Hard double parton scattering in four-jet events with the ATLAS detector

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QCD – Old Challenges and New Opportunities

WE-Heraeus Physics school

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Bad Honnef, Germany, 24-30 September 2017

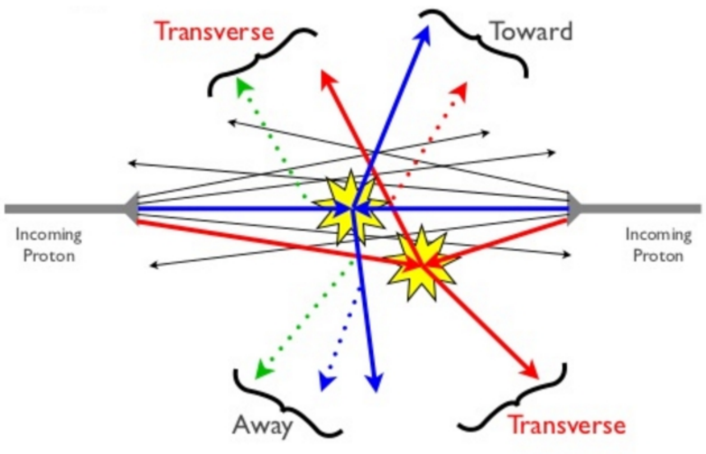
Outline

- Introduction
- Data Sample
- Events classification
- Discriminating variables
- Signal extraction
- Fraction of DPS events in 4-jet sample
- Effective proton cross section
- Unfolded distributions

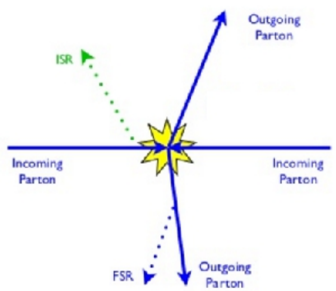
See also other talks at this school:

- Talk by Krzysztof Golec-Biernat on double parton density functions with kinematic correlation taken into account
- Talk by Antoni Szczurek (today) on DPS exploration
- Review talks by Christina Mesropian and Deniz Sunar Cerci including DPS measurements at Tevatron and CMS
- Mentioned by Frank Krauss in the “QCD at the energy frontier”

Introduction: Underlying Event

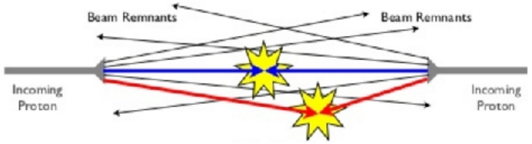


pp collision =



hard scattering

+



proton remnants

+

MPI + soft gluon emissions

Underlying Event (UE)

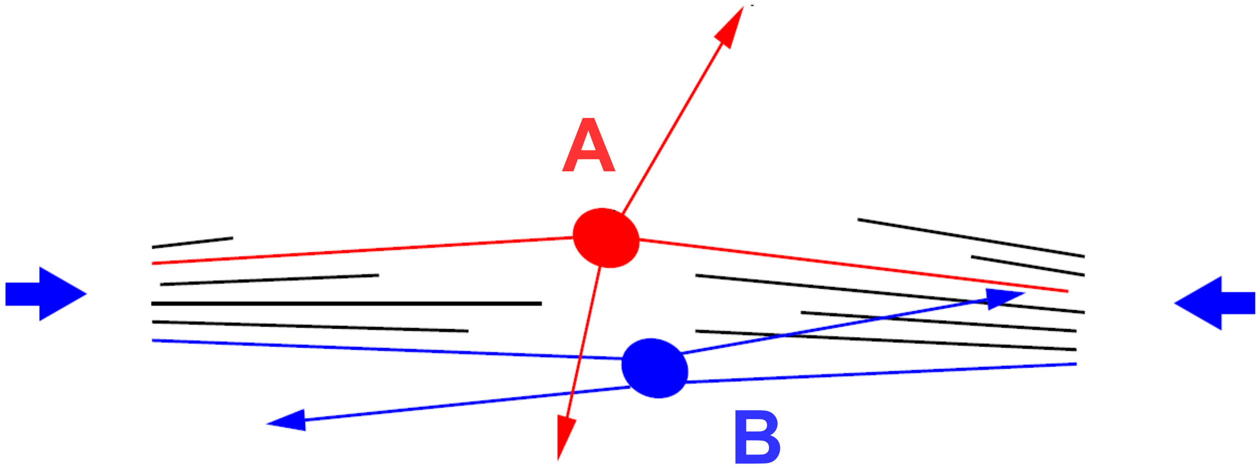
- **Figure: sketch of a typical hard proton-proton collision (hard subprocess + underlying evnet)**
- **Underlying Event refers to:**
  - Beam remnants
  - Multiple Parton Interactions (MPI)
  - Initial and Final State QCD Radiation

- It is not possible to derive properties of UE from first principles

  → Described by phenomenological Monte Carlo (MC) models including various tunes to experimental data

  → If the scale of the secondary interaction is hard, the interaction is called hard double parton scattering

Hard Double Parton Scattering (DPS)



- Two hard parton interactions occur in the same hadron-hadron collision

→ **Pocket formula:**

$$\sigma^{AB}_{DPS} = \frac{m}{2} \frac{\sigma^{A}_{SPS} \sigma^{B}_{SPS}}{\sigma_{eff}} \quad \Rightarrow$$

$$\sigma_{eff} = \frac{m}{2} \frac{\sigma^{A}_{SPS} \sigma^{B}_{SPS}}{\sigma^{AB}_{DPS}} = \frac{m}{2} \frac{\sigma^{A}_{SPS} \sigma^{B}_{SPS}}{f_{DPS} \sigma^{AB}_{tot}}$$

(symmetry factor m = 1 if A = B, m = 2 if A ∩ B = ∅)

- $\sigma^{A(B)}_{SPS}$ is the **inclusive** cross section of **single** hard scattering A (B)
- σ_{eff} is a **parameter related to the proton size:**
  - ➢ Often assumed to be process and cut independent (relies on several assumptions)
  - ➢ No dependence on $\sqrt{s}$ observed
  - ➢ Measured to be 20-30% of σ_{inel}

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) :

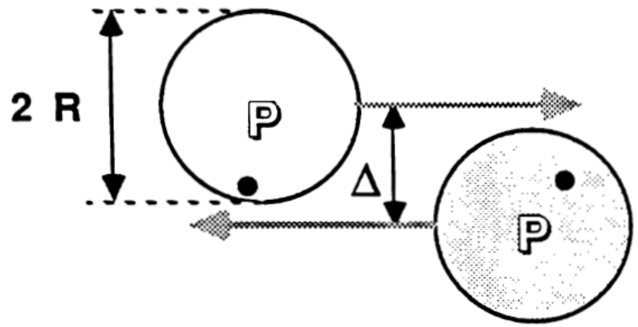
$$\frac{d\sigma(x_1,x_2,x_3,x_4)}{d\hat{t}_1\, d\hat{t}_2} = \frac{d\sigma^{13}}{d\hat{t}_1}\,\frac{d\sigma^{24}}{d\hat{t}_2} \times \int \frac{d^2\vec{\Delta}}{(2\pi)^2}\, D_a(x_1,x_2;\vec{\Delta})\, D_b(x_3,x_4;-\vec{\Delta})$$

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

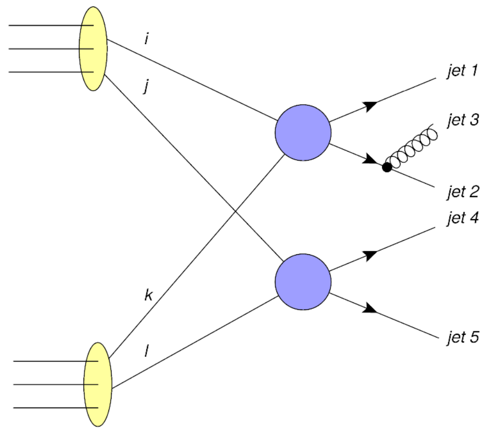
- Then $1/\sigma_{eff}$ is $\frac{1}{\pi R^2_{\text{int}}} = \int \frac{d^2\vec{\Delta}}{(2\pi)^2} \frac{D(x_1,x_2,\vec{\Delta})D(x_3,x_4,-\vec{\Delta})}{D(x_1)D(x_2)D(x_3)D(x_4)}$

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



Data Sample



- 7 TeV 2010 Data, L = 37.3 pb^{-1}, <μ> = 0.4
- Single-vertex events

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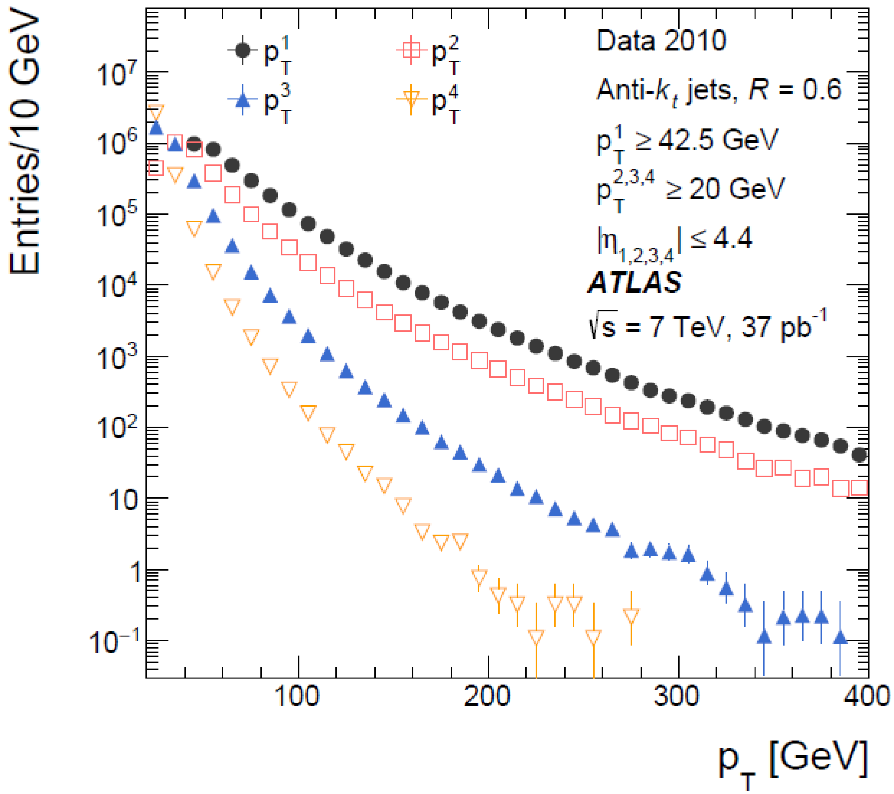
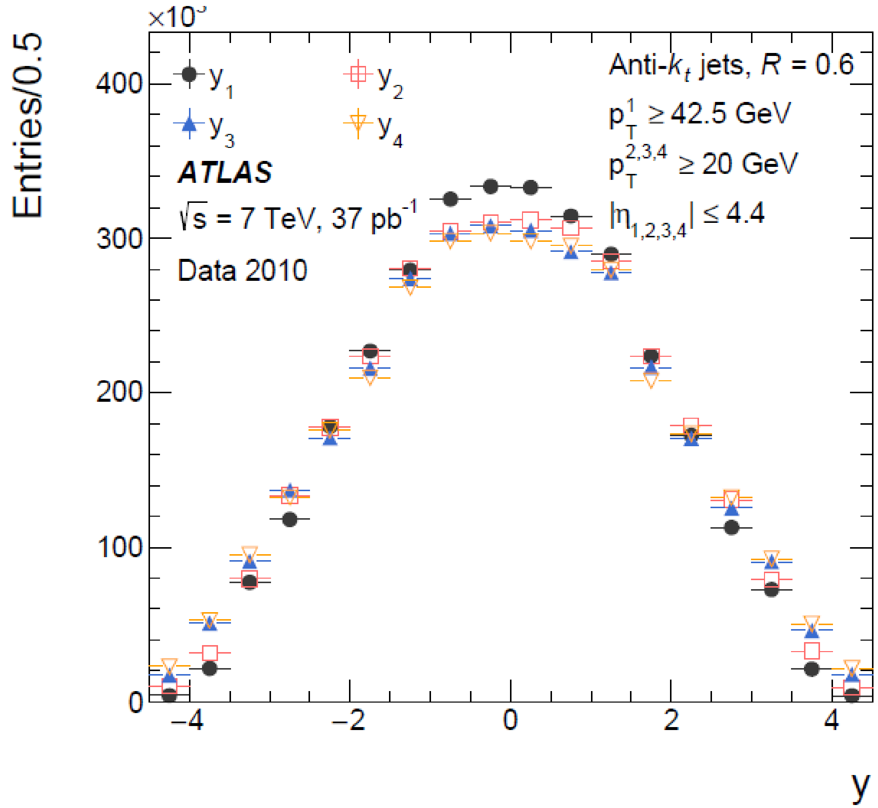
- Anti-kt jets with R = 0.6 reconstructed from clusters of calorimeter cells
- Four-jet events: p_T^1 > 42.5 GeV, $p_T^{2,3,4}$ > 20 GeV, $|\eta|$ < 4.4
  - ➢ p_T^1 threshold ensures fully efficient trigger
- Two dijet samples to match four-jet cuts: 1) $p_T^{1,2}$ > 20 GeV, 2) p_T^1 > 42.5 GeV, p_T^2 > 20 GeV



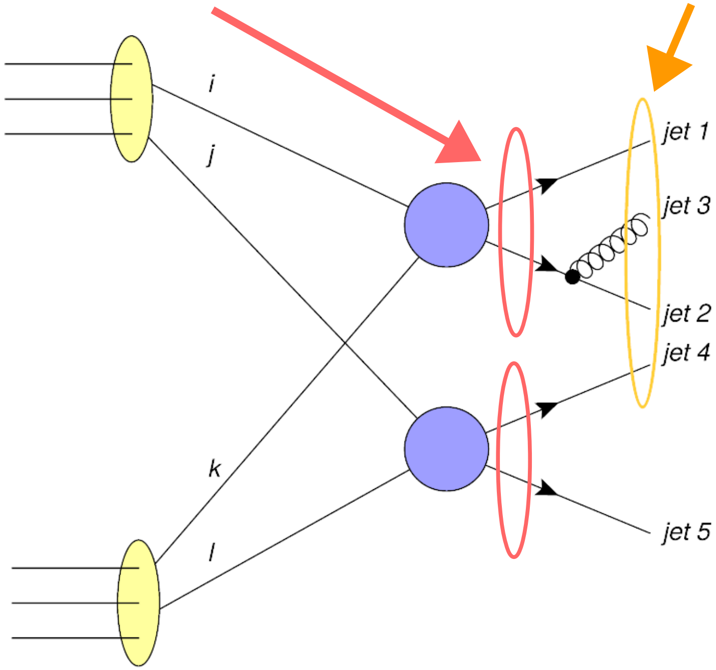


Event Classification

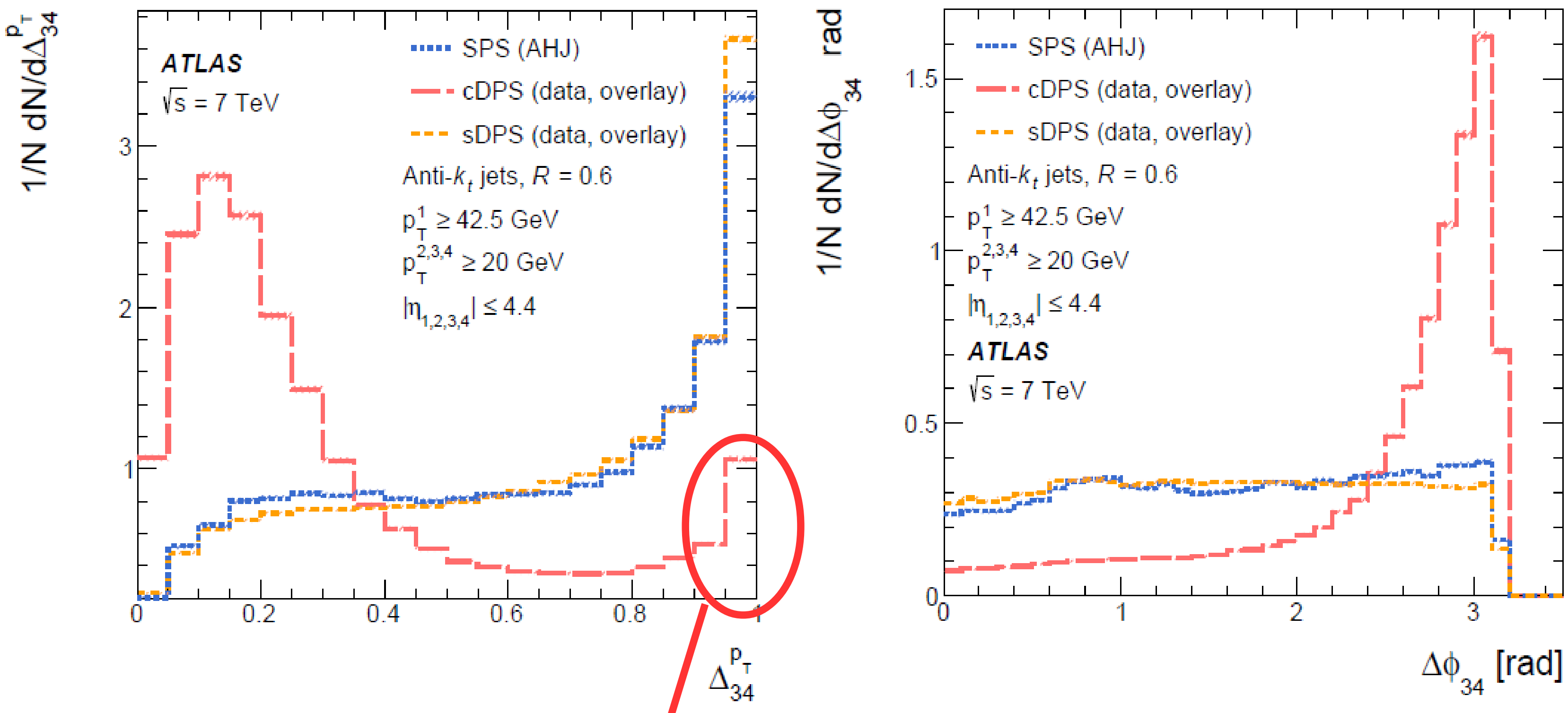
- Alpgen interfaced to Jimmy and Herwig (AHJ) for multi-jets modeling
  - ➢ Event record is used to extract Single (SPS) and Double (DPS) parton scattering events
- Sherpa for SPS multi-jets
- Data events overlay for DPS events

Process type	SPS	Complete-DPS	Semi-DPS
Number of jets matched to secondary-scatter partons	0	2	1
Modeled with	AHJ, Sherpa for validation	Overlaid data dijets, AHJ for validation	Overlaid data 3-jet + 1-jet events, AHJ for validation

- In MC, jets are matched to outgoing partons from primary and secondary interactions
- In data events overlay, require non-overlapping jets
- Jet match to closest parton with $p_T^{parton} > 15$ GeV and $\Delta R_{parton\text{-}jet} < 1$
- $f_{DPS} = f_{sDPS} + f_{cDPS}$



Discriminating variables



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

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

- $|\phi_{i+j} - \phi_{k+m}|$,

ijkm = 1234, 1324, 1423

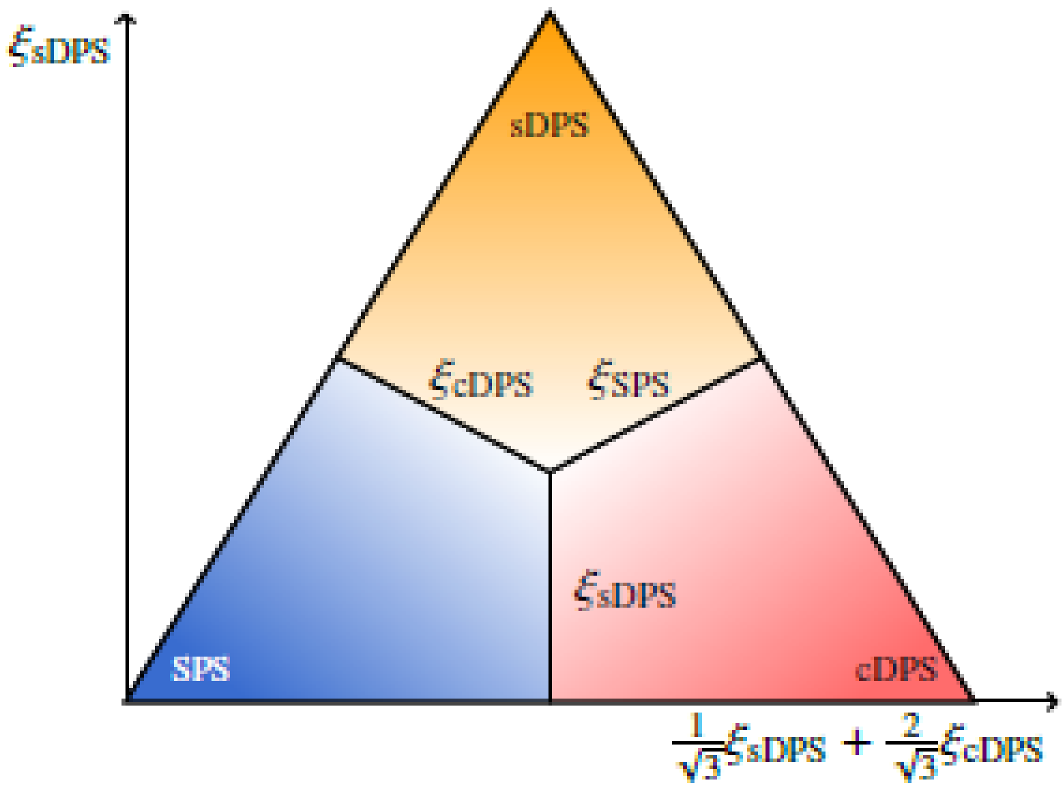
→ **jets 1,2,3,4 are p_T-ordered**

- Pairing can be ambiguous → use variables involving all possible jet combinations
- None of the variables provides clear separation between three classes
- The variables are correlated

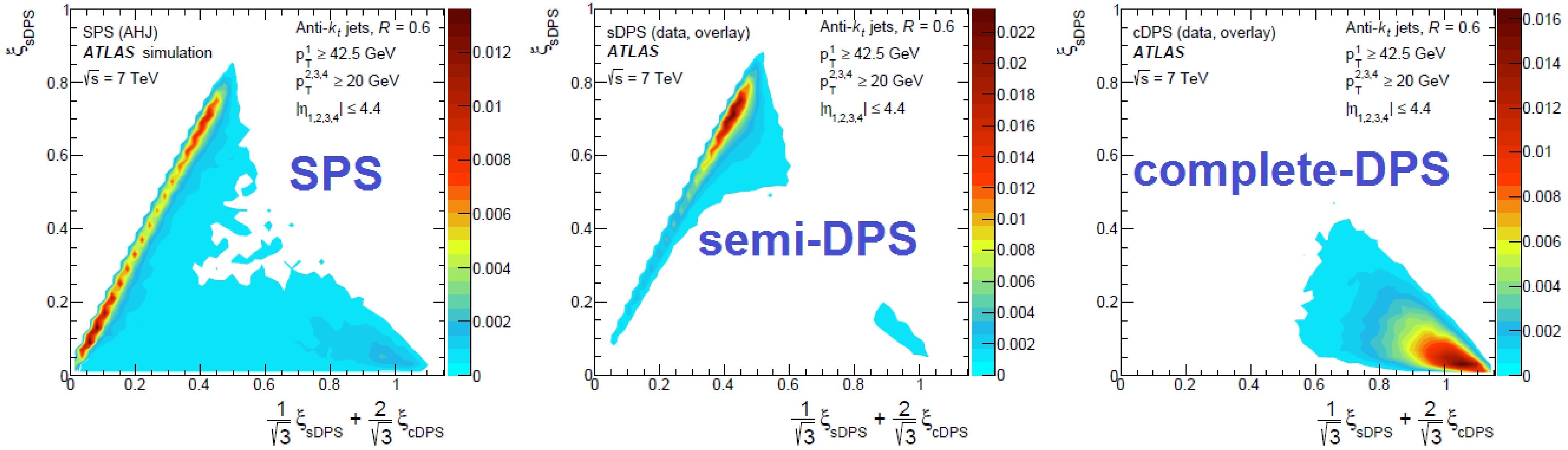
→ **Use 21 variables (all possible dijet combinations) for neural network training**

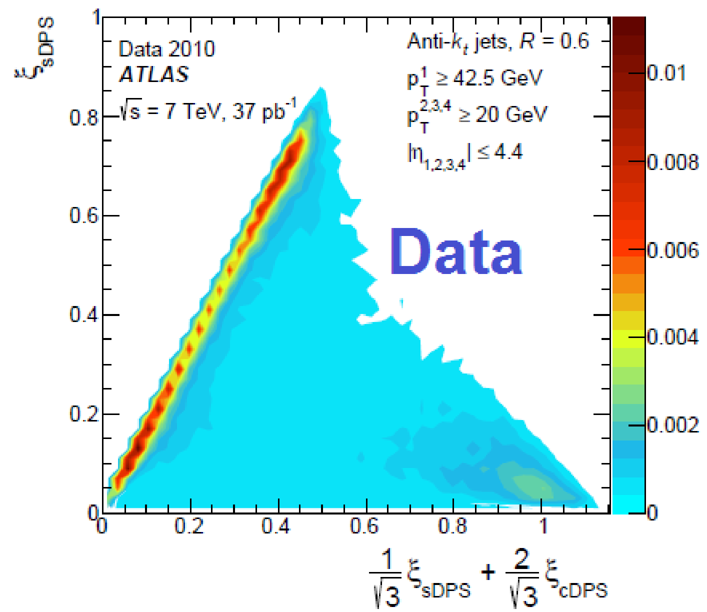
Representation of the Neural Network Output

- NN output - "probabilities" for event to look like SPS, sDPS or cDPS: $0 < \xi_i < 1$, $\Sigma\ \xi_i = 1$
- Each event can be represented as a point inside the equilateral triangle
  - Sum of distances between the point and three sides of the triangle is constant
- SPS, sDPS and cDPS events by definition populate the vertices of such triangle



Neural Network Output





- Good separation between cDPS and others
- Separation between SPS and sDPS is difficult
- Fit sum of MC profiles to data:

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

Results: f_{DPS}

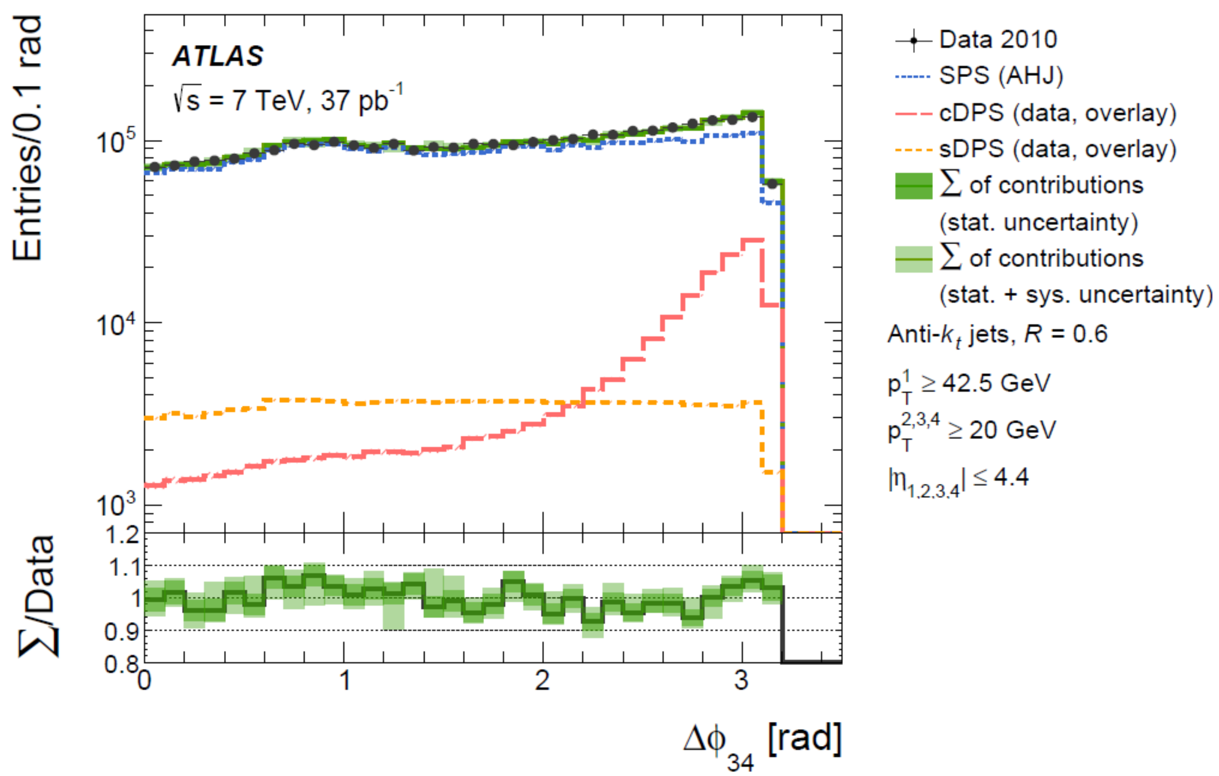
- f_{DPS}: fraction of DPS events in the inclusive 4-jet data sample

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

Sources of systematic uncertainties:

Source	Δf_{DPS}
Reweighting of AHJ	±6%
Jet energy and angular resolution	±15%
JES uncertainty	+32% -37%
Total syst. uncertainty	+36% -40%

Post-fit distribution



(9±4)% of 4-jet events originate through Double Parton Scattering

→ uncertainty dominated by jet energy scale variations

Results: Effective Cross Section

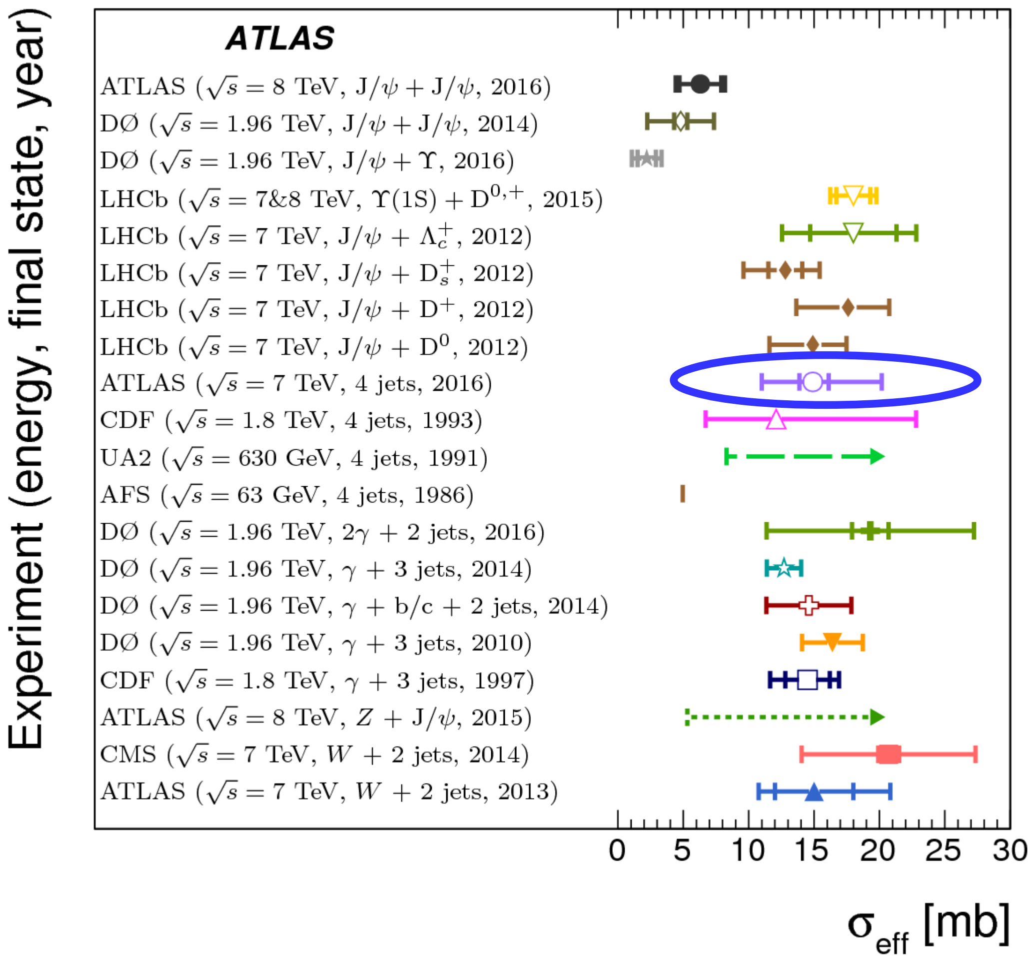
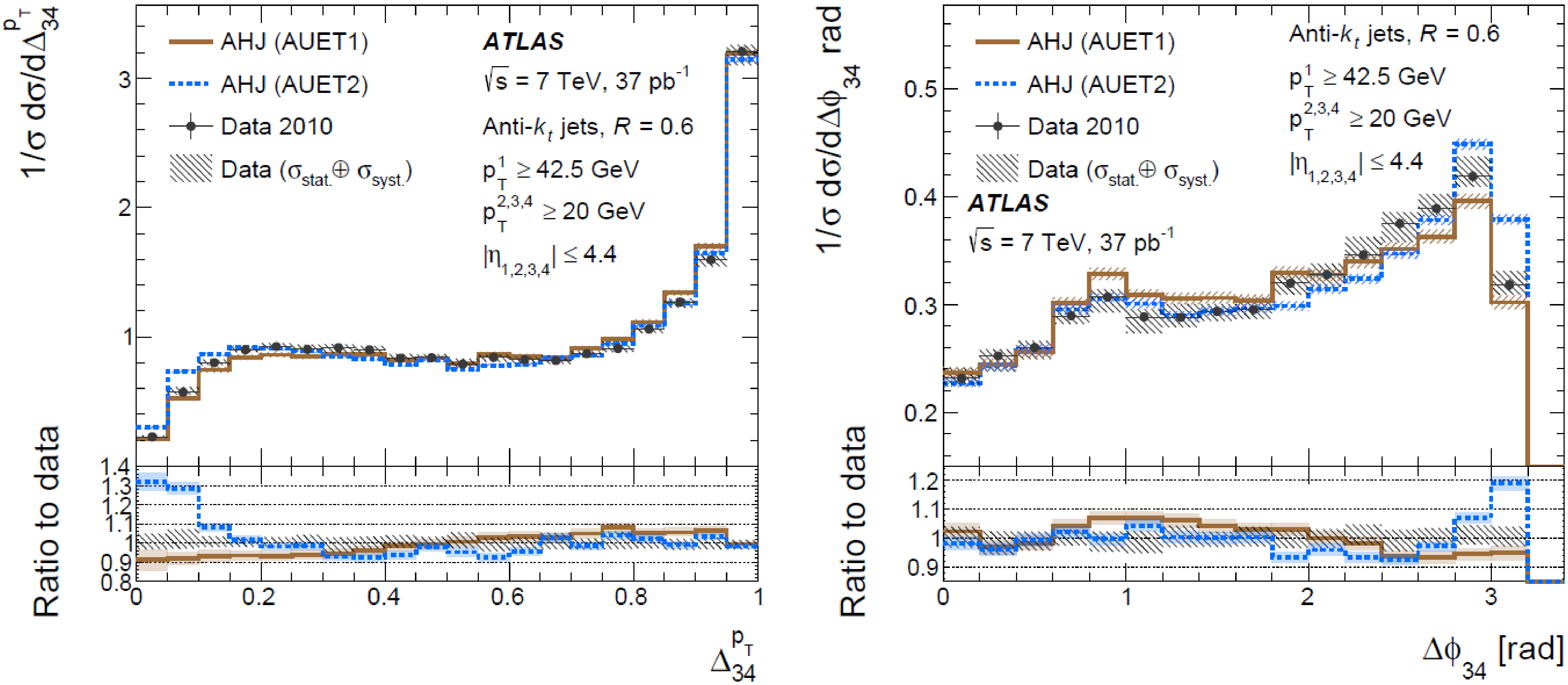


Fig. from Eur. Phys. J. C77 (2017) 76

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

- Uncertainty is systematics dominated
  → Mostly due to jet energy scale uncertainty
- Compatible with most of previous measurements performed at different centre-of-mass energies and with different final states, except for measurements with double heavy vector meson production by DØ and ATLAS

Unfolded Distributions



- Differential cross sections of variables sensitive to DPS are provided
- Gives a way to test various DPS MC models

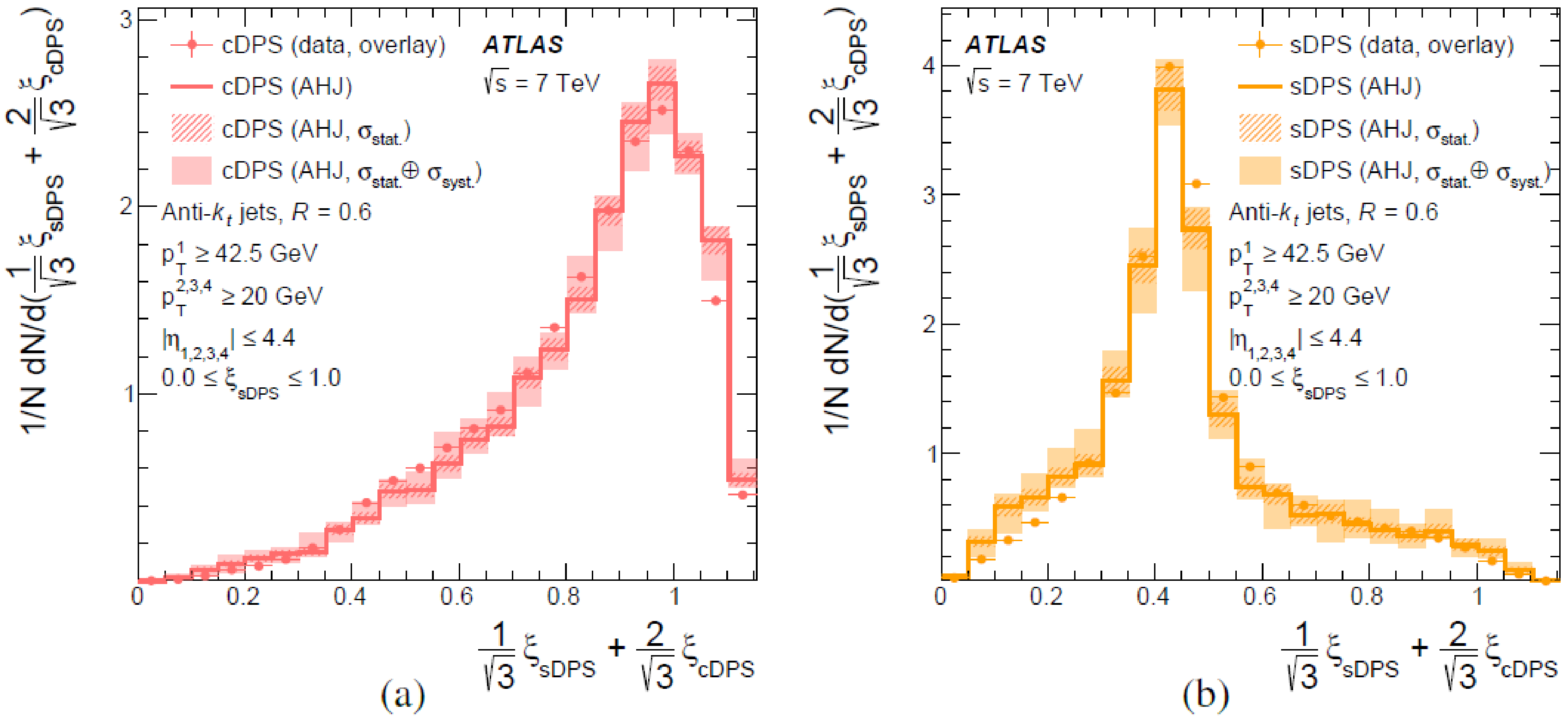
Summary

Hard double parton scattering with four jets: JHEP 11 (2016) 110

- Non-trivial due to different possibilities of four jet matching to primary and secondary partons
- High systematic uncertainty (~30%), mostly due to jet energy scale uncertainty
- **(9±4)% of inclusive 4-jet events are due to DPS**
  - For events with at least four jets with $p_T > 20$ GeV and at least one jet with $p_T > 42.5$ GeV, within $|\eta| < 4.4$
- Extracted effective cross section of **15±5 mb**
- Unfolded distributions sensitive to DPS are published

Backup

cDPS model validation



- The overlaid data dijet events were compared to DPS modeling by Alpgen + Herwig + Jimmy
- The DPS fraction was determined in the AHJ Monte Carlo using the same template fit technique and compared to the true value in the event record → a reasonable

agreement between the two was observed