Inclusive Photoproduction of Quarkonium-pair at the US EIC

Sangem Rajesh

INFN Perugia

In collaboration with

F. A. Ceccopieri, J. P Lansberg, M. Rinaldi and H. S. Shao

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Outline

- Quarkonium production
- Double parton scattering
- Di-J/ψ SPS and DPS photoproduction at EIC
- Summary

Quarkonium production Mechanism

Three models for describing the formation of Quarkonium and they are successful at different regions

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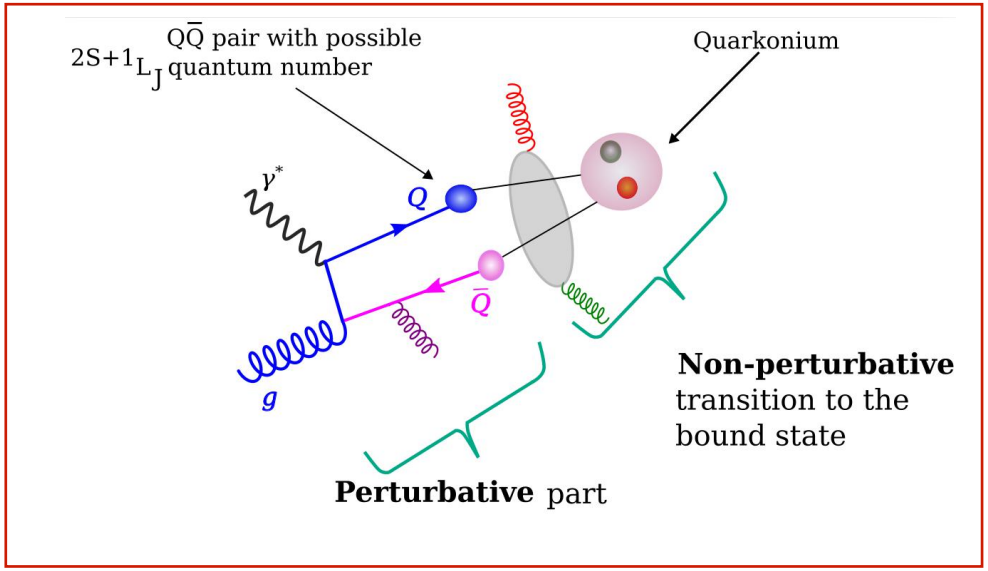

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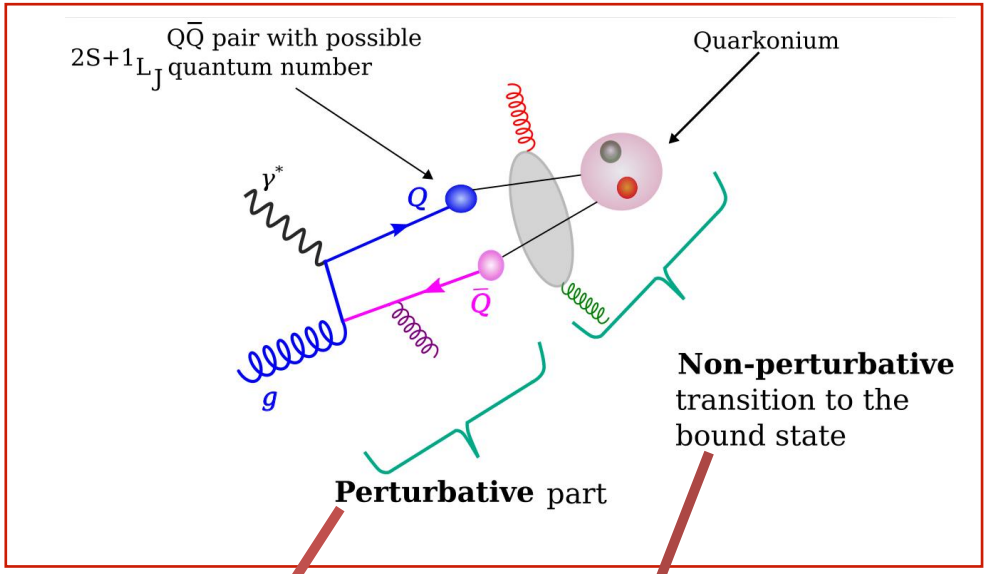

$$d\sigma^{ab\to\mathcal{Q}} = \sum_n d\hat{\sigma}\left[ab \to Q\bar{Q}(n)\right]\langle 0|\mathcal{O}_n^{\mathcal{Q}}|0\rangle$$

Quarkonium-pair measurment

- Only after 8 years of J/ψ discovery

For the first time, di-J/ψ was measured by NA3 collaboration

Phys.Lett.B 114 (1982) 457-460
Phys. Lett. B 158 (1985) 85-91

EVIDENCE FOR $\psi\psi$ PRODUCTION IN π^- INTERACTIONS AT 150 AND 280 GeV/c

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J. BADIER [d], J. BOUCROT [e], J. BOUROTTE [d], G. BURGUN [a], O. CALLOT [e], Ph. CHARPENTIER [a], M. CROZON [c], D. DECAMP [e], P. DELPIERRE [c], B. GANDOIS [a], R. HAGELBERG [b], M. HANSROUL [b], Y. KARYOTAKIS [d], W. KIENZLE [b], P. Le DÛ [a], J. LEFRANÇOIS [e], Th. LERAY [c], J. MAILLARD [c], A. MICHELINI [b], Ph. MINÉ [d], G. RAHAL [a], O. RUNOLFSSON [b], P. SIEGRIST [a], A. TILQUIN [c], J. VALENTIN [c], R. VANDERHAGHEN [d] and S. WEISZ [d]

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Received 27 May 1982

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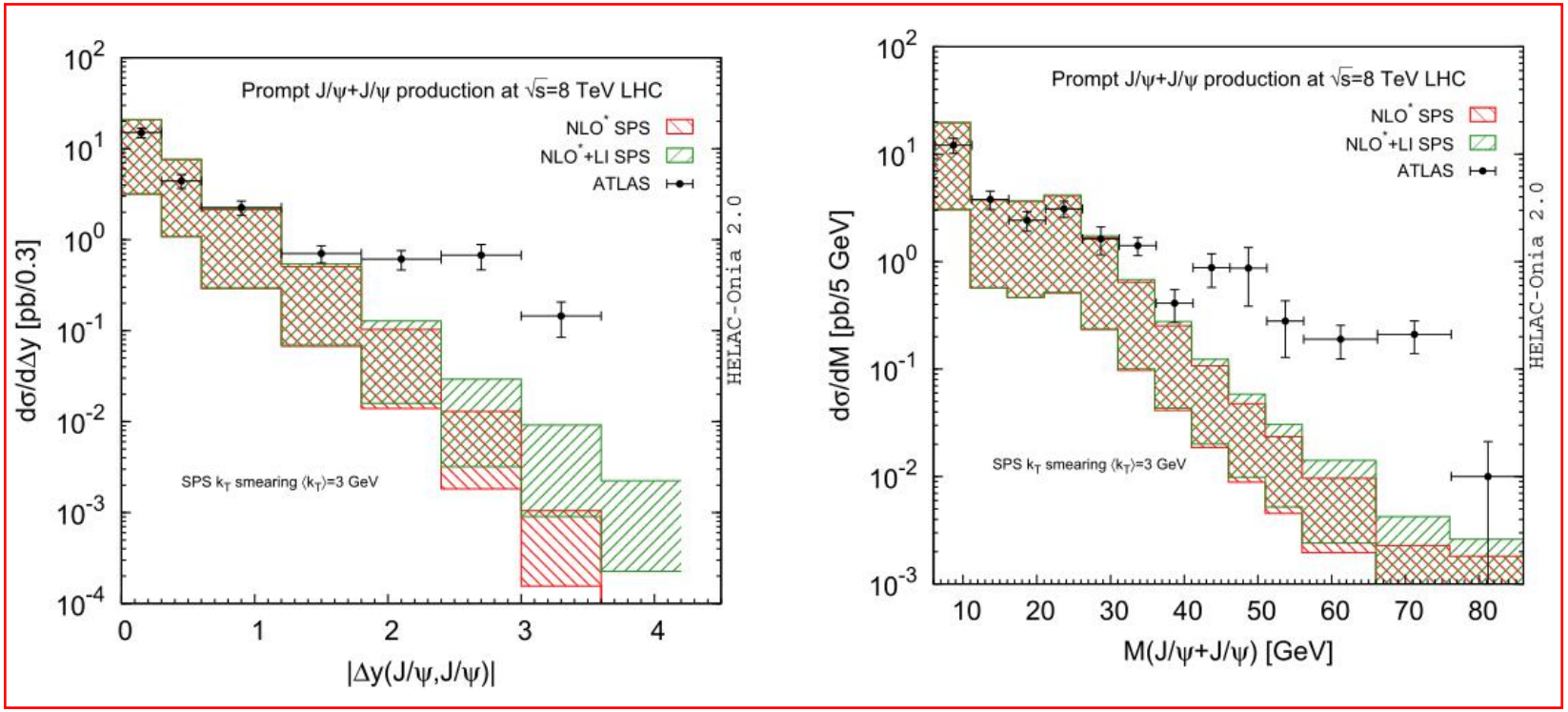
CSM LO theoretical computation

V.G. Kartvelishvili and Sh.M. Esakiya Yad.Fiz. 38 (1983) 722-726
B. Humpert and P. Mery Z. Phys. C 20 (1983) 83
C.F. Qiao, Phys. Rev. D 66 (2002) 057504

Puzzle at large Δy (M)



JP Lansberg, HS Shao, N Yamanaka, and YJ Zhang, EPJC 79 (2019) 12, 1006, PLB 807 (2020), 135559

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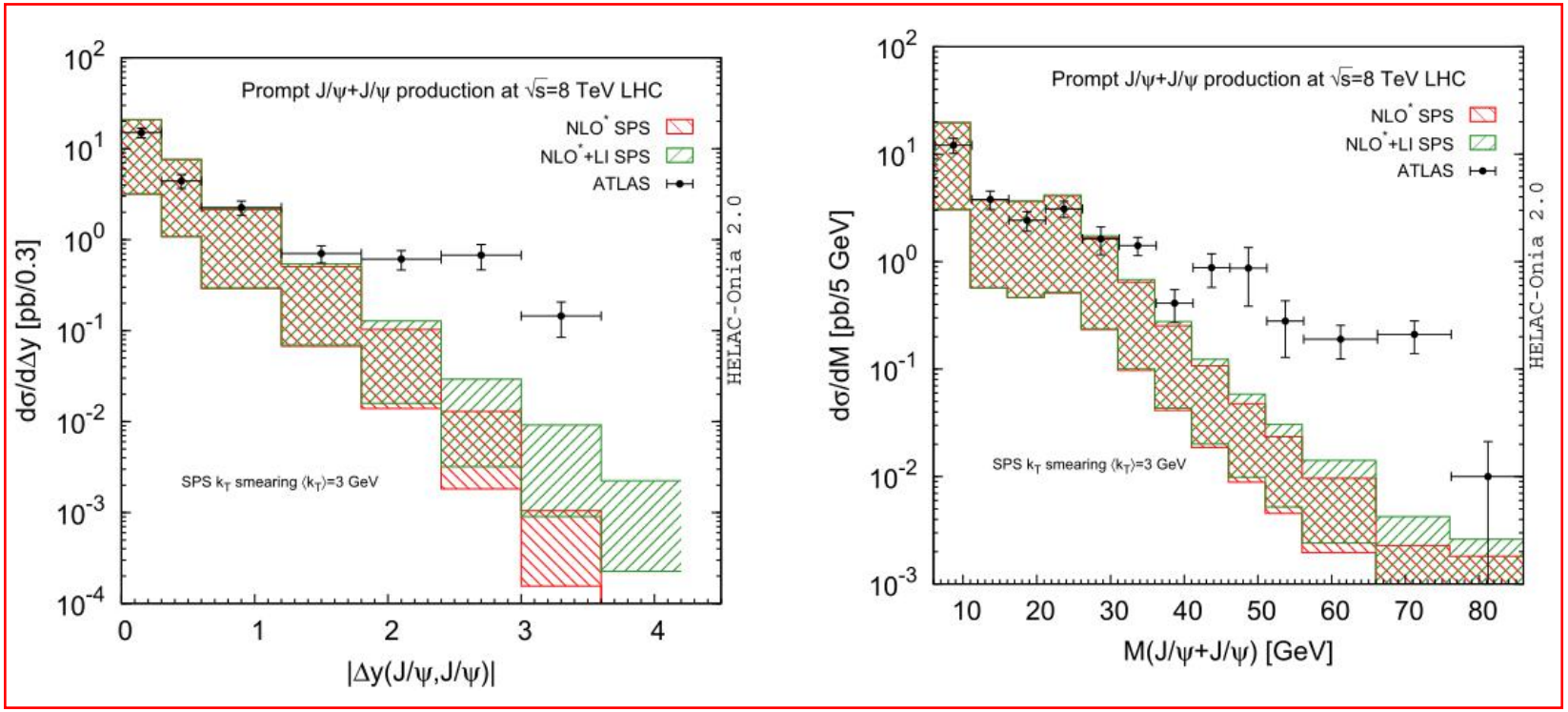

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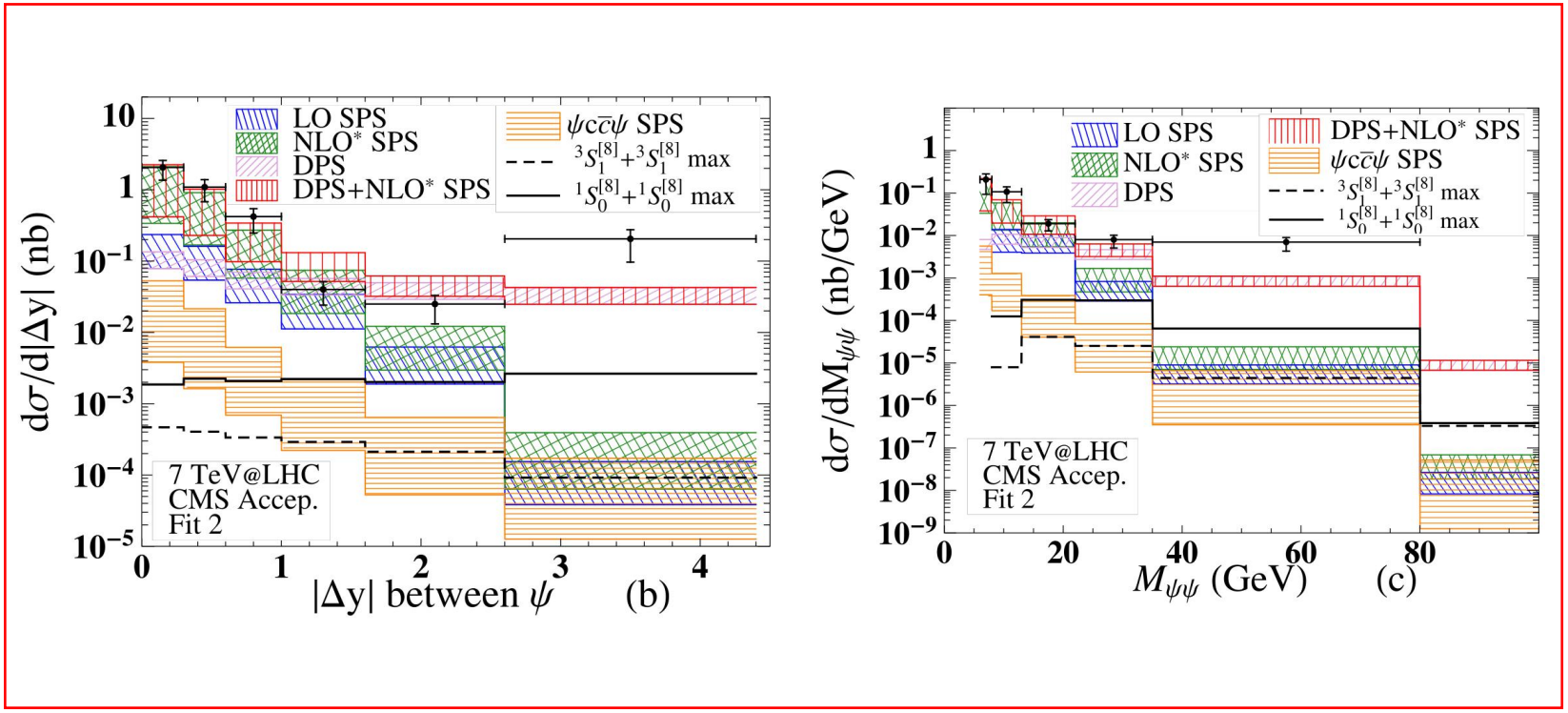
- A simple solution to this excess is the independent production of di-J/ψ

(Double Parton Scattering)

DPS and the LHC data



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CMS coll. JHEP 09 (2014) 094

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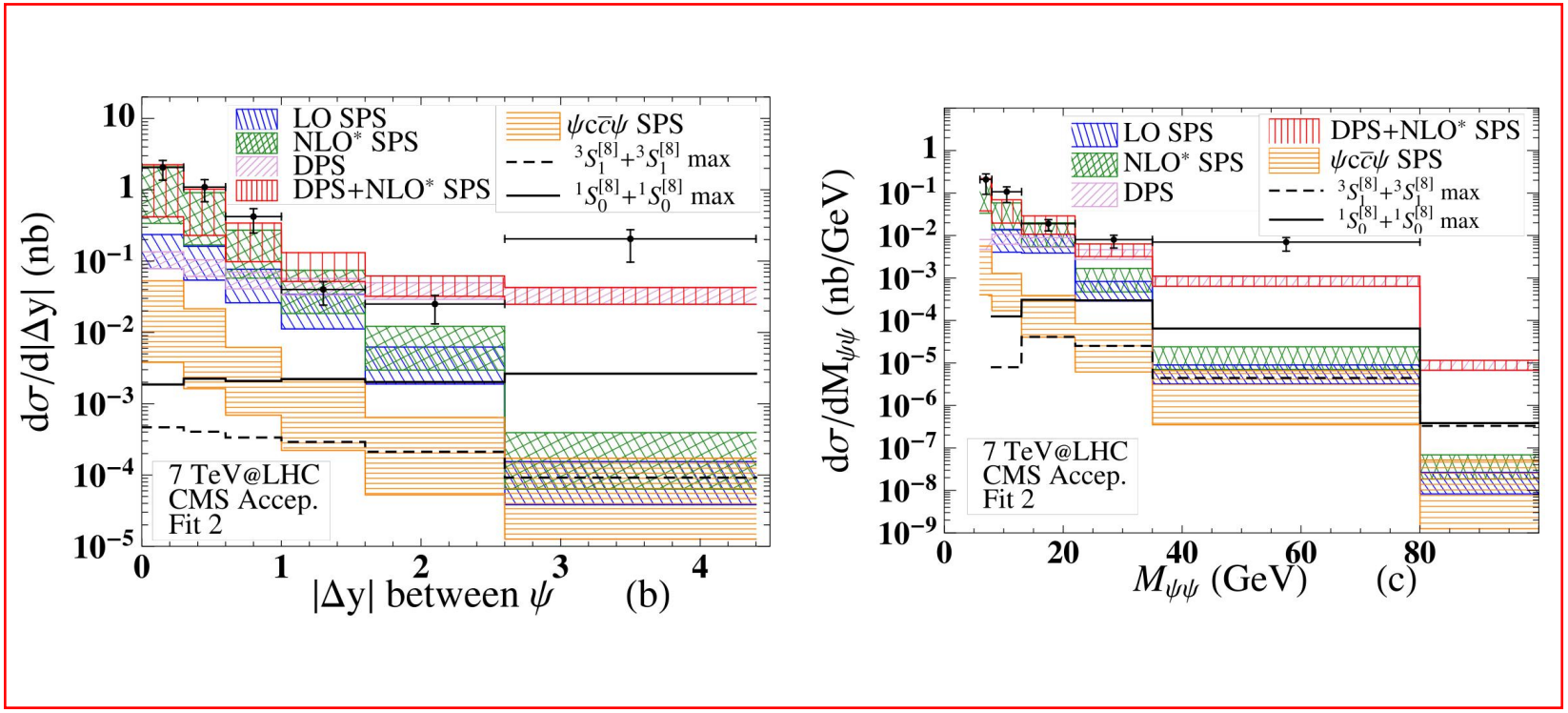

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CMS coll. JHEP 09 (2014) 094

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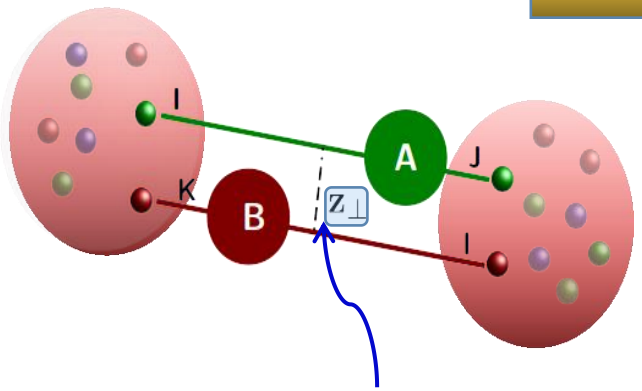
- Same observation with the ATLAS data

Double Parton Scattering

credit to M.Rinaldi



Transverse distance between partons

DPS Cross section

$$d\sigma \propto \int d^2 z_\perp \; \overbrace{F_{ik}(x_1, x_2, \vec{z}_\perp; \mu_A, \mu_B) \cdot F_{jl}(x_3, x_4, \vec{z}_\perp; \mu_A, \mu_B)}^{\text{double PDF (dPDF)}}$$

Momentum fractions carried by the parton inside the proton

Momentum scales

N. Paver, D. Treleani, Nuovo Cimento 70A, 215 (1982),
Mekhfi, PRD 32 (1985) 2371,
JR .Gaunt and WJ. Striling JHEP 03(2010)005
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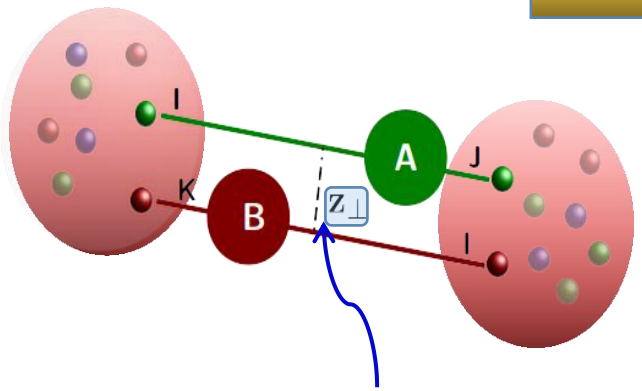

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- To quantify the background for new physics
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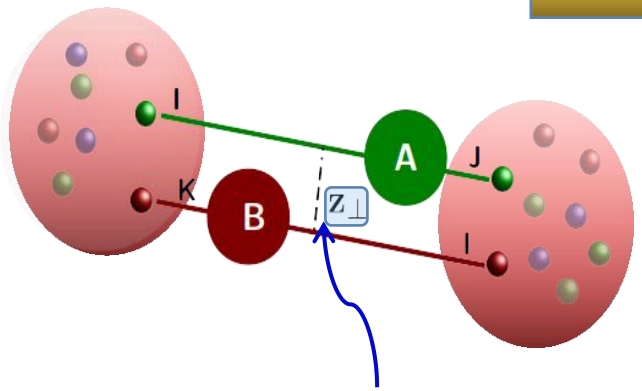

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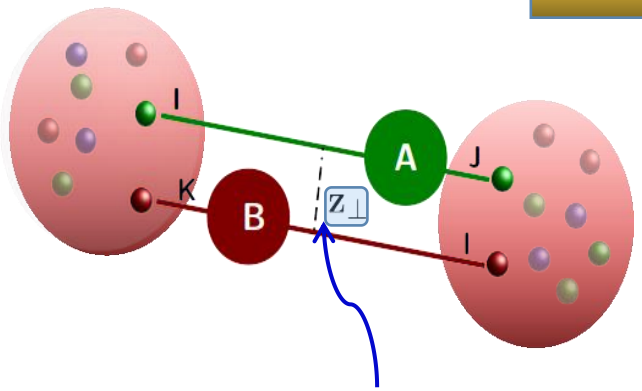

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- Generally $\frac{\sigma^{DPS}}{\sigma^{SPS}} = \mathcal{O}(\frac{\Lambda^2}{Q^2})$
- However, differential cross section of DPS could be of the same order as that of SPS $\frac{d\sigma^{SPS}}{dq_1 dq_2} \sim \frac{d\sigma^{DPS}}{dq_1 dq_2}$

Pocket Formula

- Phenomenologically, pocket formula is a tool for DPS cross section

$$\sigma_{\psi\psi}^{DPS} = \frac{1}{2}\frac{\sigma_{\psi}\sigma_{\psi}}{\sigma_{eff}}$$

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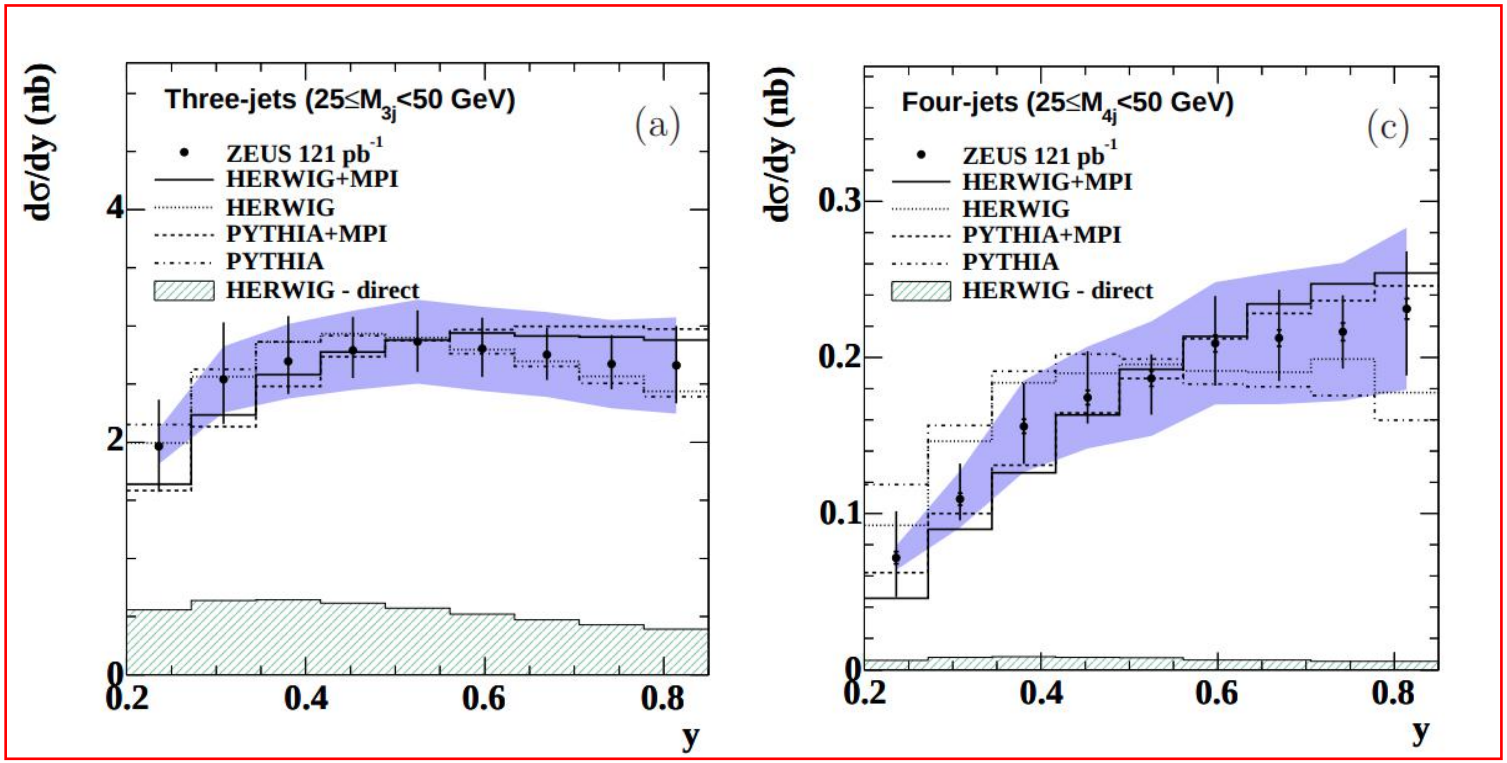
- D0 $\sigma_{eff} = 4.8 \pm 2.5$ mb Do coll. Phys.Rev.D 90 (2014) 11, 111101
- CMS $\sigma_{eff} = 8.2 \pm 2.0 \pm 2.9$ mb JP Lansberg, H.-S.Shao PLB 751 (2015) 479, CMS coll. JHEP 09 (2014) 094
- ATLAS $\sigma_{eff} = 6.3 \pm 1.6 \pm 1.0$ mb ATLAS coll. EPJC (2017) 77:76

DPS in Photoproduction(HERA)

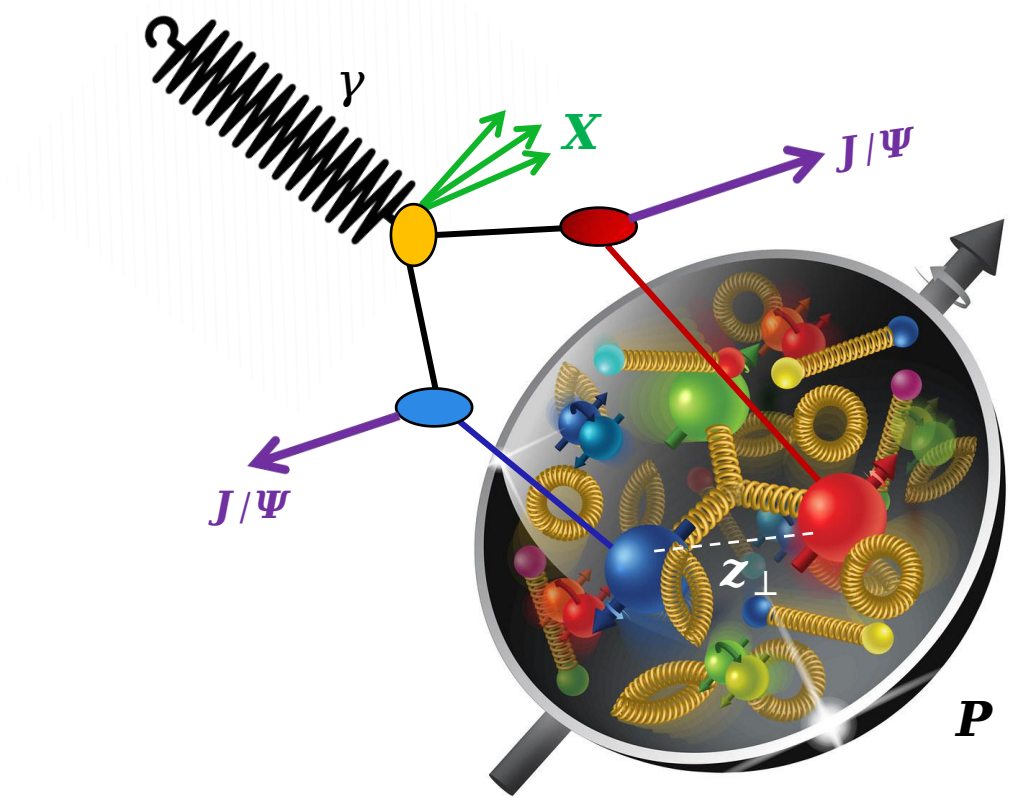


S. Chekanov et al., Nucl.Phys.B 792 (2008) 1-47

- 3, 4-jet photoproduction cross sections are better described when MPI are included

(Indication of Double Parton Scattering even in photoproduction)

Di-J/ψ photoproduction



Ilustration of DPS for $\gamma + p \rightarrow J/\psi + J/\psi + X$

We consider the possibility of **resolved** photon to estimate the DPS cross section in quarkonium-pair photoproduction at the EIC

SPS vs DPS γp cross sections

SPS cross section

(Unresolved/direct) $\sigma_{SPS}^{(J/\psi,J/\psi)} \propto \sum_{a=g,q} \int dx_{p_a}\, f_{a/p}(x_{p_a},\mu)\, d\hat{\sigma}^{\gamma a \to J/\psi + J/\psi + a}$

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DPS cross section

$$\sigma_{DPS}^{(J/\psi,J/\psi)} \propto \frac{1}{2}\frac{1}{\sigma_{eff}^{\gamma p}} \sum_{a,b,c,d} \int dx_{\gamma_a}\, dx_{p_b}\, f_{a/\gamma}(x_{\gamma_a},\mu)\, f_{b/p}(x_{p_b},\mu)\, d\hat{\sigma}_{SPS}^{ab \to J/\psi}(x_{\gamma_a}, x_{p_b})$$
$$\times\, dx_{\gamma_c}\, dx_{p_d}\, f_{c/\gamma}(x_{\gamma_c},\mu)\, f_{d/p}(x_{p_d},\mu)\, d\hat{\sigma}_{SPS}^{cd \to J/\psi}(x_{\gamma_c}, x_{p_d})$$

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Proton PDF

DPS cross section

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$$\times\, dx_{\gamma_c}\, dx_{p_d}\, f_{c/\gamma}(x_{\gamma_c},\mu)\, f_{d/p}(x_{p_d},\mu)\, d\hat{\sigma}_{SPS}^{cd \to J/\psi}(x_{\gamma_c}, x_{p_d})$$

SPS vs DPS γp cross sections

SPS cross section

(Unresolved/direct) $$\sigma_{SPS}^{(J/\psi,J/\psi)} \propto \sum_{a=g,q} \int dx_{p_a} f_{a/p}(x_{p_a},\mu)\, d\hat{\sigma}^{\gamma a \to J/\psi + J/\psi + a}$$

(Resolved) $$\sigma_{SPS}^{(J/\psi,J/\psi)} \propto \sum_{a,b=g,q} \int dx_{\gamma_a}\, dx_{p_b} f_{a/\gamma}(x_{\gamma_a},\mu)\, f_{b/p}(x_{p_b},\mu)\, d\hat{\sigma}^{ab \to J/\psi + J/\psi}$$

Photon PDF Proton PDF

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Photon PDF Proton PDF Partonic cross section

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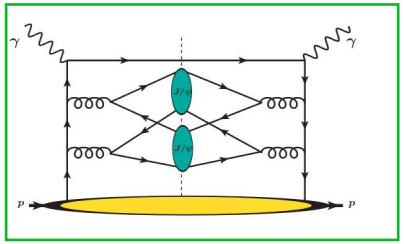
Single J/ψ SPS resolved (namely same partonic cross section as hadroproduction)

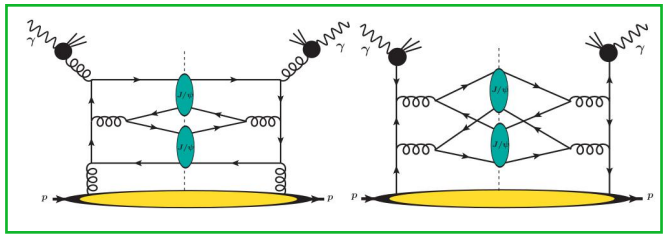
Di-J/ψ photoproduction(EIC)

SPS → **Unresolved**, **Resolved**

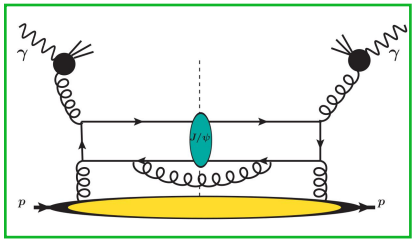
DPS → **Resolved**



$\gamma + q \to J/\psi + J/\psi + q$



$i + j \to J/\psi + J/\psi$ $\quad i, j = g, q$



$|g + g \to J/\psi + g|^2$

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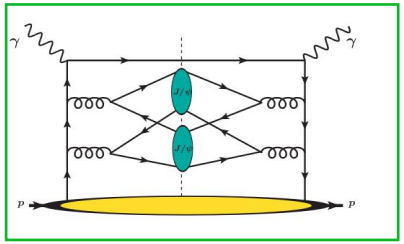
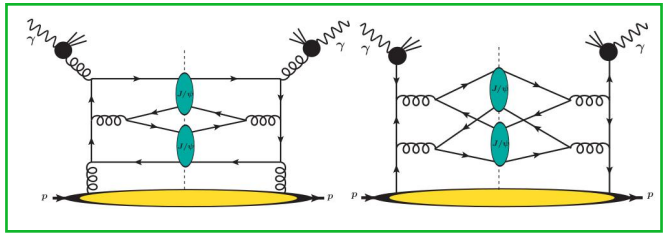


$\gamma + q \to J/\psi + J/\psi + q$



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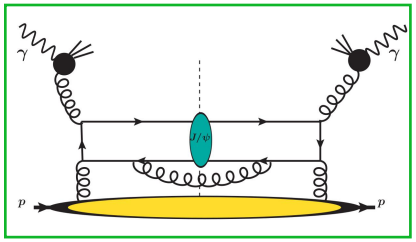

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- CO LDMEs are taken from M. Butenschoen and B. A. Kniehl, PRD 84, 051501 (2011)
- We expect at least 600 four-muon events with 100 fb^{-1} luminosity

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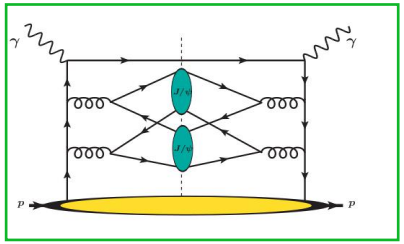
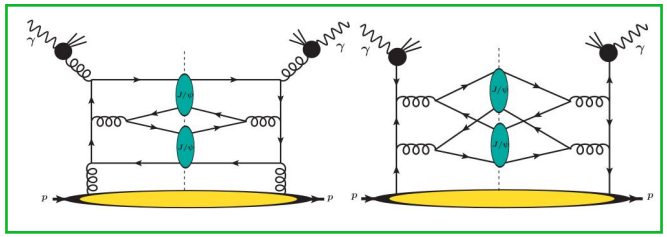


$\gamma + q \rightarrow J/\psi + J/\psi + q$



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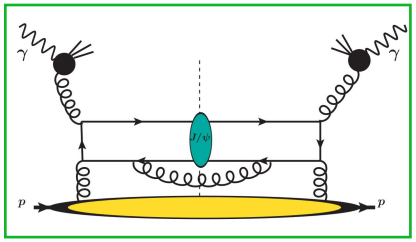

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Range of cross sections in CSM $\sqrt{S_{\gamma p}}$=100 GeV

$$\left.\begin{aligned} \sigma_{SPS}^{(J/\psi,J/\psi)} \times Br^2 &= 4 - 30 \text{ fb} \\ \sigma_{DPS}^{(J/\psi,J/\psi)} \times Br^2 &= 0.2 - 5 \text{ fb} \end{aligned}\right\} \text{(Resolved)}$$

$\sigma_{eff}^{\gamma p}$ = 10 mb for DPS

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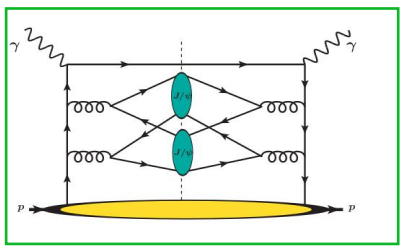

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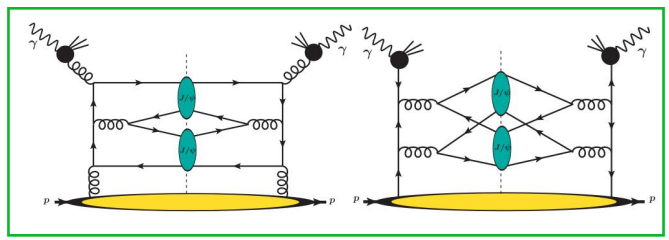

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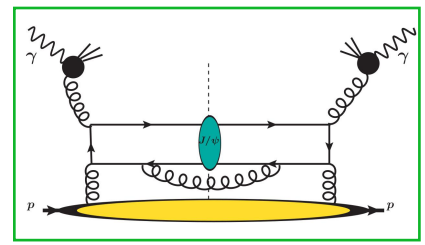

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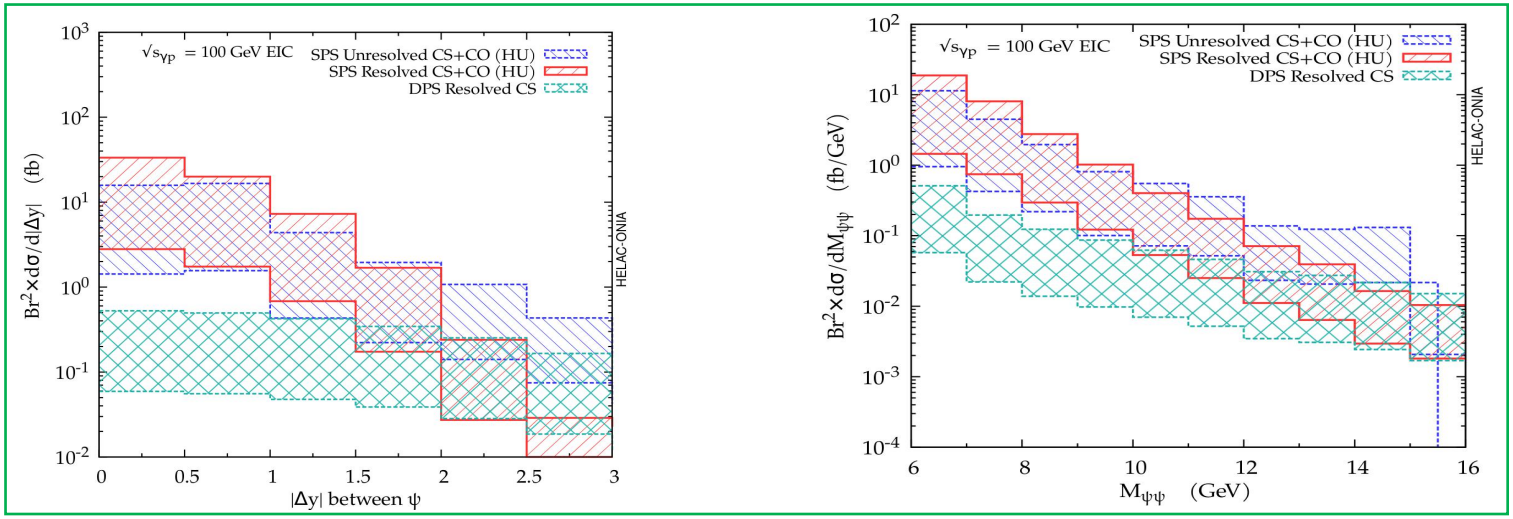
$\sigma_{eff}^{\gamma p} = 10$ mb for DPS

$$\sigma_{SPS}^{(J/\psi,J/\psi)} \times Br^2 = 2 - 12 \text{ fb (Unresolved)}$$

Δy and $M_{\psi\psi}$ at EIC

- Kinematical distributions useful to separate SPS and DPS



LDME set (HU): M. Butenschoen and B. A. Kniehl, PRD 84, 051501 (2011)

Δy and $M_{\psi\psi}$ at EIC

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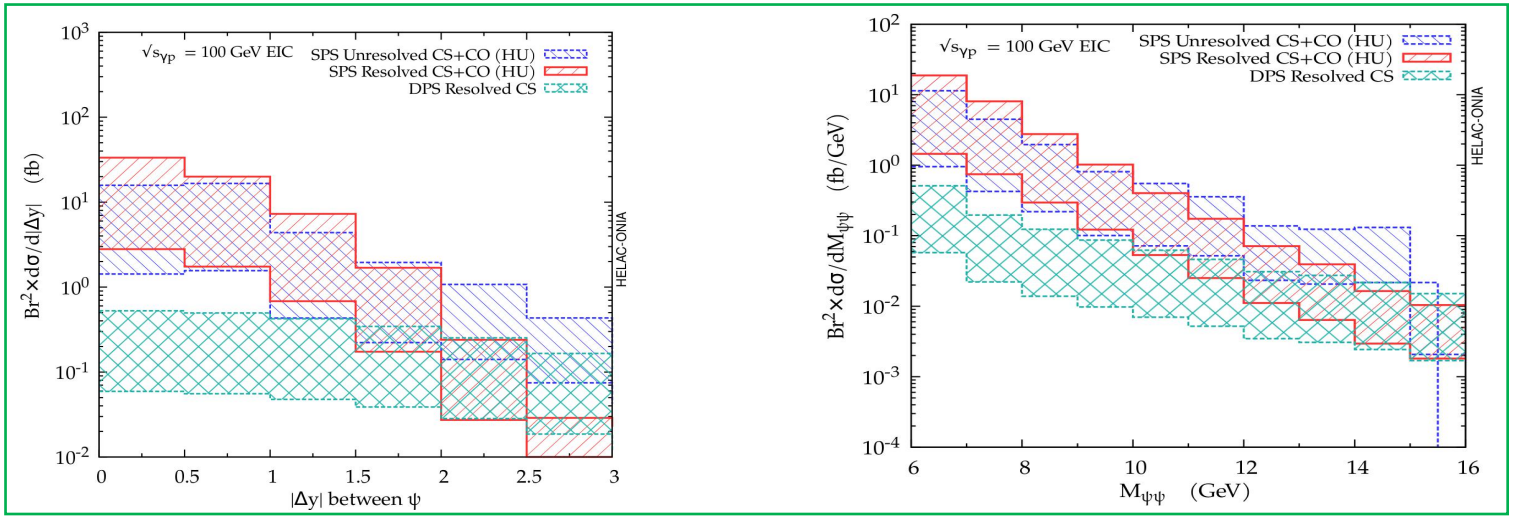

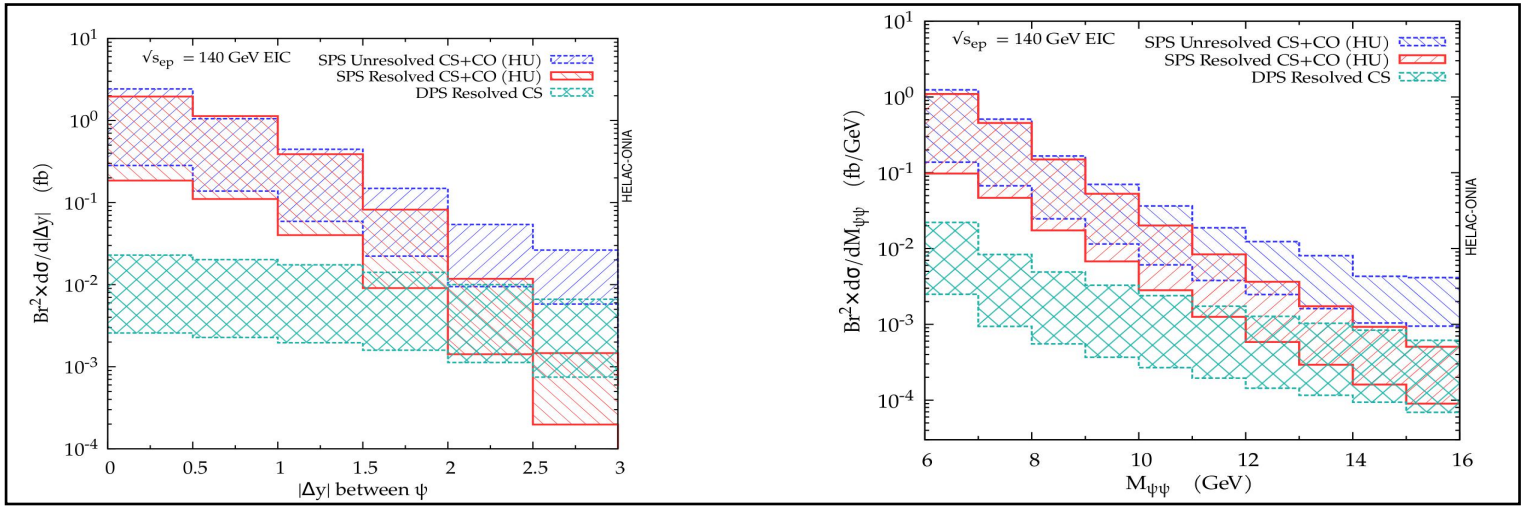

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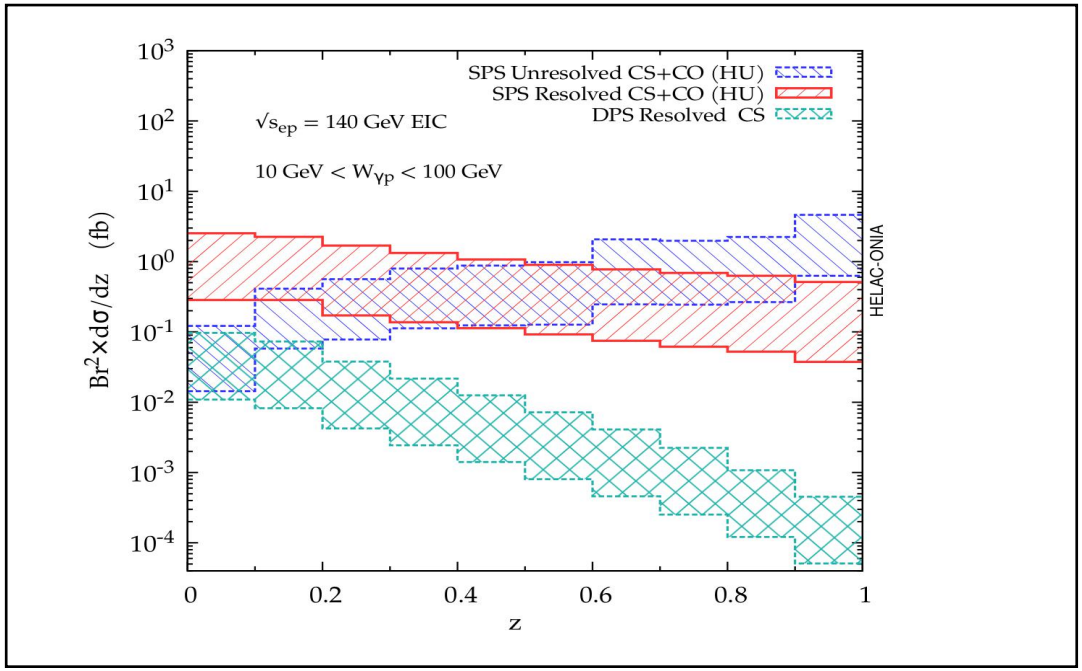
z distribution



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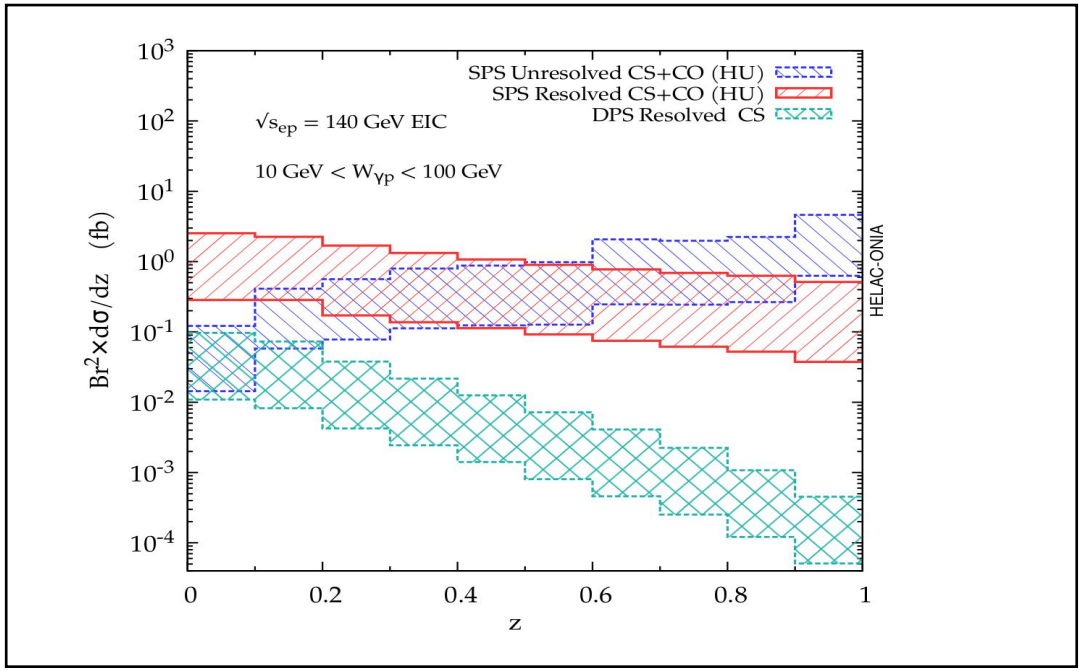


LDME set (HU): M. Butenschoen and B. A. Kniehl, PRD 84, 051501 (2011)

- For $z < 0.1$ resolved SPS dominates over unresolved/direct
- Unique opportunity to study the photon structure
- At larger z one can test quarkonium production mechanism via direct photoproduction
- Resolved case: gluon channel dominates in the low z region, and quark channel at high z
- CS and CO states are considered: CO states contribution is only significant (for some LDMEs) in unresolved but not in the resolved case

Summary

- Quarkonium production is a rich channel to probe the parton correlations through DPS
- We have estimated SPS and DPS cross sections for quarkonium-pair photoproduction at the EIC using the NRQCD framework
- DPS total cross section is small compared to the SPS but could be measured if σ_{eff} small
- Differential spectra in $|\Delta y(\psi, \psi)|$ and $M_{\psi\psi}$ are useful to separate DPS and SPS
- Differential spectrum in z is useful to separate resolved and unresolved
- Bulk of the yield at low z where resolved SPS is dominant
- Quarkonium-pair photoproduction is a promising channel to probe the gluonic content of the photon structure

Thank you for the attention

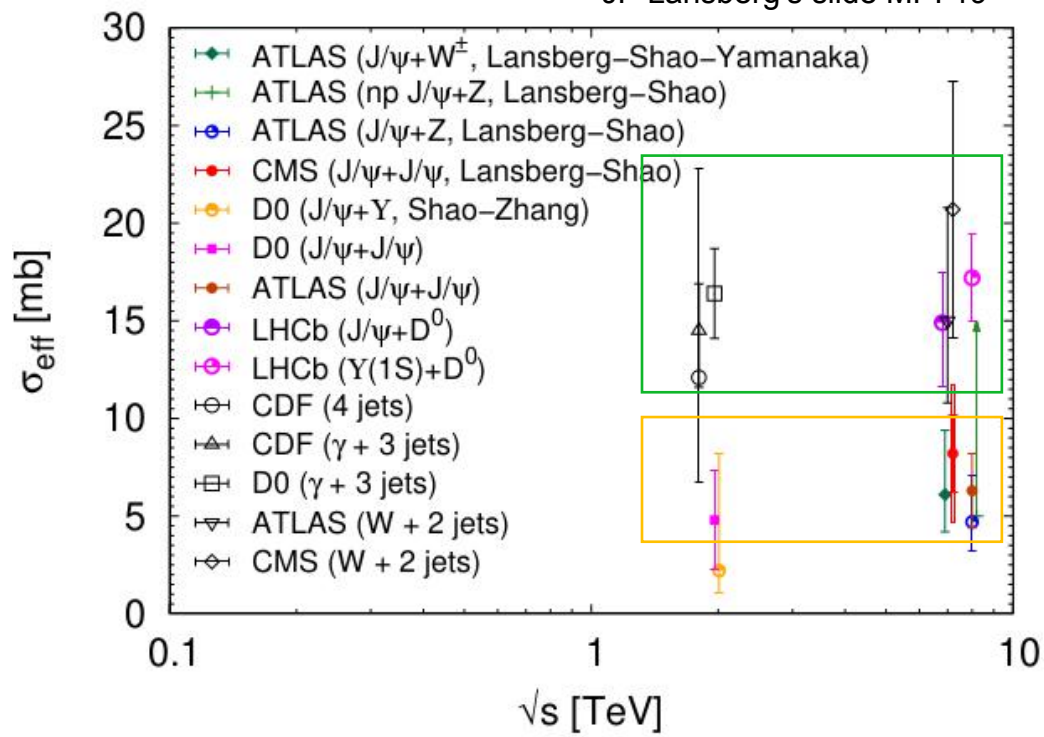
Backup slides

Effective X-section

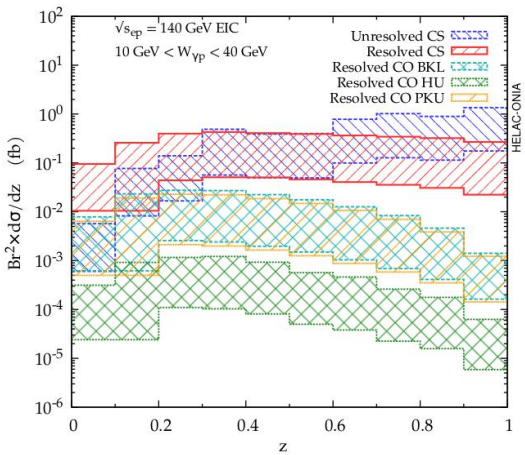
$$\sigma_{\psi\psi}^{DPS} = \frac{1}{2}\frac{\sigma_\psi \sigma_\psi}{\sigma_{eff}}$$

Process dependent?

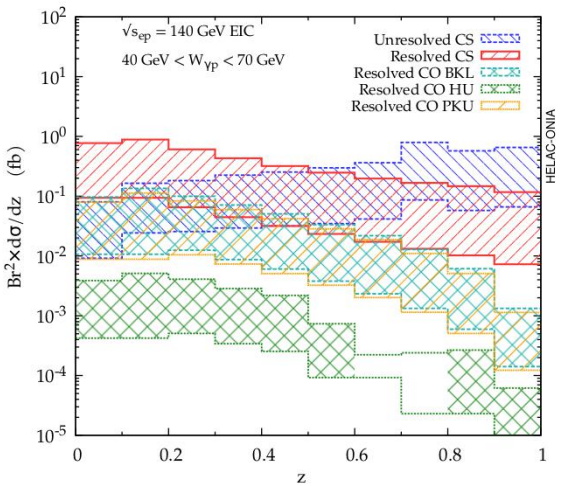
JP Lansberg's slide MPI 19



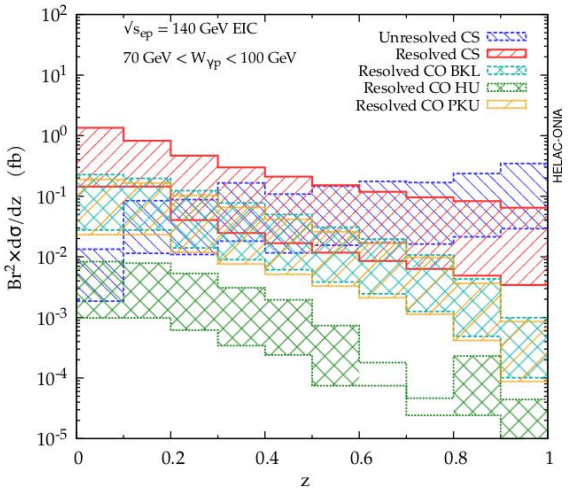
z-spectrum (Resolved)



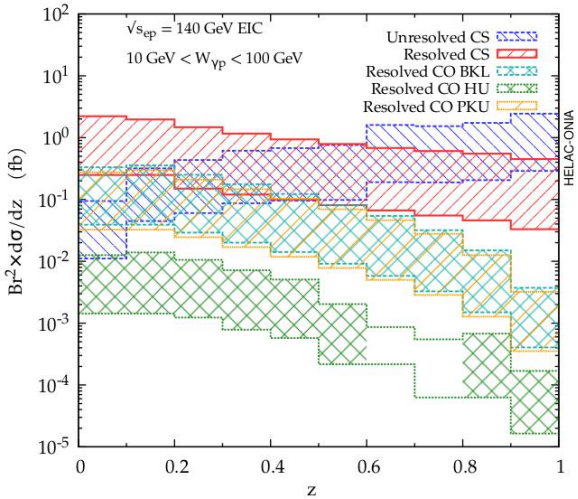
(a) $10 < W_{\gamma p} < 40$ GeV



(b) $40 < W_{\gamma p} < 70$ GeV

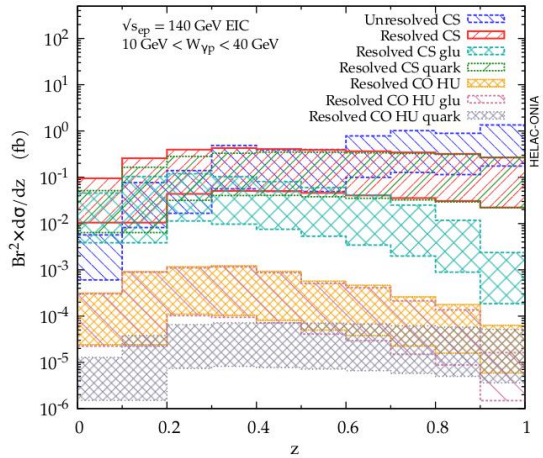


(c) $70 < W_{\gamma p} < 100$ GeV



(d) $10 < W_{\gamma p} < 100$ GeV

z-spectrum (glu-quark)



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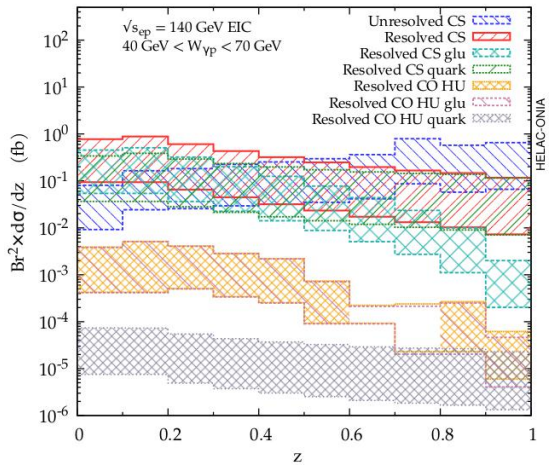
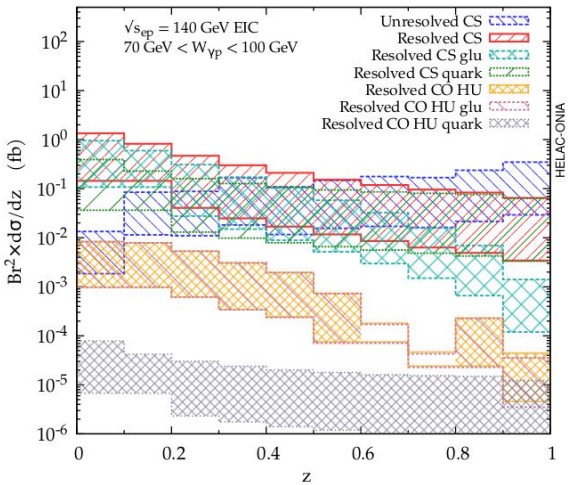


(b) $40 < W_{\gamp p} < 70$ GeV



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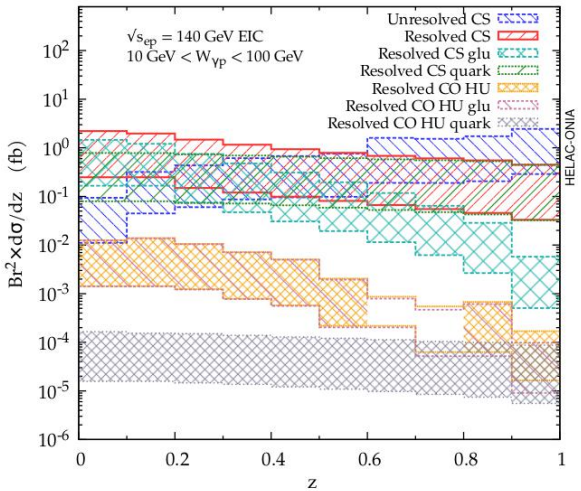

(d) $10 < W_{\gamp p} < 100$ GeV

Pocket formula details

How to build up the photon dPDFs from the PDF?

$$f_{i/\gamma}(x;\mu^2) = K\alpha f_{i/\pi}(x;\mu^2)$$

Gluck et al, PRD 46, 1973 (1992)

0.91

If we assume that evolved dPDFs can be written as product of PDFs:

$$\tilde{F}_{ij/\gamma}(x_1,x_2,k_\perp;\mu^2) = N f_{i/\gamma}(x_1;\mu^2) f_{j/\gamma}(x_2;\mu^2)\tilde{F}_\gamma(k_\perp)\theta(1-x_1-x_2)$$

Normalization constant

Effective form factor

M. Rinaldi and F. A. Ceccopieri, PRD 97 (2018) 7, 071501

Then by using sum rules: $\sum_j \int_0^{1-x_1} dx_2\ x_2 \tilde{F}_{ji/\gamma}(x_1,x_2,k_\perp=0;\mu^2) = (1-x_1) f_{i/\gamma}(x_1;\mu^2)$

J. R. Gaunt et al, JHEP 03, 005 (2010)

Therefore, from our ansatz we get: $\sum_j \int_0^{1-x_1} dx_2\ x_2 \tilde{F}_{ji/\gamma}(x_1,x_2,k_\perp=0;\mu^2) = NK\alpha f_{i/\gamma}(x_1;\mu^2)(1-x_1)$

Thus the normalization constant is $\boxed{N = \frac{1}{K\alpha}}$

The new pocket formula would be: $\sigma_{DPS}^{A+B} = \frac{m}{2\alpha K}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{eff}^{\gamma p}}$

Where the effective cross-section keeps the usual geometrical interpretation, i.e.:

$$\sigma_{eff}^{\gamma p} = \frac{1}{\int \frac{d^2k_\perp}{(2\pi^2)}\tilde{F}_\gamma(\vec{k}_\perp)\tilde{F}_p(-\vec{k}_\perp)}$$