Study of Diffractive Scattering in Proton-Proton Collisions at 13 TeV

with the ATLAS and ALFA Experiment

CDS: https://cds.cern.ch/record/2275644

Alexander Lind

Presentation of Master's Research done at the Niels Bohr Institute in Copenhagen

NExT Physics Meeting
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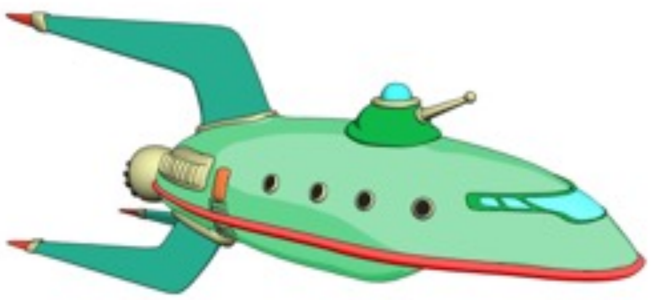
Outline



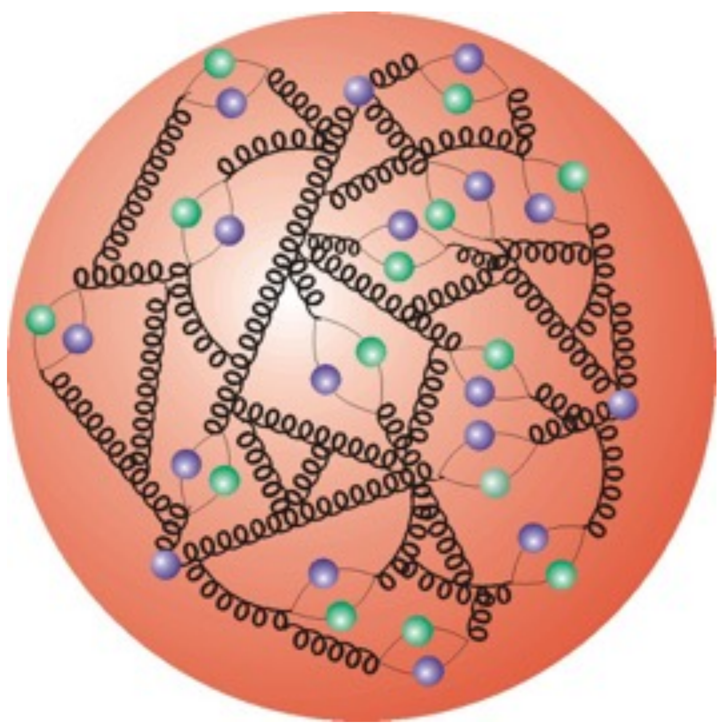
- **Theory:** What is Diffraction?
- **Experiment:** Detection of Diffractive Events
- **Simulation Framework**
- **Phenomenological Study**
- **Data Analysis** of new 13 TeV data from the LHC Run 2 period

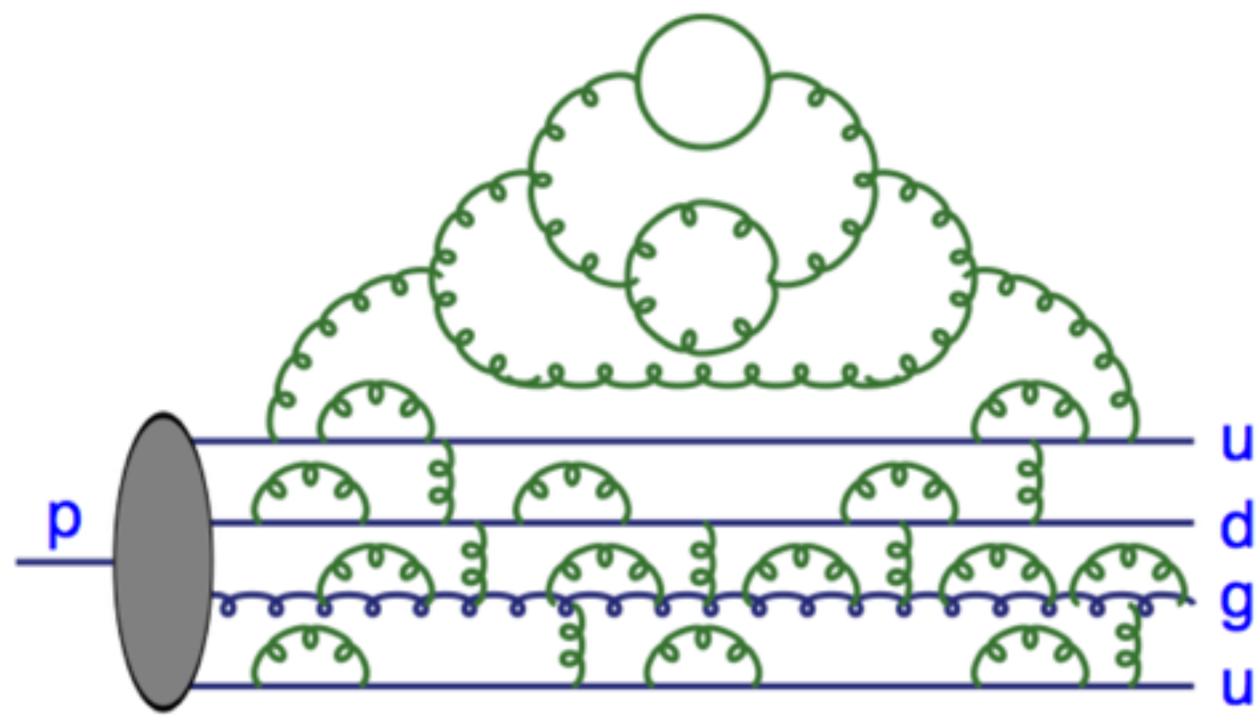
Theory

What is Diffractive Scattering of Protons?

The Proton

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





Parton distribution function (PDF):

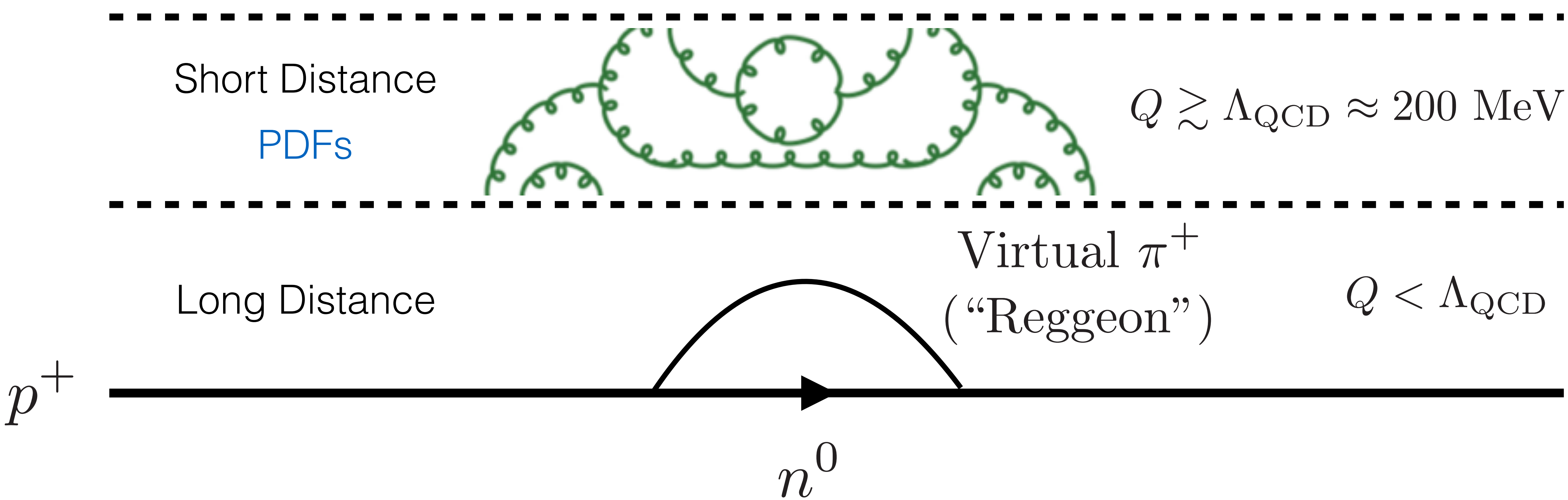
$f_i(x, Q^2)$ = number density of partons i at momentum fraction x and probing scale Q^2

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

Reggeons and Pomerons

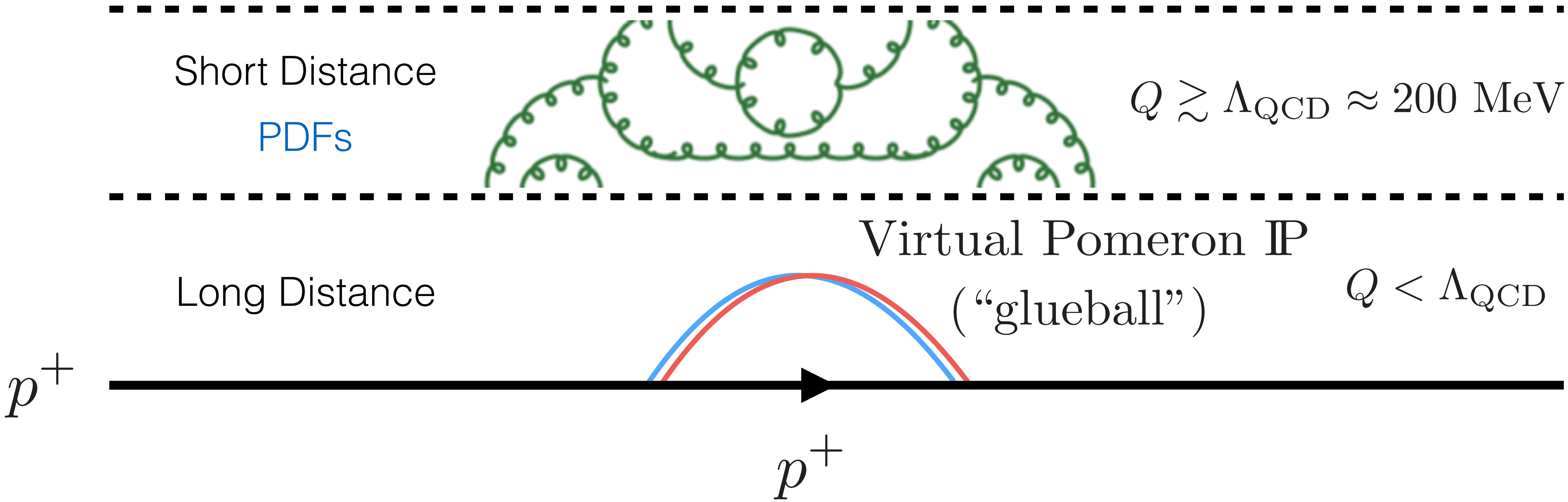
A proton minding its own business…

…can for a short (virtual) while
emit a Reggeon…

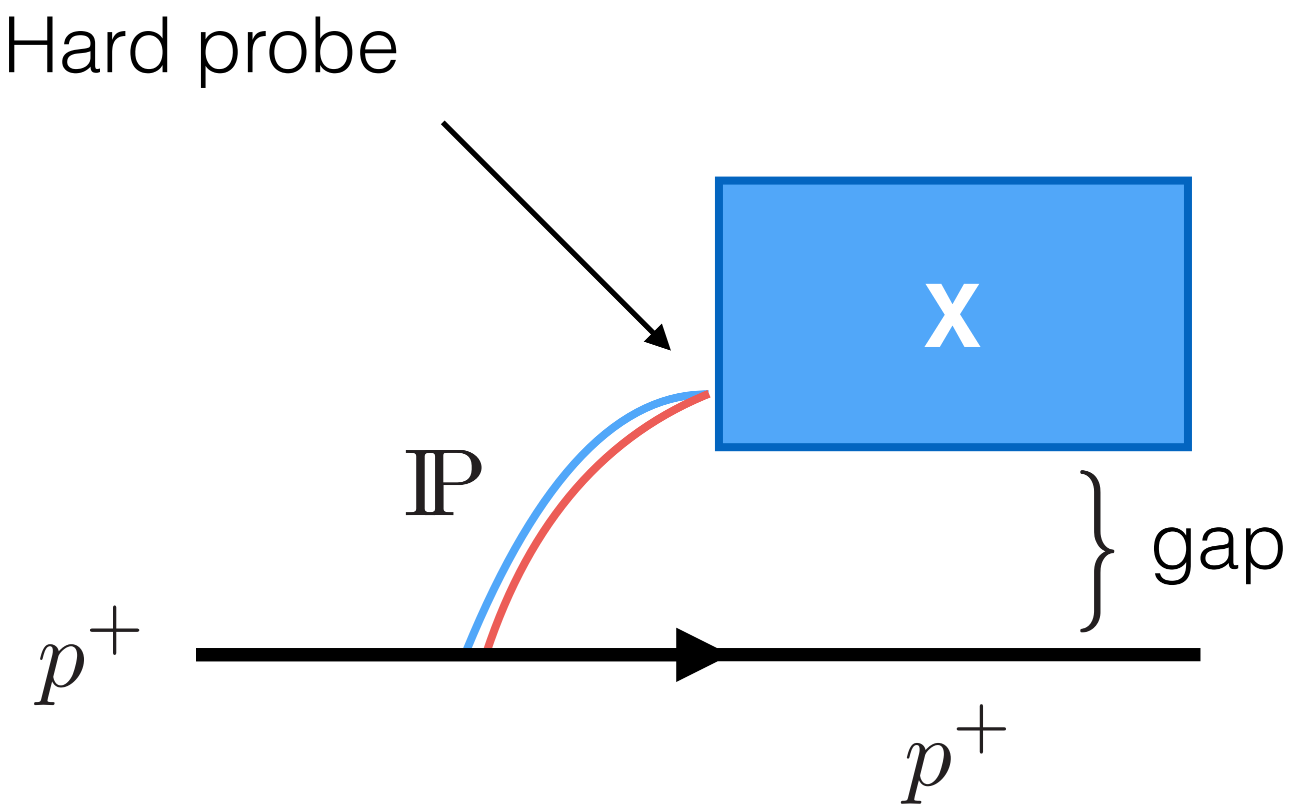


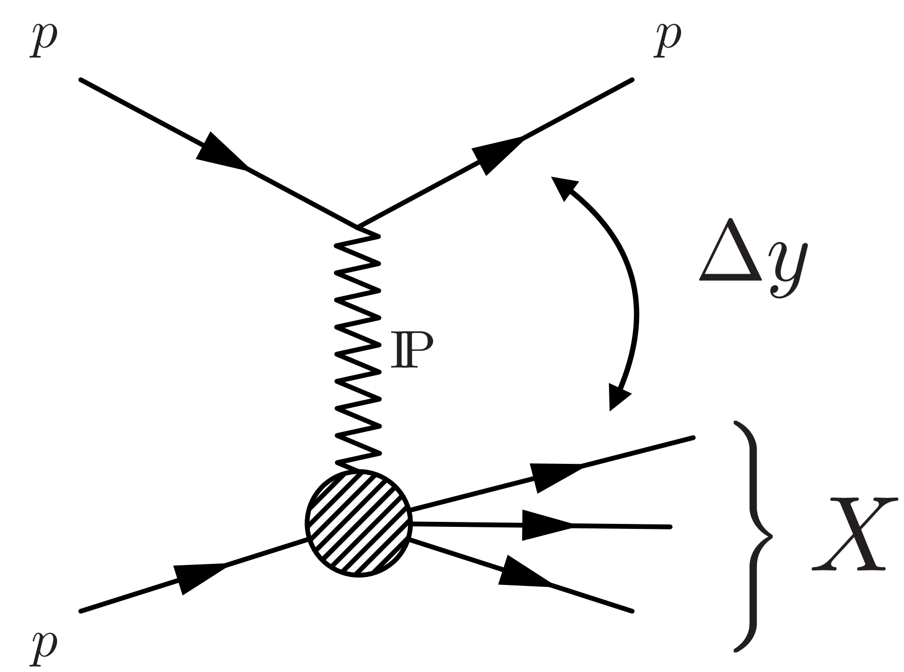
Reggeons and Pomerons

…or emit a **Pomeron**,
a hypothetical glue-ball state with
the quantum numbers of the vacuum



Diffractive Events





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

Physical to ask if there was a large rapidity gap

Hard Diffraction

Single Diffractive Cross-section using Factorization:

$$\frac{\mathrm{d}\sigma_{\mathrm{SD}}}{\mathrm{d}\xi\mathrm{d}t} = \underbrace{f_{\mathbb{P}/p}(\xi, t)}_{\text{Pomeron Flux Factor}}\sigma_{\mathbb{P}/p}$$

Pomeron Flux Factor

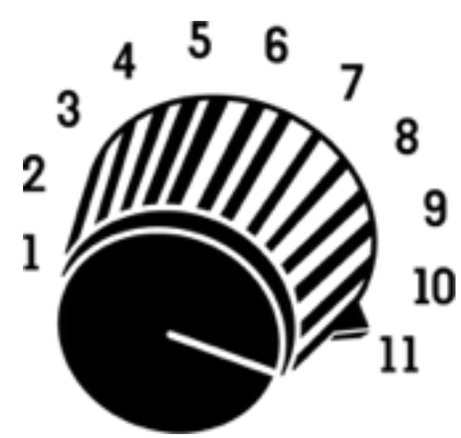
We don't know the exact Pomeron flux
(can't calculate it from first principles)
But we can phenomenologically model it

The Pomeron Flux depends on
the Regge trajectory for the Pomeron

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

The Monte Carlo Event Generator **Pythia** allows us to simulate diffractive pp collisions

ε



α'

Goal / Purpose

- Study of Diffractive Scattering at the ALFA and ATLAS detectors

- Investigate the effect of the Pomeron Flux parameterization on observables

- Fit Pomeron Flux parameters to new 13 TeV data

Motivation

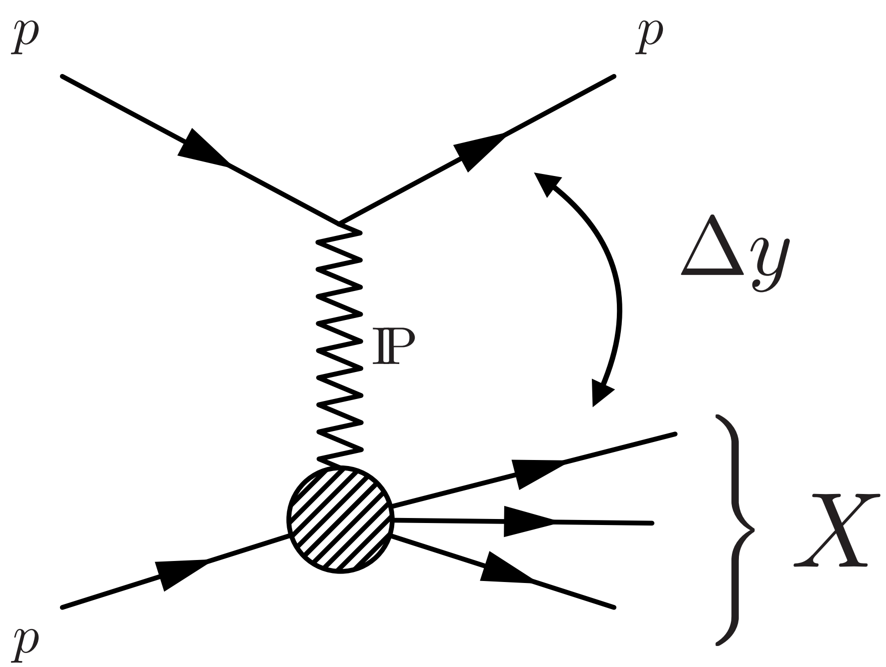
Why bother?

- Production of Minimum Bias Monte Carlo samples
- A better understanding of the Pomeron
- An understanding of Diffraction and the Pomeron may help in uniting QCD with Regge Theory

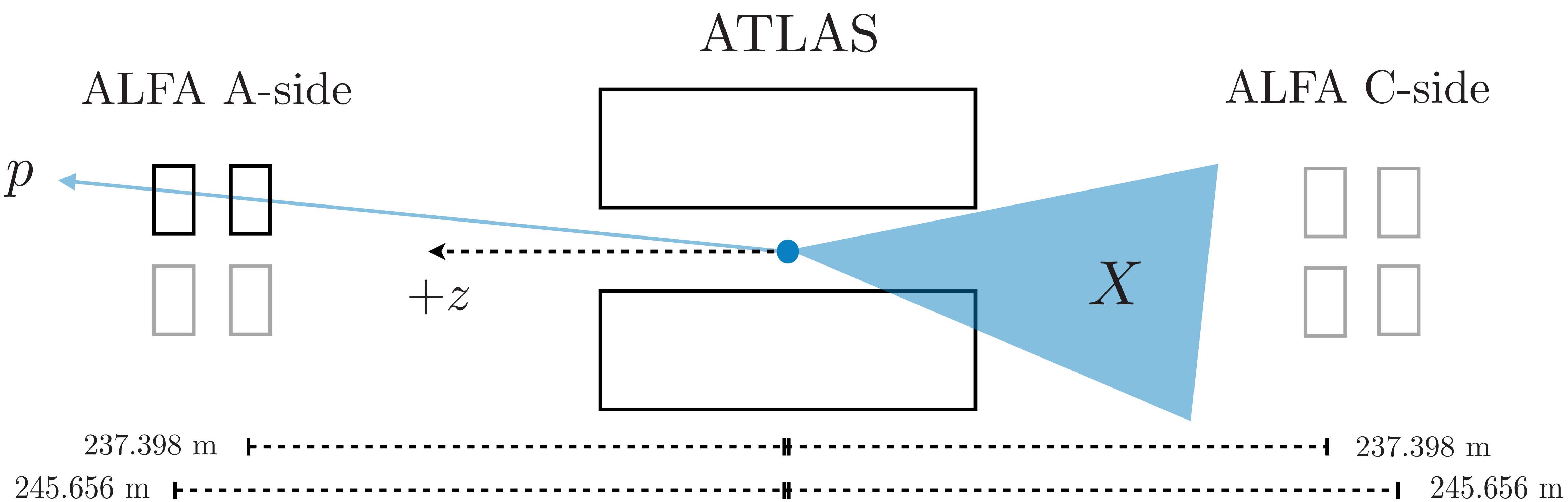
Experiment

But how do we detect Diffractive Events?

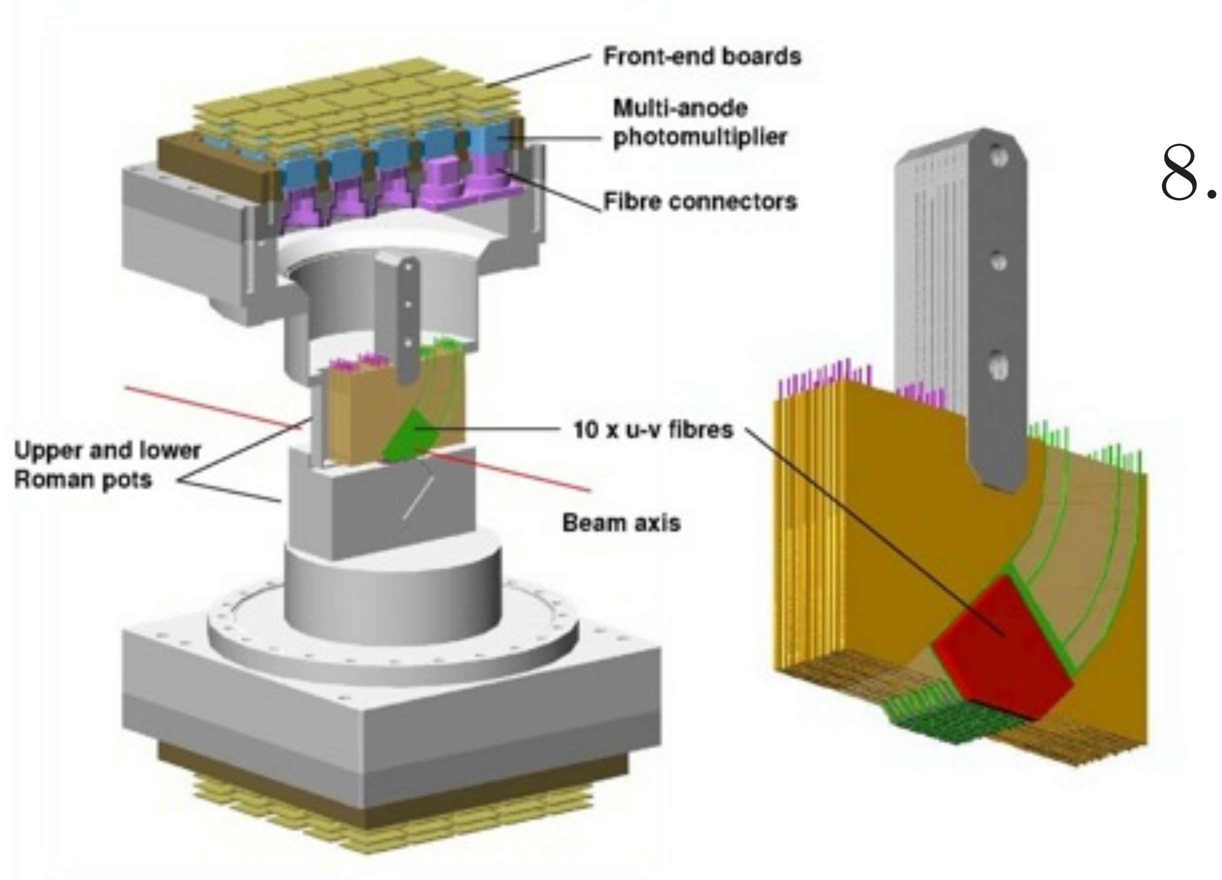
Detection of Diffractive Events



The ALFA Detector is just a ~ few mm in size located ~240 m from collision point



The ALFA Detector

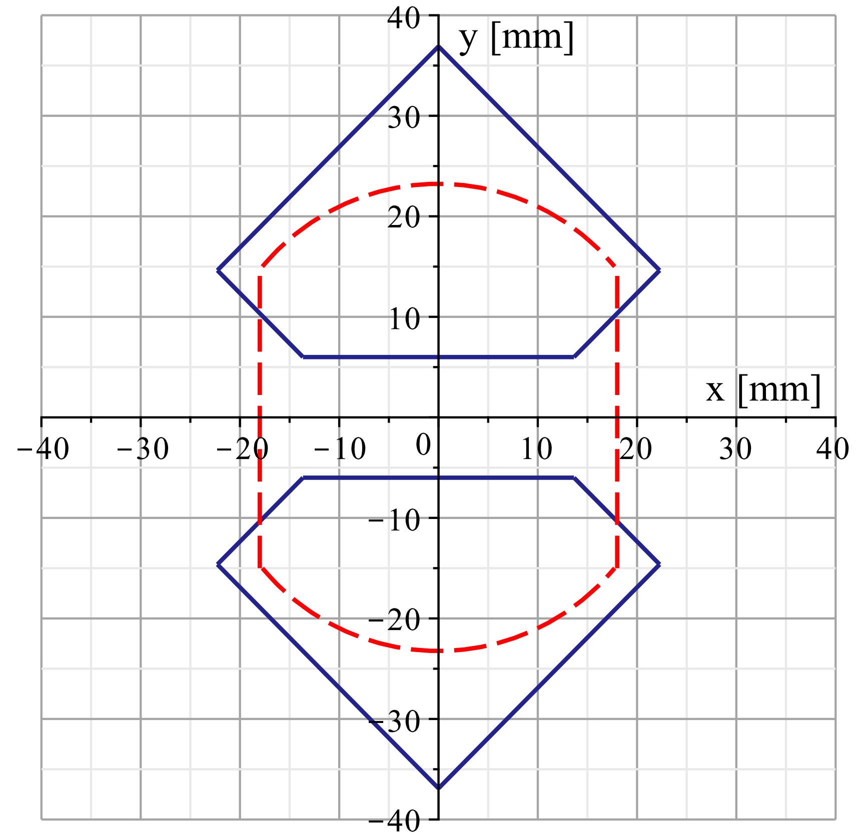


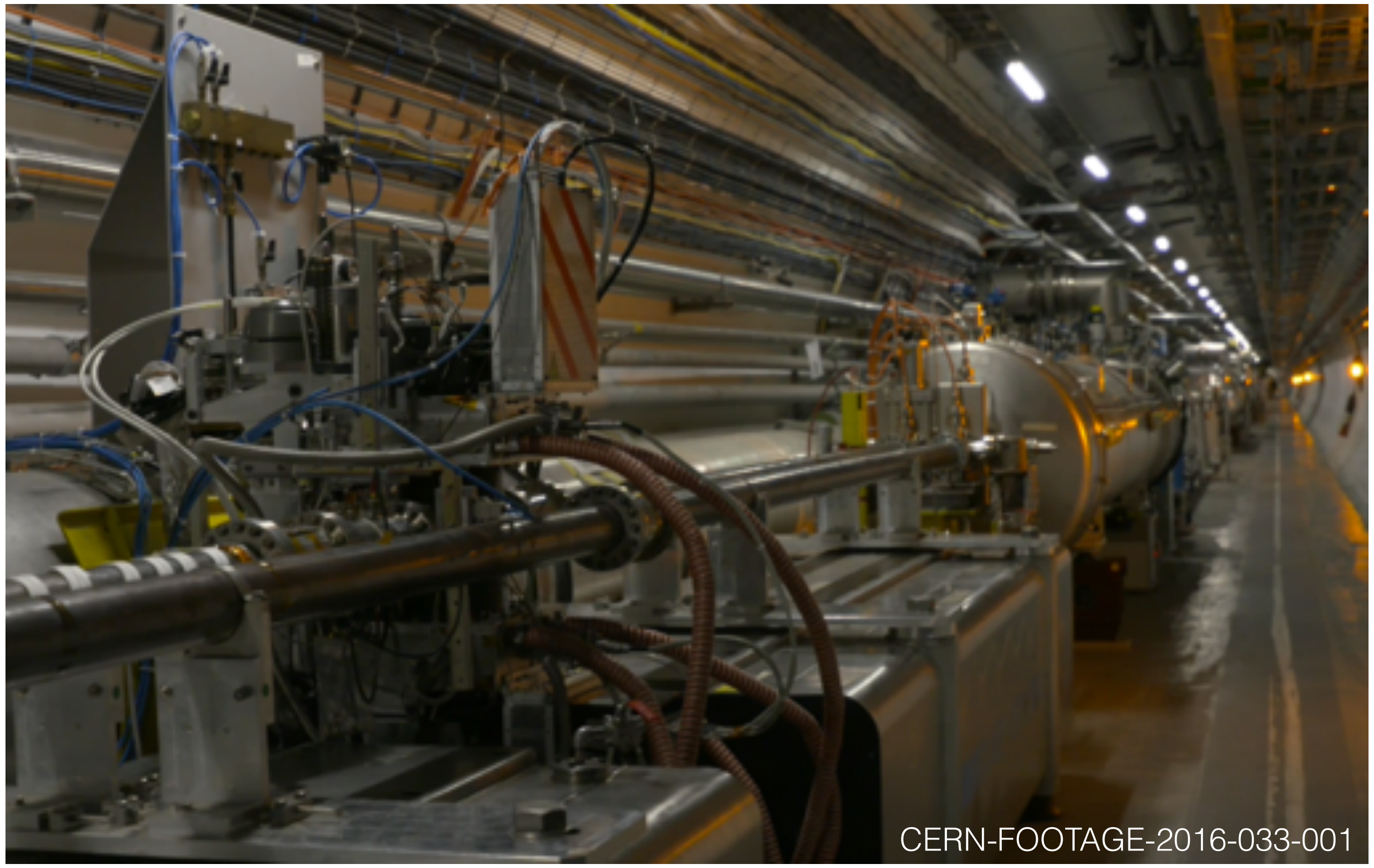
$$8.5 \lesssim |\eta| \lesssim 11.5$$

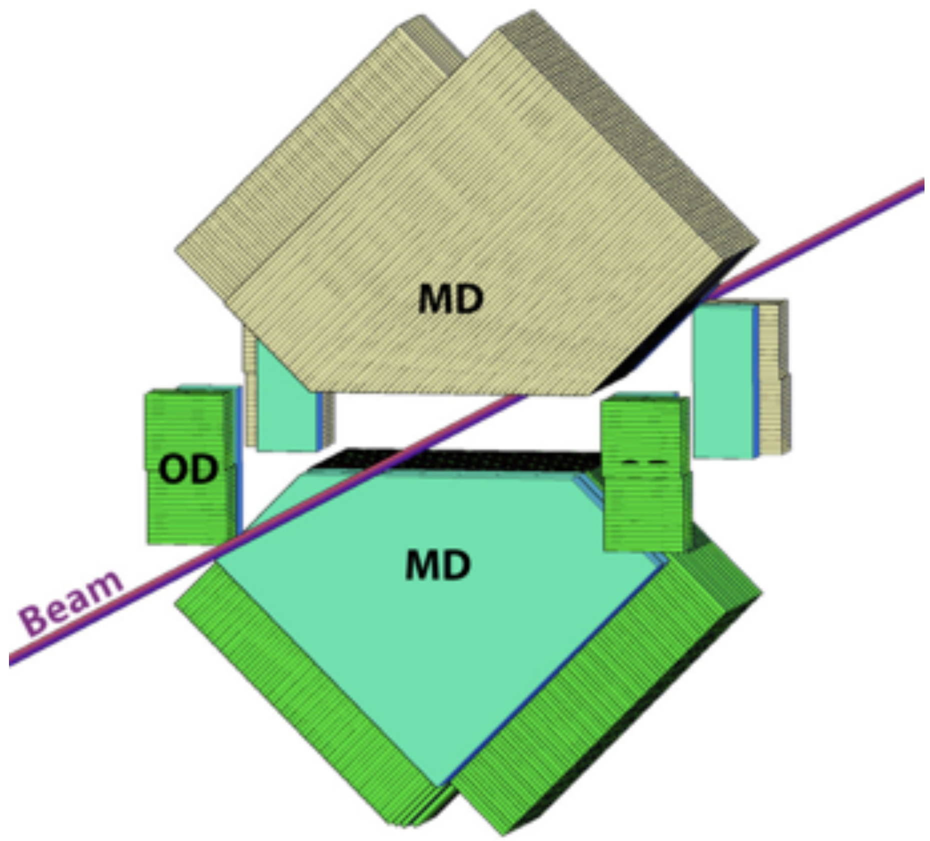
$$\xi < 0.2$$

for

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







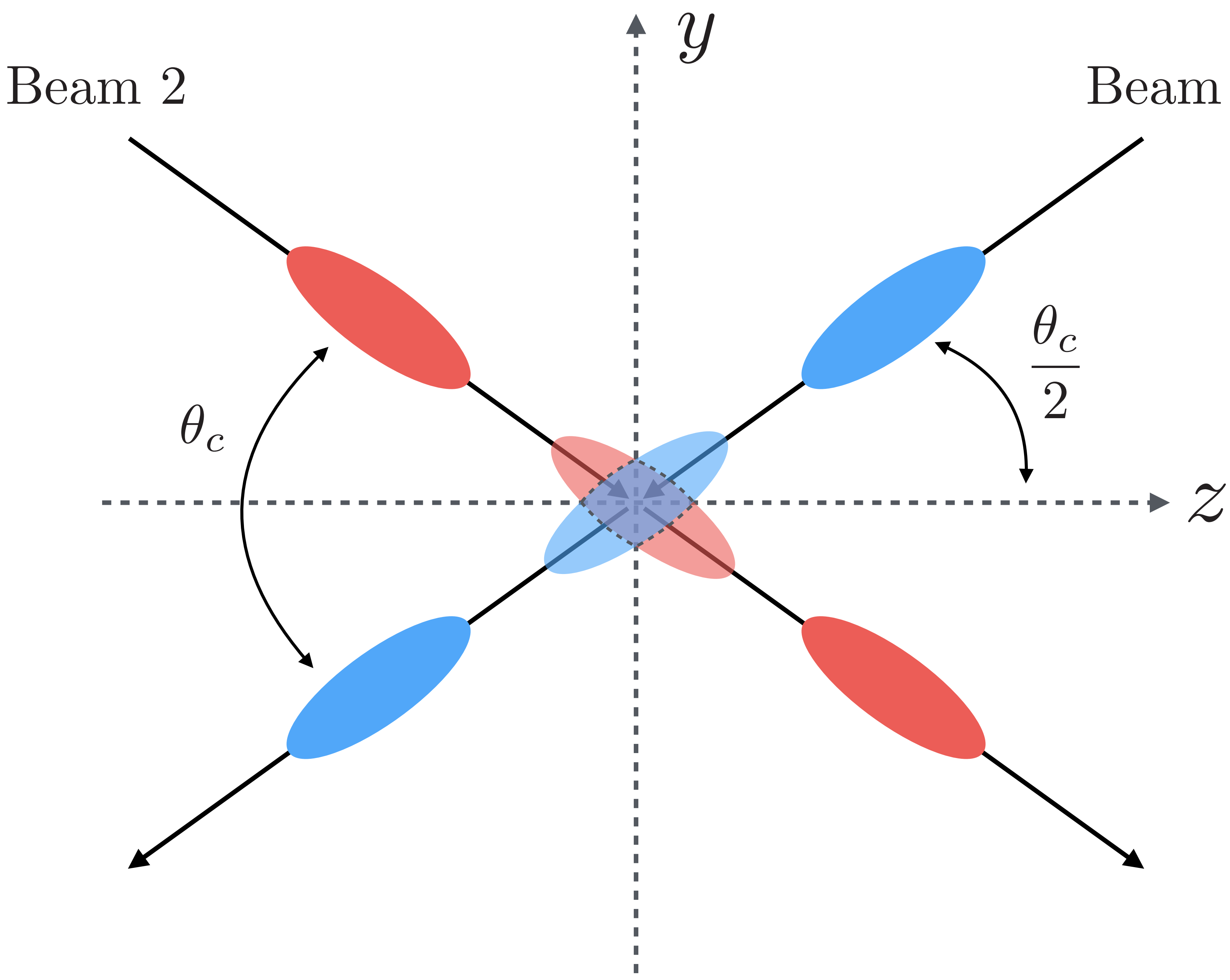
Data

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

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

Optics: $\beta^* = 90\ \text{m}$

Dates: 15 - 18 October, 2015



LHC Run 2 data

671 colliding bunches

Simulation Framework

A fast simulation of the detector response
was developed for the purposes of this thesis

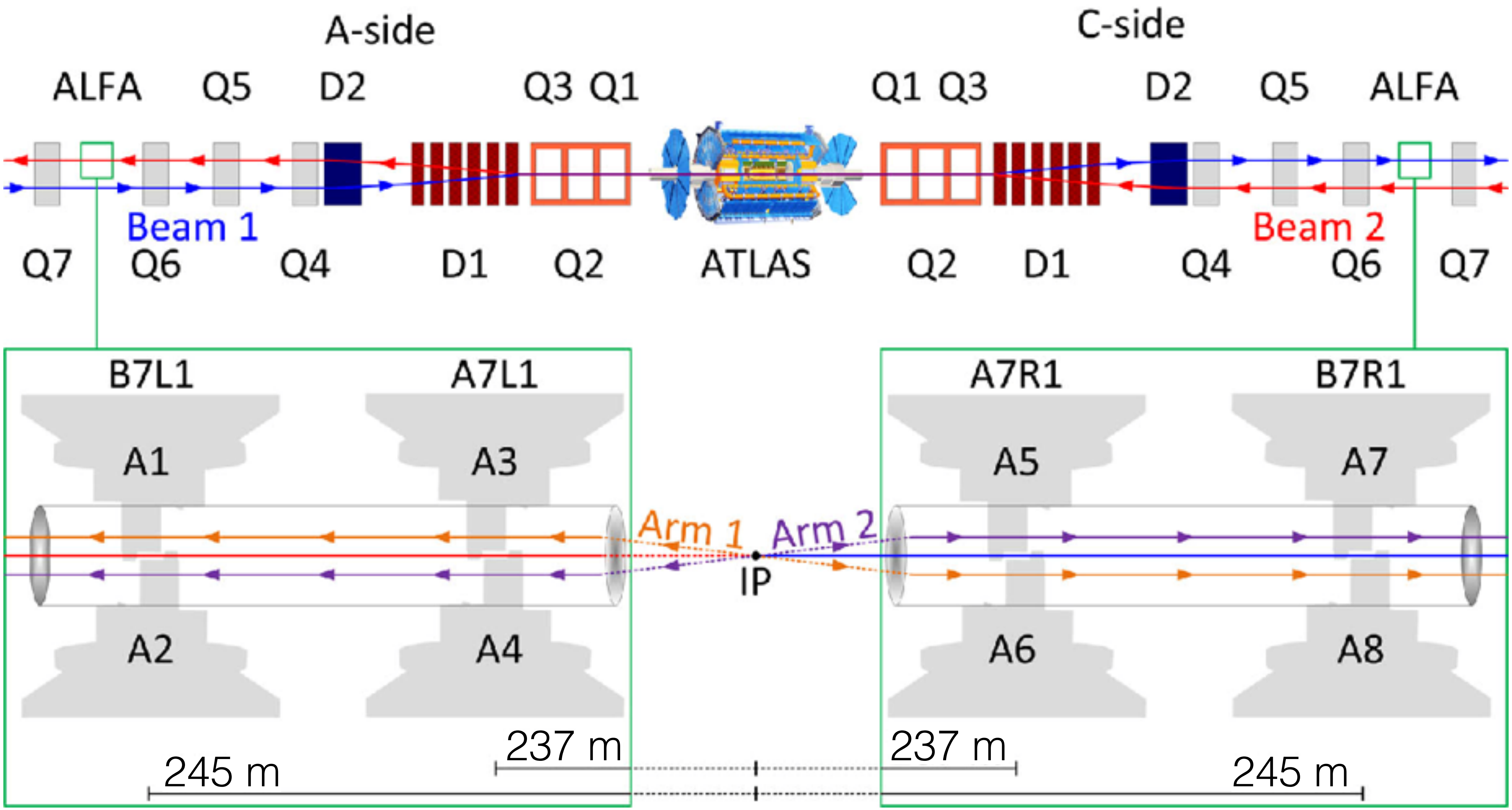
Simulation Framework

Pythia for Generation, Rivet for Analysis

- **Beam Transport:** Transport of Protons down the LHC beam pipe to ALFA
- **ALFA Acceptance and Smearing**
- **Reconstruction of Proton Kinematics**
- **ATLAS Simulation:** Inner Detector and MBTS

Beam Transport

Magnetic lattice in the LHC beam pipe from ATLAS to ALFA will affect the Proton Trajectories



Beam Transport

MAD-X can simulate and describe each element

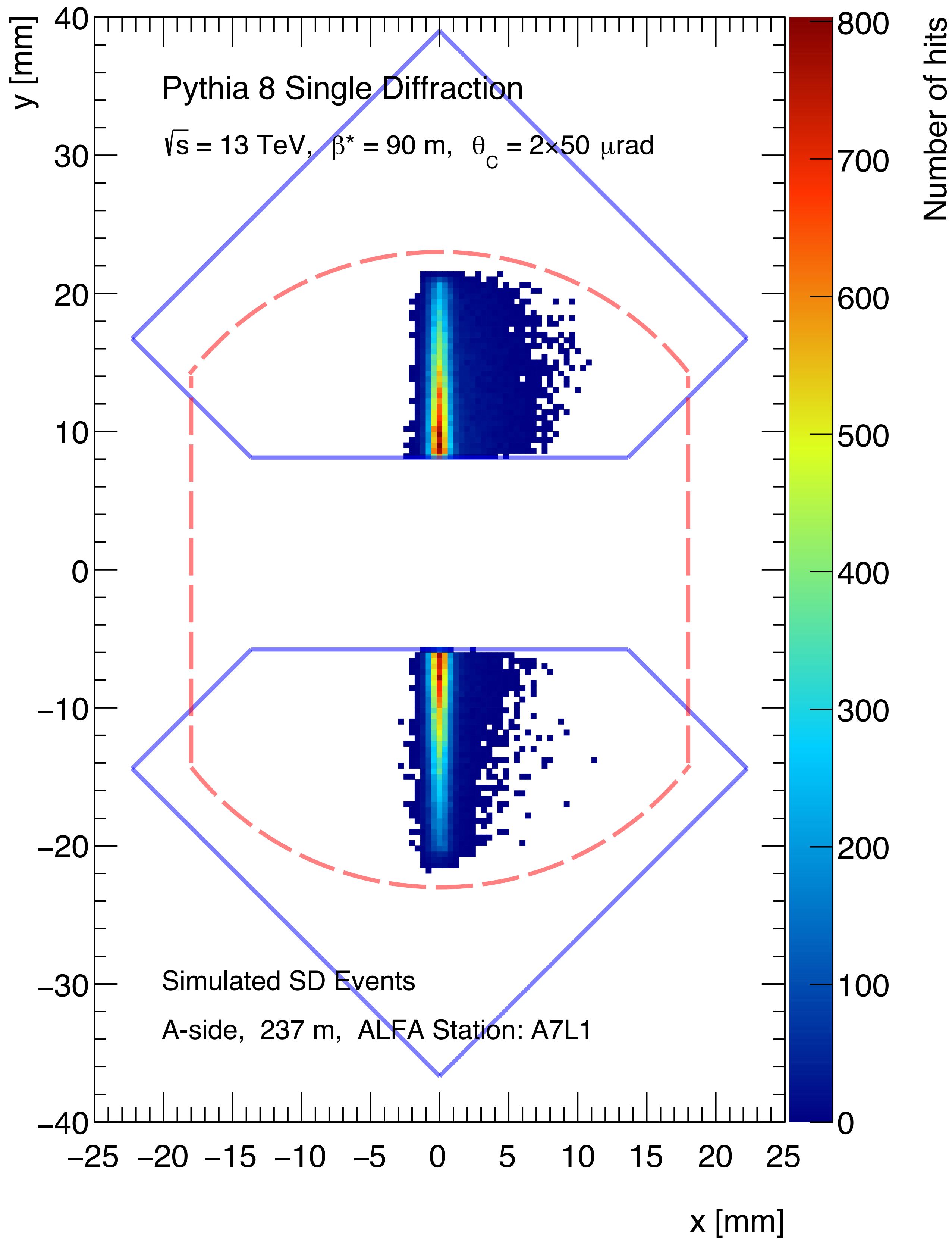
ForwardTransportFast can simulate the proton trajectory at any point down the beam pipe

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

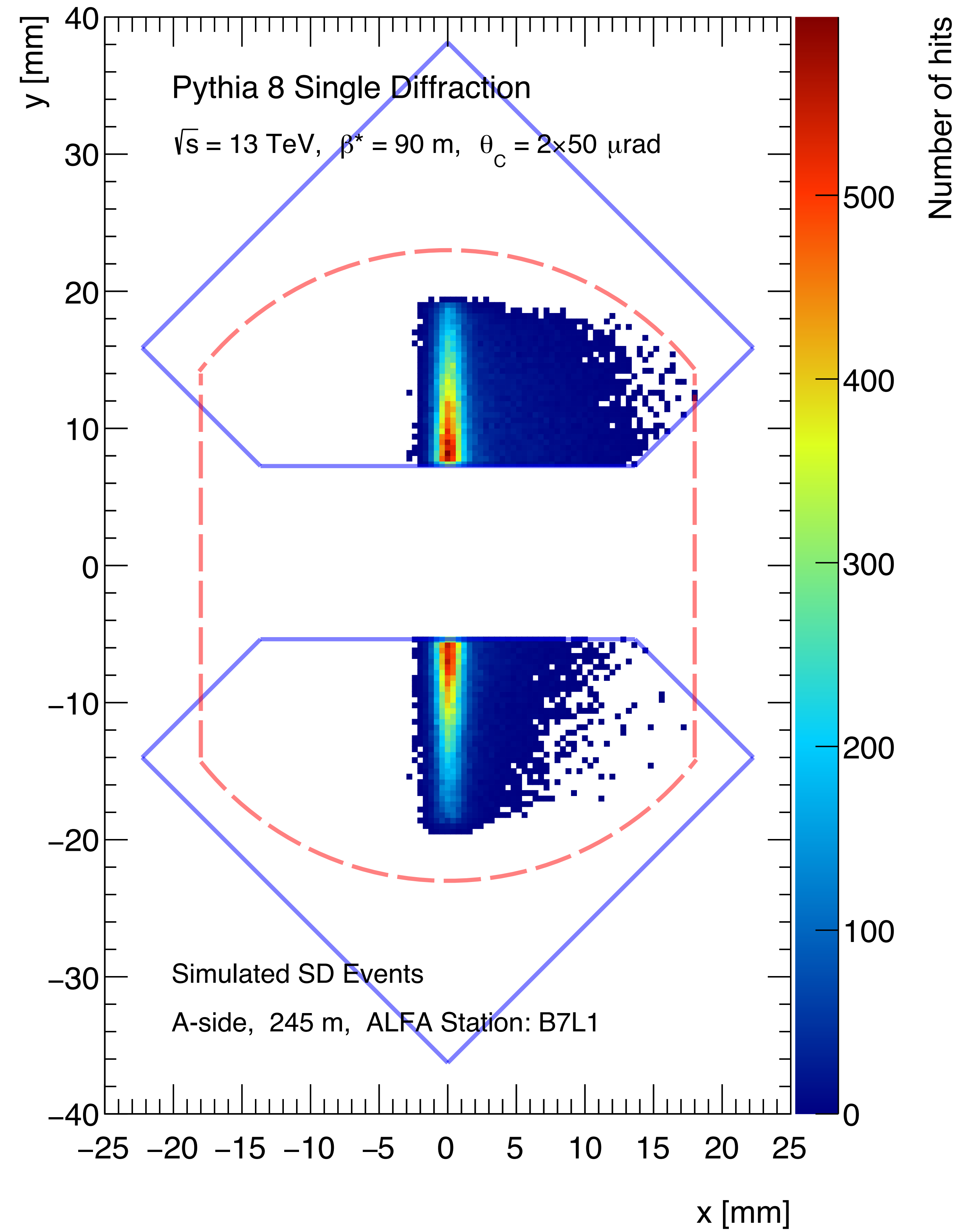
$$u = \{x, y\}$$

ALFA Hitmaps and Smearing

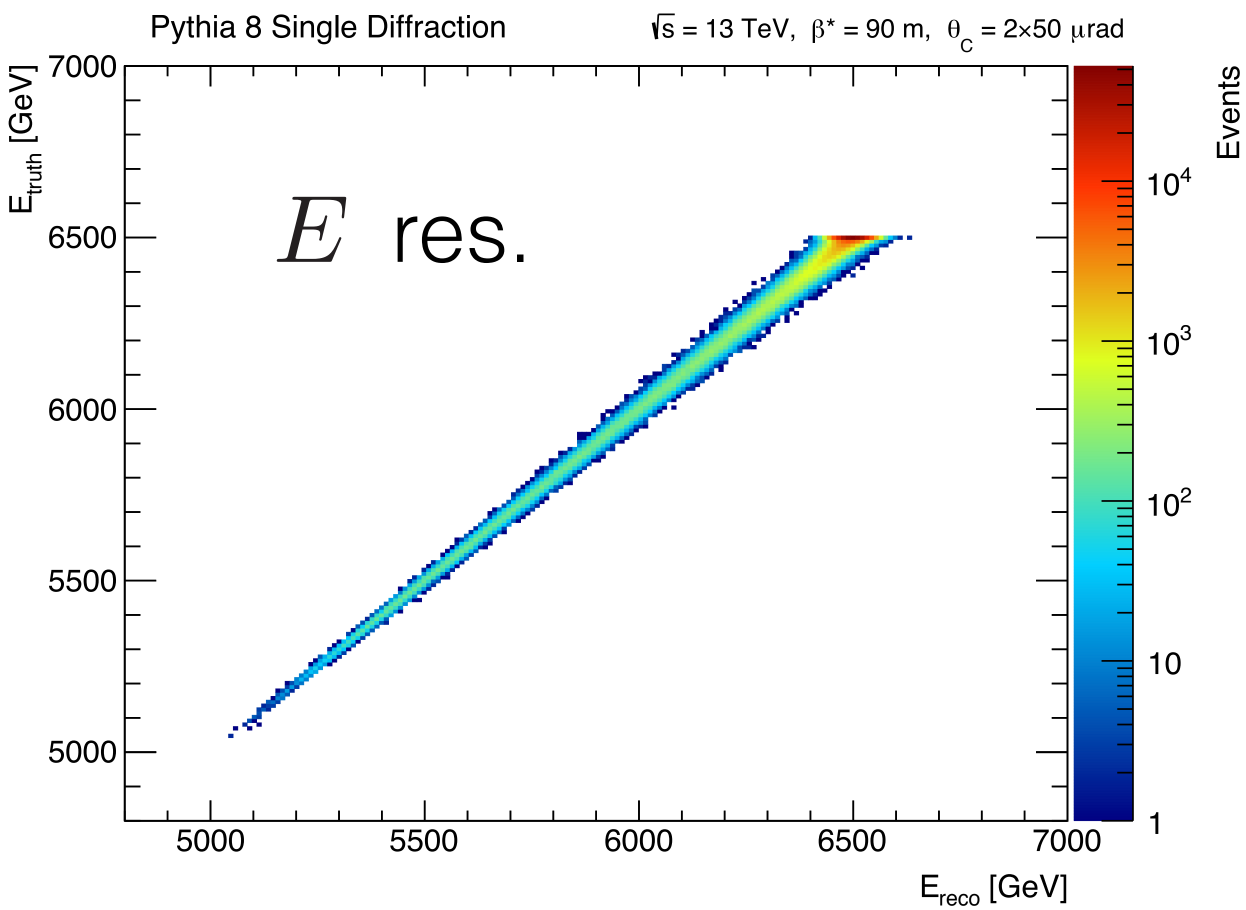
Inner: 30 μm

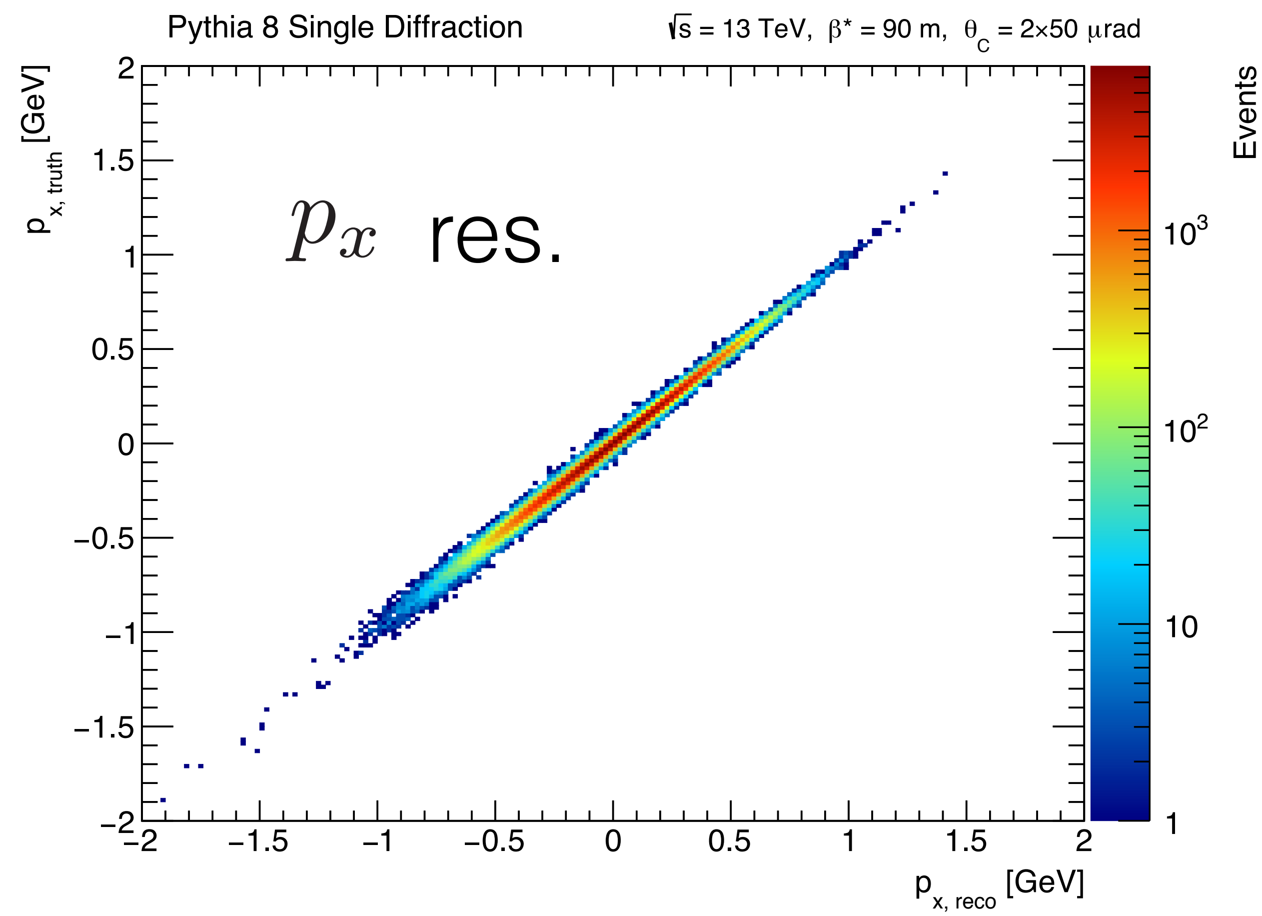


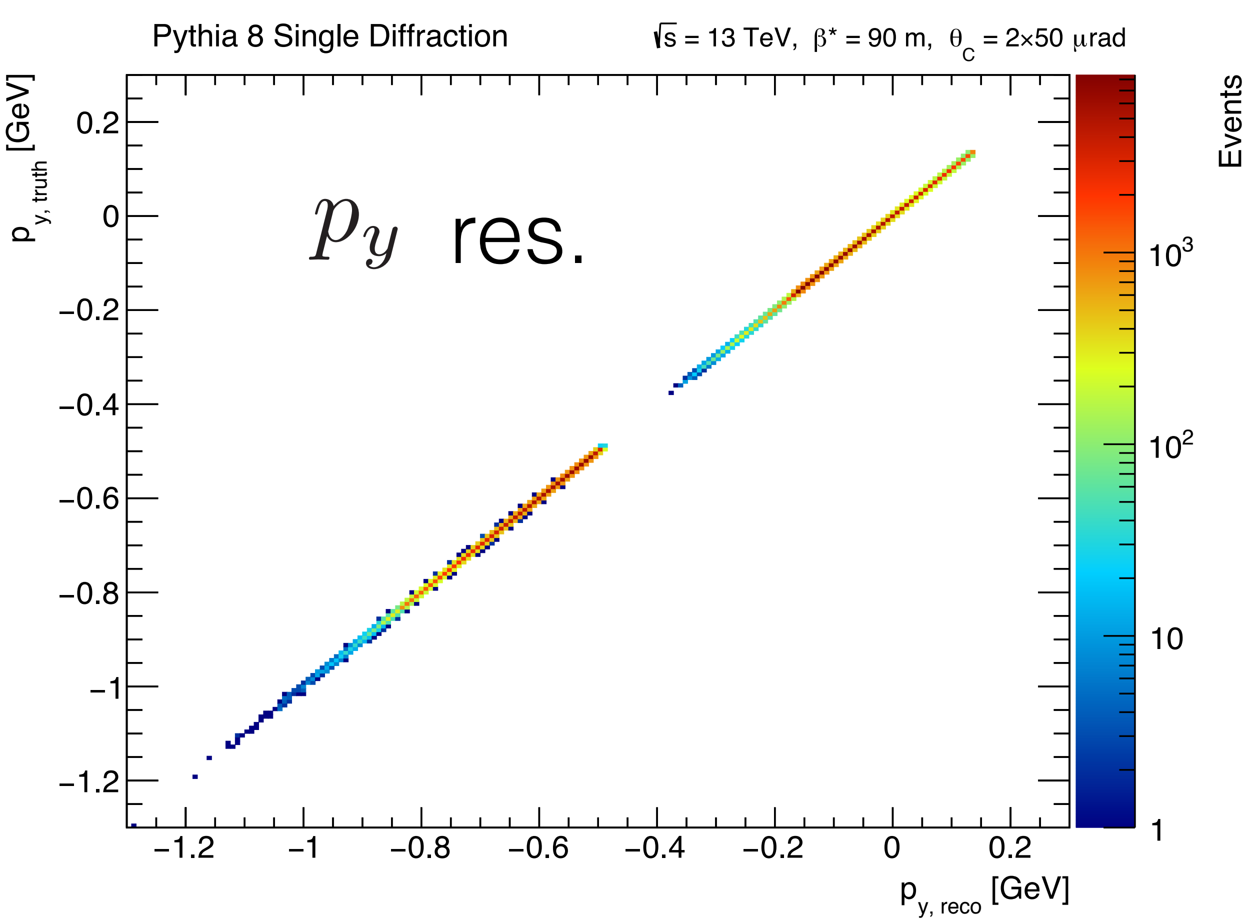
Outer: 40 μm



Reconstruction of Proton Kinematics: Resolution







ALFAReco

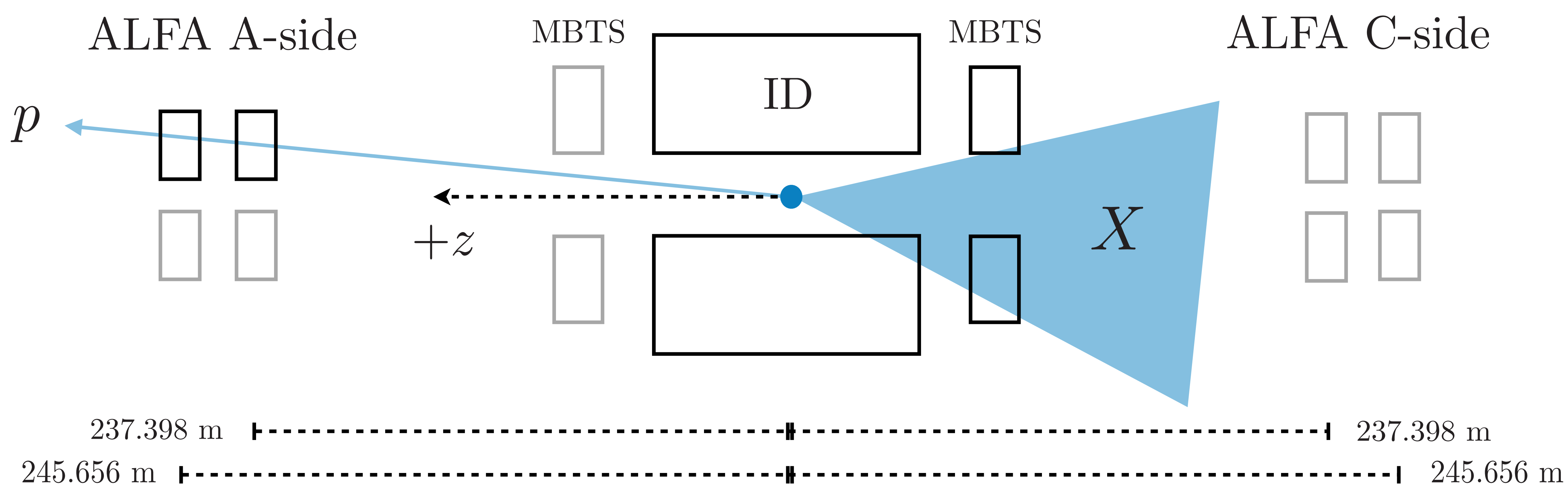
$$\rho_E = 0.99561$$

$$\rho_{p_x} = 0.99693$$

$$\rho_{p_y} = 0.99993$$

Event Selection

- Exactly 1 hit in ALFA in one of the 4 arms
  The other arms are empty
- At least 2 tracks in ATLAS inner detector
- Exactly 1 reconstructed primary vertex
- Hit in MBTS on opposite side of the ALFA Hit



Sensitivity to Model Parameters (ε, α')

Sensitivity to Model Parameters

What happens when we vary the model parameters?

Sensitivity to the model parameters come in two ways:

- Accepted Event Count
(Total Cross-section)

- Shape of the Distributions
(Differential Cross-section)

Sensitivity to Model Parameters

We have generated 9 samples
with 1 million events each

And with permutations of the parameters values:

$$\varepsilon = \{0.02, 0.085, 0.15\}$$

$$\alpha' = \{0.1, 0.25, 0.4\}\ \mathrm{GeV}^{-2}$$

Sensitivity to Model Parameters

Accepted Event Count
(Total Cross-section)

	$\varepsilon = 0.02$	$\varepsilon = 0.085$	$\varepsilon = 0.15$
$\alpha' = 0.1$ GeV^{-2}	$(19.44 \pm 0.04)\%$	$(10.11 \pm 0.03)\%$	$(4.08 \pm 0.02)\%$
$\alpha' = 0.25$ GeV^{-2}	$(21.33 \pm 0.05)\%$	$(11.28 \pm 0.03)\%$	$(4.63 \pm 0.02)\%$
$\alpha' = 0.4$ GeV^{-2}	$(21.58 \pm 0.05)\%$	$(11.62 \pm 0.03)\%$	$(4.64 \pm 0.02)\%$

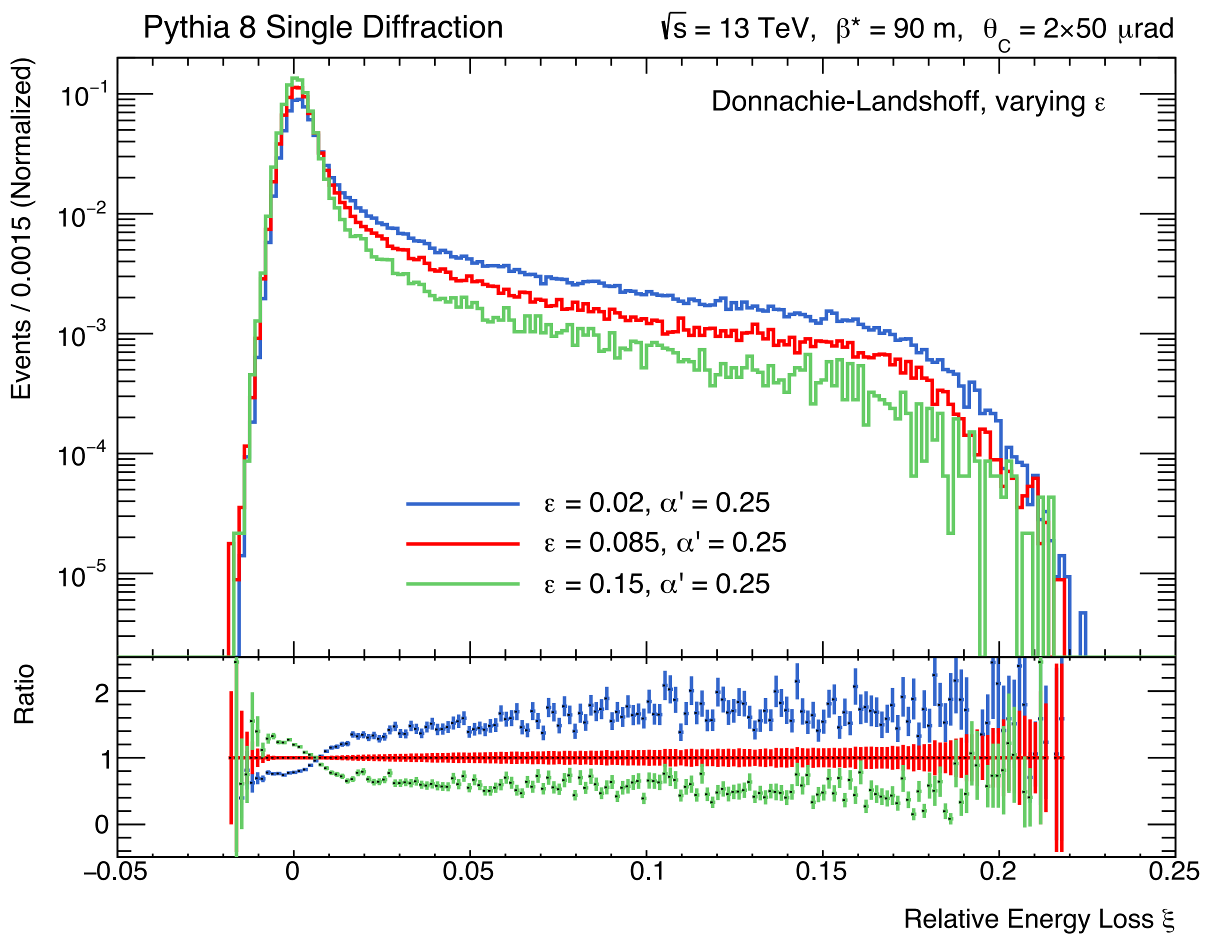
$$\text{Increasing } \varepsilon \;\Rightarrow\; \text{Lower accepted event count}$$

$$\text{Increasing } \alpha' \;\Rightarrow\; \text{Larger accepted event count}$$

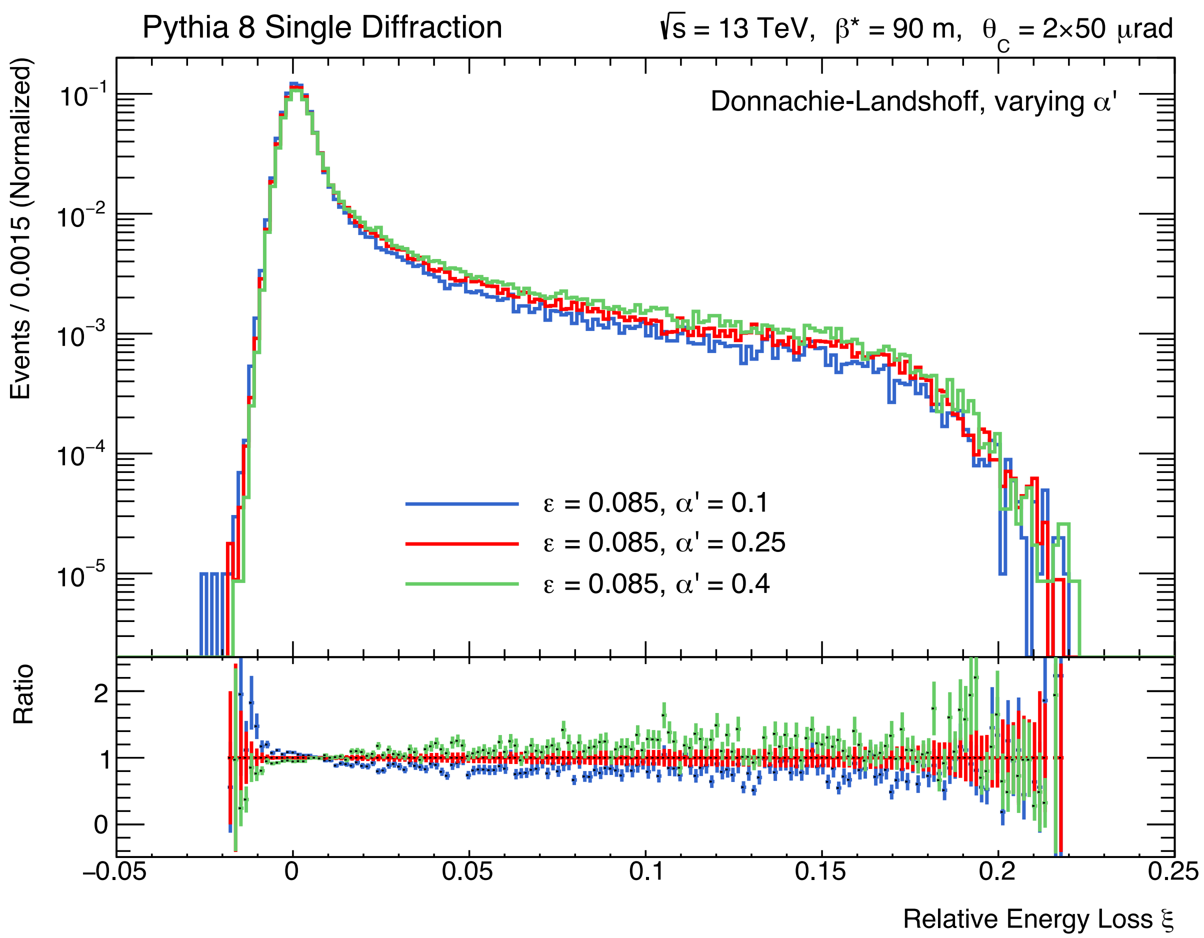
Sensitivity to Model Parameters

Relative Energy Loss ξ

Varying ε



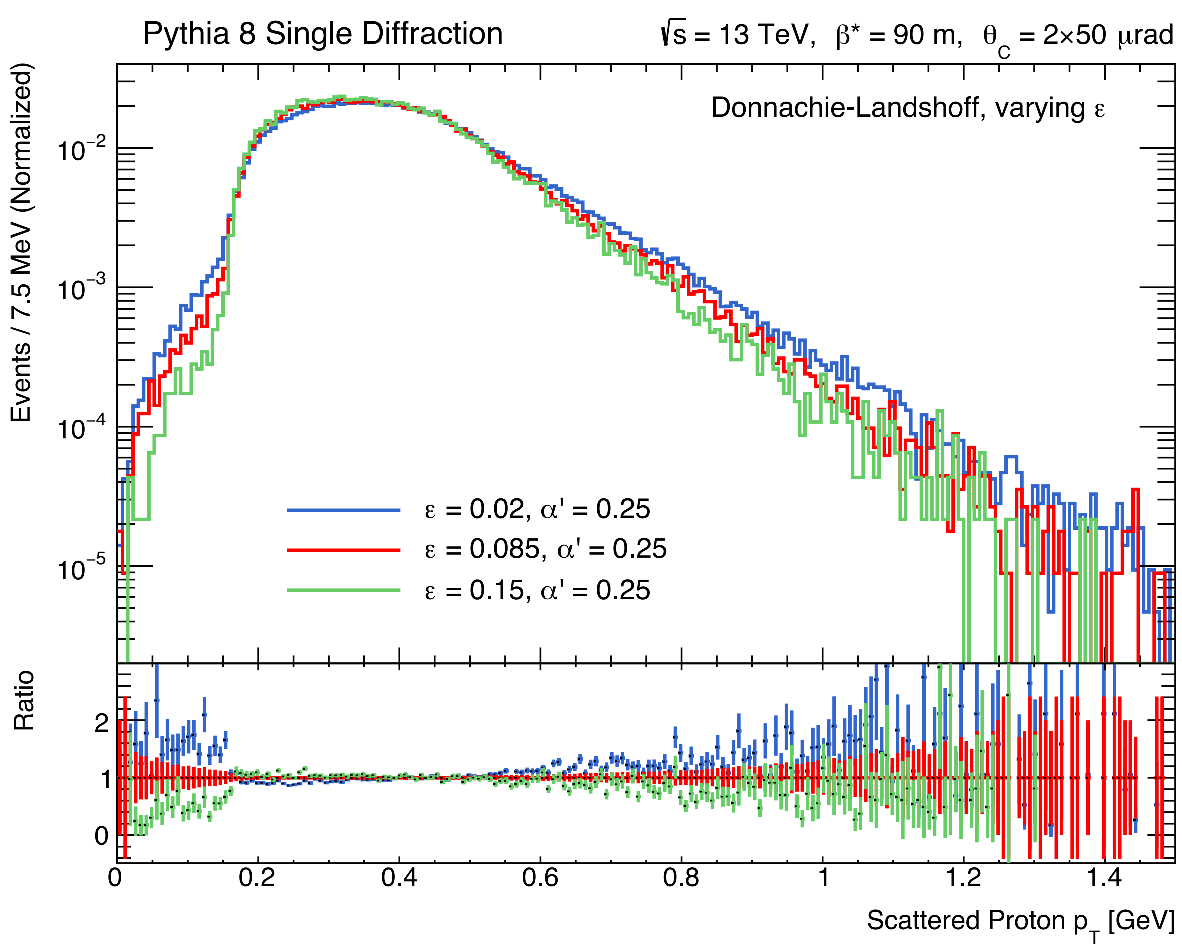
Varying α'



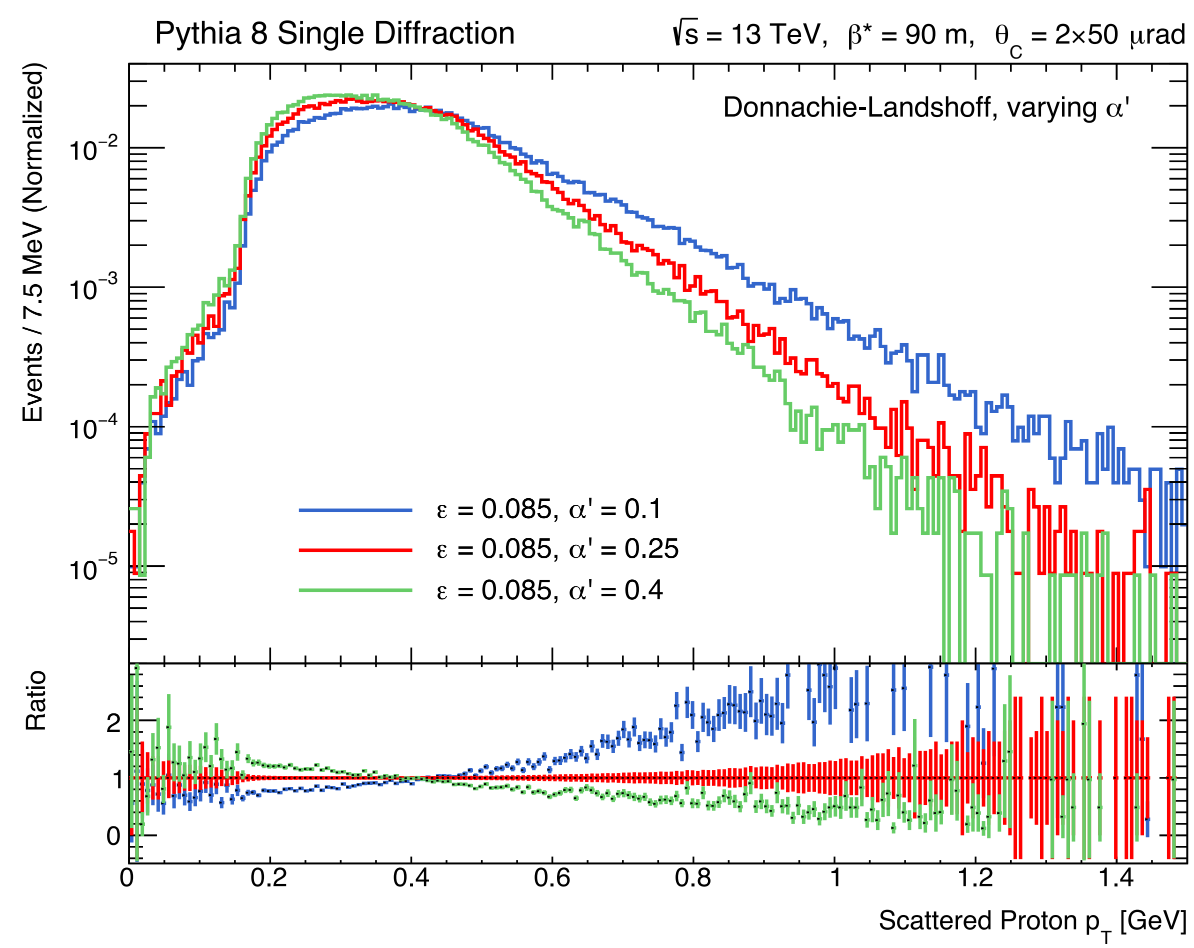
Sensitivity to Model Parameters

Transverse Momentum p_T

Varying ε



Varying α'



Fit Procedure

to determine the model parameters

Fit Procedure

Goal:

Develop a fit procedure to determine model parameters

ε and α'

We want to minimize:

$$\chi^2(\varepsilon, \alpha') = \sum_i^n \frac{(O_i - E_i(\varepsilon, \alpha'))^2}{\sigma_{O_i}^2 + \sigma_{E_i}^2}$$

Observation: O_i

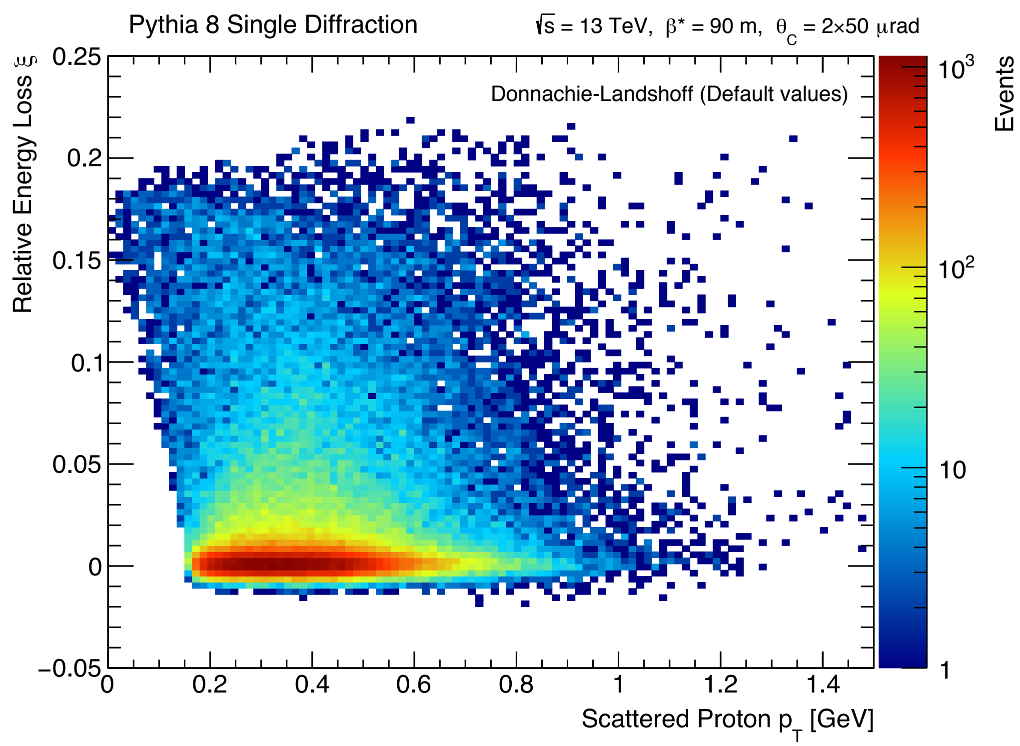
Expectation Value: $E_i(\varepsilon, \alpha')$

Fit Procedure

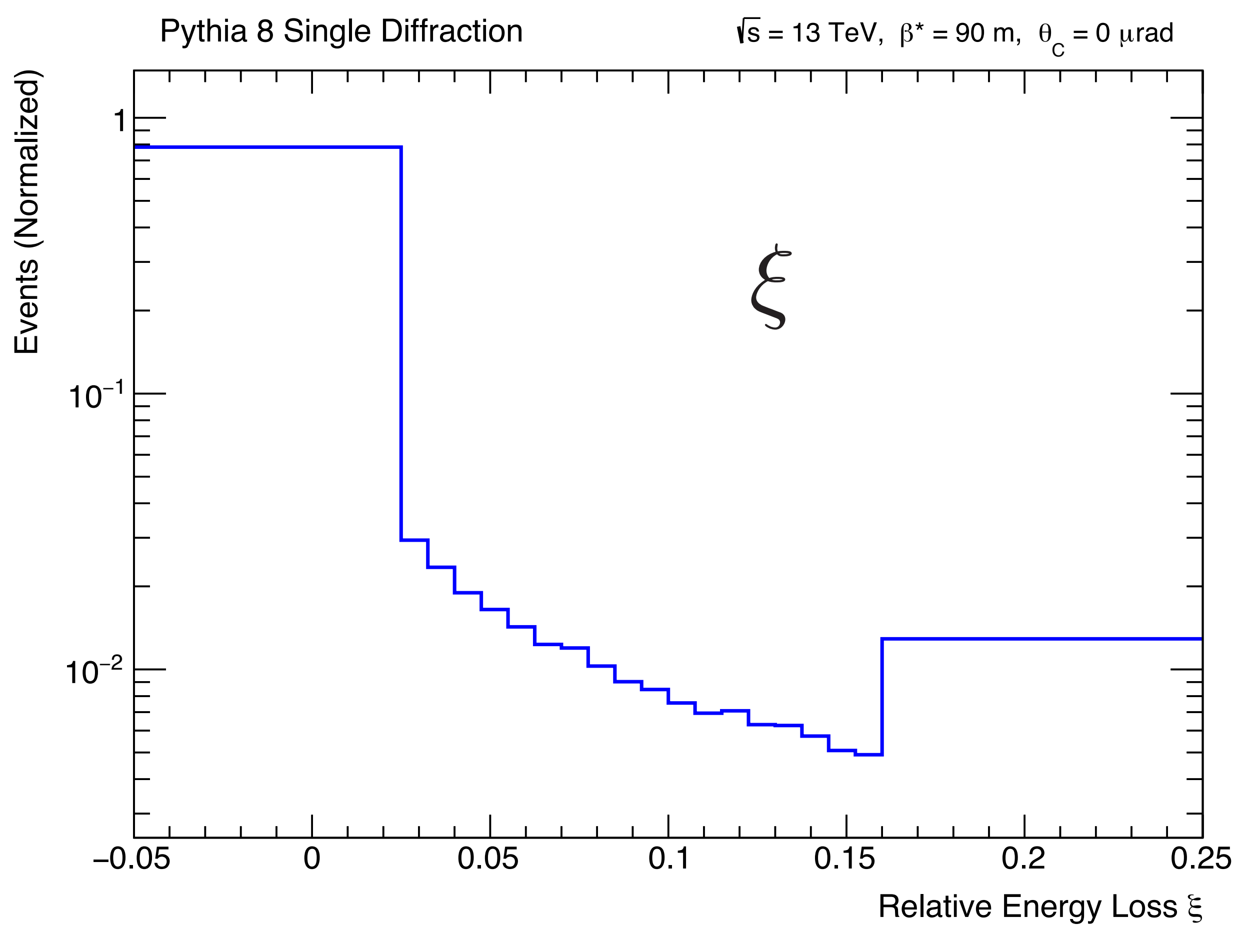
We consider: ξ and p_T

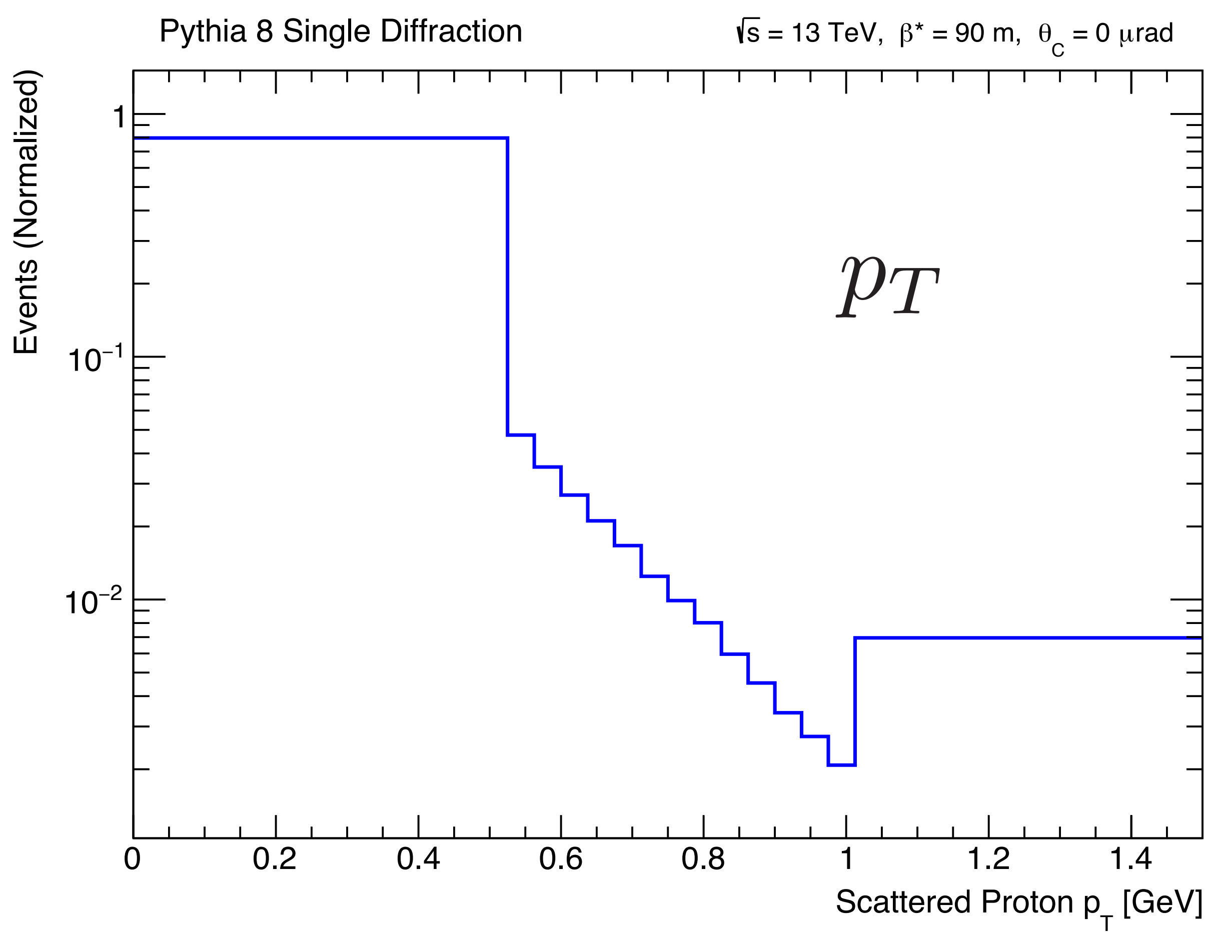
$$\rho_{\xi,t} = (12.8 \pm 0.2)\,\%$$

$$\rho_{\xi,p_T} = (-2.0 \pm 0.2)\,\%$$



Non-equidistant Binning:



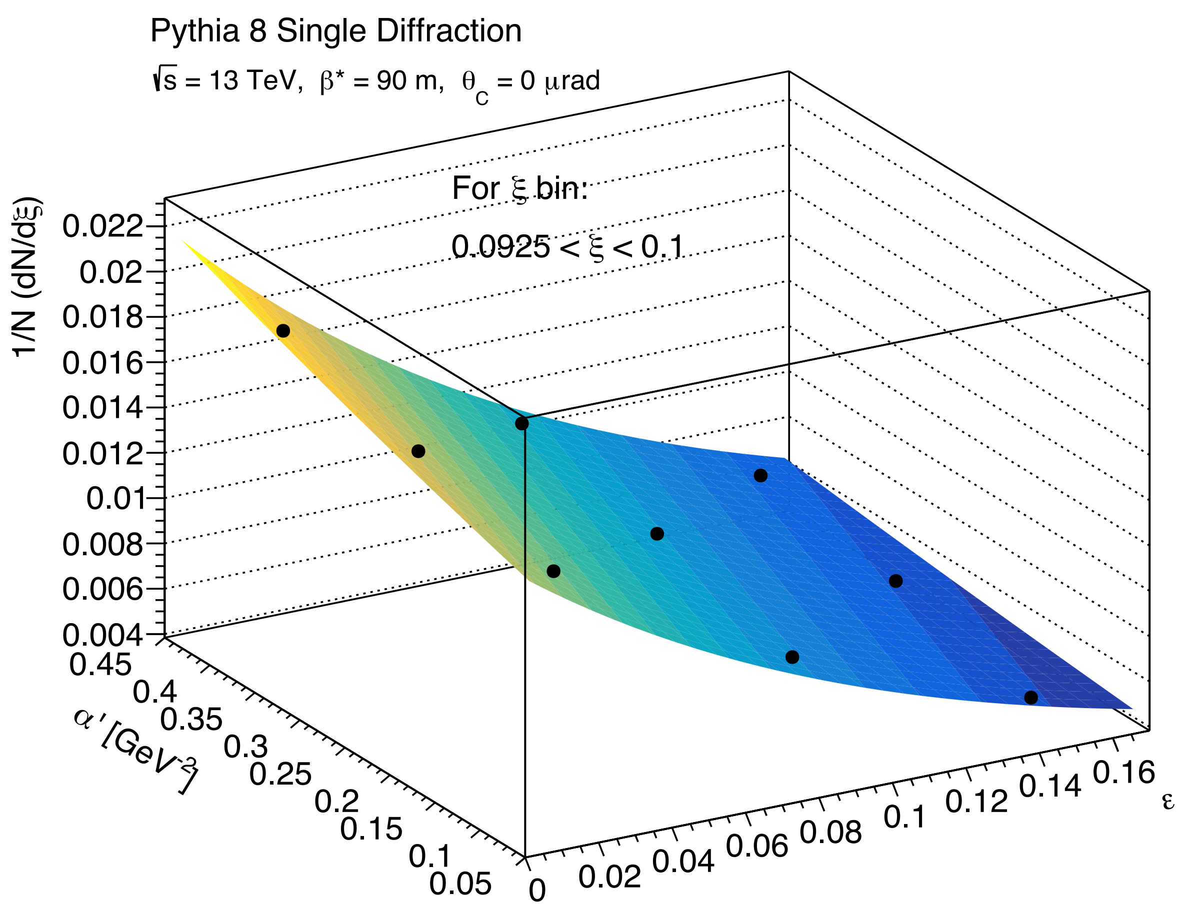


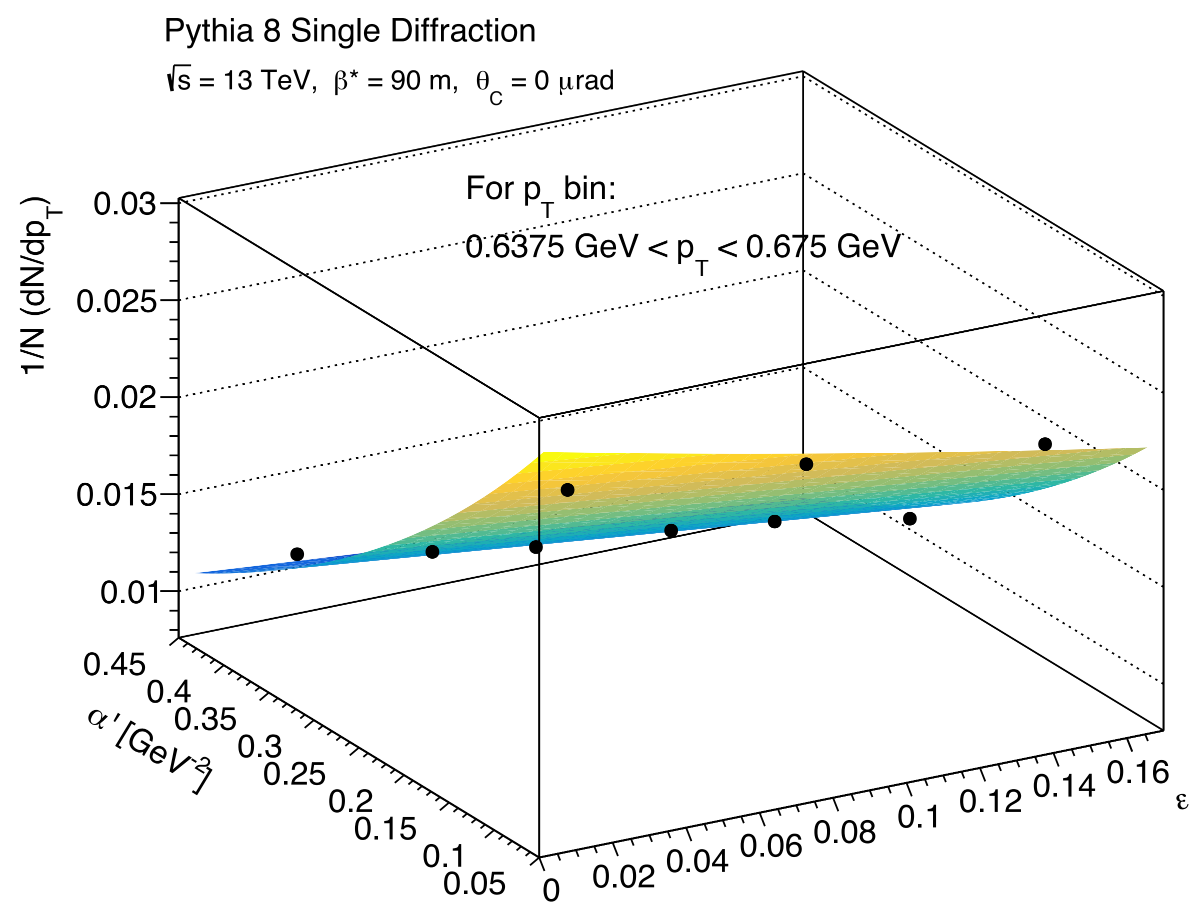
Fit Procedure - Expectation Values

Expectation Values:

Extrapolation between our 9 samples:

$$f_{\mathbb{P}/p}(\xi, t) \sim \xi^{1-2\alpha(t)} \quad \rightarrow \quad E_i(\varepsilon, \alpha') = a^{b\varepsilon + c\alpha' + d}$$

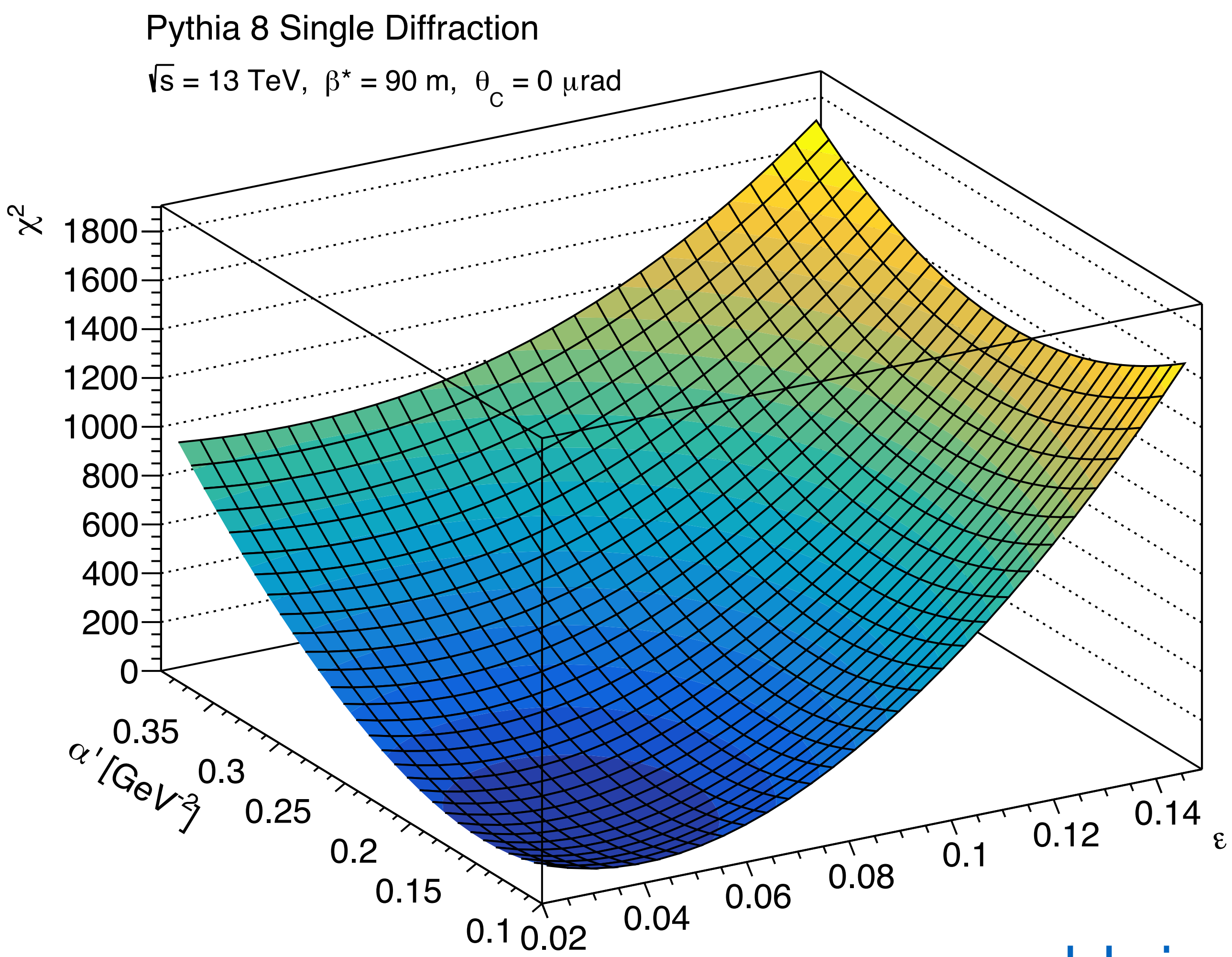


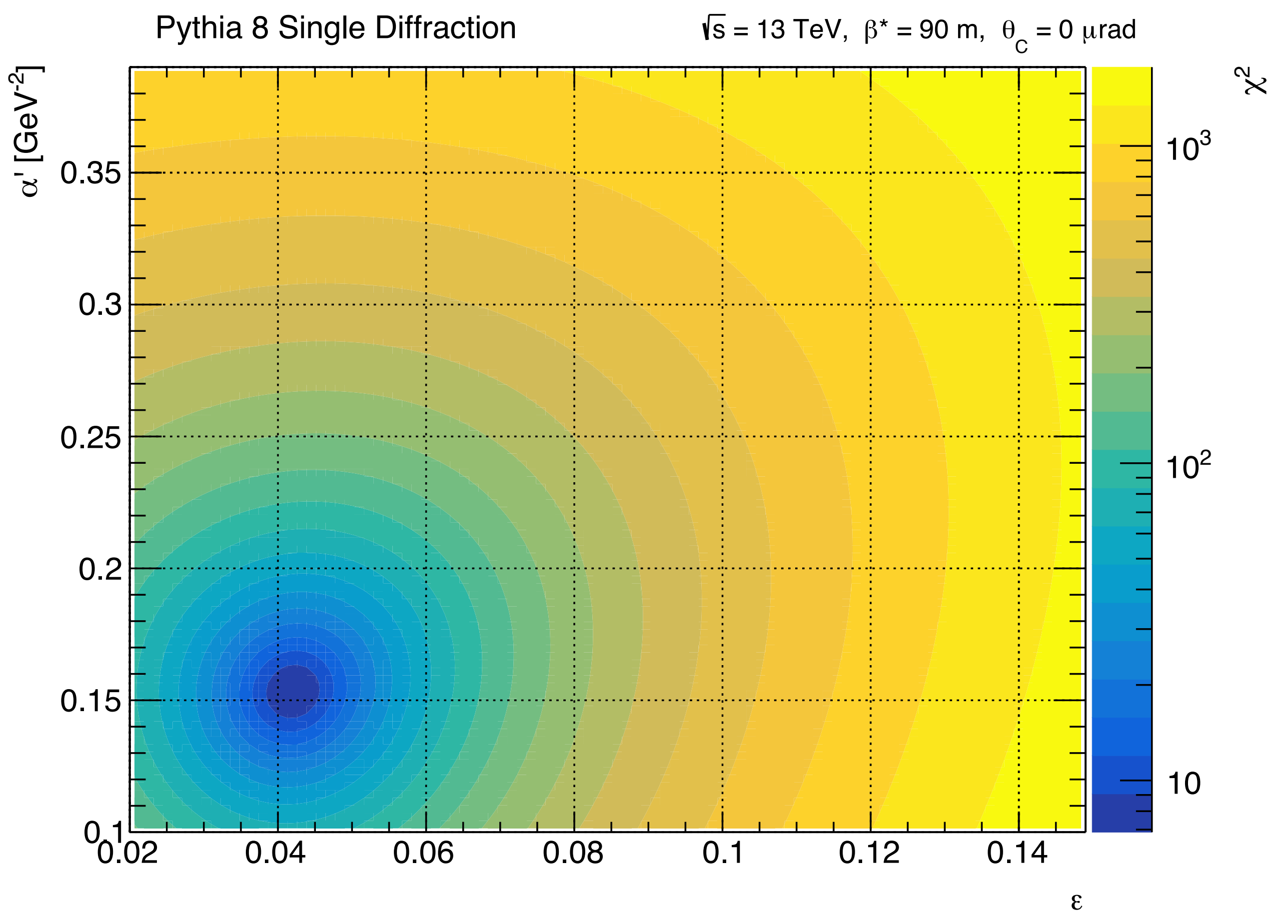


Fit Procedure - Expectation Values

Two test samples with an unknown parameterization was generated

Plot of χ^2 - function for Test Sample 1:





Using Minuit in ROOT for minimization

Fit Procedure - Results

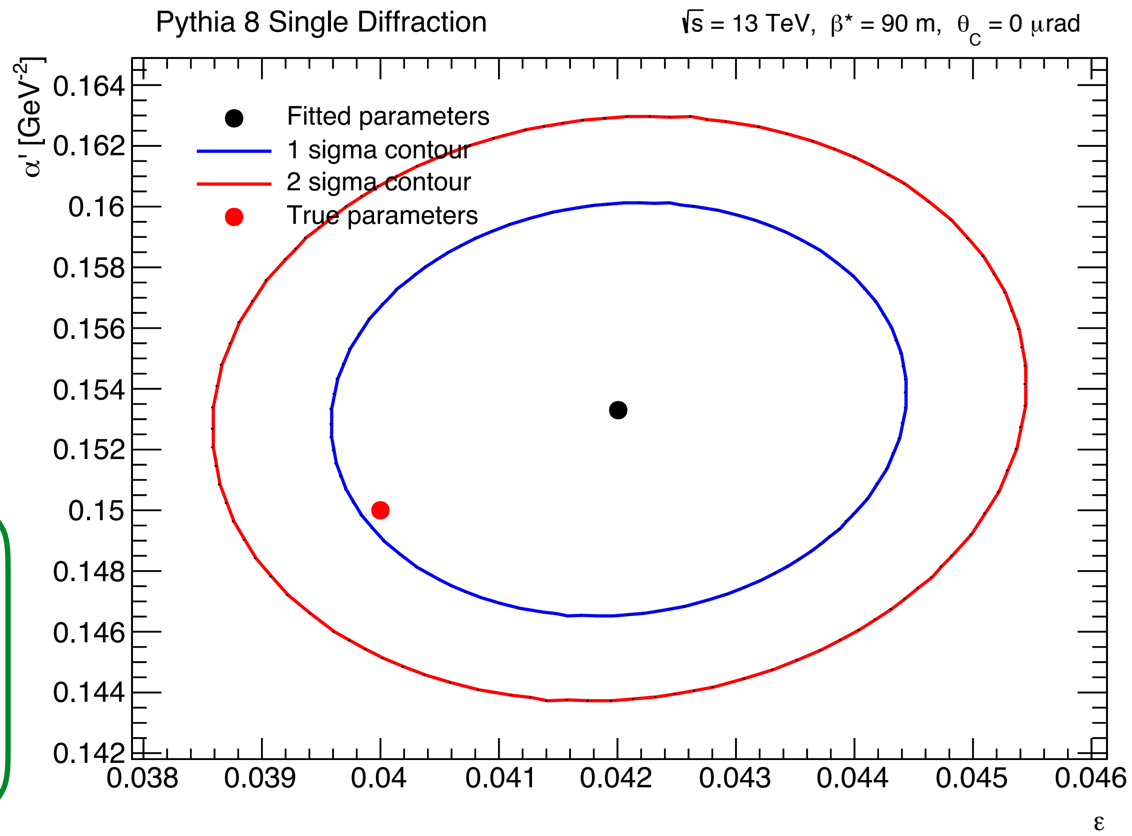
Test Sample 1:

True:

$$\varepsilon = 0.04$$
$$\alpha' = 0.15\ \text{GeV}^{-2}$$

Estimate:

$$\varepsilon = 0.042 \pm 0.002$$
$$\alpha' = 0.154 \pm 0.007\ \text{GeV}^{-2}$$



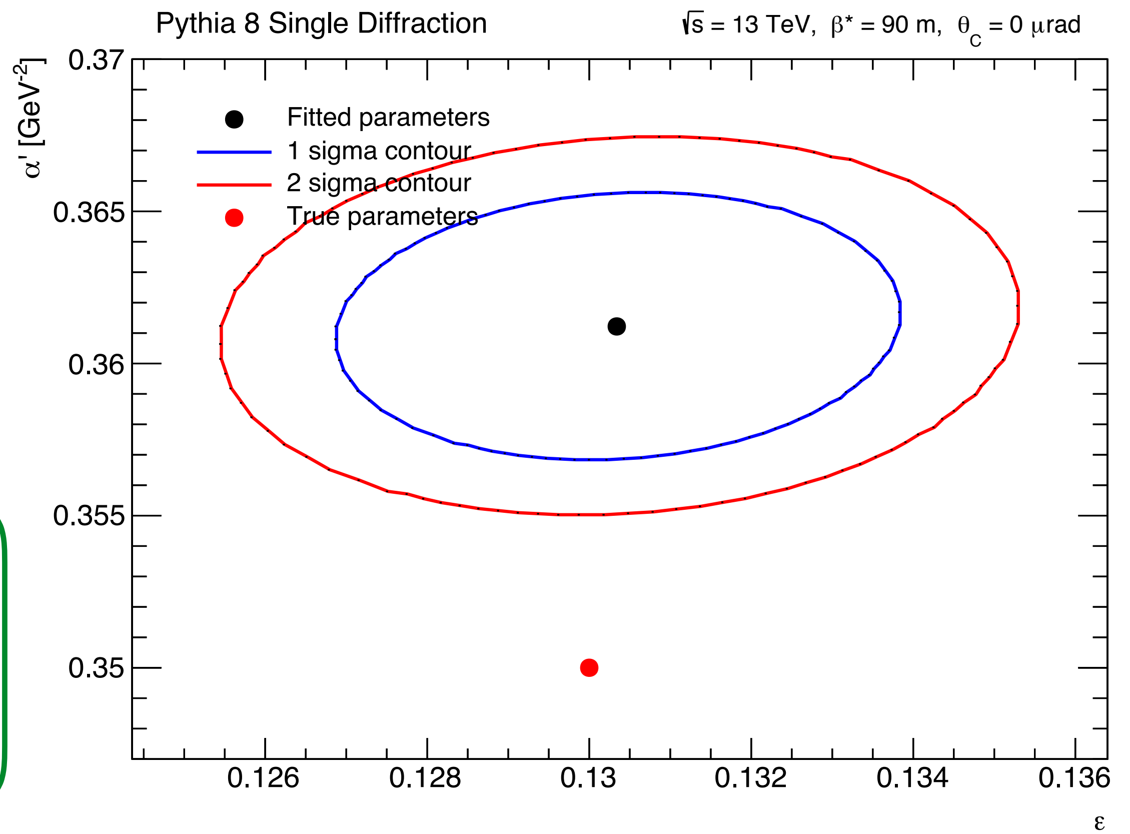
Test Sample 2:

True:

$$\varepsilon = 0.13$$
$$\alpha' = 0.35\ \text{GeV}^{-2}$$

Estimate:

$$\varepsilon = 0.130 \pm 0.004$$
$$\alpha' = 0.361 \pm 0.004\ \text{GeV}^{-2}$$



Fit Procedure - Discussion

Possible improvements to the fit procedure:

Generating more samples will improve resolution in the parameter values

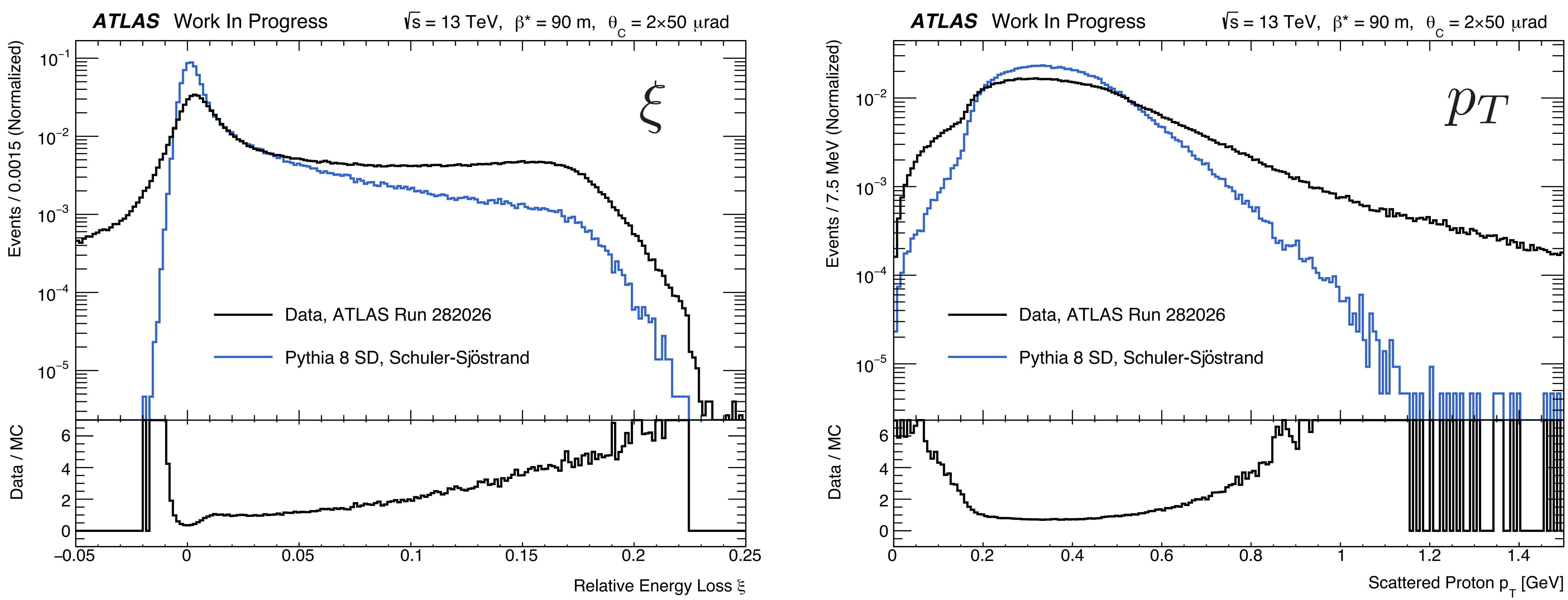
More events per sample will give better statistics

Data Analysis

A look at new 13 TeV data from ATLAS and ALFA

Data Analysis - Results

Data Results compared to Simulated SD



Regge Theory predicts $1/\xi$

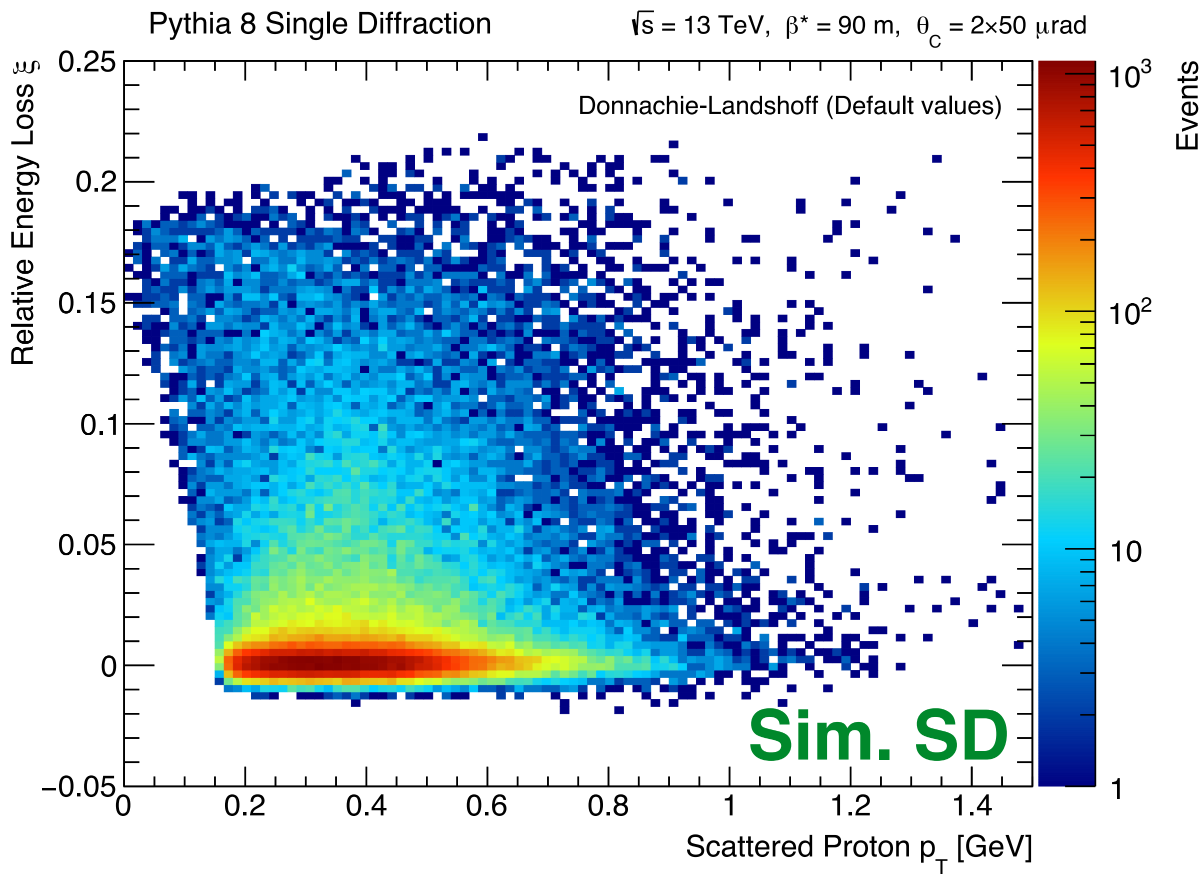
But we see a flat shoulder (seen before)

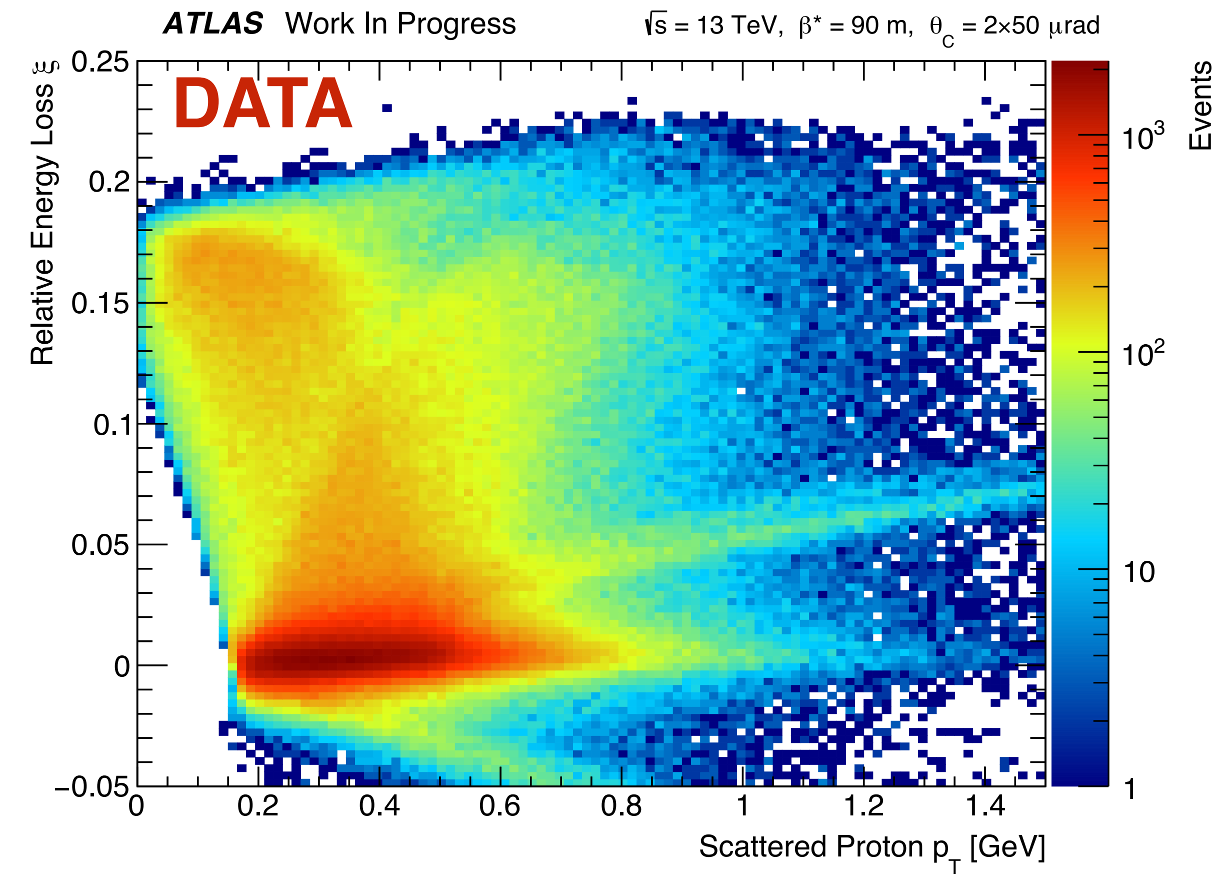
Data Analysis - Background

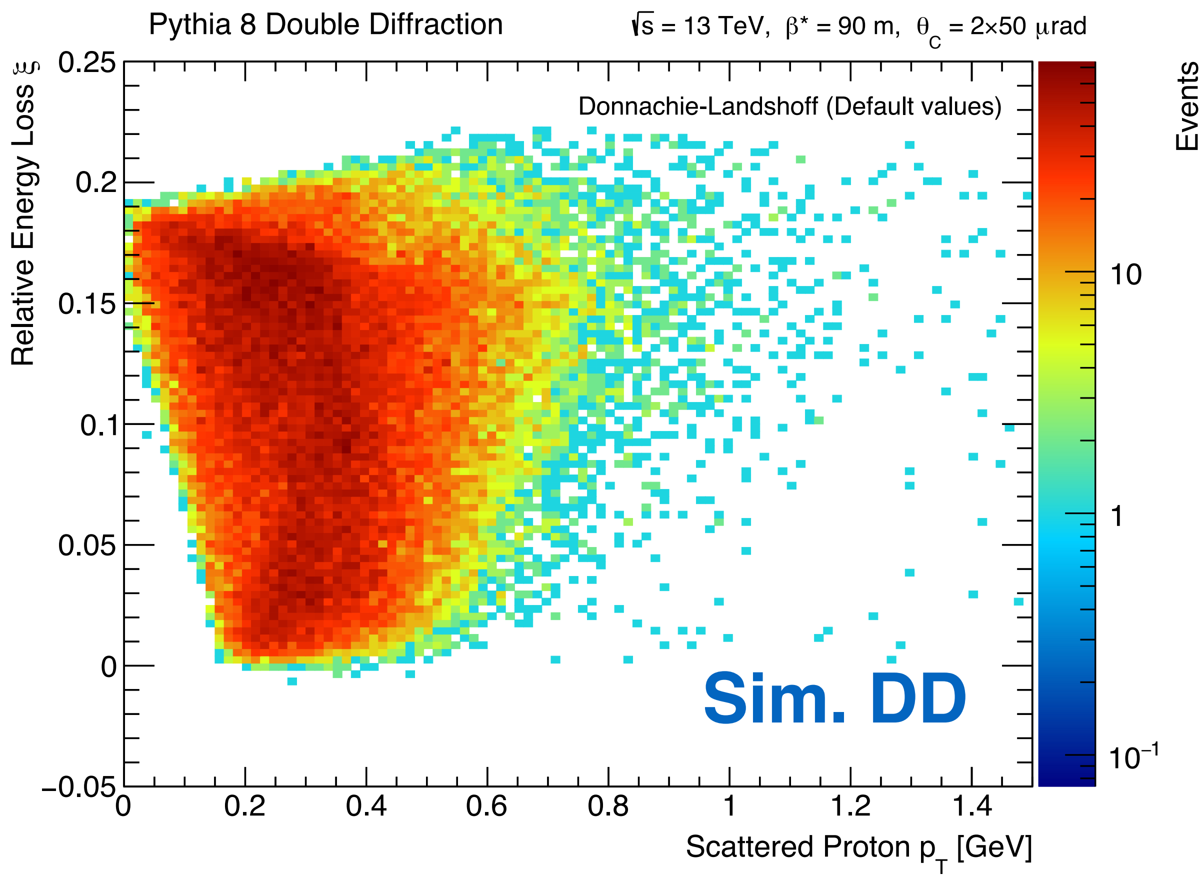
Possible Background Sources:

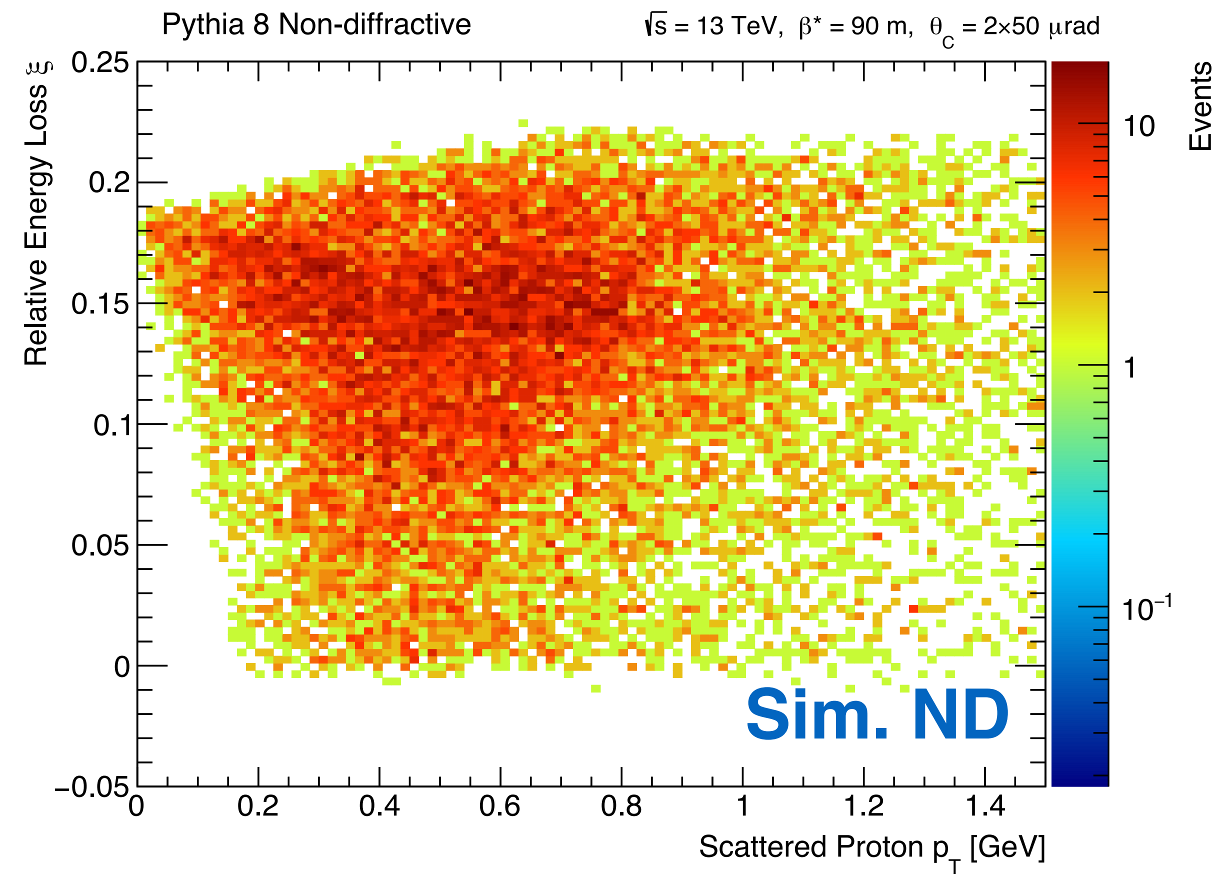
- Beam Background
- Non-diffractive background
- Double diffractive background

Data Analysis - Background

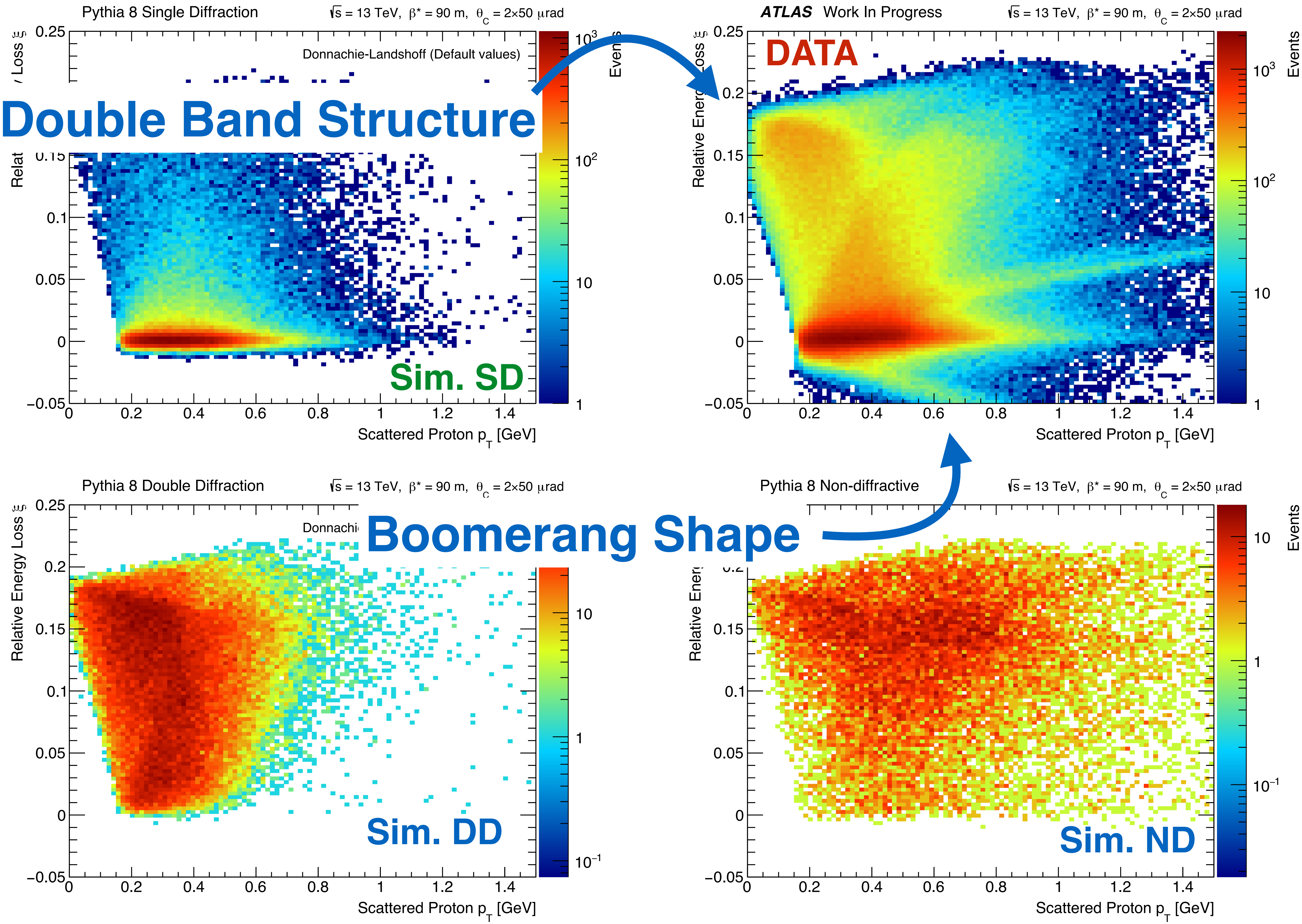




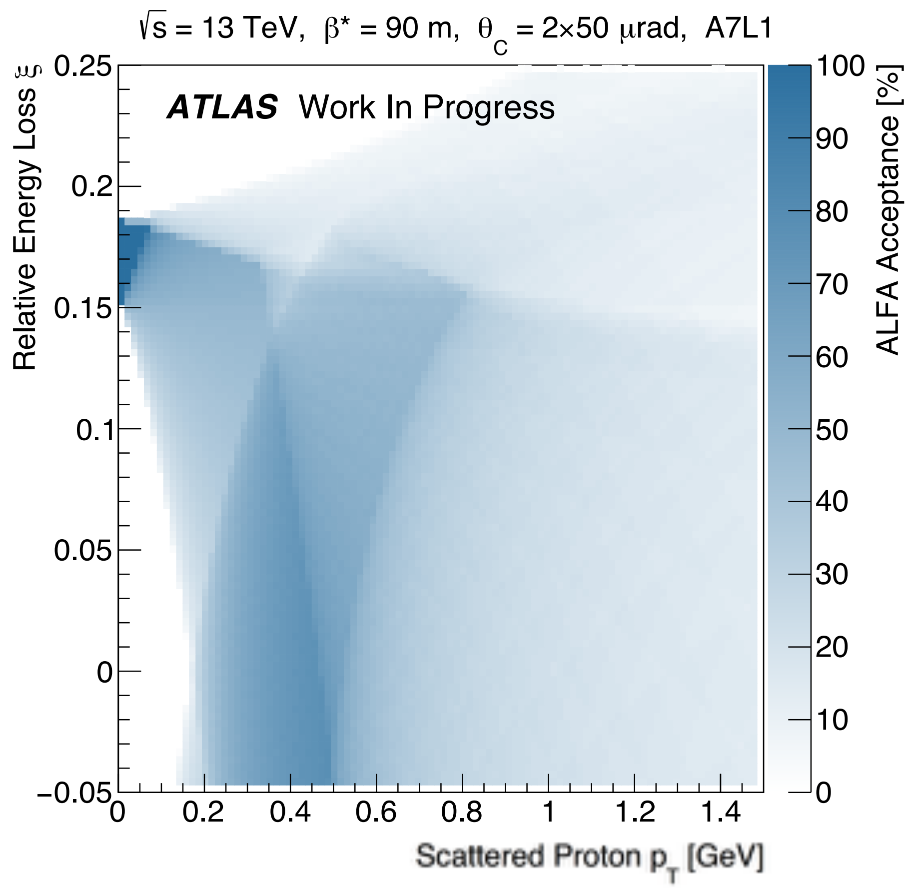


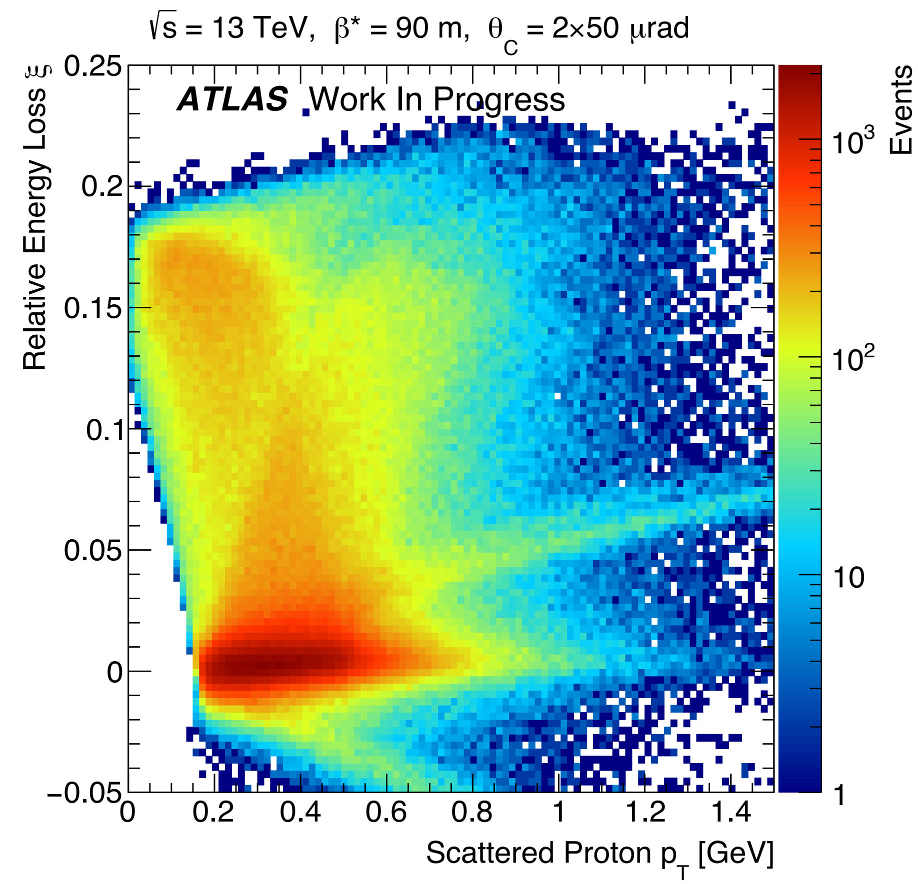


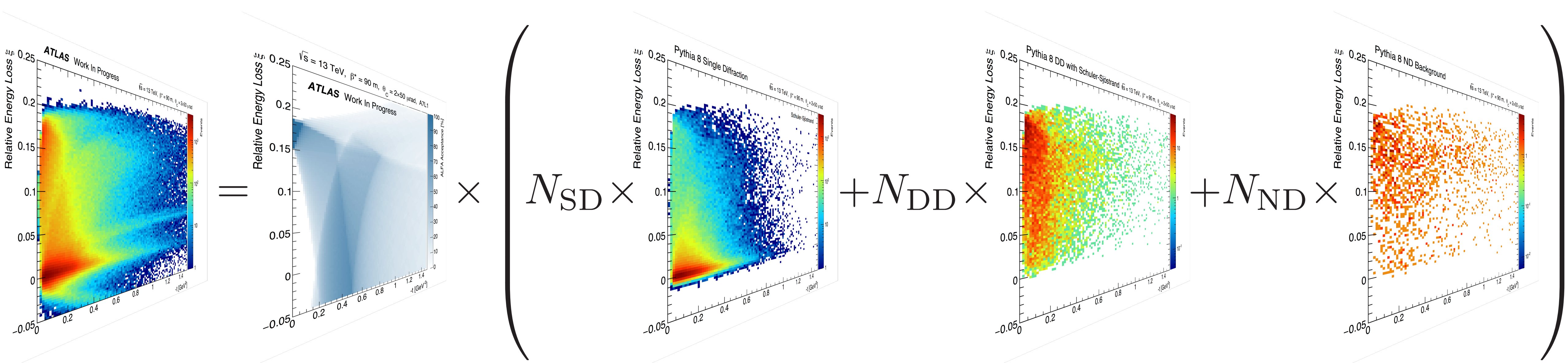
Data Analysis - Background



Mapping onto Acceptance Region:



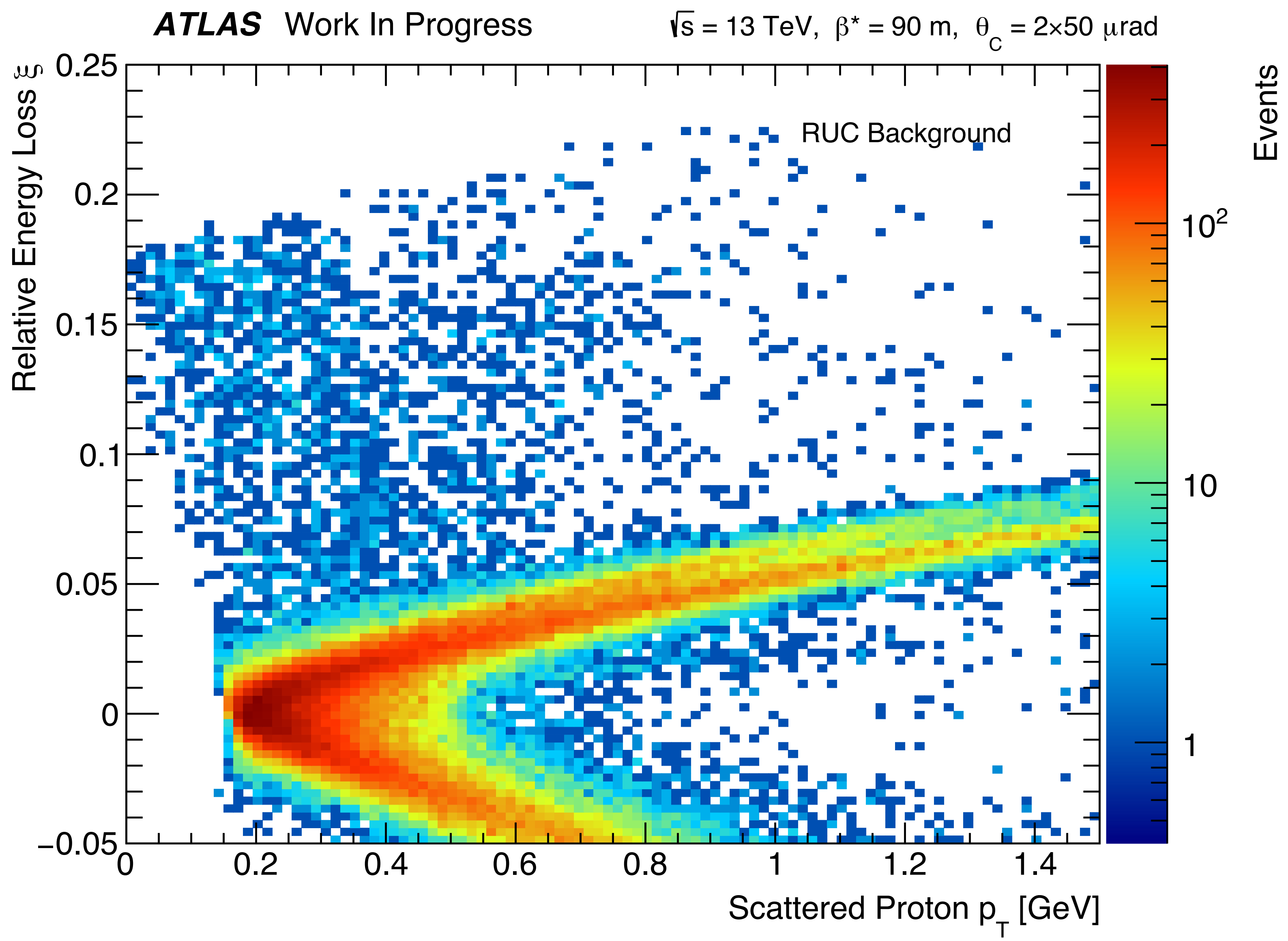




Beam Background

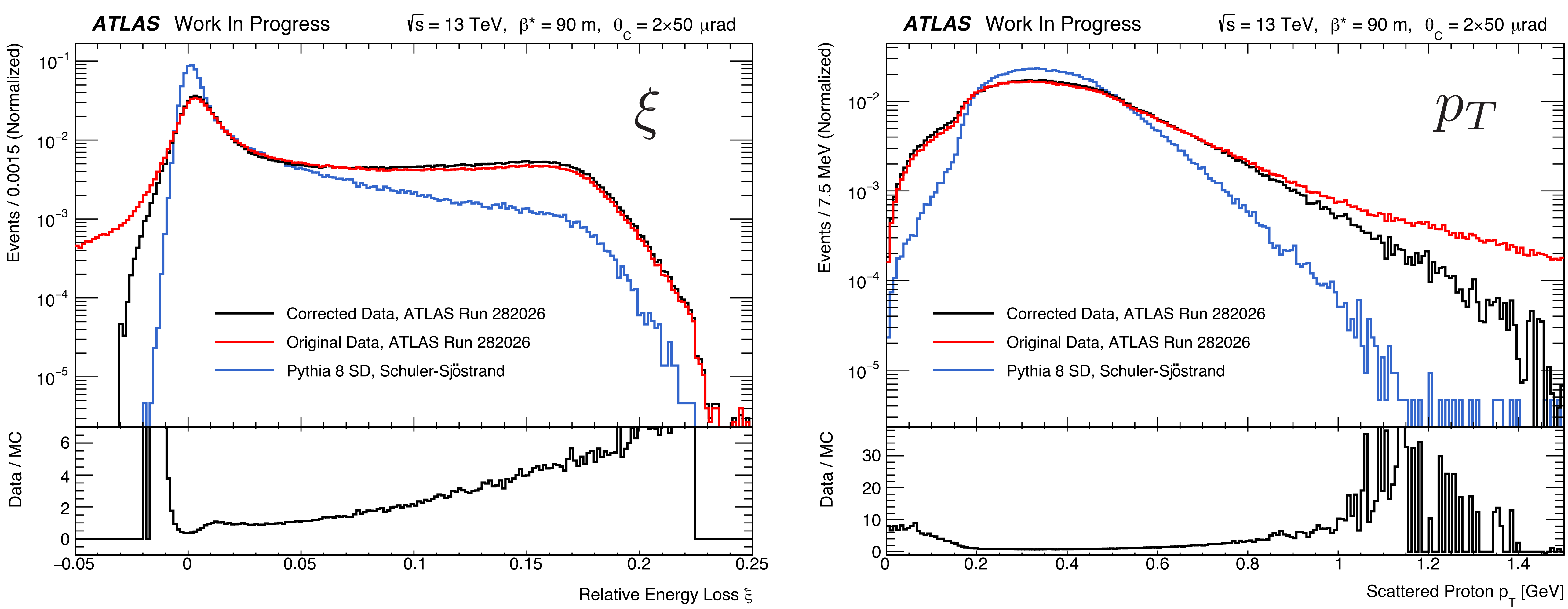
Random Uncorrelated Coincidences (RUCs)

Beam background (RUCs) give a characteristic “boomerang” shape



Data Analysis - RUCs

When knowing the normalization of the beam background the distribution of RUCs can be subtracted from data



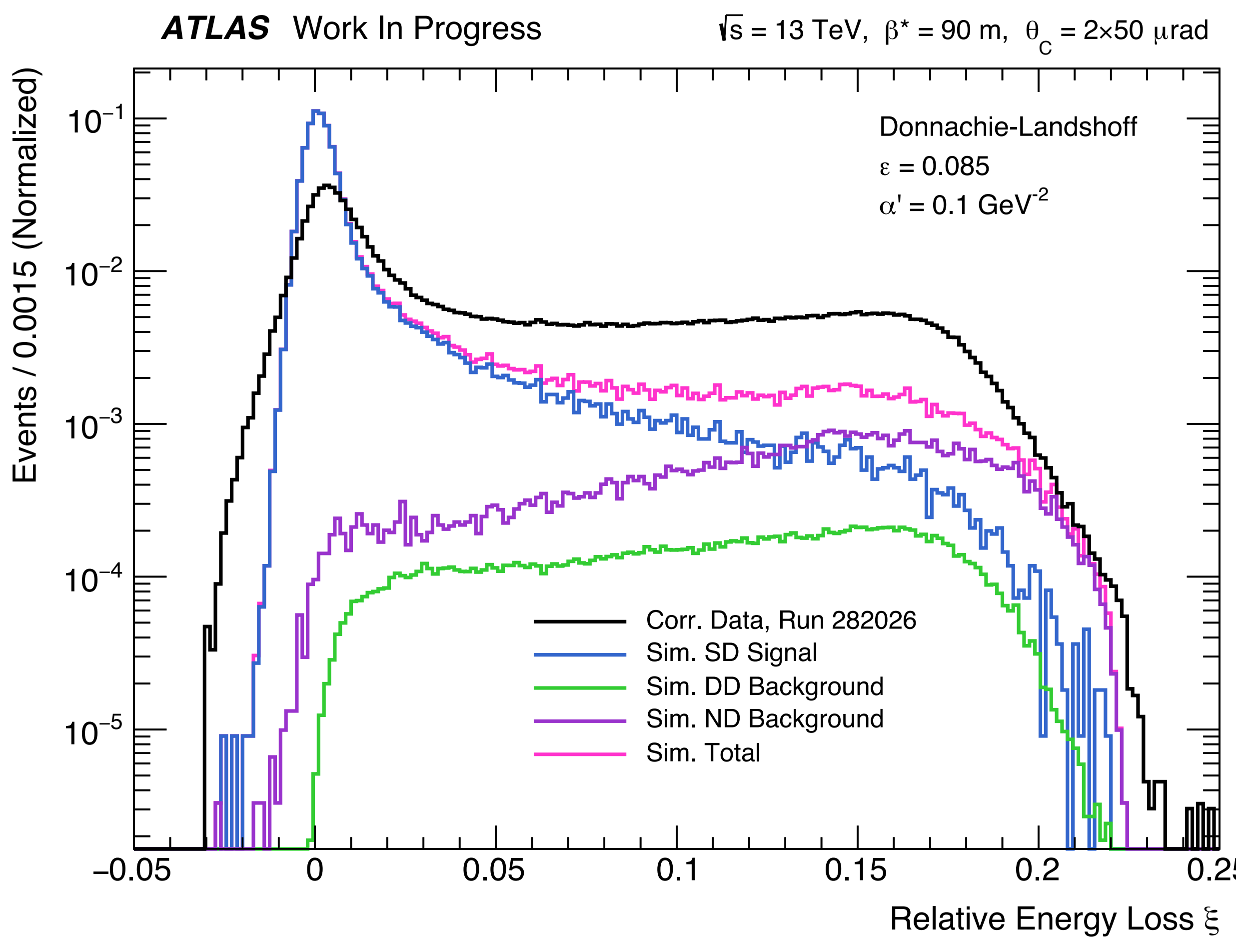
Data Analysis

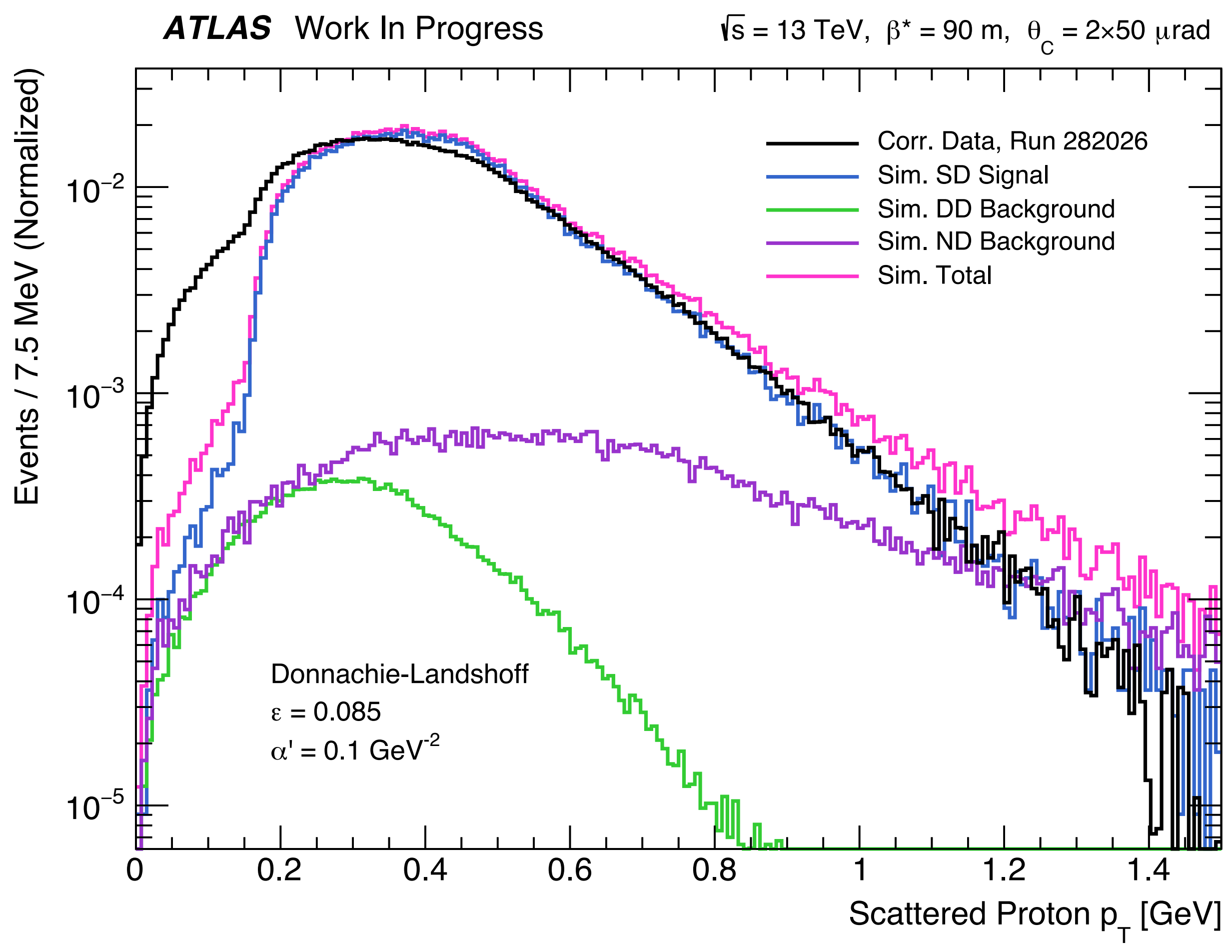
Background Levels: $\sigma_{\text{visible}} = \sigma \cdot A$

$$\sigma_{\text{tot}} = 100 \text{ mb}$$
$$\sigma_{\text{SD}} = 15 \text{ mb}$$
$$\sigma_{\text{DD}} = 5 \text{ mb}$$
$$\sigma_{\text{ND}} = 60 \text{ mb}$$

→

$$N_{\text{SD}} = 91\%$$
$$N_{\text{DD}} = 2\%$$
$$N_{\text{ND}} = 7\%$$

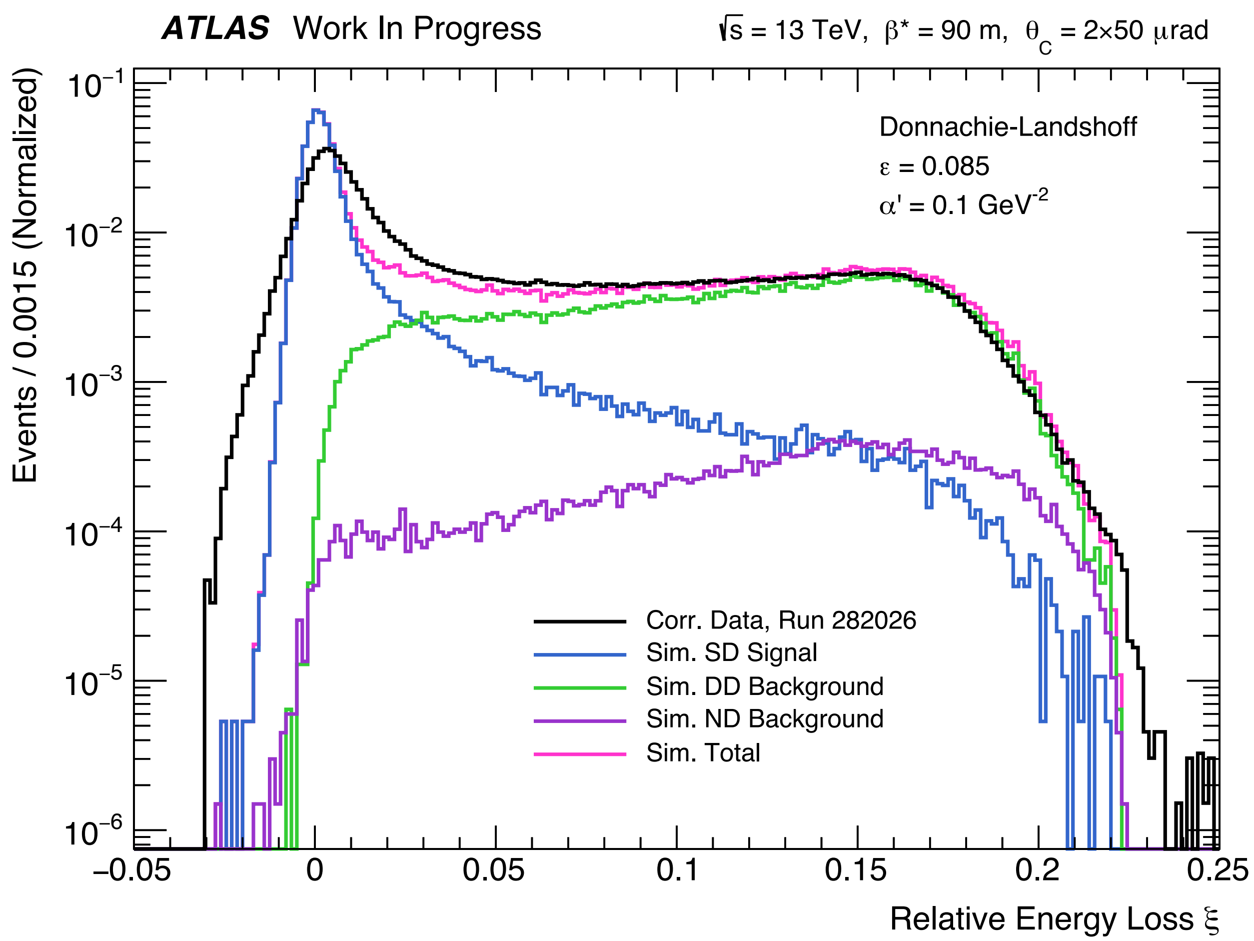


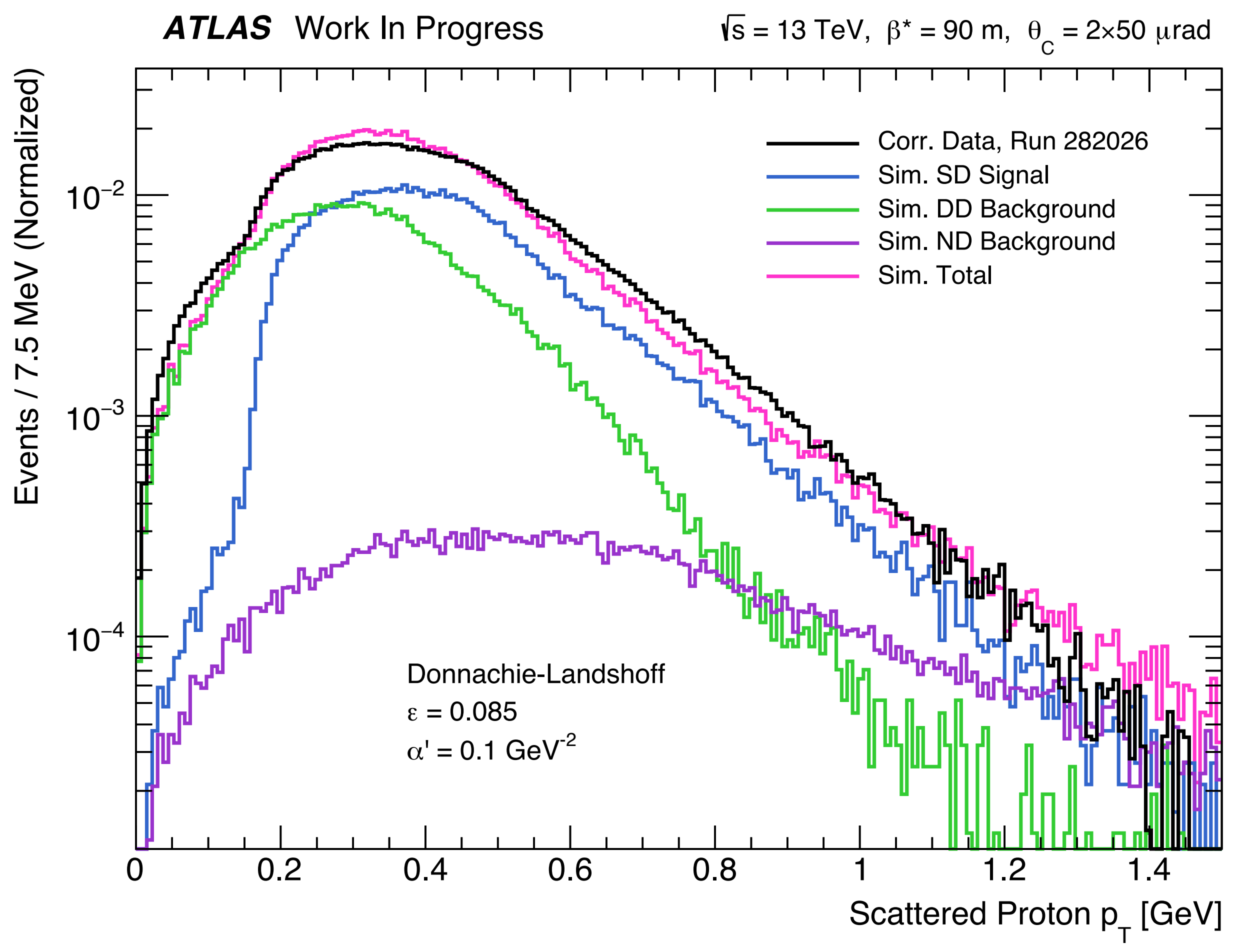


Data Analysis

Now, we let the relative normalizations be free parameters

$$N_{\mathrm{SD}} = 54\%$$
$$N_{\mathrm{DD}} = 43\%$$
$$N_{\mathrm{ND}} = 3\%$$





Summary and Conclusions

- Hadronic diffraction is not well-understood
  and many different approaches have been proposed

- A simulation framework was developed to study
  diffraction at the ATLAS and ALFA detector

- New 13 TeV data was analysed
  Flat plateau observed that is not yet fully understood

Outlook and Future Studies

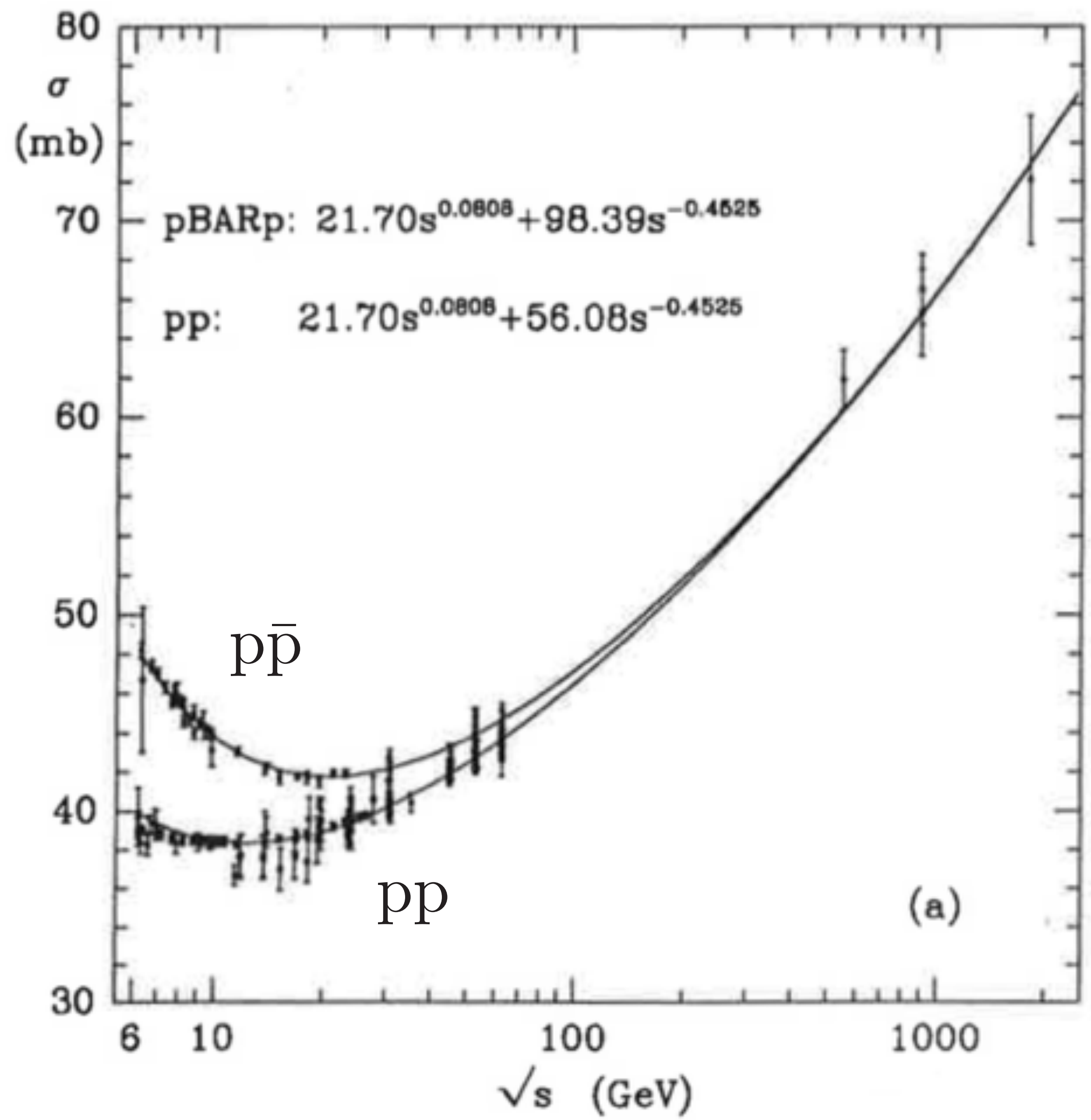
- Until we understand the flat plateau, we cannot use the fit procedure on data
- A full Geant4 simulation of ATLAS, ALFA, and the LHC magnets will provide a better understanding of the background
- Study of energy-dependent multiple scattering and its effects on the ALFA detector resolutions
- Detector Topology being main factor in Data-MC discrepancy? Track reconstruction efficiency of the ATLAS ID as a function of pseudorapidity and pT could be important

Thank you for listening!

Back-Up Slides

Behavior of the Total Cross-section

Total
Cross-section
σ



Collision energy

Rapid decrease
for low s

Reggeons (pions)
dominates

Slow increase
for large s

Pomerons
dominates

Pomeron Flux Parameterizations in Pythia

Several Models implemented in Pythia:

- Schuler-Sjöstrand
  - Default in Pythia
  - Fixed parameter values: $\varepsilon = 0, \quad \alpha' = 0.25 \text{ GeV}^{-2}$
- Donnachie-Landshoff
  - Allows varying parameter values
- Minimum Bias Rockefeller (MBR)
  - Allows varying parameter values

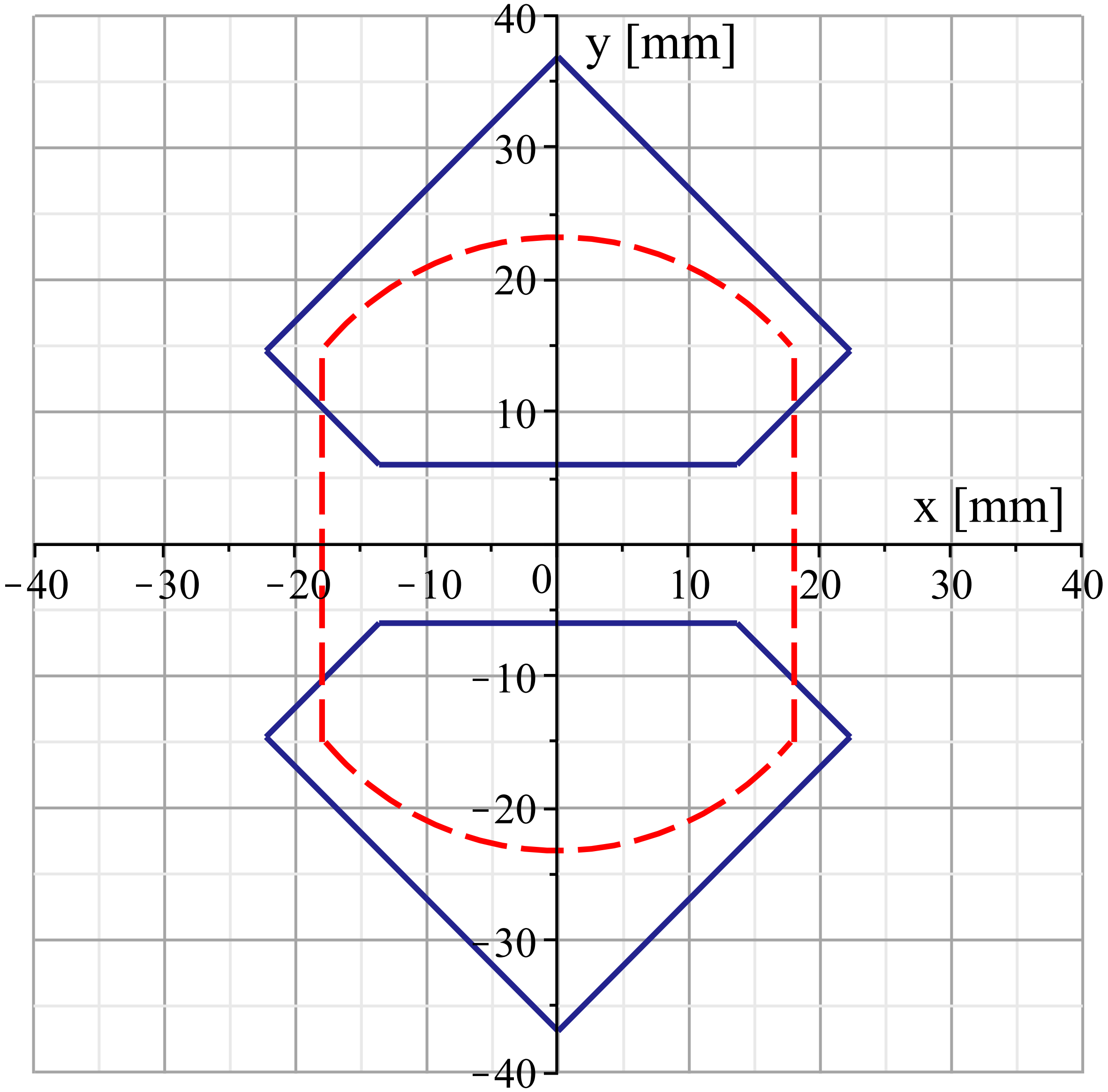
LHC and ALFA Acceptance

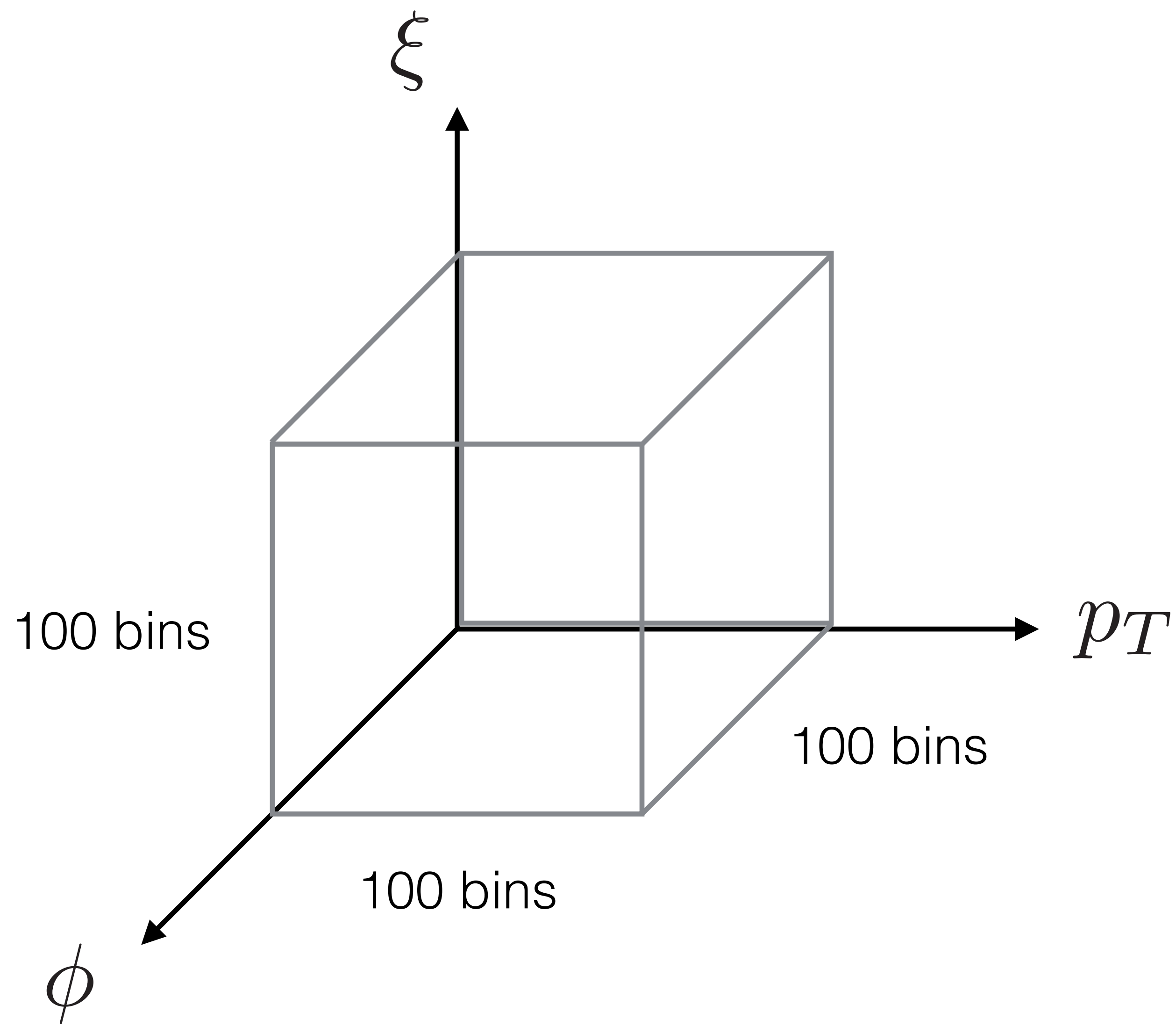
LHC Acceptance:

Protons may bend so much that they hit the wall of the beam pipe

ALFA Acceptance:

Protons hitting the ALFA detector

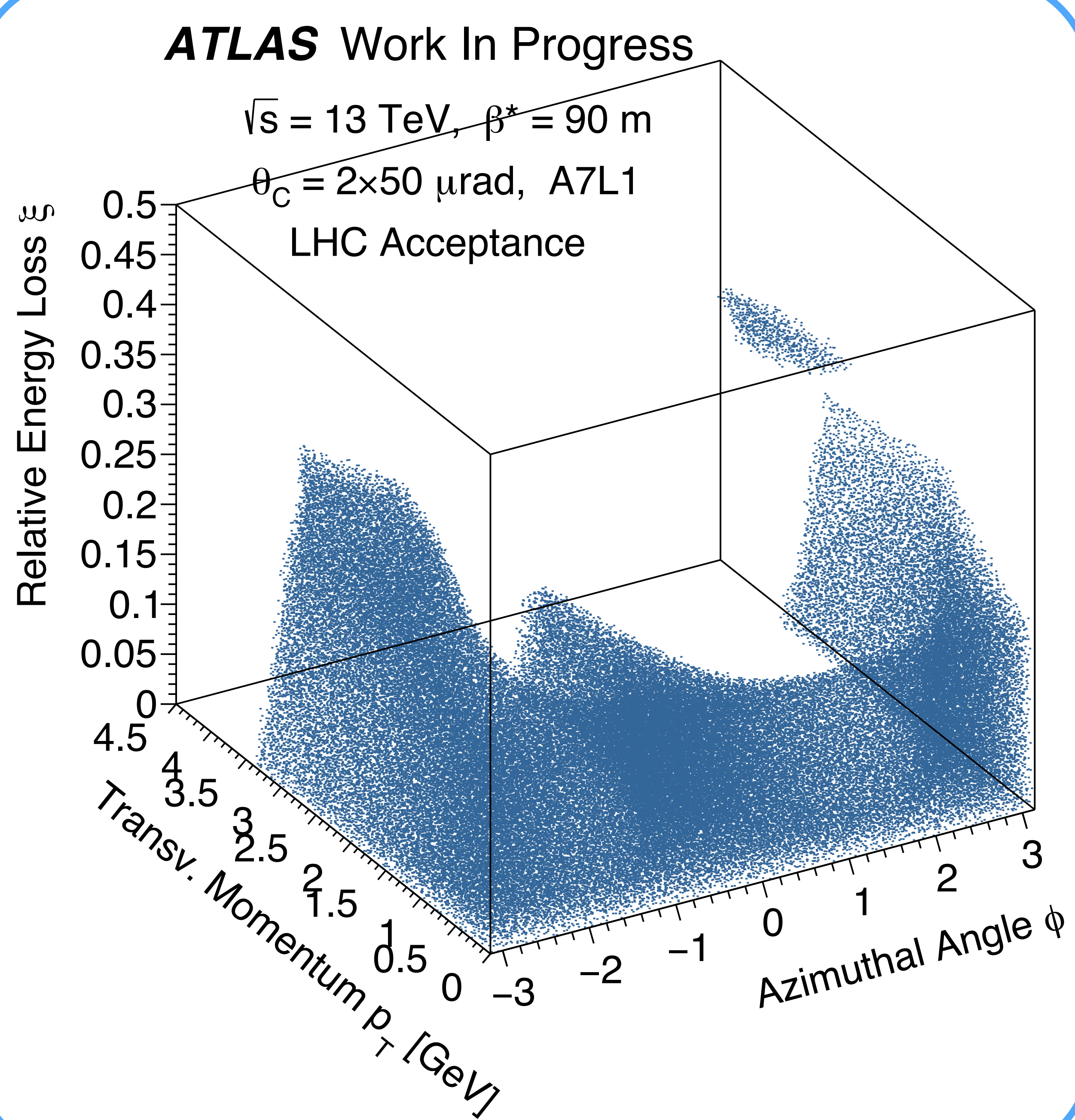




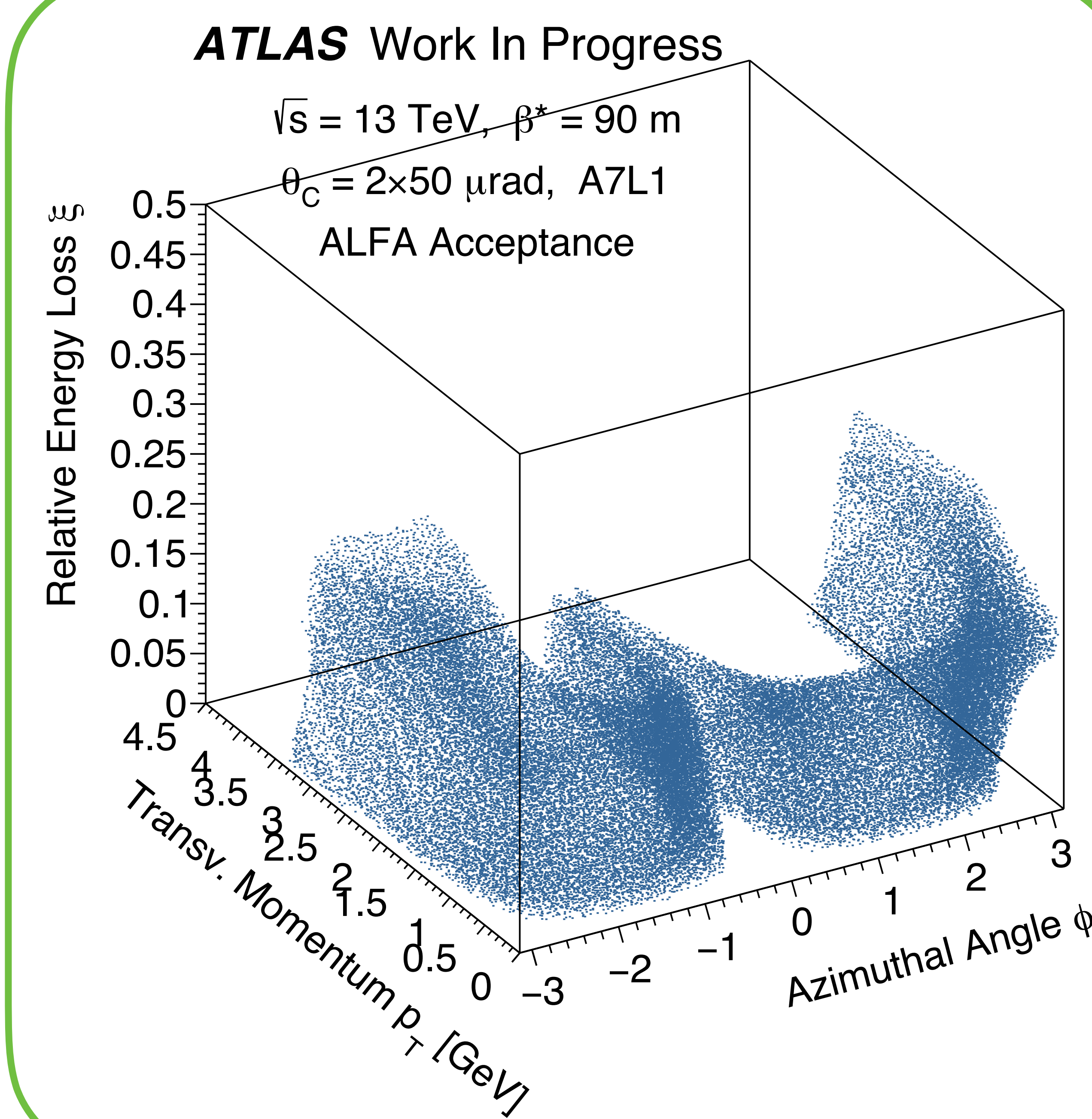
LHC and ALFA Acceptance

Acceptance Plots for ALFA Detector on A-side, 237 m

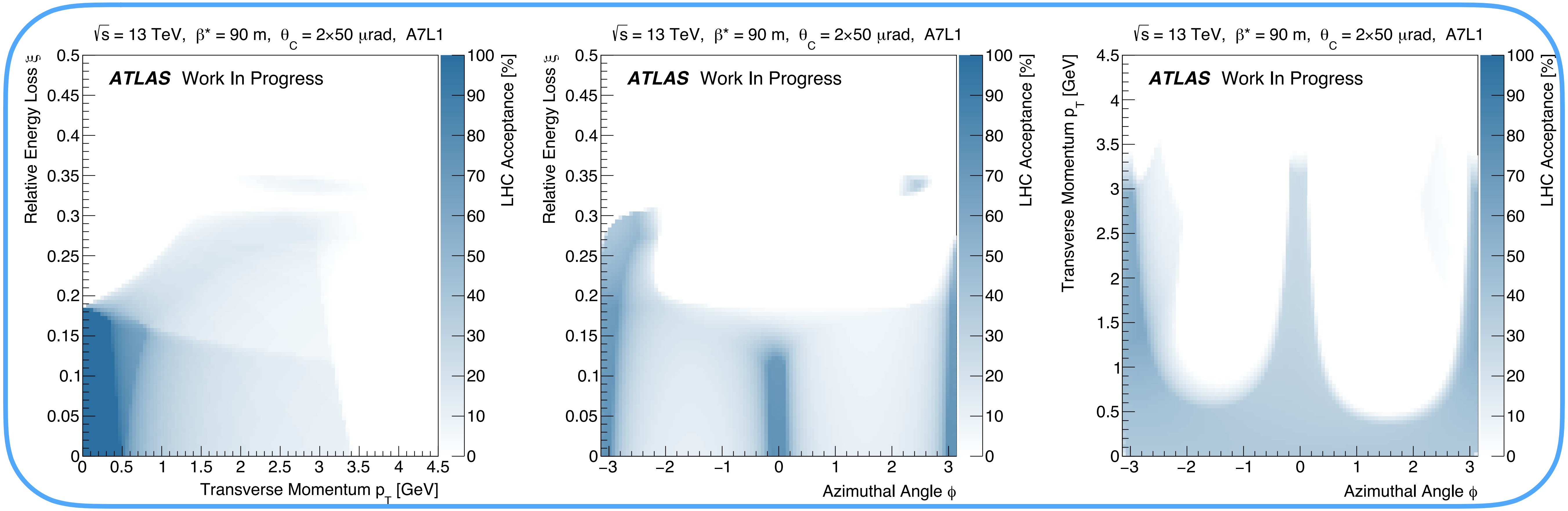
LHC Acceptance

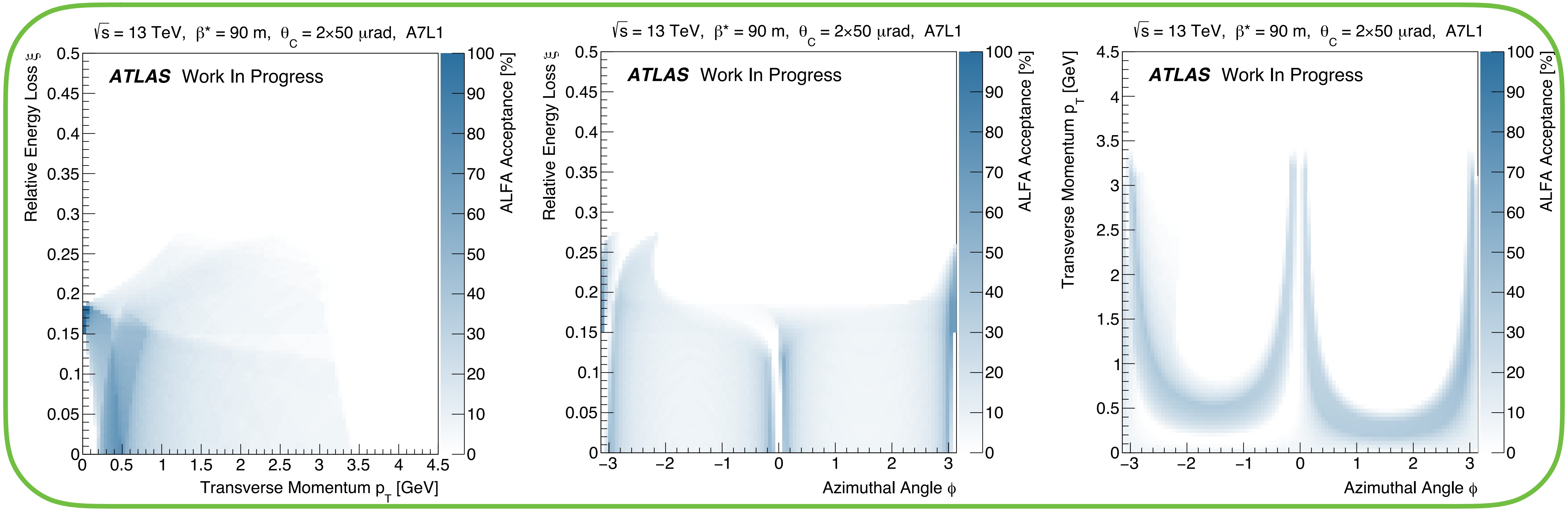


ALFA Acceptance



LHC and ALFA Acceptance

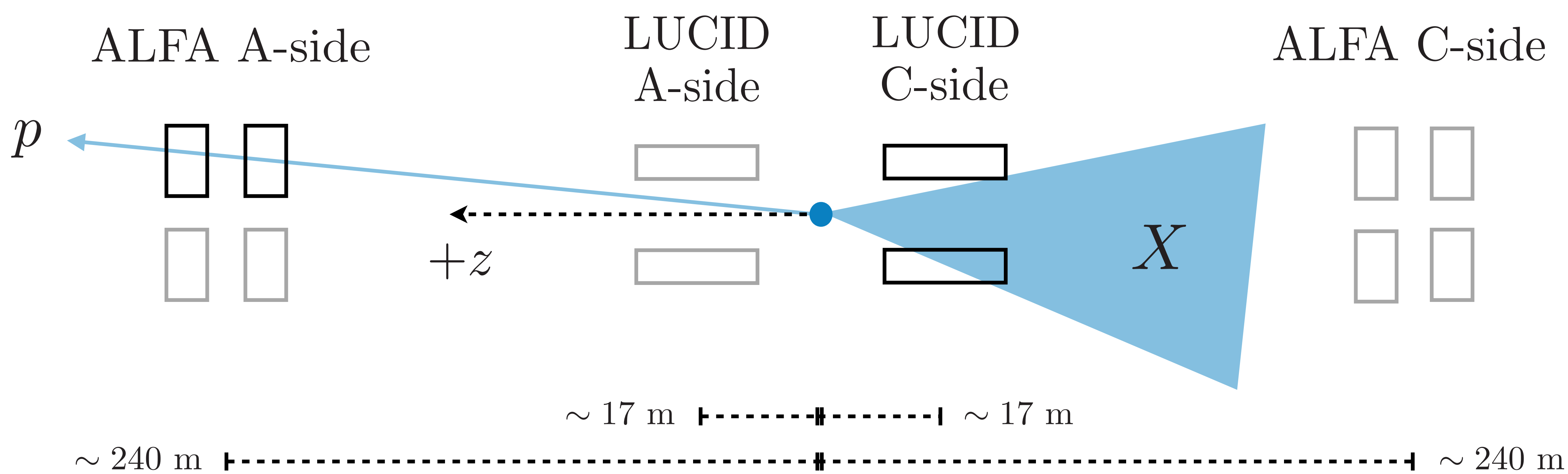




Data Analysis - LUCID

ALFA: $9 \lesssim |\eta| \lesssim 14$

LUCID: $5.6 < |\eta| < 5.9$



A SD proton will NOT hit LUCID

However, background from beam, DD and ND may hit LUCID

Data Analysis - LUCID