Double Quarkonium Studies at CMS

22ND CONFERENCE ON FLAVOR PHYSICS AND CP VIOLATION
Chulalongkorn University
Bangkok, Thailand

清華大學
Tsinghua University

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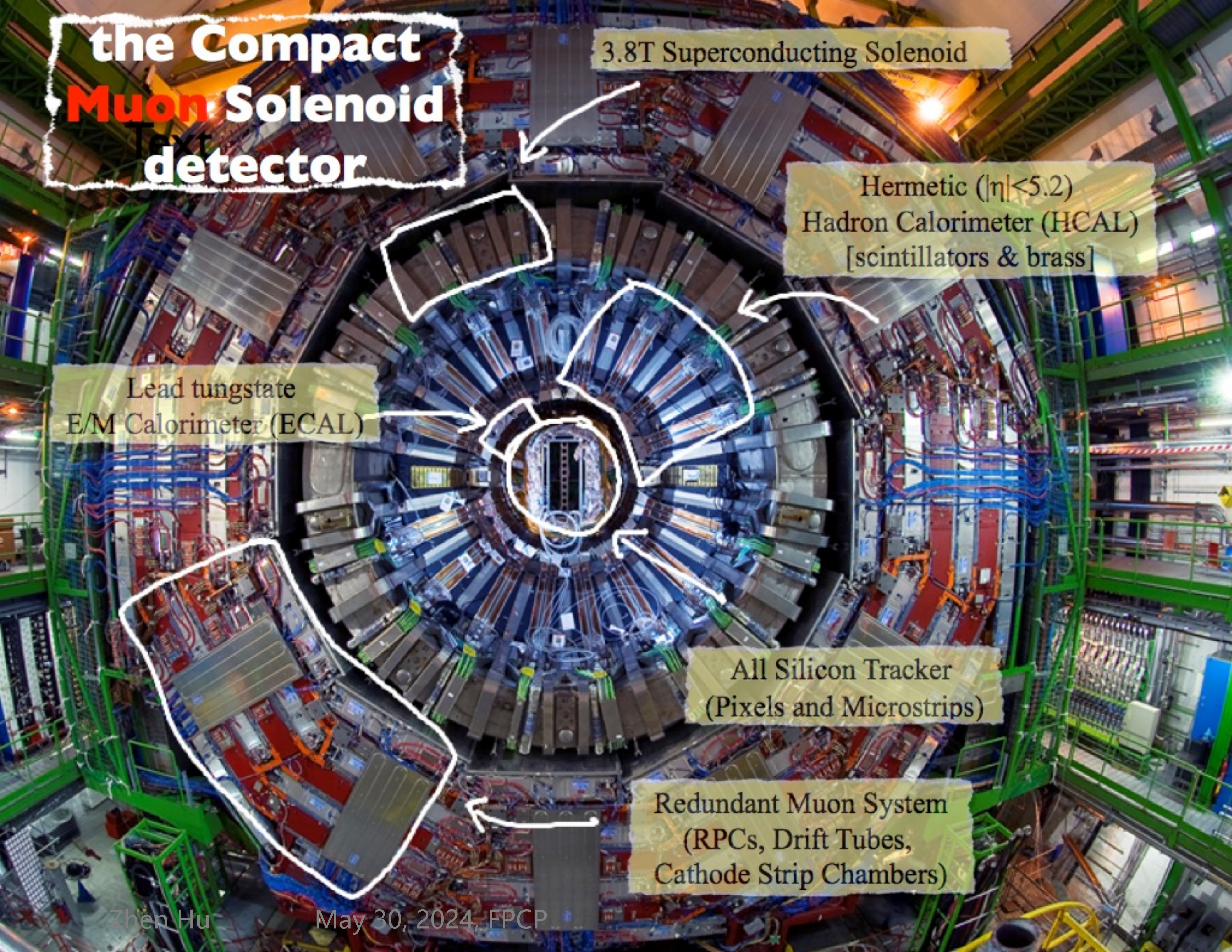
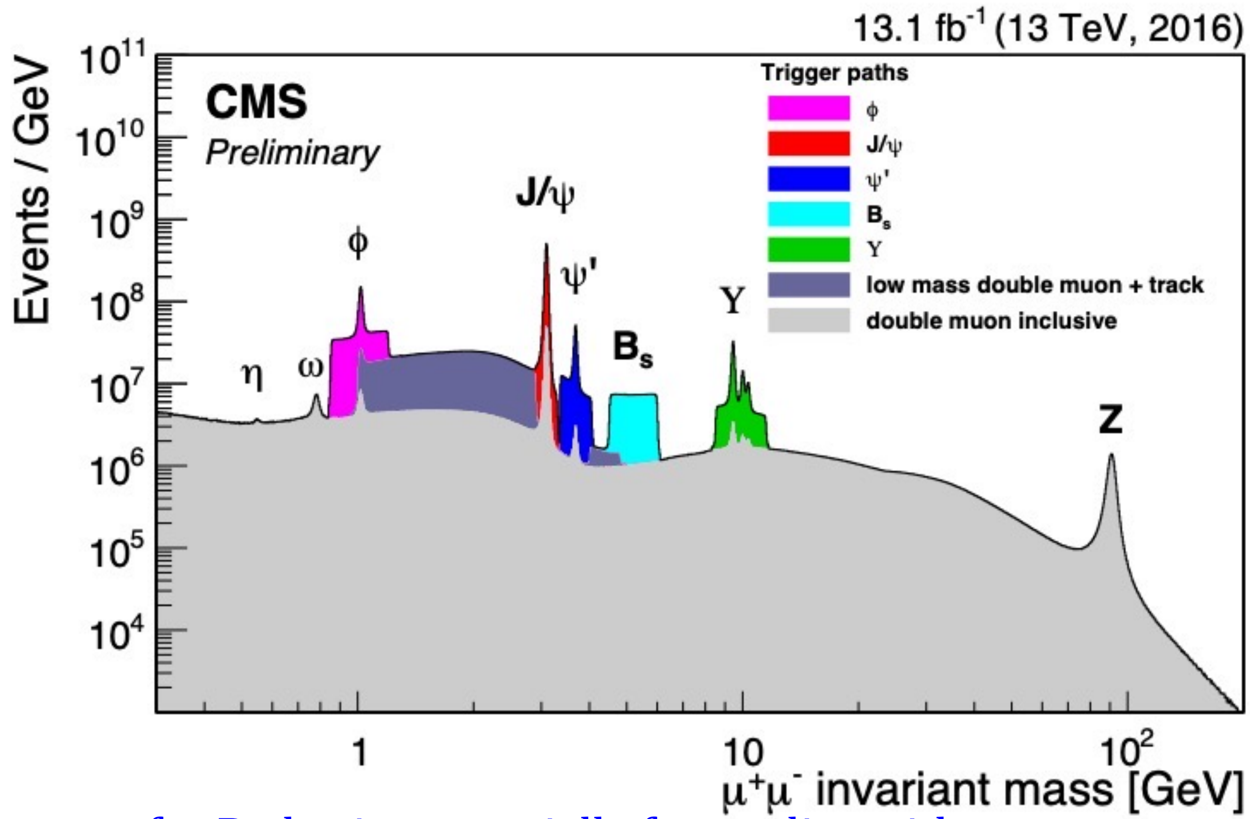
on behalf of
the CMS Collaboration

May 30, 2024

The **Large Hadron Collider** (**LHC**) at CERN is the world's largest particle collider. It lies in a tunnel 27 kilometres in circumference and as deep as 175 metres beneath the France–Switzerland border near Geneva.


the Compact Muon Solenoid detector
Text
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
Lead tungstate
E/M Calorimeter (ECAL)
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

CMS dimuon & trigger

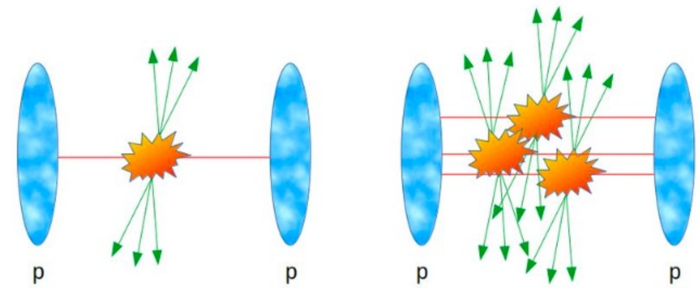


Excellent detector for B physics, especially for studies with muons

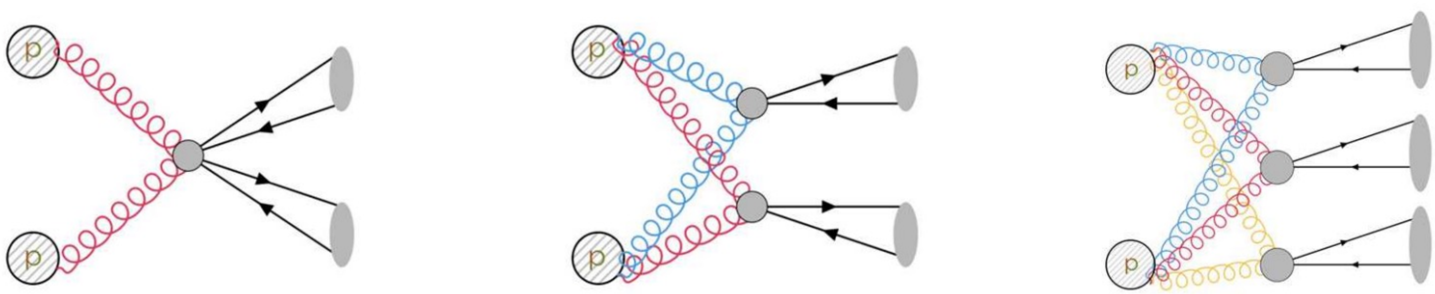
- Muon system
  - High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector, B=3.8T
  - $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses at increasing Inst. Lumi.
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and additional μ

Associated heavy flavour production

- MPI (multiple parton scattering) studies are important for
  - Probing partonic structure of proton
  - Tuning of Monte Carlo event generators
  - Background for new physics searches



- Associated heavy flavour production
  - Initial state: e.g. sensitivity to the concepts of single (SPS), double (DPS) and triple (TPS) parton scattering



  - Final state: e.g. sensitivity to heavy flavour hadron formation (colour singlet vs. colour octet), sensitivity to resonant multi-heavy-flavor states

CMS results on associated quarkomium

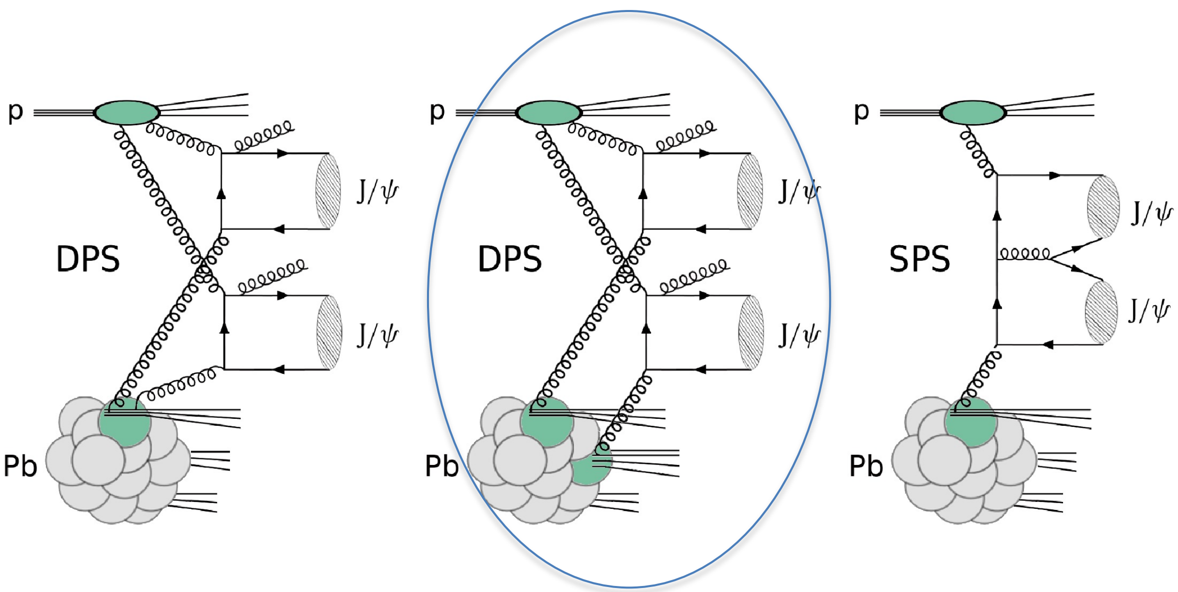
- Double J/ψ in pPb at 8.16 TeV (2024)
  - First observation
- Double J/ψ in pp at 13 TeV (2023, Kai Yi's talk)
  - New structures in double J/ψ mass spectrum
- Triple J/ψ in pp at 13 TeV (2023)
  - First observation
- Double Upsilon in pp at 13 TeV (2020)

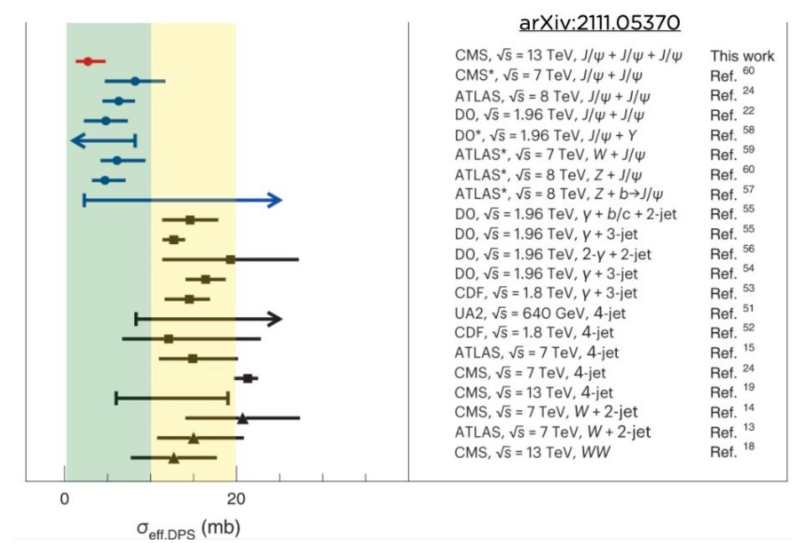
Early analyses with Run 1 data

- Double Upsilon in pp at 8 TeV (2017) – First observation
- Double J/ψ at 7 TeV (2014)

J/ψJ/ψ in pPb

- MPI cross section increases with √s; increased parton densities
  - Many measurements from UA2 to LHC
- DPS cross section can be written as $\sigma_{\mathrm{DPS}}^{\mathrm{pPb}\to\mathrm{J}/\psi\mathrm{J}/\psi+\mathrm{X}} = \left(\frac{1}{2}\right) \frac{\sigma_{\mathrm{SPS}}^{\mathrm{pPb}\to\mathrm{J}/\psi+\mathrm{X}}\,\sigma_{\mathrm{SPS}}^{\mathrm{pPb}\to\mathrm{J}/\psi+\mathrm{X}}}{\sigma_{\mathrm{eff,pA}}}$
  - Effective cross section $\sigma_{\mathrm{eff}} \equiv$ (Interpretation transverse distance)^2
- pPb data provide an independent tool to extract σ_{eff}
  - DPS is enhanced by a factor of 600 in pPb collisions as compared to pp

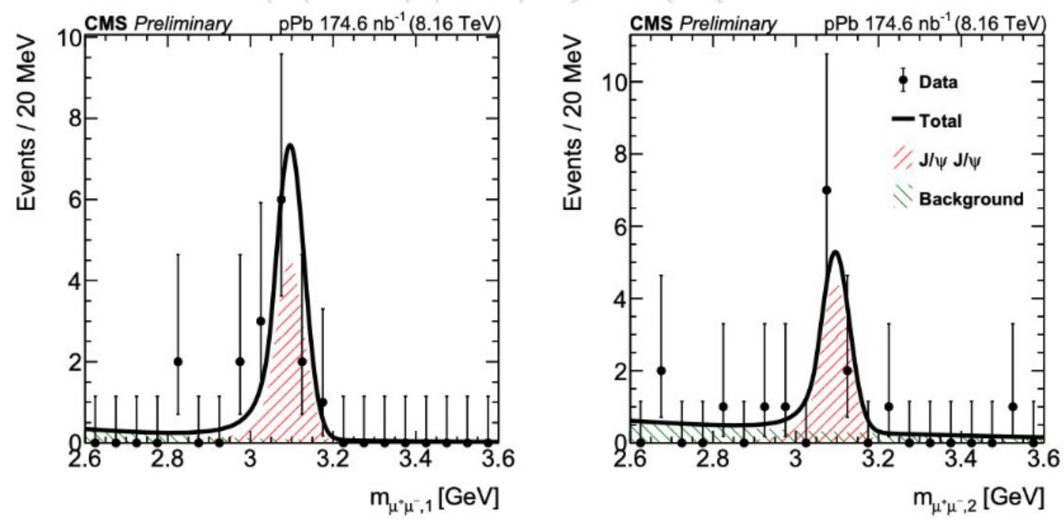




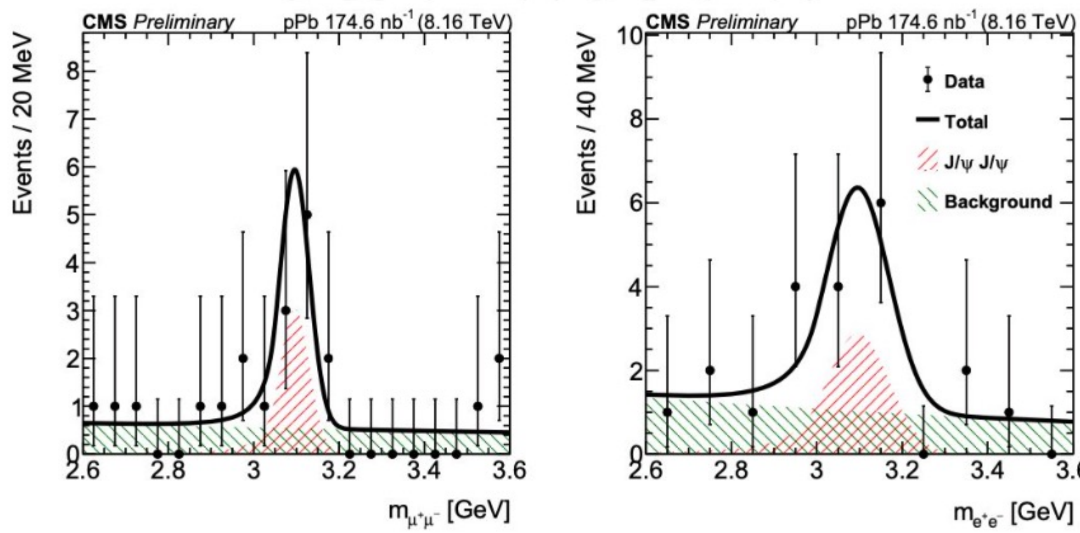
First observation of J/ψJ/ψ in pPb

- pPb data sample collected at $\sqrt{s_{NN}}$ = 8.16 TeV during 2016
  - Integrated luminosity: 174.56 nb^{-1}
- Channels considered
  - J/ψ(→μμ)J/ψ(→μμ)
  - J/ψ(→μμ)J/ψ(→ee)
- Signal Yield
  - J/ψ(→μμ)J/ψ(→μμ) : 8.5 ± 3.4
  - J/ψ(→μμ)J/ψ(→ee) : 5.7 ± 4.0
- Significance is 4.9 sigma for the 4 muon channel (Likelihood ratio of the fits + asymptotic formula under Wilks theorem)
- 5.3σ (combination with Fischer Formalism)

J/ψ(→μμ)J/ψ(→μμ)



J/ψ(→μμ)J/ψ(→ee)



CMS-PAS-HIN-23-013

J/ψJ/ψ cross section in pPb at 8.16 TeV

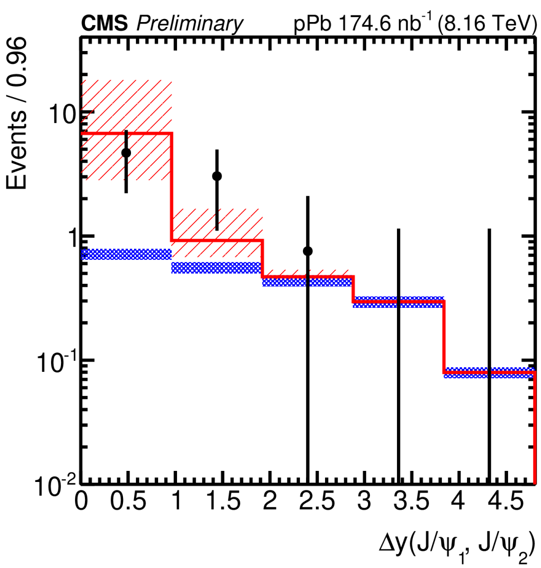
- Using J/ψ(→μμ)J/ψ(→μμ) only, fiducial cross section

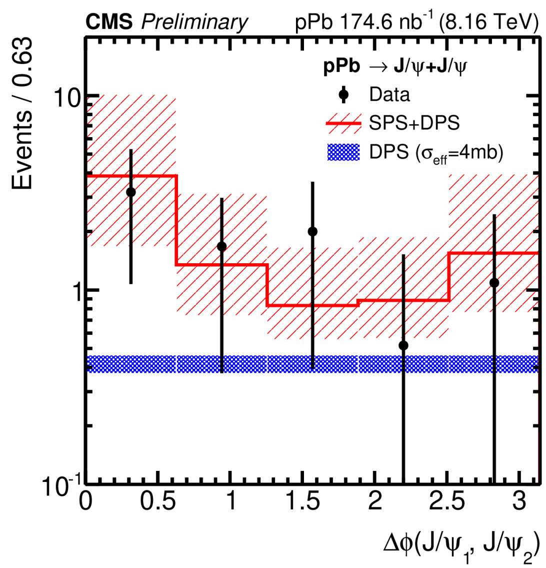
CMS-PAS-HIN-23-013

$$\sigma(\mathrm{pPb} \to \mathrm{J}/\psi\mathrm{J}/\psi + \mathrm{X}) = N_{\mathrm{sig}} / (\epsilon\, \mathcal{L}_{\mathrm{int}}\, \mathcal{B}^2_{\mathrm{J}/\psi\to\mu^+\mu^-})$$
$$= 22.0 \pm 8.9\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})\,\mathrm{nb}$$

Fiducial requirement		
For all muons	$p_T > 3.4$ GeV	for $0 < \lvert\eta\rvert < 0.3$
	$p_T > 3.3$ GeV	for $0.3 < \lvert\eta\rvert < 1.1$
	$p_T > 5.5–2.0\lvert\eta\rvert$ GeV	for $1.1 < \lvert\eta\rvert < 2.1$
	$p_T > 1.3$ GeV	for $2.1 < \lvert\eta\rvert < 2.4$
For the two J/ψ mesons	$p_T > 6.5$ GeV and $\lvert y\rvert < 2.4$	

Source of uncertainty	$\sigma(\mathrm{pPb} \to \mathrm{J}/\psi\mathrm{J}/\psi + \mathrm{X})$
J/ψ meson signal shape	4.0%
Dimuon continuum background shape	2.5%
Luminosity	3.5%
Branching fraction	1.1%
Scale factors	1.3%
Total	6.1%





Separate DPS and SPS
- events (SPS) = 6.4 ± 4.2
- events (DPS) = 2.1 ± 2.4

Fiducial cross section:
SPS: 16.5 ± 10.8 (stat) ± 0.1 (syst) nb
DPS: 5.4 ± 6.2 (stat) ± 0.4 (syst) nb

Effective cross section from pPb

$\sigma_{\text{eff,pA}}$ can be extracted using formula

$\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi+\text{X}}\mathcal{B}(\text{J}/\psi\to\mu^+\mu^-)$	$4.51\pm0.42\ \mu\text{b}$
$\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi\text{J}/\psi+\text{X}}\mathcal{B}^2(\text{J}/\psi\to\mu^+\mu^-)$	$20.2^{+38.5}_{-13.1}$ pb

from theory

$$\sigma_{\text{eff,pA}}=\left(\frac{1}{2}\right)\frac{\sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi+\text{X}}\ \sigma_{\text{SPS}}^{\text{pPb}\to\text{J}/\psi+\text{X}}}{\sigma_{\text{DPS}}^{\text{pPb}\to\text{J}/\psi\text{J}/\psi+\text{X}}}=0.53^{+\infty}_{-0.2}\ \text{b}$$

from data

large upper uncertainty indicates the possibility of the absence of DPS contribution

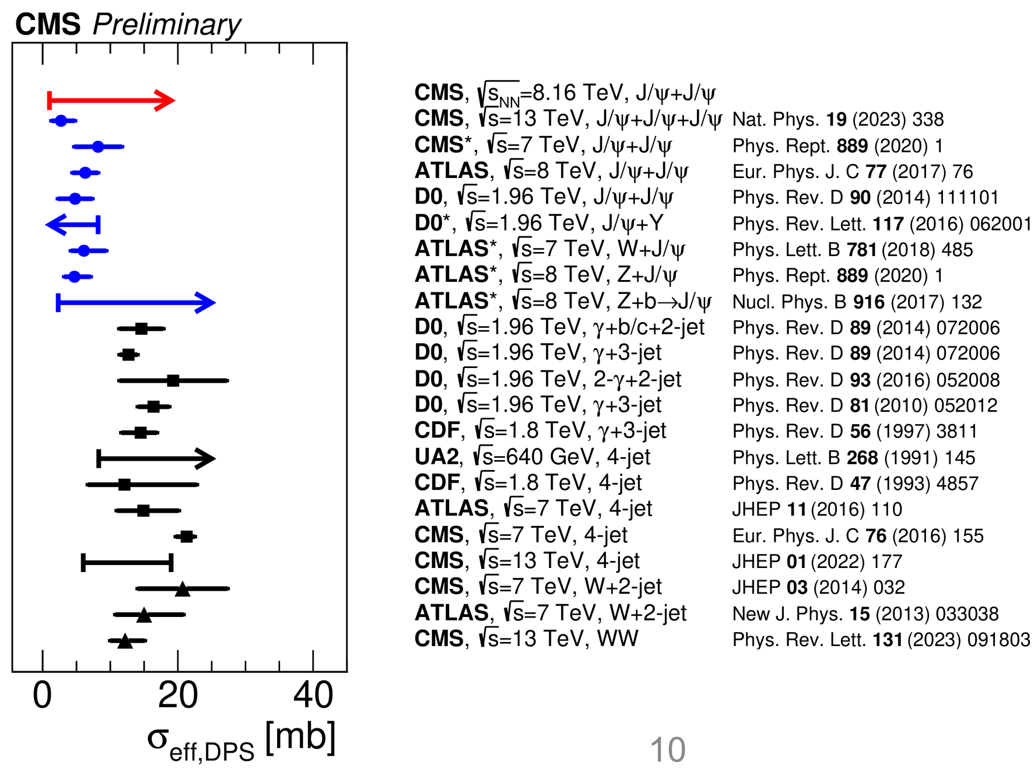
Neglecting parton correlations, factorization of double PDF in transverse and longitudinal components, σ_{eff} (pp) can be calculated as

$$\sigma_{\text{eff}}=\frac{\sigma_{\text{eff,pA}}}{A-\sigma_{\text{eff,pA}}F_{\text{pA}}/A}$$

A = 208, and F_{pA} = 29.5 mb^{-1} from Glauber MC Model

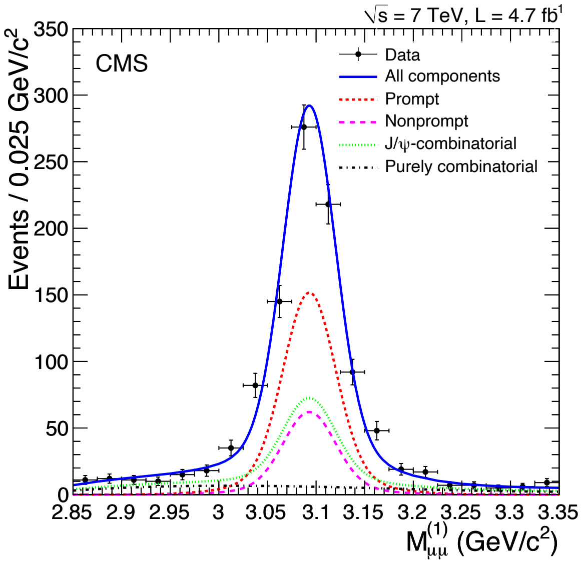
$$\sigma_{\text{eff}}\,(\text{pp})=4.0^{+\infty}_{-1.5}\ \text{mb}$$

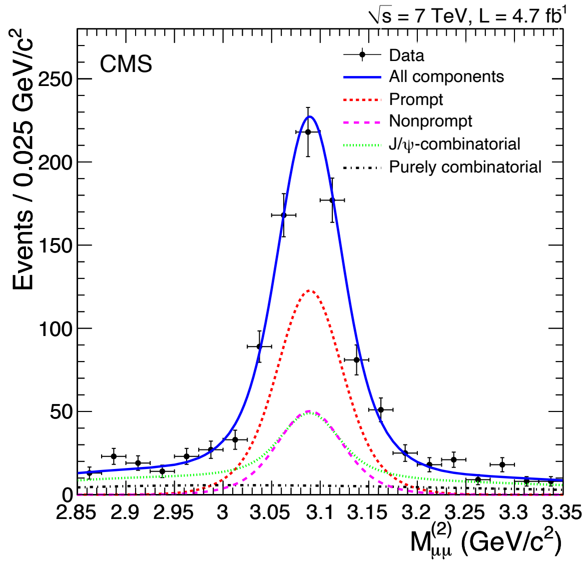
σ_{eff} > 1.0 mb at 95% CL

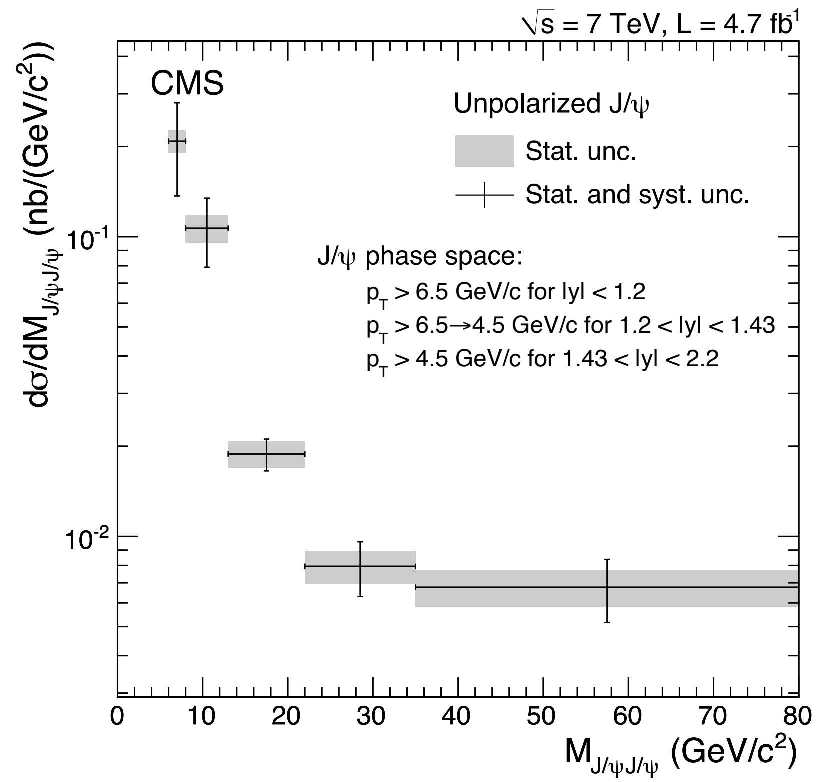


J/ψJ/ψ cross section in pp at 7 TeV

[J. High Energy Phys. 09 (2014) 094]



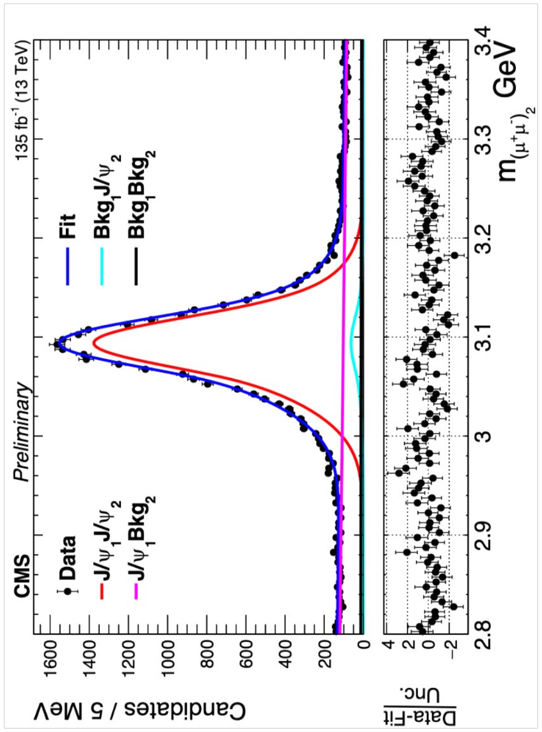


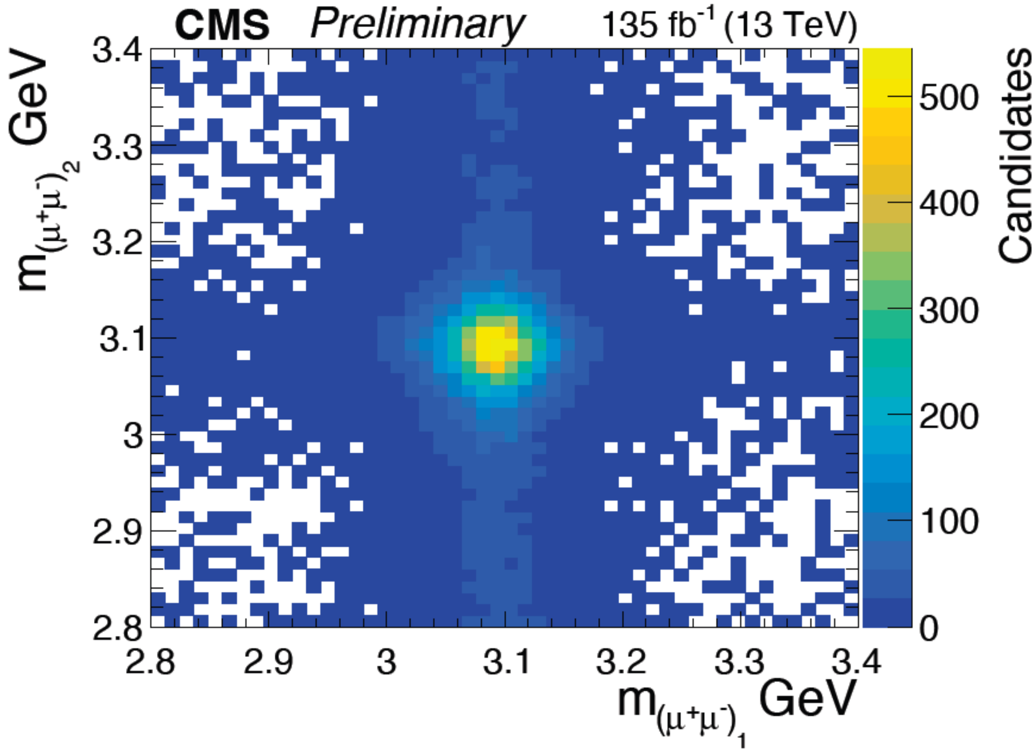


Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production
1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

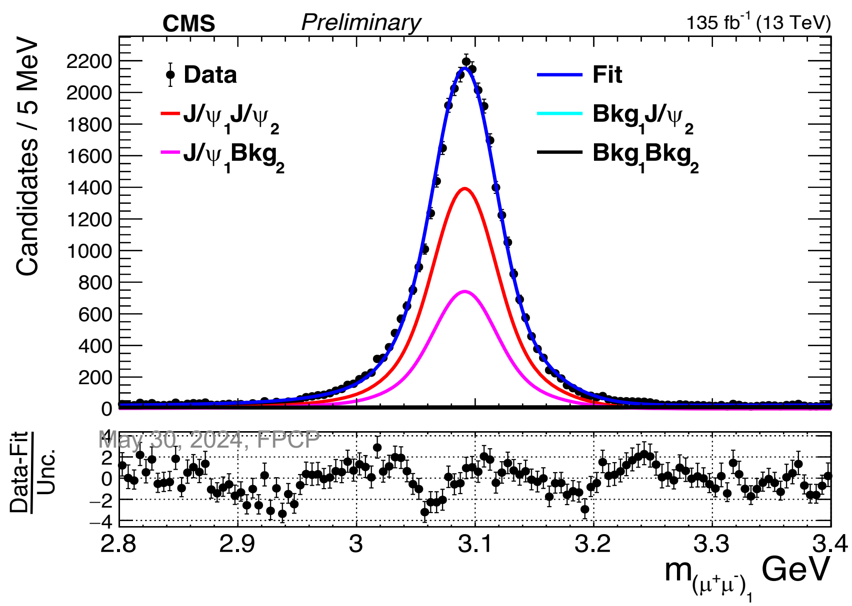
Different assumptions about the J/ψJ/ψ polarization imply modifications to the cross section ranging from -31% to +27%.

J/ψJ/ψ candidates in pp at 13 TeV

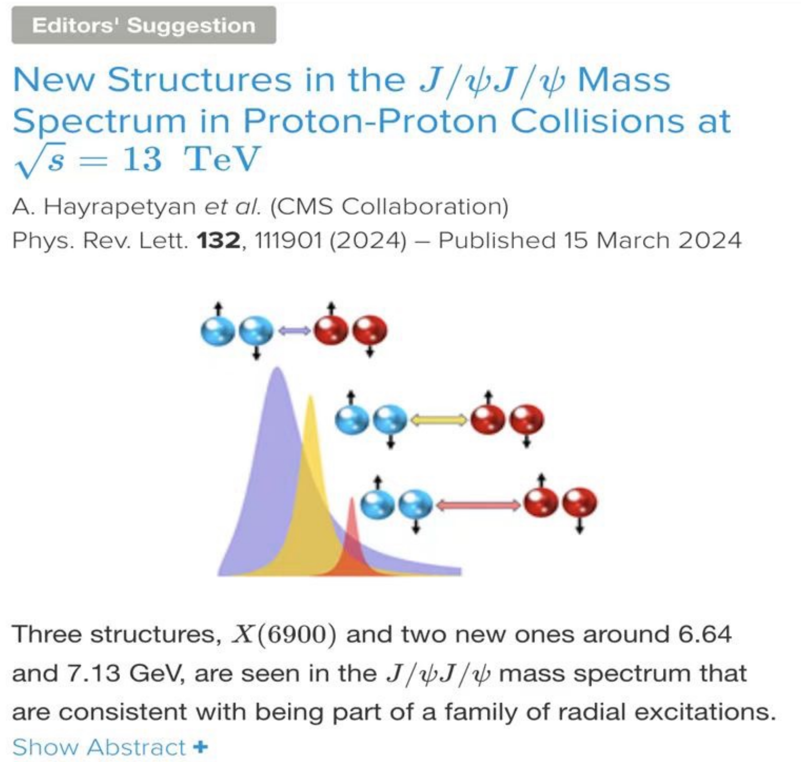




- CMS data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- J/ψ mass and vertex related cuts removed
- Clean J/ψ signals are seen



New structures in J/ψJ/ψ


Editors' Suggestion

New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

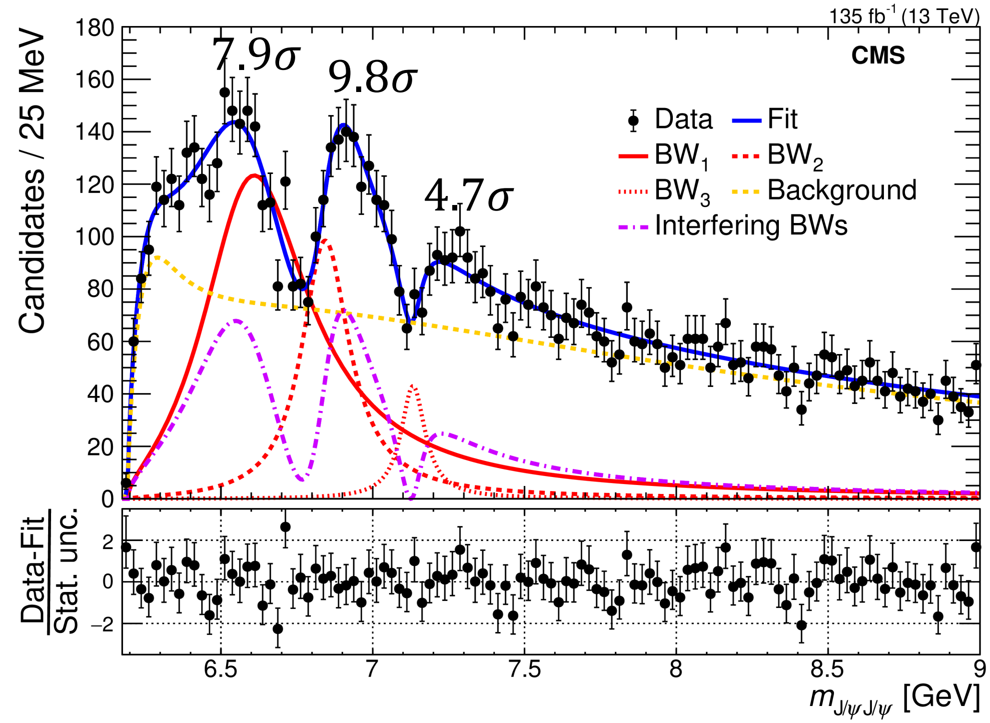
A. Hayrapetyan *et al.* (CMS Collaboration)

Phys. Rev. Lett. **132**, 111901 (2024) – Published 15 March 2024

Three structures, $X(6900)$ and two new ones around 6.64 and 7.13 GeV, are seen in the $J/\psi J/\psi$ mass spectrum that are consistent with being part of a family of radial excitations.

Show Abstract +

[Phys. Rev. Lett. 132 (2024) 111901]



- Fit with interf. among BW1, BW2, and BW3 describes data well
- Measured mass and width in the interference fit

		X(6600)	X(6900)	X(7100)
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

First observation   First evidence

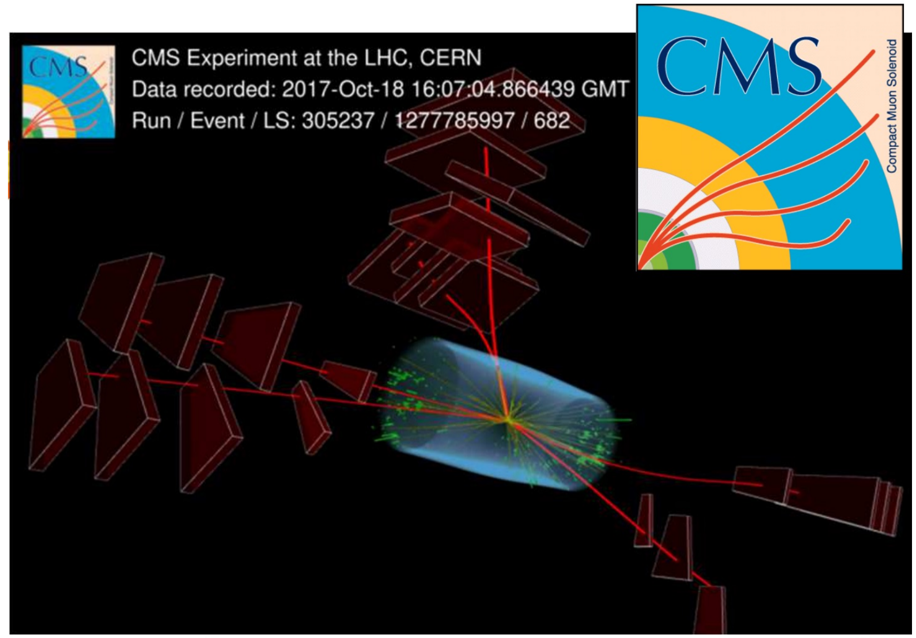
First observation of triple J/ψ in pp

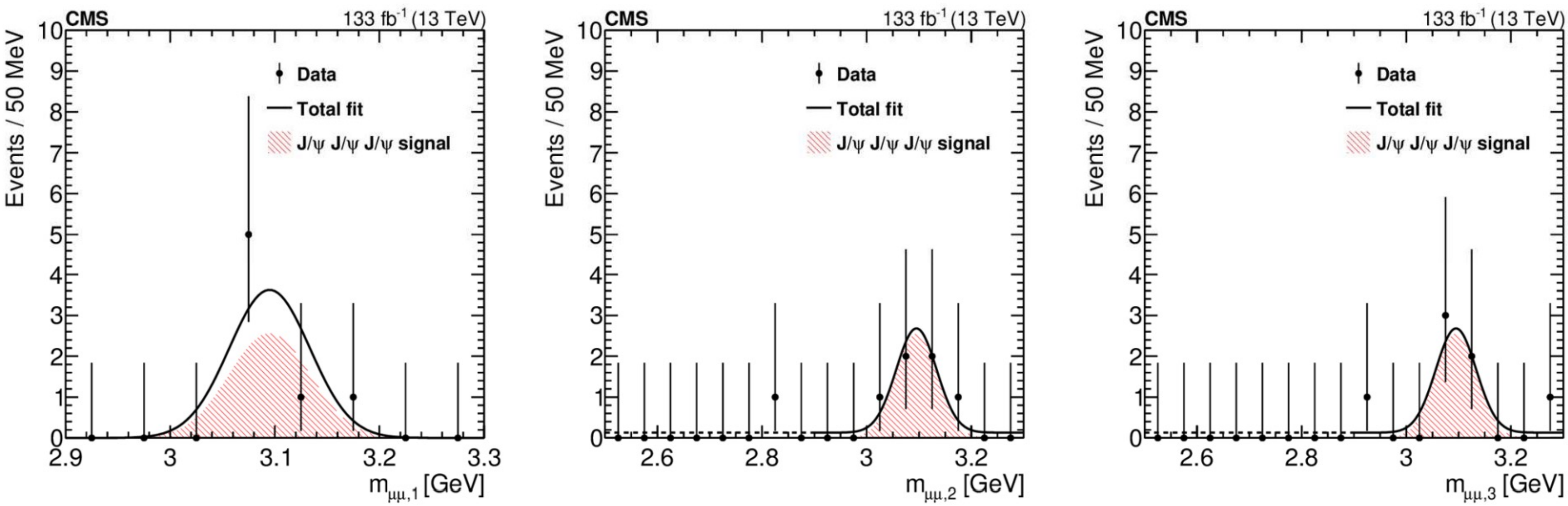
Signal yield: $5^{+2.6}_{-1.9}$ events

Significance > 5σ

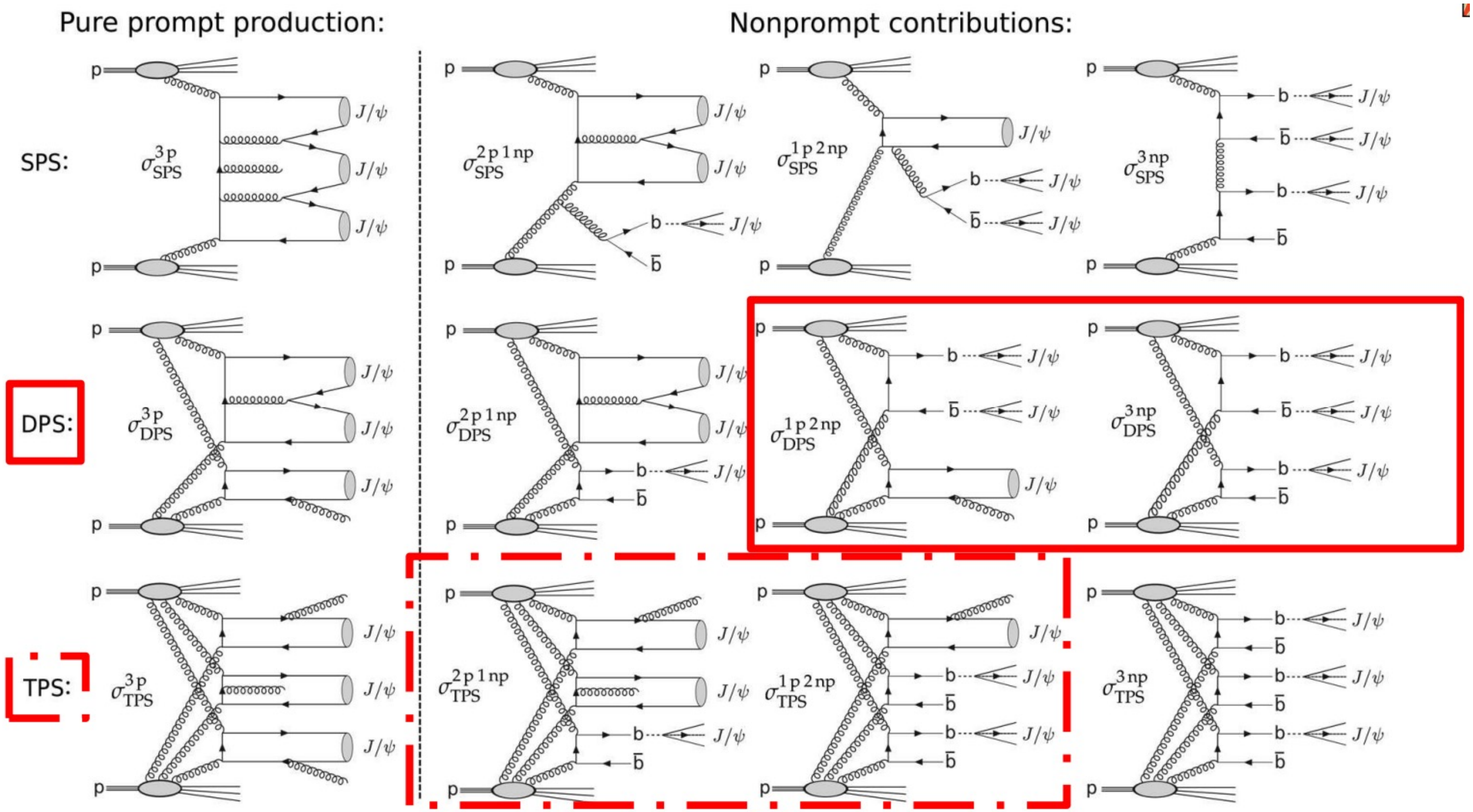
σ(pp→J/ψJ/ψJ/ψX)
= 272 $^{+141}_{-104}$ (stat) ± 17 (syst) fb

[Nature Physics 19 (2023) 338]





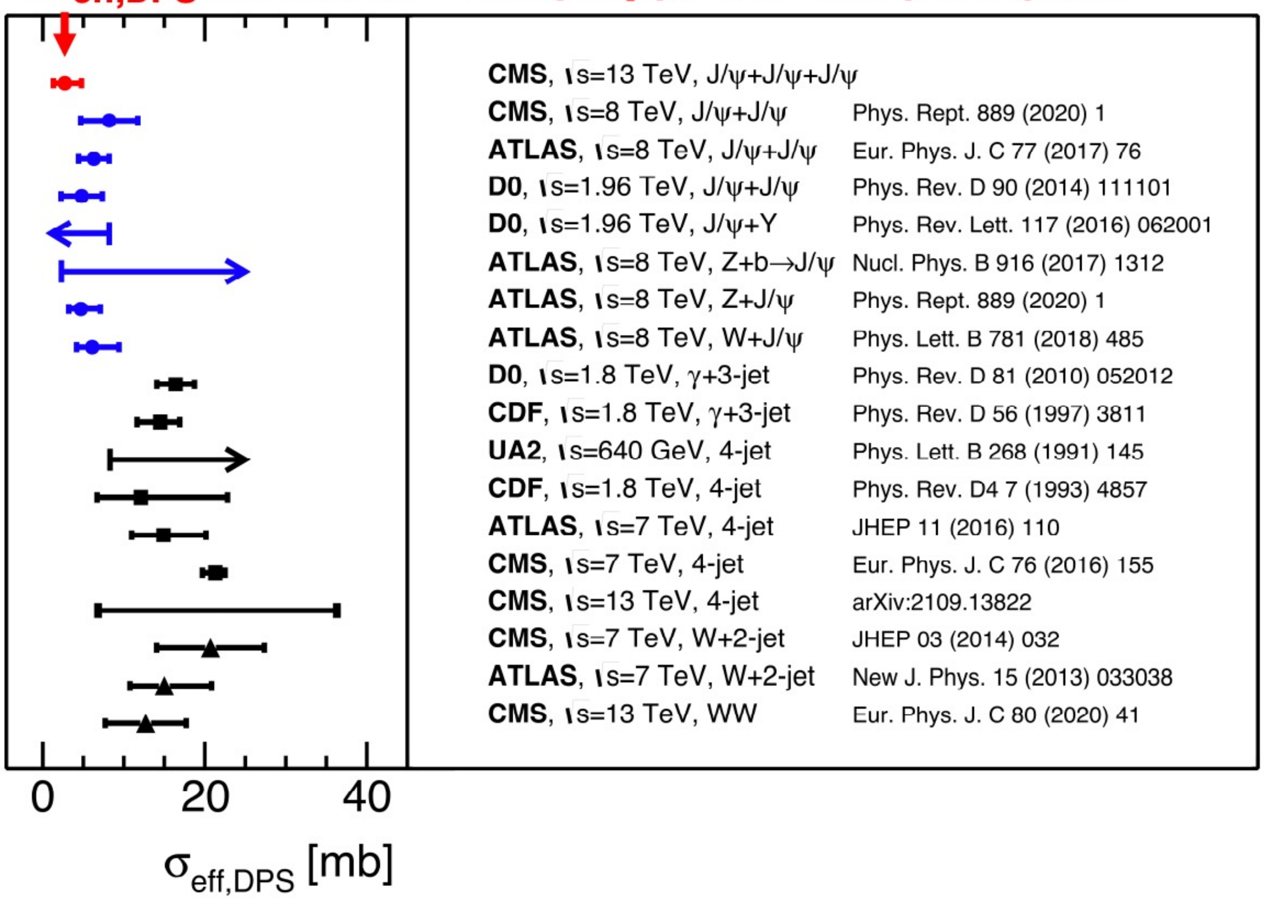
3 J/ψ: SPS, DPS and TPS processes



- Expect dominance of DPS, with some TPS and very little SPS
  - SPS: ~6%, DPS: ~74%, TPS: ~20%

DPS effective cross section

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



Consistent with results from di-quarkonium

3 – 10 mb

Inconsistent with jets, photons and W bosons

10 – 20 mb

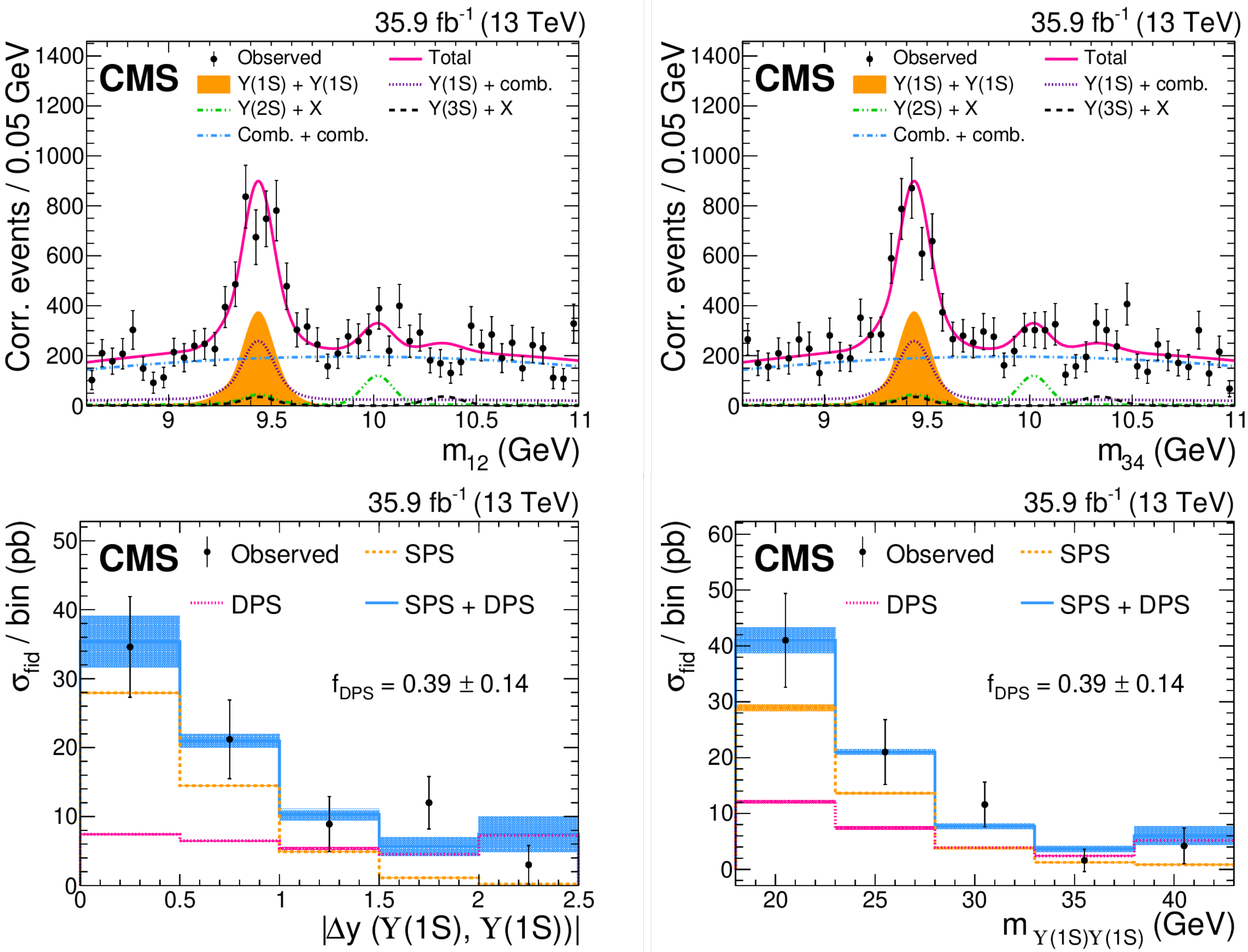
Two "clusters" of results -> σ_{eff} might not be universal

Double Upsilon at 13 TeV

- 35.9 fb^{-1} pp collision at 13 TeV, both |Y(1S)|<2

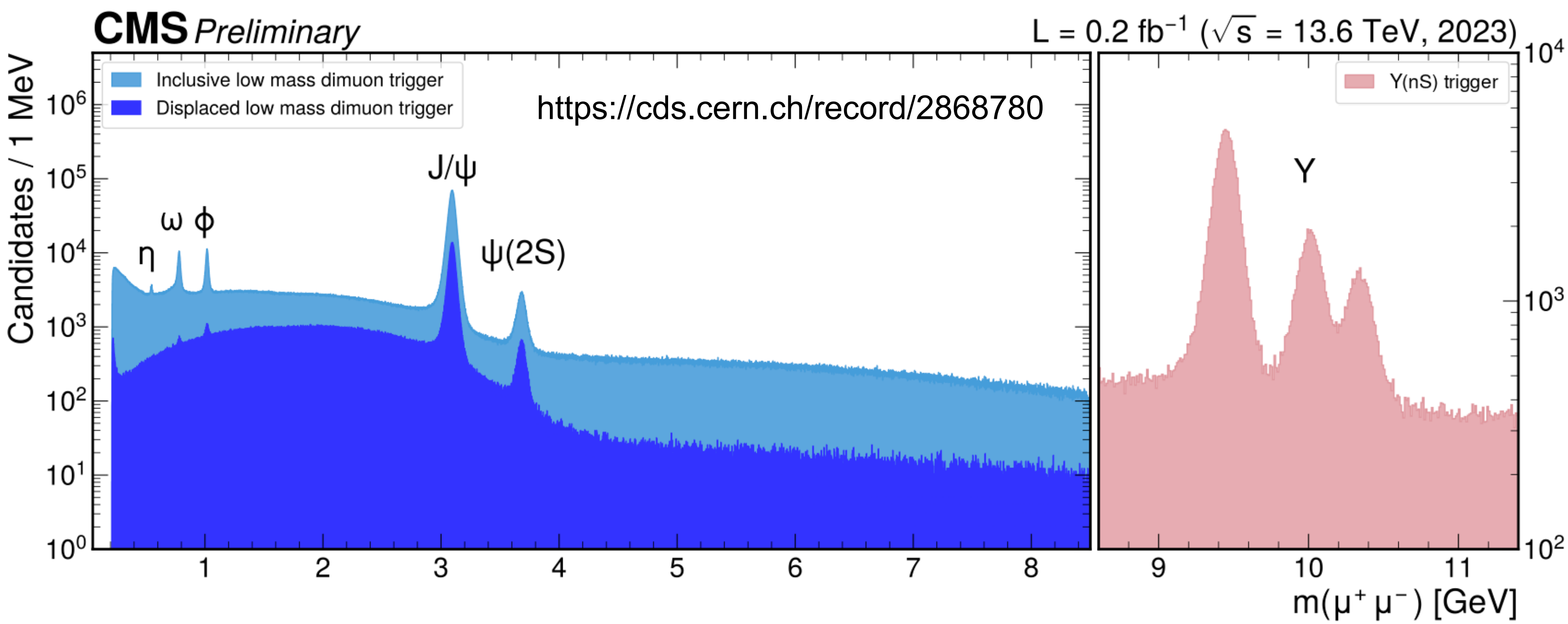
$$\sigma_{\text{fid}} = 79 \pm 11\,(\text{stat}) \pm 6\,(\text{syst}) \pm 3\,(\mathcal{B})\ \text{pb},$$

Phys. Lett. B 808 (2020) 135578



Outlook for Run 3

- New trigger at CMS for Run 3, new possibilities!
  - J/ψ + ψ(2S)
  - ψ(2S) + ψ(2S)
  - J/ψ + Upsilon
  - ψ(2S) + Upsilon



Thank you!