Single Diffraction
with ATLAS and ALFA

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Master's Thesis Work

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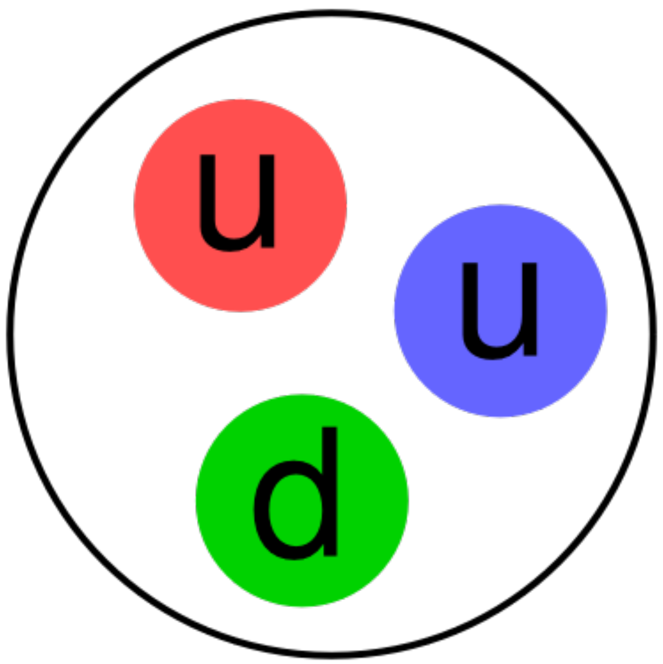
External co-supervisor: Torbjörn Sjöstrand (Lund)

Nordic Winter School 2017

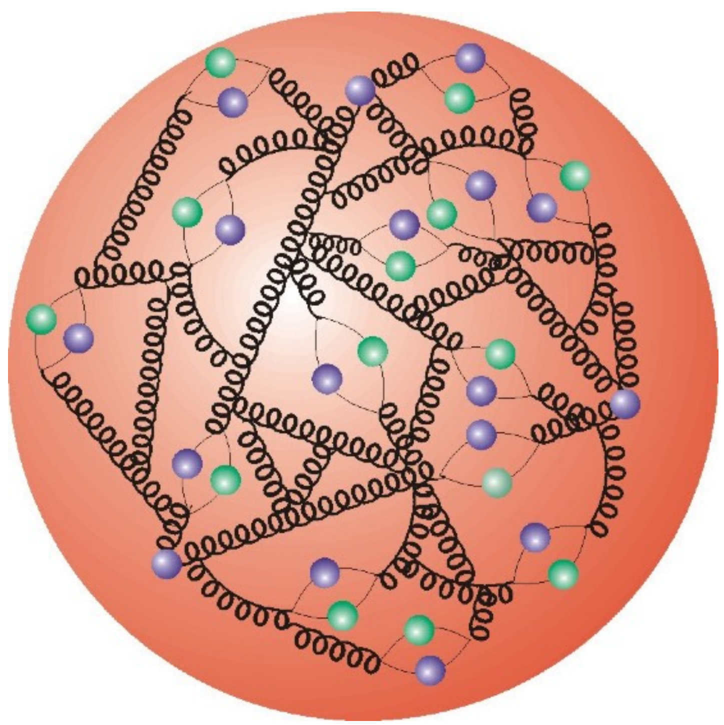
Introduction

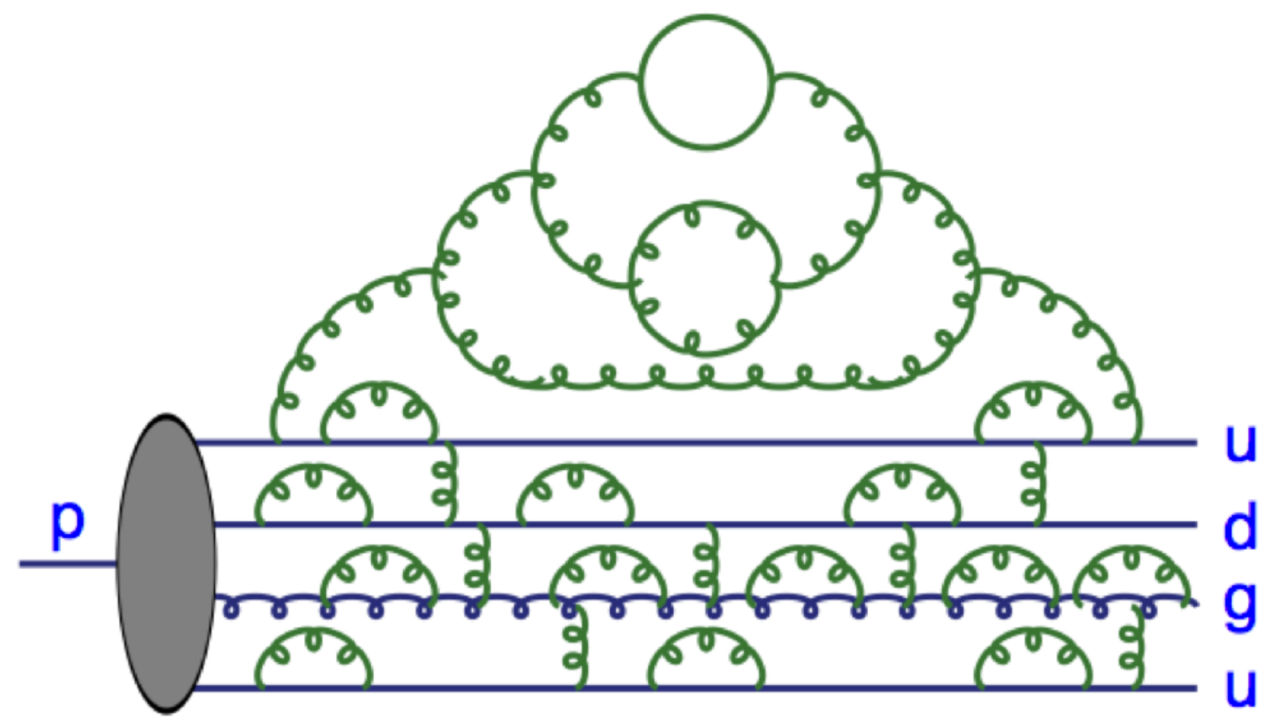


A curious
particle physicist

When probed at high energies
the proton looks more like this

Hadrons are composite objects (consists of partons, i.e. quarks and gluons) with a time-dependent structure

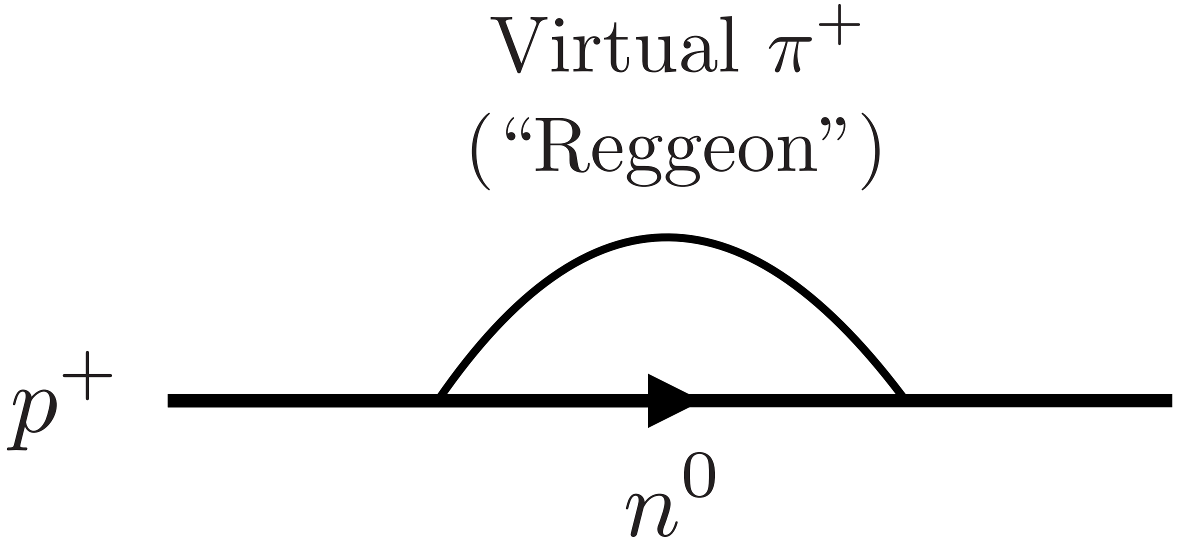


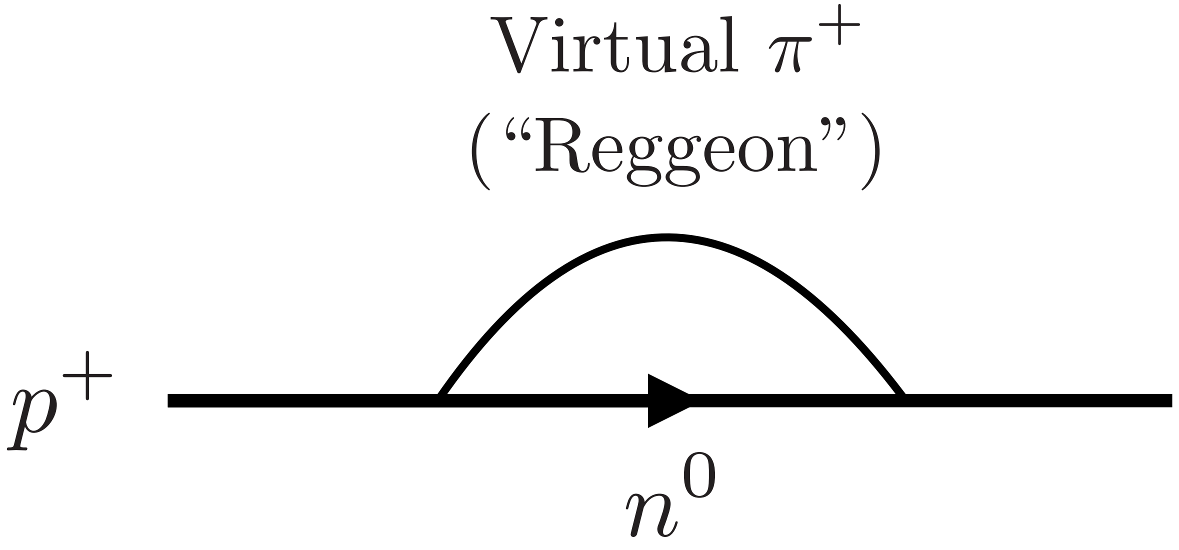


Parton distribution function (PDF):

$f_i(x, Q^2)$ = number density of partons i at momentum fraction x and probing scale Q^2

Structure function: $$F_2(x, Q^2) = \sum_i e_i^2 x f_i(x, Q^2)$$


Virtual π^+
("Reggeon")
p^+
n^0


Virtual π^+
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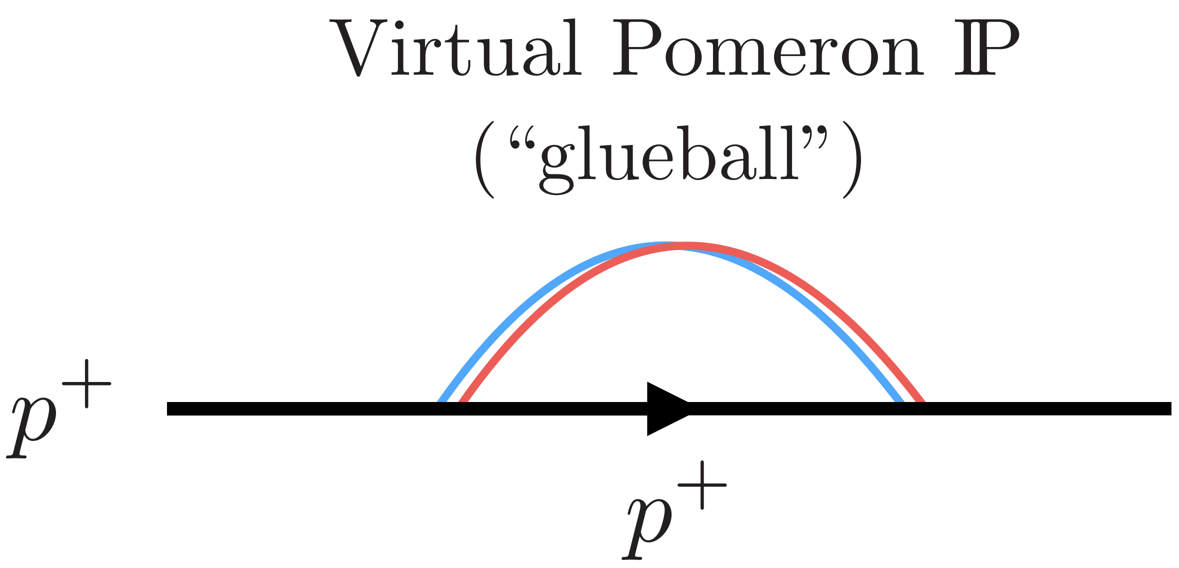
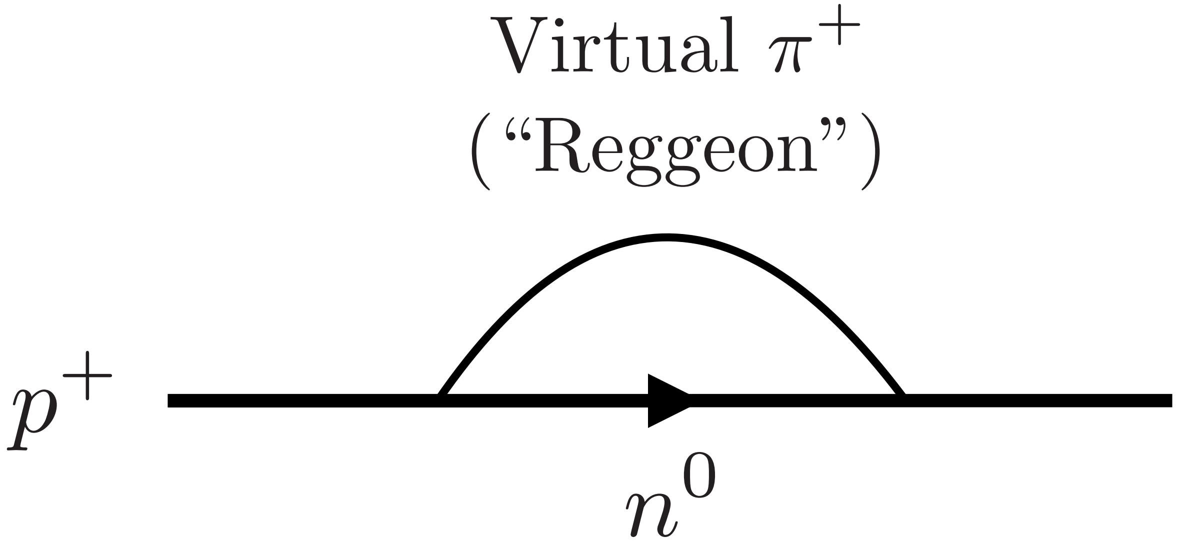
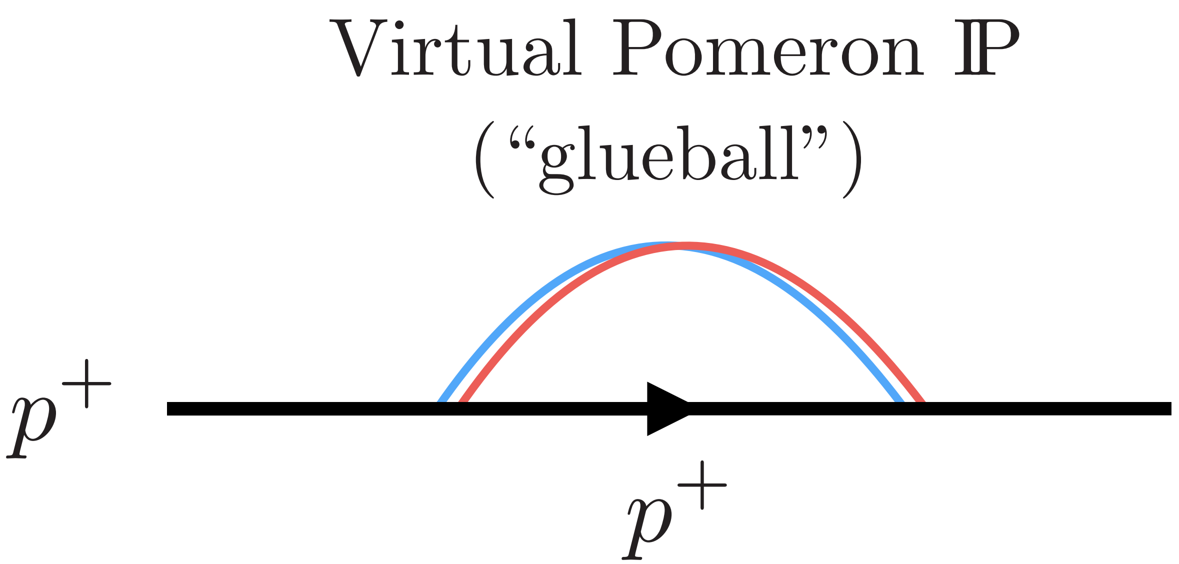
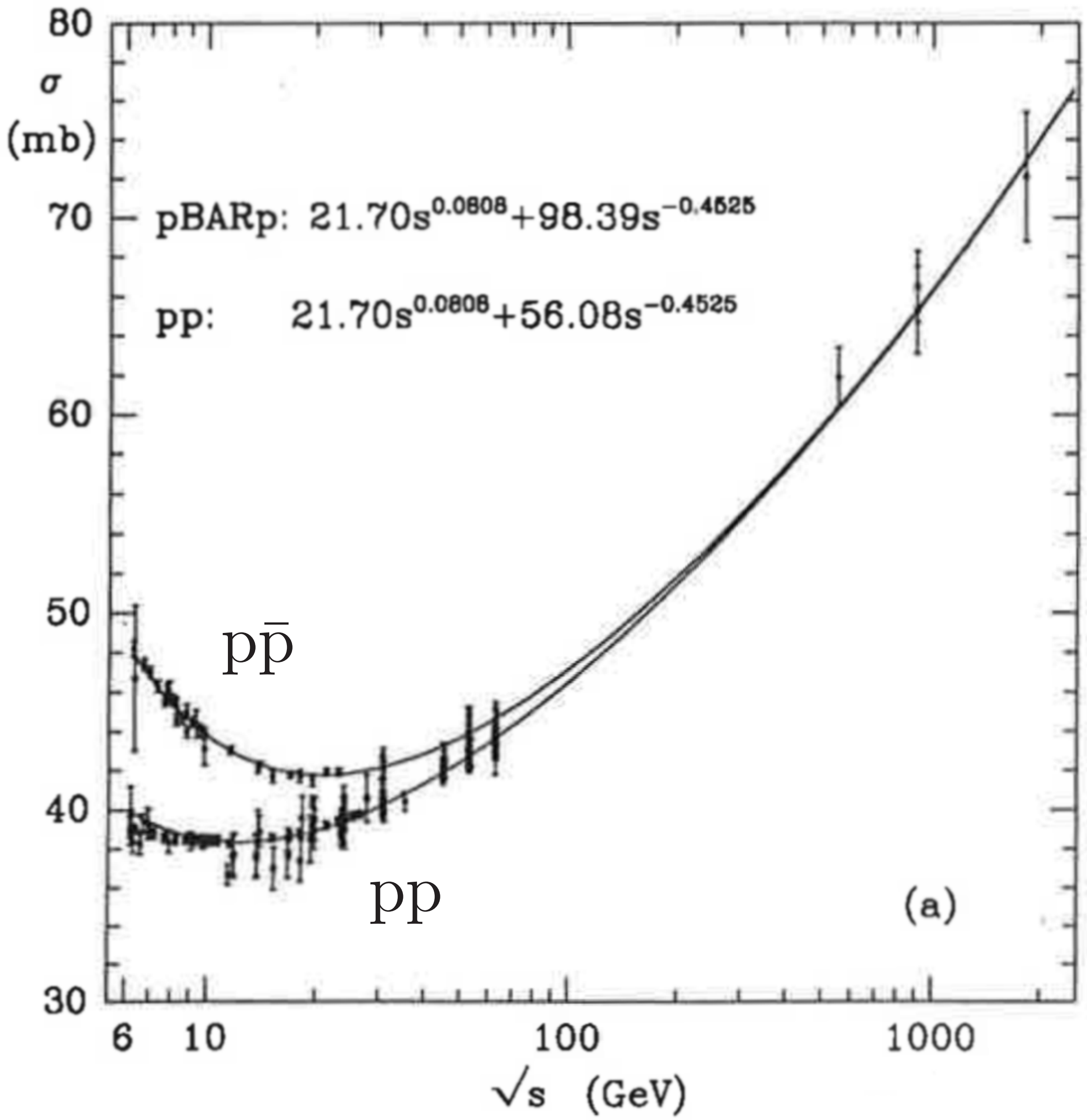

Virtual Pomeron $\mathbb{P}$
("glueball")
p^+
p^+

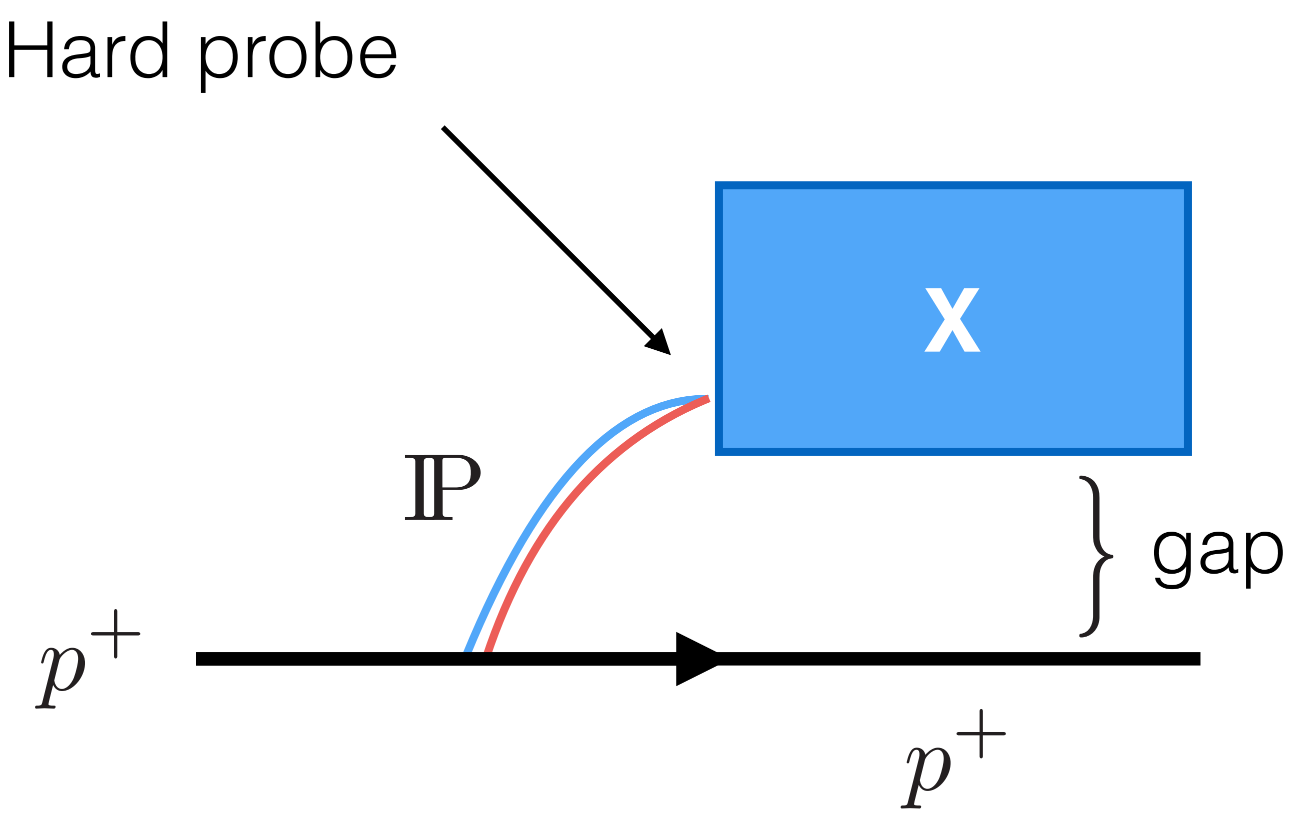


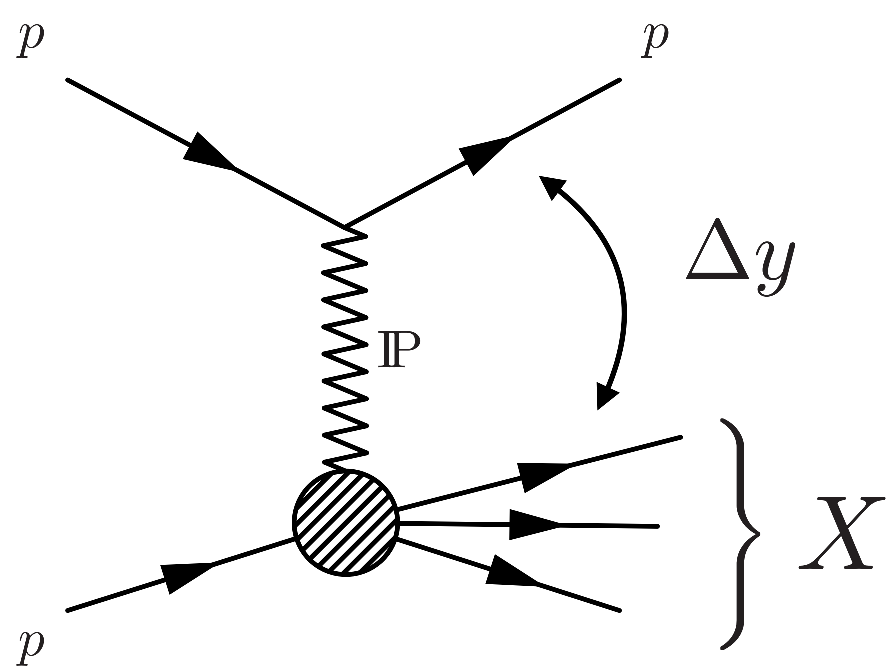


$$\sigma_{\text{tot}}^{\text{p}\bar{\text{p}}} \approx 21.7 s^{0.08} + 98.4 s^{-0.45}$$

$$\sigma_{\text{tot}}^{\text{pp}} \approx 21.7 s^{0.08} + 56.1 s^{-0.45}$$







Not physical to ask whether there was an (unmeasurable) Pomeron

Physical to ask if there was a large rapidity gap

Pomeron Flux

Relative energy loss of the scattered proton: $\xi = 1 - \frac{E_3}{E_1} \approx \frac{M_X^2}{s}$

SD cross-section: $$\frac{\mathrm{d}\sigma^2_{\mathrm{SD}}}{\mathrm{d}\xi\mathrm{d}t} = f_{\mathbb{P}/p}(\xi, t)\sigma_{\mathbb{P}/p}(M_X^2)$$

pomeron flux

The choice of Pomeron flux in Pythia 8 will affect the chosen values for ξ and t .

The Pomeron flux depends on the Regge trajectory for the Pomeron

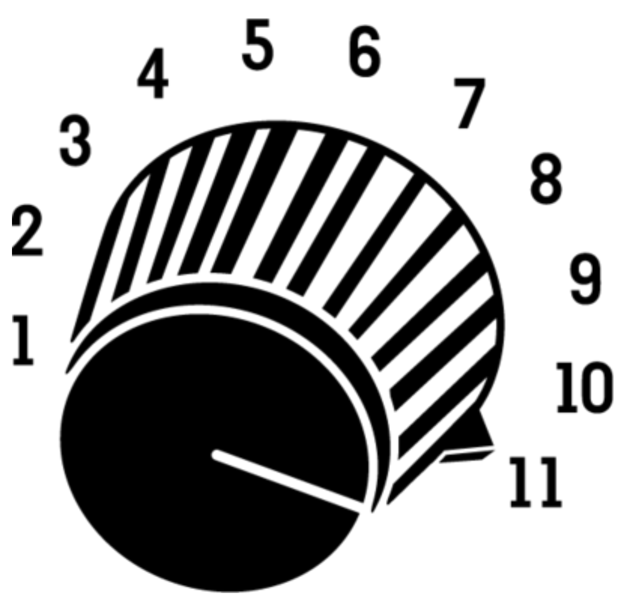
$$\alpha(t) = 1 + \varepsilon + \alpha' t$$

Pythia Monte Carlo Event Generator

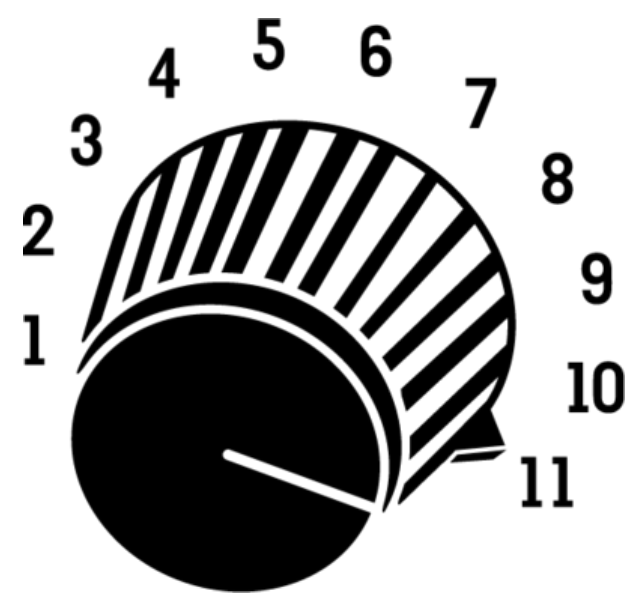
The Pomeron flux depends on the Regge trajectory for the Pomeron

$$\alpha(t) = 1 + \varepsilon + \alpha' t$$

In Pythia:

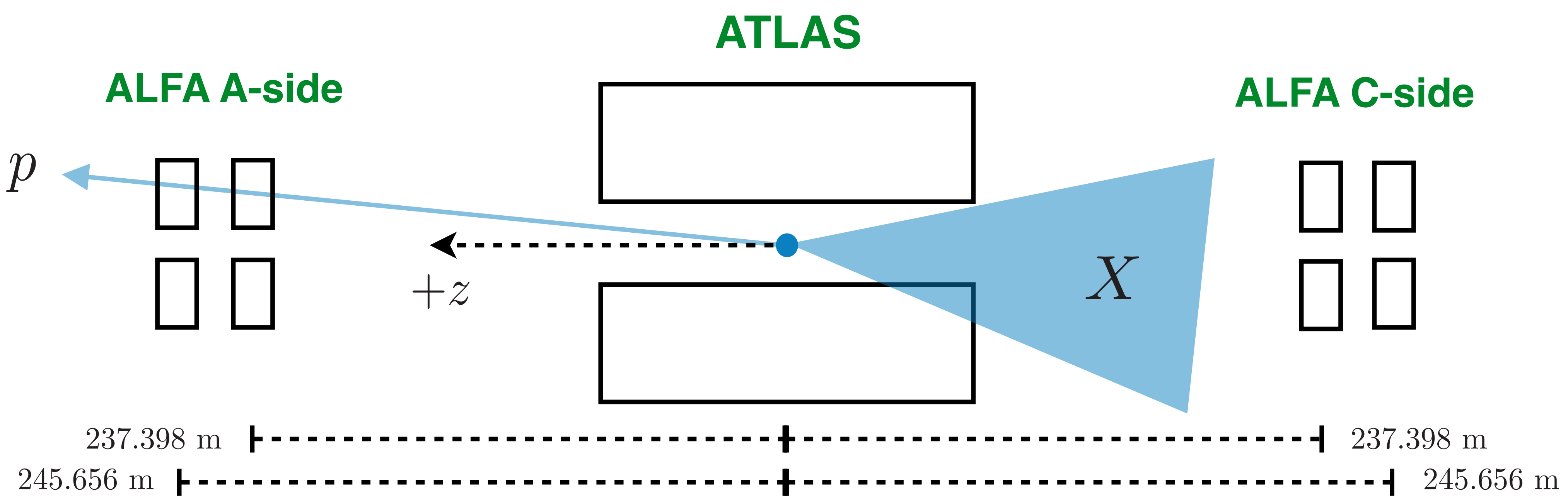


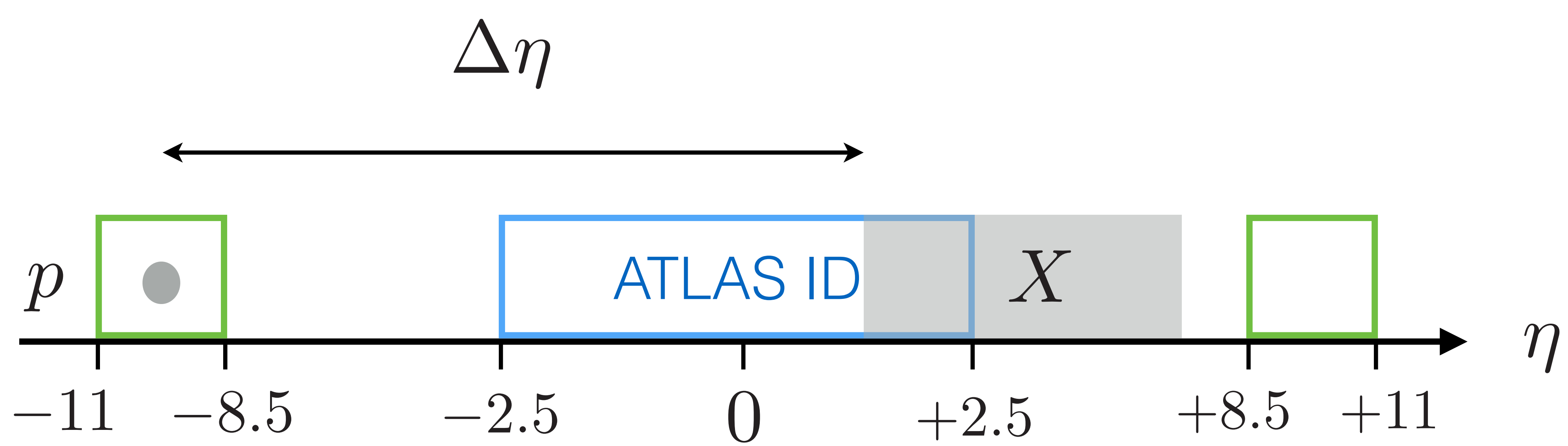
ε



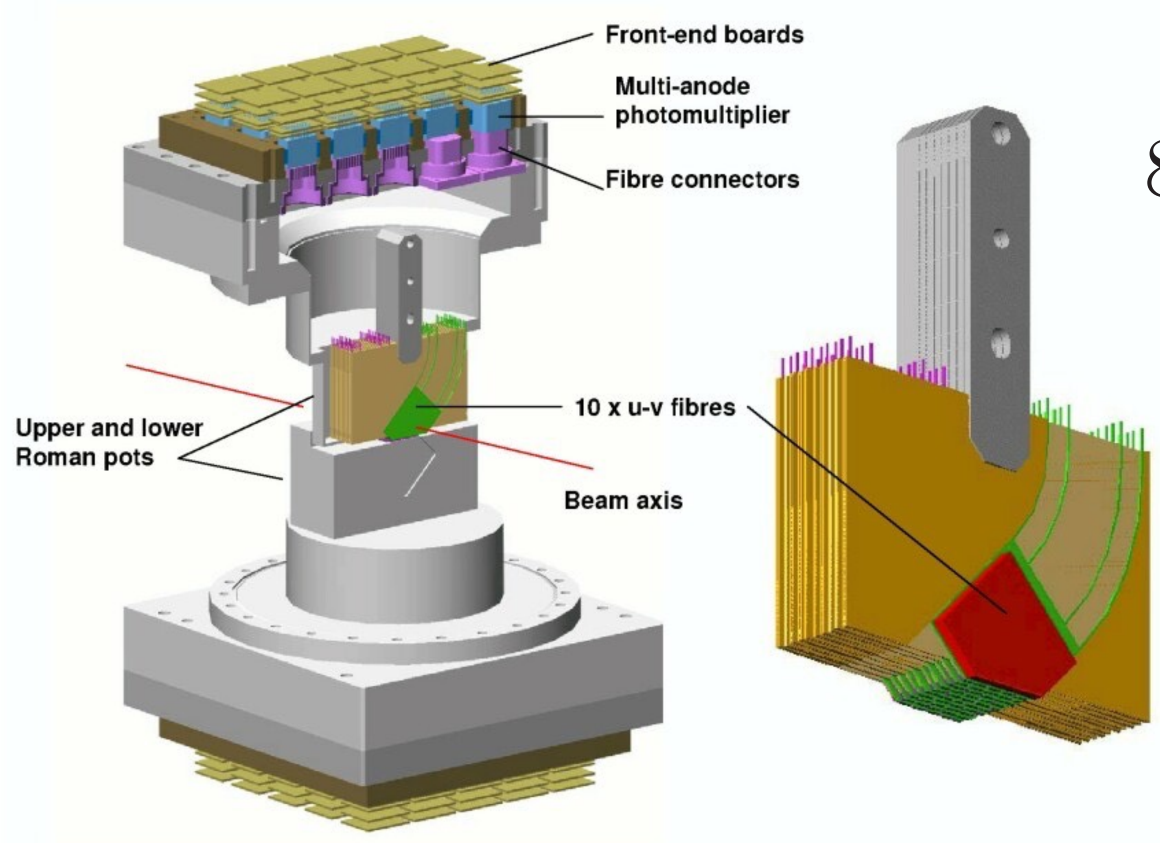
α'

Detection of Single Diffractive Events





The ALFA Detector

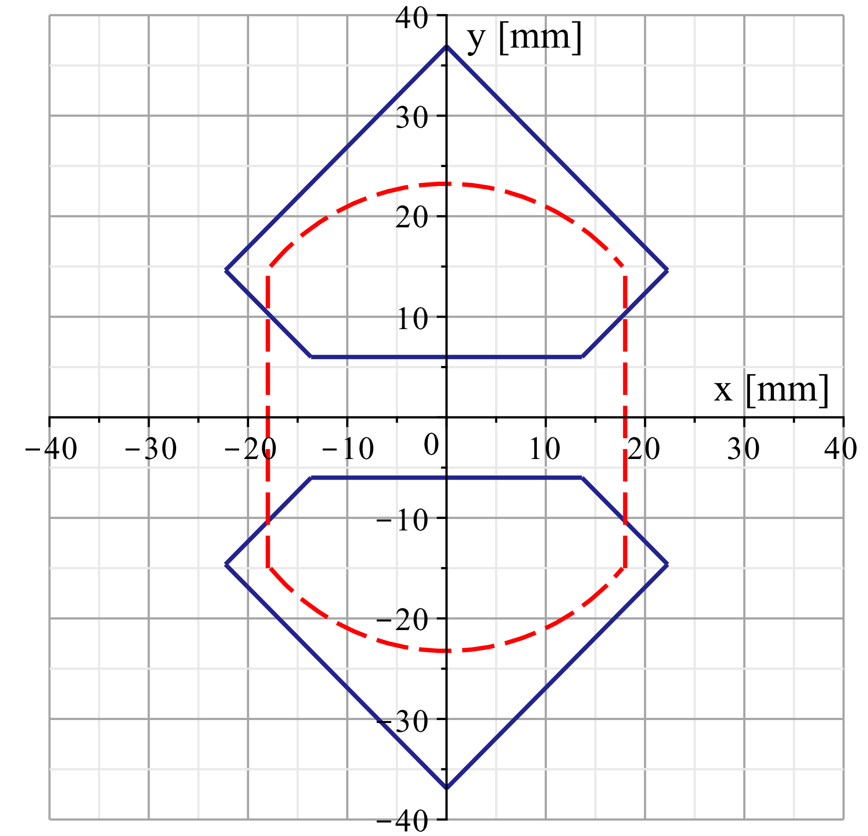


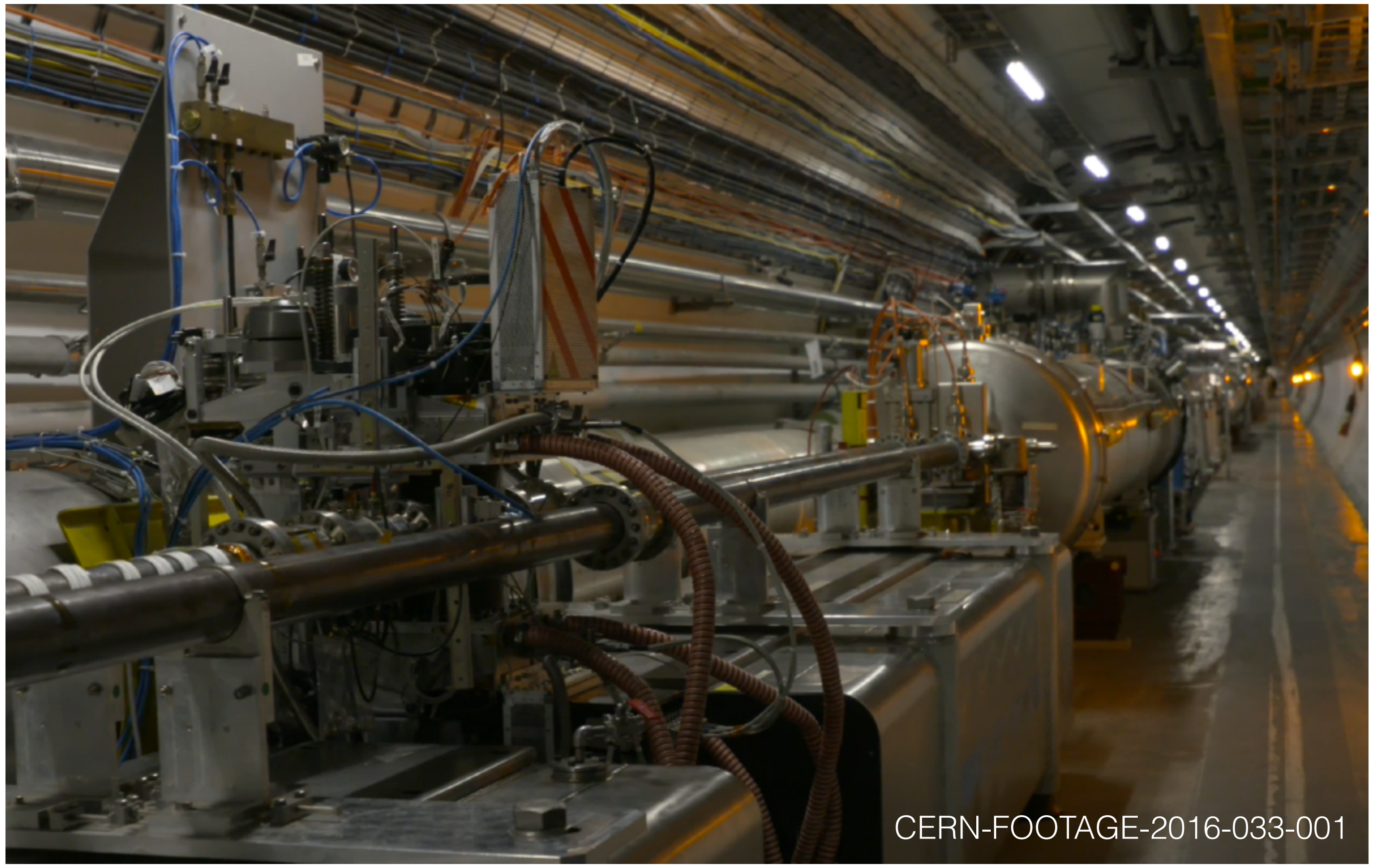
$$8.5 \lesssim |\eta| \lesssim 11.5$$

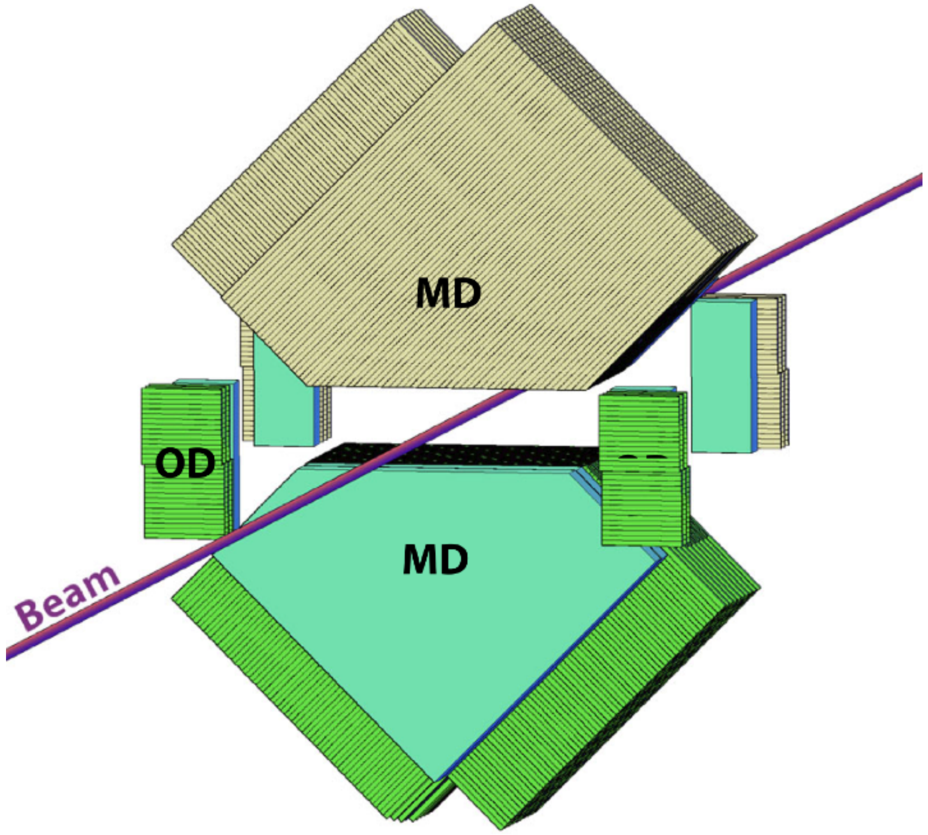
$$\xi < 0.2$$

for

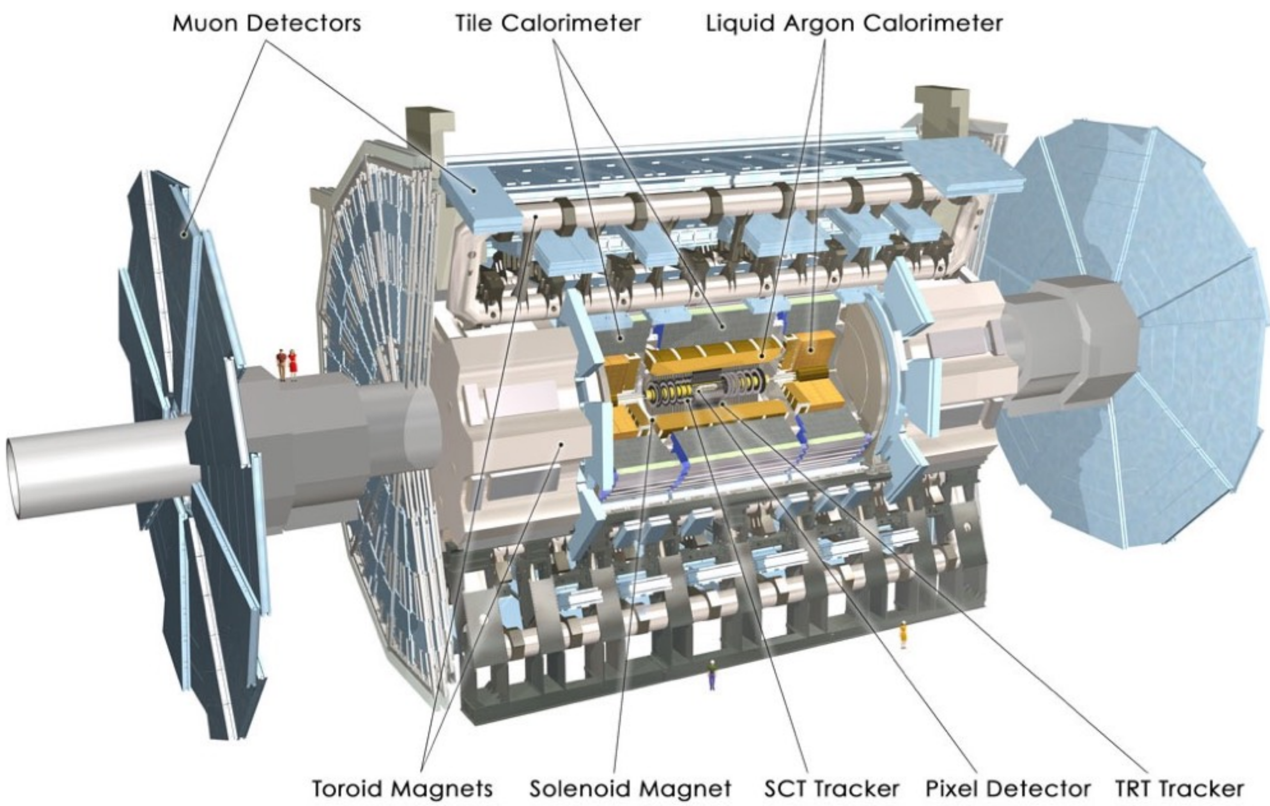
$$\sqrt{s} = 13 \text{ TeV}$$







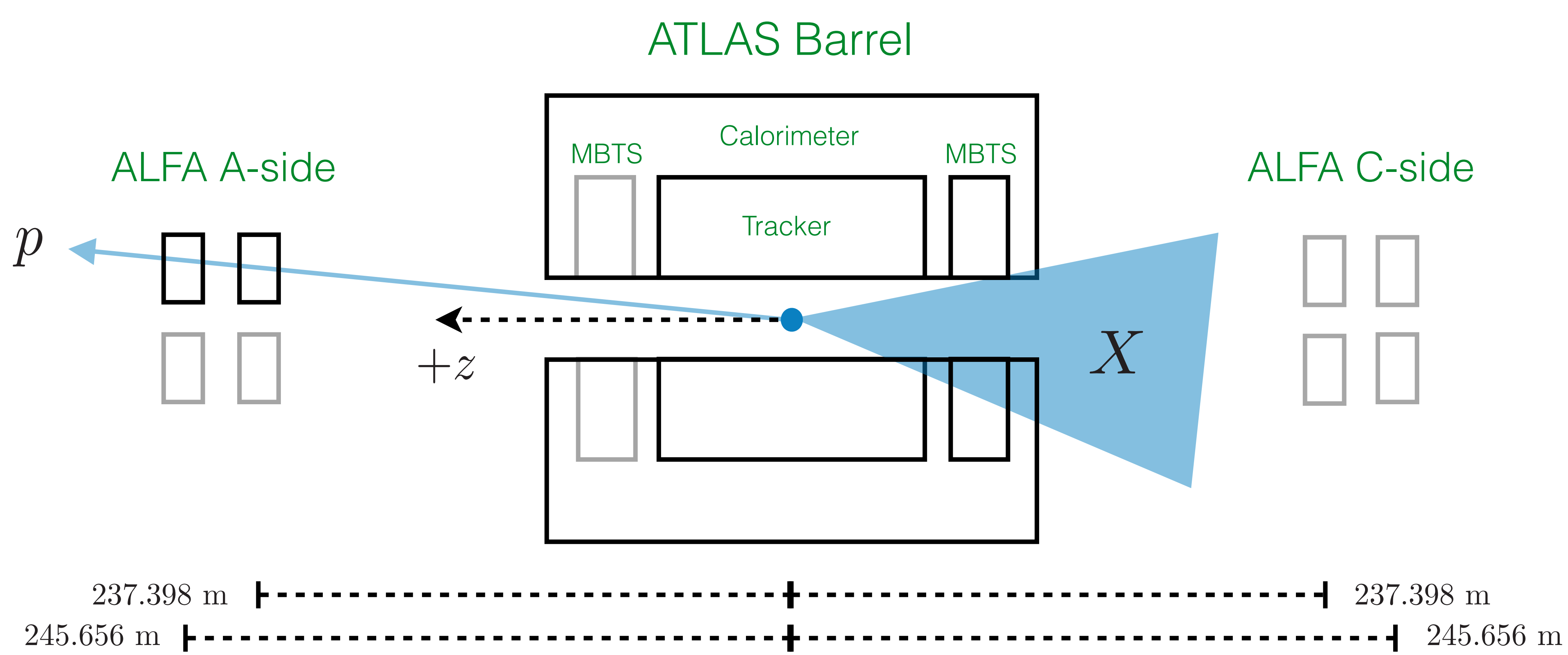
The ATLAS Detector



Tracker (ID): $|\eta| < 2.5$

Calorimeter: $|\eta| < 4.9$

MBTS: $2.09 < |\eta| < 3.84$



Data

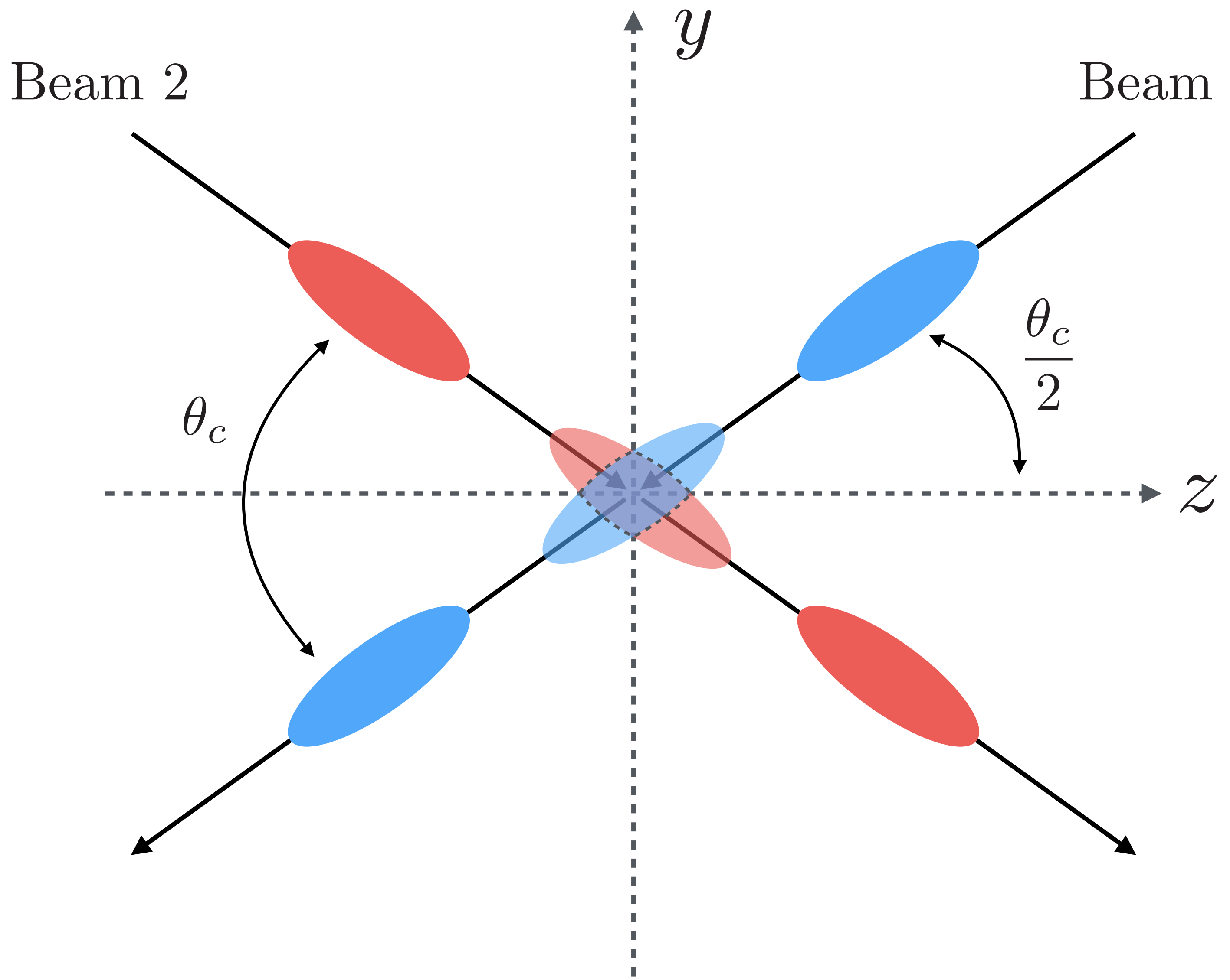
Energy: $\sqrt{s} = 13$ TeV

Crossing angle: $\theta_C = 2 \times 50\ \mu\mathrm{rad}$

Optics: $\beta^* = 90$ m

Dates: 15 - 18 October, 2015

Run 2 data with 671 colliding bunches per run



I'm going to consider both

$$\theta_C = 2 \times 50\ \mu\mathrm{rad}$$

and

$$\theta_C = 0\ \mu\mathrm{rad}$$

in the simulation for comparison

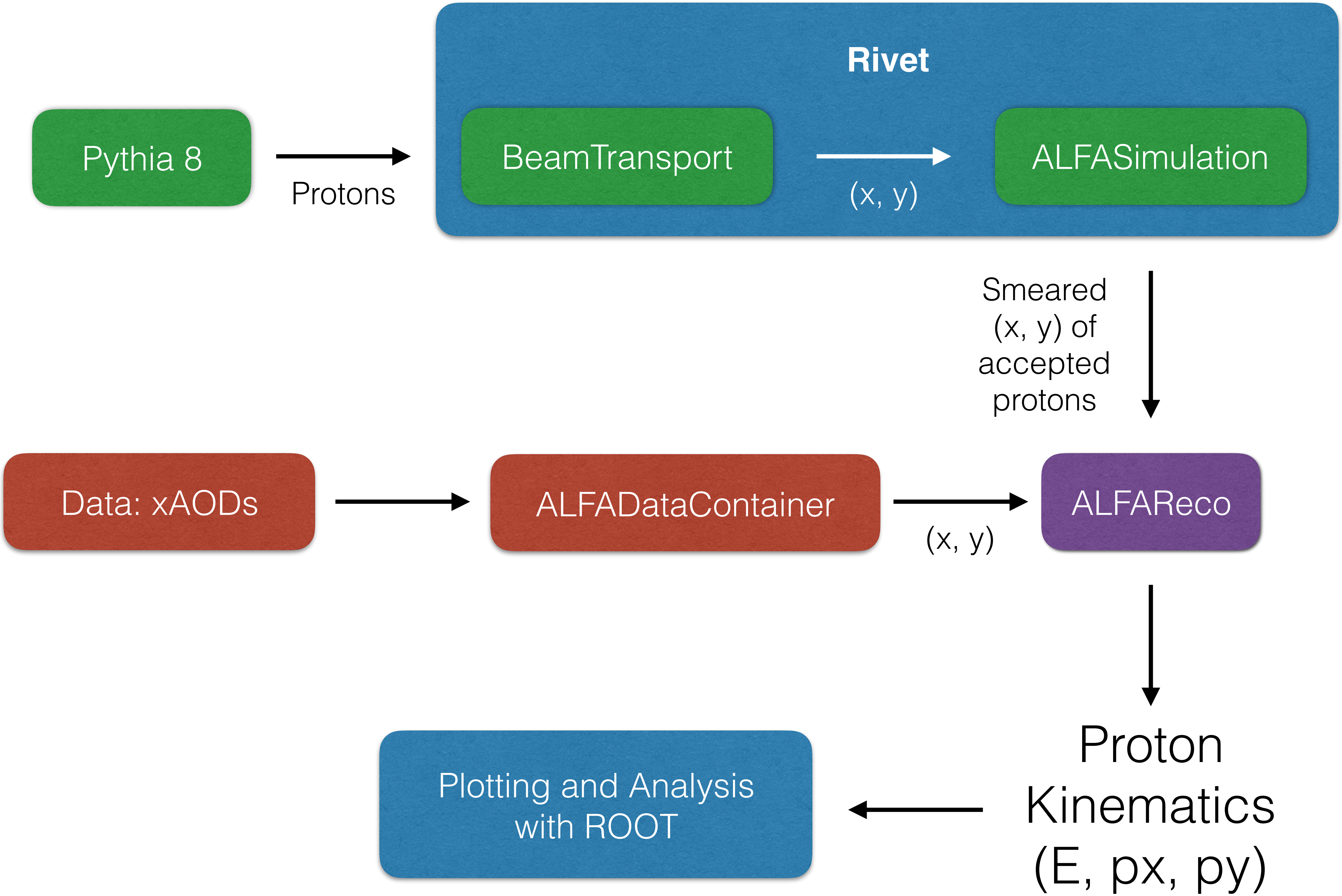
A simulation analysis has been made in Rivet

- Runs on zipped HepMC files created with Pythia 8
- BeamTransport: Handles the transport of protons from IP1 to RPs.
- ALFASimulation: Takes input from BeamTransport. Handles acceptance and smearing of protons.
- ALFAReco: Handles reconstruction of proton kinematics. Also used with Data.
- ATLAS Simulation: A simple, and rough detector simulation. Handles acceptance and smearing.

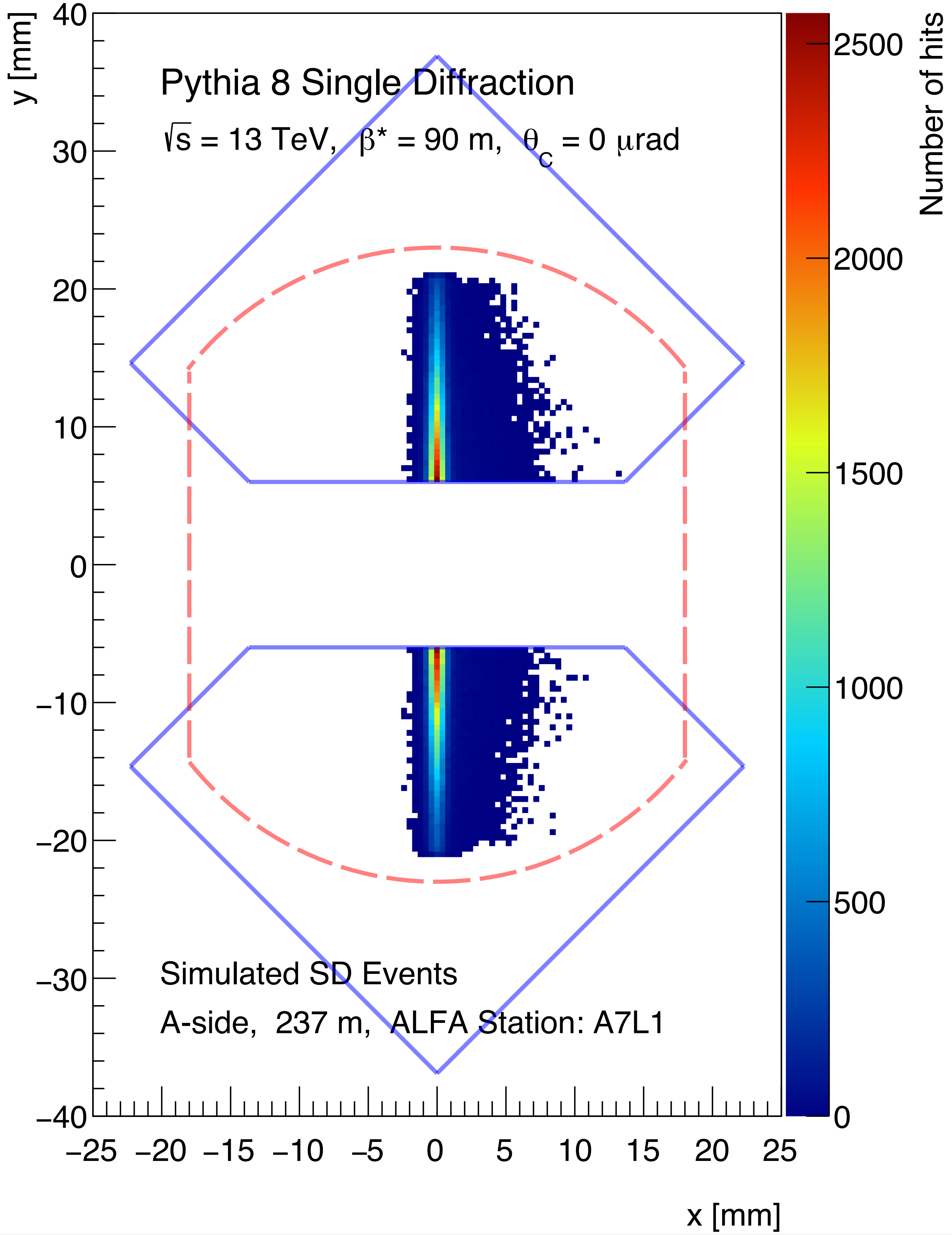
A simulation analysis has been made in Rivet

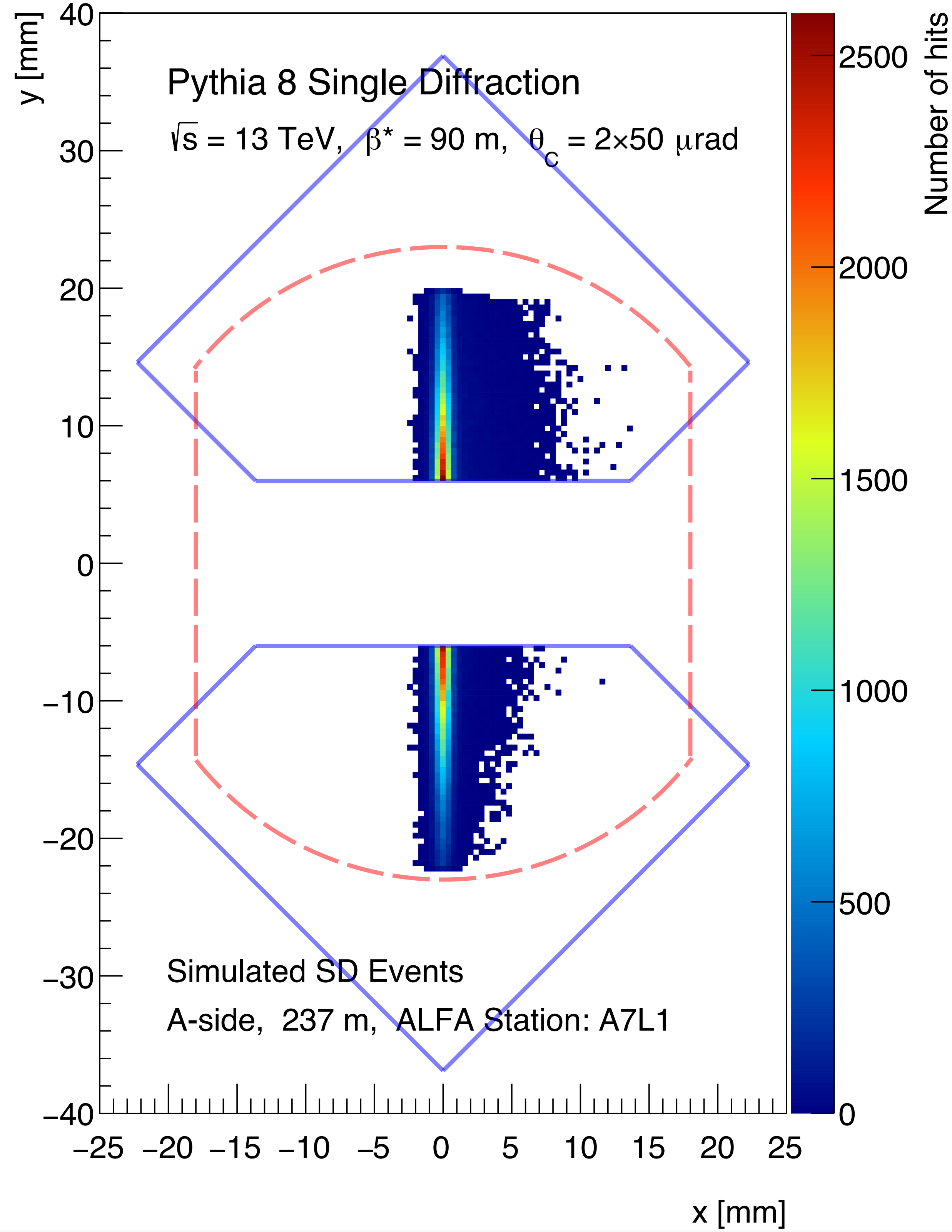
- “Quick-and-dirty” simulation
- Independent of ATLAS software
- Still being tweaked and improved
- Developed alongside Data Analysis

Simulation and Data

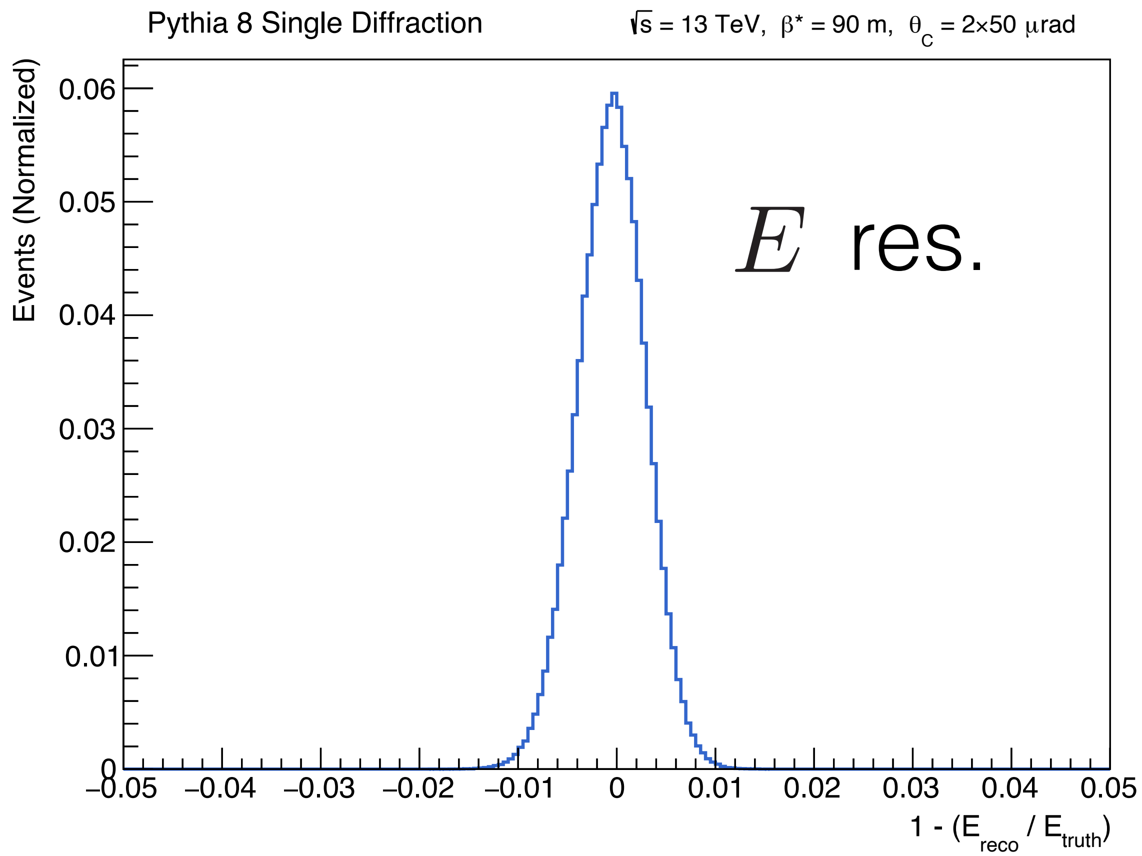


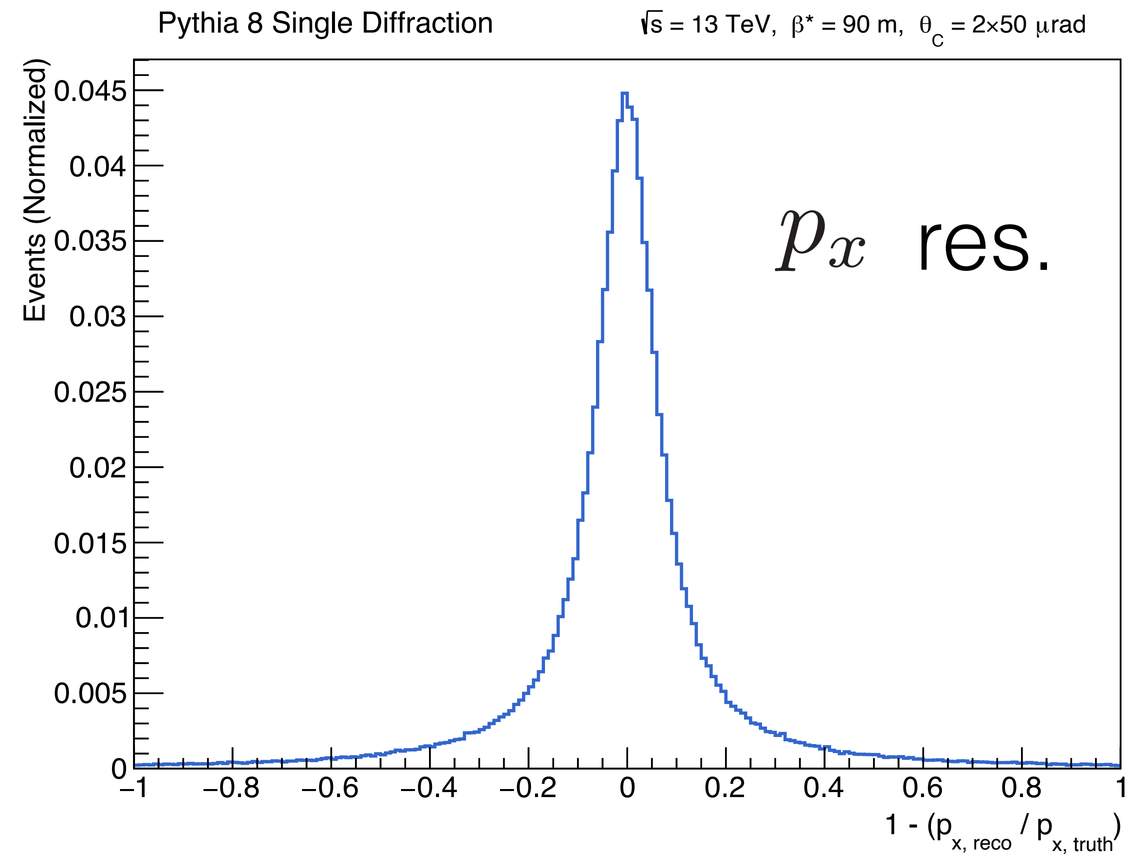
$\theta_C = 0\ \mu\text{rad}$ **Simulation** $\theta_C = 2 \times 50\ \mu\text{rad}$

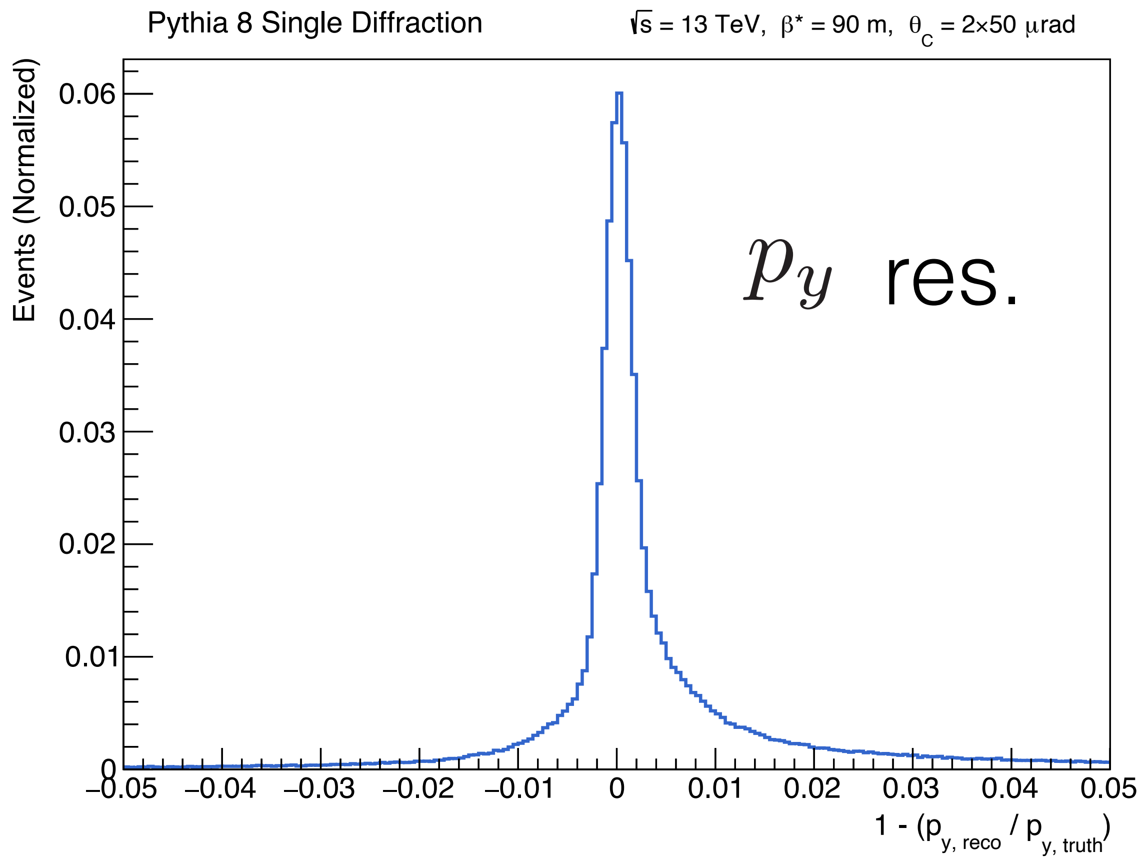




Reconstruction of the Proton Kinematics - Resolution



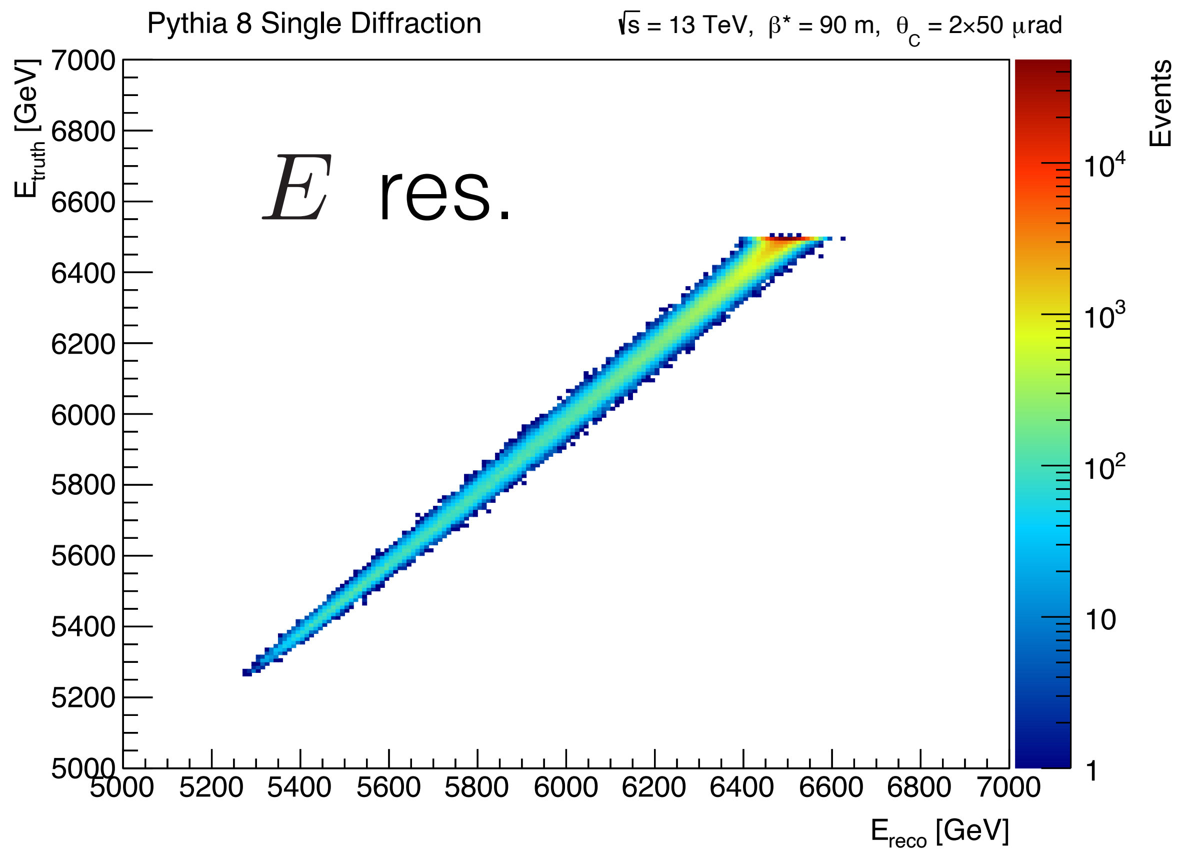


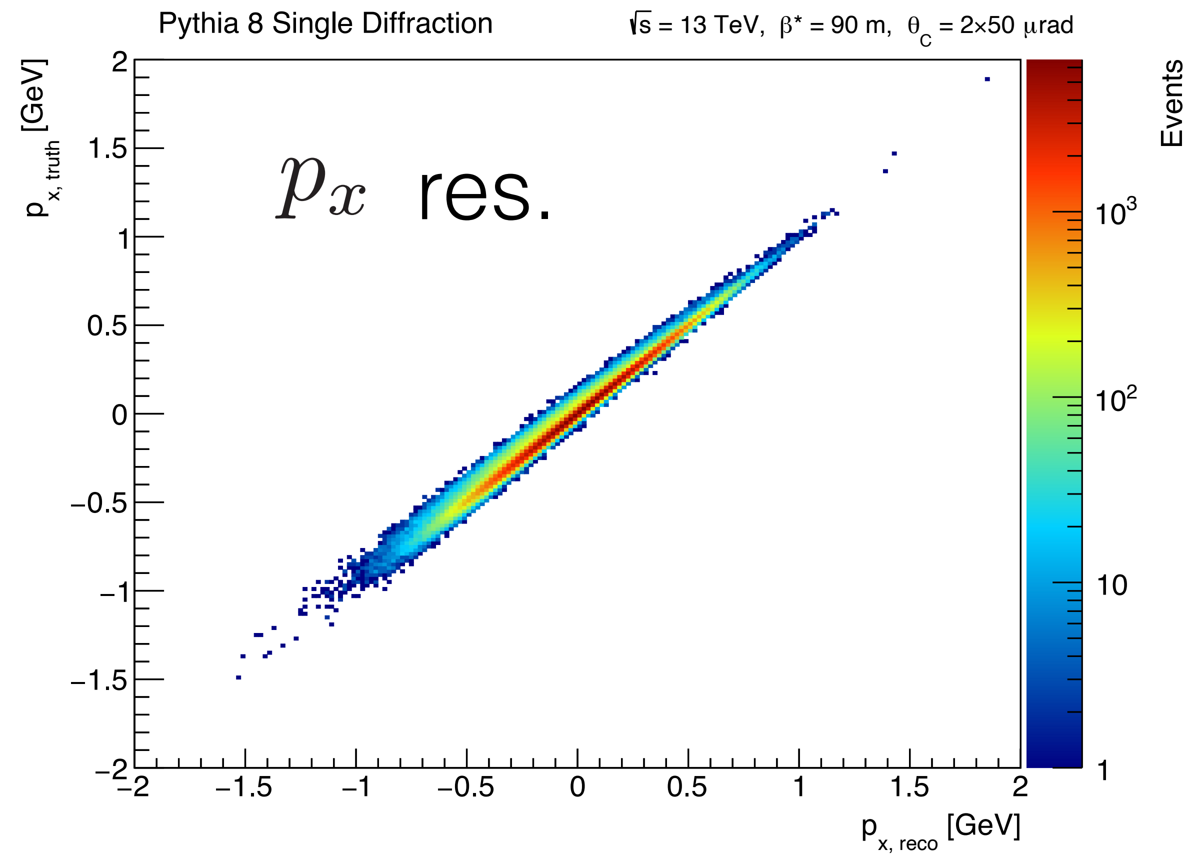


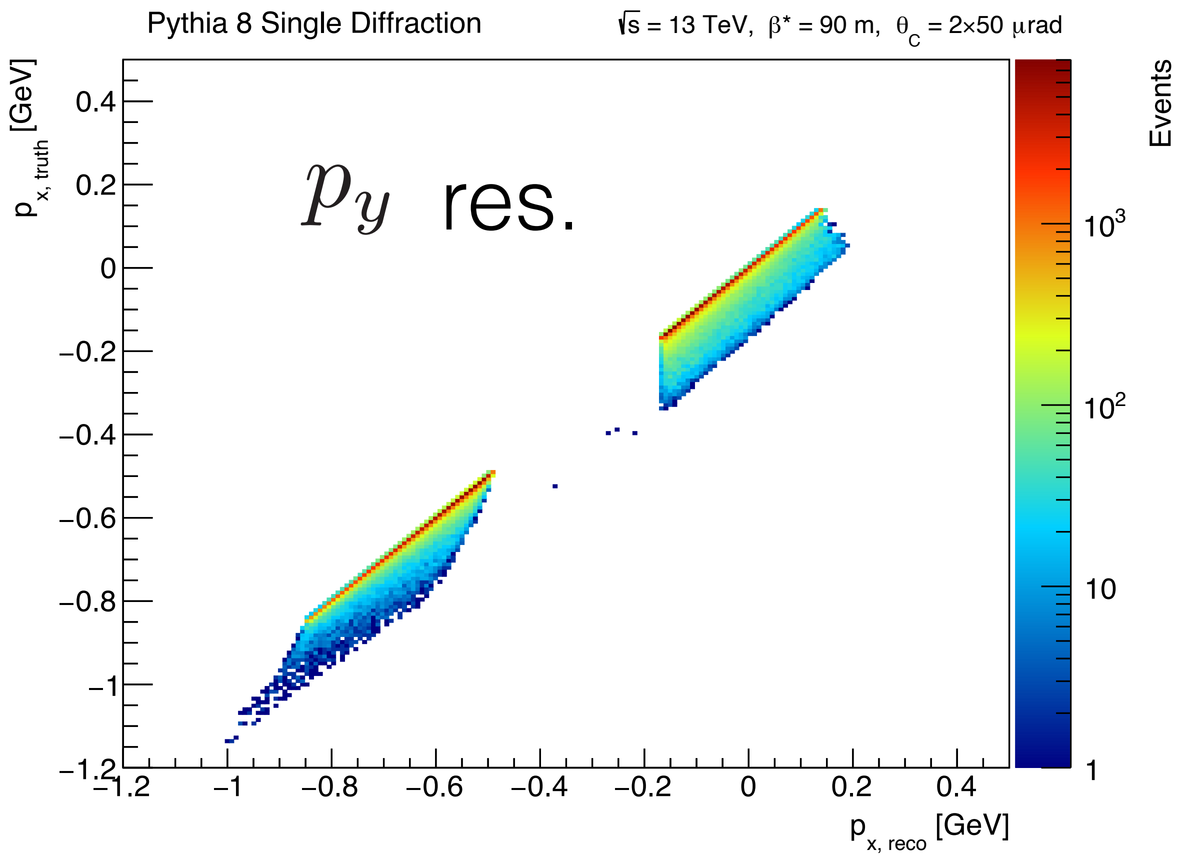
Resolution from Simulations

Reasonable
but room for improvement

Reconstruction of the Proton Kinematics - Resolution





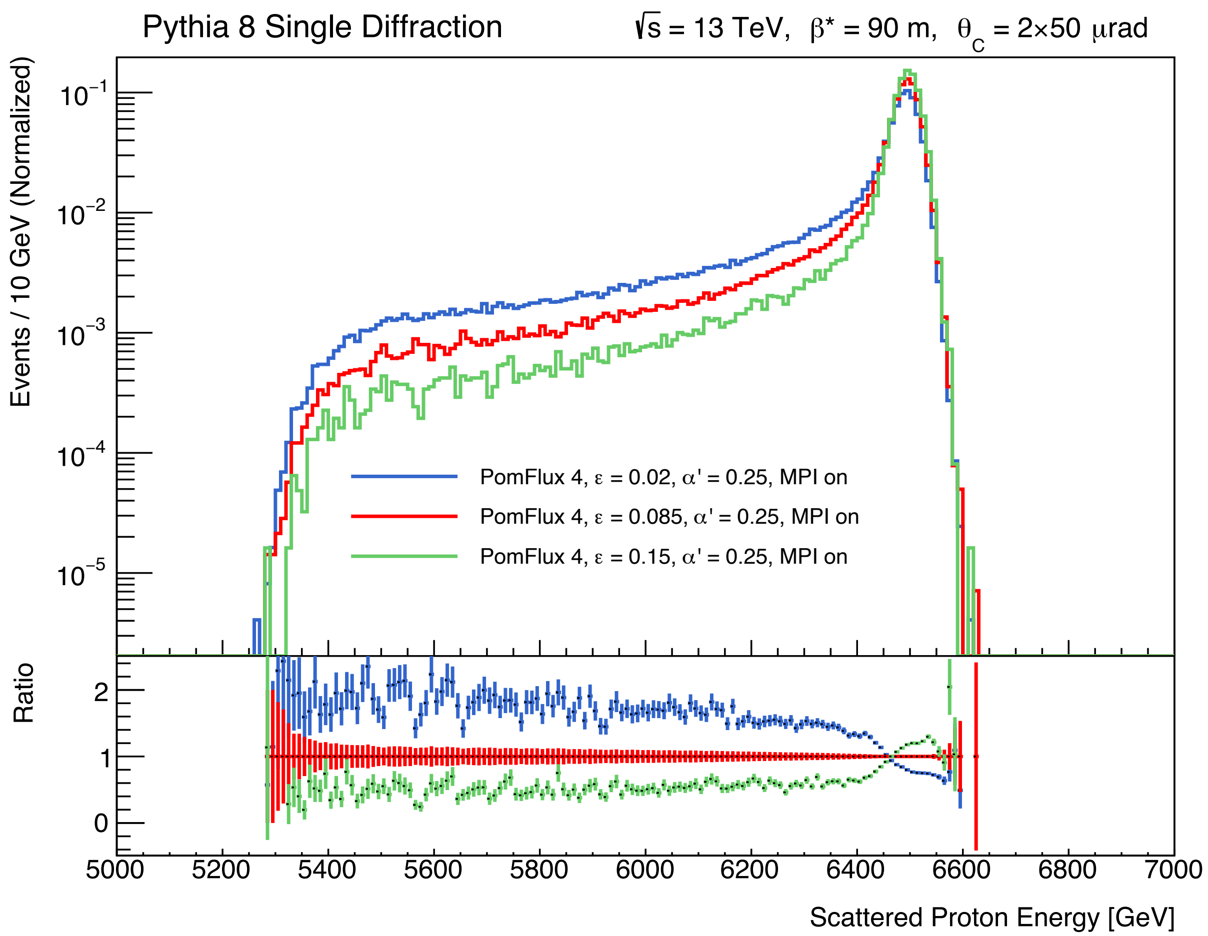


Cuts on quality of fit from ALFAReco is considered

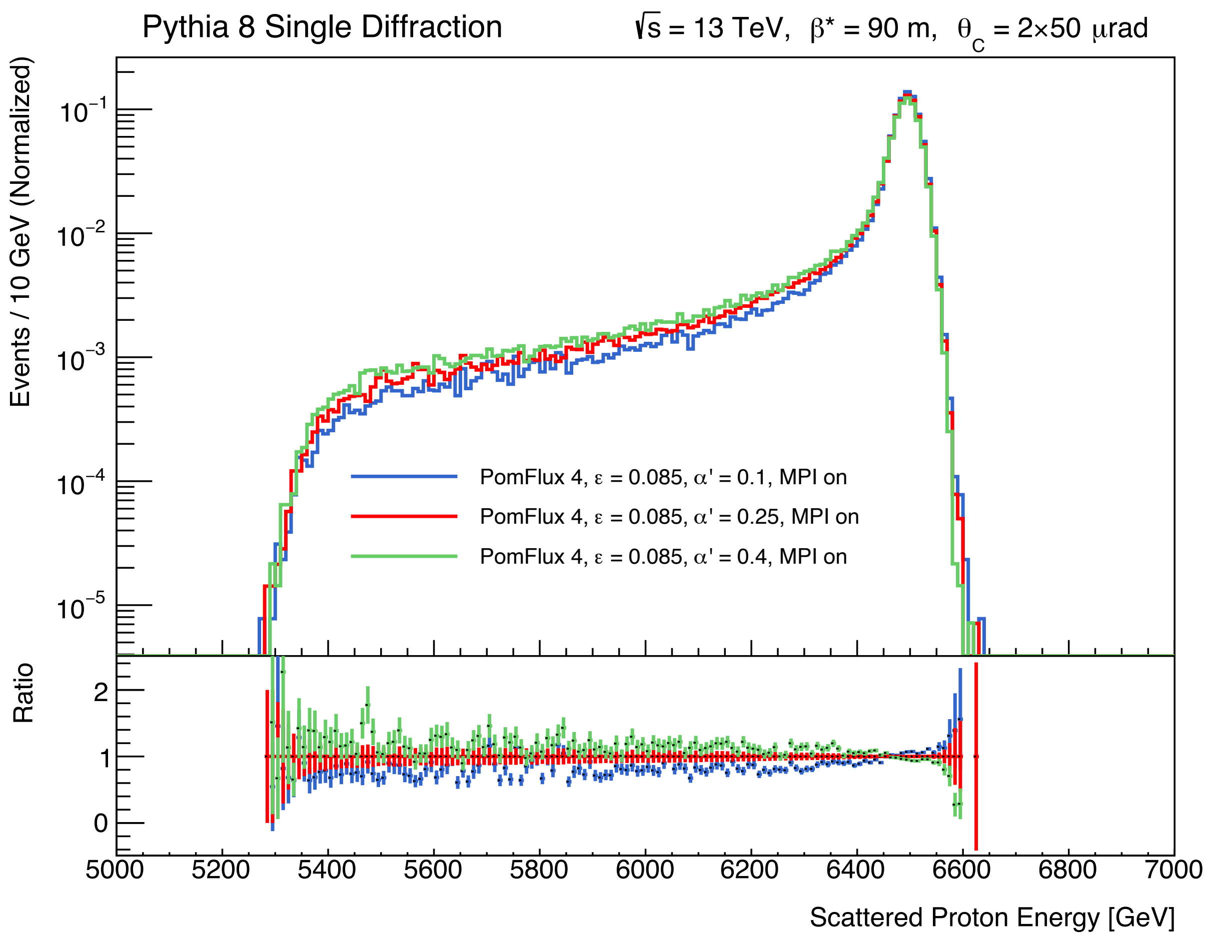
$$1 - \mathrm{Prob}(\chi^2, \mathrm{NDF}) < 68.27\%$$

Energy of Scattered Proton

Varying ε

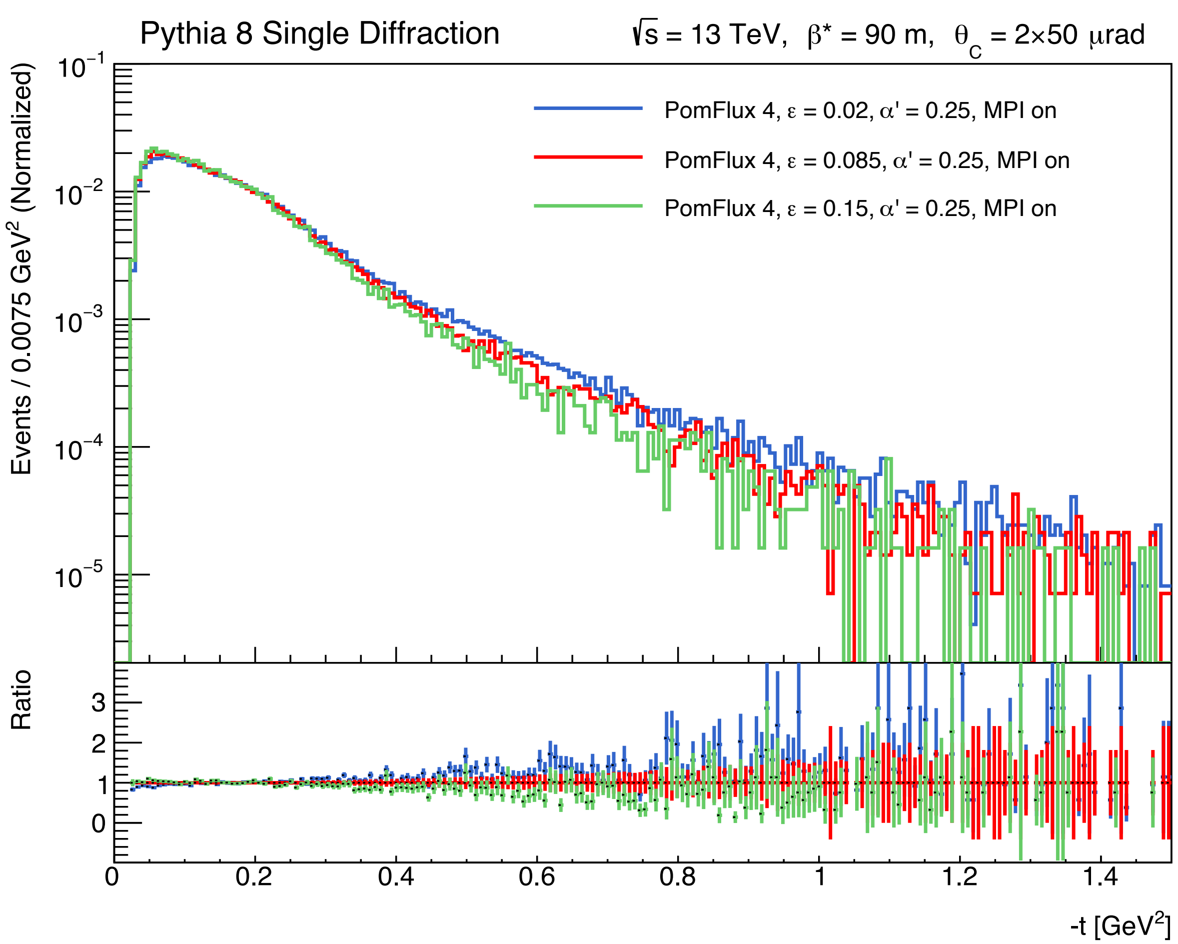


Varying α'

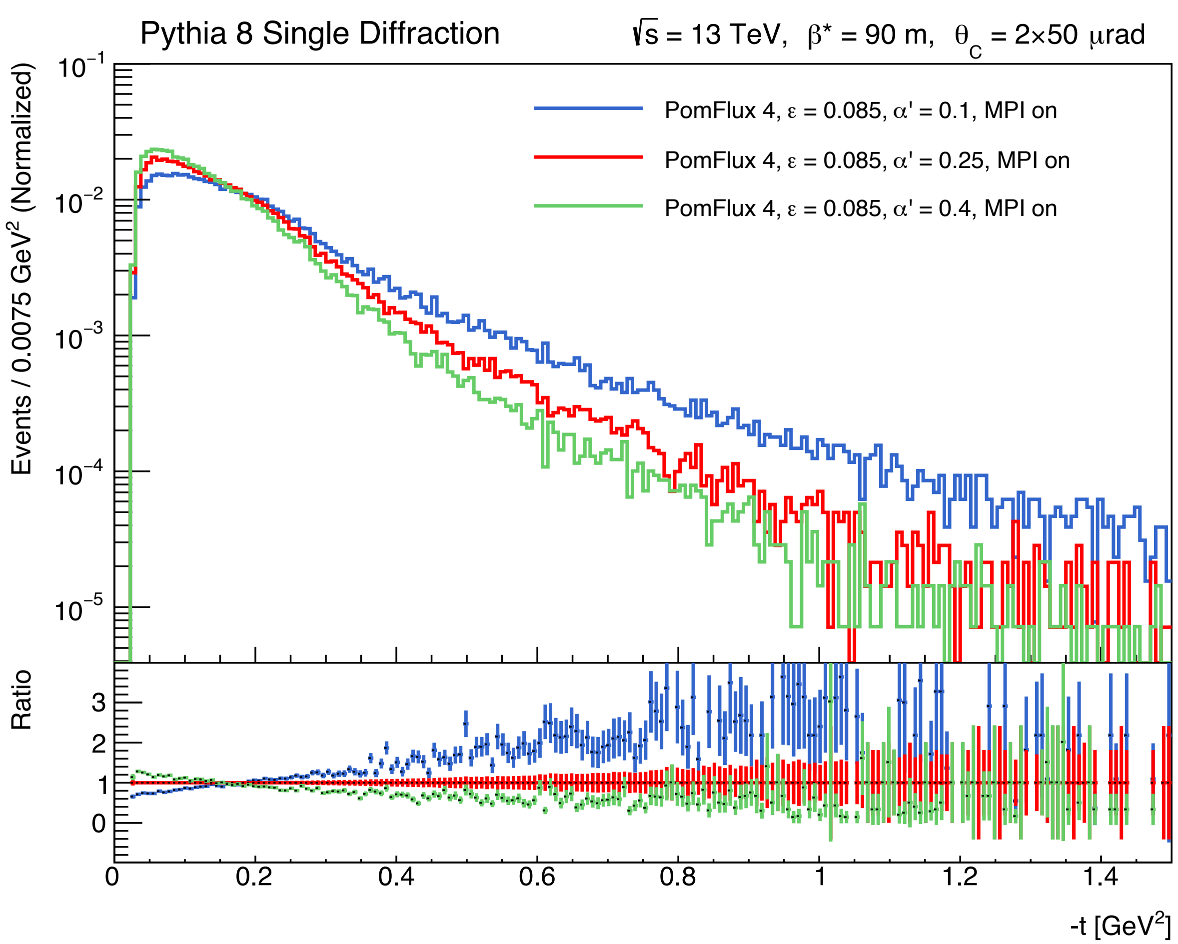


Squared Momentum Transfer (Mandelstam) -t

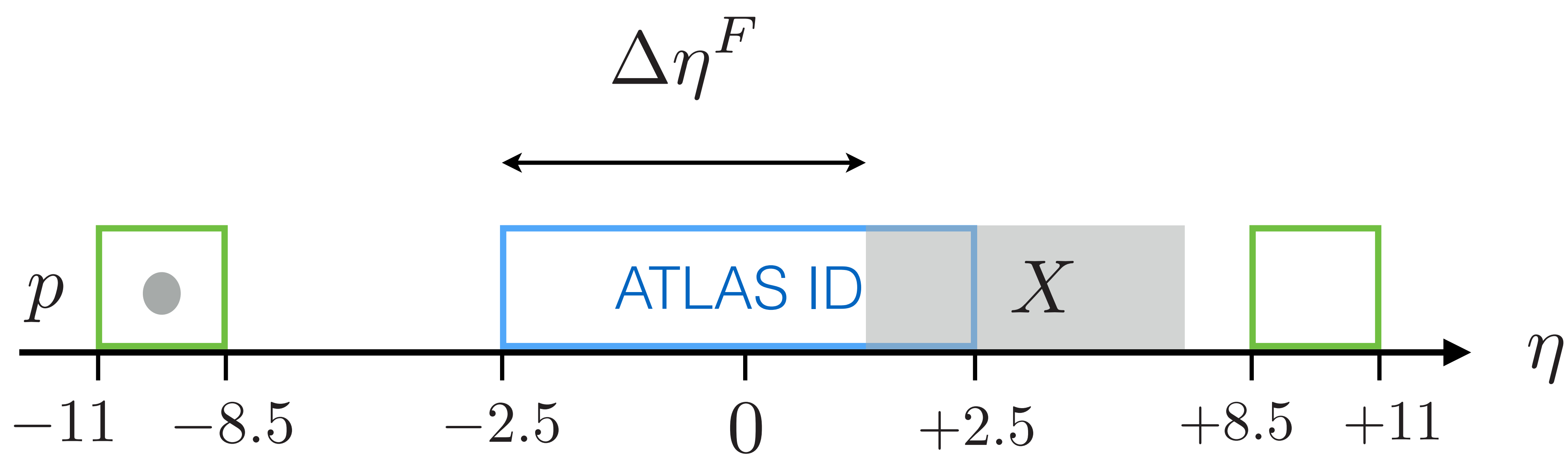
Varying ε



Varying α'



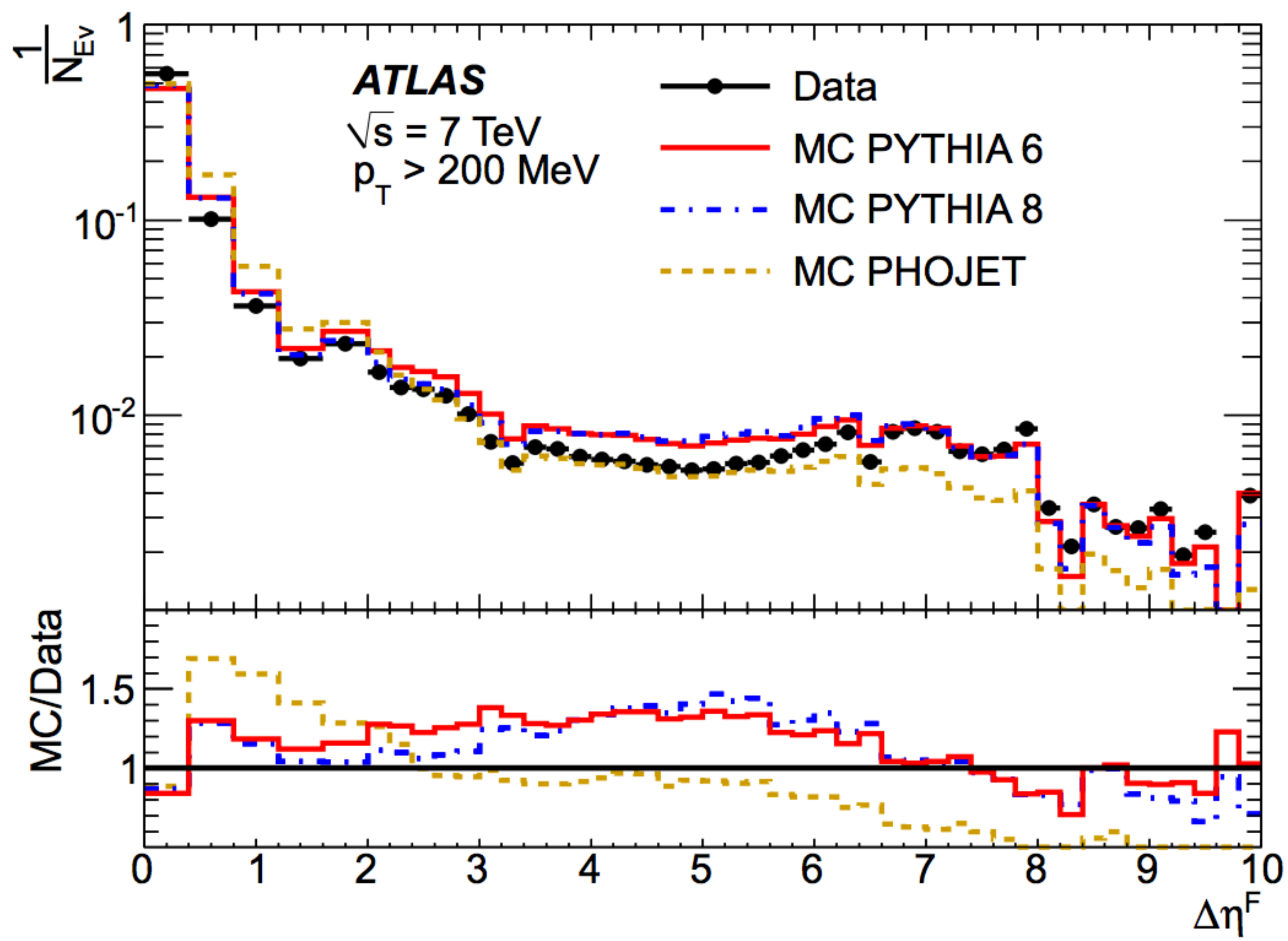
Pseudorapidity Gap in Inner Detector (Tracker)



From paper:

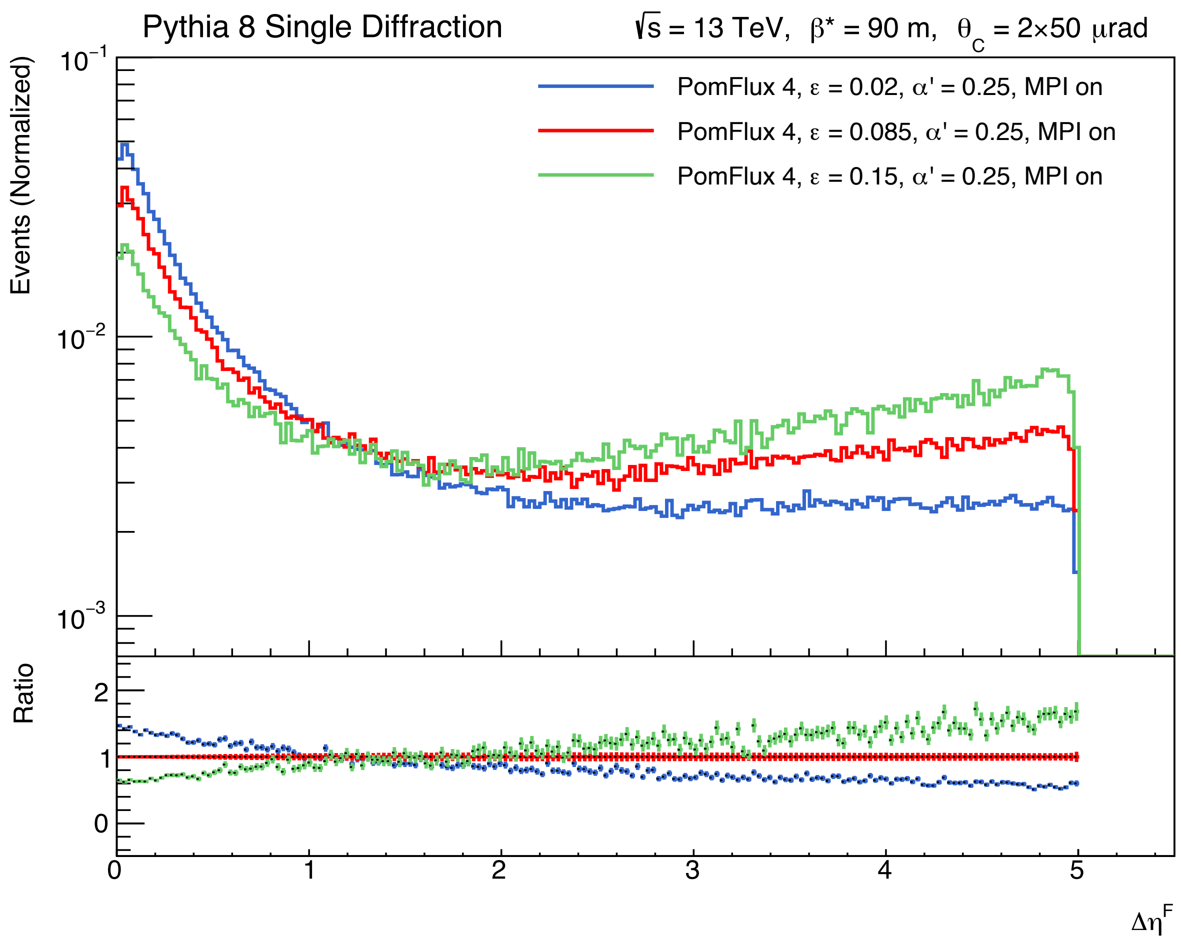
"Rapidity Gap Cross Sections measured with the ATLAS Detector in pp Collisions at $\sqrt{s} = 7$ TeV"

by the ATLAS Collaboration (2012)
arXiv:1201.2808v2 [hep-ex]

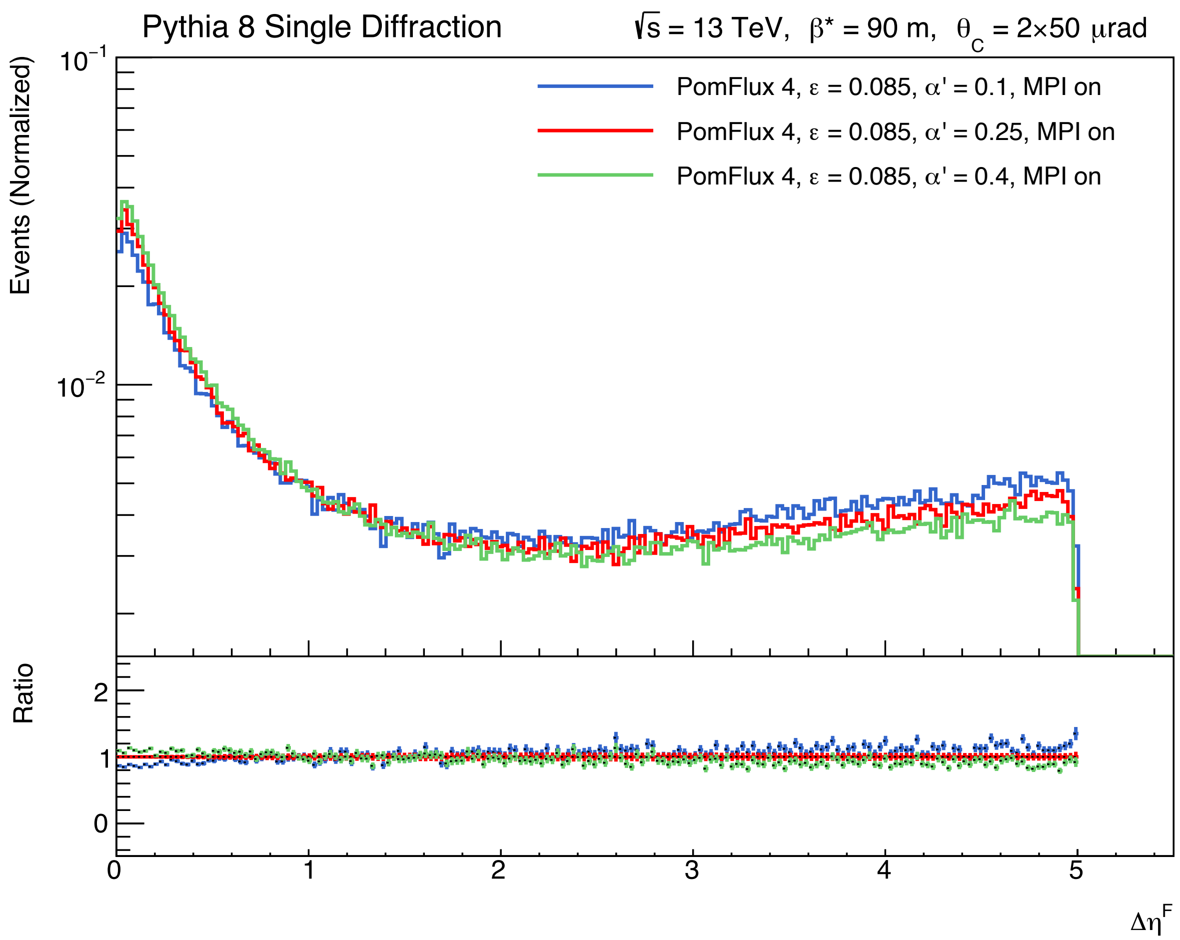


Pseudorapidity Gap in Inner Detector (Tracker)

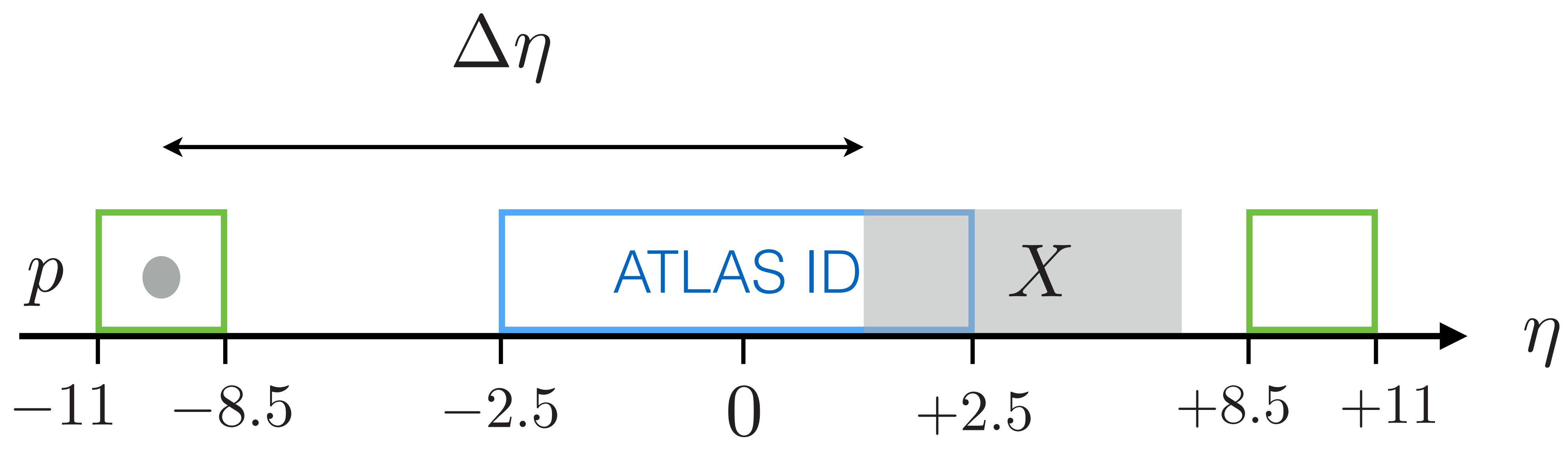
Varying ε



Varying α'

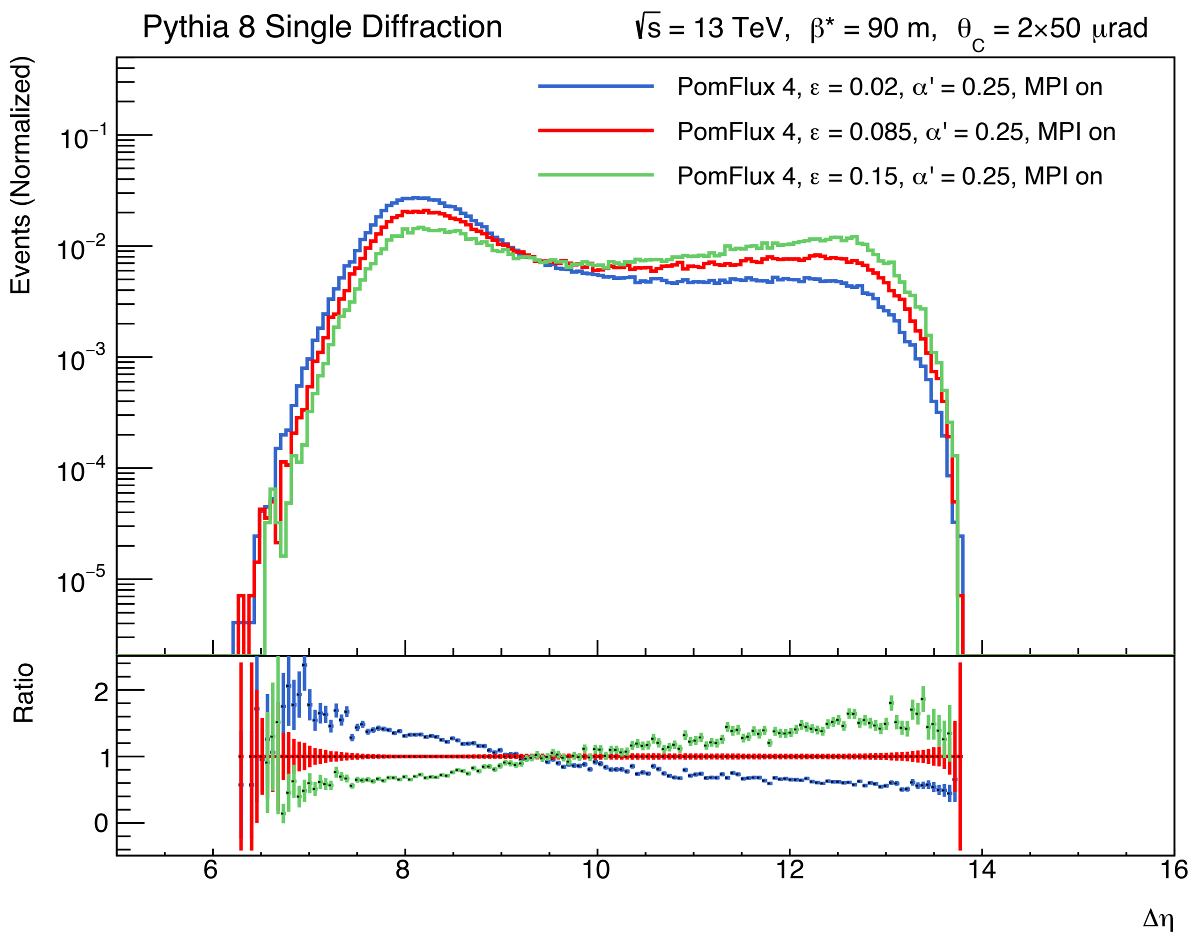


Pseudorapidity Gap using both ALFA and ID

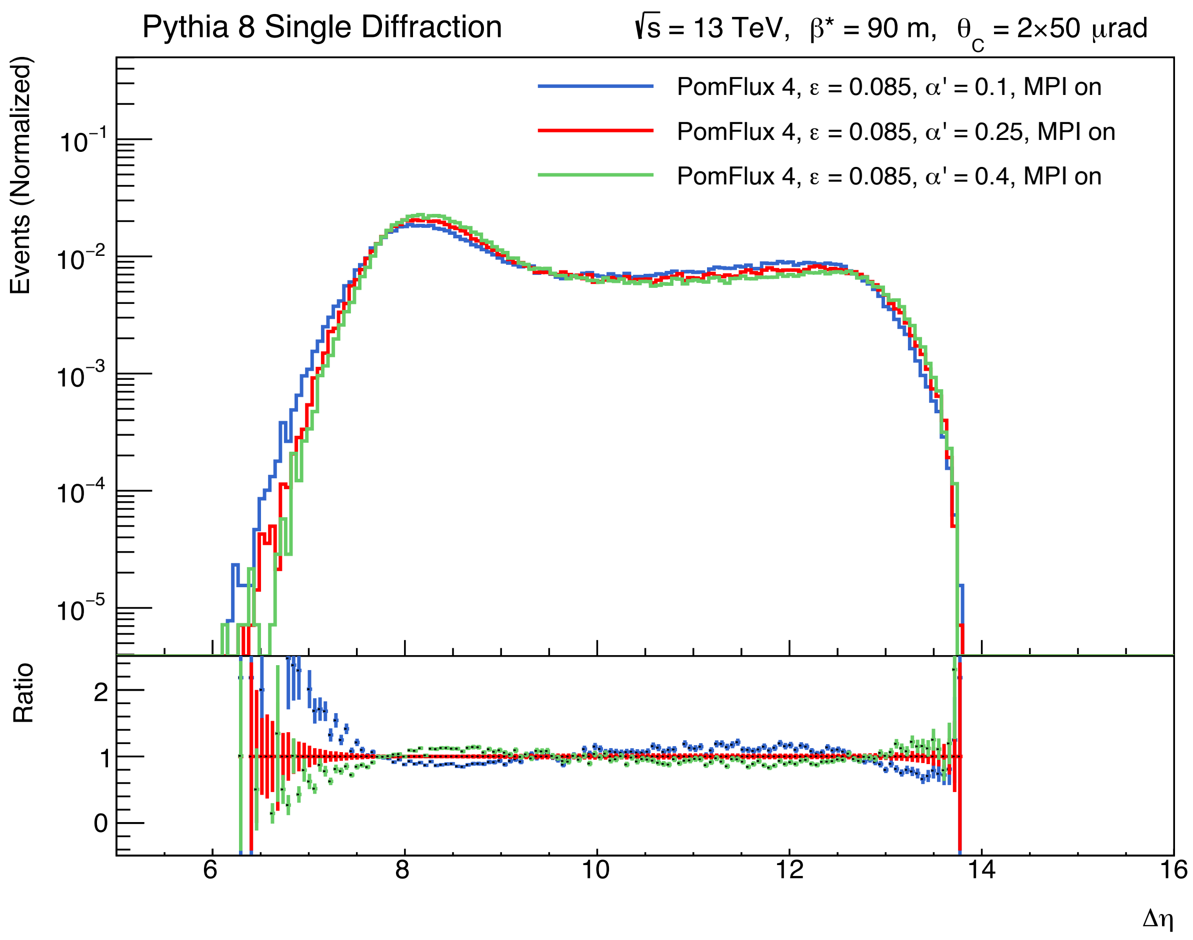


Pseudorapidity Gap using both ALFA and ID

Varying ε



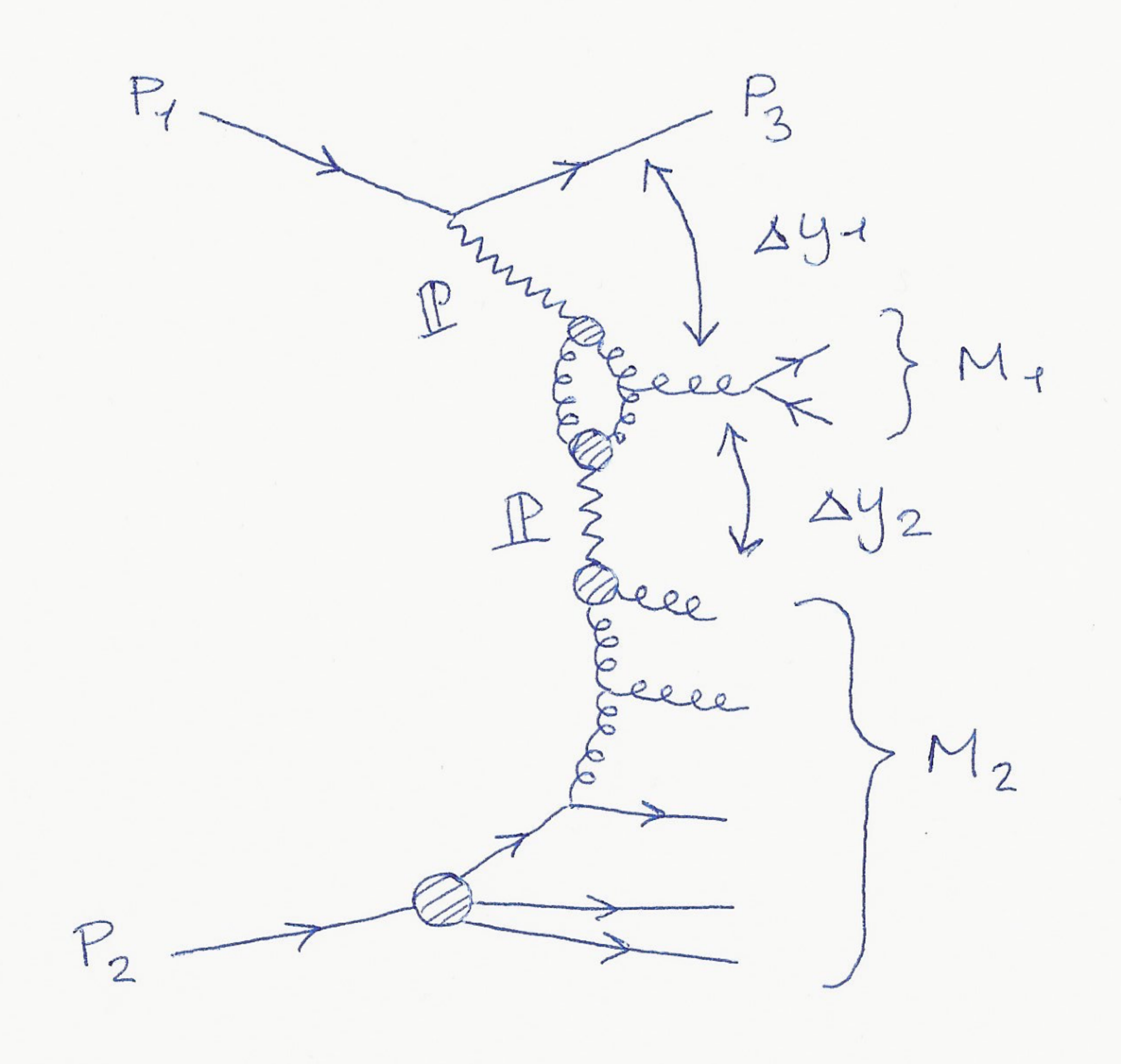
Varying α'



Work in Progress

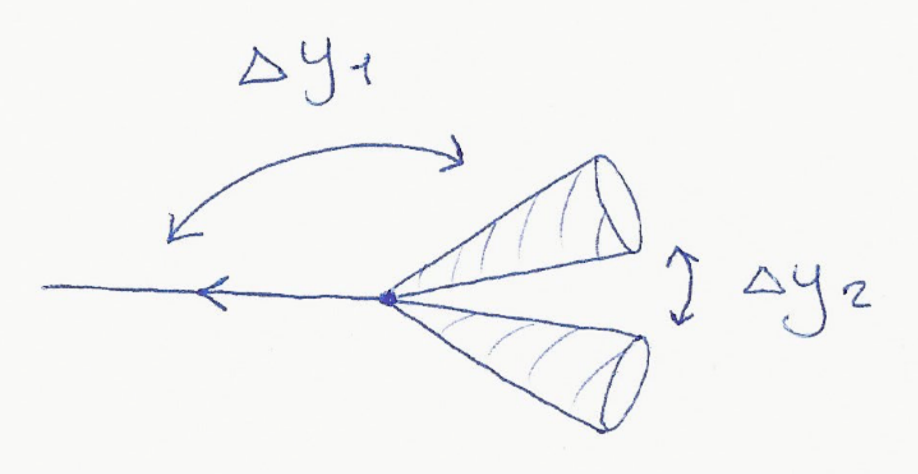
- Looked at observables sensitive to model parameters
- Compare data to simulation
- Understand background
- Add new Distributions and Analysis (!)

Single Diffraction with a Second Rapidity Gap



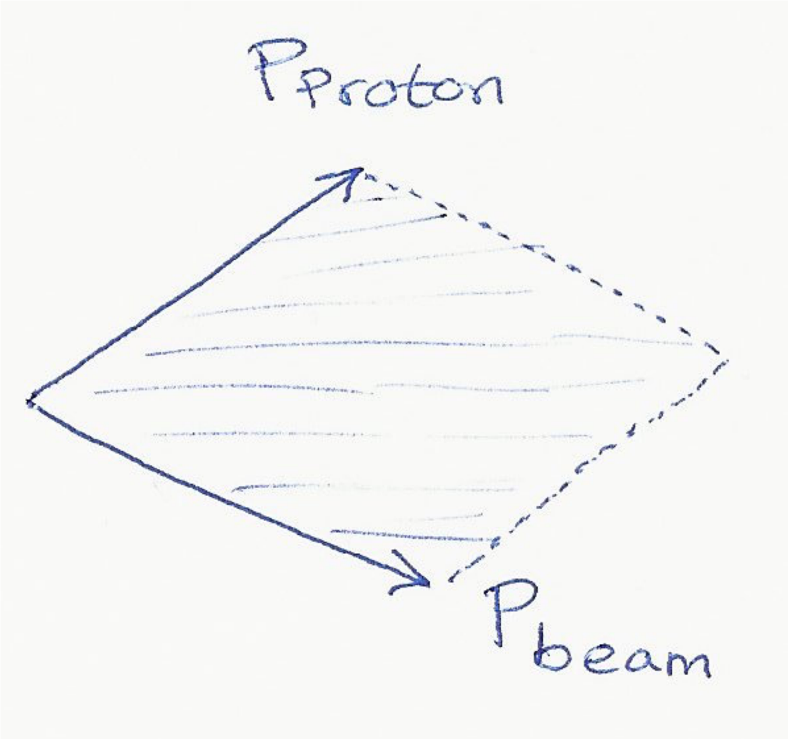
Two-gap process
in pp single diffraction:

Double-Pomeron exchange with a leading surviving proton and a rapidity gap within the rapidity space allocated to the dissociated system



Plans

The scattered proton and the beam direction extends a plane



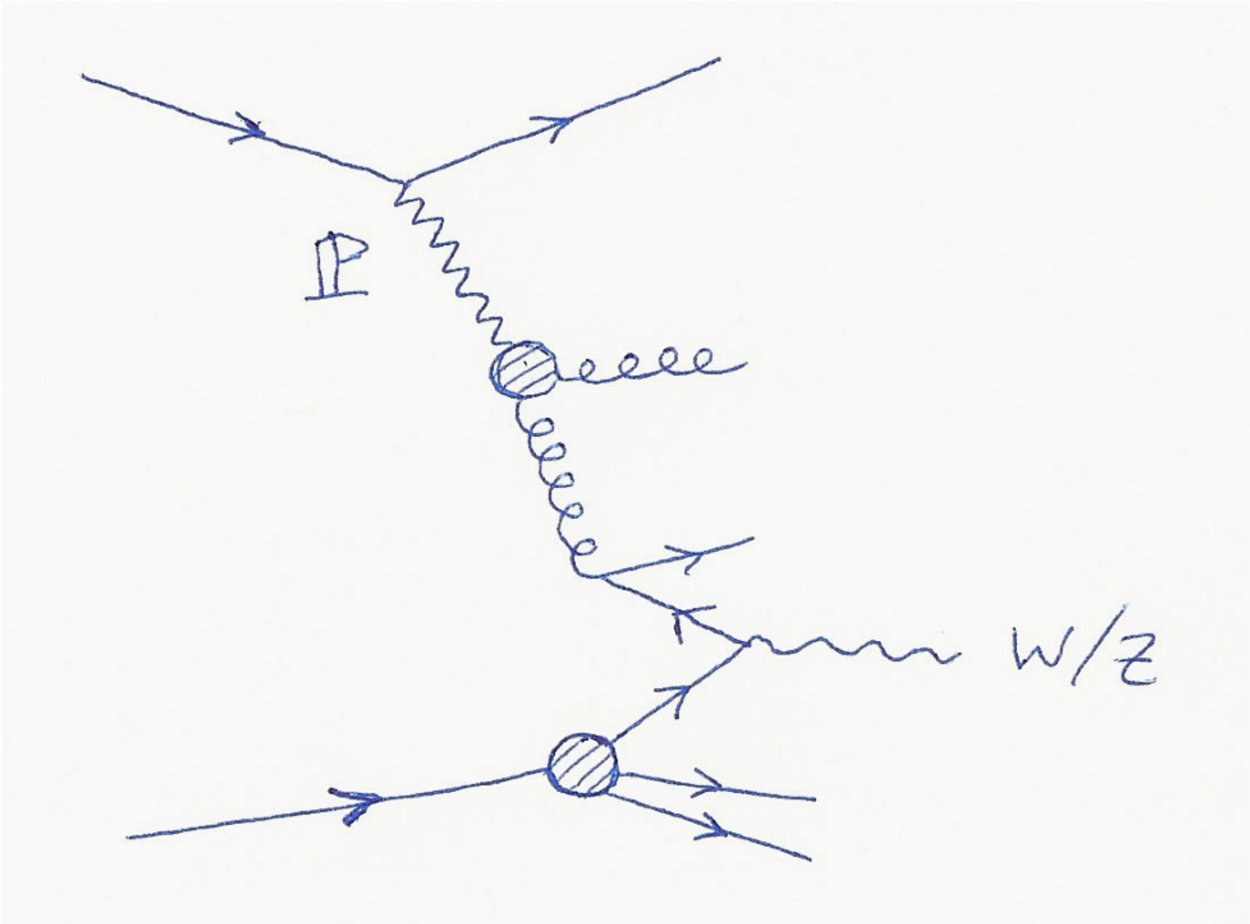
Consider 2D Sphericity and Thrust in this plane

$$S^{ab} = \frac{\sum_i \frac{p_i^a p_i^b}{|\mathbf{p}_i|}}{\sum_i |\mathbf{p}_i|}$$

$$a, b \in \{x, y, z\}$$

But will be dominated by the extremely high pz of the scattered proton - set pz = 0?

W and Z production in the dissociated proton



Sign of partonic substructure of the Pomeron

$$qq \rightarrow W^{\pm}/Z^{0}$$

Consider leptonic decay:

$$W \rightarrow \ell\nu_{\ell}$$

$$Z \rightarrow \ell^{+}\ell^{-}$$

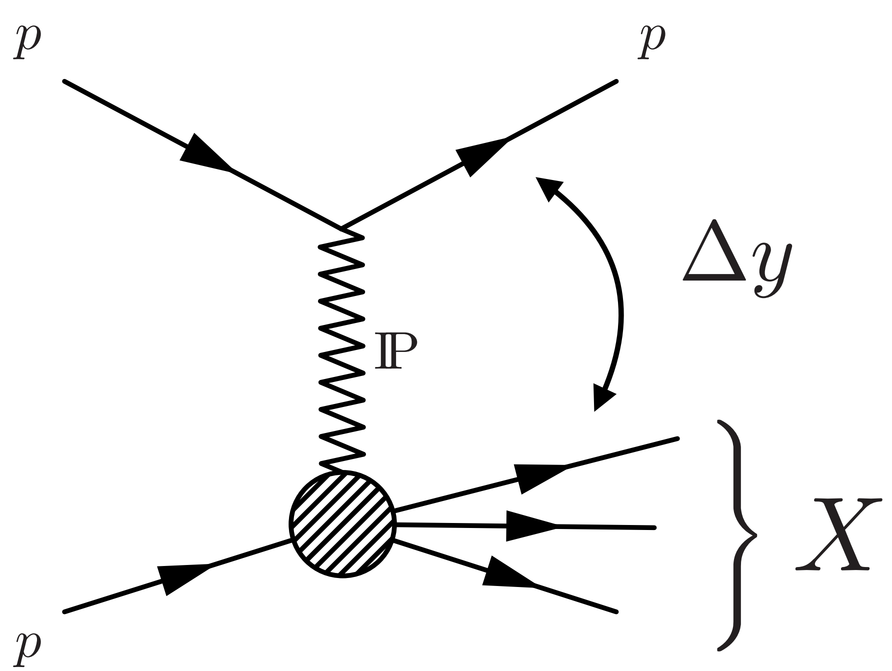
$$e, \mu : p_T > \ ? \ \mathrm{GeV}$$

$$\nu : \ \text{missing } E_T$$

Thank you for listening!

Back-Up Slides

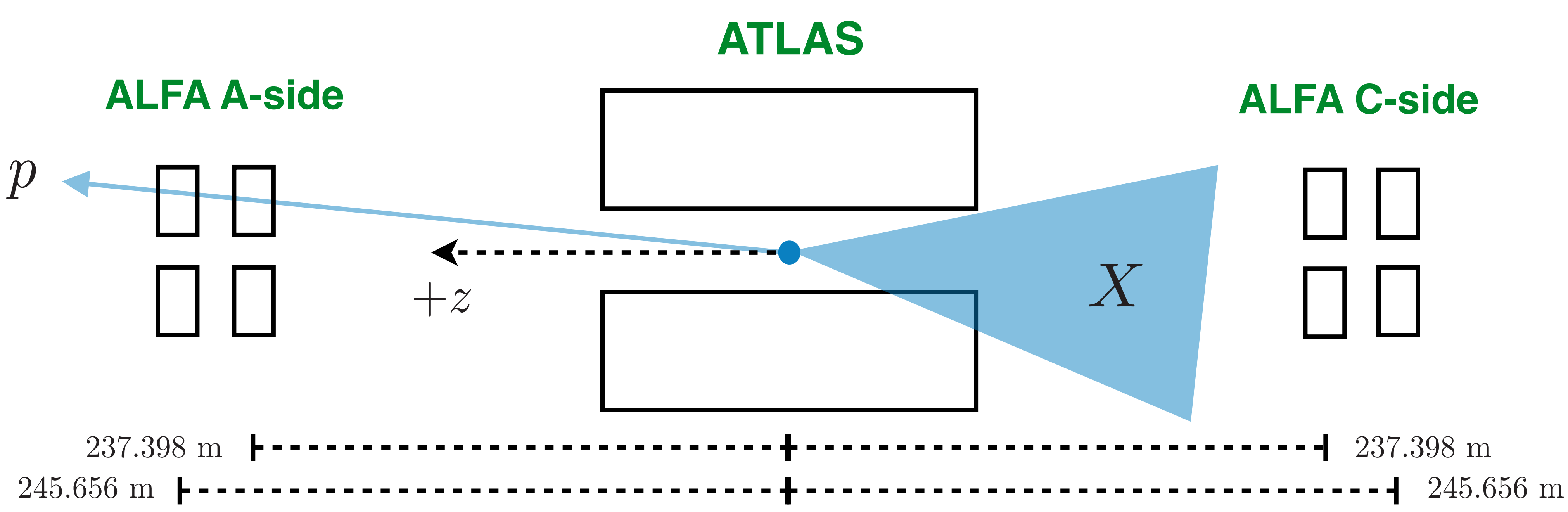
A Study of Single Diffraction with ATLAS and ALFA



Detect surviving proton with ALFA

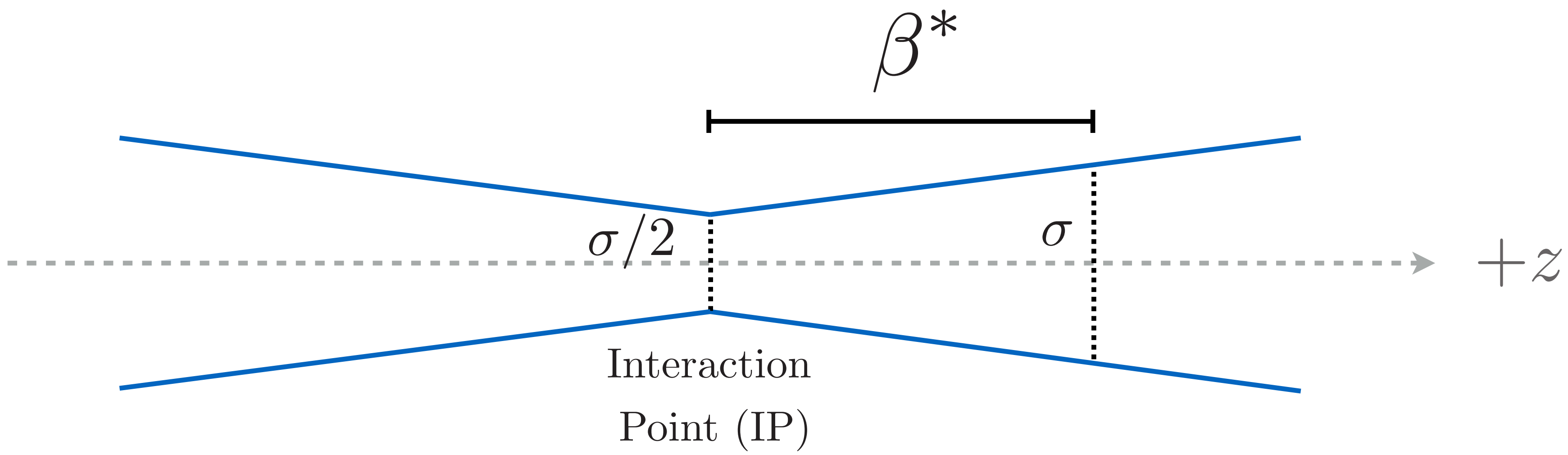
Detect the diffractive system X with ATLAS

First part is a phenomenological study of simulations with Pythia 8, second part is looking at 13 TeV data



β^* : value of the β-function at the interaction point (IP)

LHC magnets can be tuned to a different β^*



Normally, low optics → small beams → large luminosity

The optics for the data used in this study is $\beta^* = 90\ \mathrm{m}$

Large optics → large beams
but small angles of beam protons

Problems with Data

Up until November 2016, there were some problems with the mapping in the DxAODs for the Diffractive Runs

Fixed and reprocessed
on November 10, 2016

But now we have new problems! ☹

Reprocessing used wrong settings for reconstruction of the primary vertex

PV important! - No data results shown today

Generated Pythia 8 Samples

38 HepMC files in total - each with 1M events

Single Diffraction (both with MPI and without in the dissociated system)

PomFlux 1 = Schuler - Sjöstrand

PomFlux 4 = Donnachie - Landshoff

PomFlux 5 = Minimum Bias Rockefeller (MBR)

Scanning permutations of:

$\varepsilon \in \{0.02, 0.085, 0.15\}$ and $\alpha' \in \{0.1, 0.25, 0.4\}$

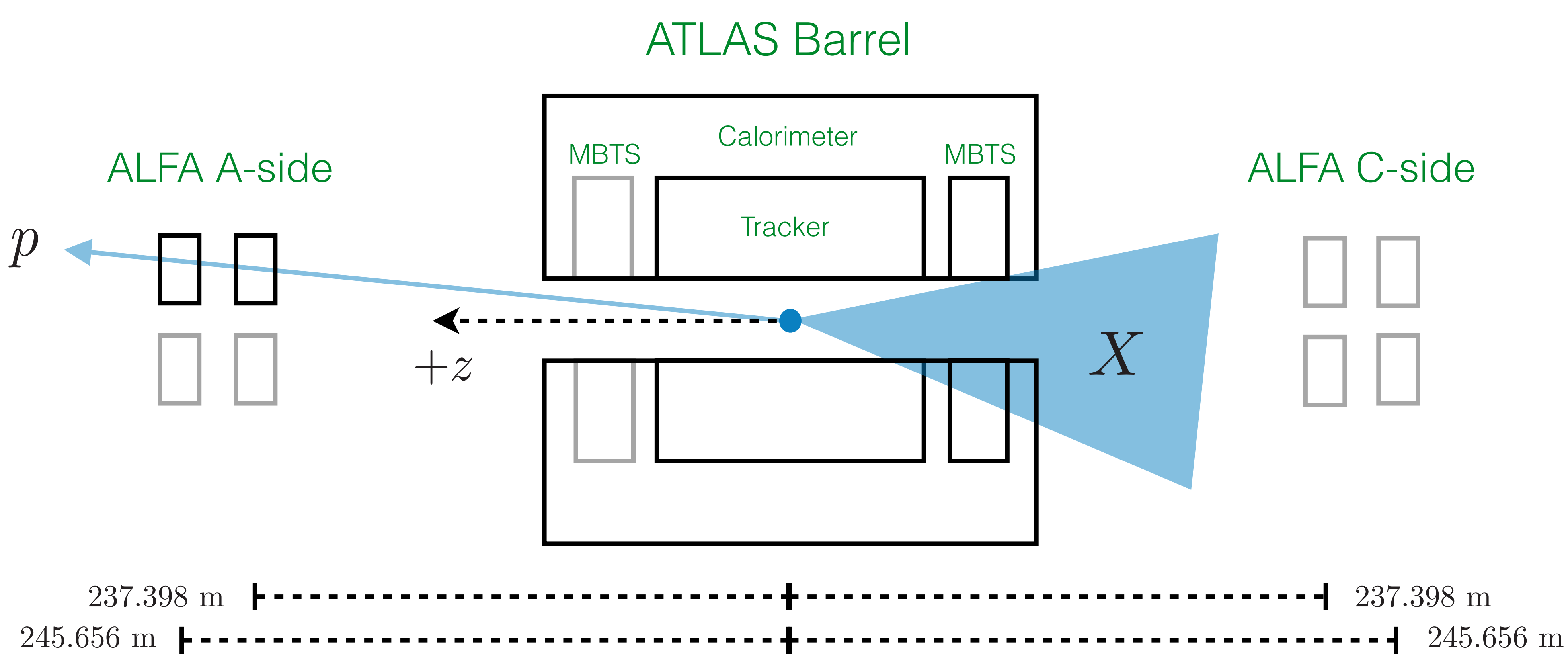
For: $\alpha(t) = 1 + \varepsilon + \alpha' t$

SD Event Selection

- One reconstructed track in each of the two ALFA stations in exactly one of the four arms (other arms are empty)
- Exactly one primary vertex
- At least one ID track passing track selection:

$$p_T > 100 \text{ MeV} \quad \text{and} \quad |\eta| < 2.5$$

- Signal in inner MBTS ring on opposite side to ALFA signal



Simulation of Background

Sources of background:

- **Elastic events** with one proton hitting ALFA and the other missing **+ pile-up** min. bias event with tracks in ATLAS (Should be very small, < 1%)
- **Non-diffractive events**, with a proton/pion hitting ALFA Exponentially suppressed rapidity gaps
- **Central-diffractive events**, with one proton hitting ALFA and the other missing
- **Double-diffractive events**, with a proton/pion hitting ALFA

Simulation of Background

More sources of background:

- **Beam-gas interaction**: proton from beam-gas interaction detected in ALFA along with event in ID
- **Beam halo**: interaction between beam and collimators upstream. Can give charged particles parallel to beam

Looking at single beam events (unpaired bunches) that satisfies SD signature indicates that the contribution is very small ~ 0.4%

- **Afterglow**: signal in ID and MBTS caused by low energy decay products from collision debris (neutrons) either from the actual (in time) collision to the ones before (out of time)
- **Instrumental noise**

In 13 TeV inelastic cross-section analysis out-of-time afterglow and instrumental noise contribution is large when MBTS multiplicity is low

Plans

Estimate SD crossing angle and Fit the t-spectrum

$$\frac{d\sigma}{dt} \sim ae^{-bt}$$

$$\frac{d\sigma}{dt} \sim a_1 e^{-b_1 t} + a_2 e^{-b_2 t}$$

$$\frac{d\sigma}{dt} \sim \left(a_1 e^{-b_1 t} + a_2 e^{-b_2 t}\right) s^{2\alpha(t)-2}$$

Fit the Pomeron Flux

$$\frac{d\sigma^2_{\mathrm{SD}}}{d\xi dt} = f_{\mathbb{P}/p}(\xi, t)\sigma_{\mathbb{P}/p}(M_X^2)$$

$$f_{\mathbb{P}/p}(\xi, t) \sim C\frac{1}{\xi}\left(a_1 e^{-b_1 t} + a_2 e^{-b_2 t}\right) s^{2\alpha(t)-2}$$

LHC and ALFA Acceptance

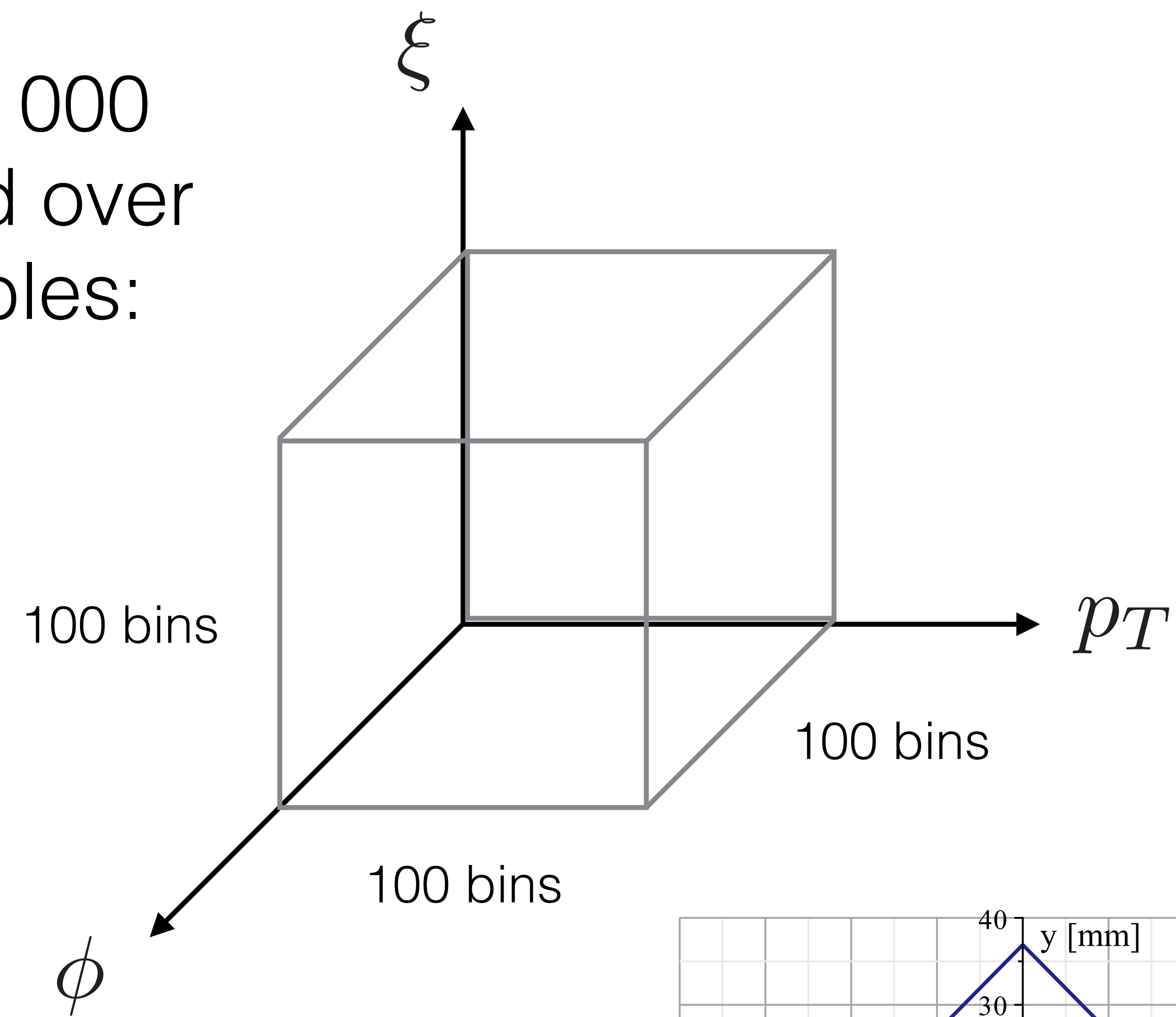
Acceptance Plots can give insight into the physics that can be explored with ALFA as well as cuts on proton kinematics in simulations

Proton kinematics can be described by 3 variables:

- Relative energy loss ξ
- Transverse momentum p_T
- Azimuthal angle ϕ

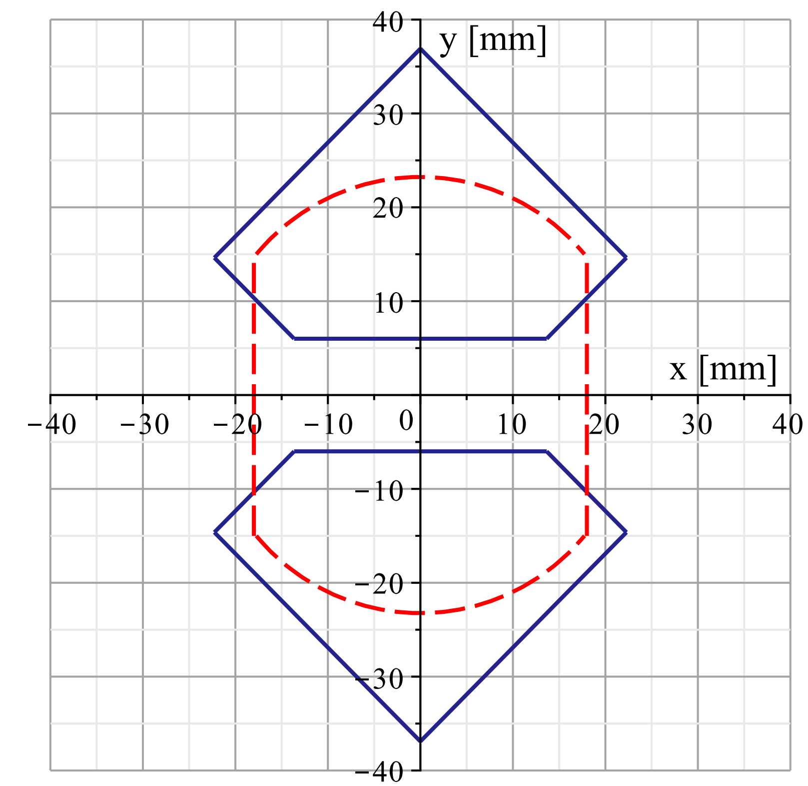
LHC and ALFA Acceptance

We have simulated 1 000 000 protons where we scanned over 100 values of the 3 variables:



We then checked for acceptance:

- LHC acceptance: did the proton survive aperture and reach the ALFA station at 237 m?
- ALFA acceptance: did the proton survive aperture and hit the ALFA station at 237 m? (Includes simulation of ALFA geometry)



LHC and ALFA Acceptance

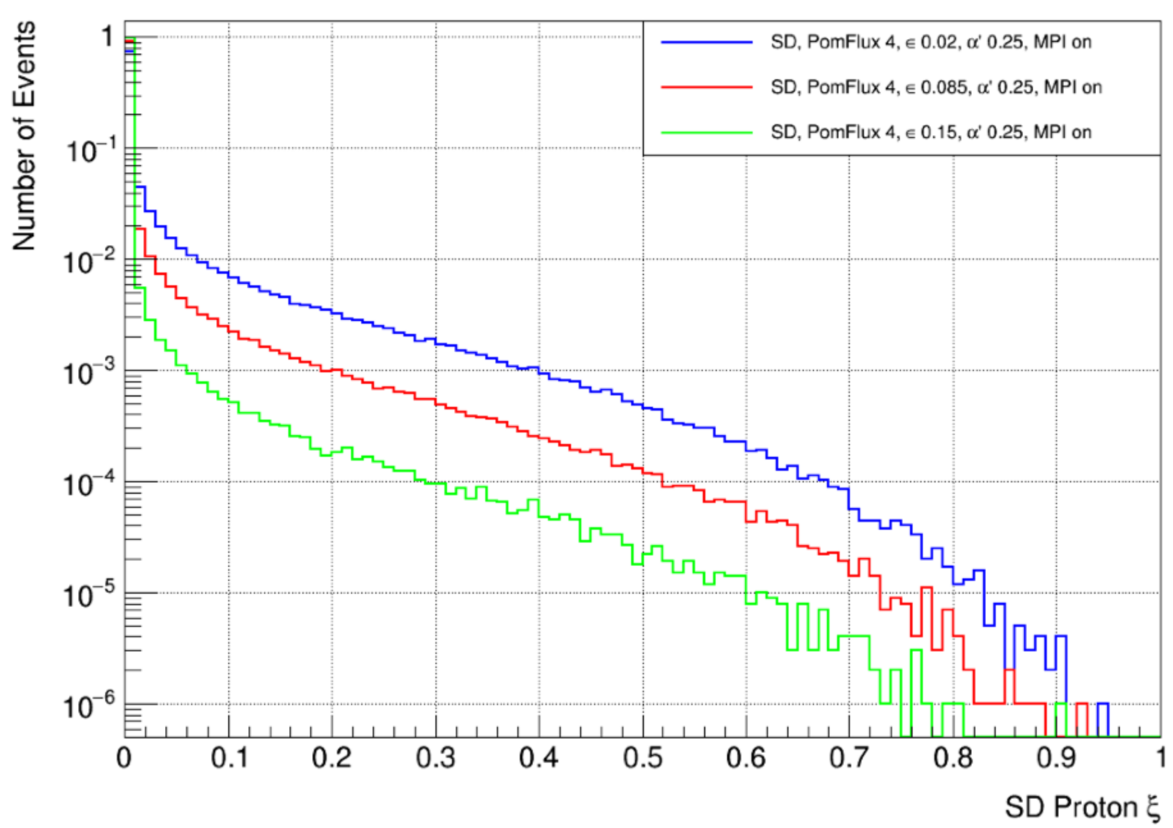
We have assumed flat distributions in the 3 variables

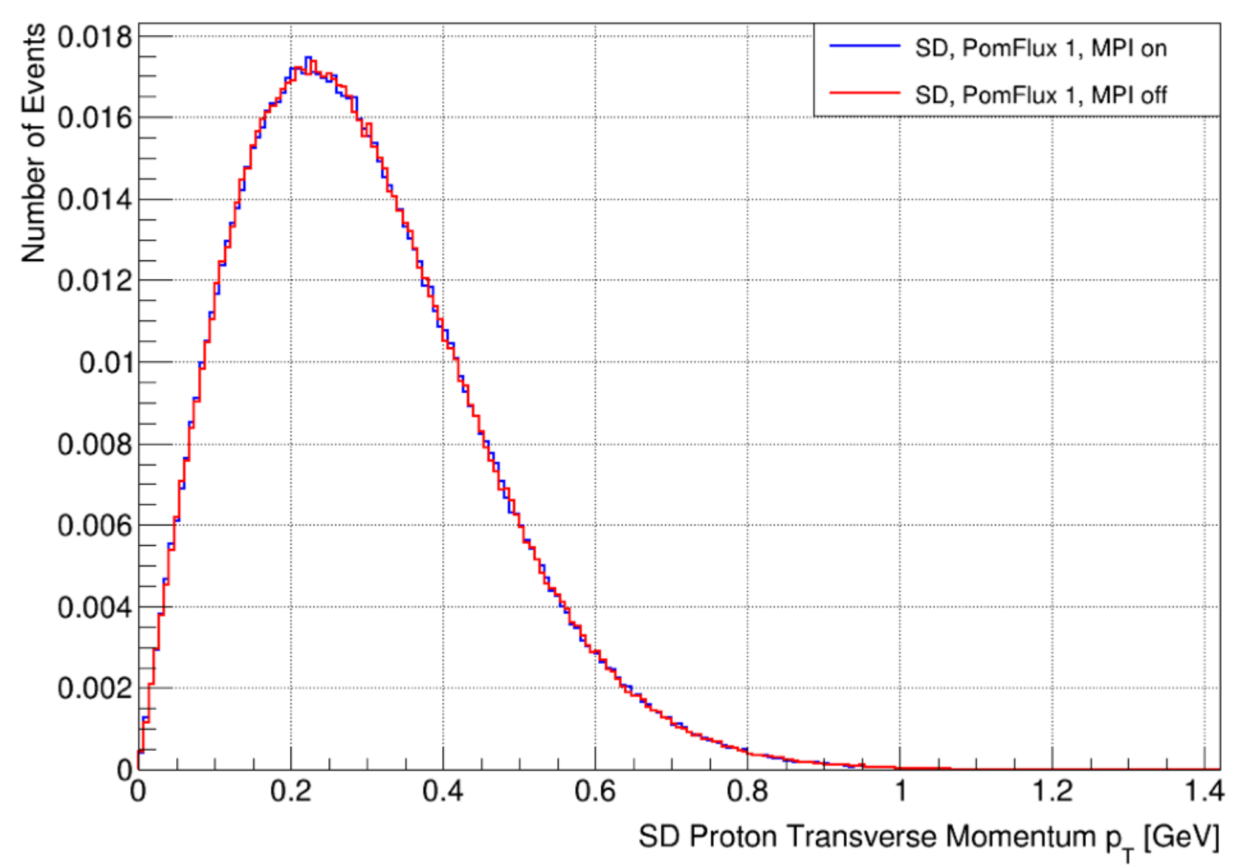
Note however:

A flat distribution in ϕ is expected

But the distribution for ξ and p_T is not expected to be flat

The acceptance plots are therefore independent of the physics



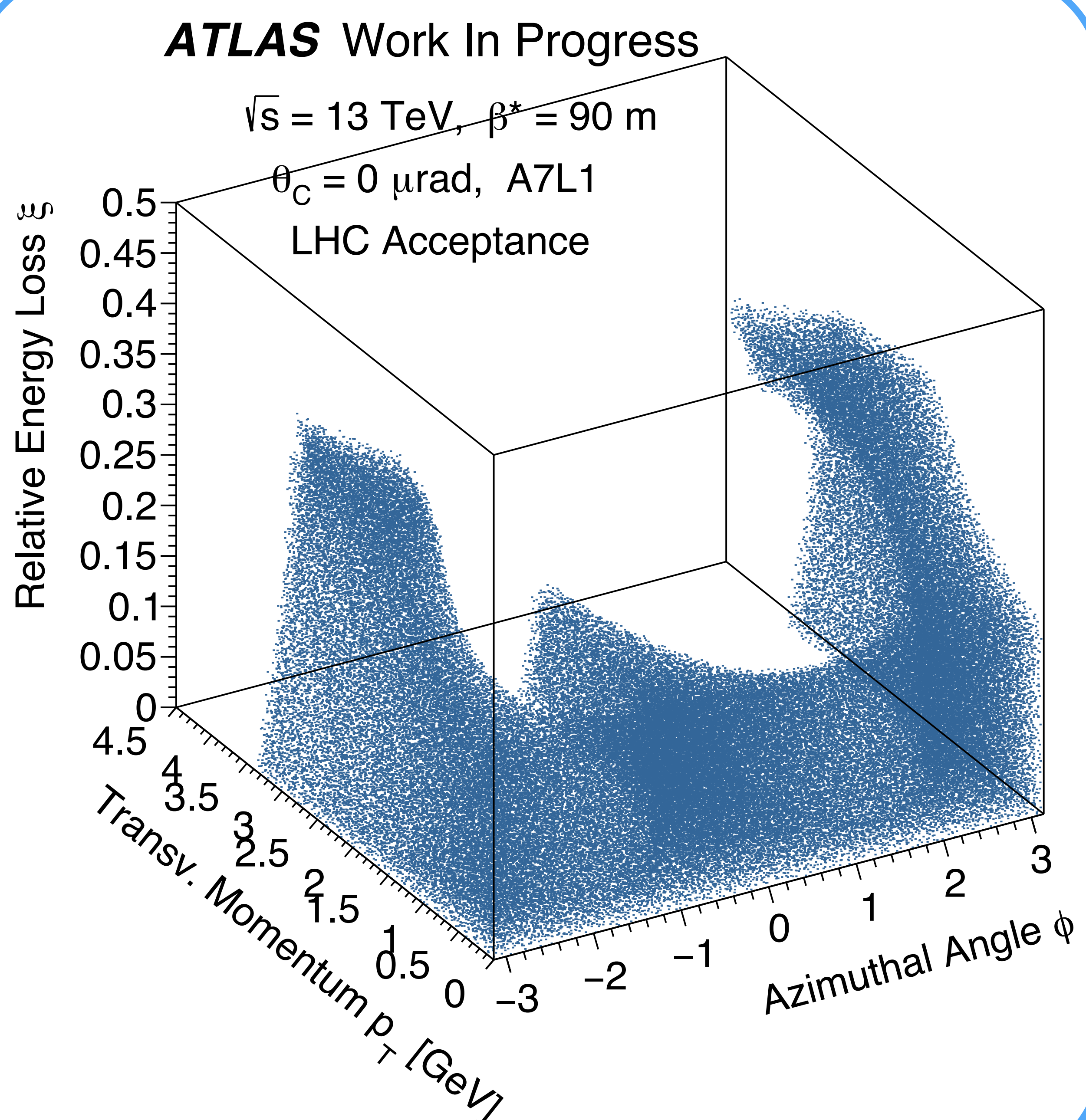


A-side
237 m

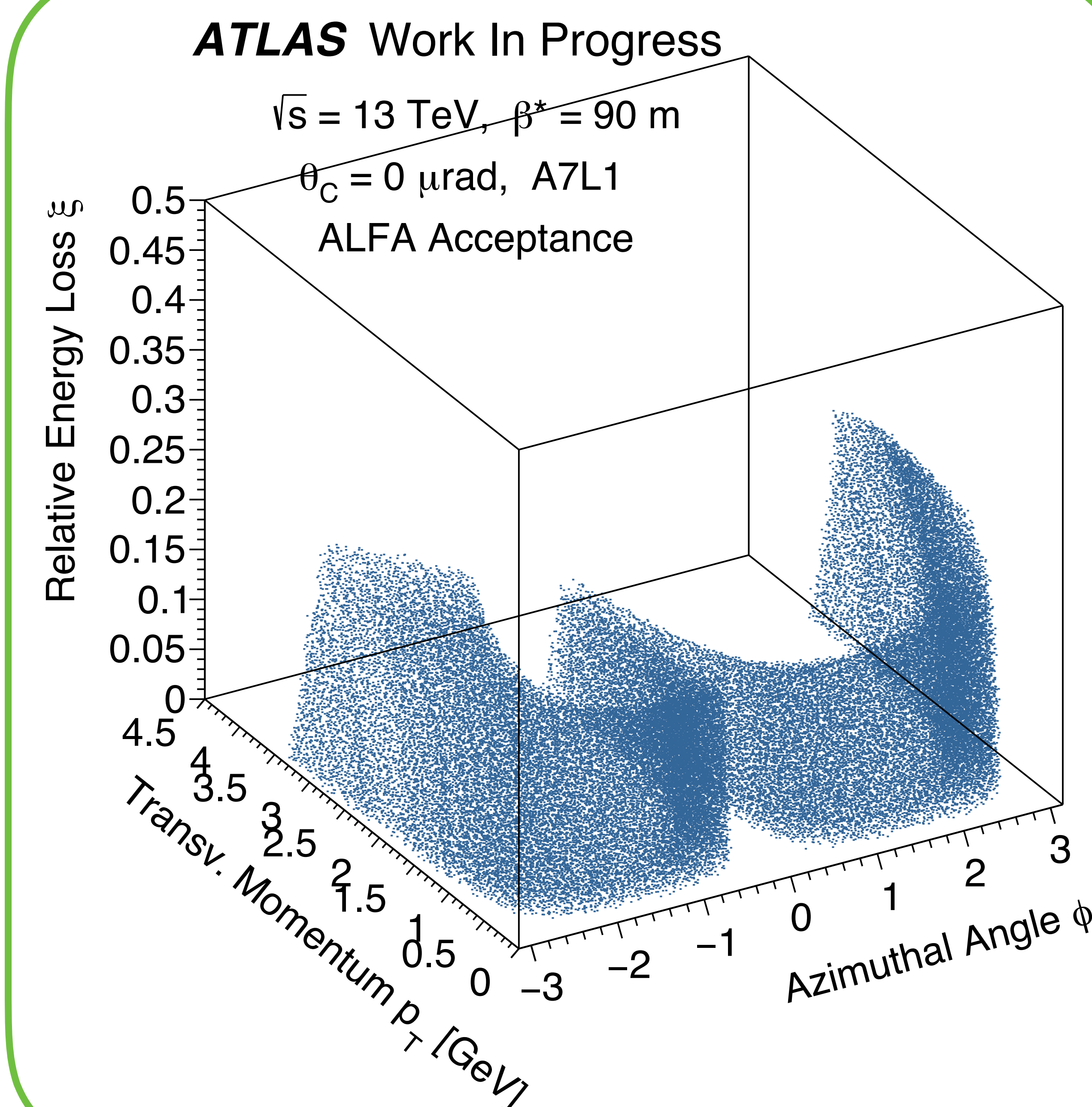
LHC and ALFA Acceptance

$\theta_C = 0\ \mu\mathrm{rad}$

LHC Acceptance



ALFA Acceptance

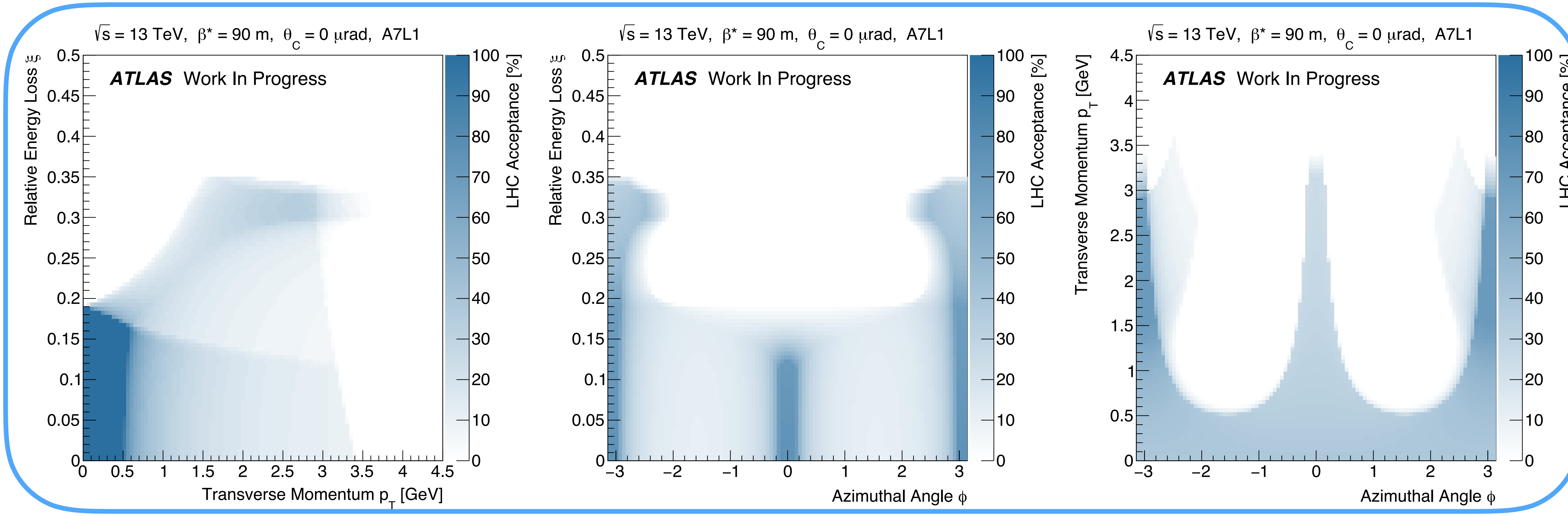


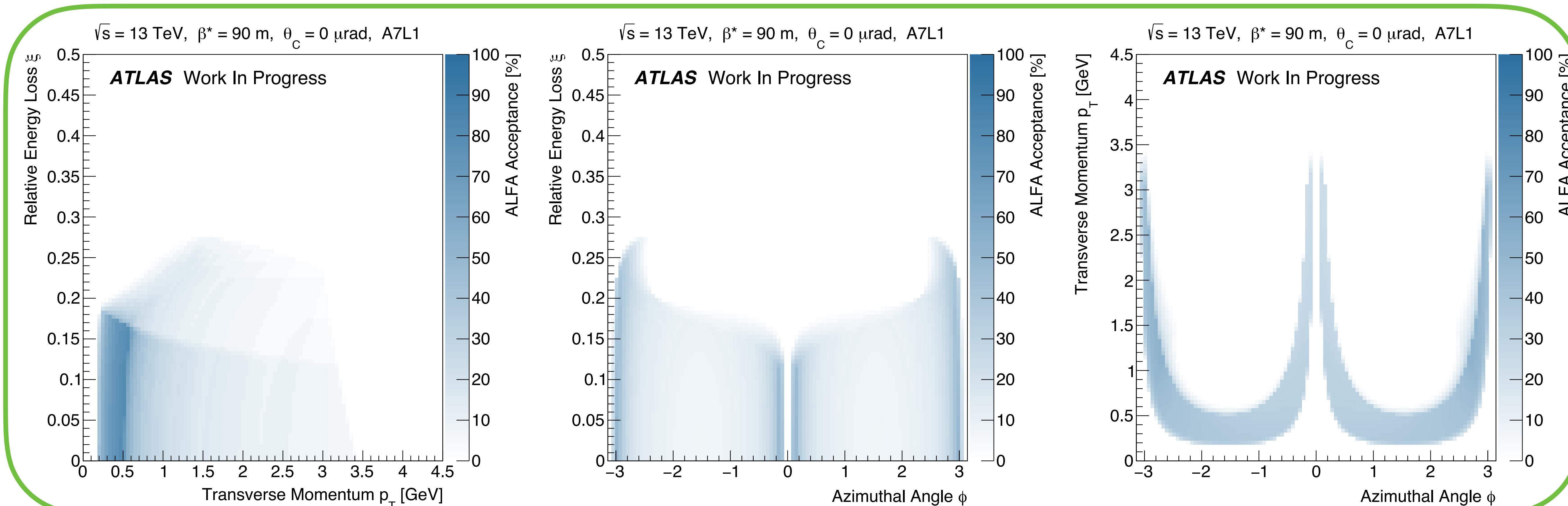
Next slide: 2D projections

A-side
237 m

LHC and ALFA Acceptance

$\theta_C = 0\ \mu\mathrm{rad}$



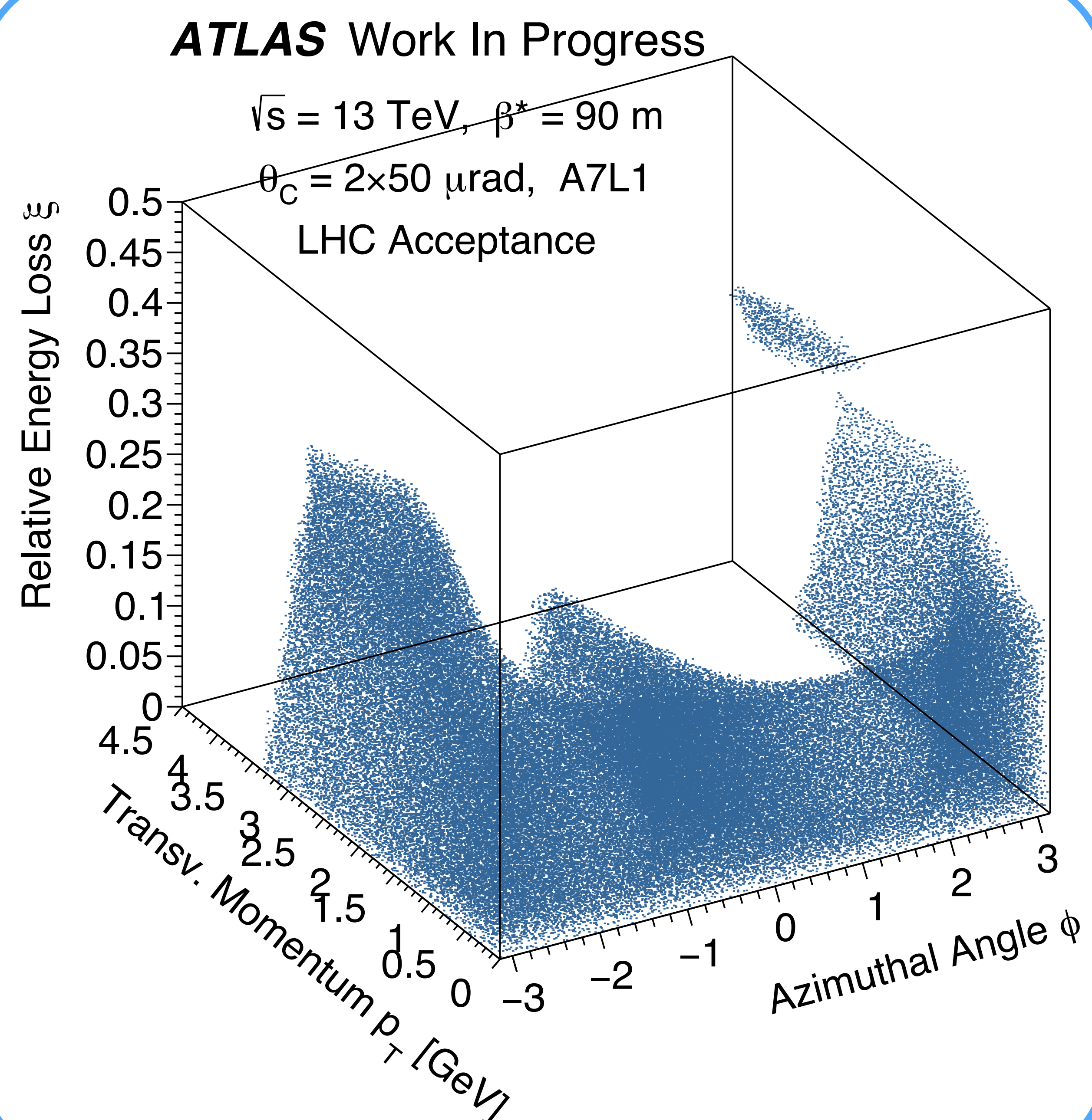


A-side
237 m

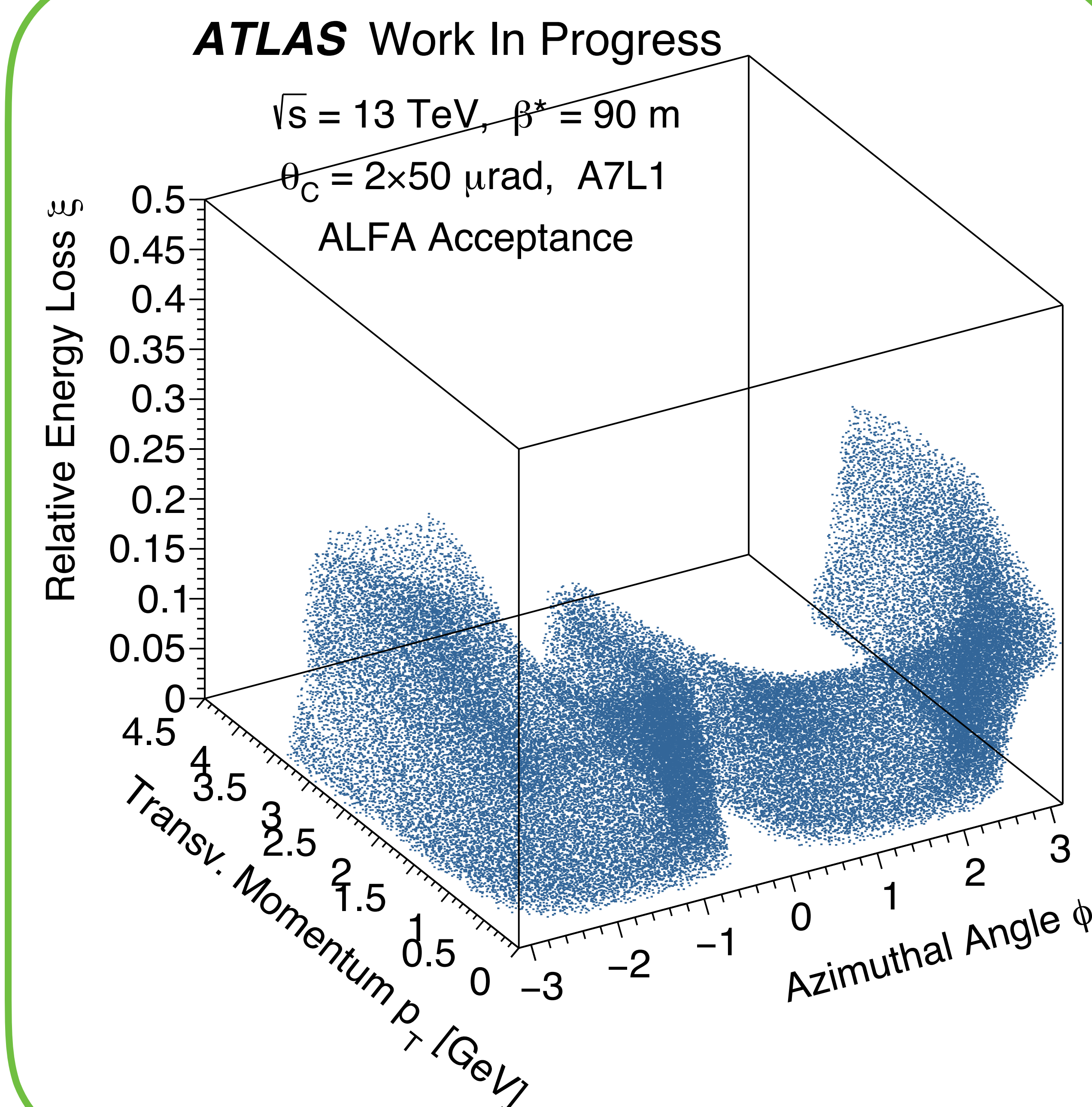
LHC and ALFA Acceptance

$\theta_C = 2 \times 50\ \mu\text{rad}$

LHC Acceptance



ALFA Acceptance

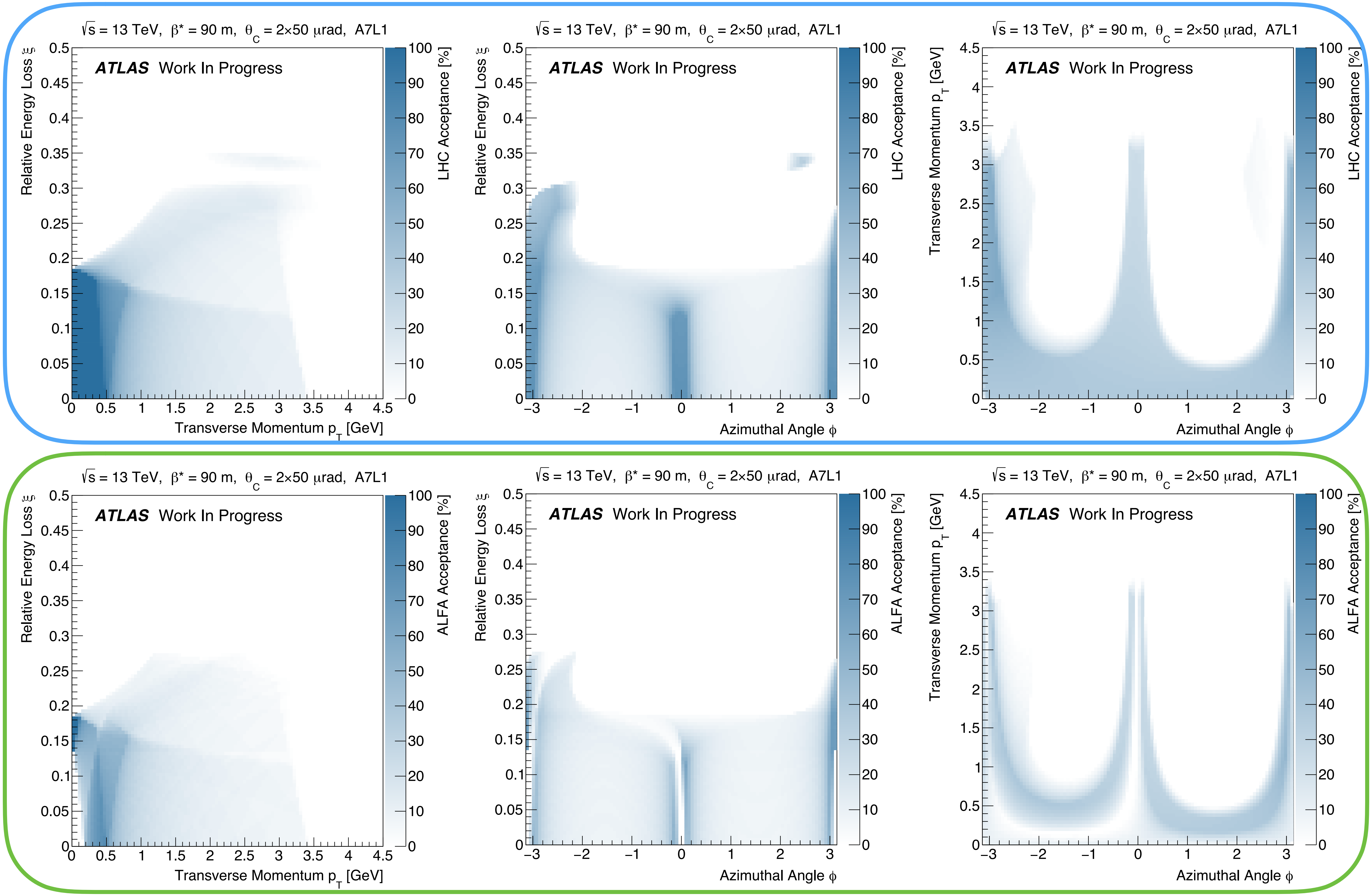


Next slide: 2D projections

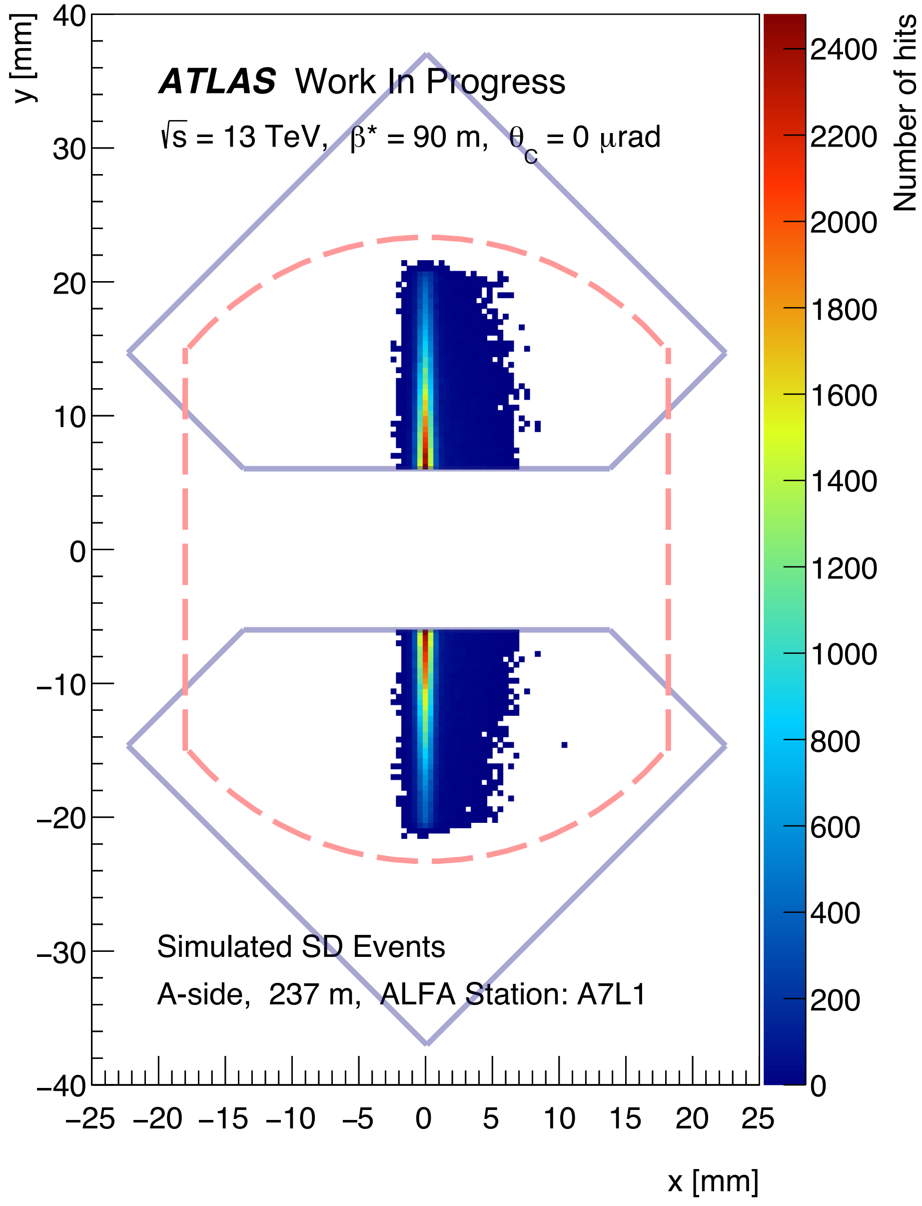
A-side
237 m

LHC and ALFA Acceptance

$\theta_C = 2 \times 50\ \mu\text{rad}$



LHC and ALFA Acceptance: Explanation



We can use this hit map to gain a better understanding of the acceptance plots

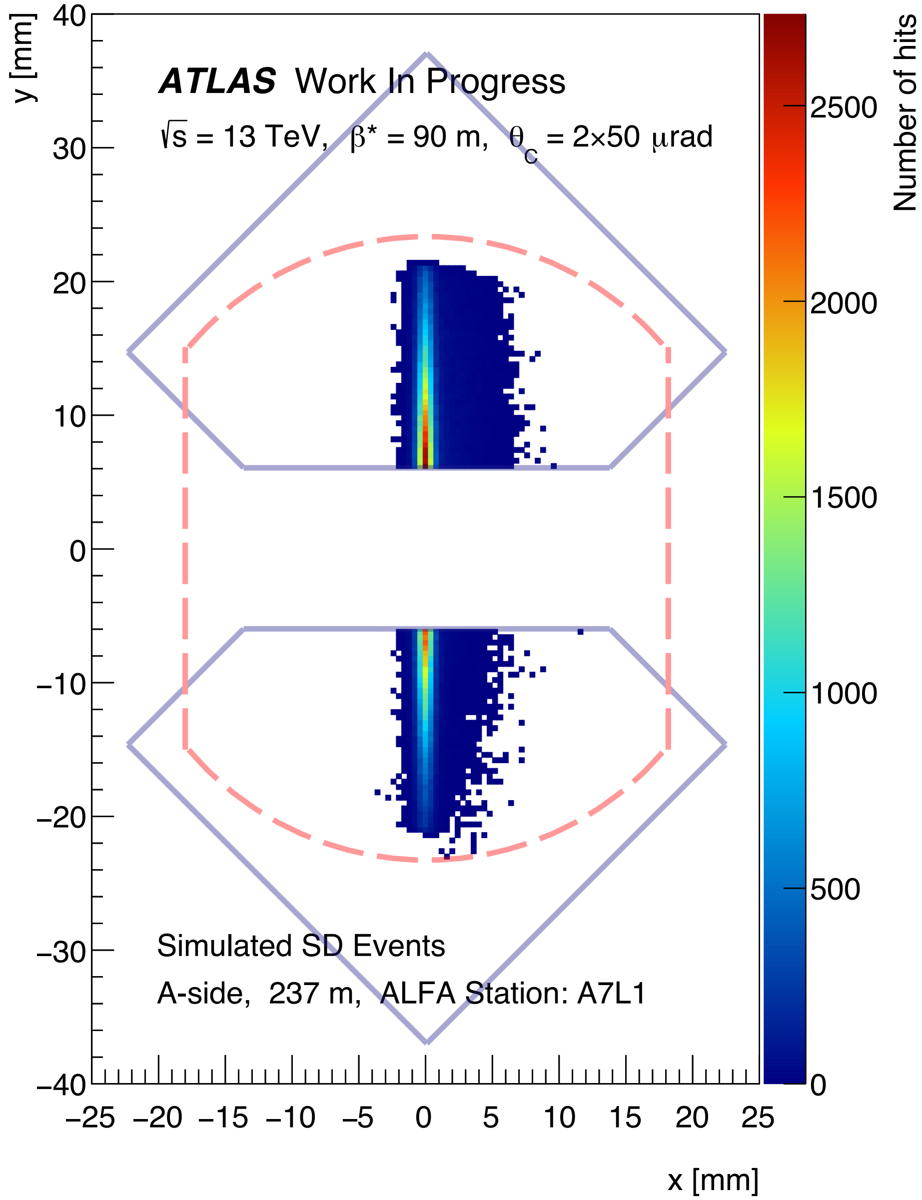
Larger energy loss will give larger x values

Larger spread in y than in x which is why a small region for $\phi = \pm\frac{\pi}{2}$ is accepted

No acceptance for protons with $p_T \approx 0$ as they will be close to the beam and miss ALFA

Symmetry between the A and C-side: Hit maps and Acceptance plots are similar for the A and C-side

LHC and ALFA Acceptance: Explanation



Hitmap for $\theta_C = 2 \times 50\ \mu\text{rad}$

Larger energy loss will give larger x values as well as larger y values

More hits in the upper detector may explain the ϕ asymmetry

Symmetry between the A and C-side: Hit maps and Acceptance plots are similar for the A and C-side

Beam Transport

From literature: to first order it's linear:

$$\begin{bmatrix} u(s) \\ u'(s) \\ (\Delta p)/p \end{bmatrix} = M \begin{bmatrix} u^* \\ u'^* \\ (\Delta p^*)/p \end{bmatrix},$$

Transport Matrix:

with the transport matrix

$$M = \begin{bmatrix} \sqrt{\beta/\beta^*}(\cos\psi + \alpha^* \sin\psi) & \sqrt{\beta\beta^*}\sin\psi & D_u \\ \frac{(\alpha^*-\alpha)\cos\psi-(1+\alpha\alpha^*)\sin\psi}{\sqrt{\beta\beta^*}} & \sqrt{\frac{\beta^*}{\beta}}(\cos\psi - \alpha\sin\psi) & D'_u \\ 0 & 0 & 1 \end{bmatrix},$$

where $u \in \{x, y\}$

From MAD-X Manual on conventions:

BETX	Amplitude function β_x, [m].
ALFX	Correlation function $\alpha_x = -\frac{1}{2}(\partial\beta_x/\partial s)$, [1]
MUX	Phase function $\mu_x = \int ds/\beta_x$, [2π]
DX	Dispersion of x: $D_x = (\partial x/\partial p_t)$, [m]
DPX	Dispersion of p_x: $D_{px} = (\partial p_x/\partial p_t)/p_s$, [1]

Beam Transport

Coordinates of particle at RP will be a function of the same variables:

$$u_{\mathrm{RP}}\left(u_{\mathrm{IP}}, \frac{p_{u,\ \mathrm{IP}}}{p}, \frac{\Delta p^*}{p}\right)$$ but is not linear!

Mad-X and ForwardTracker will not use the thin-lens approximation

The non-linearity will be in the $\Delta p^*/p$ term
So for elastic events you will have a linear dependence
But for diffraction the expression is more complex

Beam Transport

Parameterization:

$$u_{\mathrm{RP}} = F_u\left(\frac{\Delta p^*}{p}\right) \cdot u_{\mathrm{IP}} + G_u\left(\frac{\Delta p^*}{p}\right) \cdot \left(\frac{p_{u,\mathrm{IP}}}{p}\right) + H_u\left(\frac{\Delta p^*}{p}\right)$$

4th deg. pol.

$F_u\left(\frac{\Delta p^*}{p}\right)$, $G_u\left(\frac{\Delta p^*}{p}\right)$ and $H_u\left(\frac{\Delta p^*}{p}\right)$ are fitted to output from ForwardTransportFast

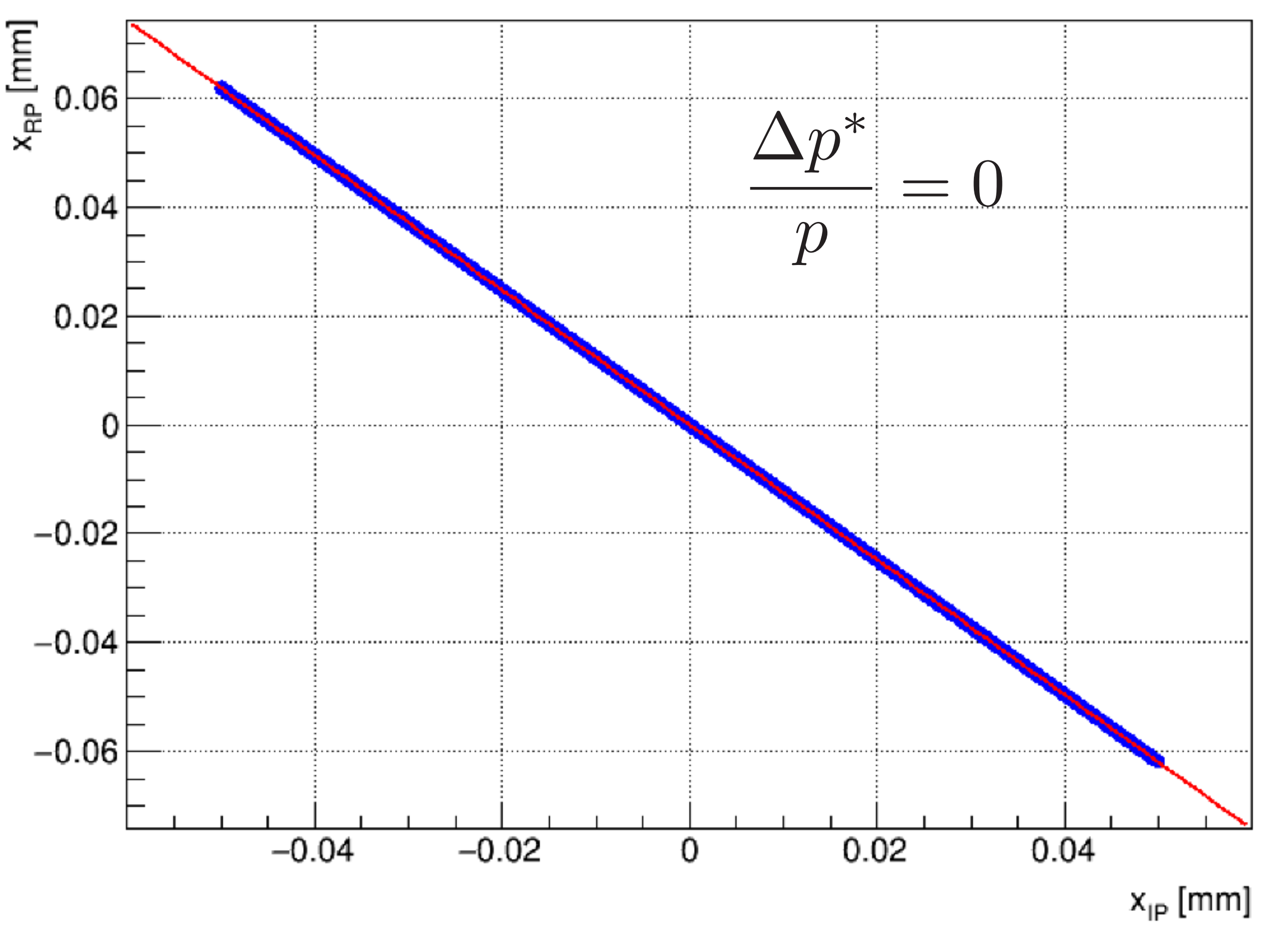
The expression for u_{RP} must be found for all stations

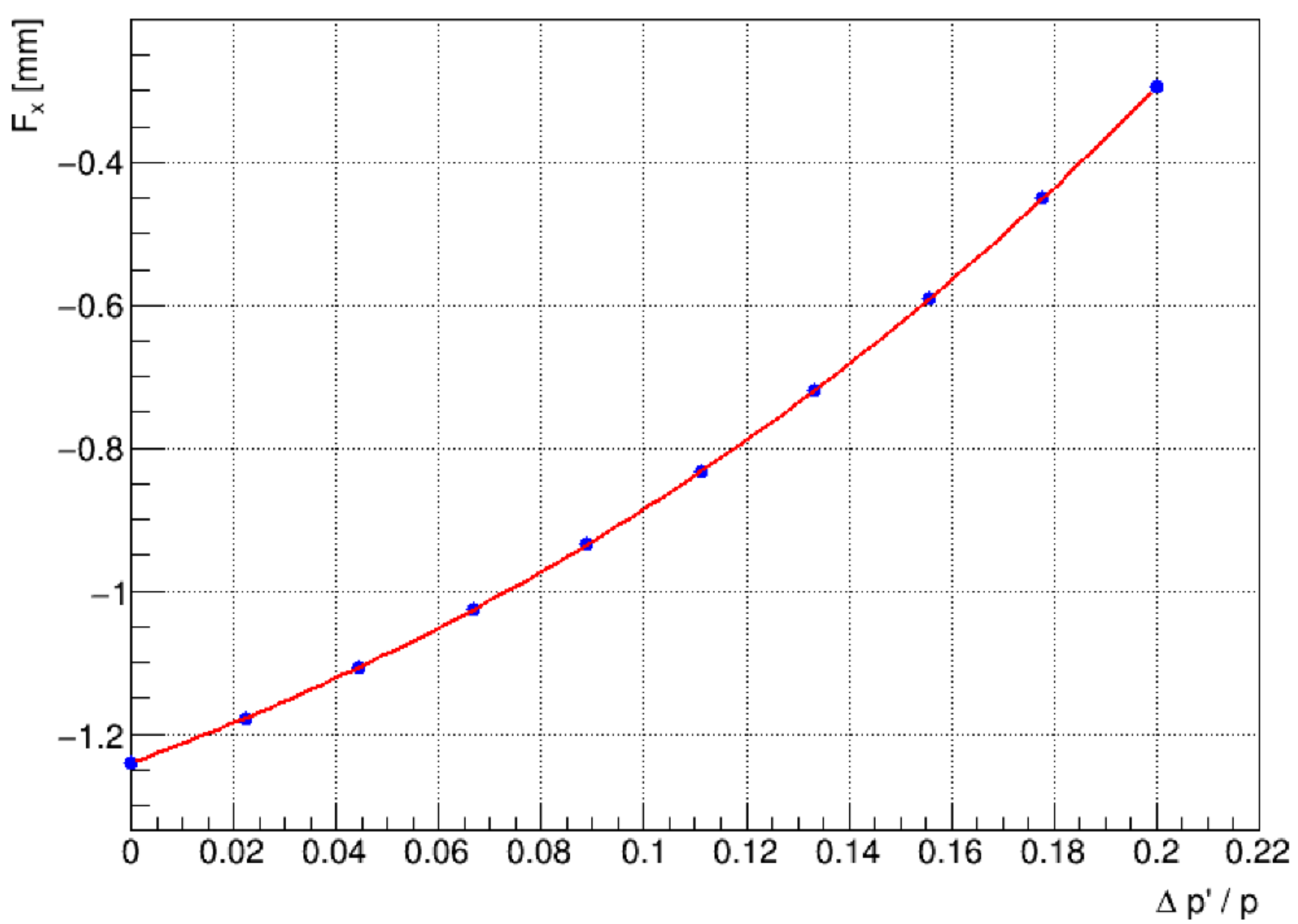
Beam Transport

The dependence on the u-position at IP is linear but the slope of that line depends on the momentum loss:

$$u_{\mathrm{RP}} \sim F_u\left(\frac{\Delta p^*}{p}\right) \cdot u_{\mathrm{IP}}$$

where $F_u\left(\frac{\Delta p^*}{p}\right)$ is fitted to a 4th deg. pol.



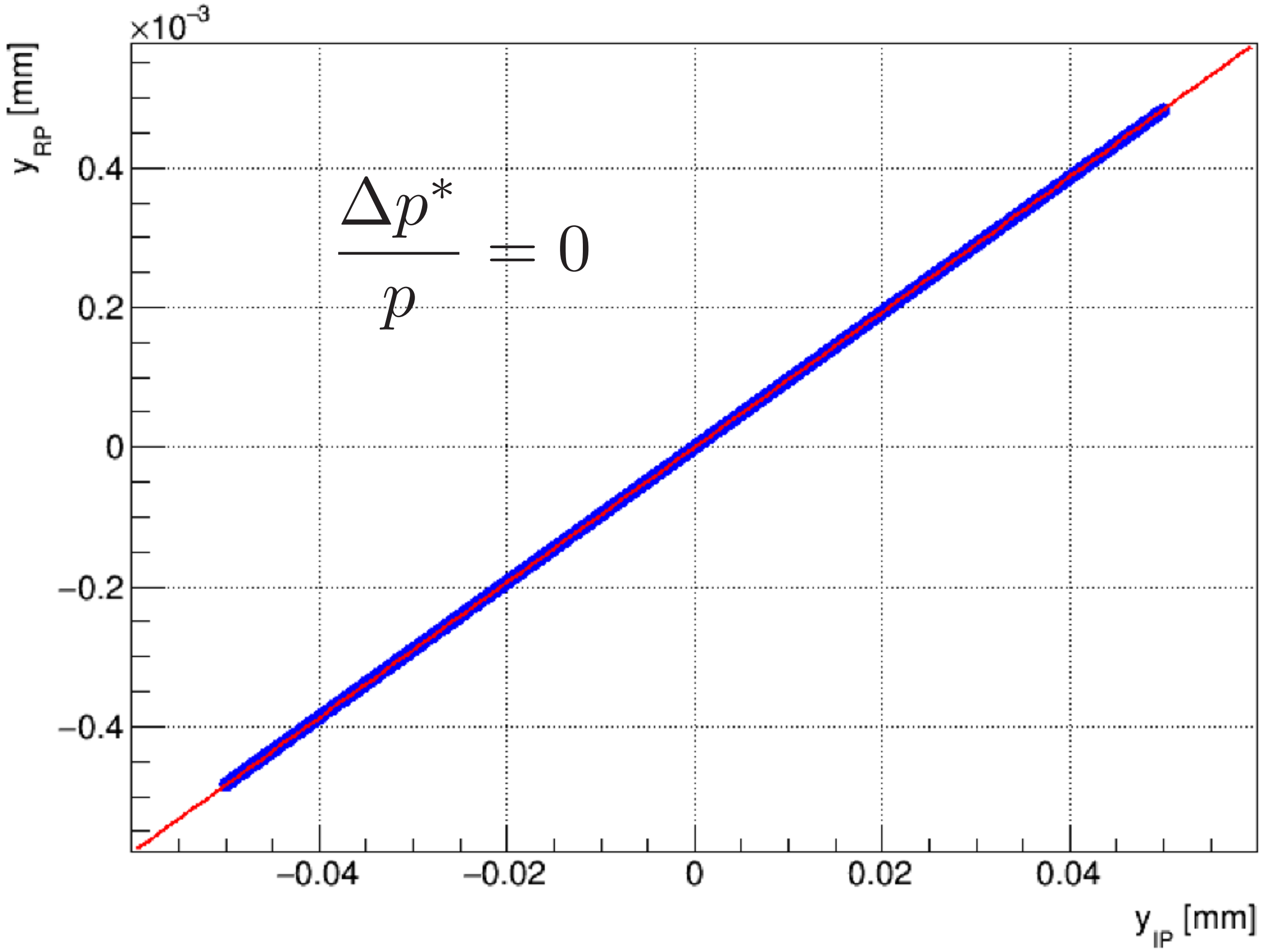


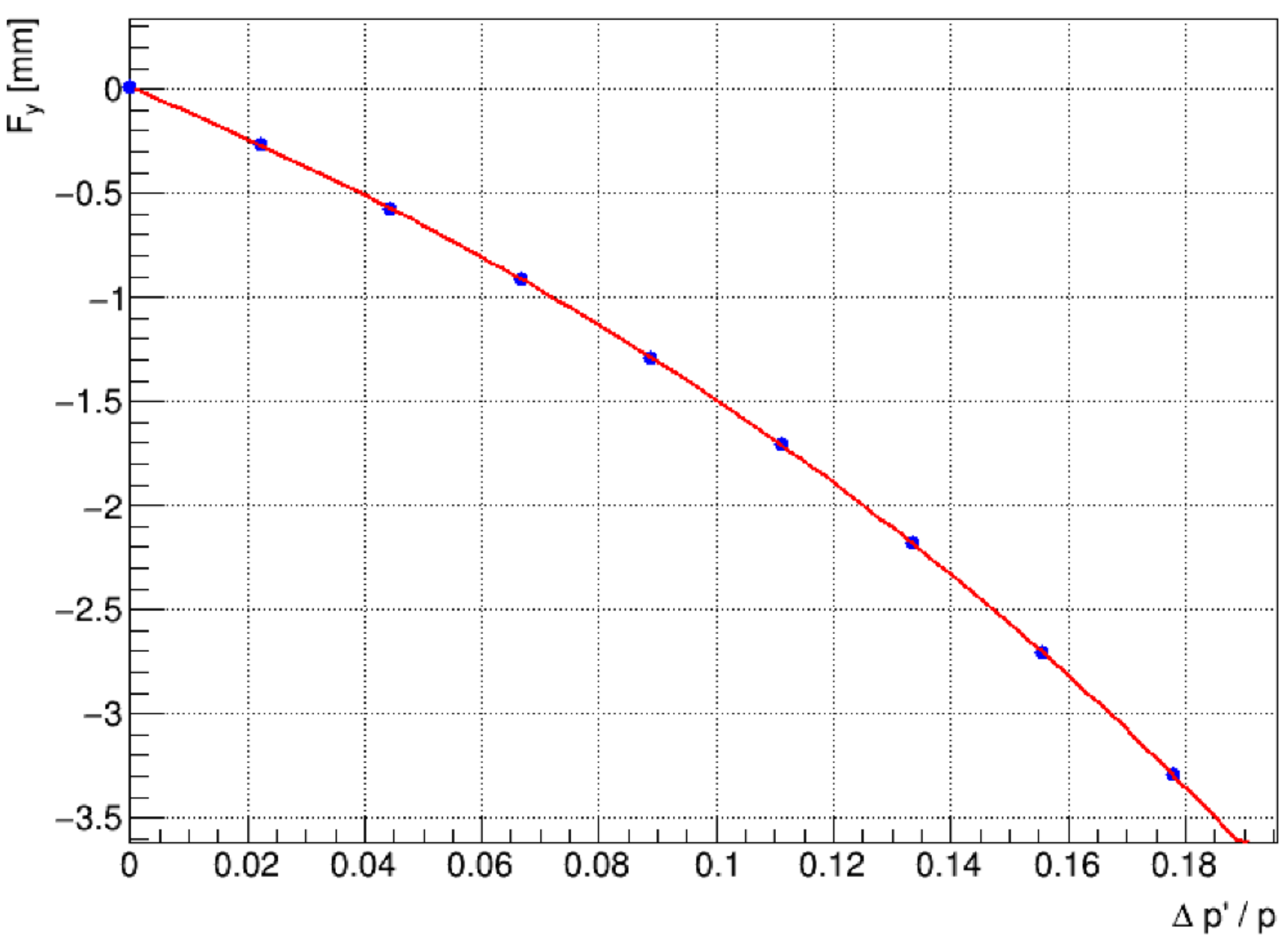
Beam Transport

The dependence on the u-position
at IP is linear but the slope of that line depends
on the momentum loss:

$$u_{\mathrm{RP}} \sim F_u\left(\frac{\Delta p^*}{p}\right) \cdot u_{\mathrm{IP}}$$

where $F_u\left(\frac{\Delta p^*}{p}\right)$ is fitted to a 4th deg. pol.



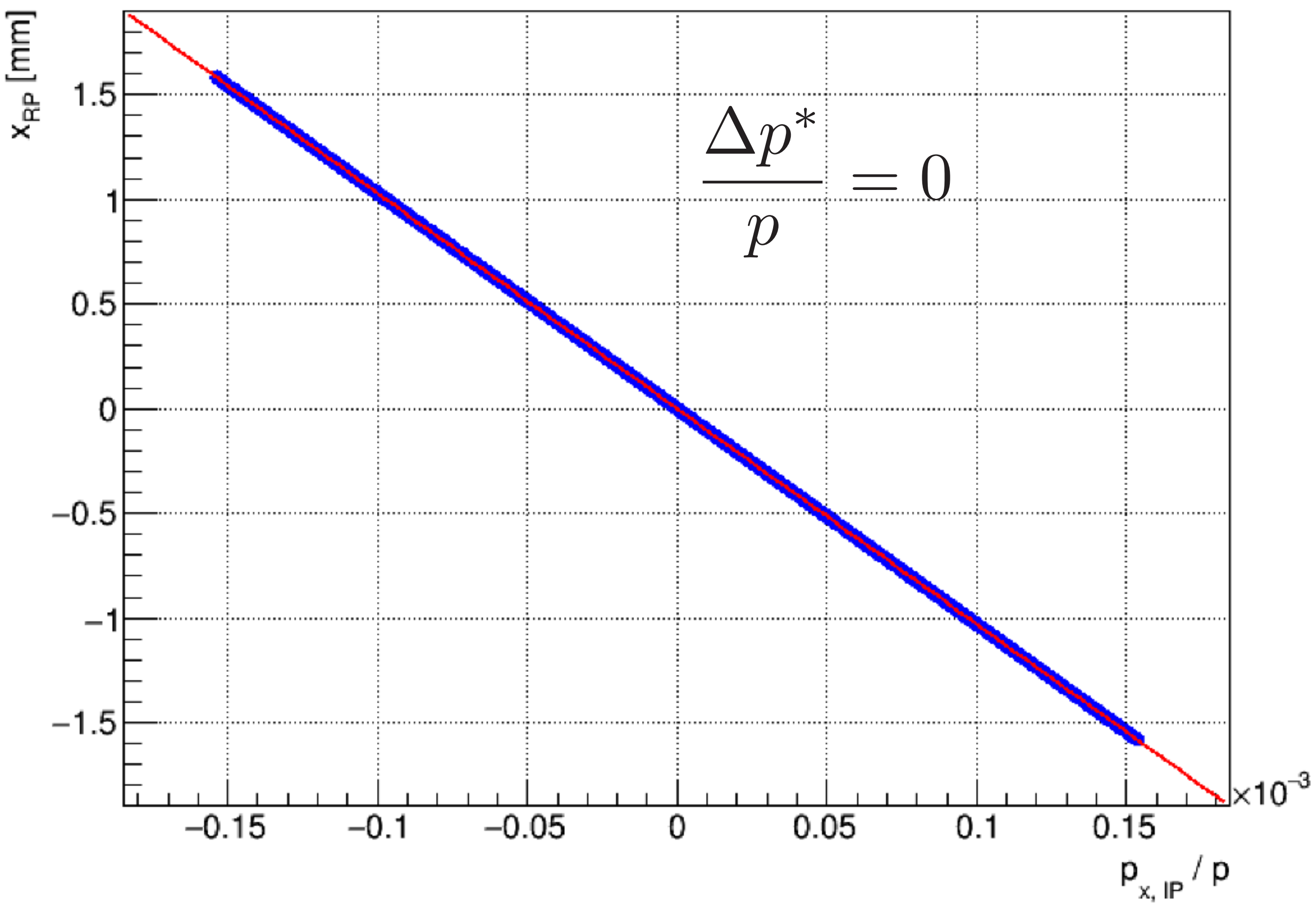


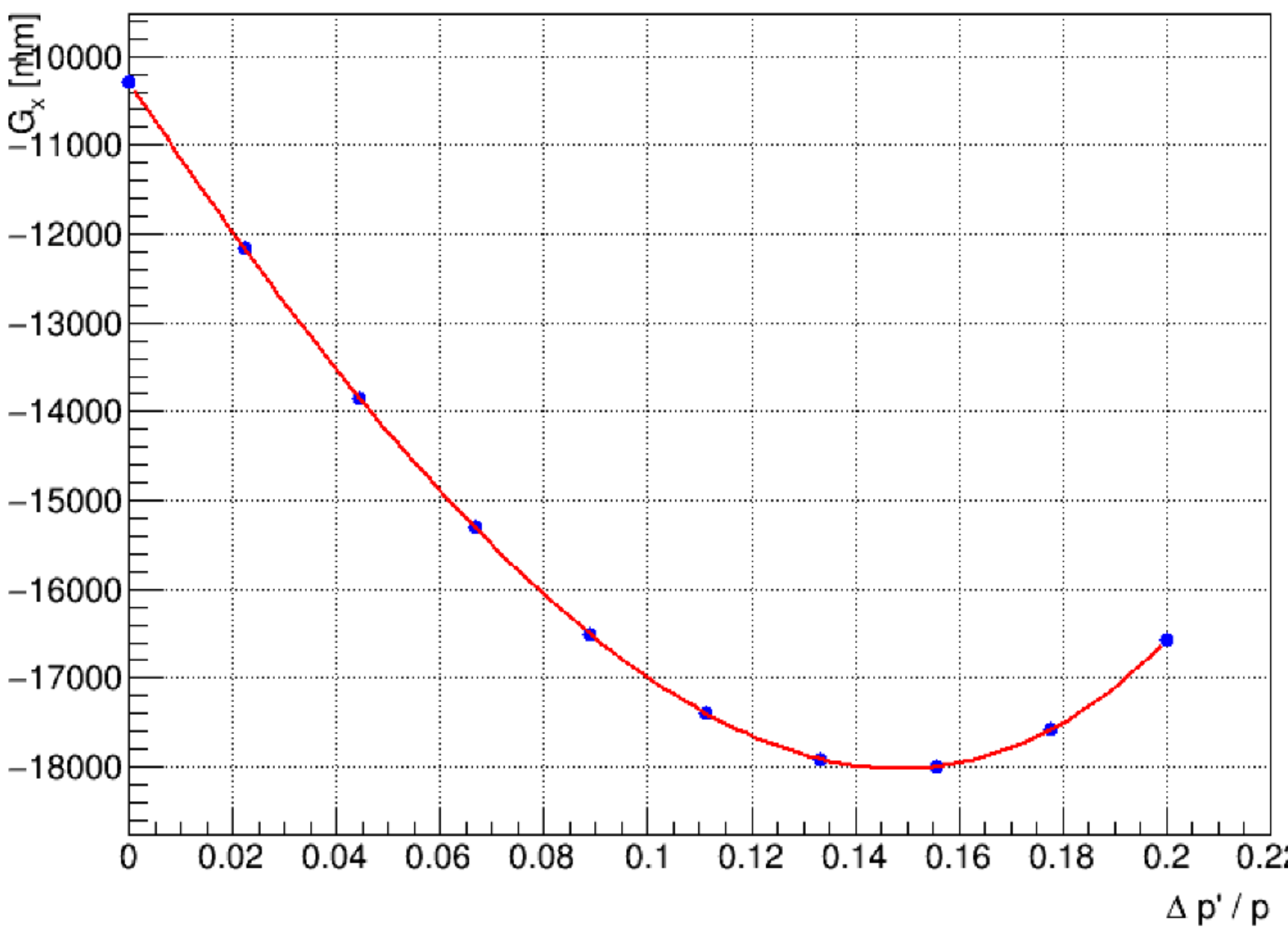
Beam Transport

The dependence on the u-component of the momentum at IP is linear but the slope of that line depends on the momentum loss:

$$u_{\mathrm{RP}} \sim G_u\left(\frac{\Delta p^*}{p}\right)\cdot\left(\frac{p_{u,\mathrm{IP}}}{p}\right)$$

where $G_u\left(\frac{\Delta p^*}{p}\right)$ is fitted to a 4th deg. pol.

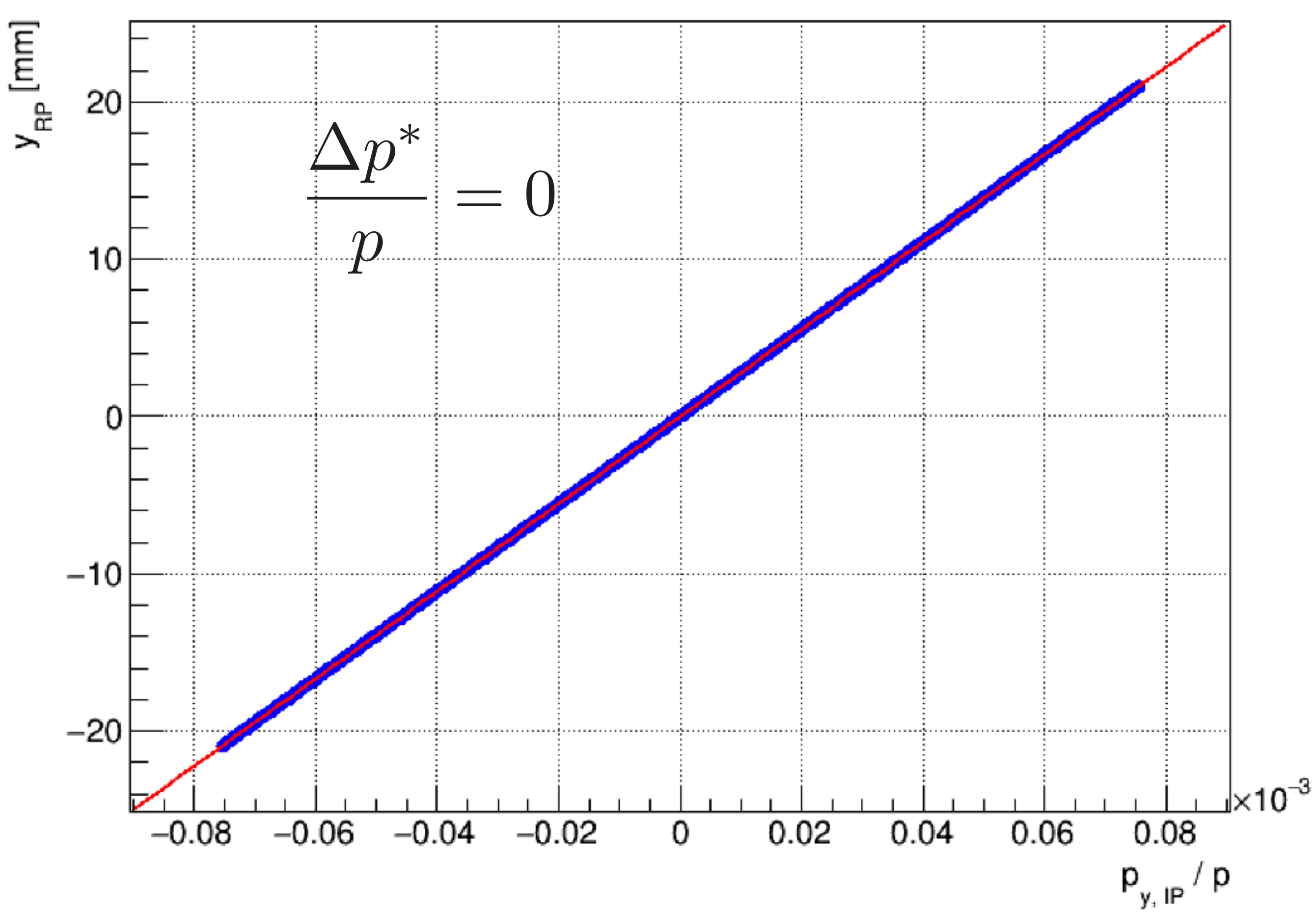


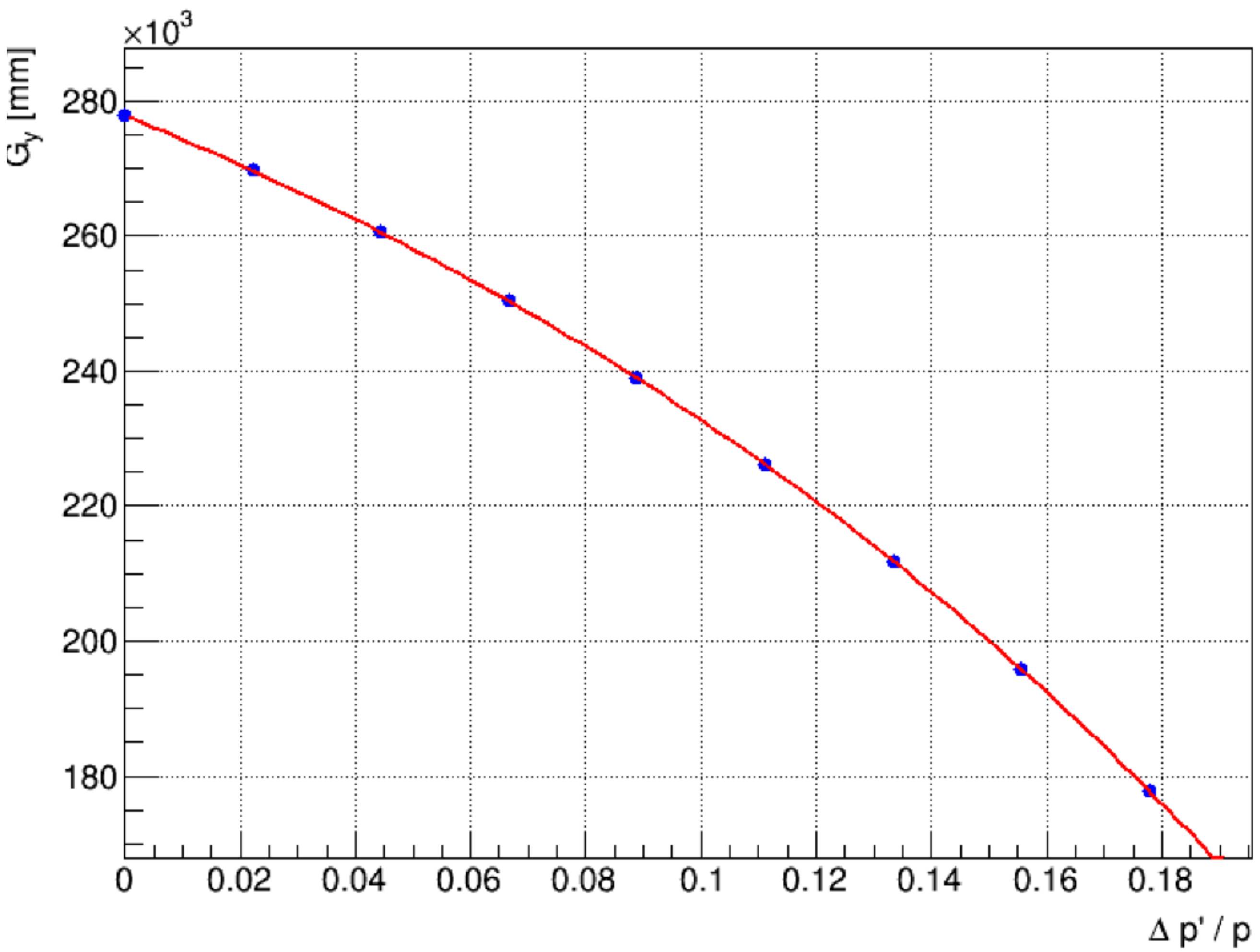


The dependence on the u-component of the momentum at IP is linear but the slope of that line depends on the momentum loss:

$$u_{\mathrm{RP}} \sim G_u\left(\frac{\Delta p^*}{p}\right) \cdot \left(\frac{p_{u,\mathrm{IP}}}{p}\right)$$

where $G_u\left(\frac{\Delta p^*}{p}\right)$ is fitted to a 4th deg. pol.

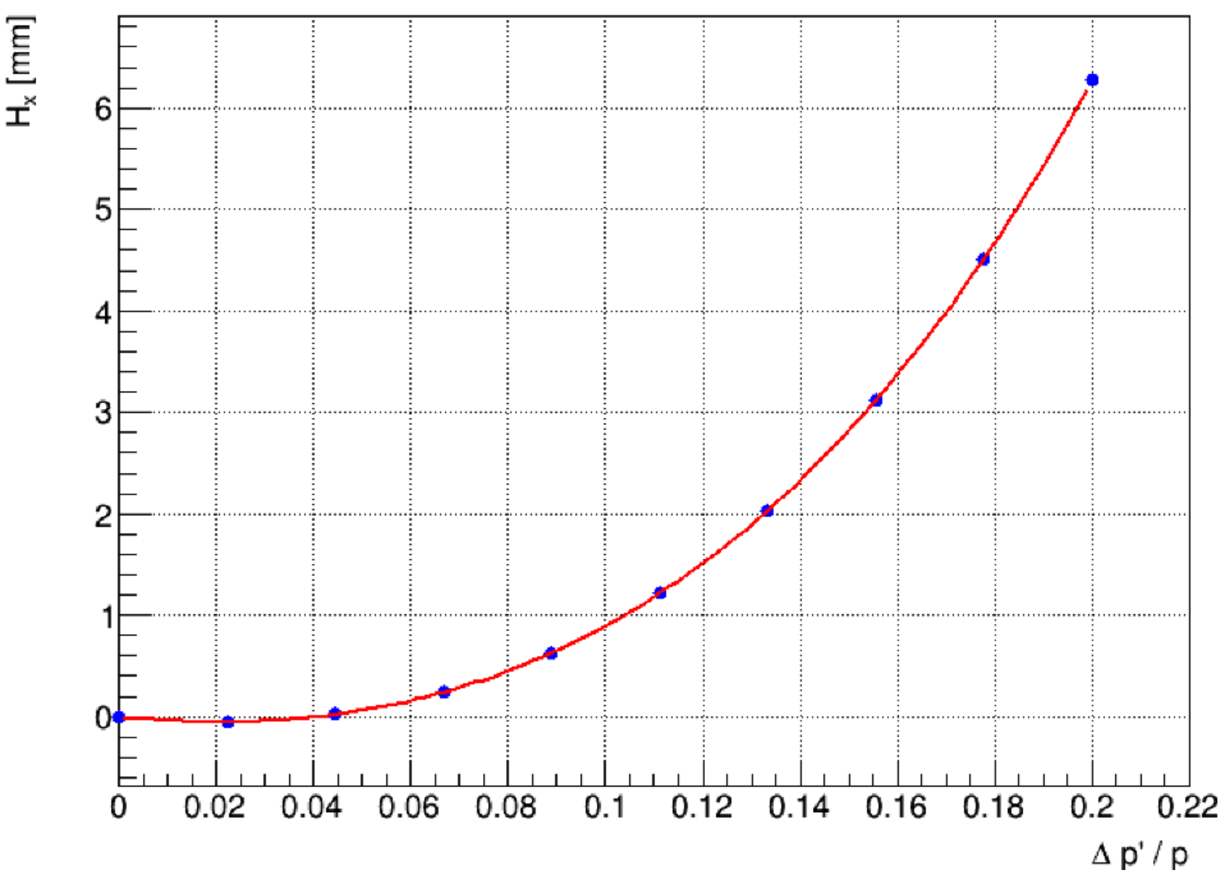


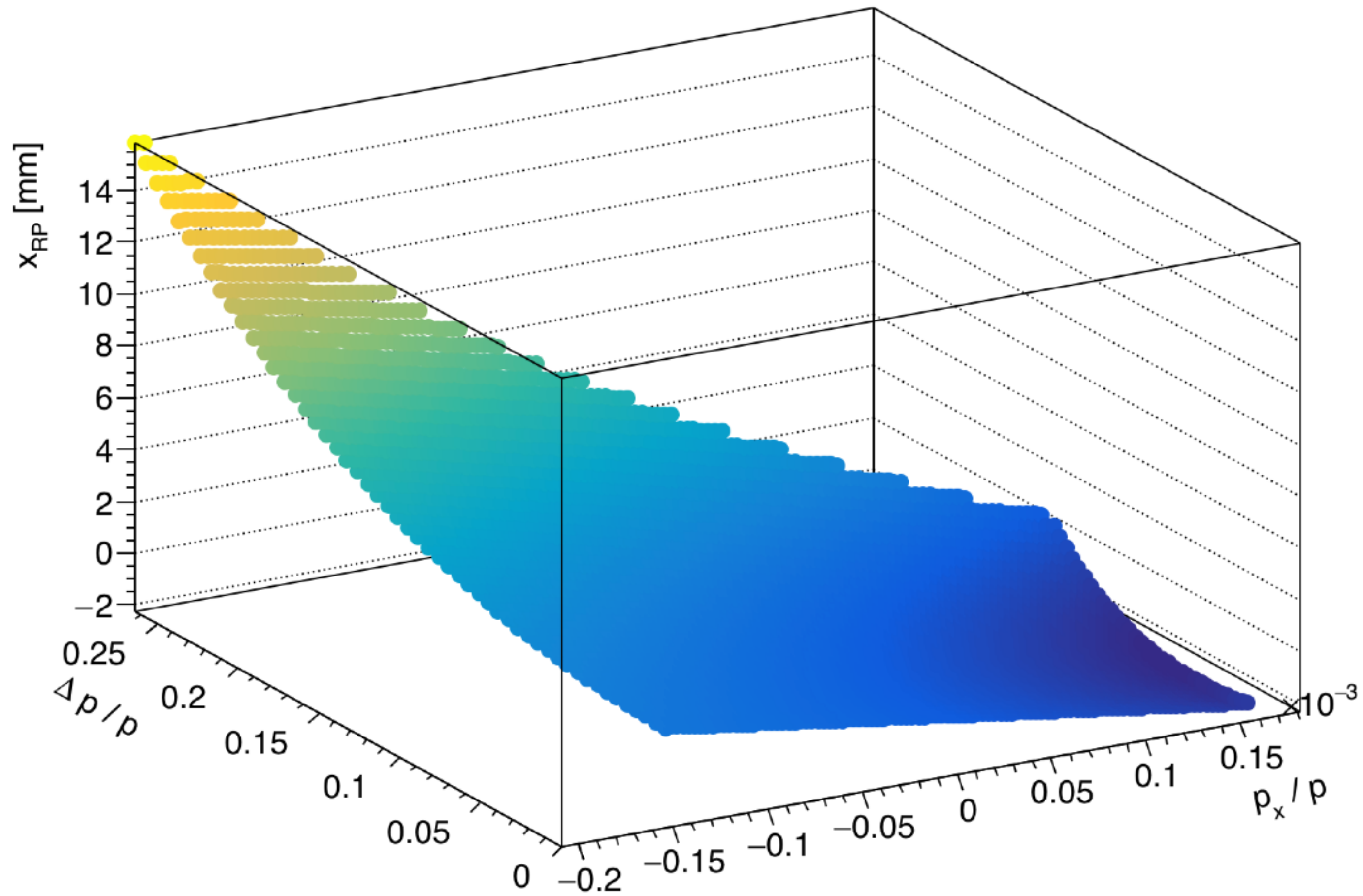


Beam Transport

The dependence on the momentum loss is not linear but seemingly quartic:

$$u_{\mathrm{RP}} \sim H_u\left(\frac{\Delta p^*}{p}\right) \quad \text{where} \quad H_u\left(\frac{\Delta p^*}{p}\right) \quad \text{is fitted to a 4th deg. pol.}$$





Beam Transport: Elastic Events

For elastic events where we have

$$\frac{\Delta p^*}{p} = 0$$

the beam transport is simplified to be linear:

$$u_{\mathrm{RP}} = m_{u,1} \cdot u_{\mathrm{IP}} + m_{u,2} \cdot \left(\frac{p_{u,\mathrm{IP}}}{p} \right)$$

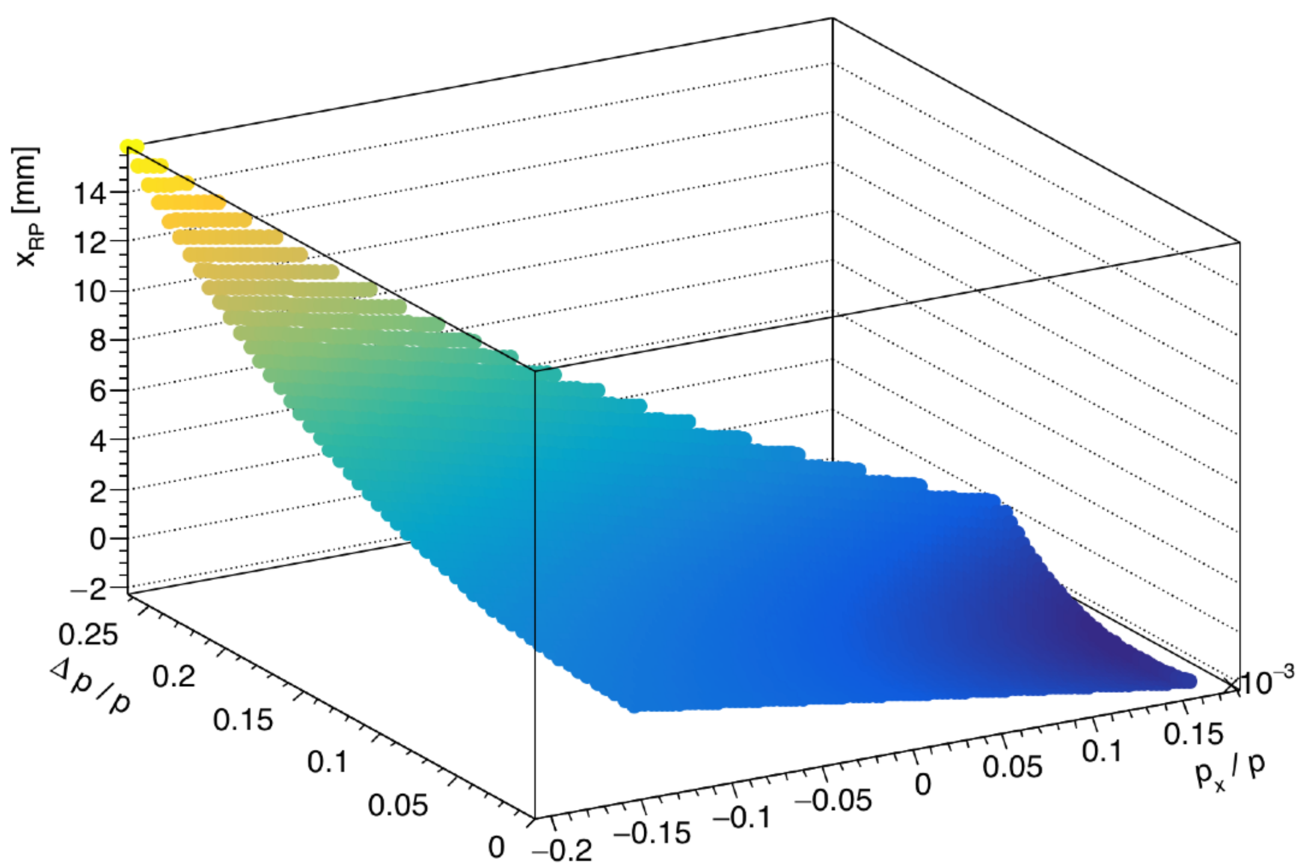
where: $m_{u,1}, m_{u,2} \in \mathbb{R}$

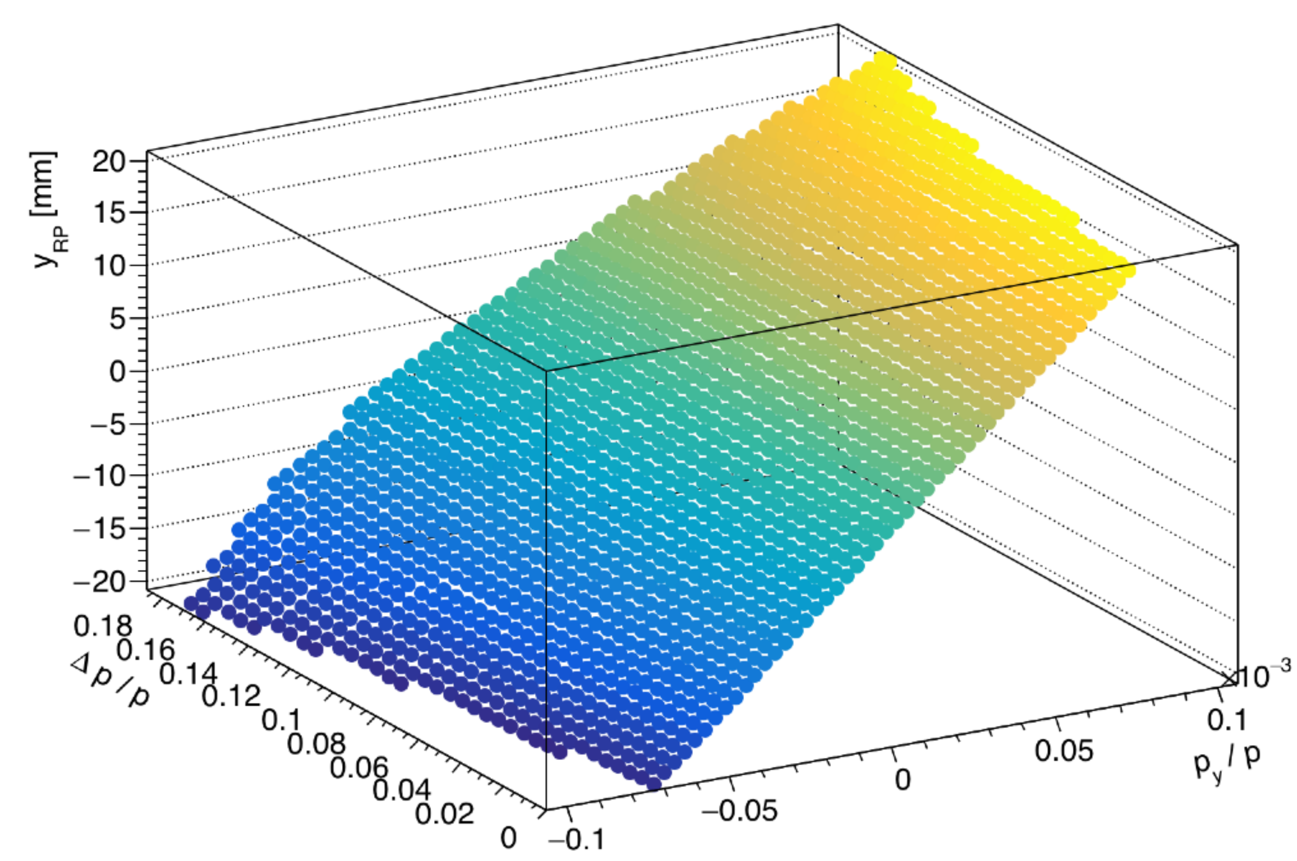
Beam Transport

Also notice the aperture survival!

Not all protons end up at the RPs. Some are lost during the transport as seen on the acceptance plots before

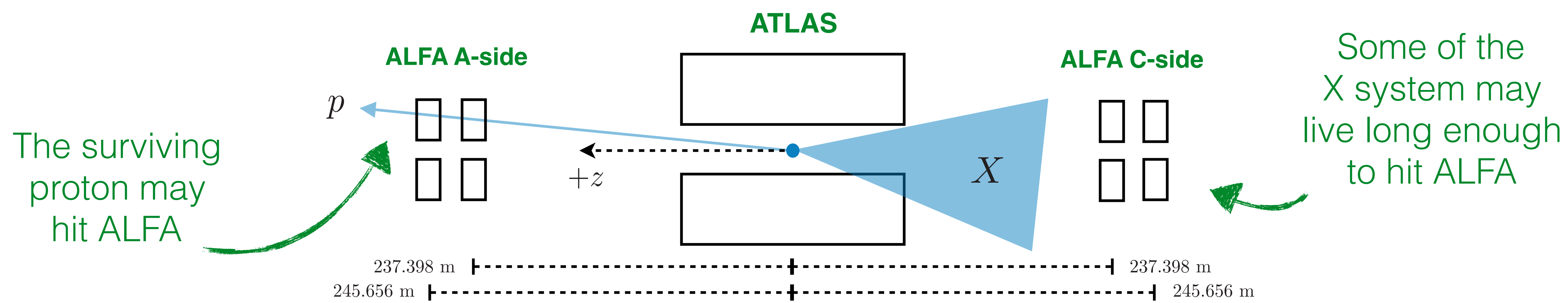
We need to include aperture survival in our Beam Transport code as well





Beam Transport: Types of Particles

Consider the particles from a single diffractive event that may hit the ALFA detectors



The X system of particles from the dissociated proton will on average per event contain:

~ 1.4 protons	~ 0.8 anti-protons
~ 12 positive pions	~ 12 negative pions
~ 0.003 muons	~ 0.003 anti-muons

Beam Transport: Negative Particles

We have neglected muons and anti-muons

Particles with the same charge (i.e. protons and pi+) will behave identical during transport

ForwardTransportFast can only transport protons (2212) and therefore also positive pions (211)

Negative particles (Antiprotons -2212, negative pions -211) have not been included in the transport code

Protons and positive pions from the X system are therefore the only source of background in our simulations

Beam Transport: Implementation

An attempt has been made to do beam transport of protons in a way that is:

- Independent of any ATLAS code
  (No Athena; can easily be run by anyone in Rivet)
- Fast (‘quick-and-dirty’, no Geant4) …
- … but still accurate (provides position and aperture survival)

Invert it and it can be used to do reconstruction!

Beam Transport: Implementation

But it is not without its flaws:

- You need specific files for your setup
  (energy, optics, crossing angle)
- Aperture survival binned/discrete instead of continous
- Cannot transport negatively charged particles
  (But neither can ForwardTransportFast)
- (Does not take LHC collimators into account)
  But not such a big problem
- … perhaps a bit overkill …