# ATLAS studies of diffraction, soft particle production and double parton scattering.

## ICHEP 2012

## 6th July 2012, Melbourne

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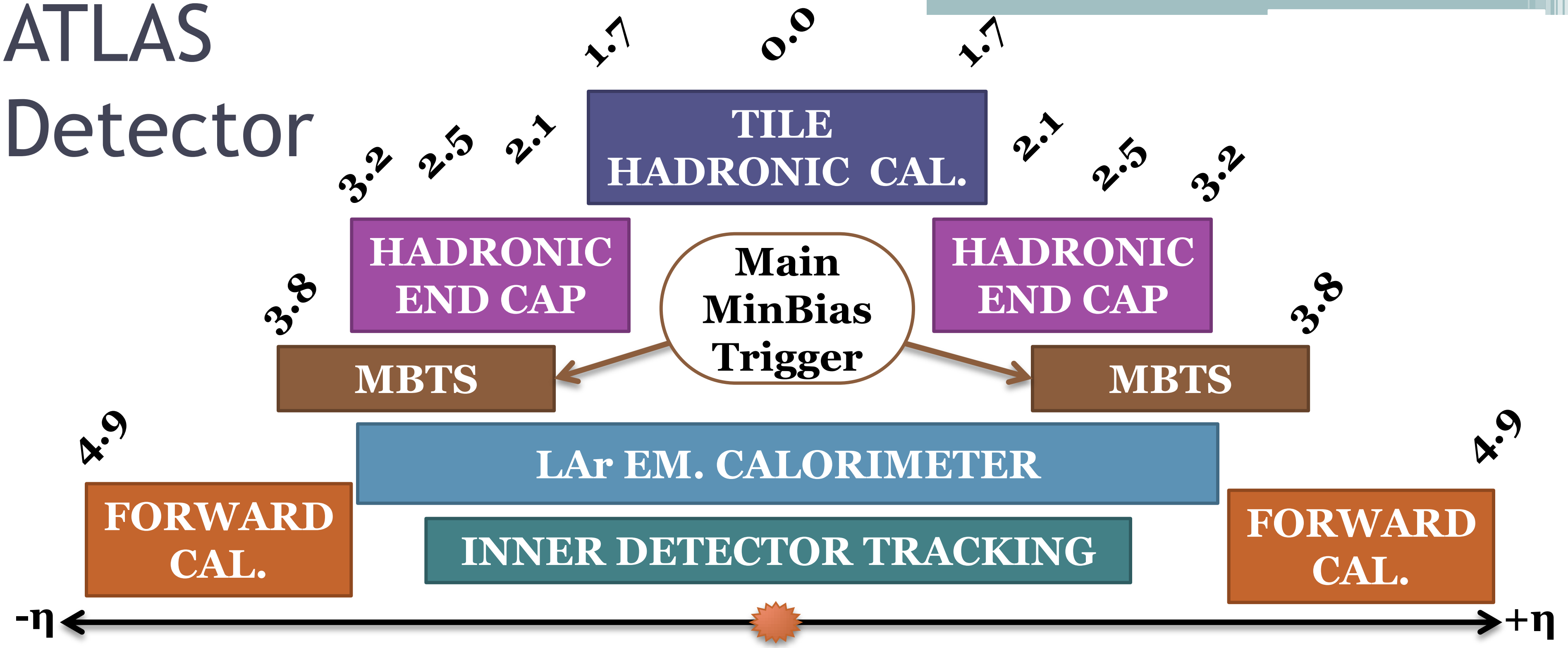
***On behalf of the ATLAS Collaboration***

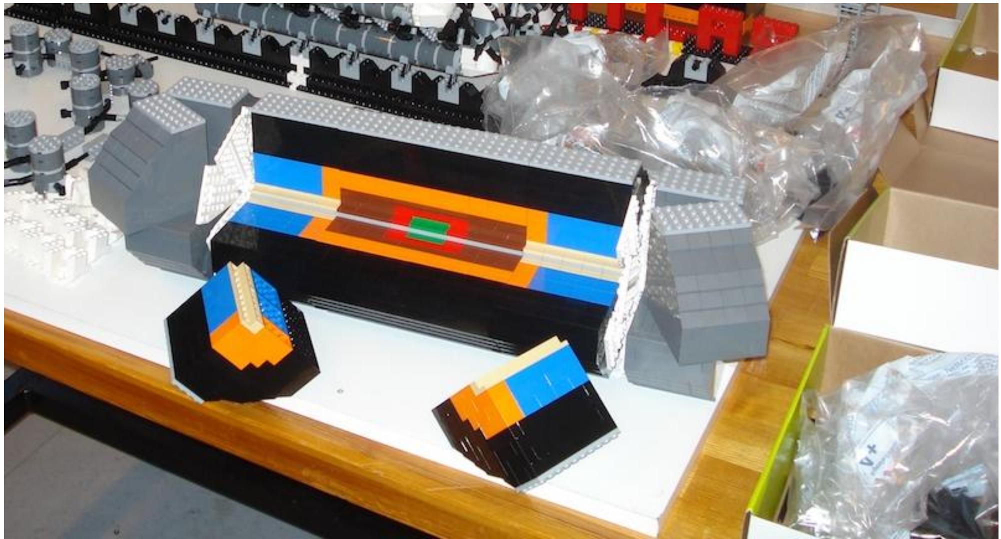
# Overview

- Inelastic & Diffractive Cross Sections
- Forward-Backward Correlations
- Azimuthal Correlations
- Track Jet Underlying Event — NeW!
- Transverse Energy Flow — NeW!
- Event Shapes — NeW!
- Double Parton Interactions in $W \rightarrow l\nu + 2$ jet
- Azimuthal Ordering
- $\Lambda$ Properties & Two Particle Correlations

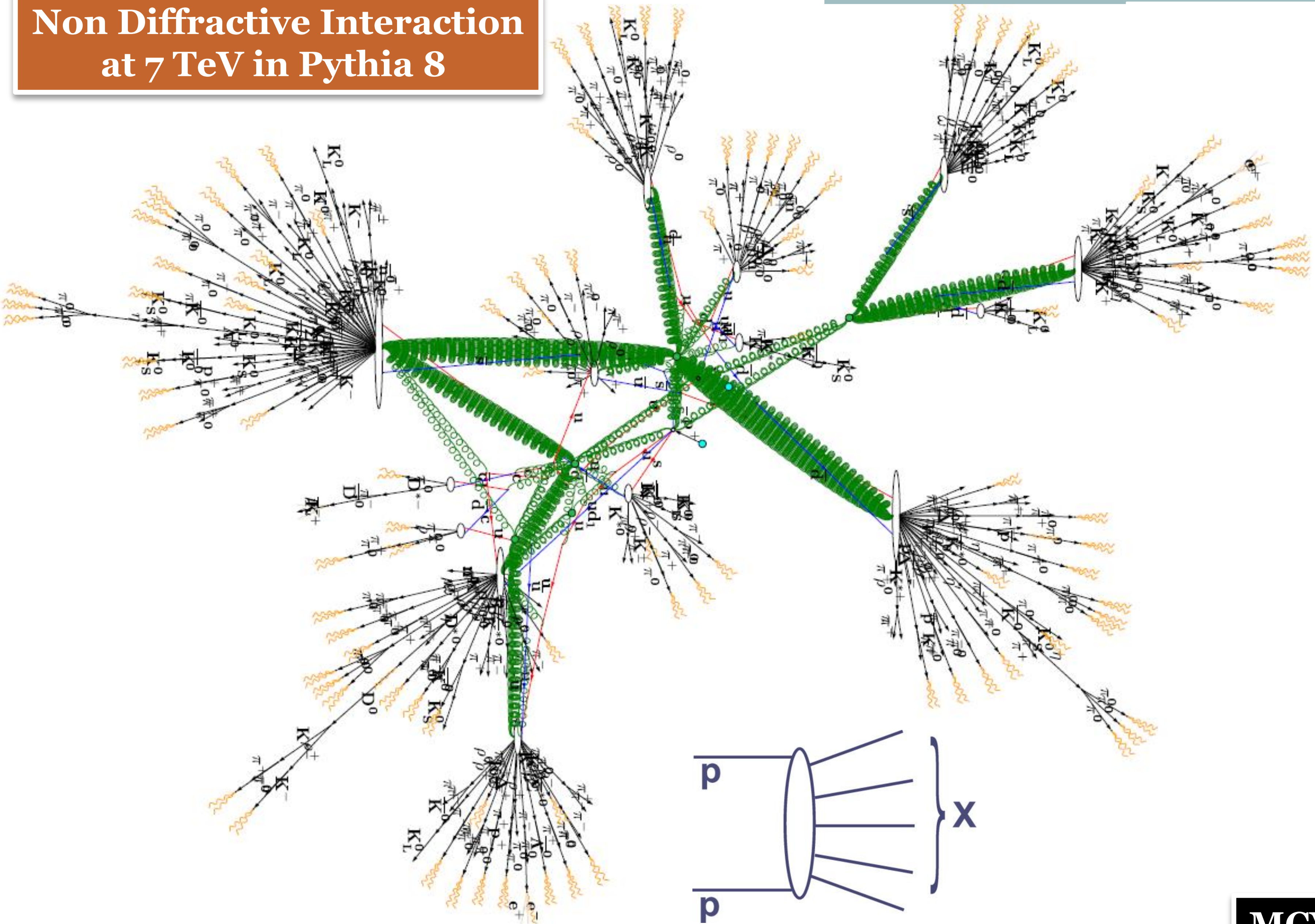
# ATLAS Detector



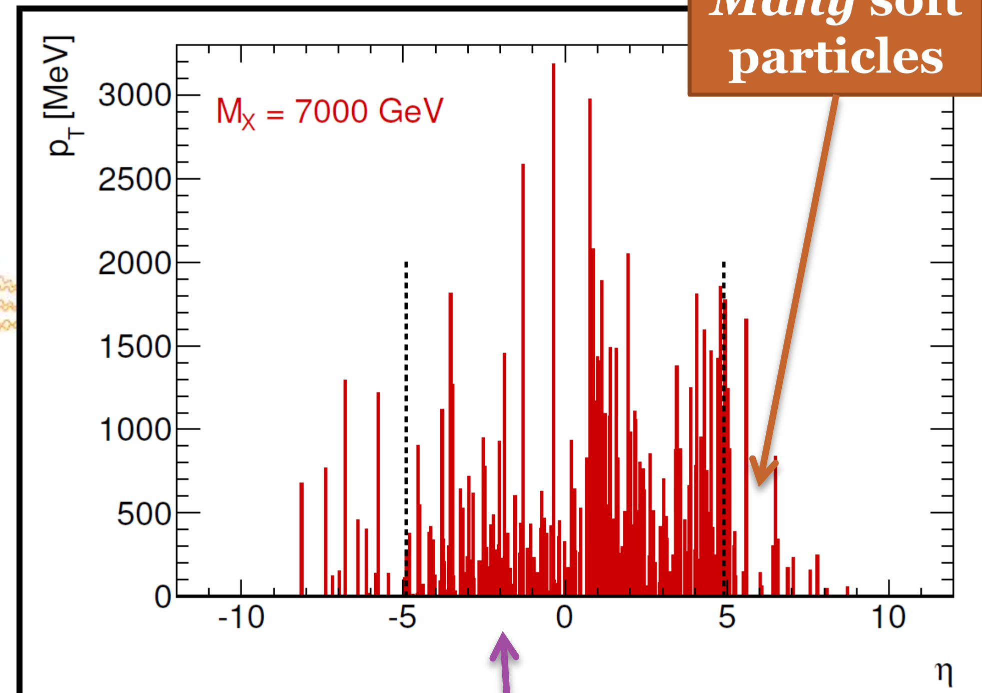

**Following analyses use a combination of Inner Detector Tracking and ATLAS calorimetry.**

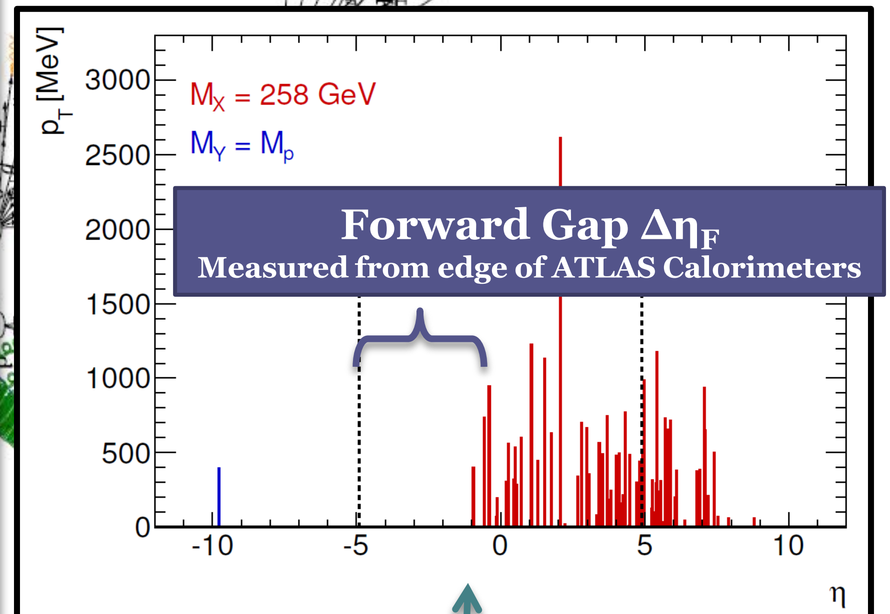


# Non Diffractive Interaction at 7 TeV in Pythia 8




MCViz




**~75% of all inelastic interactions at the LHC are non-diffractive.**

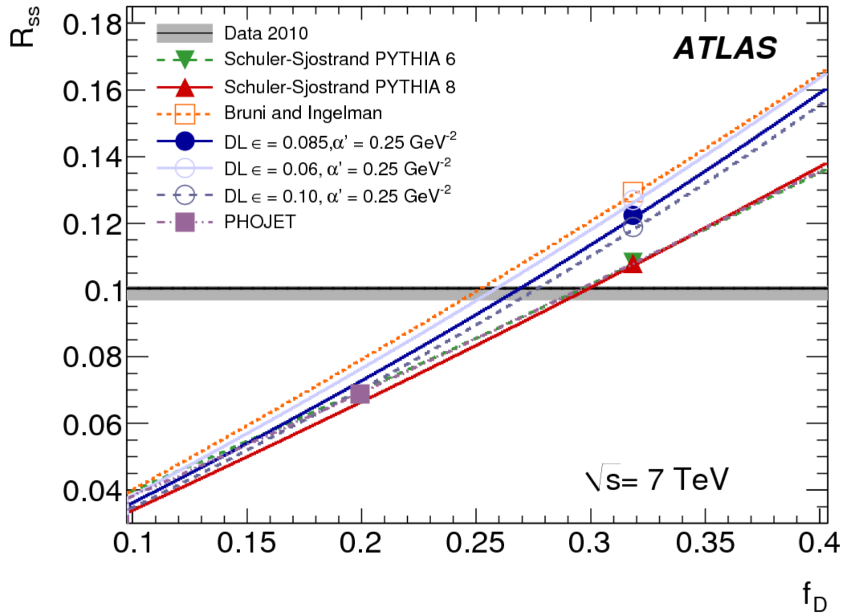
**~25% of the time the inelastic interaction is *diffractive* which can result in a characteristic rapidity gap.**

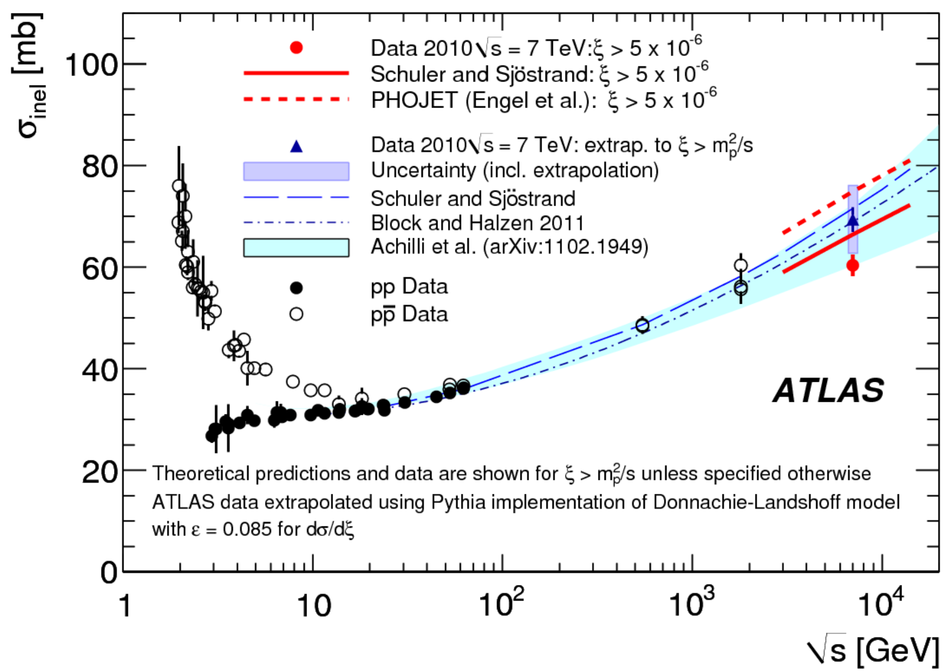
# $\sigma_{Inelastic}$

- **Inelastic *pp* cross section** measured over acceptance of **ATLAS Minimum Bias Trigger Scintillators**.

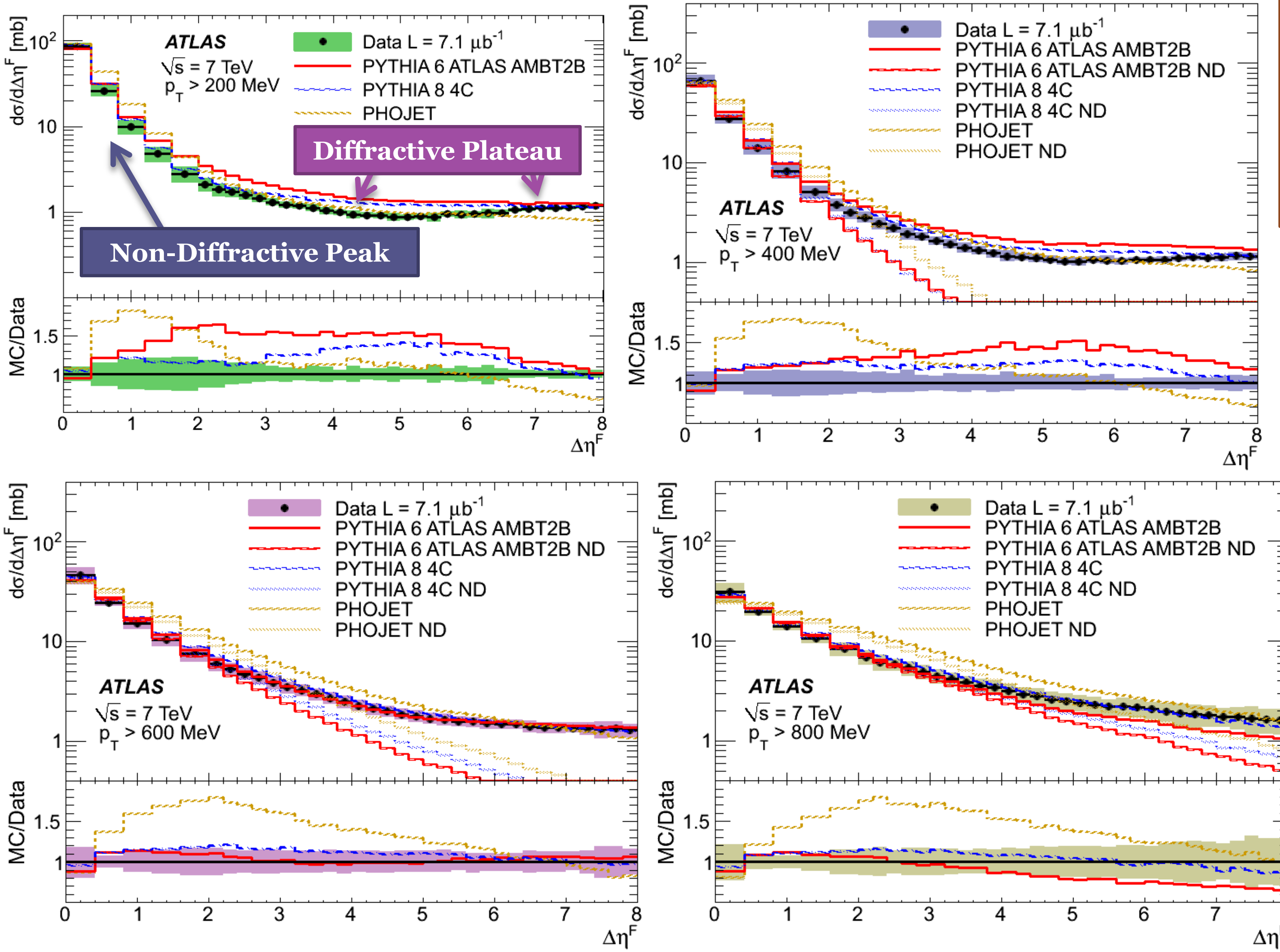
$$\sigma_{inel.} = 69.4 \pm 2.4(exp.) \pm 6.9(extrap.)$$

- **MC model uncertainty** dominates **extrapolation to full phase space**.
- Also measured the ratio of **exclusively single sided MBTS** triggered events.
- Sensitive to the magnitude of the **diffractive component**.



# $\sigma_{Inelas.}$ as a function of $\Delta\eta^F$



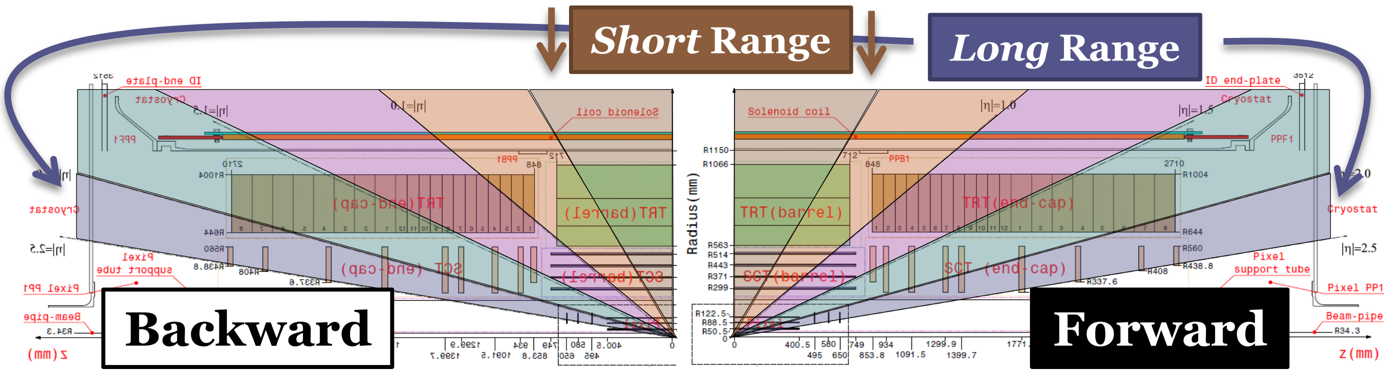

$\Delta\eta_F$ = largest, empty $\eta$ interval from edge of detector at $\eta=\pm4.9$

Corrected to charged & neutral particles $p_T$ > 200, 400, 600 & 800 MeV

Bayesian unfolding technique

# Particle Correlations

- **Forward-Backward** multiplicity and $p_T$ correlations in $\eta$.




Deviation of fwd(bkwd) multiplicities from their mean.

Sum over events

$$\rho^n_{fb} = \frac{\sum x^n_f x^n_b}{N \sigma^n_f \sigma^n_b}$$

N Events

Standard deviation of fwd(bkwd) distributions about their mean.

**$\rho^n_{fb}$ = in a forward-backward $\eta$ region is the normalised covariance between the two distributions, relative to the mean value of each.**

Deviation of fwd(bkwd) scalar $p_T$ sum of all accepted tracks from their mean.

$$\rho^{p_T}_{fb} = \frac{\sum x^{p_T}_f x^{p_T}_b}{N \sigma^{p_T}_f \sigma^{p_T}_b}$$

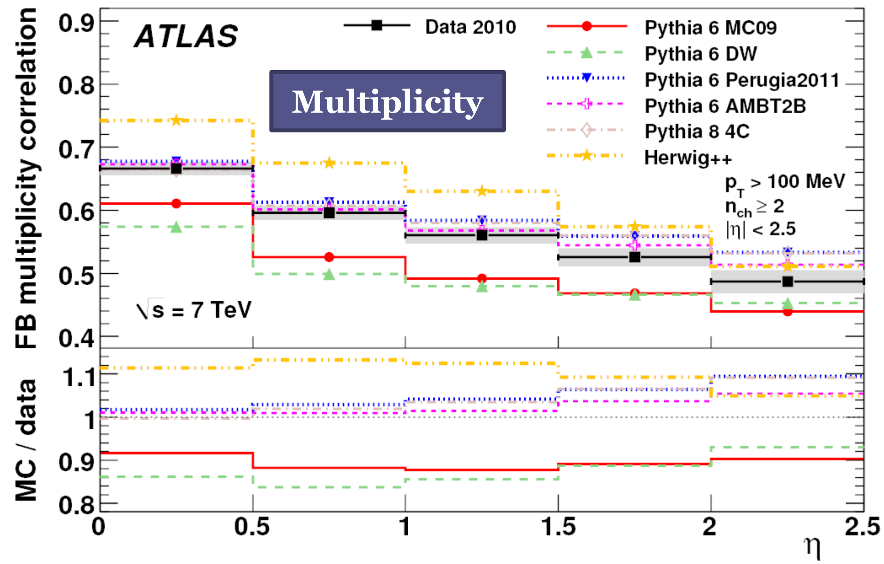
**Detector level distributions are corrected to the hadron level using linear regression technique with different MC models.**

$$\rho_{had} = \alpha + \beta\rho_{det}$$

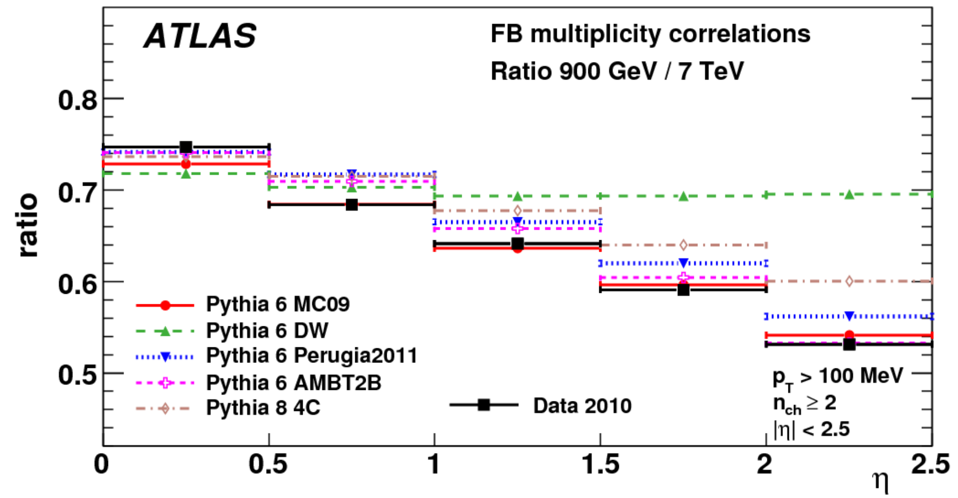
**Trigger & Vertex Eff. : $\alpha = 0.07 \pm 0.03$**

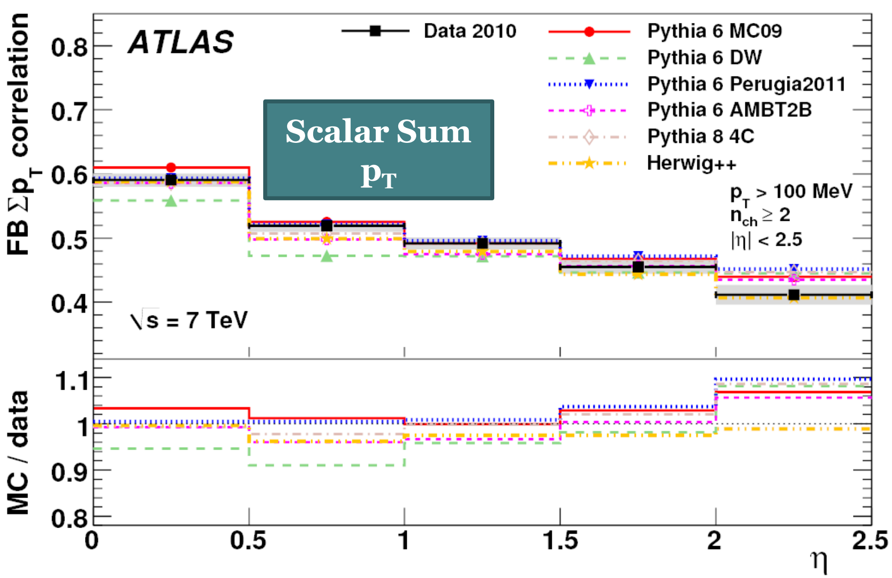
**Track Reconstruction Eff. : $\beta = 0.96\text{-}0.97$**

# Results for $\rho^{n}_{fb}$ & $\rho^{p_T}_{fb}$

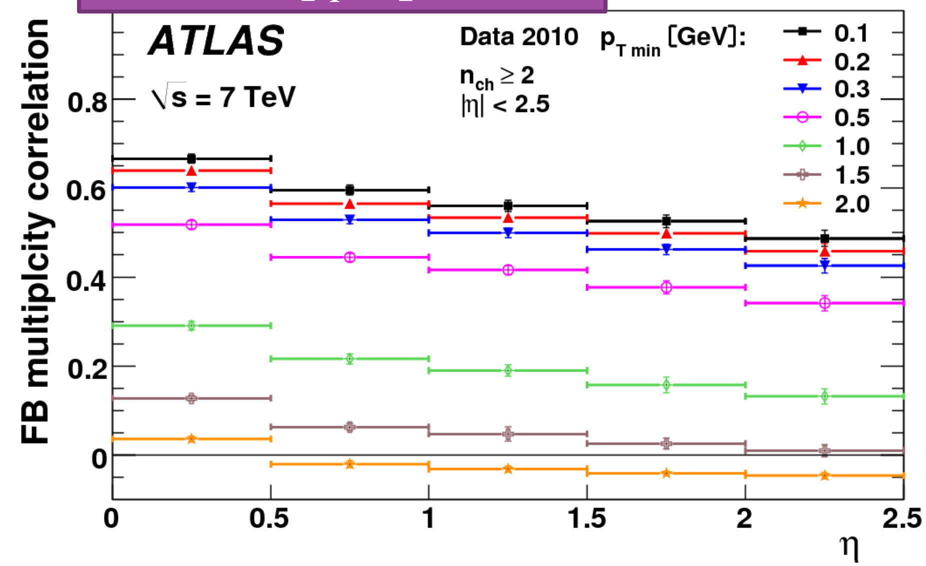



Centre of mass dependence



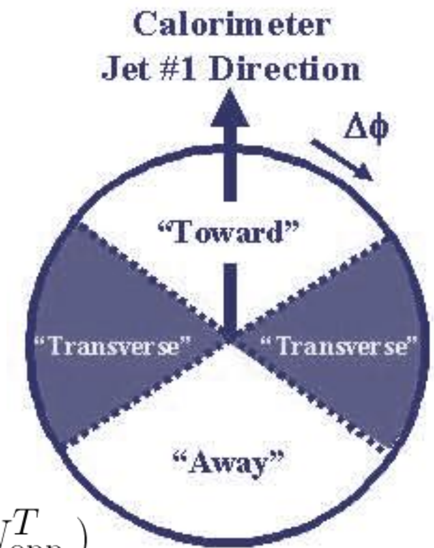



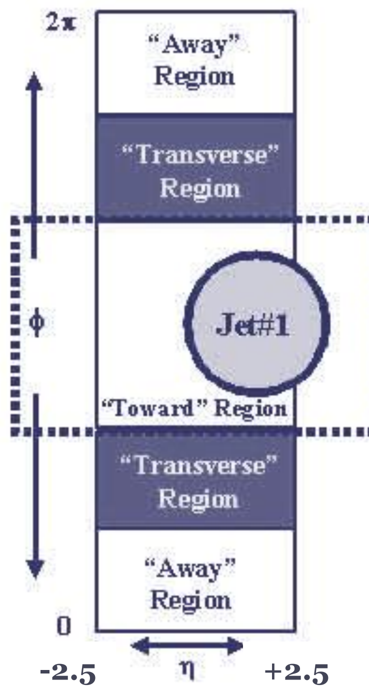

Minimum $p_T$ dependence



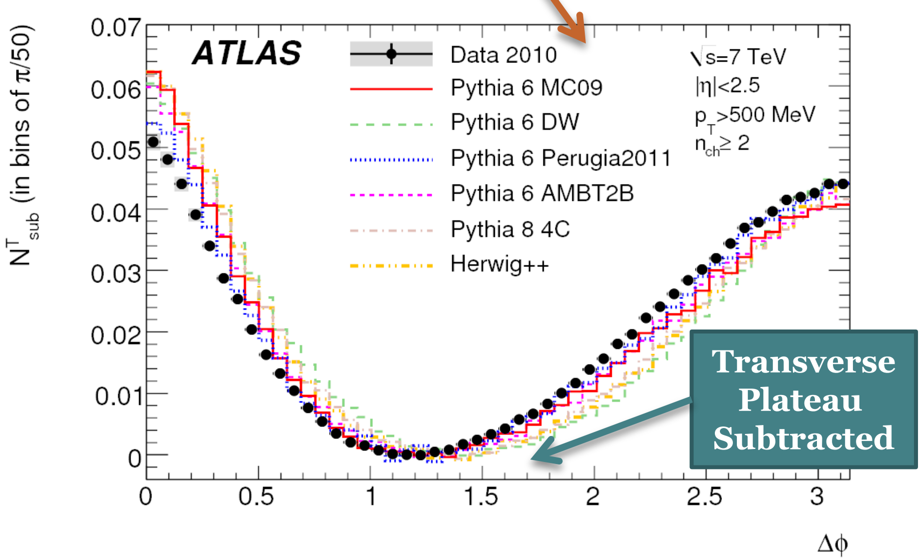
# Azimuthal Correlations

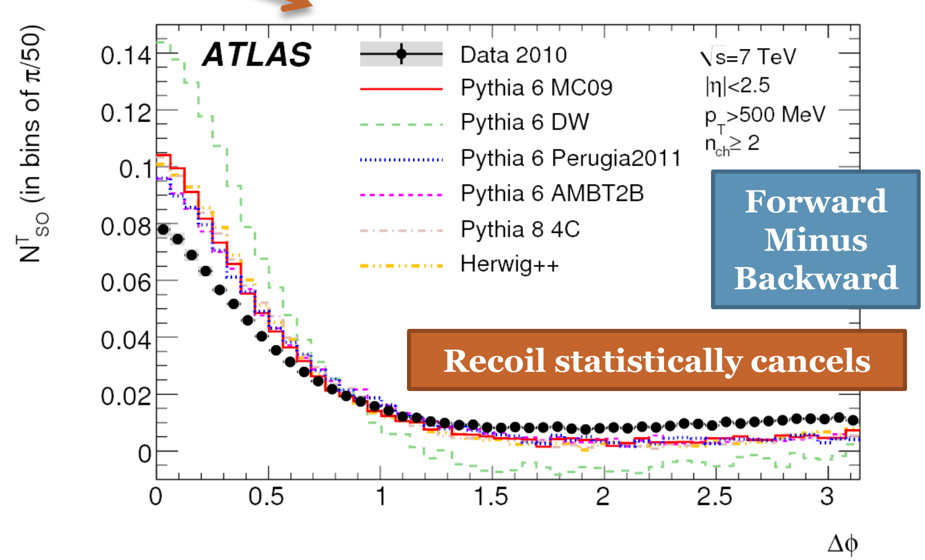
- Investigated as a function of η **region** and **fwd/bkwd correlation**.
- Primarily looking at the `**toward**' region.
- **Subtract** away the `**transverse**' region plateau for **data and MC**.
- The difference **Δφ** is plotted here vs. the **leading** (highest $p_T$) **track** in the event.




$$N^T_{sub} = \frac{(N^T - N^T_{min})}{\sum_{\text{Bins}}(N^T - N^T_{min})} \qquad N^T_{SO} = \frac{(N^T_{\text{same}} - N^T_{\text{opp.}})}{\sum_{\text{Bins}}(N^T_{\text{same}} - N^T_{\text{opp.}})}$$



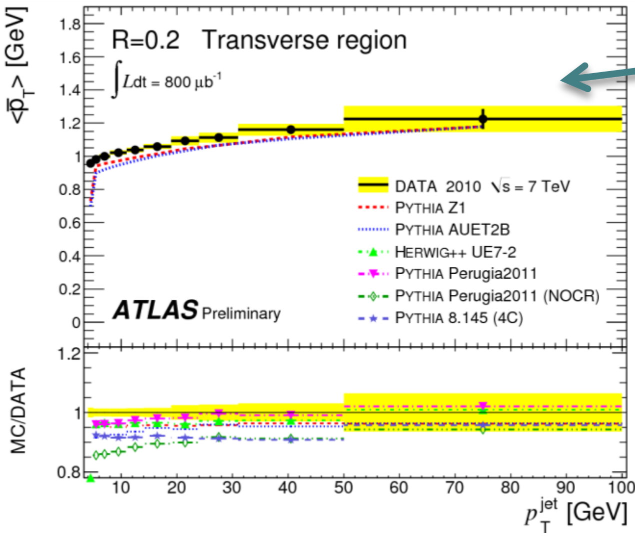



NeW!

# Track-jet Underlying Event

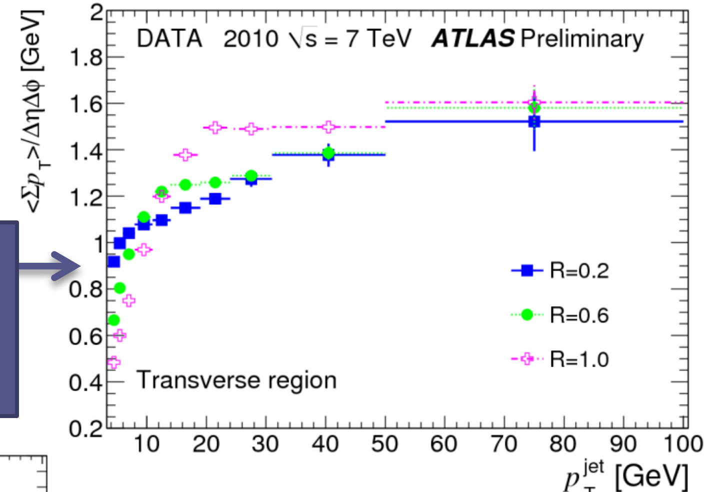
**Huge quantity of tuning data, much too much to show here.**

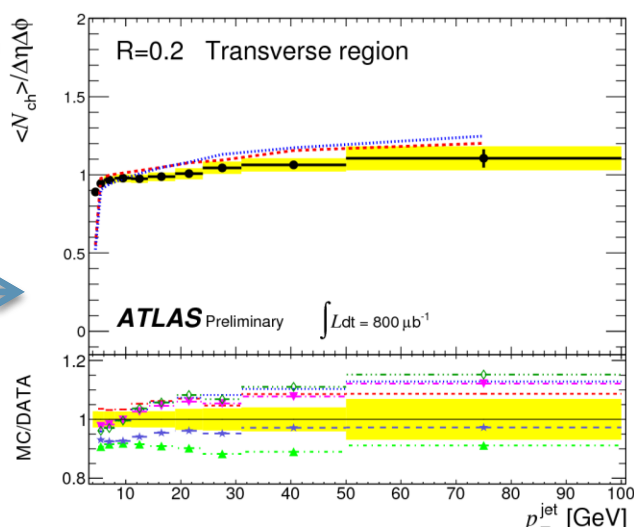
- $N_{ch}$, $\Sigma|p_T|$ and $<p_T>$. Plus as a function of $p_T^{jet}$ in the range $4 < p_T^{Jet} < 100$ GeV
- For Anti-$k_T$ Track jets with R = 0.2, 0.4, 0.6, 0.8, 1.0
- In the *Transverse* and *Away* regions.



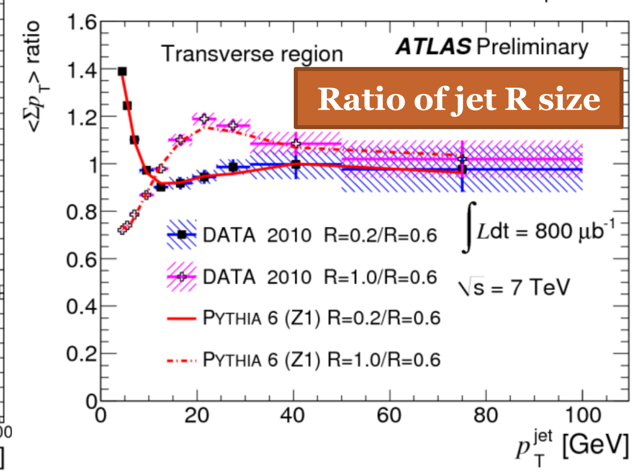

**Average of mean $p_T$ as function of $p_T^{Jet}$ for R=0.2**

**Average of Sum $p_T$ per unit ($\eta,\phi$) as function of $p_T^{Jet}$ for R=0.2-1.0**



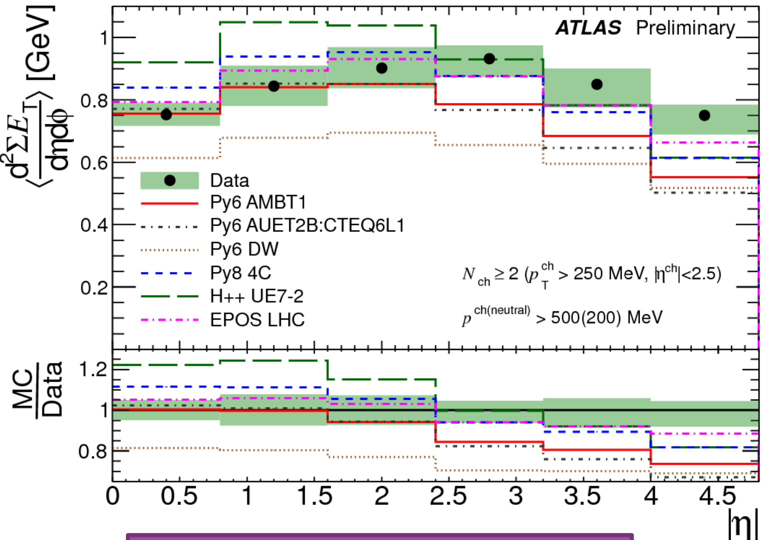

**Average of $N_{ch}$ per unit ($\eta,\phi$) as function of $p_T^{Jet}$ for R=0.2**




**Ratio of jet R size**

NeW!

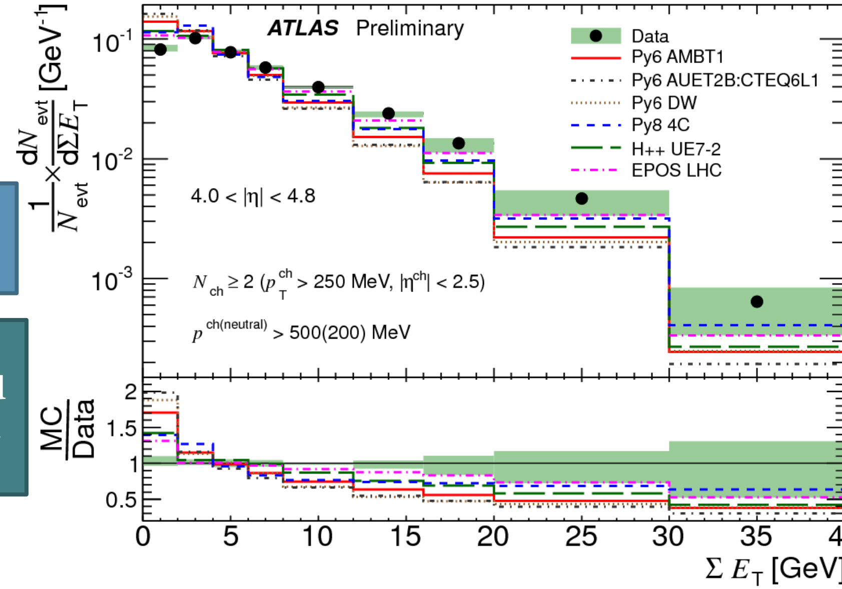
# Differential Transverse Energy Density



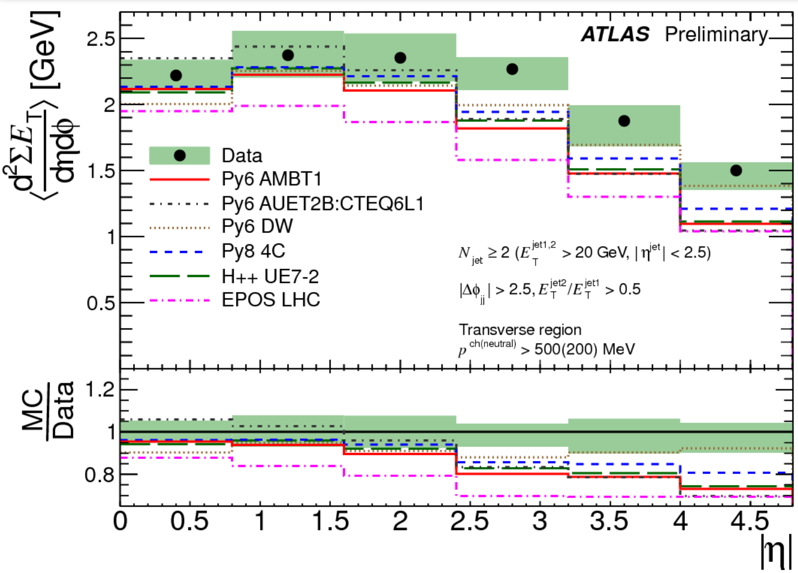

MinBias

Mid η dip from $p_T$ cuts.

Forward flow underestimated Best soft model *EPOS*

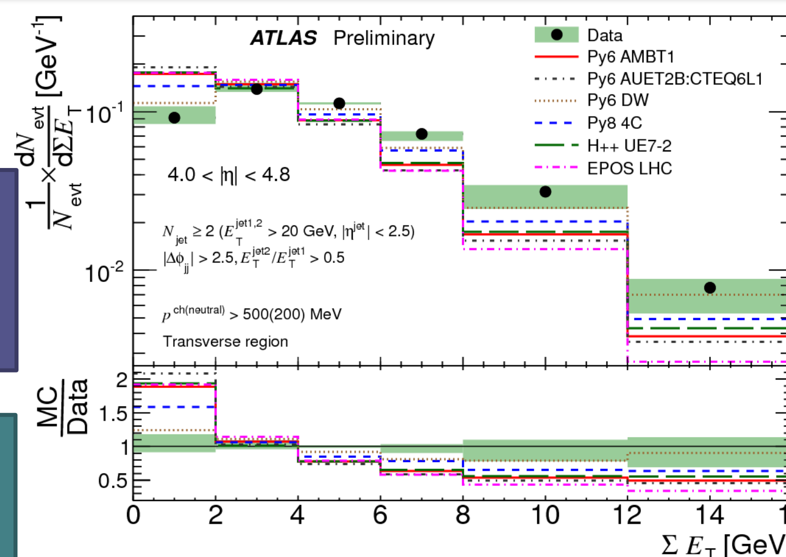



Bayesian Unfolding Technique




Underlying Event

Transverse region to di-jet system only.

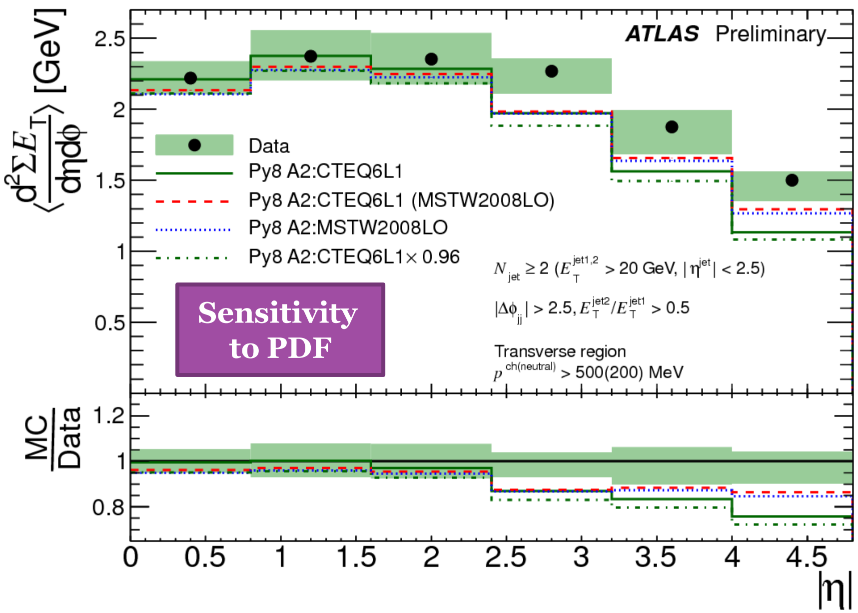


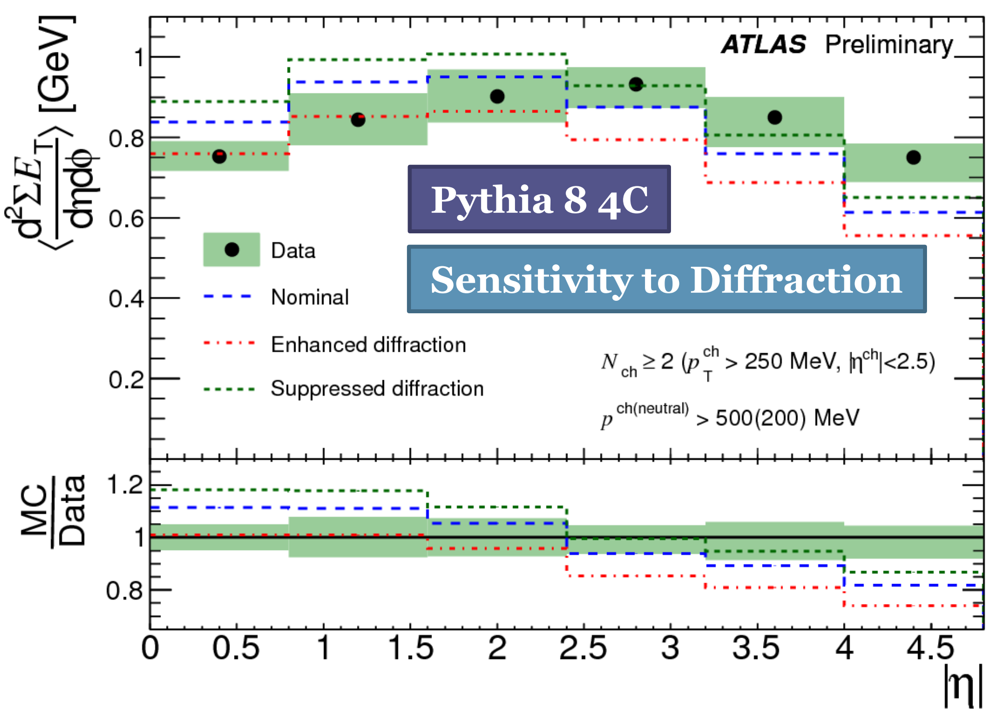

Best UE model *Pythia 6 DW*

NeW!

# Differential Transverse Energy Density

- **Diffractive** contributions **halved** and **doubled**.
- Affects the **amount of activity** (diffractive events are **softer on average**).
- Has **little effect on the shape**.




- In **MSTW2008 LO**, changes to the gluon PDF ***decreases* central** but ***increases* forward** energy.

NeW!

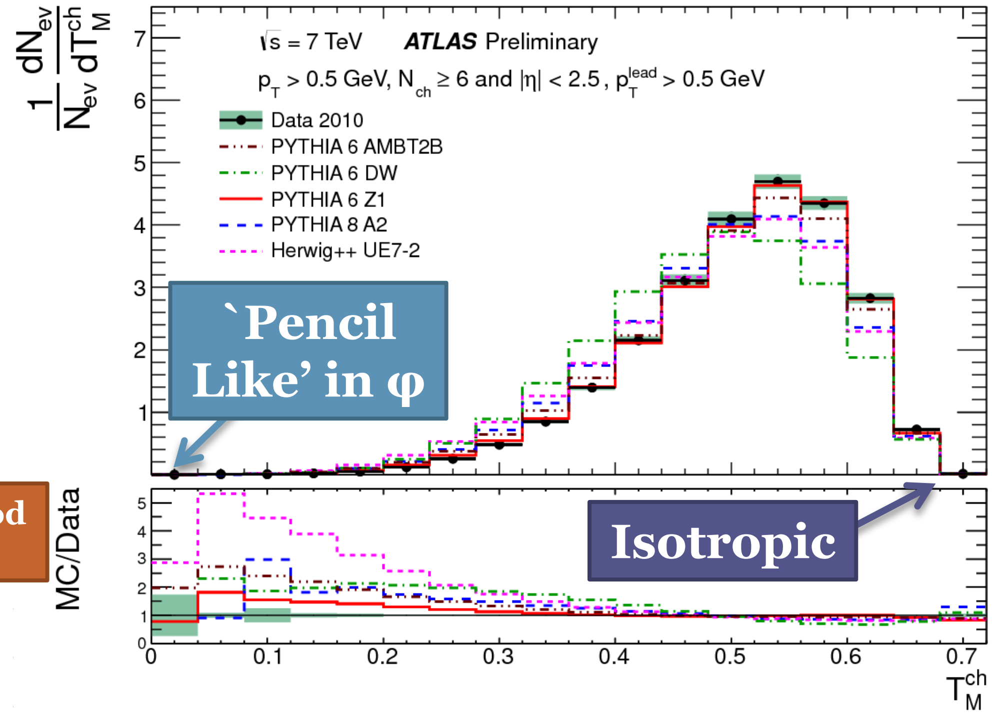
# Event Shapes

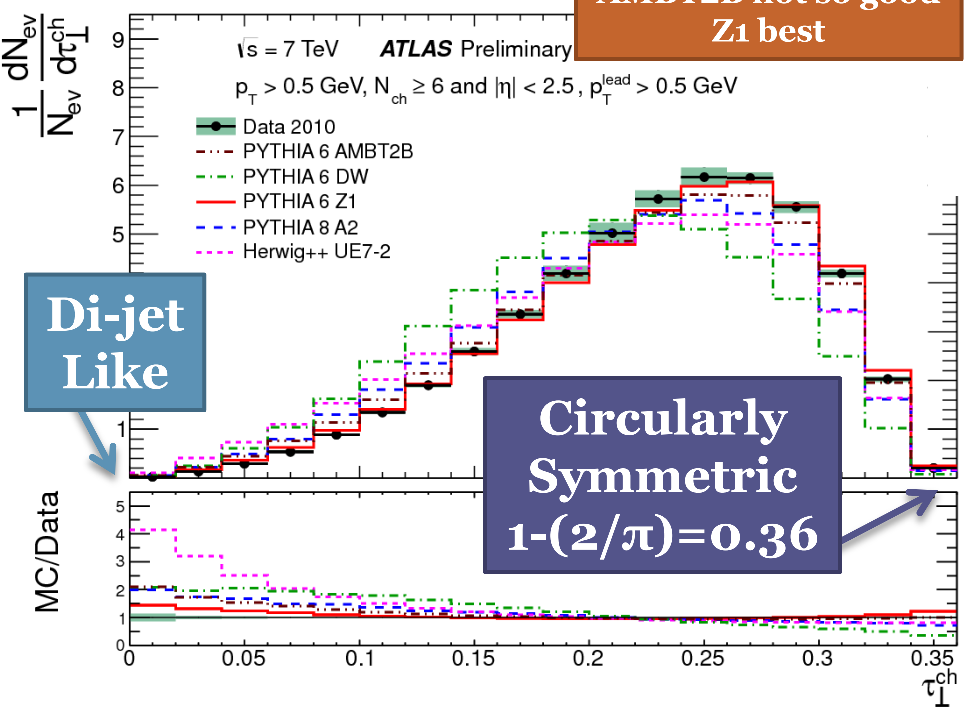
**Transverse Thrust:**

$$\tau_{\perp} = 1 - T_{\perp}$$

For Thrust Axis, unit vec. $\hat{n}_T$ for which:

$$\max_{\hat{n}} \frac{\sum_i |\vec{p}_T^{\,i} \cdot \hat{n}|}{\sum_i |\vec{p}_T^{\,i}|}$$




**Thrust Minor:**

Out of event plane energy flow.

$$\hat{n}_M = \hat{n}_T \times \hat{z}$$

Defined by *thrust axis* ($\hat{n}_T$) and *beam axis* ($\hat{z}$)

$$T_M = \frac{\sum_i |\vec{p}_T^{\,i} \cdot \hat{n}_M|}{\sum_i |\vec{p}_T^{\,i}|}$$

NeW!

# Event Shapes

**Transverse Sphericity:**

A measure of the transverse summed $p_T^2$ with respect to the event axis.

Shown here as a function of $p_T^{lead}$

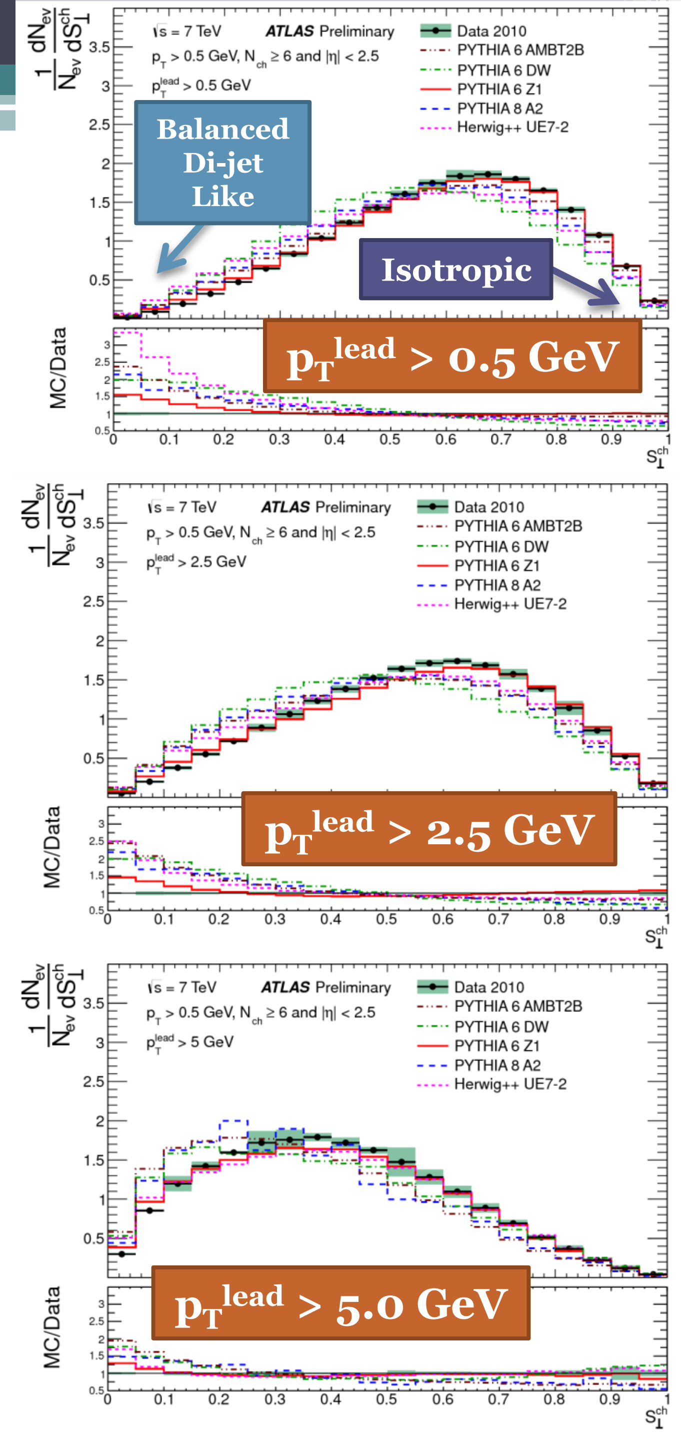
Derived from the **eigenvectors** ($\lambda^{xy}_2 < \lambda^{xy}_1$) of the **transverse** components of the **event momentum tensor**:

$$S^{xy} = \sum_i \begin{bmatrix} p_x^{2,i} & p_x^i p_y^i \\ p_x^i p_y^i & p_y^{2,i} \end{bmatrix} \qquad S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}$$

**Transverse thrust, thrust minor and transverse sphericity measured for leading particle.**

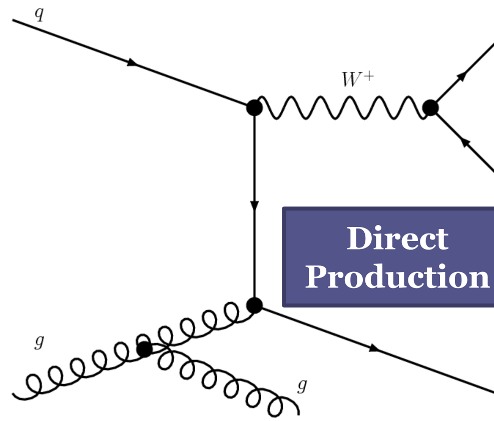
**$p_T^{lead}$ > 0.5, 2.5, 5.0 GeV**

**Along with *average values* as a function of $N_{ch}$ and $\Sigma p_T$**

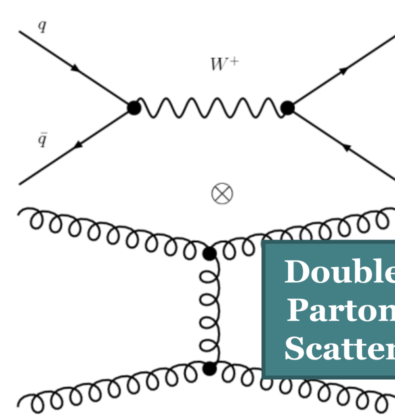


# Hard DPI: W→lν+jj

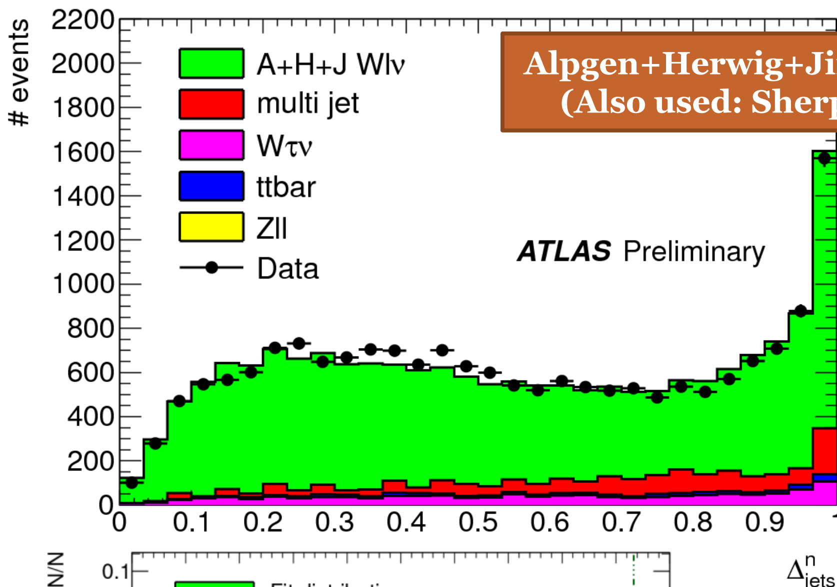
$$\Delta^{n}_{jets} = \frac{|\vec{p}_{T1} + \vec{p}_{T2}|}{|\vec{p}_{T1}| + |\vec{p}_{T2}|}$$



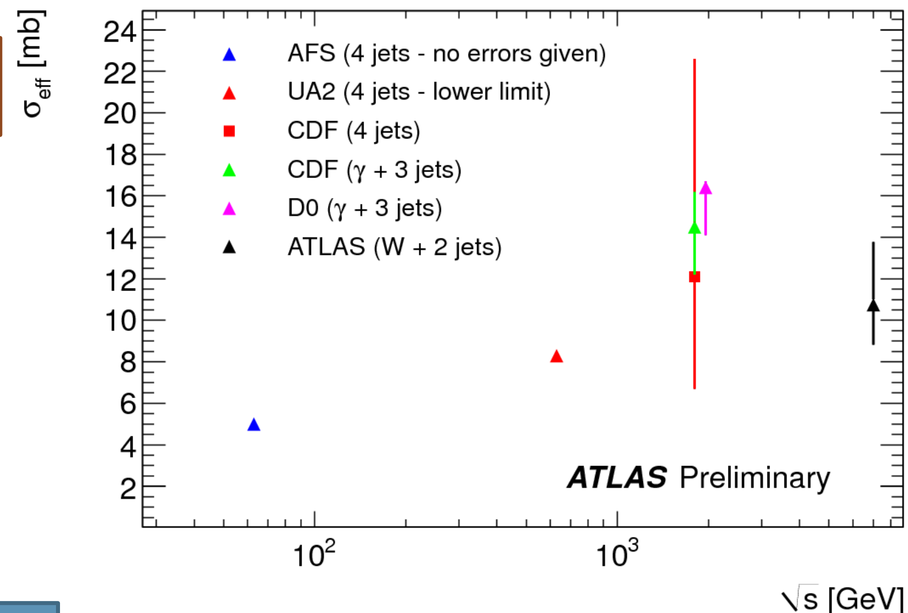

**Direct Production**

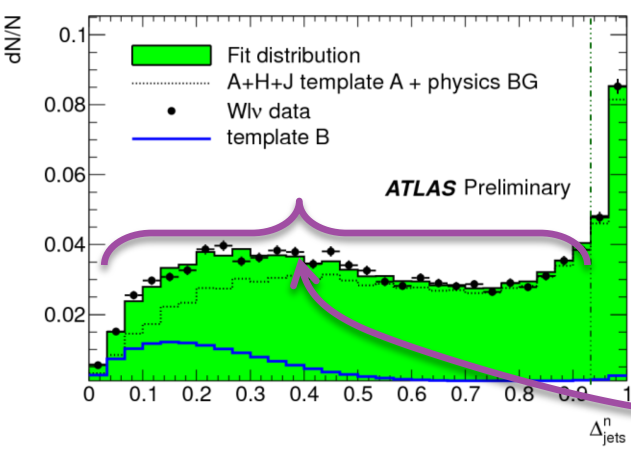



**Double Parton Scatter**




**Alpgen+Herwig+Jimmy (Also used: Sherpa)**




**Template A: Non-DPI MC**

**Template B: Di-jet Data**

**Templated χ² minimisation**

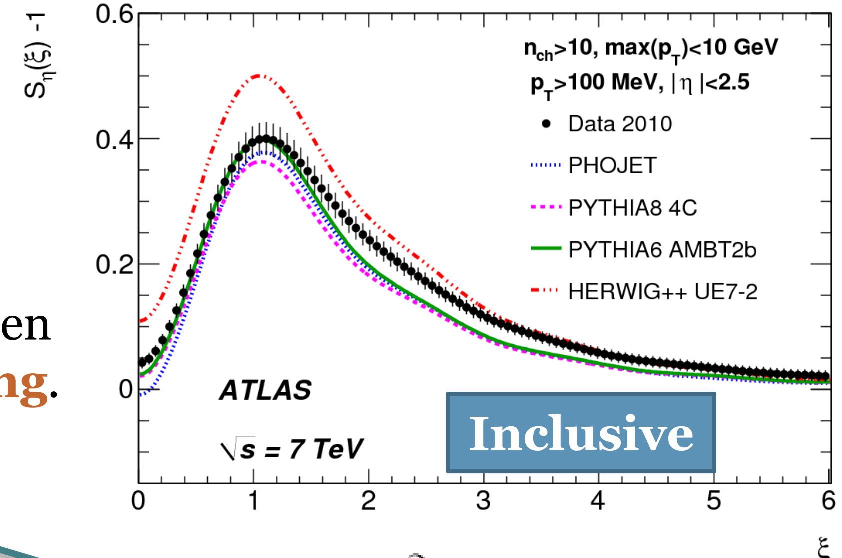
**Template extracted fraction of DPI:**
**$f^{R}_{DPI}$ = 0.16±0.01 (stat)±0.03 (sys)**

**Subsequently evaluated DPI cross section:**
**$\sigma_{DPI}^{eff}(7\,TeV) = 11\pm1(stat)^{+3}_{-2}(sys)$ mb**

# Is the gluon field helical?

Corrected via HBOM [arXiv:1111.4896v2]

- An **efficient way to pack soft gluons** into a **Lund string** formalism under **helicity conservation requirement** is the formation of a **helix structure** at the end of the parton cascade. [***Is there screwiness at the end of the QCD cascades?*** **arXiv:hep-ph/9807541v1**]
- **Correlations** in **the break points** of a **helically ordered string** will manifest as observables in the **$p_T$ distribution and azimuthal ordering** of hadrons produced **directly from string fragments**.
- Assuming string breakup through **tunneling**, φ direction of **initial hadron $p_T$ coincides with the phase of the helix string**.
- φ opening angle of **two direct hadrons** will then **measures the phase difference** between **two corresponding points along the string**.




Assumes helix winding is proportional to the rapidity difference between hadrons

φ and η of $j_{th}$ hadron.

$$S_\eta(\xi) = \frac{1}{N_{\mathrm{Ev}}} \sum_{\mathrm{Events}} \frac{1}{n_{\mathrm{Ch}}} \left| \sum_{j}^{n_{\mathrm{Ch}}} e^{i(\xi\eta_j - \phi_j)} \right|^2$$

ξ is a scale parameter.

# Is the gluon field helical?

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- Assumi… …through **tunneling**, φ d… **…al hadron $p_T$ coincides wit… …phase of the helix string**.
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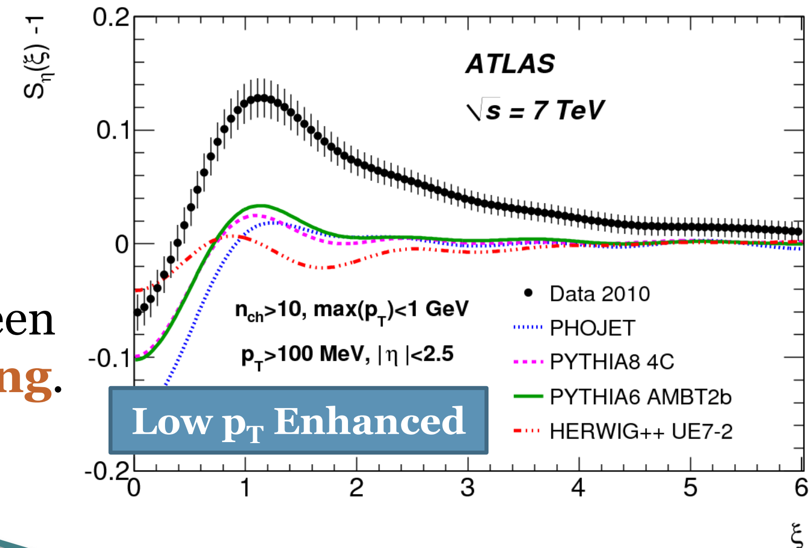
**New Pythia8 Helix Model**
**projects.hepforge.org/helix**

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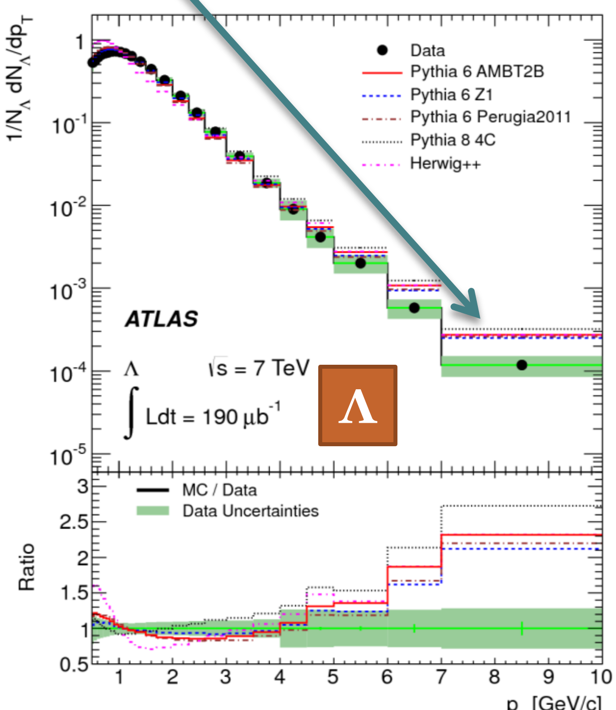
**φ and η of $j_{th}$ hadron.**

$$S_\eta(\xi) = \frac{1}{N_{\mathrm{Ev}}} \sum_{\mathrm{Events}} \frac{1}{n_{\mathrm{Ch}}} \left| \sum_{j}^{n_{\mathrm{Ch}}} e^{i(\xi\eta_j - \phi_j)} \right|^2$$

**ξ is a scale parameter.**

# $K^0_S$ and $\Lambda$

**All tunes struggle to describe $\Lambda$ data at high $p_T$**

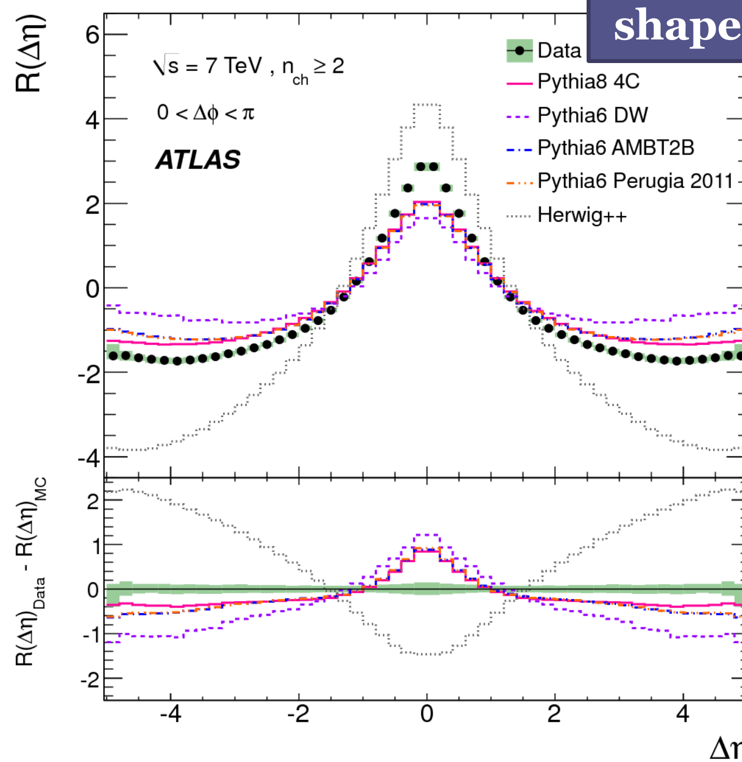


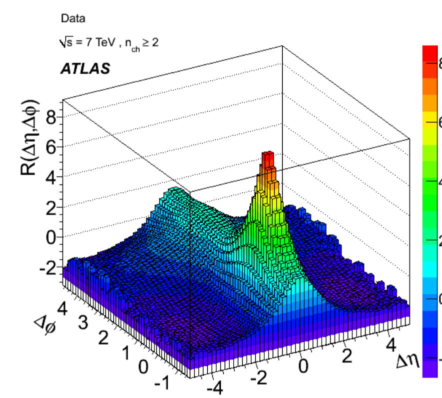

# Two Particle Correlations

- **$\Delta\eta$ and $\Delta\varphi$ correlations** between **all particles** in an event.
- **Background subtracted** by combining two particles from **different** events.
- **Normalised** to be **independent of per event particle multiplicity**.

**Corrected via HBOM [arXiv:1111.4896v2]**

**Most models (except Herwig++) reasonably predict the shape of the correlations.**



# Conclusion

- **A wealth of data from ATLAS on event characteristics, particle properties and correlations are available *at the hadron level.***
- *Measurement of charged-particle event shape variables in sqrt(s) = 7 TeV proton-proton interactions with the ATLAS detector* **[Coming soon!]**
- *Measurements of the pseudorapidity dependence of the total transverse energy in proton-proton collisions at sqrt(s)=7 TeV with ATLAS* **[Coming soon!]**
- *Measurement of charged-particle event shape variables in sqrt(s) = 7 TeV proton-proton interactions with the ATLAS detector* **[Coming soon!]**
- *Measurement of the azimuthal ordering of charged hadrons with the ATLAS detector at the LHC* **[arXiv:1203.0419]**
- *Measurement of Inclusive Two-Particle Angular Correlations in pp Collisions with the ATLAS Detector at the LHC* **[arXiv:1203.3549 ]**
- *Forward-backward correlations and charged-particle azimuthal distributions in pp interactions using the ATLAS detector* **[arXiv:1203.3100 ]**
- *Rapidity Gap Cross Sections in pp Interactions at sqrt(s) = 7 TeV measured with the ATLAS detector* **[arXiv:1201.2808 ]**
- *Kshort and Lambda production in pp interactions at sqrt(s) = 0.9 and 7 TeV measured with the ATLAS detector at the LHC* **[arXiv:1111.1297 ]**
- *Measurement of the Inelastic Proton-Proton Cross-Section at sqrt(s) = 7 TeV with the ATLAS Detector* **[arXiv:1104.0326]**
- *A measurement of hard double-partonic interactions in W --> l nu + 2 jet events with the ATLAS detector at the LHC* **[ATLAS-CONF-2011-160]**

# BACKUP

# Is the gluon field helical? Part II

- One possibility, **a static, regular helix** with **helical phase difference Δφ** proportional to the **stored energy** in the string.

**κ is string energy density**

$$\Delta\phi = \mathfrak{L}\kappa\Delta l = \mathfrak{L}\Delta E$$

***Δl* & *ΔE* are length and energy separation in string rest frame.**

- ***ΔE* is not directly observable**, but we can **approximate the string as a chain of hadrons, ordered in η**.
- Define a **second power spectrum**, based on **φ** and the **position in the chain, *X*** defined as:

$$X_j = 0.5\ E_j + \sum_{k=0}^{k<j} E_k$$

**$E_k$ is the energy of the $k_{th}$ hadron in the string.**

$$S_E(\omega) = \frac{1}{N_{\mathrm{Ev}}} \sum_{\mathrm{Events}} \frac{1}{n_{\mathrm{Ch}}} \left| \sum_{j}^{n_{\mathrm{Ch}}} e^{i(\omega X_j - \phi_j)} \right|^2$$

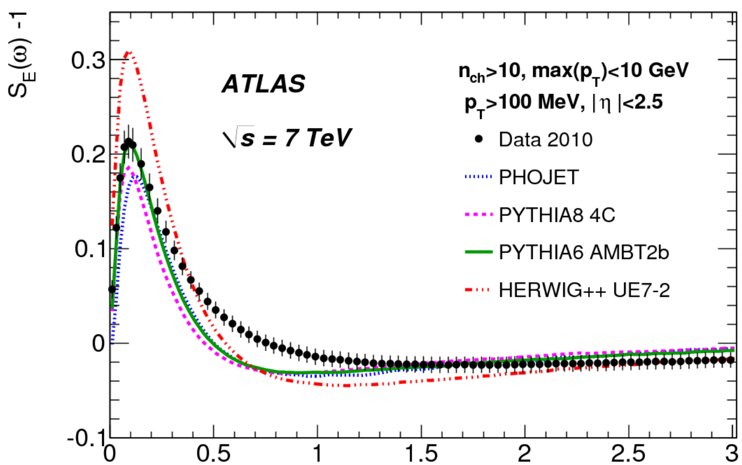
**Very similar form factor, but probing a different structure in the QCD field.**

**ω is a scale parameter.**

**Helical ordering will appear as a peak in the power spectrum, location = winding density.**

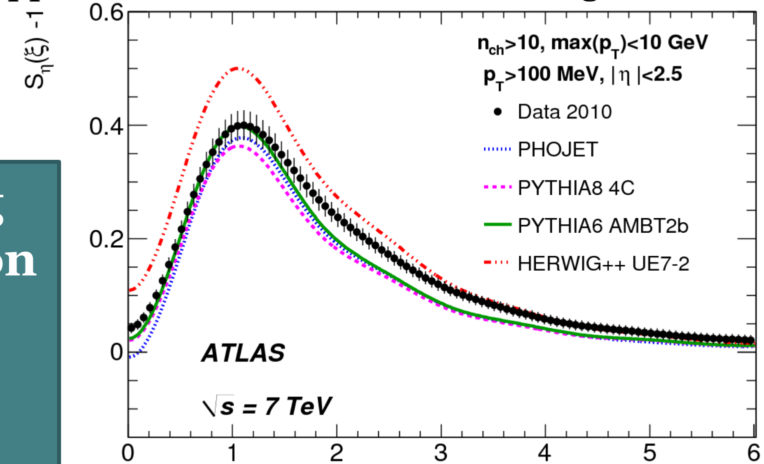
# More results for $S_E(\omega)$ & $S_\eta(\xi)$

- Data **corrected to hadron level** via **HBOM** **[arXiv:1111.4896v2]**
  (Backward extrapolation from the parametrisation of repeated applications of the detector smearing matrix)



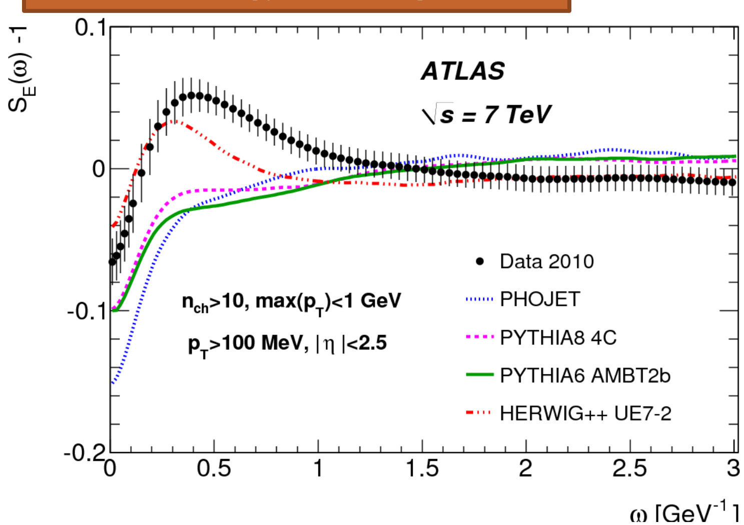

**Inclusive MinBias**

**Lund string fragmentation model roughly reproduces the data.**



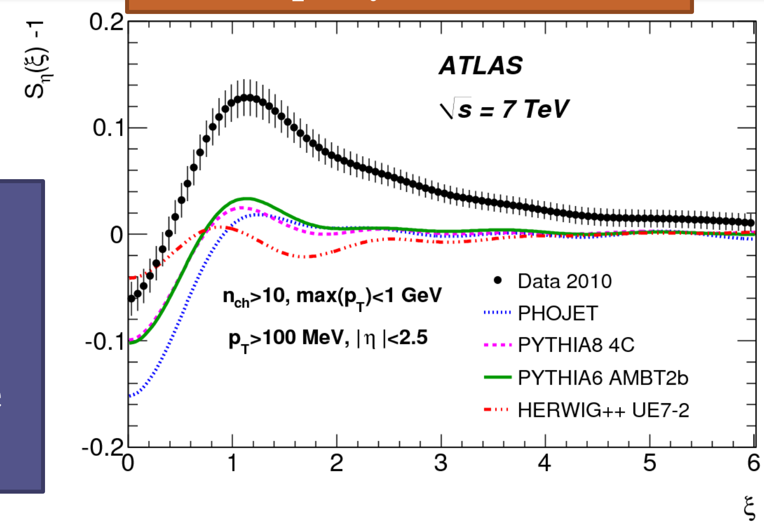

**ω:Helix proportional to stored energy in string**

**ξ:Helix proportional to particle rapidity difference**



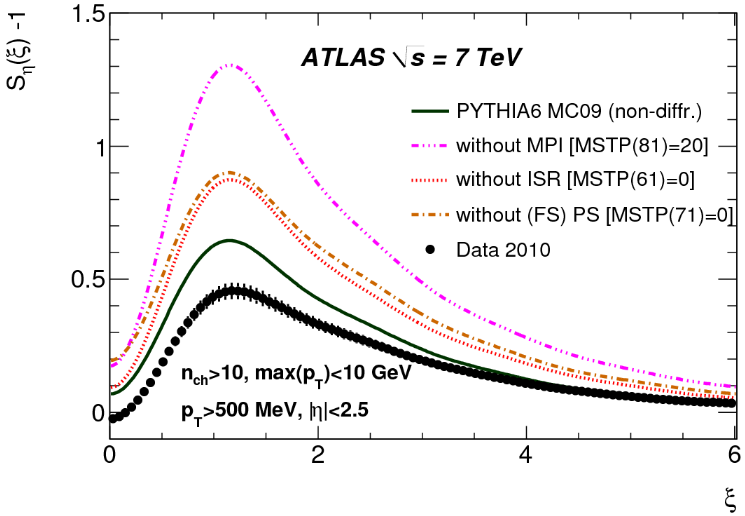

**Low $p_T$ Enhanced**

**Models unable to sufficiently describe the data.**



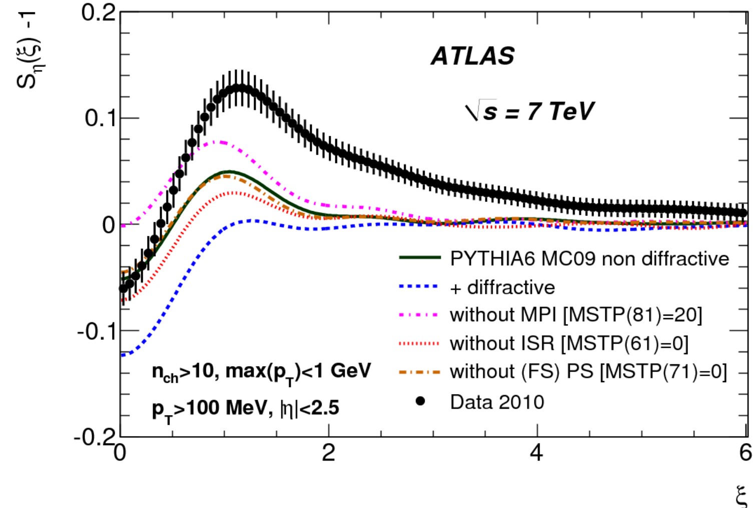
# More results for $S_E(\omega)$ & $S_\eta(\xi)$

**Low $p_T$ Depleted**

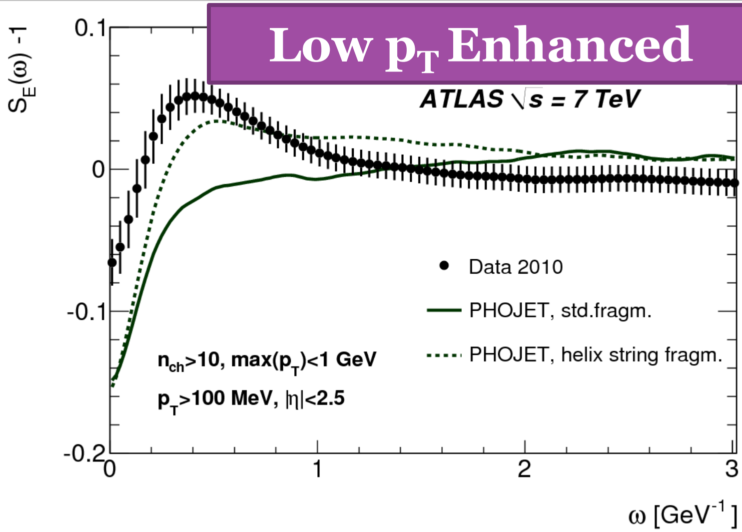



**Model Parameter Sensitivity**

**Low $p_T$ Enhanced**




**Low $p_T$ Enhanced**

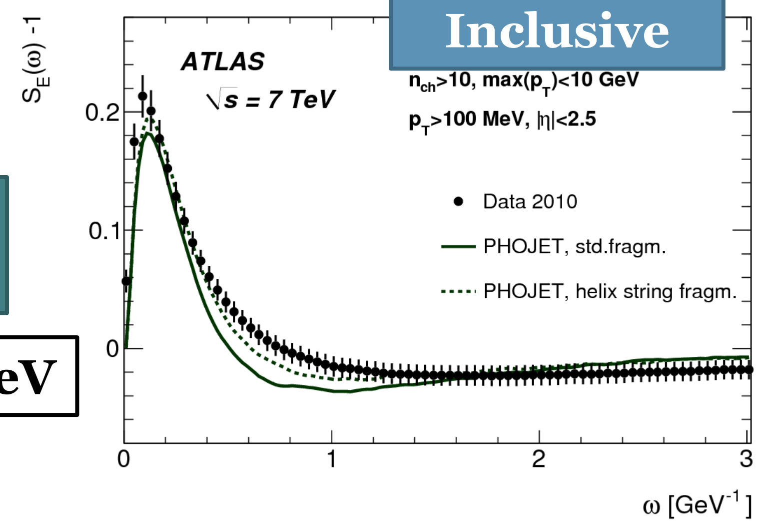



**PHOJET Helix**

**$S_E$ Definition**

**$\mathfrak{L}$ = 0.7 rad/GeV**

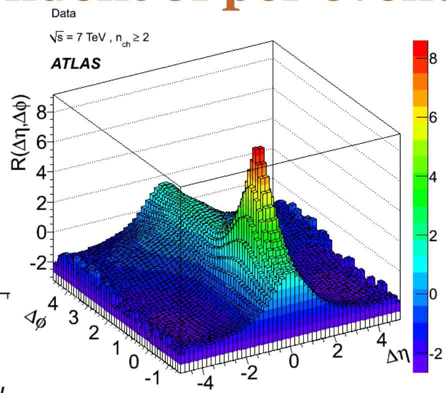
**Inclusive**



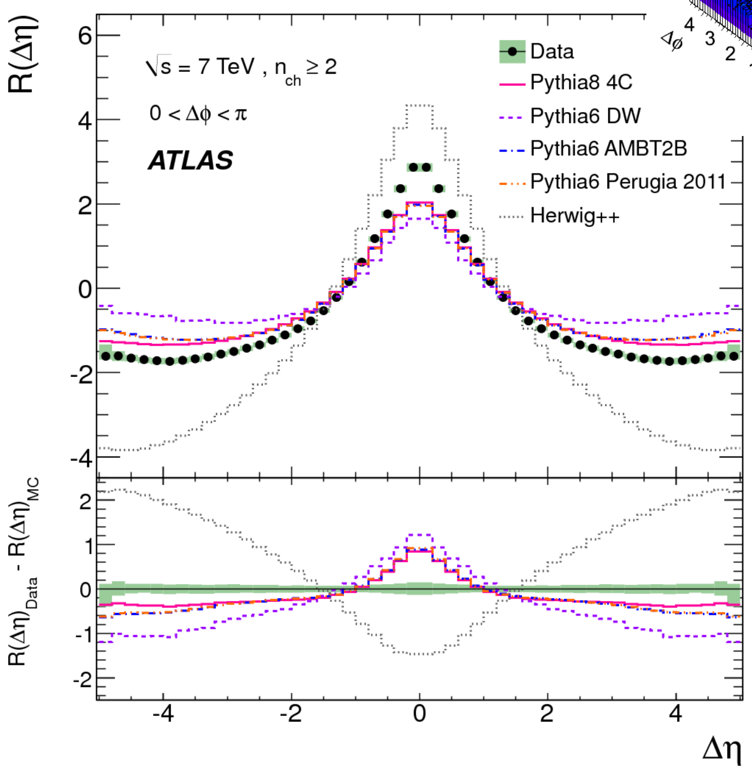
# Two Particle Correlations

- **Δη and Δφ correlations** between **all particles** in an event.
- **Background subtracted** by combining two particles from **different** events.
- **Normalised** to be **independent of per event particle multiplicity**.

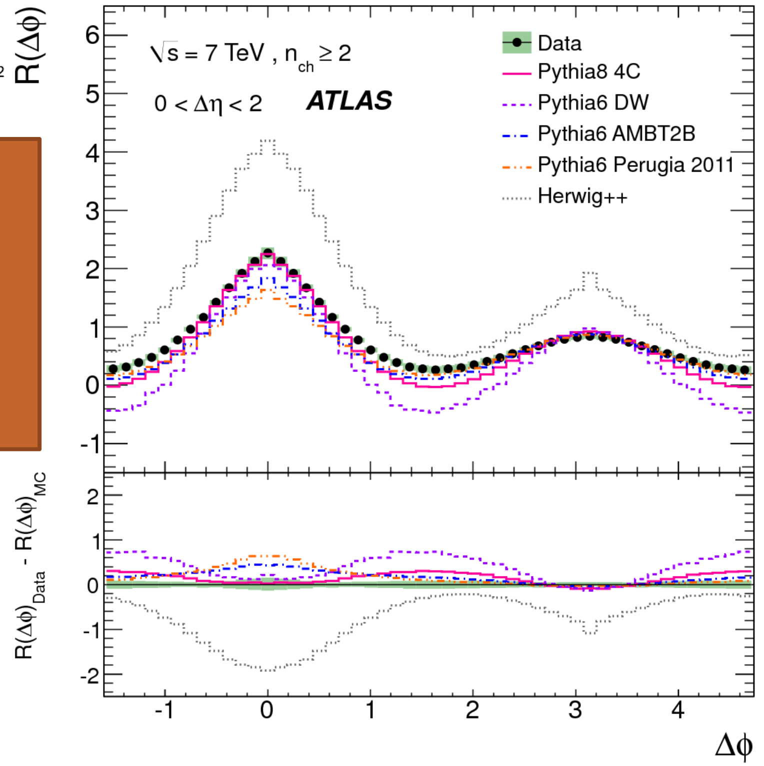
**Most models (except Herwig++) reasonably predict the shape of the correlations.**




**The strength of correlations is less well predicted.**

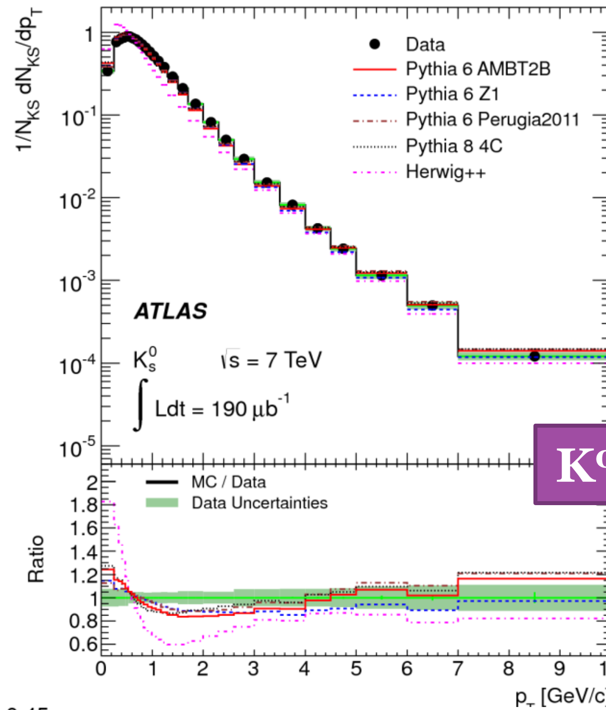



**Data corrected using HBOM method**

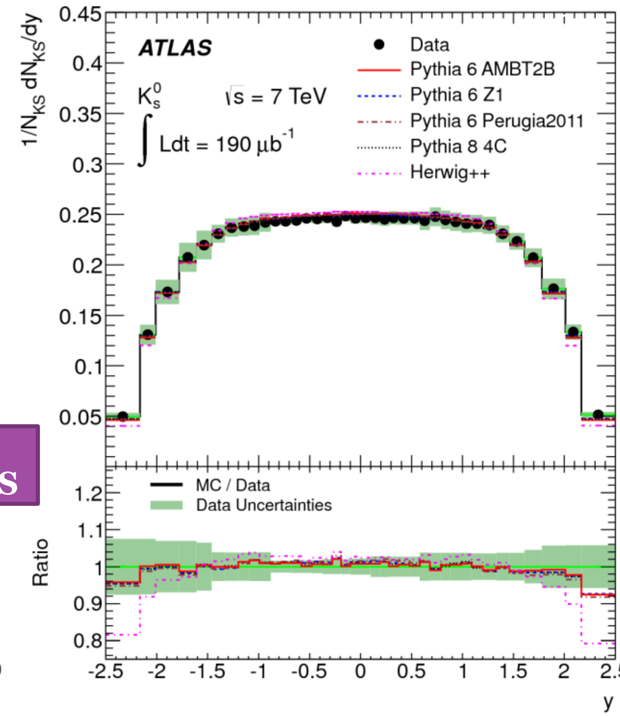


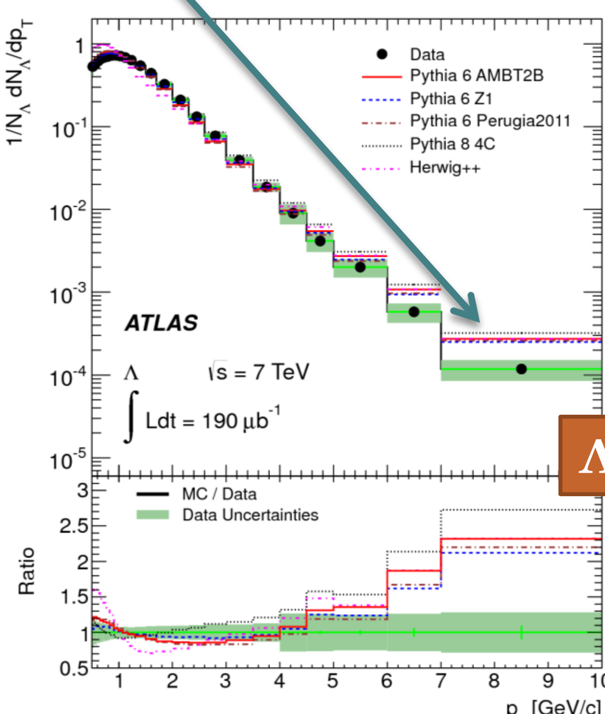
# $K^0_S$ and Λ

**All tunes struggle to describe Λ data at high $p_T$**

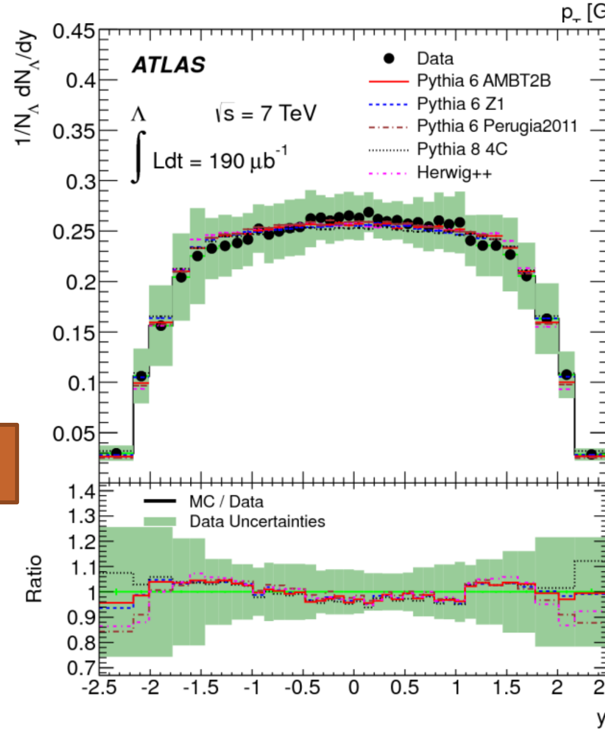



$K^0_S$




Λ

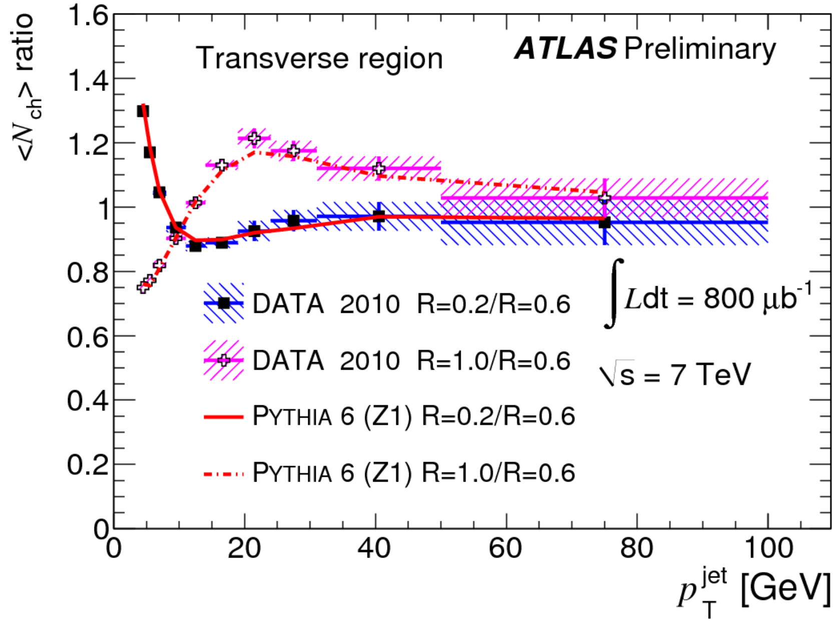



$K^0_S$: Flight distance between **4 - 450 mm**
Decay to two charged pions with **$|\eta| < 2.5$, $p_T > 100$ MeV**

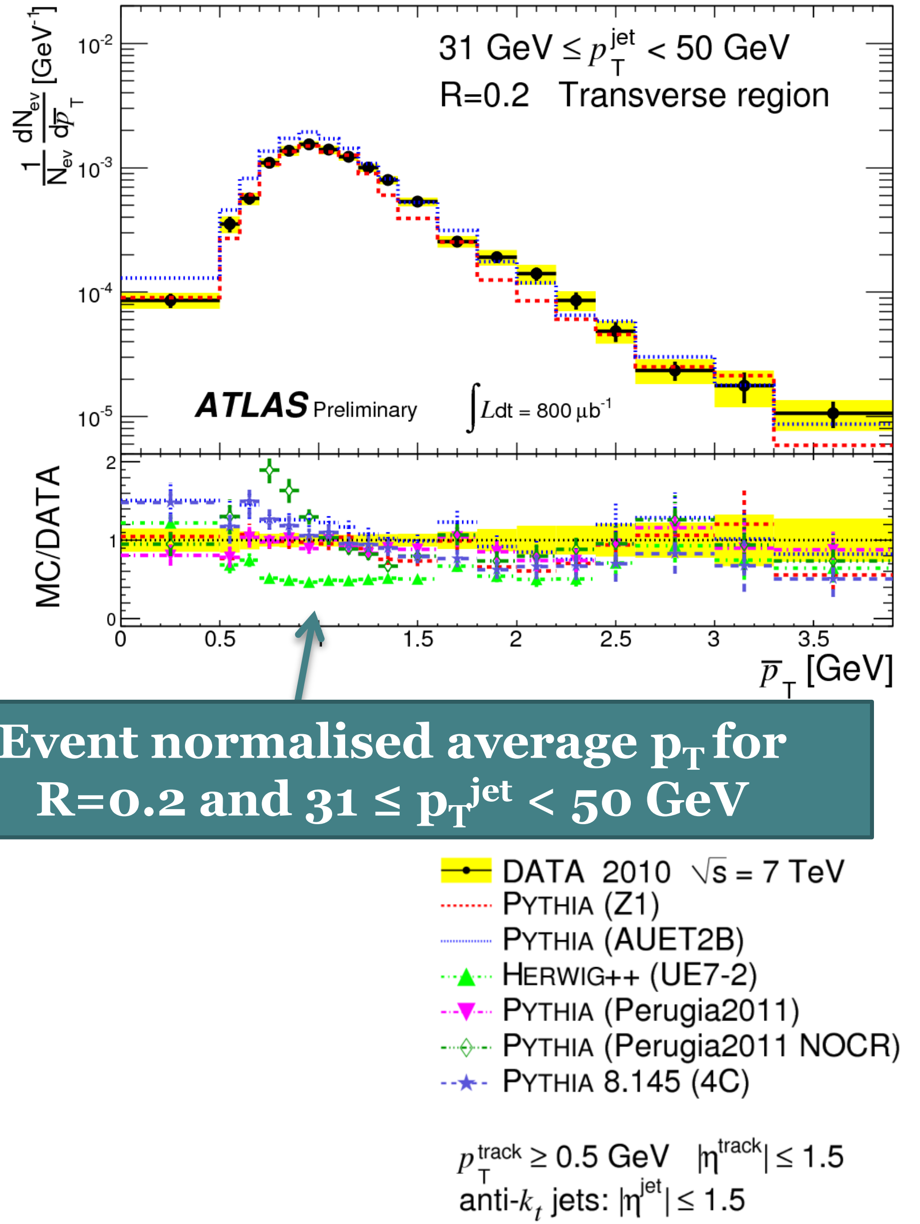
**Λ**: $p_T > 500$ MeV, flight distance between **17 mm - 450 mm**
Decay to a proton and a pion with **$|\eta| < 2.5$, $p_T > 100$ MeV**

# Track-jet Underlying Event

**Ratio of mean $N_{ch}$ for $R=0.2/R=0.6$ and $R=1.0/R=0.6$ as function of $p_T^{Jet}$**




**Event normalised average $p_T$ for $R=0.2$ and $31 \le p_T^{jet} < 50$ GeV**

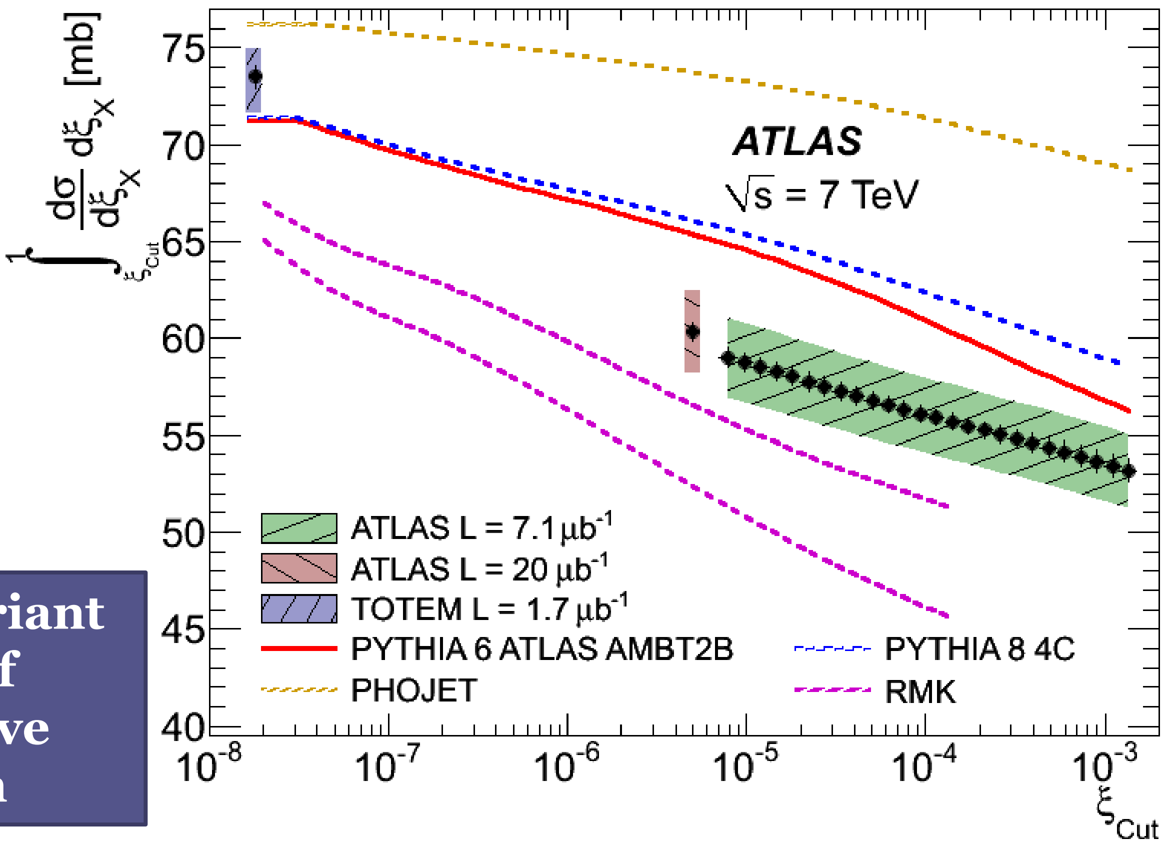


# $\int \sigma_{Inelas}(\xi)\, d\xi$

- Measure the **total inelastic cross section which produces particles in the main ATLAS detector**. Can **integrate** up to a cut point.
- Apply all **correlated systematics symmetrically** plus additional **correction** from **$\Delta\eta^F$** to **$\xi$** derived from **MC**, at most **1.1±1.1%**
- **Luminosity error** dominates.
- Comparison with published **ATLAS** paper good to **0.8%**, this is the measured **run-to-run lumi** error.
- Also included, **TOTEM**.
- And **Durham RMK** prediction.

$$\xi = \frac{M_X^2}{s}$$

**$M_X$ = Invariant mass of diffractive system**



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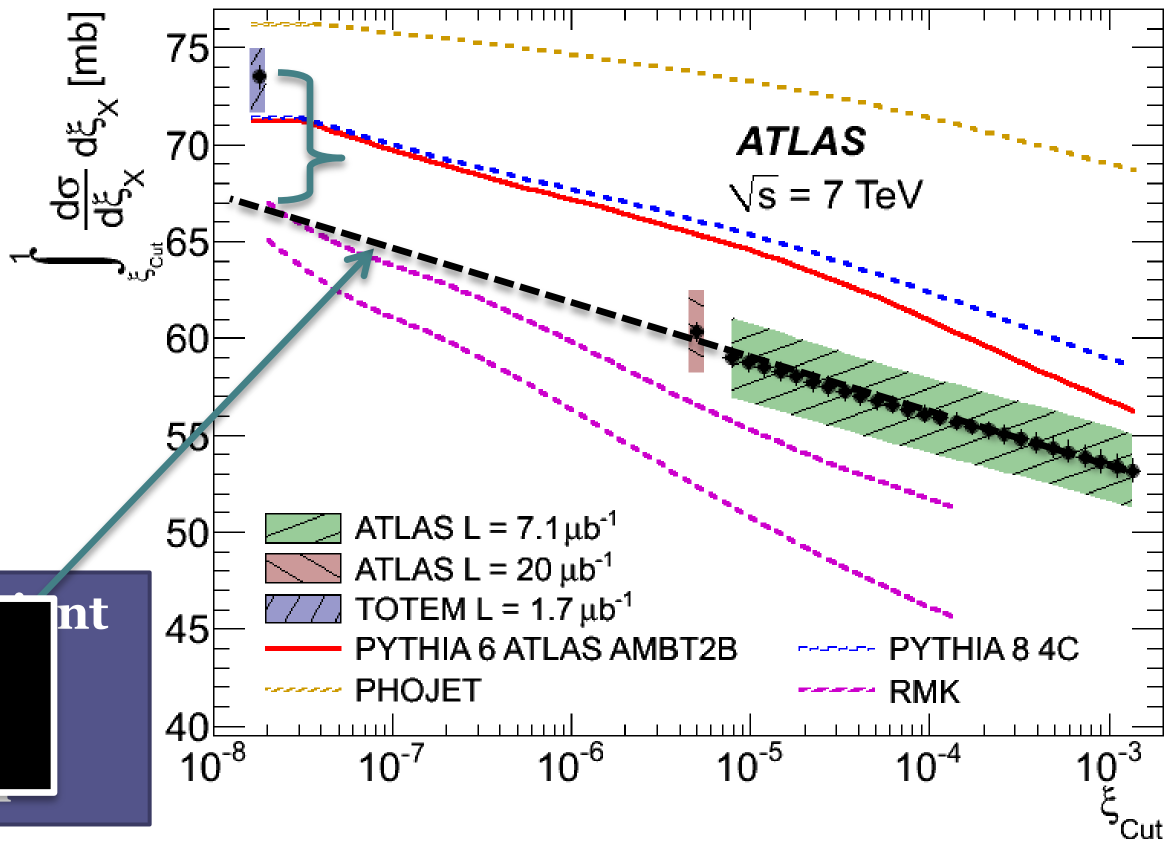
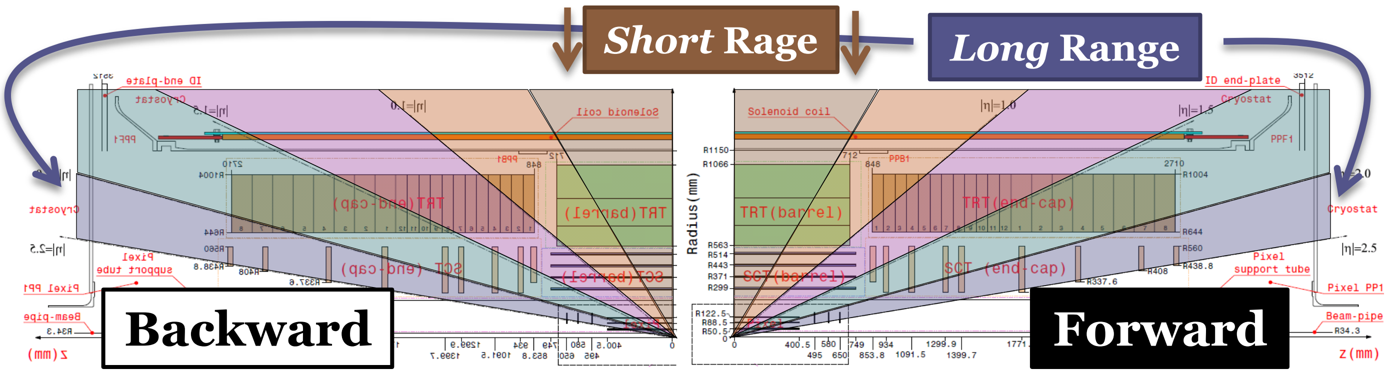



**Tension of ~7 mb of low mass diffractive cross section.**

# Particle Correlations

- **Forward-Backward** multiplicity and $p_T$ correlations in η.




Deviation of fwd(bkwd) multiplicities from their mean.

Sum over events

$$\rho^{n}_{fb} = \frac{\sum x^{n}_{f} x^{n}_{b}}{N \sigma^{n}_{f} \sigma^{n}_{b}}$$

N Events

Standard deviation of fwd(bkwd) distributions about their mean.

Deviation of fwd(bkwd) scalar $p_T$ sum of all accepted tracks from their mean.

$$\rho^{p_T}_{fb} = \frac{\sum x^{p_T}_{f} x^{p_T}_{b}}{N \sigma^{p_T}_{f} \sigma^{p_T}_{b}}$$

D

Tri

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