Charged particle multiplicities in inelastic *p-p* interactions with ATLAS

featuring the

ATLAS Minimum Bias Tune 1

Gerhard Brandt
On behalf of the ATLAS Collaboration

Results from
ATLAS-CONF-2010-024
ATLAS-CONF-2010-031
Phys Lett B 688, 2010, Issue 1, 21-42

PHYSICS AT LHC 2010
7 - 12 June 2010
DESY, Hamburg

Minimum Bias Event Measurements

Measure charged particle multiplicity distributions from inelastic events

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

Motivation

- Understand the detector and track reconstruction
- Understand soft QCD background present in events with high-p_T reactions
  - Constrain models describing minimum bias physics
  - Compare results to MC generators:
    PYTHIA 6, PYTHIA 8, PHOJET with different parameter sets (tunes)

The ATLAS Way

- Constrain measurement to experimentally and theoretically well controlled region

$$|\eta| < 2.5, \quad p_T > 500\ \mathrm{MeV}, \quad n_{ch} \geq 1$$

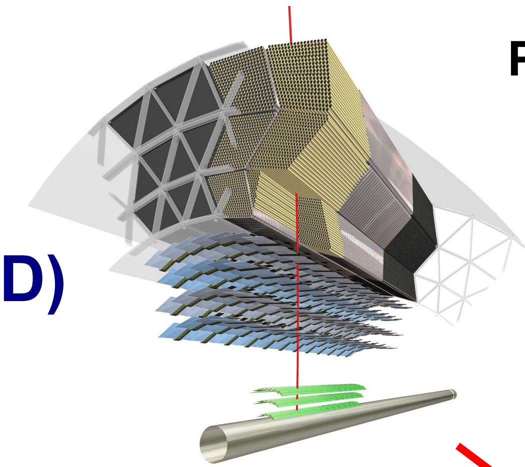
- Avoid using information from Monte Carlo (no “zero bin”)
- Derive efficiency corrections from data where possible
- No subtraction of single-diffractive component (no “NSD” measurement)

ATLAS
Experiment

The ATLAS Detector

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

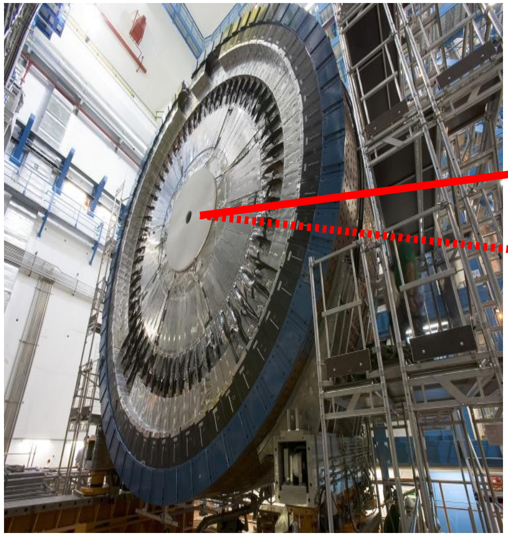
Tracks: Inner Detector (ID)

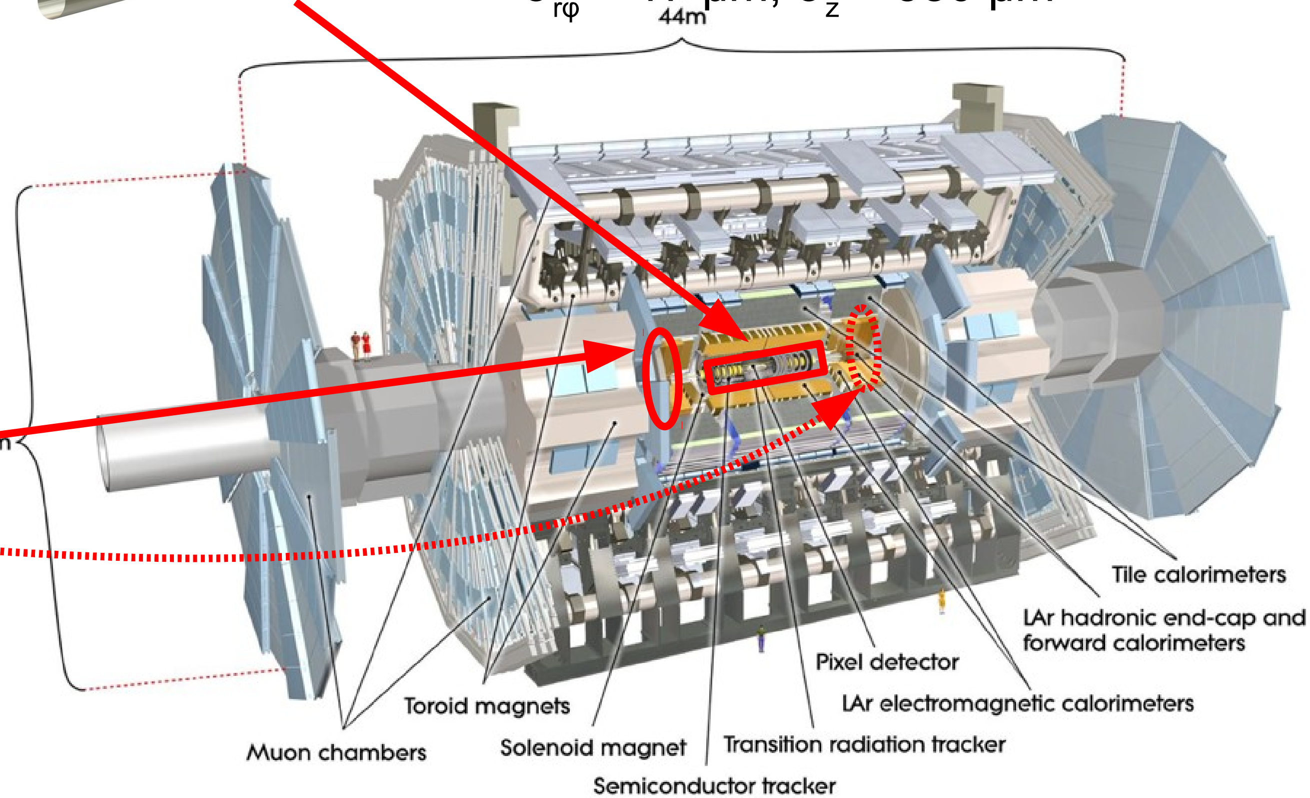


Pixel detector
- 3 barrel layers; 2 x 3 end-cap disks
- $\sigma_{r\varphi}$ ~10 μm, σ_z ~ 115 μm

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

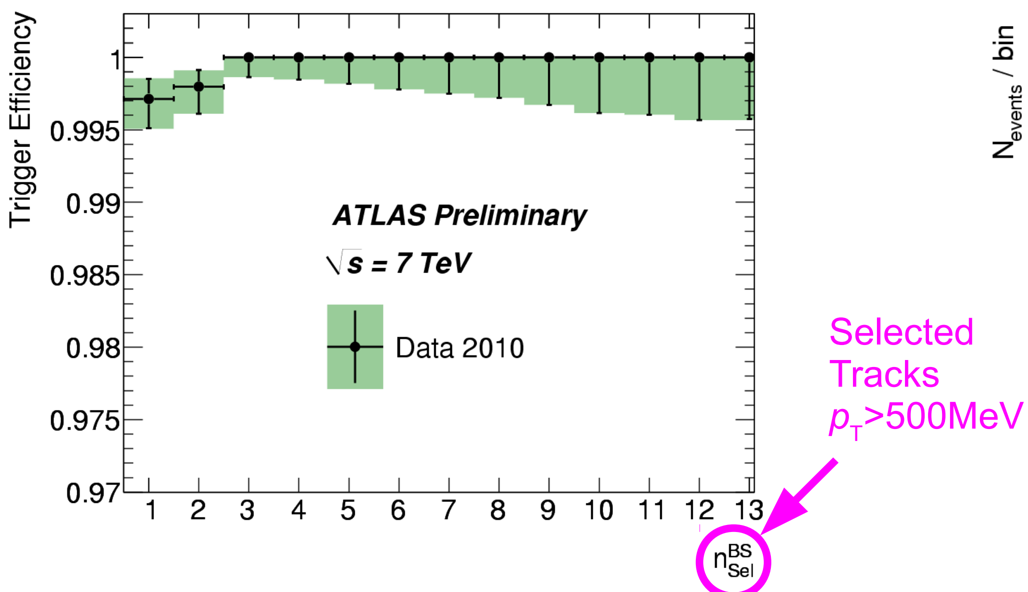
Trigger:
Minimum Bias Trigger Scintillators (MBTS)

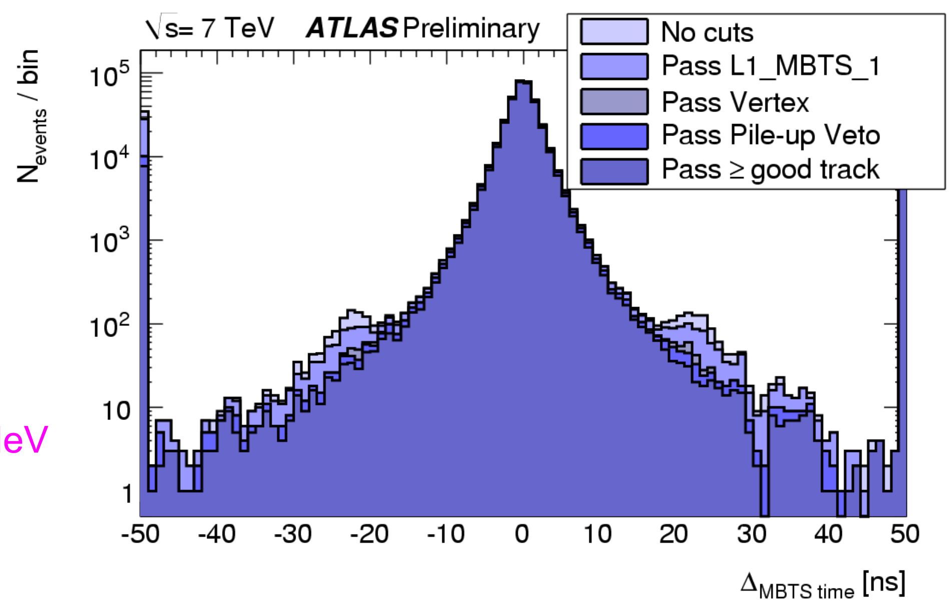




Trigger and Data Quality

- Require stable beams
- Fully operational Inner Detector, trigger and solenoid *B*-field
- Require 1 or more counter in the MBTS from **either** side above threshold (L1_MBTS_1)
  - avoid bias on event topology
- Select ~455k events at $\sqrt{s}$ =900 GeV
  ~400k events at $\sqrt{s}$ =7 TeV





Trigger Efficiency

- Defined by comparing L1_MBTS_1 to high-level SW trigger based on tracks
- Calculated in final event selection
- > 99.5% for any track multiplicity

Beam Background

- Estimated by looking at time difference between MBTS counters on both sides
- Compare collisions / single beam
- Very small: < 10^{-4} contribution

Vertex Selection and Efficiency

- Require reconstructed vertex
  - Allow precise location of primary interaction
  - Uses min. 2 tracks (p_T > 100 MeV) + beamspot

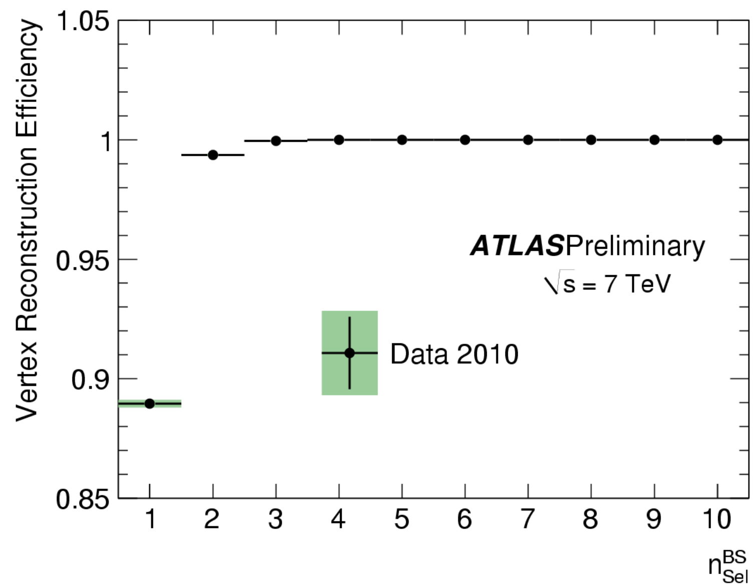
- Measure vertex efficiency from data:

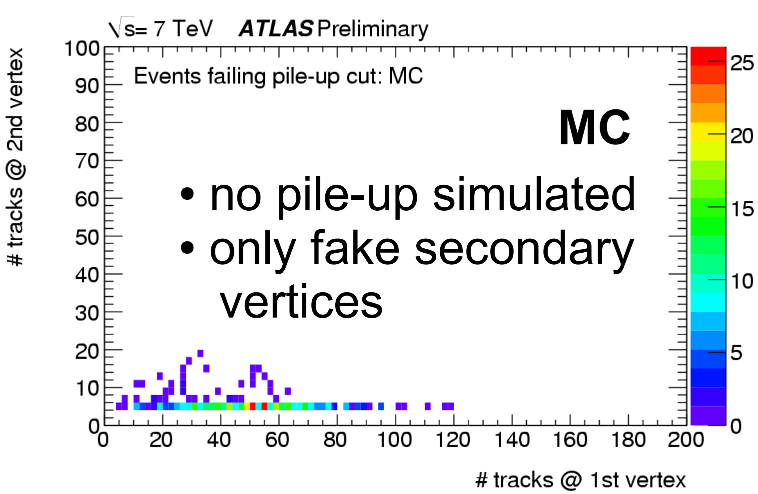
$$\frac{\text{Triggered events with vertex}}{\text{All triggered events}}$$

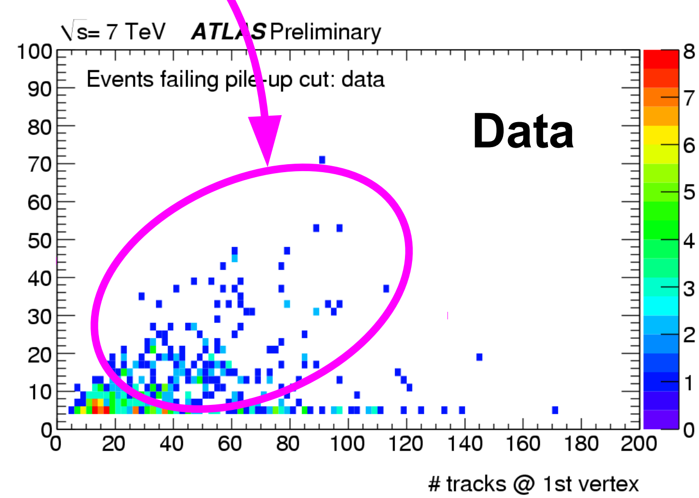
Pile-Up

- First pile-up events visible
- Secondary vertices with many tracks (high n_{ch})
- Strategy: Reject events with pile-up (contribution: ~0.1% overall, < 6% at high n_{ch})

Vertex Efficiency



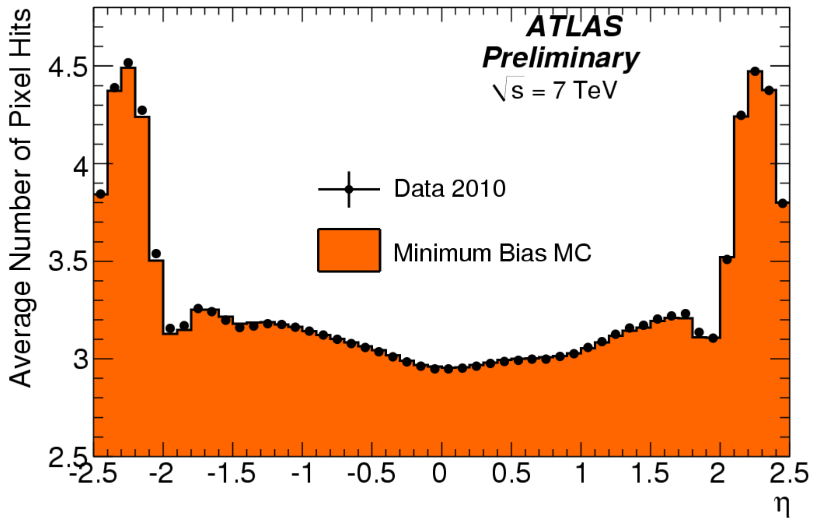




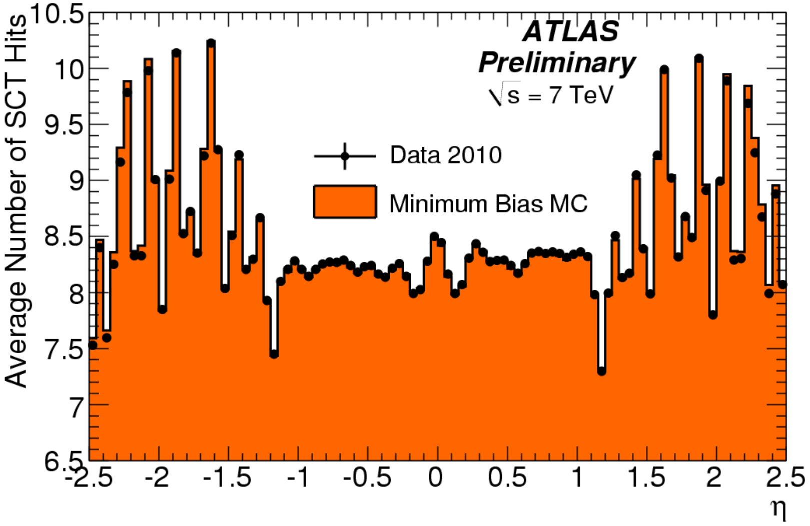
Description of Tracks in the ID

ATLAS Experiment

Avg. number of Pixel hits



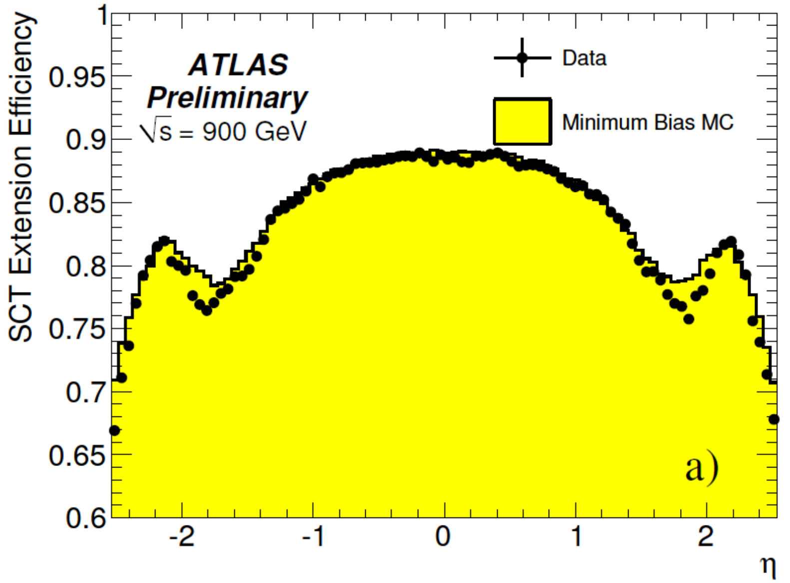
Avg. number of SCT hits



- Excellent description of track properties
- Detailed studies of material, alignment, and resolution

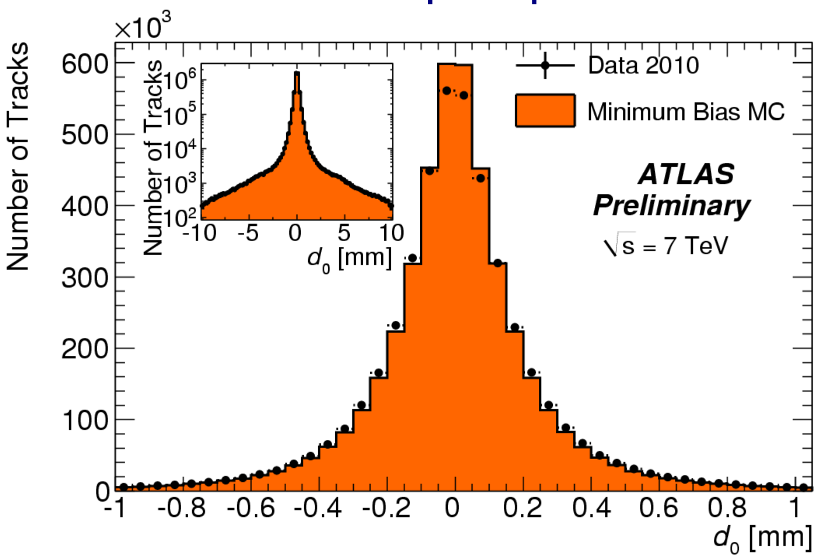
- Global systematic uncertainty on track efficiency: ~3%
- Dominated by conservative estimate of material description (depends on region)
- Material mapping workhorse:
  SCT extension efficiency – check if tracks in the Pixel detector extend to the SCT

SCT extension efficiency

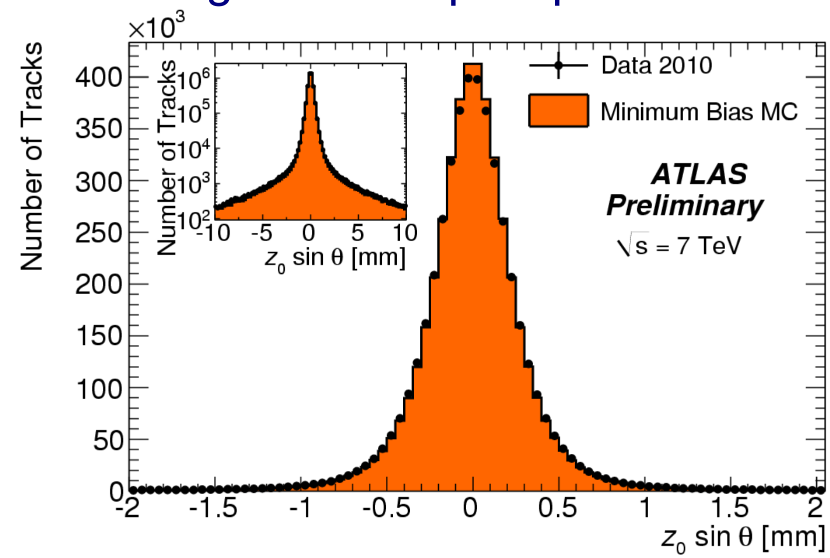


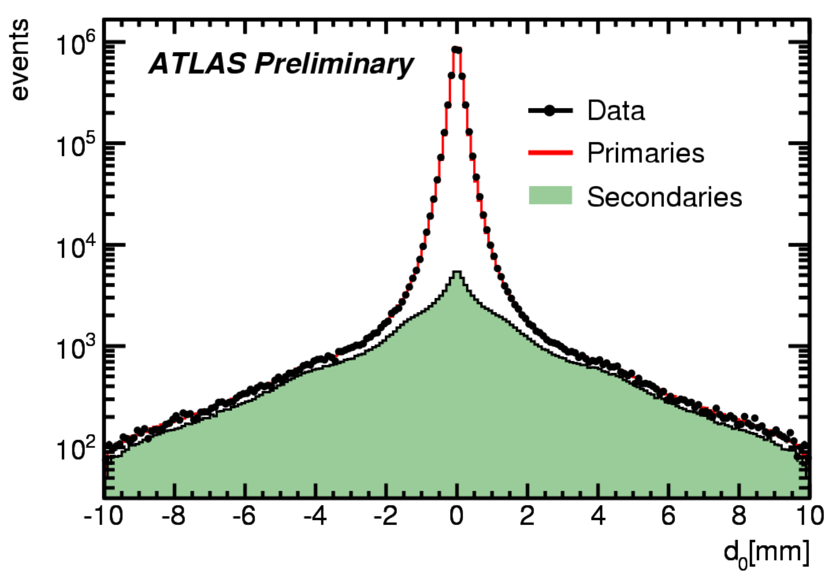
Impact Parameters and Secondary Tracks

Transverse impact parameter



Longitudinal impact parameter





- Only want to count particles from primary interaction
- Define primary particles to have lifetime $\tau < 3\text{x}10^{-11}\text{s}$
- Reduce secondary particles using impact parameter cuts

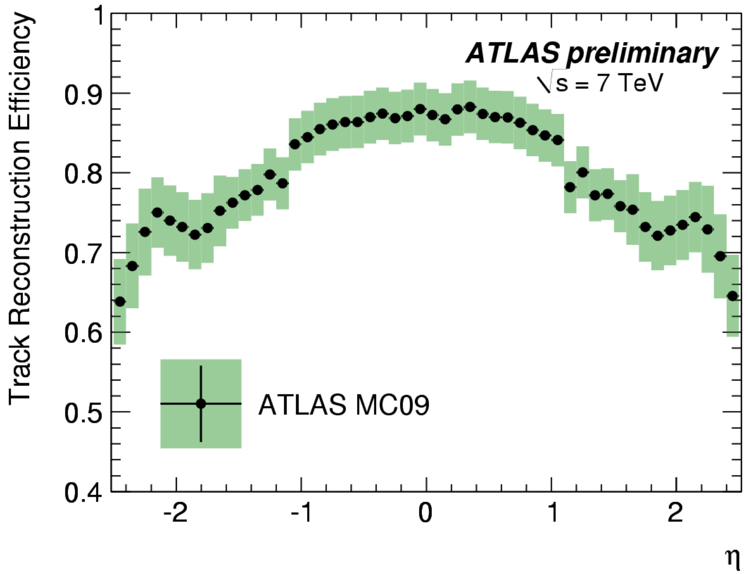
$$d_0 < 1.5 \text{ mm}$$
$$\sin\theta \bullet z_0 < 1.5 \text{ mm}$$

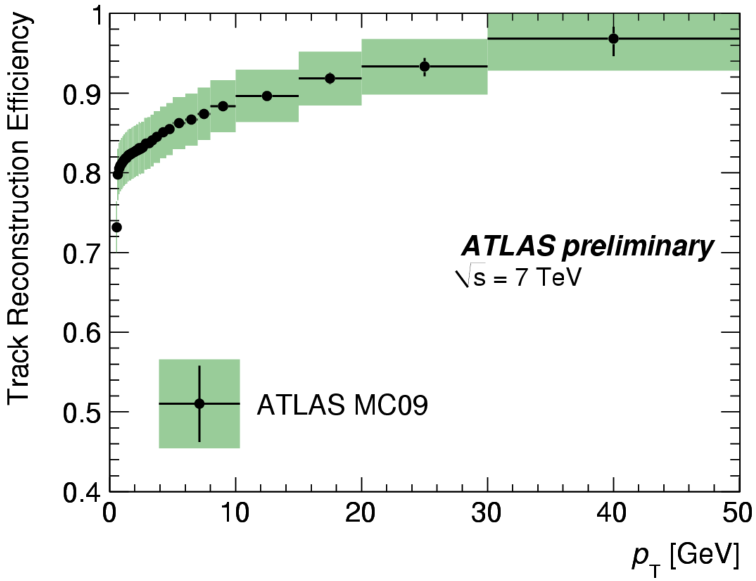
- Distributions well described by the simulation
- Subtract remainder from the data using a template fit to MC (contribution: ~2%)

Track Reconstruction Efficiency

- Excellent description of tracks allows determination of primary track efficiency from MC
- Use hit matching method to compare particles to tracks

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





Correction of distributions in n_{ch}

- Track inefficiency leads to bin migrations and event loss (at low multiplicities)
- Bayesian unfolding using track migration matrix
- Analytic event loss correction based on average track efficiency of 76%

Track-to-Particle Correction

Correction for dN_{ch}/dη, dN_{ch}/dp_T distributions

- Apply efficiencies and other corrections as weights during analysis

Event-weight

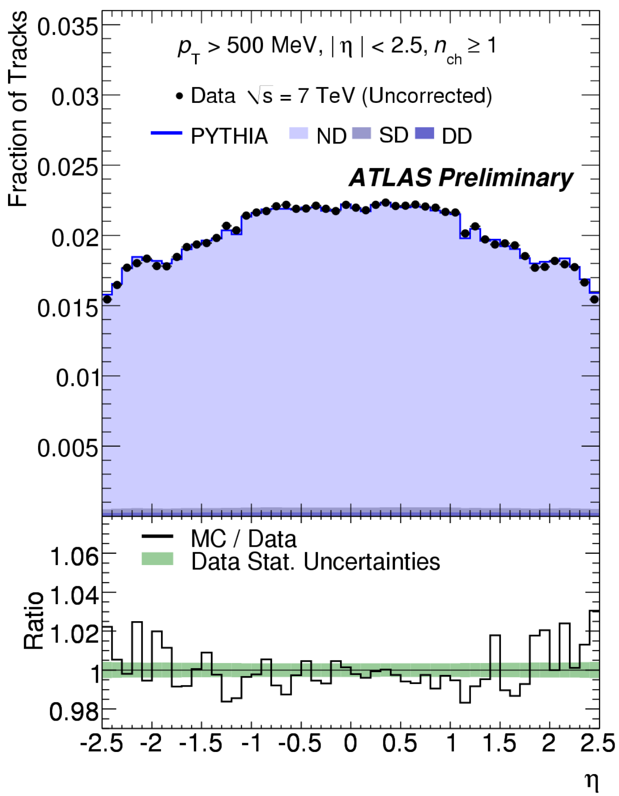
- Trigger- and vertex efficiency

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

Track-weight

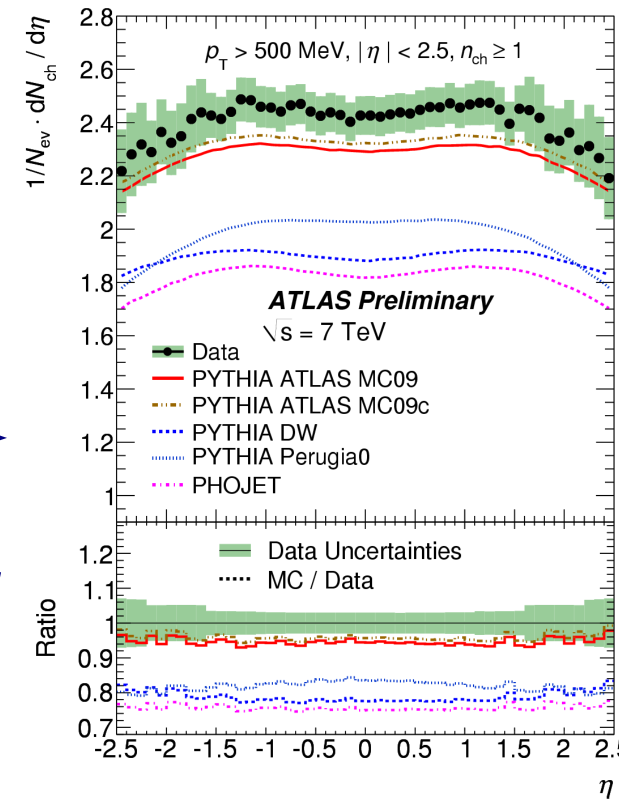
- Track efficiency
- Secondaries
- Out-of-phasespace

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



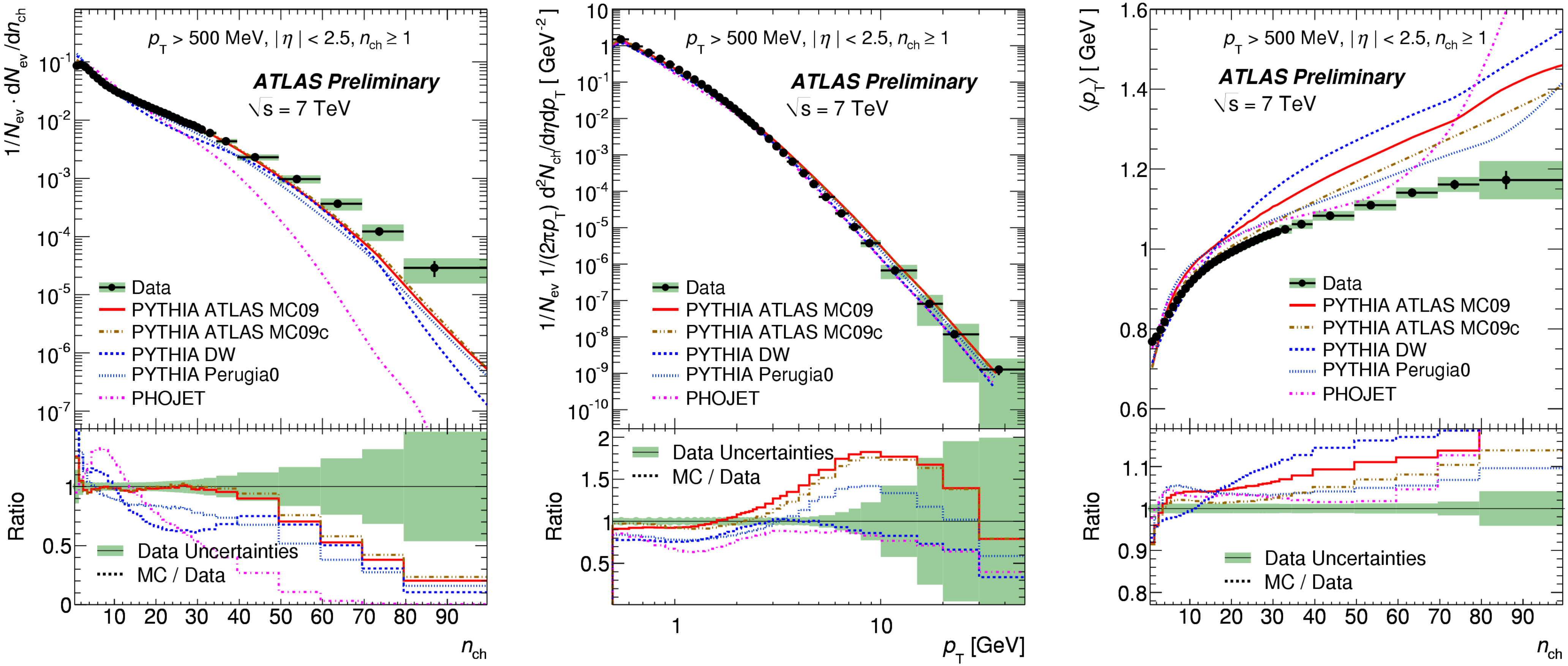
"Raw" distribution:
Measured track density

Final distribution:
Charged particle density



ATLAS Experiment — Results at $\sqrt{s}$ = 7 TeV

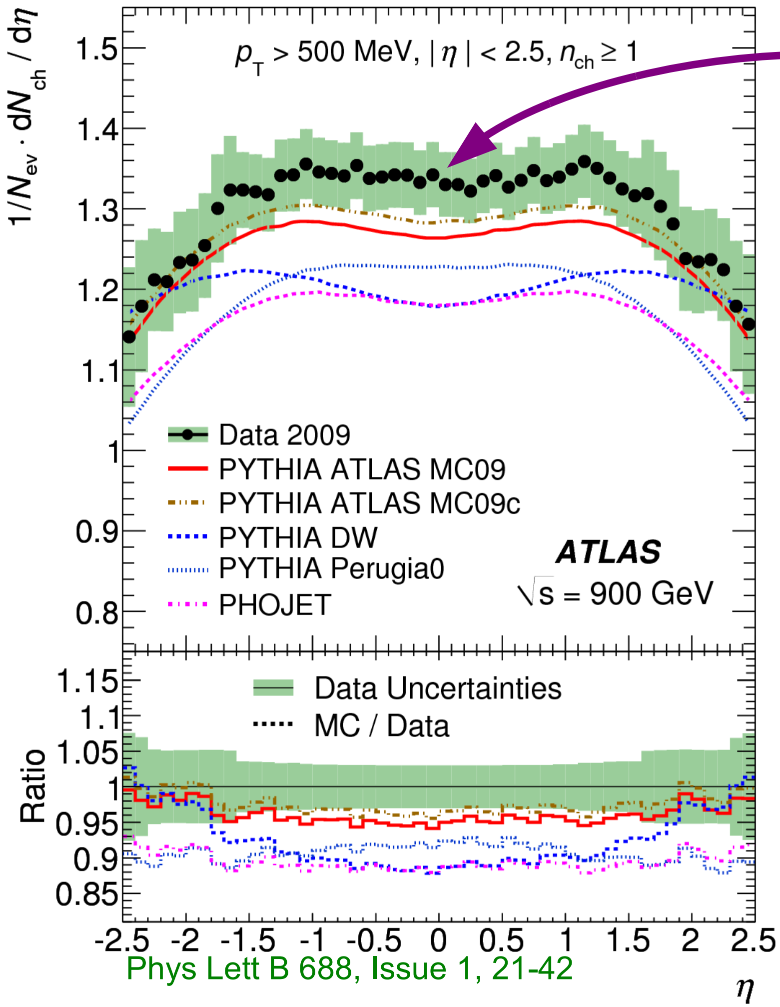
dN_{ch}/dn_{ch} | **dN_{ch}/dp_T** | **$\langle p_T \rangle$**



- Compare to selected PYTHIA tunes and PHOJET
- Particle multiplicity density overestimated at very low n_{ch}, underestimated up to 90% at n_{ch}>50
  - ATLAS MC09c tune comes closest
- Transverse momentum underestimated at p_T < 5 GeV, up to 200% discrepancy above
- Average p_T too high in all models

Charged Particle Density in η

$dN/d\eta$ at $\sqrt{s}$ = 900 GeV

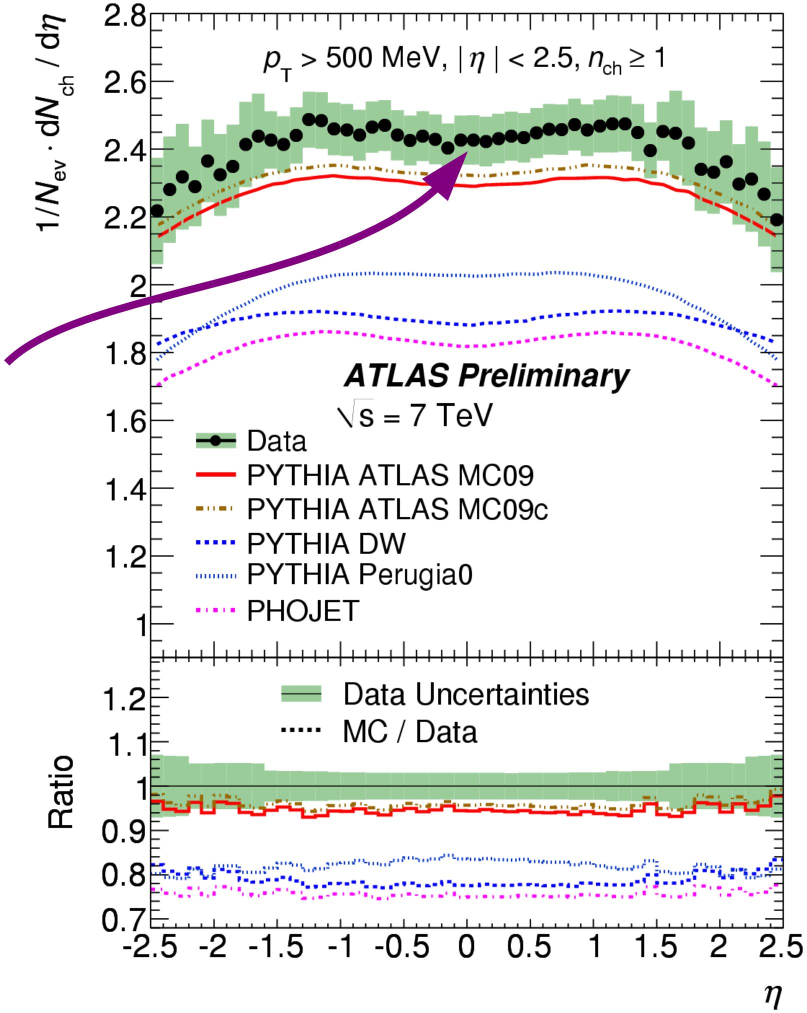


Phys Lett B 688, Issue 1, 21-42

At $dN_{ch}/d\eta$=0: 1.33 ± 0.04

At $dN_{ch}/d\eta$=0: 2.42 ± 0.08

$dN/d\eta$ at $\sqrt{s}$ =7 TeV



- For both energies the data are 5%-15% above existing Monte Carlo predictions
- Models were tuned in different phase space to data from other colliders
- Again ATLAS MC09c tune comes closest
- *Can we do better ... ?*

AMBT1: Idea and Strategy

- Data above MC for exisiting models – do our own **ATLAS Minimum Bias Tune 1**

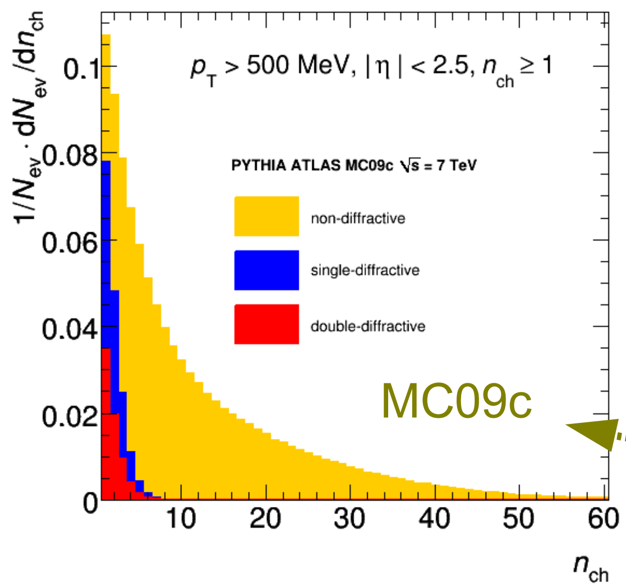
- Diffractive components: cross section and shapes not well known
- Large influence on normalisation of all distributions via N_{ev} (measured as integral of n_{ch} distribution)
- To avoid these model dependencies / uncertainties suppress influence of diffractive events: Go to $\boldsymbol{n_{ch} \geq 6}$

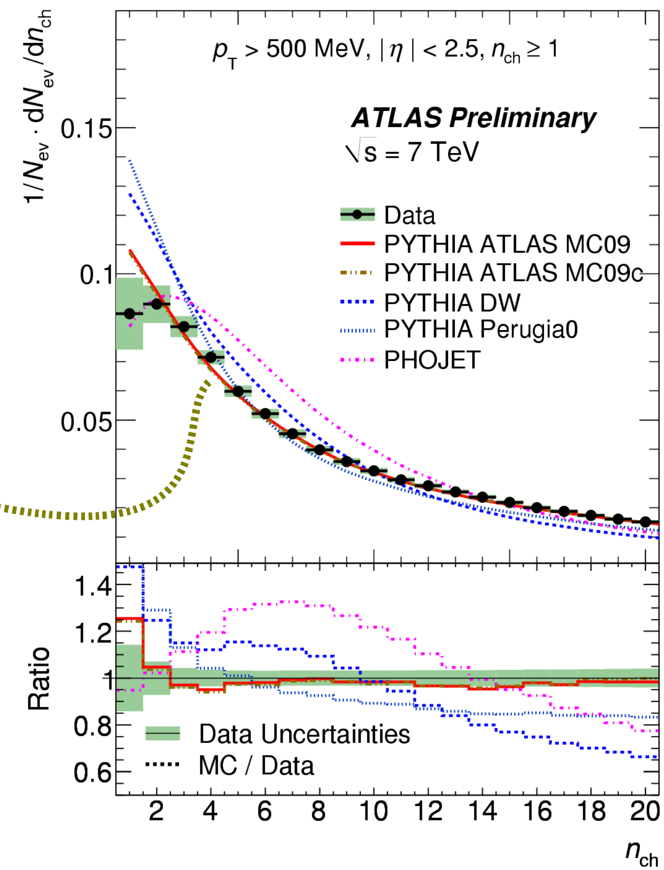
- Start from best tune MC09c
- ATLAS Tune Pedigree: MC09 → MC09c → AMBT1 (*ATL-PHYS-PUB-2010-002*)

- Systematic tuning using PROFESSOR tool (*Eur.Phys.J.C65:331-357,2010*)

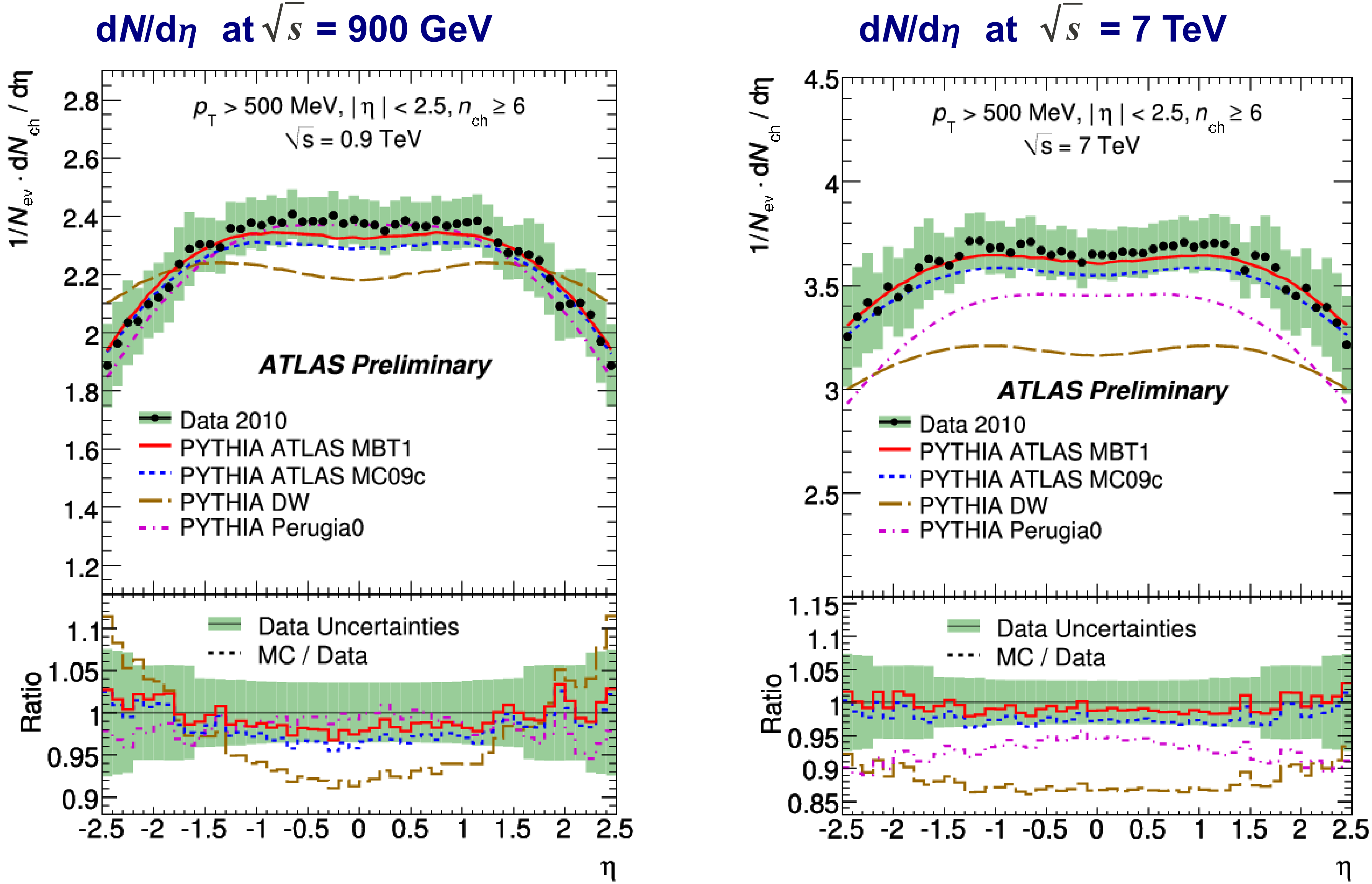
- Input Data:
  - ATLAS MB distributions at $\sqrt{s}$ = 0.9 TeV and 7 TeV
  - TeVatron data
  - ATLAS underlying event measurements

  → see talk by Markus Warsinsky [272]



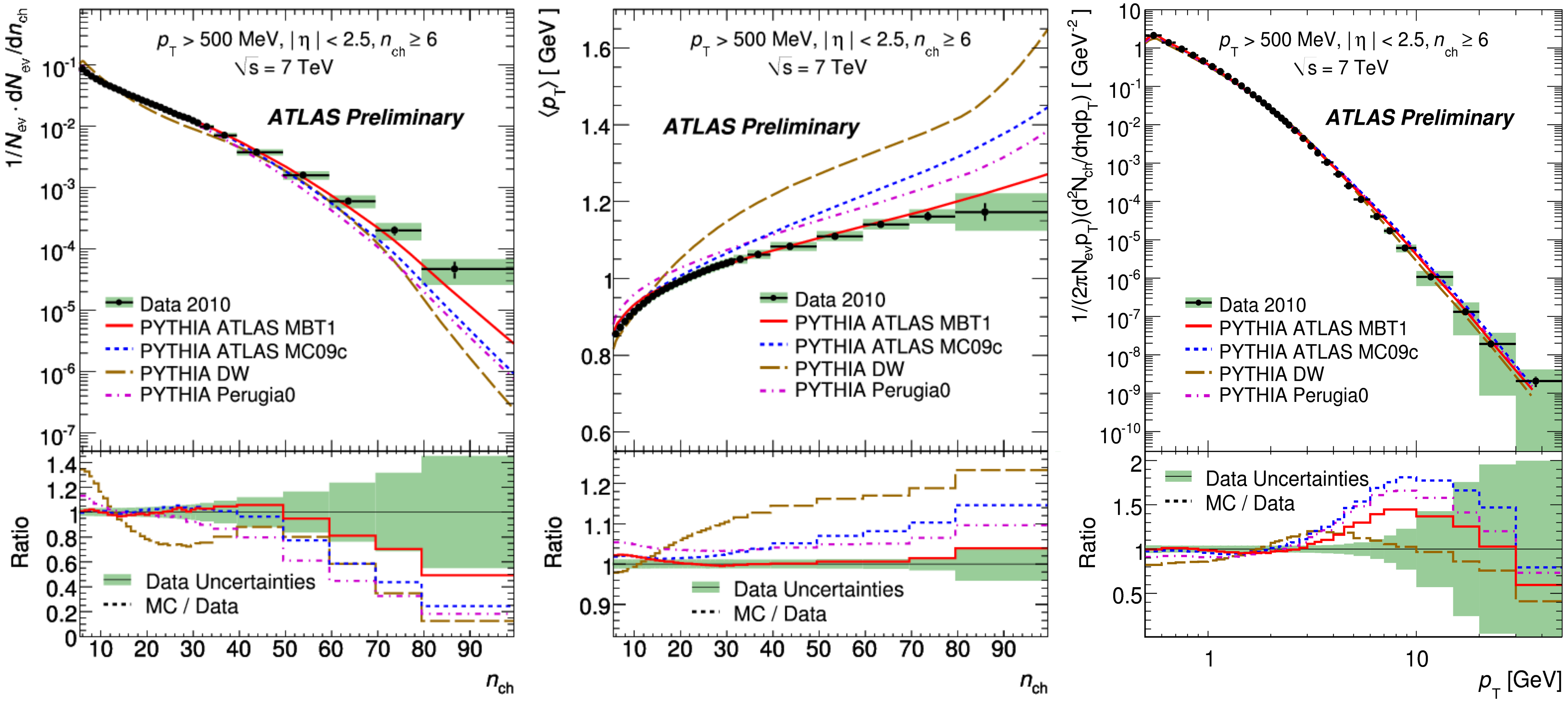


dN/dη for $n_{ch} \geq 6$ at $\sqrt{s}$ = 0.9 and 7 TeV



- Overall better description of data by MC in diffraction-reduced phasespace
- **AMBT1**: Description now within 3% ($\sqrt{s}$ = 900 GeV) and 2% ($\sqrt{s}$= 7 TeV)

ATLAS Experiment — Charged Particles in $n_{ch} \geq 6$ at $\sqrt{s}$ = 7 TeV

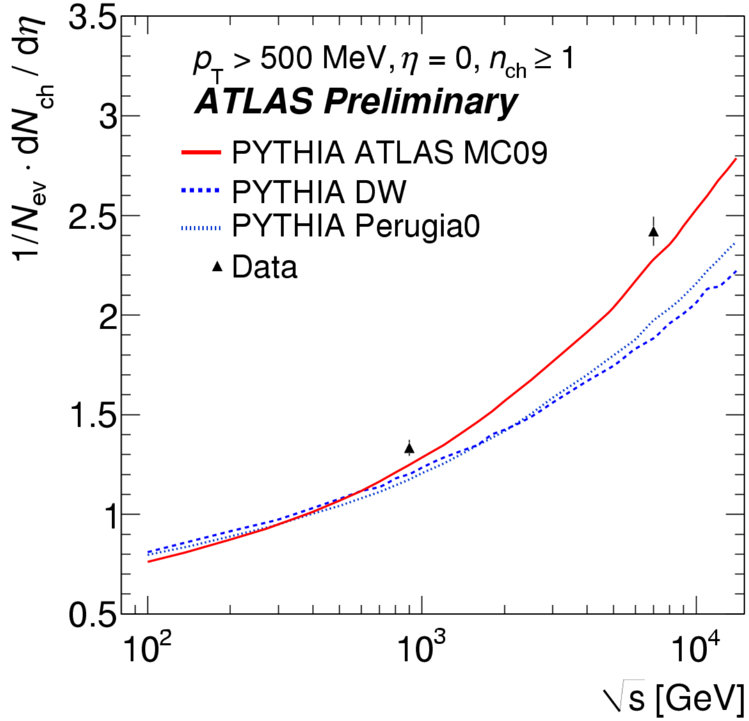


- **AMBT1**
  Description within errors up to n_{ch} < 70
- **AMBT1**
  Description within 2% (except in last bin)
- **AMBT1**
  - Good Description up to p_T < 4 GeV
  - Deviation above reduced to 50%

→ These distributions look also better at $\sqrt{s}$ = 900 GeV

ATLAS Experiment

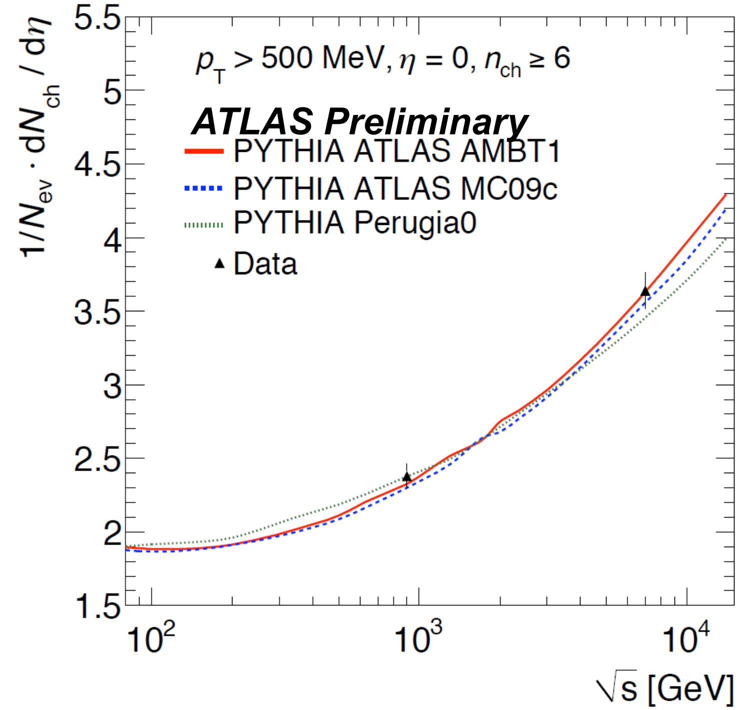
Energy Scan at $dN_{ch}/d\eta=0$



Nominal Minimum Bias Analysis
$n_{ch} \geq 1$

cms	N_{ch}
900 GeV	1.33 ± 0.003 (stat.) ± 0.040 (*syst.*)
7 TeV	2.42 ± 0.004 (stat.) ± 0.076 (*syst.*)

- Predictions from PYTHIA tunes 5% - 15% below the data



Diffraction-limited phasespace
$n_{ch} \geq 6$

cms	N_{ch}
900 GeV	2.38 ± 0.01 (stat.) ±0.08(*syst.*)
7 TeV	3.64 ± 0.01 (stat.) ±0.12(*syst.*)

- Good agreement of data and MC predictions at both cme
- *Better extrapolation to cme 14 TeV can be expected – point of the whole exercise*

Summary

Results of nominal minimum bias analysis

- Charged particle multiplicities were studied in p-p interactions at cme $\sqrt{s}$ =0.9 TeV and $\sqrt{s}$ =7 TeV in the region **$|\eta|<2.5$, p_T > 500 MeV, $n_{ch} \geq 1$**

- Excellent description of tracks in the ATLAS Inner Detector
- Data were corrected with minimal dependence on simulation
- Charged-particle multiplicity per event and unit of pseudorapidity at η=0 is measured to be 5%-15% higher than Monte Carlo models.

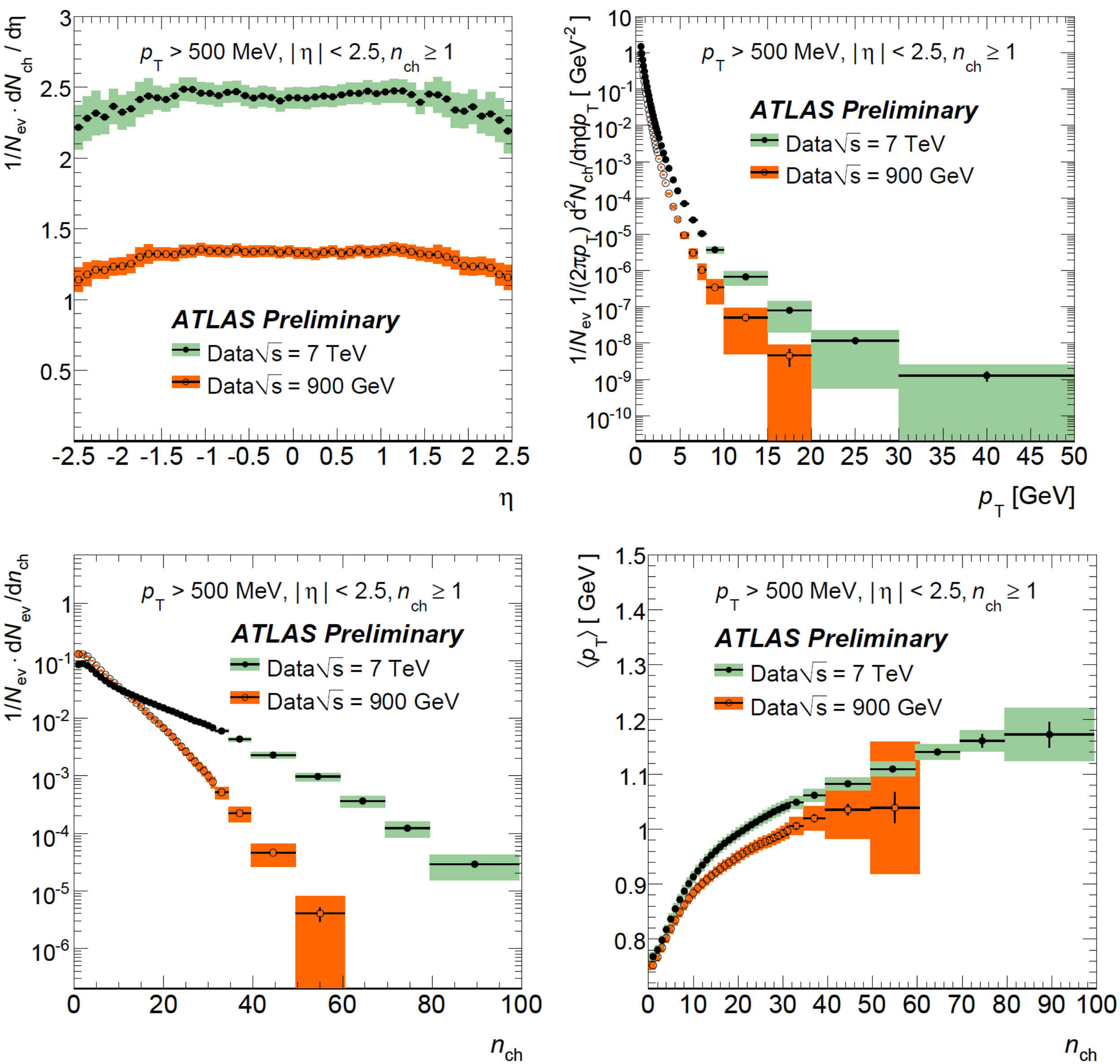
Diffraction Limited Phasespace $n_{ch} \geq 6$

- Reduced uncertainties from diffractive components
- Generated first tune to LHC data:

ATLAS Minimum Bias Tune 1

- Allows unprecedented good description of charged particle multiplicities at cme 0.9 and 7 TeV well within systematic uncertainties (2%-3%) for p_T < 4 GeV b a c k u p

Comparison of 0.9 TeV and 7 TeV Results



- 900 GeV data published in *Phys Lett B 688, Issue 1, 21-42*
- When going from $\sqrt{s}$ = 900 GeV to $\sqrt{s}$ = 7 TeV
  - Higher multiplicity
  - Harder p_T spectrum
- At 900 GeV similar comparison to Monte Carlo: Data 5%-15% higher

Parameter Changes from MC09c to AMBT1

Parameter	related model	MC09c value	scanning range	AMBT1 value
PARP(62)	ISR cut-off	1.0	fixed	1.025
PARP(93)	primordial kt	5.0	fixed	10.0
PARP(77)	CR suppression	0.0	0.25 − − − 1.15	1.016
PARP(78)	CR strength	0.224	0.2 − − − 0.6	0.538
PARP(83)	MPI (matter fraction in core)	0.8	fixed	0.356
PARP(84)	MPI (core of matter overlap)	0.7	0.0 − − − 1.0	0.651
PARP(82)	MPI (p_T^{min})	2.31	2.1 − − − 2.5	2.292
PARP(90)	MPI (energy extrapolation)	0.2487	0.18 − − − 0.28	0.250

Systematic Uncertainties

Systematic uncertainty on the number of events, N_{ev}	
Trigger efficiency	0.2%
Vertex-reconstruction efficiency	$< 0.1\%$
Track-reconstruction efficiency	0.8%
Different Monte Carlo tunes	0.4%
Total uncertainty on N_{ev}	1.2%
Systematic uncertainty on $(1/N_{ev})\cdot(dN_{ch}/d\eta)$ at $\eta = 0$	
Track-reconstruction efficiency	3.8%
Trigger and vertex efficiency	$< 0.1\%$
Secondary fraction	0.1%
Total uncertainty on N_{ev}	-0.9%
Total uncertainty on $(1/N_{ev})\cdot(dN_{ch}/d\eta)$ at $\eta = 0$	2.9%

ATLAS Data used in AMBT1

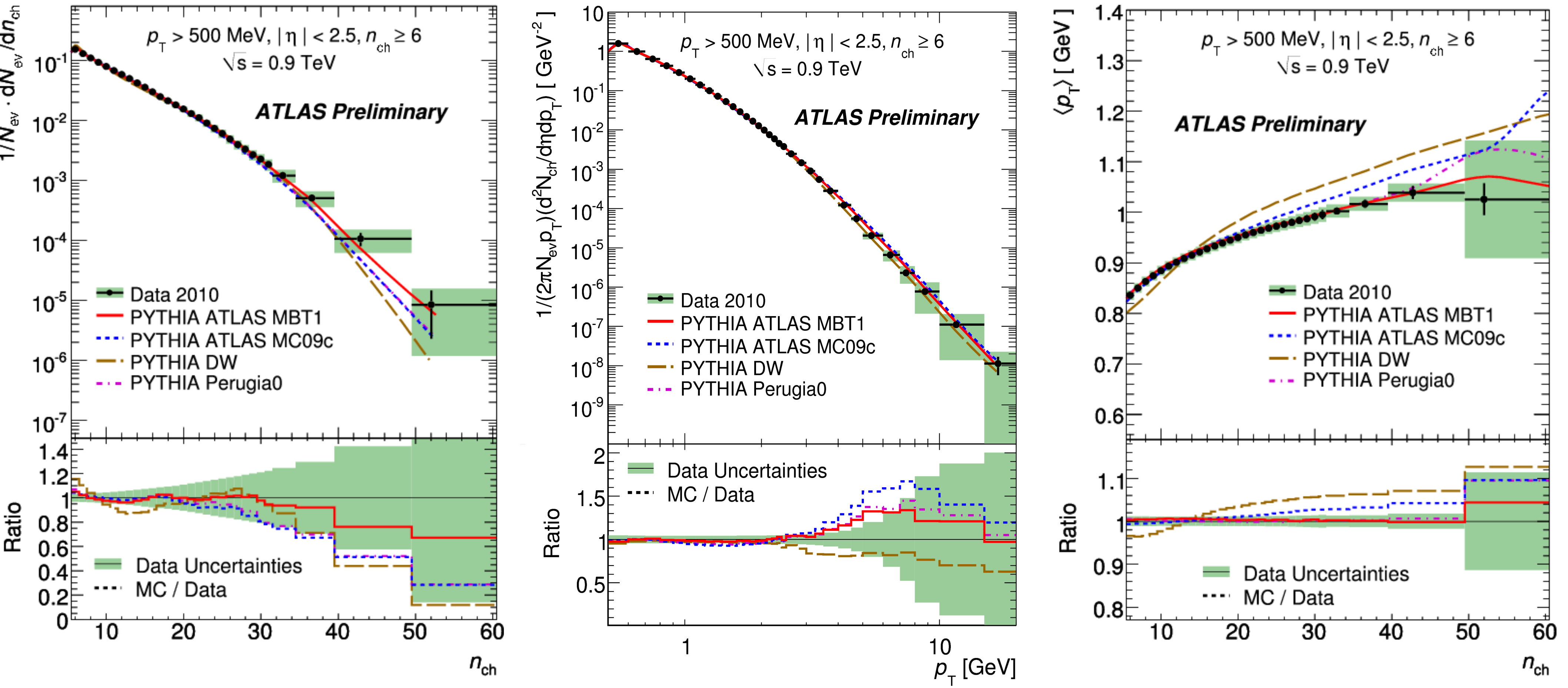
Analysis	Observable	Tuning range
ATLAS 0.9 TeV, minimum bias, $n_{ch} \geq 6$	$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}$	-2.5 – 2.5
ATLAS 0.9 TeV, minimum bias, $n_{ch} \geq 6$	$\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2N_{ch}}{d\eta dp_T}$	≥ 5.0
ATLAS 0.9 TeV, minimum bias, $n_{ch} \geq 6$	$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$	≥ 20
ATLAS 0.9 TeV, minimum bias, $n_{ch} \geq 6$	$\langle p_T \rangle$ vs. n_{ch}	≥ 10
ATLAS 0.9 TeV, UE in minimum bias	$\langle \frac{d^2N_{chg}}{d\eta d\phi} \rangle$ (towards)	≥ 5.5 GeV
ATLAS 0.9 TeV, UE in minimum bias	$\langle \frac{d^2N_{chg}}{d\eta d\phi} \rangle$ (transverse)	≥ 5.5 GeV
ATLAS 0.9 TeV, UE in minimum bias	$\langle \frac{d^2N_{chg}}{d\eta d\phi} \rangle$ (away)	≥ 5.5 GeV
ATLAS 0.9 TeV, UE in minimum bias	$\langle \frac{d^2 \sum p_T}{d\eta d\phi} \rangle$ (towards)	≥ 5.5 GeV
ATLAS 0.9 TeV, UE in minimum bias	$\langle \frac{d^2 \sum p_T}{d\eta d\phi} \rangle$ (transverse)	≥ 5.5 GeV
ATLAS 0.9 TeV, UE in minimum bias	$\langle \frac{d^2 \sum p_T}{d\eta d\phi} \rangle$ (away)	≥ 5.5 GeV
ATLAS 7 TeV, minimum bias, $n_{ch} \geq 6$	$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta}$	-2.5 – 2.5
ATLAS 7 TeV, minimum bias, $n_{ch} \geq 6$	$\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2N_{ch}}{d\eta dp_T}$	≥ 5.0
ATLAS 7 TeV, minimum bias, $n_{ch} \geq 6$	$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$	≥ 40
ATLAS 7 TeV, minimum bias, $n_{ch} \geq 6$	$\langle p_T \rangle$ vs. n_{ch}	≥ 10
ATLAS 7 TeV, UE in minimum bias	$\langle \frac{d^2N_{chg}}{d\eta d\phi} \rangle$ (towards)	≥ 10 GeV
ATLAS 7 TeV, UE in minimum bias	$\langle \frac{d^2N_{chg}}{d\eta d\phi} \rangle$ (transverse)	≥ 10 GeV
ATLAS 7 TeV, UE in minimum bias	$\langle \frac{d^2N_{chg}}{d\eta d\phi} \rangle$ (away)	≥ 10 GeV
ATLAS 7 TeV, UE in minimum bias	$\langle \frac{d^2 \sum p_T}{d\eta d\phi} \rangle$ (towards)	≥ 10 GeV
ATLAS 7 TeV, UE in minimum bias	$\langle \frac{d^2 \sum p_T}{d\eta d\phi} \rangle$ (transverse)	≥ 10 GeV
ATLAS 7 TeV, UE in minimum bias	$\langle \frac{d^2 \sum p_T}{d\eta d\phi} \rangle$ (away)	≥ 10 GeV

Other Data used in AMBT1

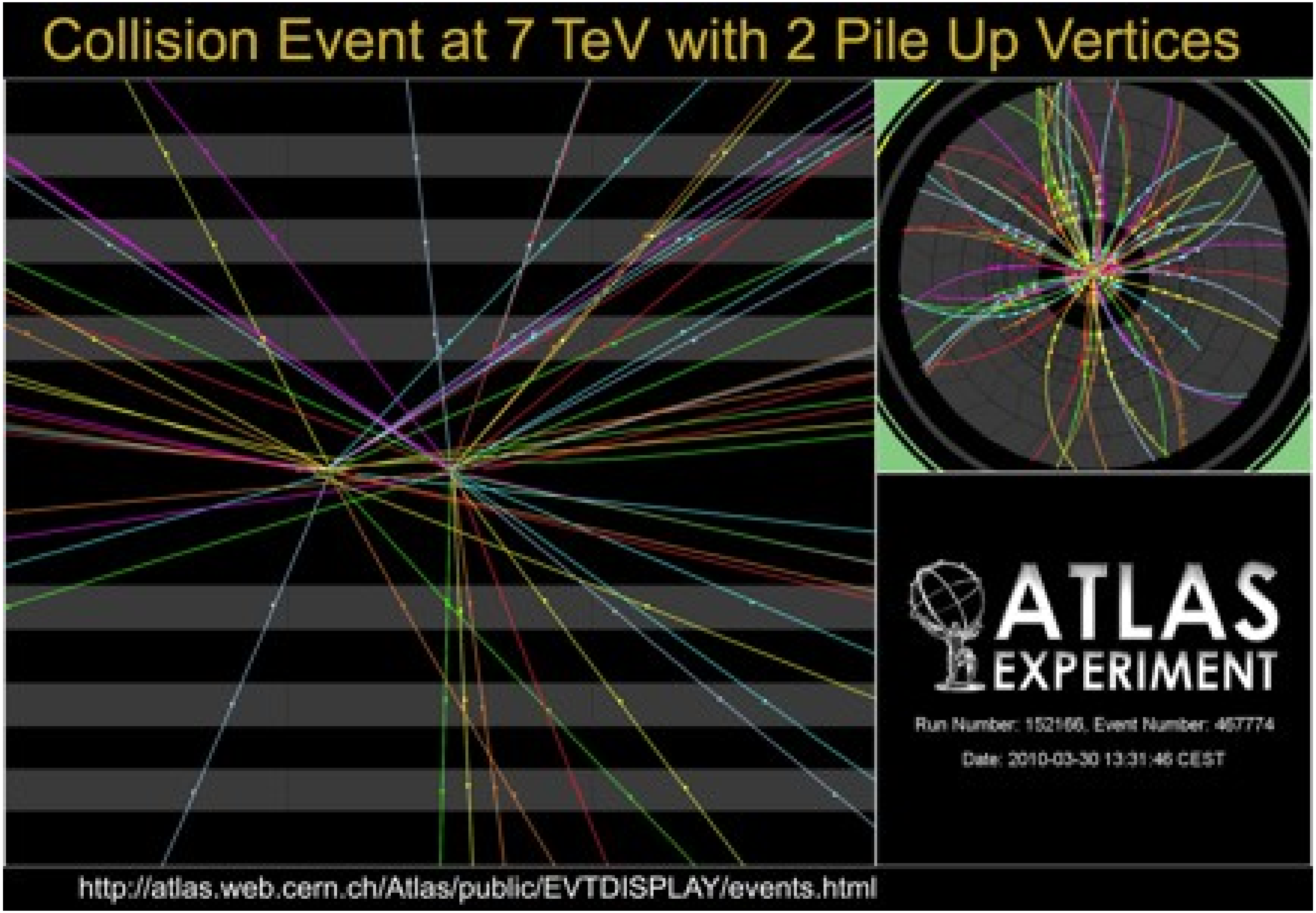
Observables
CDF Run I underlying event in dijet events[14] (leading jet analysis)
N_{ch} density vs leading jet p_T (transverse), JET20
N_{ch} density vs leading jet p_T (toward), JET20
N_{ch} density vs leading jet p_T (away), JET20
$\sum p_T$ density vs leading jet p_T (transverse), JET20
$\sum p_T$ density vs leading jet p_T (toward), JET20
$\sum p_T$ density vs leading jet p_T (away), JET20
N_{ch} density vs leading jet p_T (transverse), min bias
N_{ch} density vs leading jet p_T (toward), min bias
N_{ch} density vs leading jet p_T (away), min bias
$\sum p_T$ density vs leading jet p_T (transverse), min bias
$\sum p_T$ density vs leading jet p_T (toward), min bias
$\sum p_T$ density vs leading jet p_T (away), min bias
p_T distribution (transverse), leading $p_T > 5$ GeV
p_T distribution (transverse), leading $p_T > 30$ GeV

CDF Run I underlying event in MIN/MAX-cones[15] ("MIN-MAX" analysis)
$\langle p_T^{max} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800$ GeV
$\langle p_T^{min} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800$ GeV
$\langle p_T^{diff} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800$ GeV
$\langle N_{max} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800$ GeV
$\langle N_{min} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800$ GeV
Swiss Cheese p_T^{sum} vs. E_T^{lead} (2 jets), $\sqrt{s} = 1800$ GeV
$\langle p_T^{max} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 630$ GeV
$\langle p_T^{min} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 630$ GeV
$\langle p_T^{diff} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 630$ GeV
Swiss Cheese p_T^{sum} vs. E_T^{lead} (2 jets), $\sqrt{s} = 630$ GeV
D0 Run II dijet angular correlations[16]
Dijet azimuthal angle, $p_T^{max} \in [75, 100]$ GeV
Dijet azimuthal angle, $p_T^{max} \in [100, 130]$ GeV
Dijet azimuthal angle, $p_T^{max} \in [130, 180]$ GeV
Dijet azimuthal angle, $p_T^{max} > 180$ GeV
CDF Run II minimum bias[17]
$\langle p_{\rm T} \rangle$ of charged particles vs. N_{ch}, $\sqrt{s} = 1960$ GeV
CDF Run I Z $p_{\rm T}$[18]
$\frac{d\sigma}{dp_{\rm T}^{Z}}$, $\sqrt{s} = 1800$ GeV

Charged Particles in $n_{ch} \geq 6$ at cme 0.9 TeV




Collision Event at
7 TeV
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 with 2 Pile Up Vertices
ATLAS
EXPERIMENT
Run Number: 152166, Event Number: 467774
Date: 2010-03-30 13:31:46 CEST
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html