ATLAS Soft QCD

Stewart Martin-Haugh
On behalf of the ATLAS collaboration

Large Hadron Collider Physics Conference 2015

Science & Technology Facilities Council

Introduction

Motivation

- Soft QCD = strong interactions at low momentum transfer
- Non-perturbative: difficult to describe theoretically (see A. Siódmok's talk)
- Phenomenological models must be tuned to experimental measurements
- Comparisons between experiment and theory required to evaluate models

Analyses covered today

- Run 1
  - Two-particle Bose-Einstein correlations at $\sqrt{s} = 0.9,7$ TeV arXiv:1502.07947
  - Exclusive $\gamma\gamma \to \ell^+\ell^-$ production at $\sqrt{s} = 7$ TeV arXiv:1506.07098
- Run 2
  - Charged-particle multiplicities at $\sqrt{s} = 13$ TeV ATLAS-CONF-2015-028
  - Leading track underlying event distributions at $\sqrt{s} = 13$ TeV ATL-PHYS-PUB-2015-019
  - Inelastic cross section at $\sqrt{s} = 13$ TeV ATLAS-CONF-2015-038

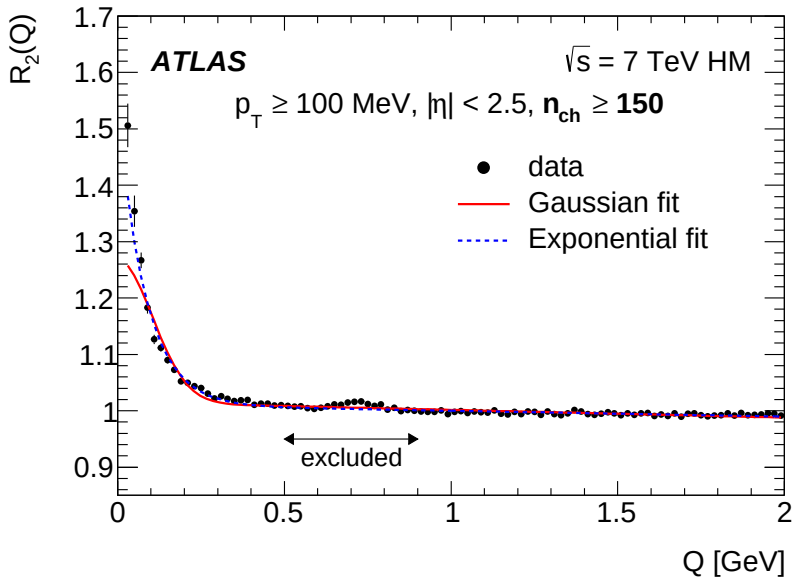
Bose-Einstein correlations arXiv:1502.07947

- Bose-Einstein correlations between identical bosons enhanced when bosons are close in phase space
  - Correlation is sensitive to the space-time geometry of the hadronisation medium
- Correlation function $C_2(Q)$ is a ratio of probabilities:

$$C_2(Q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \sim [1 + \Omega(\lambda, QR)]$$

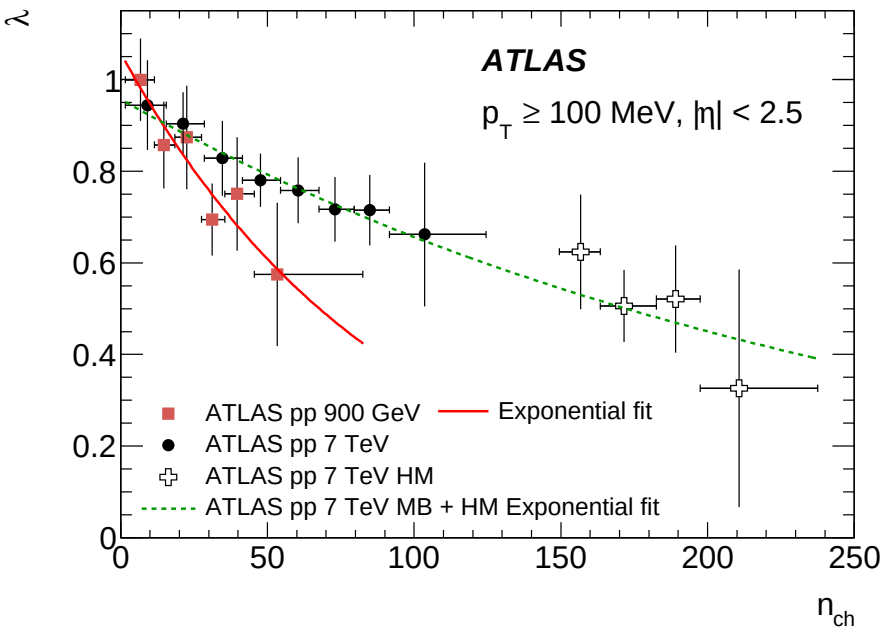
  - $Q^2 = -(p_1^2 - p_2^2)$
  - Ω = parameterisation (Gaussian, exponential)
  - R = effective source radius
  - λ = strength of effect

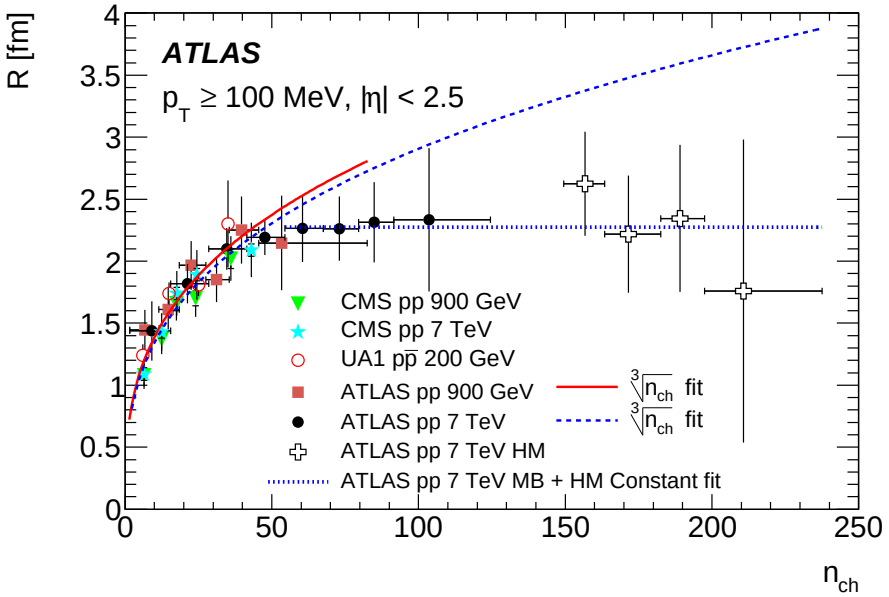
- Measure $C_2(Q) = N^{\text{ident.}}(Q)/N^{\text{non-ident.}}(Q)$
- Form $R_2(Q) = C_2^{\text{data}}(Q)/C_2^{\text{MC}}(Q)$ to remove effect of resonances etc
- Exclude region around poorly-modelled ρ resonance from R, λ fit



Results: Bose-Einstein correlations arXiv:1502.07947

- Three datasets used:
  - 0.9 TeV, $n_{\mathrm{ch}} \geq 2$, $\approx$ 4.5M events
  - 7 TeV, $n_{\mathrm{ch}} \geq 2$, $\approx$ 10M events
  - 7 TeV, $n_{\mathrm{ch}} \geq 150$, $\approx$ 18k events

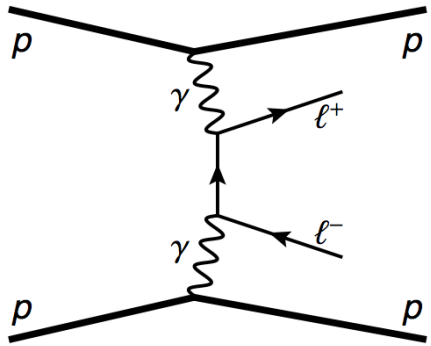




- R and λ are $\approx$ independent of energy to within uncertainties
- First evidence for saturation of R at high multiplicity, as predicted by pomeron-based models

Motivation: Exclusive $\gamma\gamma \to \ell^+\ell^-$ arXiv:1506.07098

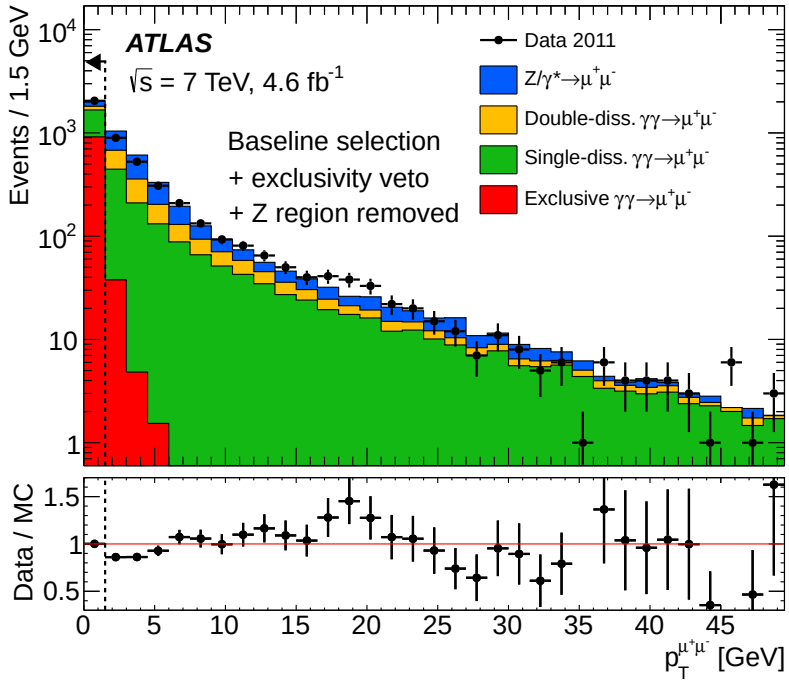
- Treat LHC like a $\gamma\gamma$ collider
- Elastic signal, diffractive background
- Background to $pp \to \gamma\gamma \to WW$ process
- Potential standard candle for luminosity



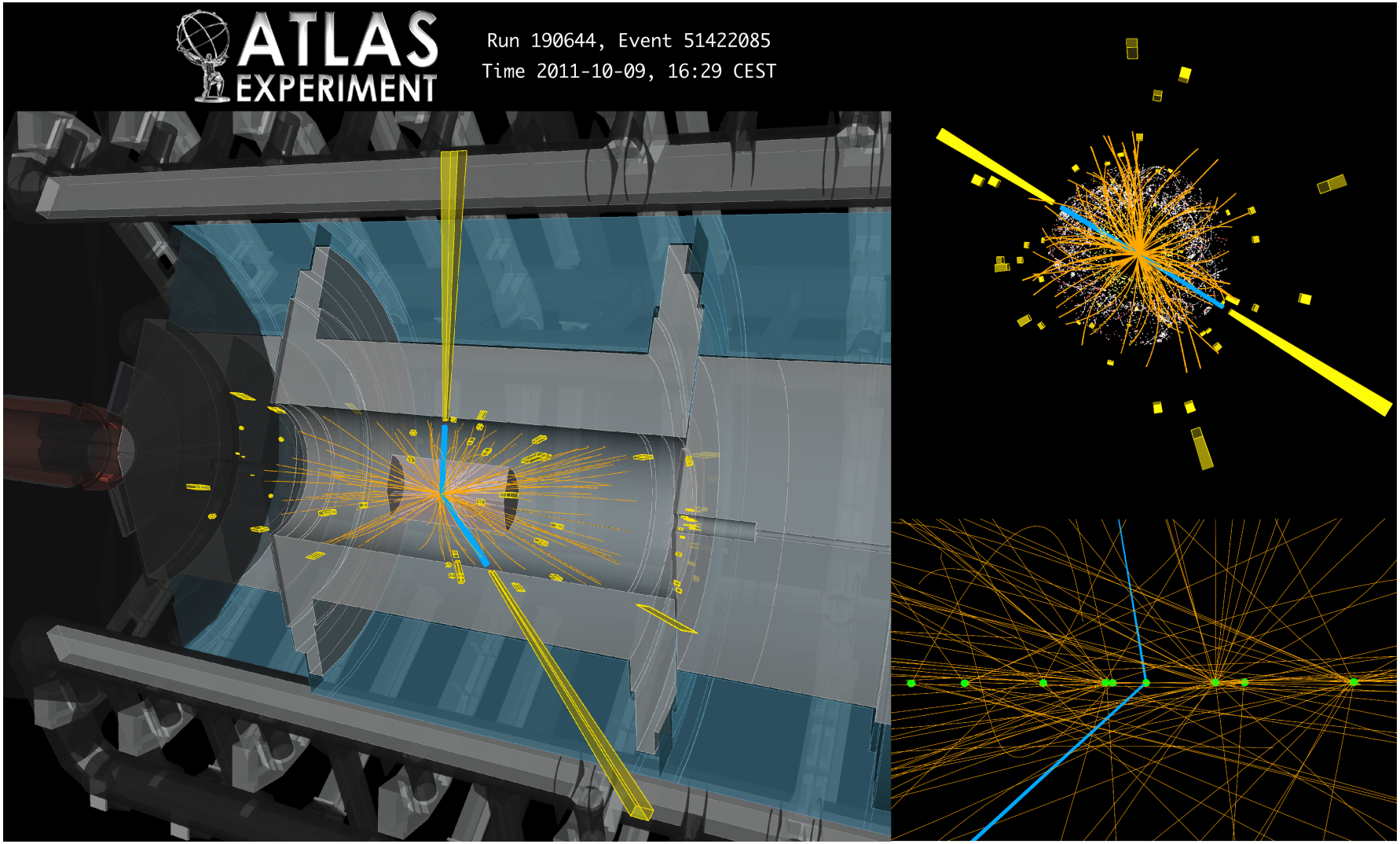
  - Precise prediction for elastic signal using equivalent photon approximation (EPA)
  - Absorptive corrections (finite proton size, QCD) not included in MCs

Event selection

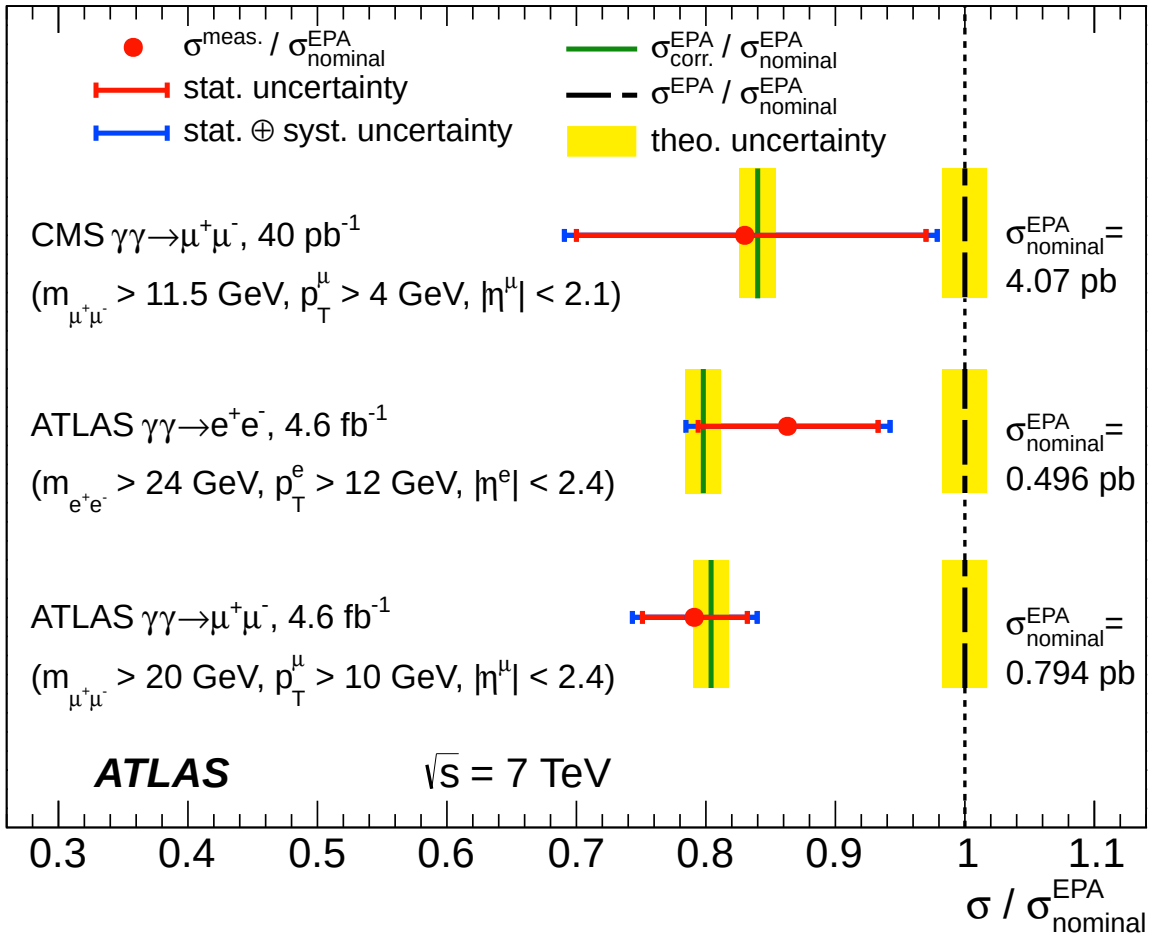
- Dilepton vertex
  - Exactly two $l = e, \mu$ at least 3 mm from all other vertices and tracks
- Veto Z/γ^* production
  - 75 GeV $< m_{\ell\ell} <$ 105 GeV
- Elastic system
  - $p_{\mathrm{T}}^{\ell\ell} <$ 1.5 GeV
- 869 dielectron events, 2124 dimuon events in total



Event display: Exclusive $\gamma\gamma \to e^+e^-$ candidate arXiv:1506.07098



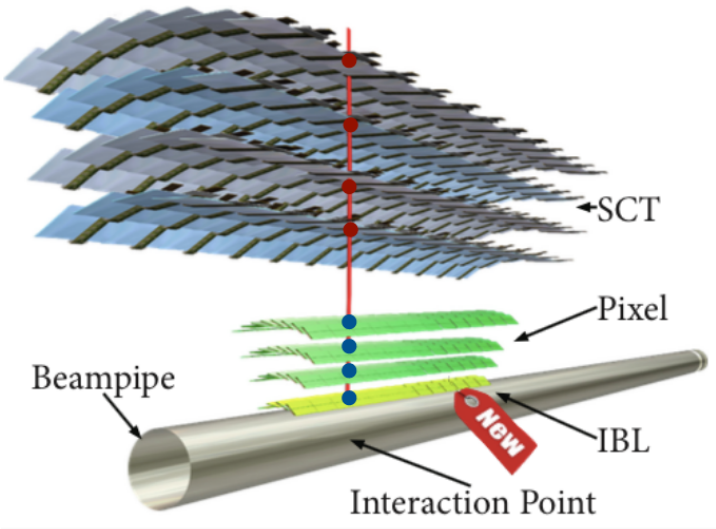
Results: Exclusive $\gamma\gamma \to \ell^+\ell^-$ arXiv:1506.07098



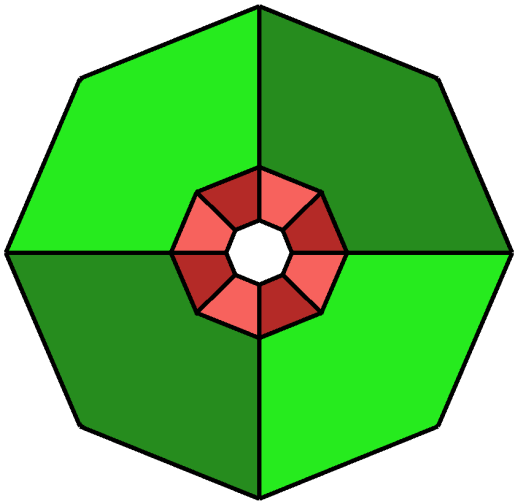
- Absorptive corrections parameterise finite proton size (deviation from $\sigma^{\mathrm{EPA}}_{\mathrm{nominal}}$)
- Compatible with theory and CMS measurement

ATLAS for Run 2

- Relevant upgrades to Inner Detector and trigger



- New Insertable B-Layer (IBL) sensitive 33 mm from the beampipe
- More precise tracking and vertexing
- New material budget to understand
  - See A. Alonso's talk

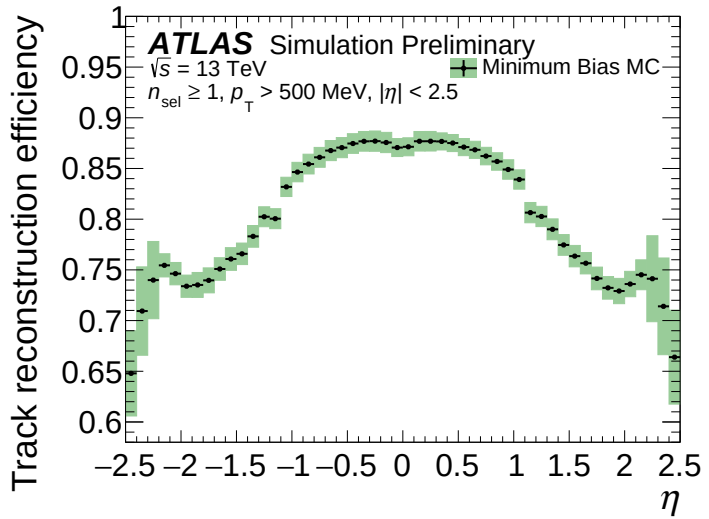


- Rebuilt Minimum Bias Trigger Scintillators (MBTS)
- $2.1 < |\eta| < 3.8$ acceptance
- High efficiency, uniform to with 1%

Charged particle multiplicities ATLAS-CONF-2015-028

- Inclusive measurement - minimal model-dependent corrections
  - Essential to tune MC generators
  - Distinguish between different hadronisation/MPI models
- Model pileup background to hard physics processes
- Measure distributions of primary charged particles corrected to particle level

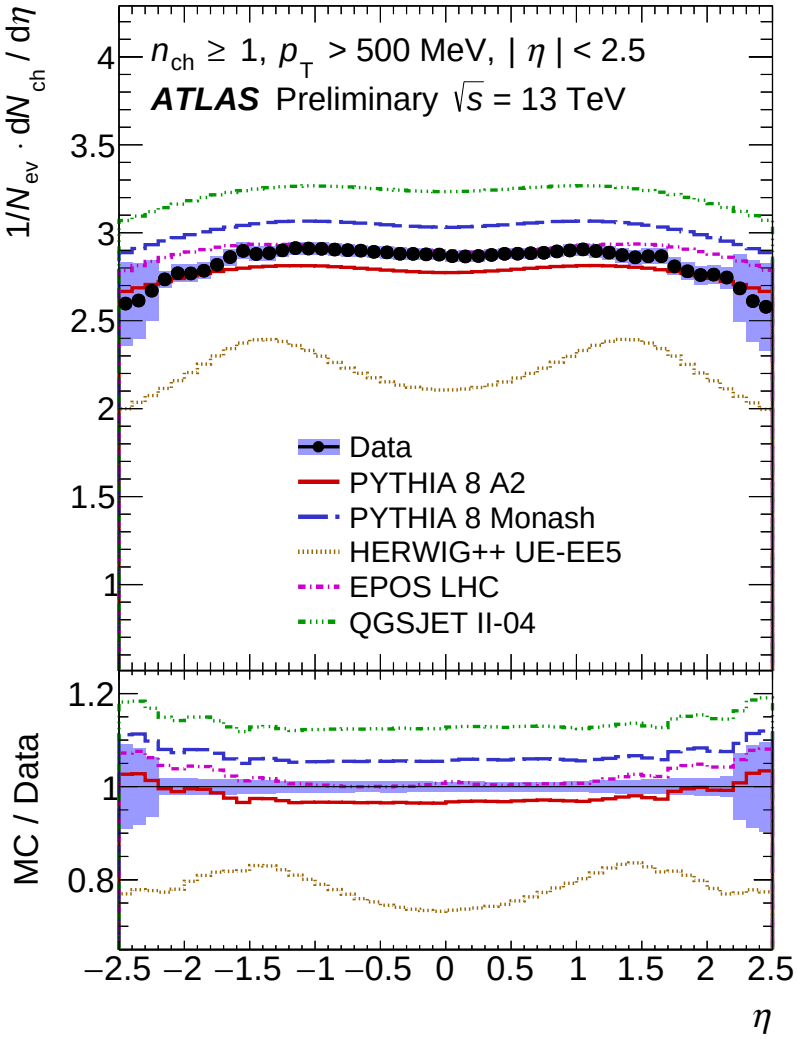
- $\geq$ 1 hit from an MBTS counter on either side
- No second vertex with $\geq$ 4 tracks
- $\geq$ 1 well-reconstructed track with
  - $p_{\mathrm{T}} > 500$ MeV, $|\eta| < 2.5$
  - $\geq$ 1 hit in innermost layer, $\geq$ 6 hits in SCT
- Data-driven trigger and vertexing efficiencies
- Dataset: 168 μb^{-1} at $\sqrt{s} = 13$ TeV, $\approx$ 10M events

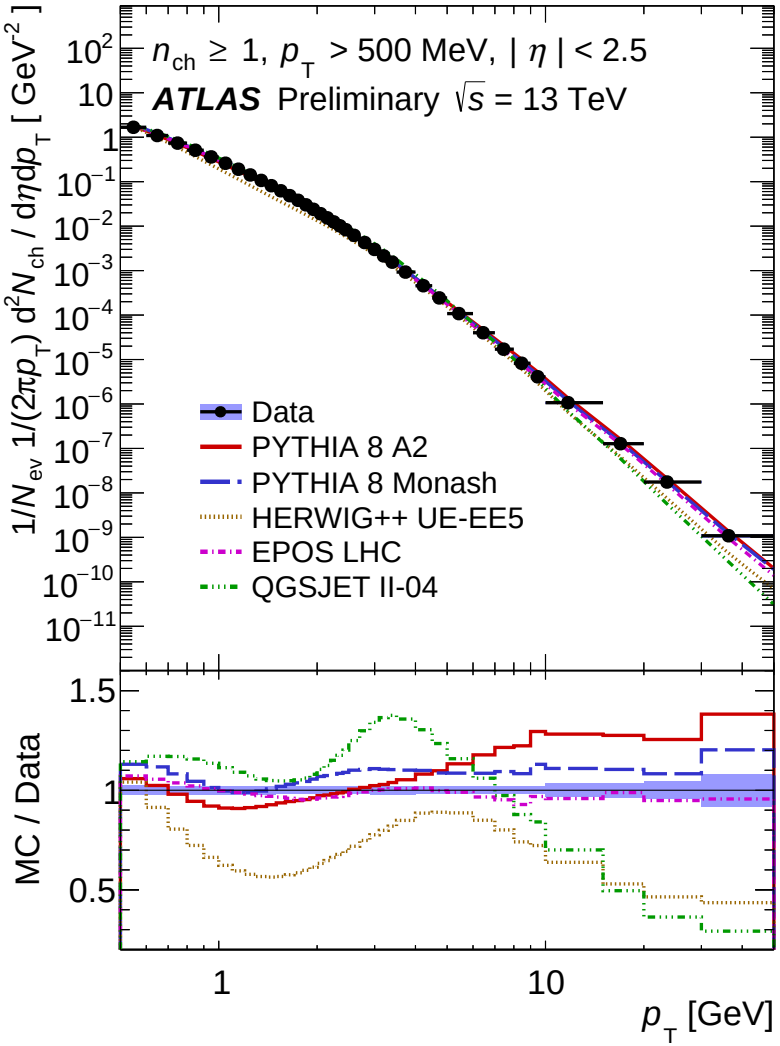


- Tracking efficiency estimated by simulation - uncertainties constrained by measurements of hadronic interactions, conversions etc

Results: Charged particle multiplicities ATLAS-CONF-2015-028

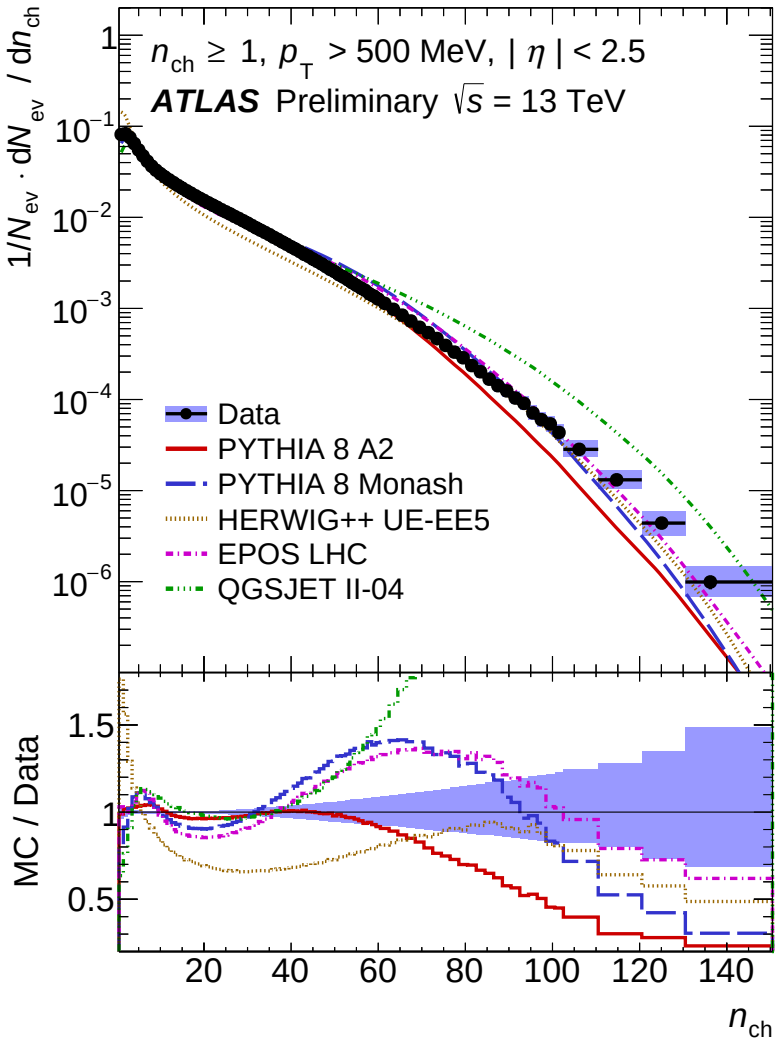
- Measurement covers ten orders in magnitude
- Differences mainly in normalisation
- Excellent agreement with Monash and A2 tunes

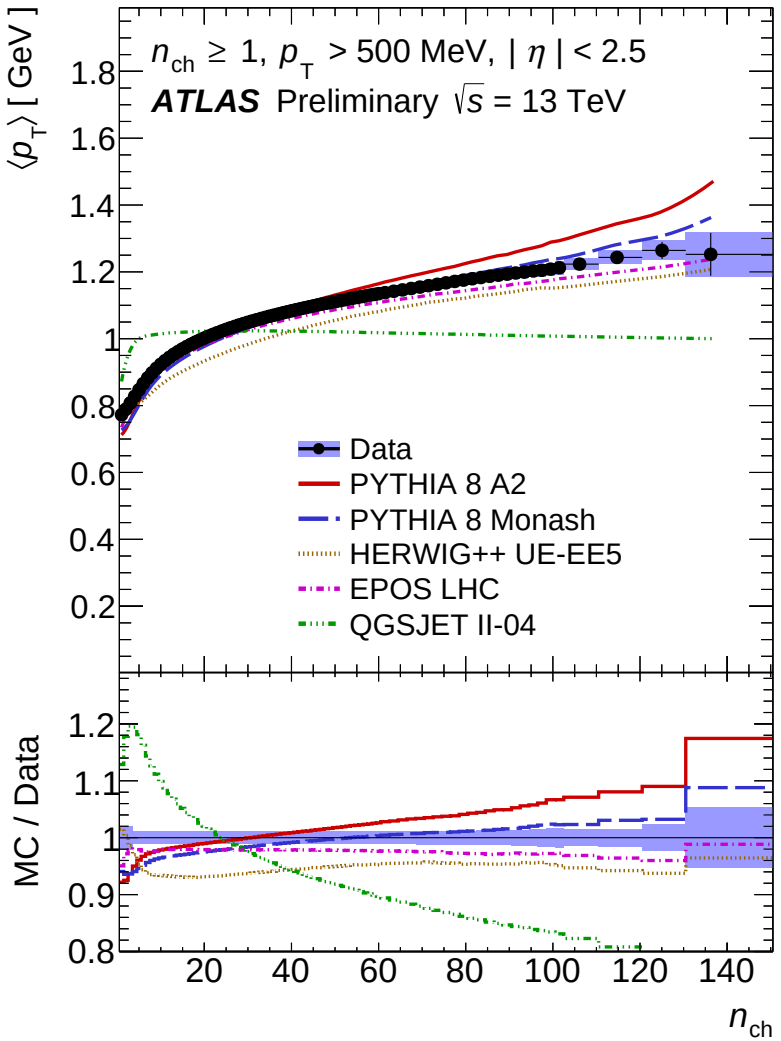




Results: Charged particle multiplicities ATLAS-CONF-2015-028

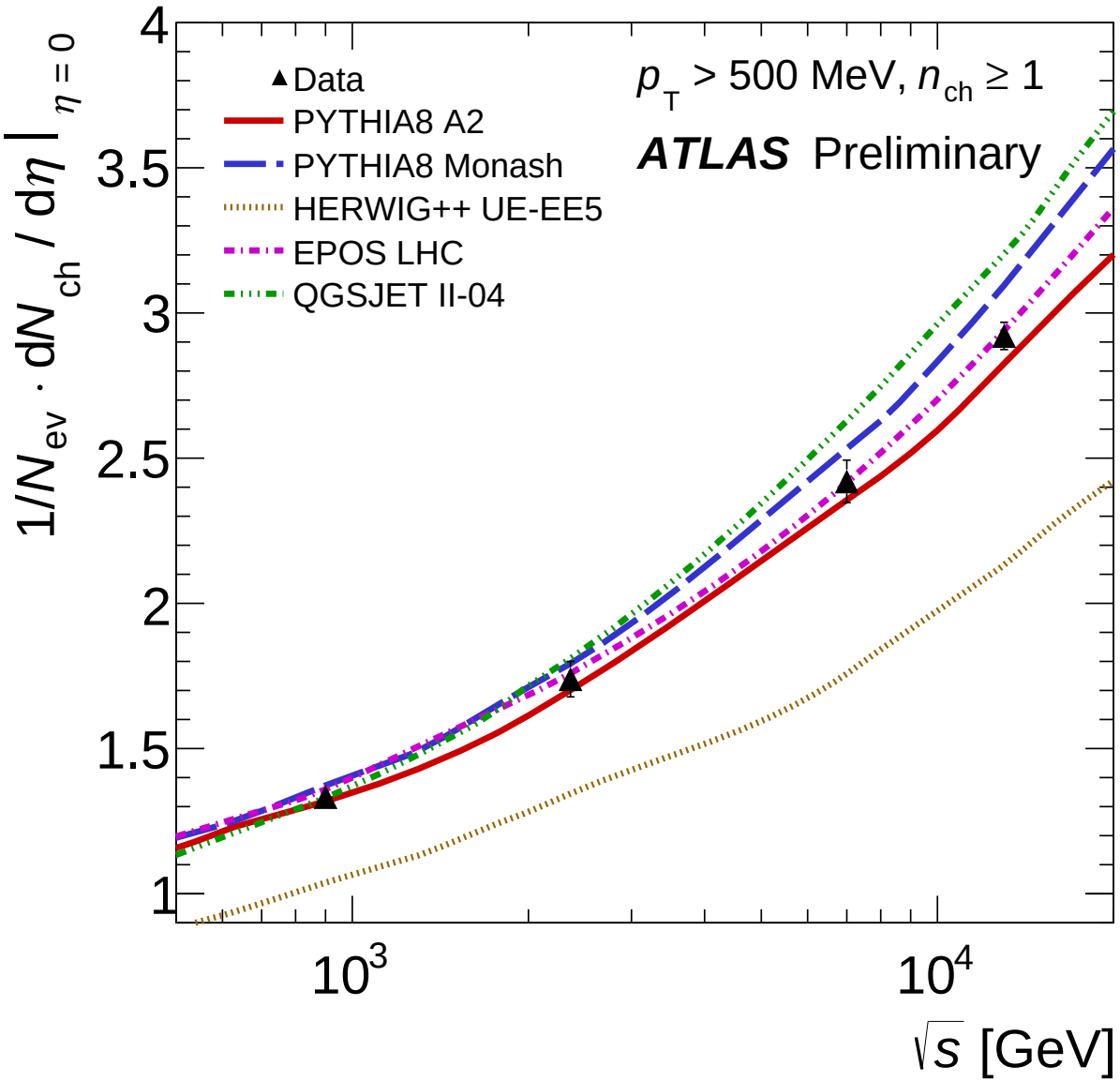
- Broad features reproduced well by several MCs
- Behaviour as a function of n_{ch} difficult to tune - not well modelled by any MC



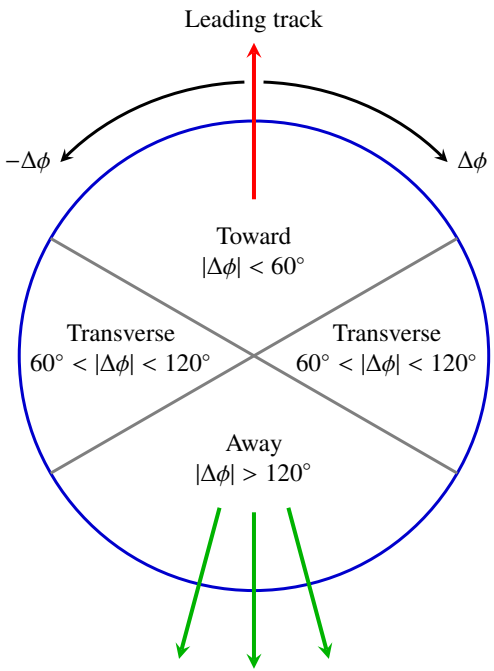


Results: Charged particle multiplicities ATLAS-CONF-2015-028

- ATLAS results at 0.9, 2.76, 7, 13 TeV

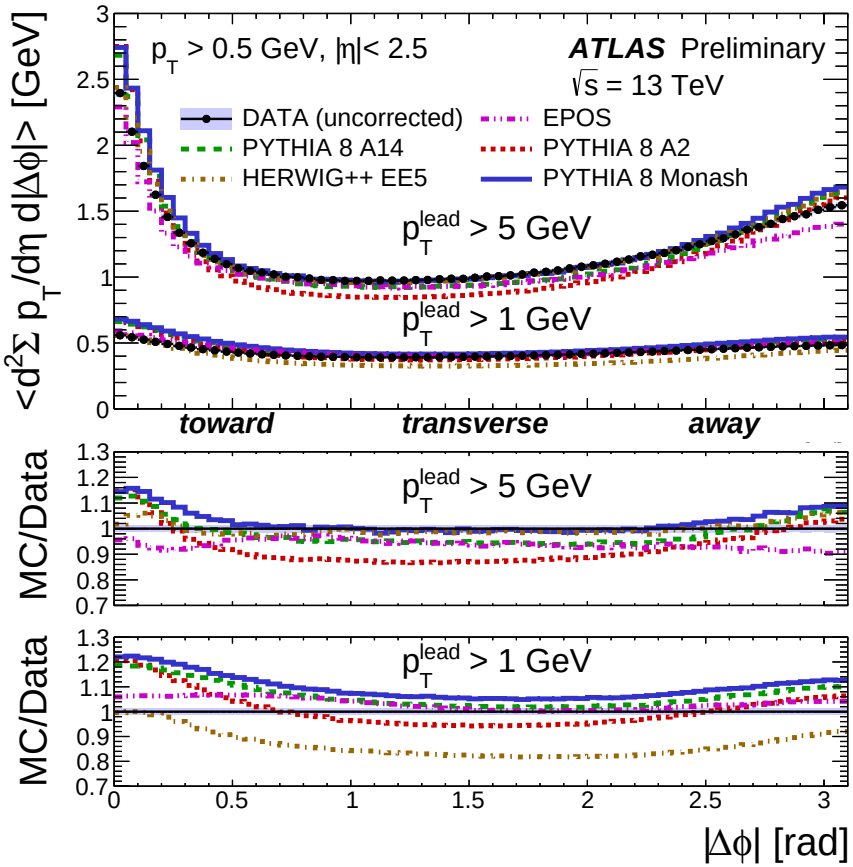


Detector-level leading track underlying event ATL-PHYS-PUB-2015-019



- MCs tuned to minimum bias data (Epos, Pythia 8 A2) describe $p_{\mathrm{T}}^{\mathrm{lead}} > 5$ GeV data better
- MCs tuned to underlying event data (HERWIG++ UEEE5, Pythia 8 Monash/A14) describe $p_{\mathrm{T}}^{\mathrm{lead}} > 1$ GeV data better

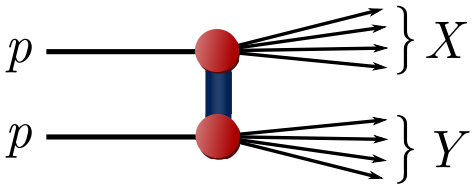
- Same dataset and selection as charged particle multiplicities plus leading track with $p_{\mathrm{T}} > 1$, 5 GeV
- Good agreement already obtained at detector level

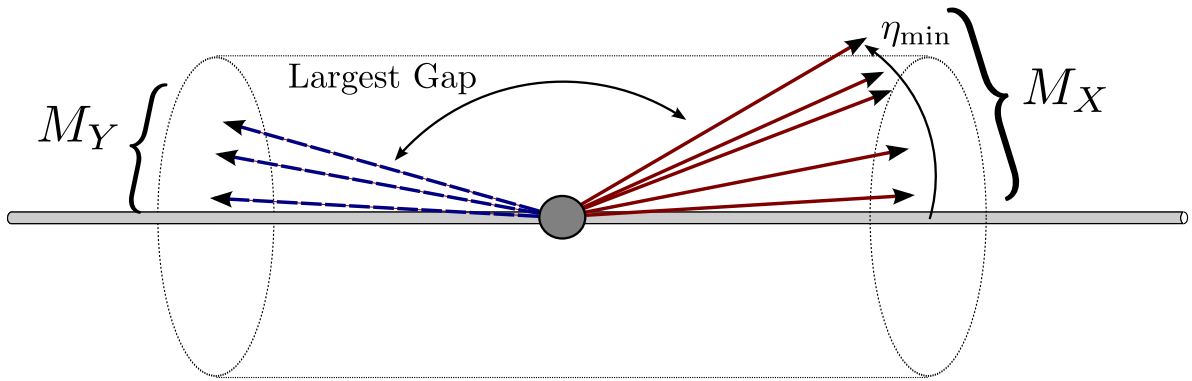


Average scalar p_{T} sum density vs. $|\Delta\phi|$

Motivation: Inelastic *pp* cross section ATLAS-CONF-2015-038

- Fundamental observable of hadron collider and cosmic ray physics, not calculable from first principles
  - Froissart-Martin bound: $\sigma_{\text{inel}}(s)$ cannot rise faster than $\ln^2(s)$
- Complementary measurements:
  - Cosmic ray air-showers
  - Inferred from elastic σ measured by forward detectors + optical theorem
  - Direct measurements at colliders





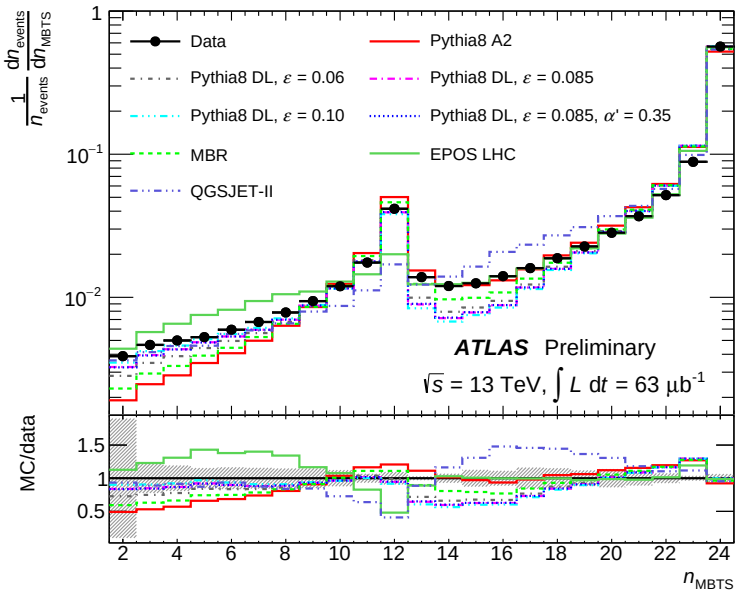
- Measurement performed in fiducial region $\tilde{\xi} = M_X^2/s > 10^{-6}$
  - M_X = Larger invariant dissociative mass
  - $\tilde{\xi} > 10^{-6}$ or $M_X > 13$ GeV chosen to obtain MBTS efficiency above 50%

Method: Inelastic *pp* cross section ATLAS-CONF-2015-038

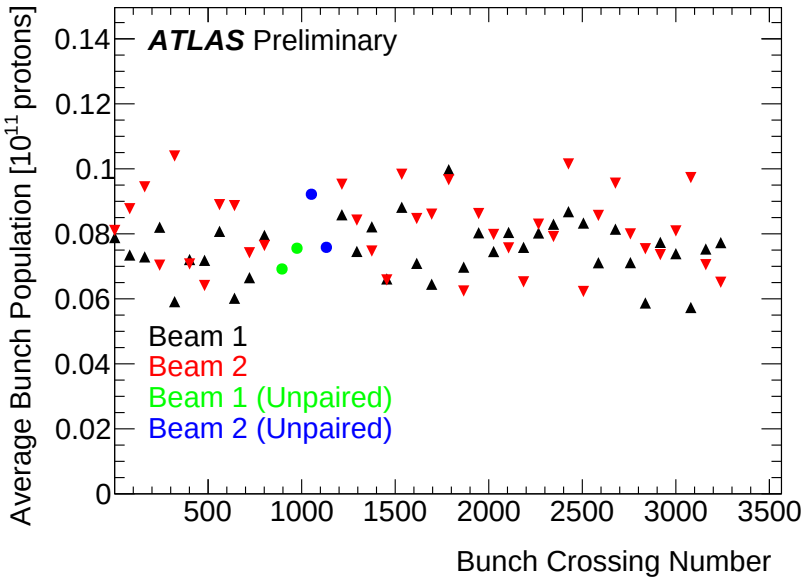
- Counting experiment:

$$\sigma_{\text{inel}}(\tilde{\xi} > 10^{-6}) = \frac{N - N_{\text{BG}}}{\epsilon_{\text{trig}} \times L} \times \frac{1 - f_{\tilde{\xi}<10^{-6}}}{\epsilon_{\text{sel}}}$$

  - N = number of events with at least two MBTS hits (offline selection)
  - N_{BG} = number of background events
  - ϵ_{trig} = trigger efficiency
  - L = luminosity
  - $(1 - f_{\tilde{\xi}<10^{-6}})/\epsilon_{\text{sel}}$ = correction for events migrating into fiducial region and selection efficiency

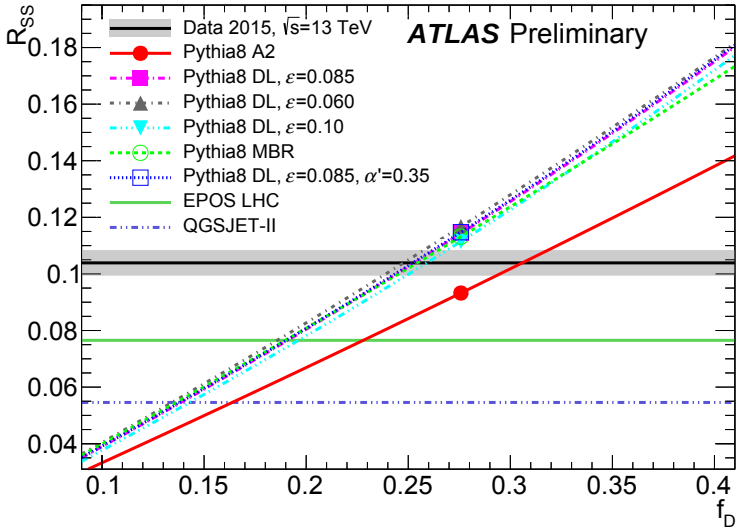


Comparison of MBTS hit distribution in data and MC



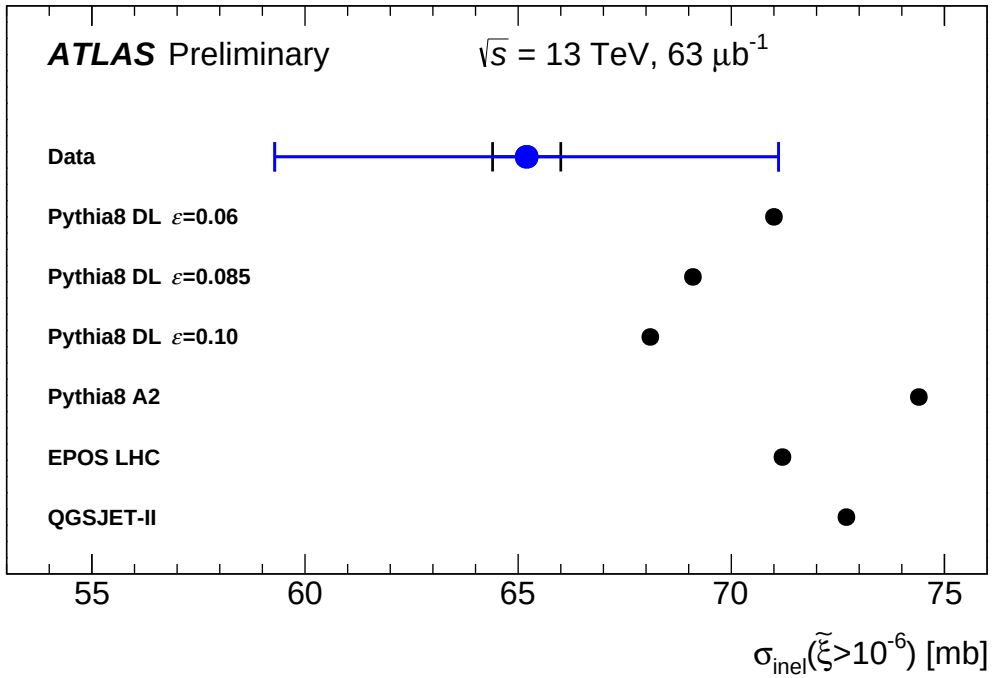
Measurements of bunch population: input to beam and non-collision background estimation

Results: Inelastic *pp* cross section ATLAS-CONF-2015-038



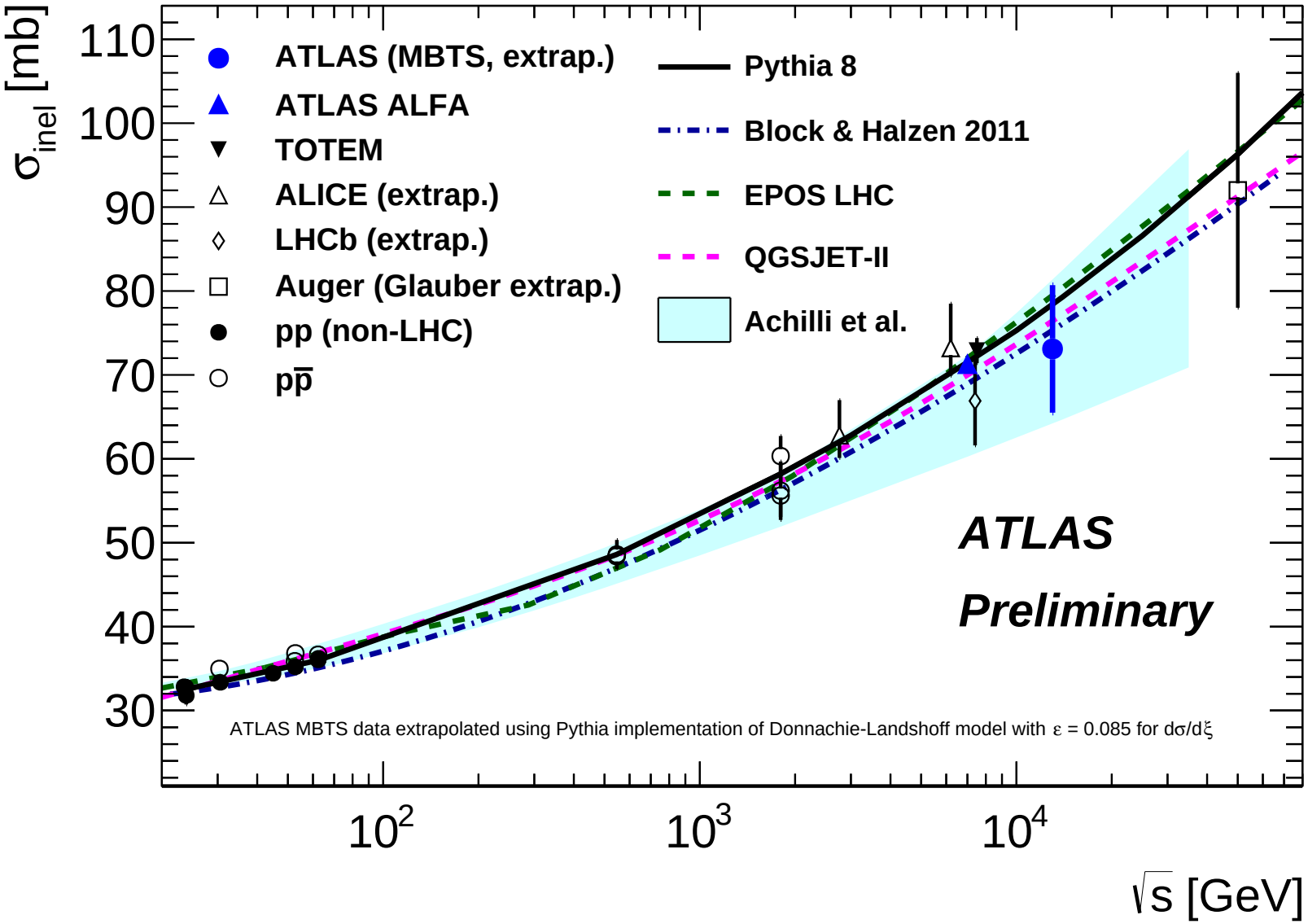
- R_{SS} = Ratio of events with MBTS hits on a single side to normal event selection
- Correlated with generator parameter $f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{\text{inel}}$
- Applied as model-dependent correction for selection efficiency and migration factors, and when extrapolating to full cross section

- $\sigma_{\text{inel}}(\tilde{\xi} > 10^{-6}) =$ 65.2 ± 0.8 (exp.) ± 5.9 (lum.) mb
- Luminosity uncertainty dominant: coming from preliminary calibration

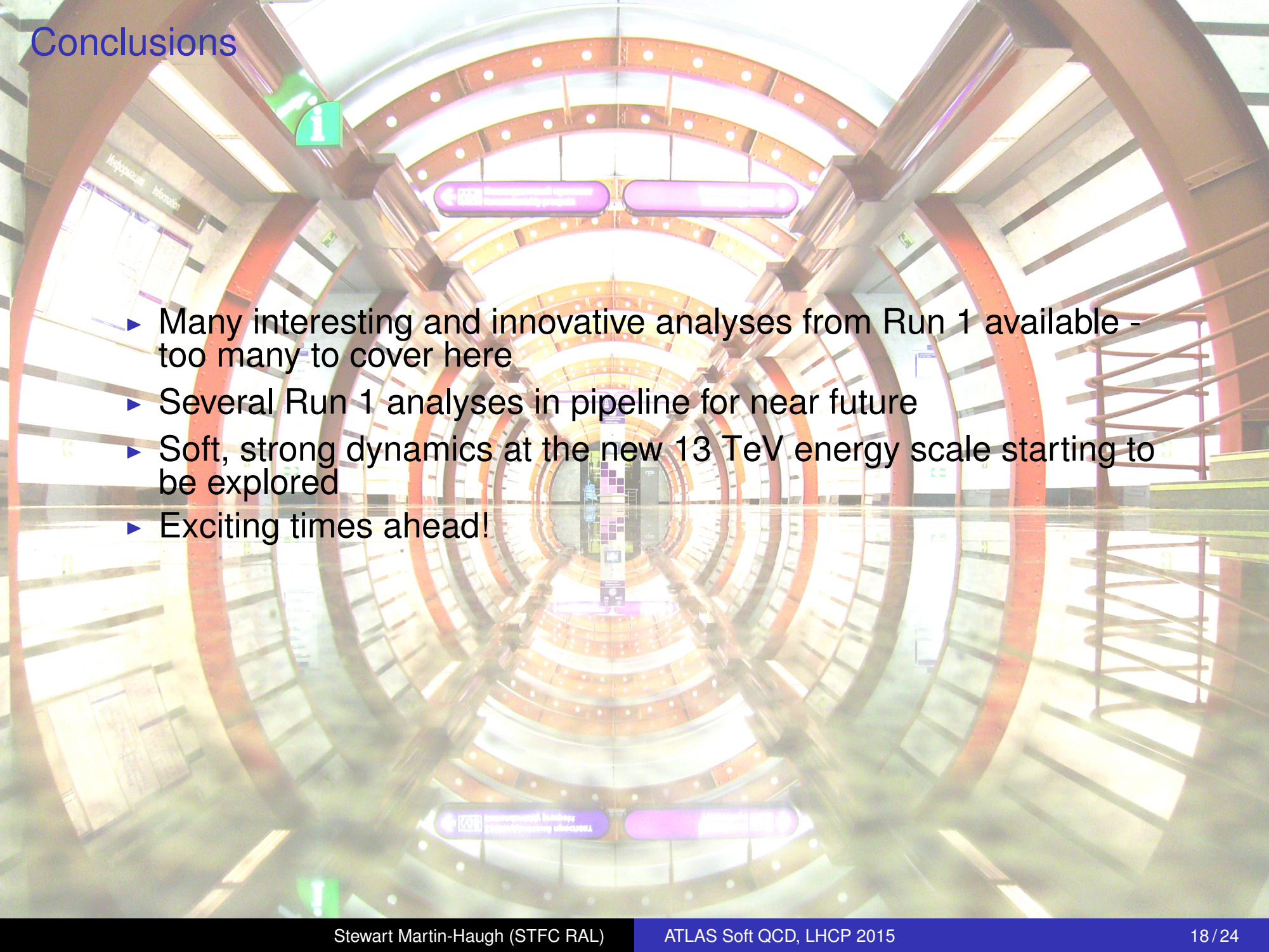


Results: Inelastic *pp* cross section ATLAS-CONF-2015-038

- Extrapolated to full $\tilde{\xi}$ phase space $\sigma_{\text{inel}} = 73.1 \pm 0.9$ (exp.) ± 6.6 (lum.) ± 3.8 (extr.) mb
- Complements precise measurement from ALFA forward flux at 7 TeV (arXiv:1408.5778)



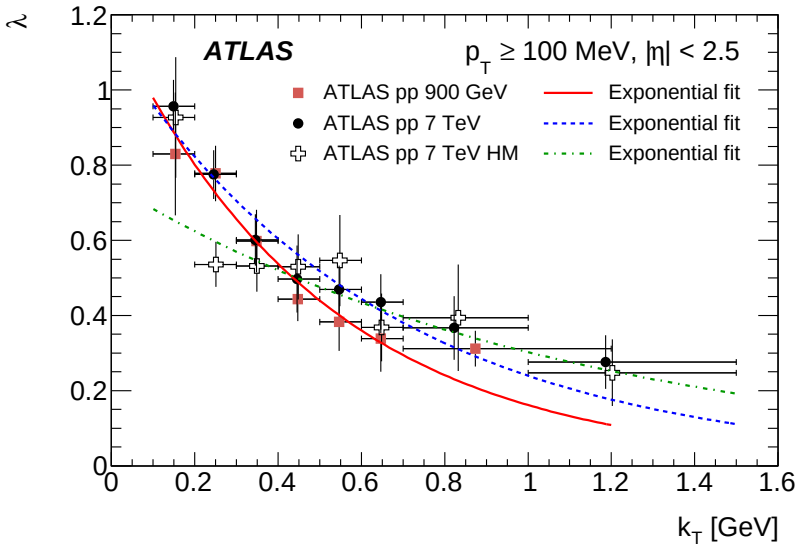
Conclusions

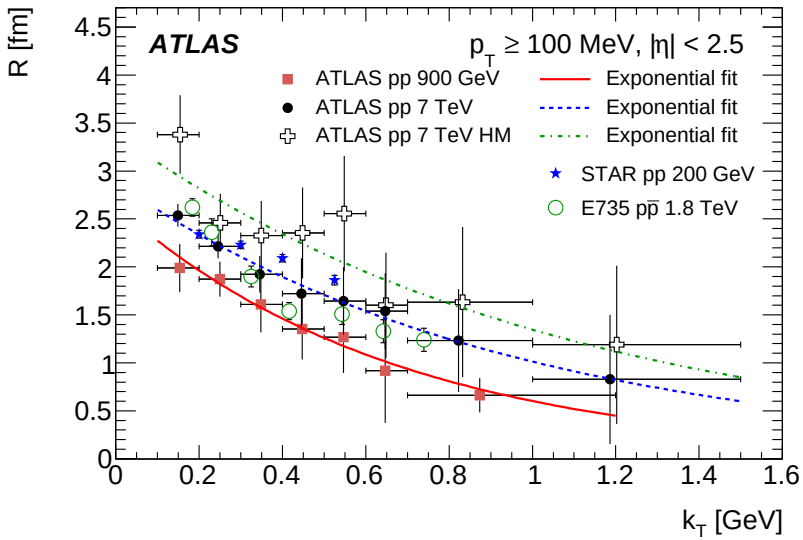


- Many interesting and innovative analyses from Run 1 available - too many to cover here
- Several Run 1 analyses in pipeline for near future
- Soft, strong dynamics at the new 13 TeV energy scale starting to be explored
- Exciting times ahead!

Backup: Bose-Einstein correlations

- Samples of non-identical bosons generated in several ways:
  - Unlike-sign: opposite charge track pairs (can suffer from resonances)
  - Mixed-event: pairs of tracks from different events
  - Opposite hemisphere: Track pairs with one of $p_x \to -p_x$, $p_y \to -p_y$, $p_z \to -p_z$
  - Rotated track: Track pairs with one of $p_x \to -p_x$, $p_y \to -p_y$



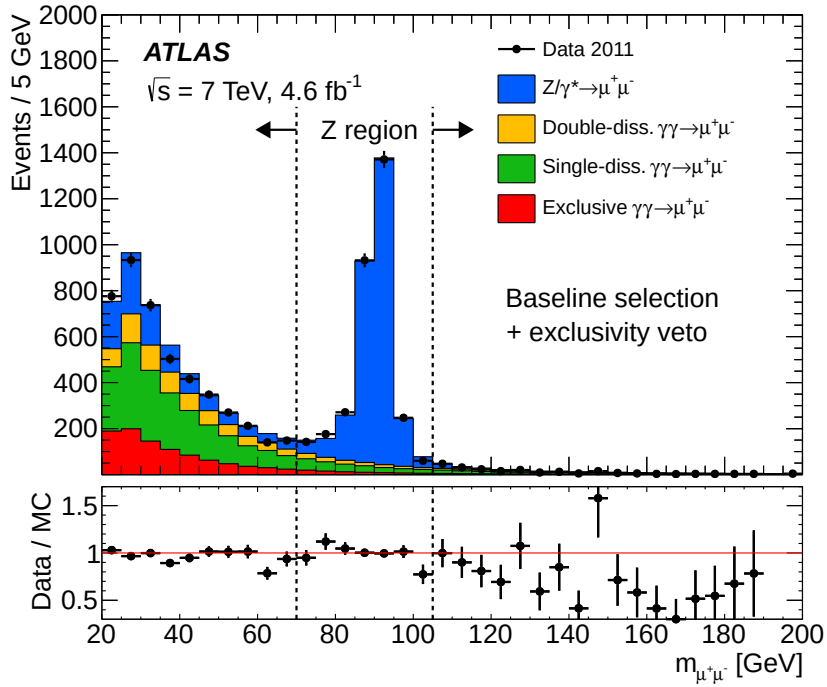


	0.9 TeV		7 TeV		7 TeV (HM)	
Source	λ	R	λ	R	λ	R
Track reconstruction efficiency	0.6%	0.7%	0.3%	0.2%	1.3%	0.3%
Track splitting and merging	negligible		negligible		negligible	
Monte Carlo samples	14.5%	12.9%	7.6%	10.4%	5.1%	8.4%
Coulomb correction	2.6%	0.1%	5.5%	0.1%	3.7%	0.5%
Fitted range of Q	1.0%	1.6%	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%

Backup: Exclusive $\gamma\gamma \to \ell^+\ell^-$ production

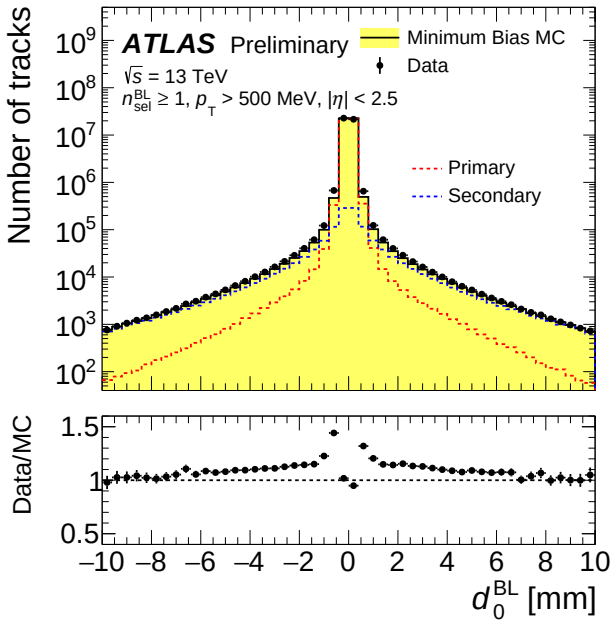
- Equivalent photon approximation: EM field of a charged particle becomes more and more transverse wrt propagation direction
- Observer in laboratory frame cannot distinguish between EM field of relativistic proton and transverse component of EM field associated with equivalent photons
- $$\sigma^{\mathrm{EPA}}_{pp(\gamma\gamma)\to\ell^+\ell^- pp} = \int\int P(x_1)P(x_2)\sigma_{\gamma\gamma\to\ell^+\ell^-}(m^2_{\ell^+\ell^-})\mathrm{d}x_1\,\mathrm{d}x_2$$
  - x_1, x_2: fractions of proton momentum carried by photons
  - $P(x_1)$, $P(x_2)$: equivalent photon spectra for each proton
  - $m_{\ell^+\ell^-}$: lepton pair invariant mass (note $m_{\ell^+\ell^-}/s = x_1 x_2$)

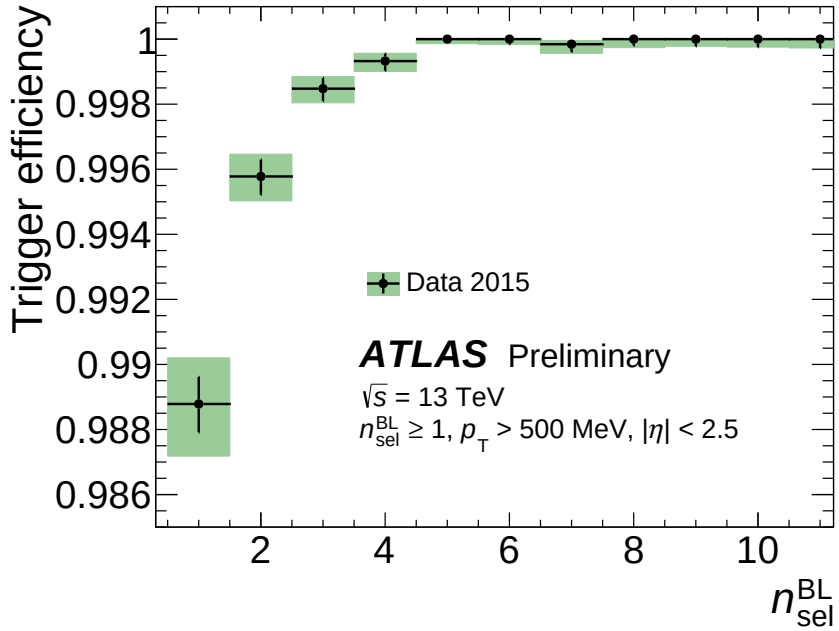
Source of uncertainty	Uncertainty [%] $\gamma\gamma \to e^+e^-$	$\gamma\gamma \to \mu^+\mu^-$
Electron reconstruction and identification efficiency	1.9	-
Electron energy scale and resolution	1.4	-
Electron trigger efficiency	0.7	-
Muon reconstruction efficiency	-	0.2
Muon momentum scale and resolution	-	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



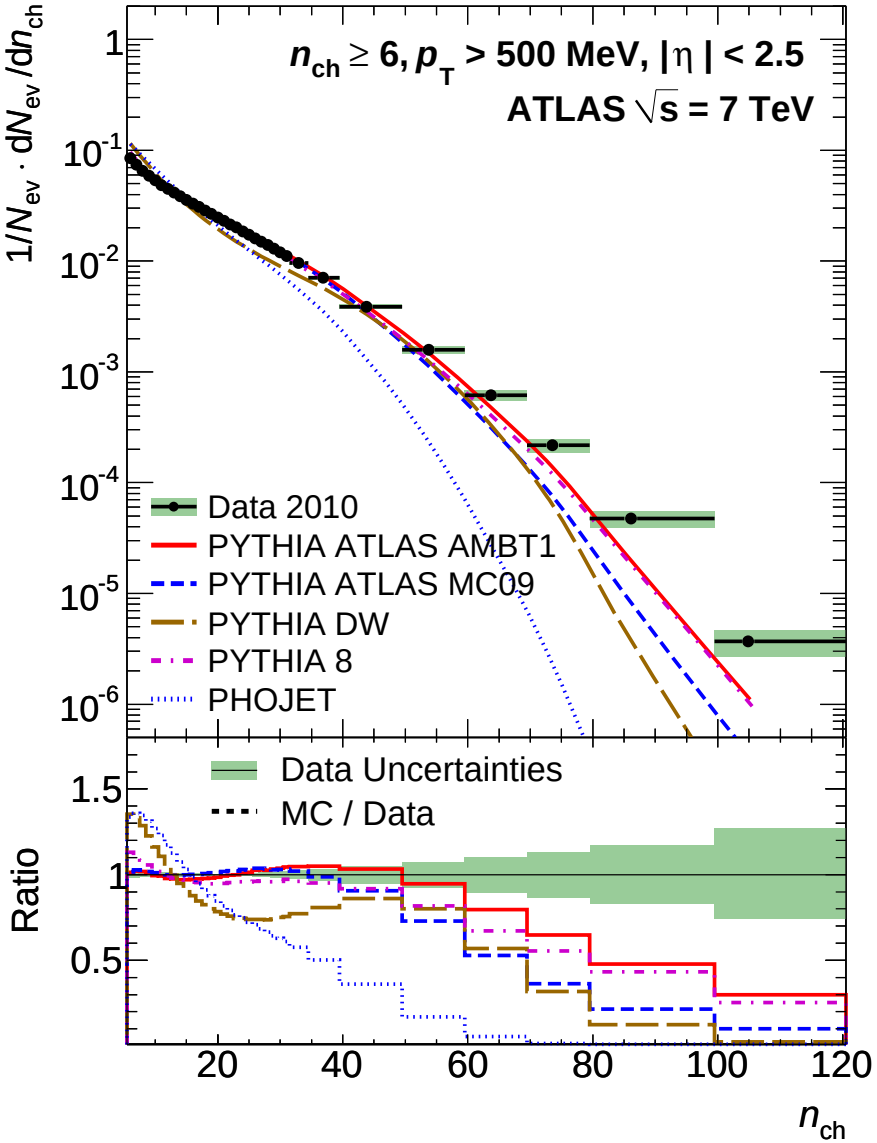
Backup: Charged particle multiplicity

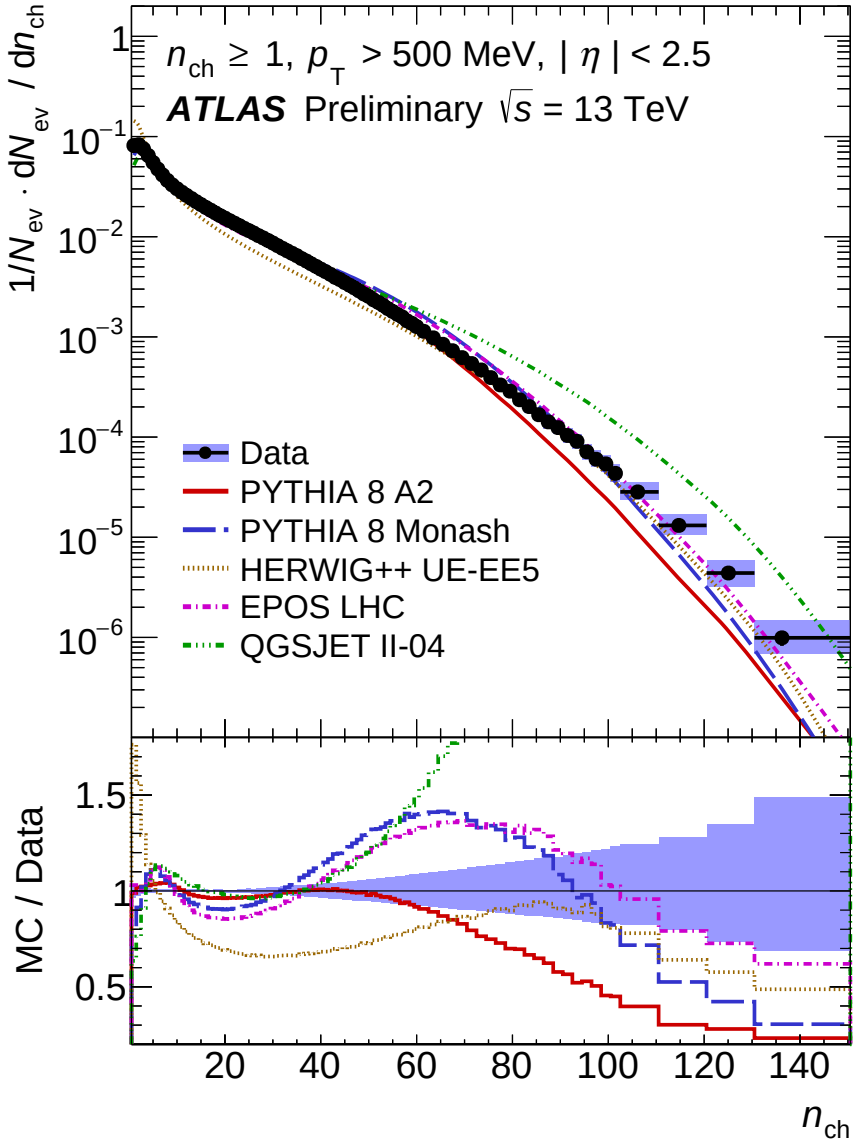
Generator	Version	Tune	PDF	7 TeV data	
				MB	UE
PYTHIA 8	8.185	A2	MSTW2008LO	yes	no
PYTHIA 8	8.186	MONASH	NNPDF2.3LO	yes	yes
HERWIG++	2.7.1	UE-EE-5-CTEQ6L1	CTEQ6L1	no	yes
EPOS	3.1	LHC	N/A	yes	no
QGSJET-II	II-04	default	N/A	yes	no





Backup: Comparison of 7 and 13 TeV charged particle multiplicity results



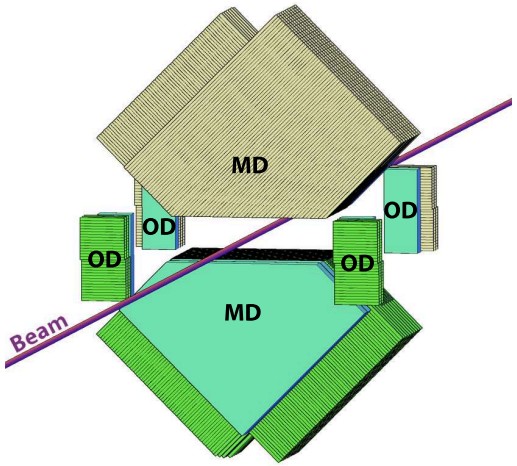


Backup: Total cross section at ALFA arXiv:1408.5778

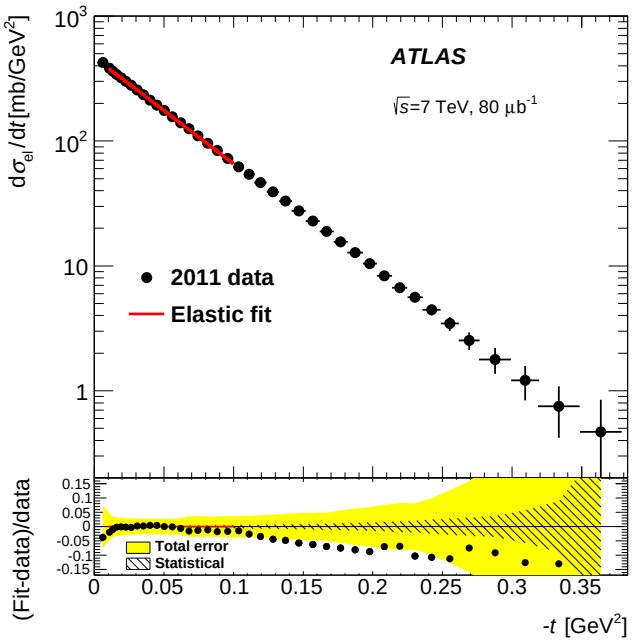
Optical theorem:

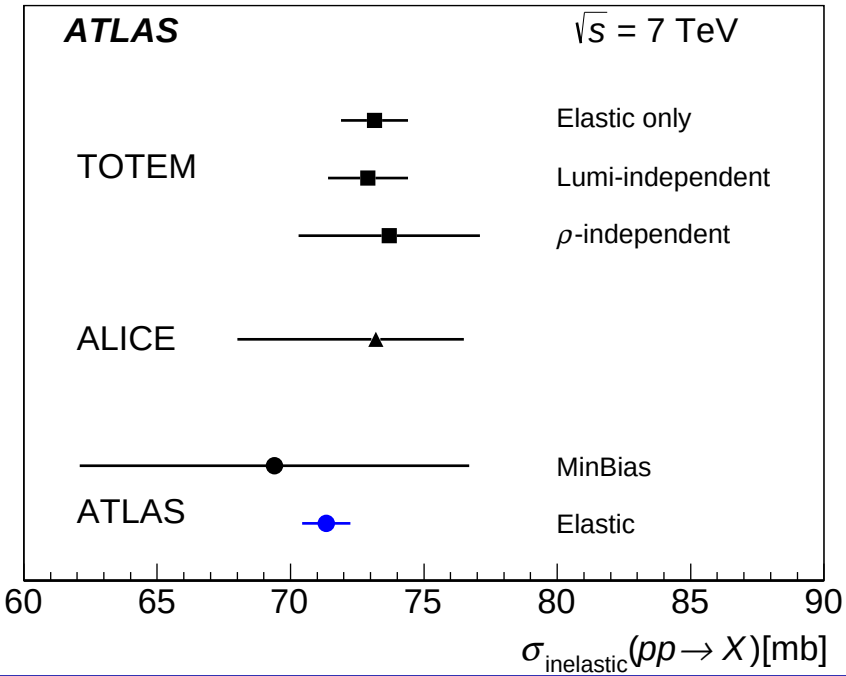
$$\sigma_{\text{tot}}^2 = \frac{16\pi}{1+\rho^2} \left.\frac{\mathrm{d}\sigma_{\text{el}}}{\mathrm{d}t}\right|_{t=0}$$

- ρ: theoretical correction
- Extrapolate measured $\mathrm{d}\sigma_{\text{el}}/\mathrm{d}t|$ to $t = 0$ to obtain total cross section



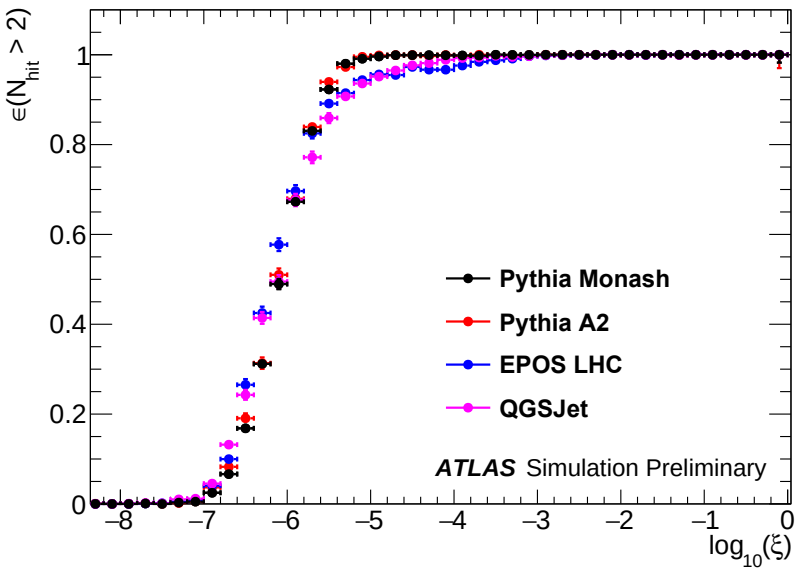
Absolute Luminosity For ATLAS (ALFA) detector schematic



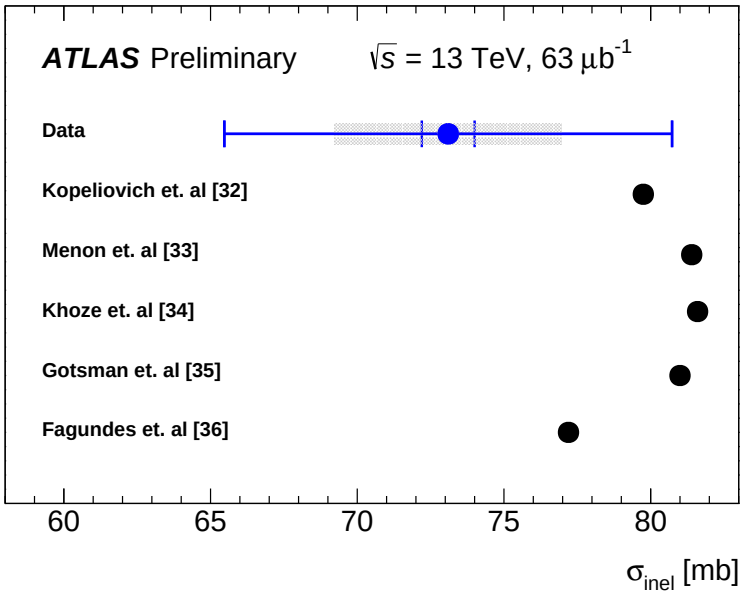


Backup: Inelastic *pp* cross section

Factor	Value	Rel. unc.
Number of selected events (N)	4159074	–
Number of background events (N_{BG})	43512	$\pm 100\,\%$
Luminosity $[\mu\mathrm{b}^{-1}]$ (L)	62.9	$\pm 9\,\%$
Trigger efficiency (ϵ_{trig})	99.7%	$\pm 0.1\,\%$
MC Correction factor ($(1 - f_{\tilde{\xi}<10^{-6}})/\epsilon_{\mathrm{sel}}$)	0.993	$\pm 0.5\,\%$



Motivation of fiducial region choice



Comparison with theory predictions