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DIPARTIMENTO
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MUR 2023/2027

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Measurements of multi-quarkonia final states in pp collisions at LHC

Quarkonia As Tools 2024, 7–13 Jan 2024, Centre Paul Langevin

On behalf of the CMS collaboration

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AGENDA

1 Introduction

2 State of the art

3 Future perspectives

4 Conclusions

1

Introduction

Quarkonia production

Rev.Mod.Phys.90(2018)015003

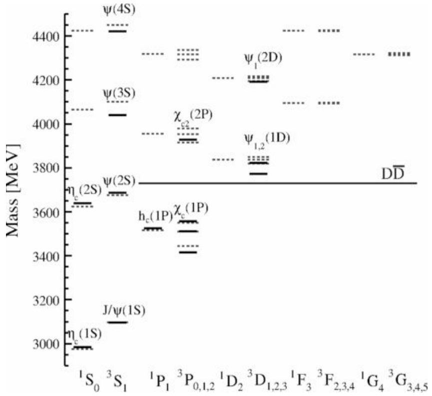
Eur.Phys.J.C.71(2011)1534

- In heavy quarkonia each quark has mass *m* much larger than the QCD confinement scale ΛQCD → **Non-relativistic QCD**.

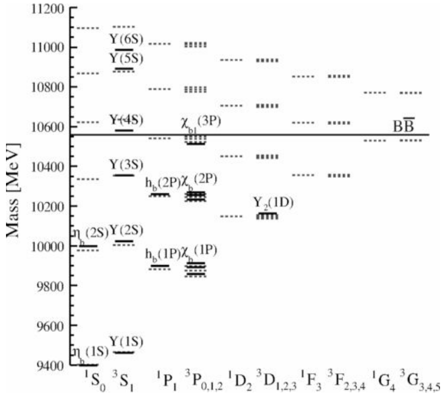
- Because the system is nonrelativistic, quarkonium is characterized:
  - by the heavy-quark **bound-state velocity**, v<<1 (v^2 ~ 0.3 for charmonia, v^2 ~ 0.1 for bottomia)
  - by a hierarchy of energy scales: the mass **m** (*hard scale*, H), the relative momentum **p ~ mv** (*soft scale*, S), a and the binding energy **E ~ mv²** (*ultrasoft scale*, US).

we are missing some pieces of both puzzles!

Charmonia



Bottomia



v^2 is the typical velocity of a heavy quark in the quarkonium rest frame

Quarkonia production

Rev.Mod.Phys.90(2018)015003

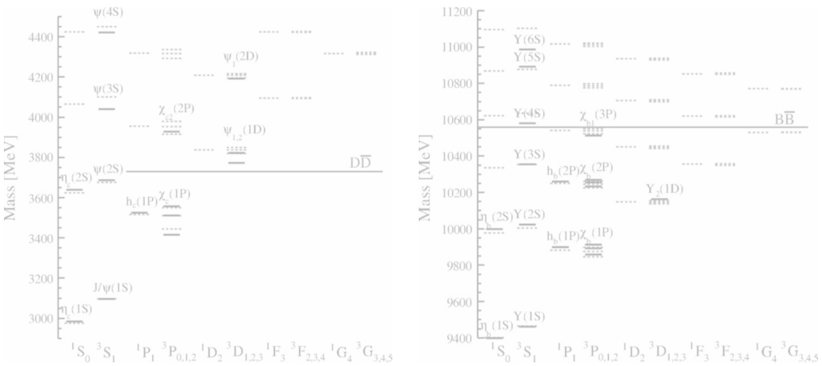
Eur.Phys.J.C.71(2011)1534

Quarkonium specifically refers to mesons composed of a heavy quark and its antiquark: charm-anticharm ($c\bar{c}$) or bottom-antibottom ($b\bar{b}$) mesons.

- In heavy quarkonia each quark has mass *m* much larger than the QCD confinement scale ΛQCD → **Non-relativistic QCD**.
- Because the system is non-relativistic, quarkonium is characterized:
    - by the heavy quark bound-state velocity, v<<1 (v^2 ~ 0.3 for charmonia, v^2 ~ 0.1 for bottomia)
    - by a hierarchy of energy scales: the mass m (hard scale, H), the relative momentum p ~ mv (soft scale, S), a and the binding energy E ~ mv^2 (ultrasoft scale, US).

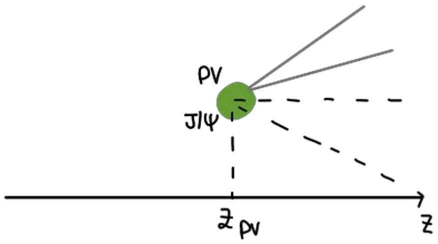
ideal probe for QCD

we are missing some pieces of both



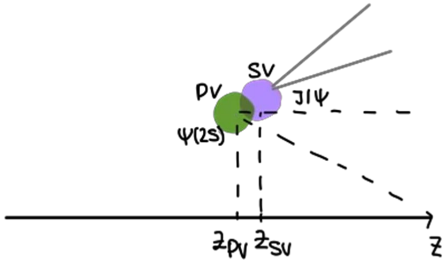
v^2 is the typical velocity of a heavy quark in the quarkonium rest frame

Quarkonia production @ LHC



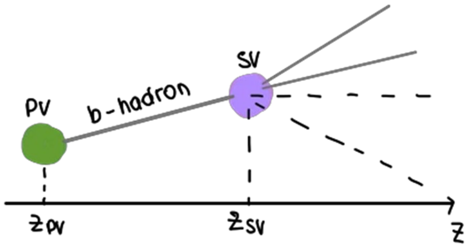
Prompt hadron production:

prompt indicates that these hadrons are created almost instantly during the interaction



Decays of higher resonances (feed-down):

involve the subsequent decay of higher-energy resonant states into lower-energy particles.

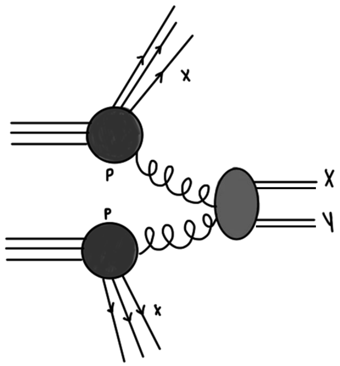


Production in b-hadron decays / non-prompt (only charmonium)

refers to the generation of charmonium states within the decay of beauty (b) hadrons.

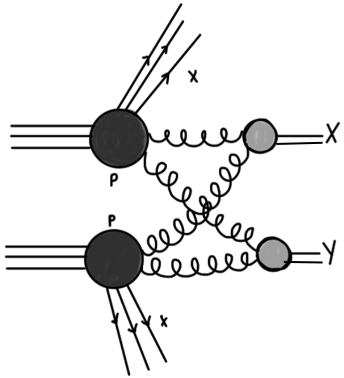
Single and Double Parton Scattering

SPS



- Single-Parton Scattering (SPS) involves the production of two or more particles through a single interaction between two partons.
- The kinematics are correlated, with the neglect of additional gluon emissions.

DPS



- Double-Parton Scattering (DPS) involves the production of two particles through a double interaction between two partons from the same proton pairs.
- To simplify, the hard scattering are assumed as uncorrelated.
- Described by the pocket formula:

$$\sigma_{DPS}^{pp\to A,B} = \left(\frac{m}{2!}\right)\frac{\sigma_{SPS}^{pp\to A}\cdot\sigma_{SPS}^{pp\to B}}{\sigma_{\text{eff},DPS}}$$

2

State of the art

News from LHCb at $\sqrt{s} = 13$ TeV

- J/ψ + Υ(nS) production: JHEP 08 (2023) 093
  - integrated and differential (for Υ(1S)) cross-section
  - effective cross-section σ_{eff}

NEW

- J/ψ + J/ψ production: arXiv:2311.14085
  - integrated and differential cross-section
  - production asymmetry
  - effective cross-section

NEW

- J/ψ + ψ(2S) production: arXiv:2311.15921
  - integrated and differential cross-section
  - ratio to J/ψ + J/ψ

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Associated production of prompt J/Ψ and ϒ mesons

JHEP 08 (2023) 093

Theoretical cross section:

$$\sigma_{\mathrm{DPS}}(J/\psi\text{-}\Upsilon) = \frac{\sigma(J/\psi) \times \sigma(\Upsilon)}{\sigma_{\mathrm{eff}}}$$

Production cross section:

$$\sigma(J/\psi\text{-}\Upsilon) = \frac{N_{\mathrm{cor}}}{\mathcal{L} \times \mathcal{B}_{J/\psi\to\mu^+\mu^-} \times \mathcal{B}_{\Upsilon\to\mu^+\mu^-}}$$

$$\mathcal{L} = 4.18 \pm 0.08\,\mathrm{fb}^{-1}$$

where the J/ψ(Y(1S)) has:
$p_{\mathrm{T}} < 10\ (30)\ \mathrm{GeV}/c$

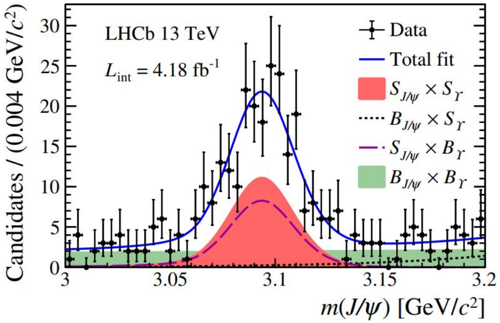
in rapidity range:
$2.0 < y < 4.5$

LHCb

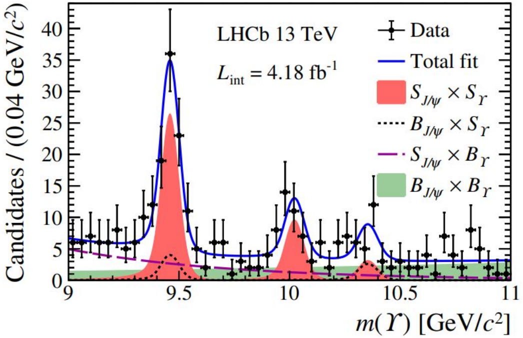
The raw yields from the fit, the efficiency-corrected yields (Ncor) and the signal significances:

Signal	Raw yields	N_{cor}	Significances
J/ψ-$\Upsilon(1S)$	76 ± 12	840 ± 140	$7.9\,\sigma$
J/ψ-$\Upsilon(2S)$	30 ± 7	370 ± 100	$4.9\,\sigma$
J/ψ-$\Upsilon(3S)$	10 ± 6	—	$1.7\,\sigma$

J/Ψ



ϒ



Associated production of prompt J/Ψ and ϒ mesons

$\sqrt{s} = 13$ TeV

JHEP 08 (2023) 093

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LHCb

First observation of J/Ψ and ϒ(1s) mesons associated production (in pp)

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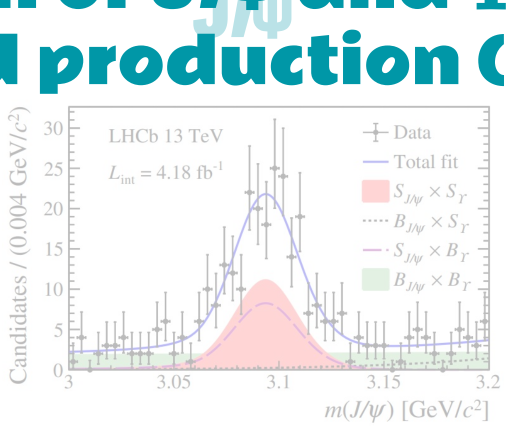

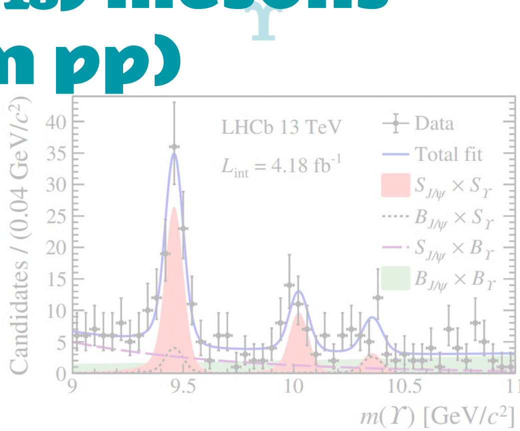

Associated production of prompt J/Ψ and ϒ mesons

JHEP 08 (2023) 093

Integrated cross-sections:

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$$\sigma(J/\psi\text{-}\Upsilon(1S)) = 133 \pm 22 \pm 7 \pm 3\,\text{pb}$$

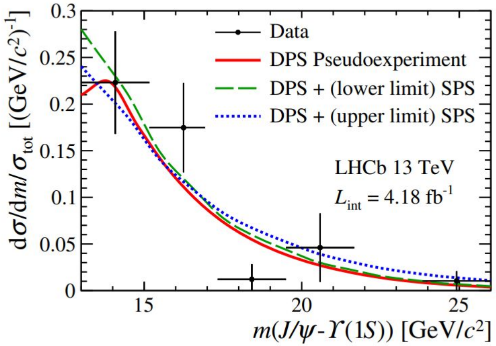
$$\sigma(J/\psi\text{-}\Upsilon(2S)) = 76 \pm 21 \pm 4 \pm 7\,\text{pb}$$

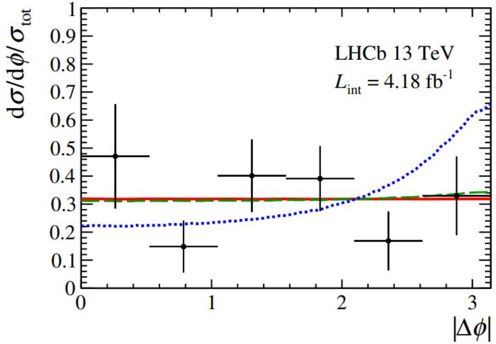
ratio of the cross-sections of J/ψ-Y(2S) and J/ψ-Y(1S) multiplied by the respective branching ratio is calculated to be:

$$\frac{\mathcal{B}_{\Upsilon(2S)\to\mu^+\mu^-} \times \sigma(J/\psi\text{-}\Upsilon(2S))}{\mathcal{B}_{\Upsilon(1S)\to\mu^+\mu^-} \times \sigma(J/\psi\text{-}\Upsilon(1S))} = 0.442 \pm 0.143 \pm 0.004$$

Results are consistent with both DPS and SPS+DPS mechanisms present.

Associated production is predicted to be dominated by the DPS process.





Associated production of prompt J/Ψ and ϒ mesons

JHEP 08 (2023) 093

DPS contribution is extracted using **SPS prediction from Shao and Zhang** [Phys. Rev. Lett. 117, 062001].

This allows us to extract the effective cross sections:

$$\sigma_{eff} = \frac{\sigma_{J/\psi} \times \sigma_{\Upsilon(1S)}}{\sigma^{DPS}_{J/\psi-\Upsilon(1S)}} = 26 \pm 14_{stat} \pm 2_{syst} \,{}^{+22_{SPS}}_{-3_{SPS}} \text{ mb}$$

$$\sigma_{eff} = \frac{\sigma_{J/\psi} \times \sigma_{\Upsilon(2S)}}{\sigma^{DPS}_{J/\psi-\Upsilon(2S)}} = 14 \pm 5_{stat} \pm 1_{syst} \,{}^{+7_{SPS}}_{-1_{SPS}} \text{ mb}$$

More data needed to extract SPS to test Colour-Singlet and Colour-Octet contributions

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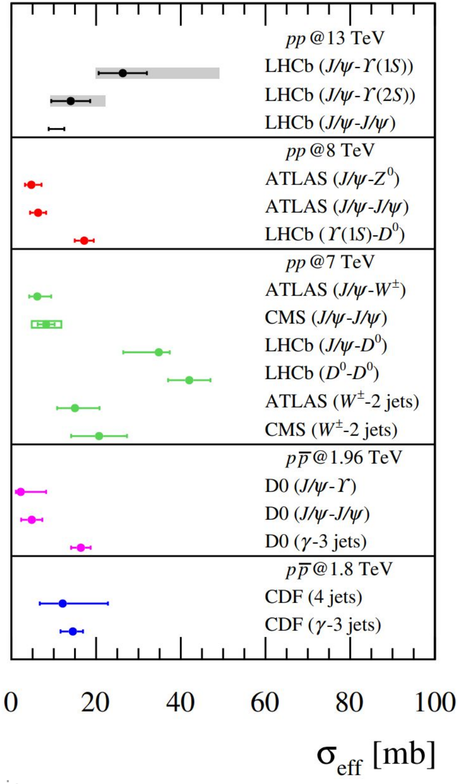

News from LHCb at $\sqrt{s} = 13$ TeV

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Production of J/Ψ + J/Ψ: where were we?

√s = 13 TeV

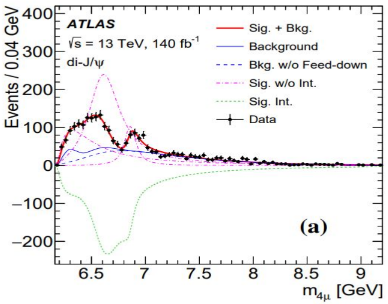
ATLAS

140 fb^{-1}

Phys. Rev. Lett. 131 (2023) 151902

New resonances:

- the LHCb's models have been used.
- Both are **consistent with a peak around 6.9 GeV** exceeding 5σ.
- decay into **J/ψ + ψ(2S)** has been considered showing a resonance near 6.9 GeV with 4.7σ.



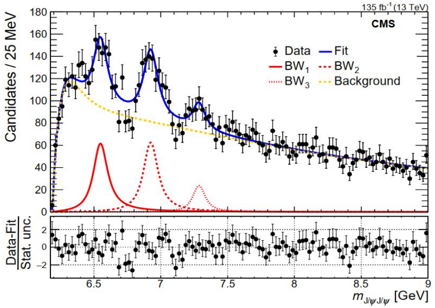
CMS

135 fb^{-1}

arXiv:2306.07164v1

New resonances:

- 6552 ± 10 (stat) ± 12 (syst) MeV (6.5σ).
- 6927 ± 9 (stat) ± 4 (syst) MeV (9.4σ), ***consistent with the X(6900).***
- 7287^{+20}_{-18}(stat) ± 5 (syst) MeV (4.1σ).
- both LHCb's models are not ideal but consistent.



LHCb

9 fb^{-1}

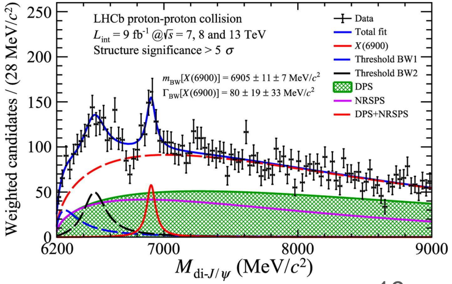
√s = 7 TeV + √s = 8 TeV + √s = 13 TeV

Valeriia ZHOVKOVSKA's slide

SB.65(2020)23,1983-1993

New resonance:

- with the first model the ***X(6900)*** is considered as a resonance. Threshold enhancement is described through a superposition of two resonances:
  m[***X(6900)***]= 6905 ± 11 ± 7 MeV/c^2.
- model II allows for interference between the NR-SPS component and a resonance for the threshold enhancement:
  m[***X(6900)***]= 6886 ±11 ±11 MeV/c^2;



$\sqrt{s} = 13$ TeV

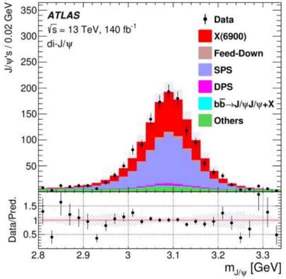
Production of J/Ψ + J/Ψ: can we learn something about DPS here?

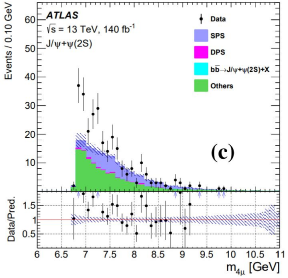
ATLAS

[Phys. Rev. Lett. 131 (2023) 151902](https://doi.org/10.1103/PhysRevLett.131.151902)

Background dominated from SPS in both the final states: J/ψJ/ψ and J/ψ + ψ(2S).

DPS contribution maybe more present in J/ψ + ψ(2S)?



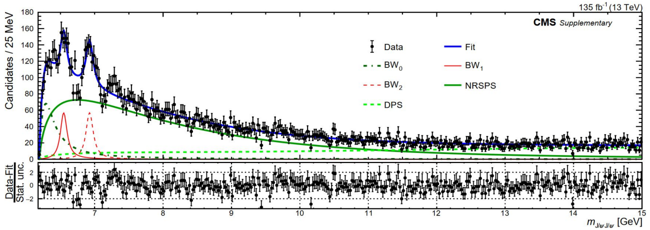


CMS

[arXiv:2306.07164v1](https://arxiv.org/abs/2306.07164v1)

Here the DPS is a background but we learned that:

- the NR-SPS contribution is expected to dominate the DPS contribution near the J/ψJ/ψ threshold
- the DPS contribution is dominating at masses above 11 GeV.



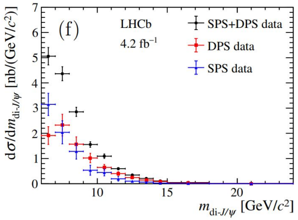
LHCb

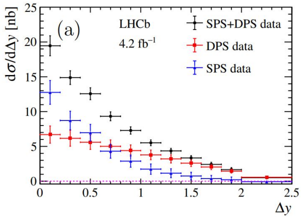
[Valeriia ZHOVKOVSKA's slide](#)

[arXiv:2311.14085](https://arxiv.org/abs/2311.14085)

We expect to learn something about:

- small SPS Color-Octet contributions
- DPS contribution is important at large Δy
- test gluon Transverse Momentum Dependent parton distribution functions (TMDs)





Production of J/Ψ + J/Ψ: can we learn something about DPS here?

$\sqrt{s} = 13$ TeV

ATLAS

[Phys. Rev. Lett. 131 (2023) 151902](#)

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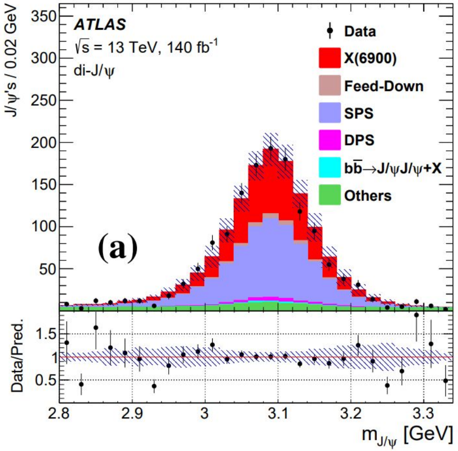

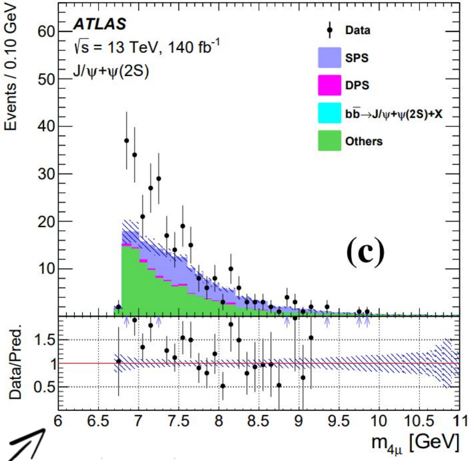

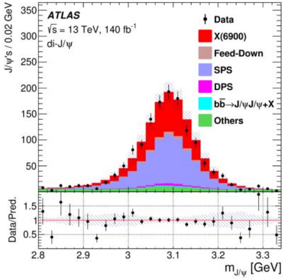

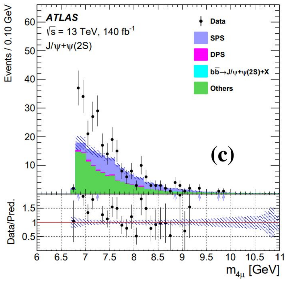

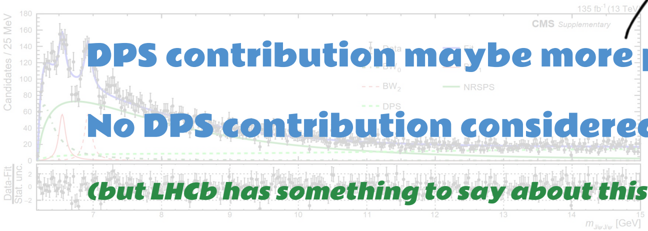

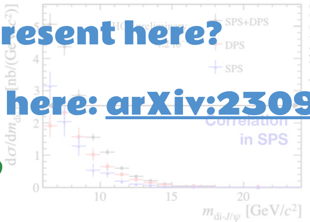

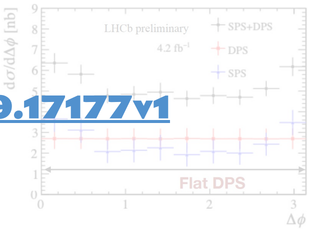

DPS contribution maybe more present here?

No DPS contribution considered here: [arXiv:2309.17177v1](#)

(but LHCb has something to say about this!)

$\sqrt{s} = 13$ TeV

Production of J/Ψ + J/Ψ: can we learn something about DPS here?

ATLAS

Phys. Rev. Lett. 131 (2023) 151902

Background ... from ... both the final states J/ψ J/ψ and J/ψ + ψ(2S).

DPS contribution maybe more present in J/ψ + ψ(2S)?

That seems a good place to look for DPS!

SPOILER ALERT! Maybe you can hear some news about it soon…

CMS

arXiv:2306.07164v1

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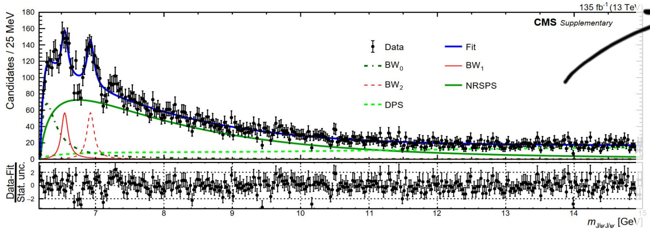

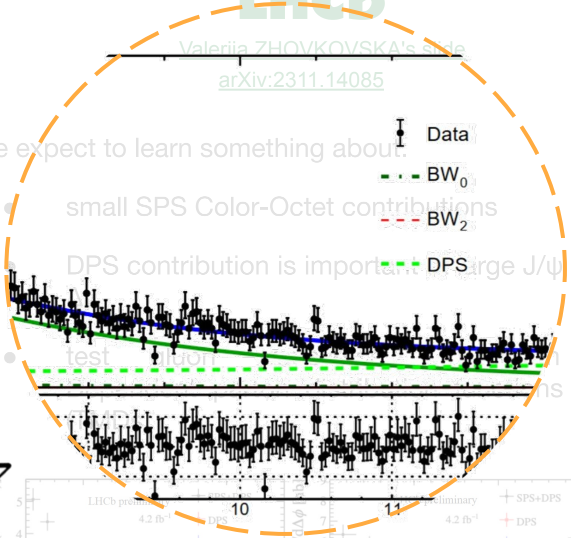

LHCb

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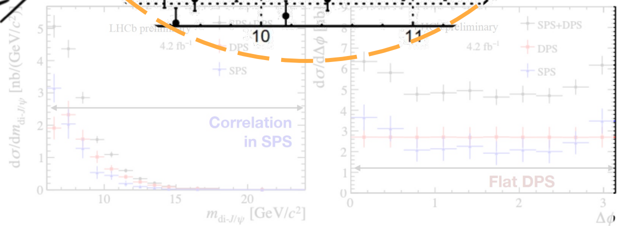
arXiv:2311.14085

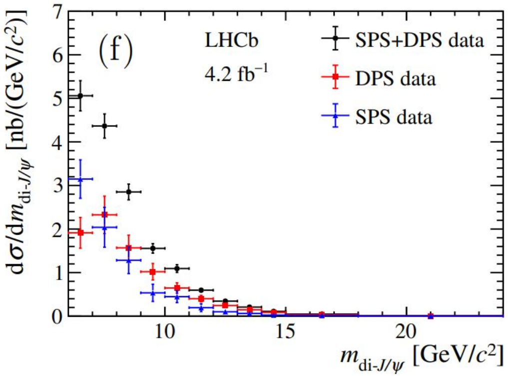
We expect to learn something about:

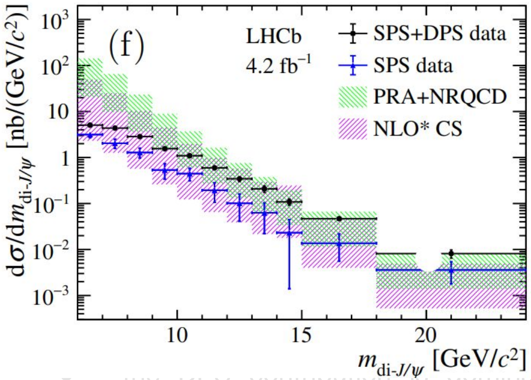
- small SPS Color-Octet contributions
- DPS contribution is important at large J/ψ
- test ... gluon ...

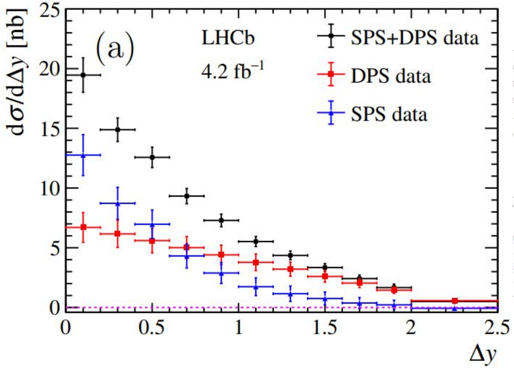


Production of J/Ψ + J/Ψ: can we learn something about DPS here?

$\sqrt{s} = 13$ TeV







- **SPS and DPS contributions are separated.**
- **Measurements are consistent with NLO* CS prediction from Lansberg and Shao [[Phys. Rev. Lett. 111, 122001]]**
- **DPS here was already expected: arXiv:1612.07451**

LHCb NEW

Valeriia ZHOVKOVSKA's slide

arXiv:2311.14085

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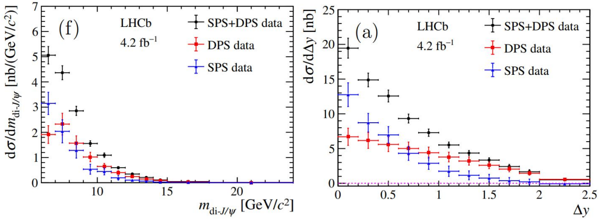
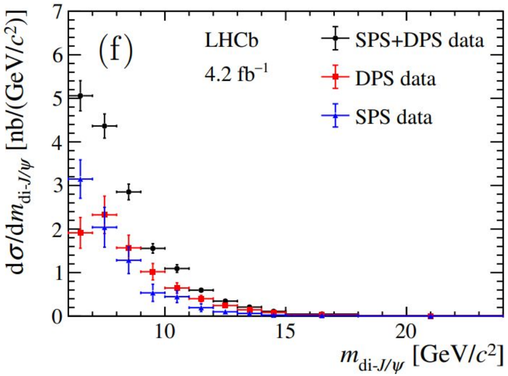
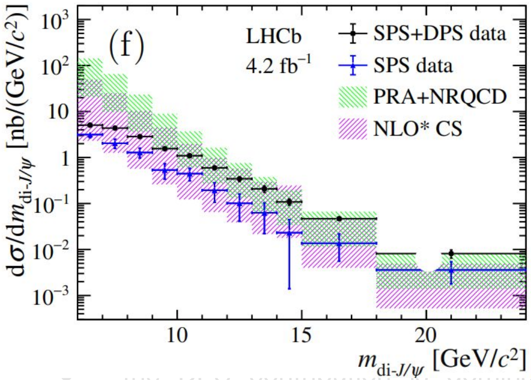


Production of J/Ψ + J/Ψ: can we learn something about DPS here?





LHCb NEW

[Valeriia ZHOVKOVSKA's slide](#)

[arXiv:2311.14085](#)

The measured cross-section is:

$$\sigma_{\text{di-}J/\psi} = 16.36 \pm 0.28\ (\text{stat}) \pm 0.88\ (\text{syst})\ \text{nb}$$

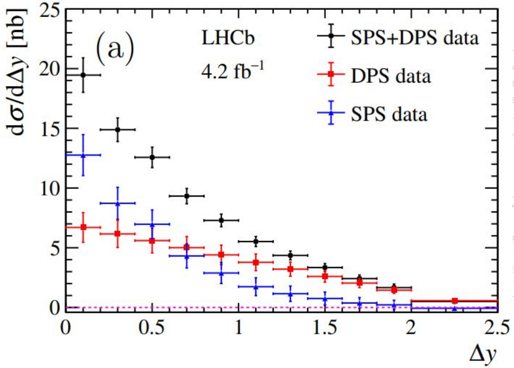
The DPS and SPS cross-sections are:

$$\sigma^{\text{DPS}}_{\text{di-}J/\psi} = 8.6 \pm 1.2\ (\text{stat}) \pm 1.0\ (\text{syst})\ \text{nb}$$

$$\sigma^{\text{SPS}}_{\text{di-}J/\psi} = 7.9 \pm 1.2\ (\text{stat}) \pm 1.1\ (\text{syst})\ \text{nb}$$

The effective cross-section:

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{\text{DPS}}_{\text{di-}J/\psi}} = 13.1 \pm 1.8\ (\text{stat}) \pm 2.3\ (\text{syst})\ \text{mb}$$



- **SPS and DPS contributions are separated.**
- **Measurements are consistent with NLO* CS prediction from Lansberg and Shao [[Phys. Rev. Lett. 111, 122001](#)]**
- **DPS here was already expected: [arXiv:1612.07451](#)**

$\sqrt{s}$ = 13 TeV

Production of J/Ψ + J/Ψ: can we learn something about TMDs here?

NEW

The prediction of the differential di-J/ψ production cross-section as a function of ϕ_{CS} through SPS is proportional to **a + b × cos(2ϕ_{CS}) + c × cos(4ϕ_{CS})**.

for more details see Jelle Bor's slides

The parameters a, b and c encode information on the gluon TMDs as:

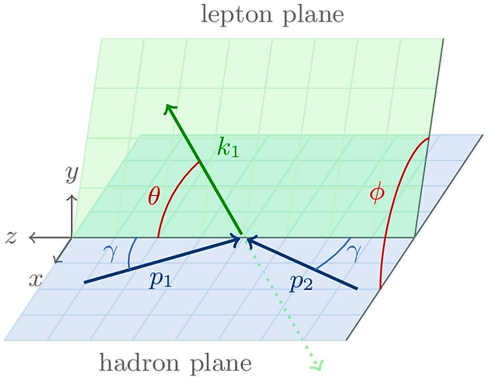
$$a = F_1 \mathcal{C}[f_1^g f_1^g] + F_2 \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}],$$
$$b = F_3 \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3' \mathcal{C}[w_3' h_1^{\perp g} f_1^g],$$
$$c = F_4 \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}],$$

while the cosine are:

$$\langle \cos 2\phi_{CS} \rangle = \frac{\sum_i \frac{d\sigma}{d\phi_{CS}}\Big|_i \Delta\phi_{CS_i} \cos 2\phi_{CS_i}}{\sum_i \frac{d\sigma}{d\phi_{CS}}\Big|_i \Delta\phi_{CS_i}}$$

$$\langle \cos 4\phi_{CS} \rangle = \frac{\sum_i \frac{d\sigma}{d\phi_{CS}}\Big|_i \Delta\phi_{CS_i} \cos 4\phi_{CS_i}}{\sum_i \frac{d\sigma}{d\phi_{CS}}\Big|_i \Delta\phi_{CS_i}}$$

This is done in the Collins-Soper (CS) frame



arXiv:2311.14085

Production of J/Ψ + J/Ψ: can we learn something about TMDs here?

$\sqrt{s}$ = 13 TeV

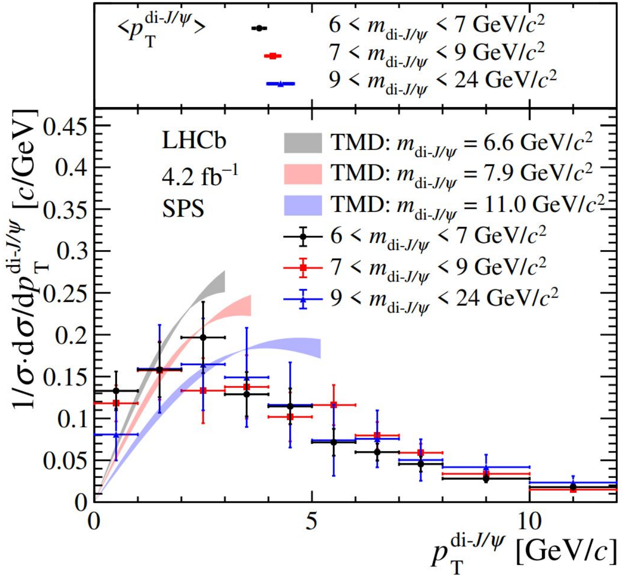
NEW

arXiv:2311.14085

The results of $\langle \cos 2\phi_{CS} \rangle$ and $\langle \cos 4\phi_{CS} \rangle$ extracted from the ϕ_{CS} distribution for SPS are:

$$\langle \cos 2\phi_{\rm CS} \rangle = -0.029 \pm 0.050 \text{ (stat)} \pm 0.009 \text{ (syst)}$$
$$\langle \cos 4\phi_{\rm CS} \rangle = -0.087 \pm 0.052 \text{ (stat)} \pm 0.013 \text{ (syst)}$$

- these are **consist with zero**, but there's a possibility of a slight azimuthal asymmetry at a few percent level.
- di-J/ψ p_T spectra exhibit consistency across various $y_{\text{di-J/}\psi}$ intervals, **peaking at lower p_T values compared to theoretical predictions**.
- the average p_T distribution shows a slight increase with di-J/ψ mass.



for more details see Jelle Bor's slides

Production of J/Ψ + J/Ψ: can we learn something about DPS here?

$\sqrt{s} = 13$ TeV

Production cross section:

$$\sigma(J/\psi\, J/\psi) = \frac{N}{\mathscr{L}_{\text{int}} \times \varepsilon \times B^2(J/\psi \to \mu^+\mu^-)}$$

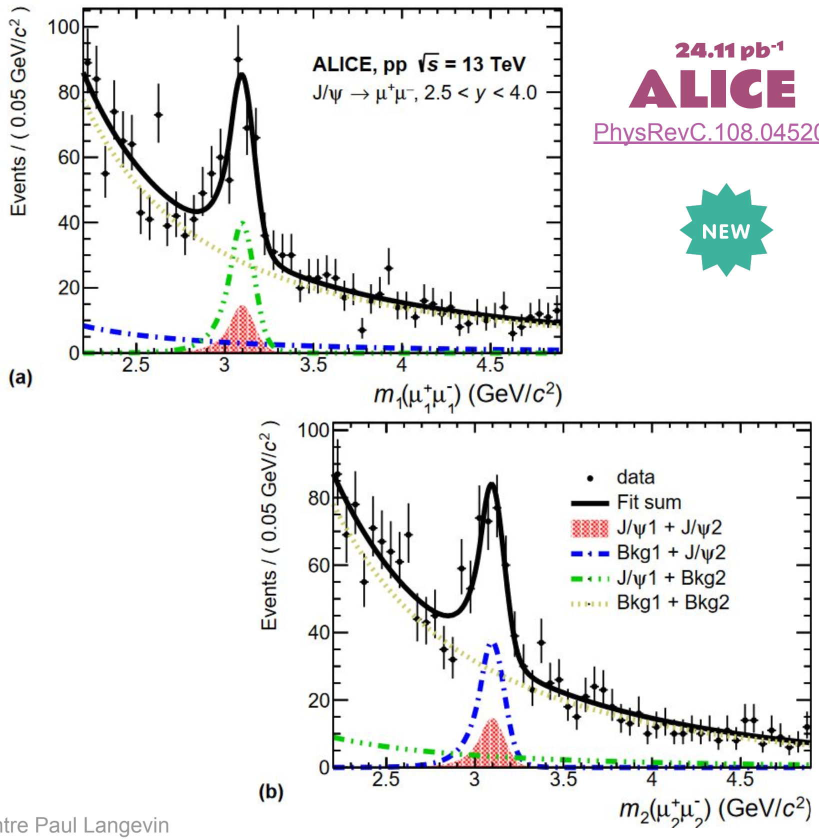
Inclusive cross section:

- inclusive: $\sigma(J/\psi\, J/\psi) = 10.3 \pm 2.3\,(\text{stat.}) \pm 1.3\,(\text{syst.})$ nb.
- prompt: $\sigma_{\text{prompt}}(J/\psi\, J/\psi) = 7.3 \pm 1.7\,(\text{stat.})^{+1.9}_{-2.1}(\text{syst.})$ nb

in $2.5 < y < 4.0$ with $p_T > 0$

Effective DPS cross-section:

- inclusive: $\frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma(J/\psi\, J/\psi)} = 6.2 \pm 1.4\,(\text{stat.}) \pm 1.1\,(\text{syst.})$ mb
- prompt: $\frac{1}{2}\frac{\sigma_{\text{prompt}}(J/\psi)^2}{\sigma_{\text{prompt}}(J/\psi\, J/\psi)} = 6.7 \pm 1.6\,(\text{stat.}) \pm 2.7\,(\text{syst.})$ mb



24.11 pb^{-1}

ALICE

PhysRevC.108.045203

NEW

$\sqrt{s}$ = 13 TeV

Production of J/Ψ + J/Ψ: can we learn something about DPS here?

Production cross section:

$$\sigma(J/\psi\, J/\psi) = \frac{N}{\mathcal{L}_{\text{int}} \times \varepsilon \times B^2(J/\psi \to \mu^+\mu^-)}$$

Inclusive cross section:

- inclusive: $\sigma(J$…
- prompt: σ_{pro}…

in $2.5 < y < 4.0$ with $p_T > 0$

Effective DPS cross-section:

- inclusive: $\frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma(J/\psi\, J/\psi)} = 6.2 \pm 1.4\,(\text{stat.}) \pm 1.1\,(\text{syst.})\text{ mb}$
- prompt: $\frac{1}{2}\frac{\sigma_{\text{prompt}}(J/\psi)^2}{\sigma_{\text{prompt}}(J/\psi\, J/\psi)} = 6.7 \pm 1.6\,(\text{stat.}) \pm 2.7\,(\text{syst.})\text{ mb}$

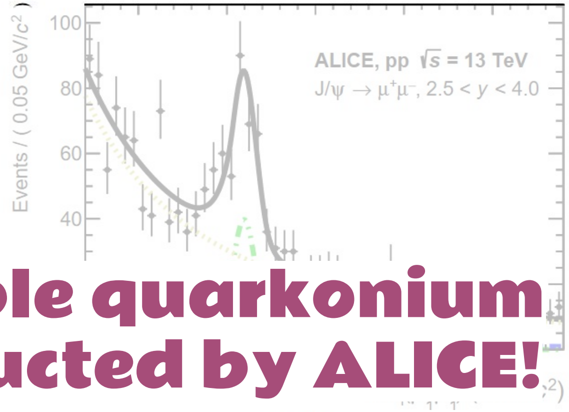
24.11 pb^{-1}

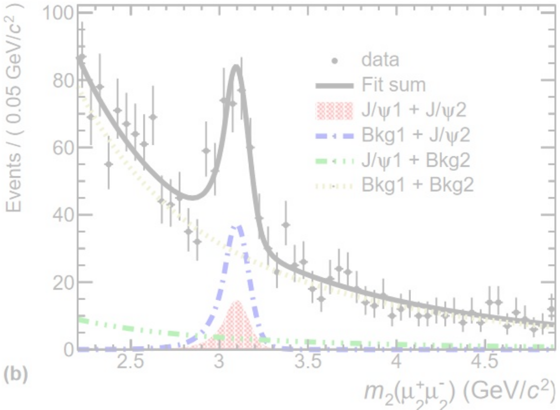
ALICE

PhysRevC.108.045203

NEW

This is the first double quarkonium measurement conducted by ALICE!





News from LHCb at $\sqrt{s} = 13$ TeV

- J/ψ + Υ(nS) production: JHEP 08 (2023) 093
  - integrated and differential (for Υ(1S)) cross-section
  - effective cross-section σ_{eff}

NEW

- J/ψ + J/ψ production: LHCb-PAPER-2023-022
  - integrated and differential cross-section
  - production asymmetry
  - effective cross-section

NEW

- J/ψ + ψ(2S) production: arXiv:2311.15921
  - integrated and differential cross-section
  - ratio to J/ψ + J/ψ

$\sqrt{s} = 13$ TeV

Associated production of prompt J/Ψ and Ψ(2S) mesons

NEW

[arXiv:2311.15921](https://arxiv.org/abs/2311.15921)

Data sample:

LHCb

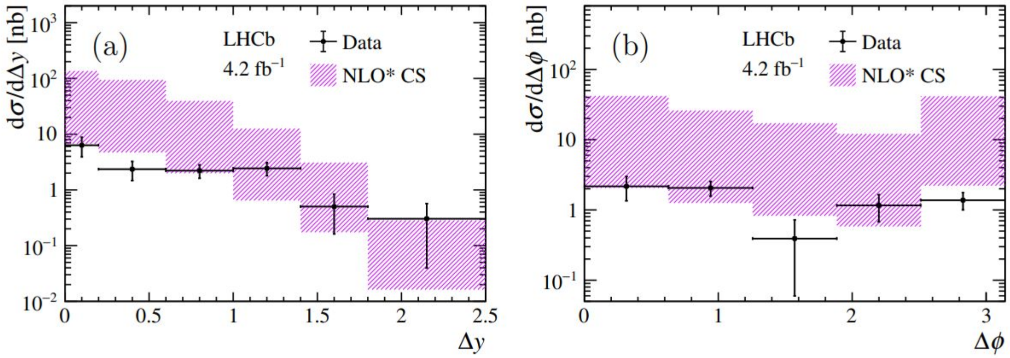
$$\mathscr{L} = 4.18 \pm 0.08 \ \mathrm{fb}^{-1}$$

with:

$p_{\mathrm{T}}^{J/\psi,\psi(2S)} < 14$ GeV/c and $2.0 < y^{J/\psi,\psi(2S)} < 4.5$

The integrated cross section is:

$$\sigma_{J/\psi\text{-}\psi(2S)} = 4.5 \pm 0.7\ (\mathrm{stat}) \pm 0.3\ (\mathrm{syst})\ \mathrm{nb}$$

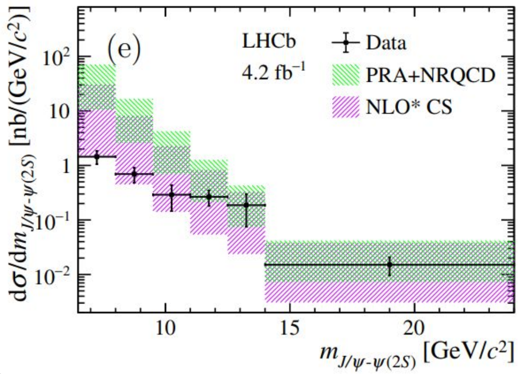


Ratio between J/ψ + ψ(2S) and J/ψ + J/ψ production

$$\mathscr{R} = \frac{\sigma_{J/\psi-\psi(2S)}}{\sigma_{J/\psi-J/\psi}} = 0.274 \pm 0.044_{stat} \pm 0.008_{syst}$$

$$\mathscr{R}_{SPS} = 0.94 \pm 0.30$$

$$\mathscr{R}_{DPS} = 0.282 \pm 0.027$$

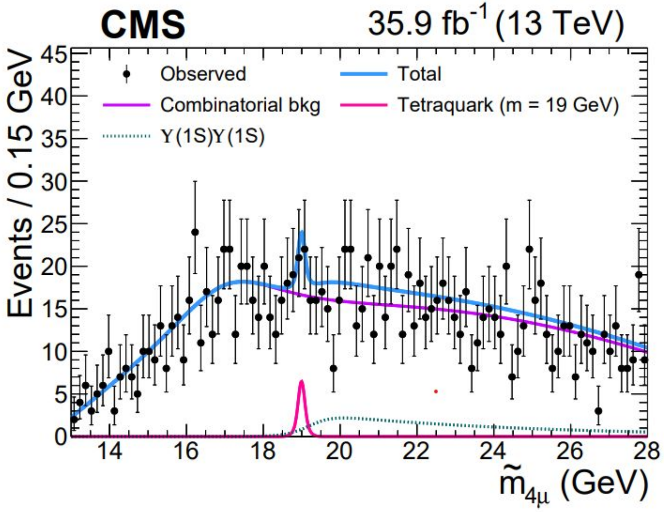


Consistent with DPS prediction + Measurements are consistent with NLO* CS predictionfrom Lansberg and Shao [[Phys. Rev. Lett. 111, 122001](https://doi.org/10.1103/PhysRevLett.111.122001)]

News from CMS

[Physics Letters B 808 (2020) 135578](#)

- **Measurement of the Υ(1S) pair production cross section** and search for resonances decaying to 4 muons ($\mu^+\mu^-$):
  - measurement is performed using data collected in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}
  - narrow resonance could indicate the existence of a tetraquark, unfortunately there is No significant excess of events compatible with a narrow resonance is observed in the data
  - **DPS contribution measured for the first time**



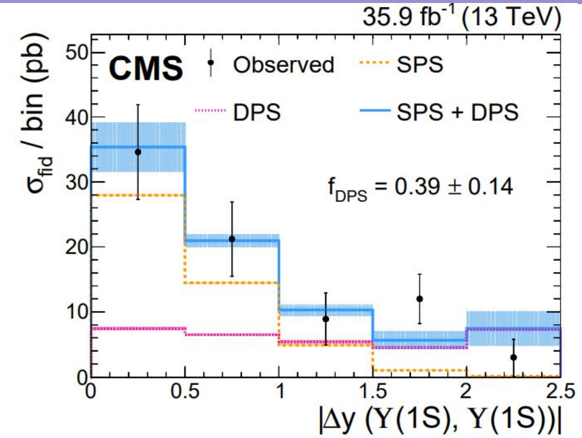
Measurement of the Υ(1S) pair production

$\sqrt{s} = 13$ TeV

Measuring Υ(1S)Υ(1S) cross sections in rapidity and mass bins helps determine the DPS fraction (f_{DPS})

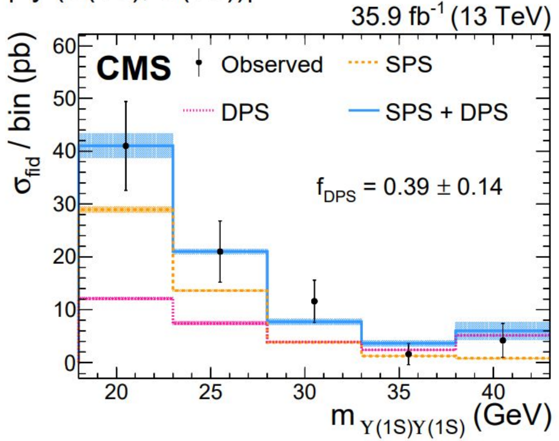
$$f_{\text{DPS}} = \frac{\sigma_{\text{fid}}^{\text{DPS}}}{\sigma_{\text{fid}}^{\text{SPS}} + \sigma_{\text{fid}}^{\text{DPS}}}$$

Using **|Δy(Υ(1S),Υ(1S))|** $\mathbf{f_{DPS}}$ measures at **(39 ± 14)%,** dominated by statistical uncertainties, while the result for $\mathbf{m_{Υ(1S)Υ(1S)}}$ is compatible but less precise at **(27 ± 22)%** due to statistical dominance.



CMS

[Physics Letters B 808 (2020) 135578]

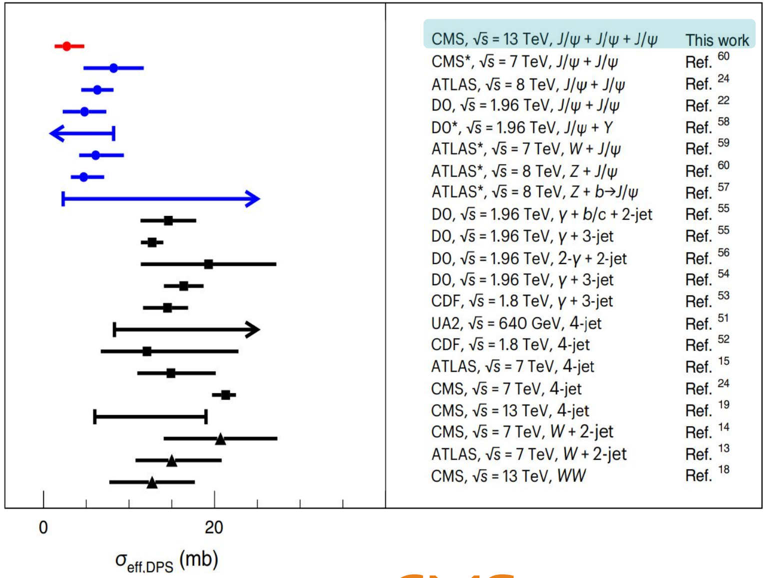


3

Future perspectives

SPS and DPS and... TPS: the future is here!

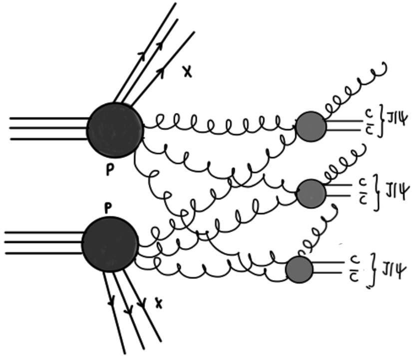
Nat. Phys. 19, 338–350 (2023) $\sigma_{\mathrm{eff,TPS}} = 0.82\,\sigma_{\mathrm{eff,DPS}} = 2.2\,\mathrm{mb}$



CMS

Pocket formula for TPS:

$$\sigma^{pp\to\psi_1\psi_2\psi_3+X}_{\mathrm{TPS}} = \left(\frac{m}{3!}\right)\frac{\sigma^{pp\to\psi_1+X}_{\mathrm{SPS}}\,\sigma^{pp\to\psi_2+X}_{\mathrm{SPS}}\,\sigma^{pp\to\psi_3+X}_{\mathrm{SPS}}}{\sigma^2_{\mathrm{eff,TPS}}}$$



m = 1, 3, or 6 (depending on whether all three, two, or none of the ψ_i states are identical).

Analyzing the whole RUNII ($\mathcal{L}$ = 133 fb^{-1}) **5 events** have been found. The expected contributions from SPS, DPS and **TPS** processes to the total triple-J/ψ cross-section amount to about 6%, 74% and **20%**, respectively.

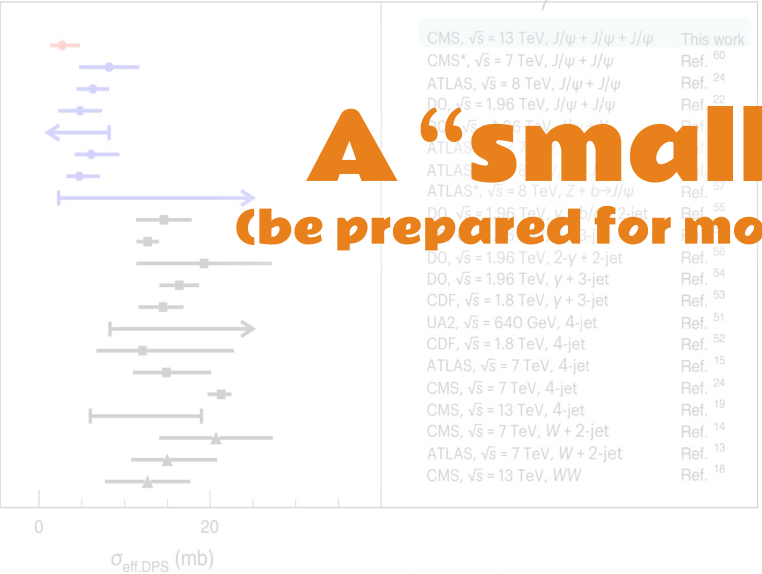
The fiducial cross section is:

$$272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}$$

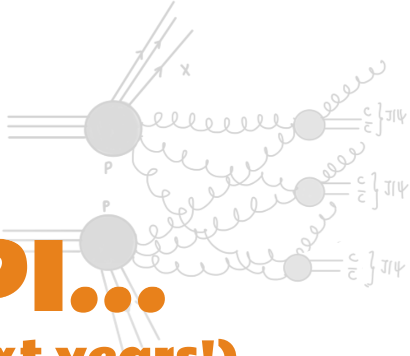
more on D'Enterria's slides

SPS and DPS and... TPS: the future is here!

[Nat. Phys. 19, 338–350 (2023)] $\sigma_{\text{eff,TPS}} = 0.82\,\sigma_{\text{eff,DPS}} = 2.2\,\text{mb}$



Pocket formula for TPS:



A "small" step for MPI...

(be prepared for more results on TPS in the next years!)

m = 1, 3, or 6 (depending on whether all three, two, or none of the ψ_i states are identical).

Analyzing the whole RUNII ($\mathcal{L}$ = 133 fb^{-1}) **5 events** have been found. The expected contributions from SPS, DPS and **TPS** processes to the total triple-J/ψ cross-section amount to about 6%, 74% and **20%**, respectively.

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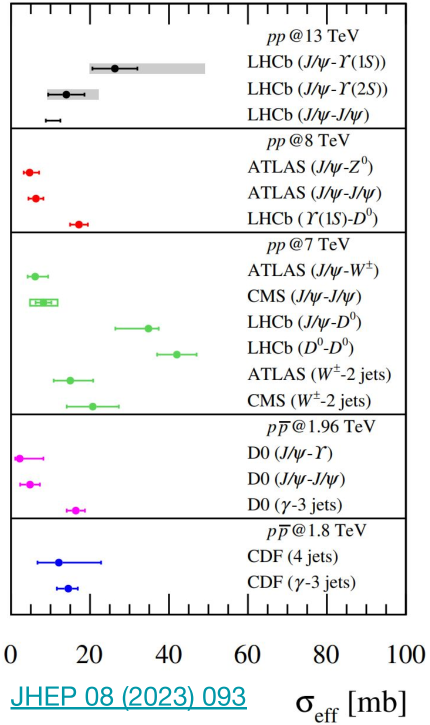
$$272^{+141}_{-104}\,(\text{stat}) \pm 17\,(\text{syst})\,\text{fb}$$

more on D'Enterria slides

4

Conclusions

Summary and conclusions



JHEP 08 (2023) 093

Take home message:

- Quarkonia have a lot to teach us about QCD.
- Especially for LHCb and CMS seem to be good chances to get important results on DPS using quarkonia.
- There is a lot work left to do:
  - more insights on the non-universality effective cross-section σ_{eff} are needed.
  - probably a lot of interesting final states produced via DPS are waiting for us.

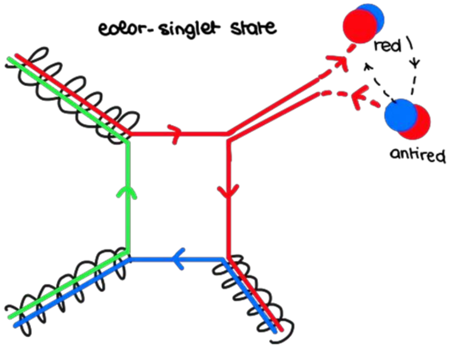
Thanks for your time!

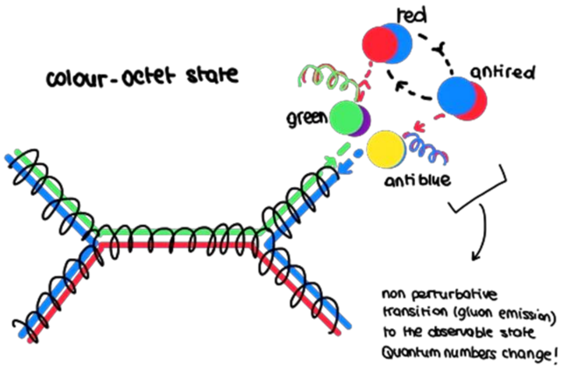
BACKUP

Color octet and color singlet

- **Colour-singlet model (CS)**: intermediate QQ state is colourless and has the same JPC as the final-state quarkonium;

- **Colour-octet model (CO)** (encapsulated in NRQCD): all viable colours and JPC allowed for the intermediate QQ state;





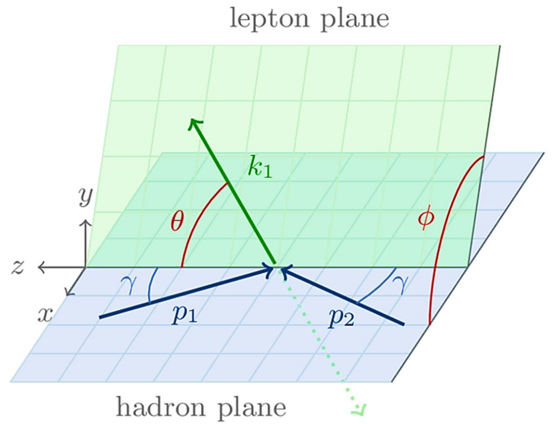
Collins-Soper frame

Purpose:

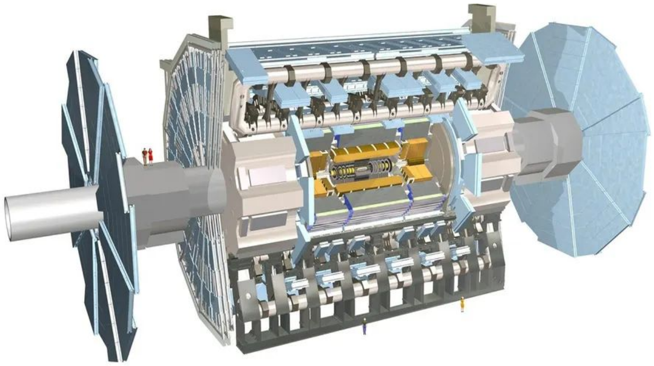
- Defining a reference system on an event-by-event basis.
- Allowing differential distributions to be approximated by the Born-level angular dependence $d\sigma/d\Omega \propto (1 + \cos^2 \theta)$.
- Minimizing sensitivity to the emitted hard QCD radiation.

Where the cosine of the angle is:

$$\cos\theta_{CS} = \frac{2(p_z^{\ell} E^{\overline{\ell'}} - p_z^{\overline{\ell'}} E^{\ell})}{M\sqrt{M^2 + p_T^2}}$$

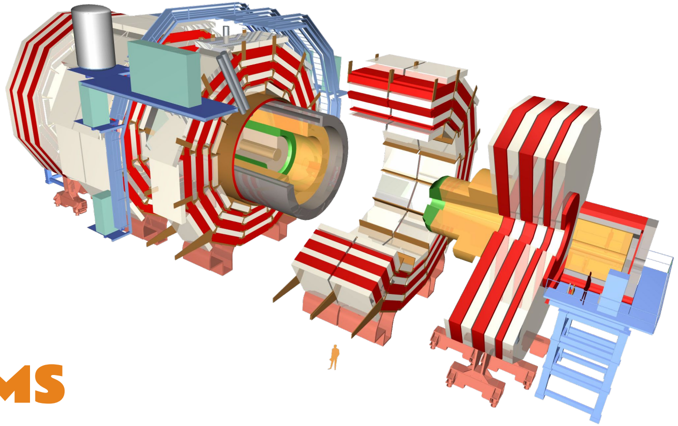


The main characters (here)



ATLAS

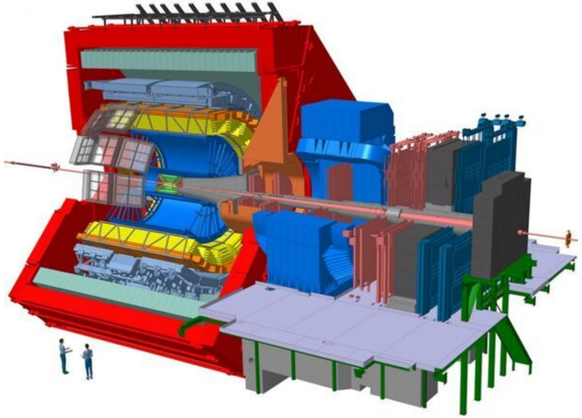
- **Pseudorapidity Range:** ATLAS covers a broad pseudorapidity range, $|\eta| < 4.9$.
- **Tracking System:** tracking system comprising pixel detectors, semiconductor trackers, and transition radiation trackers. This setup enables precise tracking of charged particles, with momentum measurements characterized by a relative uncertainty typically ranging from 0.05% to 0.2%.
- **Particle Identification (PID):** Charged hadrons are identified through tracking information and calorimetry. Photons, electrons are distinguished using electromagnetic calorimeters. Muons are identified using dedicated muon spectrometer with multiple technologies such: Thin Gap Chambers, Resistive Plate Chambers, Monitored Drift Tubes, Small-Strip Thin-Gap Chambers and Micromegas.



CMS

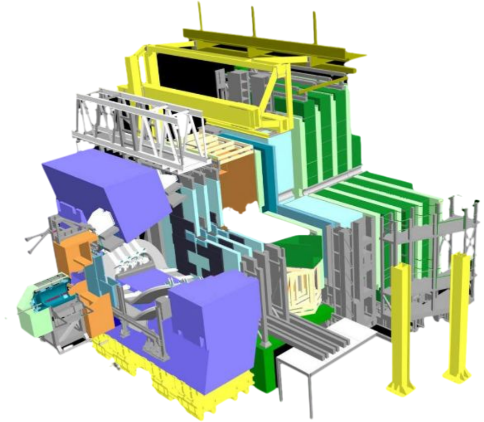
- **Pseudorapidity Range:** CMS covers a wide pseudorapidity range of $|\eta| < 5$.
- **Tracking System:** the tracking system consisting of silicon detectors, both pixel and strip detectors particles. The relative uncertainty in momentum measurements typically ranges from 0.5% to 1.0%.
- **Particle Identification (PID):** charged hadrons are identified using tracking information and the energy deposited in the calorimeters. Photons, electrons, are identified and measured using electromagnetic calorimeters. Muons are identified through dedicated muon detectors composed of layers of iron and multiple detector technologies like Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC).

The main characters (here)



ALICE

- **Pseudorapidity Range:** ALICE focuses on covering $-0.9 < \eta < 0.9$. This range is optimized for studying heavy-ion collisions and quark-gluon plasma formation.
- **Tracking System:** Its main tracking system consists of Inner Tracking System (ITS) with high-resolution silicon detectors and a Time Projection Chamber (TPC).
- **Particle Identification (PID):** it uses the ITS and TPC for tracking and identification of charged particles, while specific detectors like Time-Of-Flight (TOF) detectors and Transition Radiation Detectors (TRD) aid in distinguishing between different particle types such as pions, kaons, protons, and electrons.



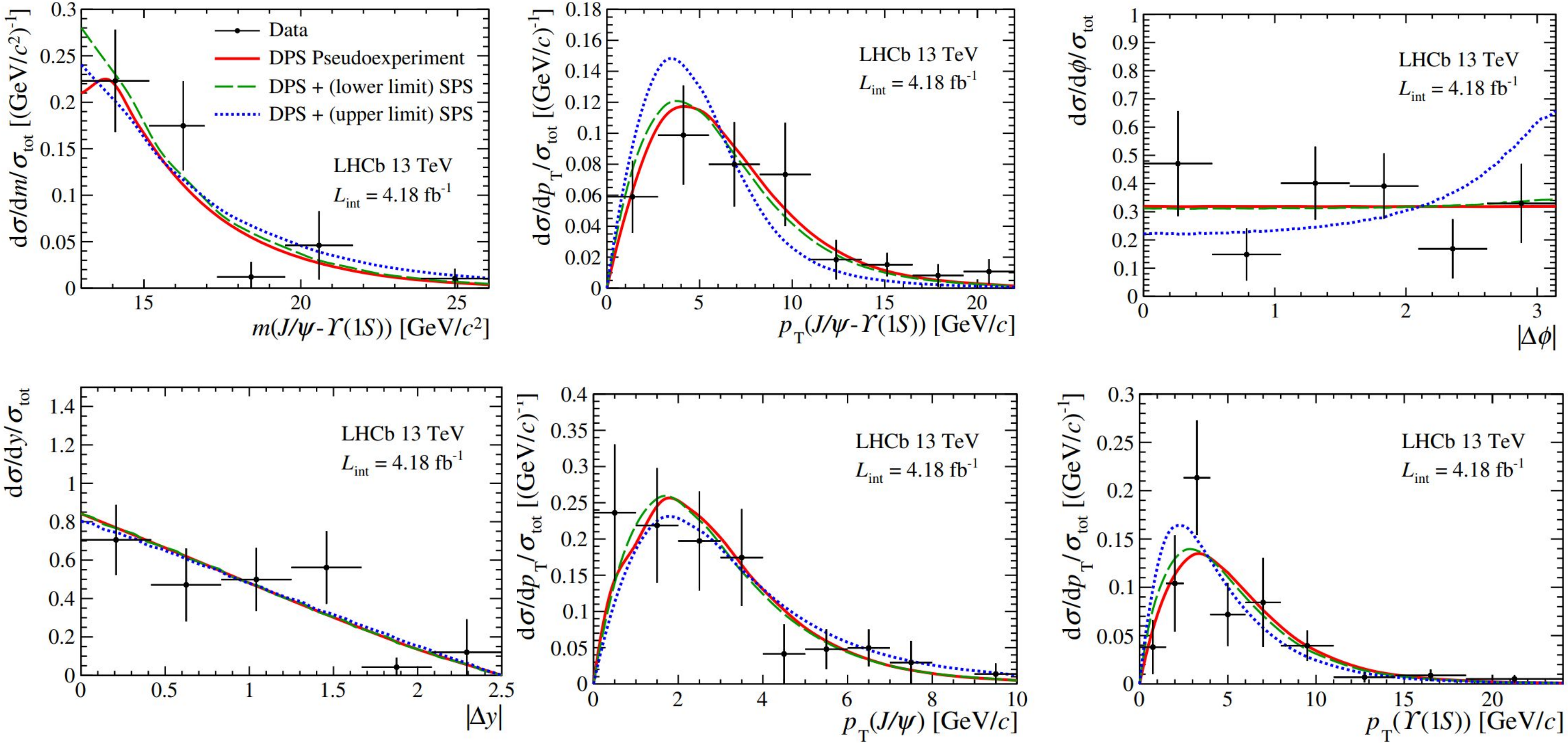
LHCb

- **Pseudorapidity Range:** LHCb is optimized for studying forward production in the pseudorapidity range of $2 < \eta < 5$.
- **Tracking System:** LHCb's tracking system includes a Vertex Locator (VELO), which is a silicon microstrip detector located very close to the collision point. Additionally, it utilizes a combination of silicon strip detectors and straw tubes that cover the entire spectrometer region.
- **Particle Identification (PID):** It utilizes Ring Imaging Cherenkov (RICH) detectors for identifying charged hadrons based on their velocity, electromagnetic and hadronic calorimeters for photons, electrons, and hadrons, and dedicated muon detectors, including Multi-Wire Proportional Chambers (MWPC) and scintillators, to identify muons.

Associated production of prompt J/Ψ and ϒ mesons

$\sqrt{s} = 13$ TeV

JHEP 08 (2023) 093



LHCb

$\sqrt{s} = 13$ TeV

Production of J/Ψ + J/Ψ: Model 1

LHCb

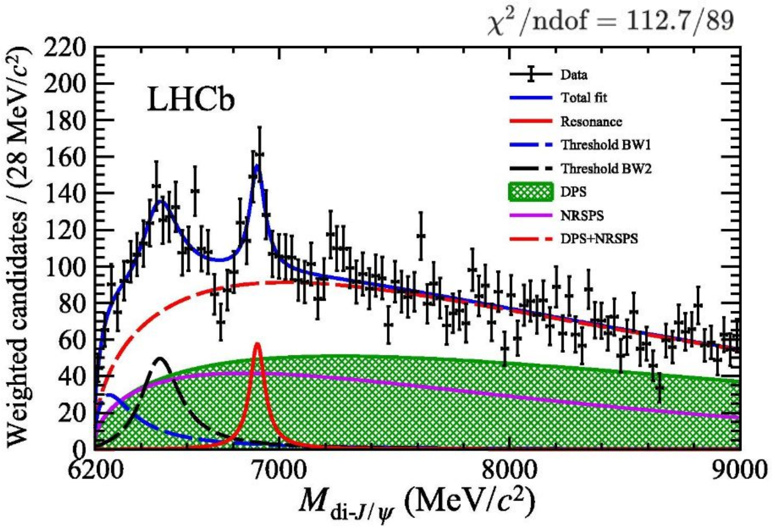
SB.65(2020)23,1983-1993

In model 1, the X(6900) structure is considered as a resonance, whereas the threshold enhancement is described through a superposition of two resonances. The lineshapes of these resonances are described by S-wave relativistic BW functions multiplied by a two-body phase-space distribution.

The mass, natural width and yield are determined to be:

$$m[X(6900)] = 6905 \pm 11 \text{ MeV}/c^2, \Gamma[X(6900)] = 80 \pm 19 \text{ MeV}$$

(b)



Production of J/Ψ + J/Ψ: Model 2

LHCb

SB.65(2020)23,1983-1993

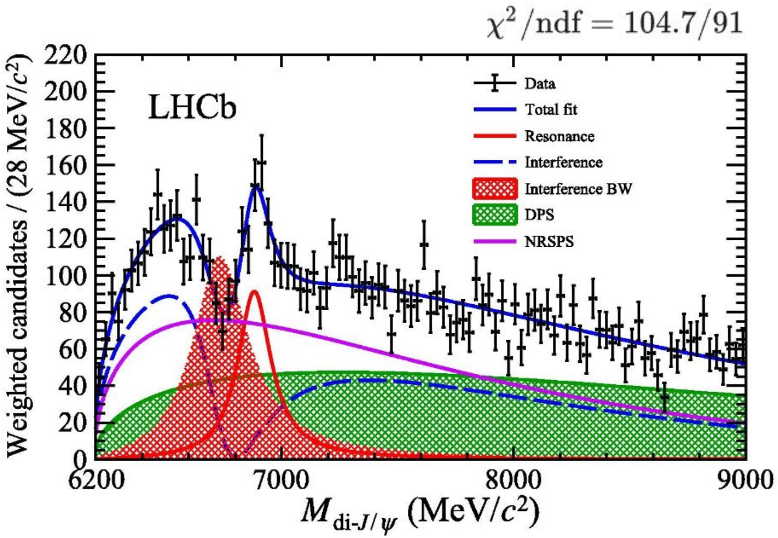
Model 2, allows for interference between the NRSPS component and a resonance for the threshold enhancement. The coherent sum of the two components is defined as:

$$\left| A e^{i\phi} \sqrt{f_{\mathrm{nr}}\left(M_{\text{di-}J/\psi}\right)} + \mathrm{BW}\left(M_{\text{di-}J/\psi}\right) \right|^2$$

where A and ϕ are the magnitude and phase of the nonresonant component, relative to the BW lineshape for the resonance, assumed to be independent of di-J/ψ mass , and $f_{\mathrm{nr}}\left(M_{\text{di-}J/\psi}\right)$s an exponential function. The interference term is then added incoherently to the BW function describing the X(96000) structure and the DPS description.
In this case:

$$m\left[X(6900)\right] = 6886 \pm 11 \text{ MeV}/c^2 \text{ , } \Gamma\left[X(6900)\right] = 168 \pm 33 \text{ MeV}$$

(c)



Production of J/Ψ + J/Ψ: early measurements

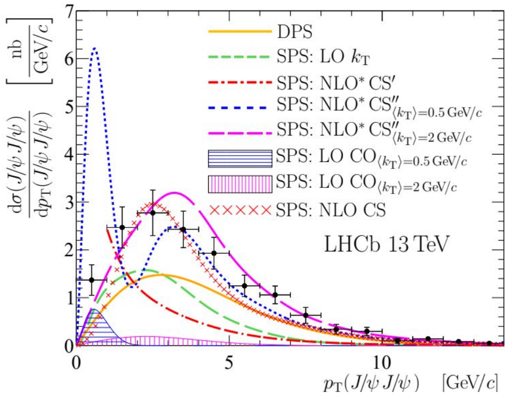
- **DPS here was already expected: arXiv:1612.07451**

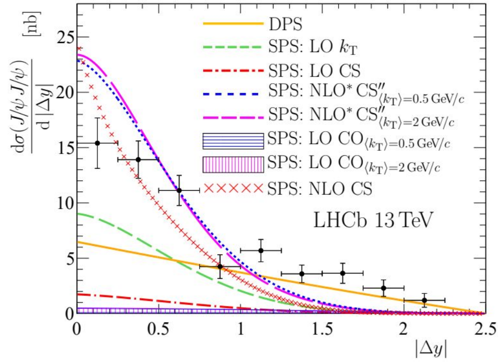
LHCb

The J/ψ pair production **cross-section** with both J/ψ mesons in the region 2.0 < y < 4.5 and pT < 10 GeV/c is measured to be **15.2±1.0 (stat)±0.9 (syst) nb**, using pp collision data collected by LHCb at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 279 pb^{-1}.

A fit to the differential cross-sections using simple DPS plus SPS models **indicates a significant DPS contribution**. The data can be reasonably well described with a sum of DPS and SPS colour-singlet contributions, with no evidence for a large SPS colour-octet contribution.

A large DPS contribution results in values of **σ_{eff} that are smaller than the values of σ_{eff} measured previously by the LHCb collaboration in the processes of multiple associated heavy quark production**, and slightly larger than those measured from central J/ψ pair production at the CMS and ATLAS experiments.





$\sqrt{s}$ = 13 TeV

Production of J/Ψ + J/Ψ: can we learn something about DPS here?

ALICE

PhysRevC.108.045203

$$\sigma_{\text{non-prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi) = 2.97 \pm 0.09\,(\text{stat.})^{+0.68}_{-0.76}(\text{syst.})\ \text{nb}$$

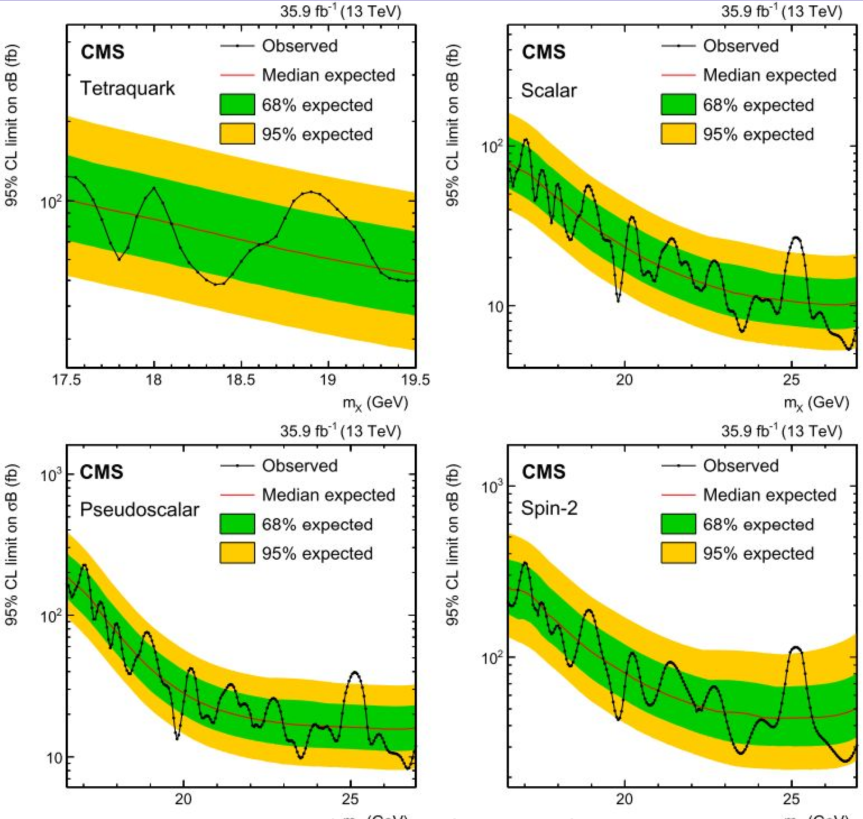
$$\sigma_{\text{prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi) = \sigma(\mathrm{J}/\psi\,\mathrm{J}/\psi) - \sigma_{\text{non-prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi) = 7.3 \pm 1.7\,(\text{stat.})^{+1.9}_{-2.1}(\text{syst.})\ \text{nb}$$

$$\sigma_{\text{non-prompt}}(\mathrm{J}/\psi) = 2 \times \sigma^{\text{total}}_{\mathrm{b\bar{b}}} \times \beta \times B(h_{\mathrm{b}} \to \mathrm{J}/\psi\ + \mathrm{X}) = 1.41 \pm 0.04\,(\text{stat.}) \pm 0.19(\text{syst.})\ \mu\text{b}$$

$$\sigma_{\text{prompt}}(\mathrm{J}/\psi) = \sigma(\mathrm{J}/\psi) - \sigma_{\text{non-prompt}}(\mathrm{J}/\psi) = 9.89 \pm 0.32\,(\text{stat.})^{+1.47}_{-1.48}(\text{syst.})\ \mu\text{b}$$

$$\frac{\sigma_{\text{prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi)}{\sigma_{\text{prompt}}(\mathrm{J}/\psi)} = (7.4 \pm 1.7\,(\text{stat.}) \pm 2.2\,(\text{syst.})) \times 10^{-4}$$

News from CMS



CMS

[Physics Letters B 808 (2020) 135578]

Masses between 17.5 and 19.5 GeV are probed in the context of the tetraquark search, using the bottomonium model, whereas the limits in the extended mass range 16.5–27 GeV are set for the generic search, using the JHUGen models.

Upper limits at 95% CL on the product of the cross section and branching fraction for a tetraquark (upper left), scalar (upper right), pseudoscalar (lower left), and spin-2 (lower right) states.