Review of DPS/TPS measurements

Quarkonia As Tools 2022

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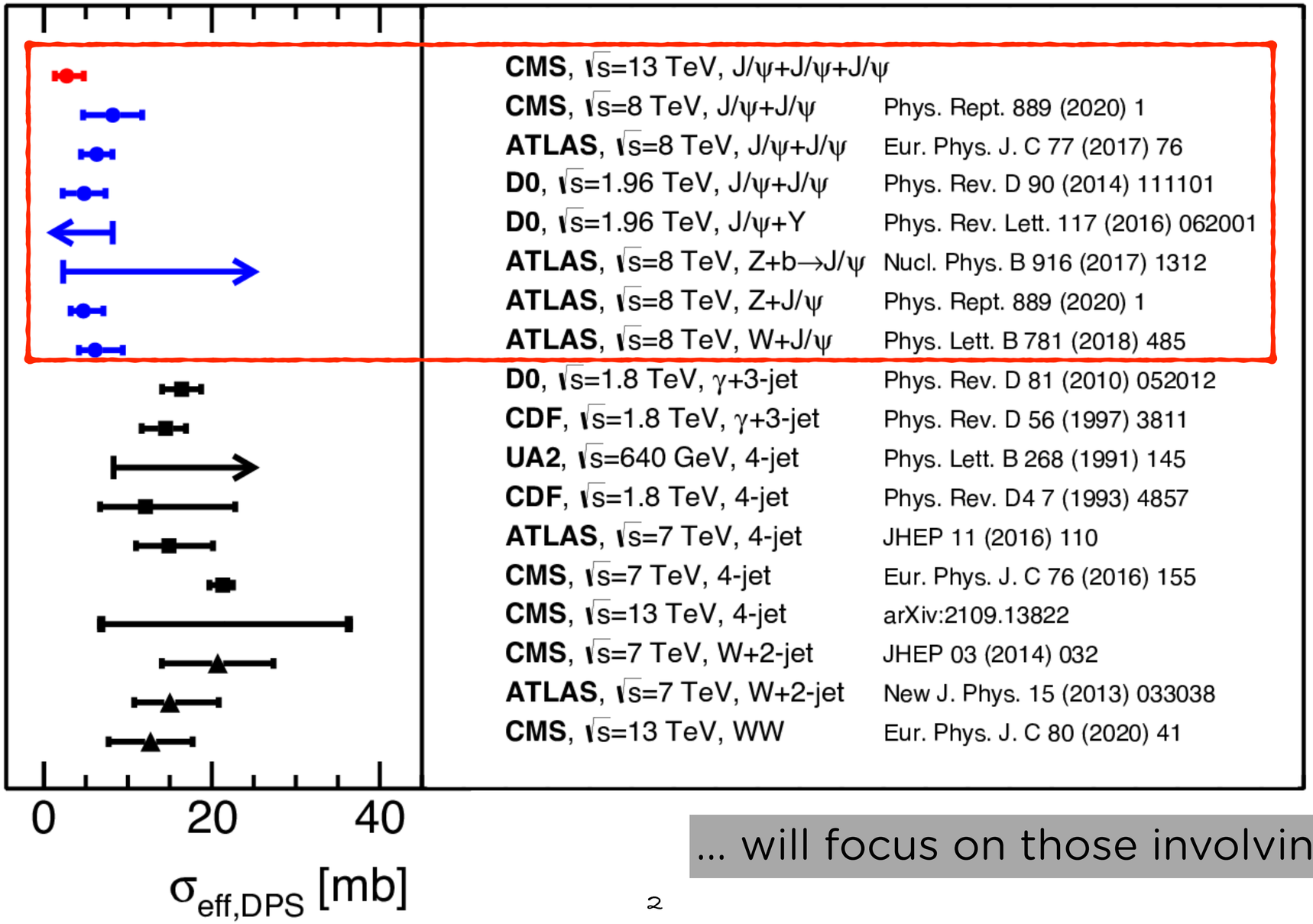
Review of DPS/TPS measurements

Many Double Parton Scattering measurements …



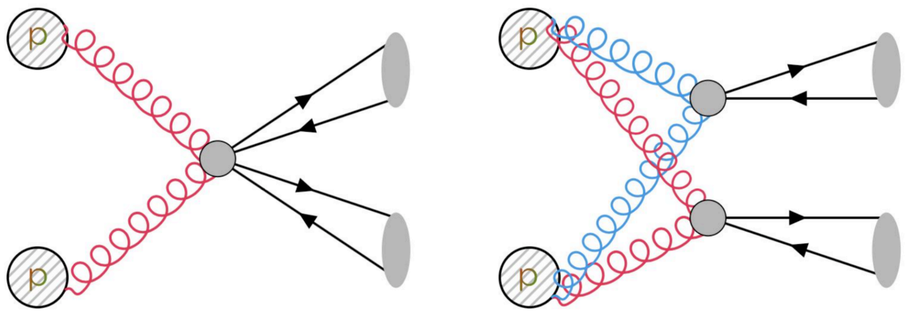
… will focus on those involving quarkonia

Review of DPS/TPS measurements

DPS introduction

- First appearance of Double Parton Scattering in theory in the 80s
- DPS is a proton-proton scattering process where two partons from each proton interact separately
- DPS cross section can be expressed as:

$$\frac{\mathrm{d}\sigma_{\mathrm{DPS}}}{\mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}\bar{x}_1\,\mathrm{d}\bar{x}_2} = \frac{1}{C}\int_{x_1}^{1-x_2}\frac{\mathrm{d}x_1'}{x_1'}\int_{x_2}^{1-x_1'}\frac{\mathrm{d}x_2'}{x_2'}\int_{\bar{x}_1}^{1-\bar{x}_2}\frac{\mathrm{d}\bar{x}_1'}{\bar{x}_1'}\int_{\bar{x}_2}^{1-\bar{x}_1'}\frac{\mathrm{d}\bar{x}_2'}{\bar{x}_2'}$$
$$\times \sum_{a_1a_2b_1b_2} {}^R\hat{\sigma}^{(1)}_{a_1b_1}(x_1'\bar{x}_1's,\mu_1)\,{}^R\hat{\sigma}^{(2)}_{a_2b_2}(x_2'\bar{x}_2's,\mu_2)$$
$$\times \int \mathrm{d}^2\boldsymbol{y}\,{}^RF_{a_1a_2}(x_1',x_2',\boldsymbol{y},\mu_1,\mu_2,\zeta)\,{}^RF_{b_1b_2}(\bar{x}_1',\bar{x}_2',\boldsymbol{y},\mu_1,\mu_2,\bar{\zeta})$$



From Riccardo Nagar's thesis

- Ignoring any correlations between the individual partons (m=2 if ψ_1 != ψ_2):

$$\sigma_{\mathrm{DPS}}^{\mathrm{pp}\to\psi_1\,\psi_2+\mathrm{X}} = \left(\frac{\mathfrak{m}}{2}\right)\frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+\mathrm{X}}}{\sigma_{\mathrm{eff,DPS}}}$$

- $\sigma_{\mathrm{eff,DPS}}$ holds the effects of the transversity and is the parameter calculated from experiments
  - plenty of measurements the past decade
  - final states (so far) include jets, photons, EW bosons and quarkonia!

Review of DPS/TPS measurements

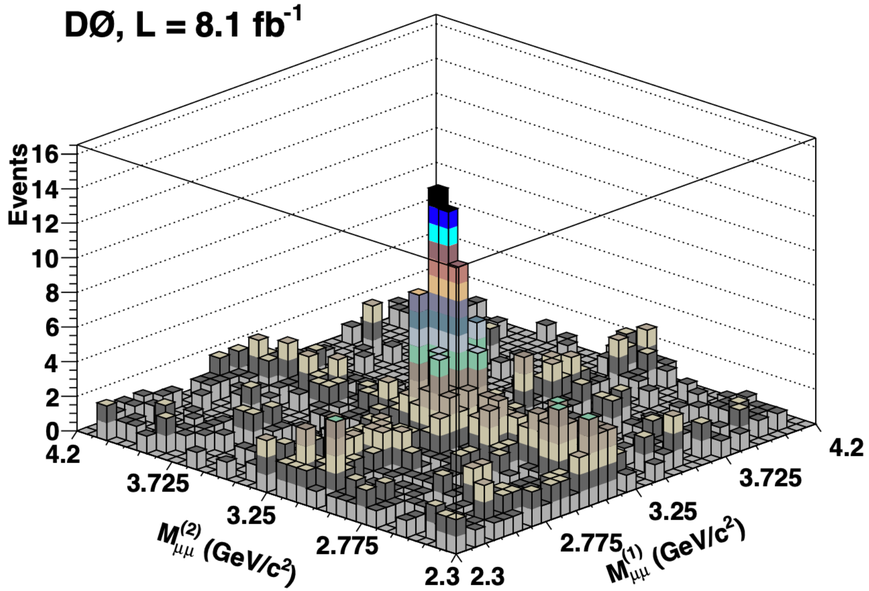
D0 - $\sqrt{s}$ = 1.96 TeV - J/ψ+J/ψ

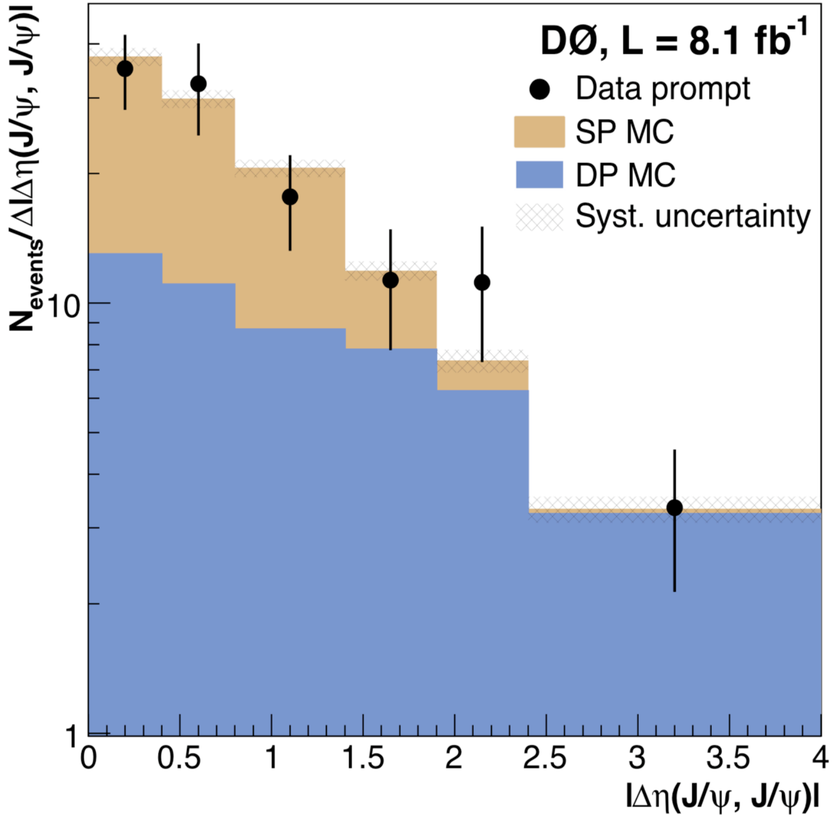
Phys. Rev. D 90 (2014) 11, 111101

- First measurement using quarkonia
- Fit the |Δη| distribution to separate SPS and DPS components
  - templates based on simulation
  - f^{DP} = 0.42 ± 0.12
- Use of pocket formula

$$\sigma_{\mathrm{eff}} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\mathrm{DP}}(J/\psi J/\psi)}$$

- $\sigma_{eff,DPS}$ = 4.8 ± 0.5 (stat) ± 2.5 (syst) mb



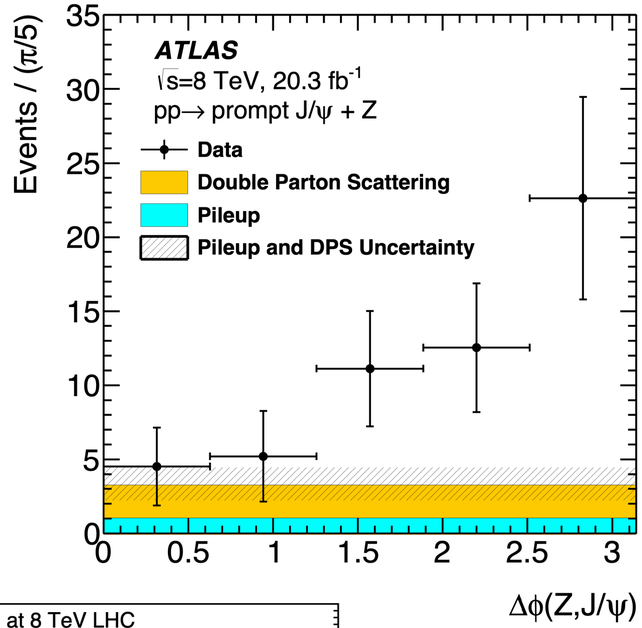


Review of DPS/TPS measurements

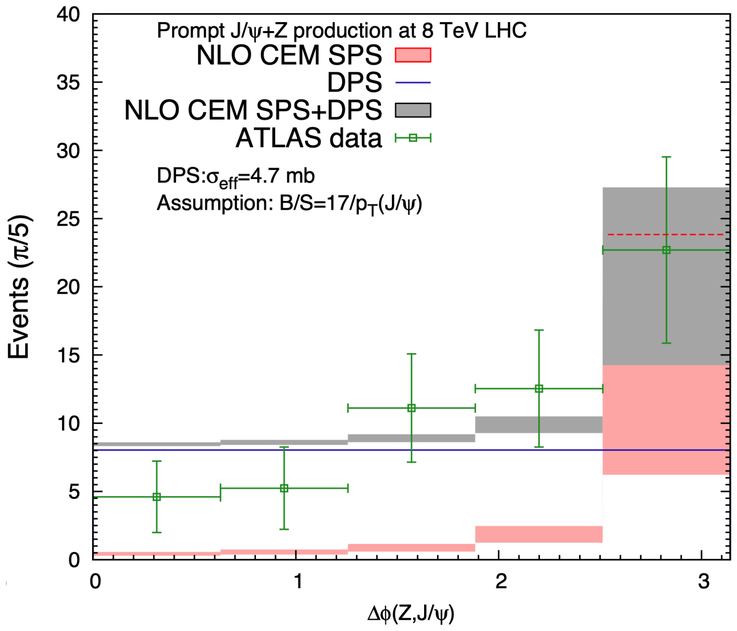
ATLAS - $\sqrt{s}$ = 8 TeV - J/ψ+Z

Eur. Phys. J. C 75 (2015) 5, 229

- Variable of choice is the Δφ(Z,J/ψ)
- Use prompt J/ψ+Z data where estimated signal contribution from DPS is largest wrt b→J/ψ+Z
- Assuming all observed signal in the first bin is purely from DPS
  - data fluctuated obtaining the lowest limit that the data can hold
  - $\sigma_{eff,DPS}$ > 5.3 mb at 68% confidence level



- Interpretation of results from Lansberg Phys. Rept. 889 (2020) 1
  - fitting the $\sigma_{eff,DPS}$ to the inclusive yield after subtracting the SPS cross section
  - $\sigma_{eff,DPS} = 4.7\ ^{+2.4}_{-1.5}$ mb

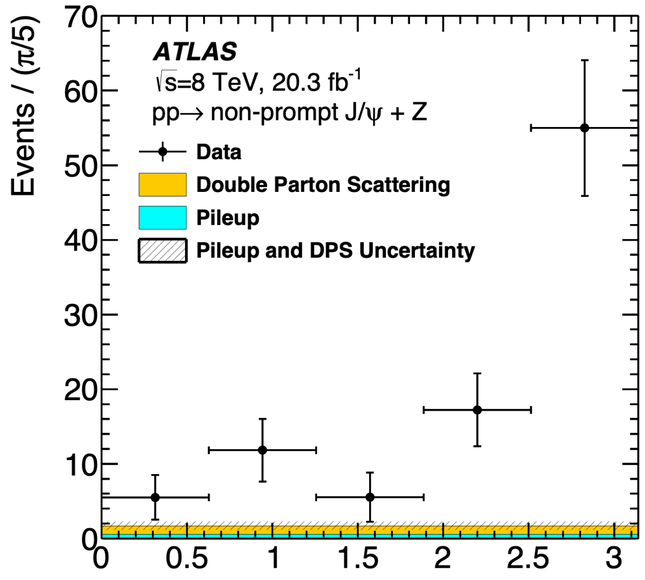


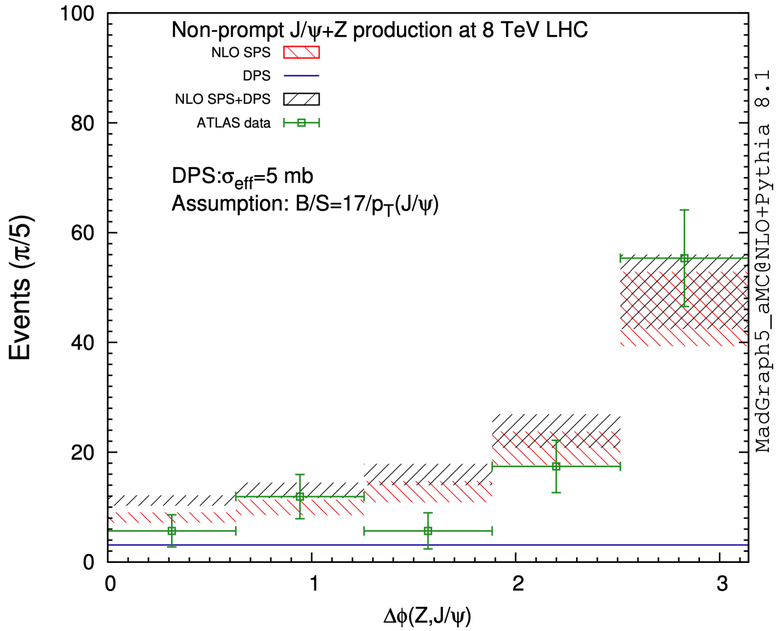
Review of DPS/TPS measurements

ATLAS - $\sqrt{s}$ = 8 TeV - b→J/ψ+Z

Nucl. Phys. B 916 (2017) 132

- Interpretation of results from Lansberg and Shao
- Upper limit using computed and measured cross sections
  - $\sigma_{eff,DPS}$ > 5.0 mb at 68% confidence level





Review of DPS/TPS measurements

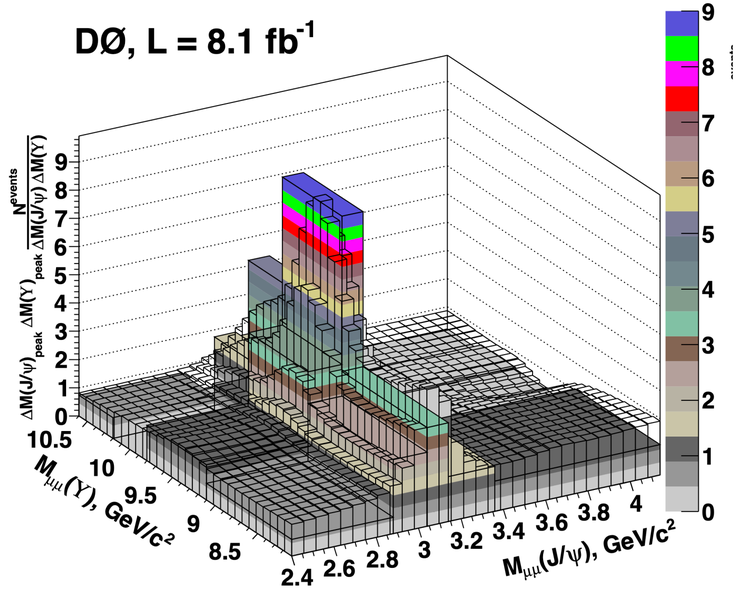
D0 - $\sqrt{s}$ = 1.96 TeV - J/ψ+Υ

Phys. Rev. Lett. 116 (2016) 8, 082002

- Use of pocket formula

$$\sigma_{\text{eff}} = \frac{\sigma(J/\psi)\sigma(\Upsilon)}{\sigma_{\text{DP}}(J/\psi + \Upsilon)}$$

- Assumption that SPS contribution is negligible
  - $\sigma_{\text{eff,DPS}}$ = 2.2 ± 0.7 (stat) ± 0.9 (syst) mb



- Interpretation of results from Shao and Zhang Phys. Rev. Lett. 117 (2016) 6, 062001
  - "even though the SPS contributions are small, they are not completely negligible"
  - $\sigma_{\text{eff,DPS}}$ <= 8.2 mb at 68% confidence level

- Thesis approved by CMS using 8 TeV on the J/ψ+Υ(1S) associated production
  - no $\sigma_{\text{eff,DPS}}$ estimation
  - σ(J/ψ+Υ) is measured to be 16.5 ± 3.6 (stat) ± 2.6 (syst) pb

Review of DPS/TPS measurements

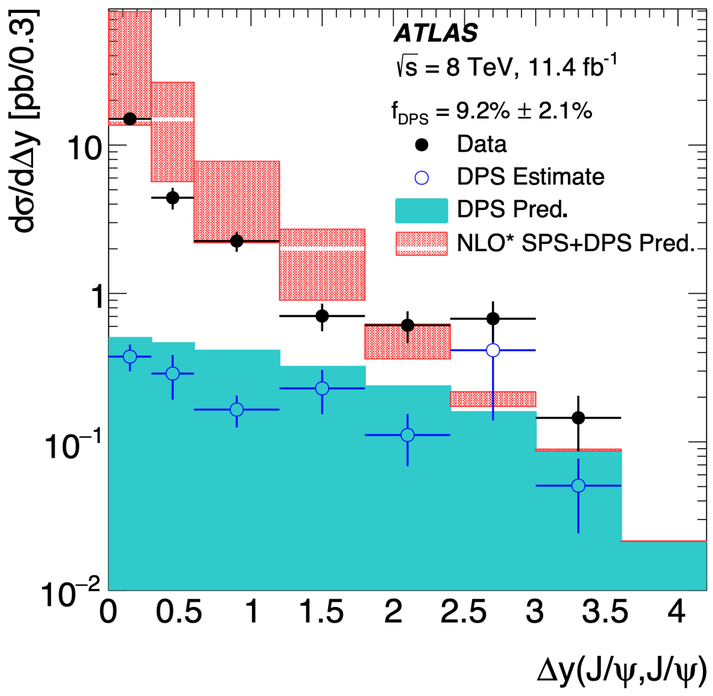
ATLAS - $\sqrt{s}$ = 8 TeV - J/ψ+J/ψ

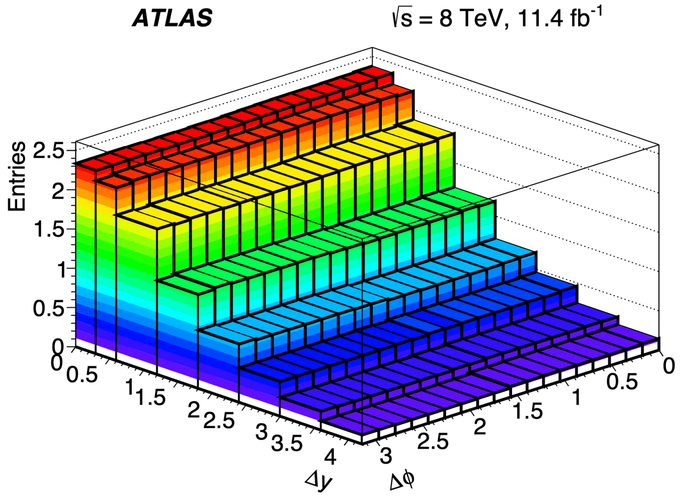
Eur. Phys. J. C 77 (2017) 2, 76

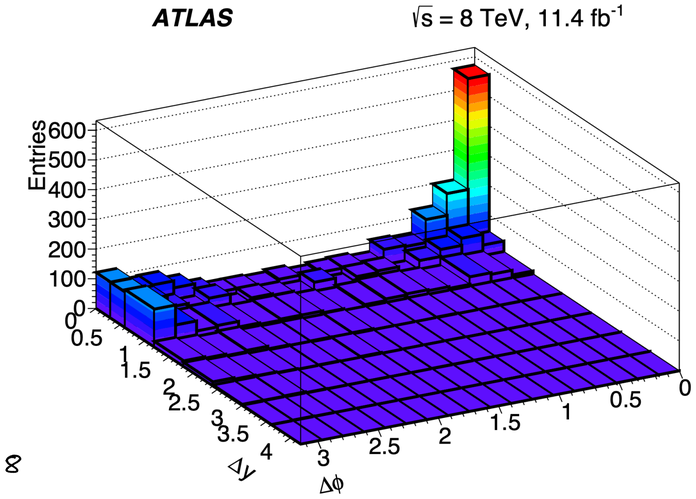
- Use of pocket formula

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\text{DPS}}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{f_{\text{DPS}} \times \sigma_{J/\psi J/\psi}}$$

  - f_{DPS} the fraction of di-J/ψ DPS events (9.2 ± 2.1 (stat) ± 0.5 (syst) %)
- Fit DPS and SPS templates to Δy variable to extract f_{DPS}
  - DPS templates: event combinatorics
    - normalisation in DPS enriched region (Δy>=1.8 and Δφ<=π/2)
    - shape agrees with MC simulated sample
  - SPS templates: subtract the DPS templates from data
  - $\sigma_{eff,DPS}$ = 6.3 ± 1.6 (stat) ± 1.0 (syst) ± 0.1 (BF) ± 0.1 (lumi) mb







Review of DPS/TPS measurements

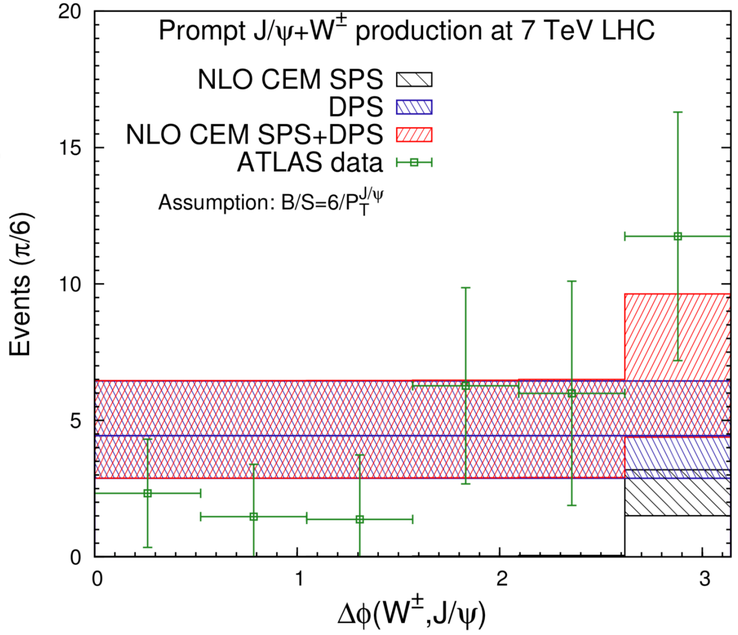
ATLAS - $\sqrt{s}$ = 7 TeV - J/ψ+W

Phys. Lett. B 781 (2018) 485

- Interpretation of results from Lansberg, Shao and Yamanaka
- Use of pocket formula

$$d\sigma^{\mathrm{DPS}}(J/\psi + W) = \frac{d\sigma(J/\psi)d\sigma(W)}{\sigma_{\mathrm{eff}}}$$

- Calculate the cross section of SPS and use the measured ATLAS total cross section
- $\sigma_{\mathrm{eff,DPS}}$ = 6.1 $^{+3.3}_{-1.9}$ (exp) $^{+0.1}_{-0.3}$ (theo) mb



- ATLAS updated their result with the 8 TeV dataset, but no $\sigma_{\mathrm{eff,DPS}}$ is extracted JHEP 01 (2020) 095

- Similarly to the J/ψ+Z case, the DPS distribution shows a small tension wrt the data points
  - effects contributing to that can be the difference in acceptance between high/low p_T objects and the different SPS/DPS ratios as a function of the J/ψ p_T

Review of DPS/TPS measurements

CMS - $\sqrt{s}$ = 7 TeV - J/ψ+J/ψ

Phys. Rept. 889 (2020) 1

- Interpretation of results from Lansberg
- Using theoretical calculations for SPS and the pocket formula
  - $\sigma_{eff,DPS}$ = 8.2 ± 2.0 (stat) ± 2.9 (templates) mb

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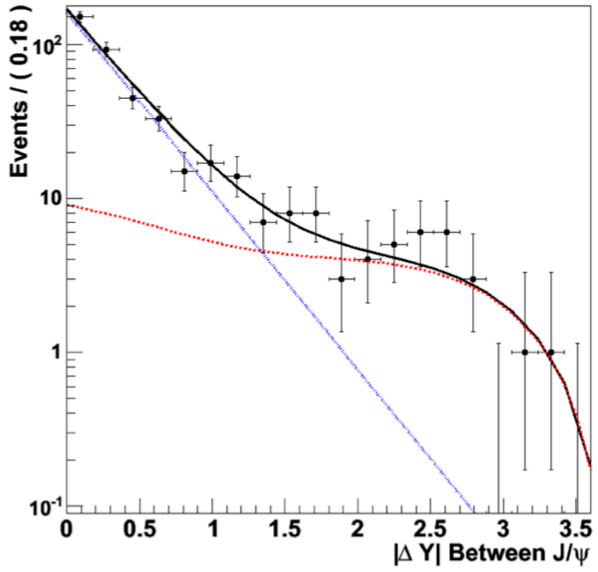
- Thesis approved by CMS uses 8 TeV
  - variable used is |Δy| to calculate the DPS di-J/ψ cross section
    - DPS template from event mixing
    - SPS template from MC
  - using pocket formula

$$\sigma_{eff} = \frac{1}{2}\frac{\sigma J/\psi^2}{\sigma^{DPS}_{J/\psi J/\psi}}$$

  - $\sigma_{eff,DPS}$ = 4.6 ± 0.7 (stat) ± 0.8 (syst) ± 0.2 (lumi) mb



Review of DPS/TPS measurements

DPS summary

- DPS effective cross section:
  - ~5 mb using quarkonia in final states
- Difference with respect to
  - 10-20 mb using jets, photons, EW bosons
  - 20-30 mb expected from pythia8/herwig
- The spread of values could be caused by
  - parton correlations in the collision neglected in the purely geometric approach
  - different dominant species in the parton distribution functions
  - poorly controlled subtractions of SPS contributions

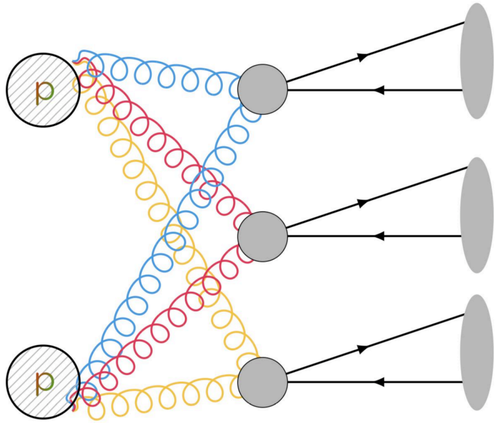
Review of DPS/TPS measurements

TPS introduction

- First appearance of Triple Parton Scattering in theory in the 10s
- TPS is a proton-proton scattering process where three partons from each proton interact separately
- TPS cross section can be expressed as:

$$\sigma^{\mathrm{TPS}}_{hh'\to abc} = \frac{m}{3!}\sum_{i,j,k,l,m,n}\int \Gamma^{ijk}_{h}(x_1,x_2,x_3;\mathbf{b_1},\mathbf{b_2},\mathbf{b_3};Q_1^2,Q_2^2,Q_3^2)$$
$$\times\hat{\sigma}^{il}_{a}(x_1,x_1',Q_1^2)\hat{\sigma}^{jm}_{b}(x_2,x_2',Q_2^2)\hat{\sigma}^{kn}_{c}(x_3,x_3',Q_3^2)$$
$$\times\Gamma^{lmn}_{h'}(x_1',x_2',x_3';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b},\mathbf{b_3}-\mathbf{b};Q_1^2,Q_2^2,Q_3^2)$$
$$\times dx_1dx_2dx_3dx_1'dx_2'dx_3'd^2b_1d^2b_2d^2b_3d^2b$$

d'Enterria and Snigirev
Phys. Rev. Lett. 118 (2017) 12, 122001



- Ignoring any correlations between the individual partons (m=1,3 or 6 according to whether ψ_1, ψ_2, ψ_3 are the same or not):

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

- $\sigma_{\mathrm{eff,TPS}}$ holds the effects of the transversity
  - is related to with DPS effective cross section - $\sigma_{\mathrm{eff,TPS}} = (0.82 \pm 0.11)\,\sigma_{\mathrm{eff,DPS}}$
  - first study of TPS done with quarkonia

Review of DPS/TPS measurements

Triple J/ψ production - golden channel for studying DPS and TPS

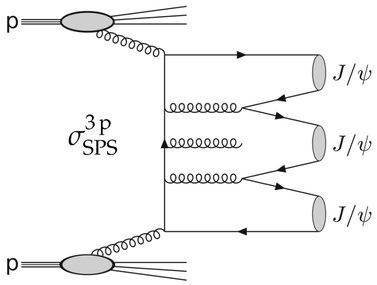
$$\sigma_{\text{tot}}^{3J/\psi} = \sigma_{\text{SPS}}^{3J/\psi} + \sigma_{\text{DPS}}^{3J/\psi} + \sigma_{\text{TPS}}^{3J/\psi}$$

6% 74% 20%

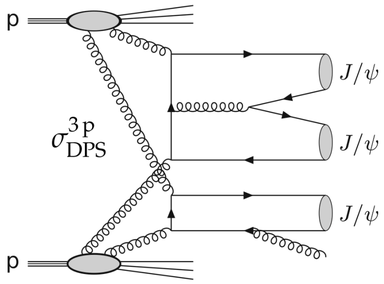
Shao and Zhang
Phys. Rev. Lett. 122 (2019) 19, 192002

Pure prompt production:

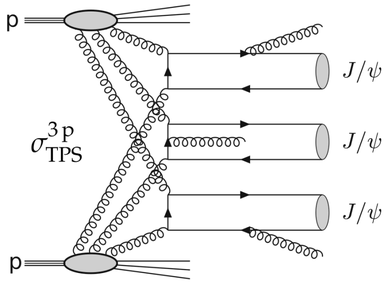
SPS:



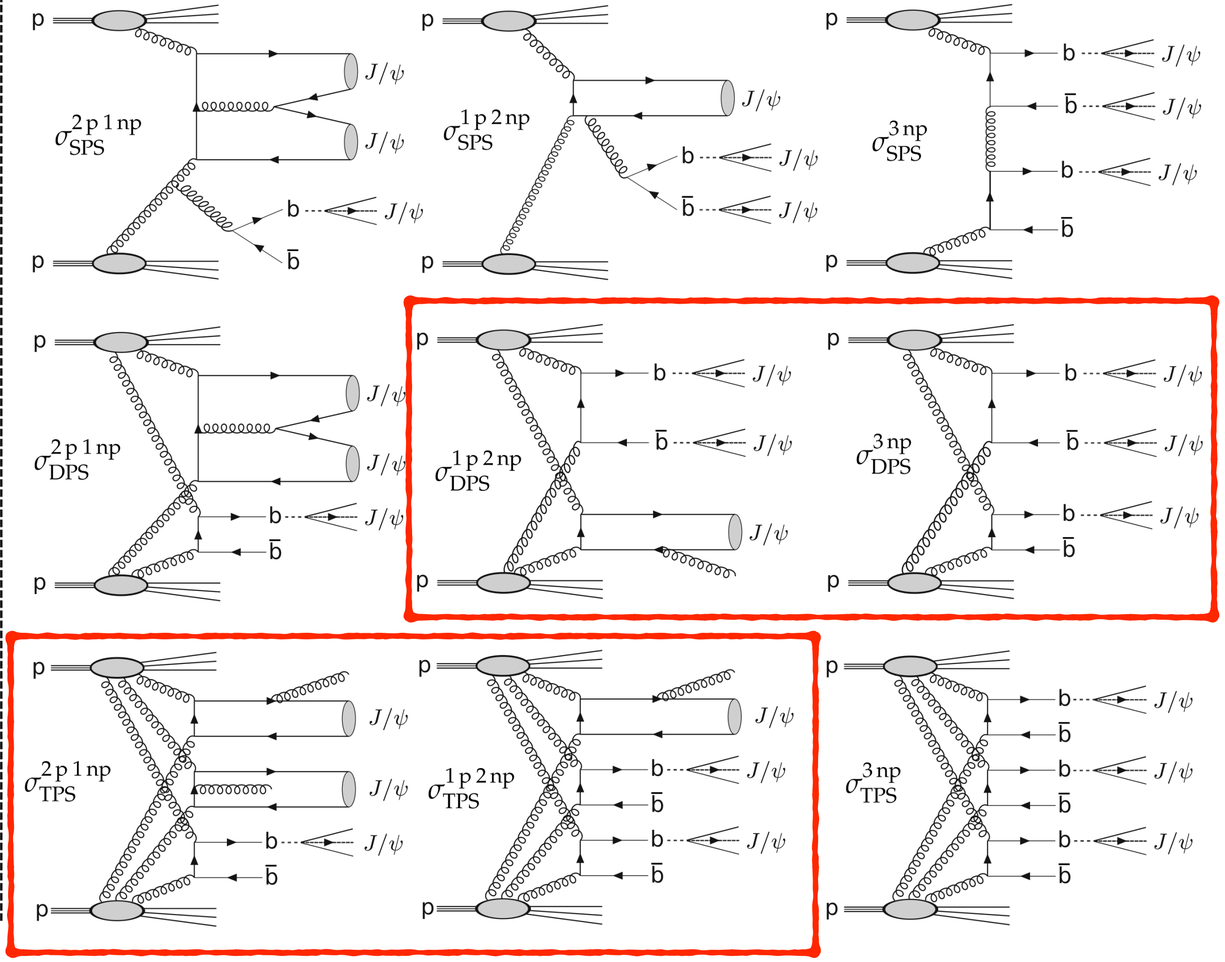
DPS:



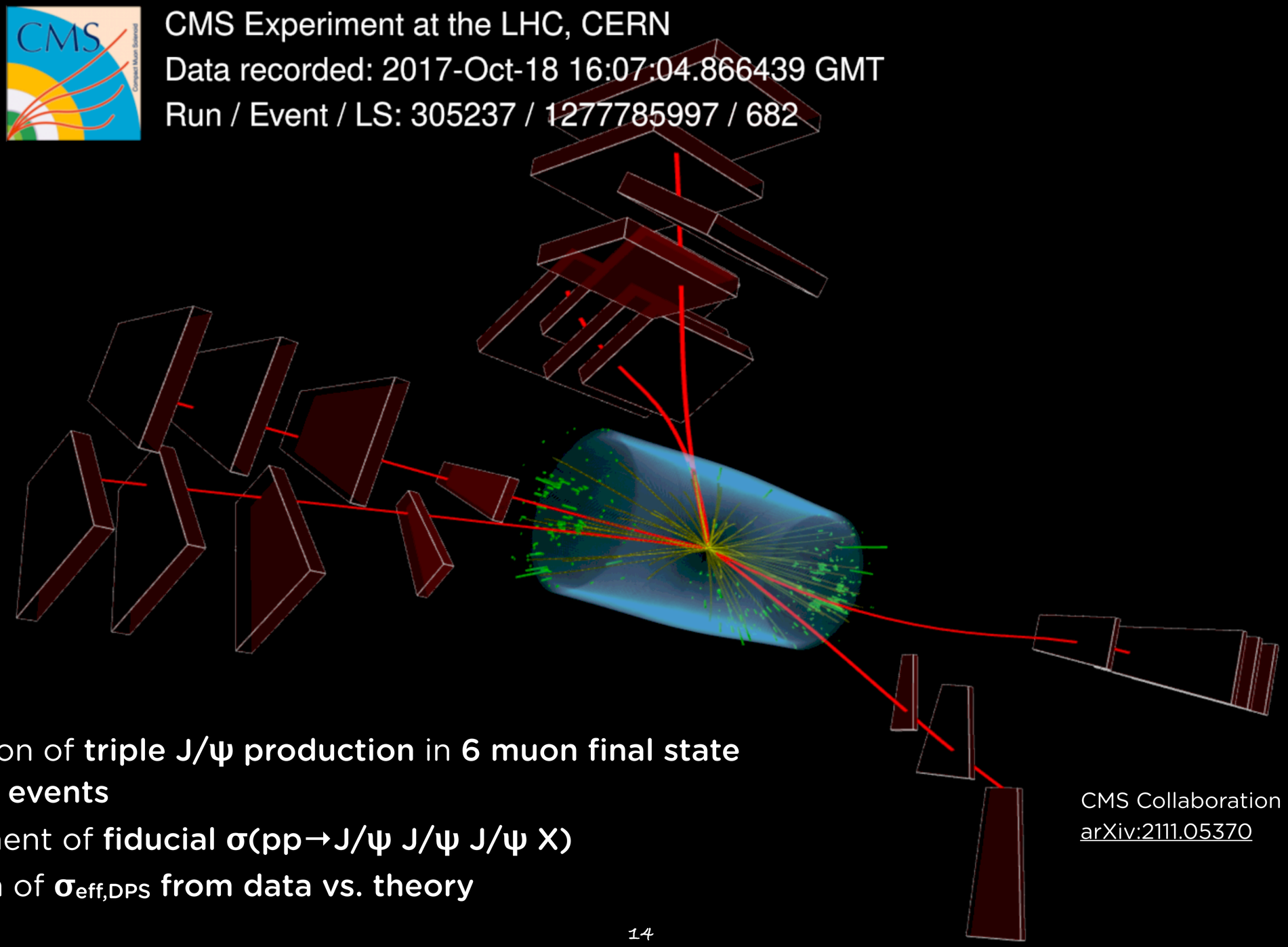
TPS:



Nonprompt contributions:



Dominant contributions



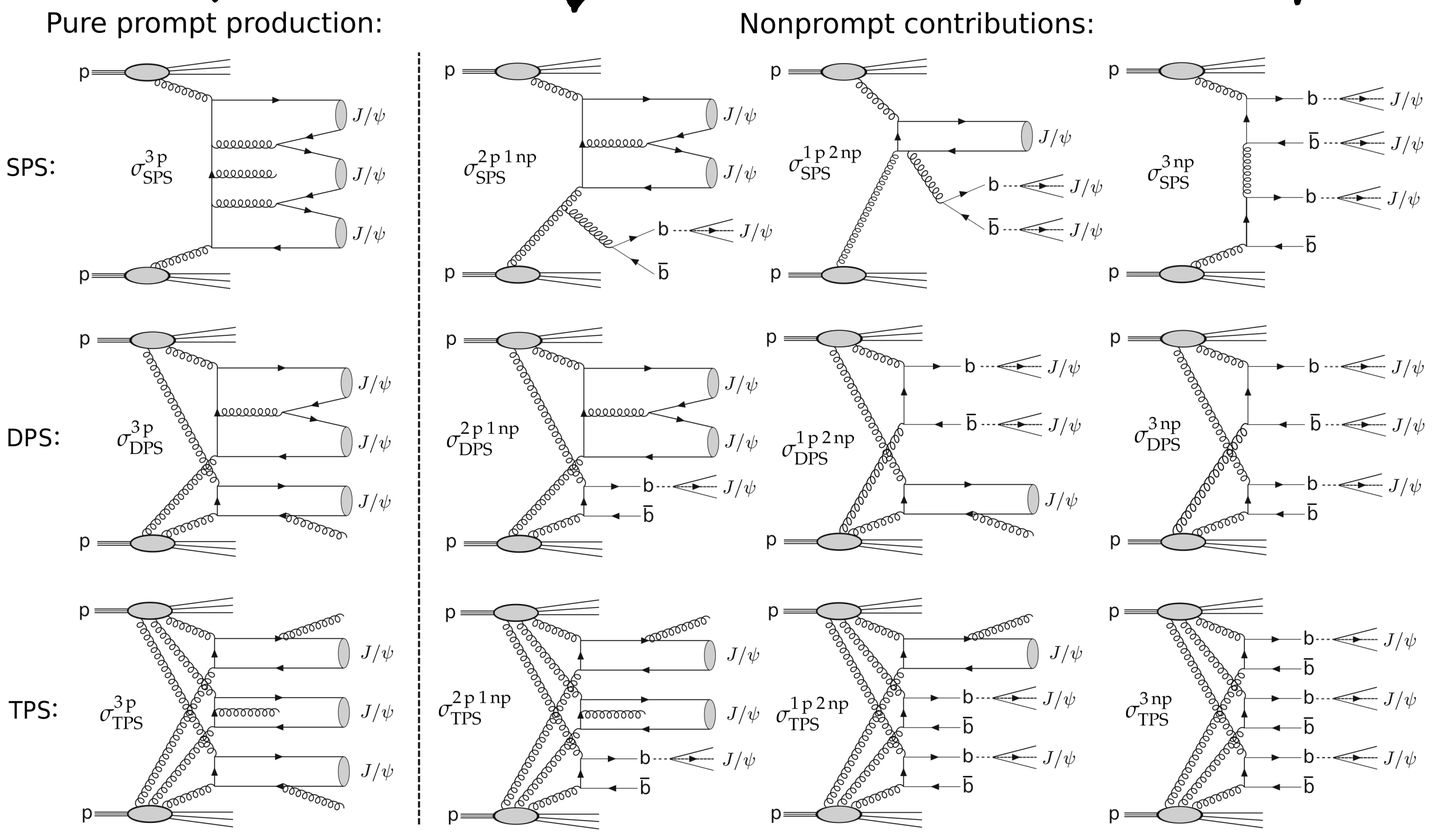
- Observation of **triple J/ψ production** in **6 muon final state**
  - **5 signal events**
- Measurement of **fiducial σ(pp→J/ψ J/ψ J/ψ X)**
- Extraction of **$\sigma_{eff,DPS}$ from data vs. theory**

CMS Collaboration
arXiv:2111.05370

Review of DPS/TPS measurements

DPS effective cross section measurement

- J/ψ mesons are classified as prompt or nonprompt based on the pseudo-proper decay length
  - 1 event: 3 nonprompt
  - 2 events: 2 nonprompt + 1 prompt
  - 1 event: 1 nonprompt + 2 prompt
  - 1 event: 3 prompt



Review of DPS/TPS measurements

DPS effective cross section measurement

- The theoretical total triple-J/ψ cross section is expressed in terms of SPS/DPS/TPS and prompt/nonprompt components

$$\begin{aligned}\sigma_{\text{tot}}^{3\text{J}/\psi} &= \sigma_{\text{SPS}}^{3\text{J}/\psi} + \sigma_{\text{DPS}}^{3\text{J}/\psi} + \sigma_{\text{TPS}}^{3\text{J}/\psi} \\ &= \left(\sigma_{\text{SPS}}^{3\text{p}} + \sigma_{\text{SPS}}^{2\text{p}1\text{np}} + \sigma_{\text{SPS}}^{1\text{p}2\text{np}} + \sigma_{\text{SPS}}^{3\text{np}}\right) \\ &\quad + \left(\sigma_{\text{DPS}}^{3\text{p}} + \sigma_{\text{DPS}}^{2\text{p}1\text{np}} + \sigma_{\text{DPS}}^{1\text{p}2\text{np}} + \sigma_{\text{DPS}}^{3\text{np}}\right) + \left(\sigma_{\text{TPS}}^{3\text{p}} + \sigma_{\text{TPS}}^{2\text{p}1\text{np}} + \sigma_{\text{TPS}}^{1\text{p}2\text{np}} + \sigma_{\text{TPS}}^{3\text{np}}\right)\end{aligned}$$

- Can be re-written as

$$\sigma_{\text{DPS}}^{3\text{J}/\psi} = \frac{\mathfrak{m}_1 \left(\sigma_{\text{SPS}}^{2\text{p}}\sigma_{\text{SPS}}^{1\text{p}} + \sigma_{\text{SPS}}^{2\text{p}}\sigma_{\text{SPS}}^{1\text{np}} + \sigma_{\text{SPS}}^{1\text{p}}\sigma_{\text{SPS}}^{1\text{p}1\text{np}} + \sigma_{\text{SPS}}^{1\text{p}1\text{np}}\sigma_{\text{SPS}}^{1\text{np}} + \sigma_{\text{SPS}}^{1\text{p}}\sigma_{\text{SPS}}^{2\text{np}} + \sigma_{\text{SPS}}^{2\text{np}}\sigma_{\text{SPS}}^{1\text{np}}\right)}{\sigma_{\text{eff,DPS}}}, \quad \text{and}$$

$$\sigma_{\text{TPS}}^{3\text{J}/\psi} = \frac{\mathfrak{m}_3 \left(\left(\sigma_{\text{SPS}}^{1\text{p}}\right)^3 + \left(\sigma_{\text{SPS}}^{1\text{np}}\right)^3\right) + \mathfrak{m}_2 \left(\left(\sigma_{\text{SPS}}^{1\text{p}}\right)^2 \sigma_{\text{SPS}}^{1\text{np}} + \sigma_{\text{SPS}}^{1\text{p}} \left(\sigma_{\text{SPS}}^{1\text{np}}\right)^2\right)}{\sigma_{\text{eff,TPS}}^2},$$

- with m_1=1, m_2=1/2 and m_3=1/6, SPS cross sections and DPS and TPS effective cross sections

Review of DPS/TPS measurements

DPS effective cross section measurement

- Theoretical single-, double-, and triple-J/ψ SPS cross sections from HELAC-ONIA(data-based, LO, NLO*) +PYTHIA8, MG5@NLO+PYTHIA8 are fitted to the experimental cross-section

SPS single-J/ψ production		SPS double-J/ψ production			SPS triple-J/ψ production			
HO(DATA)	MG5NLO+PY8	HO(NLO*)	HO(LO)+PY8	MG5NLO+PY8	HO(LO)	HO(LO)+PY8	HO(LO)+PY8	MG5NLO+PY8
σ^{1p}_{SPS}	σ^{1np}_{SPS}	σ^{2p}_{SPS}	σ^{1p1np}_{SPS}	σ^{2np}_{SPS}	σ^{3p}_{SPS}	σ^{2p1np}_{SPS}	σ^{1p2np}_{SPS}	σ^{3np}_{SPS}
570 ± 57 nb	600^{+130}_{-220} nb	40^{+80}_{-26} pb	24^{+35}_{-16} fb	430^{+95}_{-130} pb	< 5 ab	$5.2^{+9.6}_{-3.3}$ fb	14^{+17}_{-8} ab	12 ± 4 fb

- Free parameter is the $\sigma_{eff,DPS}$

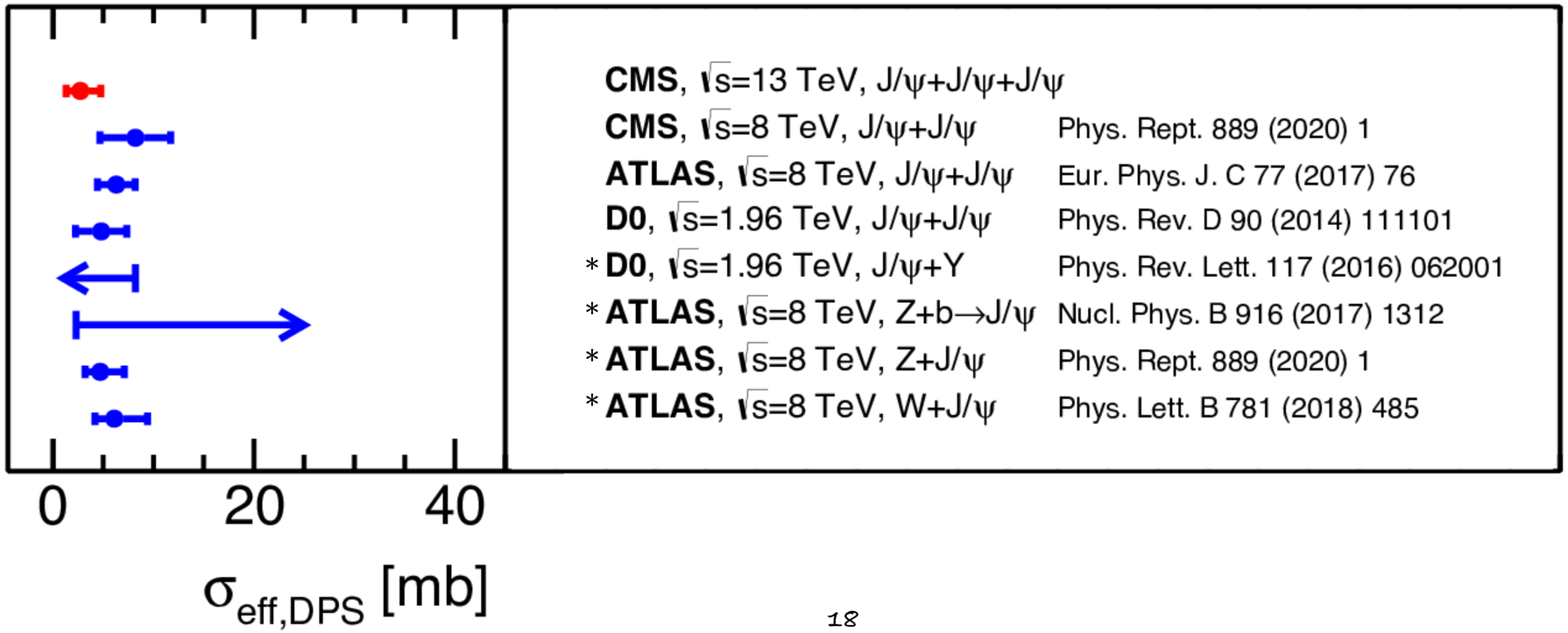
Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	Total
$\sigma^{3J/\psi}_{SPS}$ (fb)	< 0.005	5.7	0.014	12	18
$N^{3J/\psi}_{SPS}$	0.0	0.10	0.0	0.22	0.32
$\sigma^{3J/\psi}_{DPS}$ (fb)	8.4	8.9	90	95	202
$N^{3J/\psi}_{DPS}$	0.15	0.16	1.65	1.75	3.7
$\sigma^{3J/\psi}_{TPS}$ (fb)	6.1	19.4	20.4	7.2	53
$N^{3J/\psi}_{TPS}$	0.11	0.36	0.38	0.13	1.0
$\sigma^{3J/\psi}_{tot}$ (fb)	15	34	110	114	272
$N^{3J/\psi}_{tot}$	0.3	0.6	2.0	2.1	5.0

- $\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}$ (exp) $^{+1.5}_{-1.0}$ (theo) mb

Review of DPS/TPS measurements

Summary

- Many DPS measurements with quarkonia
  - good progress in understanding and interpreting the results
  - still a lot of processes to be investigated
- Run-2 gave a large dataset that can be exploited to probe TPS
  - first study with triple J/ψ meson production
  - triple parton scattering cross sections are small but rise fast with $\sqrt{s}$
    - will become very relevant in the future



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Observation of triple J/ψ meson production

Introduction

σ(pp→J/ψ J/ψ J/ψ X) = Mix of **pp→J/ψ (prompt) & pp→b→J/ψ (nonprompt)** mostly **DPS+TPS** processes:

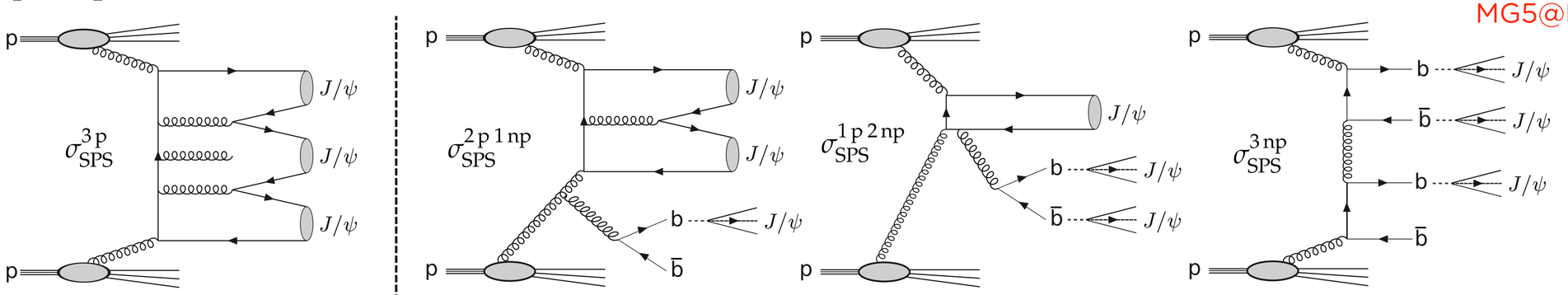
HELACONIA + MG5@NLO + PYTHIA8

Pure prompt:

Nonprompt contributions:

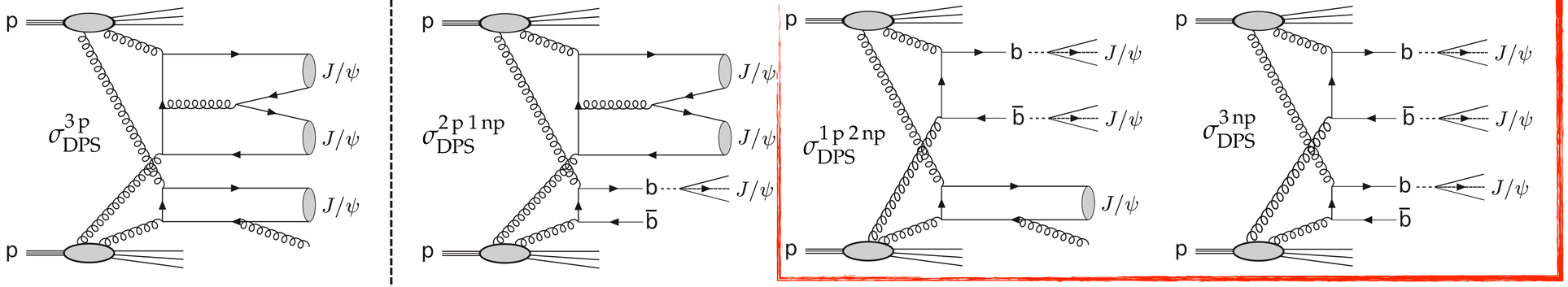
~5% of total cross section

SPS:



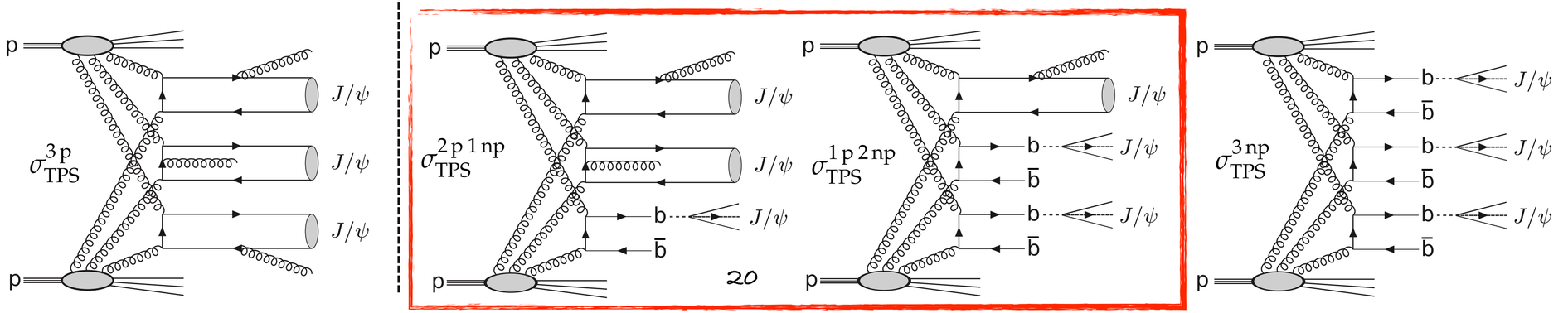
~75% of total cross section

DPS:



~20% of total cross section

TPS:



Observation of triple J/ψ meson production

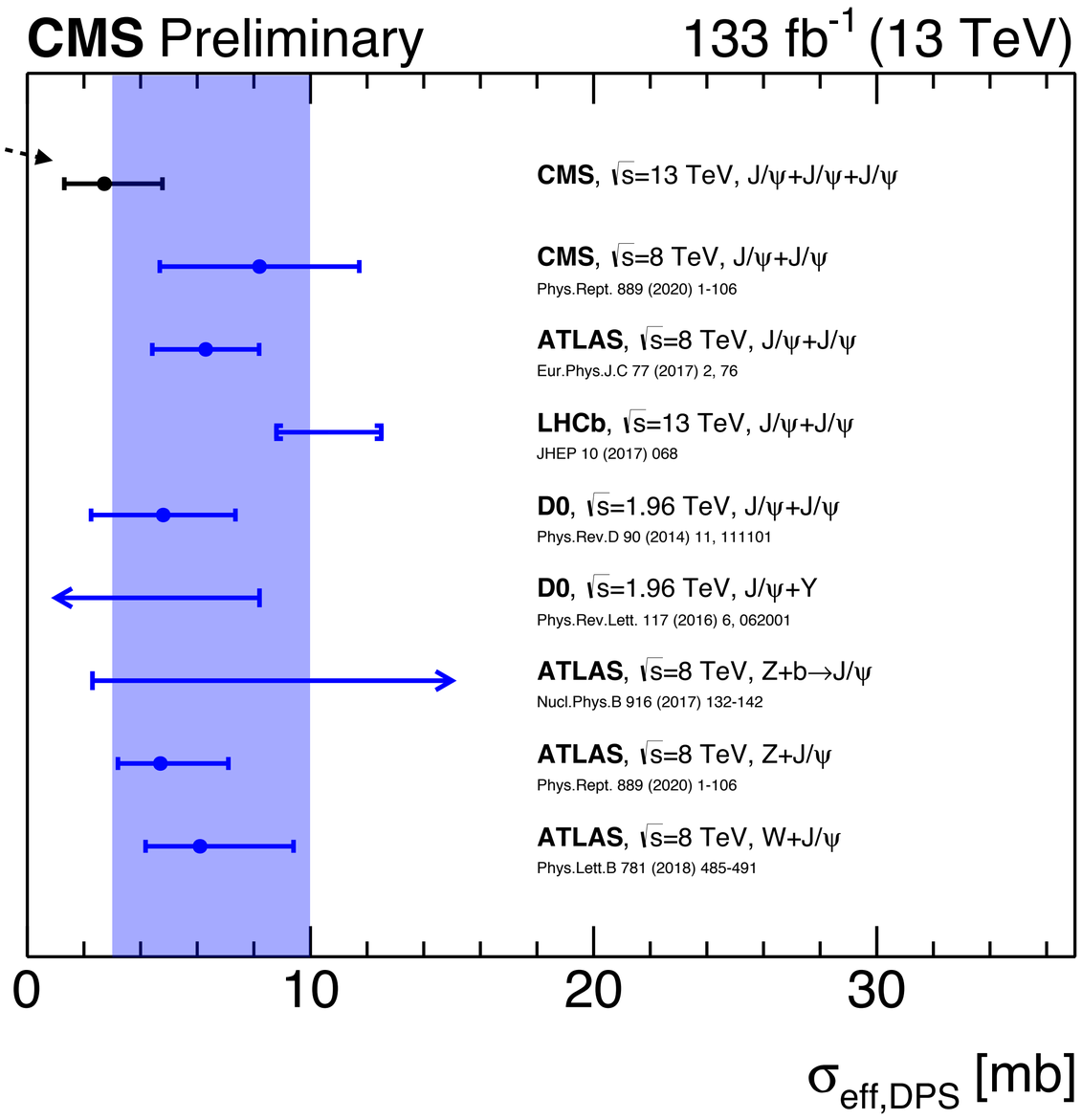
Discussion of the results

- Derived $\sigma_{eff,DPS}$ is found to amount to:

$\sigma_{eff,DPS}$ = 2.7 $^{+1.4}_{-1.0}$ (exp) $^{+1.5}_{-1.0}$ (theo) mb

- The expected contributions from SPS, DPS, TPS processes amount to about
  - SPS: 6%, DPS: 74%, TPS: 20%
  - (confirming that triple-J/ψ is an excellent process to study DPS/TPS)
- Derived $\sigma_{eff,DPS}$ value is consistent with the world-data of effective DPS cross sections obtained previously from di-quarkonium production measurements:

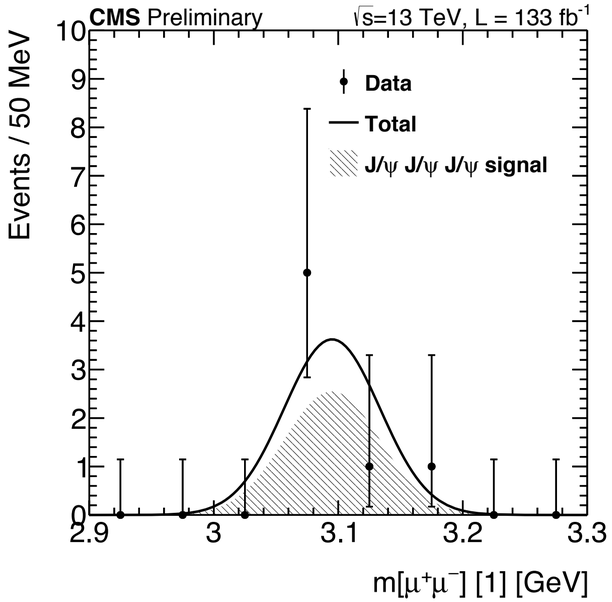
- $\sigma_{eff,DPS} \approx 3 - 10$ mb

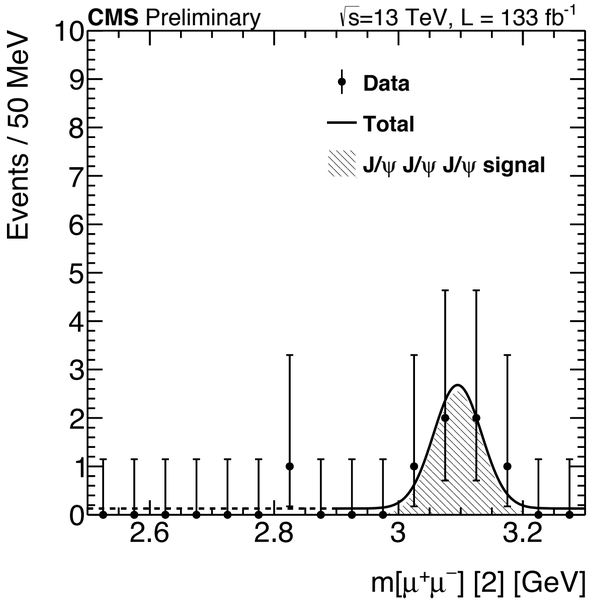


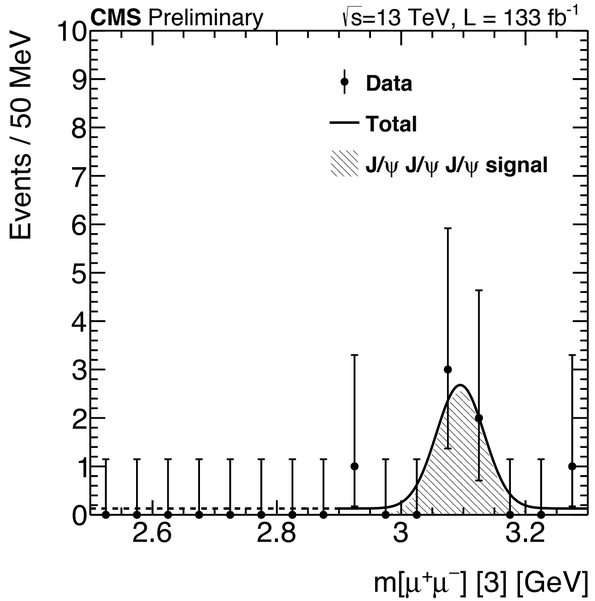
Observation of triple J/ψ meson production

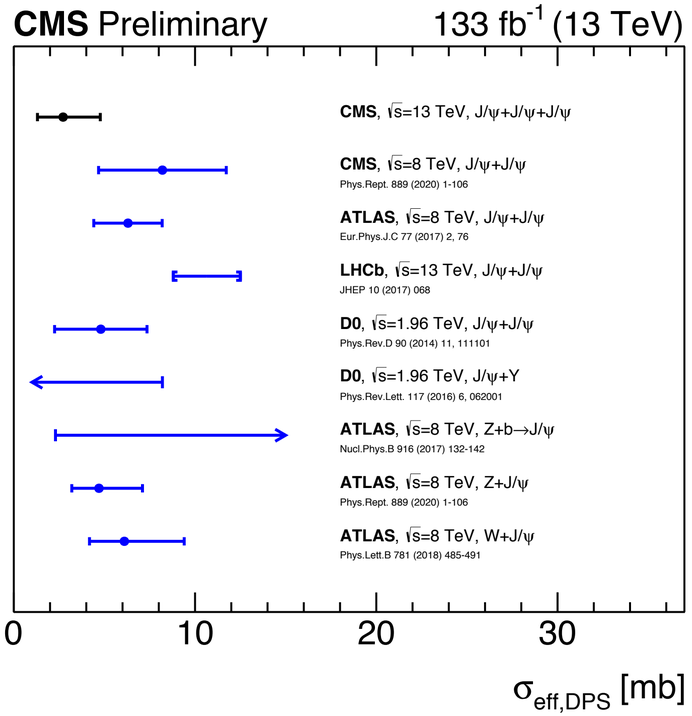
Summary

- **First observation** of triple J/ψ meson production using Run-2 data [CMS-PAS-BPH-21-004]
- Measurement of **fiducial cross section**
- $\sigma(pp \rightarrow J/\psi\ J/\psi\ J/\psi\ X) = 272\ ^{+141}_{-104}$ (stat) ± 17 (syst) fb
- ~6% SPS, ~74% DPS, ~20% TPS
- Extraction of $\boldsymbol{\sigma_{eff,DPS} = 2.7\ ^{+1.4}_{-1.0}}$ **(exp)** $^{+1.5}_{-1.0}$ **(theo) mb**, assuming that DPS and TPS cross sections can be expressed in terms of SPS single- and double-J/ψ cross sections (standard most economical, model-agnostic, assumption in the field)









Review of DPS/TPS measurements

Introduction

- Motivation for **multiple production of hard/heavy particles** studies:
  - study unknown energy evolution of **transverse (impact parameter b) proton shape**
  - probe **generalized PDFs (x,Q² and b)** of the proton
  - control **backgrounds for rare SM** resonance decays **& BSM** production of multiple heavy particles
- Studies so far focused on double-parton scatterings (DPS):
- "Pocket formula": $\sigma_{\mathrm{DPS}}^{\mathrm{pp}\to\psi_1\,\psi_2+X} = \left(\frac{m}{2}\right) \frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+X}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+X}}{\sigma_{\mathrm{eff,DPS}}}$
  - assuming no parton correlations, the effective cross section (**σ_{eff}**) is derivable from p-p transverse overlap
  - but measurements of **DPS σ_{eff}**:
    - **σ_{eff}** ~ 5 mb, from di-quarkonia final states
    - **σ_{eff}** ~ 15 mb, from jets, photons, EWK bosons
- Alternative: Study triple-parton scatterings (**TPS**).
  - process **never observed so far**
  - **$\sigma_{\mathrm{eff,TPS}}$ = (0.82 ± 0.11) $\sigma_{\mathrm{eff,DPS}}$** [PRL 118 (2017) 122001]
  - **triple prompt-J/ψ: DPS & TPS dominate** [PRL122 (2019) 192002]

PRL **118,** 122001 (2017) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2017

Triple Parton Scatterings in High-Energy Proton-Proton Collisions

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Triple Prompt J/ψ Hadroproduction as a Hard Probe of Multiple-Parton Scatterings

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Observation of triple J/ψ meson production

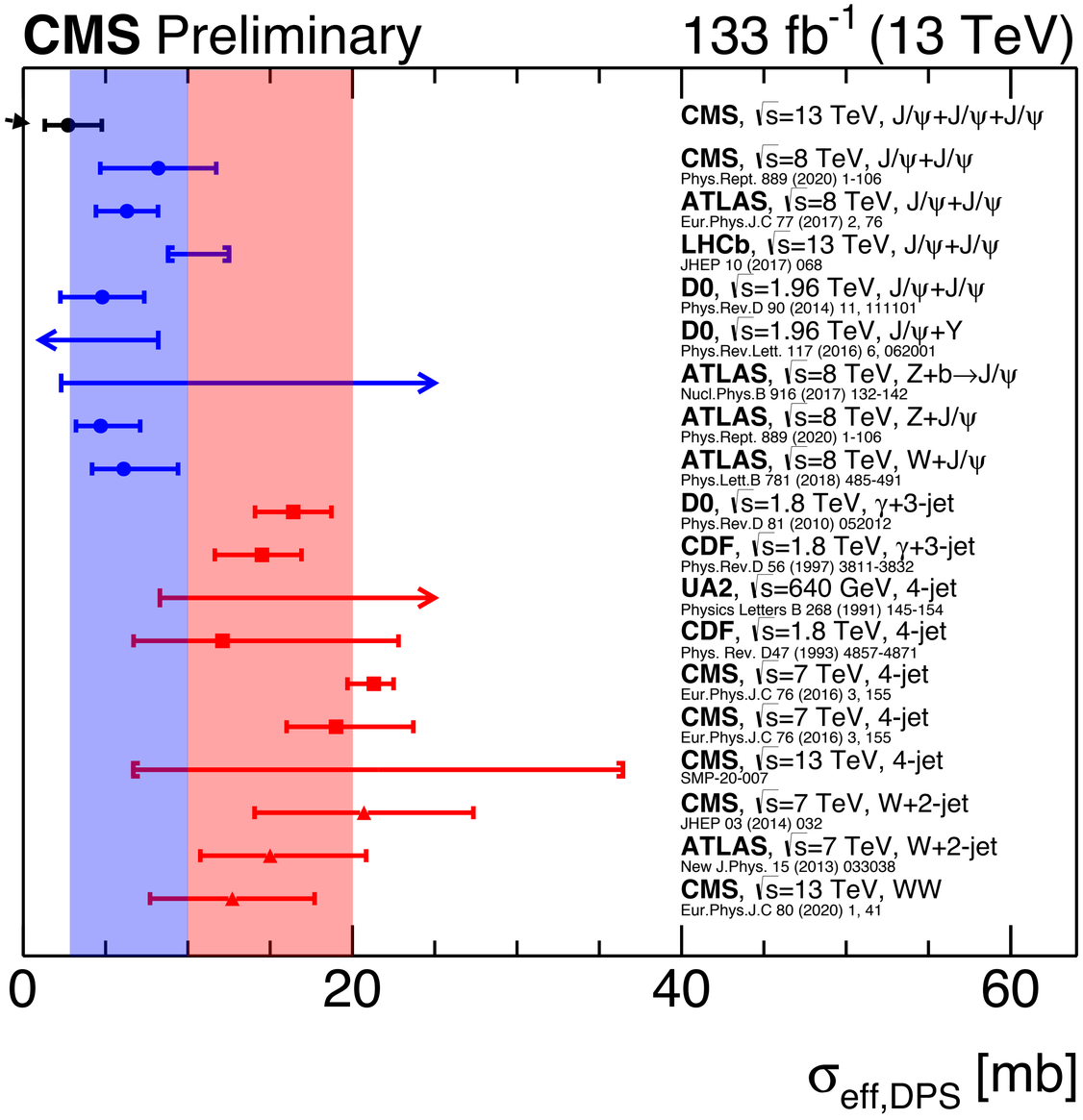
Discussion of the results

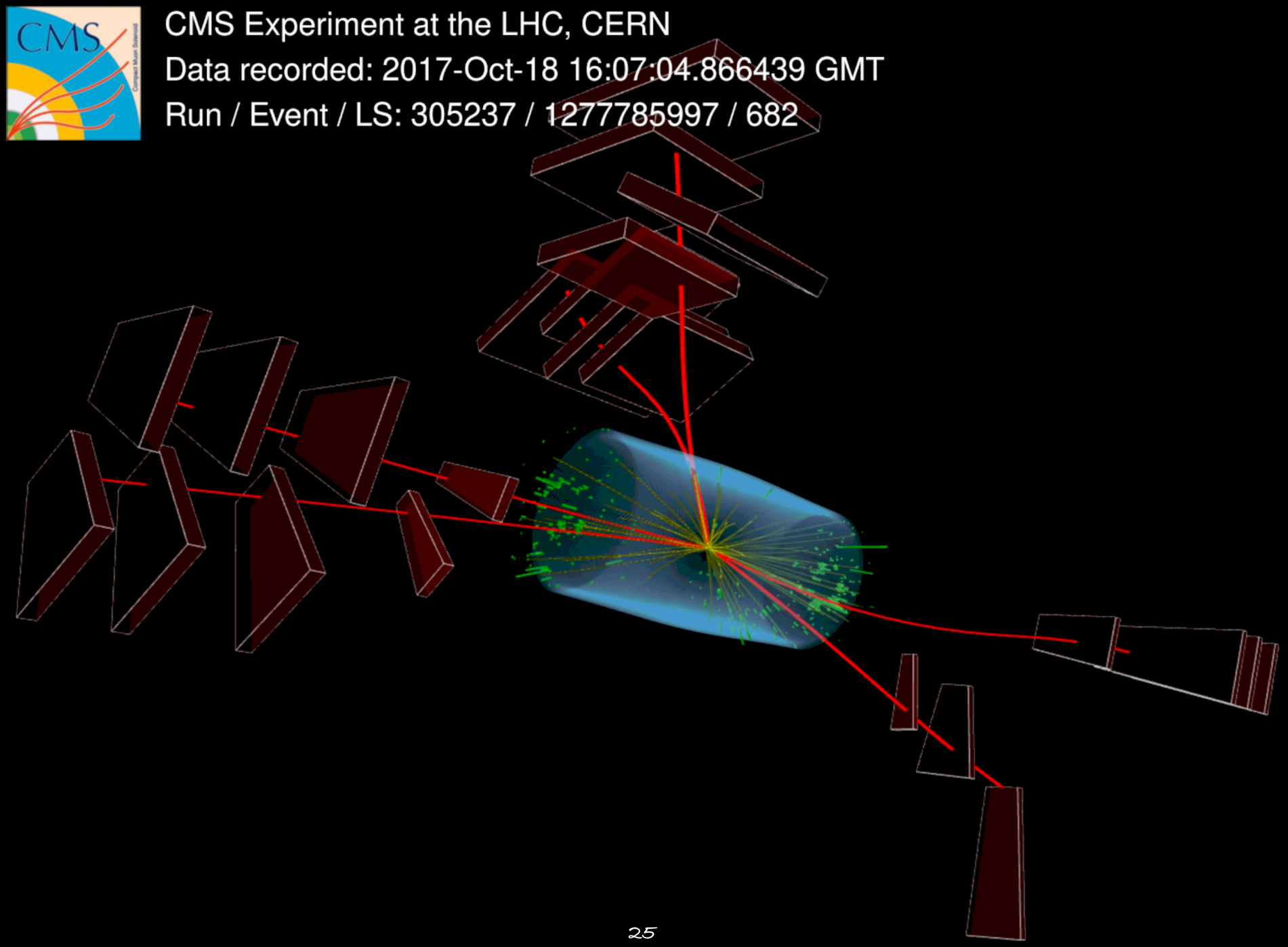
- Derived $\sigma_{eff,DPS}$ is found to amount to:

$\sigma_{eff,DPS}$ **= 2.7 $^{+1.4}_{-1.0}$ (exp) $^{+1.5}_{-1.0}$ (theo) mb**

- The expected contributions from SPS, DPS, TPS processes amount to about
  - SPS: 6%, DPS: 74%, TPS: 20%
  - (confirming that triple-J/ψ is an excellent process to study DPS/TPS)
- Derived $\sigma_{eff,DPS}$ value is consistent with the world-data of effective DPS cross sections obtained previously from di-quarkonium production measurements, but not consistent with extractions from processes with jets, photons, and W bosons:

- $\sigma_{eff,DPS} \approx 10 - 20$ mb




CMS Experiment at the LHC, CERN
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