Study of the hard double-parton scattering with 4-lepton final states with the ATLAS detector

Phys. Lett. B 790 (2019) 595

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New Trends in High-Energy Physics

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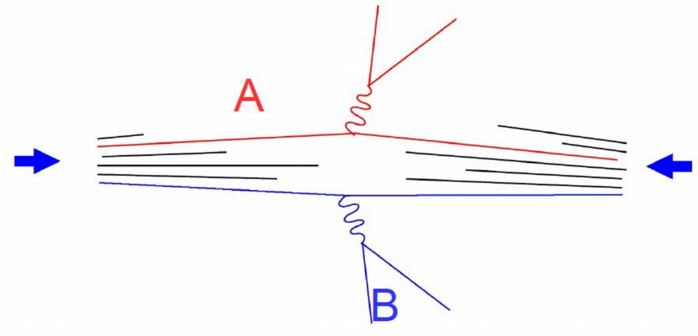
Hard double-parton scattering



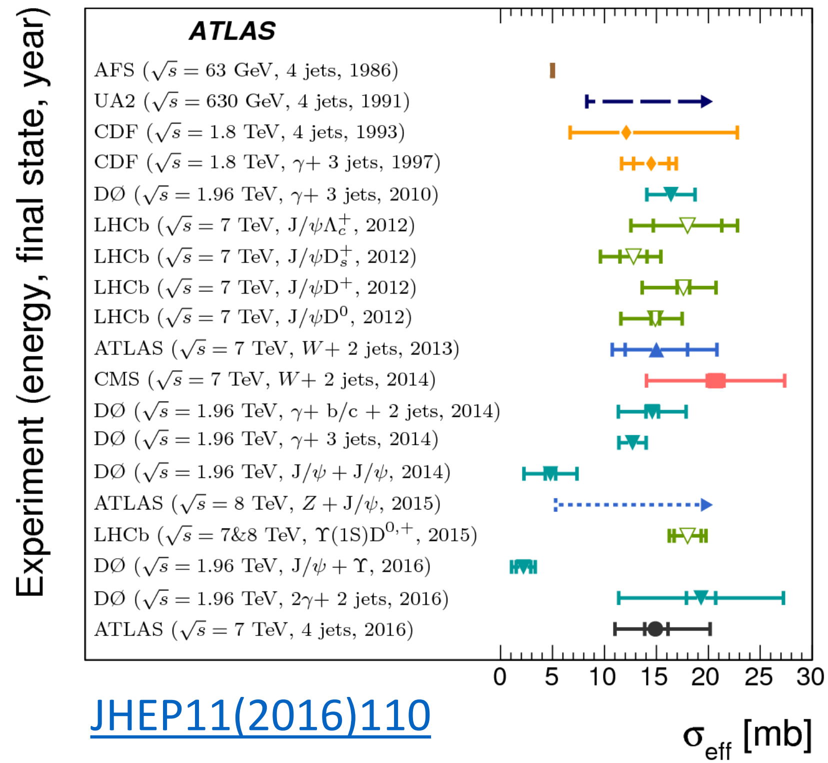
- Two disjoint hard-scattering subprocesses
- If assume factorization of double PDFs

(neglecting spin-, flavor-, color correlations)

→ **Pocket formula (phenomenological):**

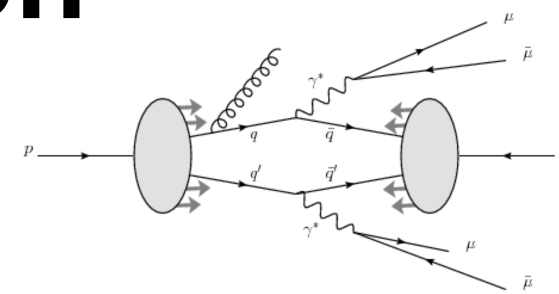
$$\sigma_{DPS}^{AB} = \frac{k}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{eff}}$$

- $\sigma_{SPS}^{A(B)}$ is the **inclusive** cross section of the **single**-parton scattering with the final state A (B)
- σ_{eff} is a **universal parameter of the proton (under assumptions above)**:
  - ➢ Related to the transverse size of the interaction region
  - ➢ Independent of the partonic process
  - ➢ Independent of the phase space
- k is a symmetry factor
  - ➢ $k = 1$ for identical A and B
  - ➢ $k = 2$ if A ∩ B = ∅



JHEP11(2016)110

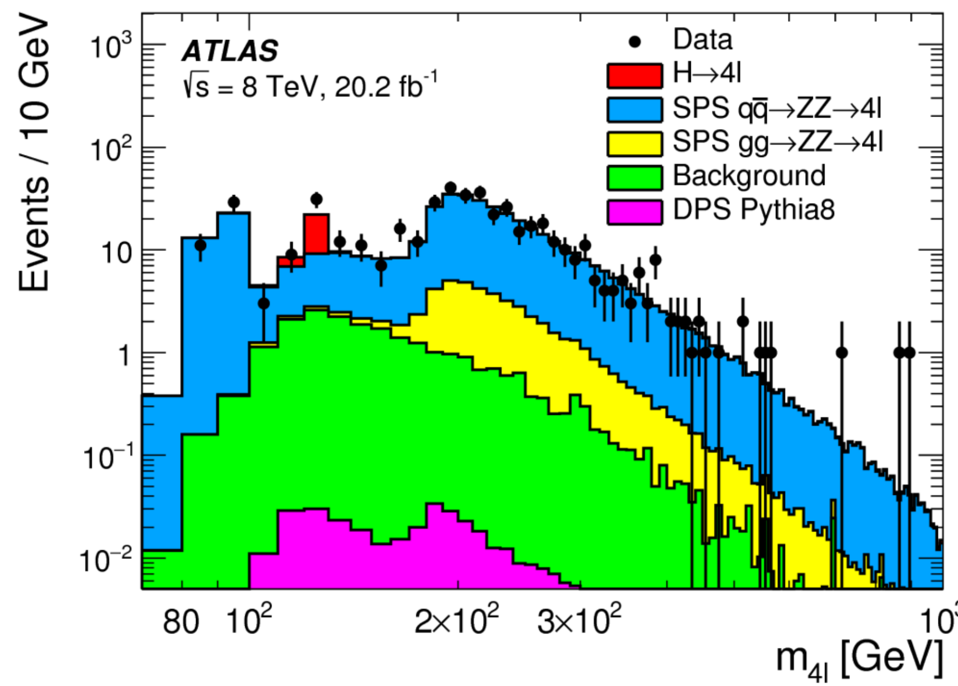
Motivation



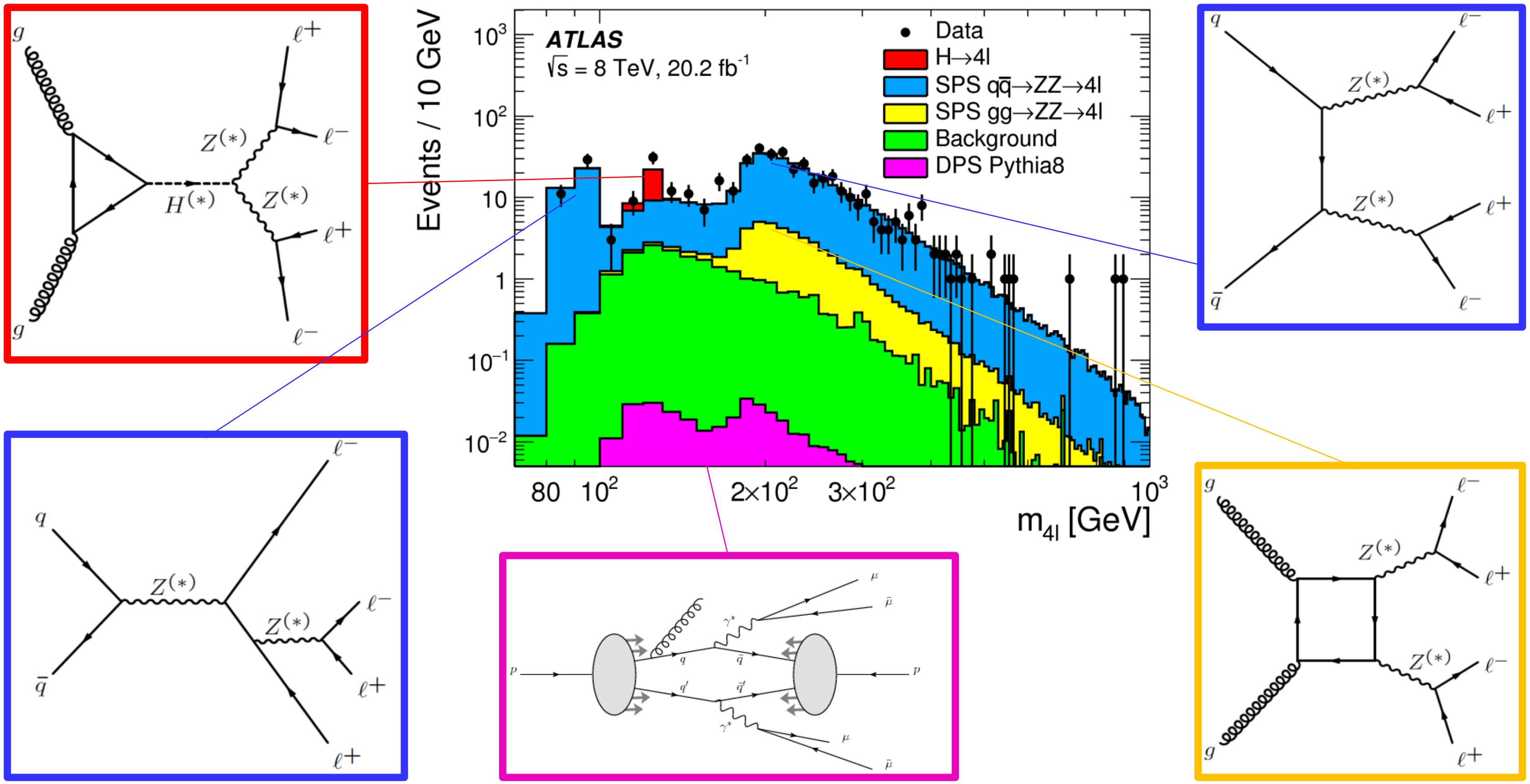
- Add-on to the "Measurements of four-lepton production in pp collisions at 8 TeV with the ATLAS detector", Phys.Lett. B753 (2016) 552-572:
  - Same event selection (originally driven by the H → ZZ → 4l measurement)

- **Measure the hard double-parton scattering (DPS) contribution to the inclusive four-lepton event sample**

1) DPS dominated by two $q\bar{q}$ initial states: test the possibility of parton density fluctuations that would lead to a large DPS contribution
2) Due to event selection requirements, the DPS M_{4l} distribution peaks around the Higgs mass

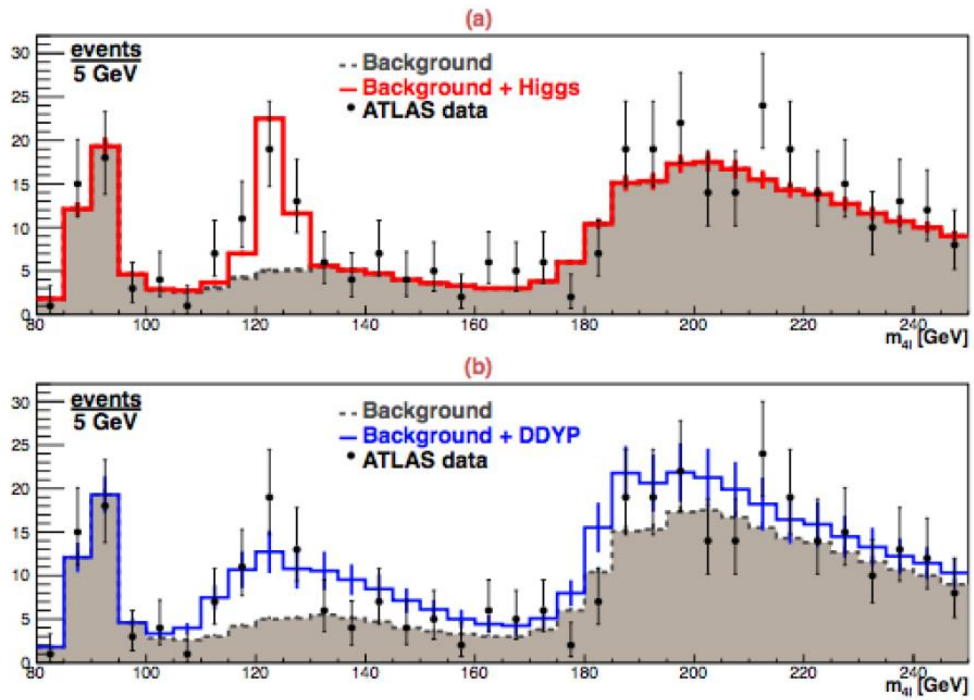


Invariant four-lepton mass



- Definition of signal: four-leptons from resonant Z and H boson decays and continuum $ZZ^{(*)}$ background
    - ➢ Produced via SPS or **DPS** mechanisms

A model suggesting large DPS contribution



arXiv 1501.04569

- M. W. Krasny and W. Placzek, The LHC excess of four-lepton events interpreted as Higgs-boson signal: Background from Double Drell-Yan process?, Acta Phys. Polon. B45 (2014) 71, arXiv: 1305.1769 [hep-ph]
- M. W. Krasny and W. Placzek, On the contribution of the double Drell-Yan process to WW and ZZ production at the LHC, Acta Phys. Polon. B47 (2016) 1045, arXiv: 1501.04569 [hep-ph]
- The upper limit on fDPS obtained in this analysis using kinematic distributions of four leptons allows qualitative testing of the model

Dataset and event selection

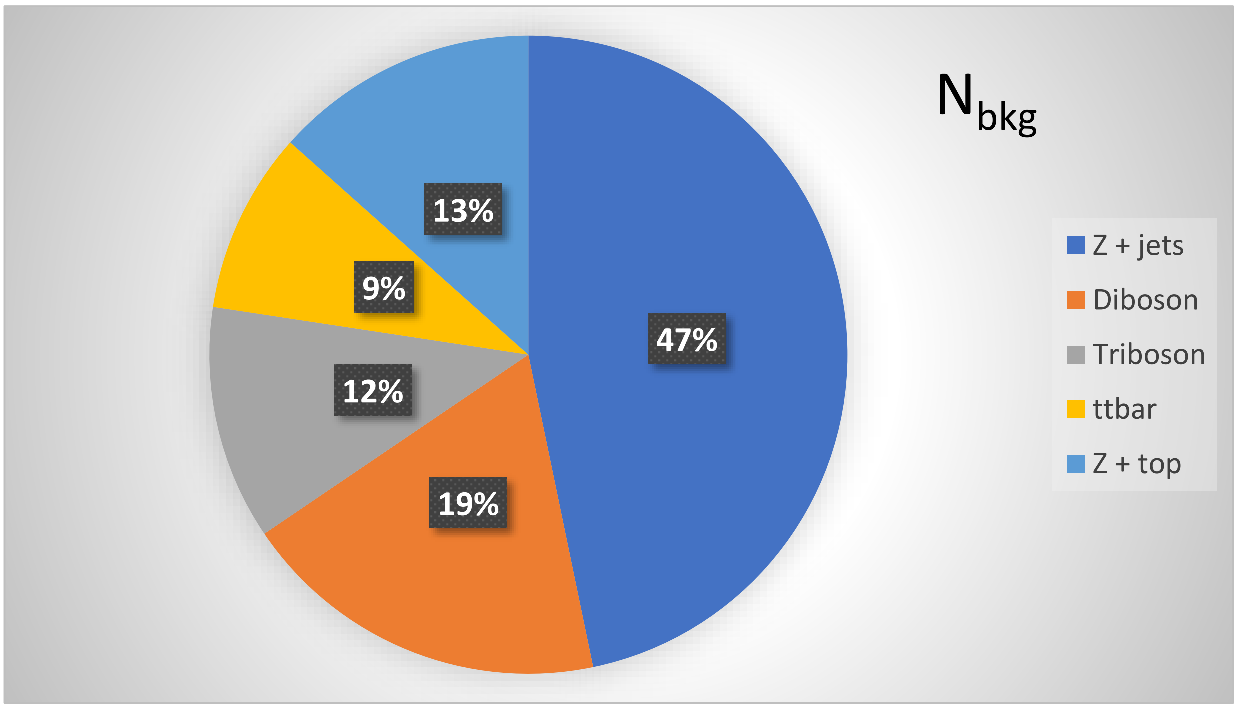
- 20.2 fb^{-1}, 8 TeV dataset and selection are the same as in [Phys. Lett. B 753 (2016) 552]

Lepton selection	
Muons:	$p_T > 6$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	The remaining SFOS with the largest $m_{\ell\ell}$
For both pairs:	$p_T^{\ell^+\ell^-} > 2$ GeV
Event selection	
Lepton $p_T^{\ell_1,\ell_2,\ell_3}$:	$> 20, 15, 10(8 \text{ if } \mu)$ GeV
Mass requirements:	$50 < m_{12} < 120$ GeV
	$12 < m_{34} < 120$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i^+, \ell_j^-) > 5$ GeV
4ℓ mass range:	$80 < m_{4\ell} < 1\,000$ GeV

- Monte Carlo modelling:
  - Double parton scattering (DPS): Pythia8 double Drell-Yan
  - Single parton scattering (SPS): gg → ZZ(*) with MCFM, Higgs ggF with Powheg, qq → ZZ(*) with Pythia8
    - ✔ For the continuum gg → ZZ, NLO k-factors are applied
      → This is in opposite to 4-lepton paper, where the scaling factor for gg → ZZ (describing the amount of missing higher-order corrections) is extracted from the M4l fit
- Background simulated with various generators and includes $t\bar{t}, tZ, Z + b\bar{b}, Z + \gamma, WZ, VH, VVV$. The $Z + b\bar{b}$ and $t\bar{t}$ background components are scaled according to data driven studies of the 4-lepton paper ($Z + b\bar{b}$ scale factors are varied by 50% for syst. unc.)

Event yields

Channel	N^{Data}	$N^{\text{Total}}_{\text{expected}}$	$N^{\text{signal}}_{\text{non}-gg}$	N^{signal}_{gg}	N^{MC}_{τ}	N_{bkg}
$4e$	85	80 ± 4	68.4 ± 3.4	6.24 ± 0.31	1.28 ± 0.06	3.6 ± 0.5
4μ	156	150.2 ± 2.9	128.2 ± 2.5	11.00 ± 0.21	2.18 ± 0.09	9.0 ± 1.5
$2e2\mu$	235	205 ± 5	172 ± 5	16.0 ± 0.4	3.08 ± 0.13	13.6 ± 2.1
Total	476	435 ± 9	369 ± 9	33.3 ± 0.8	6.54 ± 0.14	26.2 ± 3.6



- The background is dominated by Z + bbar jets
- Pythia8 DPS expectation: 0.3 events

Invariant dilepton masses

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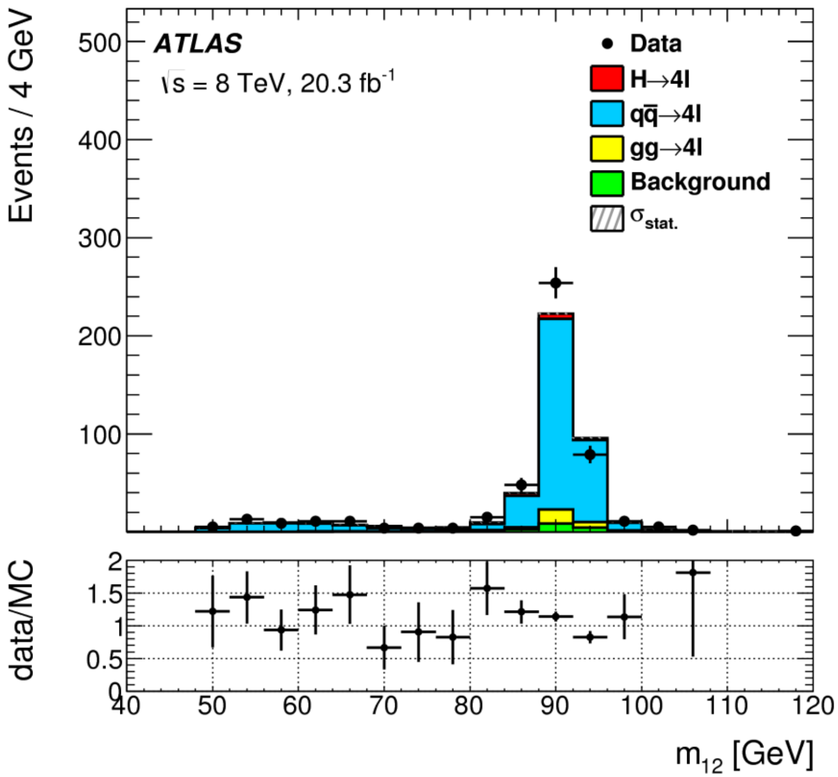
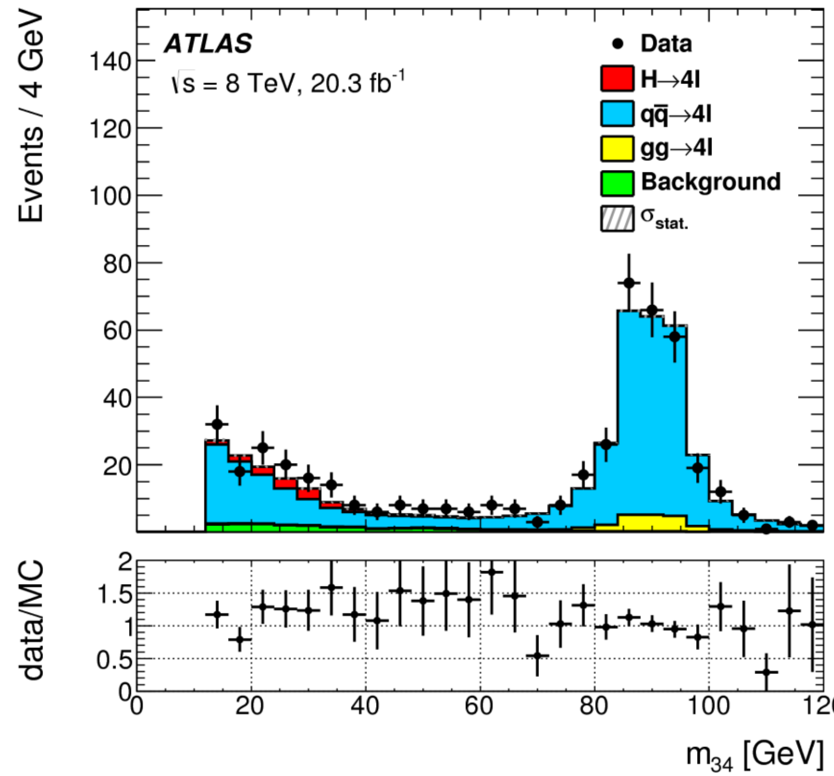


Leading dilepton



Subleading dilepton

Extraction of DPS signal and σ_{eff}

- Based on four-lepton topology
- Neural network to discriminate between DPS and non-DPS processes
- Fit of the neural network output variable to determine DPS contribution, f_{DPS}

$$\sigma_{DPS}^{AB} = \frac{k}{2} \frac{\sigma_{SPS}^{A} \sigma_{SPS}^{B}}{\sigma_{eff}} \ (1), \qquad f_{DPS} = \frac{\sigma_{DPS}^{4l}}{\sigma^{4l}} \quad \Rightarrow \quad \sigma_{eff} = \frac{k}{2} \frac{\sigma_{SPS}^{2l,A} \sigma_{SPS}^{2l,B}}{f_{DPS} \sigma^{4l}}$$

- k is defined for fully overlapping A and B ($k = 1$) or for fully disjoint A and B ($k = 2$)
  - ➢ For a partial overlap between A and B decompose Eq. (1) into the sum over phase space regions with well defined k_{ij}:

$$\sigma_{DPS}^{AB} = \sum_{i,j} \frac{k_{ij}}{2} \frac{\sigma_{SPS}^{A,i} \sigma_{SPS}^{B,j}}{\sigma_{eff}}$$

  - ➢ i, j denote lepton pT bins, dileptons mass bins, and lepton flavours
  - ➢ $\sigma_{SPS}^{A(B),i(j)}$ are determined using Powheg-Box Drell-Yan MC at NLO QCD
- $\sigma^{4l} = 32.0 \pm 1.6\,(stat.) \pm 0.7\,(syst.) \pm 0.9\,(\mathrm{lumi.})$ fb from Phys. Lett. B 753 (2016) 552

Neural network input variables

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

$$\Delta\varphi_{ij} = |\varphi_i - \varphi_j|$$

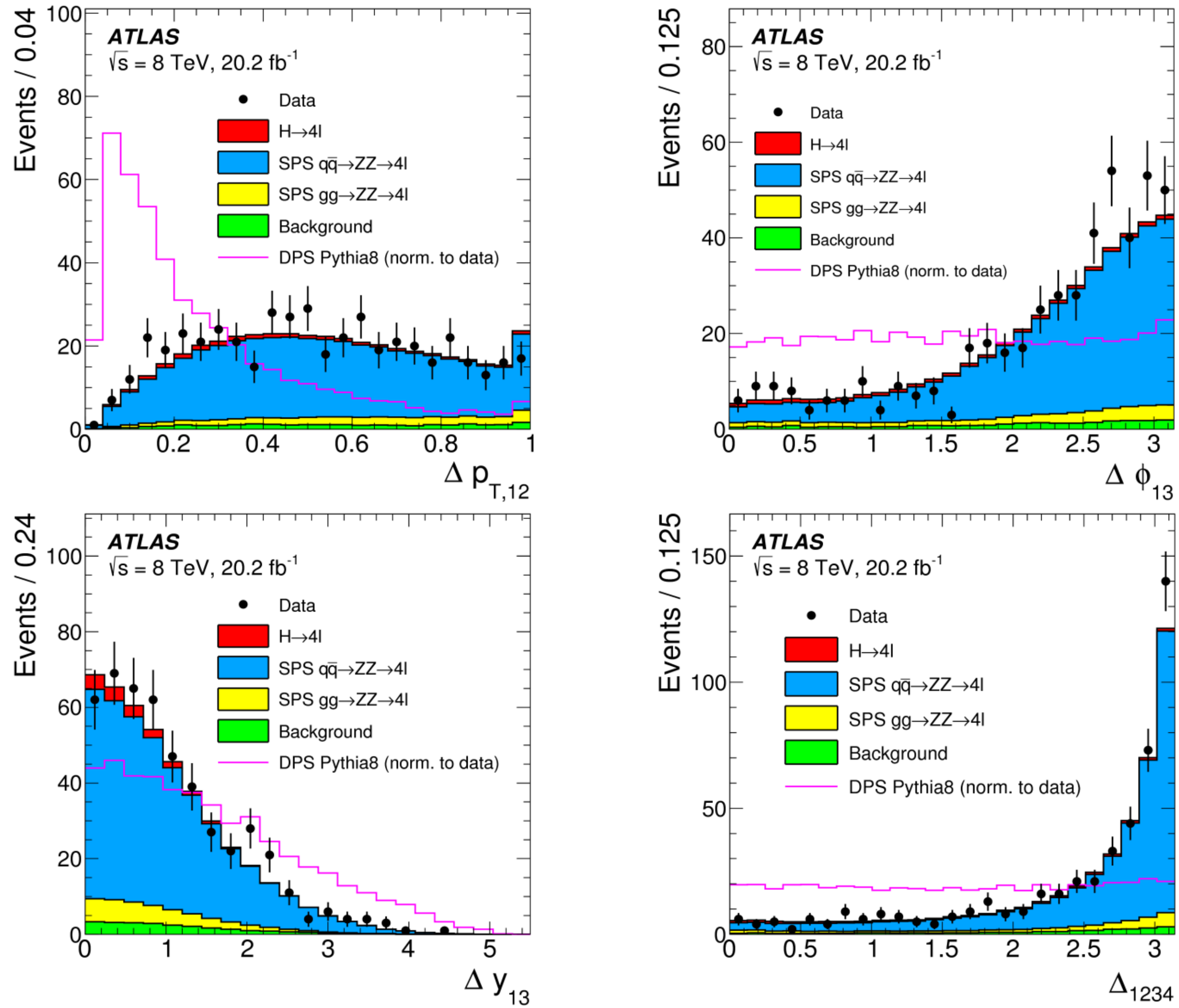
$$\Delta y_{ij} = |y_i - y_j|$$

$$ij = 12, 13, 14, 23, 24, 34$$

$$\Delta_{ijkm} = |\varphi_{i+j} - \varphi_{k+m}|$$

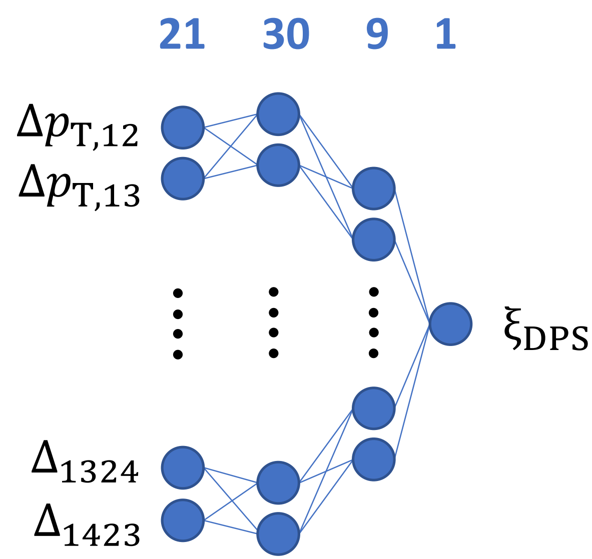
$$ijkm = 1234, 1324, 1423$$

- 21 input variables
- Leptons 1 and 2 (p_{T}-ordered) are from the leading dilepton
- 3 and 4 are from the sub-leading dilepton
- All possible lepton combinations are considered

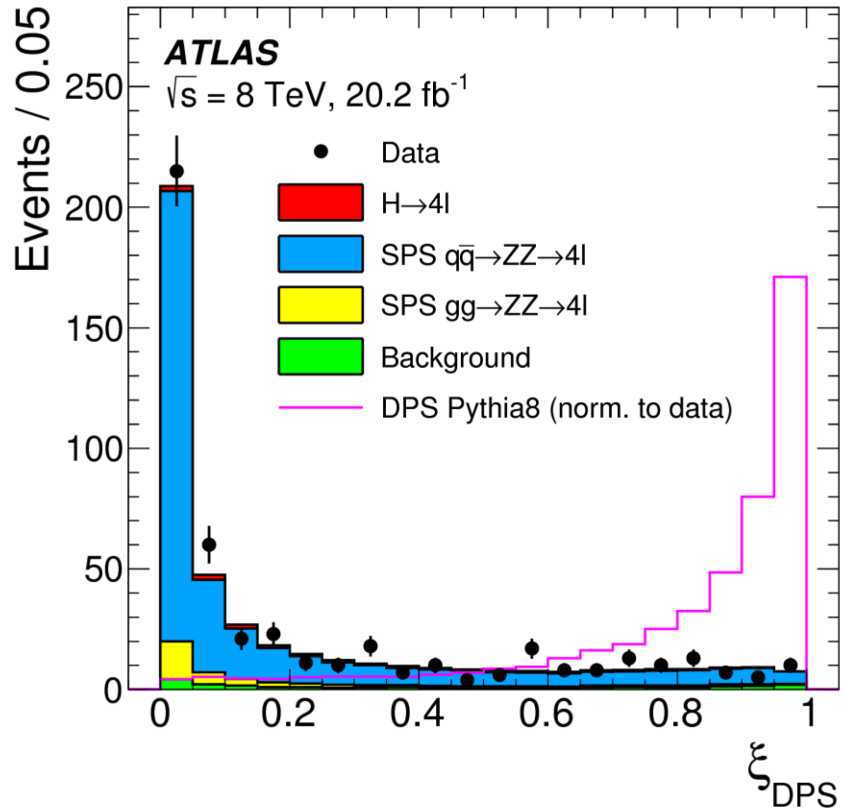


Neural network configuration

- Neural network (NN) architecture inherited from an earlier ATLAS 4-jet analysis
- Four layers with 21(input):30:9:1(output) neurons, output variable ξ_{DPS}:
  - DPS: $\xi_{\mathrm{DPS}} = 1$
  - non-DPS (SPS and background): $\xi_{\mathrm{DPS}} = 0$
- Technical implementation with the TMultilayerPerceptron class (ROOT)
  - kBFGS method for the NN training
- MC samples randomly divided into a test and training sample
  - ~10 000 DPS events, 100 000 non-DPS events
  - Event weights are applied in order to have the same effective number of events for DPS and non-DPS classes, also weights were increased for Zbb background



Fit results



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

- No hint of DPS events seen in the inclusive 4-lepton data sample
- MC profile fit yields the fraction of DPS events in the data after subtracting background, f_{DPS} = -0.009 ± 0.017 (stat.)
- Translates into the upper limit $f_{\mathrm{DPS}} < 0.042$ @ 95% CL (< 17 events)

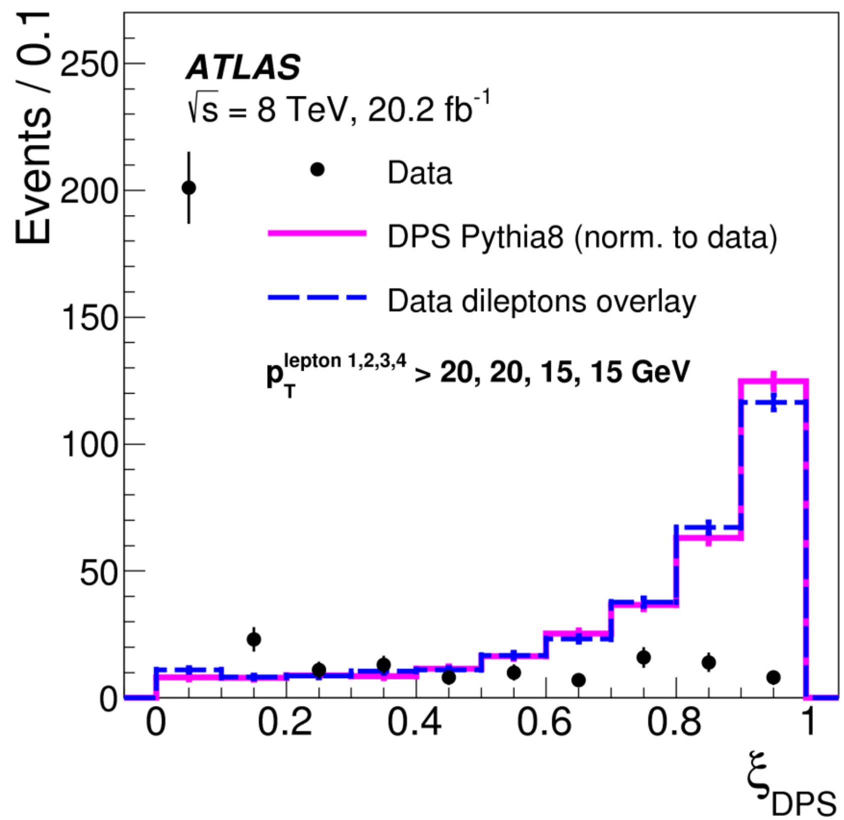
DPS model of Pythia8

- What correlations are possible between two Drell-Yan (DY) interactions within Pythia8 DPS model?
  - The x' space for the parton participating in the second subscattering is restricted to $0 < x' < 1 - x$ in order to not break the proton momentum sum rule
  - The PDF for the parton participating in the second subscattering is adjusted in both shape and normalization (e.g. if the first parton is a valence *d* quark, then the whole $d_v(x)$ PDF is gone for the second parton; needed to satisfy the quark-number sum rule)
  - Primordial k_T (Fermi motion of partons within the proton + effective parameterisation of infrared effects; k_T ~1-2 GeV): the k_T for two initial state partons become correlated by handling the beam remnant
  - Color reconnection (makes the fragmentation of outgoing colored systems dependent): initial state parton showers in case of double DY are not reconnected in the Pythia8 model
  - Initial state parton showers are interleaved between MPIs: may reduce the ISR p_T kicks compared to single parton scattering

What is the effect of these correlations?

Validation of the method

- The NN trained with MC events was applied to a set of overlaid data dilepton events
- Overlaid data dilepton events:
  - ➢ Model the DPS interaction
  - ➢ Data dilepton events are chosen randomly and overlaid if the distance between Z coordinates of vertices is less than 1 cm
  - ➢ Comparison made in a restricted phase space (high lepton pT's) due to trigger requirements



The Pythia8 model of double Drell-Yan DPS is consistent with the idea of two independent subscatterings

Systematic uncertainties

- Experimental uncertainties:
  - Uncertainties of the electron and muon energy scales
  - Energy and momentum resolution
  - Trigger, reconstruction and identification efficiencies
- SPS model uncertainties:
  - Vary the fractions of qq- and gg-initiated subprocesses. The variation is between the nominal MC prediction and the mixture giving the best description of the M4l spectrum
- Uncertainty in the background modelling:
  - Vary contribution of various background subprocesses according to the uncertainty of their normalisation factors (obtained from fits in control regions)
  - Variation of Z + bbar background gives the largest contribution to the systematic uncertainty
- The total systematic uncertainty amounts to 20% of the statistical uncertainty

Lower limit on σ_{eff}

$$\sigma_{eff} = \frac{k}{2}\frac{\sigma_{SPS}^{2l,A}\sigma_{SPS}^{2l,B}}{f_{DPS}\sigma^{4l}}$$

- The upper limit on f_{DPS} translates into the lower limit on σ_{eff}: $\sigma_{eff} > 1.0$ mb at 95% confidence level
- Compatible with previous measurements and limits on σ_{eff}
- **First limit for double Drell-Yan DPS**
- **Predominantly $q\bar{q}$ initial state**

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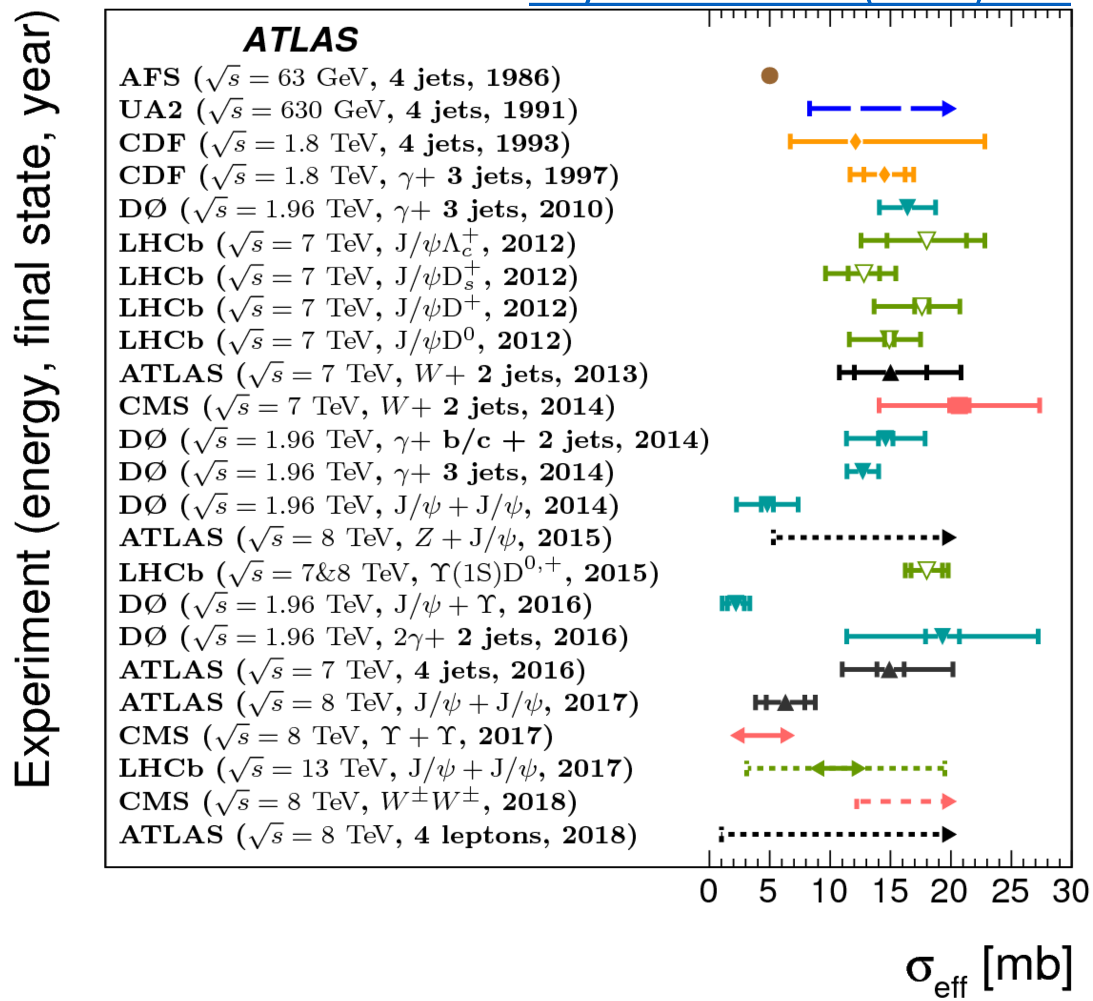

Summary

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- Inclusive 4-lepton data are analysed for presence of double-parton scattering
- First study of the double-parton scattering via double Drell-Yan mechanism
- Small experimental uncertainties (fully leptonic final state)
- No signal of DPS found using 8 TeV data set corresponding to 20.2 fb^{-1}
- Upper limit set on the fraction of events originated via double Drell-Yan DPS within the inclusive four-lepton sample: $f_{\mathrm{DPS}} < 0.042$ at 95% CL
- A corresponding lower limit on the effective cross section is extracted: $\sigma_{eff} > 1.0$ mb at 95% CL

Backup

Two Z bosons from pileup

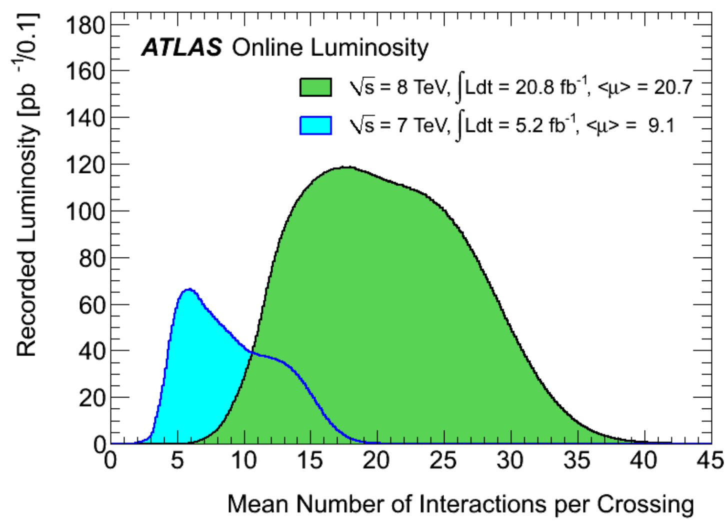
ATL-PHYS-PUB-2018-007

Study of multiple hard-scatter processes from different p p interactions in the same ATLAS event

- Number of hard pp interactions within the same bunch crossing:

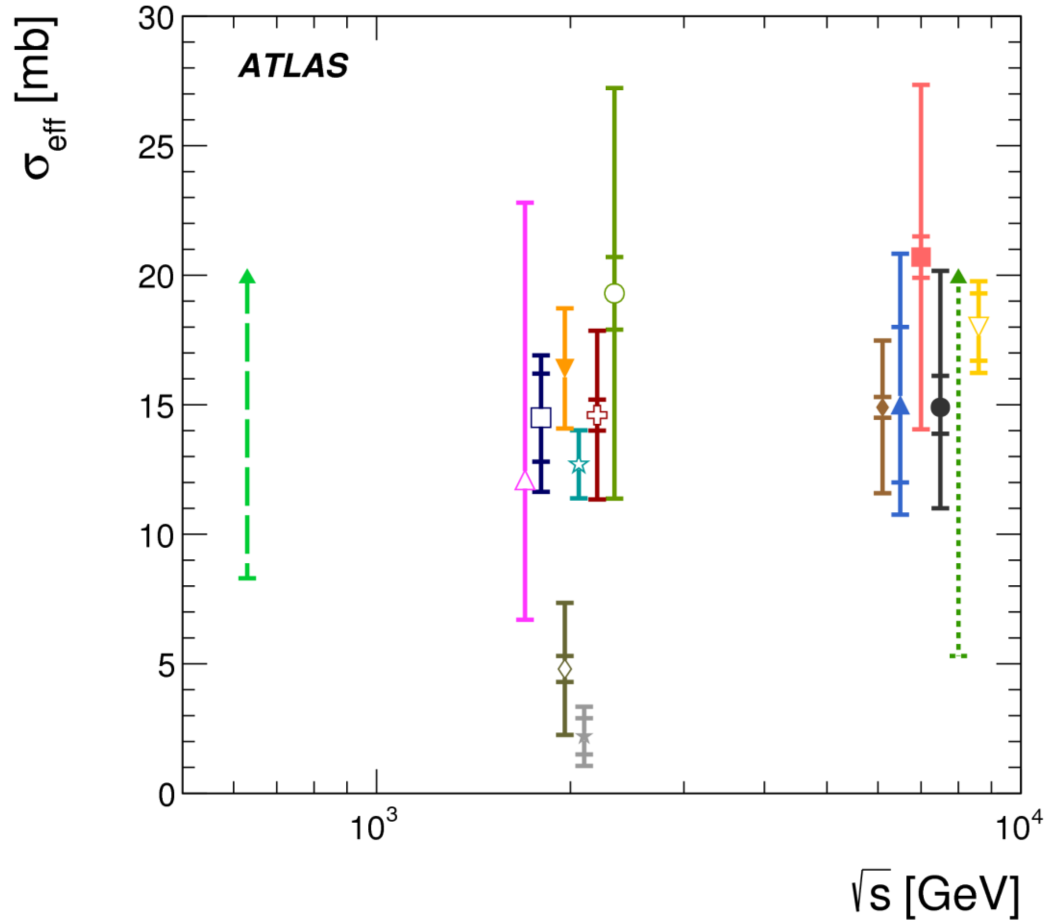
$$N_{AB} = L\sigma_A < \mu > \sigma_B/\sigma_{inelastic}$$

- For 2012 data taking conditions (average pileup of 21) evaluates to 16 double-Z events at 20fb-1, before any selection
  - ➢ Reduced by a factor of 2*10^3 if require that two Z vertices are the closest ones, and the distance between them is less than 1 cm
  - ➢ Reduced further by the 4-lepton event selection
- Pythia8 expectation is 0.4 events



Effective cross section as a function of centre-of-mass energy

JHEP11(2016)110



Effective cross section

- If assume factorisation for DPS (shown to be valid for double Drell-Yan interaction by M. Diehl et al in JHEP 01 (2016) 076) :

$$\frac{d\sigma(x_1, x_2, x_3, x_4)}{d\hat{t}_1\, d\hat{t}_2} = \frac{d\sigma^{13}}{d\hat{t}_1} \frac{d\sigma^{24}}{d\hat{t}_2} \times \int \frac{d^2\vec{\Delta}}{(2\pi)^2} D_a(x_1, x_2; \vec{\Delta})\, D_b(x_3, x_4; -\vec{\Delta})$$

  - $D(x_{1,} x_2; \vec{\Delta})$ is the generalized double parton density function
  - $\vec{\Delta}$ is a momentum parameter conjugate to transverse separation between two pairs of colliding partons

- Then $1/\sigma_{eff}$ is $\frac{1}{\pi R^2_{\text{int}}} = \int \frac{d^2\vec{\Delta}}{(2\pi)^2} \frac{D(x_1, x_2, \vec{\Delta}) D(x_3, x_4, -\vec{\Delta})}{D(x_1) D(x_2) D(x_3) D(x_4)}$

Why is the effective cross section smaller than the inelastic pp cross section?

- Simple geometric argument: the probability of DPS is higher for the full *pp* overlap
- If assume factorisation of $D(x_1, x_2; \vec{\Delta})$ against $x_1, x_2, \vec{\Delta}$ and uniform sphere parton distribution: $\sigma_{eff} \approx \sigma_{inel}/2.3$
  - If assume Gaussian parton distribution, will get an additional factor of 1/2