Observation of new structures in the J/ψJ/ψ mass spectrum at CMS

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NNU · 南京师范大学 NANJING NORMAL UNIVERSITY

第三届粒子物理前沿研讨会

2022年7月22日，中山大学

Fully charmed tetraquaks at LHC

2022年7月9日，易凯

昨天下午
3点-6点

Flavour Physics Lecture 味物理讲座

HAPOF Hadron Physics Online Forum (HAPOF) https://indico.itp.ac.cn/category/5/ 强子物理在线论坛

味物理讲座•强子物理在线论坛
联合报告会

Results on fully charmed tetraquarks at the LHC

ABSTRACT

Quarks and gluons are elementary particles of nature that participate the strong interaction. How quarks are confined to form matter is a fundamental problem of QCD, the theory for the strong interaction in the Standard Model. The last two decades witnessed observations of new types of hadrons consistent with four or five constituent quarks, which provide new insights into QCD. Among them is the observation of X(6900) by LHCb in 2020 in the di-J/psi final state, compatible with a fully charmed tetraquark . A structure close to di-J/psi mass threshold was also reported, however its nature is uncertain in LHCb analysis. Recently, new results on studies of states in di-J/psi mass spectrum are reported by ATLAS and CMS collaborations. The X(6900) state is confirmed by both experiments, with similar mass and width measurements. Besides, a new state X(6600) is observed with 5.7 sigma significance, and another new state X(7300) is reported with 4.1 sigma significance.

Fully charmed tetraquarks are likely compact objects, in which four charm quarks interact with by exchanging gluons. Other interpretations include hadron molecules where two charmonia are loosely bound with nuclear-like interaction, and coupled multiple di-quarkonia channel rescattering effect. These states provide an ideal place to study the QCD confinement. In this seminar, results of by ATLAS, CMS and LHCb as well as their impact will be discussed.

ATLAS 清华大学 许悦

许悦，2022年毕业于清华大学物理系，获得博士学位。从事ATLAS实验物理研究，主要集中于寻找超标准模型希格斯玻色子和低质量共振态。所在团队研究了ATLAS实验中的di-J/psi数据，确认了X(6900)粒子。

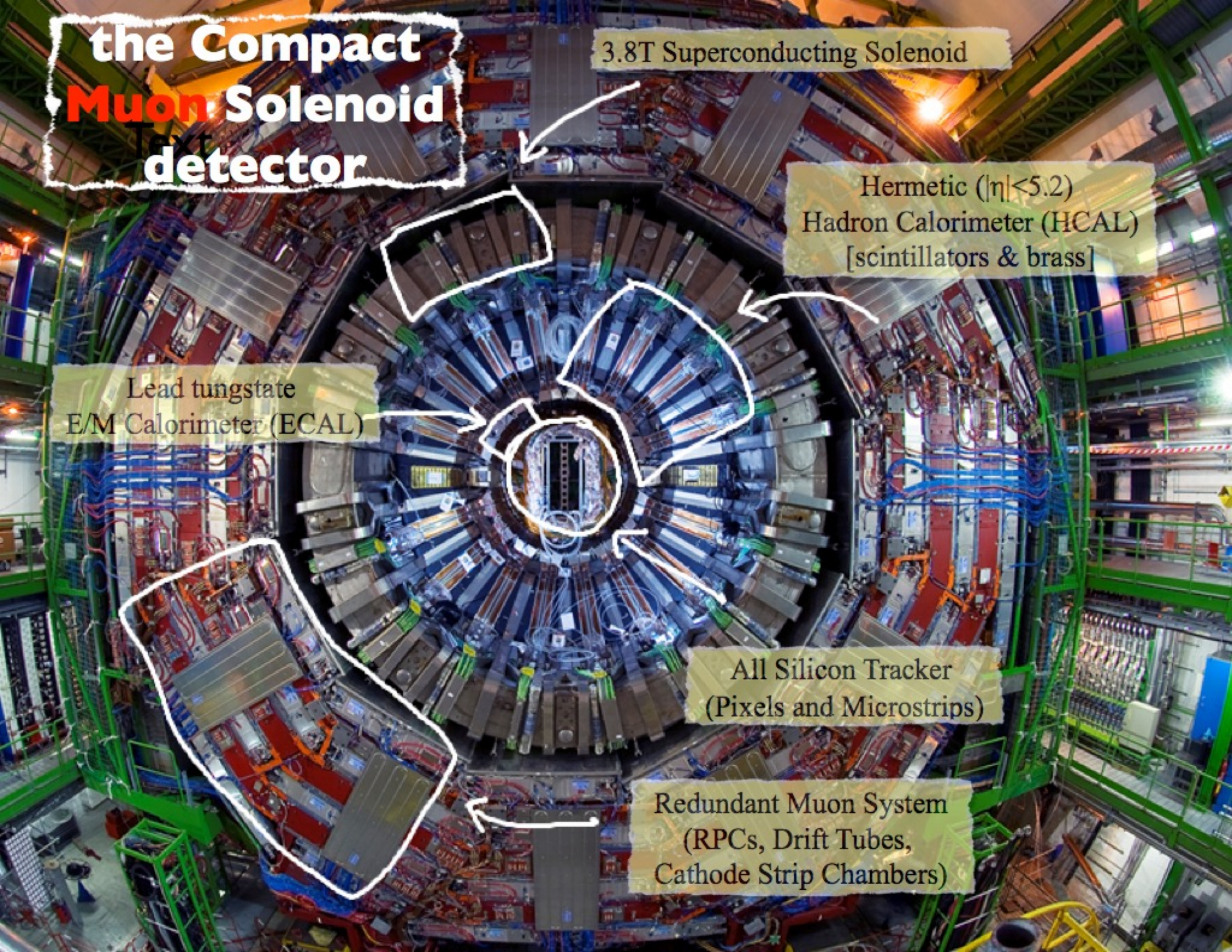
CMS 南京师范大学 张敬庆

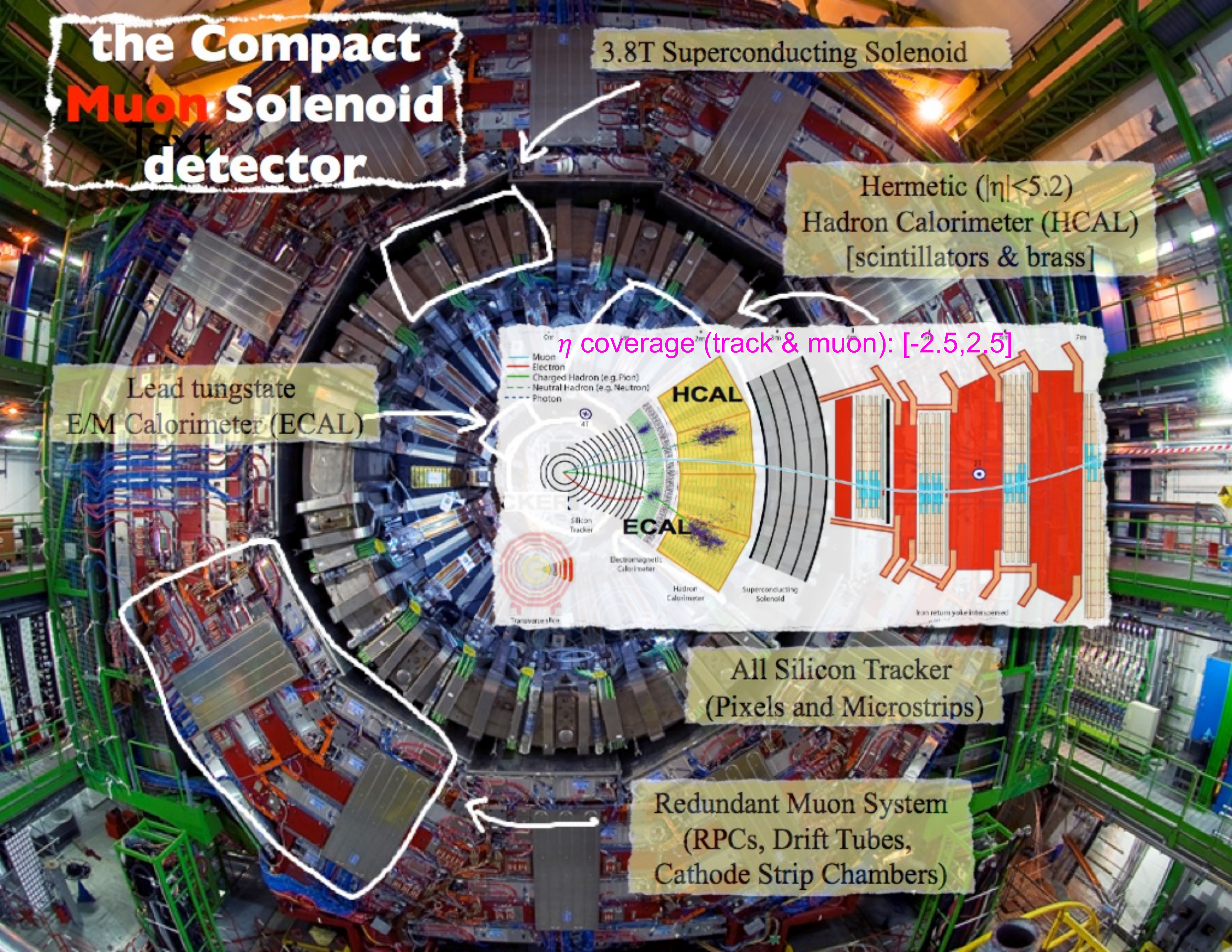
张敬庆，2014年毕业于中国科学院大学/中国科学院高能物理研究所，获得博士学位。2015至2020年，先后在高能所和德国波鸿鲁尔大学做博士后，从事BESIII实验的研究，发现了X(1840)粒子并且确认了X(1750)粒子。2020年开始在南京师范大学做博士后研究，主要工作为在CMS实验的di-J/psi数据中寻找和研究新强子。

LHCb 北京大学 张艳席

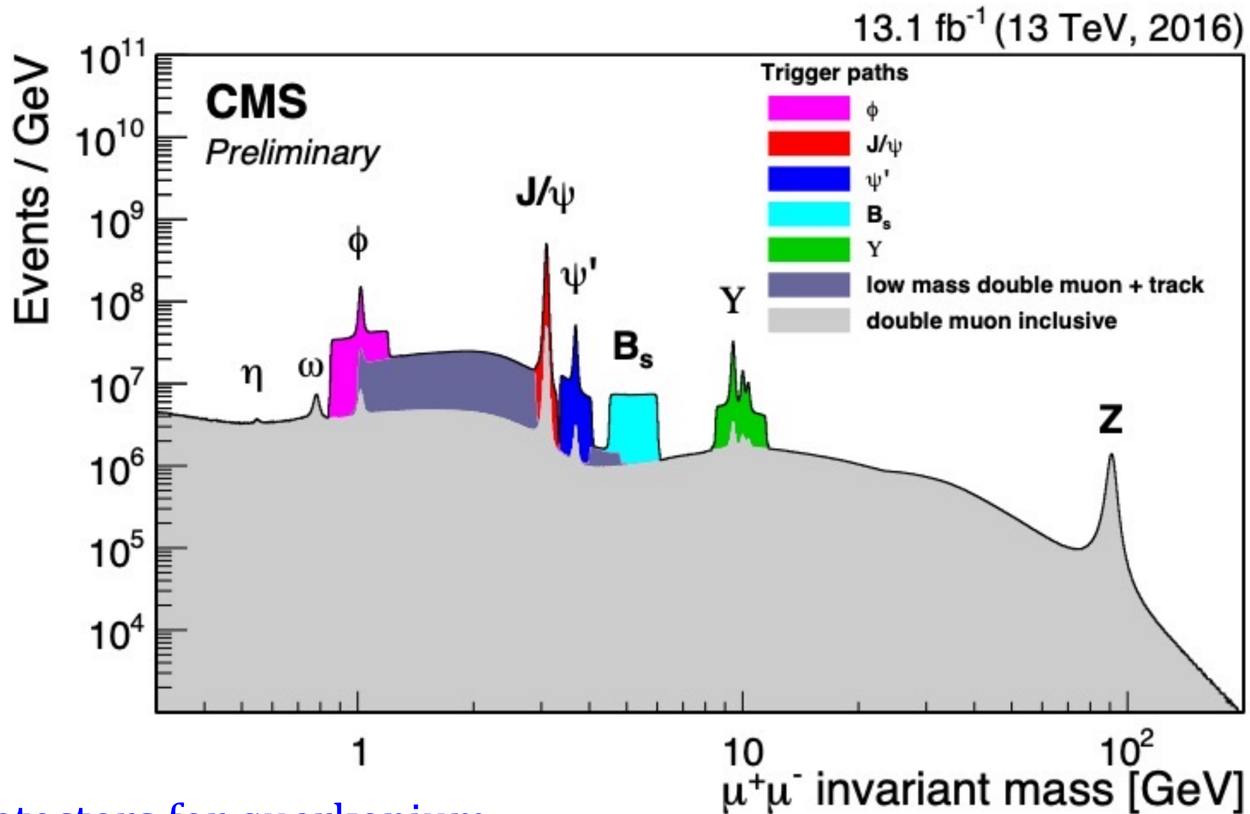
张艳席，北京大学助理教授，本科、博士毕业于清华大学，先后在清华大学、法国国家科学研究中心，欧洲核子研究中心从事博士后研究。从事欧洲核子研究中心LHCb探测器上重味夸克物理研究，研究课题包括味物理、强子物理和重离子物理，参与LHCb实验发现五夸克态、双粲重子和全粲四夸克态等工作。曾担任LHCb合作组“底强子与重夸克偶素”以及“离子与固定靶”物理分析工作组召集人。

时间：2022年7月21日，15:00 - 16:30
报告网页：https://indico.ihep.ac.cn/event/17344/
Zoom：https://cern.zoom.us/j/65571117598?pwd=cHkwZC90WG9RMjQzMnZHaIFyQzRzdz09 密码：957982
主持人：赵强 研究员，中国科学院高能物理研究所


the Compact
Muon Solenoid
detector
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)


the Compact Muon Solenoid detector
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
η coverage (track & muon): [-2.5,2.5]
Lead tungstate
E/M Calorimeter (ECAL)
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Transverse slice
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

Dimuon at CMS & trigger



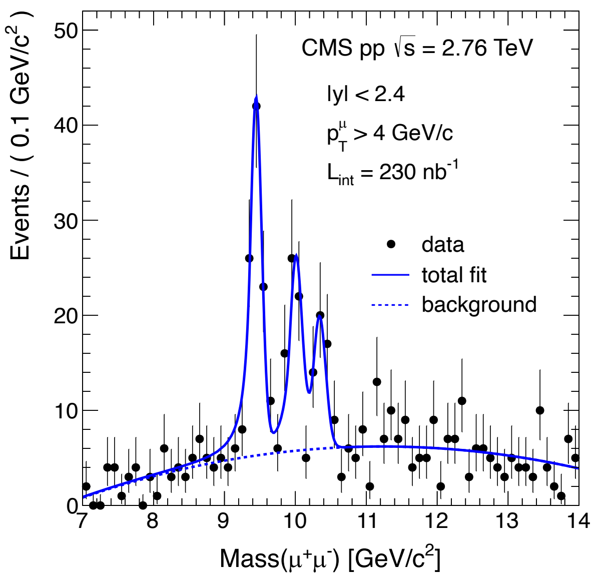
Excellent detectors for quarkonium

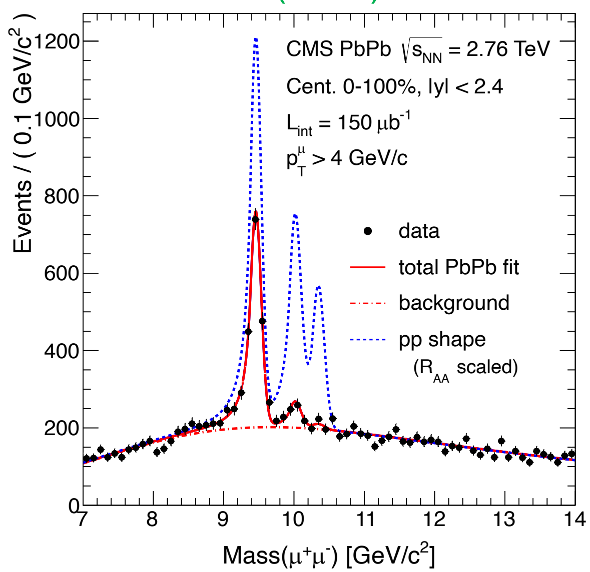
- Muon system
  - High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ
- Silicon Tracking detector, B=3.8T
  - $\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution
- Special triggers for different analyses at increasing Inst. Lumi.
  - μ p_T, $(\mu\mu)$ p_T, $(\mu\mu)$ mass, $(\mu\mu)$ vertex, and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

Selected CMS contributions with low p_T muons

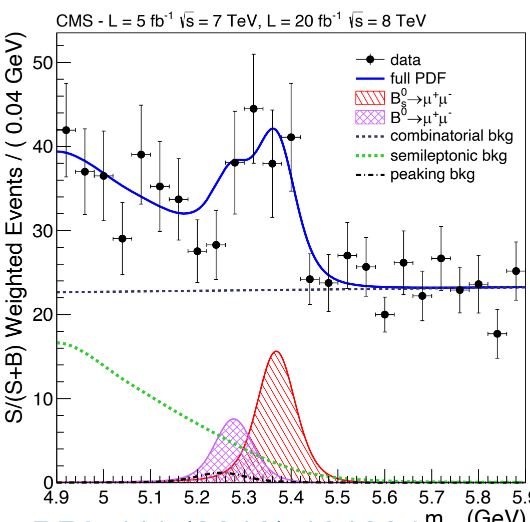
Υ suppression in PbPb collisions

PRL 109 (2012) 222301

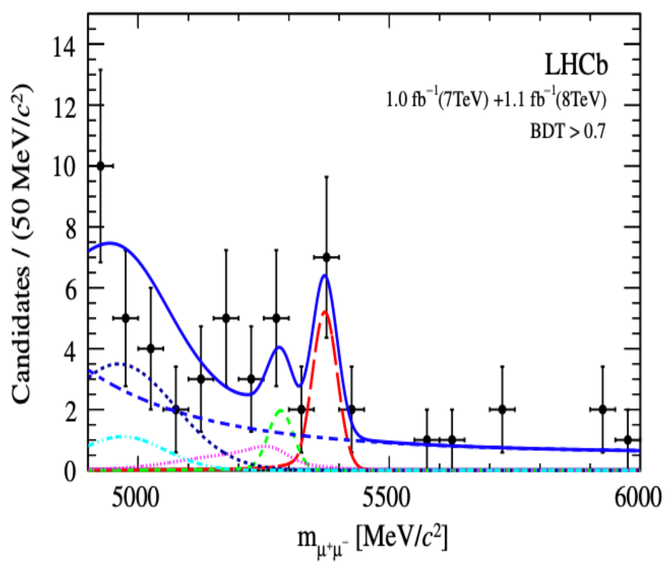


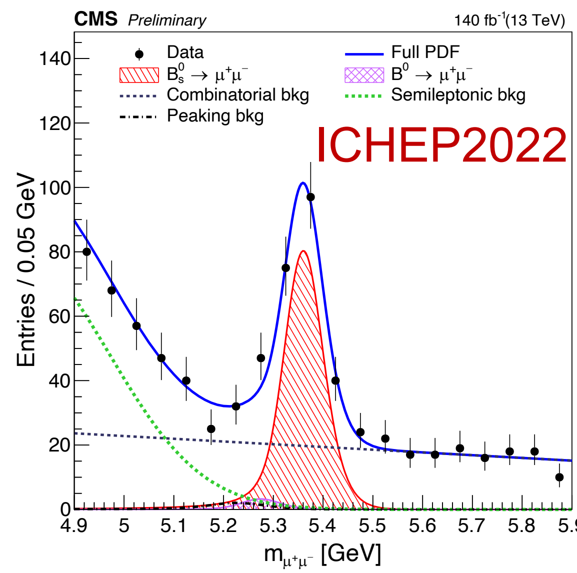


$B_S^0 \to \mu^+\mu^-$ rare decays



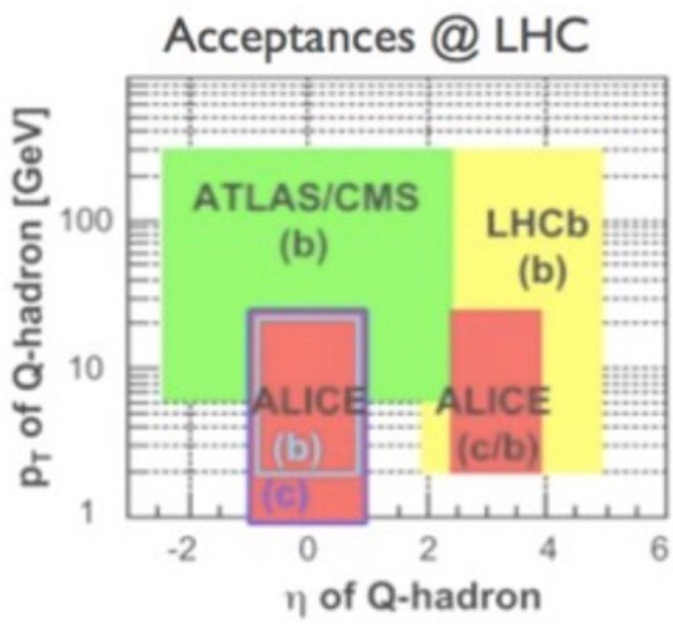
PRL 111 (2013) 101804





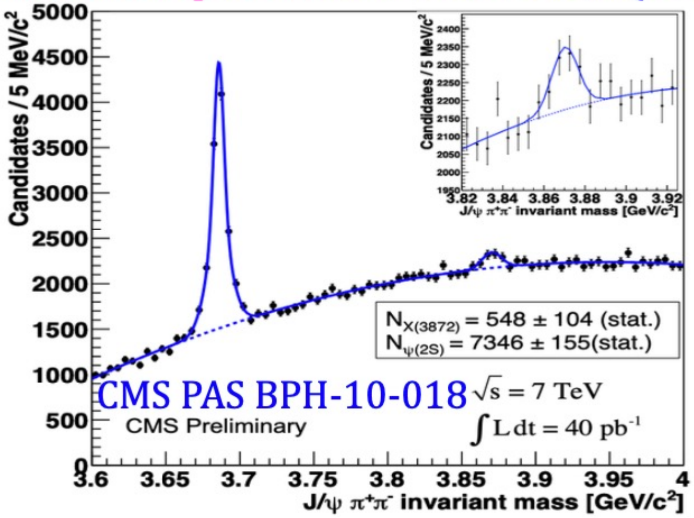
B physics at CMS

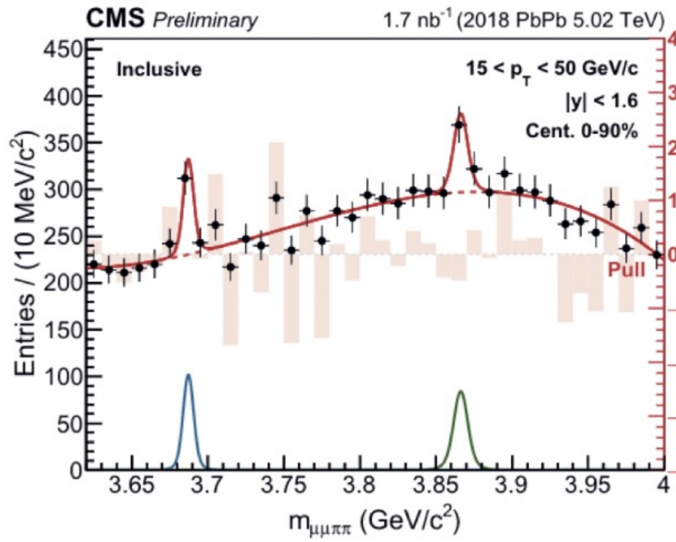
- vs RHIC
  - better resolution
    - CMS' 1st Υ(1S,2S,3S) measurements in HI
  - additional detector capability
    - CMS' 1st secondary vertex meas. in HI (eg $b \to J/\psi$)
- vs ALICE
  - complementary acceptance (ALICE access low-pt)
  - CMS better resolution
- vs Tevatron experiments
  - extend kinematic (p_T,y) acceptance
- vs ATLAS
  - more flexible trigger, better resolution
- vs LHCb
  - complementary acceptance, LHCb great particle ID
  - higher luminosity



Selected CMS contributions to heavy exotic states

First LHC experiment re-discovered X(3872)

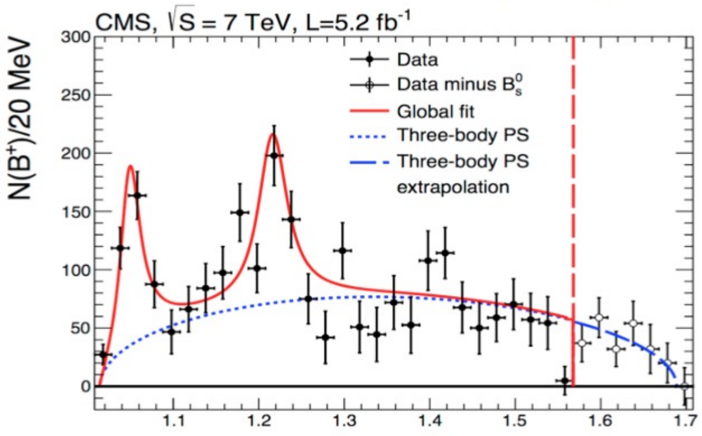




First X(3872) signal in PbPb

Nucl. Phys. Vol 1005 (2021)121781

First confirmation of Y(4140)



PLB 734 261 (2014)

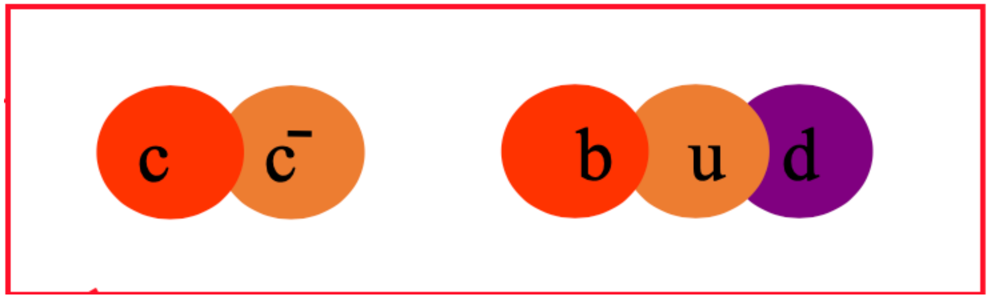
CMS played the following leading roles

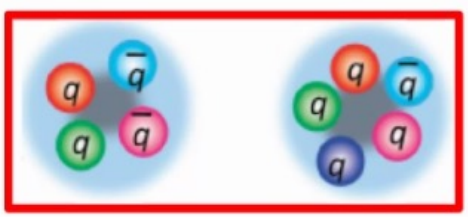
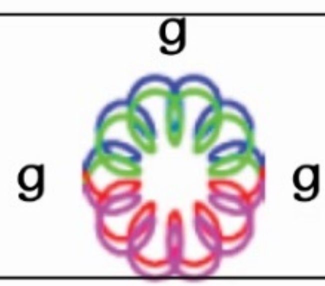
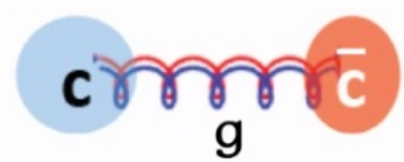
- First LHC experiment to see X(3872)
- First LHC experiment to see exotic hadron
- First LHC experiment to see X(3872) in PbPb data

7

Exotic hadron

Meson *Baryon*



QCD理论允许强子的夸克数不只是2或3		
多夸克态	胶子球	混杂态
夸克数>=4	夸克数＝0，多个胶子gg，ggg …	夸克数＝2 ＋激发胶子 :qqg，qq̄qg …
		

4c exotic meson

- First mention of 4c states at 6.2 GeV (1975)
  - Just one year after the discovery of J/ψ)

We expect at least three exotic mesons with hidden charm, $c\bar{c}(p\bar{p}-n\bar{n})$ [between 3.7~4.1 GeV], $c\bar{c}\lambda\bar{\lambda}$ [~4.1 GeV] and $c\bar{c}c\bar{c}$ [~6.2 GeV], to which we refer

Progress of Theoretical Physics, Vol. 54, No. 2, August 1975

A Possible Model for New Resonances

—Exotics and Hidden Charm—

Yoichi IWASAKI

Research Institute for Fundamental Physics
Kyoto University, Kyoto

(Received January 20, 1975)

- First calculation of 4c states (1981): Z. Phys. C 7 (1981) 317

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	2^{++}	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	3^{--}	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}, 4^{--}, 5^{--}$	

← $(cc)_{\underline{3}^*} - (\overline{cc})_{\underline{3}}$

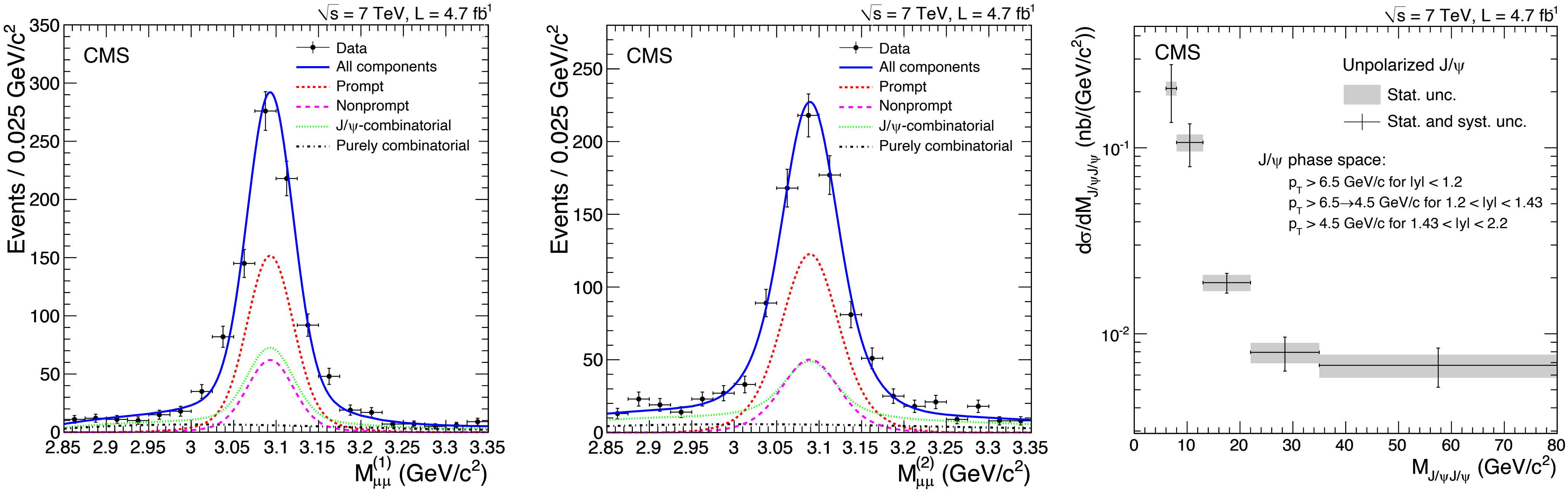
$(cc)_{\underline{6}} - (\overline{cc})_{\underline{6}^*}$ ↓

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.82
2	0	2^{++}	7.15
3	0	3^{--}	7.41

- Many recent theoretical studies on $(c\bar{c}c\bar{c})$, $(b\bar{b}b\bar{b})$, $(b\bar{b}c\bar{c})$:
  - controversial on existence of bound states below $\eta_b\eta_b$ threshold;
  - consistent on existence of resonant states above $\eta_b\eta_b$ threshold.

J/ψJ/ψ cross section at 7 TeV

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

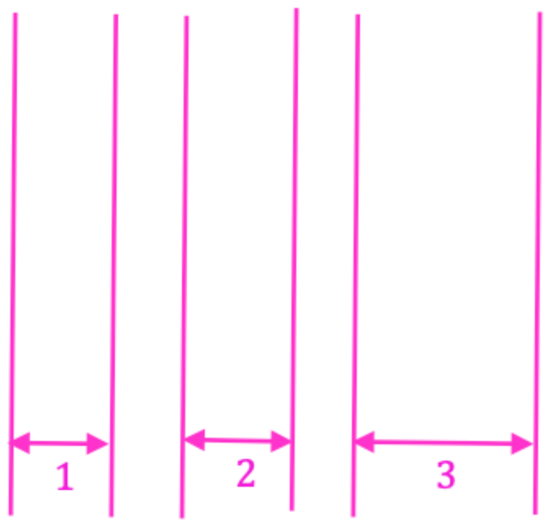


Total cross section, assuming unpolarized prompt J/ψJ/ψ pair production
1.49 ± 0.07 (stat.) ± 0.13 (syst.) nb

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

Blind mass window for 13 TeV

We saw hints at Run I data
Proposed three signal regions for Run II data



Blinded mass windows for Run II:

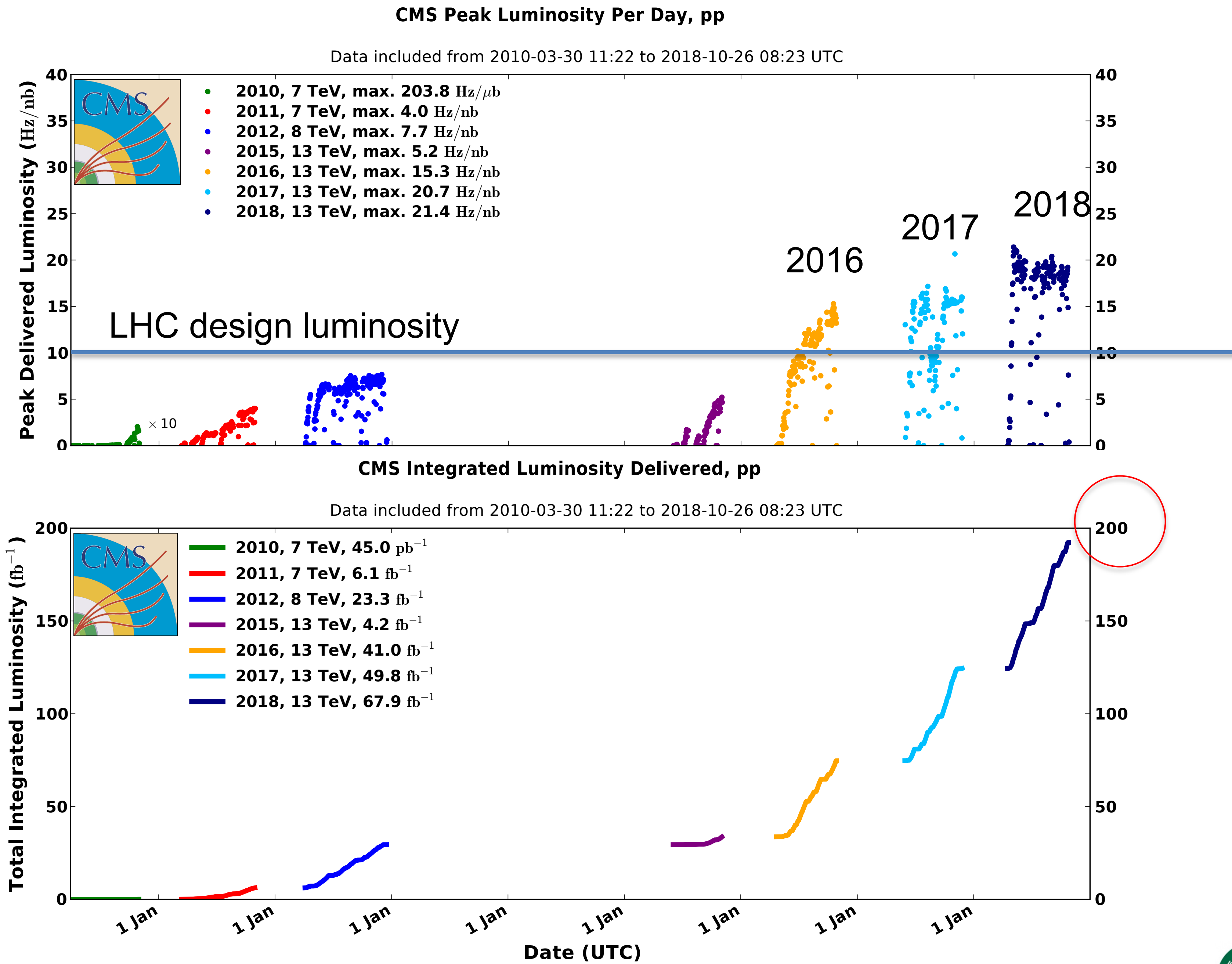
1. [6.3,6.6] GeV
2. [6.8,7.1] GeV
3. [7.2,7.8] GeV
   (for potential wide structure)

These mass windows will be windows for LEE for potential structures

Run I data will be ignored for significance calculation

CMS eventually decide to blind the whole region: [6.2, 7.8] GeV after LHCb released their result

The LHC is pushing the limit



13 TeV dataset and MC samples

- Signal: $X \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$
- Data: 135 fb^{-1}, taken in 2016, 2017 and 2018 LHC runs
- Signal MC samples:
  - $J^P = 0^+$ resonance

    -- Generator: Pythia8, JHUGen
- Background MC samples:
  - Nonresonant single-parton scattering (NRSPS)

    -- Generator: Pythia8, HelacOnia (next-to-next-to-leading order), Cascade (next-to-leading order)
  - Nonresonant double-parton scattering (NRDPS)

    -- Generator: Pythia8

Event selections

Muon selection

- $p_T(\mu^{\pm}) >$ 2.0 GeV/c
- $|\eta(\mu^{\pm})| < 2.4$
- All muons are soft
- For 2017-18 years: $p_T(\mu^{\pm}) >$ 3.5 GeV/c for at least one $\mu^+\mu^-$ pair, which has $vtxprob(\mu^+\mu^-)$ >0.5% and $2.95 < m_{\mu^+\mu^-} < 3.25$ GeV

J/ψ selection

- $2.95 < m_{J/\psi} < 3.25$ GeV
- $p_T(J/\psi) >$ 3.5 GeV/c
- $vtxprob(J/\psi)$ >0.5%
- Constrained $vtxprob(J/\psi)$ >0.1%

J/ψJ/ψ selection

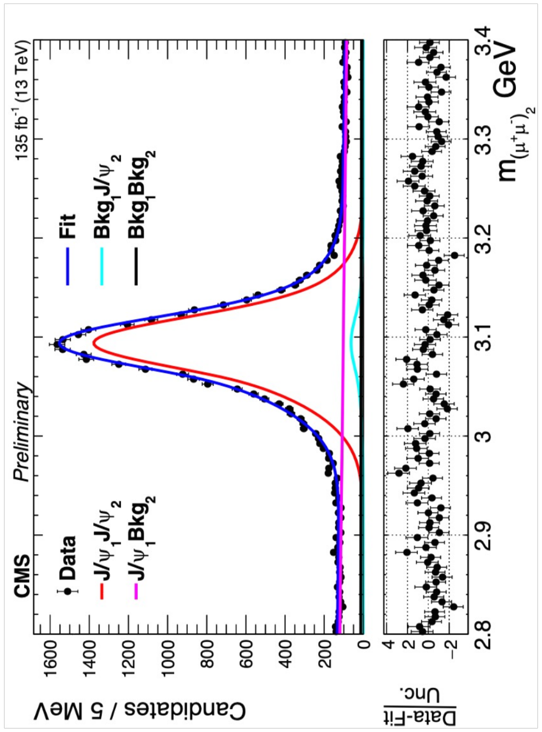
- $vtxprob(4\mu) >$ 0.5%
- $vtxprob(J/\psi J/\psi) >$ 0.1%
- Proper HLT is fired in event

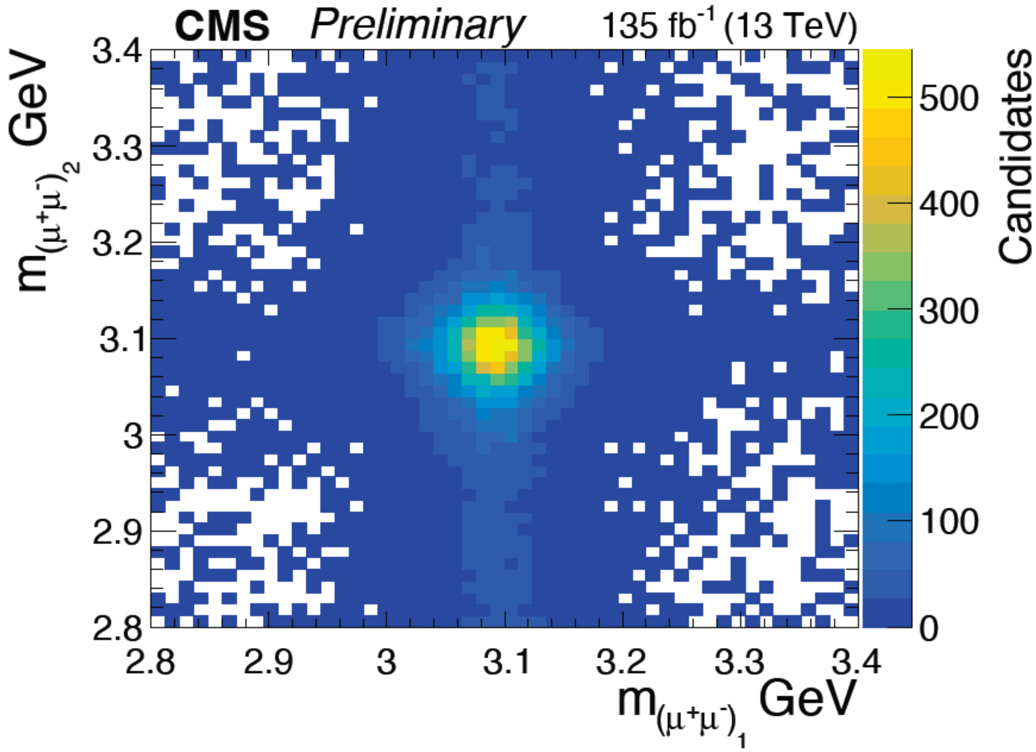
Multiple candidates

- Choose the best candidate with minimum $\left(\frac{M(J/\psi_1)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_1))}\right)^2+\left(\frac{M(J/\psi_2)-M(J/\psi_{PDG})}{\sigma(M(J/\psi_2))}\right)^2$ value if there are 4 muons in event, but more than one candidate (~0.2%)
- Keep all candidates if there are more then 4 muons in event (~0.2%)

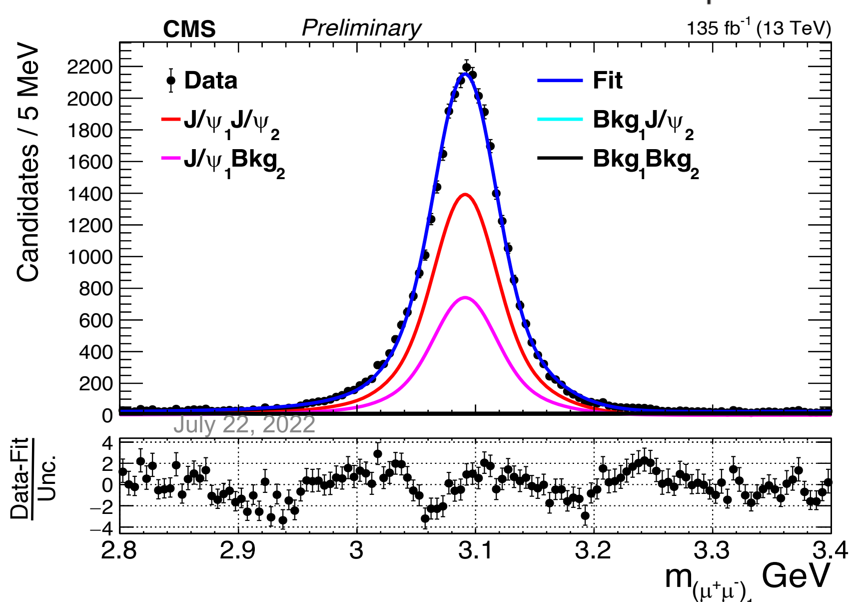
Baseline mass variable – invariant mass of two constrained J/ψ candidates

J/ψ candidates





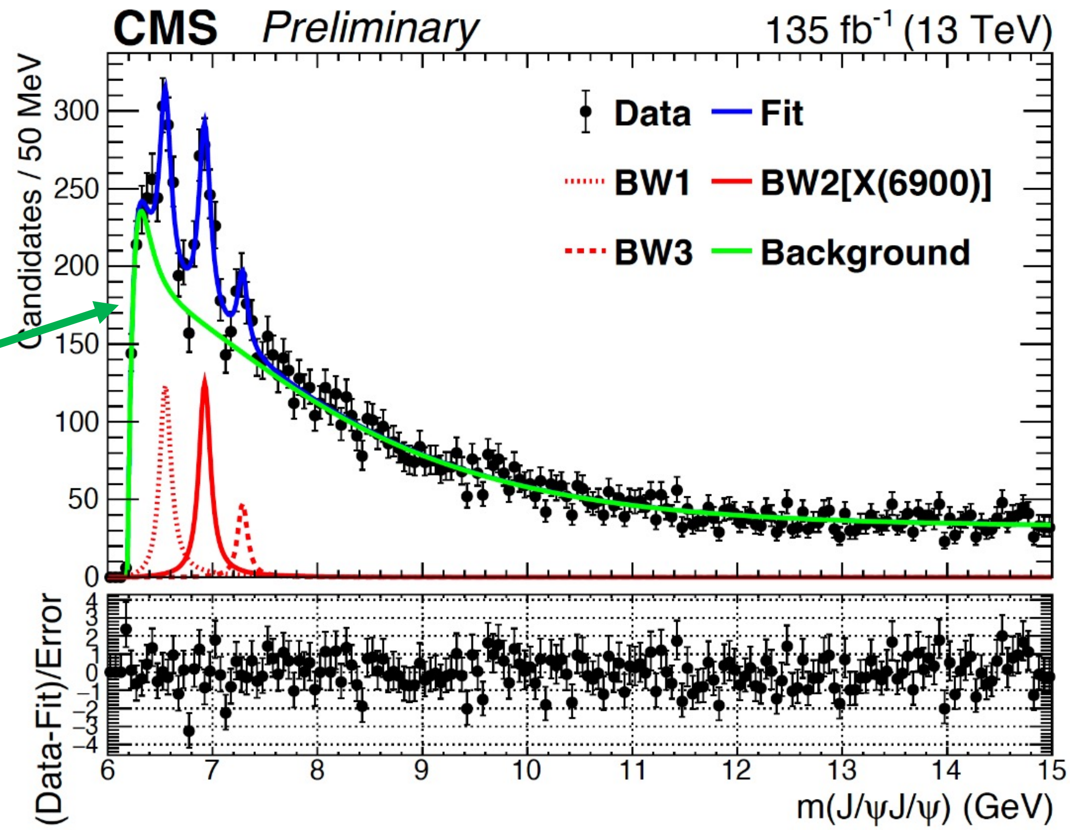
- J/ψ mass and vertex related cuts removed
- Clean J/ψ signals are seen



Zhen Hu
July 22, 2022

CMS background (BW0 + NRSPS + DPS)

CMS background (BW0 + NRSPS + DPS)



$\chi^2\ prob = 79\%$

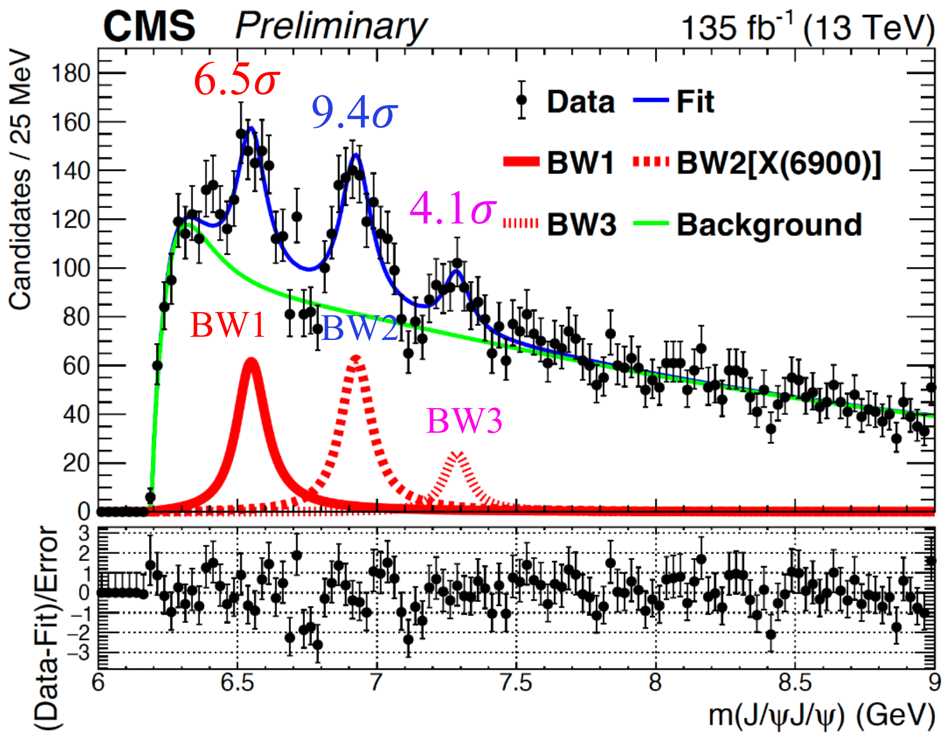
[6.2,15] GeV

- Most significant structure in first step is a BW at threshold, BW0--what is its meaning?
- Treat BW0 as part of background due to:
  - Inadequacy of our NRSPS model at threshold though one floating parameter?
  - BW0 parameters very sensitive to other model assumptions
  - A region populated by feed-down from possible higher mass states
  - Possible coupled-channel interactions, pomeron exchange processes…
- NRSPS+NRDPS+BW0 as our background

CMS model: 3 BWs + Background

χ^2 Prob. = 1%

[6.2,7.8] GeV



Statistical significance based on:

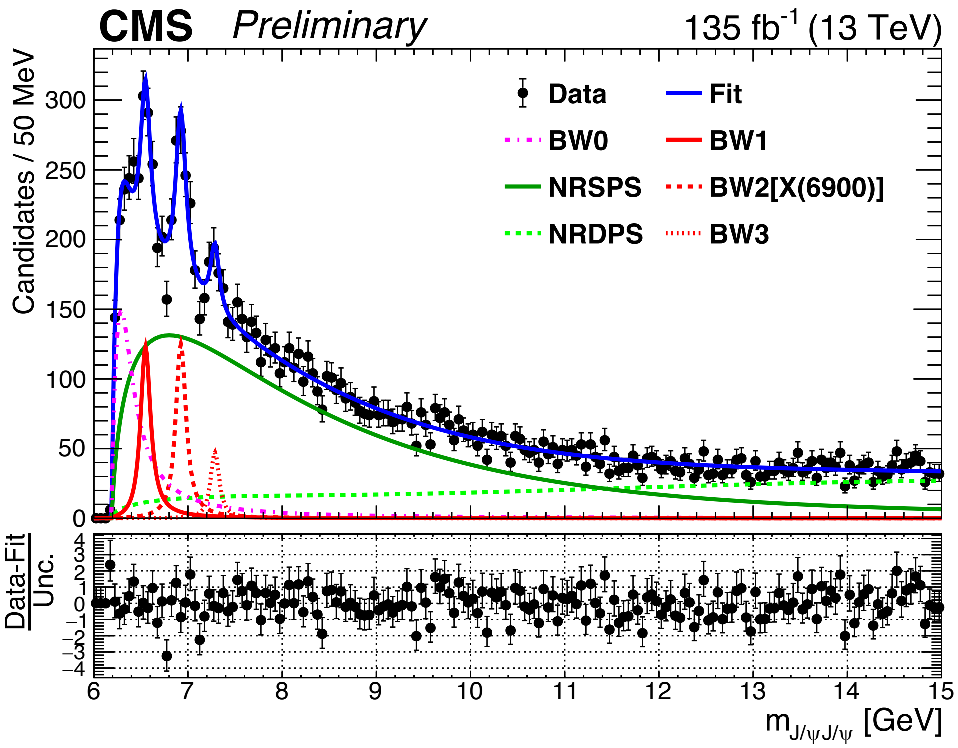
$$2\ln(L_0/L_{max})$$

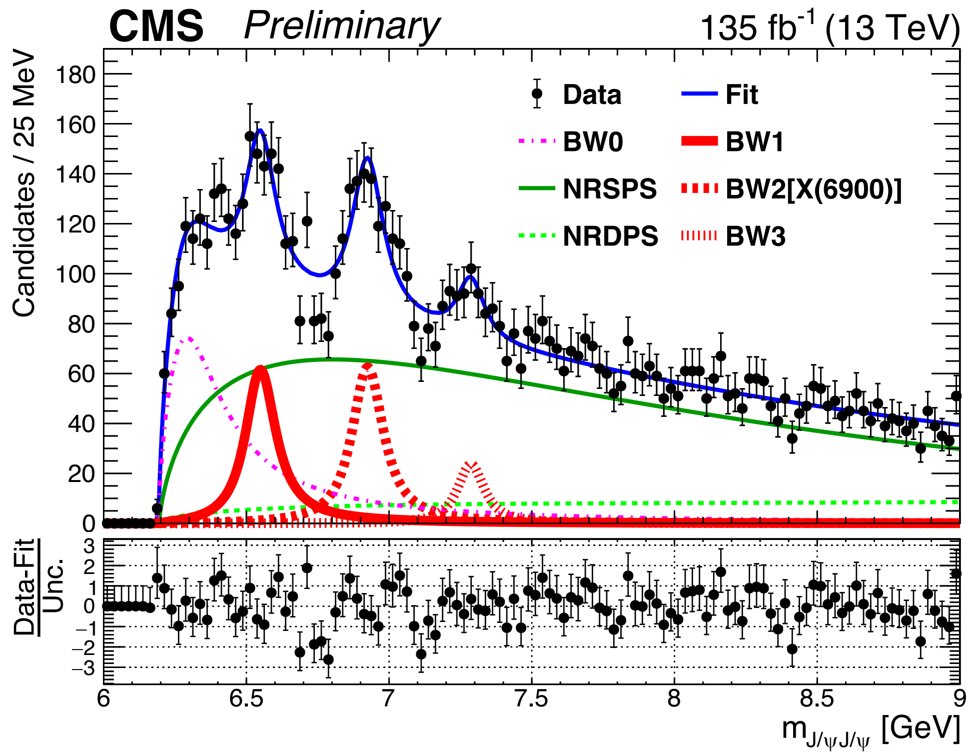
	BW1 (MeV)	BW2 (MeV)	BW3 (MeV)
m	6552 ± 10	6927 ± 9	7287 ± 19
Γ	124 ± 29	122 ± 22	95 ± 46
N	474 ± 113	492 ± 75	156 ± 56

- BW1 (6.5σ) – observation (> 5.7σ with syst.)
- BW2[X(6900)] (9.4σ) -- confirmation
- BW3 (4.1σ) -- evidence

Statistical significance only

CMS result with BW0 explicitly shown





Significance with systematics

Table 2: Systematic uncertainties on masses and widths, in MeV.

Source	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	<1	<1	3	3	4
NRSPS	3	1	1	18	15	17
feeddown shape	11	1	1	25	8	6
momentum scaling	1	3	4	-	-	-
resolution	<1	<1	<1	<1	<1	1
efficiency	<1	<1	<1	1	<1	1
combinatorial background	<1	<1	<1	2	3	3
total	12	5	5	34	19	20

- Investigated effects of systematics on local significance by a profiling procedure
  a discrete set of individual alternative signal and background hypotheses tested in minimization
  - Significant change: BW1 significance changed from 6.5σ to >5.7σ
  - No relative significance changes for BW2 and BW3

M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV	>5.7σ
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV	>9.4σ
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV	>4.1σ

Significance with systematics

consistent →

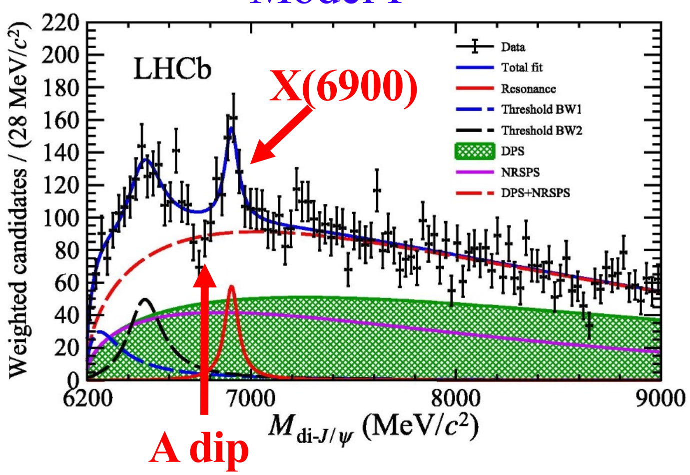
X(6900) [LHCb]
(somewhat different fit model)

M[BW2]=6905±11±7 MeV
Γ[BW2] =80±19±33 MeV

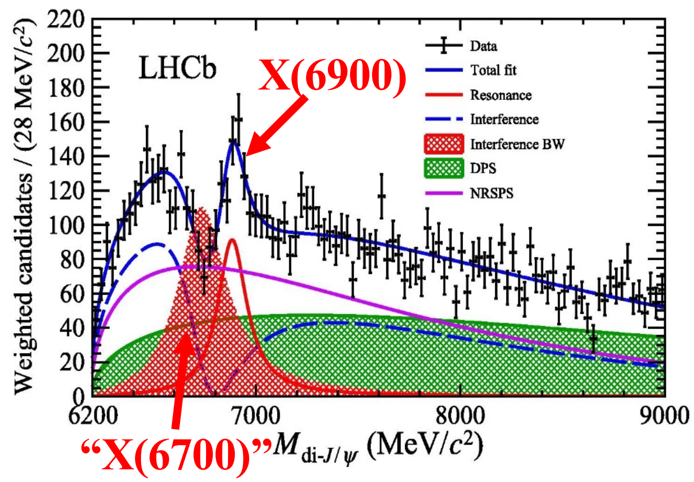
X(6900) reported by LHCb

- In 2020, LHCb reported X(6900) state in $J/\psi J/\psi$ final state, Sci.Bull.65 (2020) 23
- Tried two different models
  - Model I: background+2 auxiliary BWs+ X(6900) → poor description of 'dip' around 6.7 GeV
  - Model II: a "virtual" X(6700) to interfere with NRSPS background to account for dip
- LHCb agnostic on which one is to be preferred
- What happens if fit CMS data using LHCb models?

Model I

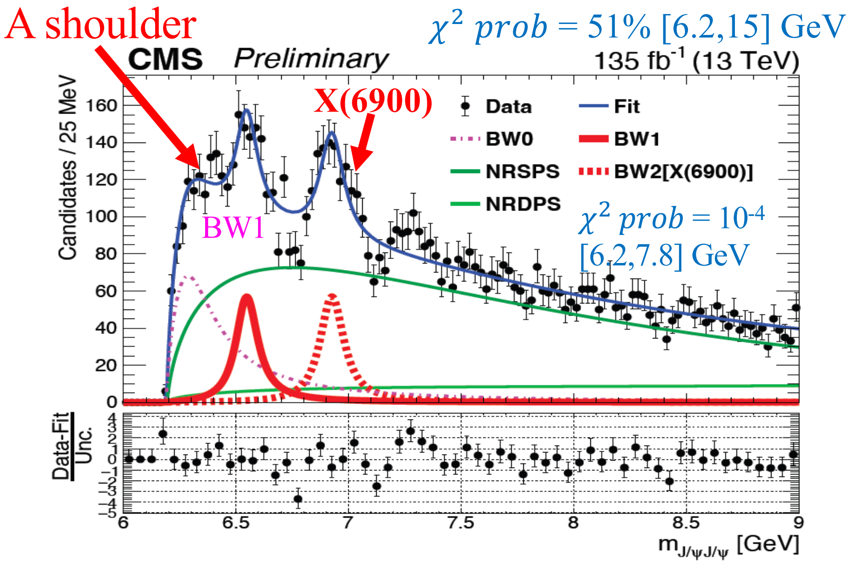


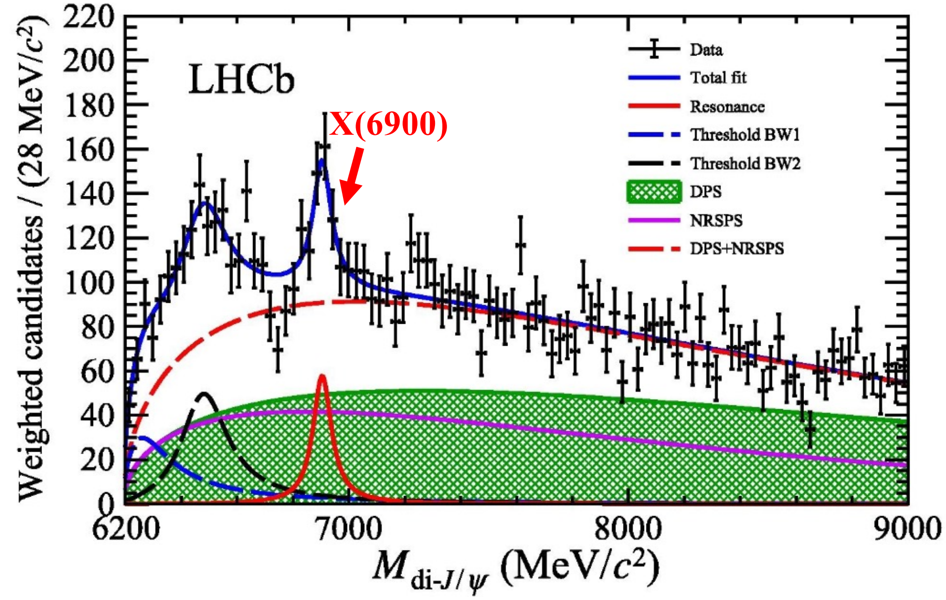
Model II



Try LHCb model 1

Background + 2 auxiliary BWs + X(6900)





Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24

X(6900) parameters are in good agreement with LHCb
LHCb did not give parameters for another 2 BWs

- CMS Data shows a shoulder before BW1
- CMS shoulder helps make BW1 distinct

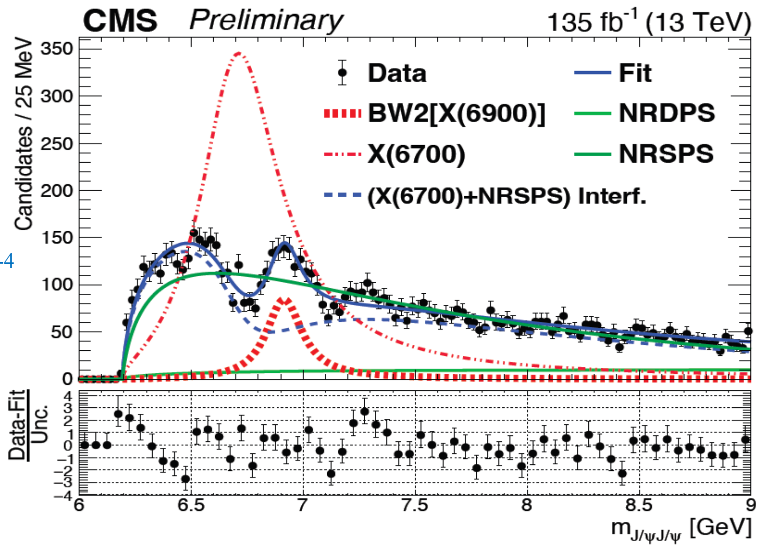
- *Does not describe well dips*

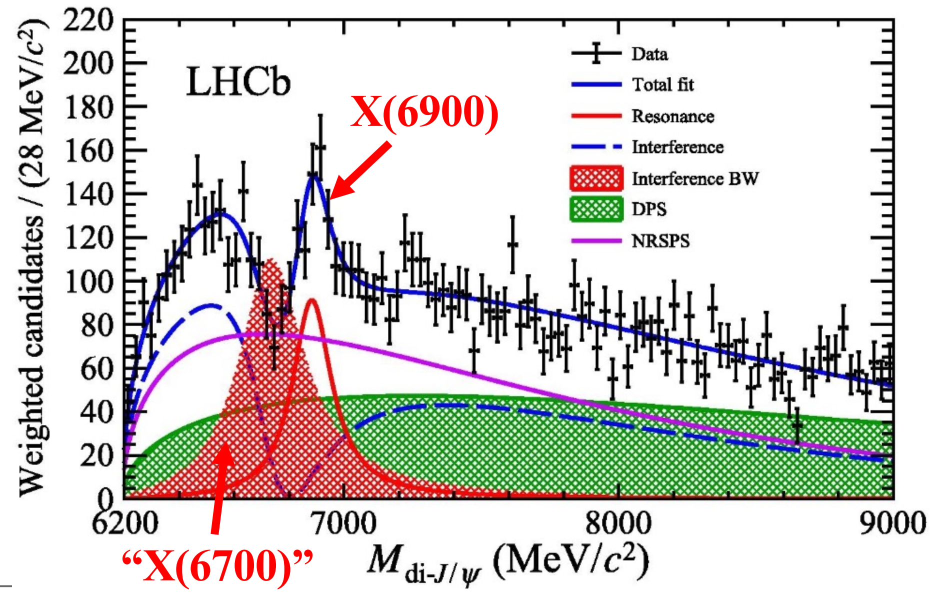
- CMS vs LHCb comparisons:
  - 135/9 ≈ 15X (int. lum.)
  - $(5/3)^4 \approx$ 8X (muon acceptance due to pseudo-rapidity range)
  - Higher muon p_T (>3.5 or 2.0 GeV vs >0.6 GeV)
    - Similar number of final events, but DPS suppressed

Try LHCb model 2

DPS + X(6900) + “X(6700)” interferes with NRSPS

χ^2 *prob* = 10^{-4}
[6.2,7.8] GeV





Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb [15]	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24
LHCb [15]	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

All CMS fits presented are not very good:
...other interference scenarios are under study in CMS

- X(6900) parameters are consistent
- CMS obtained larger amplitude and natural width for BW1
- CMS's X(6600) is 'eaten' –does not describe X6600 and below
- Does not describe X(7200) region

Summary

- CMS found 3 significant structures using 135 fb^{-1} 13 TeV data
  https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html

M[BW1] = 6552 ± 10 ± 12 MeV	Γ[BW1] = 124 ± 29 ± 34 MeV	>5.7σ
M[BW2] = 6927 ± 9 ± 5 MeV	Γ[BW2] = 122 ± 22 ± 19 MeV	>9.4σ
M[BW3] = 7287 ± 19 ± 5 MeV	Γ[BW3] = 95 ± 46 ± 20 MeV	>4.1σ

- BW2 consistent with X(6900) reported by LHCb
- Two new structures, provisionally named as X(6600) [BW1], X(7300) [BW3]
- A family of structures which are candidates for all-charm tetra-quarks!

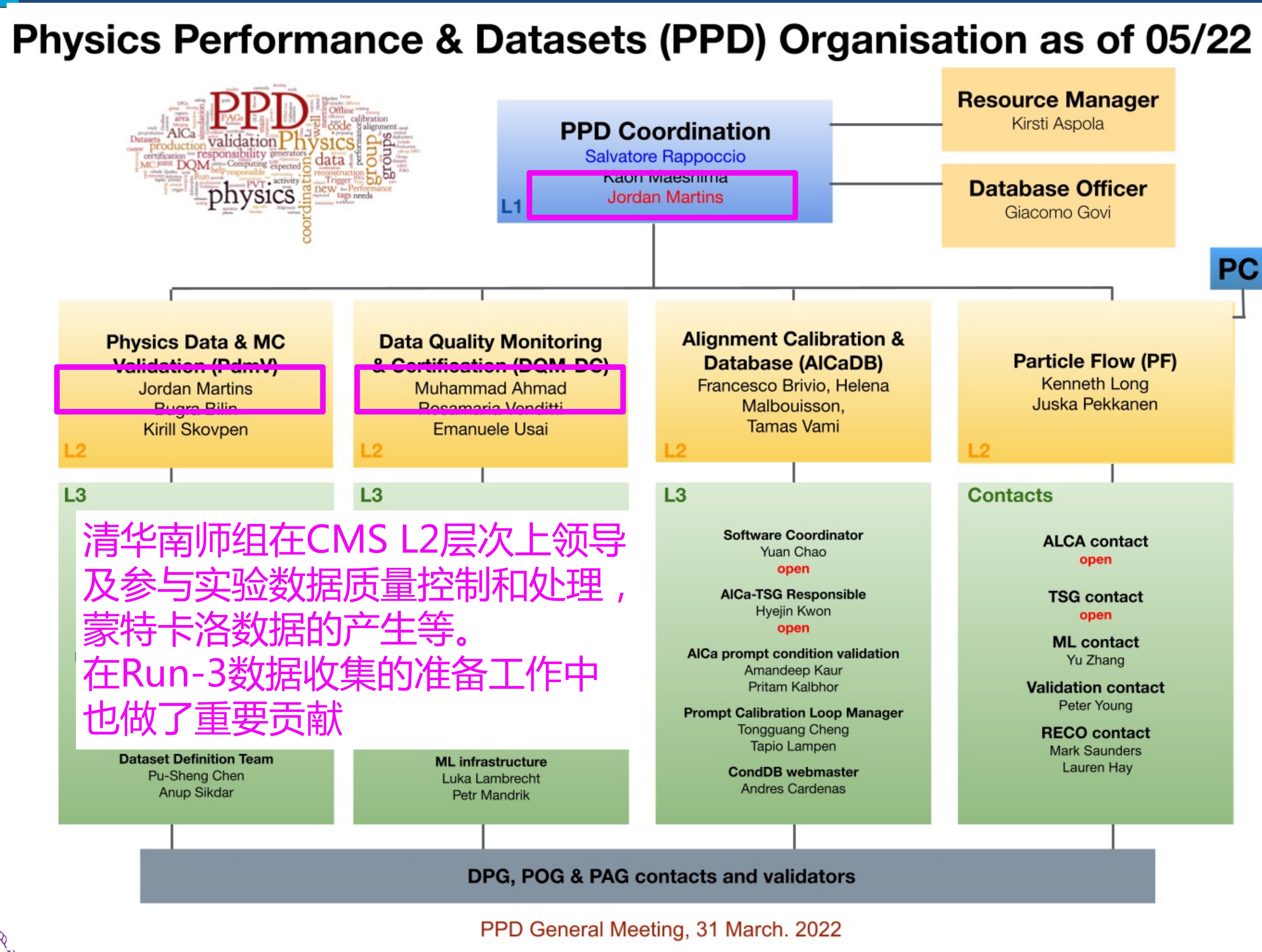
- Dips in data show possible interference effects – under study
- More data/knowledge needed to understand nature of near threshold region

- All-heavy quark exotic structures offer system easier to understand
- A new window to understand strong interaction

CMS组成员

- **“清华-南师”CMS组（2019-2022）**
  - 4 faculties：易凯，胡震，王义，Gerry Bauer
  - 3 postdocs：张敬庆，Muhammad Ahmad，Samet Lezik
  - 10 grads：刘锦枫，温宏伟，王地，崔志鹏，梁正臣，王晰宁，王雨潇，张顺亮，陈亮亮，闫豆豆
  - ~30 undergrads
  - 3 engineers and technicians
- **现任CMS实验二级管理职位1人：**
  - Muhammad Ahmad (PPD DQM)
- **现任CMS实验三级管理职位2人：**
  - 胡震(BPH P&P)，Samet Lezik (DPG Tracking)
- **曾任CMS实验二级管理职位3人次：**
  - 胡震 (PPD PdmV)，Jordan Martins (PPD PdmV)， Jordan Martins (BPH VFS)
- **曾任CMS实验三级管理职位7人次：**
  - 易凯 (B物理 Production), (Quarkonium), (Spectroscopy)
  - 胡震 (PPD PdmV)，Muhammad Ahmad (PPD PdmV)，刘锦枫 (PPD PdmV)，Jordan Martins (PPD PdmV)

Physics Performance & Datasets (PPD) organisation



清华南师组在CMS L2层次上领导及参与实验数据质量控制和处理，蒙特卡洛数据的产生等。
在Run-3数据收集的准备工作中也做了重要贡献

The Compact Muon Solenoid Collaboration
confers on
Muhammad Ahmad
Tsinghua University
a
CMS 2021 Award
For
For his excellent leadership in the operation, maintenance, and development of the CMS data-quality monitoring system.

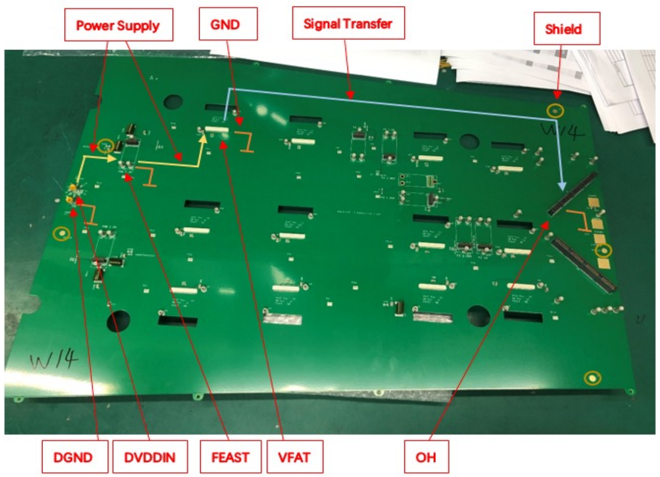
The Collaboration Board Chairperson
(Claudia Wulz)

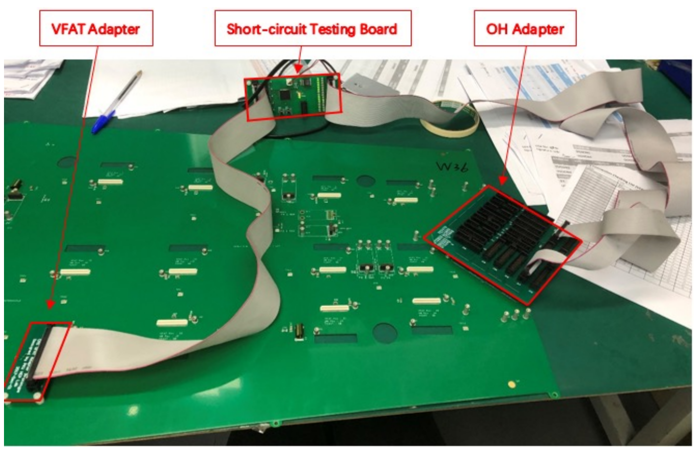
The Experiment Spokesperson
(Luca Malgeri)

June 27th, 2022

硬件贡献 — GEM，MTD

- 在北大帮助下参加了GEM探测器升级
  - 得到清华理科发展双E基金资助：已先期贡献50万材料费
  - 2019、2020、2021、2022年参加过多批电子学版的生产和检测

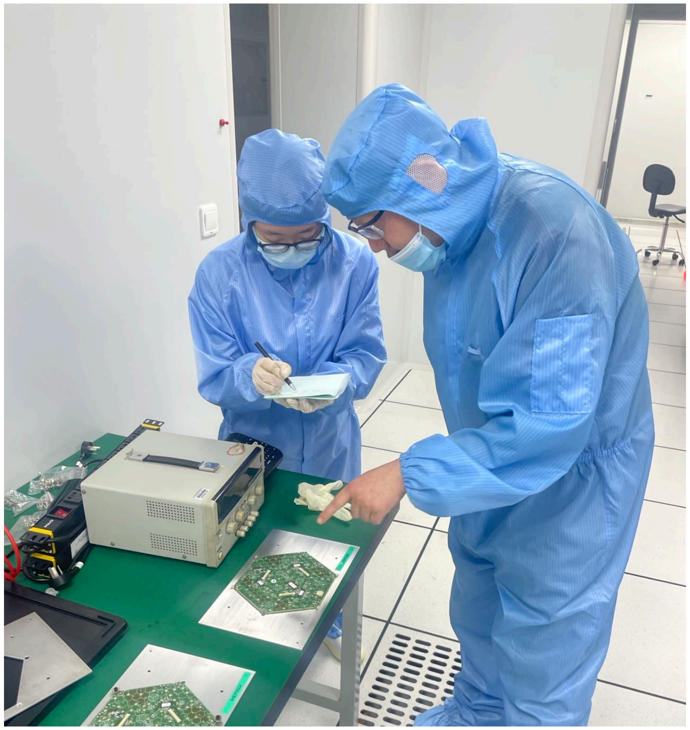


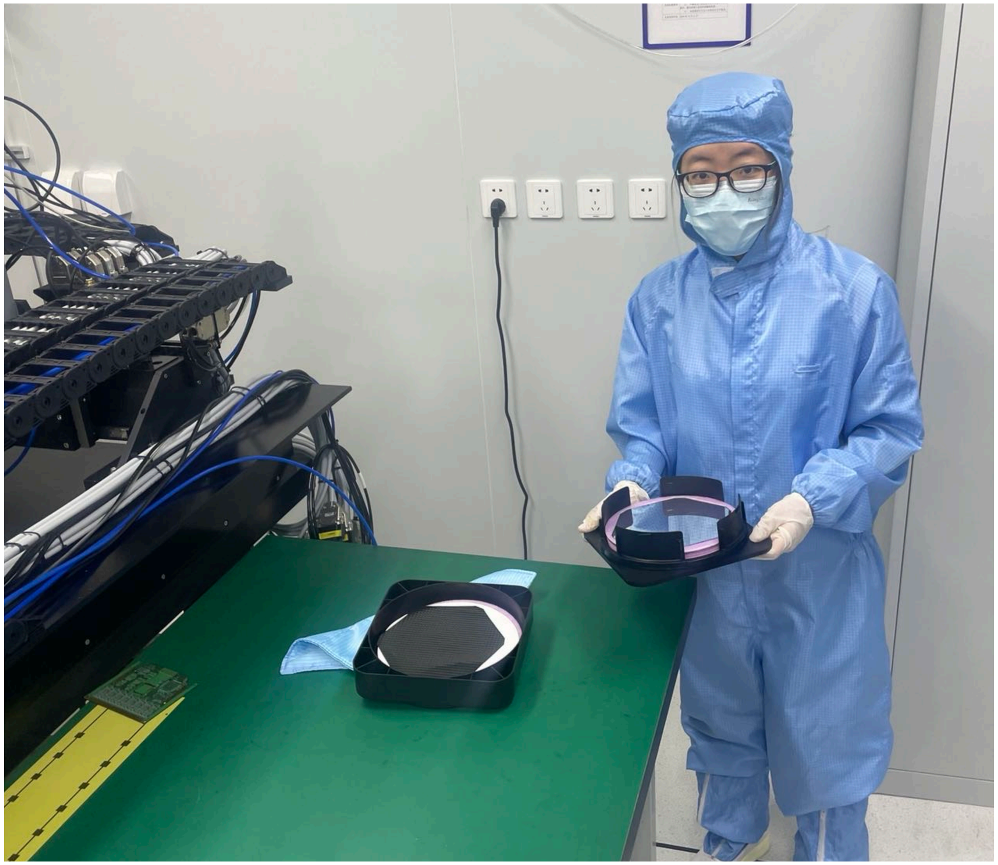


- 参加了MTD探测器升级
  - 得到清华物理系科研发展金资助：已先期贡献50万core contribution
  - 学生长期base在CERN，参加MTD研发和装配工作
  - 已经在清华物理系争取到新的实验室空间，新的设备费资助

硬件贡献 — HGCal

- 在高能所帮助下参加了HGCal探测器升级
  - 得到清华物理系科研发展金资助：已先期贡献设备30万+core contribution 100万
  - 参加高能所站点的生产和测试工作
    - QA/ QC Test before Assembly
    - Module Assembly on Gantry





线下报告

第四届重味物理与量子色动力学研讨会

湖南大学，长沙

Observation of structures in J/ψJ/ψ mass spectrum at CMS

张敬庆

2022年7月29日（周五），15:45

谢谢！

Significance with systematics

- To include systematics, alternative resonance/background shapes applied in the fit.
- Calculate signal- and null-hypothesis NLL_syst including systematic using:

$NLL\_(syst-sig)$ = Min{$NLL\_(nom-sig)$, $NLL\_(alt-i-sig)$+0.5+0.5·Δdof}

  - $NLL\_(nom-sig)$: the NLL of nominal 'signal hypothesis' fit.
  - $NLL\_(alt-i-sig)$: the NLL of i-th alternative fit of 'signal hypothesis'
  - Δdof: the additional free parameters comparing to the nominal 'signal hypothesis' fit.

- $NLL\_(syst-null)$ = Min{$NLL\_(nom-null)$, $NLL\_(alt-j-null)$+0.5+0.5·Δdof}
- Significance including systematics as usual from $NLL\_(syst-null)-NLL\_(syst-sig)$

	Significance with syst.
BW1	5.7σ
BW2	*no sensible changes*
BW3	*no sensible changes*

Line shape

- S-wave relativistic Breit-Wigner (used in default fit):

$$BW(m; m_0, \Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)}, \text{where } \Gamma(m) = \Gamma_0 \frac{qm_0}{q_0 m},$$

q is the momentum of a daughter in the mother particle rest frame; q_0 means the value at peak position ($m = m_0$).

- NRSPS and NRDPS:

$$f_{NRSPS}(x, x_0, \alpha, p_1, p_2, p_3)$$

$$= (x - x_0)^{\alpha} \cdot \left(1 - \left(\frac{1}{(15 - x_0)^2} - \frac{p_1}{10}\right) \cdot (15 - x)^2\right) \cdot \exp\left(-\frac{(x - x_0)^{p_3}}{2 \cdot p_2^{p_3}}\right),$$

$$f_{NRDPS}(x, a, p_0, p_1, p_2) = \sqrt{x_t} \cdot \exp(-a \cdot x_t) \cdot (p_0 + p_1 \cdot x_t + p_2 \cdot x_t^2),$$

where $x_0 = 2m_{J/\psi}, x_t = x - x_0$

Steps to identify structures in $J/\psi J/\psi$ mass spectrum

- Null-hypothesis (initial baseline model): NRSPS+NRDPS
- Add potential structures to baseline model
  - Add most prominent structure to baseline model
  - Calculate its local significance
  - Keep in baseline only if $> 3\sigma$ significance
  - Repeat until no more $> 3\sigma$ structures

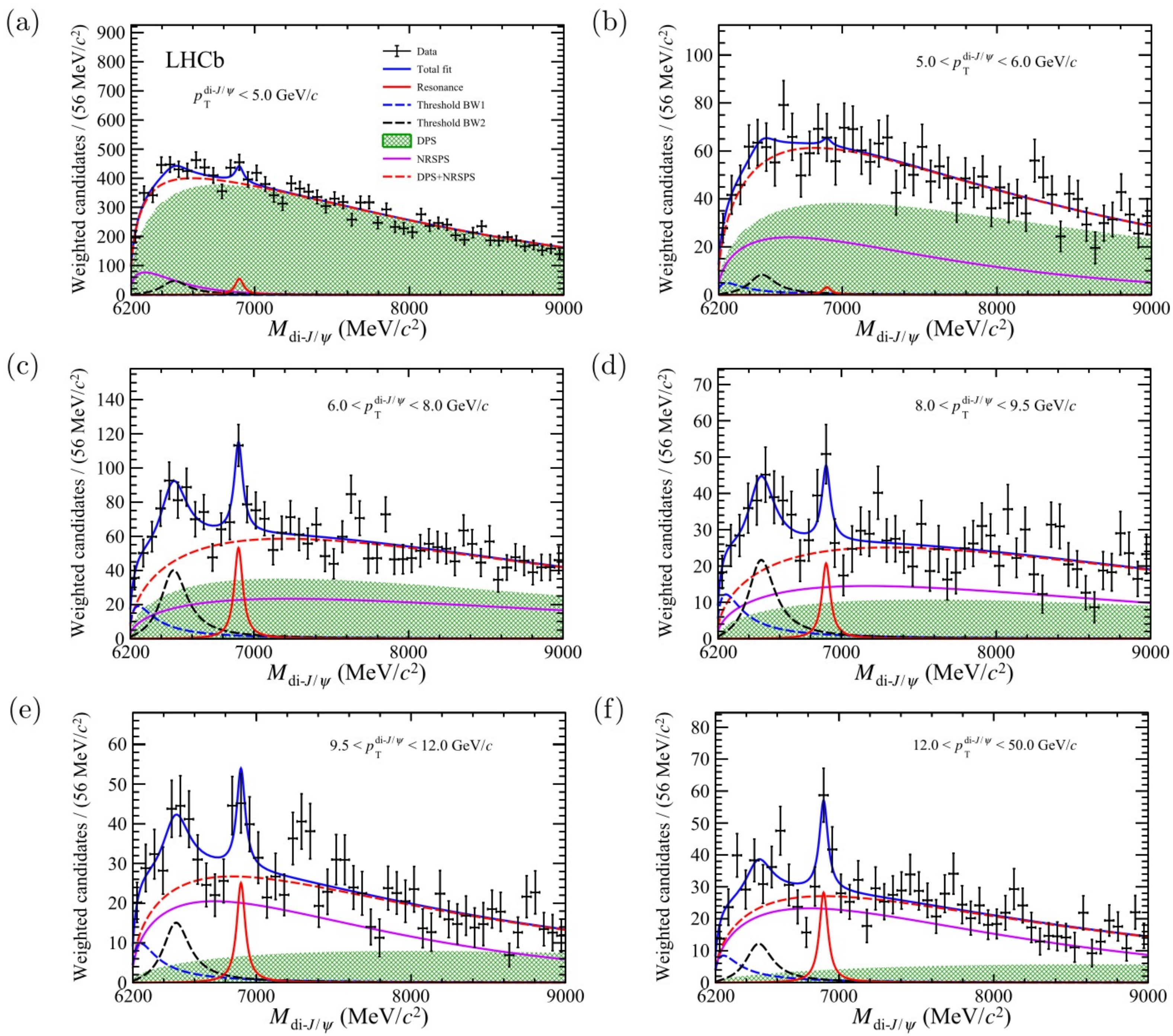


Fig. 4. Invariant mass spectra of weighted di-J/ψ candidates in bins of $p_T^{di-J/\psi}$ and overlaid projections of the $p_T^{di-J/\psi}$-binned fit with model I.