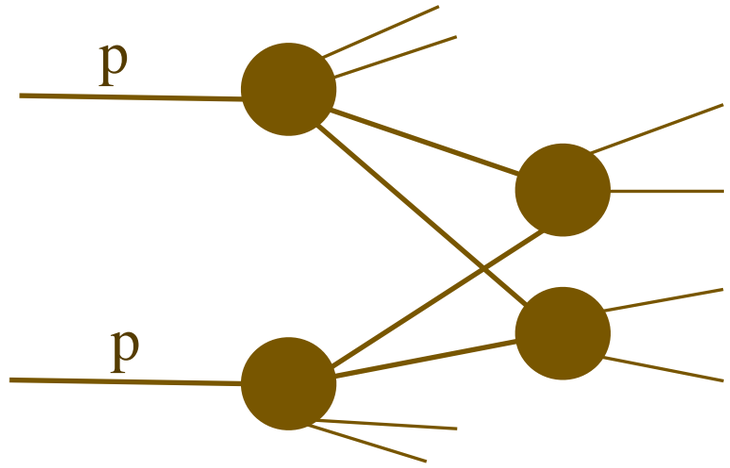

Studies of double parton scattering in ATLAS

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DESY
for the ATLAS Collaboration

Chiapas, MPI@LHC 2016

ATLAS measurements

- **Measurement of hard double-parton interactions in W->lv+ 2 jet events at sqrt(s)=7 TeV with the ATLAS detector** (New J. Phys. 15 (2013) 033038) **arXiv:1301.6872**

- **Measurement of the production cross section of prompt J/psi mesons in association with a W boson in pp collisions at sqrt{s}=7 TeV with the ATLAS detector** (J. High Energy Phys. 04 (2014) 172) **arXiv:1401.2831**

- **Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at √s=8 TeV with the ATLAS detector** (Eur. Phys. J. C75 (2015) 229) **arXiv:1412.6428**

- **Measurement of the prompt J/ψ pair production cross-section in pp collisions at √s = 8 TeV with the ATLAS detector** (ATLAS-CONF-2016-047)

- **Study of hard double-parton scattering in four-jet events in pp collisions at √s=7 TeV with the ATLAS experiment** (submitted to JHEP) **arXiv:1608.01857**

Theoretical introduction

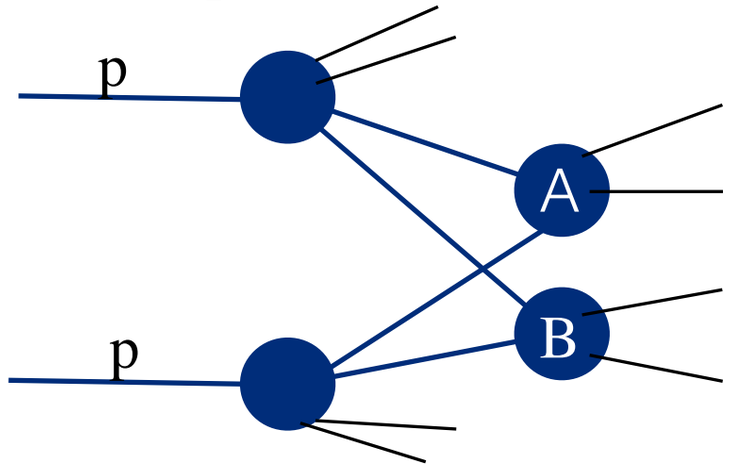
Ignoring the possible correlations between process A and B (model assumption):

$$\hat{\sigma}^{\mathrm{DPS}}_{(\mathrm{A,B})} = \frac{1}{1+\delta_{\mathrm{AB}}} \frac{\hat{\sigma}_{\mathrm{A}}\hat{\sigma}_{\mathrm{B}}}{\sigma_{\mathrm{eff}}} \,,$$

$$\Longrightarrow \quad \sigma_{\mathrm{eff}} = \frac{1}{1+\delta_{\mathrm{AB}}} \frac{\hat{\sigma}_{\mathrm{A}}\hat{\sigma}_{\mathrm{B}}}{f_{\mathrm{DPS}} \cdot \hat{\sigma}^{\mathrm{tot}}_{(\mathrm{A,B})}}$$

Kroneker δ =1, if A and B the same

fraction of DPS events



σ_{eff} - effective cross section :

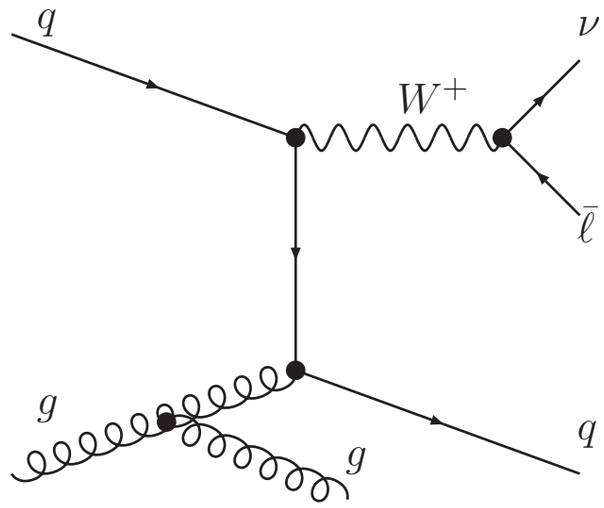
- ✦ phenomenological parameter related to the degree of overlap between the interacting hadrons,
- ✦ determines the overall size of DPS cross section,
- ✦ assumed to be process and cut independent
- ✦ measured to be 20-30% of σ_{inel}

DPS in W(→lν) + 2 jets

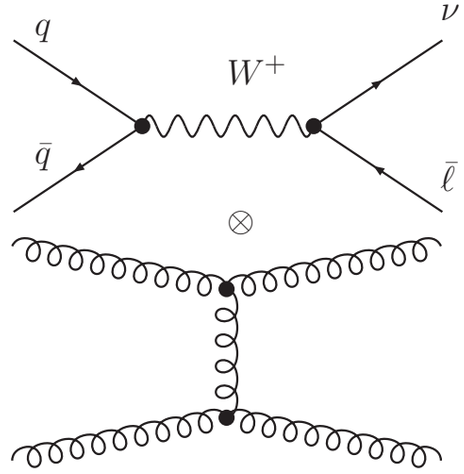
$\mathscr{L}$ = 36 pb^{-1}, year 2010
$\sqrt{s}$ = 7 TeV

Event selection:
for W:
$p_T^l > 20$ GeV
$|\eta| < 2.4$
$E_T^{miss} > 25$ GeV
$m_T > 40$ GeV
for jets:
anti-kt algorithm with R=0.4
$p_T > 20$ GeV
$|y| < 2.8$

SPI



DPI



Dijets back-to-back in the azimuthal space

Observables used in the analysis:

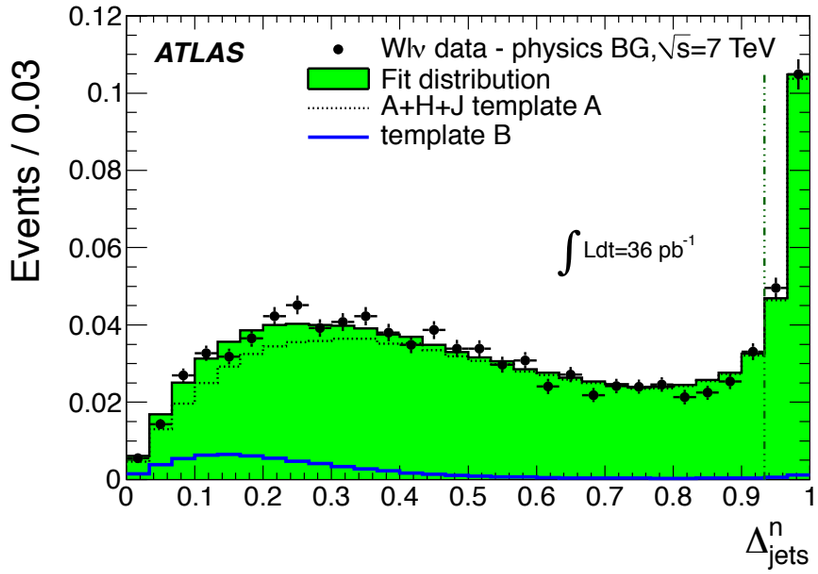
$$\Delta_{jets} = |\vec{p}_T^{J_1} + \vec{p}_T^{J_2}| \qquad \Delta_{jets}^{n} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$$

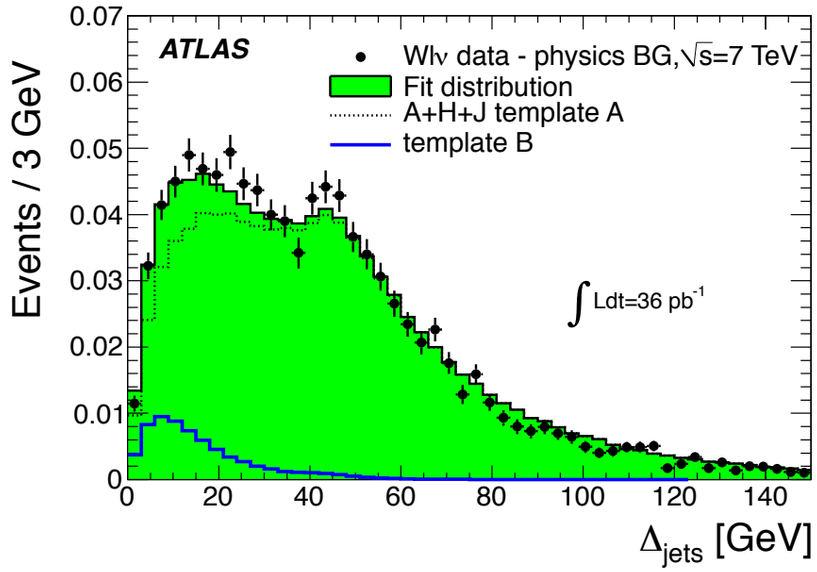
f_{DPS} extracted from fit to Δ^n_{jets} using $(1\text{-}f_{DPS}) \cdot A + f_{DPS} \cdot B$
Template A: SPS MC sample Alpgen+Herwig+Jimmy (A+H+J)
Template B: Dijet samples exteracted from data

DPS in W(→lν) + 2 jets

$$\Delta^{n}_{jets} = \frac{|\vec{p}_T^{\,J_1} + \vec{p}_T^{\,J_2}|}{|\vec{p}_T^{\,J_1}| + |\vec{p}_T^{\,J_2}|}$$

$$\Delta_{jets} = |\vec{p}_T^{\,J_1} + \vec{p}_T^{\,J_2}|$$





Systematic source f_{DPS}	Uncertainty (%)
Theory	10
Pile-up	13
Jet energy scale	12
Jet energy resolution	8
Background modelling and lepton response	11
Total systematic	24
Total statistical	17

Results:

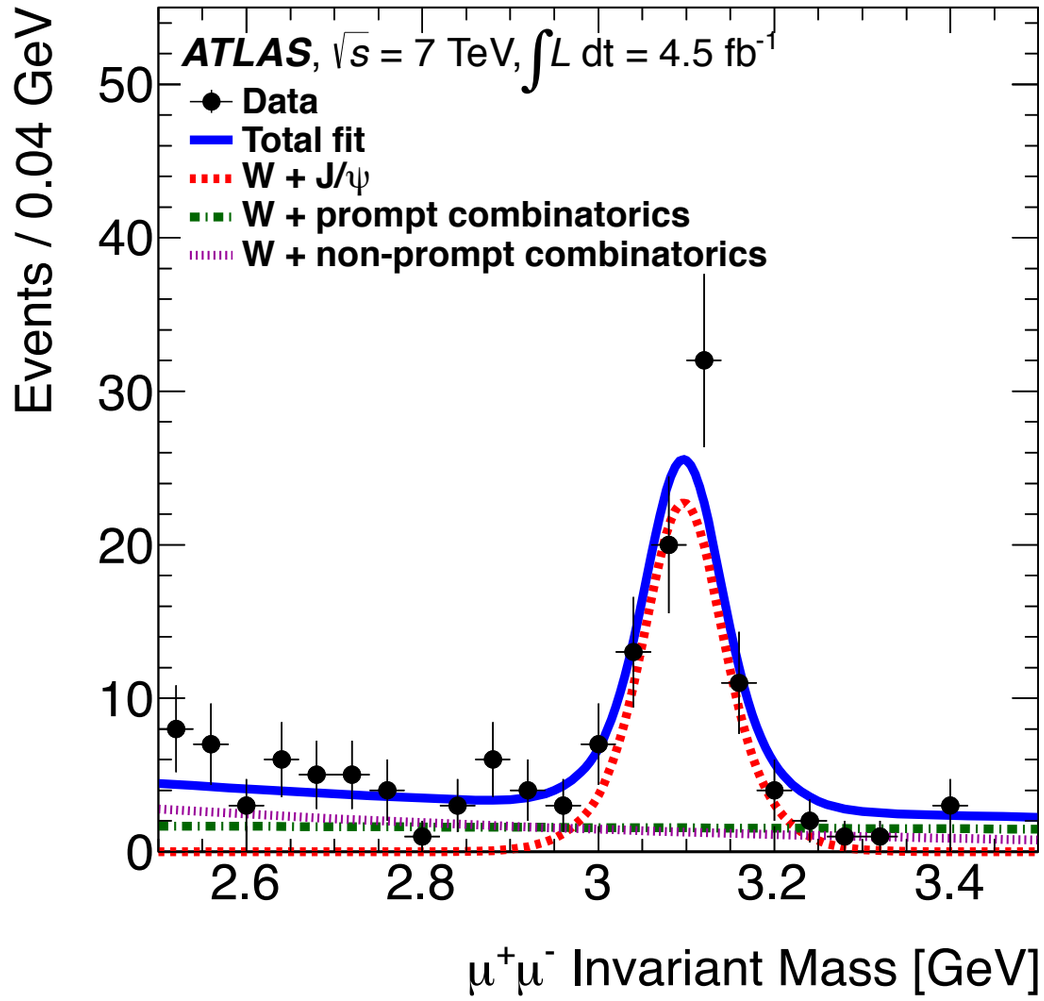
$f_{DPS} = 0.08 \pm 0.01\ (stat) \pm 0.02\ (syst.)$

$\sigma_{eff} = 15 \pm (stat.)\ ^{+5}_{-3}\ (syst.)$ mb

DPS in prompt J/ψ(→μμ) + W(→μν)

$\mathcal{L}$ = 4.5 fb^{-1}, year 2011
$\sqrt{s}$ = 7 TeV

Event selection:
for W (single muon trigger):
1 μ (matching trigger μ),
$p_T^{\mu} > 20$ GeV
$|\eta| < 2.4$
$E_T^{miss} > 20$ GeV
$m_T > 40$ GeV
for J/ψ:
2 oppositely charged μ
$|\eta| < 2.5$
$p_T(\mu_1) > 4$ GeV
$p_T(\mu_2) > 3.5$ GeV for $|\eta(\mu_2)| < 1.3$
$p_T(\mu_2) > 2.5$ GeV for $|\eta(\mu_2)| > 1.3$
$2.5 < m_{\mu^+\mu^-} < 3.5$ GeV
$8.5 < p_T^{J/\psi} < 30$ GeV
$|y^{J/\psi}| < 2.1$



Number of W + prompt J/ψ events = $29.2^{+7.5}_{-6.5}$

DPS in prompt J/ψ(→μμ) + W(→μν)

$$P_{J/\psi|W} = \sigma_{J/\psi}/\sigma_{eff}$$

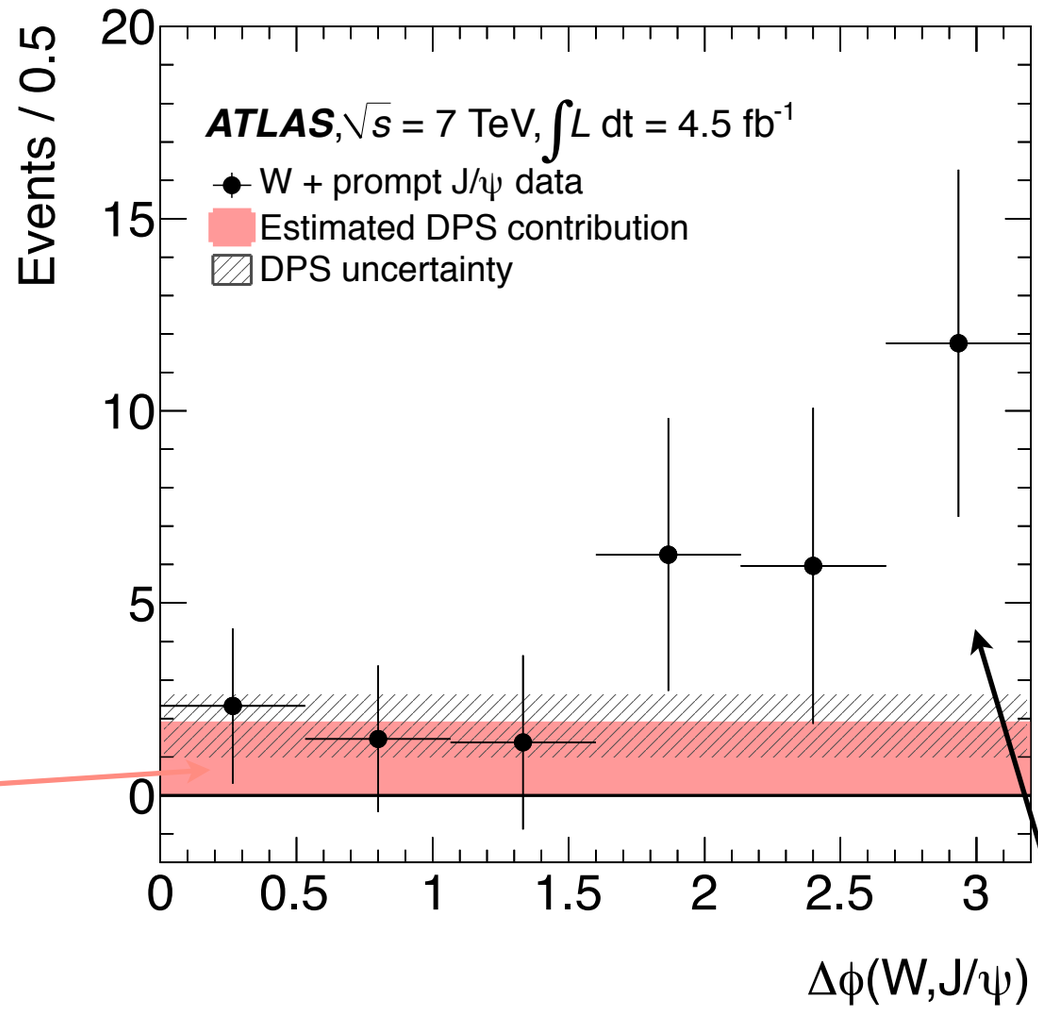
σ_{eff} ← from W+2jets measurement

Probability of J/ψ (DPS) production, when W is produced in hard scatter

$\sigma_{J/\psi}$: from ATLAS measurement, and adopted to the fiducial region

DPS contribution = 38^{+22}_{-20}%

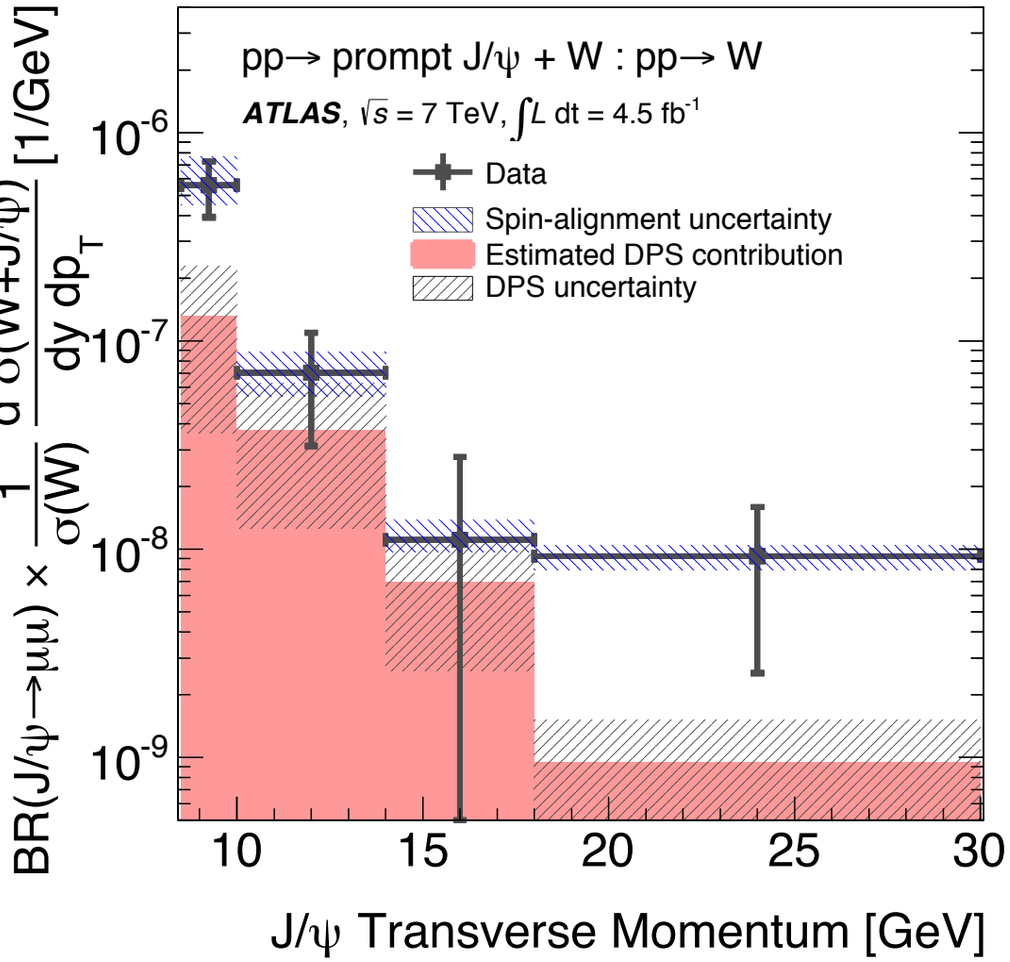
N^{DPS} (J/ψ|W) = 10.8 ± 4.2 events
uniform distribution in azimuthal angle



SPS distribution picked at π

DPS in prompt J/ψ(→μμ) + W(→μν)

Ratio of prompt J/ψ + W to inclusive W



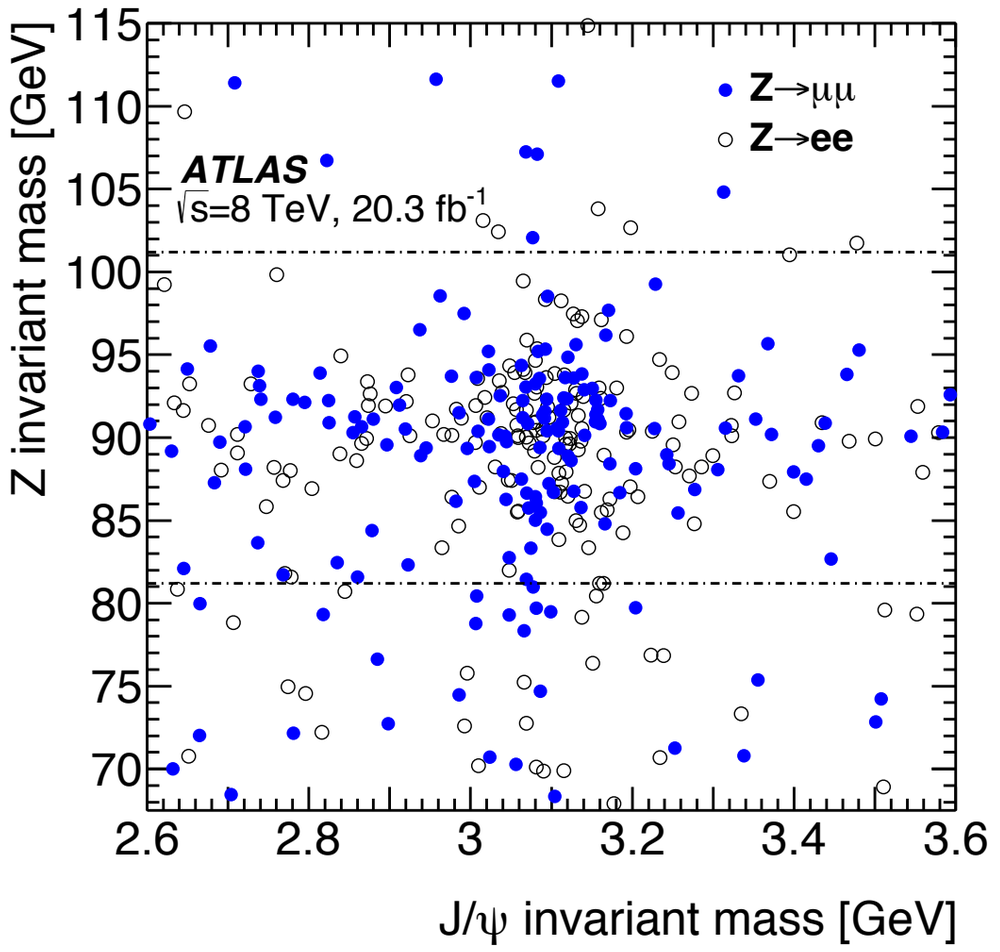
$$R_{J/\psi}^{\mathrm{incl}} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$$

SPS contribution dominant at low J/ψ transverse momentum

DPS in prompt and non-prompt J/ψ(→μμ) + Z(→ll)

$\mathcal{L}$ = 20.3 fb^{-1}, year 2012
$\sqrt{s}$ = 8 TeV

Event selection:
single lepton trigger with $p_T > 4$ TeV
for Z :
2 oppositely charged leptons
(one matching trigger lepton),
$p_T(l^+l^-) > 15$ GeV
$|\eta| < 2.5$
$81 > m_{ll} > 101$ GeV
for J/ψ:
2 oppositely charged μ
$|\eta| < 2.5$
$p_T(\mu_1) > 4$ GeV
$p_T(\mu_2) > 3.5$ GeV for $|\eta(\mu_2)| < 1.3$
$p_T(\mu_2) > 2.5$ GeV for $|\eta(\mu_2)| > 1.3$
$2.5 < m_{\mu^+\mu^-} < 3.5$ GeV
$8.5 < p_T^{J/\psi} < 30$ GeV
$|y^{J/\psi}| < 2.1$



16.15 million Z boson candidates
56±10 Z + prompt J/ψ
95±12 Z+ non-prompt J/ψ

DPS in prompt and non-prompt J/ψ(→μμ) + Z(→ll)

from W+2jets measurement

$$P_{J/\psi|Z} = \sigma_{J/\psi}/\sigma_{eff}$$

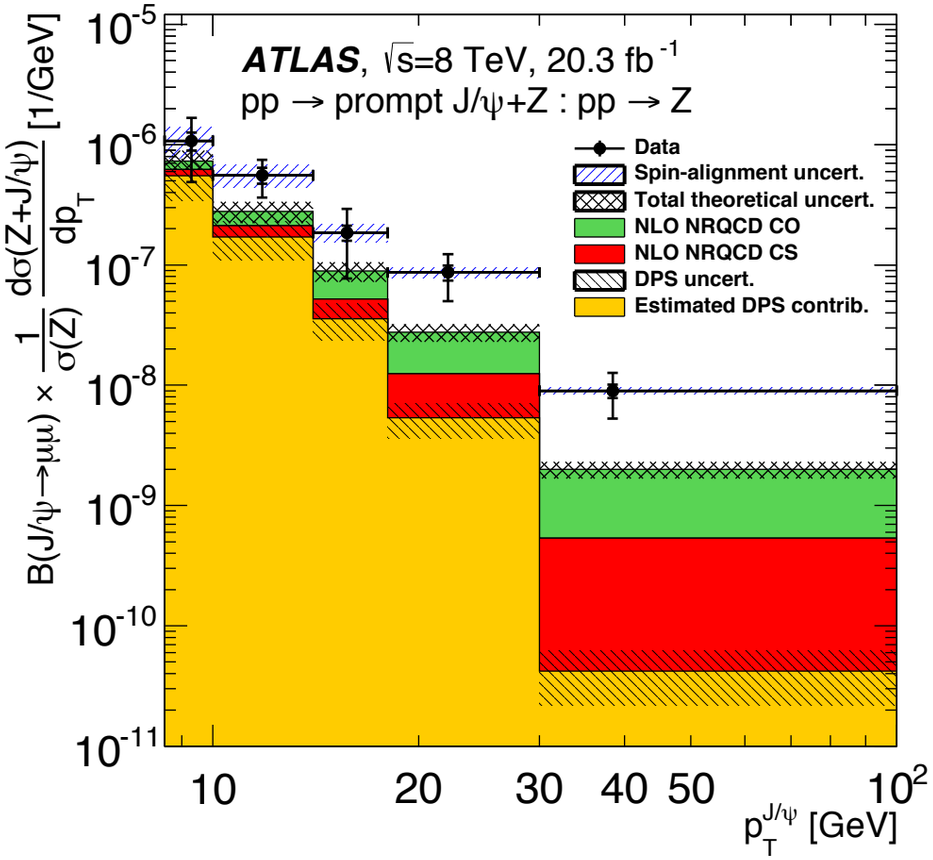
Probability of J/ψ production, when Z is produced in hard scatter

from ATLAS measurement, and adopted to the fiducial region

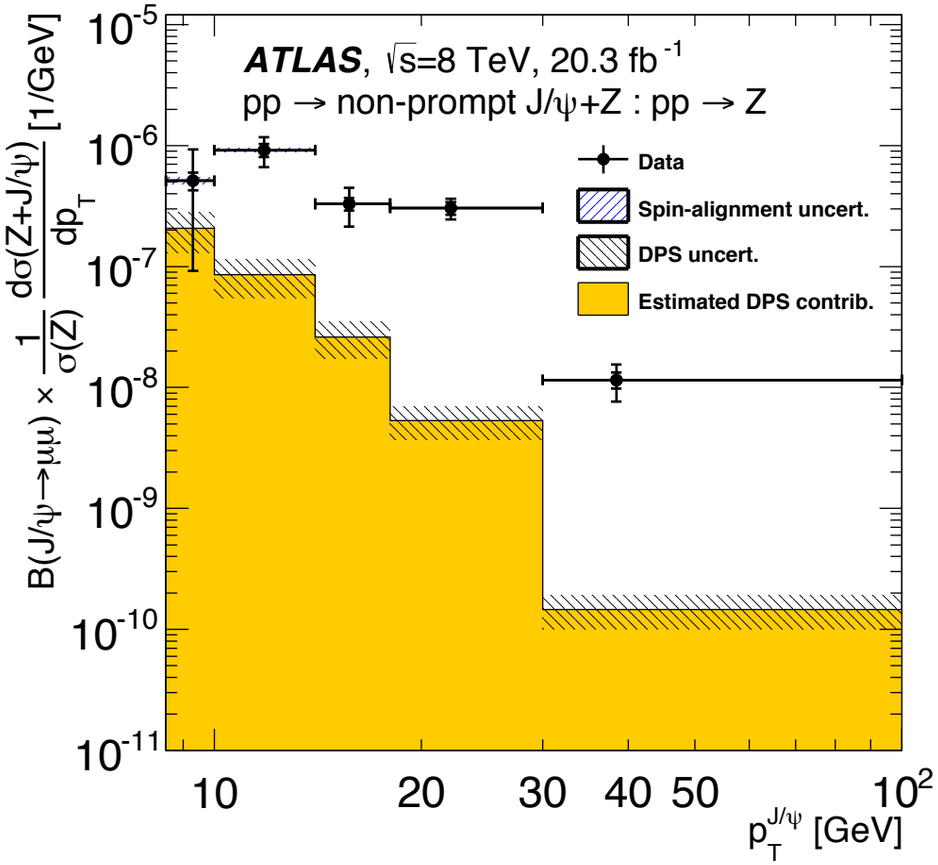
DPS for Z + prompt J/ψ = 29 ± 9 %
DPS for Z + non-prompt J/ψ = 8 ± 2 %

N^{DPS} (Z+prompt J/ψ|Z) = $11.1^{+5.7}_{-5.0}$ events
N^{DPS}(Z+non-prompt J/ψ) = $5.8^{+2.8}_{-2.6}$ events

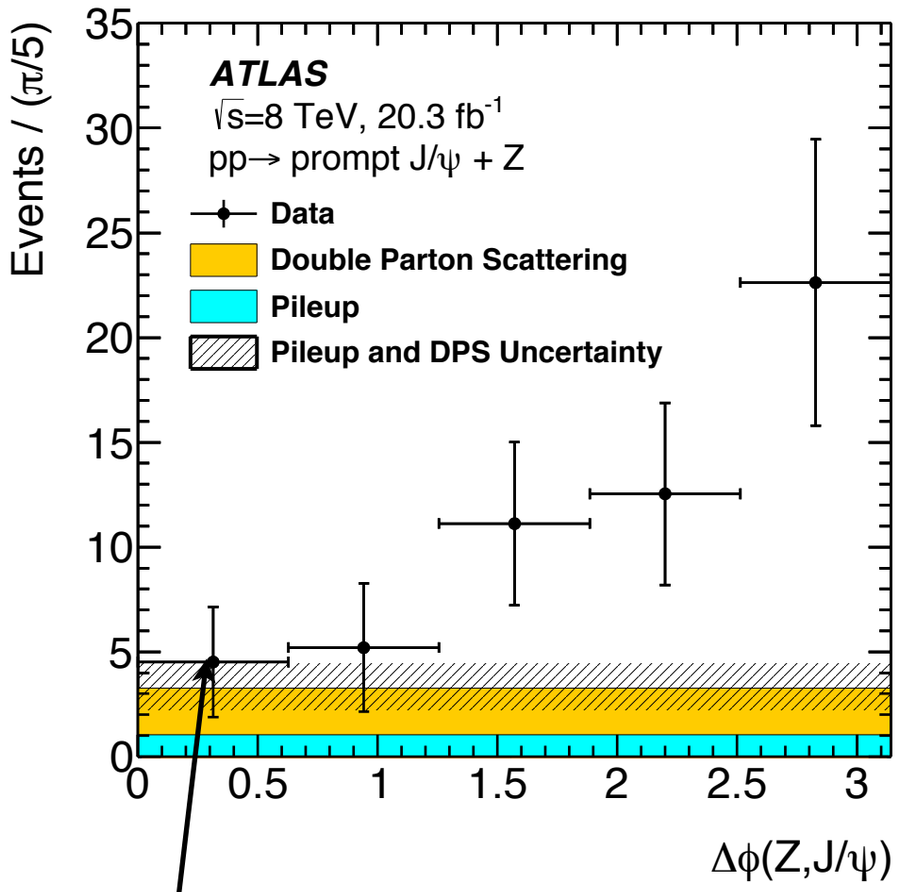
Ratio of prompt J/ψ + Z to inclusive Z

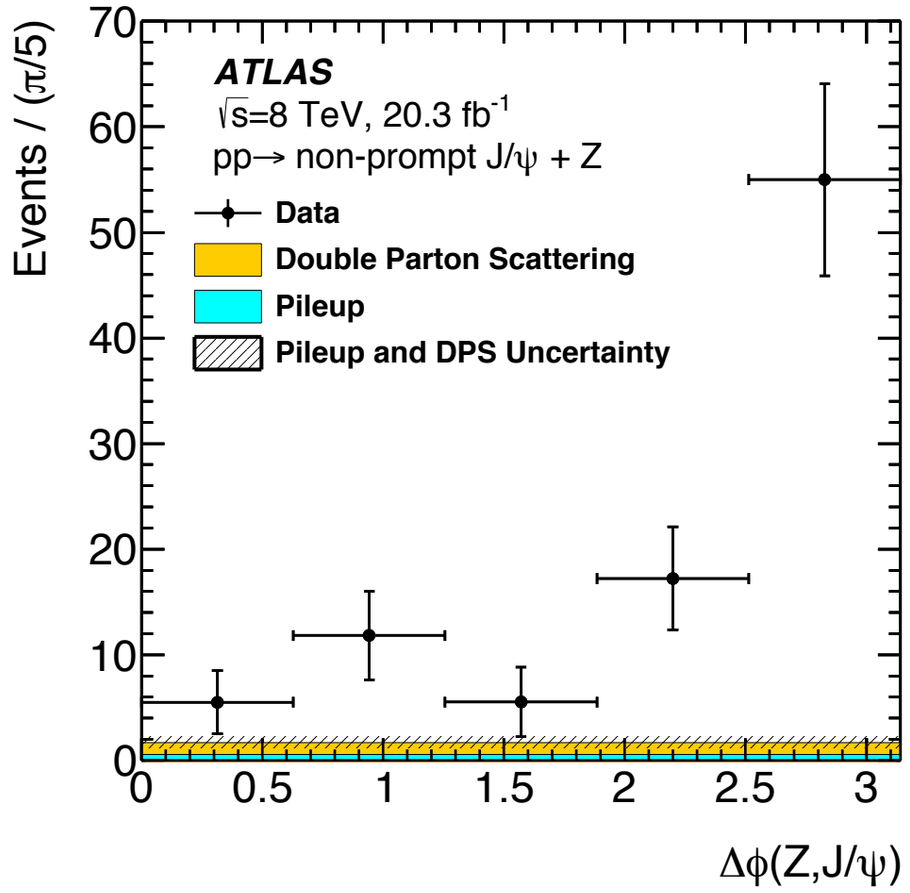


Ratio of non-prompt J/ψ + Z to inclusive Z



DPS in prompt and non-prompt J/ψ(→μμ) + Z(→ll)





DPS uniform distribution

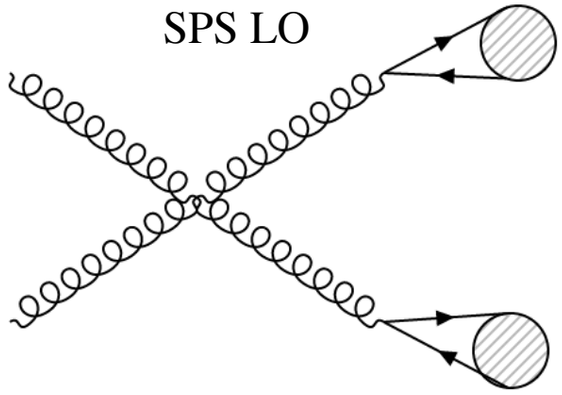
SPS peaked at π

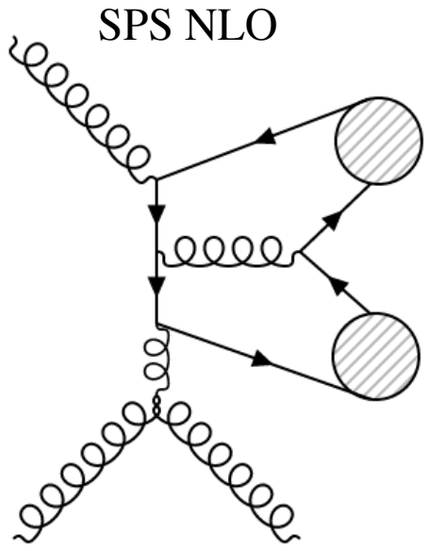
Small Δφ region - sensitive to DPS, so used to calculate max. allowed DPS contribution

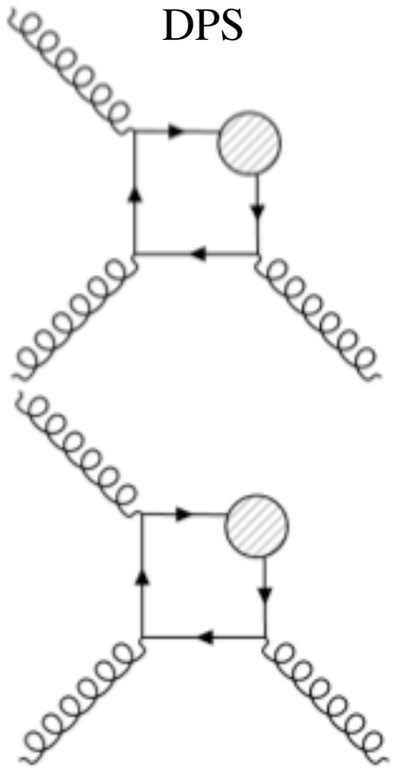
$\sigma_{eff} > 5.3$ mb (3.7 mb) at 68% (95%) confidence level

DPS in prompt J/ψ(→μμ) pair

$\mathcal{L}$ = 11.4 fb^{-1}
year 2012
$\sqrt{s}$ = 8 TeV

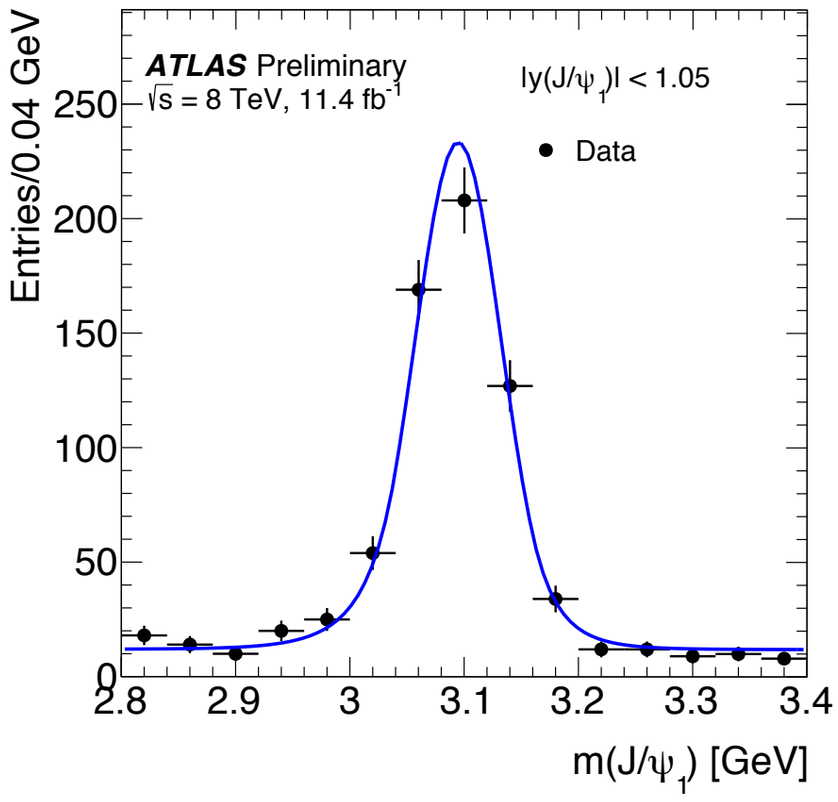






Event selection:
di-muon trigger (2 μ with p_T> 4 GeV
and 2.5 < M(μμ) < 4.3 GeV)
$p_T^{\mu} > 2.5$ GeV
$|\eta^{\mu}| < 2.3$
2.8 < M(μμ) < 3.4 GeV
$|y^{J/\psi}| < 2.1$
$p_T^{J/\psi} > 8.5$ GeV
distance between J/ψ decay vtx. $|d_z| < 1.2$ mm

1210 events found

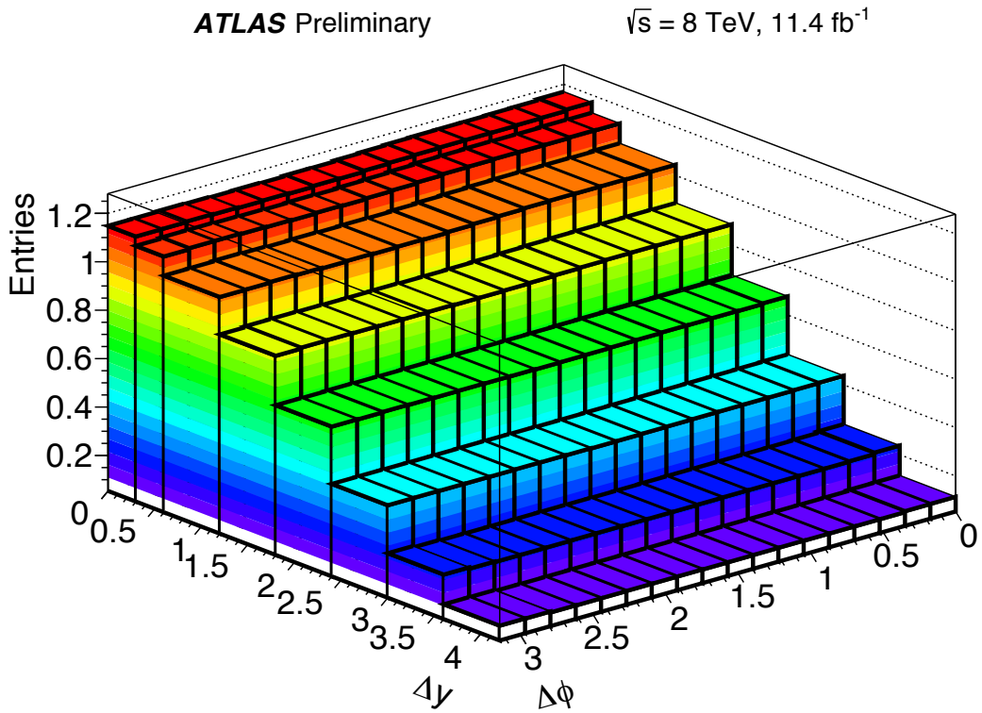


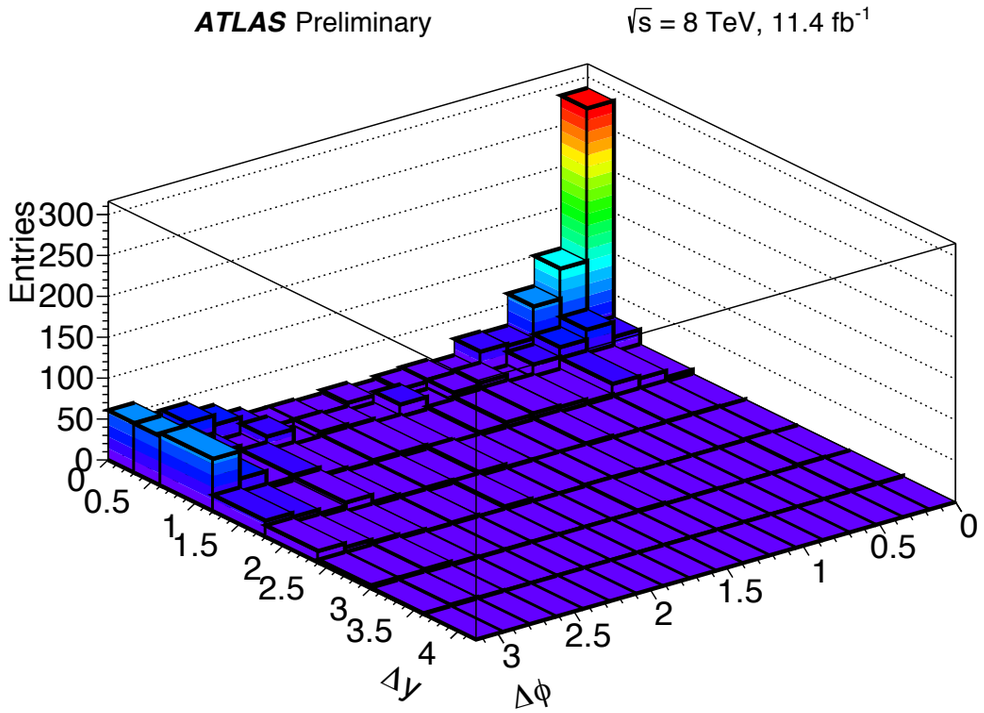
DPS in prompt J/ψ(→μμ) pair

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\text{DPS}}} = \frac{1}{2}\frac{\sigma_{J/\psi}\sigma_{J/\psi}}{f_{\text{DPS}} \times \sigma_{J/\psi J/\psi}}$$

DPS - data driven template - combined J/ψ candidates from two different events, normalised to data for $\Delta y > 1.8$ and $\Delta\phi < \pi/2$

SPS - data template - DPS contribution subtracted from data





$$w_{\text{DPS}}(\Delta\phi,\ \Delta y) = \frac{N_{\text{DPS}}(\Delta\phi,\ \Delta y)}{N_{\text{Data}}(\Delta\phi,\ \Delta y)}$$

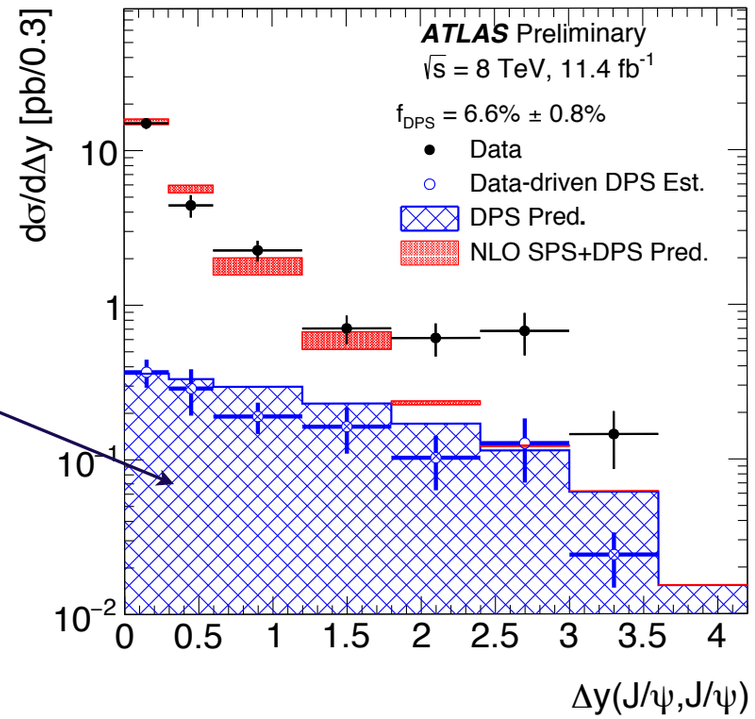
$$w_{\text{SPS}}(\Delta\phi,\ \Delta y) = \frac{N_{\text{SPS}}(\Delta\phi,\ \Delta y)}{N_{\text{Data}}(\Delta\phi,\ \Delta y)}$$

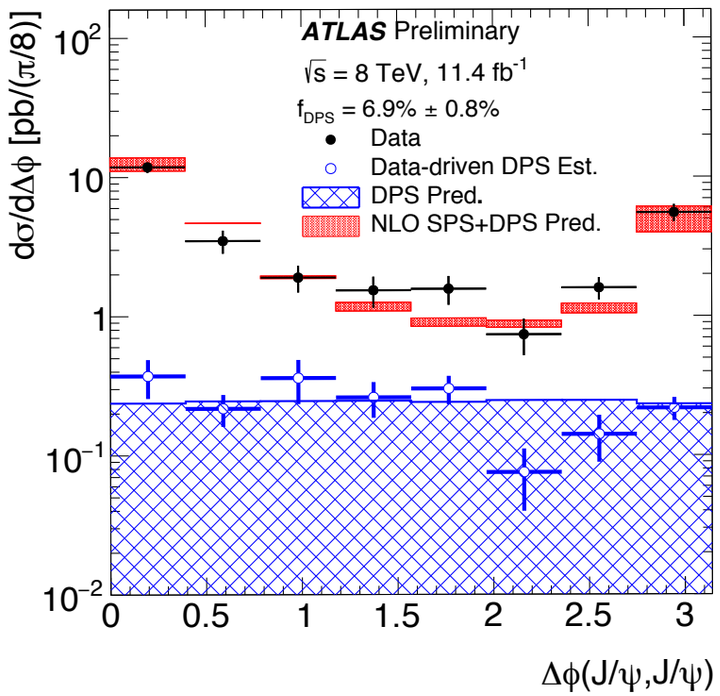
weights for SPS- and DPS-weighted distributions

DPS in prompt J/ψ(→μμ) pair

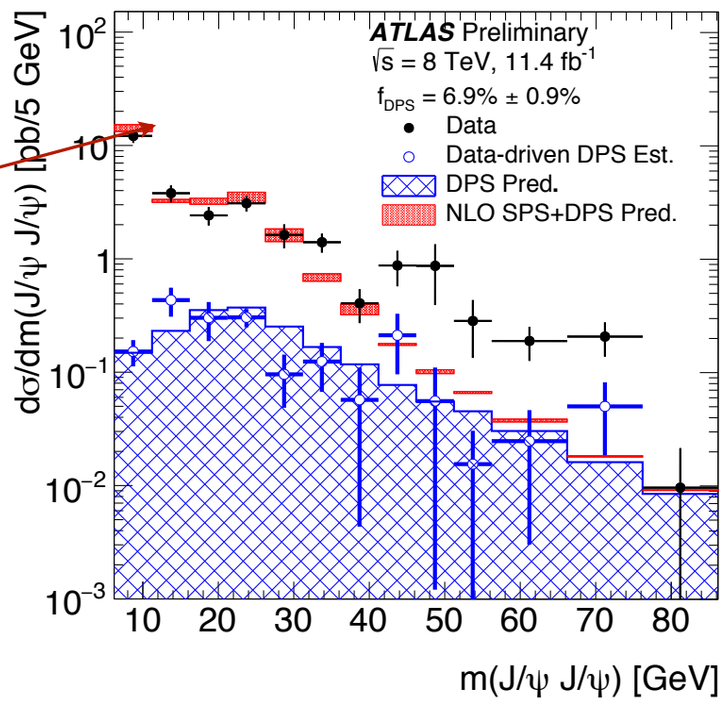
DPS and total differential cross section

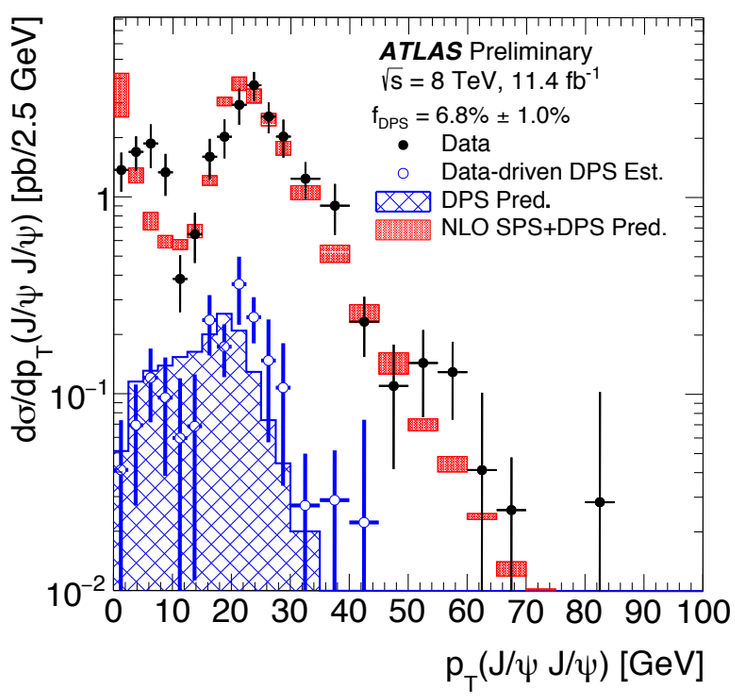
DPS prediction based on Kom, Kulesza, Stirling arXiv: 1105.4186





NLO SPS prediction based on Lansberg, Shao arXiv: 1410.8822



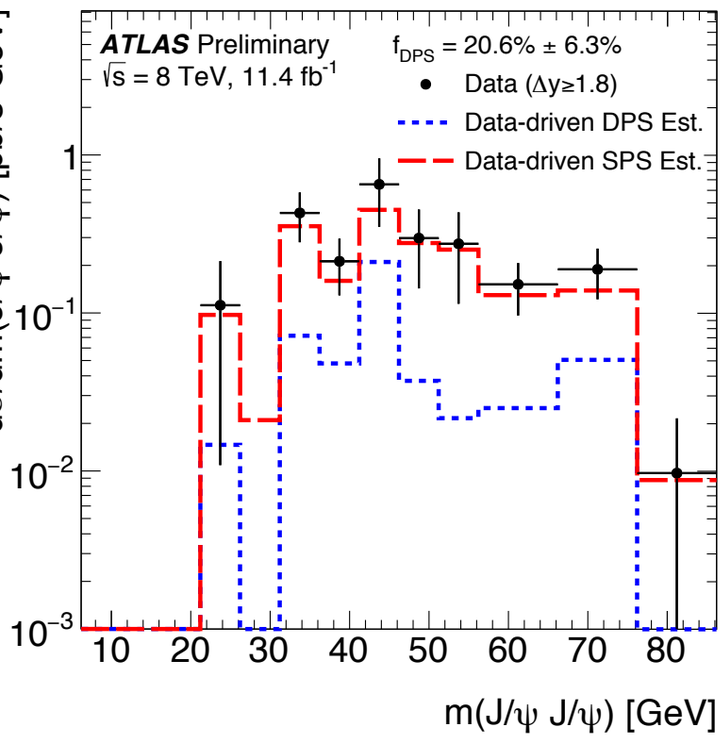


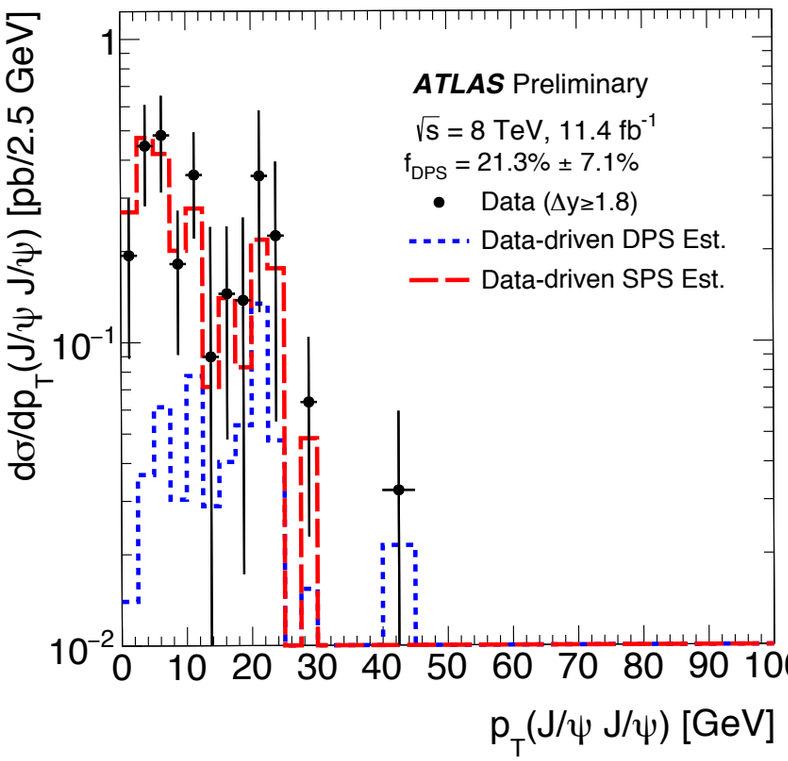
Shape of DPS data driven estimate and DPS theory prediction agree well.

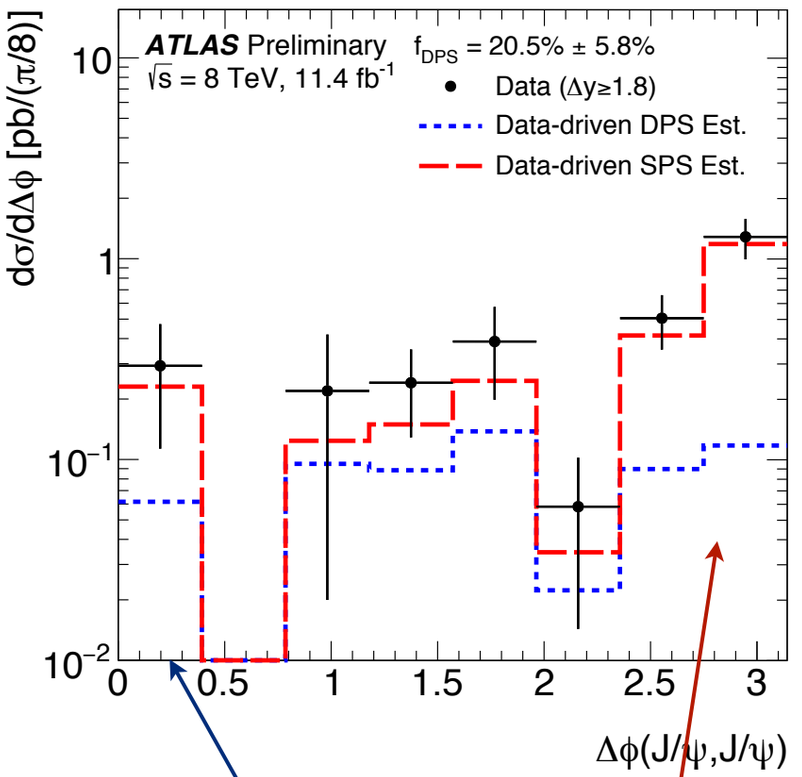
SPS prediction has problems at large Δy, large inv. mass and low p_T.
May be related to missing feed down from higher mass in the NLO SPS prediction.

DPS in prompt J/ψ(→μμ) pair

Distributions in the large Δy region





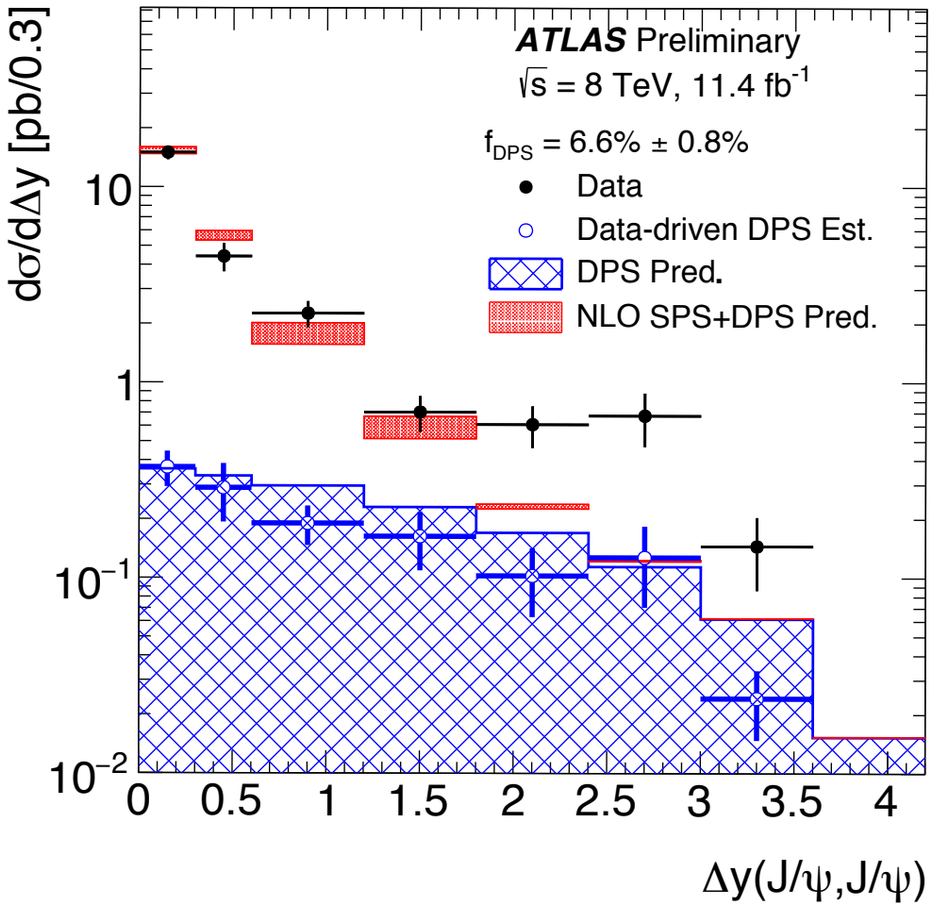


$f_{DPS} \approx 20\%$, but it does not dominate as predicted by the theory

$\Delta\phi < \pi/2$ DPS very significant

SPS peak from away topology

DPS in prompt J/ψ(→μμ) pair



$f_{DPS} = 6.6 \pm 0.8$ (stat) ± 0.2 (syst) %
in μ fiducial phase space

$\sigma_{eff} = 8.7 \pm 1.1$ (stat.) ± 1.4 (syst.) ± 0.1 (BF) ± 0.3 (lumi) mb

σ_{eff} lower than for other measurements. Di-J/ψ production is gluon dominated.
Indication of smaller average transverse distances between gluons than between quarks in the proton - as suggested by pion cloud model.

DPS in 4 jets events

$\mathcal{L}$ = 37.3 pb^{-1}, year 2010

$\sqrt{s}$ = 7 TeV

Events selection:

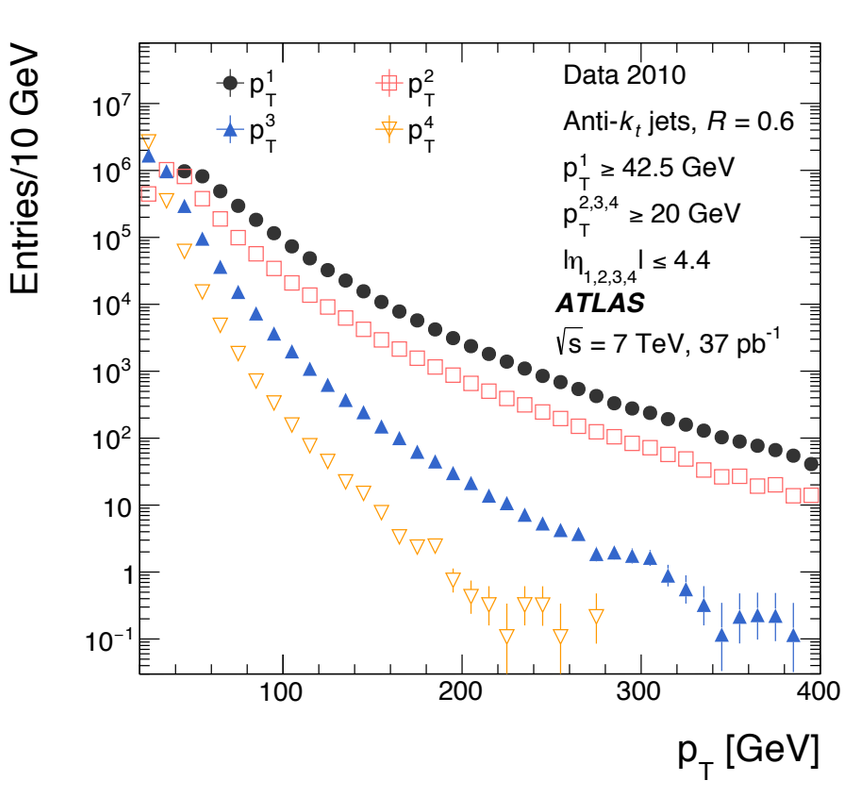
one reconstructed primary vtx.

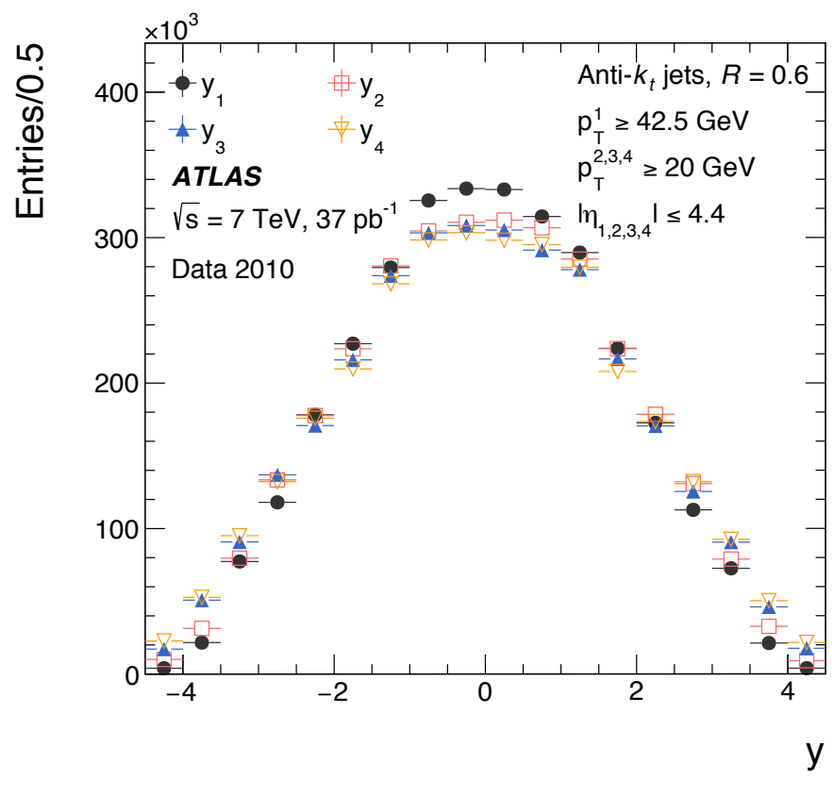
jets with anti-kt algorithm R=0.6

p_T(leading jet) > 42.5 GeV (required by the trigger)

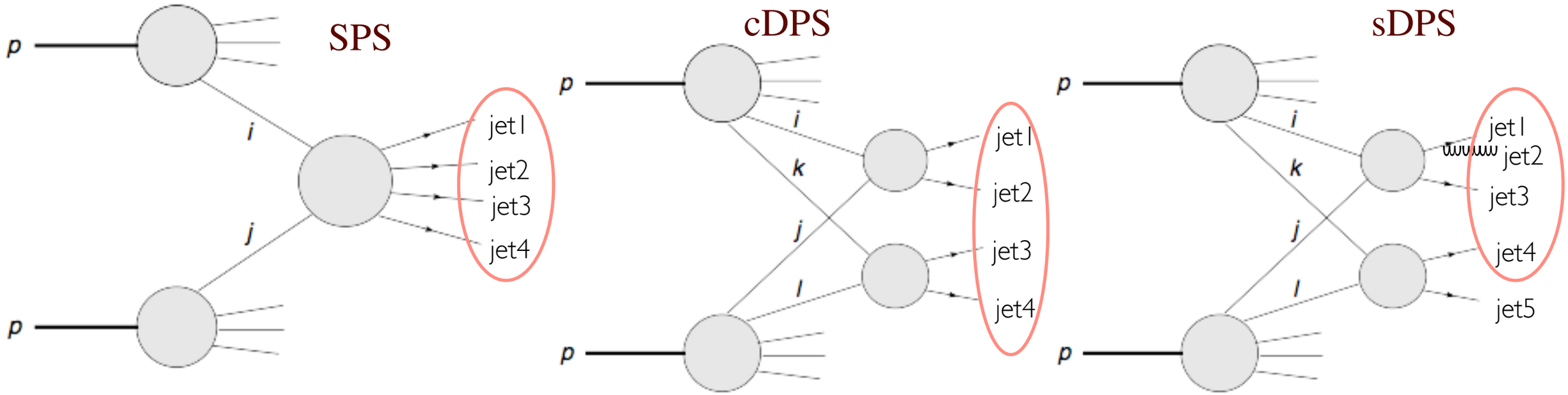
p_T(2,3,4 jet) > 20 GeV

$|\eta| < 4.4$





DPS in 4 jets events



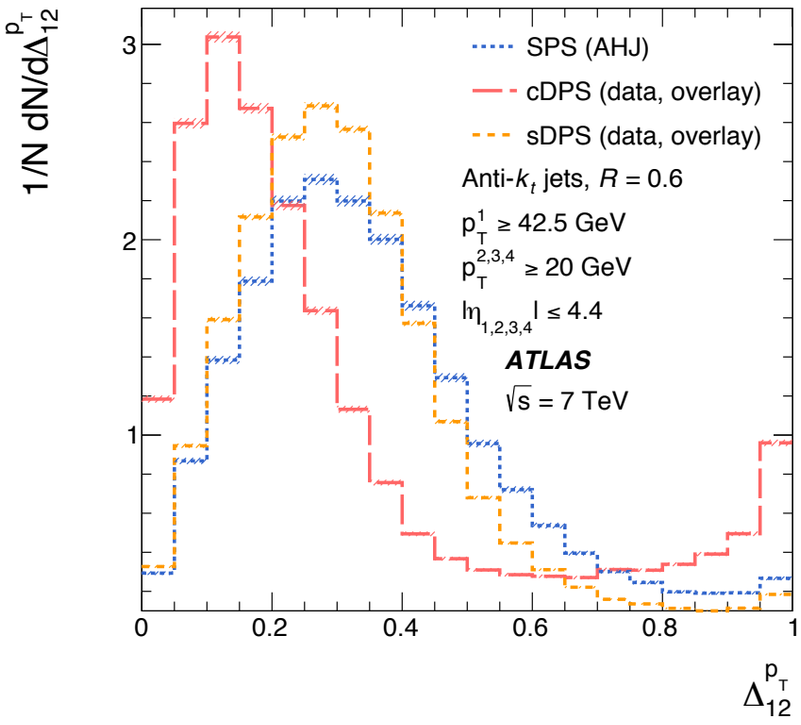
Alpgen+Herwig+Jimmi (AHJ) MC used to assign jets to primary (Alpgen) or secondary (Jimmy) partons
p_T(parton) > 15 GeV and ΔR(parton-jet) ≤ 1 in y-ϕ plane,
jets first matched to primary scatter partons

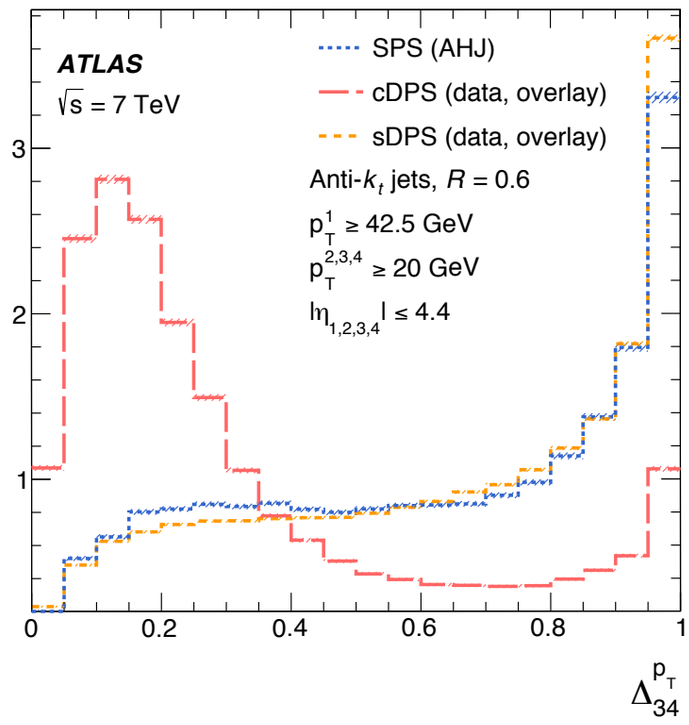
Templates :
SPS - all 4 jets from the hardest scatter, template based on AHJ MC
complete DPS (cDPS) - 2 jets from secondary scatter, template by overlying two dijet data events, require non-overlapping jets
semi DPS (sDPS) - 1 jet from the secondary scatter, template by overlying two data events (one event contribution 3 and the other 1 jet), no overlapping jets

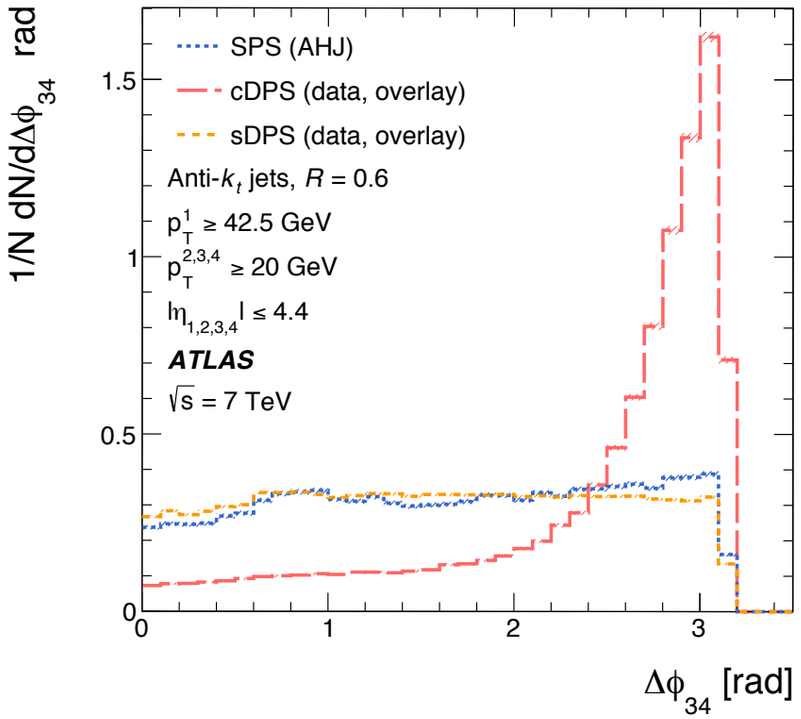
DPS in 4 jets events

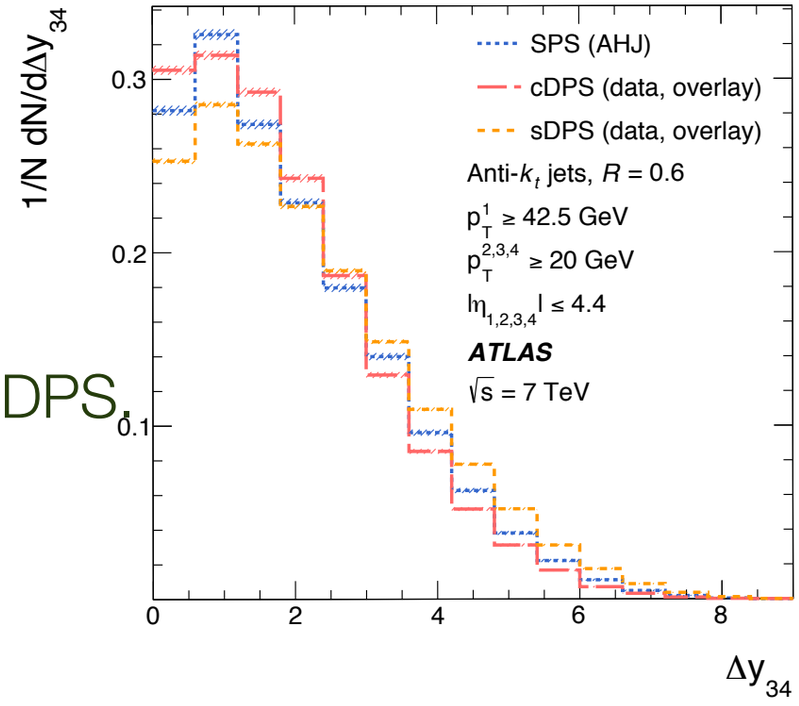
Differentiating variables:

$$\Delta_{ij}^{p_T} = \frac{\left|\vec{p}_T^{\,i} + \vec{p}_T^{\,j}\right|}{p_T^i + p_T^j}; \quad \Delta\phi_{ij} = \left|\phi_i - \phi_j\right|; \quad \Delta y_{ij} = \left|y_i - y_j\right|$$









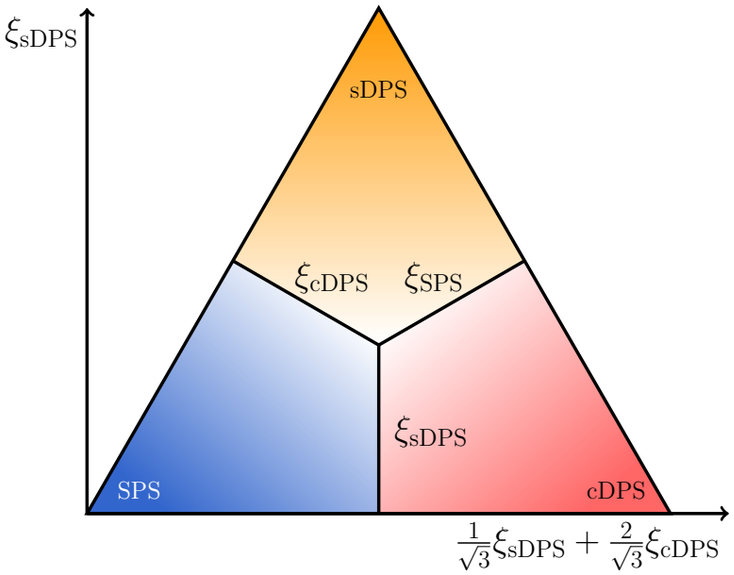
- Strong correlations between all variables.
- No variable gives a clear separation between SPS, cDPS and cDPS.
- All variables are important and should be taken into account.

⇨ neural network (NN) used for event classification (21 variables)

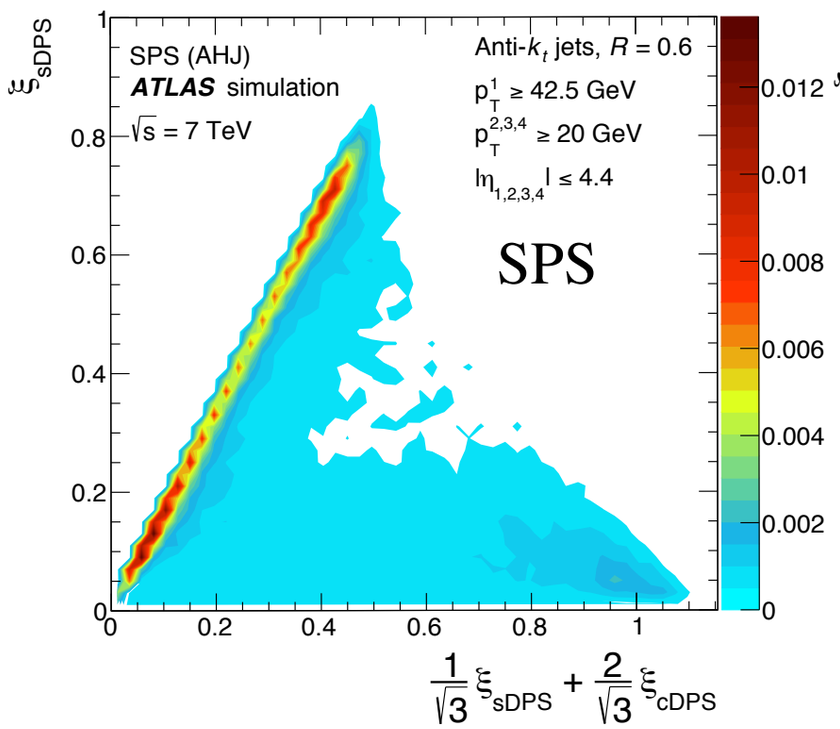
DPS in 4 jets events

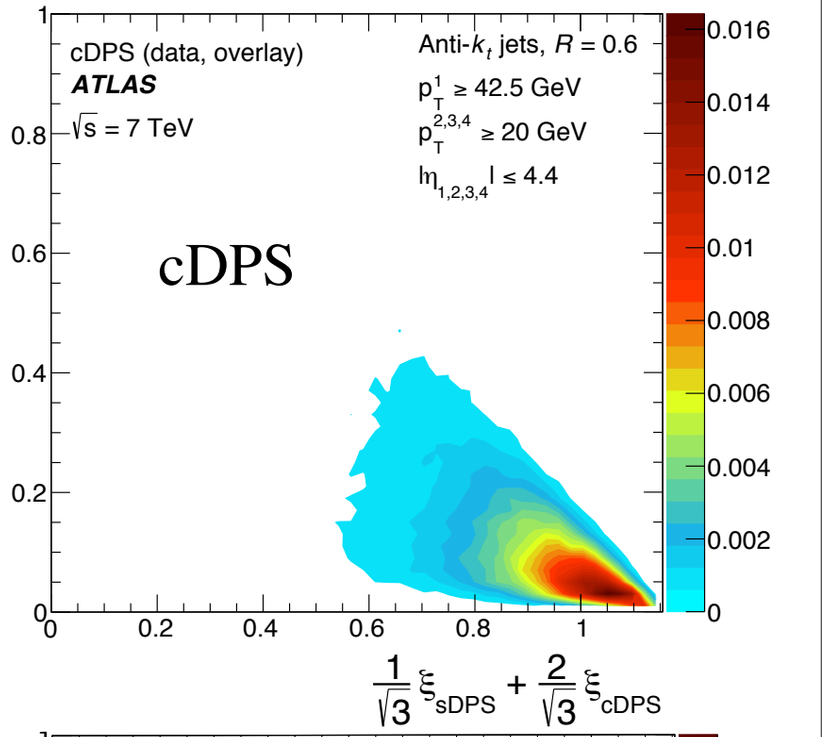
Output of NN: 3 probabilities

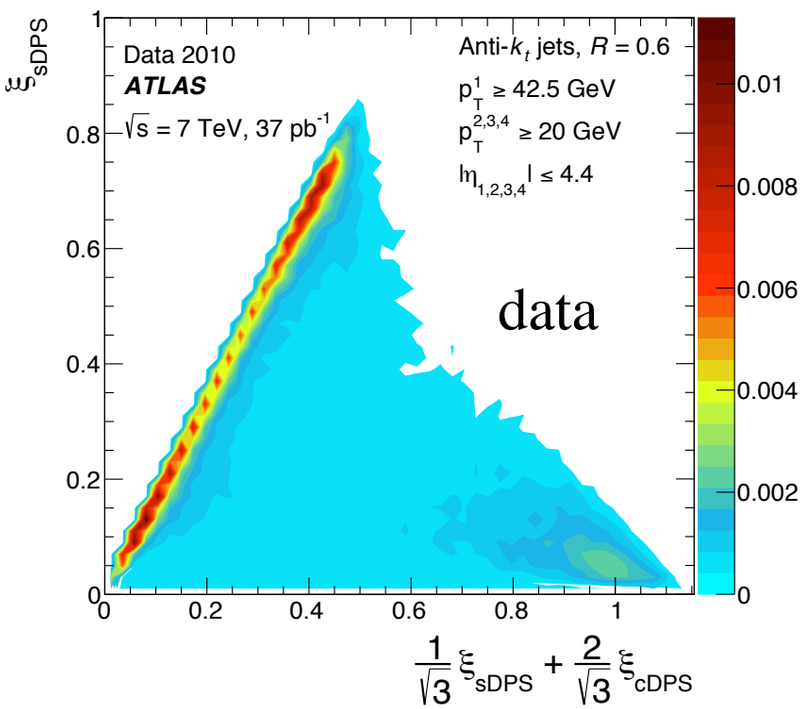
$$\xi_{SPS} + \xi_{cDPS} + \xi_{sDPS} = 1$$



2D Dalitz plots - NN output for test samples

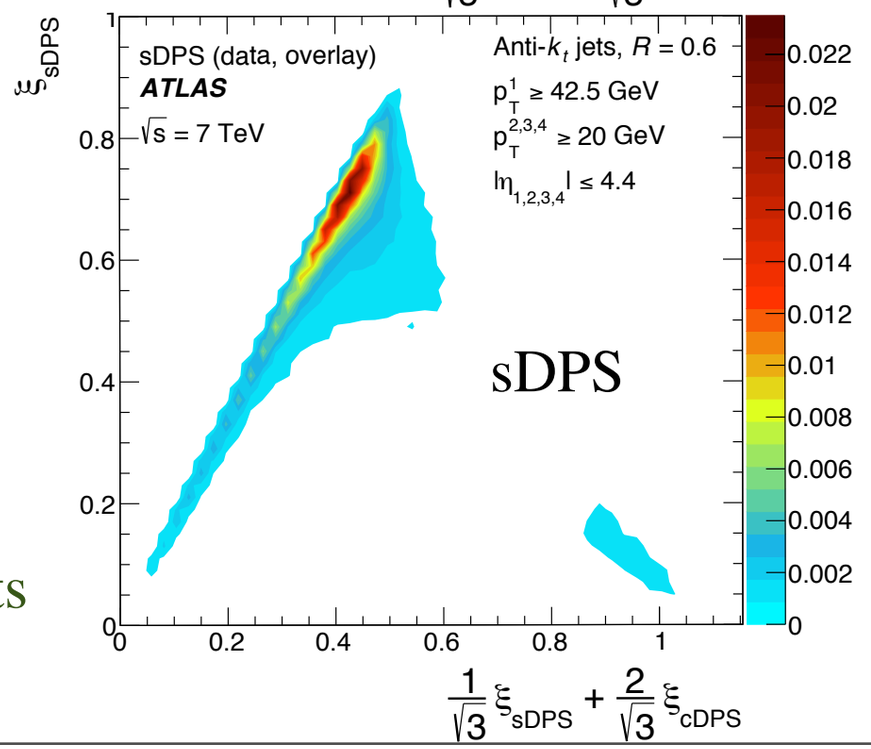






Event by event separation not possible, but estimation of different contributions may be done.

NN distribution for data visually consistent with superposition of three components



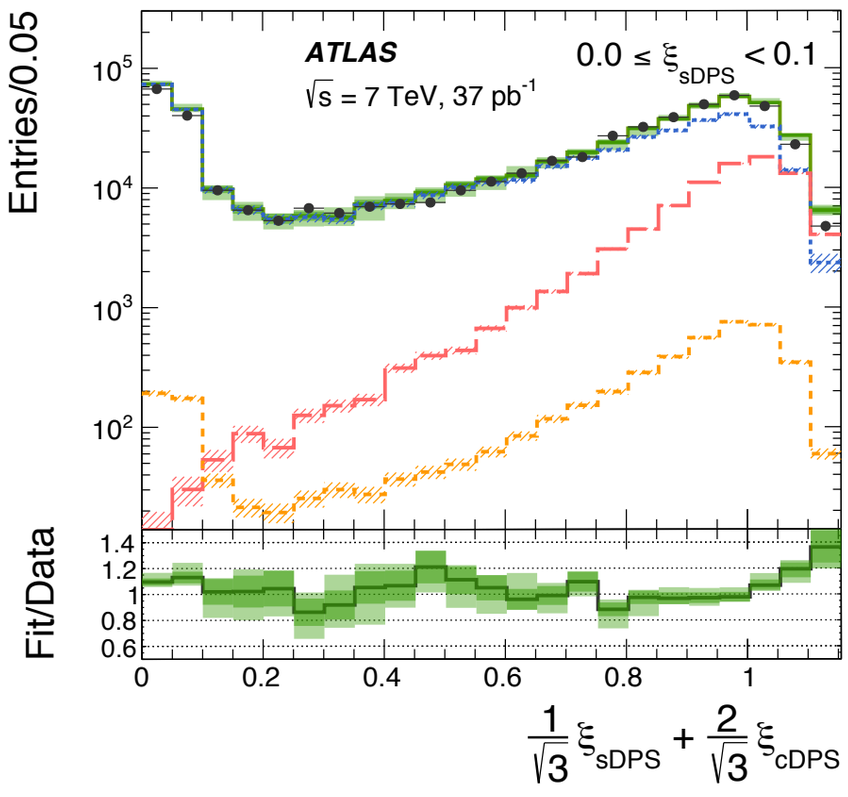
DPS in 4 jets events

ternary distribution in the data — ternary distributions in test samples normlised to measured 4-jet cross section

$$\mathcal{D} = (1\text{-}f_{cDPS} - f_{sDPS})\,\mathcal{M}_{SPS} + f_{cDPS}\,\mathcal{M}_{cDPS} + f_{sDPS}\,\mathcal{M}_{sDPS}$$

χ^2 minimisation with Minuit to find f_{cDPS} and f_{sDPS}

visualisation of the fit results by dividing tenary plot into 5 slices in ξ_{sDPS}



- Data 2010
- SPS (AHJ)
- cDPS (data, overlay)
- sDPS (data, overlay)
- Fit distribution (stat. uncertainty)
- Fit distribution (stat. + sys. uncertainty)

Anti-k_t jets, $R = 0.6$

$p_T^1 \geq 42.5$ GeV

$p_T^{2,3,4} \geq 20$ GeV

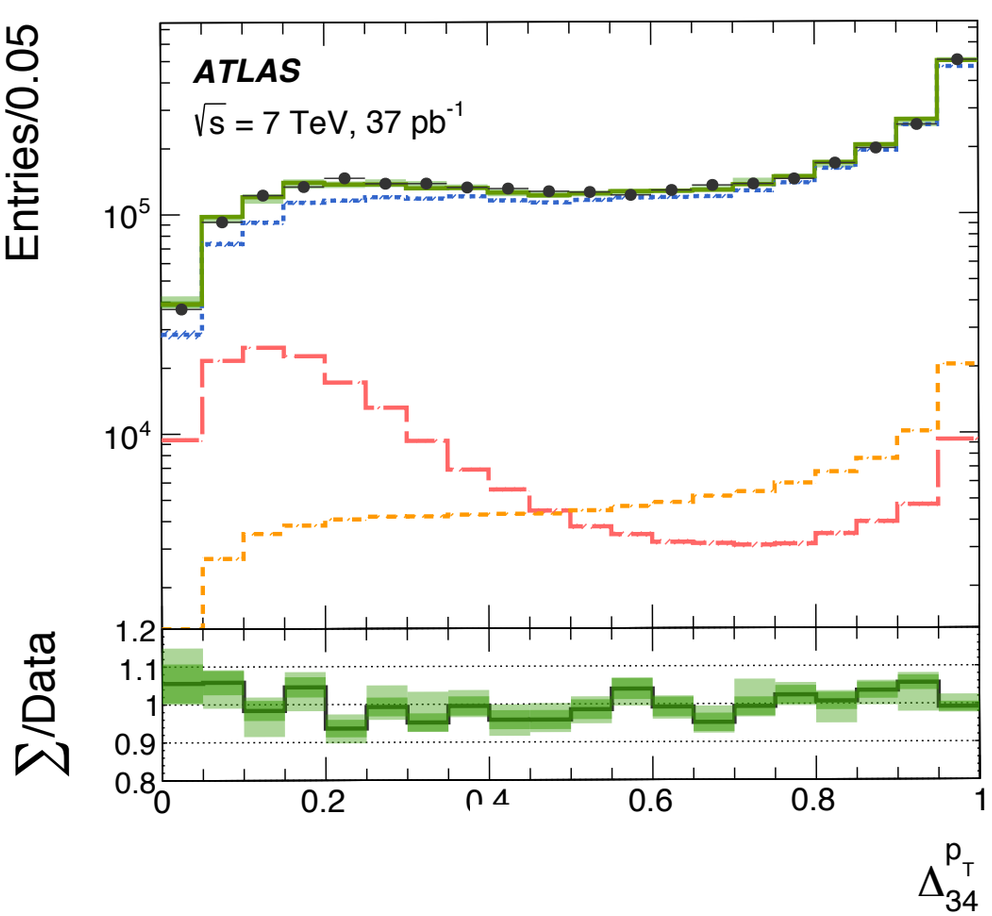
$|\eta_{1,2,3,4}| \leq 4.4$

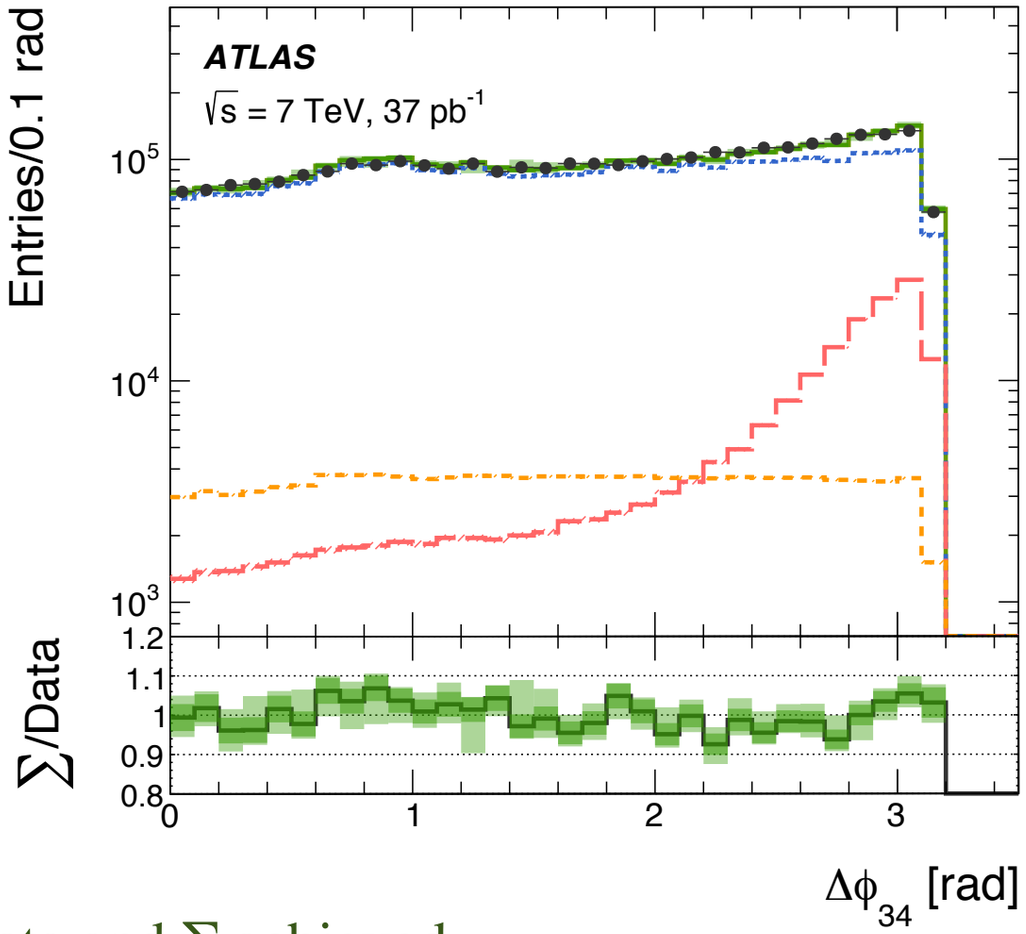
$$f_{DPS} = 0.092\ ^{+0.005}_{-0.011}\ (\text{stat.})\ ^{+0.033}_{-0.037}\ (\text{syst.})$$

contribution of f_{sDPS} to $f_{DPS} \sim 40\%$

DPS in 4 jets events

Test whether sum of all contributions (Σ) describes the data



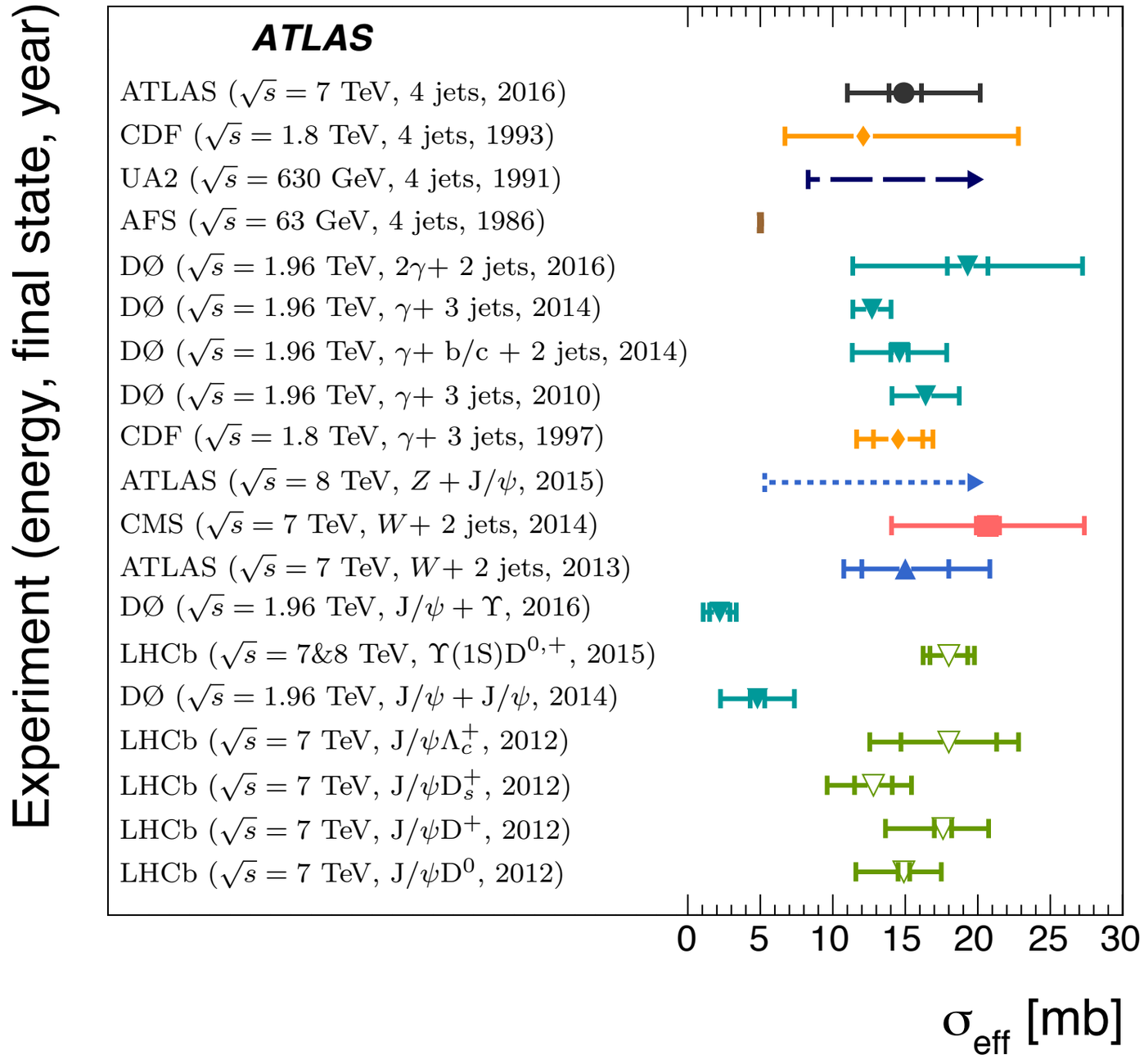


Good agreement between data and Σ achieved

Using dijet and 4-jet cross-sections, taking into account overlap in the cross-sections for dijet events:

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

DPS results overview

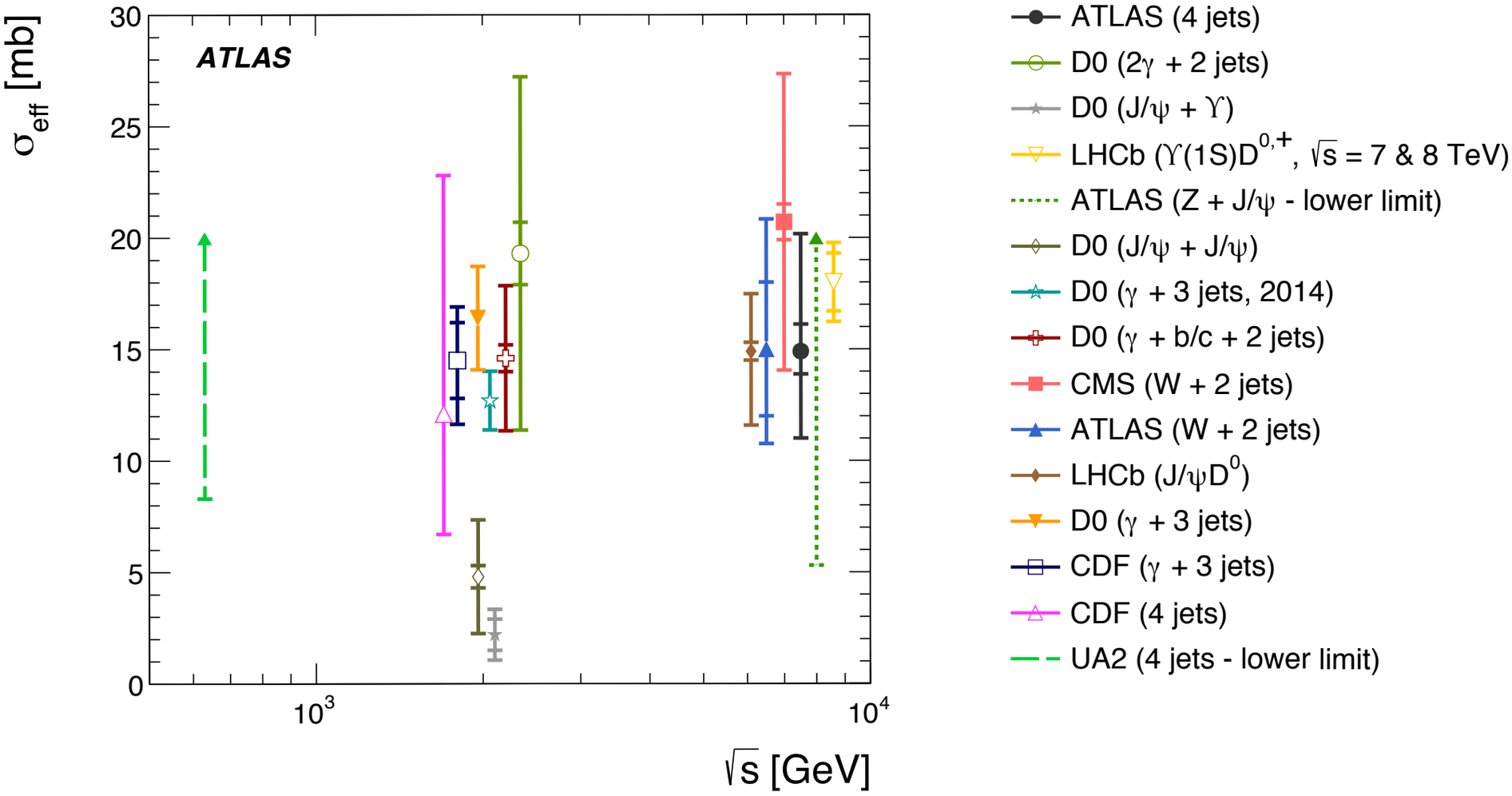


Effective cross section of DPS from different energies and final states measured by various experiments

Dashed arrows indicate lower limits

DPS results overview

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



Defining σ_{eff} assumptions are made which lead to process and energy independence.
No theoretical need for this.
More measurements at different energies would be helpful to test this assumption.

DPS summary

Presented five measurements related to DPS done by ATLAS .
Three provide measurement of σ_{eff} (W+2jets, prompt J/ψ pair, 4-jets)
Z+J/ψ measurement provides lower limit estimate of σ_{eff}
W+J/ψ shows sensitivity to DPS

Estimated fractions of DPS events in different final states:

final state	f_{DPS}
W+2jets	8%
4 jets	8%
J/ψ pair	6.6%
W+J/ψ	38%
Z+J/ψ	29%