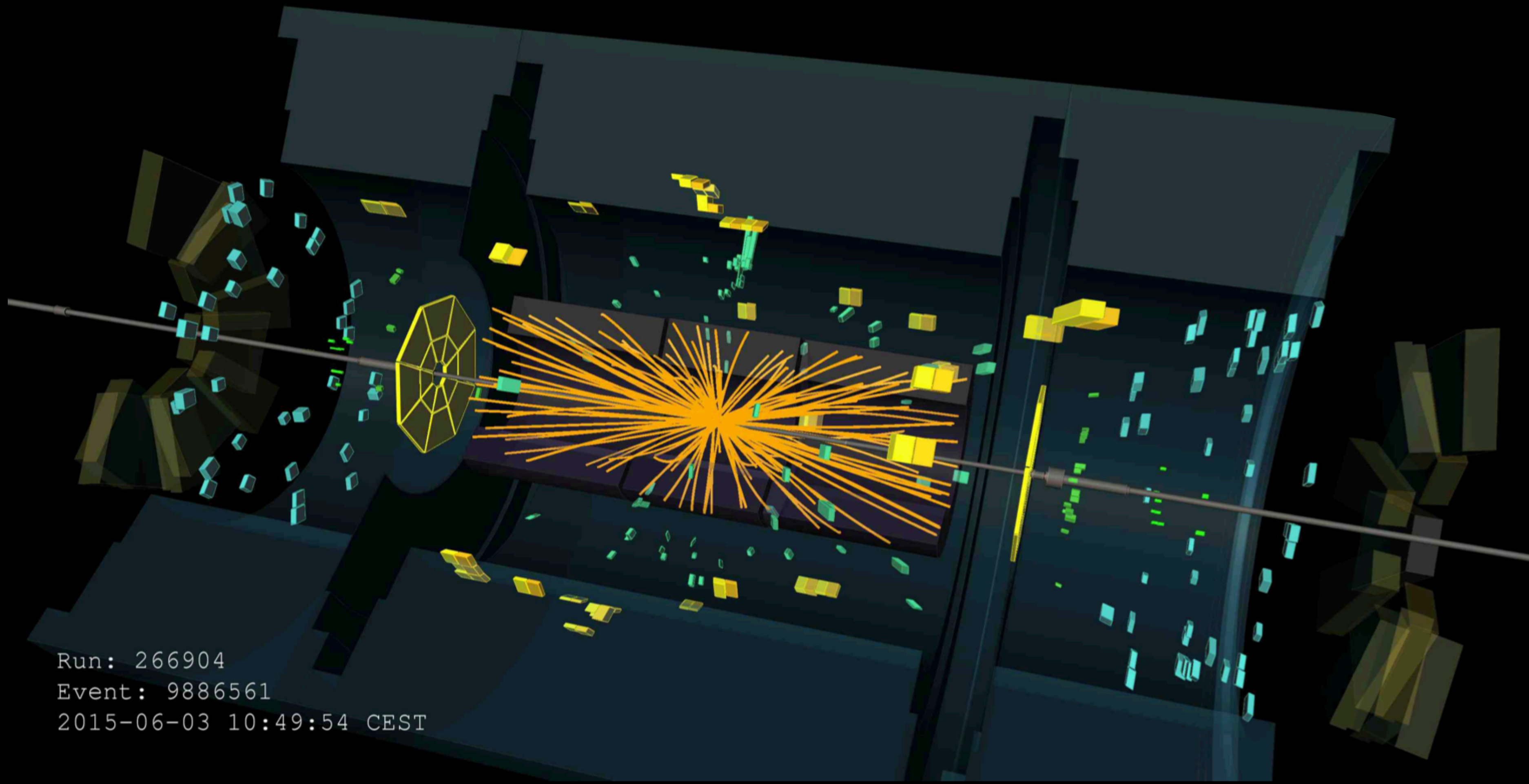
Diffractive, Elastic and Total Cross Section Physics at ATLAS

ATLAS EXPERIMENT



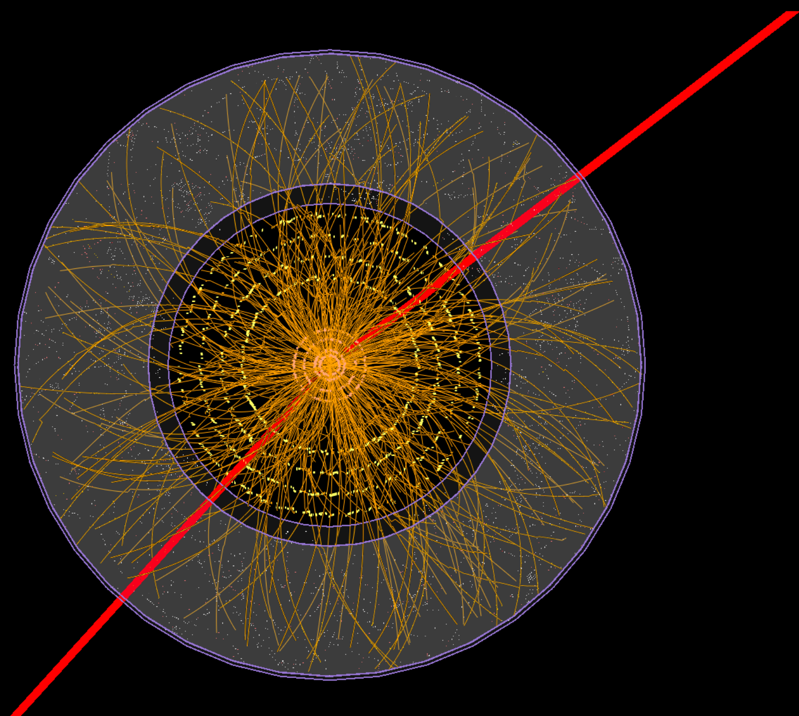
Lydia Beresford

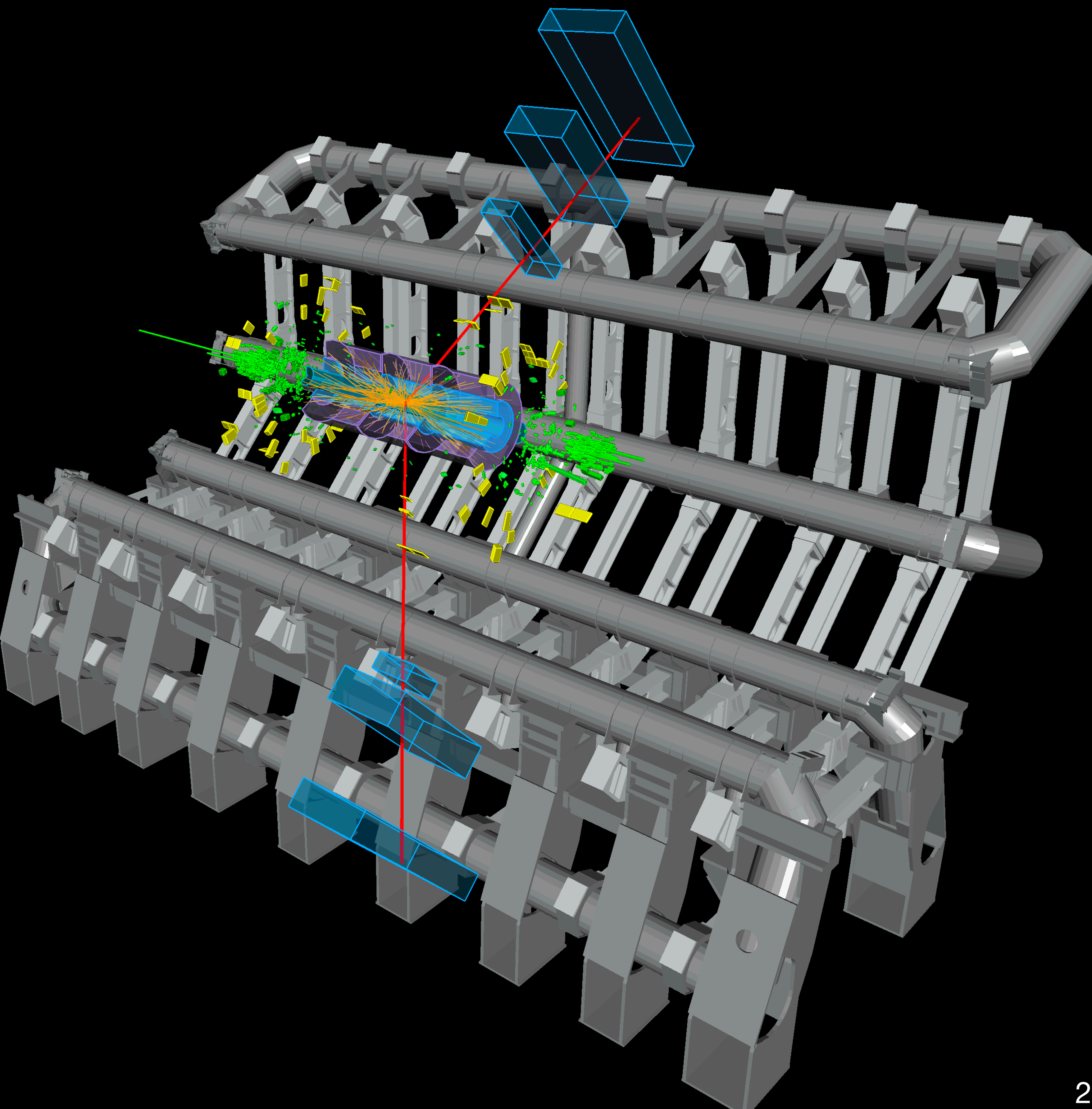
Heraeus seminar, 25th October 2023

DESY.

Soft QCD laboratory

$Z \to \mu\mu$





ATLAS EXPERIMENT

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Event: 242090708
2015-06-14 01:01:14 CEST

Soft QCD is everywhere

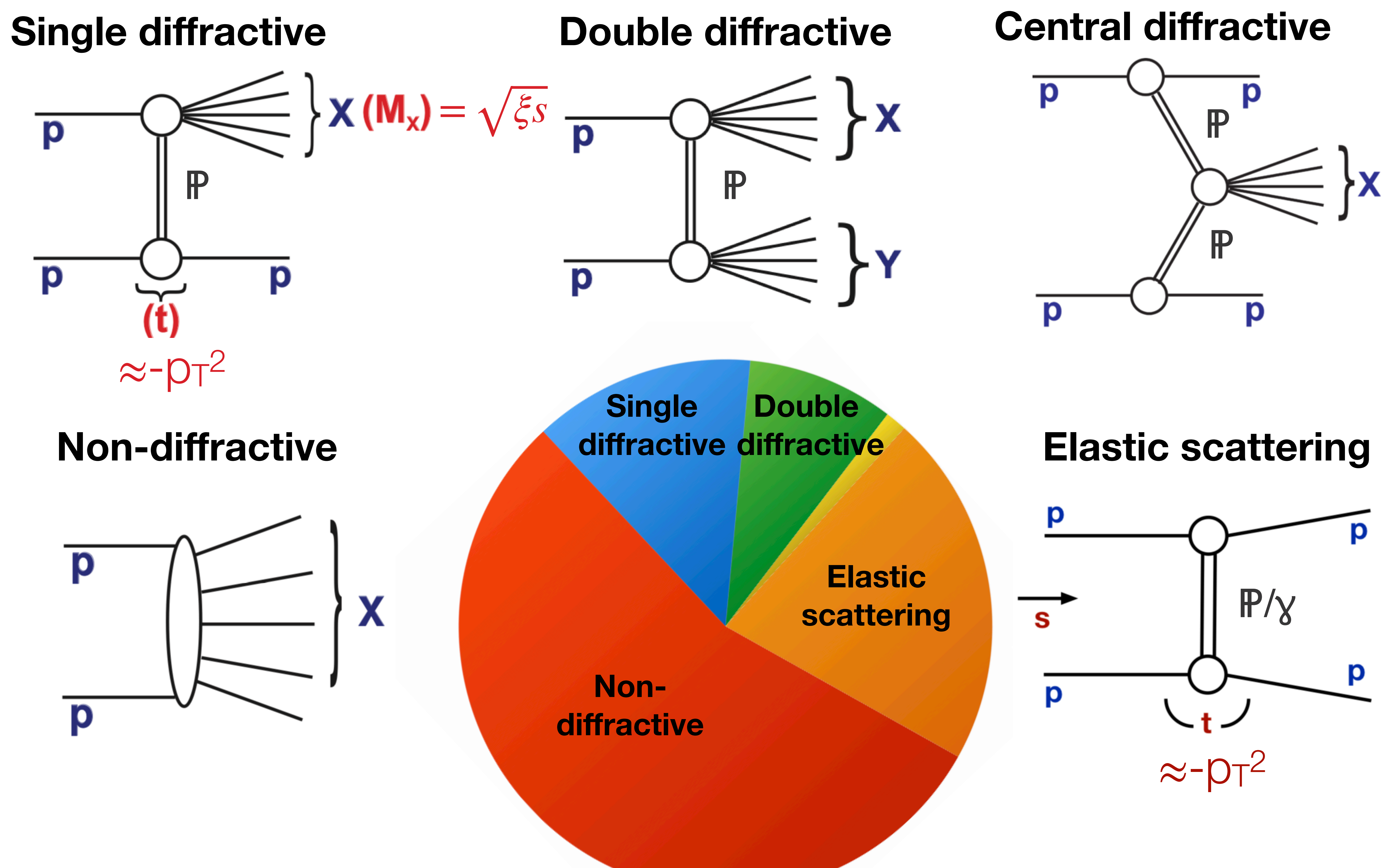
- **Key area of SM where knowledge of fundamental processes is limited**
- **Theoretically:**
  - Beyond pQCD regime
  - Employ phenomenological models with tunable parameters
  - **Measurements are vital**
- **Crucial input for other LHC searches + measurements & beyond!**

Today: Diffractive, elastic & total x-section

See also: PDG sQCD review & 50 years of QCD

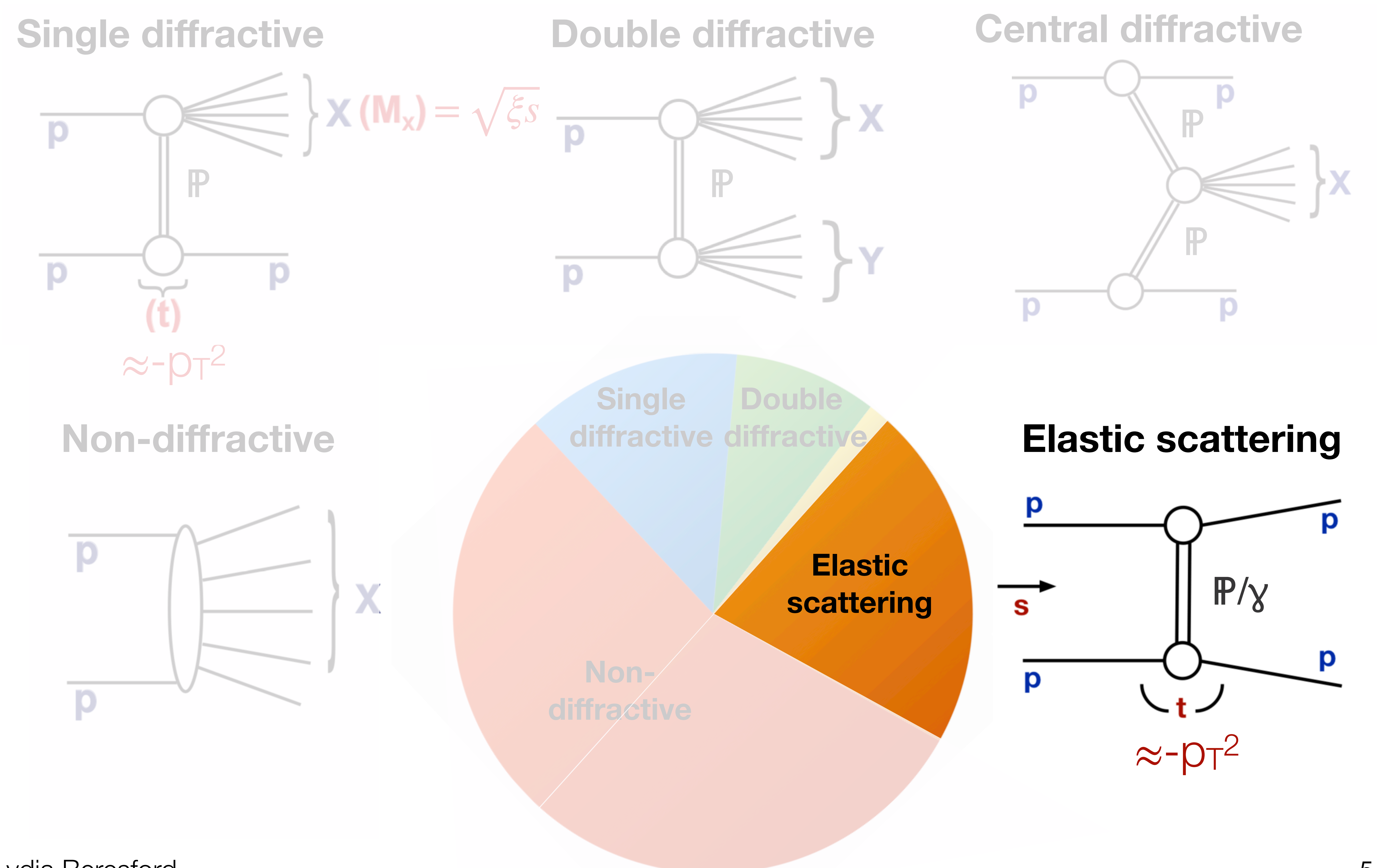
LHC Strong interactions

ℙ = Pomeron

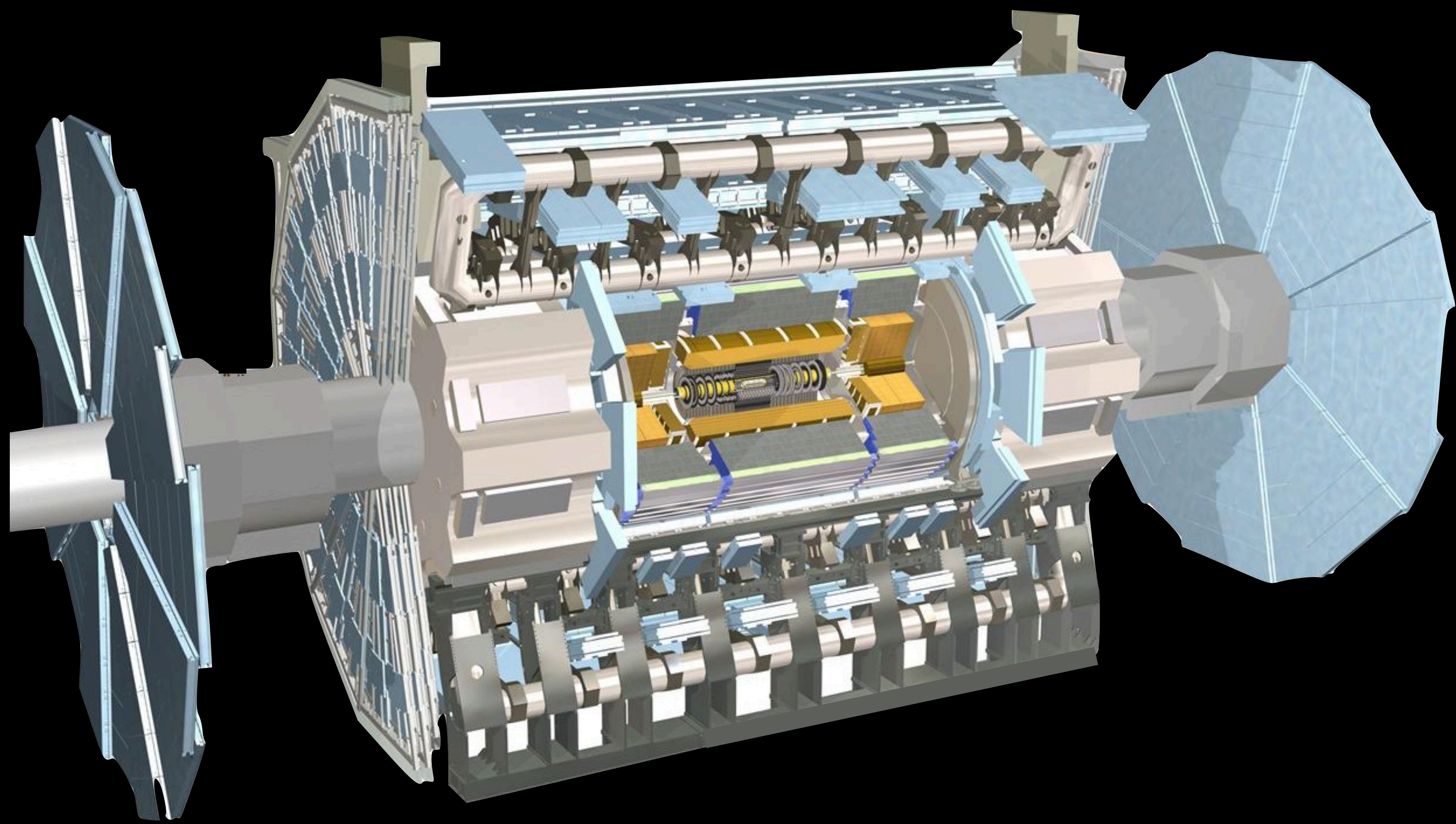


LHC Strong interactions

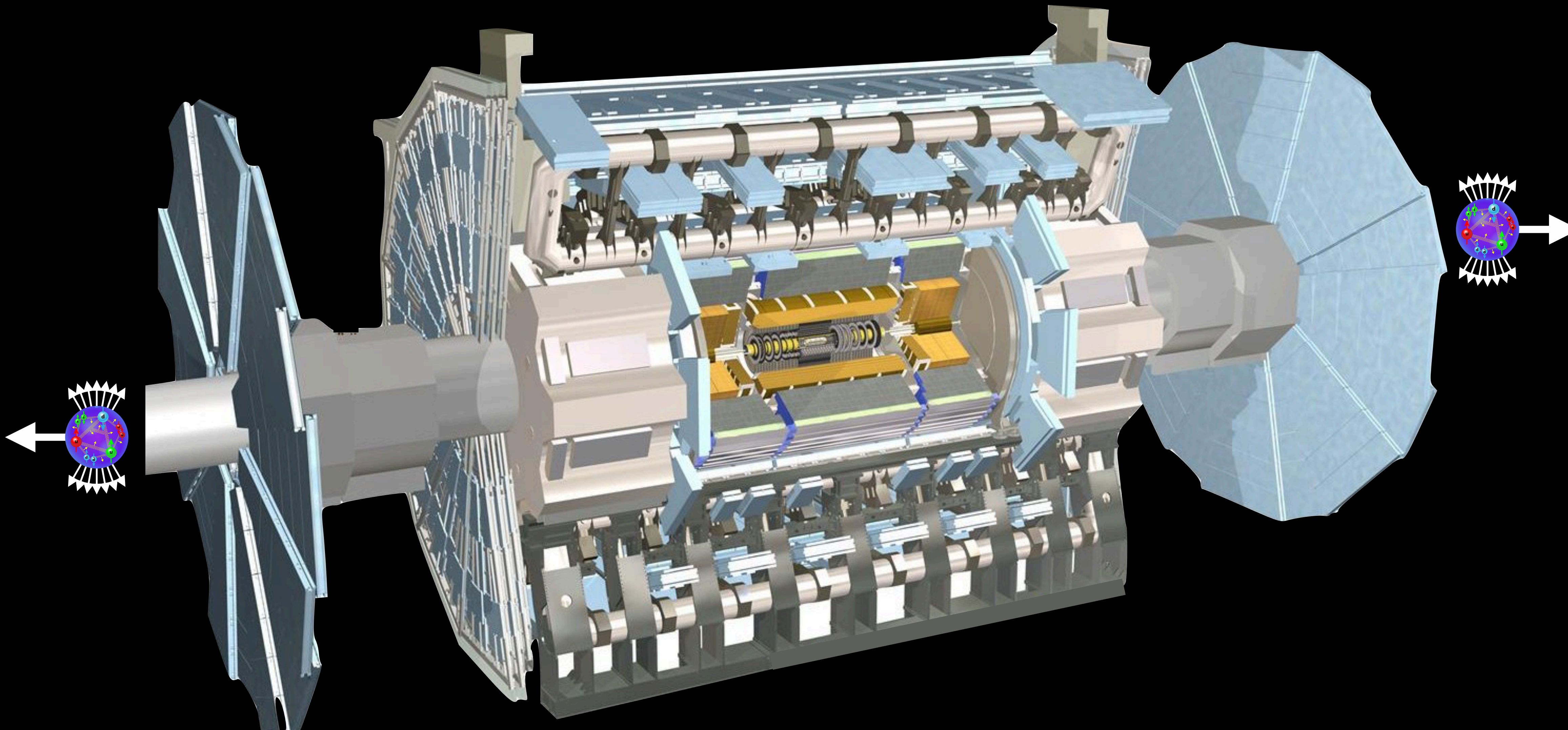
ℙ = Pomeron



Elastic scattering



Elastic scattering



ALFA

Active during dedicated low-μ high β* runs

Going forward

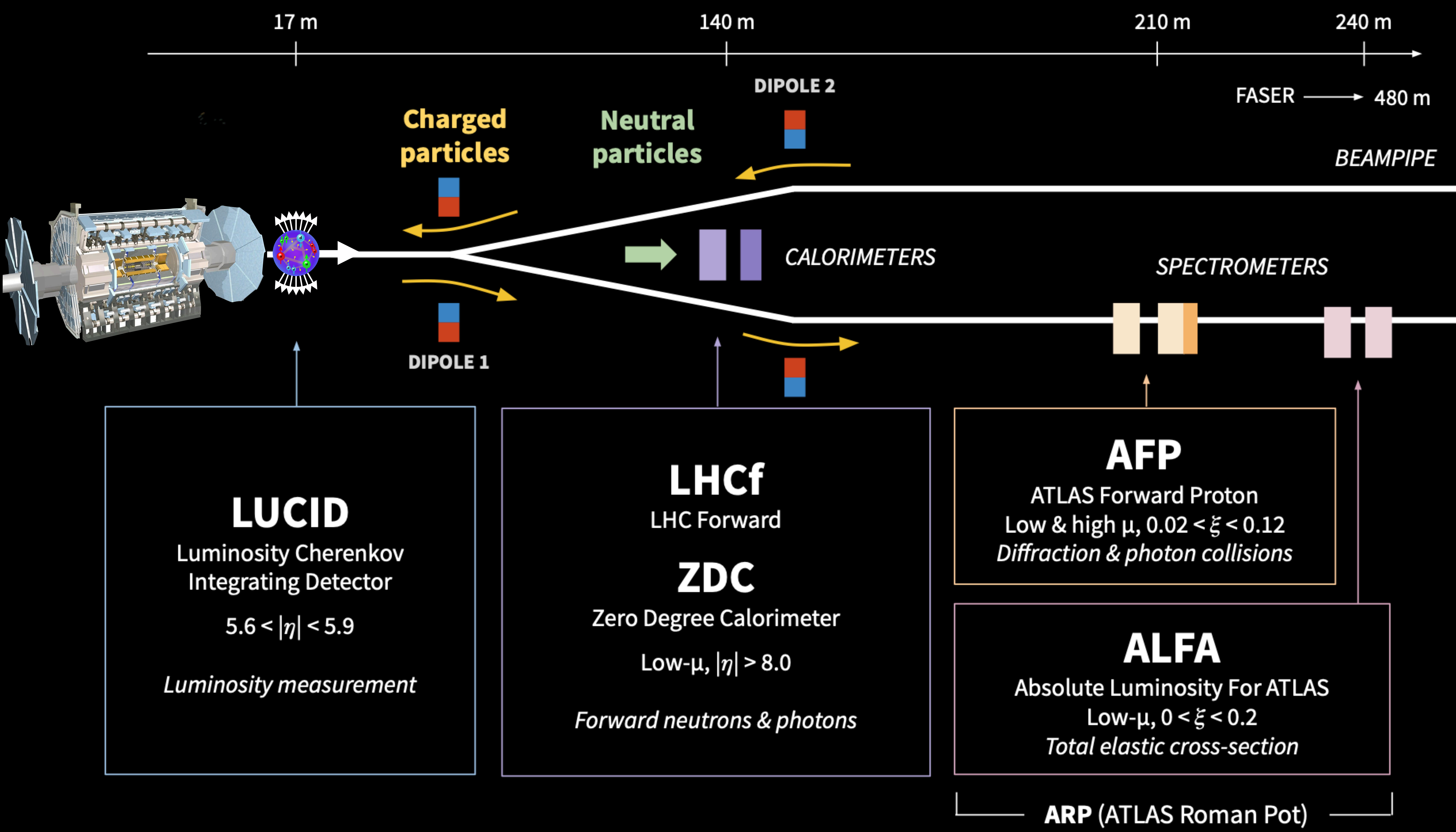
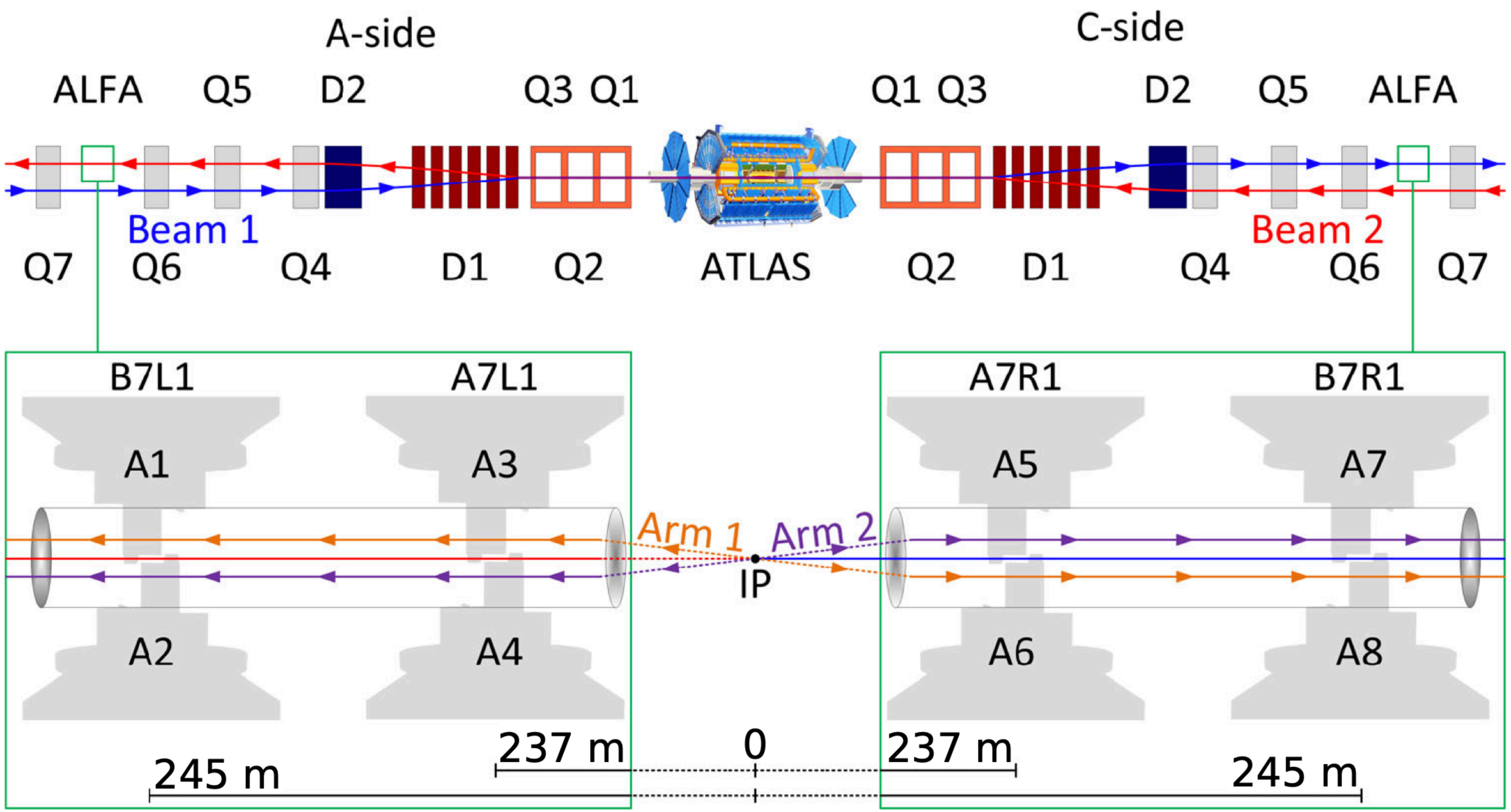


Diagram by Jesse Liu

ALFA detectors



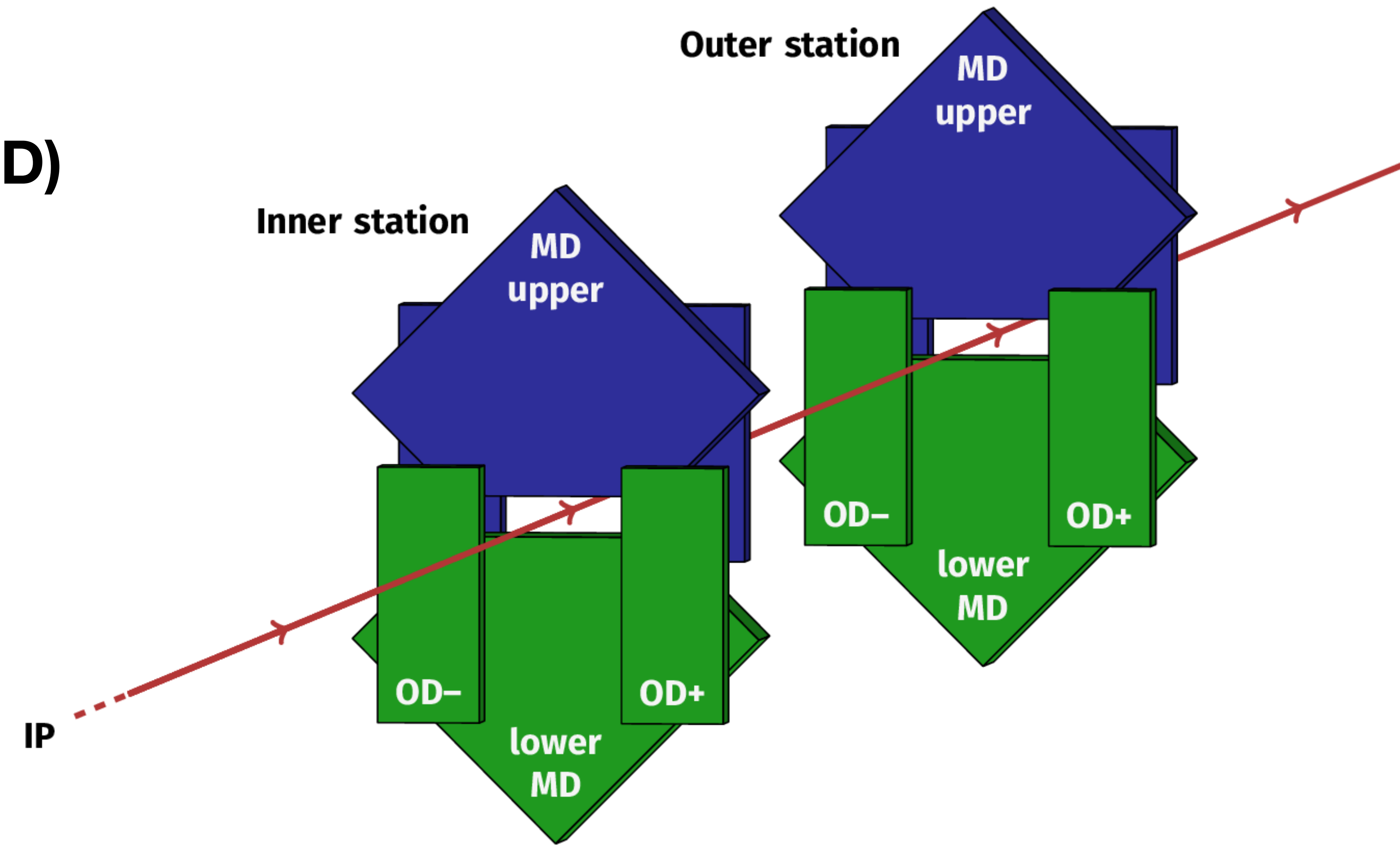
Detectors within millimetres of beam → Can measure smaller t

Position protons hit ALFA depends on kinematics & LHC magnets

ALFA detectors

Main Detector (MD)
For physics analysis

Overlap Detector (OD)
For alignment

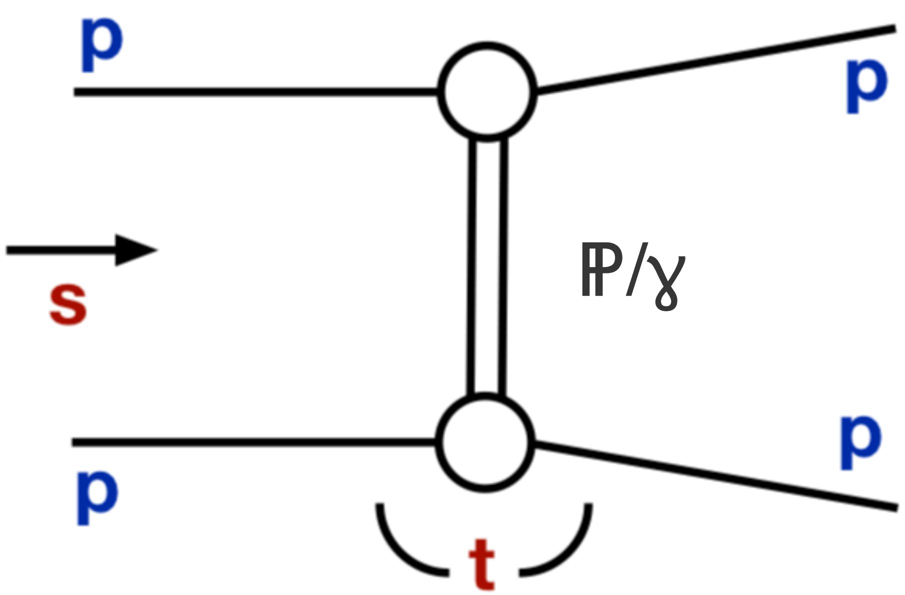


Challenge: Need good understanding of detector alignment & performance

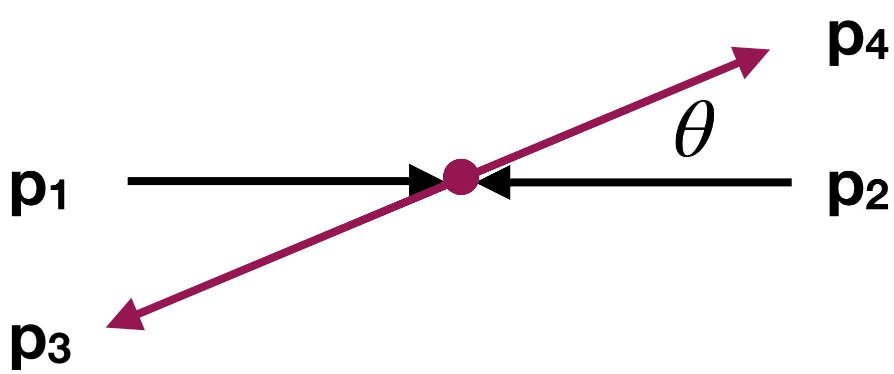
Elastic scattering with ALFA

Fundamental LHC process: Proton-proton scattering

Colour singlet exchange



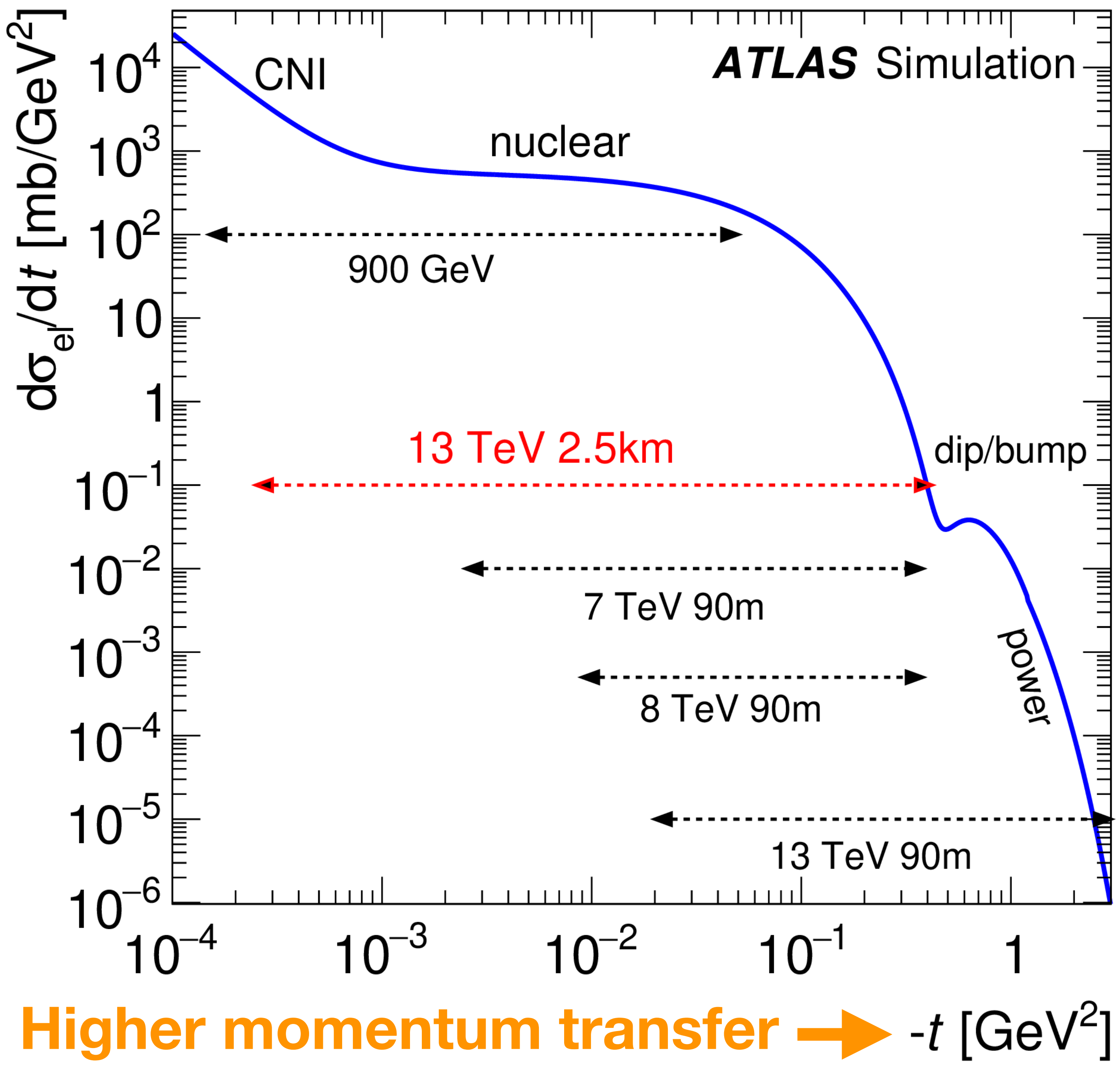
$\approx -p_T^2$



$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$\approx -(p\theta)^2 = -p_T^2$$

Proton t determined from proton position measured by ALFA

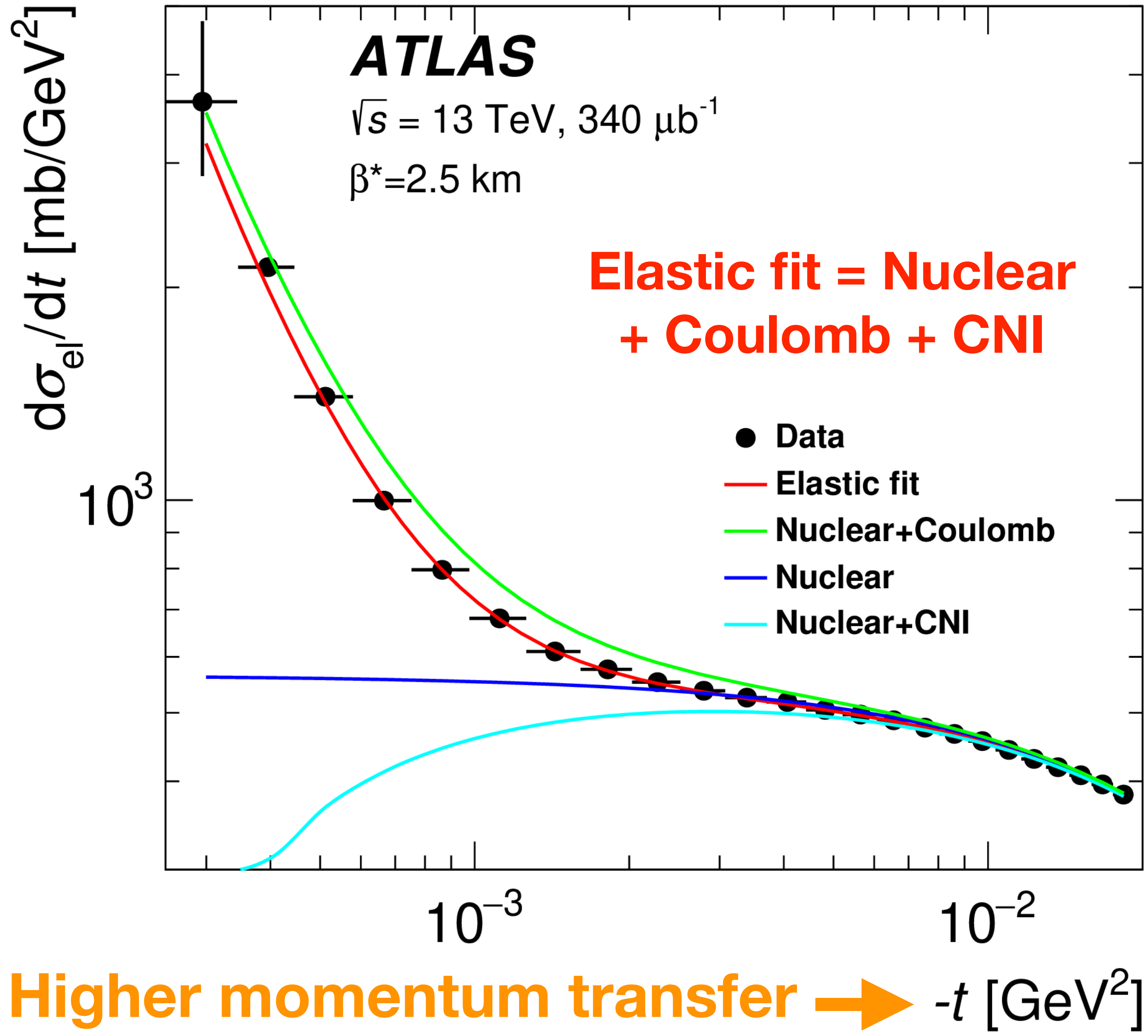
Elastic scattering with ALFA



Probe smaller t via: Less focused beams (higher β*), lower $\sqrt{s}$

Elastic scattering with ALFA

Coulomb-Nuclear-Interference (CNI) region



Elastic scattering with ALFA

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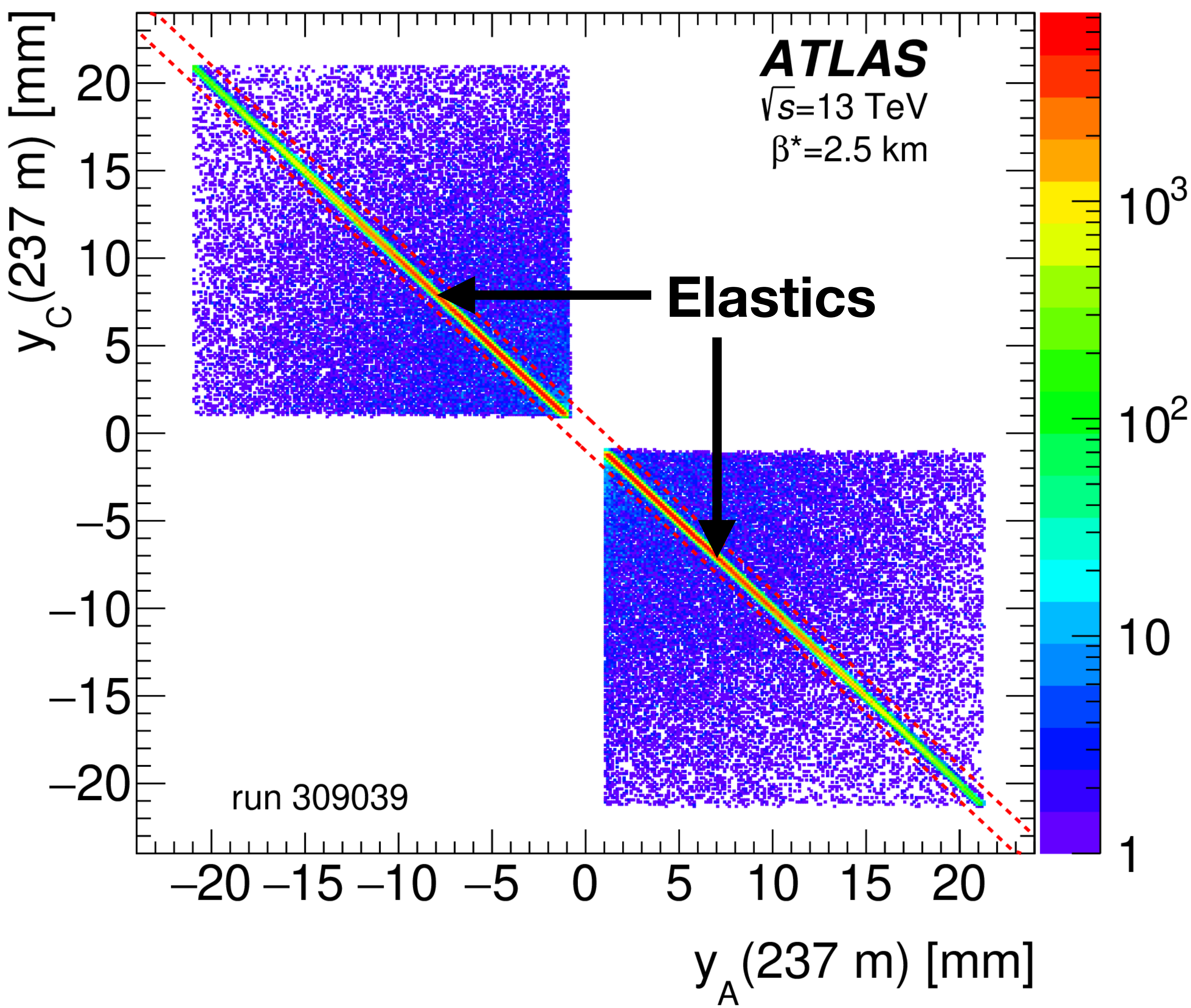
Dataset: $\sqrt{s}$ = 13 TeV with β* = 2.5 km

Selection: data quality, trigger, reco, acceptance + exploit correlations e.g.



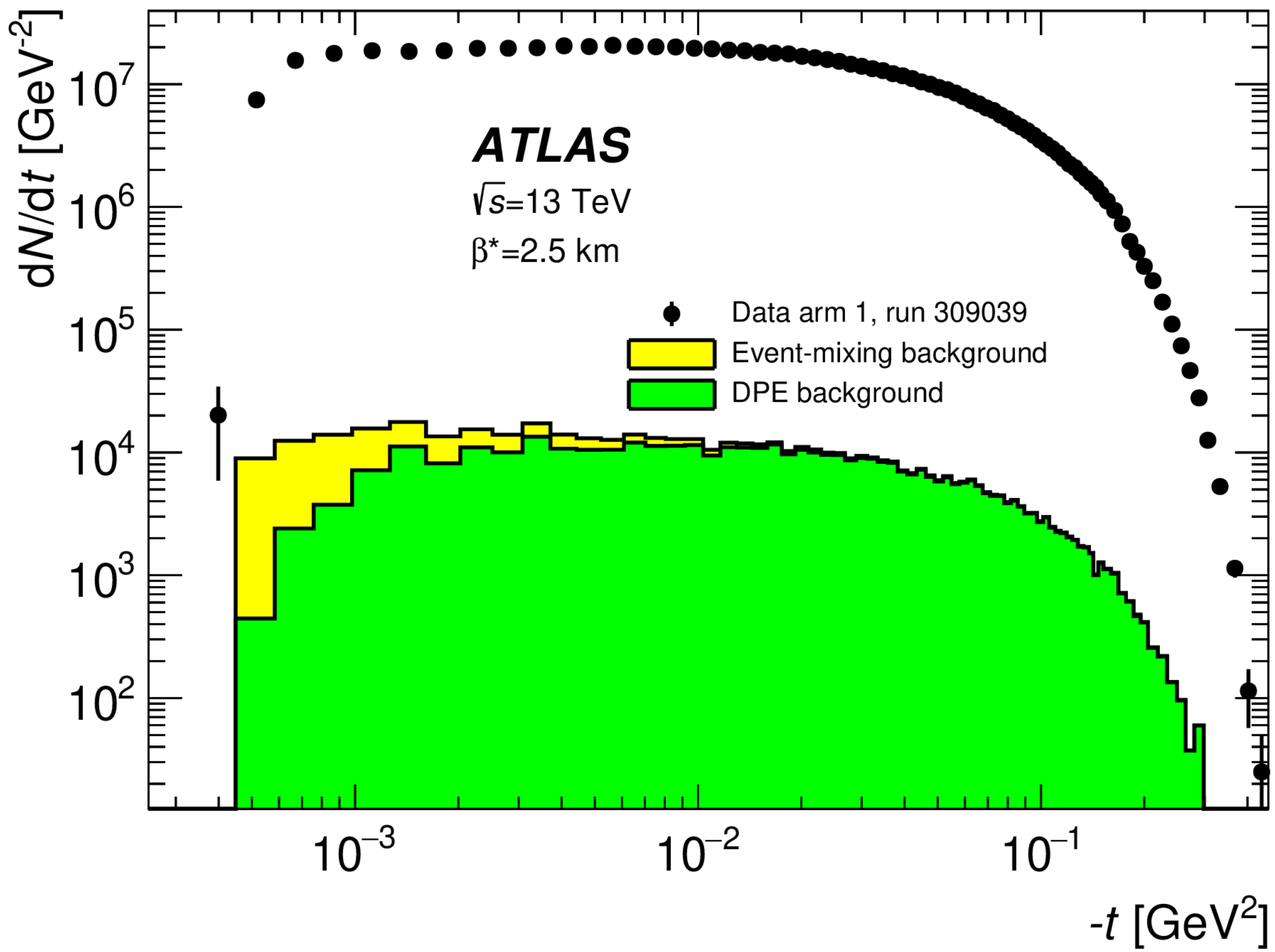
Background estimation

Small bkg fraction ~ 0.75%

Two sources:

- Central diffraction (MC simulation)
- Accidental coincidences halo + halo & halo + single diffraction (data-driven)

Normalise in control regions

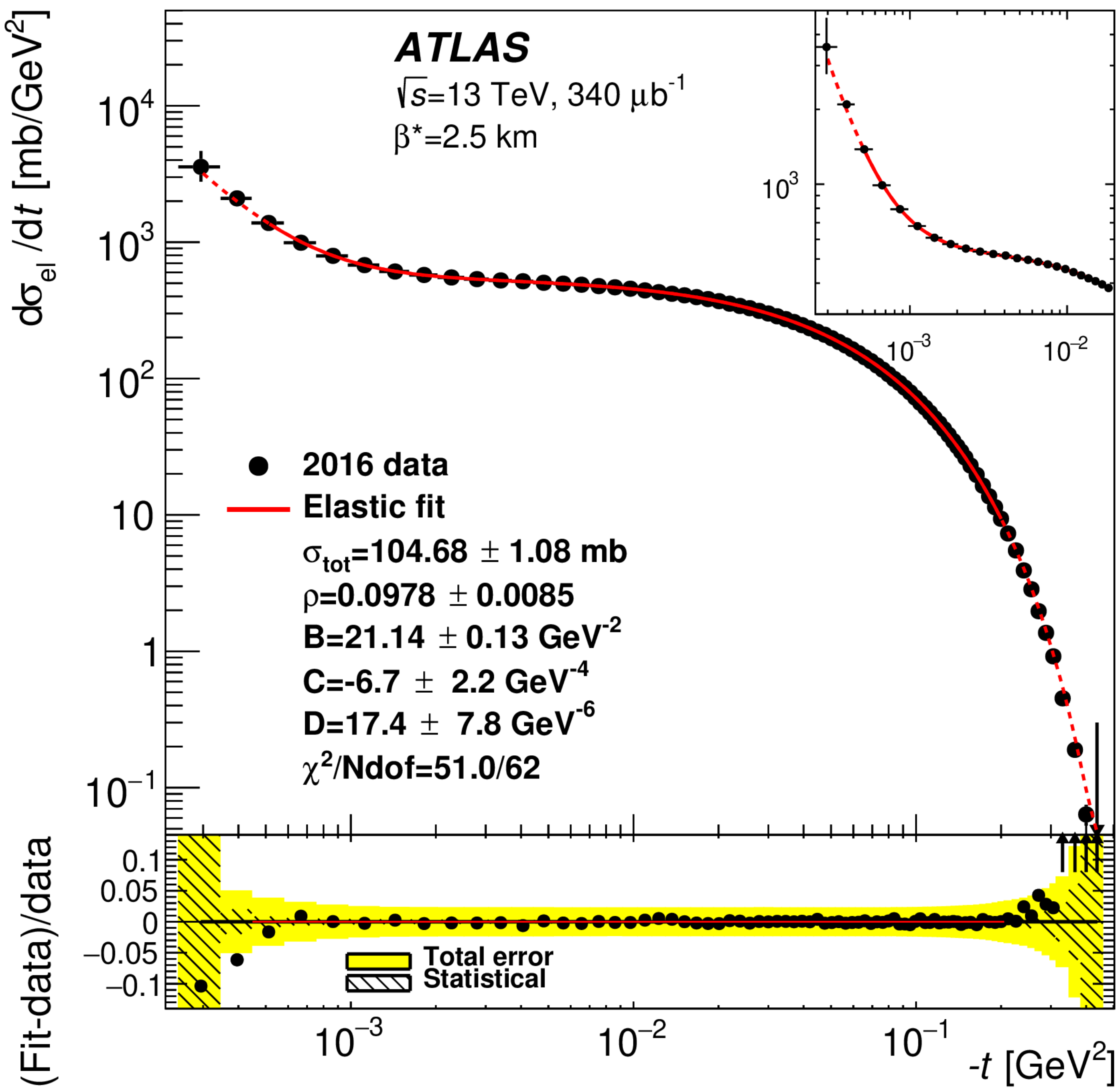


Many aspects of analysis utilise data based approaches:

Alignment, reconstruction efficiency, optics

Elastic differential cross-section

Corrected for experimental effects: acceptance, efficiencies etc



Extract physics parameters from profile fit

Elastic fit function:

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

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

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

$$\rho = \left.\frac{\mathrm{Re}[f_{el}(t)]}{\mathrm{Im}[f_{el}(t)]}\right|_{t\to 0}$$

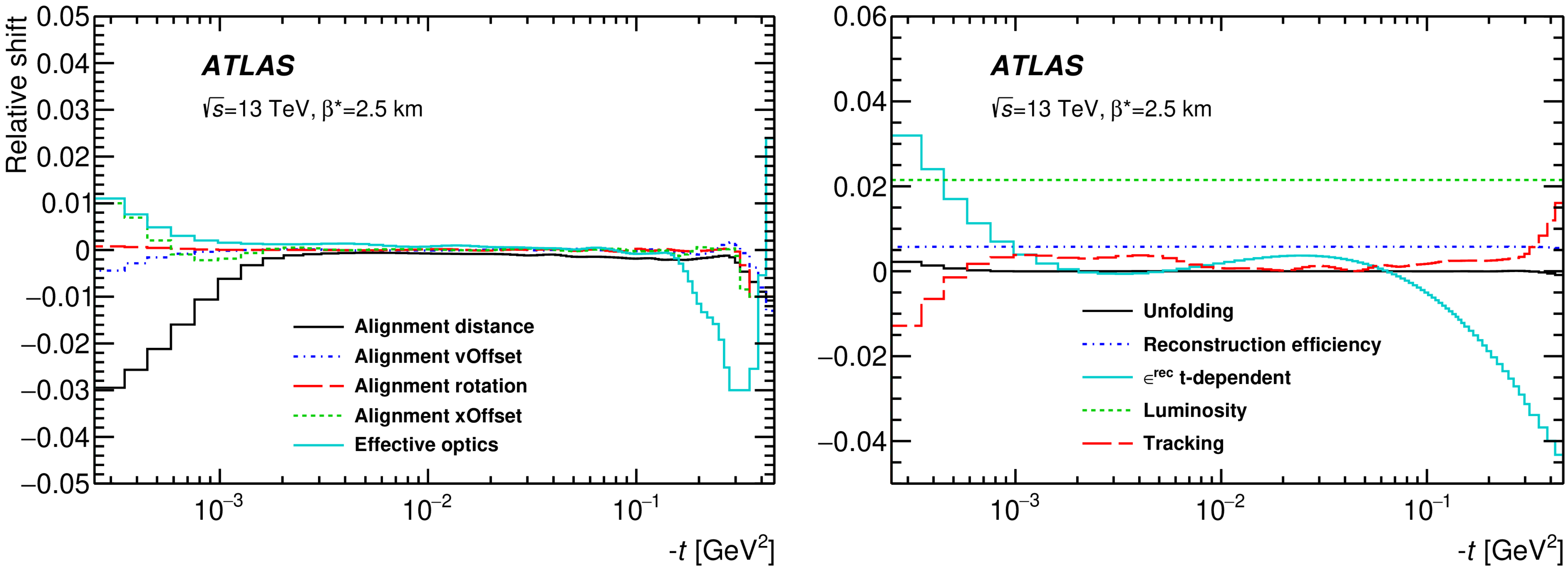
Systematic uncertainties

Fit takes into account: statistical & systematic uncertainties & correlations

Main uncertainties: Alignment, luminosity, reconstruction efficiency

Dedicated luminosity analysis performed for these ALFA runs:

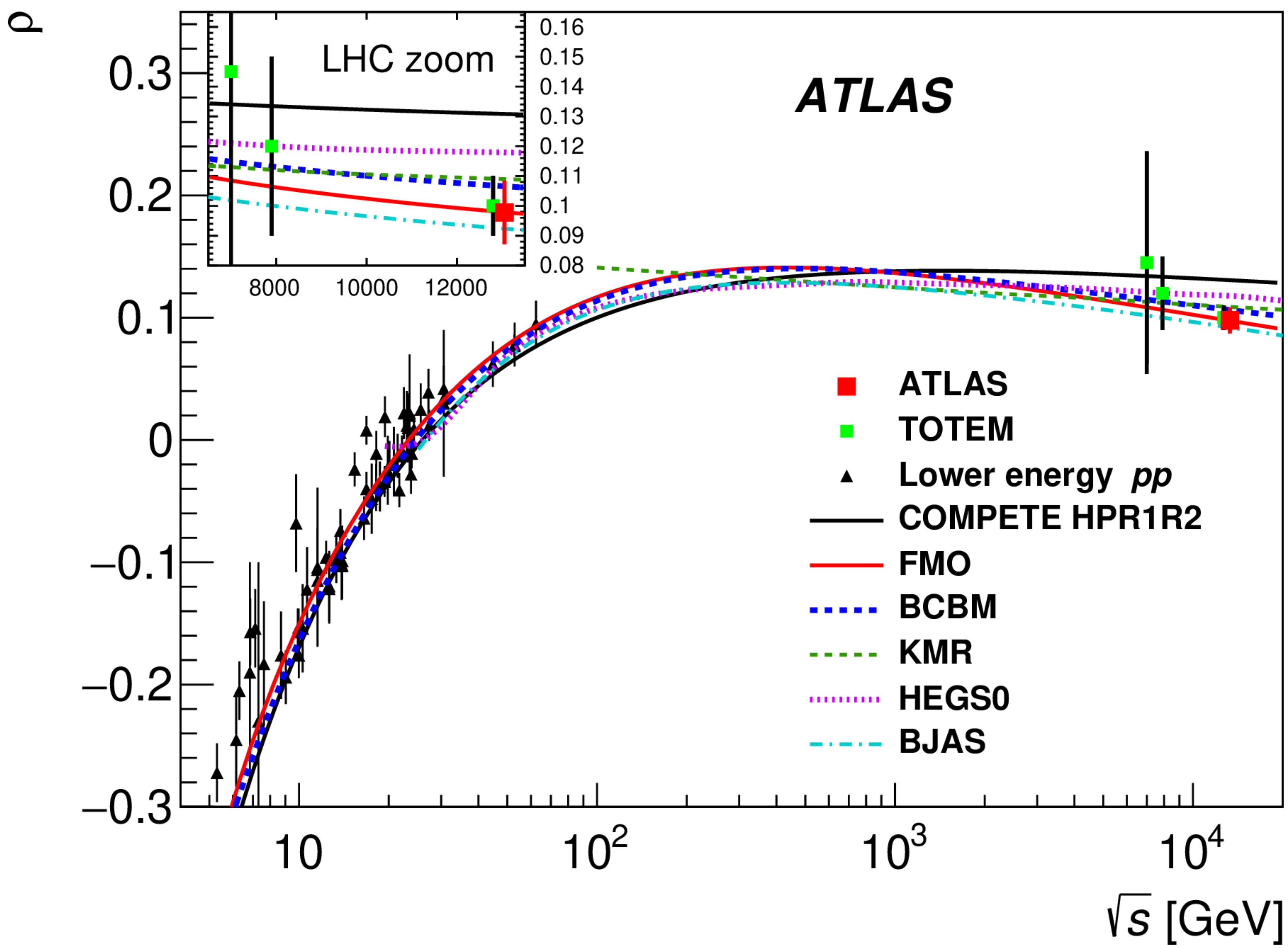
$$L_{\text{int}} = 339.9 \pm 0.1\ (\text{stat.}) \pm 7.3\ (\text{syst.})\ \mu\text{b}^{-1}$$



ρ measurement

COMPETE = a standard evolution model based on semi-empirical fits

$$\rho = 0.0978 \pm 0.0085 \text{ (exp.)} \pm 0.0064 \text{ (th.)}$$

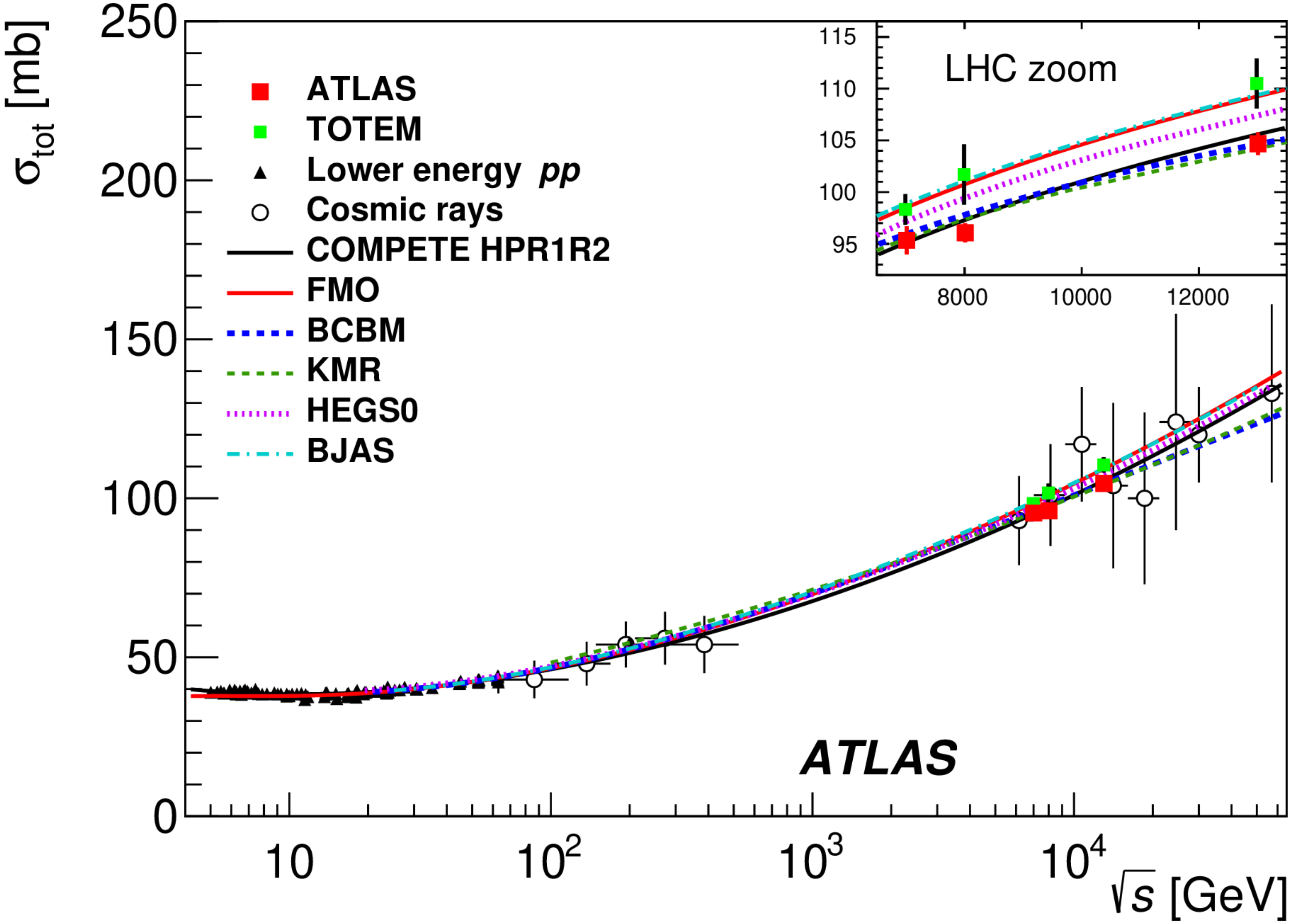


ρ probes CNI region, low value in tension with COMPETE

→ Could be explained by Odderon or a slowdown in rise of σ_{tot} at high $\sqrt{s}$

Total hadronic cross-section

$$\sigma_{tot}(pp \rightarrow X) = 104.68 \pm 1.08\ (\text{exp.}) \pm 0.12\ (\text{th.})\ \text{mb}$$



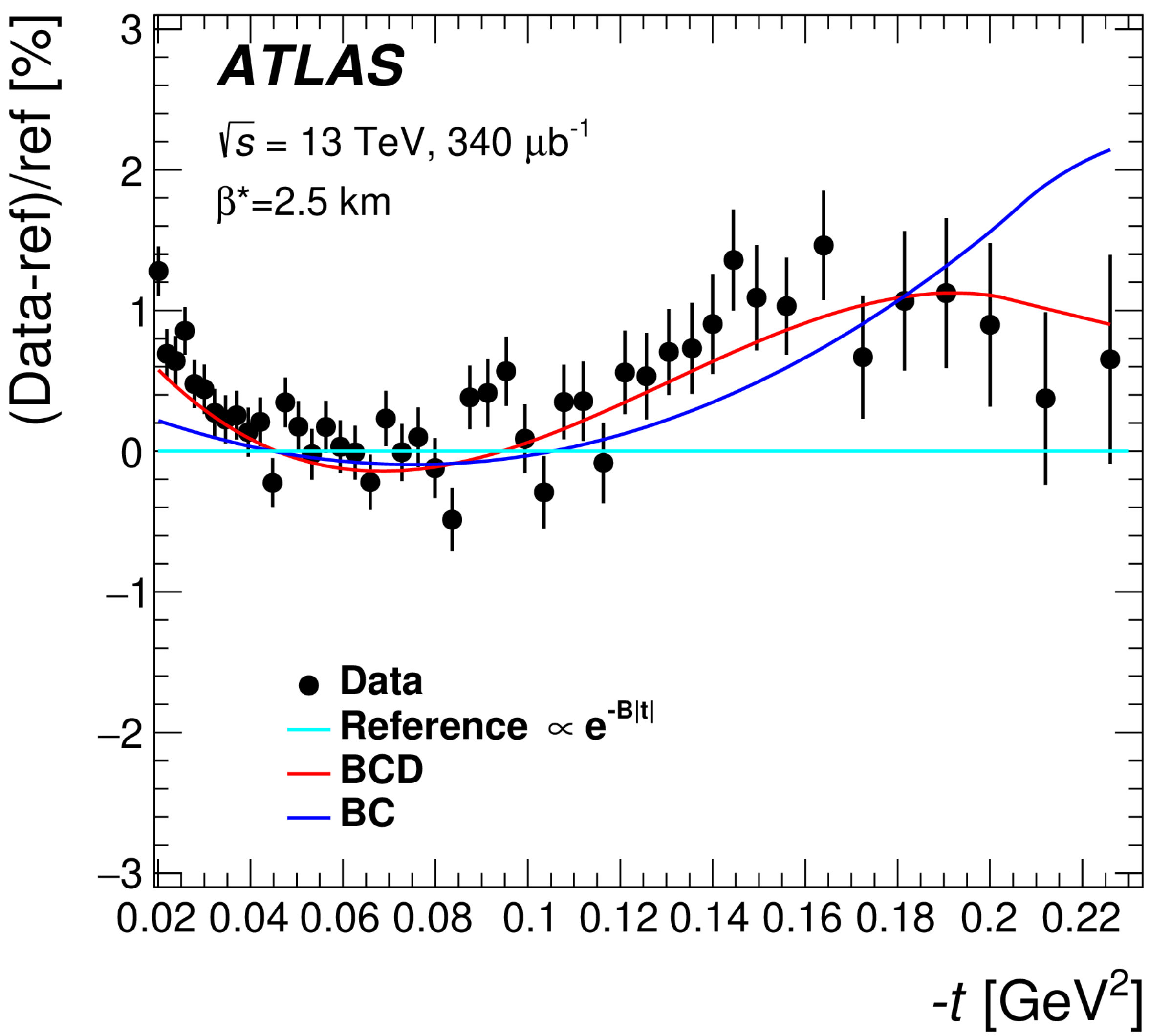
2.2 σ tension with TOTEM σ_{tot} result, similar trend seen at 7 & 8 TeV

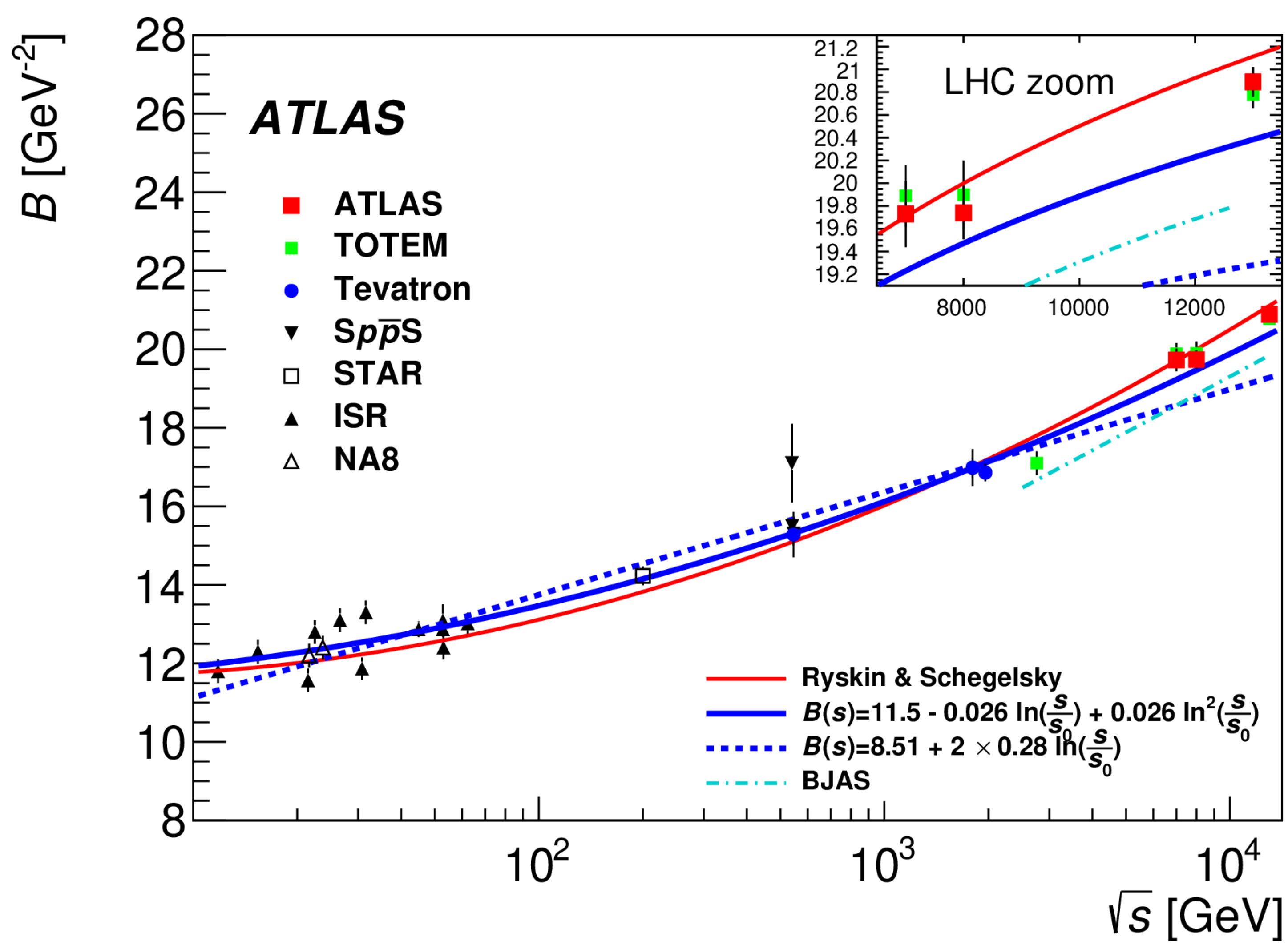
Nuclear slope

$d\sigma/dt$ can't be described by a simple exponent

For comparison measure B-slope in dedicated fit at small $|t|$ (slope ~ const.)

B-slope in agreement with totem





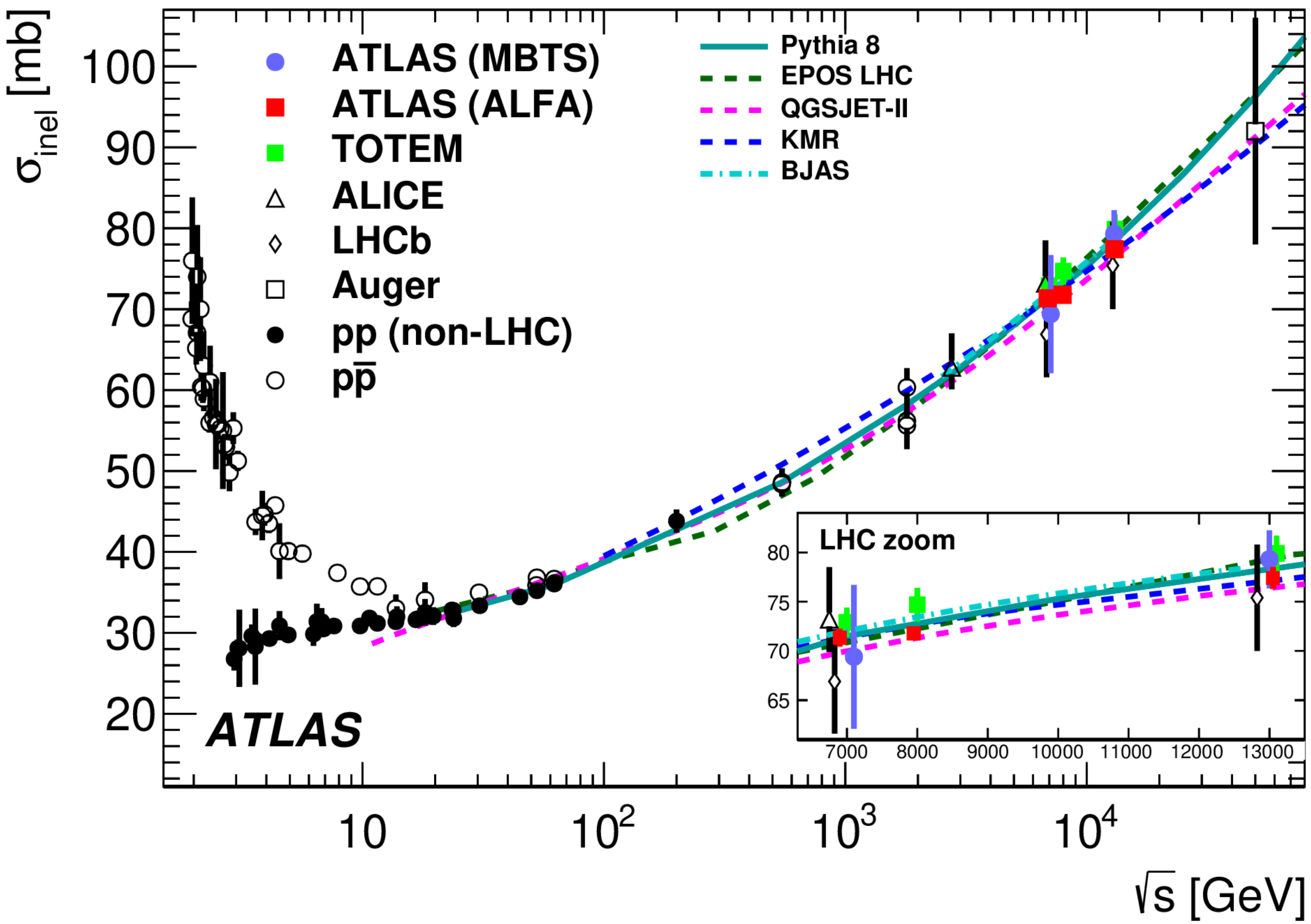
ref = reference exponential function

$$B = 21.14 \pm 0.13\ \text{GeV}^{-2}$$

Derived quantity

Important for modelling cosmic ray air showers

Total inelastic cross-section agrees with ATLAS MBTS measurements

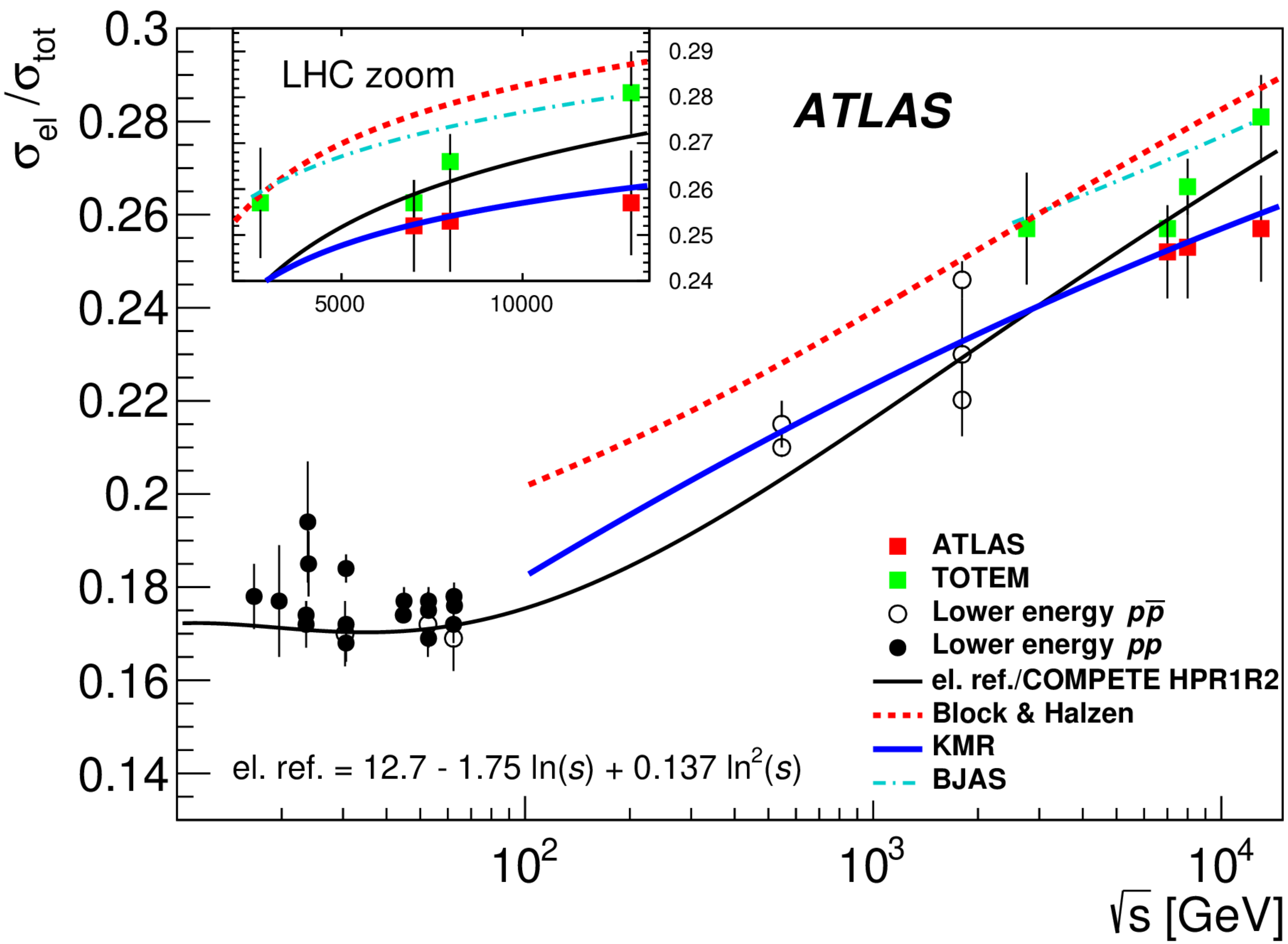


$$\sigma_{\text{inel}} = 77.41 \pm 1.07\ (\text{exp.}) \pm 0.18\ (\text{th.})\ \text{mb}$$

Derived quantity

Some uncertainties can cancel in the ratio

Ratio of elastic to total cross-section in tension with TOTEM results

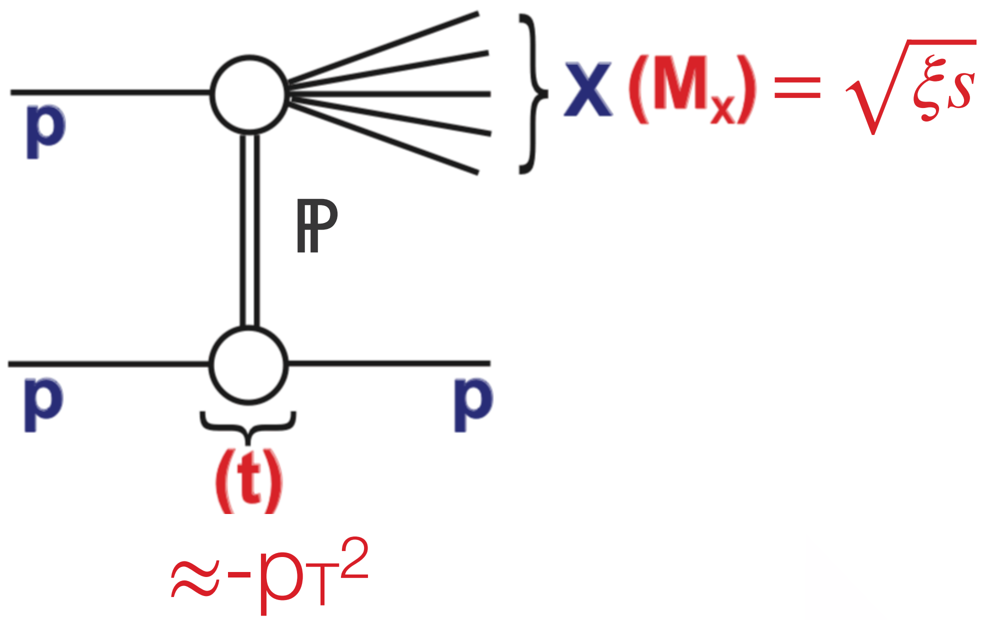


$$\frac{\sigma_{\mathrm{el}}}{\sigma_{\mathrm{tot}}} = 0.257 \pm 0.008\ (\mathrm{exp.}) \pm 0.009\ (\mathrm{th.})$$

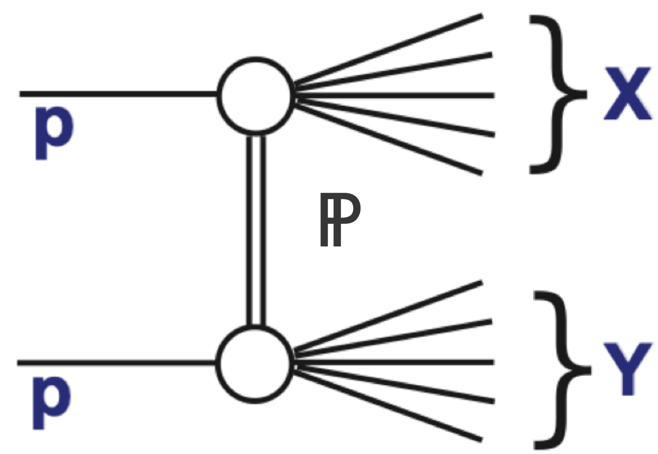
Diffractive processes

$\mathbb{P}$ = Pomeron

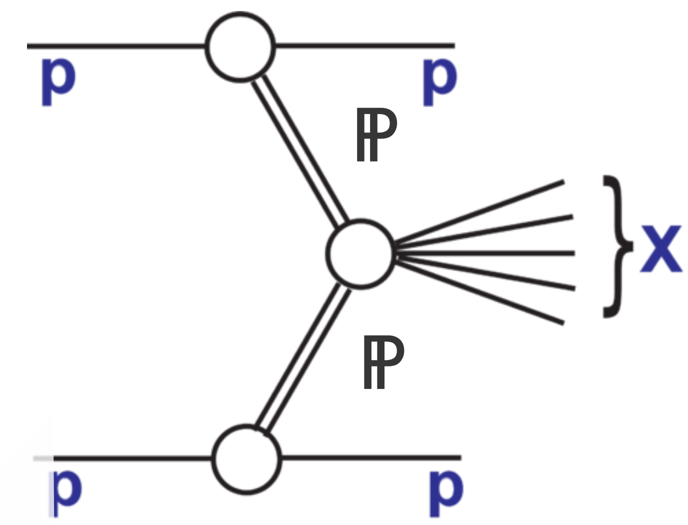
Single diffractive

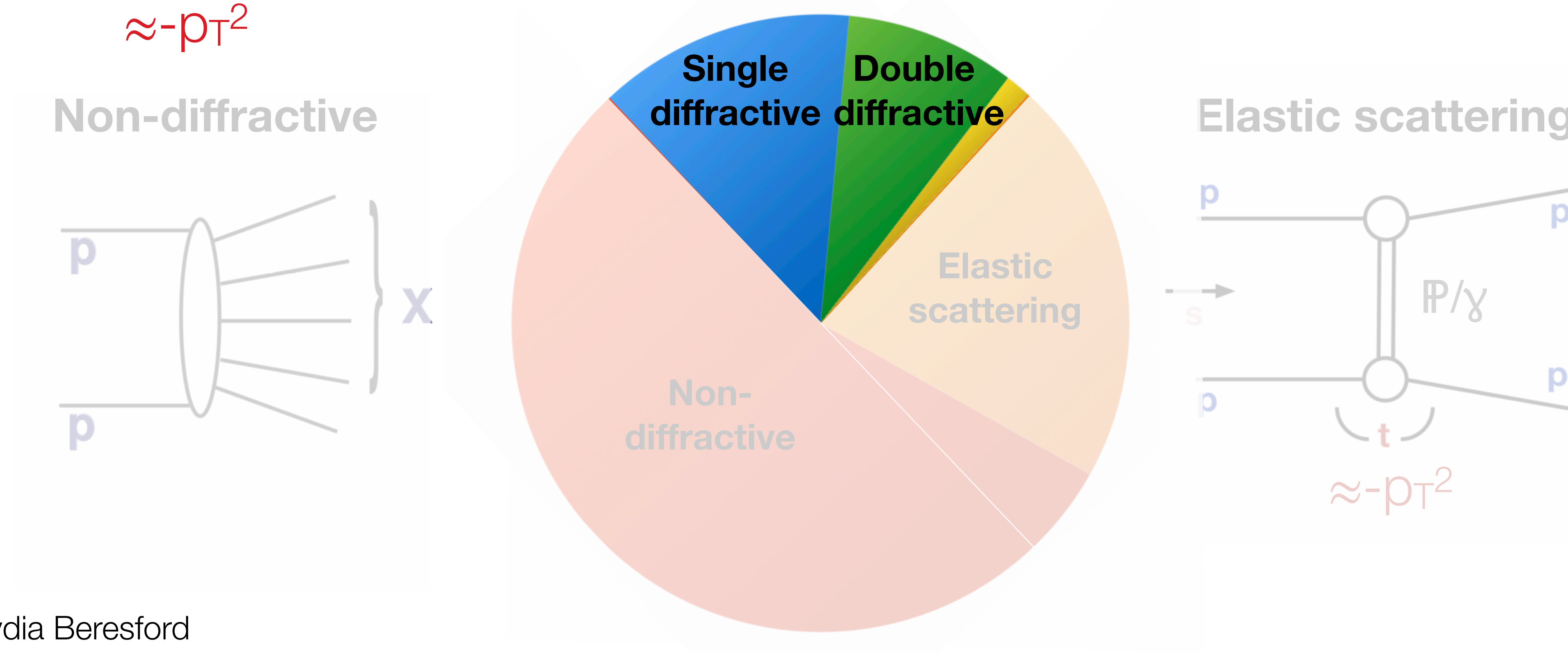


Double diffractive



Central diffractive

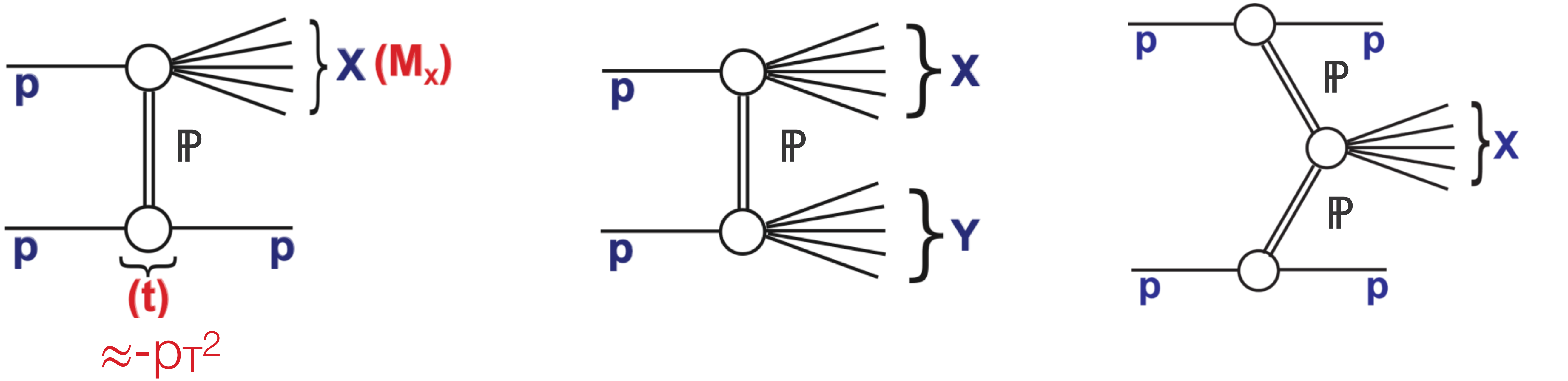




Diffractive processes

$\mathbb{P}$ = Pomeron

Single diffractive (SD) **Double diffractive (DD)** **Central diffractive (CD)**



Pomeron exchange with dissociation into diffractive system

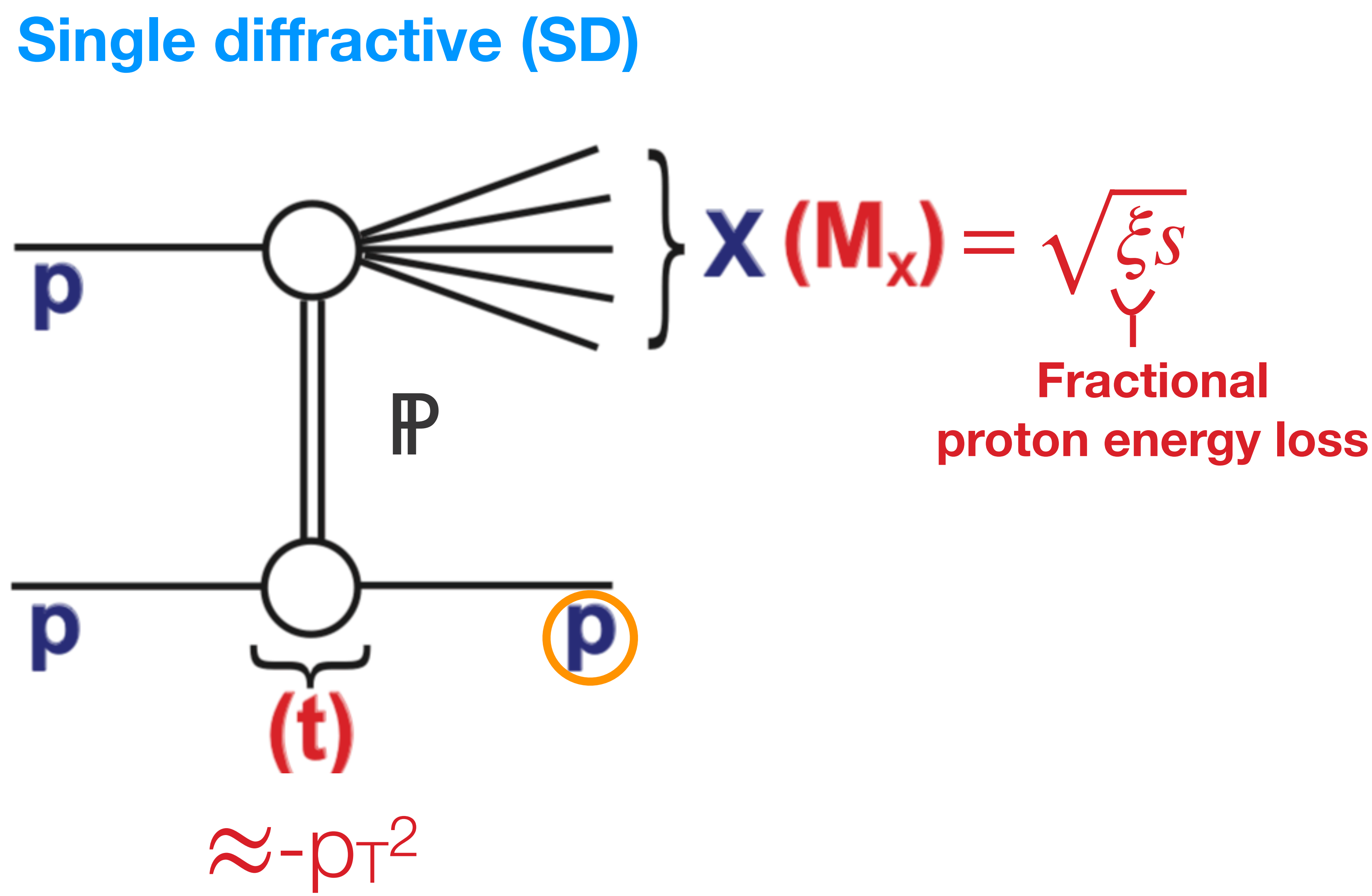
Large (~10% of total LHC cross-section) but poorly constrained

Input for MC generators, improve:

- Pile-up modelling
- Modelling of cosmic-ray air showers

Measuring diffractive events

ℙ = Pomeron



Diffractive system X:

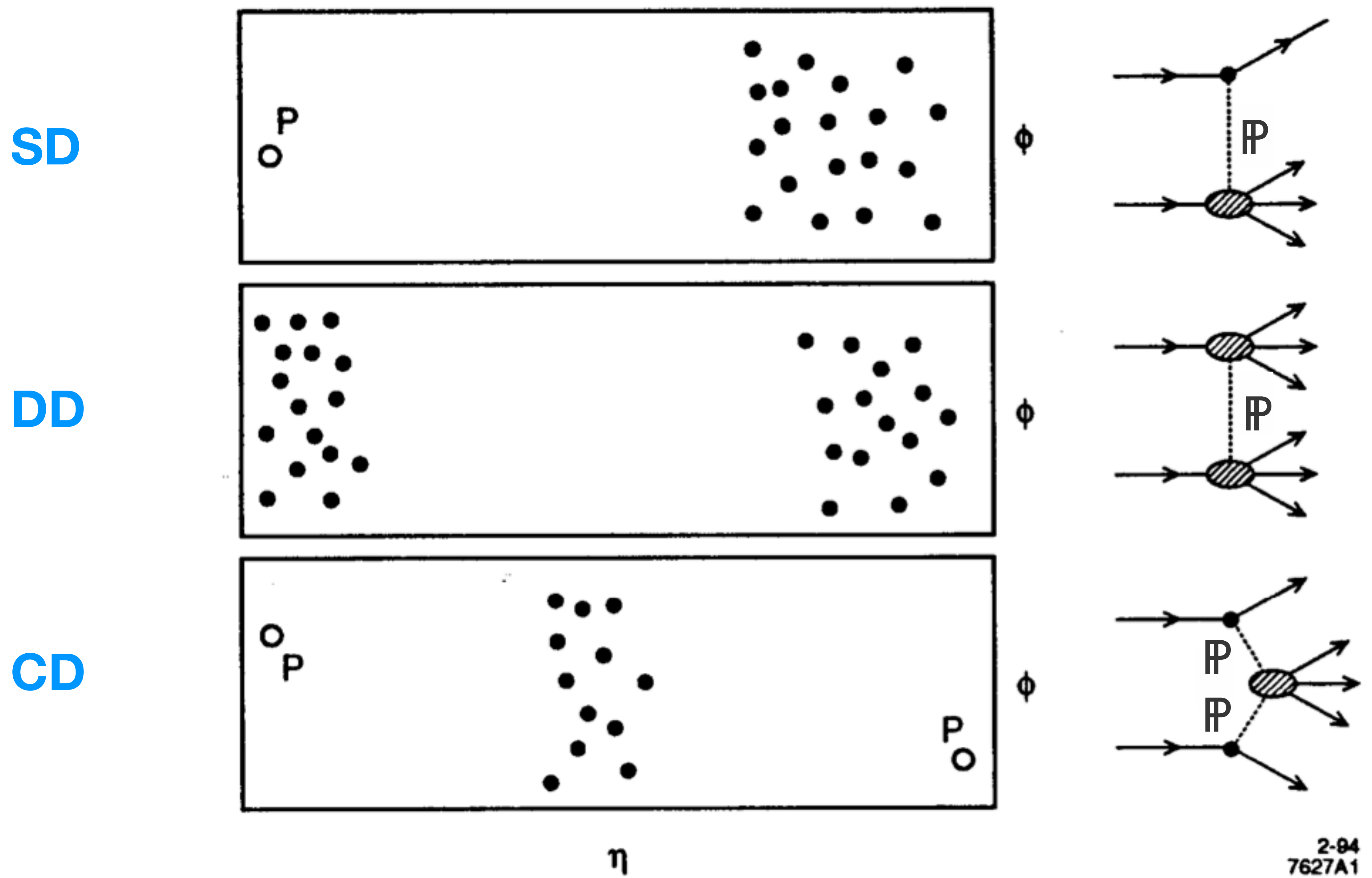
- Rapidity gaps using ATLAS tracks or calorimeters
- Low number of tracks in ATLAS

Measuring diffractive events

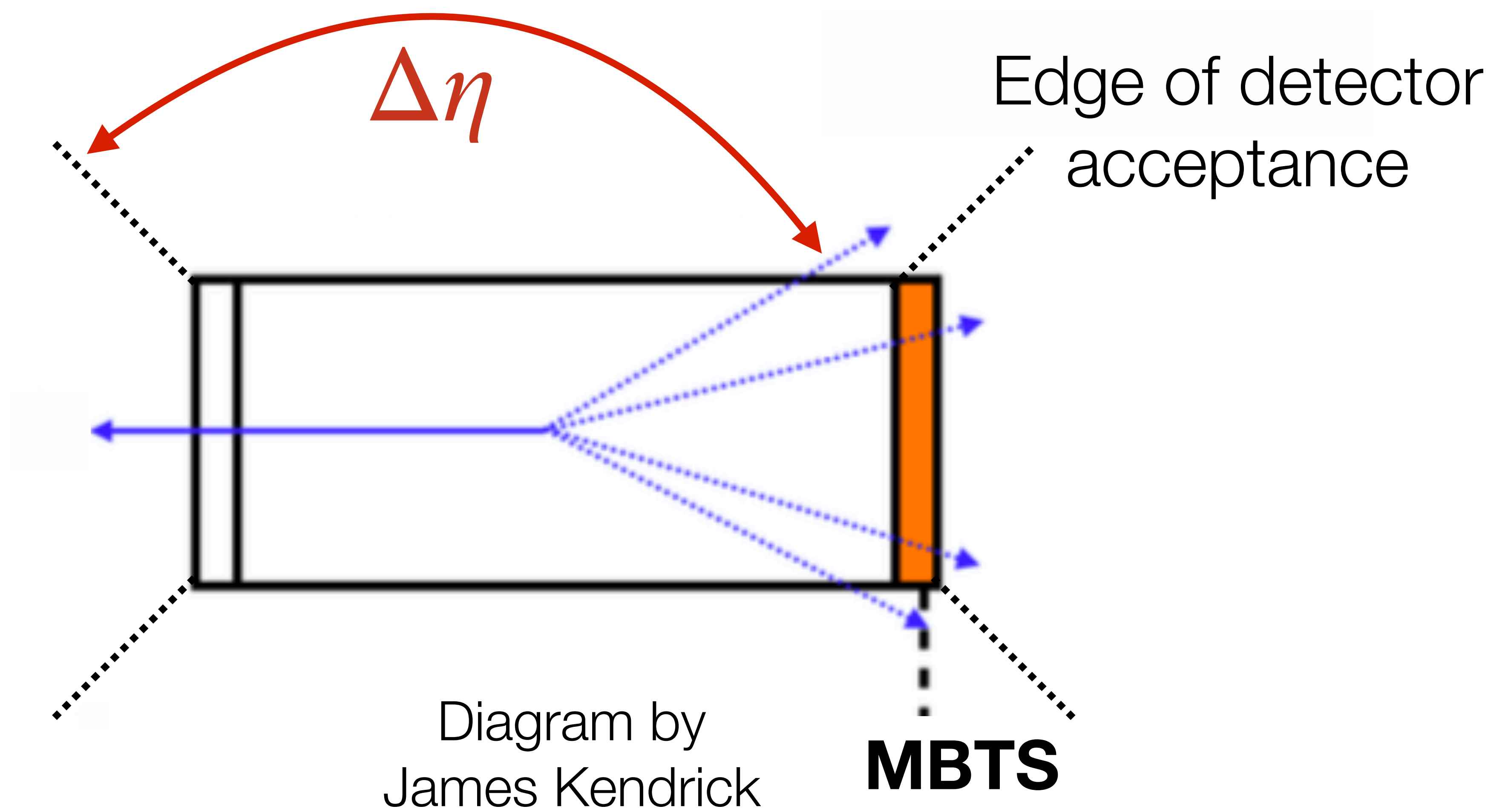
ℙ = Pomeron

slac-pub-6463

Rapidity gaps



Rapidity gaps

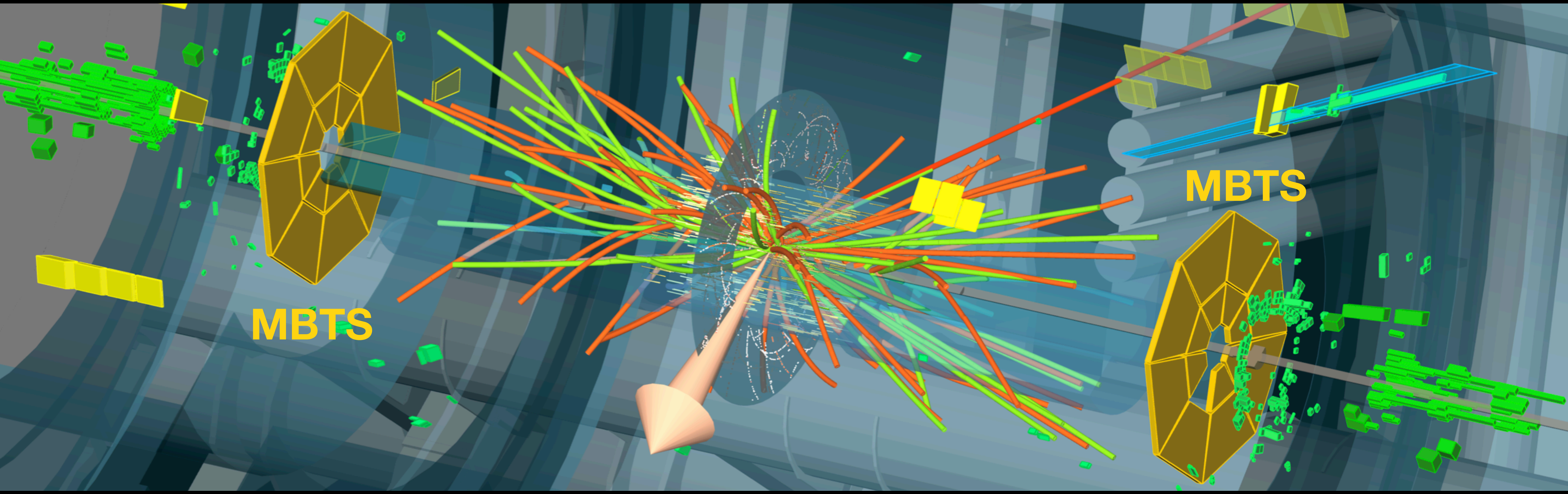


Larger of two empty η regions wrt edge of detector acceptance

Tracks only wrt $\eta = \pm\ 2.5$, tracks & calorimeter clusters wrt $\eta = \pm\ 4.9$

MBTS (Min Bias Trigger Scintillators)

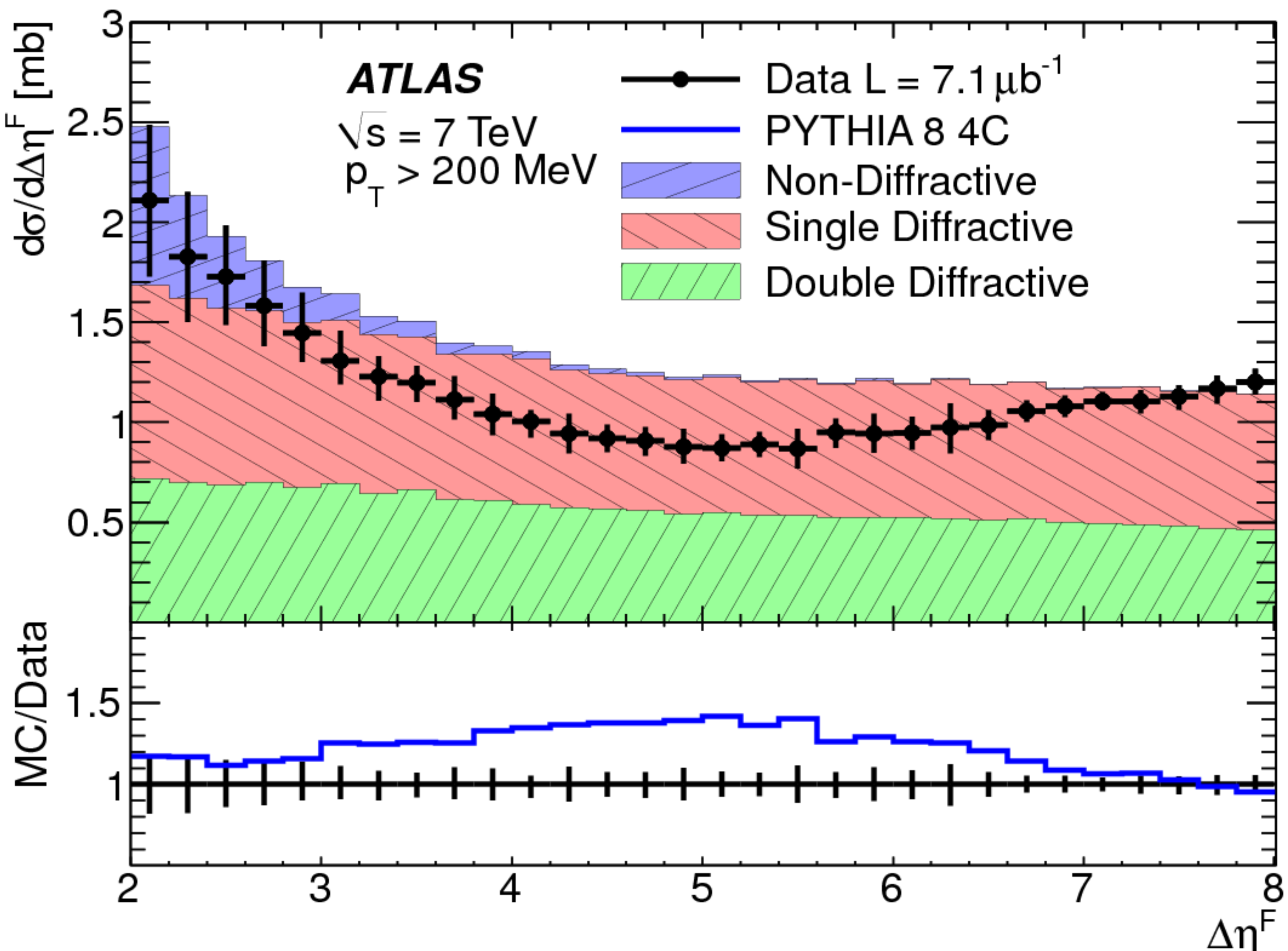
Select events with as little bias as possible



In forward region $2.08 \leq |\eta| < 3.75$, in front of end-cap calorimeters

Single diffractive

EPJC 72 (2012)1926



Rapidity gap using tracks & calo clusters

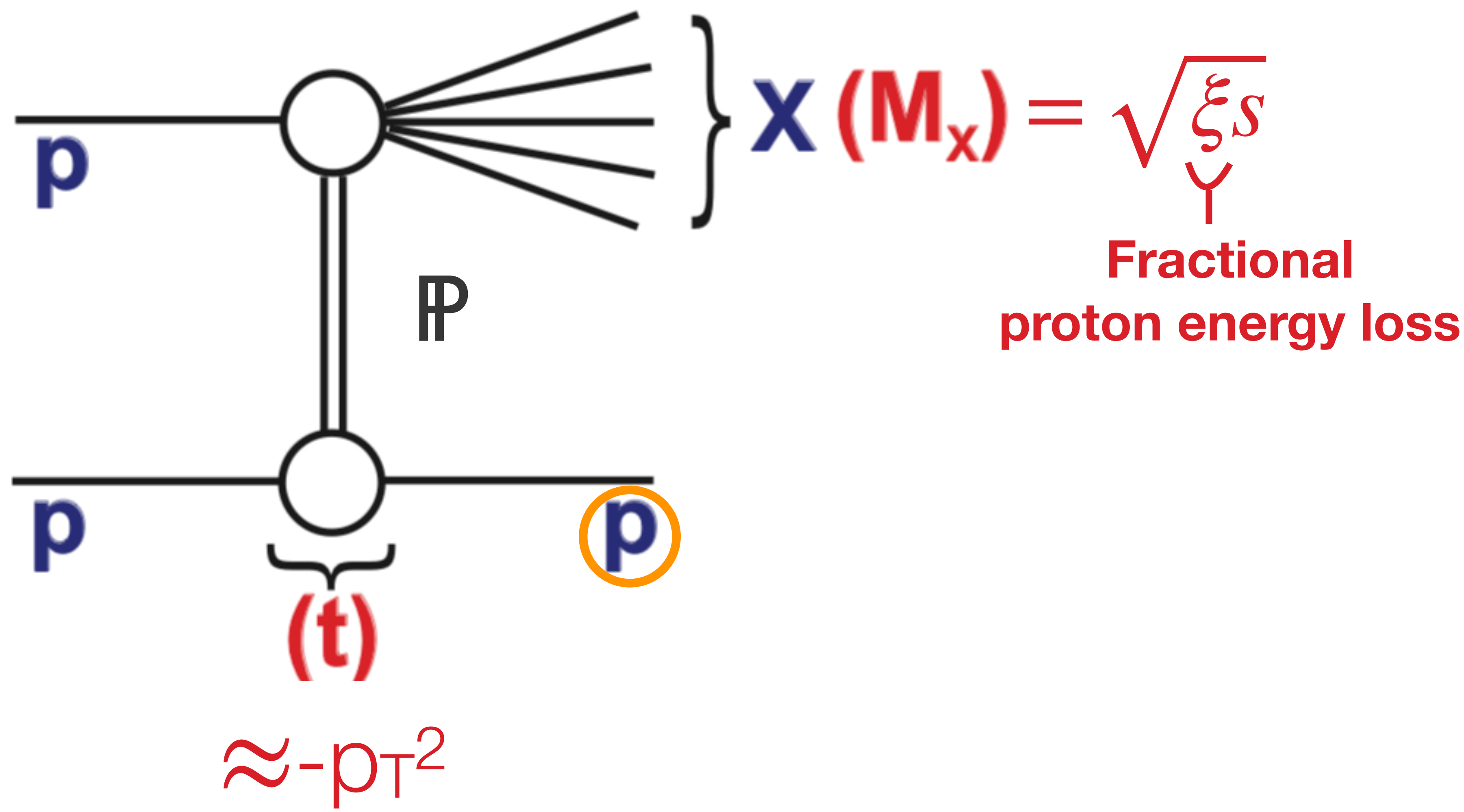
Possible to separate diffractive and non-diffractive

Not possible to fully separation single and double diffractive

Measuring diffractive events

$\mathbb{P}$ = Pomeron

Single diffractive (SD)



Intact forward scattered protons: Measure using ALFA or AFP

ALFA

AFP

AFP: active in high & low-μ runs, very fast Time-Of-Flight detectors, acceptance at higher mass, horizontal insertion, good ξ resolution

ALFA: vertical insertion, complementary acceptance to AFP, good t resolution

Going forward

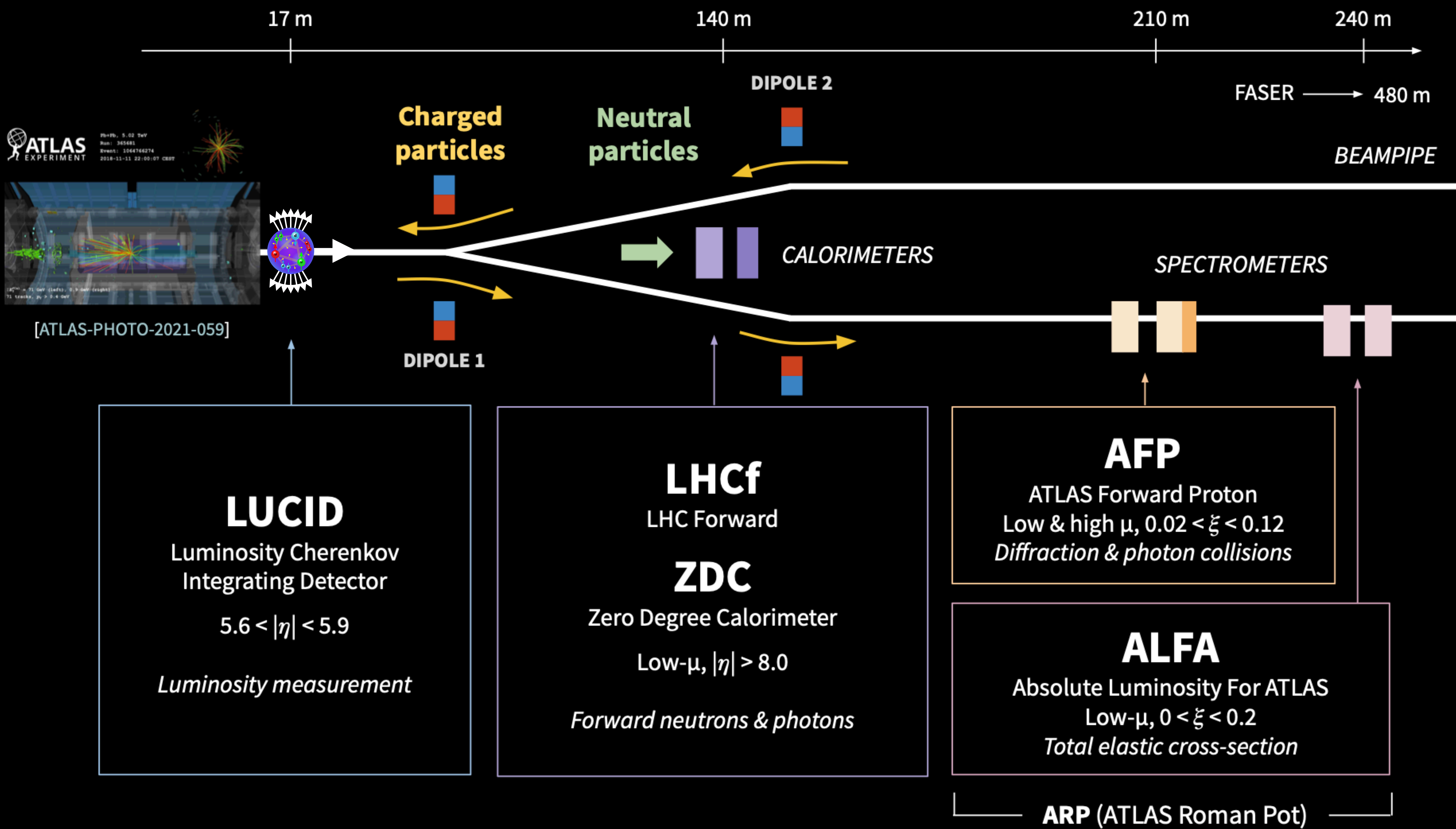
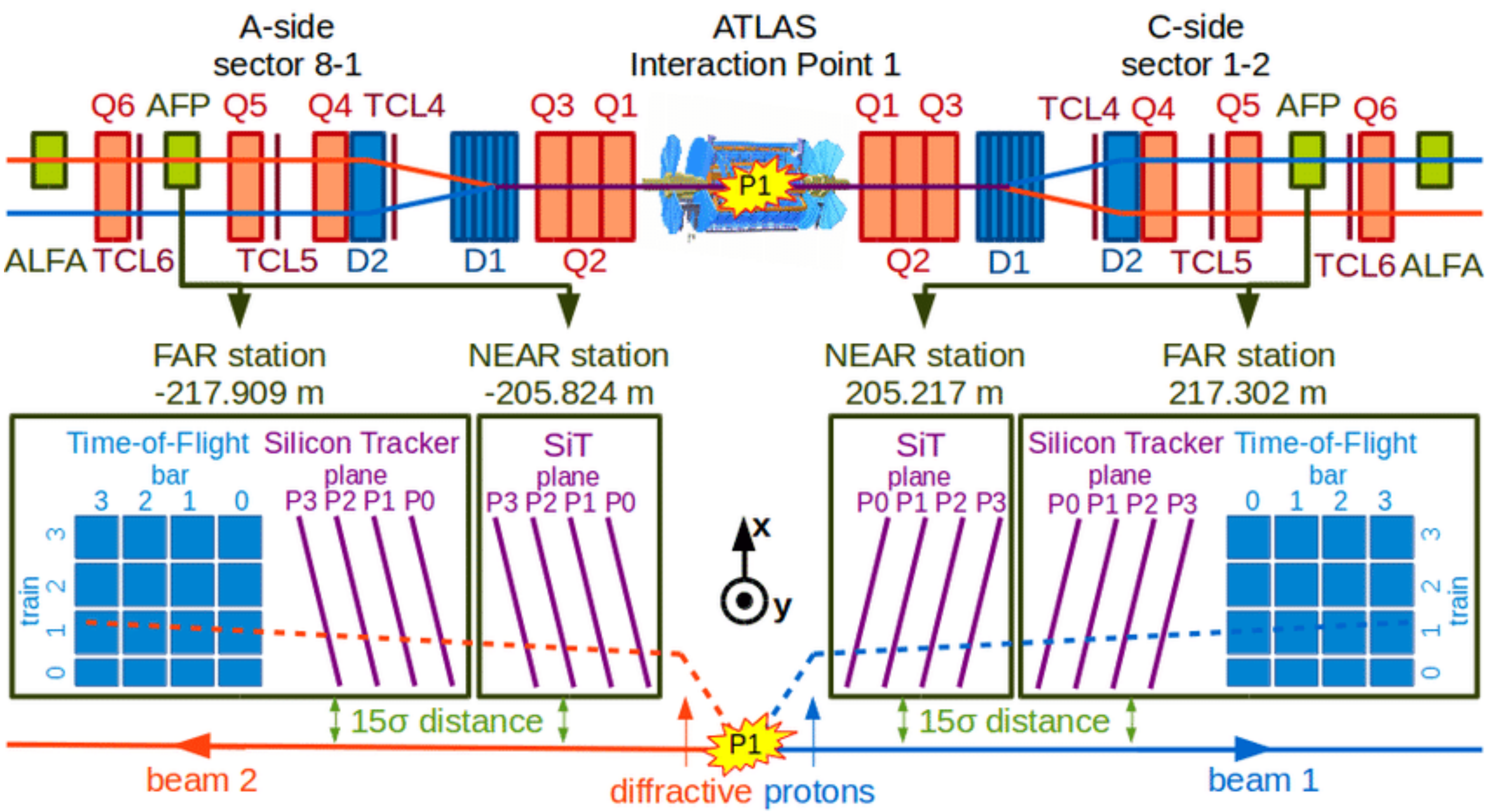


Diagram by Jesse Liu

AFP detectors

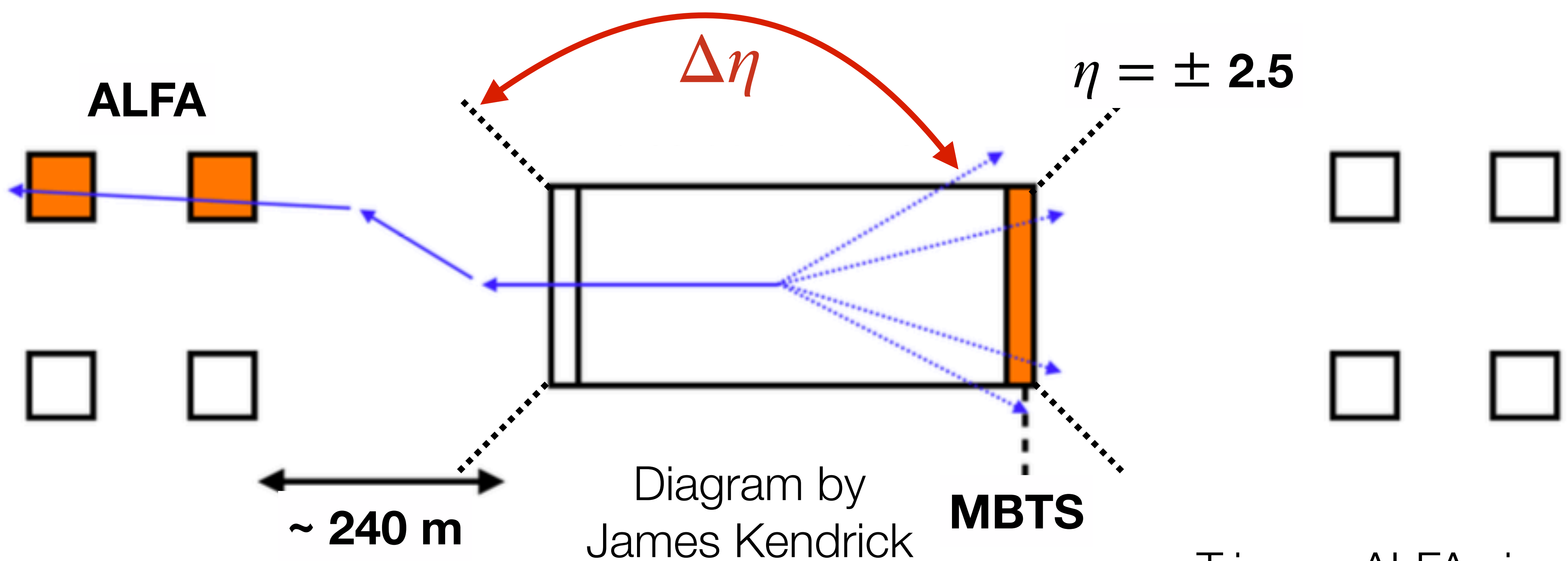


Single diffractive with ALFA

JHEP 02 (2020) 042

$\sqrt{s}$ = 8 TeV data with ALFA inserted, low pile-up $\langle \mu \rangle$ < 0.08 & high-β*

Measure from edge of inner detector on side of intact proton



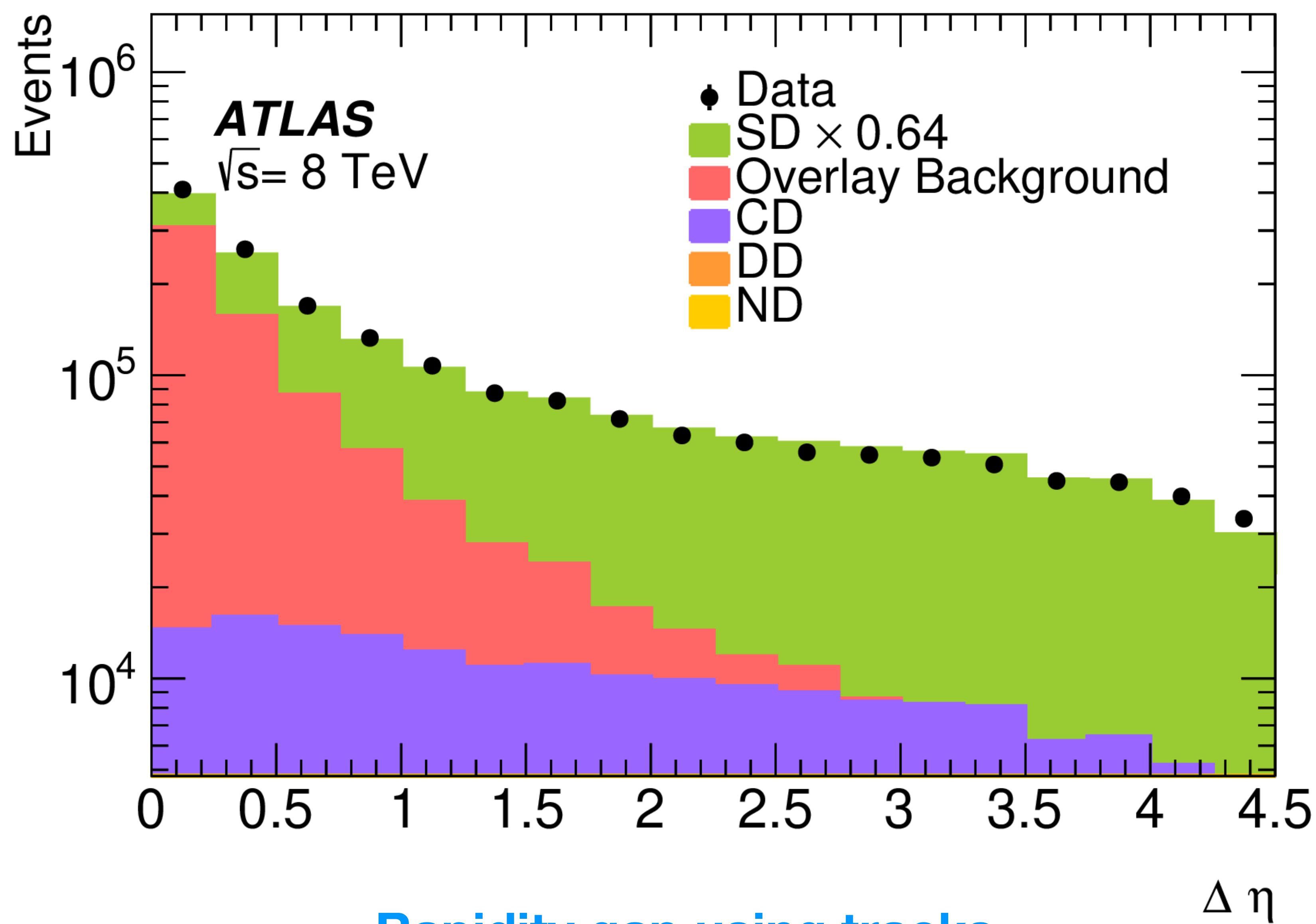
Trigger: ALFA signal + MBTS

Single proton in ALFA
& one good vertex

Tag intact proton:

- Suppress double diffractive
- Can measure t dependence (& alternative ξ measurement)

Single diffractive with ALFA



Rapidity gap using tracks

Non-diffractive and double diffractive now negligible

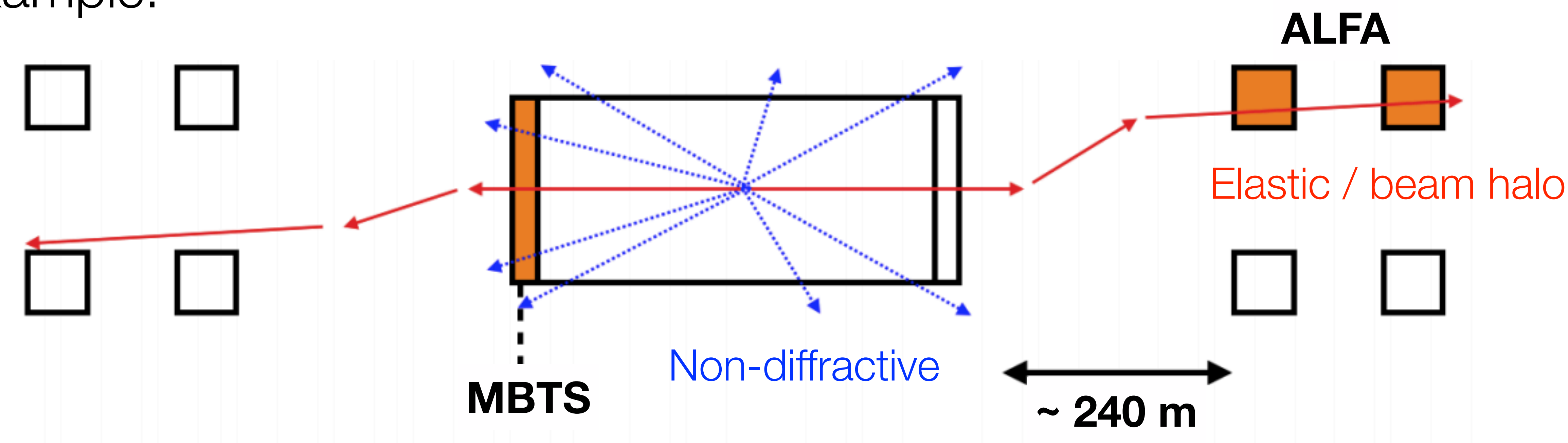
Overlay & central diffractive are main backgrounds

SD Backgrounds

CD estimated using simulation (& correction in CR)

'Overlay': coincidence of signal in ALFA + uncorrelated signal in ALFA
partially data-driven technique

Example:

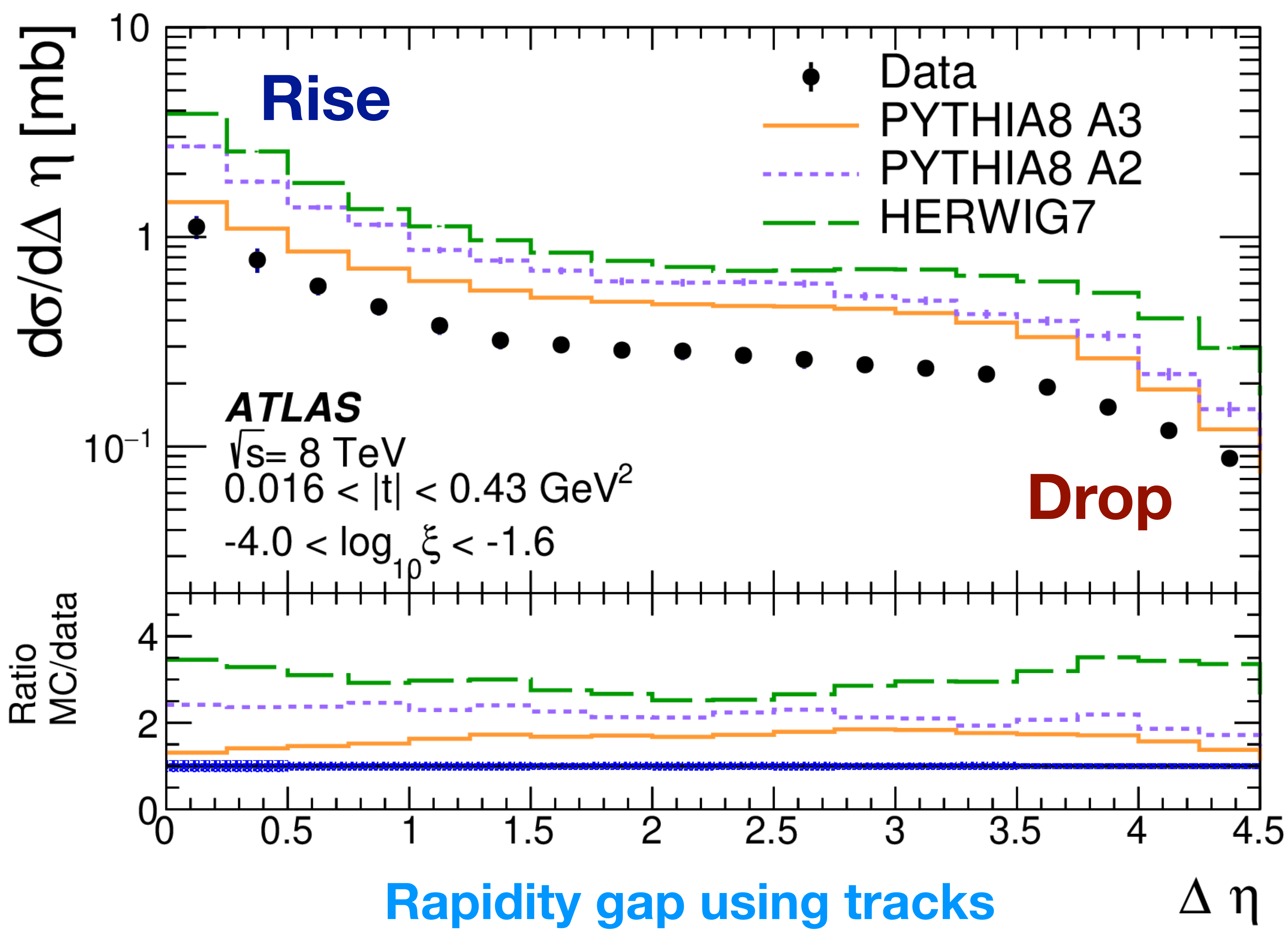


Uncertainty on overlay background is one of the largest systematics

Results

Measurements vs |t| & ξ in backup

Differential SD hadron level cross-section after bkg subtraction



Rapidity gap using tracks

Rise due to limited ATLAS tracker acceptance

Drop due to vertex requirement

Shape well-modelled but not overall cross-section

Results

Inclusive SD cross-section measurement

Distribution	$\sigma_{\text{SD}}^{\text{fiducial}(\xi,t)}$ [mb]
Data	1.59 ± 0.13
Pythia8 A2 (Schuler–Sjöstrand)	3.69
Pythia8 A3 (Donnachie–Landshoff)	2.52
Herwig7	4.96

Fiducial region:

$-4.0 < \log_{10} \xi \leq -1.6$

$\& \ 0.016 < |t| \leq 0.43 \text{ GeV}^2$

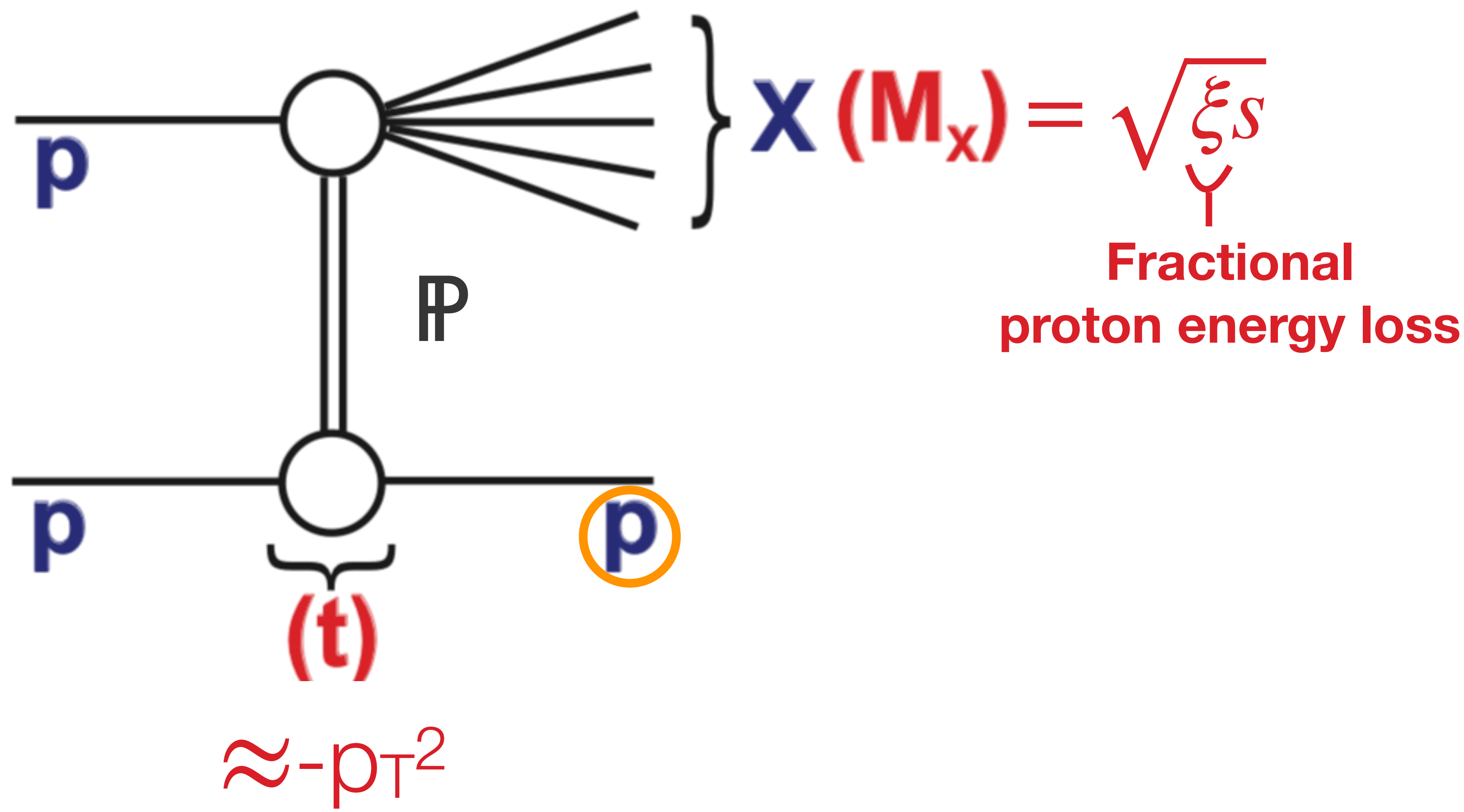
Large over-prediction by MC: $\sigma_{\text{Data}} / \sigma_{\text{Pythia8 A3}} \sim 0.6$

→ Important to measure hard-to-model processes

Measuring diffractive events

$\mathbb{P}$ = Pomeron

Example: Single diffractive (SD)



Diffractive system X:

- Neutral particles can be measured using LHCf + ZDC calorimeters (π^0, γ, n)
- For hard diffraction you can also have jets - not covered in this talk

Going forward

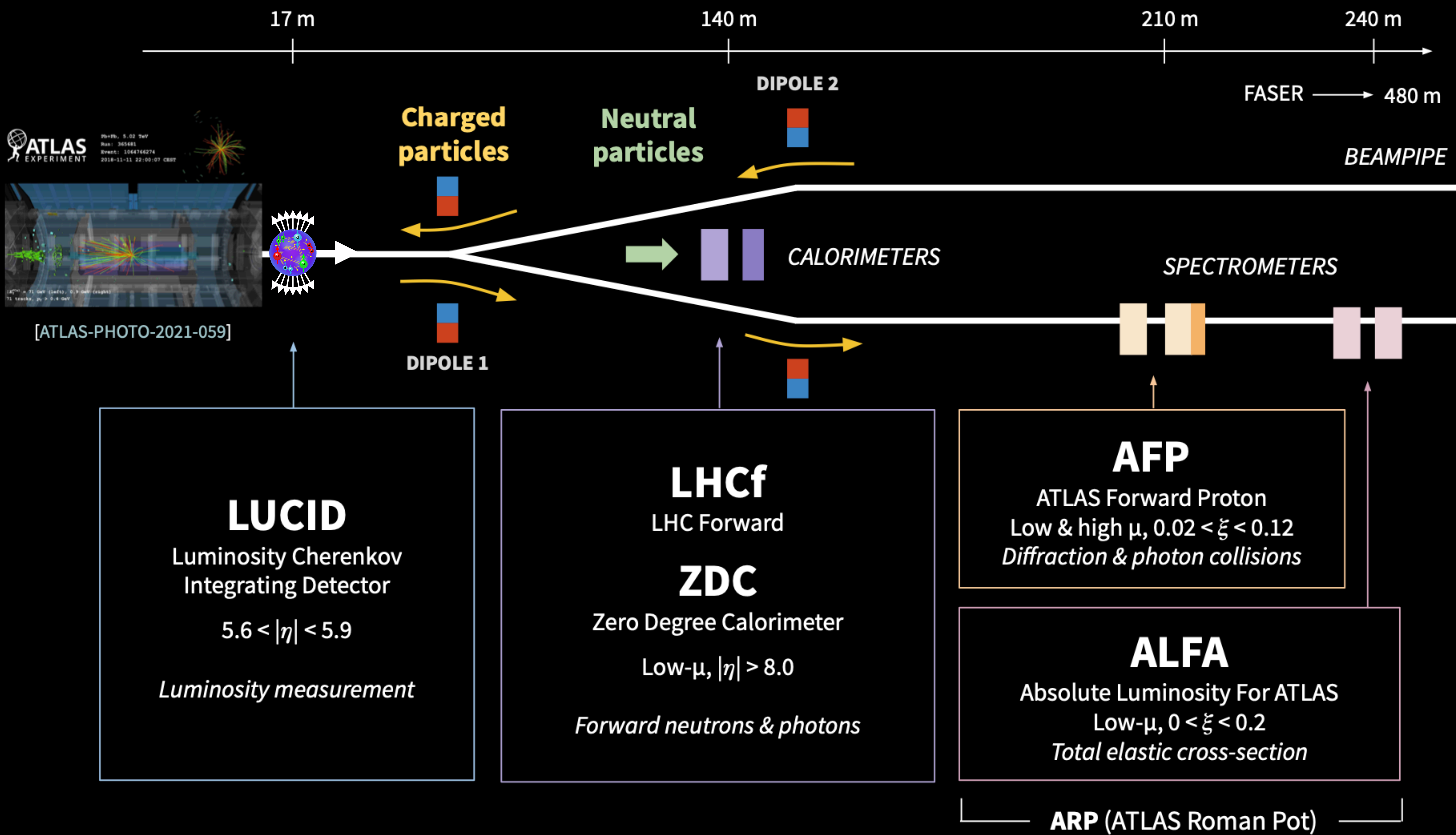


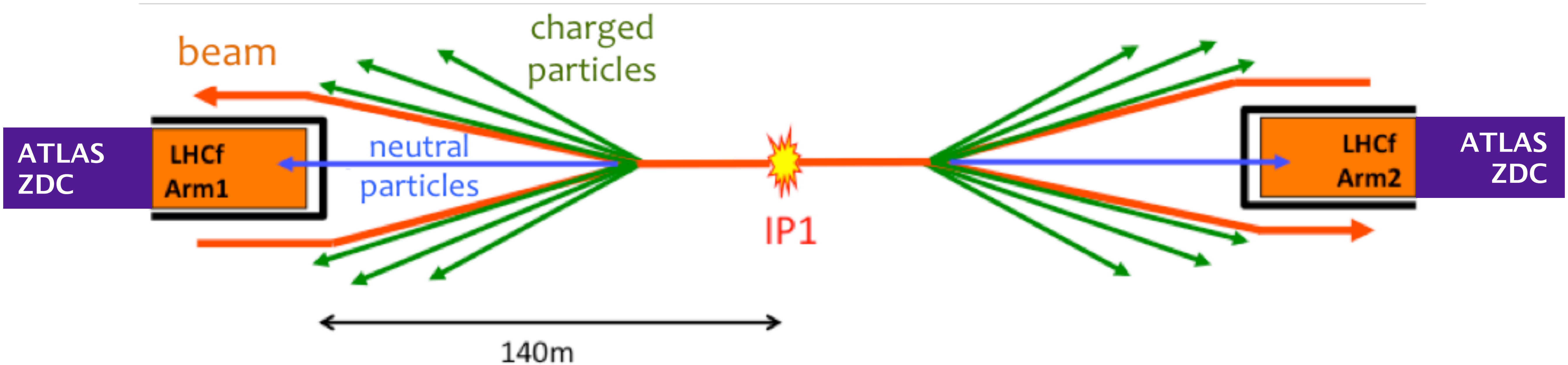
Diagram by Jesse Liu

Single diffractive with ALFA/AFP + LHCf/ZDC

LHC forward (LHCf) + ATLAS Zero Degree Calorimeter (ZDC):

Measure forward neutral particles in 0 degree region

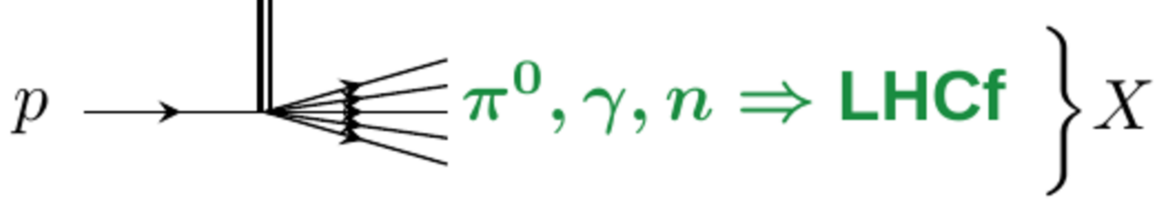
→ Combining both improves hadronic shower containment & neutron resolution

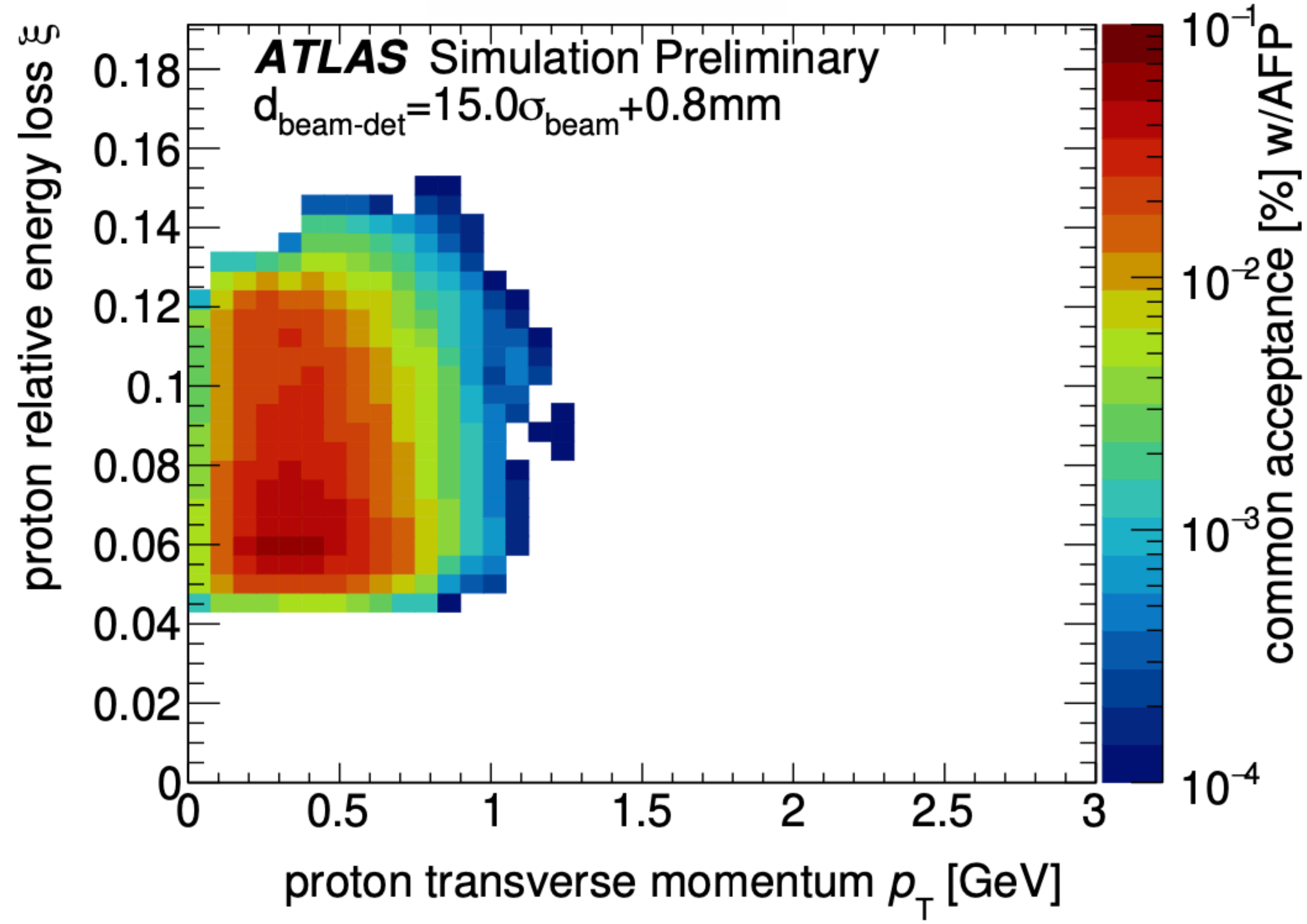


What about including forward proton detectors?

Single diffractive with ALFA/AFP + LHCf/ZDC

Physics potential of joint data taking with ALFA or AFP PUB-2023-024:





Sufficient common detector acceptance with AFP!

→ Motivated inclusion of AFP detectors during LHCf run in September 2022

→ 1st data-taking with LHCf, ZDC, ATLAS + AFP detectors included

Summary

Range of interesting elastic & diffractive measurements presented + planned

Many special + novel techniques & detectors, close ties to performance

See the following talks/posters for more ALFA + AFP:

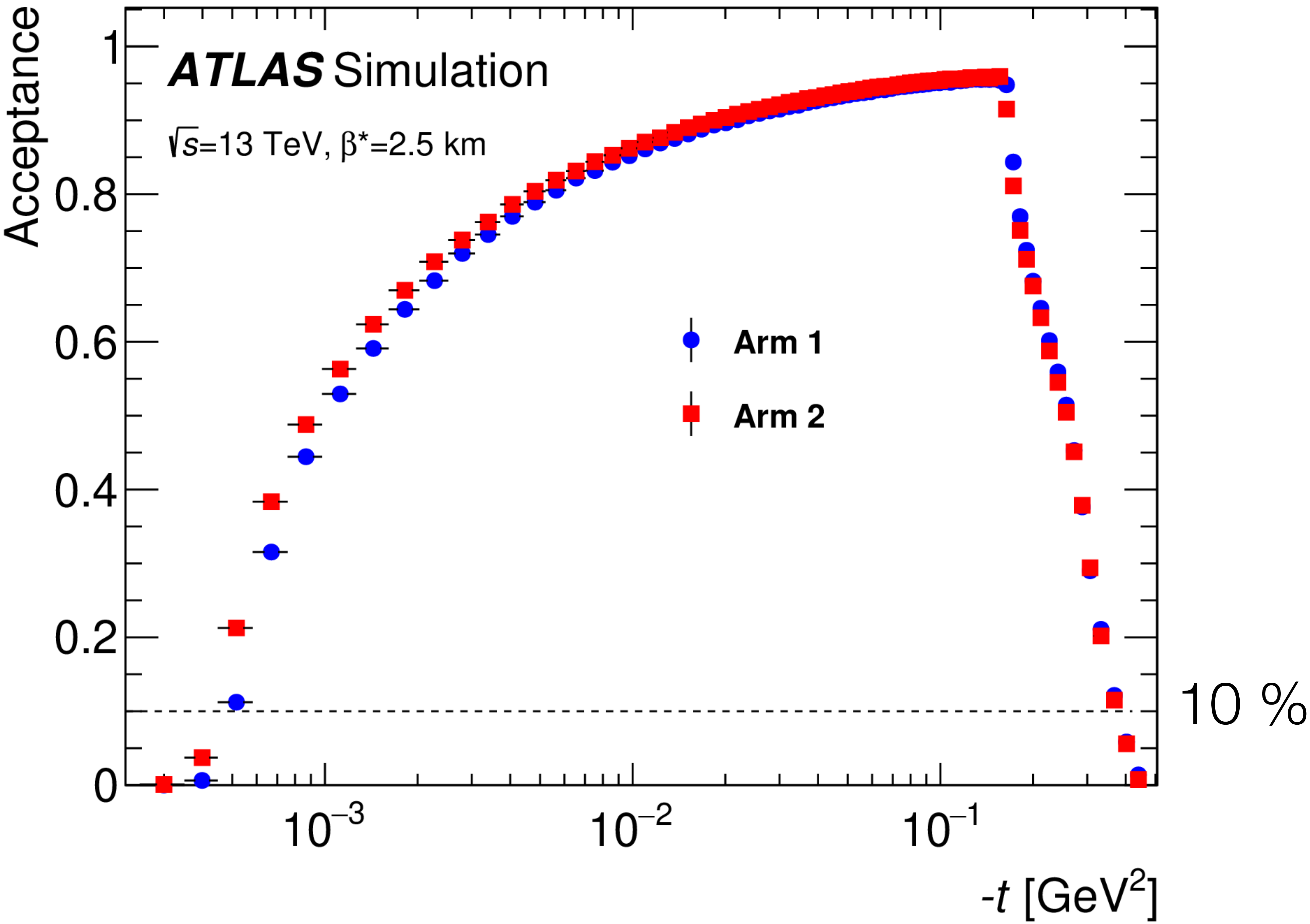
- Savannah Clawson
- Sergio Javier Arbiol Val
- Maciej Lewicki
- Maciej Trzebinski

Advance our understanding of nature

Backup

ALFA Elastics acceptance

Mainly depends on ALFA geometry & distance to beam



OD based alignment

K.W. Janas

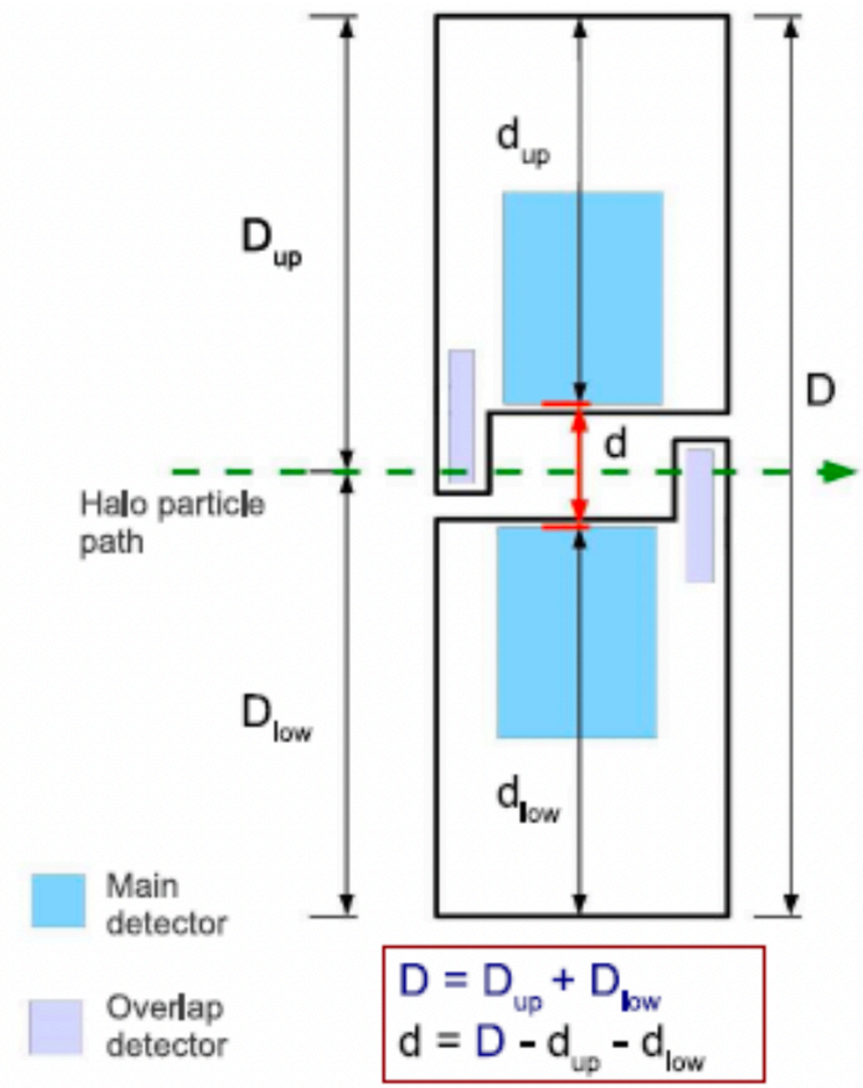


Figure 5: Scheme of the Overlap Detectors concept: halo particle hit fibers in upper and lower OD in the ALFA station with the same vertical position [2]. The measured positions can be used to determine the distance **d** between upper and lower MD.

Measurement methods for σ_{tot}

R Staszewski

Luminosity-dependent (ATLAS)

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

Requires a dedicated luminosity measurement

Luminosity-independent (TOTEM)

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

Requires correction for not measured small-mass diffraction

ATLAS vs TOTEM

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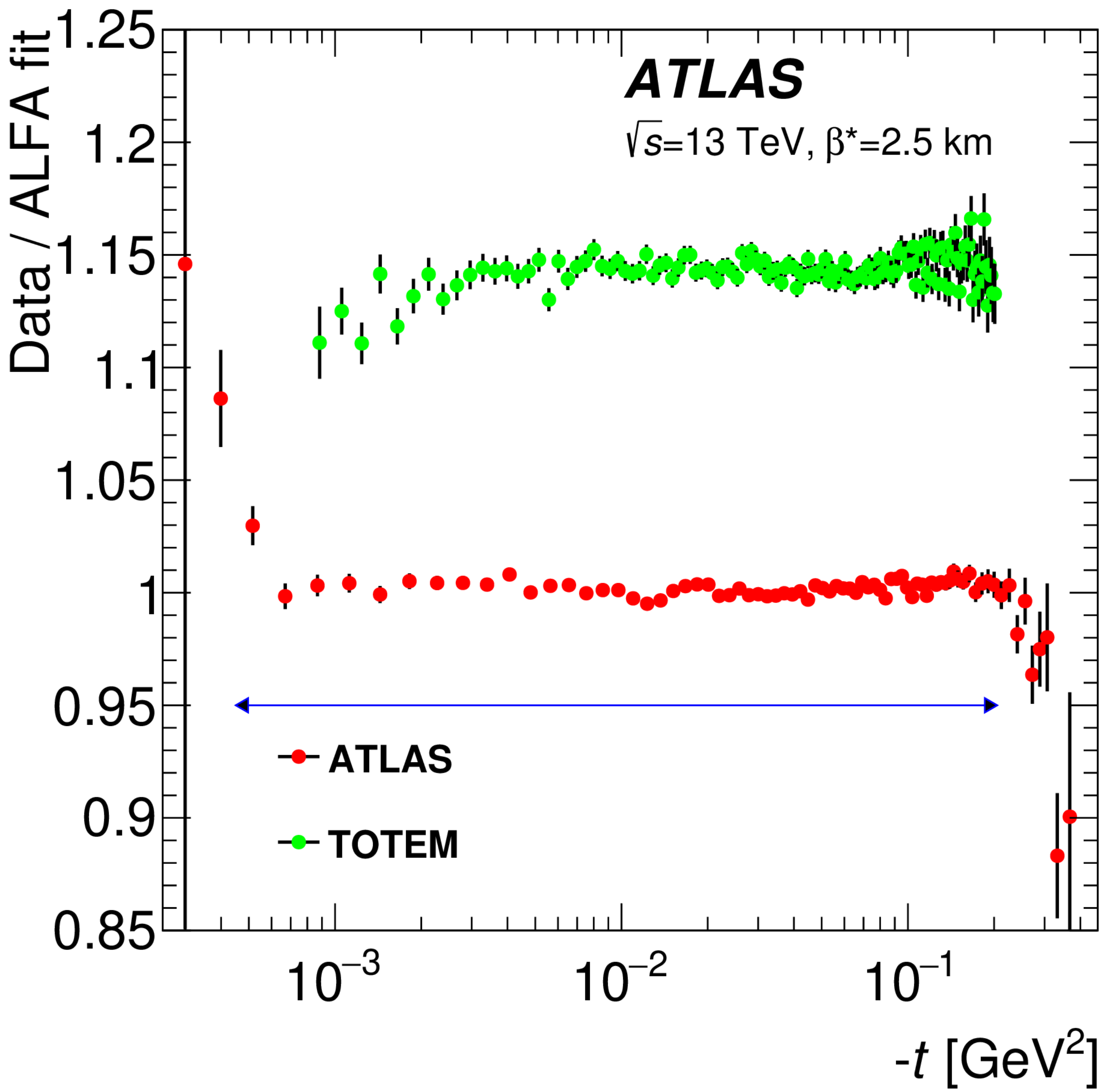


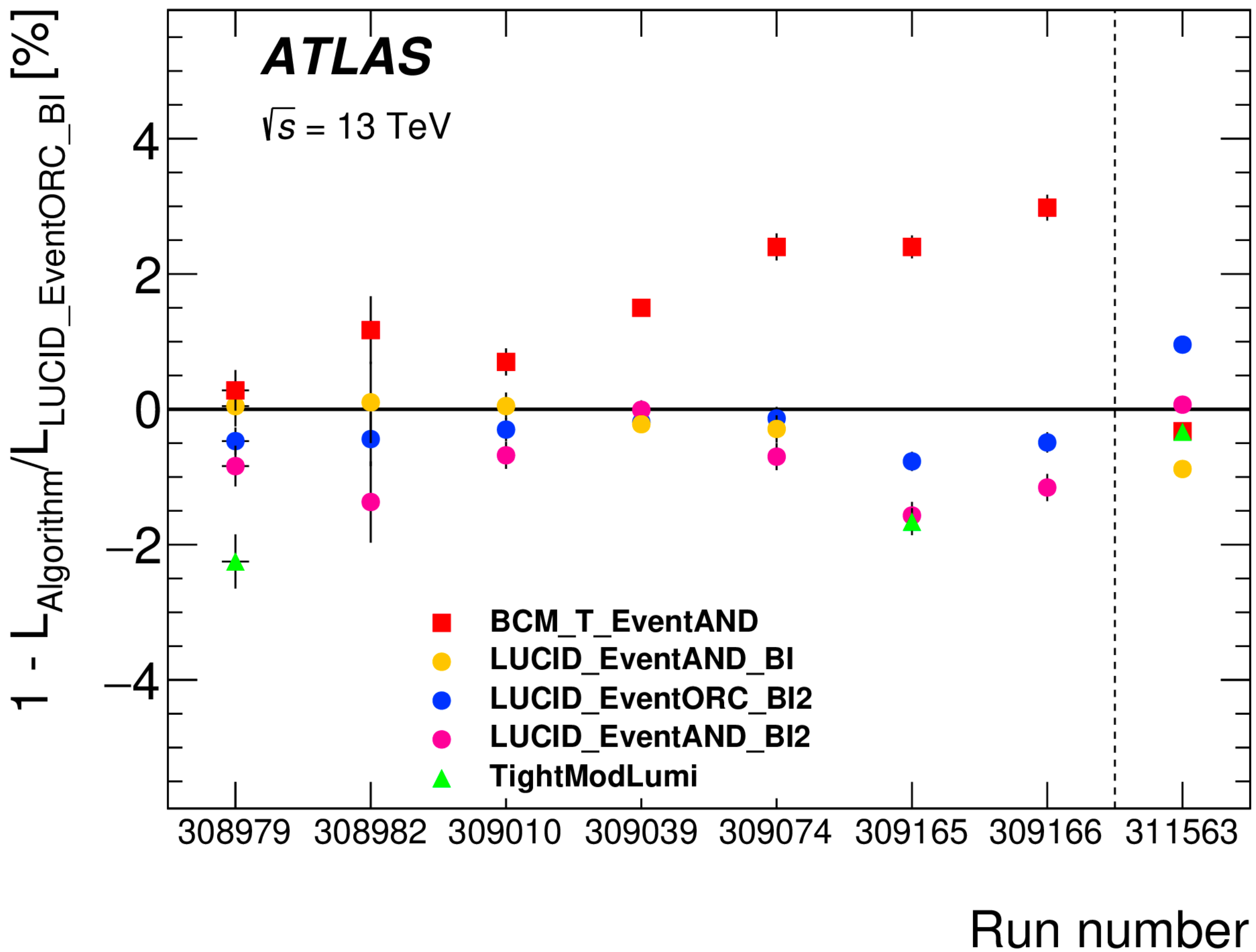
Differential elastic cross section comparison for ATLAS & TOTEM
Data are in both cases divided by the model fit to the ATLAS data
Model is fit in range in t indicated by the blue arrow
Only statistical uncertainties are shown

Luminosity for elastics measurement

Total uncertainty: 2.15%

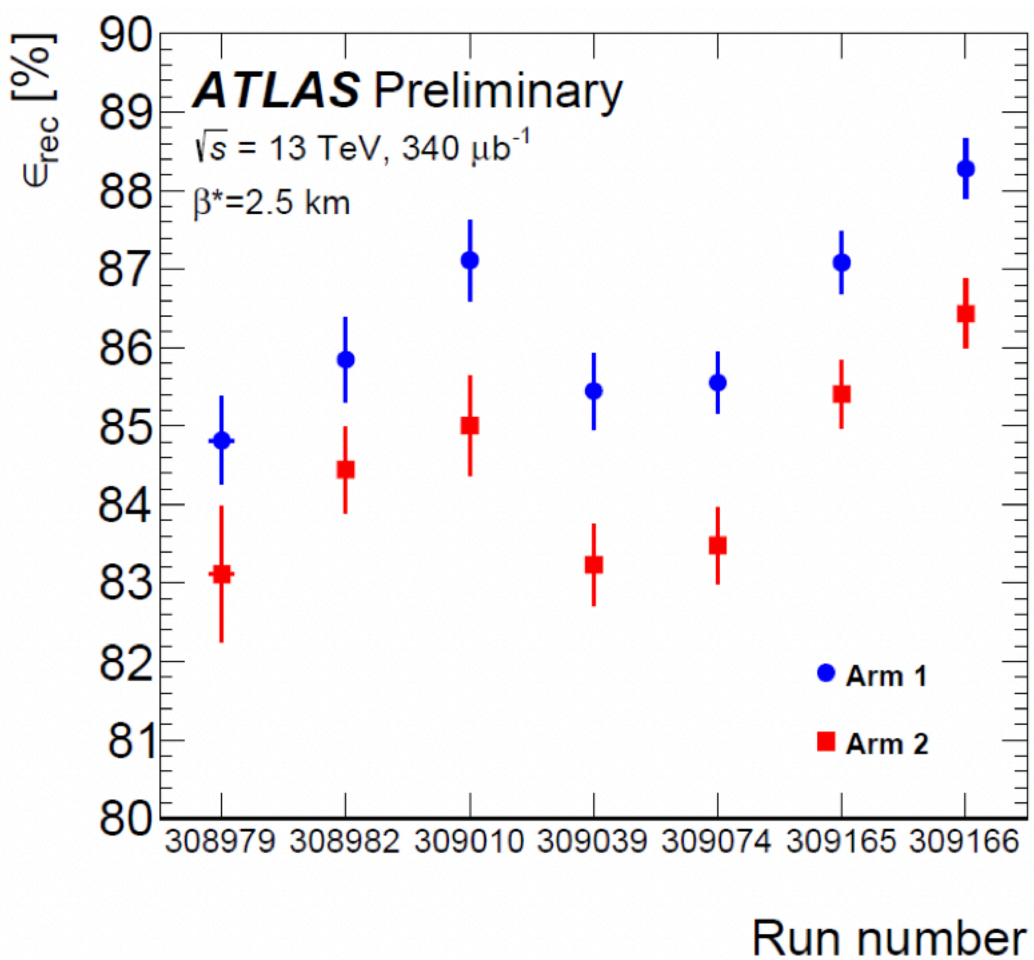
Main contributions:

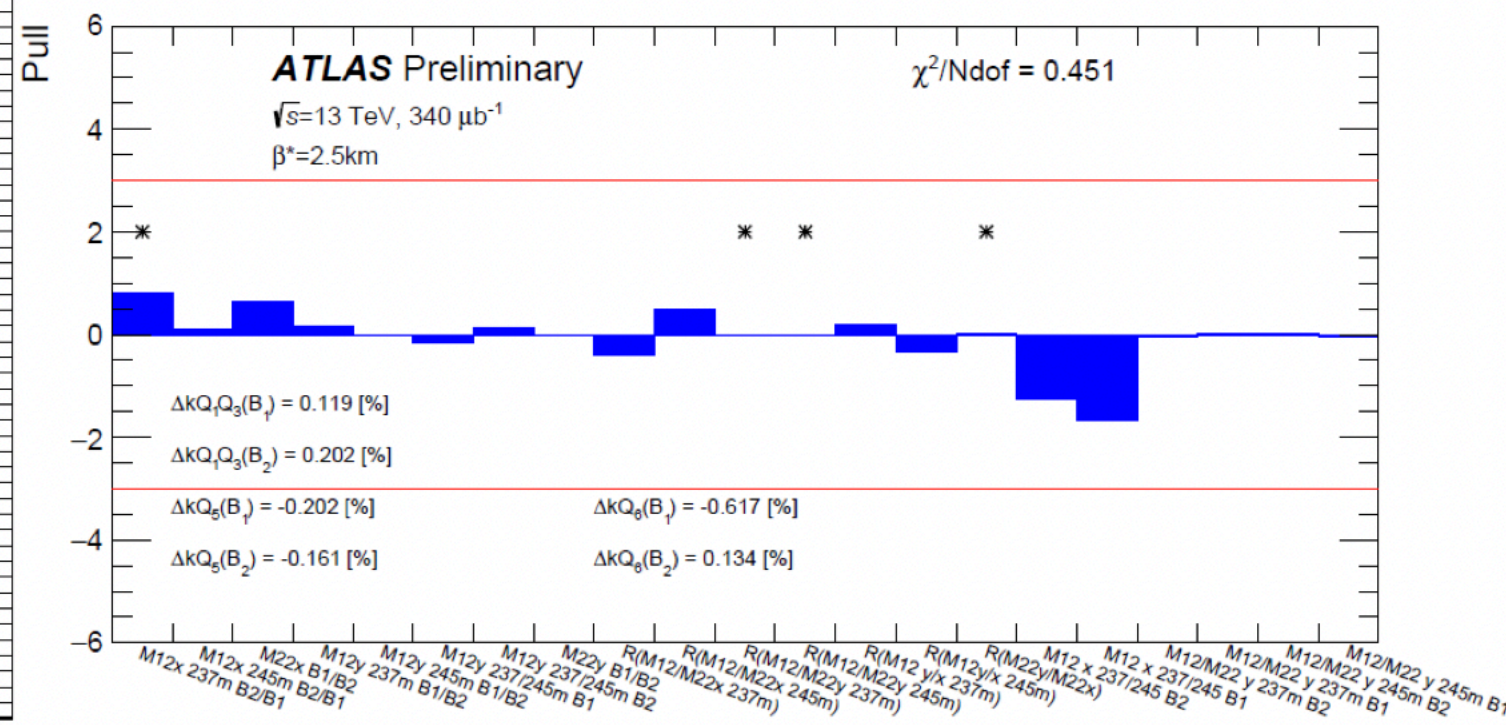
vdM calibration, calibration transfer, stability over time & background



Elastics Reco efficiency and beam optics

H Stenzel





Reconstruction efficiency by a tag-and-probe method (data-driven)

- Reconstruction can fail because of shower development
- Efficiency in arm1 slightly higher because of material distribution

Beam optics (transport matrix elements) needed for *t*-reconstruction

- An effective optics model is tuned using correlations in ALFA variables
- small corrections are derived to the strength of the quadrupoles

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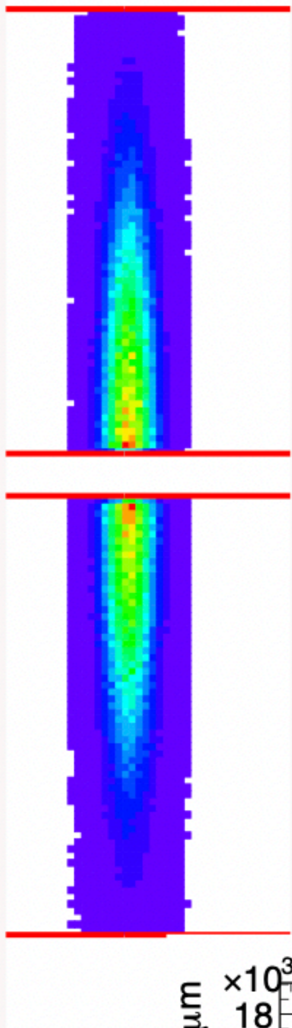
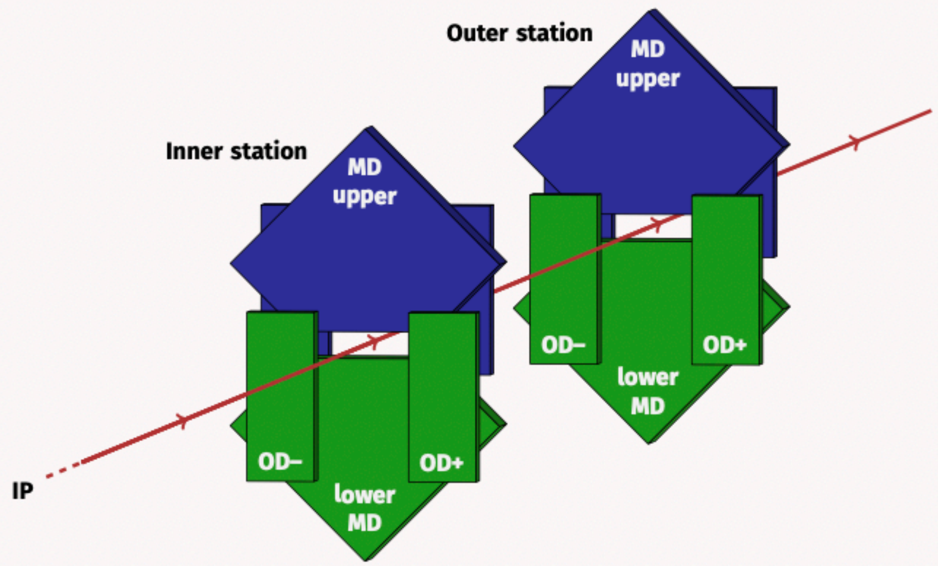
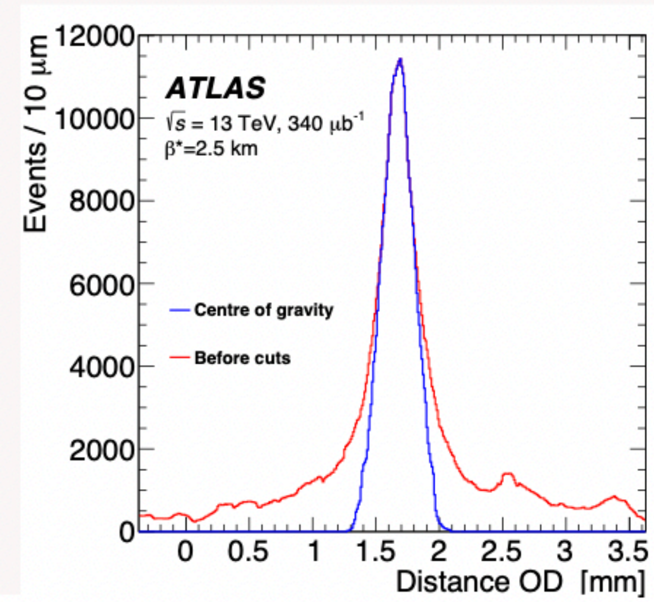
Elastics alignment

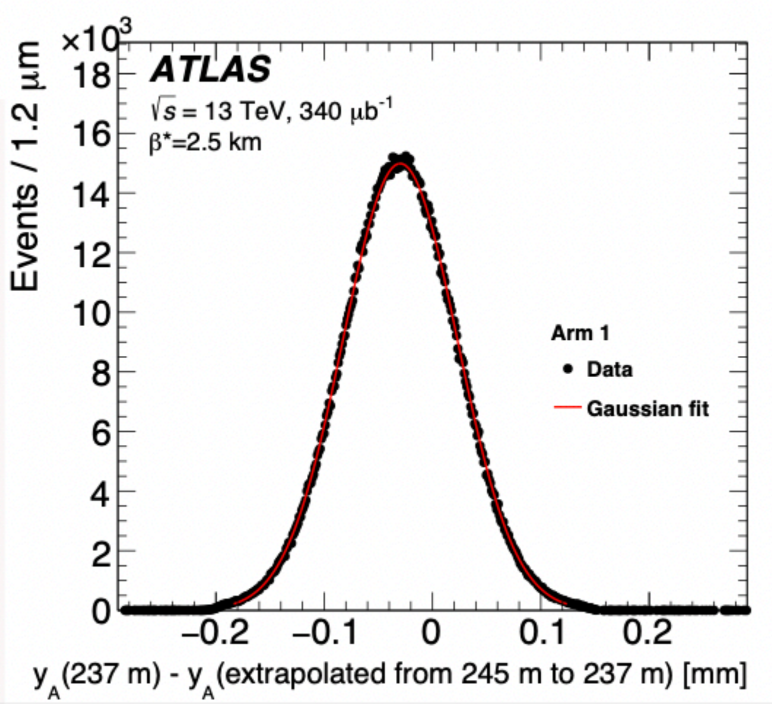
R Staszewski

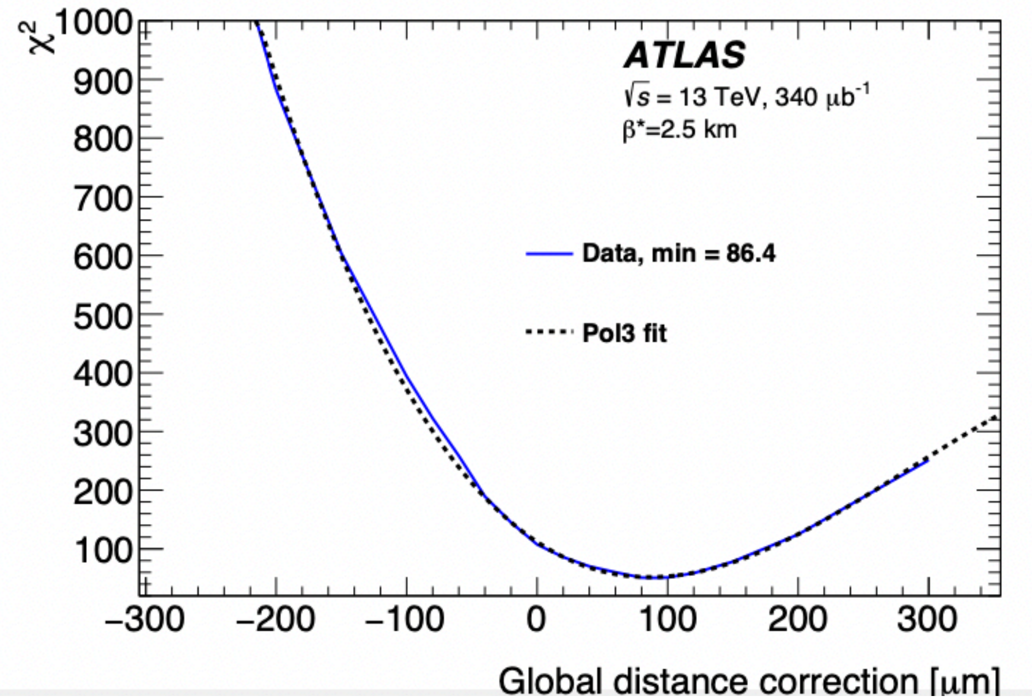


- Rotation, horizontal and vertical offsets obtained from left–right and up–down symmetry of the elastic pattern
- Multi-step procedure of distance evaluation









Elastics uncertainties

Main uncertainties:

- Luminosity (for σ_{tot})
- Alignment & theory uncertainties (for ρ)

	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

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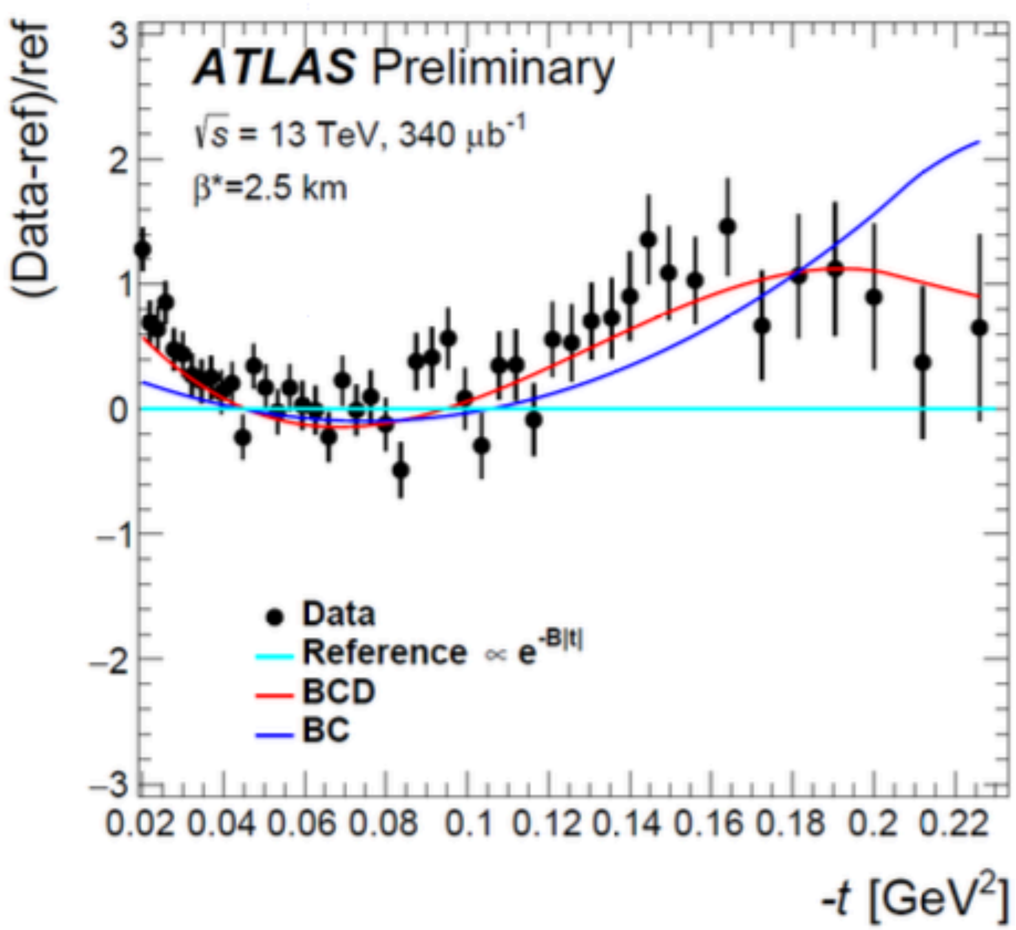

Theoretical uncertainties:

- 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

Elastics theoretical predictions

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Cross section from squared amplitudes.

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

Coulomb amplitude

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

Proton form factor

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

Nuclear amplitude with curvature terms *C* and *D*.

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

Coulomb phase

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

Full prediction

$$\begin{aligned}\frac{d\sigma}{dt} &= \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2}\times G^4(t)\\ &- \sigma_{tot}\times\frac{\alpha G^2(t)}{|t|}\left[\sin\left(\alpha\phi(t)\right) + \rho\cos\left(\alpha\phi(t)\right)\right]\times\exp\frac{-B|t| - Ct^2 - D|t|^3}{2}\\ &+ \sigma_{tot}^2\frac{1+\rho^2}{16\pi(\hbar c)^2}\times\exp\left(-B|t| - Ct^2 - D|t|^3\right)\ ,\end{aligned}$$

N.b.: Also several models of strong phase tested.

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Elastics FMO & BCBM models

FMO (Froissaron Maximal Odderon):

Tuned to TOTEM data, ALFA cross-section data at 7 & 8 TeV not included in the tuning

BCBM (Block & Cahn & Bourely & Martin):

$\sigma_{\rm tot}$ grows slightly slower than $\ln^2 s$ evolution assumed by COMPETE

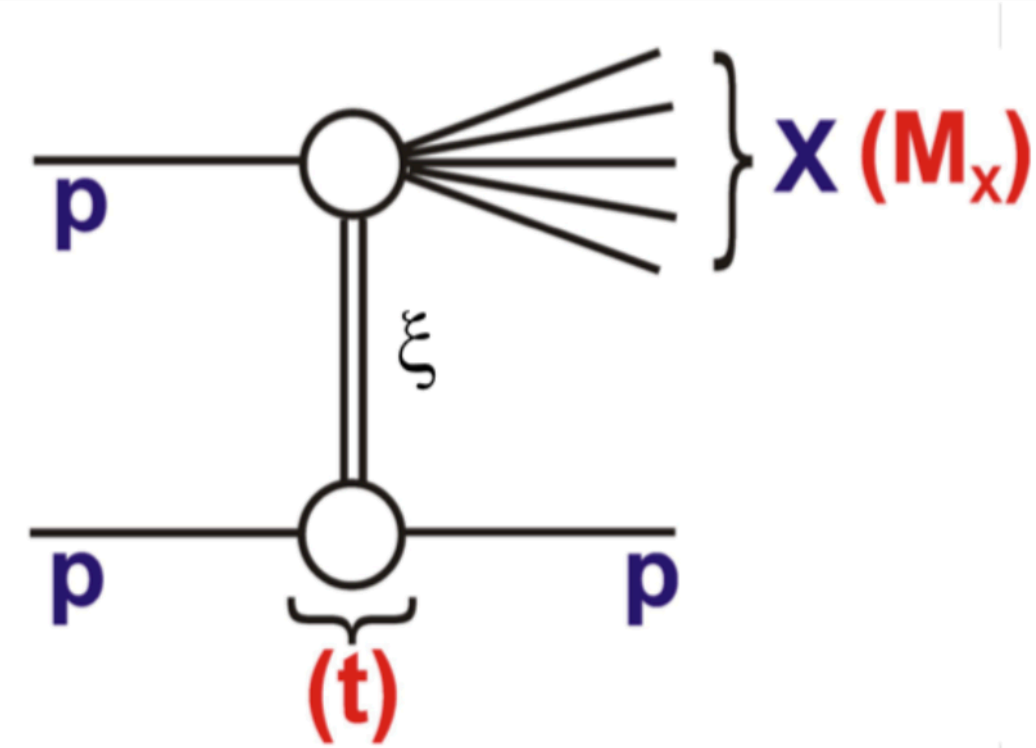
→ damped $\ln^2 s$ amplitude with energy dependence of form $\ln^2 s/(1+\alpha \ln^2 s)$

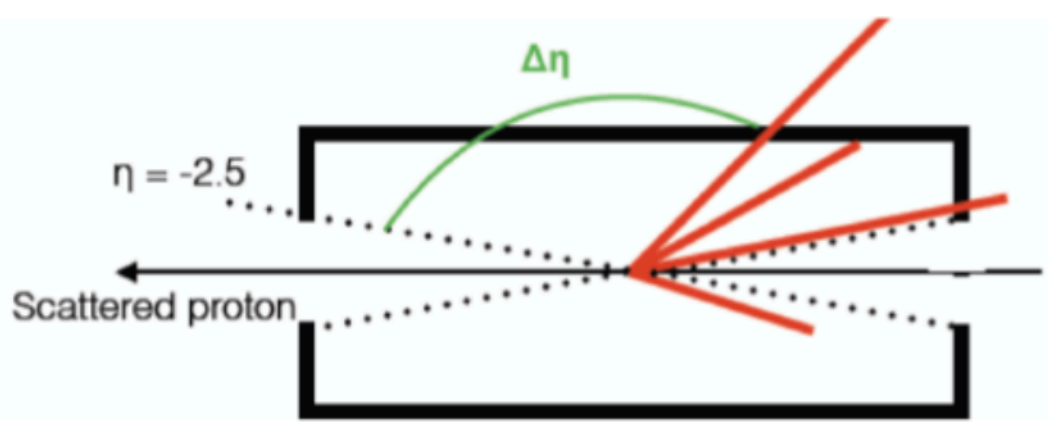
α is the damping factor (modifies high energy behaviour of ρ and $\sigma_{\rm tot}$)

Fair description of ALFA data for α=0.0014

Single Diffractive kinematic variables

R Staszewski





- t – squared four-momentum transferred from the proton (related to proton transverse momentum)

$$t \approx -p_T^2$$

- ξ – momentum fraction of the proton carried by the pomeron

$$\xi = 1 - E/E_0$$
$$= M_X^2/s \approx \sum_i (E^i \pm p_z^i)/\sqrt{s}$$

E – proton energy
$E_0 0$ – proton initial energy
E^i, p_z^i – energy and longitudinal momentum of particles in the dissociated state

s – centre-of-mass energy

- $\Delta\eta$ – (pseudo)rapidity gap from the tracker edge

For SD: $\Delta\eta \approx -\ln(\xi)$

Single Diffractive analysis MC

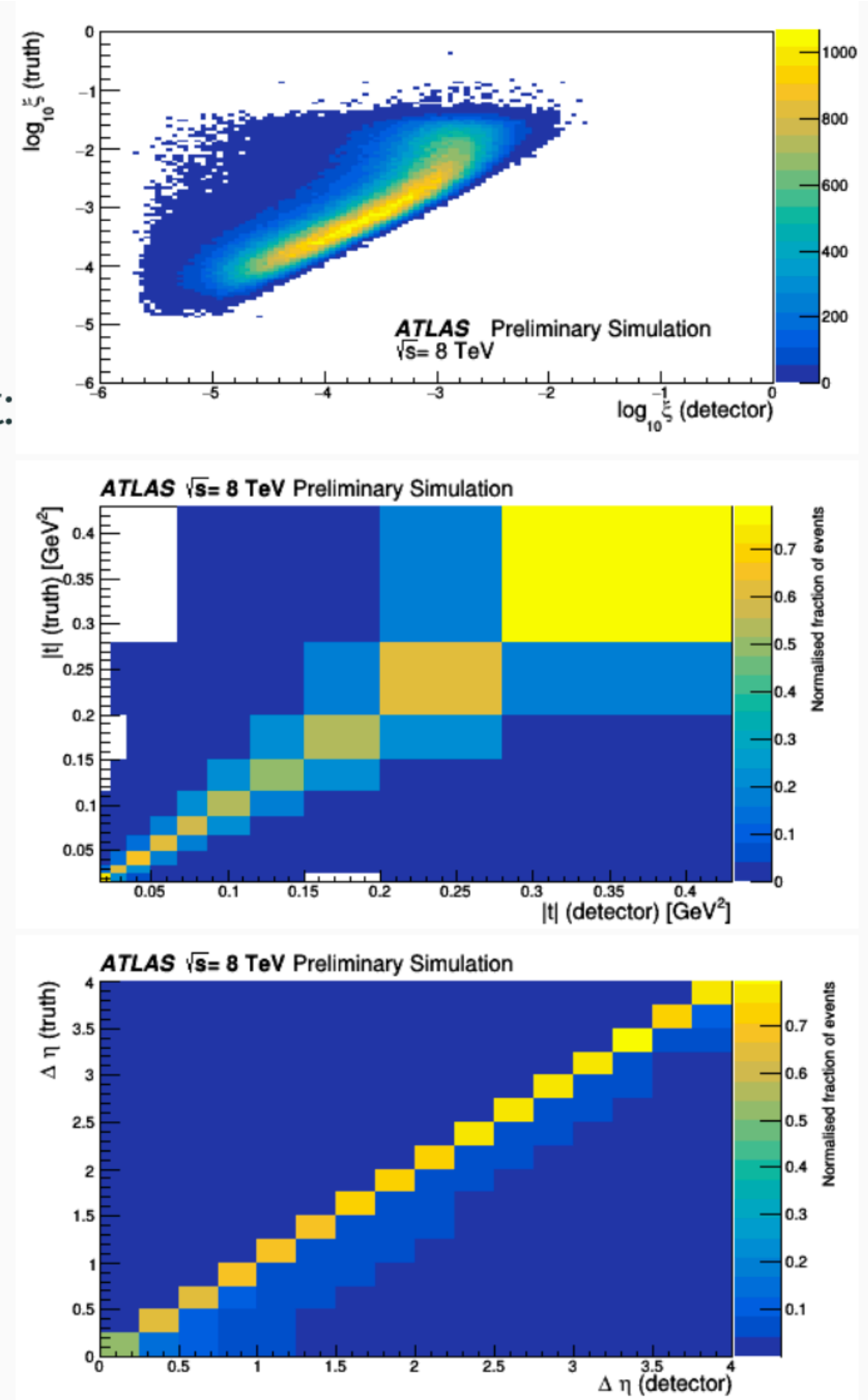
R Staszewski

Main MC:

- PYTHIA8 A3 tune (ATL-PHYS-PUB-2016-017):
- Proton PDF = NNPDF23 LO
- Pomeron : PDF = H1 2006 Fit B; Flux: intercept: 1.06, slope: 0.25 (Donnachie-Landshoff)
- SD for unfolding
- CD, DD, ND for background subtraction
- Elastics for ALFA Reconstruction efficiency

For systematics:

- PYTHIA 8 A2 tune (ATL-PHYS-PUB-2012-003)
- HERWIG 7.1:
    - Proton PDF = MMHT2014lo68cl
    - Pomeron : PDF = H1 2006 Fit A; Flux: intercept: 1.00, slope: 0.25

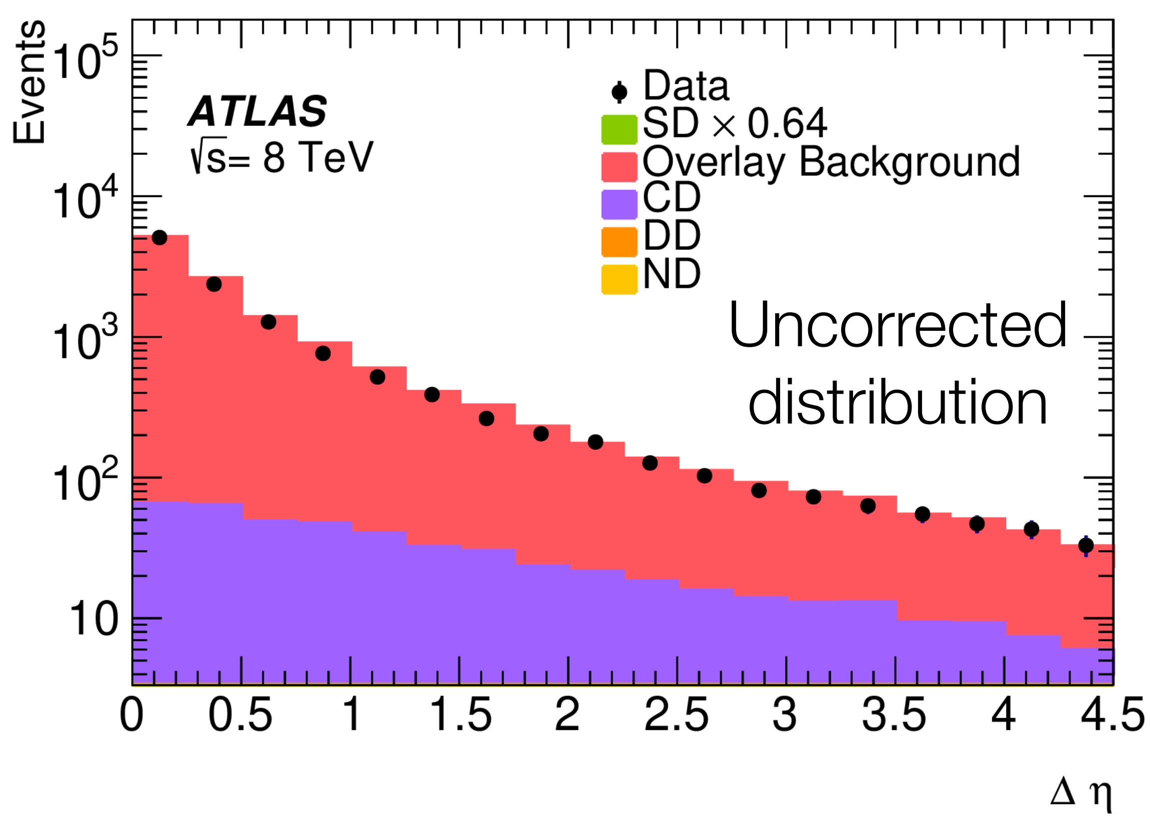


Single diffractive with ALFA

'overlay'

Bkg estimate: ND enriched sample (32 MBTS segments fired & tracks within 0.5 η of both edges of ID acceptance)

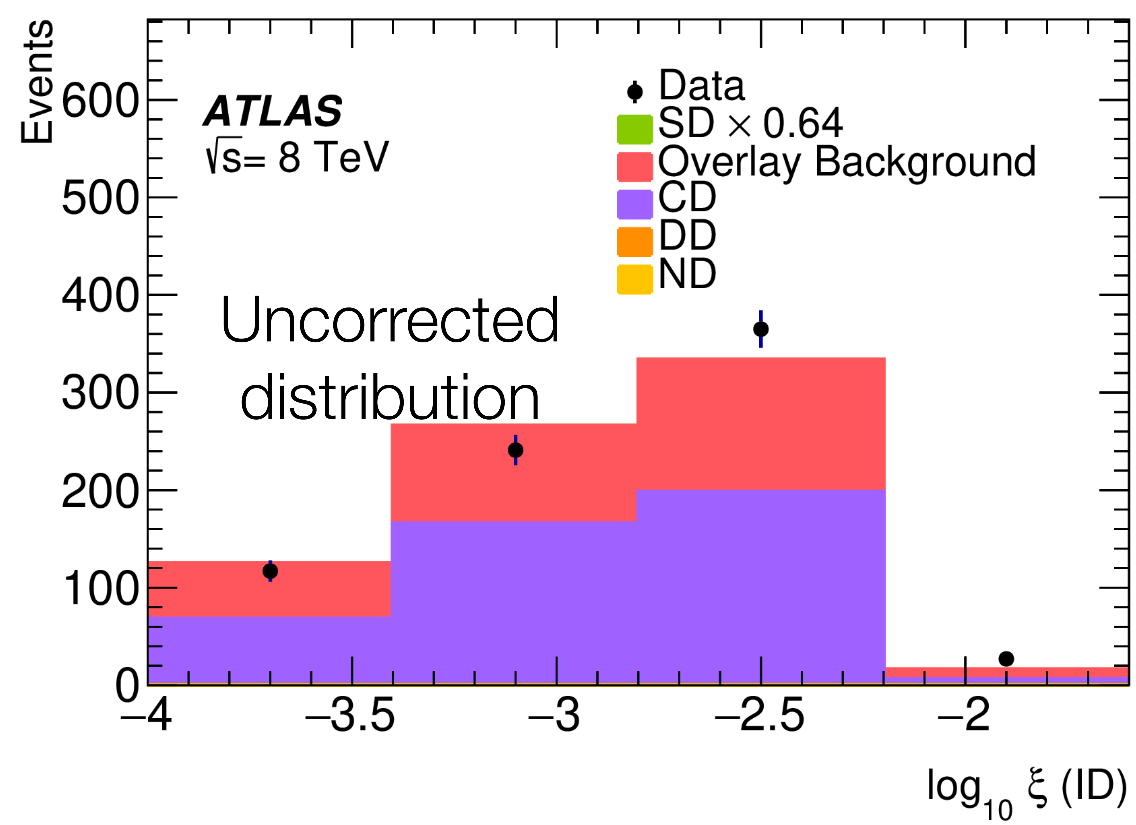
- Gives t distributions
- Gives normalisation for ξ and $\Delta\eta$



CR: nominal selection but with protons in two armlets

Central Diffraction

Bkg estimate: MC + re-weight ξ distributions to match data in CR (preserving normalisation)



CR: nominal selection but with protons in two armlets & 2-10 MBTS segments fired

Single diffractive with ALFA

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Slope parameter: $B = 7.65 \pm 0.26(\text{stat.}) \pm 0.22(\text{syst.})\ \text{GeV}^{-2}$

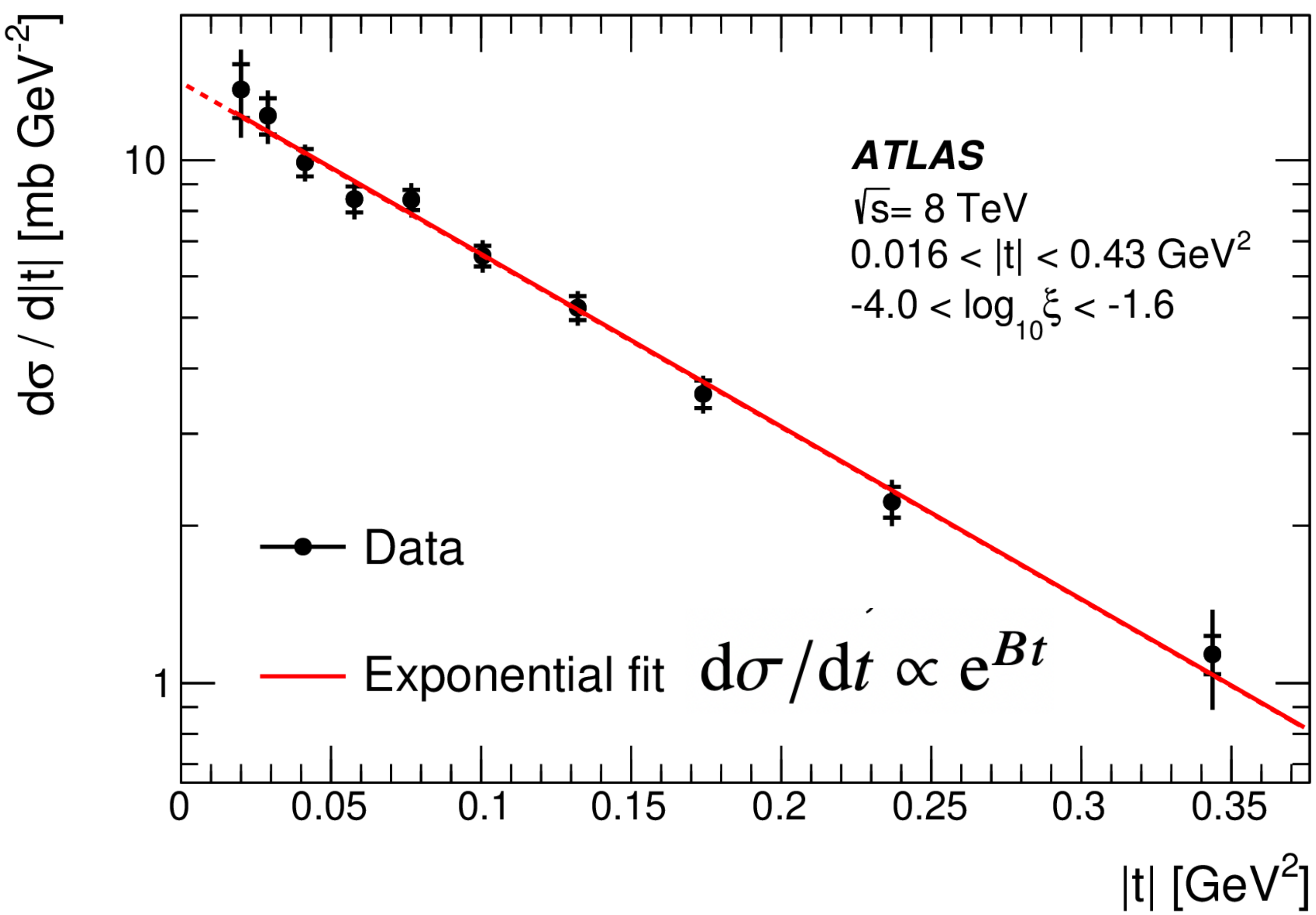
Compatible with predictions:

7.10 GeV^{-2} Donnachie-Landshoff flux (Pythia8 A3 turn)

At 1.6σ

7.82 GeV^{-2} Schuler-Sjöstrand (Pythia8 A2 tune)

At 0.5σ



Largest uncertainty from overlay background subtraction

Single diffractive with ALFA

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Pomeron intercept: $\alpha(0) = 1.07 \pm 0.02\ (\text{stat.}) \pm 0.06\ (\text{syst.}) \pm 0.06\ (\alpha')$

Triple Regge Fit:

$$\frac{d\sigma}{d\xi} \propto \left(\frac{1}{\xi}\right)^{\alpha(0)} \frac{e^{Bt_{\text{high}}} - e^{Bt_{\text{low}}}}{B}$$

$$B = B_0 - 2\alpha' \ln \xi$$

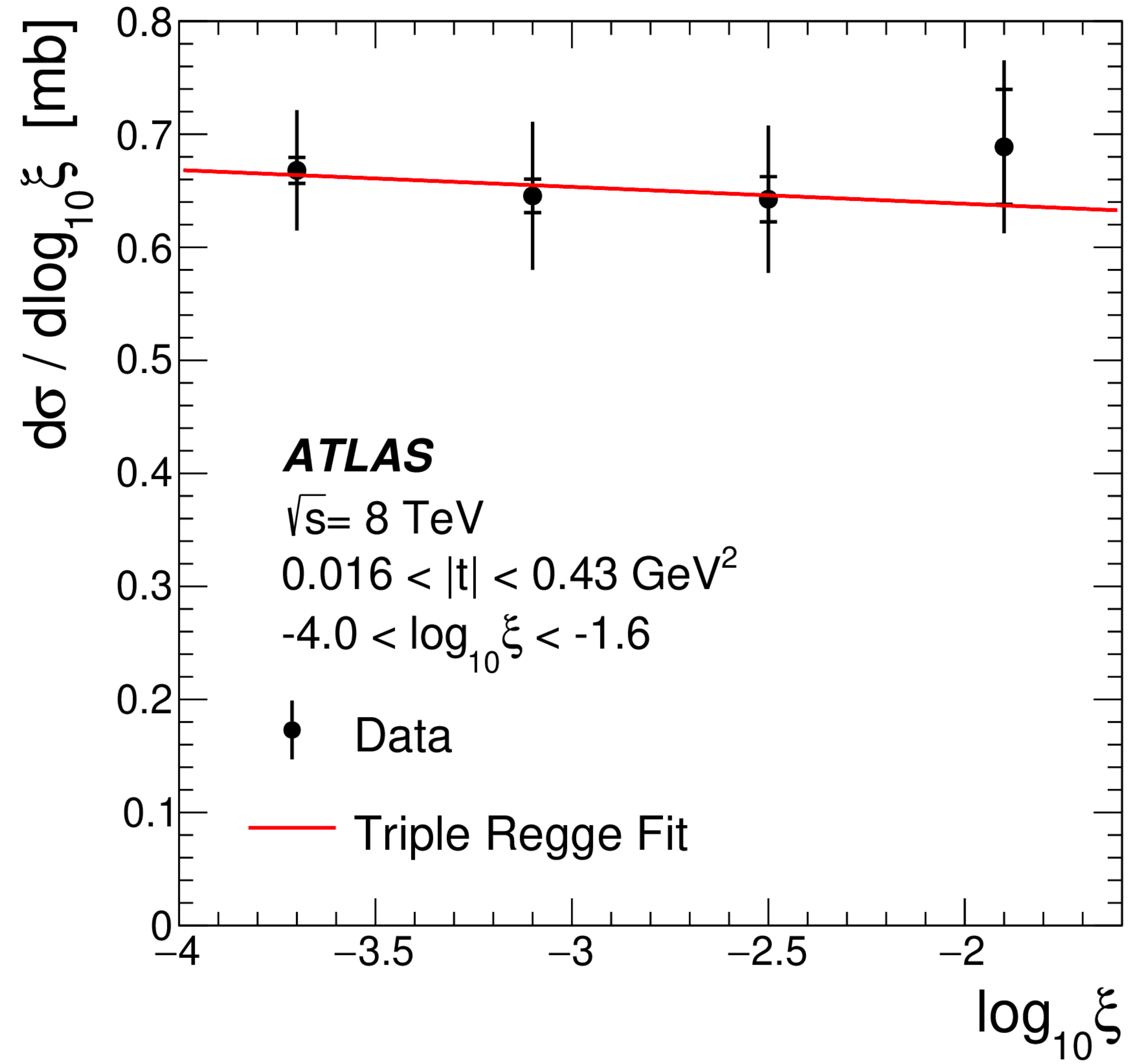
Predictions
(using triple Regge formalism):

Pythia 8 A3: 1.14

Pythia8 A2: 1.00

Largest uncertainty from

$$\alpha' = 0.25 \pm 0.25\ \text{GeV}^{-2}$$

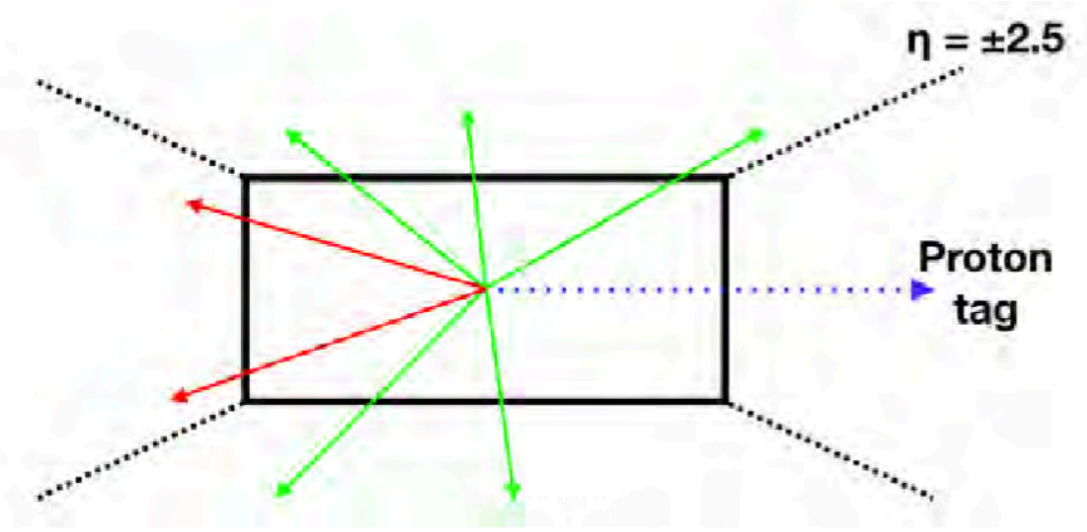


ξ from charged particles in inner detector

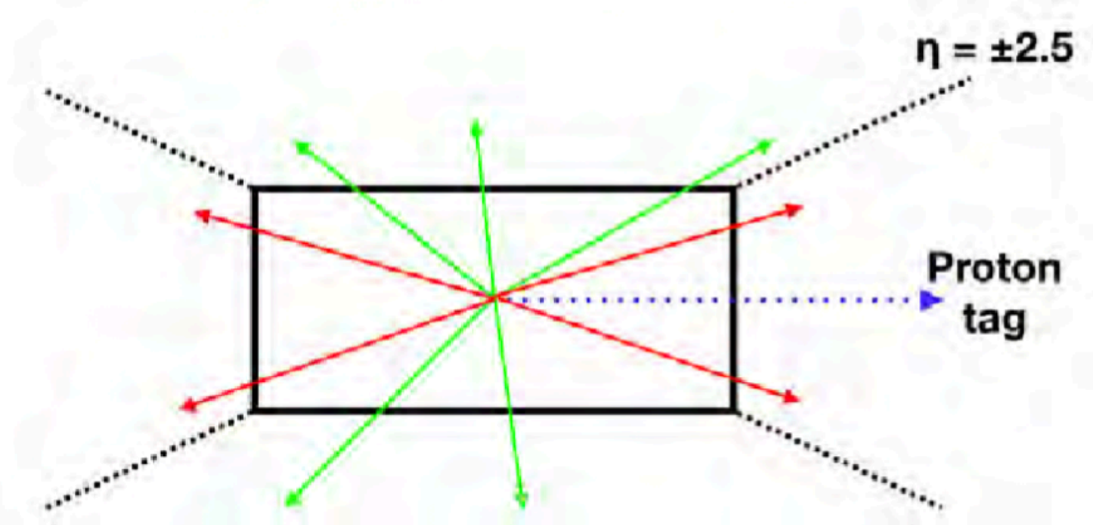
Compatible results for ξ from ALFA

Single diffractive with ALFA: Stacking up of events

J Kendrick thesis



(a)

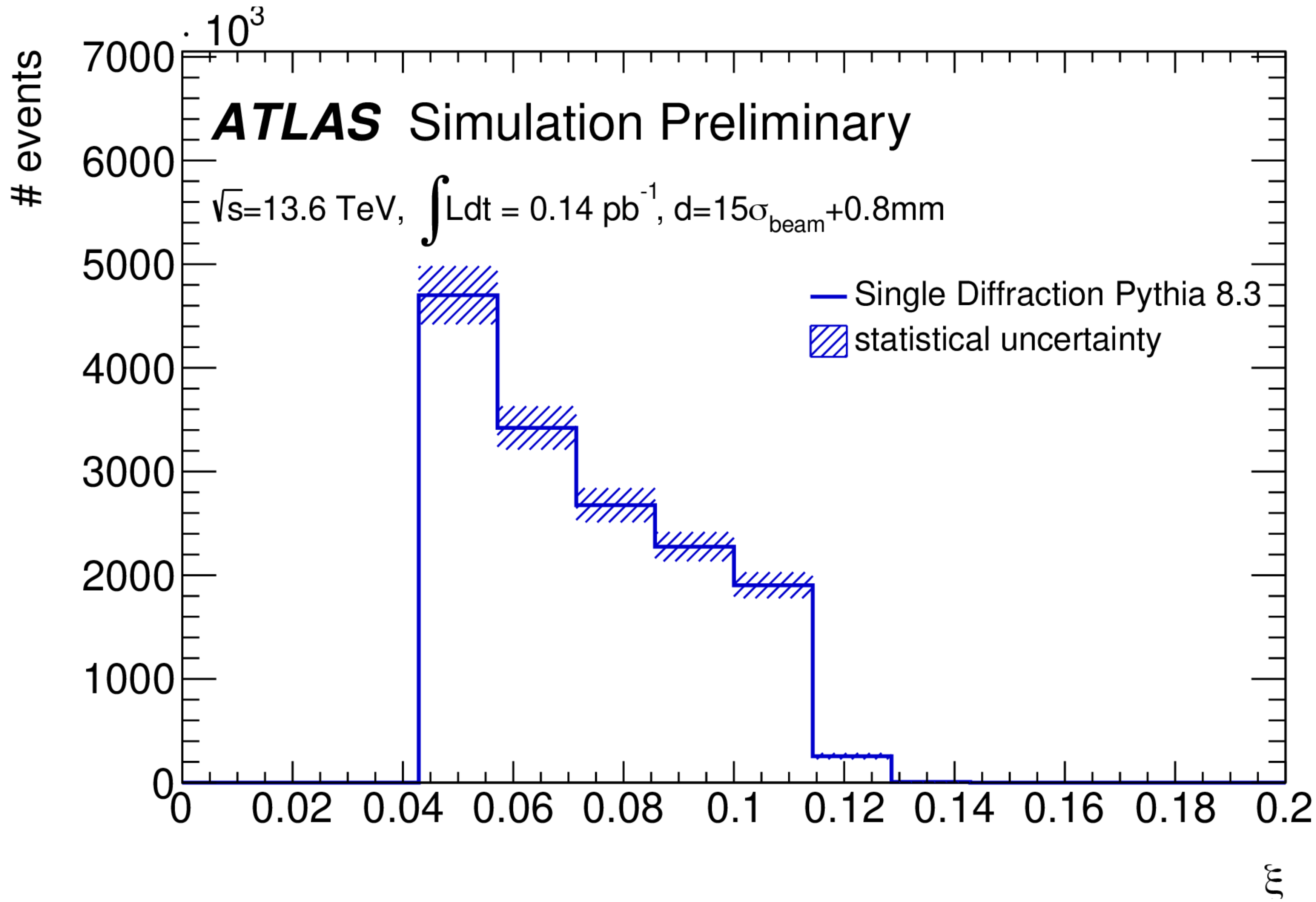


(b)

Figure 4.2: 'Stacking up' of events at low values of $\Delta\eta$: Both diagrams show high ξ events with $\Delta\eta$ reconstructed as ~ 0. The proton tag is on the right side of the detector (dotted blue lines) and $\Delta\eta$ is measured from the edge of the detector on that side (dashed black lines marked as $\eta = \pm 2.5$). Measured final state particles are shown in green and ones that fall out of the detector coverage are shown in red. The event shown in (a) does not contain any tracks outside the sensitive region of the detector on the side of tag. The event shown in (b) does. Both events are reconstructed as $\Delta\eta \sim 0$.

Single diffractive + LHCf + AFP

Predicted:

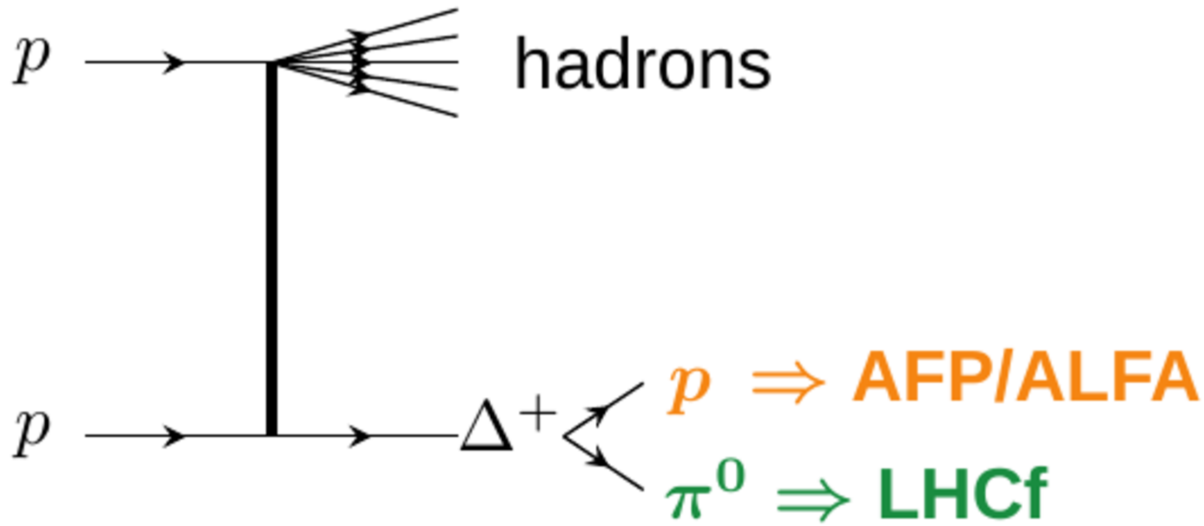


Predicted:

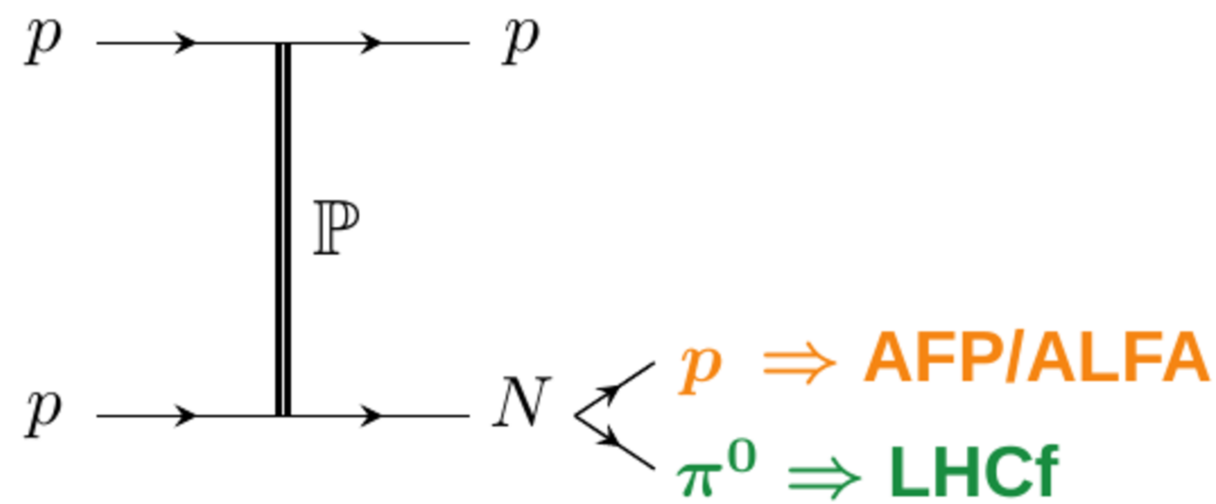
	Single diffraction	
	event rate [Hz] (σ_{vis} [mb])	event count (2 days)
AFP near station	46.5 ± 1.3 (0.11)	8.0 ± 0.3 million
AFP far station	46.5 ± 1.3 (0.11)	8.0 ± 0.3 million
ALFA near station	3.8 ± 0.2 (0.01)	0.7 ± 0.1 million
ALFA far station	2.8 ± 0.2 ($7 \cdot 10^{-3}$)	0.5 ± 0.1 million

Single diffractive + LHCf + AFP

Other processes studied:



Δ^+(1232) baryon



N(1440) baryon from proton excitation

Predicted:

	$\Delta^+(1232)$ production	
	event rate [mHz] ($\sigma_{\rm vis}$ [nb])	event count (2 days)
AFP near station	17.7 ± 0.6 (41.3)	3050 ± 100
AFP far station	17.7 ± 0.6 (41.3)	3050 ± 100
ALFA near station	2.2 ± 0.2 (5.2)	380 ± 30
ALFA far station	1.6 ± 0.2 (3.7)	270 ± 30

	$N(1440)$ production	
	event rate [mHz] ($\sigma_{\rm vis}$ [nb])	event count (2 days)
AFP near station	13.6 ± 1.3 (31.8)	2350 ± 220
AFP far station	13.6 ± 1.3 (31.8)	2350 ± 220
ALFA near station	4.2 ± 0.5 (9.9)	730 ± 90
ALFA far station	3.2 ± 0.4 (7.4)	550 ± 70