Observation of simultaneous production of 3 J/Ψ mesons in pp collisions

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On behalf of the CMS collaboration

ICHEP2022: 41st International Conference on High Energy Physics, 6-13 Jul 2022, Bologna (Italy)

arXiv:2111.05370,
CMS-BPH-21-004; CERN-EP-2021-215
Submitted to Nature Physics

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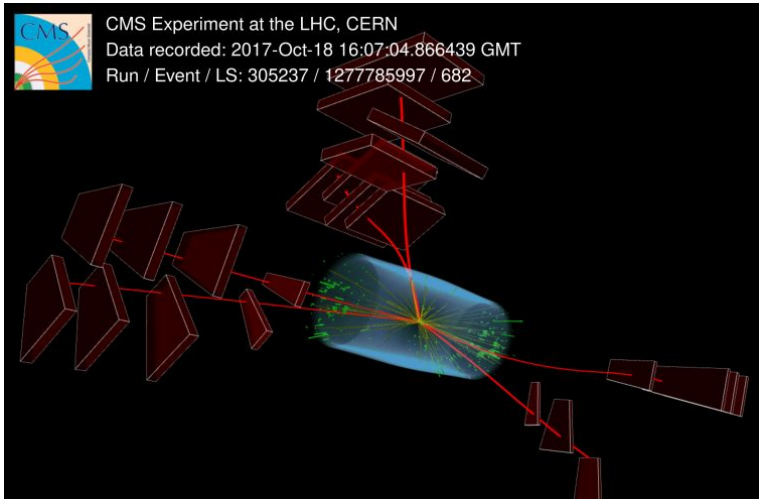


Motivation

- ➔ The triple-parton scattering process has only been proposed recently for study at the LHC[link].
- ➔ Searched for the **very rare process of three J/ψ particles** being produced in a single p-p collision
  - ◆ **Such a process has never been observed before!**
  - ◆ It provides an alternative way to estimate the effective transverse distance among the interacting constituents inside the proton.
- ➔ **Many of the features between individual partons, are very difficult to calculate theoretically[link].**
- ➔ **Measurements of such processes allow for a deeper understanding of the proton structure.**
- ➔ **Besides, also of relevance at the LHC to predict backgrounds in rare Standard Model processes, and in searches for New Physics[link1,link2].**

$\sigma_{eff,DPS}$ effective cross section

In the simplest approach[link], ignoring any correlations between the individual partons

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

$\sigma_{eff,DPS}$ is an effective cross section that, in a purely geometric approach, can be determined from the pp transverse overlap.

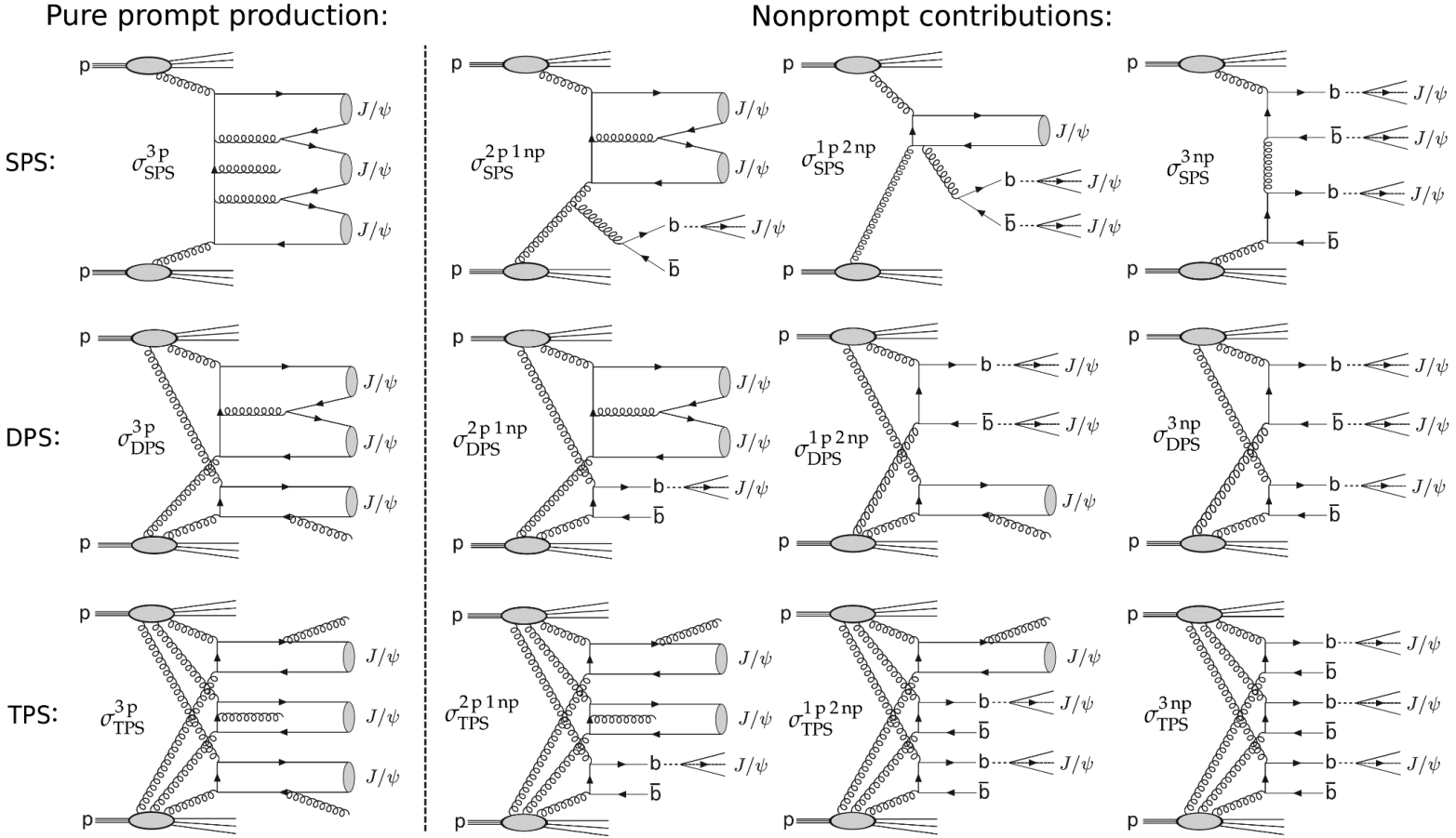
- **actually, in PYTHIA8 and HERWIG++ ~~20-30 mb**
- **from processes involving pairs of high-pT jets and/or EW bosons ~~10-20 mb**
- **from measurements of quarkonium pair production ~~3-10 mb**

The study of TPS via triple-J/ψ production can help

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

From HELAC-ONIA[link], in the production of three prompt-J/ψ the pure **SPS contributions are negligible** compared to those from DPS and TPS. **Golden Channel**.

Inclusive triple-J/ψ production via n-parton scatterings (NPS)



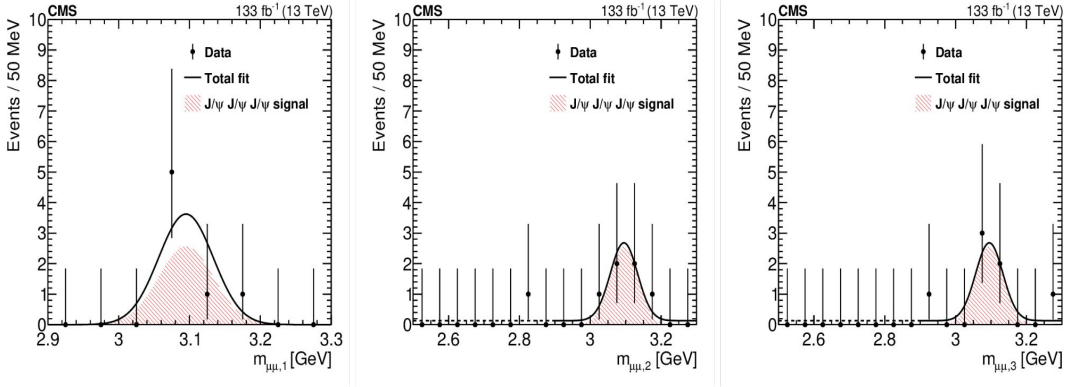
Selection and fit

Trigger: **J/ψ→μ+μ−** candidate plus an additional muon
pT>3.5 GeV for |η|<1.2 (barrel)
pT>2.5 GeV for 1.2<|η|<2.4 (endcap)

- ➢ 6 muons
- ➢ Dimuon invariant mass between 2.9 and 3.3 GeV
  - muons in pair must have opposite charge
  - no muon is shared between 2 J/ψ candidates

Defined to maximize the signal purity and the detector acceptance and efficiency.

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 $\lvert y\rvert < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3\,\text{GeV}$



Ordered (left to right) by decreasing pair pT

Yield is extracted using a 3D unbinned extended maximum likelihood fit:

- ➔ Signal: Gaussian with resolution fixed from MC.
- ➔ Background: exponential

Signal yield 5.0 ± 2.0 events

Significance exceeding 5σ

Cross section calculation and systematic uncertainties

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

Signal yield 5.0 ± 2.0 events

L total integrated luminosity 133 fb-1

ε total efficiency coming from:
1) **trigger 0.84% (MC)**
2) **Reconstruction*muonID**
   0.78% (data driven[link])

Dimuon branching fraction:
$B^3(J/\psi\to\mu\mu) = (5.961\% \pm 0.033\%)^3$

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

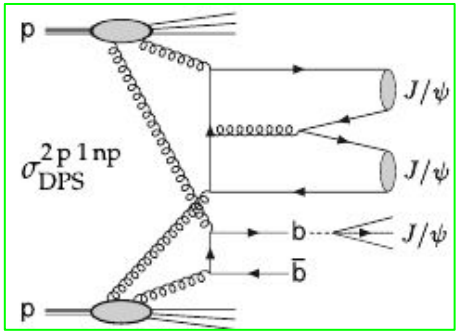
$$\sigma(\mathrm{pp} \to \mathrm{J/\psi J/\psi J/\psi\,X}) = 272^{+141}_{-104}\,(\mathrm{stat}) \pm 17\,(\mathrm{syst})\,\mathrm{fb}$$

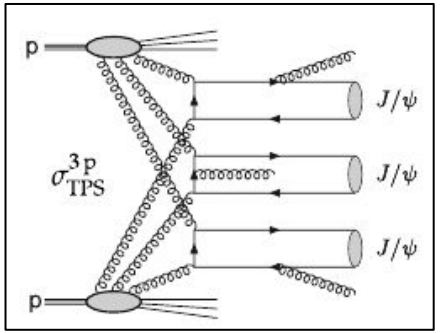
The total uncertainty is dominated by the statistical term

Prompt and nonprompt J/ψ mesons

A classification of prompt and non-prompt events is attempted. Prompt J/ψ mesons are defined as those having J/ψ proper decay length below 60 μm.

- **2 events 2np+1p**
- **1 event 1np+2p**
- **2 event 3np**
- **1 event 3p**





Some kinematic properties of the J/ψ candidates

Event	$m^{J/\psi,1}$ (GeV)	$m^{J/\psi,2}$ (GeV)	$m^{J/\psi,3}$ (GeV)	$L^{J/\psi,1}$ (mm)	$L^{J/\psi,2}$ (mm)	$L^{J/\psi,3}$ (mm)
1	3.08	3.10	3.07	1.77	0.24	−0.01
2	3.15	3.06	3.09	0.05	0.36	0.02
3	3.10	3.14	3.11	−0.04	0.03	0.05
4	3.07	3.03	3.09	0.48	0.81	0.82
5	3.12	3.14	3.14	−0.25	0.13	−0.02
6	3.06	3.17	2.94	0.11	0.38	0.61

Discussion

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

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

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

➢ **Similar for TPS**

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

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:

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

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

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

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

Discussion

➔ Using 8 theoretical SPS cross sections from HELACONIA(LO,NLO*)+data,PYTHIA8, and G5@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_{SPS}^{1p}	σ_{SPS}^{1np}	σ_{SPS}^{2p}	σ_{SPS}^{1p1np}	σ_{SPS}^{2np}	σ_{SPS}^{3p}	σ_{SPS}^{2p1np}	σ_{SPS}^{1p2np}	σ_{SPS}^{3np}
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 $\sigma_{eff,TPS} = (0.82 \pm 0.11)\ \sigma_{eff,DPS}$ [link], 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
$\sigma_{SPS}^{3J/\psi}$ (fb)	< 0.005	5.7	0.014	12	18
$N_{SPS}^{3J/\psi}$	0.0	0.10	0.0	0.22	0.32
$\sigma_{DPS}^{3J/\psi}$ (fb)	8.4	8.9	90	95	202
$N_{DPS}^{3J/\psi}$	0.15	0.16	1.65	1.75	3.7
$\sigma_{TPS}^{3J/\psi}$ (fb)	6.1	19.4	20.4	7.2	53
$N_{TPS}^{3J/\psi}$	0.11	0.36	0.38	0.13	1.0
$\sigma_{tot}^{3J/\psi}$ (fb)	15	34	110	114	272
$N_{tot}^{3J/\psi}$	0.3	0.6	2.0	2.1	5.0

Discussion

➔ Derived $\sigma_{eff,DPS}$ is found to be $\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}(exp)\ ^{+1.5}_{-1.0}(theo)$ 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**

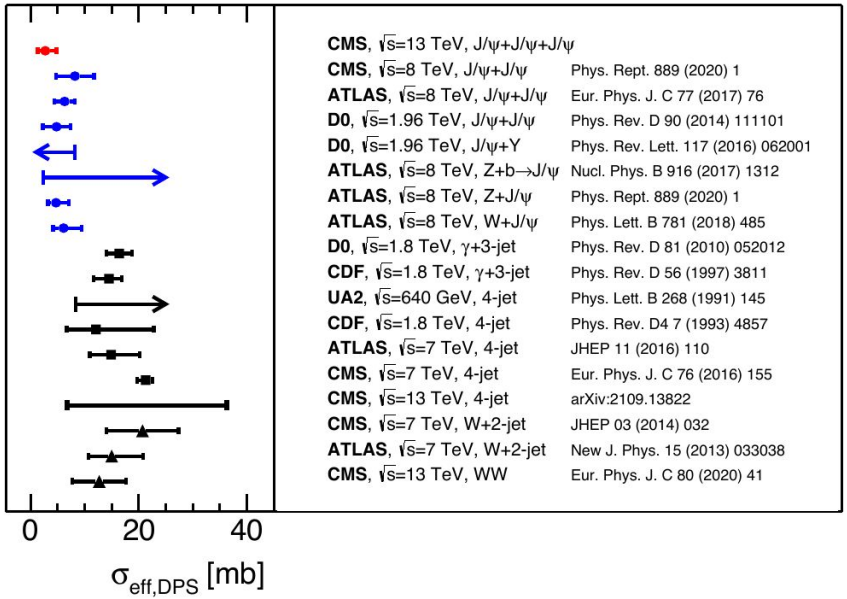
Derived $\sigma_{eff,DPS}$ value is consistent with the world-data of effective DPS cross sections obtained previously from diquarkonium production measurements:

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

but not consistent with extractions from processes with jets, photons, and W bosons:

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

Speculative educated guesses: it is because quarkonia are produced mostly in gluon-gluon scatterings, whereas mostly quarks intervene in the production of EW bosons.



Summary

First observation of triple J/ψ meson production

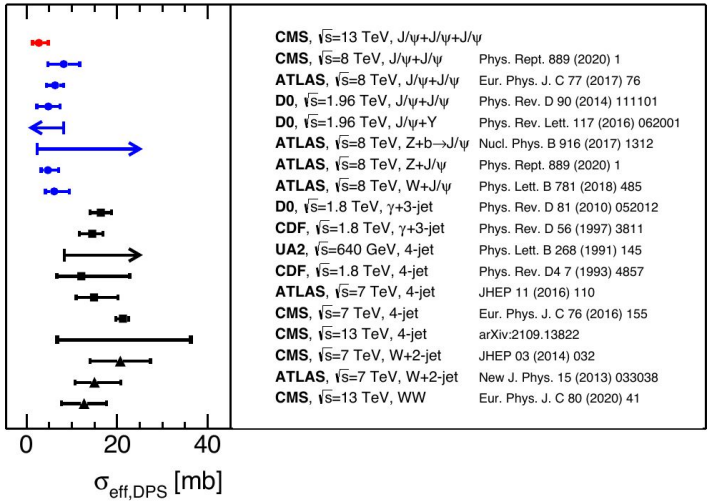
First experimental study of the simultaneous production of three particles in n-parton scatterings

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

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

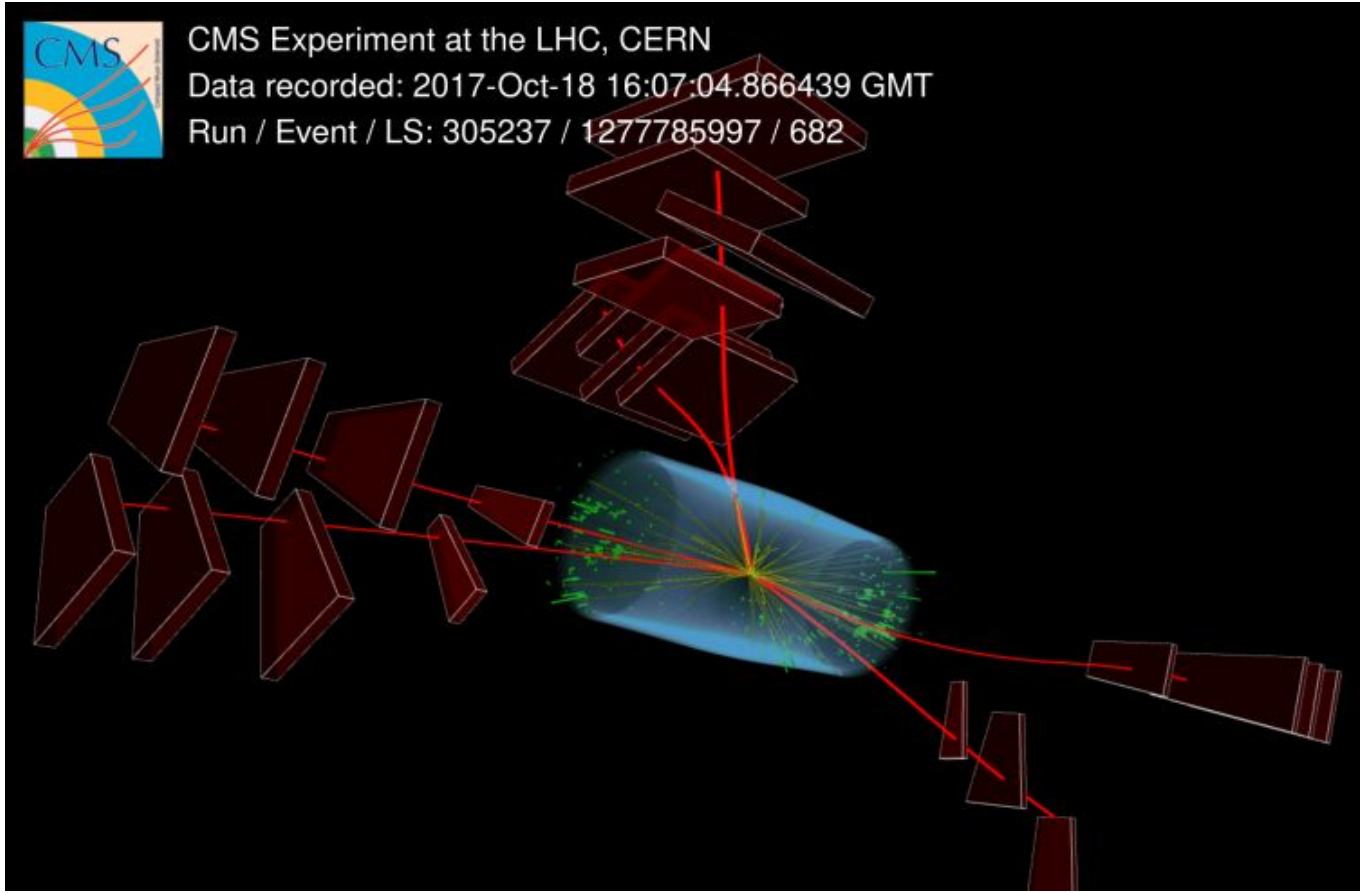
Novel input for further theoretical and experimental progress in understanding the n-parton scatterings dynamics.

Important step in a half-a-century old quest towards understanding the proton structure.



Backup slides

Event display



Event display of a proton-proton collision with 6 muons (red lines) produced in the decays of 3 different J/ψ mesons, as observed in the CMS detector.

Physics Briefing

Kinematic properties of the J/ψ candidates

Event	$m^{J/\psi,1}$ (GeV)	$m^{J/\psi,2}$ (GeV)	$m^{J/\psi,3}$ (GeV)	$L^{J/\psi,1}$ (mm)	$L^{J/\psi,2}$ (mm)	$L^{J/\psi,3}$ (mm)
1	3.08	3.10	3.07	1.77	0.24	−0.01
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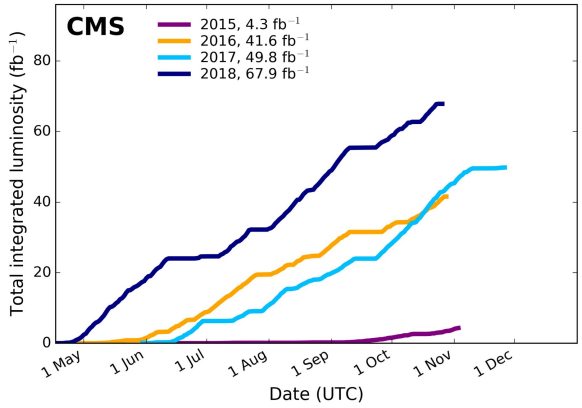
Event	$p_T^{J/\psi,1}$ (GeV)	$p_T^{J/\psi,2}$ (GeV)	$p_T^{J/\psi,3}$ (GeV)	$y^{J/\psi,1}$	$y^{J/\psi,2}$	$y^{J/\psi,3}$
1	17.64	17.50	8.68	−2.25	−0.39	1.53
2	91.50	54.04	11.81	1.99	0.81	−0.71
3	11.29	10.29	6.98	−0.50	−0.37	−1.64
4	15.46	10.61	7.84	−0.83	−2.24	−1.78
5	8.67	7.71	6.75	2.03	−1.14	−1.87
6	60.70	19.09	17.03	1.59	2.29	1.58

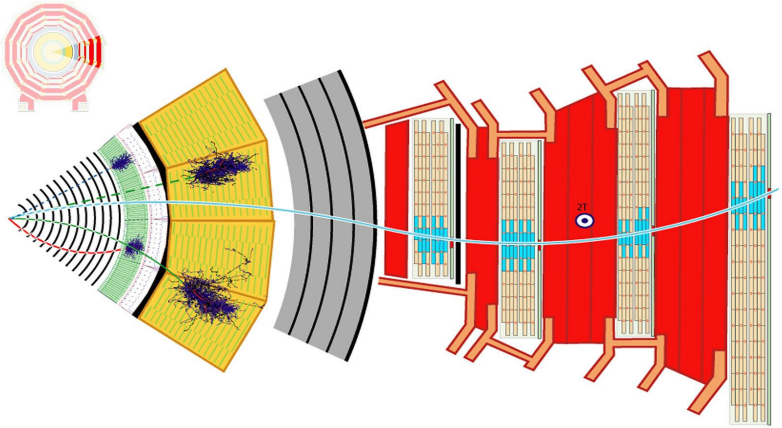
Event	$\phi^{J/\psi,1}$	$\phi^{J/\psi,2}$	$\phi^{J/\psi,3}$
1	−1.98	2.06	−1.56
2	2.60	−2.14	−0.38
3	−0.87	−1.50	0.66
4	1.00	−2.07	−1.77
5	−1.77	1.99	2.91
6	−1.98	−1.74	−2.17

Dimuon invariant mass, proper decay-length, transverse momentum, rapidity, and azimuthal angle of each of the three J/ψ candidates measured in the six triple-J/ψ events passing our selection criteria.

CMS experiment



CMS has accumulated ~5 fb^{-1} at 7 TeV, ~20 fb^{-1} at 8 TeV, and ~160 fb^{-1} at 13 TeV of data for physics



Excellent detector for quarkonium physics