Considering the Haystack: the pp Inelastic Cross Section at $\sqrt{s}$ = 7 TeV with ATLAS

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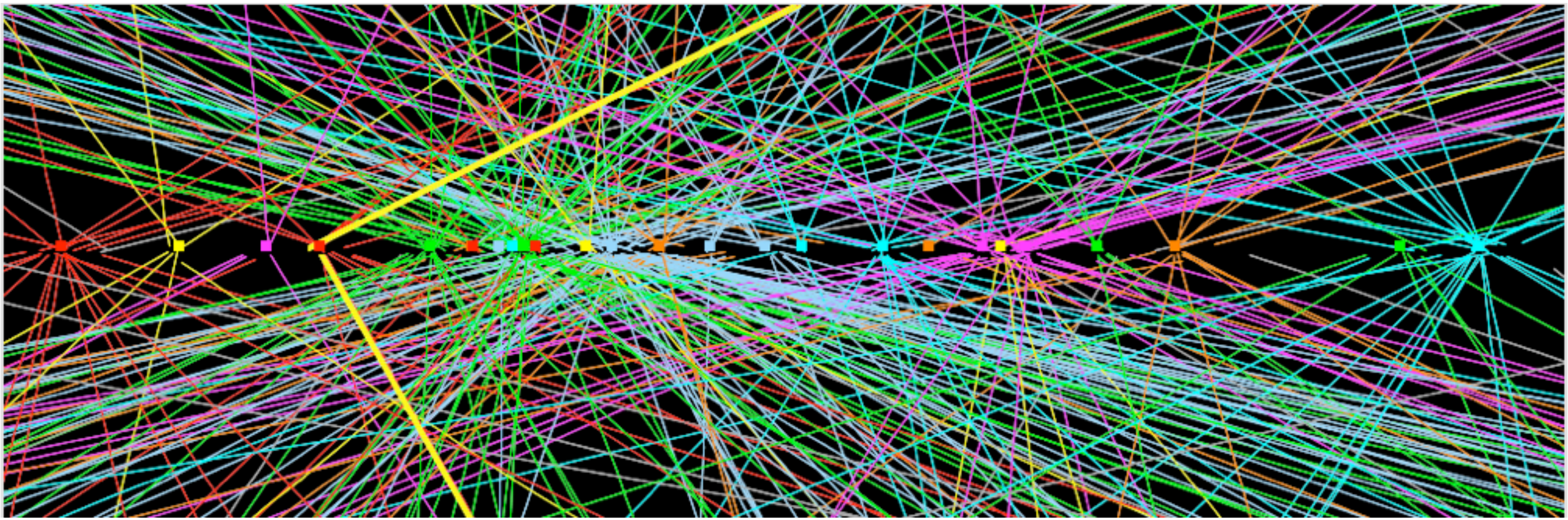
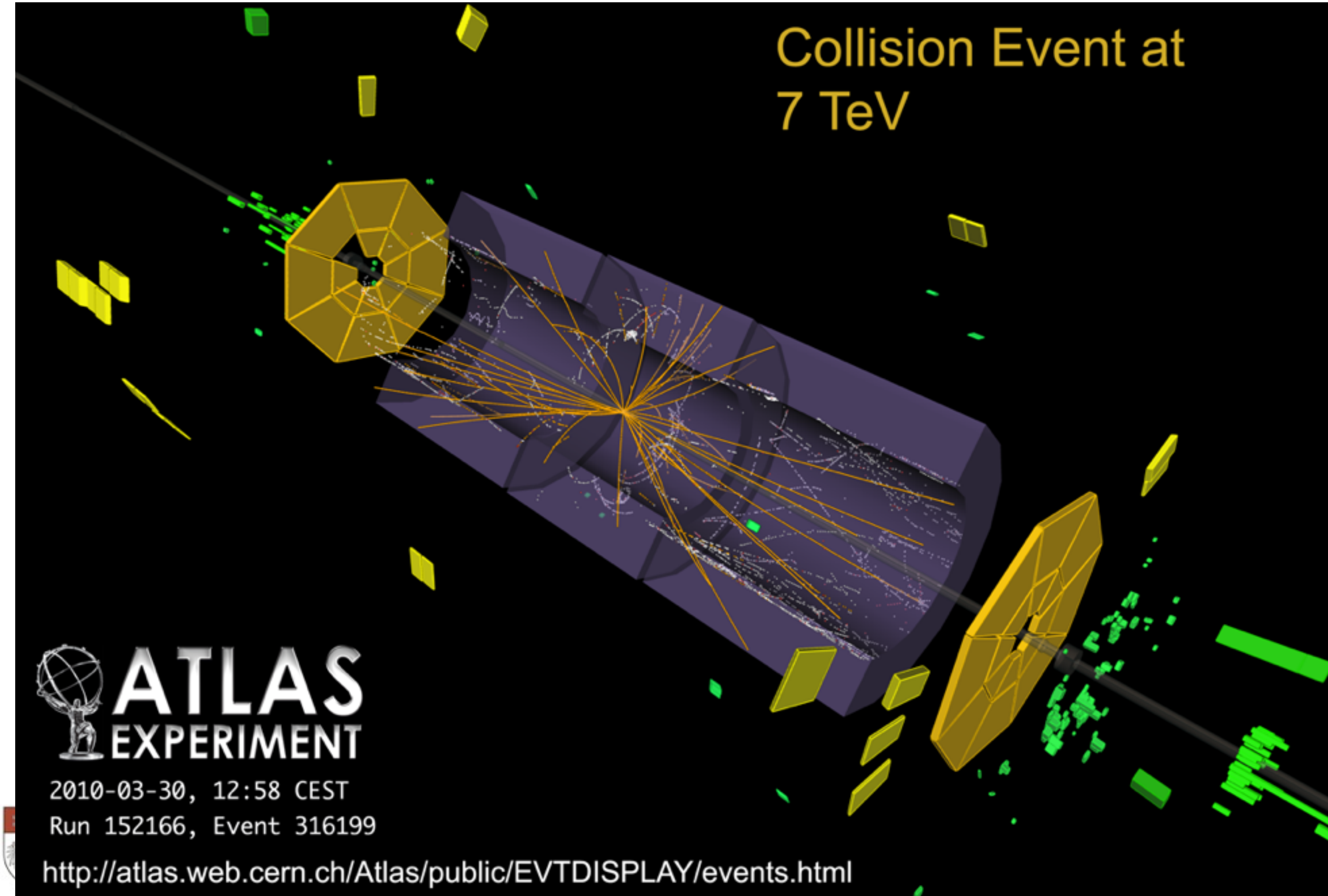
The present



- April 15th 2012, 25 reconstructed vertices, $Z \rightarrow \mu\mu$ candidate event

Revisiting the Past



Outline

- Soft Physics at the Energy Frontier
- Overview of ATLAS and Relevant Subdetectors
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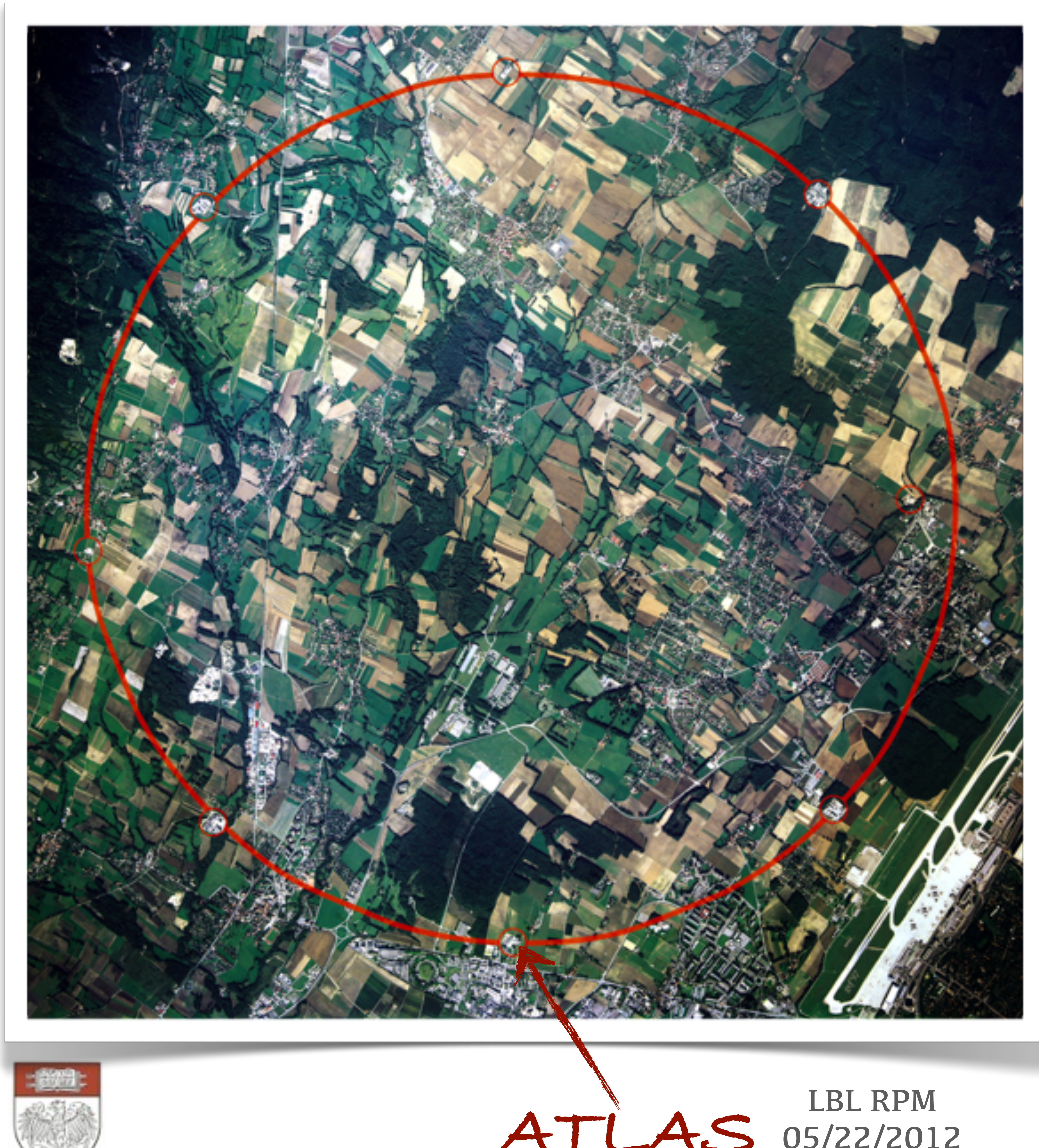
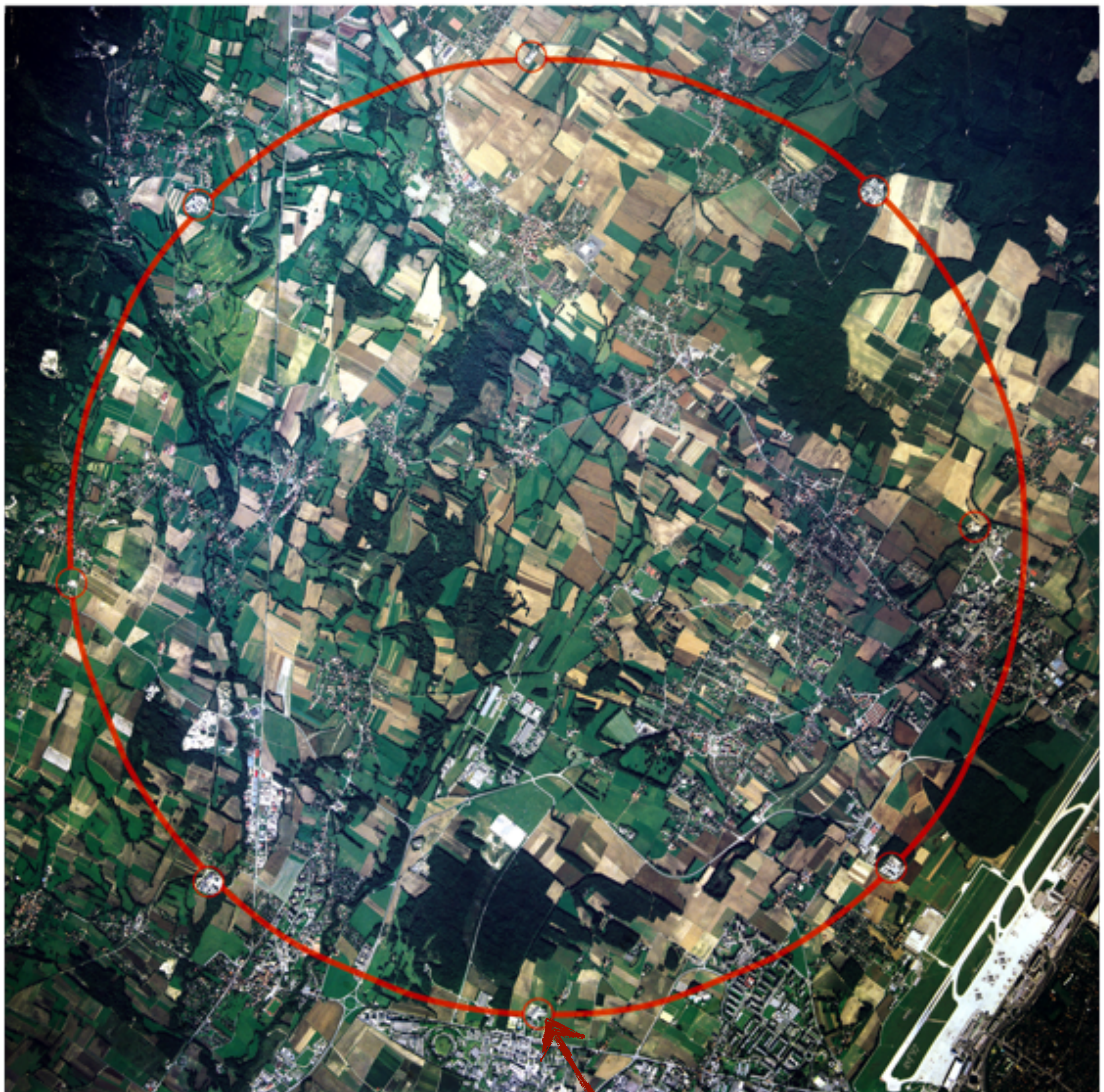
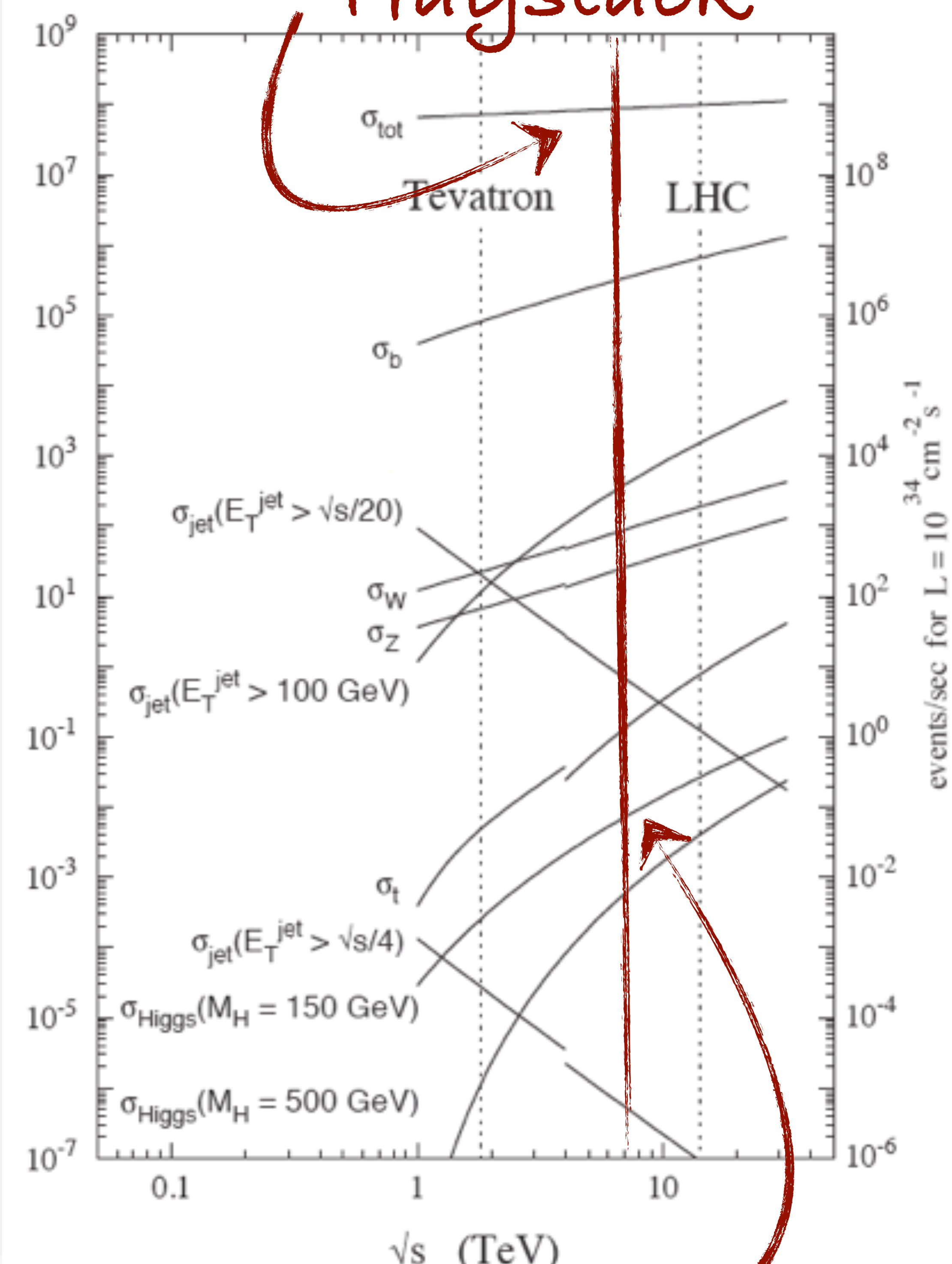
LHC: The Energy Frontier



- pp collider at $\sqrt{s}$ = 7 TeV
  - Design lumi: $10^{34}\ s^{-1}\ cm^{-2}$
  - Interaction rate: ~100 MHz
- 2010 stats:
  - Initial lumi: $10^{27}\ s^{-1}\ cm^{-2}$
  - Peak lumi: $10^{32}\ s^{-1}\ cm^{-2}$
  - Interaction rate: ~1 MHz
- Promises to shed light on the origins of electroweak symmetry breaking

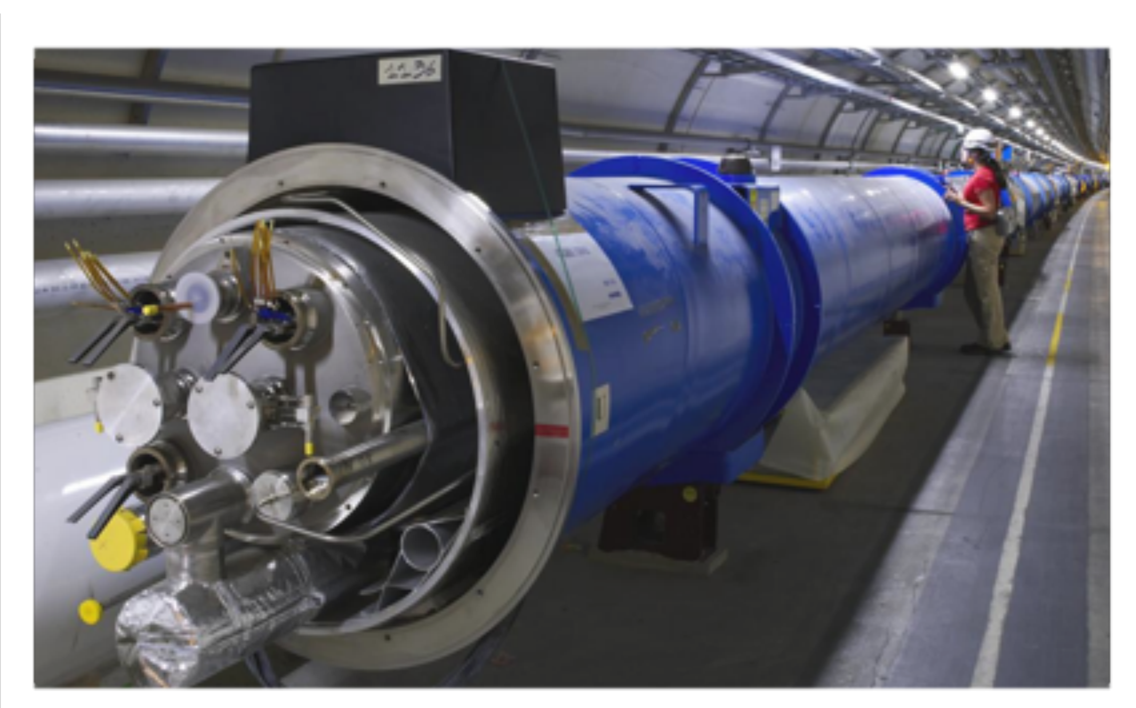
LHC: The Energy Frontier





Why Measure the pp cross section?

- High center-of-mass (s), low momentum transfer interactions are complex phenomena which QCD is currently unable to address
  - One of the most challenging open problems in strong interactions
- Many basic unknowns:
  - What is the dependence of the interaction rate on s?
  - What is the division between color exchanging and color neutral interactions?



- Start-up of LHC allows access to a new energy range to test models
- Practically, measurement is useful for pile-up predictions for LHC high luminosity & energy running.

Theoretical Picture

Soft Gluon Resummation

Analytic Amplitudes

Minijet & multi-parton interactions

Froissart-Martin Bound

$\sigma_{tot,inel}(s) \leq \ln^2(s)$

Reggeon Field Theory

AdS/CFT Correspondence

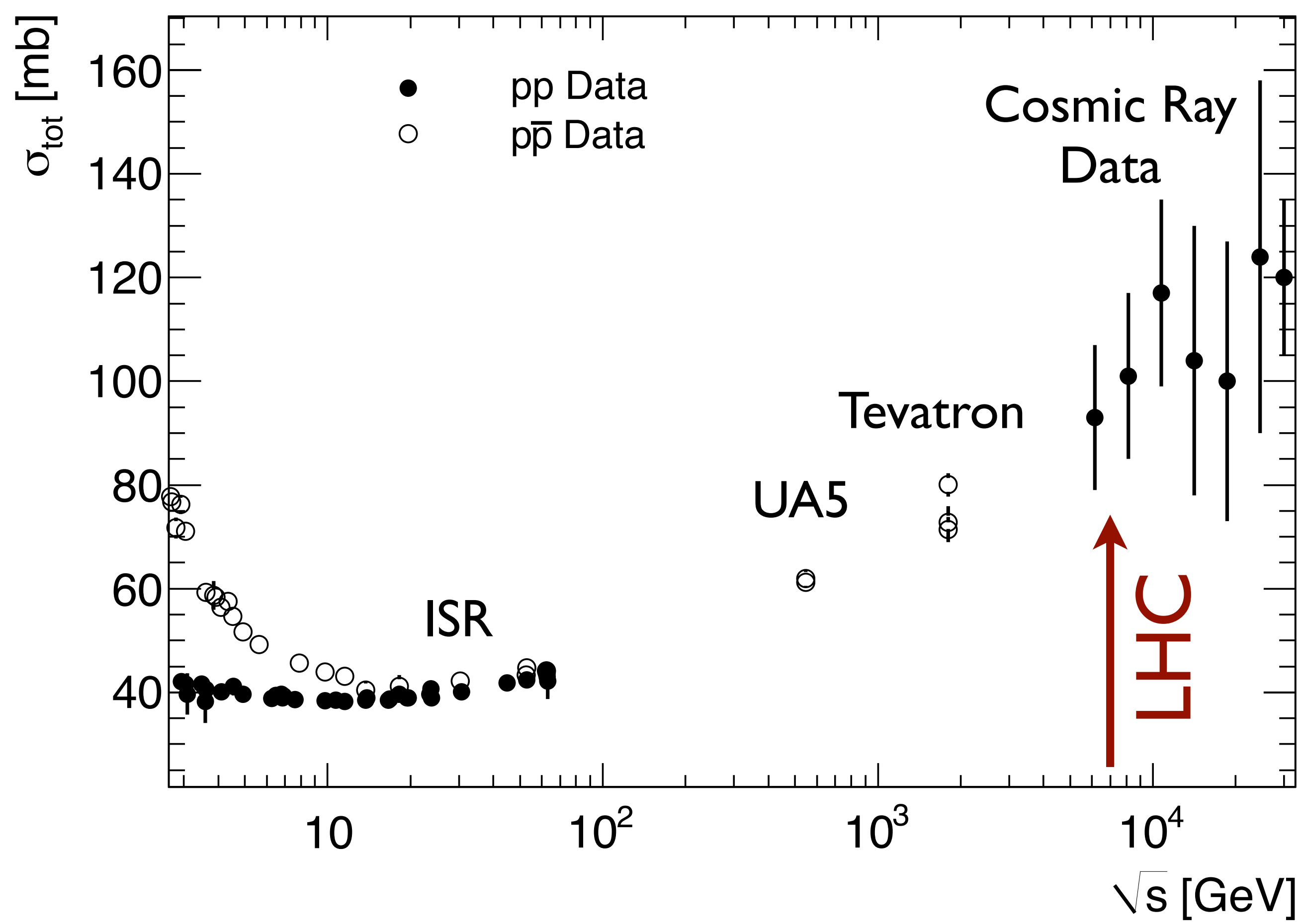
Factorized Eikonal-Pomeron exchange

The Total and Elastic Cross Sections

- Total proton cross section is typically measured 2 ways:
  - Forward elastic cross section at colliders (Optical Theorem)
  - Cosmic ray air showers

- Specialized experiments/ detectors exists at LHC for these measurements
  - Totem
  - Alfa

Data prior to 2011



- **Well-defined**, direct measurements of σ_{inel} is an important complement to these measurements

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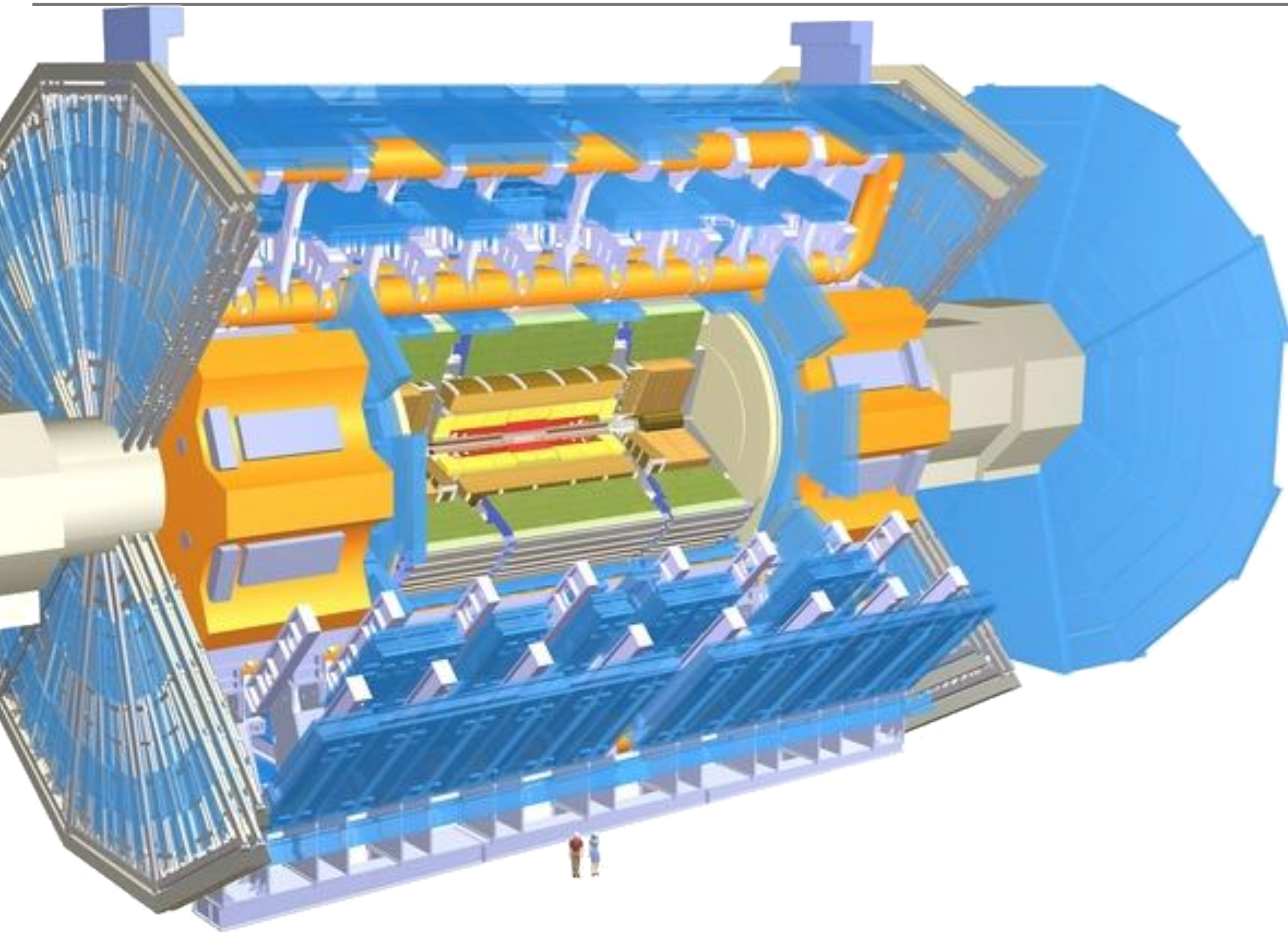
ATLAS



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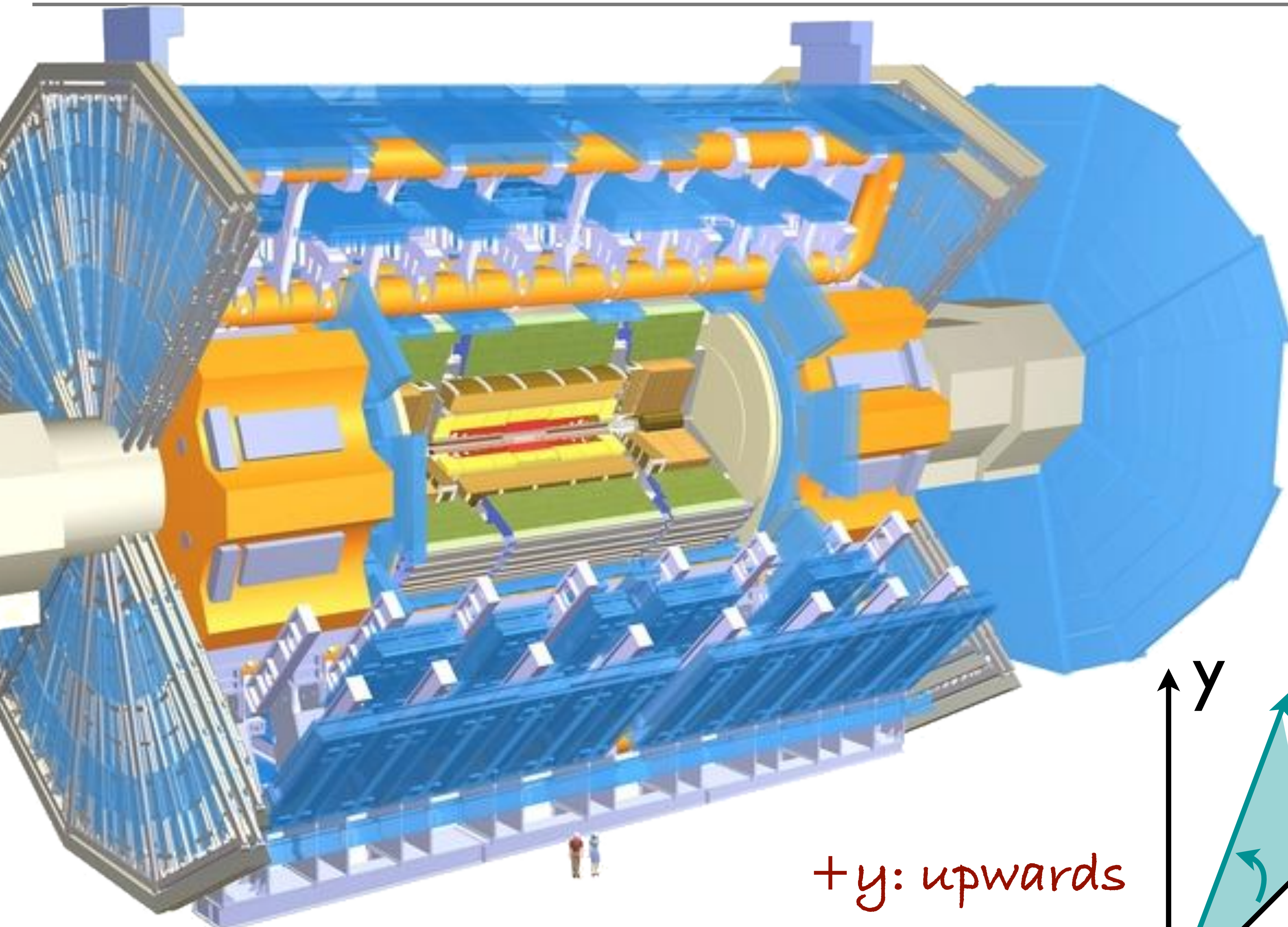
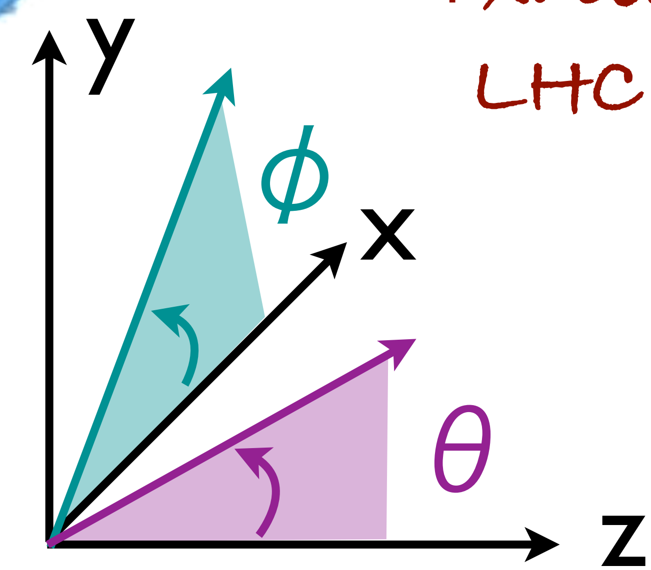
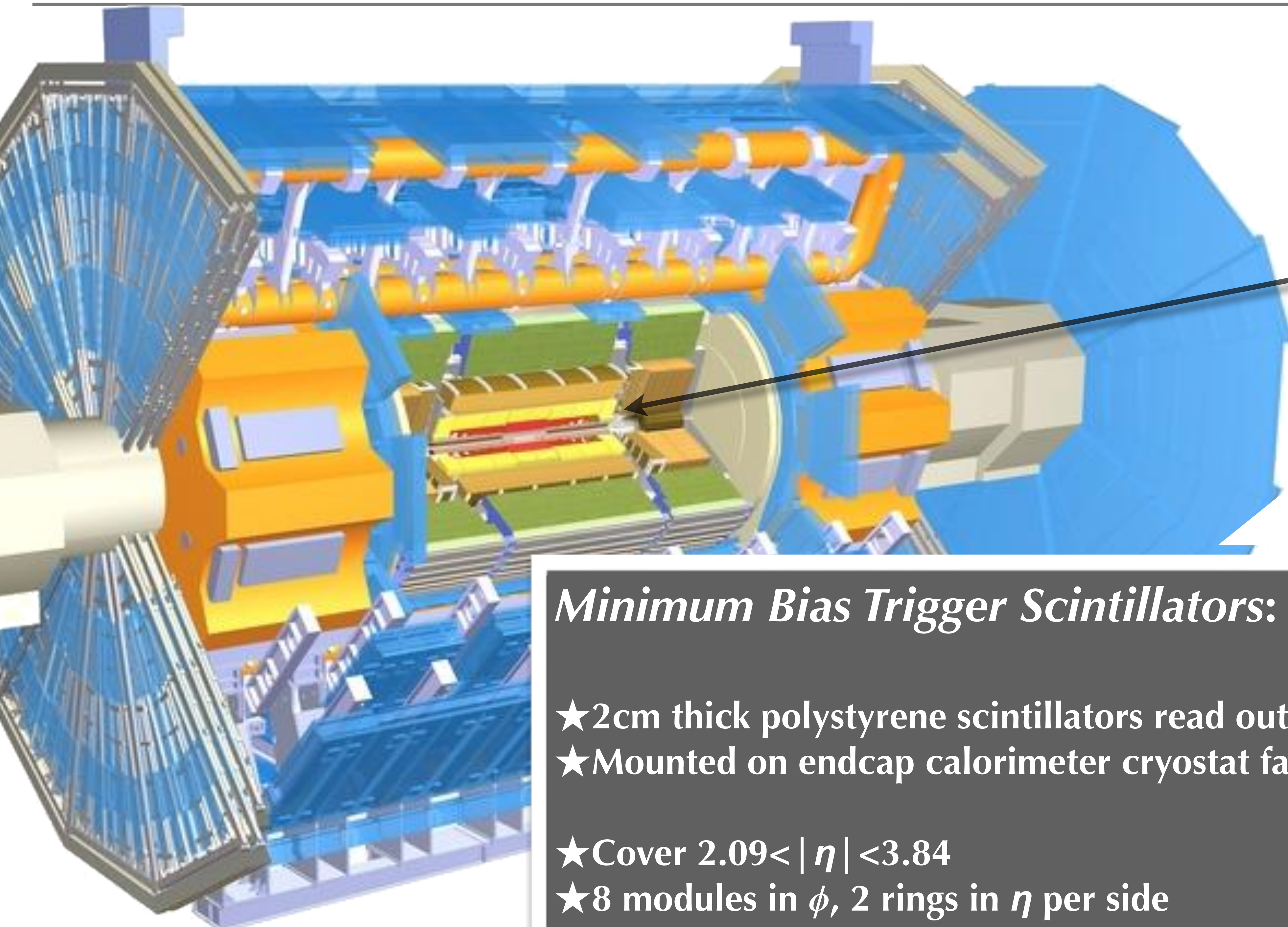




$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

ATLAS



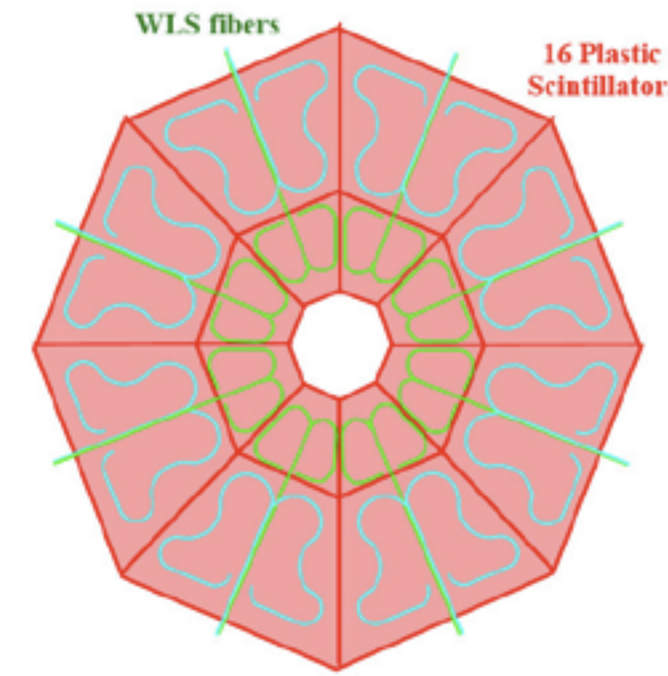


Figure 1: MBTS disk configuration.

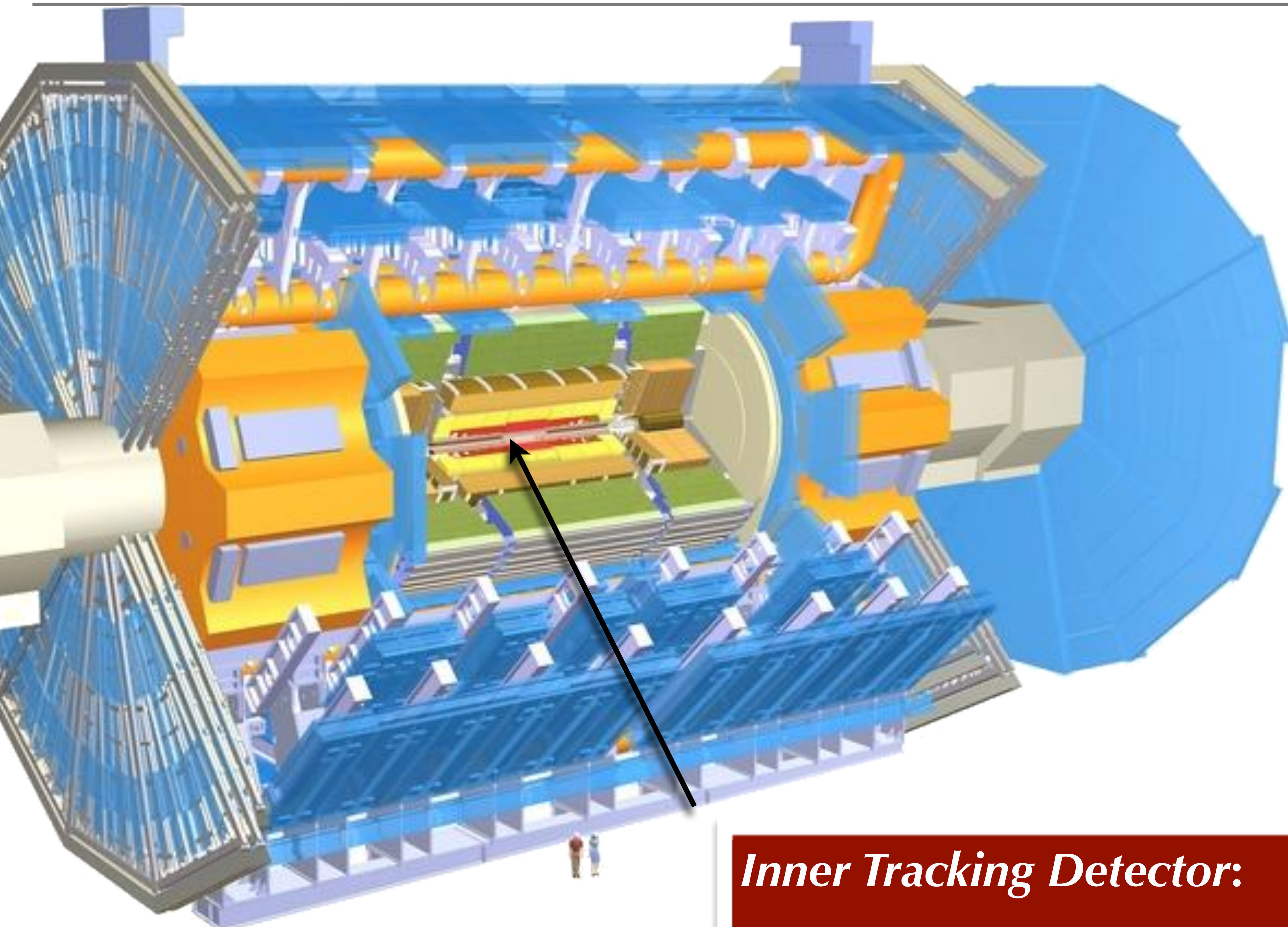
Minimum Bias Trigger Scintillators:

★2cm thick polystyrene scintillators read out by PMTs
★Mounted on endcap calorimeter cryostat face plates (Z = 3.6 m)

★Cover $2.09<|\eta|<3.84$
★8 modules in ϕ, 2 rings in η per side

★Designed specifically for early LHC running: highly efficient, simple
★Primary trigger for low luminosity running

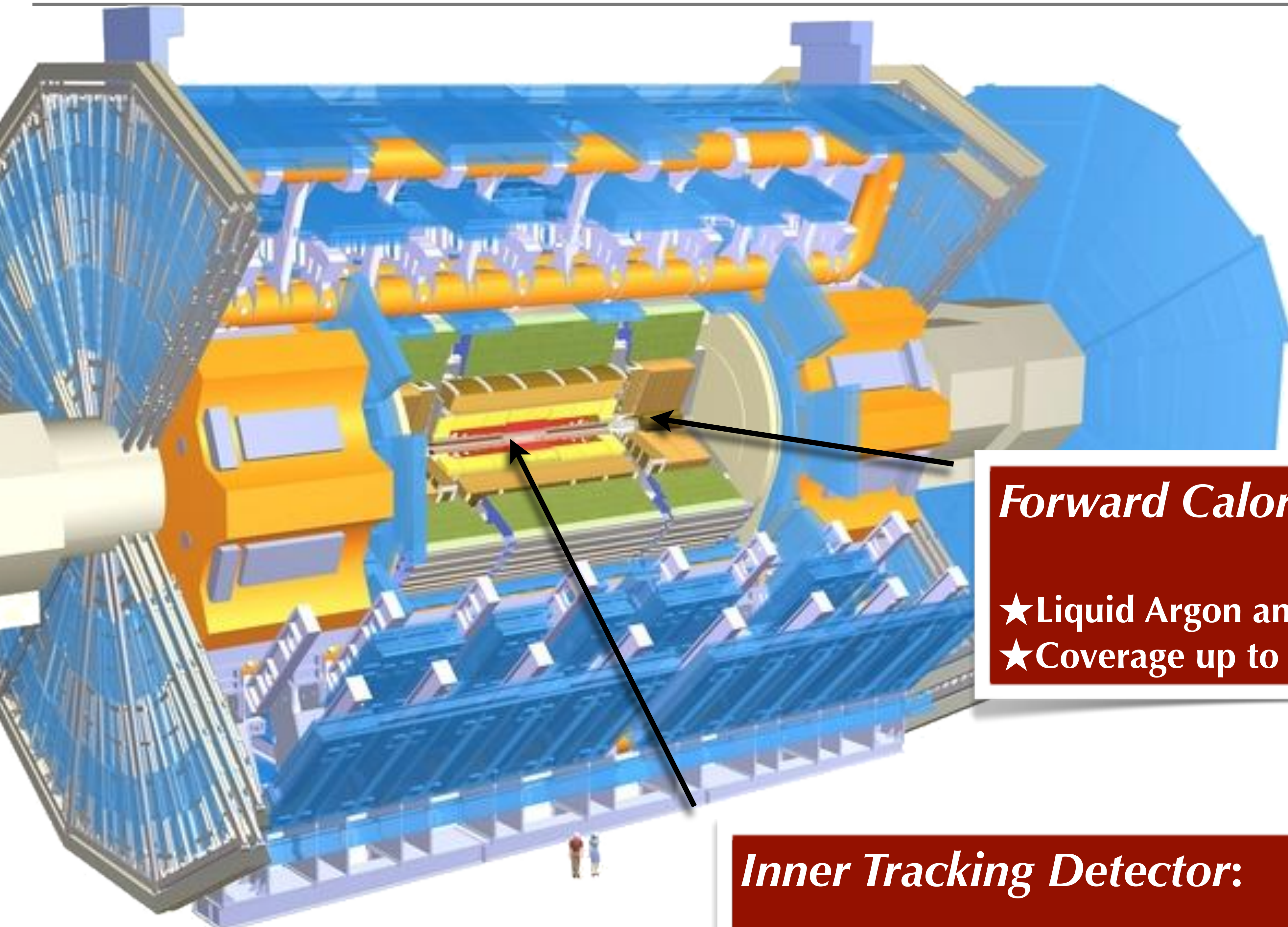
ATLAS



***Inner Tracking Detector*:**

★Silicon and transition radiation technologies
★Coverage up to $|\eta| < 2.5$
★Tracking for charged particle with $p_T > 100$ MeV

ATLAS



Forward Calorimeters

★Liquid Argon and Copper/Steel absorbers
★Coverage up to $|\eta| < 4.9$

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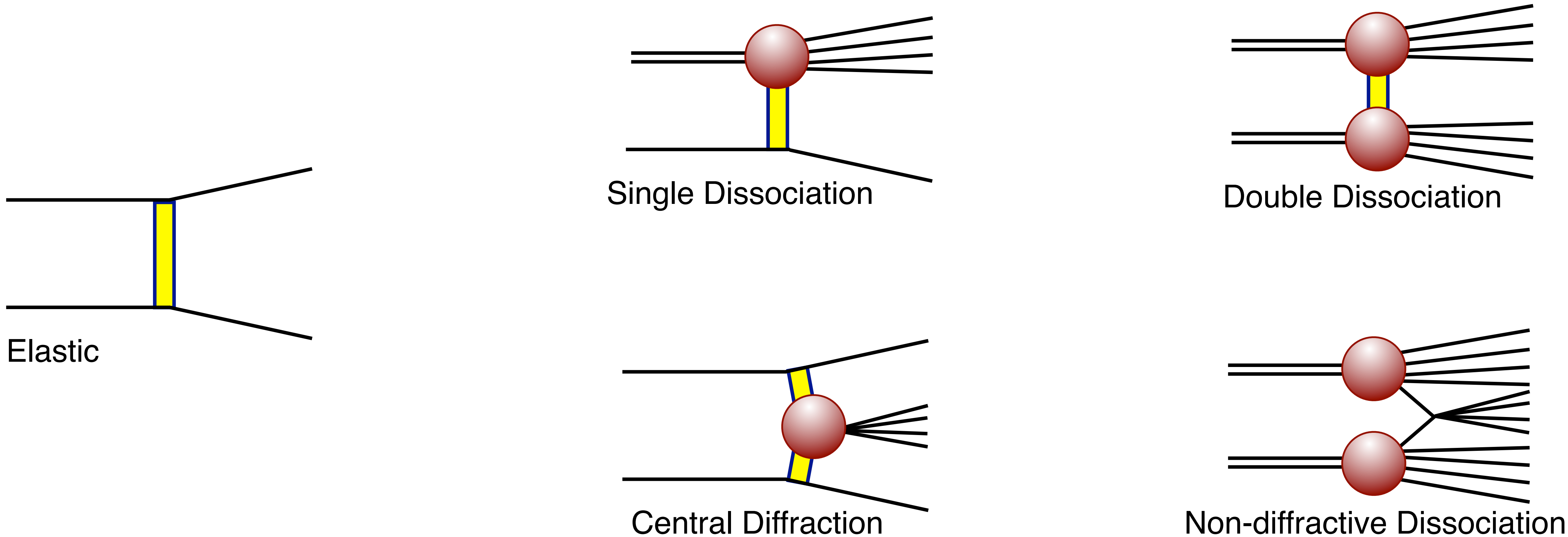
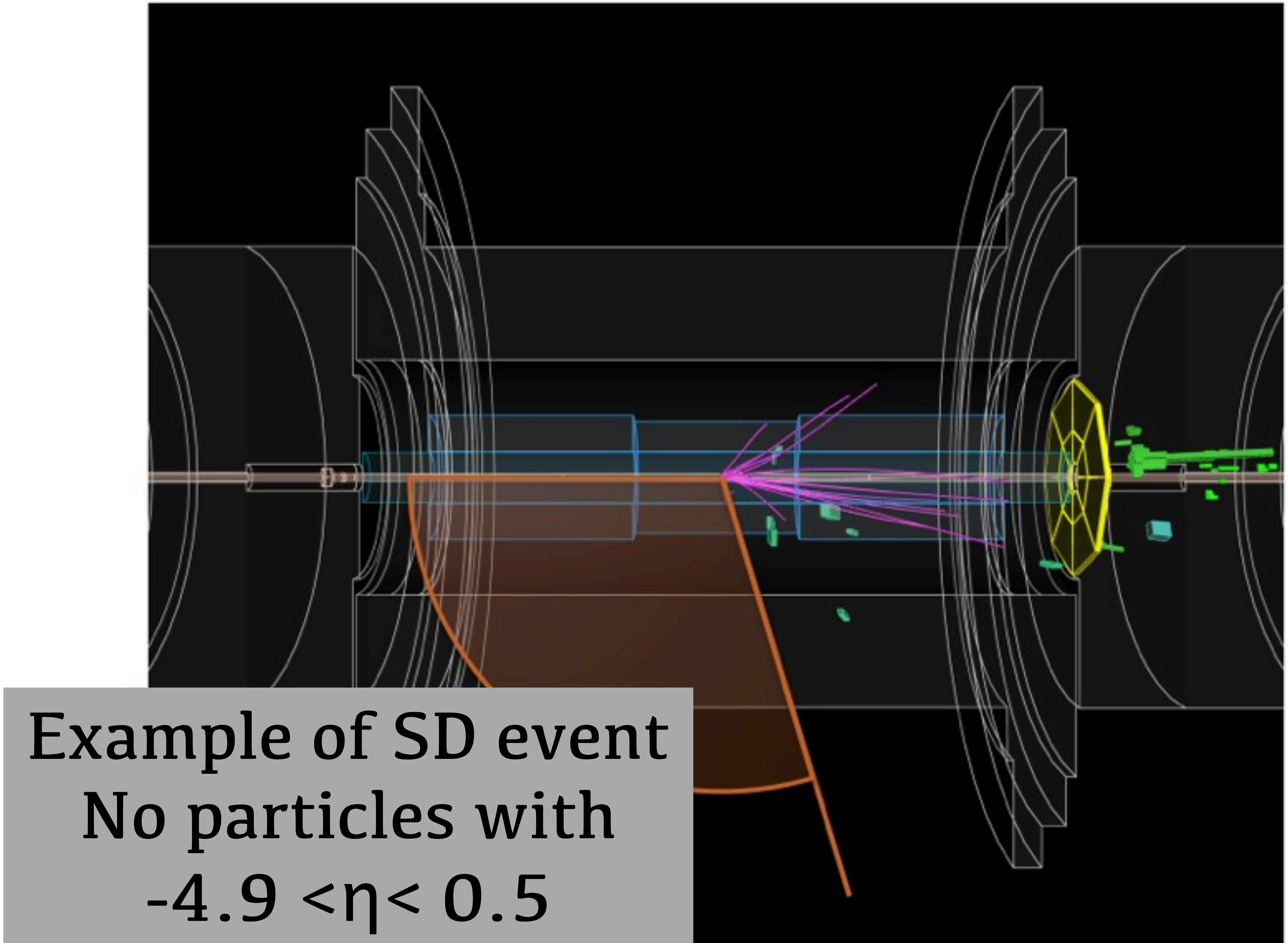
Classifying pp Interactions

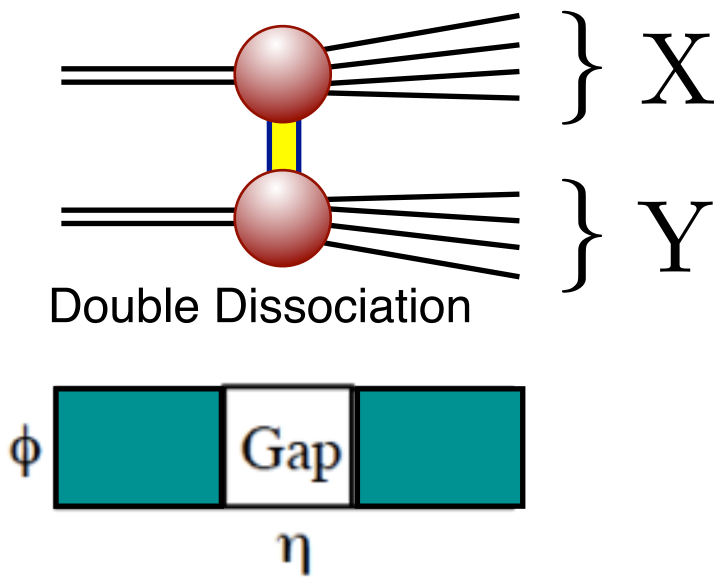


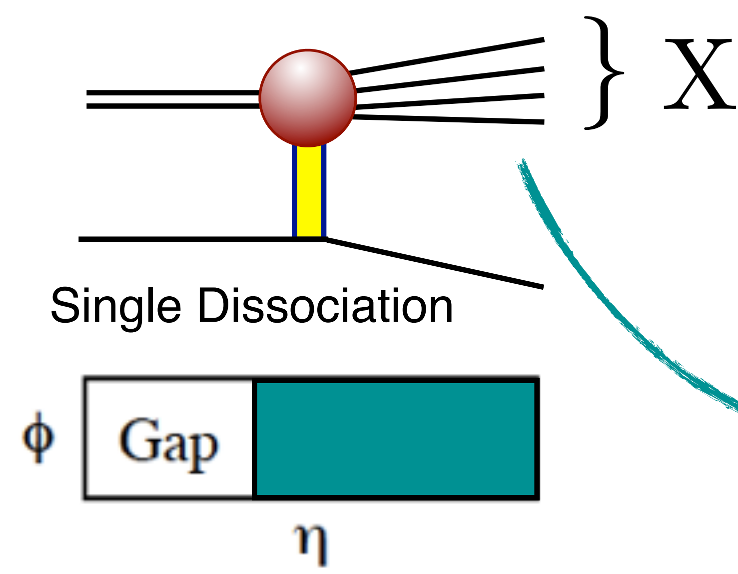
- Elastic interactions: p+p→p+p (20% of σ_{tot})
- Inelastic: p+p→ something new (80% of σ_{tot})
  - Predictions at 7 TeV vary between 65mb & 100mb for σ_{inel}
- Color neutral processes make up 30% of σ_{inel} but are poorly understood

Single Dissociation



Diffractive Dissociation





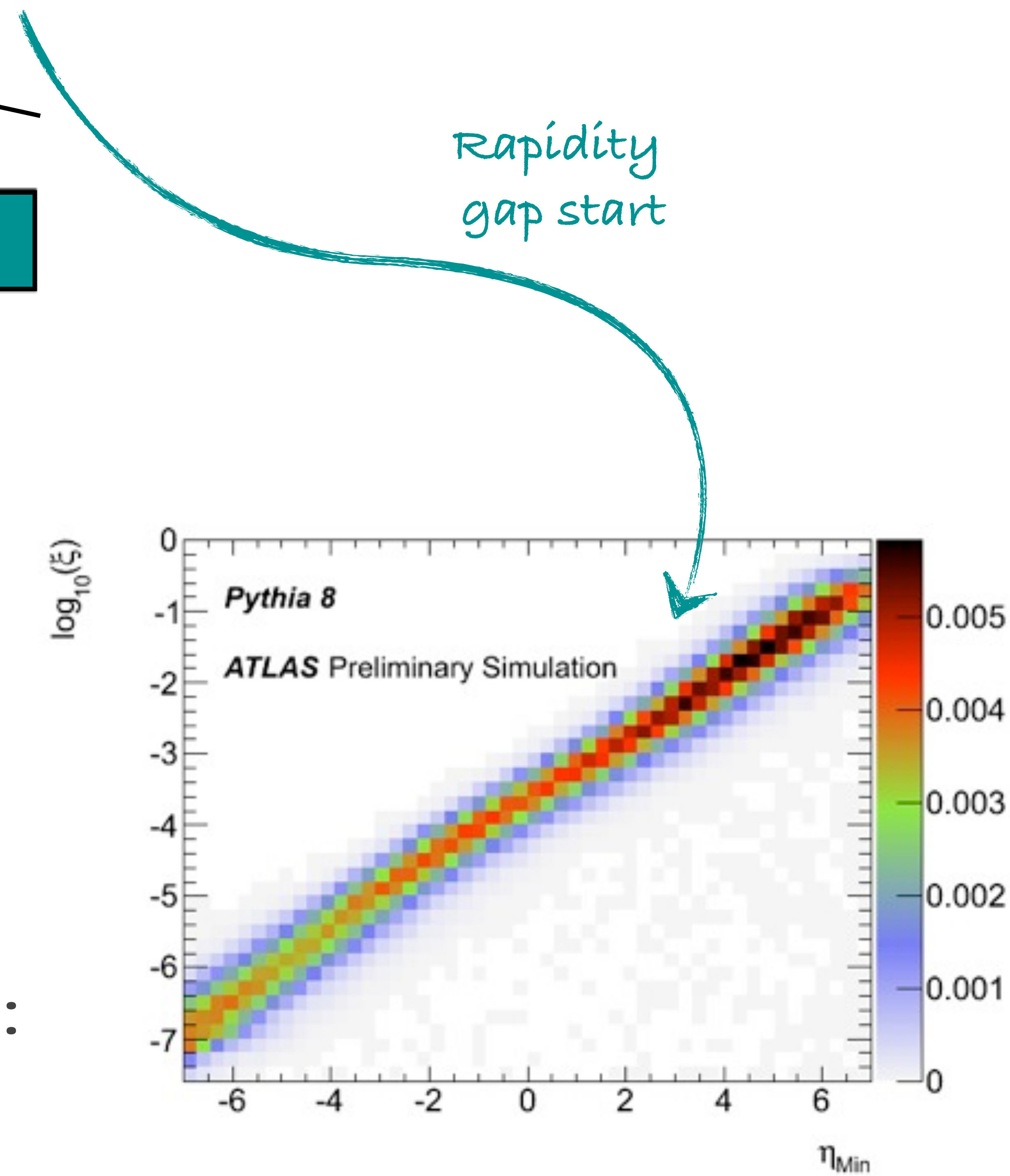
- Color singlet exchange leads to **rapidity gaps**

- Mass of dissociation product describes systems:

$$\xi = M_X^2 / s$$

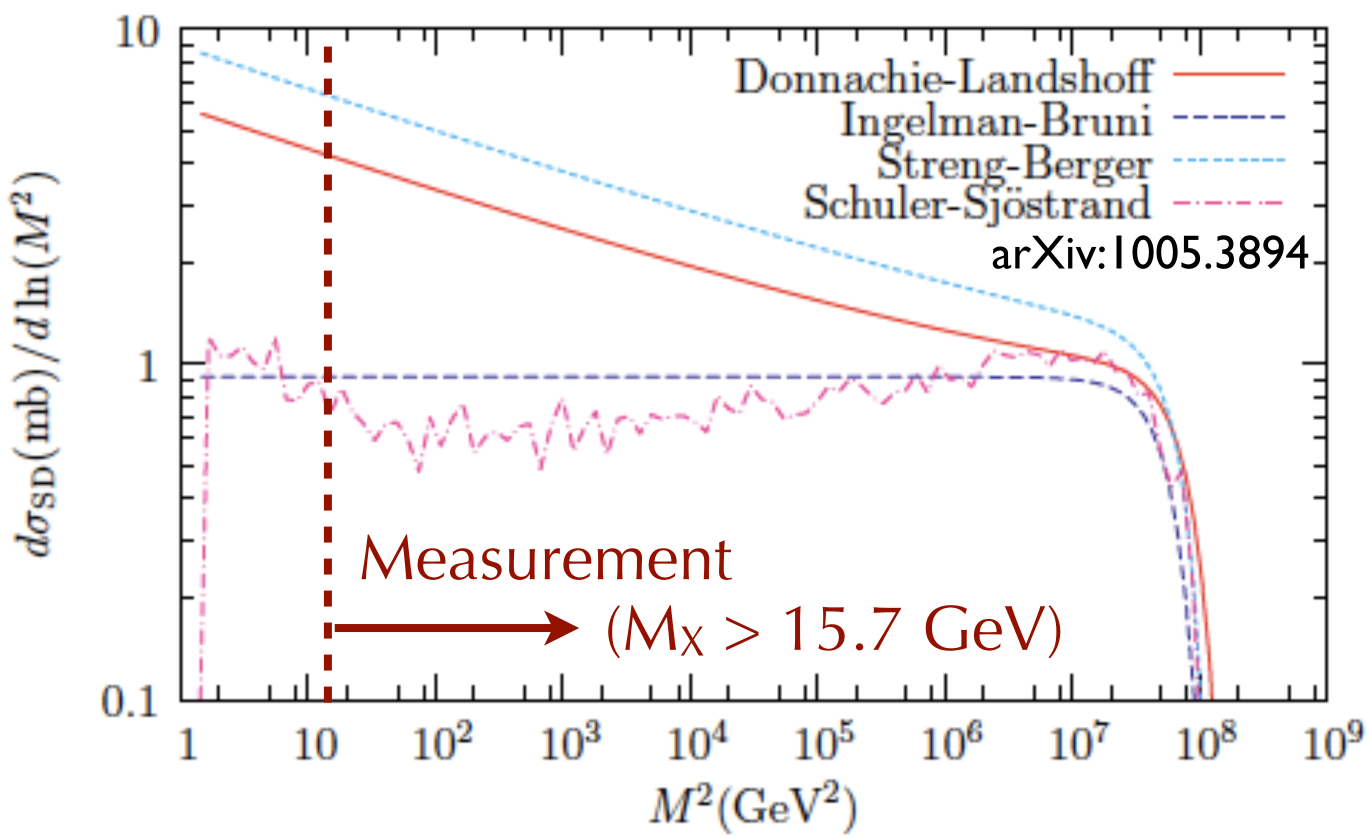
- ξ relates to (pseudo)rapidity gap start, therefore **detector acceptance**:

$$\eta_{\min} \propto \log \frac{M_X^2}{s}$$



Diffractive Models

- Total detector acceptance **depends on M_X distribution** near ξ cut
  - But we can't measure M_X!
  - Use a variety of models to assess dependence on M_X distribution



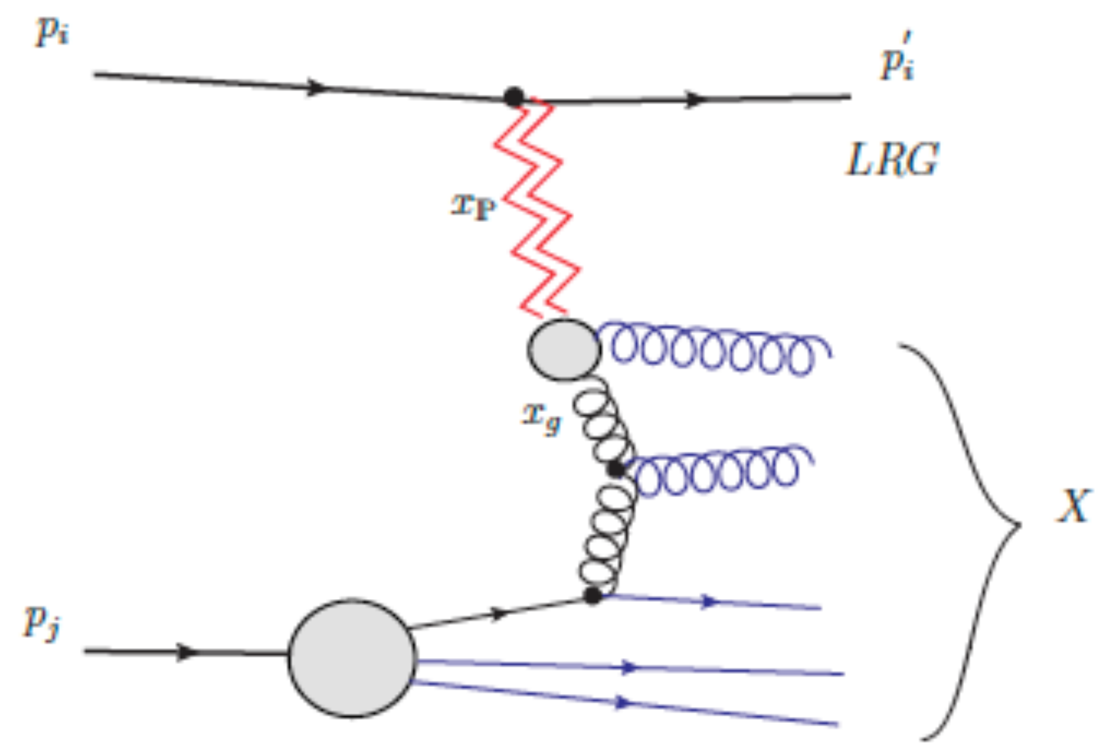
- Consider many models for the diffractive mass distribution
  - Generators: Pythia, Phojet
    - 2 different fragmentation schemes (Pythia 6 vs Pythia 8)
  - Flat
  - Multiple variations of power law
- Default model is **Donnachie and Landshoff** with ε = 0.085, α'= 0.25 GeV^{-2} :

$$\frac{\mathrm{d}\sigma_{SD}}{\mathrm{d}M^2} \propto \left(\frac{s}{M}\right)^{2\alpha(t)-1}$$

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

Monte Carlo Models of Particle Production

- **Pythia 6:** String fragmentation to produce particles for given M_X
- **Pythia 8:** Perturbative particle production using pomeron PDFs for M_X > 10 GeV
  - Default MC for this measurement
  - Multiple models for differential diffractive spectrum
- **Phojet:** Dual Parton Model with cutoff to separate hard and soft diffractive processes



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The Measurement

At least two MBTS hits

Background and trigger efficiency measured in Data

$$\sigma(\xi > 5 \times 10^{-6}) = \frac{(N - N_{BG})}{\epsilon_{trig} \times \int L\mathrm{d}t} \times \frac{1 - f_{\xi < 5 \times 10^{-6}}}{\epsilon_{sel}}$$

Limit measurement to detector acceptance
(M_X > 15.7 GeV)

From Beam Scan Calibration

Correction factors taken from MC, detector response tuned on data

Dataset: 1.2M events
(2nd day of 7 TeV Stable LHC Beams)

ATLAS paper: arXiv:1104.0326

Backgrounds (N_{BG}) & Trigger (ε_{trig})

- Beam gas and beam halo:
  - Measure with unpaired bunches : 0.13% of total event sample
- "Afterglow": cavern radiation produced after a collision
  - Out-of-time afterglow measured by unpaired bunches
  - In-time afterglow measured from fractions of late hits in MBTS (0.4%)
- Take 100% uncertainty on backgrounds:0.42%
- Trigger is single MBTS trigger hit:
  - Measured with respect to offline selection to be 99.98% with an uncertainty of 0.09%

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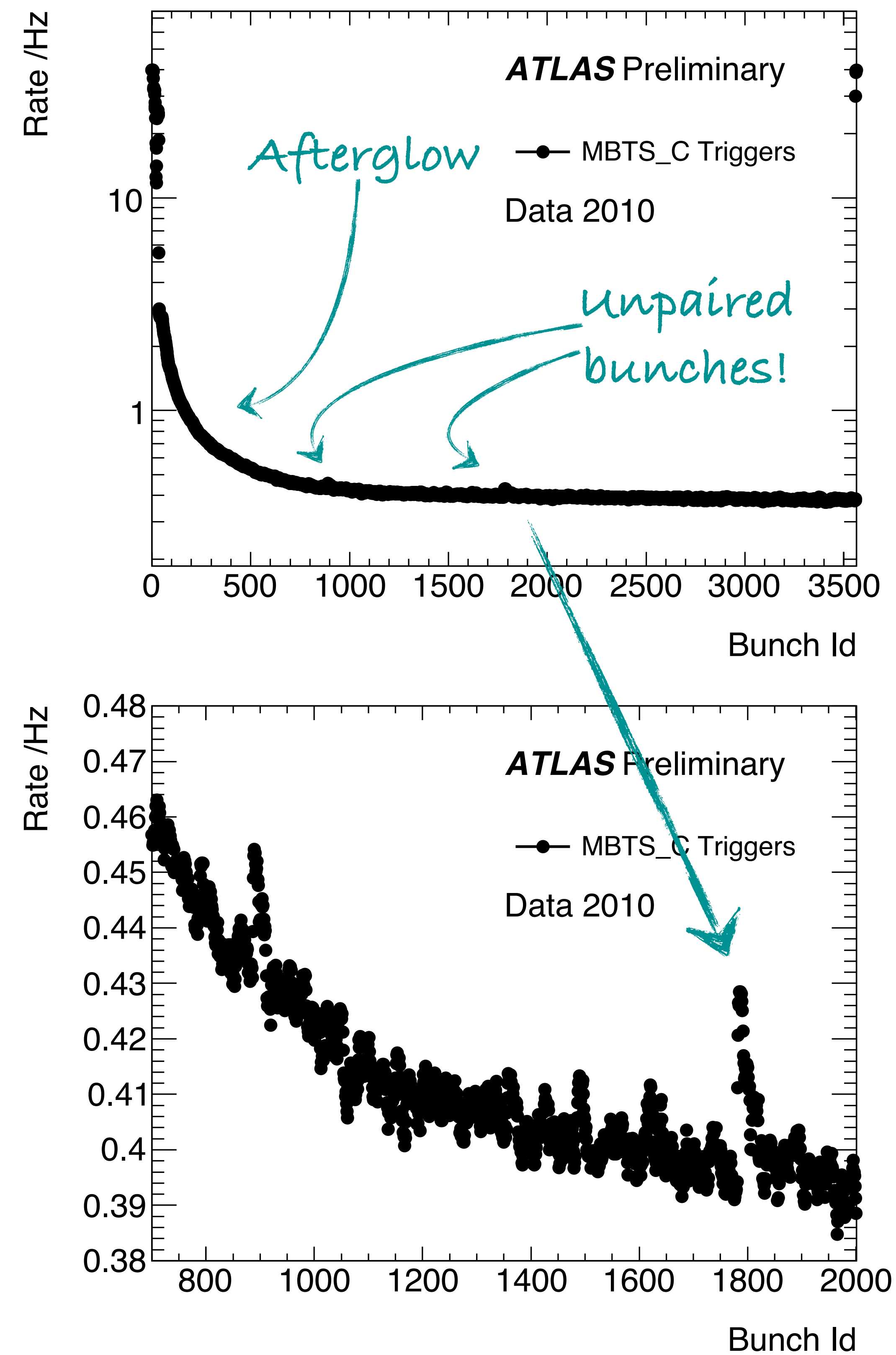

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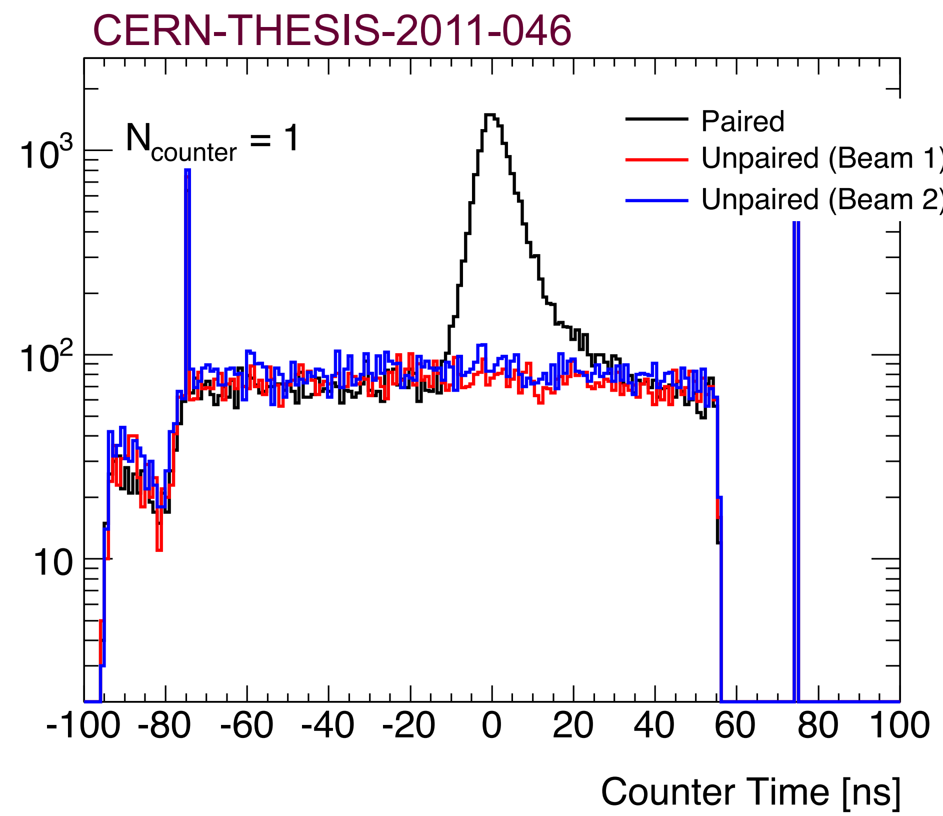
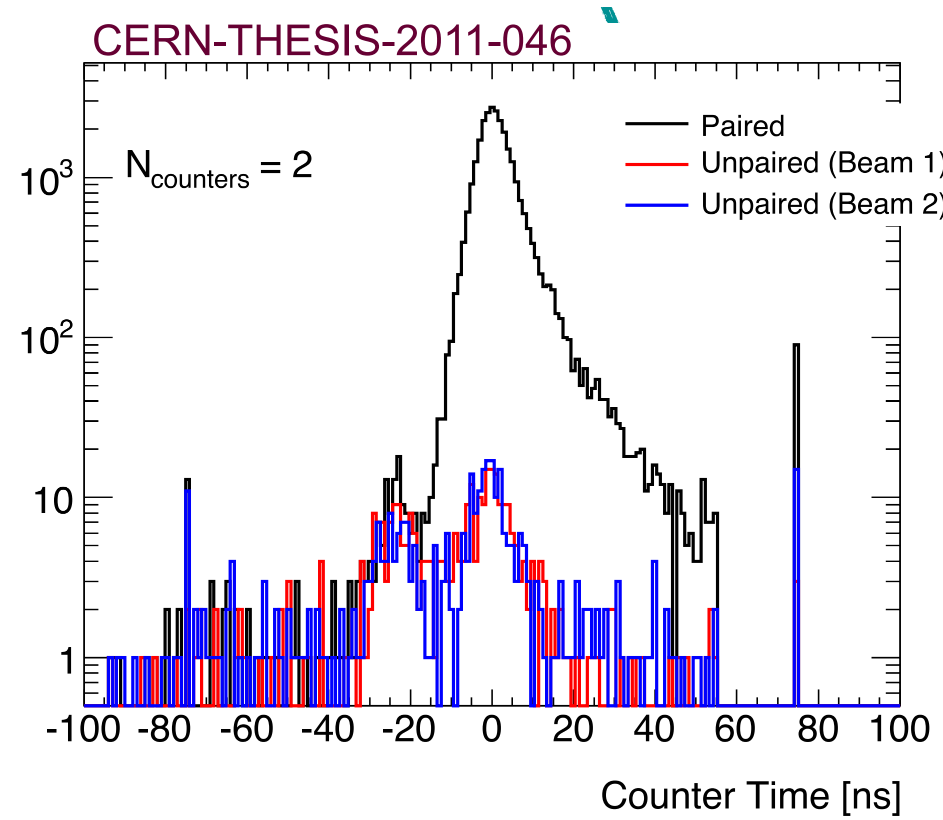


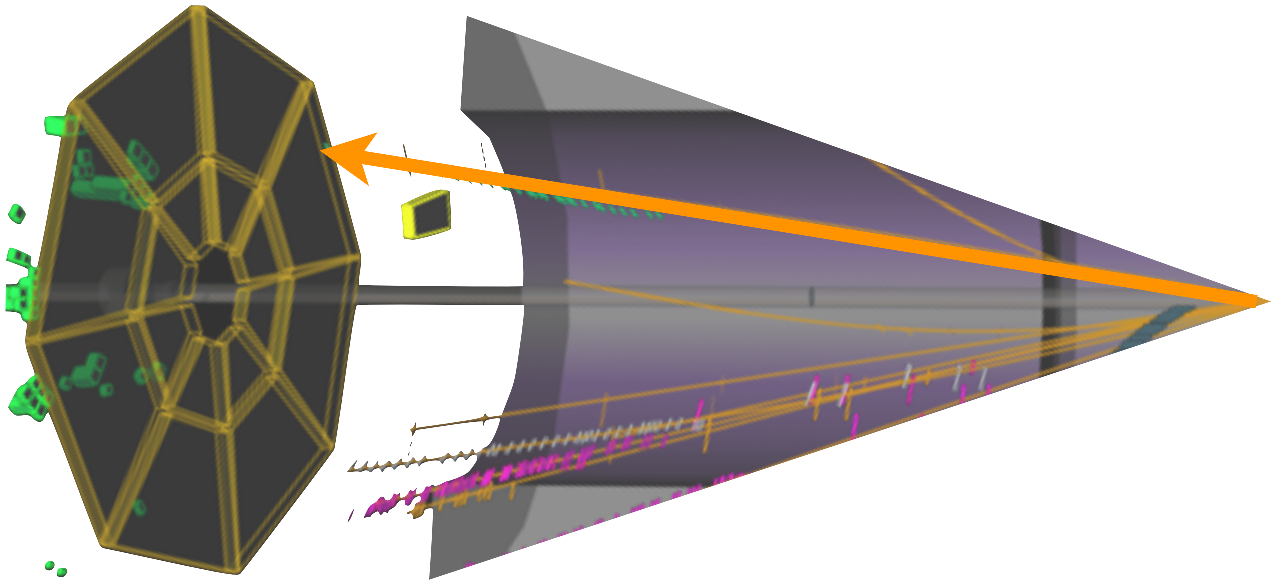


Modeling Detector Response

- Evaluated agreement of data and MC for MBTS counter response
  - Inner Counters: use calorimeters as tag
  - Outer Counters: use tracks as tag

- Use track or calorimeter cell to tag counter, define efficiency as fraction of tagged counters with Q over threshold.
  - Correct for extrapolation error (track) and neutral component (calo)
  - Adjust MC threshold to match observed efficiency in data

- Systematic taken as MC threshold which reproduces efficiency in "worst" data counter
  - Done separately for +/- (η) sides and Inner, Outer counters



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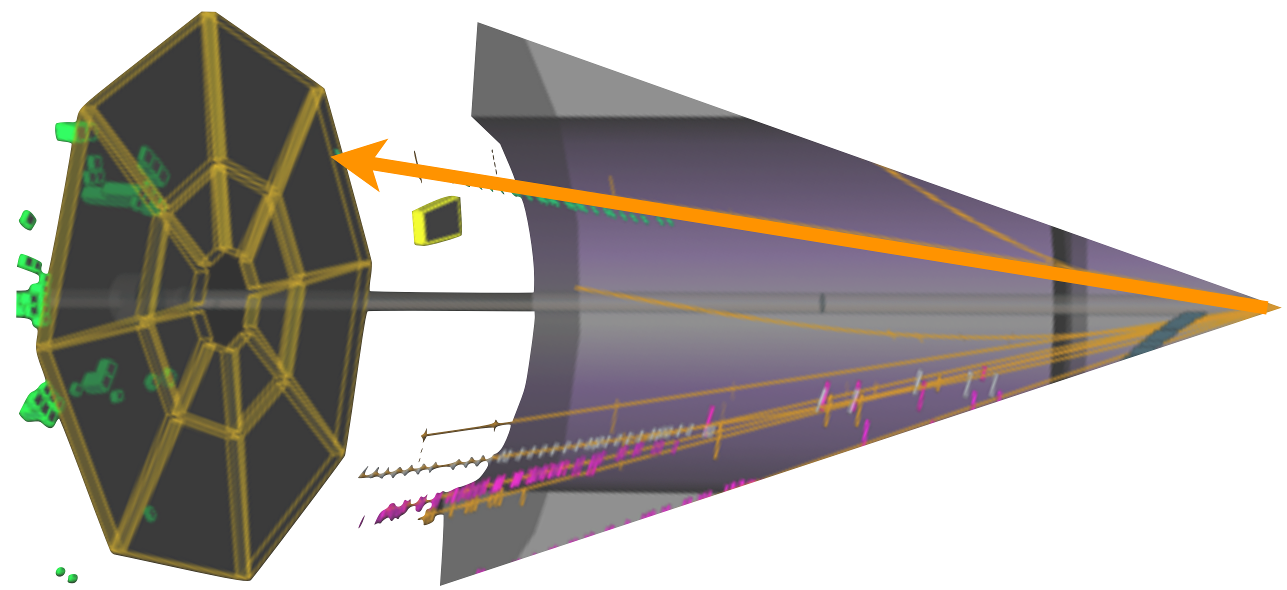

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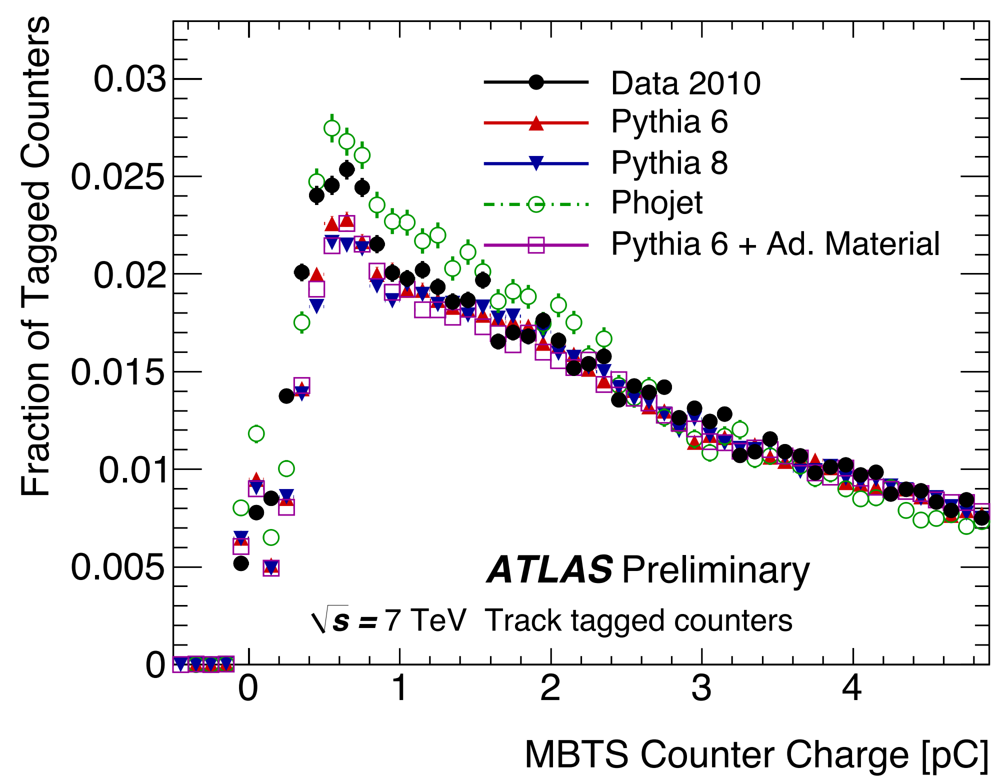

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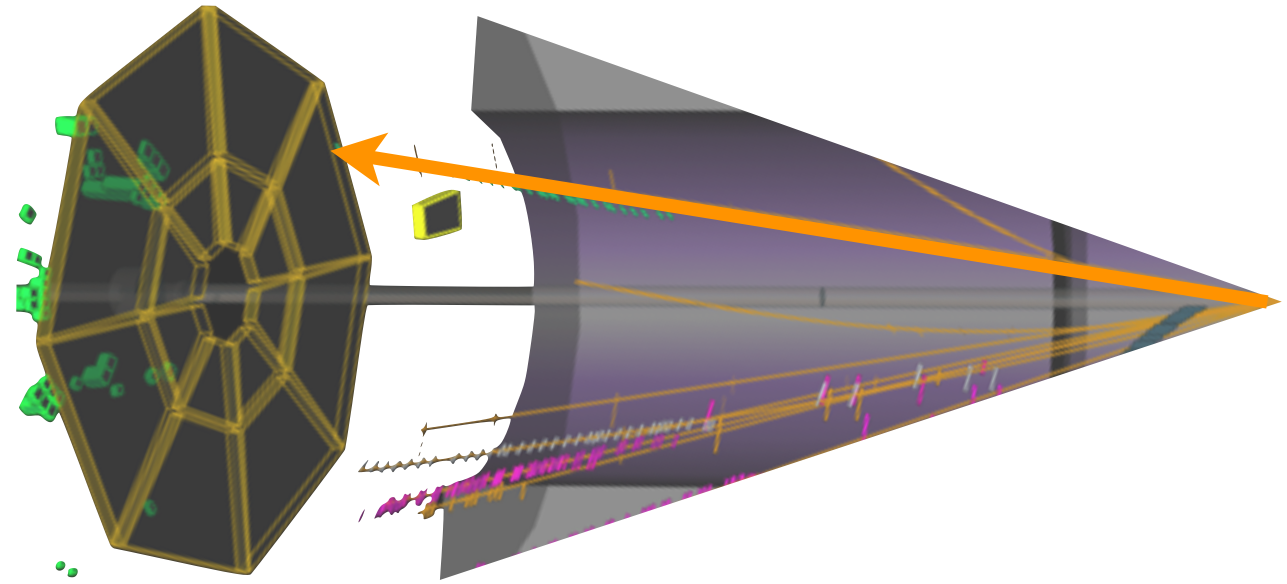

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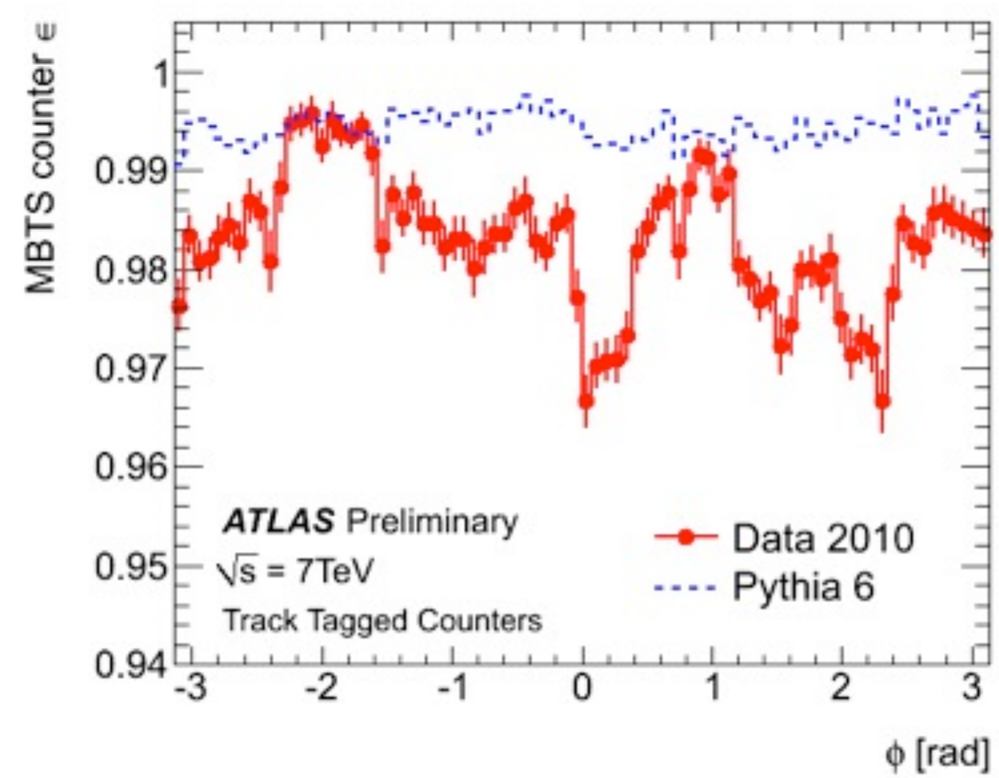

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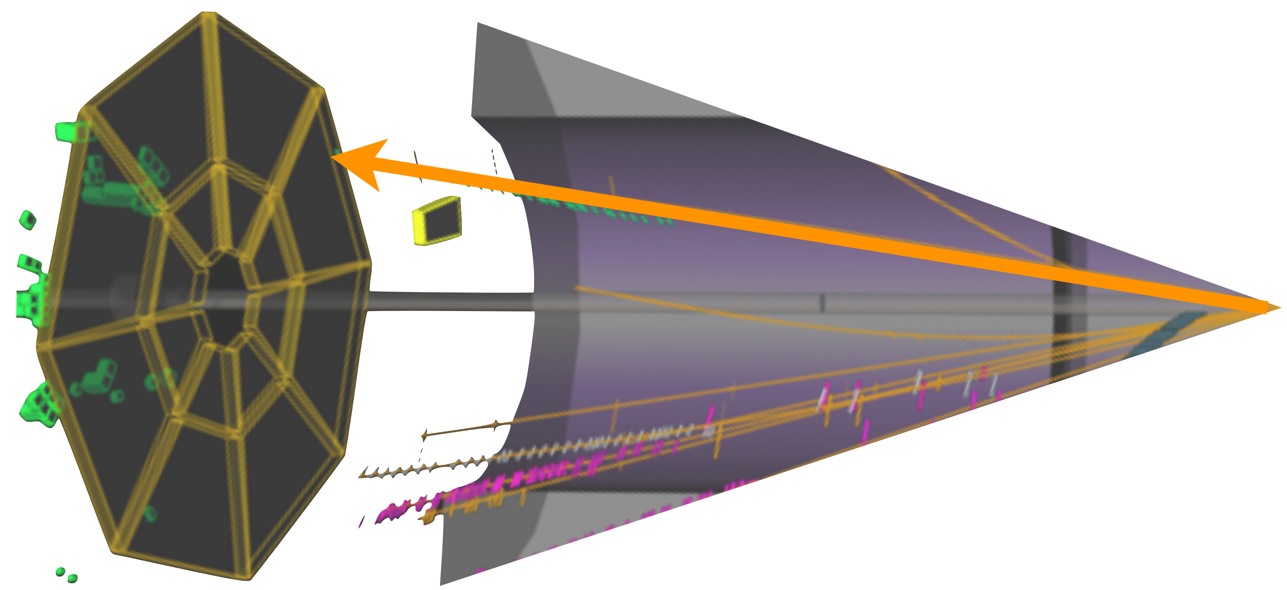
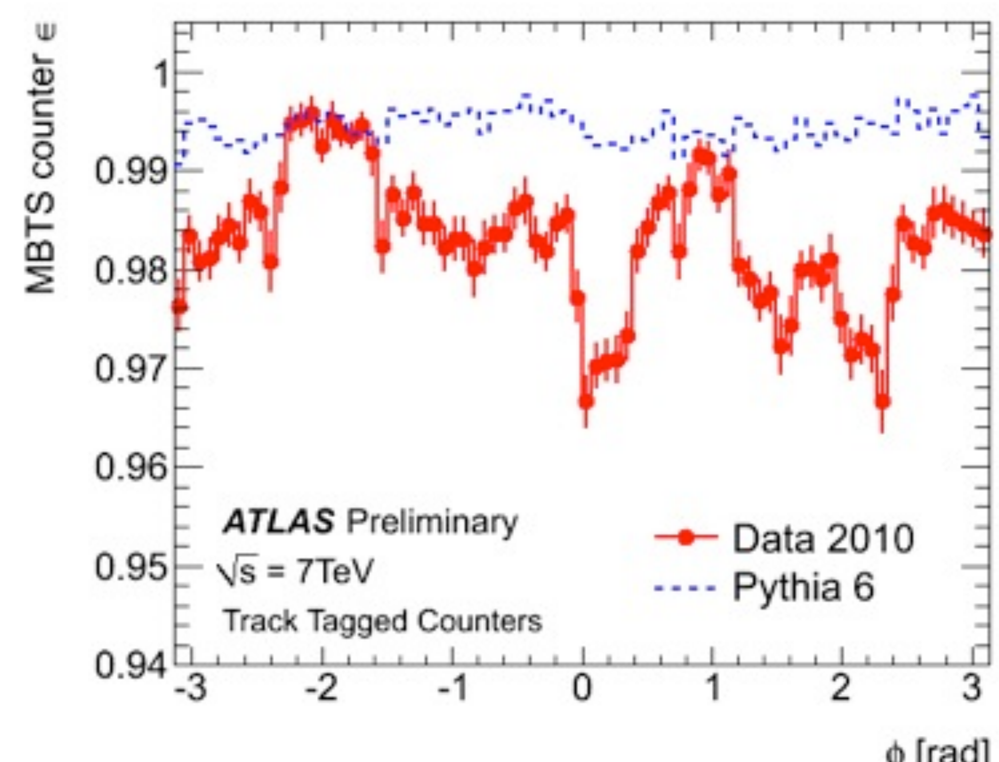
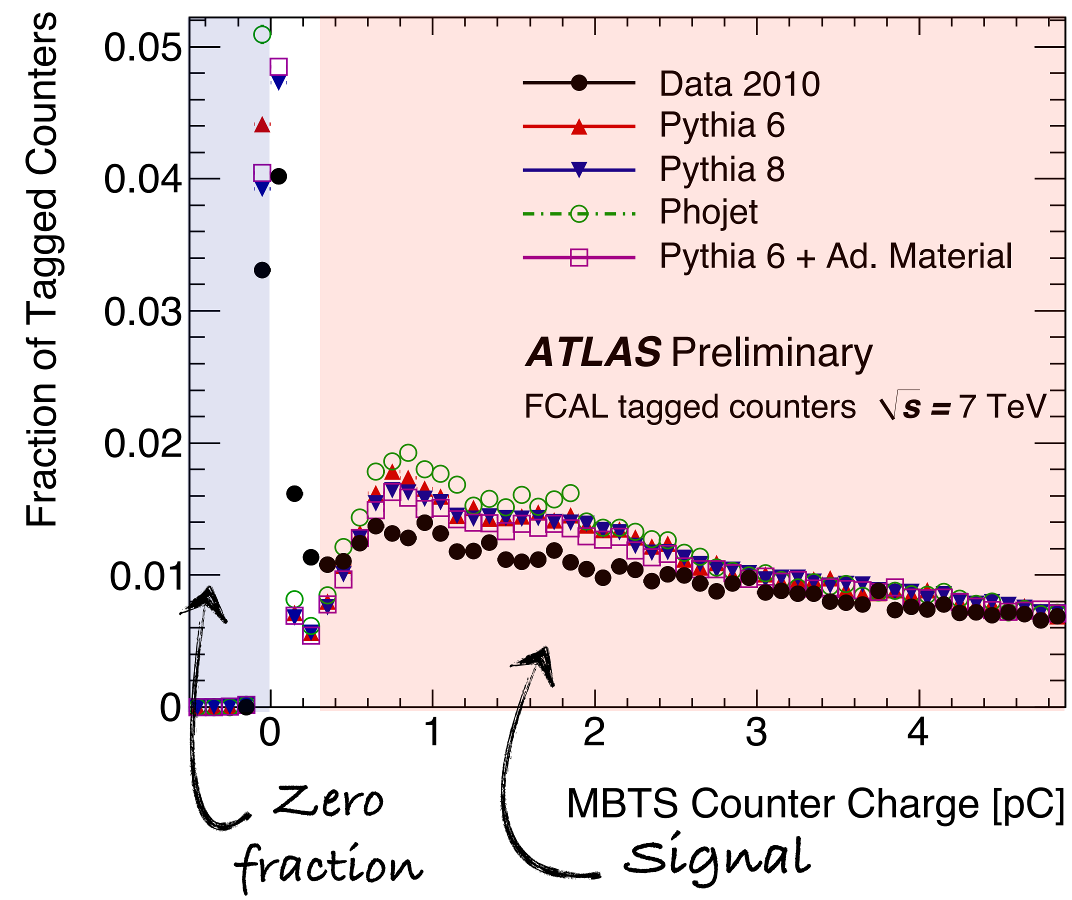




Uncertainty on σ: 0.1%

Modeling Detector Material

- Material increases efficiency/ acceptance by increasing rate of conversions.
  - MBTS only “sees” charged particles
- Exploit calorimeter’s sensitivity to neutral particles
  - Plot fraction of tagged counters seen as noise by the MBTS
- Used a Pythia 6 sample reconstructed 20% extra material in the pixel services to estimate material effects
  - Used **twice** difference (same as Pythia 6 - Data) as the systematic



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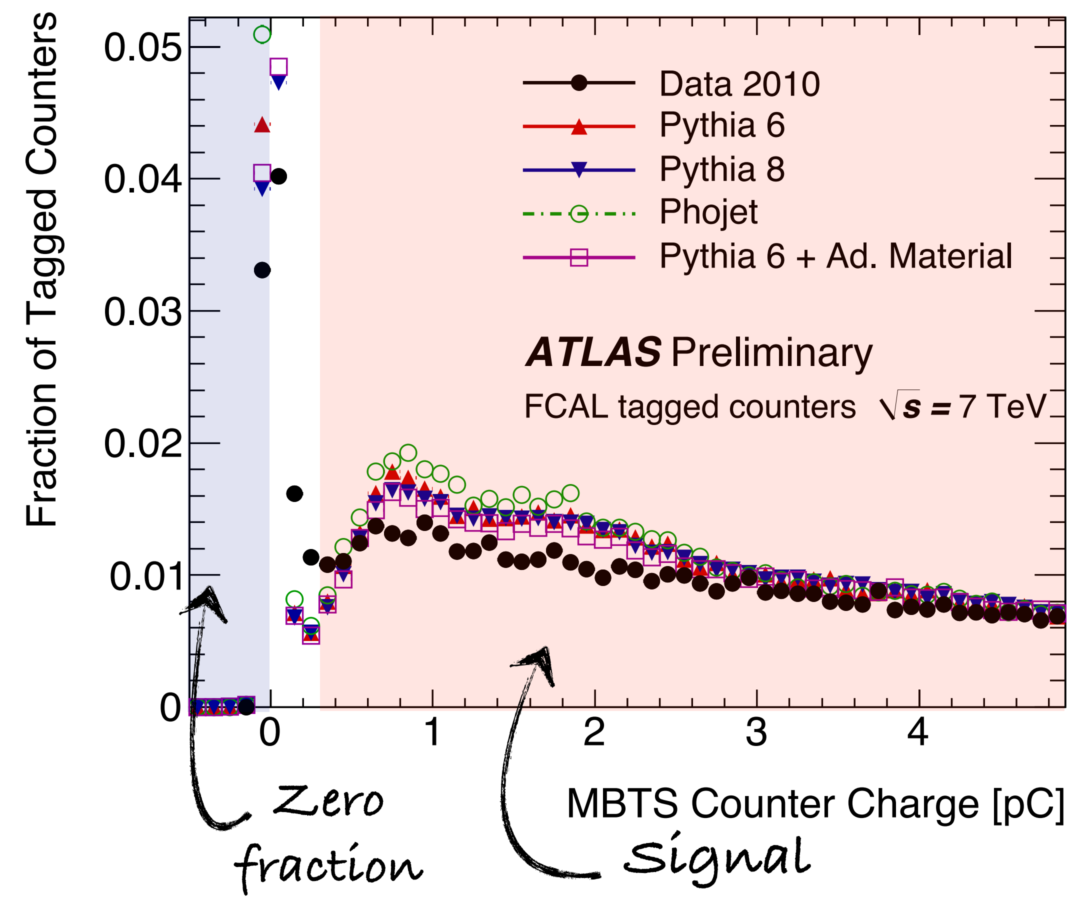

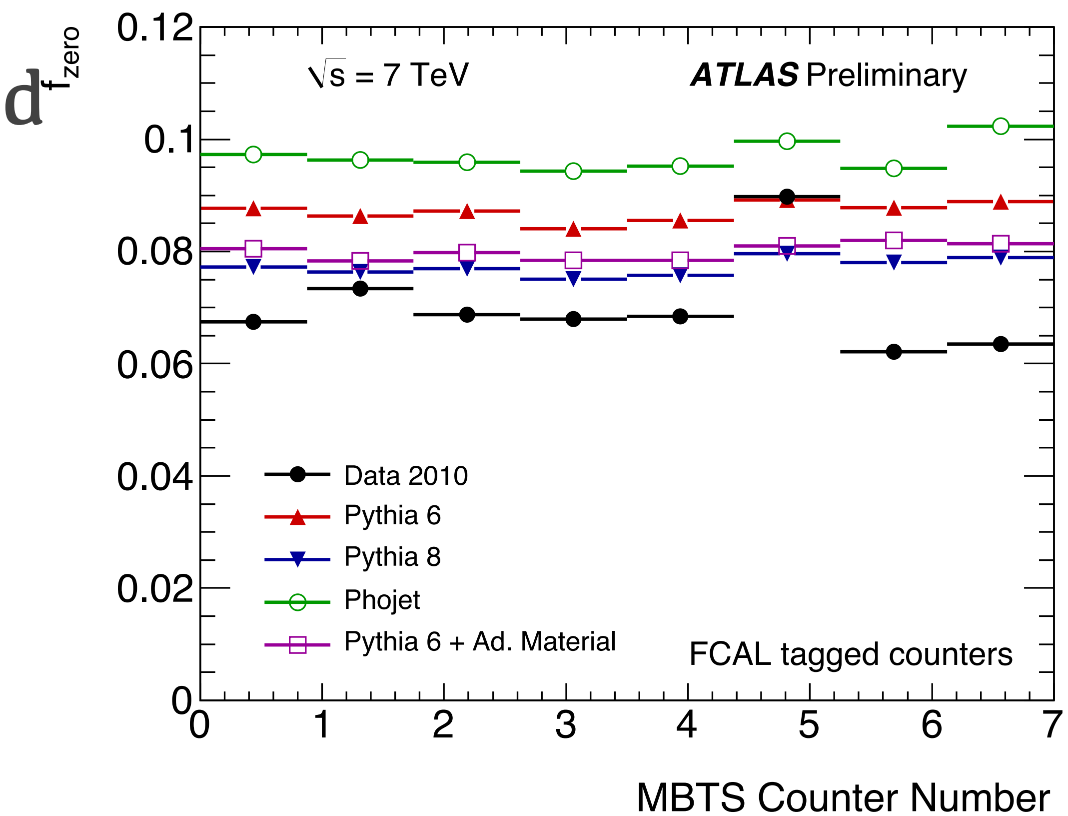

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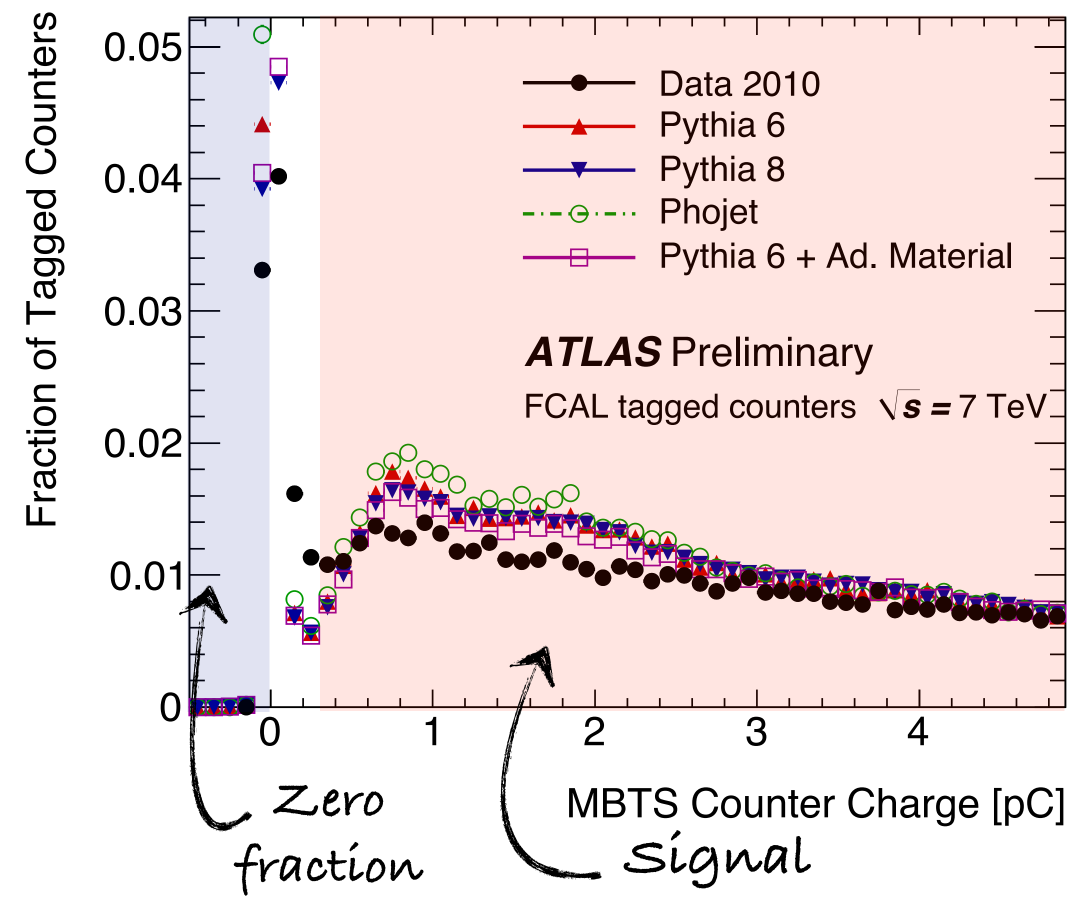
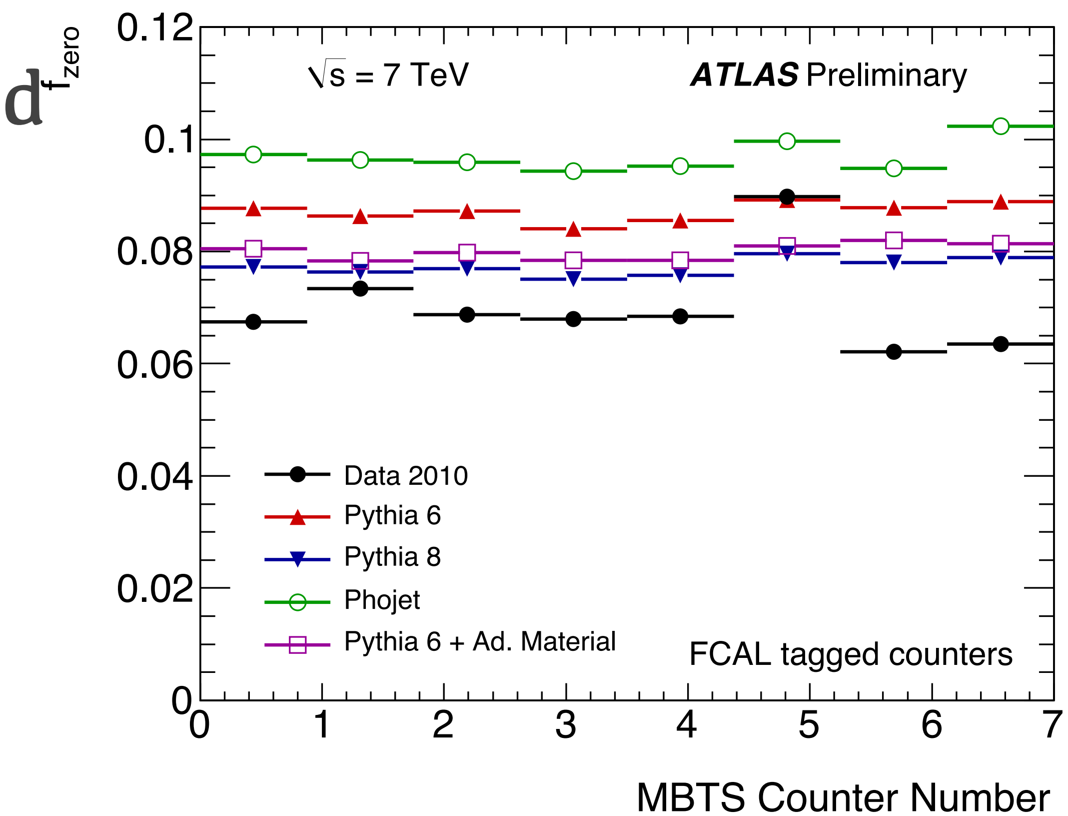
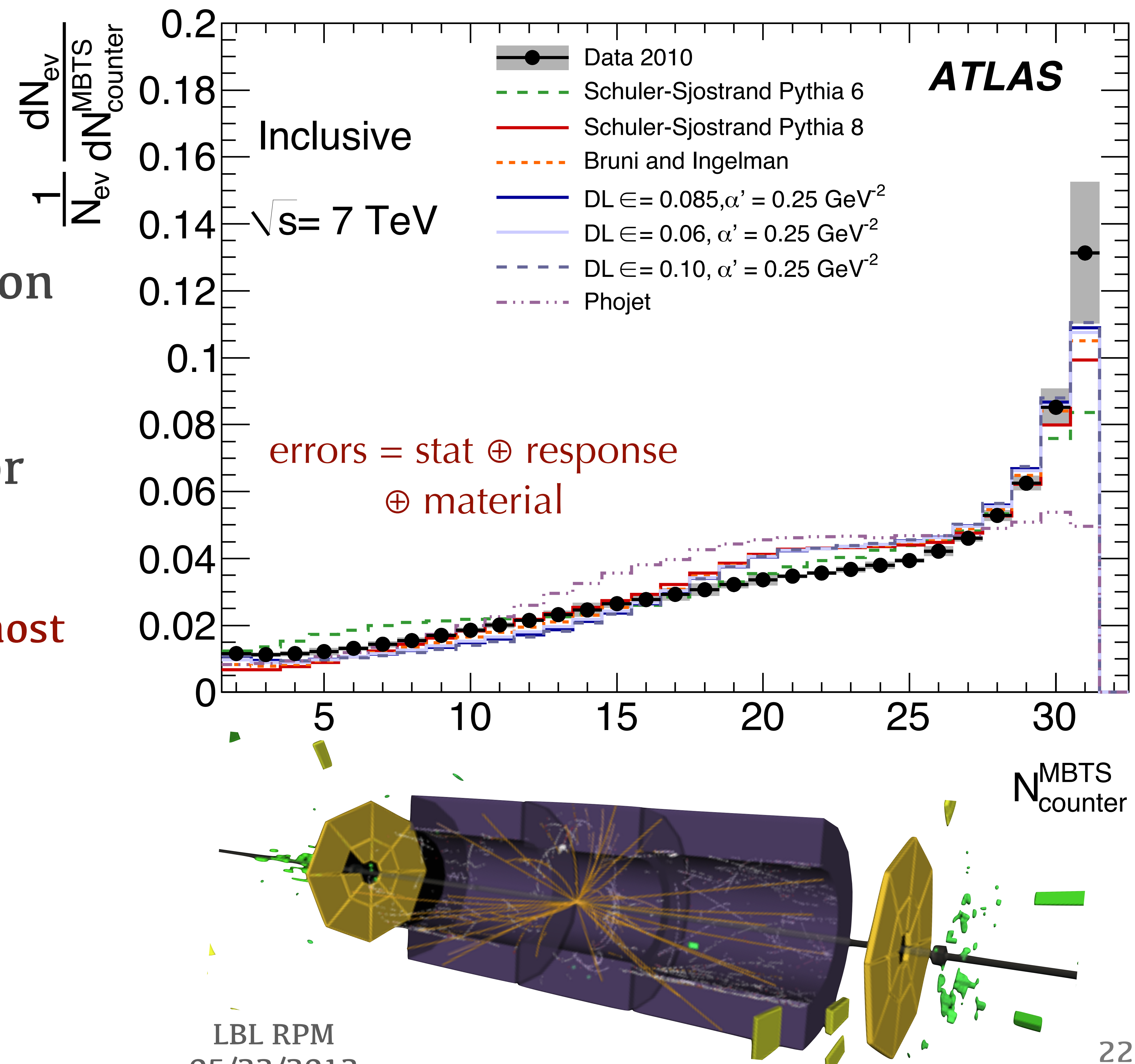




Uncertainty on σ: 0.2%

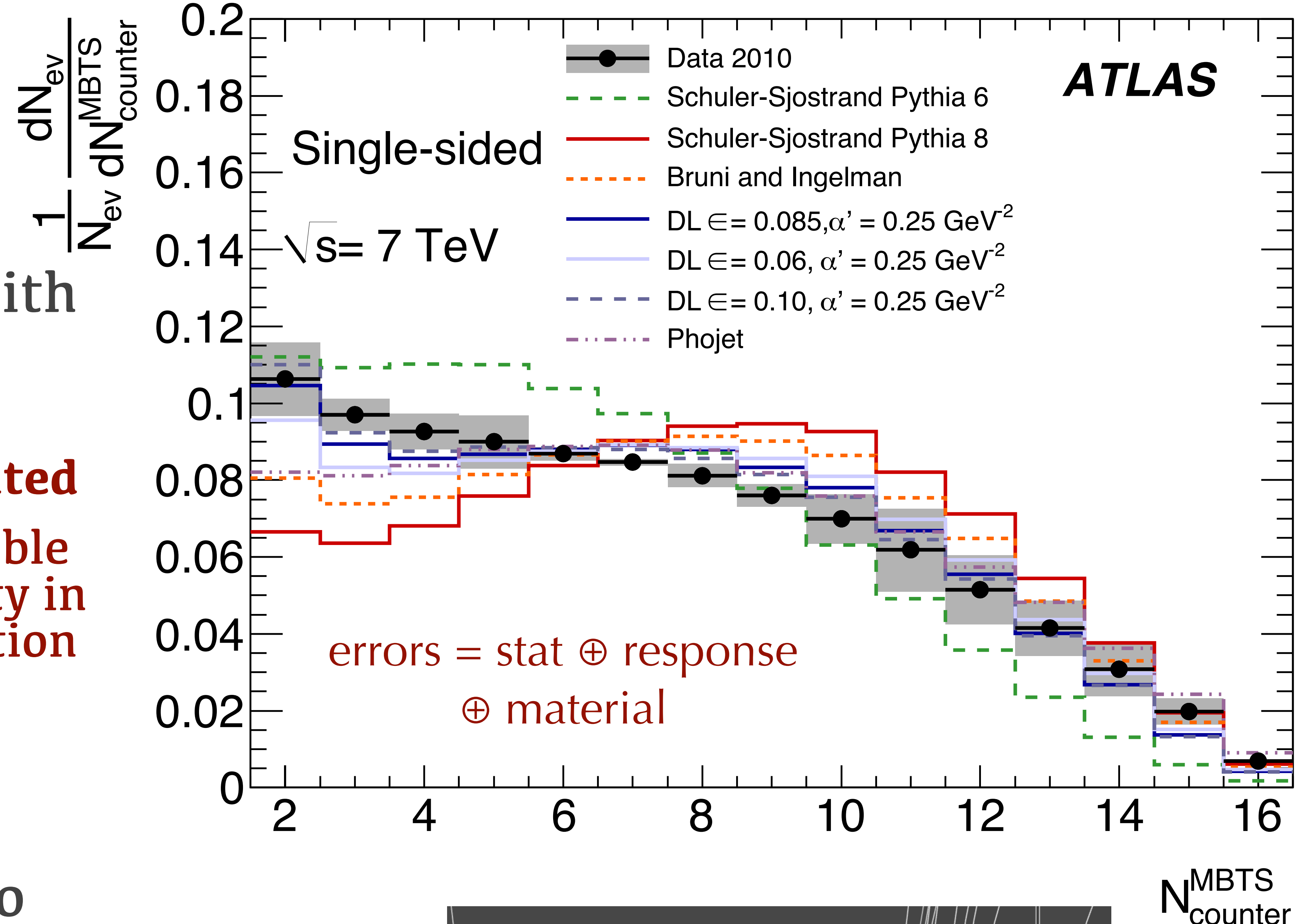
Inclusive Event Sample: N

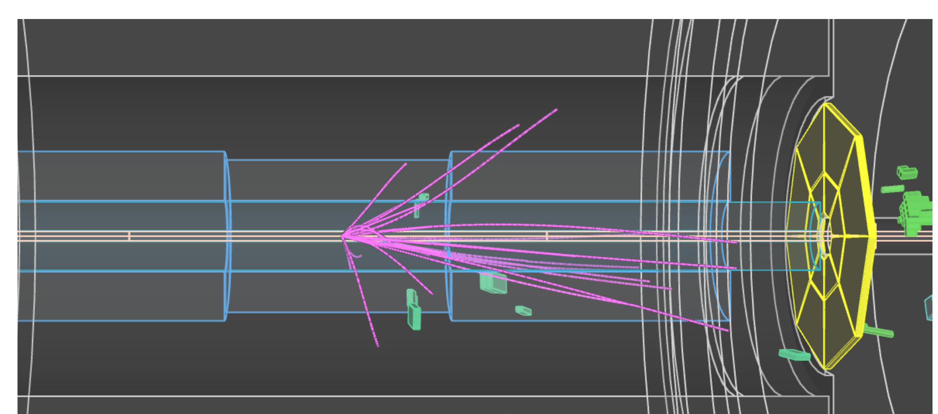
- Used for cross-section measurement
- Models span data for most of multiplicity range
  - Low $N_{counter}$ region most important for measurement



Single-Sided Event Sample: N_{SS}

- Sample of events with hits on one side of MBTS
  - **Diffraction-dominated**
  - Models give reasonable spread of uncertainty in diffractive contribution
- Used to **constrain** contribution of diffractive events to inclusive event sample

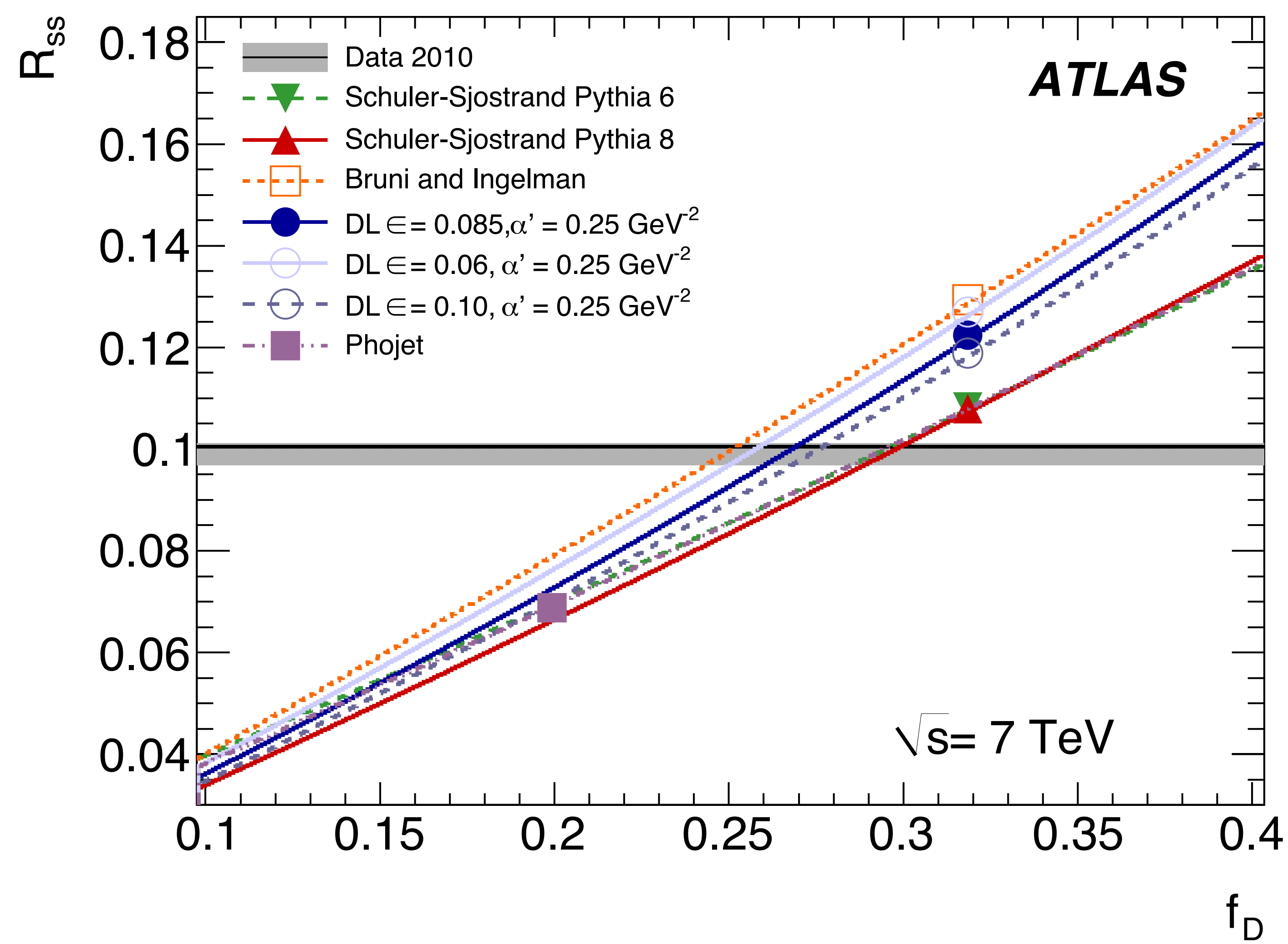




Relative Diffractive Contribution

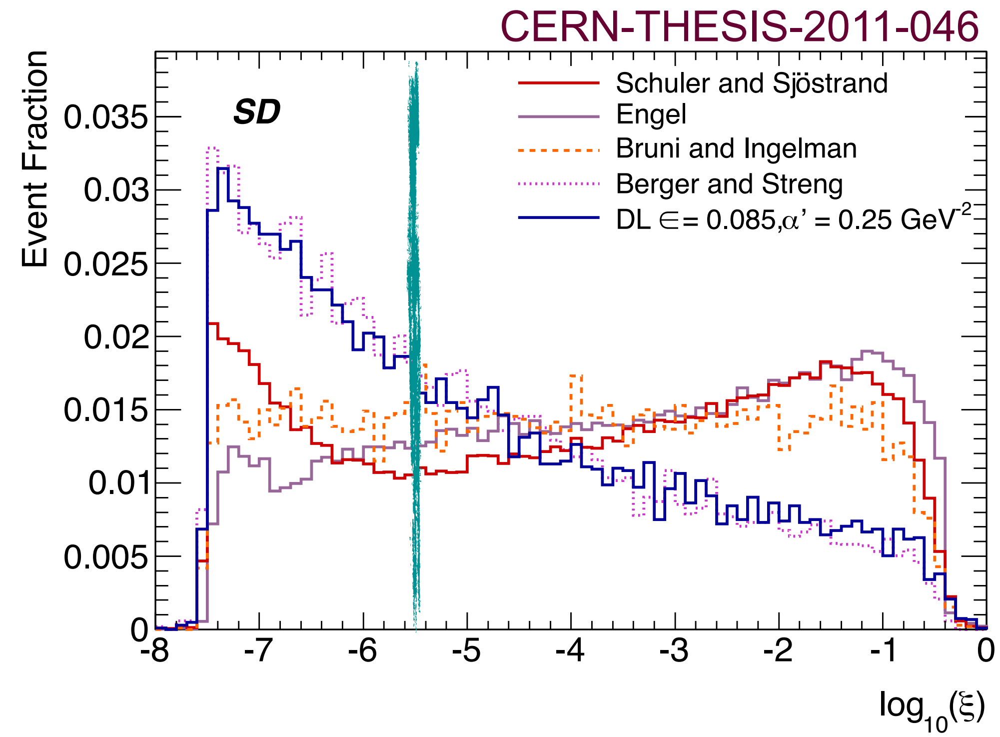
$$R_{ss}(f_D) = \frac{N_{SS}}{N_{inc}} = \frac{A^D_{SS} f_D + A^{ND}_{SS}(1-f_D)}{A^D_{inc} f_D + A^{ND}_{inc}(1-f_D)}$$

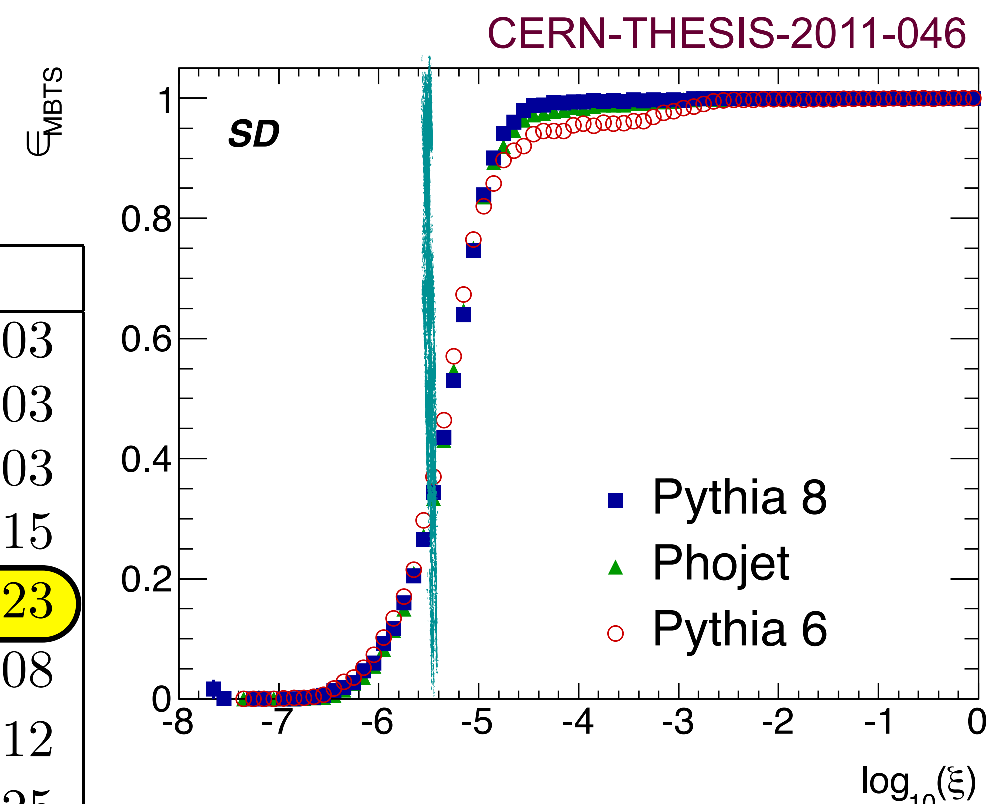
- Fractional contribution of diffractive process (f_D) varies significantly between generators
  - Model dependent quantity
- Constrain f_D for **each model** by finding value which produces same ratio of single-sided to inclusive event sample (R_{ss}) as data
  - **Default model yields $f_D = 26.9^{+2.5}_{-1.0}$ %**



ε_{sel} and $f_{\xi<10^{-5}}$

- To get ε_{sel} and $f_{\xi<5x10^{-6}}$ weight ND,SD &DD components by measured f_D
- MBTS selection efficiency has similar shape for all MCs
  - Once the ξ cut is applied efficiencies are very similar and high > 98%
- Contamination from events failing ξ cut ($f_{\xi<5x10^{-6}}$)is 0.3-1%





Generator	ϵ_{sel}	$f_{\xi<5\cdot10^{-6}}$
PYTHIA 6 Schuler-Sjöstrand	0.9881±0.0003	0.0056±0.0003
PHOJET	0.9928±0.0003	0.0033±0.0003
PYTHIA 8 Schuler-Sjöstrand	0.9922±0.0003	0.0050±0.0003
Bruni and Ingelman	0.9906±0.0017	0.0064±0.0015
DL $\epsilon = 0.085, \alpha' = 0.25$ GeV^{-2}	0.9877±0.0025	0.0096±0.0023
DL $\epsilon = 0.06, \alpha' = 0.25$ GeV^{-2}	0.9887±0.0009	0.0083±0.0008
DL $\epsilon = 0.10, \alpha' = 0.25$ GeV^{-2}	0.9871±0.0012	0.0105±0.0012
DL $\epsilon = 0.085, \alpha' = 0.10$ GeV^{-2}	0.9881±0.0026	0.0100±0.0025

MC Uncertainties on ε_{sel} and $f_{\xi<10^{-5}}$

- Multiplicity for a given ξ:
  - Pythia 6 & Pythia 8 have different fragmentation models
  - Leads to 0.4% systematic
- Underlying ξ distribution in cut range:
  - Differences in distribution cause different migration of events into and out of sample
  - Leads to 0.4% systematic

MC Modeling total uncertainty: 0.35%

Summary of Systematic Uncertainties

- Trigger: Difference between measurement with 2 independent triggers
- MBTS Response: Vary thresholds over full range of data efficiencies
- Material: 40% uncertainty on material in $|\eta|> 2.5$.
- Relative Diffractive Contribution: Vary f_D within uncertainties
- Background: 100% uncertainty
- MC Multiplicity: Difference between Pythia 8 and Pythia 6
- ξ Distribution: largest difference between default and alternative models

Source	Uncertainty (%)
Trigger Efficiency	0.1
MBTS Response	0.1
Material	0.2
f_D	0.3
Beam Background	0.4
MC Multiplicity	0.4
ξ distribution	0.4
Luminosity	3.4
Total	3.5

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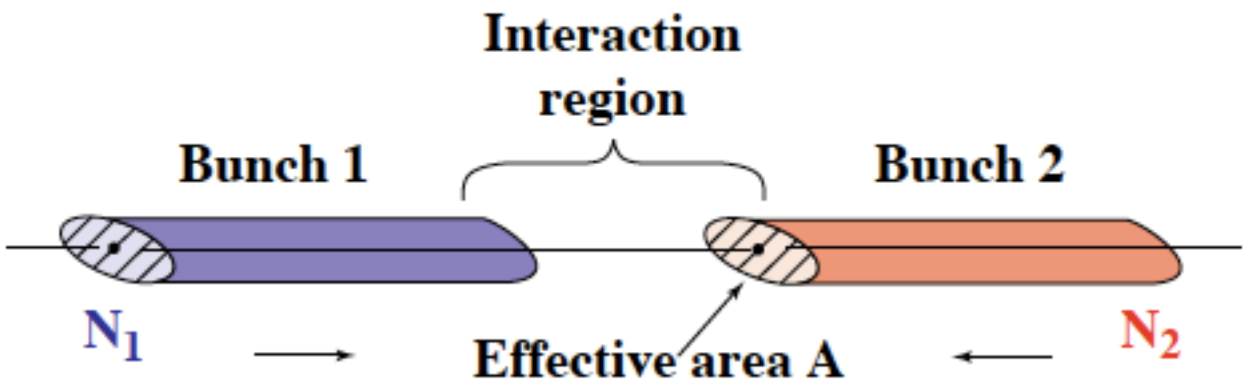
Luminosity Basics



$$\mathcal{L} = \frac{N_1 N_2 f}{A_{\text{eff}}}$$

- Luminosity is a measure of the beam collision intensity: depends on N_p/bunch, N_{bunches}, crossing frequency, & beam size.

- Can be determined 2 ways:
  - Using a theoretically well known cross section and event counting:

$$\mathcal{L} \cdot \sigma = N_{ev}$$

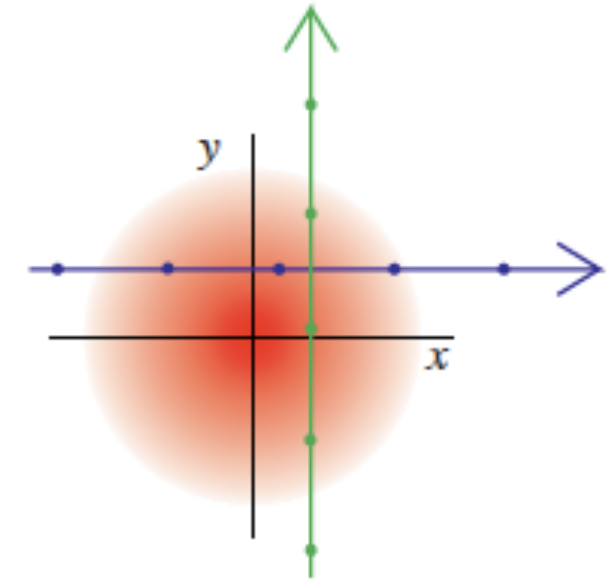
  - From accelerator parameters:

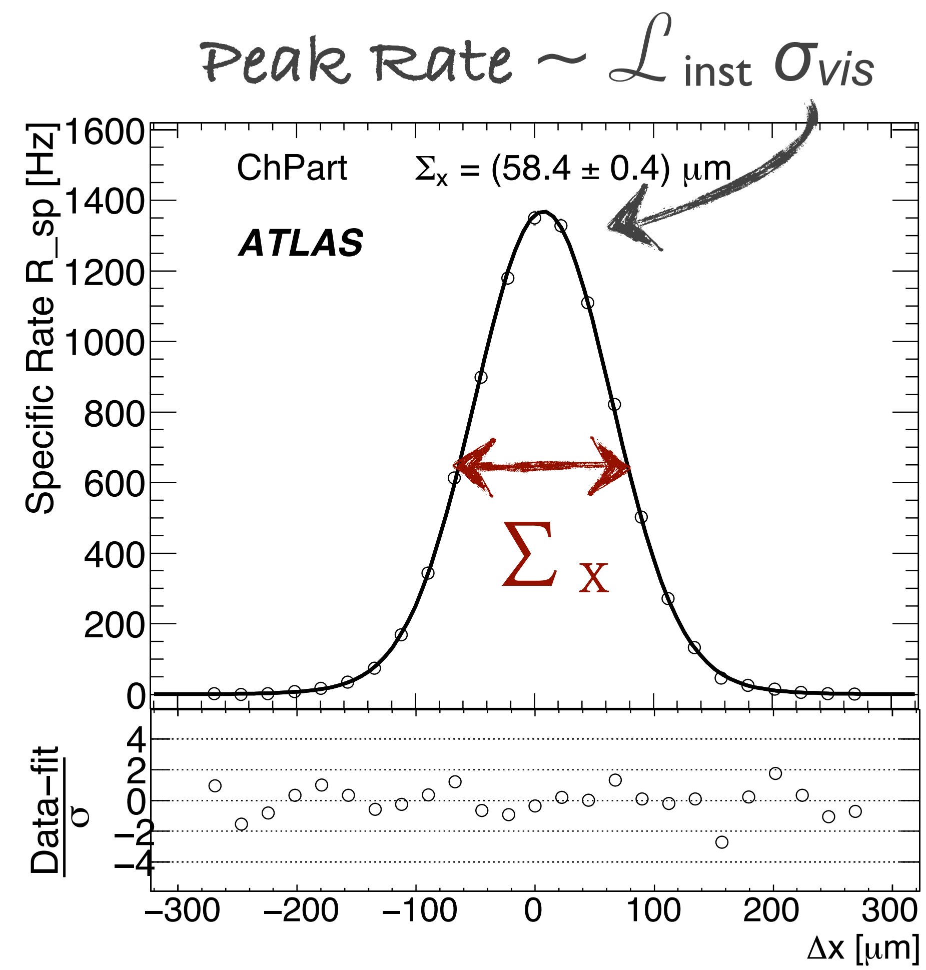
$$\mathcal{L} = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y}$$

$$\left(\Sigma_x = (\sigma_{1x}^2 + \sigma_{2x}^2)^{1/2} \right)$$

Beam Separation Scans

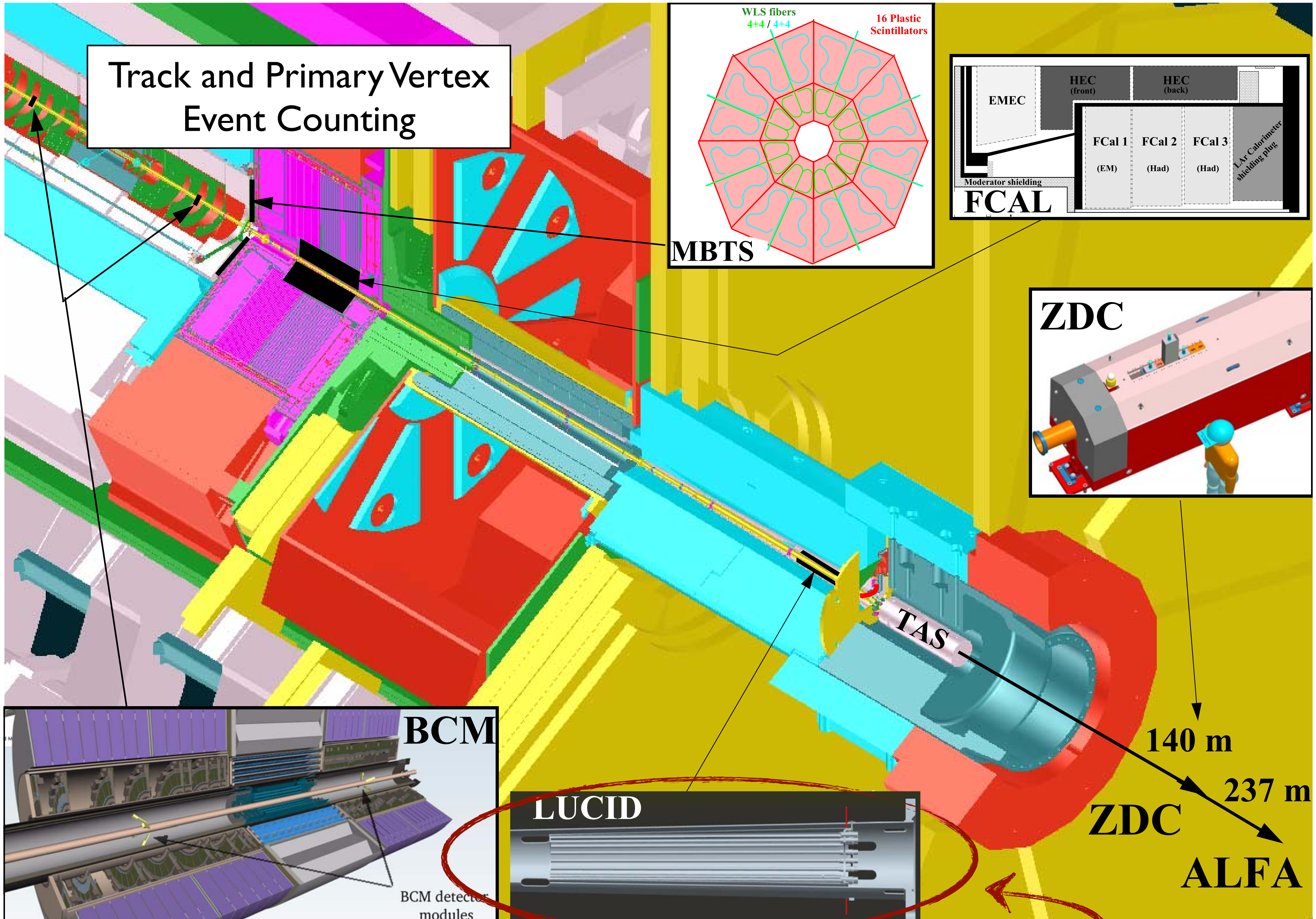
- Proposed in 1968 by Simon van der Meer as a means of measuring beam sizes at the ISR.
- Principle:
  - Measure the beam widths by scanning interaction rate as a function of beam separation
  - Can simultaneously measure visible cross-section, σ_{vis}
  - Then use σ_{vis} as calibration constant for future luminosity determination





$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{n_b f_r I_1 I_2}{2\pi\Sigma_x\Sigma_y}\sigma_{vis}$$

ATLAS Luminosity Detectors



Primary Luminosity Measurement

Luminosity Uncertainties

- Calibration determined from 5 different scans in 2010
  - O(10) different methods/detectors used!
- Uncertainty is dominated by knowledge of bunch charge ($I_1 I_2$)
- Already surpassed precision expected for beam scans!

Scan Number Fill Number	I 1059	II–III 1089	IV–V 1386	
Bunch charge product	5.6%	4.4%	3.1%	Partially correlated
Beam centering	2%	2%	0.04%	Uncorrelated
Emittance growth and other non-reproducibility	3%	3%	0.5%	Uncorrelated
Beam-position jitter	–	–	0.3%	Uncorrelated
Length scale calibration	2%	2%	0.3%	Partially Correlated
Absolute ID length scale	0.3%	0.3%	0.3%	Correlated
Fit model	1%	1%	0.2%	Partially Correlated
Transverse correlations	3%	2%	0.9%	Partially Correlated
μ dependence	2%	2%	0.5%	Correlated
Total	7.8%	6.8%	3.4%	

ATLAS-CONF-2011-011
arXiv:1101.2185v1

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Results

- Calculate cross-section using:
  - ε_{sel} = 98.8%,
  - ε_{trig} = 99.8%,
  - $f_{\xi<5x10^{-6}}$ = 1.0%
  - and L =20 μb^{-1}

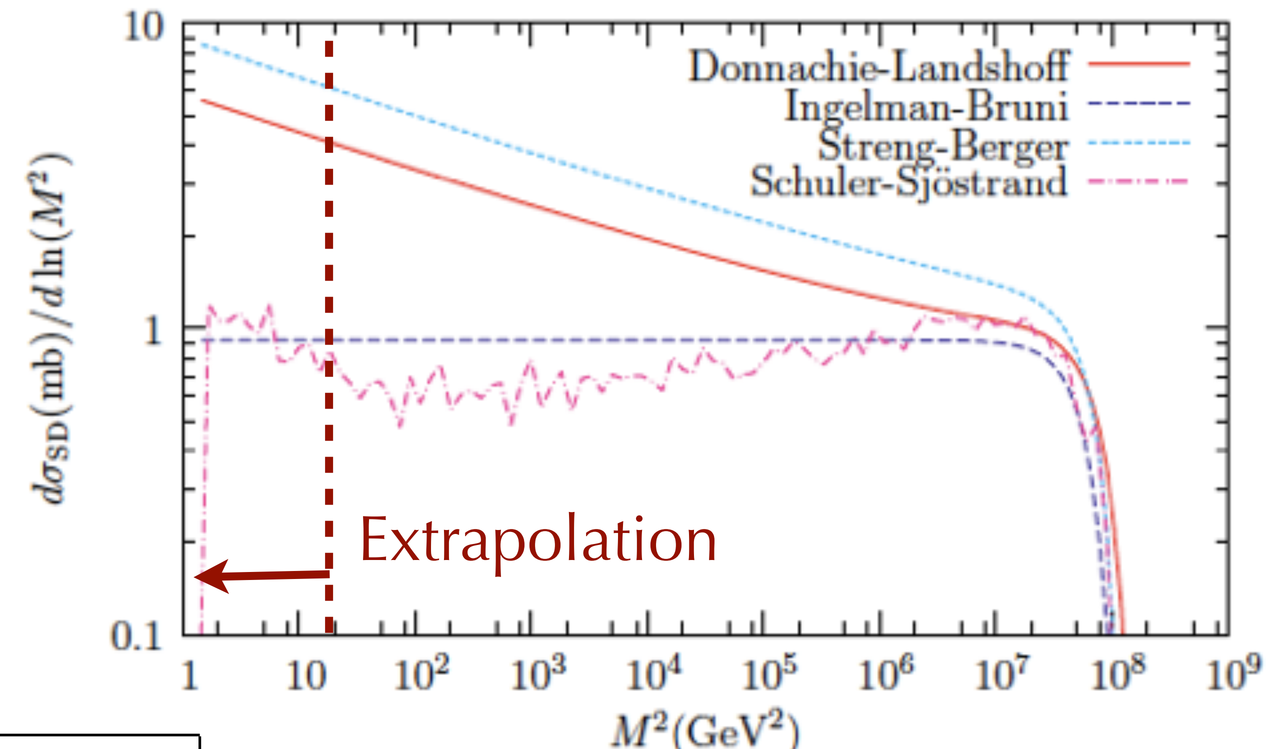
} 0.4% correction factor

$\sigma(\xi > 5 \times 10^{-6})$ [mb]	
ATLAS Data 2010	$60.33 \pm 2.10(\text{exp.})$
Schuler and Sjöstrand	66.4
PHOJET	74.2
Ryskin *et al.*	51.8 – 56.2

- Data are lower than MC generator predictions, higher than analytic calculation from Ryskin et. al.

Extrapolating to σ_{inel}

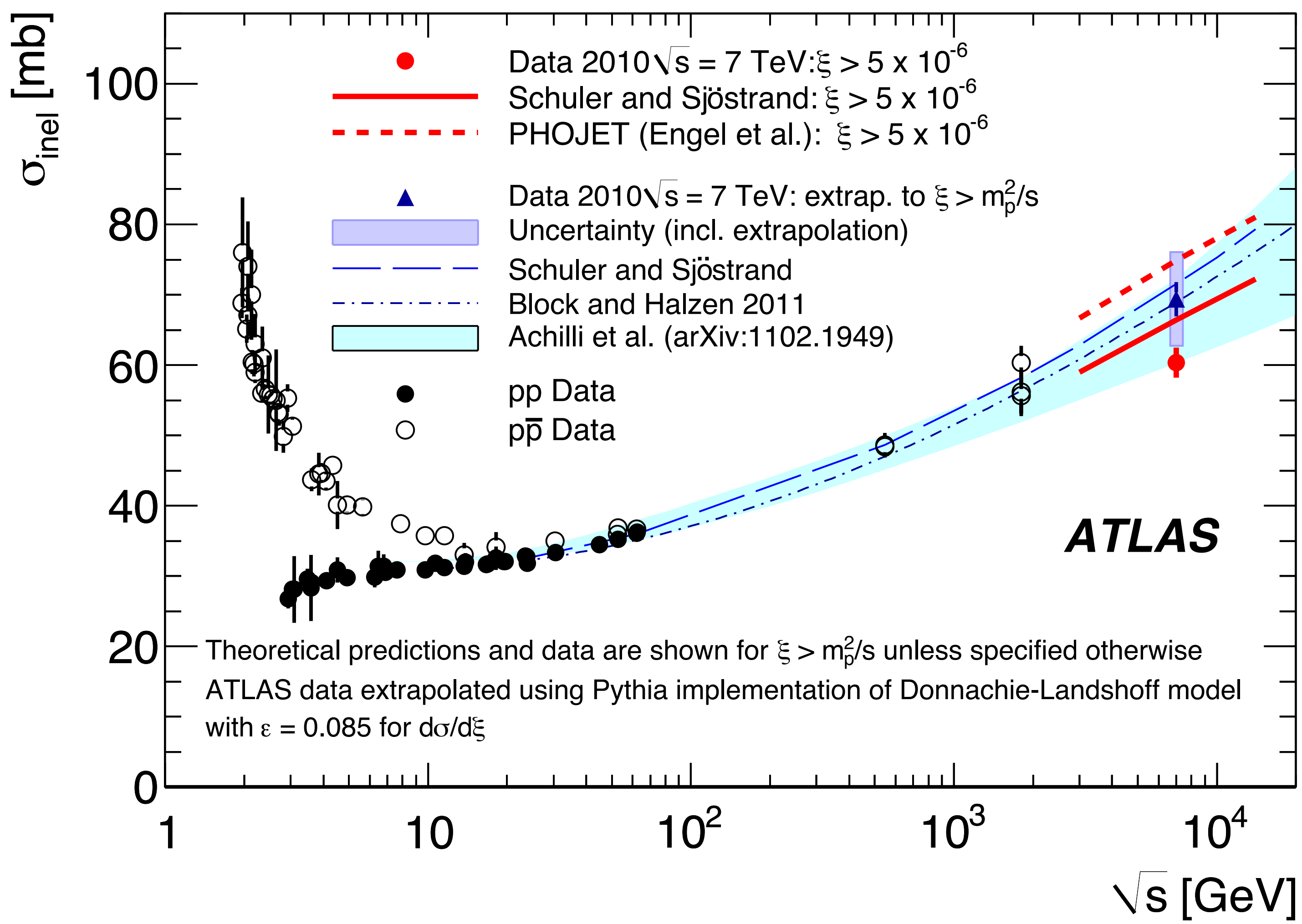
- To compare with previous measurements extrapolate using DL model (+15%)
  - Other models range from 5 to 25% extrapolations
  - Take +/- 10% as extrapolation uncertainty



$\sigma(\xi > m_p^2/s)$ [mb]	
ATLAS Data 2010	$69.4 \pm 2.4(exp.) \pm 6.9(extr.)$
Schuler and Sjöstrand	71.5
PHOJET	77.3
Block and Halzen	69
Ryskin *et al.*	65.2 – 67.1
Gotsman *et al.*	68
Achilli *et al.*	60 – 75

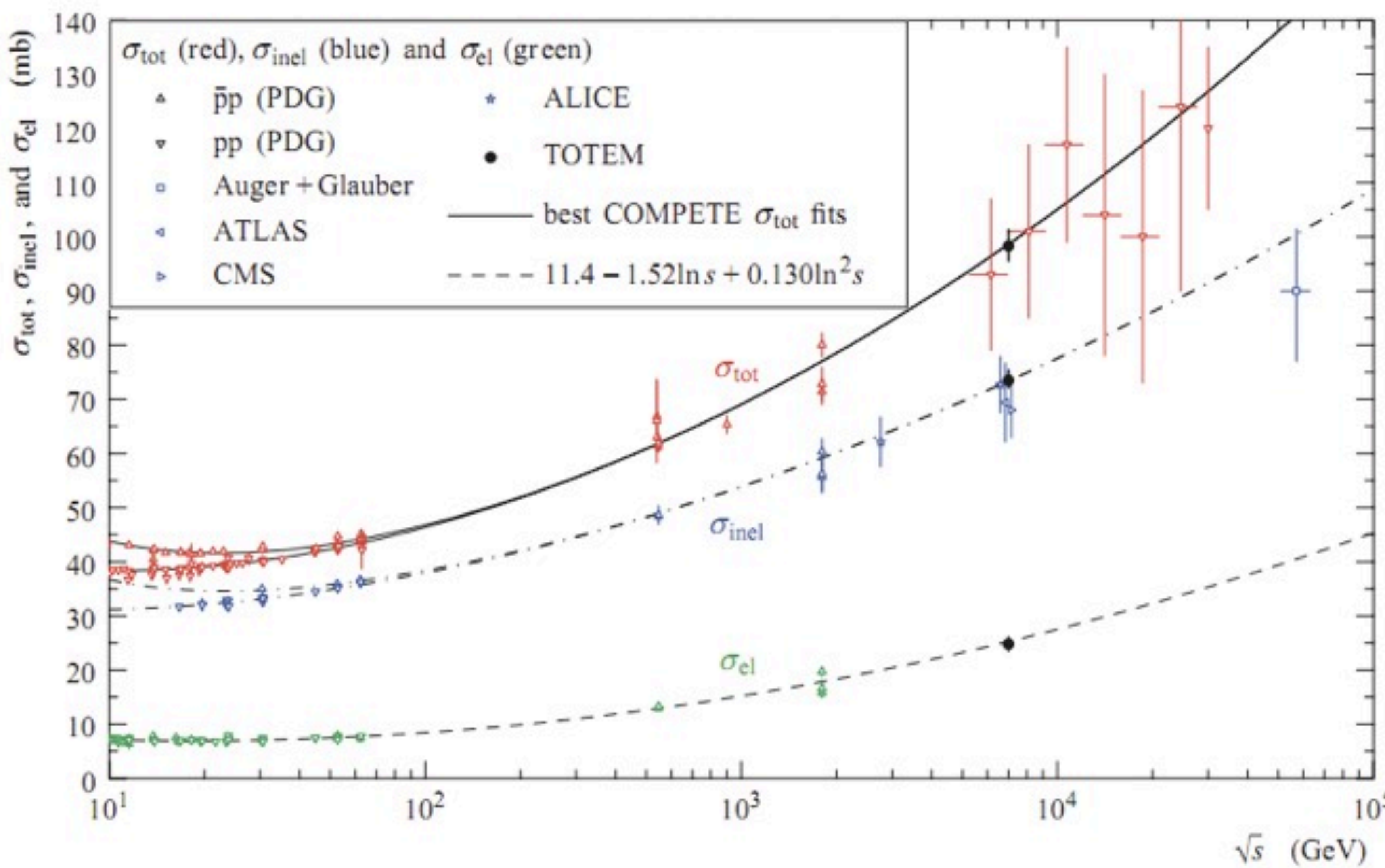
- **Data agree** with most analytic calculations, lower than Phojet

Spring 2011



- Presented the first measurement of inelastic cross-section
  - Data are lower than MC predictions, extrapolated value agrees with most analytic models

Fall 2011

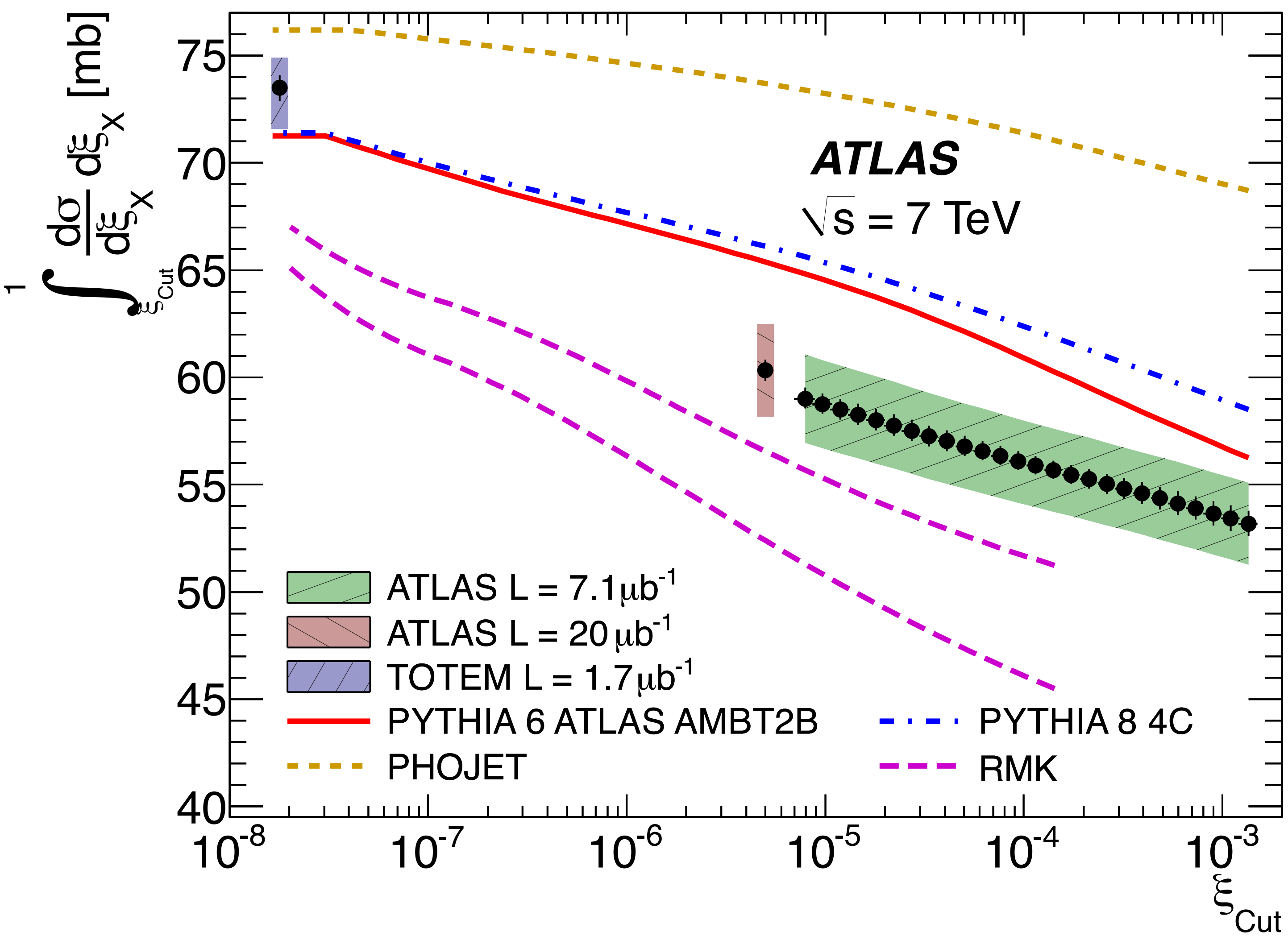


EPL 96 (2011) 21002

- ALICE & CMS measured inelastic cross-section in limited phase space
  - Widely varying techniques with good agreement
- TOTEM used 90m β^* run to measure σ_{tot}, σ_{inel} and σ_{el}
  - Very precise measurement not subject to extrapolation uncertainties

The Visible Cross Section

arXiv:1201.2808



- Atlas also measured cross section as a function of rapidity gap (ξ)
- Comparison with with TOTEM shows models don't predict correct dependence
- Important for pile-up modeling!

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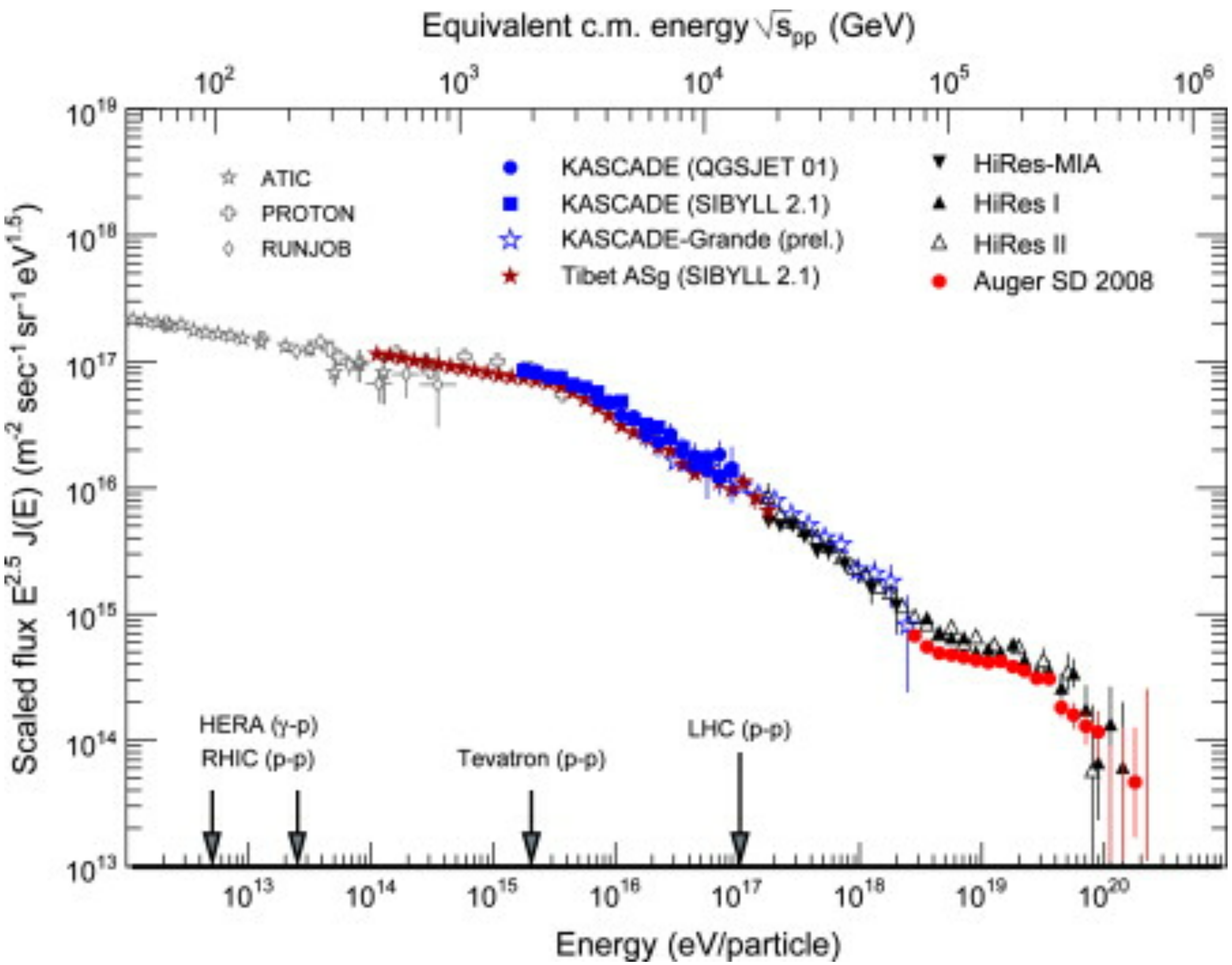
Connection to Cosmic Rays



- Shower MC used to determine primary CR energy up to GZK cut off
  - Big extrapolation!
- LHC data useful to for:
  - Better p-air cross-section
  - Better shower modeling

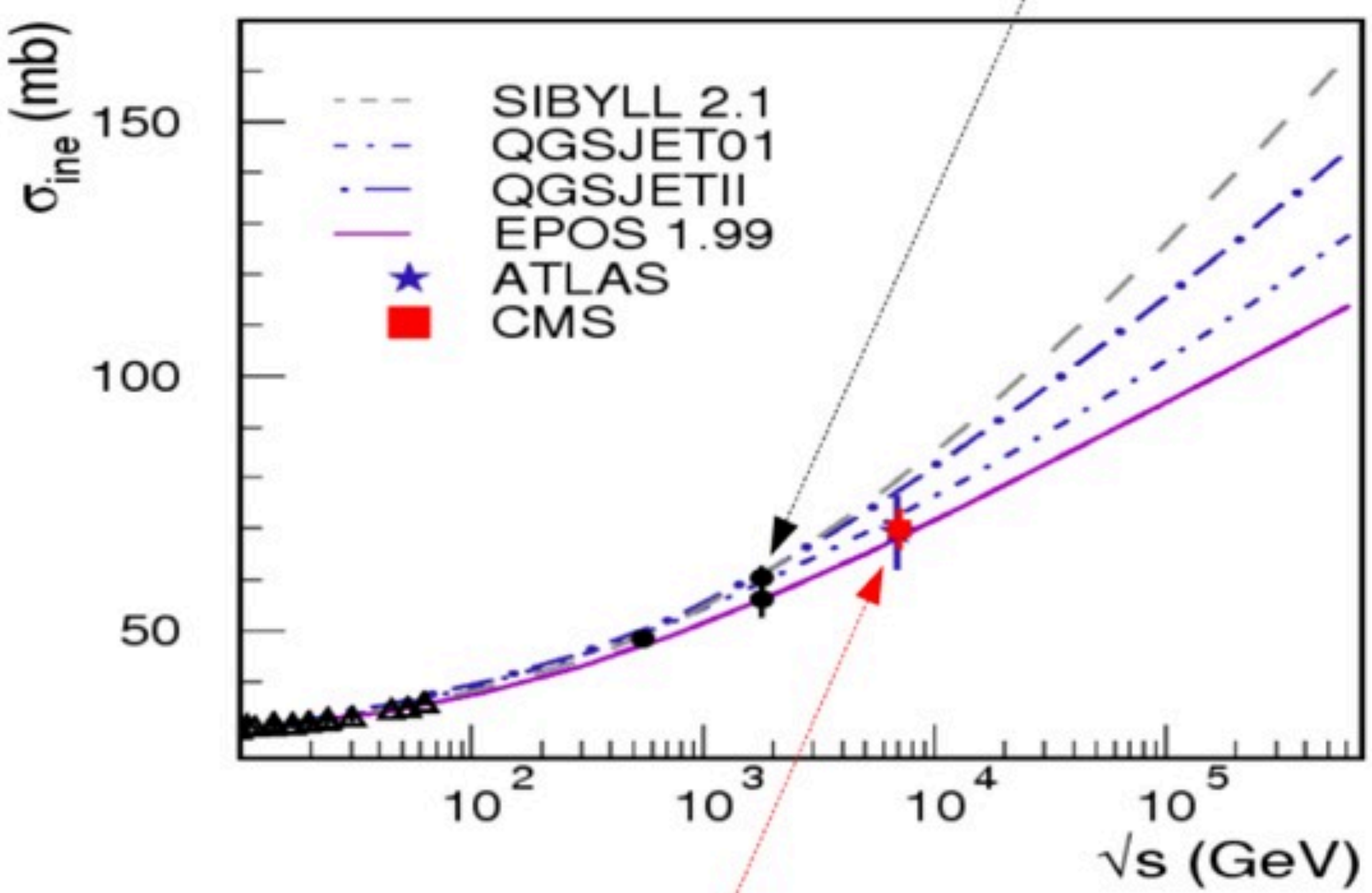
Blümer, Engel, Hörandel, arXiv:0904.0725

Constraining CR Models

http://indico.cern.ch/getFile.py/access?contribId=21&sessionId=0&resId=0&materialId=slides&confId=140054

LHC inelastic p-p cross sections

- Current model uncertainties driven by E710–CDF 2.6σ disagreement



- σ_{inel} ~ 64(CMS) – 70(ATLAS) mb seem to favour E710 value at 1.8 TeV
- sqrt(s)-evolution better reproduced by EPOS1.99 & QGSJET01

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Conclusions

- Have made the first measurement of the proton-proton inelastic cross section at 7 TeV
  - Measurement made possible by the efficiency & simplicity of the MBTS detector and strength of the ATLAS detector to validate results
- Current results are consistent with Froissart-Martin bound and agree with most analytic calculations
- Already have generated interest in the Soft QCD/LHC community
  - Theory: collaborated with several theorists to obtain predictions at 7 TeV
  - Experiment: results from ALICE & CMS consistent with us, complimentary to TOTEM results
- Extrapolation uncertainty on measurement will decrease as diffractive component is better understood

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P. Bruni and G. Ingelman, Phys. Lett. B311 (1993) 317.

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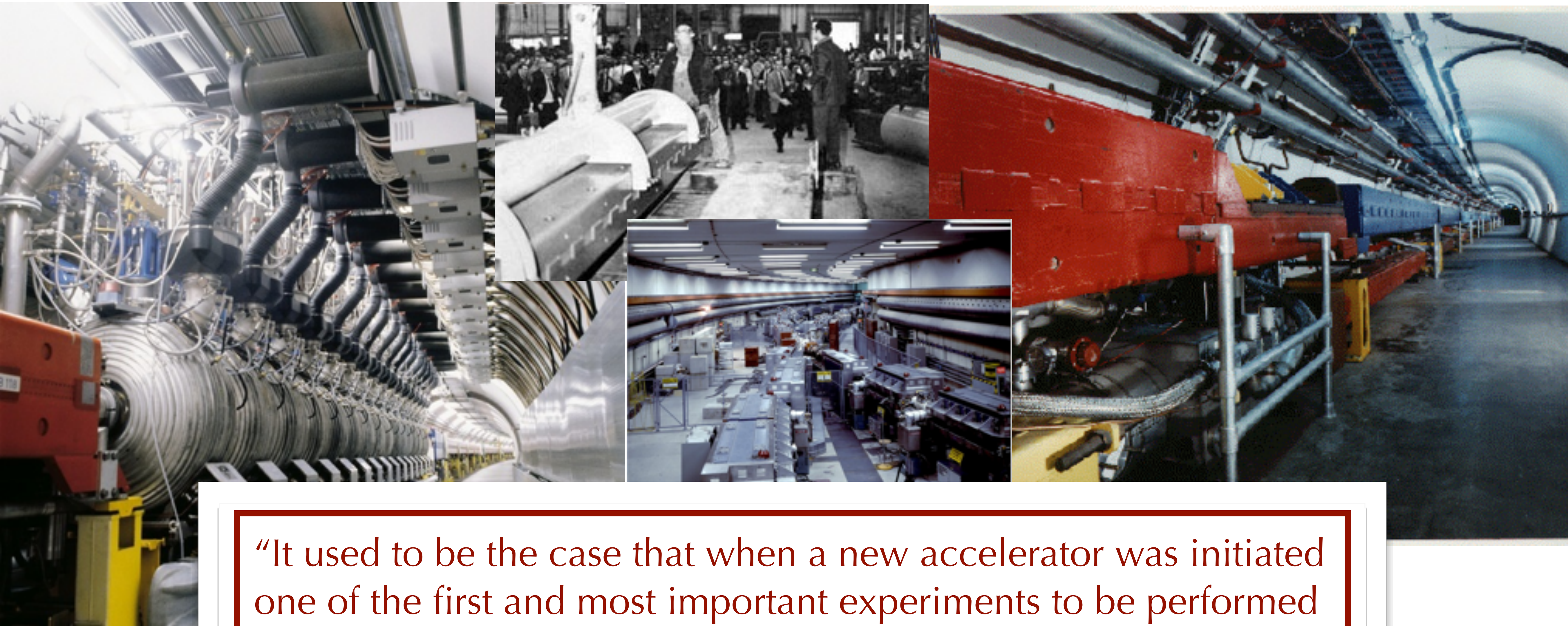
E. Gotsman, E. Levin, U. Maor, J. S. Miller, Eur. Phys. J. C**57** (2008) 689-709; E. Gotsman, E. Levin, U. Maor, arXiv:1010.5323.

Additional Slides

Why Measure the pp cross-



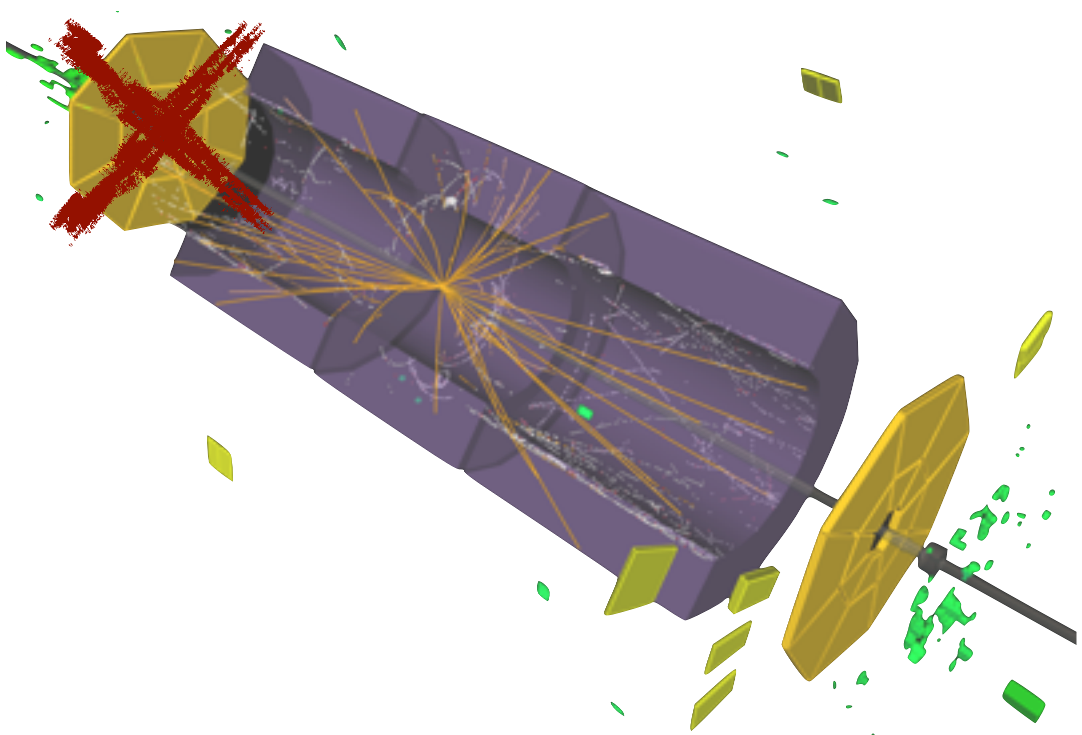
"It used to be the case that when a new accelerator was initiated one of the first and most important experiments to be performed was the measurement of the total p-p cross section. Nowadays, this experiment is regarded with little interest, even though the explanation of Regge behavior remains an interesting, unsolved and complicated problem for QCD."

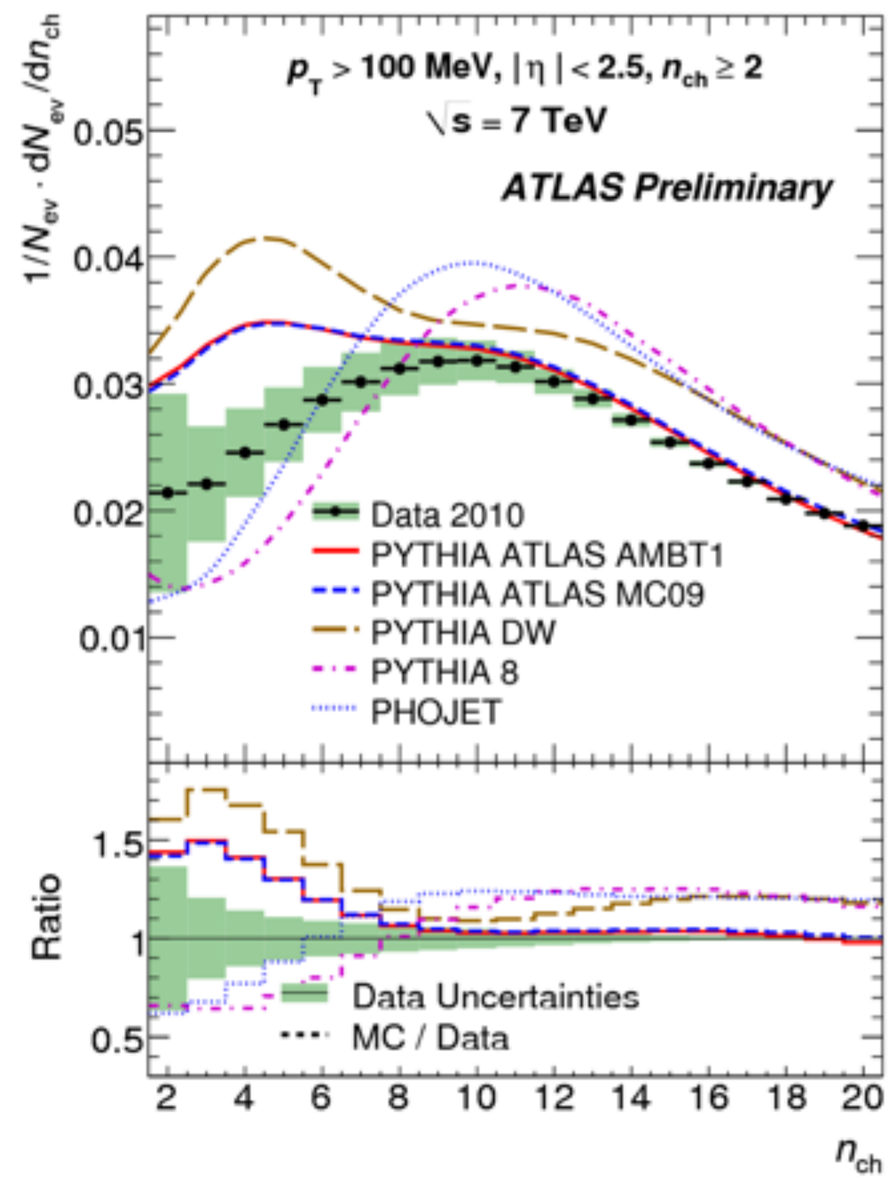
-David Gross, 1998, 25th Anniversary of the discovery of Asymptotic Freedom

Creating a diffraction enhanced

- Diffractive processes make MC tuning difficult

- To study kinematics look at tracks in the single-sided event sample

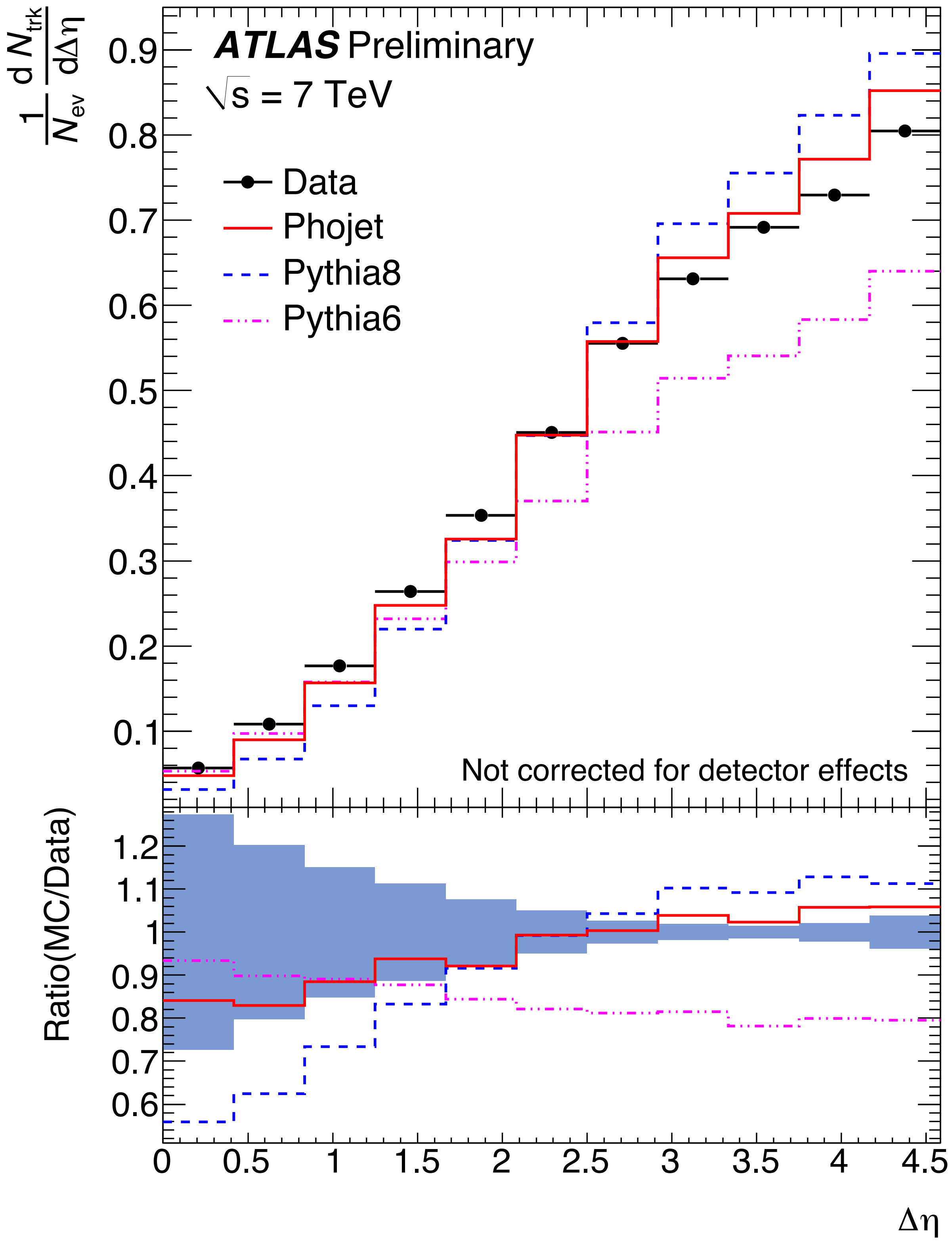


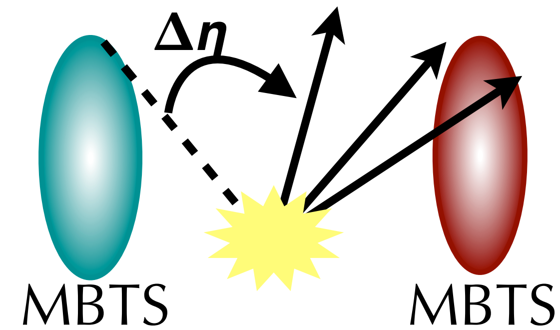


- For ICHEP used tracks with p_T > 500 MeV
  - No detector corrections

ATLAS-CONF-2010-048

Rapidity Gaps





- $\Delta\eta = |\eta_{MBTS} - \eta_{trk}|$ is sensitive to gap structure
- Phojet shows best agreement
  - Favors dominantly SD contributions
- Pythia 6 worst overall agreement, Pythia 8 favors high $\Delta\eta$

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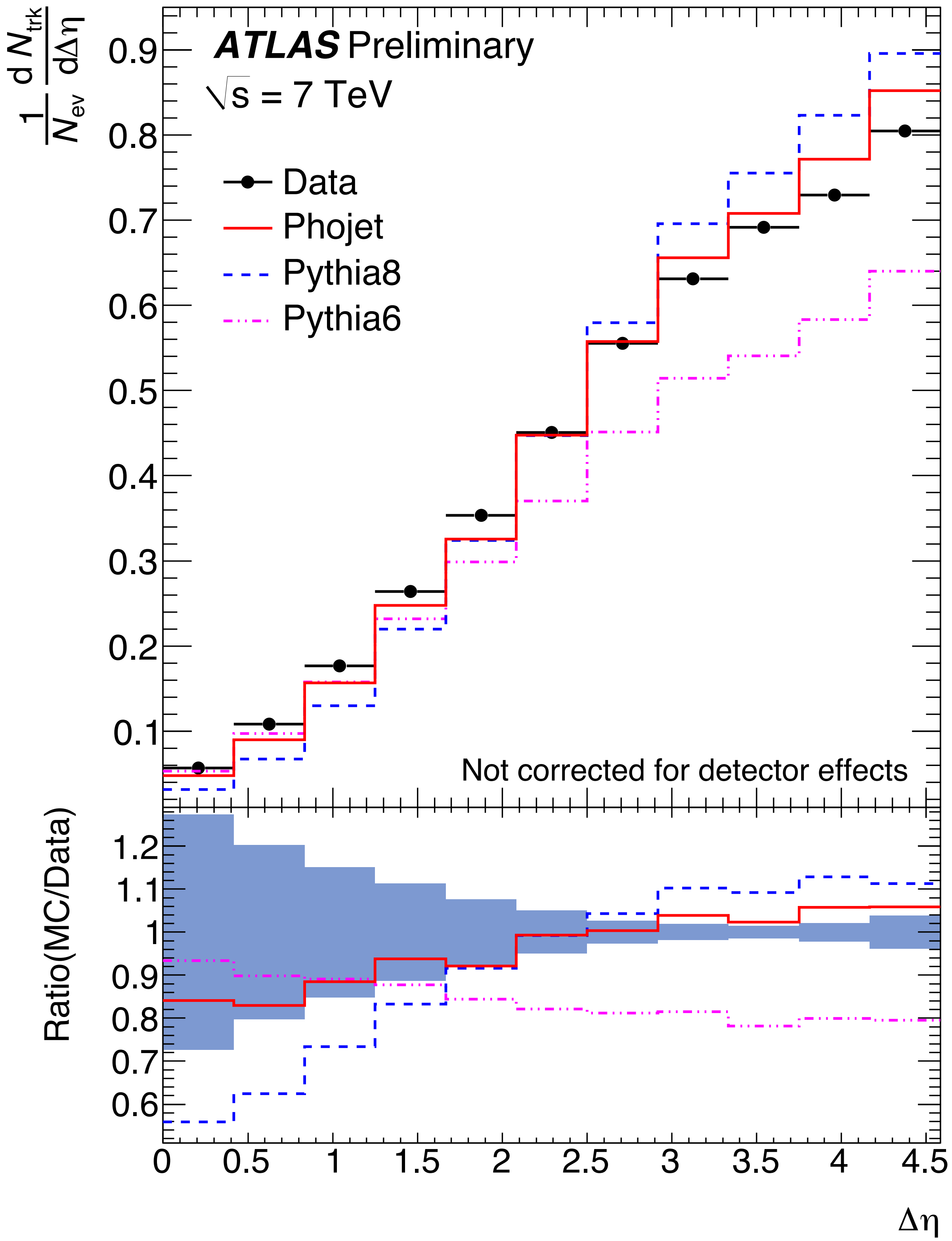

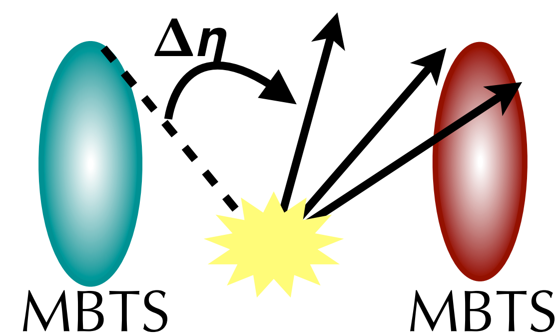

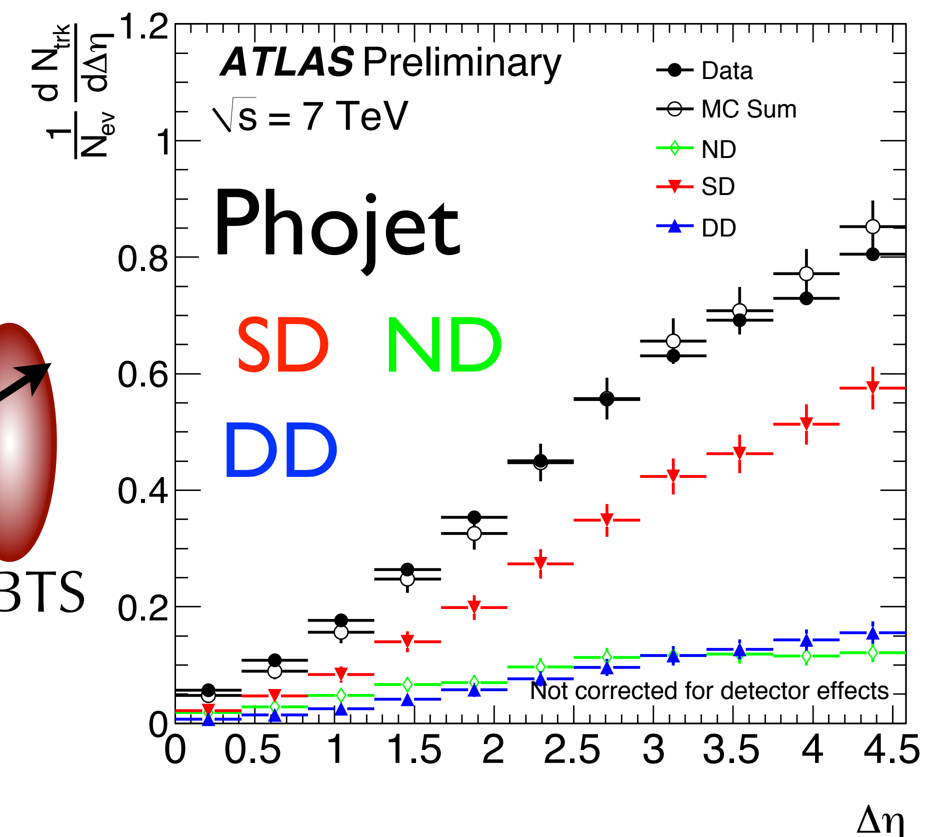

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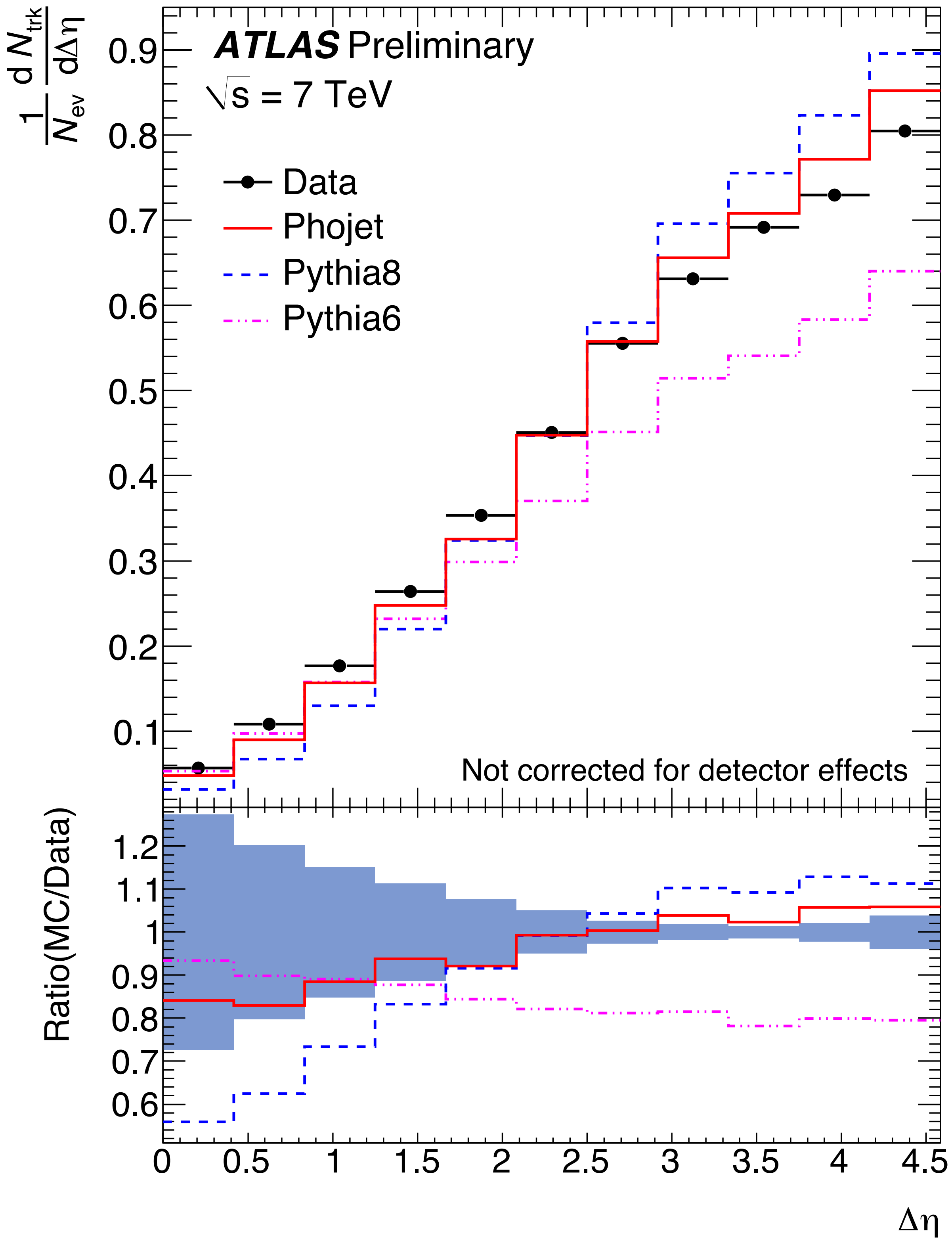

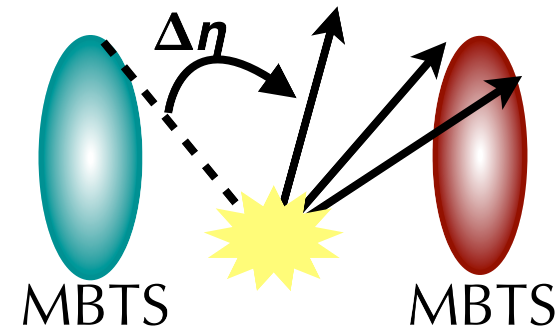

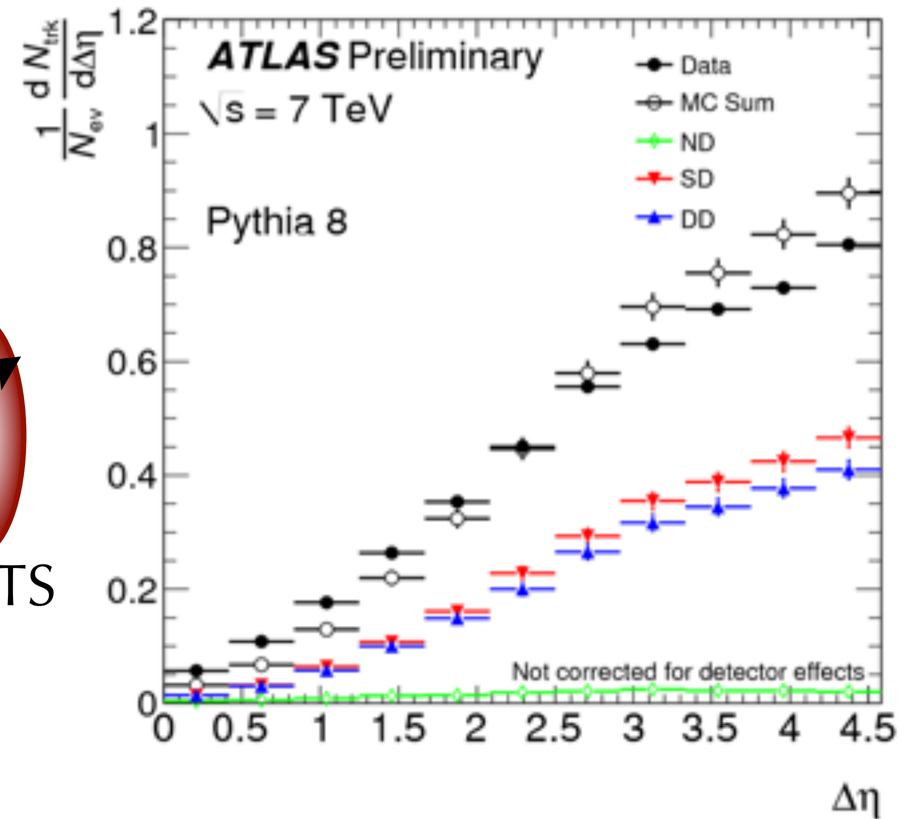

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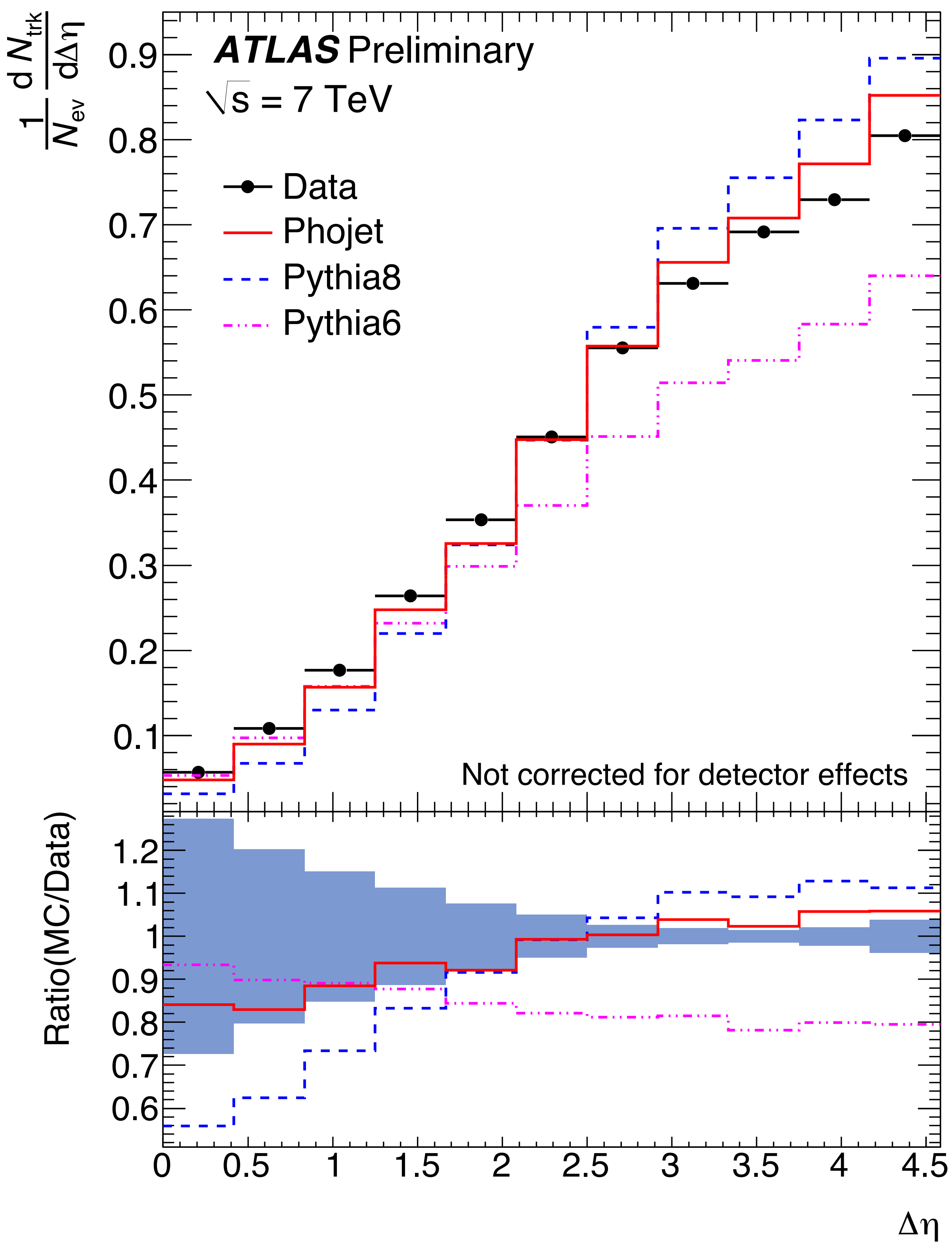

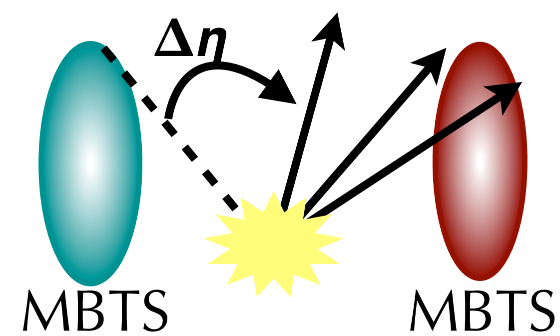

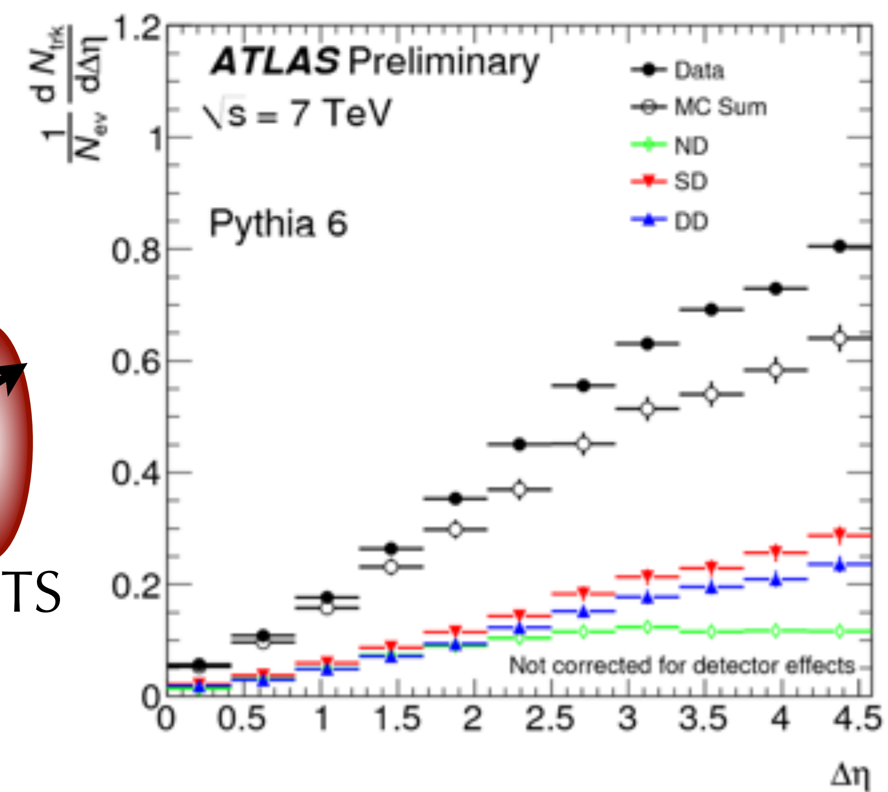

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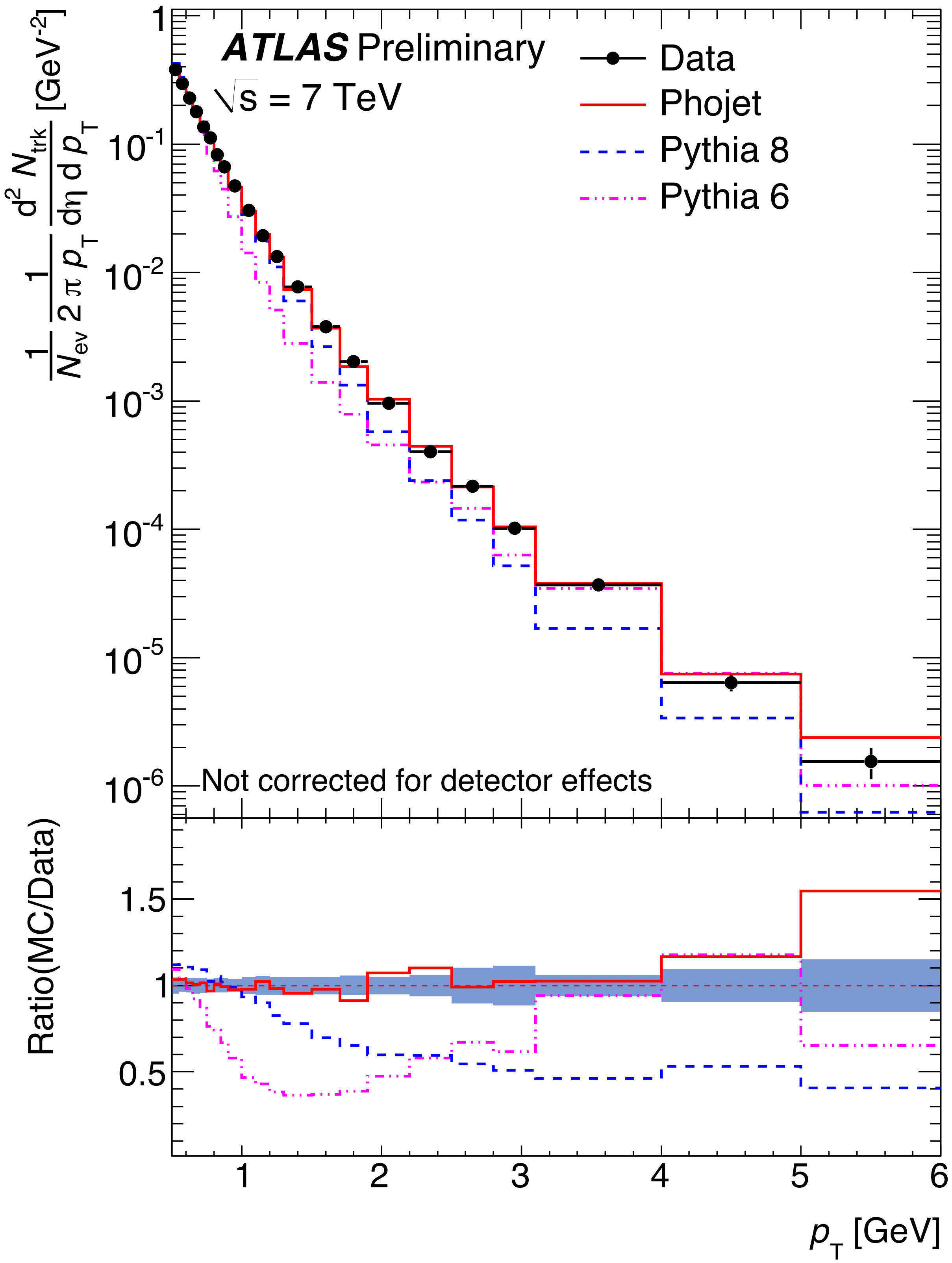
p_T Spectrum



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- Pythia 6 diffractive component very soft
  - Agrees fairly well in high p_T tail where ND component dominates

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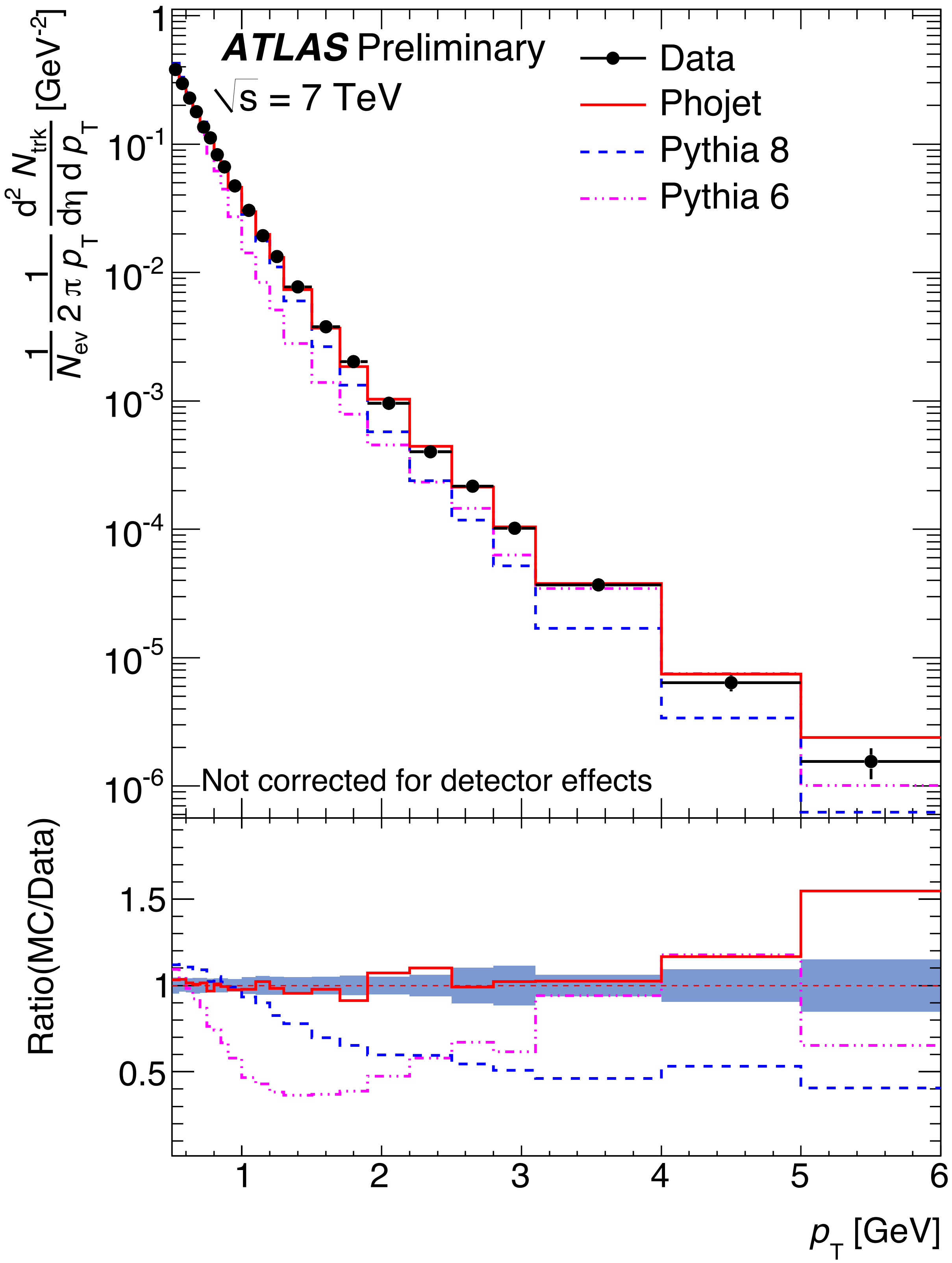

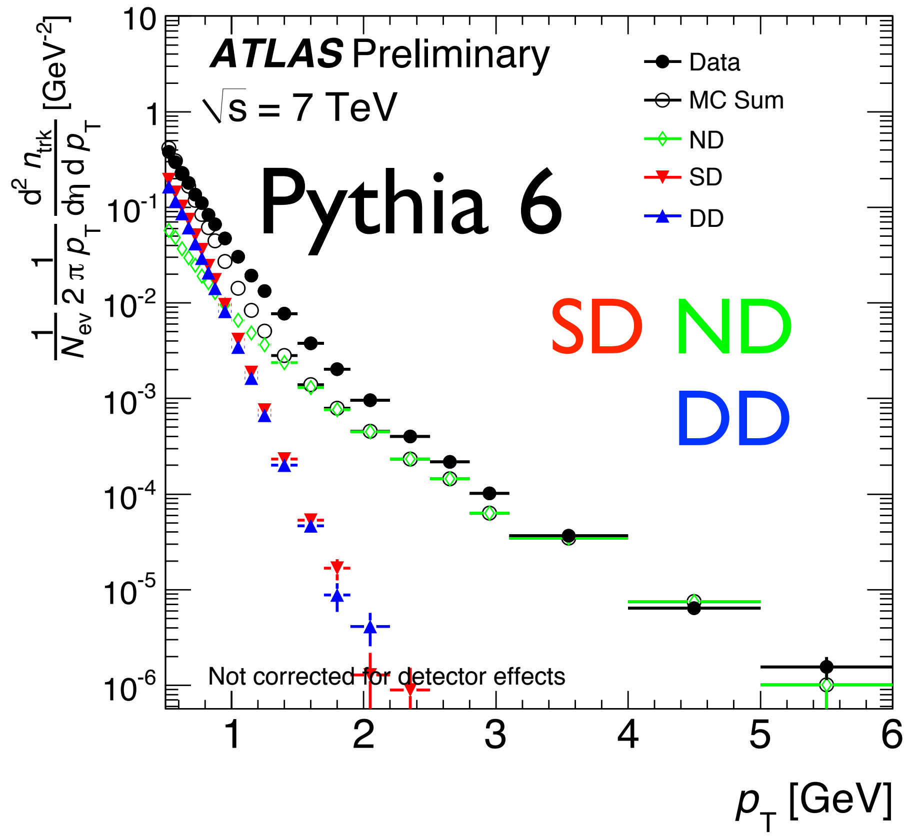

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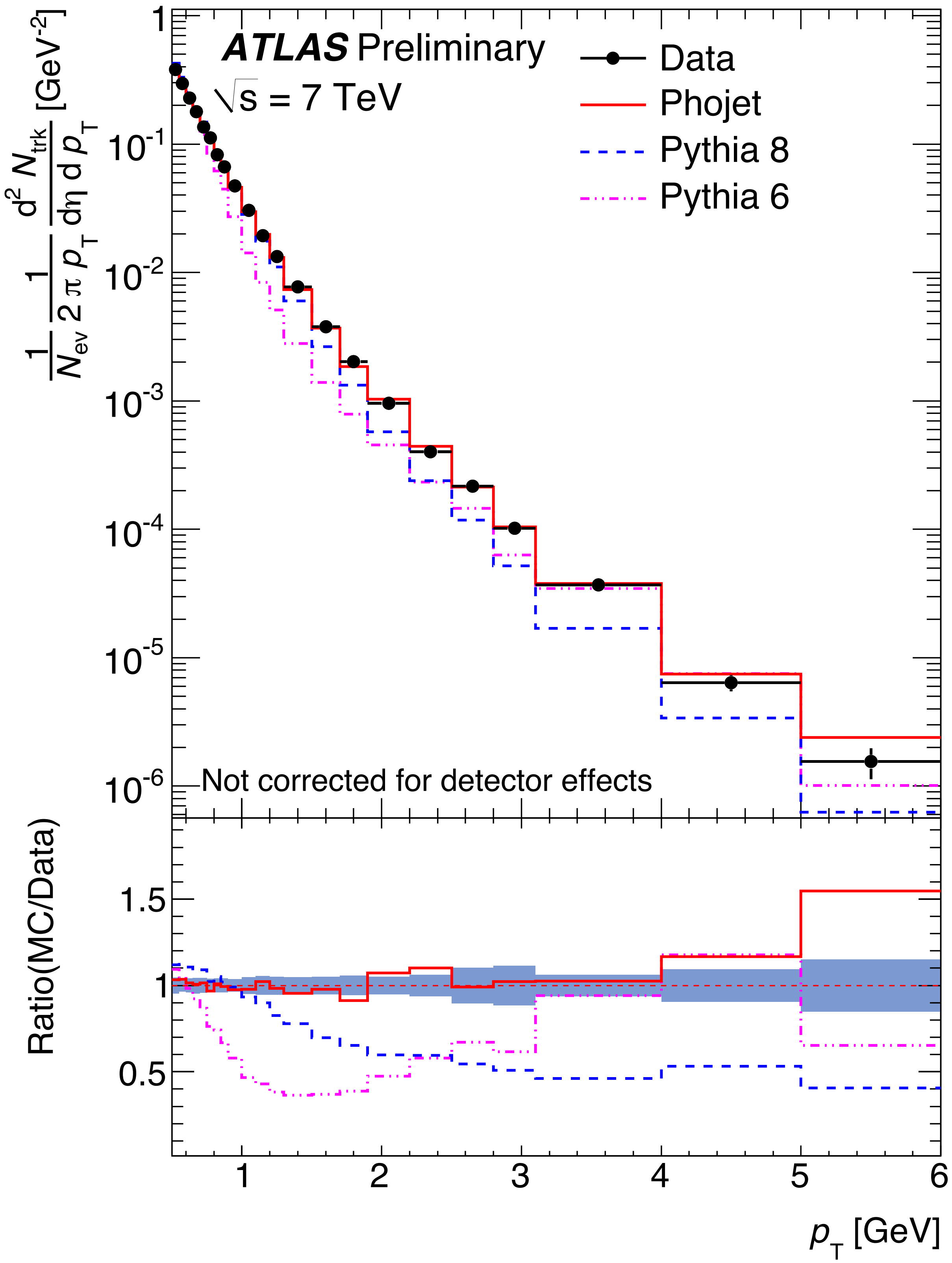

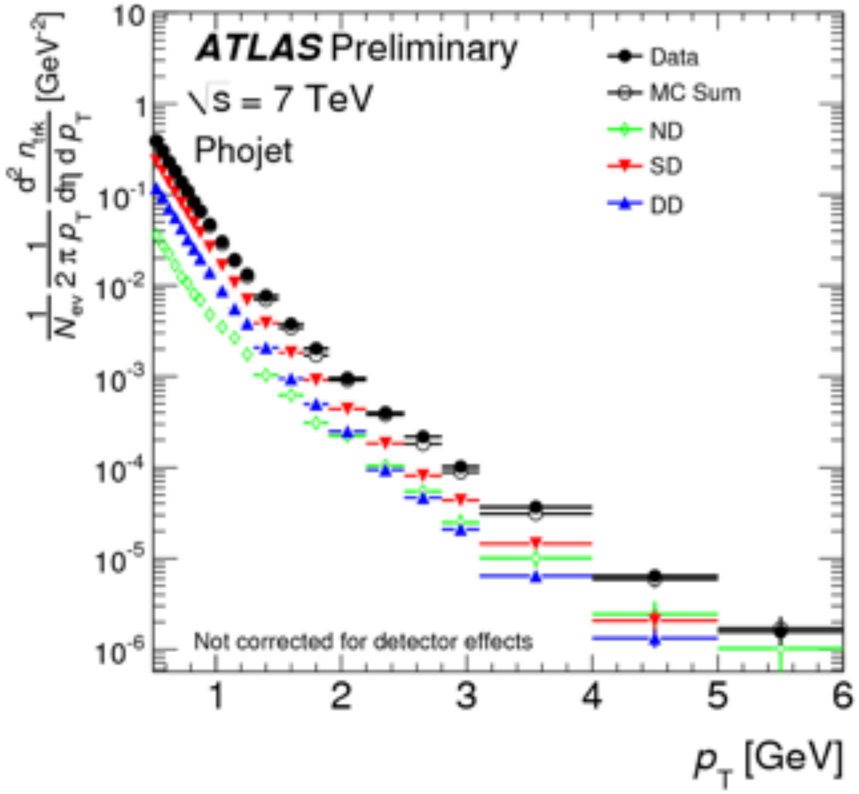

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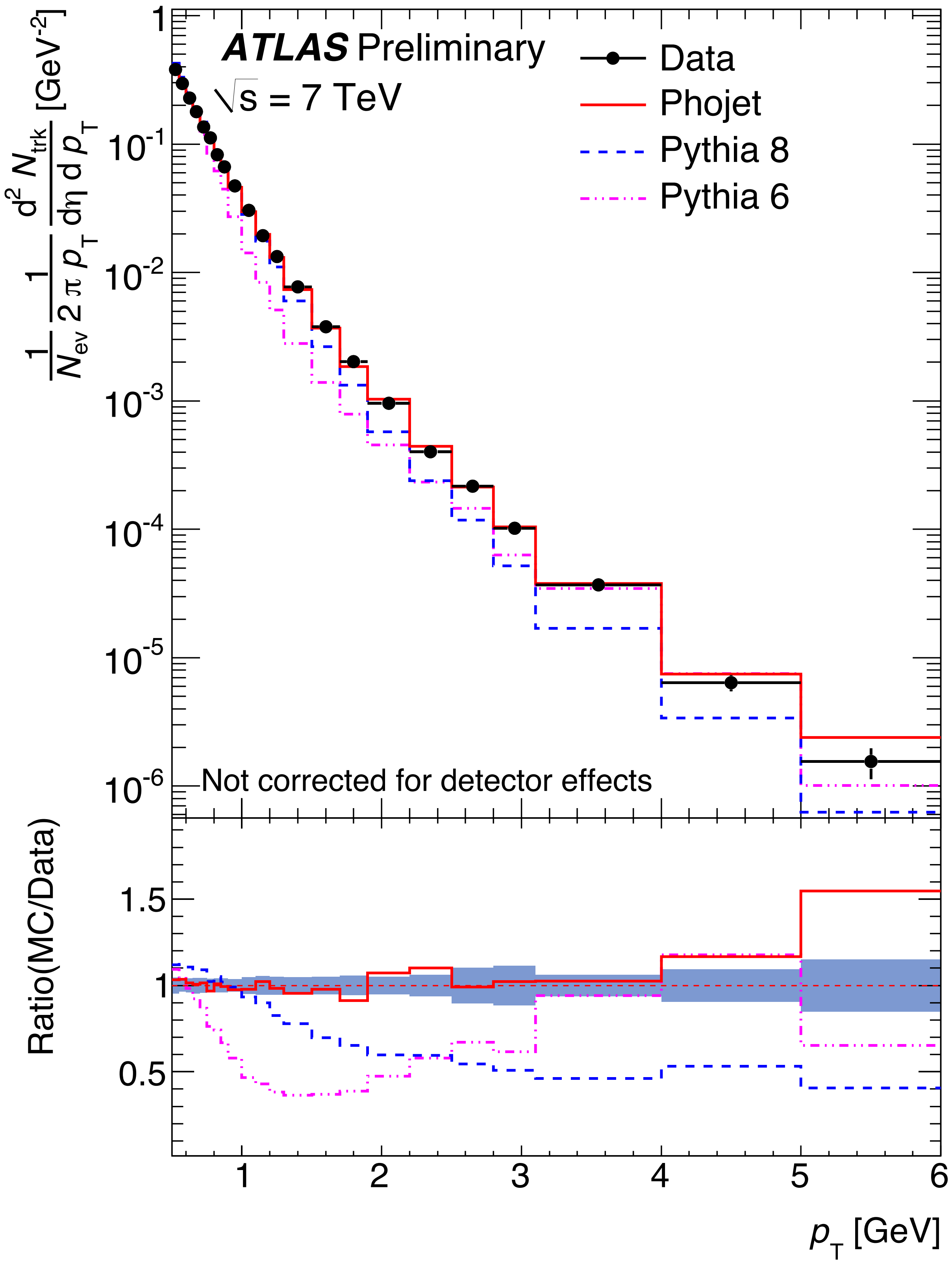

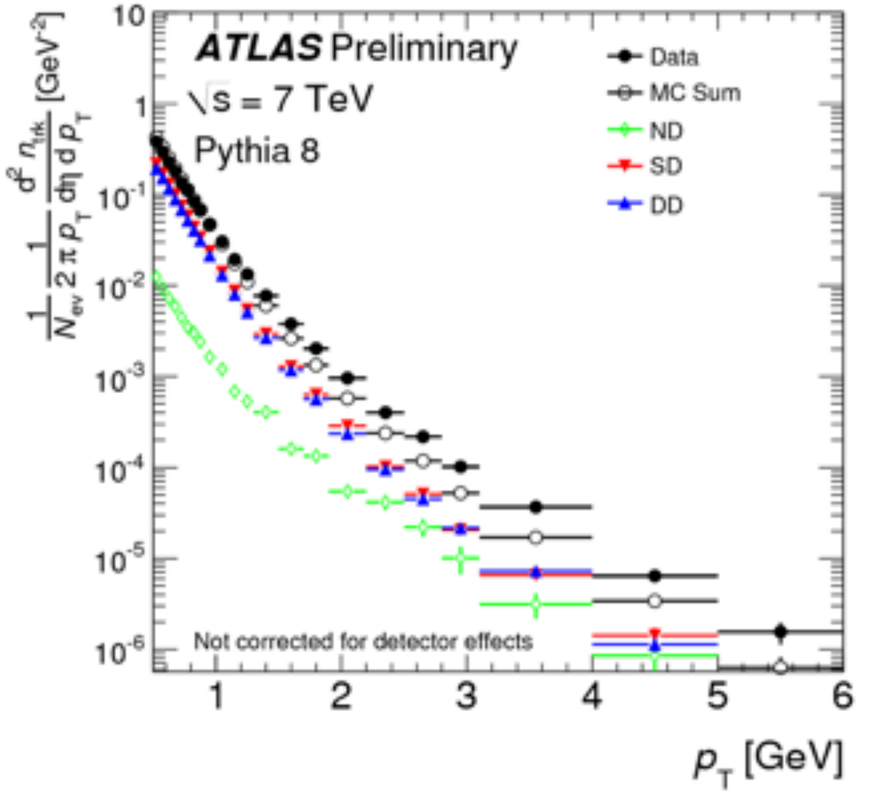

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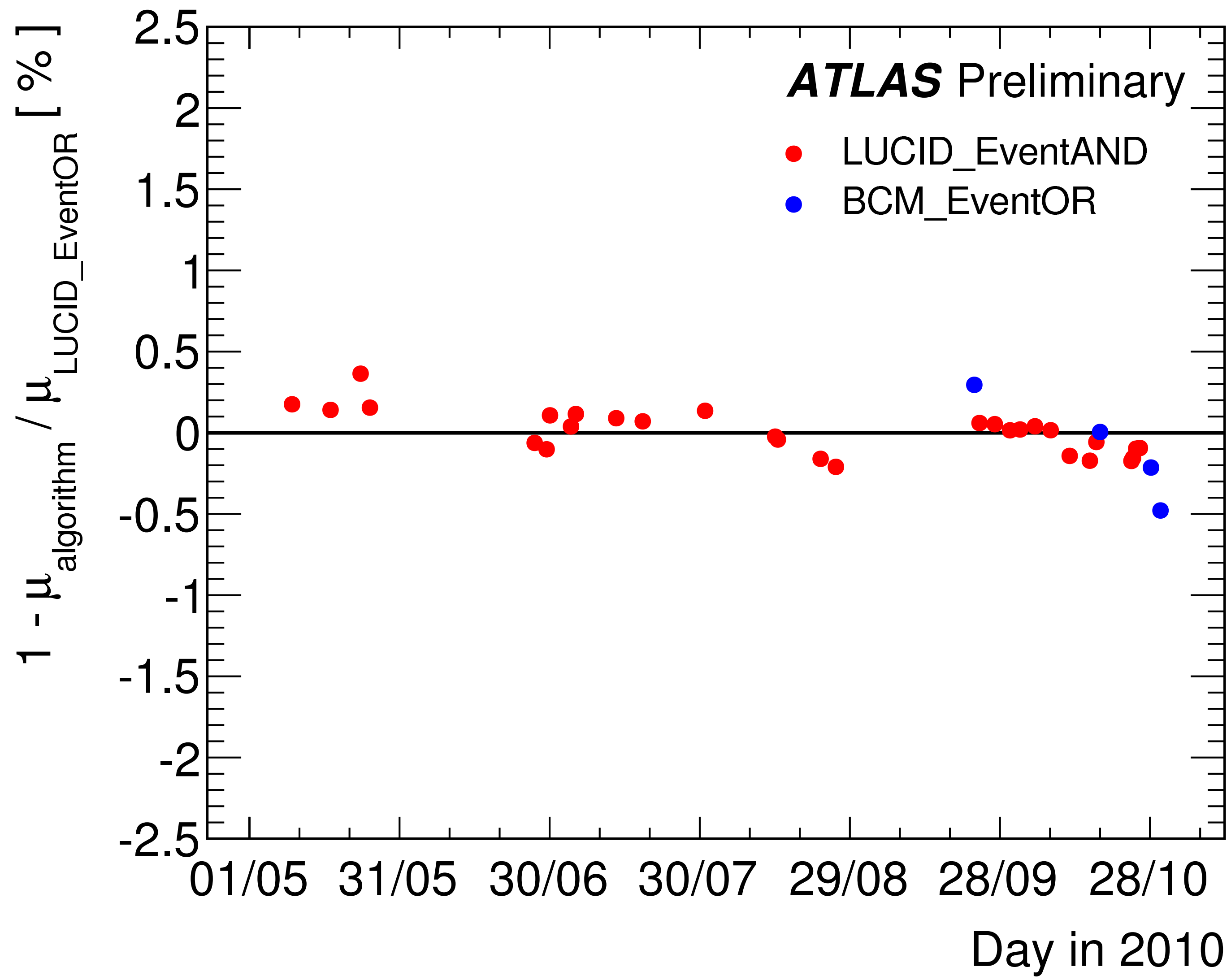
Luminosity Stability over 2010



- Variations of 0.5% or less between different luminosity determinations over full 2010 run.