Study of hard double parton scattering in four-jet events with the ATLAS detector

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and TRIUMF

- on behalf of the -

ATLAS Collaboration

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See ATLAS Collaboration, JHEP11 (2016) 110

Motivation

- *Measure the probability for the interaction of more than one pair of incident partons in the same proton-proton collision*
- *Study correlations in parton distributions*
- *Can be done in a variety of final states: 4 jets, 4 leptons (double Drell-Yan), 3 jets + γ, leptonically decaying gauge boson + 2 jets*

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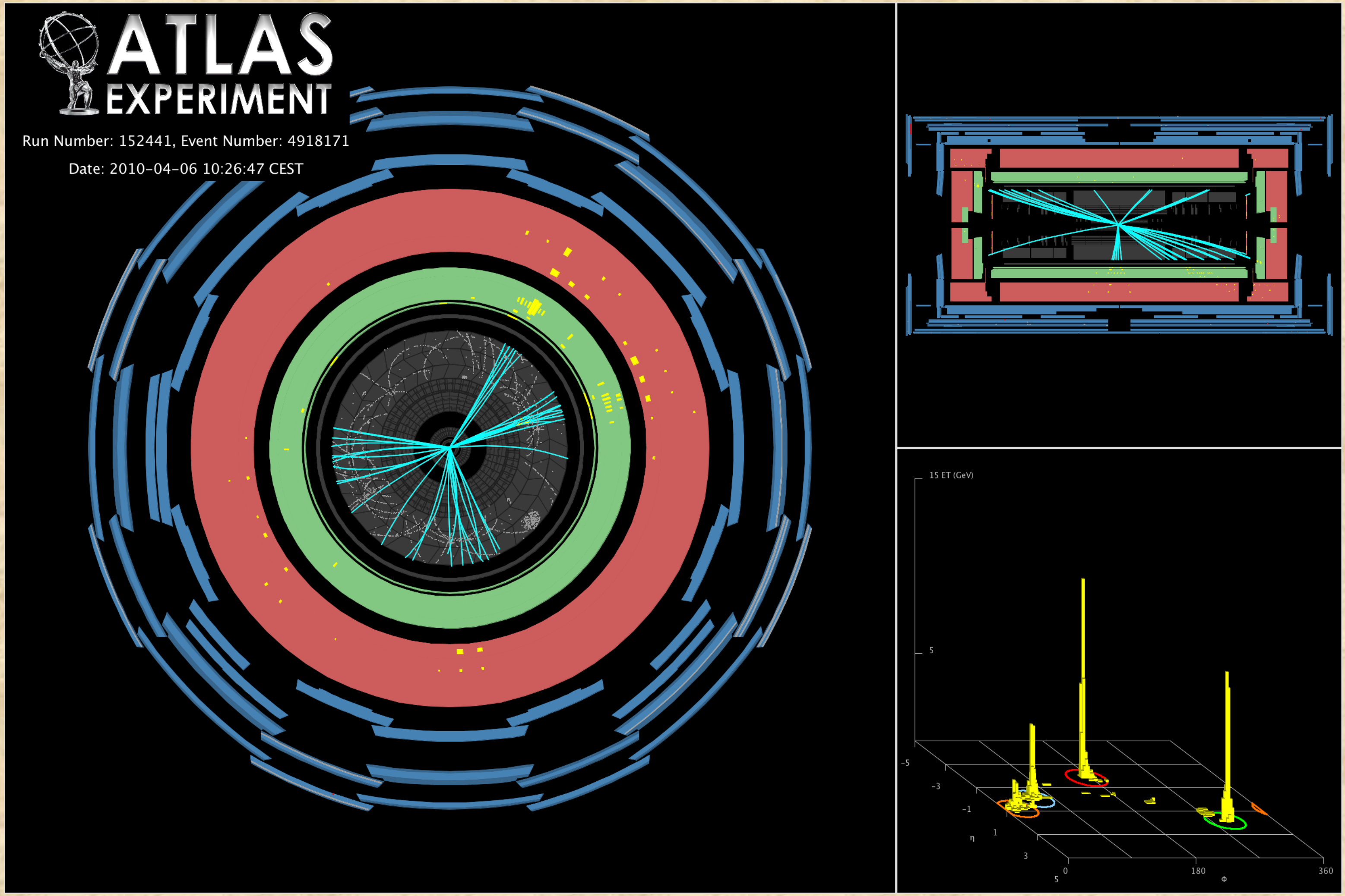
- *Can be done in a variety of final states: 4 jets, 4 leptons (double Drell-Yan), 3 jets + γ, leptonically decaying gauge boson + 2 jets*
- *As the CM energy increases, the average x of the partons involved in the collision decreases. Their density therefore increases, which makes it more probable that there will be more than one hard scattering. DPS more important @ the LHC*
- *A good description of the QCD contribution to multi-jet events is needed for searches for new physics at the LHC.*

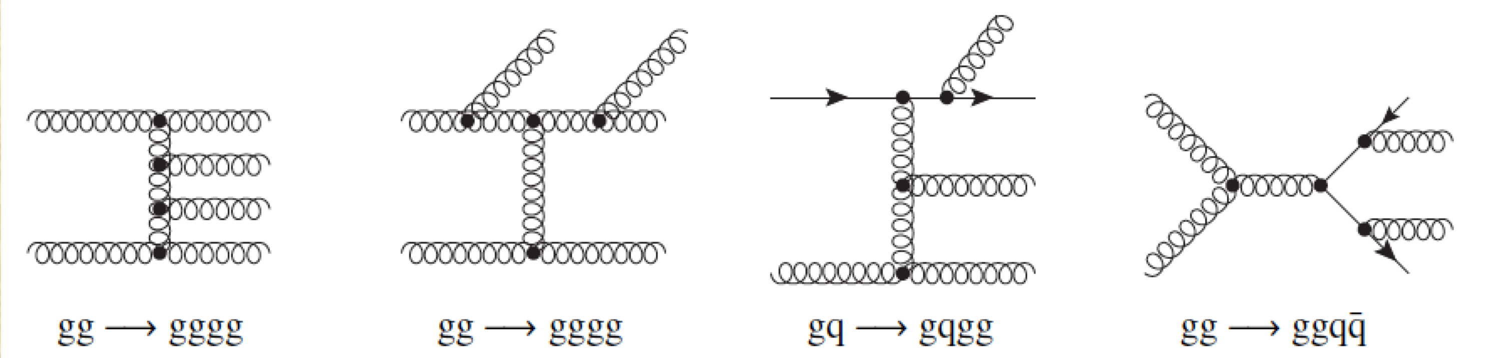
ATLAS 4-jet Event Display



Nice, clean event because of low pileup

Event Types

Single Parton Scattering (SPS)



Extra jets from radiation

Event Types

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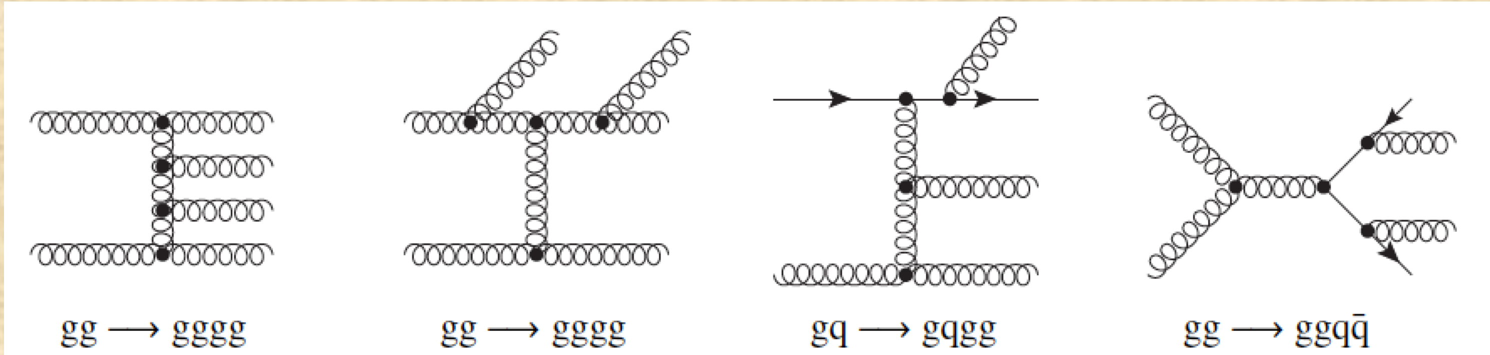

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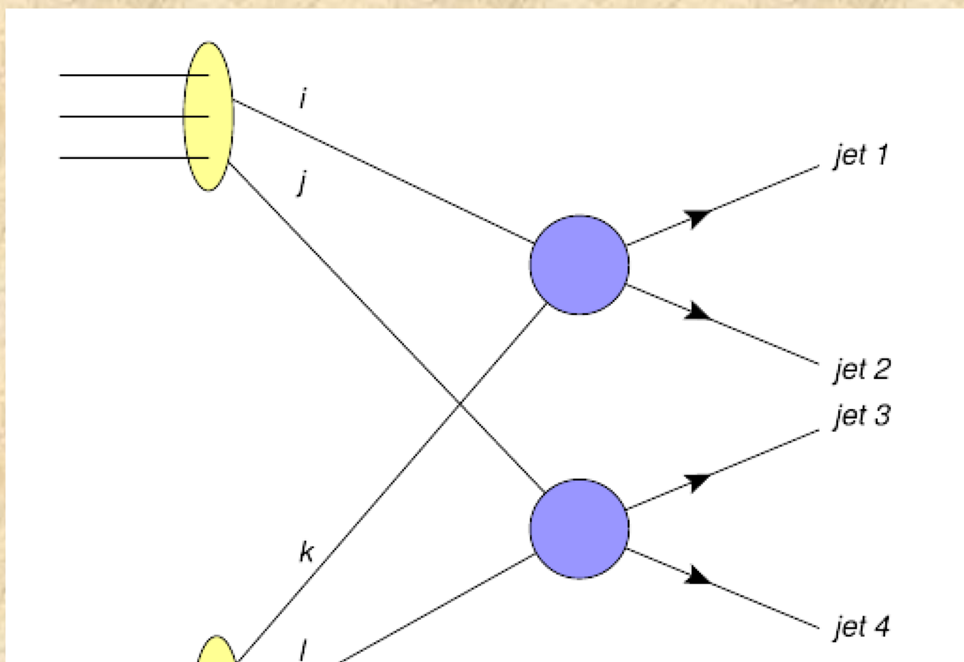

Complete Double Parton Scattering (cDPS)

Jets are ordered in p_T

Event Types

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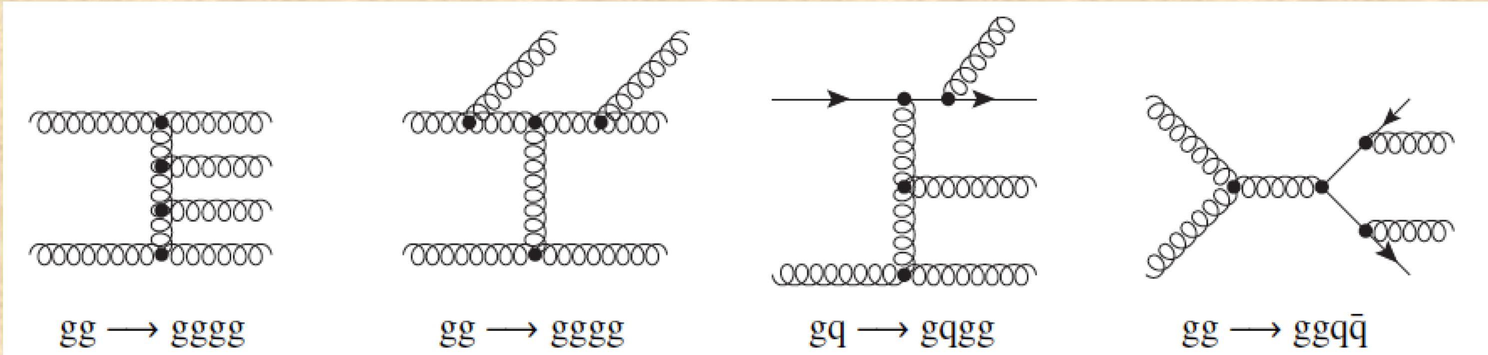

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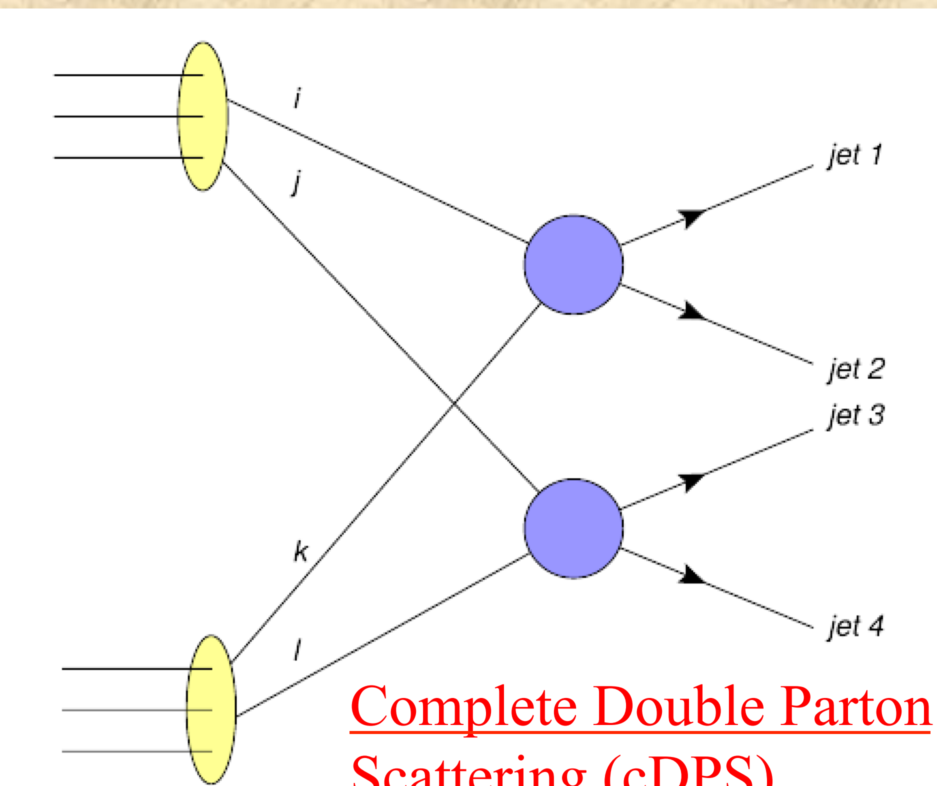
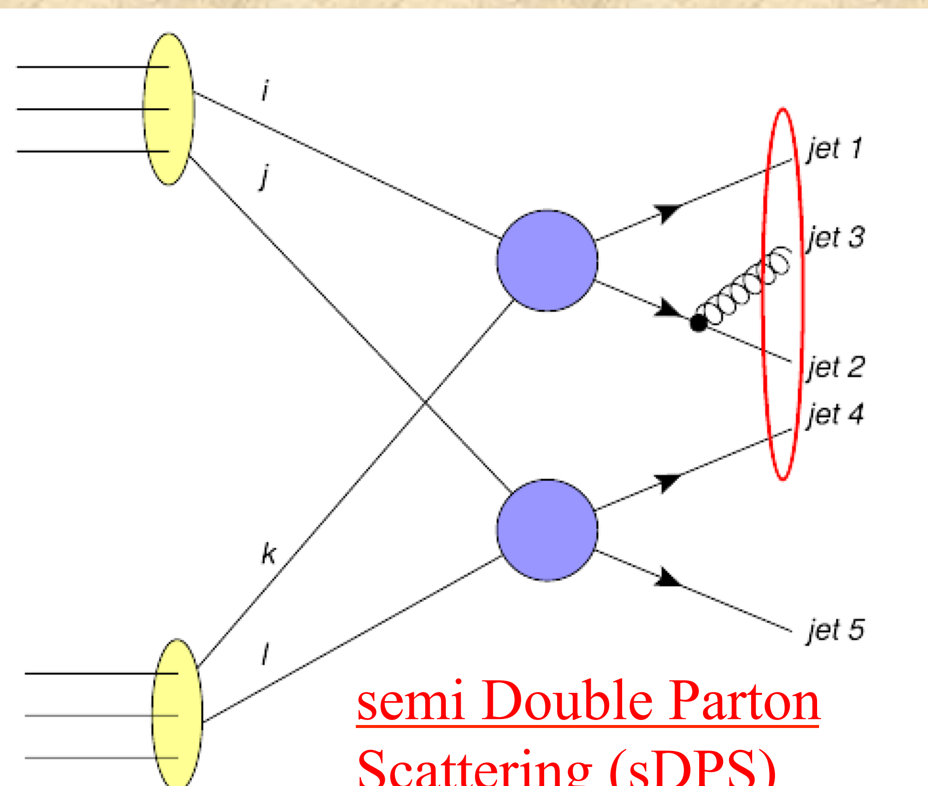


Complete Double Parton Scattering (cDPS)



semi Double Parton Scattering (sDPS)

Jets are ordered in p_t

Radiated jet with large p_t

DPS Formalism

Factorised cross-section for simultaneous processes A & B

$$d\hat{\sigma}^{\mathrm{DPS}}_{(\mathrm{A,B})}(s) = \frac{1}{1+\delta_{\mathrm{AB}}} \sum_{i,j,k,l} \int \underline{\Gamma_{ij}(x_1, x_2, r_\perp; Q_\mathrm{A}, Q_\mathrm{B})}\, \underline{d\hat{\sigma}^{(\mathrm{A})}_{ik}(x_1, x_1')}\, \underline{d\hat{\sigma}^{(\mathrm{B})}_{jl}(x_2, x_2')}$$

$$\times \underline{\Gamma_{kl}(x_1', x_2', r_\perp; Q_\mathrm{A}, Q_\mathrm{B})}\, dx_1 dx_2 dx_1' dx_2' d^2 r_\perp .$$

δ_{AB} is a symmetry term to avoid double-counting (=1 if A=B)

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$$\times \Gamma_{kl}(x_1', x_2', r_\perp; Q_\mathrm{A}, Q_\mathrm{B})\, dx_1 dx_2 dx_1' dx_2' d^2 r_\perp .$$

δ_{AB} is a symmetry term to avoid double-counting (=1 if A=B)

Factor out the longitudinal and transverse parton distributions:

$$\Gamma_{ij}(x_1, x_2, r_\perp; Q_\mathrm{A}, Q_\mathrm{B}) \simeq F(r_\perp) D_{ij}(x_1, x_2; Q_\mathrm{A}, Q_\mathrm{B}).$$

Integrate over the transverse distribution:

$$\sigma_{\mathrm{eff}}(s) = \left[\int d^2 r_\perp \, (F(r_\perp))^2 \right]^{-1}$$

Measure of the transverse parton correlations

DPS Formalism

- *Further factor out x_1, x_2, x'_1 and x'_2 and integrate*
- *Write:* $\sigma_{\mathrm{DPS}} = f_{\mathrm{DPS}} \cdot \sigma_{4j}$ *to get* $\sigma_{\mathrm{eff}} = \frac{1}{1+\delta_{\mathrm{AB}}} \frac{1}{f_{\mathrm{DPS}}} \frac{\sigma_{2j}^{\mathrm{A}} \sigma_{2j}^{\mathrm{B}}}{\sigma_{4j}}$
- *And also use:* $f_{\mathrm{DPS}} = f_{\mathrm{cDPS}} + f_{\mathrm{sDPS}}$

Determine σ_{eff} by measuring the 2-jet and 4-jet cross-section, and extracting f_{DPS}

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Analysis Strategy

$$\sigma_{nj} = \frac{N_{nj}}{\mathcal{C}_{nj}\mathcal{L}_{nj}}$$

C_{nj}: detector effects; L_{nj}: luminosity

$$\mathcal{S}_{nj} = \frac{N_{nj}}{\mathcal{L}_{nj}}$$

$$\alpha_{2j}^{4j} = \frac{\mathcal{C}_{4j}}{\mathcal{C}_{2j}^{A}\mathcal{C}_{2j}^{B}} = 0.93 \pm 0.01$$

Systematics cancel

$$\sigma_{\text{eff}} = \frac{1}{1+\delta_{\text{AB}}} \frac{\alpha_{2j}^{4j}}{f_{\text{cDPS}} + f_{\text{sDPS}}} \frac{\mathcal{S}_{2j}^{A}\mathcal{S}_{2j}^{B}}{\mathcal{S}_{4j}}$$

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Event Selection

- Dataset: full ATLAS 2010 data sample: $\sqrt{s}$ = 7 TeV; lumi = 37.3 pb^{-1}; $\langle\mu\rangle$ = 0.4

- N_{PV} = 1 (5 tracks with p_t > 150 MeV); no pileup

- R = 0.6 anti-kt jets reconstructed

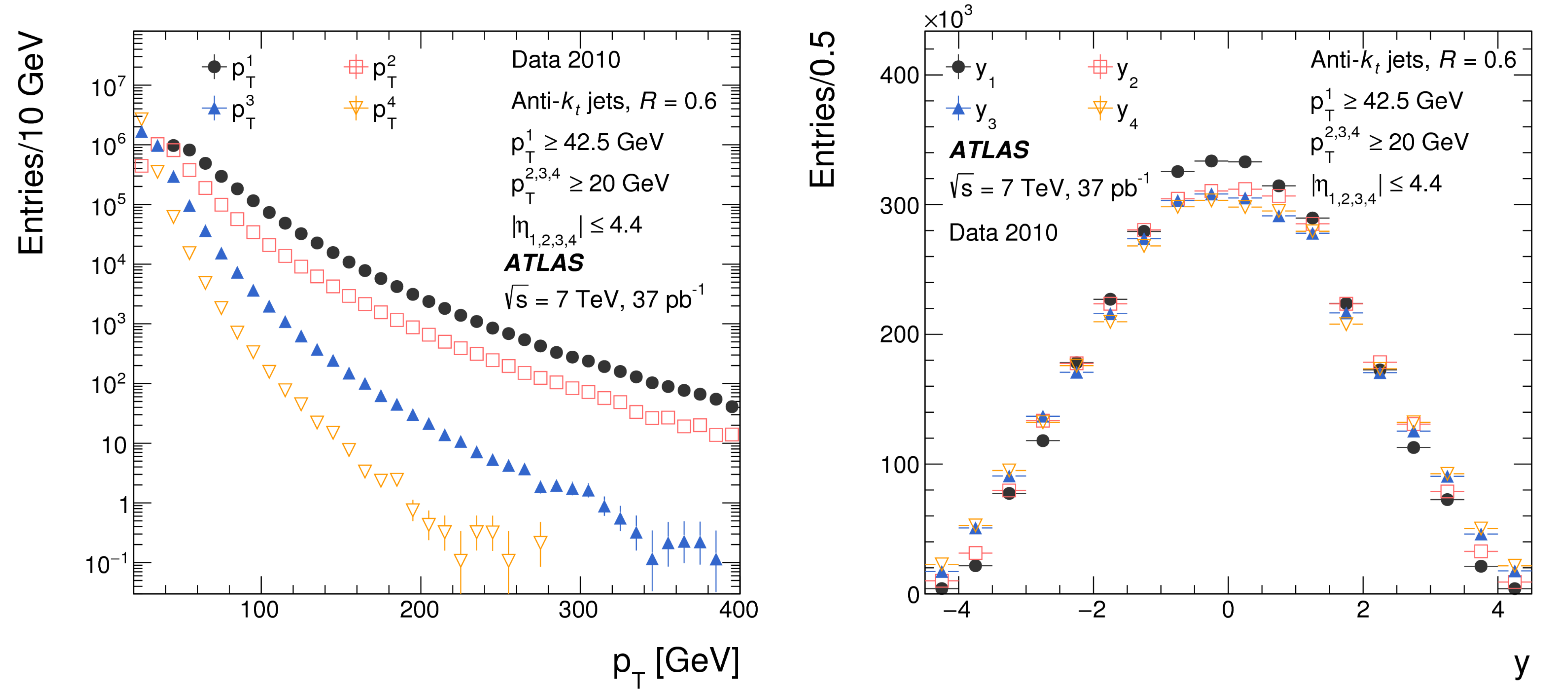
- p_t thresholds chosen so triggers are fully efficient
  Two classes of dijet events are used (A & B)

$$(\text{dijet A}) \quad \mathrm{N_{PV}} = 1\,, \quad N_{\mathrm{jet}} = 2\,, \quad p_T^{1,2} \geq 20\ \mathrm{GeV}\,, \quad |\eta_{1,2}| \leq 4.4\,,$$

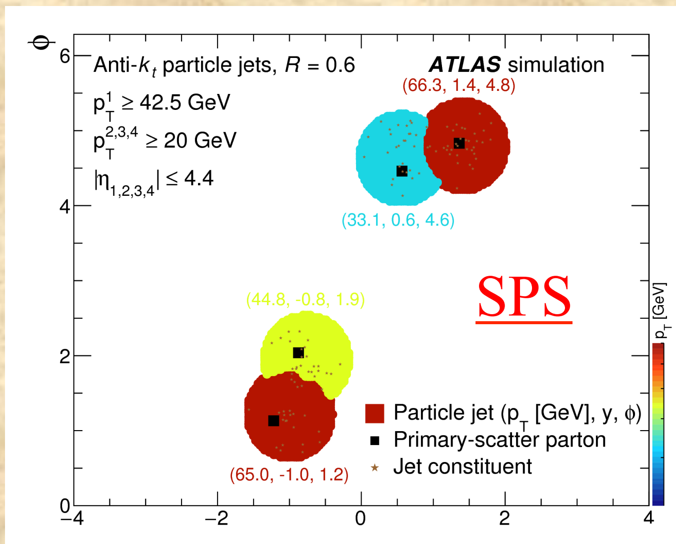
$$(\text{dijet B}) \quad \mathrm{N_{PV}} = 1\,, \quad N_{\mathrm{jet}} = 2\,, \quad p_T^{1} \geq 42.5\ \mathrm{GeV}\,, \quad p_T^{2} \geq 20\ \mathrm{GeV}\,, \quad |\eta_{1,2}| \leq 4.4\,,$$

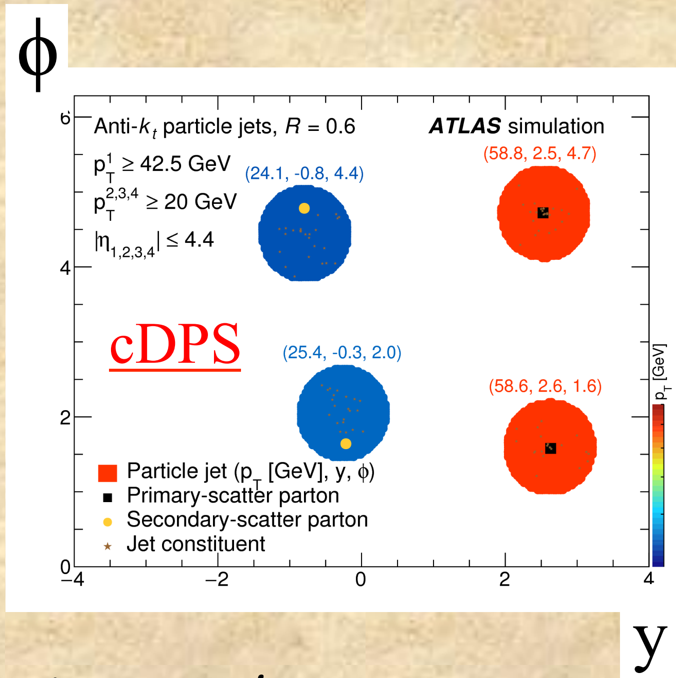
$$(\text{four-jet}) \quad \mathrm{N_{PV}} = 1\,, \quad N_{\mathrm{jet}} = 4\,, \quad p_T^{1} \geq 42.5\ \mathrm{GeV}\,, \quad p_T^{2-4} \geq 20\ \mathrm{GeV}\,, \quad |\eta_{1-4}| \leq 4.4$$

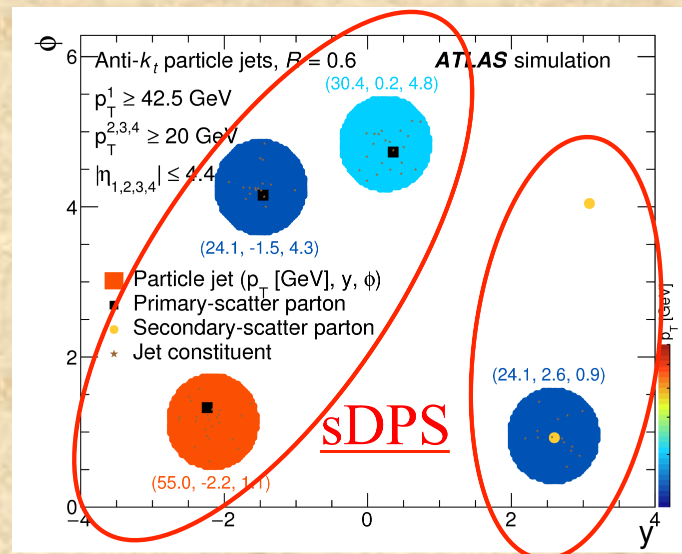
Kinematic Distributions



Event-type Discrimination





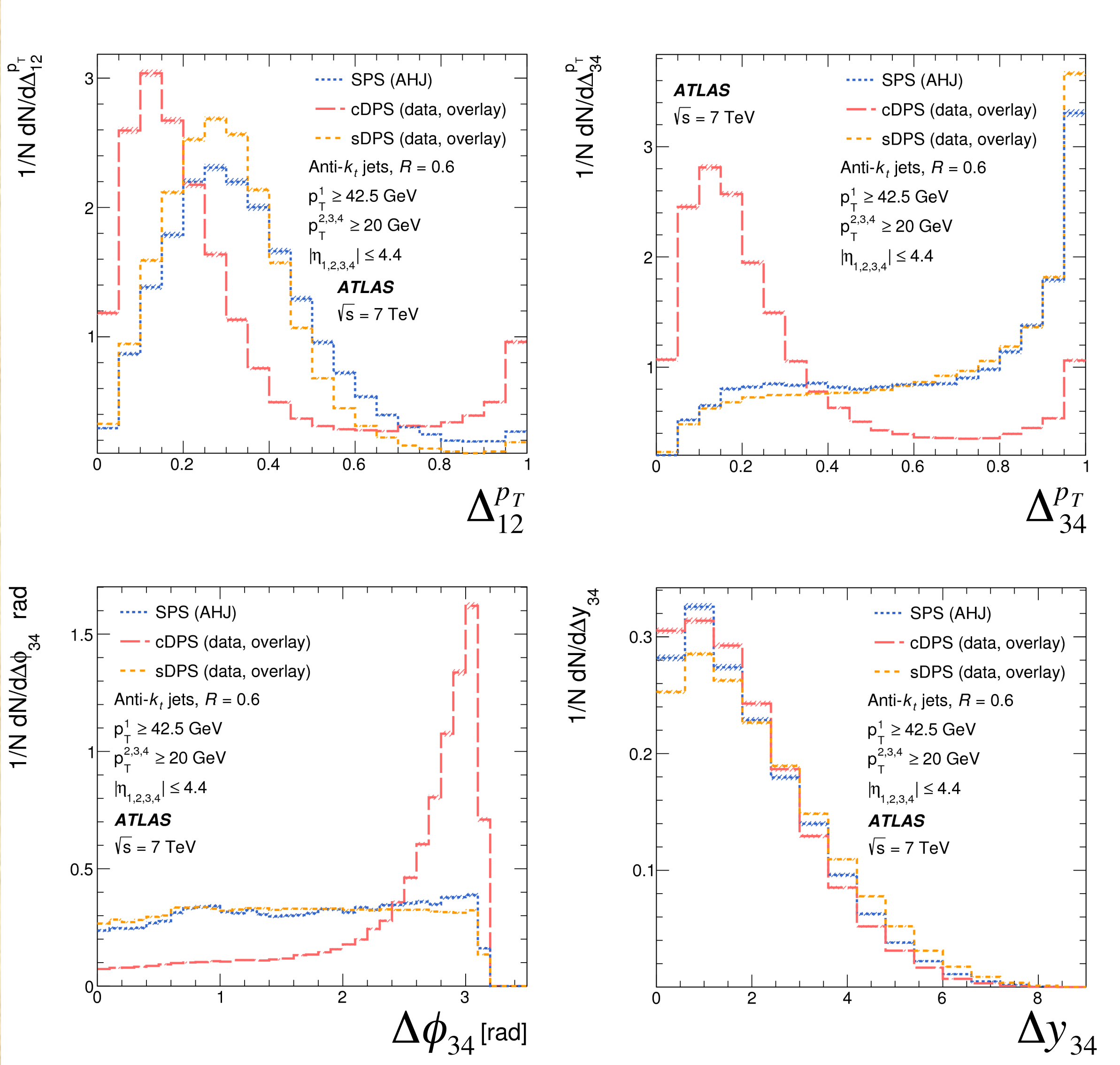


Use p_t balance and relative angular variables to discriminate between the three types of scattering

Discrimination Variables

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

$$|\phi_{1+2} - \phi_{3+4}|; \quad |\phi_{1+3} - \phi_{2+4}|; \quad |\phi_{1+4} - \phi_{2+3}|;$$



- *DPS jet pairs should each balance in p_t (Δ_{12}, Δ_{34}); no correlation between jet pairs*

- *Extra jets from SPS are from radiation; only approximate balance in 1-2 pair and no p_t balance in 3-4 pair*

- *Jets from each DPS pair should be back-to back; radiation jets should be collinear with originating jet in SPS*

- *Jets planes should not be correlated in DPS*

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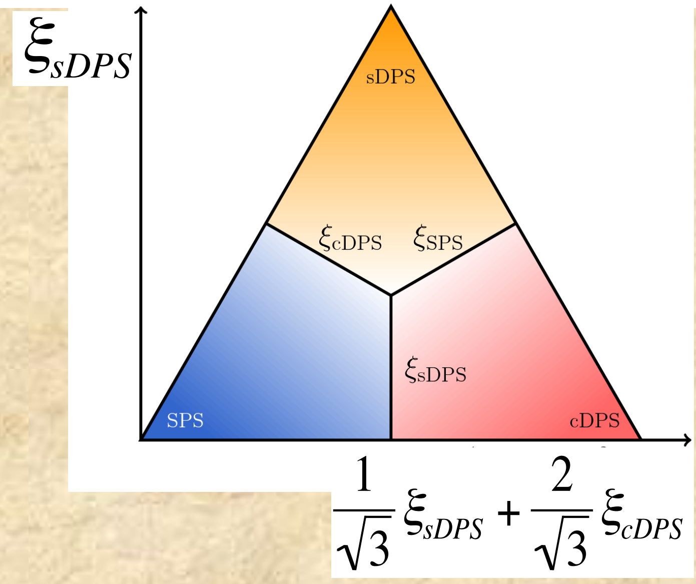
Neural Net Output

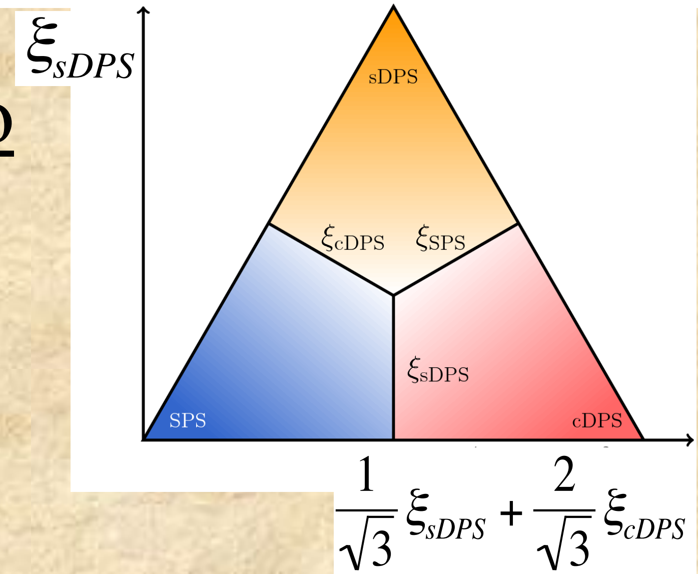


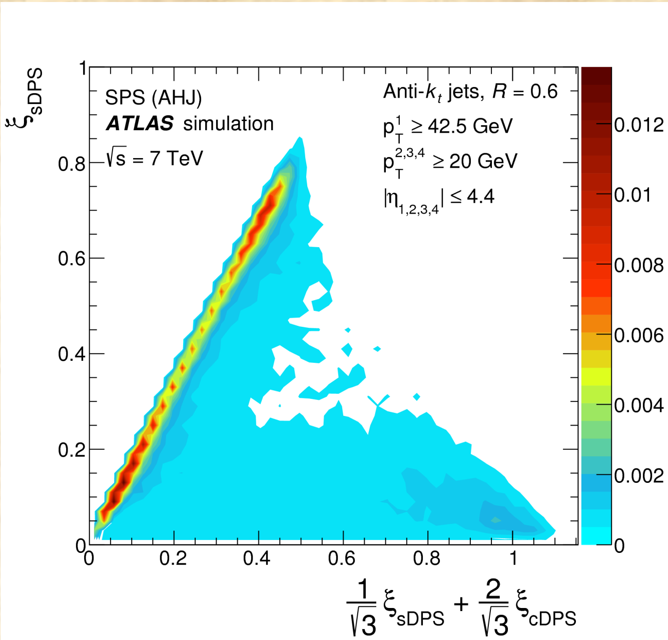
Use an Artificial Neural Network:

21 inputs; 2 hidden layers; 3 outputs: $\xi_{SPS}, \xi_{cDPS}, \xi_{sDPS}$

Plotted as perpendicular distance from an edge of the triangle

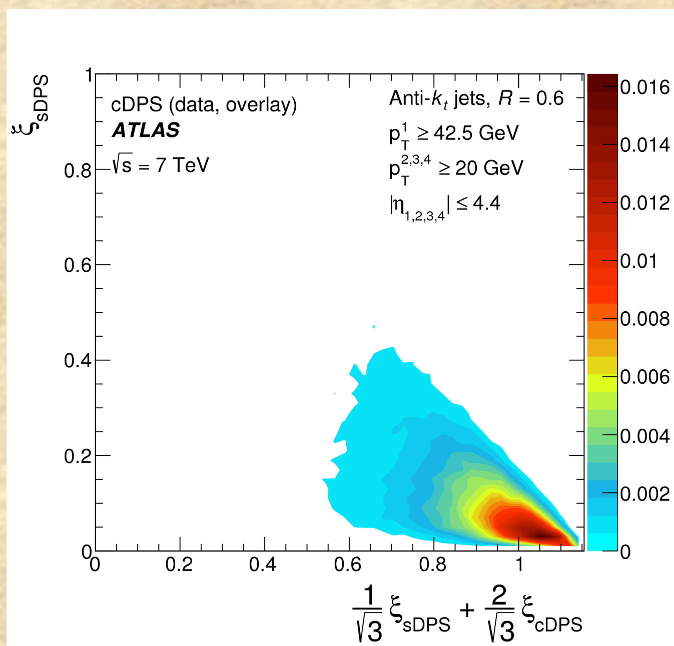
Neural Net Output | Monte Carlo



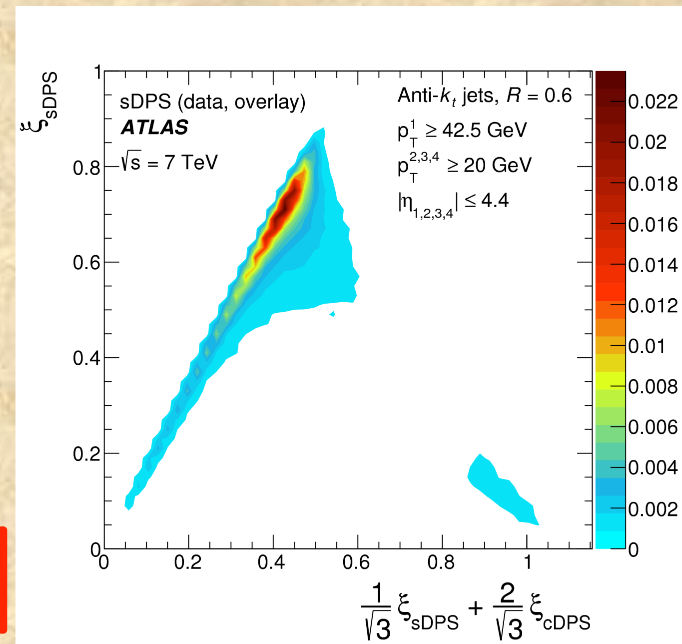


SPS: leaks into sDPS region

cDPS: clear peak in lower RH corner



sDPS: mostly at the top but leaks into SPS & cDPS



Use an Artificial Neural Network:

21 inputs; 2 hidden layers; 3 outputs: ξ_{SPS}, ξ_{cDPS}, ξ_{sDPS}

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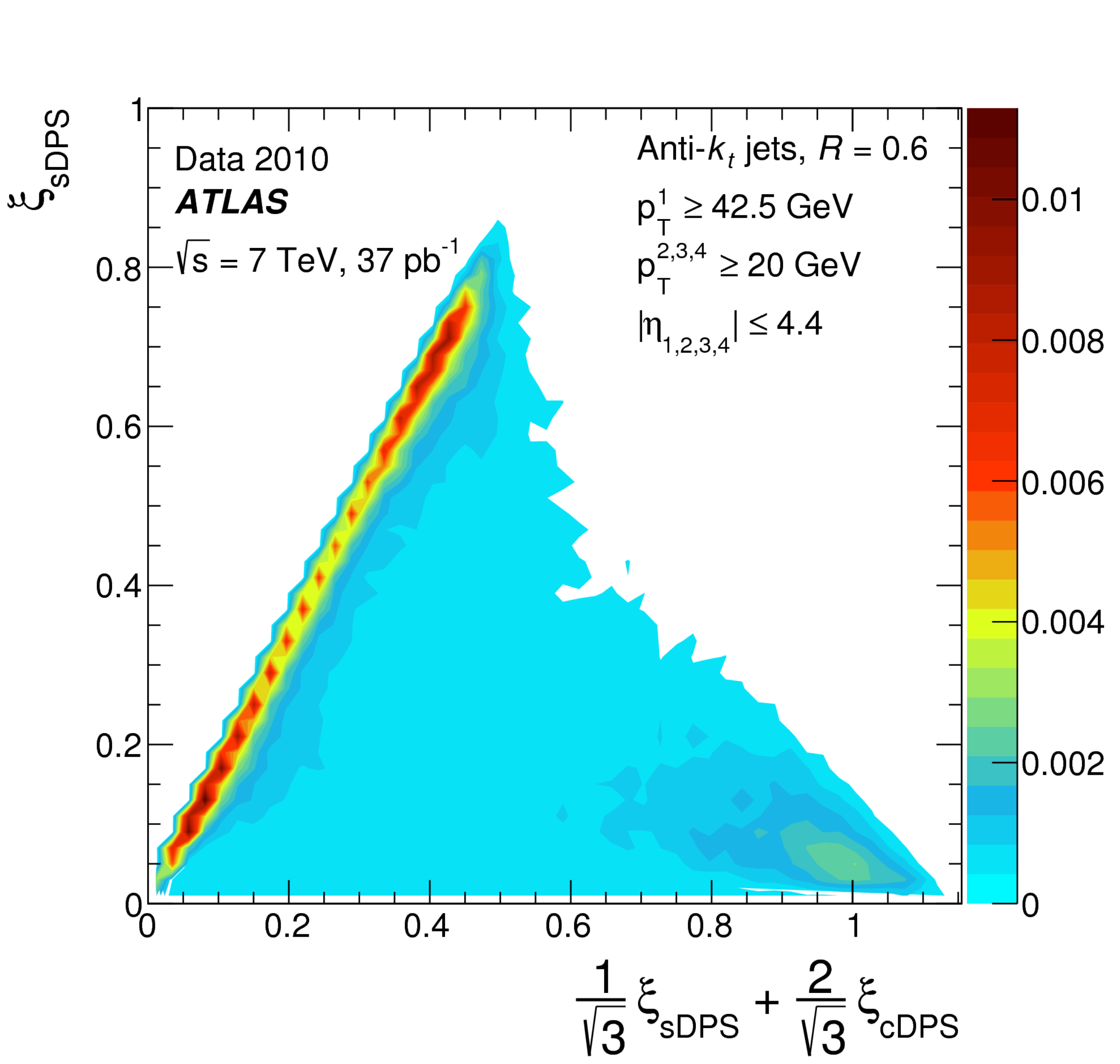
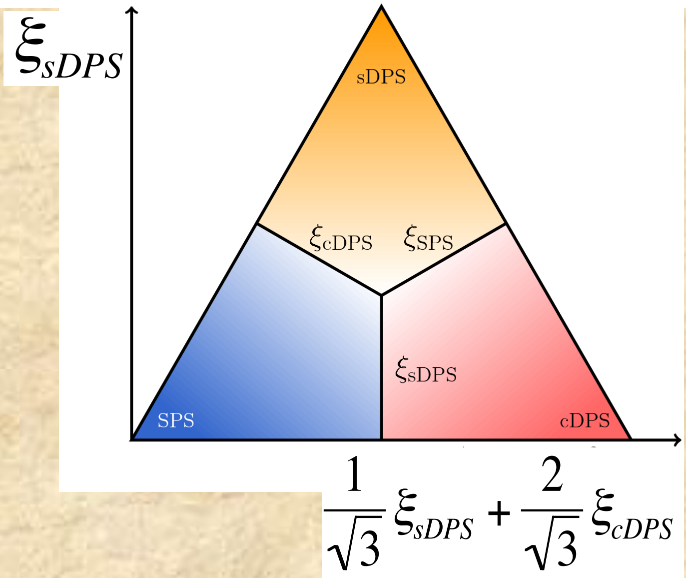
Neural Net Output

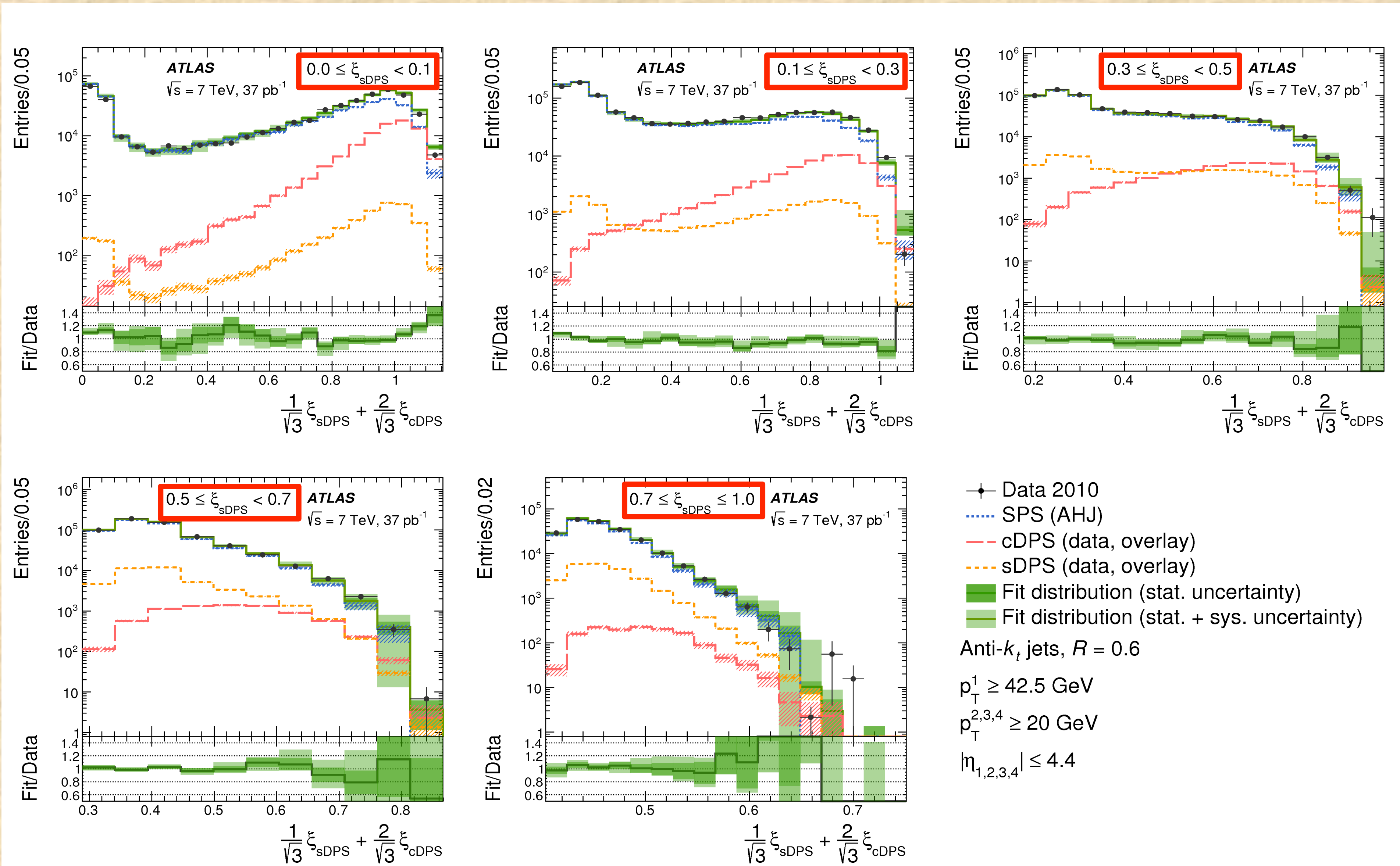
Data 2010





- *All 3 contributions are visible, with a clear cDPS component*
- *Do a multi-dimensional fit to extract* ξ_{SPS}, ξ_{cDPS}, ξ_{sDPS}

NN Fits in Various Projections



Systematic Uncertainties

Source of systematic uncertainty	Δf_{DPS}	$\Delta\alpha_{2\mathrm{j}}^{4\mathrm{j}}$	$\Delta\sigma_{\mathrm{eff}}$
Luminosity			$\pm 3.5\,\%$
Model dependence for detector corrections		$\pm 2\,\%$	$\pm 2\,\%$
Reweighting of AHJ	$\pm 6\,\%$		$\pm 6\,\%$
Jet reconstruction efficiency			$\pm 0.1\,\%$
Single-vertex events selection			$\pm 0.1\,\%$
Jet energy and angular resolution	$\pm 15\,\%$	$\pm 3\,\%$	$\pm 15\,\%$
JES uncertainty	$^{+32}_{-37}\,\%$	$\pm 12\,\%$	$^{+31}_{-19}\,\%$
Total systematic uncertainty	$^{+36}_{-40}\,\%$	$\pm 13\,\%$	$^{+35}_{-25}\,\%$

Dominated by the Jet-Energy scale and resolution
Uncertainties on the acceptances and x-sections largely cancel in ratios

Results

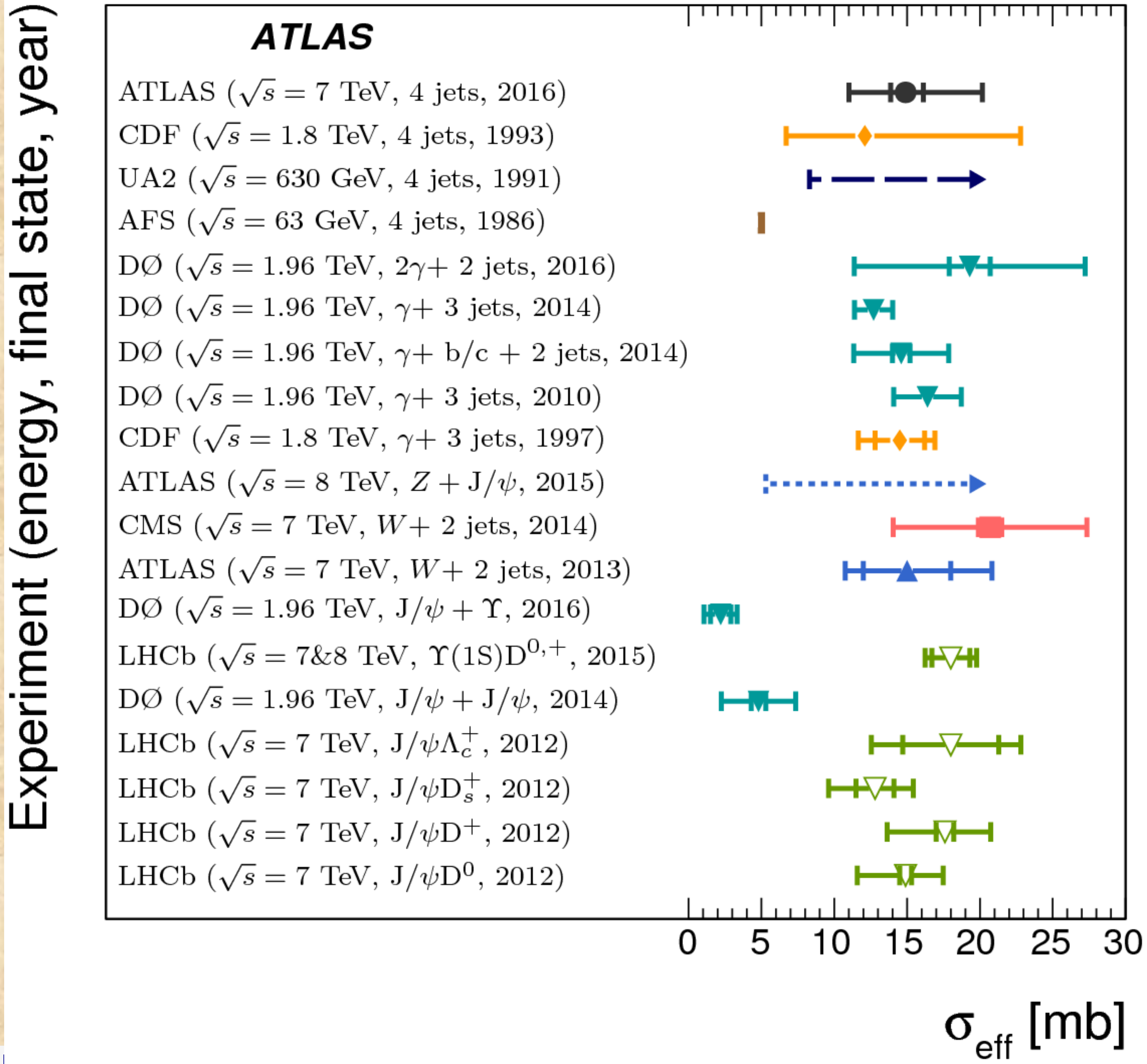
$$f_{\mathrm{DPS}} = 0.092\ ^{+0.005}_{-0.011}\ (\mathrm{stat.})\ ^{+0.033}_{-0.037}\ (\mathrm{syst.})$$

≈ 40% from sDPS

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

σ_{eff} is 21^{+7}_{-6}% of the inelastic cross-section measured by ATLAS at 7 TeV

Comparison to Other Experiments



Current data are consistent with the fact that σ_{eff} does not depend on the scattering process or the CM energy

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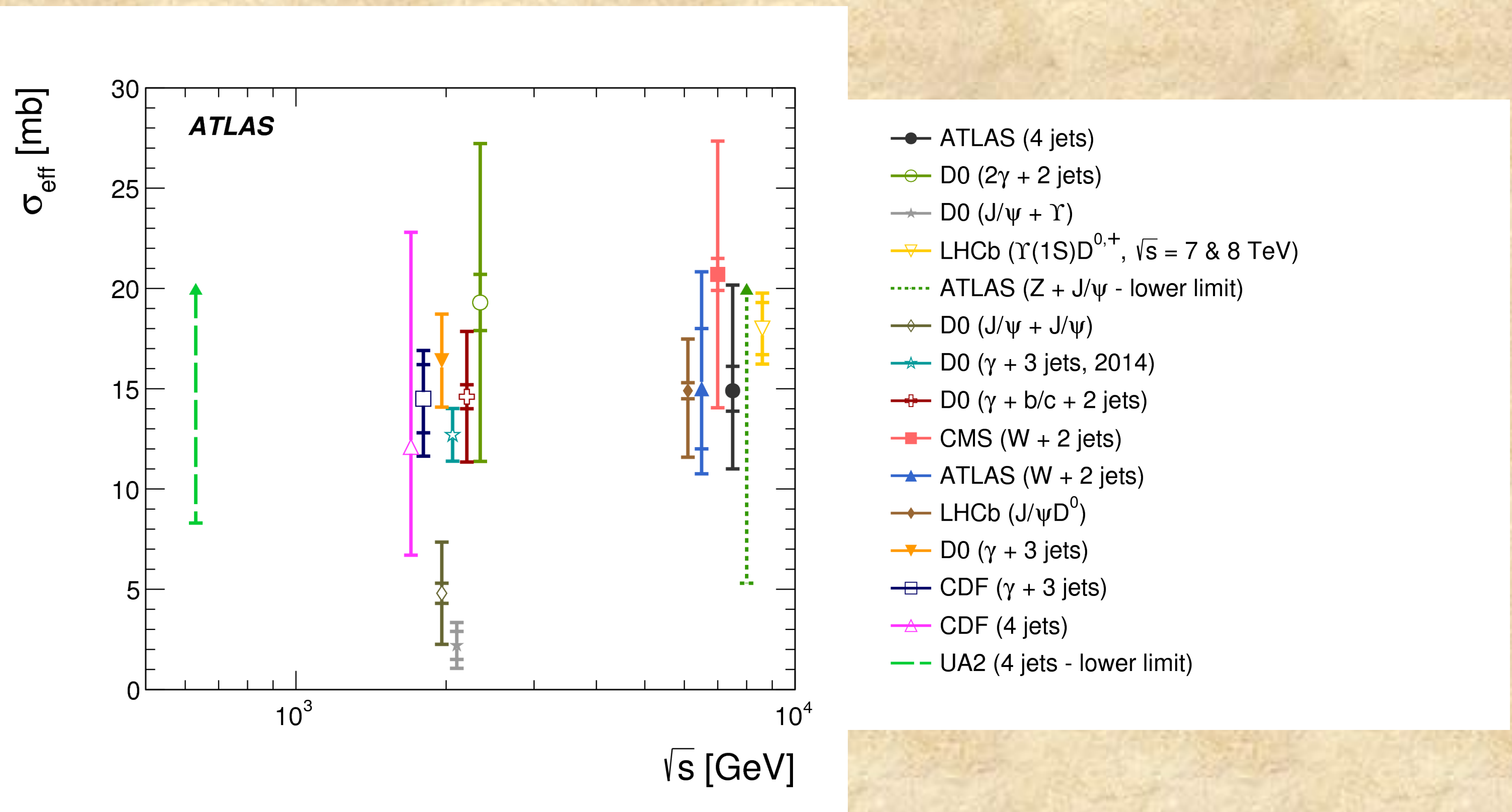
σ_{eff} vs $\sqrt{s}$

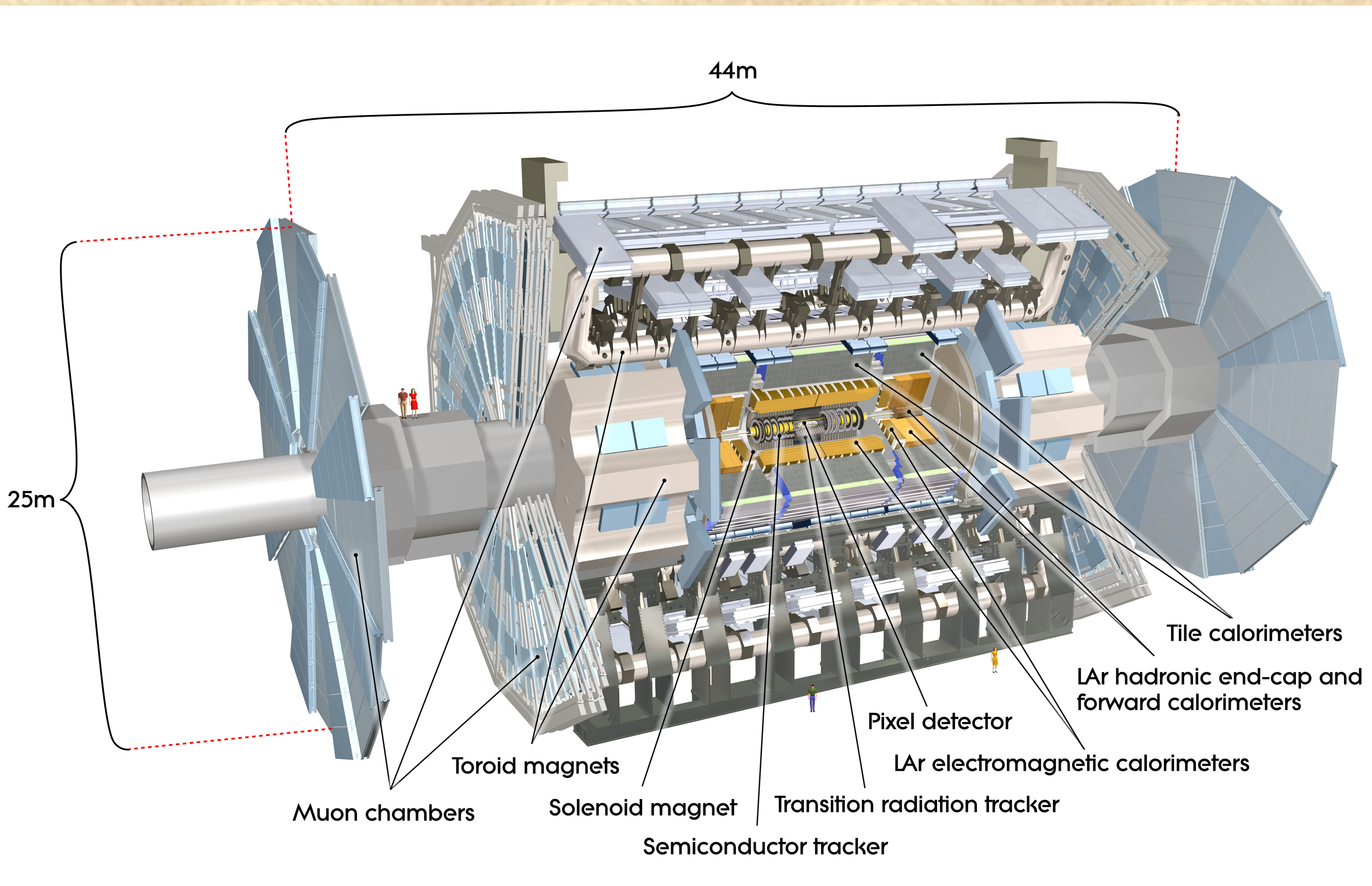


Conclusions

- *4-jet production has been used at ATLAS to study Double Parton Interactions in 7 TeV pp collisions*
- *An artificial neural network was used to extract the fraction of the 4-jet cross-section due to DPS, which was found to be about 9%*
- *The effective cross-section σ_{eff} , which is a measure of the transverse correlations of partons in the proton, was found to be consistent with previous measurements at other CM energies and using various final states.*
- *Work is continuing on the 13 TeV dataset*

Backup

ATLAS Spectrometer in a Nutshell



Inner Tracker:
Pixels, SCT, TRT

Calorimeters:
EM, Hadronic, FCAL

Muon Spectrometer

Hermetic (almost):
Good MET measurement => crucial for searches for new physics

Monte Carlo Generators

- **Main:** Alpgen (2.14) + Herwig (6.520) + Jimmy ➔ AHJ
  CTEQ6L1 PDFs and the AUET2 tune
  (MLM matching scale set to 15 GeV – partons of interest come from the ME)
  5 Alpgen samples: $2 \rightarrow n$ ($n = 2,3,\ldots,6$); combined using ME x-sections

- **Geometrical Acceptance**: Pythia 6.425
  with MRST LO* PDFs and the AMBT1 tune

- **Alternative:** Sherpa 1.4.2 with CT10 PDFs
  CKKW matching scale set to 15 GeV
  Compared to AHJ for the SPS sample

- **ATLAS detector:** GEANT4

Validity of Dijet Overlay