UIC
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AT CHICAGO

Quarkonium-Pair Production
at the SPS, the Tevatron and the LHC

2 March 2016

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University of Illinois at Chicago

Outline
1) Analyses overview
2) Brief history lesson
3) Where we stand

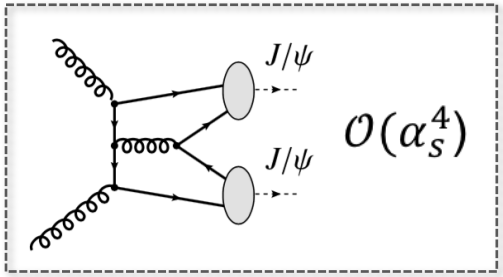
Motivation for Di-Quarkonia

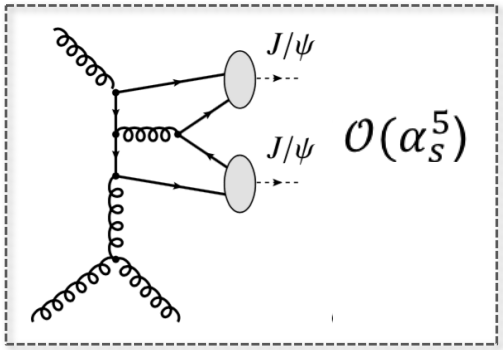
Single Parton Scattering (SPS)

- Probe higher-order diagrams
- Color Octet vs Singlet

Double Parton Scattering (DPS)

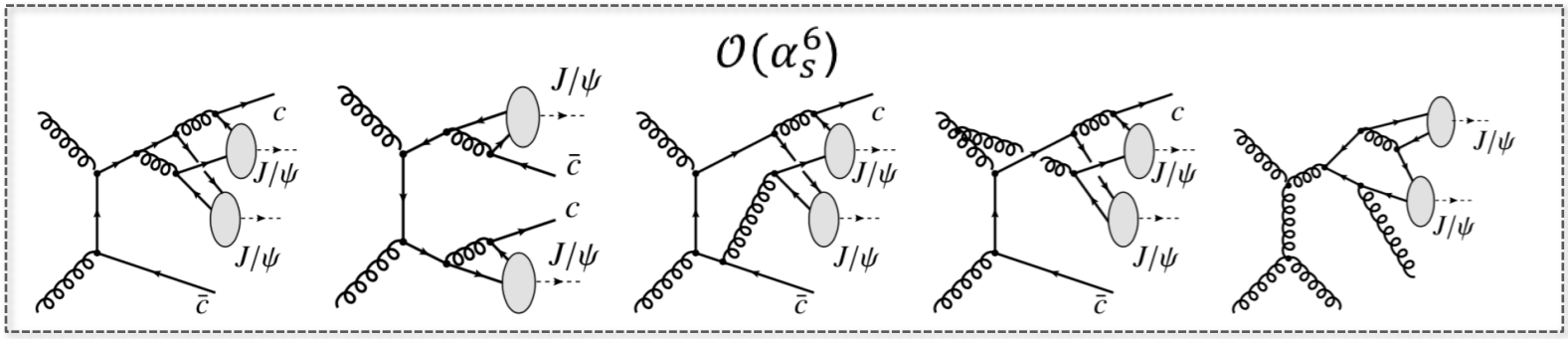
- Increasingly important at higher $\sqrt{s}$
- Probe transverse profile of proton PDF





Results Covered

- NA3, $\sqrt{s}$ ~25 GeV
  Phys.Lett.B114 (1982), Phys.Lett.B158 (1985)
- D0, $\sqrt{s}$ = 1.96 TeV
  Phys.Rev.D90 (2014), PRL116 (2016)
- LHCb, $\sqrt{s}$ = 7 TeV
  Phys.Lett.B707 (2012)
- CMS, $\sqrt{s}$ = 7 TeV
  JHEP 1409 (2014) (w/ PRL111(2013))



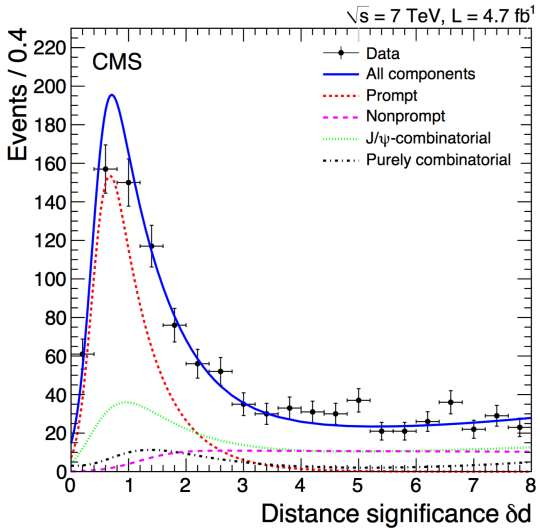
Lansberg, Shao Phys.Let.B751 (2015)

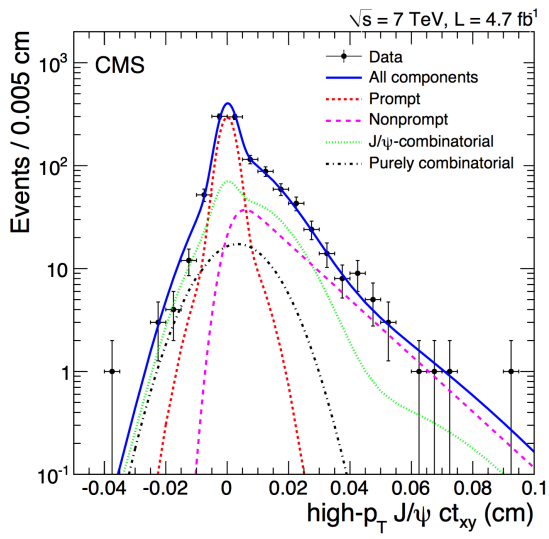
General Analysis Overview

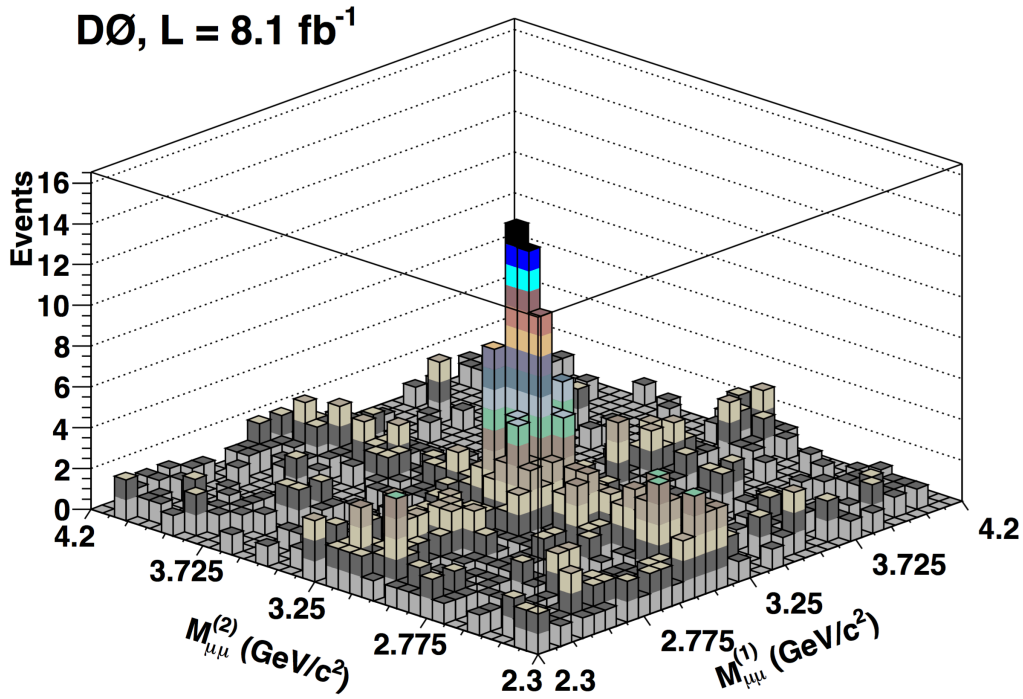
$J/\psi - J/\psi \rightarrow \mu^+\mu^- \mu^+\mu^-$

Types of Events

- Sig: prompt $J/\psi - J/\psi$
- Bkg: non-prompt J/ψ (B decays)
- Bkg: prompt J/ψ + unassoct'd $\mu\mu$
- Bkg: unassoct'd $\mu\mu$ + unassoct'd $\mu\mu$







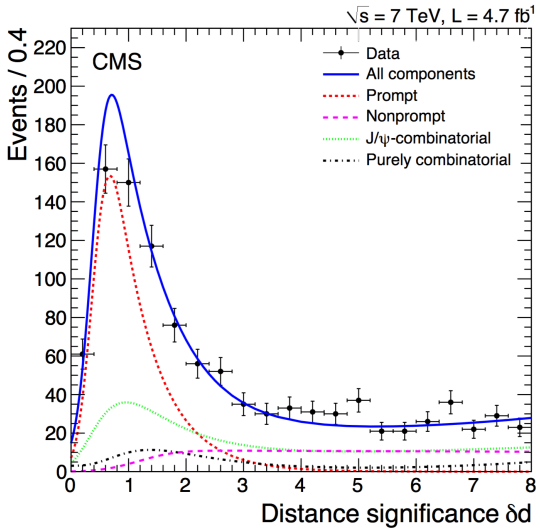
General Analysis Strategy

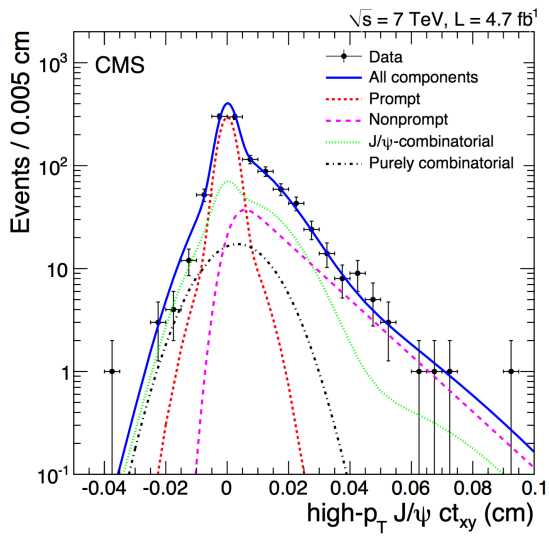
$J/\psi - J/\psi \rightarrow \mu^+\mu^- \mu^+\mu^-$

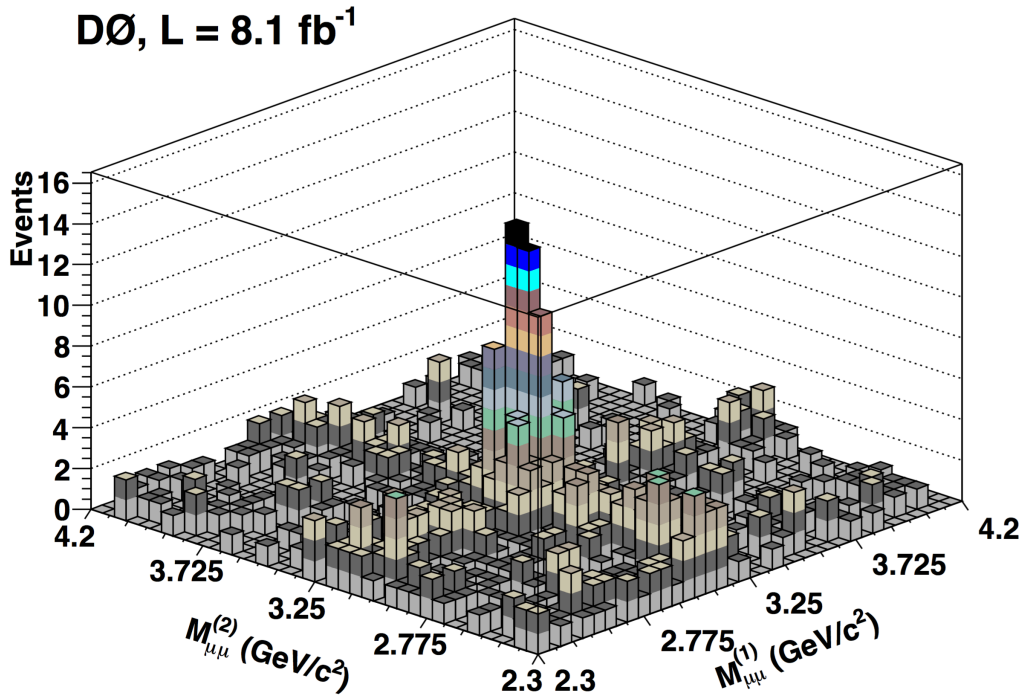
Types of Events

General Cuts

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







Main Observables

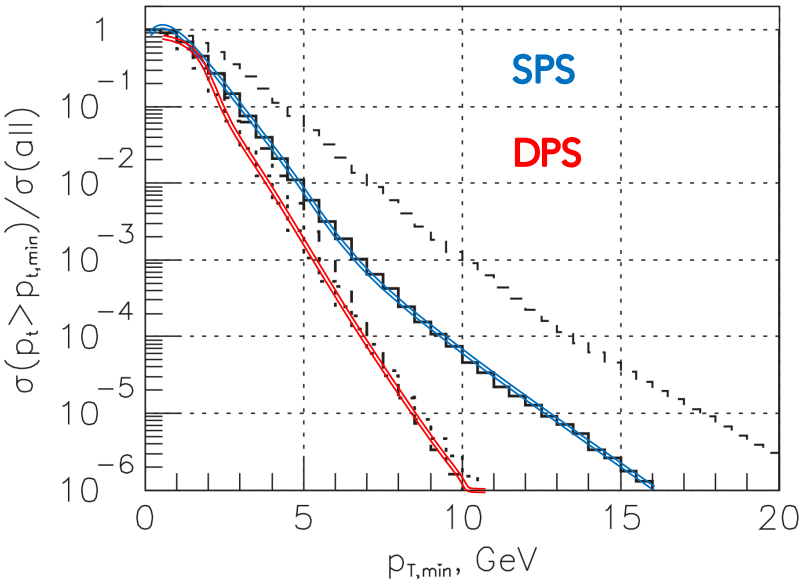
- $\Delta\eta_{\psi\psi}$, $\Delta\varphi_{\psi\psi}$, $M_{\psi\psi}$, $p_T^{\psi\psi}$

How to separate SPS from DPS ?

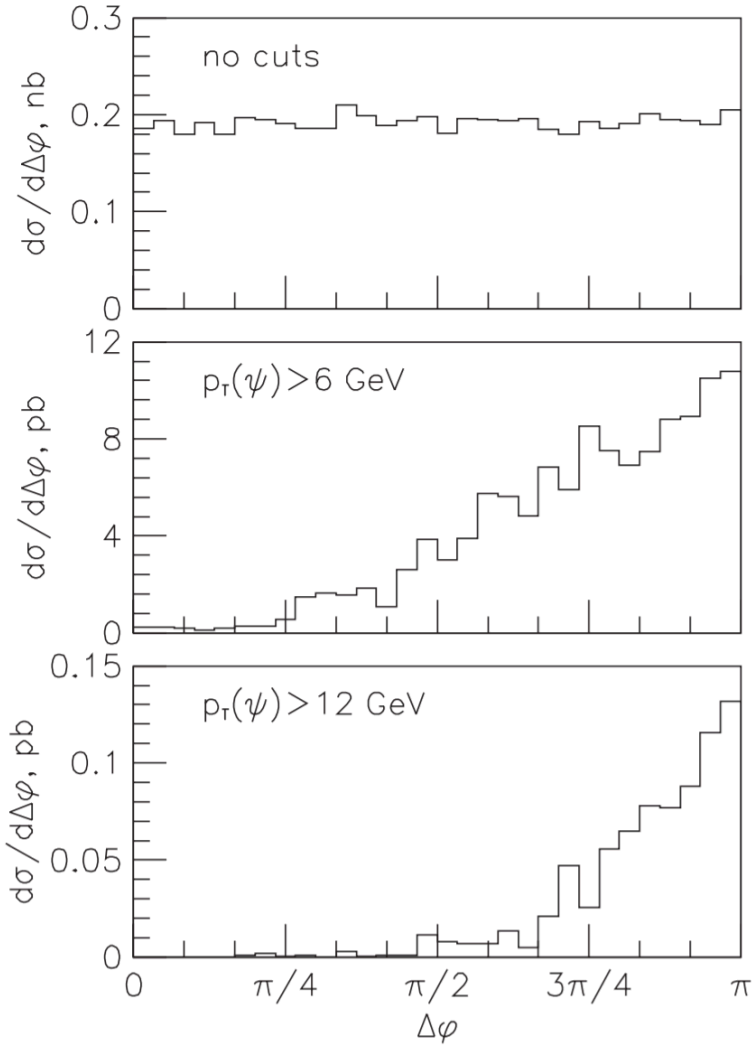
- Naïve idea –
  J/ψ's in SPS are mostly back-to-back
  → just cut on $\Delta\varphi_{\psi\psi}$!

- 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)

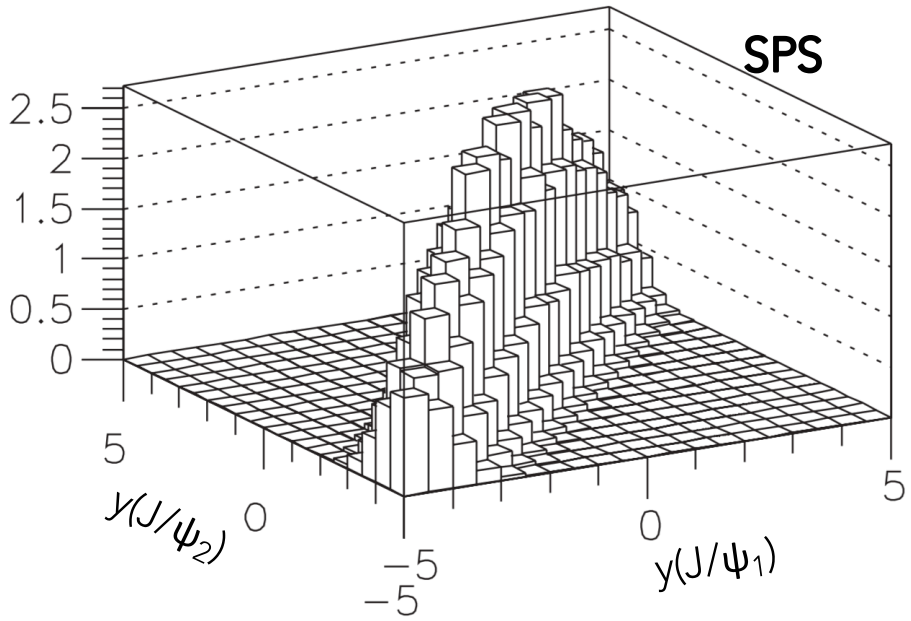
- DPS

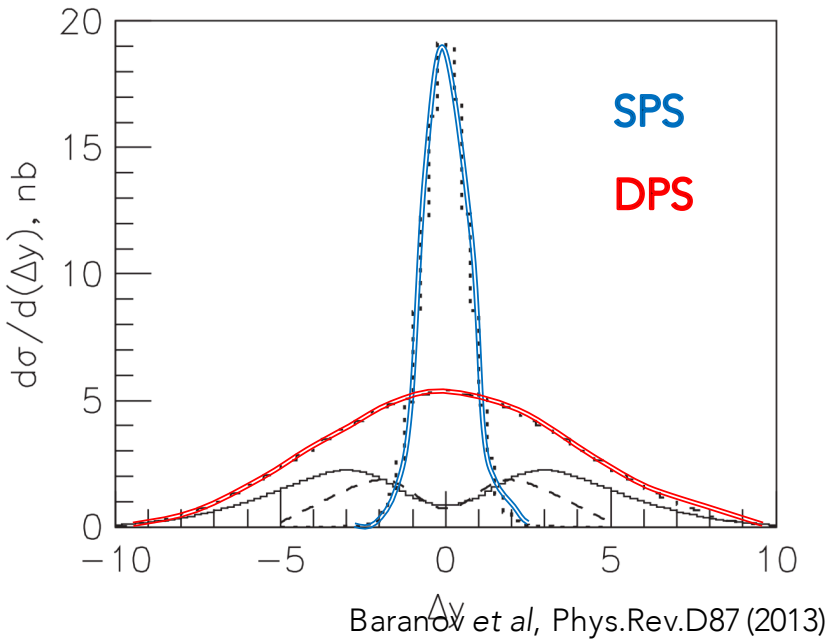
  $\Delta\eta_{\psi\psi}$ much broader

- Kinematically cleaner way to proceed

  (along with $M_{\psi\psi}$, $p_T^{\psi\psi}$)

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



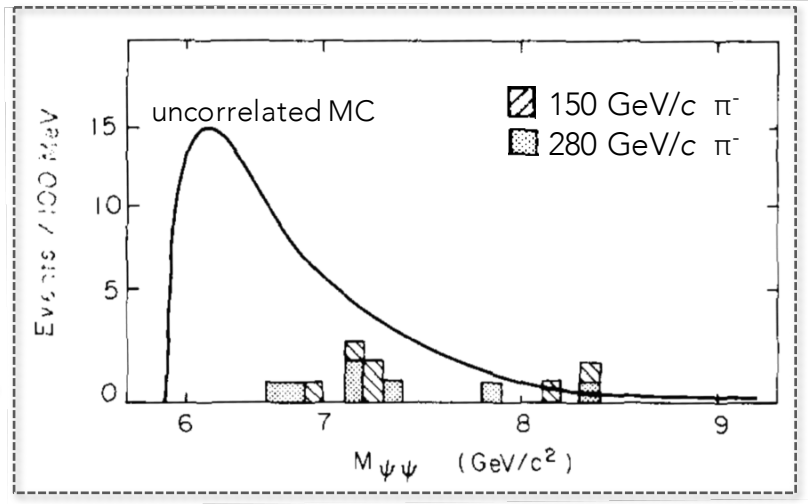


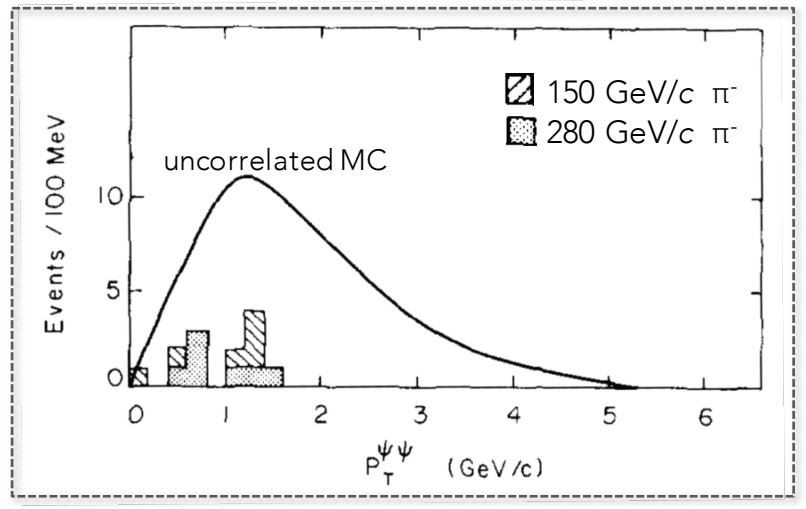
Baranov *et al*, Phys.Rev.D87 (2013)

Things aren't always as they as naïvely seem…

NA3 at CERN SPS

- 150, 280, (400) GeV/c π^-(p) beam → Pt target
  - $\sqrt{s} \approx 17\ \mathrm{GeV}/c$ $\sqrt{s} \approx 25\ \mathrm{GeV}/c$ $\sqrt{s} \approx 29\ \mathrm{GeV}/c$
- only consider SPS production
  - used kinematic MC to show J/ψ-J/ψ pairs were *correlated*.
- 13 counts !





150 GeV/c : $\sigma_{J/\psi\text{-}J/\psi} = 18 \pm 8$ pb
280 GeV/c : $\sigma_{J/\psi\text{-}J/\psi} = 30 \pm 10$ pb

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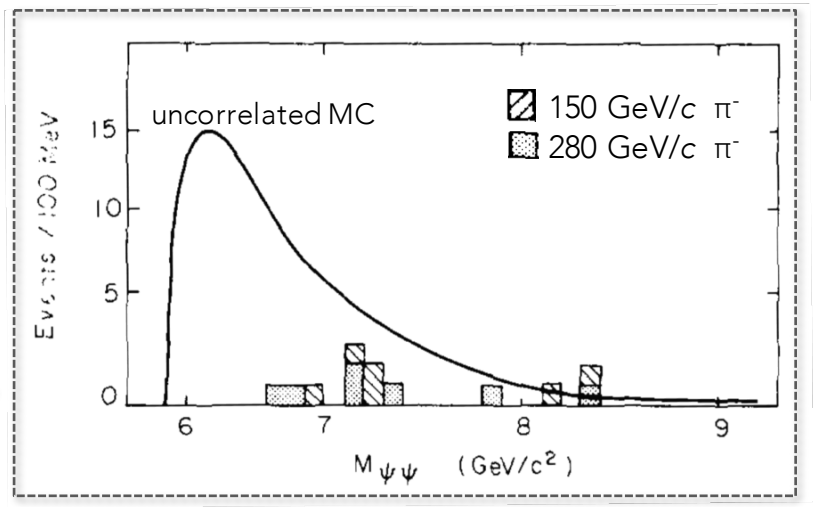
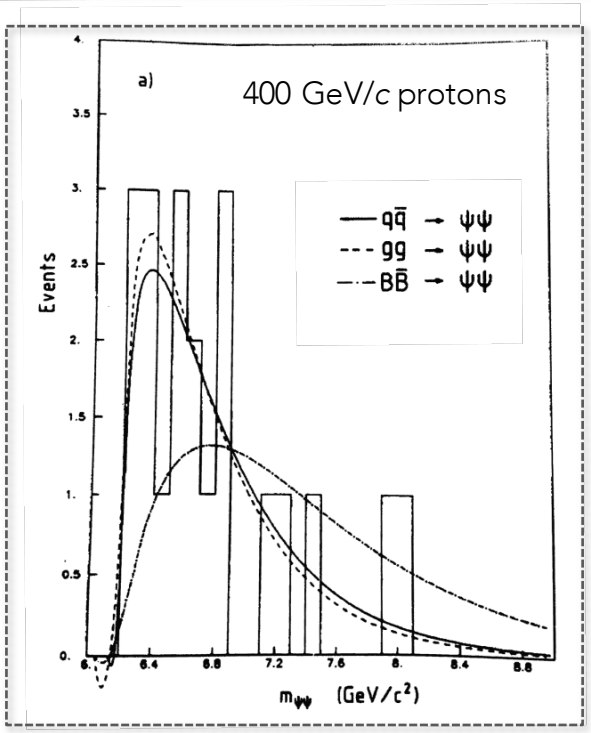


- Include QCD calculation
  Ecclestone & Scott Z.Phys.C19 (1983)
- Good agreement w/ data



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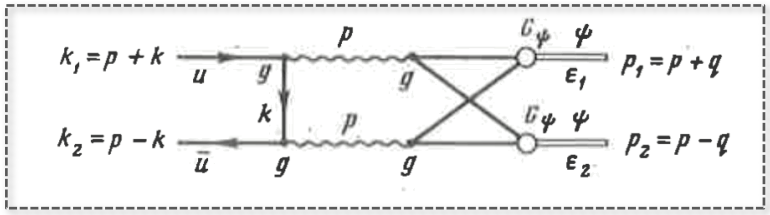
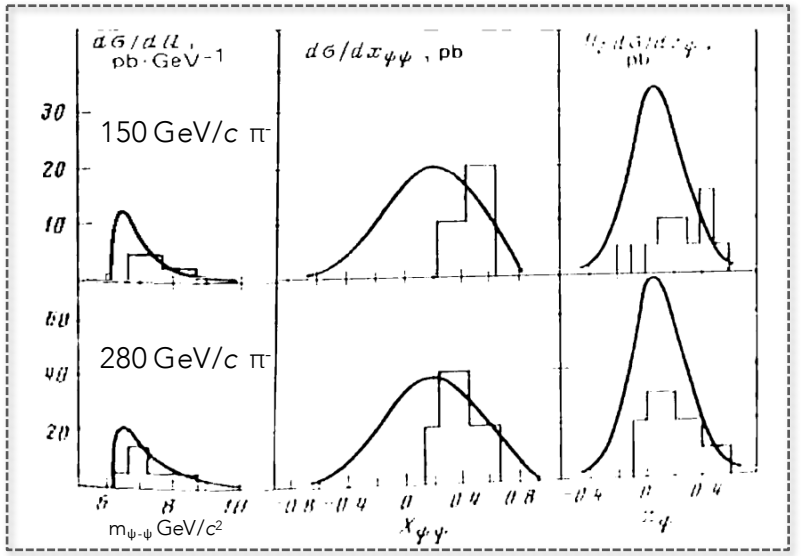
- only consider SPS production
  - $u\bar{u}$ annihilation calculation describes data →

Kartvelishvili *& Ésakiya Sov.J.Nucl.Phys.38(3) (1983)*





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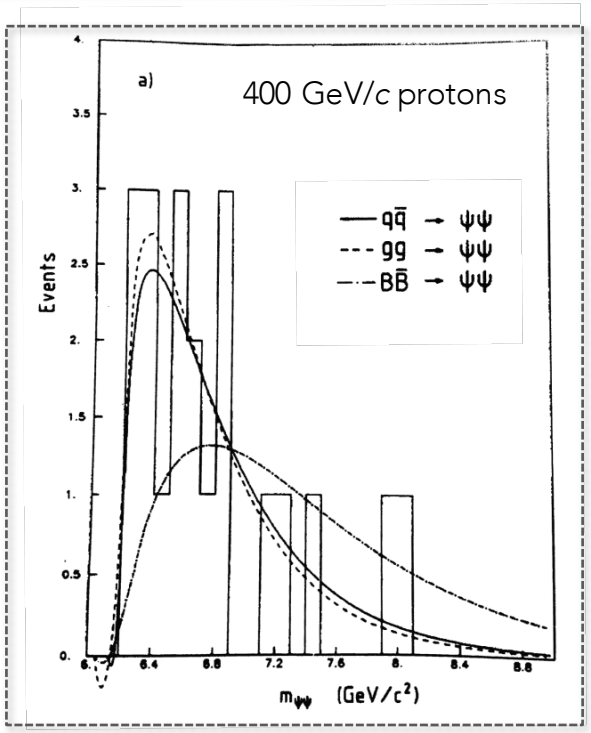

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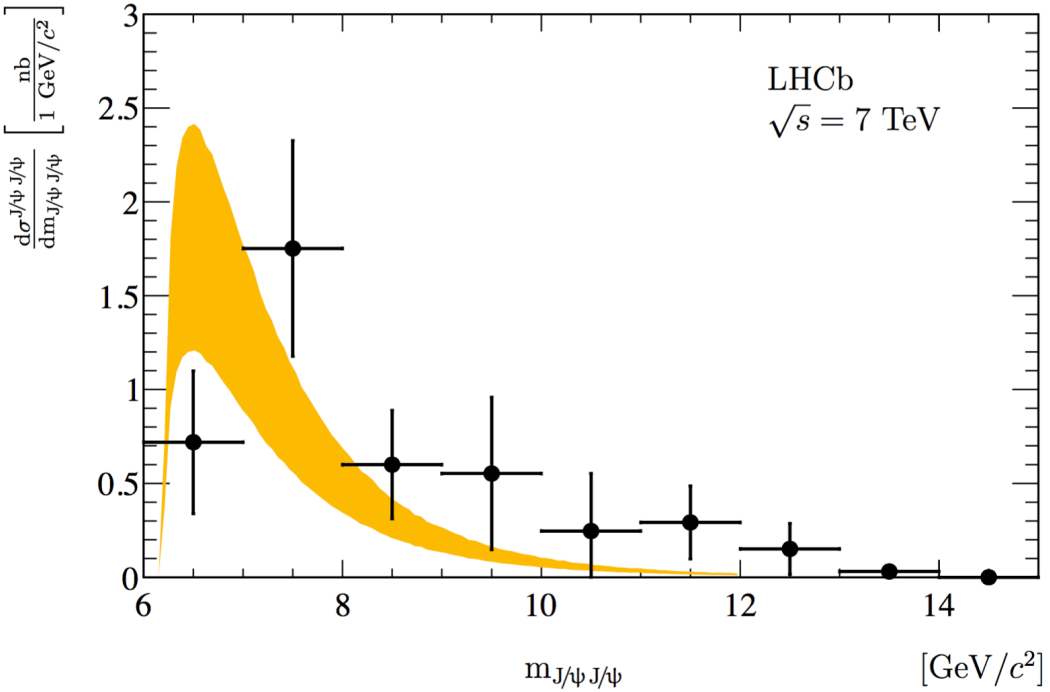
Respect your elders…

LHCb at CERN LHC

- 7 TeV pp

- Leading order pQCD (Berezhnov *et al.*)
  - gg → J/ψ-J/ψ, J/ψ-ψ(2S), ψ(2S)-ψ(2S)
  - SPS only
    *does **not** include DPS contributions*

- Claims "reasonable" agreement



Result
- $\sigma_{J/\psi\text{-}J/\psi}$ = 5.1 ± 1.0 ± 1.1 nb
- $\sigma_{J/\psi}$ = 10.52 ± 0.04 ± 1.40 ub

LHCb, arXiv:1103.0423

Fiducial Acceptance
- J/ψ: p_T < 10 GeV/c
- J/ψ: 2 < y < 4.5

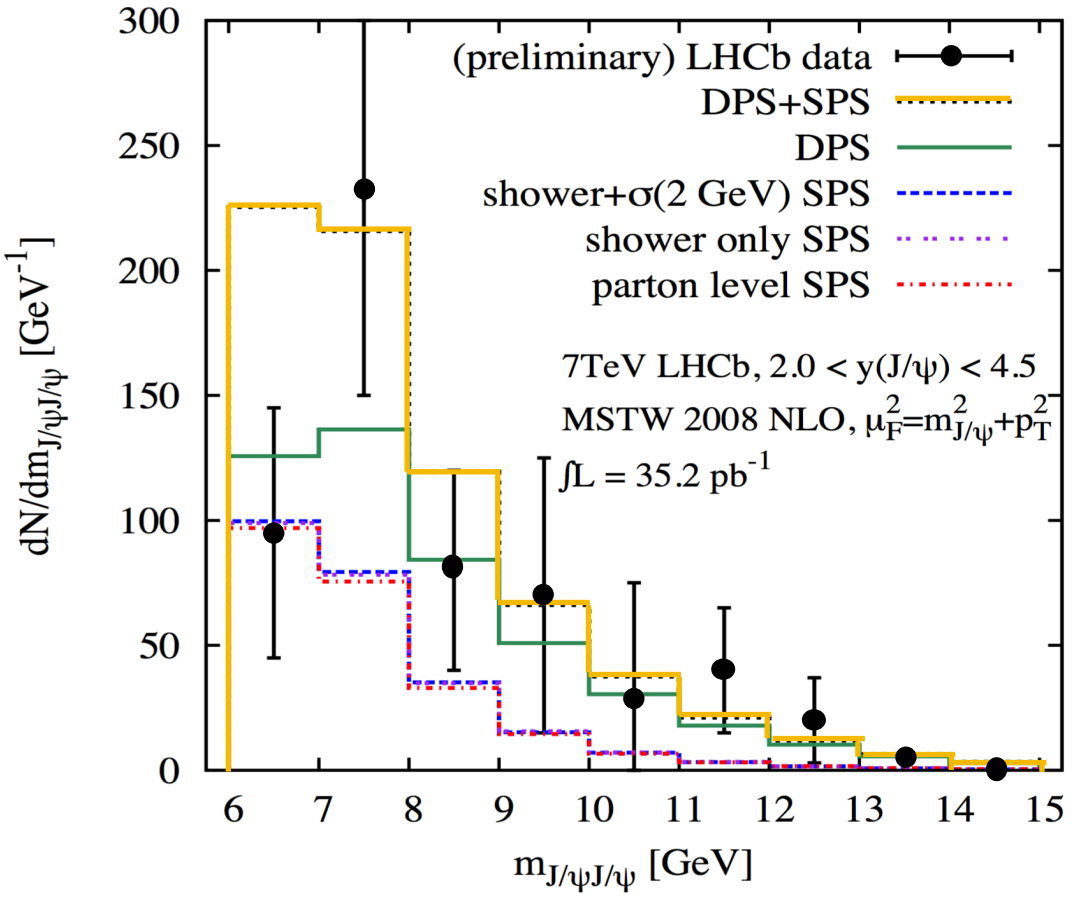
Berezhnoy *et al*, arXiv:1101.5881

LHCb at CERN LHC

- 7 TeV pp

- SPS calculation (Kom *et al.*)
- DPS calculation
- SPS + DPS

- Evidence of DPS ??
  (*exciting*!)



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LHCb, arXiv:1103.0423

Fiducial Acceptance
- J/ψ: $p_T < 10$ GeV/c
- J/ψ: $2 < y < 4.5$

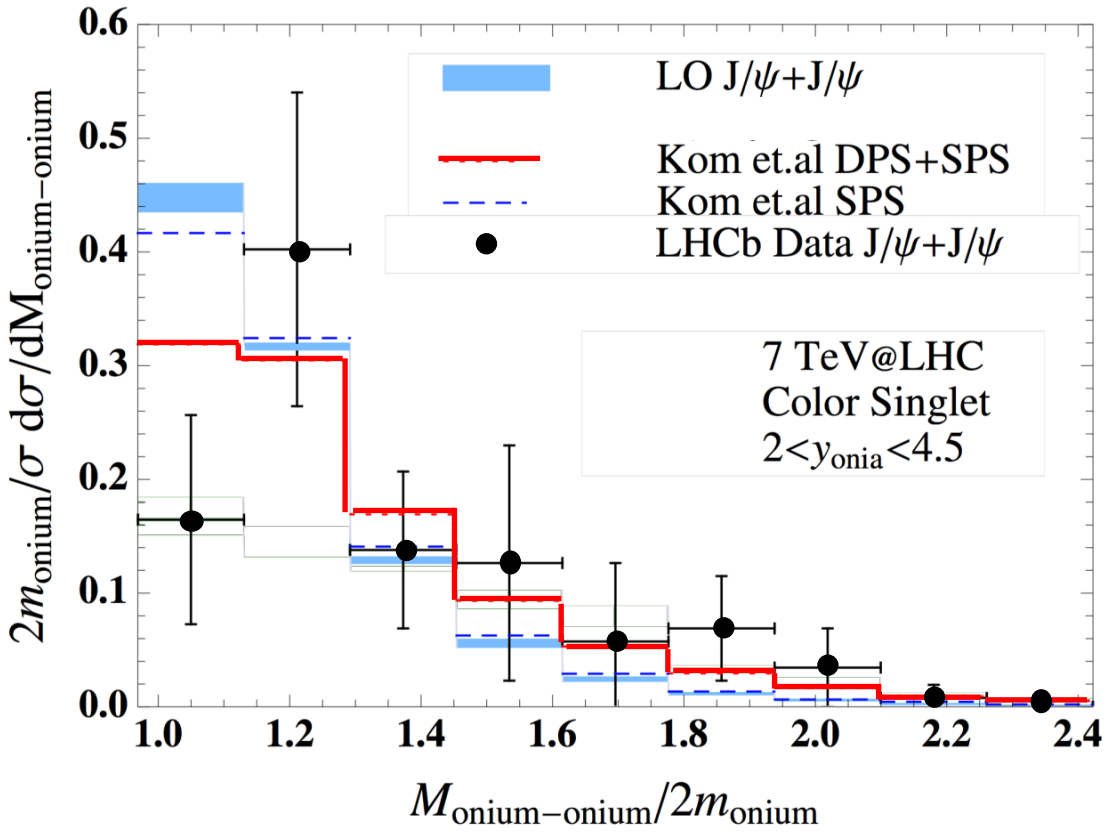
Kom *et al*, PRL107 (2011)

LHCb at CERN LHC

- 7 TeV pp

- LO J/ψ SPS (*Lansberg/Shao*)
- Conclude that errors are too large to say much…
  - Large data errors
  - Scale uncert – shift curves ⇔
- Each curve normalized, integral=1

- Quantitative shape comparison not performed



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LHCb, arXiv:1103.0423

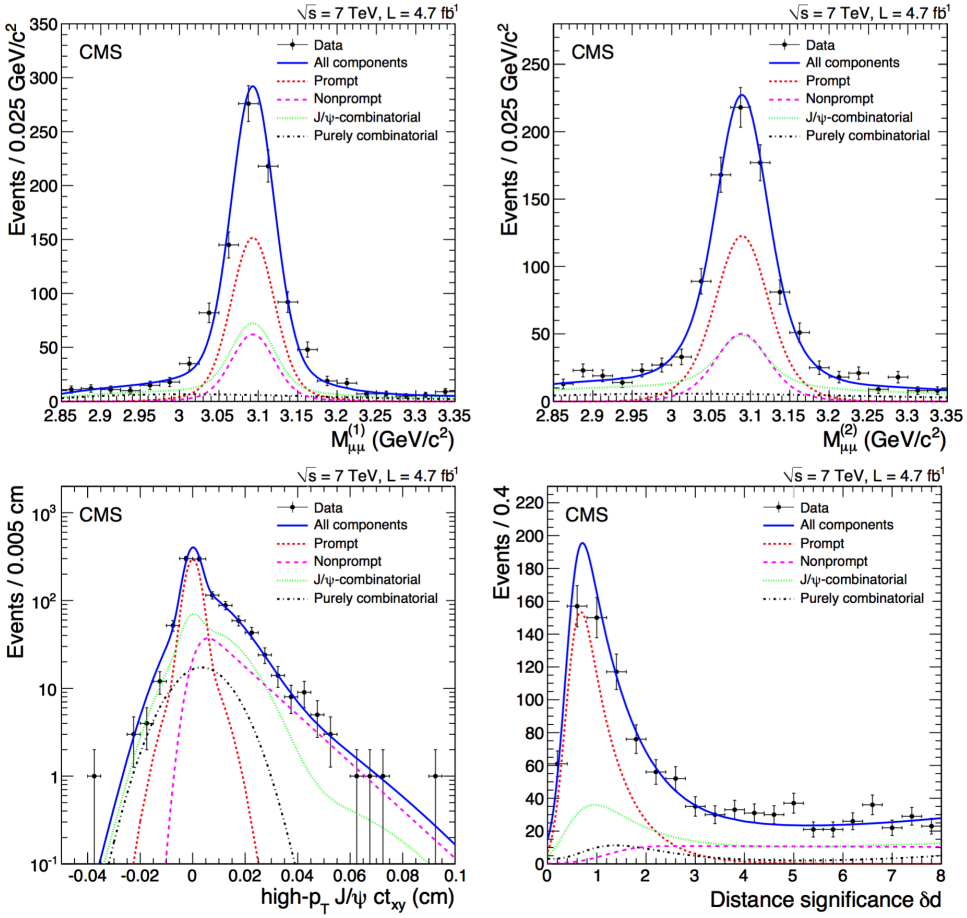
Fiducial Acceptance
- J/ψ: p_T < 10 GeV/c
- J/ψ: 2 < y < 4.5

Lansberg, Shao Phys.Rev.Let.111 (2013)

Error bars matter…

CMS at CERN LHC

- 7 TeV pp
- Simultaneous fit in
  $M_{\mu\mu}^{1}$, $M_{\mu\mu}^{2}$, production vertex, production separation



Result

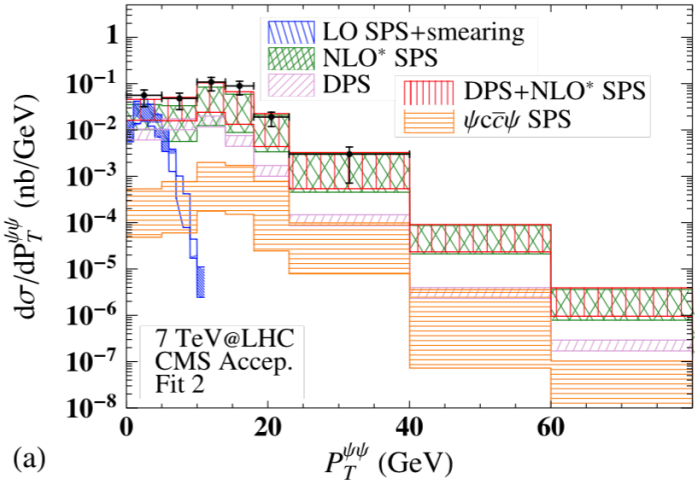
- $\sigma_{J/\psi\text{-}J/\psi} = 1.49 \pm 0.07 \pm 0.13$ nb

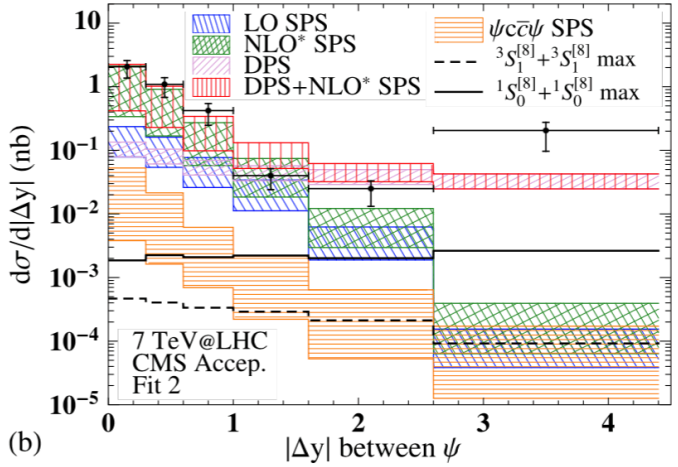
Fiducial Acceptance (J/ψ)

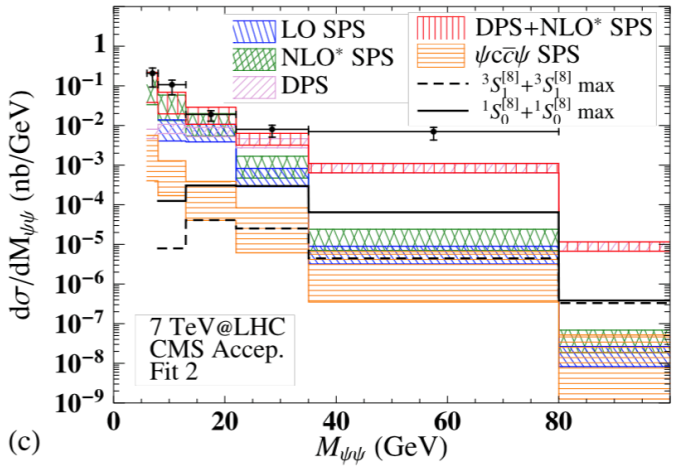
- $p_T > 6.5$ GeV/c for $|y| < 1.2$
- $p_T > 6.5 \rightarrow 4.5$ GeV/c for $1.2 < |y| < 1.43$
- $p_T > 4.5$ GeV/c for $1.43 < |y| < 2.2$

CMS at CERN LHC

- 7 TeV pp
- Simultaneous fit in $M_{\mu\mu}^1$, $M_{\mu\mu}^2$, prod vtx, production separation







- Lansberg & Shao perform multi-dimensional fits in $\Delta\eta_{\psi\psi}$, $M_{\psi\psi}$, $p_T^{\psi\psi}$
- Extract σ_{DPS} → σ_{eff} for CMS

Result

- $\sigma_{J/\psi\text{-}J/\psi} = 1.49 \pm 0.07 \pm 0.13$ nb
- $\sigma_{eff} = 8.2 \pm 2.0 \pm 2.9$ mb

Fiducial Acceptance (J/ψ)

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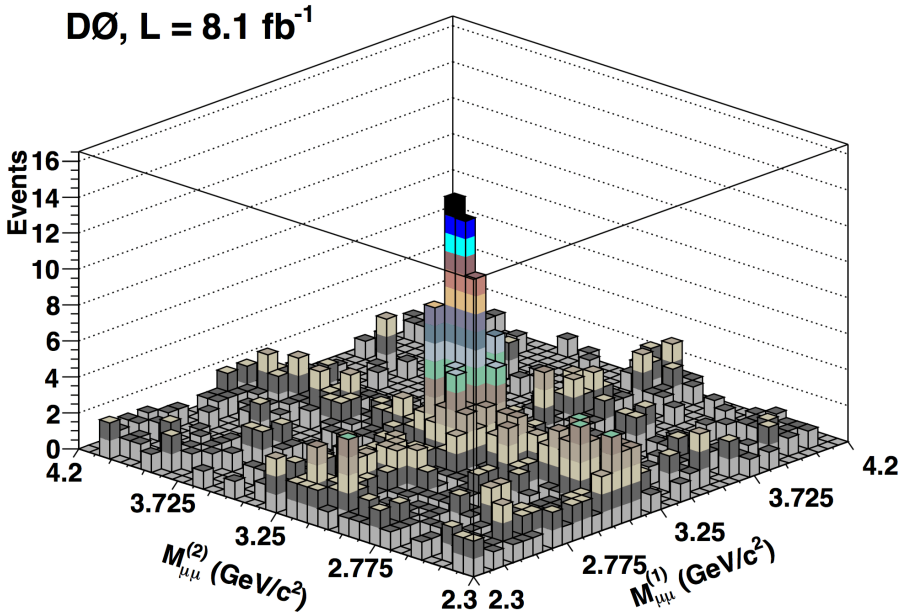
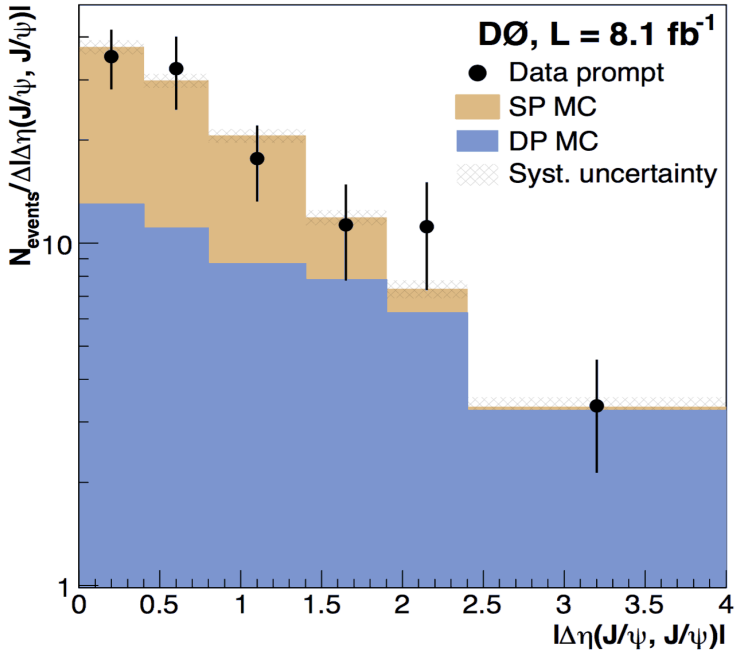
Lansberg, Shao Phys.Let.B751 (2015)

Never leave for others what you can do for yourself…

D0 at Tevatron

- 1.96 TeV $p\bar{p}$
- Use template fit to $\Delta\eta_{\psi\psi}$ (and decay vertex)
- Subtract background





Result

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

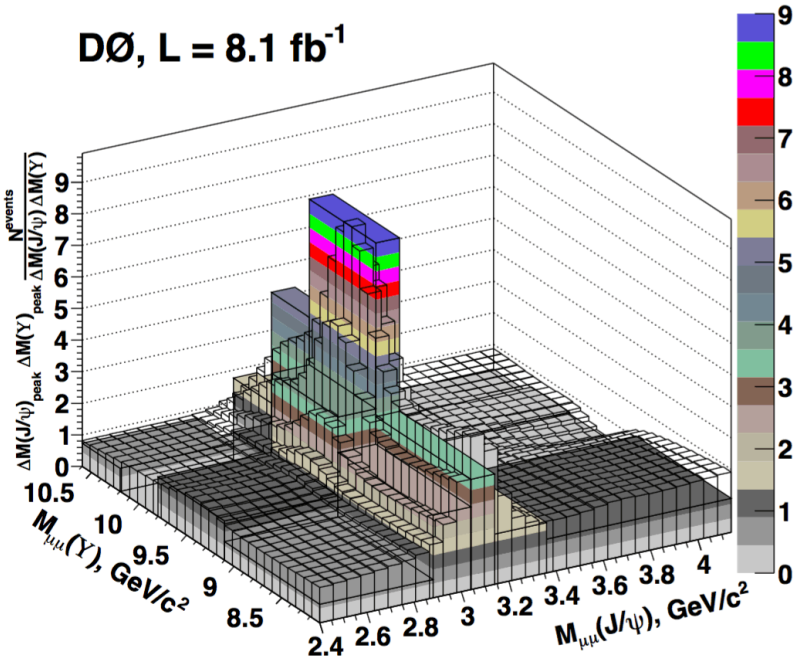
Fiducial Acceptance (J/ψ)

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

D0 at Tevatron

- 1.96 TeV pp
- J/ψ-Υ production

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

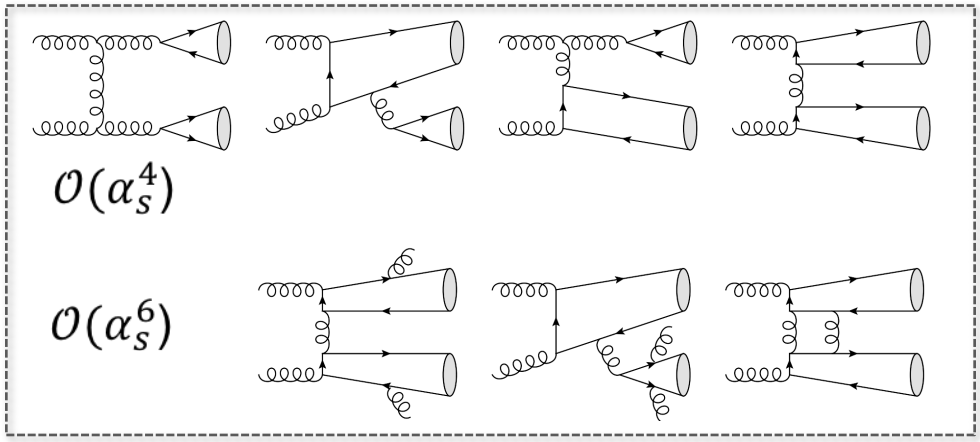


Result

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

Fiducial Acceptance (μ)

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



D0 at Tevatron

- 1.96 TeV pp
- J/ψ-Υ production

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

Result

- $\sigma(J/\psi) = 28 \pm 7$ nb
- $\sigma(\Upsilon) = 2.1 \pm 0.3$ nb
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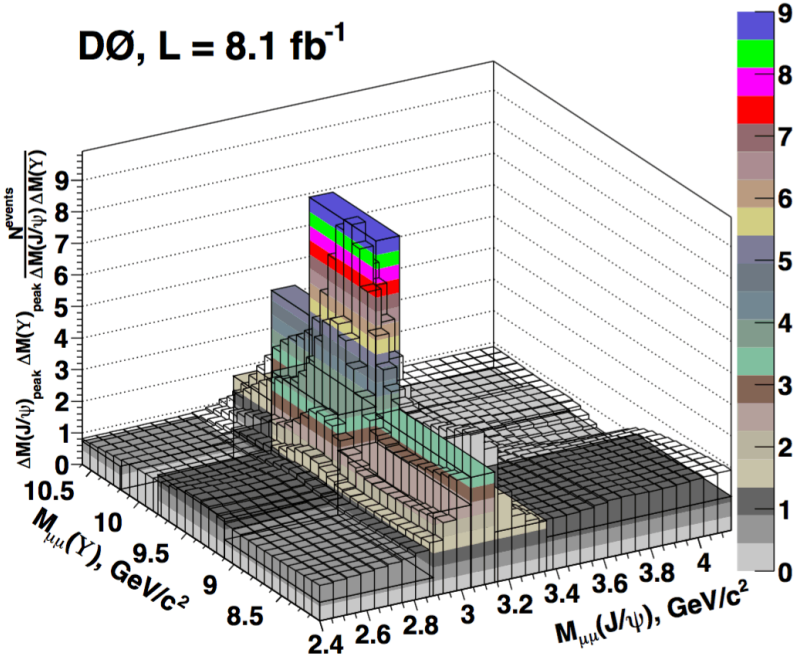
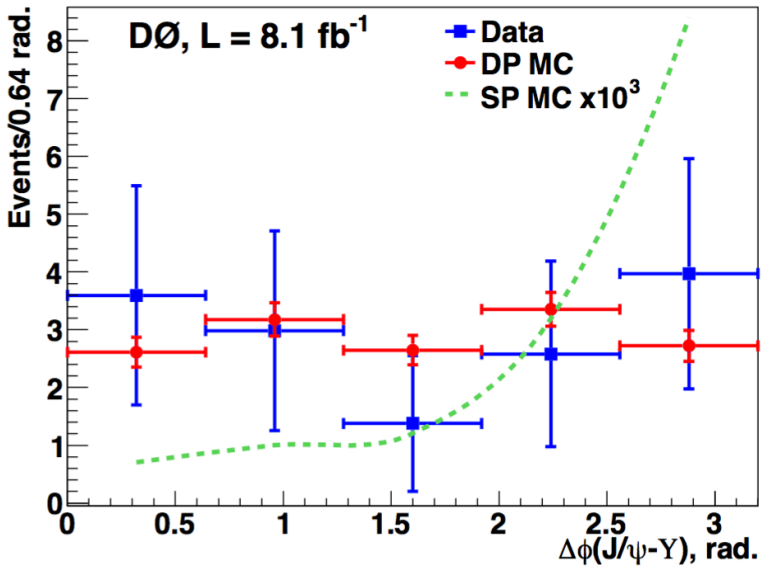
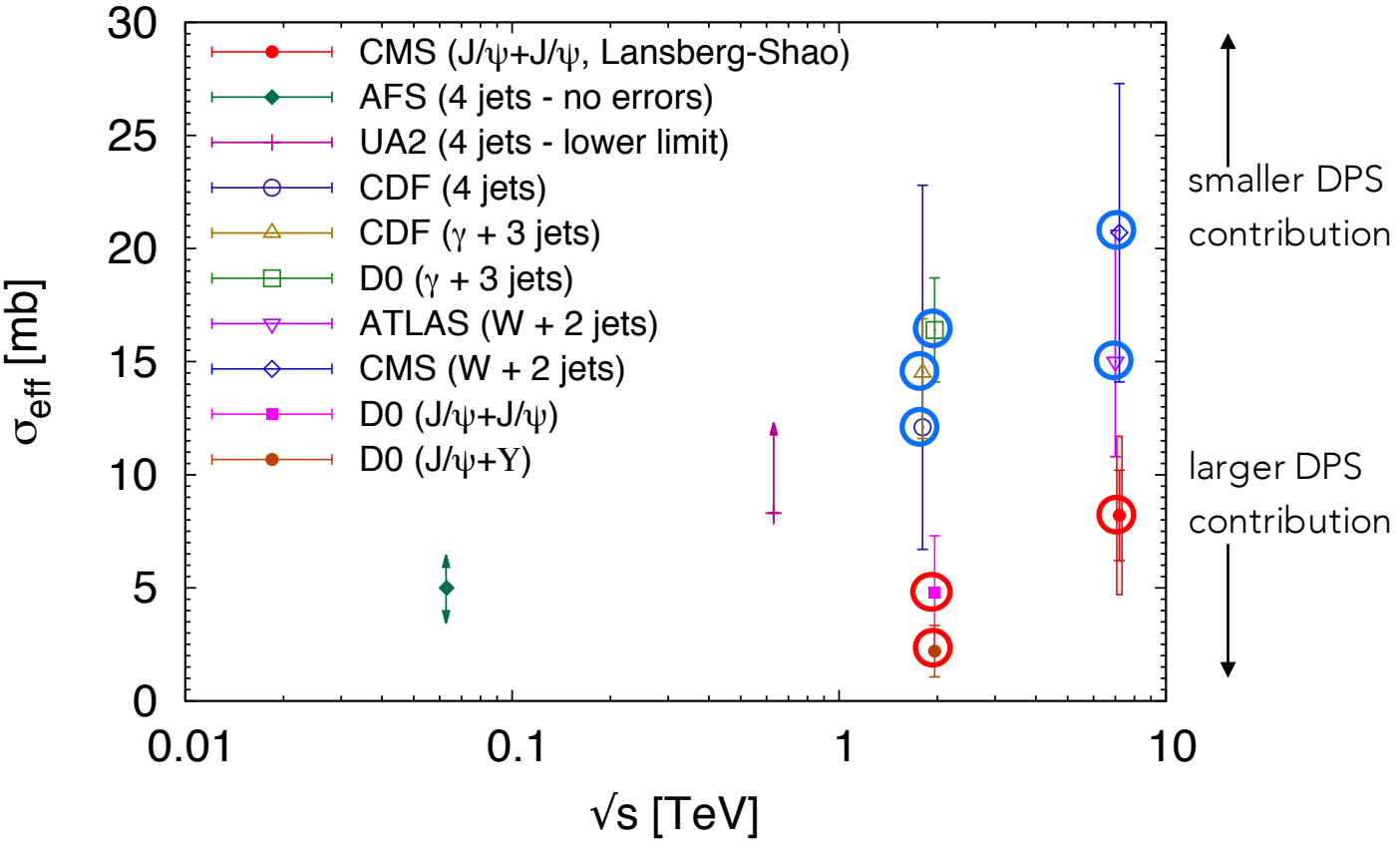




Plotsmanship matters…

Compiling Data…

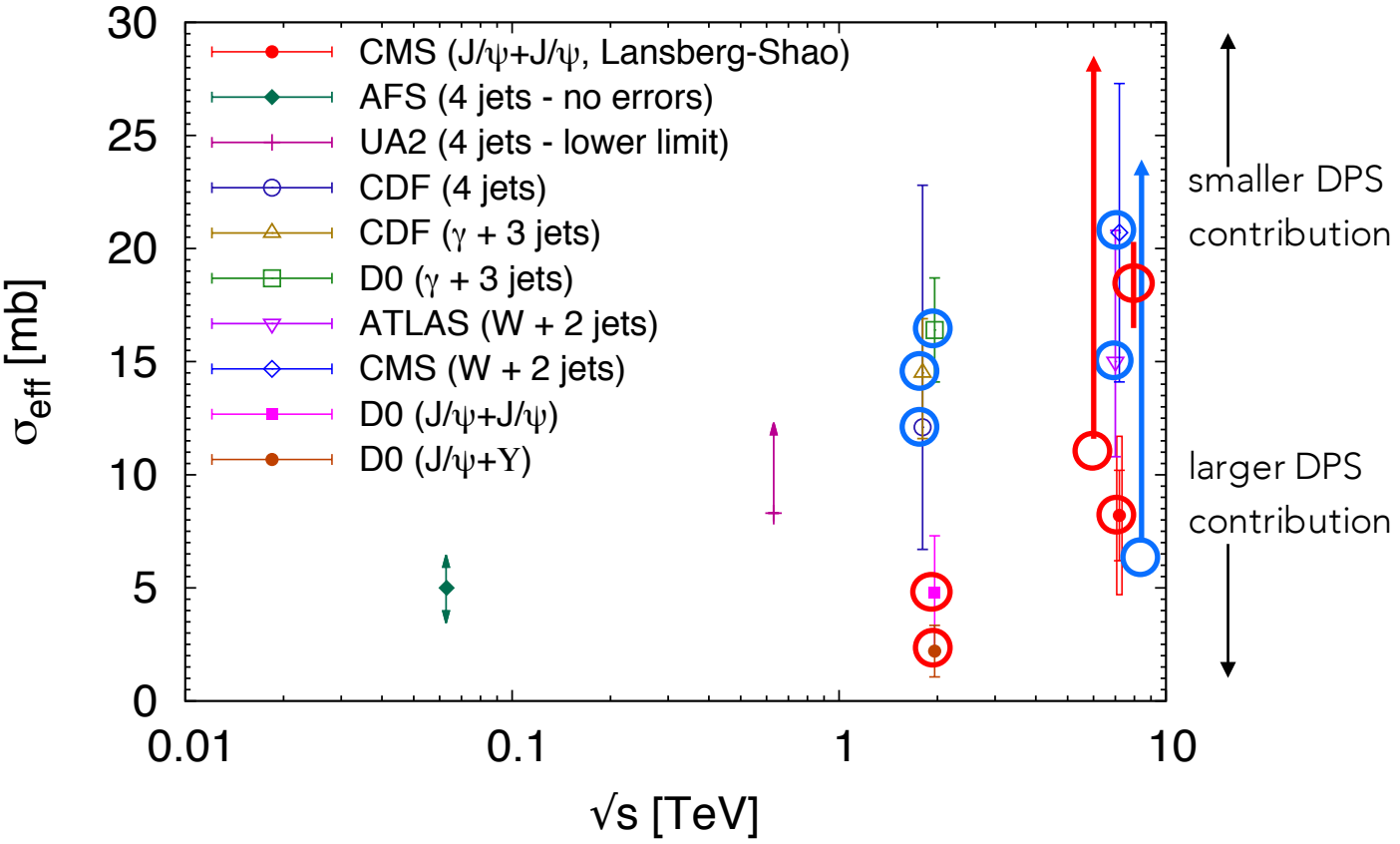
- Extracting σ_{eff} for various processes



- gg processes appear lower than qg processes
- Imply that gluon transverse PDF < quark transverse PDF ?

Compiling Data…

- Extracting σ_{eff} for various processes



- gg processes appear lower than qg processes
- Imply that gluon transverse PDF < quark transverse PDF ?
- LHCb (J/ψ+J/ψ), LHCb (D+Y), ATLAS (J/ψ+Z)

Maybe we don't know as much as we think we do…

Summary

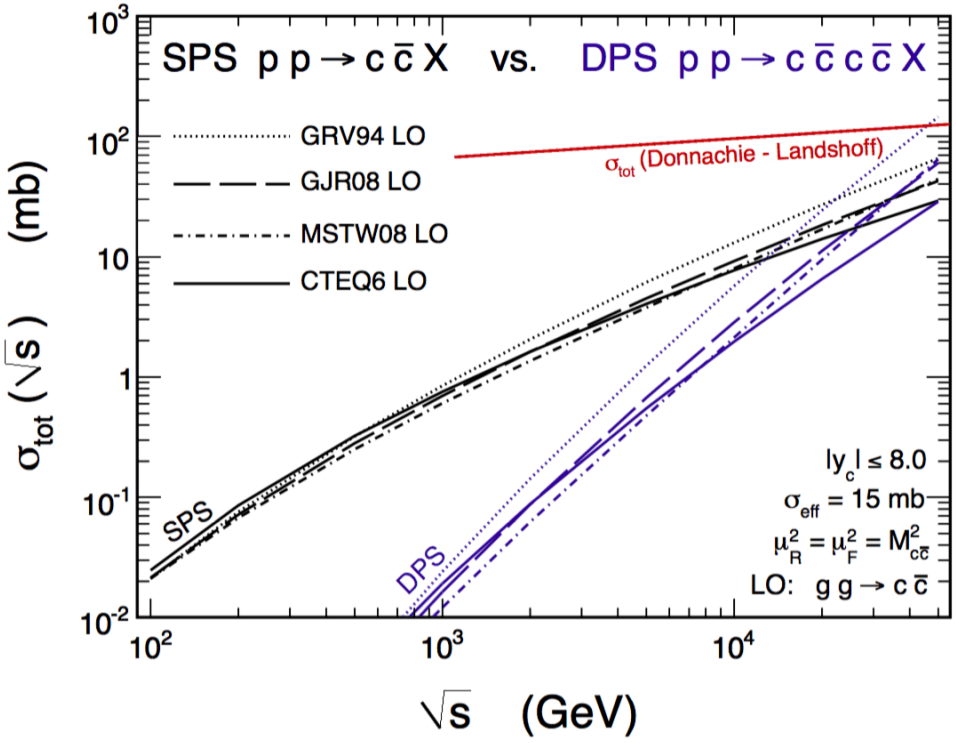
Di-Quarkonia are new way to access quarkonium production

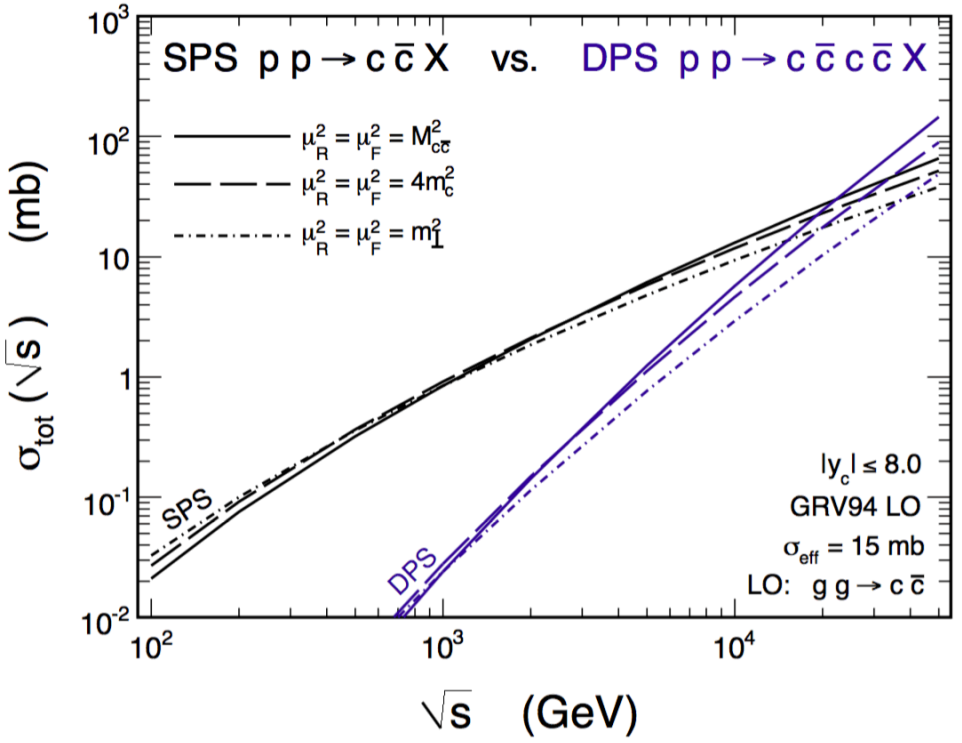
Clean way to access Single/Double Parton Scattering
Provides reasonable separation power between SPS and DPS

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

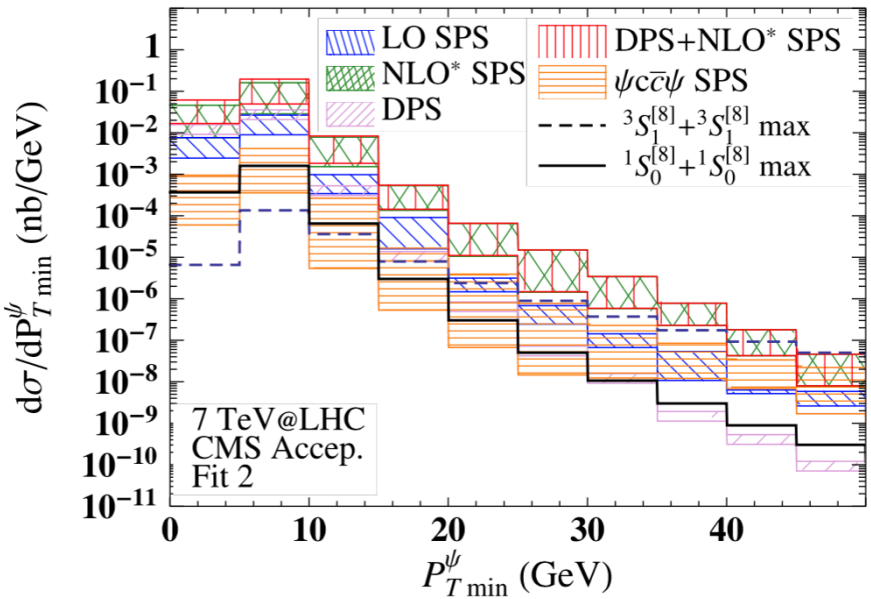
Higher $\sqrt{s}$… higher luminosities… larger systems (pA)...
Future is exciting !

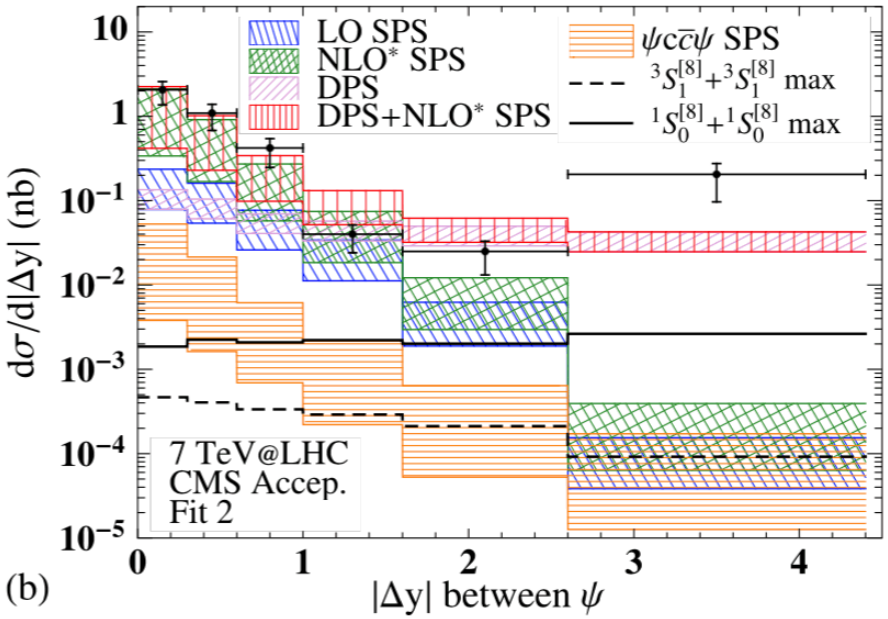
backup

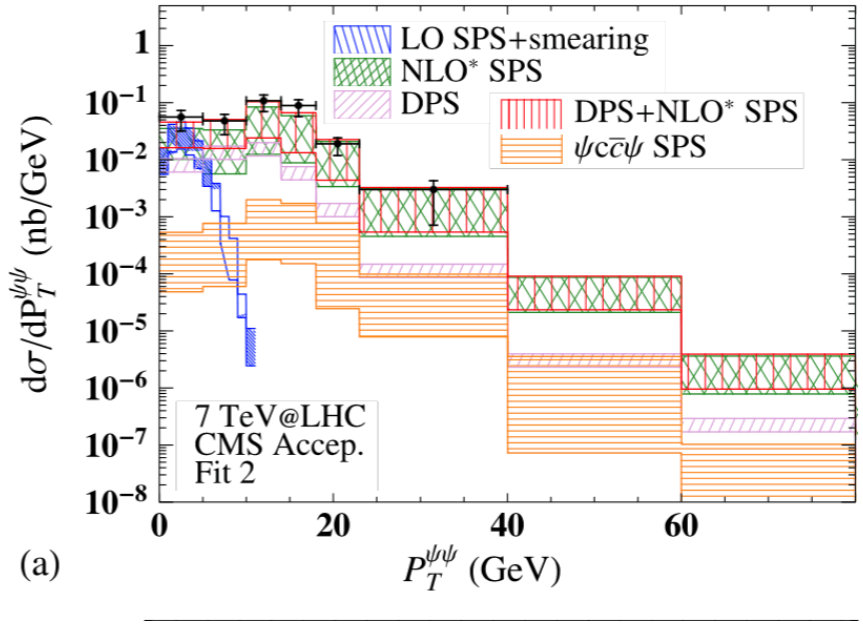


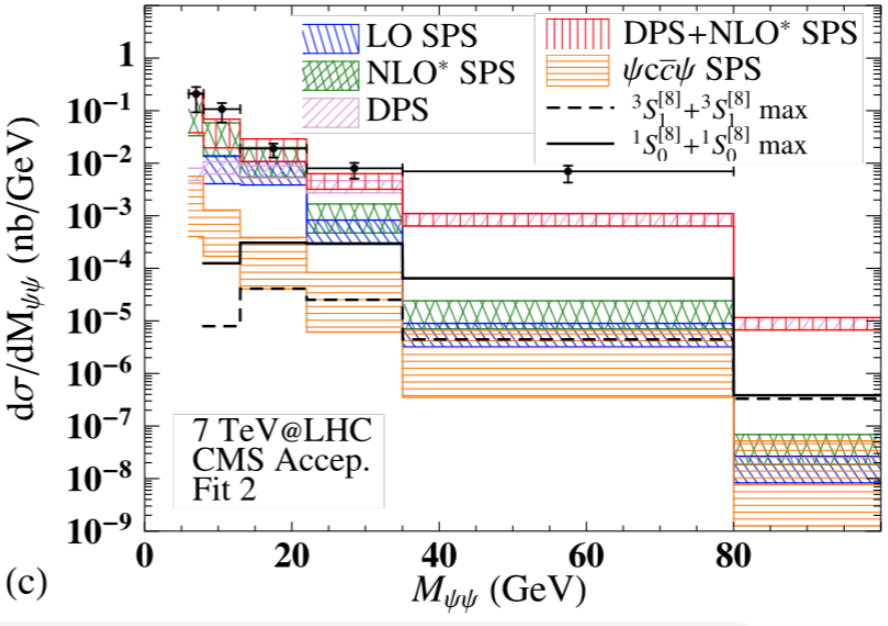


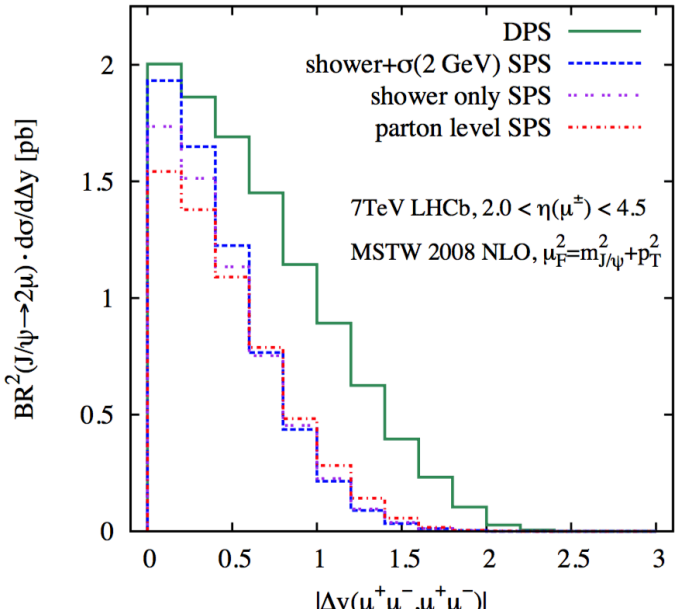
"This is a completely new situation. "

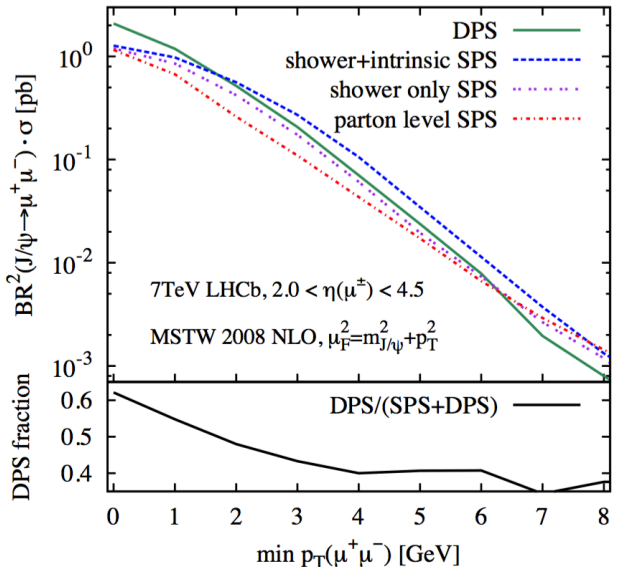

LO SPS
NLO* SPS
DPS
DPS+NLO* SPS
ψcc̄ψ SPS
$^3S_1^{[8]}+^3S_1^{[8]}$ max
$^1S_0^{[8]}+^1S_0^{[8]}$ max
7 TeV@LHC
CMS Accep.
Fit 2
$d\sigma/dP^{\psi}_{T\,min}$ (nb/GeV)
$P^{\psi}_{T\,min}$ (GeV)

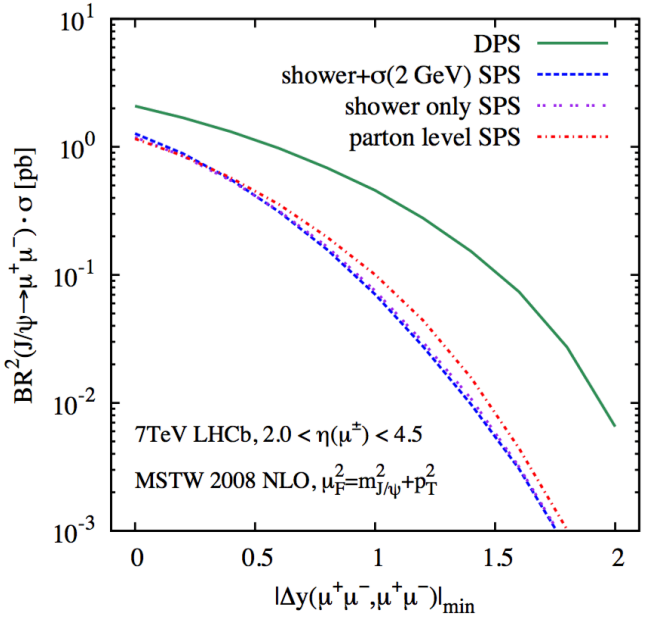

LO SPS
NLO* SPS
DPS
DPS+NLO* SPS
ψcc̄ψ SPS
$^3S_1^{[8]}+^3S_1^{[8]}$ max
$^1S_0^{[8]}+^1S_0^{[8]}$ max
7 TeV@LHC
CMS Accep.
Fit 2
$d\sigma/d|\Delta y|$ (nb)
|Δy| between ψ
(b)

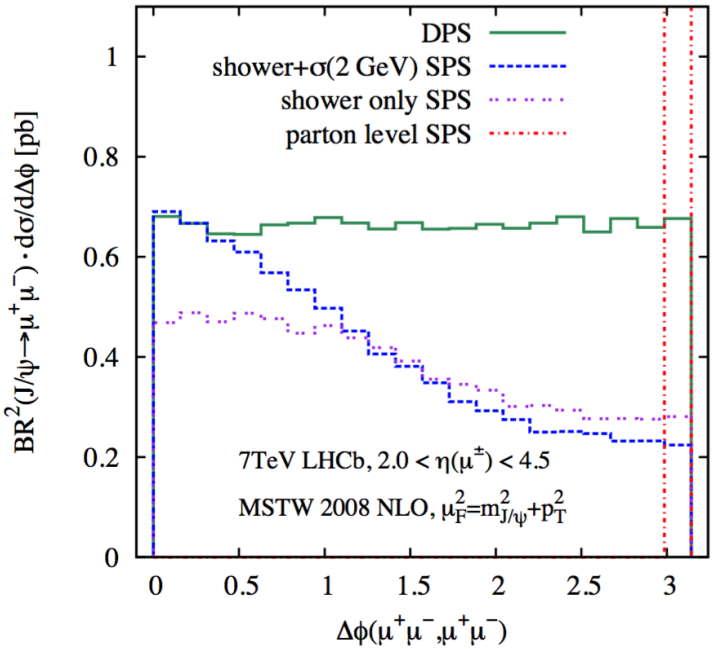

LO SPS+smearing
NLO* SPS
DPS
DPS+NLO* SPS
ψcc̄ψ SPS
7 TeV@LHC
CMS Accep.
Fit 2
$d\sigma/dP_T^{\psi\psi}$ (nb/GeV)
$P_T^{\psi\psi}$ (GeV)
(a)


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
$d\sigma/dM_{\psi\psi}$ (nb/GeV)
$M_{\psi\psi}$ (GeV)
(c)









Main Observables

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