Double Parton Scattering
at hadron colliders

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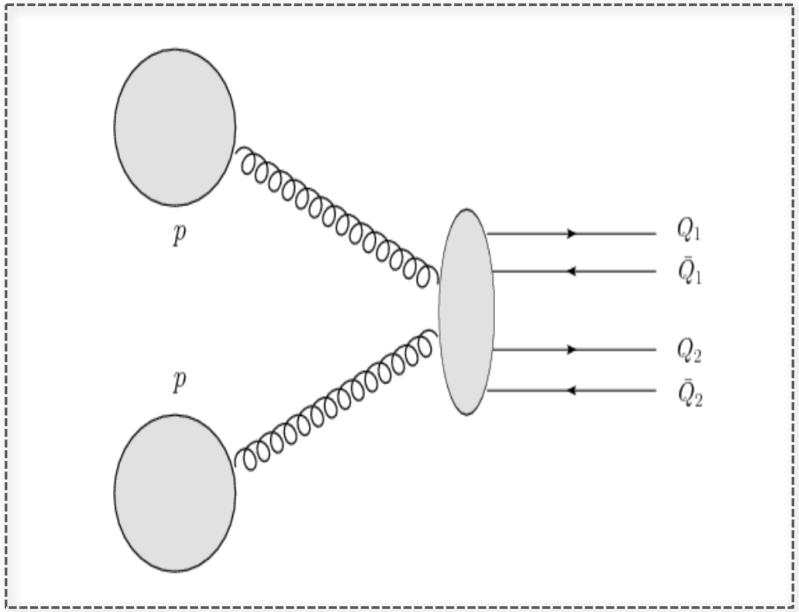
Outline
1) Intro to DPS
2) Review analyses
 ~ $2\gamma + 2j$
 ~ *2 b-jets + 2 light-jets*
 ~ *4 jets*
 ~ *di-quarkonia*
 ~ *same-sign WW*
3) Outlook / Overview

Double Parton Scattering

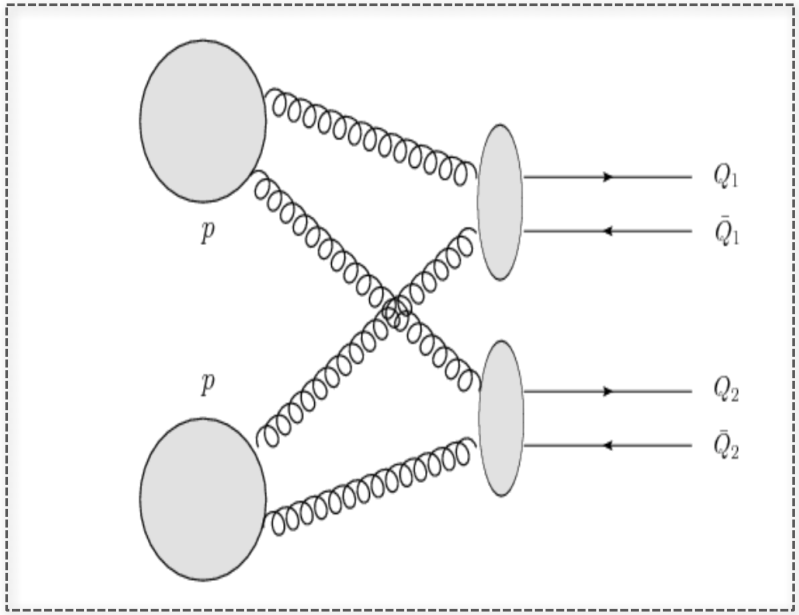
Single Parton Scattering (SPS)

- one hard parton-parton scatter



Double Parton Scattering (DPS)

- two hard scatters within same protons



Why Study DPS ?

Single Parton Scattering (SPS)

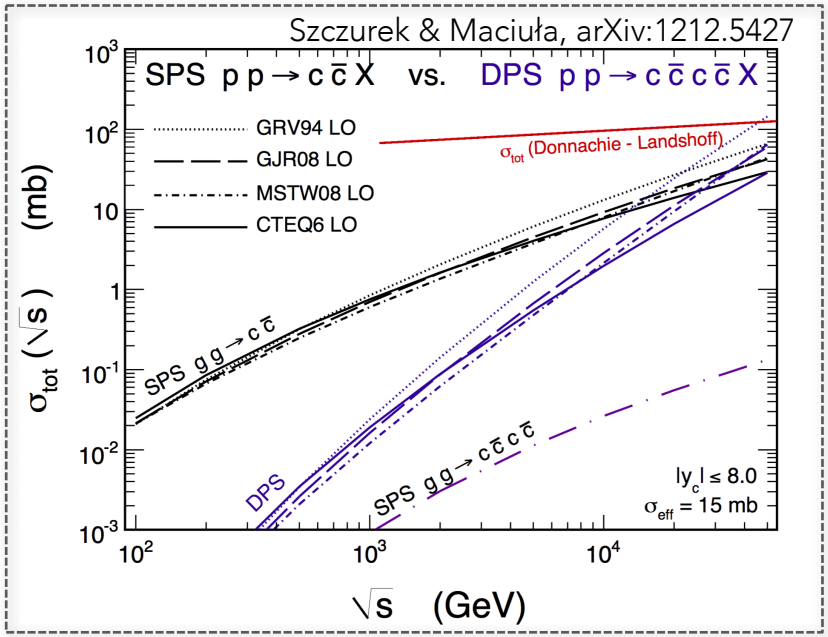
- Probe higher-order diagrams
- Disentangle backgrounds at higher $\sqrt{s}$
- Color Octet vs Singlet models in quarkonia production

Double Parton Scattering (DPS)

- Increasingly important at higher $\sqrt{s}$
- Probe transverse profile of proton PDF
- Partonic correlations ?
  – color, flavor interference, spin effects ?

Next-to-Leading Order SPS vs **Leading Order DPS**

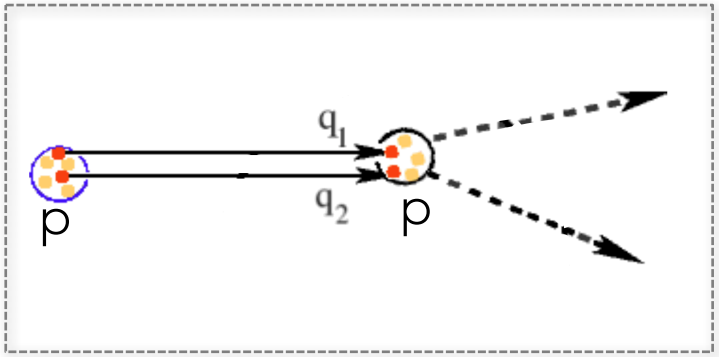
$\sigma_{SPS} \sim (\text{parton density})^2$ $\sigma_{DPS} \sim (\text{parton density})^4$



DPS cross section

- convolution of PDFs & elementary xsecs summed over all partons

$$\sigma^{\rm DPS}_{hh'\to ab} = \left(\frac{m}{2}\right)\sum_{i,j,k,l}\int \Gamma^{ij}_h(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2) \times \hat{\sigma}^{ik}_a(x_1,x_1',Q_1^2)\,\hat{\sigma}^{jl}_b(x_2,x_2',Q_2^2) \times \Gamma^{kl}_{h'}(x_1',x_2';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b};Q_1^2,Q_2^2)\,dx_1dx_2dx_1'dx_2'd^2b_1d^2b_2d^2b$$



- reduces to 'pocket formula' after assumptions
  - longitudinal, transverse components factorize
  - long'tl comps = 2 independent single-PDFs

$$\sigma^{\rm DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\frac{\sigma^{\rm SPS}_{(hh'\to a)}\cdot\sigma^{\rm SPS}_{(hh'\to b)}}{\sigma_{\rm eff}}$$

- *where m* is number of "distinguishable partonic subprocesses" (eg. m=1 for J/ψ-J/ψ, m=2 for J/ψ-Y)

What is "$\sigma_{\rm eff}$" ?

- ~effective transverse overlap area
- ~transverse distance btwn partons
- ~partonic density
- ~tells about "conditional prob" to have a second hard scatter
- theory estimates ~30 mb
- data says ~5-25 mb
- ~15 mb typically used for calculations

World Data for σ_{eff}

Sigma Effective

$$\sigma_{\text{eff}} = \left(\frac{m}{2}\right) \frac{\sigma^{\text{SPS}}_{(hh'\to a)} \cdot \sigma^{\text{SPS}}_{(hh'\to b)}}{\sigma^{\text{DPS}}_{(hh'\to ab)}}$$

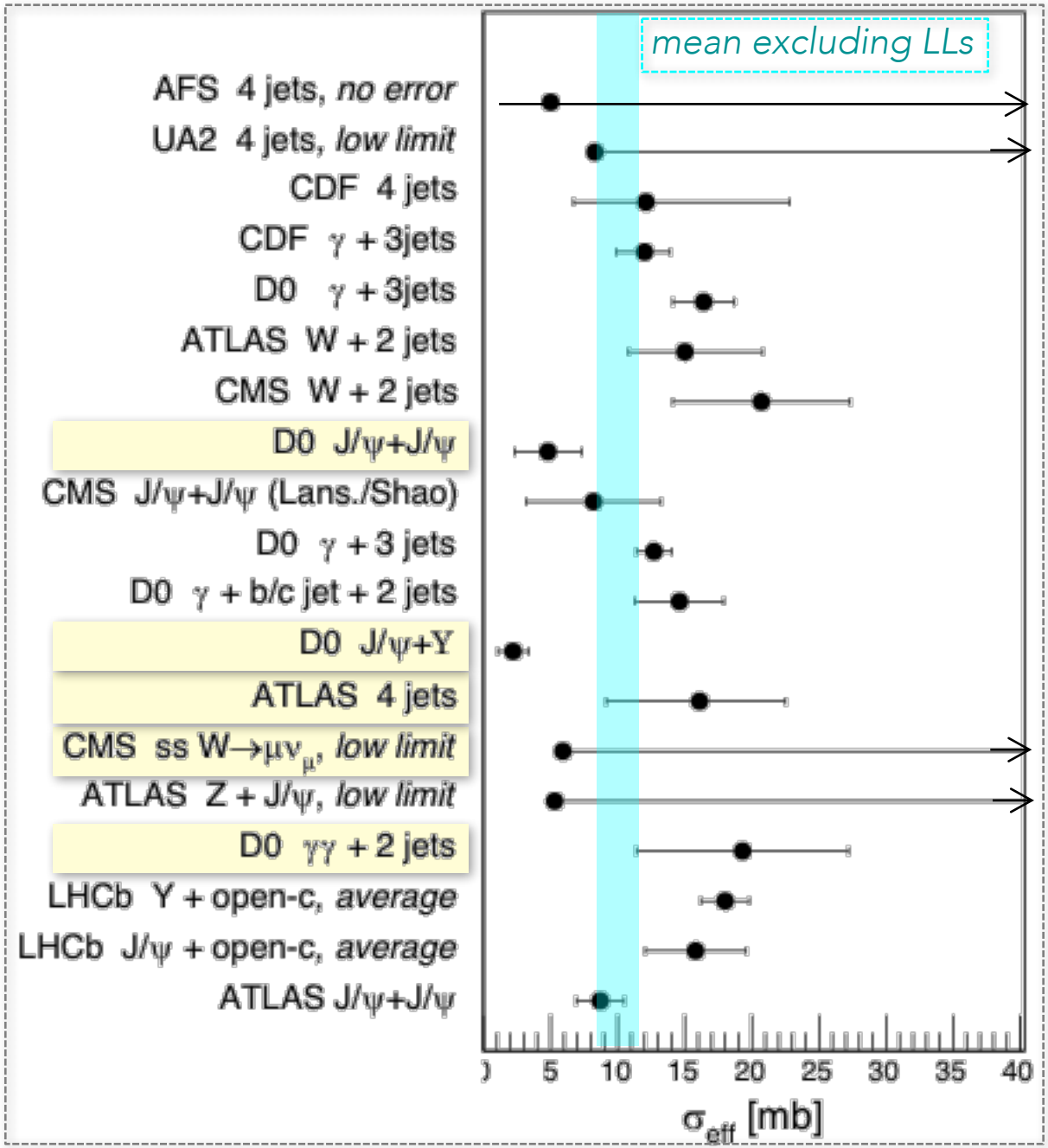
When does DPS play a role ?

- several particles in final state (typically 4 or more)
- high-energy hadron collisions (probing low-x)

A few examples:

- multi-jets (4 jets, 3 jets + γ, etc)
- di-quarkonia
- double open-charm/beauty
- Z/W + (jets / quarkonia / etc)
- double same-sign W

addressed in this talk



2 photons + 2 jets

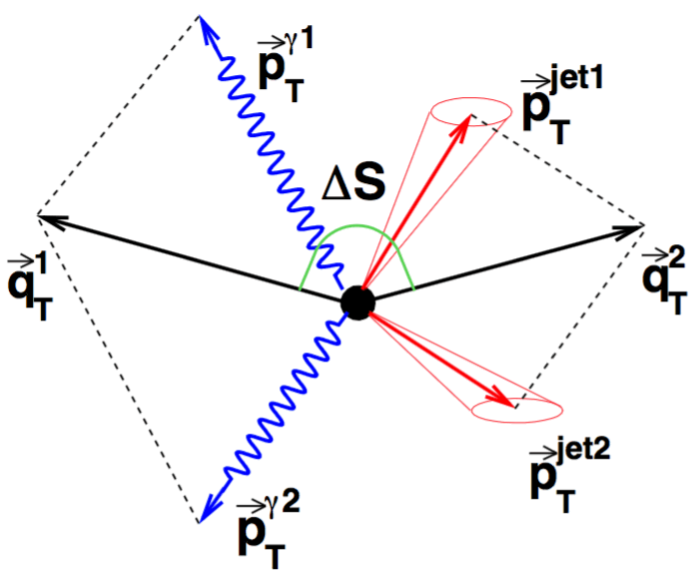
D0 – Tevatron 1.96 TeV

- Key discriminant:
  azimuthal angle between di-photon & di-jet

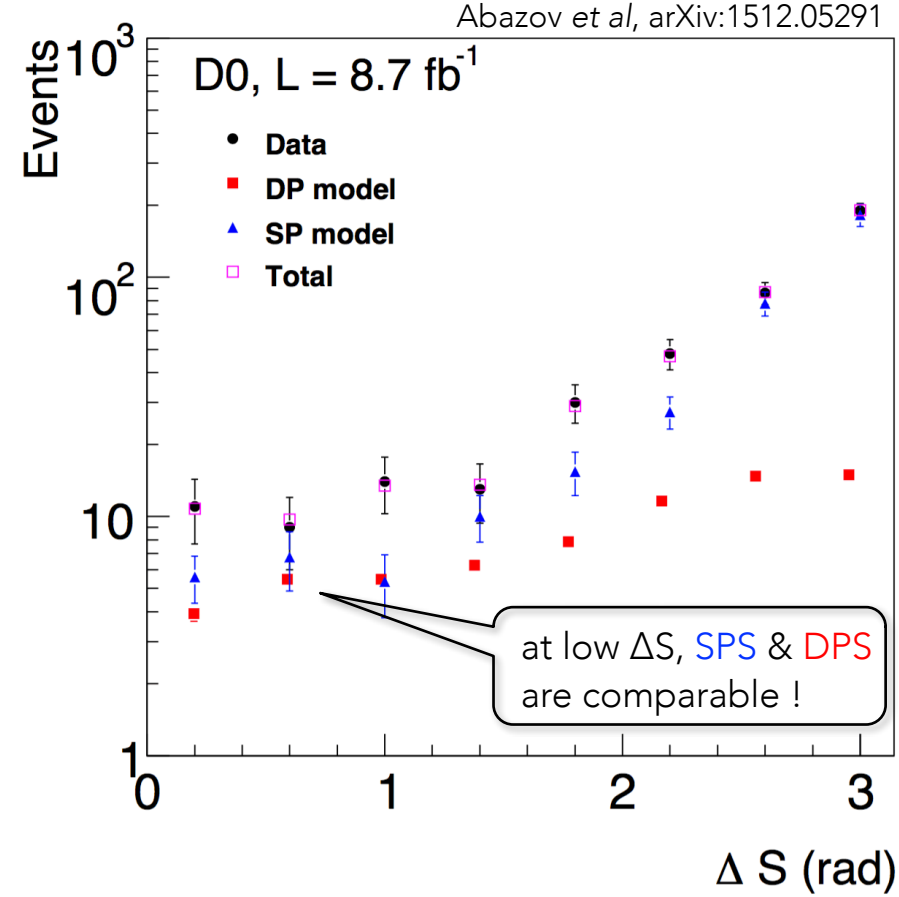
$$\Delta S \equiv \Delta\phi\left(\vec{q}_{\mathrm{T}}^{\,1},\ \vec{q}_{\mathrm{T}}^{\,2}\right)$$

$$\vec{q}_{\mathrm{T}}^{\,1} = \vec{p}_{\mathrm{T}}^{\,\gamma_1} + \vec{p}_{\mathrm{T}}^{\,\gamma_2}$$

$$\vec{q}_{\mathrm{T}}^{\,2} = \vec{p}_{\mathrm{T}}^{\,\mathrm{jet}_1} + \vec{p}_{\mathrm{T}}^{\,\mathrm{jet}_2}$$



Abazov *et al*, arXiv:1512.05291



- templates based on Sherpa (& Pythia)
- $\sigma_{SPS}^{\gamma\gamma} \cdot \sigma_{SPS}^{jj}$ estimated via PU evts with 2 vertices and $\gamma\gamma$ + jet-jet

- σ_{eff} =19.3 ± 1.4(stat) ± 7.8(syst)mb

2 b-jets + 2 jets

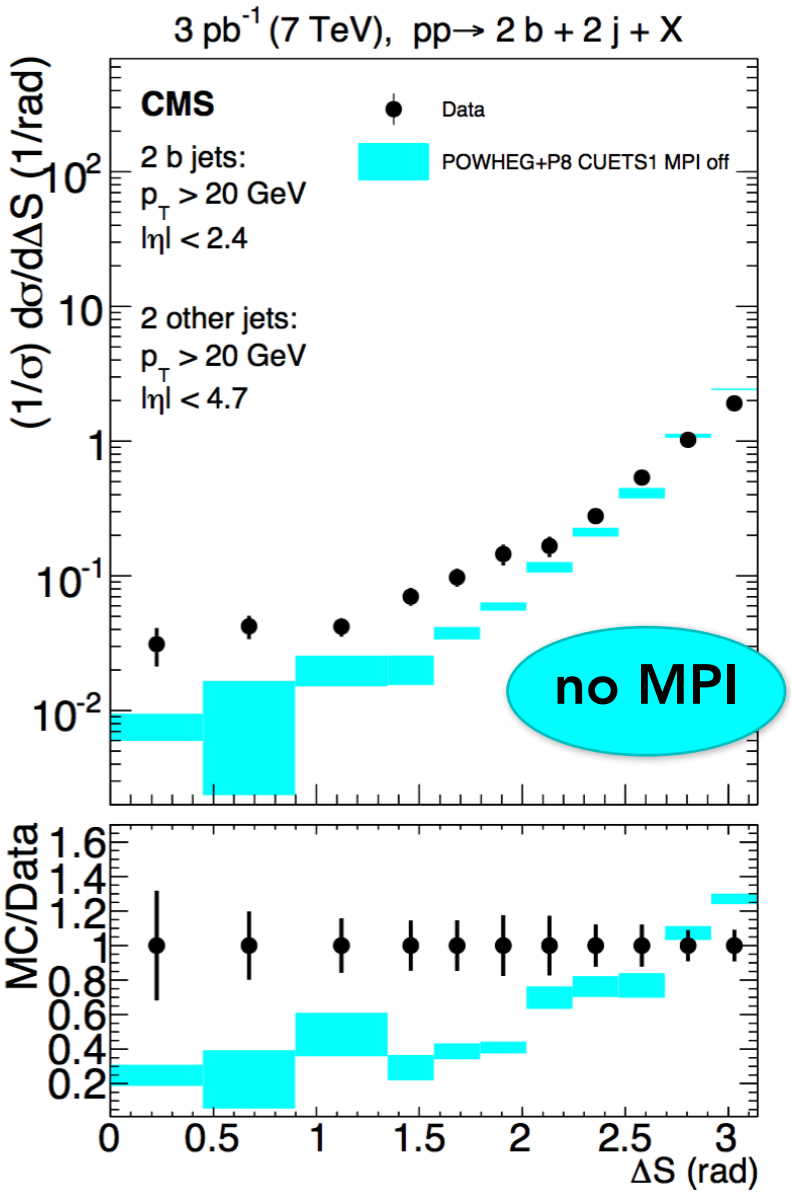
CMS – LHC 7 TeV

- Key discriminant:
  azimuthal angle between b-jets and light jets

$$\Delta S \equiv \Delta\phi\left(\vec{q}_{\mathrm{T}}^{\,1},\ \vec{q}_{\mathrm{T}}^{\,2}\right)$$

- addt'nl handle via relative p_T balance btwn two lighter jets

- without Multi Parton Interactions included, MC cannot reproduce data (~60% low!)



CMS-PAS-FSQ-13-010

2 b-jets + 2 jets

CMS – LHC 7 TeV

- Key discriminant:
  azimuthal angle between b-jets and light jets

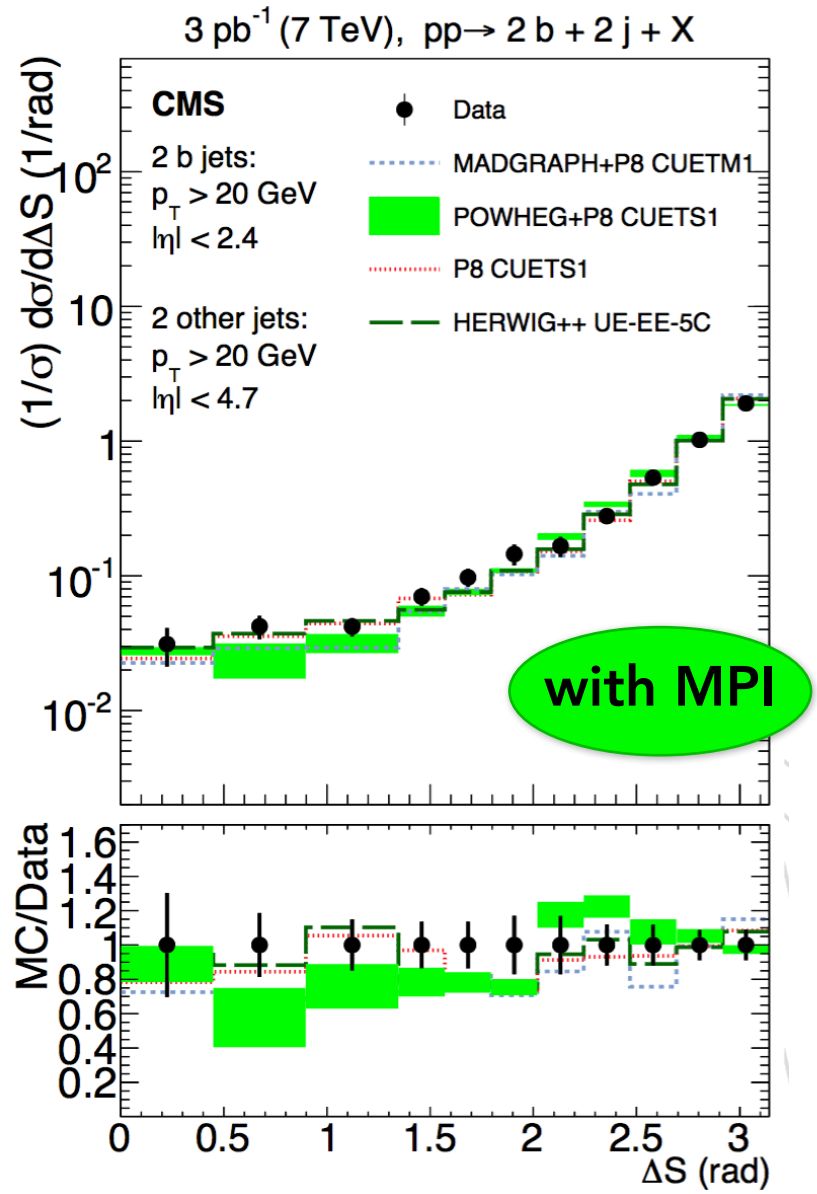
$$\Delta S \equiv \Delta\phi\left(\vec{q}_{\mathrm{T}}^{\,1},\ \vec{q}_{\mathrm{T}}^{\,2}\right)$$

- addt'nl handle via relative p_T balance btwn two lighter jets

- without Multi Parton Interactions included, MC cannot reproduce data

- *with* MPI, MC agrees with data !
- no σ_{eff} estimation… stay tuned ?

- note: MPI models tuned at soft scales (~3-5 GeV) but still work when extended to DPS regime



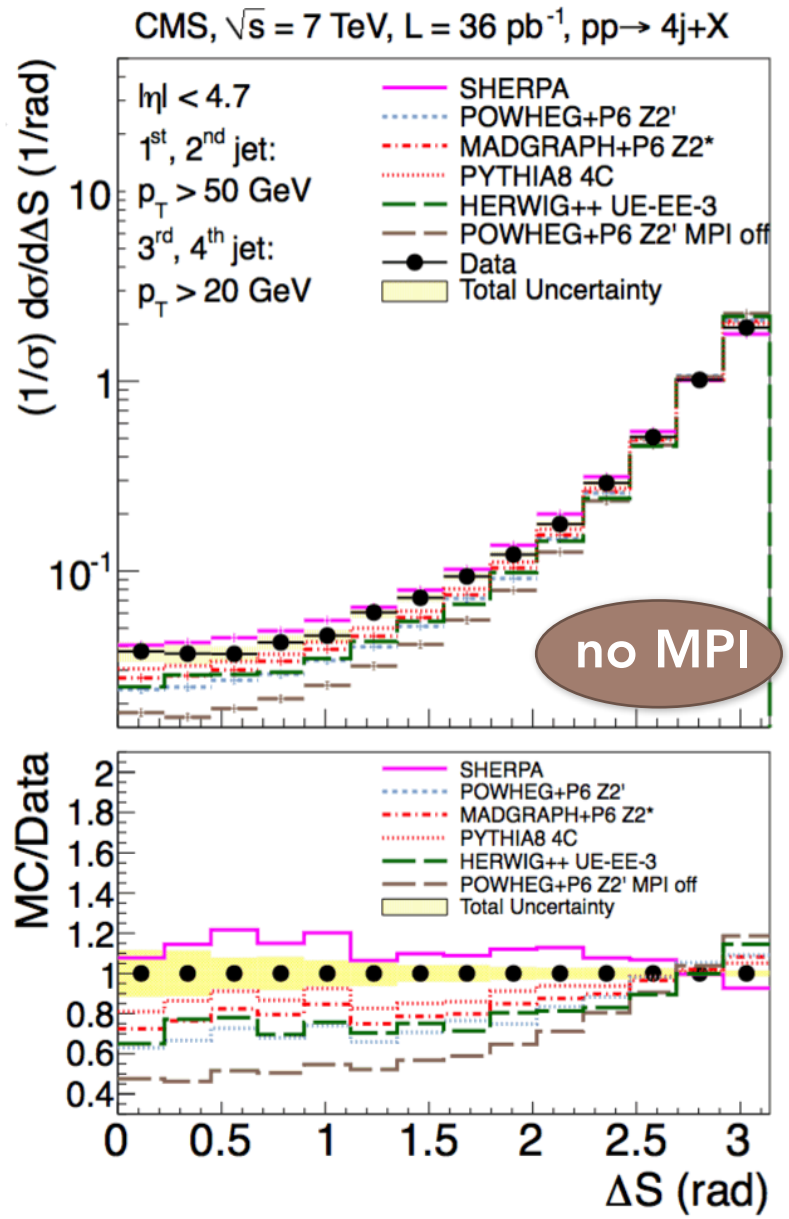
CMS-PAS-FSQ-13-010

Exclusive 4 jets

CMS – LHC 7 TeV

- Key discriminant:
  azimuthal angle between hard- and light-jet pairs

$$\Delta S \equiv \Delta\phi\left(\vec{q}_{\mathrm{T}}^{\,1},\ \vec{q}_{\mathrm{T}}^{\,2}\right)$$



Phys.Rev.D89, *(2014)*

- without MPI included,
  MC cannot reproduce data (~50% low)
- with MPI, MC still ~20% low (except Sherpa)

Exclusive 4 jets

CMS – LHC 7 TeV

- Key discriminant:
  azimuthal angle between hard- and light-jet pairs

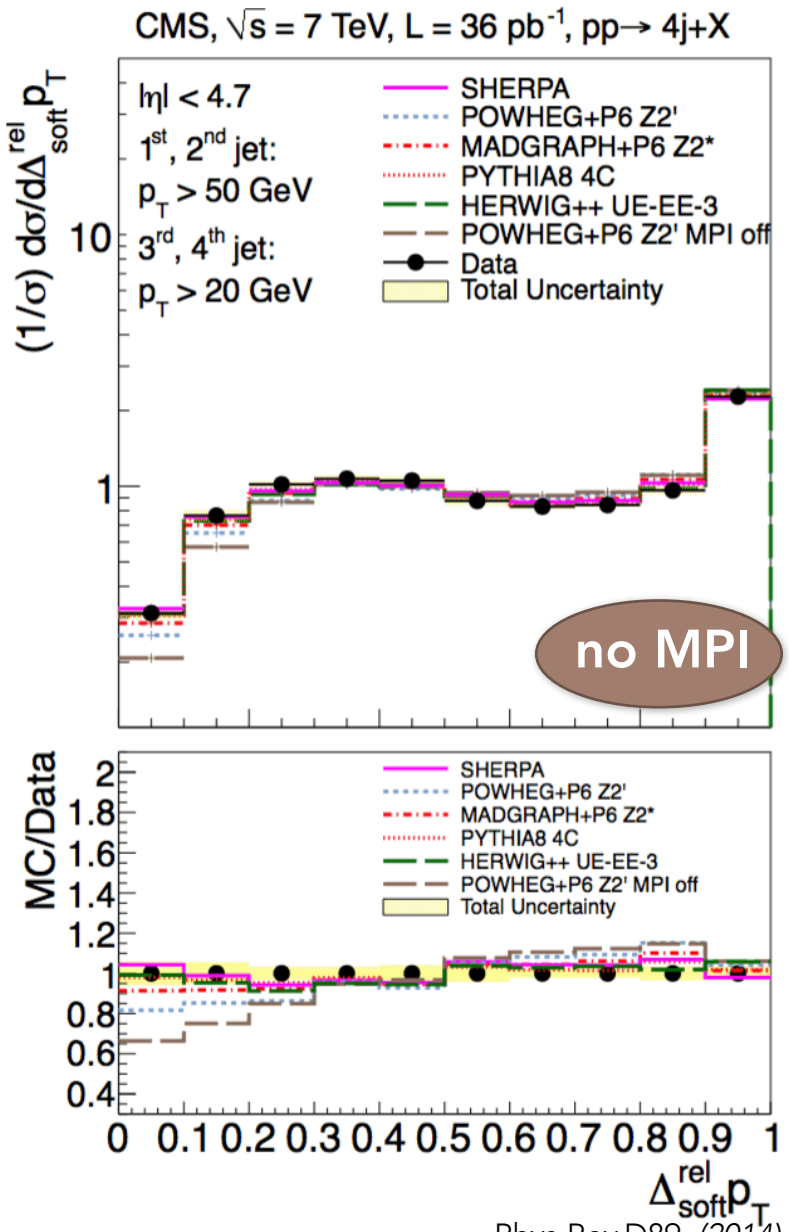
$$\Delta S \equiv \Delta\phi\left(\vec{q}_{\mathrm{T}}^{\,1},\ \vec{q}_{\mathrm{T}}^{\,2}\right)$$

- some sensitivity via relative p_T balance
  btwn 2 softer jets

$$\Delta^{\mathrm{rel}}_{\mathrm{soft}} p_{\mathrm{T}} = \frac{|\vec{p}_{\mathrm{T}}(\mathrm{j}^{\mathrm{soft}_1}) + \vec{p}_{\mathrm{T}}(\mathrm{j}^{\mathrm{soft}_2})|}{|\vec{p}_{\mathrm{T}}(\mathrm{j}^{\mathrm{soft}_1})| + |\vec{p}_{\mathrm{T}}(\mathrm{j}^{\mathrm{soft}_2})|}$$

- without MPI included,
  MC has some trouble at low $\Delta^{\mathrm{rel}}_{\mathrm{soft}} p_{\mathrm{T}}$

- 4 jets less sensitive to DPS than 2 b-jets + 2 jets
- needs more kinematic study of MPI with UE data
  → no σ_{eff} estimation



Phys.Rev.D89, *(2014)*

Inclusive 4 jets

ATLAS – LHC 7 TeV

- Neural Nets:
  input kinematic variables →

$$\Delta_{ij}^{p_T} = \frac{\left|\vec{p}_T^{\,i} + \vec{p}_T^{\,j}\right|}{p_T^i + p_T^j}$$

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

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

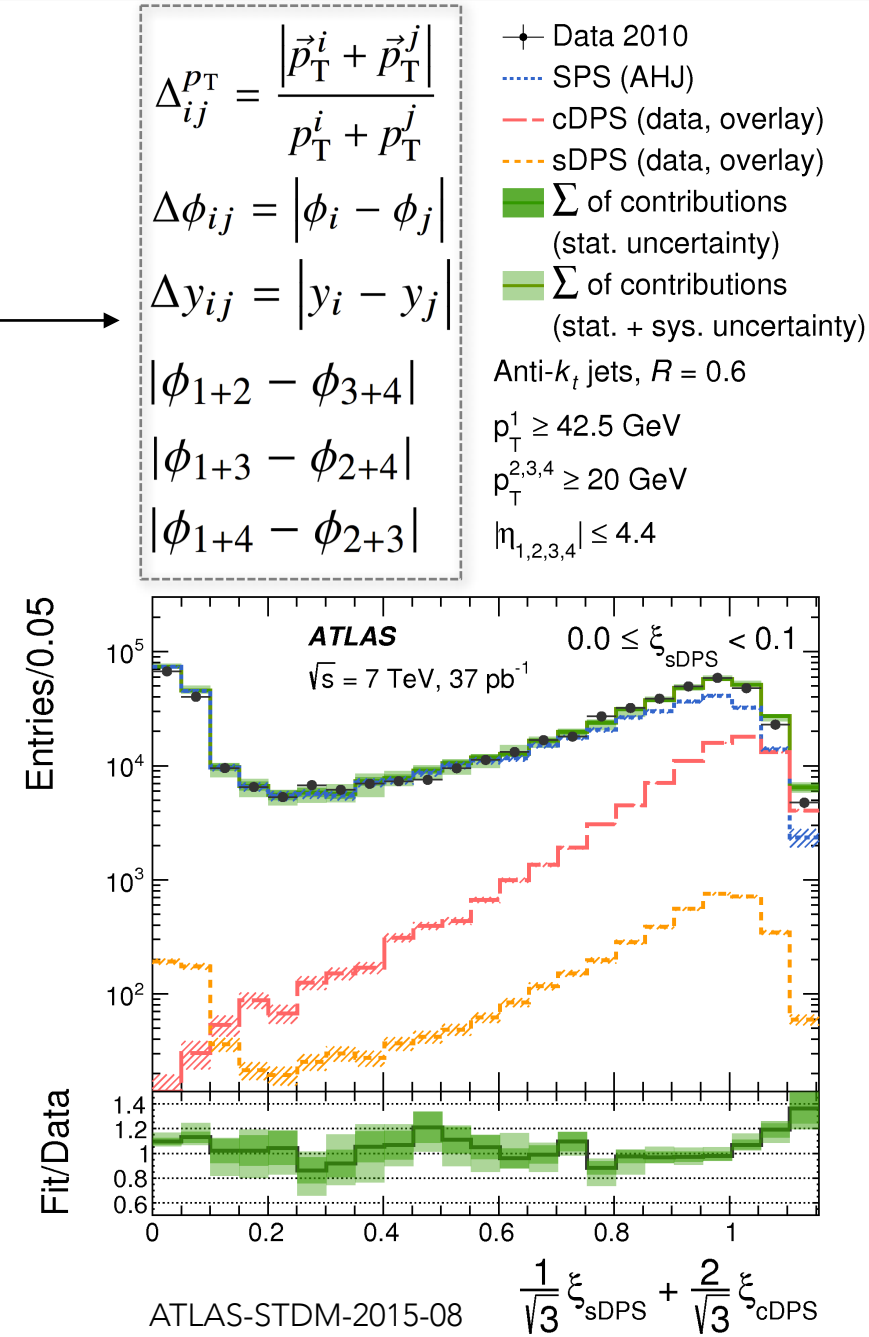
$$|\phi_{1+2} - \phi_{3+4}|$$

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

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

- SPS
  determined from MC (Alpgen+Herwig+Jimmy)
- cDPS – complete DPS (2 jets +2 jets)
  determined from data (overlaying 2 evts)
- sDPS – semi DPS (3 jets + 1 jet)
  determined from data (overlaying 2 evts)

- NN outputs in slices of ξ



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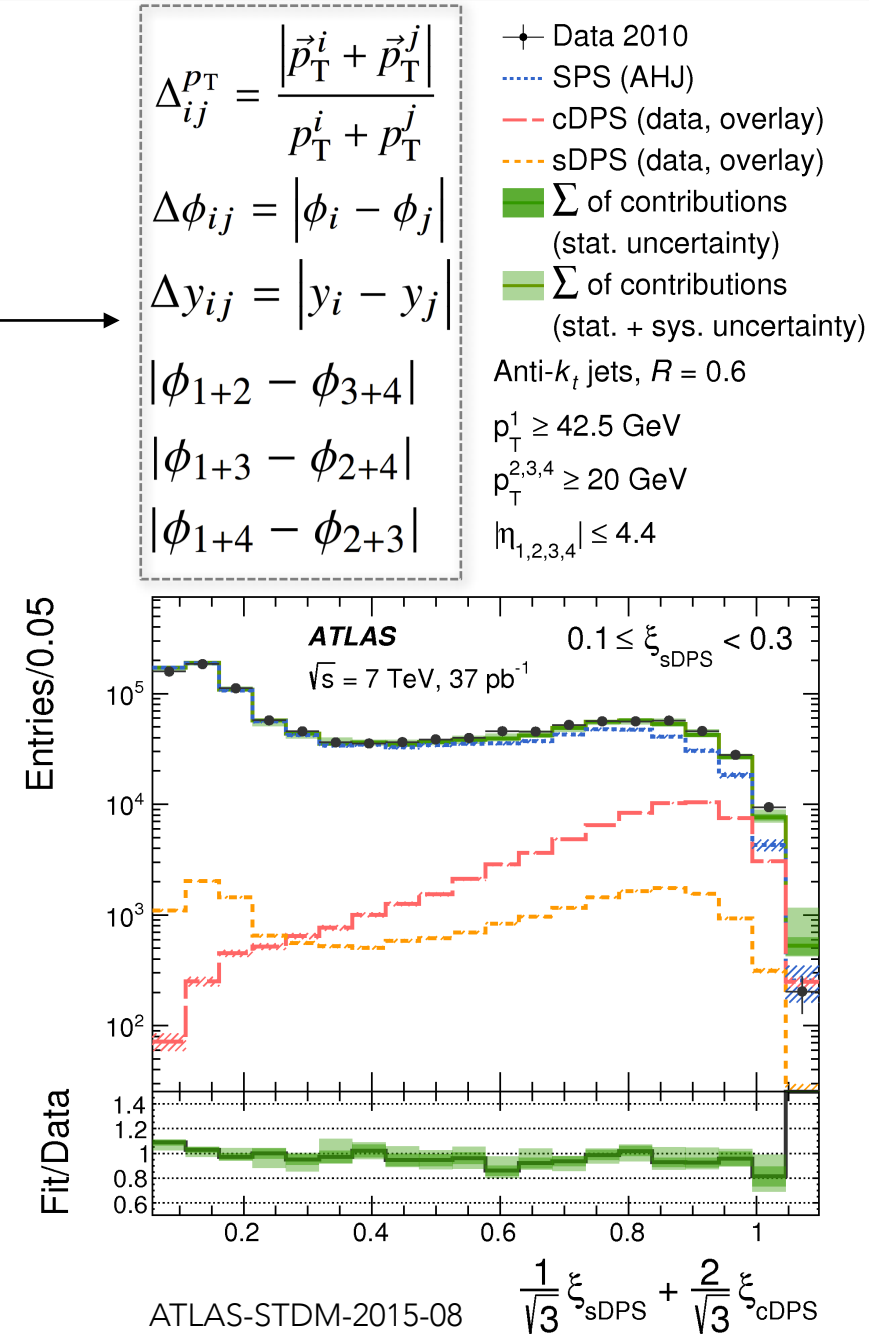

ATLAS-STDM-2015-08

Inclusive 4 jets

ATLAS – LHC 7 TeV

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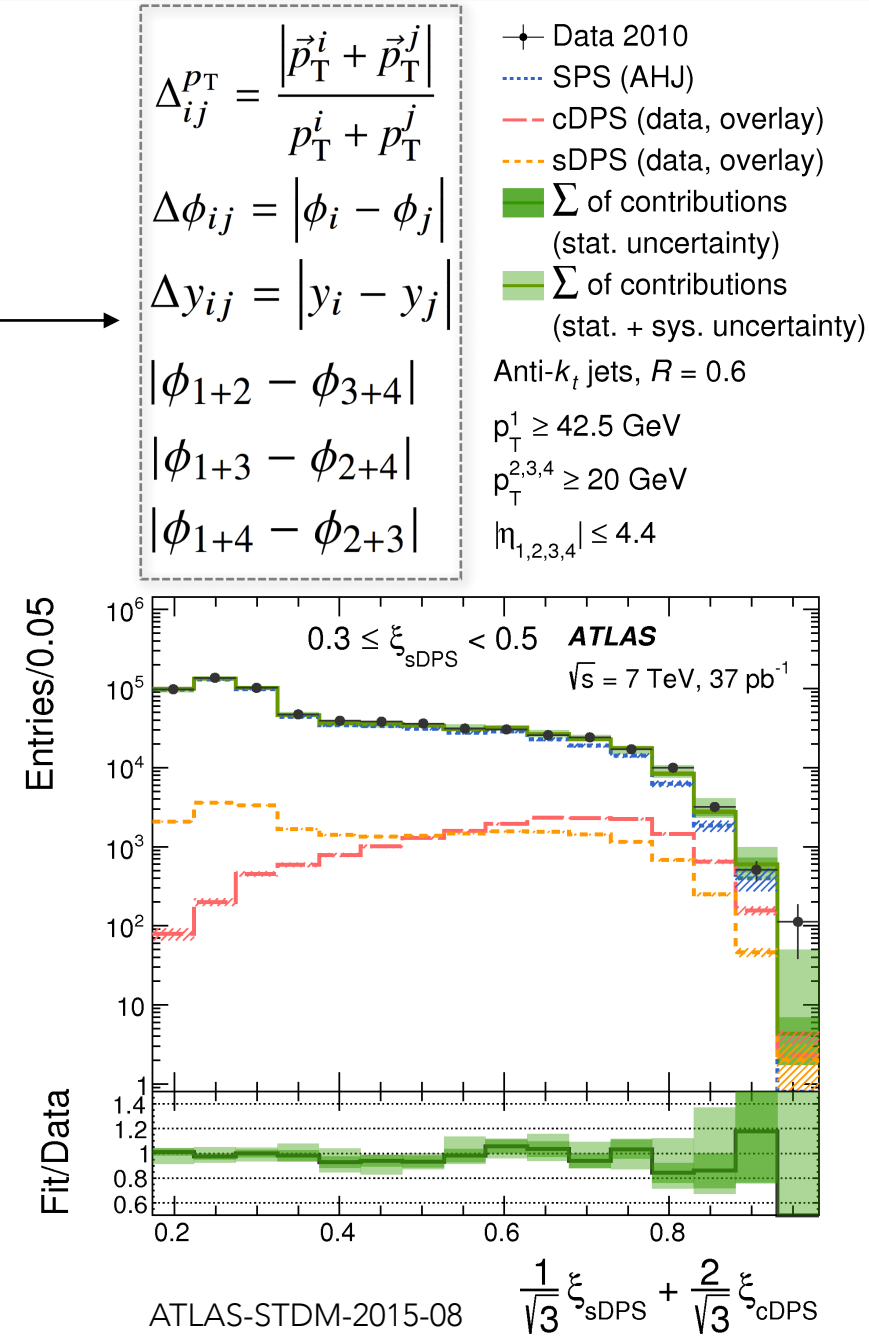

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ATLAS – LHC 7 TeV

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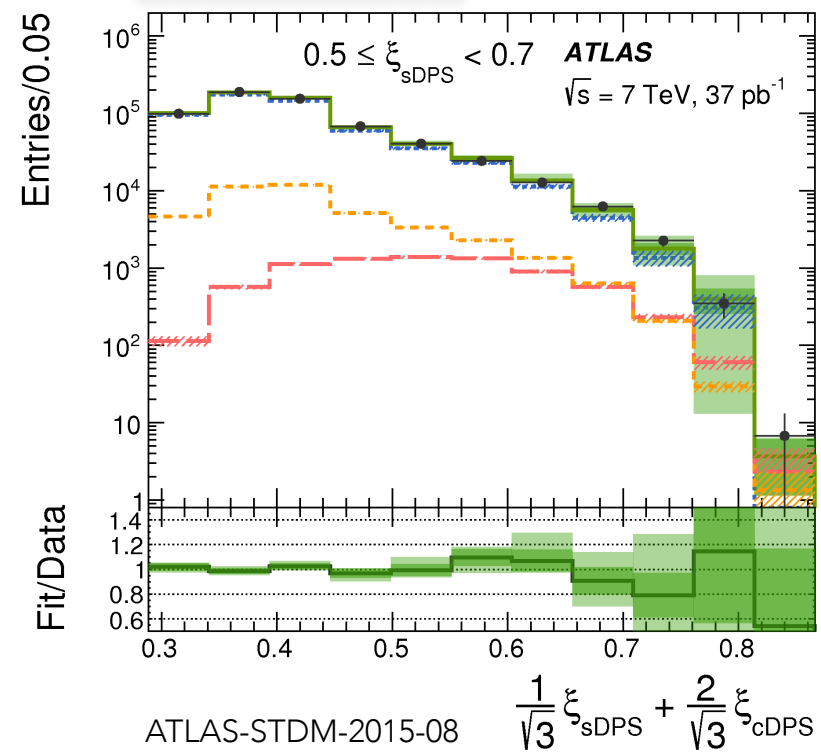

ATLAS-STDM-2015-08

Inclusive 4 jets

ATLAS – LHC 7 TeV

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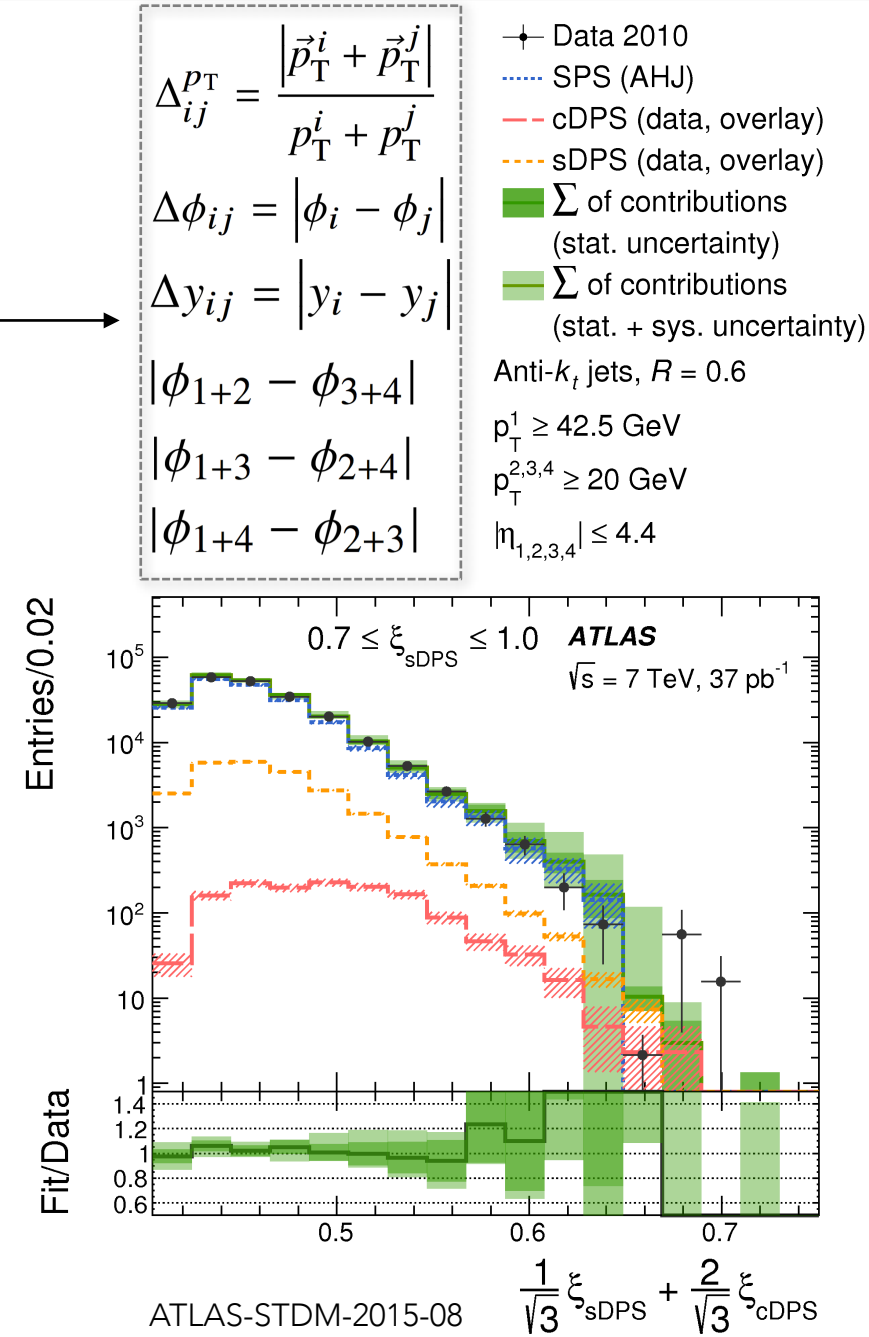


ATLAS-STDM-2015-08

Inclusive 4 jets

ATLAS – LHC 7 TeV

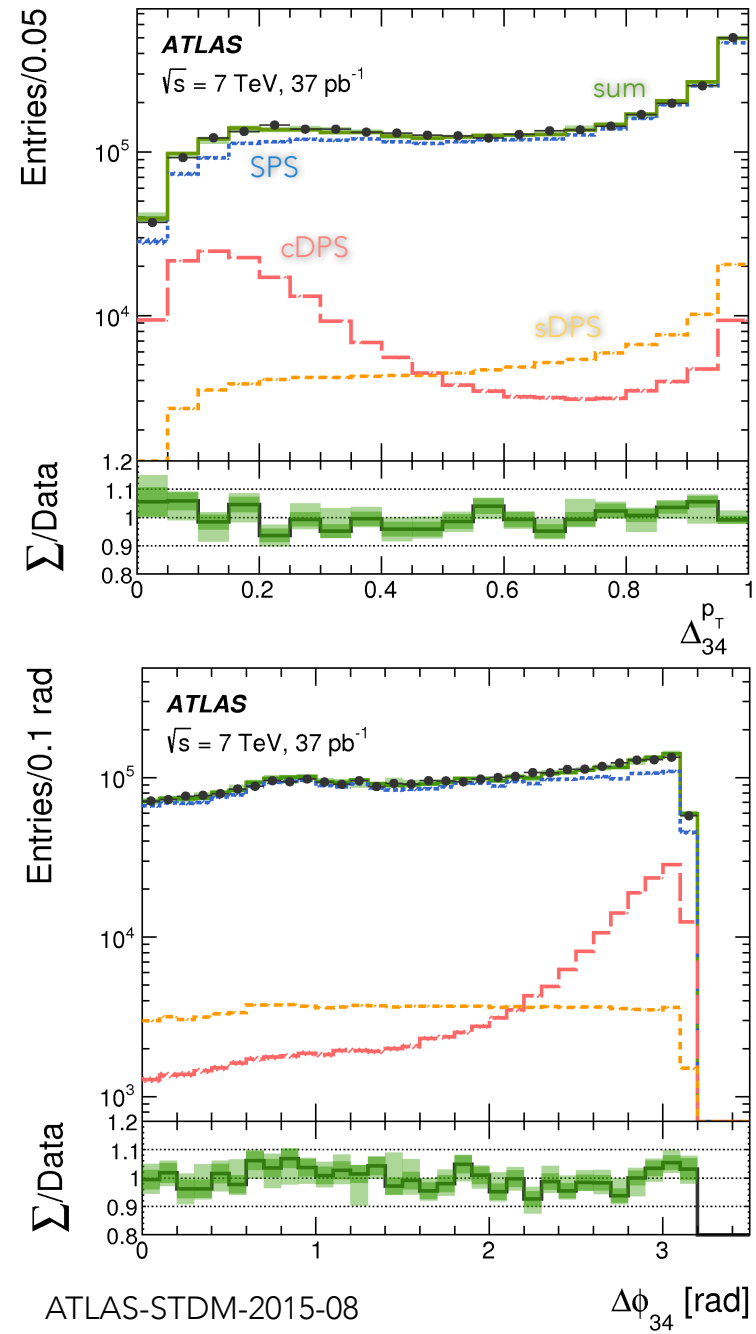
- Neural Net – cross-check of sensitive variables
  - Focus on correlations btwn **two lightest jets**

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

- cDPS – complete DPS (2 jets +2 jets) determined from data (overlaying 2 evts)
- sDPS – semi DPS (3 jets + 1 jet) determined from MC (Alpgen+Herwig+Jimmy)

- NN returns robust results
- estimate ~8% of 4-jet events originate from DPS

- $\sigma_{\text{eff}} = 16.1\ ^{+2.0}_{-1.5}\ (\text{stat.})\ ^{+6.1}_{-6.8}\ (\text{syst.})\ \text{mb}$



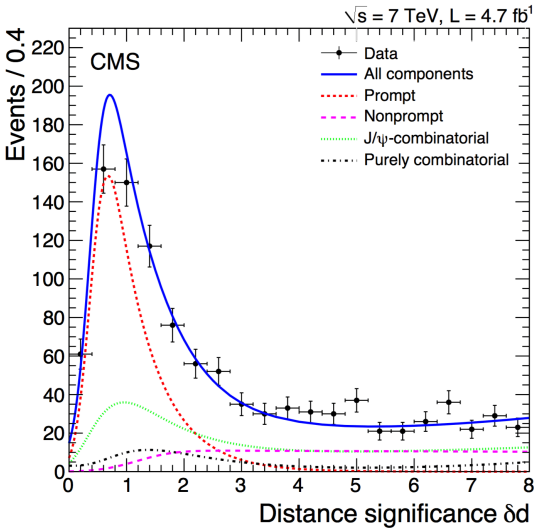
ATLAS-STDM-2015-08

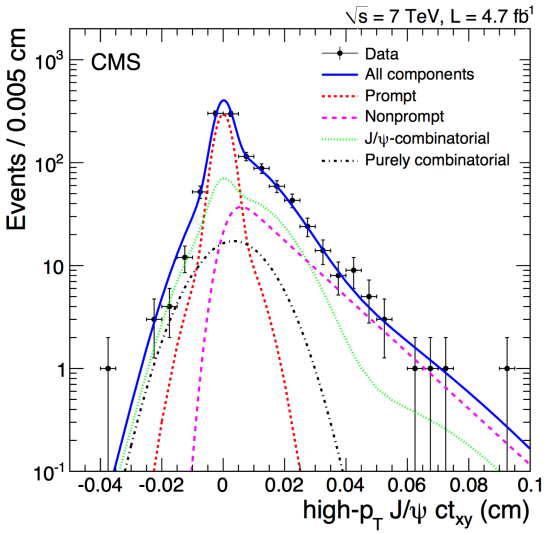
Double Quarkonia

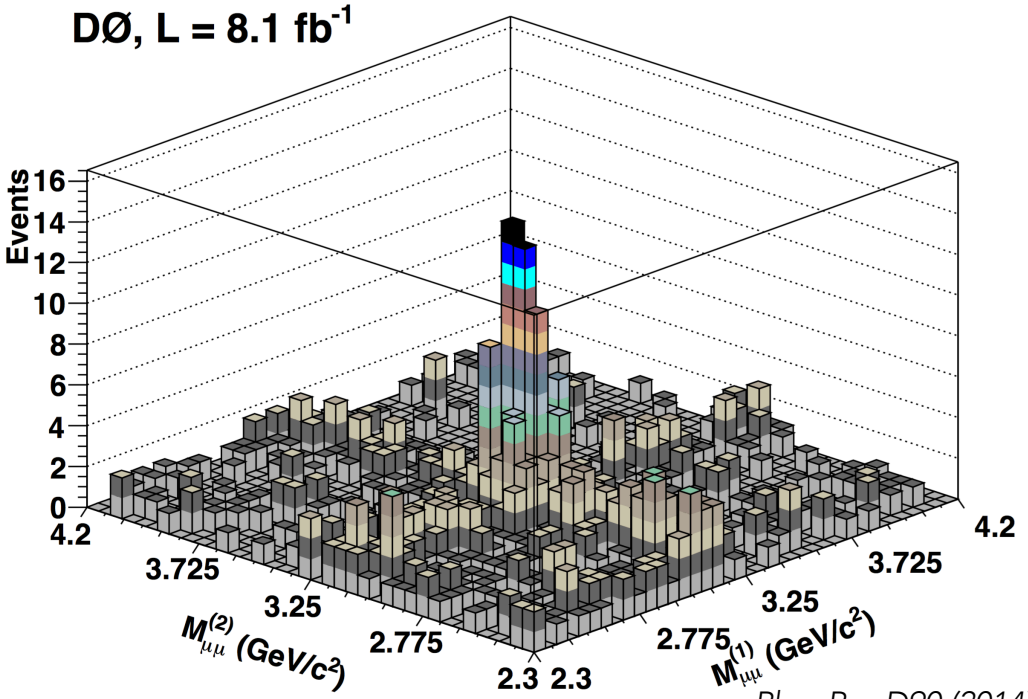
Clean Signature via Mass

Types of Events

- Sig: prompt J/ψ + J/ψ
- Bkg: non-prompt J/ψ (B decays)
- Bkg: prompt J/ψ + unassoct'd μμ
- Bkg: unassoct'd μμ + unassoct'd μμ







Phys.Rev.D90 (2014)

Main Observables

- $\Delta\eta_{\psi\psi}$, $\Delta\varphi_{\psi\psi}$, $M_{\psi\psi}$, $p_T^{\psi\psi}$

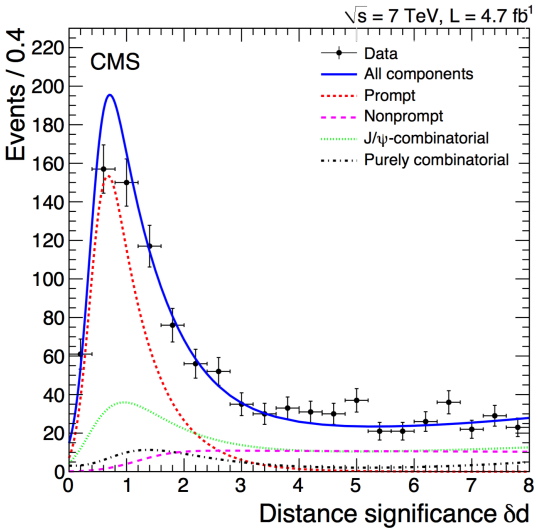
Double Quarkonia

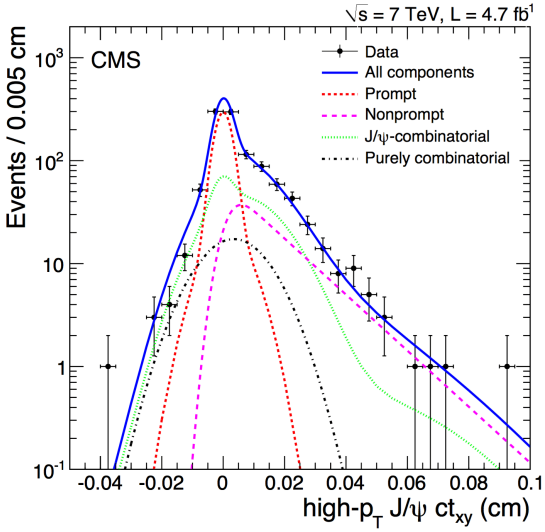
Clean Signature via Mass

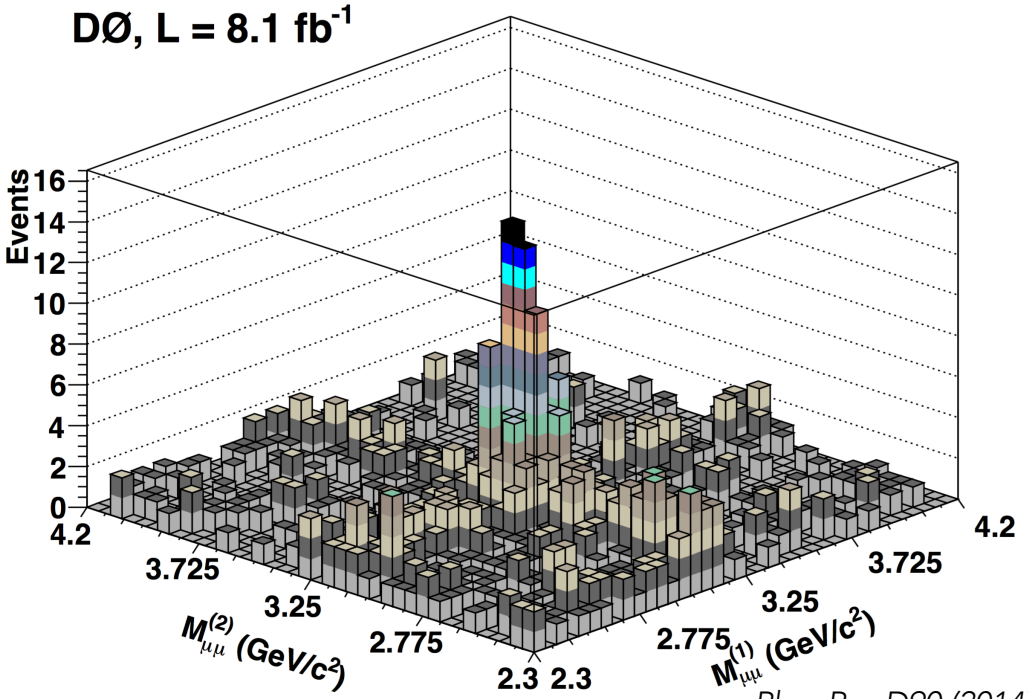
Types of Events

General Cuts

- Sig: prompt J/ψ + J/ψ
  mass cut (x2)
- Bkg: non-prompt J/ψ (B decays)
  di-muon decay vertex cuts
  J/ψ – J/ψ separation distance
- Bkg: prompt J/ψ + unassoct'd μμ
- Bkg: unassoct'd μμ + unassoct'd μμ
  mass cut (x2), fit combinatorial/bkg







Phys.Rev.D90 (2014)

Main Observables

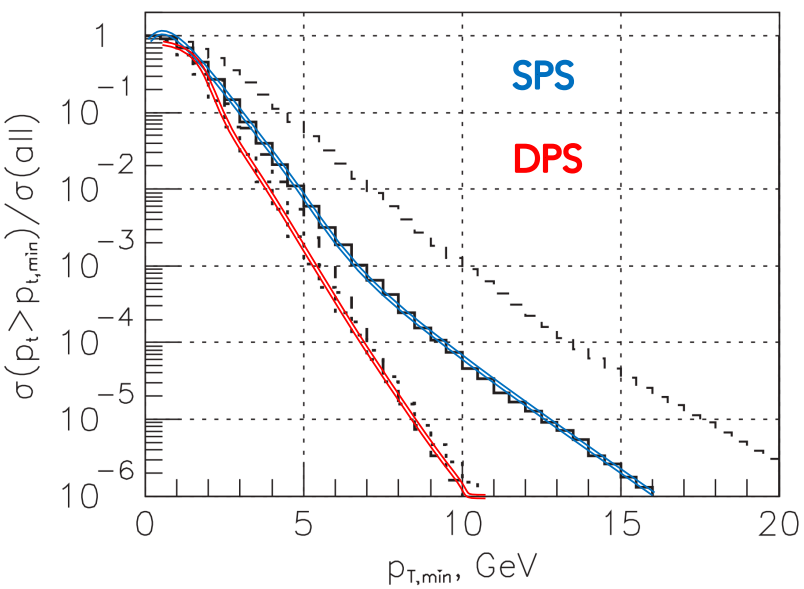
- $\Delta\eta_{\psi\psi}$, $\Delta\varphi_{\psi\psi}$, $M_{\psi\psi}$, $p_T^{\psi\psi}$

How to separate SPS from DPS ?

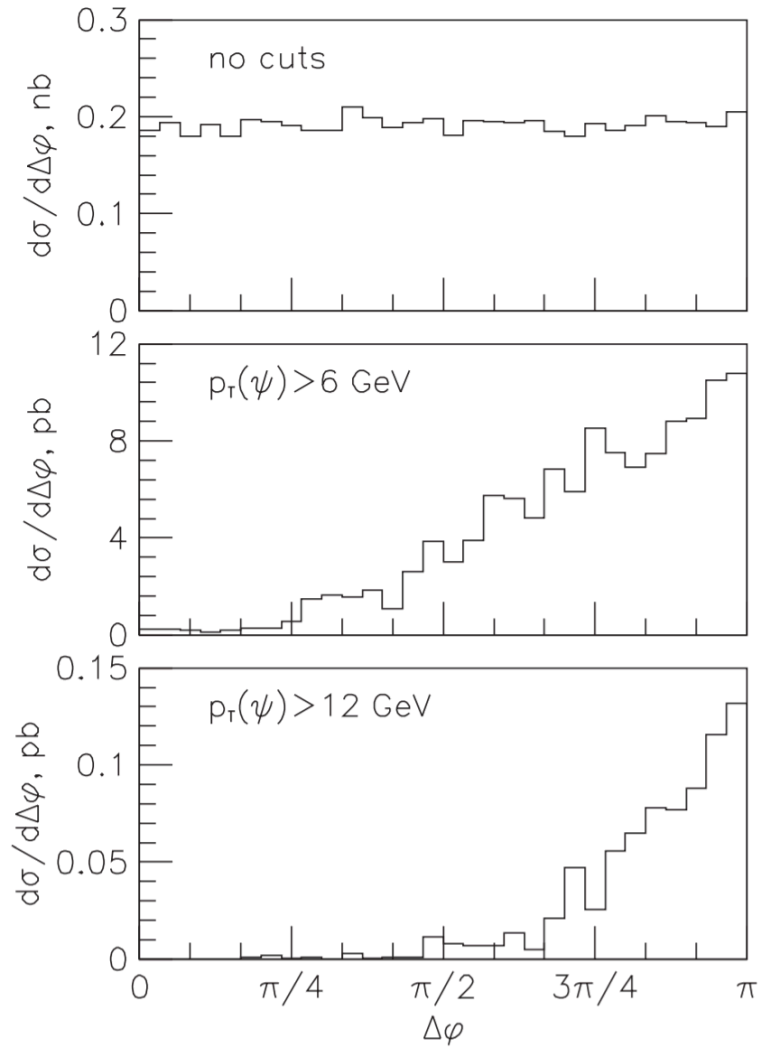
- Naïve idea –
  J/ψ's in SPS are mostly back-to-back
  → **just cut on $\Delta\varphi_{\psi\psi}$!** (*à la multi-jets*)

- However, only true for high p_T J/ψ

- Meanwhile, DPS/SPS is dropping…



increasing min p_T cut



Baranov *et al*, Phys.Rev.D87 (2013)

Separation Power

$\Delta\eta_{\psi\psi}$

How to separate SPS from DPS ?

- Much cleaner separation in $\Delta\eta_{\psi\psi}$

- SPS

  J/ψ's highly correlated in Δη

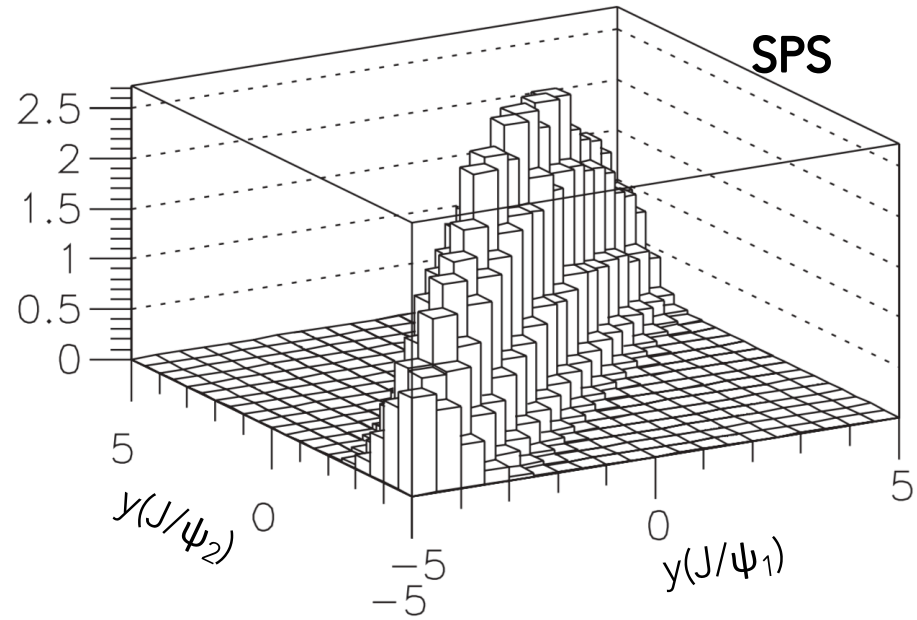
  one gluon exchange x1000 (dotted)

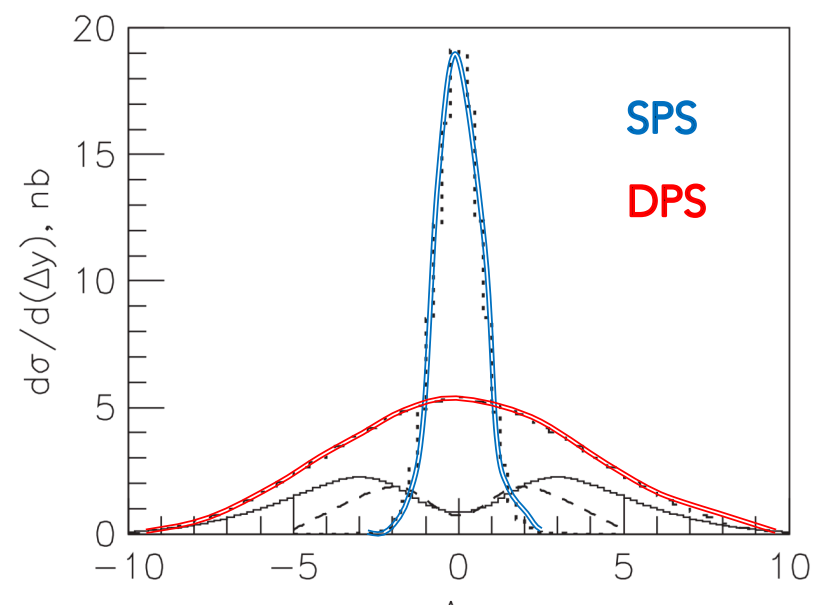
  two gluon exchange x25 (solid)

- DPS

  $\Delta\eta_{\psi\psi}$ much broader

- Kinematically cleaner way to proceed for quarkonia (along with $M_{\psi\psi}$, $p_T^{\psi\psi}$)





Baranov *et al*, Phys.Rev.D87 (2013)

Double J/ψ

D0 – Tevatron

- 1.96 TeV $p\bar{p}$
- Observable: J/ψ + J/ψ
- Use template fit to $\Delta\eta_{\psi\psi}$ (and decay vertex)
- Subtract background

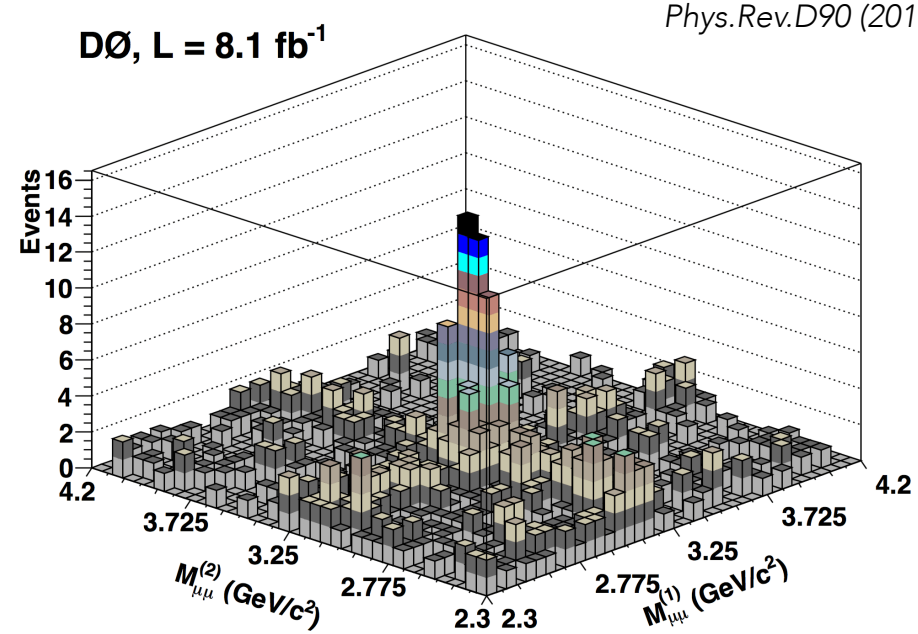
Result

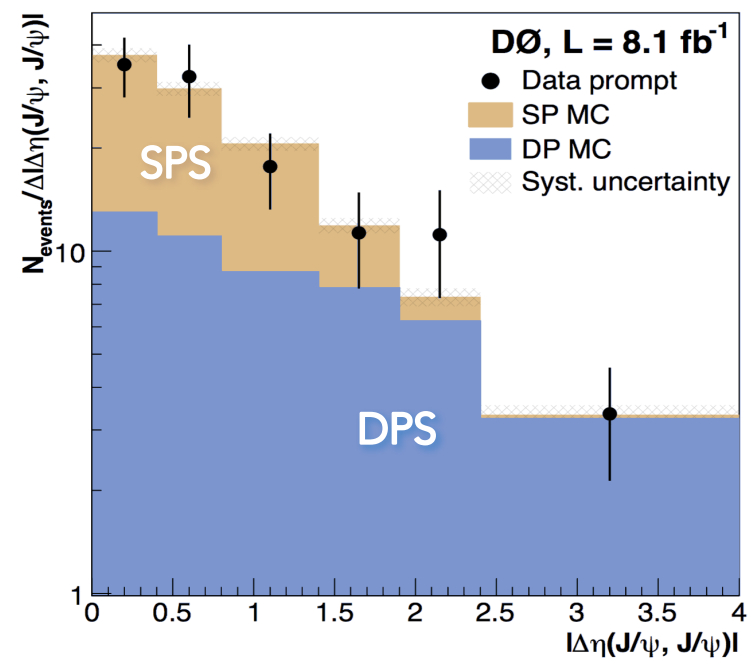
- $\sigma_{DPS}(J/\psi+J/\psi) = 59 \pm 6 \pm 22$ fb
- $\sigma_{SPS}(J/\psi+J/\psi) = 70 \pm 6 \pm 22$ fb
- $\sigma_{eff} = 4.8 \pm 0.5 \pm 2.5$ mb

Fiducial Acceptance (J/ψ)

- $p_T > 4$ GeV/c
- $|\eta| < 2$

Phys.Rev.D90 (2014)





Next Frontier

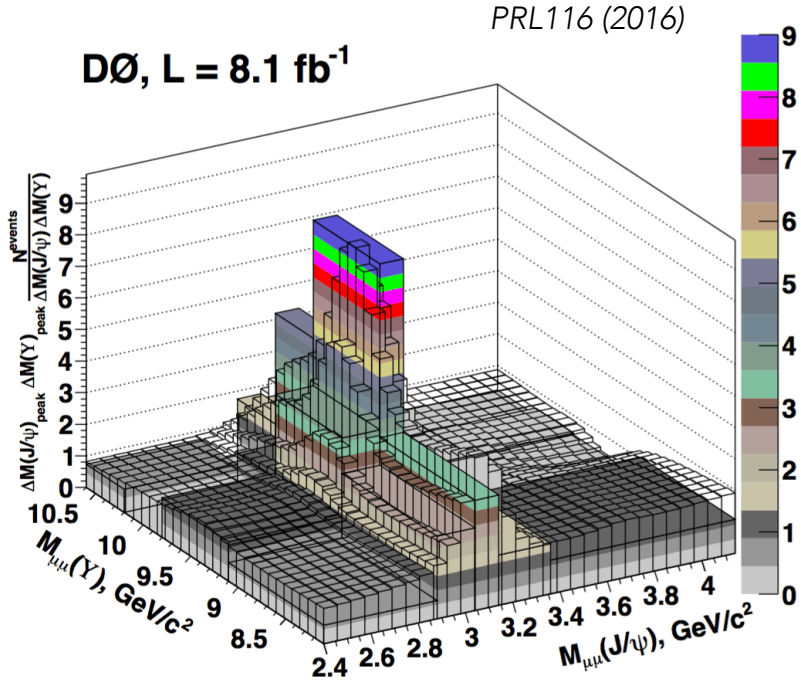
J/ψ+Υ

D0 – Tevatron

- 1.96 TeV $p\bar{p}$
- Observable: J/ψ + Υ

- Baranov *et al* calculate DPS ~97% of xsec
- D0 assumes it's all DPS

PRL116 (2016)

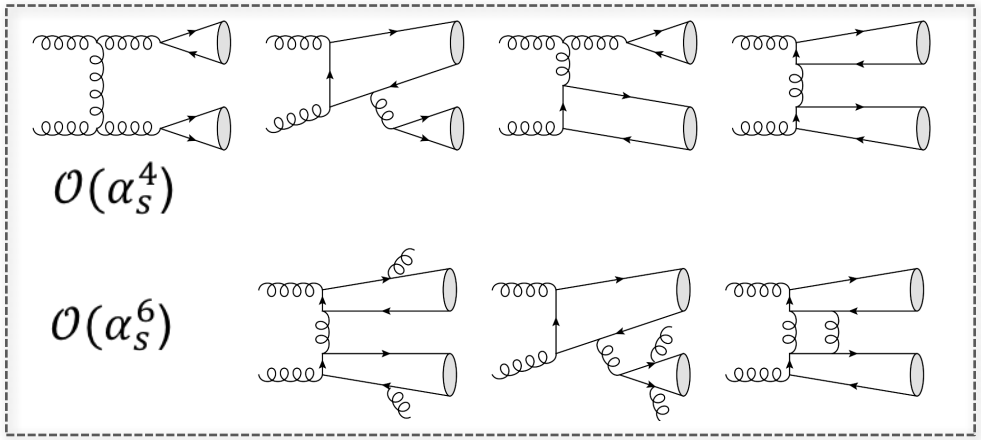


Result

- $\sigma(J/\psi) = 28 \pm 7$ nb
- $\sigma(\Upsilon) = 2.1 \pm 0.3$ nb
- $\sigma_{DPS}(J/\psi+\Upsilon) = 27 \pm 9 \pm 7$ fb
- $\boldsymbol{\sigma_{eff} = 2.2 \pm 0.7 \pm 0.9}$ **mb**

Fiducial Acceptance (μ)

- $p_T > 2$ GeV/c
- $|\eta| < 2.0$



Next Frontier

J/ψ+Υ

D0 – Tevatron

- 1.96 TeV $p\bar{p}$
- Observable: J/ψ + Υ

- Baranov *et al* calculate DPS ~97% of xsec
- D0 assumes it's all DPS
- Consistent with DPS MC

Result

- $\sigma(J/\psi) = 28 \pm 7$ nb
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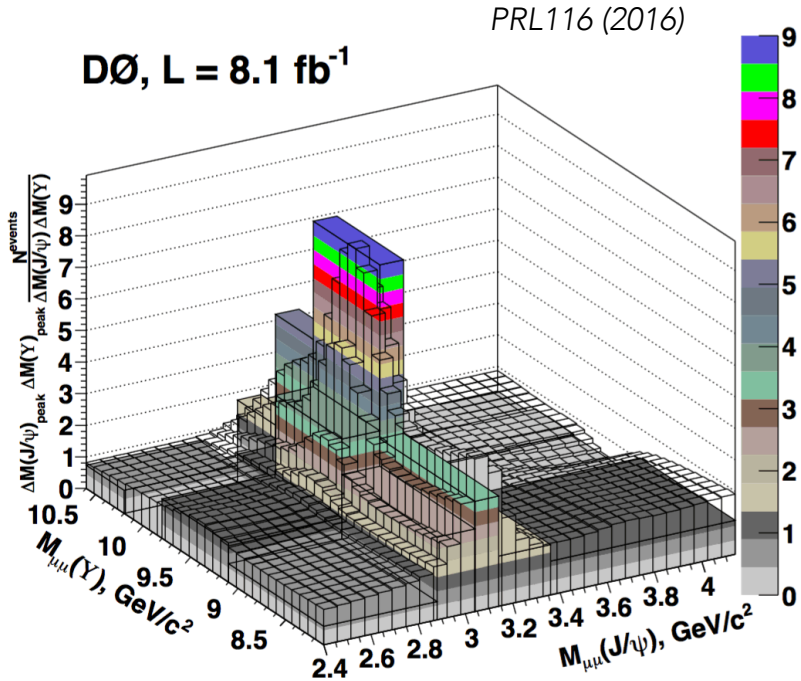
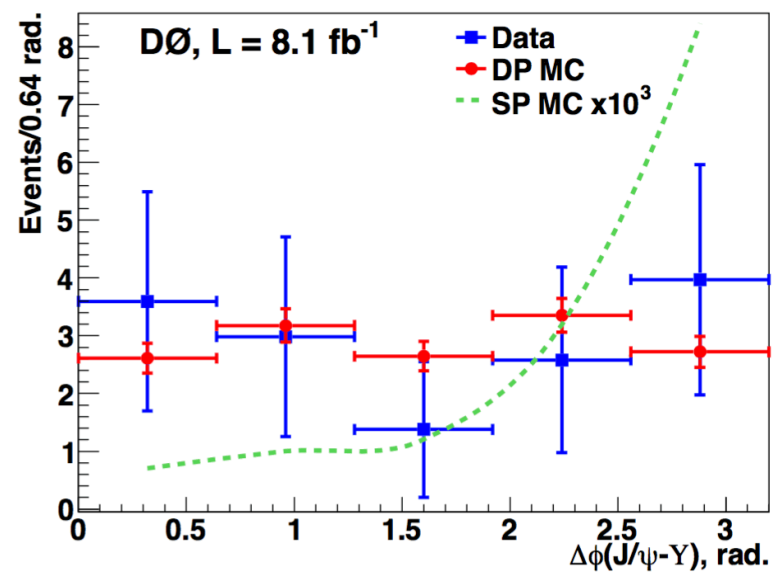


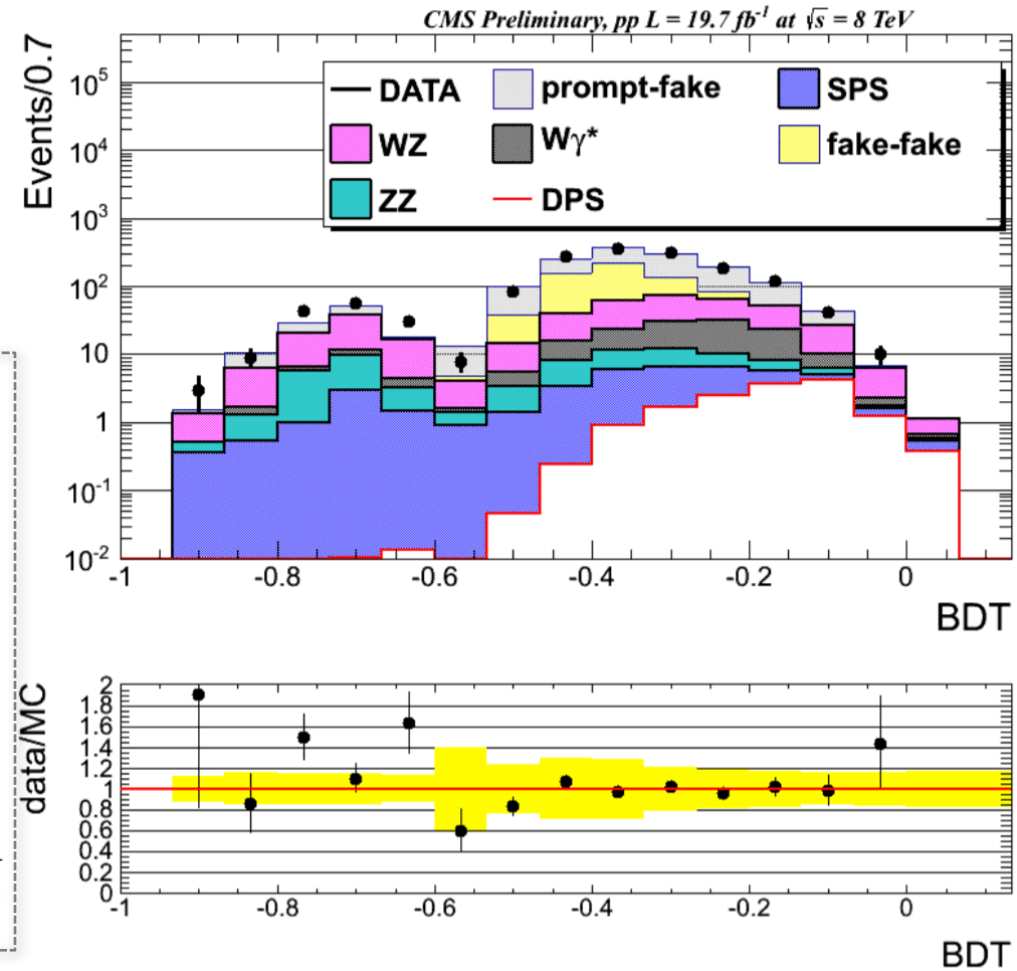


CMS – LHC 8 TeV

- DPS/SPS contributions comparable
- W suffers from contamination
- Currently, statistics quite low

BDT input variables:

leading muon (μ_1) p_T
subleading muon (μ_2) p_T
E_T^{miss}
$M_T(\mu_1, \mu_2)$ di-muon invariant transverse mass
$\Delta\phi(\mu_1, \mu_2)$
$\Delta\phi(\mu_1, E_T^{miss})$
$\Delta\phi(\mu_2, E_T^{miss})$
$\Delta\phi(\mu_1 + \mu_2, E_T^{miss})$: where $\mu_1 + \mu_2$ is the vector sum of muon four-momenta
$m_T(W_{1/2}) = \sqrt{2 \cdot p_T^{\mu_{1/2}} \cdot E_T^{miss} \cdot (1 - cos(\Delta\phi(\mu_{1/2}, E_T^{miss})))}$



CMS PAS FSQ-13-001

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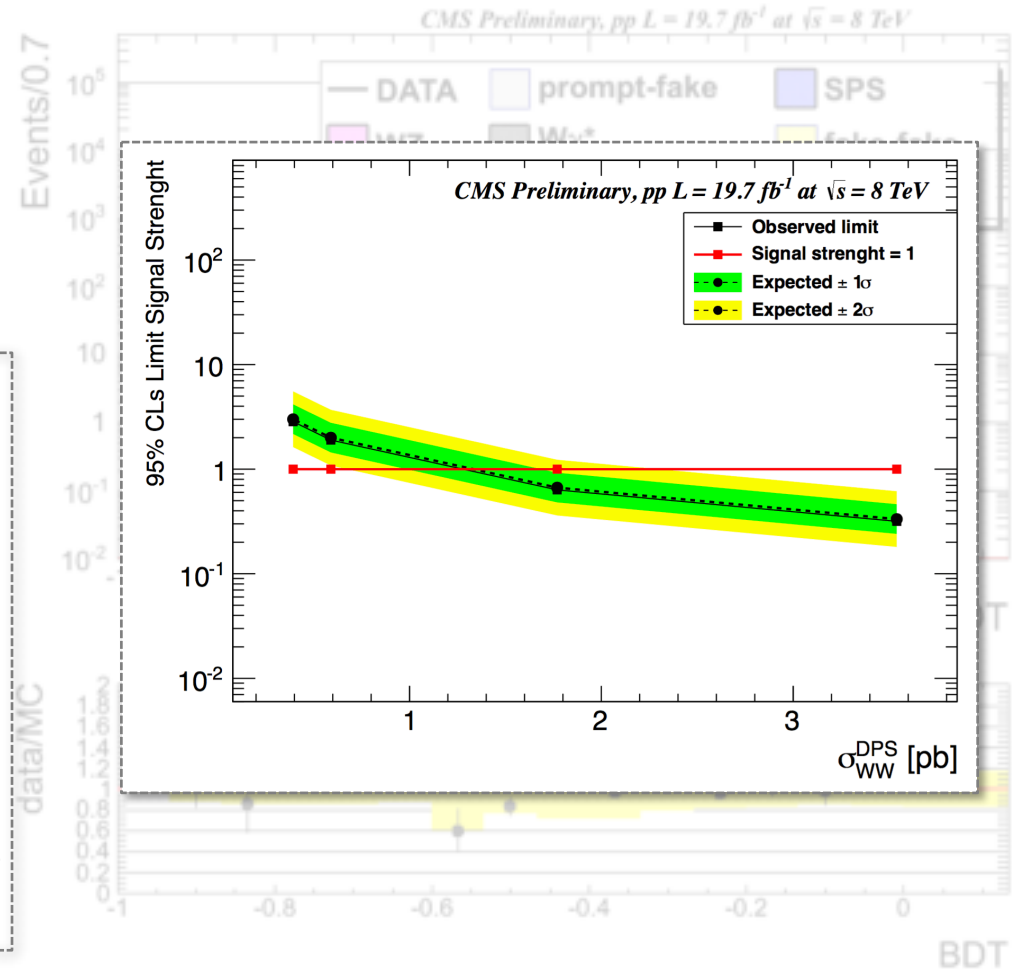
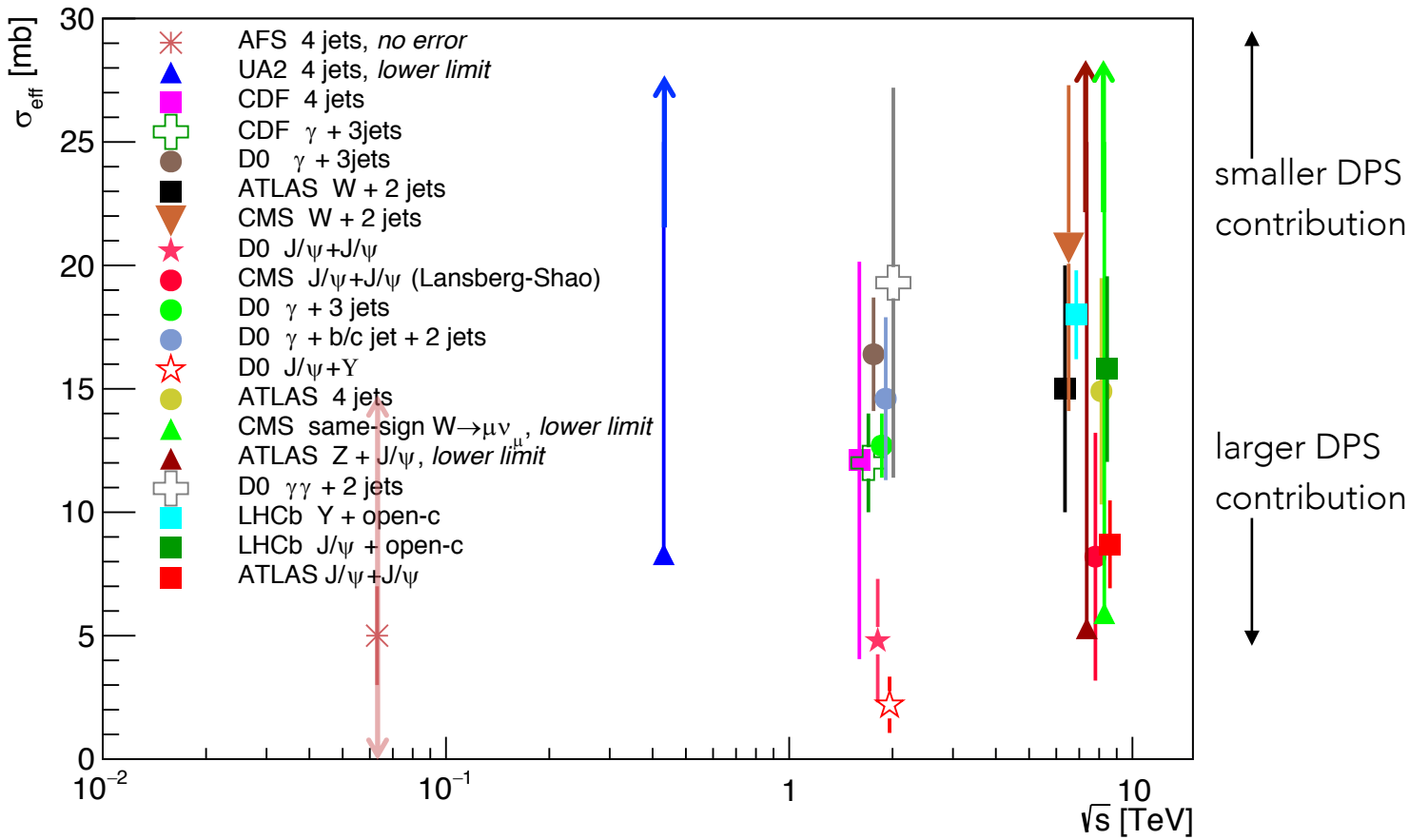


Set lower limit:

- $\sigma_{eff} > 5.91$ mb (95% cf)

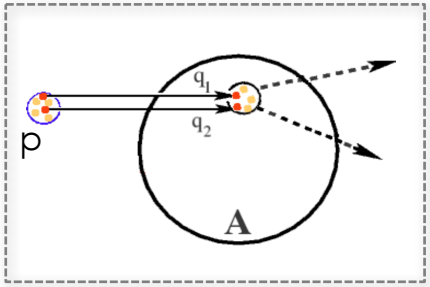
CMS PAS FSQ-13-001

Compiling Data...

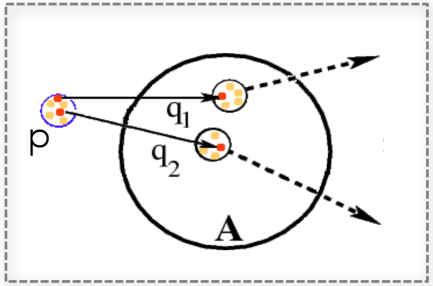


- Can σ_{eff} for some final states be systematically different than others ?
- Can we differentiate g dominated processes from q dominated ?
  - gluon transverse PDF ≠ quark transverse PDF ?

Various ways to have two hard scatters in pA collisions



+



$$\sigma^{DPS}_{pA\to ab} = \sigma^{DPS,1}_{pA\to ab} + \sigma^{DPS,2}_{pA\to ab}$$

$$\sigma^{DPS}_{pA\to ab} = A\cdot\sigma^{DPS}_{pN\to ab} + \sigma^{DPS}_{pN\to ab}\cdot\sigma_{\mathrm{eff,pp}}\cdot F_{pA}$$

nuclear overlap:

$$F_{pA} = \frac{A-1}{A}\int T^2_{pA}(\mathbf{r})\,d^2r \approx 30\ \mathrm{mb}^{-1}$$

now write

$$\sigma^{DPS}_{pA\to ab} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{pN\to a}\cdot\sigma^{SPS}_{pN\to b}}{\sigma_{\mathrm{eff,pA}}}$$

with $\sigma_{\mathrm{eff,pA}} = \dfrac{\sigma_{\mathrm{eff,pp}}}{A+\sigma_{\mathrm{eff,pp}}F_{pA}}$ —glauber→ $\sigma_{eff,pA} \approx \dfrac{1}{3A}\sigma_{eff,pp}$

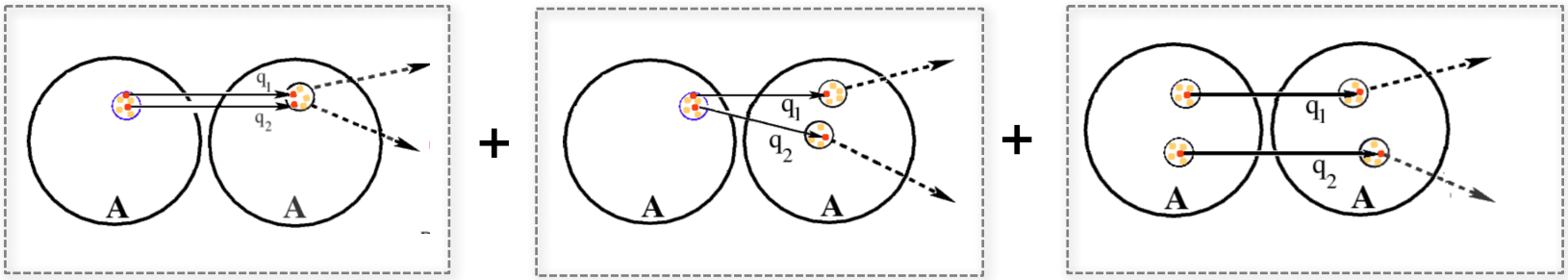
- cross sections for DPS go up by x3 compared to SPS
- significance of measurement (S/√B) can increase by x40

D'Enterria & Snigirev, PLB 718 (2013)

DPS Prospects

lead-lead

Various ways to have two hard scatters in AA collisions



$$\sigma^{DPS}_{(AA\to ab)} = \sigma^{DPS,1}_{(AA\to ab)} + \sigma^{DPS,2}_{(AA\to ab)} + \sigma^{DPS,3}_{(AA\to ab)}$$

$$\sigma^{DPS}_{(AA\to ab)} = A^2 \cdot \sigma^{DPS}_{(NN\to ab)} + 2\sigma^{DPS}_{(NN\to ab)} \cdot \sigma_{eff,pp} \cdot \underbrace{T_{2,AA}}_{(A-1)\cdot T_{AA}} + \sigma^{DPS}_{(NN\to ab)} \cdot \sigma_{eff,pp} \cdot A^2/2 \cdot T_{AA}$$

$$\sigma^{DPS,1}_{(AA\to ab)} : \sigma^{DPS,2}_{(AA\to ab)} : \sigma^{DPS,3}_{(AA\to ab)} \longrightarrow \mathbf{1:4:200}$$

- Third term is dominant
- "Genuine" DPS only ~2.5% of two-hard-scatterings
  → **not an efficient system to measure DPS**

D'Enterria & Snigirev, PLB 727 (2013)

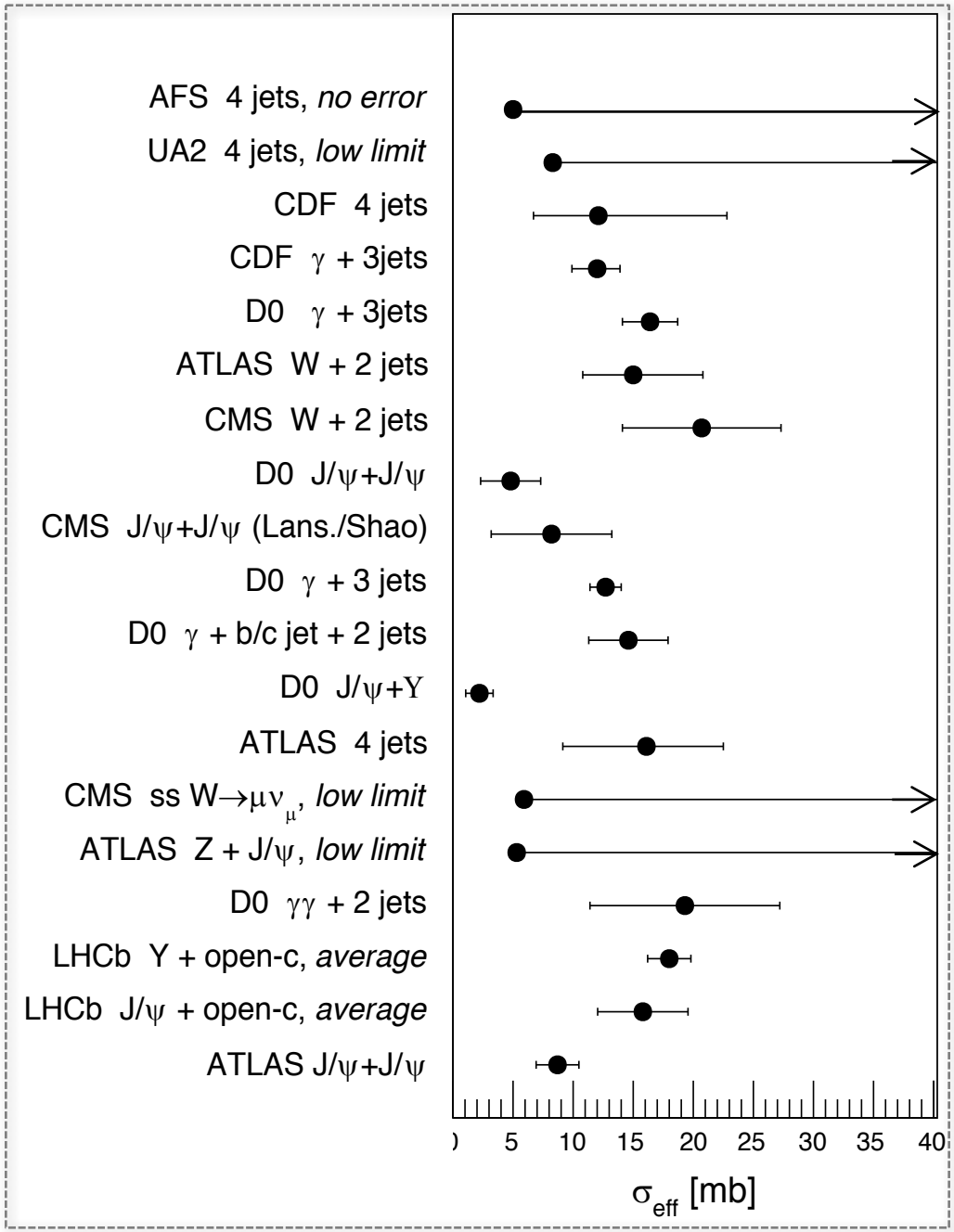
Summary

DPS probe transverse parton dist profile as well as illuminate backgrounds for NLO SPS processes

Can give insight to partonic correlations inside proton

Beginning to map $\sqrt{s}$ dependence of σ_{eff}
Access to transverse PDFs
Gluon / quark separation ?

Higher $\sqrt{s}$… higher luminosities… larger systems (pA)...
Future is exciting !



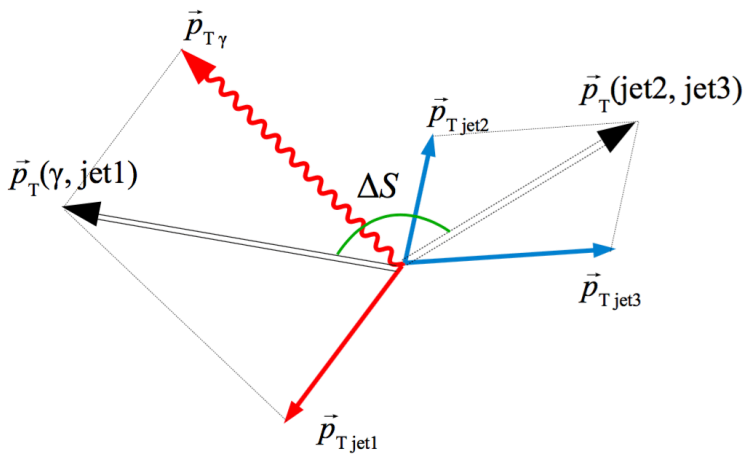
backup

γ-jet + 2 jets

CMS – LHC 7 TeV

- Key discriminant:
  azimuthal angle between γ-jet & di-jet

$$\Delta S \equiv \Delta\phi(\vec{p}_{\mathrm{T}}(\gamma, \mathrm{jet1}), \vec{p}_{\mathrm{T}}(\mathrm{jet2}, \mathrm{jet3}))$$

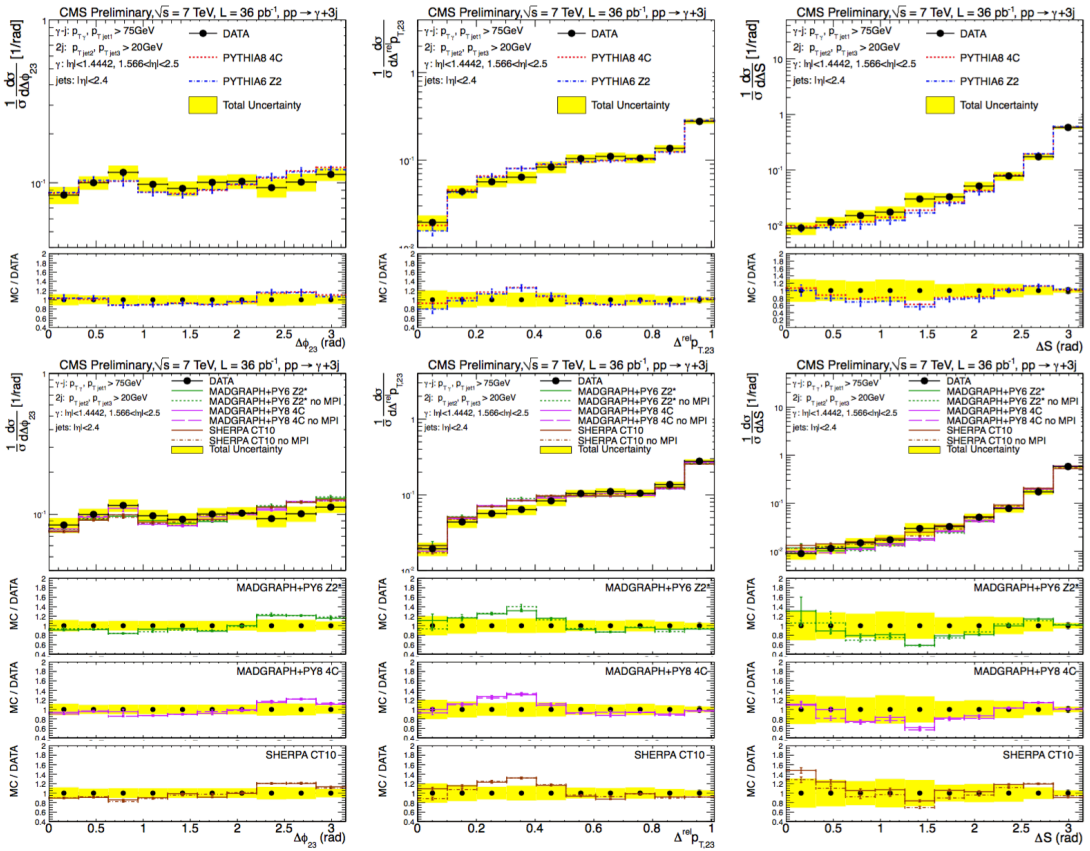


the difference in azimuthal angle between the jets belonging to the di-jet pair,

$$\Delta\phi_{23} = \phi_{\mathrm{jet2}} - \phi_{\mathrm{jet3}}; \qquad (2)$$

the transverse momentum balance of the jets belonging to the di-jet pair,

$$\Delta^{\mathrm{rel}} p_{\mathrm{T},23} = \frac{|\vec{p}_{\mathrm{T\,jet2}} + \vec{p}_{\mathrm{T\,jet3}}|}{|\vec{p}_{\mathrm{T\,jet2}}| + |\vec{p}_{\mathrm{T\,jet3}}|}; \qquad (3)$$



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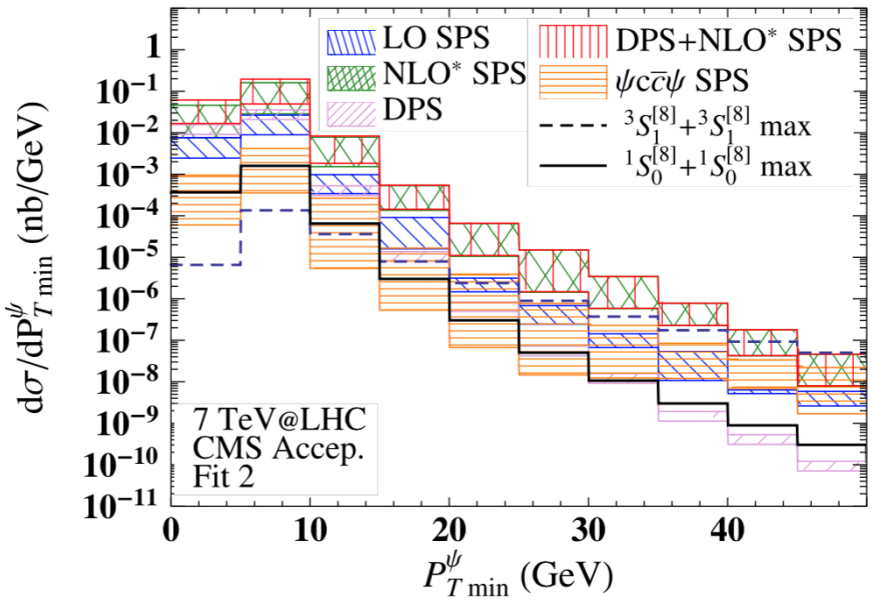
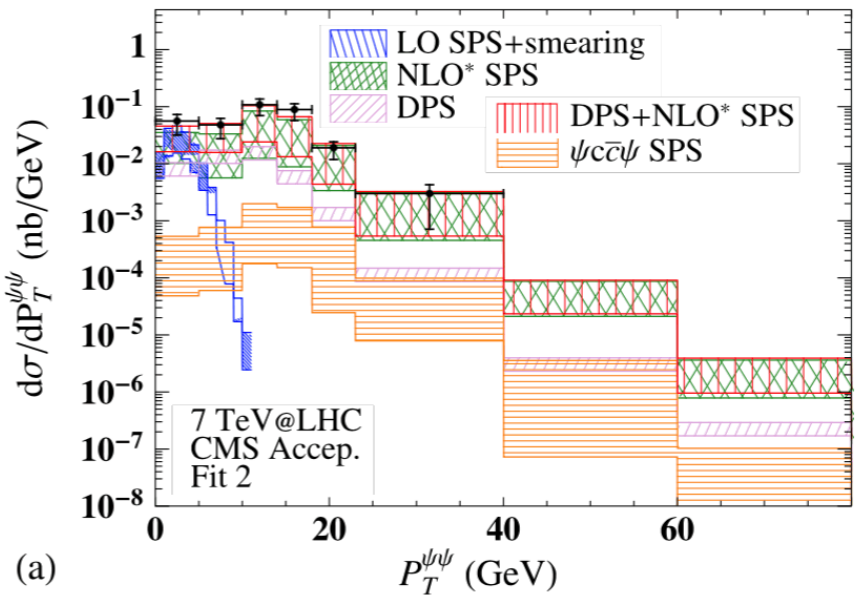
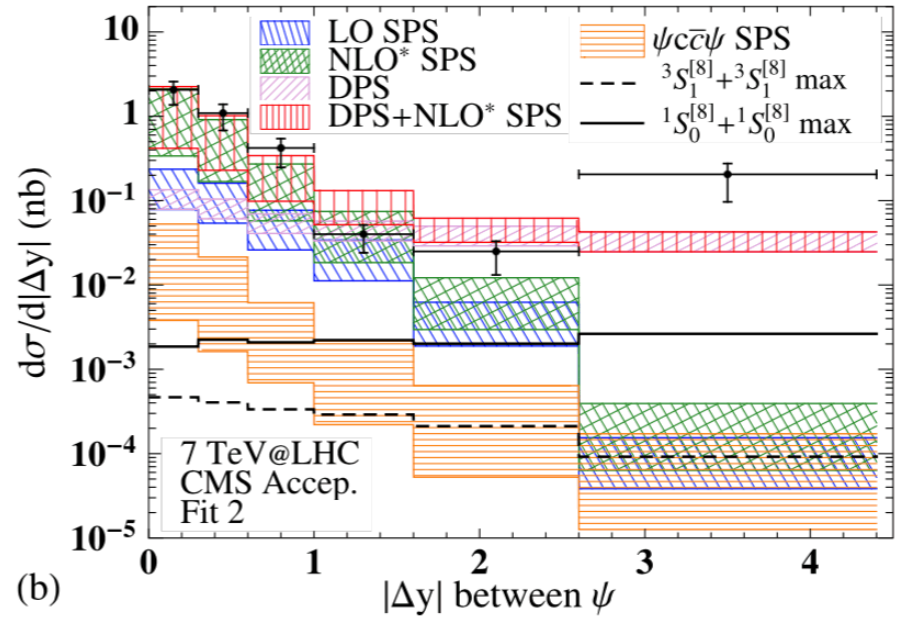
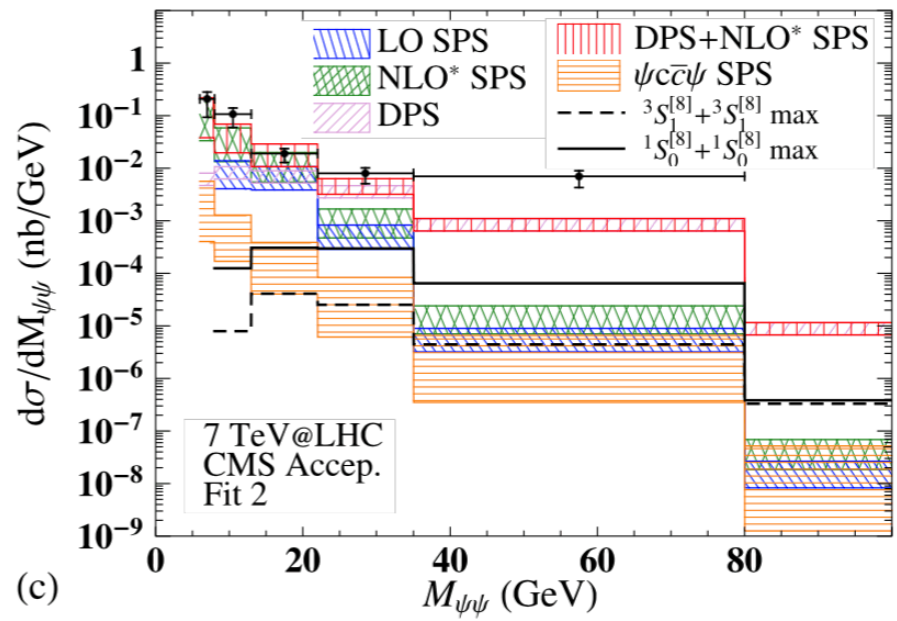
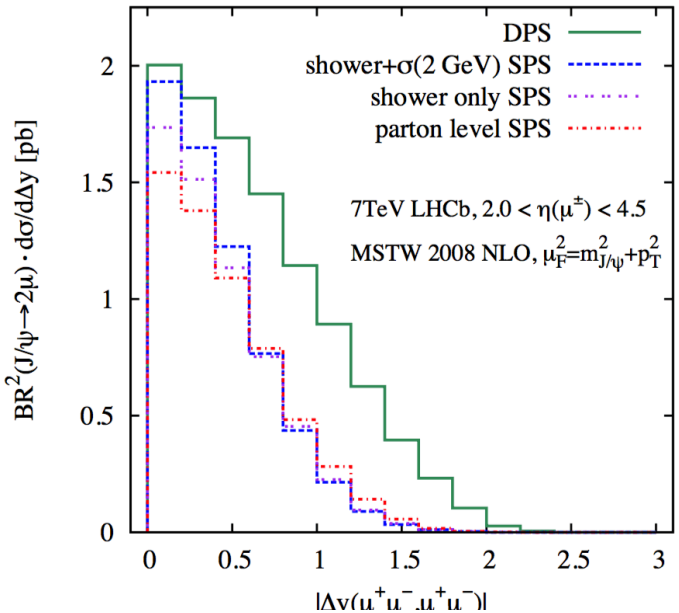

LO SPS
NLO* SPS
DPS
DPS+NLO* SPS
ψcc̄ψ SPS
$^3S_1^{[8]}+^3S_1^{[8]}$ max
$^1S_0^{[8]}+^1S_0^{[8]}$ max
7 TeV@LHC
CMS Accep.
Fit 2
$d\sigma/dP^{\psi}_{T\,min}$ (nb/GeV)
$P^{\psi}_{T\,min}$ (GeV)

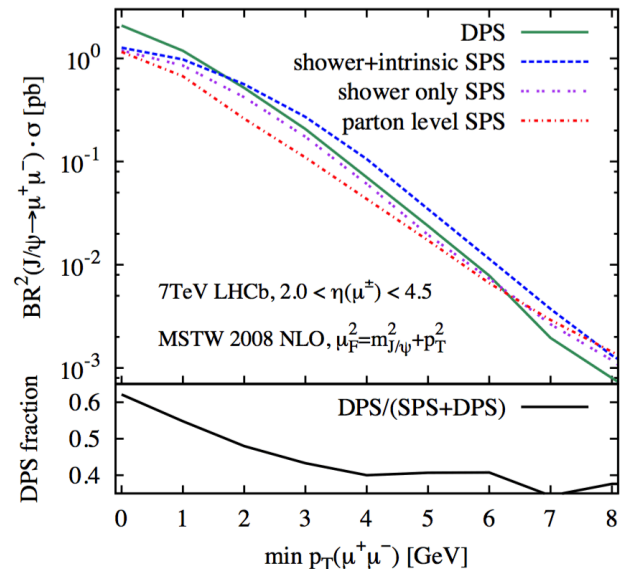

LO SPS+smearing
NLO* SPS
DPS
DPS+NLO* SPS
ψcc̄ψ SPS
7 TeV@LHC
CMS Accep.
Fit 2
$d\sigma/dP_T^{\psi\psi}$ (nb/GeV)
$P_T^{\psi\psi}$ (GeV)
(a)

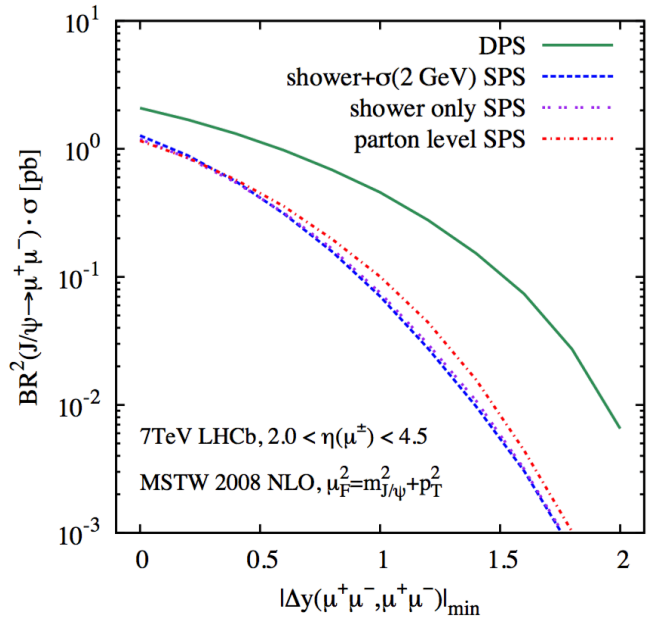

LO SPS
NLO* SPS
DPS
DPS+NLO* SPS
ψcc̄ψ SPS
$^3S_1^{[8]}+^3S_1^{[8]}$ max
$^1S_0^{[8]}+^1S_0^{[8]}$ max
7 TeV@LHC
CMS Accep.
Fit 2
$d\sigma/d|\Delta y|$ (nb)
|Δy| between ψ
(b)

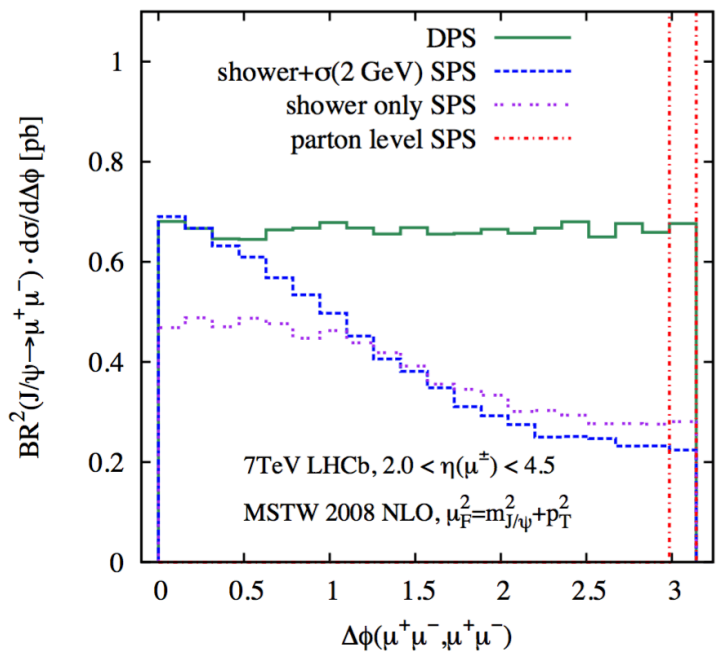

LO SPS
NLO* SPS
DPS
DPS+NLO* SPS
ψcc̄ψ SPS
$^3S_1^{[8]}+^3S_1^{[8]}$ max
$^1S_0^{[8]}+^1S_0^{[8]}$ max
7 TeV@LHC
CMS Accep.
Fit 2
$d\sigma/dM_{\psi\psi}$ (nb/GeV)
$M_{\psi\psi}$ (GeV)
(c)

backup









Main Observables

- $\Delta\eta_{\psi\psi}$, $\Delta\varphi_{\psi\psi}$, $M_{\psi\psi}$, $p_T^{\psi\psi}$