Particle Production and Exclusive Production in pp collisions in ATLAS

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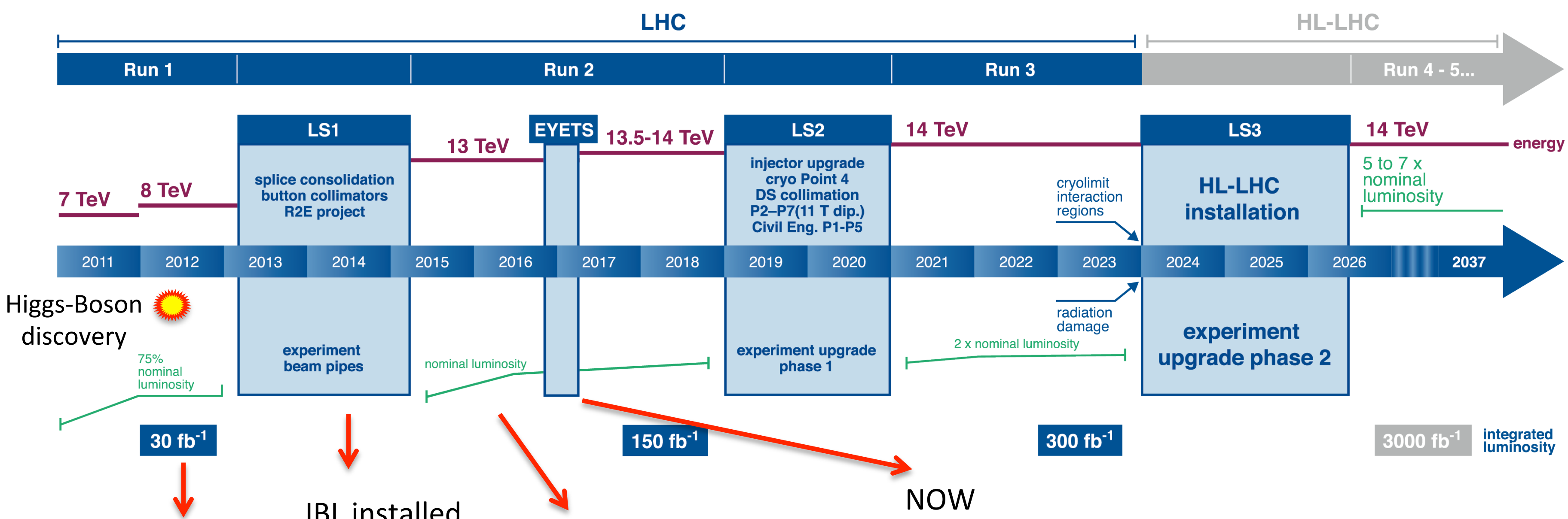
University of Calabria – INFN/CS

& CERN

QCD Challenges 2017
Trento, Italy
February 27th – March 3rd 2017

Timeline



4.6 fb^{-1} of 7 TeV data and 20.2fb^{-1} of 8 TeV data still being analysed

IBL installed in the ATAS Inner Detector

Early Standard Model Measurements released

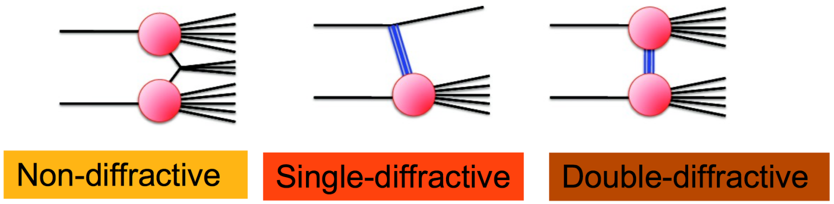
NOW
~40 fb^{-1} of 13 TeV data being exploited and much more to come before LS2

- In this talk
  - Focus on 13 TeV Charged-Particle Distributions and comparison with results at lower centre-of-mass energies
  - Overview of :
    - Bose-Einstein Correlation at 0.9 and 7 TeV
    - Exclusive di-lepton production at 7 TeV
    - Exclusive W^+W^- production at 8 TeV

Why is Minimum Bias important?

- Inclusive charged-particle measurements in *pp* collisions provide insight into the strong interaction in the low energy, non-perturbative QCD region

- Inelastic *pp* collisions have different compositions



- Main source of background when more than one interaction per bunch crossing → good modeling of min bias events needed for pile-up simulation

- Perturbative QCD can not be used for low transfer momentum interactions
  - ND described by QCD-inspired phenomenological models (tunable)
  - SD and DD hardly described and few measurements available

Goal:

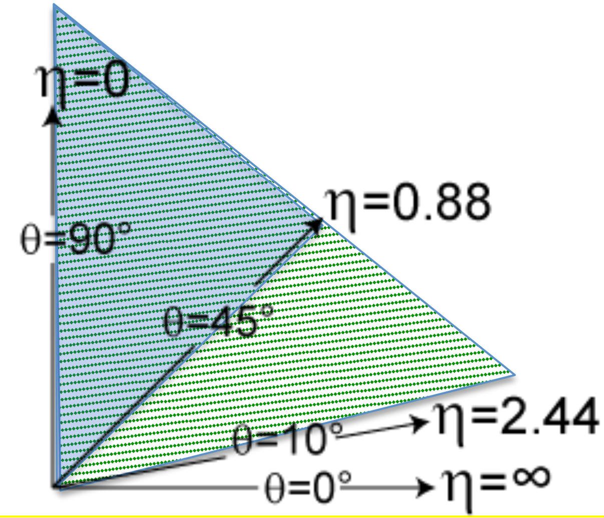
Measure spectra of primary charged particles corrected to hadron level

Inclusive measurement – do not apply model dependent corrections -> allow theoreticians to tune their models to data measured in well defined kinematic ranges

Minimum Bias at the LHC

Minimum Bias measurements in ATLAS:

- 0.9 TeV (03/2010)
  - 1 phase space (1 charged particle, 500 MeV, |η|<2.5)
- 0.9, 2.36, 7 TeV (12/2010)
  - 3 phase spaces (1, 2, 6 charged particles, 100-500 MeV, |η|<2.5)
- 0.9, 7 TeV (12/2010)
  - CONFNote – 2 phase spaces (1 charged particle, 500-1000 MeV, |η|<0.8)
- 8 TeV (03/2016)
  - 5 phase spaces (1, 2, 6, 20, 50 charged particles, 100-500 MeV, |η|<2.5)
- 13 TeV (02/2016)
  - 2 phase spaces (1 charged particle, 500 MeV, |η|<2.5, 0.8)
- 13 TeV (06/2016)
  - 1 phase space (2 charged particles, 100 MeV, |η|<2.5)



Latest Minimum Bias measurements in ALICE:

- 13 TeV (12/2015)
  - Pseudorapidity distribution in |η|<1.8 is reported for inelastic events and for events with at least one charged particle in |η|< 1
  - Transverse momentum distribution in 0.15 < p_T < 20 GeV/c and |η|< 0.8 for events with at least one charged particle in |η|< 1

Minimum Bias measurements in CMS:

- 0.9, 2.36 (02/2010)
  - Charged hadrons
- 7 TeV (02/2010)
  - Charged hadrons
- 0.9, 2.36, 7 TeV (11/2010)
  - 5 pseudorapidity ranges from |eta|<0.5 to |eta|<2.4
- 8 TeV (05/2014) – with Totem
  - |η|<2.2, 5.3<|η|<6.4
- 13 TeV (07/2015)
  - no magnetic field

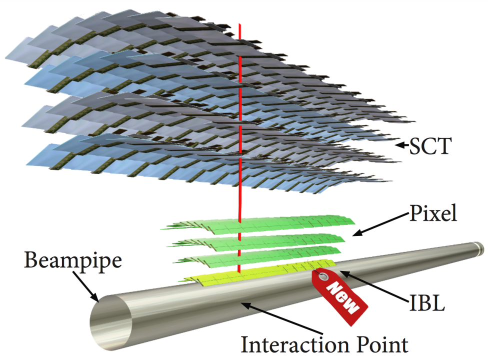
Minimum Bias measurements in LHCb:

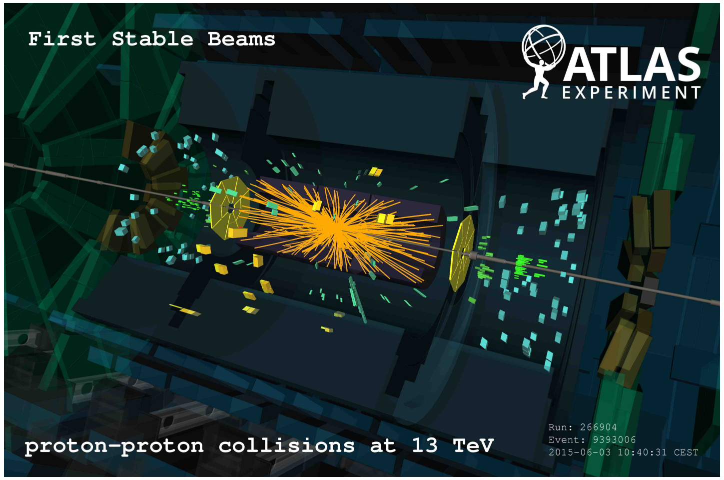
- 7 TeV (12/2011)
  - p_T > 1 GeV, -2.5<η<-2.0, 2.0<η<4.5

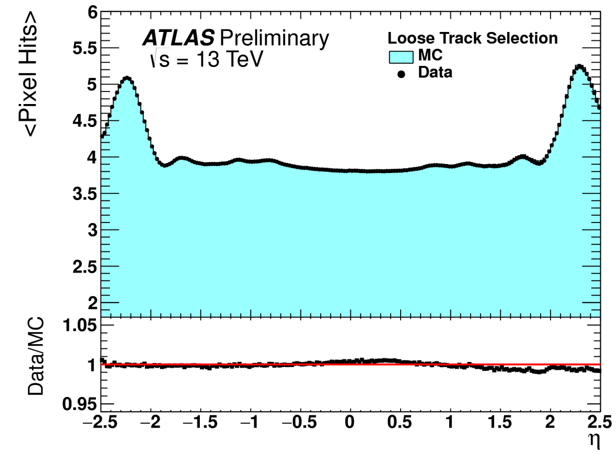
Summarising:
Very different detectors, but trying to have some common phase space to compare results!

Minimum Bias in ATLAS

- ATLAS is a general purpose detector with a tracking system ideal for the measurement of particle kinematics
  - New **Insertable B-Layer** (**IBL**) added to the tracking system during Long Shutdown 1

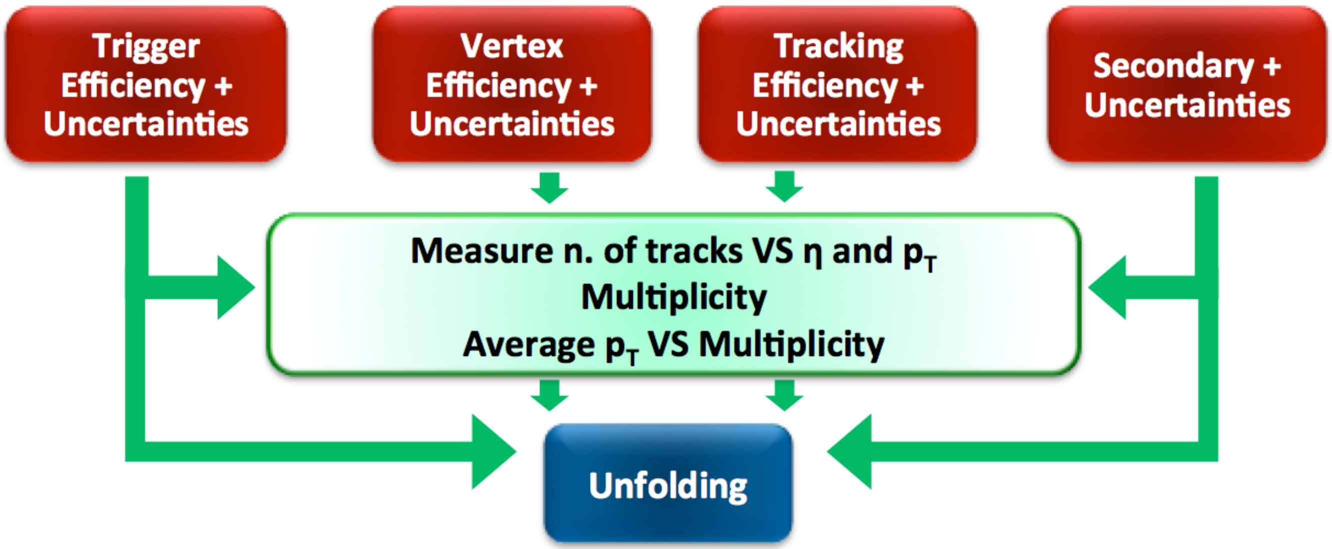






- To study an **Extended Phase Space** with p_T > 100 MeV a **robust low p_T reconstruction** is fundamental!
- Possible in Run 1, but much improved in RUN 2 thanks to the **IBL** which allows to use an extra measurement point
- **Critical evaluation of the systematics** when going to very low p_T
  - Main source is the accuracy with which the amount of material in the Inner Detector is known
  - **Material studies are fundamental** → details in the next slides

Analysis Overview

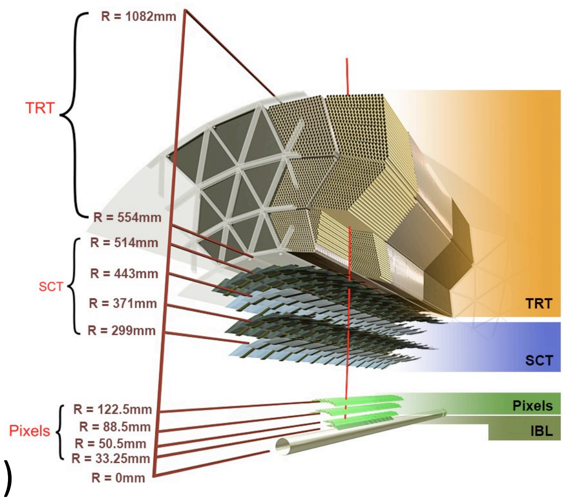


In this talk:

- **Focus on** the nominal phase space investigated within the **Minimum Bias analysis at 13 TeV** and comparison with the other phase spaces, where relevant:
  - Nominal: $p_T > 500$ MeV, $|\eta| < 2.5$ (All the details in the next slides, Phys. Lett. B **758**, 67–88 (2016))
  - Reduced: $p_T > 500$ MeV, $|\eta| < 0.8$ (For comparison to the various detectors, Phys. Lett. B **758**, 67–88 (2016))
  - Extended: $p_T > 100$ MeV, $|\eta| < 2.5$ (To investigate the low p_T region - Eur. Phys. J. C (2016) 76:502)
- Comparison with results at lower center-of-mass energy
  - **8 TeV** results recently published, Eur. Phys. J. C (2016) 76:403
  - High multiplicity phase spaces (**n_{ch}>20,50**) investigated for the first time in ATLAS for a more comprehensive understanding of the minimum bias events

Minimum Bias Analysis at 13 TeV: Event Selection

- Accepted on single-arm Minimum Bias Trigger Scintillator (MBTS)
- Primary vertex (2 tracks with p_T >100 MeV)
- Veto on any additional vertices with ≥ 4 tracks
- At least 1 selected track:
  - p_T > 500 MeV and $|\eta| < 2.5$ (Nominal phase space) or $|\eta| < 0.8$ (Reduced phase space)
- Or at least 2 selected tracks:
  - p_T > 100 MeV and $|\eta| < 2.5$ (Extended phase space)
- For each track:
  - At least 1 Pixel hit
  - At least
    - 2 SCT hits if p_T < 300 MeV
    - 4 SCT hits if p_T < 400 MeV
    - 6 SCT hits if p_T > 400 MeV
  - IBL hit required
  - $|d_0^{BL}| < 1.5$ mm (transverse impact parameter w.r.t beam line)
  - $|\Delta z_0 \sin\vartheta| < 1.5$ mm (Δz_0 is the difference between track z_0 and vertex z position)
  - Track fit χ^2 probability > 0.01 for tracks with p_T > 10 GeV



Primary Charged Particles: charged particles with a mean lifetime > 300 ps, either directly produced in pp interactions or from subsequent decays of directly produced particles with < 30 ps → strange baryons excluded (more details in the next slides)

Data and Simulation Samples

Simulation:

- **Pythia8**
  - A2 → ATLAS Minimum Bias tune, based on MSTW2008LO
  - Monash → alternative tune, based on NNPDF2.3LO
- **EPOS 3.1** → effective QCD-inspired field theory, tuned on cosmic rays data
- **QGSJET-II** → based on Reggeon Field Theory, no color reconnection

Data:

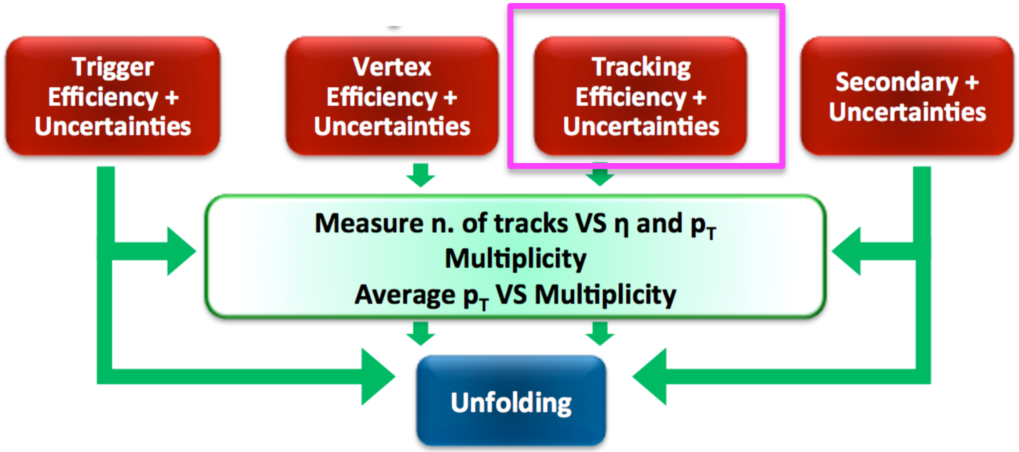
Using the two 13 TeV runs with low mean number of interactions per bunch crossing (<μ> ~ 0.005)

→

151 μb^{-1}
8,870,790 events selected, with
106,353,390 selected **tracks**
(500 MeV)

In the 100 MeV case: nearly double tracks, but more difficult measurement due to increased impact from multiple scattering at low pt and imprecise knowledge of the material in the ID

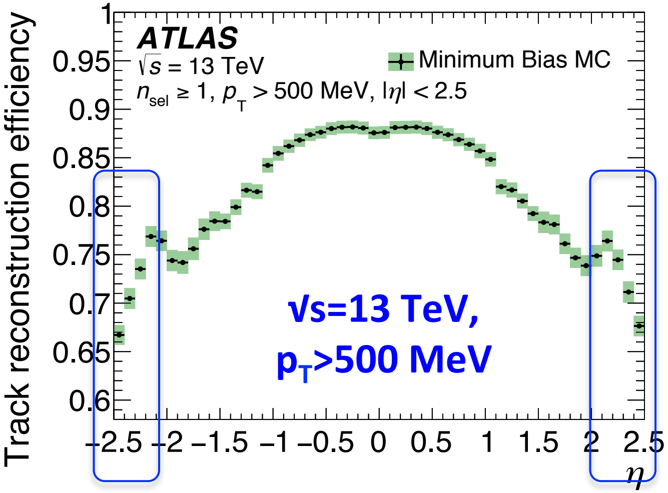
Track Reconstruction Efficiency

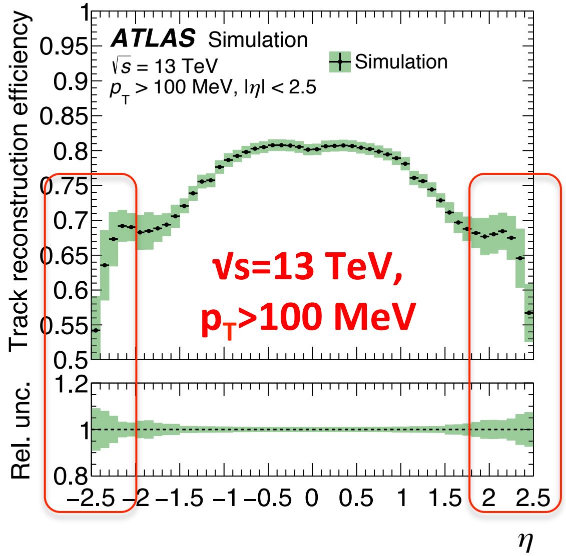


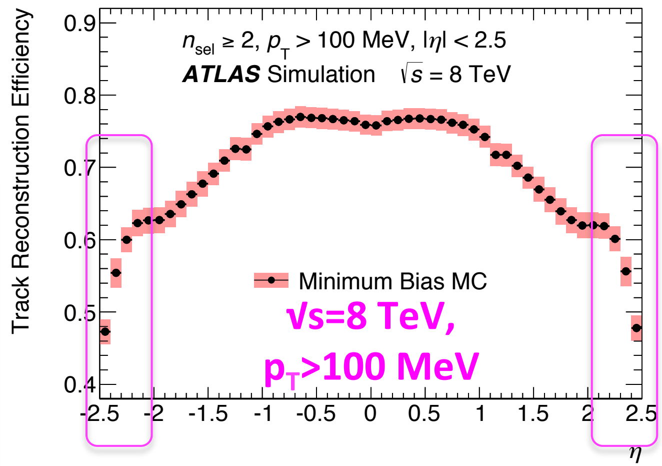
- Main ingredient for the Minimum Bias analysis
- Critical evaluation of the systematics when going to very low p_T
- At 13 TeV, different approaches taken for the nominal and the extended phase space → discussed in the next slides

Track Reconstruction Efficiency

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







Systematic Uncertainty	Size ($\sqrt{s}$=13 TeV, p_T>500 MeV)	Size ($\sqrt{s}$=13 TeV, p_T>100 MeV)	Size ($\sqrt{s}$=8 TeV, p_T>100 MeV)
Track Selection	0.5%	0.5%	0.5% - 8%
χ^2 probability	0.5% - 5%	0.2% - 7%	
Material	0.6% - 1.5%	1% - 9%	1.6% - 3.5% (up to 8% for p_T < 150 MeV)

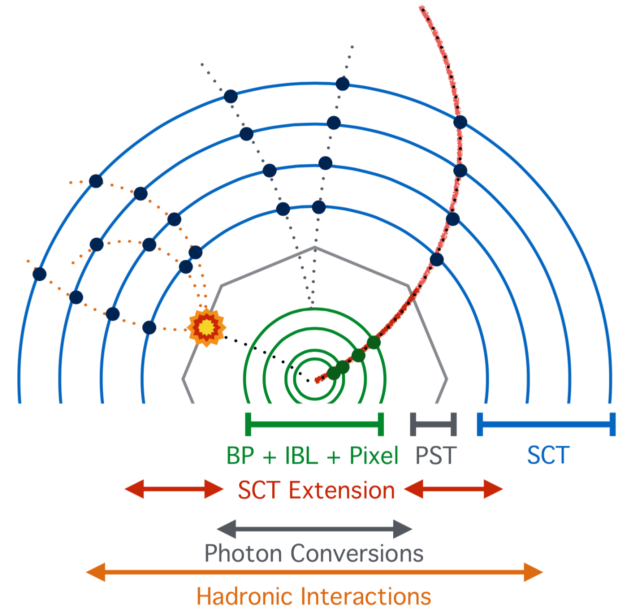
Systematic uncertainty dominated by the lack of knowledge of the material distribution!

Material Studies

- The accuracy with which the amount of material in the ID is known contributes the **largest source of uncertainty on** the simulation-based estimate of the **track reconstruction efficiency**

- Complementary tracking studies to probe the changes made to the ID during LS1
  - new **smaller beam pipe installed together with the IBL**
  - new **more robust pixel service connections** installed at the same time

METHOD	SENSITIVE REGION
Hadronic Interactions Rate	Beam Pipe – Pixel – First SCT layer
Photon Conversions Rate	Beam Pipe – Pixel – First SCT layer
SCT Extension Efficiency	**Pixel Services**

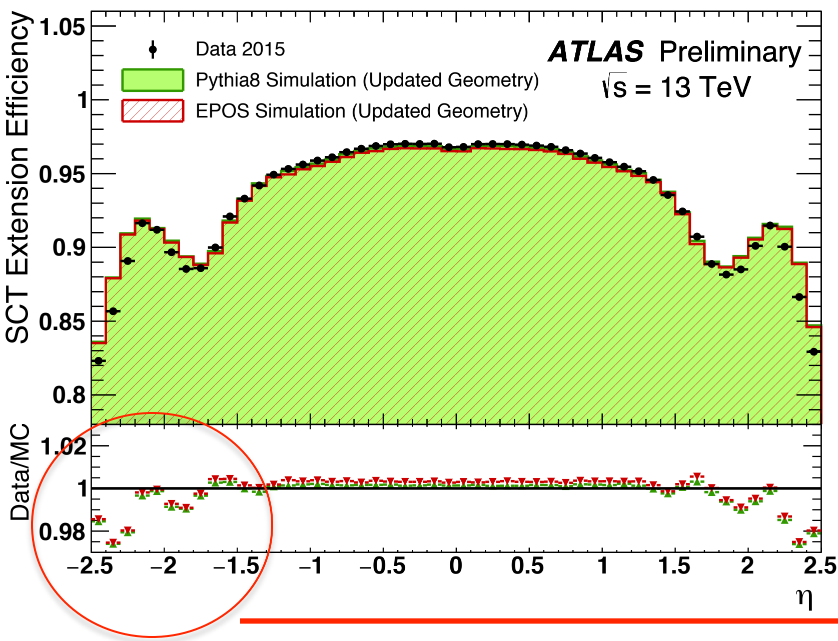


- First qualitative results released in a PUBNote (ATL-PHYS-PUB-2015-050) in November 2015

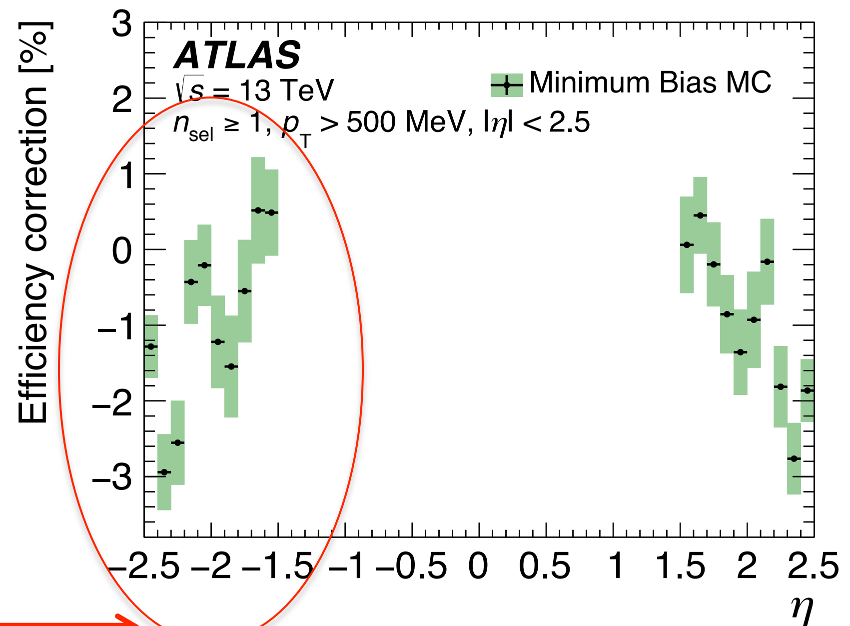
Data-driven correction to the Tracking Efficiency

- **SCT-Extension Efficiency**: rate of pixel stand-alone tracks successfully extended to include SCT clusters and to build a full silicon track → $\varepsilon_{ext} \equiv \frac{N_{tracklet}(\text{matched})}{N_{tracklet}}$
- In the **500 MeV** phase space, the track reconstruction efficiency in the region **1.5 < |η| < 2.5** is corrected using the results from the SCT-Extension Efficiency

SCT-Extension Efficiency

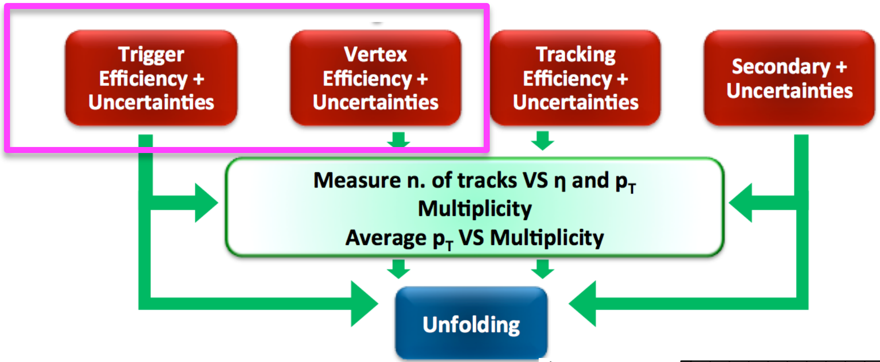


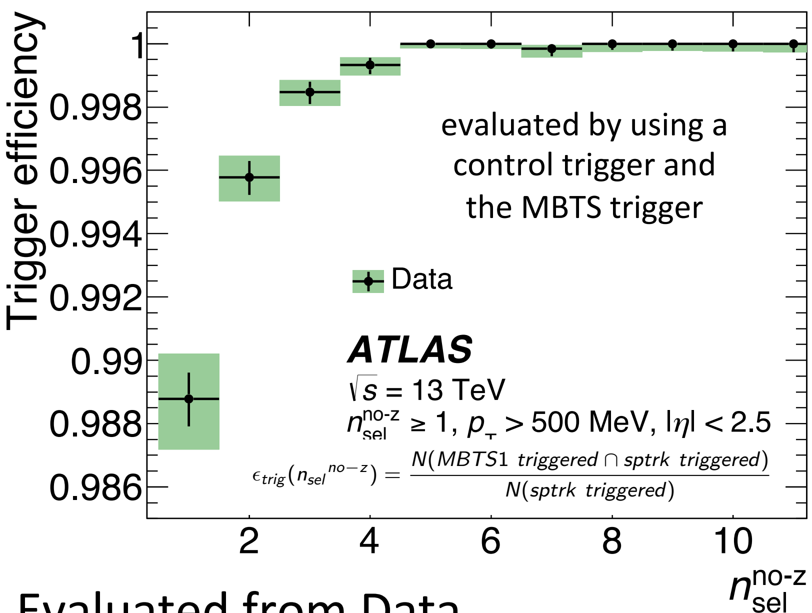
Tracking Efficiency Correction

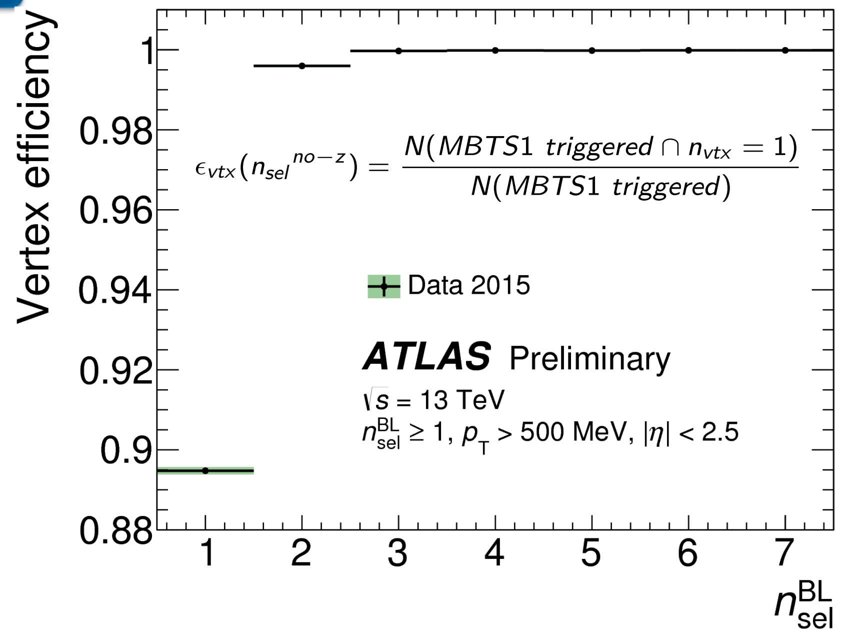


- Shape of the Data to Simulation ratio of the SCT-Extension Efficiency reflected into the shape of the correction applied to the Tracking Efficiency
- **Big reduction of the systematic uncertainties**
- Only applied in the Nominal phase space due to issues extrapolating to low p_T

Trigger and Vertex Reconstruction Efficiency

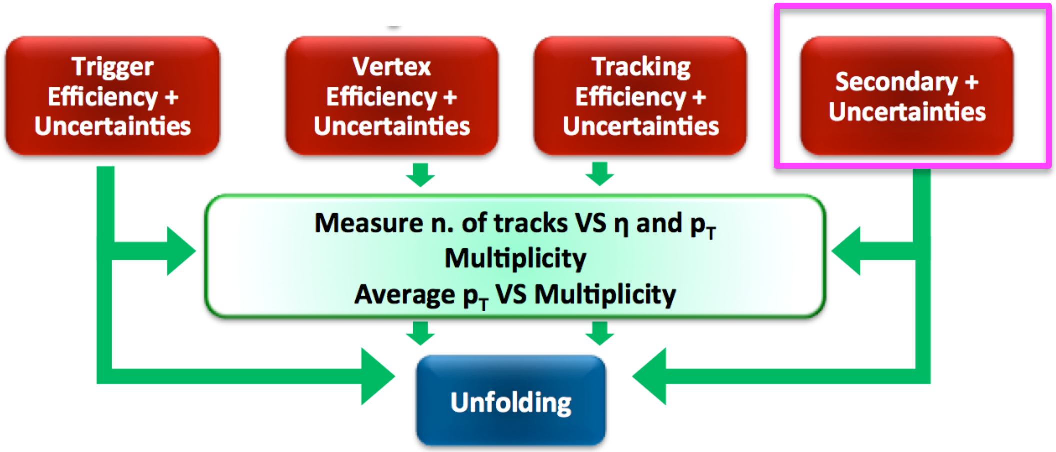






- Evaluated from Data
- Dependence on kinematic quantities studied:
  - negligible p_T-dependence
  - visible n_{sel}-dependence
  - negligible systematic uncertainties

Background evaluation



Background contributions to the tracks from primary particles include:

- Strange baryons
- Secondary particles
- Fake tracks
  - Negligible in the 500 MeV phase space
  - Non-negligible in the 100 MeV phase space
  - Treated as part of the background

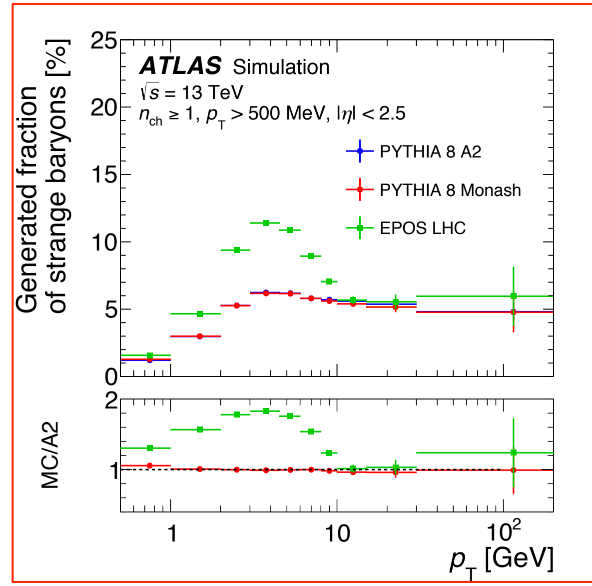
Strange Baryons

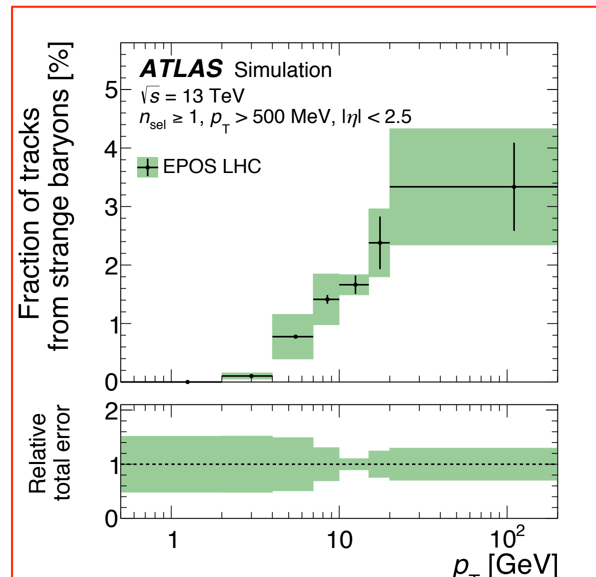
Common treatment of the Strange Baryons in all the 8 and 13 TeV analyses

- Particles with lifetime 30 ps < τ < 300 ps (**strange baryons**) are **no longer considered primary particles** in the analysis, decay products are treated like secondary particles

- **Low reconstruction efficiency** (<0.1%) and **large variations in predicted rates** lead to a model dependence (very different predictions in Pythia8 and EPOS)

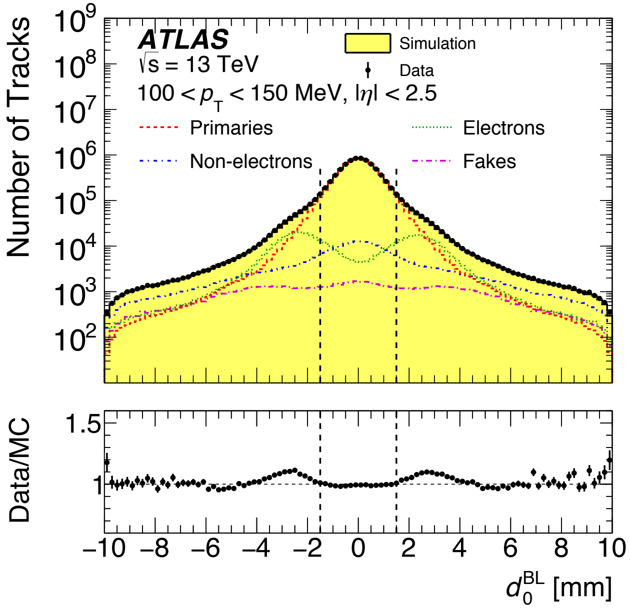
- **Final results produced with and without the strange baryons** to allow comparison with previous measurements





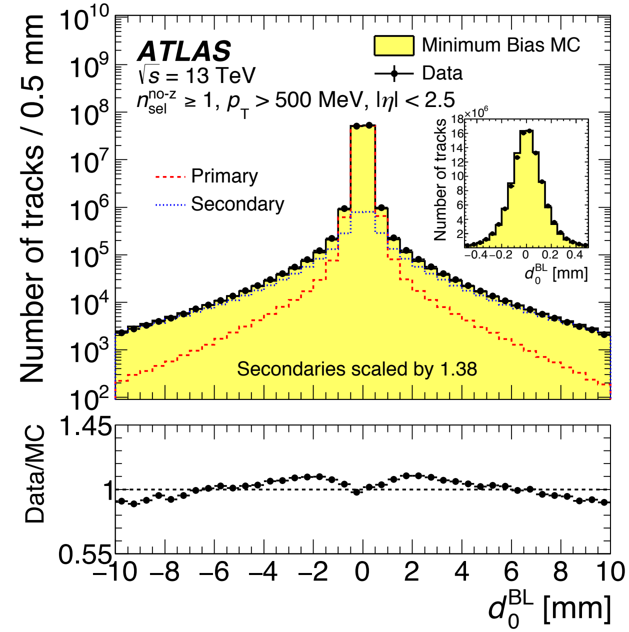
Secondaries

- Rate measured in data by performing a fit to the transverse impact parameter distribution
- **More detailed evaluation of secondaries in the 100 MeV phase-space with respect to the 500 MeV**



Create templates from:

- p_T < 500 MeV, split templates: primary, non-electrons, electrons and fakes
- p_T ≥ 500 MeV, combined template: primary and secondary



- Split templates only for p_T < 500 MeV:
  - Different shape of the transverse impact parameter distribution for electron and non-electron secondary particles → d_0^{BL} reflects the radial location at which the secondaries were produced
  - Different processes for conversion and hadronic interaction leading to differences in the radial distributions → electrons mostly produced from conversions in the beam pipe
  - Fraction of electrons increases as p_T decreases

Systematic Uncertainties Breakdown

- Zooming-in on some of the systematic uncertainties at 13 TeV (full list in the extra slides)

Systematic Uncertainty	Distribution	Size ($\sqrt{s}$=13 TeV, p_T>500 MeV)	Size ($\sqrt{s}$=13 TeV, p_T>100 MeV)
Track Reconstruction Efficiency	η	0.5% - 1.4%	1 – 7%
	p_T	0.7%	1 – 6%
Non-primaries	η	0.5%	0.5%
	p_T	0.5% - 0.9%	0.5% -1 %
Non-closure	η	0.7%	0.4-1%
	p_T	0% - 2%	1% -3%

- **Main systematic uncertainty** on the final measurement **due to the uncertainty on the track reconstruction efficiency**

- **Smaller systematics** in the nominal phase space than in the extended one **thanks to the data-driven correction** applied to the tracking efficiency

Corrections

- Trigger and Vertex efficiency: event-wise correction

$$w_{\mathrm{ev}}(n_{\mathrm{sel}}^{\mathrm{BL}}, \eta) = \frac{1}{\varepsilon_{\mathrm{trig}}(n_{\mathrm{sel}}^{\mathrm{BL}})} \cdot \frac{1}{\varepsilon_{\mathrm{vtx}}(n_{\mathrm{sel}}^{\mathrm{BL}}, \eta)},$$

- Tracking efficiency: track-wise correction

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

f_{sec} → secondary tracks

f_{sb} → strange baryons

f_{okr} → outside kinematic range

- Bayesian unfolding to correct both the multiplicity n_{ch} and p_T
  - Additional correction for events out of kinematic range e.g. events with ≥1 particles but < 1 track

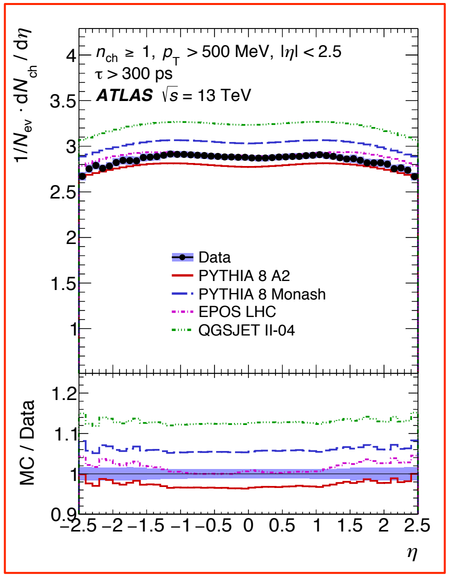
- Mean p_T vs n_{ch} bin-by-bin correction of average p_T, then n_{ch} migration

Final Results – 13 TeV

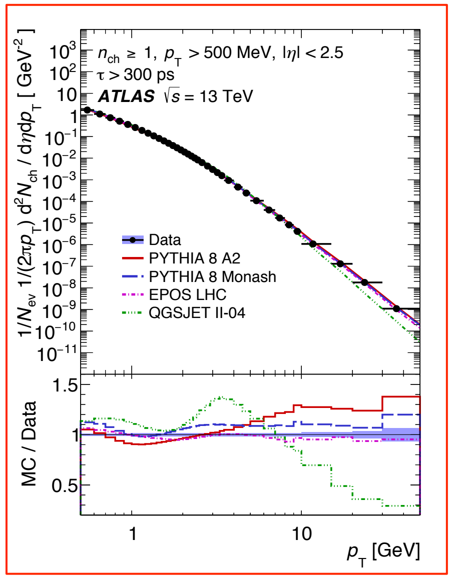
Data
PYTHIA 8 A2
PYTHIA 8 Monash
EPOS LHC
QGSJET II-04

- Nominal Phase Space (p_T > 500 MeV, |η|< 2.5)

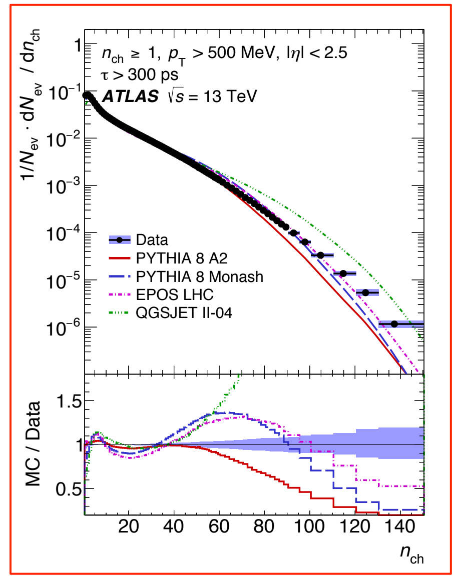
$dN_{ch}/d\eta$



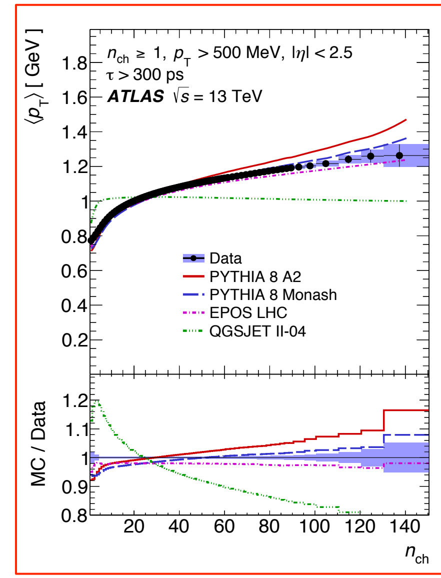
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



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



Models differ mainly in normalisation, shape similar

Measurement spans 10 orders of magnitude

Low n_{ch} not well modelled by any MC; large contribution from diffraction;
Models without colour reconnection (QGSJET) fail to model scaling with nch very well

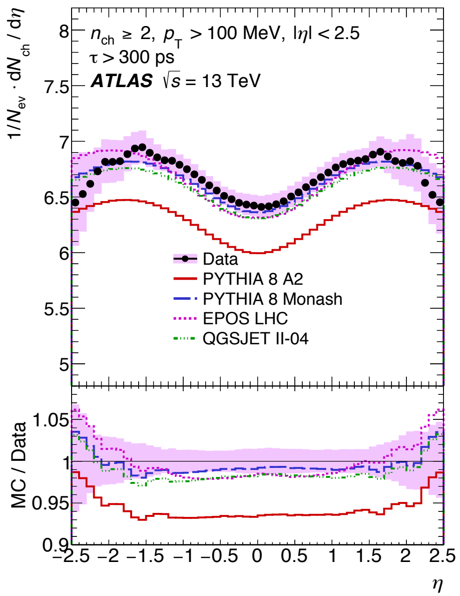
Some Models/Tunes give remarkably good predictions (EPOS, Pythia8)

Final Results – 13 TeV

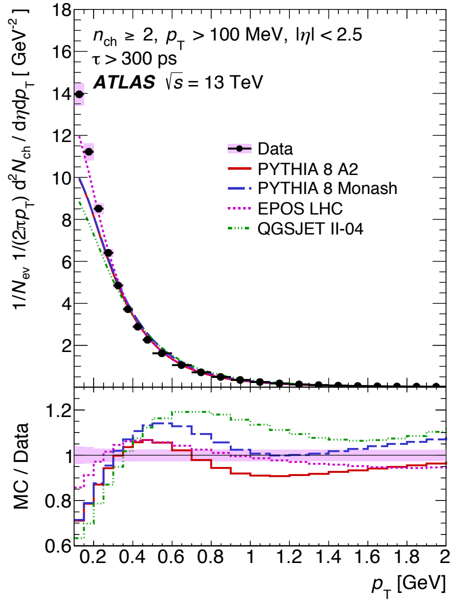
Data
PYTHIA 8 A2
PYTHIA 8 Monash
EPOS LHC
QGSJET II-04

- Extended Phase Space (p_T > 100 MeV, $|\eta|$< 2.5)

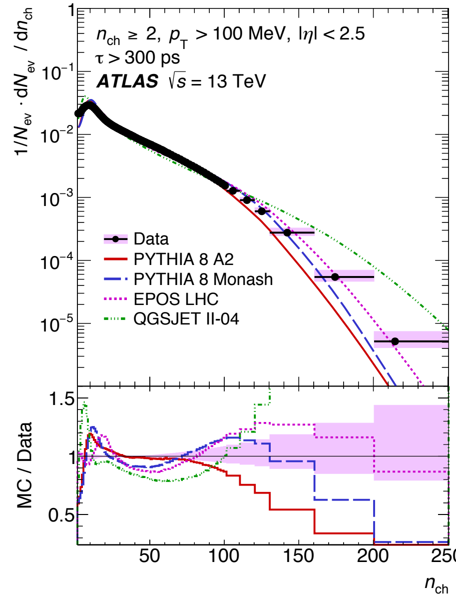
$dN_{ch}/d\eta$



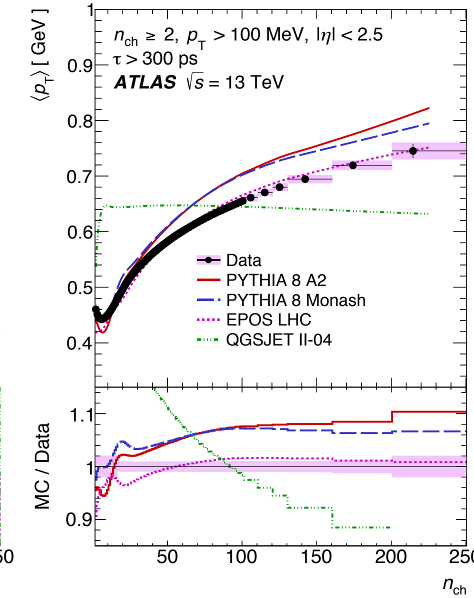
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



- Up to 7% of systematics in the high eta region
- Good prediction by all the generator, except Pythia 8 A2 which lies below the data

Difficult predictions in the low p_T region

Good data/MC agreement given by EPOS (within 2%), worse predictions given by the other generators

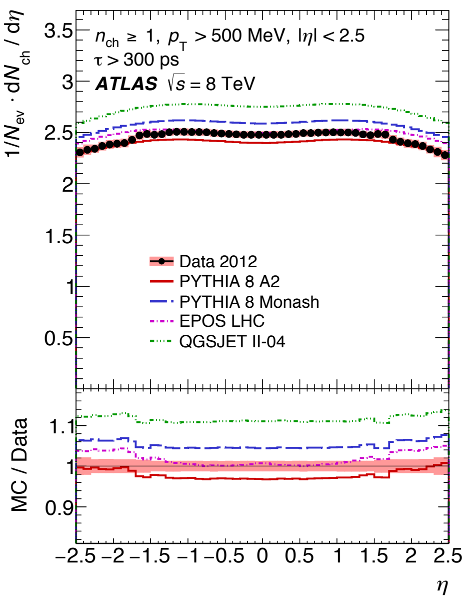
EPOS gives the best prediction!
Much clearer in this low p_T regime than in the nominal phase space!

Final Results – 8 TeV

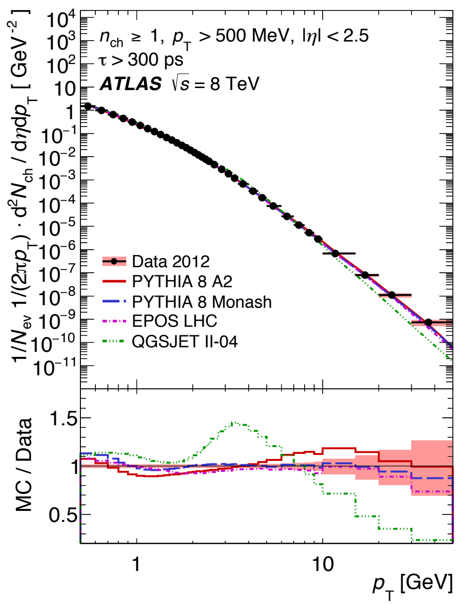
- Data 2012
- PYTHIA 8 A2
- PYTHIA 8 Monash
- EPOS LHC
- QGSJET II-04

- Nominal Phase Space (p_T > 500 MeV, $|\eta|$< 2.5)

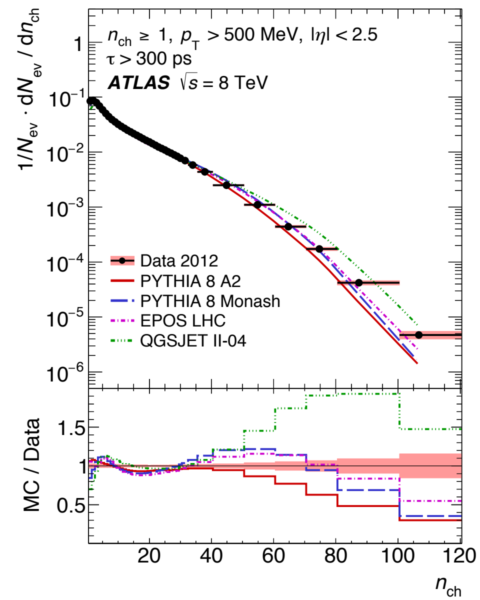
$dN_{ch}/d\eta$



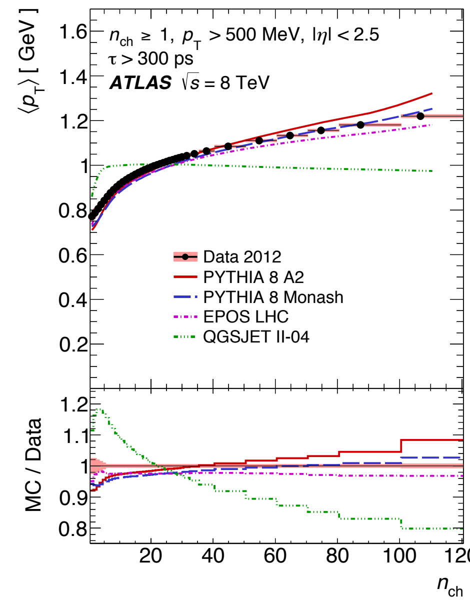
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



- EPOS gives good prediction in the central region and overestimates data in the forward region
- Pythia 8 A2 lies below the data, while Pythia 8 Monash and QGSJet overestimate data

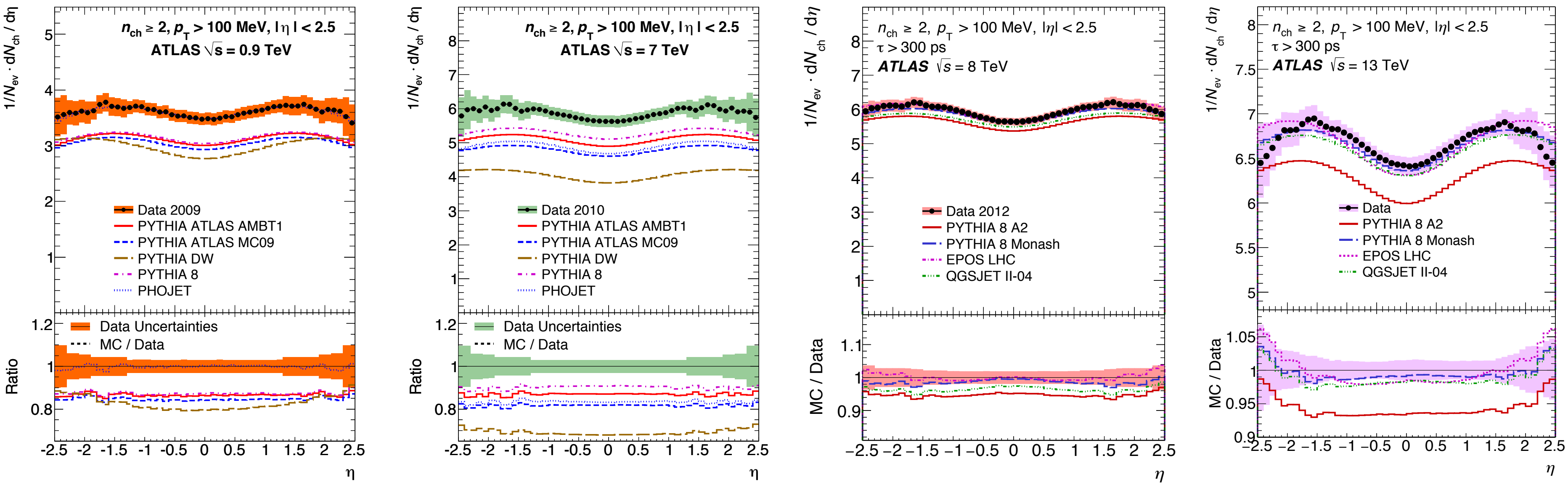
Above 1 GeV, good predictions given by Pythia 8 Monash

None of the models is consistent with the data although the Epos LHC model provides a fair description

EPOS gives the best prediction!

Final Results – Comparison with previous analyses

- Extended Phase Space (p_T >100 MeV, |η|< 2.5)



- **Strong dependence on the ID material in the forward region!**

- From 7 to 8 TeV, up to 50% improvement in the central region and 65% improvement in the high eta region thanks to the good knowledge of the material in the ID achieved at the end of Run 1

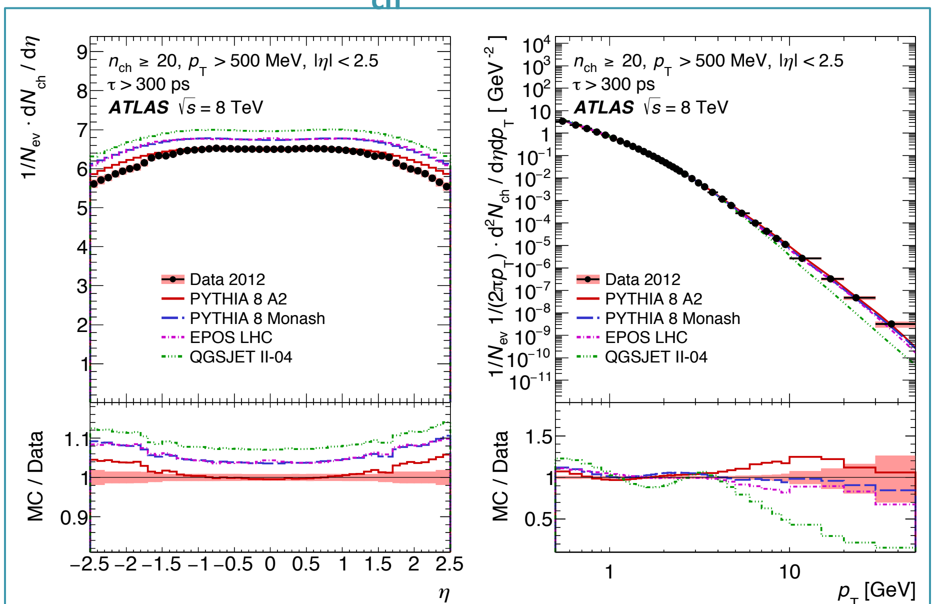
Bonus 1 – High Multiplicity Regime at 8 TeV

- Compared with earlier studies, the 8 TeV analysis also presents ATLAS measurements of final states at high multiplicities of $n_{ch} \geq 20$ and $n_{ch} \geq 50$

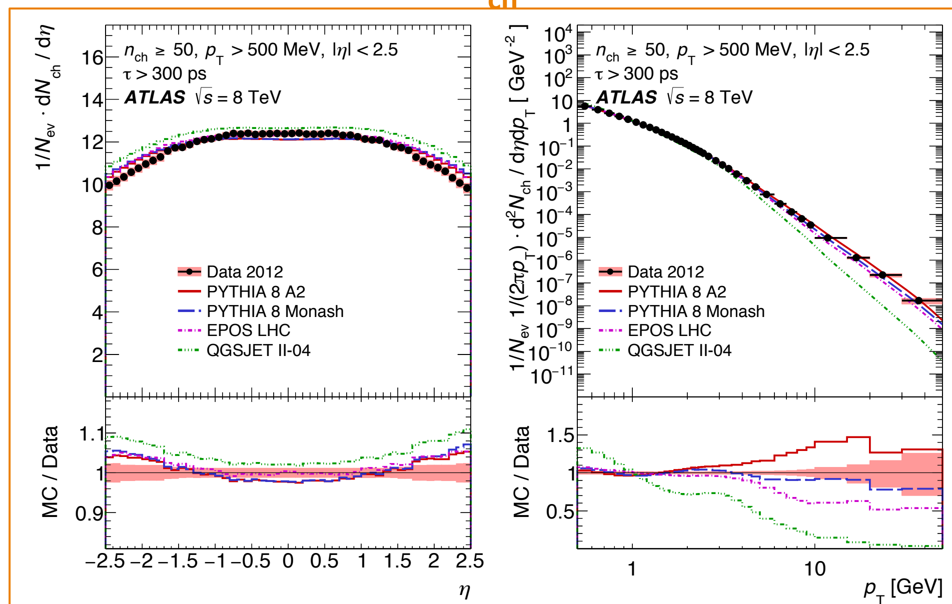
Phase Space		$1/N_{ev} \cdot dN_{ch}/d\eta$ **at** $\eta = 0$	
$n_{ch} \geq$	p_T[MeV] $>$	$\tau > 300$ ps (fiducial)	$\tau > 30$ ps (extrapolated)
2	100	5.64 ± 0.10	5.71 ± 0.11
1	500	2.477 ± 0.031	2.54 ± 0.04
6	500	3.68 ± 0.04	3.78 ± 0.05
20	500	6.50 ± 0.05	6.66 ± 0.07
50	500	12.40 ± 0.15	12.71 ± 0.18

Data 2012
PYTHIA 8 A2
PYTHIA 8 Monash
EPOS LHC
QGSJET II-04

$n_{ch} \geq 20$



$n_{ch} \geq 50$



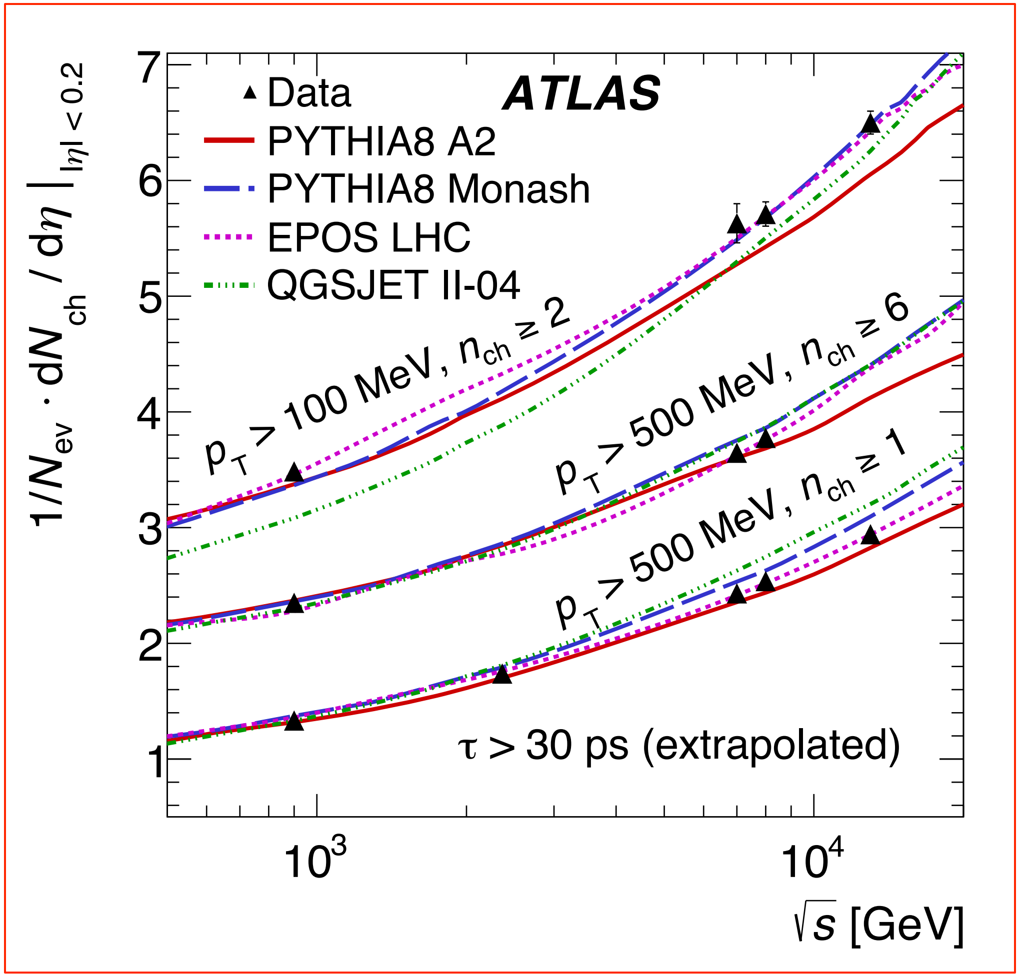
Pythia 8 A2 describes the plateau in the central region well

Fair prediction by Pythia8 and EPOS at low p_T, but large deviation at high p_T

All models overestimate data at $|\eta| > 1.7$ but better description in the central region

Fair prediction by Pythia8 and EPOS at low p_T, but large deviation at high p_T

Final Results



- Mean number of **primary charged particles increases by a factor of 2.2** when √s increases by a factor of about 14 **from 0.9 TeV to 13 TeV**!
- Looking at the overall picture, **best predictions for this observable is given by EPOS followed by Pythia 8 A2 and Monash**!

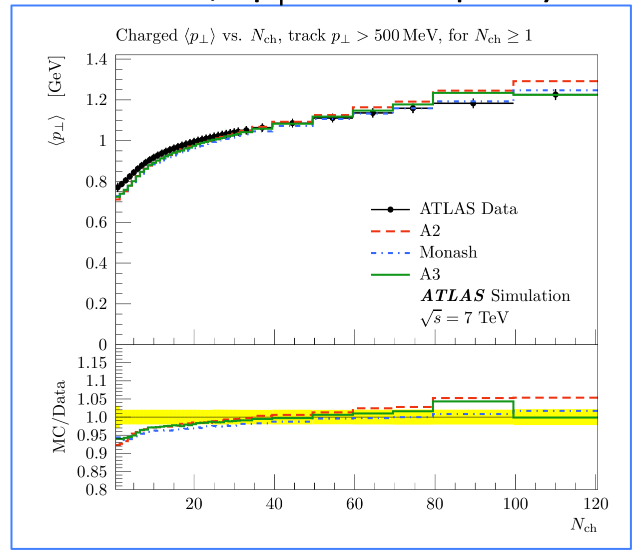
Bonus 2 – Pythia 8 A3

13 TeV MinBias results already used for a new Pythia 8 Tune: Pythia 8 – A3 (ATL-PHYS-PUB-2016-017)

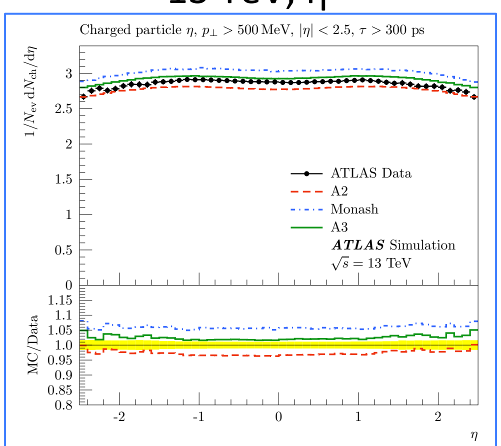
$\sqrt{s}$	Measurement type	Rivet name
13 TeV	MB	ATLAS_2016_I1419652 [3]
13 TeV	INEL XS	MC_XS [5]
7 TeV	MB	ATLAS_2010_S8918562 [11]
7 TeV	INEL XS	ATLAS_2011_I89486 [4]
7 TeV	RAPGAP	ATLAS_2012_I1084540 [15]
7 TeV	ETFLOW	ATLAS_2012_I1183818 [14]
900 GeV	MB	ATLAS_2010_S8918562 [11]
2.36 TeV	MB	ATLAS_2010_S8918562 [11]
8 TeV	MB	ATLAS_2016_I1426695 [16]

Not directly used for the tuning, but compared with A3 after the tuning

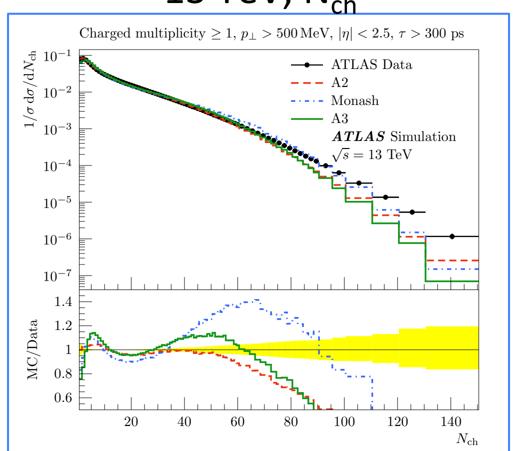
13 TeV, $\langle p_T \rangle$ vs multiplicity



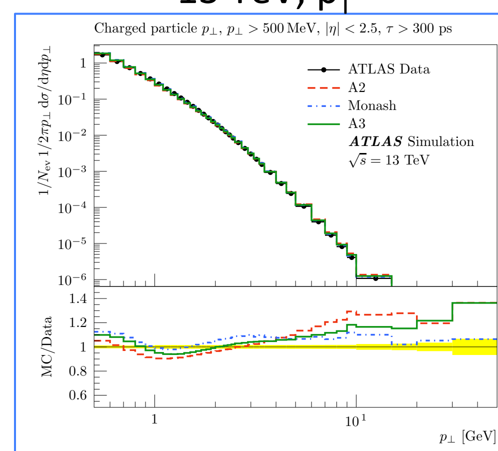
13 TeV, η



13 TeV, N_{ch}



13 TeV, p_T



arXiv:1502.07947

Bose-Einstein Correlation

- Particle correlations play an important role in the understanding of multi-particle production
- Correlations between identical bosons, called **Bose-Einstein Correlations** (**BEC**), are a well-known phenomenon in high-energy and nuclear physics

$$C_2(p_1,p_2) = \frac{\rho(p_1,p_2)}{\rho_0(p_1,p_2)}$$

Two-particle probability density function

Reference probability density function constructed to exclude BEC effects

Four-momenta of two identical bosons

- They represent a sensitive probe of the space-time geometry of the hadronization region and allow the determination of the size and the shape of the source from which particles are emitted
- Analysis of BEC dependence on particle multiplicity and transverse momentum helps to understand the multi-particle production mechanism
- Studies of one-dimensional BEC effects in pp collisions at centre-of-mass energies of 0.9 and 7 TeV are presented for both minimum bias and high-multiplicities data

$$Q^2 = -(p_1 - p_2)^2$$ →

$$C_2(Q) = \frac{\rho(Q)}{\rho_0(Q)} = C_0[1+\Omega(\lambda, QR)](1+\varepsilon Q)$$ →

$$R_2(Q) = \frac{C_2(Q)}{C_2^{MC}(Q)} = \frac{\rho(++,--)}{\rho(+-)} \Big/ \frac{\rho^{MC}(++,--)}{\rho^{MC}(+-)}$$

The BEC effect is usually described by a function with two parameters:

- effective radius **R**
- strength (or incoherence) parameter **λ**

In this studies, the density function is calculated for like-sign charged-particle pairs, with both the ++ and -- combinations included

Event Selection and Samples

- Same even selection and unfolding procedure as in the minimum bias analysis
  - Same MBTS trigger
  - Same track quality criteria
- Same approach applied to High Multiplicity (HM) events (> 120 tracks)
  - Studies showed that there is less than 1 pile-up track selected in the HM sample, negligible influence on BEC studies

Data:

- 0.9 TeV min Bias: 3.6 • 10^5 events, 4.5 • 10^6 tracks
- 7 TeV min Bias: 1 • 10^7 events, 2.1 • 10^8 tracks
- 7 TeV HM: 1.8 • 10^4 events, 2.7 • 10^6 tracks

Simulation:

- Pythia 6.421 – MC09 ATLAS tune, for both min Bias and HM samples (non-, single-, double-diffractive as in the predicted cross-section
- For Systematics:
  - PHOJET 1.12.1.35
  - Pythia – Perugia0 tune
  - EPOS 1.99_v2965 LHC tune

	0.9 TeV		7 TeV		7 TeV (HM)	
Source	λ	R	λ	R	λ	R
Track reconstruction efficiency	0.6%	0.7%	0.3%	0.2%	1.3%	0.3%
Track splitting and merging	negligible		negligible		negligible	
Monte Carlo samples	14.5%	12.9%	7.6%	10.4%	5.1%	8.4%
Coulomb correction	2.6%	0.1%	5.5%	0.1%	3.7%	0.5%
Fitted range of Q	1.0%	1.6%	1.6%	2.2%	5.5%	6.0%
Starting value of Q	0.4%	0.3%	0.9%	0.6%	0.5%	0.3%
Bin size	0.2%	0.2%	0.9%	0.5%	4.1%	3.4%
Exclusion interval	0.2%	0.2%	1%	0.6%	0.7%	1.1%
Total	14.8%	13.0%	9.6%	10.7%	9.4%	10.9%

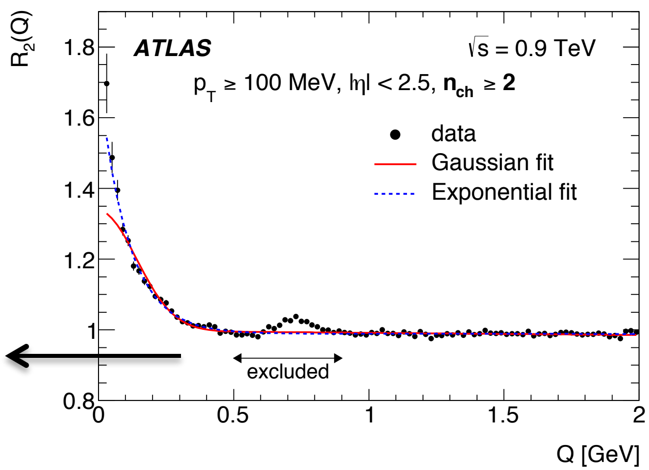
arXiv:1502.07947

Bose-Einstein Correlation Function

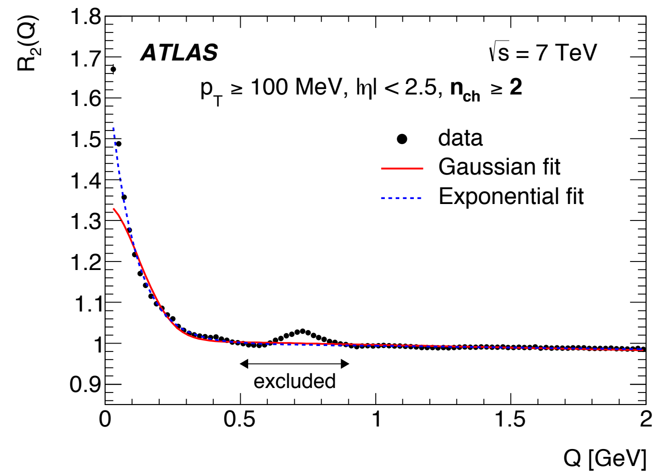
- Two parameterizations of the Ω(λ,QR) function have been investigated:

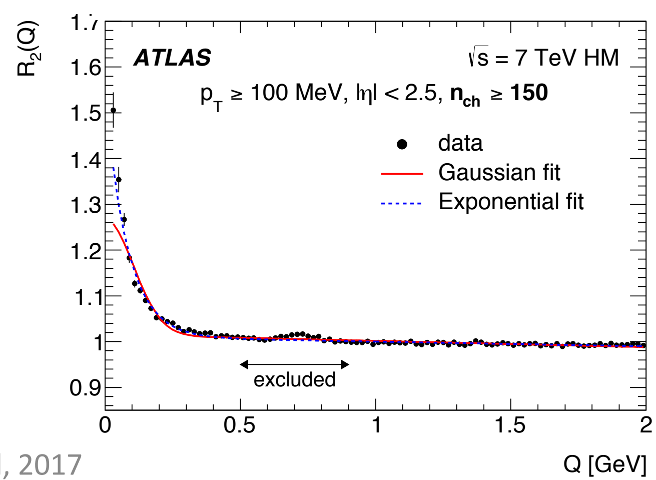
$$\Omega = \lambda \cdot \exp\left(-R^2Q^2\right)$$ → Goldhaber, spherical shape with a radial Gaussian distribution of the source

$$\Omega = \lambda \cdot \exp\left(-RQ\right)$$ → Exponential, radial Lorentzian distribution of the source



overestimate of $\rho \to \pi^+\pi^-$ decays in the Monte Carlo simulation





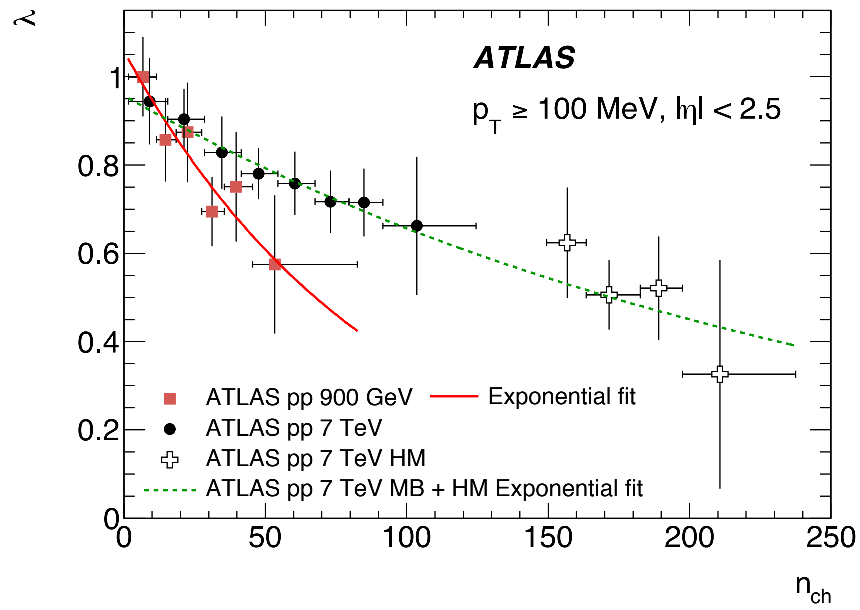
Good agreement between data and exponential fit:

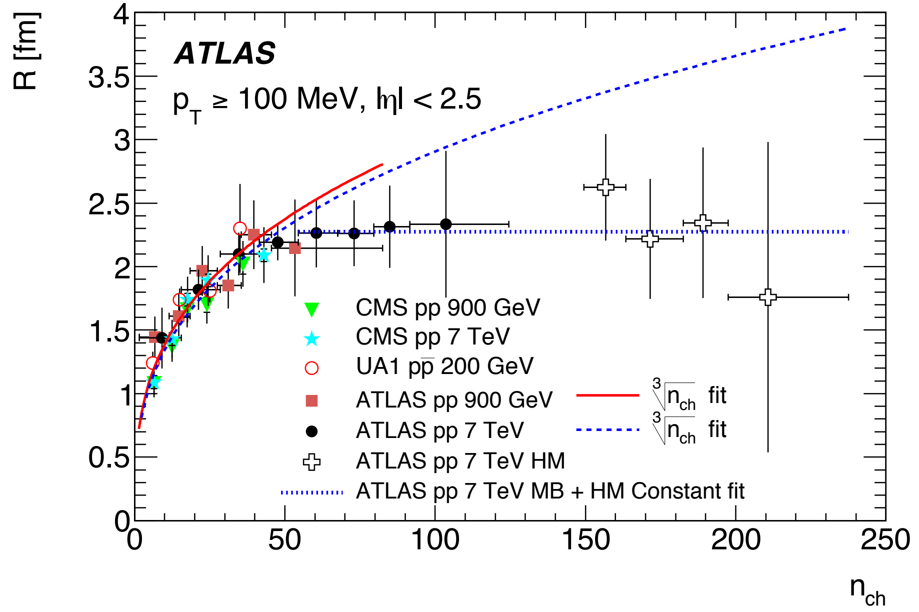
$$\lambda = 0.74 \pm 0.11,\ R = 1.83 \pm 0.25 \text{ at } \sqrt{s} = 0.9 \text{ TeV for } n_{\rm ch} \geq 2,$$
$$\lambda = 0.71 \pm 0.07,\ R = 2.06 \pm 0.22 \text{ at } \sqrt{s} = 7 \text{ TeV for } n_{\rm ch} \geq 2,$$
$$\lambda = 0.52 \pm 0.06,\ R = 2.36 \pm 0.30 \text{ at } \sqrt{s} = 7 \text{ TeV for } n_{\rm ch} \geq 150.$$

arXiv:1502.07947

BEC fit parameters

- **Multiplicity dependence**





- The λ parameter decreases with multiplicity, faster for 0.9 TeV than for 7 TeV interactions

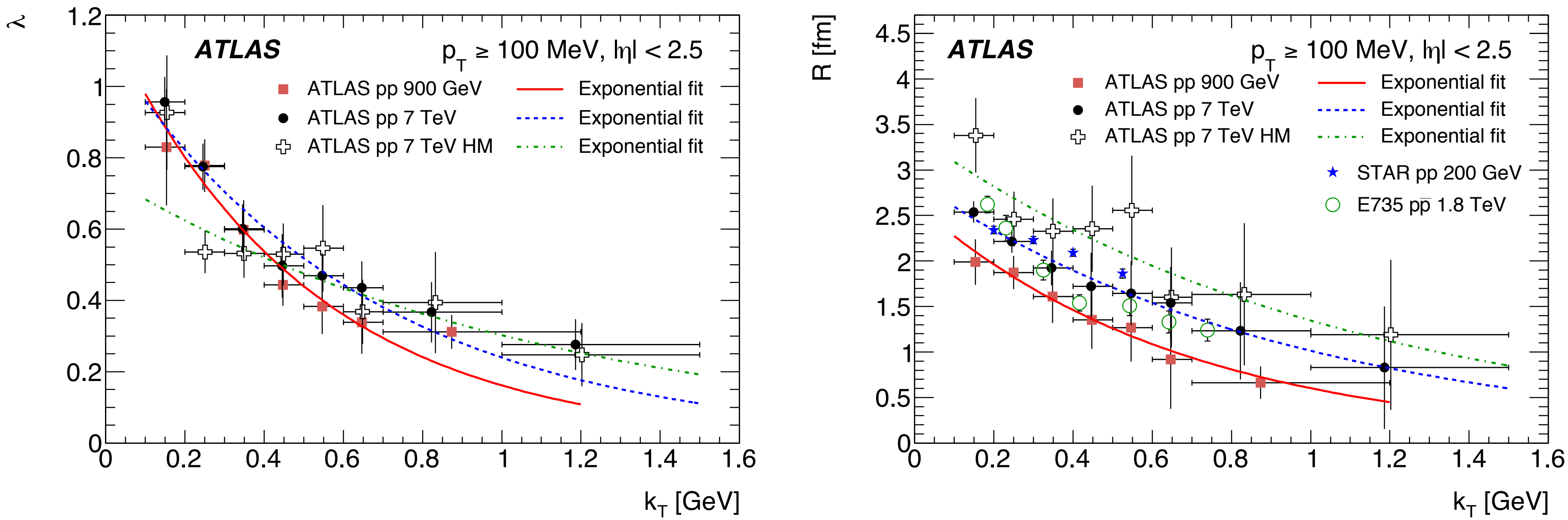
- λ = 0 -> fully coherent
- λ = 1-> chaotic

- The size of the emitting source increases with multiplicity up to about nch ≃ 50 independently of the center of mass energy
- For higher multiplicities, the measured R parameter is observed to be independent of multiplicity

arXiv:1502.07947

BEC fit parameters

- **Transverse momentum dependence**



- The λ and R parameters decreases with k_T faster for 0.9 TeV than for 7 TeV interactions, following exponential behavior
- For λ similar shape for 7 TeV min bias and HM events
- The values of the R parameters are observed to be energy-independent within the uncertainties

arXiv:1506.07098

Exclusive γγ → l^+l^- production

- Exclusive γγ → l^+l^- (l = e, μ) production studied with 7 TeV ATLAS data set
- **Clean signature** (two muons or electrons back-to-back, with no associated activity in the central detector)
- **Significant suppression factor** (~20%) due to additional interaction between the elastically scattered protons
- Cross-section of the photon measured with Equivalent Photon Approximation (EPA)

$$\sigma^{\mathrm{EPA}}_{pp(\gamma\gamma)\to\ell^+\ell^- pp} = \iint P(x_1)\, P(x_2)\, \sigma_{\gamma\gamma\to\ell^+\ell^-}(m^2_{\ell^+\ell^-})\, \mathrm{d}x_1\, \mathrm{d}x_2$$

Monte Carlo Samples:

- **Signal**: **Herwig++ 2.6.3** (implements EPA)
- **Photon-induced single-dissociative dilepton production** (dominant Background): **LPair** 4.0 with the Brasse and Suri-Yennie structure functions for proton dissociation
  - LPair interfaced to JetSet 7.408 with Lund fragmentation model
- **Double diffractive reactions**: **Pythia 8.175** with **NNPDF2.3QED**
- **DY Z/γ*→e^+e^-** and **Z/γ* → $\mu^+\mu^-$**: **Powheg 1.0** with **CT10** PDF interfaced with **Pythia 6.425** using **CTEQ6L1** PDF and **AUET2B** tune
- **DY Z/γ*→$\tau^+\tau^-$**: **Pythia 6.425** with **MRST LO*** PDF
- **Top-quark pair**: **MC@NLO 3.42**
- **W^+W^-, $W^\pm Z$, ZZ**: **Herwig 6.520**
- Generators used for Z/γ*, ttbar, di-boson events are interfaced with **Photos 3.0** to simulate **QED FSR** corrections
- **Pile-up**: **Pythia 6.425** with **AUET2B** tune and **CTEQ6L1** PDF

arXiv:1506.07098

Event Pre-Selection and Backgrounds

Pre-selection

- At least one collision vertex with at least 2 charged-particle tracks with $p_T > 400$ MeV
- At least 2 lepton candidates
  - Electron channel
    - Single electron trigger ($p_T > 20$-22 GeV, threshold increased during data-taking) and Di-electron trigger ($p_T > 12$ GeV)
    - Electron: $p_T > 12$ GeV, $|\eta| < 2.4$, with $1.37 < |\eta| < 1.52$ excluded, *medium* ID
    - $m_{e+e-} > 24$ GeV
  - Muon channel
    - Single electron trigger ($p_T > 18$GeV) and Di-electron trigger ($p_T > 10$ GeV)
    - MS-ID combined tracks
    - Muon: $p_T > 10$ GeV, $|\eta| < 2.4$, with $1.37 < |\eta| < 1.52$ excluded, *isolated* muon
    - $m_{\mu+\mu-} > 20$ GeV
- $1.57 \cdot 10^6$ di-electron and $2.42 \cdot 10^6$ di-muon candidates after the above selection

Backgrounds:

- $\gamma\gamma \rightarrow \tau^+\tau$ and $\gamma\gamma \rightarrow W^+W^-$ negligible
- Dissociative backgrounds estimated from MC
- Electroweak (Z/γ^*, di-bosons) and ttbar from MC, normalization to pQCD cross sections
- Multi-jet from data-driven methods (electron: all pre-selection except medium ID; muons same-charge muon pair passing pre-selection)

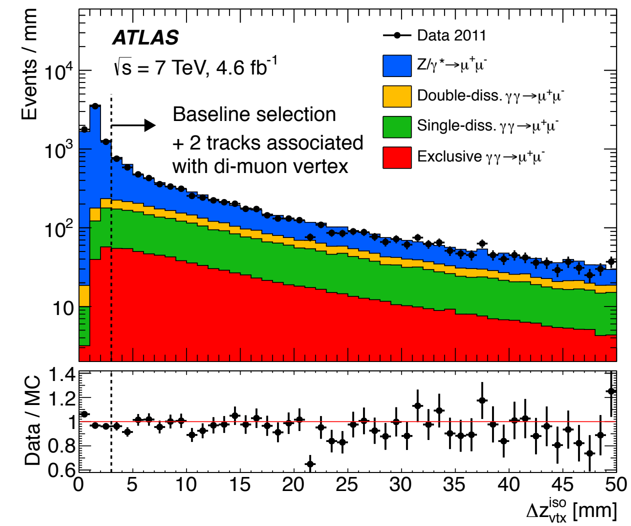
arXiv:1506.07098

Exclusive Event Selection

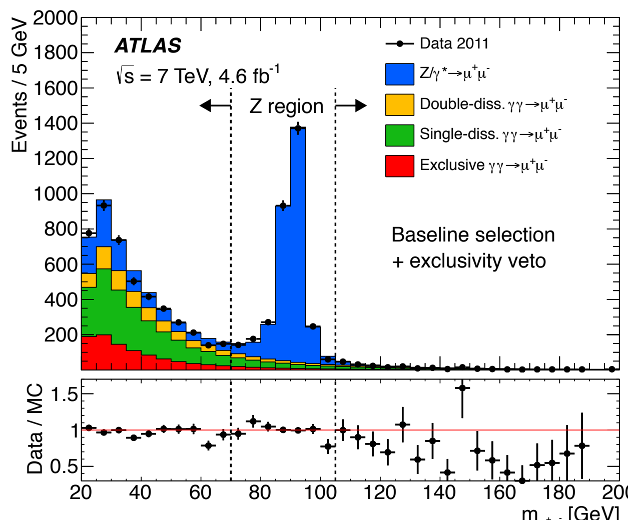
After pre-selection, additional requirements are needed to select exclusive di-lepton events:

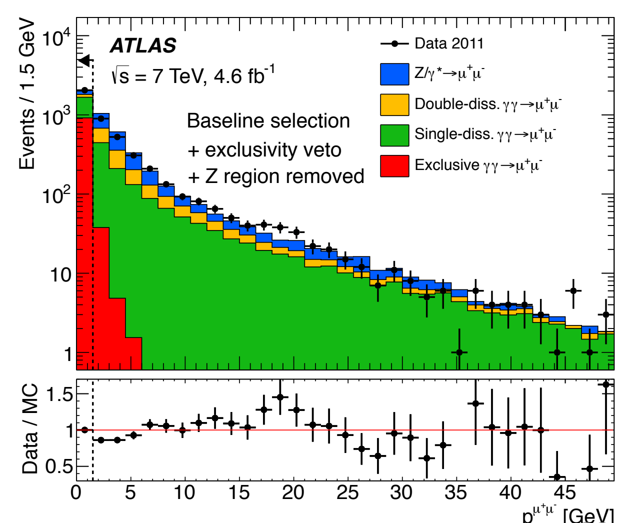
- Exclusivity veto: no additional tracks associated with the primary vertex, no additional vertex within 3 mm Δz_{vtx}^{iso}
- Remove Z-boson mass window 70 GeV < m_{l+l-} < 105 GeV
- p_T^{l+l-} < 1.5 GeV

Selection	$\gamma\gamma \to \ell^+\ell^-$ Signal	$\gamma\gamma \to \ell^+\ell^-$ S-diss.	$\gamma\gamma \to \ell^+\ell^-$ D-diss.	$Z/\gamma^* \to \ell^+\ell^-$	Multi-jet	$Z/\gamma^* \to \tau^+\tau^-$	$t\bar{t}$	Di-boson	Total predicted	Data
Electron channel ($\ell = e$)										
Preselection	898	2096	2070	1 460 000	83 000	3760	4610	1950	1 560 000	1 572 271
Exclusivity veto	661	1480	470	3140	0	9	0	5	5780	5410
Z region removed	569	1276	380	600	0	8	0	3	2840	2586
$p_T^{\ell^+\ell^-} < 1.5$ GeV	438	414	80	100	0	2	0	0	1030	869
Muon channel ($\ell = \mu$)										
Preselection	1774	3964	4390	2 300 000	98 000	7610	6710	2870	2 420 000	2 422 745
Exclusivity veto	1313	2892	860	3960	3	8	0	6	9040	7940
Z region removed	1215	2618	760	1160	3	8	0	3	5760	4729
$p_T^{\ell^+\ell^-} < 1.5$ GeV	1174	1085	160	210	0	3	0	0	2630	2124



Even after exclusive selection, still significant contamination from DY, single- and double-dissociative processes…





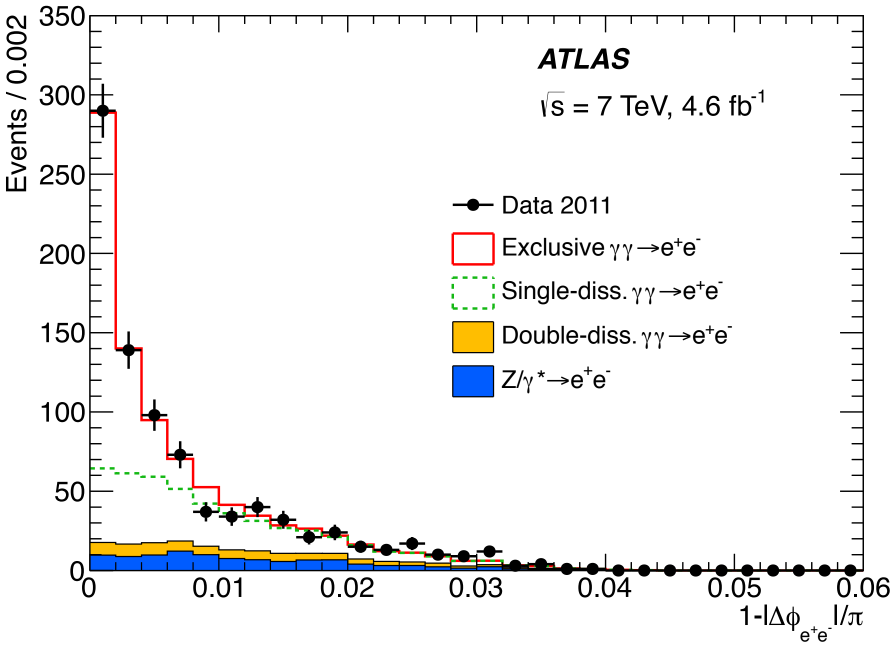
arXiv:1506.07098

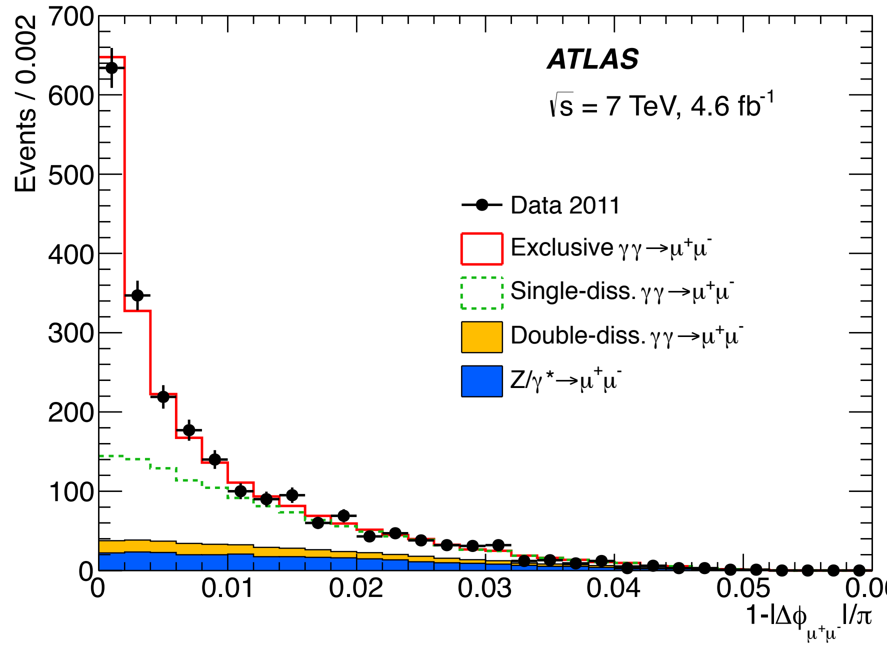
Scale Factors

- Even after exclusive selection, still significant contamination from DY, single- and double-dissociative processes

$R^{\mathrm{excl.}}_{\gamma\gamma\to e^+e^-}$ $R^{\mathrm{excl.}}_{\gamma\gamma\to\mu^+\mu^-}$

- Scale factors of exclusive (electrons: 0.863 ± 0.070 stat; muons: 0.791 ± 0.041 stat) and single-diffractive events (electrons: 0.759 ± 0.080 stat; muons: 0.762 ± 0.049 stat) determined by binned maximum-likelihood fit of the acoplanarity distribution, double diffractive and DY scale factors fixed to the MC prediction in the fit





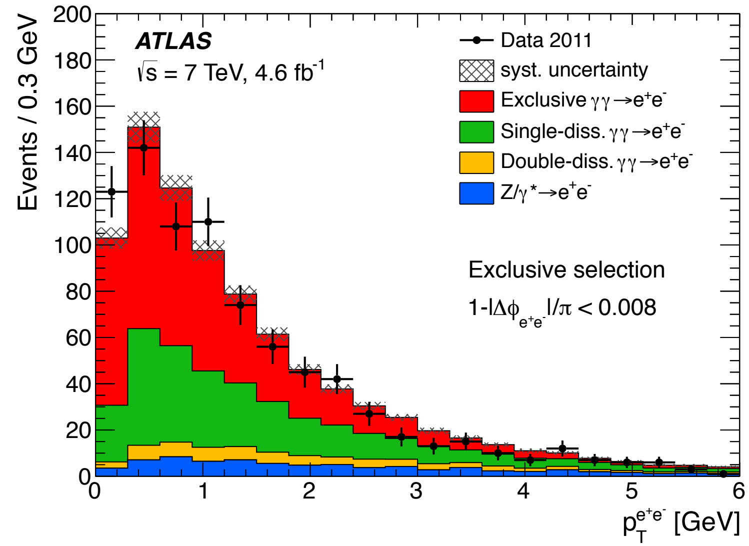
arXiv:1506.07098

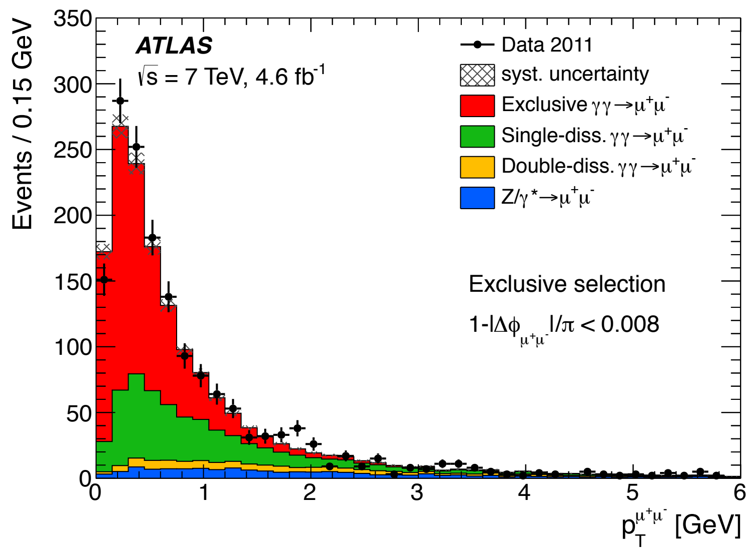
Systematics

- Main systematics from background modelling

Source of uncertainty	Uncertainty [%] $\gamma\gamma \to e^+e^-$	$\gamma\gamma \to \mu^+\mu^-$
Electron reconstruction and identification efficiency	1.9	-
Electron energy scale and resolution	1.4	-
Electron trigger efficiency	0.7	-
Muon reconstruction efficiency	-	0.2
Muon momentum scale and resolution	-	0.5
Muon trigger efficiency	-	0.6
Backgrounds	2.3	2.0
Template shapes	1.0	0.9
Pile-up description	0.5	0.5
Vertex isolation efficiency	1.2	1.2
LHC beam effects	0.5	0.5
QED FSR in DY e^+e^-	0.8	-
Luminosity	1.8	1.8
Total systematic uncertainty	4.3	3.3
Data statistical uncertainty	8.2	5.1

- Measurement statistically dominated





arXiv:1506.07098

Results

Variable	Electron channel	Muon channel
p_T^ℓ	> 12 GeV	> 10 GeV
$\lvert\eta^\ell\rvert$	< 2.4	< 2.4
$m_{\ell^+\ell^-}$	> 24 GeV	> 20 GeV

- Exclusive di-lepton production measured in specific fiducial regions
- Fiducial cross-sections given by the product of the measured signal scale factors by the exclusive cross-sections predicted by the EPA calculation:

$$\sigma^{\text{excl.}}_{\gamma\gamma\to\ell^+\ell^-} = R^{\text{excl.}}_{\gamma\gamma\to\ell^+\ell^-} \cdot \sigma^{\text{EPA}}_{\gamma\gamma\to\ell^+\ell^-}$$

Electrons

$$R^{\text{excl.}}_{\gamma\gamma\to e^+e^-} = 0.863 \pm 0.070\,(\text{stat.}) \pm 0.037\,(\text{syst.}) \pm 0.015\,(\text{theor.})$$
$$\sigma^{\text{EPA}}_{\gamma\gamma\to e^+e^-} = 0.496 \pm 0.008\,(\text{theor.})\text{ pb}.$$

$$\sigma^{\text{excl.}}_{\gamma\gamma\to e^+e^-} = 0.428 \pm 0.035\,(\text{stat.}) \pm 0.018\,(\text{syst.})\text{ pb}$$

$$\sigma^{\text{EPA, corr.}}_{\gamma\gamma\to e^+e^-} = 0.398 \pm 0.007\,(\text{theor.})\text{ pb}$$

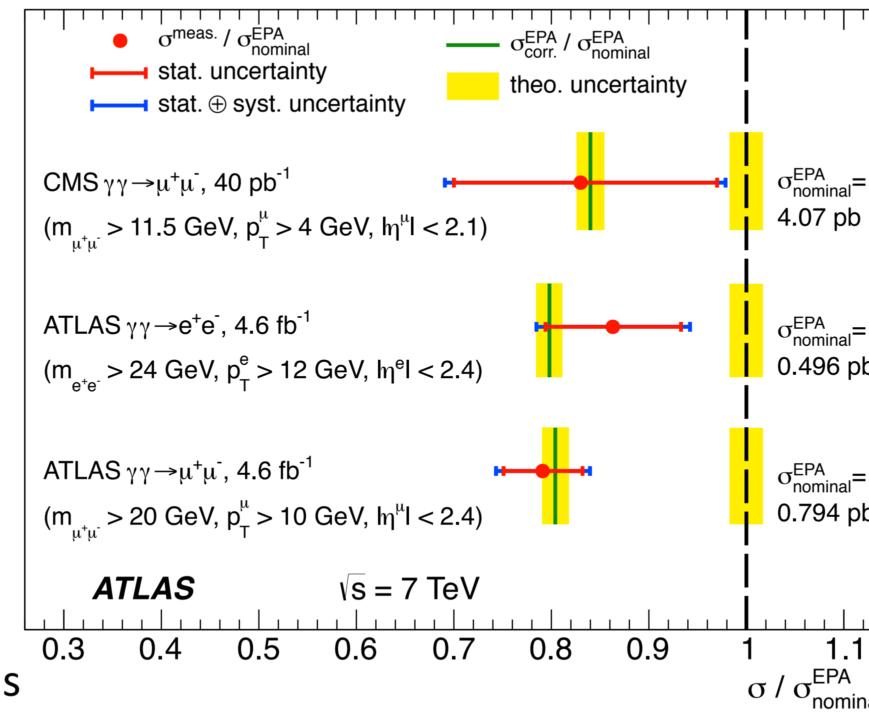
Muons

$$R^{\text{excl.}}_{\gamma\gamma\to\mu^+\mu^-} = 0.791 \pm 0.041\,(\text{stat.}) \pm 0.026\,(\text{syst.}) \pm 0.013\,(\text{theor.}),$$
$$\sigma^{\text{EPA}}_{\gamma\gamma\to\mu^+\mu^-} = 0.794 \pm 0.013\,(\text{theor.})\text{ pb}.$$

$$\sigma^{\text{excl.}}_{\gamma\gamma\to\mu^+\mu^-} = 0.628 \pm 0.032\,(\text{stat.}) \pm 0.021\,(\text{syst.})\text{ pb}$$

$$\sigma^{\text{EPA, corr.}}_{\gamma\gamma\to\mu^+\mu^-} = 0.638 \pm 0.011\,(\text{theor.})\text{ pb}$$

Measurements 20% below EPA predictions, but consistent with the suppression expected due to proton absorption



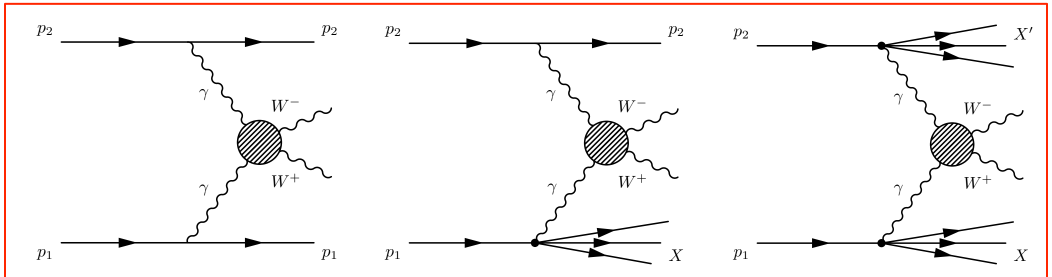
- Improved statistical precision compared to previous measurements
- Better understanding of two-photon interactions at hadron colliders

arXiv:1607.03745

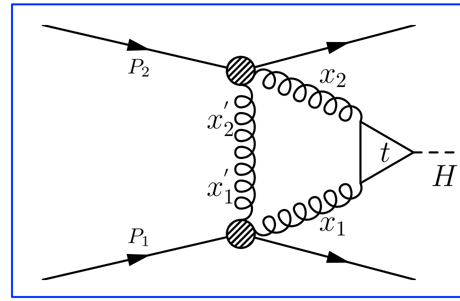
Exclusive $\gamma\gamma \rightarrow W^+W^-$ production

- Exclusive $\gamma\gamma \rightarrow W^+W^-$ production measured with ~20 fb^{-1} of 8 TeV ATLAS data while also searching for exclusive Higgs boson production

Blobs can be *t* or *u* channels, or quartic coupling (SM and non) → process sensitive to new Phyics



(a) Elastic production (b) Single-dissociation (c) Double-dissociation



Higgs produced via gluons exchange and *t*-loop

Process	MC Generator
Exclusive W^+W^- signal	
$\gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$ $(\ell, \ell' = e, \mu, \tau)$	Herwig++
aQGC signal	
$\gamma\gamma \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$ with $a^W_{0,C}/\Lambda^2 \neq 0$	FPMC
Exclusive Higgs boson signal	
Exclusive $gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$	FPMC
Exclusive dilepton	
$\gamma\gamma \rightarrow \ell^+\ell^-$ $(\ell = e, \mu, \tau)$	Herwig++, LPAIR, Pythia8
Inclusive W^+W^-	
$W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$ $(\ell, \ell' = e, \mu, \tau)$	Powheg+Pythia8, gg2ww+Herwig
Inclusive $gg \rightarrow H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$	Powheg+Pythia8
Vector-boson fusion $W^+W^- \rightarrow \ell^+\nu\ell'^-\bar{\nu}$	Sherpa
Non-W^+W^- diboson (Other-VV diboson)	
WZ, ZZ	Powheg+Pythia8
Other background	
W + jets	Alpgen+Pythia6
Z + jets	Alpgen+Pythia6, Alpgen+Herwig
$t\bar{t}$, single top-quark, Wt	Powheg+Pythia6, AcerMC+Pythia6, MC@NLO+Herwig

As described in previous slides

Many backgrounds to be studied!

arXiv:1607.03745

Selection

Good Objects:

- Electron: $p_T > 10$ GeV, $|\eta| < 2.47$, with $1.37 < |\eta| < 1.52$ excluded, very tight" likelihood criteria (efficiencies from 60% to 70%)
- Muon: $p_T > 10$ GeV, $|\eta| < 2.5$, with $1.37 < |\eta| < 1.52$ excluded, combined MS-ID, muon id efficiencies up to 95%
- Jets: $|\eta| < 4.5$, $p_T > 25$ GeV, anti-k_t 0.4
- Charged-particles: $p_T > 0.4$ GeV, $|\eta| < 2.5$, $N_{pix} > 1$, $N_{SCT} > 4$

Exclusive candidates (both W^+W^- and Higgs) characterised by large rapidity gaps, in contrast inclusive production is accompanied by underlying event → exclusivity selection is applied:

No additional tracks with $p_T > 0.4$ GeV near z_0^{av} with $|z_0^{track} - z_0^{av}| < \Delta z_0^{iso}$ with $\Delta z_0^{iso} = 1$ mm

- Exclusive W^+W^- large background for exclusive Higgs,
- Exclusive Higgs negligible background for exclusive W^+W^-

Trigger	Lepton p_T criteria [GeV]
Single electron	$p_T^e > 24$
Single muon	$p_T^\mu > 24$
Symmetric dielectron	$p_T^{e_1} > 12,\ p_T^{e_2} > 12$
Asymmetric dimuon	$p_T^{\mu_1} > 18,\ p_T^{\mu_2} > 8$
Electron-muon	$p_T^e > 12,\ p_T^\mu > 8$

	W^+W^- selection	Higgs boson selection
Preselection	Oppositely charged $e\mu$ final states	
	$p_T^{\ell 1} > 25$ GeV and $p_T^{\ell 2} > 20$ GeV	$p_T^{\ell 1} > 25$ GeV and $p_T^{\ell 2} > 15$ GeV
	$m_{e\mu} > 20$ GeV	$m_{e\mu} > 10$ GeV
	$p_T^{e\mu} > 30$ GeV	
	Exclusivity selection, Δz_0^{iso}	
aQGC signal	$p_T^{e\mu} > 120$ GeV	–
Spin-0 Higgs boson	–	$m_{e\mu} < 55$ GeV
	–	$\Delta\phi_{e\mu} < 1.8$
	–	$m_T < 140$ GeV

Some cuts are common for W^+W^- and Higgs, some others are specific to remove backgrounds affecting each channel, e.g. p_T and m threshold are lowered for the Higgs Boson selection because one W is on-shell and the other is off-shell

arXiv:1607.03745

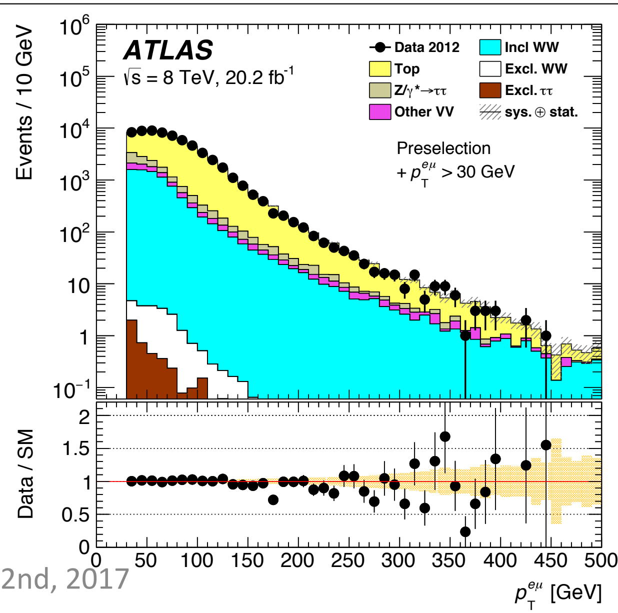
Backgrounds and Systematics

- Exclusive $\gamma\gamma \rightarrow W^+W^-$ measurement is statistically dominated (33%)
- Total systematics ~21% with 18% arising from background determination (details in the reference, many control regions needed to probe elastic vs dissociative, multiplicity, inclusive W^+W^-)
- Total uncertainty 39%

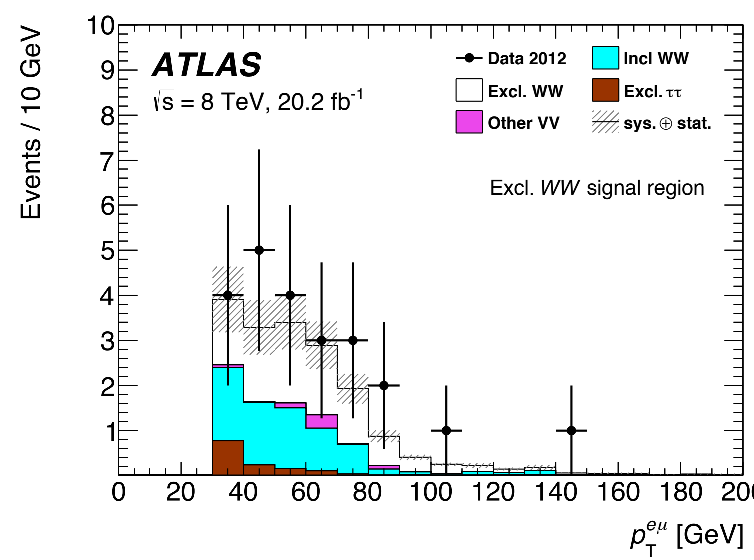
Source of uncertainty	Uncertainty [%]
Statistics	33%
Background determination	18%
Exclusivity signal efficiency	10%
All other	< 5%
Total	39%

Top, DY ττ, W+jets

	Expected Signal	Data	Total Bkg	Incl W^+W^-	Excl. $\tau\tau$	Other-VV	Other Bkg	SM/Data	ϵA (Signal)
Preselection	22.6 ± 1.9	99424	97877	11443	21.4	1385	85029	0.98	0.254
$p_T^{\ell\ell} > 30$ GeV	17.6 ± 1.5	63329	63023	8072	4.30	896.3	54051	1.00	0.198
Δz_0^{iso} requirement	9.3 ± 1.2	23	8.3 ± 2.6	6.6 ± 2.5	1.4 ± 0.3	0.3 ± 0.2	–	0.77	0.105 ± 0.012
aQGC signal region									
$p_T^{\ell\ell} > 120$ GeV	0.37 ± 0.04	1	0.37 ± 0.13	0.32 ± 0.12	0.05 ± 0.03	0	–	0.74	0.0042 ± 0.0005



Main background from top largely reduced by the exclusivity veto



arXiv:1607.03745

Cross Section

- The predicted cross-section corrected for BR($W^+W^- \rightarrow e^\pm\mu^\mp X$) = 3.23% and including the dissociative contributions through the normalization f_γ = 3.30 ± 0.23 becomes:

$$\sigma^{\text{Predicted}}_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\mp X} = f_\gamma \cdot \sigma^{\text{HERWIG++}}_{\gamma\gamma\to W^+W^-} \cdot \text{BR}(W^+W^- \to e^\pm\mu^\mp X) = 4.4 \pm 0.3 \text{ fb}$$

$$\sigma^{\text{HERWIG++}}_{\gamma\gamma\to W^+W^-} = 41.6 \text{ fb}$$

- which corresponds to the prediction of $N_{\text{Predicted}}$ = 9.3 ± 1.2 signal event. The number of candidates observed in the data is N_{Data} = 23, while the predicted background is $N_{\text{Background}}$ = 8.3 ± 2.6 events. So the observation exceeds the prediction by a ratio:

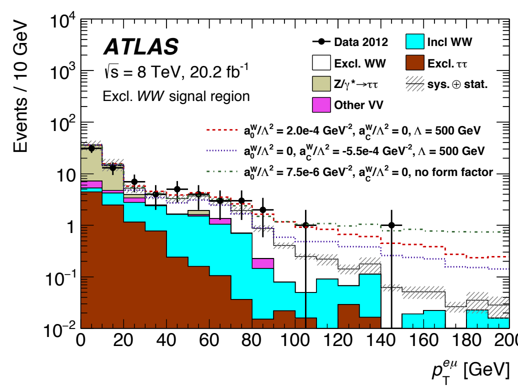
$$R = (N_{\text{Data}} - N_{\text{Background}})/N_{\text{Predicted}} = 1.57 \pm 0.62$$

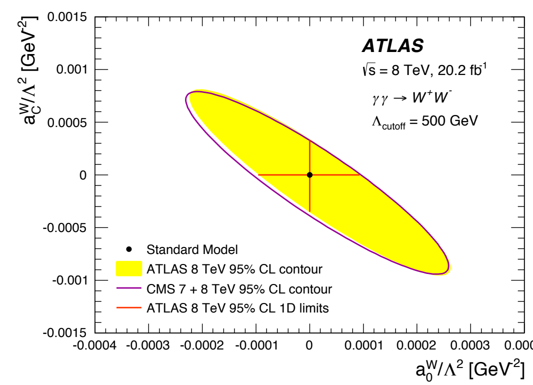
$$\sigma^{\text{Measured}}_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\mp X} = (N_{\text{Data}} - N_{\text{Background}})/(\mathcal{L}\,\epsilon A) = 6.9 \pm 2.2 \text{ (stat.)} \pm 1.4 \text{ (sys.) fb}$$

$\mathcal{L}$ = 20.2 ± 0.4 fb^{-1}
ε = 0.37 ± 0.04
A = 0.280 ± 0.001

- The background-only hypothesis has a *p*-value about 0.0012, corresponding to a significance of 3.0σ.

- Limits were also set on the aQGC
  - No evidence seen
- 6 candidates consistent with exclusive Higgs boson observed in the data, expected SM background 3.0 ± 0.8 events. Upper limit at 95% CL on the total production cross-section of 1.2 pb, whereas the expected limit is 0.7 pb





$+2\sigma$ [pb]	$+1\sigma$ [pb]	Expected [pb]	-1σ [pb]	-2σ [pb]	Observed [pb]
1.6	1.0	0.7	0.5	0.4	1.2

Summary

ATLAS: efficient detector to study particle production and exclusive production

- **Minimum Bias Studies:**
  - **Track-based analysis**
    - Main systematic uncertainties from Inner Detector material estimate
  - **Charged Particle Multiplicities @ 13 TeV**
    - Nominal: $p_T > 500$ MeV, $|\eta| < 2.5$
    - Reduced: $p_T > 500$ MeV, $|\eta| < 0.8$
    - Extended: $p_T > 100$ MeV, $|\eta| < 2.5$
  - **Charged Particle Multiplicities @ 8 TeV**
    - Many phase spaces investigated
      - Reduced systematics with respect to the 7 TeV measurements
      - High multiplicity region (n_{ch}>20,50) studied extensively for the first time
  - **In general, best predictions given by EPOS-LHC**

- **Bose-Einstein Correlation at 0.9 and 7 TeV pp collisions:**
  - **BEC studied as a function of multiplicity and transverse momentum**

- **Exclusive di-lepton production at 7 TeV:**
  - **Observation consistent with SM, improved sensitivity wrt previous measurements**

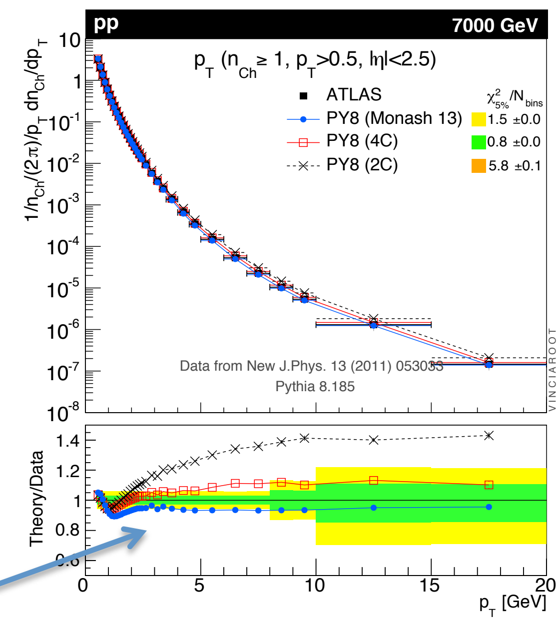
- **Exclusive W^+W^- production at 8 TeV:**
  - **Observation consistent with SM, no evidence of aQGC**

Extra Slides

Pythia 8 – MB & UE tunes

- Hadron-hadron interactions described by a model that splits the total inelastic cross section into **non-diffractive** (**ND**) and diffractive processes:
  - Non-diffractive part dominated by *t*-channel gluon exchange (simulation includes MPIs)
  - Diffractive part involves a color-singlet exchange (further divided into **single-diffractive** (**SD**) and **double-diffractive** (**DD**) dissociation)

- Tunes used in the latest measurements:
  - **A2** (MSTW2008 LO PDF)
    - Using 7 TeV ATLAS measurements of MB plus leading track and cluster UE
    - Specific Minimum Bias Tune (A2)
    - Specific Underlying event tune (AU2)
  - **Monash** (NNPDF2.3 LO PDF)
    - Updated fragmentation parameters, minimum-bias, Drell-Yan and underlying-event data from the LHC to constrain ISR and MPI parameters. SPS and Tevatron data to constrain the energy scaling.
    - Excellent description of 7 TeV MB p_T spectrum.

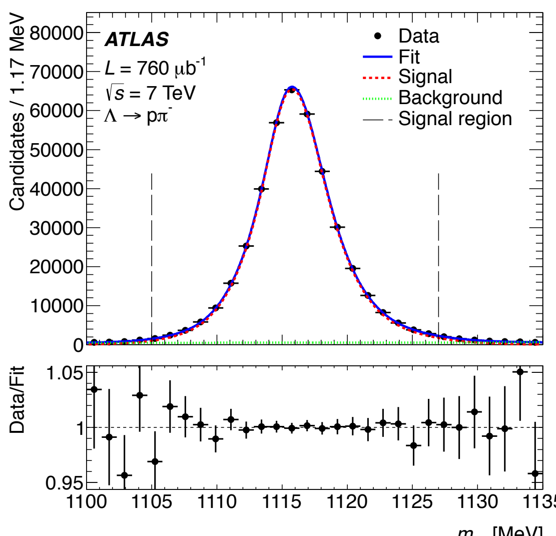


https://arxiv.org/pdf/1404.5630v1.pdf

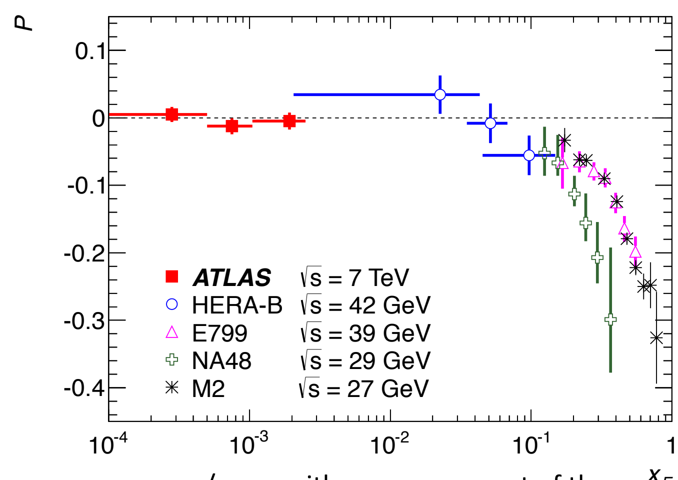
arXiv:1502.07947

Λ polarisation in the transverse plane

- The Λ hyperons are spin-1/2 particles and their polarization is characterized by a polarization vector **P**. Its component, P, transverse to the Λ momentum is of interest since for hyperons produced via the strong interaction parity conservation requires that the parallel component is zero
- Huge Λ sample allows to measure Λ polarisation P by measuring the decay angle $\cos\theta^*$ between the decay proton and Λ flight directions
- $P(\Lambda) = (1 + \alpha P \cos\theta^*)$; Decay asymmetry : $\alpha = 0.642 \pm 0.013$
- Results:
  - $P(\Lambda) = -0.010 \pm 0.005(\text{stat}) \pm 0.004(\text{syst})$
  - $P(\overline{\Lambda}) = \ \ 0.002 \pm 0.006\ (\text{stat}) \pm 0.004(\text{syst})$
- Consistent to previous measurement which expect a degradation of the Λ polarisation at high energy



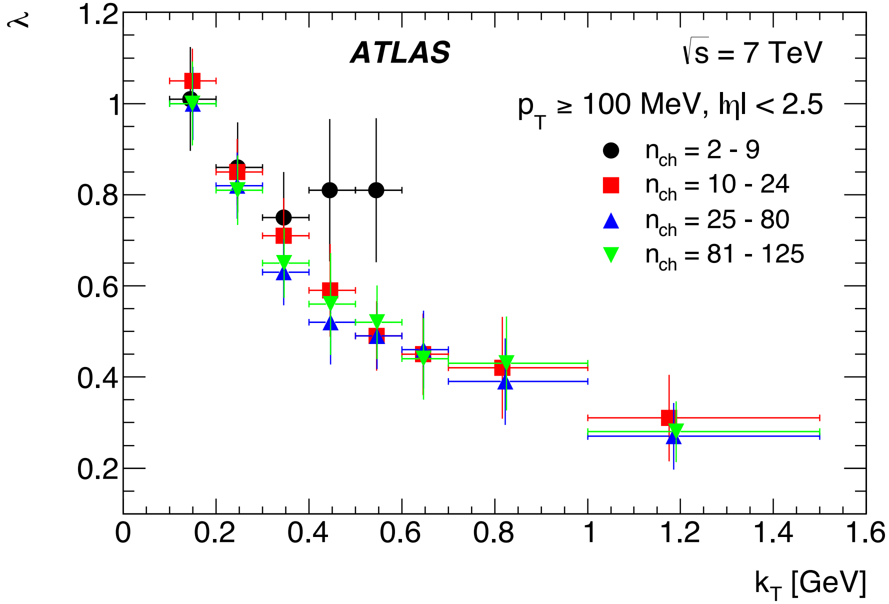
Λ transverse polarization

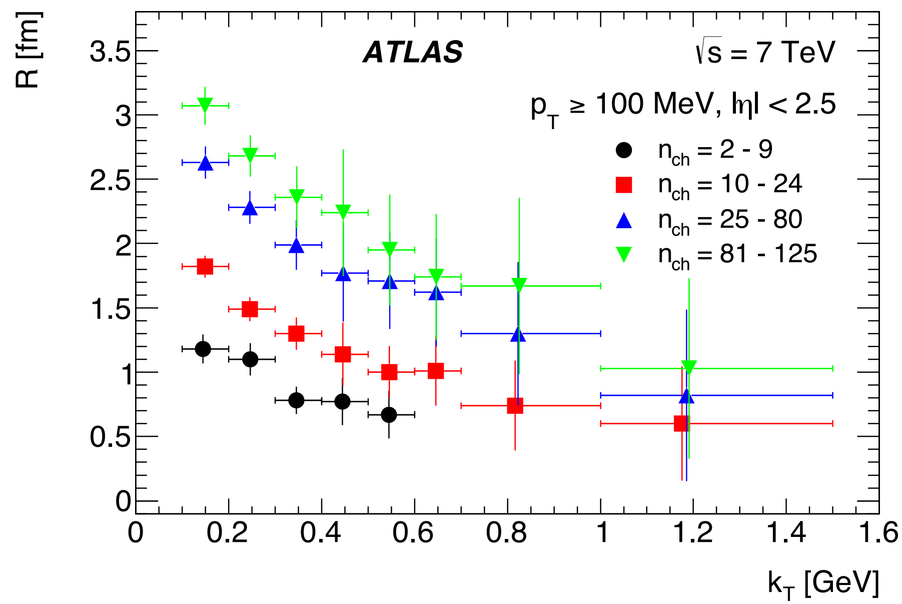


$x_F = p_z/p_{beam}$, with p_z z-component of the Λ momentum and p_{beam} = 3.5 TeV

BEC fit parameters

- **Transverse momentum dependence**



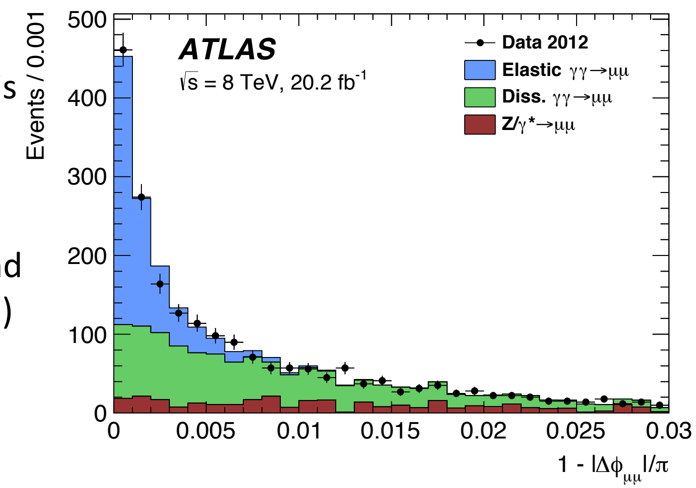


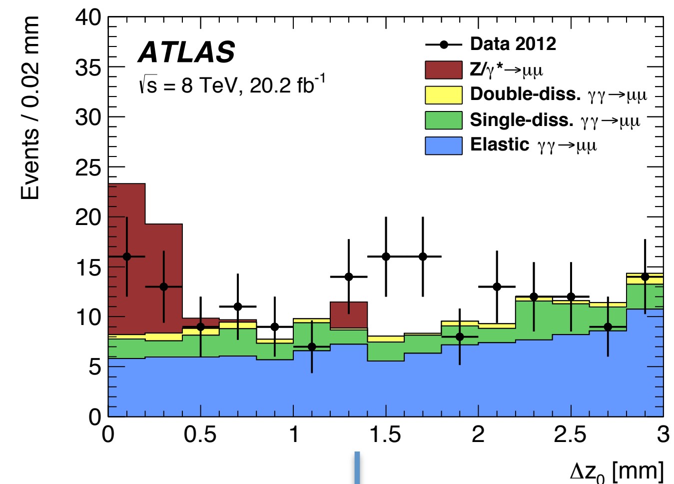
- The decrease of λ with k_T is nearly independent of multiplicity for $n_{ch} > 9$ and the same as for the inclusive case.
- For $n_{ch} \leq 9$ no conclusions can be drawn due to the large uncertainties.
- The R-parameter decreases with k_T and exhibits an increase with increasing multiplicity as was observed for the fully inclusive case.

Scale Factors

- Di-lepton acoplanarity is used in this measurement of exclusive W^+W^- to determine elastic process scale factors, as it was done for exclusive di-lepton production (similar process, except for aQGCs) f_{EL} = 0.76 ± 0.04(stat.) ± 0.10(sys.) (compatible with that measure in the exclusive di-lepton case) $R^{\text{excl.}}_{\gamma\gamma\to\mu^+\mu^-} = 0.791 \pm 0.041\,(\text{stat.}) \pm 0.026\,(\text{syst.}) \pm 0.013\,(\text{theor.})$,

The value of f_{EL} is extracted from template fits in acoplanarity, combined SD and DD (Dissociative) shapes





This correction factor is used to correct the number of γγ → τ+τ− candidates predicted by simulation in both the exclusive W+W− and the exclusive Higgs boson signal regions. Similar suppression is expected and observed in dissociative events, so the fEL factor is applied to dissociative events as well.

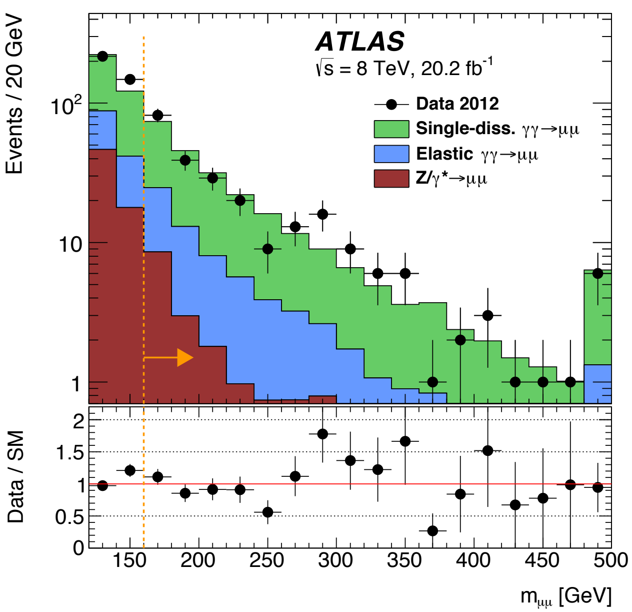
In the case of exclusive signal, when there is one extra track, the extra track is from pileup and its Δz0 = |ztrack −zav| has a locally constant distribution while for any inclusive background the track originates from the same vertex and the Δz0 distribution peaks at zero

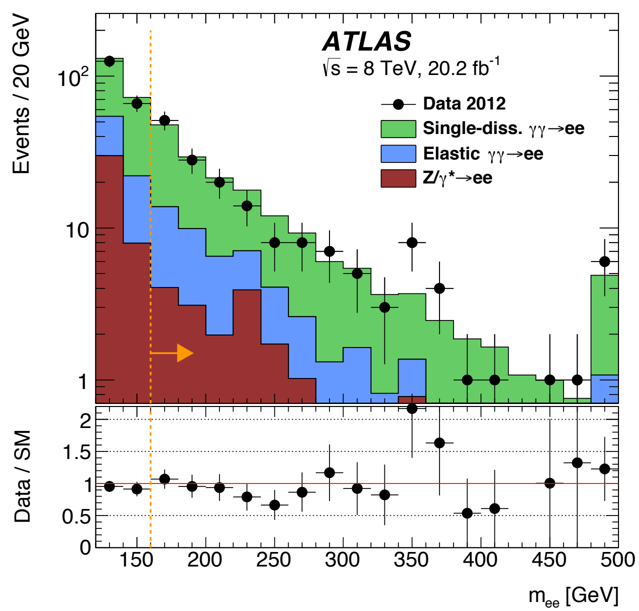
arXiv:1607.03745

Single and double diffractive contributions

- Without detecting the outgoing protons, the elastic $\gamma\gamma \rightarrow W^+W^-$ events are indistinguishable from SD and DD candidates. However, simulations are only available for the elastic $\gamma\gamma \rightarrow W^+W^-$ process; predictions for dissociative production of W^+W^- are not available.
- This factor is used to correct the prediction for elastic $\gamma\gamma \rightarrow W^+W^-$ to account for dissociative events. It is computed from data using $\gamma\gamma \rightarrow \mu^+\mu^-$ candidates that satisfy the exclusivity selection with $\Delta z^{iso} = 1$ mm, $p_T^{\mu} > 20$ GeV and $m_{\mu\mu} > 160$ GeV (~ $2m_W$). The factor f_γ is defined as the ratio of observed dimuons in data to the Herwig++ prediction for elastic dimuon production:

$$f_\gamma = \left. \frac{N_{\text{Data}} - N^{\text{Powheg}}_{\text{Background}}}{N^{\text{Herwig++}}_{\text{Elastic}}} \right|_{m_{\mu\mu}>160\ \text{GeV}} = 3.30 \pm 0.22(\text{stat.}) \pm 0.06(\text{sys.})$$



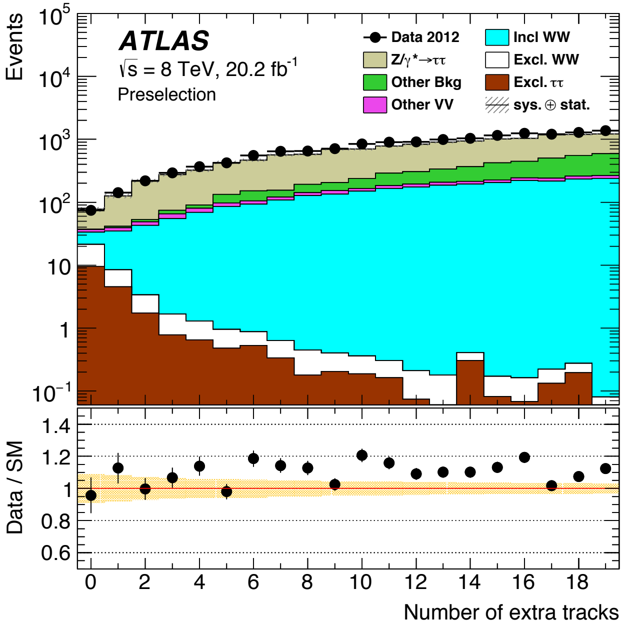


→ f_γ is also valid for the electron channel → total expected $\gamma\gamma \rightarrow W^+W^-$ event yield in both the exclusive W^+W^- and the exclusive Higgs boson channels is taken to be the product of f_γ times the Herwig++ prediction for elastic $\gamma\gamma \rightarrow W^+W^-$ production.

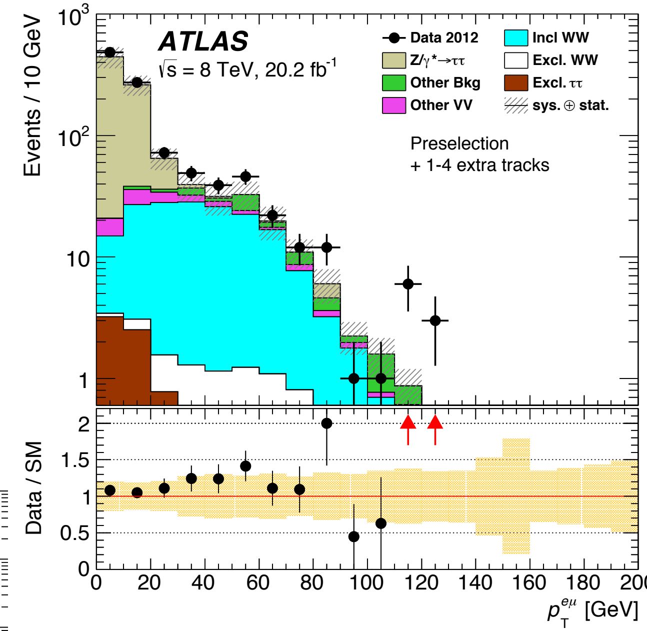
arXiv:1607.03745

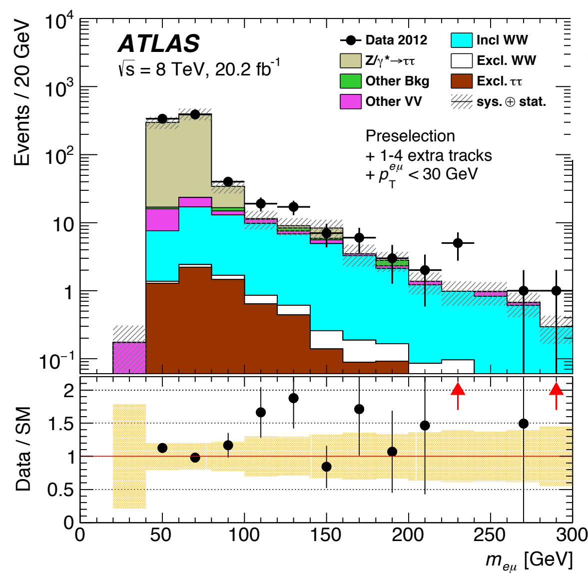
Track multiplicity modelling

- The exclusivity selection is designed to reject such inclusive candidates that have additional tracks near the dilepton vertex, control regions after relaxing the exclusivity are used to estimate backgrounds due to events accompanied by many tracks



To estimate inclusive backgrounds from Drell-Yan production of τ+τ− and inclusive W+W− production, the track multiplicity modeling of low-multiplicity candidates is studied with a high-purity Z boson sample and scaled with appropriate correction factors.

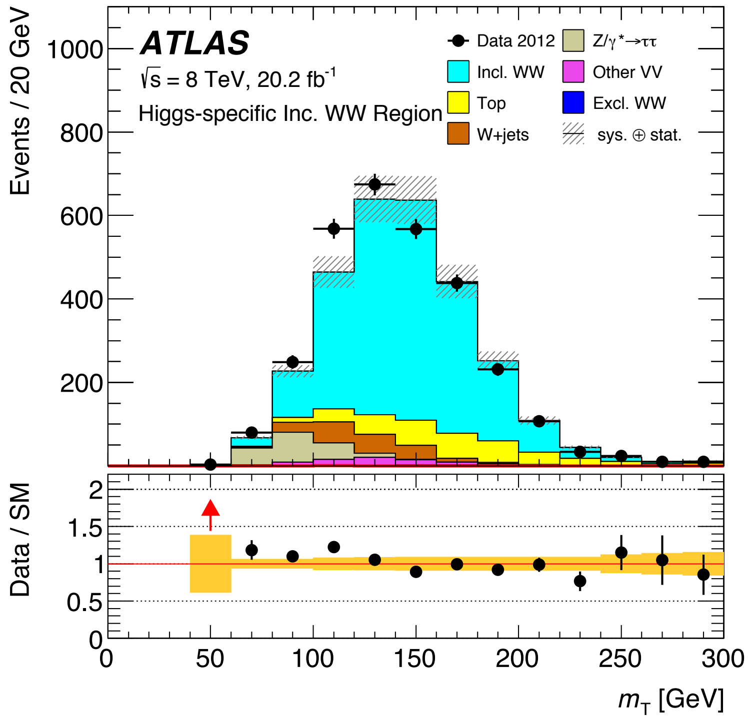




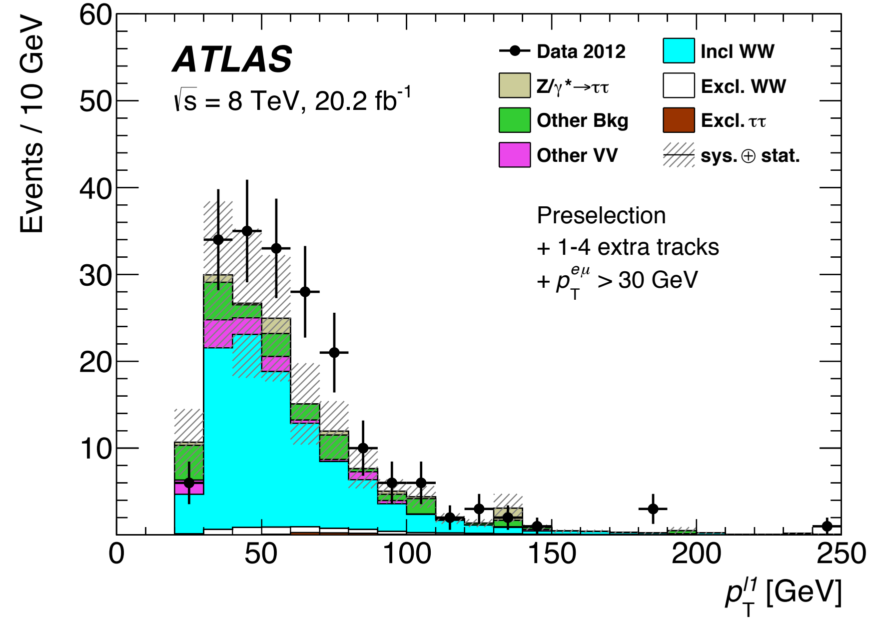
arXiv:1607.03745

Signal and background control regions

Inclusive W^+W^- normalization



Sum of inclusive W^+W^- and other background



A region close in phase space to the exclusive Higgs boson signal region is chosen, referred to here as the Higgs-specific inclusive W+W− control region. It has the same definition except: 55 < meμ < 110 GeV, Δϕeμ < 2.6 to reduce Drell-Yan background, no jets to reduce tt̄ background, and no requirement on exclusivity. This region is dominated by inclusive W+W− production and has a purity of 60%. After subtracting the predicted backgrounds from data, (20 ± 5)% more data is observed than is predicted by Powheg+Pythia8. A normalization factor of 1.20 ± 0.05(stat.) is therefore taken as a correction to the cross-section and applied to the inclusive W+W− prediction in all regions of phase space

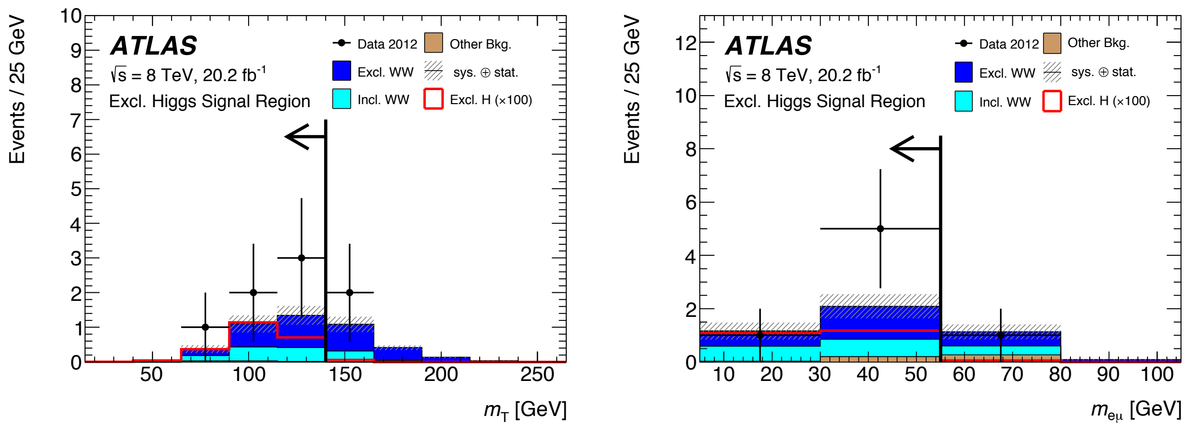
$$N_0^{\text{Estimated}} = N_{1-4}^{\text{Estimated}} \times \frac{N_{WW,0}^{\text{Predicted}}}{N_{WW,1-4}^{\text{Predicted}}},$$

arXiv:1607.03745

Exclusive Higgs boson

Six candidates are observed in the data, while 3.0 ± 0.8 events are predicted from background, and 0.023 ± 0.003 from signal. The quoted uncertainty is the sum in quadrature of systematic uncertainties. The exclusive Higgs boson prediction quoted here is from elastic contribution only. Observed data reasonably agrees with predictions. Figure 15 shows kinematic distributions in the signal region.

	Excl. H Signal	Data	Total Bkg	Incl. W^+W^-	Excl. W^+W^-	Other Bkg
Preselection	0.065 ± 0.005	129018	120090	12844	43	107200
$p_T^{e\mu}$ >30 GeV, $m_{e\mu}$ < 55 GeV, $\Delta\phi_{e\mu}$ < 1.8	0.043 ± 0.004	18568	17060	2026	5.7	15030
Δz_0^{iso} requirement	0.023 ± 0.003	8	4.7 ± 1.3	1.4 ± 0.5	3.1 ± 1.3	0.2 ± 0.1
m_T < 140 GeV [Signal Region]	0.023 ± 0.003	6	3.0 ± 0.8	1.0 ± 0.4	1.8 ± 0.8	0.2 ± 0.1

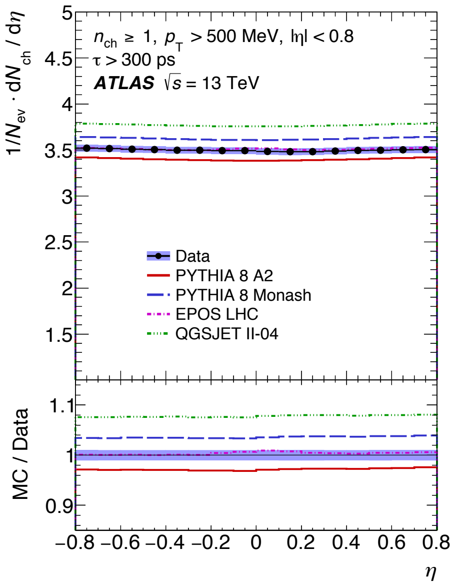


Yields are converted to upper limits on the exclusive Higgs boson total production cross-section using the CLS technique. The branching ratio BR(H → W+W−) used to compute these limits is (21.5±0.9)% . The observed upper limit is 1.2 pb, which is 1.1σ higher than the expected upper limit of 0.7 pb. The statistical uncertainty in the predicted background dominates the uncertainty involved in calculating this upper limit, while systematic uncertainties worsen the upper limits by at most 10%. This upper limit value is 400 times the cross-section predicted [24]. However, the limit would not change if the model prediction, which is for elastic production only, in- creased by an order of magnitude. This limit calculation inherently assumes that the acceptance and efficiency for dissociative events is not significantly different than for elastic events, hence the associated systematic uncertainty is insignificant.

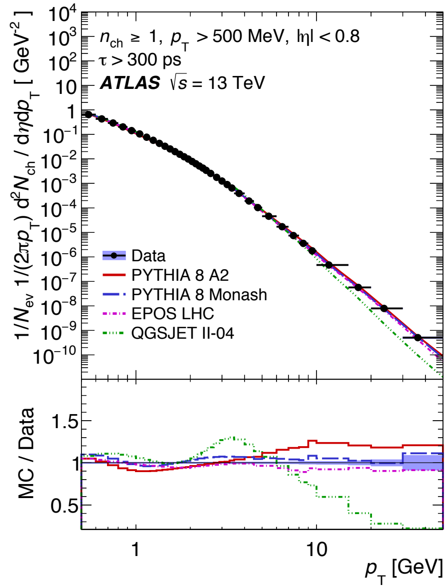
Final Results – 13 TeV

- Reduced Phase Space (p_T > 500 MeV, $|\eta|$< 0.8)

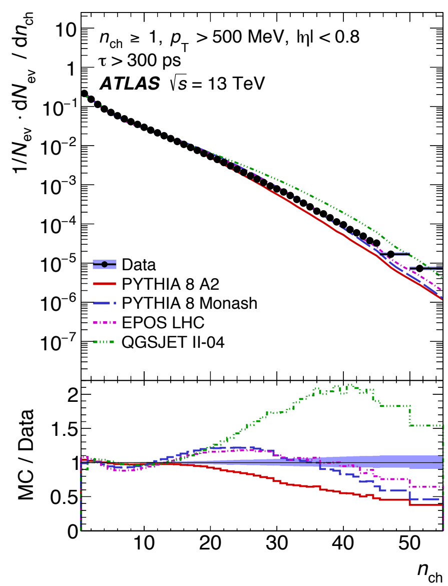
$dN_{ch}/d\eta$



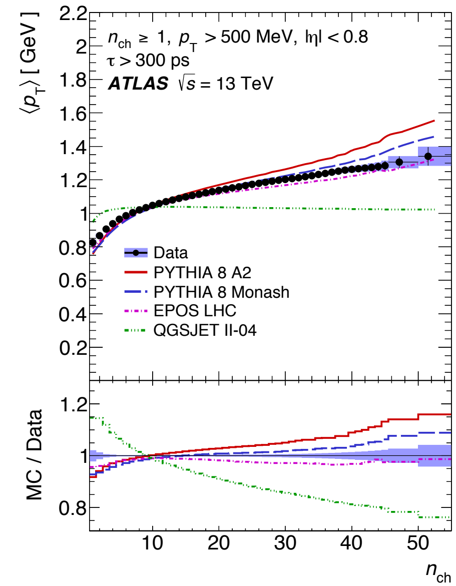
$d^2N_{ev}/d\eta dp_T$



dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



Models differ mainly in normalisation, shape similar

Measurement spans 10 orders of magnitude

Low n_{ch} not well modelled by any MC; large contribution from diffraction;
Models without colour reconnection (QGSJET) fail to model scaling with nch very well

The level of agreement between the data and MC generator predictions follows the same pattern as seen in the main phase space:
Some Models/Tunes give remarkably good predictions (EPOS, Pythia8)

Hadronic Interactions and Photon Conversions

Inelastic **hadronic interactions** produce multiple charged particles when hadrons interact with the detector material.

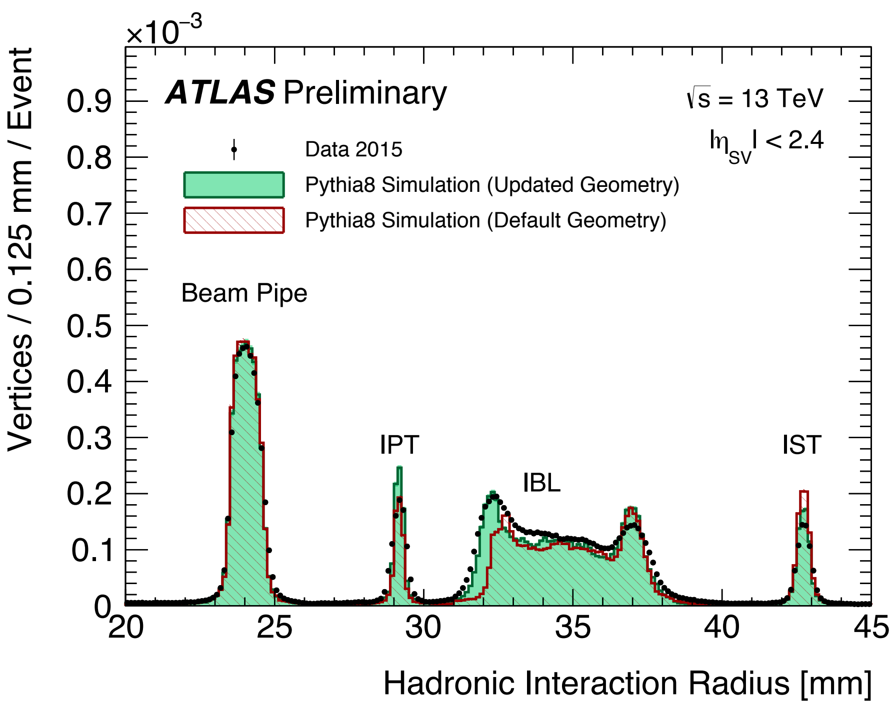
Excellent **radial resolution** (between **65 and 230 µm** from the beam pipe to Layer-1 depending on radius).

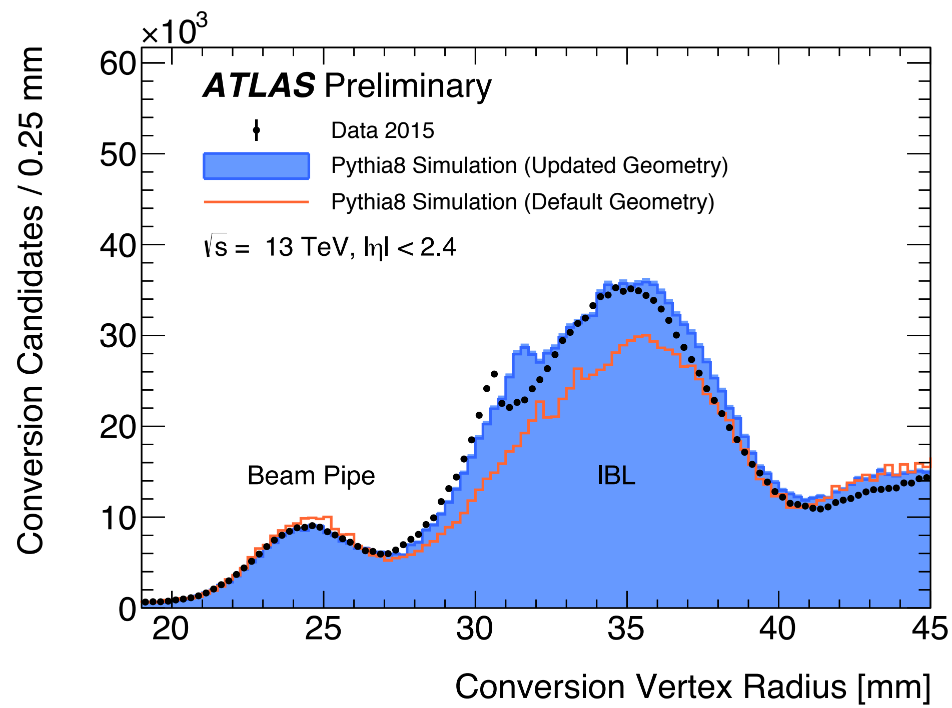
Probability for a **photon conversion** (very clean signal) is proportional to the traversed material.

High statistics source of photon conversions from di-photon decays of light neutral mesons copiously produced in *pp* collisions

These methods allowed to improve the IBL description in simulation

- **30% of material was missing in the "default geometry"**





Fakes

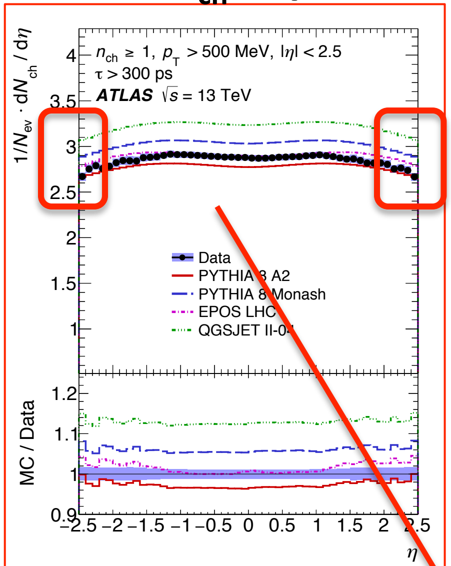
- In the 500 MeV phase space, the fakes are neglected because they drop rapidly with p_T such that the rate is negligible in that phase space

- In the 100 MeV case, fakes are treated as part of the background with a 50% systematic uncertainty following the recommendation of Inner Detector Combined Performance group

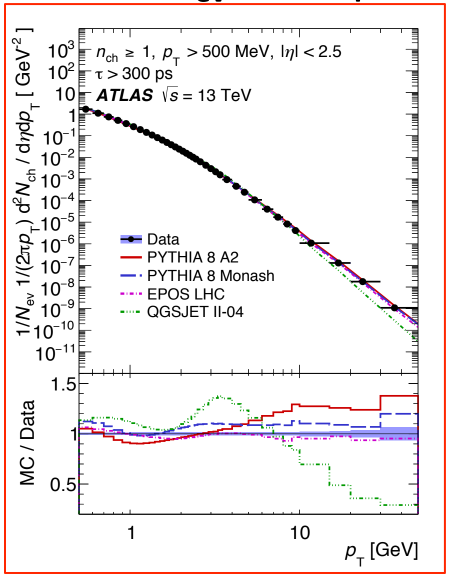
Final Results

- Nominal Phase Space (500 MeV)

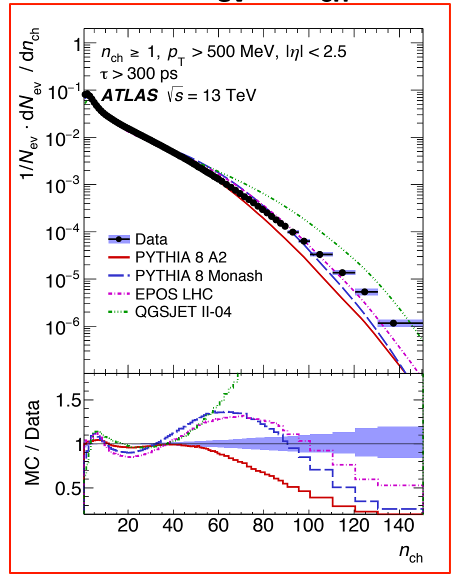
$dN_{ch}/d\eta$



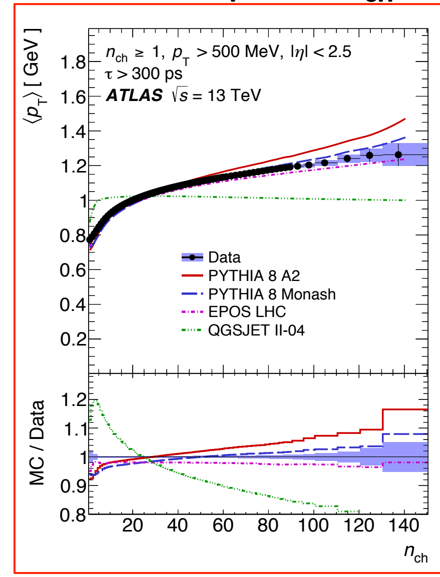
$d^2N_{ev}/d\eta dp_T$

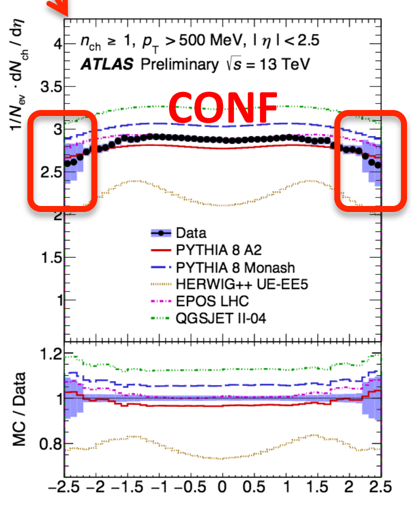


dN_{ev}/dn_{ch}



$<p_T>$ VS n_{ch}



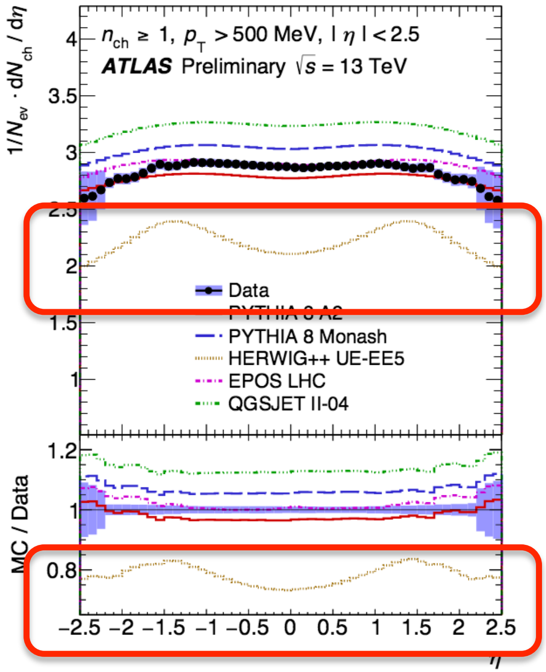


Big improvements in the systematic uncertainty evaluation thanks to the correction to the tracking efficiency driven by material studies

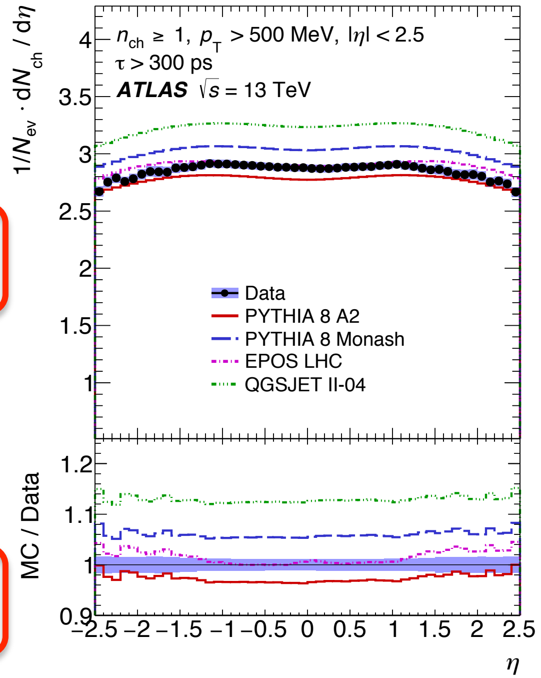
Final Results – Extra Generators Comparison

- Nominal Phase Space (500 MeV)

CONF



Paper



- Herwig was dropped bacause the tune (based on CTEQ6L1 PDF) used for the CONFNote was not the optimal one
  → updated plots with the tune (based on MRST PDF) suggested by the expert
  → improved data/MC agreement

Corrections (100 MeV phase space)

- Trigger and Vertex efficiency: event-wise correction

$$w_{\mathrm{ev}}(n_{\mathrm{sel}}^{\text{no-z}}, \Delta z_{\mathrm{tracks}}) = \frac{1}{\varepsilon_{\mathrm{trig}}(n_{\mathrm{sel}}^{\text{no-z}})} \cdot \frac{1}{\varepsilon_{\mathrm{vtx}}(n_{\mathrm{sel}}^{\text{no-z}}, \Delta z_{\mathrm{tracks}})}.$$

- Tracking efficiency: track-wise correction

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

non-primary tracks

strange baryons

outside kinematic range

fake tracks

- Bayesian unfolding to correct both the multiplicity n_{ch} and p_T
    - Additional correction for events out of kinematic range e.g. events with ≥1 particles but < 1 track

- Mean p_T vs n_{ch} bin-by-bin correction of average p_T, then n_{ch} migration

Data-driven correction to the Tracking Efficiency

- When trying to use the data-driven correction in the low p_T phase space, it leads to un-physical fluctuations

- Many checks performed, but issue not found → therefore, this correction is not applied in the 100 MeV phase-space analysis and instead larger systematic uncertainties are applied, as recommended by the Inner Detector Combined Performance group:
  - 5% extra material overall
  - 10% extra material IBL (Minimum Bias is the only 2015 ATLAS analysis which used the improved IBL geometry)
  - 50% extra material in the Pixel Services Region

- Final results discussed in the next slides

Additional checks

Problems that may be encountered when extrapolating the data-driven correction to low p_T tracks:

- Errors in the propagation of the systematics and correction → checked

- Track parameters resolution → checked → negligible

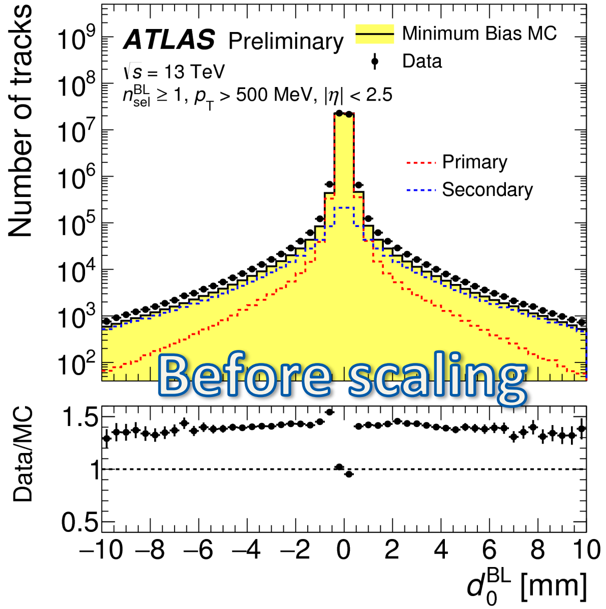
- Eta bin-to-bin migration → checked → negligible

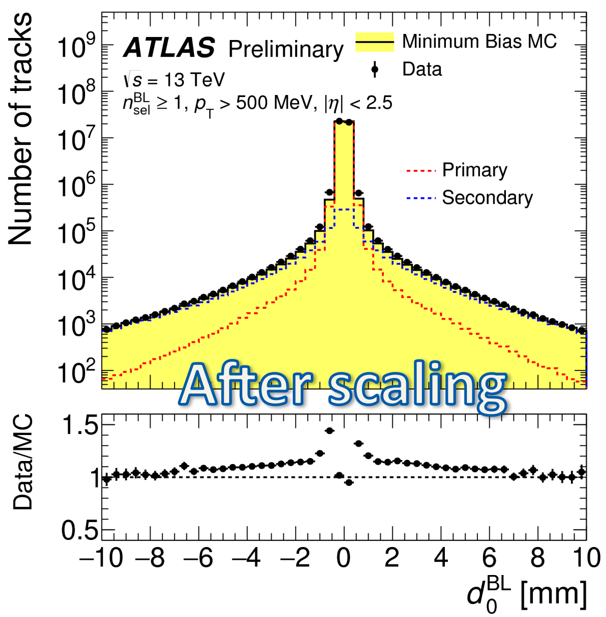
- Linearity of the tracking efficiency with the material in the low p_T regime → checked

The issue was not found → Therefore this correction is not applied in the 100 MeV analysis and instead larger systematic uncertainties are applied

Non-Primary Tracks Estimation

- Non primary tracks are the biggest background
  - Rate measured in data by performing a fit to the transverse impact parameter distribution
  - 2.2% ± 0.6% of our reconstructed tracks within the signal region
- High pT tracks
  - measurable fraction of the tracks originate from low pT tracks (scattering, in flight decays)
  - Our ability to select & remove these tracks was assessed in data
  - At most 1% of tracks between 30-50GeV





N-1 cut Systematic Uncertainty

$$\epsilon_{\mathrm{cut}}(p_{\mathrm{T}},\eta) = \frac{N^{\mathrm{tracks}}_{\mathrm{all\,cuts}}(p_{\mathrm{T}},\eta)}{N^{\mathrm{tracks}}_{\mathrm{N-1\,cuts}}(p_{\mathrm{T}},\eta)}$$

- All Pixel hit requirements and all SCT hit requirements removed for the N-1 test

0.5%

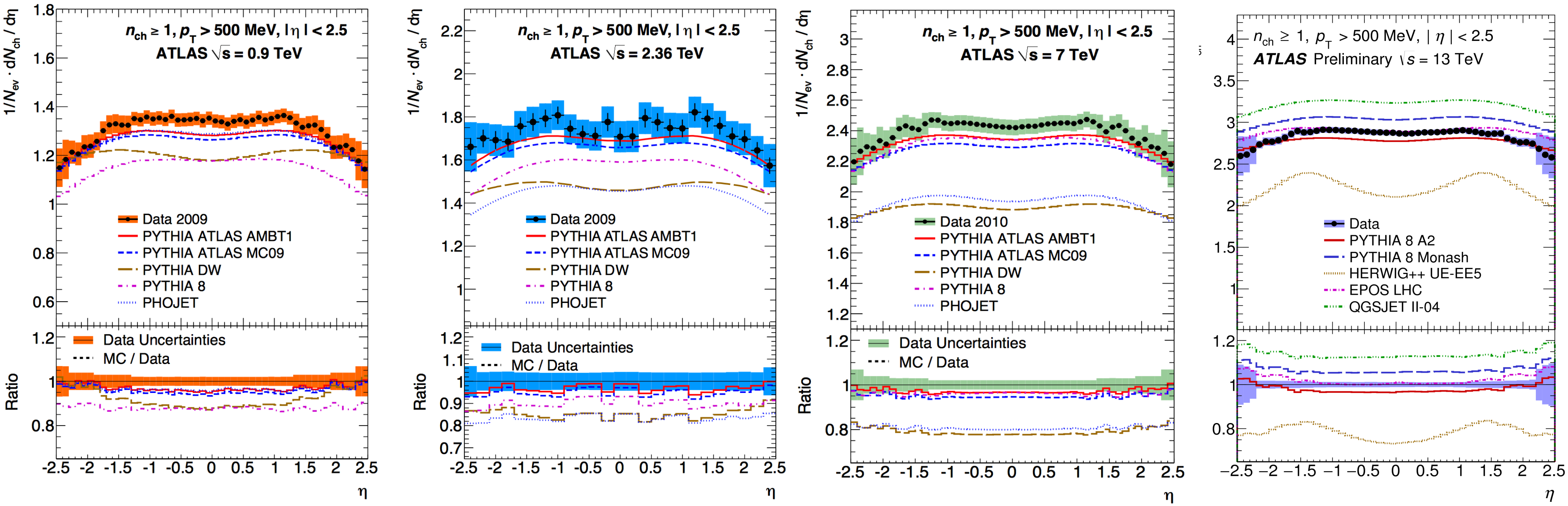
- Large differences are observed at high p_T for the efficiency of both cuts, this is the result of a high fraction of poorly measured tracks entering the denominator when loosening the cuts

X^2 Probability Cut Systematic Uncertainty

- Badly measured low momentum charged particles are sometimes reconstructed as a high momentum track
- These tracks are a sizeable fraction at high reconstructed p_T because of the steeply falling p_T distribution and they are caused by interactions and multiple scattering with the material -> usually have a bad χ2 fit probability
- A cut on χ2 probability of $P(\chi 2, n_{dof}) > 0.01$ is applied for tracks with $p_T > 10$ GeV to remove bad measured tracks
- The uncertainty on the remaining amount of mis-measured tracks has been determined to be less than 0.2% at 10 GeV rising up to 7% above above 50 GeV
- The uncertainty in the efficiency of the cut is assessed to be to 0.5% below 50 GeV and 5% above 50 GeV

Different Centre of Mass Energy

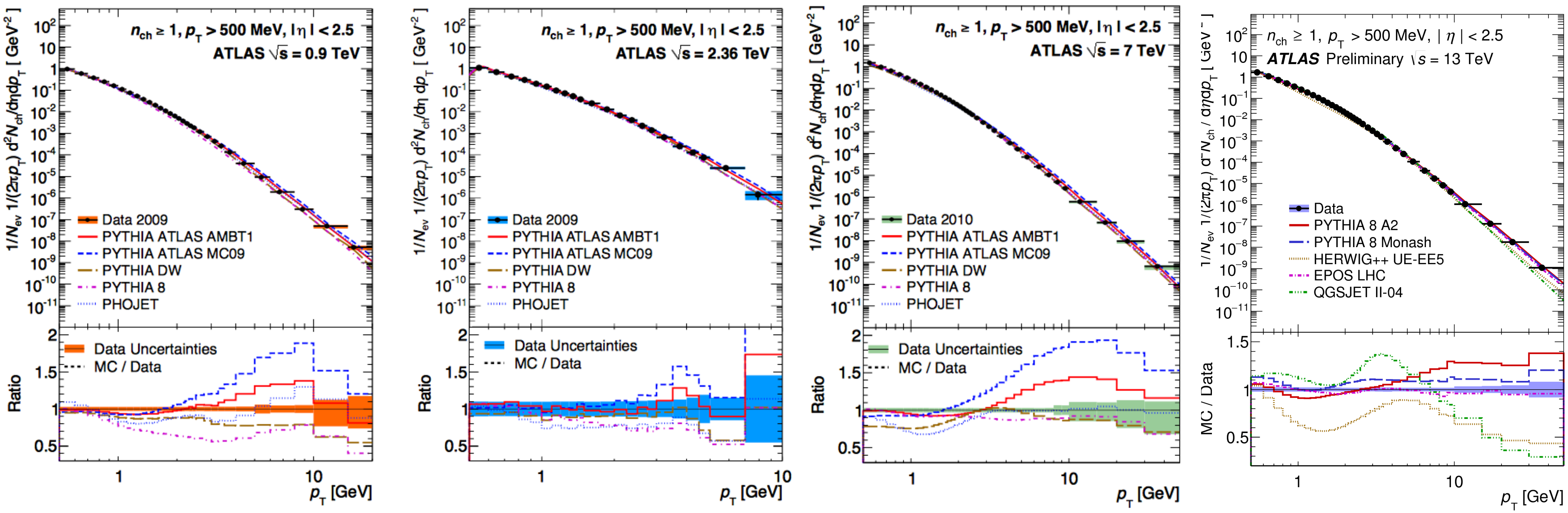
$dN_{ch}/d\eta$ http://arxiv.org/pdf/1012.5104v2.pdf



- Models differ mainly in normalisation, shape similar
- Track multiplicity underestimated

Different Centre of Mass Energy

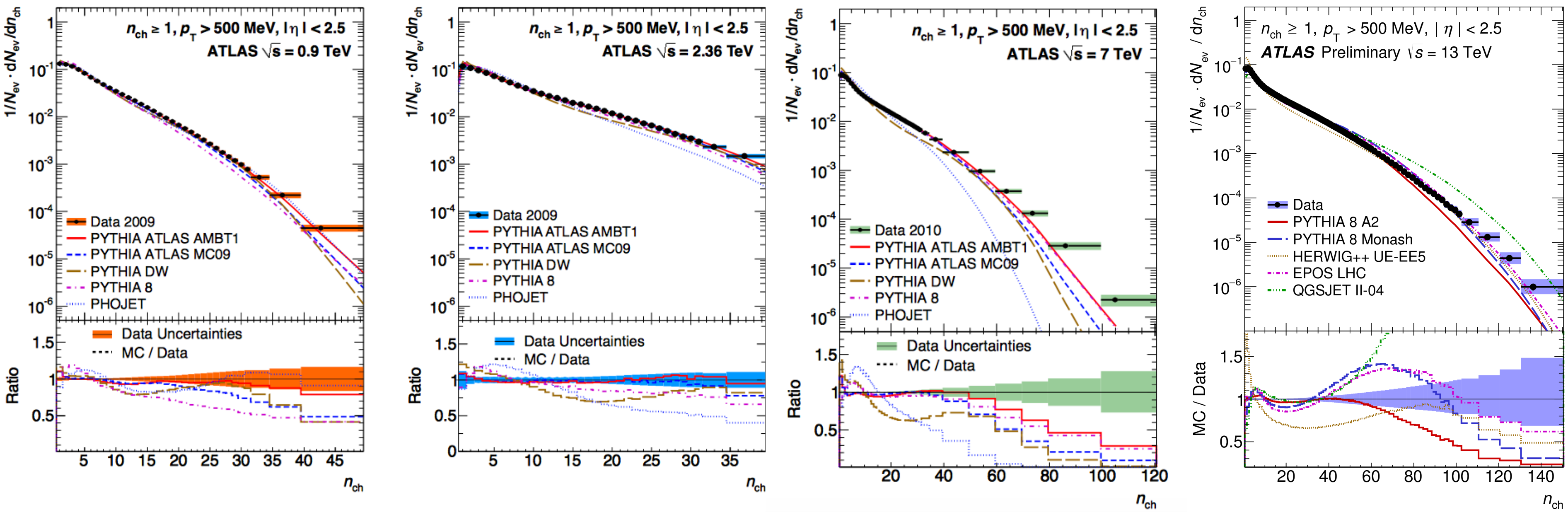
$d^2N_{ev}/d\eta dp_T$ http://arxiv.org/pdf/1012.5104v2.pdf



- Large disagreement at low p_T and high p_T

Different Centre of Mass Energy

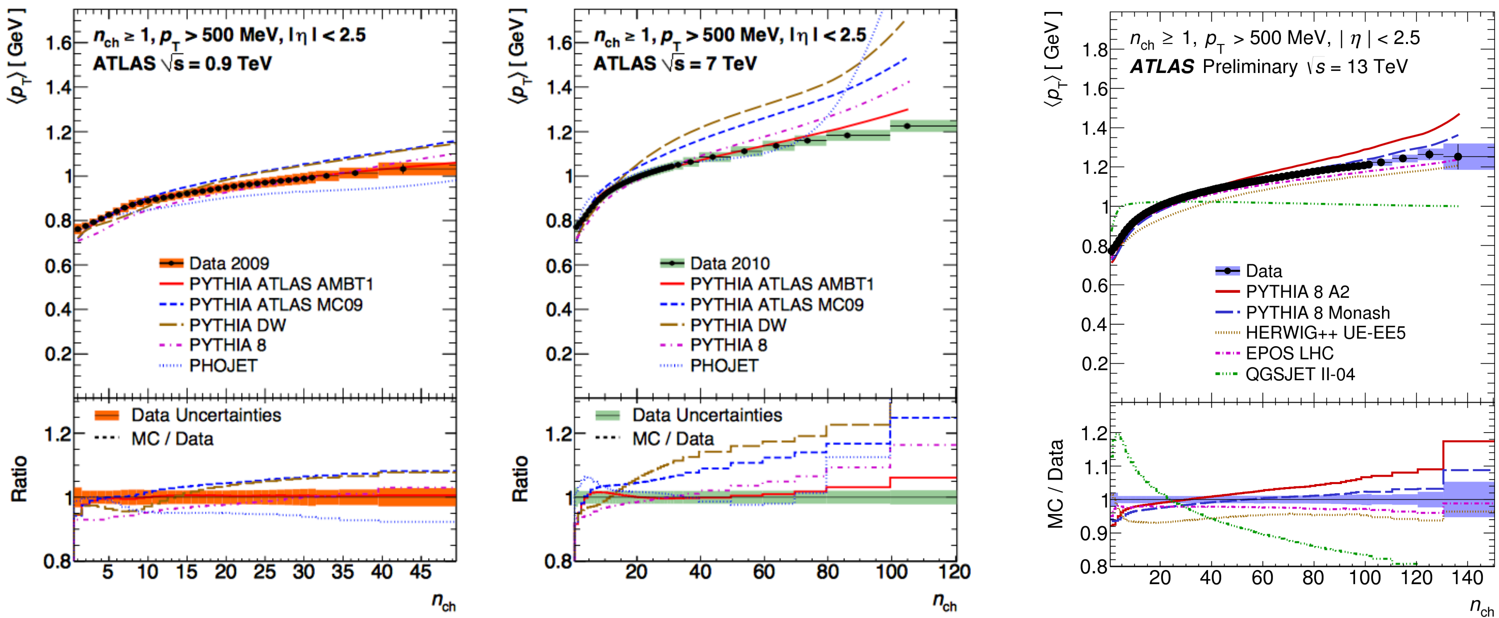
dN_{ev}/dn_{ch} http://arxiv.org/pdf/1012.5104v2.pdf



- Low n_{ch} not well modelled by any MC; large contribution from diffraction

Different Centre of Mass Energy

$\langle p_T \rangle$ vs. n_{ch} http://arxiv.org/pdf/1012.5104v2.pdf

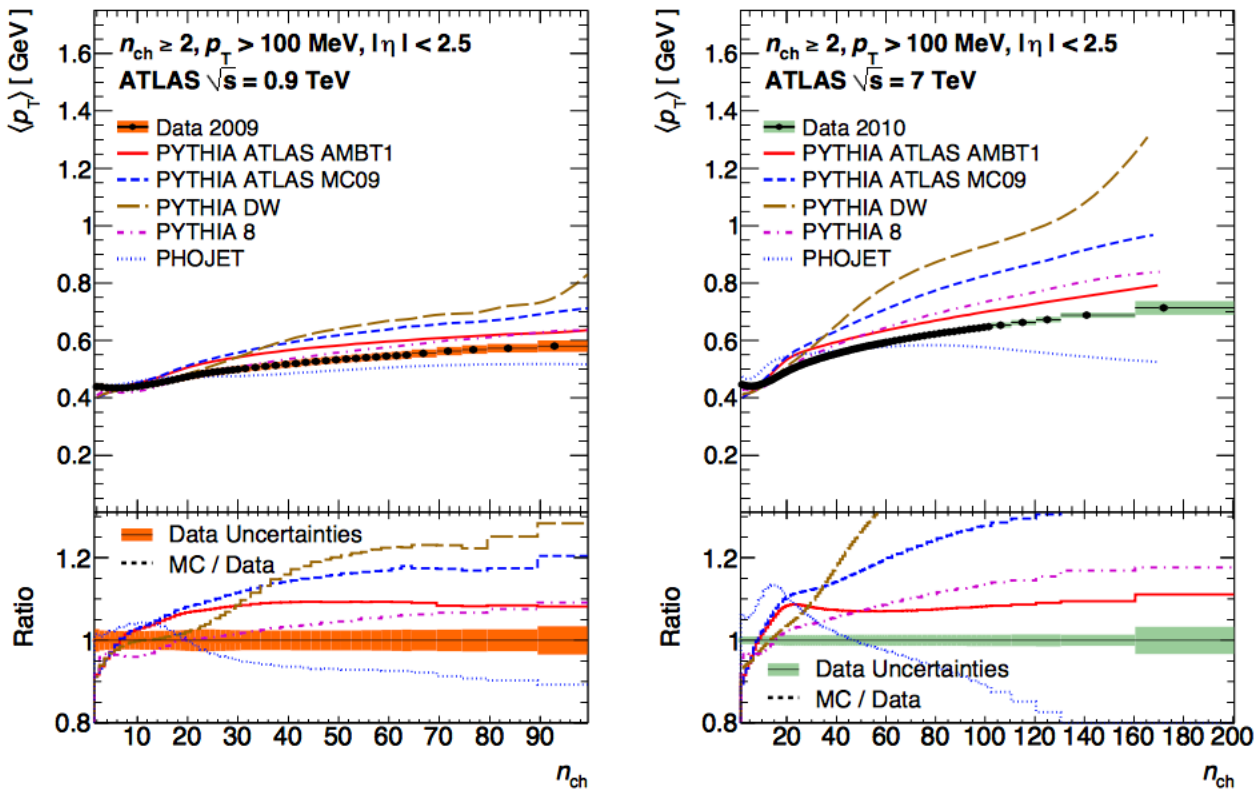


The measurement of ⟨pT⟩ as a function of charged multiplicity at s = 2.36 TeV is not shown because different track reconstruction methods are used for determining the pT and multiplicity distributions

- Pythia8 with hard diffractive component give best description
- Shape at low n_{ch} sensitive to ND, SD, DD fractions especially when using a 100 MeV selection

Different Centre of Mass Energy

$\langle p_T \rangle$ vs. n_{ch} http://arxiv.org/pdf/1012.5104v2.pdf



- Pythia8 with hard diffractive component give best description
- Shape at low n_{ch} sensitive to ND, SD, DD fractions especially when using a 100 MeV selection

Different Centre of Mass Energy

The measurement of ⟨pT⟩ as a function of charged multiplicity at s = 2.36 TeV is not shown because different track reconstruction methods are used for determining the pT and multiplicity distributions

$<p_T>$ vs. n_{ch}

http://arxiv.org/pdf/1012.5104v2.pdf

4.3.2 Track Reconstruction Algorithms at 2.36 TeV

Operation of the SCT at standby voltage during 2.36 TeV data taking led to reduced SCT hit efficiency. Consequently, ID tracks are reconstructed at this centre-of-mass energy using looser requirements on the numbers of hits and holes [4] [44, 45]. There are no simulation samples that fully describe the SCT operating at reduced voltage. A technique to emulate the impact of operating the SCT in standby was developed in simulation; this corrects the Monte Carlo without re-simulation by modifying the silicon clusterisation algorithm used to study the tracking performance. However, the final ID track efficiency at $\sqrt{s}$ = 2.36 TeV was determined using a correction to the track reconstruction efficiency derived from data at $\sqrt{s}$ = 0.9 TeV.

Pixel tracks were reconstructed using the standard track reconstruction algorithms limited to Pixel hits and with different track requirements. There is little redundant information, because at least three measurement points are needed to obtain a momentum measurement and the average number of Pixel hits per track is three in the barrel. Therefore the Pixel track reconstruction efficiency is very sensitive to the location of inactive Pixel modules. The total distance between the first and the last measurement point in the pixel detector, as well as the limited number of measurement points per track, limit the momentum resolution of the tracks; therefore the Pixel tracks were refit using the reconstructed primary vertex as an additional measurement point. The refitting improves the momentum resolution by almost a factor of two. However, the Pixel track momentum resolution remains a factor of three worse than the resolution of ID tracks.

The selection criteria used to define good Pixel and ID tracks are shown in Table 3. The total number of accepted events and tracks at this energy are shown in Table 4. These two track reconstruction methods have different limitations; the method with the best possible measurement for a given variable is chosen when producing the final plots. The Pixel track method is used for the n_{ch} and η distributions, while the ID track method is used for the p_T spectrum measurement; the $\langle p_T \rangle$ distribution is not produced for this energy as neither method is able to describe both the number of particles and their p_T accurately.

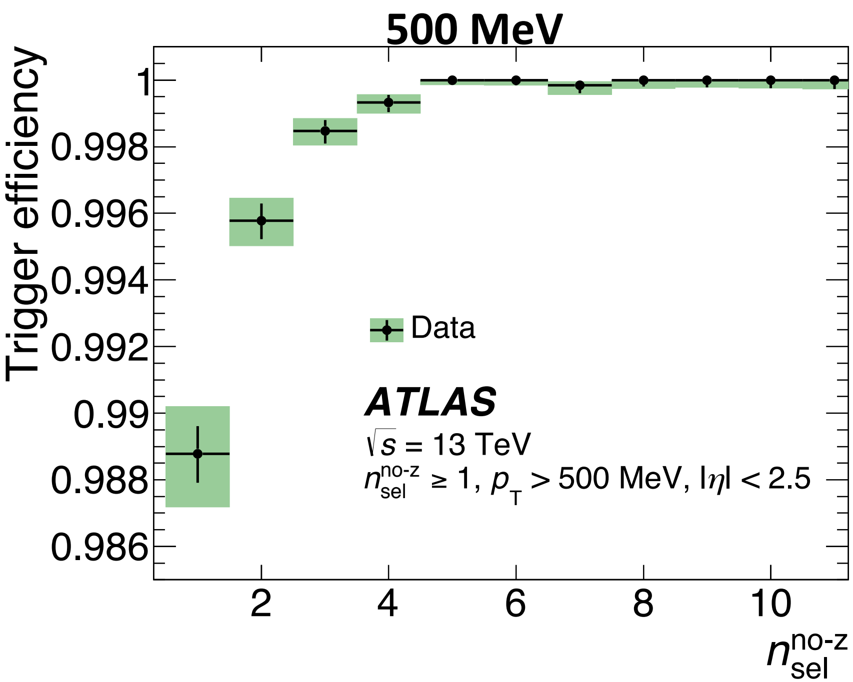
Strange Baryons

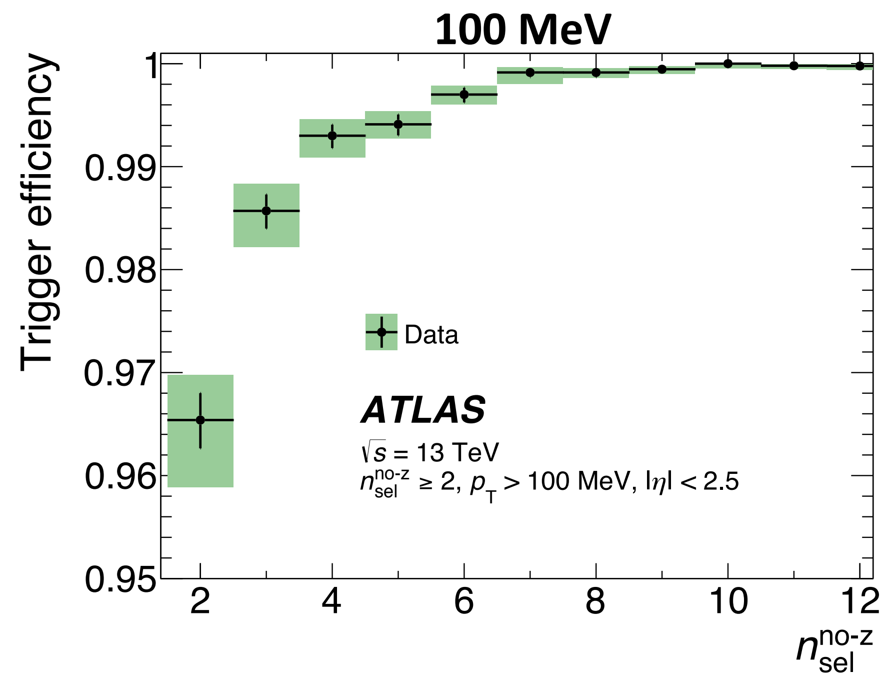
STRANGE BARYONS	
Λ	3122
Σ^+	3222
Σ^0	3212
Σ^-	3112
Σ^{*+}	3224^d
Σ^{*0}	3214^d
Σ^{*-}	3114^d
Ξ^0	3322
Ξ^-	3312
Ξ^{*0}	3324^d
Ξ^{*-}	3314^d
Ω^-	3334

Trigger Efficiency

- Trigger efficiency is evaluated by using a control trigger and the MBTS trigger:

$$\epsilon_{trig}(n_{sel}{}^{no-z}) = \frac{N(MBTS1\ triggered \cap sptrk\ triggered)}{N(sptrk\ triggered)}$$

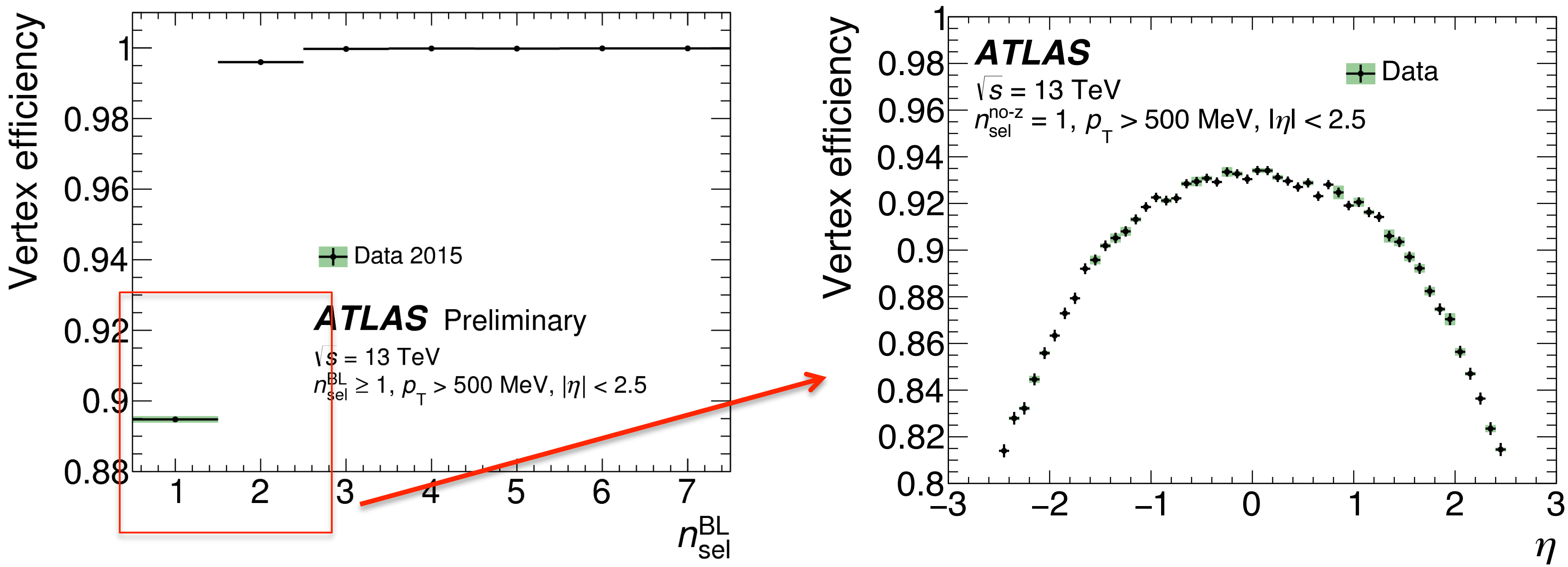




Systematic uncertainty:
- variation of the track selection; differences between MBTS A and C side ; non-collision beam background
- MC based: events failing both triggers

Vertex Efficiency

$$\epsilon_{vtx}(n_{sel}{}^{no-z}) = \frac{N(MBTS1\ triggered \cap n_{vtx} = 1)}{N(MBTS1\ triggered)}$$



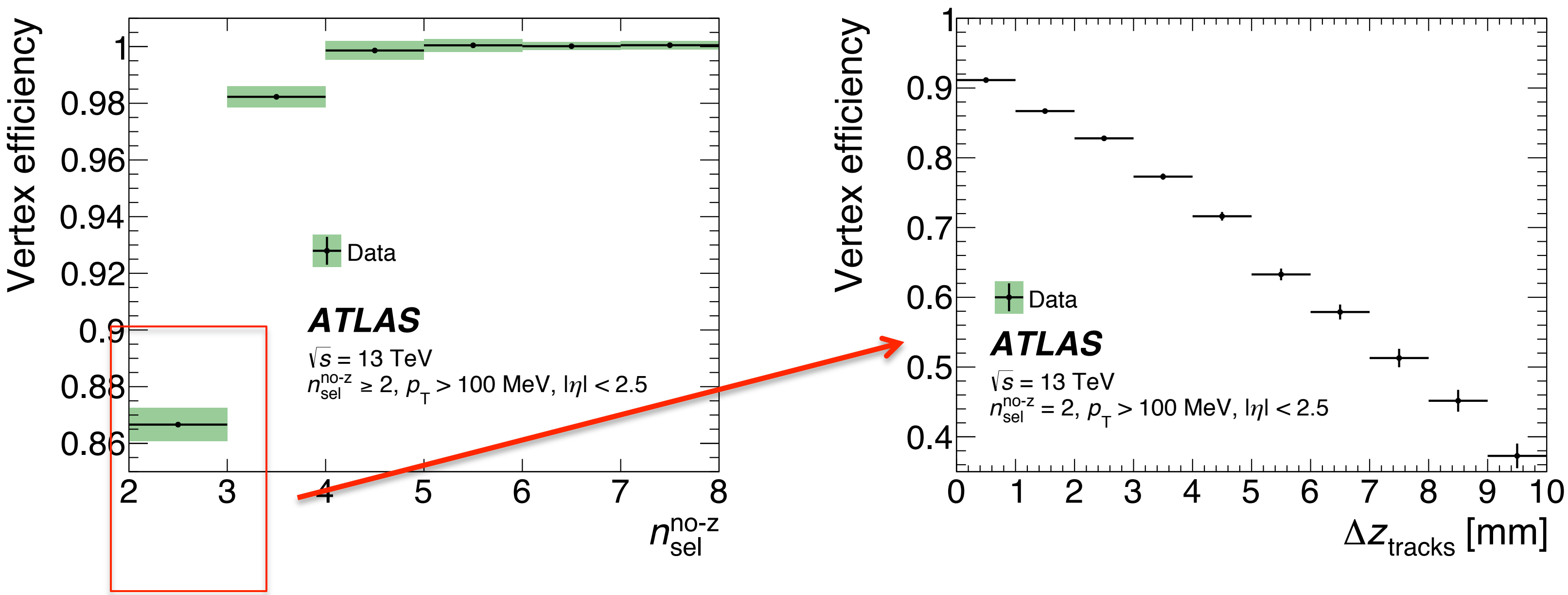
Efficiency for the first $n_{sel}{}^{no-z}$ bin depends on eta of the track

Systematic uncertainty:

- non-collision beam background which is strongly reduced by the vertex requirement

Vertex Efficiency

$$\epsilon_{vtx}(n_{sel}{}^{no-z}) = \frac{N(MBTS1\ triggered \cap n_{vtx} = 1)}{N(MBTS1\ triggered)}$$



Efficiency for the first $n_{sel}{}^{no\text{-}z}$ bin depends on Δz between the tracks

Systematic uncertainty:
- non-collision beam background which is strongly reduced by the vertex requirement

Systematic Uncertainties Breakdown

500 MeV

Source	Distribution	Range of values
Track reconstruction efficiency	η	0.5% – 1.4%
	p_T	0.7%
	n_{ch}	$0\% - ^{+17\%}_{-14\%}$
Non-primaries	η	0.5%
	p_T	0.5% – 0.9%
	n_{ch}	$0\% - ^{+10\%}_{-8\%}$
Non-closure	η	0.7%
	p_T	0% – 2%
	n_{ch}	0% – 4%
p_T-bias	p_T	0% – 5%
High-p_T	p_T	0% – 1%

100 MeV

Distribution	$\left\lvert \frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\eta} \right\rvert$	$\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta dp_T}$	$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$	$\langle p_T \rangle$ vs. n_{ch}
Range	0 – 2.5	0.1 – 50 GeV	2 – 250	0 – 160 GeV
Track reconstruction	1 – 7%	1% – 6%	$0\% - ^{+38\%}_{-20\%}$	0% – 0.7%
Track background	0.5%	0.5% – 1%	$0\% - ^{+7\%}_{-1\%}$	0% – 0.1%
p_T spectrum	–	–	$0\% - ^{+3\%}_{-9\%}$	$0\% - ^{+0.3\%}_{-0.1\%}$
Non-closure	0.4% – 1%	1% – 3%	0% – 4%	0.5% – 2%

Table 1: Summary of MC tunes used to compare to the corrected data. The generator and its version are given in the first two columns, the tune name and the PDF used are given in the next two columns.

Generator	Version	Tune	PDF
PYTHIA 8	8.185	A2	MSTW2008LO [21]
PYTHIA 8	8.186	MONASH	NNPDF2.3LO [22]
EPOS	LHCv3400	LHC	N/A
QGSJET-II	II-04	default	N/A

In PYTHIA 8 inclusive hadron–hadron interactions are described by a model that splits the total inelastic cross section into non-diffractive (ND) processes, dominated by t-channel gluon exchange, and diffractive processes involving a colour-singlet exchange. The simulation of ND processes includes multiple parton–parton interactions (MPI). The diffractive processes are further divided into single-diffractive dissociation (SD), where one of the initial protons remains intact and the other is diffractively excited and dissociates, and double-diffractive dissociation (DD) where both protons dissociate. The sample contains approximately 22% SD and 12% DD processes. Such events tend to have large gaps in particle production at central rapidity. A pomeron-based approach is used to describe these events [15].

EPOS provides an implementation of a parton-based Gribov–Regge [16] theory, which is an effective QCD-inspired field theory describing hard and soft scattering simultaneously.

QGSJET-II provides a phenomenological treatment of hadronic and nuclear interactions in the Reggeon field theory framework [17]. The soft and semi-hard parton processes are included in the model within the "semi-hard pomeron" approach. EPOS and QGSJET-II calculations do not rely on the standard parton distribution functions (PDFs) as used in generators such as PYTHIA 8.

Different settings of model parameters optimised to reproduce existing experimental data are used in the simulation. These settings are referred to as tunes. For PYTHIA 8 two tunes are used, A2 [18] and MONASH [19]; for EPOS the LHC [20] tune is used. QGSJET-II uses the default tune from the generator. Each tune utilises 7 TeV minimum-bias data and is summarised in Table 1, together with the version of each generator used to produce the samples. The PYTHIA 8 A2 sample, combined with a single-particle MC simulation used to populate the high-p_T region, is used to derive the detector corrections for these measurements. All the events are processed through the ATLAS detector simulation program [23], which is based on GEANT4 [24]. They are then reconstructed and analysed by the same program chain used for the data.

The PYTHIA 8 [3], HERWIG++ [4], EPOS [5] and QGSJET-II [6] event generators are used in this analysis.

- In PYTHIA 8 [3], inclusive hadron-hadron interactions are described by a model that splits the total inelastic cross section into non-diffractive and diffractive processes. The non-diffractive part is dominated by t-channel gluon exchange. Its simulation includes multiple parton-parton interactions (MPI). The diffractive part involves a color-singlet exchange. It is further divided into single-diffractive dissociation (SD) where one of the initial hadrons remains intact and the other is diffractively excited and dissociates, and double-diffractive dissociation (DD) where both hadrons dissociate. The sample contains ~22% SD and ~12% DD processes.

  To reproduce experimental data, the ATLAS minimum-bias tune A2 [7] is used, which is based on the MSTW2008LO PDF [8]. It provides a good description of minimum bias events and of the transverse energy flow data, a calorimeter-based minimum bias analysis performed with $\sqrt{s} = 7$ TeV data [9].

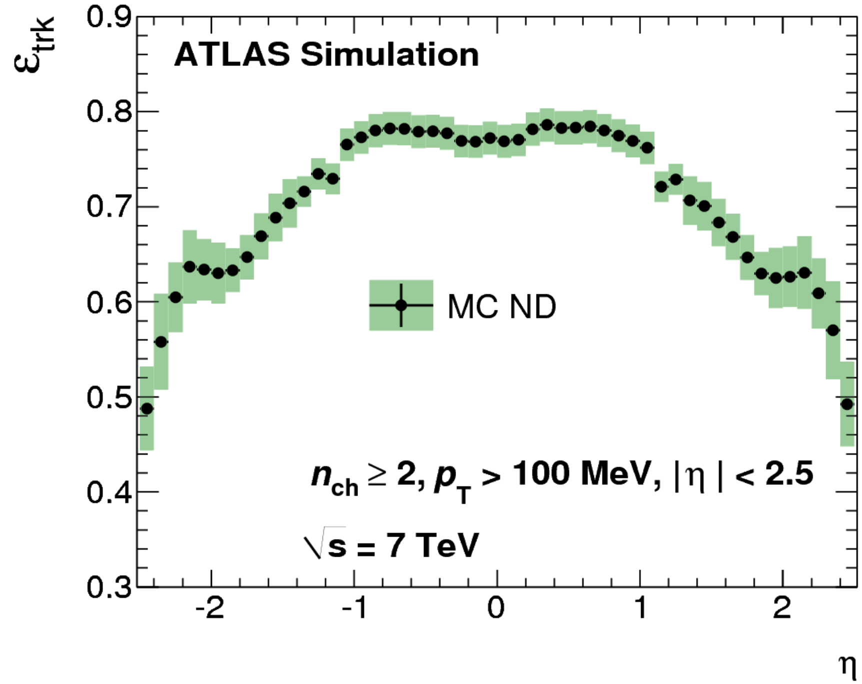
  An alternative tune, Monash [10], is used for comparison. It uses updated fragmentation parameters compared to A2 and minimum-bias, Drell-Yan, and underlying-event data from the LHC to constrain ISR and MPI parameters. In addition, it uses SPS and Tevatron data to constrain the energy scaling. It uses the NNPDF2.3LO PDF [11]. This tune gives an excellent description of 7 TeV minimum bias p_T spectrum.

- EPOS stands for *Energy conserving quantum mechanical approach, based on Partons, parton ladders, strings, Off-shell remnants, and Splitting of parton ladders*. The latest version 3.4 is used, which is equivalent to 1.99 version with the so called LHC tune. It provides an implementation of a parton-based Gribov-Regge theory, which is an effective QCD-inspired field theory describing the hard and soft scattering simultaneously. Hence, the calculations do not rely on the standard parton distribution functions (PDFs) as used in generators like PYTHIA 8 and HERWIG++.

- QGSJET-II offers a phenomenological treatment of hadronic and nuclear collisions at high energies, being developed in the Reggeon Field Theory framework. The soft and semi hard parton processes are included in the model within the “semi hard Pomeron” approach. Nonlinear interaction effects are treated by means of Pomeron Pomeron interaction diagrams.The latest model version comprises three important updates: treatment of all significant enhanced diagram contributions to the underlying dynamics, including ones of Pomeron loops, re-calibration of the model with new LHC data, and improved treatment of charge exchange processes in pion-proton and pion-nucleus collisions.

Track Reconstruction Efficiency

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



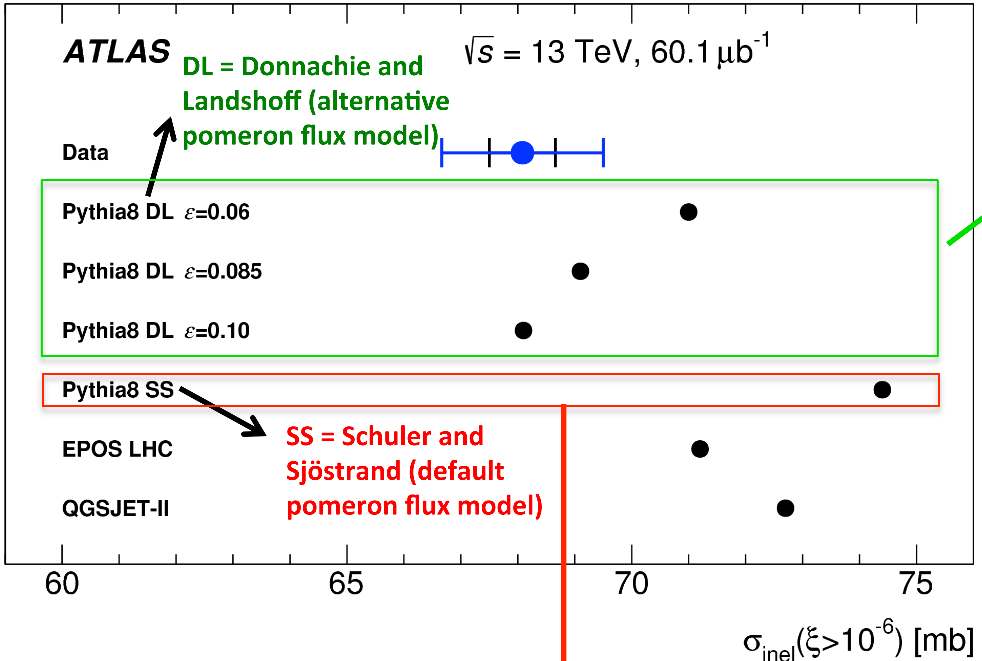
Systematic Uncertainty	Size (7 TeV, similar in all phase spaces)
Track Selection	1%
Material	2% - 15%
χ^2 probability	10% (only for p_T > 10 GeV)

Systematic uncertainty dominated by the lack of knowledge of the material distribution!

The Context – Inelastic cross-section

- Primary MC samples for inelastic cross-section measurements are based on the Pythia 8 generator either with the A2 tune and the MSTW 2008 LO PDF set or with the Monash tune and the NNPDF 2.3 LO PDF set (same tunes as for MinBias)

In the DL model, the Pomeron Regge trajectory is given by $\alpha(t)=1+\varepsilon+\alpha' t$ with ε and α' free parameters. Default value (0.25) was used for α', but different values (from 0.06 to 0.10) were used for ε



DL models are all giving predictions compatible with the data (the best one being DL with ε=0.10)

SS model predicts 74.4 mb, and thus exceeds the measured value by ~ 4 σ

The Idea Behind Pythia8 - A3

- Summarising what shown in the previous slides:
  - ATLAS used Run 1 data at the center-of-mass energy of 7 TeV to tune Pythia's MPI parameters → **A2 tune for MB & pile-up event simulation**
  - **Reasonably good description of the ATLAS Run 2 charged particle distributions**, but overestimation of **the fiducial inelastic cross-section** compared to the ATLAS measurements **at both √s= 7 and 13 TeV**
  - <μ> in simulation reweighted to match data
    - rescaling factor (driven by the fraction of the visible cross section wrt the total inelastic cross section for data and for MC) of 1.11 with large uncertainties
- In this scenario, the idea was to try and get **an improved tune** which better **describes the visible inelastic cross-section** by still **giving good predictions of the charged particle distributions**…

Pythia8 - A3

- **Pythia 8** (v. 8.186) with PDFs taken from LHAPDF version 6.1.3
- **Rivet** Analysis Toolkit (v. 2.4.1)
- **PROFESSOR** MC tuning system (v. 1.4.beta)
- Many parameters used for the tuning, each of them evaluated in a sampling range
- Starting point is **Monash** :
  - The parameters not mentioned here are left unchanged wrt Monash
  - But… two important aspects changed:
    - **Double Gaussian profile with 2 free parameters** used in place of the exponential overlap function used by Monash
    - **DL diffraction model** used in place of the SS model used in Monash (and in all the others Pythia tunes)

Parameter	Sampling range		
MultipartonInteractions:pT0Ref	1.00	–	3.60
MultipartonInteractions:ecmPow	0.10	–	0.35
MultipartonInteractions:coreRadius	0.40	–	1.00
MultipartonInteractions:coreFraction	0.50	–	1.00
BeamRemnants:reconnectRange	0.50	–	10.0
Diffraction:PomFluxEpsilon	0.02	–	0.12
Diffraction:PomFluxAlphaPrime	0.10	–	0.40

DL models has two tunable parameters, which control the Pomeron Regge trajectory

Pythia8 - A3

- A wide range of analyses used for the tuning

$\sqrt{s}$	Measurement type	Rivet name
13 TeV	MB	ATLAS_2016_I1419652 [3]
13 TeV	INEL XS	MC_XS [5]
7 TeV	MB	ATLAS_2010_S8918562 [11]
7 TeV	INEL XS	ATLAS_2011_I89486 [4]
7 TeV	RAPGAP	ATLAS_2012_I1084540 [15]
7 TeV	ETFLOW	ATLAS_2012_I1183818 [14]
900 GeV	MB	ATLAS_2010_S8918562 [11]
2.36 TeV	MB	ATLAS_2010_S8918562 [11]
8 TeV	MB	ATLAS_2016_I1426695 [16]

Not directly used for the tuning, but compared with A3 after the tuning

Pythia8 - A3: Tuning Strategy

- New approach:
  - PROFESSOR was used in the past to parameterise each bin of each observable as a N-dimensional 3rd order polynomial (N being the number of tuned parameters). The χ^2 wrt the reference data was then minimised;
  - Now:
    1. Generate soft QCD inelastic *pp* events
    2. Tune to the MB observables first (only measurements available at many √s)
    3. Add other measurements and check effects on parameters
    4. Tune everything together and ensure things look reasonable
    5. Pick-up the values which give the best results compared to data

Parameter	Observation from Step 2	Observation from Step 3
`MultipartonInteractions:pT0Ref`	Within 2.4 and 2.5	-
`MultipartonInteractions:ecmPow`	Fixed at 0.21	Fixed at 0.21
`MultipartonInteractions:coreRadius`	Poorly constrained	Around 0.5
`MultipartonInteractions:coreFraction`	Poorly constrained	Poorly constrained
`BeamRemnants:reconnectRange`	Around 6 or between 1.5 to 2	Between 1.5 to 2
`Diffraction:PomFluxEpsilon`	Not constrained	Between 0.055 and 0.075
`Diffraction:PomFluxAlphaPrime`	Not constrained	0.25

Pythia8 - A3: Final Tune

- Weight files containing all available measurements at all centre-of-mass energies constructed to be used in Professor framework
- Final parameters chosen to get the best description of MB observables at $\sqrt{s}$ = 13 TeV
  - Not dramatic disagreement with MB distributions at lower $\sqrt{s}$
- It was controlled that Diffraction:PomFluxEpsilon parameter was within an appropriate range to get a description of the inelastic cross section

Parameter	A3 value	A2 value	Monash value
`MultipartonInteractions:pT0Ref`	2.45	1.90	2.28
`MultipartonInteractions:ecmPow`	0.21	0.30	0.215
`MultipartonInteractions:coreRadius`	0.55	-	-
`MultipartonInteractions:coreFraction`	0.90	-	-
`MultipartonInteractions:a1`	-	0.03	-
`MultipartonInteractions:expPow`	-	-	1.85
`BeamRemnants:reconnectRange`	1.8	2.28	1.8
`Diffraction:PomFluxEpsilon`	0.07 (0.085)	-	-
`Diffraction:PomFluxAlphaPrime`	0.25 (0.25)	-	-

Pythia8 Tunes Comparison

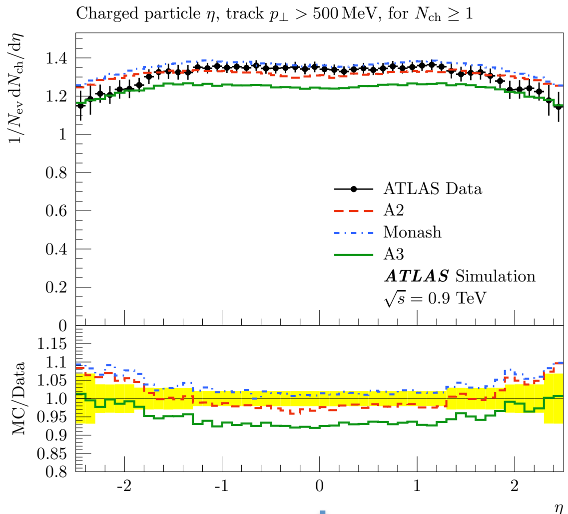
Wrt other tunes based on SS diffraction model:

- **Better description of the Fiducial Inelastic Cross section**

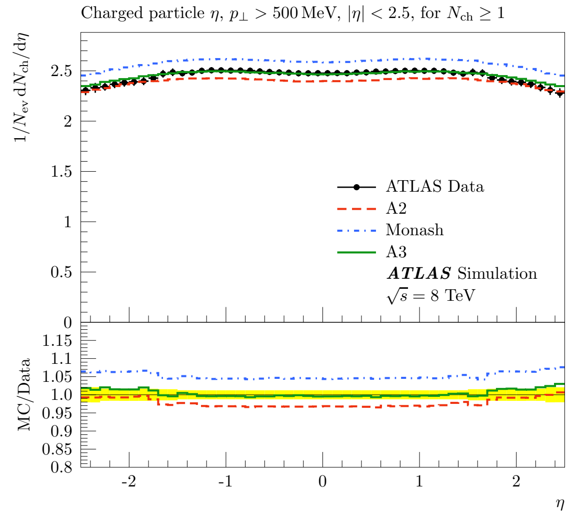
	ATLAS data (mb)	SS (mb)	A3 (mb)
At $\sqrt{s}$ = 13 TeV	68.1 ± 1.4	74.4	69.9
At $\sqrt{s}$ = 7 TeV	60.3 ± 2.1	66.1	62.3

- **Better description of charged particles η distributions at the highest centre-of-mass energy**

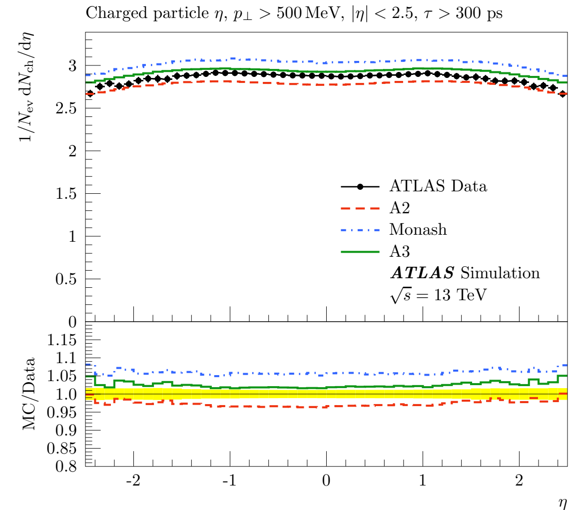
0.9 TeV



8 TeV



13 TeV



A3 underestimates the data at 0.9 TeV, but the focus of the study is the pile-up simulation at 13 TeV, thus this effect is negligible

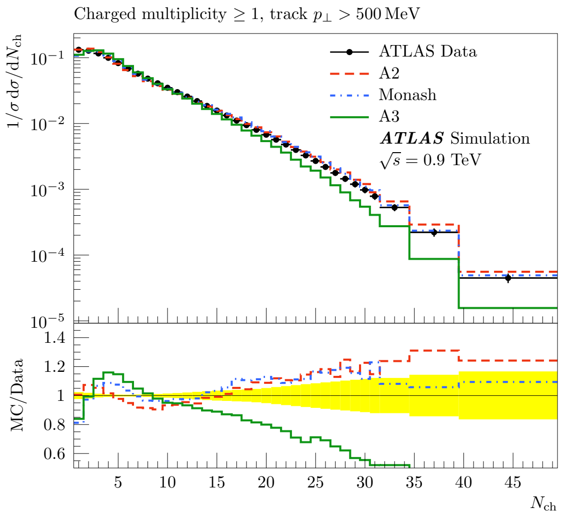
Very good description by A3!

N.B. Distributions for every √s are in back-up

Pythia8 Tunes Comparison

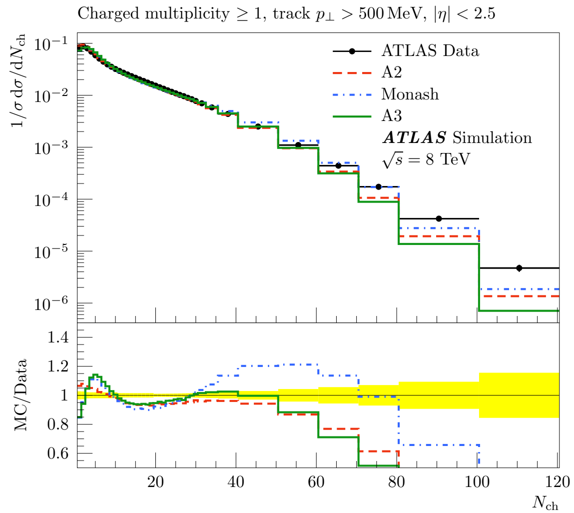
- **Charged particles multiplicity** predicted with a similar level of agreement by all generators at all √*s*, except at 0.9 TeV

0.9 TeV



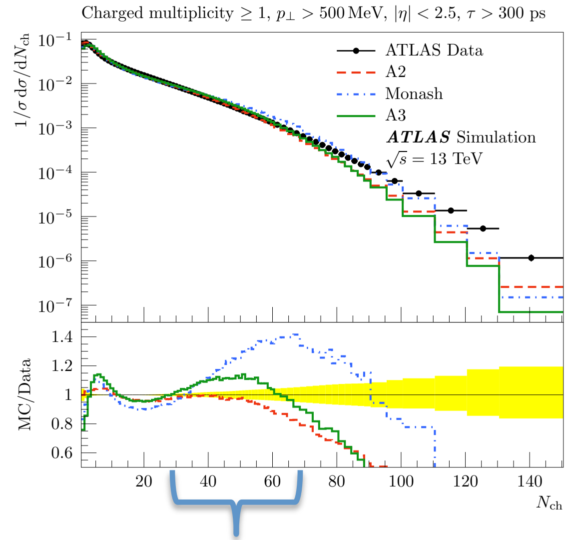
Not very good predictions given by A3 at the lowest √*s*

8 TeV



Shape of A3 prediction similar at all √*s*

13 TeV



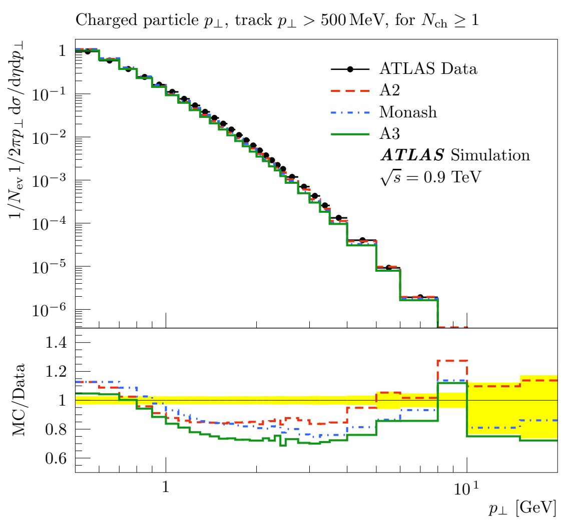
A2 describes the multiplicity better than A3

N.B. Distributions for every √*s* are in back-up

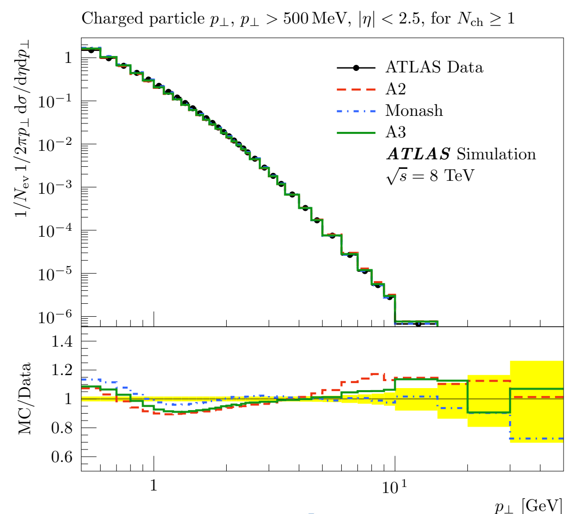
Pythia8 Tunes Comparison

- **Charged particles p_T** predicted similarly by A3 and Monash

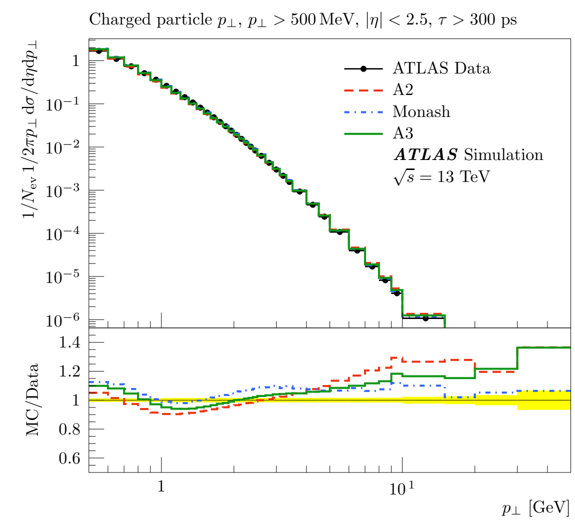
0.9 TeV



8 TeV



13 TeV



Not very good predictions given by A3 at the lowest √*s*

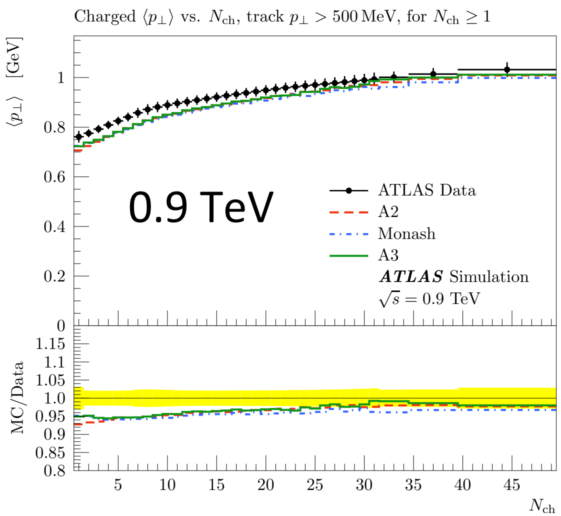
Similar predictions by all generators

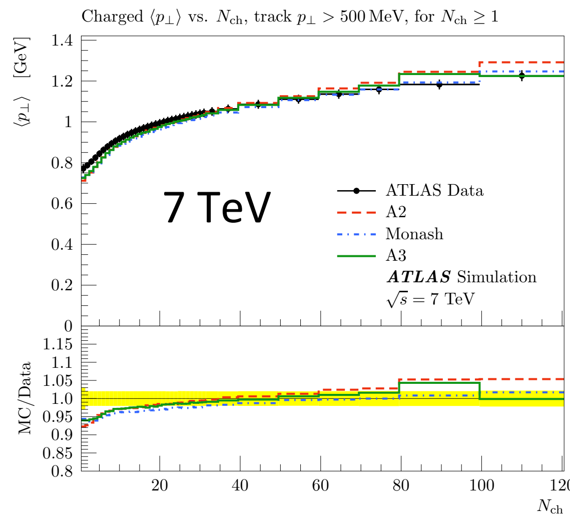
A3 describes the p_T spectrum better than A2

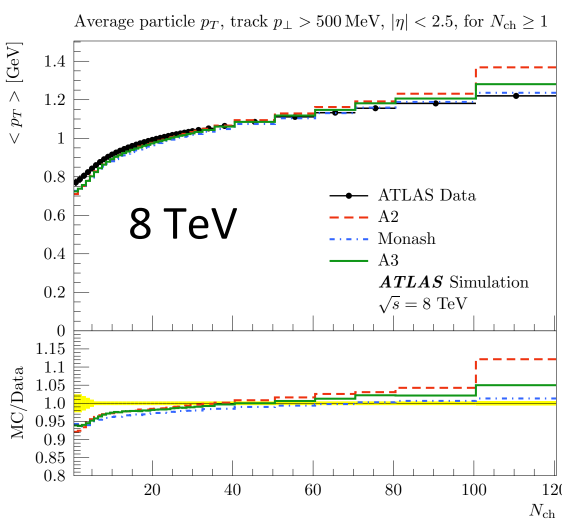
N.B. Distributions for every √*s* are in back-up

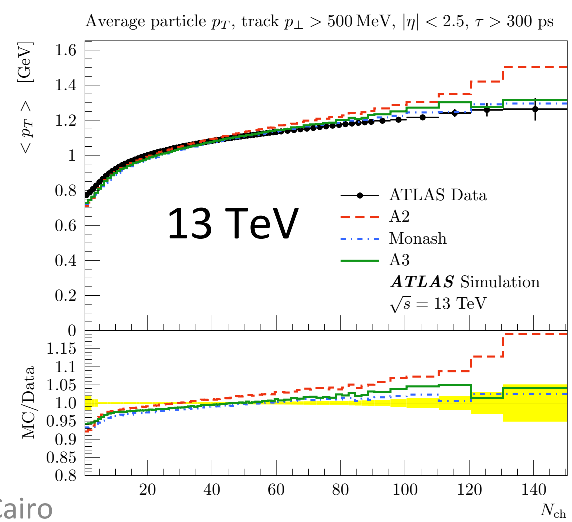
Pythia8 Tunes Comparison

- **Charged particles <p_T> vs multiplicity:** the choice of lower colour reconnection strength (*BeamRemnants:reconnectRange* = 1.8 in A3 and Monash, 2.28 in A2) led to slight improvement over A2



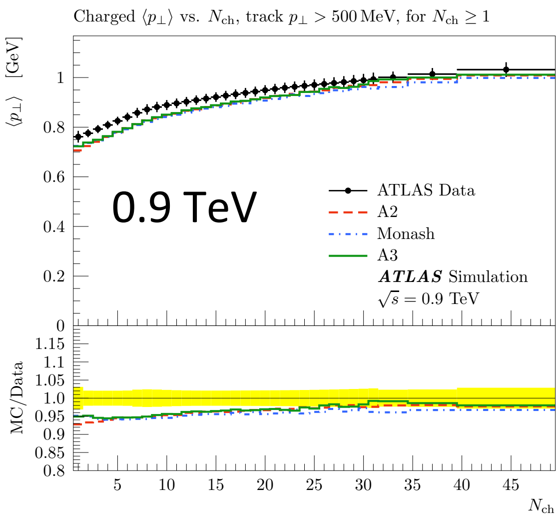


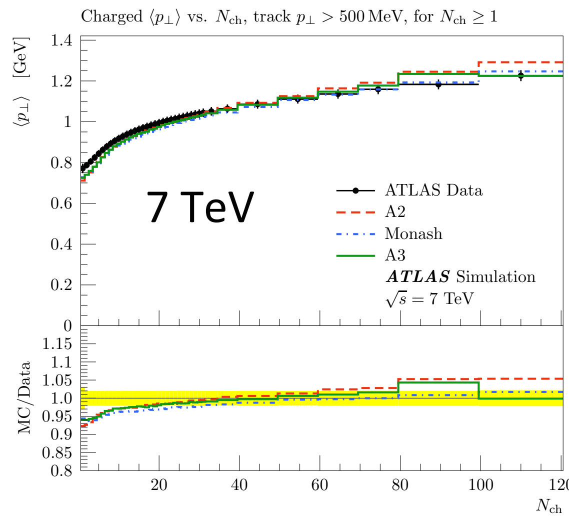


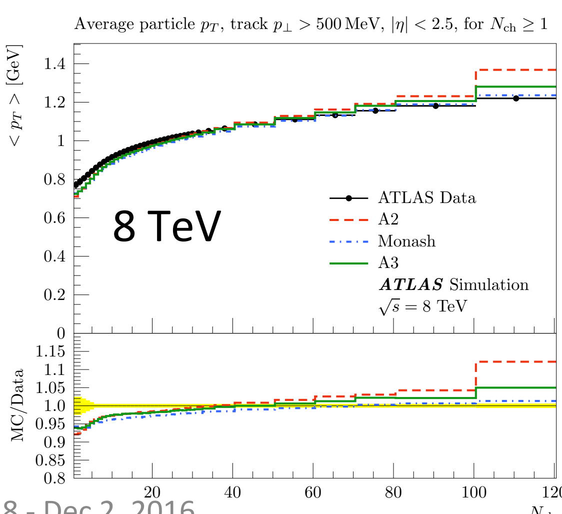


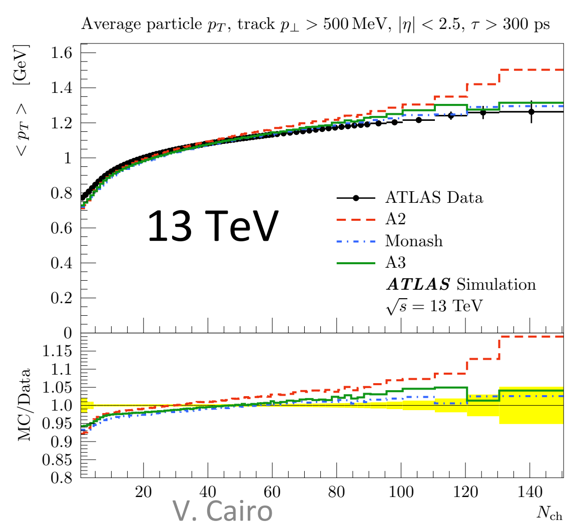
Pythia8 Tunes Comparison

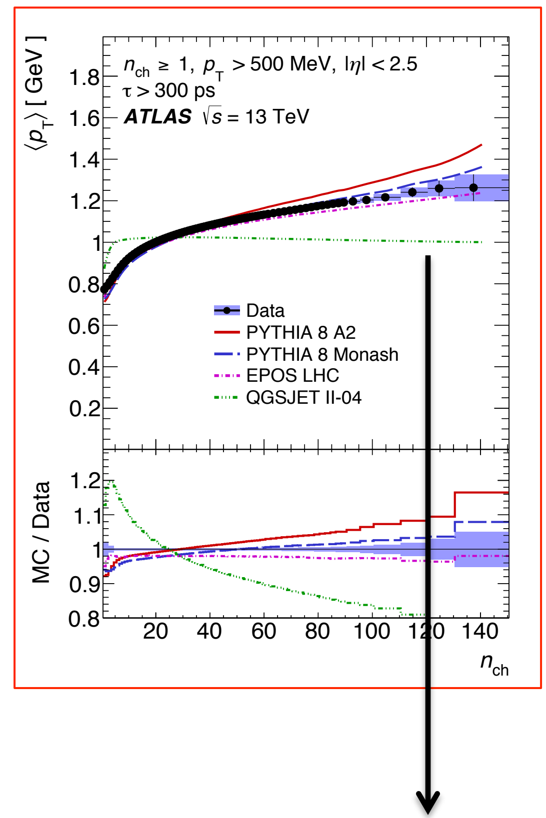
- **Charged particles <p$_T$> vs multiplicity:** the choice of lower colour reconnection strength (*BeamRemnants:reconnectRange* = 1.8 in A3 and Monash, 2.28 in A2) led to slight improvement over A2









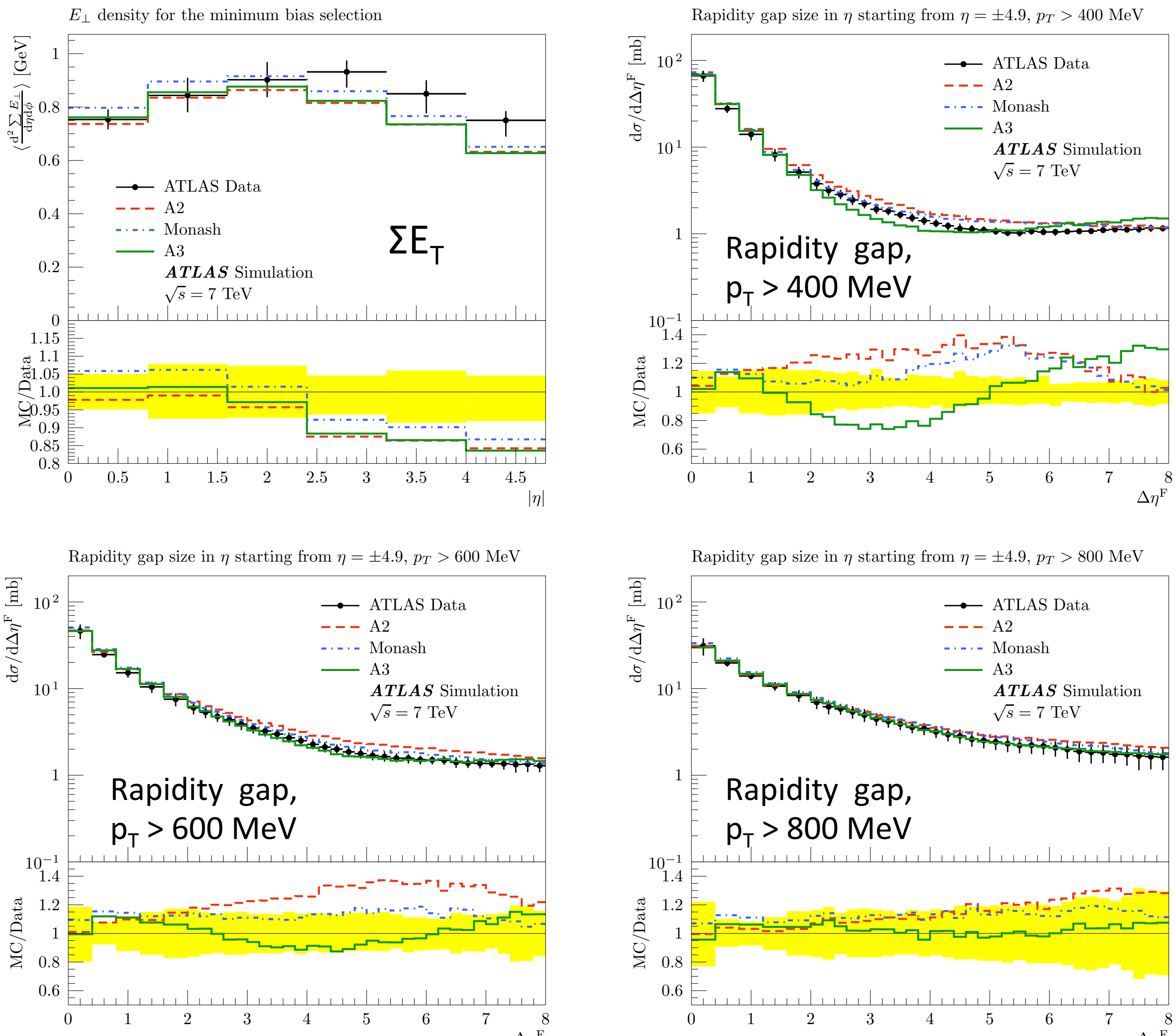


QGCJET has no colour reconnection

Pythia8 Tunes Comparison

- **Transverse Energy Flow and Rapidity Gap distributions at 7 TeV**

Good predictions given by A3 in the first bins



Good predictions given by A3 at high p_T, low p_T dominated by diffraction

Summary of Pythia 8 - A3

- **Features of A3:**

  - Aimed at modeling low-p_T QCD processes at the highest energies
  - Different diffraction model wrt other tunes (DL vs SS)
  - Early ATLAS Run 2 soft-QCD results at 13 TeV added in the tuning

- **Performance:**

  - Predictions of inelastic cross-sections closer to the measured values
  - Reasonable predictions of charged particles distributions

- **Message to take away:**

  - Acceptable description of data can be achieved by using the Donnachie-Landshoff model for diffraction
  - Possible starting point for further systematic studies of soft-QCD tunes
  - An improved and more reliable simulation of pile-up overlay can be obtained

Now moving to something else…