ATLAS measurements of Double Parton Scattering

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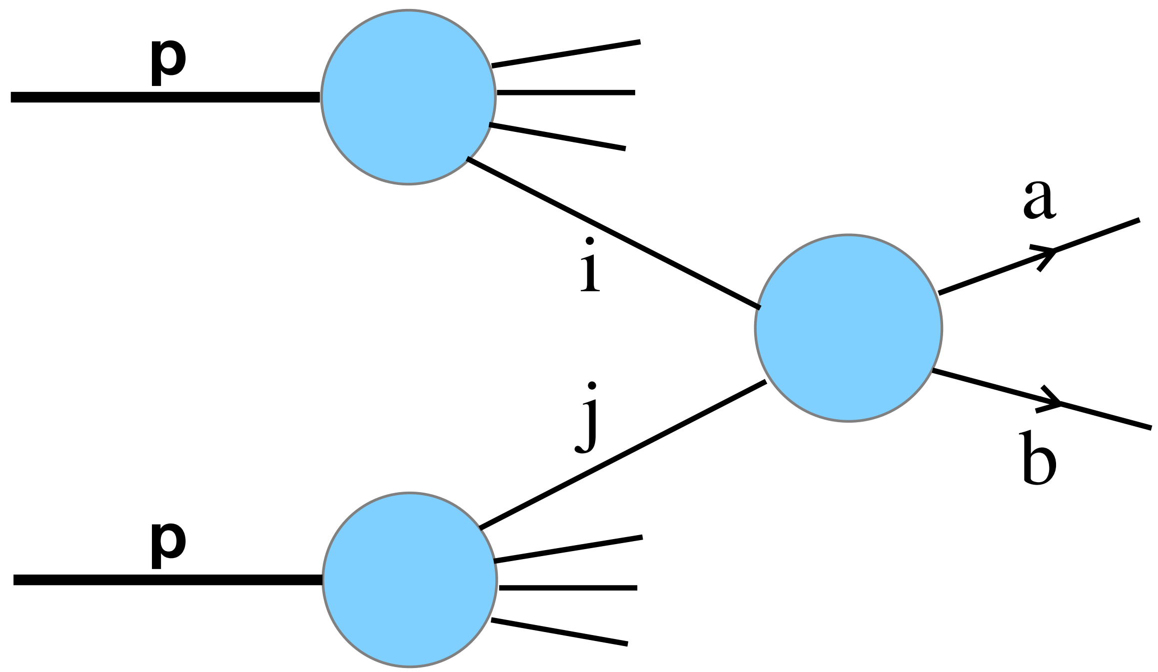
Overview

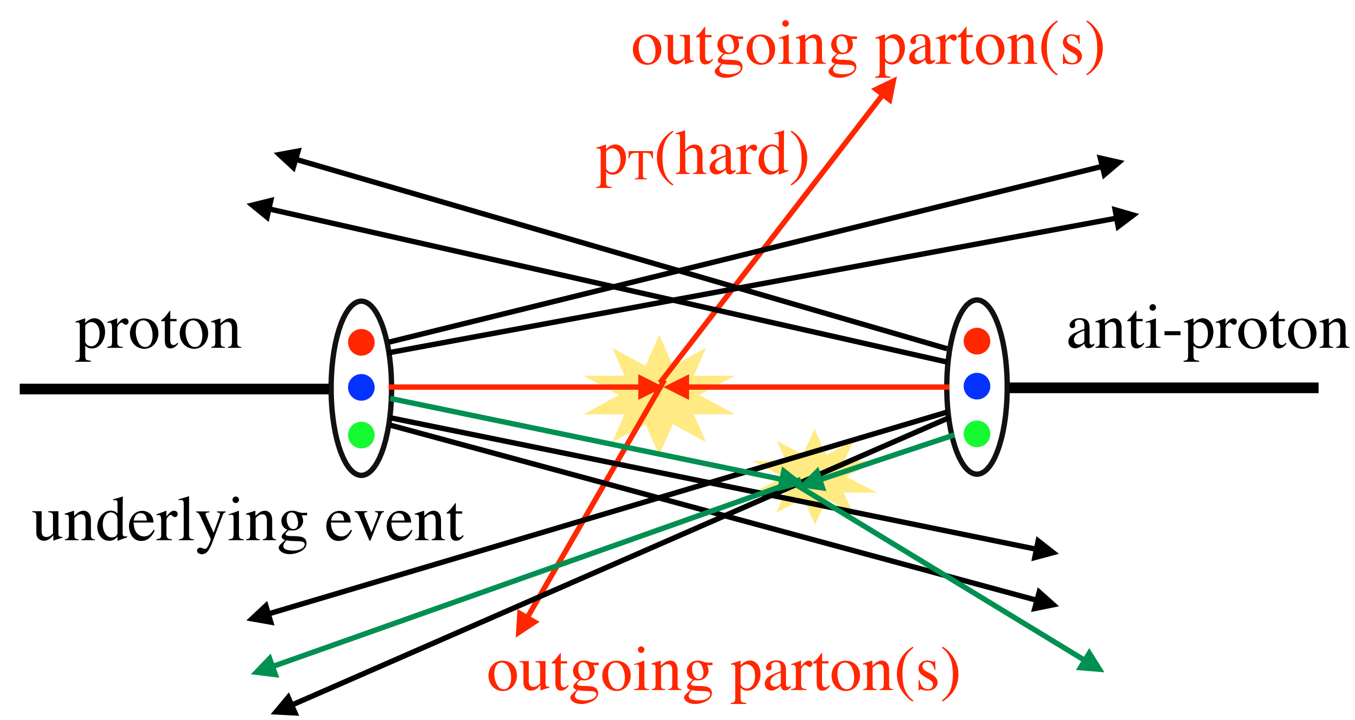
- Introduction of double parton scattering (DPS)
- Physics motivation of the DPS in ATLAS
- DPS of 4 leptons (Phys.Lett. B 790 (2019) 595)
- DPS of 4 jets (JHEP 11 (2016) 110)
- Conclusion

Introduction

pp collisions in theory



In reality



(Hard subprocess + underlying event)

Single Parton Scattering (SPS)

$$d\sigma^{SPS} = \sum_{i}^{j} \int f_P^i(x_1,\mu) f_P^j(x_1',\mu)\, d\hat{\sigma}_{ij\to ab}(x_1,x_1',\mu)\, dx_1 dx_1'$$

$f(x_i, \mu)$ = non perturbative PDF's

dσ = partonic cross section

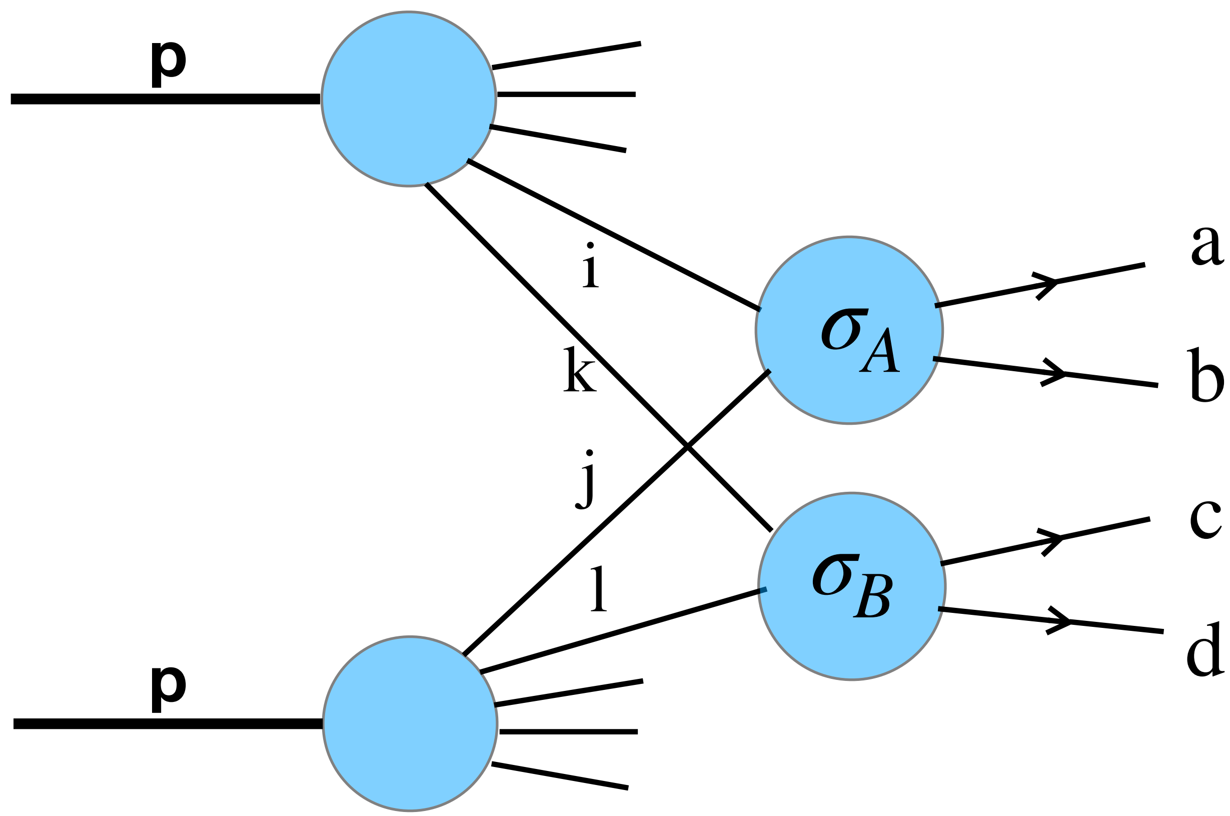
Underlying event:

- Beam remnants
- Multiple parton interaction
- Initial and final QCD radiation

At high LHC cme also hard double parton scattering is expected

Introduction

Hard Double Parton Scattering (two independent scatterings in one pp collision)



Cross section: $\sigma^{AB}_{DPS} = \frac{m}{2}\frac{\sigma^{A}_{SPS}\sigma^{B}_{SPS}}{\sigma_{eff}}$

$$m \begin{cases} = 1 & \text{if } A = B \\ = 2 & \text{if } A \neq B \end{cases}$$

If any correlation (kinematical and dynamical) between subscatterings is neglected, DPS cross section is expressed as product of two single SPS cross sections, modified by the two proton overlap function (space distribution of patrons in the proton). The latter depends on the impact parameter, implicitly integrated over in the formula (expressed by $\boldsymbol{\sigma}_{\text{eff}}$)

$$d\sigma^{DPS} = \frac{m}{2\sigma_{eff}} \sum_{i,j,k,l} \int H^{i,k}_p(x_1, x_2, \mu_A, \mu_B) H^{j,l}_p(x_1', x_2', \mu_A, \mu_B) \times d\hat{\sigma}^A_{i,j}(x_1, x_1', \mu_A) d\hat{\sigma}^B_{k,l}(x_2, x_2', \mu_B) dx_1 dx_2 dx_1' dx_2' \,.$$

Where, $H^{i,k}_p(x_1, x_2, \mu_A, \mu_B) = f^i_P(x_1, \mu_A) f^k_P(x_2, \mu_B)\,.$

Physics Motivation

- Size of the partonic core measured by σ_{eff}
- Spatial parton distributions in the proton
- Potential background to Higgs and new physics searches

<u>Why σ_{eff} :</u>

- σ_{DPS} depends on investigated phase space, so measurements are in terms of σ_{eff}

- Seems to be independent of hadronic centre of mass energy

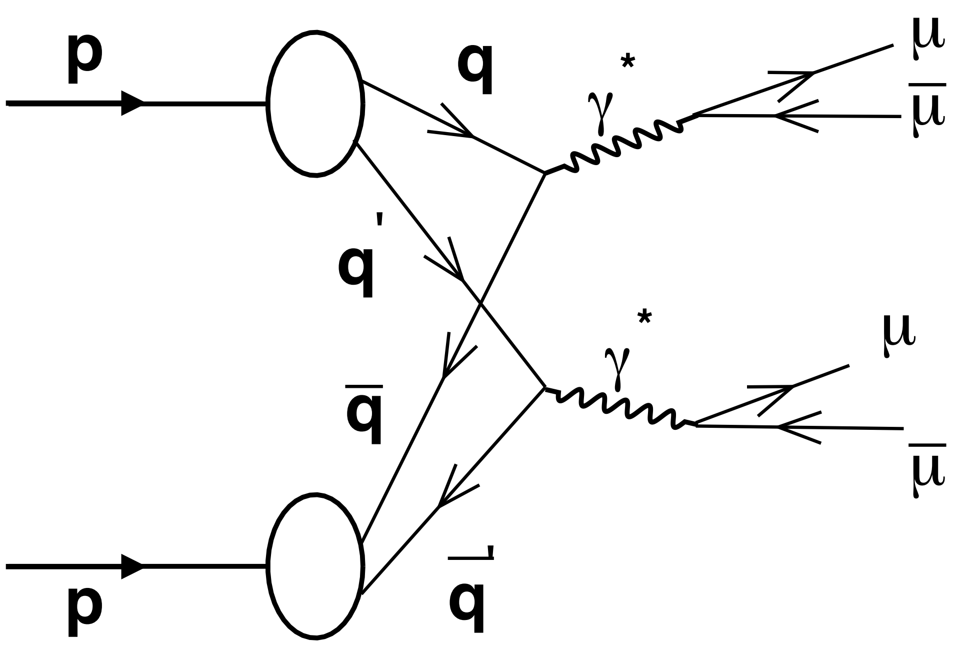
- Expected to be process independent

Four leptons study

Phys.Lett. B 790 (2019) 595

- Measure the hard DPS contribution to the inclusive 4-leptons event sample.
- Dominated by two $q\bar{q}$ initial states: possibility of parton density fluctuations —> large DPS
- m_{4l} distribution peaks around Higgs mass due to event selection requirements.

20.2 fb^{-1}, 8 TeV dataset



Pairing:

Leading pair: SFOC lepton pair with smallest $|m_z - m_{ll}|$

Sub leading pair: remaining SFOC with largest m_{ll}

For both pairs: $p_T^{l^+l^-} > 2$ GeV

Lepton selection:

$p_T > 6$ GeV, $|\eta| < 2.7$ (muons)

$p_T > 7$ GeV, $|\eta| < 2.5$ (electrons)

Event selection

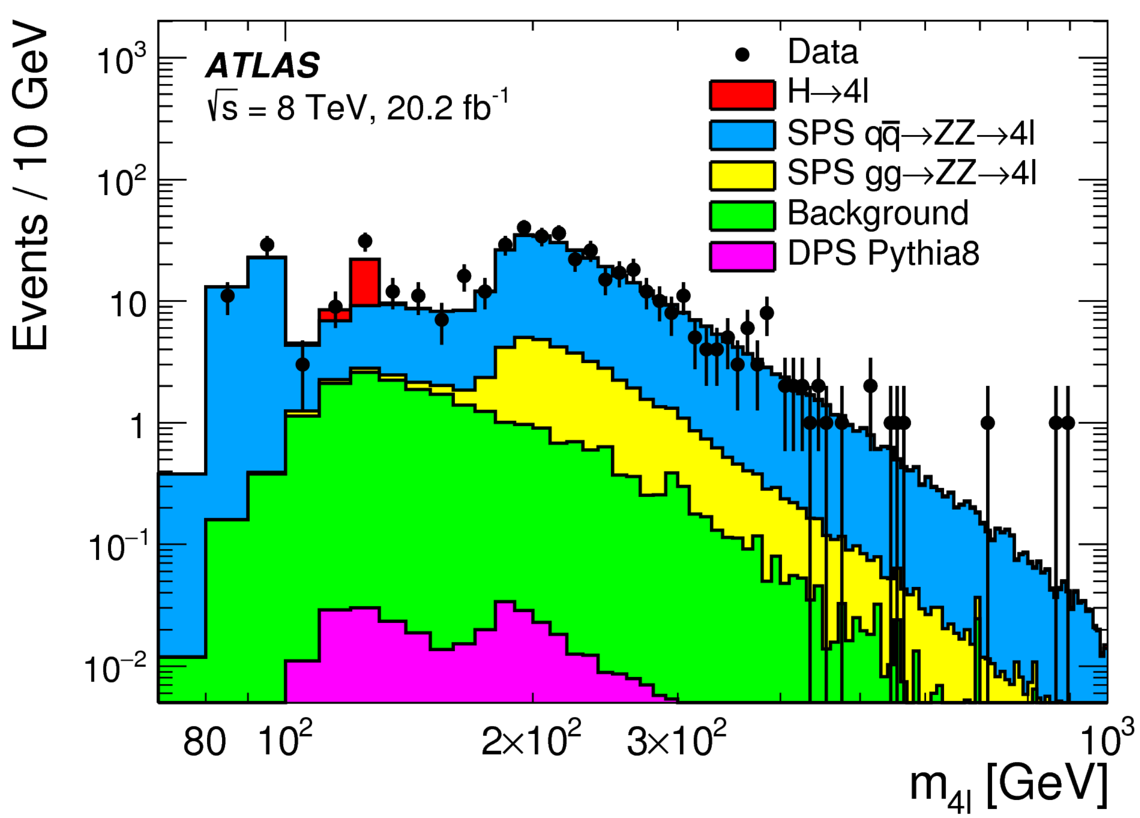
Lepton $p_T^{l_1,l_2,l_3}$: $> 20,15,10$ (8 if μ) GeV

Mass : $50 < m_{12} < 120$ GeV, $12 < m_{34} < 120$ GeV

Separation: $\Delta R(l_i, l_j) > 0.1(0.2)$ for same (different) flavour leptons

J/ψ **veto**: $m(l_i^+, l_j^-) > 5$ GeV

$4l$ **mass range**: $80 < m_{4l} < 1000$ GeV



Simulation

Monte Carlo modelling

Double parton scattering (DPS): Pythia8 double Drell-Yan
Single parton scattering (SPS): 1. $gg \to ZZ^{(*)}$ with MCMF
2. Higgs ggF with Powheg
3. $qq \to ZZ^{(*)}$ with Pythia8

For the continuum $gg \to ZZ$, NLO k-factors are applied.
This is in opposite to 4-leptons paper, where the scaling factor for gg → ZZ (describing the amount of missing higher-order corrections) is extracted from the m_{4l} fit. PLB 753 (2016) 552

Background: Simulated with various generators and includes

$$t\bar{t}, tZ, Z+b\bar{b}, Z+\gamma, WZ, VH, VVV$$

$Z+b\bar{b}$ and $t\bar{t}$ background components are scaled according to data driven studies by the 4-leptons paper.

Extraction of DPS

- ✶Neural network (NN) is considered to discriminate between SPS and DPS
- ✶Fit the NN output variable to determine DPS contribution, f_{DPS}

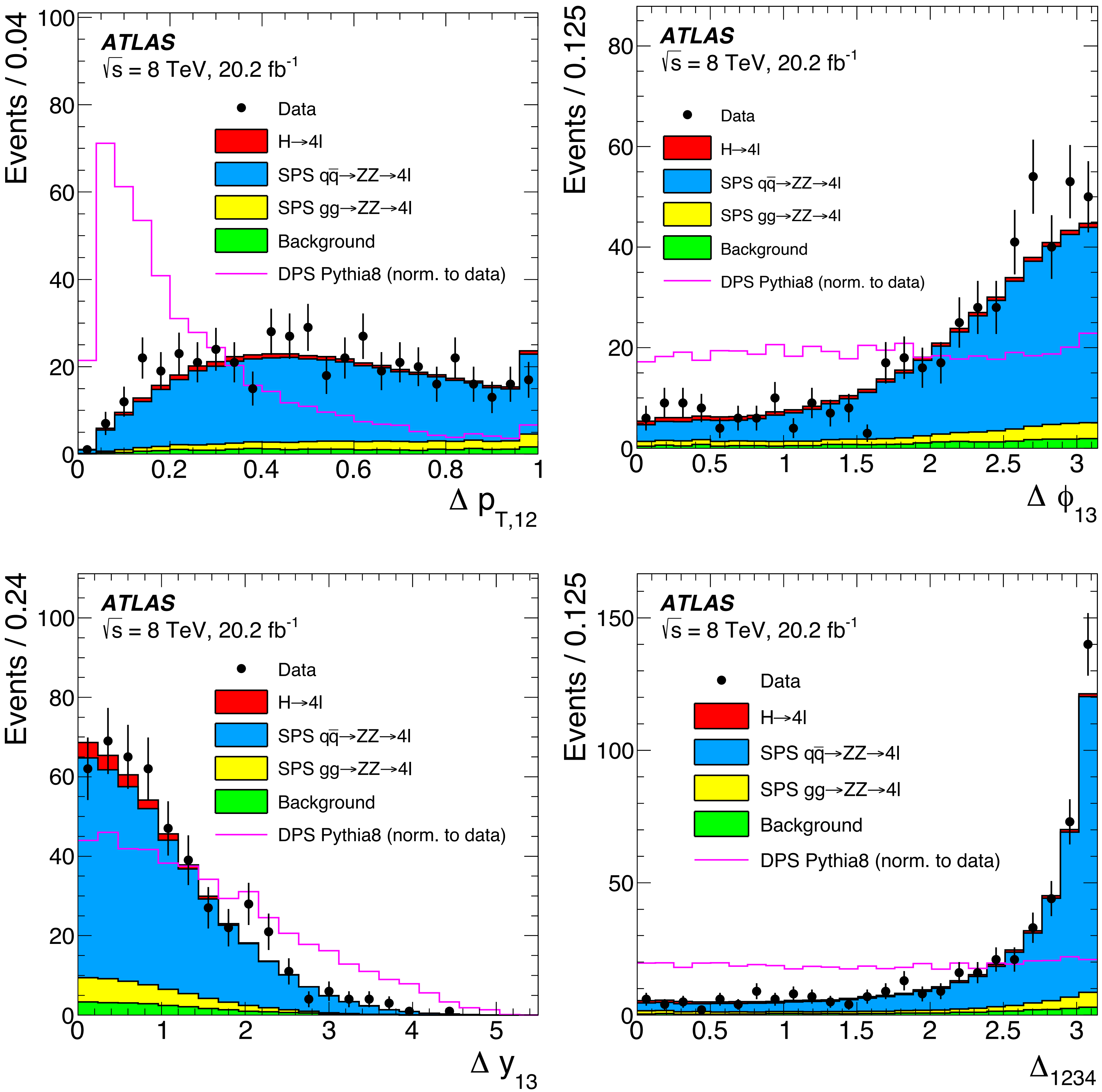
$$\sigma^{AB}_{DPS} = \frac{m}{2}\frac{\sigma^{A}_{SPS}\sigma^{B}_{SPS}}{\sigma_{eff}}, \qquad f_{DPS} = \frac{\sigma^{4l}_{DPS}}{\sigma^{4l}} \;\; => \;\; \sigma_{eff} = \frac{m}{2}\frac{\sigma^{2l,A}_{SPS}\sigma^{2l,B}_{SPS}}{f_{DPS}\sigma^{4l}}$$ (fully overlap of A & B)

$$\sigma^{AB}_{DPS} = \sum_{i,j}\frac{k_{ij}}{2}\frac{\sigma^{A,i}_{SPS}\sigma^{B,j}_{SPS}}{\sigma_{eff}}$$ (partial overlap of A & B)

i,j denotes p_T bins, dilepton mass bins and lepton flavours

$\sigma^{4l} = 32 \pm 1.6$ (stat) ± 0.7 (syst) ± 0.9 (lumi) fb PLB 753 (2016) 552

NN input variables



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

$$\Delta\phi_{ij} = |\phi_i - \phi_j|$$

$$\Delta y = |y_i - y_j|$$

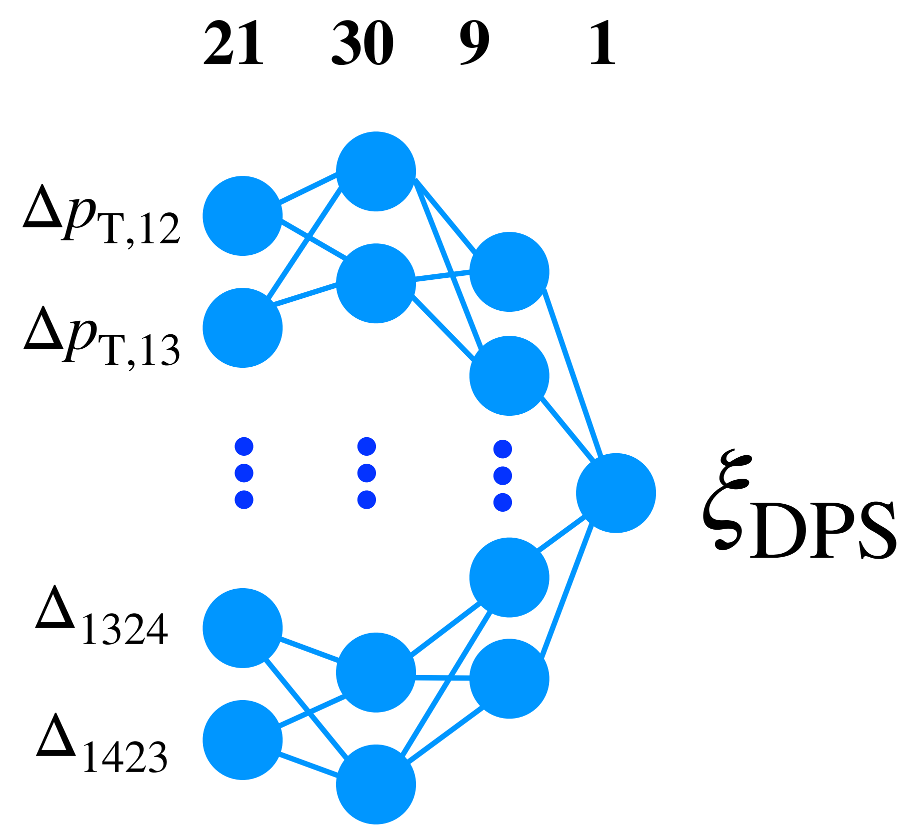
$$i,j = 1,2,3,4, \quad i \neq j$$

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

$$ijkm = 1234,\ 1324, 1423$$

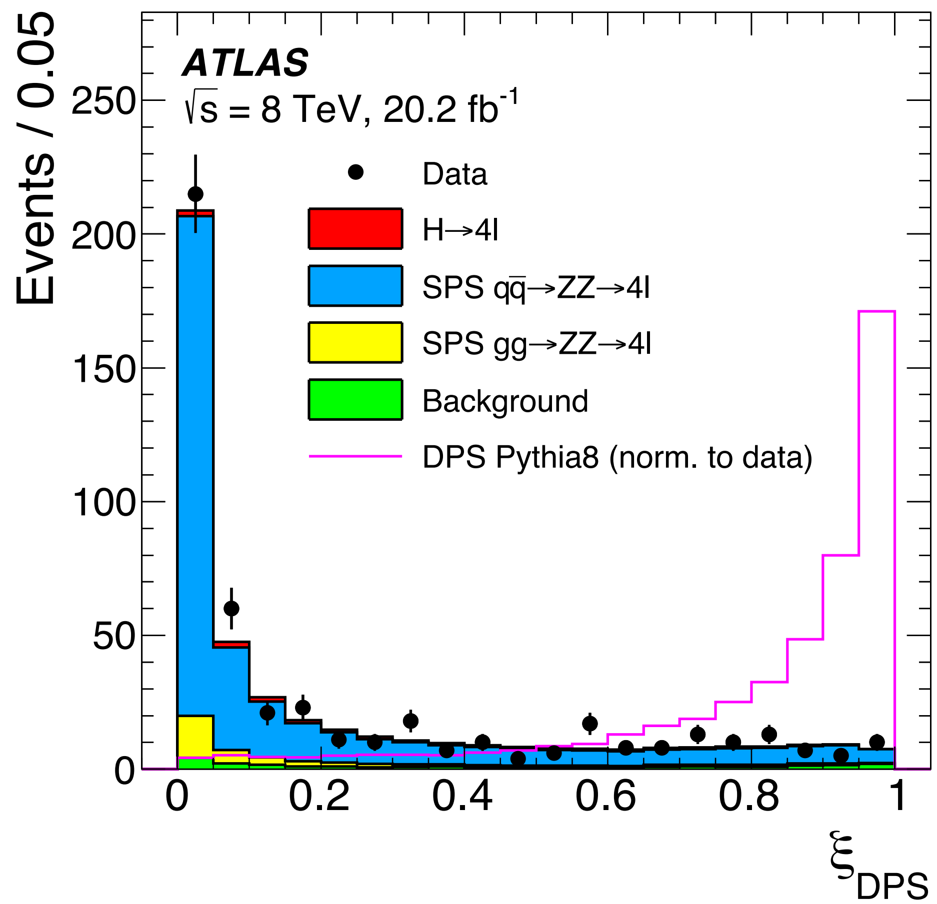
- 21 variables are considered
- All leptons are ordered in p_{T}
- Lepton 1 and 2 are leading dilepton
- Lepton 3 and 4 from sub-leading
- All combinations are taken

Neural network architecture



- TMVA is considered for NN analysis
- Two hidden layers are considered with 30:9 neurons
- For DPS: output $\xi_{DPS} = 1$
- SPS and background: $\xi_{DPS} = 0$
- TMVA::MLP classifier is used
- MC samples randomly divided into test and training
  - 100000 DPS events, 100000 non-DPS events
  - Event weights are applied

Fit results of NN output



- No hint of DPS events seen in the inclusive 4-leptons data sample

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

$$\chi^2 = \mathbf{8.6/9}$$

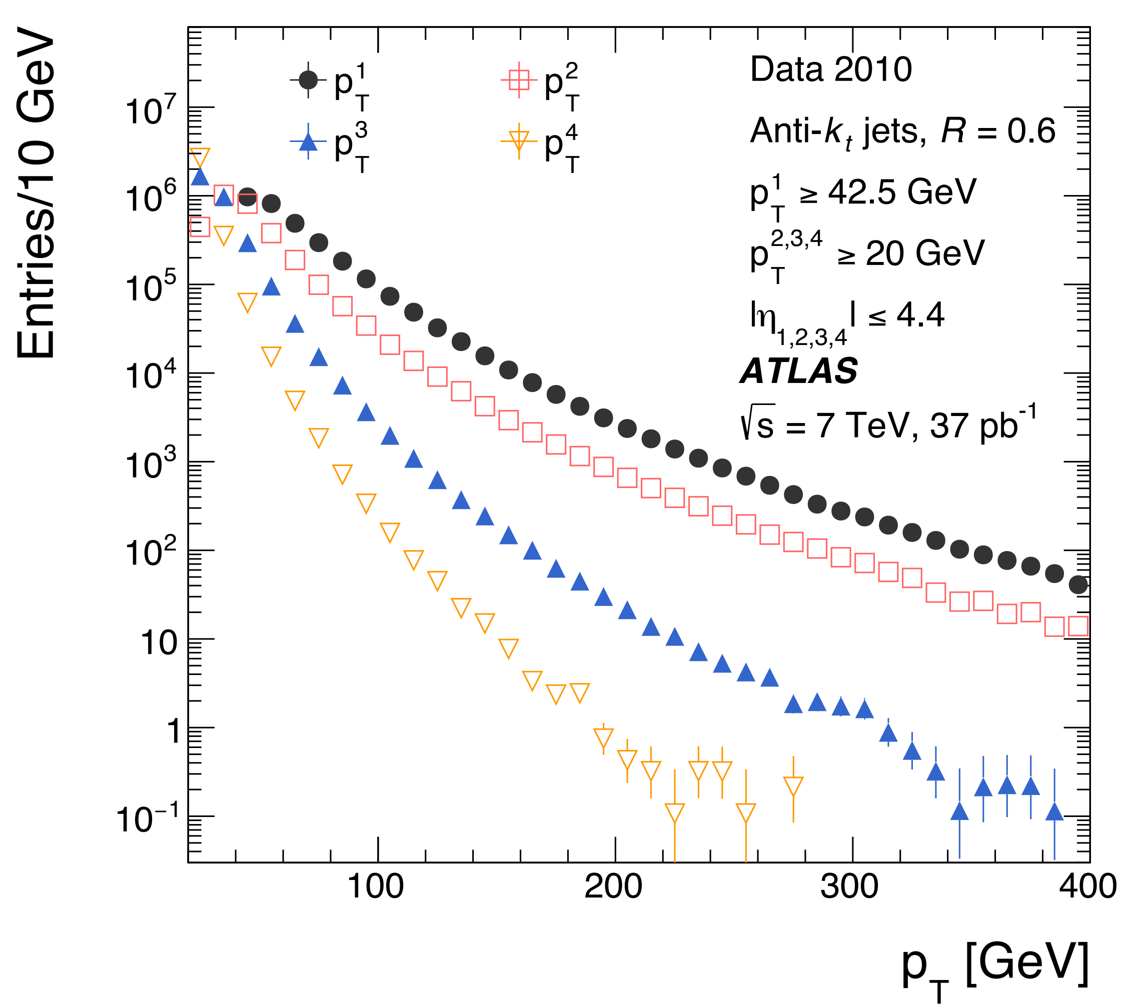
- After subtraction of background the fit yields, f_{DPS} = -0.009±0.017 (stat.)
- Translates into the upper limit $f_{\mathrm{DPS}} < 0.042$ at 95% CL
- Extract lower limit on $\sigma_{eff} > 1.0$ mb at 95% CL.

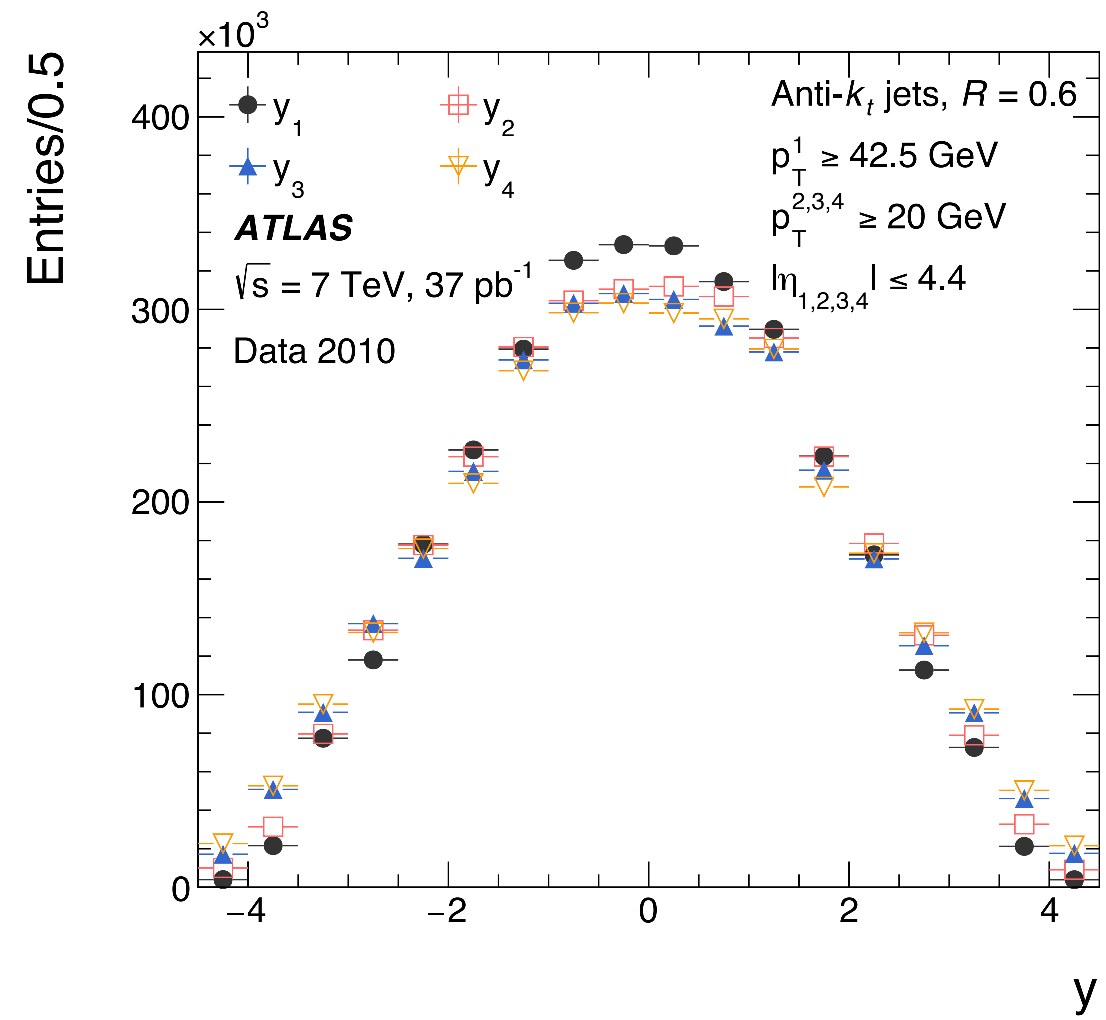
Four jets study

JHEP 11 (2016) 110

37.3 pb^{-1}, 7 TeV dataset and $\langle \mu \rangle = 0.4$

- Single vertex events
- Anti-kt jets with R = 0.6
- $p_T^1 > 42.5$ GeV, $p_T^{2,3,4} > 20$ GeV (due to trigger requirements), $|\eta| < 4.4$
    - p_T^1 threshold ensures fully efficient trigger
- Kinematic cuts for dijet samples to match four jet cuts: 1. $p_T^{1,2} > 20$ GeV
  2. $p_T^1 > 42.5$ GeV, $p_T^2 > 20$ GeV





Various event categories

- AHJ (Alpgen interfaced to Jimmy and Herwig) is considered for multi jet modelling and its event record is used to assign SPS and DPS
- Sherpa is considered for SPS events
- Two events from data (< 10 mm apart in vertices) overlaid for DPS

Matching of jets: Closest parton with $p_{\mathrm{T}}^{parton} > 15$ GeV and $\Delta R_{\mathrm{parton-jet}} < 1$

MC: Jets are matched to outgoing partons from primary and secondary interactions

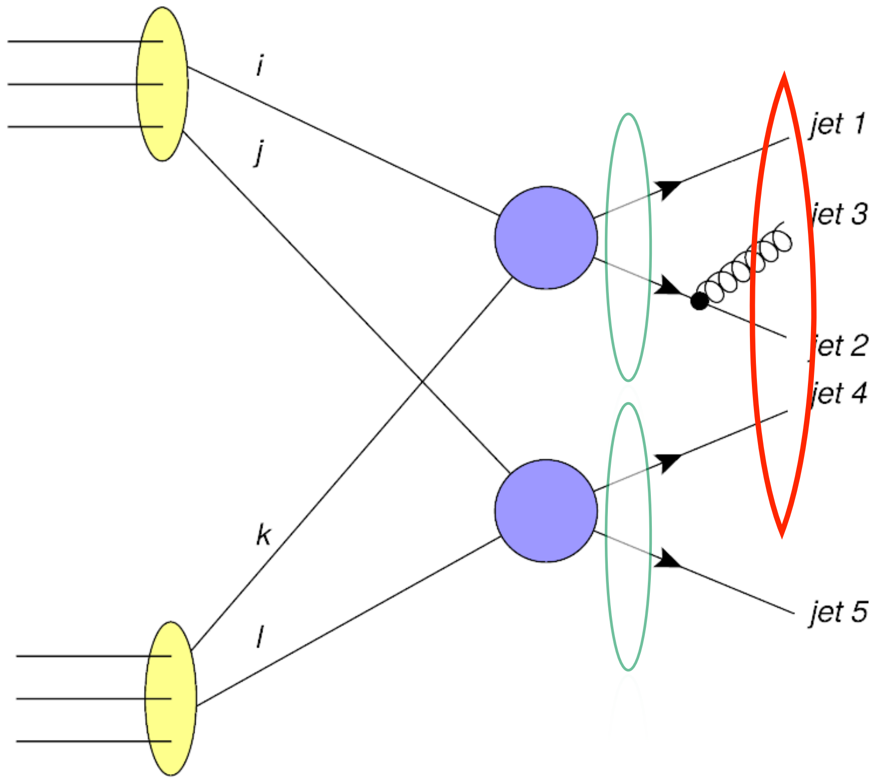
Data: Overlay requires non overlapping jets

✓ No jets matched to secondary scatter parton: SPS (AHJ, Sherpa for validation)

✓ 1 jet matched to secondary scatter parton: sDPS (overlaid data (3j+1j) and AHJ for validation)

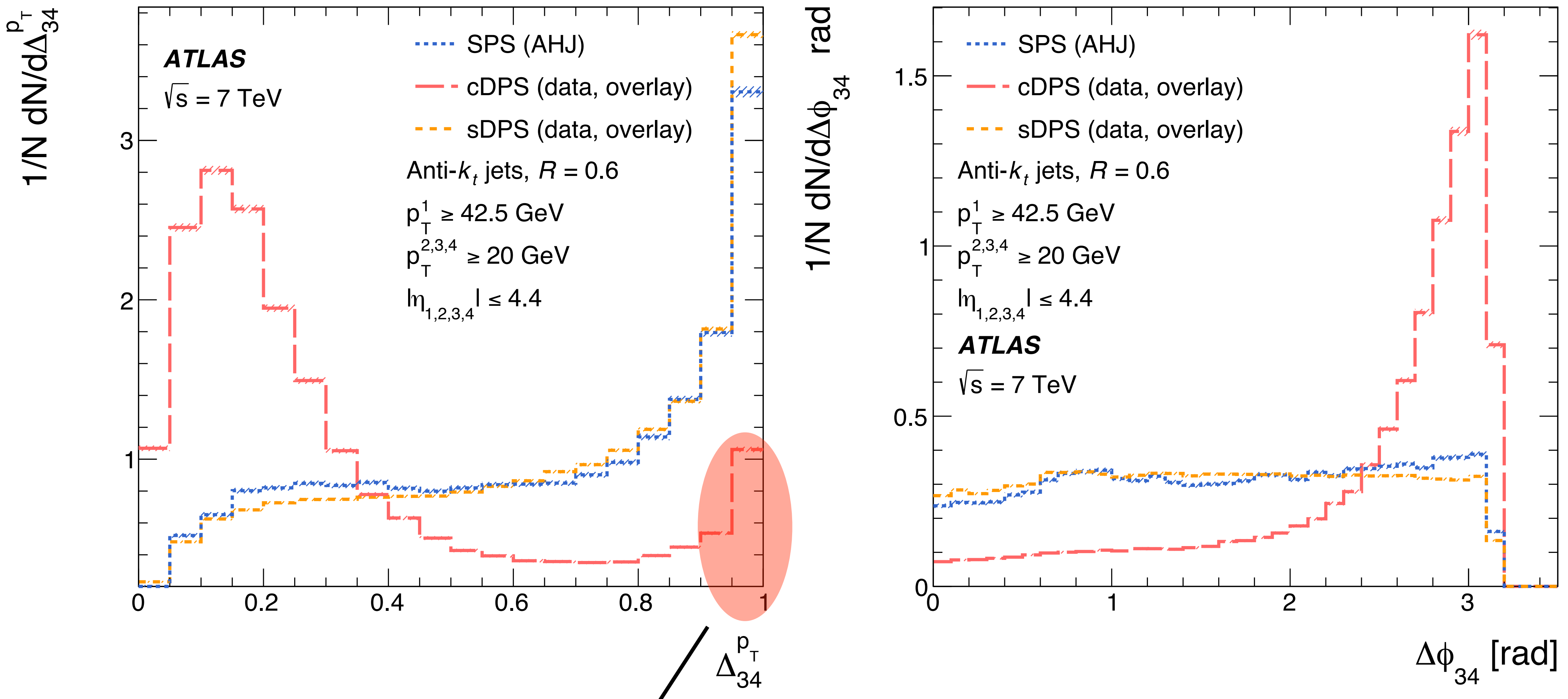
✓ 2 jets matched to secondary scatter parton: cDPS (overlaid data dijets and AHJ)

$$f_{\mathrm{DPS}} = f_{\mathrm{cDPS}} + f_{\mathrm{sDPS}}$$



Discriminating variables

- Jets are ordered in p_T



Peak at 1: pairing can be ambiguous

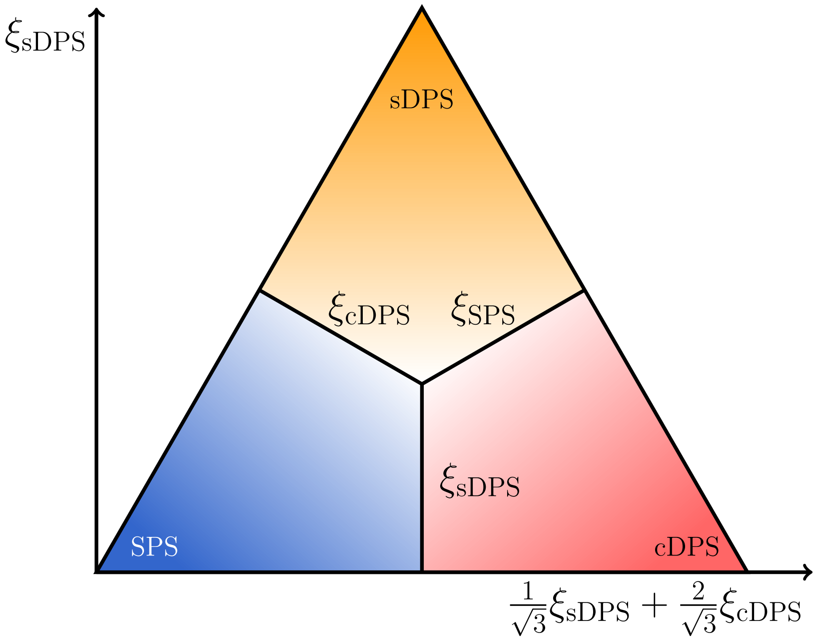
- Variables didn't provide clean separation between different event classes
- Strong correlation observed in variables
- 21 variables consisting of all possible dijet combinations are considered for training NN

NN output

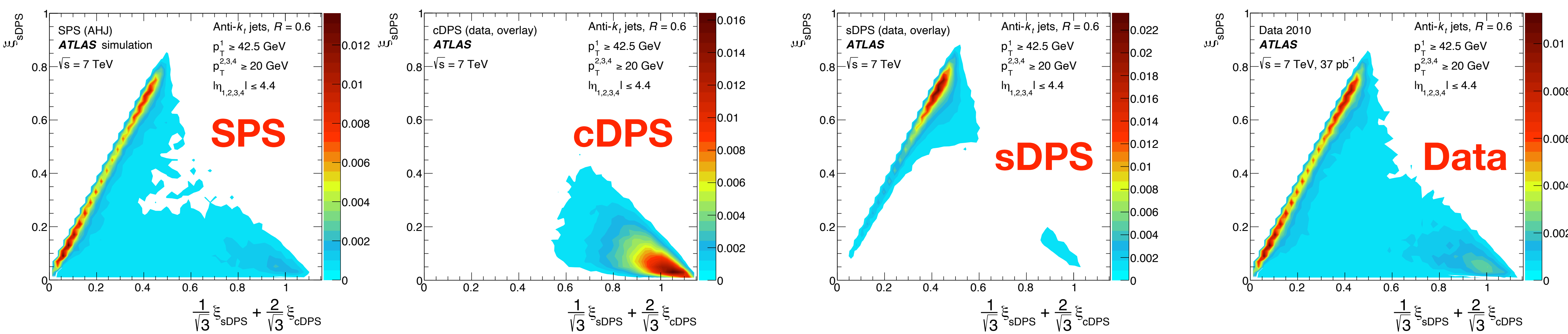
- 3 outputs in each event: ξ_{SPS}, ξ_{cDPS}, ξ_{sDPS} and

$$\sum \xi_i = 1$$

Can be represented inside equilateral triangle



2d Dalitz plot:



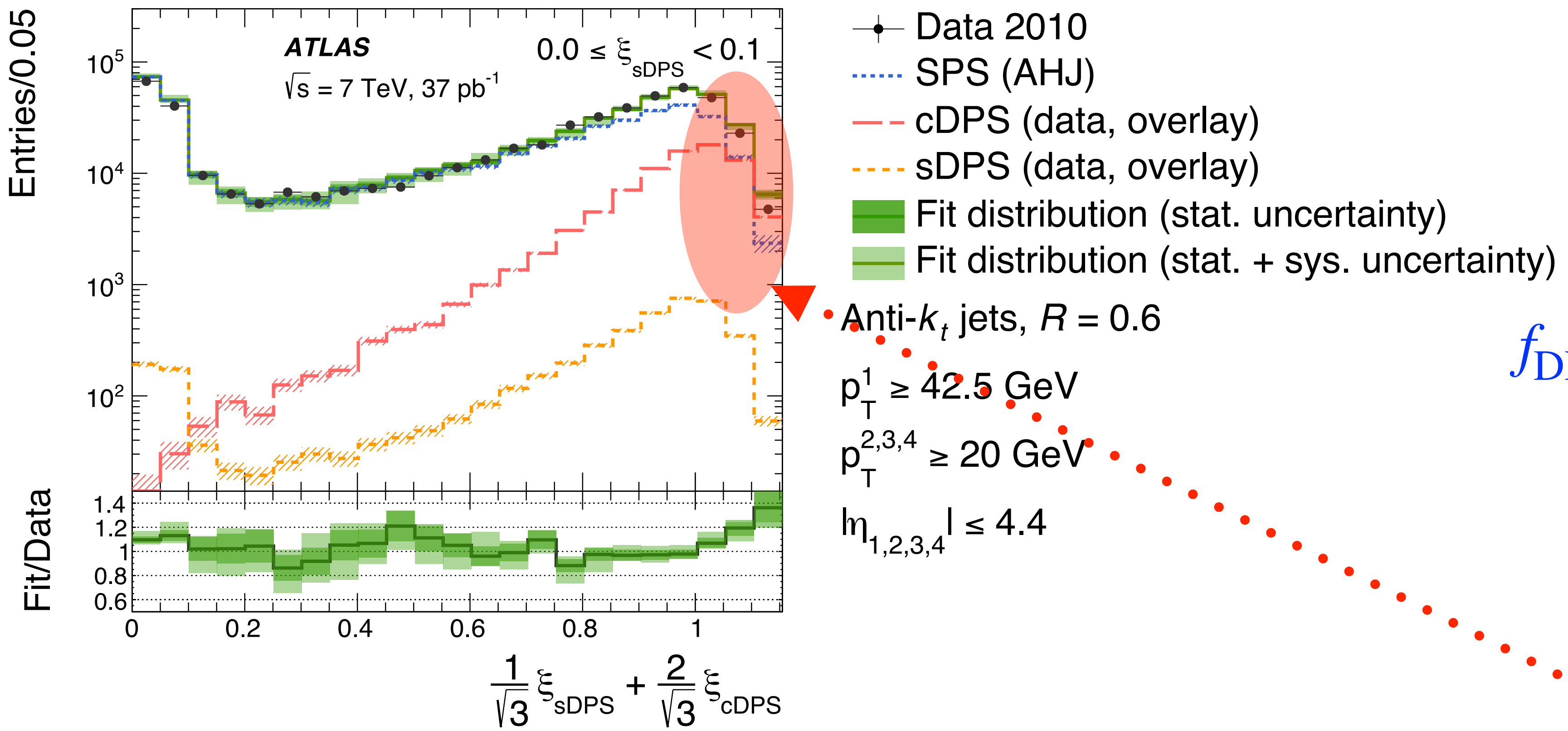
✓ Good separation between events categories

✓ SPS and sDPS separation is difficult

✓ Fit sum of MC profile to data:

$$D = (1 - f_{cDPS} - f_{sDPS})M_{SPS} + f_{cDPS}M_{cDPS} + f_{sDPS}M_{sDPS}$$

Results: f_{DPS}

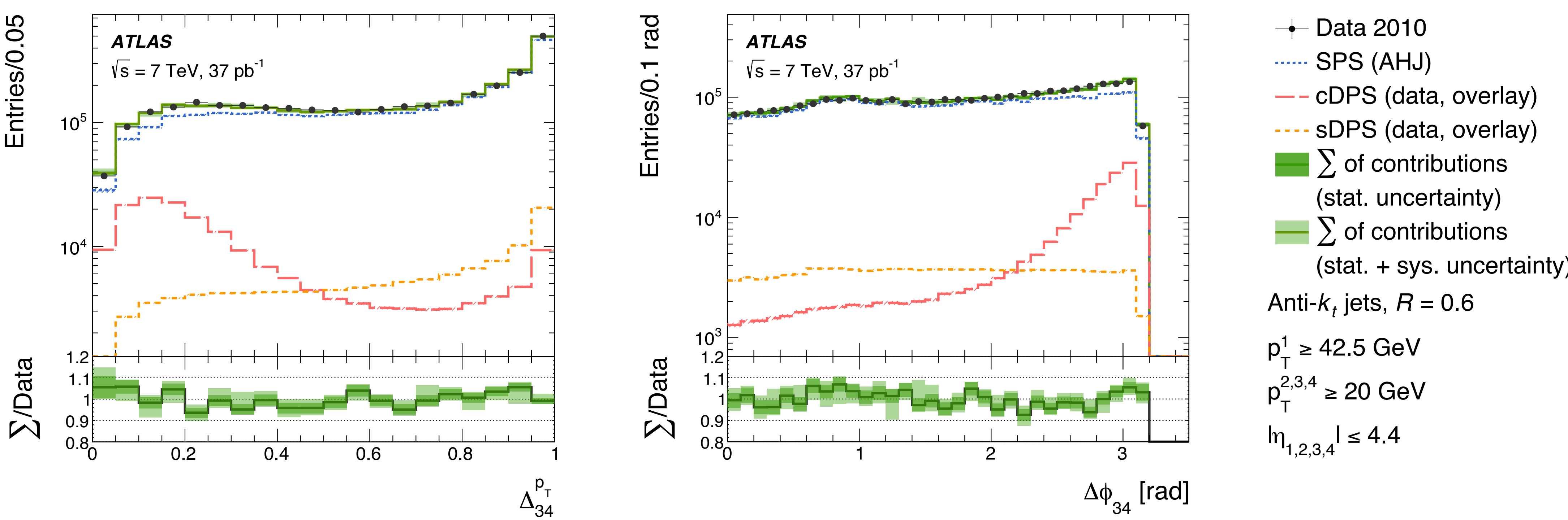


2D fit is performed to extract f_{cDPS} and f_{sDPS}

$$f_{DPS} = 0.092^{+0.005}_{-0.011}(\text{stat.})^{+0.033}_{-0.037}(\text{syst.})$$

Significant disagreement in SPS dominated bins —> negligible effect on DPS

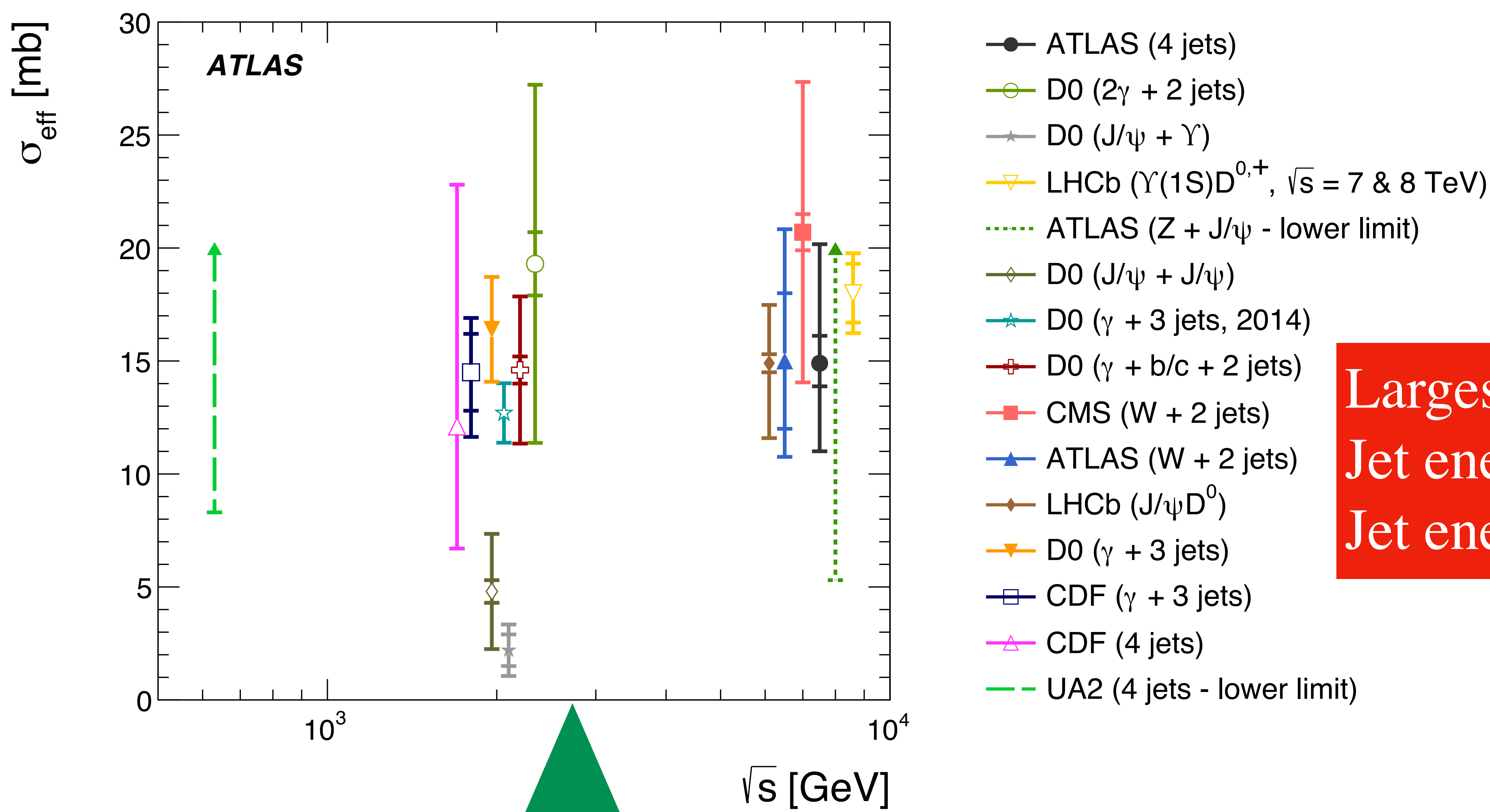
30% contributions from cDPS



Good description of data by the sum of distributions

$$\sigma_{eff} = 14.9^{+1.2}_{-1.0}(\text{stat.})^{+5.1}_{-3.8}(\text{syst.})\text{mb}$$

Results: σ_{eff} vs $\sqrt{s}$



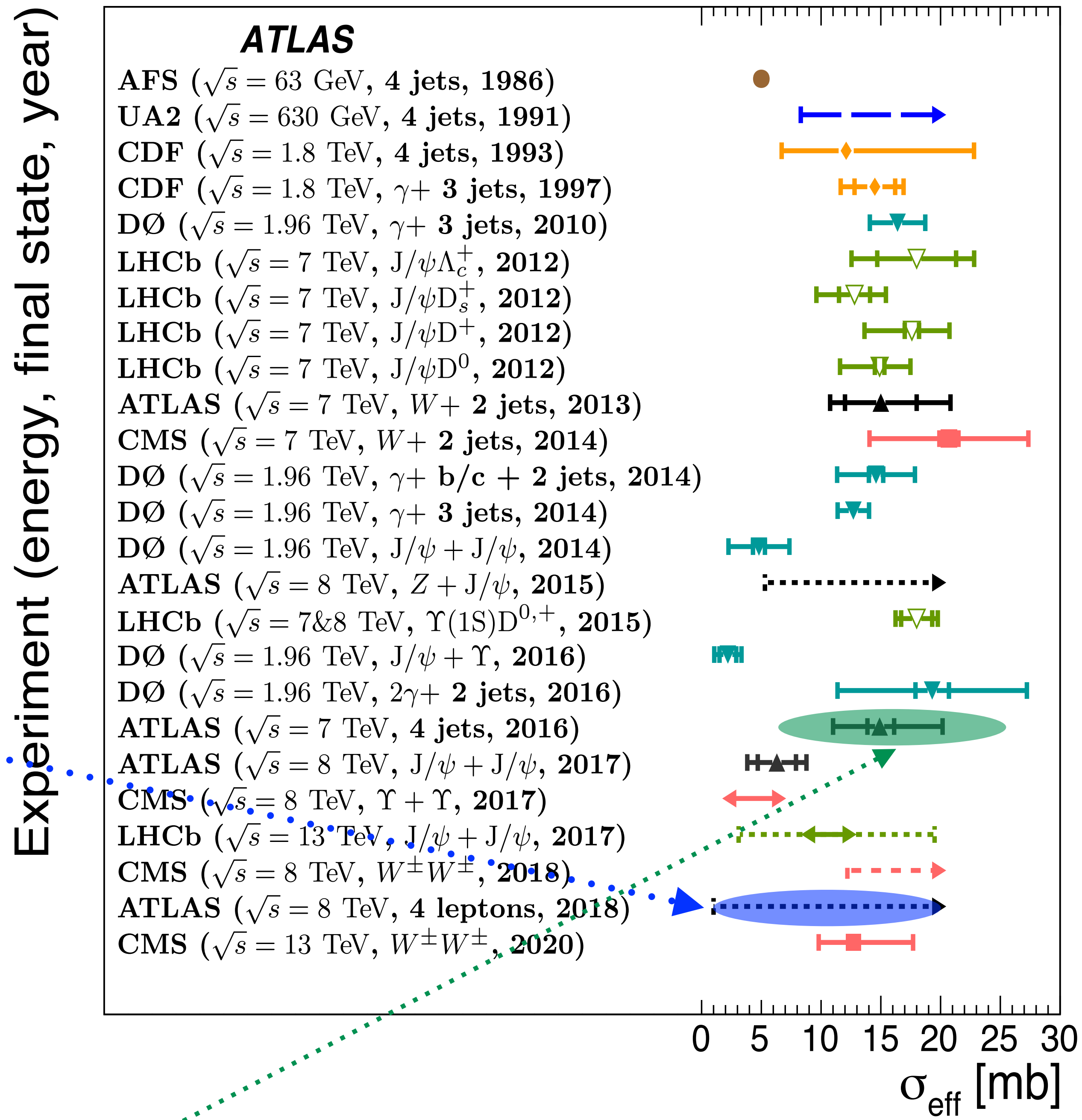
No indication of energy dependence

Largest source of uncertainty:
Jet energy resolution (±15 %)
Jet energy scale ($^{+31}_{-19}$ %)

Conclusion

Updated

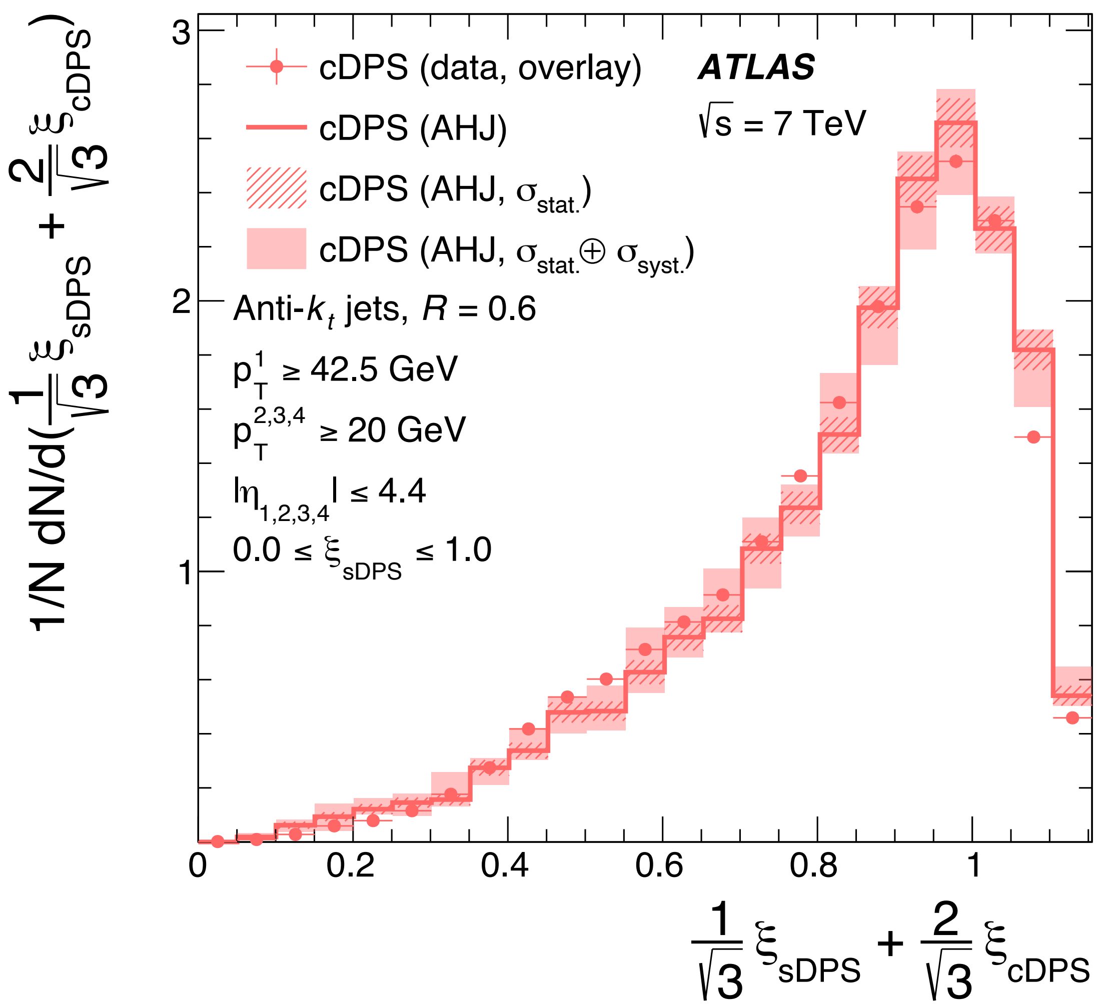
- **Inclusive 4-lepton data are analysed for presence of double-parton scattering**
- **Upper limit set on the fraction of events originated via double Drell-Yan DPS within the inclusive four-lepton sample**
  $f_{\mathrm{DPS}} < 0.042$ **at 95% CL**
- **Lower limit extracted:**
  $\sigma_{eff} > 1.0$ **mb at 95% CL**
- **Hard double parton scattering in four-jets extracted using NN.**
- **Fraction of DPS events in four-jets:**
  $f_{\mathrm{DPS}} = 0.092^{+0.005}_{-0.011}(\mathrm{stat.})^{+0.033}_{-0.037}(\mathrm{syst.})$
- **Combination of f_{DPS} with dijet and four-jet cross section yields**
  $\sigma_{eff} = 14.9^{+1.2}_{-1.0}(\mathrm{stat.})^{+5.1}_{-3.8}(\mathrm{syst.})\mathrm{mb}$

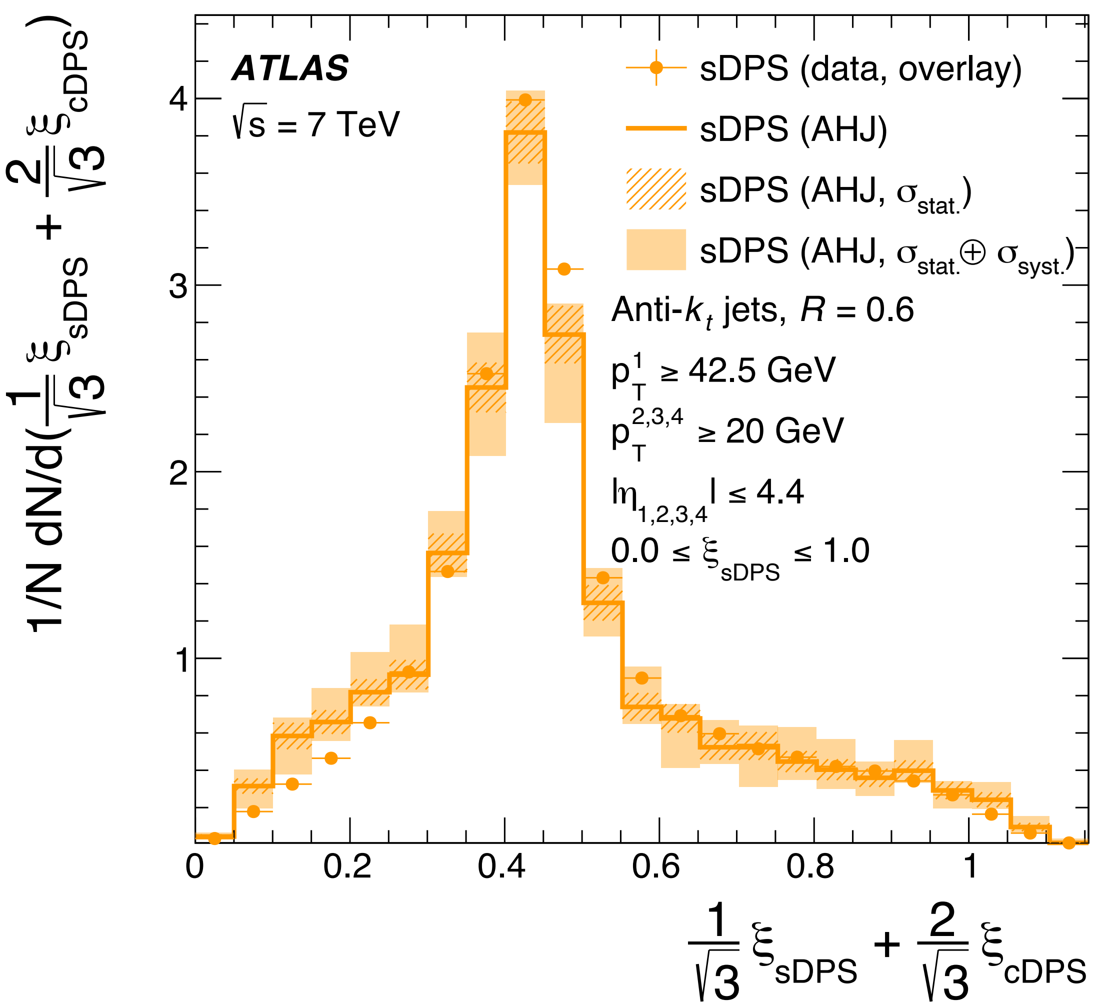


Back-up

Methodology validation (4-jets)

- Dijets events in data are overlaid and compared to DPS modelling by AHJ
- Good agreement is observed



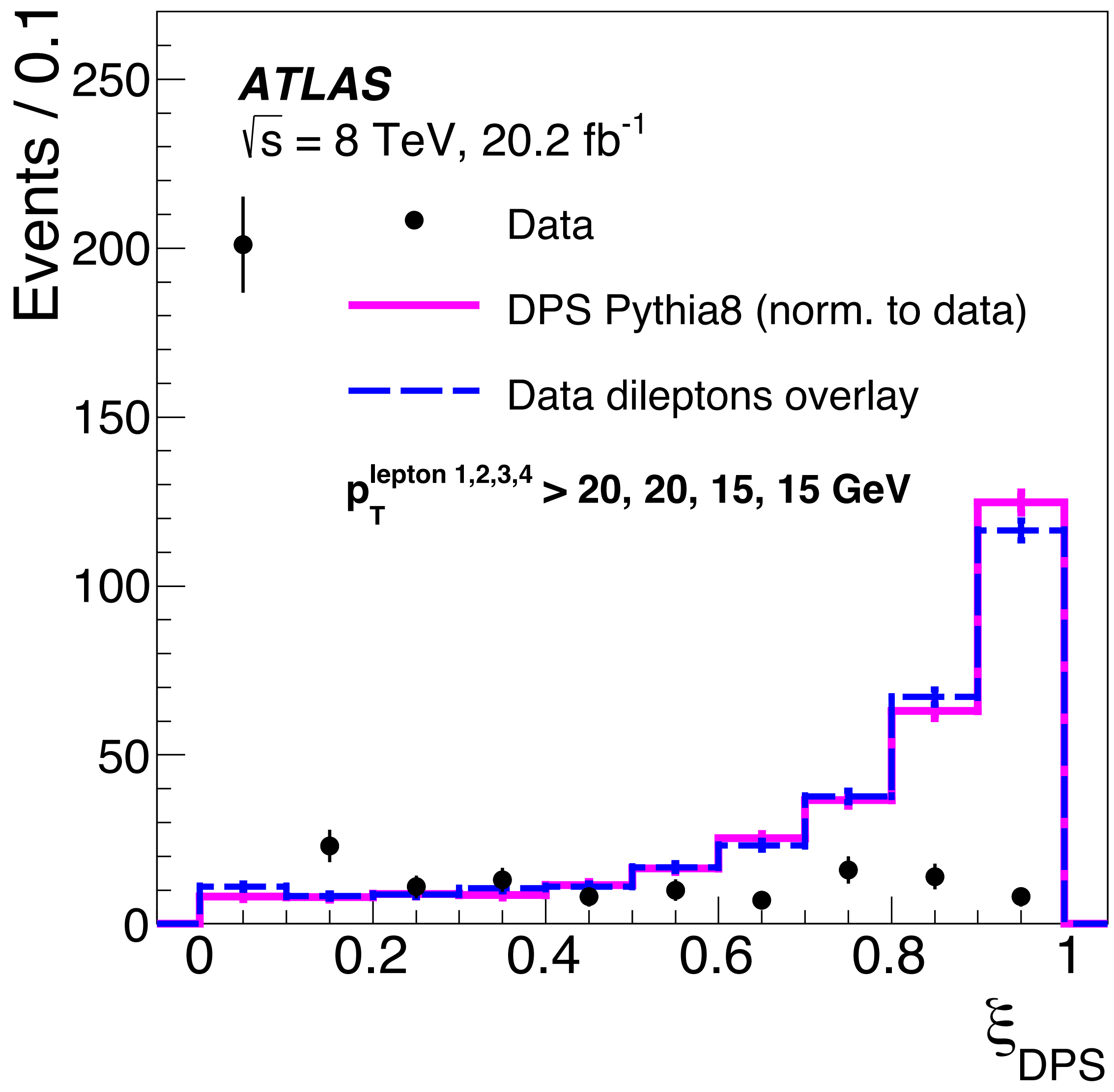


- **Advantage of overlaid dijets events in data: same jet energy scale as four-jets events in data**

⇓

Smaller systematic uncertainty in the final result

Methodology validation (4-leptons)



- NN training is applied to overlaid data dilepton events
- Comparison made in a restricted phase space due to trigger requirements
- Pythia8 DPS is consistent with the idea of two independent subscatterings