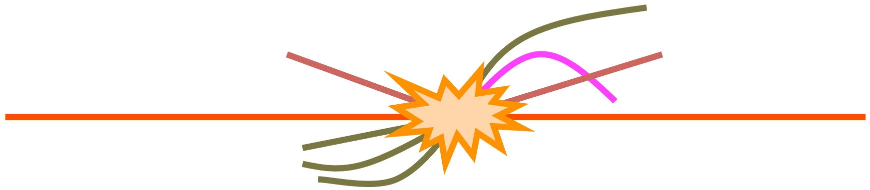
First LHC Results: Minimum Bias



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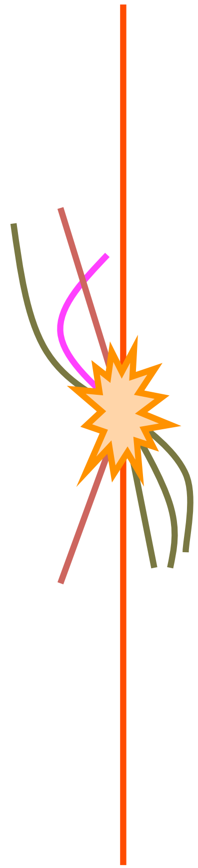
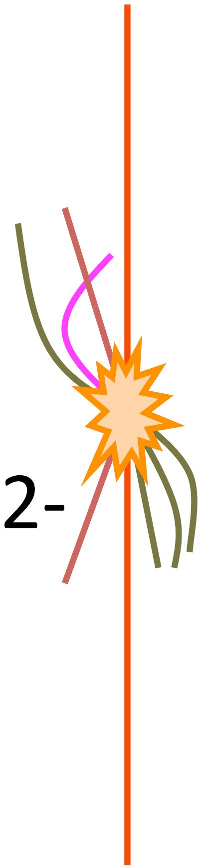
Overview



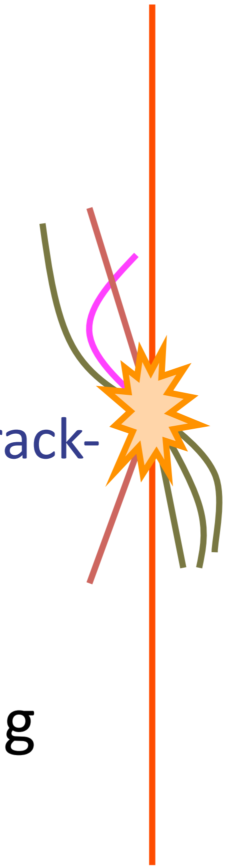
- Minimum bias
  - Motivation
  - Defining measurement and experimental issues
  - Results from ALICE, CMS, and ATLAS.
  - Detailed discussion of ATLAS analysis.
- Underlying event.
  - Motivation and definition.
  - Summary of results.
- Conclusions

Charged-particle multiplicity distributions



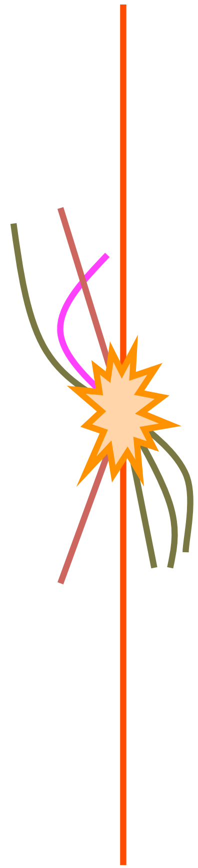
- Basic underlying physics of *pp* interactions.
- MC attempt to describe low-p_T processes using 2-to-2 scatters and phenomenological models.
  - Multiple-parton scattering
  - Partonic matter distributions
  - Scattering between unresolved protons
  - Colour reconnection.
- Phenomenological models tuned using measurements.
  - Measurements needed to constraint behaviour at different centre-of-mass energies.

Making a measurement



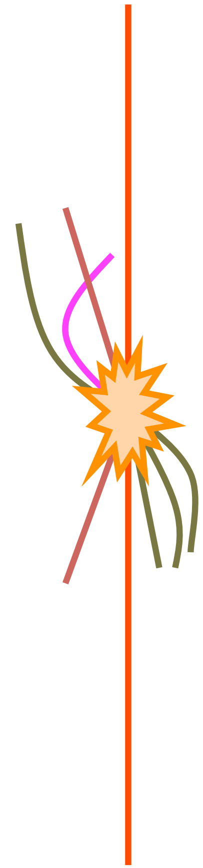
- Select inelastic *pp* interactions using minimal bias.
  - Trigger scintillators with a large coverage overlapping with track-reconstruction volume.
  - The tracking detector itself.
  - Beam bunch requirement.
- Reconstruct charged particles using silicon or gas tracking detectors.
  - Magnetic field surrounding tracking volume needed for momentum measurements.
- Reconstruct the primary vertex or use the beam position to select primary tracks.
- Correct for event and track selection and provide a particle level result.

Experimental issues



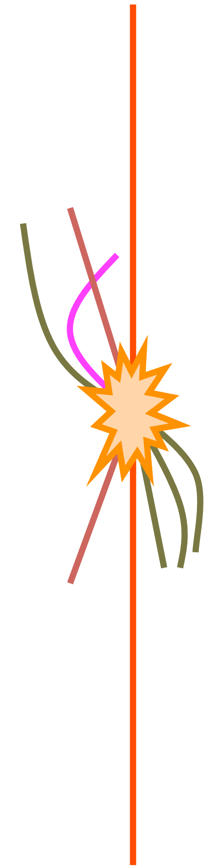
- Trigger scintillators can select cosmic ray and beam-background.
  - Cosmic rays can be reduced to ~0
    - Require proton bunches.
    - Use arrays of counters perpendicular to beam axis.
  - Protons scrape collimators and collide with gas molecules within beam pipe vacuum.
    - Beam-gas collisions within experiment similar to diffractive physics – reduce by using NEG coating and primary vertex requirement.
    - Muons from upstream beam-collimator or beam-gas collisions – removed by using primary vertex requirement.

Experimental issues



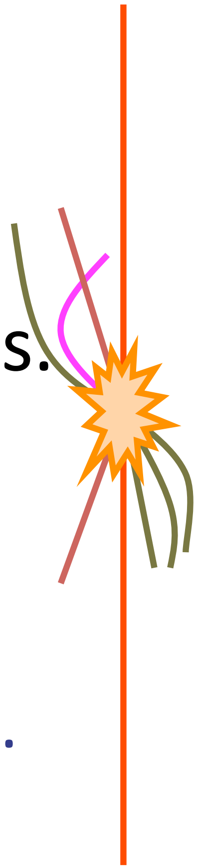
- Additional *pp* interactions.
- Multiple scattering within tracking detector.
- Nuclear interactions, which result in badly measured tracks.
- p_T resolution as p_T becomes large.

Types of measurement



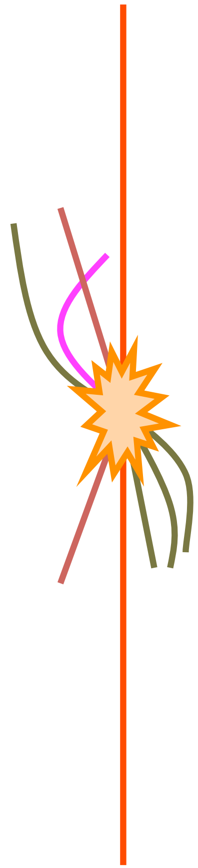
- No corrections
  - Easy to produce this result, hard for someone else outside the experiment to understand.
- Non-single-diffractive
  - Removal of single-diffractive events within acceptance.
  - Addition of double-diffractive and non-diffractive events with $n_{ch} = 0$ using MC generator.
- Fully corrected within kinematic range.
  - Data used for trigger and vertex corrections.
  - Only events with $n_{ch} >= 1$ included in distributions.

Correction factors



- Trigger selection is sensitive to physics processes.
  - Trigger correction with MC model folds in physics assumptions from MC into data distribution.
- Extrapolation back to $p_T = 0$.
  - Fold in model based assumptions about distribution.
- Correction of tracking acceptance using MC.
  - Folds in n_{ch} distribution from MC for low multiplicity bins.
- Need to avoid sources of model dependence and present results within acceptance.

Distributions



$$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}$$

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

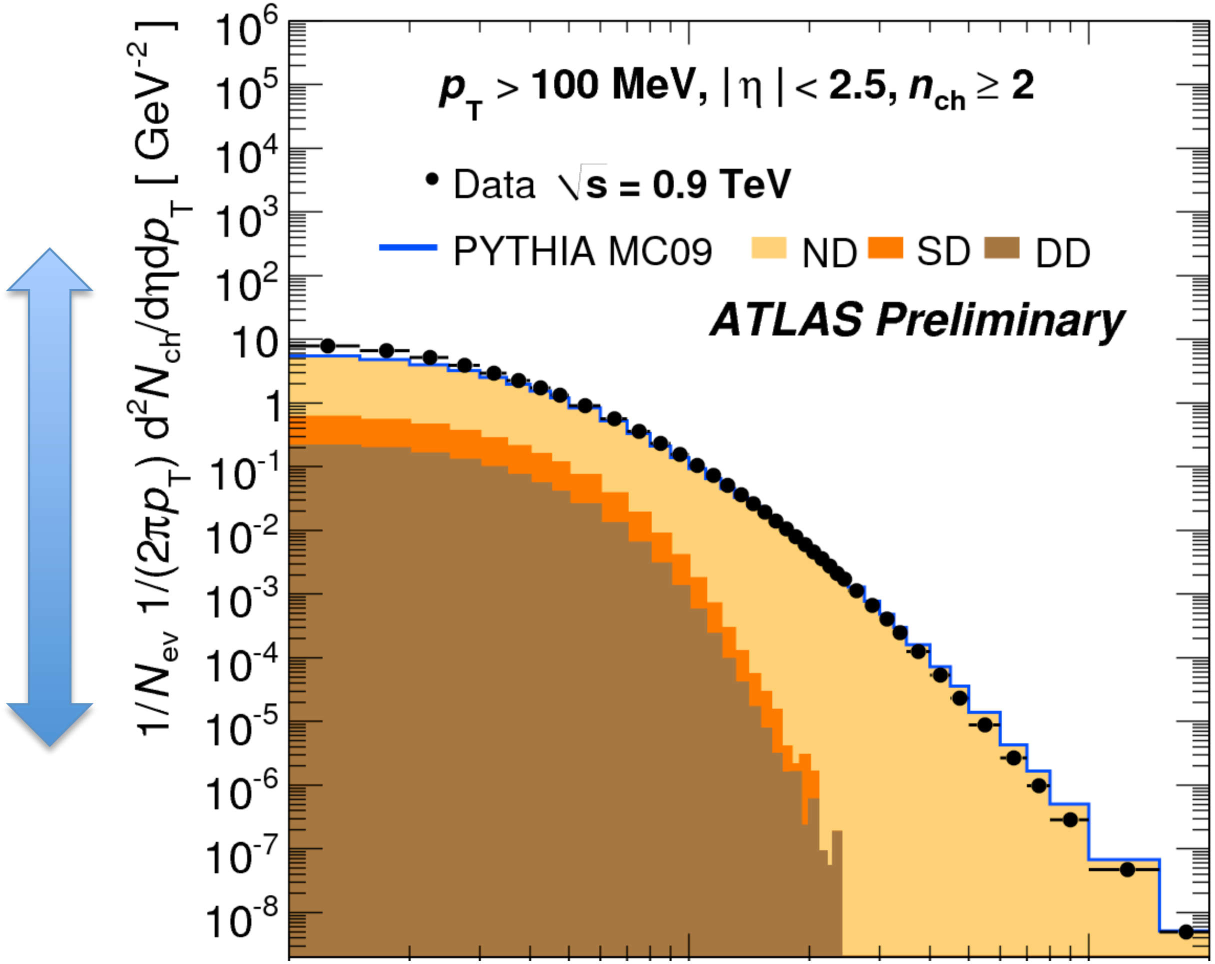
$$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$$

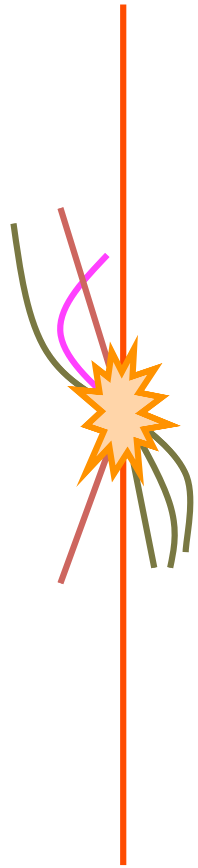
$$\langle p_T \rangle \text{ vs. } n_{Ch}$$

Different distributions to highlight properties of selected events.

Variables defined for a particular measurement.

n_{ch}=0 and diffraction





Adding in n_{ch}=0 events effects normalisation of distribution.

Removing single diffractive diffractive component implies p_T spectrum of generator removed from measured distribution.

Corrections typically made using PYTHIA 6.4.21 i.e. poor diffractive model.

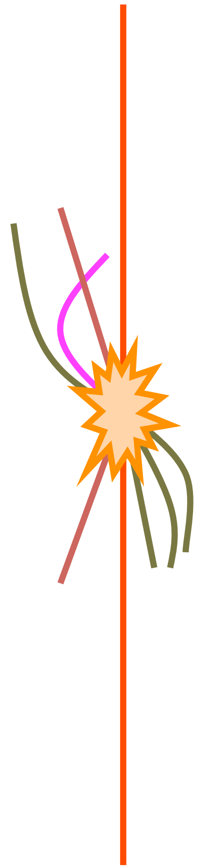
These corrections are not made on the ATLAS data and this Fig. is used for illustrative purposes only.

Primary charged particles

- Measurements of charged particles and charged hadrons are not quite the same.

π^0 **DECAY MODES**	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67
$e^+ e^- \gamma$	(1.174 ± 0.035) %	S=1.5	67

- Define charged particles as: having mean lifetime $\tau > 0.3 \times 10^{-10}$ s directly produced in *pp* interactions or from subsequent decays of particles with a shorter lifetime.
  - Includes electrons and positrons from Dalitz decays
  - Does not include K_s and Λ particles.



LHC Minimum bias results

- ALICE, CMS and ATLAS have released measurements with 900GeV, 2.36TeV and 7TeV *pp* data.

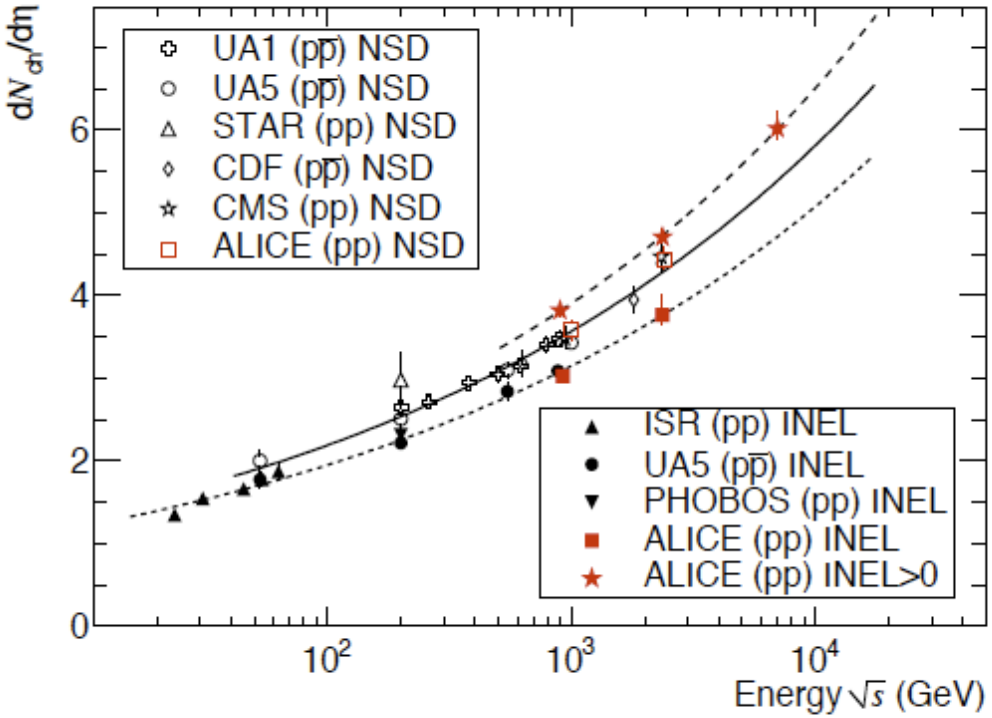
ALICE
arXiv:0911.5430 [hep-ex]
arXiv:1004.3034 [hep-ex]
arXiv:1004.3514 [hep-ex]

CMS
arXiv:1002.0621 [hep-ex]
arXiv:1005.3299 [hep-ex]
CMS PAS QCD-10-004

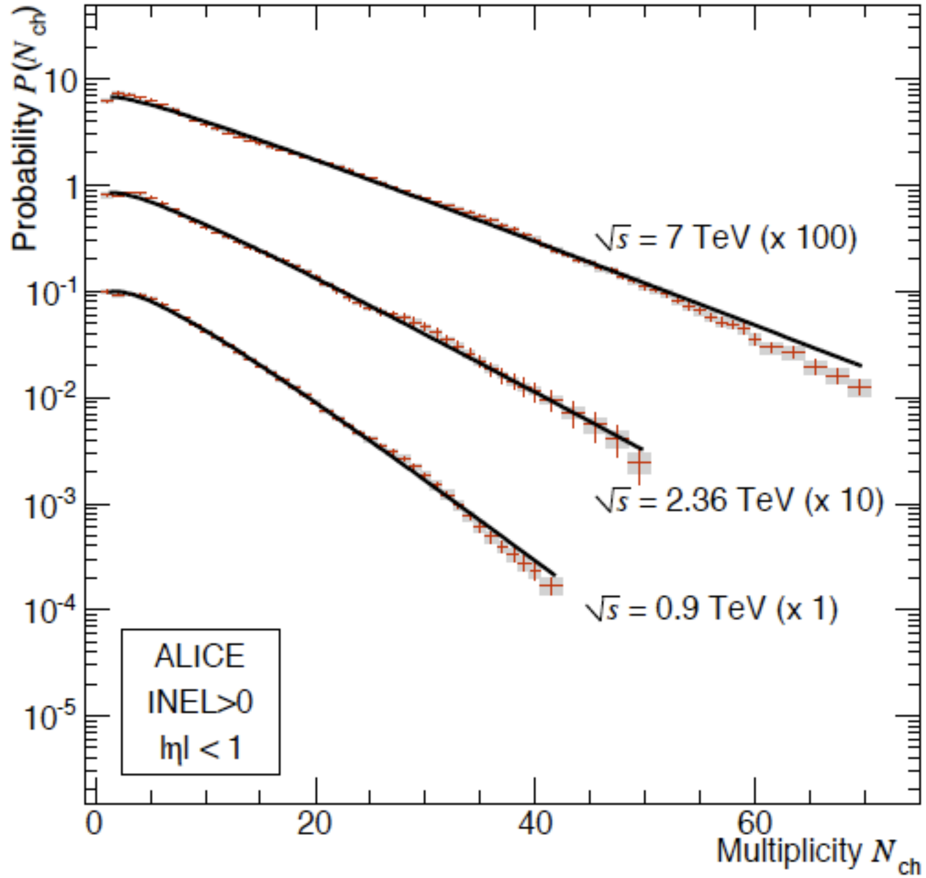
ATLAS
Phys. Lett. B688 (2010) 21–42.
ATLAS-CONF-2010-024
ATLAS-CONF-2010-031
ATLAS-CONF-2010-046
ATLAS-CONF-2010-047
ATLAS-CONF-2010-048

Documents are easily obtained from the public web pages of these collaborations

Results from ALICE



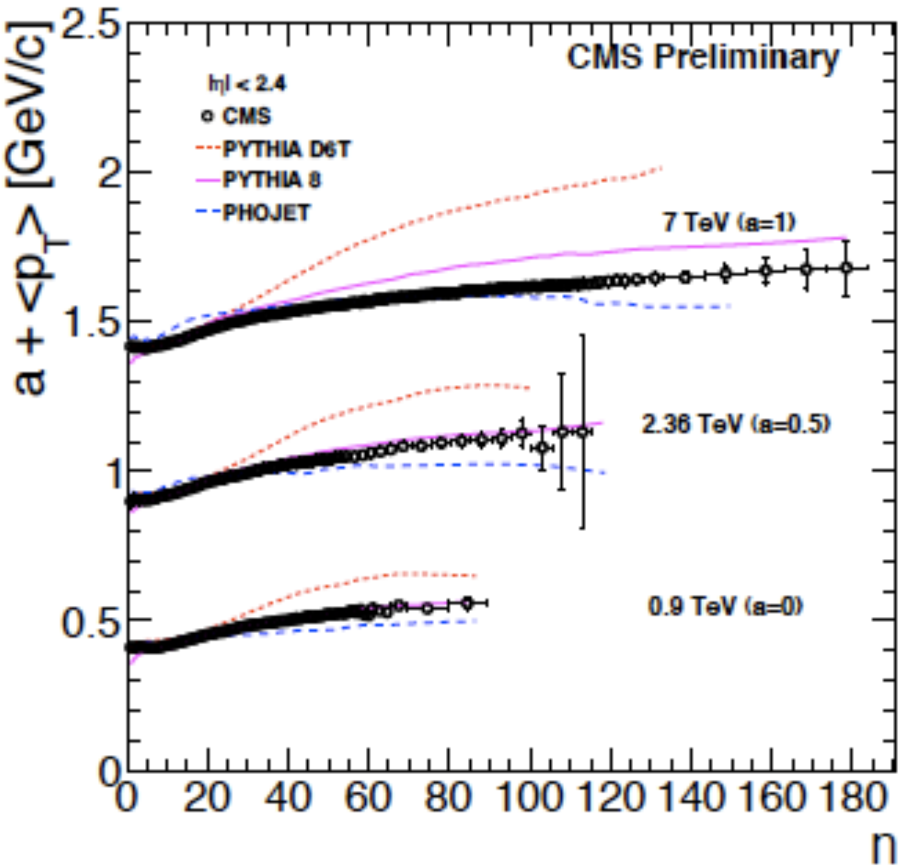
Charged-particle multiplicity per event and unit of pseudorapidity within $|\eta| < 0.5$



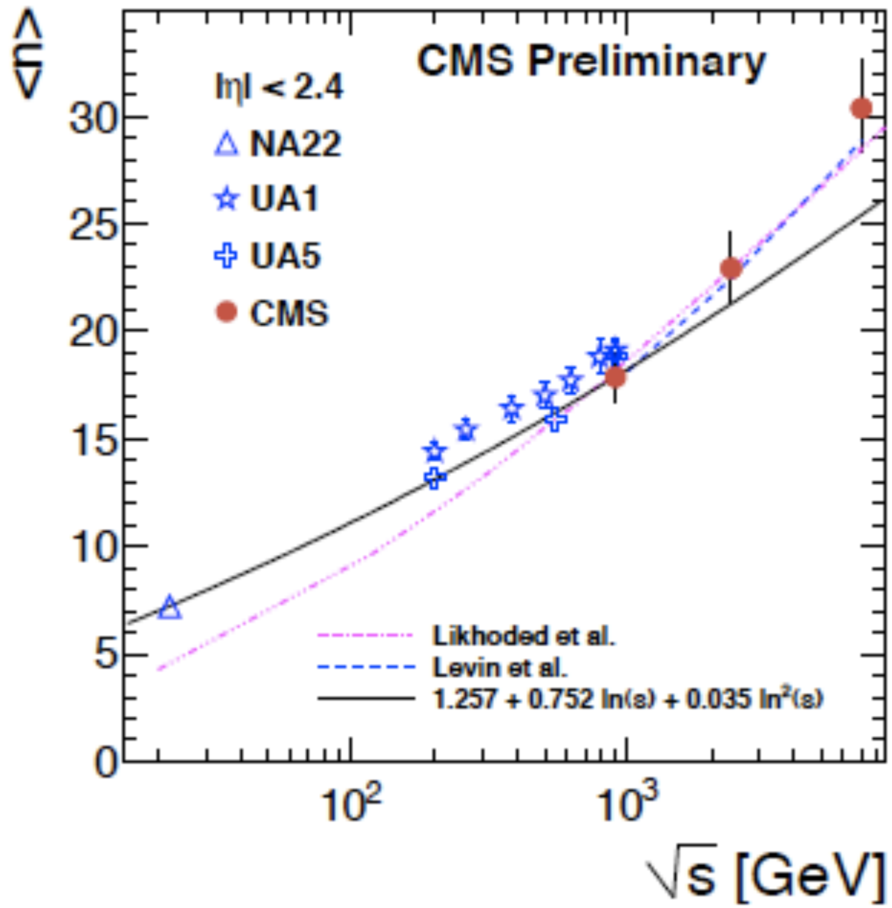
Charged-particle multiplicity for events with at least one charged-particle within $|\eta| < 1$

More results can be found in references

Results from CMS

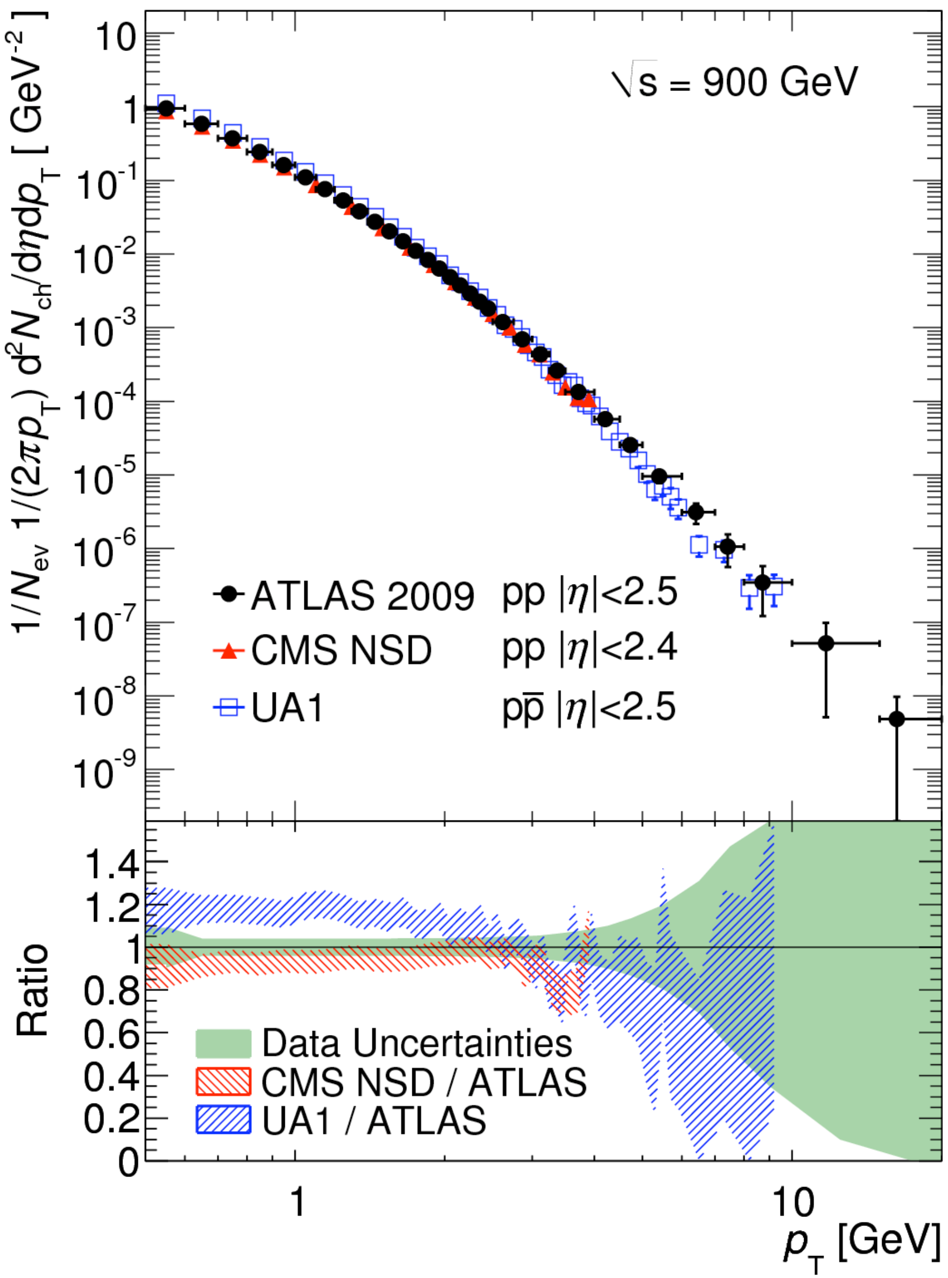


A comparison of $<p_T>$ versus n for |η| < 2.4

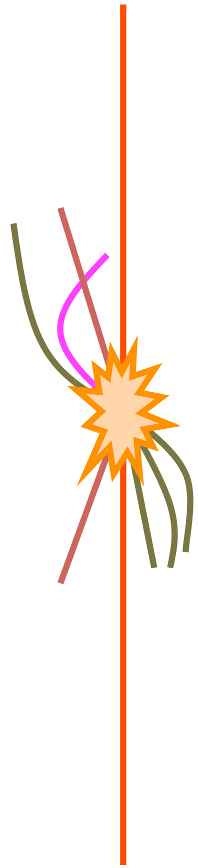


Mean charged-particle multiplicity per event and unit of pseudorapidity within |η| < 0.5

More results can be found in references

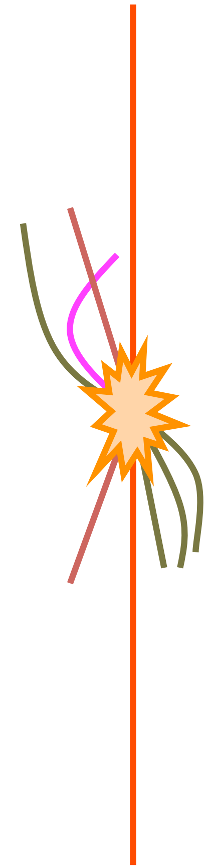


Comparison: $1/p_T\ d^2N_{ch}/d\eta dp_T$



- p_T spectrum similar to CMS NSD result.
  - Agree within uncertainties when ATLAS is converted to CMS NSD.
- Interpreted UA1 data are higher at low p_T
  - Expect this is a measurement definition difference.

ATLAS analysis discussion

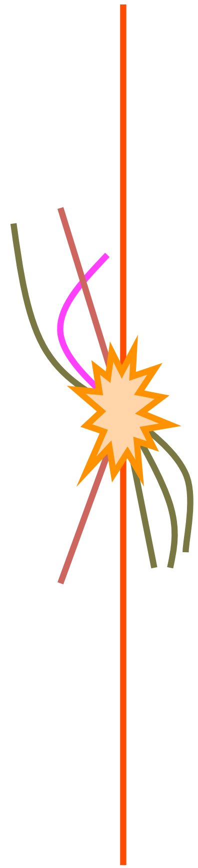


- Kinematic ranges
- Event selection
  - Trigger
  - Vertex
- Corrections
- Results
- Systematics

Distributions

$$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}$$

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



$$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$$

$$\langle p_T \rangle \text{ vs. } n_{Ch}$$

N_{ev}, N_{ch}:

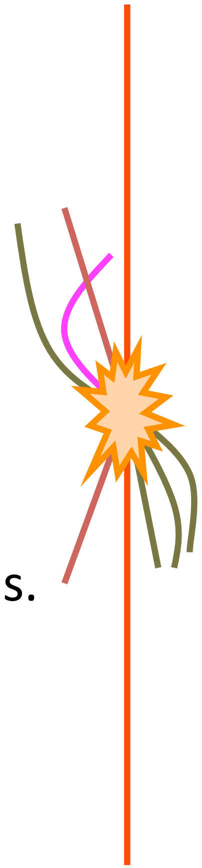
(1) Events with $n_{ch} \geq 1$ ($|\eta|<2.5$ & $p_T > 500$MeV)

(2) Events with $n_{ch} \geq 2$ ($|\eta|<2.5$ & $p_T > 100$MeV)

Discussion will follow (2) and sqrt(s) = 7TeV measurements

Overview

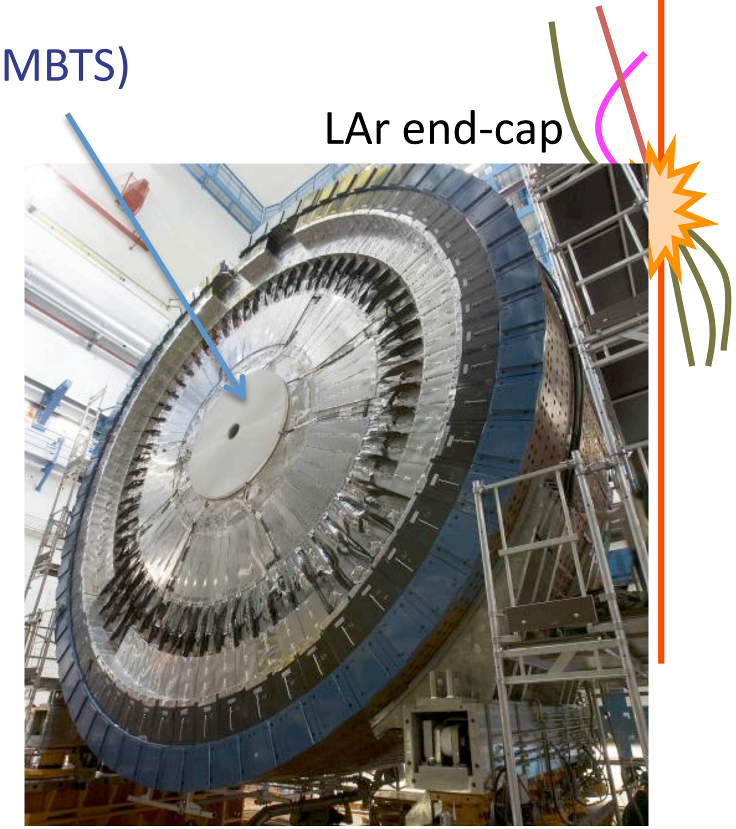
- Measure charged particle multiplicity distributions from inelastic events within $|\eta|<2.5$ & $p_T > 100$MeV
  - Require $n_{ch} \geq 2$ ($|\eta|<2.5$ & $p_T > 100$MeV)
    - Removes model dependence from trigger and vertex corrections.
  - No removal of single-diffractive-component.
  - No removal of Dalitz decays.
  - No extrapolation to $p_T = 0$ or correction for acceptance using models.
- Correct reconstructed-track distributions back to particle level for all detector effects.
  - Measure trigger and vertex corrections from data.



Analysis trigger: L1 MBTS

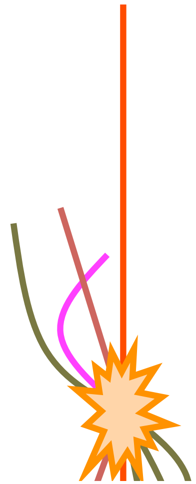
Minimum Bias Trigger Scintillators (MBTS)

- Require 1 or more counter from either side above threshold (L1_MBTS_1)
  - Single-arm rather than a double-arm requirement.
- Selected events where the inner detector, trigger, and solenoid B-field were running normally.

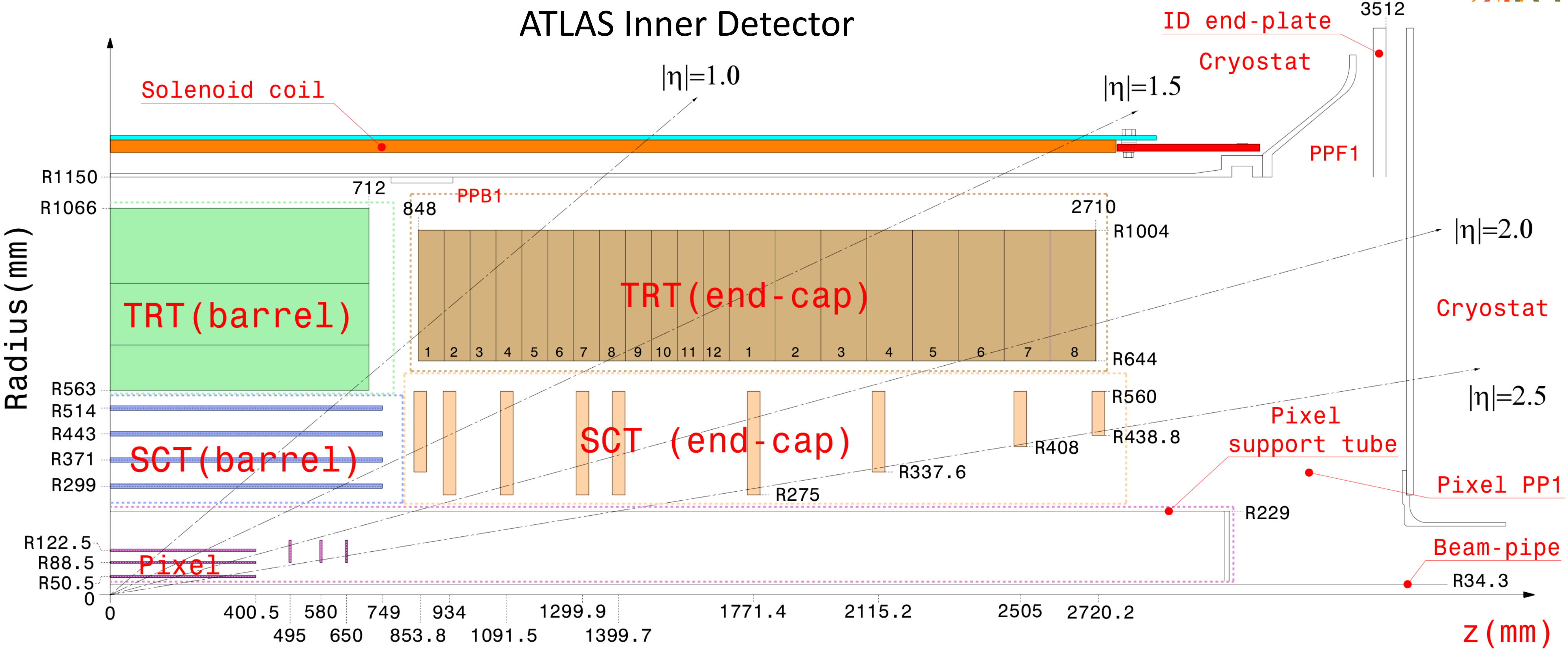


$z = \pm 3560$ mm, 8 units in ϕ, 2 units in η ($2.09 < \eta < 2.82$, $2.82 < \eta < 3.84$)

Control trigger

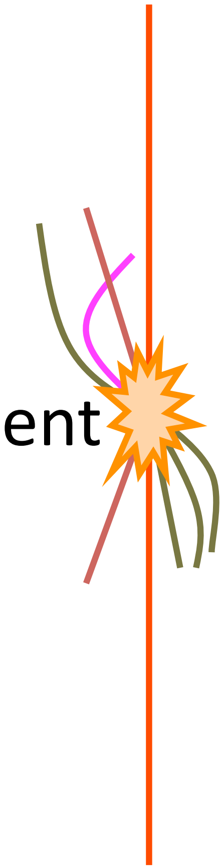


- L1 Beam-pickup, filtered by L2 Pixel and Silicon microstrip (SCT) spacepoints, and EF track.

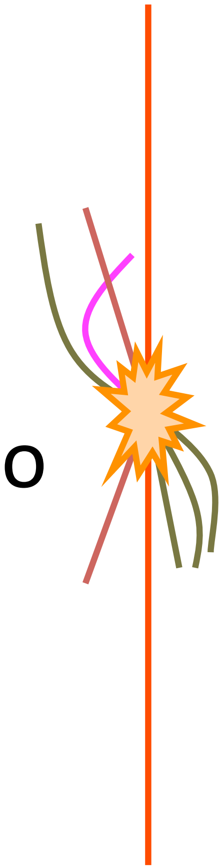


Selected tracks

- p_T > 100 MeV and η < 2.5
- Reconstructed by initial NewT inside-out or subsequent low p_T tracking algorithms
- At least one Pixel B-layer hit if expected
- At least one Pixel hit
- At least two (p_T > 100 MeV), four (p_T > 200 MeV) or six (p_T > 300 MeV) SCT hits
- Transverse and longitudinal distance of closest approach with respect to the primary vertex of d_0 < 1.5 mm and z_0 sin(θ) < 1.5 mm respectively
- For p_T > 10 GeV the fit probability was required to be greater than or equal to 0.01

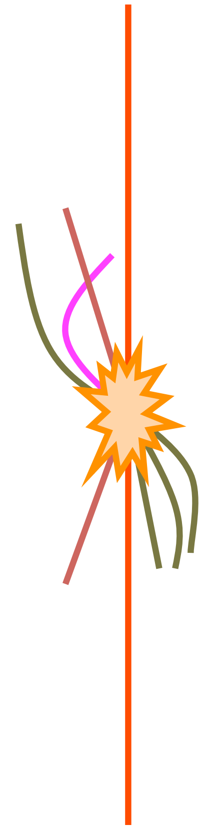


Selected events



- L1 MBTS trigger
- A reconstructed primary vertex including two or more tracks and the beamspot.
  - Vertices were ordered by the p_T sum.
    - Take the vertex with highest p_T sum as the primary vertex.
  - Reject events with one or more secondary vertices including four or more tracks.
- At least two selected tracks.

Correction procedure



- Correct for the effect of the trigger and primary vertex reconstruction efficiency on an event-by-event basis:

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

- Correct for track-reconstruction efficiency (p_T, η) on a track-by-track basis:

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

p_T resolution effect

- Correct n_{Sel} to n_{ch} using using (Bayesian unfolding) $M_{ch,sel}$
  - Filled from MC, applied, refilled, converges after 4 iterations.
- Correct for events with $n_{Sel} < 2$ and $n_{ch} > 0$ using:

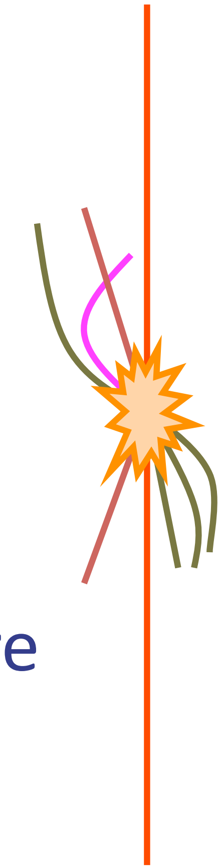
$$1/(1 - (1 - \epsilon_{\text{trk}})^{n_{\text{ch}}} - n_{\text{ch}} \cdot \epsilon_{\text{trk}} \cdot (1 - \epsilon_{\text{trk}})^{(n_{\text{ch}}-1)})$$

Mean track reconstruction efficiency

Corrections procedure

- Similar iterative Bayesian unfolding was applied to the p_T spectra.
  - G. D'Agostini (NIM A362, 487-498, 1995)
  - http://www.roma1.infn.it/~dagos/prob+stat.html
- <p_T> vs n_{ch}: bin by bin correction of average p_T then n_{ch} migration.
- Corrections procedure was tested with MC ‘data’ samples, from which the input particle level distributions were recovered.

Trigger efficiency

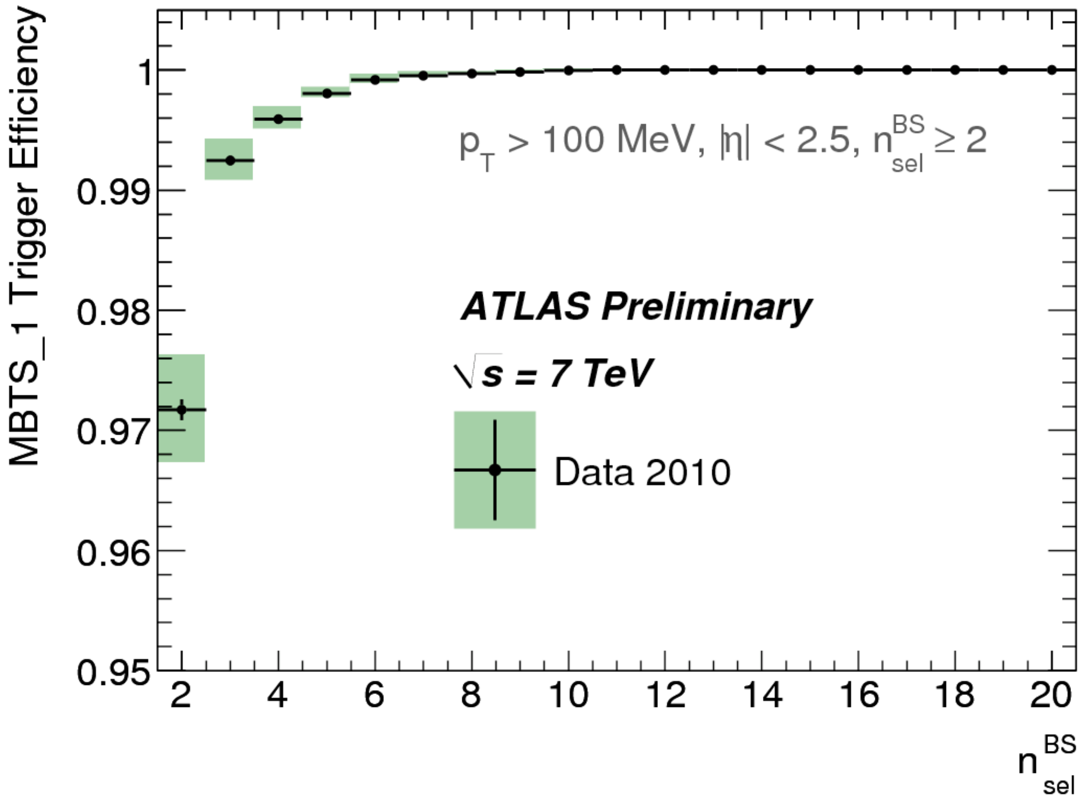


- Measured from data using Inner Detector trigger (mbSpTrk) sample.
  - Efficiency of the L1 MBTS trigger for two or more selected tracks.

$$\varepsilon(L1\_MBTS\_1) = \frac{L1\_MBTS\_1 \,\&\, offline \,\&\, mbSpTrk}{offline \,\&\, mbSpTrk}$$

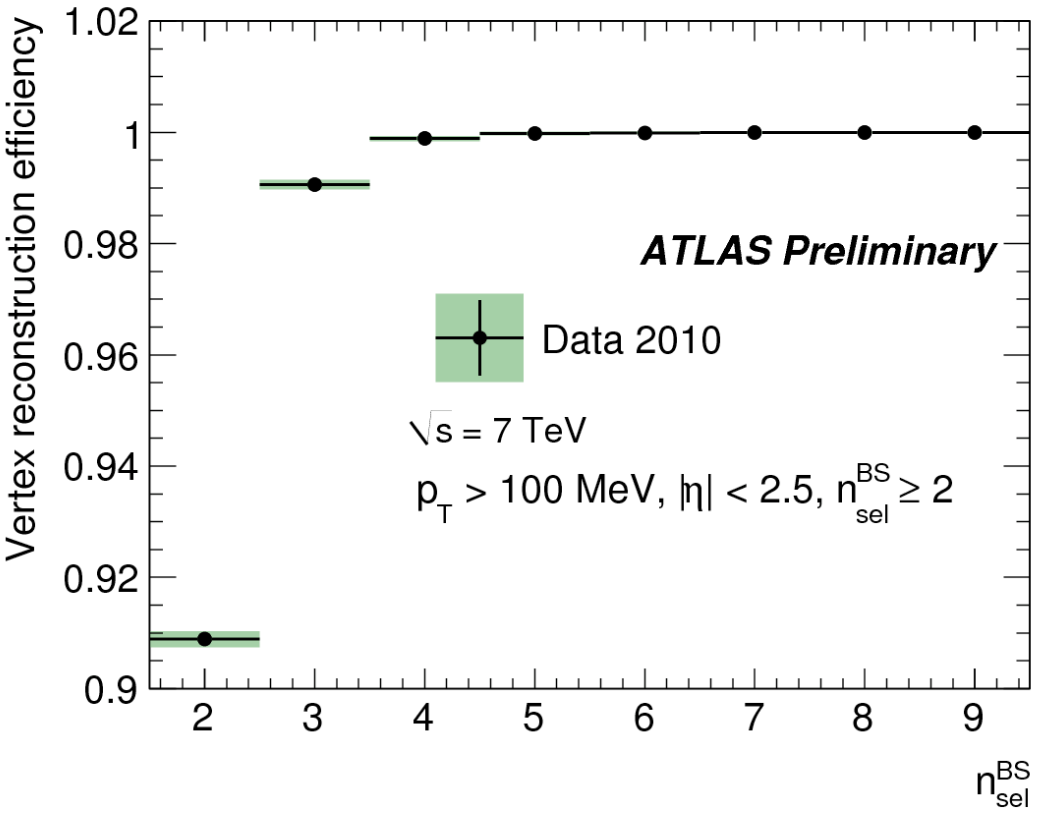
L1 MBTS trigger efficiency

Measured from data using control trigger.
No effect on p_T and η spectrum within statistical uncertainties.

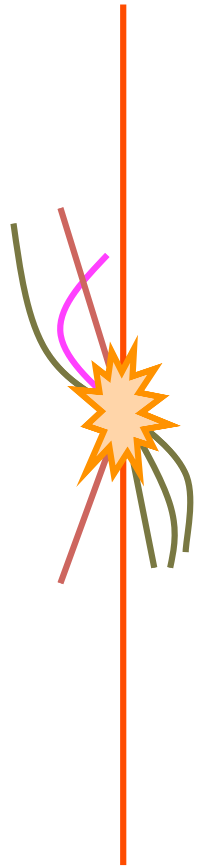


- Efficiency is close to 1 for offline selection.
  - Selected tracks, but dropping
    - $|d_0| < 1.5$mm
    - $|z_0 \sin(\theta)| < 1.5$mm
  - Using $|d_0^{BS}| < 1.8$mm
- Small systematic error contributions:
  - Trigger correlation
  - Different track selection.
  - Statistical limit on p_T and η bias

Vertex reconstruction efficiency

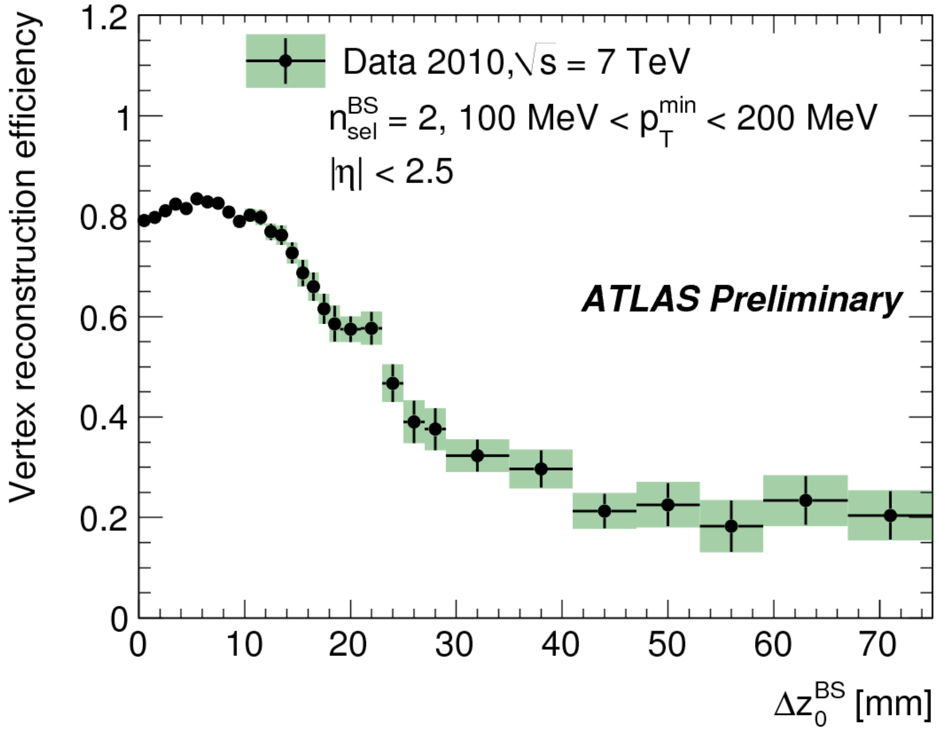


- Measured from data:
  - L1 MBTS selected events.
  - Selected tracks, but dropping
    - $|d_0| < 1.5$mm
    - $|z_0 \sin(\theta)| < 1.5$mm
  - Using $|d_0^{BS}| < 1.8$mm
- Tiny systematic from beam background.

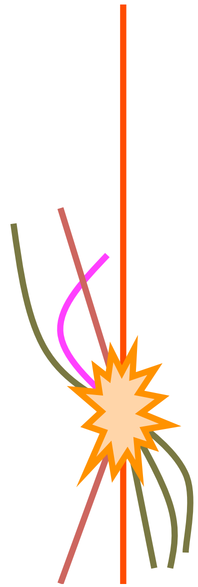


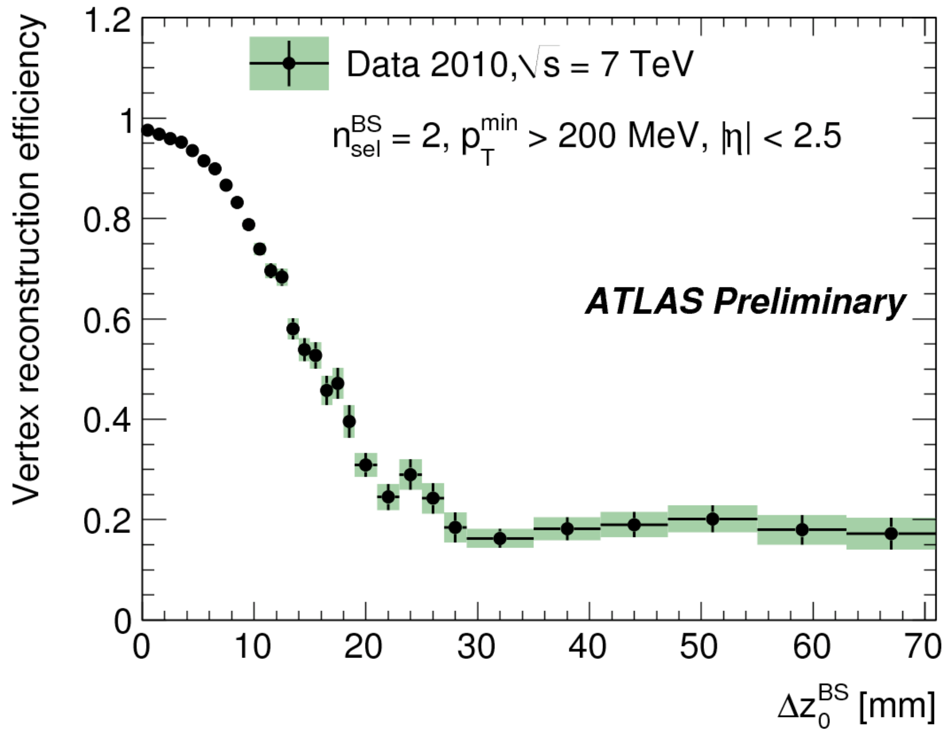
No effect on p_T spectrum within statistical uncertainties.

Vertex reconstruction efficiency

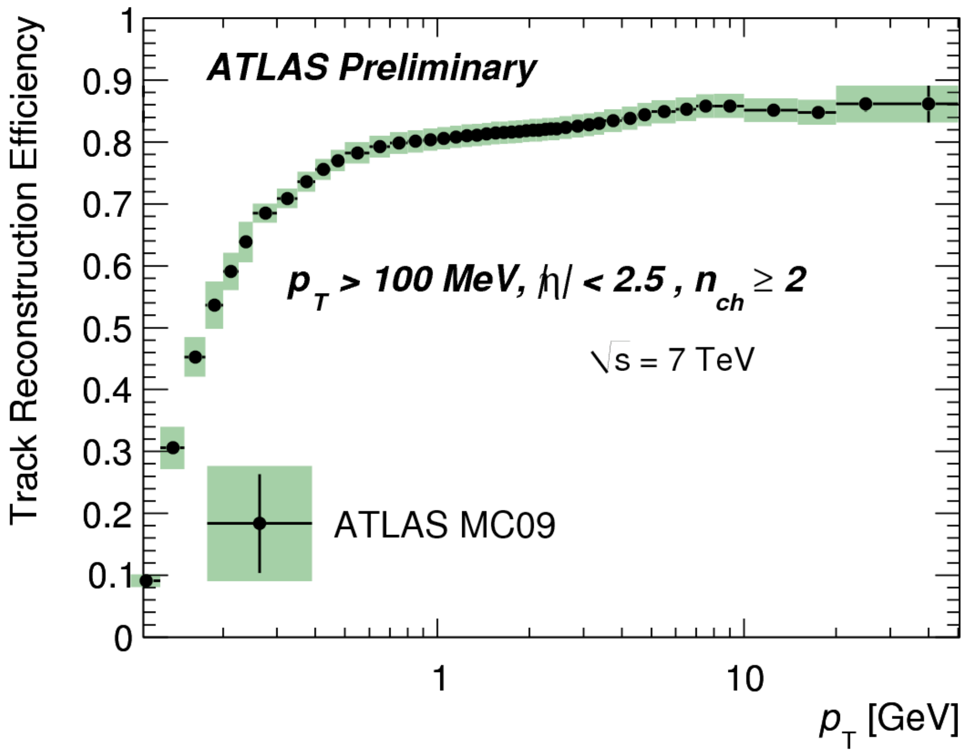


Correct for shaping of Δz_0^{BS} distribution in events with two tracks, in two p_T ranges.

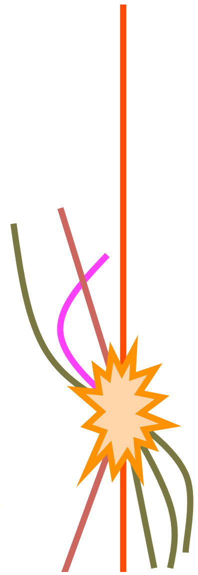




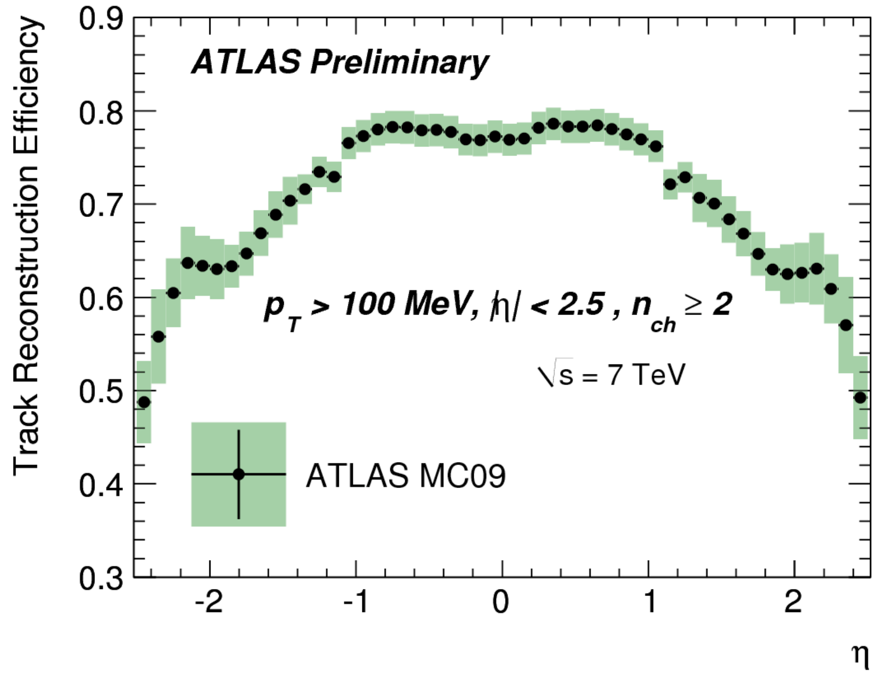
Track reconstruction efficiency



Best match between track and MC particle within a cone and one common hit.



$$\epsilon_{\rm bin}(p_{\rm T},\eta) = \frac{N_{\rm rec}^{\rm matched}(p_{\rm T},\eta)}{N_{\rm gen}(p_{\rm T},\eta)}$$

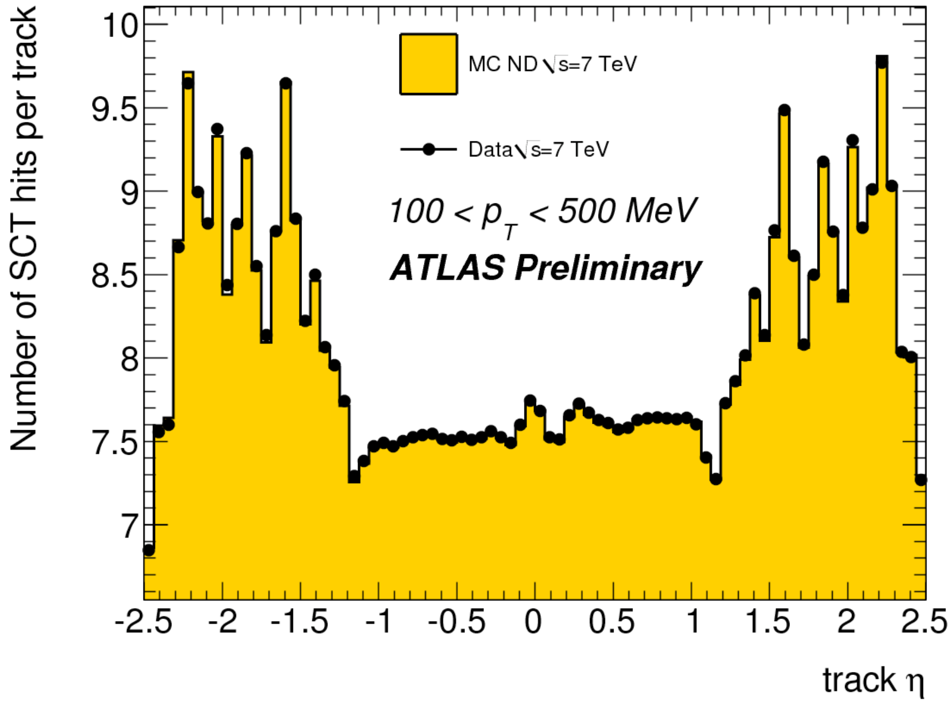


Global systematic dominated by conservative material estimate.

Higher systematic uncertainties in regions with more material

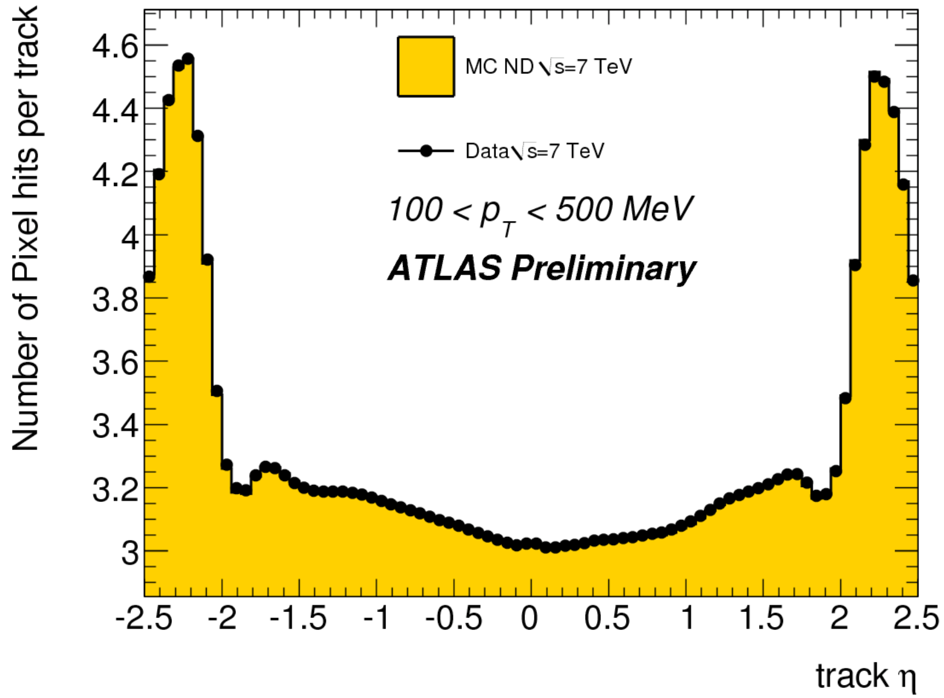
Correction taken from Geant4 detector simulation

Validating Geant4 simulation

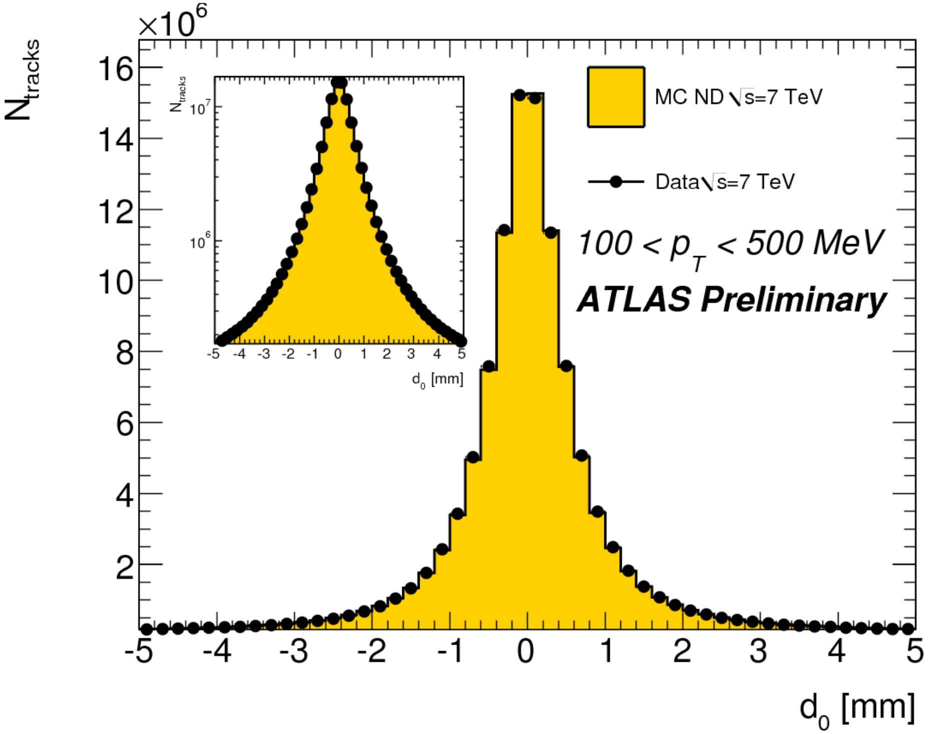


Structure of overlapping modules and detector inefficiencies match.

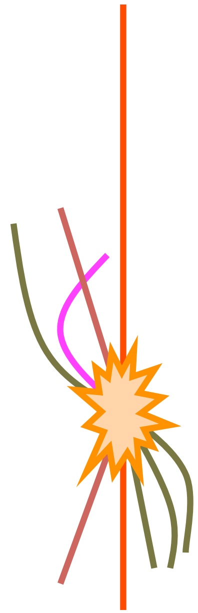
Simulated hits on track distributions match distributions from data.

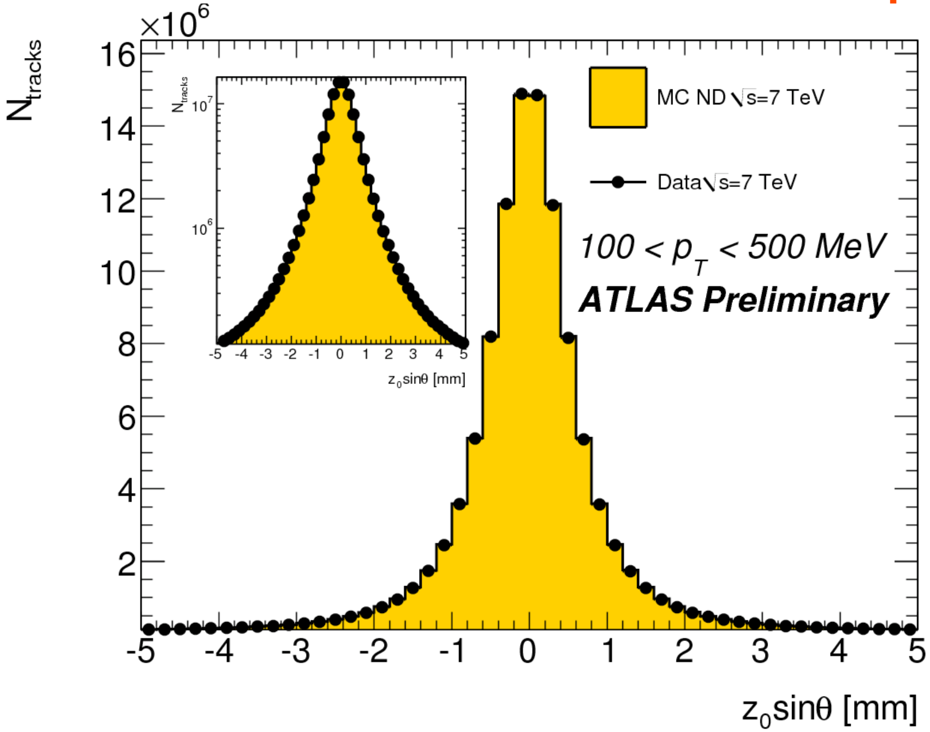


Validating Geant4 simulation

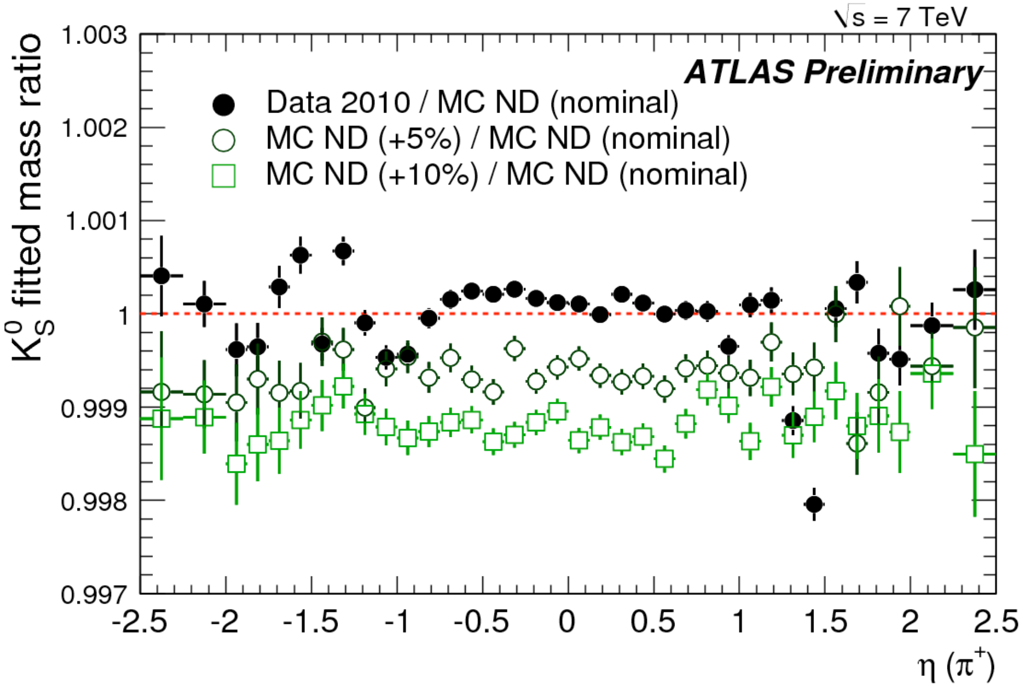


Resolution on transverse and longitudinal impact parameter match to high accuracy.



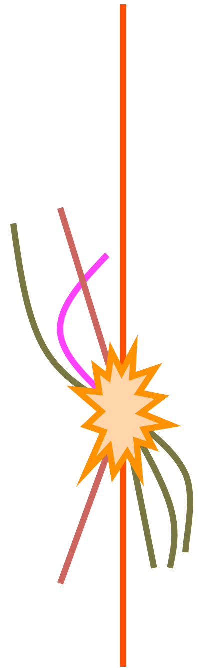


Validating Geant4 simulation

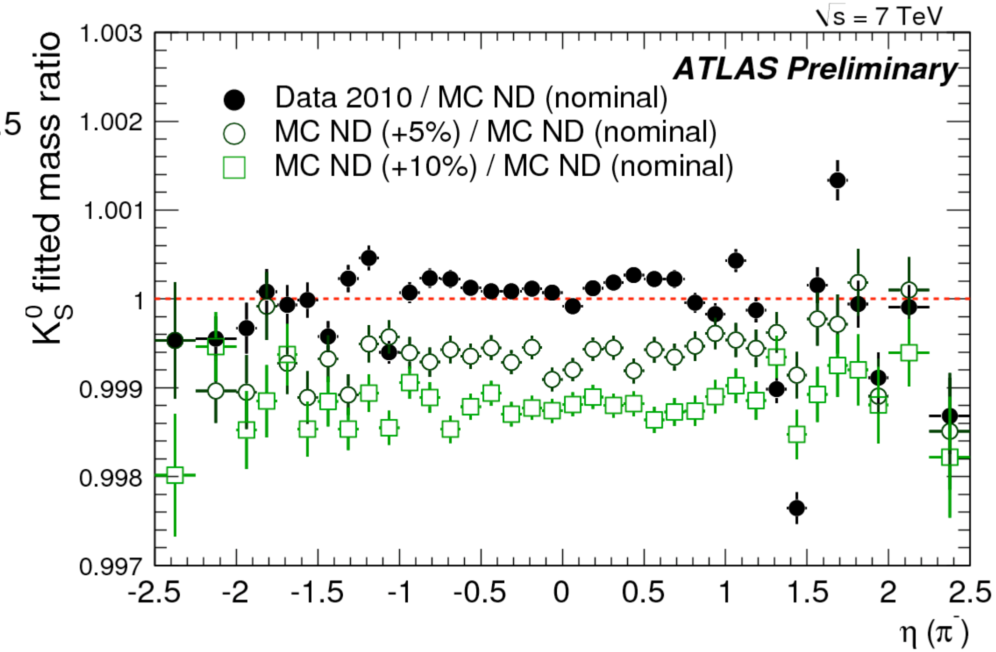


Use K_s mass reconstruction to check the amount of material in the sample.

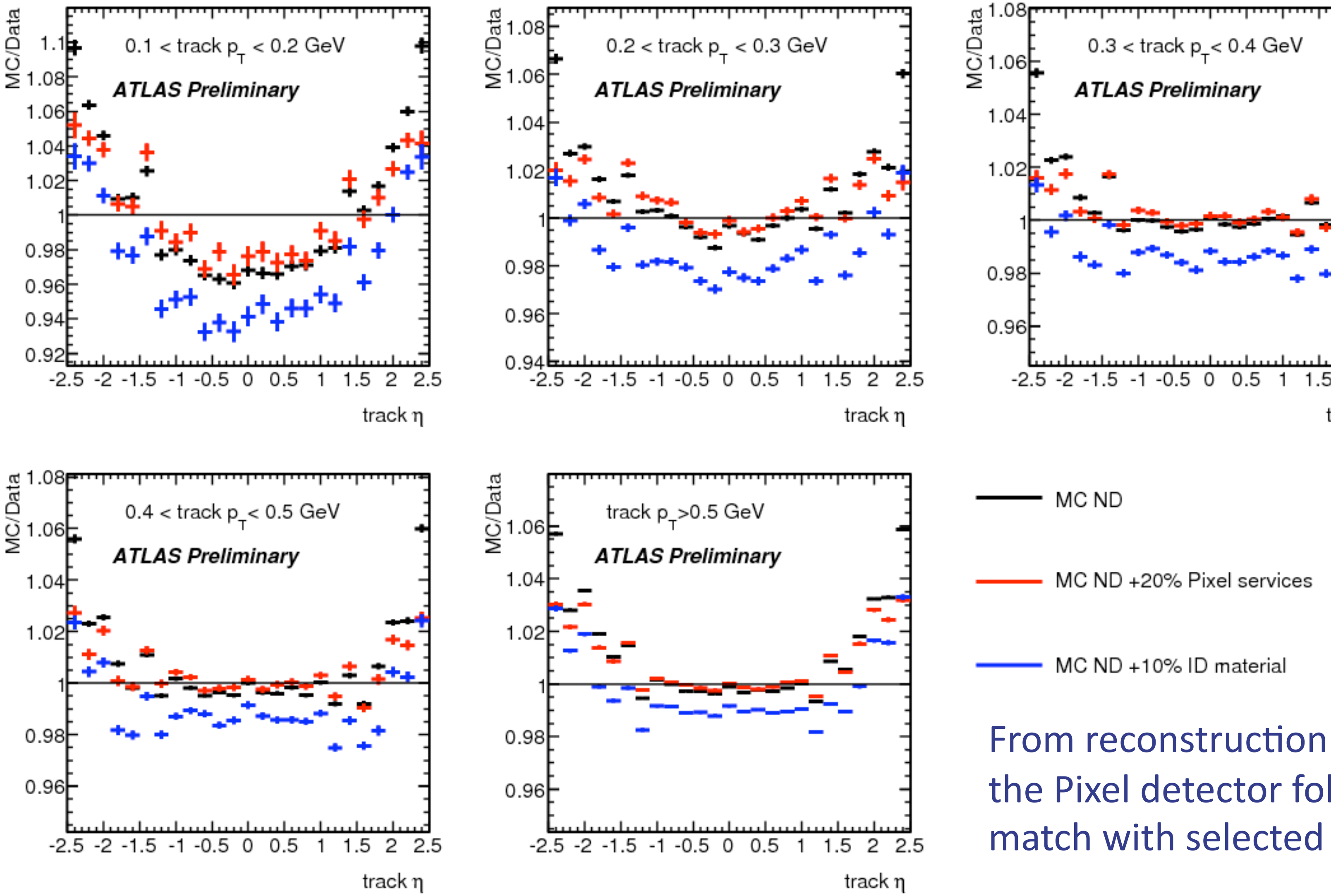
Checked π^+ and π^-

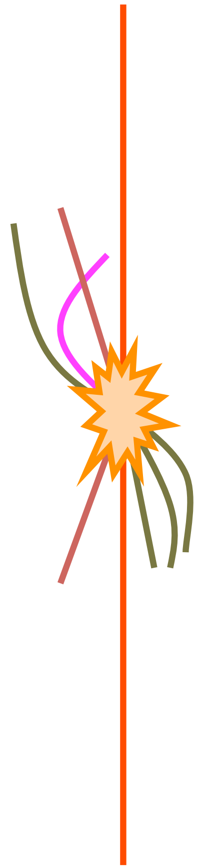


K^0_S DECAY MODES	Fraction (Γ_i/Γ)
	Hadronic modes
$\pi^0\pi^0$	(30.69 ± 0.05) %
$\pi^+\pi^-$	(69.20 ± 0.05) %



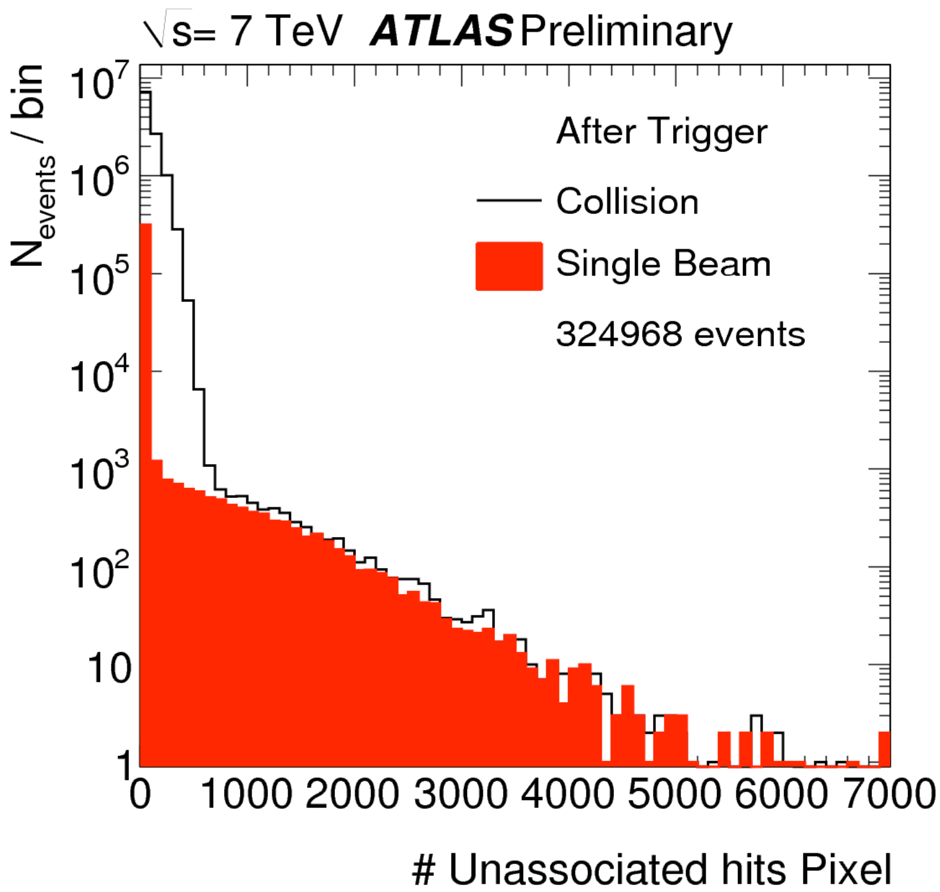
Track extension efficiency



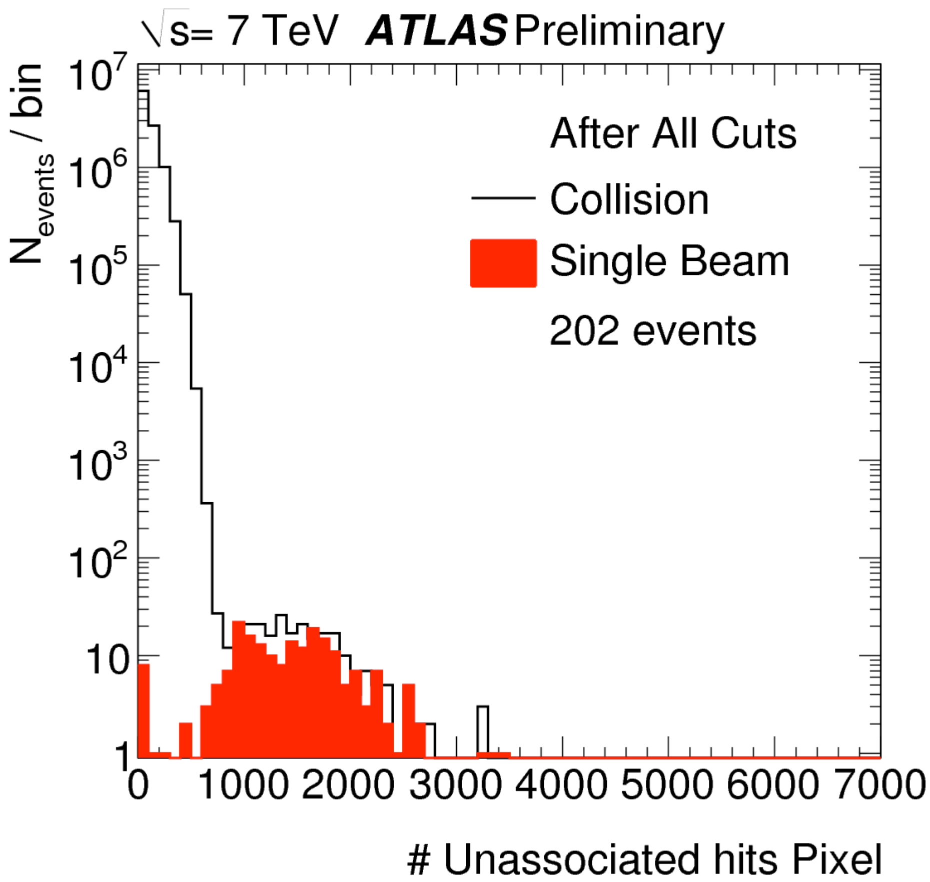


From reconstruction just within the Pixel detector followed by match with selected track.

Beam background

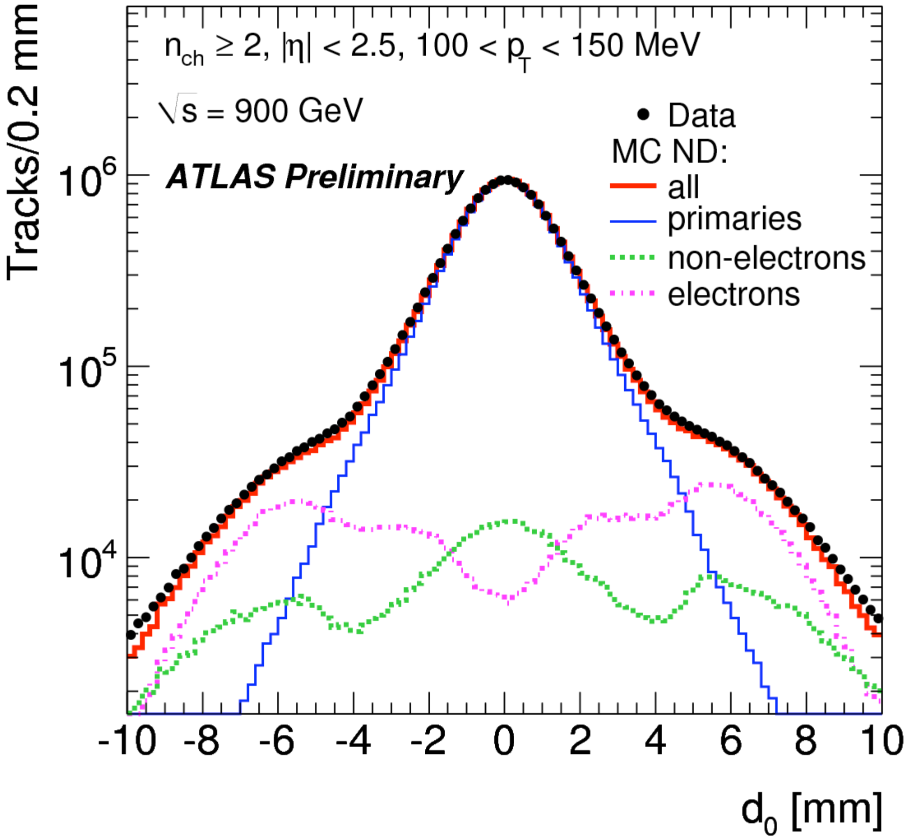


Estimate residual beam background contamination using unassociated Pixel detector hits.

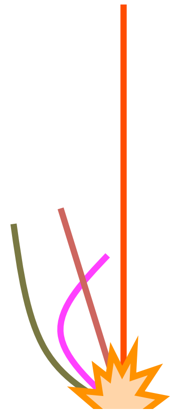


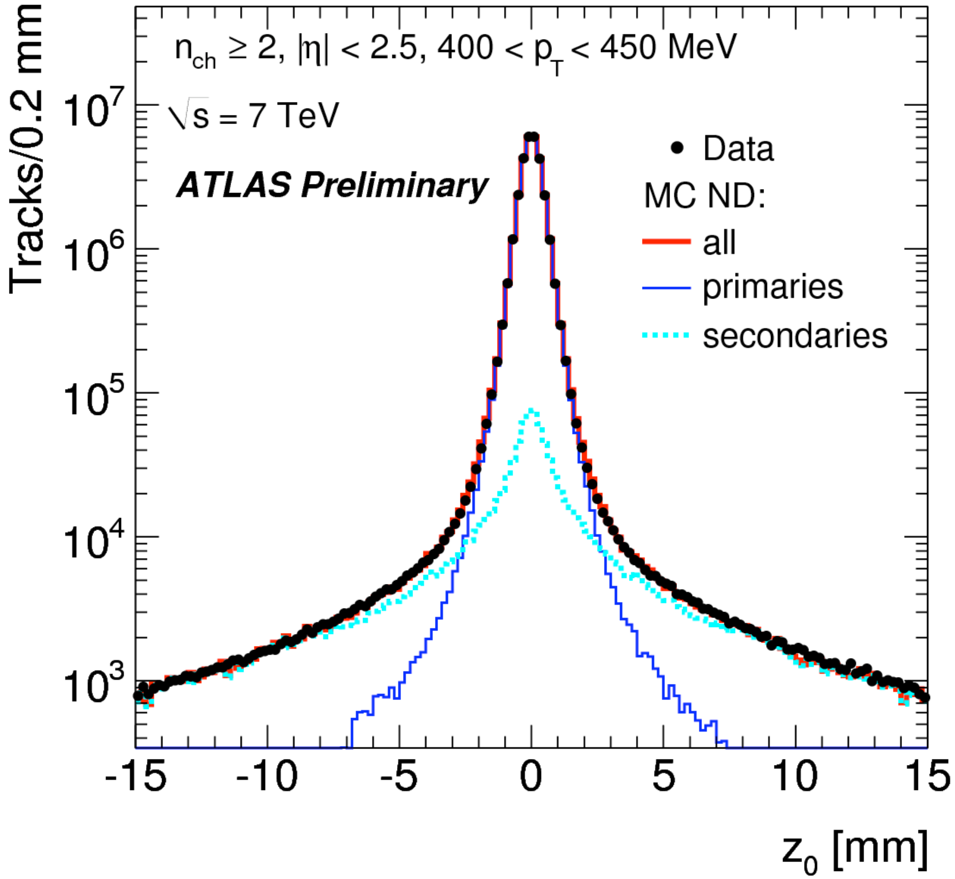
Selection requirements reduce effect of beam background to the level of 10^{-4}

Non-primary particles



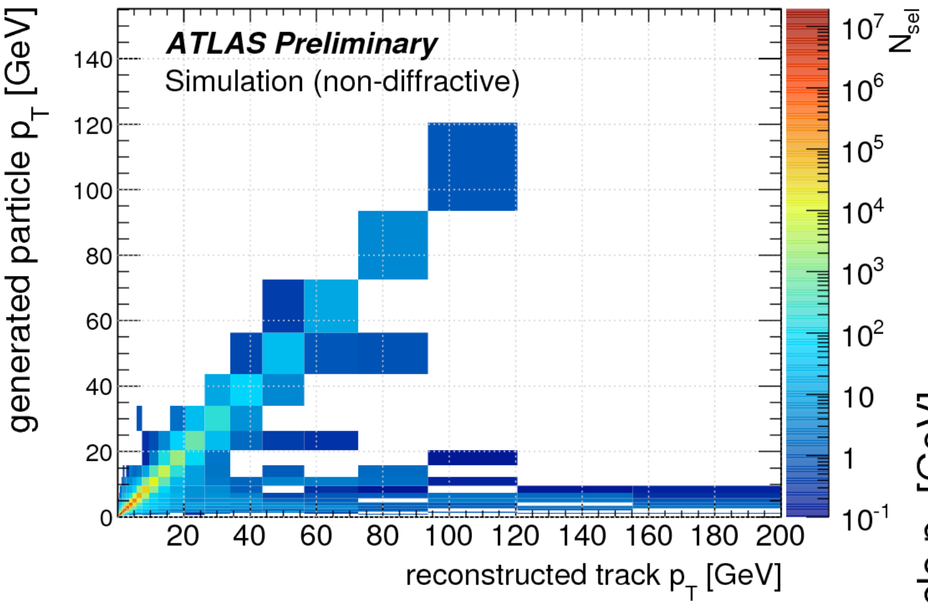
Fit side bands of data distribution with simulation.



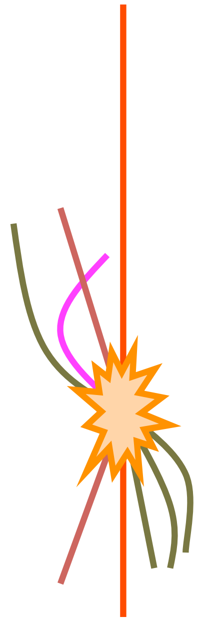


Determine fraction of non-primary particles within acceptance.

Tracks with p_T > 10GeV



Remove tracks reconstructed from nuclear interactions with matter.



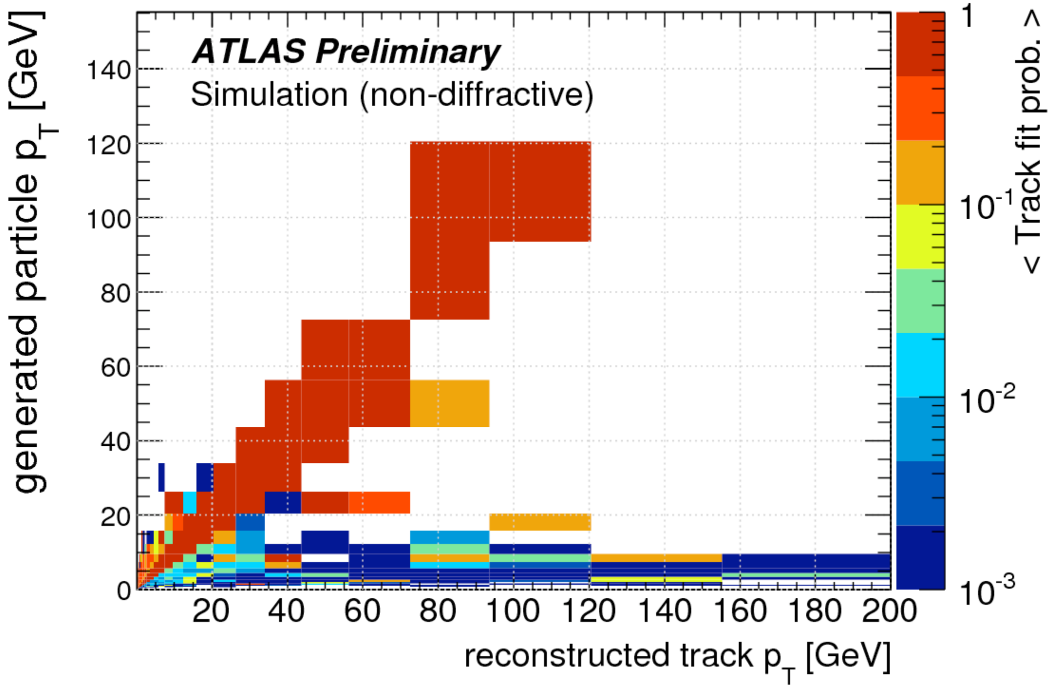
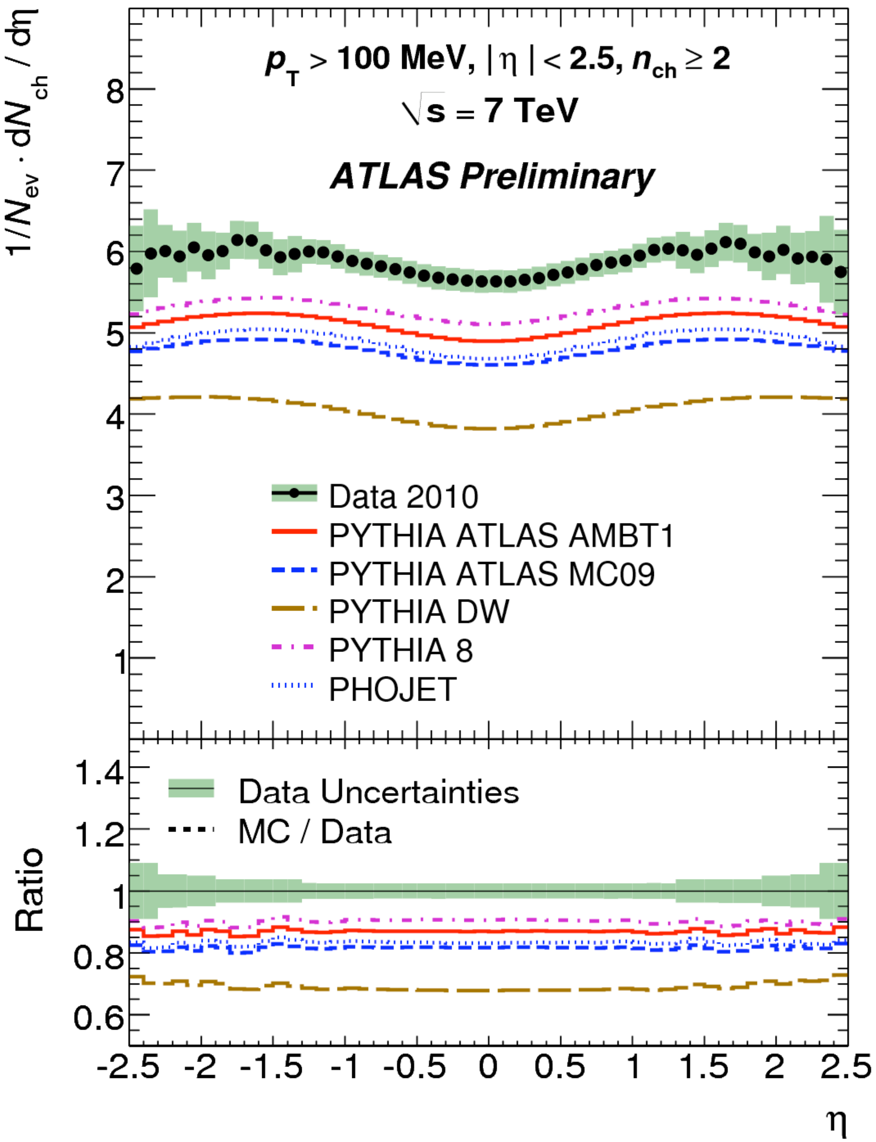


Table of systematic uncertainties

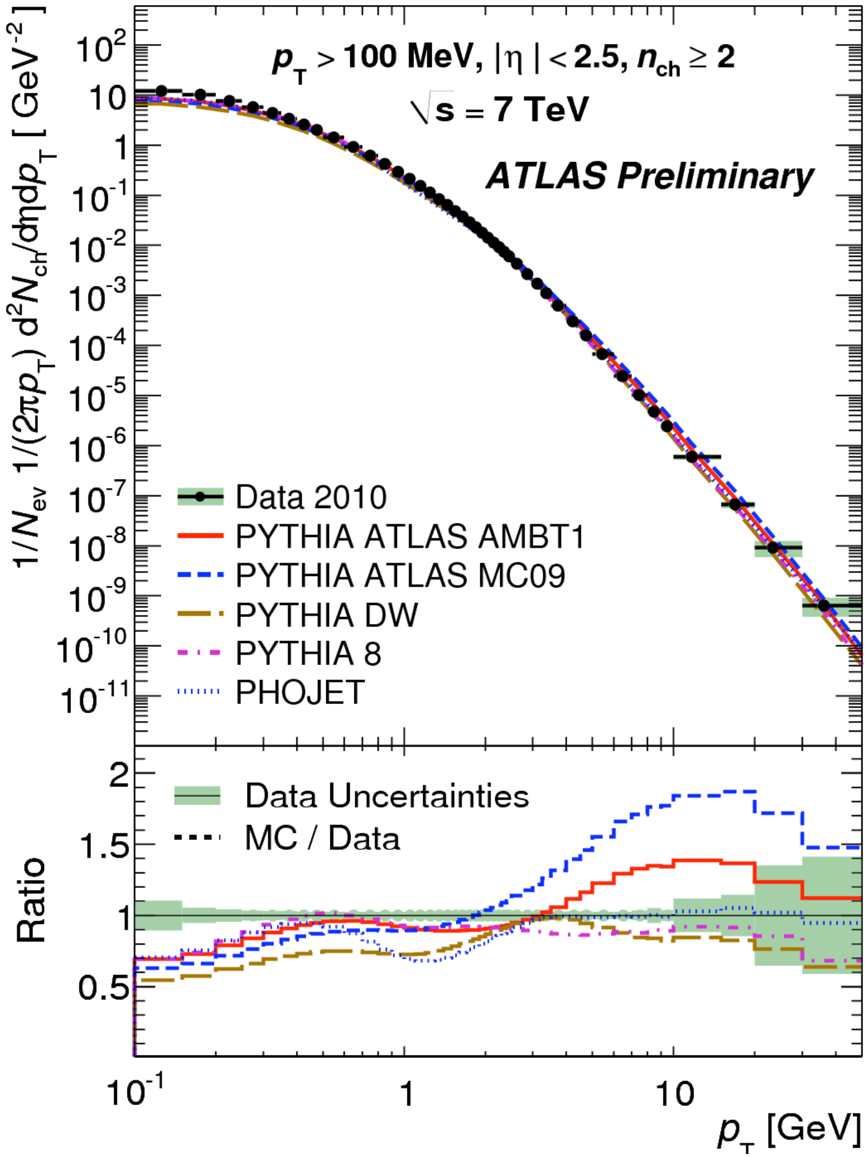
ATLAS Preliminary

Systematic uncertainty on the number of events, N_{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_{ev}	1.1%	0.8%
Systematic uncertainty on $(1/N_{ev})\cdot(dN_{ch}/d\eta)$ 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_{ev}	−1.1%	−0.8%
Total uncertainty on $(1/N_{ev})\cdot(dN_{ch}/d\eta)$ at $\eta = 0$	2.1%	2.3%

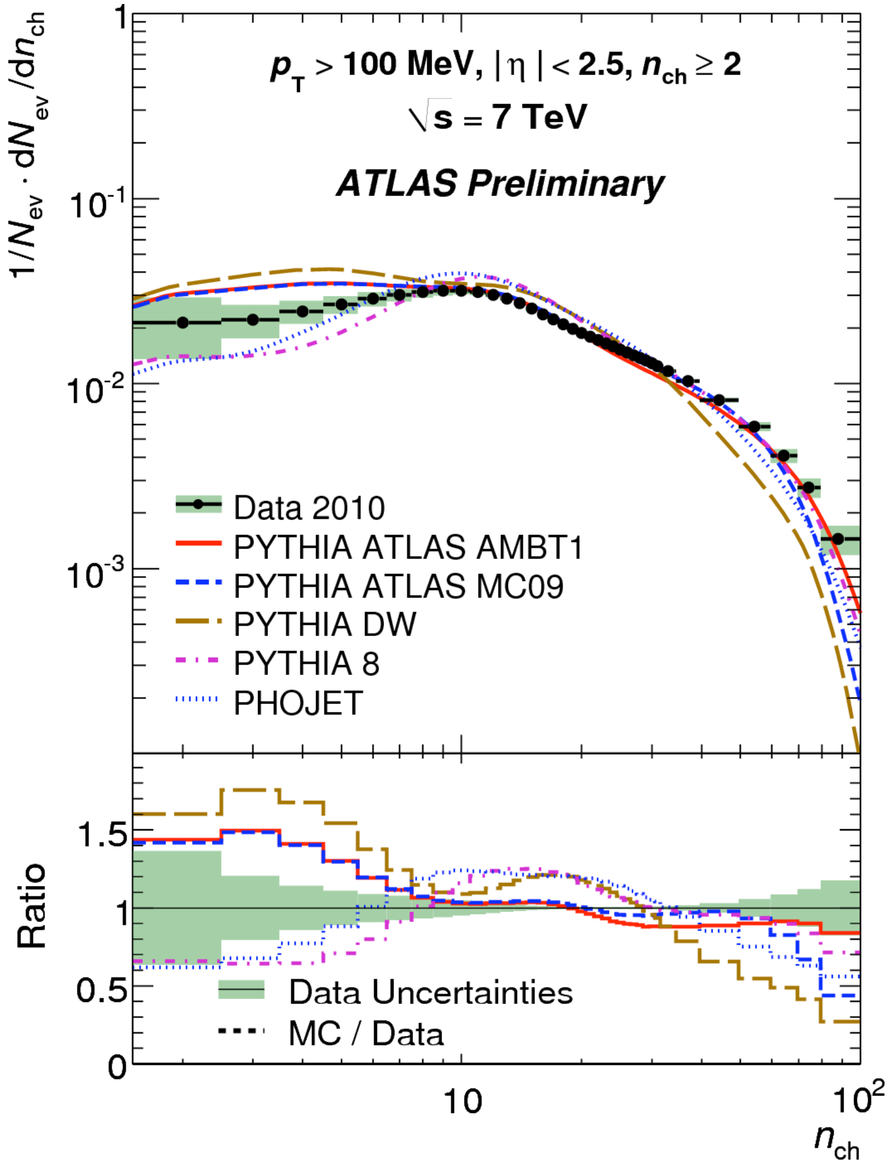
$dN_{ch}/d\eta$



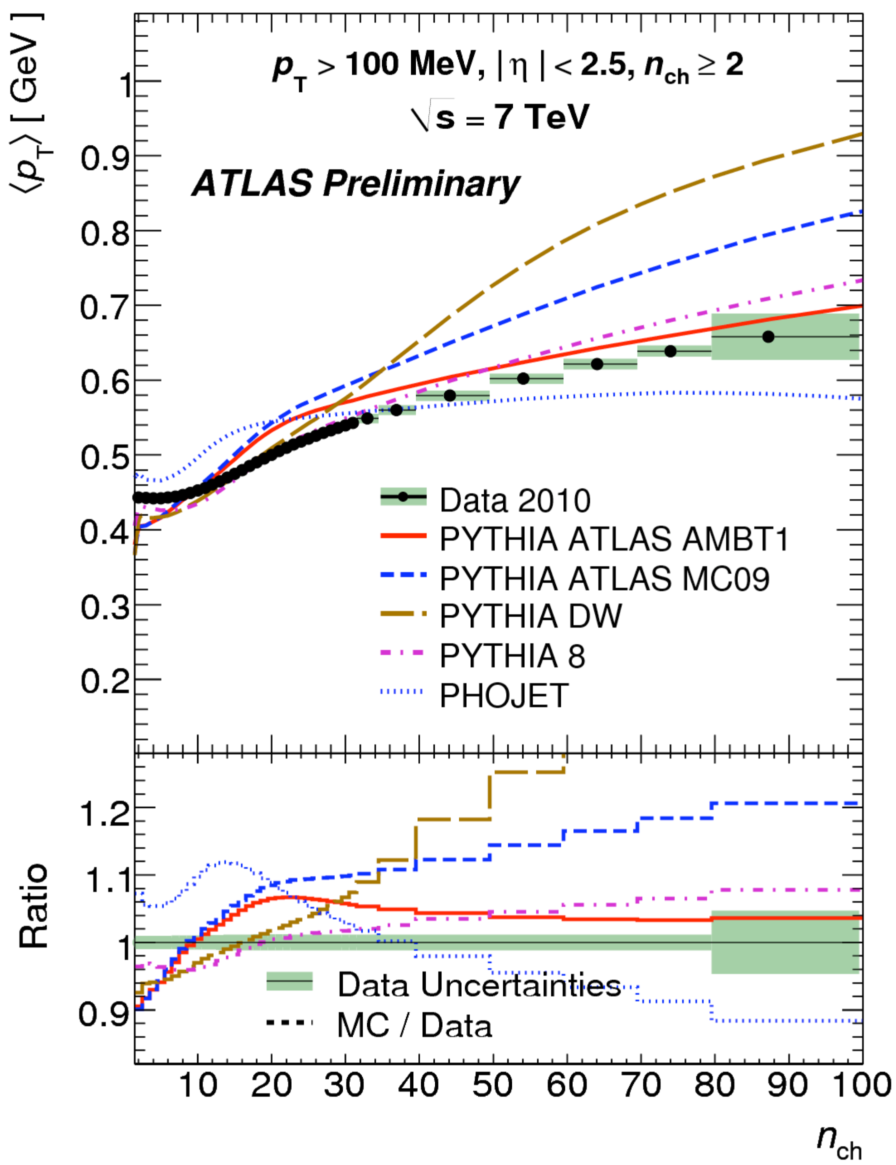
$1/(2\pi p_T)\, d^2N_{ch}/d\eta dp_T$



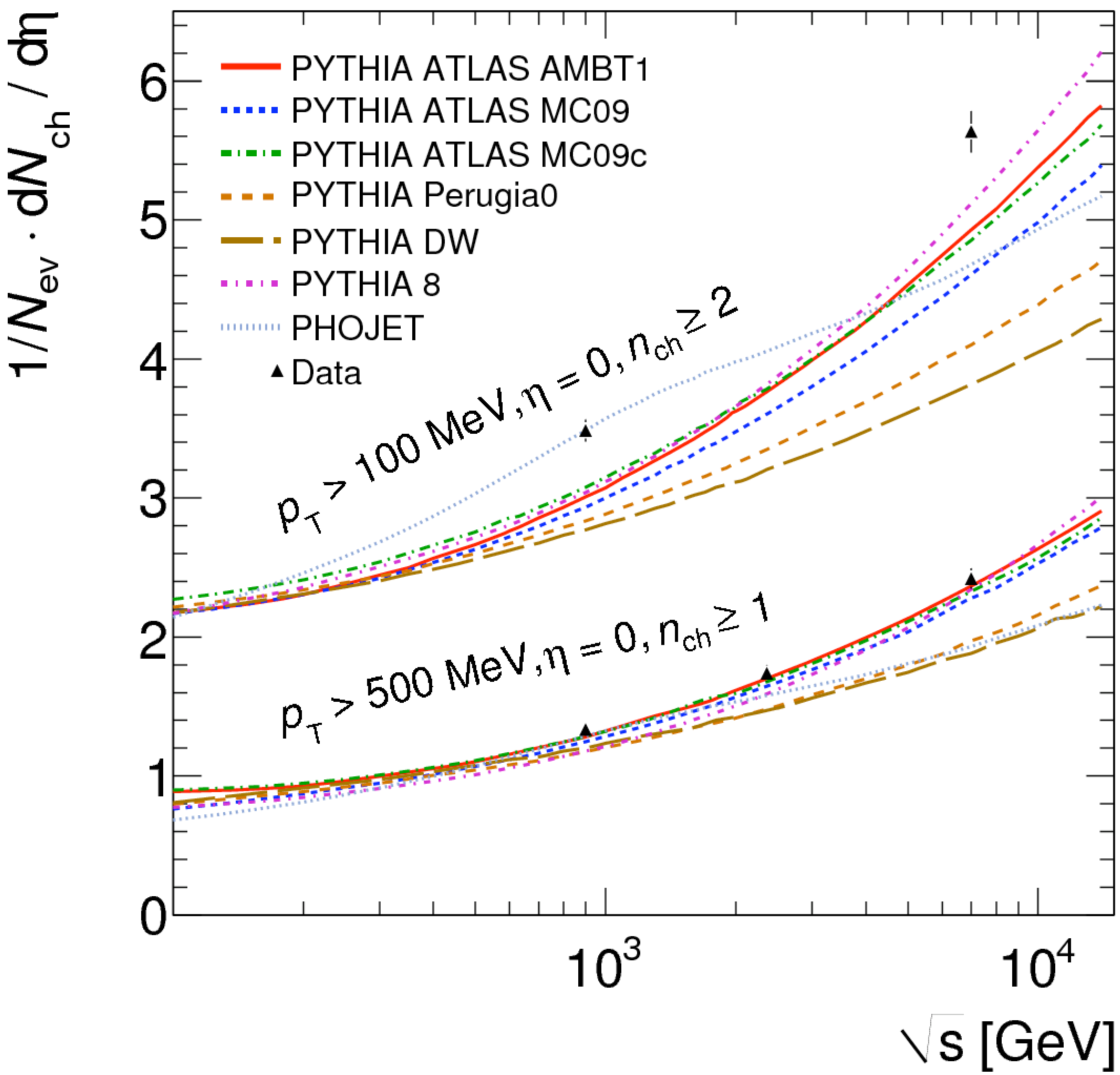
dN_{ev}/dn_{ch}

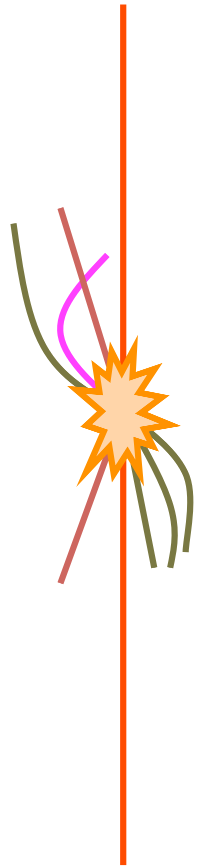


$\langle p_T \rangle$ vs n_{ch}



$dN_{ch}/d\eta$ at $\eta = 0$ vs $\sqrt{s}$





Conclusions

- Careful measurement definition important to produce useful results.
- MC diverge from data below $p_T < 300$MeV.
- The AMBT1 PYTHIA tune describes the energy dependence for $p_T > 500$MeV.
- Expect more tuning following measurements.

LHC Underlying event results

- CMS and ATLAS have released measurements with 900GeV and 7TeV *pp* data.

ATLAS

ATLAS-CONF-2010-029

CMS

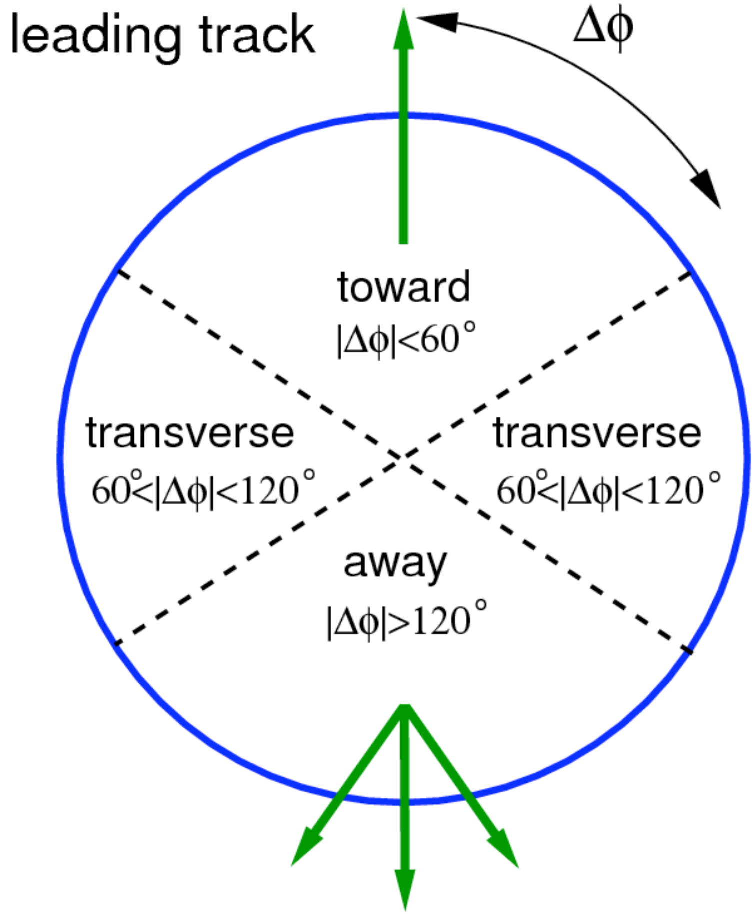
arXiv:1006.2083v1 [hep-ex]

CMS PAS QCD-10-005

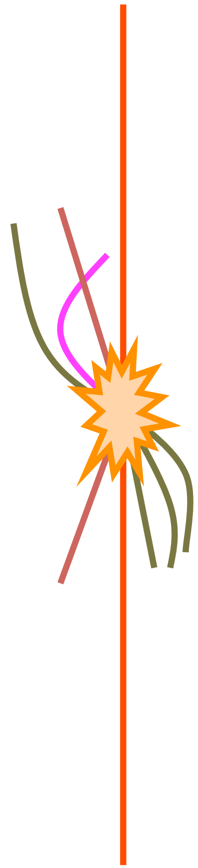
CMS PAS QCD-10-010

Documents are easily obtained from the public web pages of these collaborations

Underlying Event



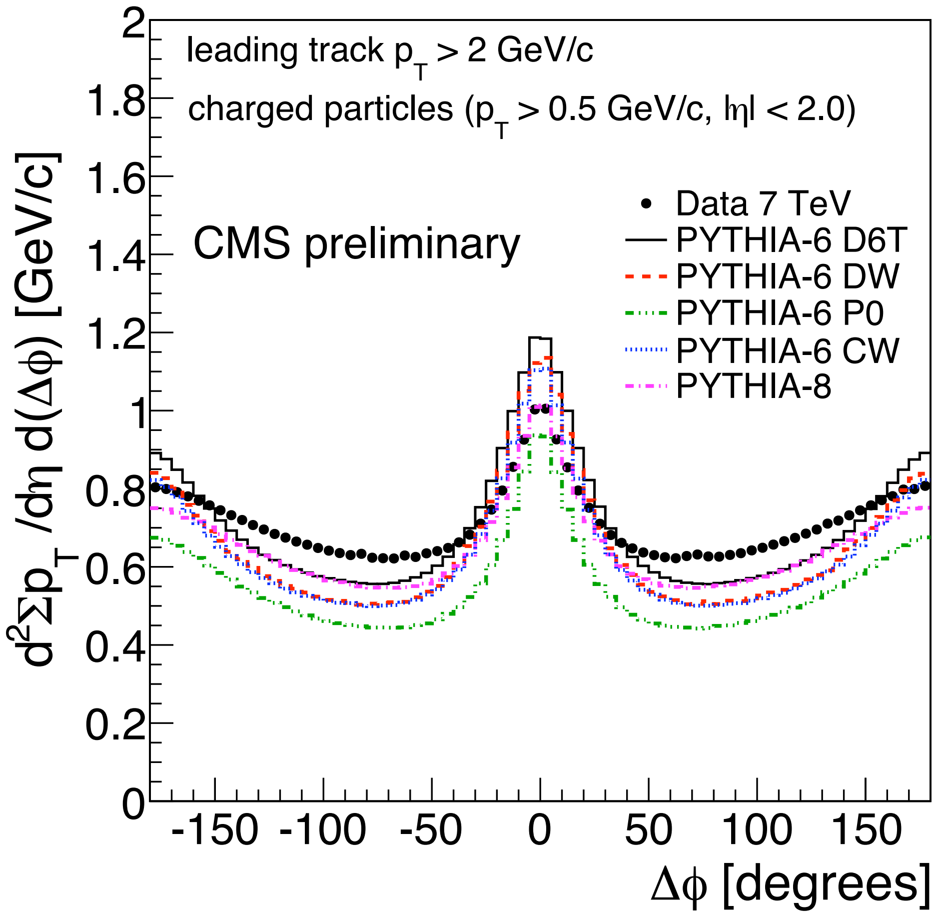
- Look in the region transverse to the leading jet or the leading track.
- Several possible observables defined by R. Field et al.
  [T. Sjostrand, lecture 4]



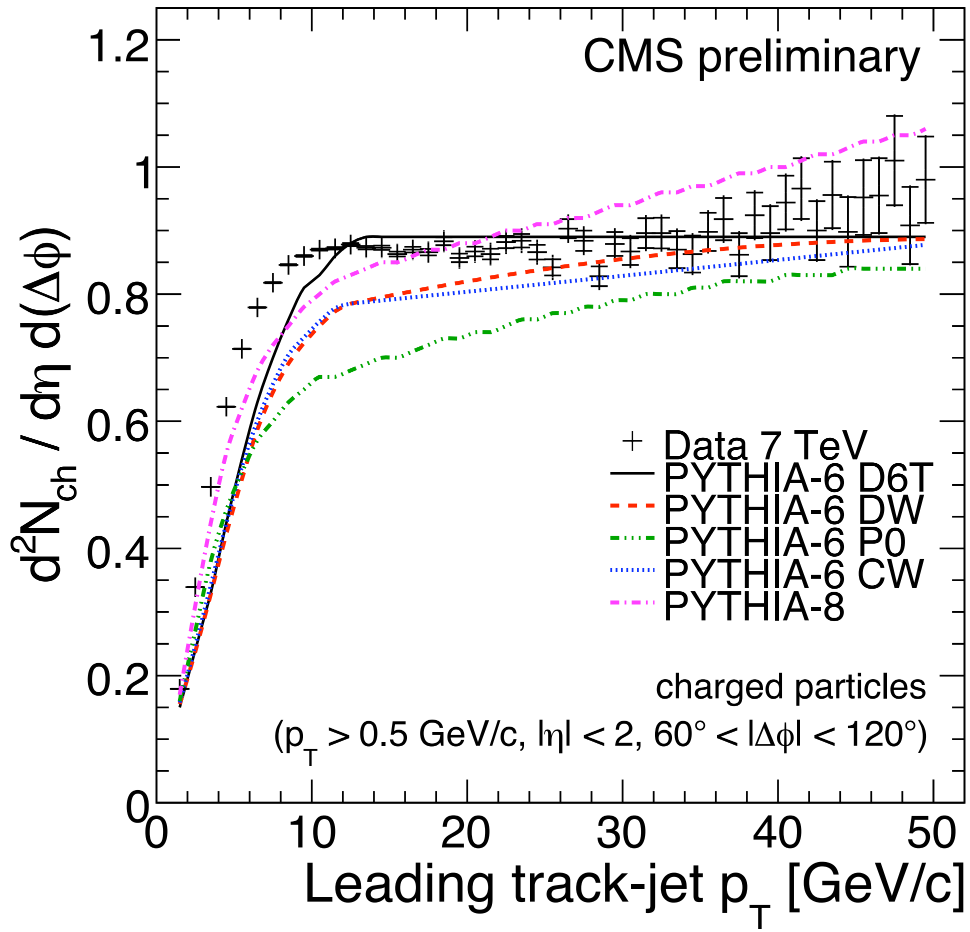
Observables

Observable	Particle level	Detector level
$p_{\mathrm{T}}^{\mathrm{lead}}$	Maximum p_{T} stable charged particle in the event	Maximum p_{T} selected track in the event
$\langle \mathrm{d}^2 N_{\mathrm{chg}}/\mathrm{d}\eta\,\mathrm{d}\phi \rangle$	Number of stable charged particles per unit η–ϕ	Number of selected tracks per unit η–ϕ
$\langle \mathrm{d}^2 \sum p_{\mathrm{T}}/\mathrm{d}\eta\,\mathrm{d}\phi \rangle$	Scalar p_{T} sum of stable charged particles per unit η–ϕ	Scalar p_{T} sum of selected tracks per unit η–ϕ
$\langle$Std.Deviation of $\mathrm{d}^2 N_{\mathrm{chg}}/\mathrm{d}\eta\,\mathrm{d}\phi \rangle$	Standard deviation of number of stable charged particles per unit η–ϕ	Standard deviation of number of selected tracks per unit η–ϕ
$\langle$Std.Deviation of $\mathrm{d}^2 \sum p_{\mathrm{T}}/\mathrm{d}\eta\,\mathrm{d}\phi \rangle$	Standard deviation of scalar p_{T} sum of stable charged particles per unit η–ϕ	Standard deviation of scalar p_{T} sum of selected tracks per unit η–ϕ
$\langle p_{\mathrm{T}} \rangle$	Average p_{T} of stable charged particles (require at least 1 charged particle)	Average p_{T} of selected tracks (require at least 1 selected track)

CMS at √s = 7TeV

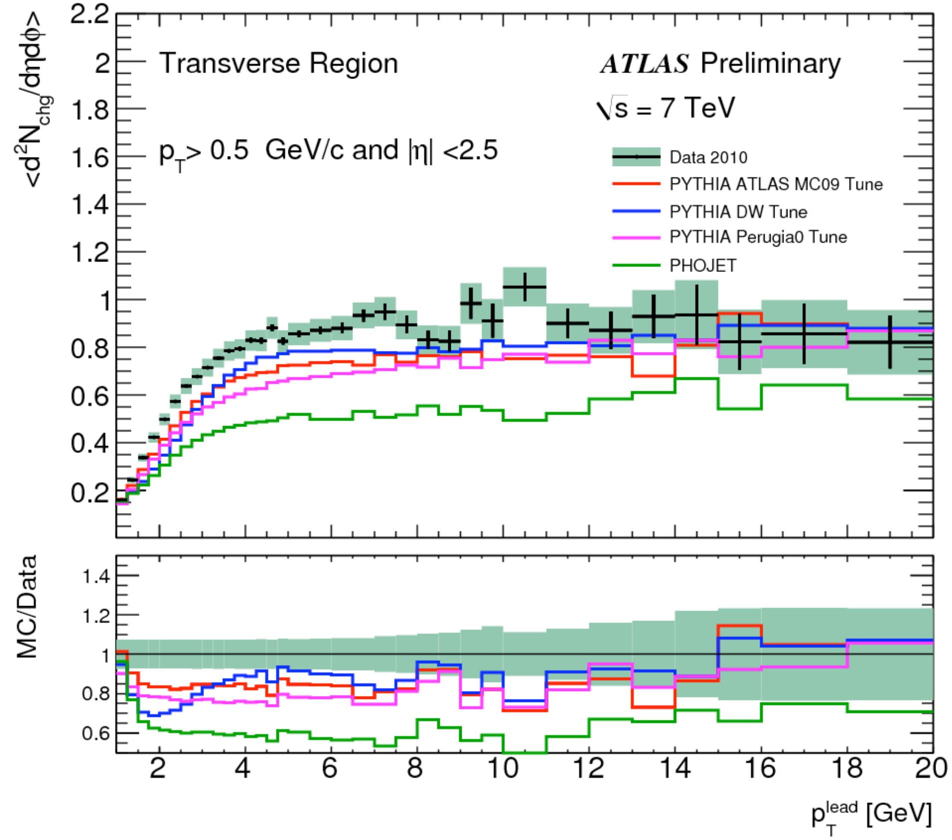


Mean scalar sum of charged-particle p_T as a function of the azimuthal angle from the leading object

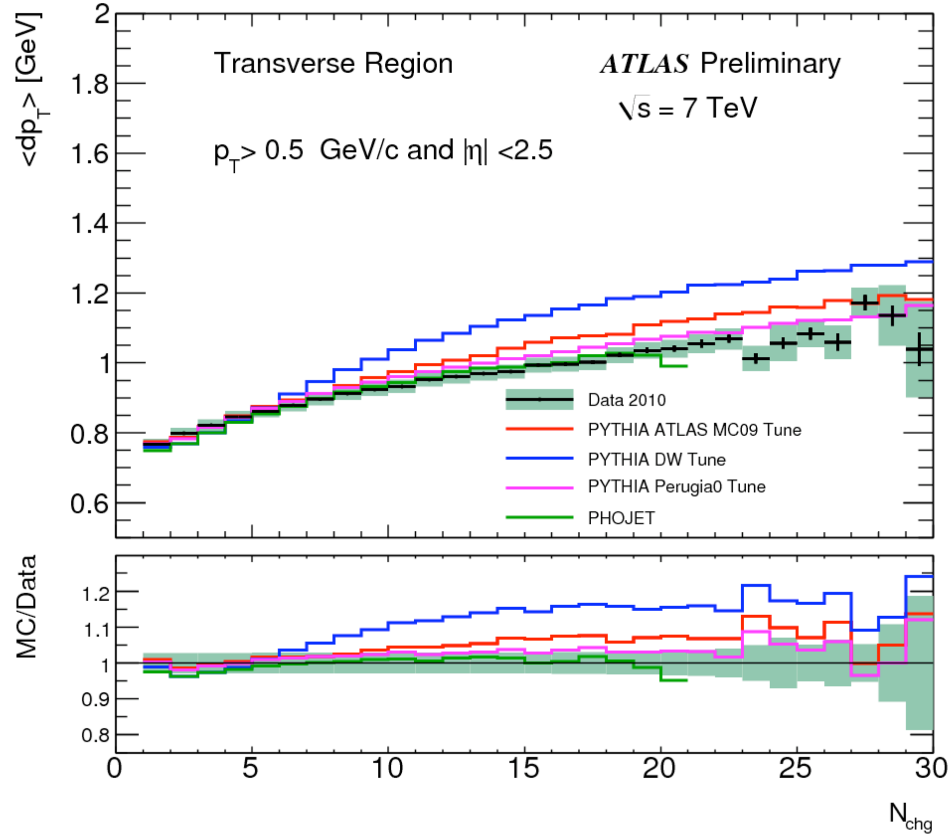


Mean particle multiplicity as a function of p_T of the leading track-jet.

ATLAS at √s = 7TeV

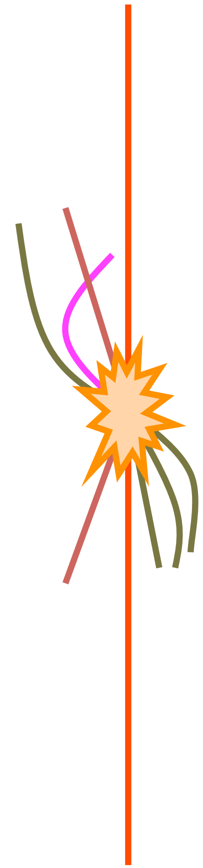


Mean particle multiplicity as a function of p_T of the leading track.



$<p_T>$ vs n_{ch} for the region transverse to the leading track.

Conclusions



- Models predict lower number of charged particles than observed in the transverse region.
- The PYTHIA DW tune predicts a harder $\langle p_{T} \rangle$ vs n_{ch} spectrum for events with $n_{ch} > 7$.
- For a leading track-jet above 2GeV all models predict a lower mean scalar sum p_{T} in the transverse region.