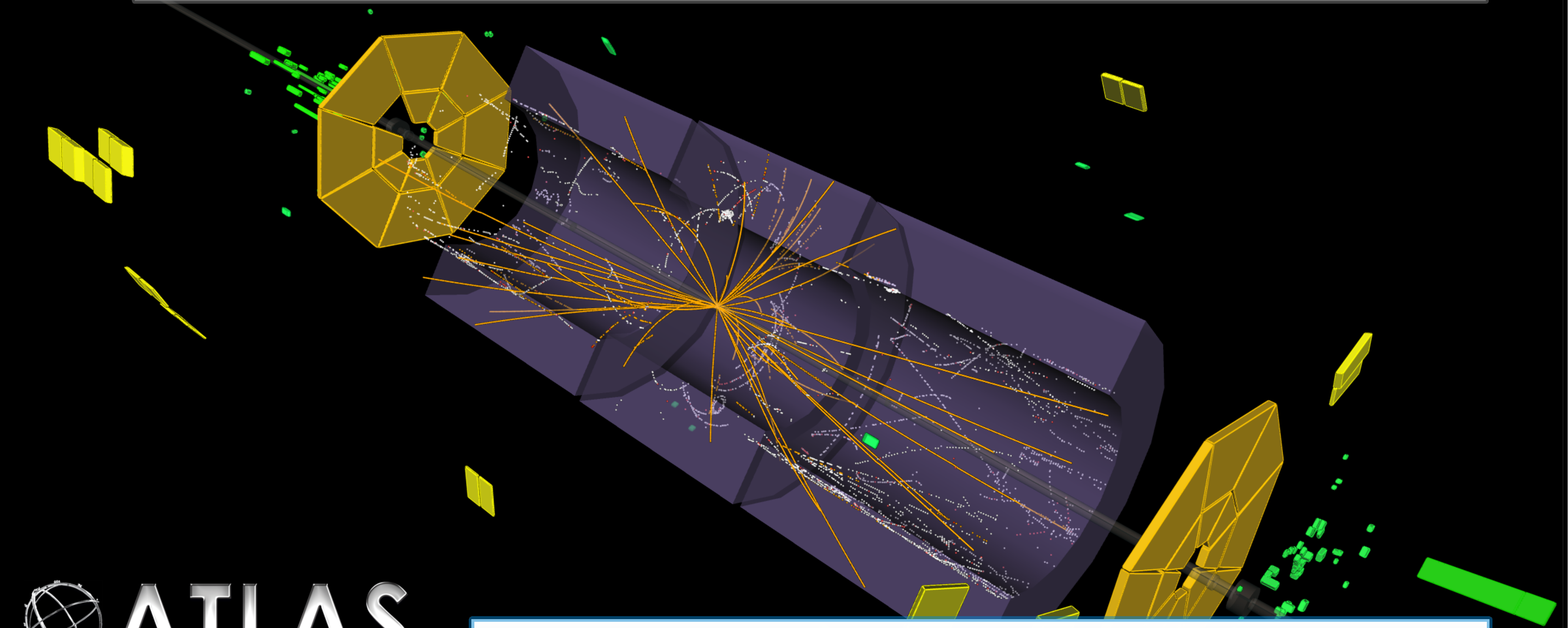
# Charged particle multiplicities in inelastic pp events with the ATLAS detector at the LHC



5th International Workshop on High-Pt Physics at LHC

Thomas Kittelmann (University of Pittsburgh)

**On behalf of the ATLAS collaboration**

ATLAS EXPERIMENT

2010-03-30, 12:58 CEST
Run 152166, Event 316199

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

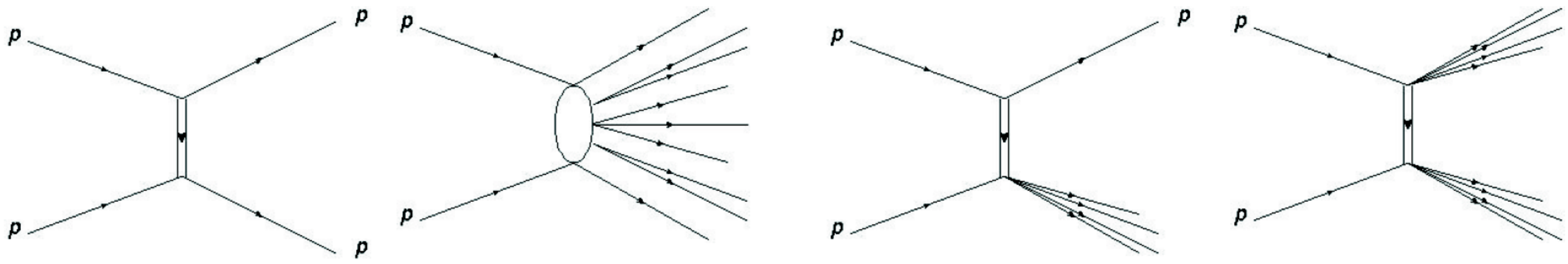
*Collision event at 7 TeV*

# Brief motivation

- Physics motivation: Improve understanding of non-perturbative soft QCD processes.
  - Study the properties of inelastic proton-proton collisions.
- Experimental motivation: model the pile-up and underlying event.
  - Necessary for measuring physics processes at high energies.

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

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



# Measurement strategy

- As inclusive and model-independent as possible
  - Single-arm trigger (enhanced sensitivity to diffractive components)
  - No (model-dependent) corrections back to particular components (e.g. non-single-diffractive).
  - Correct for detector effects
  - Well defined phase space

  ⇒ Facilitates comparison with and tuning of MC models

- Measurements provided:
  - $\frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{1}{2\pi p_{\mathrm{T}}} \cdot \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{\mathrm{d}\eta \mathrm{d}p_{\mathrm{T}}}, \quad \frac{1}{N_{\mathrm{ev}}} \cdot \frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}n_{\mathrm{ch}}}$ and $\langle p_{\mathrm{T}} \rangle$ vs. $n_{\mathrm{ch}}$
  - Angular correlations.

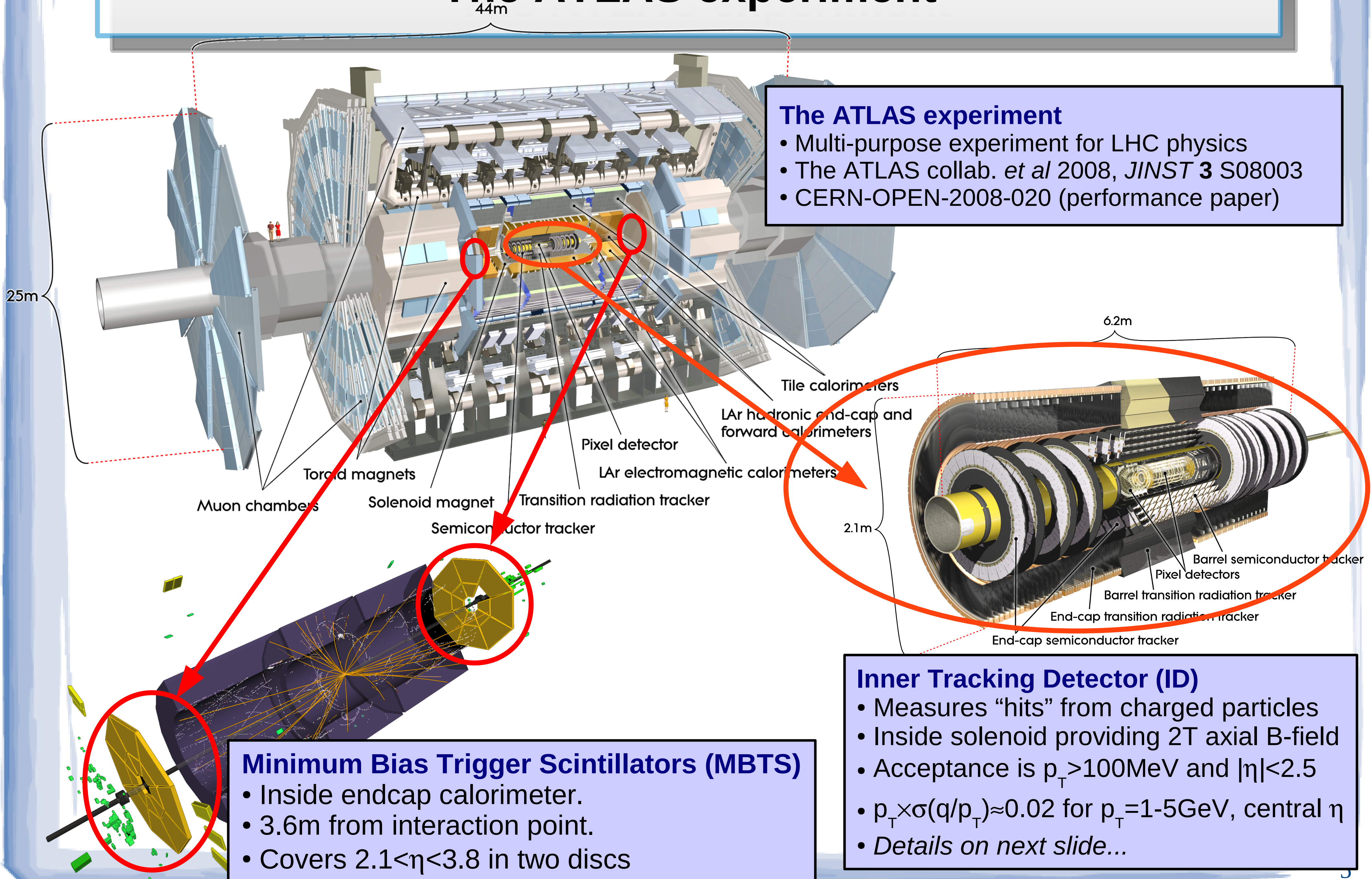
$n_{ch}$ : Number of particles in event in chosen phase-space
$N_{ev}$ : Total number of events in sample satisfying cut on $n_{ch}$
$N_{ch}$ : Sum of $n_{ch}$ over all $N_{ev}$ events

For Underlying Event results
cf. talk by D. Kar this afternoon

# Studied phase-spaces

- ***Multiplicity and $p_T$ related distributions:***
- ≥ 1 particle, $p_T > 500$ MeV, $|\eta| < 2.5$: *0.9 TeV, 2.36 TeV, 7.0 TeV*
  - 2.36 TeV analysis based on runs with lowered SCT voltage
- ≥ 2 particles, $p_T > 100$ MeV, $|\eta| < 2.5$: *0.9 TeV, 7.0 TeV*
- ≥ 6 particles, $p_T > 500$ MeV, $|\eta| < 2.5$: *0.9 TeV, 7.0 TeV*
  - Suppressed diffractive contribution.
  - Used for new AMBT1 Pythia 6 tune.
- ***Angular correlations:***
- ≥ 2 particles, $p_T > 500$ MeV, $|\eta| < 1/2/2.5$: *0.9 TeV, 7.0 TeV*
  - $p_T > 500$ MeV for more uniform tracking efficiency
  - Multiple eta ranges increase information for MC comparisons

# The ATLAS experiment

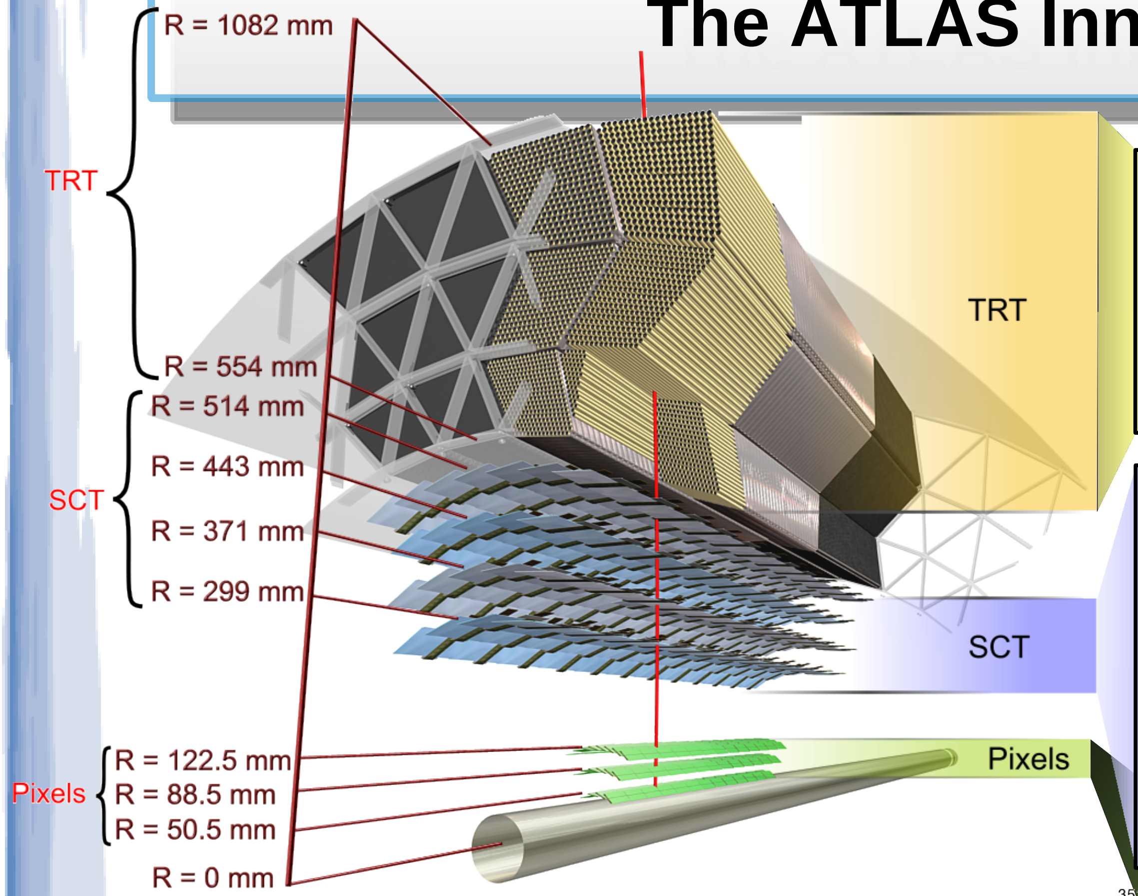


**The ATLAS experiment**
- Multi-purpose experiment for LHC physics
- The ATLAS collab. *et al* 2008, *JINST* **3** S08003
- CERN-OPEN-2008-020 (performance paper)

**Inner Tracking Detector (ID)**
- Measures “hits” from charged particles
- Inside solenoid providing 2T axial B-field
- Acceptance is $p_T$>100MeV and $|\eta|<2.5$
- $p_T \times \sigma(q/p_T) \approx 0.02$ for $p_T$=1-5GeV, central $\eta$
- *Details on next slide...*

**Minimum Bias Trigger Scintillators (MBTS)**
- Inside endcap calorimeter.
- 3.6m from interaction point.
- Covers $2.1<\eta<3.8$ in two discs

# The ATLAS Inner Tracker



**Transition radiation tracker (TRT)**

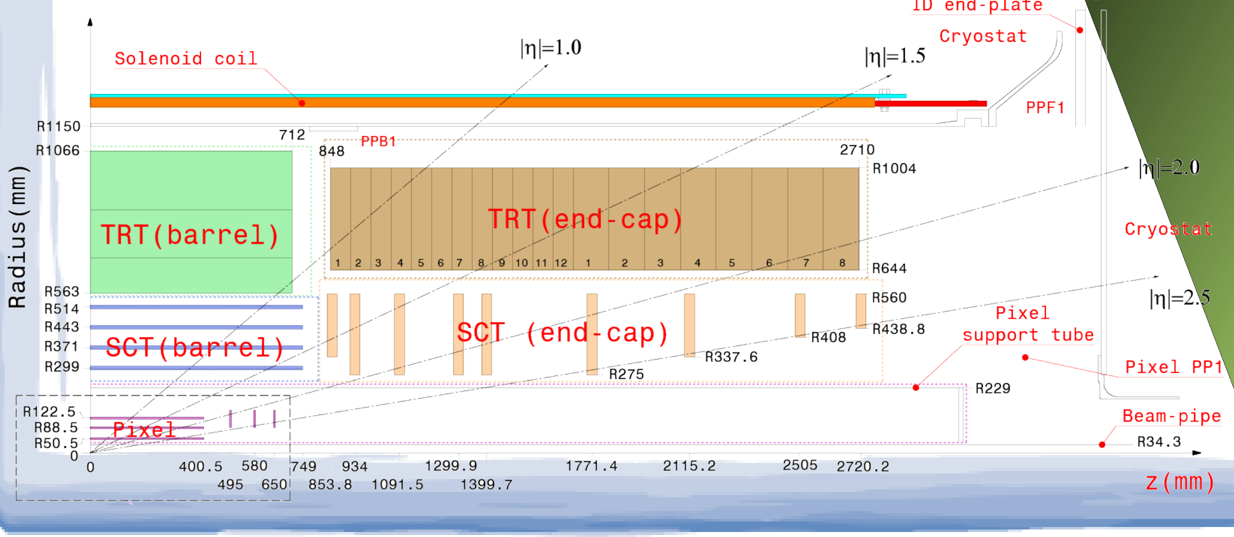
- 300K thin r=2mm drift-tubes, low density
- Provides ~35 hits/track at |η|<2
- Significantly improves momentum resolution
- Doubles as transition radiation detector (e PID)
  *(not relevant for present analyses)*

**Silicon micro-strip tracker (SCT)**

- 4 barrel cylindrical double-layers
  9 endcap disk double-layers
- A double-layer has overlapping modules
  with small stereo angle (40mrad)
- Strip pitch 80µm
- Provides ~8 hits/track at |η|<2.5
- NB: In standby mode during 2.36 TeV data taking

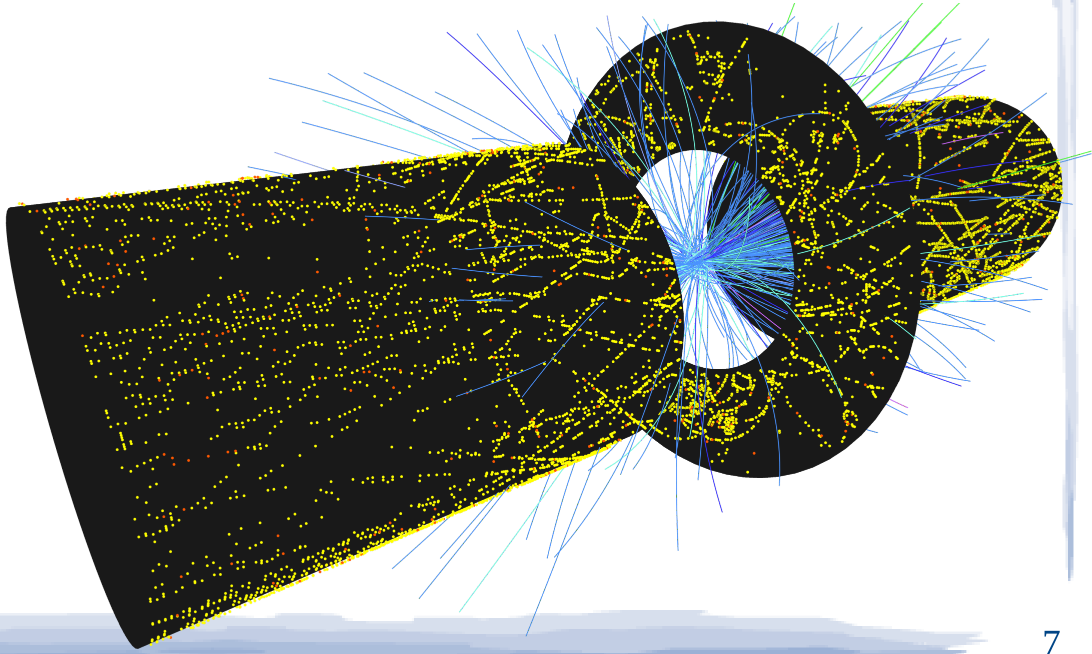
**Silicon pixel tracker (Pixel)**

- 3 barrel layers, 3 endcap disks
- Sensor elements 50x400µm$^2$
- Provides 3-4 hits/track at |η|<2.5
- Innermost barrel layer alone covers
  all of |η|<2.5 (the "B-layer")
  ⇒ longitudinal impact parameter
  distribution Gaussian in sin(θ)·$z_0$



# A word on ATLAS Monte Carlo Simulation

- Generator output is propagated through detailed detector geometry with GEANT4
    - Geometry presently mainly based on technical drawings, test-beam & cosmics studies, component weighing, etc.
- Custom code simulates detailed response of sensors and electronics
    - Includes detailed detector conditions (thresholds, inactive modules, ...)
- Output reconstructed with same reconstruction algorithms as are used for actual data
- Simulation time: ~20 mins/event
    - Frameworks for faster simulation based on parameterisations available, but not directly used in analyses presented here.



# Datasets and event selection

| | | |
|---|---|---|
| 0.9 TeV (~7$\mu b^{-1}$) | 350k | 4.5M tracks |
| 2.36 TeV (~0.1$\mu b^{-1}$) | 6k events | ~40k tracks |
| 7.0 TeV (~190$\mu b^{-1}$) | 10M events | 210M tracks |

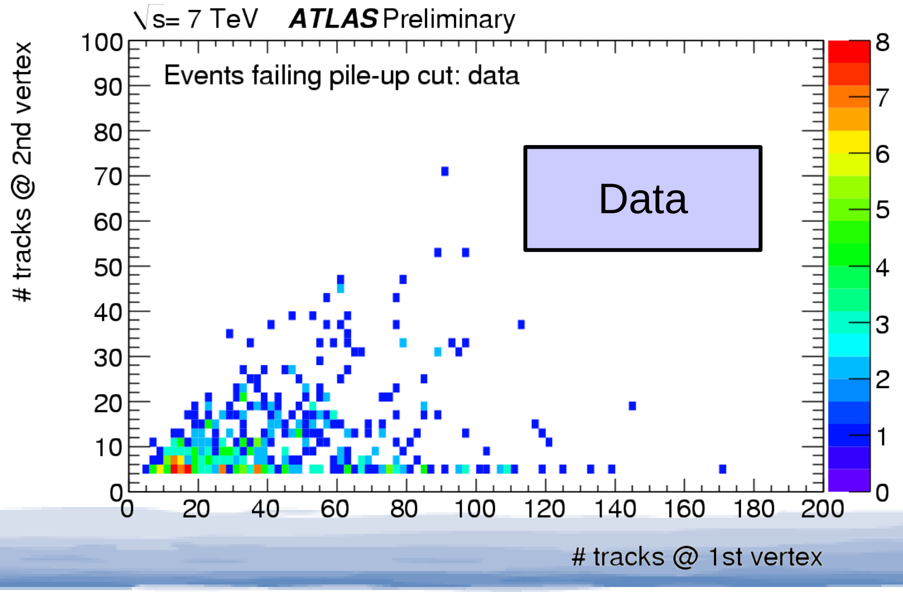
- Crossing bunches, MBTS single hit trigger
- Detector ready (2.36 TeV special case)
- Vertex formed from 2+ tracks ($p_T$ > 100 MeV) + beam spot constraint
  - Used tracks compatible with beam spot ($d_0^{BS}$ < 4mm)
- Reject events with a second vertex with at least 4 tracks.
  - Rejects events with multiple collisions (pile-up)

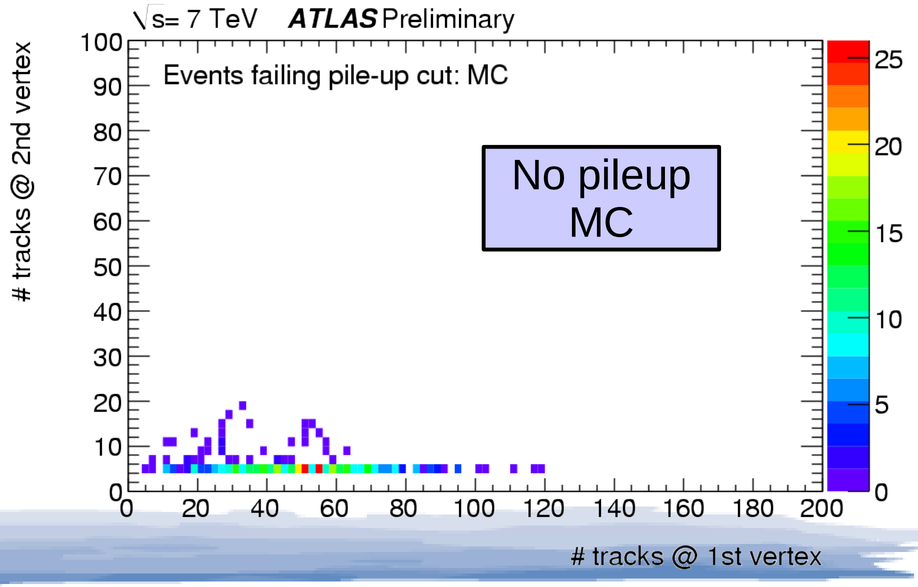
*Later data has significant pile-up ⇒ only small fraction of integrated lumi. used here*

- Phase-space dependent cut, requiring at least 1, 2 or 6 selected tracks with:
  - $p_T$ > 100 MeV or 500 MeV, $|\eta| < 1.0$ or 2.0 or 2.5
- Selected tracks must furthermore satisfy certain quality cuts:
  - Minimal number of hits (depending on $p_T$ and direction)
  - Impact par. cut: $d_0$<1.5mm, $|z_0|\sin(\theta)$<1.5mm (reduce secondaries)
  - Track $\chi^2$ prob. cut when $p_T$ > 10 GeV (against low-$p_T$ contamination)

# Background: Events with multiple pp collisions

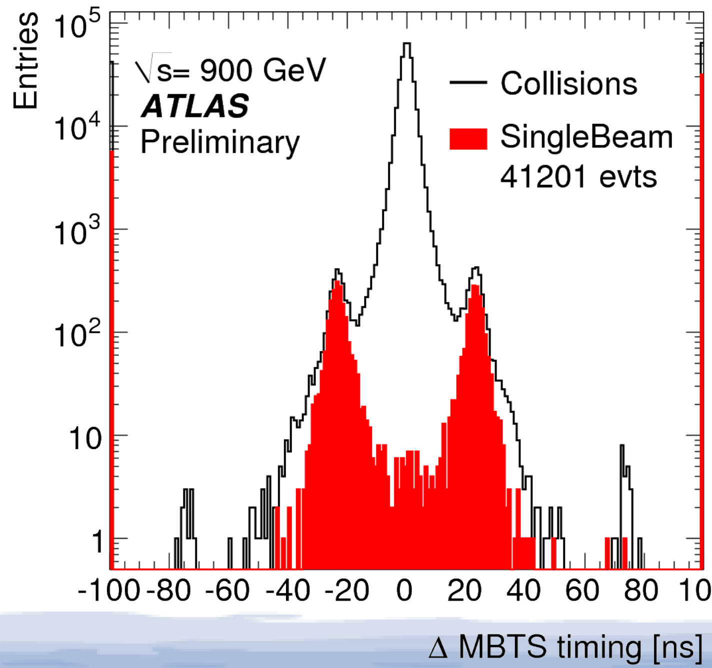
- The fraction of events with more than 1 pp interaction is estimated to be around 0.1% for the 7 TeV data sample considered for this analysis.
    - Such events might bias the tail of the $n_{ch}$ distribution
    - Expect 1% of events with second vertex (mostly fakes and low multiplicity decays of secondaries)
- Remove events with more than 3 tracks in a second vertex
- Residual effects after this removal:
    - Non pileup events removed: 0.03%
    - Pileup events not removed: 0.01%

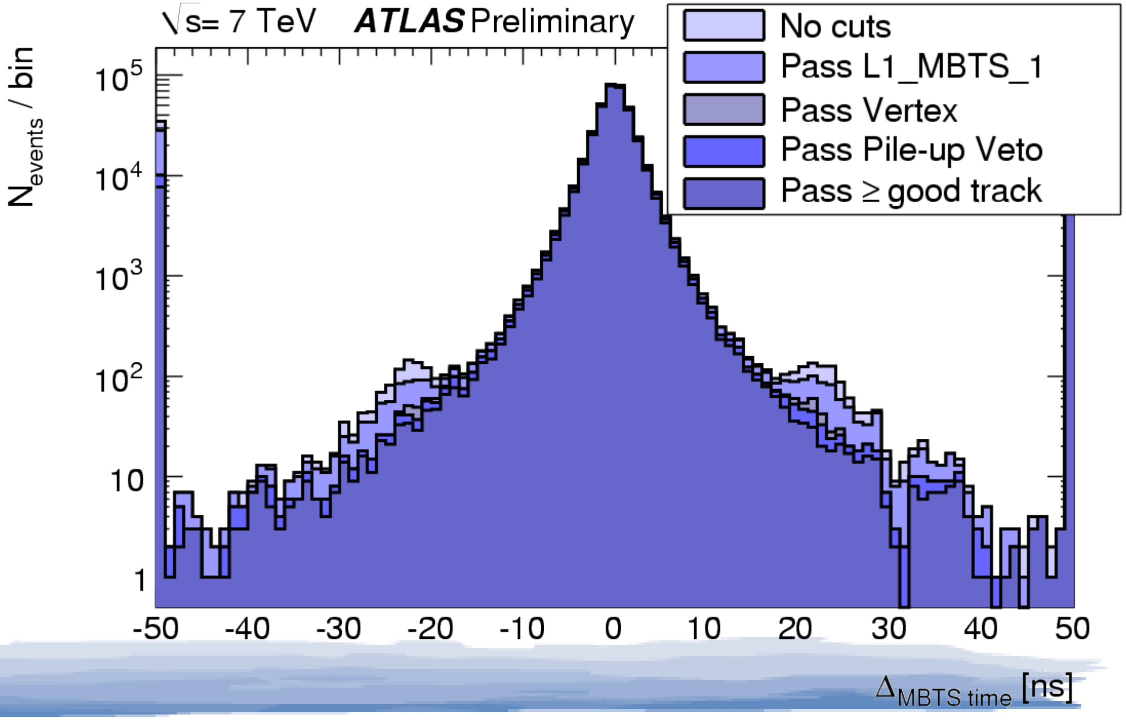




# Other backgrounds

- Cosmic ray events passing MBTS trigger ⇒ negligible level of $< 10^{-6}$
    - Based on cosmic ray studies, number of proton bunches and the trigger window of 25ns.
- Beam-background events passing MBTS trigger at low level before cuts
    - Single-beam data provides robust cross-check
    - Requirement of reconstructed vertex particularly powerful
    - Final contamination $< 10^{-4}$





# Correcting back to particle level

$n_{ch}$ : *Number of charged particles*
$n_{Sel}$ : *Number of selected tracks*
$n^{BS}_{Sel}$ : *Same, but without vertex constraints (substituting beam-spot)*

- Event wise (events lost to trigger & vertexing):

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

- Track wise:
  - Tracking efficiency (directly from MC)
  - Contamination from secondaries
  - Contamination from particles outside kinematic range

**From MC (small effect)**

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

**from MC (biggest systematics)**

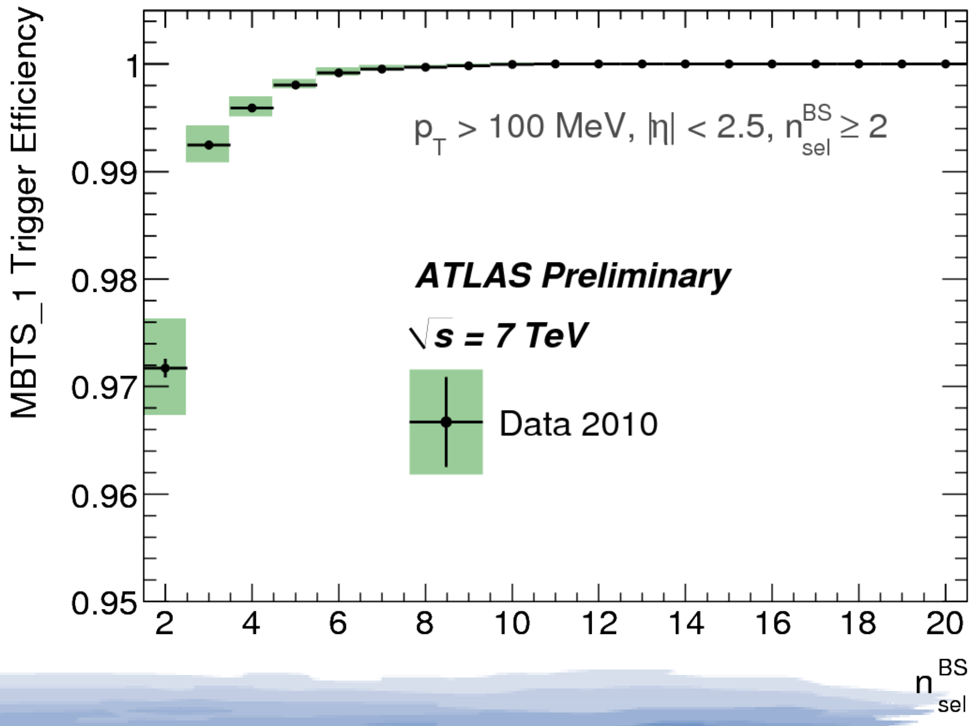
- Correct for bin-migrations in both $n_{ch}$ and $p_T$ (iterative Bayesian unfolding)

- Correct content of each $n_{ch}$ bin for events lost. E.g. for ≥2 particles cut, this happens when had ≥2 particles but <2 tracks:

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

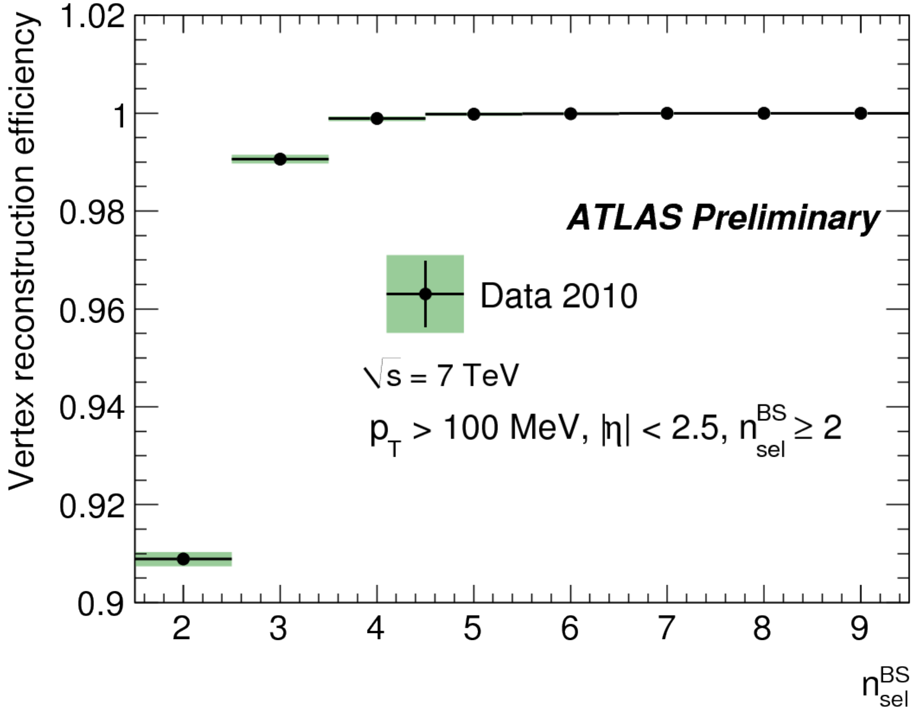
# Trigger efficiency

- Determined from data by comparison with orthogonal trigger:
  - Random beam-pickup based trigger selects crossings with colliding bunches
  - Require inner tracker activity (a number of pixel and SCT hits)
- Study performed without vertexing requirement to avoid correlation with vertex efficiency (⇒ use beam spot instead of vertex)
  - Introduces no observable bias on $p_T$ and eta distributions.
  - Above lowest multiplicities, efficiency essentially 100%



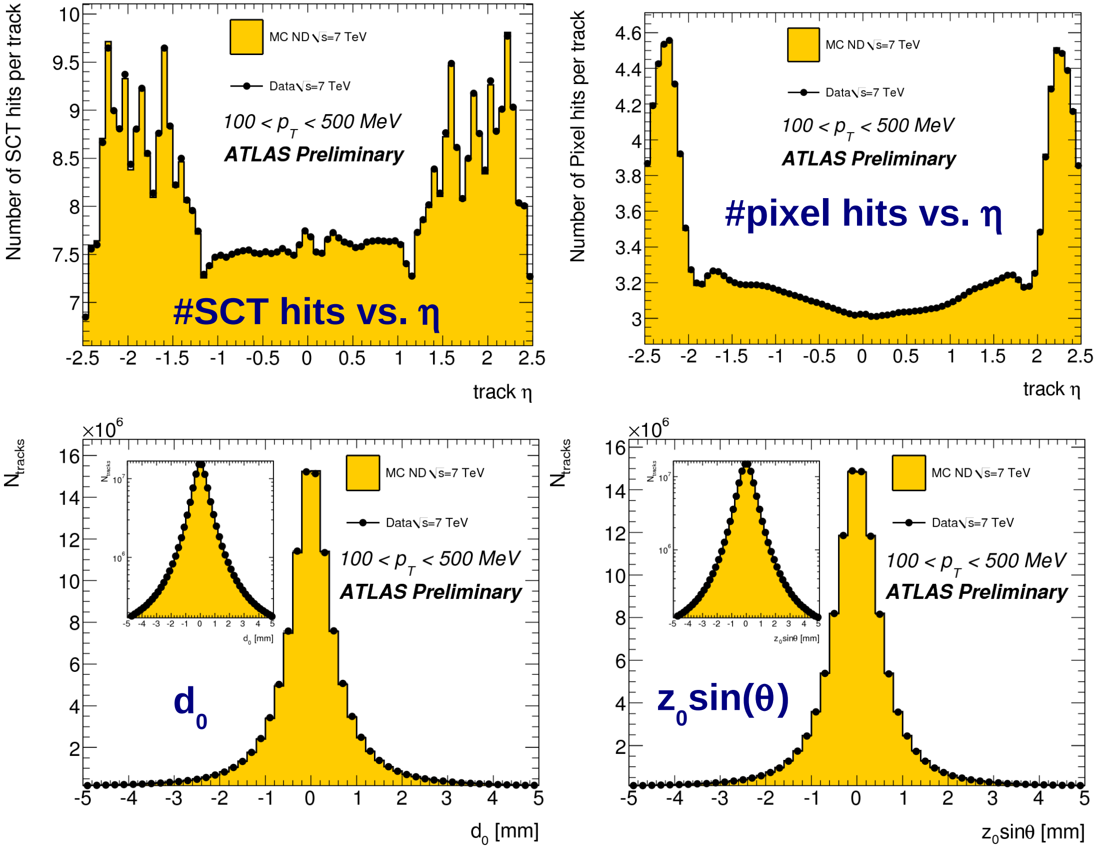
# Efficiency of vertexing

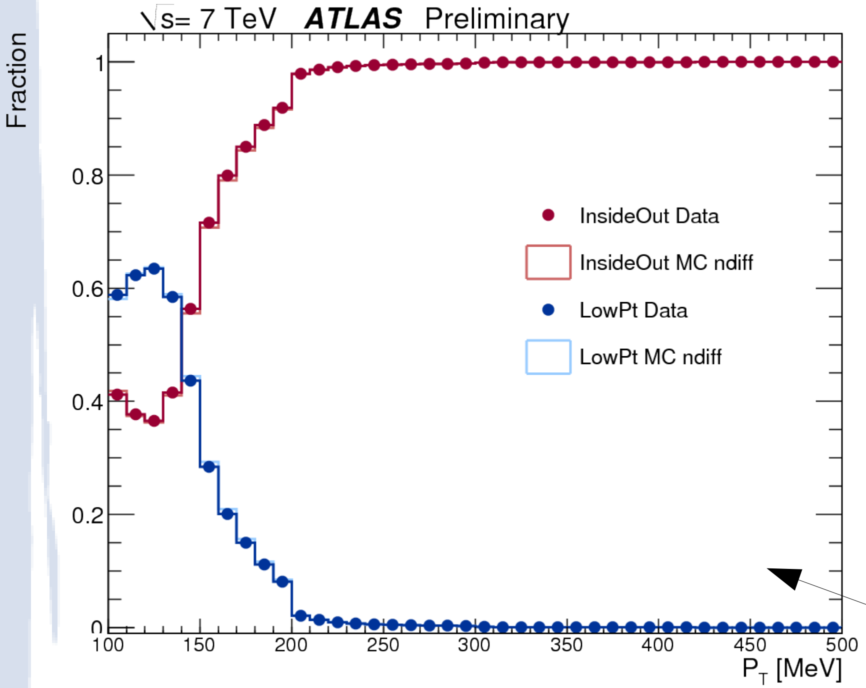
- Determined from data by looking at the number of events before and after the vertexing requirement.
- Taking into account beam-backgrounds, estimated from single-beam data
  - Contamination less than 0.8% even at $n_{sel}^{BS}=2$



# Tracking efficiency

- $\varepsilon_{trk}$ $(p_T,\eta)$ determined from MC.
- Related quantities show very good agreement.





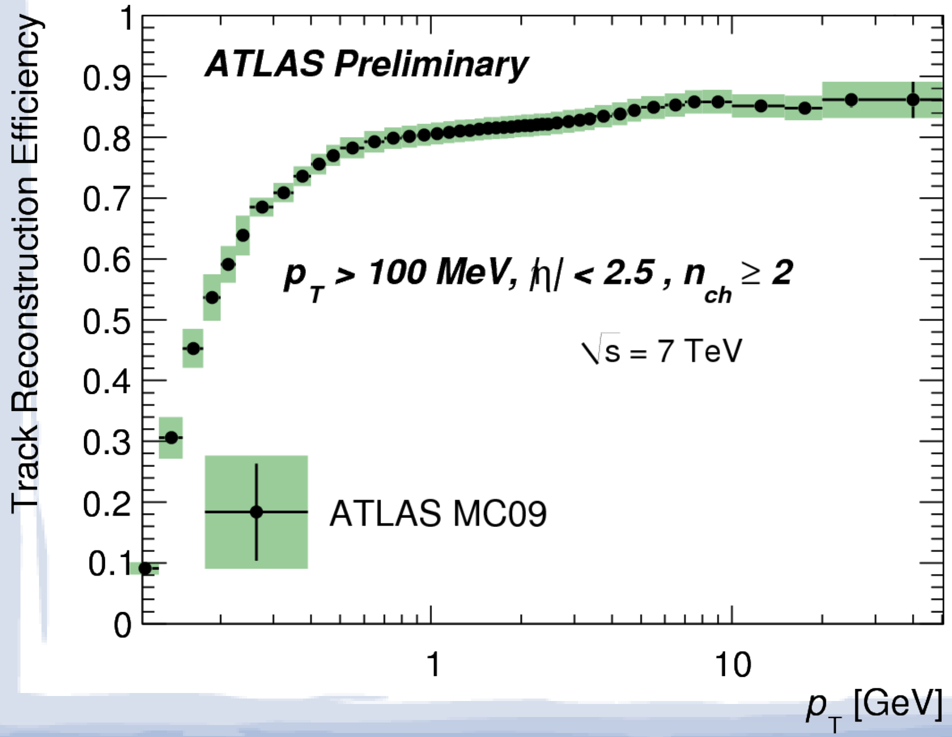
Two tracking algorithms: **inside-out** and **lowpt**.
**lowpt** recovers soft tracks by focusing on leftover hits and using less stringent quality cuts.
Relative yield consistent between data and MC.

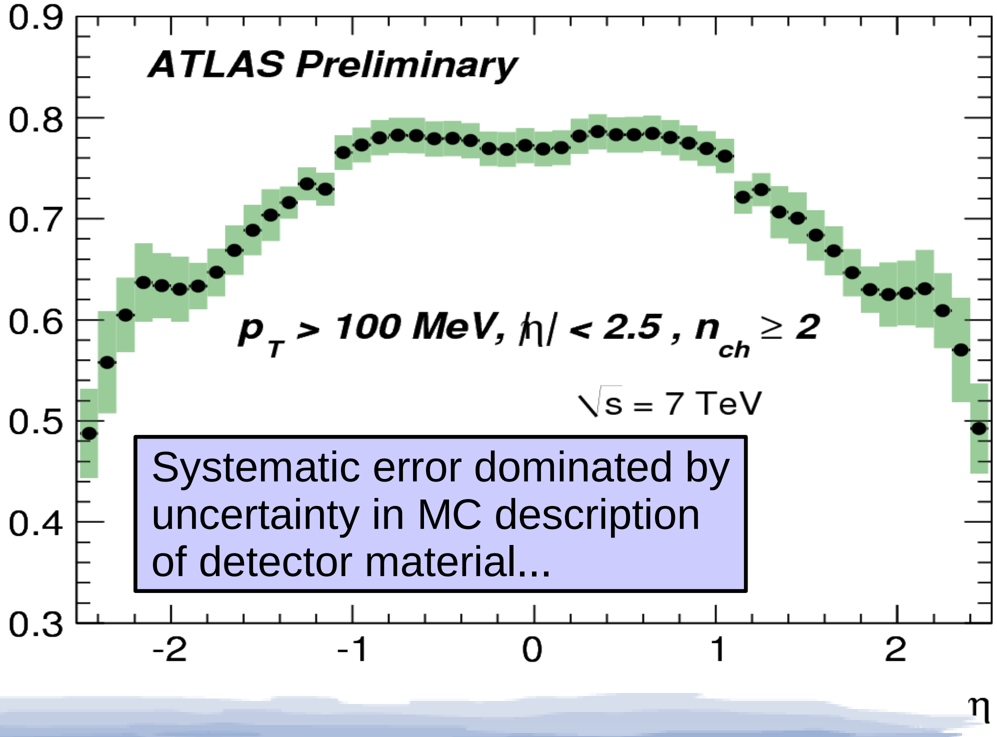
# Tracking efficiency

- Final tracking efficiency is gained from MC by matching reco-level tracks to generated particles:

$$\epsilon_{\mathrm{trk}}(p_{\mathrm{T}},\eta) = \frac{N^{\mathrm{matched}}_{\mathrm{rec}}(p_{\mathrm{T}},\eta)}{N_{\mathrm{gen}}(p_{\mathrm{T}},\eta)}$$

- Matching is done to minimal $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ within a cone
- Plus requirement of at least one shared hit to reduce fakes

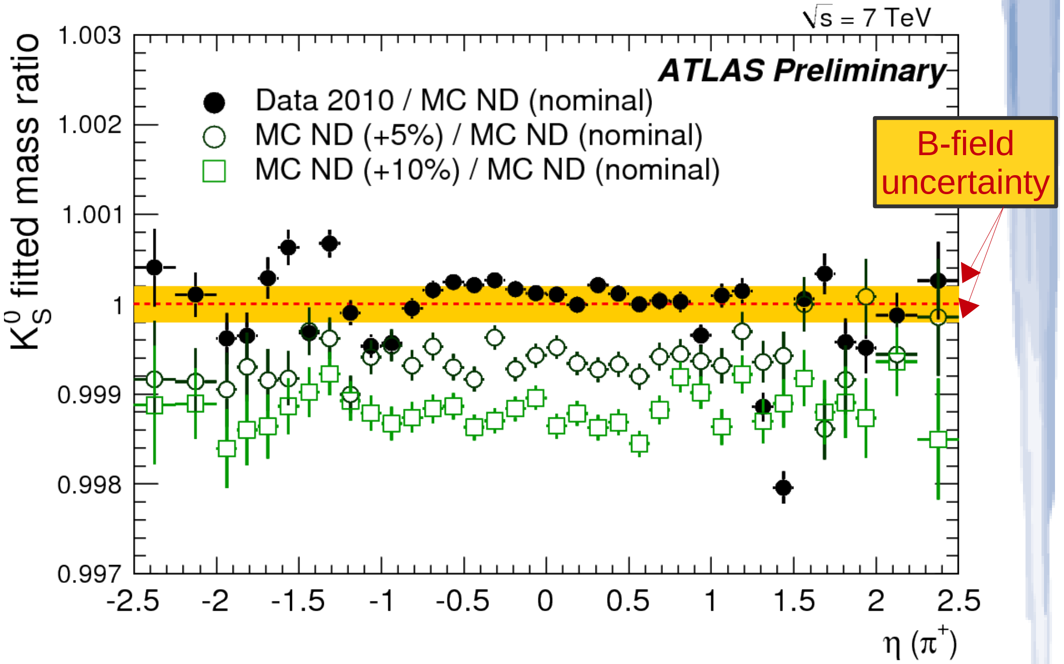


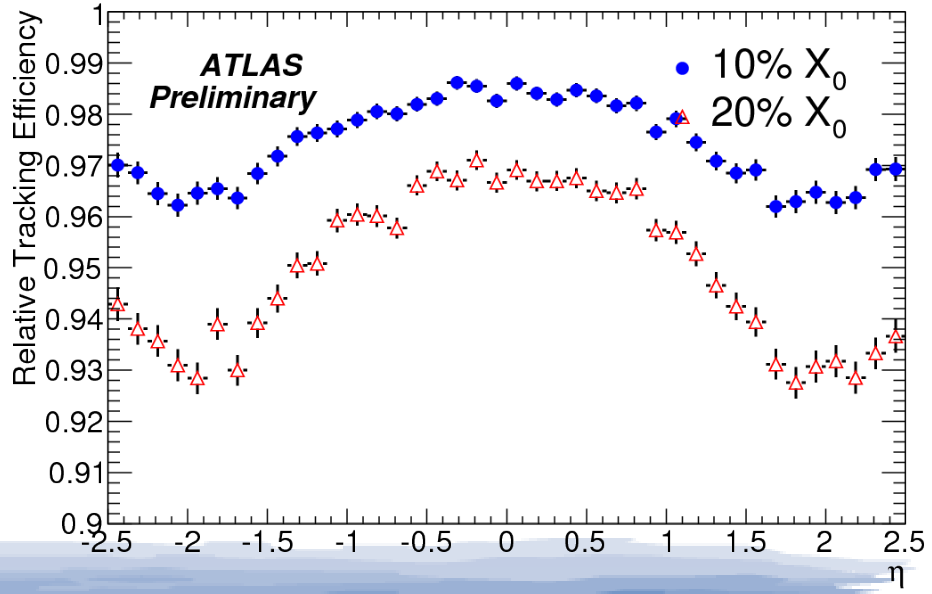


Systematic error dominated by uncertainty in MC description of detector material...

# Tracking efficiency: Impact from material description

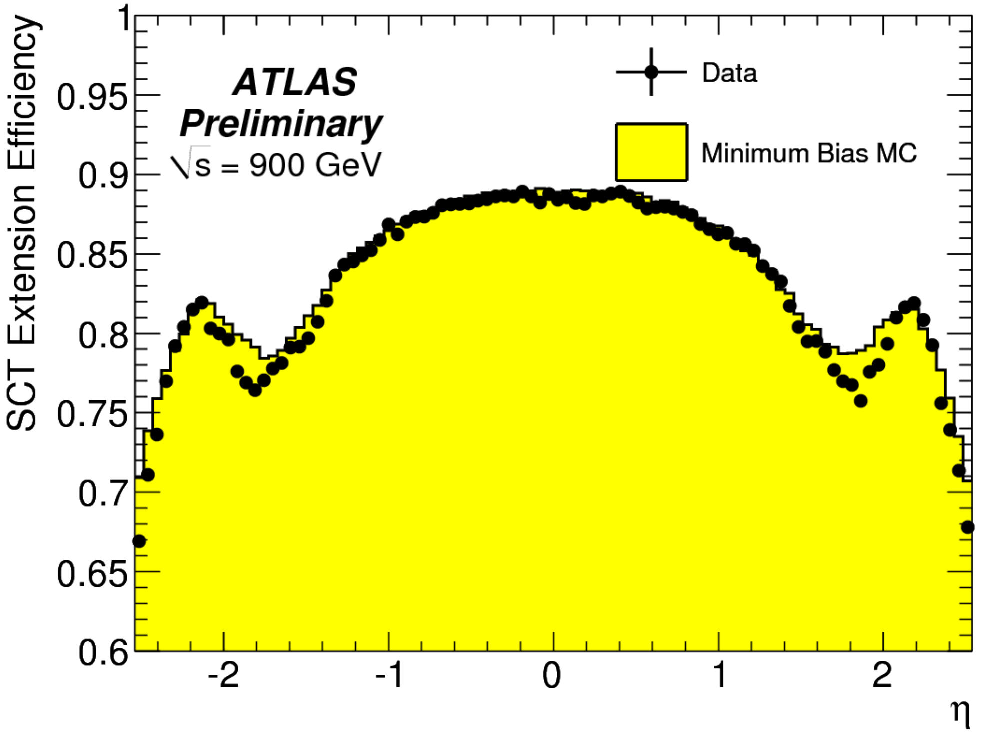
- Level of material inaccuracy (in radiation lengths) in ***beampipe*** and ***Pixels*** is sensitive to Ks-mass:
  - Pion momentum determination depends on energy-loss correction, based on MC material
  - Comparison with MC samples with inflated material densities indicates +10% to be conservative level
- Impact on tracking efficiency found by comparing efficiencies on nominal and +10% material MC samples
  - Taken as systematic error
  - Only probes *radiation lengths* directly





# Tracking efficiency: Impact from material description

- Service material between Pixels and SCT directly probed from data by track extension efficiency:
  - Fraction of pixel-only “tracklets” which gets extended into the SCT
  - Sensitive to hadronic interactions, i.e. interaction lengths of material
  - Difference also taken as independent systematic error



Very conservative: Adding syst. error from both this effect and previous slide

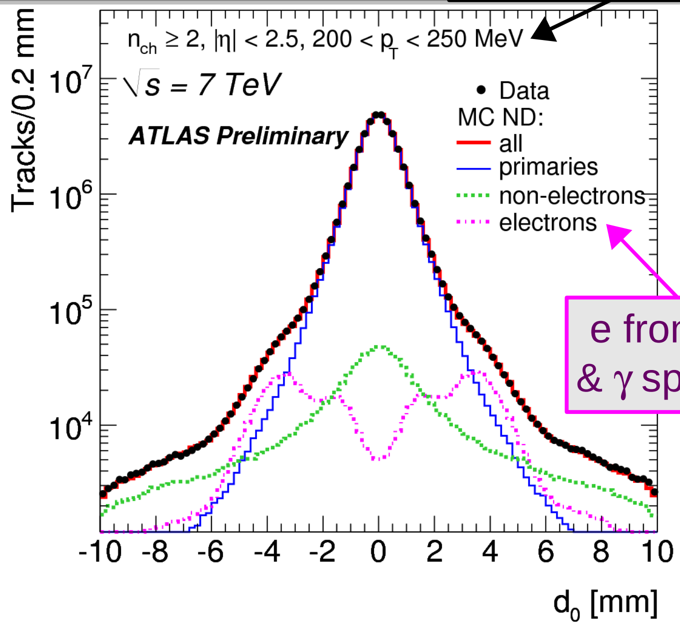
Obviously work is ongoing to continue to improve the material description

# Secondaries

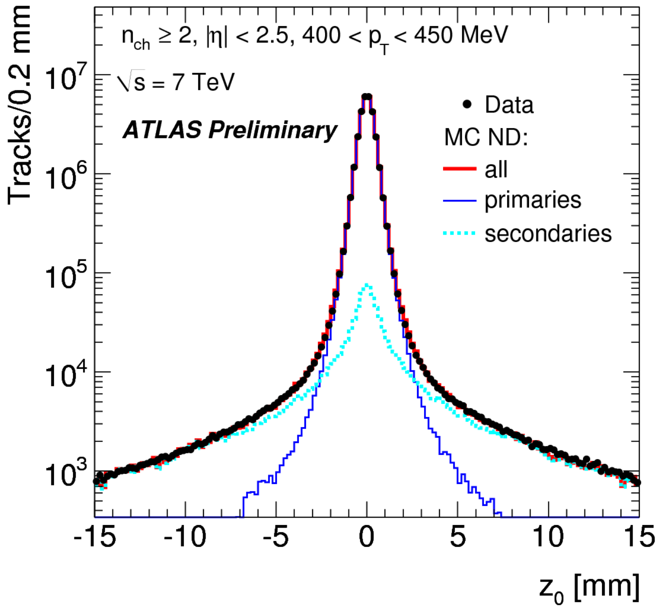
- Secondary contamination reduced by cuts:
  - Small impact parameters: $|d_0|<1.5$mm, $|z_0\sin(\theta)|<1.5$mm.
  - Requirement of hit in innermost pixel layer (against conversion electrons)
- Remaining fraction estimated by fit to $d_0$ sidebands on data:
  - Contribution from conversion electrons and other types fitted simultaneously
- Validated by fit to longitudinal impact parameter, $z_0$.
  - Here contribution from conversion electrons and other secondaries look identical

NB: Primaries are charged particles with $\tau > 0.3\cdot10^{-10}$ s

binned in $p_T$ and $\eta$

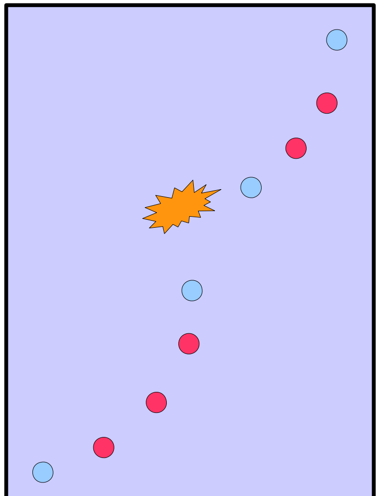


e from mat. & $\gamma$ spectrum

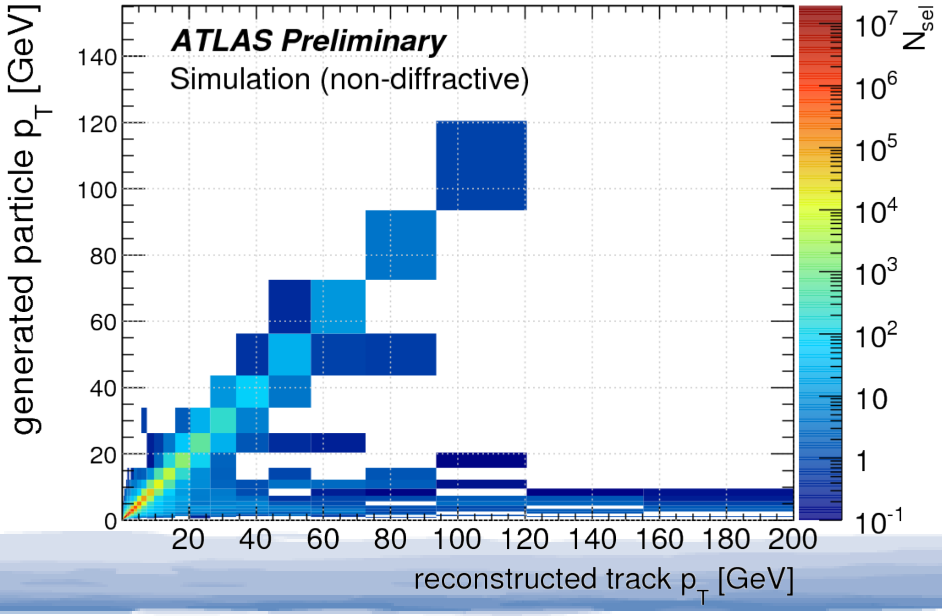


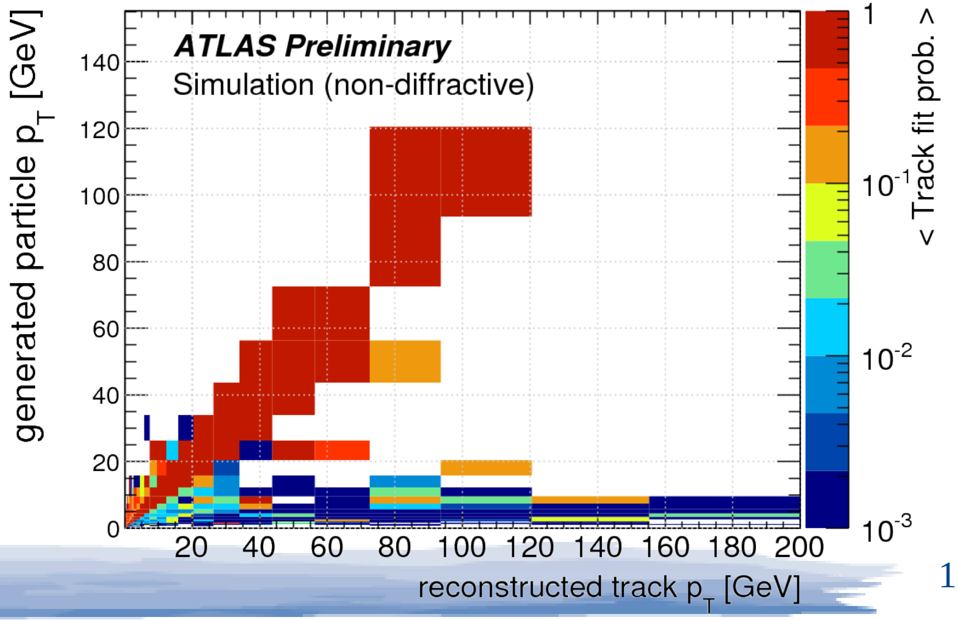
# High-$p_T$ tracks

- High-$p_T$ spectrum has significant contamination from low-$p_T$ tracks
  - Steeply falling $p_T$ spectrum in min. bias events (9 orders of magnitude between 100 MeV and 50 GeV)
  - Non-Gaussian tail in track-momentum response. Mainly due to hadronic interactions (in MC effect present for $\pi^\pm$, not $\mu^\pm$)
  - Problem mainly outside TRT acceptance of $|\eta|<2.1$
- Reduces by requirement of track fit prob. > 0.01 when $p_T$ > 10GeV
- Remaining effect accounted for as part of the spectrum unfolding (bin-migration correction)



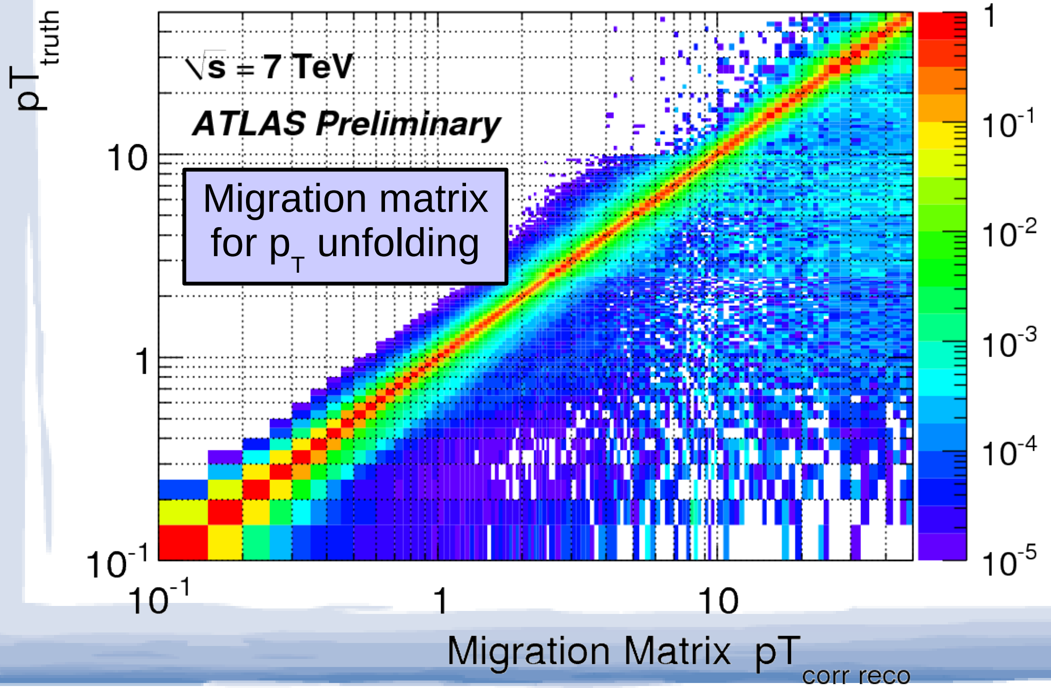
*A hard interaction producing a fake high $p_T$ track*

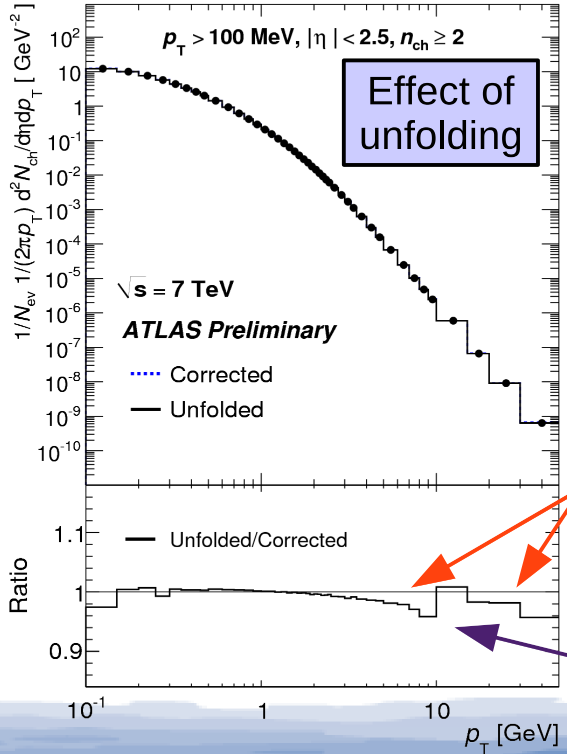




# Bayesian unfolding: Correct for bin-migrations

- Unfold observed $p_T$ and $n_{sel}$ distributions to get particle-level $p_T$ and $n_{ch}$
  - Use MC sample to get initial guess at migration matrix connecting particle-level distribution with reconstructed distribution.
  - Apply this matrix on data to get first guess at particle-level distributions
  - Use this distribution to get updated estimate for matrix. Reiterate until convergence achieved ⇒ Final unfolding is data driven
- Unfolding $p_T$ and $n_{ch}$ separately for simplicity and numerical stability
  - ⇒ negligible systematic error





Corrects for residual low-$p_T$ to high-$p_T$ contamination

Track fit prob. cut when $p_T$>10GeV

# Systematic errors

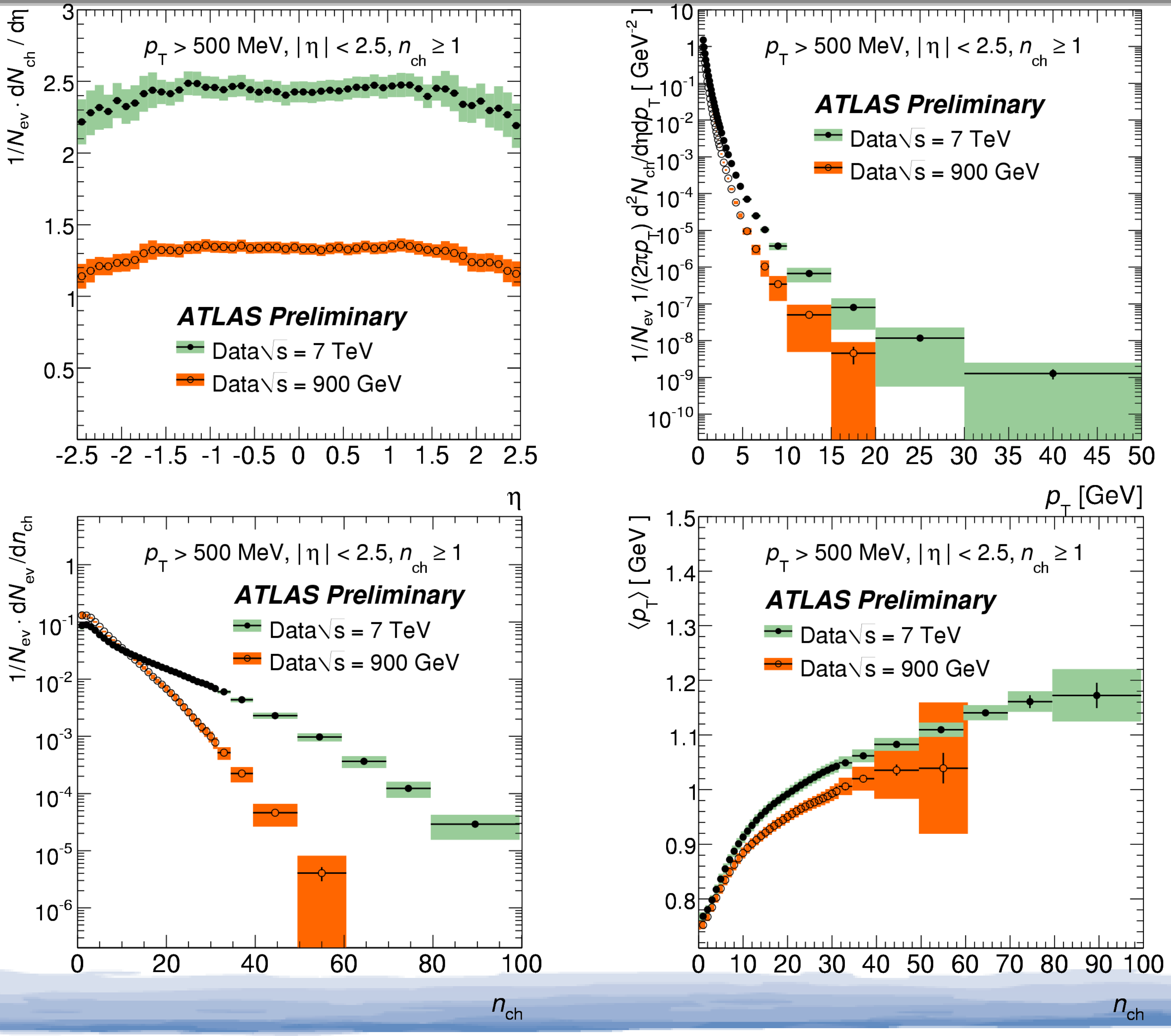
| **Systematic uncertainty on the number of events, $N_{\mathrm{ev}}$** | | |
|---|---|---|
| | $\sqrt{s} = 0.9$ TeV | $\sqrt{s} = 7$ TeV |
| Trigger efficiency | 0.2% | 0.2% |
| Vertex-reconstruction efficiency | $< 0.1\%$ | $< 0.1\%$ |
| Track-reconstruction efficiency | 1.0% | 0.7% |
| Different Monte Carlo tunes | 0.4% | 0.4% |
| Total uncertainty on $N_{\mathrm{ev}}$ | 1.1% | 0.8% |
| **Systematic uncertainty on $(1/N_{\mathrm{ev}})\cdot(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)$ at $\eta = 0$** | | |
| Track-reconstruction efficiency | 3.1% | 3.1% |
| Trigger and vertex efficiency | $< 0.1\%$ | $< 0.1\%$ |
| Secondary fraction | 0.4% | 0.4% |
| Total uncertainty on $N_{\mathrm{ev}}$ | $-1.1\%$ | $-0.8\%$ |
| Total uncertainty on $(1/N_{\mathrm{ev}})\cdot(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)$ at $\eta = 0$ | 2.1% | 2.3% |

**Tracking eff. main source**

**Normalisation cancels errors**

Shown here for one measurement and for $p_T$>100MeV analyses
In general systematic errors are applied per-bin as relevant

# Results at 0.9 and 7 TeV (≥1 particle, $p_T$>500MeV)

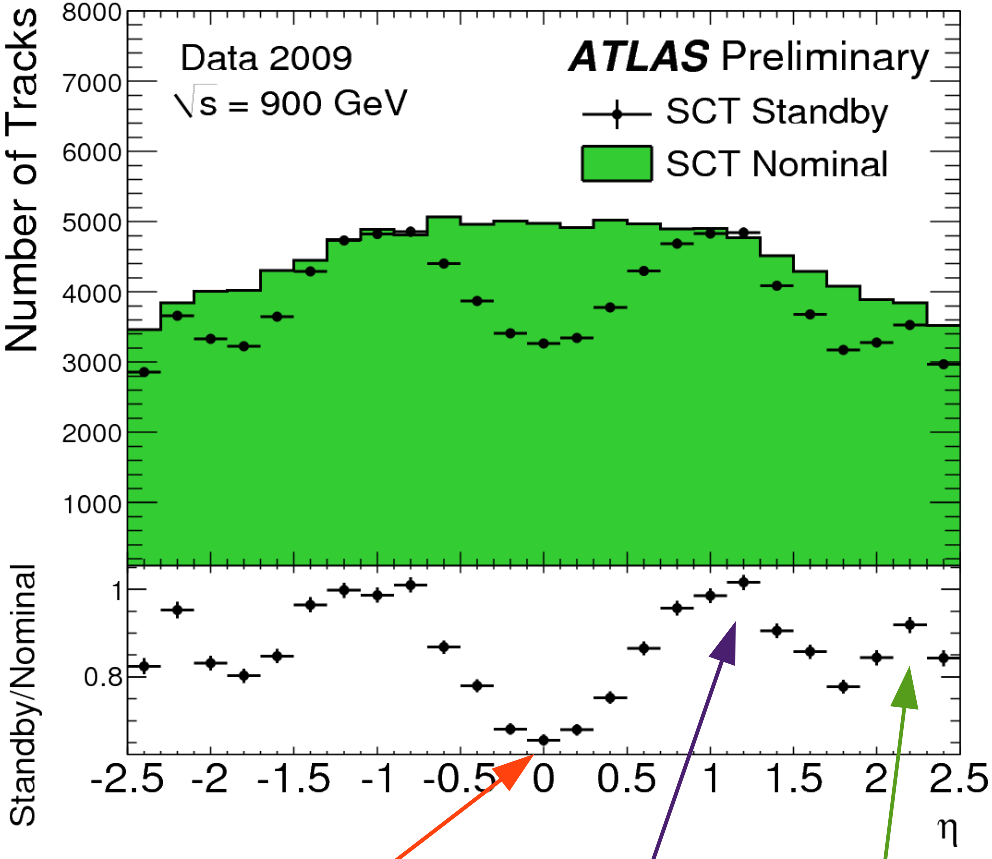


# Special conditions for the 2.36 TeV data sample

- December 13 & 15 2009 LHC delivered pp collisions at 2.36 TeV (*then world record*). Stable beams were not declared ⇒ SCT in *standby* mode for safety reasons:
  - sensor bias voltage 20V (nominal setting is 150V)
  - ⇒ heavily degraded performance
- Fortunately:
  - Pixels at nominal settings
  - Nearby reference run at 900GeV had similar detector conditions (apart from beam-spot)
- Two complementary strategies for recovering use of 2.36 TeV data sample:
  - ***ID-track method***: Perform variant of standard analysis, but with relaxed tracking cuts to allow for reduced SCT performance. Correct for degraded performance.
  - ***Pixel-track method***: Perform tracking with pixel detector only, ignoring SCT+TRT. Cons: Bad $p_T$ resolution. Pros: Less material uncertainty.
- 900 GeV reference run used both as input for data-driven efficiency determinations and general validation of method (must reproduce known 900 GeV results)
- Results from the two methods are cross-checked with each other

# Efficiency at 2.36 TeV for ID-track method

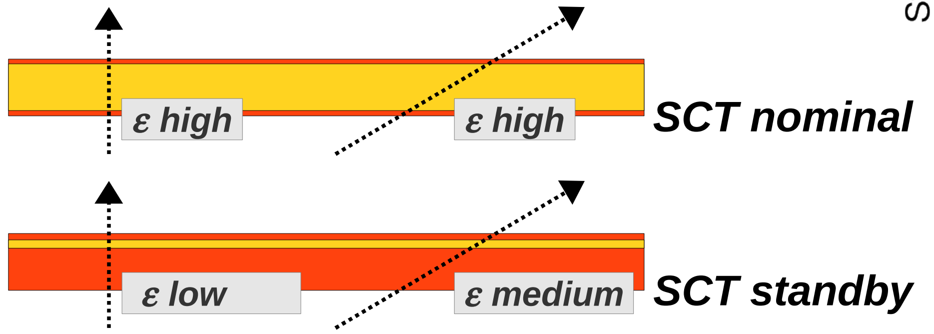
- SCT at standby voltage means narrower depletion zone:
    - ⇒ Reduced hit efficiency
    - ⇒ Lower intrinsic resolution
    - ⇒ Higher relative noise level
- Effects pronounced at low incidence on the wafers
- Tracking cuts are relaxed to minimise effects, but still present



Incidence angle of zero

Higher incidence angle

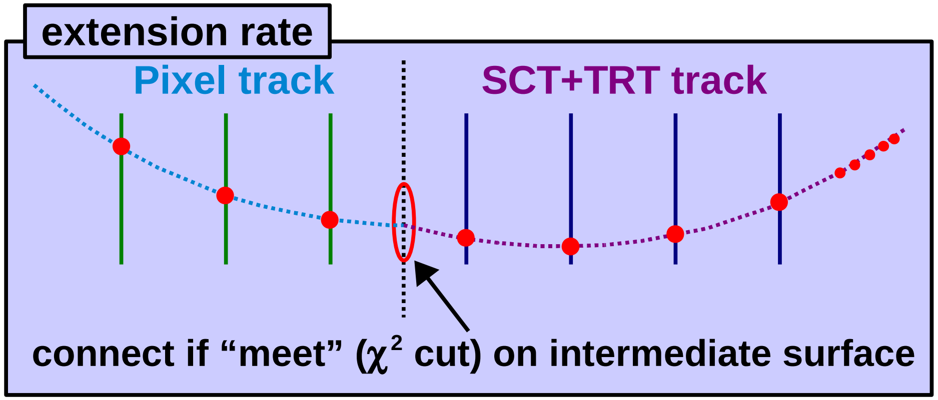
More layers traversed



Relative standby/nominal efficiency can thus be found in 900 GeV data and applied to 2.36 TeV analysis (after reweighing to beam-spot)

# Pixel-track method at 2.36 TeV: Tracking efficiency

- Unused trackers, SCT+TRT, used for data-driven tracking eff. correction:



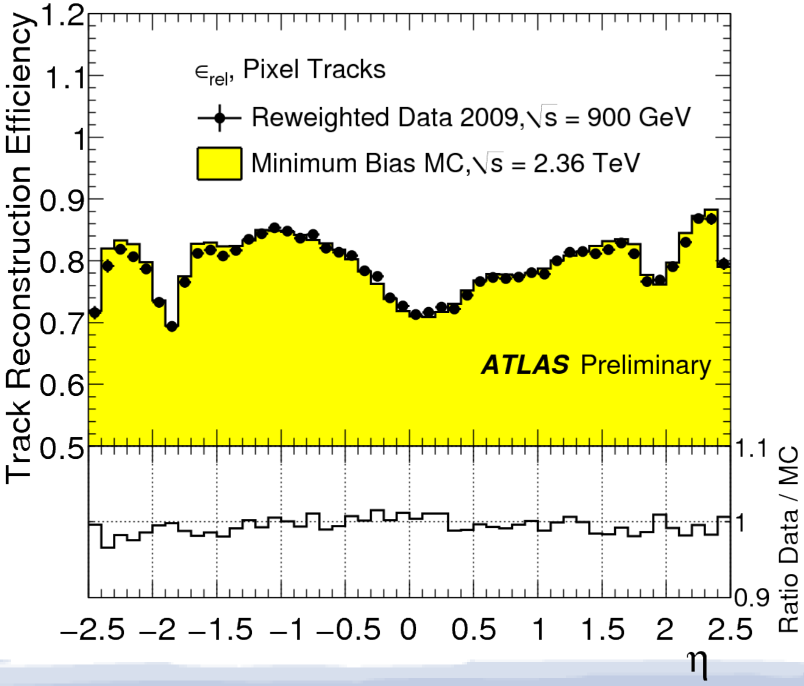
**extension rate**

**Pixel track**

**SCT+TRT track**

**connect if “meet” ($\chi^2$ cut) on intermediate surface**

$$\epsilon_{\mathrm{trk}}(\eta) = \epsilon^{\mathrm{MC,2.36TeV}}_{\mathrm{truth\ match}}(\eta) \cdot \frac{\epsilon^{\mathrm{data,900GeV}}_{\mathrm{extension}}(\eta)}{\epsilon^{\mathrm{MC,2.36TeV}}_{\mathrm{extension}}(\eta)}$$

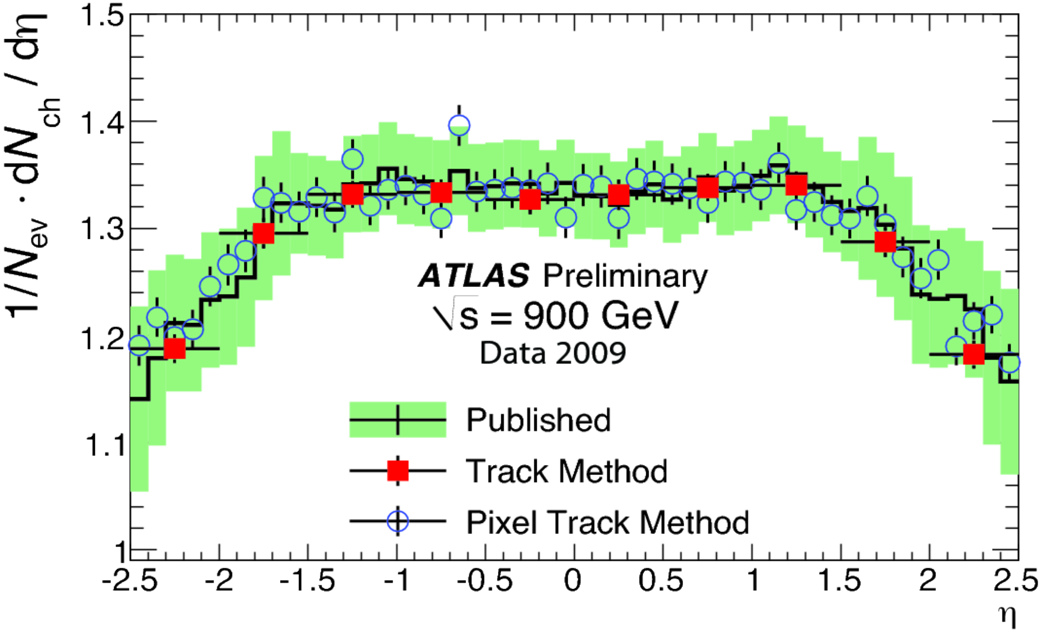


Correction of just a few percent verifies robustness of Pixel-track method

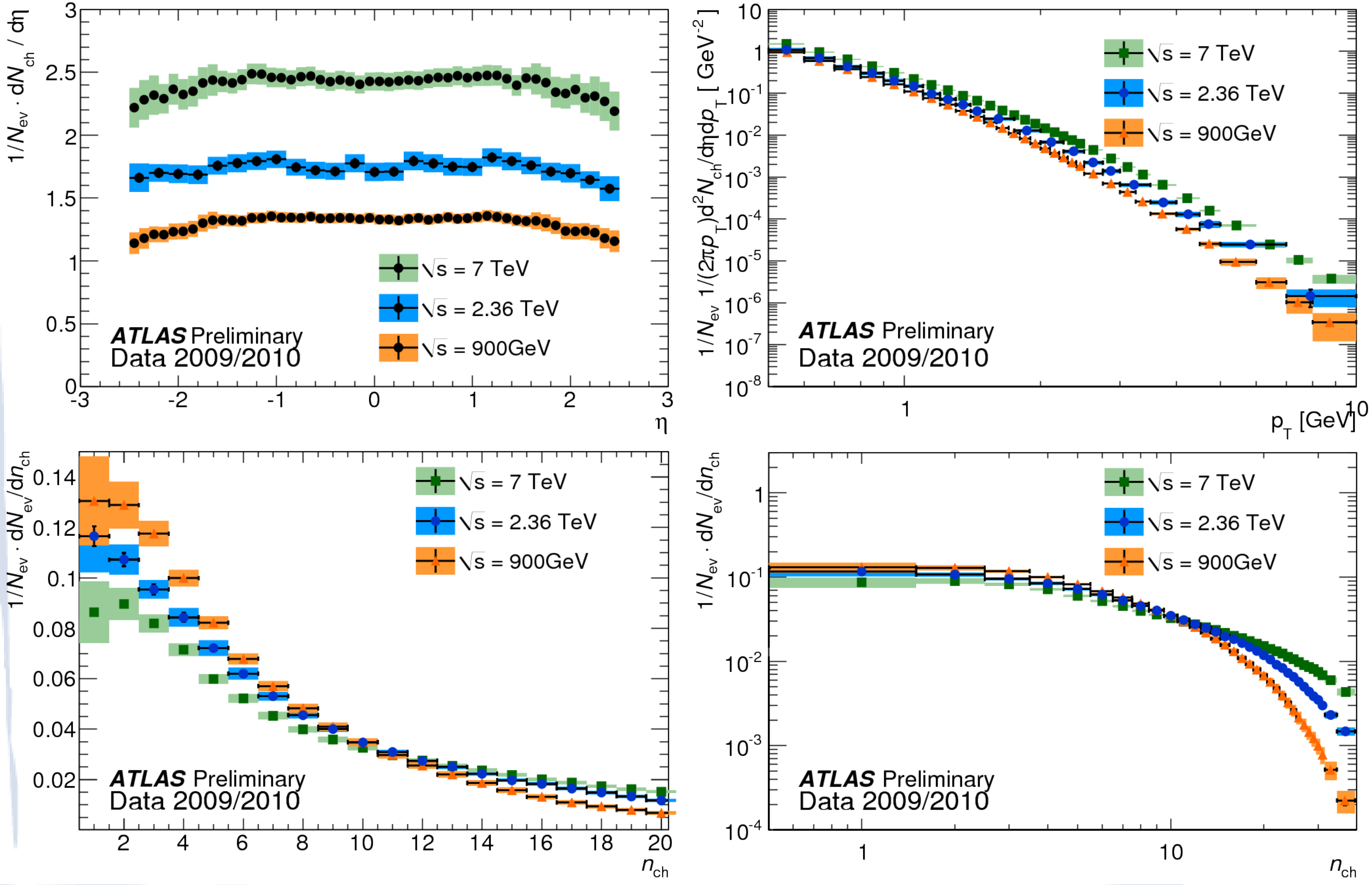
We still assign syst. error for tracking eff. by comparing with +10% mat. MC. *Very conservative for Pixel-tracks*

# ID-track versus Pixel-track method at 2.36 TeV

- Main drawback of pixel-track method is shortened track length, leading to degraded $p_T$ resolution by about an order of magnitude compared to ID-tracks
- But systematic errors on multiplicities significantly smaller for Pixel-track method
  - Use Pixel-track method for all distributions apart from $p_T$ spectrum
  - Publish no $\langle p_T \rangle$ vs. $n_{ch}$ result due to correlations
- Agreement between methods and published 900 GeV results



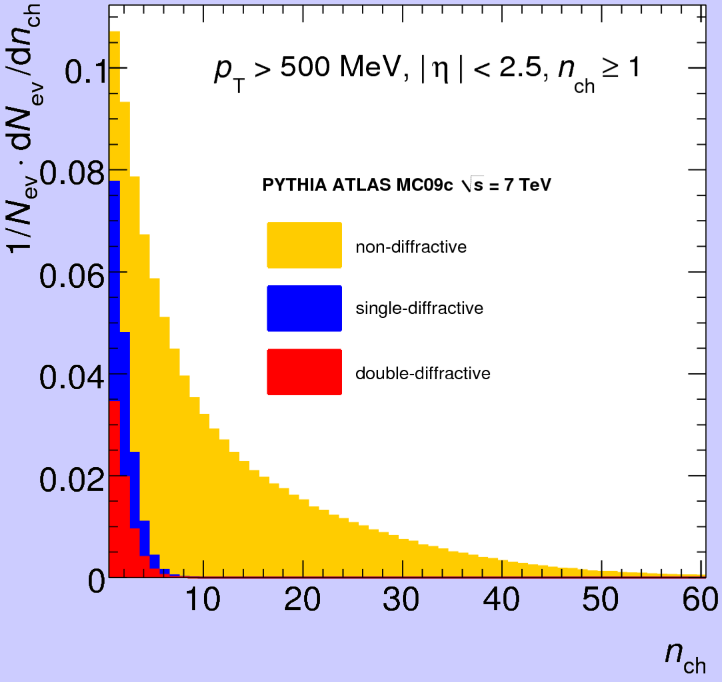
# Results at 3 energies (≥1 particle, $p_T$>500MeV)



# Results from diffractive-limited phase-space

- Modelling of diffraction and its interference with the ND part is problematic
- Provide results also in a diffractive limited phase-space:
  - $n_{ch} \geq 6$, $p_T > 500$ MeV
- Gives one more handle for MC comparisons and tuning
- Analysis analogous to $n_{ch} \geq 2$, apart from also using tracks from events with $n_{Sel} \leq 5$:
  - Otherwise lose most statistics for $n_{ch}$ just above 5 as $(\varepsilon_{trk})^6$ is low
  - In such event, weigh contribution from each track with probability the track originated in event above threshold

**PYTHIA ATLAS MC09c:**
Essentially no diffractive component above cut (all generators predicts greatly limited contribution)



# First ATLAS PYTHIA tune to LHC data: AMBT1

- Motivation: Provide LHC-centric tune which leans towards describing the part of the spectra which is most important for future ATLAS analyses.
- ATLAS Input:
  - $n_{ch} \geq 6$, $p_T > 500$ MeV at 900 GeV & 7 TeV distributions:
  - Underlying Event distributions with hard $p_T$ cuts (talk today by D. Kar)
- Various Tevatron input from 630 GeV to 1960 GeV
  - For consistency, but with 1/10 weight to ensure results optimised for LHC studies
- Pars related to fragmentation, FSR, hadronisation not tuned (constrained by LEP data)

**Results (base is MC09c tune)**

| 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 |

AMBT1 mainly changes matter distributions and CR strength

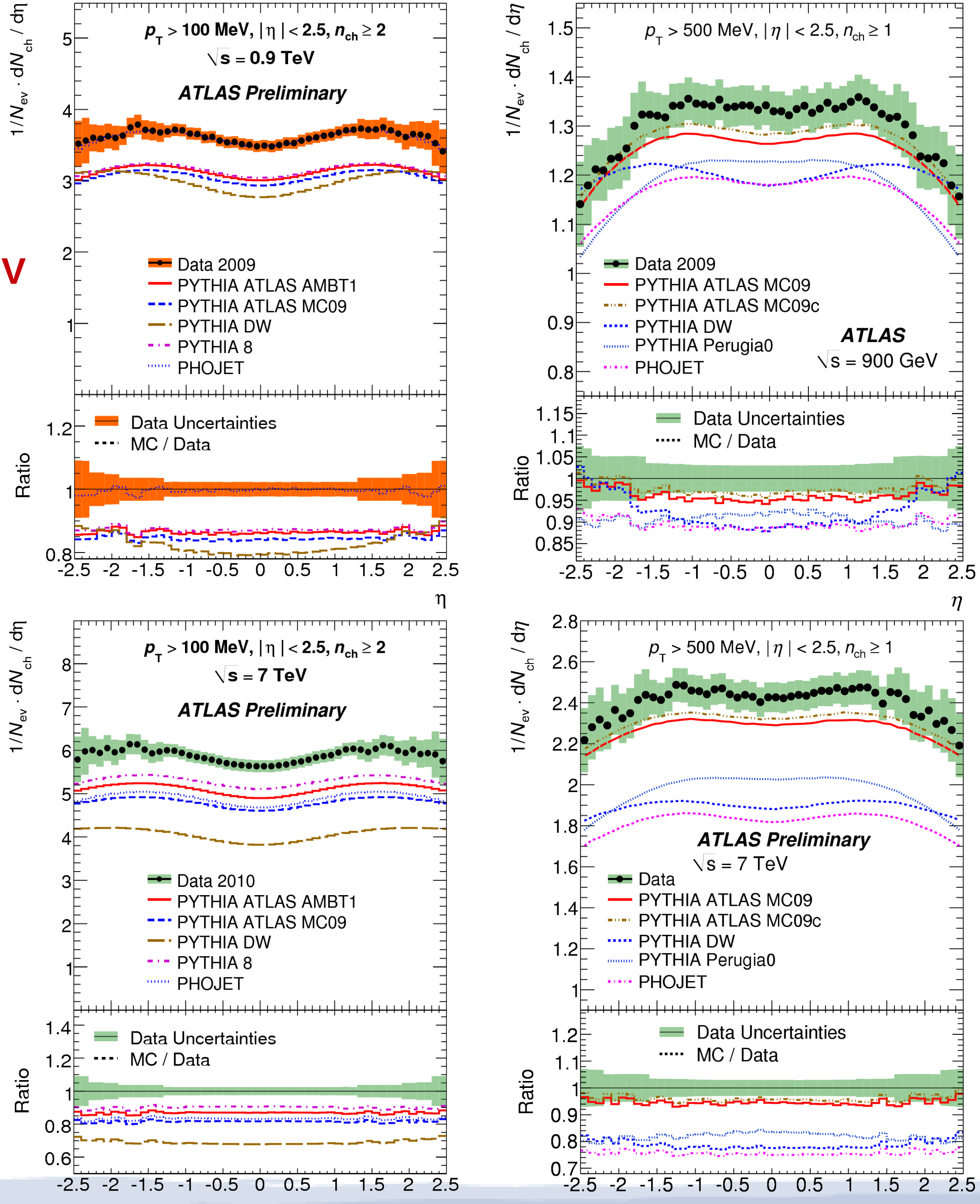
Higher probability for high-multiplicity events

Shorter strings ⇒ fewer, higher-$p_T$ hadrons

# Results: η-distributions

**0.9 TeV**

**7 TeV**



**$p_T$>100MeV** **$p_T$>500MeV**

Distributions more flat for more inclusive PS
- Feature of higher diffractive component

Shapes mostly OK (except for PYTHIA DW)

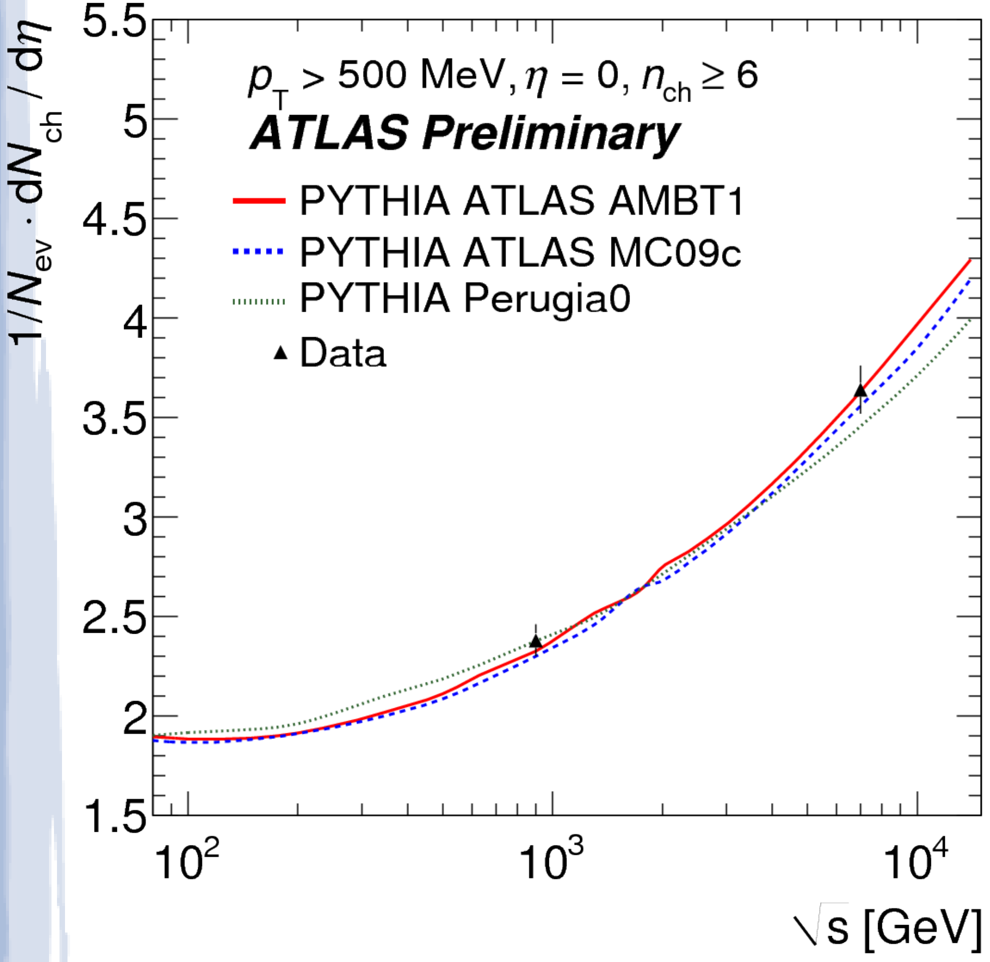
Multiplicity in data higher than any MC
- Pronounced for more inclusive PS

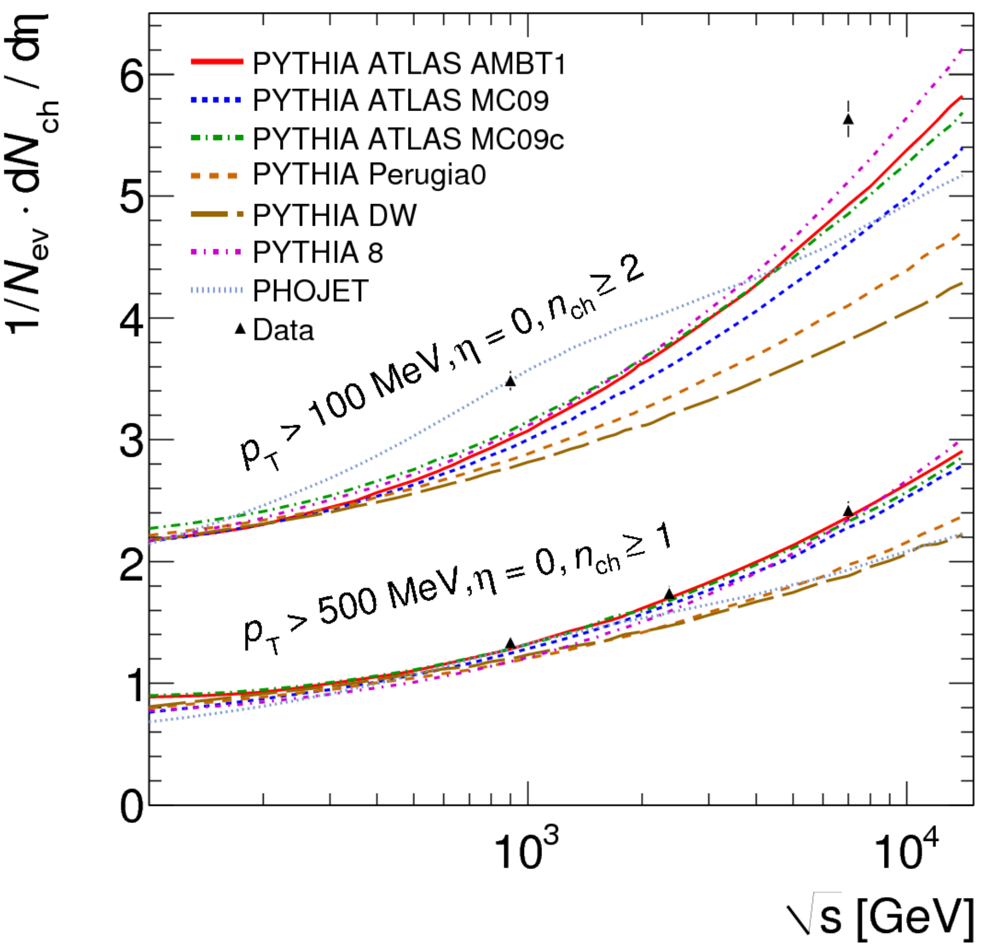
⇒ MC has too few particles at low $p_T$
- Looks like problem describing diffraction
- Or at least that global tunes have too limited input in diffractive regime
- Feature also affecting other distributions

*NB: Slight differences in set of MC models shown in different plots...*

*NB: To be brief, not showing plots at 2.36 TeV or for phase-space with $n_{ch} \geq 6$, $p_T$>500MeV*

# Results: Energy scaling of central multiplicity





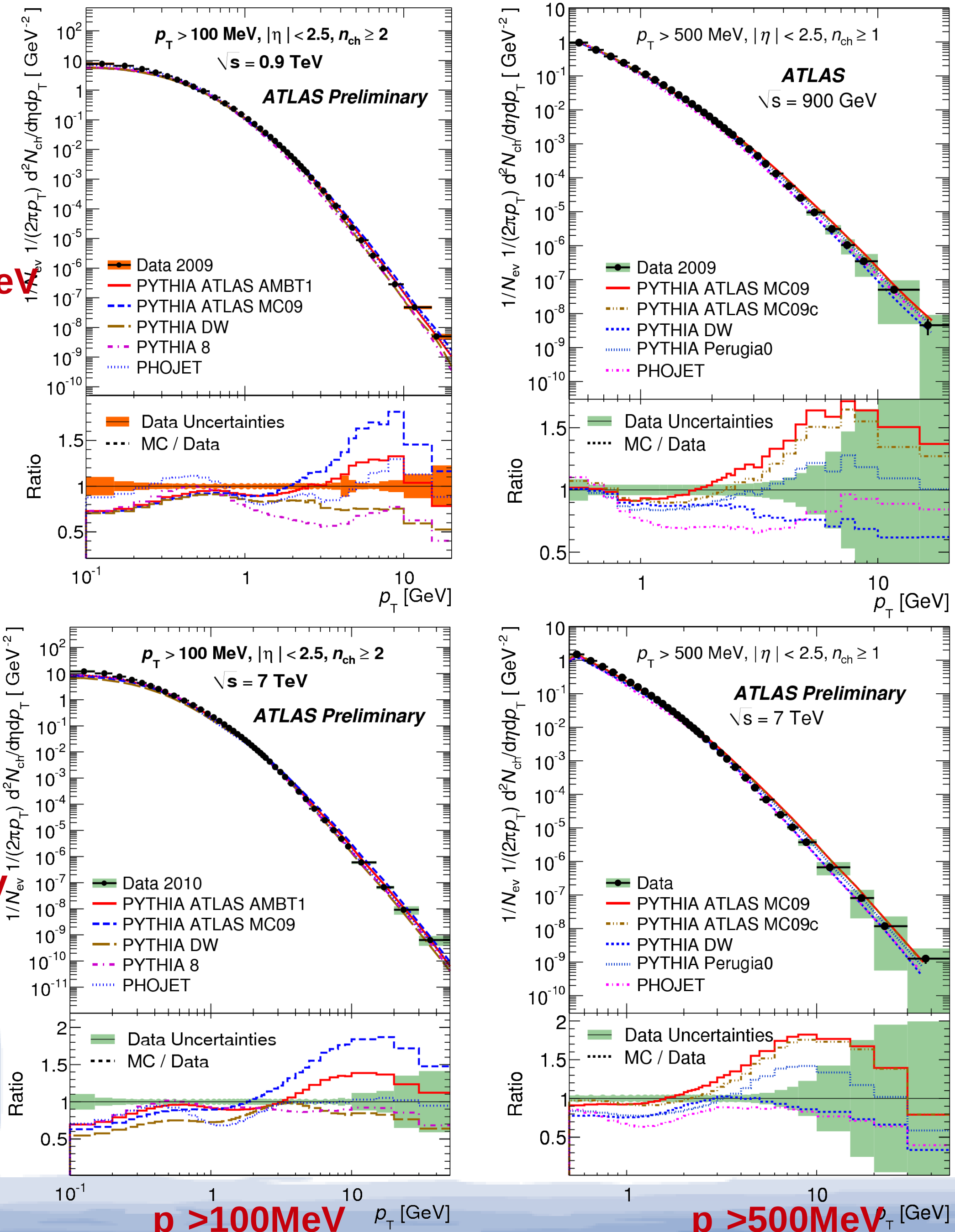
Best agreement found in diffraction-limited phase-spaces

- *Several models have very good fit here - AMBT1 excellent*

Bad fit for $p_T$>100MeV phase-space where the diffractive component is large

- *Large model to model fluctuations in this phase-space*

# Results: $p_T$ distributions



**0.9 TeV**

**7 TeV**

**$p_T$>100MeV**

**$p_T$>500MeV**

Measurement spans 10 orders of magnitude!

No MC model describes data at all $p_T$

- Best fit at intermediate range

Models predict too few particles at low $p_T$

- Already observed from η-distributions

Larger spread in model predictions at higher $p_T$ values

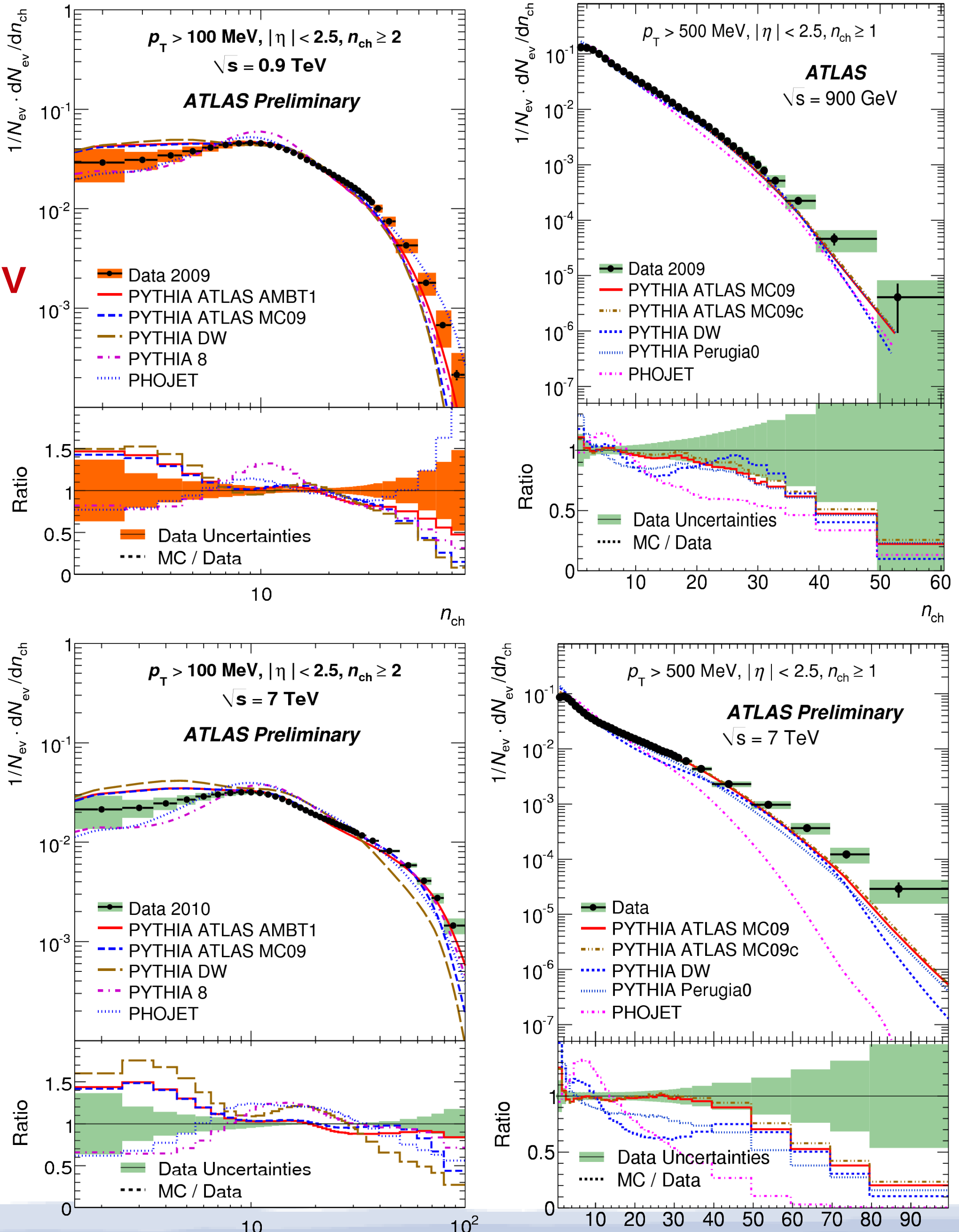
# Results: Multiplicity distributions

Most models overshoots at low $n_{ch}$ and undershoots at high $n_{ch}$

- Connected through normalisation
- Intermediate range better
- ⇒ models have too low multiplicity, as seen on η-distributions
- Discrepancy pronounced at 7 TeV

**0.9 TeV**

**7 TeV**



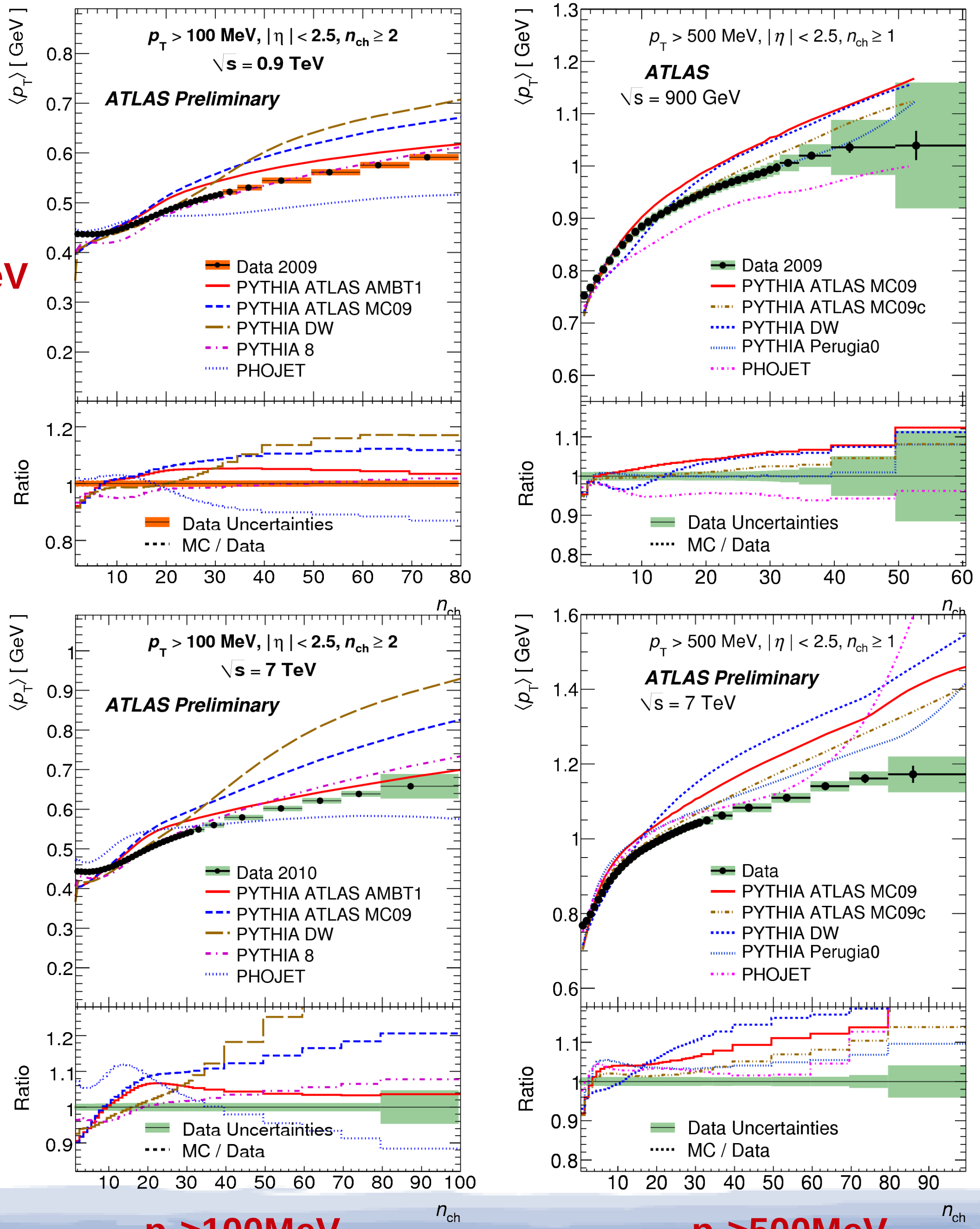
**$p_T$>100MeV** **$p_T$>500MeV**

*NB: The two leftmost plots are double-log plots while the two rightmost are single-log*

# Results: $<p_T>$ vs. $n_{ch}$

0.9 TeV

7 TeV



$p_T$>100MeV

$p_T$>500MeV

In both phase-spaces curves exhibits change in slope around $n_{ch}$ ≈10

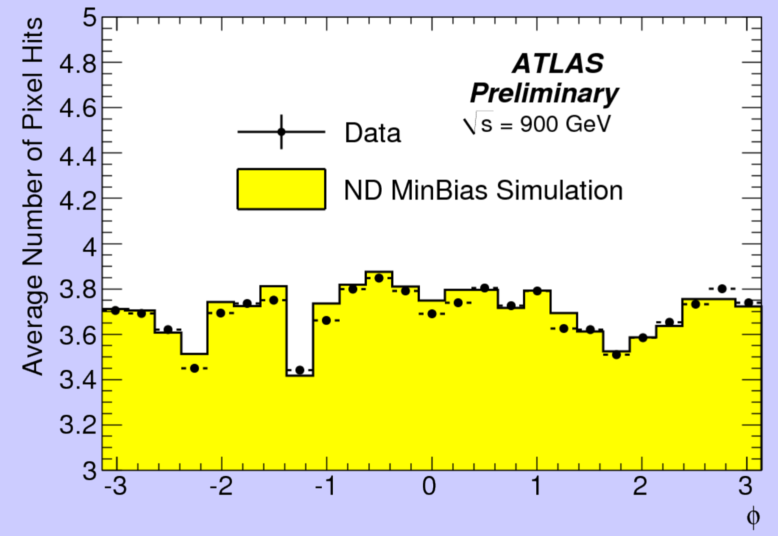
- Hinting at multiple production mechanisms?

Big variations in model predictions

- Low $n_{ch}$ difficult (diffraction again?)
- Slopes at high $n_{ch}$ mostly OK

# Angular correlations

- In addition to multiplicity distributions, event shapes can also provide constraints for MC tunes and insights into QCD
  - Underlying Event studies to be presented by D. Kar in the afternoon
  - Angular correlations discussed here
- Define leading particle as particle in phase-space with highest $p_T$
- Define $\Delta\phi$ for each non-leading particle as unsigned azimuthal angle with respect to leading particle
- Construct robust distributions with minimal systematic errors in light of detector level tracking inefficiencies and phi-assymetries
- Use phase-space with more uniform tracking efficiencies:
  - $p_T > 500\text{MeV}$, $n_{ch} \geq 2$
  - $|\eta| <$ 1.0, 2.0 or 2.5 (multiple to provide more handles)



*Small phi-asymmetries in the detector due to imperfections such as disabled modules*

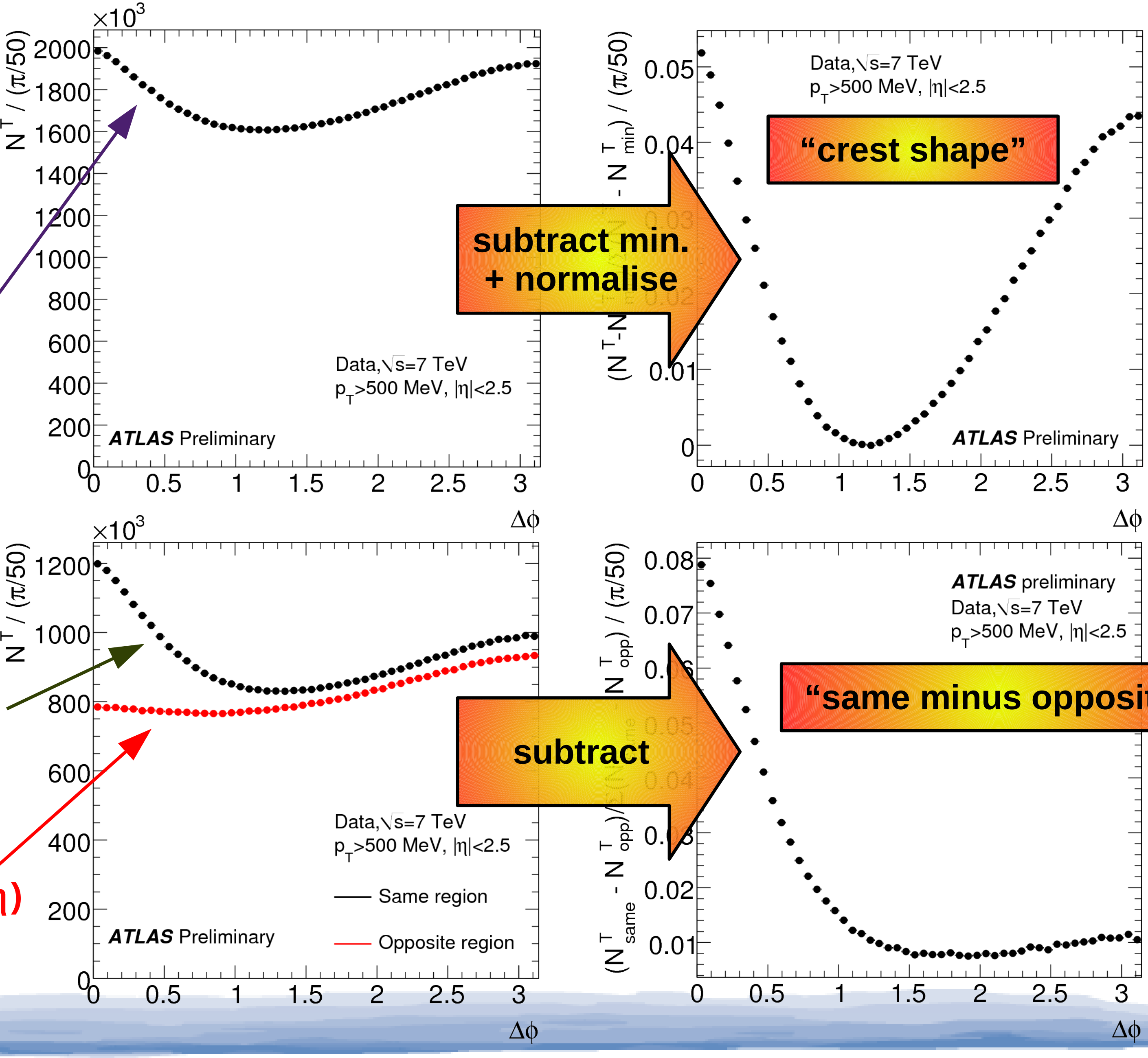
# Angular correlations: Distributions

Two distributions chosen for robustness and low systematic uncertainties

**Δϕ for all non-leading particles**

**Δϕ for non-leading particles with same sign(η) as leading particle**

**...and for those with opposite sign(η)**



**subtract min. + normalise**

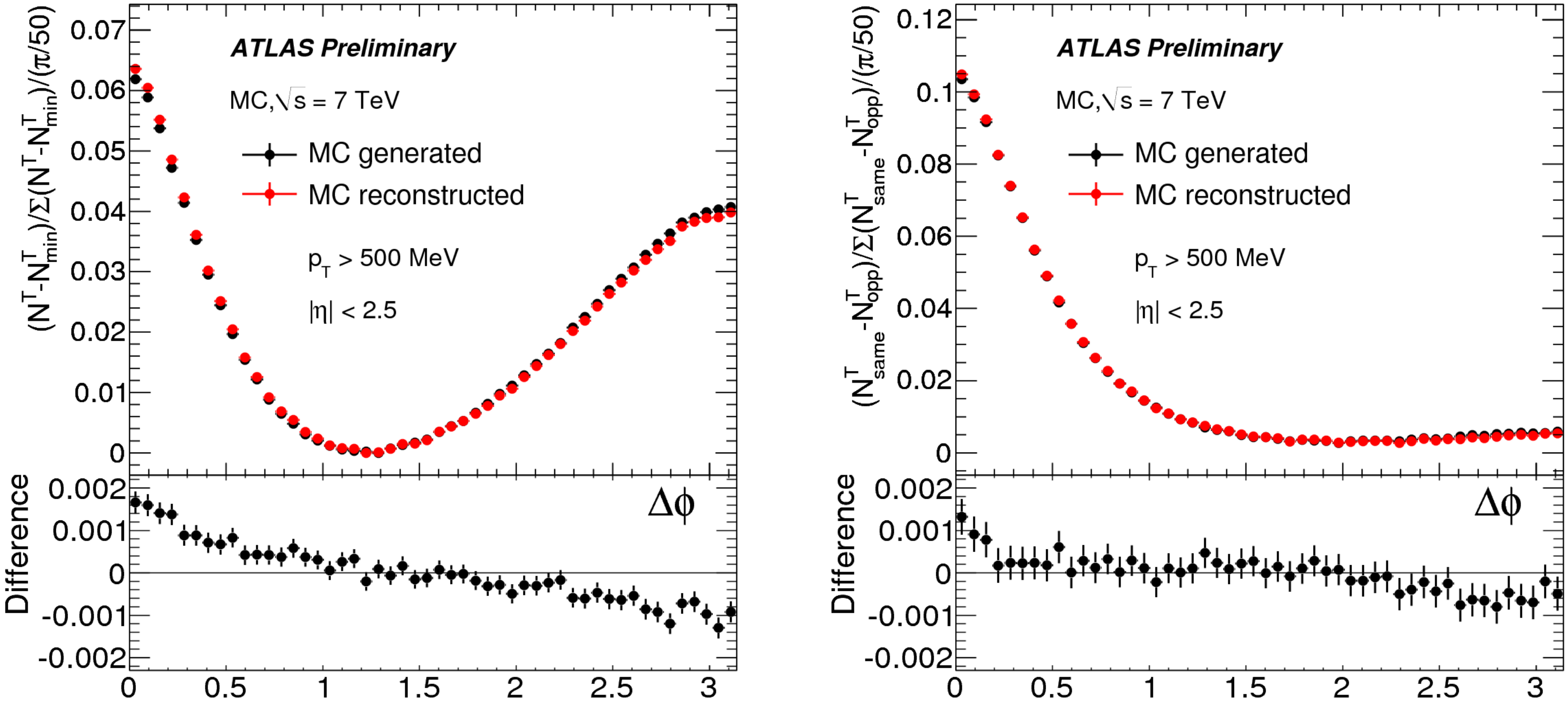
**“crest shape”**

**subtract**

**“same minus opposite”**

# Angular correlations: Uncorrected test on MC

- Even without any special corrections, MC tests with raw distributions prove the methods to be quite robust:



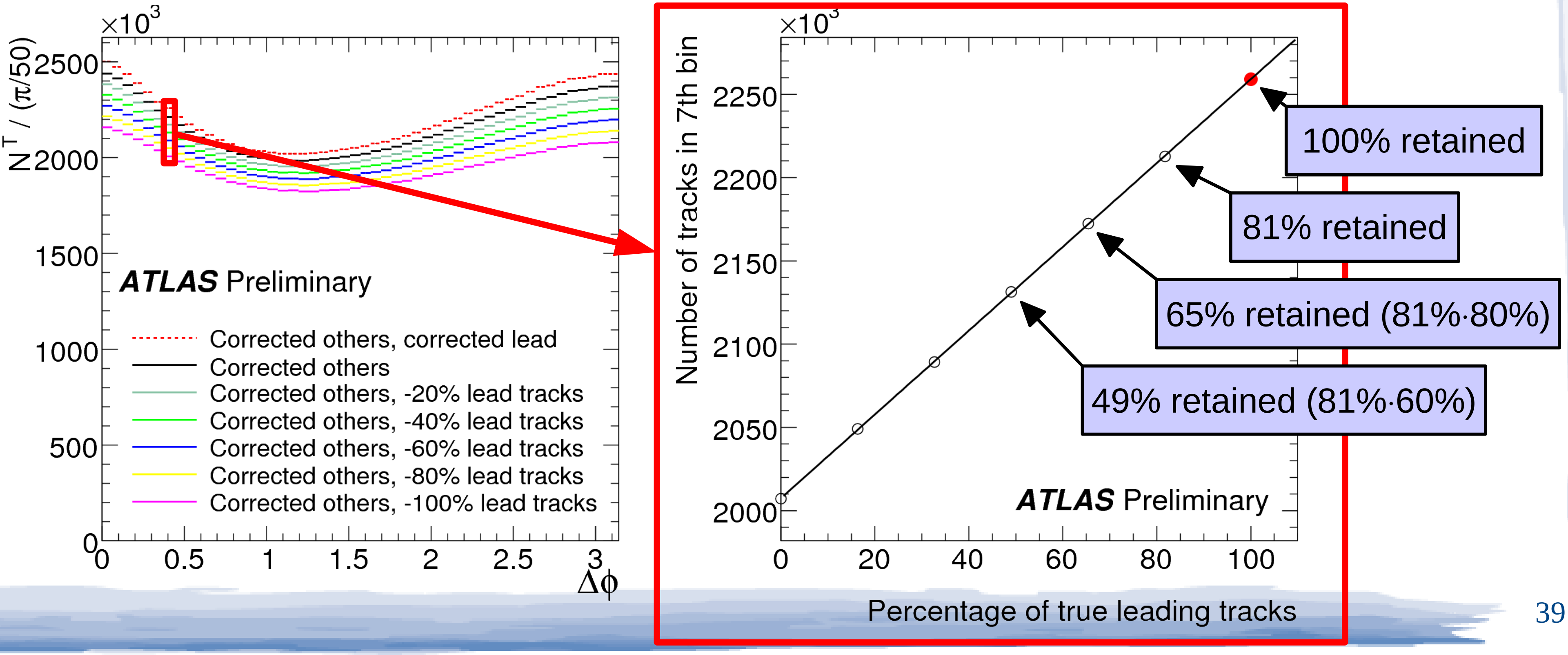
- Remaining bias mainly due to lost tracks ⇒ corrections applied

# Angular correlations: Corrections

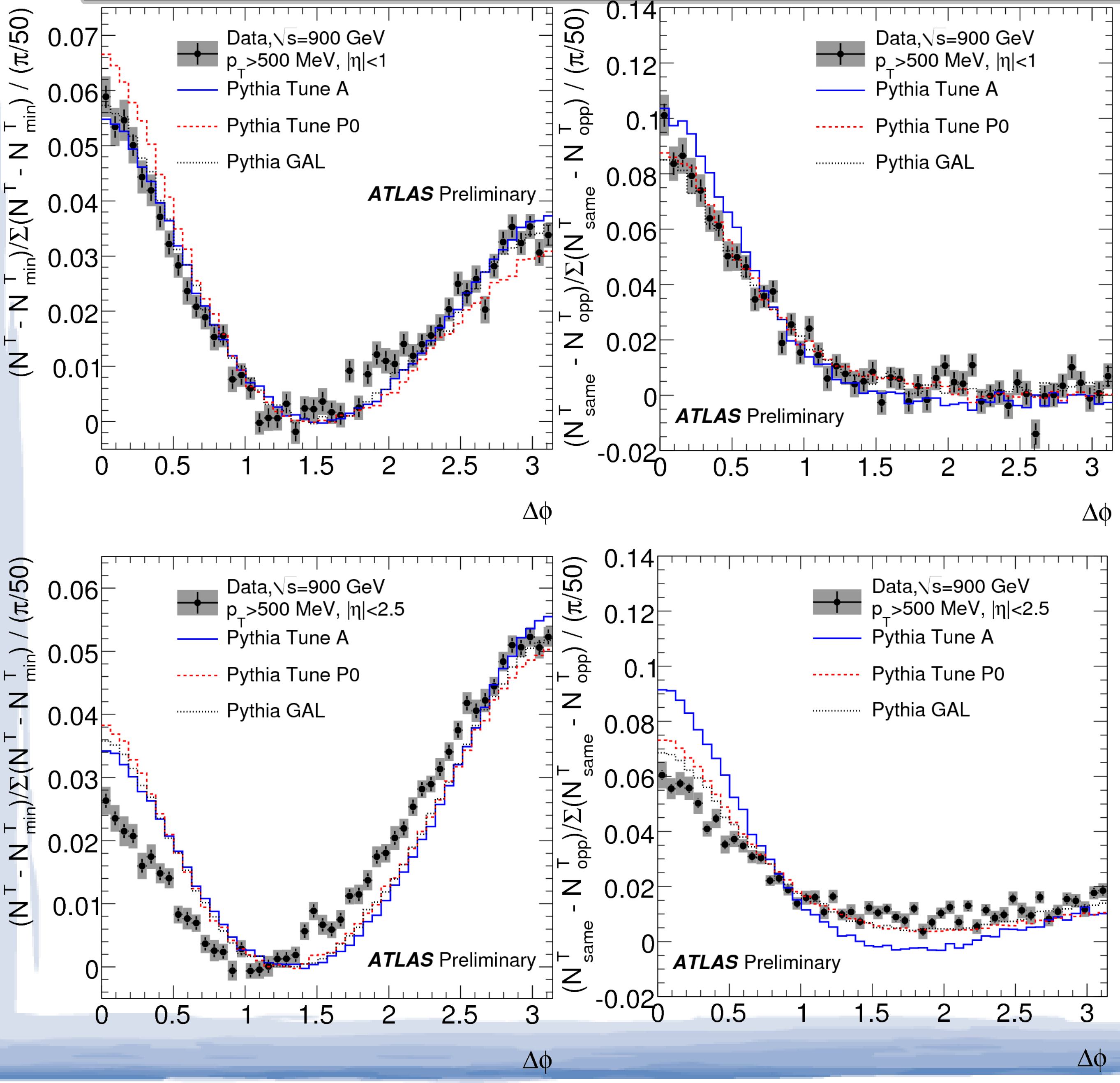
- **Event selection**:
  - Only events with low $n_{Sel}$ are lost. These contribute with few entries.
- **Background tracks not correlated with leading track** (from pileup, secondaries from non-leading particles, ...):
  - Contributes relatively uniformly to $\Delta\phi \Rightarrow$ cancels out in subtractions.
- **Background tracks correlated with leading track**:
  - Estimate fraction $f_{bkg}$ from MC and apply weight: $1-f_{bkg}$
- **Misclassified due to $p_T$ resolution** (e.g. swap leading and 2nd leading):
  - Small effect since distributions will be similar when $p_{T1} \approx p_{T2}$
- **Non-leading particles lost to tracking inefficiency**:
  - Correct by tracking efficiency known from MC: $1/\varepsilon_{trk}(p_T,\eta)$
- **Leading particle lost to tracking inefficiency**:
  - Bigger effect since angular distributions to 2nd leading track can be somewhat different ⇒ ***Data-driven correction implemented...***

# Angular correlations: Correct for loss of leading part.

- Estimate fraction of leading particles reconstructed as tracks:
    - Integrate $\varepsilon^{MC}_{trk}(p_T,\eta)$ over $p_T$ and $\eta$ spectrum from data
    - For $|\eta|<2.5$ this gives 81% chance to retain track
- Artificially ignore the leading track in 0%, 20%, ..., 100% of events
- Extrapolate to 100% retained leading particles bin-by-bin



# Angular correlations: Results at 900 GeV

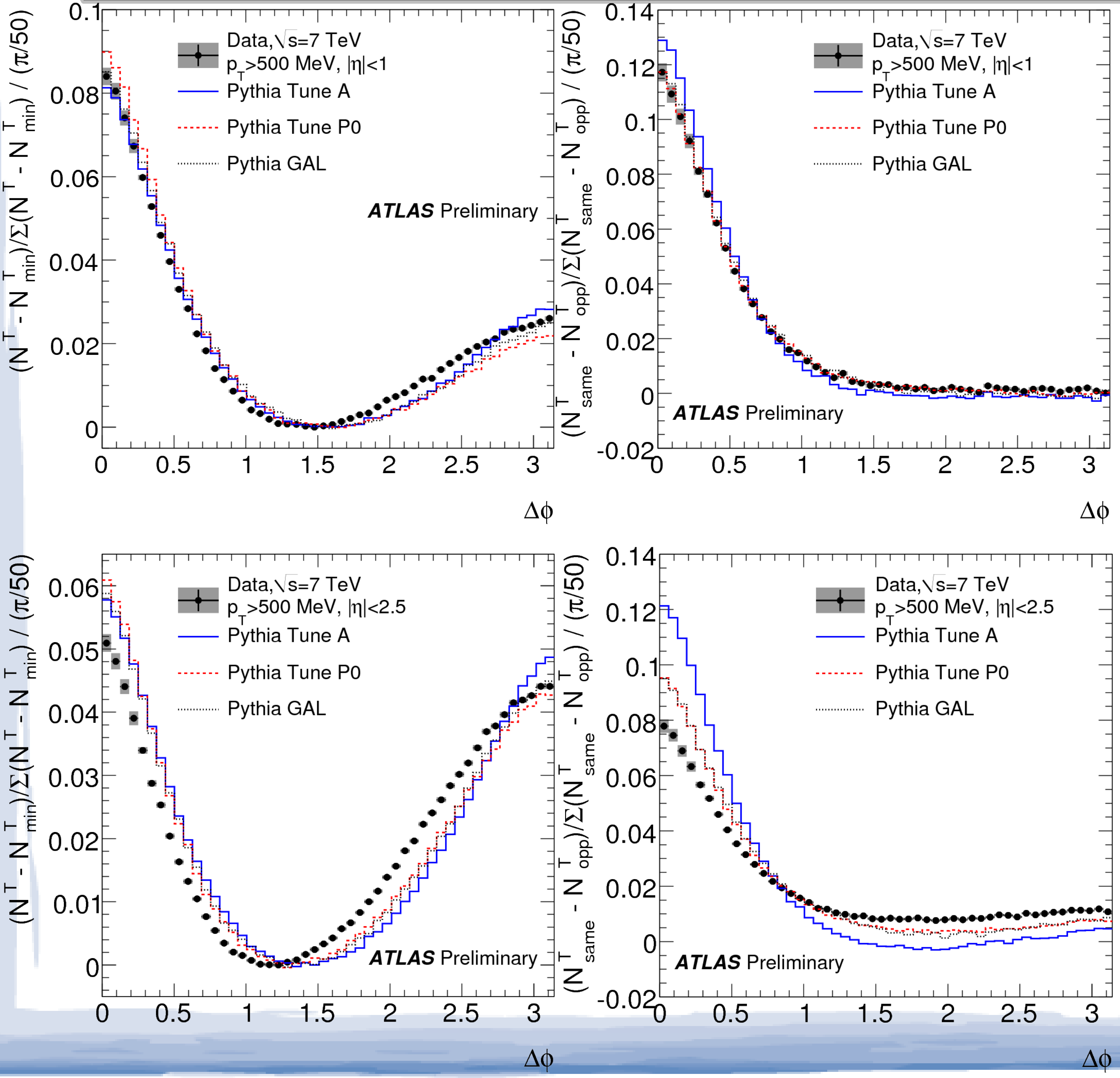


Relatively OK agreement with MC for |η|<1 distributions *(perhaps not surprising since many tunes use CDF data)*

Less OK agreement for |η|<2.5 distributions *Can distinguish models!*

|η|<2 distributions not shown here

# Angular correlations: Results at 7 TeV



Increased energy gives enhancement at low Δϕ

Similar MC agreement as at 900 GeV, but better resolution

# References

- **Charged-particle multiplicities in pp interactions at $\sqrt{s}$ = 900 GeV measured with the ATLAS detector at the LHC**
  - $p_T$>500MeV, Phys Lett B 688, Issue 1 (2010), 21-42
- **Charged particle multiplicities in pp interactions at s = 7 TeV measured with the ATLAS detector at the LHC**
  - $p_T$>500MeV, ATLAS conference note: ATLAS-CONF-2010-024
- **Charged particle multiplicities in pp interactions for track PT > 100MeV at sqrt(s) = 0.9 and 7 TeV measured with the ATLAS detector at the LHC**
  - ATLAS conference 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**
  - $p_T$>500MeV, ATLAS conference note: ATLAS-CONF-2010-047
- **Angular correlations between charged particles from proton-proton collisions at sqrt(s) = 900 GeV and sqrt(s) = 7 TeV measured with ATLAS detector**
  - ATLAS conference note: ATLAS-CONF-2010-082
- **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 a new PYTHIA6 tune**
  - ATLAS Minimum Bias Tune 1 (AMBT1), ATLAS-CONF-2010-031

# Summary

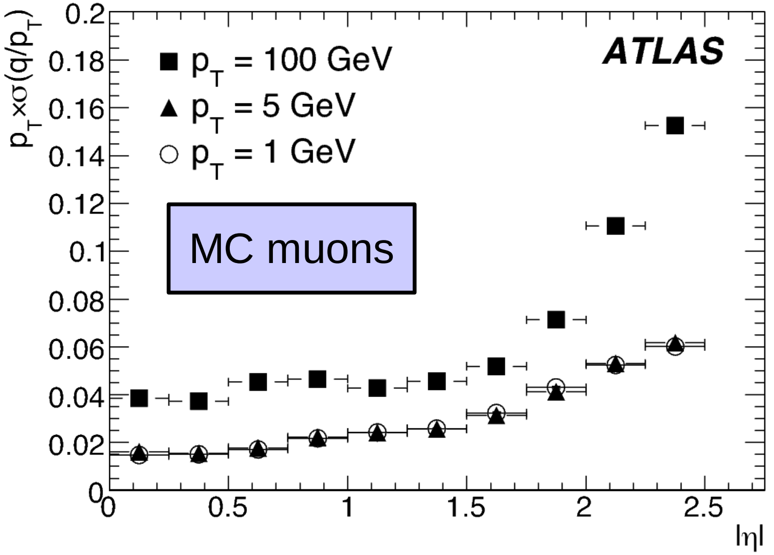
- Several minimum bias results from ATLAS available:
  - Inclusive distributions measured at 0.9 and 7 TeV with well-defined phase-spaces down to 100 MeV and 500 MeV with just 1 or 2 particles and at |η|<2.5:

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

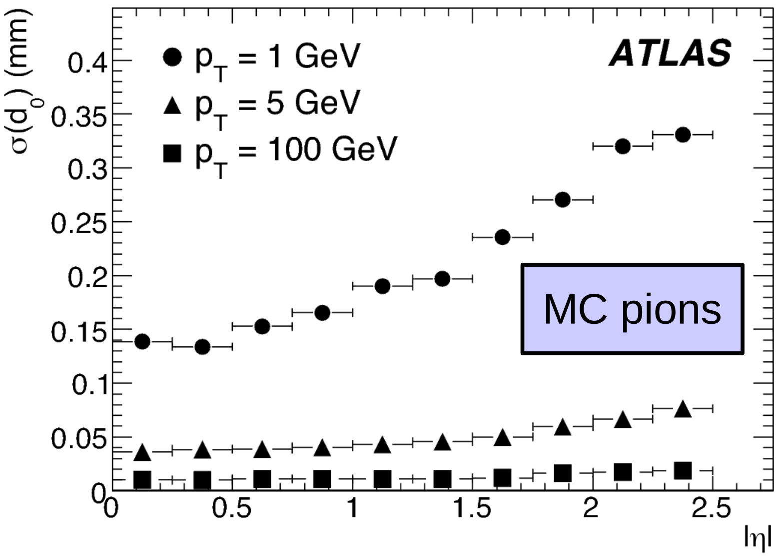
  - Data point at 2.36 TeV where SCT was at standby was recovered for the first three distributions
  - Diffractive limited phase-space used for new PYTHIA6 tune
  - Angular correlations
- All data corrected back to particle level in a model-independent fashion facilitating easy comparison with MC models
  - Many features reproduced by models, but significant discrepancies remain
- Subsystems of ATLAS relevant for such studies are all performing very well and in a well-understood manner:
  - MBTS trigger, Inner Tracker, software, ...

# Backup material

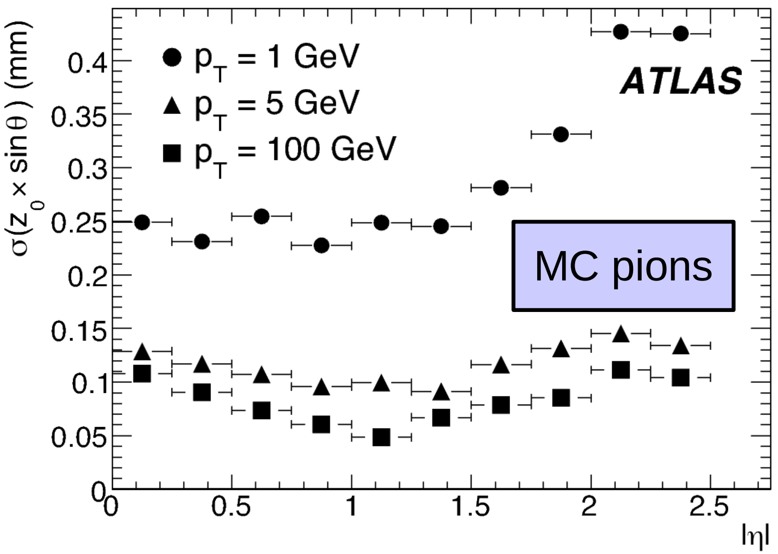
# Inner Tracker Performance



MC muons



MC pions

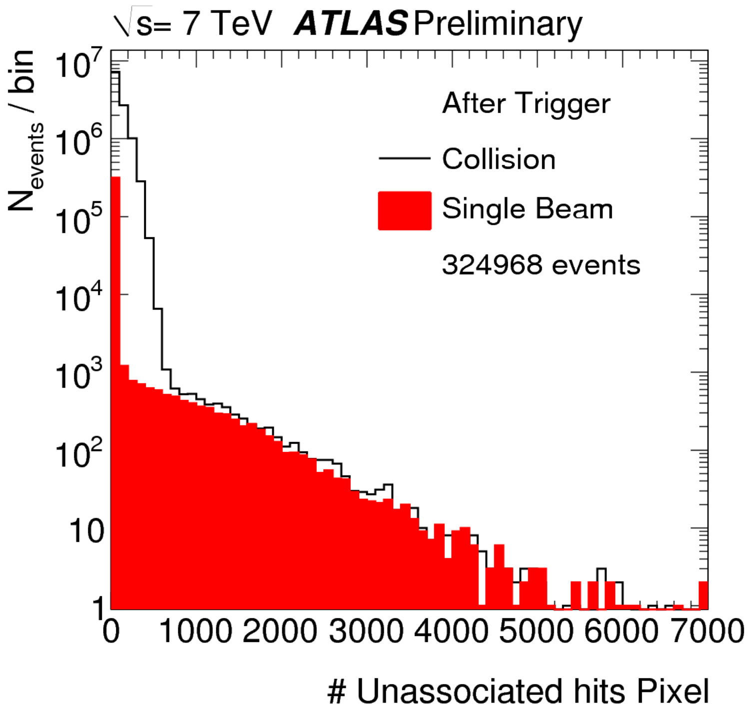


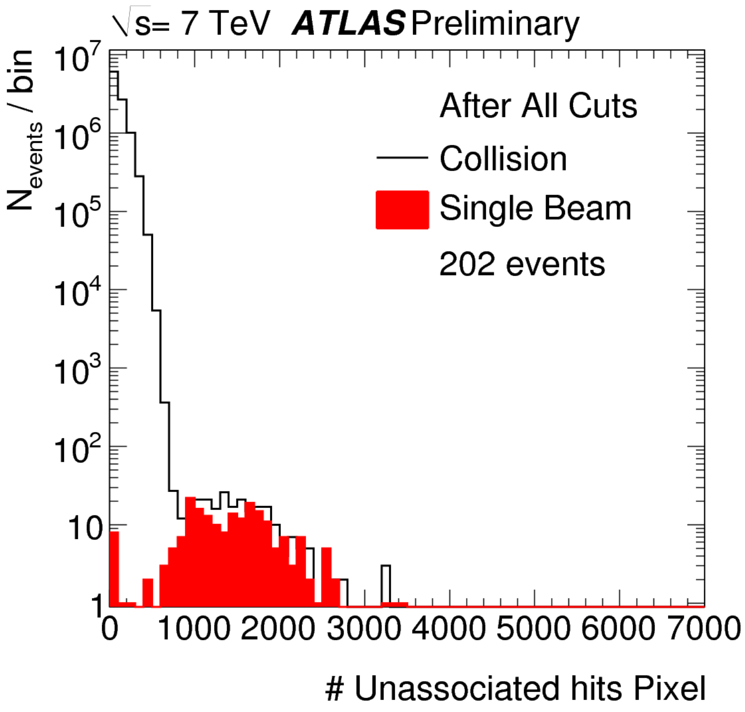
MC pions

Multiple scattering dominated at low momentum

# More plots on beam-backgrounds

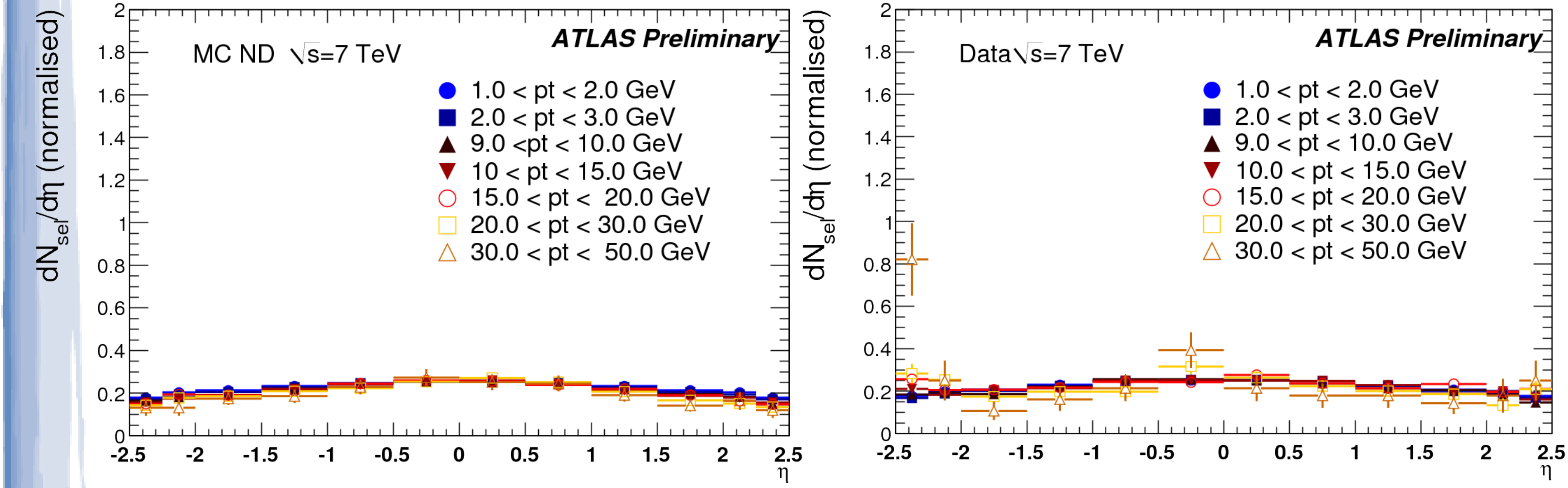
- Another way to estimate the level of beam-background which does not depend on MBTS timing differences (which are not always available with a single-arm trigger):





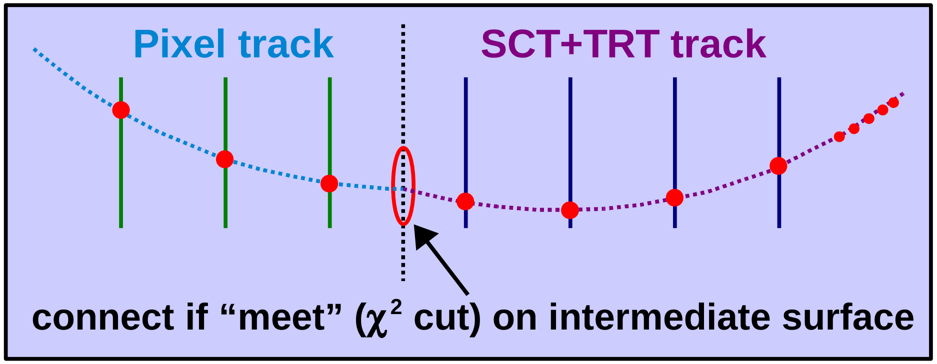
# η-dependence of $p_T$ reco performance

- Flatness of $p_T$ vs. η used to gauge uncertainty due to mis-alignments and mis-measured tracks.
- Effects enhanced outside TRT acceptance at 2.1<|η|<2.5



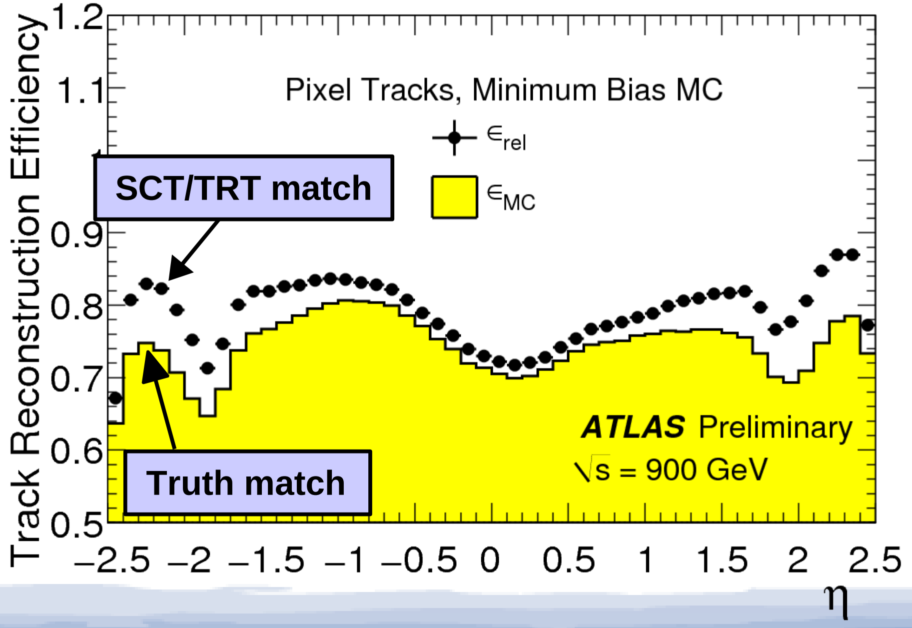
# More on pixel-track method at 2.36 TeV

- No SCT dependence ⇒ Determine tracking efficiency from nominal MC as always
- However presence of unused trackers SCT+TRT allows data-driven correction
- Find tracks using only SCT+TRT trackers and find how often they can be connected with a Pixel track (“extension rate”)



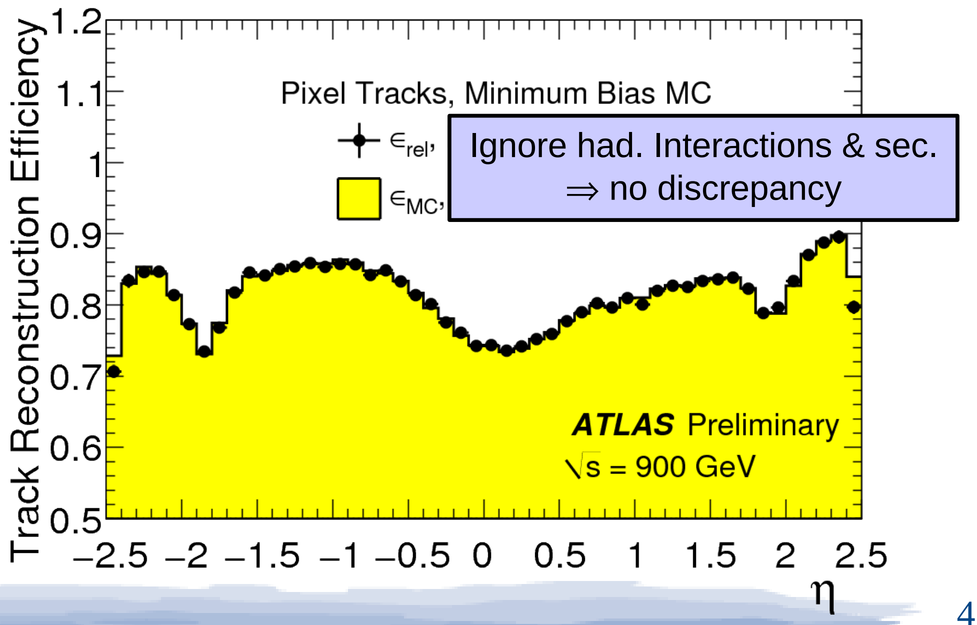
**connect if “meet” ($\chi^2$ cut) on intermediate surface**

- In MC, only hard scatterings between Pixel & SCT should lead to difference between this extension rate and standard efficiency from pixel-track to truth particle matching:



**SCT/TRT match**

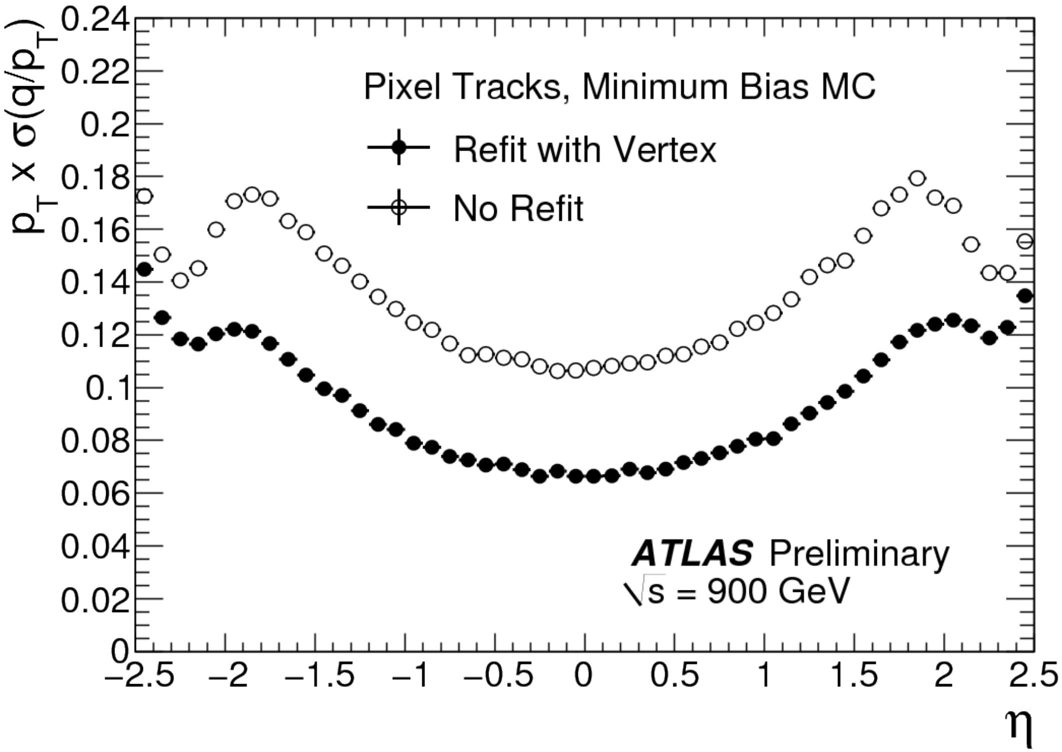
**Truth match**



Ignore had. Interactions & sec.
⇒ no discrepancy

# Pixel-track $p_T$ resolution at 2.36 TeV

- Main drawback of pixel-track method is shortened track length, leading to degraded $p_T$ resolution by about an order of magnitude compared to ID-tracks
  - Can be improved by refitting selected tracks using vertex as additional measurement
  - Still ~6 times worse



# Systematic errors for 2.36 TeV analysis

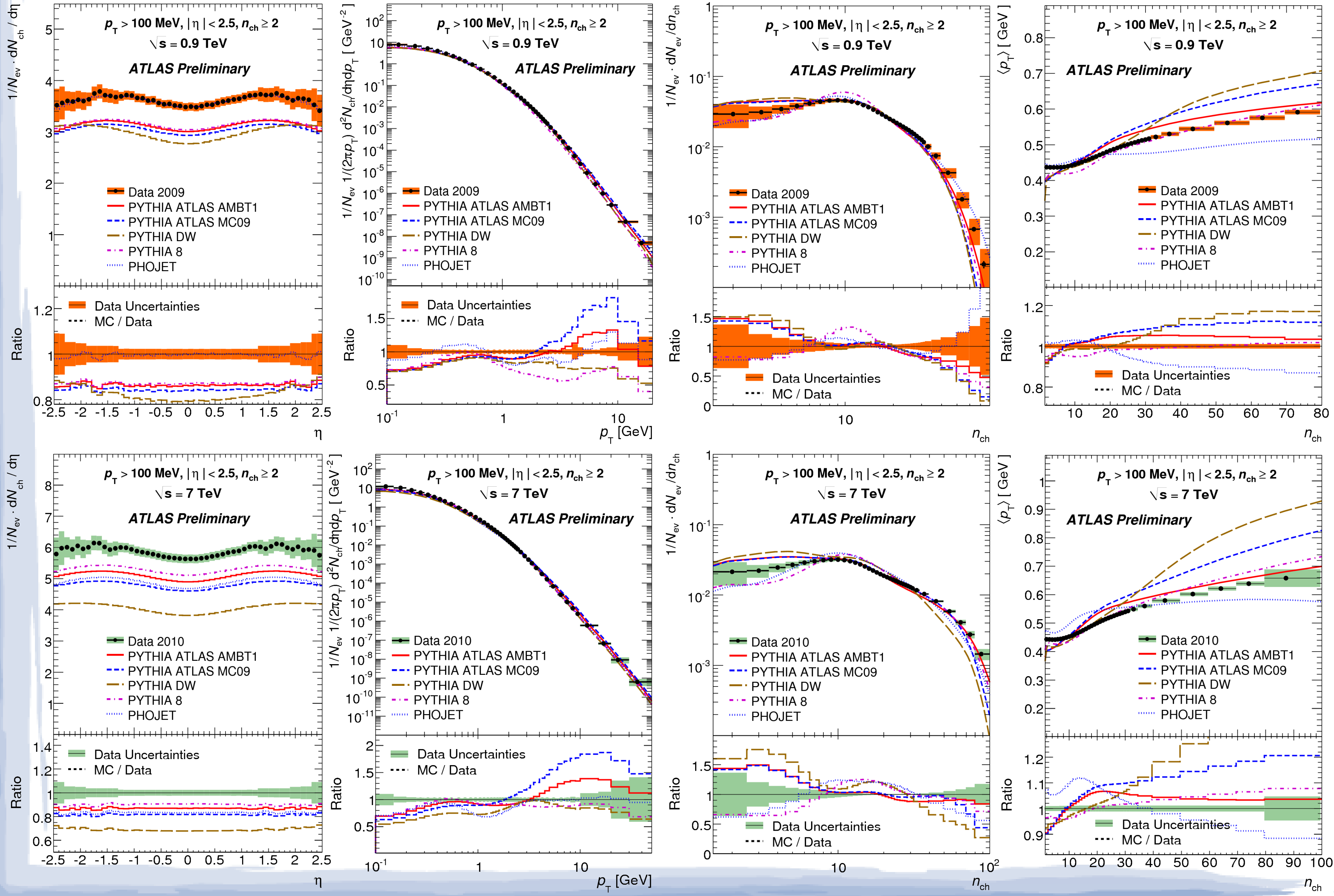
| Uncertainty on $N_{\mathrm{ev}}$ | | |
|---|---|---|
| Source of uncertainty | Pixel track Method | ID track Method |
| Vertex reconstruction efficiency | 0.4% | $< 0.1\%$ |
| Track reconstruction efficiency | 0.5% | 1.8% |
| Different Monte Carlo Tunes | 0.1% | 0.4% |
| Statistical uncertainty | 1.2% | 1.2% |
| Total uncertainty on $N_{\mathrm{ev}}$ | 1.4% | 2.6% |

| Systematic uncertainty on $(1/N_{\mathrm{ev}}) \cdot (\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)$ | | |
|---|---|---|
| Source of systematic uncertainty | Pixel track method | Track method |
| Trigger and Vertex reconstruction efficiency | 0.1% | $< 0.1\%$ |
| Track reconstruction efficiency | 3.4% | 6 % |
| Out of phase space correction | 1.1% | $< 0.1\%$ |
| Secondary fraction | 0.6% | 0.1% |
| Correlated Uncertainty on $N_{\mathrm{ev}}$ | -0.5% | -1.8% |
| Uncorrelated Uncertainties from $N_{\mathrm{ev}}$ | 1.3% | 1.7% |
| Total systematic uncertainty on $(1/N_{\mathrm{ev}}) \cdot (\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta)$ | 3.5% | 4.5 % |

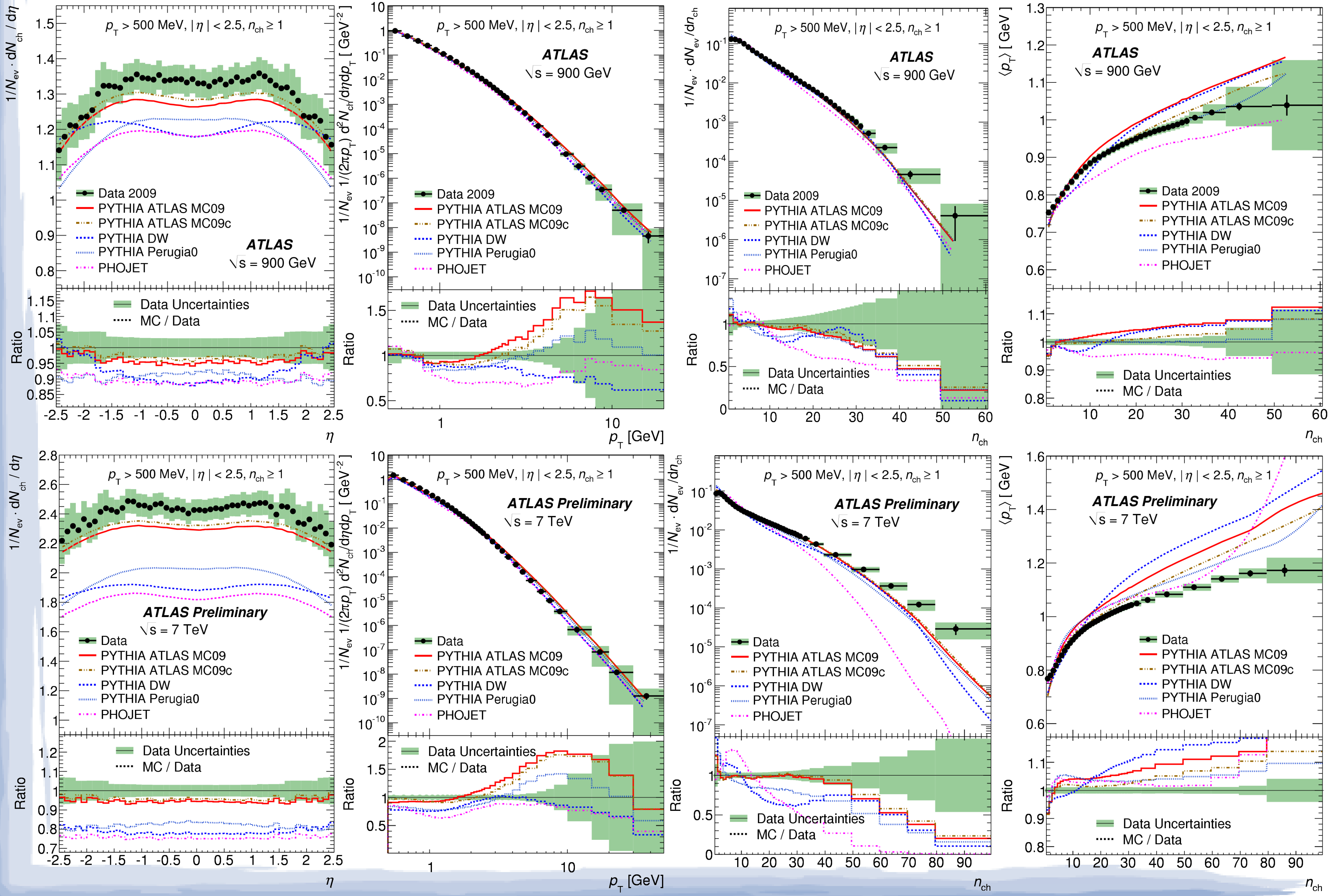
**Pixel-track method better for multiplicity results due to tracking eff.**

Again, just shown here for one measurement

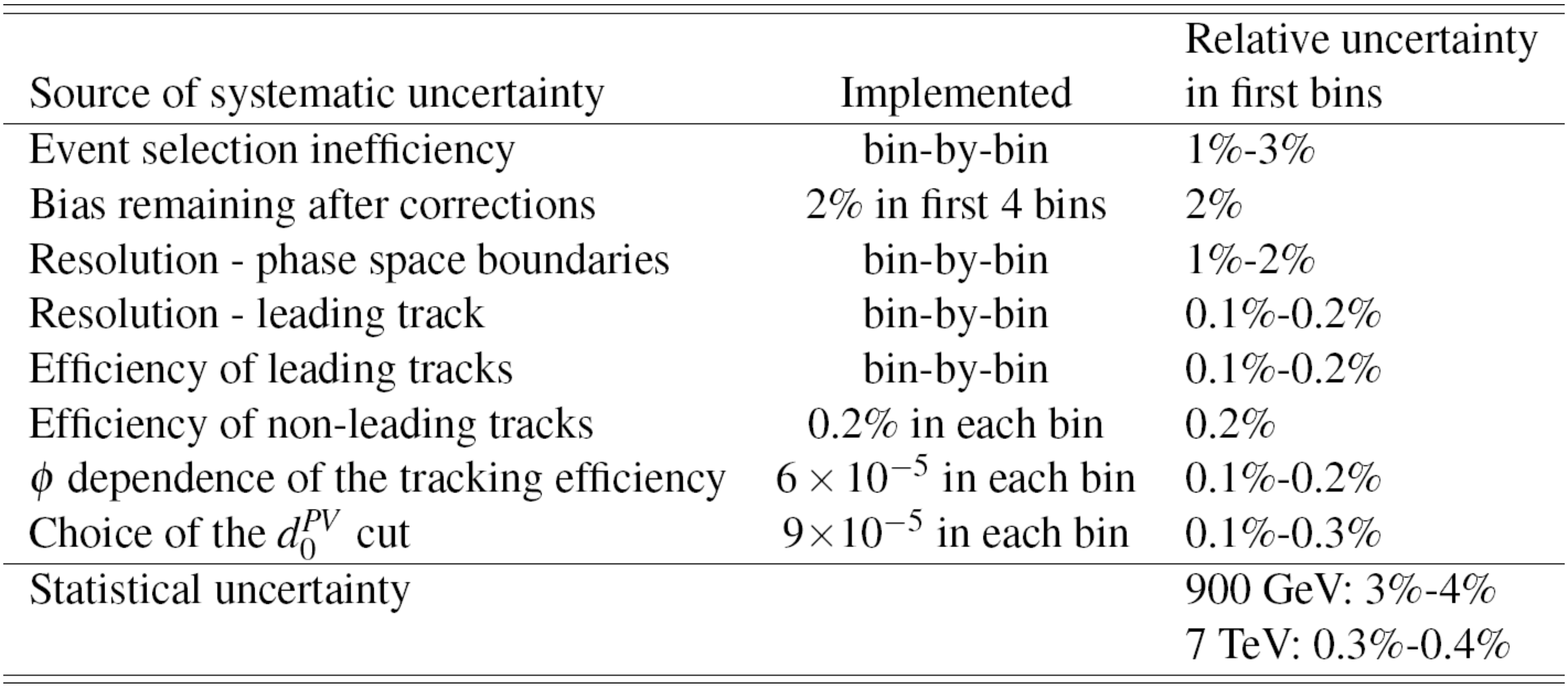
# $p_T$>100MeV results: 900 GeV (top) & 7 TeV (bottom)



# $p_T$>500MeV results: 900 GeV (top) & 7 TeV (bottom)



# Angular correlations: Uncertainties



| Source of systematic uncertainty | Implemented | Relative uncertainty in first bins |
|---|---|---|
| Event selection inefficiency | bin-by-bin | 1%-3% |
| Bias remaining after corrections | 2% in first 4 bins | 2% |
| Resolution - phase space boundaries | bin-by-bin | 1%-2% |
| Resolution - leading track | bin-by-bin | 0.1%-0.2% |
| Efficiency of leading tracks | bin-by-bin | 0.1%-0.2% |
| Efficiency of non-leading tracks | 0.2% in each bin | 0.2% |
| $\phi$ dependence of the tracking efficiency | $6 \times 10^{-5}$ in each bin | 0.1%-0.2% |
| Choice of the $d_0^{PV}$ cut | $9 \times 10^{-5}$ in each bin | 0.1%-0.3% |
| Statistical uncertainty | | 900 GeV: 3%-4%<br>7 TeV: 0.3%-0.4% |

**Remaining systematic uncertainties contribute mainly in the first few bins...**

**Two-fold reason for better statistics at 7 TeV: More events and more entries per event**