Diffraction Physics with ATLAS

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On behalf of the ATLAS collaboration

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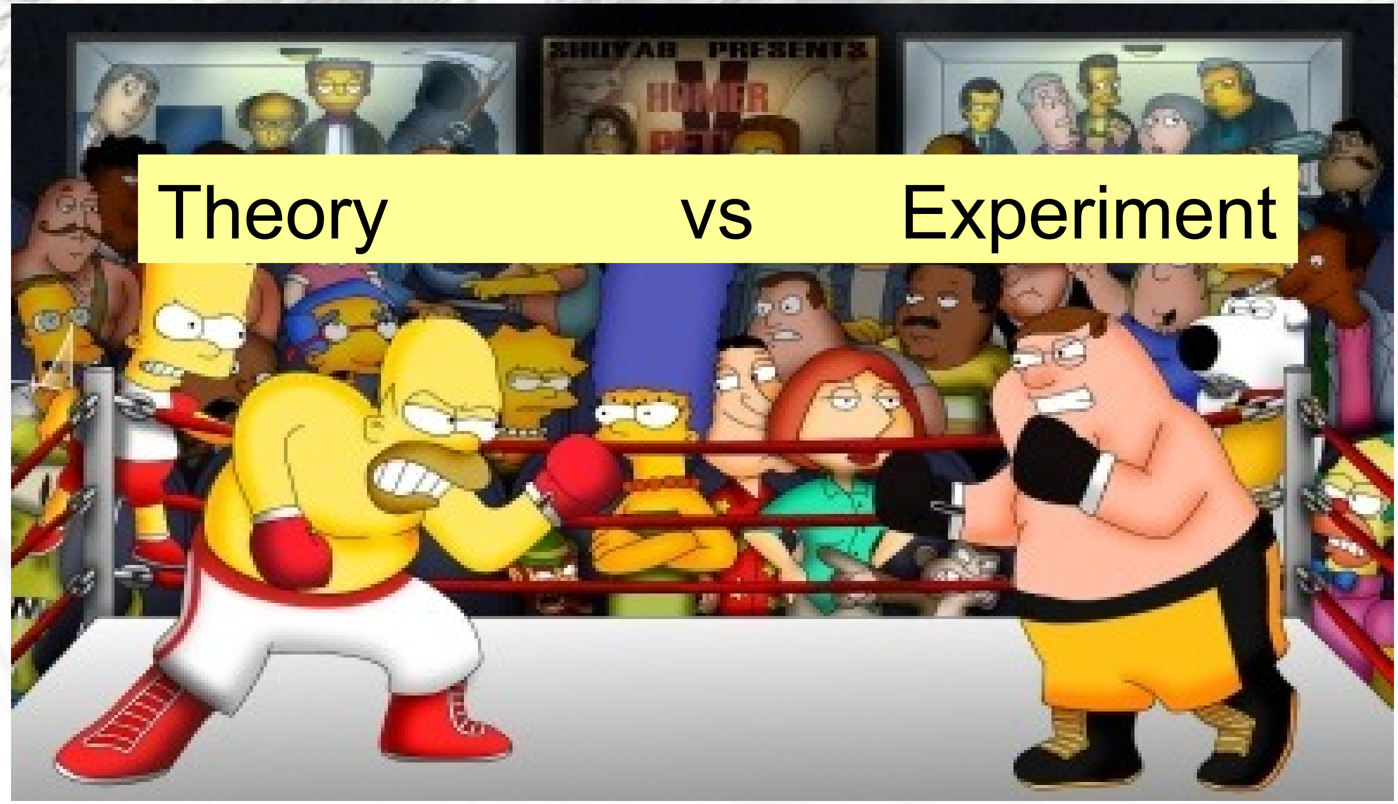
Outline

- Diffraction: Theory vs Experiment
- Experimental Tools and Measurements
  - Asymmetry → inelastic cross section measurement
  - Forward Rapidity “gaps” → Diffraction studies (npQCD)

    → Rapidity Gaps in Dijet production
  - Elastic scattering protons taggers → Toward proton-proton elastic cross section measurement

    → ATLAS upgrade (AFP)

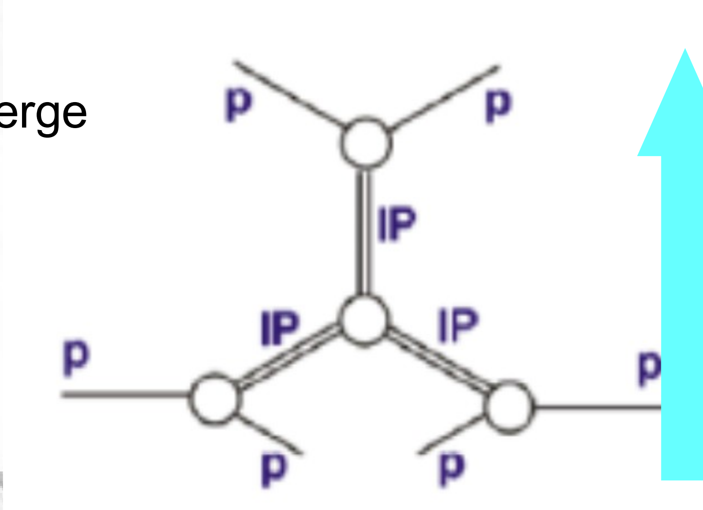


Theory:

Interactions where the beam particles (one or both) emerge intact or dissociated into low mass states.

OR

Interactions mediated by t-channel exchange of object (ladder of gluons) with the quantum numbers of the vacuum, i.e. color singlet exchange called “Pomeron”



Theory vs Experiment

Experimentally:

- No energy/momentum flow in “forward regions” → Rapidity gaps
- Tag one or both protons in the final state (“very very close” to beam axis) → ALFA, AFP (ATLAS), TOTEM (CMS)

$$\sigma_{Total} = \sigma_{Elastic} + \sigma_{Inel}$$

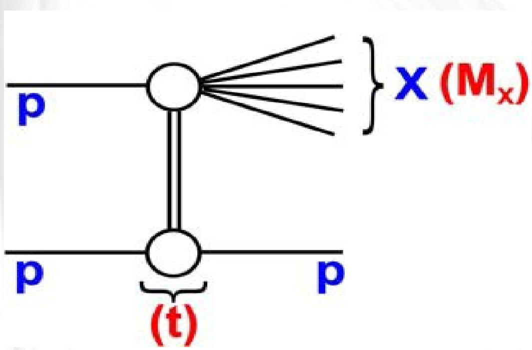
$$= \sigma_{Elastic} + \sigma_{ND} + \boxed{\sigma_{SD} + \sigma_{DD} + \sigma_{CD}}$$

This talk

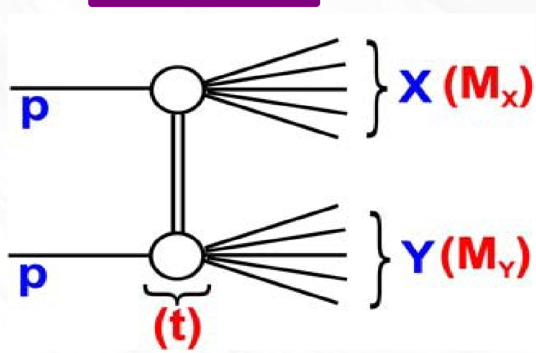
Kinematics is determined by:

- t → 4-momentum exchanged by protons
- Mass of diffractive system (M_x)

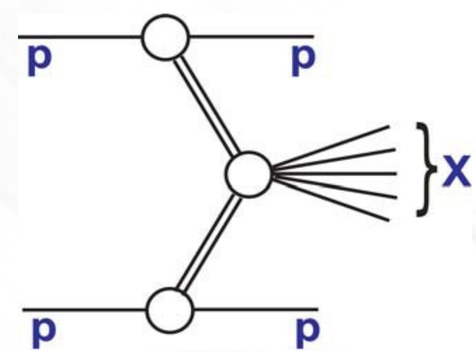
$$\boxed{\xi = M_X^2/s}$$



Single Diffractive (SD)
~ 14mb

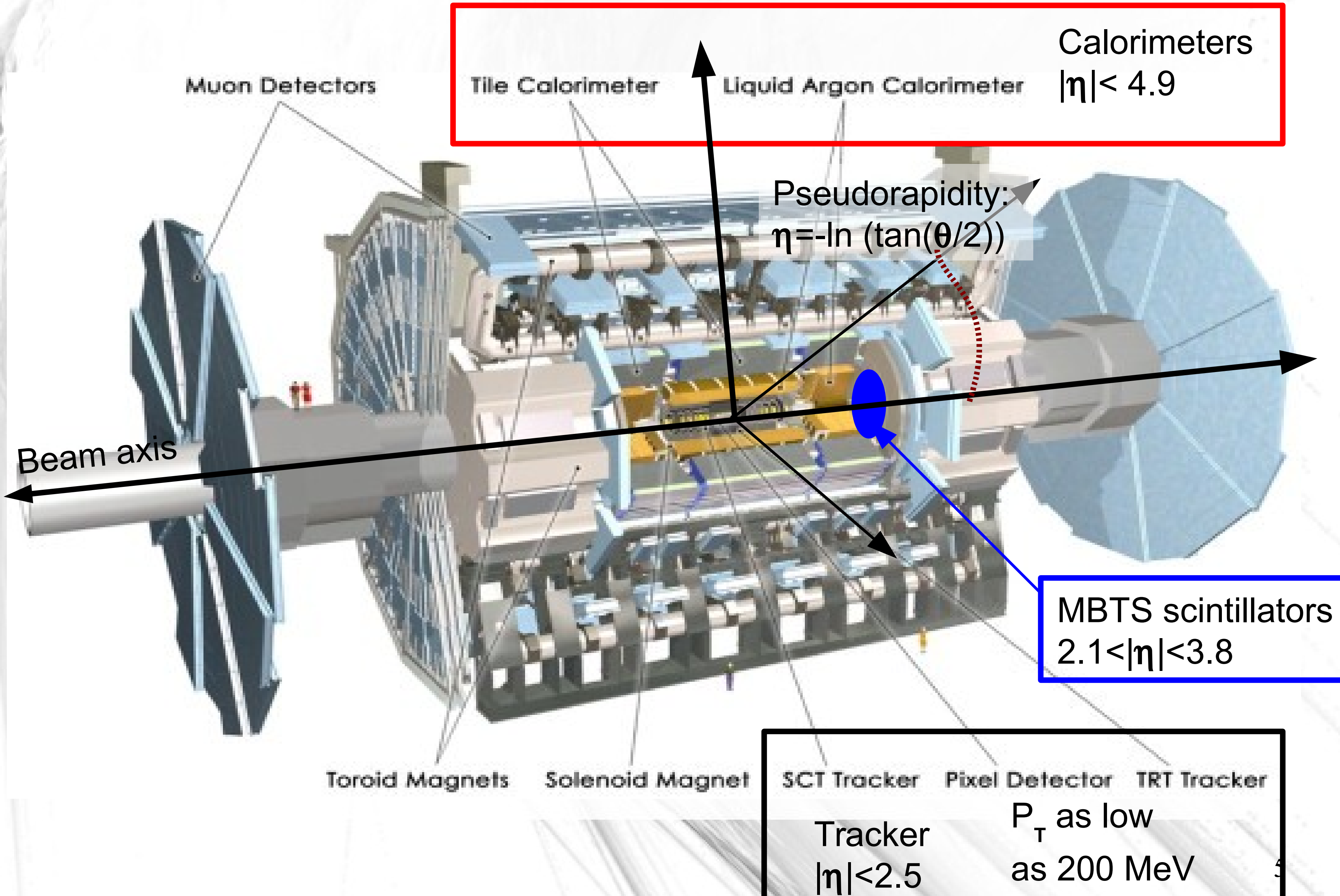


Double Diffractive (DD)
~9 mb



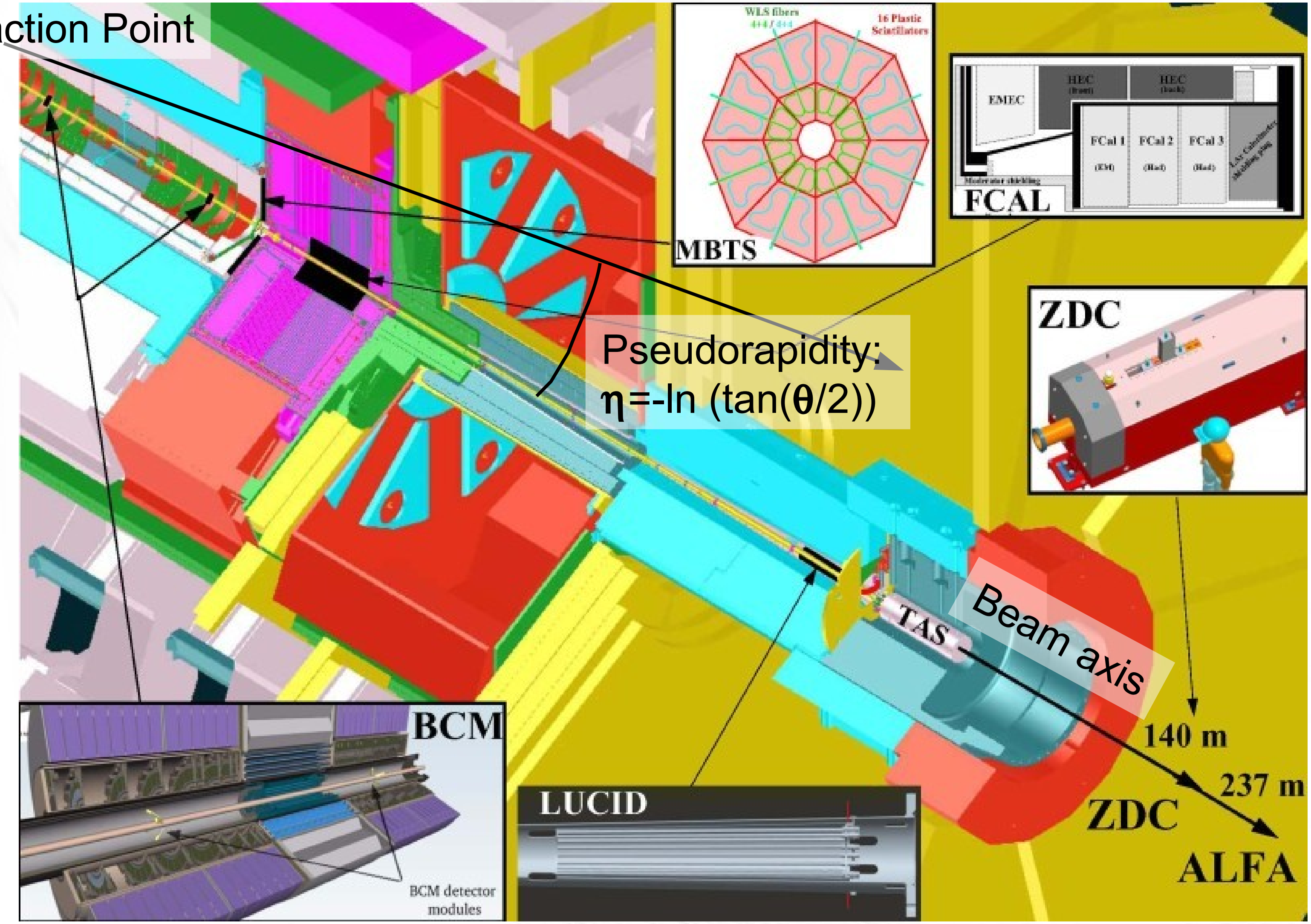
Central Diffractive (CD)
~ 10% of SD

The ATLAS detector



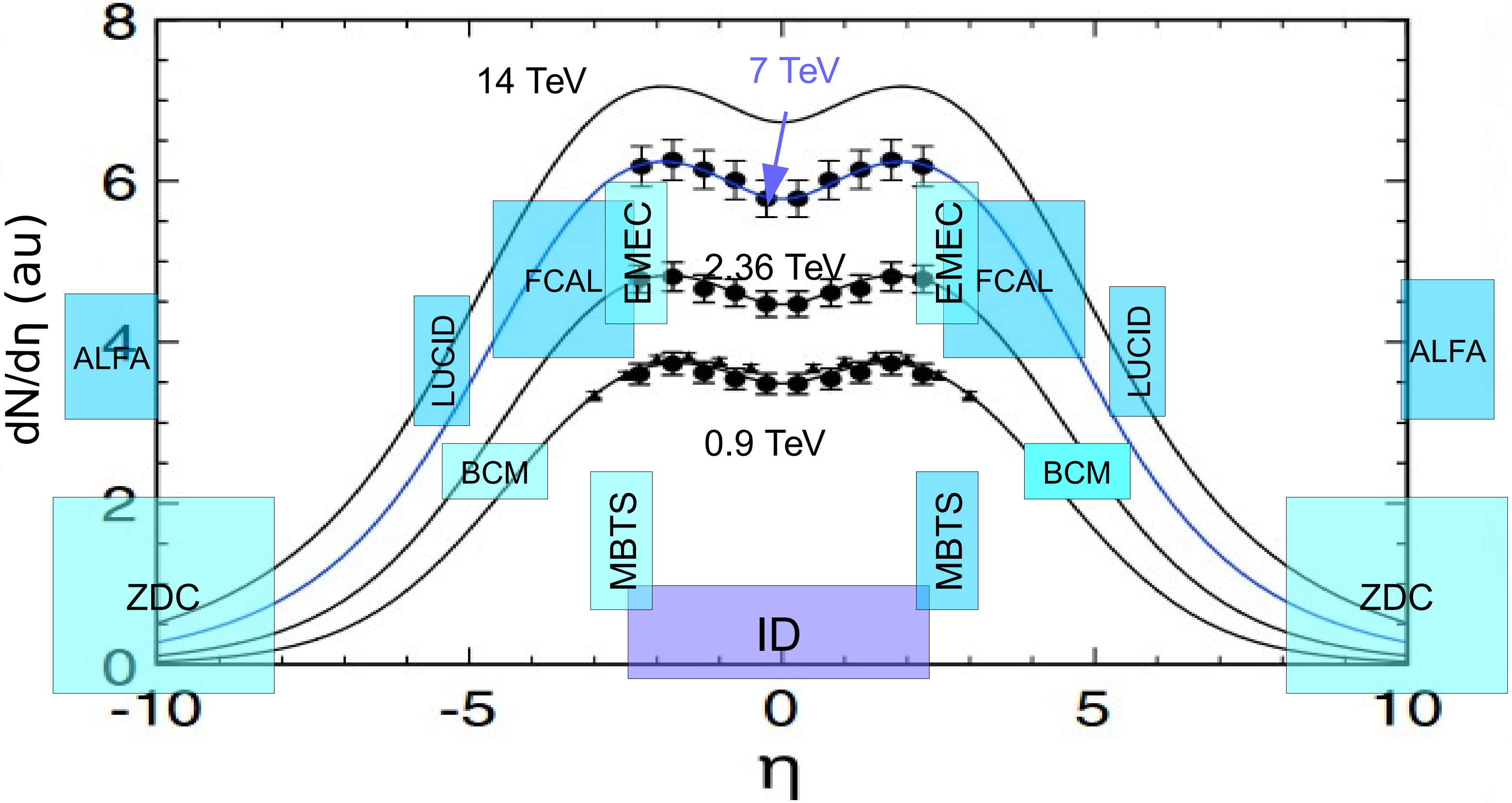
The ATLAS Run I Forward Detectors

IP:
Interaction Point



PseudoRapidity Coverage

From G. Wolshin EPL **95** 61001 (2011)



Detector	η coverage
ID (Pix + SCT)	$\|\eta\|<2.5$
ID (TRT)	$\|\eta\|<2.0$
MBTS	$2.08<\|\eta\|<3.75$
Calo: EMEC	$2.5<\|\eta\|<3.2$
Calo: FCal	$3.1<\|\eta\|<4.9$

Detector	η coverage
BCM	$\|\eta\|=4.2$
LUCID	$5.6<\|\eta\|<6.0$
ZDC	$\|\eta\|>8.3$
ALFA	$10.6<\|\eta\|<13.5$

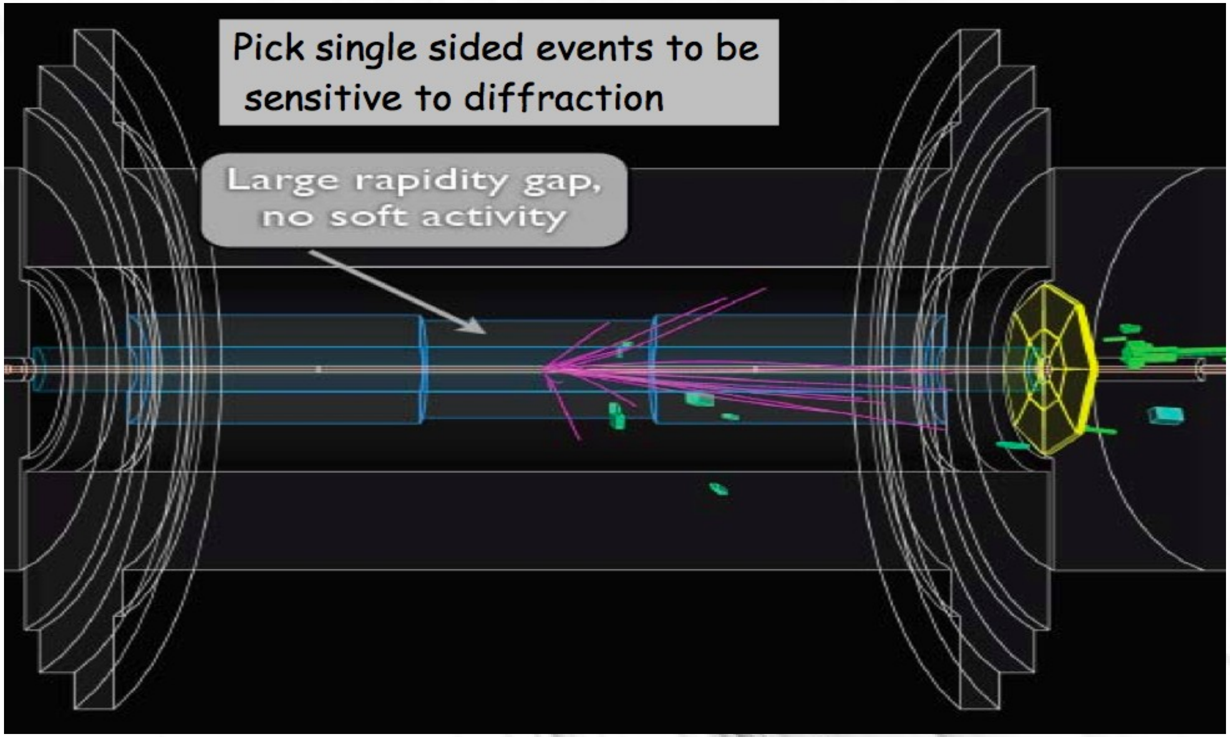
Experimental Tools I: Asymmetry

Asymmetric events:
→ Measure R_{ss}: ratio of **single sided** MBTS events wrt total inelastic events

$$\boxed{R_{ss} = \frac{N_{ss}}{N_{incl}}}$$

From R_{ss} → Measure ratio

$$f_D = \frac{\sigma_{DD} + \sigma_{SD} + \sigma_{CD}}{\sigma_{Inel}}$$



Inelastic Cross Section $\sqrt{s}$=7 TeV

f_D is one of the key components of the total inelastic cross section measurement

$$\sigma_{inel} = \frac{N - N_{bg}}{\epsilon \times A_{inel} \times \int \mathcal{L} dt}$$

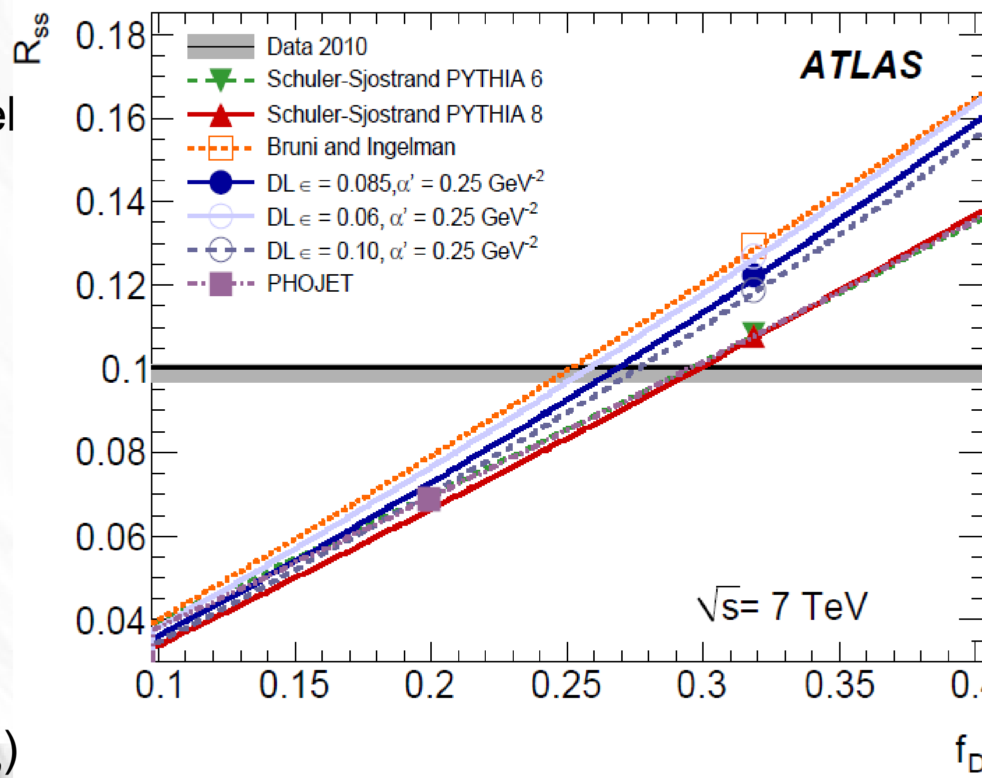
$\int \mathcal{L}\, dt = 20\ \mu b^{-1}$

Measured R_{ss}=10.02±0.03 (stat)$^{+0.1}_{-0.4}$ (syst) %

Several models

Rss→ Constraint f_D for each model

$f_D = 26.9^{+2.5}_{-1.0}$ %



for Pythia 8 +DL with ξ dependence parametrized with pomeron intercept:

α(t)=α(0)+α't

With **α'**=0.25GeV^{-2}

ε=α(0)-1=0.085

$$\frac{d\sigma_{SD}}{d\xi} \sim \frac{1}{\xi^{(1+\varepsilon)}}(1+\xi)$$

Inelastic Cross Section √s=7 TeV

Measured cross section is for $\xi > 5\times10^{-6}$

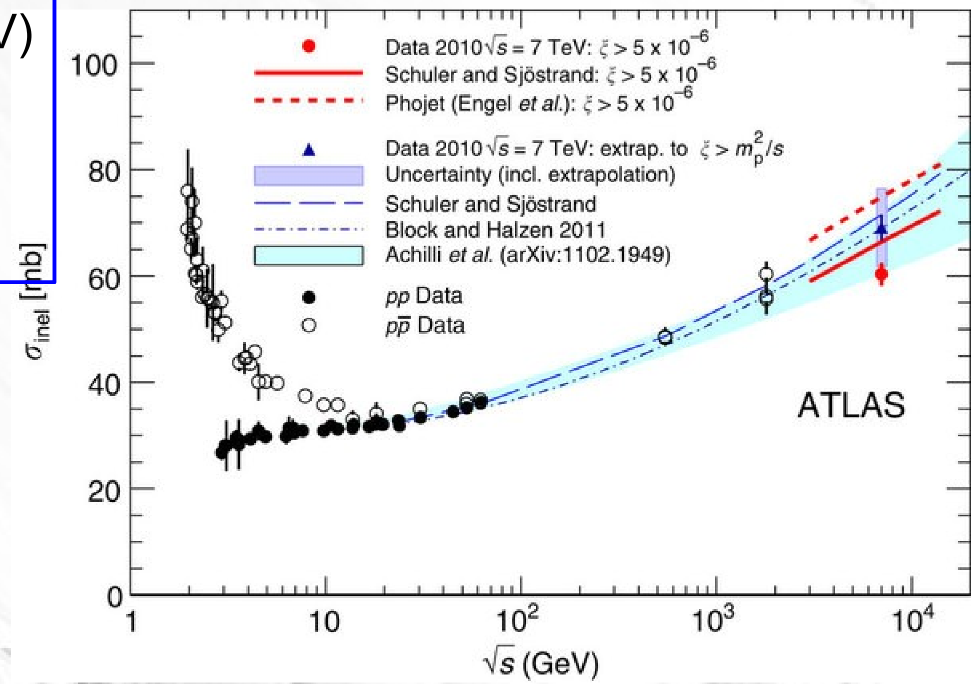
$$\xi = \frac{M_X^2}{s} > 5\times10^{-6} M_X > 15.7\,\mathrm{GeV}$$

$$\sigma_{inel}(\xi > 5\times10^{-6}) = \sigma_{inel} \times (1 - f_{\xi<5\times10^{-6}})$$

Use DL MC to extrapolate to full range $\xi > m_p^2/s$

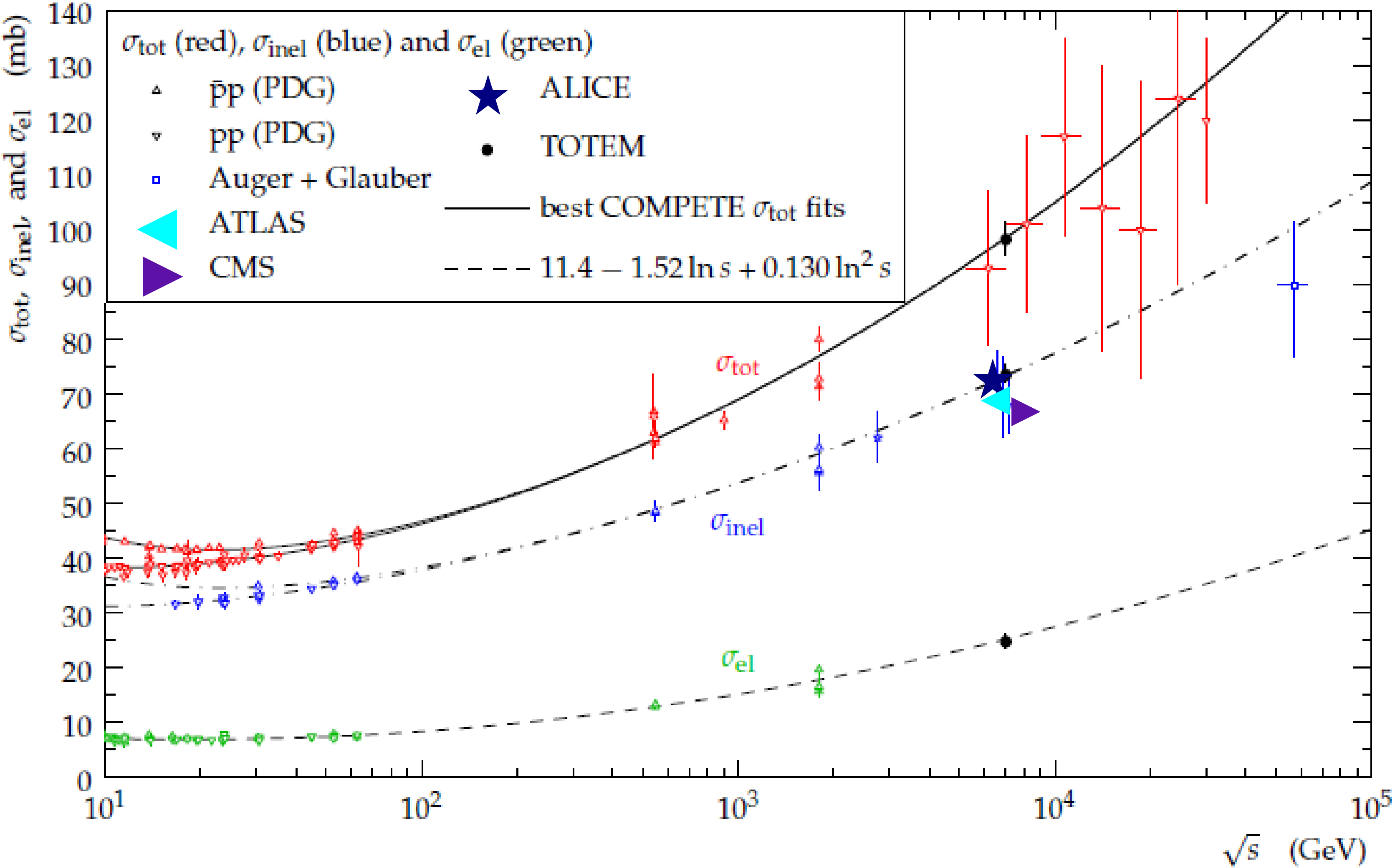
$\sigma(\xi>5\times10^{-6})=60.33\pm2.10$ mb ($M_x>15.7$ GeV)

$\sigma(\xi>m^2_p/s)=69.4\pm2.4\pm6.9(\mathrm{extr})$ mb



Nature Comm. **2** (2011) 463

pp Cross Section Measurements *vs* √s



Experimental Tools II: Rapidity Gaps

For ND events $dN/d\eta \sim 6$ and $<\eta_j - \eta_k> \sim 0.15$

→ Large η gaps are exponentially suppressed except for Diffractive events

Measuring $\Delta\eta$ is a measurement of $M_{X(y)}$

$$\Delta\eta = \ln s/M_X^2 = -\ln\xi$$

Difficult measurement of $M_{X(Y)}$ → Produced particles escape undetected in the beam pipe

η acceptance is defined in the largest η range $-4.9<\eta<4.9$

→ However max η gap determined by MBTS position (→ trigger) (Max $\Delta\eta \sim 8$)

Using ID+EM+HEC+FCAL

$0<\Delta\eta^F<8$ → $\sim 10^{-6} < \xi < \sim 10^{-2}$ → ~ 7 GeV $< M_x < \sim 700$ GeV

Experimentally (detector) η rings (variable width 0.2, 0.4 according to η region):

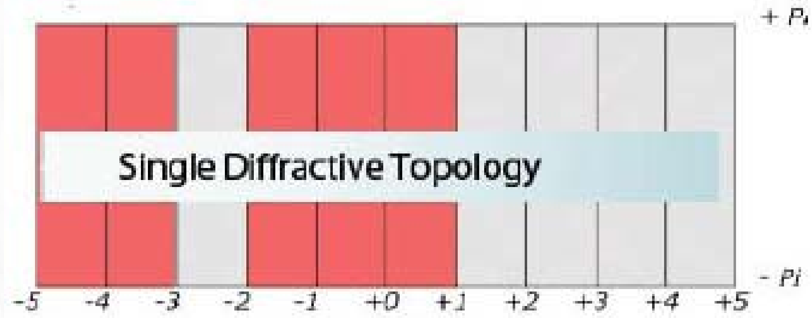
Active ring if:

- At least one track with $P_T>200$ MeV (also checked P_T threshold=400,600,800 MeV/c)
- At least one calorimeter cell above noise threshold (η-dependent threshold, no noise in Tile calorimeter) and E_T cut (same as track)

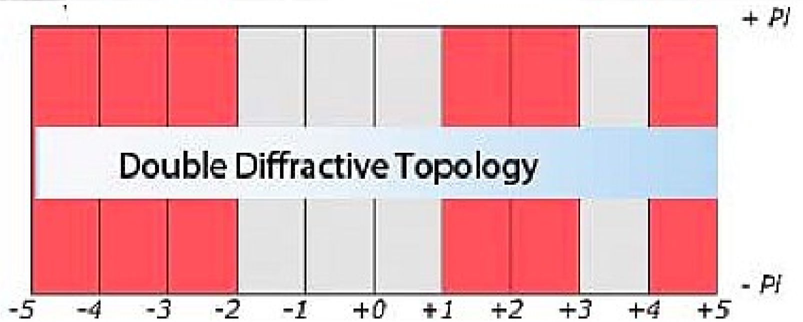
Large Forward Rapidity Gaps

$\Delta\eta_F$ is defined as "largest η gap in the event"

Large $\Delta\eta_F$ sample is composed by SD + DD Events



$\Delta\eta_F$=4

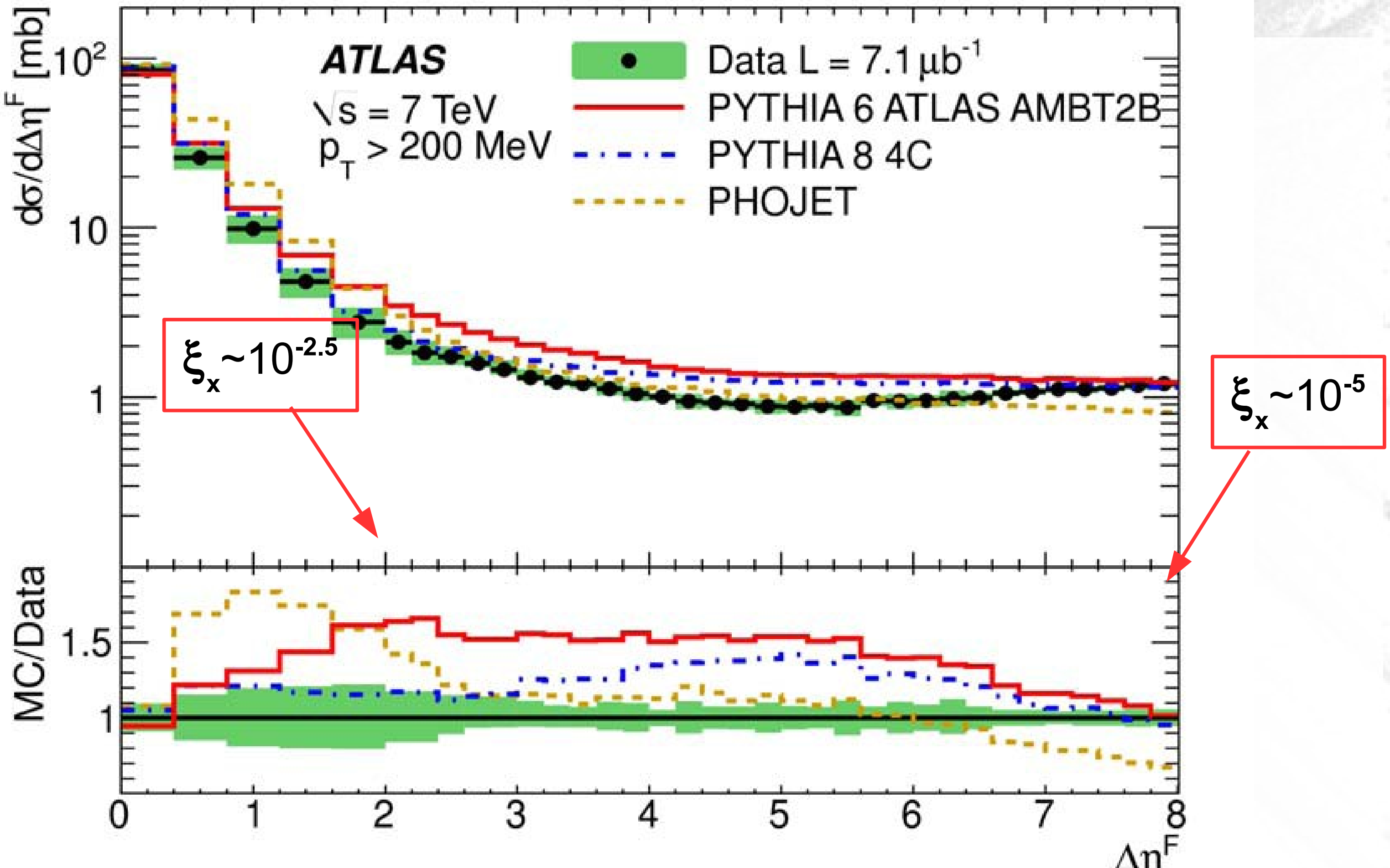


$\Delta\eta_F$=0 since Forward Rapidity gaps start at η edge

Measure differential cross section

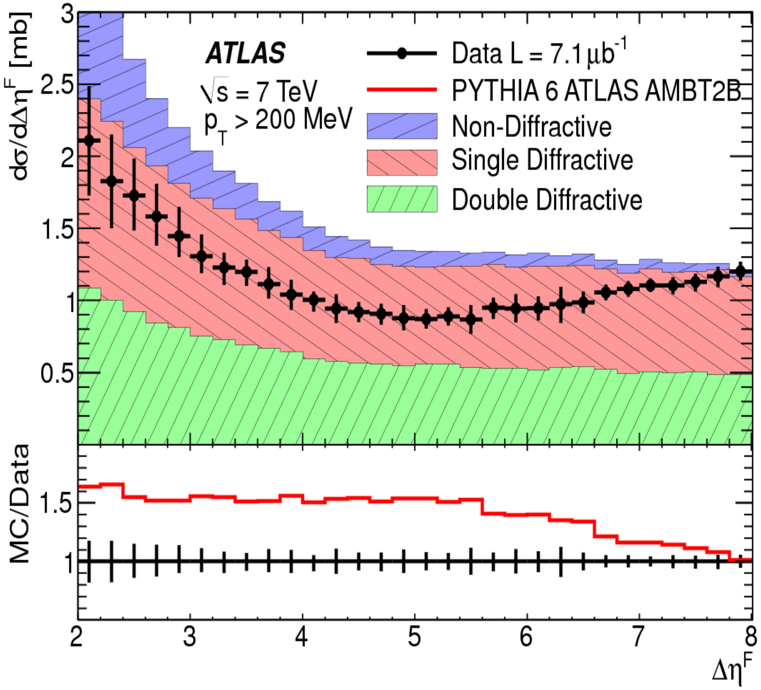
$$\frac{d\sigma}{d\Delta\eta_F}$$

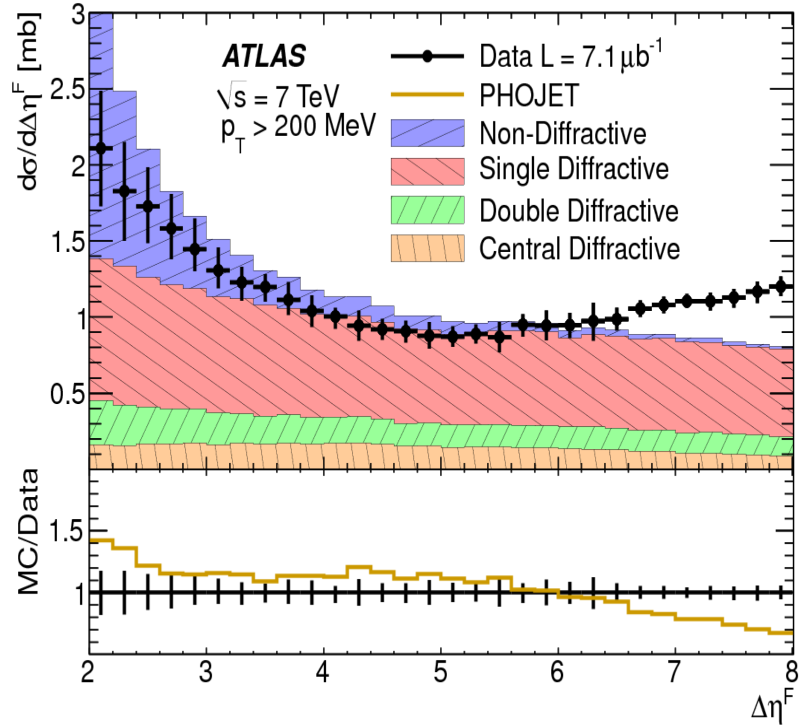
varying P_T thresholds and comparing different MC (PHOJET, Pythia 6 and Pythia 8)

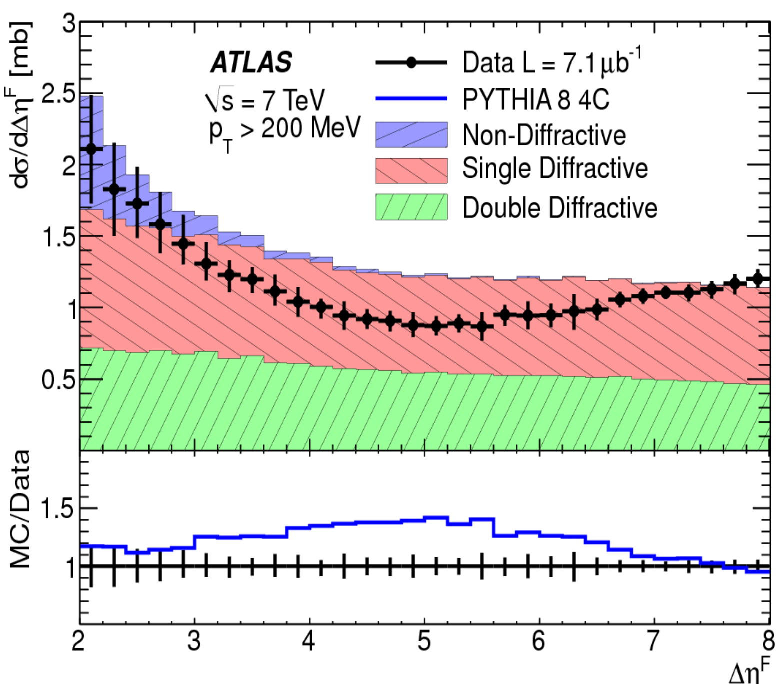


Both PHOJET and Pythia 8 (no CD component in Pythia) reproduce trend but agreement not perfect:

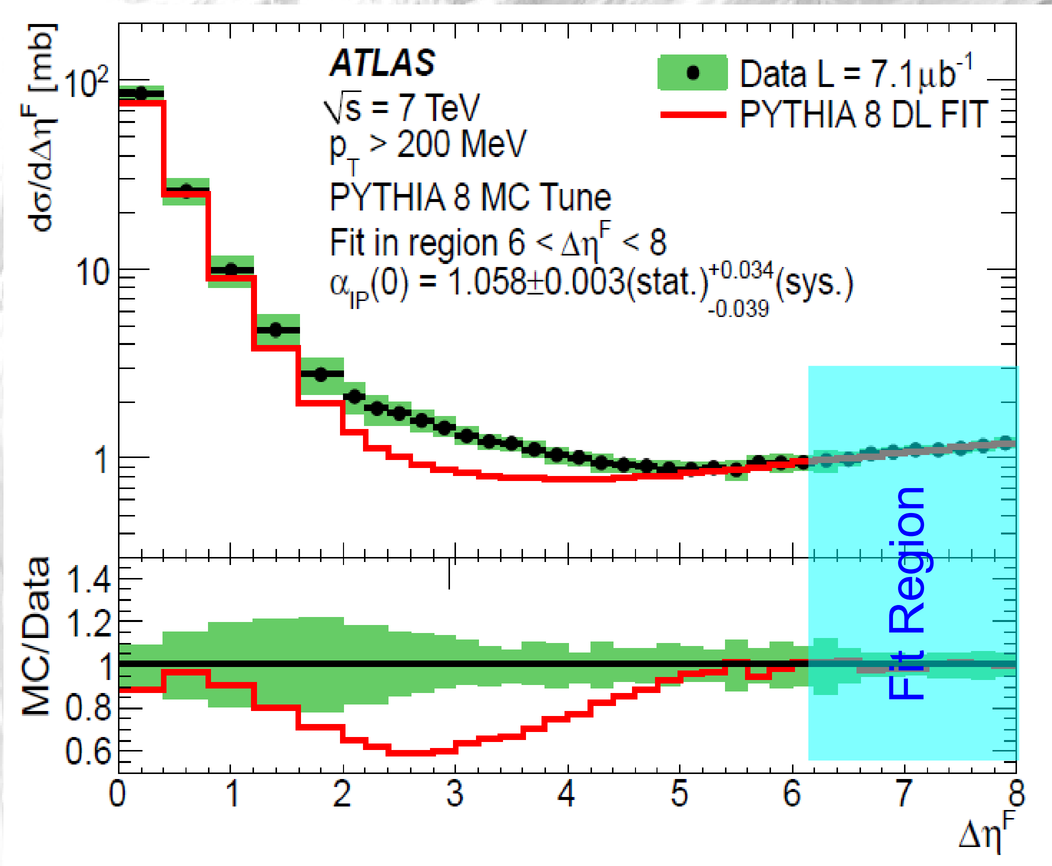
- PHOJET better at large $\Delta\eta_F$ → SD and DD diffraction xsection
- Pythia better for smaller $\Delta\eta_F$→ Sensitivity to hadronization fluctuations and MPI







For large rapidity gaps
Plateau reproduced by both models
Raise at $\boldsymbol{\Delta\eta_F}$ >~5 not predicted by models (Triple Pomeron exchange)



Default Pythia and Phojet $\alpha(t=0) = 1$

Increase at large $\Delta\eta_F$ is expected from the IPIPIP term in triple Regge models with a Pomeron intercept $\alpha_{IP}(t=0)>1$

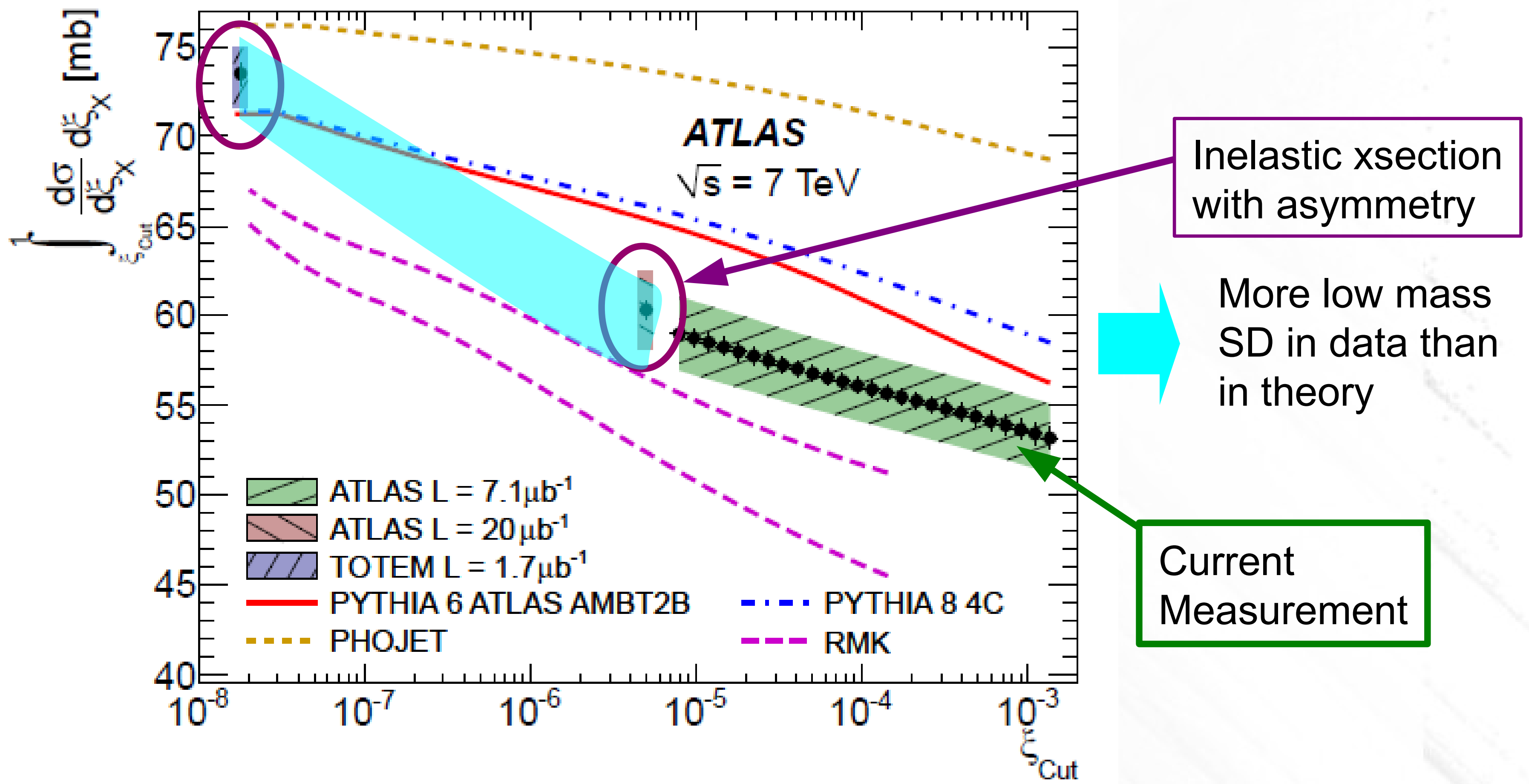
→ Supercriticality of the Pomeron Regge intercept

Intercept determined by χ^2 fit for $6<\Delta\eta_F$

Low dependence on slope

$$\alpha_{I\!P}(t=0) = 1.058 \pm 0.003(\text{stat})^{+0.034}_{-0.039}(\text{syst})$$

Cross Section as a function of Mx



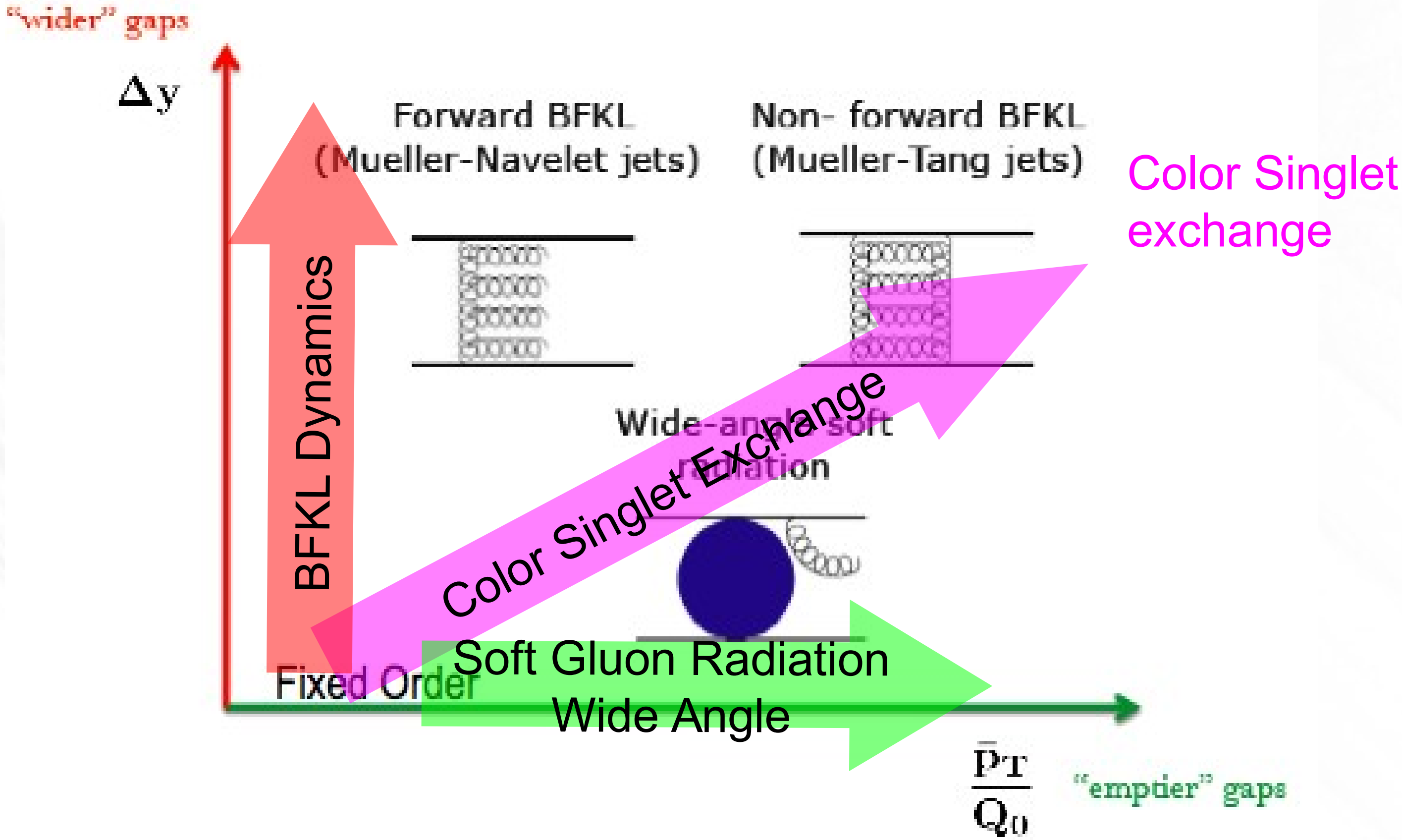
More low mass SD in data than in theory

Vertical bars → all uncertainty except luminosity

Single cross section measurements performed with detectors at different η

Eur. .Phys. J. C72 (2012) 1926, arXiv1201:2808

Experimental Tool II.1: Dijet with central Veto



Veto energy scale Q_0 (20 GeV)>> Λ_s → Insensitive to nPQCD effects

→ Different pQCD phenomena can be studied:

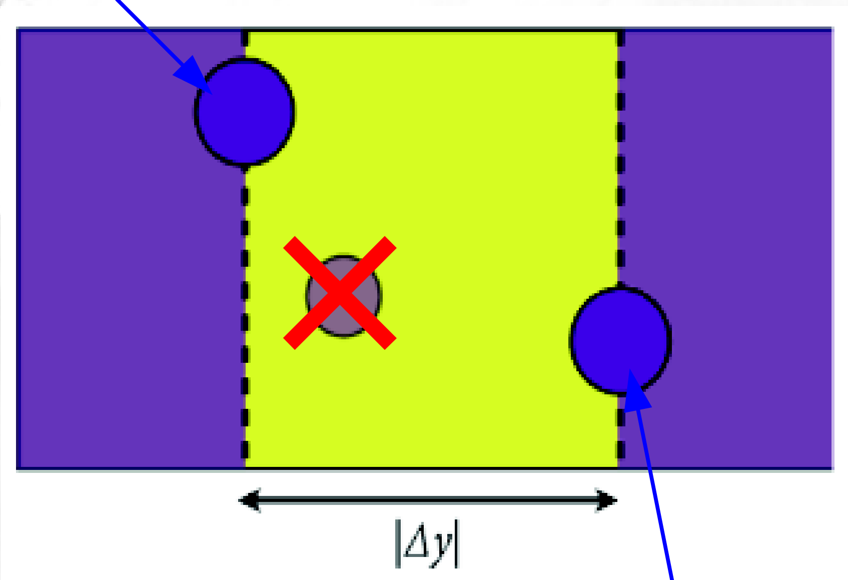
Large Δy → BFKL dynamics

Large dijet transverse momentum wrt Q_0 → Wide Angle Soft Gluon Radiation

Both Large → Color Singlet exchange

Reference: JHEP 1109 (2011), 053, arXiv:1107.1641 Update (CERN-PH-EP-2014-132)

Experimental “Setup”



Reconstruct jet with anti-K_T(R=0.6)

Jet thresholds P_T>20 GeV |y|<4.4

Boundary jets requested to have $\bar{P}_T = (P_{TJet1} + P_{TJet2})/2 > 50$ GeV. In addition:

Leading P_T jets

OR

Most Forward/Backward

Additional radiation in “gap” defined by:

- Gap fraction: Fraction of events with no additional jet with $P_T > Q_0$ in gap
- Mean number of jets in gap with $P_T > Q_0$

Reported as a function of:

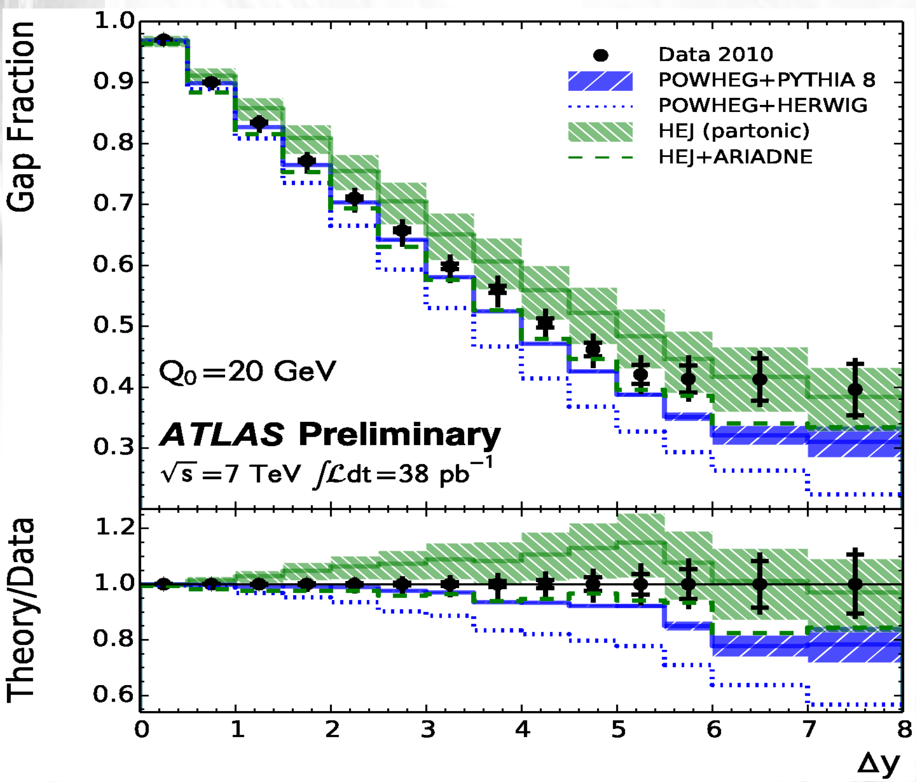
- Δy
- $\bar{P}_T$

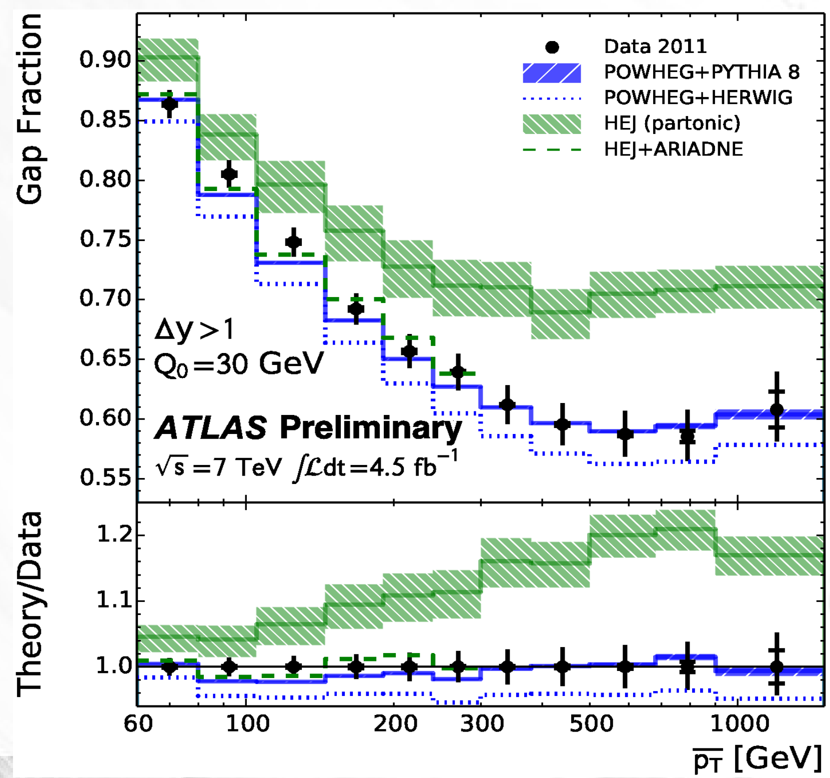
All measurement unfolded to “hadron” level

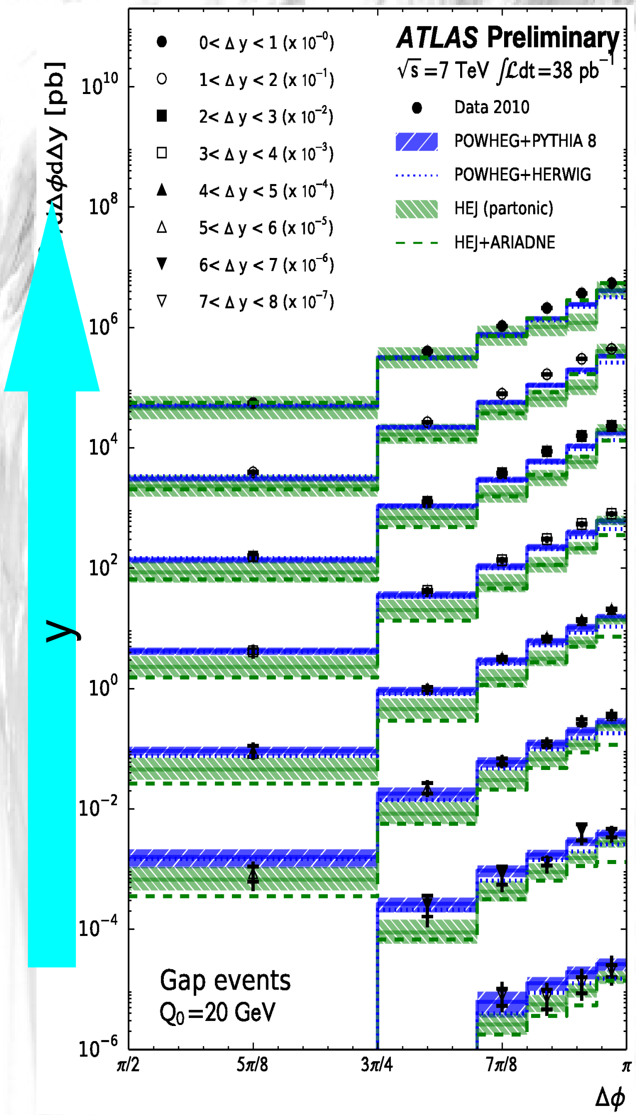
LO (ALPGEN, PYTHIA, HERWIG) tested in previous analysis
State of art simulations studied in most recent analysis:

- POWHEG NLO
- HEJ (LL) with and without shower (hybrid model)

Gap fraction and Leading P_T



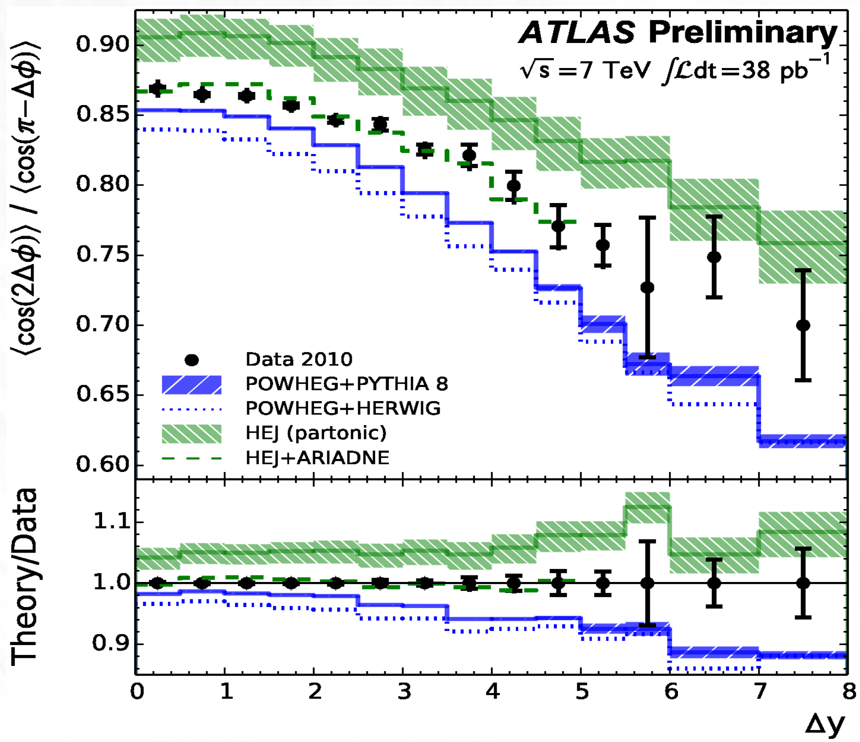




Comparison with higher order MC:

HEJ: LL parton level generator to all orders for wide-angle soft-gluon radiation of similar P_T

Emulates BFKL (large Δy)

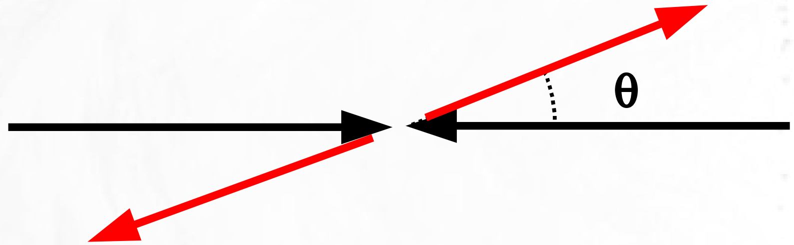


POWEG: NLO dijet + Pythia/Herwig parton shower: fails at large Δy because higher order QCD are relevant for that region

Gap fraction

Experimental Tool III: Forward Proton ID

Detect elastic scattered protons (forward):
Easy in theory, complicated in practice



Need very forward detectors closed to beam → ALFA Roman Pots
Main goal of ALFA is the absolute measurement of the elastic cross section → total cross section via the optical theorem

$$\sigma_{\text{tot}} = 4\pi \cdot Im\left(f_{\text{el}}(0)\right)$$

Need independent luminosity measurement
→ σ_{el} is measured
→ extrapolation to t = 0

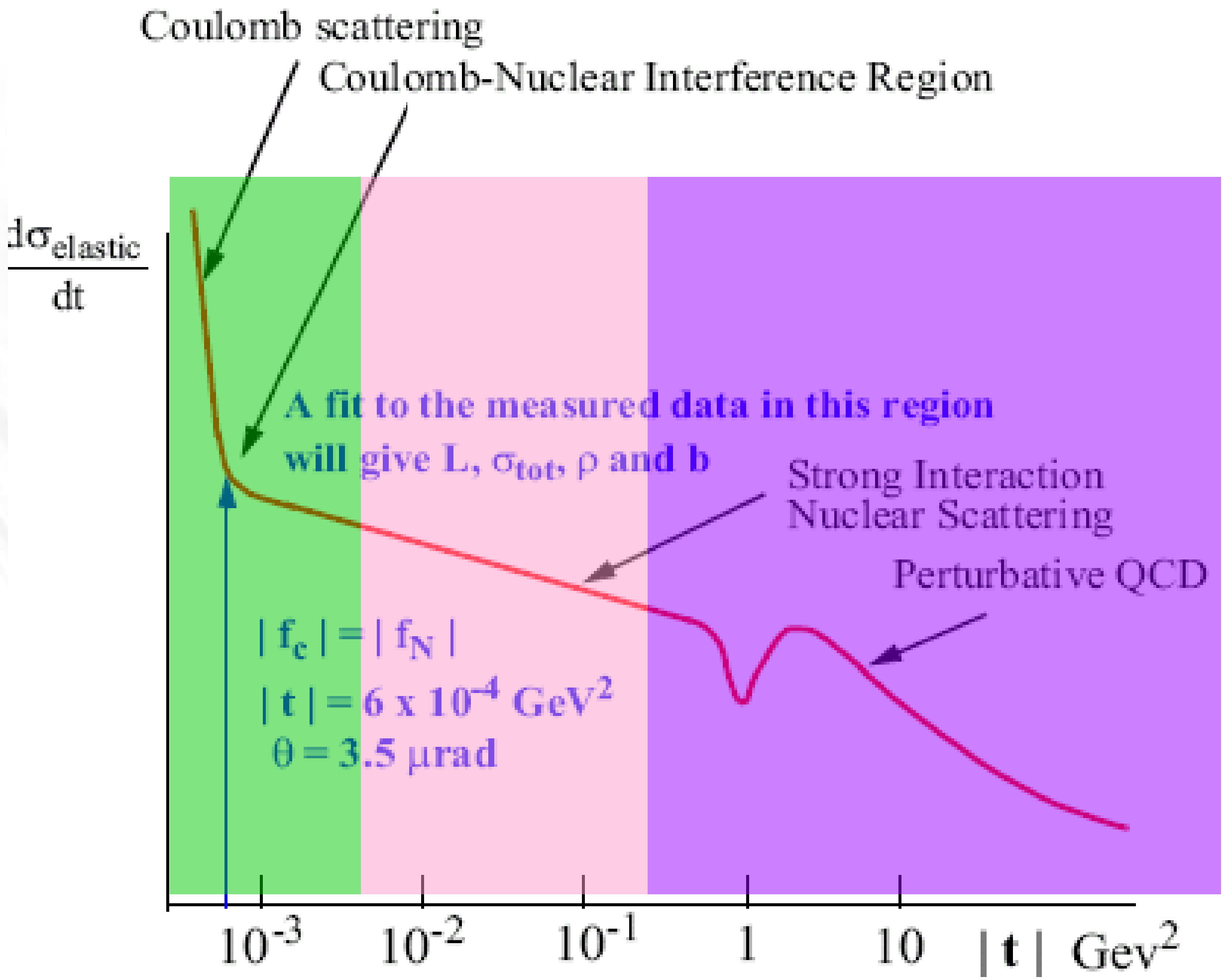
$$\sigma_{tot}^2 = \frac{16\pi(\hbar c)^2}{1+\boxed{\rho^2}} \boxed{\left.\frac{d\sigma_{el}}{dt}\right|_{t=0}}$$

ρ = ℜe[fel(0)]/ℑm[fel(0)]
→ from theory

ISR-like measurement
Measure at the same time inelastic and elastic rate

Coulomb Amplitude
Elastic rate measured down to small t where Coulomb amplitude is dominant
→ normalization from calculable e.m. amplitude

Cross Section Measurement



Extrapolation for t=0 → Min Reachable t:

~0.3~1 GeV^2 β*=0.5m,3m (Standard pp runs)

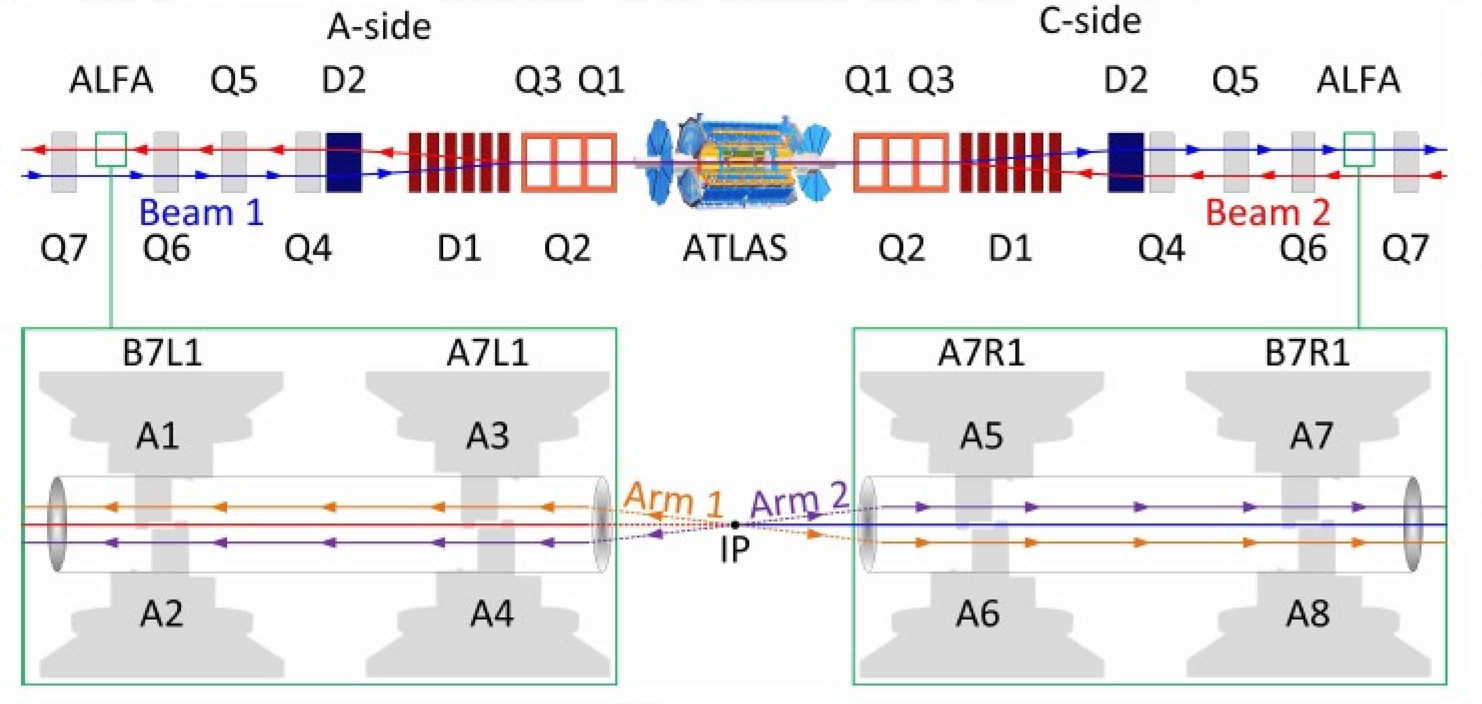
~10^{-2} GeV^2 β*=90m (2011/2012 special runs)

~10^{-4} GeV^2 β*=2900m (later)

ALFA detector

Can trigger on each individual station → Combine also with other detectors for several topologies:

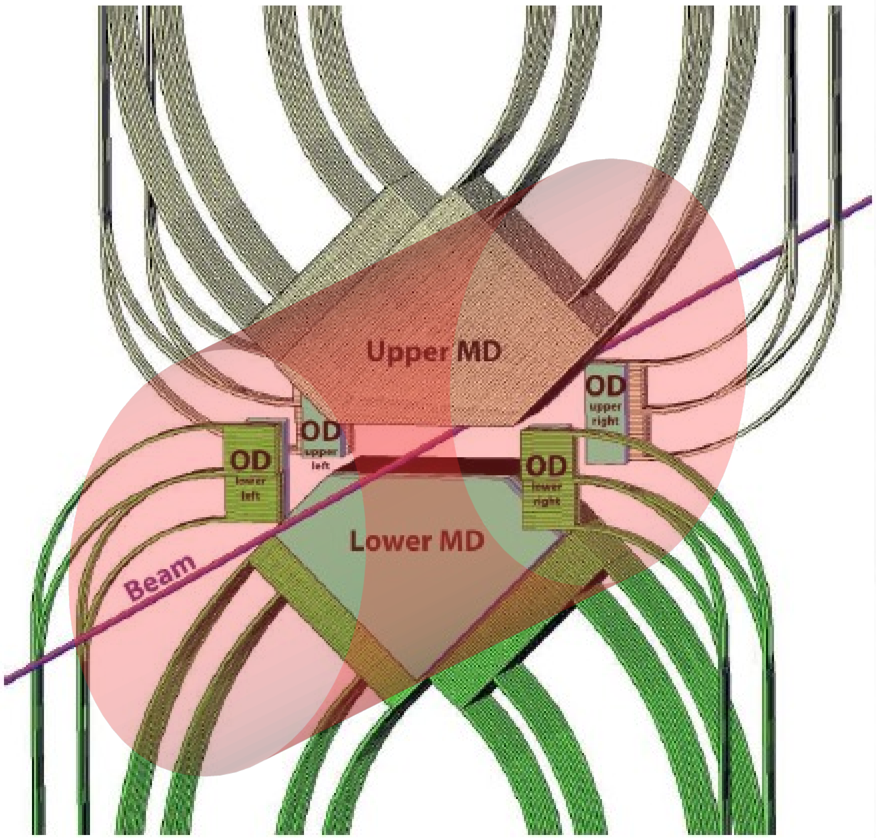
- Elastic
- Single Diffractive



237 m 241 m

Data taking at β^*=90 with one colliding bunch only

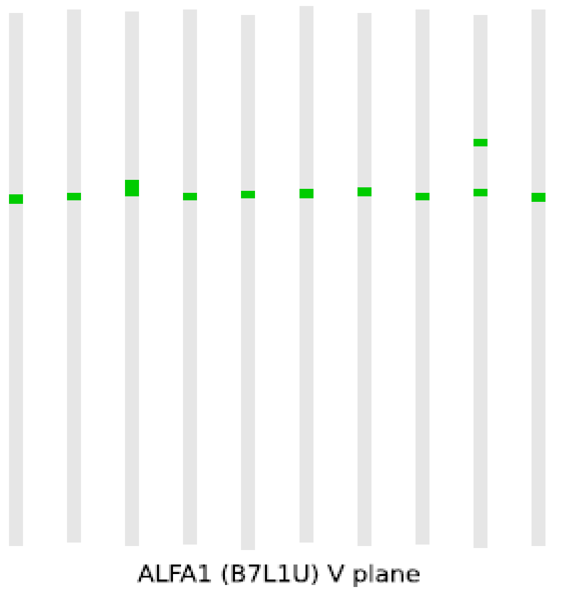
ALFA detector



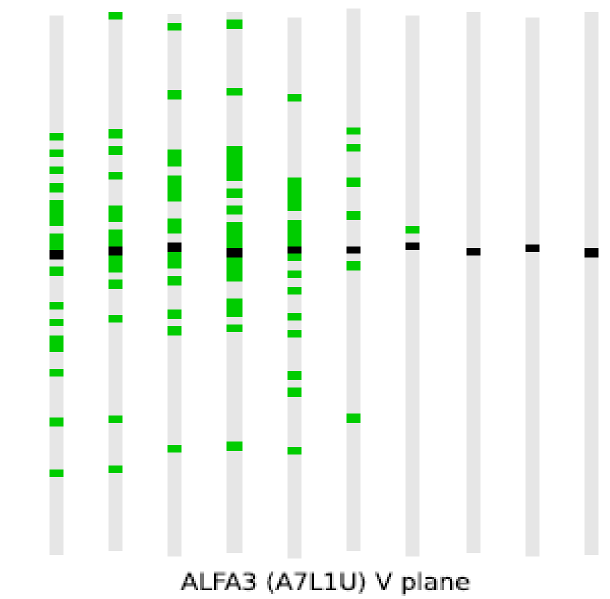
- Edgeless detector
- Single cladded 0.5 mm square fibers
- Main Detector
- For MD 10 staggered layers arranged in U and V direction
- → position resolution obtained ~25~35 μm
- 93% efficiency *per* layer
- Overlap Detector → track alignement
- Trigger Detector
  - 3mm thick scintillators
- Closest beam approach 6.5**σ** → (between 3 and 5 mm from beam 1 and 2)

Data taking at **β***=90 with one colliding bunch only

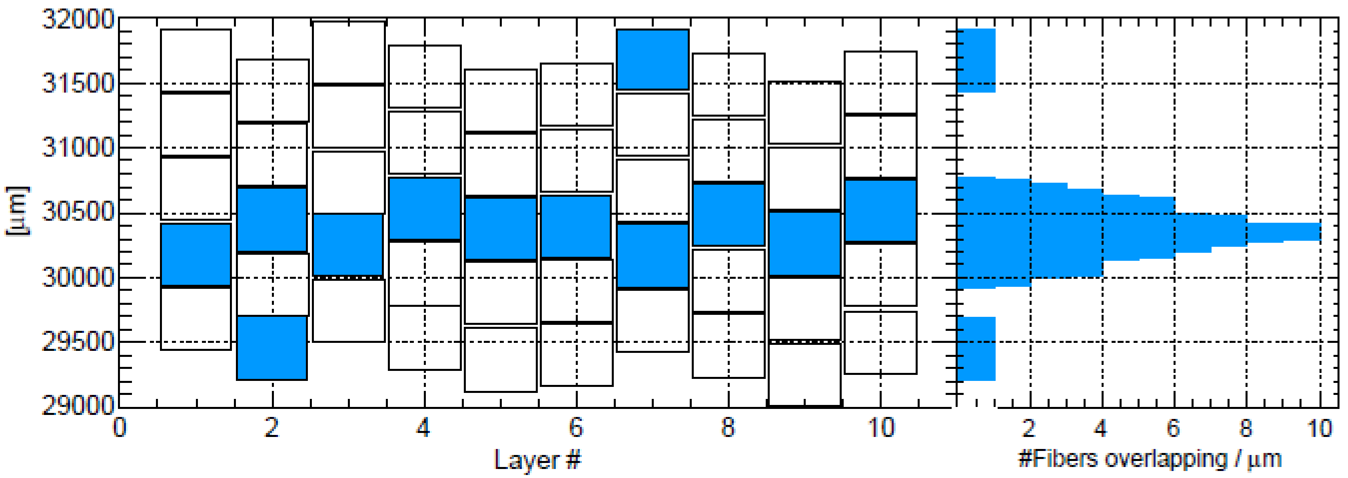
Track reconstruction



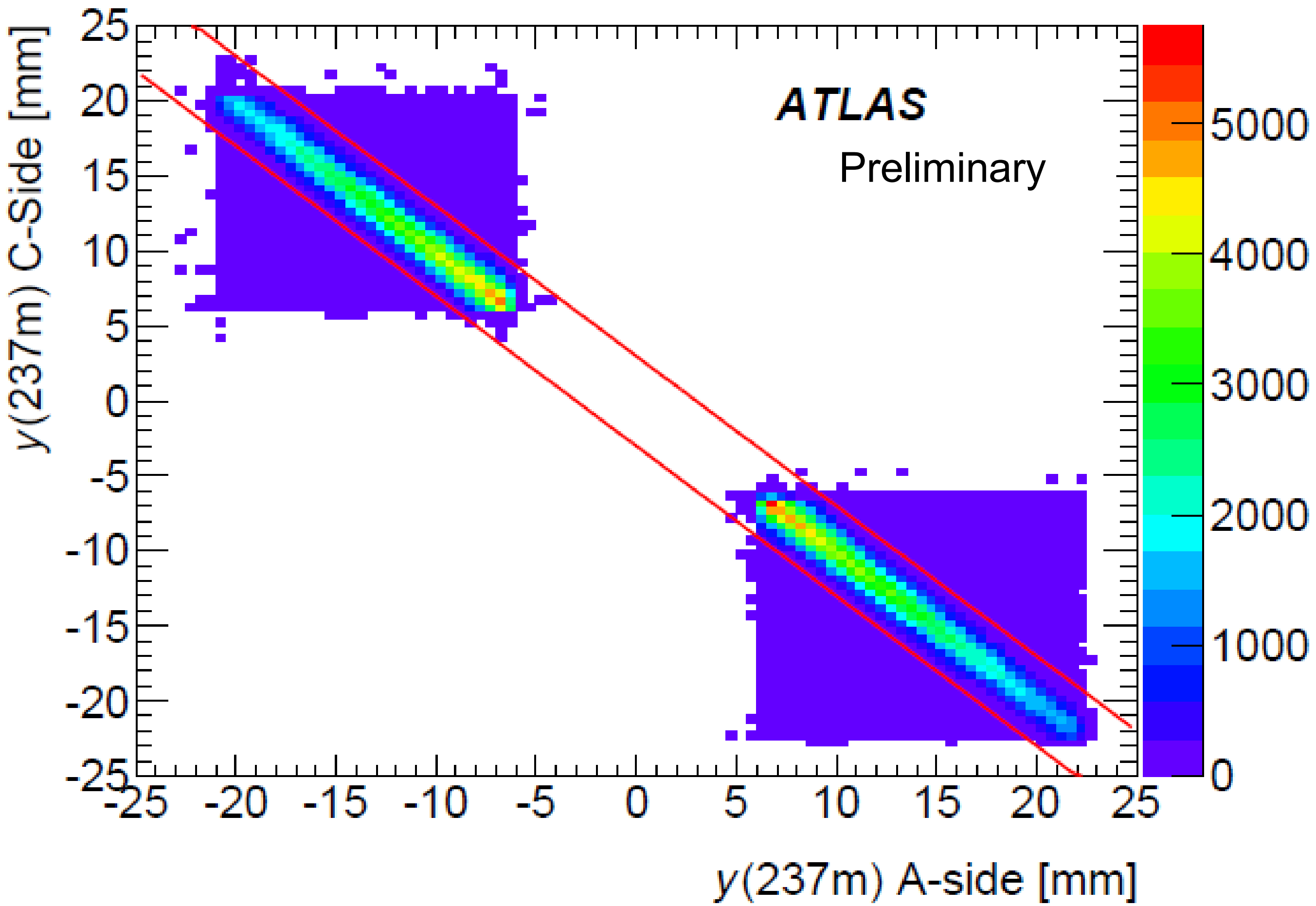
Track from elastic event



Track from inelastic/beam halo/ event



Measuring θ

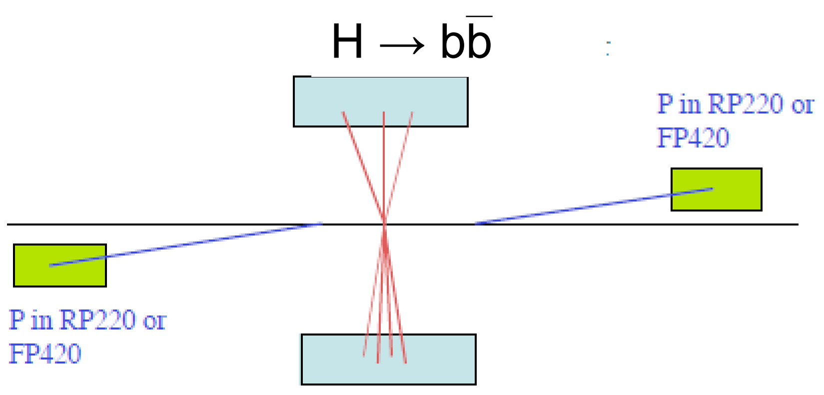


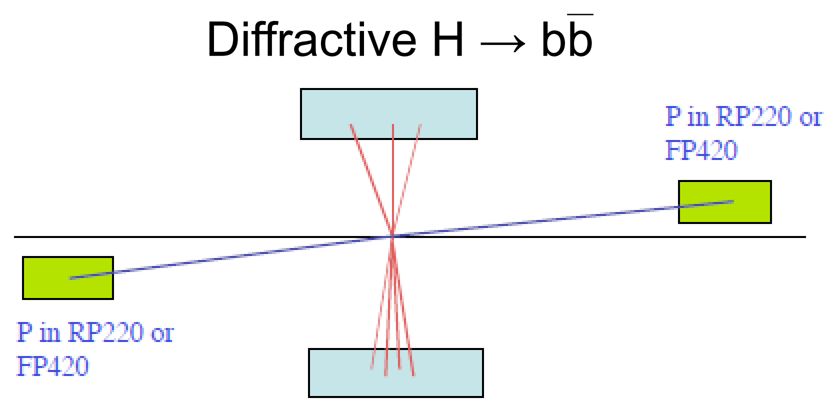
Correlation plot for A-C Side arms (more than 560 m distance)

Selection for elastic events

ATLAS total xsection measurement will be released next week

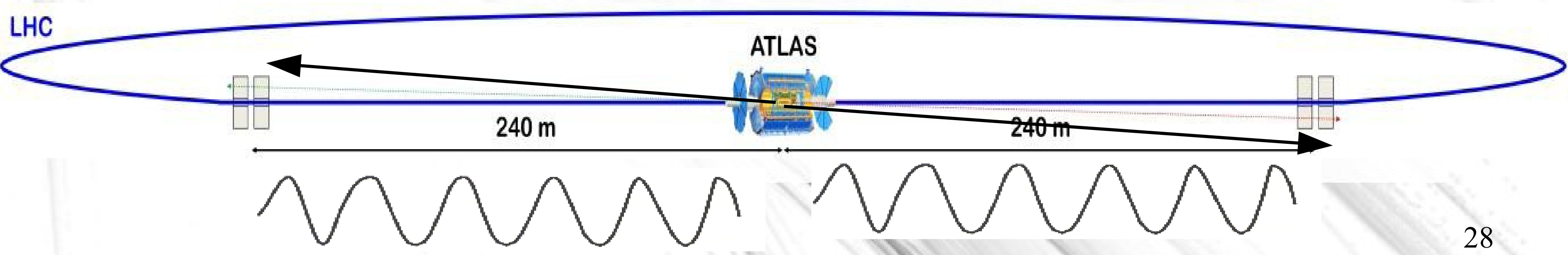
Experimental Issues





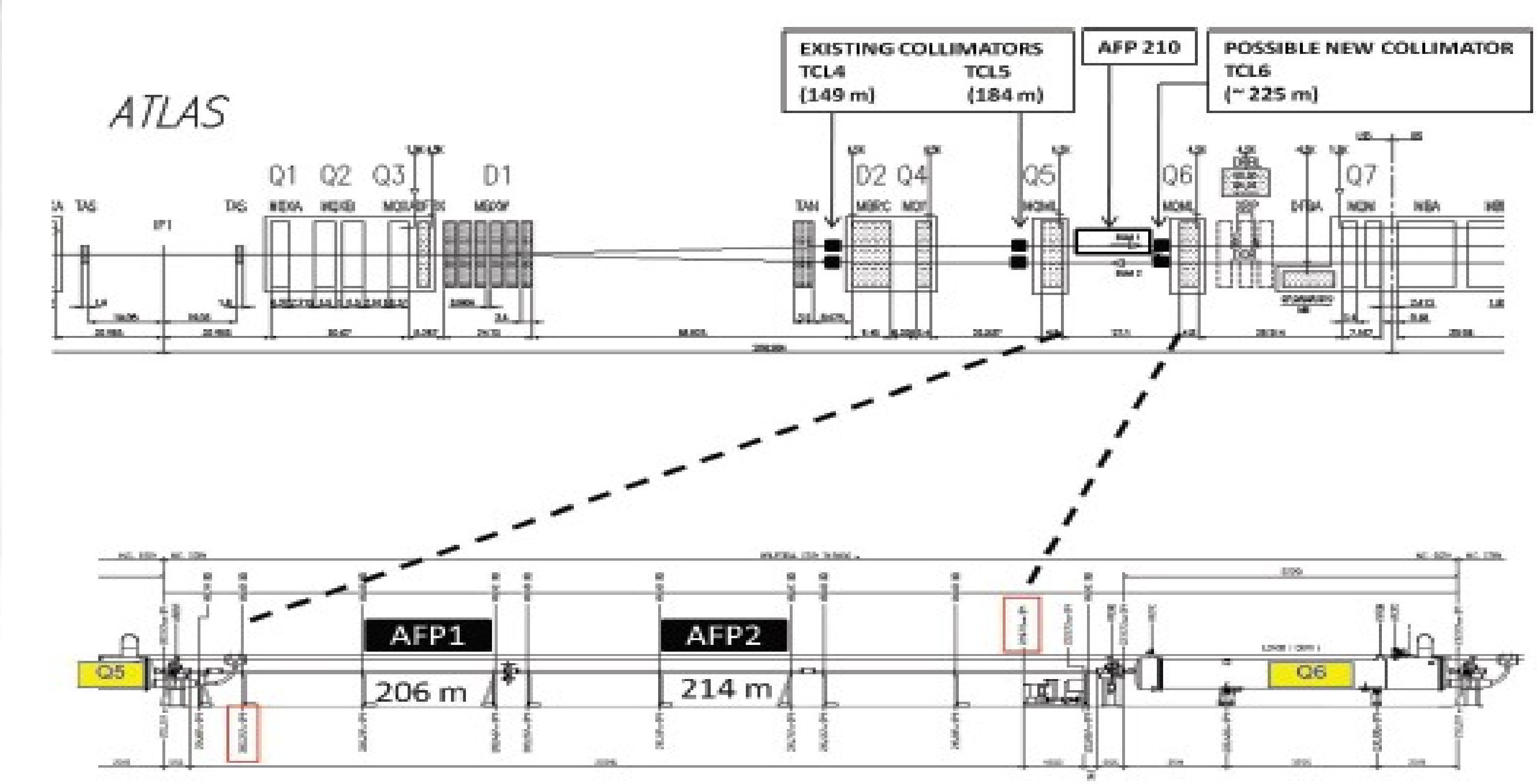
- PileUp
- Specific LHC fills with specific optics (large β^*) → Low luminosity
- Move the devices close to beam (few mm) → Beams **ABSOLUTELY** stable
- When running with the whole detector → time latency issues:

Protons have to travel 240m + signals have to travel 240m back to ATLAS for TDAQ → Event fragments collected by the ATLAS subdetectors might be close to the L1 latency (2.5μs) → Need to run ATLAS TDAQ with extended latency (+20BC=+250ns) All but muon detectors can accommodate that

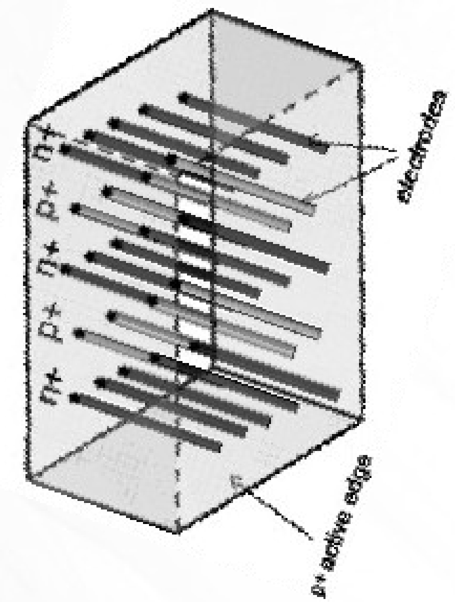


Plans for ATLAS Upgrade: AFP

AFP: Atlas Forward Program (AFP1 and AFP2) for ATLAS Upgrade Phase2 (2020)
AFP1 Detectors located in two stations: 206/214 m from IP
AFP2 420m from IP (later)



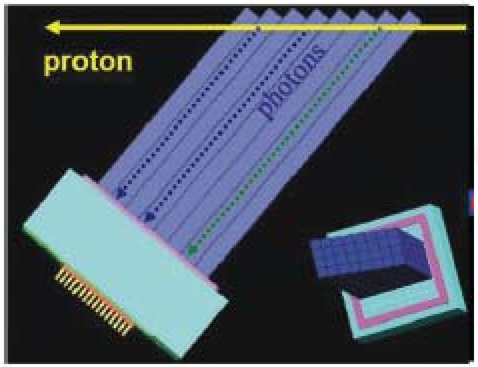
Plans for ATLAS Upgrade: AFP



Silicon Tracking Detectors:
- Measure position and angle
- Radiation hardness (~30 kGy/year @ 10^{34} cm^{-2}s^{-1})
- → Silicon 3D detectors

Timing detectors:
- MHz rate capability
- Trigger capability
- Quartz based Cherenkov detector + Microchannel plate PMT
- Timing resolution: $\sigma(t)$~10~20ps → $\sigma(z)$ few mm

→ factor 40 of background from pileup rejection (μ=50)



Summary and Future

- Summary of Results:
  - Asymmetry → fraction of diffractive vs Inelastic cross section → inelastic cross section measurement
  - Rapidity “gaps” → Diffraction studies (npQCD)

- Ongoing Measurements:
  - ATLAS total cross section measurement with ALFA next week
  - Possibility of exclusive measurements with ALFA

- AFP program for ATLAS phase 2 upgrade → under approval

References

Asymmetry → inelastic cross section measurement

- Nature Commun. **2** (2011) 463, arXiv: 1104.0326

Forward Rapidity “gaps” → Diffraction studies (npQCD)

- Eur. Phys. J. **C72** (2012) 1926, arXiv: 1201.2808

Rapidity Gaps in Dijet production

- JHEP 1109 (2011) 053, arXiv 1107.1641 (Update soon: CERN-PH-EP-2014-132)

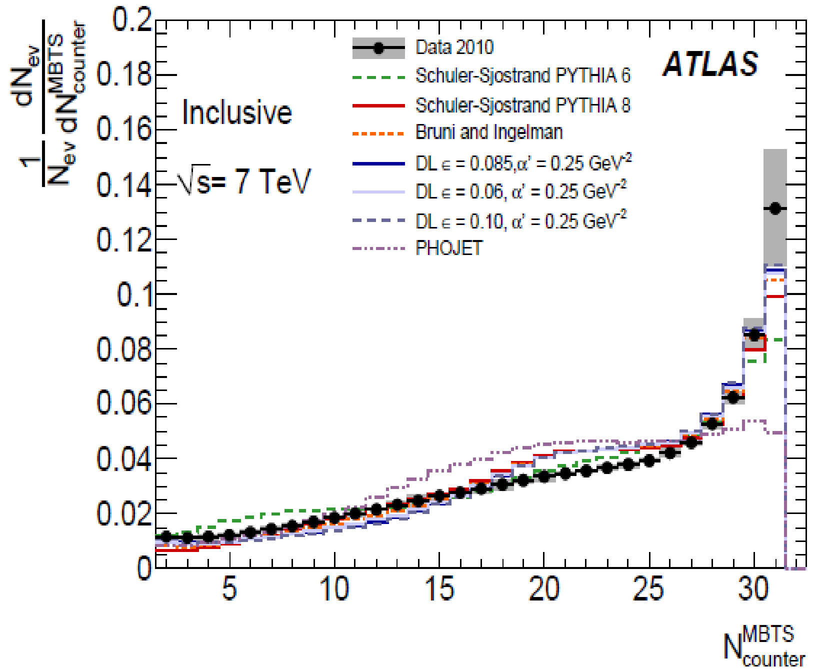
Proton-proton elastic cross section measurement

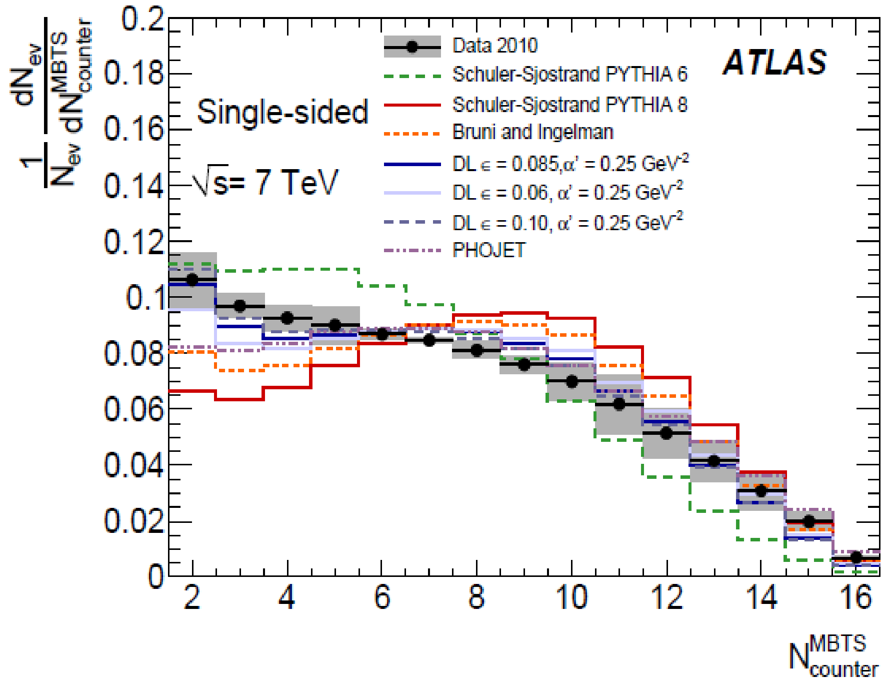
- (Coming soon!)

BackUp

Xsection Measurement

Data-MC comparison of MBTS multiplicities

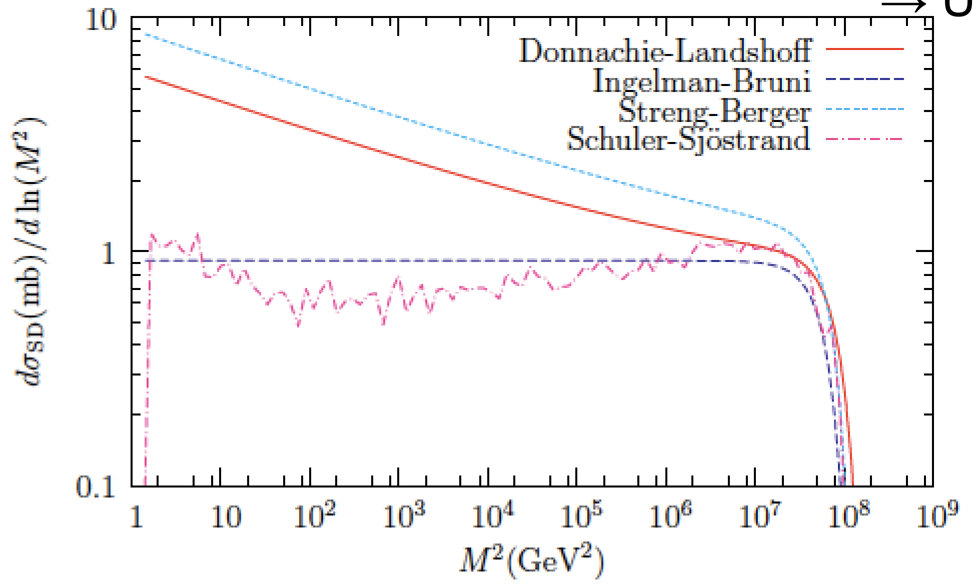


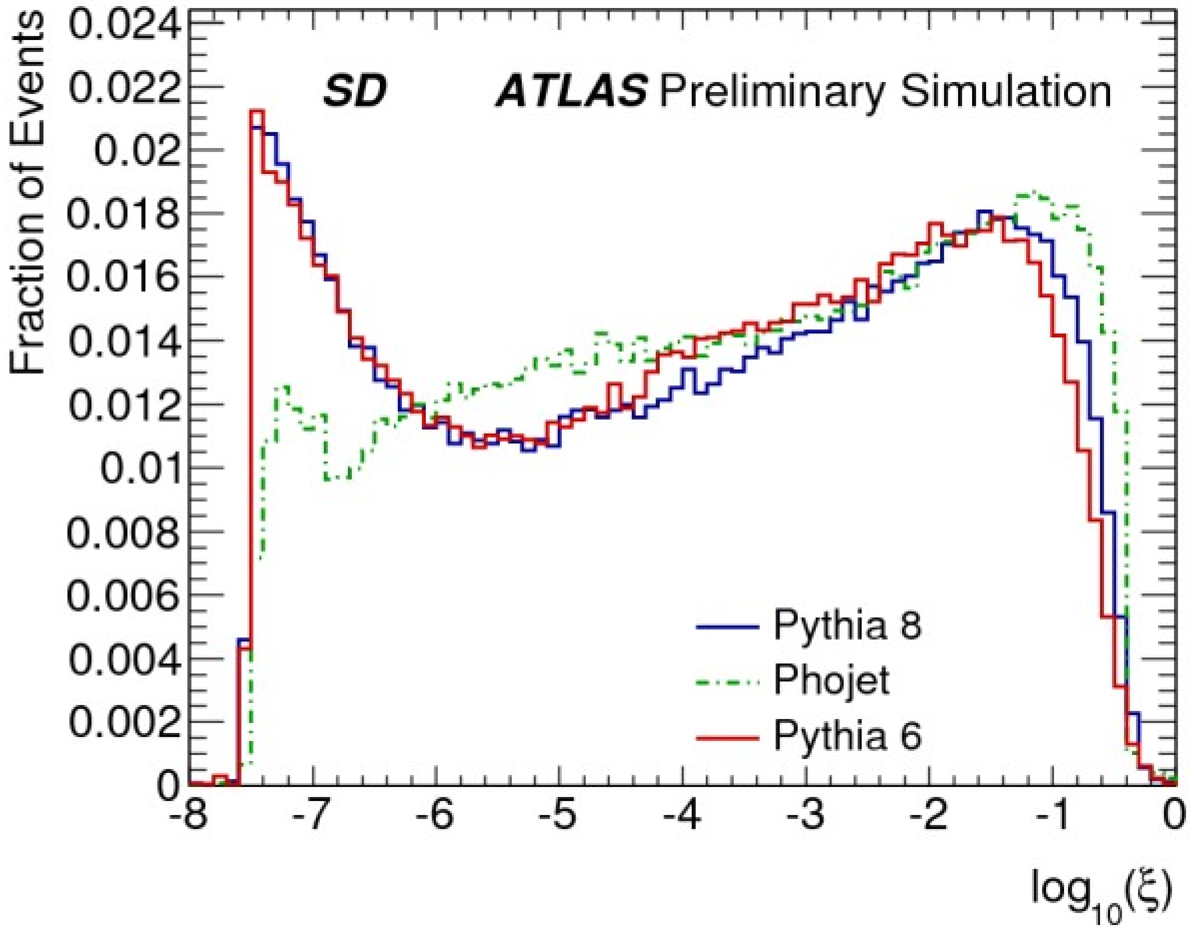


Xsection Measurement

Extrapolation to total inelastic xsection

87.3% for DL
Other models 79% Ryskin
96% PHOJET
→ Uncertainty 10%




SD
ATLAS Preliminary Simulation
Fraction of Events
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-8
-7
-6
-5
-4
-3
-2
-1
0
log10(ξ)
Pythia 8
Phojet
Pythia 6

Measure ratio $f_D=(\sigma_{SD}+\sigma_{DD}+\sigma_{CD})/\sigma_{Inel}$

Measured R_{ss}:

Several models → Constraint f_D for each model

$f_D=26.9^{+2.5}_{-1.0}$ % for Donanchie and Landshoff: Pythia 8 +DL with **ξ** dependence parametrized with pomeron intercept:

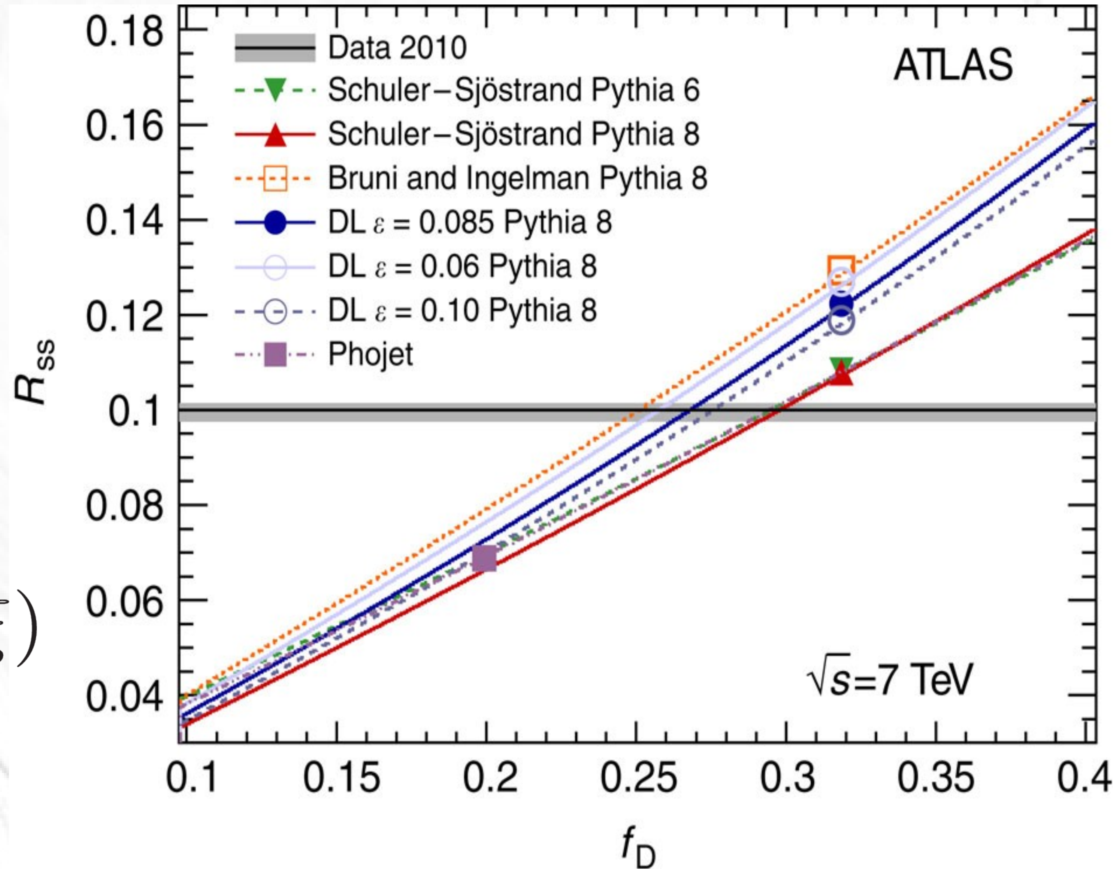
$\alpha(t)=\alpha(0)+\alpha' t$

With α' $=0.36\,GeV^{-2}$

ε $=0.085$

$$\frac{d\sigma_{SD}}{d\xi} \propto \frac{1}{\xi^{1+\epsilon}}(1+\xi)$$

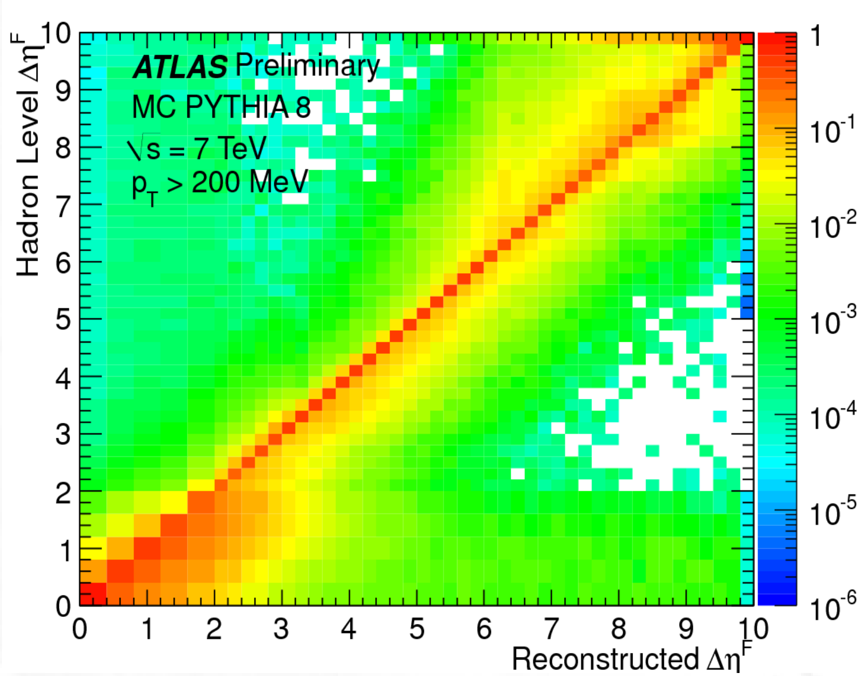
$$\epsilon = \alpha(t=0) - 1$$



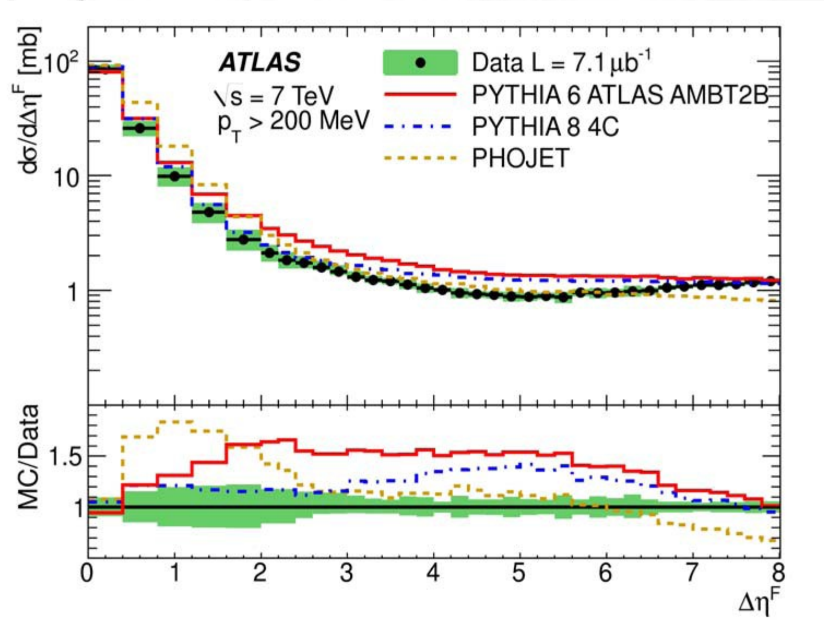
Systematic uncertainties

Main systematic uncertainties come from:

- “Unfolding”: procedure to go from “detector” level (tracks and calorimeter deposit) to hadron level (“stable” MC particle after hadronization)
- Calorimeter Energy scale



→ For some $\Delta\eta_F$ values uncertainties up to ~20%



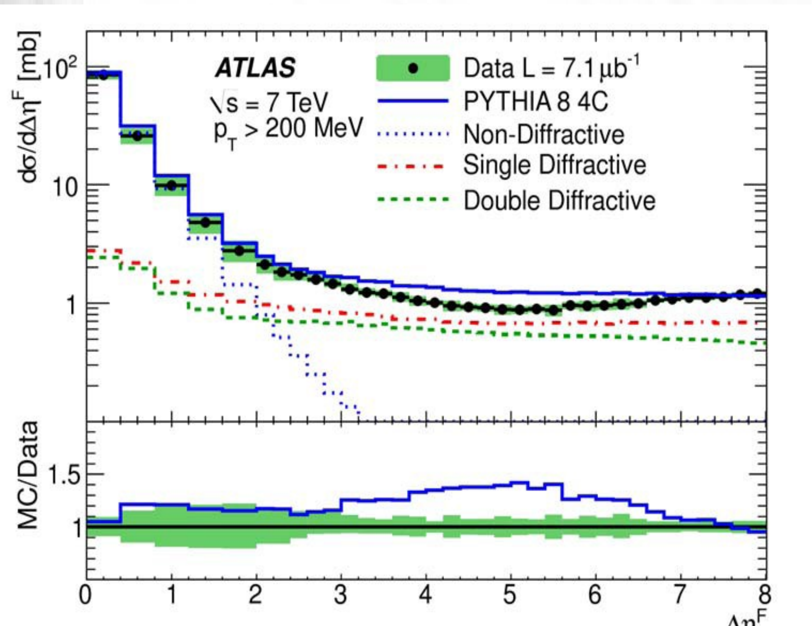
Both PHOJET and Pythia 8 (no CD component in Pythia) reproduce trend but agreement not perfect:

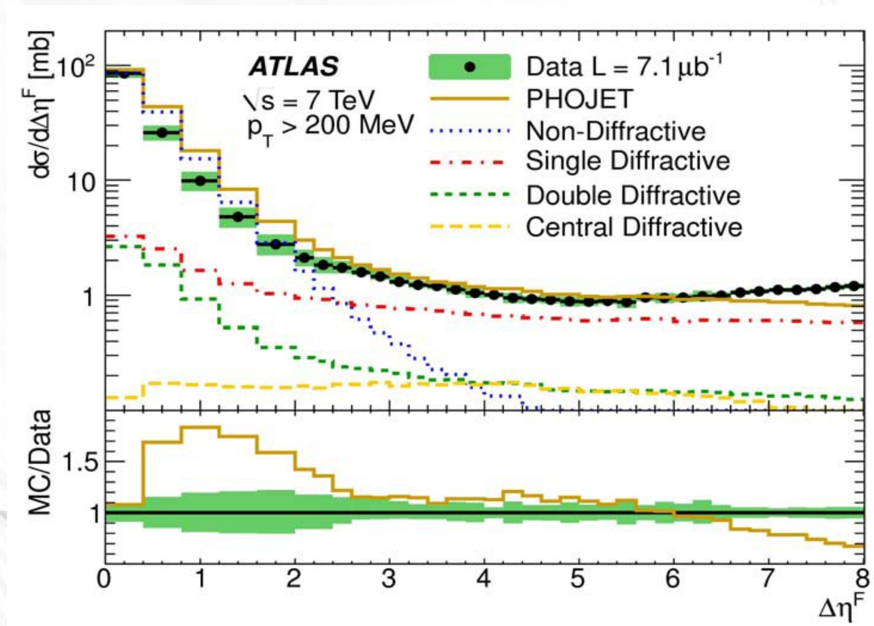
- PHOJET better at large $\mathbf{\Delta\eta_F}$
- Pythia better for smaller $\mathbf{\Delta\eta_F}$

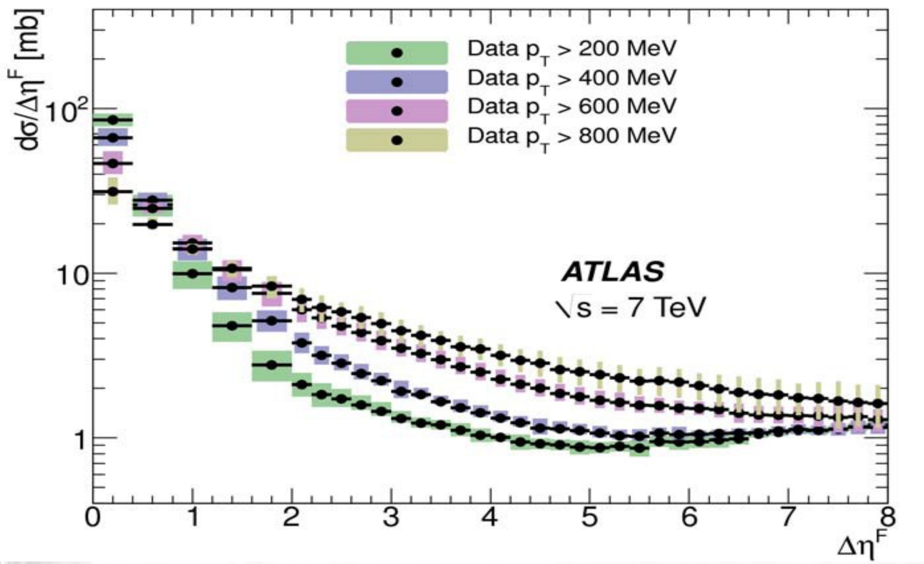
Low $\mathbf{\Delta\eta_F}$ → ND dominant (exponential decrease)

Overestimation of $\boldsymbol{\sigma}_{\mathbf{inel}}$

Large $\mathbf{\Delta\eta_F}$ → Flat contribution from diffraction





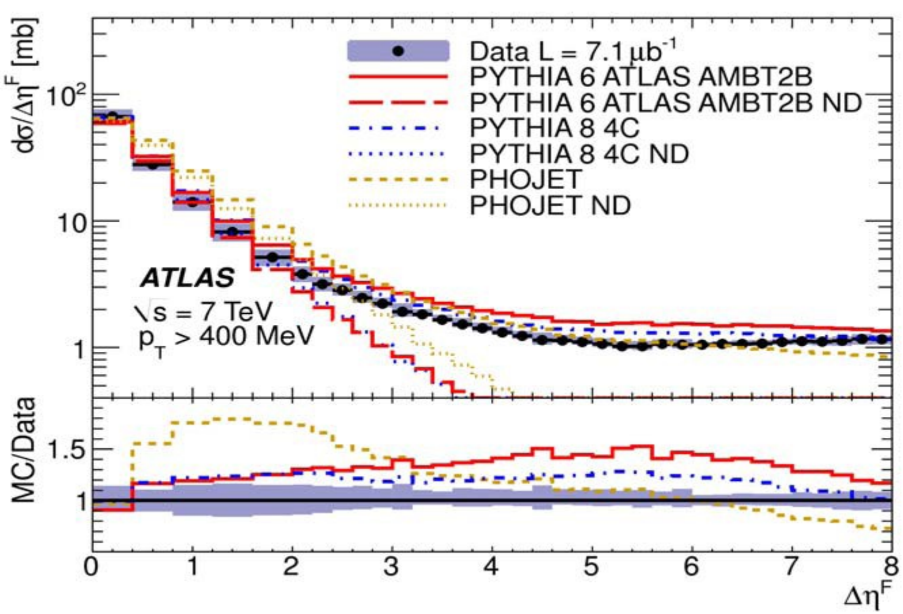


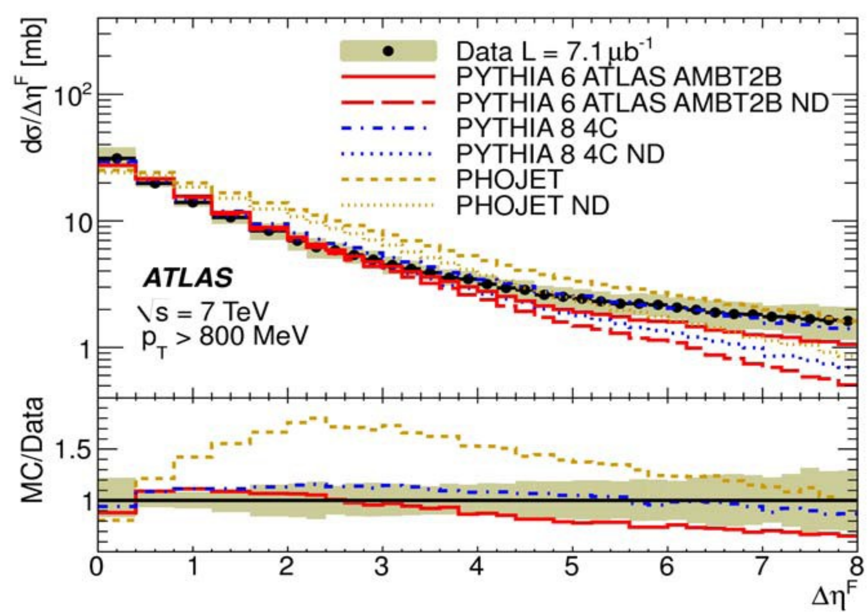
Increasing P_T threshold → Increase ND contribution

P_T Thresh=200,400,600,800 MeV

Exponential decrease for both ND and SD/DD contributions

Pythia better in shape and value

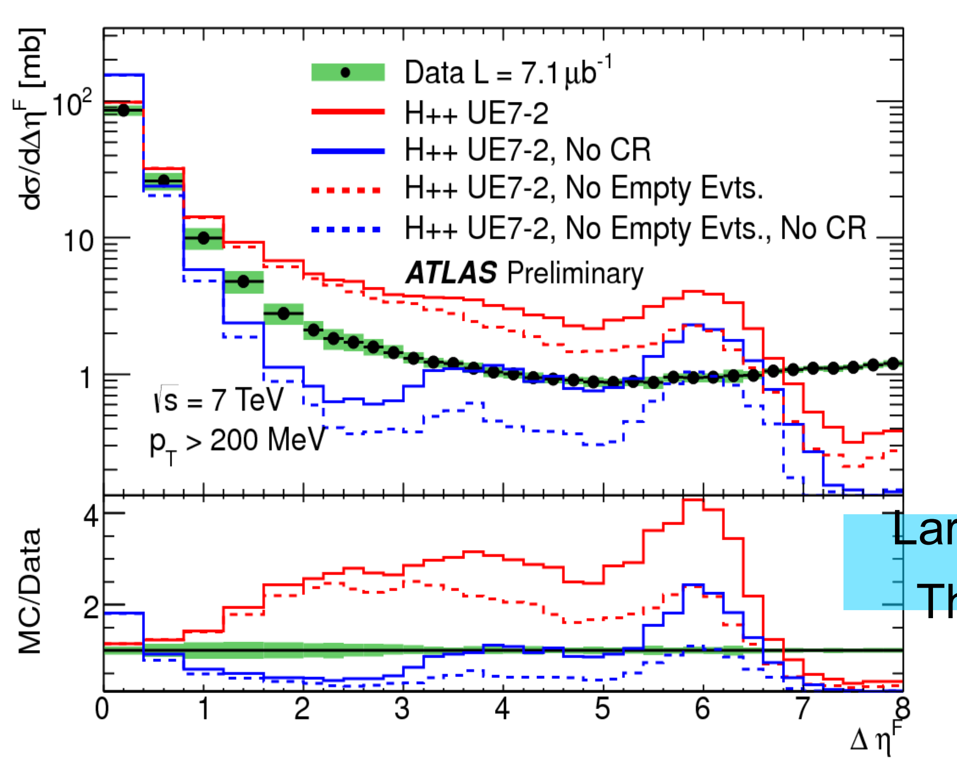


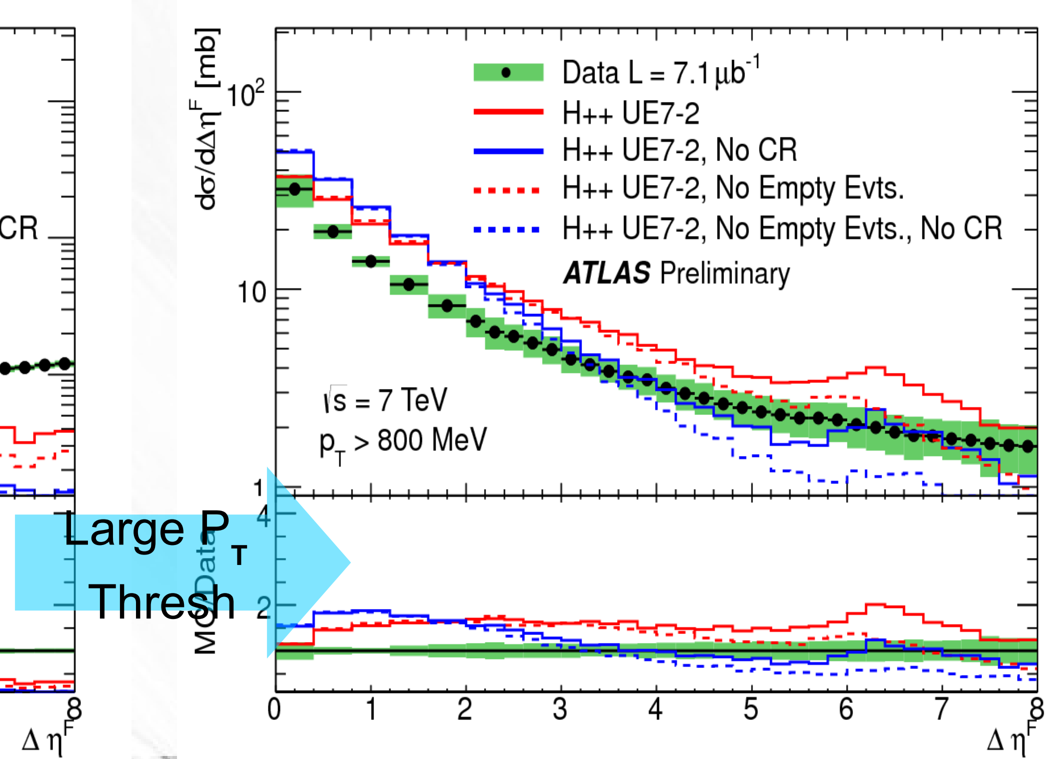


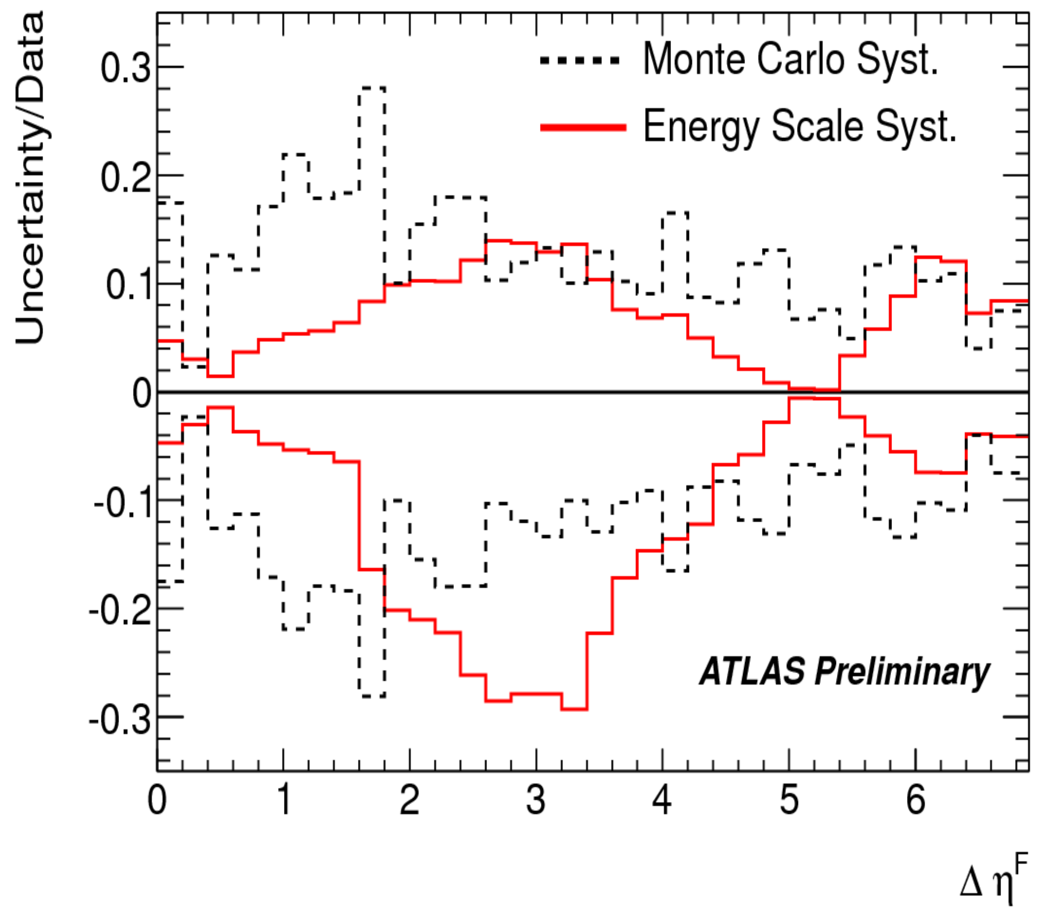
No diffractive in Herwig++

However non negligible (“bump”) contribution in large $\Delta\eta_F$ region

Disabling color reconnection (No CR) and excluding soft events (Empty Events) → xsection reduction but bump is still there → intrinsic feature of cluster hadronization



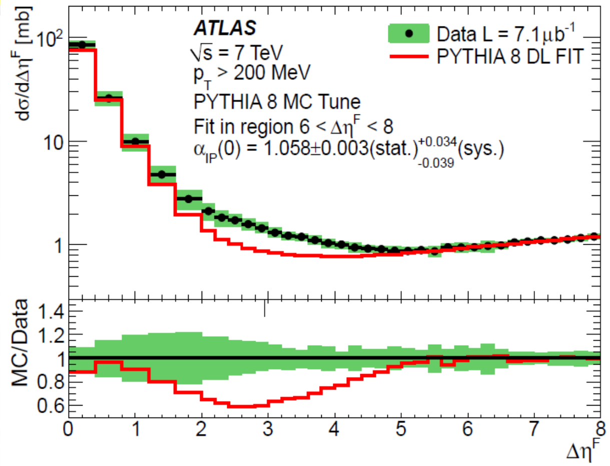



Uncertainty/Data
Monte Carlo Syst.
Energy Scale Syst.
ATLAS Preliminary
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
1
2
3
4
5
6
Δ η^F

Cross Section as a function of Mx

$$\int_0^{\Delta\eta^F_{Cut}} \frac{d\sigma}{d\Delta\eta^F}\, d\Delta\eta^F$$

Measured



$\Delta\eta_F$ Cut

$$\log_{10}\xi_{Cut} = -0.45\,\Delta\eta^F_{Cut} - {}^{1.52}_{1.56}$$

Pythia8
PHOJET

$$\int_{\xi_{Cut}}^{1} \frac{d\sigma}{d\xi_X}\, d\xi_X$$

Correction for:

- particles with P_T<200 MeV
- ND contribution

→ small correction: ~1.1±1.1%

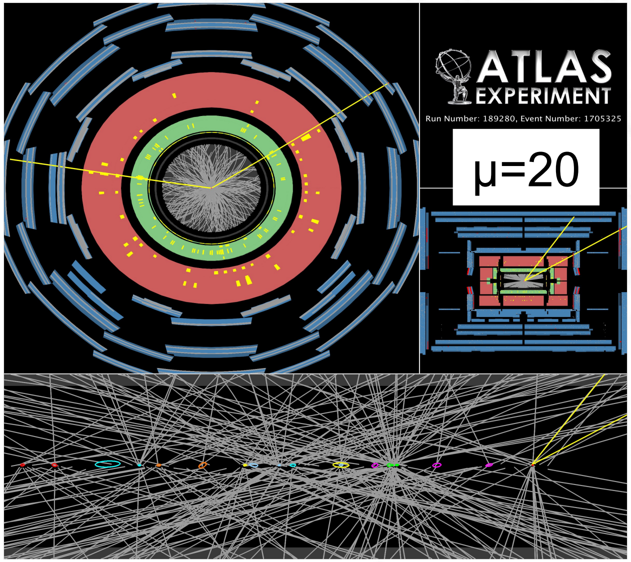
Experimental Issues: Pile Up

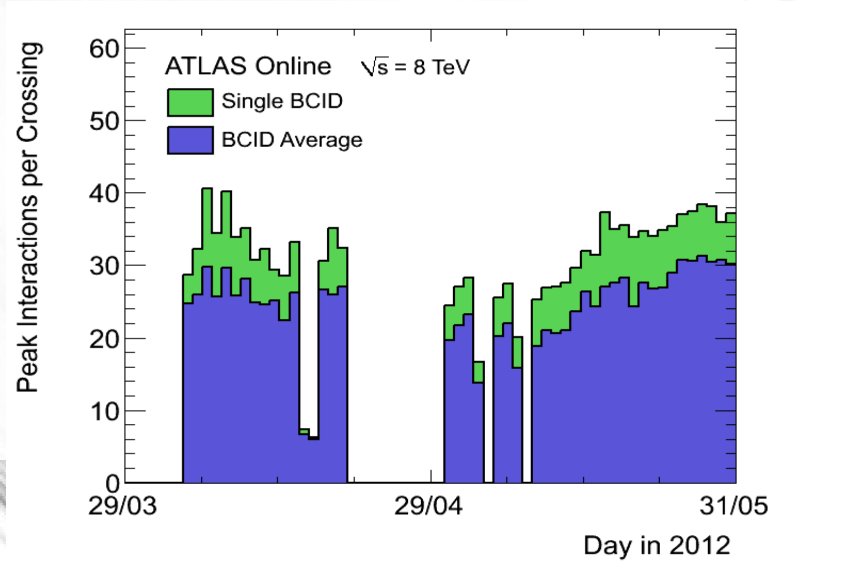
To collect large statistics (large integrated luminosity)

- Large charge stored in bunches
- "squeezed" bunches

→ Large pile up (μ mean number of collisions per bunch crossing)

Large μ spoils experimental tools to study diffraction
Most 2012 periods have μ~30
Use limited amount of data ~20μb^{-1} (Present) collected with μ<<1
If well motivated LHC could run with some bunches with small charge → μ~0.1-1
→ Trade off between loosing some % of integrated luminosity, possibility to increase diffractive physics potential





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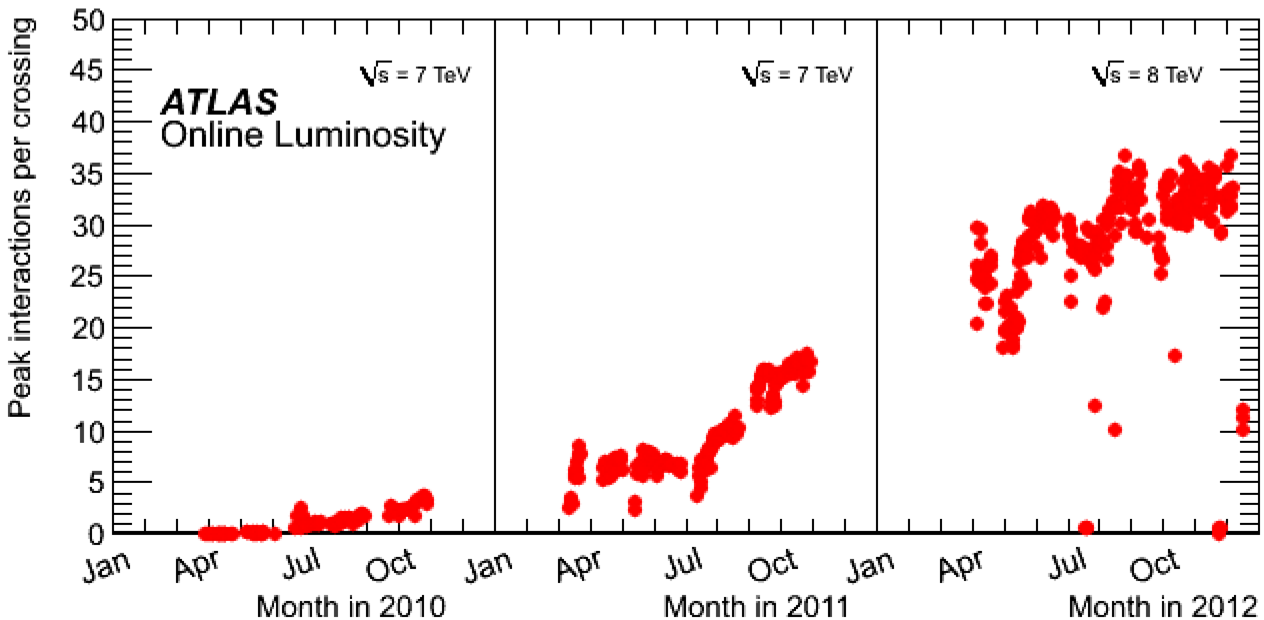
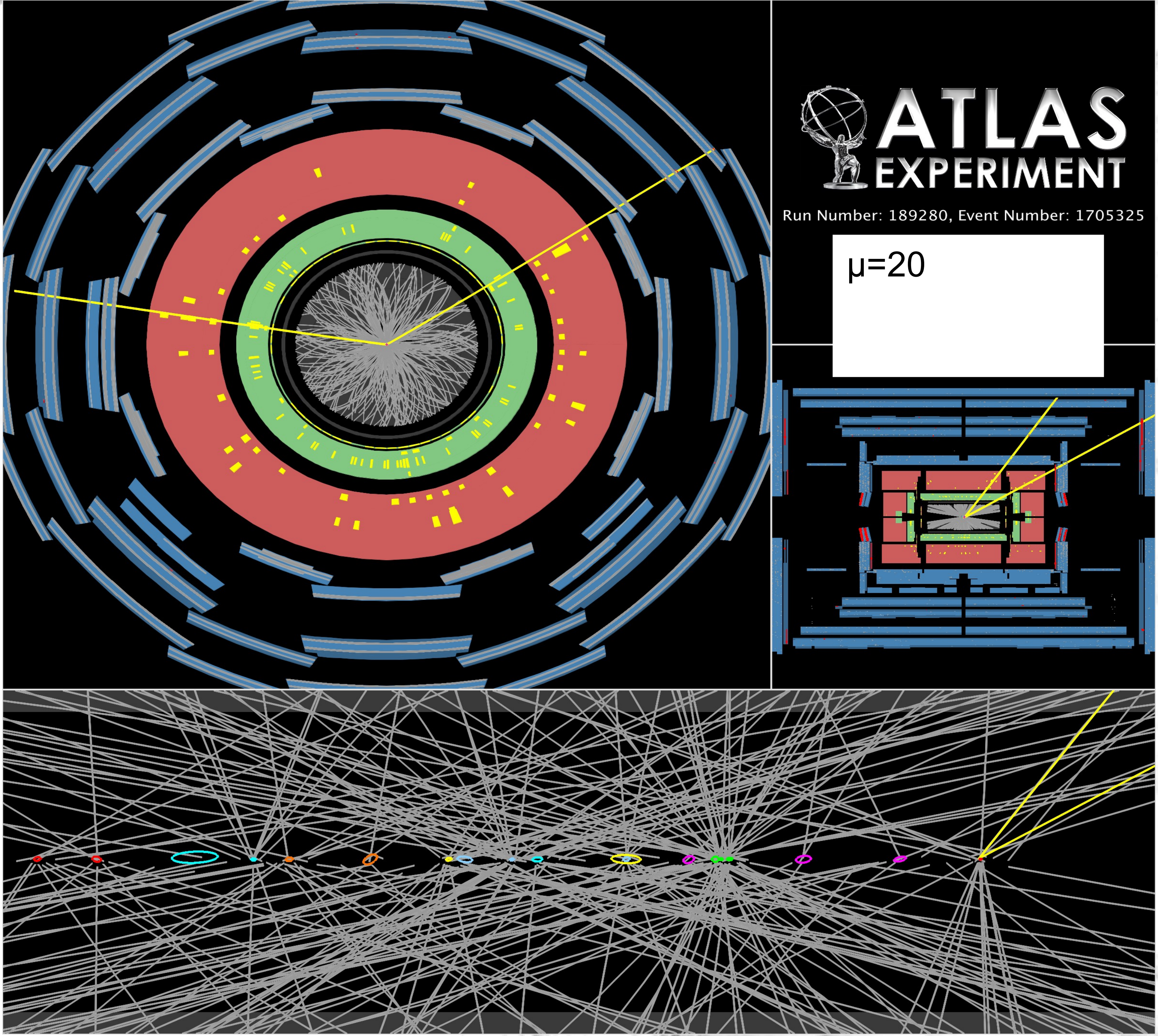


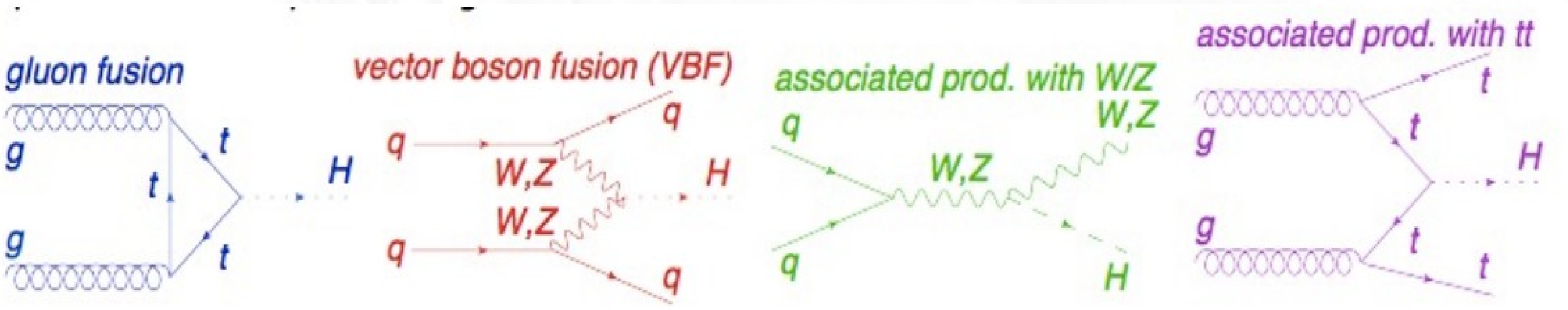

ATLAS
EXPERIMENT
Run Number: 189280, Event Number: 1705325
μ=20

Physics Motivations

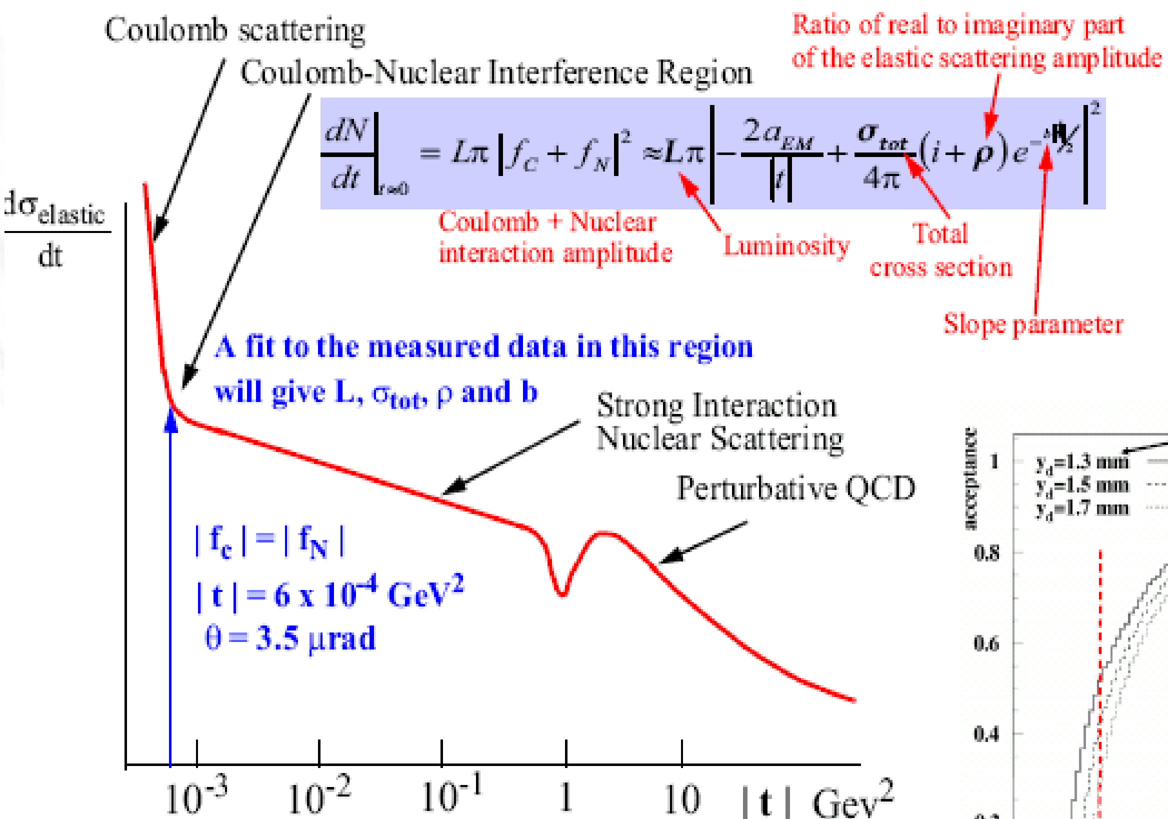
Small cross section processes (Higgs production, SUSY, exotics) superimposed with large number of "Minimum Bias", Single and Double Diffractive events

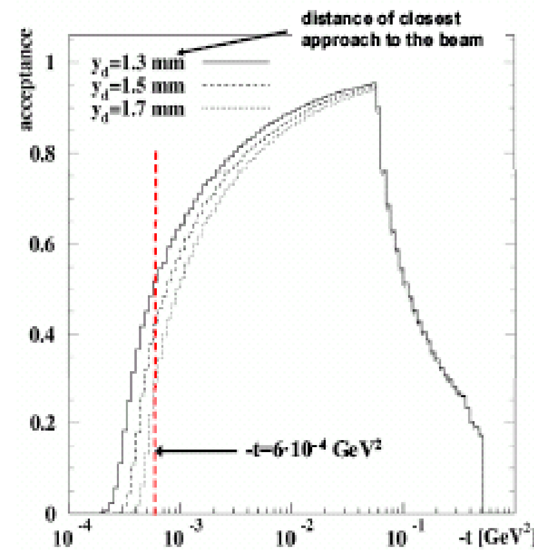
Events with central jets veto are key signature for some Higgs production processes (Vector Boson Fusion, ttH production)

→ Excellent understanding/simulation of MB/SD/DD and events with central jets veto crucial for the ATLAS physics potential discoveries

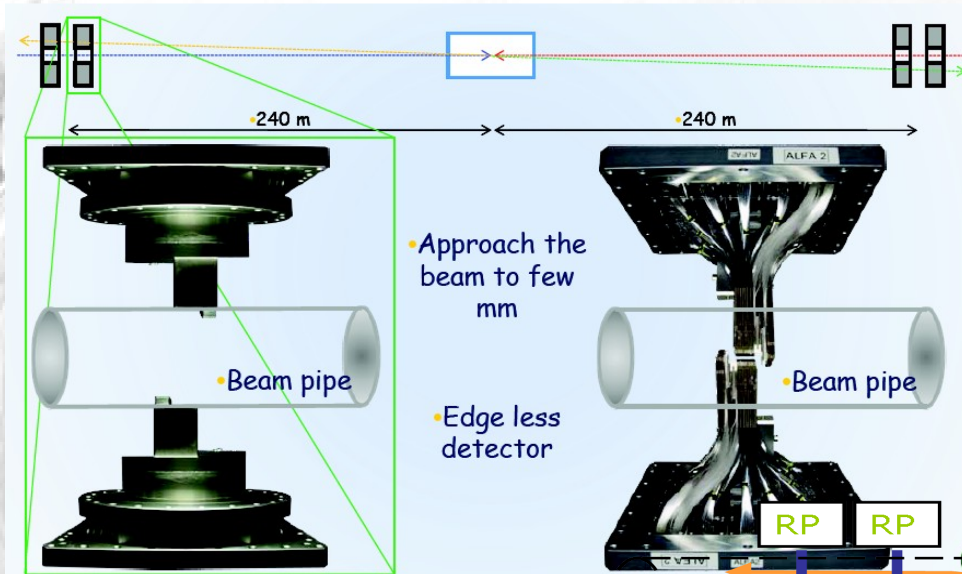


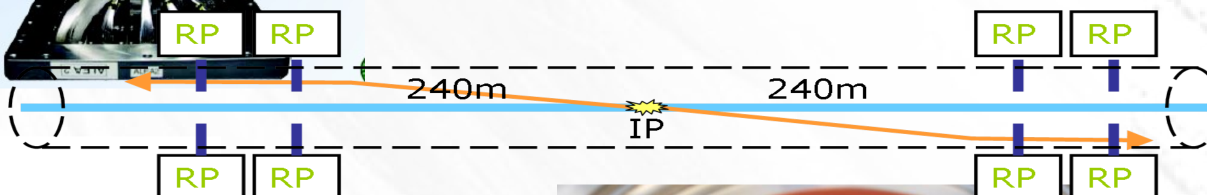
ALFA Measurement

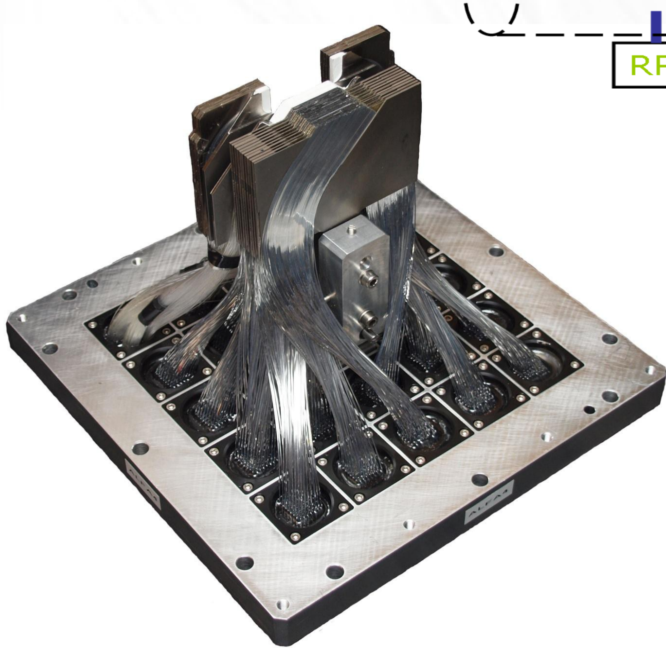


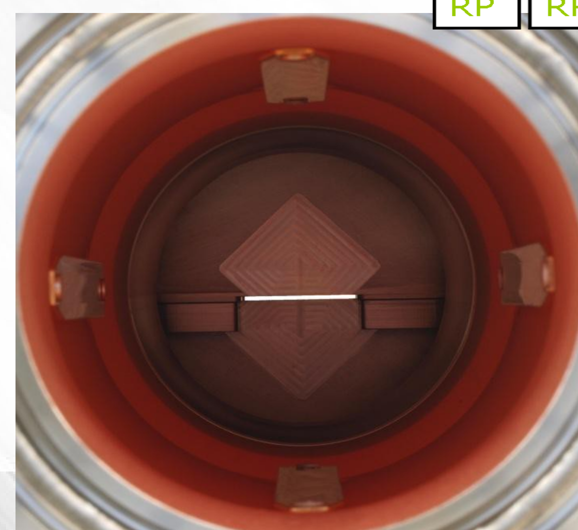


ALFA detector







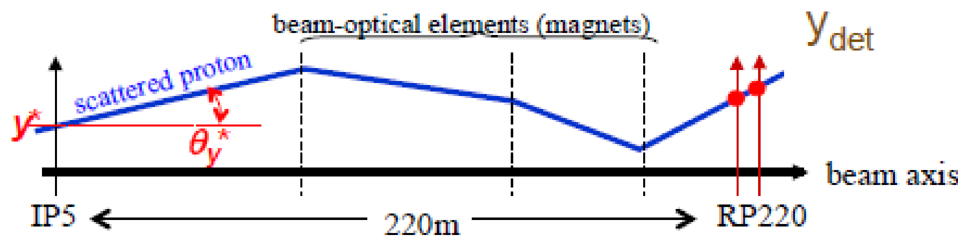


Beam Optics

(x^*, y^*): vertex position

(θ_x^*, θ_y^*): emission angle: $t \approx -p^2 (\theta_x^{*2} + \theta_y^{*2})$

$\xi = \Delta p/p$: momentum loss (diffraction)



$$\boxed{y_{det} = L_y \theta_y^* + v_y y^*}$$

$\beta^* = 90$ m: $L_y = 263$ m, $v_y \approx 0$

$\beta^* = 3.5$ m: $L_y \sim 20$ m, $v_y = 4.3$

→ Reconstruct via track positions

$$\boxed{x_{det} = L_x \theta_x^* + v_x x^* + \cancel{D\xi}}$$

Elastic: $\xi = 0$

$\beta^* = 90$ m: $L_x \approx 0$, $v_x = -1.9$

$\beta^* = 3.5$ m: $L_x \approx 0$, $v_x = 3.1$

→ Use derivative (reconstruct via local track angles):

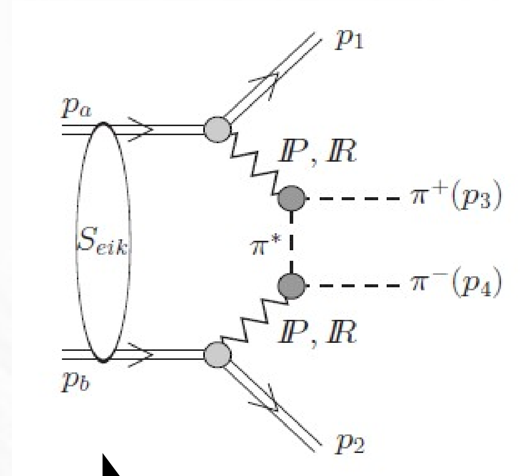
$$\boxed{\frac{dx_{det}}{ds} = \frac{dL_x}{ds}\theta_x^* + \frac{dv_x}{ds}x^*}$$

		Beam width @ vertex $\sigma^*_{x,y} = \sqrt{\frac{\varepsilon_n \beta^*}{\gamma}}$	Angular beam divergence $\sigma^{*}_{x,y} = \sqrt{\frac{\varepsilon_n}{\beta^* \gamma}}$	Min. reachable $\lvert t\rvert$ $\lvert t_{min}\rvert = \frac{n_\sigma^2 p \varepsilon_n m_p}{\beta^*}$
Standard optics	$\beta^* \sim 1$–3.5 m	$\sigma_{x,y}^*$ small	$\sigma(\theta_{x,y}^*)$ large	$\lvert t_{min}\rvert \sim 0.3$–$1$ GeV^2
Special optics	$\beta^* = 90$ m	$\sigma_{x,y}^*$ large	$\sigma(\theta_{x,y}^*)$ small	$\lvert t_{min}\rvert \sim 10^{-2}$ GeV^2

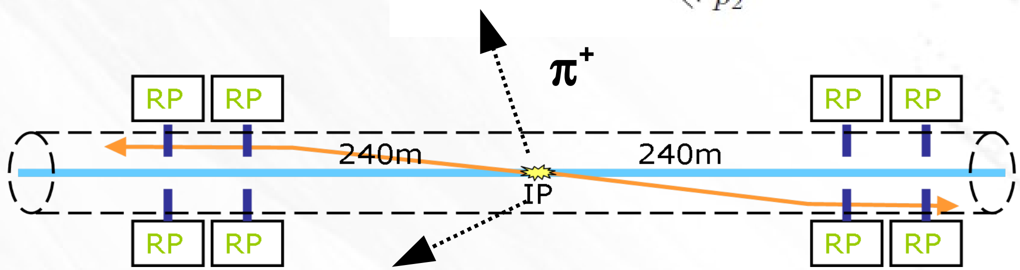
ALFA and Diffractive Physics

Detecting scattered protons powerful tool to investigate also the following processes:

- Single Diffractive
- Central Diffractive
- Electromagnetic
- Central Exclusive



Example of Central Exclusive Processes:
Look for exclusive processes:eg pp → pp$\pi^+\pi^-$

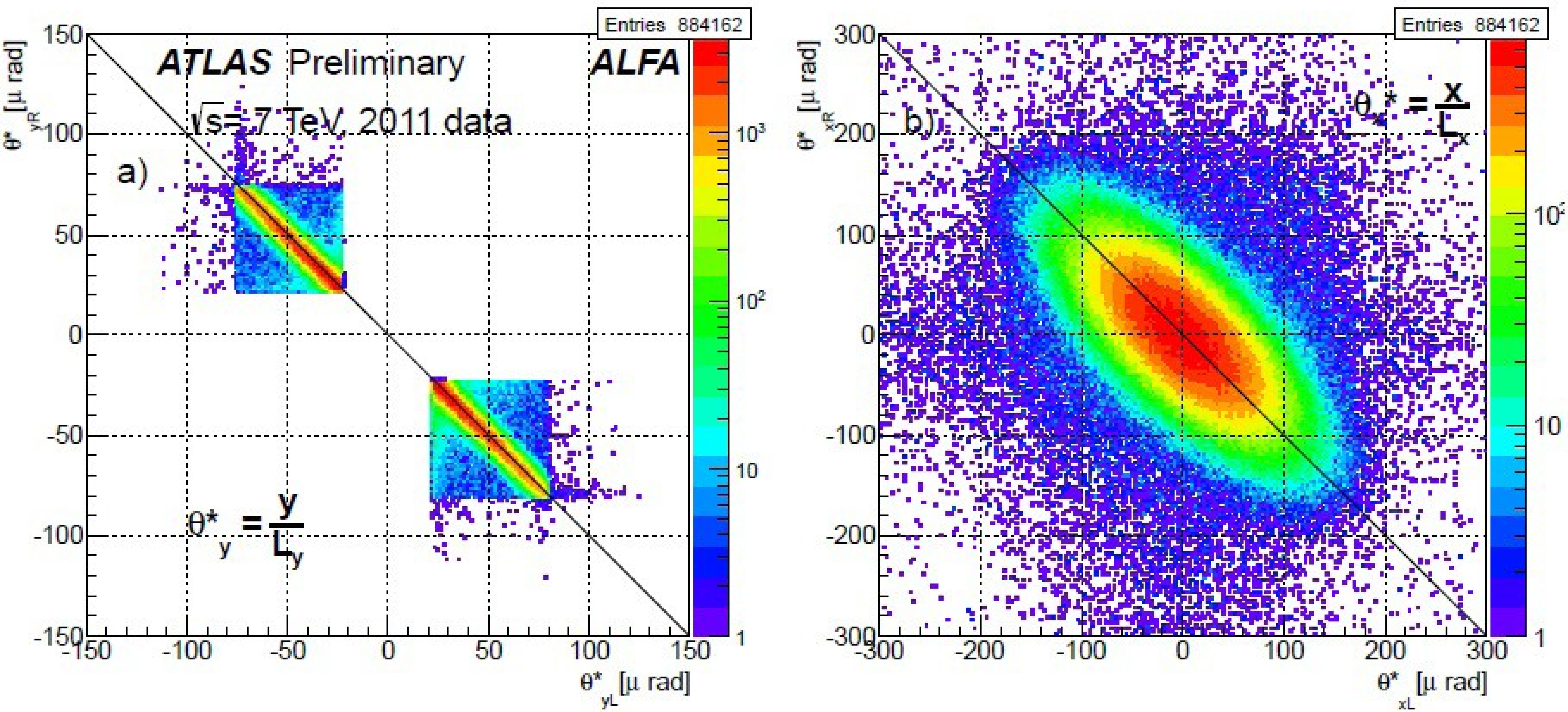


Expect 2000 events for $L=10^{27}cm^{-2}s^{-1}$ in 30 hours
Trigger on ALFA (elastic) + low P_T tracking

Only measurement was at $\sqrt{s}$=62 GeV (ISR!)
Also possible exlcusive processes K^+K^-,$p\bar{p}$,charmonia etc...

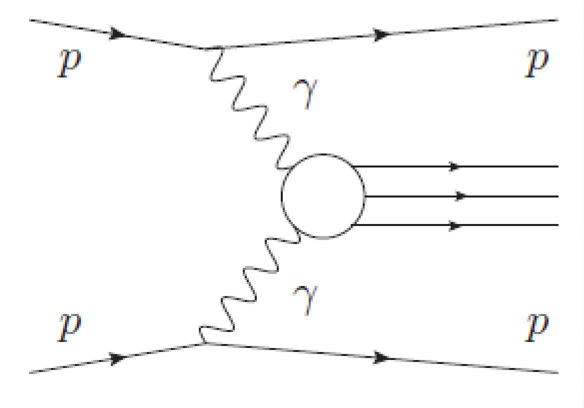
P. Lebiedowicz, A. Szczurek, Phys Rev D81 (2010), 0360
R. Staszewski et al arXiv:1104.3568

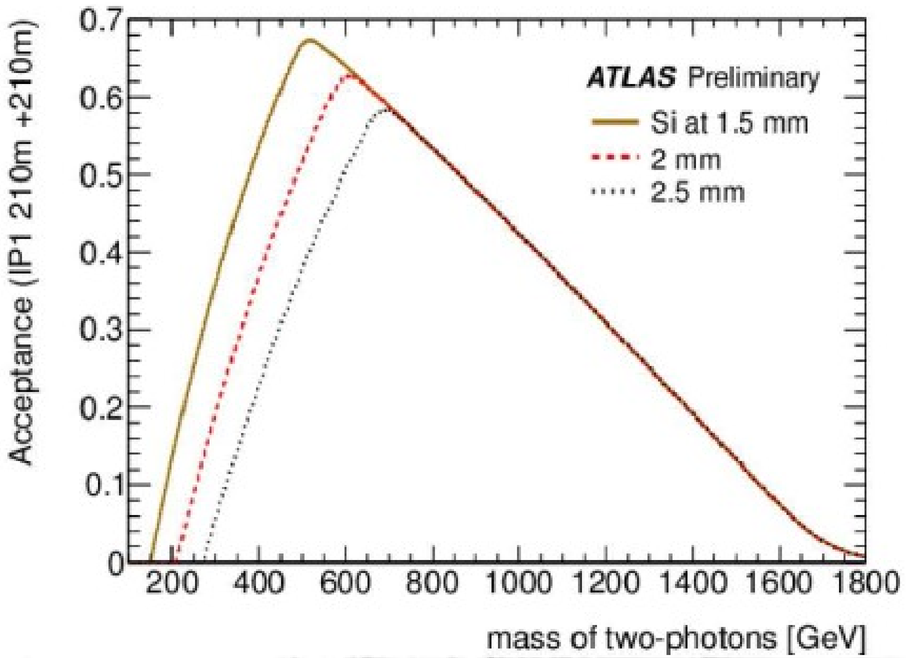
Scattering angles from October 2011 Run
→ Alignement checks on elastic scattered protons
Distance measurement with σ=20μm and knowledge of beam optics



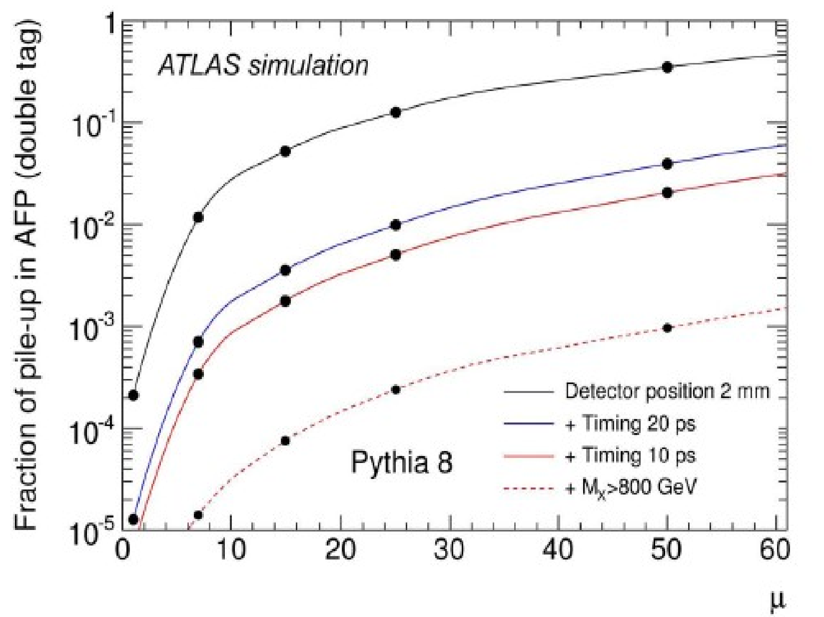
Vertical plane

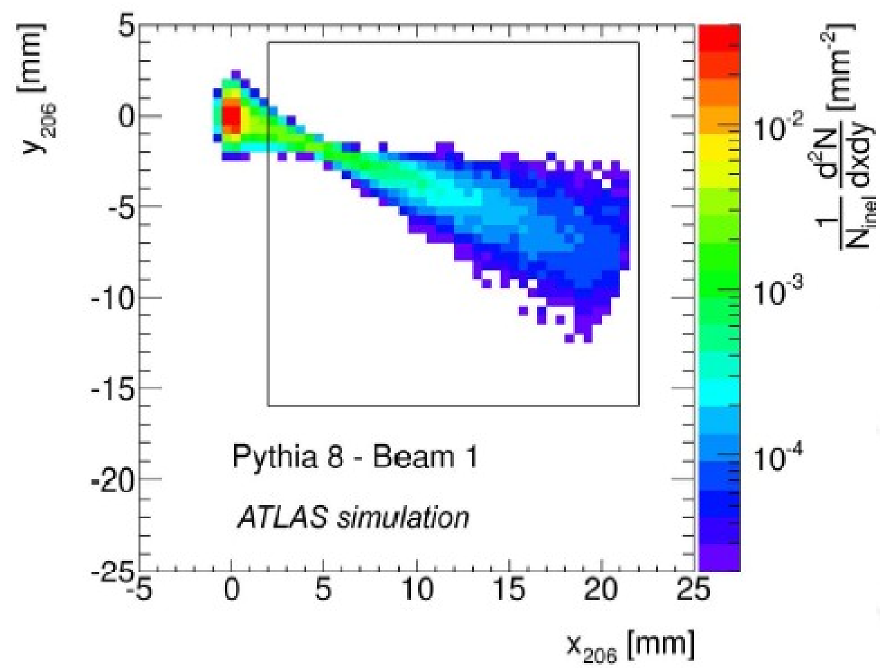
Horizontal plane


p
p
γ
γ
p
p


ATLAS Preliminary
Si at 1.5 mm
2 mm
2.5 mm
Acceptance (IP1 210m +210m)
mass of two-photons [GeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
200
400
600
800
1000
1200
1400
1600
1800

Plans for ATLAS Upgrade: AFP





Fraction of pileup events in AFP acceptance
→ time of flight measurements with **σ**~20ps fraction rejection factor ~100 (**μ**~25)

Acceptance of AFP@206m detector for protons from diffraction