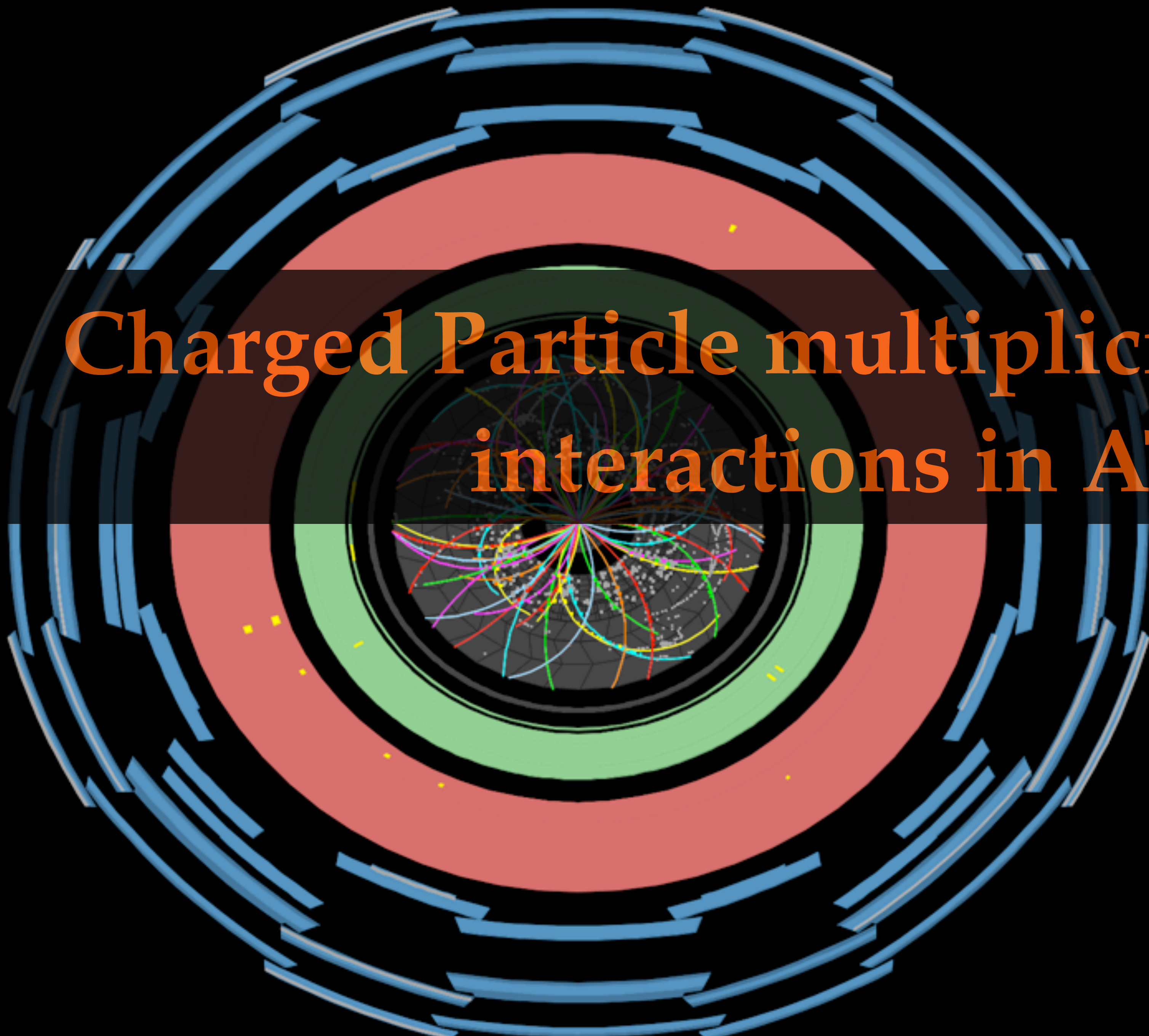
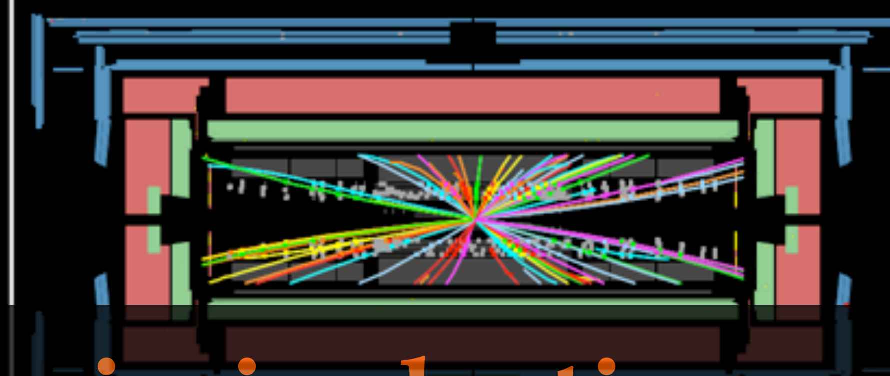
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

One of the first 7 TeV collisions





Charged Particle multiplicities in inelastic interactions in ATLAS

ATLAS EXPERIMENT

Run Number: 152166, Event Number: 316199

Date: 2010-03-30 12:58:23 CEST

Implications of First LHC Data, Berkeley-MIT workshop, Aug. 10-13, 2010

Till Eifert (CERN)
on behalf of the ATLAS Collaboration

Brief Motivation

- Physics motivation: Improve understanding of non-perturbative soft QCD processes

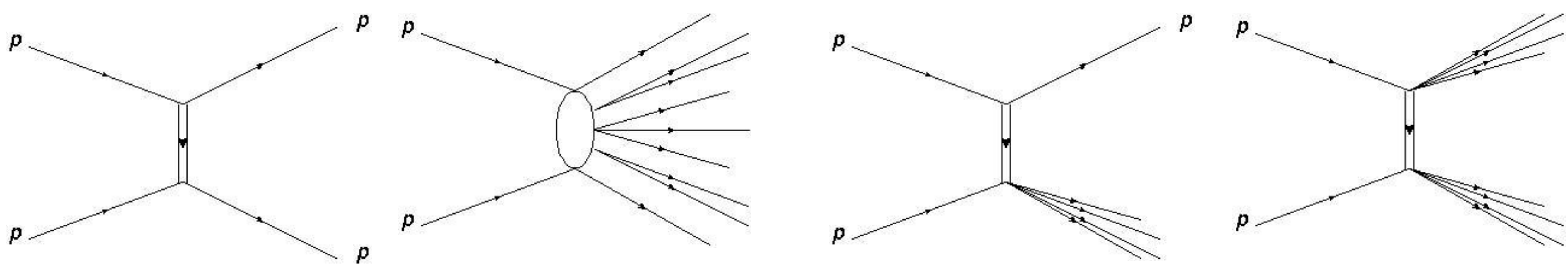
  study the properties of inelastic proton-proton collisions

- Experimental motivation: model the pileup and underlying event

  Necessary for measuring physics processes at high energies.

$$\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}}$$

$$\sigma_{\text{inelastic}} = \sigma_{\text{non-diffractive}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}}$$



Measurement Strategy

- **Measurements made:**

  Charged particle multiplicity, its dependence on p_T and η, its correlation with p_T

$$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}, \quad \frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta d p_T}, \quad \frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}} \quad \text{and} \quad \langle p_T \rangle \text{ vs. } n_{ch}$$

- **Strategy: As inclusive and model-independent as possible**
  - Single-arm trigger
  - No (model-dependent) corrections back to particular component (e.g. non-single-diffractive)
  - Well-defined phase-space → facilitates MC tuning

- **Studied phase-spaces:**

shown here

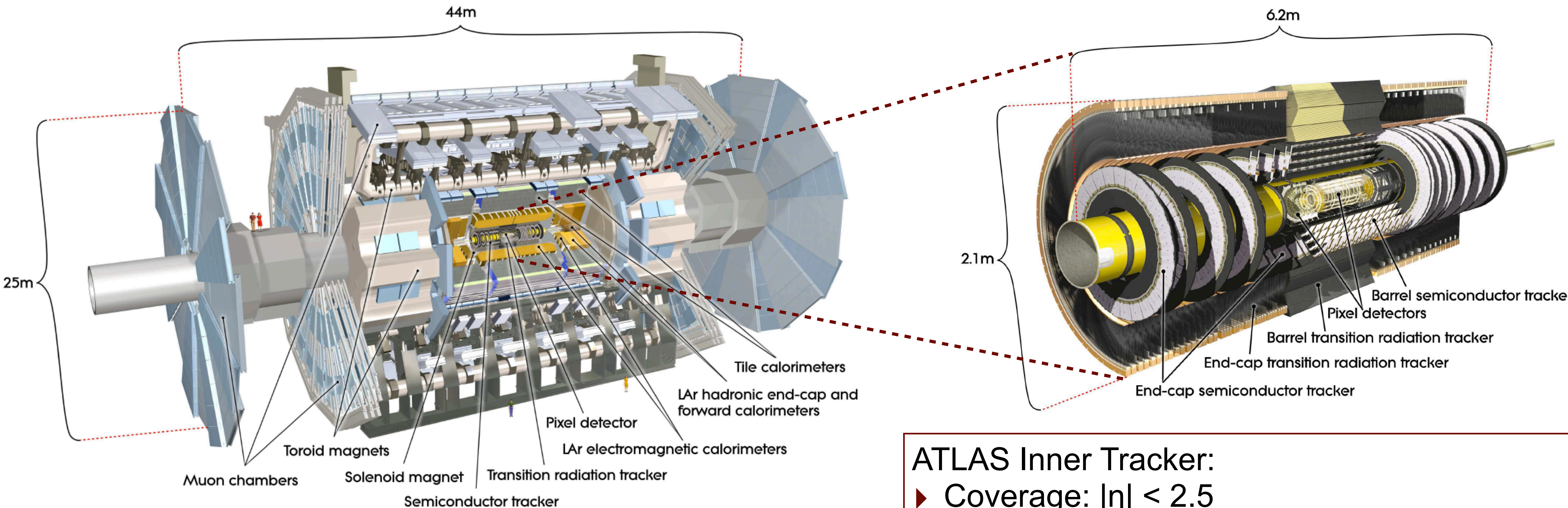
$\geq$ 1 particle : $p_T > 500$ MeV, $|\eta| < 2.5$: studied at $\sqrt{s}$ = 0.9, 2.36, 7 TeV — *Possible for all $\sqrt{s}$*

$\geq$ 2 particles: $p_T > 100$ MeV, $|\eta| < 2.5$: studied at $\sqrt{s}$ = 0.9, 7 TeV — *Most inclusive*

$\geq$ 6 particles: $p_T > 500$ MeV, $|\eta| < 2.5$: studied at $\sqrt{s}$ = 0.9, 7 TeV — *Diffractive limited*

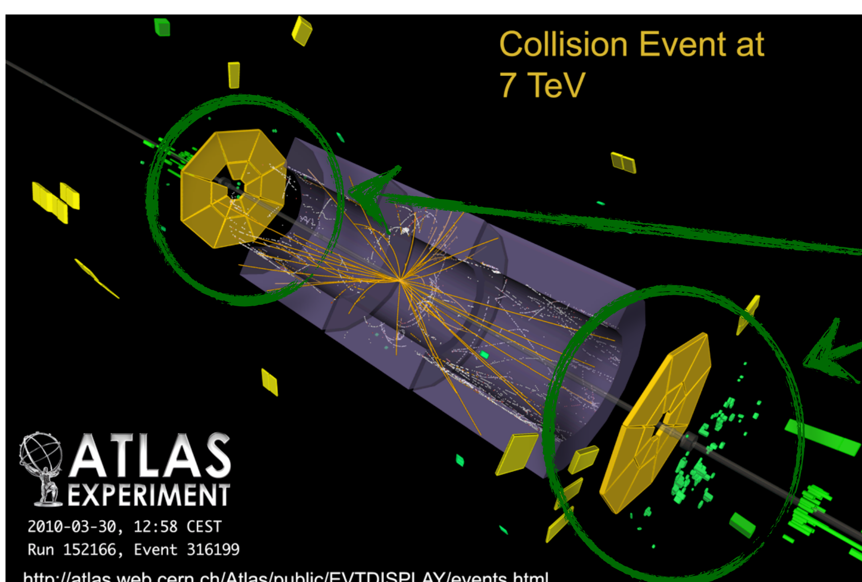
Used in new AMBT1 Pythia 6 tune

ATLAS Detector Overview



ATLAS Inner Tracker:

- Coverage: $|\eta| < 2.5$
- Pixel
  3 barrel layers, 3 endcap disks
- Silicon Tracker (SCT)
  4 double-sided barrel layers, 9 endcap disks
- Transition Radiation Tracker (TRT)
  ~ 32 hits per track

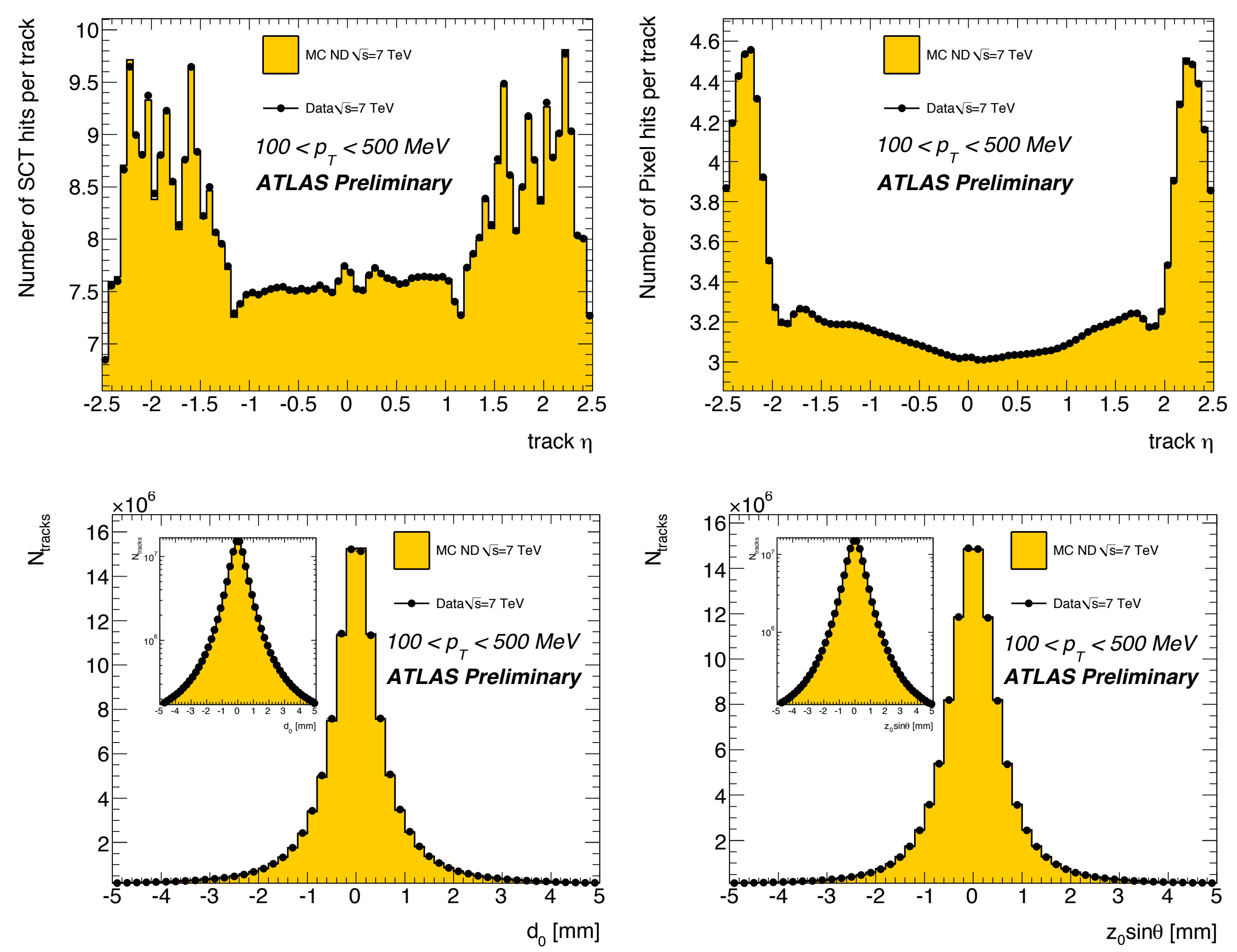


Minimum Bias Trigger Scintillator (MBTS)

- Inside the endap calorimeters
- 3.6m from interaction point
- Coverage $2.1<|\eta| < 3.8$ in 2 disks

Datasets and Event Selection

- MBTS single hit trigger
- 1 Reconstructed Primary Vertex
  - 2 tracks + beam-spot
  - Remove pileup events, i.e. second vertex with >= 4 tracks
- Track Selection
  - various quality cuts and remove non-primary tracks by cutting on impact parameters at the primary vertex.



Excellent agreement btw. Data/MC

0.9 TeV (~7 μb-1)	360k events	4.5M tracks
7 TeV (~190 μb-1)	10M events	210M tracks
2.36 TeV	6k events	~40k tracks

Correction Procedure

n_{sel}^{BS}: number of tracks; cuts as close to final selection as possible without a vertex

- Corrections applied event-wise
  - Trigger, Vertex

$$w_{\mathrm{ev}}(n_{\mathrm{Sel}}^{\mathrm{BS}}) = \frac{1}{\epsilon_{\mathrm{trig}}(n_{\mathrm{Sel}}^{\mathrm{BS}})} \cdot \frac{1}{\epsilon_{\mathrm{vtx}}(n_{\mathrm{Sel}}^{\mathrm{BS}})}$$

- Track-level correction for tracking efficiency, non-primary tracks and tracks from outside of the kinematic range (okr):

$$w_{\mathrm{trk}}(p_{\mathrm{T}}, \eta) = \frac{1}{\epsilon_{\mathrm{bin}}(p_{\mathrm{T}}, \eta)} \cdot (1 - f_{\mathrm{sec}}(p_{\mathrm{T}})) \cdot (1 - f_{\mathrm{okr}}(p_{\mathrm{T}}, \eta))$$

- Iterative Bayesian unfolding method applied to both number of particles (n_{ch}) and p_T

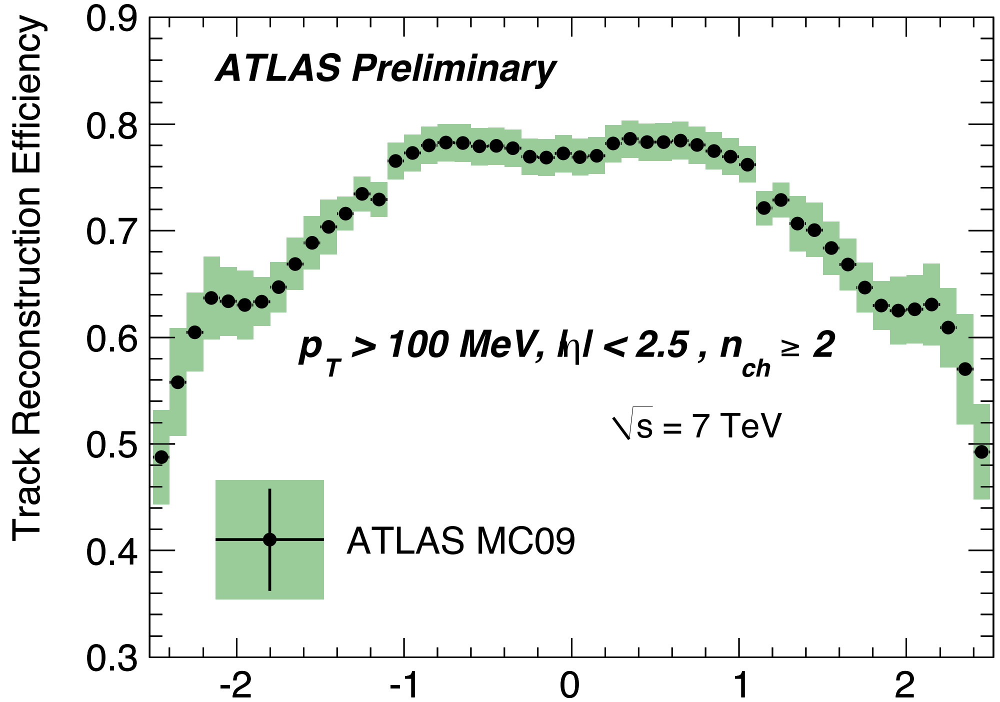
- Correct for events lost in the n_{sel}=0,1 bins:
  - i.e. events with ≥2 particles but <2 tracks

$$w_{out}(n_{ch}) = \frac{1}{(1 - (1 - \epsilon_{trk})^{n_{ch}} - n_{ch} \cdot \epsilon_{trk} \cdot (1 - \epsilon_{trk})^{(n_{ch}-1)})}$$

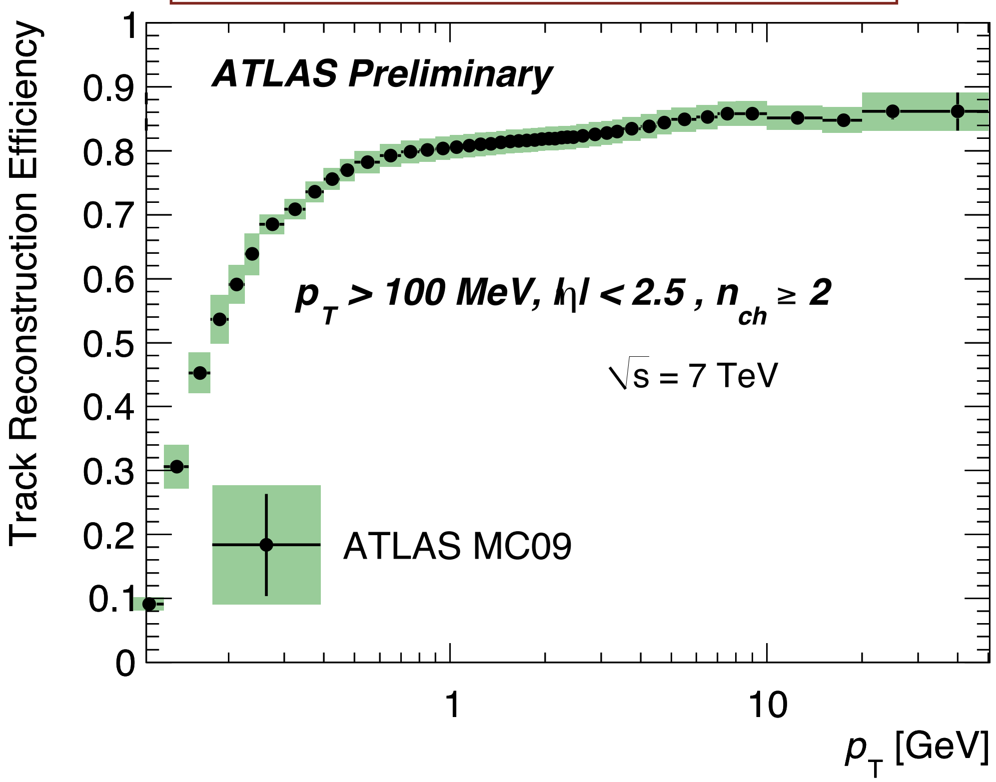
- <p_T> vs n_{ch}: bin by bin correction of average p_T then n_{ch} migration

Tracking Efficiencies & its Systematics

- Tracking efficiency is determined from MC
  - MC is validated against data
  - parameterized as function of p_T and η.
- Main systematic uncertainties
  - low-p_T : MC material description
    (estimated using Ks mass, and track extension rate)
  - high-p_T : migration of low momentum particles, mis-alignment
    (estimated using various tracking quantities in data, and width of invariant mass)
- Rate of non-primary tracks is estimated from data
  - fitting tails of impact parameter distributions



Tracking efficiency from MC

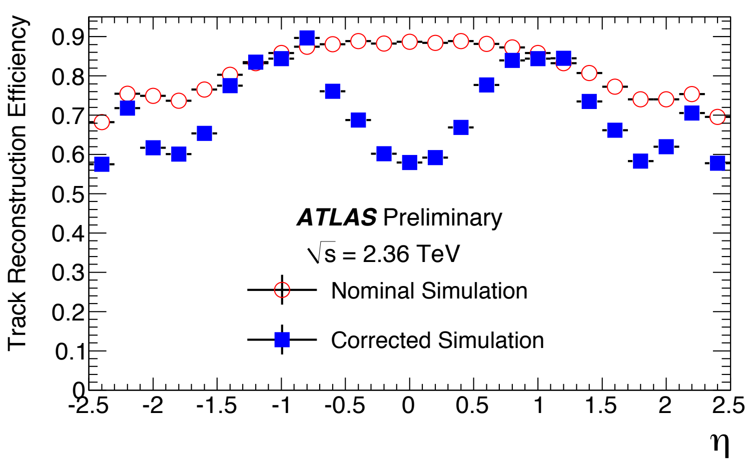


Track Reconstruction @ 2.36 TeV

- 2 Track reconstruction methods
  - Could not use standard tracking as SCT not at nominal configuration
  - HV= 20V (nominal: 150V)
  - Reduced hit efficiency (~100% → O(50%))
- Test run @ 900 GeV with both SCT configurations

ID tracks

- Use full ID information
- Relaxed track cuts
- p_T resolution similar to full tracks
- Used for p_T distribution
- Relative efficiency wrt. nominal tracks from test run @ 900 GeV
- Apply ratio as correction factor



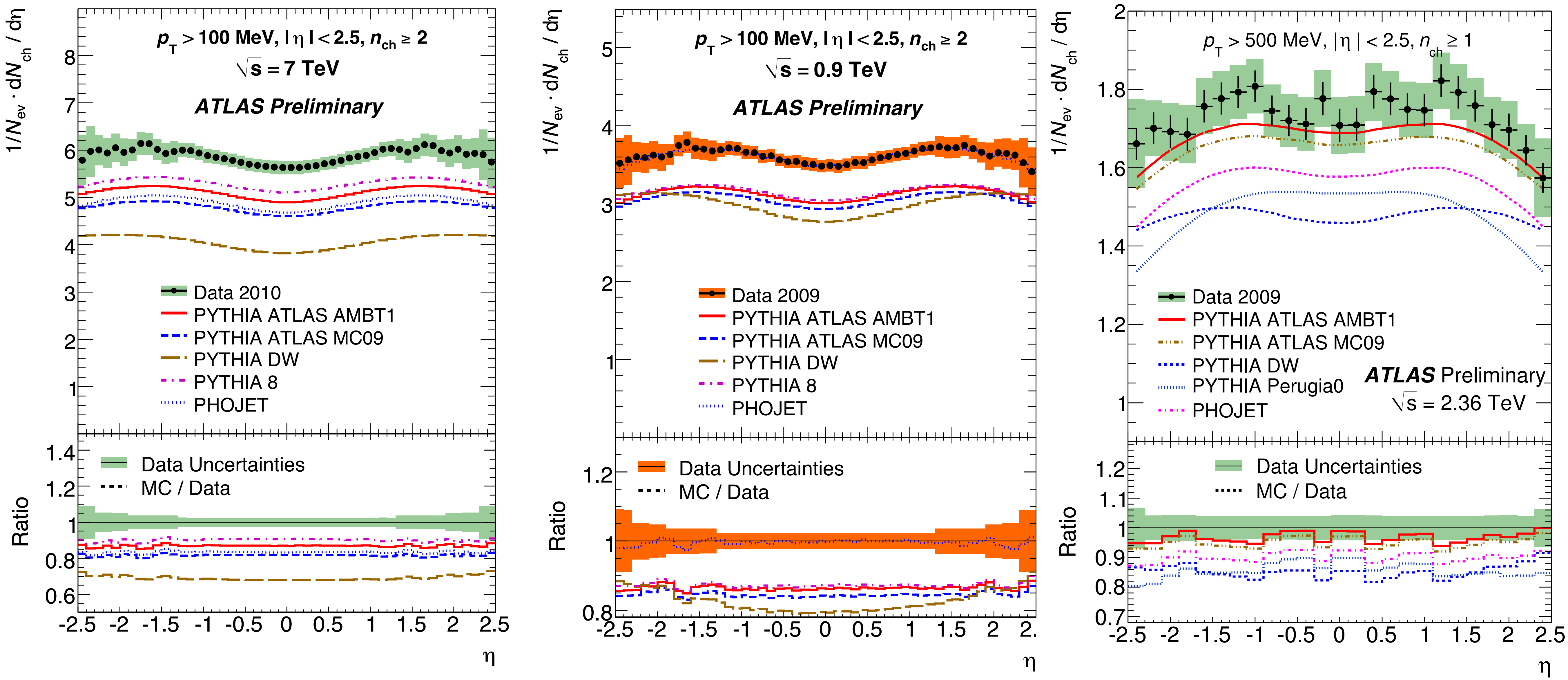
Pixel tracks

- Hits from Pixel layers + primary vertex
- Smaller material systematic
- Degraded p_T resolution
- Used for n_{ch} and η distributions
- Relative Pixel efficiency from SCT +TRT tracks (from Data)
- Small correction factor from MC → absolute Pixel efficiency

$1/N_{ev}\ dN_{ch}/d\eta$

>= 2 particles, pT > 100 MeV

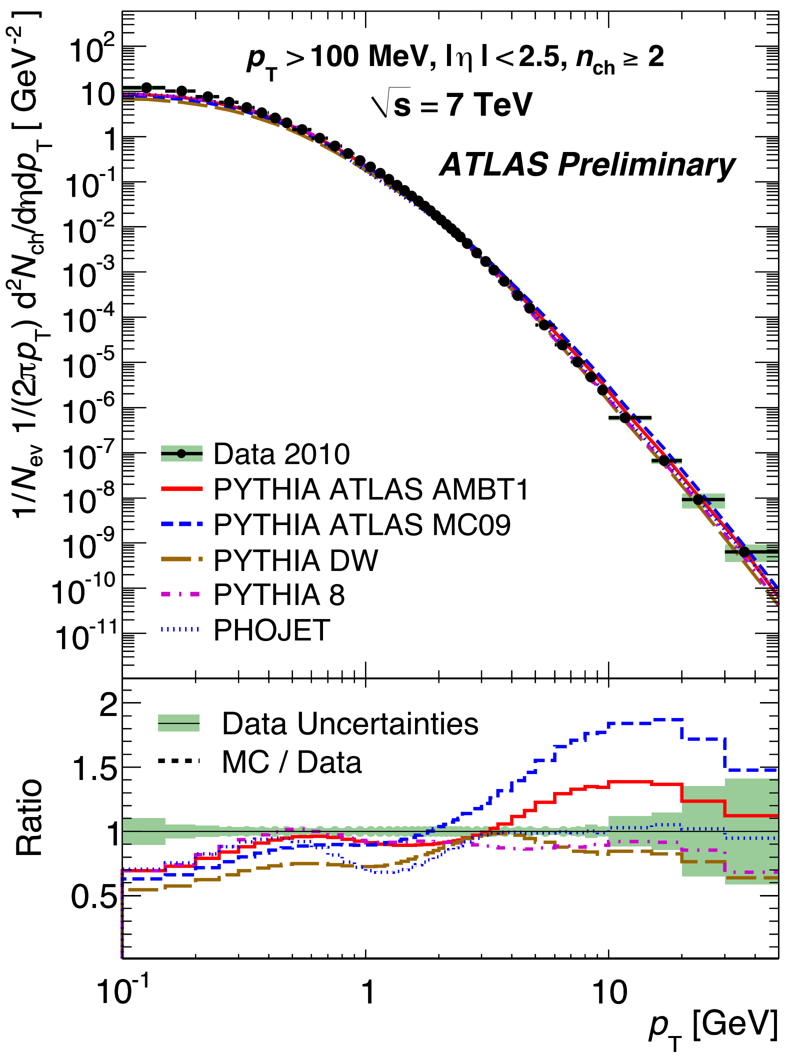
>= 1 particles, pT > 500 MeV

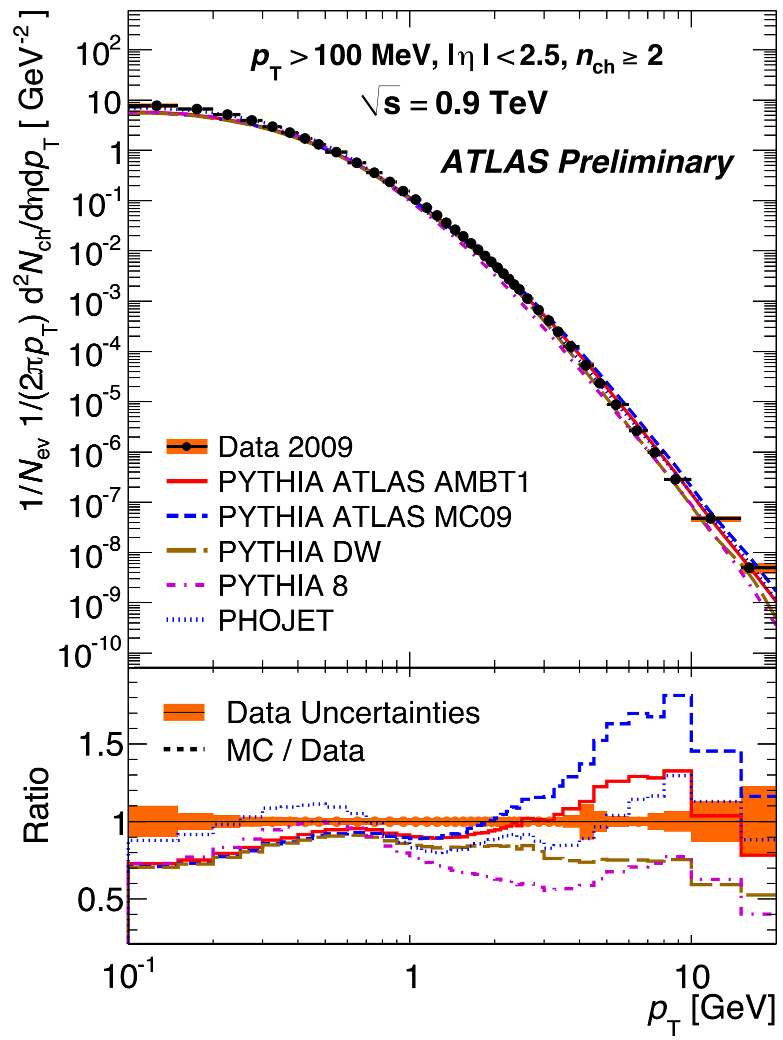


- Very little shape variation between models
- Difference mostly in normalisation

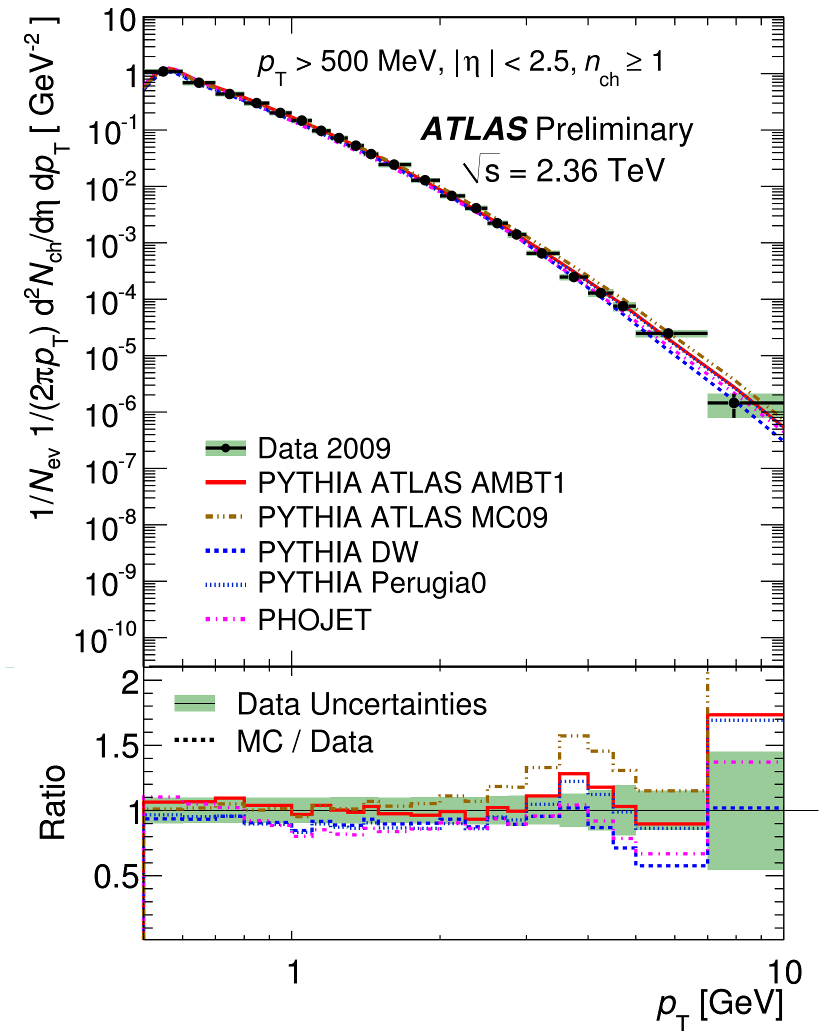
$1/2\pi p_T\ 1/N_{ev}\ d^2N_{ch}/d\eta dp_T$

>= 2 particles, pT > 100 MeV





>= 1 particles, pT > 500 MeV

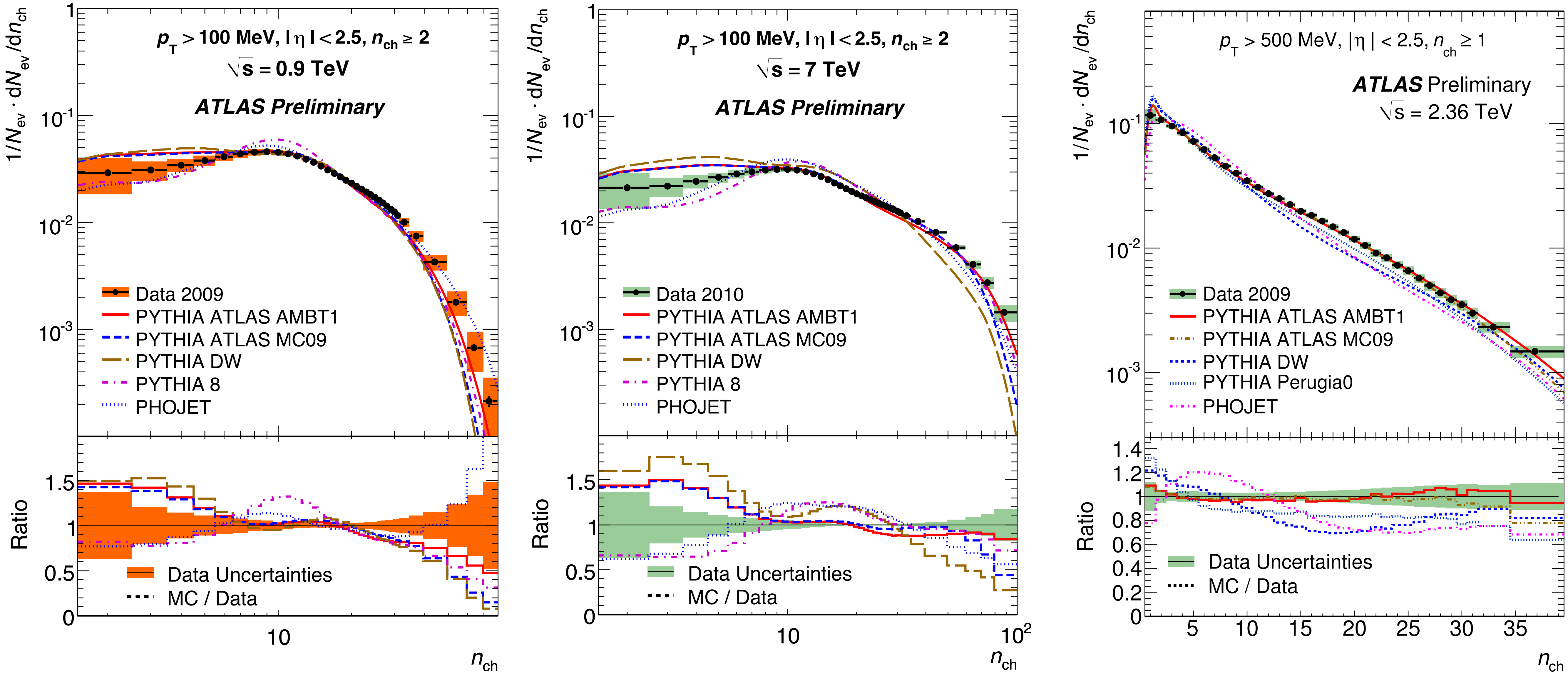


- Measurements span ~ 10 orders of magnitude
- Large disagreements at lowest p_T
- At Intermediate p_T much better agreement of new AMBT1 tune

$1/N_{ev}\ dN_{ev}/dn_{ch}$

>= 2 particles, pT > 100 MeV

>= 1 particles, pT > 500 MeV



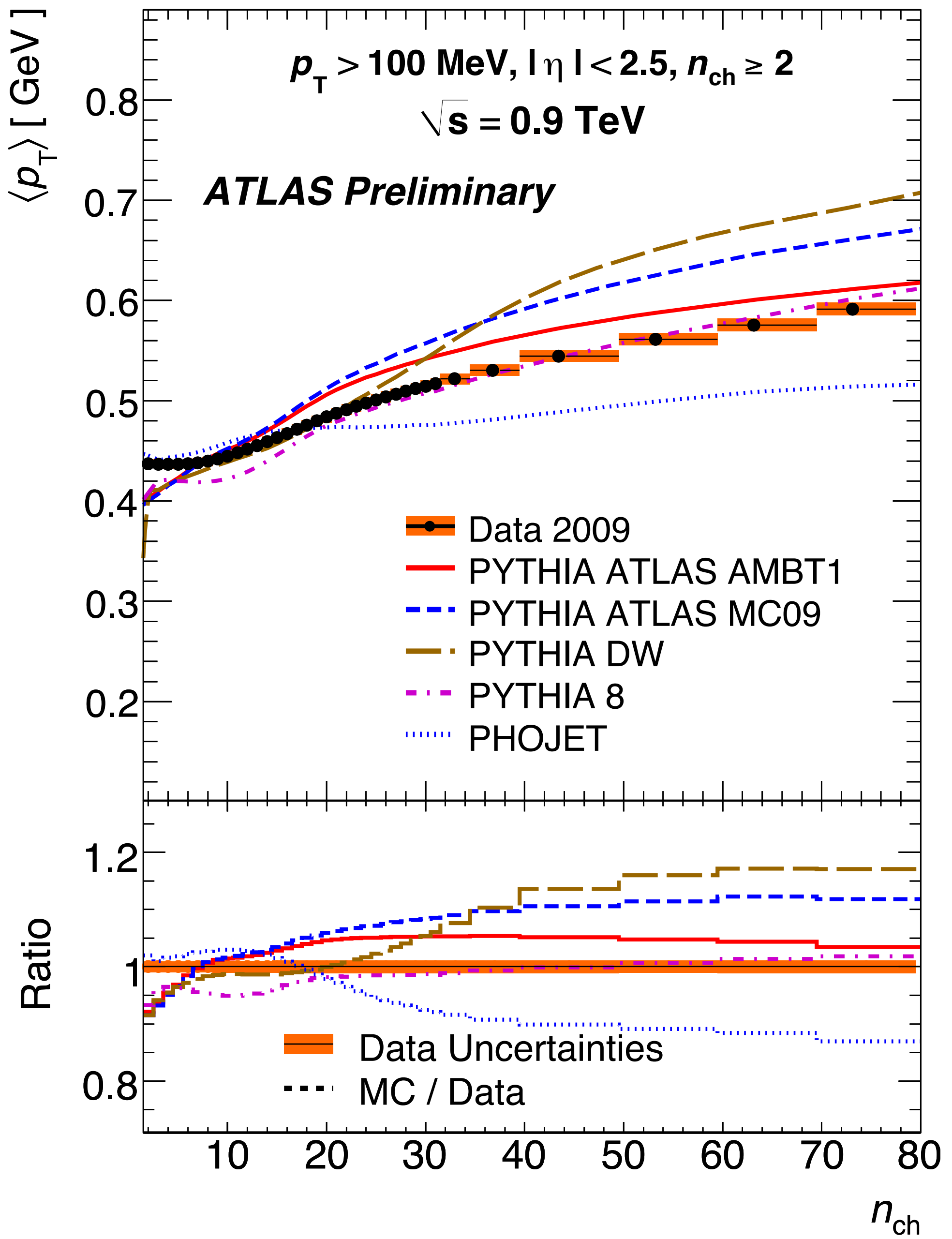
At low p_T threshold

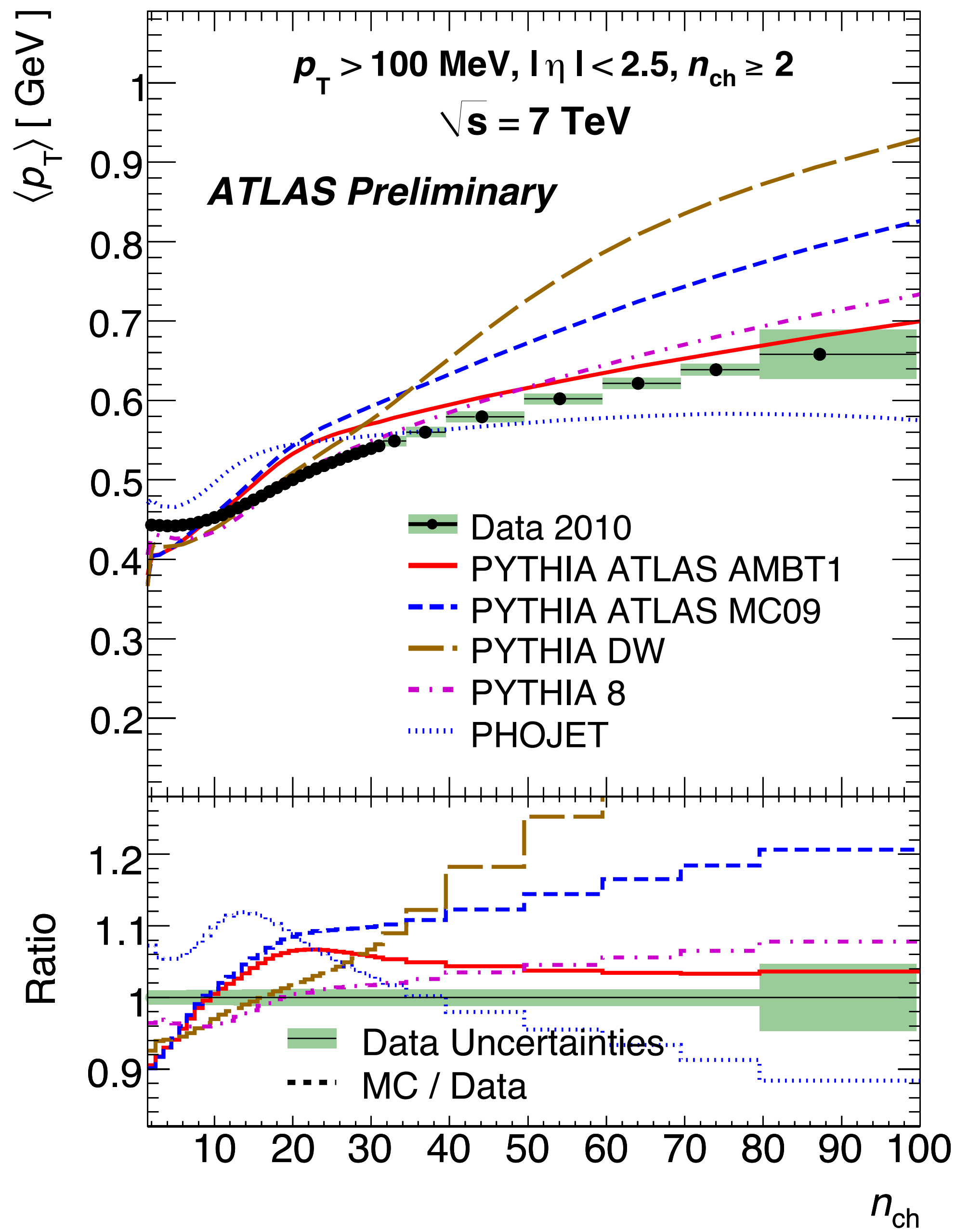
- Peak around 10 particles per event
- Both low and high values not well described by current MC

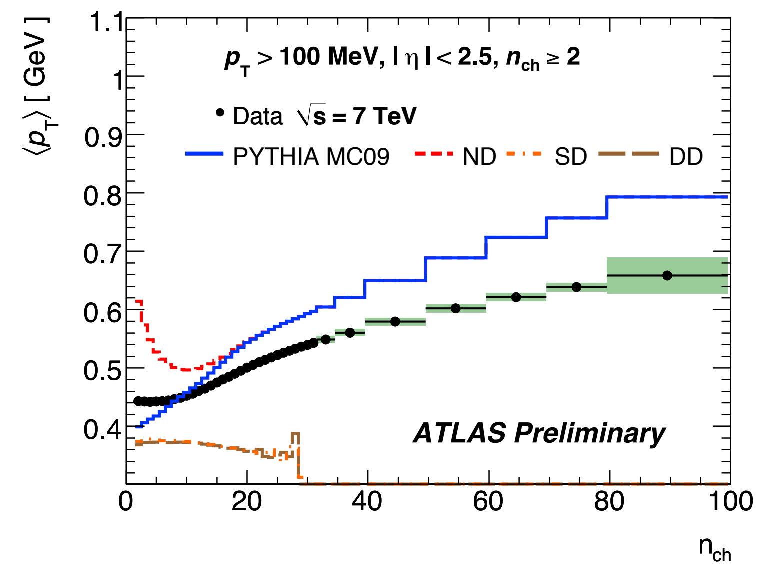
At high p_T threshold

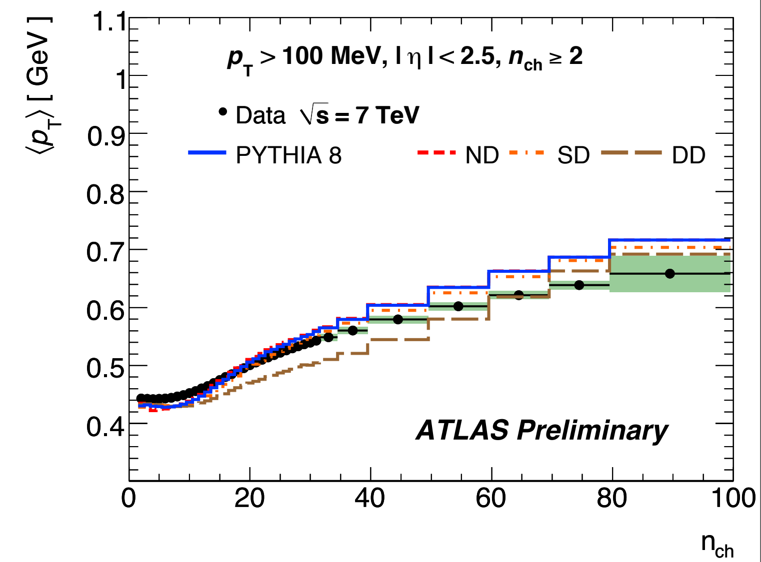
- AMBT1 describes full spectrum better than 10%
- Other tunes have different shapes in intermediate regions

<p_T> vs n_{ch}





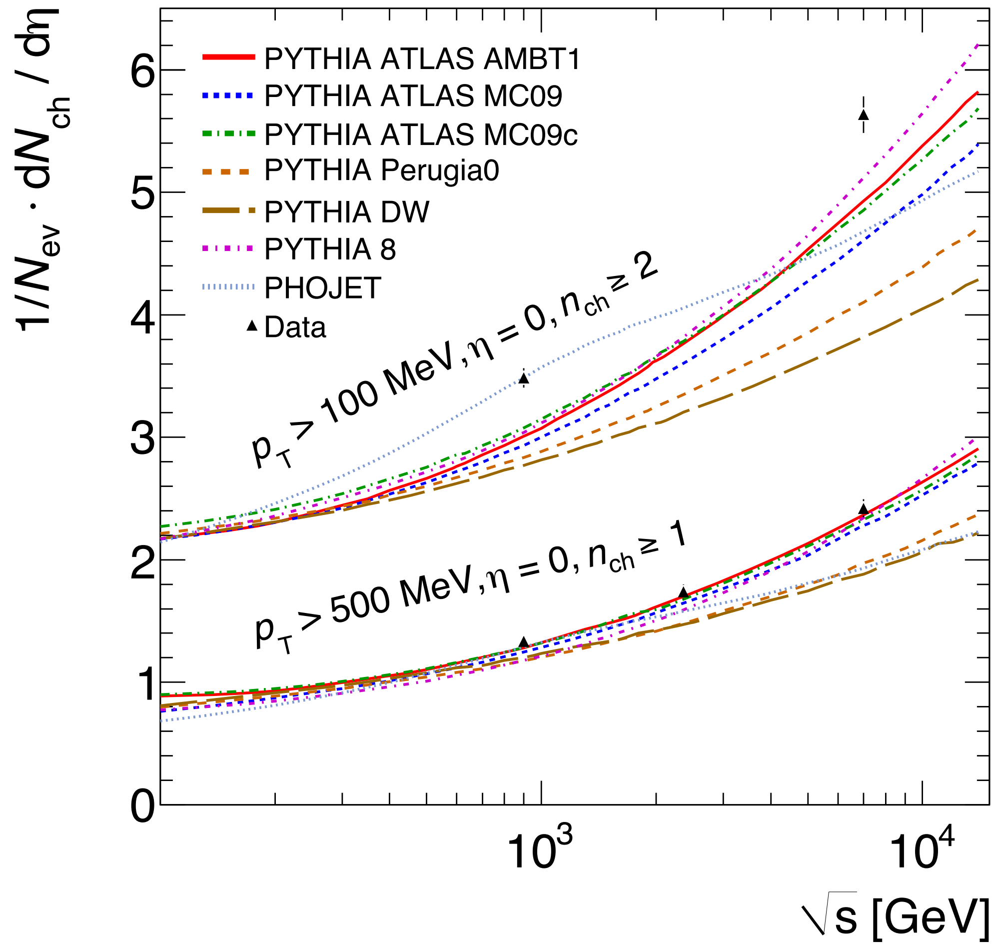




- Shape at high n_{ch} well-modelled
- AMBT1 and Pythia8 reproduce the spectrum the best
- Low n_{ch} shape sensitive to ND,SD,DD fractions

Summary

- ATLAS Inner Tracker performing very well
- Measured charged particles down to pT > 100 MeV
  (√s = 0.9 and 7 TeV)
- Fully corrected for detector effects
- Measurement possible at √s = 2.36 TeV
  (>= 1 particle, pT > 500 MeV)
- No model-dependent corrections applied
- Measurement as inclusive as possible
  - Significant fraction of diffractive events (order 20%)
  - MC models don't agree as well as for $p_T > 500$ MeV

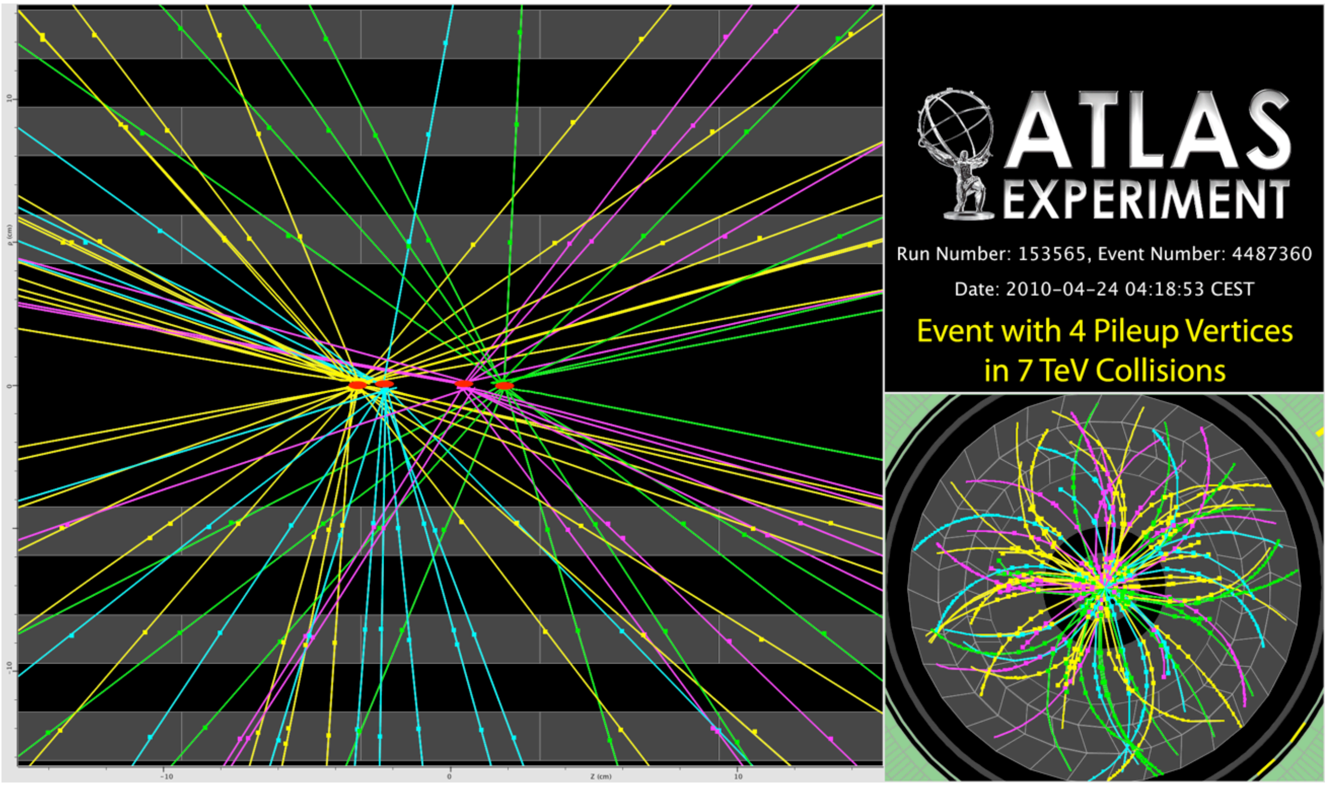


References

- Charged-particle multiplicities in pp interactions at sqrt(s) = 900 GeV measured with the ATLAS detector at the LHC
  - CERN-PH-EP/2010-004 (15 March 2010), Phys Lett B 688, Issue 1, 21-42
  - Phase-space: $p_T > 500$ MeV
- Charged particle multiplicities in pp interactions for track $p_T > 100$ MeV at sqrt(s) = 0.9 and 7 TeV measured with the ATLAS detector at the LHC
  - ATLAS CONF NOTE: ATLAS-CONF-2010-046
- Charged particle multiplicities in pp interactions at sqrt(s) = 2.36 TeV measured with the ATLAS detector at the LHC
  - ATLAS CONF NOTE: ATLAS-CONF-2010-047
  - Phase-space: pT > 500 MeV
- Monte Carlo tunes
  - Charged particle multiplicities in pp interactions at sqrt(s) = 0.9 and 7 TeV in a diffractive limited phase-space measured with the ATLAS detector at the LHC and new PYTHIA6 tune
    - Atlas Minimum Bias Tune 1 (AMBT1), ATLAS-CONF-2010-031
  - ATLAS Monte Carlo tunes for MC09
    - ATLAS MC09 tunes, PHYS-PUB-2010-002

Pile-Up removal

- The fraction of events with more than one p-p interaction is estimated to be around 0.1% for the data collected at 7 TeV.
- The presence of such events might bias the tails on the nch distribution.
- Expect ~1% of events with a second reconstructed vertex:
    - mostly fakes and secondary vertices with few tracks.
- Remove events with a second vertex with more than 3 tracks.
- Residual effects after pileup removal:
    - Fake pileup events removed: 0.03%
    - True pileup events not removed : 0.01%
    - True Pileup events reconstructed as single vertex: 0.01%



Track Selection

Track Reconstruction algorithms: tracks from ***inside-out*** and ***low p_T***

Impact Parameter Requirements: $|d_0^{PV}|<1.5$ mm, $|z_0^{PV}| \sin\theta<1.5$ mm

Track Length Requirement (2/4/6 cut):

$100 < p_T <= 200$ MeV : $N_{SCT} >= 2$

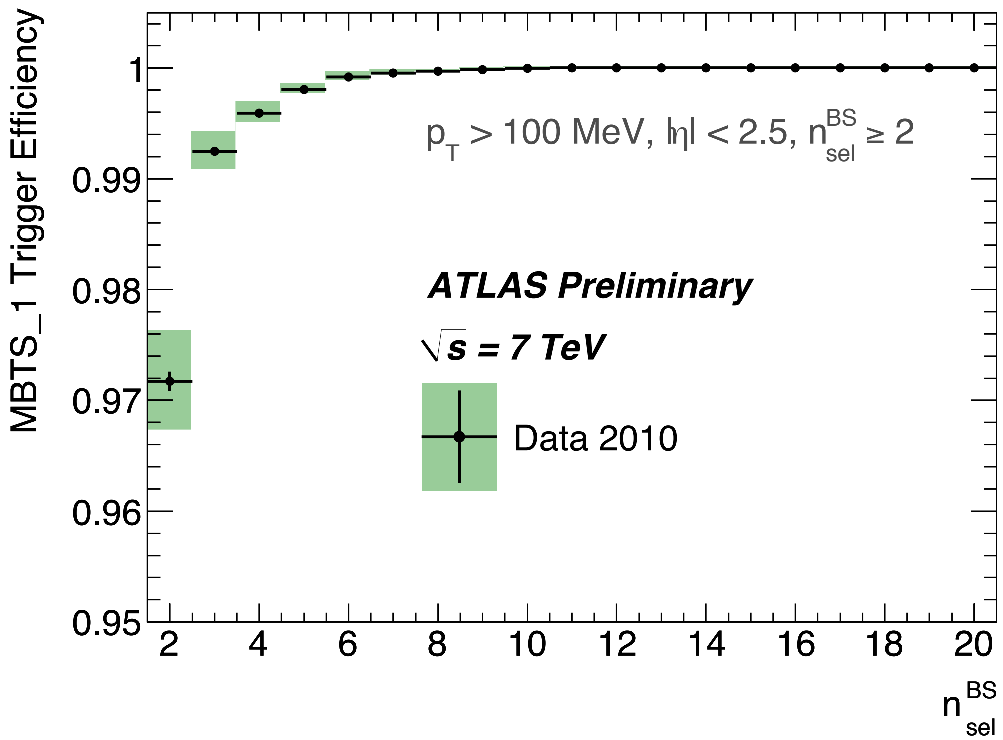
$200 < p_T <= 300$ MeV : $N_{SCT} >= 4$

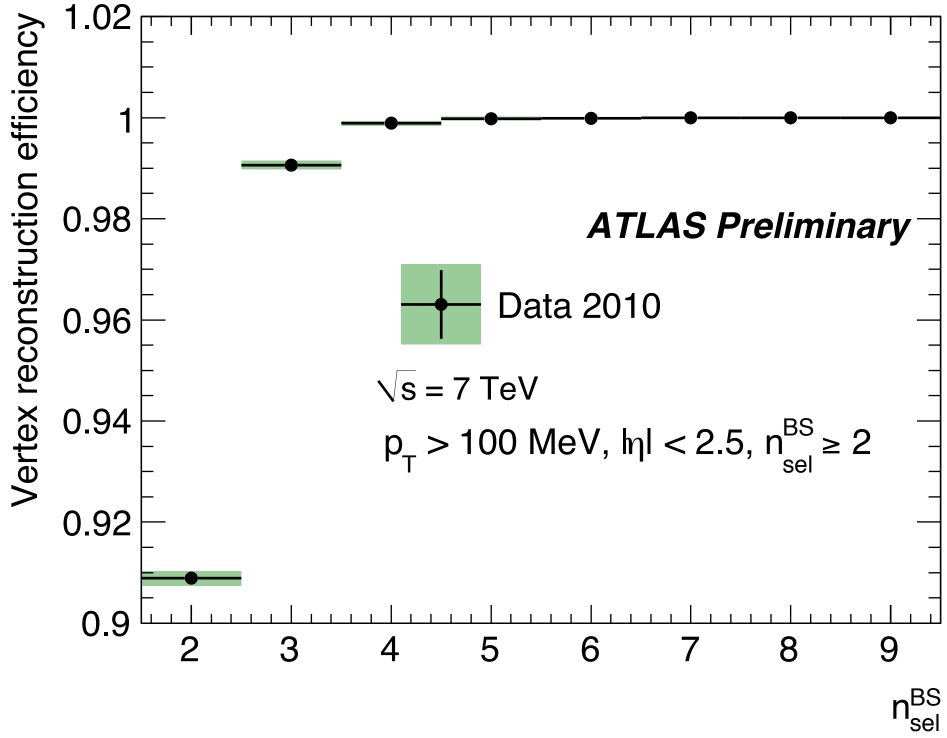
$p_T > 300$ MeV : $N_{SCT} >= 6$

Pixel Hit Cut: if B-Layer hit is expected, require B-Layer, otherwise 1 Pixel hit

Tracks with p_T > 10 GeV : Prob(χ^2,Ndof) > 0.01

Trigger & Vertex Efficiencies





Trigger efficiency from data:

- measured with respect to a random trigger with a loose requirement on activity in the Inner Tracker
- Efficiency was checked to be flat in p_T and η
- Tracks are extrapolated to beam spot instead of primary vertex in the absence of the vertex

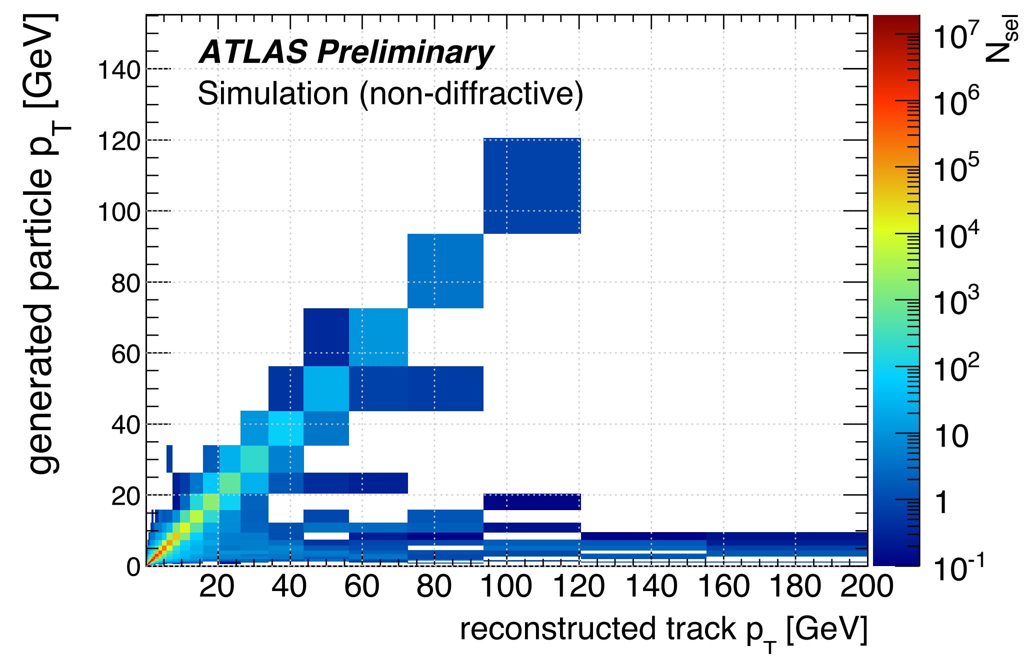
Vertex efficiency from data:

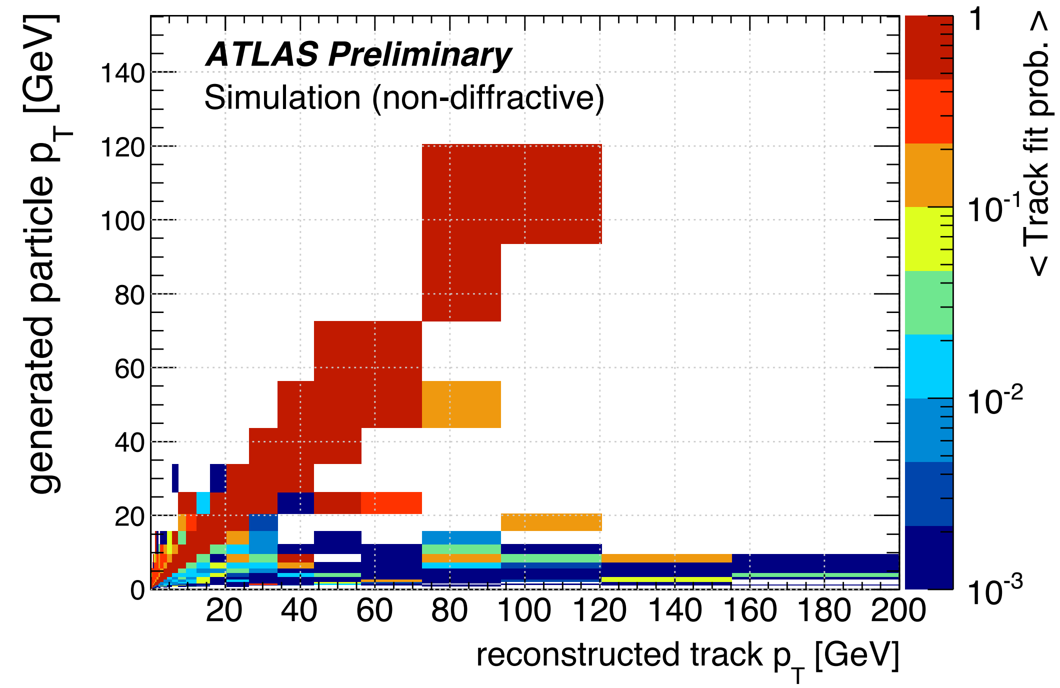
- Dependencies on the longitudinal impact parameter spread (Δz_0) and p_T for events with low track multiplicity are also taken into account.

High-p_T Tracks

A fraction of high-p_T tracks is caused by low p_T particles:

- *Non-Gaussian tail in track momentum response*
- *Steeply falling p_T spectrum in min. bias events (9 orders of magnitude between 100 MeV and 50 GeV)*



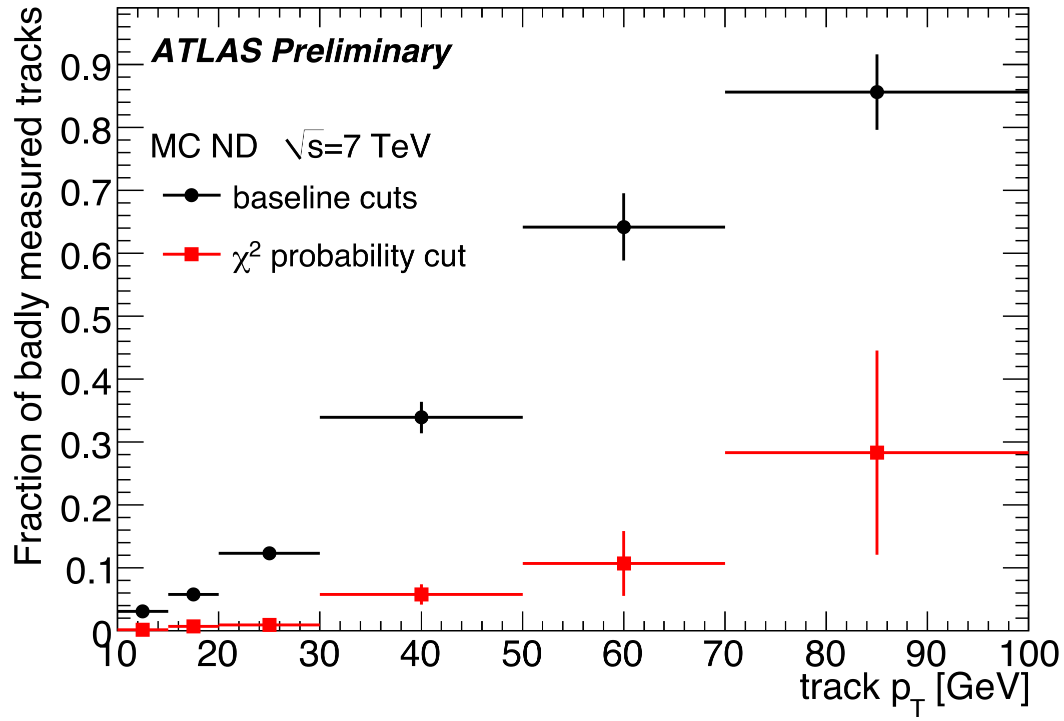


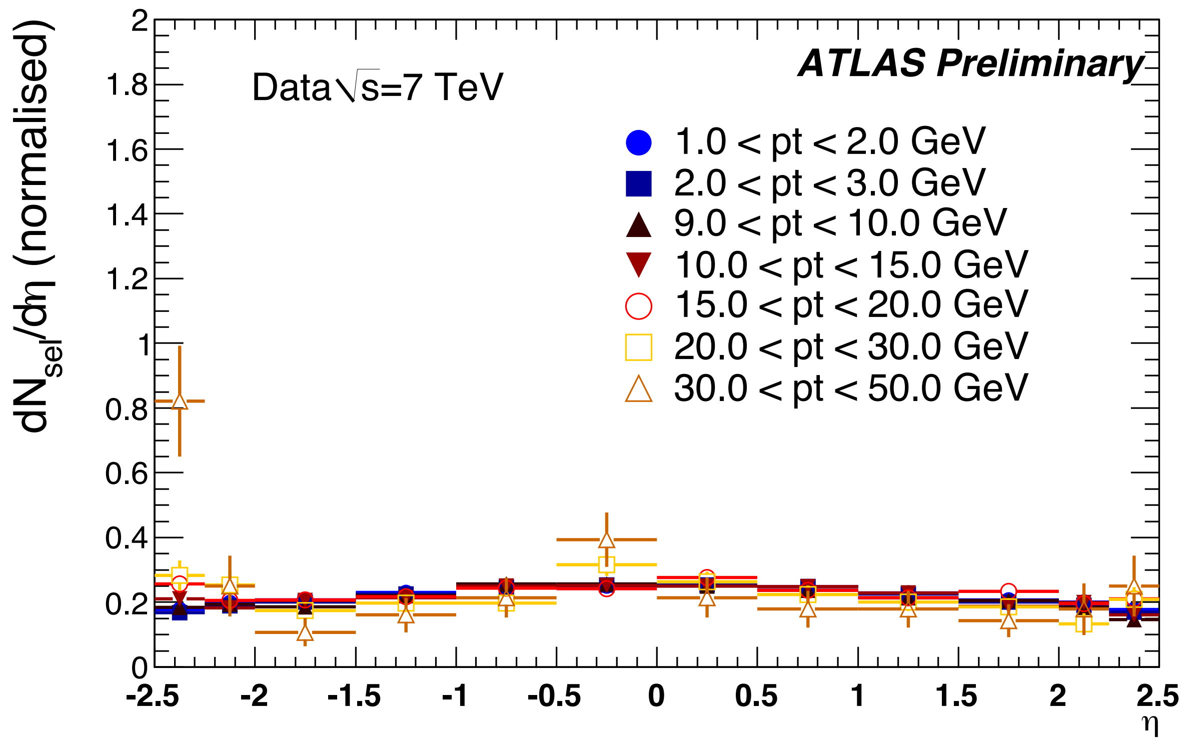
Single particle MC:

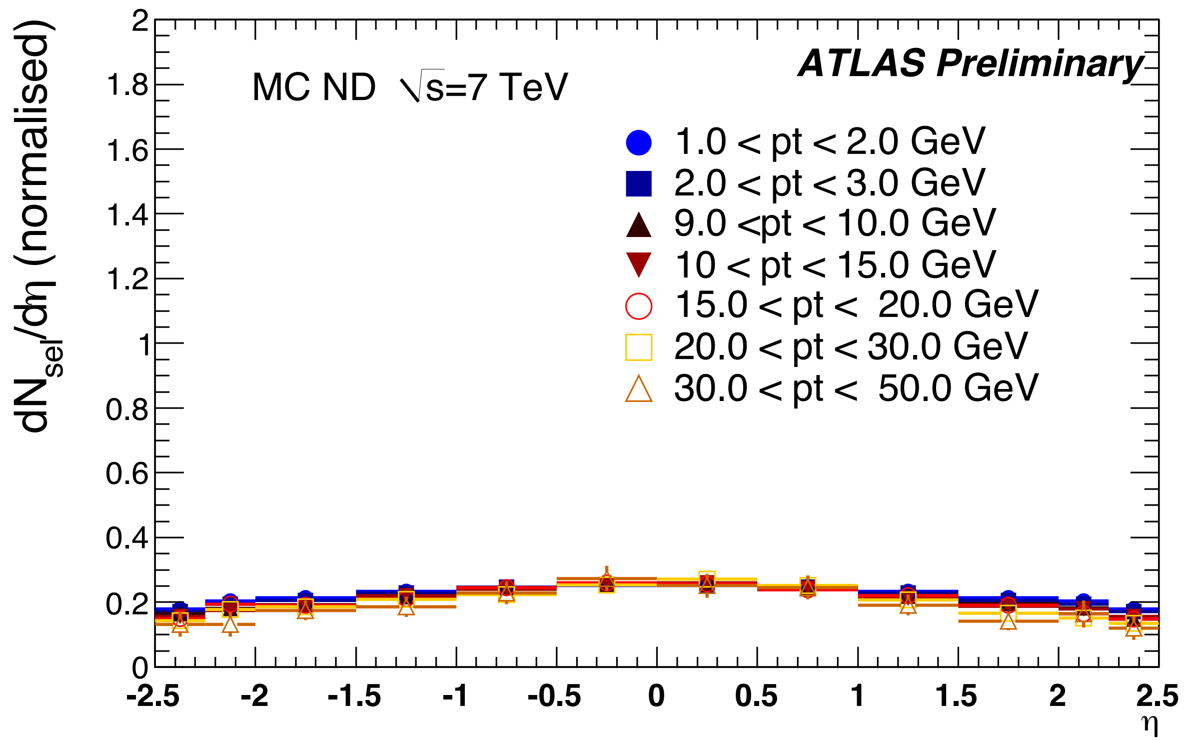
- *Single pions show same behavior (once re-weighted to p_T spectrum)*
- *Single muons well behaved up to highest momentum*

High-p_T Tracks

- Cut on track-fit-probabilty greatly reduces fraction of mis-measured tracks
- Remaining fraction in Data is estimated form e.g. eta-shape

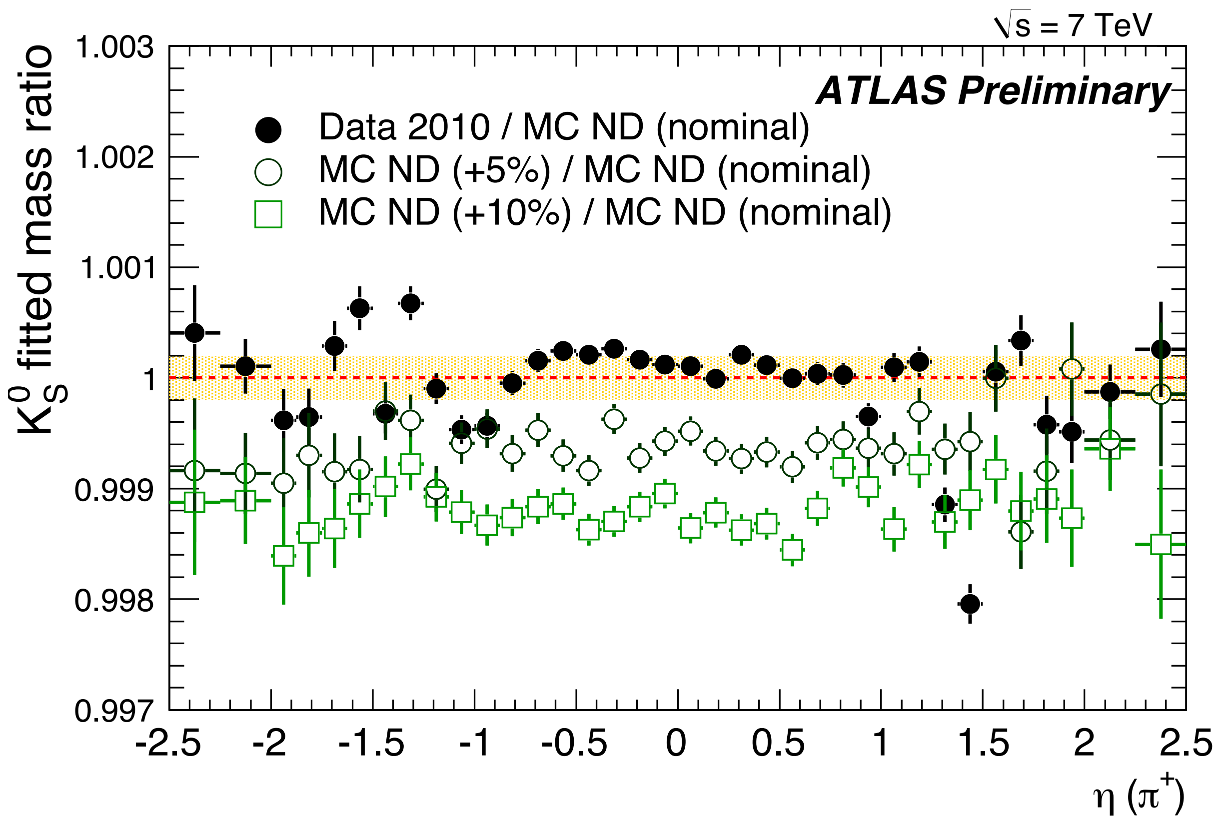


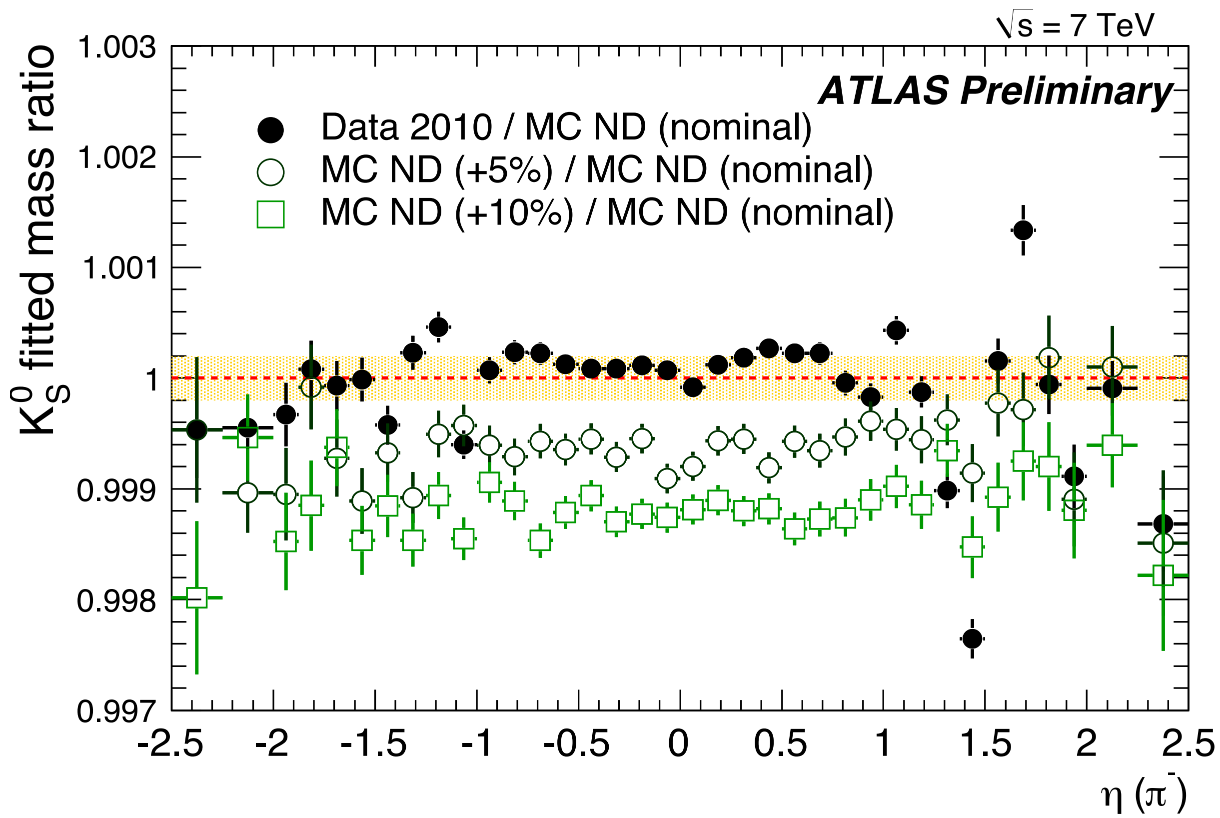




Material uncertainty

- Two data driven methods to estimate difference between the real detector and the material description in the simulation:
  - Invariant mass of $K^0 \rightarrow \pi^+\pi^-$ measured as function of η, φ and decay radius. Greatest sensitivity to small decay radii.
  - Compare track lengths in Data and MC. Probes material description in terms of nuclear radiation length, starting after the Pixel detector.

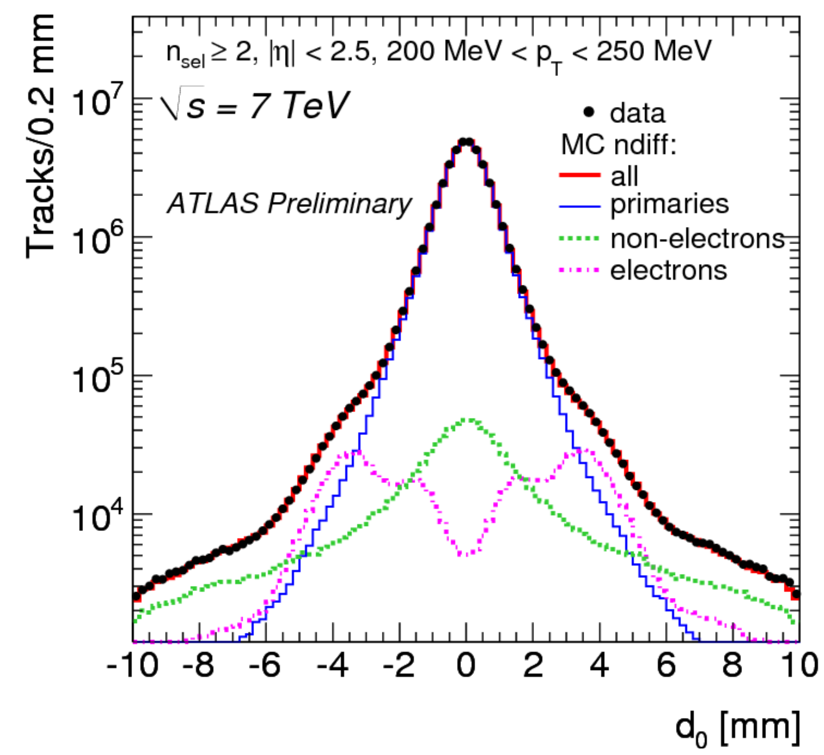


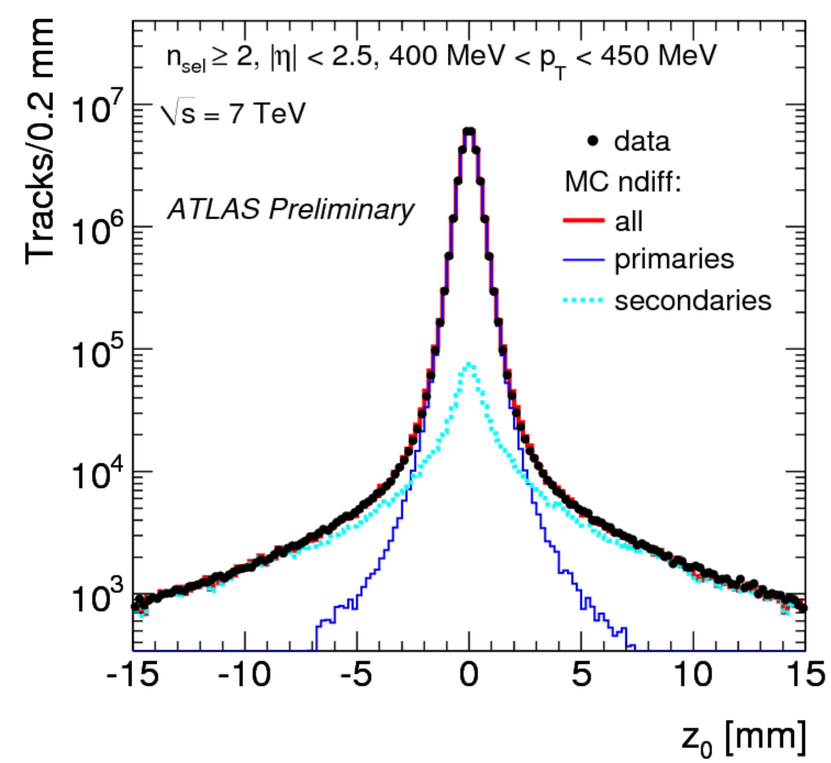


Non-primary Tracks

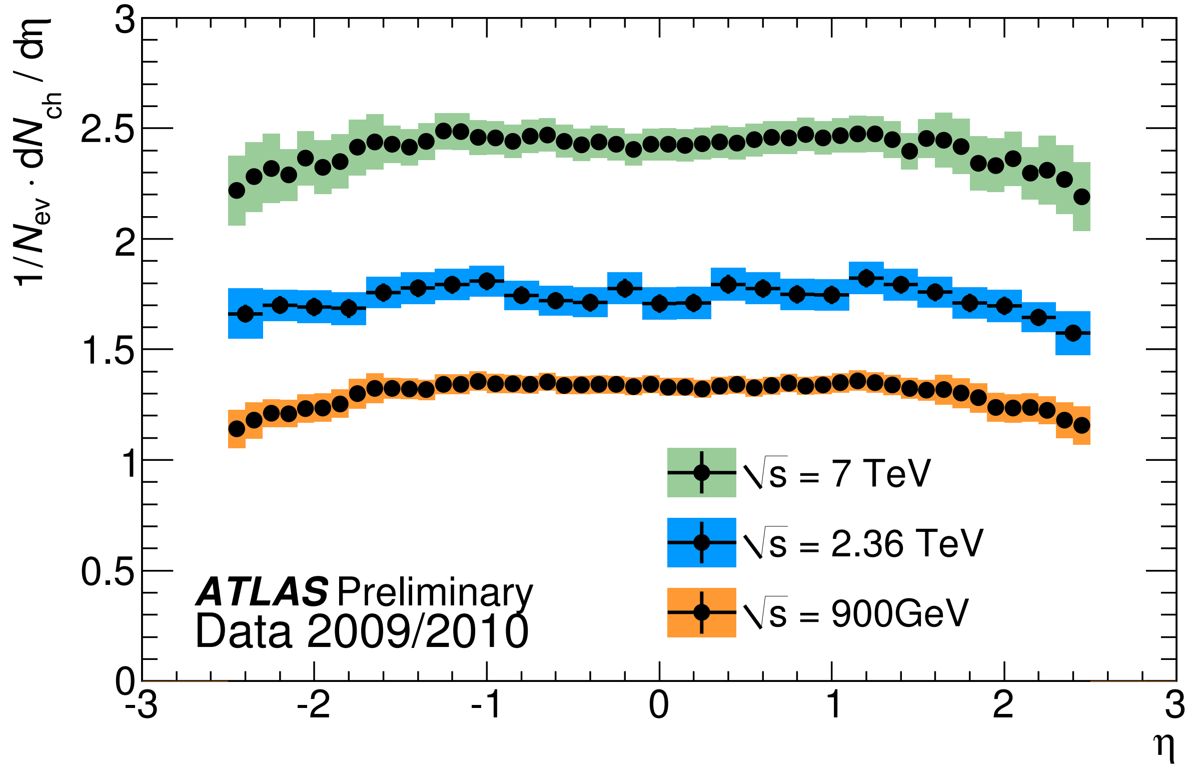
The rate of non-primary tracks is estimated by fitting the tails of the transverse impact parameter distribution on data:

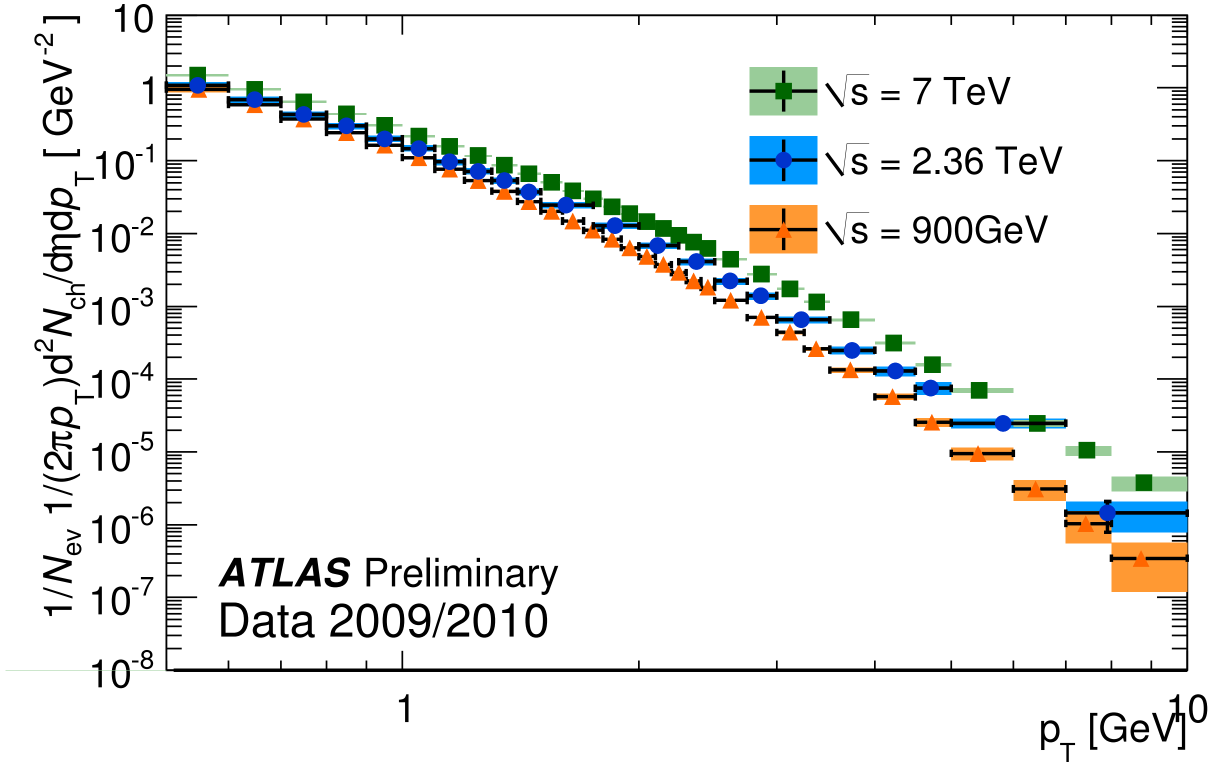
- Contribution from conversion electrons and other types of non- primaries are fitted simultaneously.
- Results validated by fitting the longitudinal impact parameter as electrons from conversion look identical to other type of non- primary tracks.

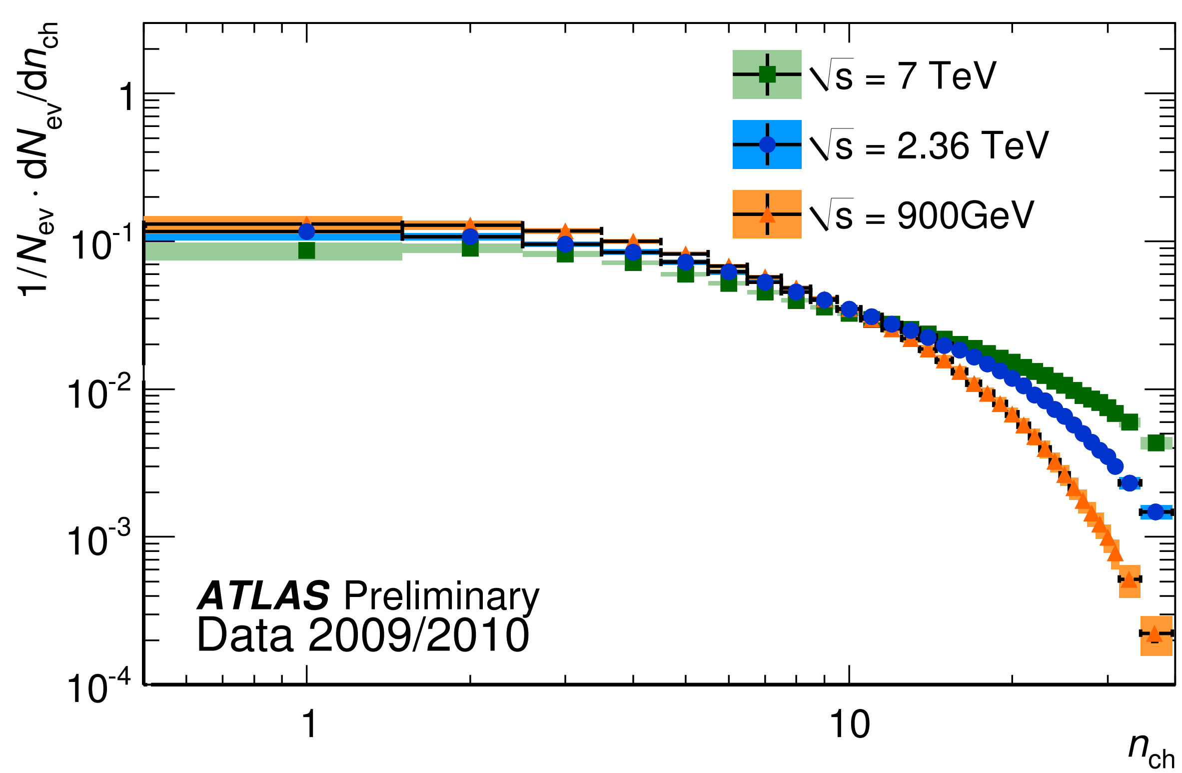




Energy Comparison

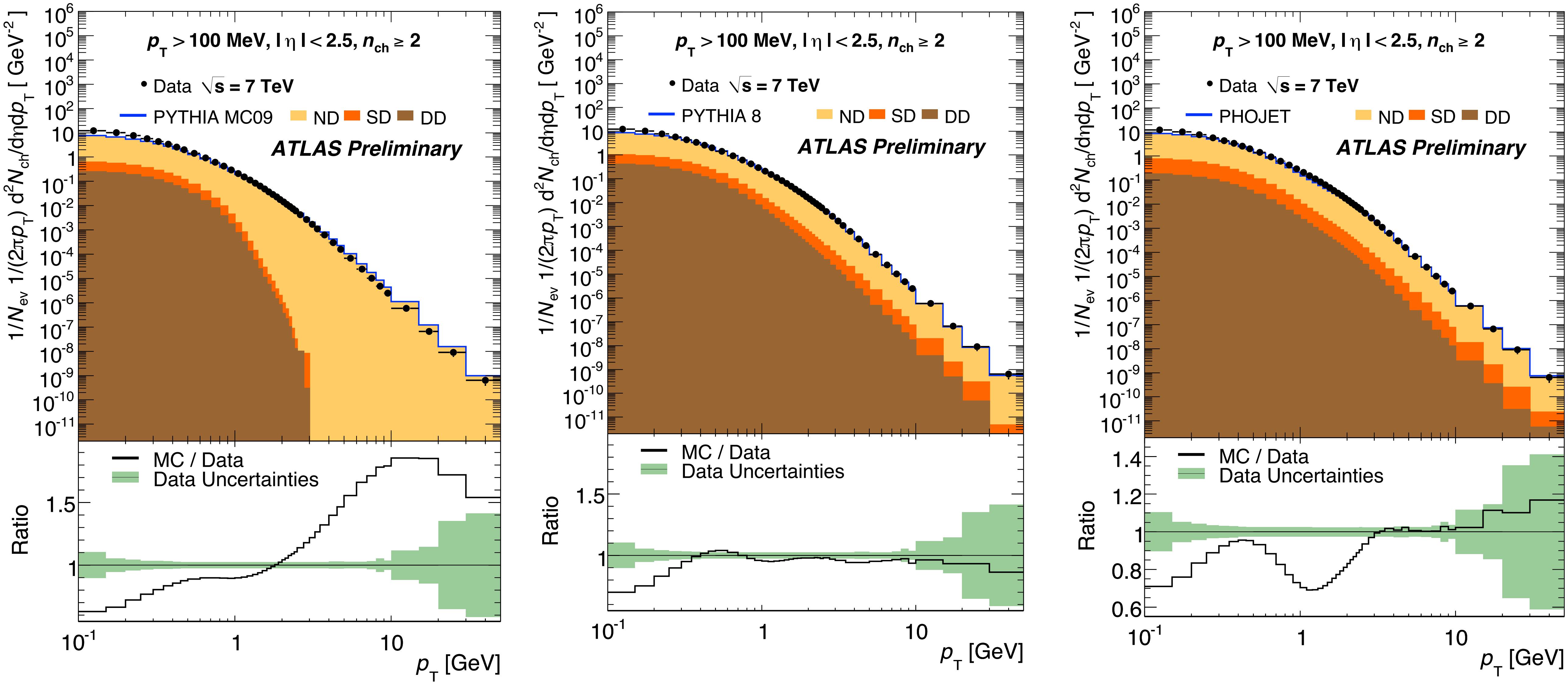






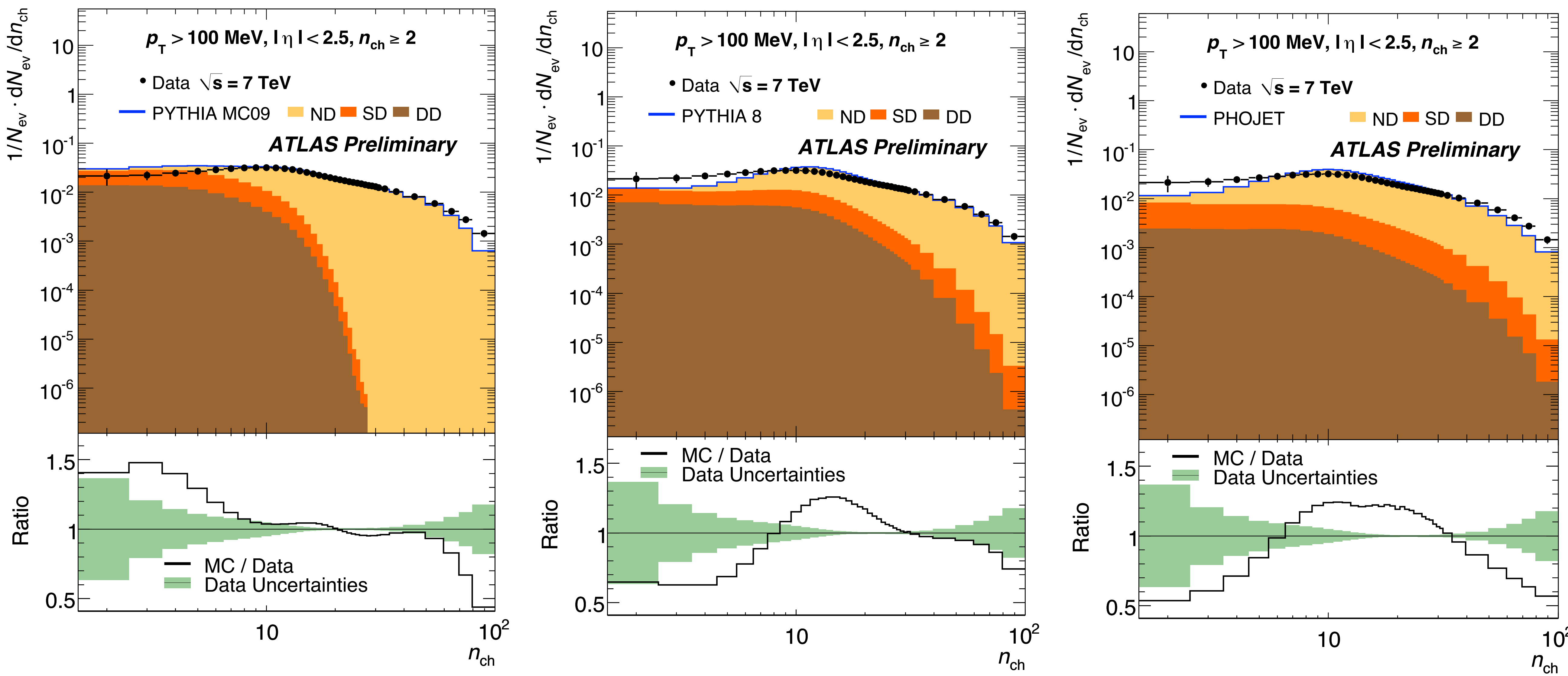
$1/2\pi p_T \; 1/N_{ev} \; d^2N_{ch}/d\eta dp_T$

Comparing spectra from different diffraction models
Pythia 6 has no hard component to diffraction

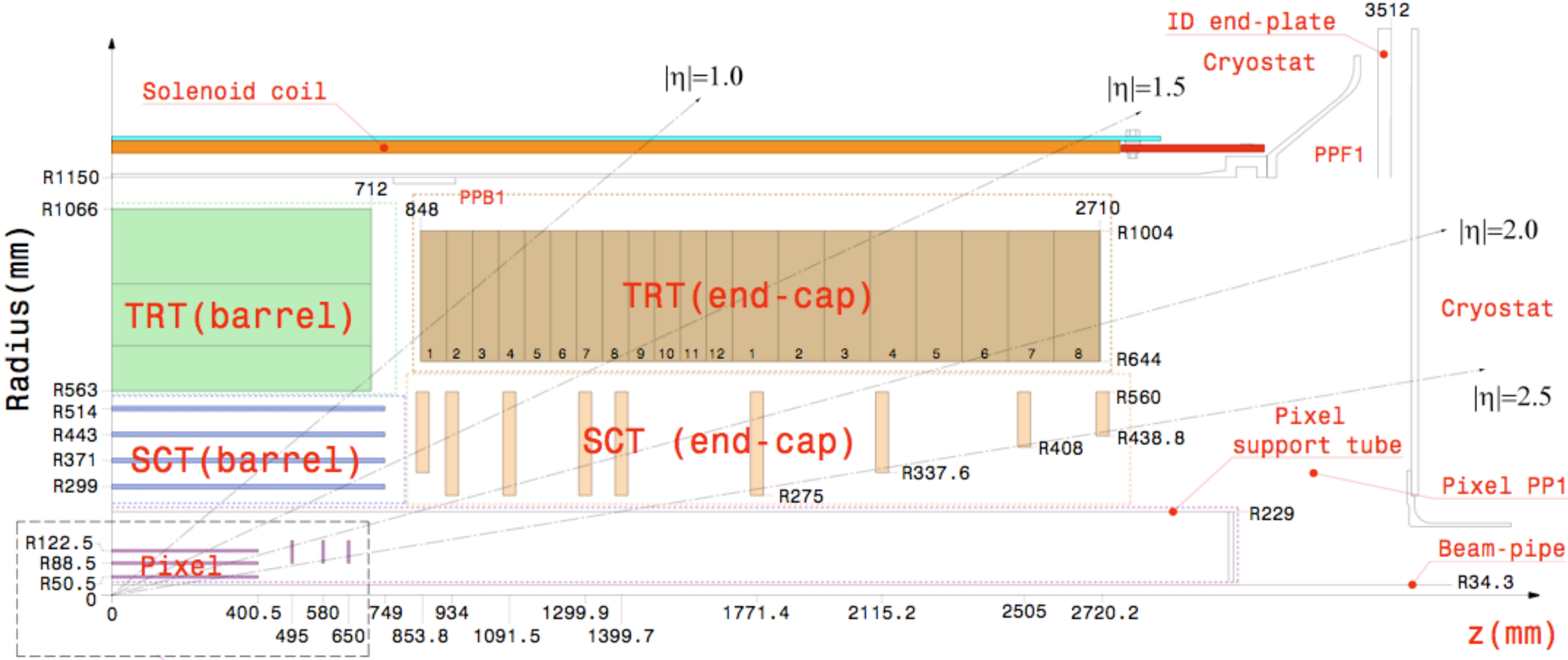


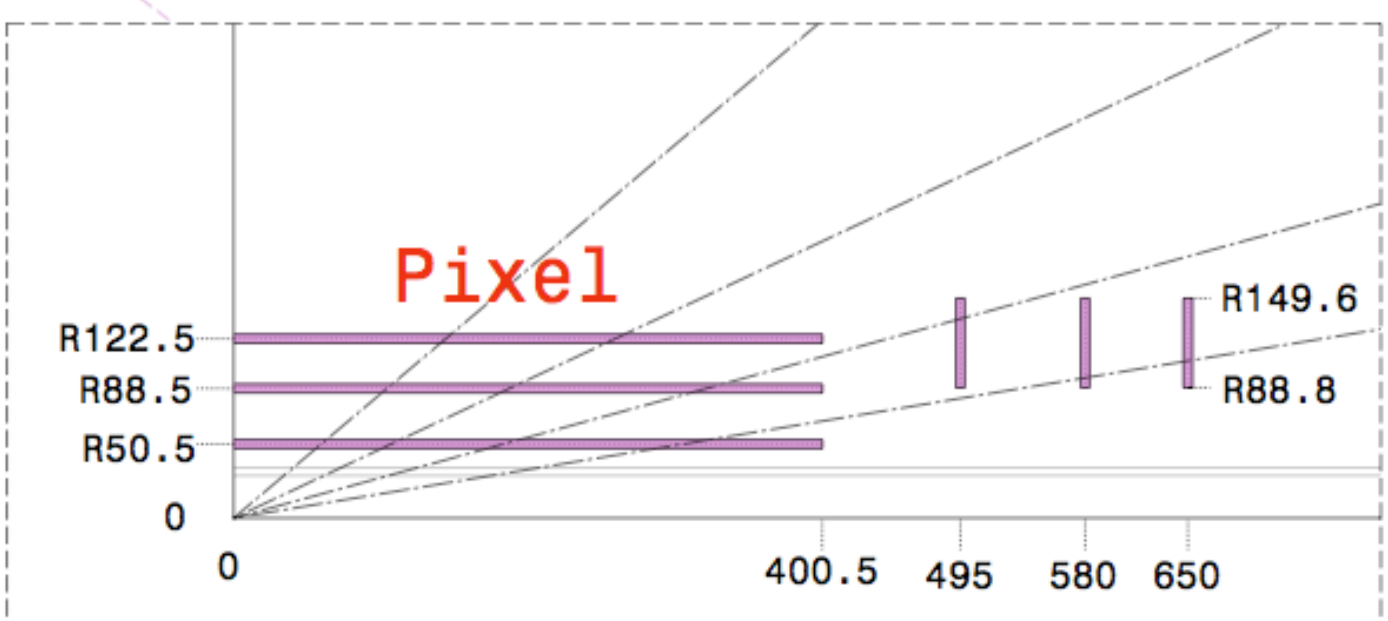
$1/N_{ev}\ dN_{ev}/dn_{ch}$

Comparing spectra from different diffraction models
Pythia 6 has no hard component to diffraction



ATLAS Inner Detector





Envelopes

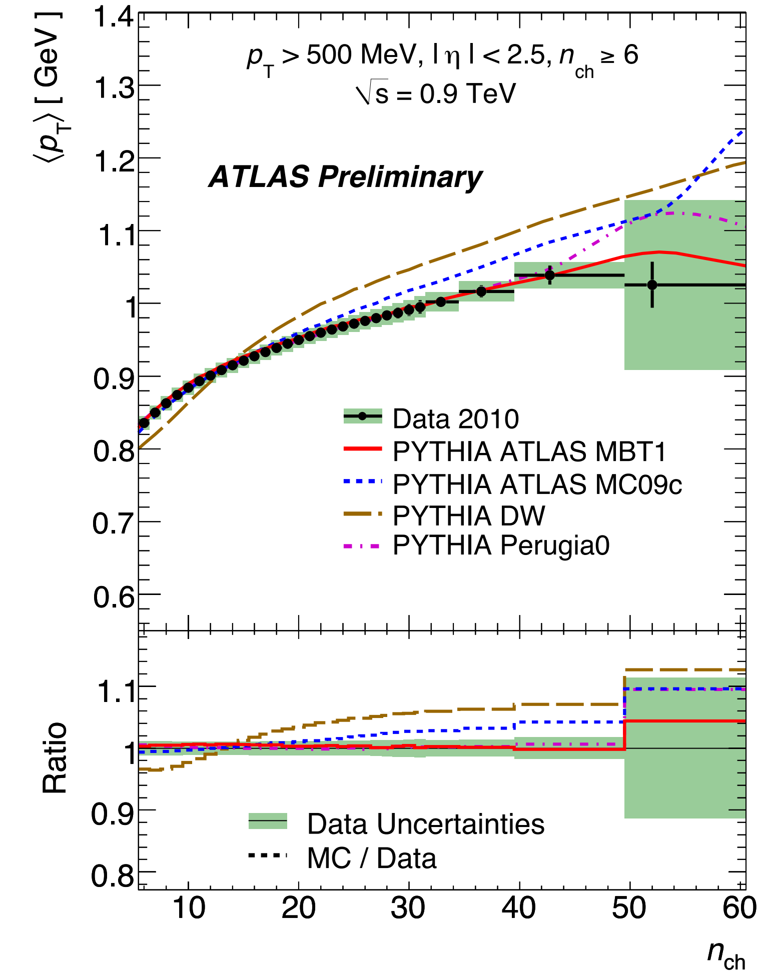
Pixel		45.5<R<242mm |Z|<3092mm
SCT barrel		255<R<549mm |Z|<805mm
SCT end-cap		251<R<610mm 810<|Z|<2797mm
TRT barrel		554<R<1082mm |Z|<780mm
TRT end-cap		617<R<1106mm 827<|Z|<2744mm

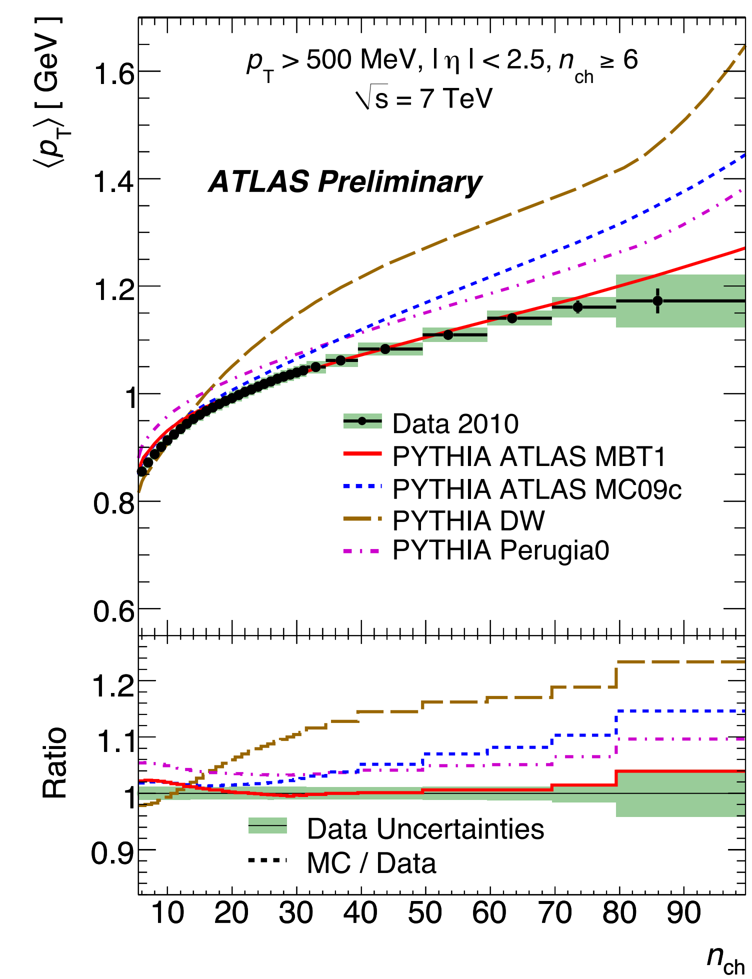
Tuning to
Minimum Bias
& Underlying Event

Tuning Selections

- New AMBT1 tune of Pythia 6.4, based on the MC09 tune with reduced color reconnection. (Denoted by MC09c.)
- AMBT1 focusses on matching ATLAS measurements in non-diffractive regimes.
- For Minimum Bias measurements, events were considered only if they included ≥ 6 Selected Tracks.
  - The Pythia 6.4 diffractive processes have negligible contributions to these events.

Model	Parameter	Parameter ID	MC09c	AMBT1
MPI: Incoming Partons	Minimum p_T	PARP[82]	2.31	2.292
	Energy Extrapolation	PARP[90]	0.2487	0.250
MPI: Matter Distribution	Core Matter Fraction	PARP[83]	0.8	0.356
	Core Radial Fraction	PARP[84]	0.7	0.651
Color Reconnection	Reconnection Strength	PARP[78]	0.224	0.538
	High p_T Suppression	PARP[77]	0.0	1.016





Tune Interpretation

- MPI Incoming Partons: $p_{T\text{-min}} = PARP[82](E_{HS}/1.8TeV)^{PARP[90]}$
  - $p_{T\text{-min}}$ defines a cutoff (interpreted as screening) for MPI only.
  - ➡ Reducing PARP[82] increases MPI in general.
  - ➡ Increasing PARP[90] increases MPI at 900 GeV & reduces it at 7 TeV.
- MPI Matter Distribution:
  - Matter is distributed in a wide gaussian (proton radius) and a core narrow gaussian.
  - Given an impact parameter for colliding protons the overlap determines the MPI probability.
  - A higher probability for parton interactions raises the typical highest energy interaction.
    - Above some Hard Scatter energy there is typically complete overlap, yielding the Underlying Event plateau.
  - ➡ AMBT1 yields a higher probability for high-multiplicity events.
- Color Reconnection: $P_{Reconnect} = PARP[78] / \left(1 + \left(PARP[77] * p_{StrAvg}\right)^2\right)$
  - Reconnection shortens average Lund string lengths.
  - Shorter strings yield fewer, higher p_T hadrons.
  - ➡ AMBT1 yields a higher multiplicity from higher p_T strings.