac{\chi_2(\omega')}{\omega' - \omega}\, d\omega'$$

derivation based upon the Cauchy integral theorem

Thus the Kramers-Kronig theorem gives a relation between the real and imaginary part of a complex analytic function.

Applied in many different field of physics

Rho measurement



When they hold ?

- 3 basic principles:
  1. Analiticity (see before)
  2. Crossing symmetry
  3. Unitarity ➔ from the Optical Theorem
- Very general assumptions

Since $T_{fk}(s, t)$ is a function of kinematical invariants (not on the sign of P_i), the same function describes the following reactions:

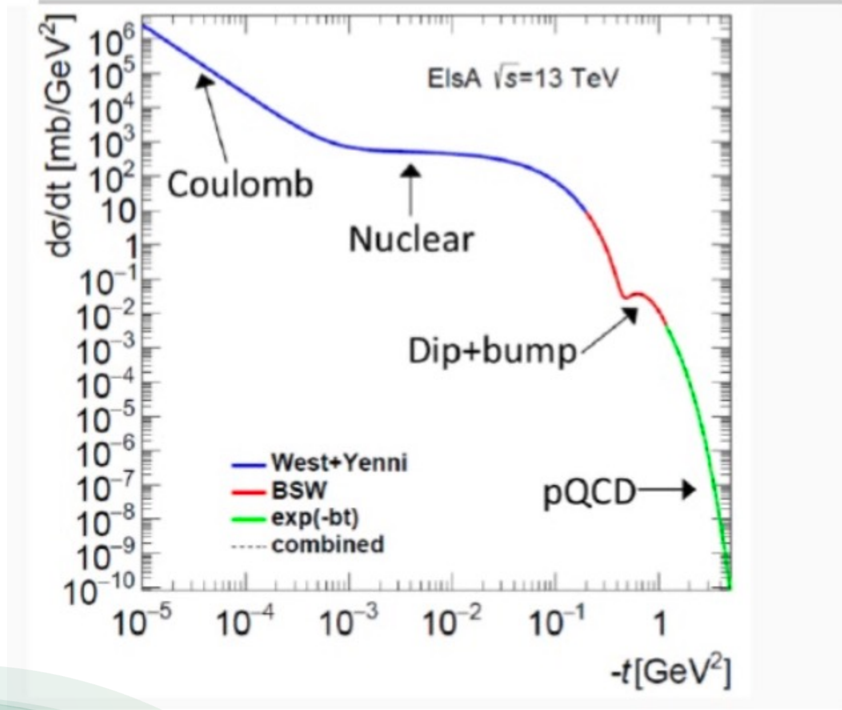
$1+2 \rightarrow 3+4$ for $P_1, P_2, P_3, P_4 > 0$ $\quad$ s – channel ($s > 4m^2$, $t, u < 0$)

$1+\overline{3} \rightarrow \overline{2}+4$ for $P_1, P_4 > 0$ and $P_2, P_3 < 0$ $\quad$ t – channel ($t > 4m^2$, $s, u < 0$)

$1+\overline{4} \rightarrow \overline{2}+3$ for $P_1, P_3 > 0$ and $P_2, P_4 < 0$ $\quad$ u – channel ($u > 4m^2$, $s, t < 0$)

$1 \rightarrow \overline{2}+ 3+4$ for unstable particle ($P_1, P_3, P_4 > 0$ and $P_2 < 0$)

Elastic scattering



- $p + p \longrightarrow p + p$
- Large range depending on the transferred momentum: $t = (p\theta)^2$
- Each t-range dominated by different processes
  - Need measurements in each t-range to access the different physics processes involved

1. The Coulomb interaction dominates at very-low t
2. Coulomb-Nuclear interference region
3. Pure nuclear region
4. the dip-region
5. pQCD region

Disp. Rel in elastic scattering

Analyticity of the elastic scattering amplitude $f_{el}(s,t)$ and ***crossing symmetry*** →
Re $f_{el}(s,t)$ is related to Im $f_{el}(s,t)$ via dispersion relations

$$\mathrm{Re}\ f_+(E) = C + \frac{E}{\pi}\int_m^\infty dE' \ \frac{\mathrm{Im}\ f_+(E')}{E'(E'-E)} - \frac{\mathrm{Im}\ f_-(E')}{E'(E'+E)}$$

Note: this relation is valid IF crossing symmetry holds. This implies that pp and pbar-p cross sections are the same asymptotically. If there is Odderon exchange this is no more True (Odderon is CP=--)

where C is real constant and + refers to proton-proton amplitude
and - to anti proton-proton amplitude

Unitarity → the optical theorem : $\sigma_{tot} = 4\pi/p$ Im $f_{el}(0)$

$$\mathrm{Re}\, f_+(E) = C + \frac{E}{4\pi^2}\int_m^\infty dE' p' \left(\frac{\sigma_+(E')}{E'(E'-E)} - \frac{\sigma_-(E')}{E'(E'+E)}\right) \rightarrow$$

$$\rho_\pm\sigma_\pm = \frac{B}{p} + \frac{E}{\pi p}\mathrm{P}\int_{m_p}^\infty \left[\frac{\sigma_\pm}{E'(E'-E)} - \frac{\sigma_\mp}{E'(E'+E)}\right] p'\, dE'$$

where σ_+ is the proton-proton total cross section and σ_- the anti-proton proton total cross section

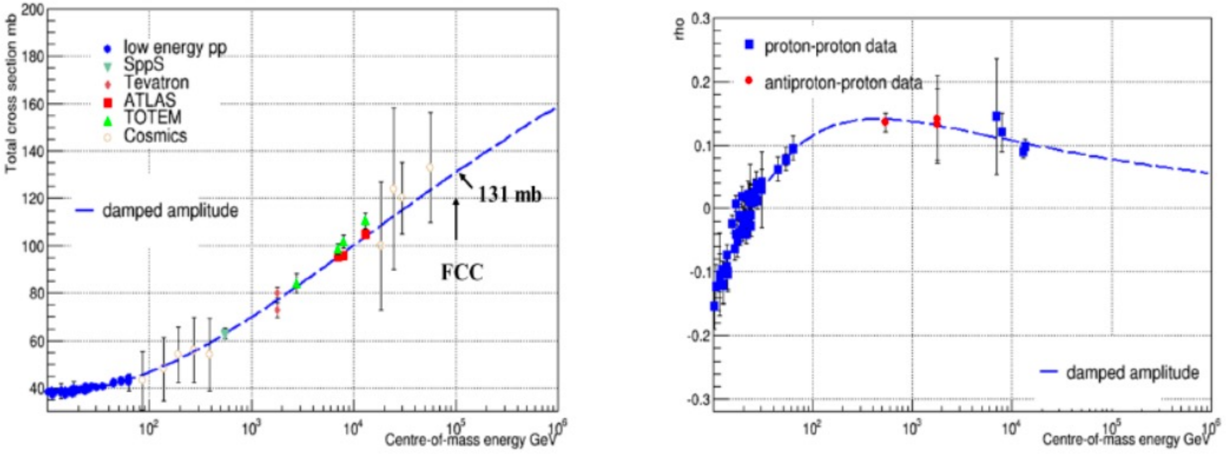
ρ = Re $f_{el}(s,t=0)$/Im $f_{el}(s,t=0)$

38

16

Predictions at FCC: slowing of sigmaTOT

$$\frac{ln^2\,(s)}{1+\alpha\; ln^2\,(s)}$$



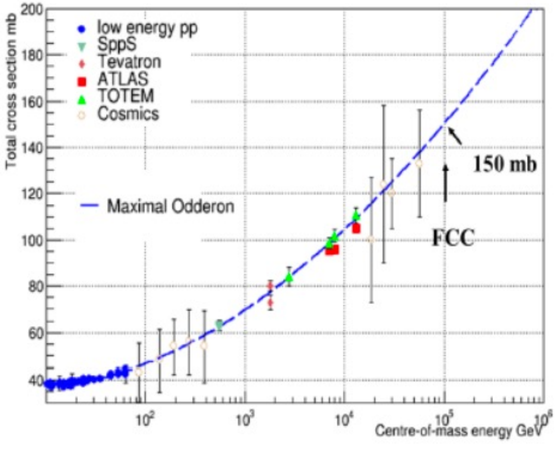
(a) σ_{tot} (b) ρ

Per Grafstrom

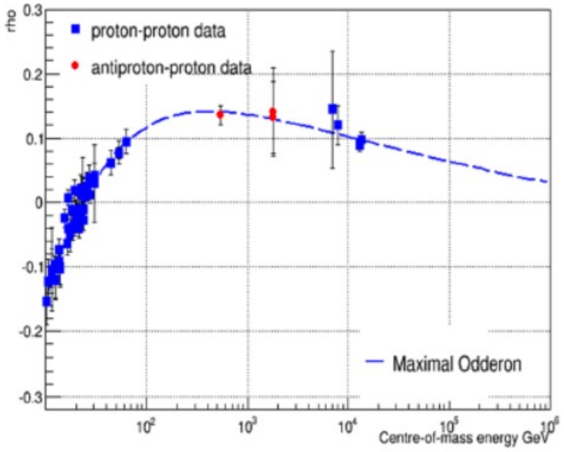
arXiv:2306.15449 [hep-ph]

- α included in the fit ➔ α = 0.0016
- Good fit of σ_{TOT} and ρ TOTEM and ATLAS data at 13 TeV
- σ_{TOT} flattens out at very high energy (original purpose of the proposed parametrization)
- σ_{TOT} at FCC energy (100 TeV) about 130 mb

Predictions at FCC: odderon



(a) σ_{tot}



(b) ρ

Per Grafstrom

arXiv:2306.15449
[hep-ph]

- Use of Maximal Odderon parametrization (see reference)
- Fit to TOTEM data of σ_{TOT} but discarded ATLAS data
- FCC predicted σ_{TOT} = 150 mb

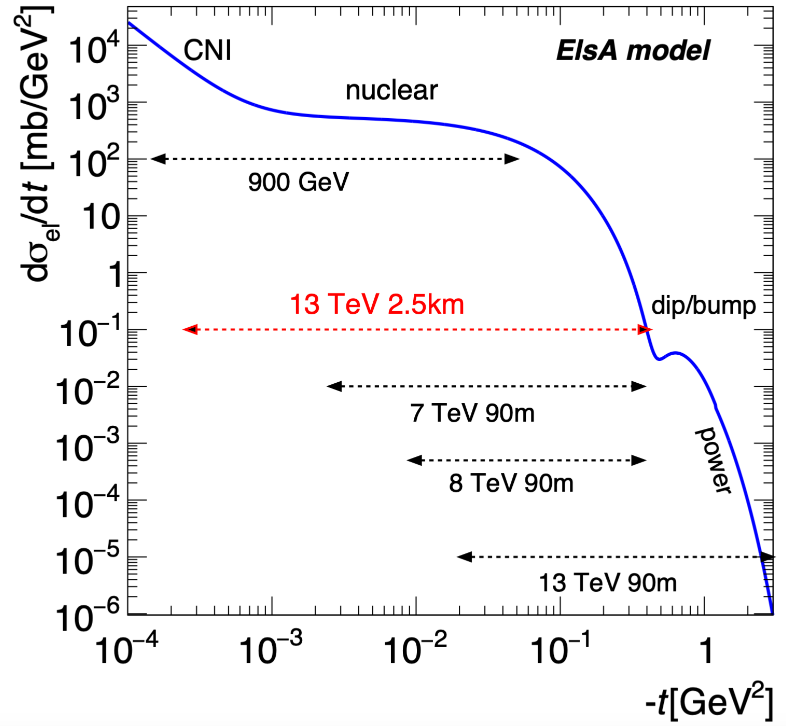
Analysis di ALFA

differential elastic cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{1}{16\pi}\left|f_{\mathrm{N}}(t) + f_{\mathrm{C}}(t)\mathrm{e}^{\mathrm{i}\alpha\phi(t)}\right|^2$$

$$\begin{aligned} f_{\mathrm{C}}(t) &= -8\pi\alpha\hbar c\frac{G^2(t)}{|t|} \quad , \\ f_{\mathrm{N}}(t) &= (\rho + \mathrm{i})\,\frac{\sigma_{\mathrm{tot}}}{\hbar c}\mathrm{e}^{-B|t|/2} \quad , \end{aligned}$$

f_{C} Coulomb amplitude
f_{N} purely strongly interacting amplitude
G electric form factor of the proton
B nuclear slope



We can then write

$$\begin{aligned} \frac{\mathrm{d}\sigma}{\mathrm{d}t} &= \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2} \times G^4(t) \\ &- \sigma_{\mathrm{tot}} \times \frac{\alpha G^2(t)}{|t|}\left[\sin\left(\alpha\phi(t)\right) + \rho\cos\left(\alpha\phi(t)\right)\right] \times \exp\frac{-B|t|}{2} \\ &+ \sigma_{\mathrm{tot}}^2 \frac{1+\rho^2}{16\pi(\hbar c)^2} \times \exp\left(-B|t|\right) \end{aligned}$$

← Coulomb interaction

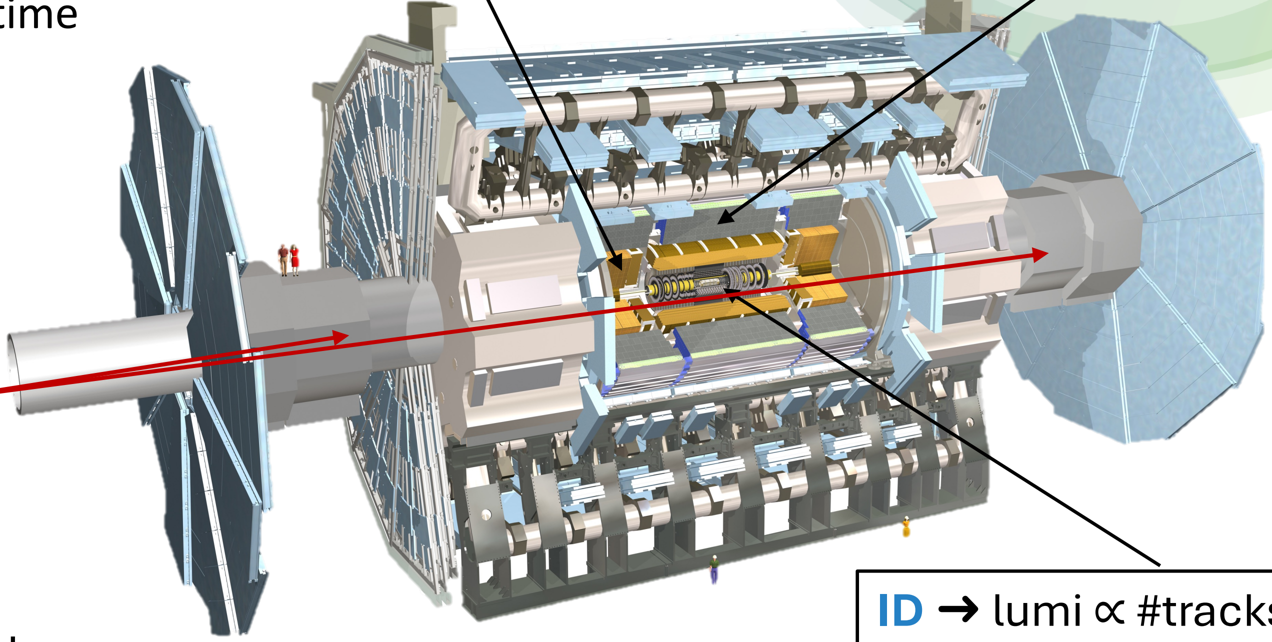
← Coulomb–nuclear interference

← Hadronic interaction

LUMINOSITY in ATLAS

$$\mathscr{L} = \frac{R}{\sigma} = \frac{\mu n_b f_r}{\sigma} = \frac{\mu_{vis} n_b f_r}{\sigma_{vis}}$$

$$\mu_{vis} = \epsilon\mu$$
$$\sigma_{vis} = \epsilon\sigma$$



LAr (ECAL and FCAL) ➔ read out LAr gap HV currents, O(1)s integration time

Tile ➔ lumi ∝ PMT current, integrates over O(10) ms

LUCID II ➔ ATLAS reference luminometer

- ➢ Only one which provides absolute luminosity measurement → vdM calibration
- ➢ Can provide online and offline lumi, both per-bunch and integrated, for any μ range

Except LUCID, in ALFA runs only tracks are available!

ID ➔ lumi ∝ #tracks, can provide per-bunch lumi

$\mu =$ average number of inelastic interactions per bunch crossing
$n_b =$ bunch pairs colliding per revolution
$f_r =$ revolution frequency

BCM ➔ only for low ⟨μ⟩ and HI runs **TPX** ➔ for radiation monitoring
Z-counting ➔ Cross-check of baseline luminosity vs time and μ