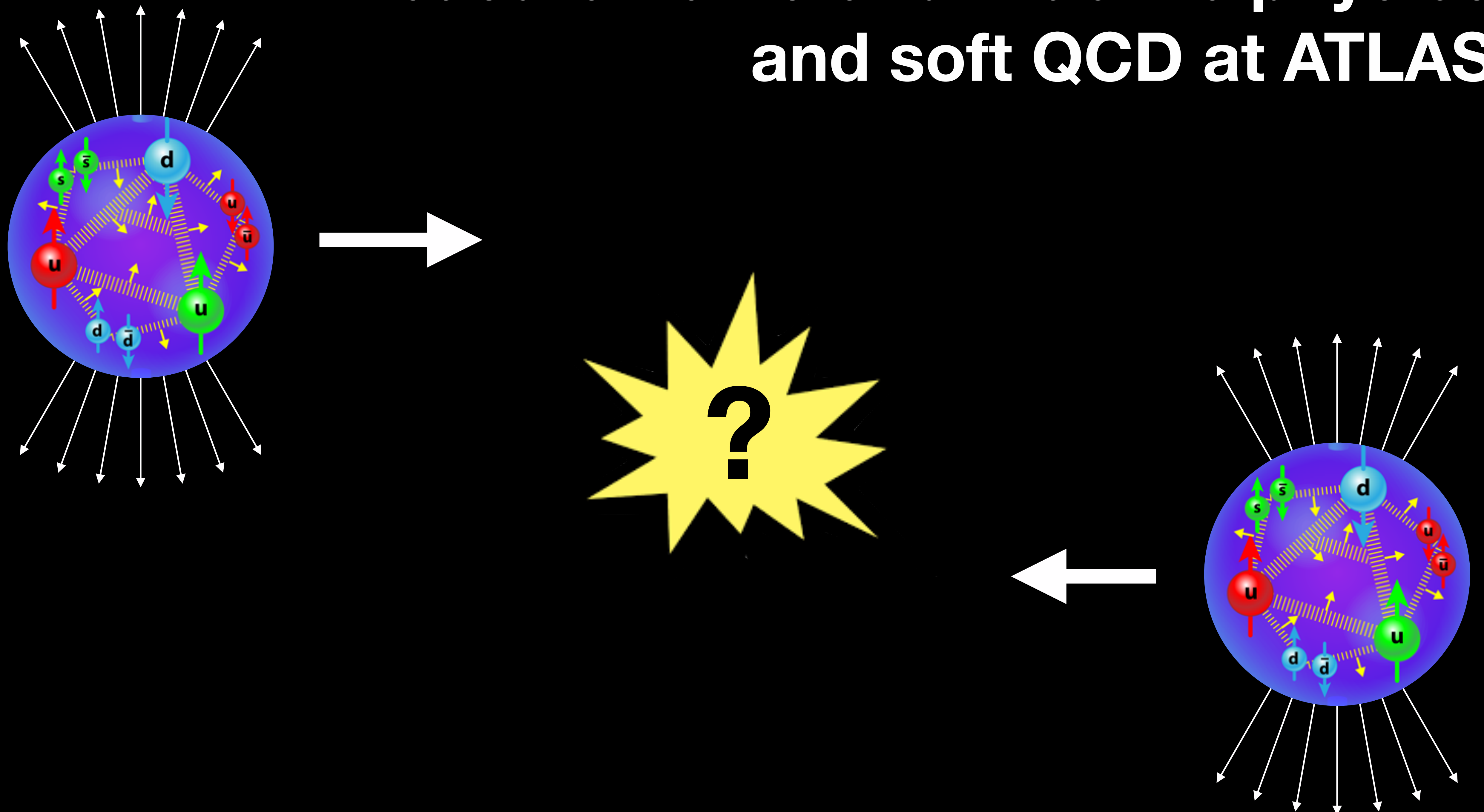
Measurements of diffractive physics and soft QCD at ATLAS

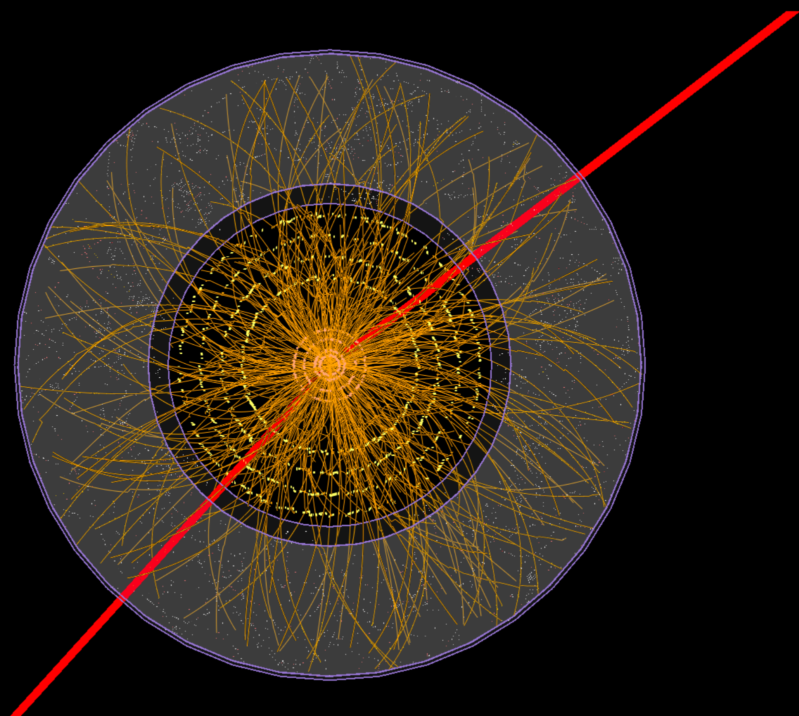


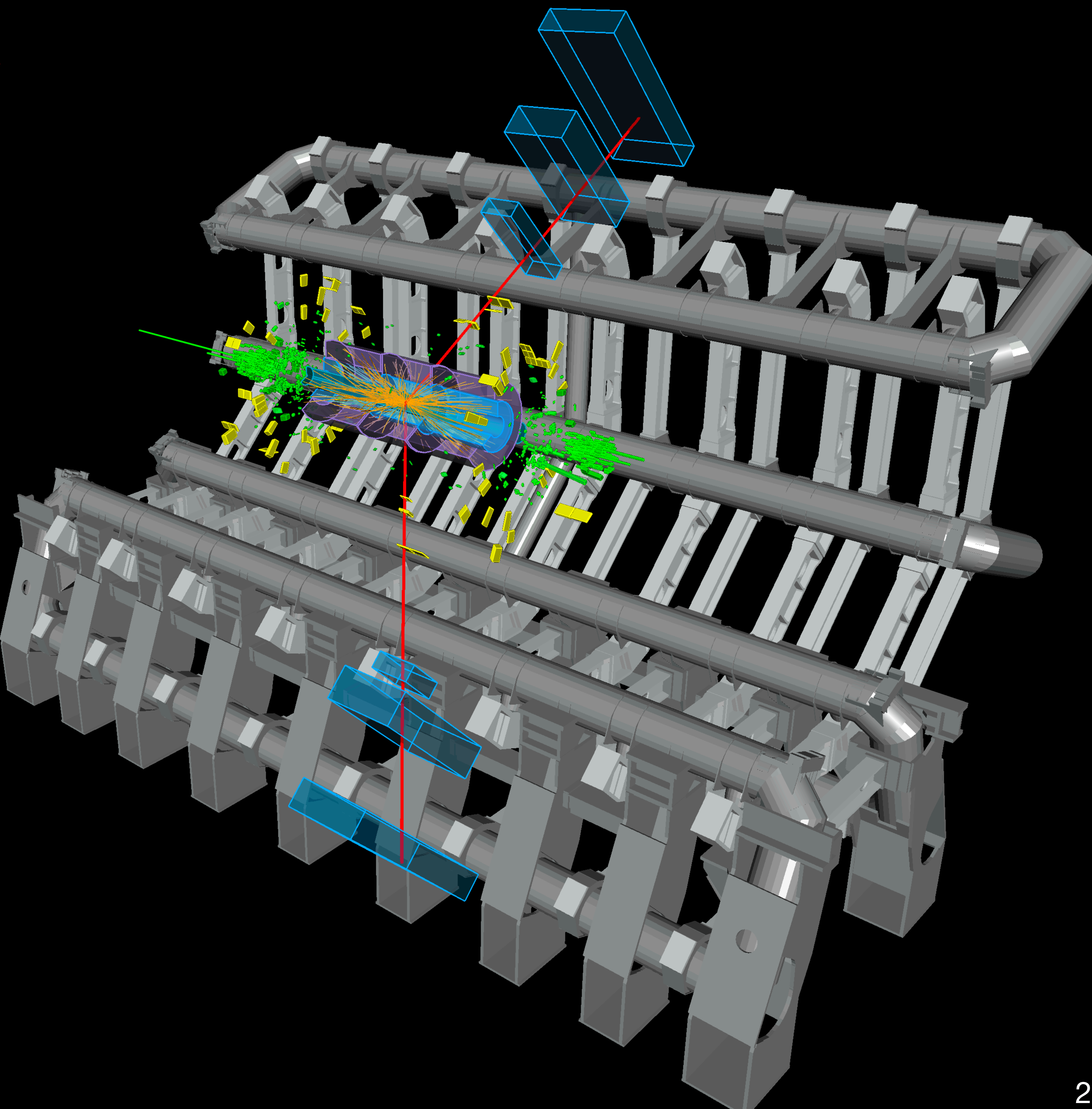
Lydia Beresford on behalf of the ATLAS Collaboration

EPS-HEP Conference, 26th July 2021

Soft QCD laboratory

$Z \rightarrow \mu\mu$





ATLAS EXPERIMENT

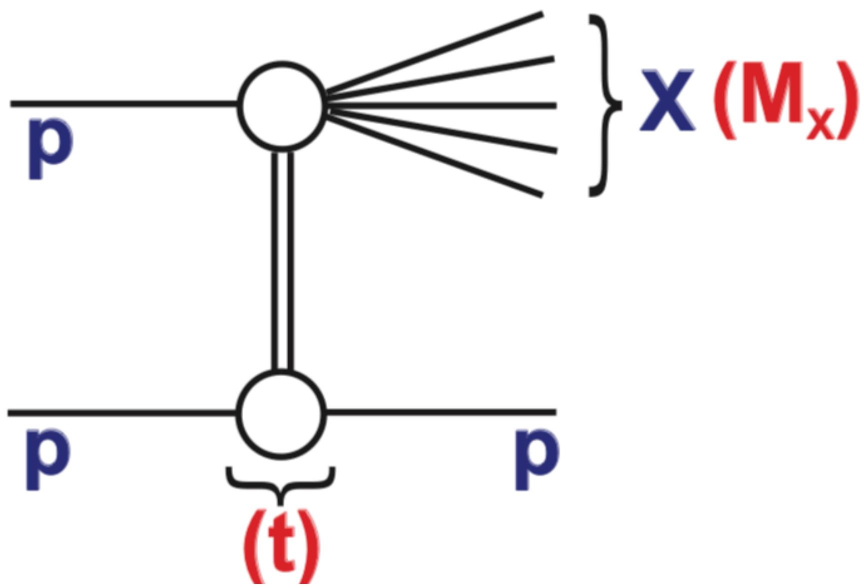
Run: 267638
Event: 242090708
2015-06-14 01:01:14 CEST

Motivation

- **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!**

Focus: Proton tagging to probe QCD

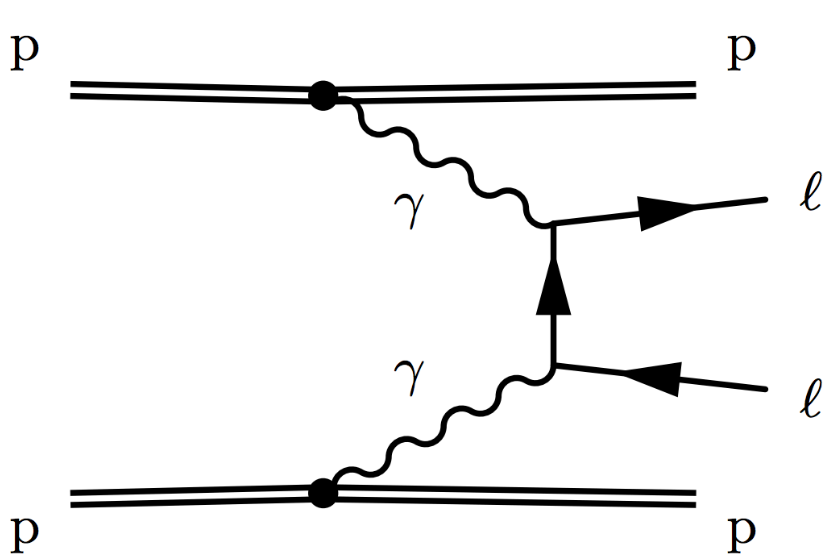
Measurement of single diffraction using ALFA



JHEP 02 (2020) 042

$\sqrt{s} = 8$ TeV, very low $\langle\mu\rangle$

Observation & measurement of $(\gamma\gamma \to \ell\ell) + p$ using AFP



PRL 125 (2020) 261801

$\sqrt{s} = 13$ TeV, standard high $\langle\mu\rangle$

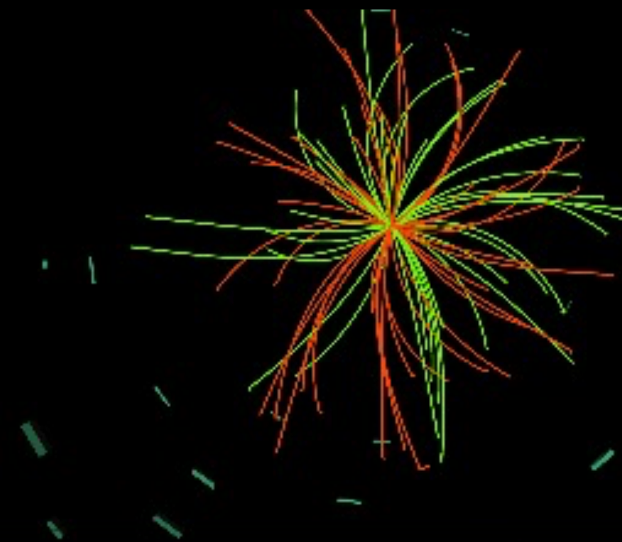
$\langle\mu\rangle$ = mean number of interactions per bunch crossing

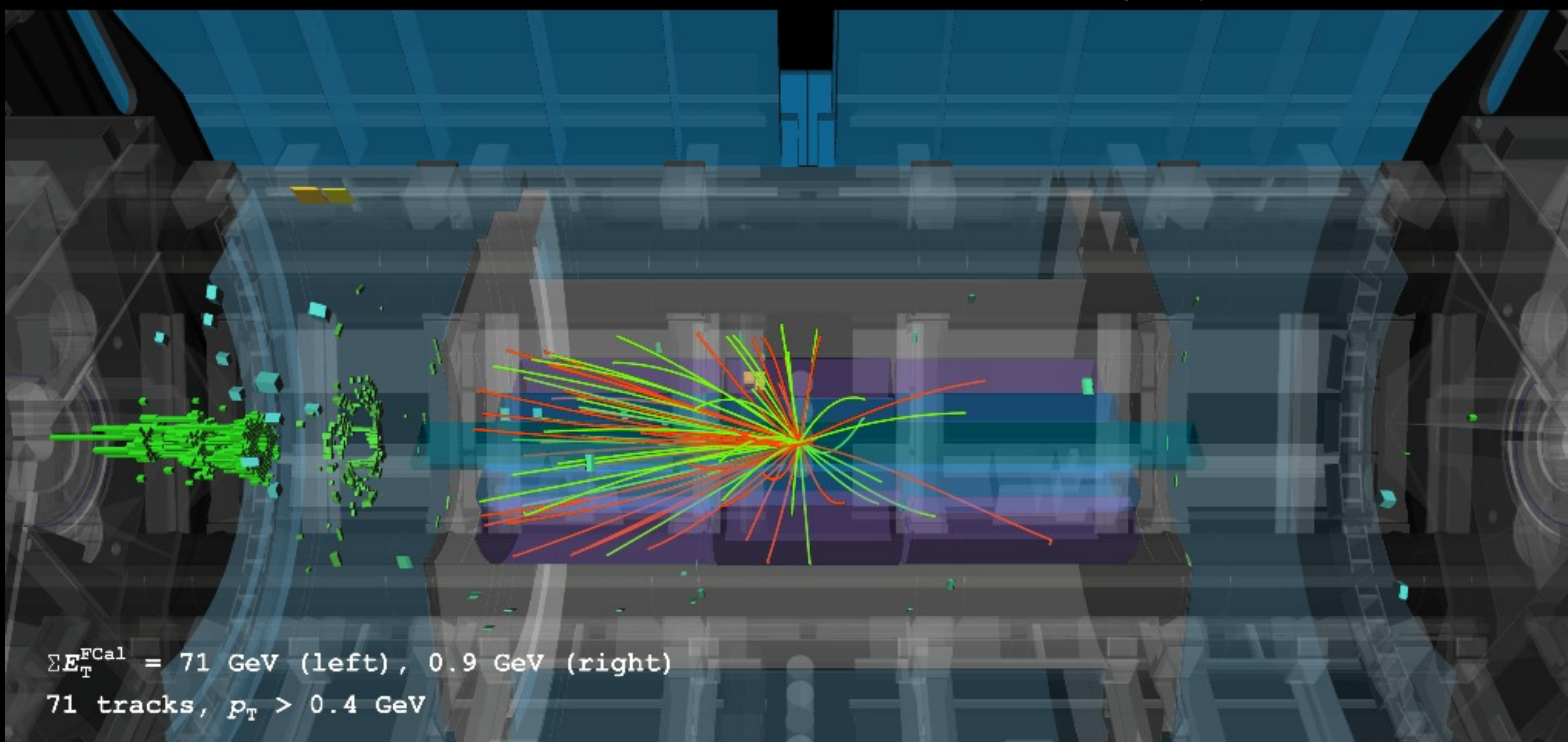
Single diffraction

Rapidity gap example in PbPb

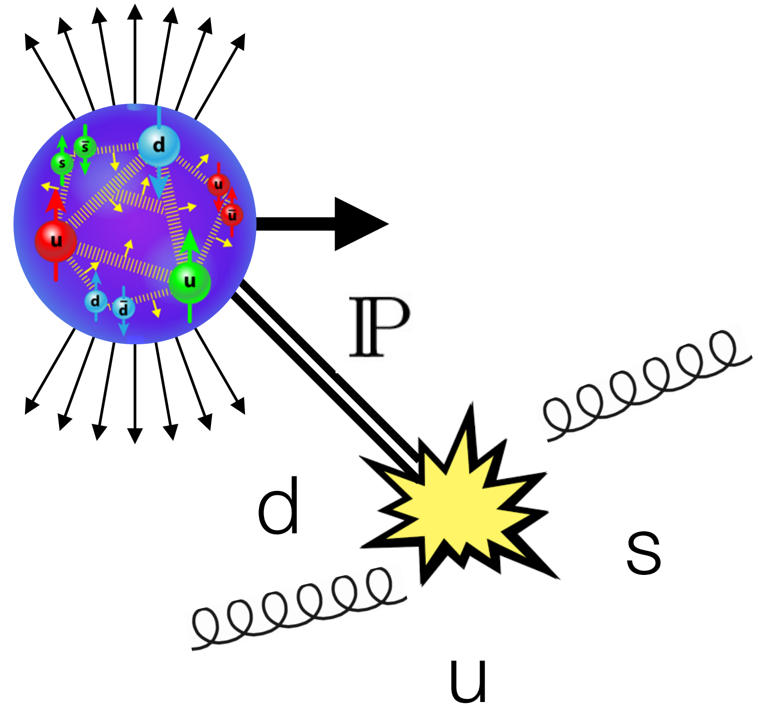
ATLAS EXPERIMENT

Pb+Pb, 5.02 TeV
Run: 365681
Event: 1064766274
2018-11-11 22:00:07 CEST





Single Diffraction



Colour singlet 'pomeron' exchange

Diffractive system X as result of interaction between proton and pomeron

Large cross-section: **~10%** of total LHC cross-section but poorly understood

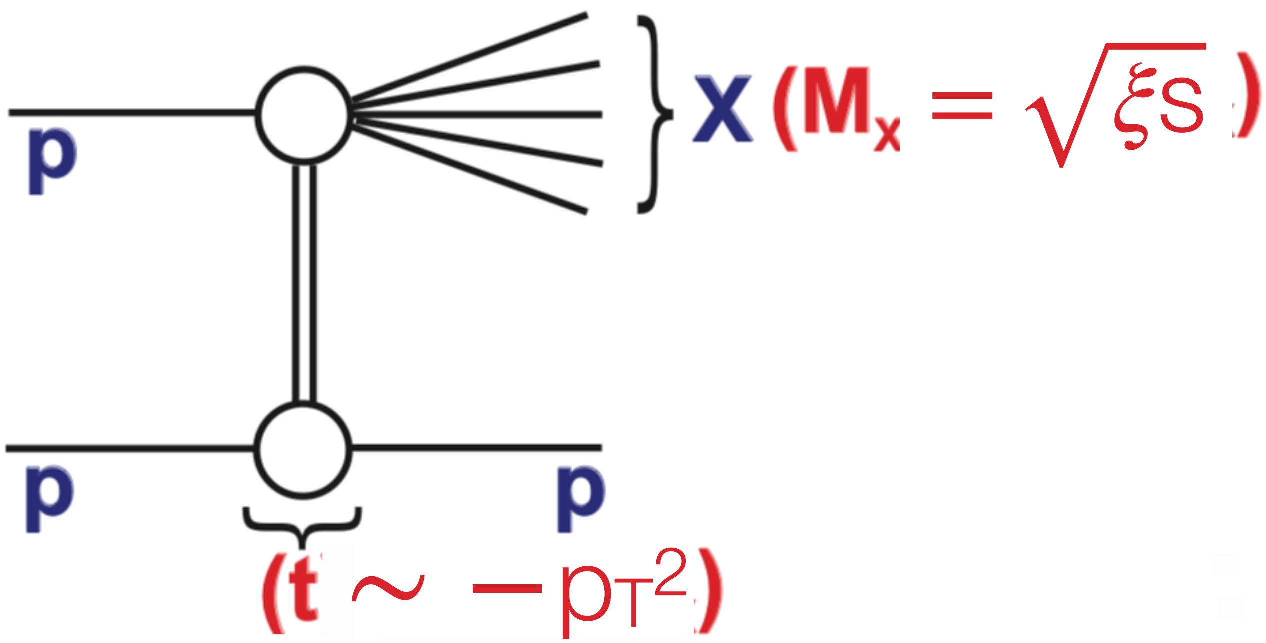
Input for MC generators, improve:

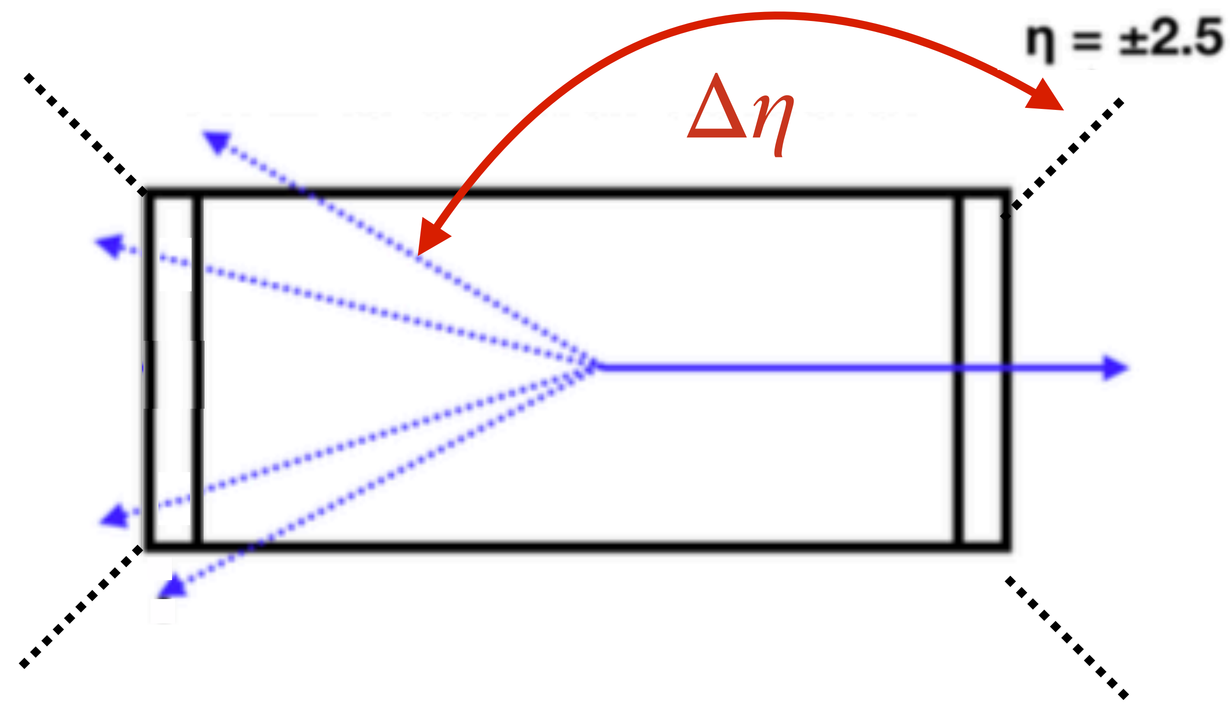
- Pile-up modelling
- Modelling of cosmic ray air showers

Goals & motivation

Proton fractional energy loss

Measure cross-section differentially in Δη, |t| & ξ





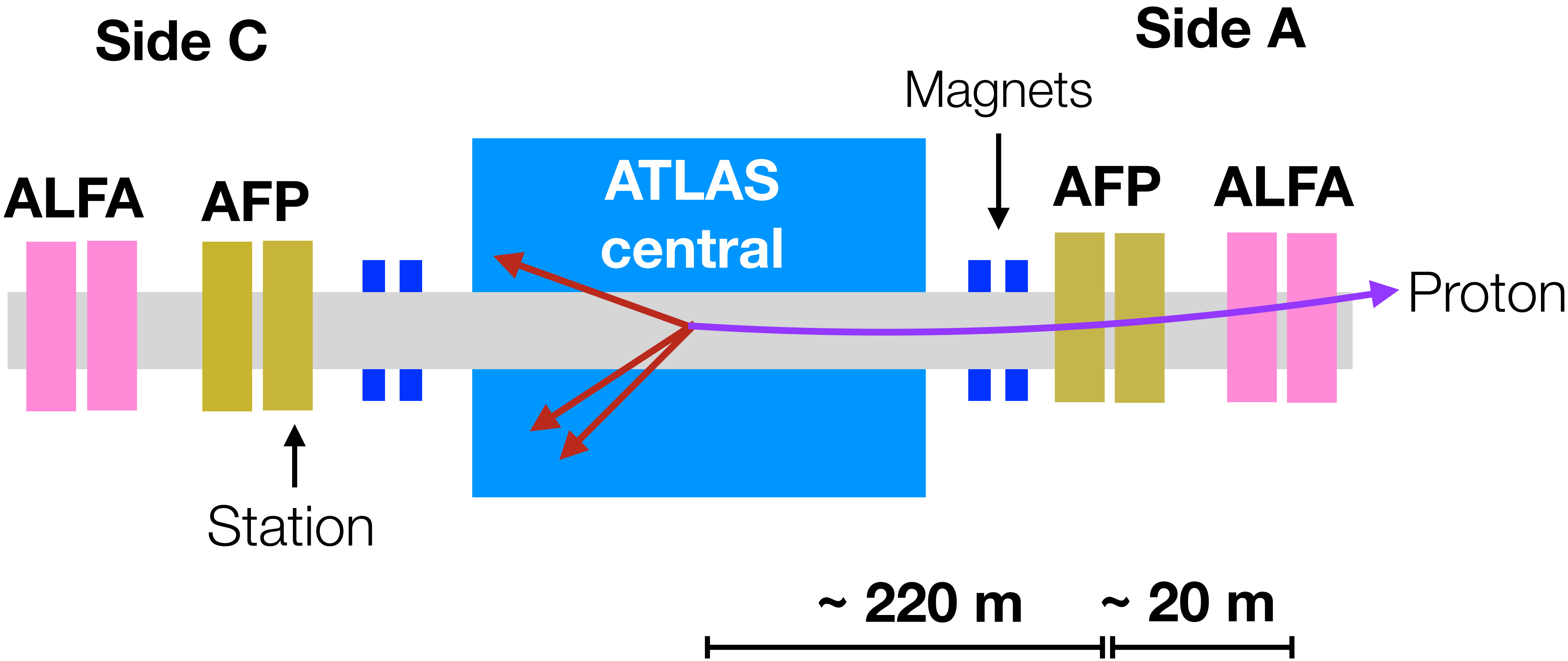
Measured wrt edge of inner detector on side of intact proton

Measure intact proton:

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

ALFA & AFP detectors

Detectors reach inside beam pipe down to 2 mm of incoming proton beam



Reconstruct tracks in station → Proton

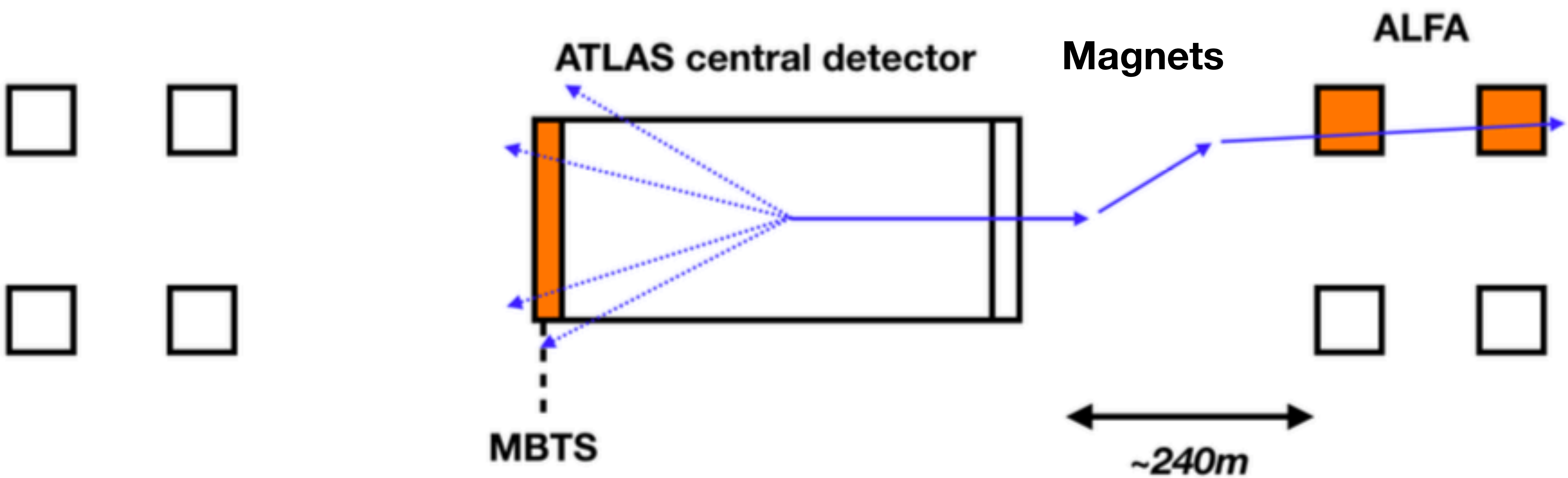
Complementary acceptance in AFP & ALFA

ALFA active during special low pile-up, high β* runs

How?

Track $p_T > 200$ MeV

Special run from 2012: $\sqrt{s} = 8$ TeV, $\langle \mu \rangle < 0.08$, high β^*



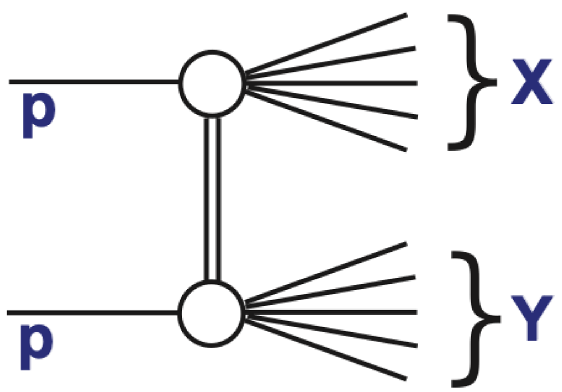
Trigger: ALFA signal & Min Bias Trigger Scintillator

Single proton in ALFA & one good vertex

How?

Backgrounds estimated & subtracted

Overlay e.g.

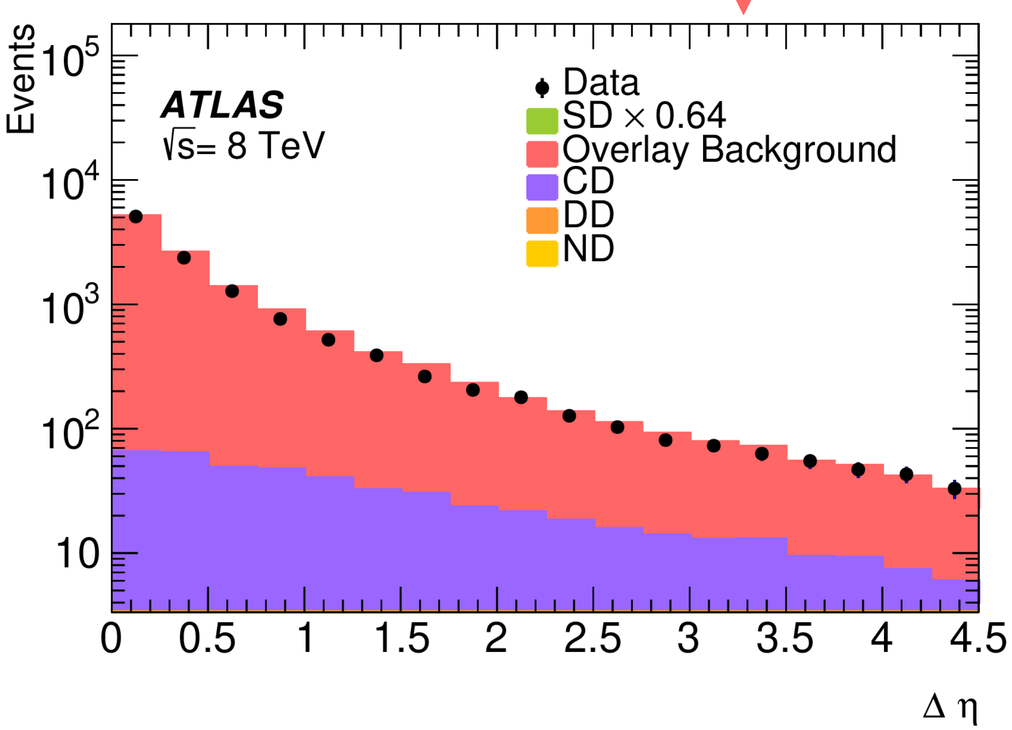


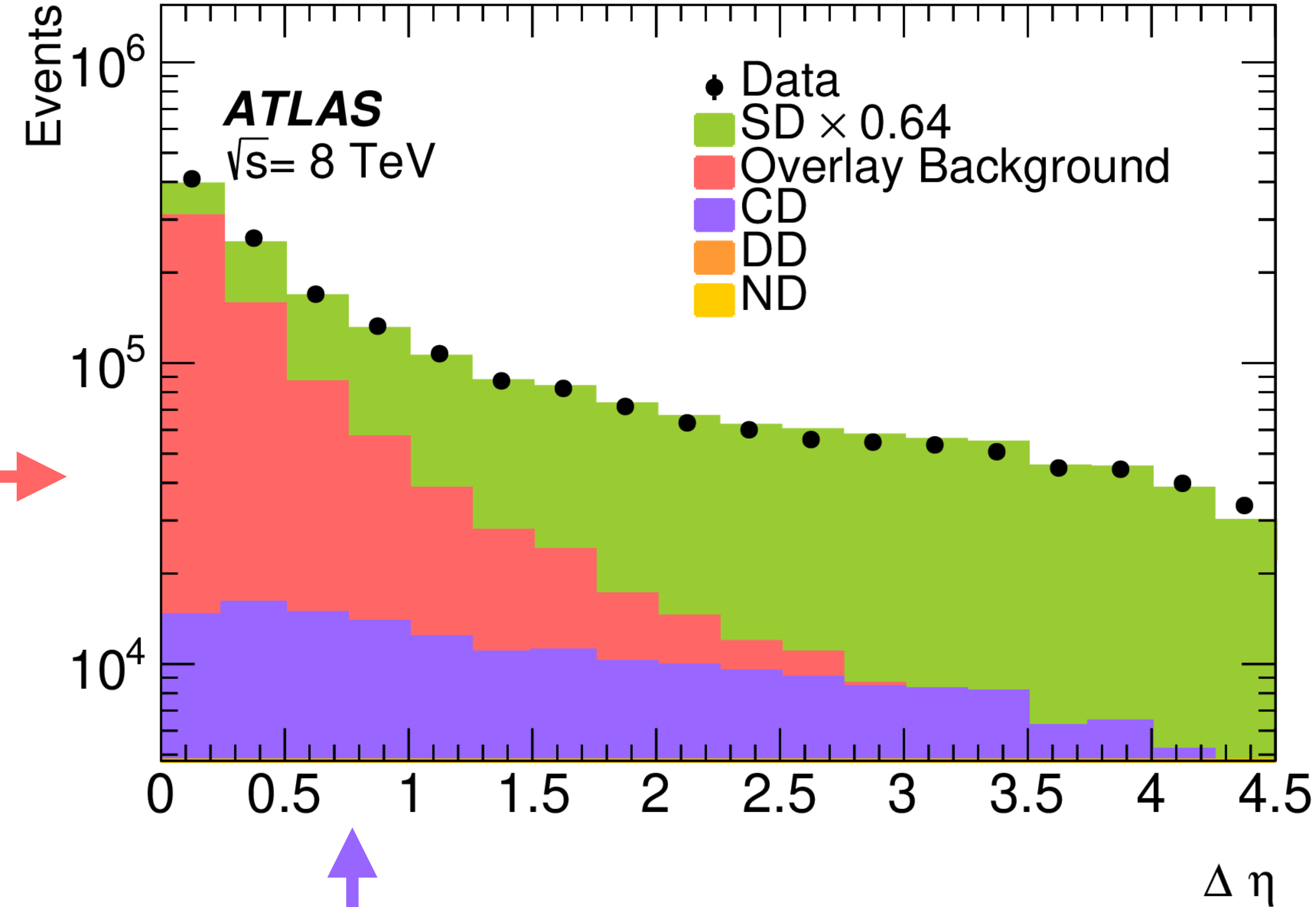
+ pile-up proton

Data-driven estimate

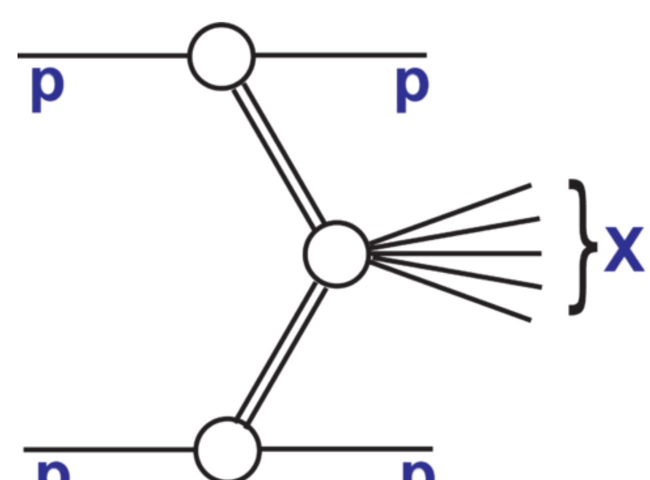
using overlay control region

Largest systematic





Central diffractive



MC estimate +

reweighting in central diffractive control region

Results

$0.016 < |t| < 0.43$ GeV^2

$-4.0 < \log_{10}(\xi) < -1.6$ ($80 < M_X < 1270$ GeV)

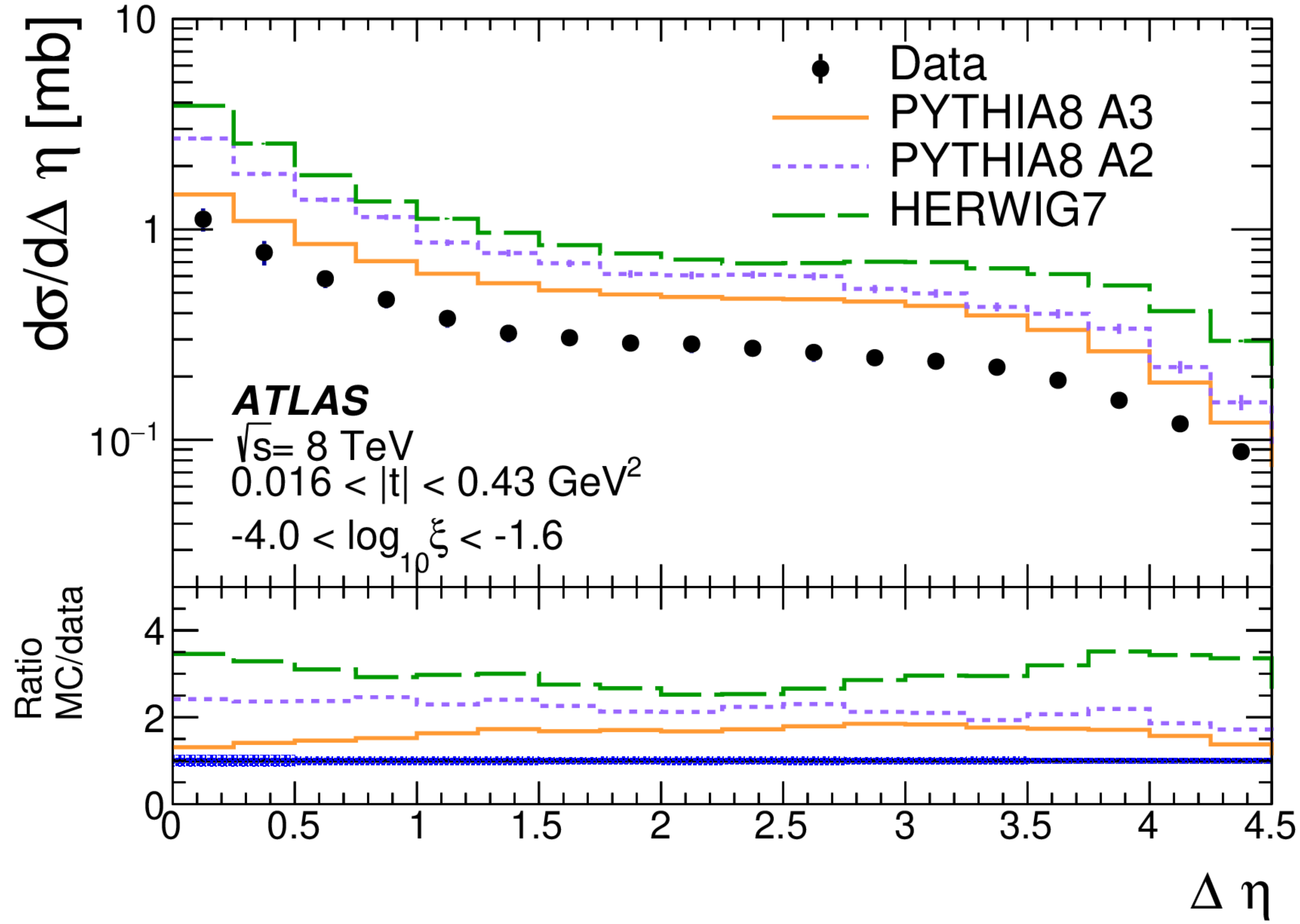
↓

MC over-prediction

Distribution	$\sigma_{SD}^{\text{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t\text{-extrap}}$ [mb]
Data	1.59 ± 0.13	1.88 ± 0.15
PYTHIA8 A2 (Schuler–Sjöstrand)	3.69	4.35
PYTHIA8 A3 (Donnachie–Landshoff)	2.52	2.98
HERWIG7	4.96	6.11

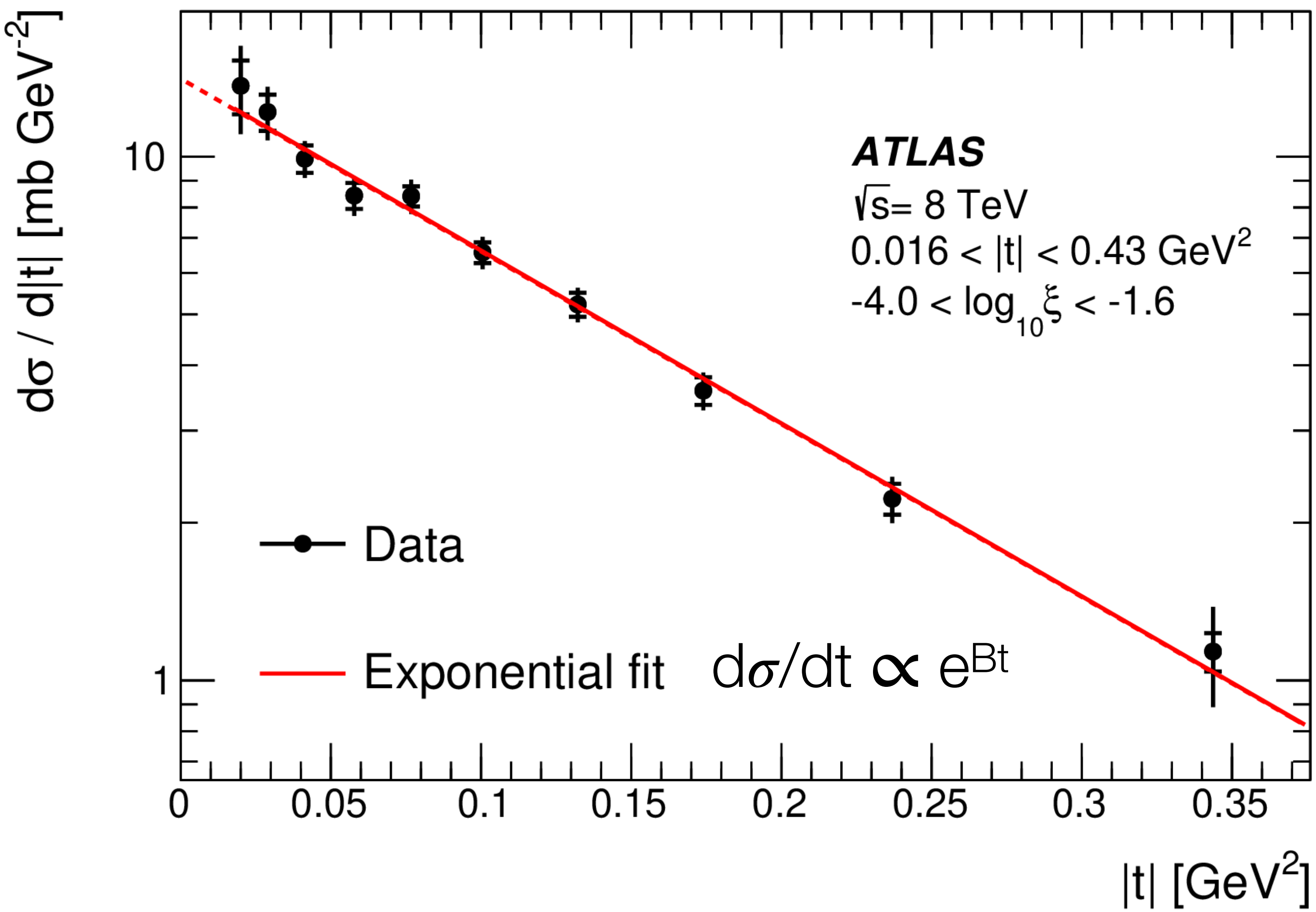
Cross-section as function of rapidity gap size $\Delta\eta$

Mild shape mismodellings



Results

Cross-section as function of momentum transfer |t|



Measurements as function of |t| are scarce at LHC

Fit to data

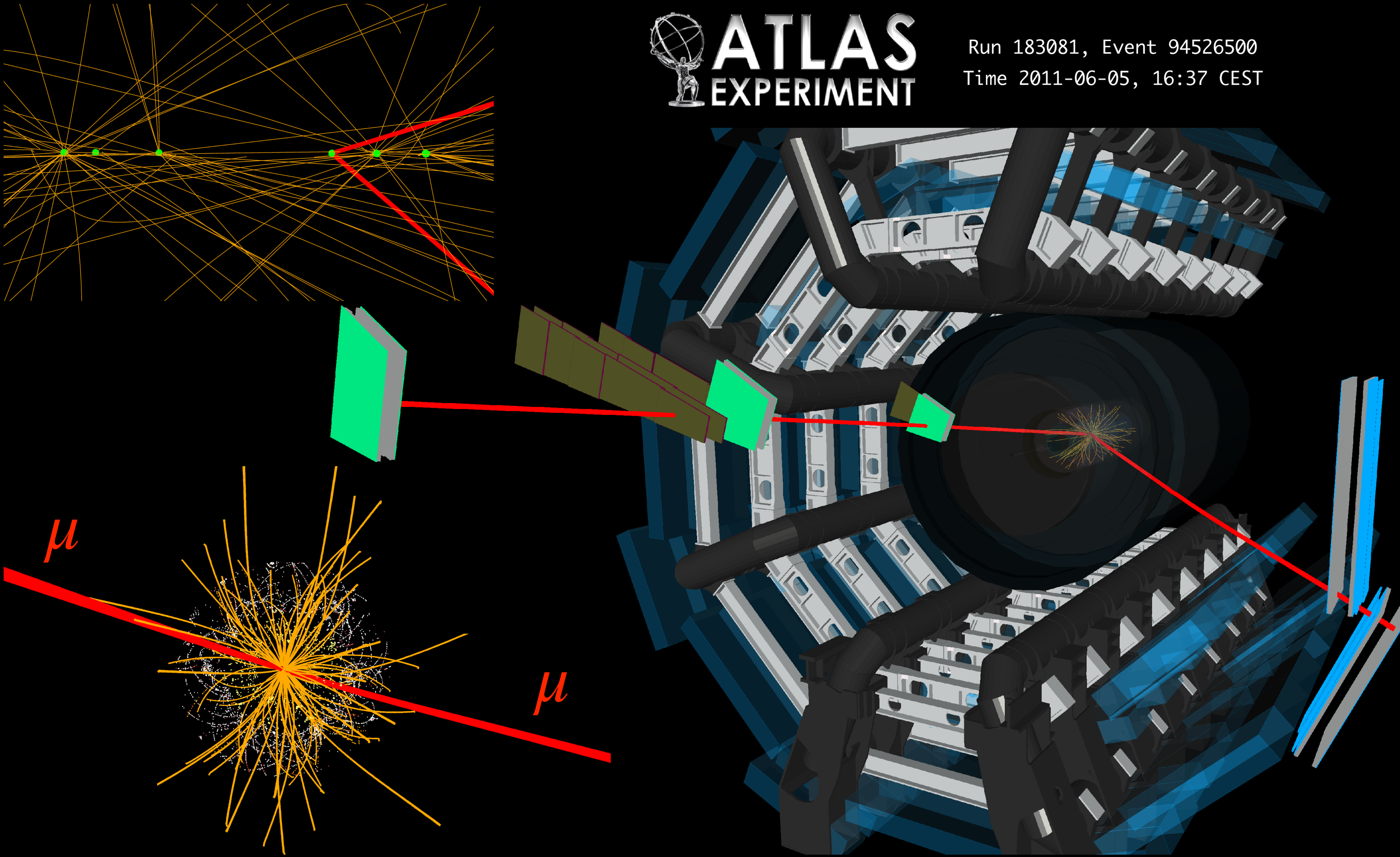
$B = 7.65 \pm 0.26$ (stat.) ± 0.22 (syst.) GeV^{-2}

MC Predictions

Pythia8 A2: $B = 7.82\ GeV^{-2}$
Pythia8 A3: $B = 7.10\ GeV^{-2}$

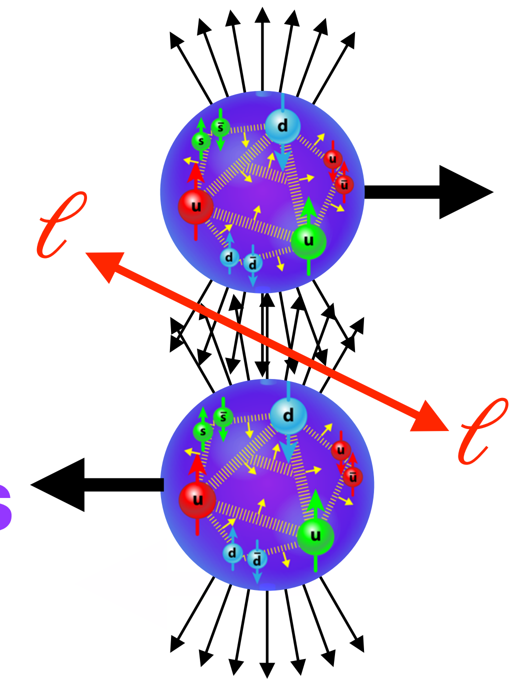
Photon collision

$\gamma\gamma \to \mu\mu$



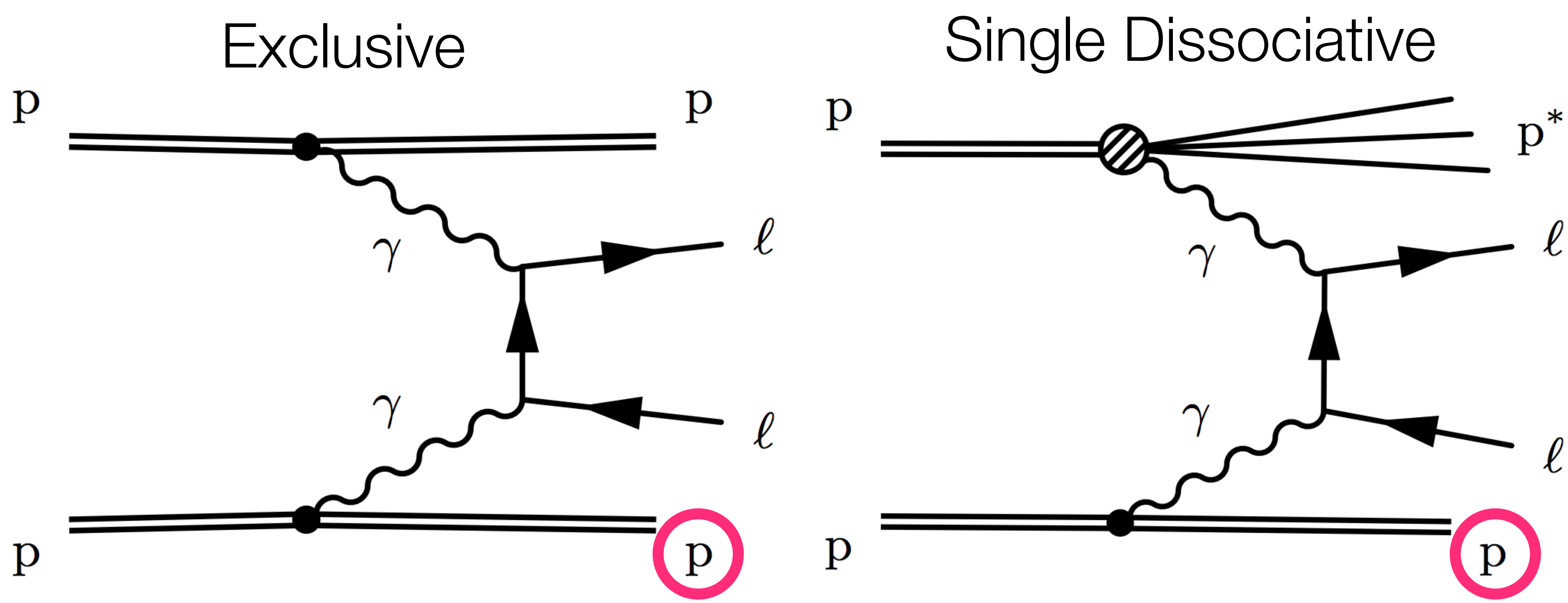
LHC is world's highest energy photon collider

Goals & motivation



Observe & measure $(\gamma\gamma \to \ell\ell) + p$

First high-$\langle\mu\rangle$ physics publication using **AFP detectors**



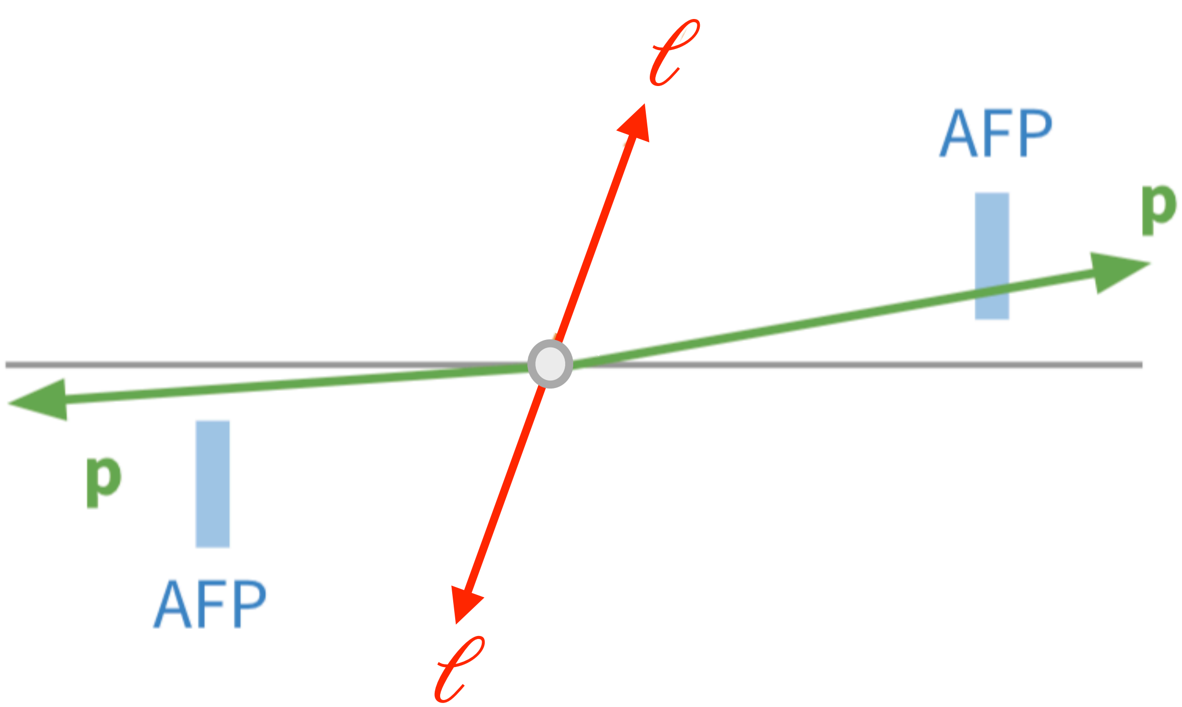
Direct access to protons provides truly new info to exploit!

- Powerful background rejection
- Novel constraints on proton soft survival probability

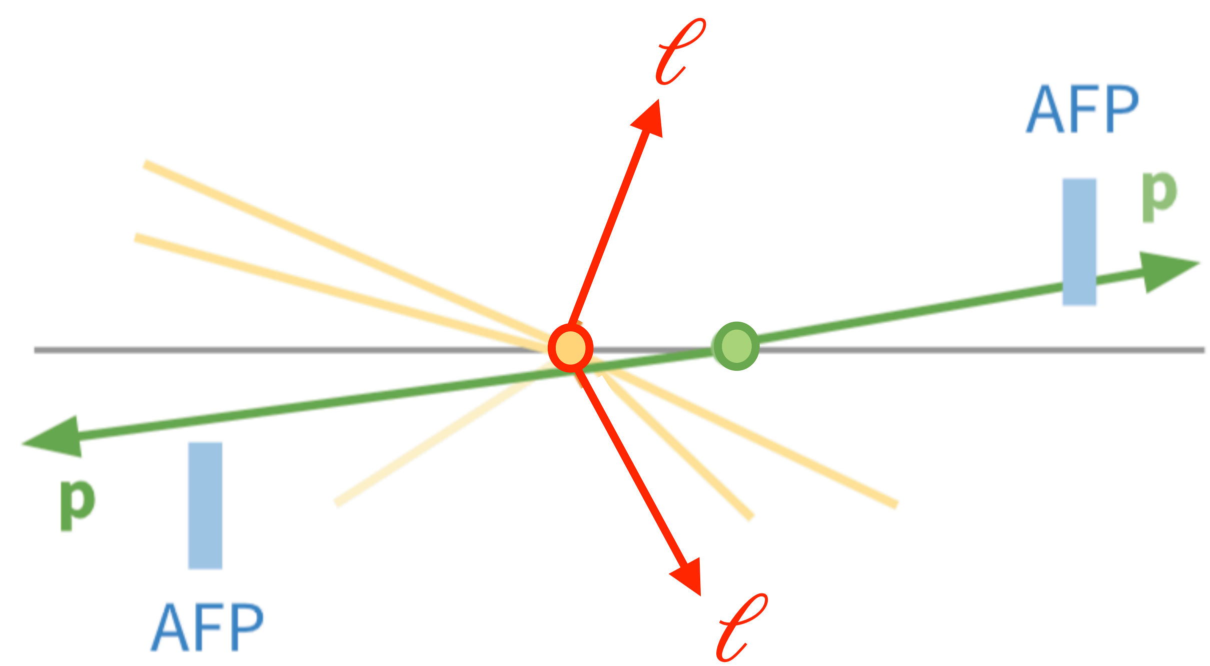
How?

Use 2017 standard high $\langle \mu \rangle$ dataset $\sqrt{s} = 13$ TeV

Signal



Background



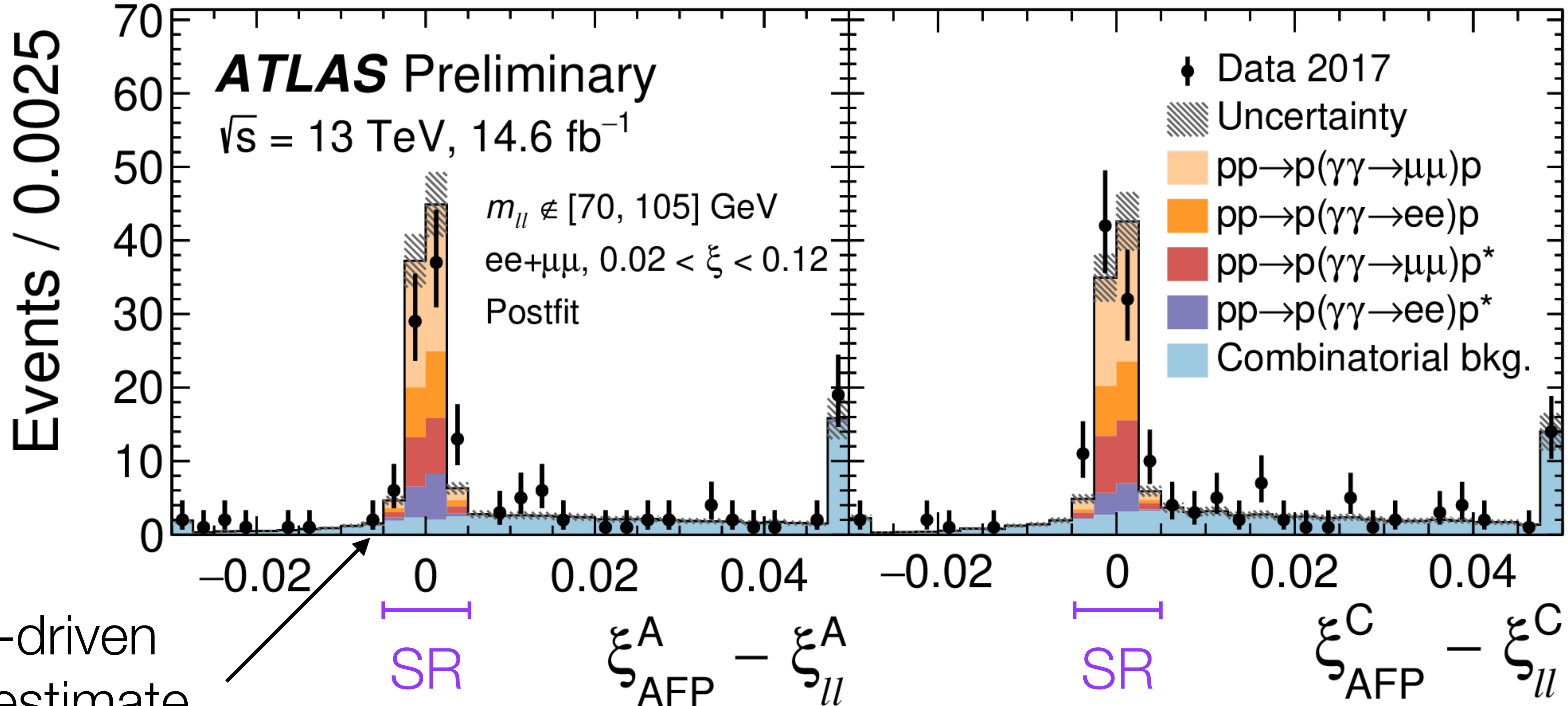
e.g. $Z \rightarrow \ell\ell$

+ pileup proton

How?

SR: 95% signal retention
85% bkg rejection

Observe ee+p and $\mu\mu$+p > 9σ in each channel



Data-driven bkg estimate

Measured with AFP

$$\xi^{A,C}_{AFP} = 1 - E_{forward}/E_{beam}$$

Measured with central ATLAS

$$\xi^{\pm}_{ll} = \frac{m_{ll}}{\sqrt{s}} e^{\pm y_{ll}}$$

Results

1st LHC cross-section measurements for this process with a tagged proton

$\sigma_{\mathrm{HERWIG+LPAIR}} \times S_{\mathrm{surv}}$	$\sigma^{\mathrm{fid.}}_{ee+p}$ (fb)	$\sigma^{\mathrm{fid.}}_{\mu\mu+p}$ (fb)
$S_{\mathrm{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [33,34]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [97]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

Fiducial cross-sections $\xi \in [0.035, 0.08]$ compared to proton soft survival models

[33] Harland-Lang et al EPJC 76 (2016) 9
[34] Dyndal & Schoffel PLB 741 (2015) 66
[97] Harland-Lang et al EPJC 80, 925 (2020)

Outlook:

- Statistically limited → Improvements with larger dataset in LHC Run 3
- Inclusive measurement → Differential measurements e.g. versus m_{ll}, y_{ll}
- Single proton tag → Measure both single and double tag events

Summary

Diverse array of QCD phenomena at the LHC, including:

- Single diffraction
- Proton break up

Target using array of techniques:

- Rapidity gaps
- Forward proton detectors

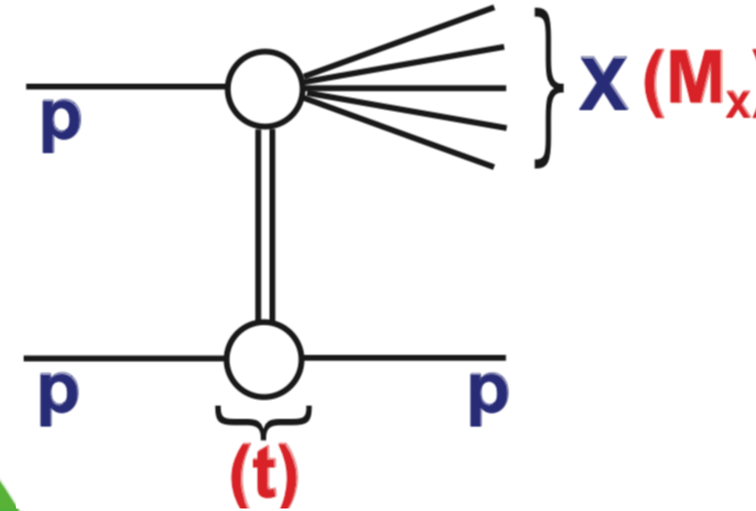
Advance our understanding of nature

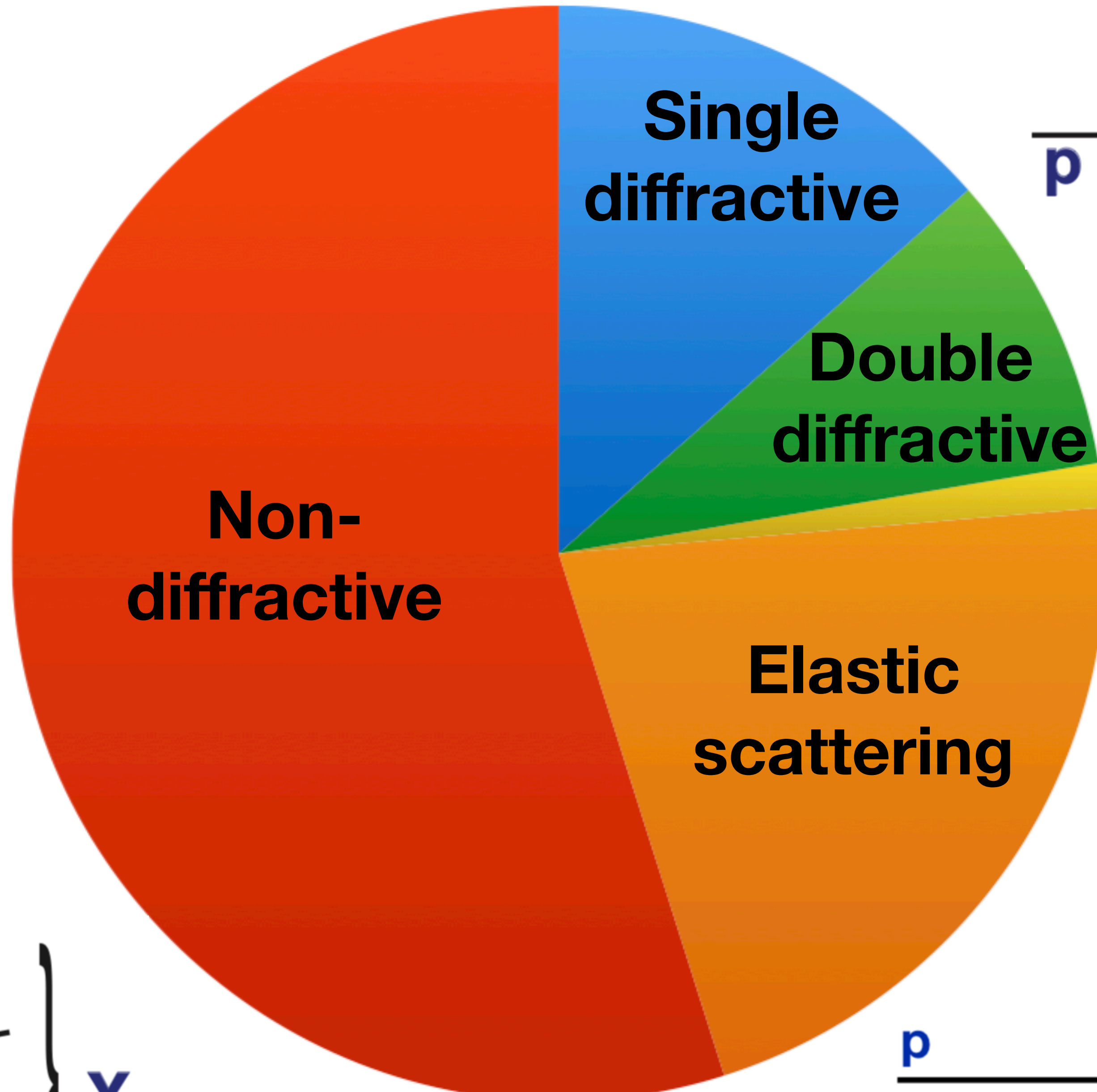
Just as nonperturbative QED contains very interesting phenomena, nonperturbative QCD is a most interesting portion of that theory. To me, it is *the* most interesting and most important portion of QCD to address, despite the evident difficulty in doing so.
Bjorken 1996

Backup

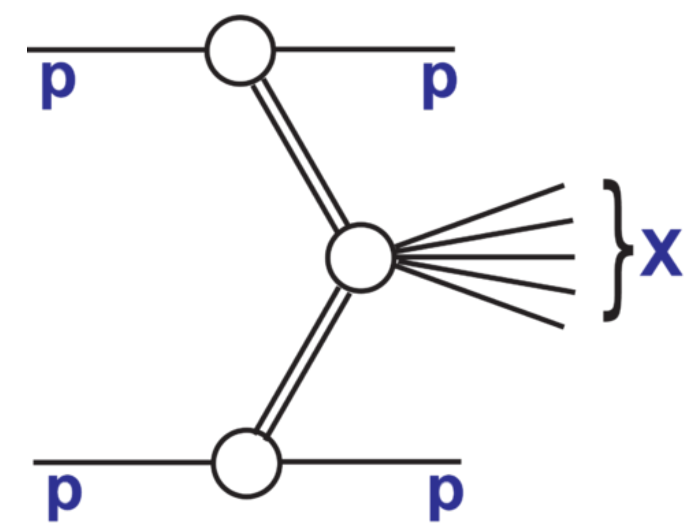
LHC interactions

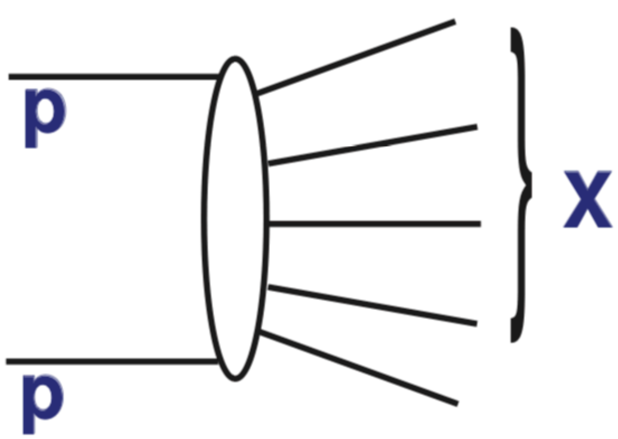
Double line = Pomeron
Pair of gluons (colourless)

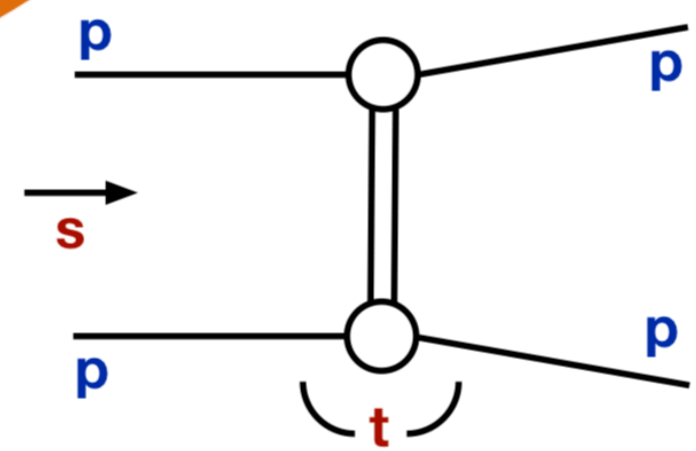




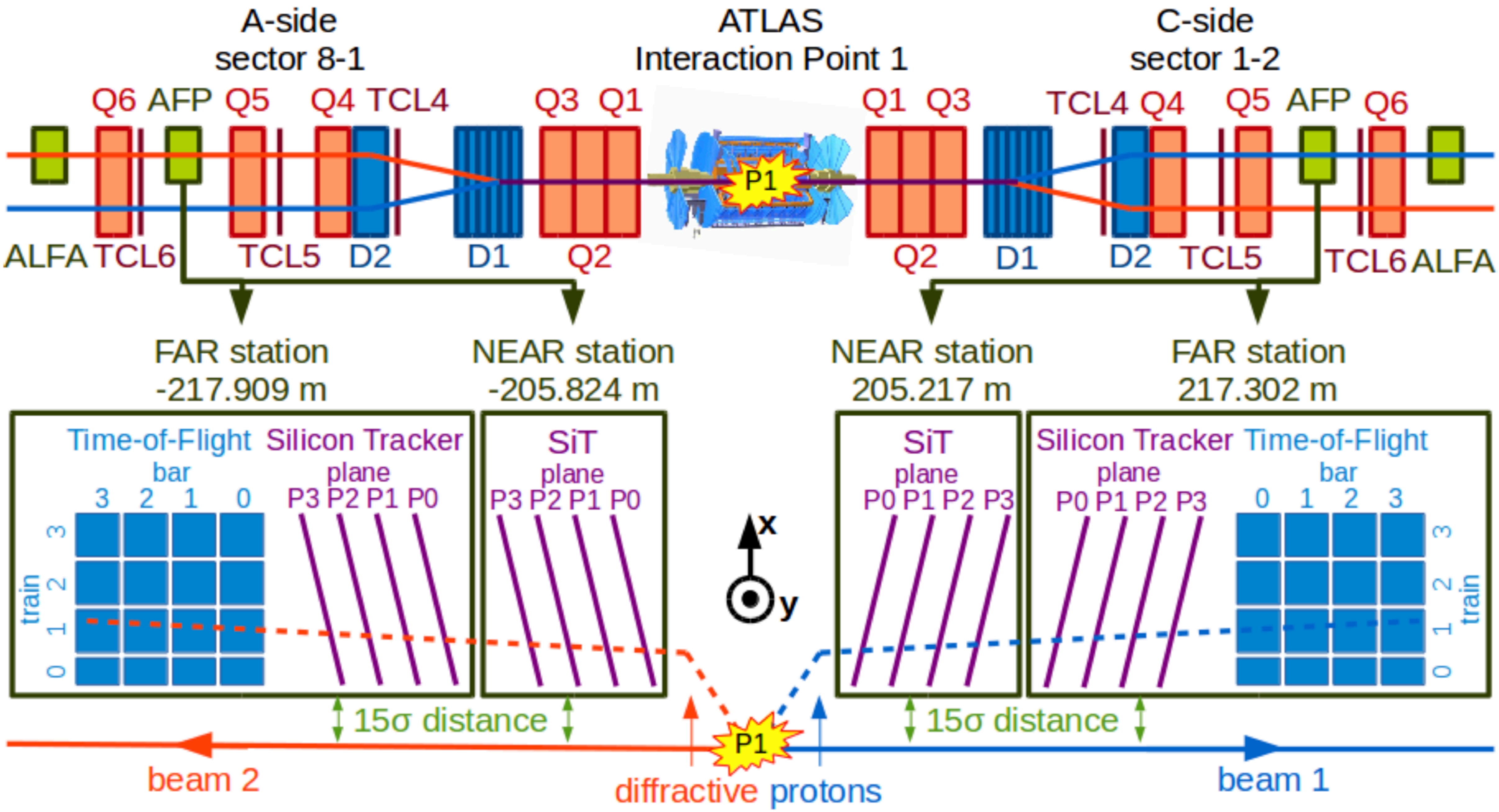
Central diffractive



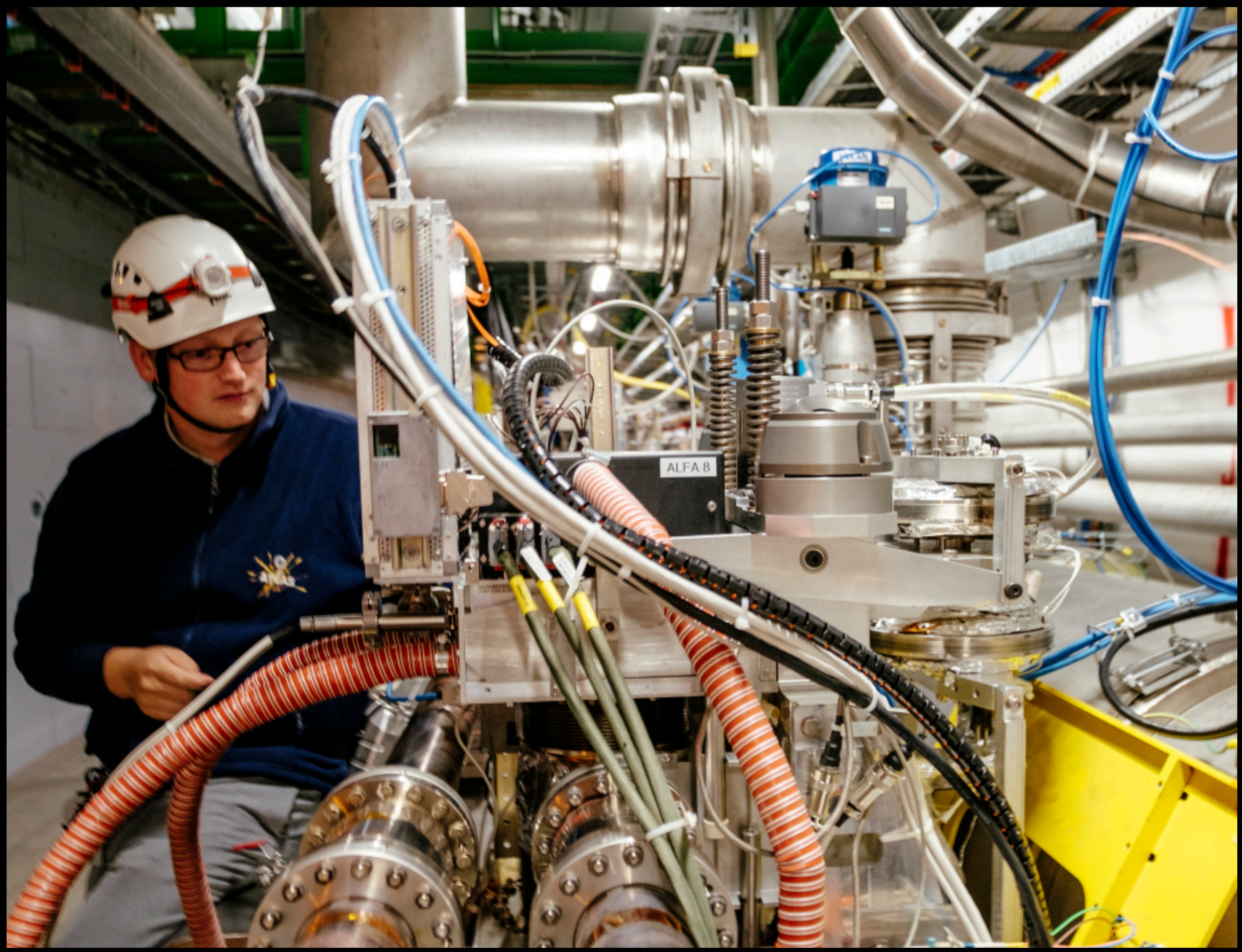


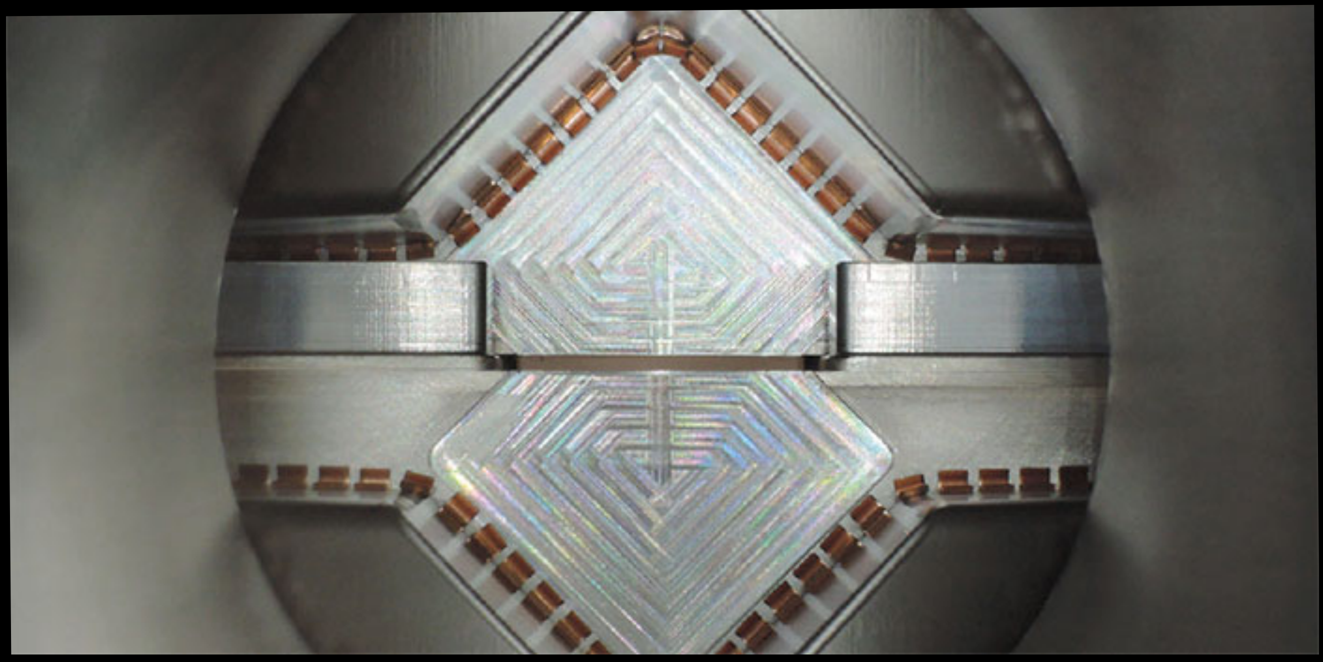


ALFA & AFP


A-side
sector 8-1
ATLAS
Interaction Point 1
C-side
sector 1-2
Q6 AFP Q5 Q4 TCL4 Q3 Q1
Q1 Q3 TCL4 Q4 Q5 AFP Q6
P1
ALFA TCL6 TCL5 D2 D1 Q2
Q2 D1 D2 TCL5 TCL6 ALFA
FAR station
-217.909 m
NEAR station
-205.824 m
NEAR station
205.217 m
FAR station
217.302 m
Time-of-Flight
bar
3 2 1 0
Silicon Tracker
plane
P3 P2 P1 P0
SiT
plane
P3 P2 P1 P0
train
0 1 2 3
x
y
SiT
plane
P0 P1 P2 P3
Silicon Tracker
plane
P0 P1 P2 P3
Time-of-Flight
bar
0 1 2 3
train
15σ distance
15σ distance
beam 2
diffractive protons
beam 1

ALFA detector





AFP detector

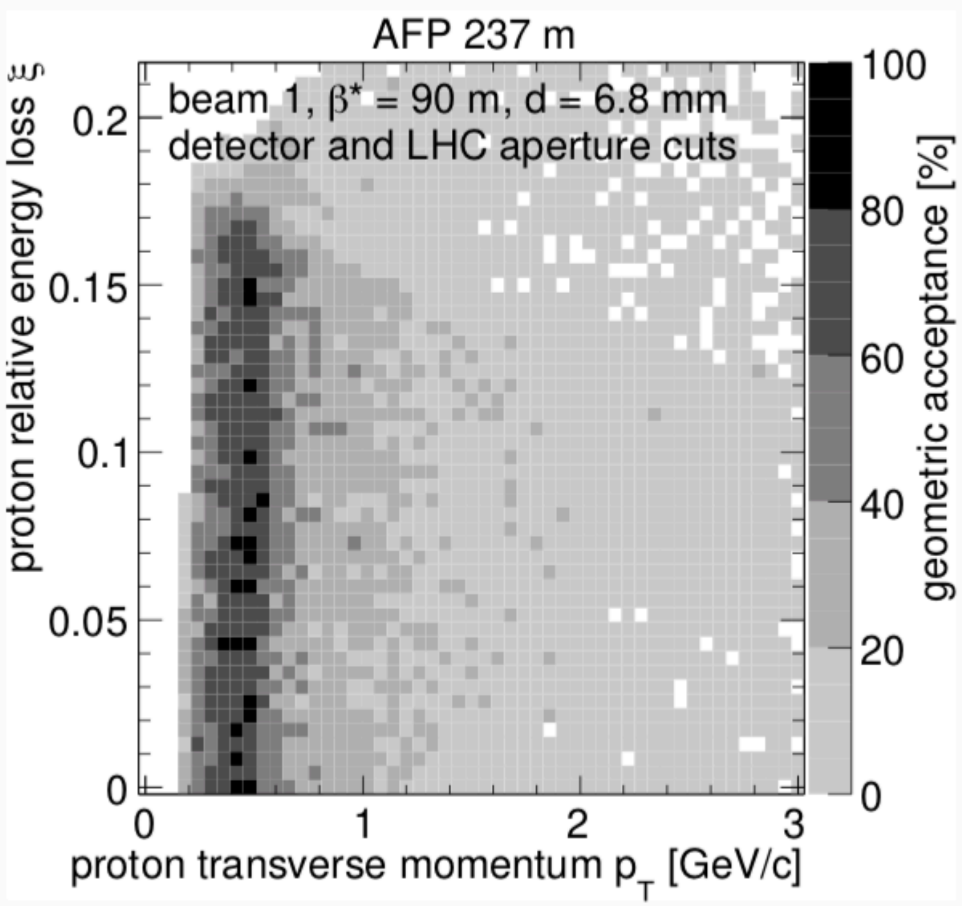
Complementarity of ALFA and AFP

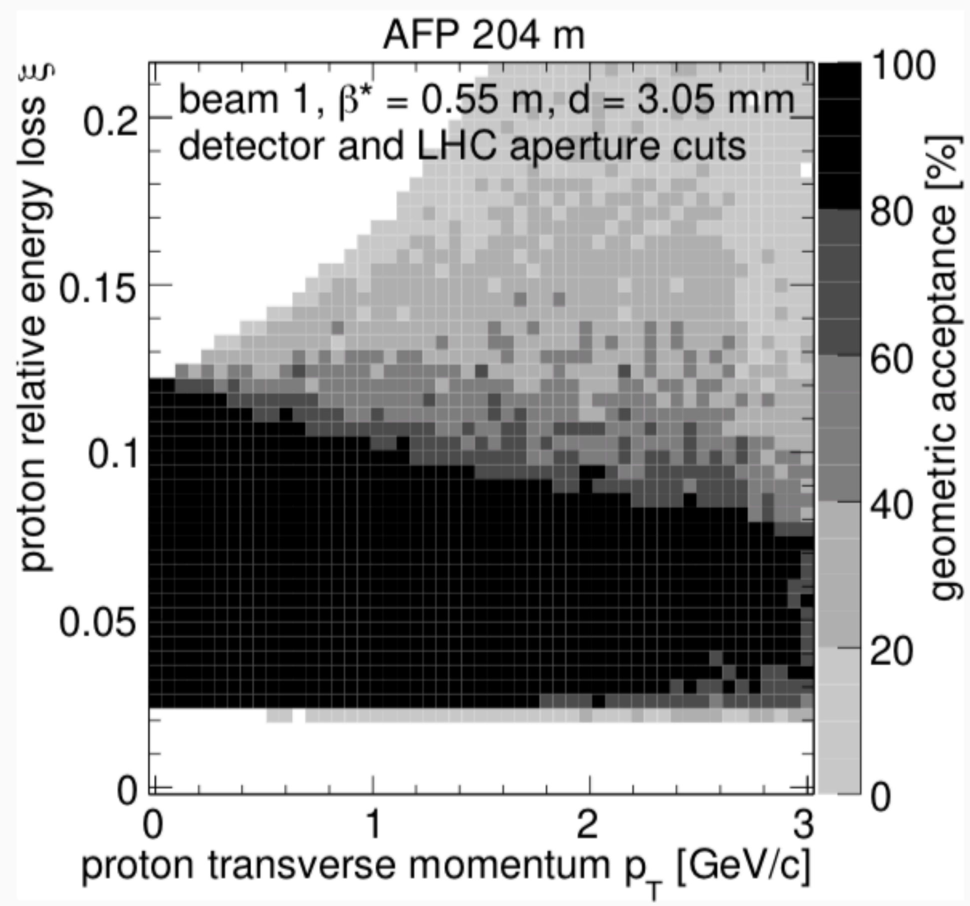
ALFA

- vertical roman pots
- special optics
- (almost) full acceptance in ξ
- good resolution in t

AFP

- horizontal roman pots
- standard optics
- (almost) full acceptance in t
- good resolution in ξ

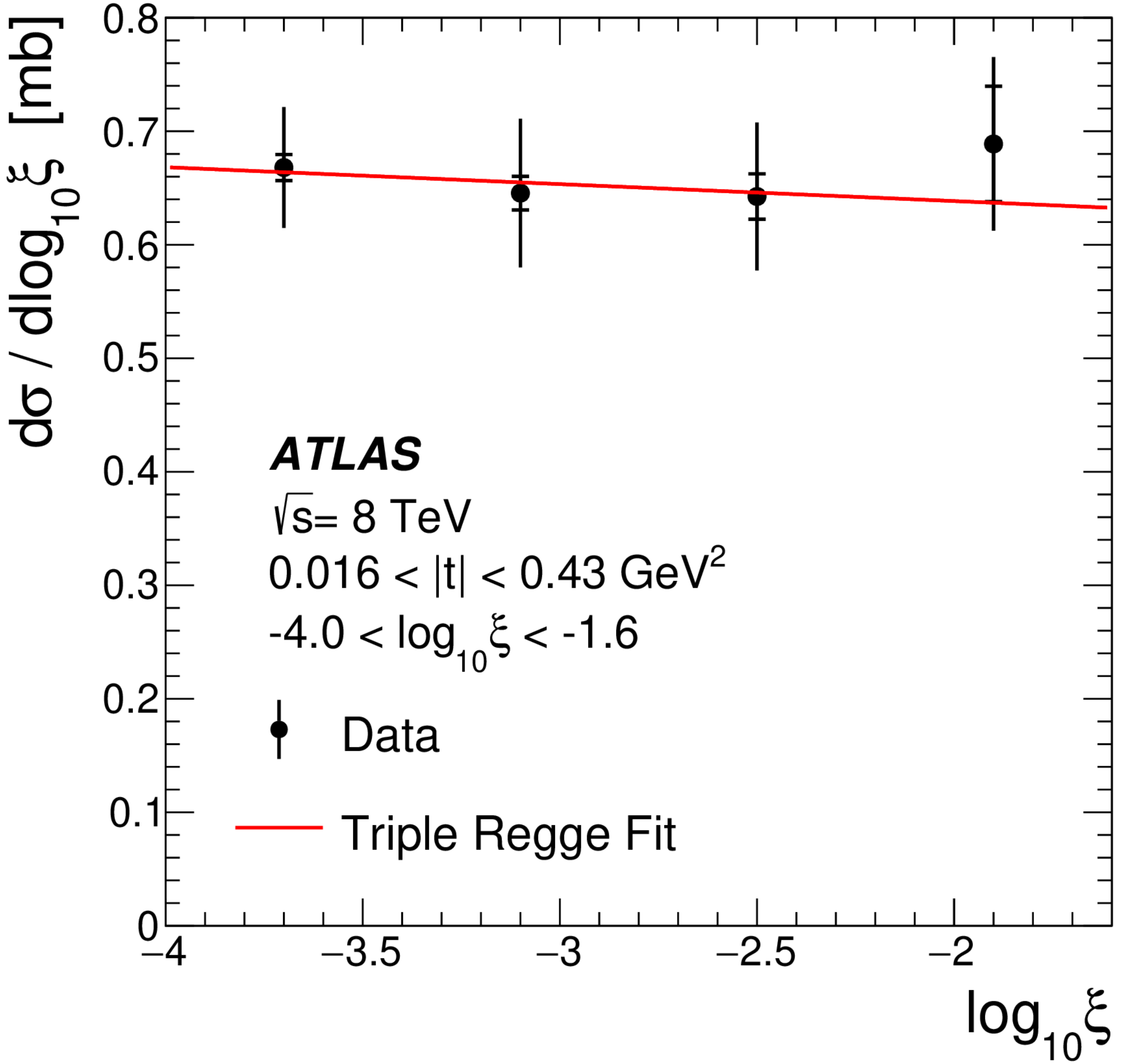




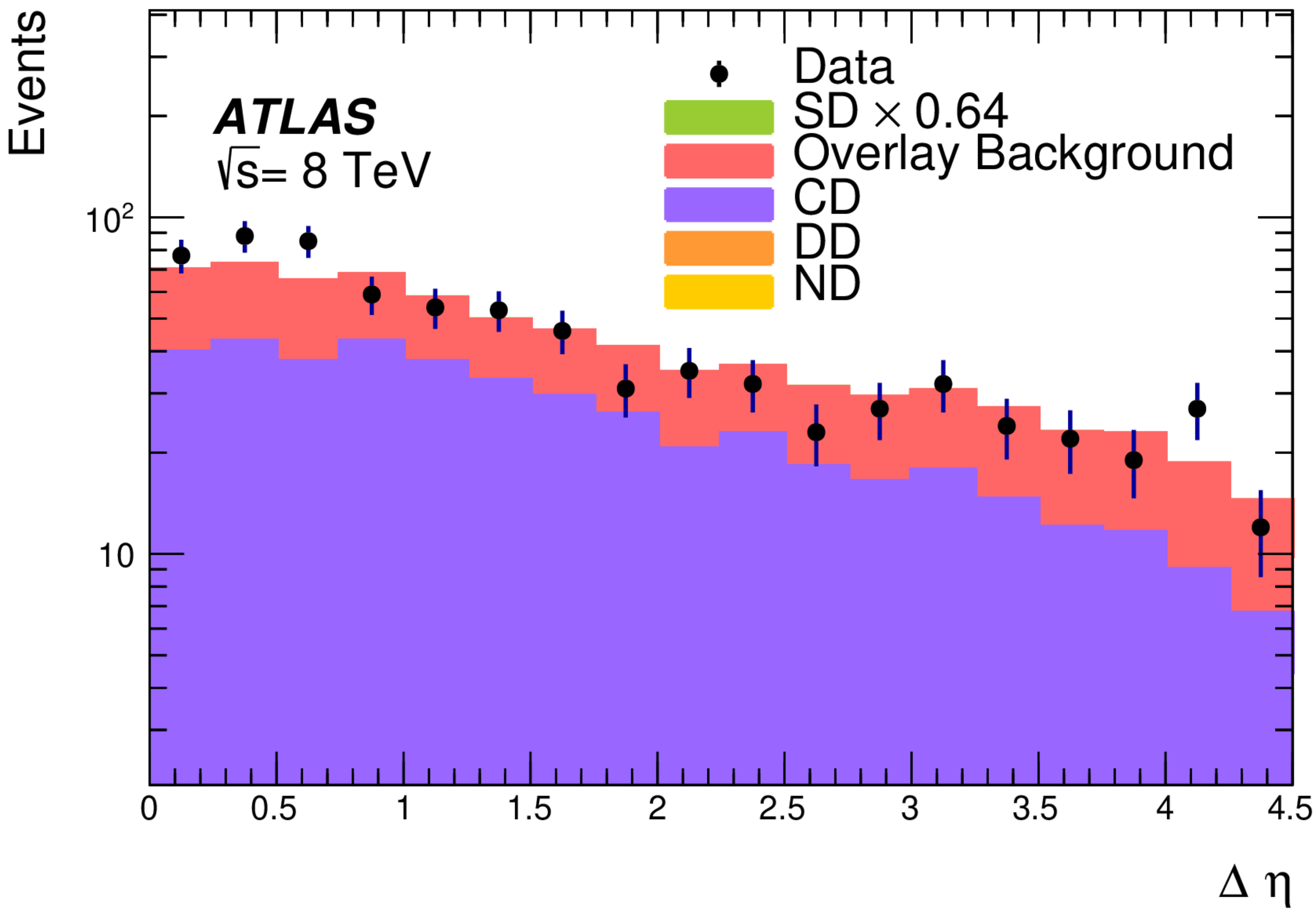
ALFA analysis MC

Monte Carlo (MC) simulations are used for the modelling of background contributions, unfolding of instrumental effects, and comparisons of models with the hadron-level cross-section measurements. The PYTHIA8 [21] generator was used to produce the main SD, ND and DD samples and also that for the 'central diffractive' (CD, $pp \to pXp$, Figure 1(c)) process. The SD, DD and CD models in PYTHIA8 are based on the exchange of a pomeron with trajectory $\alpha(t) = \alpha(0) + \alpha' t$, assuming 'triple Regge' [22] formalism (see Section 10). The models [23] are tuned using previous ATLAS data, including the total inelastic cross section [11] and rapidity gap spectra [14]. By default, the 'A3' tune [24] was used, which adopts the 'Donnachie–Landshoff' [25] choice for the pomeron flux factor to describe the ξ and t dependences in the diffractive channels with pomeron intercept $\alpha(0) = 1.07$. An alternative SD sample was produced using the A2 tune [26] and the Schuler–Sjöstrand model for the pomeron flux factor [23], which has $\alpha(0) = 1$ and therefore differs from Donnachie–Landshoff mainly in its ξ dependence. Both tunes use the H1 2006 Fit B diffractive parton densities [27] as an input to model the hadronisation in the diffractive channels. For the non-diffractive channel, the A3 tune uses the NNPDF23LO [28] proton parton densities. Generated central particles were propagated through the GEANT4 based simulation of ATLAS [29, 30] to produce the simulated signals in the central detector components. The generated protons in diffractive processes are transported from the interaction point to the ALFA detectors by representing each element of the LHC optical lattice (quadrupole and dipole magnets) as a simple matrix under the thin-lens approximation, giving the total transfer matrix once multiplied together.

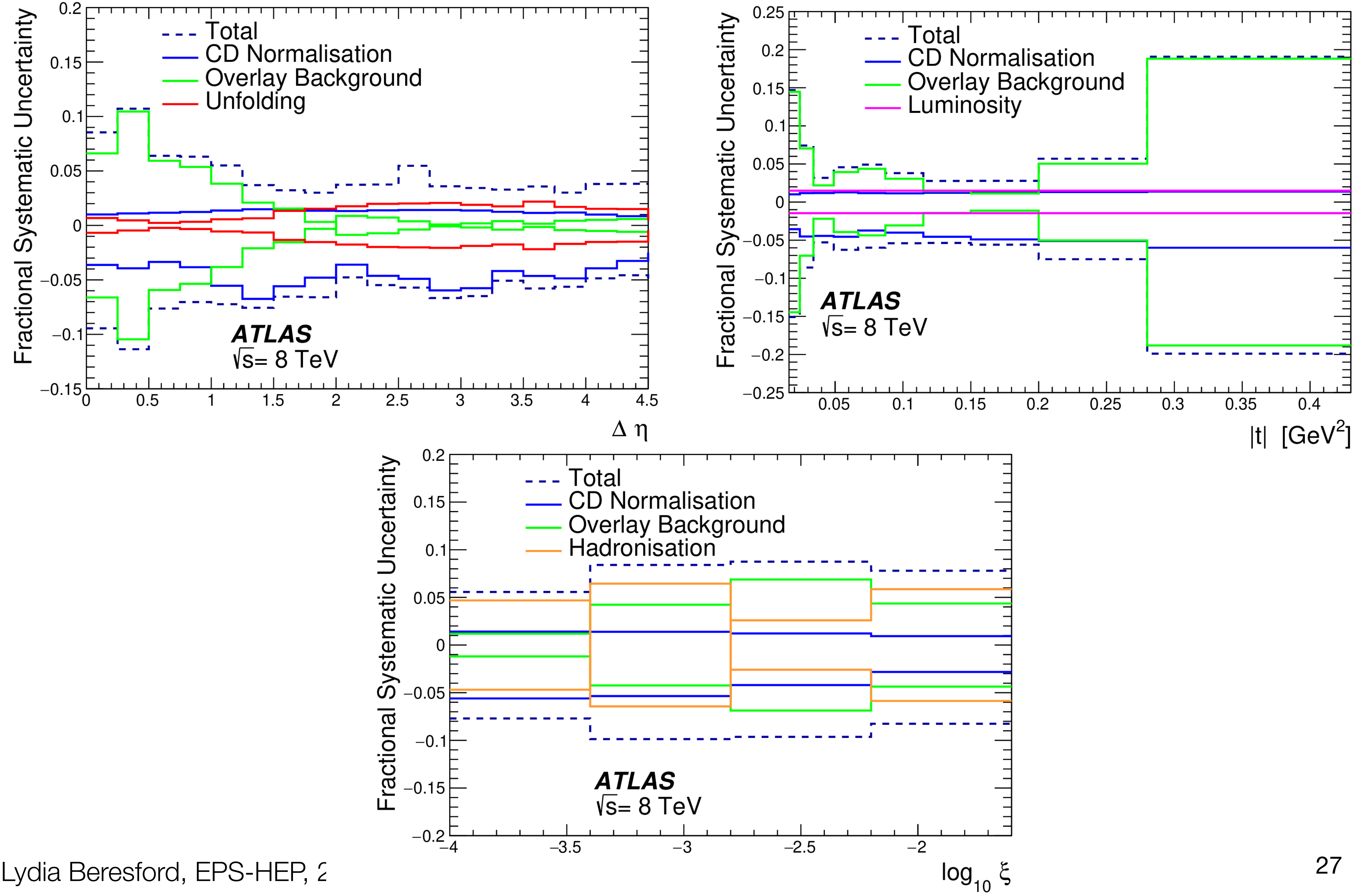
ALFA measurement



ALFA CD control region



SD analysis uncertainties



AFP MC

Simulated events of the exclusive signal $pp \rightarrow p(\gamma\gamma \rightarrow \ell^+\ell^-)p$ were produced using the HERWIG7 Monte Carlo (MC) generator [64, 65]. The single-dissociative signal $pp \rightarrow p(\gamma\gamma \rightarrow \ell^+\ell^-)p^*$ was generated using LPAIR4.0 [66], with proton dissociation modeled using the Brasse et al. [67] and Suri-Yennie [68] structure functions interfaced with JETSET7.408 [69, 70]. Simulation of these processes is detailed in Ref. [5]. To model the central-detector response, the exclusive signal sample underwent full detector simulation based on GEANT4 [71]. The single-dissociative samples employed a fast simulation [72], which uses a parametrization of the calorimeter response [73]. The response of the AFP spectrometer is modeled by a fast simulation, where a Gaussian smearing is applied to track positions based on the AFP spatial resolution. Simulated samples include the effect on the central detector of multiple pp interactions in the same and neighboring bunch crossing (pileup), as detailed in Ref. [5].

AFP selection

Reconstructed events must contain at least one interaction vertex with two or more associated inner-detector tracks that satisfy $p_T > 500$ MeV, $|\eta| < 2.5$, and the "Loose" criterion [74, 75]. Electrons (muons) must satisfy $p_T > 18\,(15)$ GeV, $|\eta| < 2.47\,(2.4)$, the "LooseAndBLayer" [76] ("Medium" [77]) identification criterion, and $|z_0 \sin\theta| < 0.5$ mm [78]. Electrons sharing an inner-detector track with a muon are discarded. To suppress fake and/or nonprompt lepton backgrounds, remaining electrons (muons) must satisfy transverse impact parameter significance $\left|d_0/\sigma_{d_0}\right| < 5\,(3)$ and isolation requirements described in Ref. [79] (Ref. [80]). Electrons must also satisfy "Medium" identification [76]. Small corrections are applied to leptons in simulated samples to match reconstruction and trigger efficiencies measured in data, as described in Refs. [76, 77].

Selected events must have exactly two same-flavor leptons with opposite electric charge (e^+e^- or $\mu^+\mu^-$) and be matched to the leptons that triggered the event. To suppress quarkonia and Z boson resonances, the dilepton invariant mass must satisfy $m_{\ell\ell} > 20$ and $m_{\ell\ell} \notin [70, 105]$ GeV. To select events compatible with $pp \to p(\gamma\gamma \to \ell^+\ell^-)p^{(*)}$ processes based on the simulated signals, the dilepton transverse momentum must satisfy $p_T^{\ell\ell} < 5$ GeV. This set of criteria is referred to as the preselection. Signal event candidates must additionally have small acoplanarity $A_\phi^{\ell\ell} = 1 - |\Delta\phi_{\ell\ell}|/\pi < 0.01$. These events must have no inner-detector tracks ($N_{\text{tracks}}^{0.5\,\text{mm}} = 0$) that satisfy $\Delta R(\text{track}, \ell) > 0.01$ for both leptons and $|z_0^{\text{track}} - z_0^{\ell\ell}| < 0.5$ mm, where z_0^{track} is the track z_0 position and $z_0^{\ell\ell} = (z_0^{\ell_1} + z_0^{\ell_2})/2$ with $\ell_{1,2}$ denoting the two leptons. The expected proton energy loss based on lepton kinematics $\xi_{\ell\ell}$ is determined from $m_{\ell\ell}$ and the dilepton rapidity $y_{\ell\ell}$ by momentum conservation $\xi_{\ell\ell}^{\pm} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{\ell\ell}}$, where + (−) corresponds to the proton on side A (C).

AFP cutflow

	Number of events	
Requirement	$pp \to p(\gamma\gamma \to ee)p$	$pp \to p(\gamma\gamma \to \mu\mu)p$
$\sigma \times \mathcal{L}$	44790	44740
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}}$	11570	11560
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}} \times w_{\text{SF}}$	11440	11190
Exactly two signal leptons	1217	3628
Trigger matched	968	2641
Opposite charge	964	2641
Same flavor	964	2641
$p_{\text{T}}^{\ell\ell} < 5\ GeV$	931	2594
$A_{\phi}^{\ell\ell} < 0.01$	913	2520
$N_{\text{tracks}}^{0.5\text{ mm}} = 0$	378	1138
$m_{\ell\ell} > 20\ GeV$	378	1138
$m_{\ell\ell} \notin [70, 105]\ GeV$	283	960
$\xi_{\ell\ell}^{\text{A}} \in [0.02, 0.12]$ or $\xi_{\ell\ell}^{\text{C}} \in [0.02, 0.12]$	69.8	155
$\xi_{\ell\ell}^{\text{A}} \in [0.035, 0.08]$ or $\xi_{\ell\ell}^{\text{C}} \in [0.035, 0.08]$	18.2	28.9
$\lvert\xi_{\text{AFP}} - \xi_{\ell\ell}\rvert < 0.005$	17.8	27.8

AFP matched event kinematics

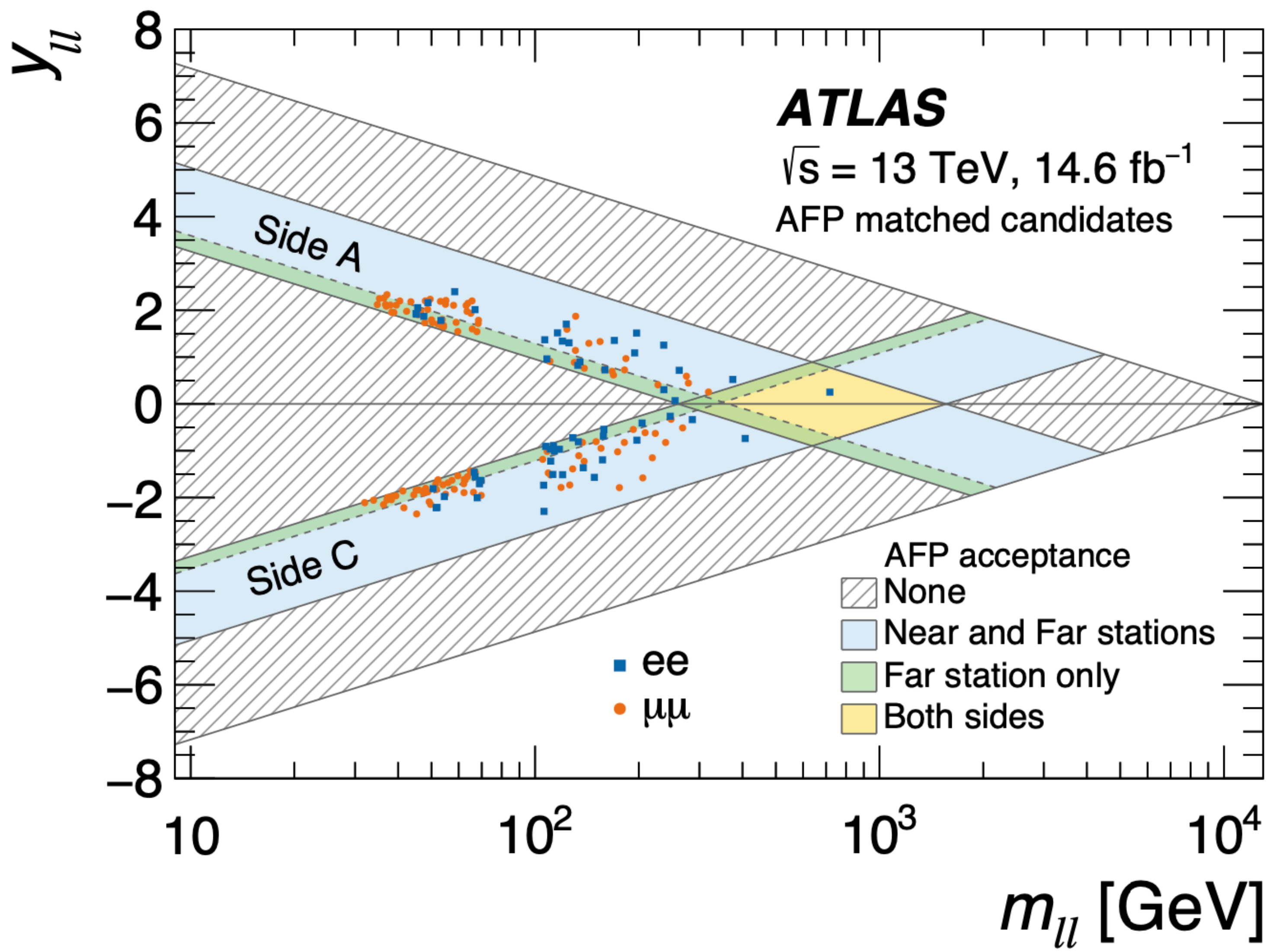


Figure 2: The 57 (123) ee ($\mu\mu$) data event candidates in the dilepton rapidity $y_{\ell\ell}$ vs $m_{\ell\ell}$ plane satisfying event selection and kinematic matching, $|\xi_{\mathrm{AFP}} - \xi_{\ell\ell}| < 0.005$, on at least one side. Shaded (hatched) areas denote the acceptance (no acceptance) for the AFP stations indicated in the legend. Areas neither shaded nor hatched correspond to $\xi \notin [0, 1]$.

Probing masses up to ∼ 700 GeV

AFP matched event kinematics

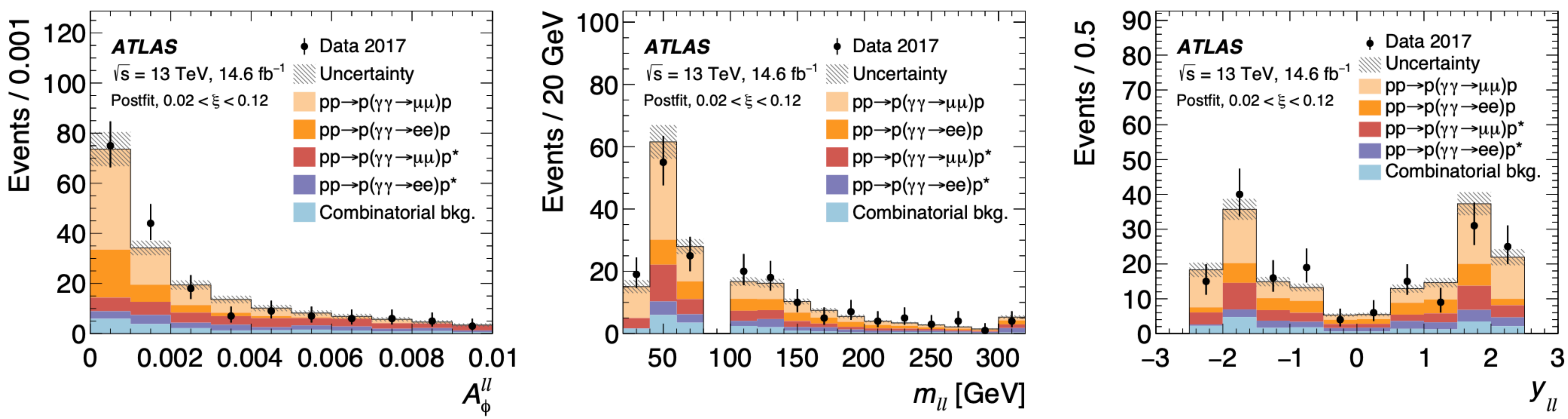


Figure 3: Distributions of dilepton acoplanarity $A_\phi^{\ell\ell}$ (left), invariant mass $m_{\ell\ell}$ (center), rapidity $y_{\ell\ell}$ (right) satisfying $\xi_{\ell\ell}, \xi_{\mathrm{AFP}} \in [0.02, 0.12]$, and $|\xi_{\mathrm{AFP}} - \xi_{\ell\ell}| < 0.005$ for at least one AFP side. Events with $70 < m_{\ell\ell} < 105$ GeV are vetoed. The total prediction comprises the signal and combinatorial background processes, where p^* denotes a dissociated proton. The simulated predictions are normalized to data to illustrate the expected signal composition. The rightmost bin of the $m_{\ell\ell}$ distribution includes overflow. The hatched band indicates the combined statistical and systematic uncertainties of the prediction. Error bars denote statistical uncertainties of the data.

AFP Efficiency

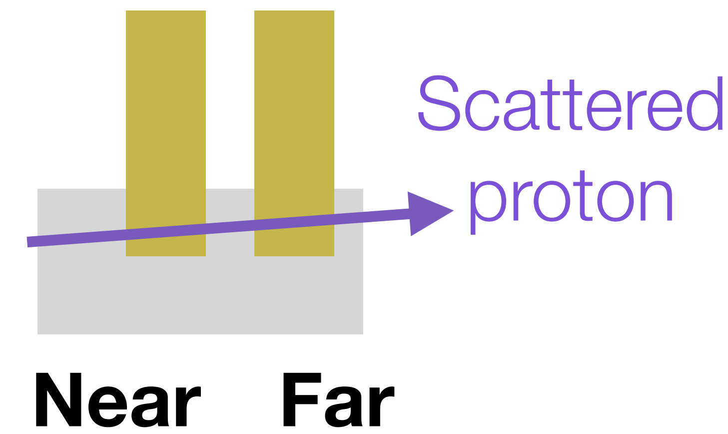
Needed to correct for detector effects

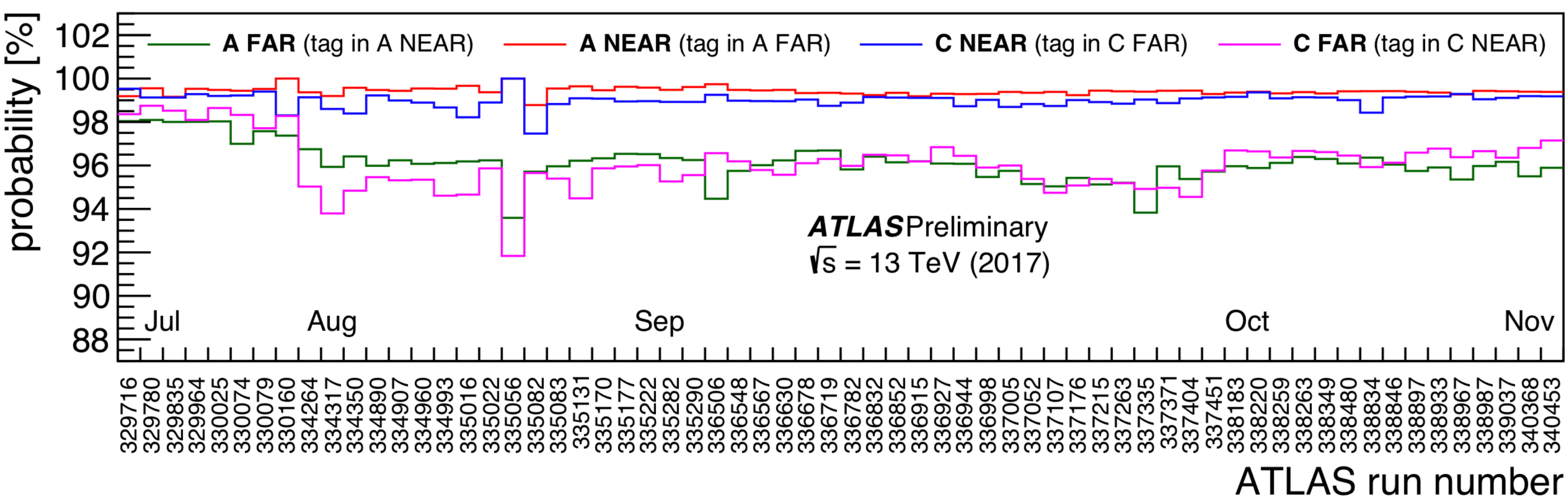
Station tag and probe:

- ‘Tag’ track in near station (require exactly 1)
- Check if track in far (within $|x_{near}-x_{far}| < 2$ mm)

& vice versa

AFP side A





Lower efficiency in far station due to showers

AFP cross-section break down

The measured fiducial cross sections in the ee and $\mu\mu$ channels are $\sigma^{\text{fid.}}_{ee+p} = 11.0 \pm 2.6\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 0.3\,(\text{lumi})$ and $\sigma^{\text{fid.}}_{\mu\mu+p} = 7.2 \pm 1.6\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 0.2\,(\text{lumi})$ fb, respectively. Table 1 compares these with the combined HERWIG and LPAIR predictions assuming unit soft-survival factors $S_{\text{surv}} = 1$. Soft-survival effects are included using an $m_{\ell\ell}$-dependent reweighting of these predictions to S_{surv} calculated for exclusive processes from Ref. [34]; LPAIR predictions are additionally scaled down by 15% to account for S_{surv} being lower for single-dissociative processes [33]. SUPERCHIC 4 [97] predictions include full kinematic dependence on S_{surv} for exclusive, single-, and double-dissociative processes. The predictions for ee are higher than for $\mu\mu$ due to the looser $\eta(e)$ requirement [94].

Uncertainties of 7% (17%) are assigned for predictions of the exclusive (single-dissociative) processes [98].

AFP cross-section break down

	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
Measurement	11.0 ± 2.9	7.2 ± 1.8
Predictions		
$S_{\text{surv}} = 1$		
Herwig+Lpair	15.5 ± 1.2	13.5 ± 1.1
Herwig	9.3 ± 0.7	8.0 ± 0.6
Lpair	6.2 ± 1.1	5.5 ± 0.9
S_{surv} using Refs. [31,30]		
Herwig+Lpair	10.9 ± 0.8	9.2 ± 0.7
Herwig	7.0 ± 0.5	5.9 ± 0.4
Lpair	3.9 ± 0.7	3.4 ± 0.6
SuperChic 4 [94]		
Exclusive + single-dissociative	12.2 ± 0.9	10.4 ± 0.7
Exclusive	8.6 ± 0.6	7.3 ± 0.5
Single-dissociative	3.6 ± 0.6	3.1 ± 0.5

Uncertainties

Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	< 1%
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon scale and resolution	3%
Muon trigger, isolation, reconstruction efficiencies	1%
Electron trigger, isolation, reconstruction efficiencies	1%
Electron scale and resolution	1%
Background modeling	2%
Luminosity	2%

Table 4: Summary of sources of systematic uncertainty and their impact on the cross-section measurement.

AFP background rejection

Powerful background suppression

Can see photo-production of di-leptons above Drell-Yan background