on behalf of
The CMS Collaboration

B physics results from CMS

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Introduction

Recent B Physics and Quarkonia Preliminary Results at CMS (July 2021):

- **CMS-PAS-BPH-18-004** - Observation of $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$ and $B_s^0 \rightarrow \psi(2S)K_S^0$ decays
- **CMS-PAS-BPH-21-004** - Observation of triple J/ψ meson production in proton-proton collisions at √s= 13 TeV

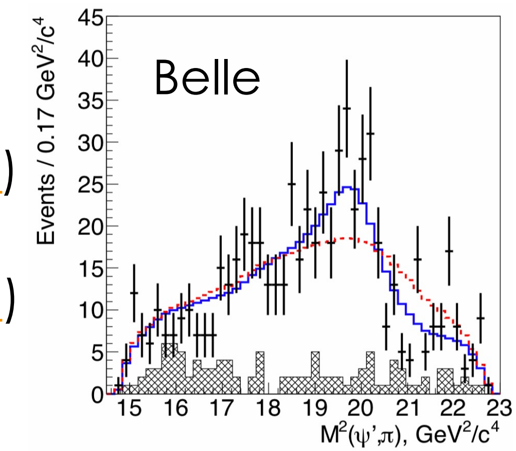
I. Observation of $B^0 \to \psi(2S) K_S^0 \pi^+ \pi^-$ and $B_s^0 \to \psi(2S) K_S^0$ decays

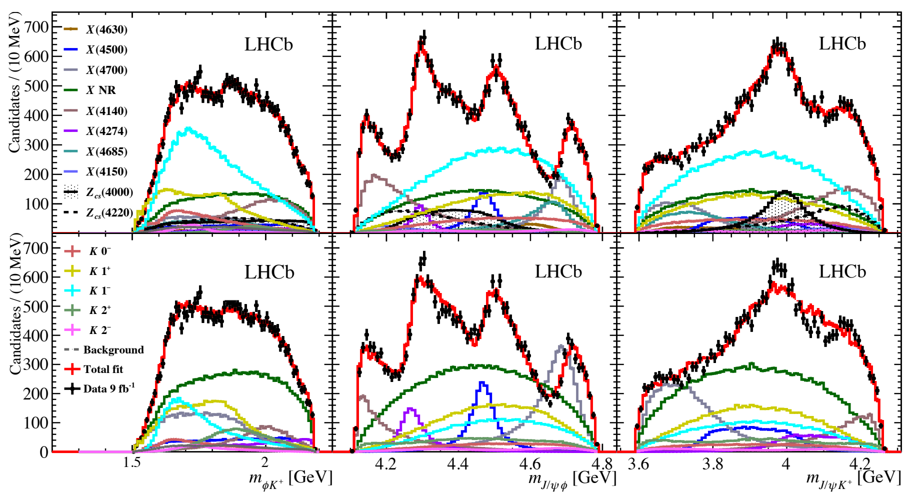
CMS-PAS-BPH-18-004

Motivation

Many exotic states have been observed in the last 15 years, and the nature of most of them is still unclear

- $Z_c(3900)^{\pm} \to J/\psi\, \pi^{+}$ BELLE (10.1103/PhysRevD.88.074026)
- $Z_c(4200)^{\pm} \to J/\psi\, \pi^{\pm}$ BaBar (10.1103/PhysRevD.79.112001)
- $Z_c(4430)^{\pm} \to \psi(2S)\, \pi^{\pm}$ BELLE (10.1103/PhysRevD.80.031104)
- $X(3915) \to J/\psi \omega$ BELLE (10.1103/PhysRevD.81.031103)
- $P_c(4457)^{+} \to J/\psi\, p$ LHCb (10.1103/PhysRevLett.115.072001)
- $Z_{cs}(4220)^{+} \to J/\psi\, K^{+}$ LHCb (CERN-EP-2021-025)





Decays with charmonium in final states could be a good laboratory for CP-violation measurements.

Introduction

We search for the new $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_S^0$ decays with CMS pp collision 2017-2018 data. The relative branching fraction ratios are measured using the relations:

$$R_s \cdot \frac{f_s}{f_d} \equiv \frac{\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} \cdot \frac{f_s}{f_d} = \frac{\epsilon\,(B^0 \to \psi(2S)K_S^0)}{\epsilon\,(B_s^0 \to \psi(2S)K_S^0)} \cdot \frac{N\,(B_s^0 \to \psi(2S)K_S^0)}{N\,(B^0 \to \psi(2S)K_S^0)}, \text{ and}$$

$$R_{\pi^+\pi^-} \equiv \frac{\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} = \frac{\epsilon\,(B^0 \to \psi(2S)K_S^0)}{\epsilon\,(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)} \cdot \frac{N\,(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{N\,(B^0 \to \psi(2S)K_S^0)},$$

Where N is number of signal events in data, ϵ is efficiency.
The $B^0 \to \psi(2S)K_S^0$ decay is used for the normalization thanks to it's similar topology and kinematics to the decays of interest.

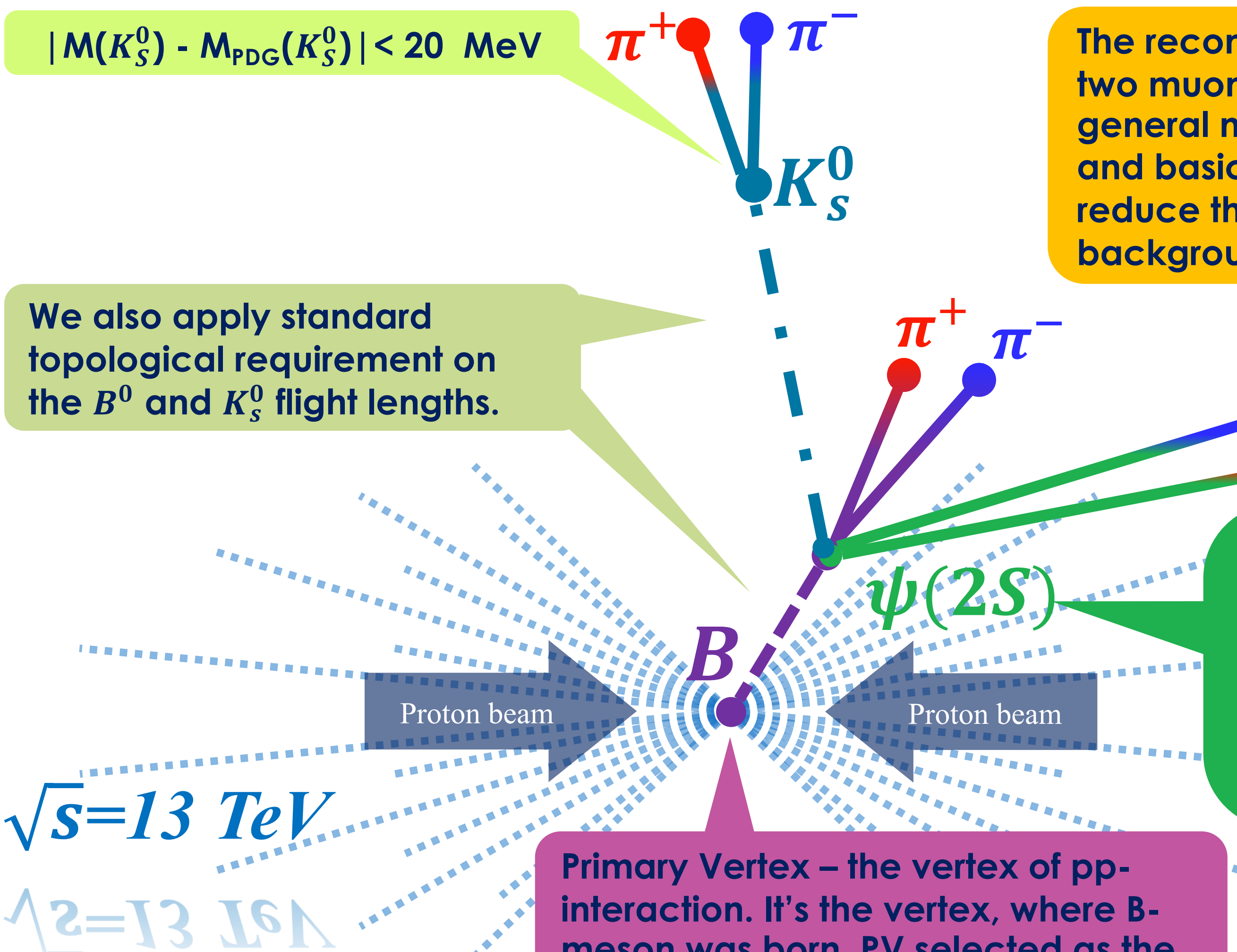
f_s/f_d – the ratio of the B_s^0 and B^0 production cross sections.

Selection criteria

$|M(K_S^0) - M_{PDG}(K_S^0)| < 20$ MeV

The reconstructed $\psi(2S)$ decays into two muons that must also satisfy general muon identification criteria and basic kinematic requirements to reduce the combinatorial background.

We also apply standard topological requirement on the B^0 and K_S^0 flight lengths.



The CMS experiment has a perfect muon identification: in dimuon channel, $\psi(2S)$ separates from other charmonium states by only requiring mass window: $M(\psi(2S))$ in [3.55, 3.95] GeV

Primary Vertex – the vertex of pp-interaction. It's the vertex, where B-meson was born. PV selected as the one with the smallest pointing angle.

Efficiencies

Efficiencies were obtained from phase-space MC samples.
Measured ratios of efficiencies are:

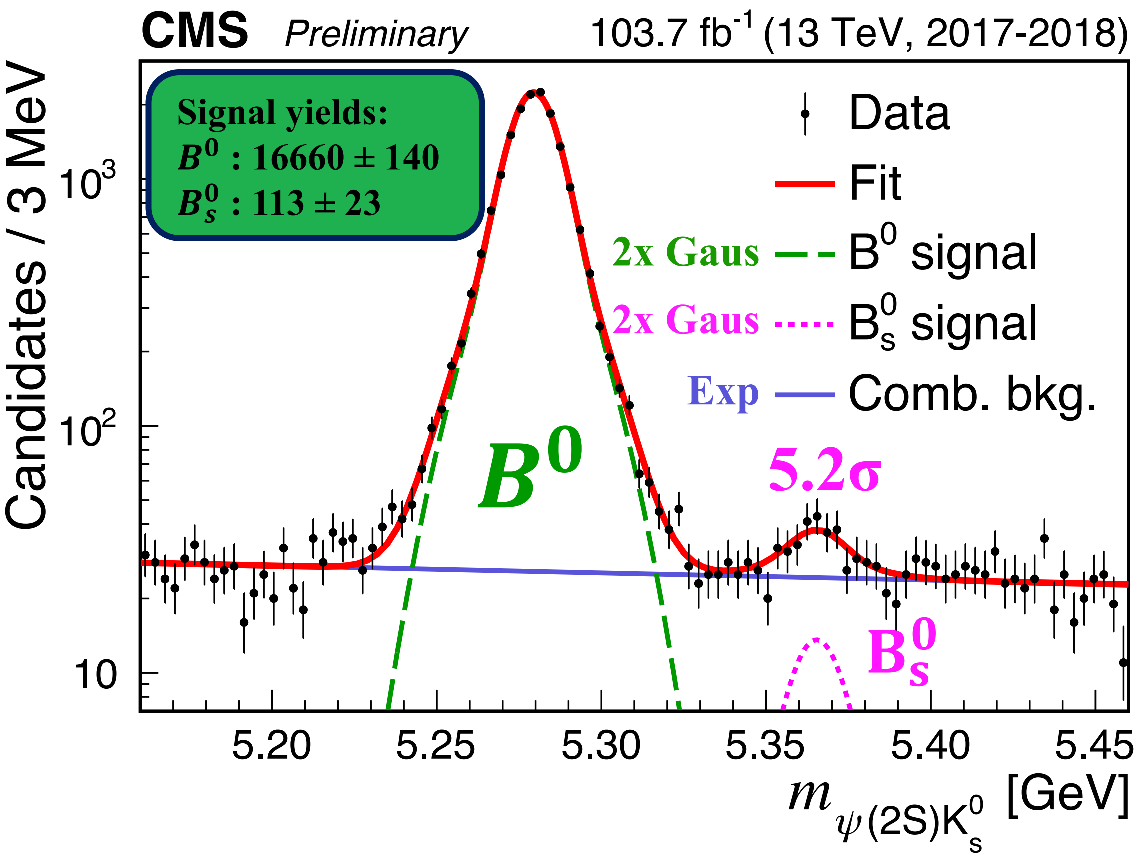
$$\frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B_s^0 \to \psi(2S)K_S^0)} = 1.019 \pm 0.013;$$

$$\frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)} = 2.29 \pm 0.03$$

- For the B_s^0 channel efficiency is very close to the one for B^0 due to the same products of the reactions and similar masses of the decaying particles.
- The efficiency is lower for $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ channel due to additional track reconstruction.

<u>The ratios agree with our expectations</u>

$\psi(2S)K_S^0$ mass distribution



Background: exponential function

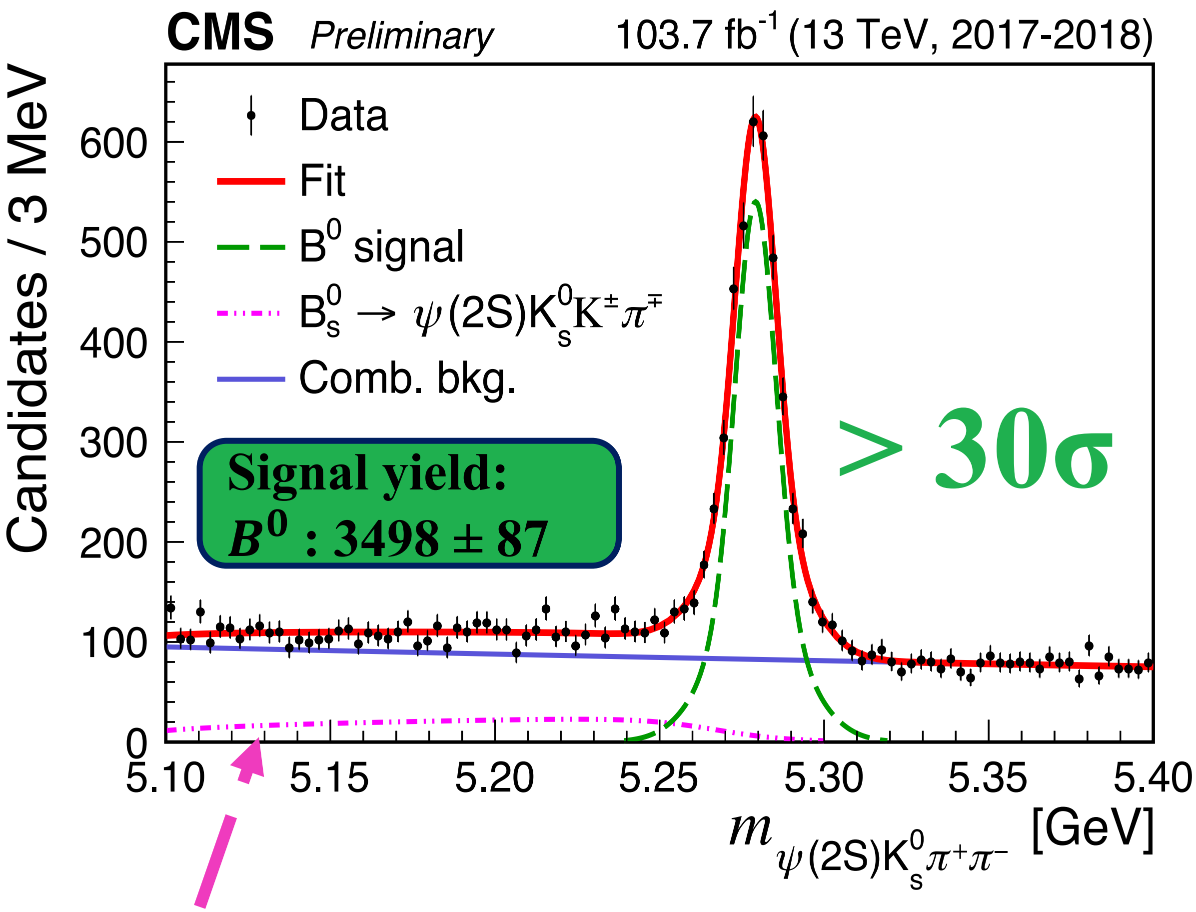
Signal: 2-x Gaus with common mean for both peaks. $B^0 \to \psi(2S)K_S^0$ parameters are floating.

$$\frac{\sigma(B_s^0)}{\sigma(B^0)} = \frac{\sigma^{MC}(B_s^0)}{\sigma^{MC}(B^0)}$$

First observation!

The **obtained significance is 5.2σ** and varies in the range 5.1–5.4σ within the variations of the fit model used in the estimation of the systematic uncertainties. (See next slides)

$\psi(2S)K_S^0\pi^+\pi^-$ mass distribution



Background: exponential function

Signal: 2-x Gaus with common mean

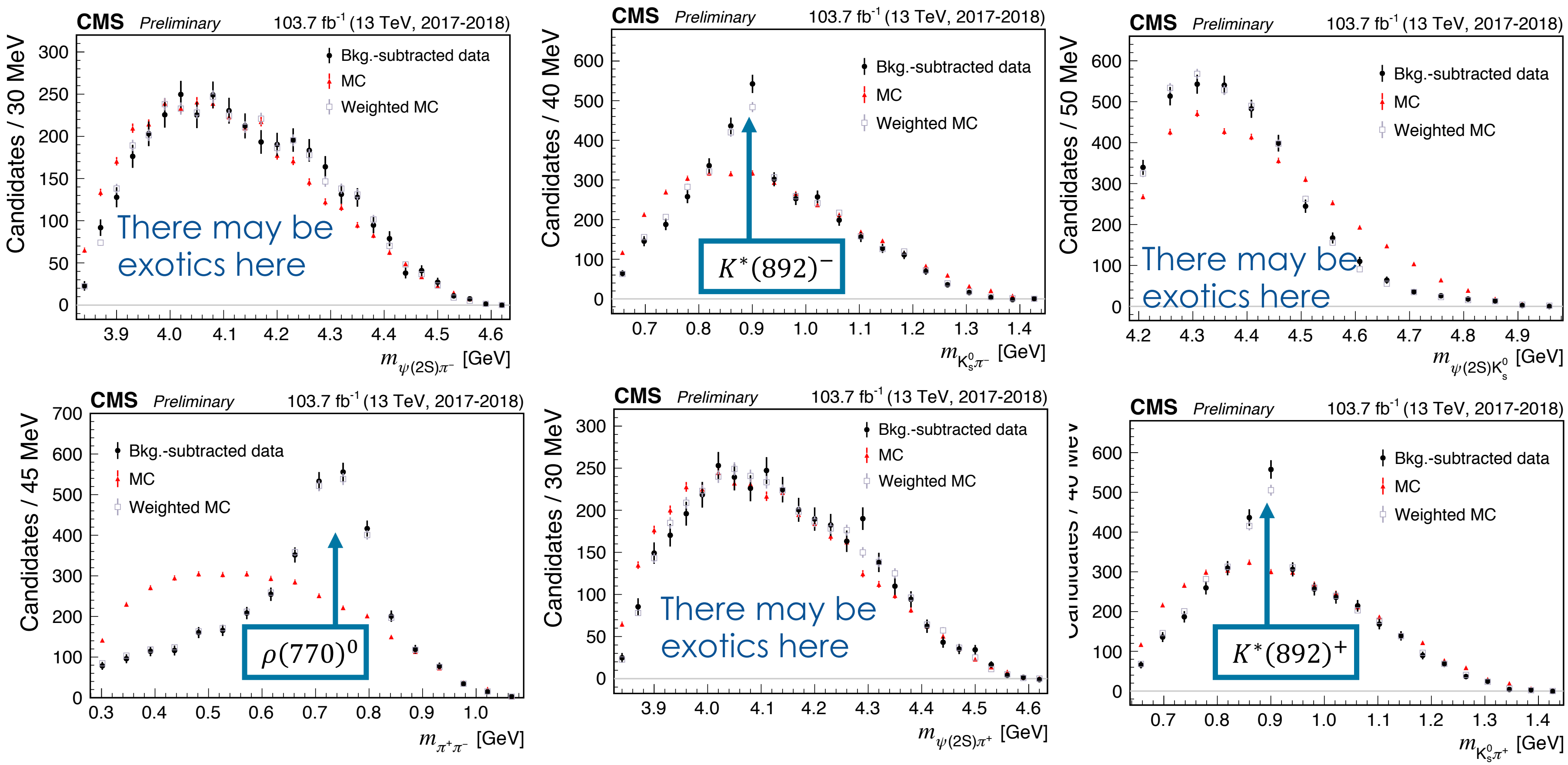
The **significance of the peak exceeds 30σ**

First observation!

$B_s^0 \to \psi(2S)K_S^0K^\pm\pi^\mp$: "**Reflection**" from misreconstructed $B_s^0 \to \psi(2S)K_S^0\boldsymbol{K}^\pm\pi^\mp$ decay with **kaon** reconstructed as pion. The shape parameters are fixed to the MC values and the normalization is free.

In search of exotics

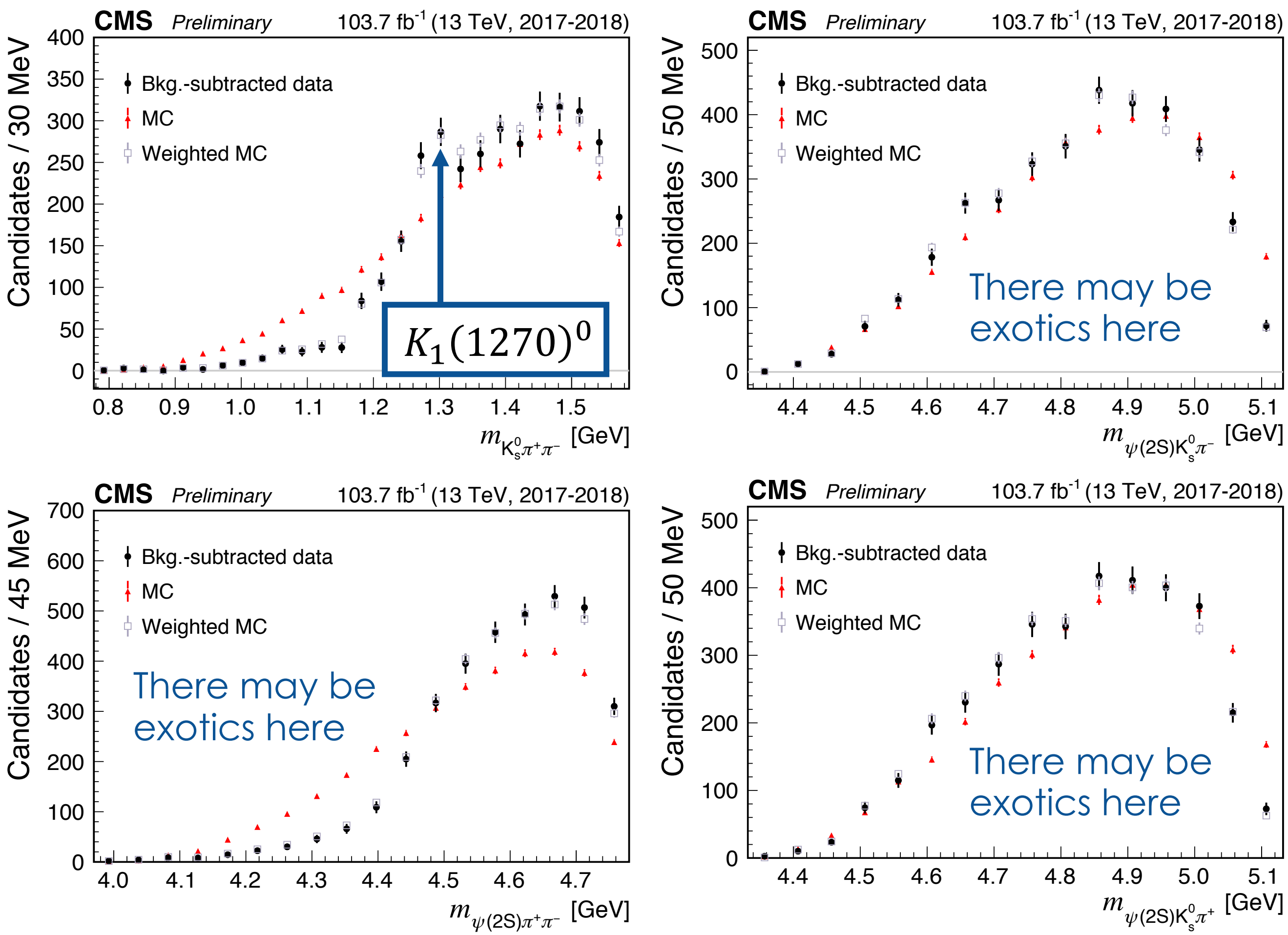
sPlot distributions of six 2-body intermediate invariant masses from the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay in data compared to MC.



The data (black) shows clear signs of the known $K^*(892)^{\pm}$ and $\rho(770)^0$ resonances in $K_S^0\ \pi^{\pm}$ and $\pi^+\pi^-$ systems, but not the exotics like $Z_{cs}(4220)^+$…

In search of exotics

sPlot distributions of four 3-body intermediate invariant masses from the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay in data compared to MC



The data (black) shows a hint of the $K_1(1270)^0 \to K_S^0\pi^+\pi^-$ but not the narrow exotic structure…

Systematic uncertainties

The systematic uncertainty related to the choice of the fit model is evaluated by testing different fit models: the largest deviation in the measured ratio from the baseline value is taken as systematic uncertainty.

MC samples have finite volume

MC simulation does not take into account the intermediate resonance structure, leading to significant disagreement between data and MC in intermediate mass distributions, what leads to a potential bias in the efficiency. To estimate the corresponding systematic uncertainty, the MC sample is reweighted to be consistent with the data, and the difference between the baseline efficiency and the efficiency obtained on the weighted MC is taken as a systematic uncertainty.

Source	R_s	$R_{\pi^+\pi^-}$
Background model	2.5	0.8
Signal model	1.5	0.8
Shape of reflection	—	0.5
Finite size of MC	1.3	1.1
Intermediate resonances	—	5.0
Tracking efficiency	—	4.2
Total	3.2	6.7

For the ratio $R_{\pi^+\pi^-}$, we consider an additional uncertainty due to tracking efficiency of 2 additional pions of 4.2%

Results

The first observation **of the decays** $\boldsymbol{B_s^0 \to \psi(2S)K_S^0}$ **and** $\boldsymbol{B^0 \to \psi(2S)K_S^0\pi^+\pi^-}$ and estimation the branching fraction ratios:

$$\frac{\mathcal{B}(\mathrm{B_s^0} \to \psi(2\mathrm{S})\mathrm{K_S^0})}{\mathcal{B}(\mathrm{B^0} \to \psi(2\mathrm{S})\mathrm{K_S^0})} \cdot \frac{f_s}{f_d} = (0.69 \pm 0.14\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst}))\%,$$

$$\frac{\mathcal{B}(\mathrm{B^0} \to \psi(2\mathrm{S})\mathrm{K_S^0}\pi^+\pi^-)}{\mathcal{B}(\mathrm{B^0} \to \psi(2\mathrm{S})\mathrm{K_S^0})} = (48.0 \pm 1.3\,(\mathrm{stat}) \pm 3.2\,(\mathrm{syst}))\%.$$

Inspection of the phase-space distributions of the $B^0 \to \psi(2S)K_S^0\pi^+\pi^-$ decay **does not reveal any additional exotic narrow structure.**

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

CMS-PAS-BPH-21-004

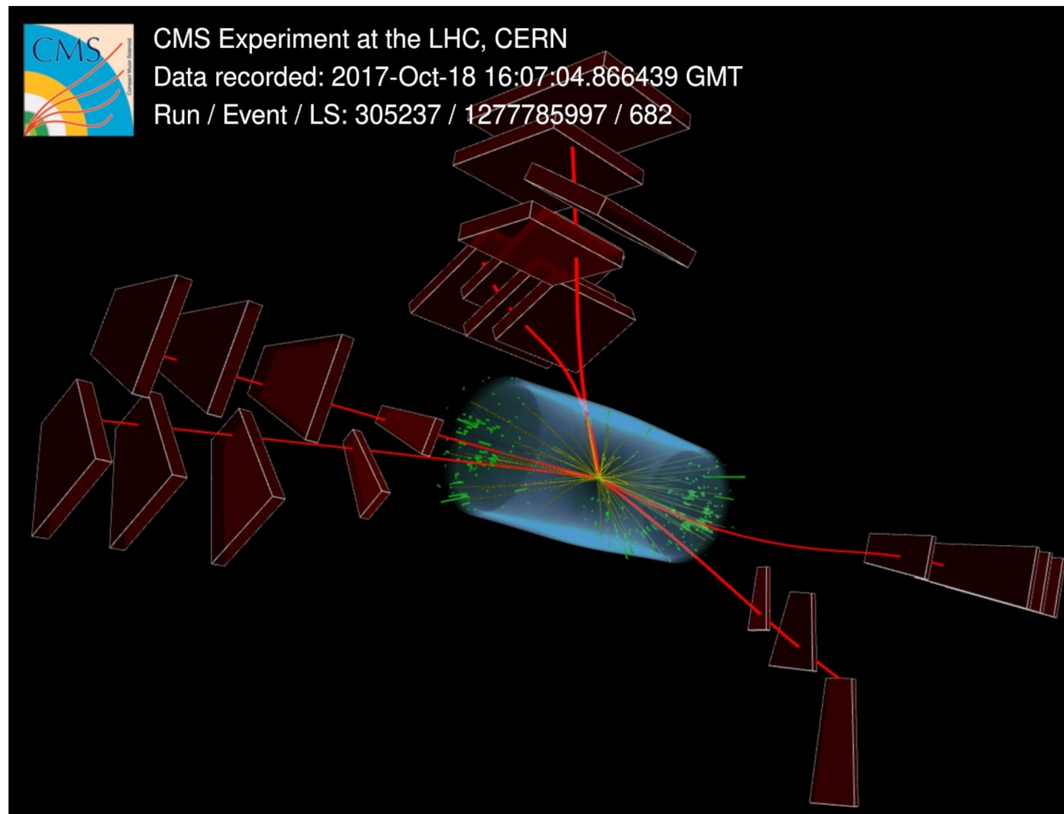
Motivation

- 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), triple-parton scatterings (TPS) process never observed so far

Introduction

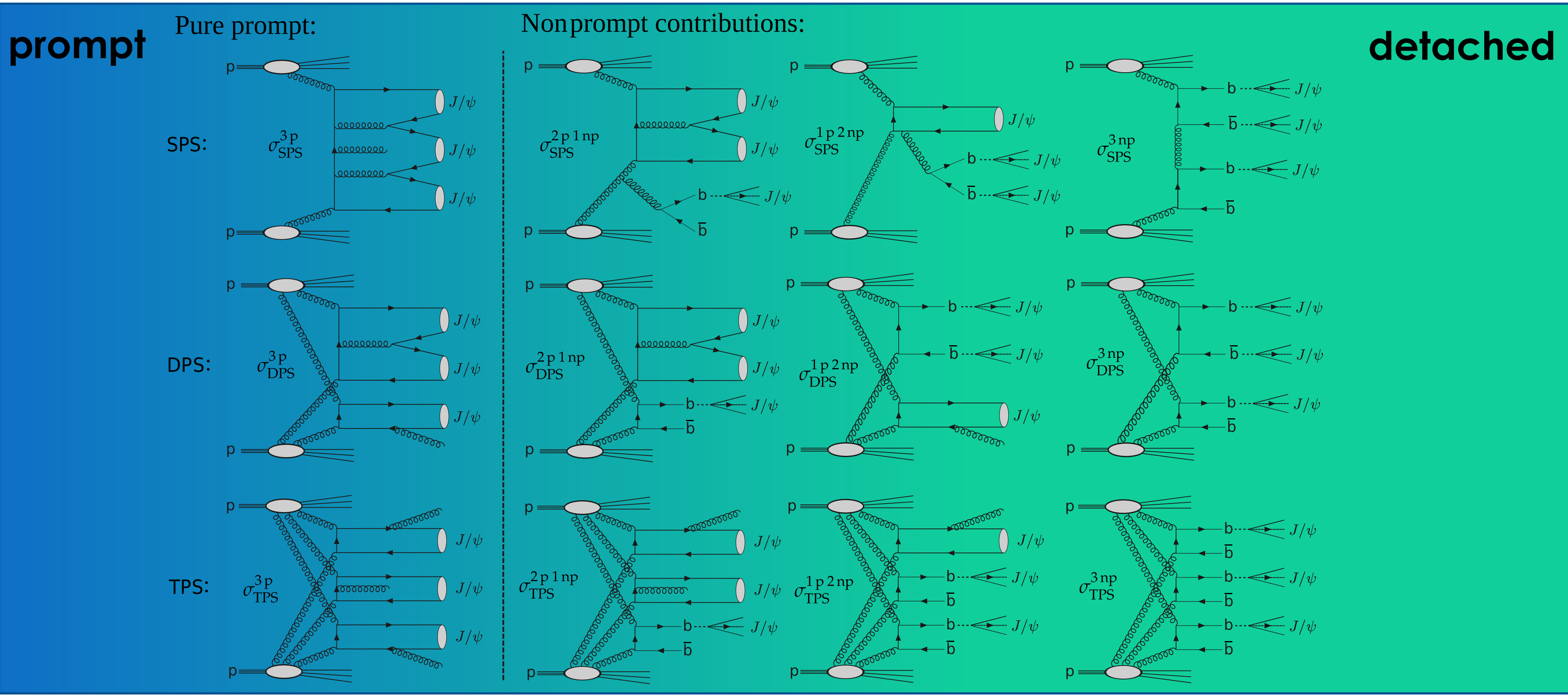
This work presents the first observation of the production of three J/ψ mesons in pp collisions, using 133 fb^{-1} of data collected at $\sqrt{s}$ = 13 TeV by the CMS experiment.
The J/ψ mesons are reconstructed in their **dimuon decay mode**.

The extracted cross section is compared to theoretical expectations based on SPS, DPS, and TPS contributions, and the effective DPS cross section $\sigma_{eff,DPS}$ associated to the process is derived.



Prompt and non prompt contributions

The analysis of the *6μ* final state offers a very clean experimental signature for triple-J/*ψ* production, **including prompt and non prompt J/*ψ* mesons**



Selection & Reconstruction

$$pp \to J/\psi\, J/\psi\, J/\psi\, X$$

6μ

Each of the reconstructed J/ψ decays into two oppositely charged muons. No muon is shared between 2 J/ψ candidates

The CMS experiment has a perfect muon identification: in dimuon channel, J/ψ separates from other charmonium states by only requiring mass window: $2.9\ GeV < m(\mu^+\mu^-) < 3.3$ GeV

Eliminating the possibility of accidental combinations of muons from different pp pileup collisions

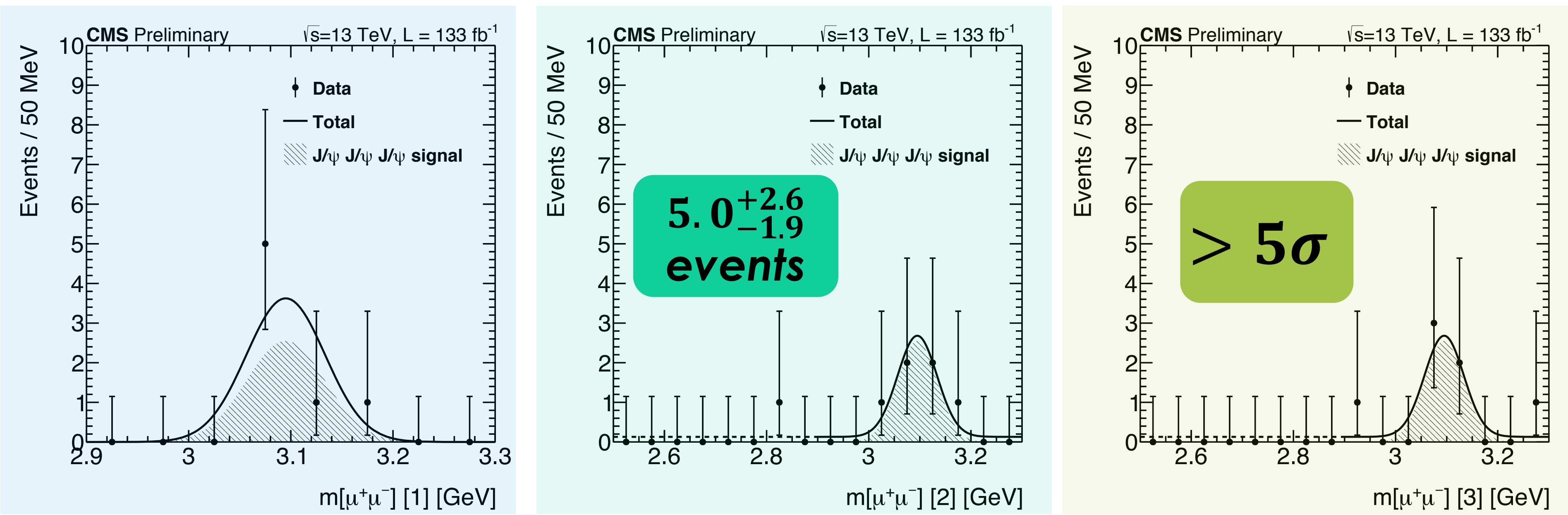
For all muons	$p_T > 3.5\,\text{GeV}$ for $\lvert\eta\rvert < 1.2$ $p_T > 2.5\,\text{GeV}$ for $1.2 < \lvert\eta\rvert < 2.4$
For all J/ψ mesons	$p_T > 6\,\text{GeV}$ and $\lvert y\rvert < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3\,\text{GeV}$

Each of the candidates have to originate from a common vertex with a probability greater than 0.5%, as determined by a Kalman vertex fit.

Signal extraction

The signal is extracted with a three-dimensional unbinned extended maximum likelihood fit, in the three dimuon invariant mass $m[\mu^+\mu^-][1,2,3]$ variables.

Signal: gaussian with resolution fixed from MC fit and mean fixed to PDG J/ψ mass - $J/\psi_1^{(signal)} \cap J/\psi_2^{(signal)} \cap J/\psi_3^{(signal)}$
Background: exponential function – 7 rest of the combinations of the three J/ψ to be signal or background



Cross section measurement

$$\sigma(\mathrm{pp} \to \mathrm{J}/\psi\, \mathrm{J}/\psi\, \mathrm{J}/\psi\, \mathrm{X}) = N_{\mathrm{sig}}^{3\mathrm{J}/\psi} \,/\, (\epsilon\, \mathcal{L}_{\mathrm{int}}\, \mathcal{B}^3_{\mathrm{J}/\psi \to \mu^+\mu^-})$$

Number of extracted signal events - $\mathbf{5.0^{+2.6}_{-1.9}}$

total efficiency coming from trigger (84%), reconstruction (78%)

the total integrated luminosity - 133 fb^{-1}

$(5.96\% \pm 0.03\%)^3$

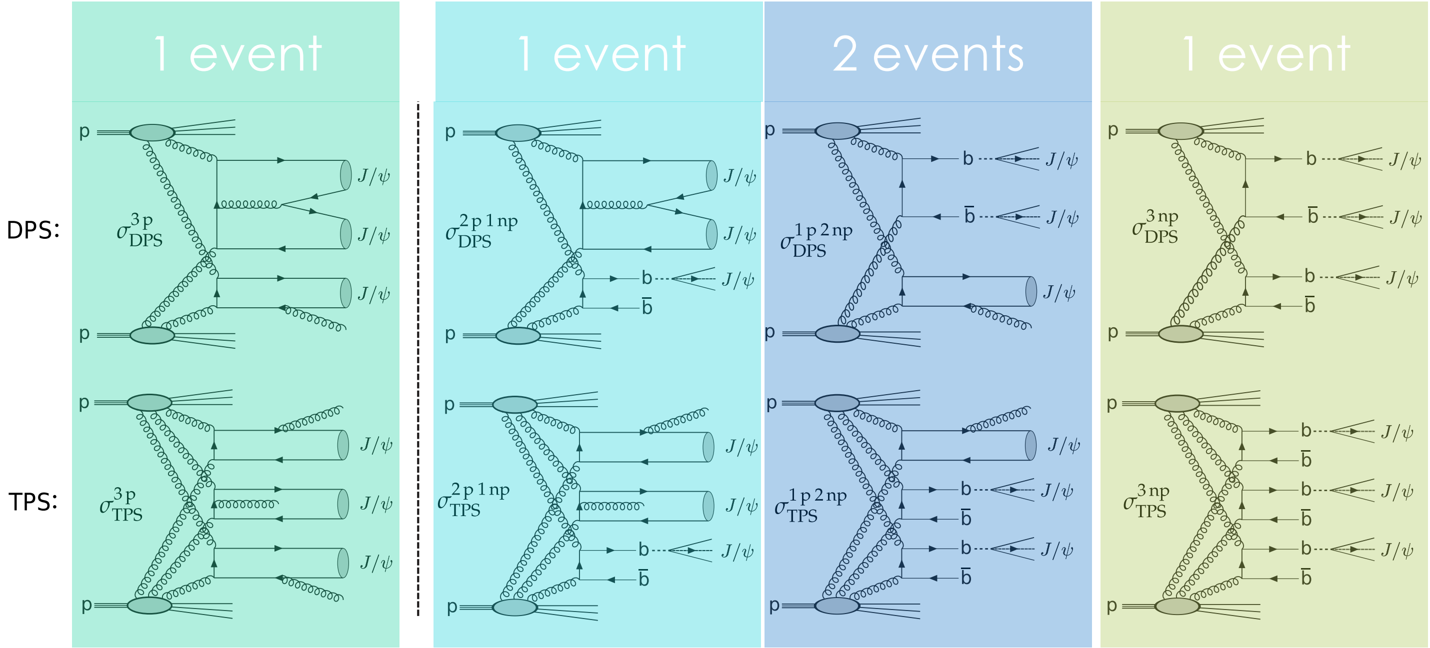
$$\sigma(\mathrm{pp} \to \mathrm{J}/\psi \mathrm{J}/\psi \mathrm{J}/\psi\, \mathrm{X}) = 272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}.$$

Are J/ψ prompt or from b hadron decays?

A classification of prompt and non prompt events is attempted via 2 approaches using J/ψ's proper decay length ($L^{J/\psi}$):

1. Cut on $L^{J/\psi}$ at 60μm
2. Fit all individual measurements with prompt and nonprompt templates derived from MC.

Both methods leads to same classification:



Systematic uncertainties

Alternatives:
- Crystal ball
- Gaussian with floating resolution

- first- order polynomial
- zeroth-order polynomial

Obtained as the largest deviation while varying the composition of the MC event sample

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%

The total systematic uncertainty of the cross section measurement is 6.2%. Measured cross section for triple J/ψ production, within the fiducial region is

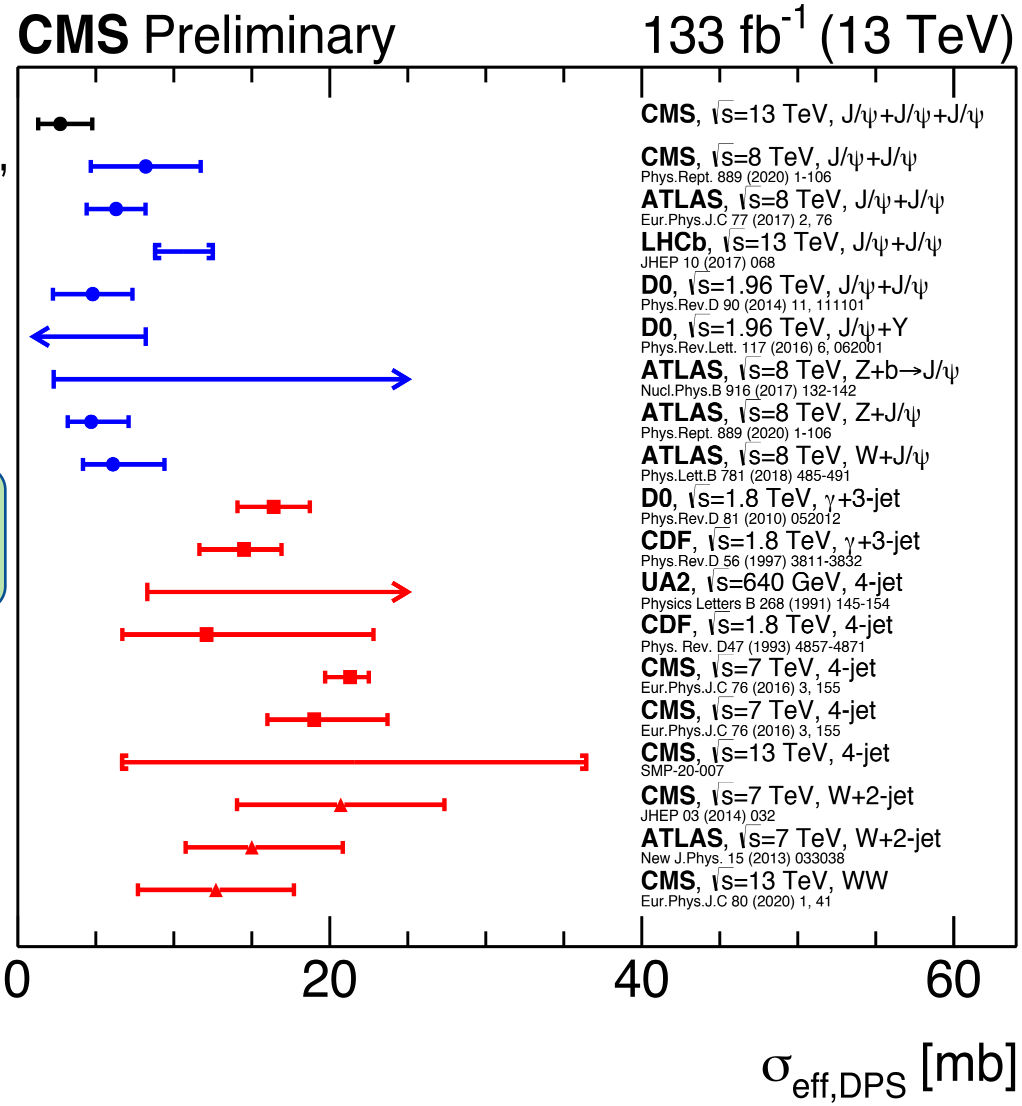
$$\sigma(\mathrm{pp} \to \mathrm{J}/\psi\mathrm{J}/\psi\mathrm{J}/\psi\,\mathrm{X}) = 272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}.$$

DPS cross section

Using the obtained result ($\sigma_{tot}^{3J/\psi}$), theoretical predictions and MC modeling, in a baseline "geometric" approach that ignores parton correlations, one can extract the value of the effective DPS cross section:

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

where the first uncertainty is due to the experimental precision of $\sigma_{tot}^{3J/\psi}$ and the second one is due to the propagation of all sources of theoretical uncertainties



Results

- The first observation of the concurrent production of 3 J/ψ mesons
- The fiducial cross section is measured to be

$$\sigma(\mathrm{pp} \to \mathrm{J}/\psi\mathrm{J}/\psi\mathrm{J}/\psi\,\mathrm{X}) = 272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}.$$

- Under “geometric” approach that ignores parton correlations, effective DPS cross section parameter is obtained

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

Within its large uncertainty, this value is consistent with similarly extracted parameters from double-quarkonium measurements, but significantly smaller than the effective DPS cross sections derived from double-particle final states that include high-p_T jets, photons, and electroweak bosons.

Conclusion

The CMS collaboration is still continuing the investigations in the B-physics and quarkonia sector.

With RUN III data we will have great opportunities for researching possible BSM processes.

More CMS publications here:

https://cms-results.web.cern.ch/cms-results/public-results/publications

THANK YOU FOR YOUR ATTENTION