Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s}$ = 13 TeV

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Observation of triple J/ψ meson production

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,Q^2 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]

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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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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:

Pure prompt:

Nonprompt contributions:

HELACONIA + MG5@NLO + PYTHIA8

~5% of total cross section

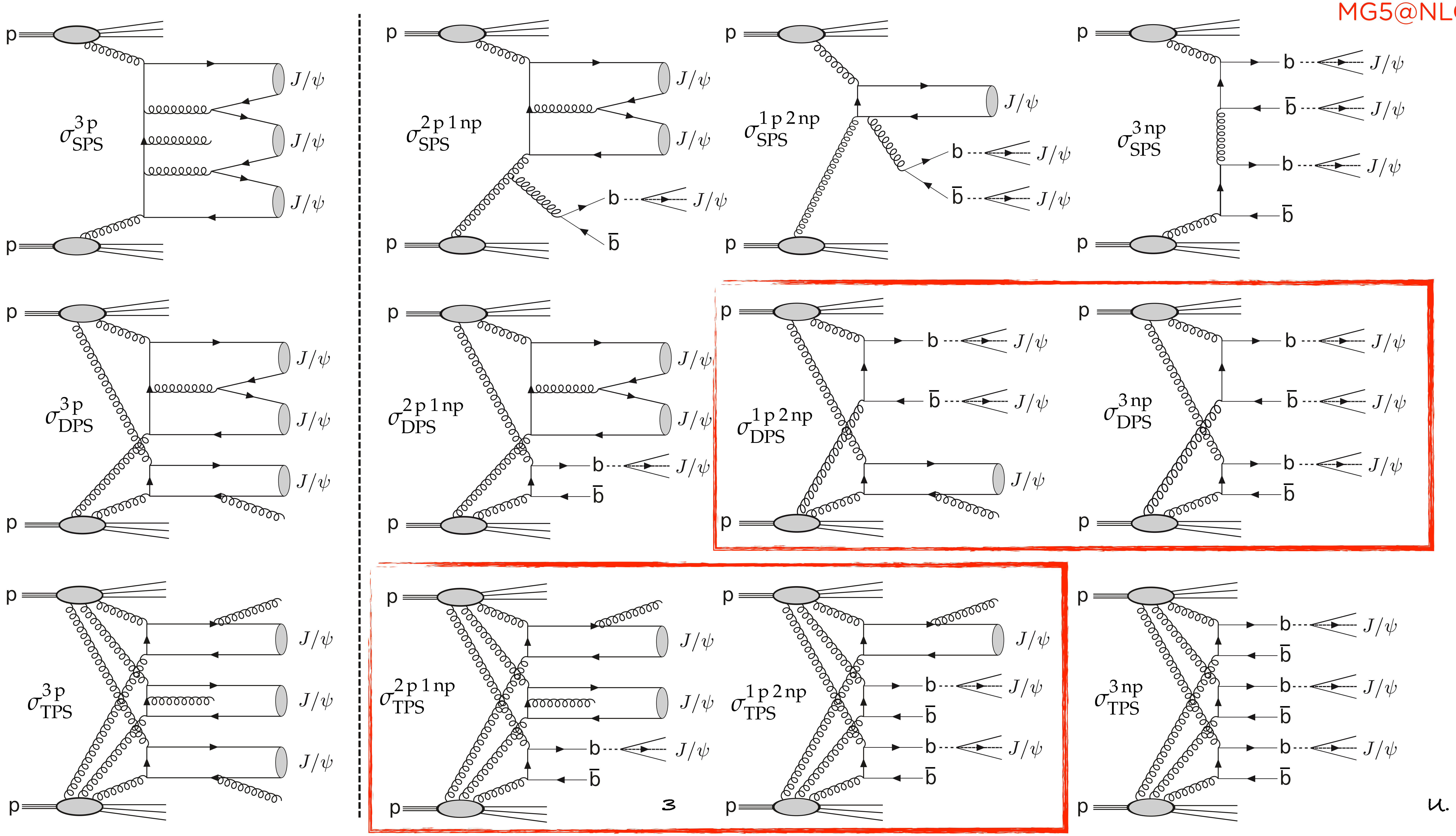
SPS:

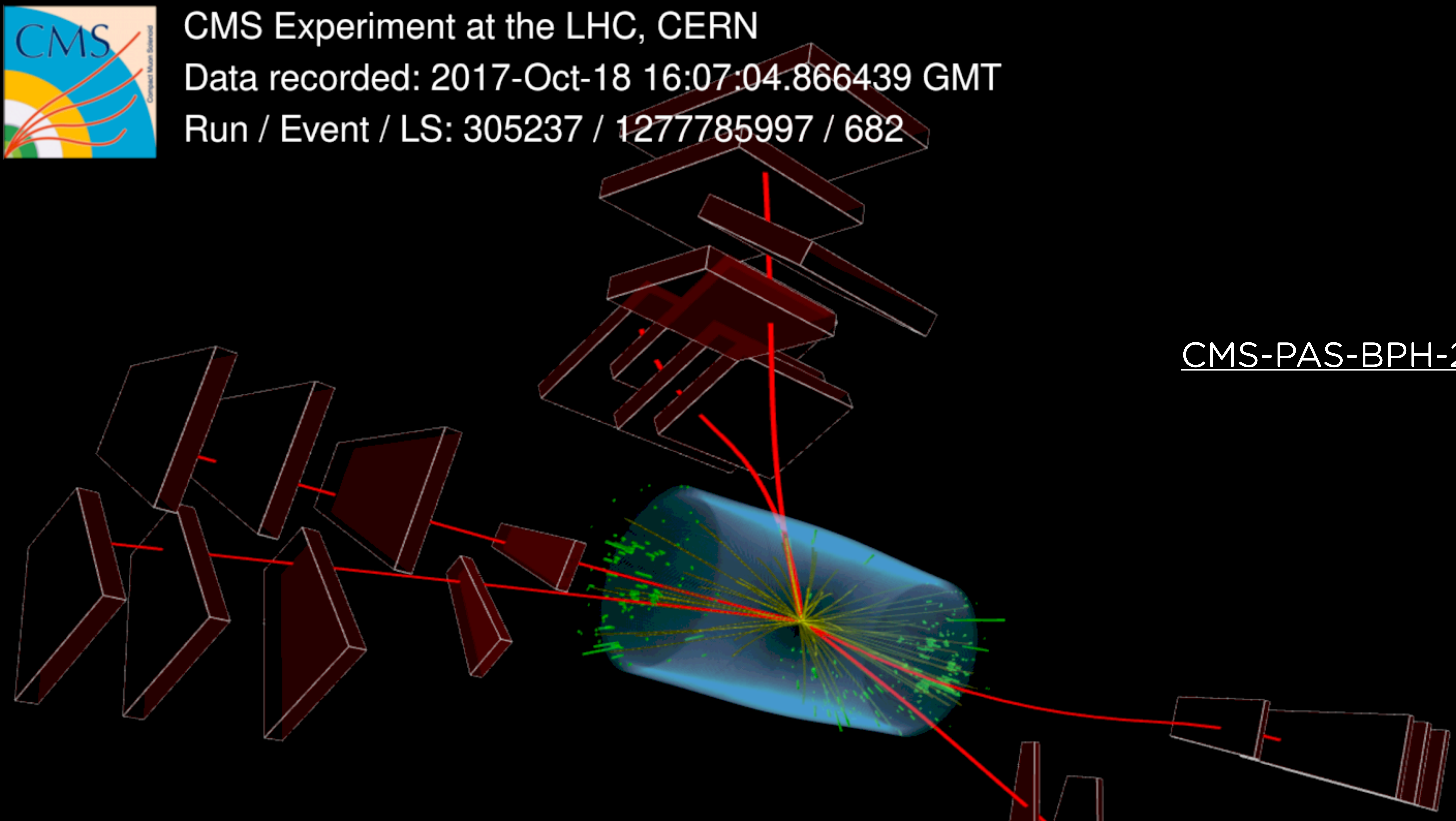
~75% of total cross section

DPS:

~20% of total cross section

TPS:





CMS-PAS-BPH-21-004

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

Data reconstruction and selection

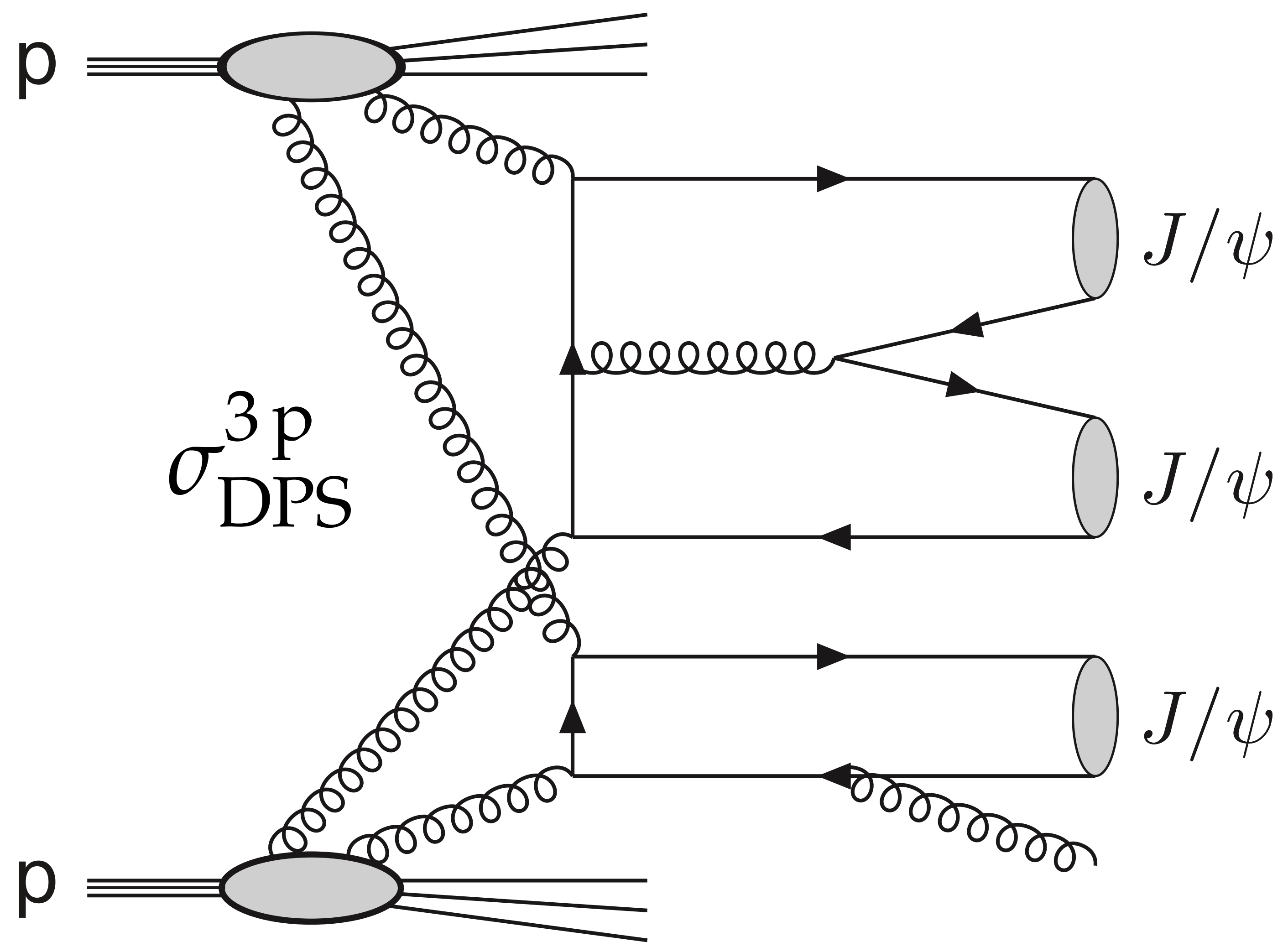
- Run-2 dataset - 133 fb^{-1}
- 6 or more muons
- muon $p_T > 2.5$ GeV for $1.2<|\eta|<2.4$ or $p_T > 3.5$ GeV for $|\eta|<1.2$
- muons reconstructed by combining information from the silicon tracker and the muon system
- dimuon invariant mass between 2.9 and 3.3 GeV
  - muons in pair have opposite charge
  - no muon is shared between 2 J/ψ candidates
  - dimuon vertex probability greater than 0.5%
  - dimuon $p_T > 6.5$ GeV and $|y| < 2.4$
- Selected muons are matched either to their common PV or to a secondary vertex consistent with the PV one
  - eliminating the possibility of accidental combinations of muons from different pp pileup collisions

- Yield is **6 events**
  - 4 from the 2018 and 2 from the 2017 dataset

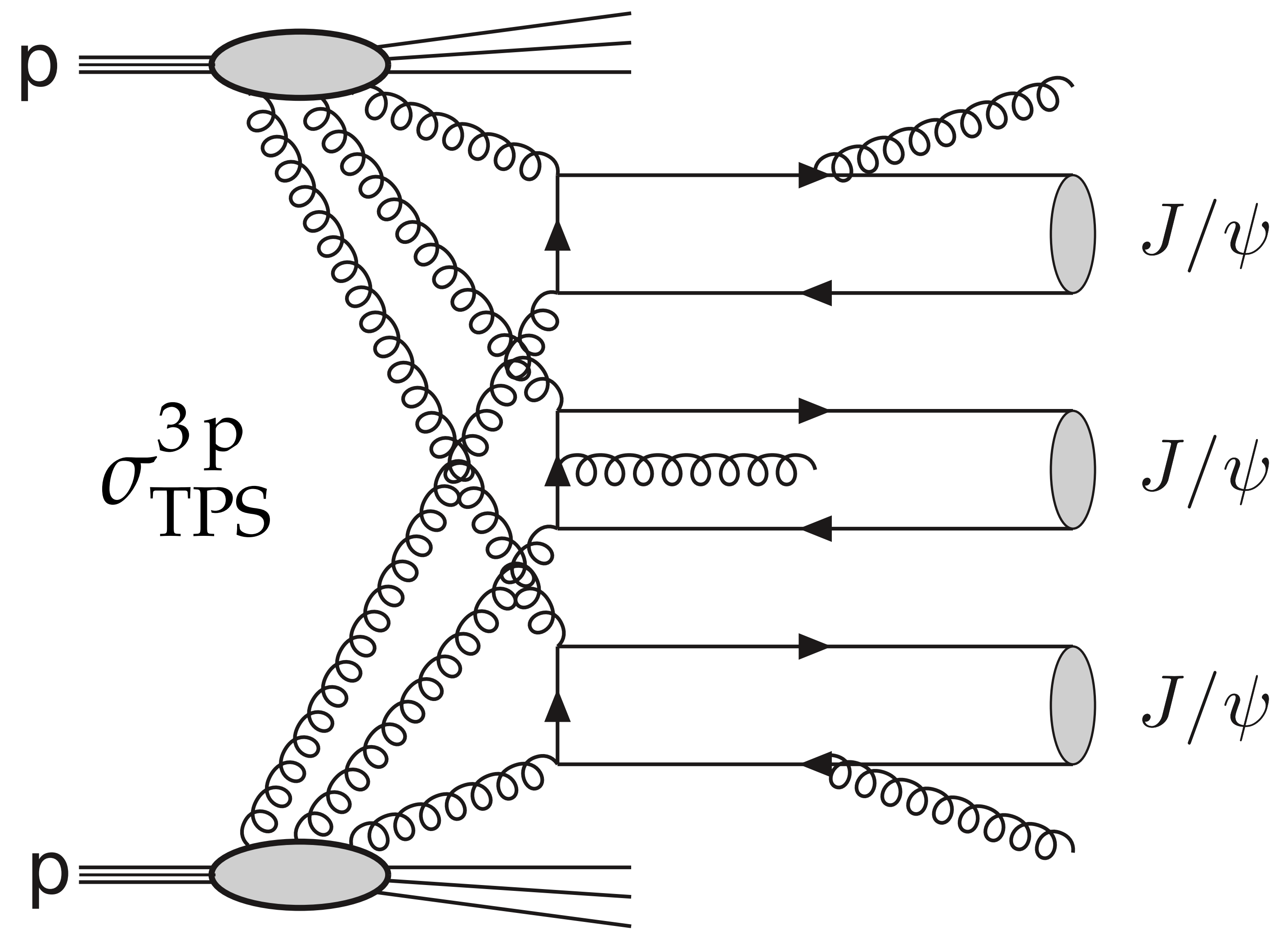
Simulation

- Two sets of **MC** samples are generated using **HelacOnia**
  - dedicated for heavy quarkonia production
  - can produce SPS $(J/\psi+J/\psi+J/\psi)_{sps}$
- SPS not generated due to small yield expectation

- **DPS** triple J/ψ production
  - a mixture of $\mathbf{(J/\psi+J/\psi)_{sps} + J/\psi_{sps}}$

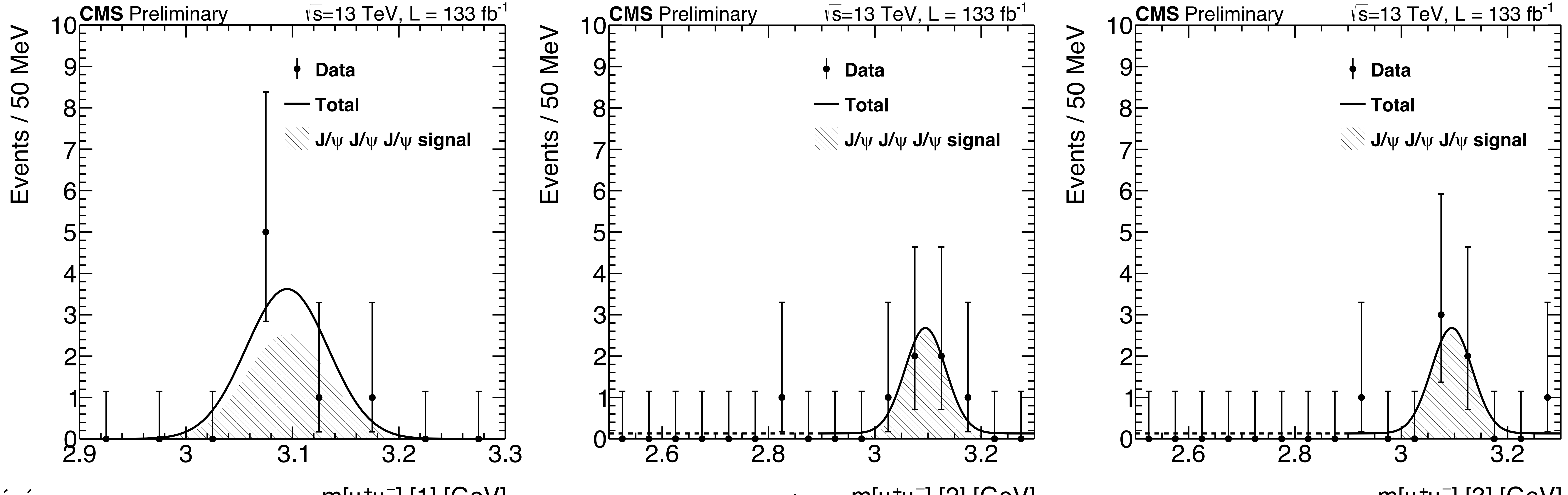


- **TPS** triple J/ψ production
  - a mixture of $\mathbf{J/\psi_{sps} + J/\psi_{sps} + J/\psi_{sps}}$



Signal extraction

- Yield is extracted using a **3D unbinned extended maximum likelihood** fit
  - signal: gaussian with resolution fixed from MC fit and mean fixed to PDG J/ψ mass
  - background: exponential
  - accounting all combinations of signals and background dimuon pairs:
    - 8 yields extending the likelihood
      - 1 signal - $J/\psi^{1}_{signal} + J/\psi^{2}_{signal} + J/\psi^{3}_{signal}$
      - 7 background (combinations of the three J/ψ to be signal or background)
- Signal yield **5.0 $^{+2.6}_{-1.9}$ events**



Cross section calculation

- **Fiducial cross section** $\sigma(pp \rightarrow J/\psi\ J/\psi\ J/\psi\ X) = N/(\varepsilon \times L \times B^3_{J/\psi\rightarrow\mu\mu})$
  - N number of signal events
    - $5.0^{+2.6}_{-1.9}$
  - L total integrated luminosity
    - 133 fb^{-1}
  - ε total efficiency coming from
    - trigger 84%
    - reconstruction 78%
  - $B^3_{J/\psi\rightarrow\mu\mu} = (5.96\% \pm 0.03\%)^3$

Fiducial requirement	
For all muons	$p_T > 3.5$ GeV for $\|\eta\| <= 1.2$ $p_T > 2.5$ GeV for $1.2 < \|\eta\| < 2.4$
For all J/ψ mesons	$p_T > 6$ GeV and $\|y\| < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3$ GeV

Observation of triple J/ψ meson production

Systematics

- Signal shape
  - change Gaussian to a crystal-ball and Gaussian without a resolution constraint
- Background shape
  - change exponential to zero and first order polynomial
- Muon reconstruction efficiency
  - allowing the correction factors of each (p_T, η) bin to float within their assigned precision, and checking the effect on the cross section extraction
- Trigger efficiency
  - change to TPS MC sample to calculate σ
- Luminosity
  - 1.8% from LUMI POG
- MC statistics
  - due to size of the MC sample
- Branching fraction
  - 1.7%
- **Total is 6.2%**

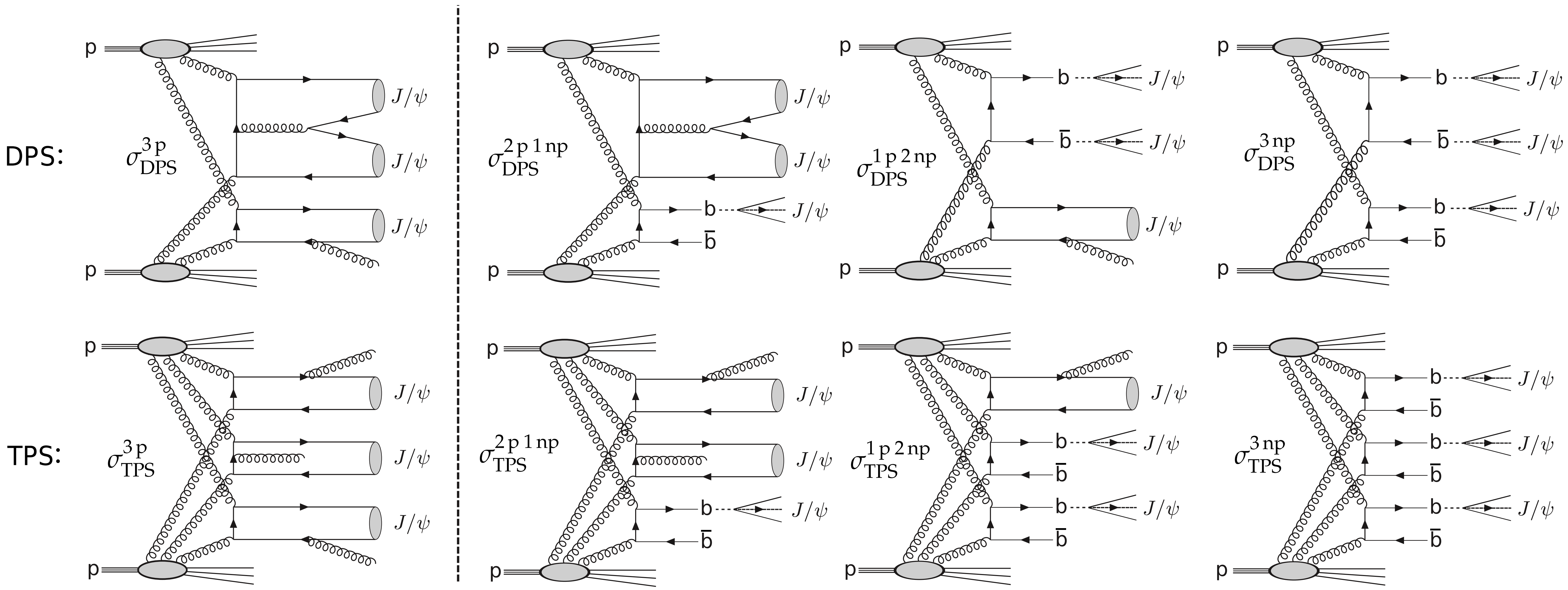
Source	Relative uncertainty
J/ψ meson signal shape	0.8%
Dimuon continuum background shape	3.4%
Muon reconstruction efficiency	1.0%
Trigger efficiency measurement	3.4%
MC sample size	3.0%
Integrated luminosity	1.6%
Branching fraction	1.7%
Total	6.2%

- **Measured cross section for triple J/ψ production, within the fiducial region**
  - **$\sigma(pp \to J/\psi\, J/\psi\, J/\psi\, X) = 272\,^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})$ fb**

Nature of the J/ψ mesons

- A classification of prompt and nonprompt events is attempted
  - 2 approaches
    - cut on J/ψ proper decay length at 60μm
    - fit proper decay length
      - fit all individual measurements with prompt and nonprompt templates derived from MC
      - unbinned maximum likelihood fit with 2 variables extending it: prompt and nonprompt
      - compare the sPlot prompt and nonprompt weights per event

- Same answer from both methods
  - 2 events: 2 nonprompt + 1 prompt
  - 1 event: 1 nonprompt + 2 prompt
  - 1 event: 3 nonprompt
  - 1 event: 3 prompt



Discussion of the results

- Cross section to produce two charmonium mesons in a DPS can be written as

$$\sigma_{\mathrm{DPS}}^{\mathrm{pp}\to\psi_1\psi_2+X} = \binom{m}{2} \frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+X}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+X}}{\sigma_{\mathrm{eff,DPS}}}$$

, where m=1 for $\psi_1=\psi_2$, and m=2 if $\psi_1\neq\psi_2$

- Similar "Pocket formula" for TPS:

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

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

- Theoretical total triple-J/ψ cross section expected to correspond to the sum of the contributions from SPS, DPS, and TPS processes:

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

- With the DPS and TPS triple-J/ψ cross sections derivable from the single- and double-J/ψ SPS cross sections:

$$\sigma_{\mathrm{DPS}}^{3\mathrm{J}/\psi} = \frac{m_1\left(\sigma_{\mathrm{SPS}}^{2\mathrm{p}}\sigma_{\mathrm{SPS}}^{1\mathrm{p}} + \sigma_{\mathrm{SPS}}^{2\mathrm{p}}\sigma_{\mathrm{SPS}}^{1\mathrm{np}} + \sigma_{\mathrm{SPS}}^{1\mathrm{p}}\sigma_{\mathrm{SPS}}^{1\mathrm{p}1\mathrm{np}} + \sigma_{\mathrm{SPS}}^{1\mathrm{p}1\mathrm{np}}\sigma_{\mathrm{SPS}}^{1\mathrm{np}} + \sigma_{\mathrm{SPS}}^{1\mathrm{p}}\sigma_{\mathrm{SPS}}^{2\mathrm{np}} + \sigma_{\mathrm{SPS}}^{2\mathrm{np}}\sigma_{\mathrm{SPS}}^{1\mathrm{np}}\right)}{\sigma_{\mathrm{eff,DPS}}}$$

$$\sigma_{\mathrm{TPS}}^{3\mathrm{J}/\psi} = \frac{m_3\left(\left(\sigma_{\mathrm{SPS}}^{1\mathrm{p}}\right)^3 + \left(\sigma_{\mathrm{SPS}}^{1\mathrm{np}}\right)^3\right) + m_2\left(\left(\sigma_{\mathrm{SPS}}^{1\mathrm{p}}\right)^2\sigma_{\mathrm{SPS}}^{1\mathrm{np}} + \sigma_{\mathrm{SPS}}^{1\mathrm{p}}\left(\sigma_{\mathrm{SPS}}^{1\mathrm{np}}\right)^2\right)}{\sigma_{\mathrm{eff,TPS}}^2},$$

with $m_1=1$, $m_2=1/2$, $m_3=1/6$

Discussion of the results

- Using 8 theoretical SPS cross sections from HELACONIA(LO,NLO*)+data,PYTHIA8, and MG5@NLO+PYTHIA8:

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

- Nonprompt cross sections scaled to NNLO (x1.15). Theoretical uncertainties dominated by scale (then PDF).
- Using the sum Equation of previous slide, assuming **$\sigma_{eff,TPS}$ = (0.82 ± 0.11) $\sigma_{eff,DPS}$**, the DPS effective cross section can be extracted requiring that total triple-J/ψ cross section matches the measured value:

Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	total
SPS:					
$\sigma^{3J/\psi}_{SPS}$ (fb)	$<5\,10^{-3}$	5.7	0.014	12	18
$N^{3J/\psi}_{SPS}$	0.0	0.1	0.0	0.22	0.32
DPS:					
$\sigma^{3J/\psi}_{DPS}$ (fb)	8.4	8.9	90	95	202
$N^{3J/\psi}_{DPS}$	0.15	0.16	1.7	1.7	3.7
TPS:					
$\sigma^{3J/\psi}_{TPS}$ (fb)	6.1	19.4	20.4	7.2	53
$N^{3J/\psi}_{TPS}$	0.11	0.36	0.38	0.13	1.0
SPS+DPS+TPS:					
$\sigma^{3J/\psi}_{tot}$ (fb)	15	34	110	114	272
$N^{3J/\psi}_{tot}$	0.3	0.6	2.0	2.1	5.0

Observation of triple J/ψ meson production

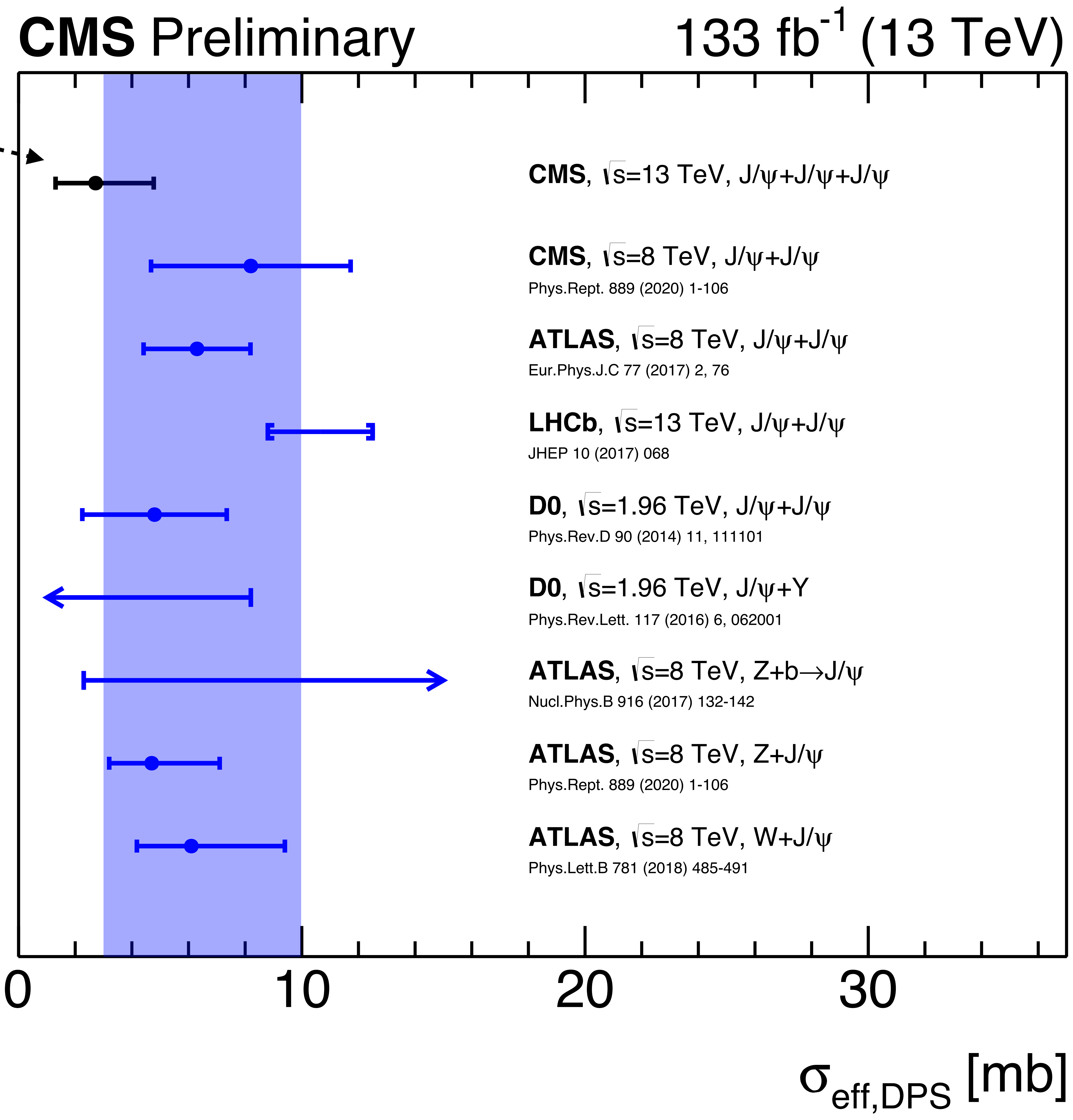
Discussion of the results

- 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



Discussion of the results

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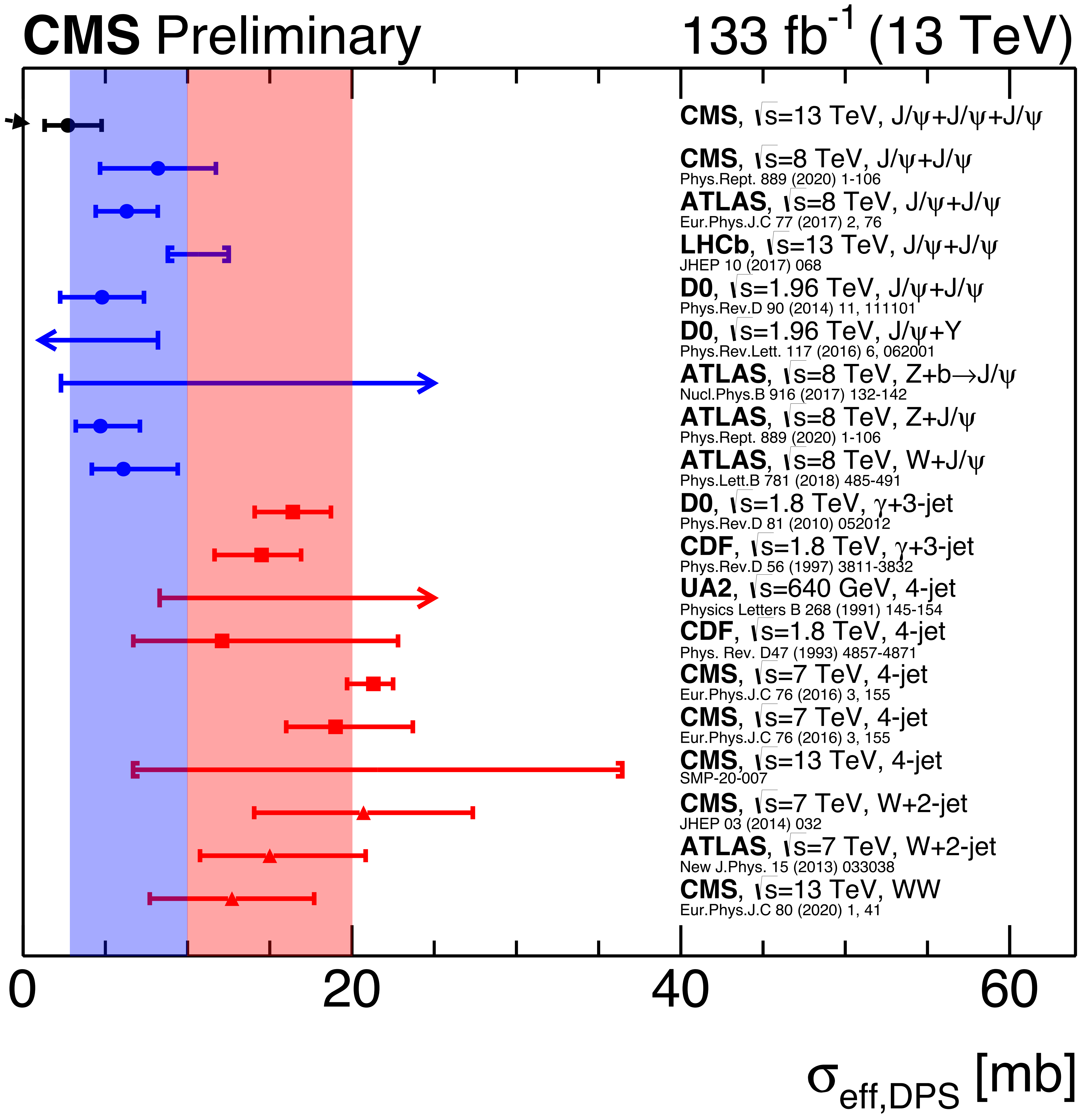
$\sigma_{eff,DPS}$ = 2.7 $^{+1.4}_{-1.0}$ (exp) $^{+1.5}_{-1.0}$ (theo) mb

- 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:

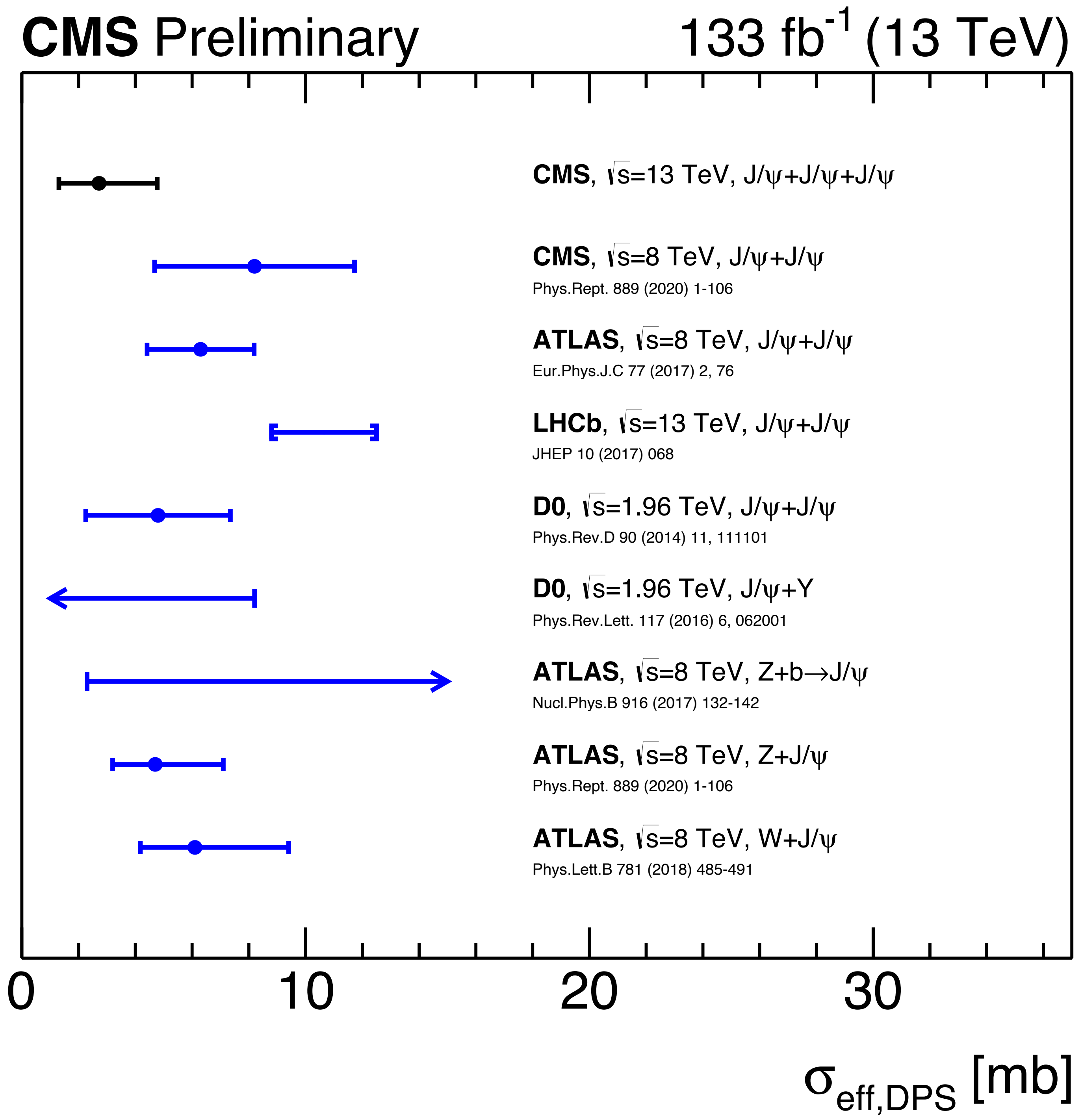


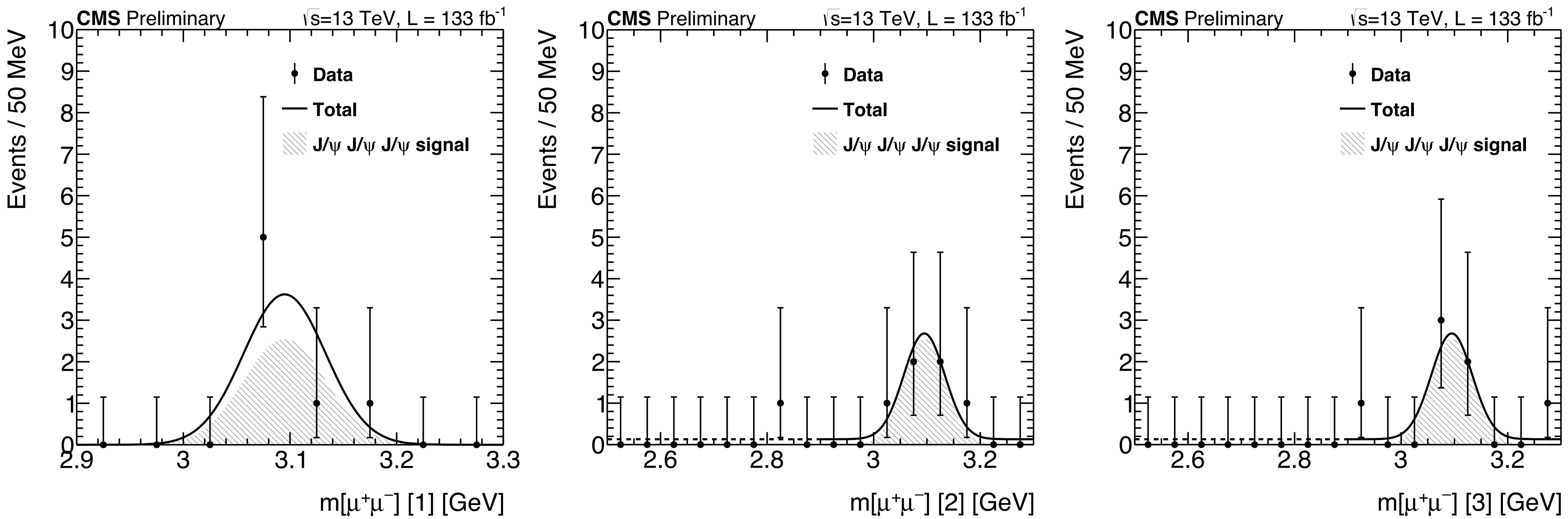
- $\sigma_{eff,DPS}$ ≈ 10 – 20 mb

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**
- $\sigma(pp \rightarrow J/\psi\ J/\psi\ J/\psi\ X) = 272\ ^{+141}_{-104}\ (\text{stat}) \pm 17\ (\text{syst})$ fb
- ~6% SPS, ~74% DPS, ~20% TPS
- Extraction of **$\sigma_{eff,DPS}$ = 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)





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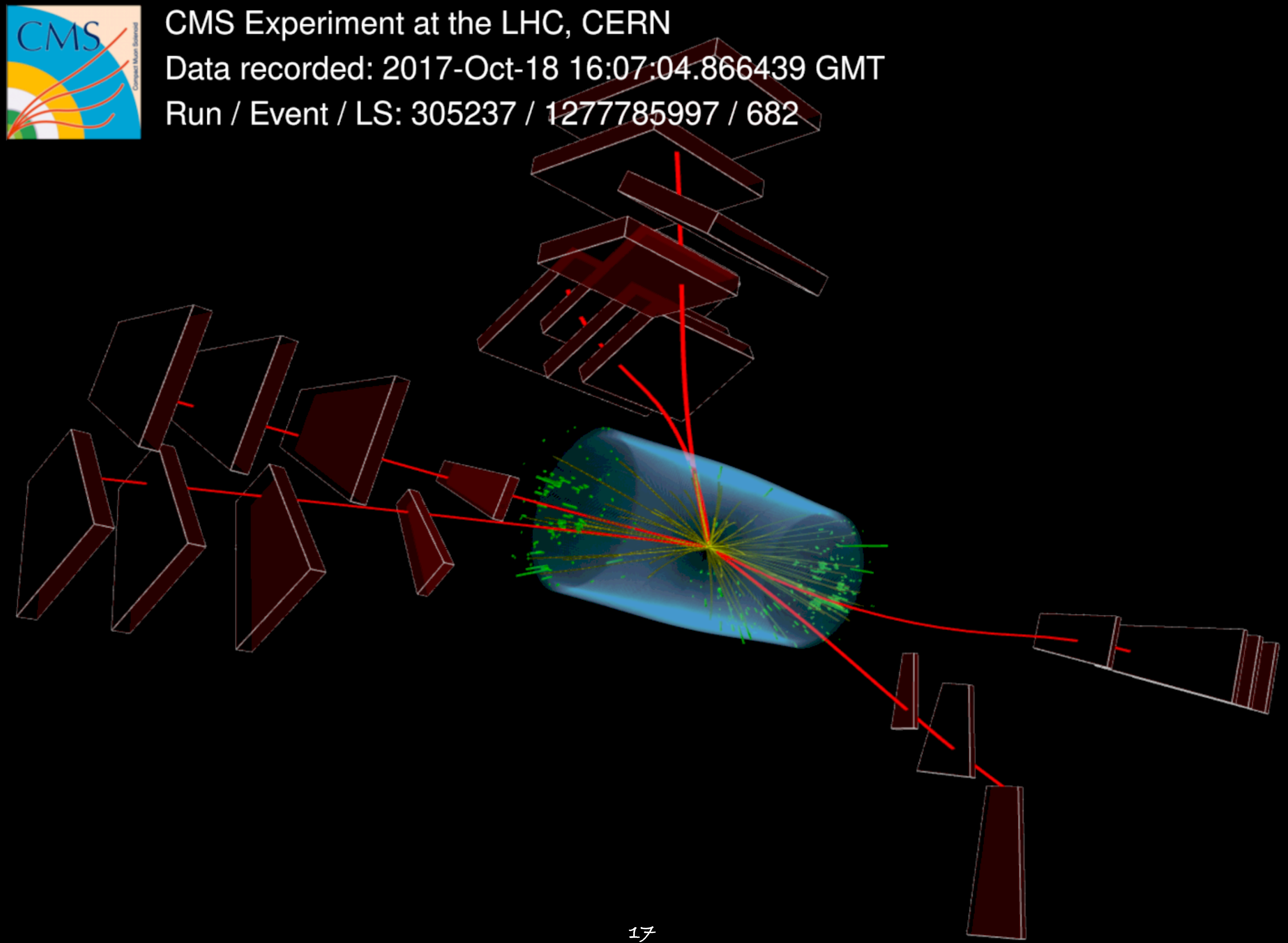
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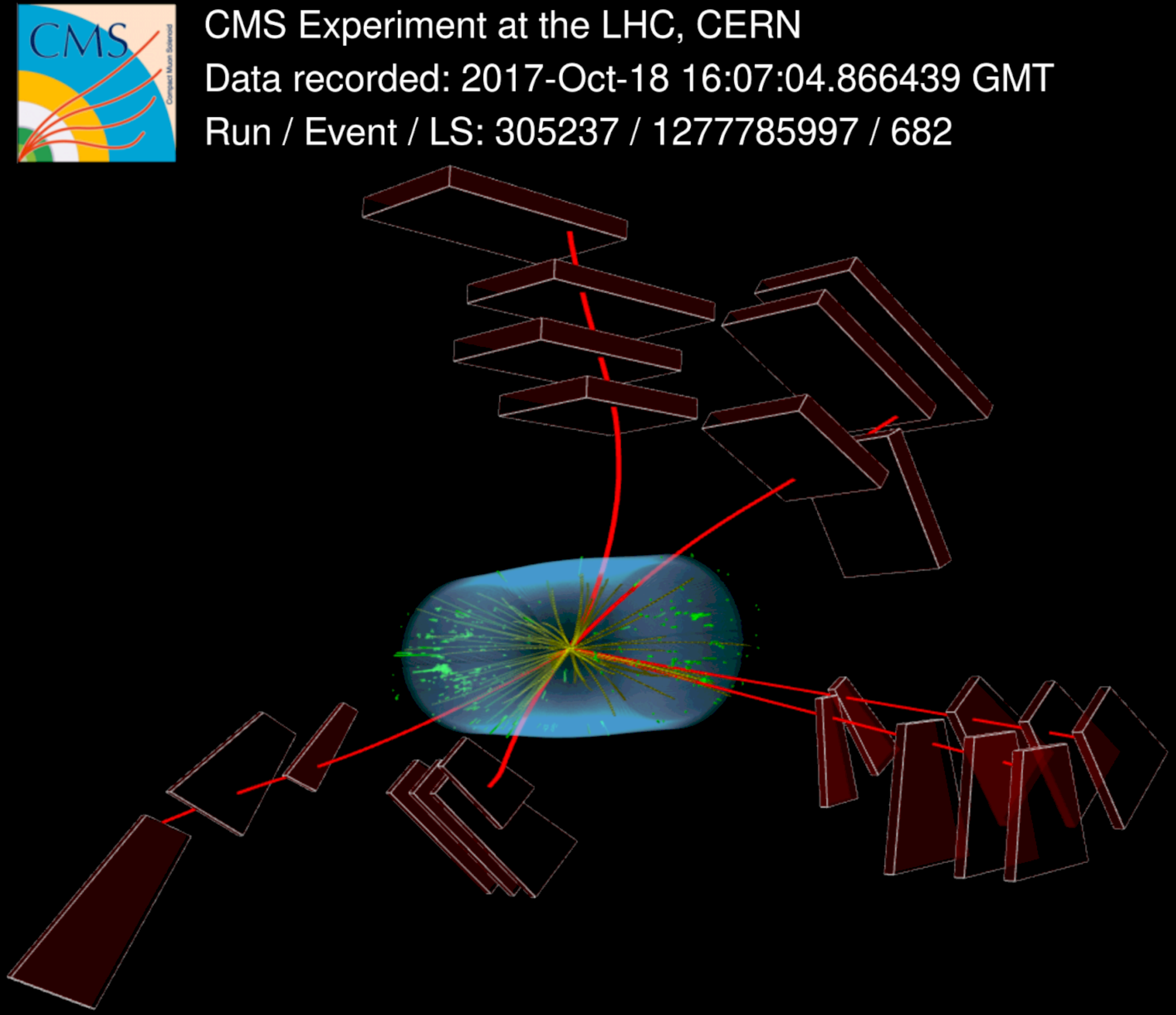
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