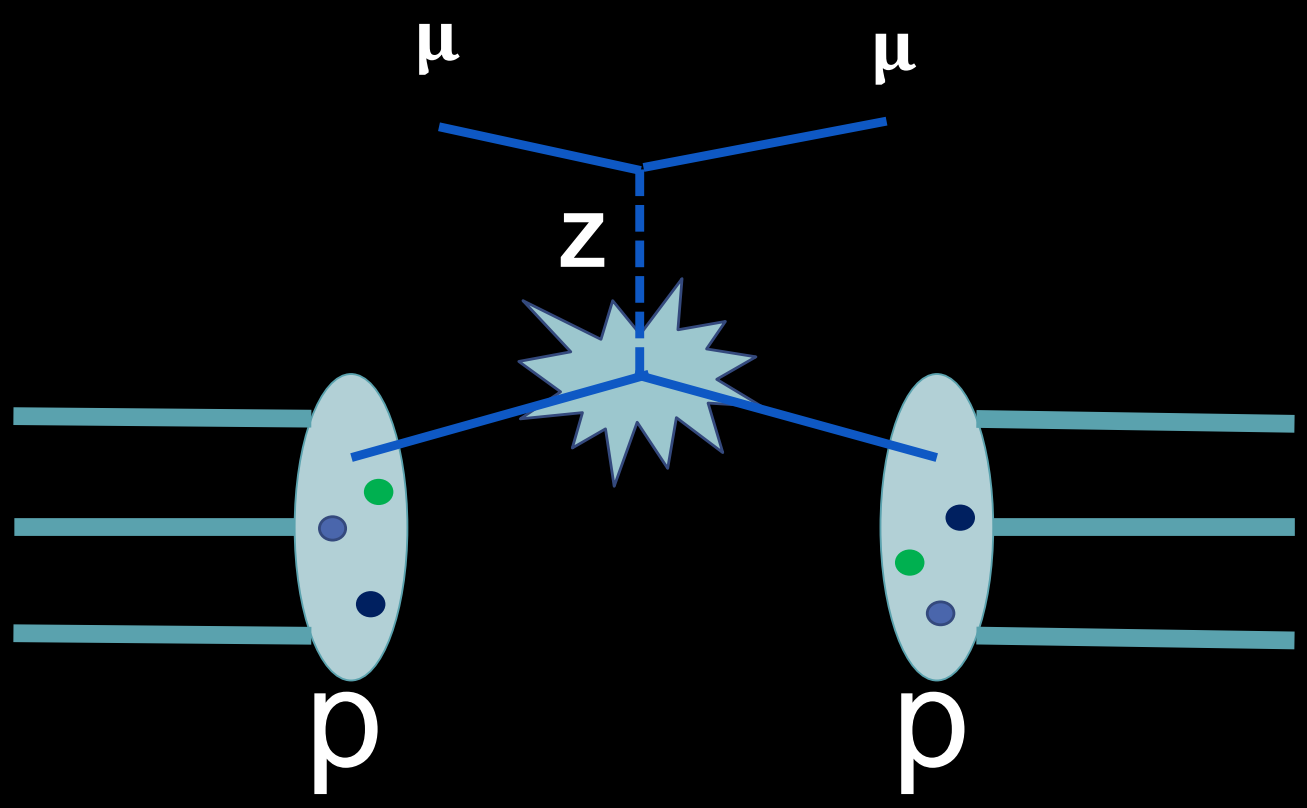
Measurements of multiparton interactions at ATLAS

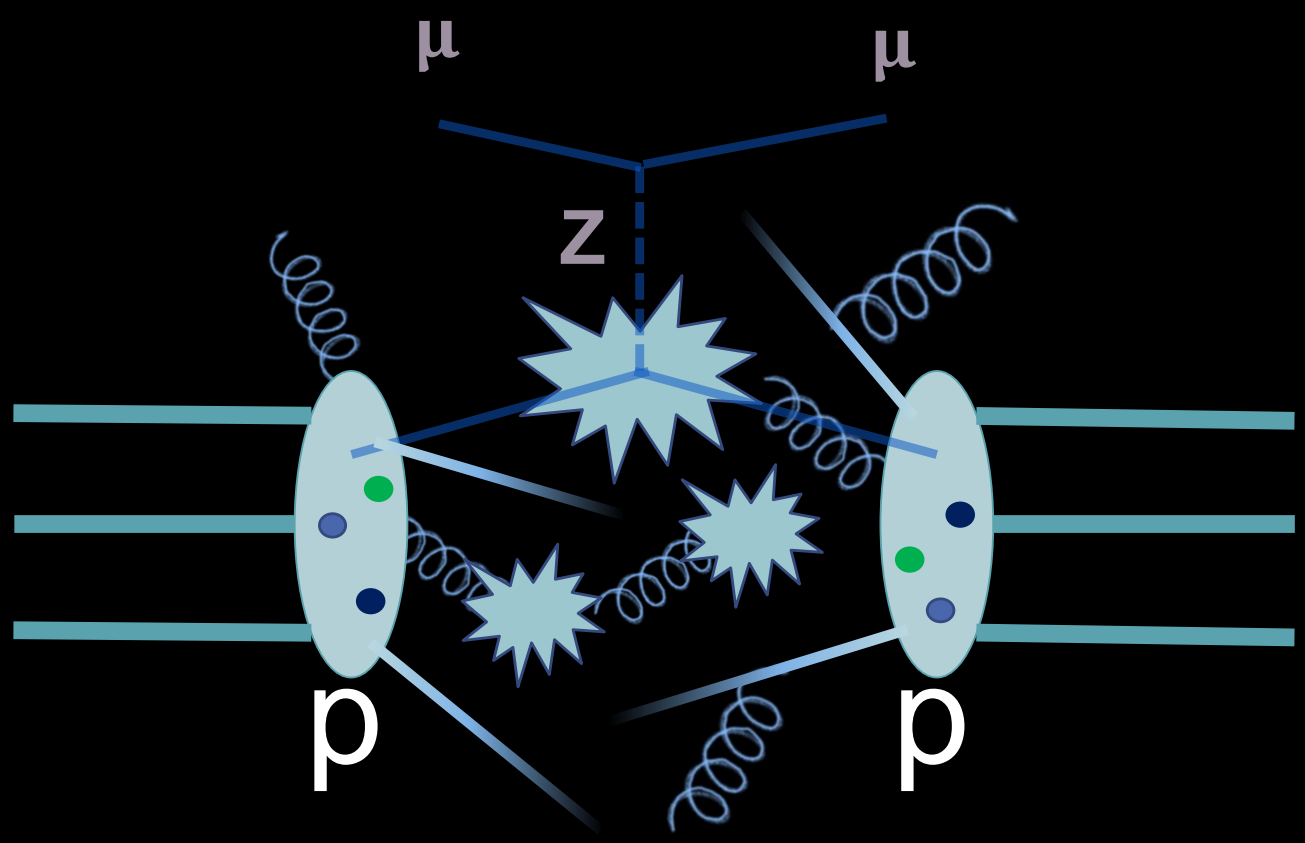
Double parton scattering contribution to 4 lepton events @ 8TeV

Underlying event in Z boson events @ 13TeV

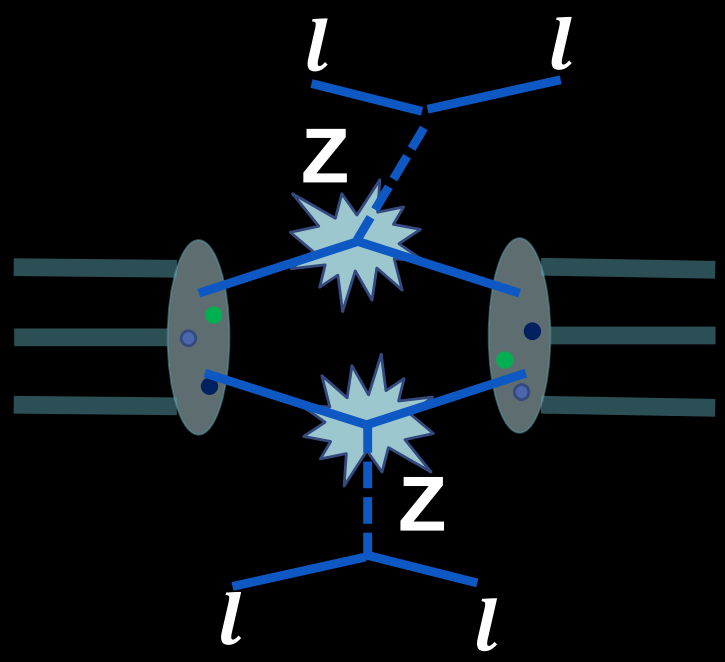
Motivation



Motivation

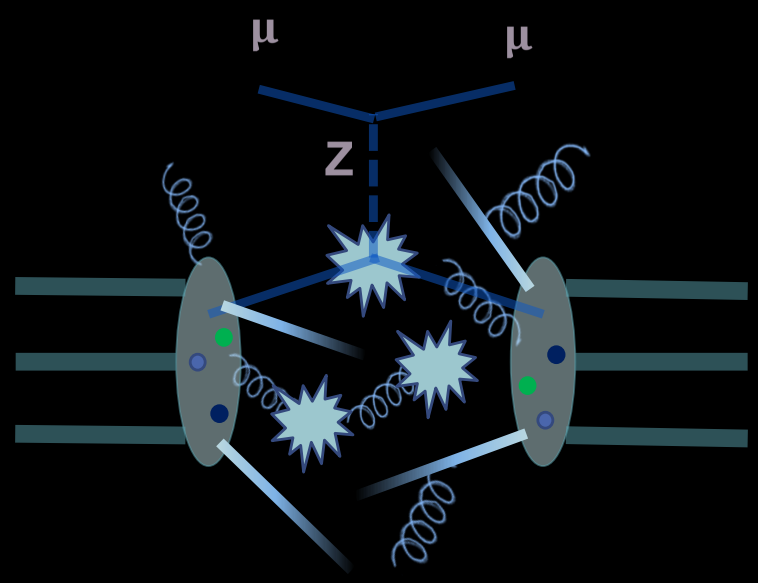


Double Parton scattering (DPS)



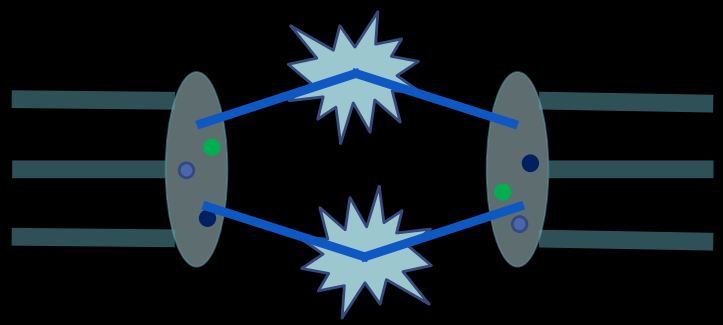
- pp – collisions at 8TeV
- $\int \mathcal{L}\, dt = 20.2 fb^{-1}$

Activity of the underlying event



- pp – collisions at 13TeV
- $\int \mathcal{L}\, dt = 3.2 fb^{-1}$ (2015)

DPS measurements review



Aim to measure σ_{eff}
(effective transverse overlap area containing interacting partons)

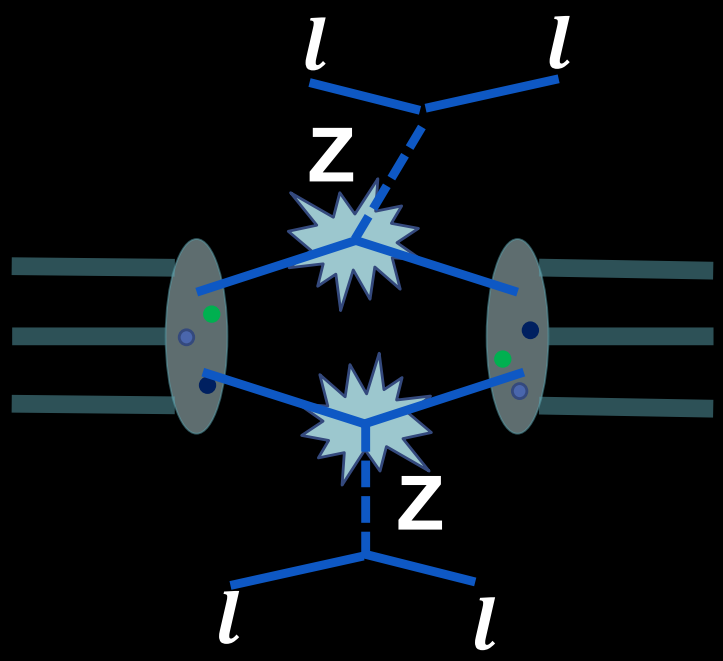
ATLAS measurements

- 4 jets (2016)
- W + 2 Jets (2013)
- 2 prompt J/ψ (2017)

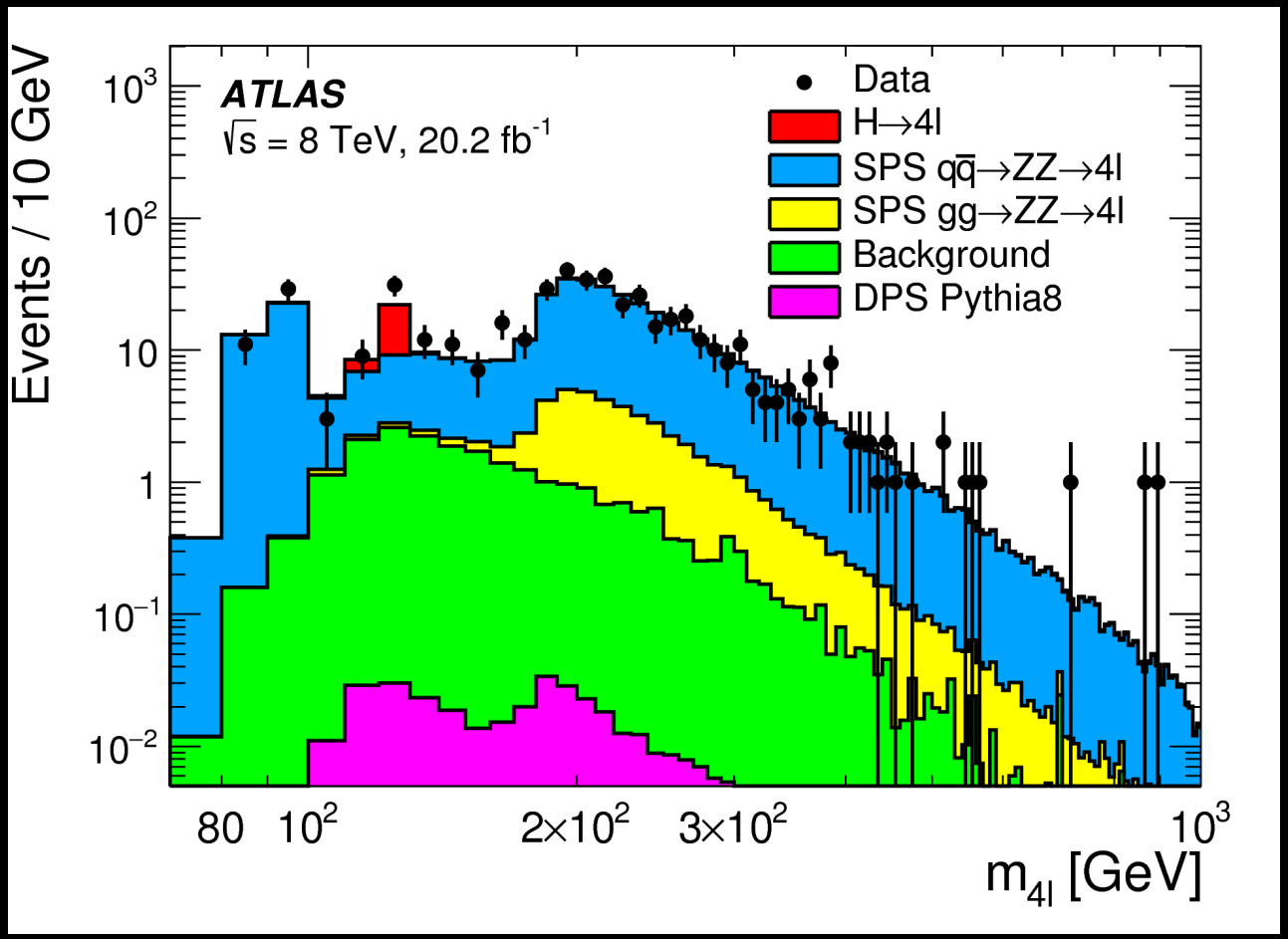
DPS contribution to 4 lepton production

- driven by gg-fusion and similar final state as Higgs „golden channel“:
- $H \rightarrow Z^* Z^* \rightarrow 4l$

Event selection



- two $Z \to l^+l^-$ candidates: same flavour opposite charge pairs
  - leading $50\ \mathrm{GeV} < m_{ll} < 120\ \mathrm{GeV}$ (inv. mass closer to m_Z)
  - sub-leading $20\ \mathrm{GeV} < m_{ll} < 120\ \mathrm{GeV}$
  - 4 lepton mass $80\ \mathrm{GeV} < m_{4l} < 1000\ \mathrm{GeV}$
  - $p_T^{l+l-} > 2\ \mathrm{GeV}$
- veto J/Ψ : $5\ \mathrm{GeV} < m_{2l}$
- 476 candidate events selected



Simulation samples

Signal DPS (0.4 events)

- Pythia8.175 using LO version CTEQ6L1

Backgrounds from single parton scattering (SPS)

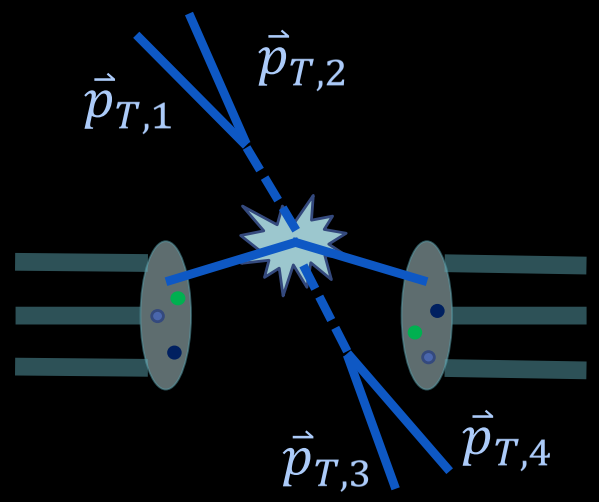
- Z*+$b\bar{b}$
- 2 times Drell-Yan
- …

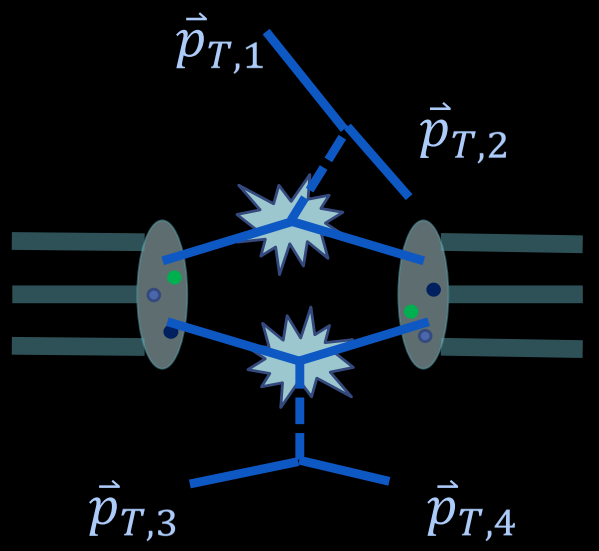
DPS signal extraction

- exploit kinematic correlation
  - SPS: both <u>pairs</u> balance each other
  - DPS: leptons back-to-back (low p_t^Z)

Train artificial neural network (ANN) with:

- $\Delta p_{T,ij} = \frac{|\vec{p}_{T,i}+\vec{p}_{T,j}|}{p_{T,i}+p_{T,j}}$
- $\Delta\phi_{ij} = |\phi_i - \phi_j|$
- $\Delta y_{ij} = |y_i - y_j|$
- $\Delta_{ijkm} = |\phi_{i+j} - \phi_{k+m}|$



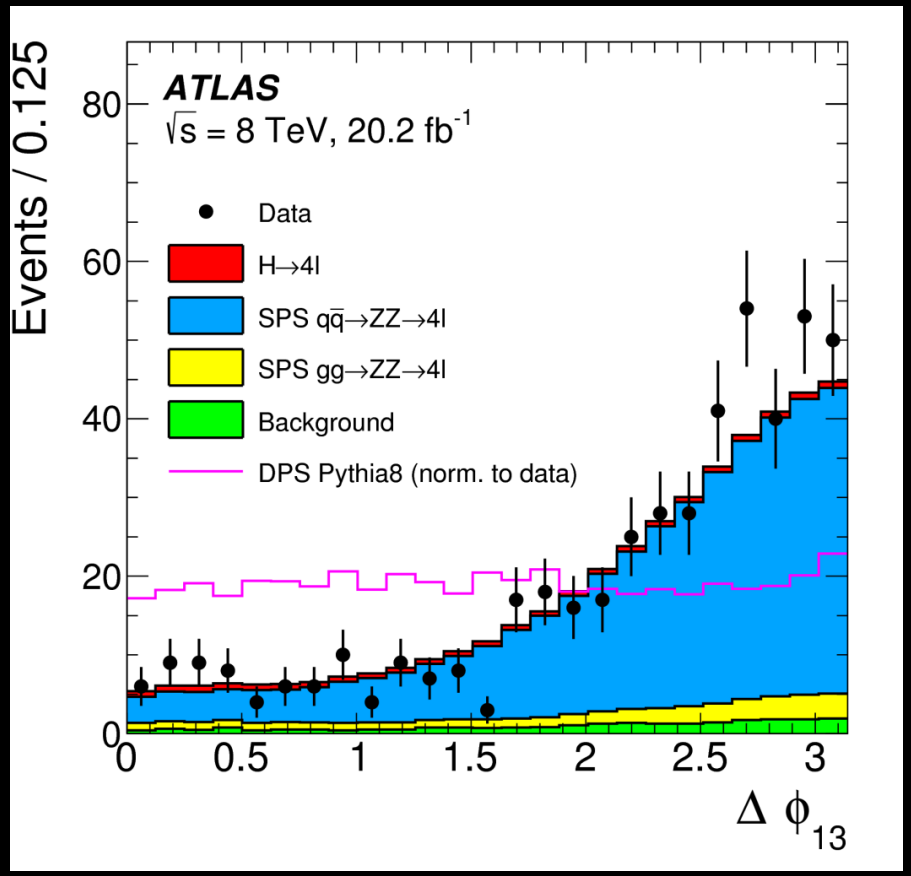


DPS signal extraction

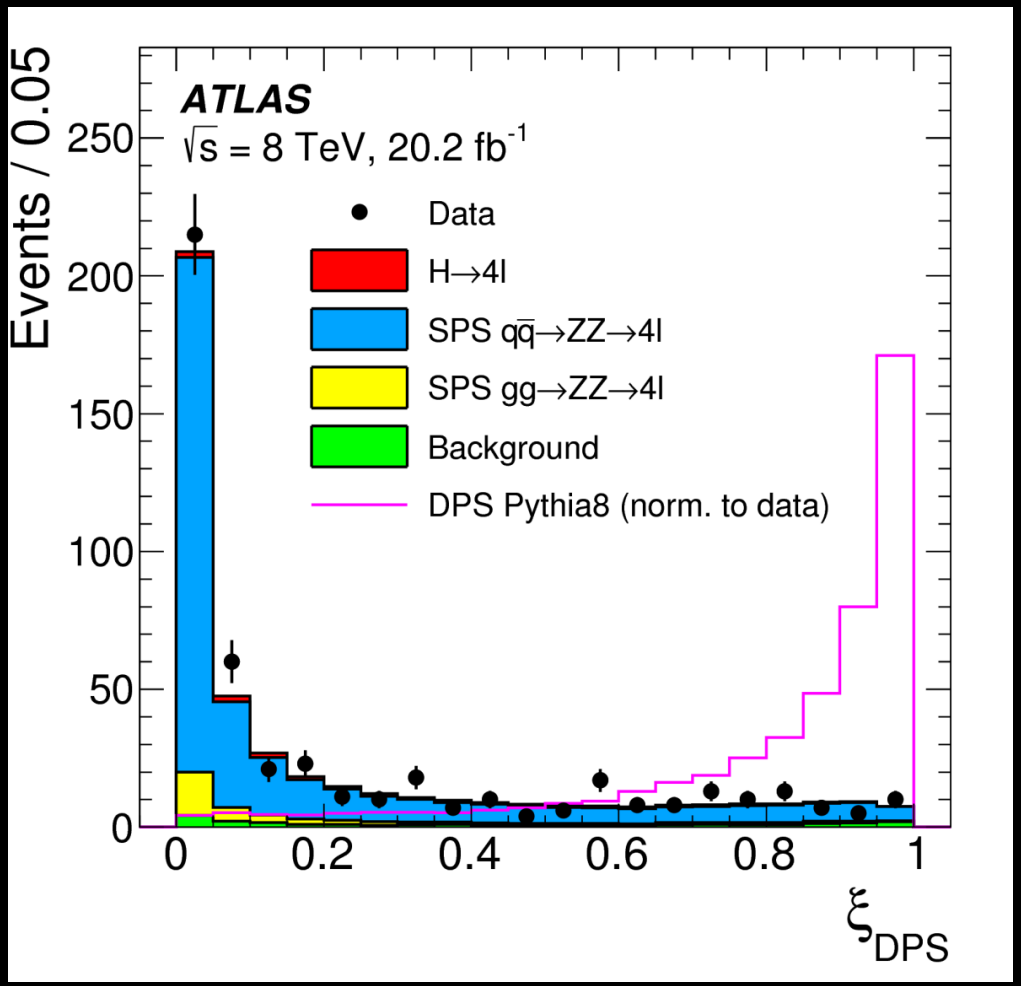
- exploit kinematic correlation
  - SPS: both pairs balance each other
  - DPS: leptons back-to-back (low p_t^Z)

Train artificial neural network (ANN) with:

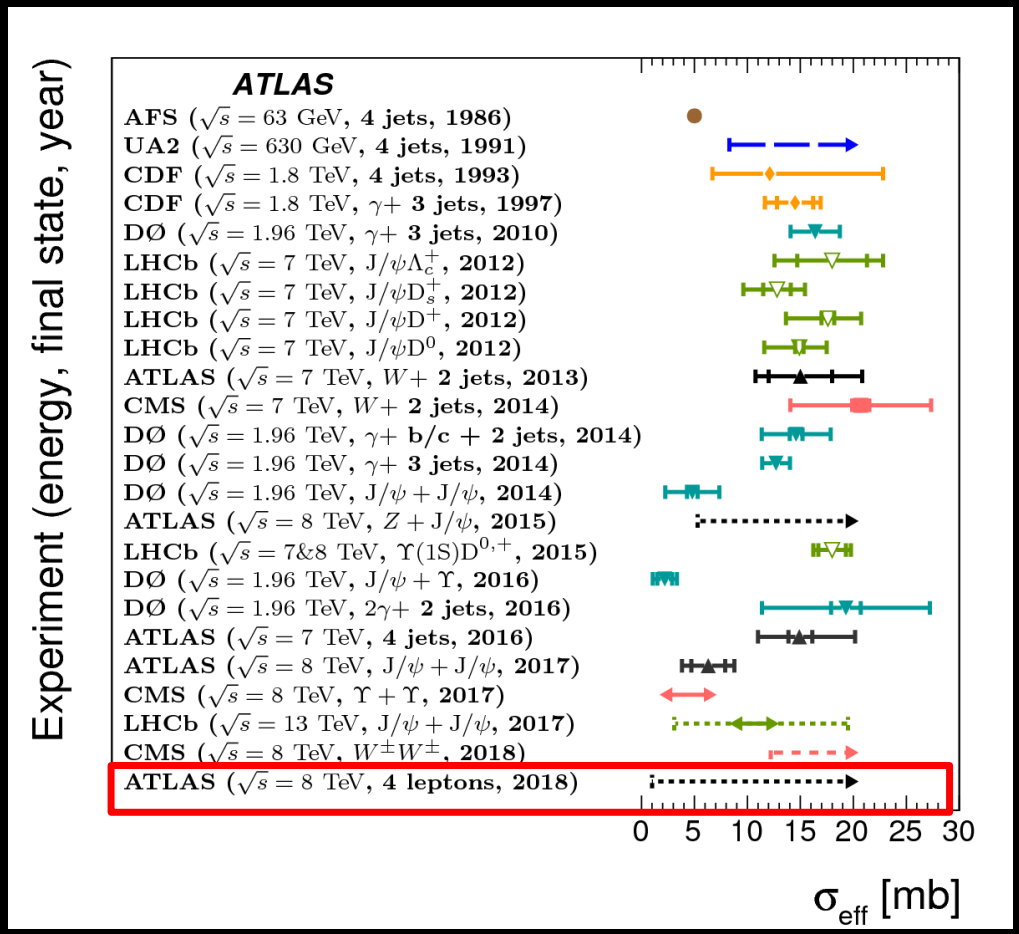
- $\Delta p_{T,ij} = \frac{|\vec{p}_{T,i}+\vec{p}_{T,j}|}{p_{T,i}+p_{T,j}}$
- $\Delta\phi_{ij} = |\phi_i - \phi_j|$
- $\Delta y_{ij} = |y_i - y_j|$
- $\Delta_{ijkm} = |\phi_{i+j} - \phi_{k+m}|$



Likelihood (ξ) from ANN



- Trained to discriminate between DPS and SPS
- Feed-forward multilayer perceptron
  - 21 input neurons (eq. from before)
  - 30 and 9 neurons in hidden layers
- Output between 0 and 1 representing likelihood for belonging to DPS
- Equal number of SPS and DPS events used for training
- Weighting backgrounds by importance



Limit setting

- MC template fit to data on ξ

  fraction of DPS events

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

- profile likelihood ratio with 95% confidence limit:

  $$f_{DPS} \leq 0.042$$

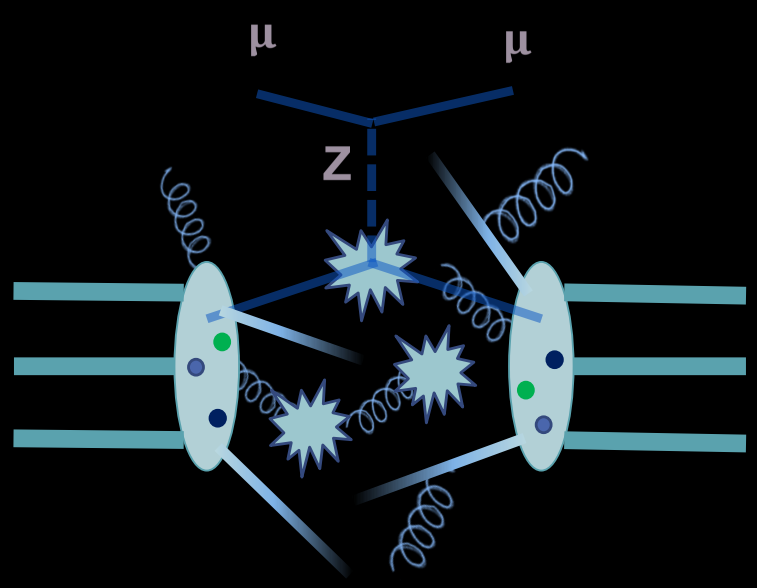
  translates to

  $$\sigma_{DPS}^{eff} \geq 1.0\ mb$$

Underlying event in Z boson events @13TeV

Observables sensitive to the activity of the underlying event

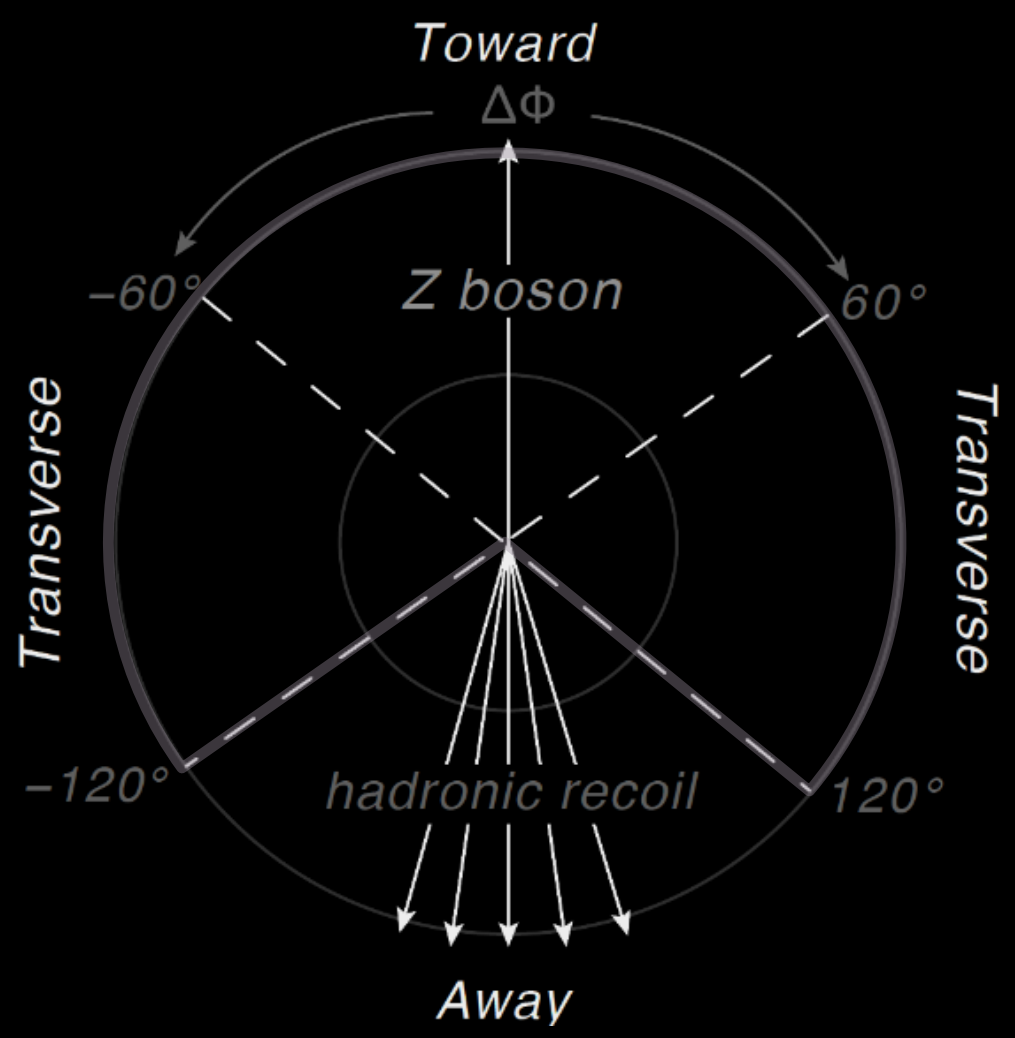
Count all tracks excluding muons:



As a function of hard scatter (p_t^Z):

- Charged particle multiplicity N_{ch}
- Sum of transverse momenta $\sum p_T$
- $mean\ p_T$
- p_T spectrum over all events

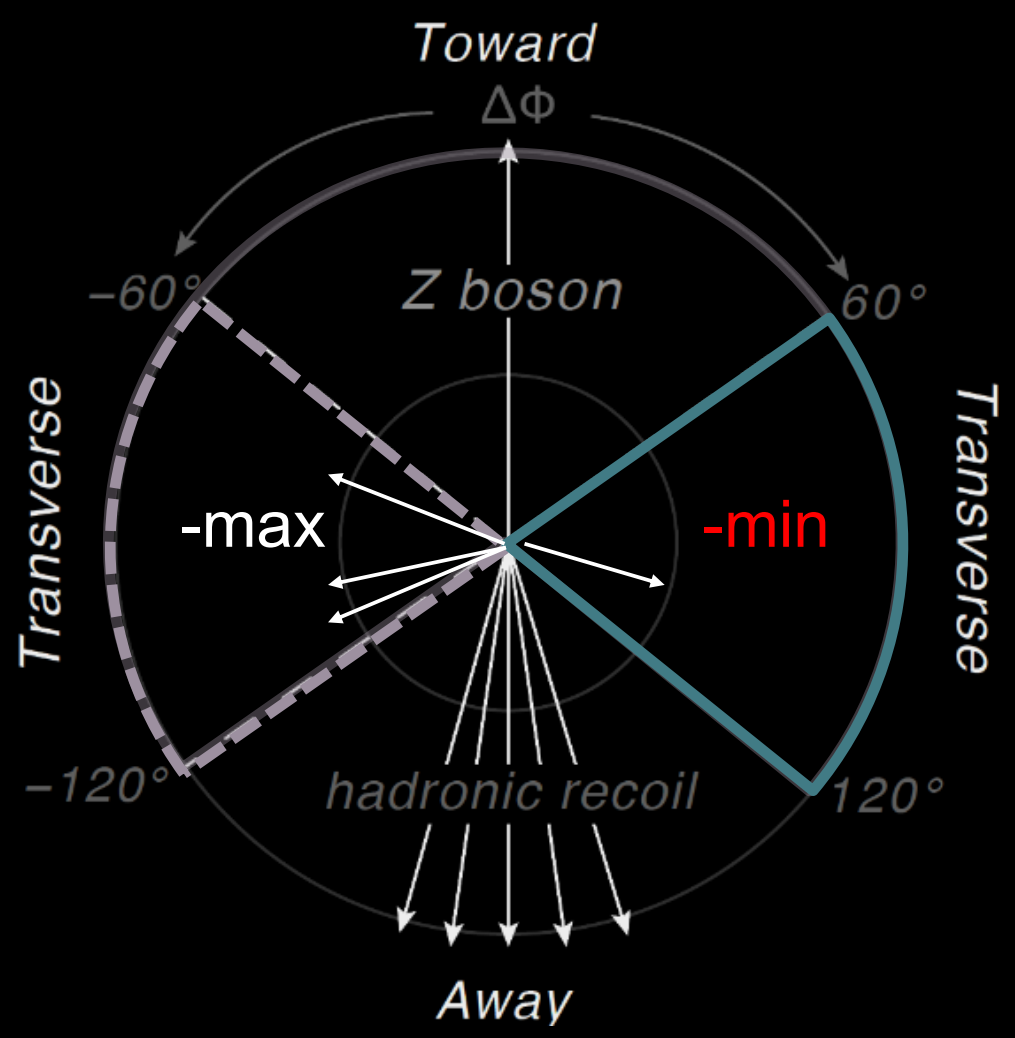
UE regions



- Separation from hard scatter via regions with respect to leading object ($Z \rightarrow \mu^{+}\mu^{-}$)

- Regions in azimuthal plane:
  - Away (recoil jets)
  - Toward
  - Transverse

UE regions

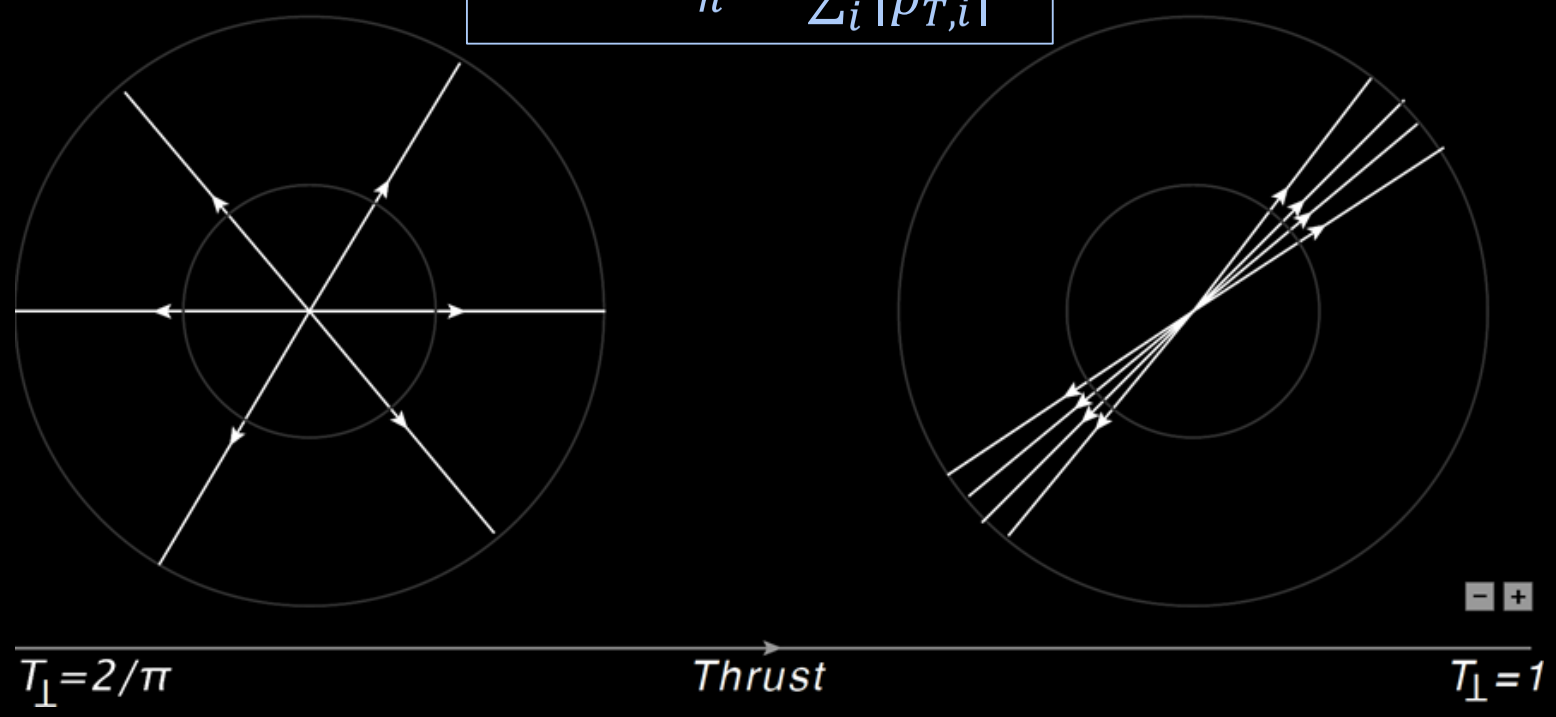


- Separation from hard scatter via regions with respect to leading object ($Z \rightarrow \mu^{+}\mu^{-}$)

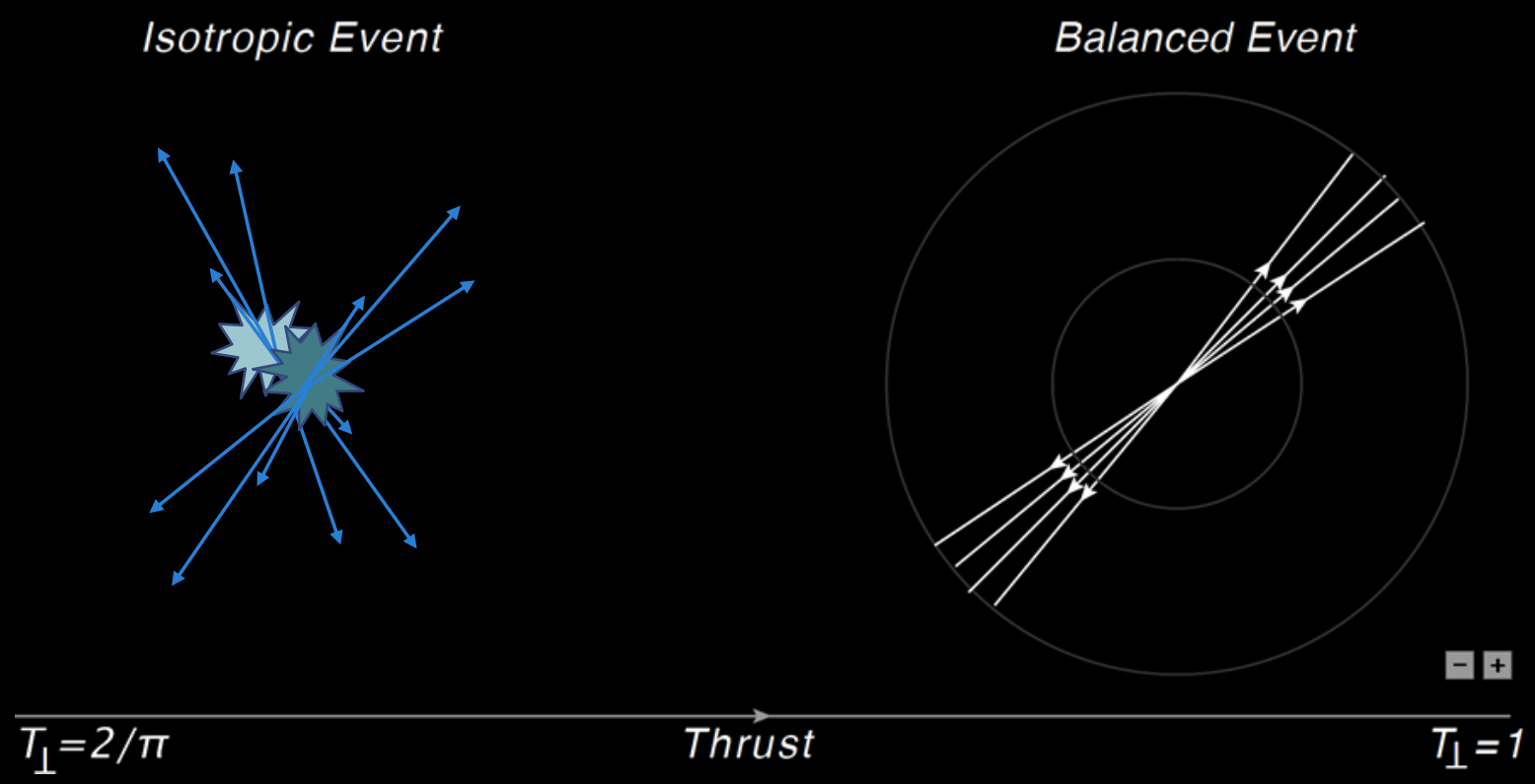
- Regions in azimuthal plane:
  - Away (recoil jets)
  - Toward
  - Transverse
    - Trans-max
    - Trans-min

MPI-enriched: low transverse thrust ($T_\perp$)

$$T_\perp = \max_{\hat{n}} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i |\vec{p}_{T,i}|}$$



MPI-enriched: low transverse thrust ($T_\perp$)



- Low thrust ($T_\perp \leq 0.75$): sensitive to MPI
- distinguish UE from extra jet activity (from HS)

Corrections

Correct MC samples to data

- Reweighting to account for position of interaction vertex along beamline
- Reweighting to match simulated pile up distribution to data

Correction to particle level
Unfolding procedure

- Bayesian iterative unfolding
  - 8 iterations for N_{ch}, $\sum p_T$ and $mean\, p_T$
  - 2 iterations for p_T spectrum to converge
- Unfolding corrects for pile up effects
  - Simulation and data driven cross check on pile up correction
- Baseline unfolding with PowhegPythia8 sample
  - Cross-check with Sherpa

Uncertainties

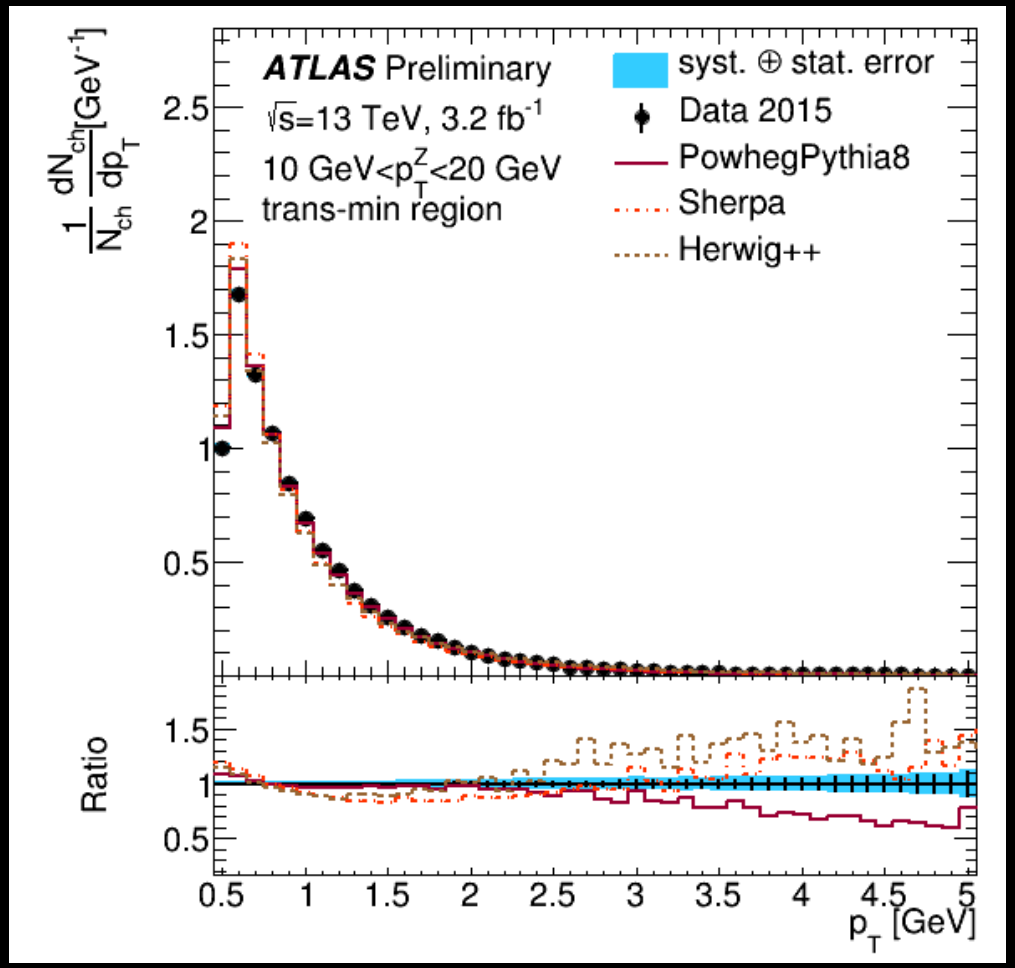
Category	Estimation method	Contribution
Statistical	Pseudo-experiments	(depending on p_T^Z) <<1% to ~10%
Detector related • Reconstruction of leptons and tracks • Pile-up simulation	MC simulation Data-driven cross checks	2%-5%
Unfolding uncertainties (MC prior dependence)	Data driven closure test Cross validation different MC samples	4%-8%
Backgrounds • $t\bar{t}$, Electroweak, Multijet	MC simulation varied cross section Data driven analysis	Negligible (<<0.1%)

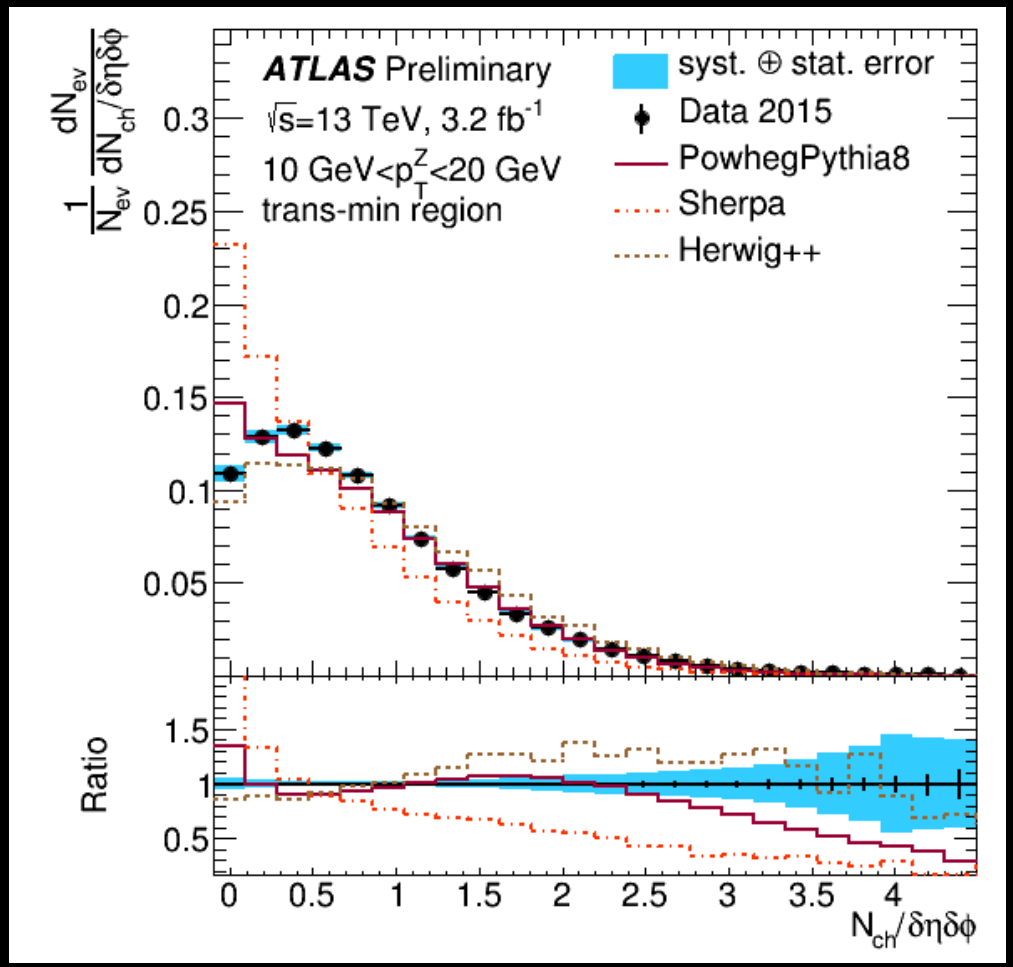
Unfolded results: p_T spectrum

- accumulated over all events
- Y-axis fraction of particles per p_T-range

- general performance
  - all generators produce higher fraction of particles with lowest p_T
  - Herwig++ tends to higher p_T particles

  - Generator performance insensitive to
    - region (except away)
    - thrust
    - hard scatter (p_T^Z)





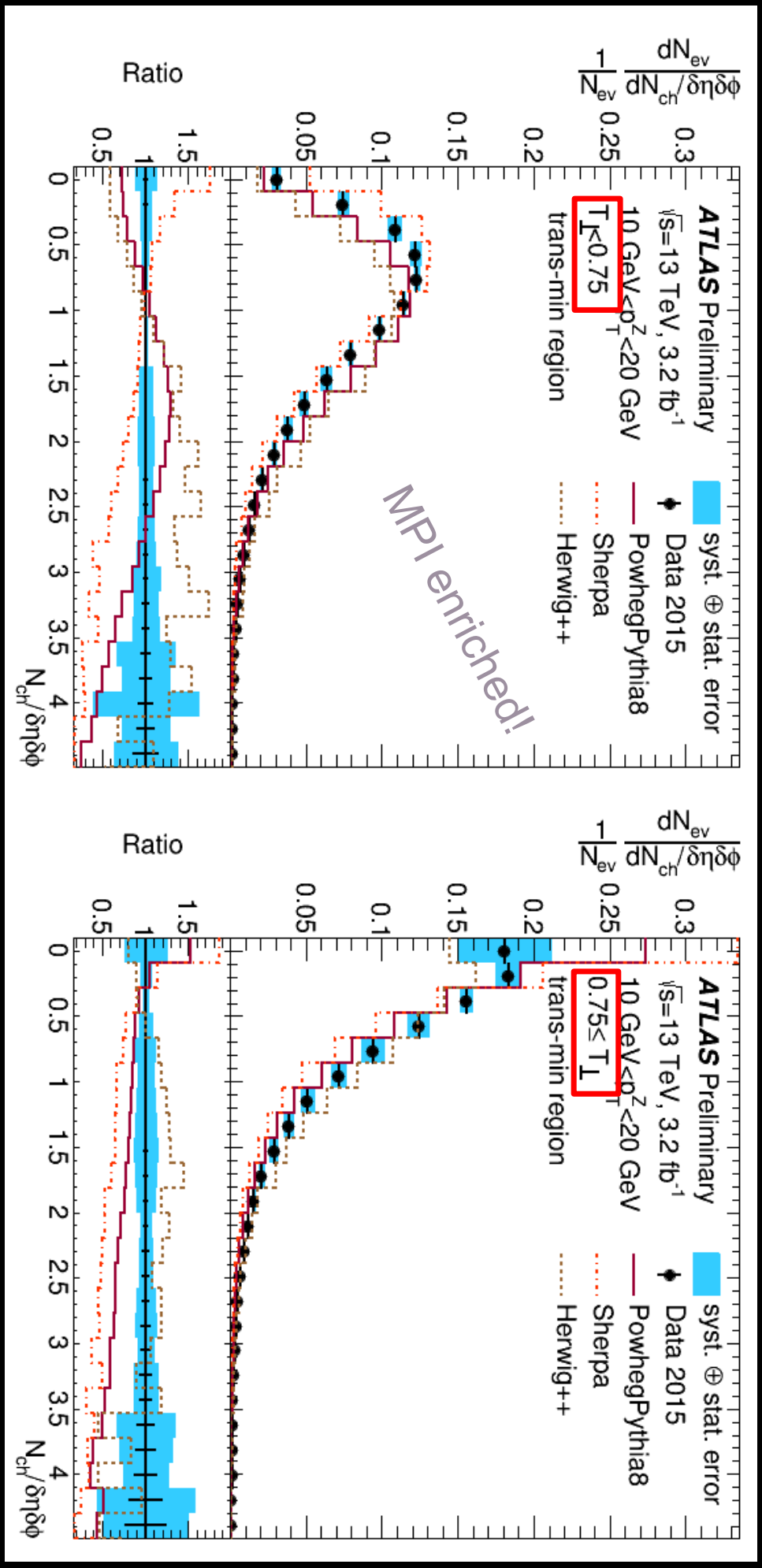
Results for N_{ch}

- X-axis observable
- Y-axis fraction of events per observable bin
- Normalized to size of azimuthal region ($\delta\eta\delta\phi$)
- Sherpa fails shape
- PowhegPythia undershoots activity
- Herwig++ shape okay'ish

Summary on results

- General shape expectations agree with measurement
  - higher p_T^Z ⇒ higher UE activity (impact parameter, …)
  - away/trans-max region dominated by HS

- Generator performance
  - away region well modelled (HS)
  - consistent within UE sensitive regions (toward/transmin)
  - predictions improve for higher p_T^Z



PowhegPythia : overshoots MPI

undershoots extra jet activity

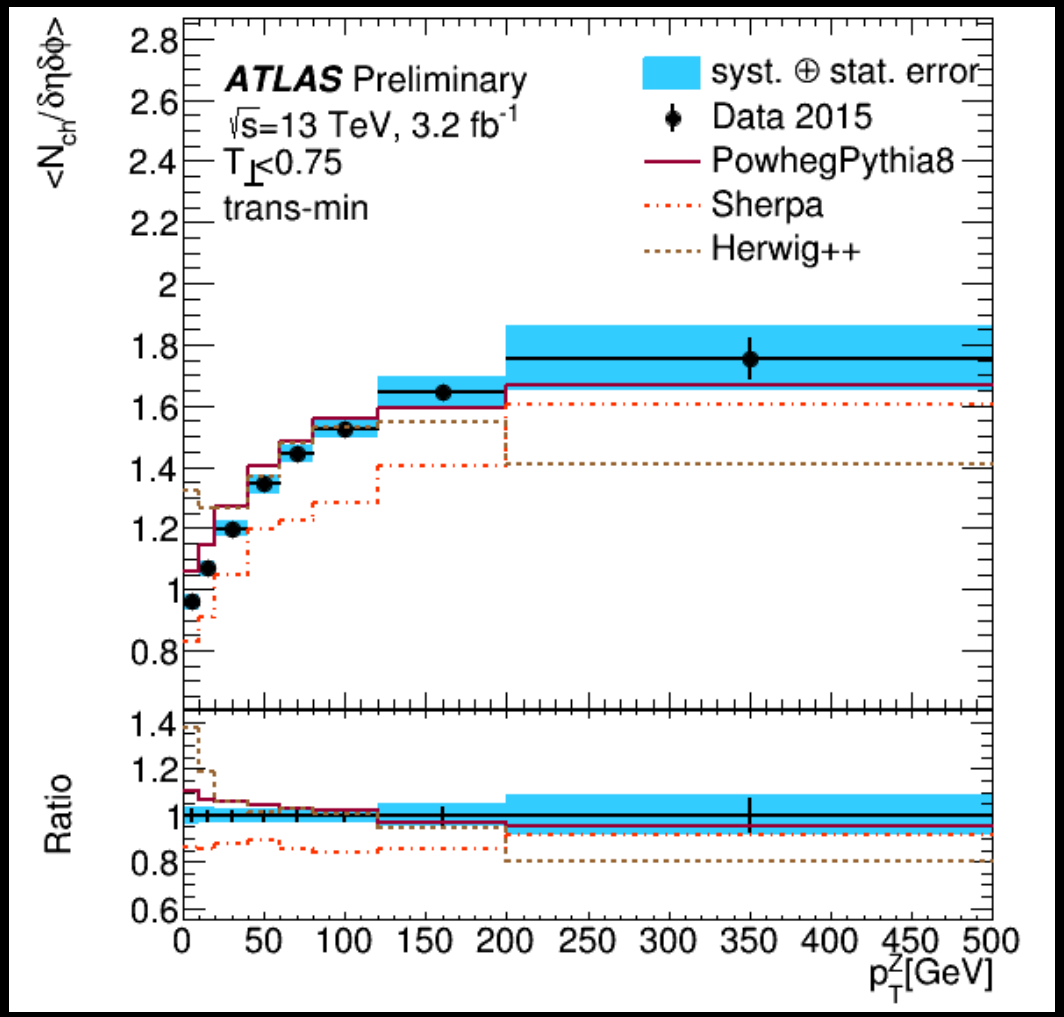
Mean values

- Activity as function of p_T^Z
- Visible jet pedestal
- Manifests underestimation

Sherpa consistent slope

PowhegPythia too flat (consistent with performance on extra jet activity)

Herwig++ strange feature at low p_T^Z



Comparison with other measurements

ATLAS at 7TeV

- served as template for 13TeV measurement
- similar kinematic selections
- similar unfolding technique
- different PU treatment
- thrust and p_T spectrum not included then

CDF at 1.96GeV

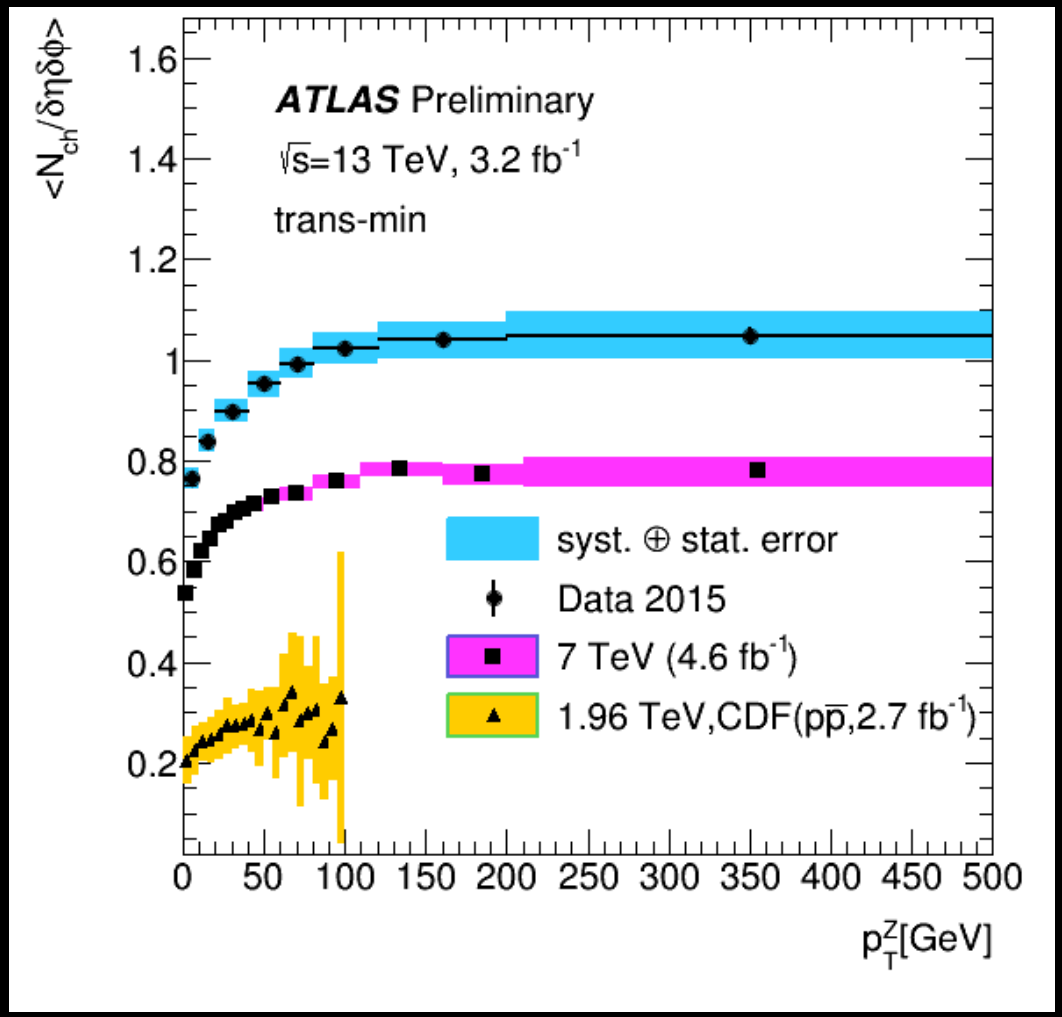
- Drell-Yan lepton pairs from proton-antiproton
- similar selection for tracks
- slight difference for leptons
- bin-by-bin unfolding

Measurements at different $\sqrt{s}$

- Matches expected increment with $\sqrt{s}$

(Not in shown in plot)

- Energy extrapolation of PowhegPythia consistent for ATLAS measurements
- Sherpa inverts behaviour



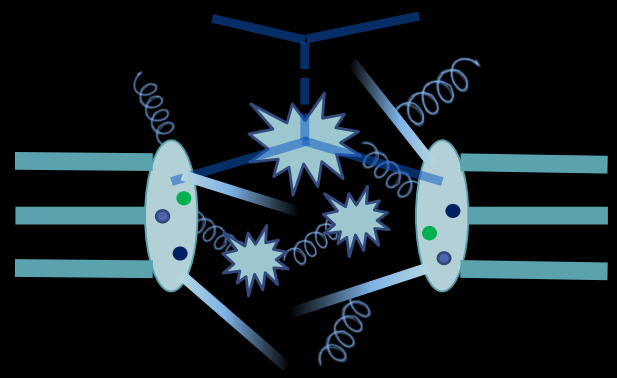
Summary

Underlying event

- Study on UE activity
  - in transverse regions
  - as function of hard scatter
  - MPI enriched (low thrust)
- High need for tuning on UE for all generators
- Powheg+Pythia8 with consistent modelling of MPI and energy extrapolation
- Herwig++ qualitatively good performance

DPS with 2 Z bosons

- two $Z \rightarrow l^+ l^-$ candidates from PS
- ANN for discrimiation from SPS
- $\sigma_{DPS}^{eff} \geq 1.0\ mb$



Backup

Simulation Samples

Generator	PDF	Tune	Characteristics
Powheg+Pythia8	CTEQ6L1	AZNLO	• Hard scatter @ NLO • Lund string model for hadronization
Sherpa 2.2.0	NNPDF3.0	Author	• MPI model similar to Pythia8 • Cluster model for hadronization
HERWIG++	CTEQ6L1	UE-EE5	• Only generator level available • Cluster model for hadronization