Soft QCD at the LHC with the ATLAS Detector

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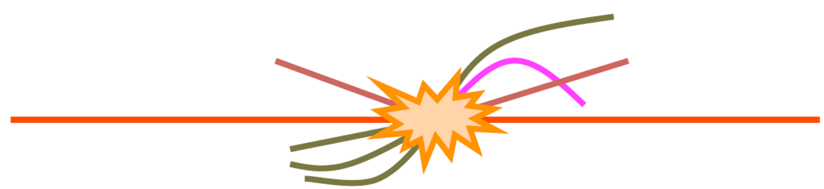


LAPP Annecy – Seminar ***28 January 2011***

Outline

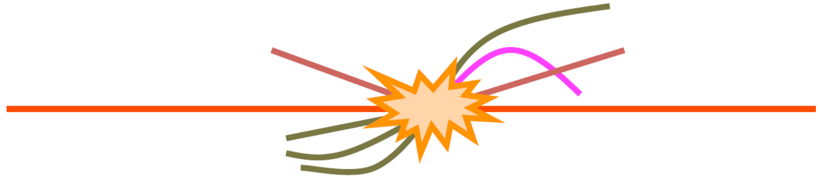
Motivation

Measurements of Charged Particle Production

- Distributions in minimum bias events
  - Diffraction suppressed
  - Diffraction enhanced
- Underlying event
- Angular correlations

Applications

- Comparisons between LHC experiments
- Luminosity measurement from minimum bias event rates



References

- Contents correspond to all latest public ATLAS results on soft QCD
- Main publication is 2nd minimum bias paper

“Charged particle multiplicities in pp interactions measured with the ATLAS detector at the LHC”,
CERN-PH-EP-2010-079 (Submitted to New J. Phys.), arXiv:1012.5104

“Measurement of underlying event characteristics using charged particles in pp collisions at sqrt(s) = 900 GeV and 7 TeV with the ATLAS detector”,
arXiv:1012.0791 ; CERN-PH-EP-2010-063 (Submitted to PRD)

“Studies of Diffractive Enhanced Minimum Bias Events in ATLAS“,
ATLAS-CONF-2010-048

“Angular correlations between charged particles from proton-proton collisions at sqrt(s) = 900 GeV and sqrt(s) = 7 TeV measured with ATLAS detector”,
ATLAS-CONF-2010-082

“Central charged-particle multiplicities in pp interactions with |eta| < 0.8 and pT > 0.5 and 1 GeV measured with the ATLAS detector at the LHC”,
ATLAS-CONF-2010-101

“First tuning of HERWIG/JIMMY to ATLAS data”,
ATL-PHYS-PUB-2010-014

“Luminosity Determination in pp Collisions at sqrt(s)=7 TeV Using the ATLAS Detector at the LHC”, **arXiv:1101.2185 (Submitted to EPJC)**

LHC Cross Sections

- Bulk of physics happening at LHC are low-p_T *pp* collisions (non-perturbative, soft QCD)
- Need to understand their properties since they will be overlayed on events with interesting high-p_T interactions
- Expect ~18 *pp*-interactions per bunch crossing at LHC design luminosity 10^{34} cm^{-2}s^{-1} and centre-of-mass energy $\sqrt{s}$ = 14 TeV

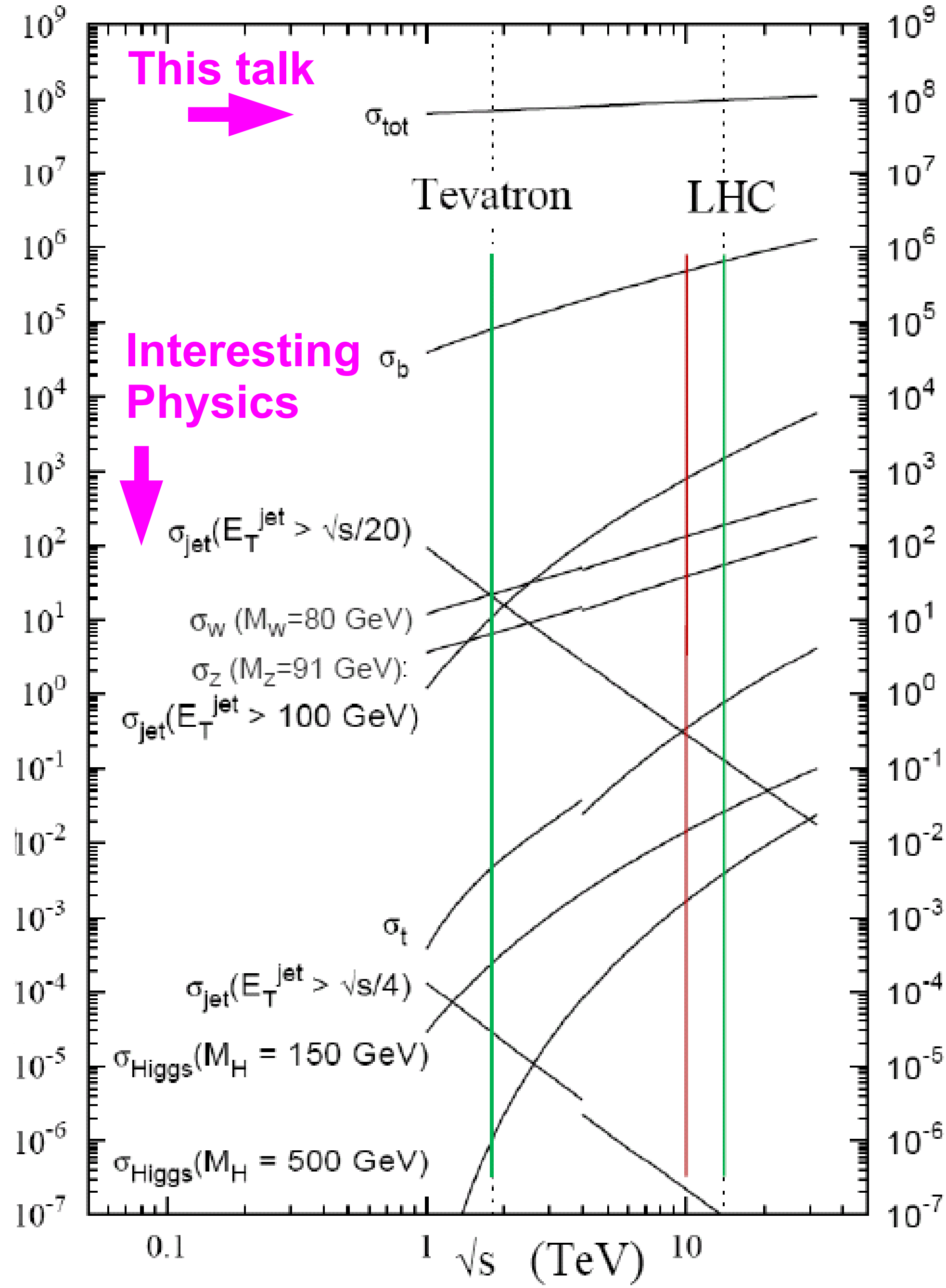
- Ideally should measure all properties of particle production at the

total cross section

plus the

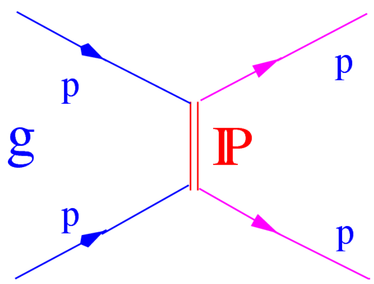
underlying event

Proton-proton cross sections

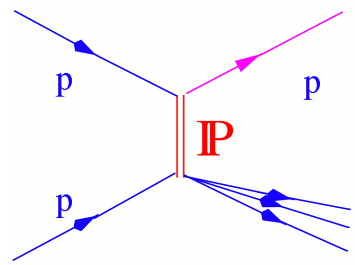


Components of the Total Cross Section

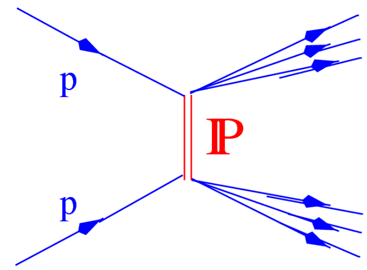
$$\sigma_{tot} = \sigma_{elas} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$$



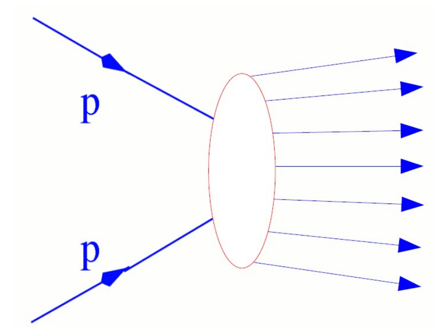
elastic



single diffractive



double diffractive



non-diffractive

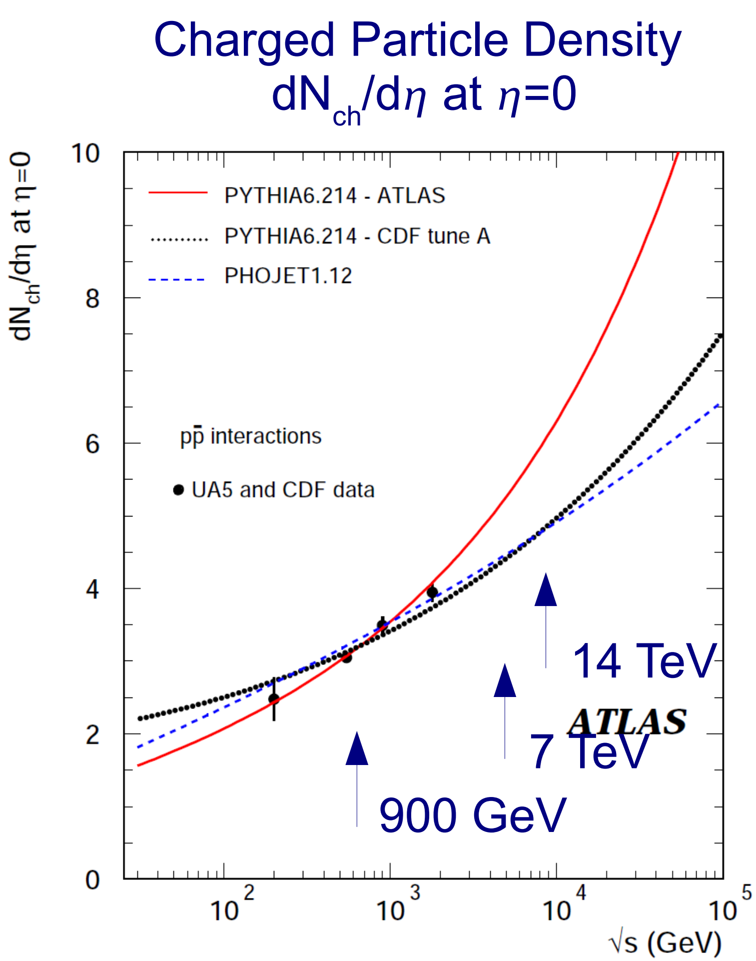
$$\sigma_{nsd} = \sigma_{tot} - \sigma_{elas} - \sigma_{sd}$$

- Bulk: non-diffractive inelastic processes
  - Neutral and charged particle production
- About 20%-30% diffractive events: Exchange of colorless object (Pomeron)
  - Event signature are rapidity gaps on one side (SD) or the center (DD)

Generator	σ_{DD} (mb)	σ_{SD} (mb)	σ_{ND} (mb)	σ_{inel} (mb)	$(\sigma_{SD}+\sigma_{DD})/\sigma_{inel}$
Pythia	9.3	13.7	48.5	71.5	32.2%
Phojet	3.9	10.7	61.6	76.2	19.2%

@ 7 TeV

Predicting the total cross section



A plot from before data taking:
14 TeV CSC Note NSD Predictions
arXiv 0901.0512

Models tuned to agree to ISR, SppS and Tevatron

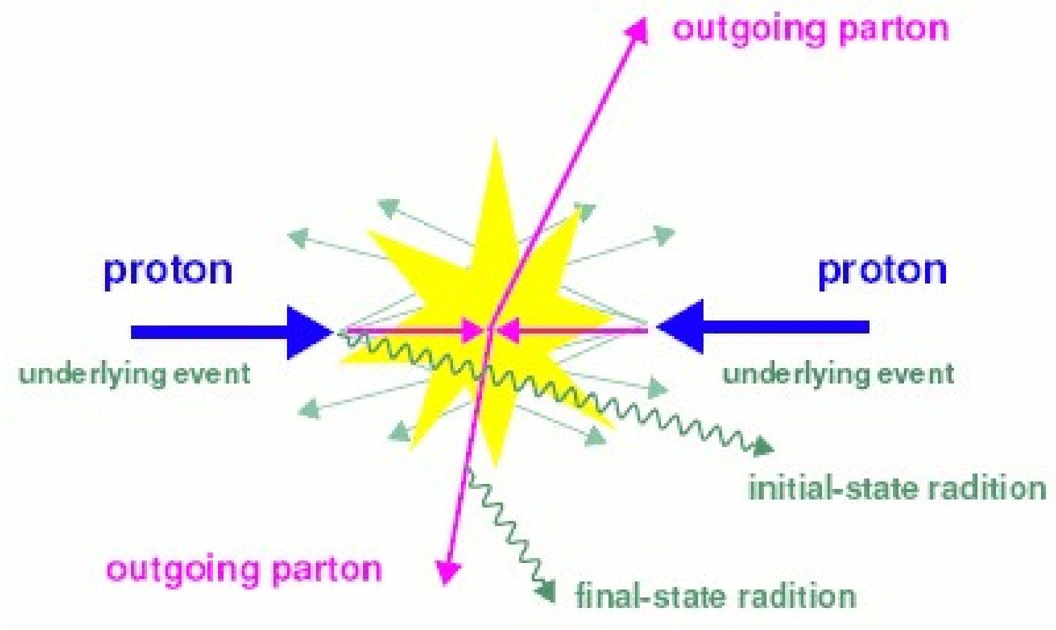
- Need non-perturbative phenomenological models to predict total cross section
- Predictions by different generators (PYTHIA6, PYTHIA8, PHOJET) and different PYTHIA tunes (ATLAS MC09, CDF Tune A, …) diverge towards large centre-of-mass energies
- Large uncertainties ~ 20% at $\sqrt{s}$ = 14 TeV
  - σ_{tot} : 102 – 119 mb
  - $dn_{ch}/d\eta$ at $\eta=0$: 5.1 – 6.8
  - $\langle n_{ch} \rangle$: 70 – 91
  - $\langle p_T \rangle$ at $\eta=0$: 550 – 640 MeV

- Need to measure to constrain phenomenological models with LHC data and derive new tunes

Components of the Underlying Event

Everything that happens in addition to the primary (hard) parton-parton interaction

- Initial and final state radiation
- Additional soft multi-parton interactions
- Beam remnants



Uncertainties connected to all of these components due to ...

- Parton Density Functions
- ISR/FSR gluon radiation
- Model of Multiple Parton Interactions

- Modeling of UE important for precise high-p_T measurements
- Important ingredient for jet and lepton isolation, energy flow, jet tagging

Experimental Challenges

In reality cannot measure total cross section directly because:

- need to make minimal selection criteria to select inelastic processes
  - "minimum bias"

- If using tracker for measurement
  - see only charged particles
  - limited geometrical and momentum acceptance and tracking inefficiencies

- Historically, minimum bias measurements have often been reported as non-single-diffractive (NSD) total cross section

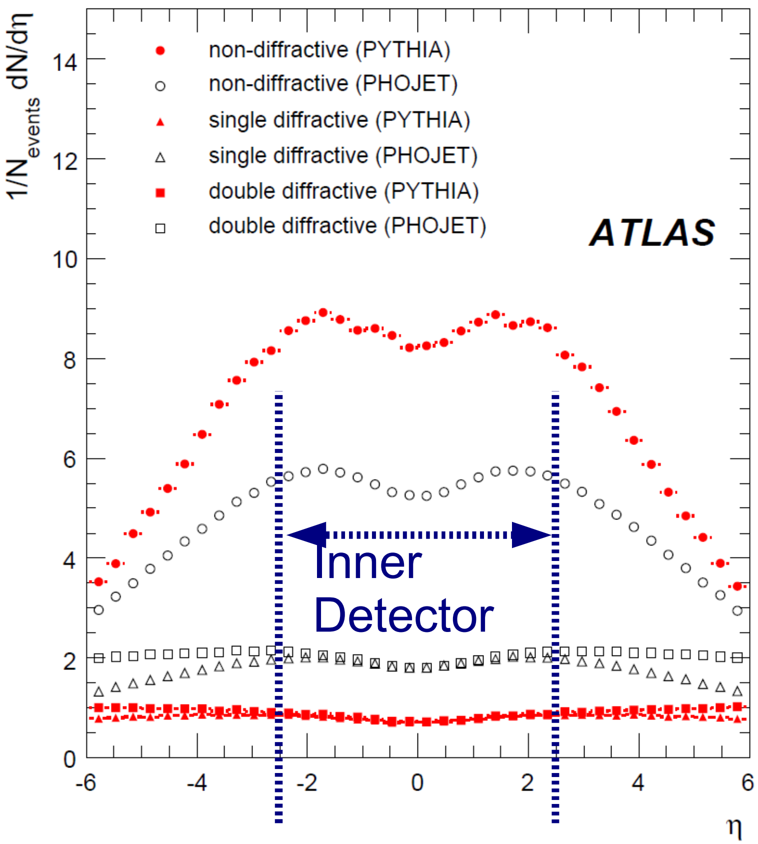
  - Reduce single-diffractive component using a coincidence trigger (double-arm)
  - Remove remaining single-diffractive contribution using MC

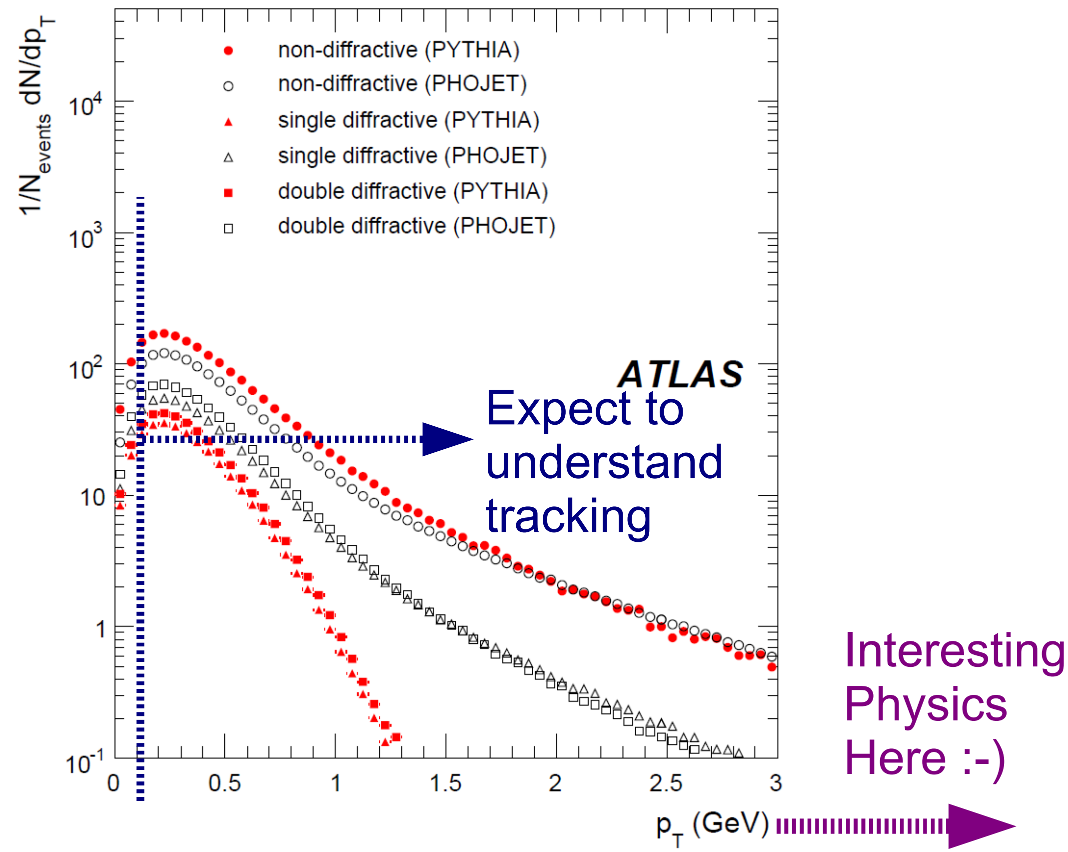
  - Extrapolate down to $p_T > 0$ GeV and $n_{ch} = 0$ → also take from fit or MC

Previous measurements
- Measure only part of the total cross section
- Already rely on predictions that should be measured!

The ATLAS Minimum Bias Measurement

- Measure charged particle multiplicities in triggered inelastic events within geometrical acceptance $|\eta|<2.5$ in regime of well-understood tracking (p_T > 100 MeV)
- Avoiding model dependences as much as possible
  - No NSD measurement: Use single arm trigger, no sd-removal
  - Don't take $N_{ch}=0$ from Monte Carlo: $N_{ch} > 0$
  - No extrapolation to $p_T=0$ (only optionally)
  - Measure corrections from data if possible



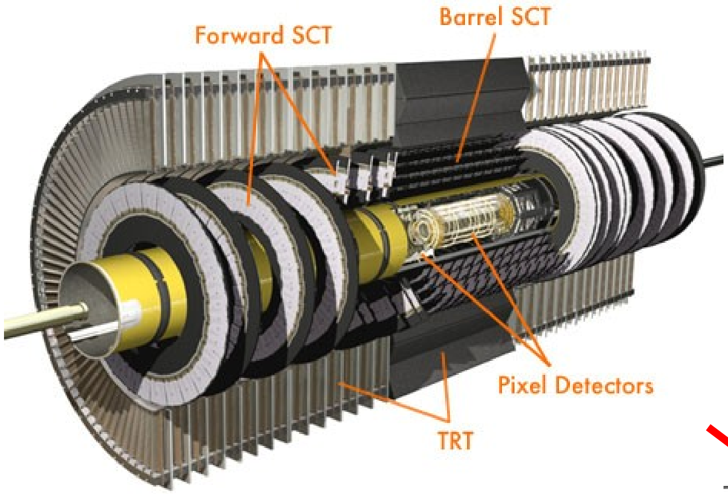


14 TeV CSC Note NSD Predictions

The ATLAS Detector

Subsystems most relevant for measuring inelastic minimum bias events with charged tracks

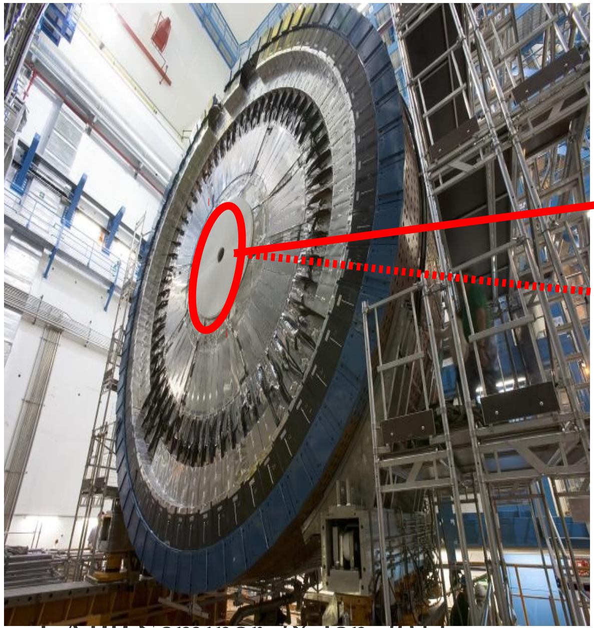
Tracks: Inner Detector
$|\eta|<2.5$

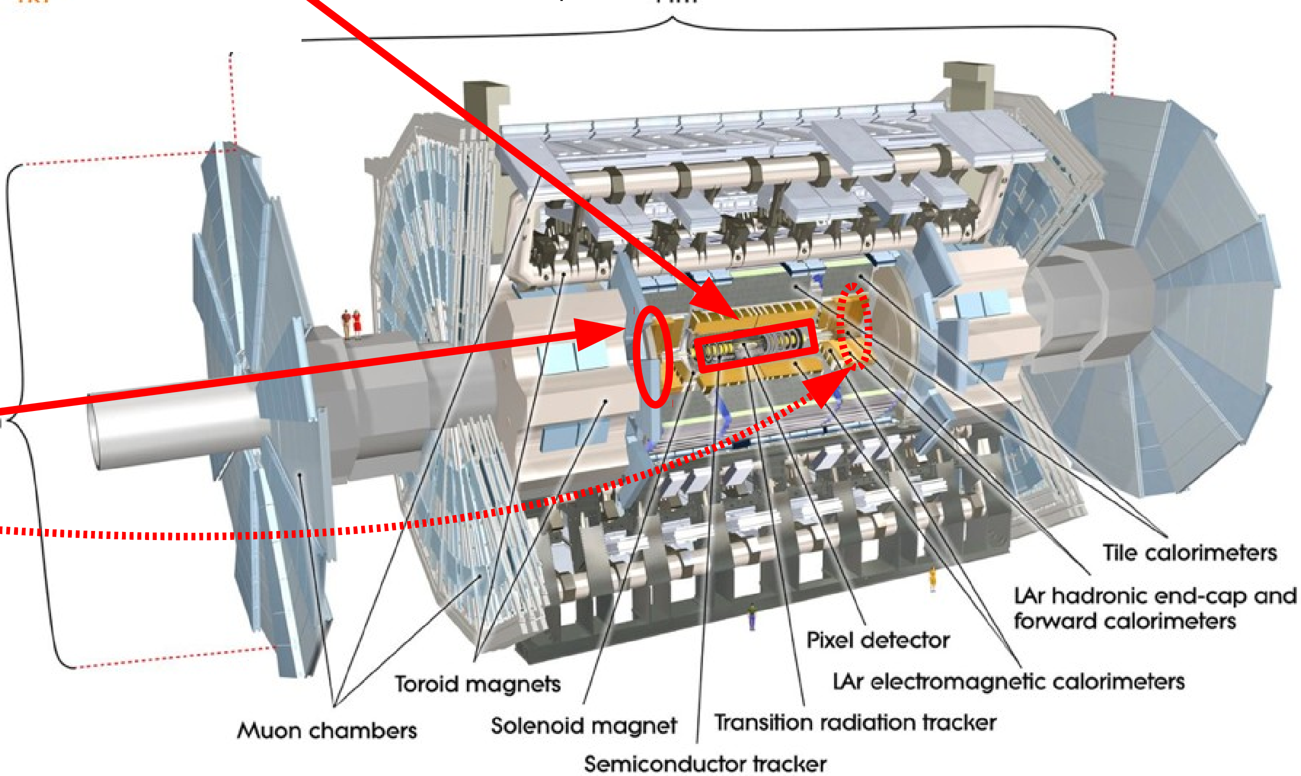


Pixel Detector
- 3 barrel layers; 2 x 3 end-cap disks
- $\sigma_{r\varphi}$ ~10 μm, σ_z ~ 115 μm

Silicon Strip Detector (SCT)
- 4 barrel layers; 2 x 9 end-cap disks; stereo pairs of single sided sensors
- $\sigma_{r\varphi}$ ~ 17 μm, σ_z ~ 580 μm

Trigger:
Minimum Bias Trigger Scintillators (MBTS) 2.09 < $|\eta|$ < 3.84



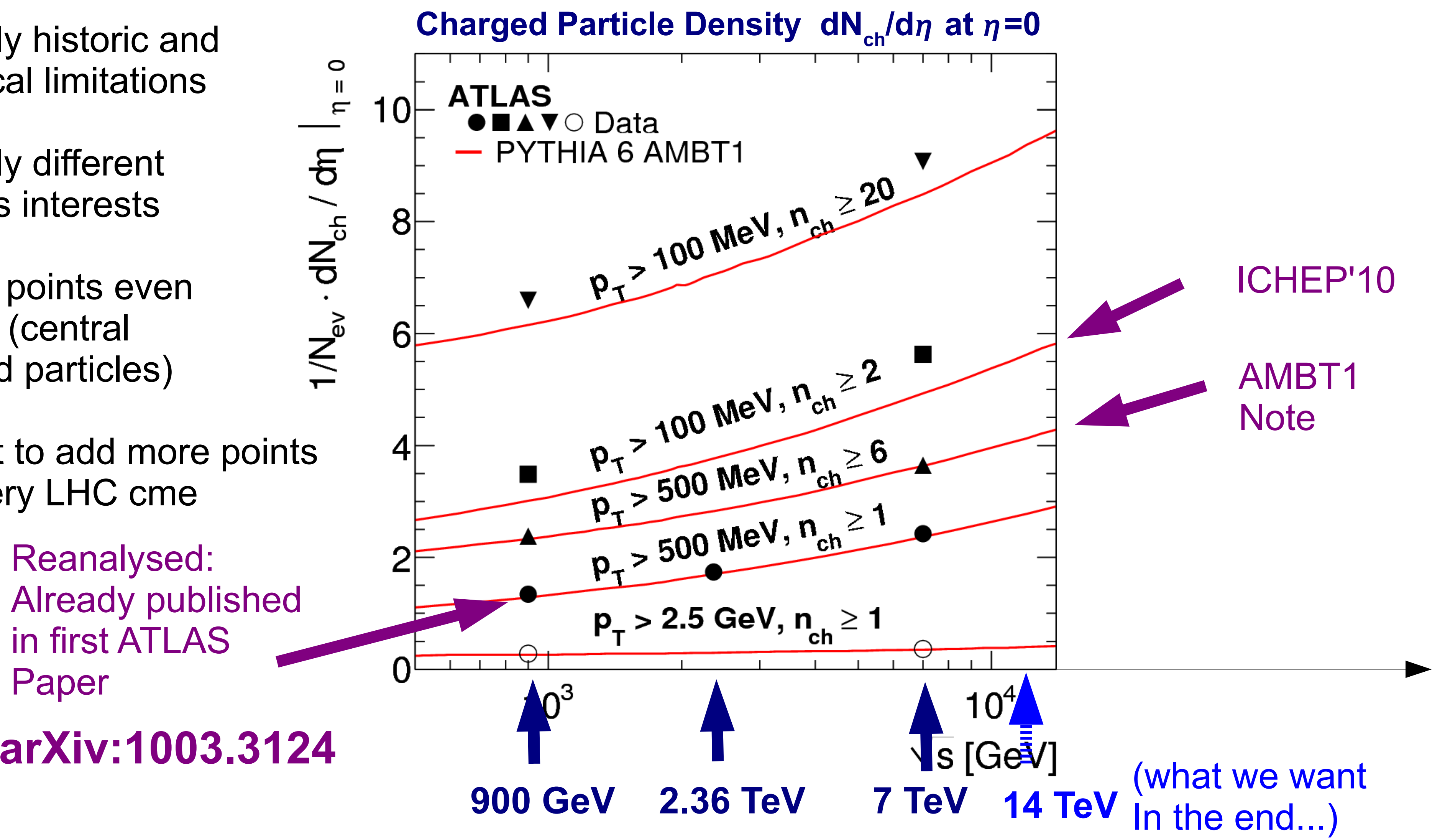


Example Event Display

Results Overview

- We measure 11 independent points in minimum bias, different in
  - sqrt(s) - LHC centre of mass energy
  - p_T – minimum track transverse momentum
  - n_{ch} – mimimum number of charged particles in event

- Partially historic and technical limitations
- Partially different physics interests
- Not all points even shown (central charged particles)
- Expect to add more points for every LHC cme

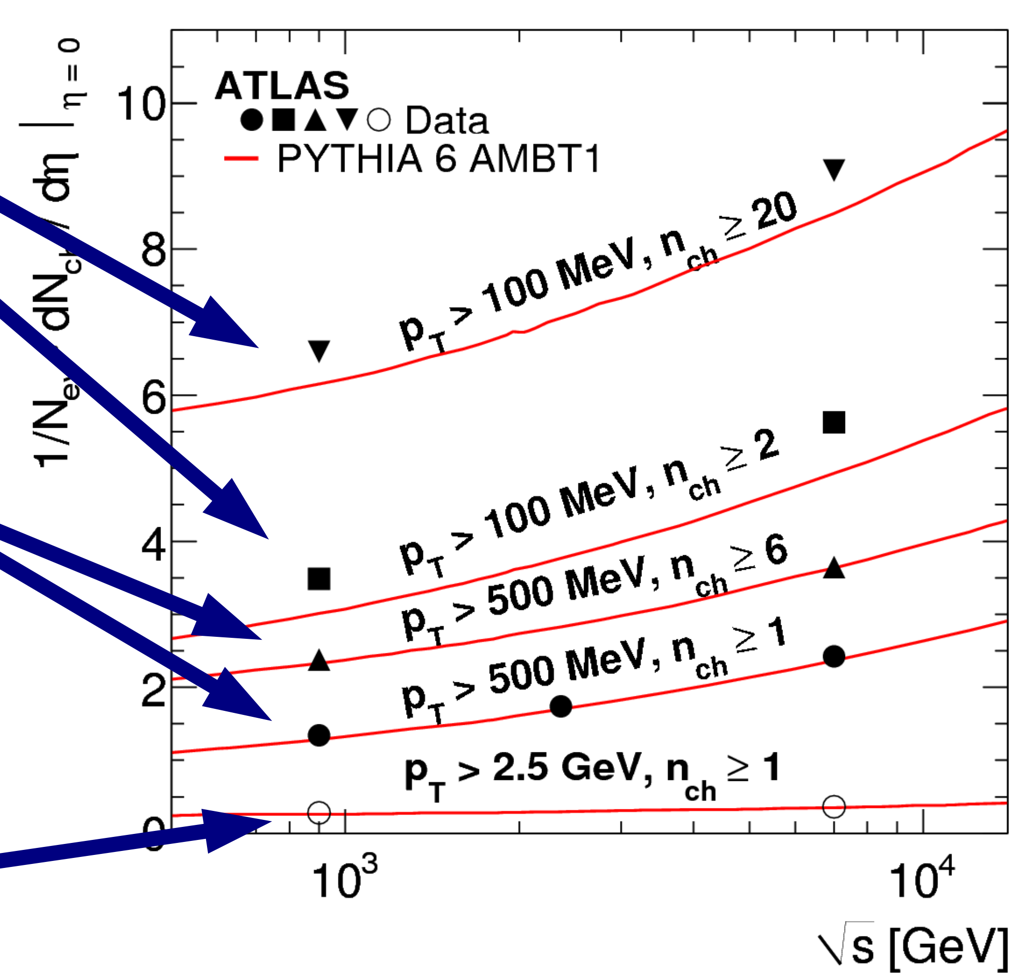


arXiv:1003.3124

p_T Ranges of Measurement Points

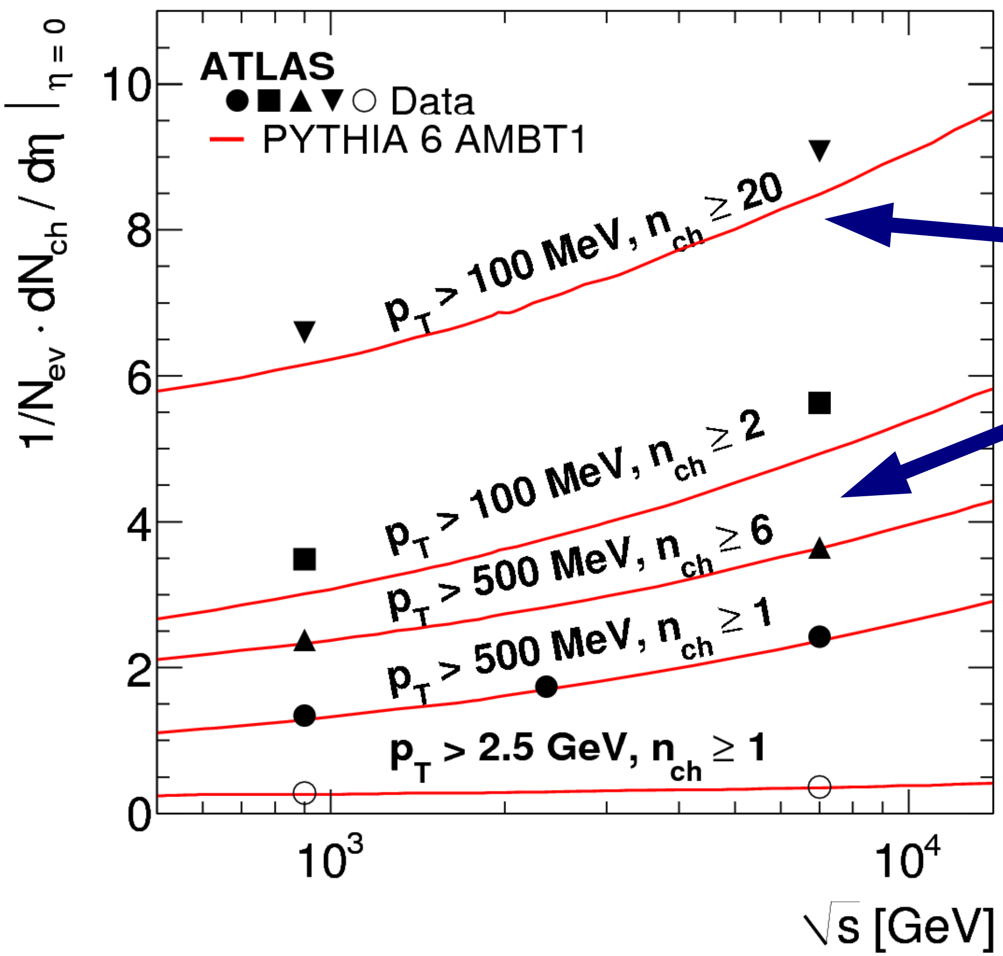
Three different minimum track transverse momentum cuts

- **p_T> 100 GeV**
  - Most inclusive
  - Ideally want p_T > 0
  - Low-p_T tracks difficult to reconstruct
- **p_T> 500 GeV**
  - First measurement points
  - Considered safe in the beginning of LHC running
- **p_T> 2.5 GeV**
  - Hard part of spectrum
  - Interesting for higher luminosities
  - Can be used for
    - Pile-up studies
    - Trigger studies



n_{ch} Cuts of Measurement Points

- Diffraction has largest contribution at lowest multiplicities
- Needs to be suppressed for example for tuning



Diffractive limited phase space

- Used for MC Tuning (AMBT1)

Measured Distributions

- For each point we measure

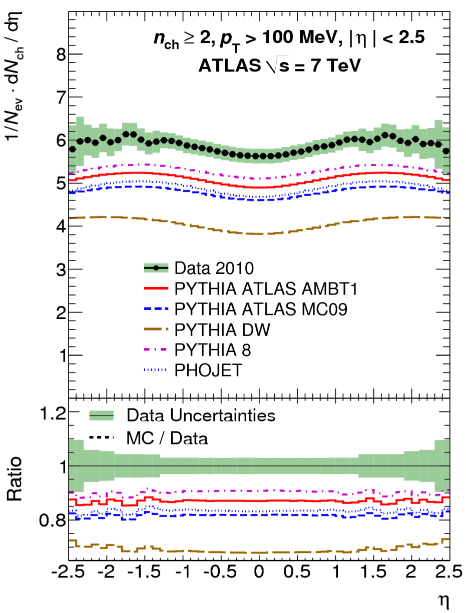
$$\frac{1}{N_{\rm ev}}\cdot\frac{{\rm d}N_{\rm ch}}{{\rm d}\eta},\quad \frac{1}{N_{\rm ev}}\cdot\frac{1}{2\pi p_{\rm T}}\cdot\frac{{\rm d}^2N_{\rm ch}}{{\rm d}\eta{\rm d}p_{\rm T}},\quad \frac{1}{N_{\rm ev}}\cdot\frac{{\rm d}N_{\rm ev}}{{\rm d}n_{\rm ch}} \quad \text{and} \quad \langle p_{\rm T}\rangle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

Average multiplicity as a function of track η

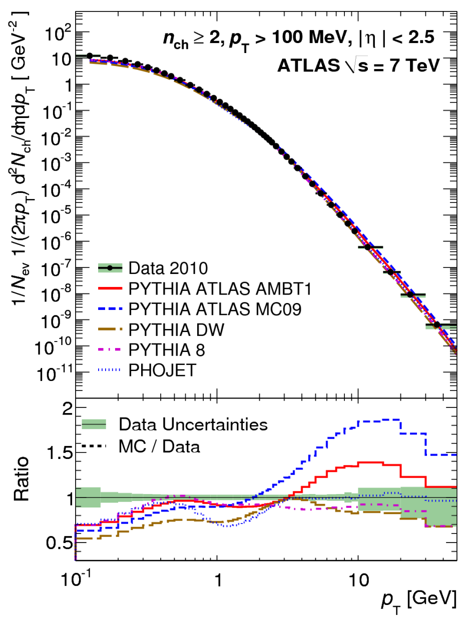
Average multiplicity as function of track $p_{\rm T}$

Average charged particle multiplicity

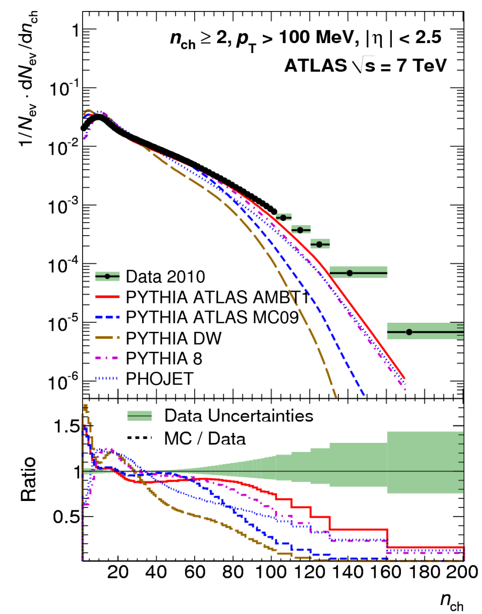
Average track $p_{\rm T}$ as function of multiplicity



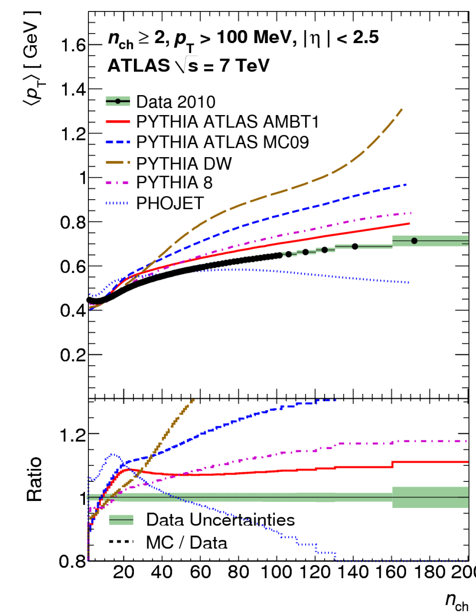
Full ID Coverage



Up to 50 GeV,
10 orders of magnitude



Up to 200 particles
Per event



Precise
Observable

Selection Overview

Event Selection

- Data Quality
- Trigger
- Vertex
- Multiplicity

Track Selection

- Hit Multiplicities
- Impact Parameters
- Phasespace

- GRL selection
- First 7 runs @ 7 TeV
- All 2009 data @ 900 GeV
- All runs @ 2.36 TeV
- Exclude LB during lumi scans

- Pass L1_MBTS_1 trigger

- 1 primary vertex
- Beamspot constrained
- Vertex algo requires ≥2 tracks
- Pile-up veto
- No second vertex with ≥4 tracks

- ≥ n (1,2) good tracks (nsel)

- Quality
- Inside-out + low pT tracking algorithms
- Layer-0 hit if expected
- ≥ 1 Pixel hit
- ≥ 2,4,6 SCT hits
  for $p_T \geq$ 100,200,300 MeV

- $|d_0|^{vtx} \leq$ 1.5mm
- $|z_0 \sin\theta|^{vtx} \leq$ 1.5mm

- χ^2 prob > 0.01 for p_T > 10 GeV

- Phase-space:
  - $|\eta| \leq 2.5$
  - $p_T \geq$ 100, 500, 2500 GeV

Data Sets and Data Quality

- Minimum bias measurements are not statistically limited
  - Very few runs of every new energy setting are enough
  - Do not need luminosity measurement (normalise to $1/N_{ev}$)
  - But need suitable trigger prescale and low luminosity (no pile-up)

All 2009 data @ 900 GeV
As in first ATLAS MB paper

First 7 runs @ 7 TeV
L ≈ 168*1.13 ≈ 190 μb-1

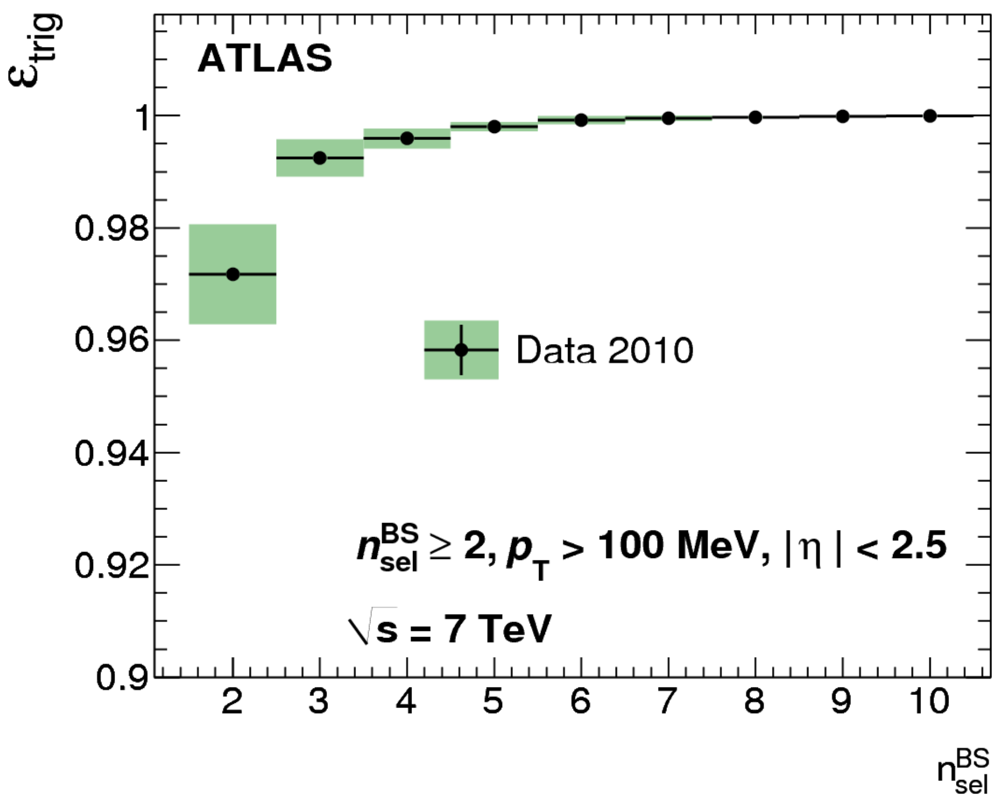
2009 Data
2.36 TeV runs included

Phase-Space Region		$\sqrt{s}$ = 0.9 TeV Full Tracks		$\sqrt{s}$ = 7 TeV Full Tracks		$\sqrt{s}$ = 2.36 TeV ID Tracks (Pixel Tracks)	
n_{ch}	min p_T (MeV)	Events	Tracks	Events	Tracks	Events	Tracks
2	100	357,523	4,532,663	10,066,072	209,809,430	-	-
1	500	334,411	1,854,930	9,619,049	97,224,268	5,929 (5,983)	38,983 (44,788)
6	500	124,782	1,287,898	5,395,381	85,587,104	-	-

- Require Good Runs List
  - Stable beams
  - Fully operational Inner Detector, trigger and solenoid *B*-field
  - Exclude LB (Luminosity Blocks) during lumi scans

Trigger Requirement and Efficiency

- Require 1 or more counter in the MBTS from **either** side above threshold (L1_MBTS_1)
  - avoid bias on event topology



Trigger Efficiency

- Defined by comparing L1_MBTS_1 to high-level software trigger (HLT) based on tracks

MbSpTrk

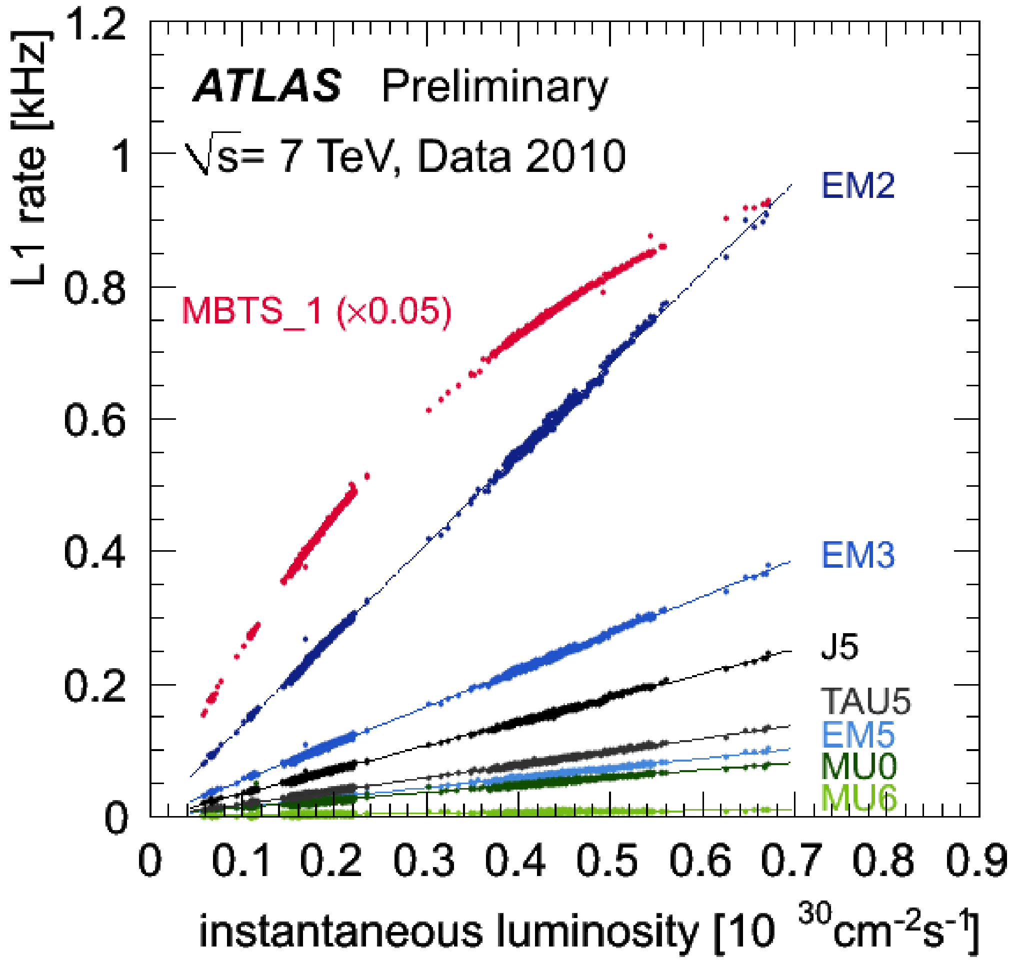
- L1 Beam-pickup (BPTX) filtered by L2 Pixel and SCT spacepoints and EF track.

- Calculated in final event selection
- > 96% for any track multiplicity

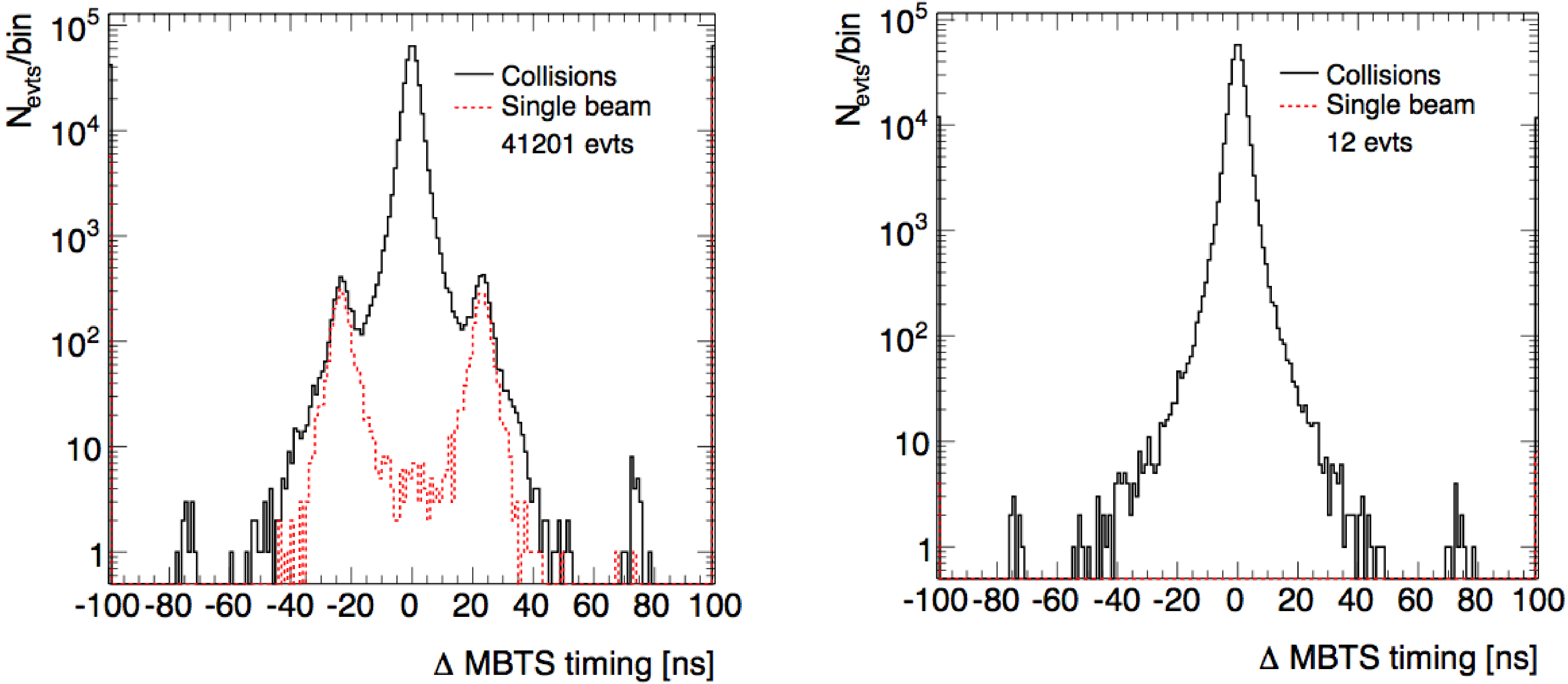
MB Triggers at higher Lumi

- For future MB measurements at new centre-of-mass energies we will need a very low luminosity run to take a few MB runs

- At time of plot two colliding bunches in LHC (n_b=2)
- Electromagnetic, muon, tau and jet trigger rates show a nicely linear behavior
- MBTS rate saturates as it approaches two times the LHC revolution frequency (nb*f_{LHC}~22 kHz) due to pile-up



Beam Background

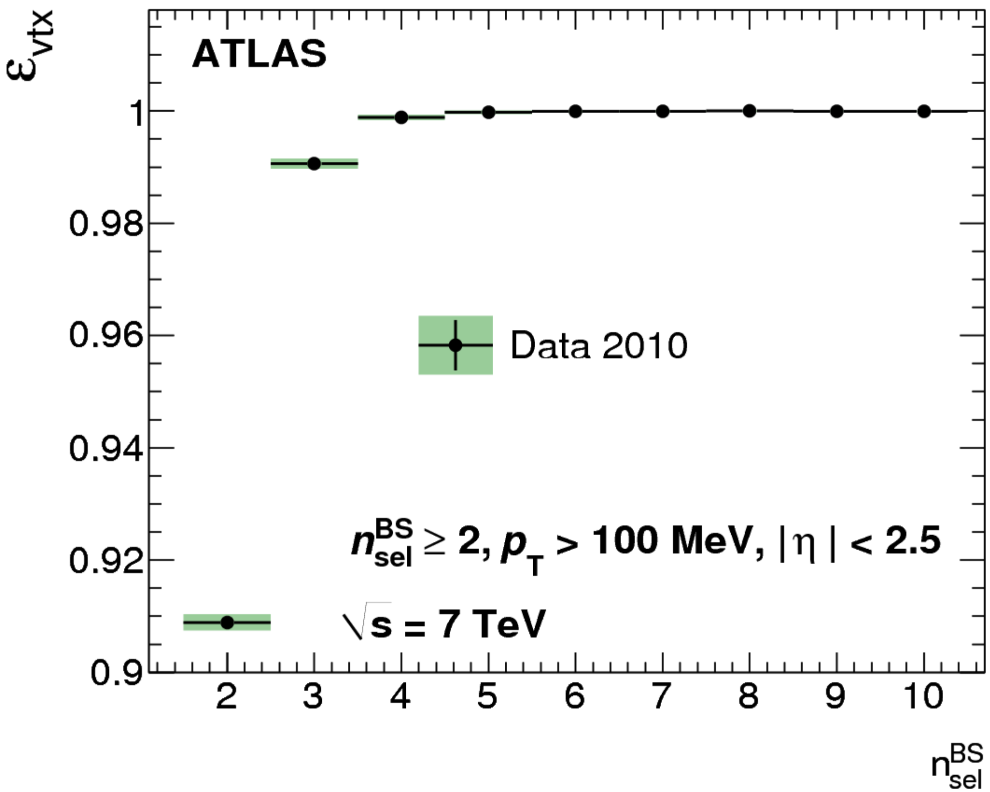


Trigger Selection | **Final selection**

- Measure time difference from offline readout of MBTS (Timing cut is not used in analysis selection.)
- Look at collisions events (paired bunches) and single beam (unpaired bunches)
- Beam background rate at 10^{-4} level

Vertex Selection and Efficiency

- Require 1 reconstructed primary vertex
  - Allow precise location of primary interaction
- Use Beamspot constraint
- Require min. 2 tracks (p_T > 100 MeV) in algorithm



- Measure vertex efficiency from data:

$$\frac{\text{Triggered events with vertex}}{\text{all triggered events}}$$

Pile-up

- small but visible in MB 7 TeV data set
  - Negligible in 900 GeV and 2.36 TeV
- Shows up as secondary vertices with many tracks (high n_{ch})
- Strategy: Reject events with pile-up (contribution: ~0.1% overall, < 6% at high n_{ch})

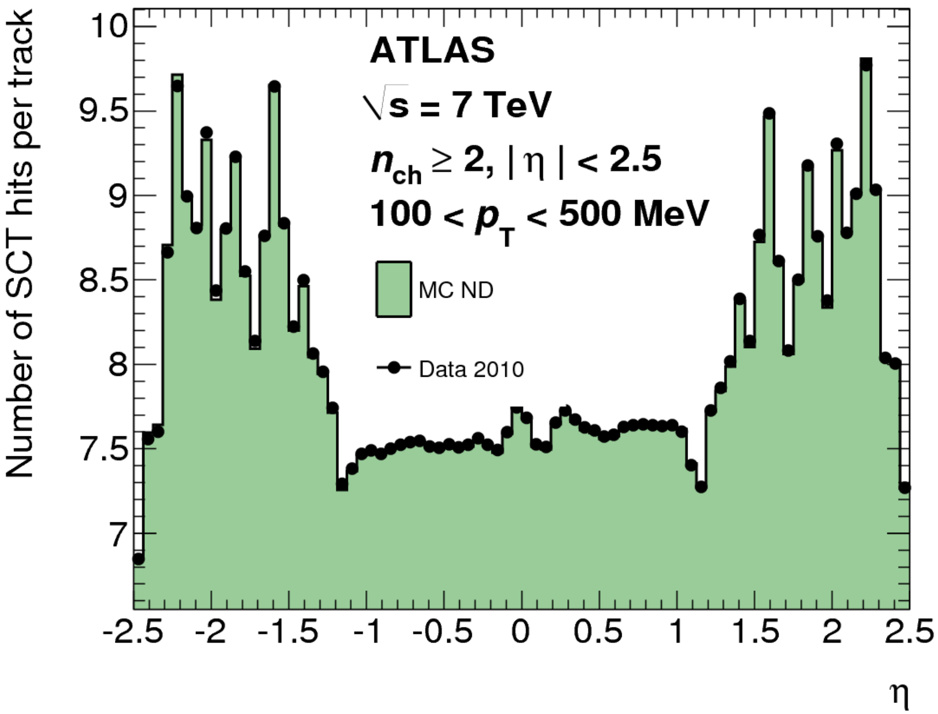
- No second vertex with ≥4 tracks

Hit Multiplicities on Tracks

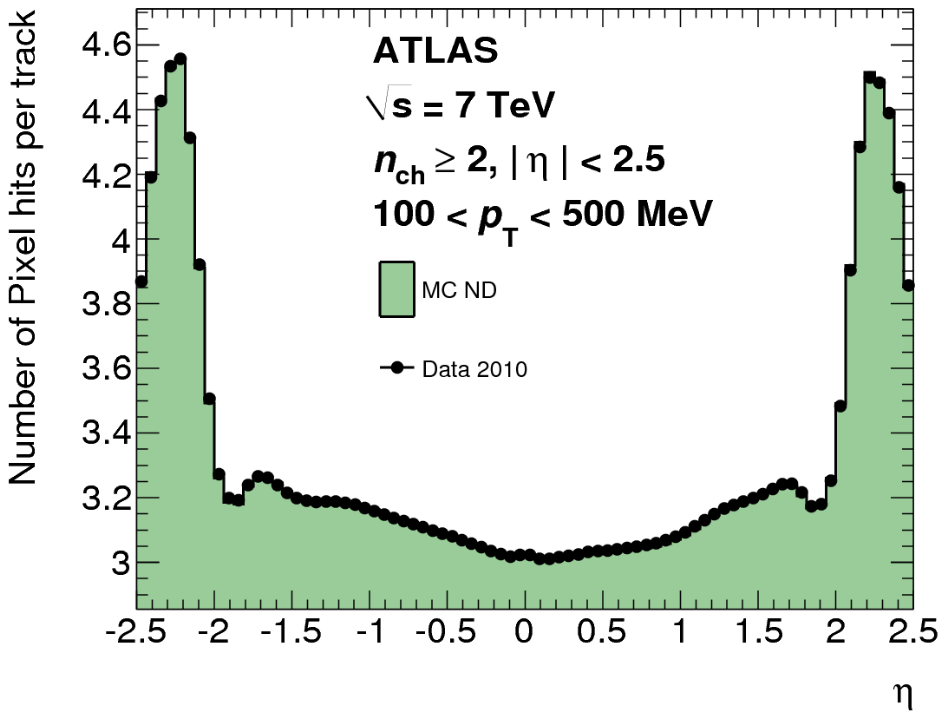
Track Requirements

- Use "inside-out" + "low pT" tracking algorithms
- Require 1 Pixel layer-0 ("*b*-Layer") hit if expected
- ≥ 1 pixel hit
- ≥ 2, 4, 6 SCT hits for: $p_T \geq$ 100, 200, 300 MeV

Average N_{Hits} in SCT



Average N_{Hits} in Pixels

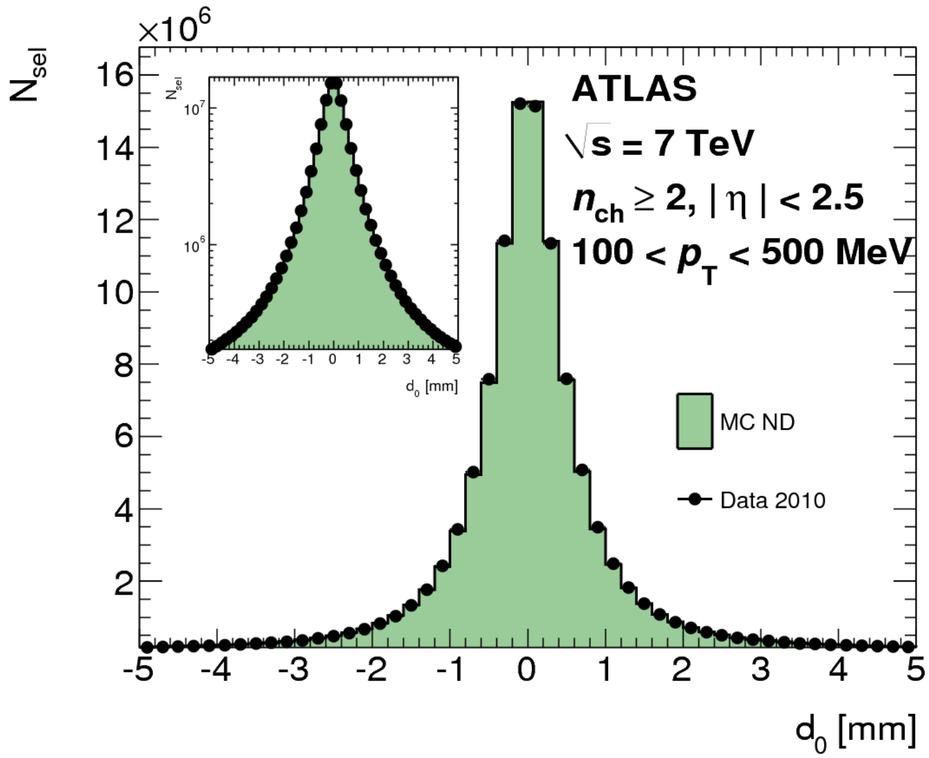


- Excellent description of track properties up to edge of ID acceptance
- Allow detailed studies of material, alignment, and resolution
- Shown for 100 < p_T < 500 MeV (Similar for p_T>500 MeV, shown in first paper)

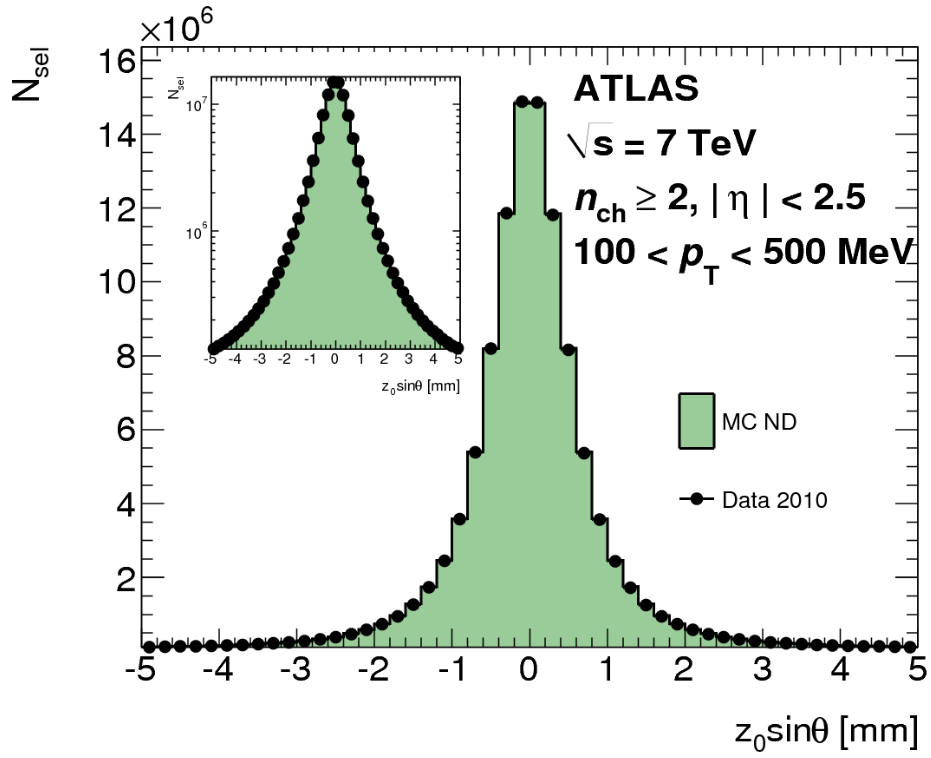
Impact Parameters

- $|d0|_{vtx}$ ≤ 1.5mm – Reduce non-primary particles
- $|Z0 \sin\theta|_{vtx}$ ≤ 1.5mm

Transverse impact parameter



Longitudinal impact parameter



Also very well modelled – allows to further reduce remaining non-primary tracks

Removal of non-primary Particles

- Need to subtract the non-primary particles ("secondaries") from the primary particles

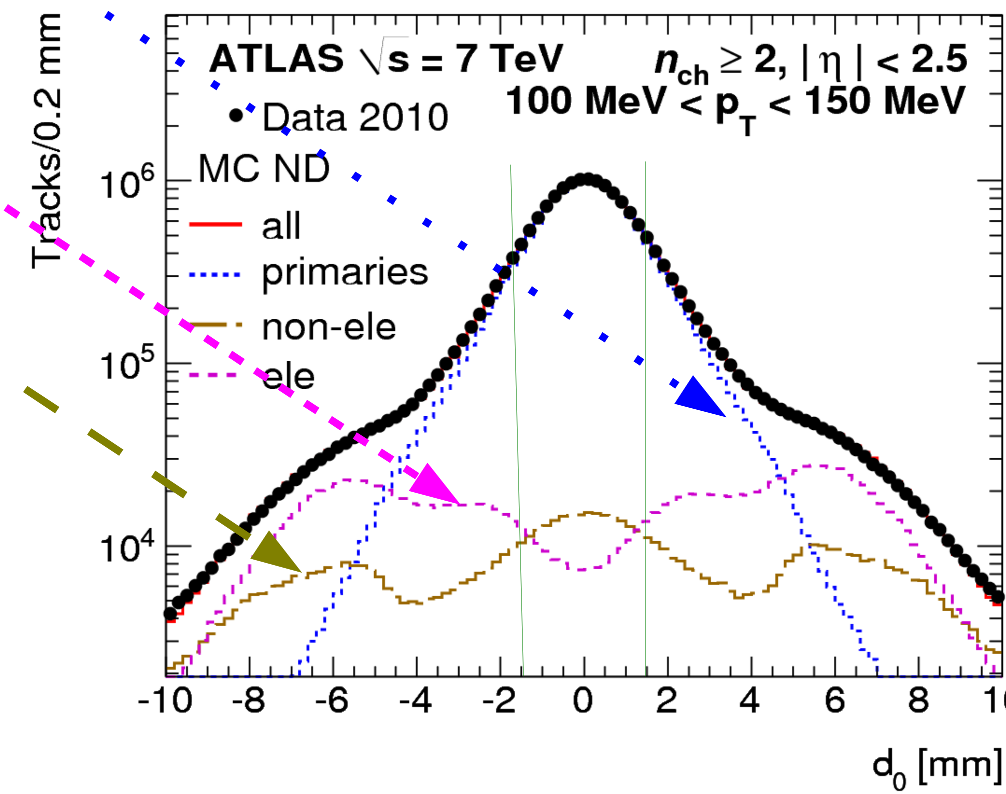
Sources

- Photon Conversions
  - Electrons – depend on geometry description
- Non-electrons – depend on physics
  - Long-Lived Particles ($\tau > 3\text{x}10^{-11}$s)
- Hadronic Interactions
- Fake Tracks
  - Small - depend on reconstruction algorithm

- Shape of contributions taken from MC
- Fit to data outside analysis acceptance
- |d0| > 1.5 mm in bins of p_T:

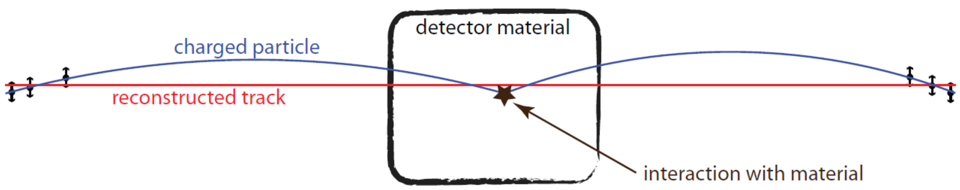
Range	Non-primaries
• 100 < p_T < 150 GeV	3.4%
• p_T > 500 GeV	1.6%

Transverse impact parameter



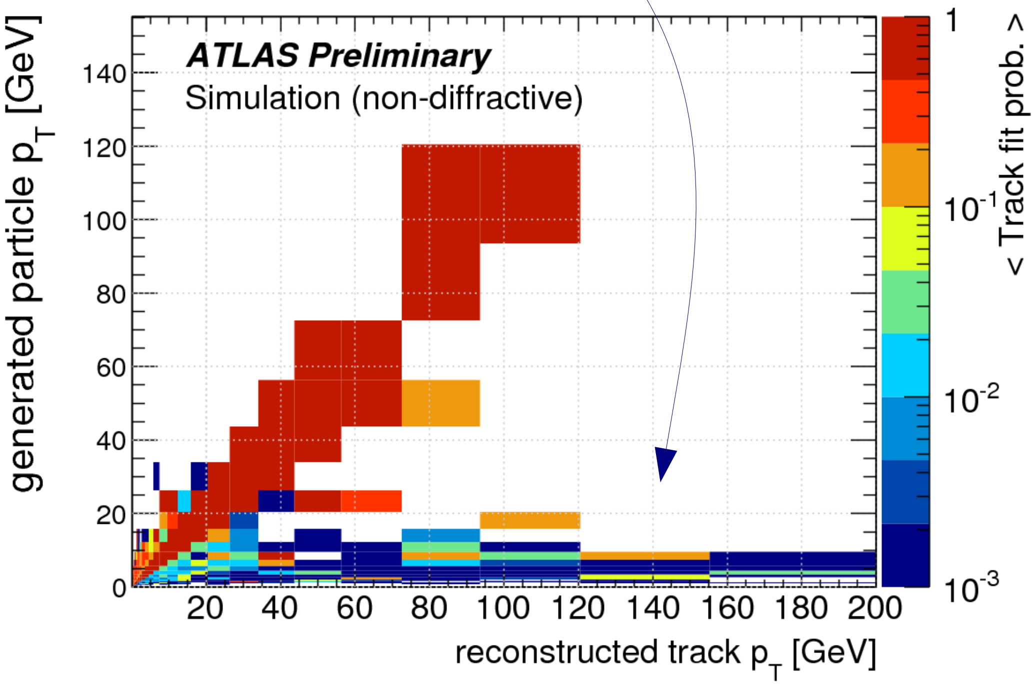
Removal of Mismeasured Tracks

- Mis-measured high-pT tracks
  - Due to large extrapolation distance (~1m) between Pixel and SCT at high pseudorapidities |eta|



- Also known alignment problem in endcap C
- Particles mis-reconstructed as high-p_T tracks
- Partially removed using P(χ2) cut
- Problem for unfolding: no correlation between rec and gen p_T

Non-Gaussian tails in resolution



Reduce with cut

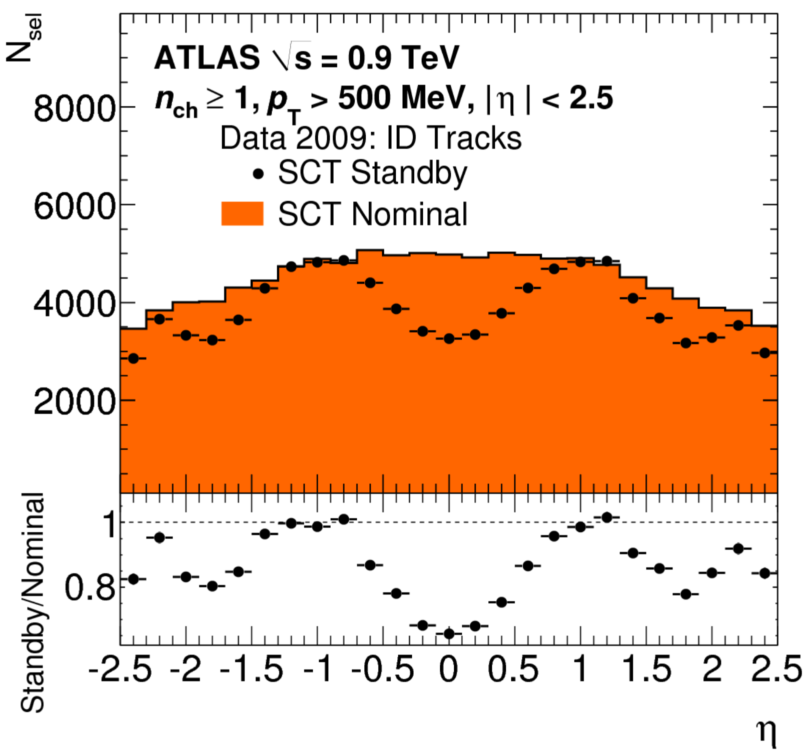
- χ^2 prob > 0.01 for p_T > 10 GeV

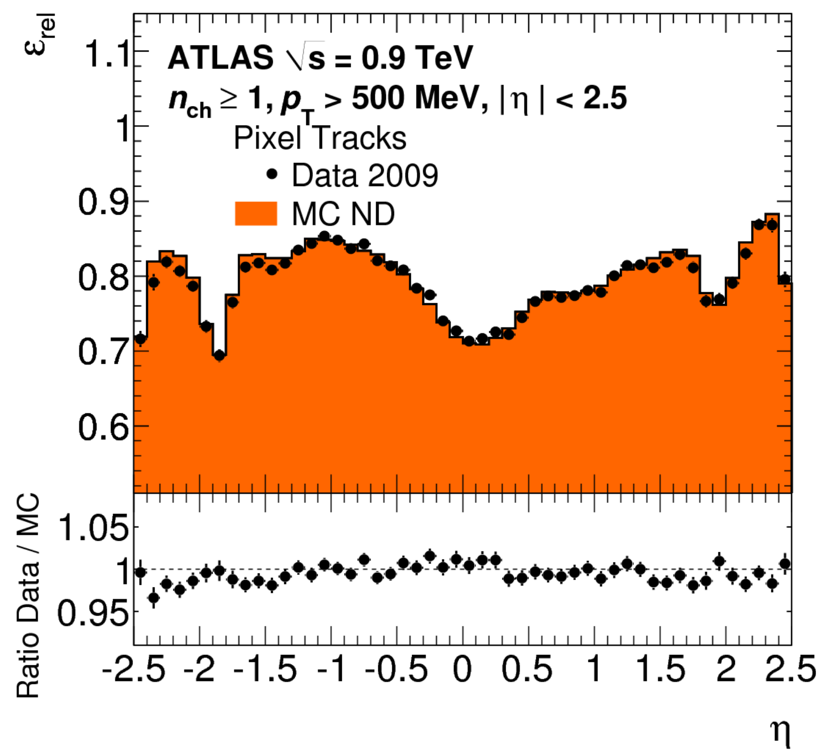
- Large systematic uncertainty ~ 10%
  Determined from discrepancy in data/MC efficiency on cut

Tracking in 2.36 TeV Analysis

- SCT was on standby voltage during 2.36 TeV data taking

- Use standard track reconstruction algorithms with relaxed requirements
  - SCT hits never required
  - ID Tracks: All ID detectors allowed **– use for p_T plots (leverage)**
  - Pixel Tracks: Pixels only **– use for n_{ch} and eta plots**
  - Can not make accurate plot for <pT>





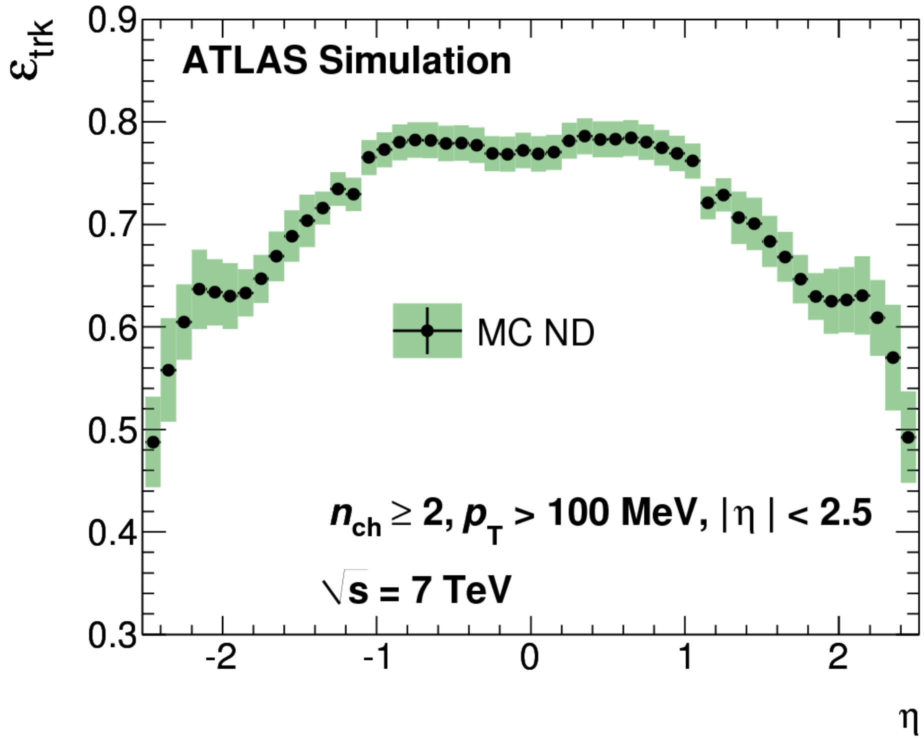
Track Reconstruction Efficiency

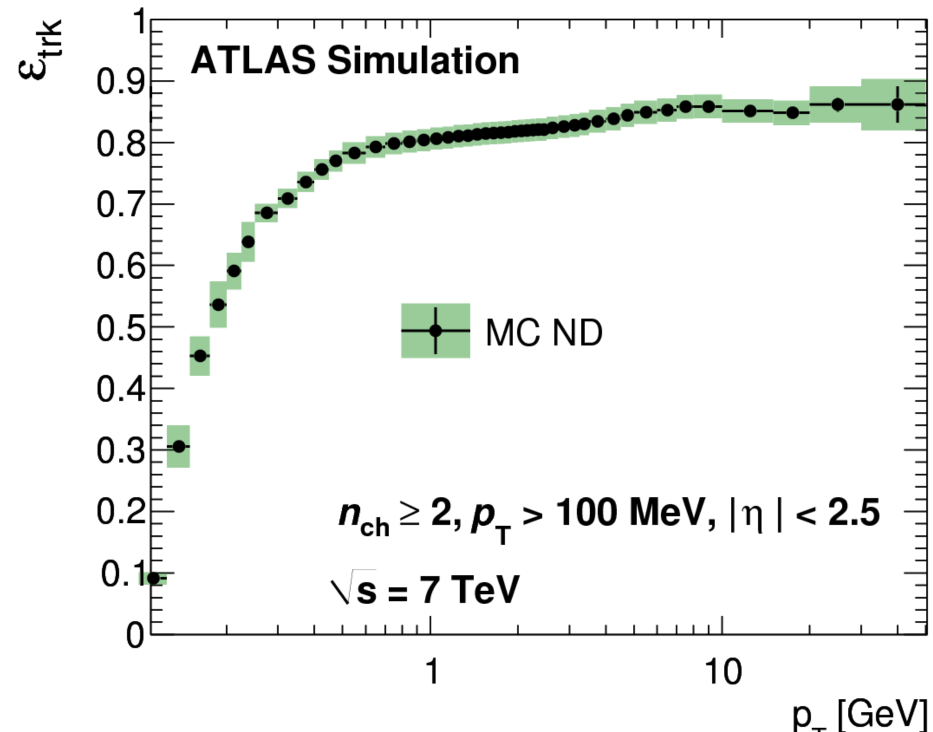
- Excellent understanding of tracking allows determination of primary track efficiency from MC

- Match particles to tracks
  - Cone match $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.15$
  - Require hit compatibility

Binned Track Efficiency: $$\varepsilon_{\mathrm{trk}}(p_{\mathrm{T}}, \eta) = \frac{N_{\mathrm{rec}}^{\mathrm{matched}}(p_{\mathrm{T}}, \eta)}{N_{\mathrm{gen}}(p_{\mathrm{T}}, \eta)}$$

- Calculate average track efficiency of 76% (from **data** distributions)
  - Main source of inefficiency: hadronic interactions





Systematics on Track Efficiency

Systematic Uncertainty	Size	Region
Material	$\pm 2 - 15\%$	decreases with p_T, increases with $\|\eta\|$
χ^2 prob. cut	$\pm 10\%$	flat, only for $p_T > 10$ GeV
Resolution	$\pm 5\%$ negligible -7%	$100 < p_T < 150$ MeV $0.15 < p_T < 10$ GeV $p_T > 10$ GeV
Track Selection	$\pm 1\%$	flat in p_T and η
Truth Matching	$\pm 1\%$	only for $\sqrt{s} = 2.36$ TeV Pixel Tracks
Efficiency correction factor	$\pm 4\%$	only for $\sqrt{s} = 2.36$ TeV ID Track
Alignment and other high p_T	-3% to -30%	only for $p_T > 10$ GeV averaged over η, increases with increasing p_T

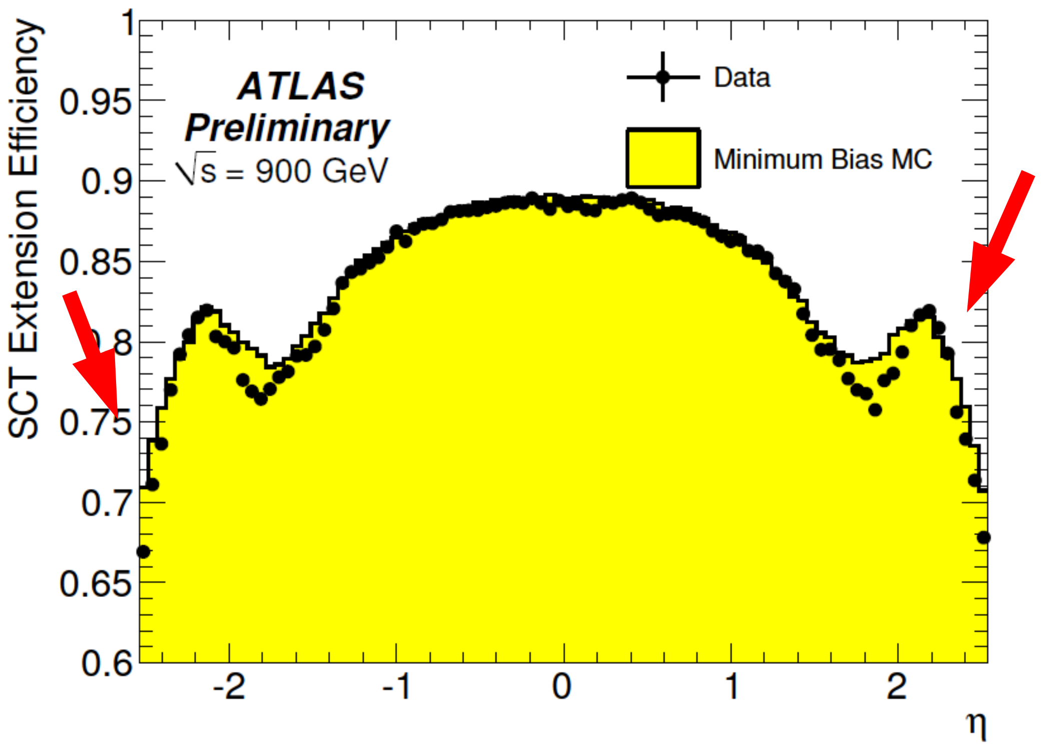
- Overall largest uncertainty comes from material uncertainty

Estimated using several methods:

- K^0_s mass vs decay radius
- Track length
- SCT Extension Efficiency
  - Check if tracks in the Pixel detector extend to the SCT

Large discrepancies in endcaps visible
Now fixed in geometry description

SCT extension efficiency



Corrections Overview

- Want to count particles, not tracks – need to correct back from tracks to particles
- Apply efficiencies and other corrections as weights during analysis

Event-weight

Trigger- and vertex efficiency

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

Track-weight

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

- ϵ_{trk} Track reconstruction efficiency
- f_{nonp} Non-primary particles
- f_{okr} Out-of-phasespace

Unfolding

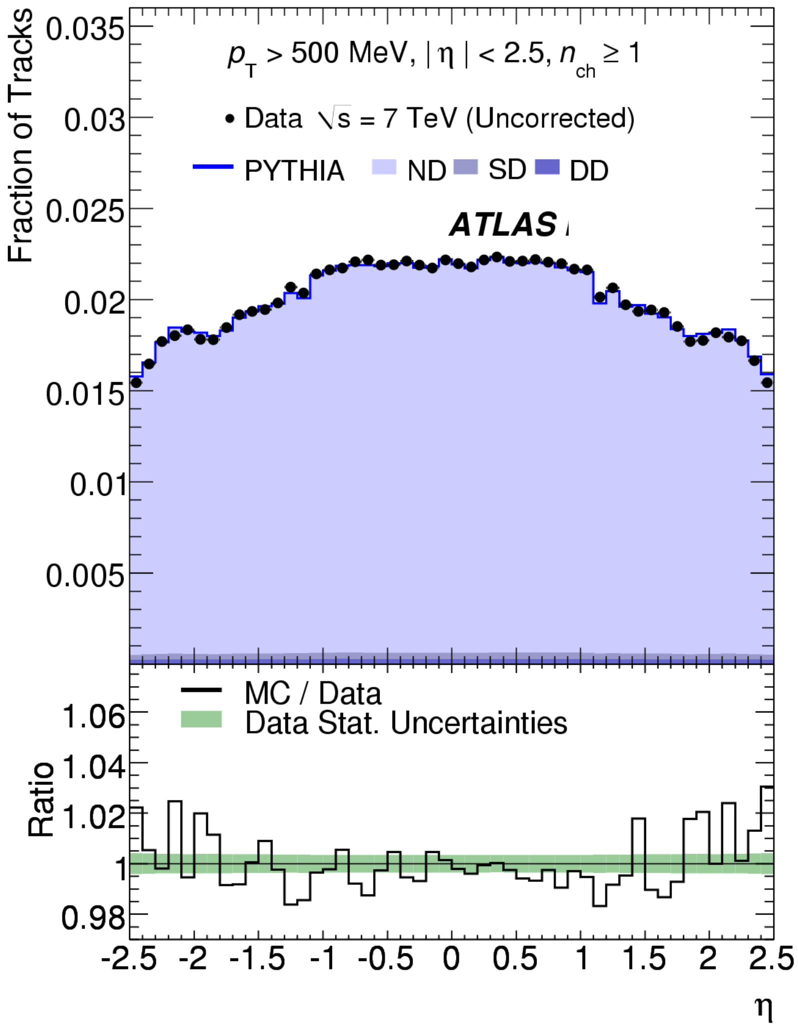
n_{ch} and p_{T}:
Correct bin migrations using
1D iterative Bayesian unfolding

A note on nomenclature

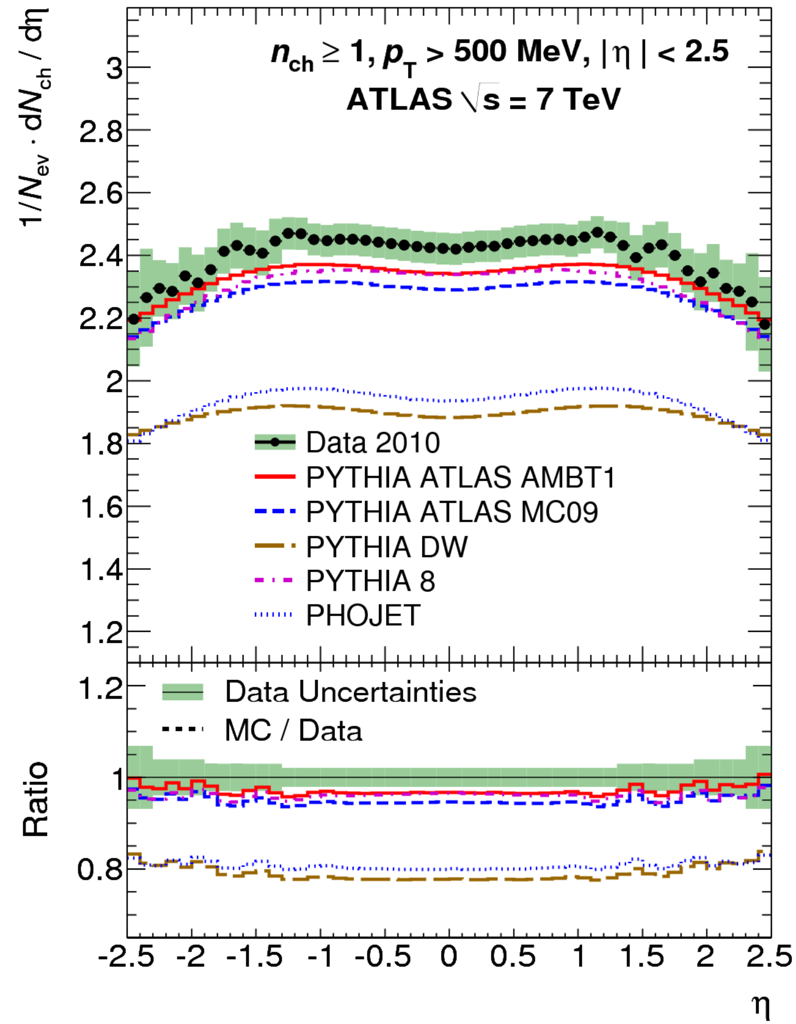
n_{ch} = number of charged particles
n_{sel} = number of selected tracks

n^{BS} = measured wrt beamspot
n^{VTX} = measured wrt vertex

dN/dη Correction



"Raw" distribution:
Measured track density



Final distribution:
Charged particle density

n_{ch} Correction: Bayesian Unfolding

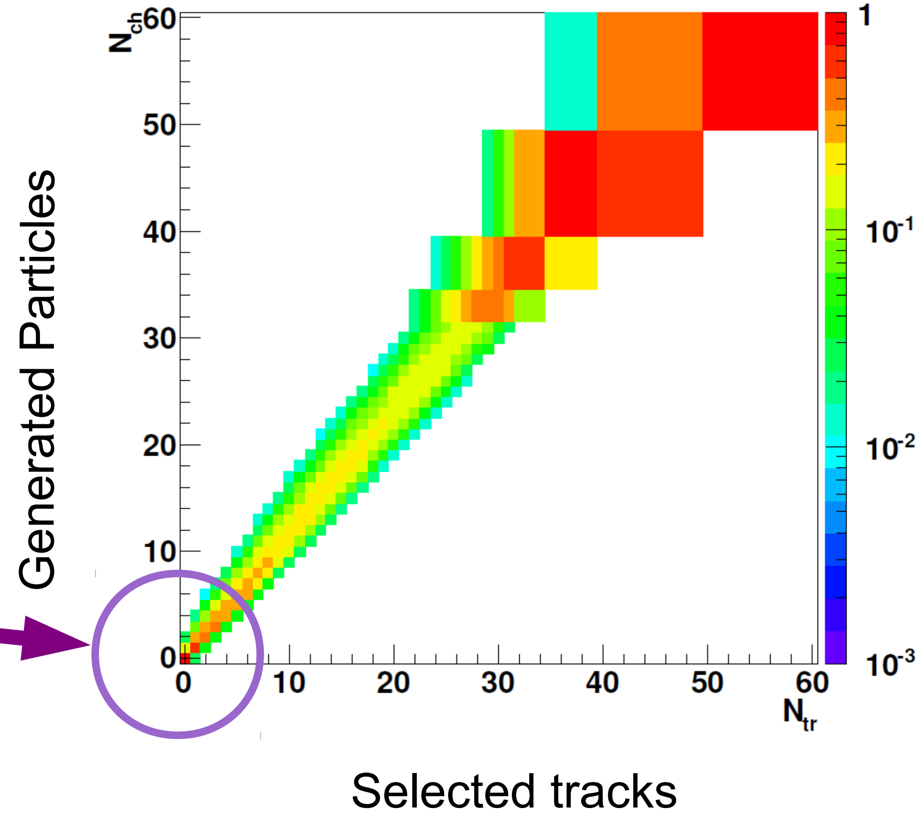
For distributions in n_{ch}

- Have to correct for tracks lost due to track inefficiency
  - Leads to bin migrations and event loss (at low multiplicities)
  - Bayesian unfolding using track migration matrix

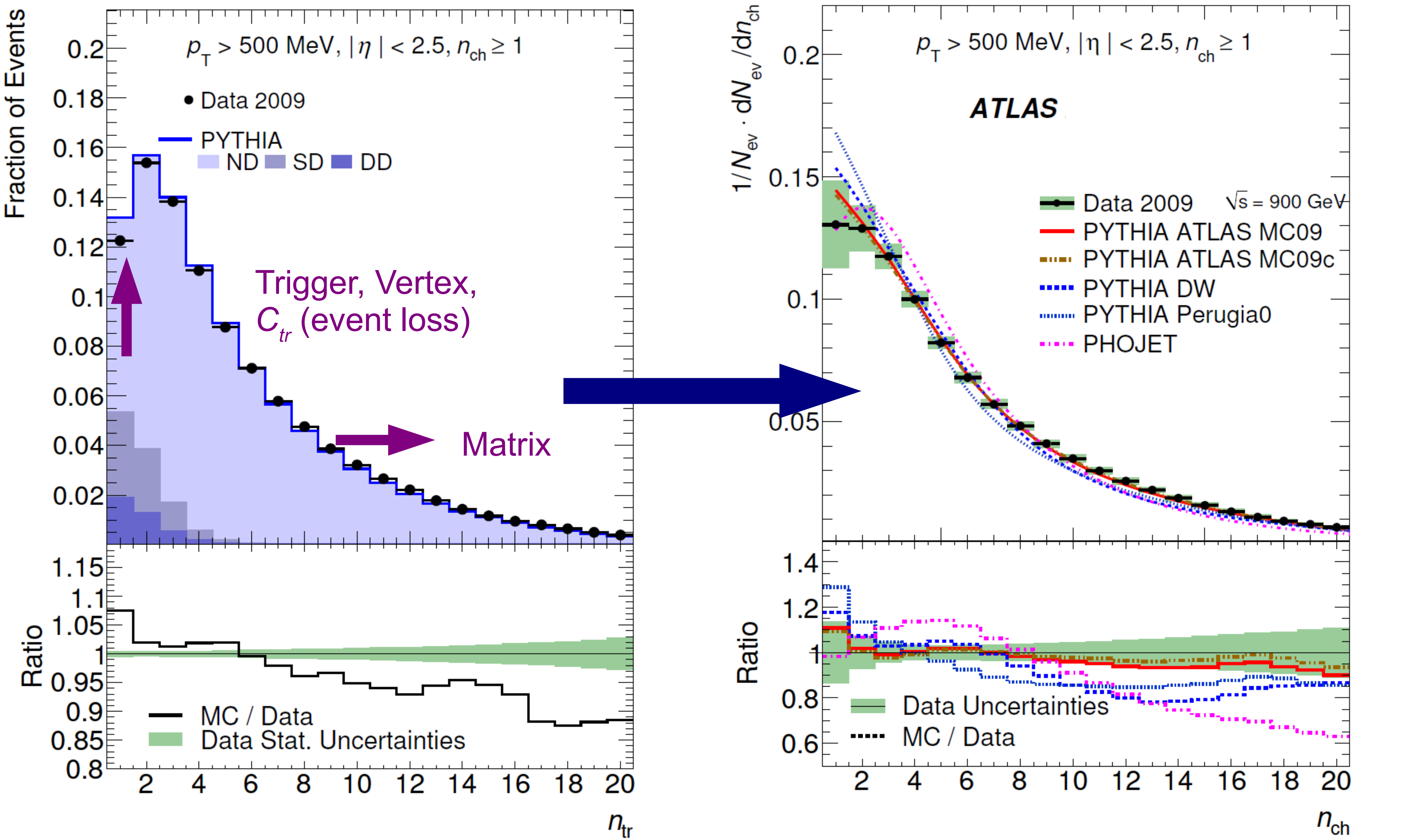
- Distributions in n_{ch} need to be corrected for bin migrations due to track efficiency
- Use a matrix to distribute tracks to their particle multiplicity bins
- “Iterative 1D Bayesian Unfolding” (d'Agostini)

- Unfolding does not change number of particles
- Need additional analytic event loss correction based on average track efficiency of 76%

$$1/(1-(1-\varepsilon_{\rm trk})^{n_{\rm ch}}-n_{\rm ch}\cdot\varepsilon_{\rm trk}\cdot(1-\varepsilon_{\rm trk})^{(n_{\rm ch}-1)})$$

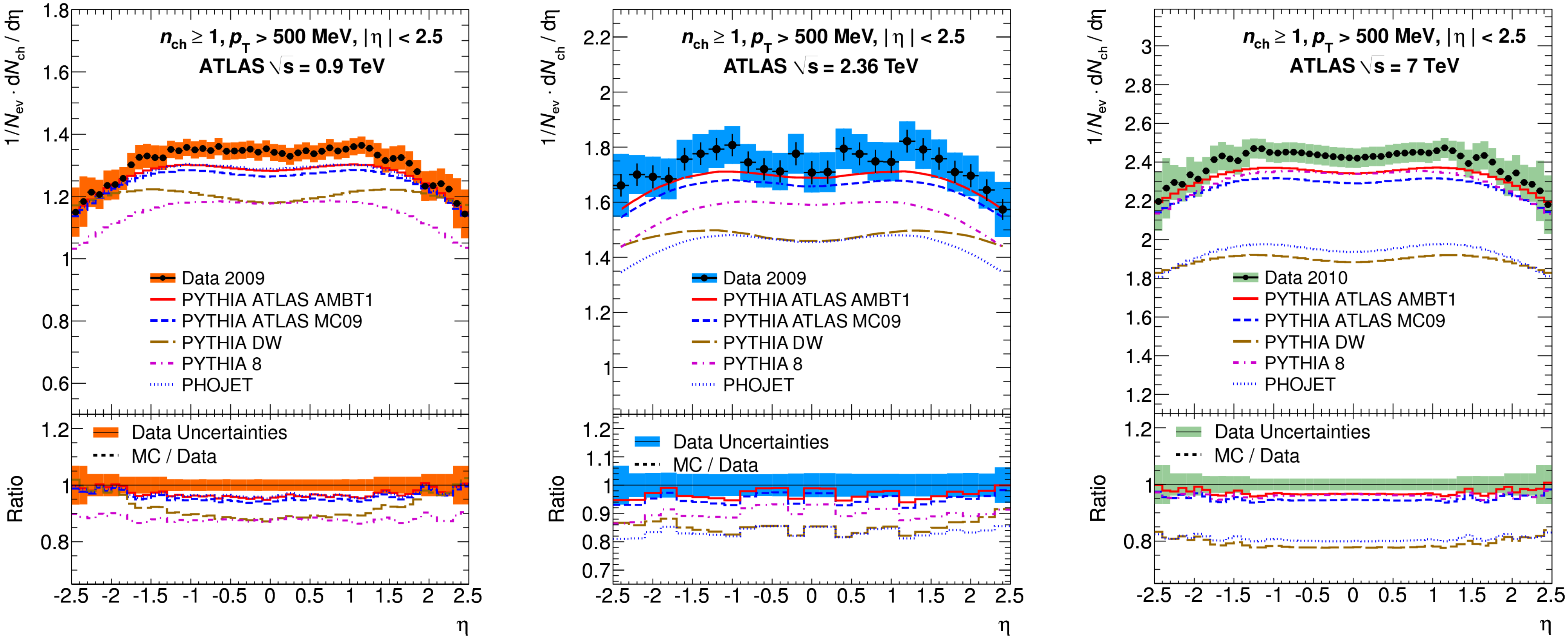


n_{ch} Correction



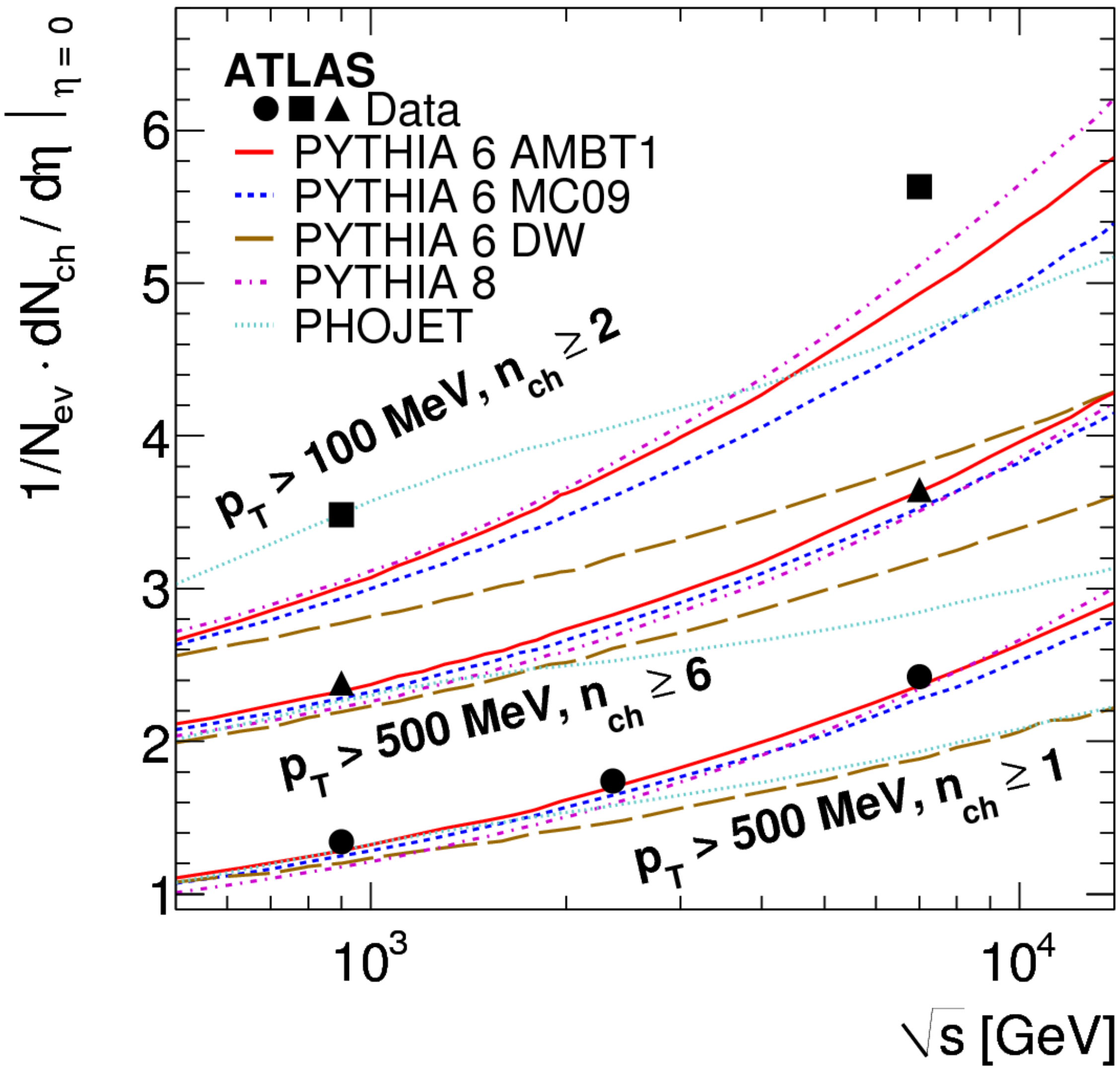
Integral over nch distribution give corrected N_{ev}

dN/dη for Different Energies



Main Result:
All models underestimate central charged particle density
Even with AMBT1 Tune

Results for dN/dη at η=0

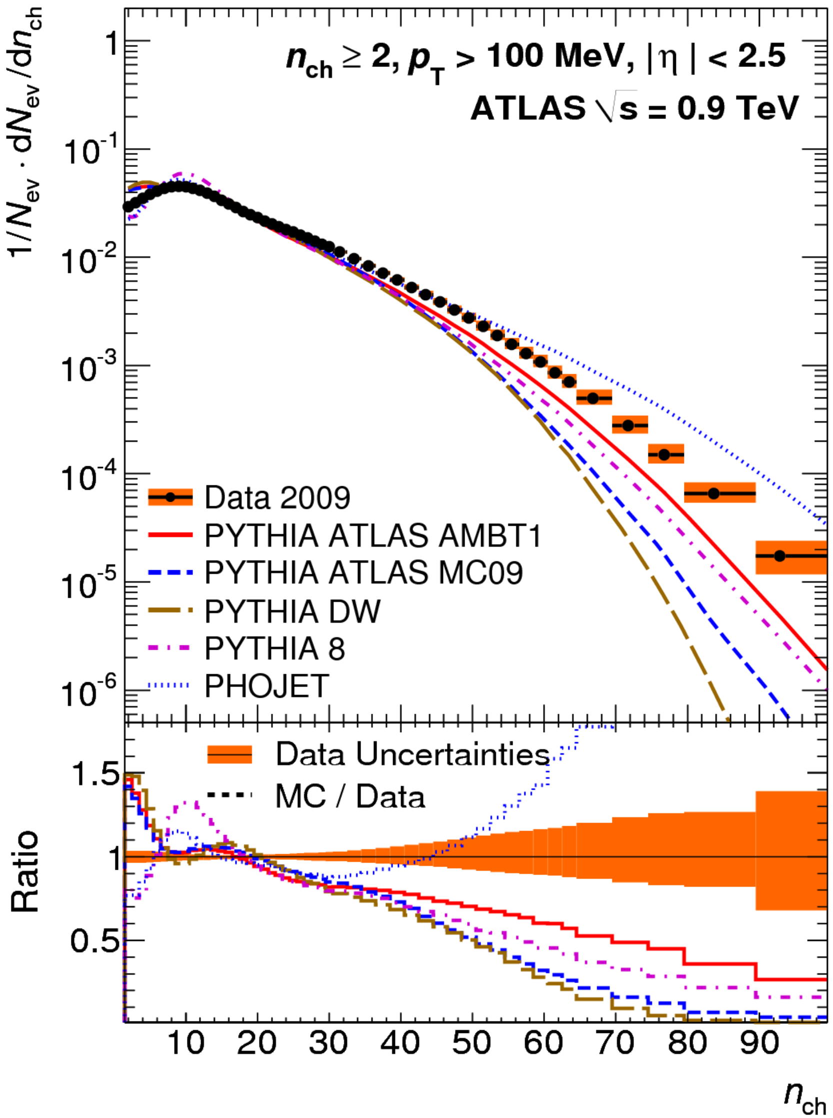


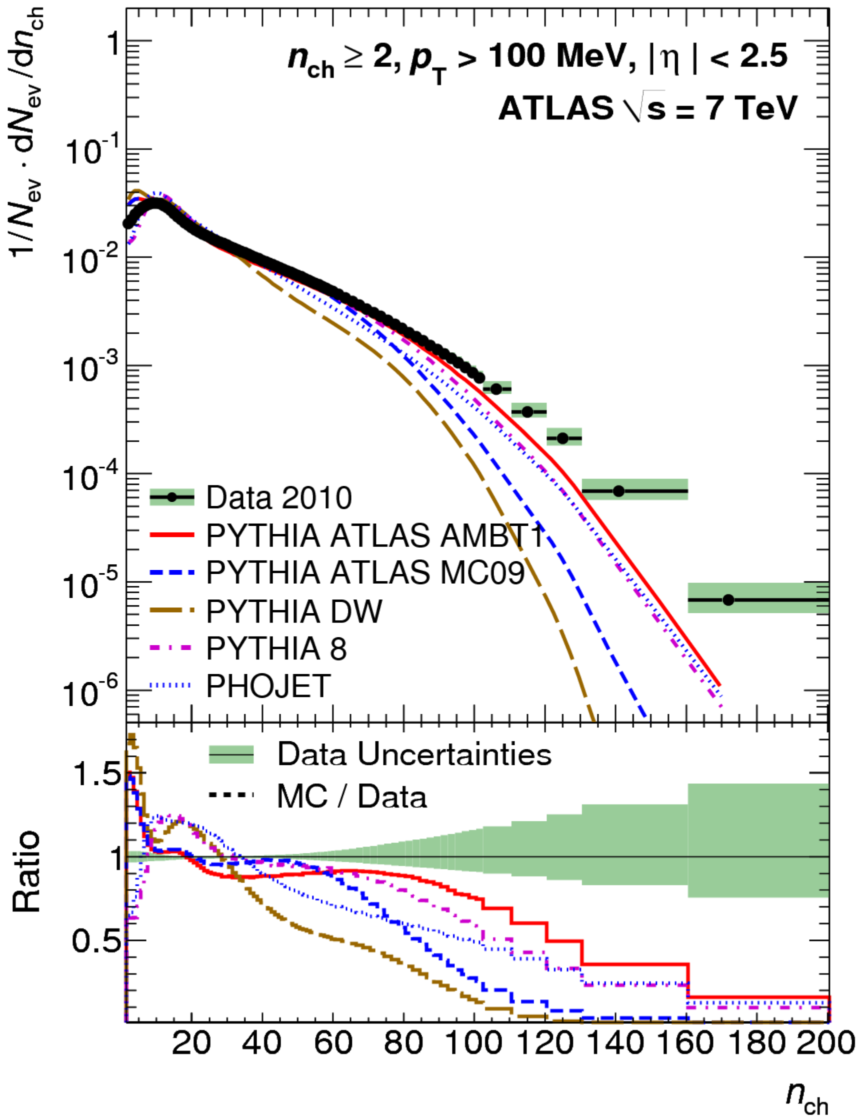
AMBT1 works best

Details later

- p_T > 100 MeV: Models underestimate central charged particle density
- Better for p_T > 500 MeV
- Perfect in diffraction limited phase space

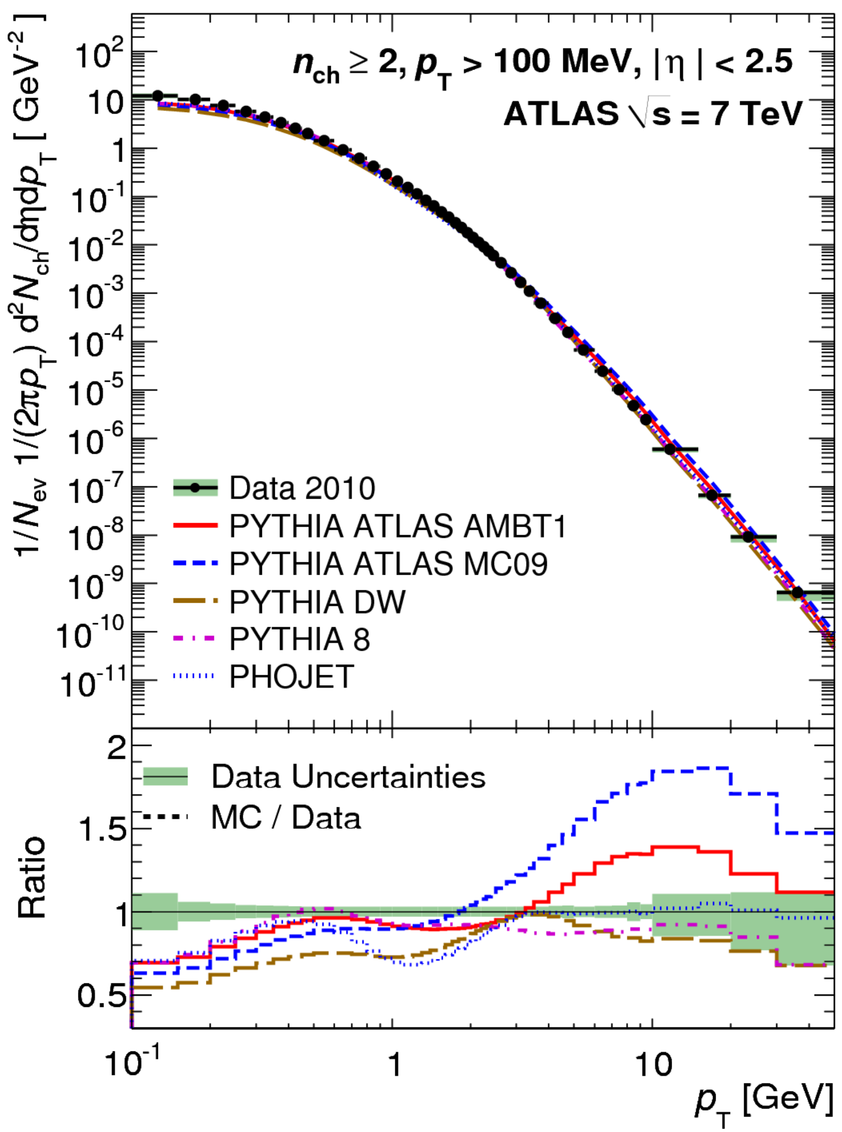
Results for dN/dn_{ch}



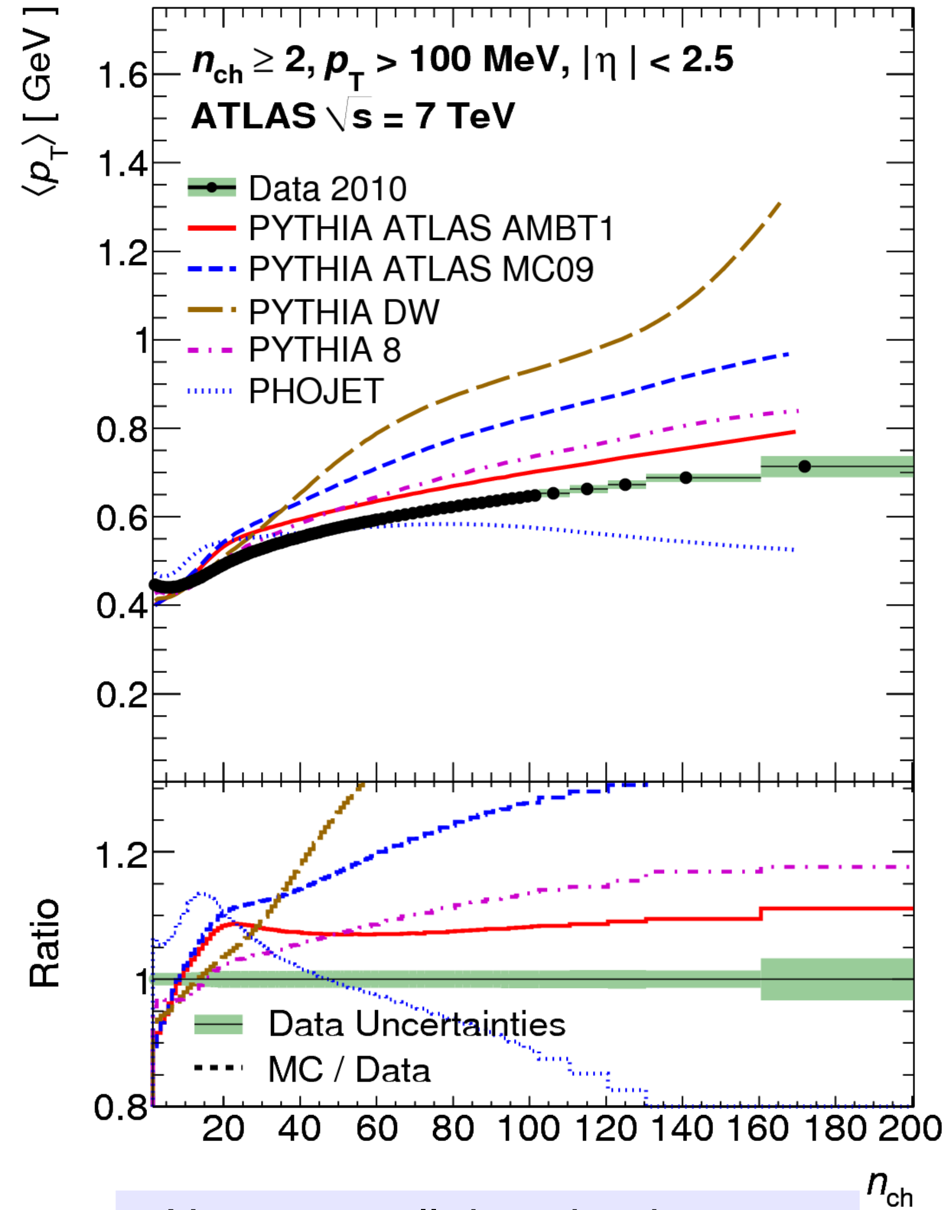


- Too few high multiplicity events in all models at 900 GeV and 7 TeV
- PHOJET behaves very differently at 900 GeV

Results dN/dp_T and <pT>(nch)



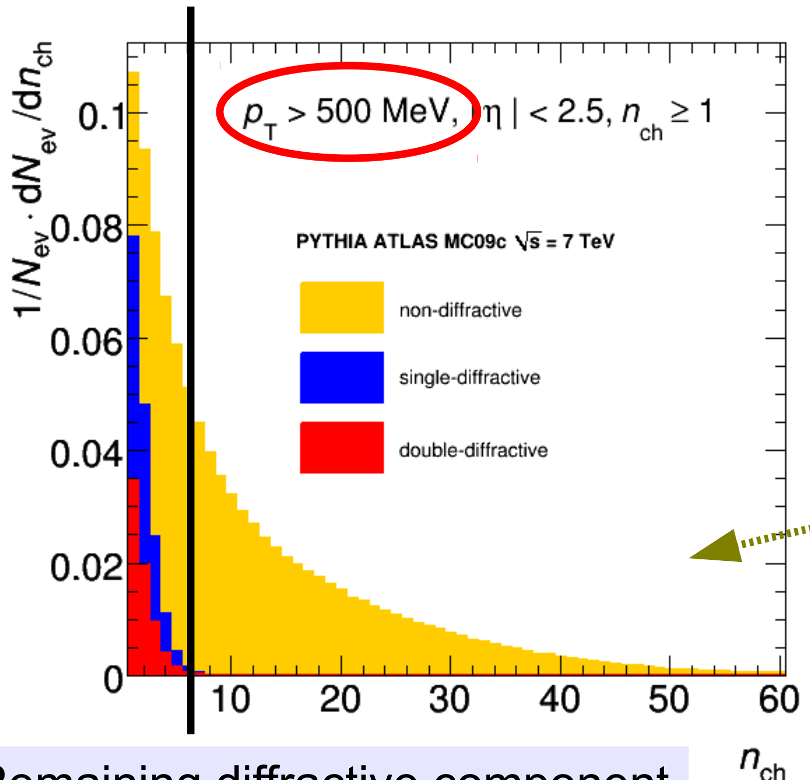
Description worse towards high p_T even with new AMBT1 tune



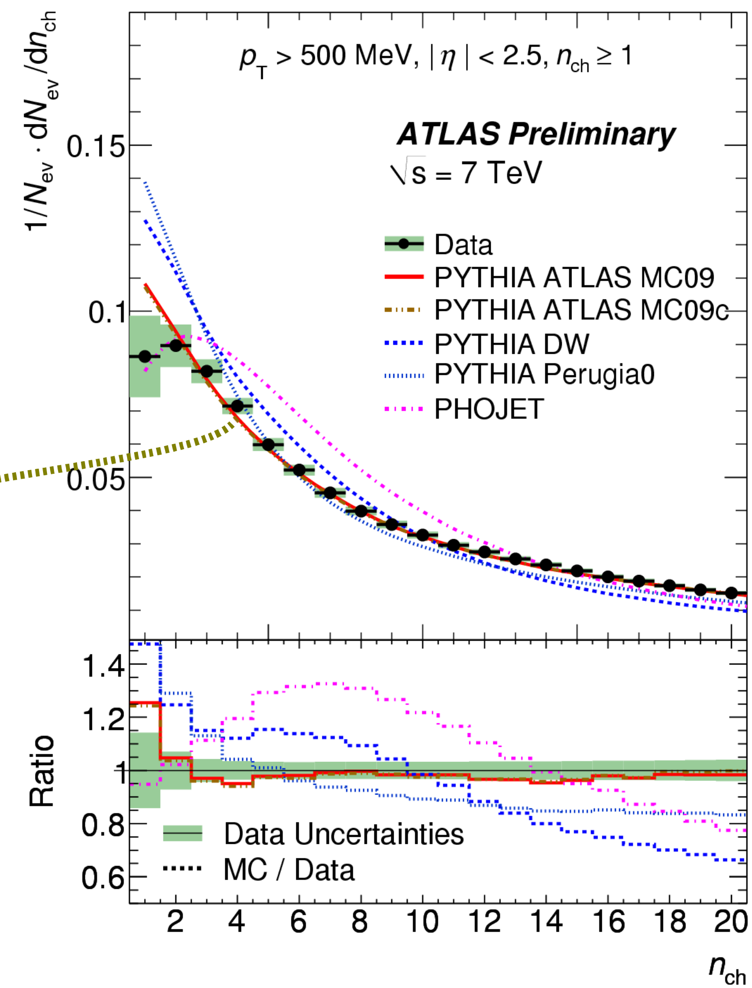
- Not very well descriped
- Sensitive to diffraction at low n_{ch}

AMBT1 Idea

- Data above MC for exisiting models – do our own **ATLAS Minimum Bias Tune 1**
- Diffractive components: cross section and shapes not well known
- Large influence on normalisation of all distributions via N_{ev} (measured as integral of n_{ch} distribution)
- To avoid these model dependencies / uncertainties suppress influence of diffractive events: Go to $\boldsymbol{n_{ch} \geq 6}$



MC09c

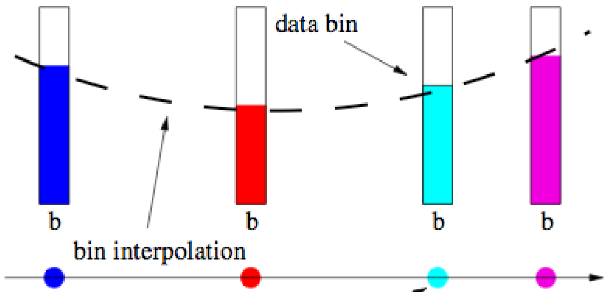


- Remaining diffractive component
  - 0.4% in PYTHIA6
  - 10% in PYTHIA8

AMBT 1 Strategy

- Start from previously best ATLAS tune: MC09c
- ATLAS Tune Pedigree: MC09 → MC09c → AMBT1 (***ATL-PHYS-PUB-2010-002***)
- Systematic tuning using PROFESSOR tool (***Eur.Phys.J.C65:331-357,2010***)
- Input Data:
  - ATLAS MB distributions at $\sqrt{s}$ = 0.9 TeV and 7 TeV
  - TeVatron data – remove some parts not compatible with ATLAS data

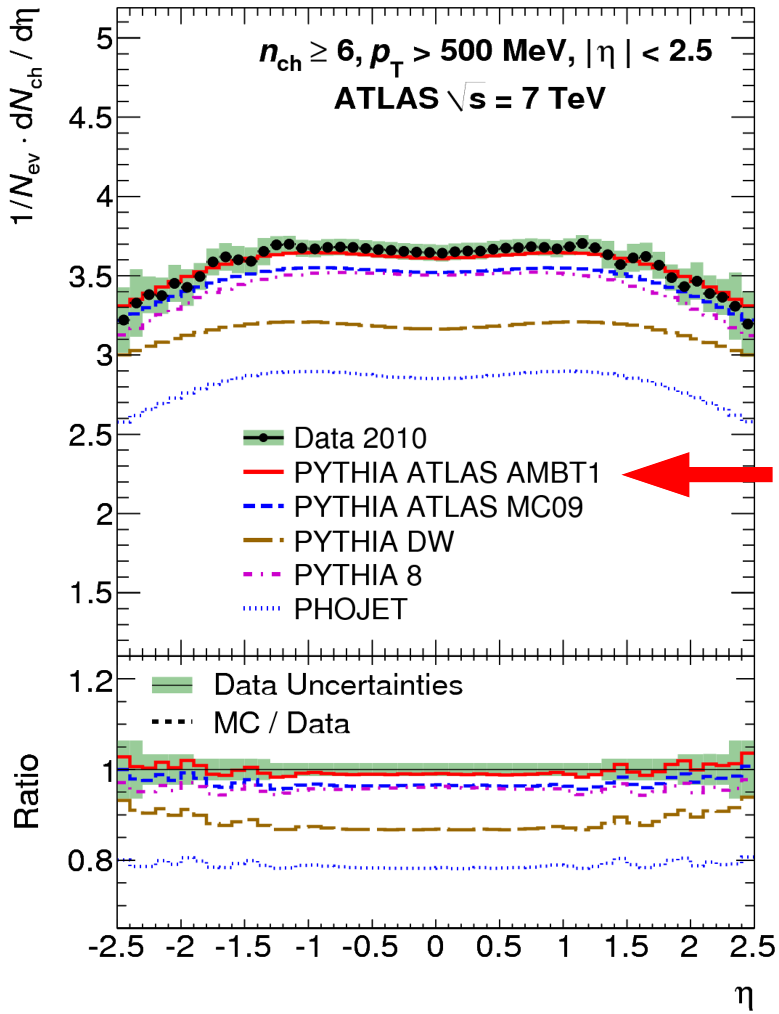
1. Build fast analytic model of the generator:
   - Random sampling: N parameter points in n-dimensional space
   - Run generator and fill histograms (Rivet)
   - For (each) bin: use $\tilde{N}$ points to fit interpolation (2^{nd} or 3^{rd} order polynomial)
2. Construct overall (now trivial) $\chi^2 = \sum_{bins} \frac{(interpolation - data)^2}{error^2}$
3. Numerically minimize using `pyMinuit`, `SciPy`



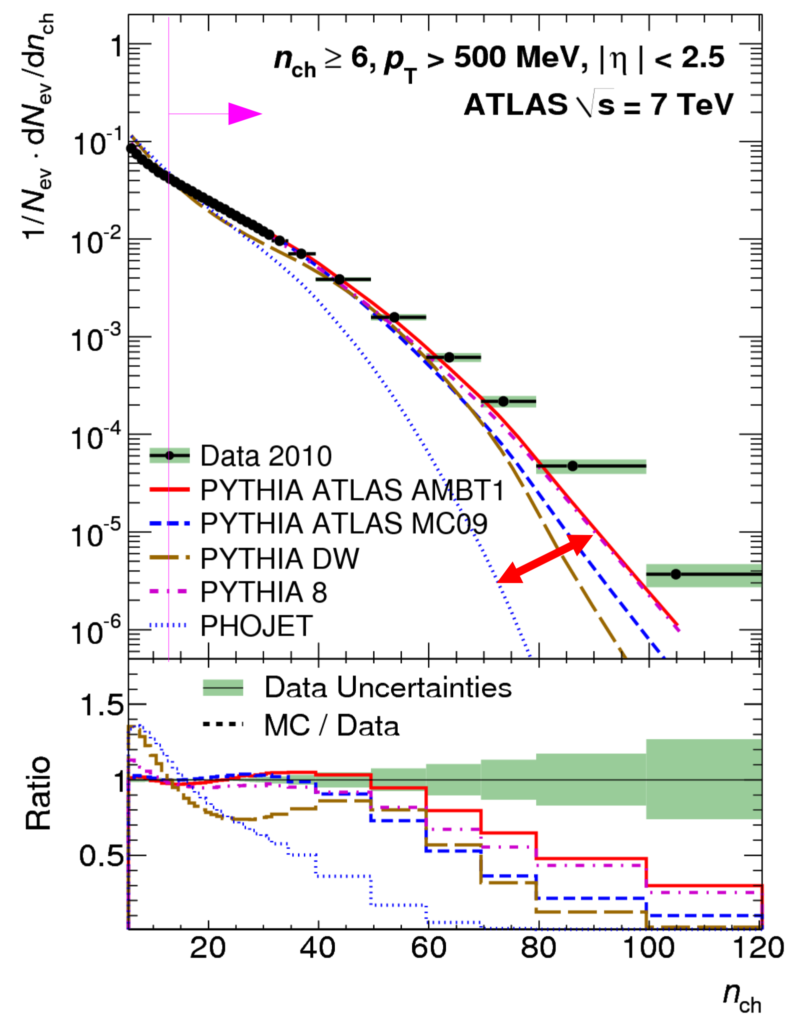
- Biggest parameter changes
- PARP(84): MPI
  - Reduce width of proton matter distribution
  - Increases activity / head-on collisions
  - → Increase multiplicities in $\langle n_{ch} \rangle$ and at high n_{ch}
- PARP(77): Color-reconnection
  - Suppression for high p hadrons
  - Softens p_T and $\langle p_T \rangle (n_{ch})$ distributions

dN/dη and dN/dn_{ch} in diff. suppressed sample

from MPI parameter adjustment



Tuning Region



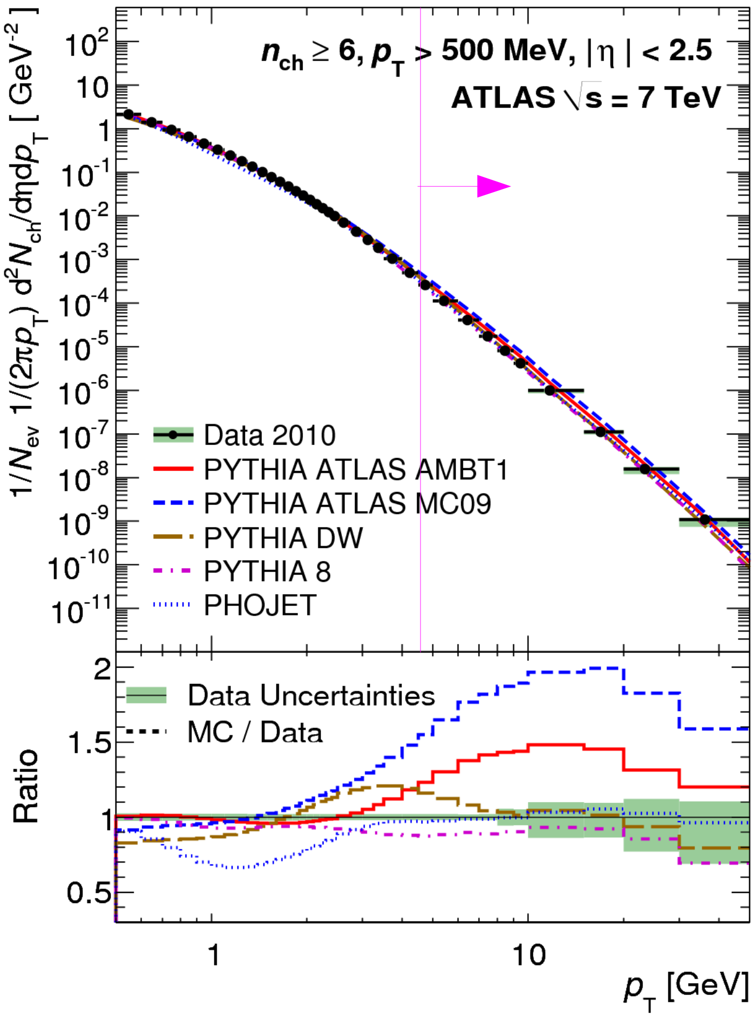
Data very well described now
- Already for previous tunes
- Perfect agreement for AMBT1

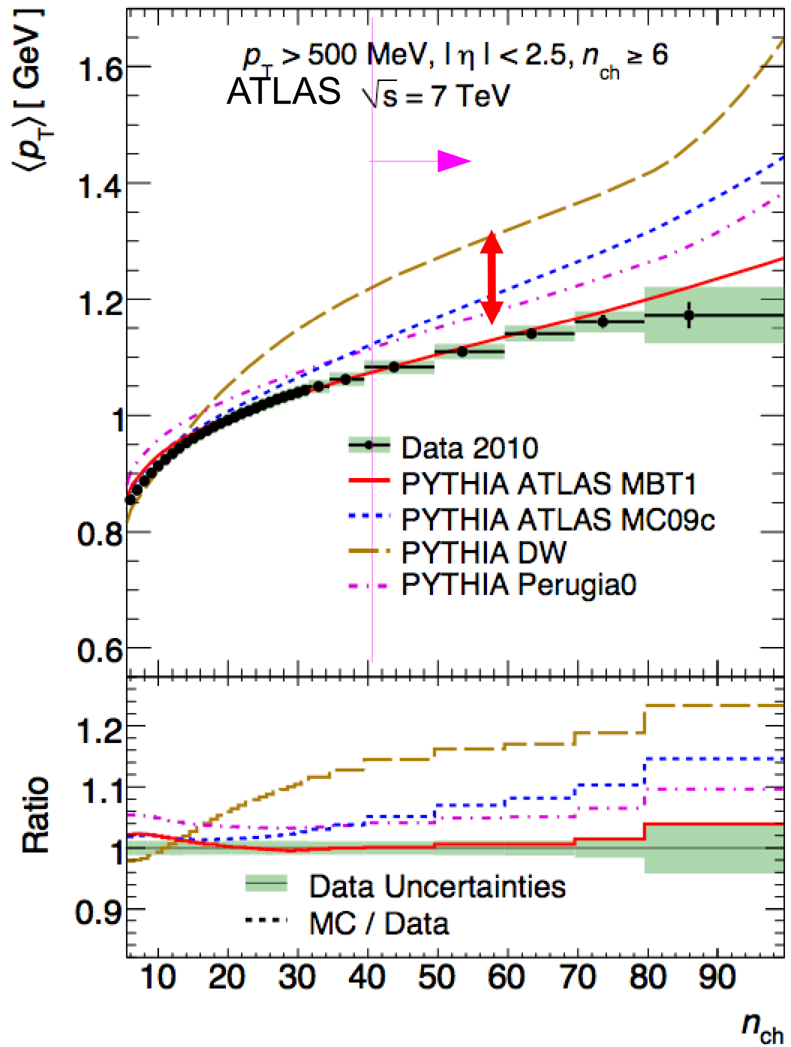
Increase in high n_{ch} tails

dN/dp$_T$ and <p_T>(n_{ch}) in diff. suppr. sample

Effect of tuning color reconnection strength and suppression of fast moving string pieces

Tuning Region



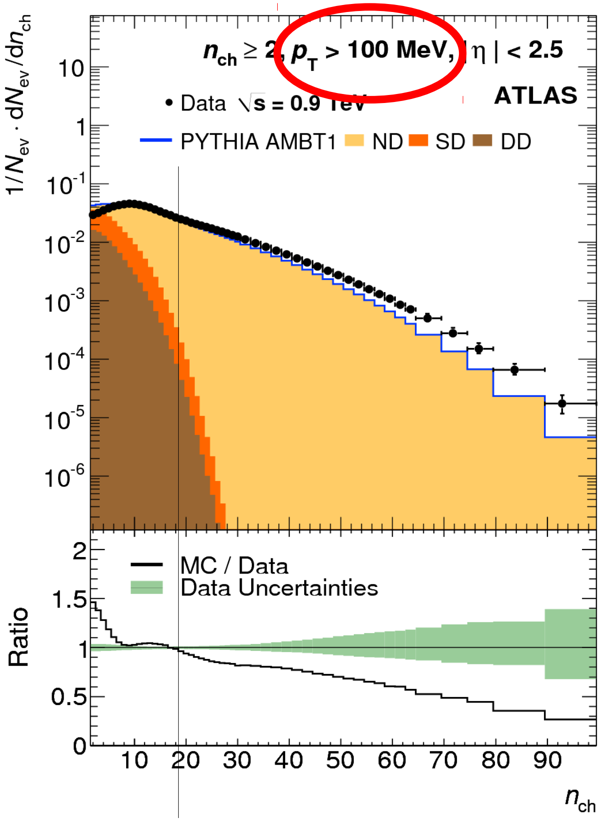


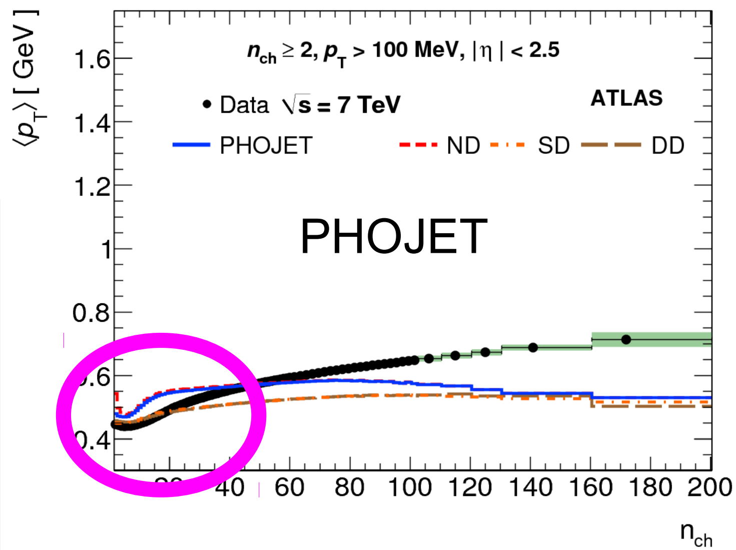
Decrease in high p_T tails and of <pT>

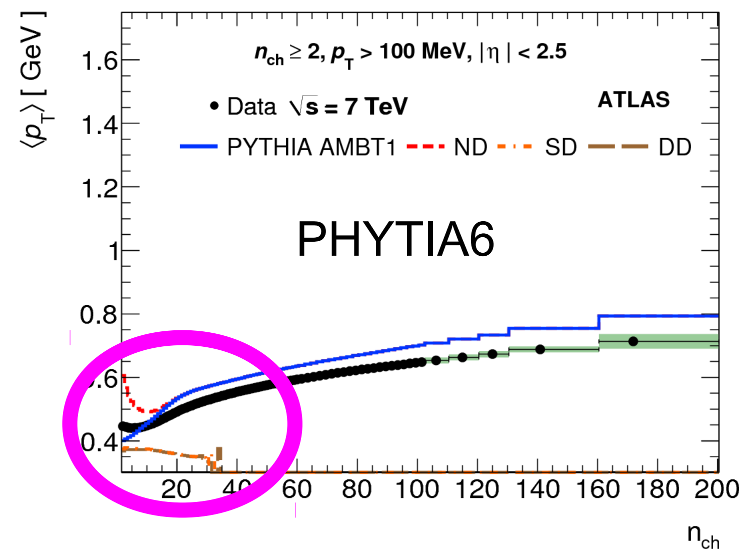
More on Diffraction Description

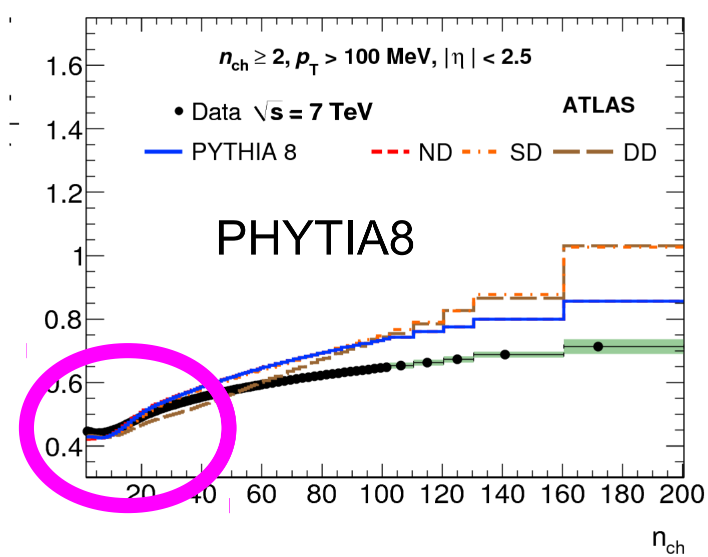
At p_T > 100 MeV events with up to 20 particles mostly diffractive in PYTHIA6

AMBT 1 was done with p_T>500 GeV analysis
Here show some relevant plots for p_T > 100



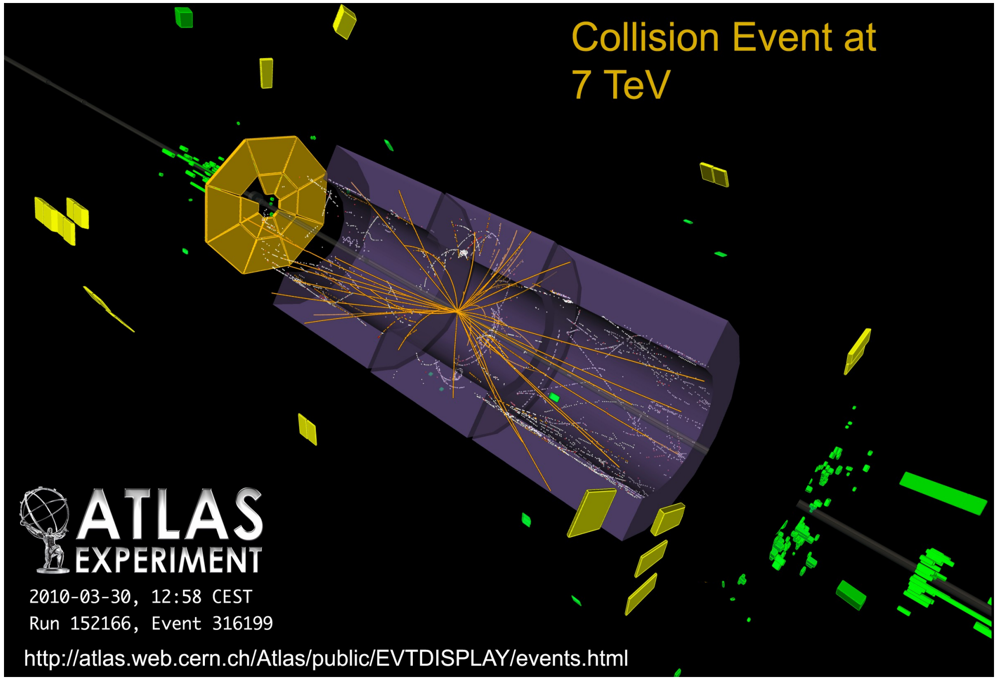






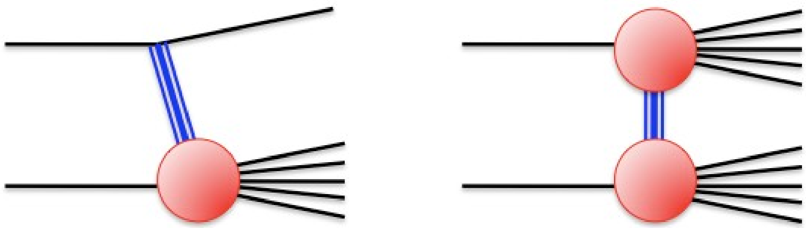
- Diffraction models differ vastly in PYTHIA 6, PHYTIA 8, PHOJET
- Need to measure it

Diffraction Enhanced MB Analysis



- Enhance diffractive events by selecting a "rapidity gap"
- veto activity on one MBTS side

{2.09<η < 3.84 OR -2.09 > η > -3.84 }



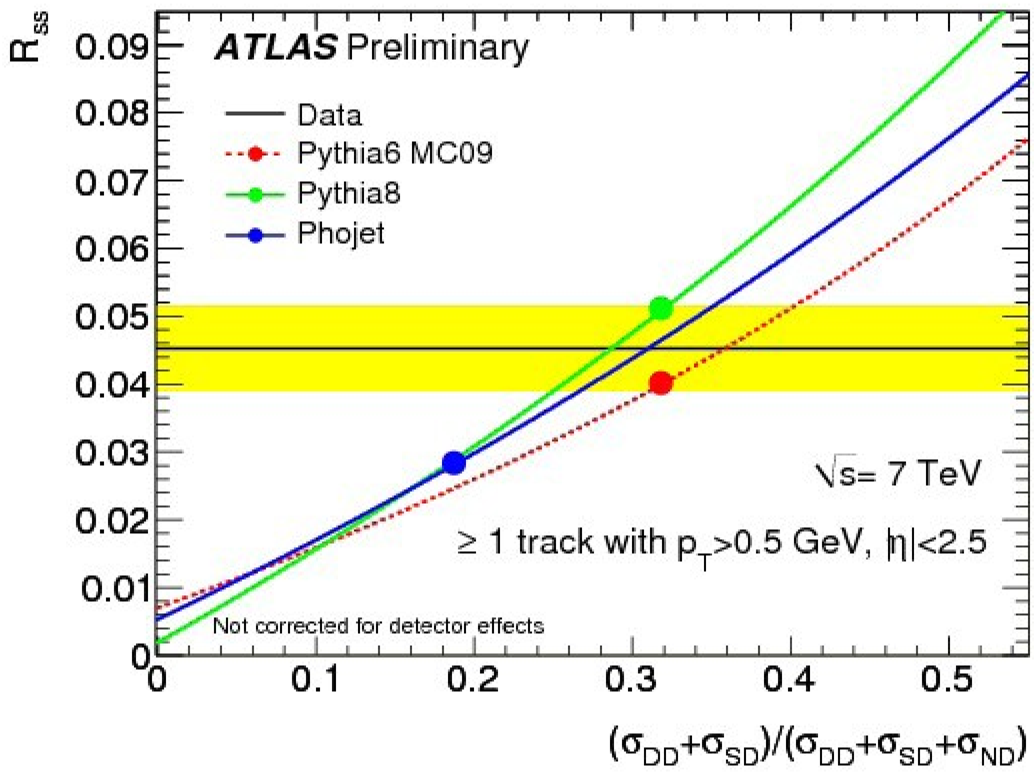
- Select inelastic events similar to minimum bias analysis
- No corrections applied for now – distributions compared after full simulation

- Measure ratio of single-sided to any events and compare data / MC

$$R_{ss} = \frac{N_{ss}}{N_{any}} = \frac{A^{D}_{ss} + A^{ND}_{ss}}{A^{D}_{any} + A^{ND}_{any}}$$

A: MBTS Acceptances for single-sided (ss) or any events

Diffraction Enhanced MB Analysis

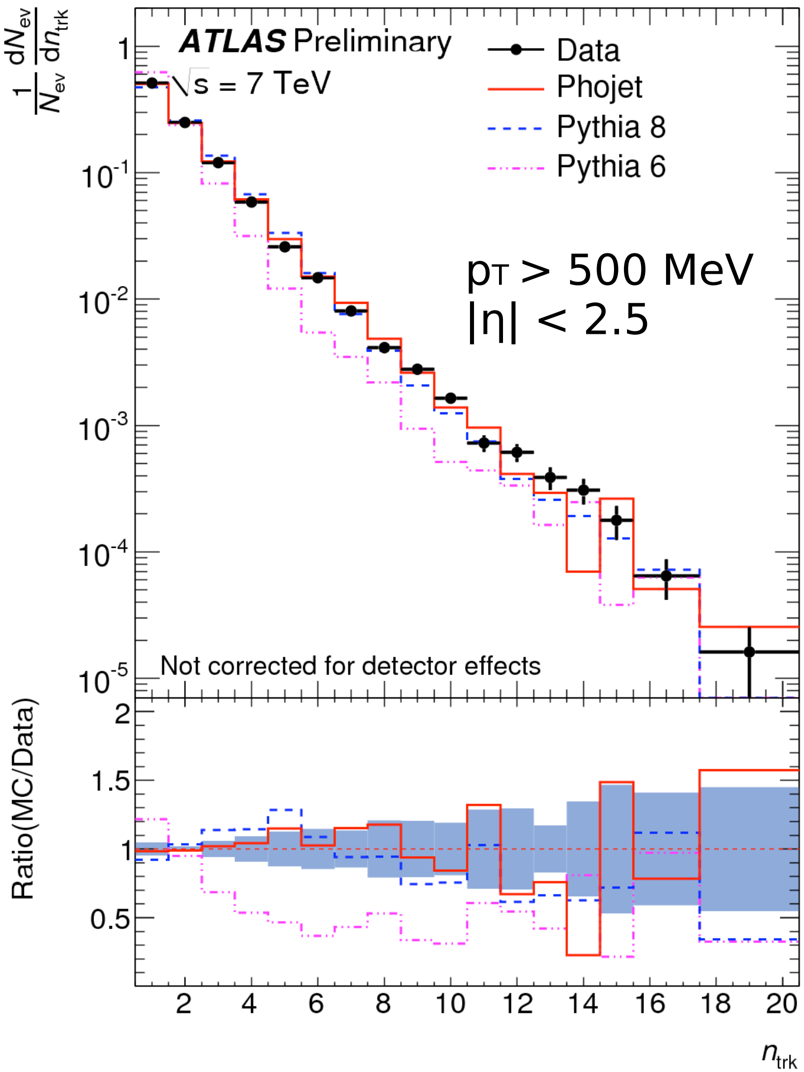


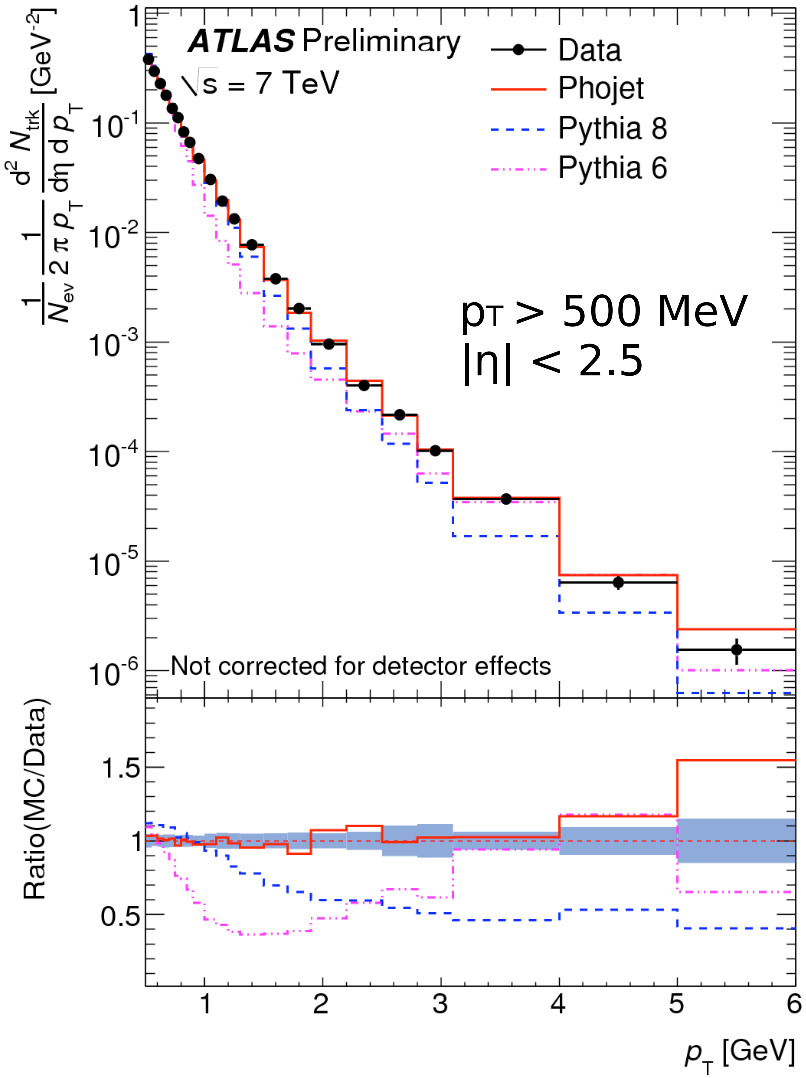
MC Curves

- Keep ratio SD/DD fixed
- Float total diffractive fraction

- PHOJET needs to increase diffractive component from 20 % to 30 %
- Pythia6 and Pythia8 are in good agreement with data

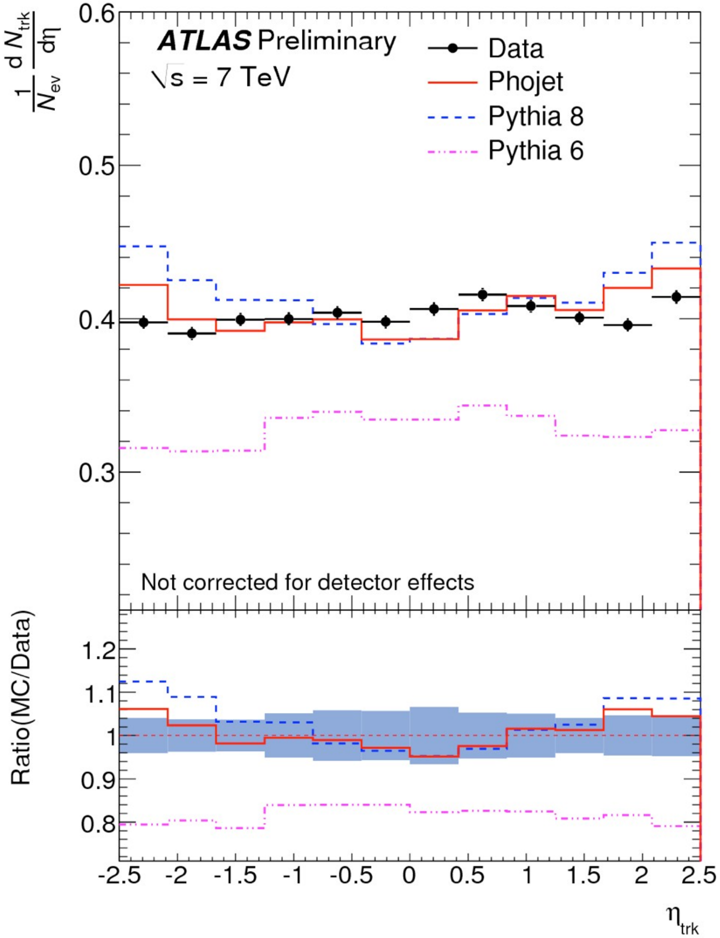
Diffraction Enhanced MB Analysis



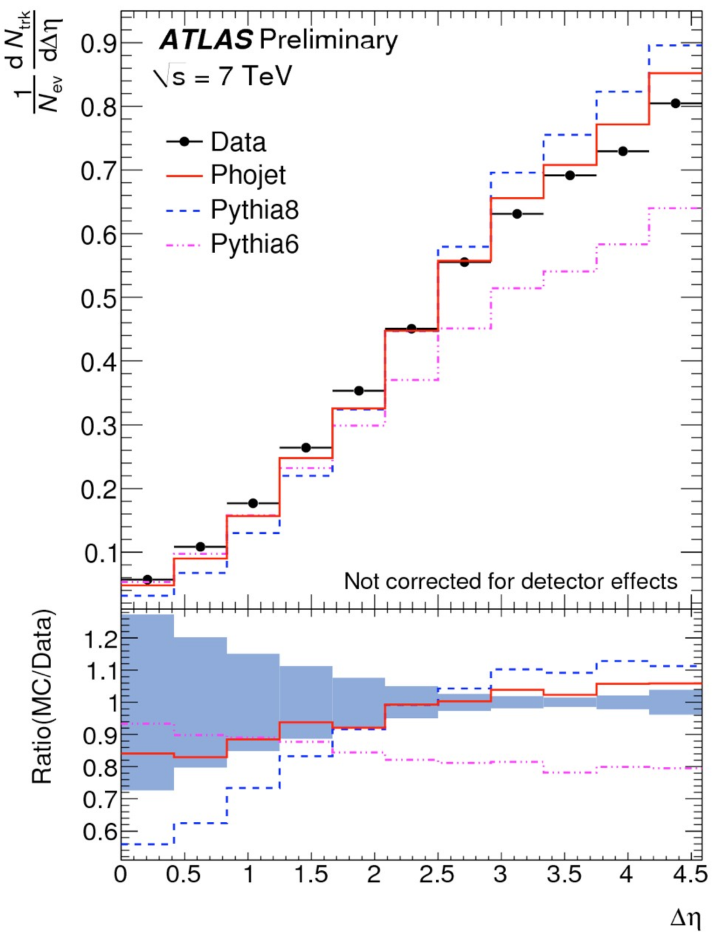


- PHOJET: Excellent agreement
- PYTHIA8 also good – includes hard diffraction
- PYTHIA6 fails

Diffraction Enhanced MB Analysis



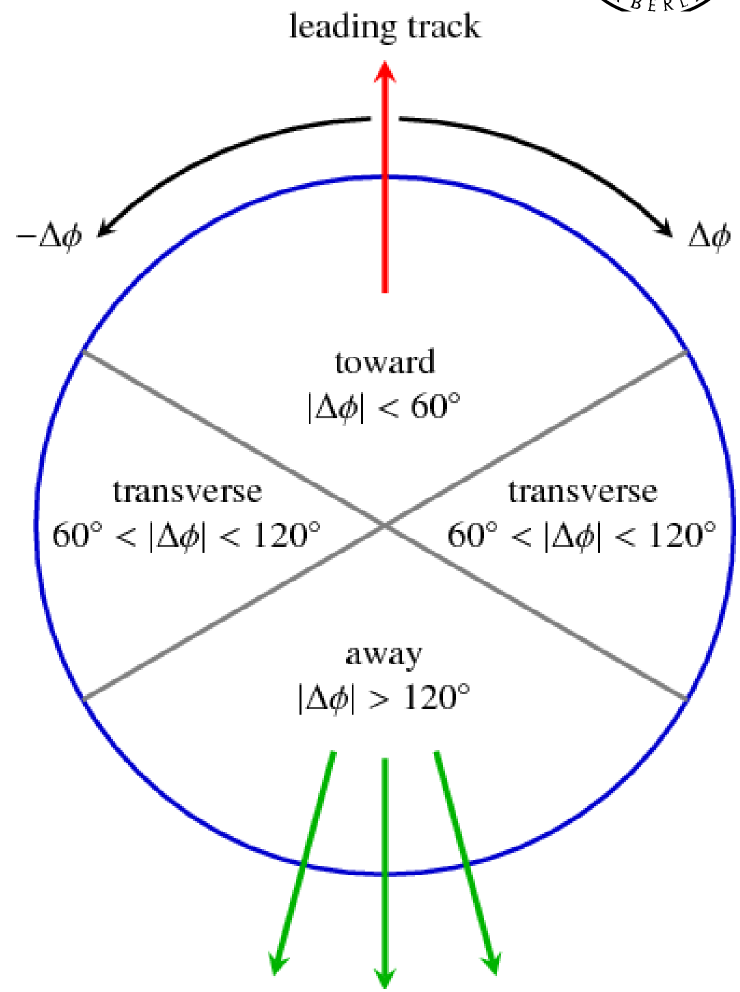
Rapidity gap



- PHOJET describes the p_T dependence of the diffractive enhanced sample very well except at the largest p_T
- PYTHIA6 models are much softer than the data
- PHOJET also provides the best overall description of the rapidity gap in the event

Underlying Event Distributions

- Select events with ≥1 charged particles, p_T > 1 GeV
- Direction of hard scatter strongly correlated to leading charged particle (toward region)
- recoil in opposite direction (away region)
- Look in **transverse region** for underlying event
  - Study charged particle and p_T density as a function of the lead p_T in different regions.



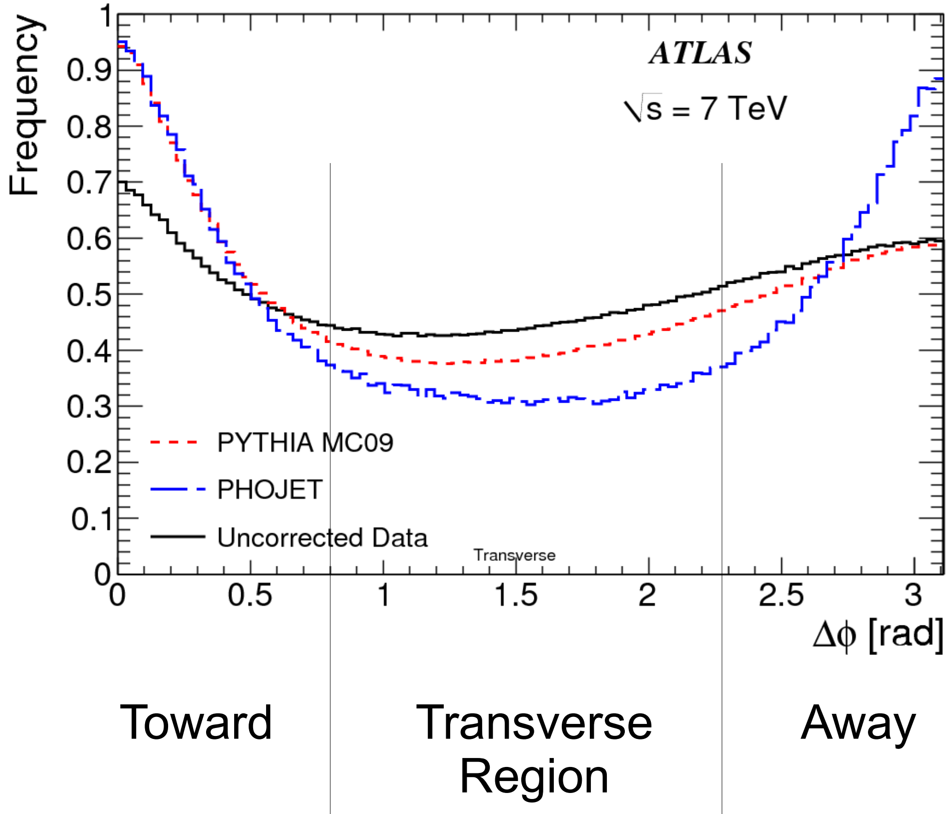
Underlying Event Corrections

- Track-to-particle corrections similar to minimum bias
  - Two extra corrections needed due to defintion of a leading track
  - If leading track not measured due to track inefficiency its replaced by second leading track

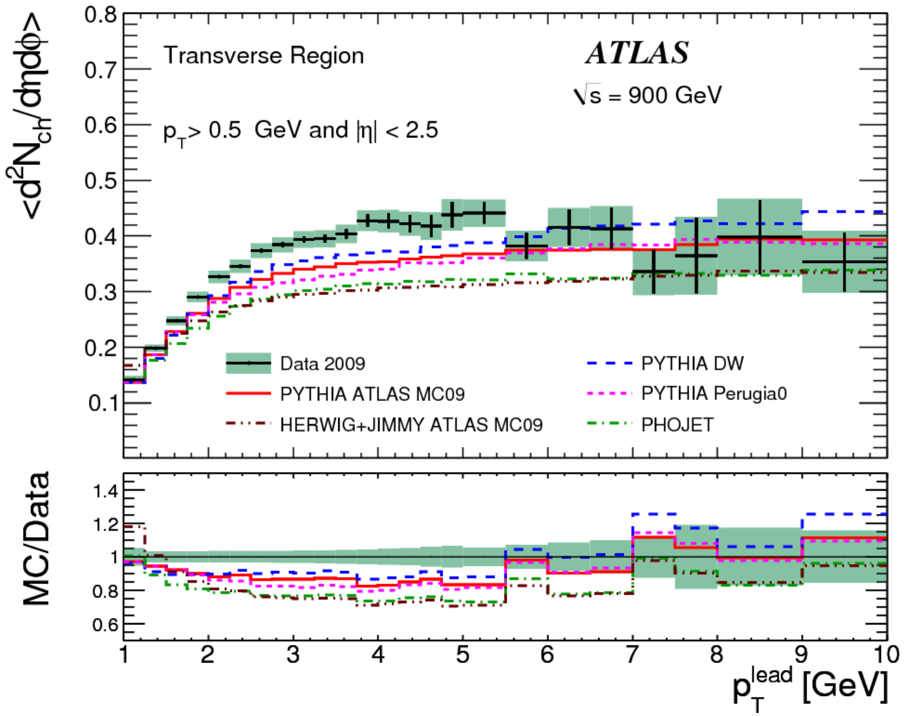
- p_T-migration towards lower bins
  - p_T density too high at low p_T (rise)
- Reorientation of event
  - Contribution from hard scatter to underlying event

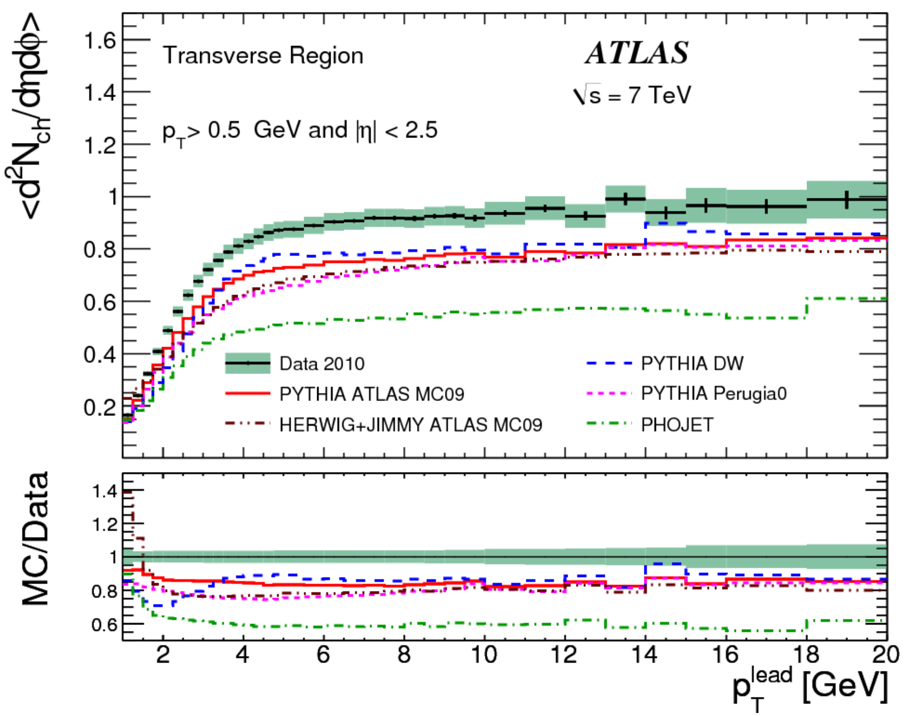
- Correct using bin-by-bin corrections from Monte Carlo
- Systematic error: Difference between PYTHIA and PHOJET (dominated by MC stats)

Azimuthal difference between leading and subleading track



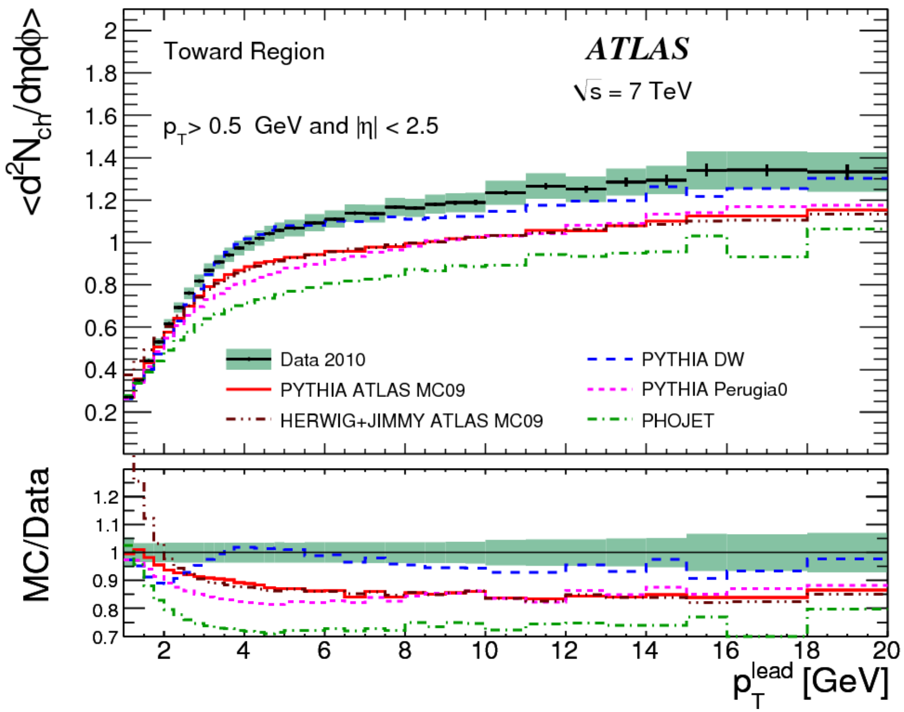
Number Density in Transverse Region

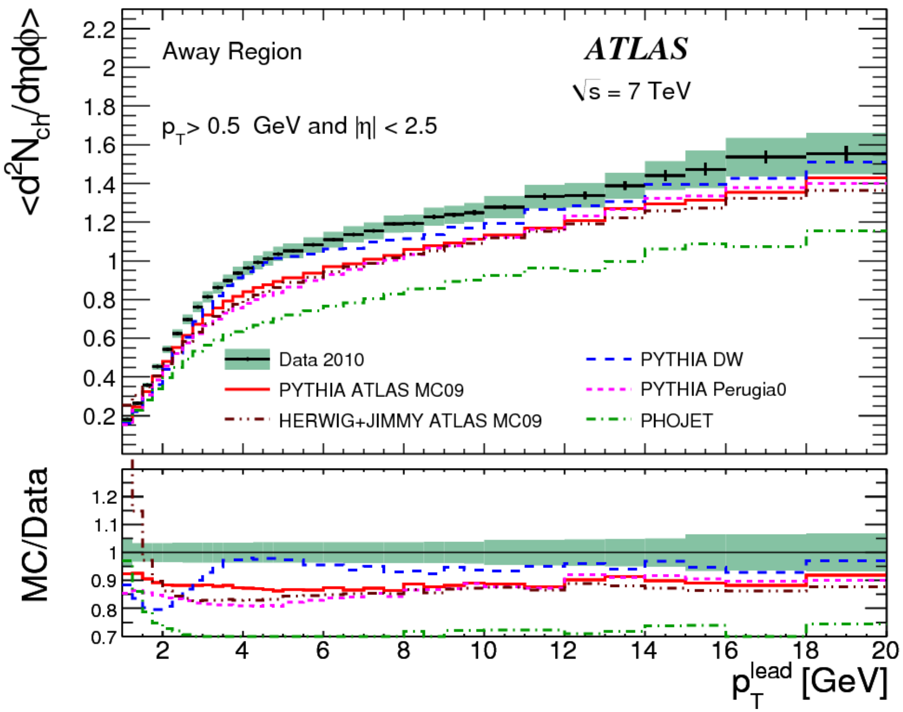




- The number density is higher than predicted by any of the MC tunes.
  - Clearest in events with lower lead p_T.
  - More significant at 7 TeV.
- Underlying event activity saturates after p_T^{lead} > 5 GeV – “plateau region”

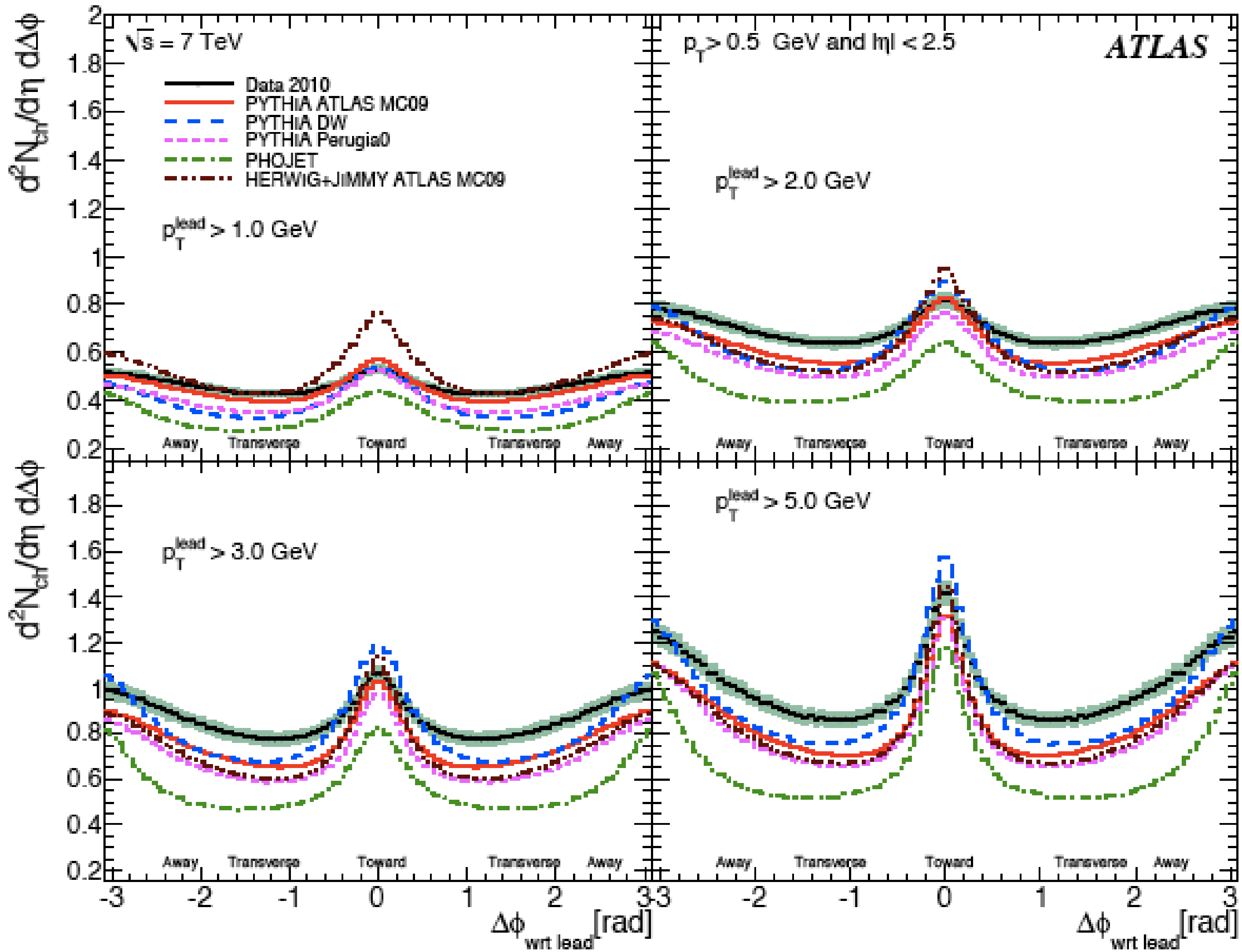
Number Density in toward and away region





- Activity also underestimated by predictions
- Rise of multiplicity with pTlead hints a jet activity
- No plateau region like in transverse region

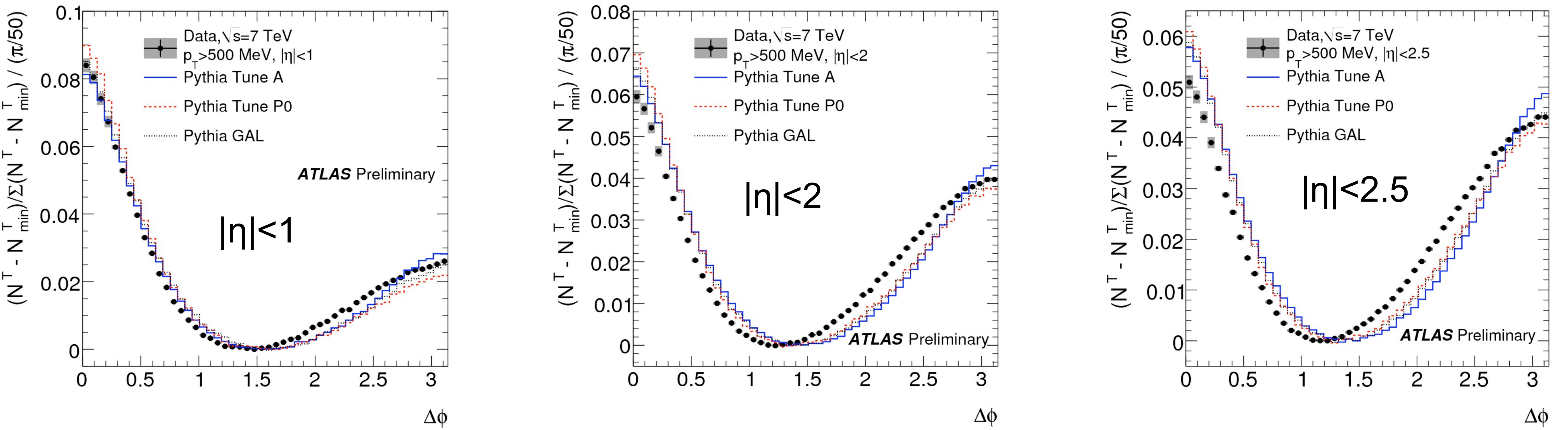
Number Density Angular Correlations



- Number density Δϕ distribution around leading track (removed from plot)
- Models do not reproduce the particle correlations, especially at low minimum p_T^{lead} where the shape is also not described

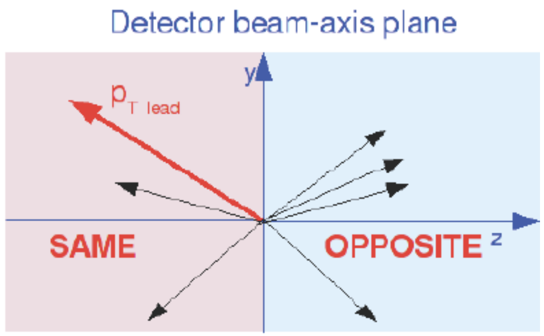
Angular Correlation Measurements

- Dedicated analysis looking at global correlations between tracks



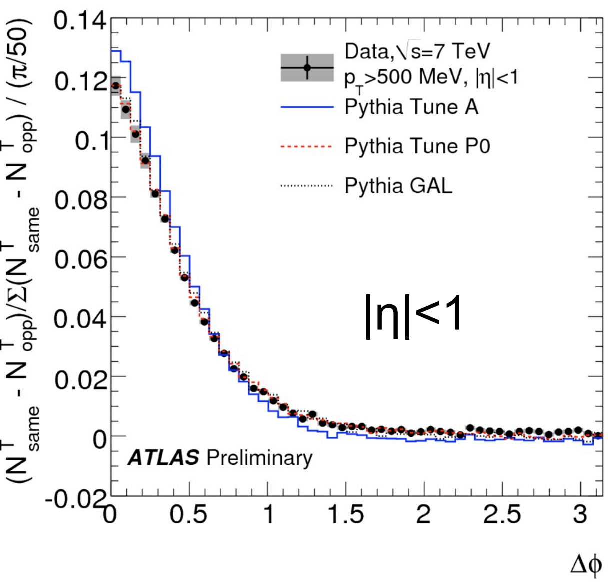
- Look for correlations in Δϕ in different *η* regions in particle production above this background of activity - "crest shape"
- Subtract the average background activity
- Expected toward and away structure clearly observed
- At central rapidities, the models describe the data reasonably well
  (Tuned to Tevatron – which had this acceptance)
- At larger rapidities the models fail to describe the data

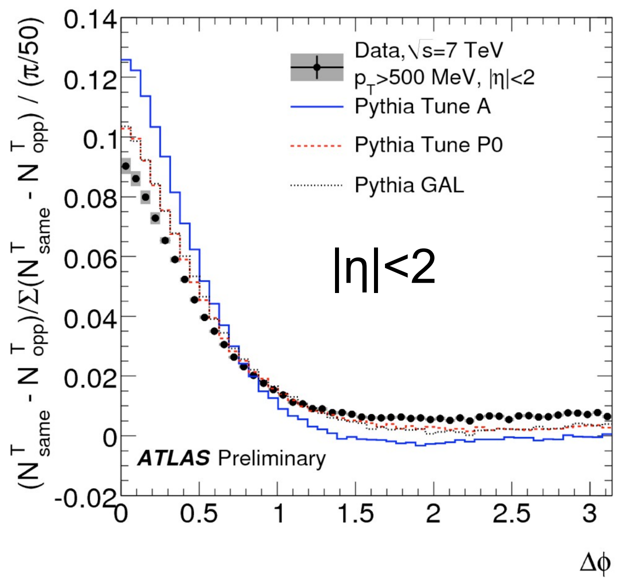
Angular Correlation Measurements

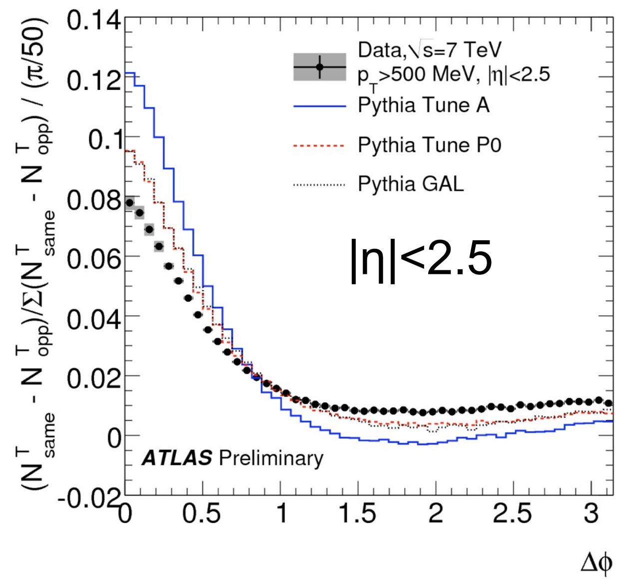


subtract opposite hemispheres in ±z

Look at correlations in Δϕ in different η regions





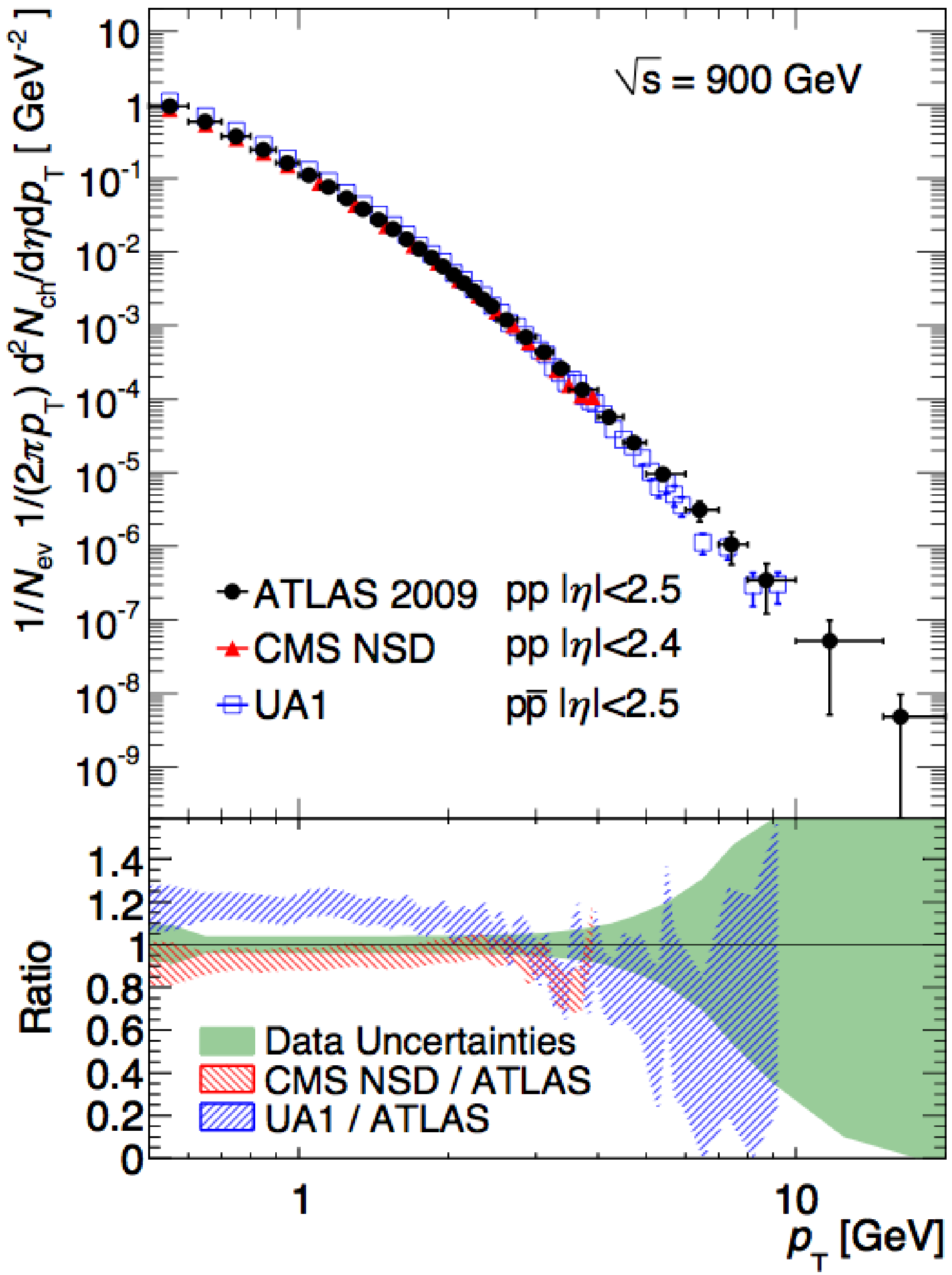


- At central rapidities, the models describe the data reasonably well
- At larger rapidities the models fail to describe the data

p_T: Comparison to UA1 and CMS

An "old" result from first 900 GeV paper

- dN/dpT: What is the phasespace factor good for?
- Can use invariant yield to compare different experiments



- 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.

Modern ATLAS strategy prevent such Problems in comparsion → let's try again

Central Charged Particles

- Measurements in a phase-space accessible to several LHC experiments allow for direct comparison of general properties of charged-particles in minimum bias events

- LHC-wide MB&UE group started in the context of the LPCC (M. Mangano)

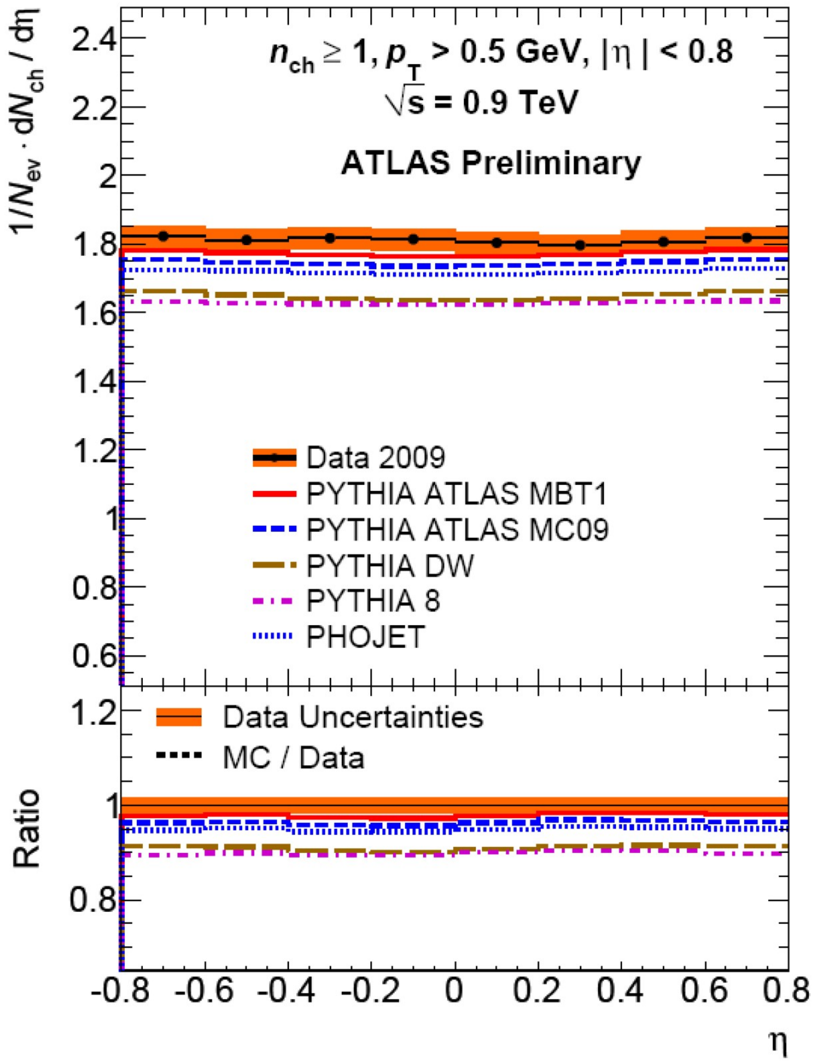
- ALICE, ATLAS and CMS agreed on MB (and UE) on 2 phase-spaces at $\sqrt{s}$ = 0.9 and7 TeV:

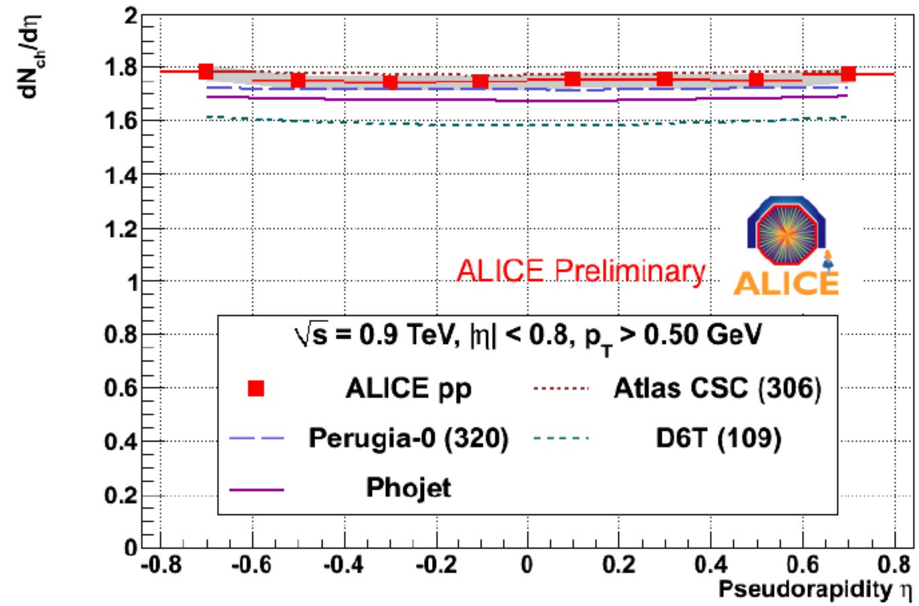
  - nch>= 1, $|\eta| < 0.8$, pT> 0.5 GeV
  - nch>= 1, $|\eta| < 0.8$, pT> 1 GeV

- In particular it was agreed to use the ATLAS strategy of NOT correcting to NSD distributions or similar (be as model independent as possible)

Central Charged Particles

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





1/Nev dNch/dη at η = 0

ATLAS	ALICE		
		stat	syst
1.809 +- 0.006 (stat) +- 0.030 (syst)	1.76	± 0.01	+ 0.02 - 0.03
1.809 +- 0.031	1.76 + 0.02 - 0.03		

Diff = 0.05 + 0.06 – 0.05

Track Lumi Measurement

- Use measured and fully corrected event yield N_{ev} and MC cross section predictions to calculate luminosity

$$\int \mathscr{L} dt = \frac{N_{ev}}{\sigma_{vis}} = \frac{N_{ev}}{\varepsilon_{ND}\sigma_{ND} + \varepsilon_{SD}\sigma_{SD} + \varepsilon_{DD}\sigma_{DD}}$$

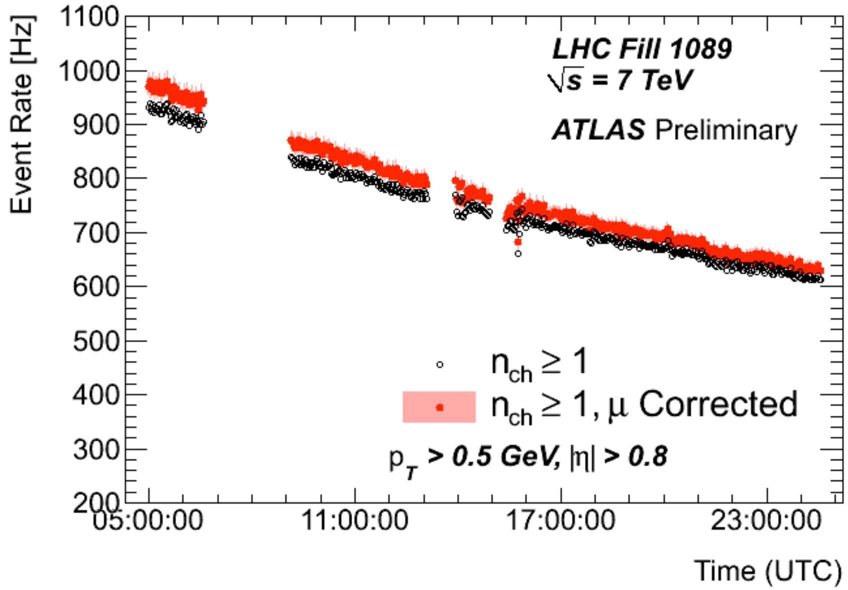
- Compare to other methods (LAr timing) and especially other experiments (ALICE, CMS)

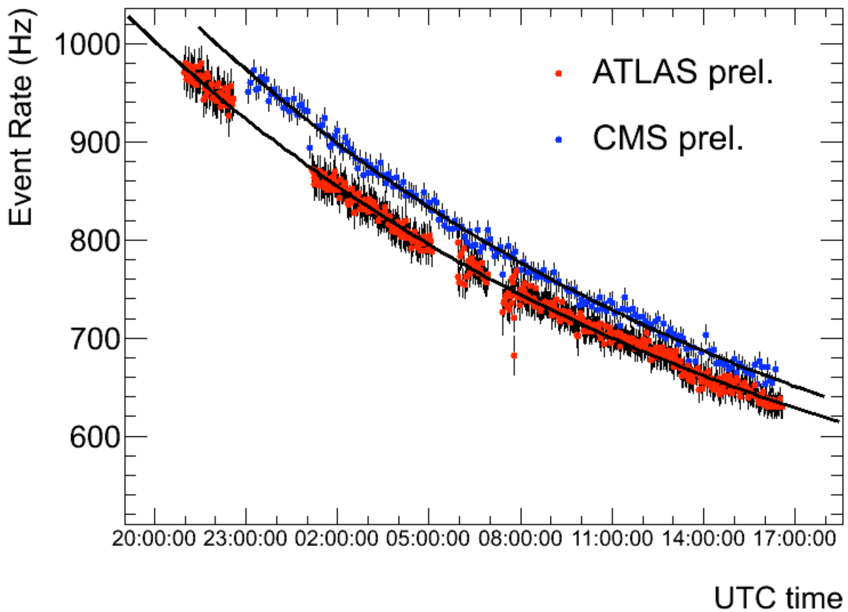
For This:

- Repeat analysis in restricted, common phase space (η<0.8) accessible by all experiments to derive correction factor for N_{ev}
- Measure event rate as function of UTC time
- Calculate instantaneous luminosity using MC cross section and acceptance predictions

Charged Particle Event Rate

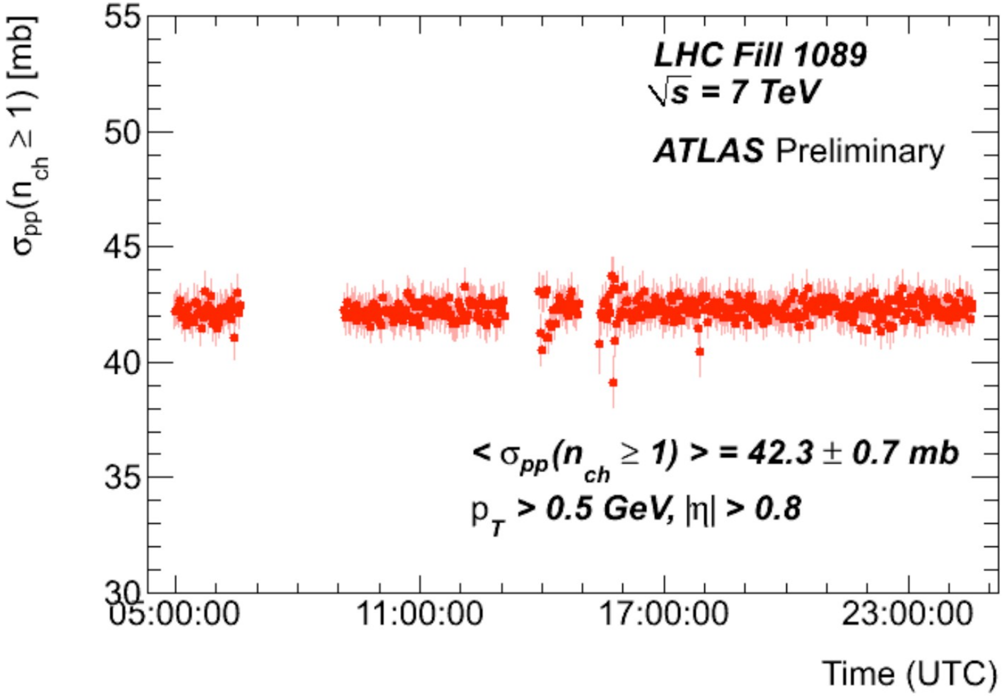
- Can use fully corrected event rate to compare results between experiments
  - First presented at LPCC Lumi Days 13/14.1.2011
- ATLAS and CMS have produced corrected event rates for Fill 1089

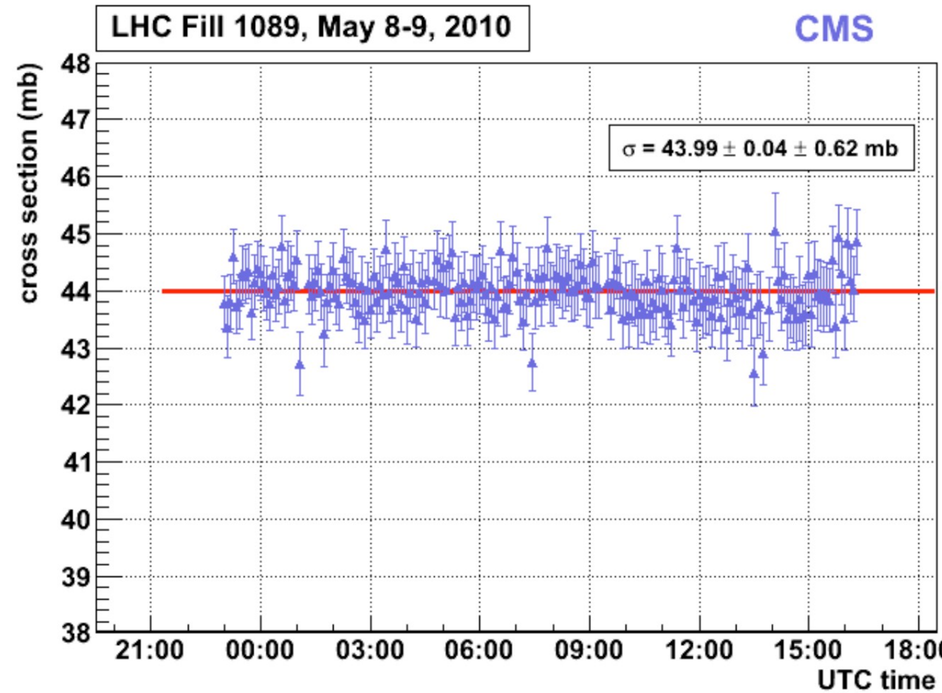




- Gaps in rate due to ongoing VdM scan or due to interruptions in data taking
- Overall analysis corrections about 10%
- Ratio of ATLAS over CMS rate:
  - Differs by ~5% at start and ~3% at end of fill

Charged Particle Cross Section





- ATLAS: 42.3 ± 0.7 mb , CMS: 43.99 ± 0.62 mb
  - Systematic errors quoted do not include luminosity uncertainty
- $\sigma_{CMS}/\sigma_{ATLAS}$= 1.040 ± 0.022 (stat+sys) ± 0.063 (unc. lumi)
  - Difference corresponds to 1.8σ (stat.+syst) and 0.6σ (stat+syst+lumi)

- ATLAS and CMS lumi differs within 2% (well within uncertainties from VdM lumi)
- Higher precision statements will be possible with more fills, new VdM scans...

Summary

- Charged particle multiplicites measured at various points in phase space
- Properties of Underlying event with a leading track investigated

- Results used for MC tunes to data (AMBT1, AUET1)
  - Improves description of distributions
  - Used already for MC production
  - **BUT** still problems at high n_{ch} and p_T

    Tuning is not enough – need to improve models
    - Different models perform better in different situations
  - Important to measure diffractive component and MPI
    - Measurement in diffractive enhanced phase space on-going

- Measurement can be used to compare to other experiments to cross check experimental procedures
  - Central Charged Particle Densities
  - Track Rate and Luminostiy Measurement Comparison

BACKUP

Correction and Results dN/dp_T

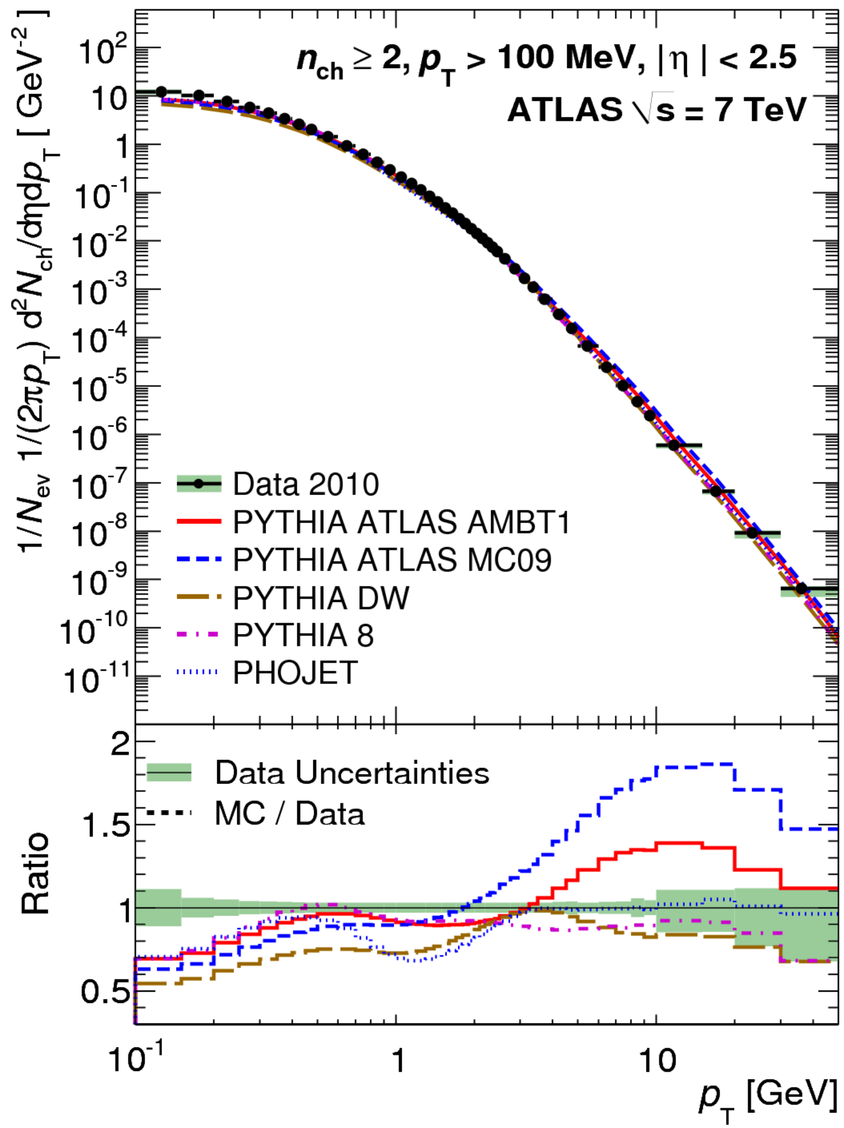
Correction

- Also 1D bayesian unfolding
- Correction much smaller than n_{ch}

Systematics:

At high p_T asymmetric as now data is worse than MC

- Up to 30% for 7 TeV, 30<pT<50 GeV
- At low pT dominated by material uncertainty



Description worse towards high p_T
Even with new AMBT1 tune

Correction and Results for $\langle p_T \rangle (n_{ch})$

Unfold separately

- Σi 1 = total number of tracks in given n_{ch} bin
- $\Sigma i\, p_T(i)$ = total p_T of all tracks in given n_{ch} bin

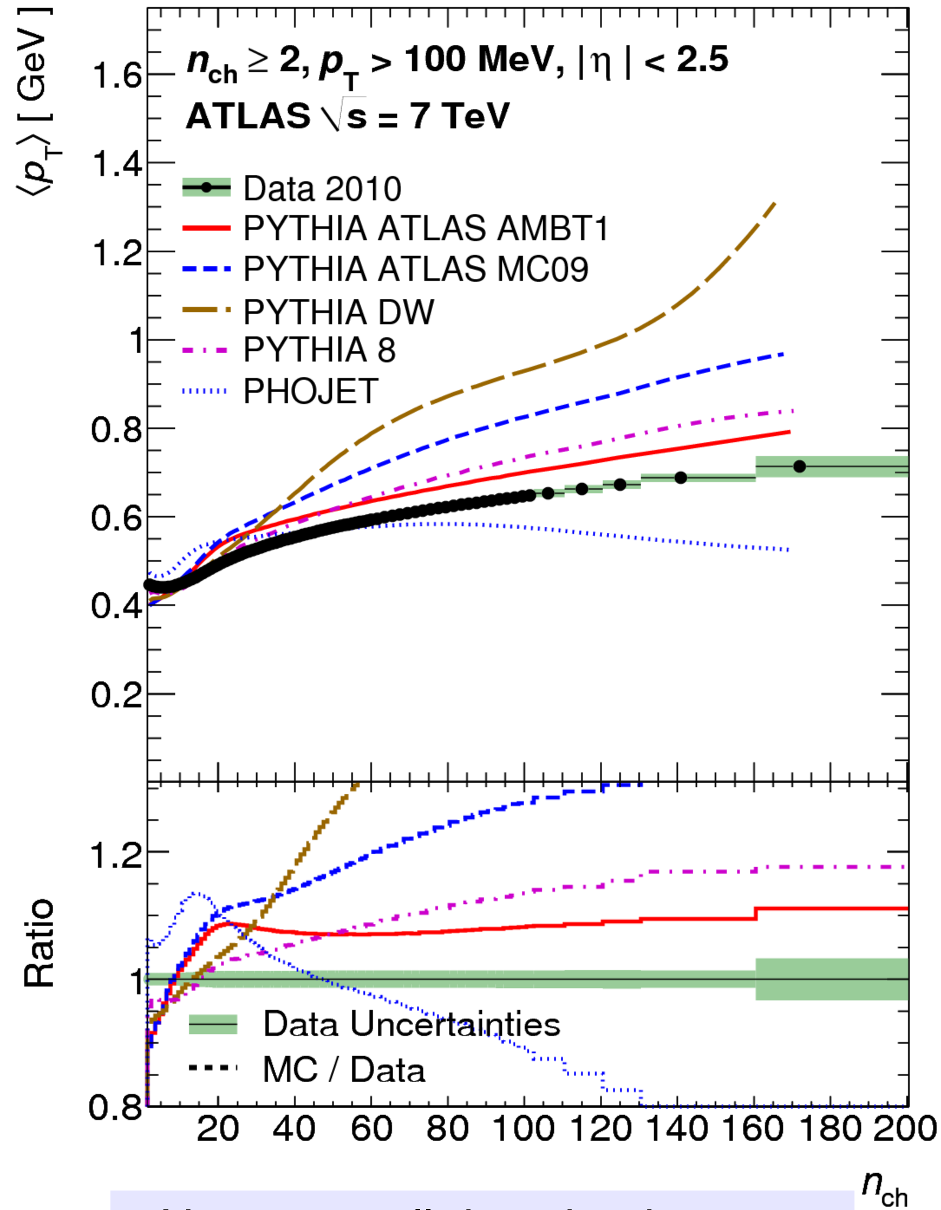
Use 2-step unfolding

- Track-by-track basis correct the p_T
  - Does not rely on MC pT spectrum
- Unfold n_{ch} using same matrix as n_{ch} distribution

- Assumptions of method
  - Tracking efficiency only depends on p_T and η but not n_{ch}
  - p_T of tracks that migrate $n_{sel} \rightarrow n_{ch}$ only depend on n_{sel}

Systematics

- Assume non-closure is due to method
- Non-closure taken as a systematic
- 2% except for few bins at 3%

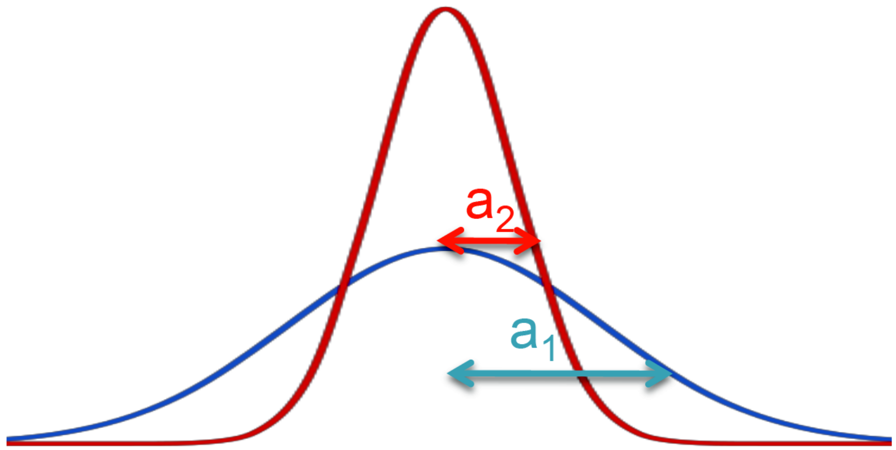


- Not very well descriped
- Sensitive to diffraction at low n_{ch}

AMBT 1 Details

slide: E. Nurse

Matter distribution of protons described by double Gaussian



PARP(83) = fraction in core Gaussian
PARP(84) = a_2 / a_1

Regularisation of divergence in 2→2 scattering via $1/p_T^4 \rightarrow 1/(p_T^2 + p_{T0}^2)^2$

p_{T0} = PARP(82) $(E_{COM} / 1.8\ \mathrm{TeV})^{\mathrm{PARP(90)}}$

	MC09c	AMBT1	Approximate effect
PARP(83)	0.8	0.356	Less fluctuations in n_{ch}
PARP(84)	0.7	0.651	Increase n_{ch} tails, more activity
PARP(82)	2.31 GeV	2.292 GeV	More activity
PARP(90)	0.2487	0.250	More(less) activity at 0.9(7) TeV

PARP(83), PARP(84): overall increase in n_{ch} tail

PARP(82), PARP(90): overall increase in activity

AMBT 1 Details

slide: E. Nurse

Start with MC09c (ATLAS tune to CDF minbias+UE data and D0 dijet angular correlations with LO* PDFs [PHYS-PUB-2010-002]).

<u>Initial State Radiation :</u>

- Proton intrinsic p_T distribution cut-off (PARP(93))
- Cut-off in initial state radiation (PARP(62))

<u>Colour reconnection :</u>

- Probability that a string piece *does not* participate in colour annealing : $(1 - \text{PARP(78)})^{n_{MI}}$ (n_{MI} =# of MPI)
- Suppression factor for colour annealing : $1 / (1 + \text{PARP(77)}^2 \bullet p_{avg}^2)$

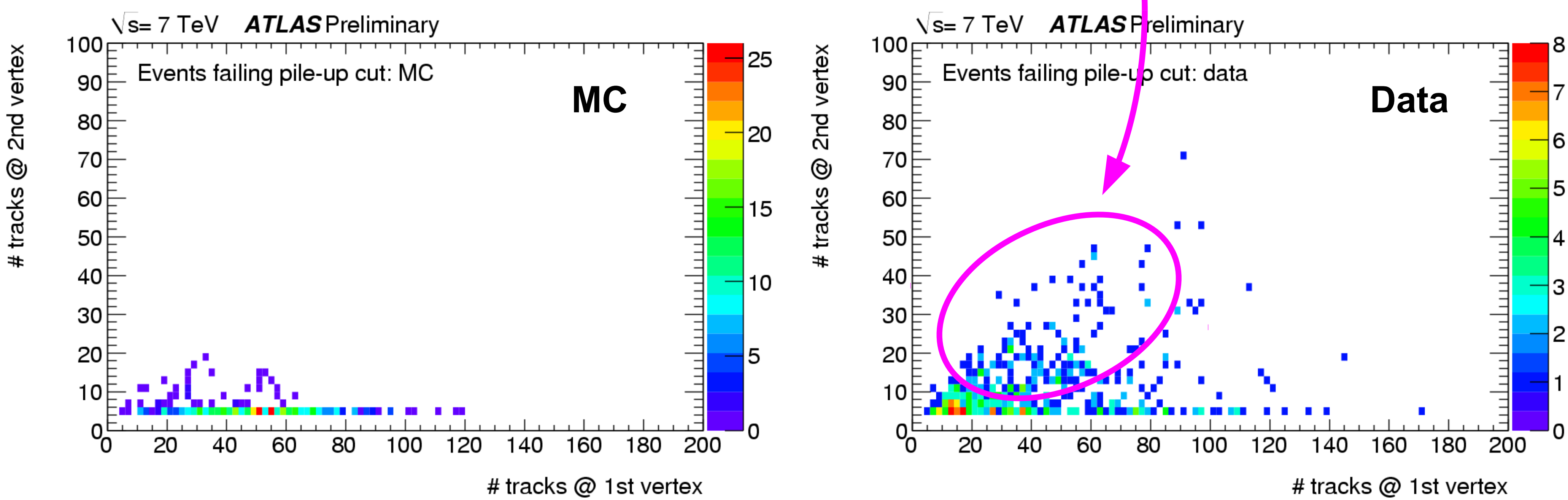
	MC09c	AMBT1	Approximate effect
PARP(62)	1.0	1.025	Very little affect
PARP(93)	5.0	10.0	Very little affect
PARP(77)	0.0	1.016	Decrease $<p_T>$ and p_T tail
PARP(78)	0.224	0.538	Increase $<p_T>$ and p_T tail

} overall decrease in p_T tail and $<p_T>$ vs n_{ch}

Pile-Up Removal

- No second vertex with ≥4 tracks

- Pile-up was small but visible in MB 7 TeV data set
  - Negligible in 900 GeV and 2.36 TeV
- Shows up as secondary vertices with many tracks (high n_{ch})
- Strategy: Reject events with pile-up (contribution: ~0.1% overall, < 6% at high n_{ch})



- MC: no pile-up simulated
  - only fake secondary vertices from misreconstruction
- Overall: No evidence of significant effect due to pileup

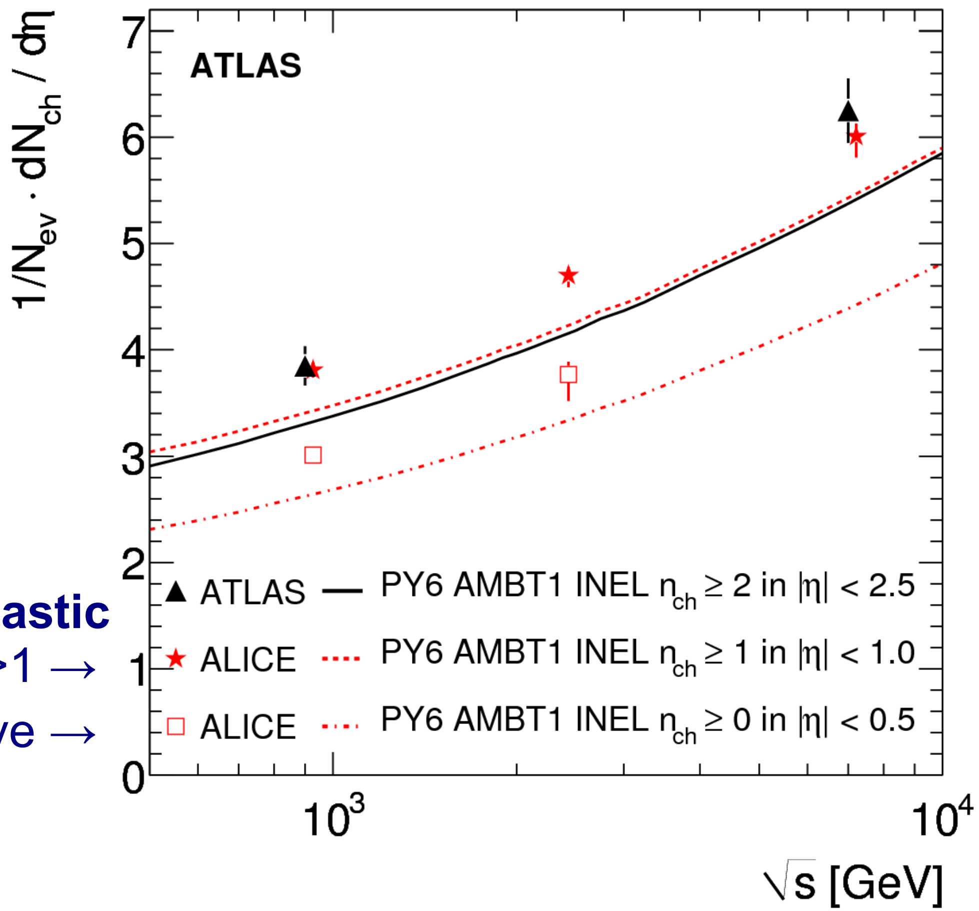
Extrapolation to $p_T = 0$

- Use a modified Tsallis function
- 2 components for pions and protons
- Term to account for fact that we measure η not y

$$f(p_T) = \frac{1}{2\pi\eta'} \sum_{i=\pi,p} \frac{dN_{ch}}{dy}\bigg|_{y=0,i} \frac{(n_i-1)(n_i-2)}{(n_iT_i + m_{0,i}(n_i-1))(n_iT_i+m_{0,i})} \cdot \left[\frac{n_iT_i + m_T(p_T)_i}{n_iT_i + m_{0,i}}\right]^{-n_i} \tanh^{-1}\left(\frac{p_T \sinh\eta'}{\sqrt{m_{0,i}^2 + p_T^2\cosh^2\eta'}}\right)\bigg|_{\eta'=2.5},$$

- Use to extrapolate fraction of tracks with p_T < 100 MeV
- Inclusive pT extrapolation
  - ~5% correction (1.05 factor)
- Keep nch≥2 requirement

ALICE inelastic
N_{ch}>1 →
Inclusive →



- Resulting ATLAS correction to dN/dn_{ch} at η = 0 for pt > 100 MeV @ 7 TeV: 5.881 → 6.177
- Can compare to ALICE results
- Good agreement