Measurements of multi-parton interactions at ATLAS

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on behalf of the ATLAS Collaboration

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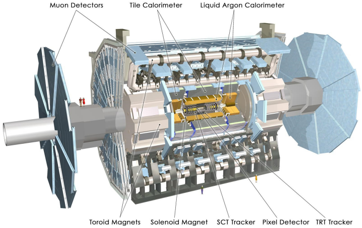
Overview

- Measurement of distributions sensitive to the underlying event in inclusive Z boson production in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
  Submitted to EPJC, arXiv:1905.09752

- Study of the hard double-parton scattering contribution to inclusive four-lepton production in *pp* collisions at $\sqrt{s} = 8\ \mathrm{TeV}$ with the ATLAS Detector
  Phys. Lett. B **790** (2019) 595, arXiv:1811.11094



Underlying event in *Z* boson production - Motivation

- **Underlying Event** (UE) = soft processes unavoidably accompanying hard parton-parton scatterings in *pp* collisions with a high momentum transfer
  - interactions between proton remnants, MPI, initial and final state QCD radiation

- soft interactions not reliably calculable by theory – dominated by low-scale QCD interactions, in which the strong coupling strength diverges and perturbative methods of QCD lose predictivity

$\Rightarrow$ described by phenomenological models, implemented in MC event generators

$\Rightarrow$ contain many free parameters which are needed to be constrained by measurements.

- processes with leptonic final states experimentally clean and theoretically well understood $\Rightarrow$ allowing reliable identification of particles from UE

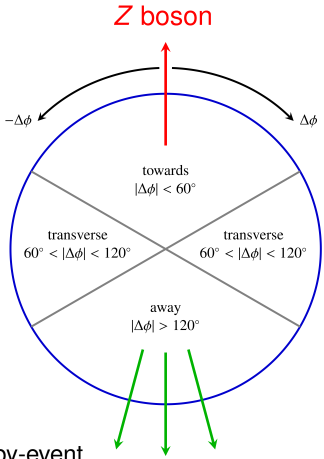
absence of FSR $\Rightarrow$ study of different kinematic regions with varying p_{T} of the *Z* boson due to harder or softer ISR

Measurement of Underlying Event

final-state Z boson: well-identified and colour neutral
→ interaction between FS lead. par. and UE minimal

however ISR important: gives rest of the event
a non-zero p_T and changes the kinematics of FS

- η, φ plane divided into regions around Z boson:
    - $|\Delta\varphi| < 60^\circ$ - **toward**
    - $60^\circ < |\Delta\varphi| < 120^\circ$ - **transverse**
    - $|\Delta\varphi| > 120^\circ$ - **away**
- **away** region dominated by hadronic recoil against the Z boson from ISR
- **toward** and **transverse**: less hard process contamination after subtraction of 2μ from Z



further subdivision of the observables on an event-by-event basis depending on which side of the event is more activity:

- **trans-max**: observables in the more-active transverse region (higher $\sum p_\mathrm{T}$)
- **trans-min**: observables in the less-active transverse region (lower $\sum p_\mathrm{T}$)
  less likely that activity from recoiling jets leaks into this region

Measured Observables

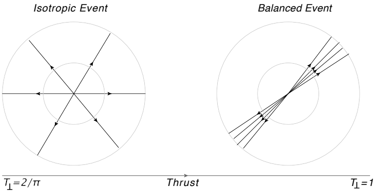
variables over all events:	
$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}p_{\mathrm{T}}^{\mathrm{ch}}$	charged particle transverse momentum
event-by event variables:	
$\mathrm{d}N_{\mathrm{ev}}/\mathrm{d}(N_{\mathrm{ch}}/\delta\eta\delta\phi)$	charged-particle multiplicity
$\mathrm{d}N_{\mathrm{ev}}/\mathrm{d}(\sum p_{\mathrm{T}}/\delta\eta\delta\phi)$	scalar sum of transverse momenta of charged particles
$\mathrm{d}N_{\mathrm{ev}}/\mathrm{d}(\sum p_{\mathrm{T}}/N_{\mathrm{ch}})$	mean transverse momentum

distributions in 8 ranges of $p_{\mathrm{T}}^{\mathrm{Z}}$: (0, 10, 20, 40, 60, 80, 120, 200, 500) GeV and for 2 regions of transverse thrust:

$$T_{\perp} = \max_{\hat{\boldsymbol{n}}_{\perp}} \frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i} \cdot \hat{\boldsymbol{n}}_{\perp}|}{\sum_i p_{\mathrm{T}i}}$$

sum over $\vec{p}_{\mathrm{T},i}$ of all charged particles in the event

$\hat{\boldsymbol{n}}_{\perp}$ - the unit vector of the *thrust axis* maximizing the expression found iteratively



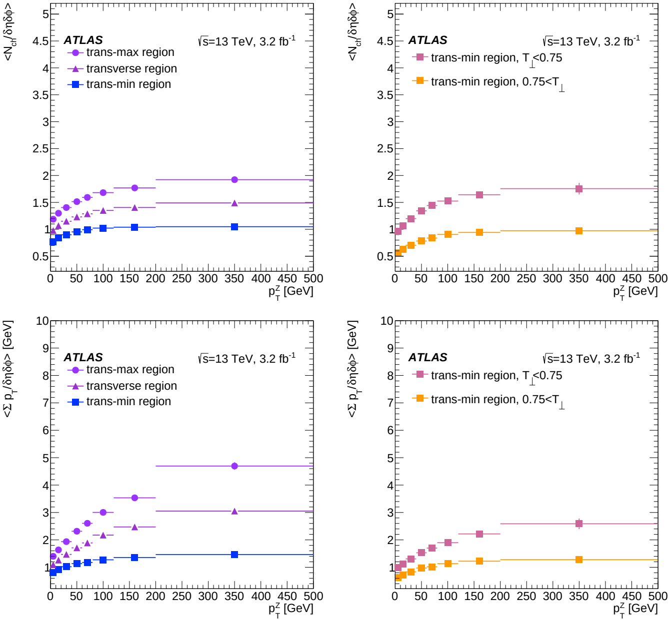
events with lower values of $T_{\perp}$ more sensitive to MPI component of UE

regions of thrust $T_{\perp} \leq 0.75$ and $T_{\perp} > 0.75$ optimised to distinguish extra jet activity from the actual UE activity

Event and Track Selection

- $\sqrt{s} = 13$ TeV data taken in 2015, integrated luminosity of 3.2 fb^{-1}
- trigger: ≥ 1 MBTS counters above threshold on either side of the detector
- events: required to have exactly 2 opposite-charged muons
  dimuon system invariant mass: 66 GeV$< m^{\mu\mu} <$ 116 GeV
- muons: $p_{\mathrm{T}} > 25$ GeV; $|\eta| < 2.4$
  associated to the PV: $|z_0 \sin\theta| < 0.5$ mm
  originating from decay of a heavy quark rejected by d_0
- other tracks: $p_{\mathrm{T}} > 0.5\ \mathrm{GeV}$; $|\eta| < 2.5$
- background: $Z \to \tau\tau$, $t\bar{t}$ & $WW \to \mu\nu\mu\nu$: 0.7% (MC simulation)
  multi-jet processes: < 0.1% (data-driven technique)
- iterative Bayesian unfolding after background subtraction
- $Z \to \mu\mu$ simulated by NLO Powheg EG, CT10 set of PDFs, interfaced to the Pythia 8.170 to simulate the parton shower, hadronization and UE

Arithmetic means of the observables



trans-min:
$\langle N_{\mathrm{ch}}\rangle$ and $\langle \sum p_{\mathrm{T}}\rangle$
rise slowly with p_{T}^{Z}

trans-max:
strong p_{T}^{Z} dependence
$\Rightarrow$ contaminated with
Z boson hadronic recoil
leaking into transverse

higher $T_\perp$:

- slope similar to inclusive
- activity lower than for inclusive due to correlation of activity in transverse and $T_\perp$

lower $T_\perp$:

- UE activity higher and p_{T}^{Z} dependence increased

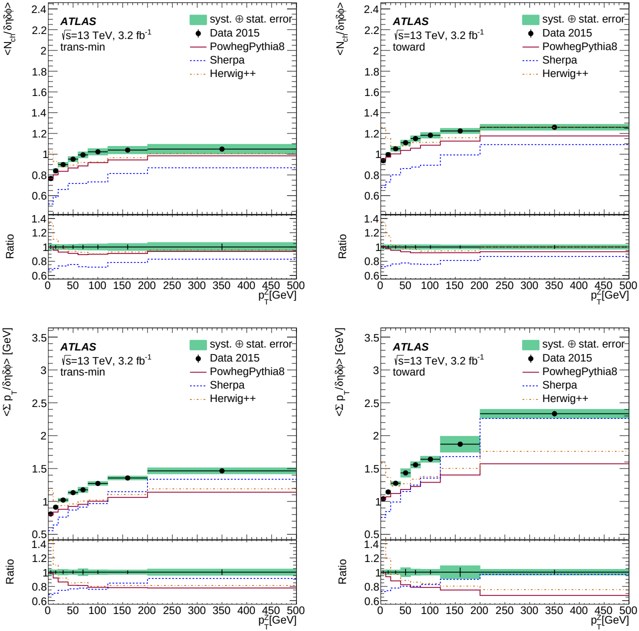
MC tunes predictions

- NLO Powheg EG, CT10 set of PDFs, interfaced to the Pythia 8.170 to simulate the parton shower, hadronization and UE with the CTEQ6L1 PDF set and the AZNLO set (tunes the event generator to the p_{T}^{Z} measurement at $\sqrt{s} = 7$ TeV) of tuned parameters → retunes overall UE by adjusting Pythia MPI cut-off parameter to UE activity of previous measurement in the lowest p_{T}^{Z} bin (0 to 5 GeV). Photos used to simulate final-state electromagnetic radiation. p_{T}-ordered parton showers and hadronization model based on fragmentation of colour strings. Its MPI model interleaves ISR and FSR emissions with MPI scatters.

- Sherpa 2.2.0 (the nominal tune set of version) utilizes the NNPDF30NNLO PDF set, an independent implementation of the parton shower, hadronization, UE and FSR, uses LO matrix elements with a model for MPI similar to Pythia 8 but without interleaving the FSR

- Herwig++ UE-EE-5 tune with CTEQ6L1 PDF set, uses energy extrapolation, developed to describe the UE and double parton interaction effective cross-section. Similarly to Pythia, a leading-logarithm parton shower model matched to leading-order matrix element calculations, but it implements a cluster hadronization scheme with parton showering ordered by emission angle.

MC tunes - arithmetic means of the observables



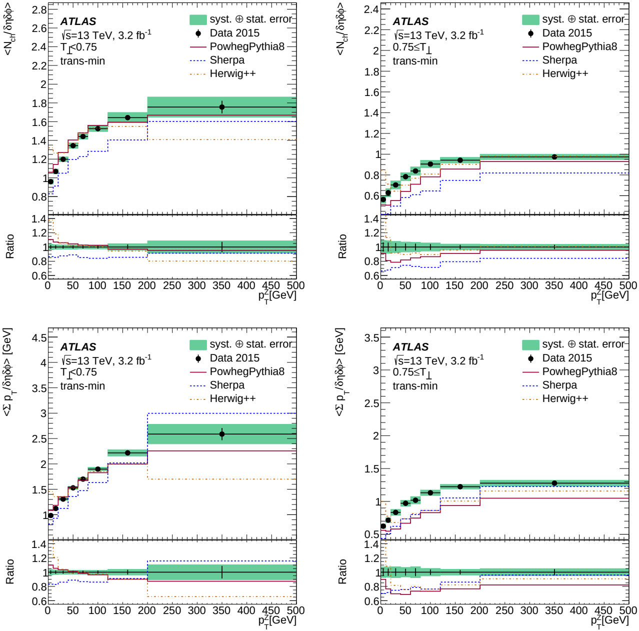
all tunes:

- significant deviations from the data
- underestimate the activity of UE

HERWIG++:

- fails to reproduce the turn-on effect at low p_T^Z
- predicts that the UE activity decreases with p_T^Z for $p_T^Z < 20$ GeV

Intervals of transverse thrust $T_\perp$



$T_\perp < 0.75$:

- MPI-sensitive region
- generators predict the mean values better

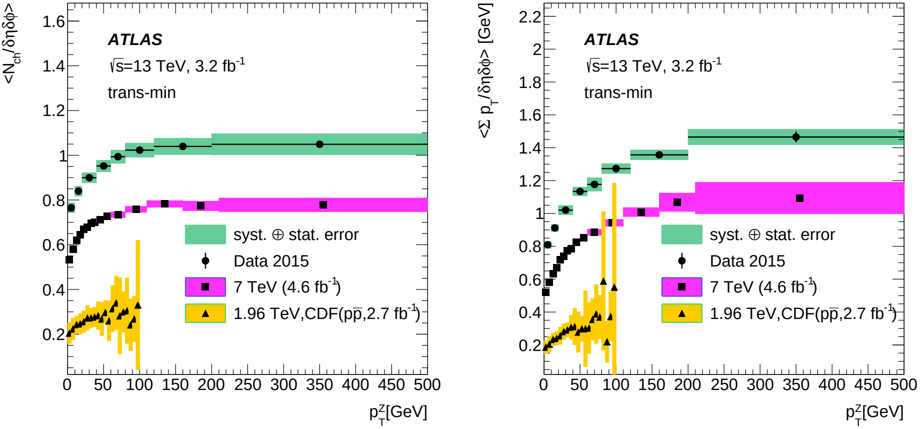
Powheg+Pythia8 $T_\perp < 0.75$:

- in agreement with data within the uncertainties
- adequate handling of the MPI activity

Powheg+Pythia8 $T_\perp \geq 0.75$:

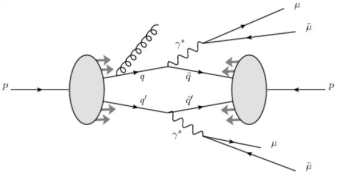
- predictive power shrinks ⇒ contributions other than MPI to the UE activity to be improved
- region dominated by extra jet activity
- possible improvement of MC prediction

Comparison with other centre-of-mass energies



- all measurements reveal the turn-on effect of UE activity in the fiducial region
- higher $\sqrt{s} \rightarrow$ more energy available for the processes forming the UE e.g. MPI
  $\Rightarrow$ the rise of the UE activity as a function of $\sqrt{s}$

Hard double-parton scattering contribution to 4ℓ



- high energy *pp* interactions
  ⇒ high density of low-x partons
  ⇒ enough energy to produce
  hard multi-parton interactions
  - simplest example: hard double-parton scattering (DPS):
    2 partons from each proton interact ⇒ perturbative final states
- Motivation: DPS probability & potential correlations between the products of 2
  perturbative interactions → dynamics of proton partonic structure

  may constitute a background to reactions proceeding through SPS
- production of 4 charged leptons: dominated by SPS production of 2 Z bosons
  → also can be 2 Drell-Yan processes occurring simultaneously
- for $pp \to A + B + X$, expected DPS cross section for producing A and B in two independent scatterings is:

$$\sigma^{AB}_{\mathrm{DPS}} = \frac{k}{2}\frac{\sigma^{A}_{\mathrm{SPS}}\sigma^{B}_{\mathrm{SPS}}}{\sigma_{\mathrm{eff}}} \qquad k = \left\{ \begin{array}{cc} 1 & \mathrm{A} = \mathrm{B} \\ 2 & \mathrm{A} \neq \mathrm{B} \end{array} \right\}$$

  $\sigma_{\mathrm{eff}} \approx 15$ mb - effective transverse overlap area containing interacting partons
- DPS events that contribute to the 4 lepton production simulated with Pythia 8.175 using LO version of CTEQ6L1 PDFs

Event Selection

$\sqrt{s} = 8$ TeV data, integrated luminosity 20.2 fb^{-1}

Triggers:

- single-lepton trigger: $E_T^e > 24$ GeV or $p_T^\mu > 24$ GeV
- dielectron trigger: $E_T^e > 12$ GeV for both electrons
- dimuon trigger: $p_T^\mu > 13$ GeV for both muons or $p_T^{\mu_1} > 18$ GeV & $p_T^{\mu_2} > 8$ GeV
- electron-muon trigger: $E_T^e > 12$ GeV & $p_T^\mu > 8$ GeV

events $\geq 4\ell$: required to form 2 same-flavour opposite-charge (SFOC) lepton pairs:

- $50 < m_{\mathrm{leading}} < 120$ GeV – pair with invariant mass closer to Z boson mass
- $12 < m_{\mathrm{sub-leading}} < 120$ GeV – the other pair

J/ψ veto – for every SFOC lepton combination: $m_{2\ell} > 5$ GeV

four-lepton invariant mass: $80 < m_{4\ell} < 1000$ GeV

transverse momentum of dileptons: $p_T^{\ell^+\ell^-} > 2$ GeV

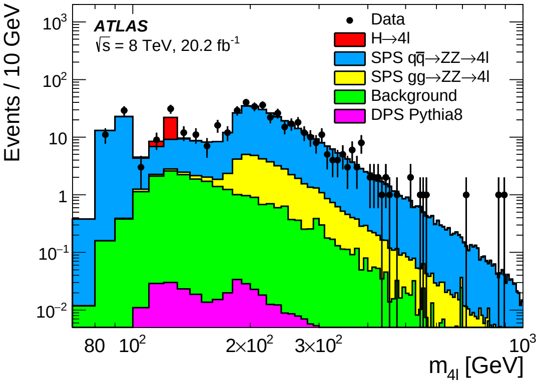
transverse momenta of selected leptons $p_T > \left\{ \begin{array}{cc} 20, 15, 10, 7 \text{ GeV} & \text{electron} \\ 20, 15, \ \ 8, 6 \text{ GeV} & \text{muon} \end{array} \right\}$

pseudorapidity: $|\eta^e| < 2.5$ & $|\eta^\mu| < 2.7$

separation requirement between any 2 leptons: $\Delta R > 0.1$ (same flavour)
$\Delta R > 0.2$ (different flavour)

DPS signal extraction

data sample after all selection contains 476 events
DPS contribution of 0.4 events predicted by PYTHIA 8.175 simulation



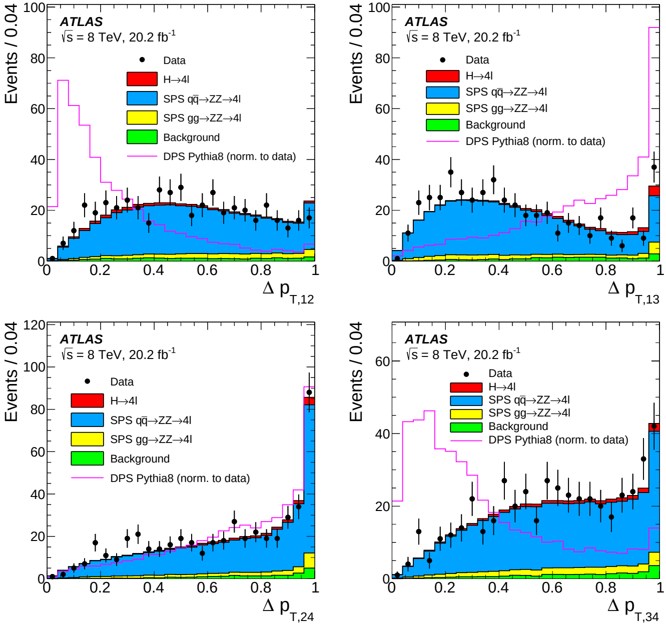
distributions of 21 kinematic variables of the 4 leptons used to distinguish between DPS and SPS events

used to train an artificial neural network (ANN)
→ discriminate DPS and non-DPS (SPS and background) classes

DPS: 2 scatters distinct & dominance of low-p_T Z production
$\Rightarrow$ 2 leptons of each dilepton tend to be balanced in p_T
$\Rightarrow$ back-to-back in azimuthal angle ϕ

SPS: leading and sub-leading pairs expected to balance each other in p_T

Kinematic variables - sum of $\vec{p}_{\mathrm{T}}$



$$\Delta p_{\mathrm{T,ij}} = \frac{\left|\vec{p}_{\mathrm{T,i}}+\vec{p}_{\mathrm{T,j}}\right|}{p_{\mathrm{T,i}}+p_{\mathrm{T,j}}}$$

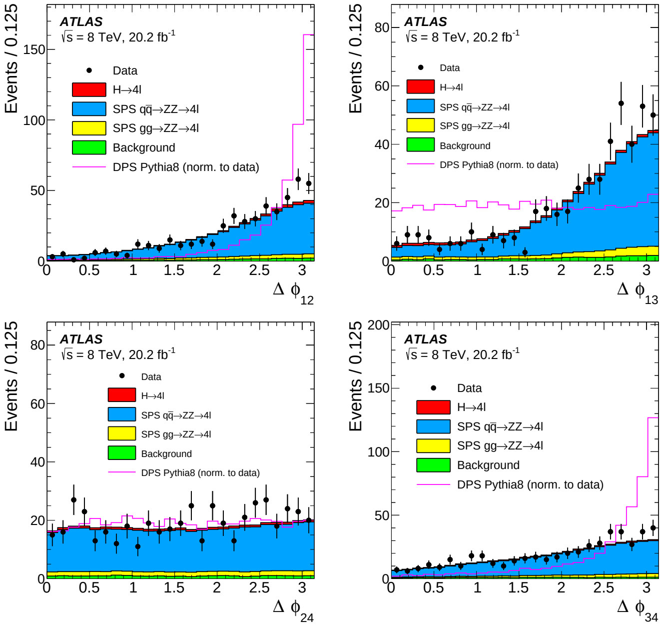
$\mathrm{i,j} = 1,2,3,4 \quad \mathrm{i} \neq \mathrm{j}$
(6 combinations)

1,2 – leading dilepton

3,4 – sub-leading

$p_{\mathrm{T},1} > p_{\mathrm{T},2}$ & $p_{\mathrm{T},3} > p_{\mathrm{T},4}$

Kinematic variables - difference in azimuthal angle ϕ



$$\Delta\phi_{\mathrm{ij}} = |\phi_{\mathrm{i}} - \phi_{\mathrm{j}}|$$

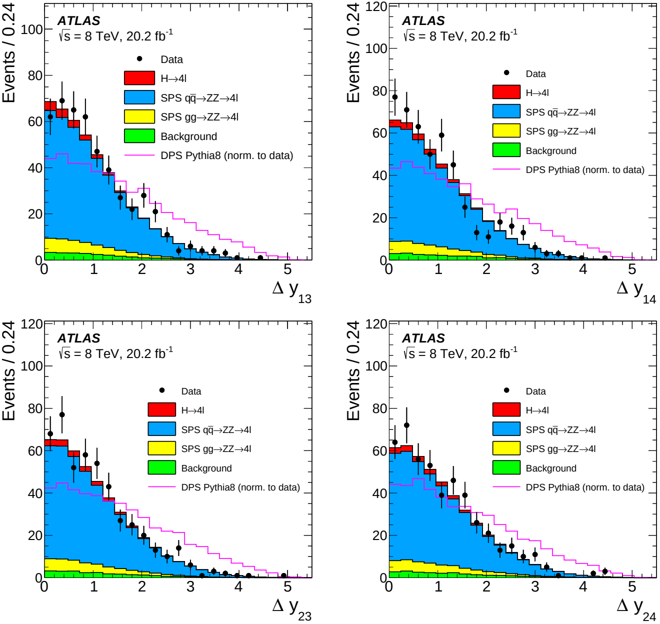
$\mathrm{i,j} = 1, 2, 3, 4 \quad \mathrm{i} \neq \mathrm{j}$
(6 combinations)

1,2 – leading dilepton

3,4 – sub-leading

$p_{\mathrm{T},1} > p_{\mathrm{T},2}$ & $p_{\mathrm{T},3} > p_{\mathrm{T},4}$

Kinematic variables - difference in rapidity *y*



$$\Delta y_{\mathrm{ij}} = |y_{\mathrm{i}} - y_{\mathrm{j}}|$$

$\mathrm{i}, \mathrm{j} = 1, 2, 3, 4 \quad \mathrm{i} \neq \mathrm{j}$

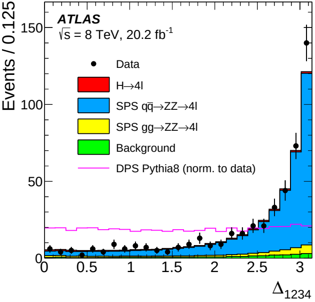
(6 combinations)

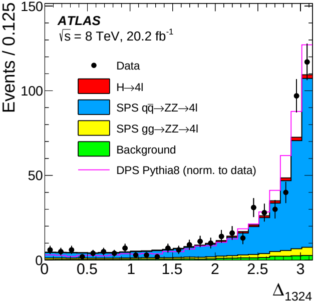
1,2 – leading dilepton

3,4 – sub-leading

$p_{\mathrm{T},1} > p_{\mathrm{T},2}$ & $p_{\mathrm{T},3} > p_{\mathrm{T},4}$

Difference in azimuthal angle of dilepton pair Δ

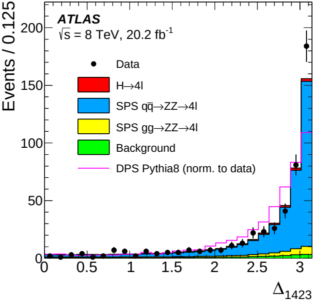




1,2 – leading dilepton

3,4 – sub-leading

$p_{\mathrm{T},1} > p_{\mathrm{T},2}$ & $p_{\mathrm{T},3} > p_{\mathrm{T},4}$



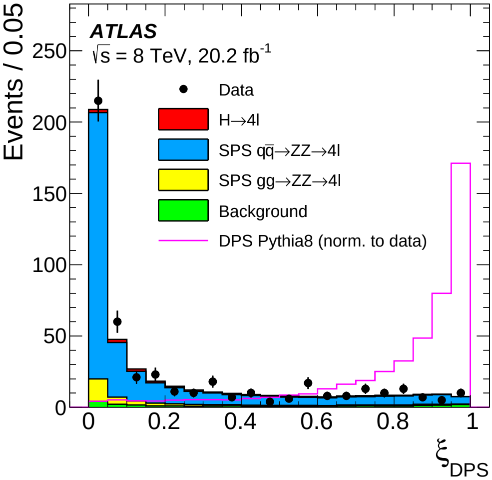
$$\Delta_{\mathrm{ijkm}} = \left|\phi_{\mathrm{i+j}} - \phi_{\mathrm{k+m}}\right|$$

$\mathrm{ijkm} = 1234, 1324, 1423$

$\phi_{\mathrm{i+j}}$ – azimuthal angle of the momentum vector composed by the sum of momenta of leptons i and j

Ratio of the number of DPS events

- optimisation: 21 kinematic variables → 30 neurons → 9 neurons → ξ_{DPS}
- ξ_{DPS} is between 0 and 1: likelihood for an event to belong to DPS class
- increased weights of SPS *gg* initiated events and background $Z + b\bar{b}$ jets to achieve a better separation



ratio of the number of DPS events:

$$f_{\mathrm{DPS}} = \frac{N_{\mathrm{DPS},4\ell}}{N_{\mathrm{SPS},4\ell}+N_{\mathrm{DPS},4\ell}}$$

MC template fit result:

$f_{\mathrm{DPS}} = -0.009 \pm 0.017$

(χ^2/dof = 8.6/9)

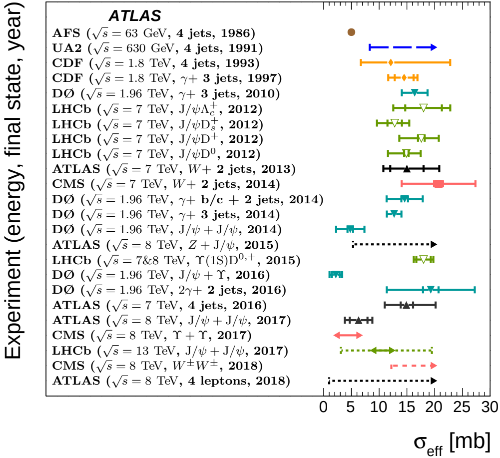
compatible with 0

agreement with parton-level test:

- pseudo-datasets with predefined $f_{\mathrm{DPS}}^{\mathrm{parton}}$ constructed
- f_{DPS} determined by fit
- $f_{\mathrm{DPS}} < f_{\mathrm{DPS}}^{\mathrm{parton}}$ by 2%
- different detector acceptance for DPS and SPS events

Limits on f_{DPS} and σ_{eff}

- upper limit on f_{DPS} determined using distributions of the ξ_{DPS} variable in data, SPS, DPS, and background MC samples
- test statistic for upper limits based on the profile likelihood ratio
- upper limit on f_{DPS} at 95% CL: 0.042



effective cross section:

$$\frac{1}{\sigma_{\mathrm{eff}}} = \frac{f_{\mathrm{DPS}}\sigma^{4\ell}}{\frac{k}{2}\sigma^{A}_{\mathrm{SPS}}\sigma^{B}_{\mathrm{SPS}}}$$

fiducial cross section for inclusive four-lepton production:

$$\sigma^{4\ell} = 32.0 \pm 1.6\ (\text{stat.}) \pm 0.7\ (\text{syst.}) \pm 0.9\ (\text{lumi.})\ \text{fb}$$

summing contributions from different dilepton phase-space regions:

$$\frac{k}{2}\sigma^{A}_{\mathrm{SPS}}\sigma^{B}_{\mathrm{SPS}} = (13.9 \pm 0.1\ (\text{stat}) \pm 3.6\ (\text{syst})) \cdot 10^{11}\,\text{fb}^2$$

lower limit on σ_{eff} is 1.0 mb (95% CL) consistent with previously measured values of the effective cross section

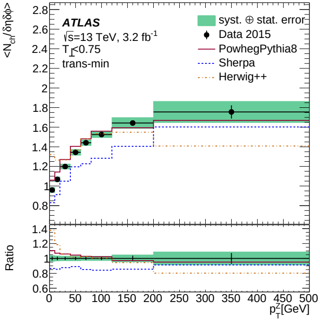
Summary

- tunes underestimate activity of UE, HERWIG++ fails to reproduce the turn-on effect at low p_T^Z

  PowhegPythia8 $T_\perp < 0.75$: in agreement with data within the uncertainties

  PowhegPythia8 $T_\perp \geq 0.75$: contributions other than MPI to the UE activity to be improved

  Submitted to EPJC, arXiv:1905.09752



- ratio of the number of DPS events at 8 TeV: $f_{\mathrm{DPS}} = -0.009 \pm 0.017$ – compatible with 0

  upper limit on f_{DPS} at 95% CL: 0.042

  lower limit on σ_{eff} at 95% CL: 1.0 mb
  → consistent with previously measured values of the effective cross section

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