强子物理实验研究进展

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中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

2022.8.8-11 辽宁 大连

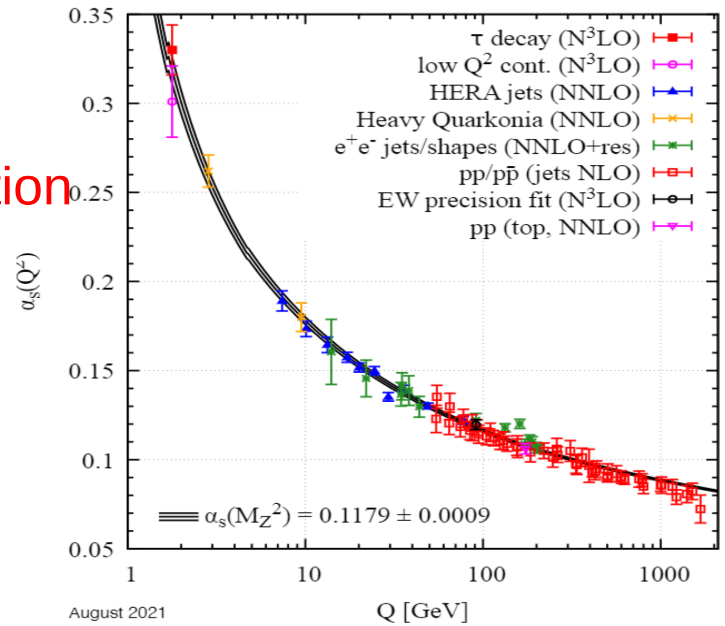
Outline

- **Introduction**
  - ➢ Perturbative QCD and Hadrons
  - ➢ Experimental approach
- **Hadron Production**
- **Highlights in Hadron Spectroscopy**
  - ➢ Light “nonstandard” hadrons
  - ➢ Heavy “nonstandard” hadrons
- **Summary**

I apologize for missing many important results

Introduction

- The standard model of particle physics is a well-tested theoretical framework.
- However, the SM has a number of issues need further investigation
    - ☐ **The nature of quark confinement**
    - ☐ Matter-antimatter asymmetry of the Universe
    - ☐ Gravity, dark matter, numbers of flavors, etc.



- The rich hadronic spectra provide valuable information to disentangle the hadron inner structure and non-perturbative region of QCD.

- Precision measurements of hadron production help make QCD-related models more prophetically and test SM parameters.

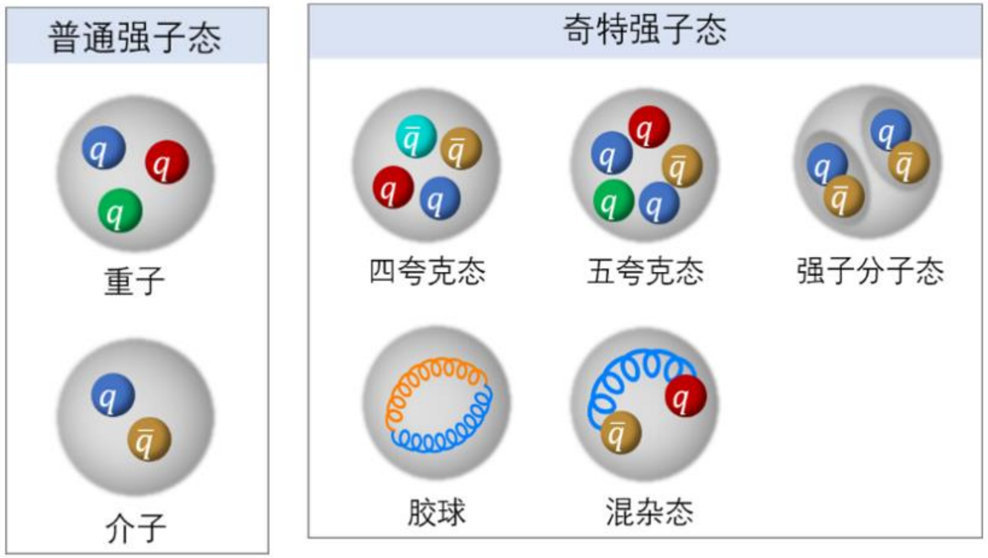
Hadrons Spectrum

- Experiments at particle accelerators in last fifties and sixties created many hadrons except e, p, n➔ "hadronic zoo".
- Quark model established order in the hadronic zoo.

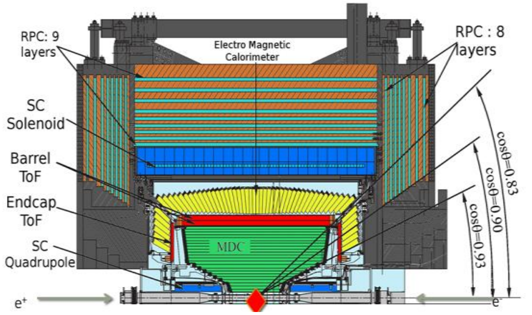
M. Gell-Mann, A schematic model of baryons and mesons: Phys.Lett. 8 (1964) 214-215
"Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc".

G. Zweig, An SU(3) model for strong interaction symmetry and its breaking. CERN-TH-401
"In general, we would expect that baryons are built not only from the product of these aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$, etc".

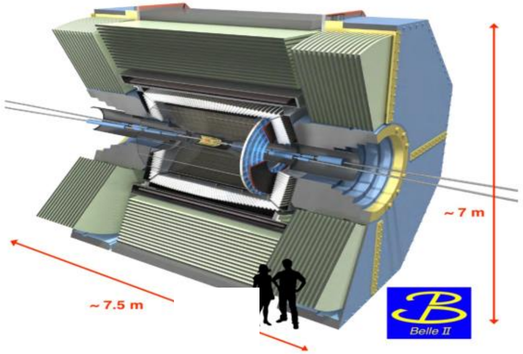
- Suggested by self-coupling of gluons of QCD, glueballs and hybrids exist.
- Experimental searches for exotic hadrons have a long history.
- Recent high-quality data allows study properties of established mesons, and search for new states.



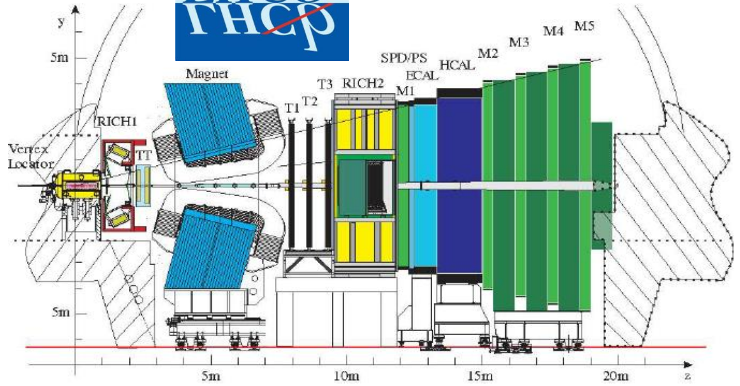
Experimental Approaches



- Symmetric e$^+$e$^-$ energy
- E$_{cm}$= 2.0-4.95 GeV (tau-charm region)
- Peak luminosity $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int L$ ~ 38 fb^{-1}
- To be upgraded in 2024 to increase luminosity at high c.m.s

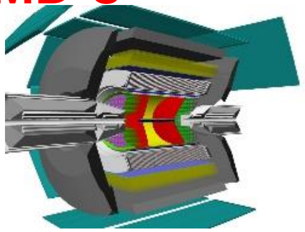


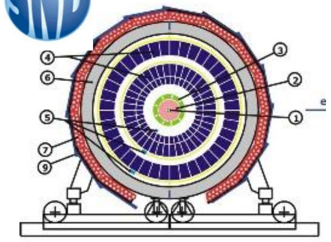
- Asymmetric energy e$^+$e$^-$
- Belle: e$^+$ (8.0 GeV) e$^-$ (3.5 GeV) ,$\int L$ ~ 1 ab^{-1}
- BelleII: e$^+$ (7.0 GeV) e$^-$ (4.0 GeV)
- ➢ New luminosity world record, 4.7x10^{34} cm^{-2}s^{-1}
- ➢ $\int L$ = 424 fb^{-1}

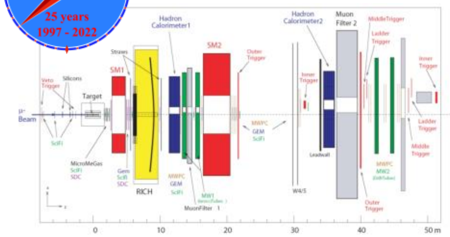


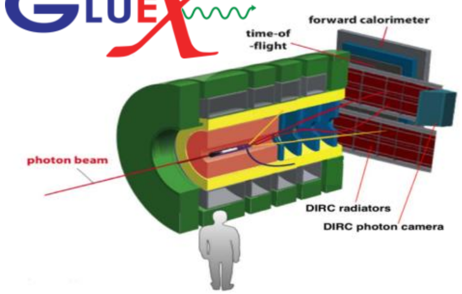
- Hadron Collider
- Covering 2 < η < 5, forward rapidity
- 25% of $b\bar{b}$ pairs inside acceptance
- Luminosity: 3 fb^{-1} at $\sqrt{s}$ = 7,8 TeV, 6 fb^{-1} at $\sqrt{s}$ =13 TeV

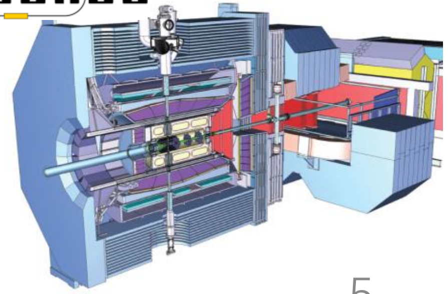
CMD-3









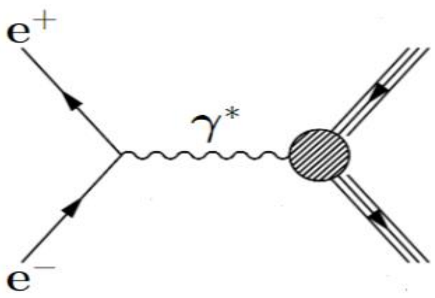


There are many experiments, sorry I can not cover them all

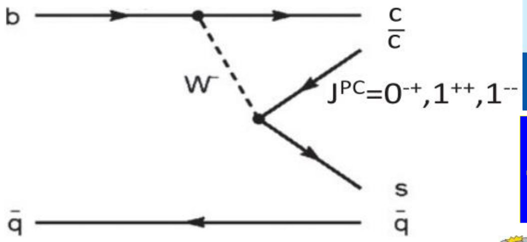
Production Processes

Take $c\bar{c}$ production as a example

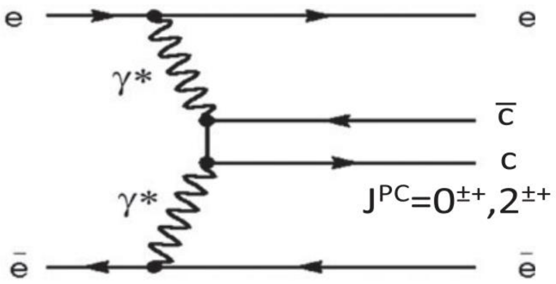
Direct production in e^+e^- collisions



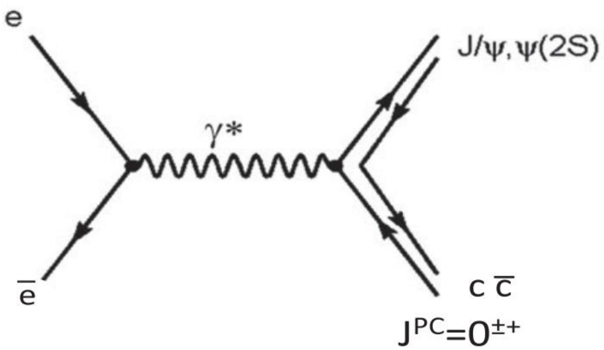
Production in b decays



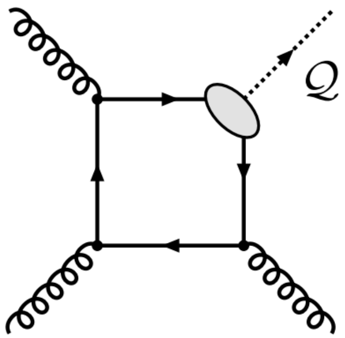
Two-photon fusion processes



Double-charmonium production $e^+e^- \to c\bar{c}c\bar{c}$

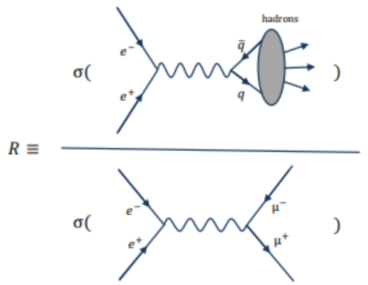


Prompt production



Highlights in Hadron Production

R value



$$R \equiv \frac{\sigma^0(e^+e^- \to \text{hadrons})}{\sigma^0(e^+e^- \to \mu^+\mu^-)} \equiv \frac{\sigma^0_{\text{had}}}{\sigma^0_{\mu\mu}}$$

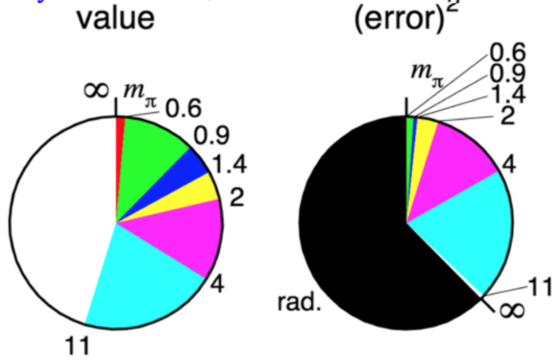
- Running of fine structure constant $\Delta\alpha_{\text{em}}$

$$\Delta\alpha(s) = 1 - \alpha(0)/\alpha(s) = \Delta\alpha_{\text{lepton}}(s) + \Delta\alpha^{(5)}_{\text{had}}(s) + \Delta\alpha_{\text{top}}(s)$$

Eur. Phys. J. C 80, 241 (2020)

Source	Contribution($\times 10^{-4}$)
$\Delta\alpha_{\text{lepton}}(M_Z^2)$	314.979 ± 0.002
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$	276.0 ± 1.0
$\Delta\alpha_{\text{top}}(M_Z^2)$	-0.7180 ± 0.0054

Fractional contribution to $\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$:
Phys. Rev. D 97, 114025 (2018)

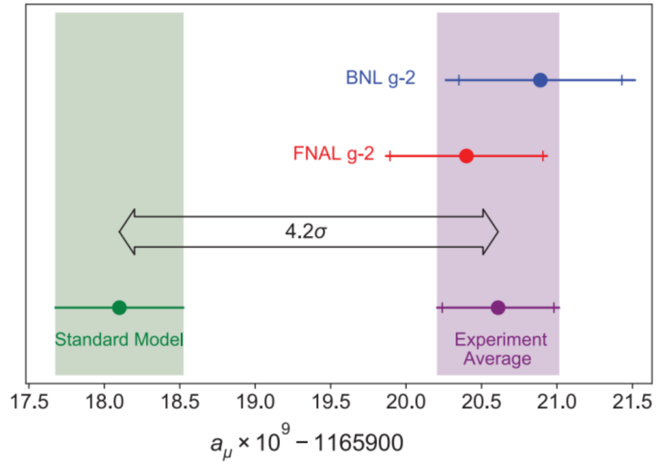


- $\Delta\alpha^{(5)}_{had}(s)$ should be calculated with R value:

$$\Delta\alpha^{(5)}_{\text{had}}(s) = -\frac{\alpha s}{3\pi}\,\text{Re}\int_{E_{\text{th}}}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\varepsilon)}$$

- Muon anomalous magnetic moment a_μ

PRL126.141801 (2021)

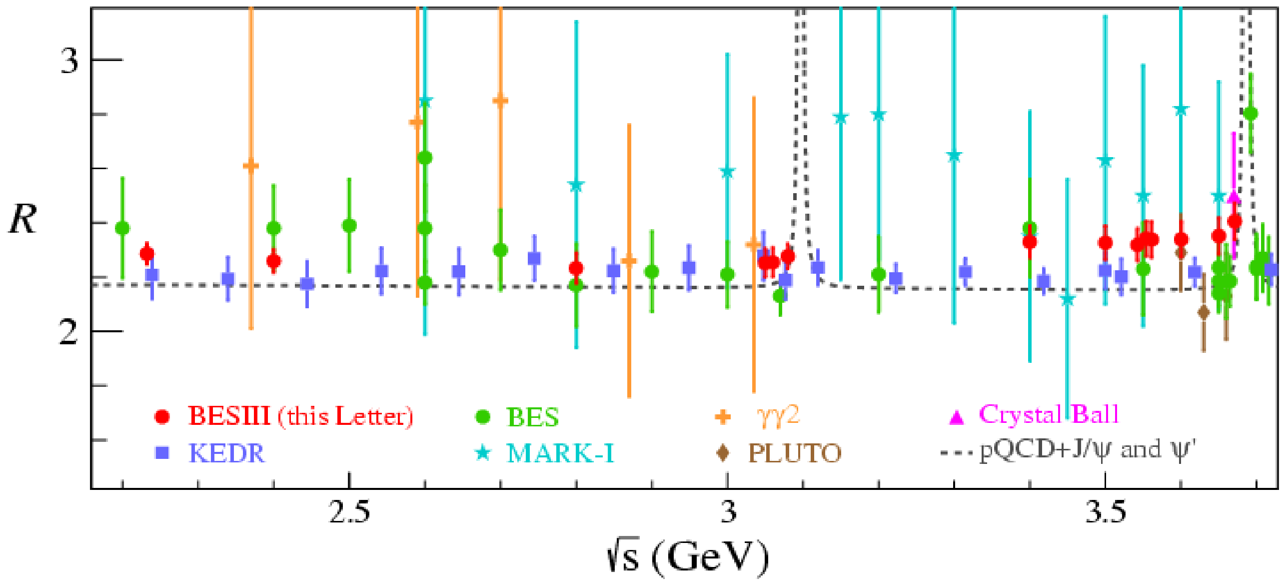


- SM prediction: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{Had}$
  - ➢ Hadronic Vacuum Polarization (HVP) and Light-by-Light (HLbL) in a_μ^{Had} dominate uncertainty
- HVP contribution is calculated with R value using dispersion relation:

$$a_\mu^{\text{LO-HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$$

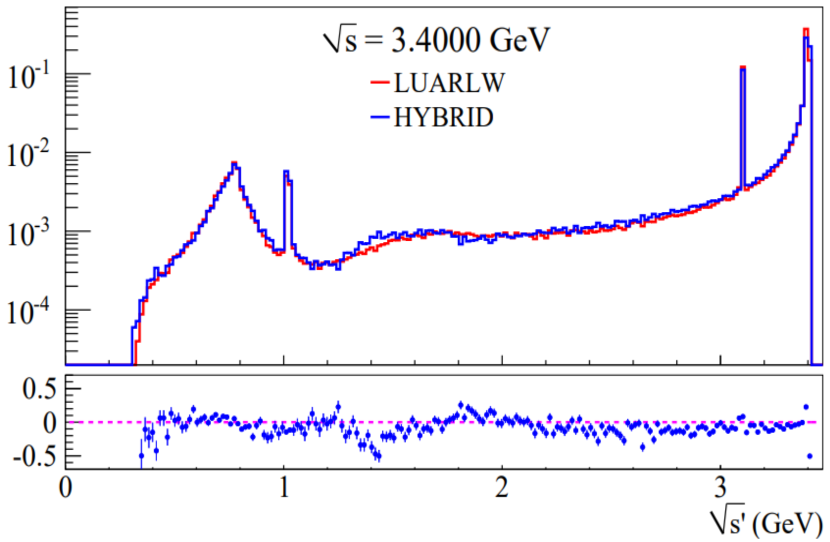
Precision measurement of R value

PRL 128, 062004 (2022)



$$R = \frac{N_{\rm had}^{\rm obs} - N_{\rm bkg}}{\sigma^0_{\mu\mu}\mathcal{L}_{\rm int.}\varepsilon_{\rm trig}\varepsilon_{\rm had}(1+\delta)}$$

- Very challenging to determine ε_{had}
- Two simulation models developed, consistent ISR-return $\sqrt{s'}$ spectrum.



- R value measured at 14 c.m. energies from 2.2324 to 3.671 GeV.
- Accuracy better than 2.6% below 3.1 GeV and 3.0% above.
- Larger than the pQCD prediction by 2.7σ in 3.4 ~ 3.6 GeV.

For details, see talk #4 in parallel session VIII (2)

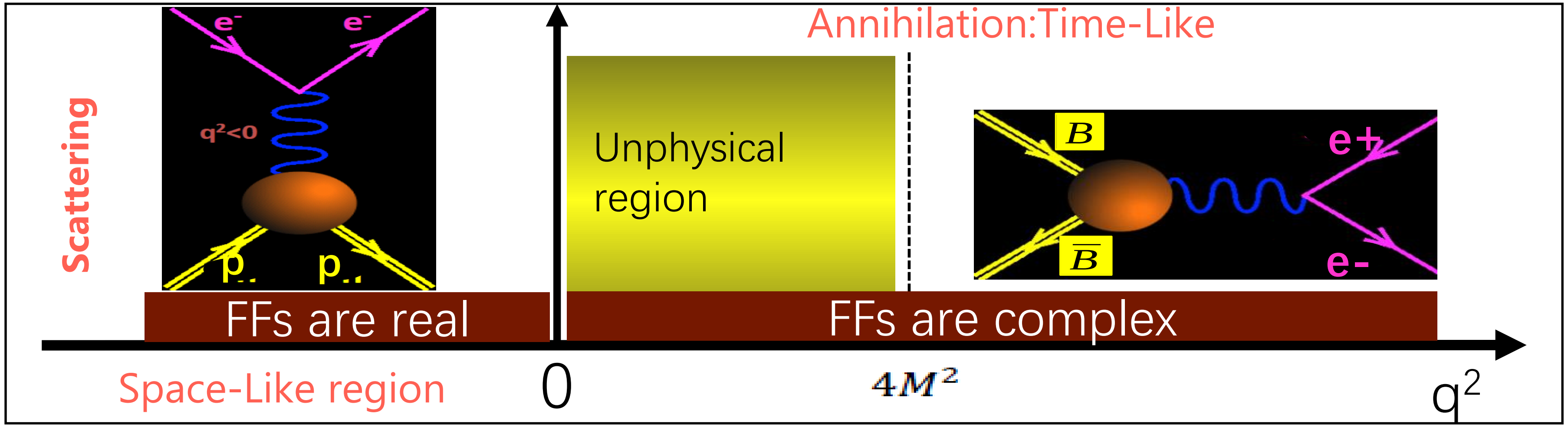
Nucleon Electromagnetic Form Factors

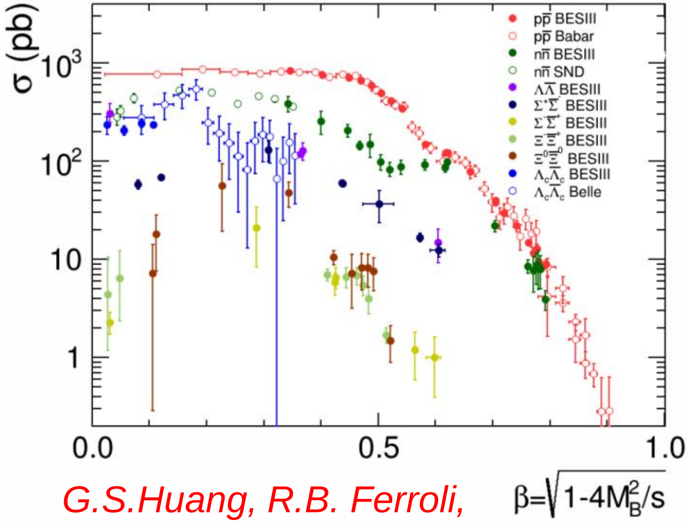
- Nucleons are composite objects with inner structure. At low Q, perturbative QCD not possible.

  ⇒ Nucleon structure must be measured in experiments!

- Electromagnetic Form Factors are fundamental properties of the nucleon.
  - ➢ Connected to charge, magnetization distribution.
  - ➢ Crucial testing ground for models of the nucleon internal structure.

- Threshold effects observed in various $B\bar{B}$ thresholds.



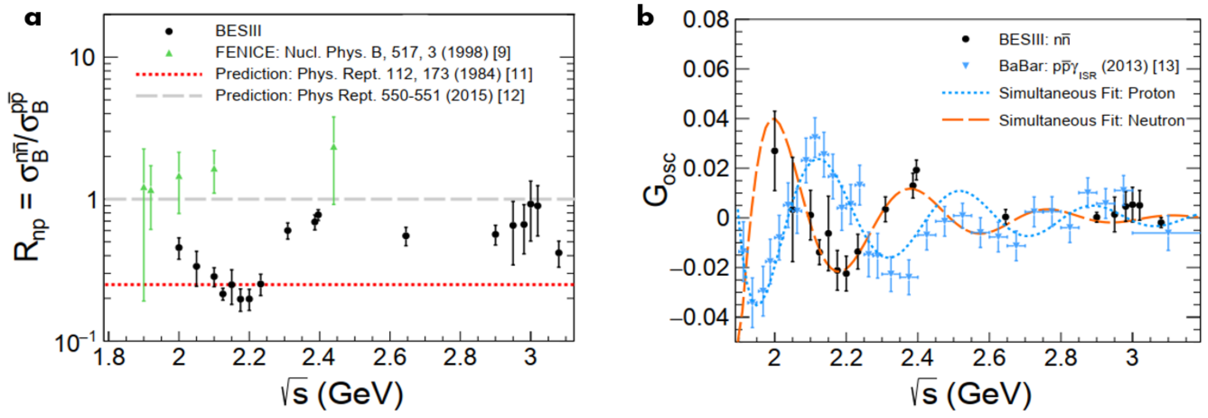


G.S.Huang, R.B. Ferroli, Natl.Sci.Rev. 8 (2021) 11, nwab187

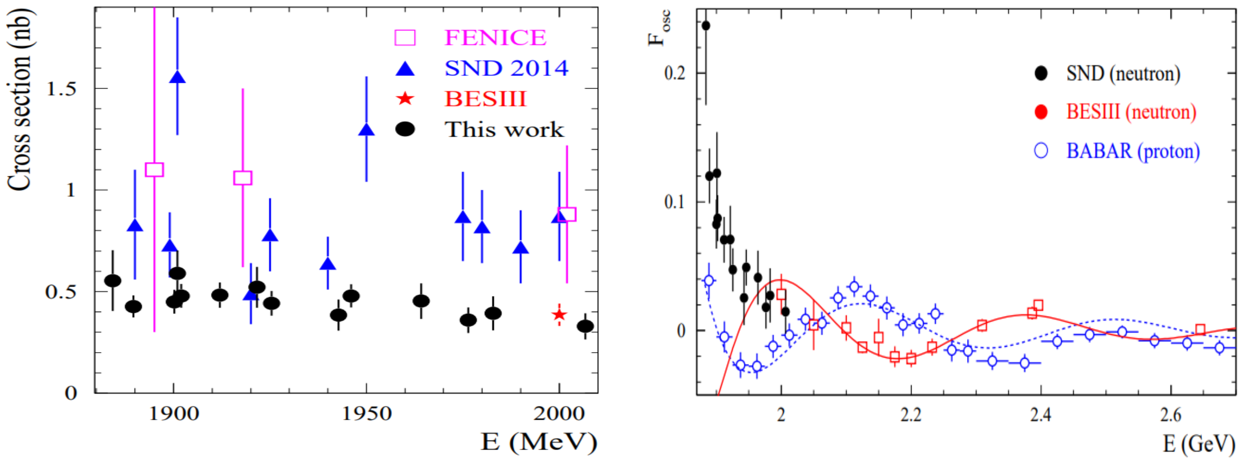
New Results of Nucleon EMFFs

- $e^+e^- \to n\bar{n}$ from 2.0-3.08 GeV, 647.9 pb^{-1}.
- $\gamma - p$ coupling larger than $\gamma - n$ coupling => consistent with theoretical predictions: VMD, Skyrme etc.
- Oscillation of reduced-|G| observed in neutron with a phase orthogonal to that of proton.

- $e^+e^- \to n\bar{n}$ from 1.884 to 2.007 GeV, ~30 pb^{-1}.
- $\sigma \approx 0.4$ nb below 2 GeV. Possible threshold effect.
- Reduced-|G| contracts the common proton /neutron oscillation frequency



Nat. Phys. 17, 1200–1204 (2021)

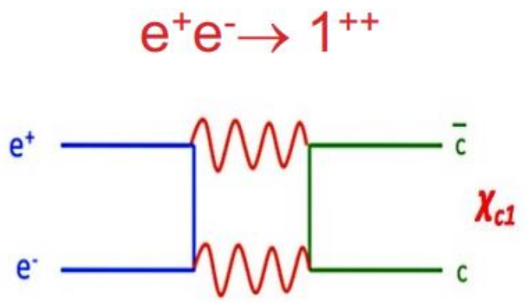


arXiv: 2206.13047

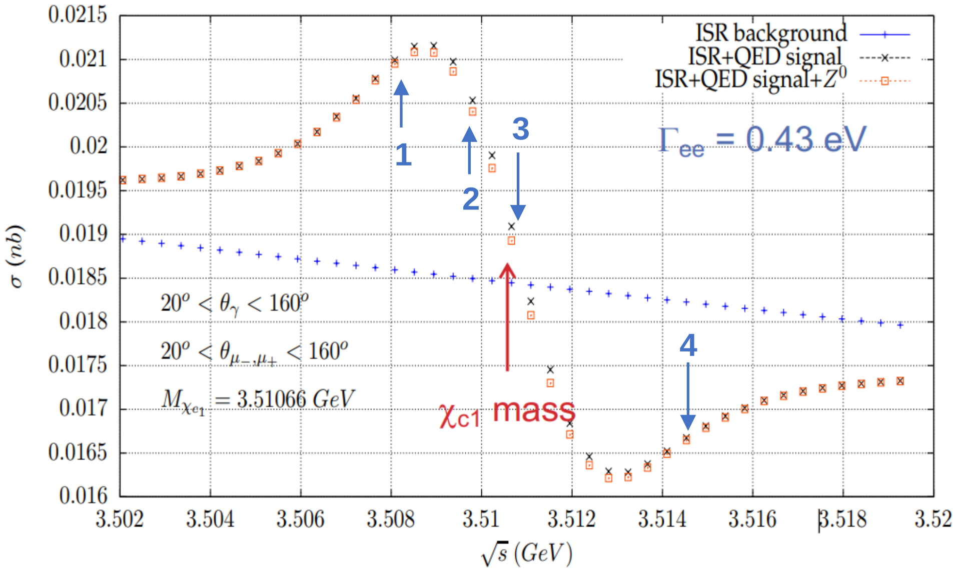
For details, see talk #4 in parallel session V (2)

Direct C-even production in e^+e^- annihlation

- The C-even states, *i.e.* $\eta, f_1(1285), \chi_c, X(3872)$, can be produced directly from e^+e^- annihlation through two virtual photons or neutral current reaction.
- The production rate is predicted with the electronic width Γ_{ee} of the states.



H. Czyz, J. H. Kühn, S. Tracz, PRD 94, 034033 (2016)



- Revisit calculation with Large interference effects
  distortion of the total cross section
- Interference effects implemented in PHOKHARA

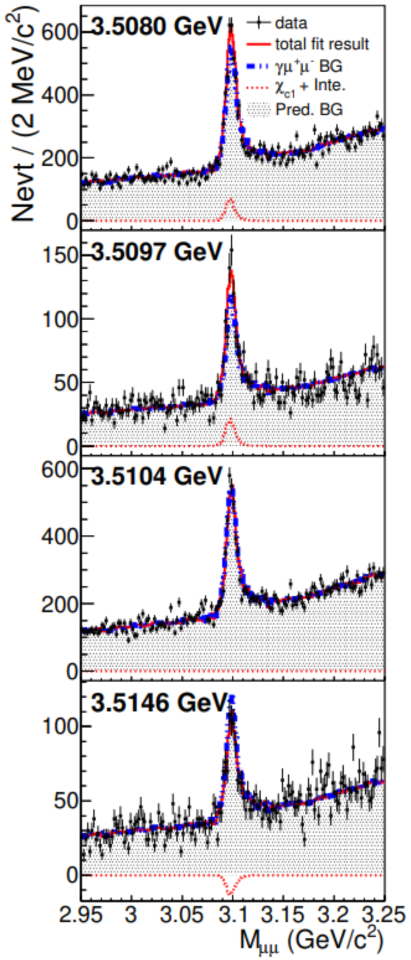
- BESIII is an ideal place for hunting $e^+e^- \to \chi_{c1}$
  - Uncertainty of E_{cms}: $\pm$0.05 MeV
  - Beam energy spread: (736 $\pm$ 27) keV

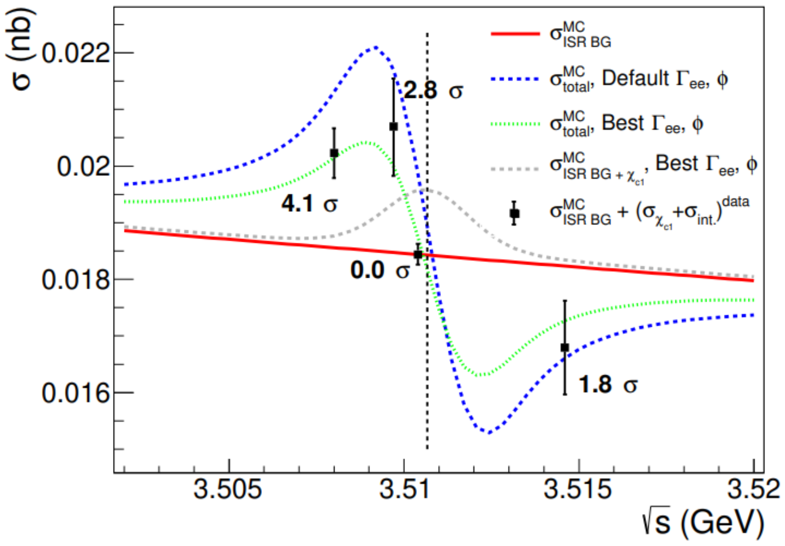
✱ ISR background: $e^+e^- \to \gamma\mu^+\mu^-$; ISR + QED signal ($+Z^0$): $e^+e^- \to \gamma\mu^+\mu^- + e^+e^- \to \chi_{c1} \to \gamma J/\psi \to \gamma\mu^+\mu^-$

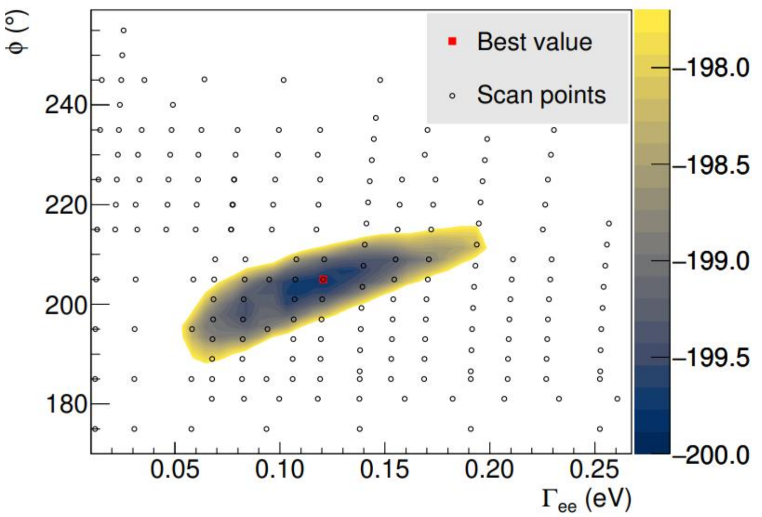
✱ $\theta_{\gamma/\mu}$: polar angle of γ/μ; $M\chi_{c1}$: nominal mass of χ_{c1} state

First observation of χ_{c1} production

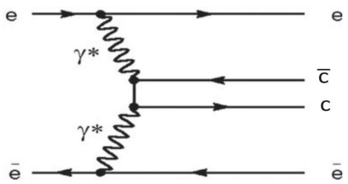
arXiv: 2203.13782



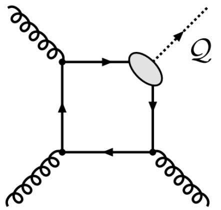




- Direct production of $e^+e^- \to \chi_{c1}(1^{++})$ is observed with statistical significance > 5σ; $\Gamma_{ee}=0.12^{+0.13}_{-0.08}$ eV and $\phi=205^{+15.4}_{-22.4}$ degree
- Interference pattern around the χ_{c1} mass is observed, as predicted
- New production method of C-even states (conventional or exotic) in e^+e^- experiments

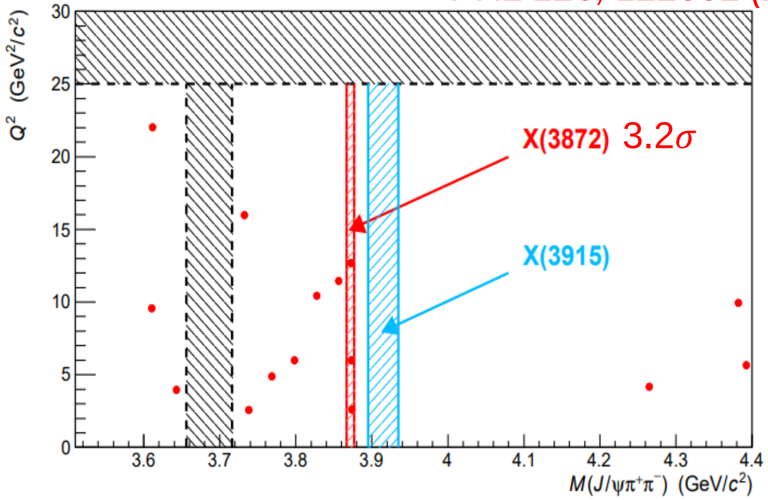


Production of $X(3872)$



- single-tag two-photon $\gamma\gamma^*$ interaction, 825 fb^{-1}

PRL 126, 122001 (2021)



- Three $X(3872)$ signal observed. Assuming Q^2 dependence of a $c\bar{c}$ meson model:

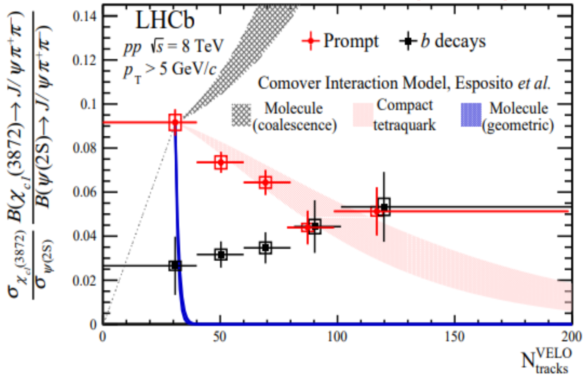
$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}(\text{stat.}) \pm 0.7(\text{syst.})\ \text{eV}$$

$\Rightarrow$ $\tilde{\Gamma}_{\gamma\gamma}$ range :20-500 eV (consistent with prediction from $c\bar{c}$ model)

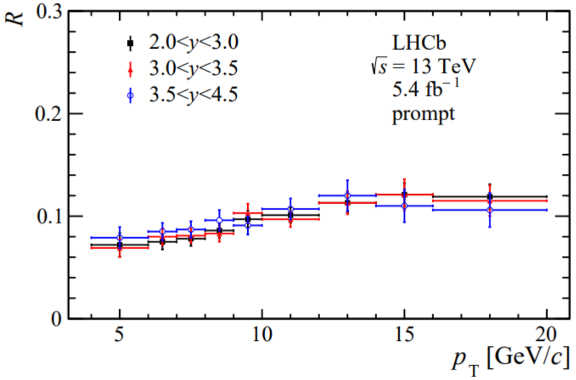
G. A. Schuler et al., NPB 523, 423 (1998)

- Prompt production from $p-p$ collision

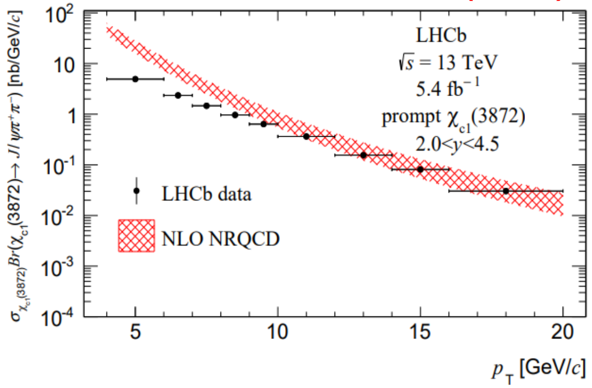
PRL 126, 092001 (2021)



- Prompt $X(3872)$ is suppressed relative to $\psi(2S)$ as multiplicity increases
- Behavior consist with compact tetraquark.



JHEP 01, 131 (2022)

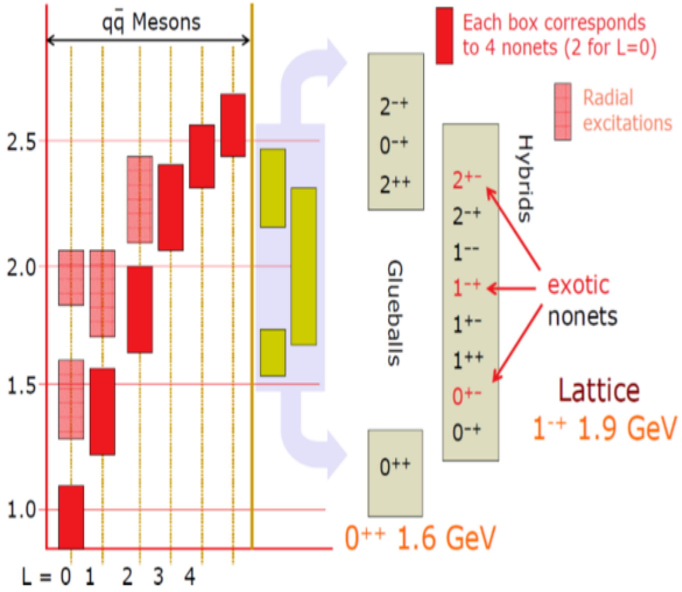


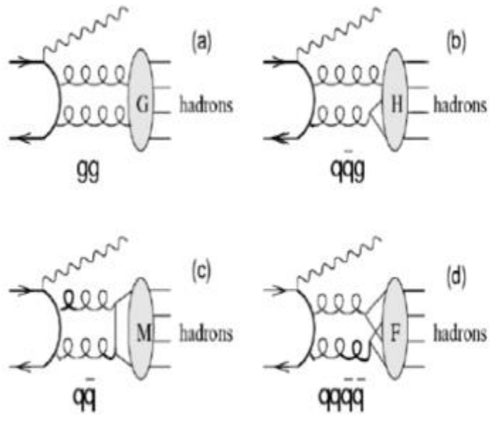
NLO NRQCD: $\mathrm{X}(3872)$ could be a mixture of $\chi_{c1}(2\mathrm{P})$ and $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$ molecular

C. Meng, H. Han, K. T. Chao, PRD 96, 074014 (2017)

Highlights in Hadron Spectroscopy

Glueballs and Hybrids



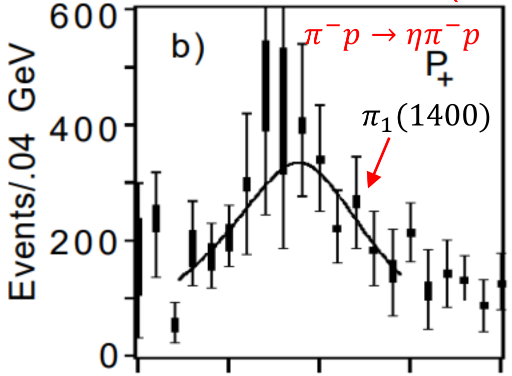


$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3),$

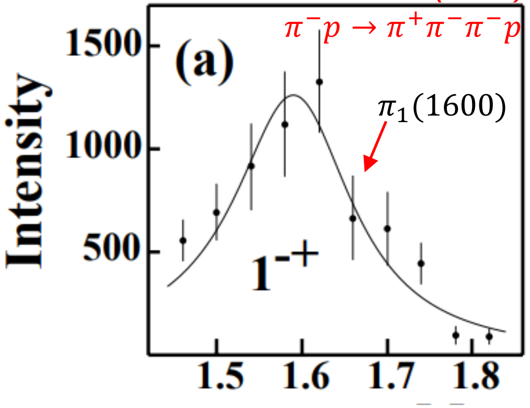
$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$

- Experimental evidence for three isovector states with $J^{PC} = 1^{-+}$:
  - $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$

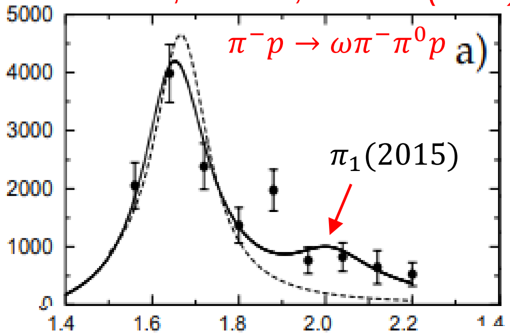
E852, *PRL* 79, 1630 (1997)



E852, *PRL 81, 5760 (1998)*



E852, *PRL 94, 032002 (2005)*



- Charmonium decays are ideal hunting grounds for light glueballs and exotics
  - "Glue-rich" environment
  - Clean high statistics data samples from e^+e^- production

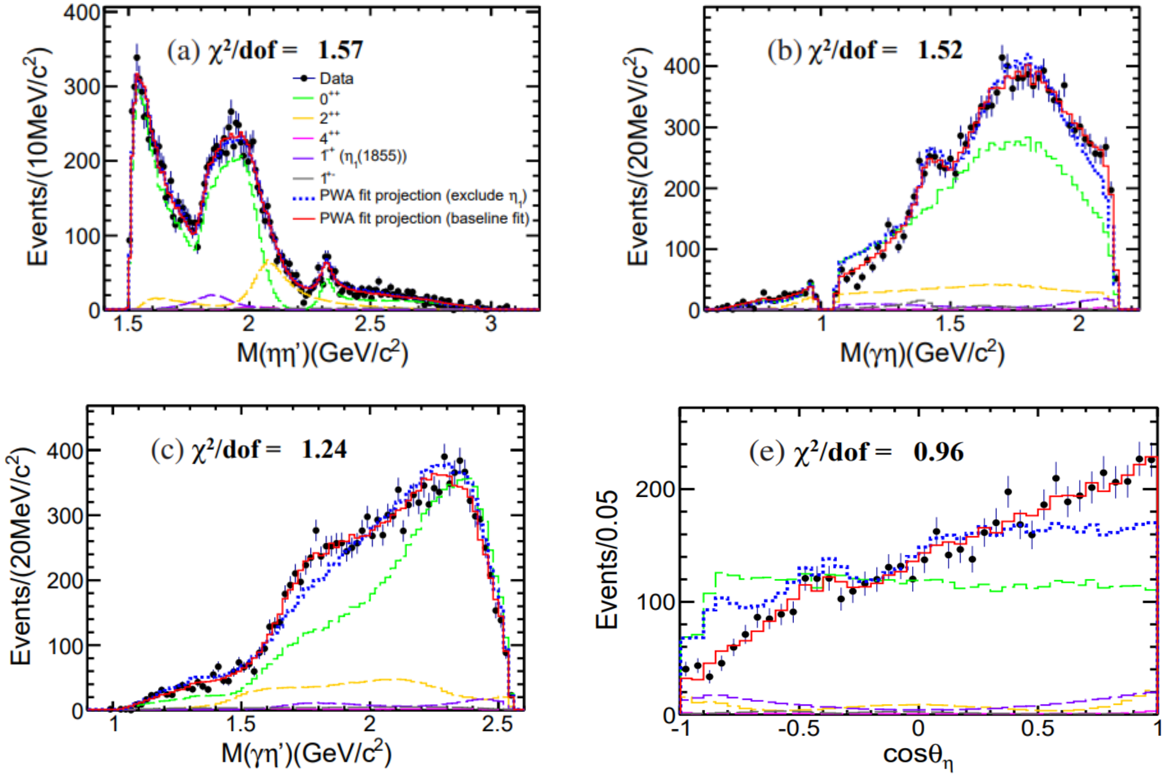
Crucial task: finding an isoscalar 1^{-+} state

Observation of Exotic Isoscalar $\eta_1(1855)$ (1^{-+})

arXiv:2202.00621, 2202.00623

- 10B J/ψ, $J/\psi \to \gamma\eta\eta'$: quasi two-body decay amplitudes in $\gamma X(\to \eta\eta')$ and $\eta' X(\to \gamma\eta)$

Resonance	M (MeV/c^2)	Γ (MeV)	B.F.($\times 10^{-5}$)	Sig.
$f_0(1500)$	1506	112	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg 30\sigma$
$f_0(1810)$	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
$f_2(1565)$	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
$f_4(2050)$	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
0^{++} PHSP	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$h_1(1415)$	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
$h_1(1595)$	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

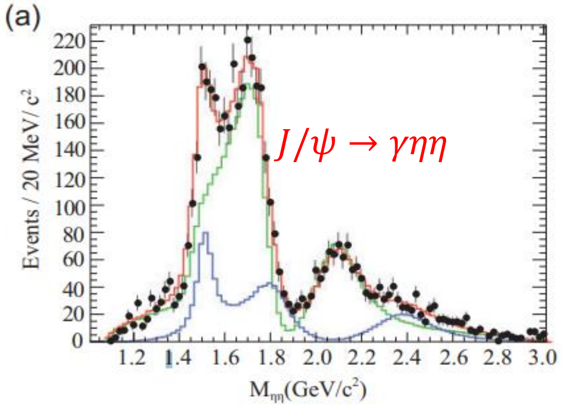


- **1^{-+} in $\eta\eta'$ observed**
  - ➢ Consistent with 1^{-+} hybrid of LQCD calculation
  - ➢ The isoscalar 1^{-+} hybrid helps complete the hybrid multiplet, with isovector states.

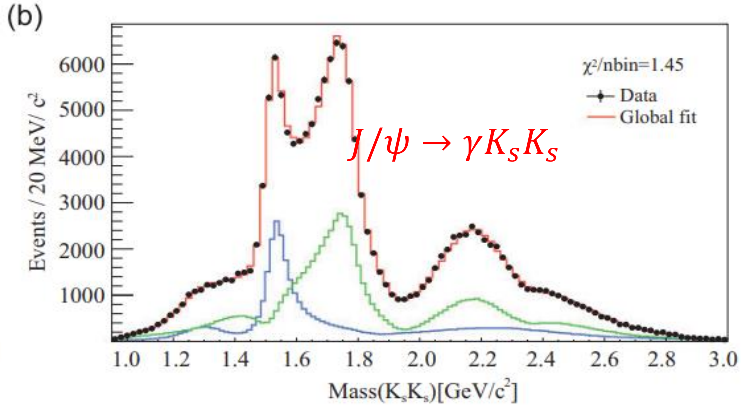
$f_0(1500)\&f_0(1710)$ from J/ψ Radiative Decay

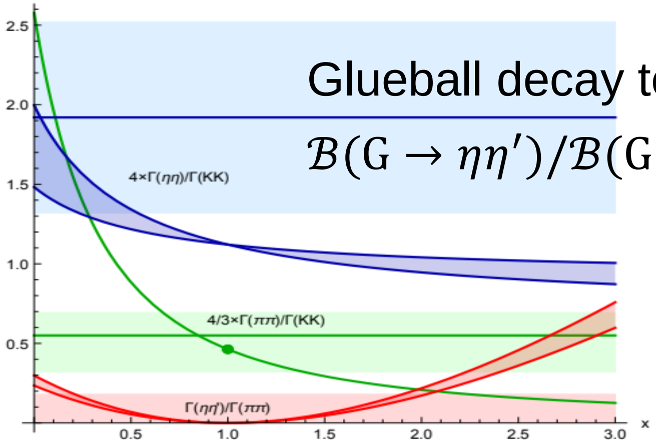
- LQCD predicts the lightest glueball lying in 1.5 and 1.7 GeV/c^2 and $J^{PC}=0^{++}$, with a large BF ~$\mathcal{O}(10^{-3})$.
- Supernumerary isoscalars of $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ => one scalar glueball candidate exists.

PRD 98, 072003 (2018)



PRD 87, 092009 (2013)





Glueball decay to $\eta\eta'$ is suppressed

$\mathcal{B}(G\to\eta\eta')/\mathcal{B}(G\to\pi\pi) < 0.04$

*F. Brünner and A. Rebhan, PRD **92**, 121902 (2015)*

Exp: $\mathcal{B}(J/\psi\to\gamma f_0(1500))\sim 0.29\times10^{-3}$ $\quad\mathcal{B}(J/\psi\to\gamma f_0(1710))\sim 2.2\times10^{-3}$

Theory: $\mathcal{B}(J/\psi\to\gamma G)\sim 3.8(8)\times10^{-3}$

L.C. Gui et al., [CLQCD],Phys. Rev. Lett. 110, 021601 (2013)

$$\frac{\mathcal{B}(f_0(1500)\to\eta\eta')}{\mathcal{B}(f_0(1500)\to\pi\pi)} = (8.96^{+2.95}_{-2.87})\times10^{-2}$$

$$\frac{\mathcal{B}(f_0(1710)\to\eta\eta')}{\mathcal{B}(f_0(1710)\to\pi\pi)} < 1.61\times10^{-3} \text{ at 90\% C.L.}$$

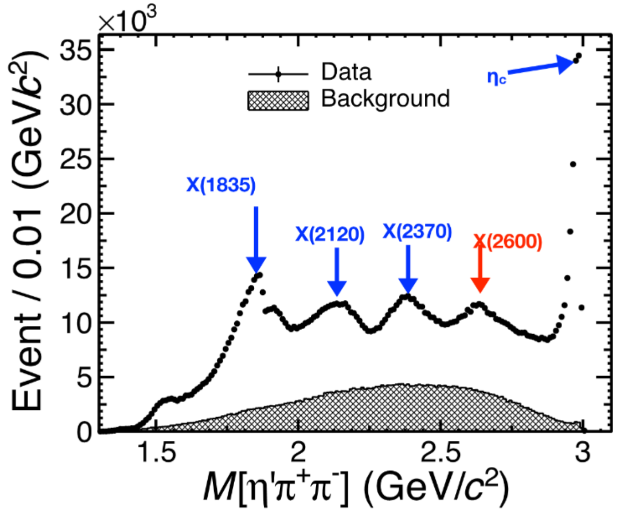
- These results support the hypothesis that $f_0(1710)$ has a large glueball component.

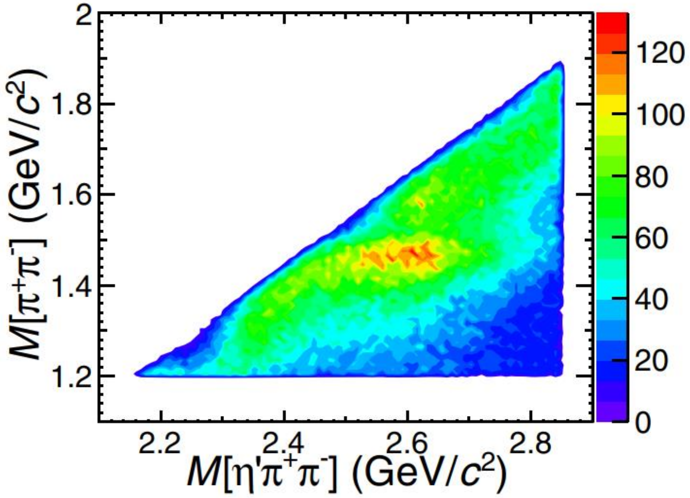
For details, see talk #1 in parallel session VIII (2)

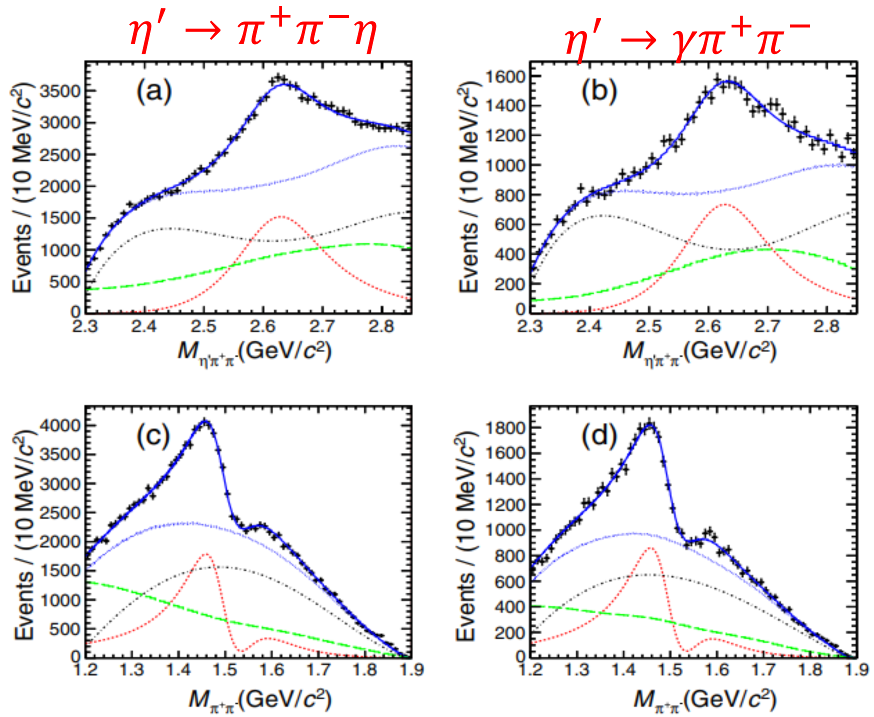
Observation of $X(2600)$ in $J/\psi \to \gamma\eta'\pi^+\pi^-$

PRL 129, 042001 (2022)

- $X(2600)$ observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$, >20σ
- Simultaneous fit of $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ mass spectra







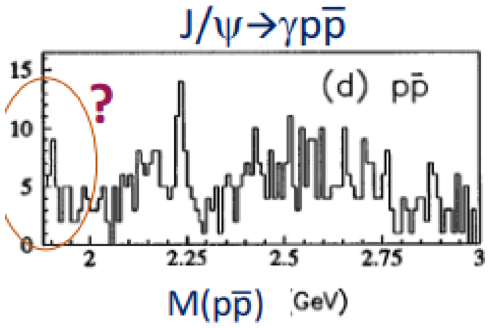
Resonance	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

BFs of sequential decay in $J/\psi \to \gamma X(2600)$:

Case	$f_0(1500)$	$X(1540)$
Events	24585 ± 1689	21203 ± 1456
BF ($\times 10^{-5}$)	$3.09 \pm 0.21^{+1.14}_{-0.77}$	$2.69 \pm 0.19^{+0.38}_{-1.21}$

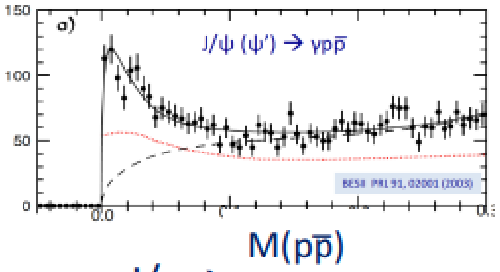
States in $\eta'\pi^+\pi^-$ lineshape

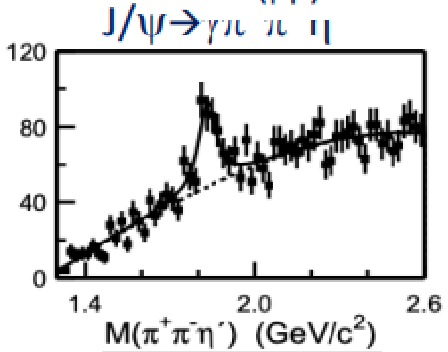
1996: 8 M J/ψ's



PRL 76, 3502

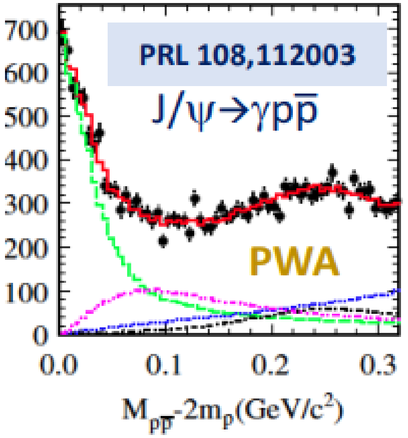
2002: 58 M J/ψ's

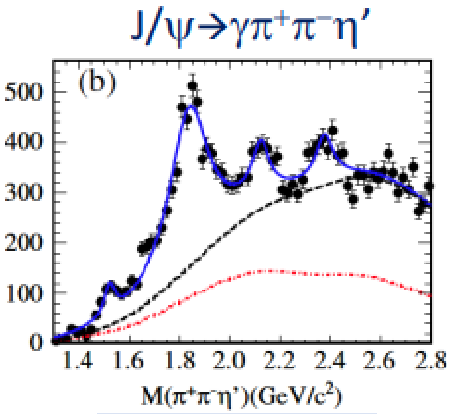




PRL 95,262001

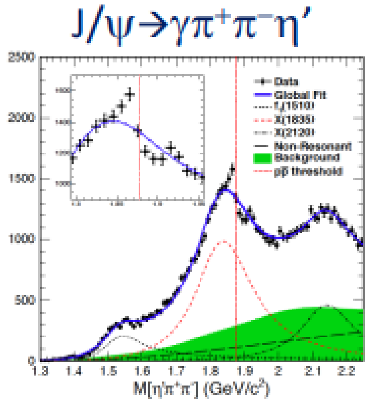
2011: 225 M J/ψ's





PRL 106,072002

2016: 1.3 B J/ψ's

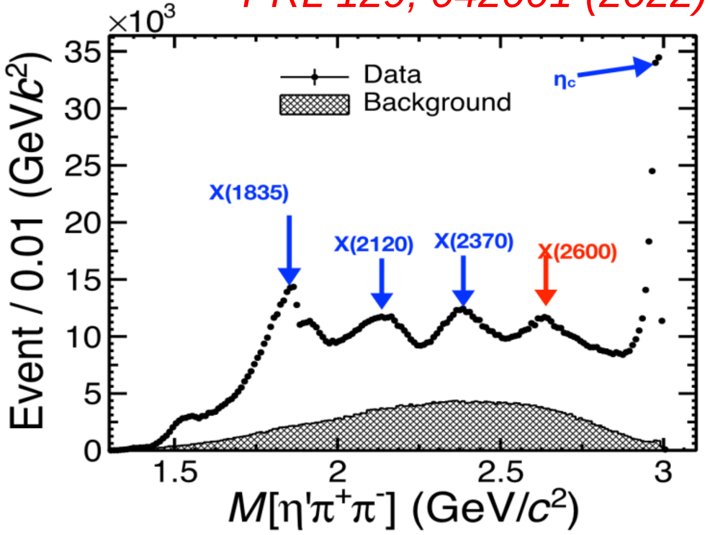


PRL 117,042002

2019: 10 B J/ψ's

???

PRL 129, 042001 (2022)



You never have enough J/ψ events!

— Stephen Lars Olsen

Heavy “Nonstandard” Hadrons Candidates

- Large amount of experimental activity on the “nonstandard” heavy sector
  - B, Λ_b decays: Belle, Babar, LHCb
  - e^+e^- direct production: BESIII, Belle, BaBar
  - $pp/p\bar{p}$ prompt production: LHCb, CMS, ALTAS…
  - Quarkonia decay: BESIII, Belle, BaBar

2003-
X(3872)

2005-
X(3915)
Y(4260)
$Y_b(10860)$

2007-
X(3940)
X(4160)
Y(4360)
Y(4660)
X(4050)
X(4250)
Z(4430)

2009-
X(4140)
X(4350)

2011-
$Z_b(10610)$
$Z_b(10650)$

2013-
$Z_c(3900)$
$Z_c(4020)$
Z(4200)

2015-
$P_c(4380)$
$P_c(4450)$

2017-
X(4274)
X(4500)
X(4700)
Y(4220)
Y(4390)

2019-
$P_c(4457)$
$P_c(4440)$
$P_c(4312)$
X(3842)
X(6900)
$X_0(2900)$
$X_1(2900)$

2021-

X(4685)	$X(4685)$
X(4630)	$X(4630)$
$Z_{cs}(3985)$	$T_{\psi s1}(3985)^+$
$Z_{cs}(4220)$	$T_{\psi s1}(4220)^+$
$Z_{cs}(4000)$	$T_{\psi s1}^{\theta}(4000)^+$
$T_{cc}(3875)$	$T_{cc}(3875)^+$
$X(2900)^0$	$T_{c\bar{s}0}^{a}(2900)^0$
$X(2900)^{++}$	$T_{c\bar{s}0}^{a}(2900)^{++}$
X(6600)	$T_{\psi\psi}(6600)$
X(7300)	$T_{\psi\psi}(7300)$
$P_{cs}(4338)$	$P_{\psi s}^{\Lambda}(4459)$
$P_{cs}(4459)$	$P_{\psi s}^{\Lambda}(4338)^0$

- Pentaquark candidates labeled as P
- Charged meson states as Z
- $J^{PC} = 1^{--}$ as Y
- All the rest as X

New naming scheme arXiv: 2206.15233
e.g. $Z_{cs}(4000)^+$ $(c\bar{c}u\bar{s}, J^P = 1^+)$ => $T_{\psi s1}^{\theta}(4000)^+$

X States: News on $X(3872)$

- $X(3872)$, the most well established X meson, observed in:

$$J^{PC} = 1^{++}$$

$$\left\{ \begin{array}{ll} B \to K(J/\psi\pi^+\pi^-) & B \to K(\psi'\gamma) \\ p\bar{p} \to (J/\psi\pi^+\pi^-) + \cdots & pp \to (J/\psi\pi^+\pi^-) + \cdots \\ B \to K(J/\psi\pi^+\pi^-\pi^0) & e^+e^- \to \gamma(J/\psi\pi^+\pi^-) \\ B \to K(D^0\bar{D}^0\pi^0) & e^+e^- \to \gamma(\pi^0\chi_{c1}) \\ B \to K(J/\psi\gamma) & e^+e^- \to e^+e^- J/\psi\pi^+\pi^- \end{array} \right.$$

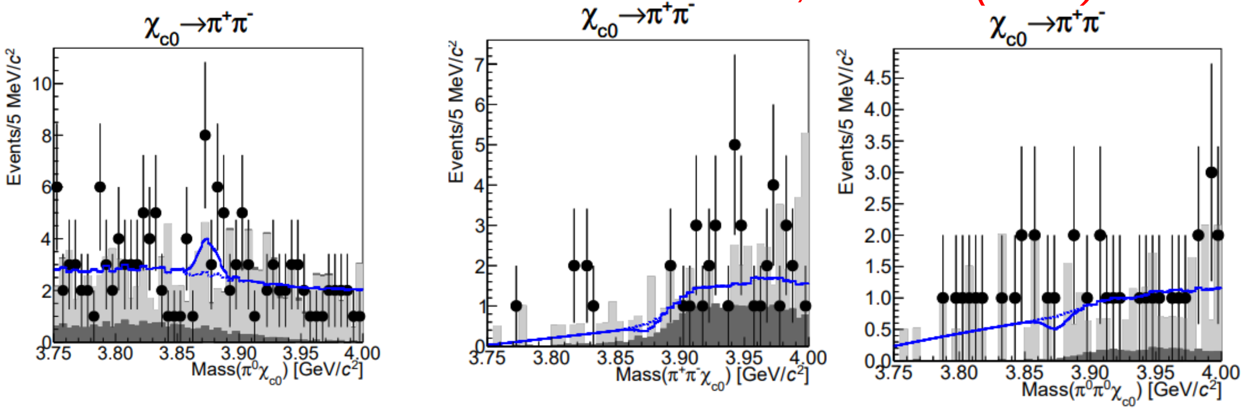
- The ratio $\frac{\mathcal{B}(X/(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X/(3872)\to\pi^+\pi^- J/\psi\ )}$ and $\frac{\mathcal{B}(X/(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X/(3872)\to\pi^0\chi_{c1})}$ sensitive to physics interpretation[1]

- EFT predict $\frac{\mathcal{B}(X/(3872)\to\pi\pi\chi_{c0})}{\mathcal{B}(X/(3872)\to\pi^0\chi_{c0})} \approx \mathcal{O}(10^{-3}) - \mathcal{O}(10^{-5})$ based on molecular structure [2]

Interpretation	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$
Four-quark/molecule	NA	2.97
$\chi_{c1}(2P)$	0.0	0.0
$D^0\overline{D}^{0*}$	NA	2.84 to 2.98
$D^0\overline{D}^{0*} + D^+D^{-*}$	1.3 to 2.07	1.65 to 1.77
$D^0\overline{D}^{0*} + D^+D^{-*}$	NA	3.72
$D^0\overline{D}^{0*} + D^+D^{-*} + \chi_{c1}(2P)$	0.094	1.15

BESIII

PRD 105, 072009 (2022)



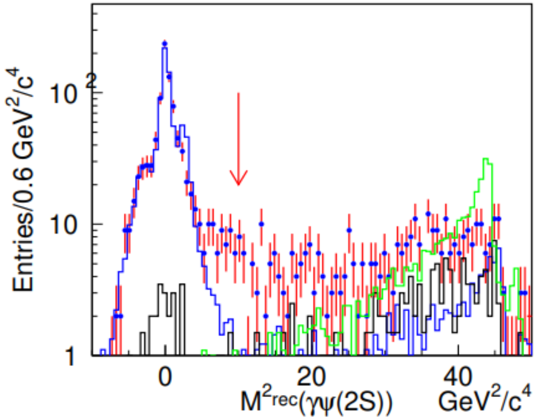
Ratio	90% C.L Upper Limit
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	3.6
$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}$	4.5
$\frac{\mathcal{B}(X(3872)\to\pi^+\pi^-\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.56
$\frac{\mathcal{B}(X(3872)\to\pi^0\pi^0\chi_{c0})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	1.7

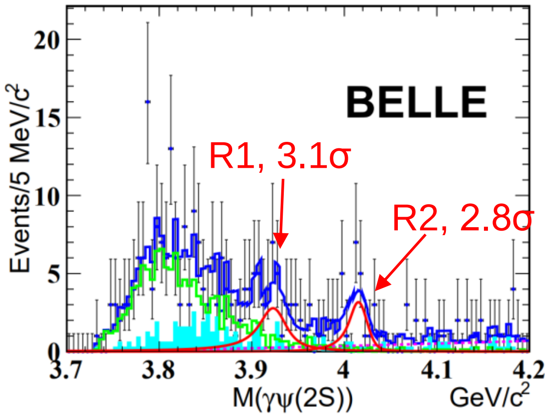
[1] PRD77,014013(2008), PRD78,094019(2008). EPJC81,193(2021), PRD79,094013(2009),PRD100,094025(2019)
[2] PRD79,094013(2009), PRD78, 094019(2008)

X States: $\gamma\gamma \to \gamma\psi(2S)$

- P-wave triplets near 3.9 GeV/c² remains puzzle, where $X(3930)$, as a good candidate of $\chi_{c2}(2P)$, has a hyperfine splitting of 12 MeV/c² between $\chi_{c2}(2P)$ and $X(3915)$

PRD 105, 112011 (2022)





Resonant parameters	$J=0$	$J=2$
M_{R_1}	$3922.4 \pm 6.5 \pm 2.0$	
Γ_{R_1}	$22 \pm 17 \pm 4$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$9.8 \pm 3.6 \pm 1.2$	$2.0 \pm 0.7 \pm 0.2$
M_{R_2}	$4014.3 \pm 4.0 \pm 1.5$	
Γ_{R_2}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

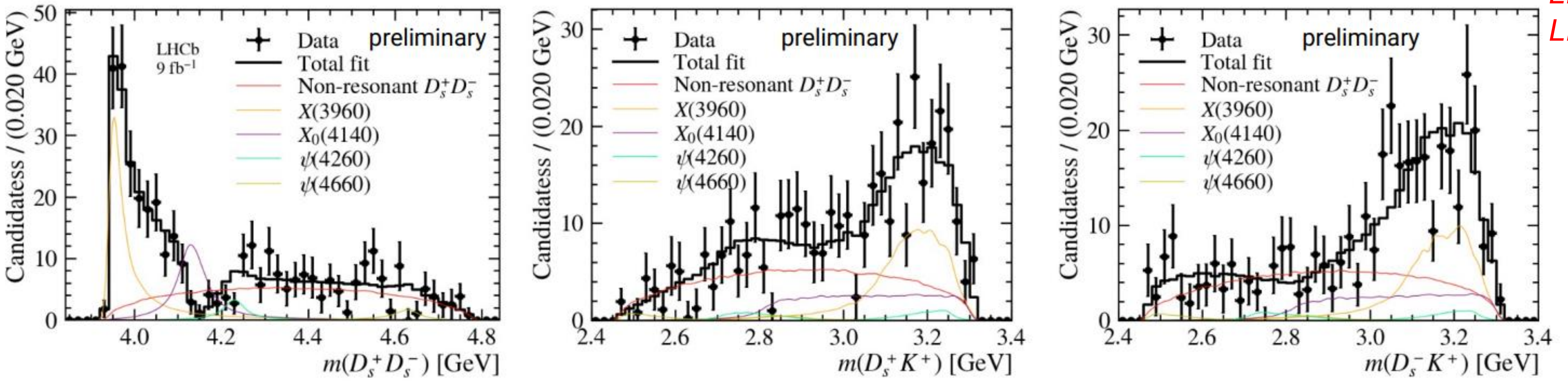
- Evidence of $X(3872)$ production in two-photon collisions => see p13.
- 0^{++} and 2^{++} can be produced in two-photon collisions and decay to $\gamma\psi(2S)$ via E1 transition.
- Evidence of structure R$_1$ near 3.92 GeV/c² => $X(3915)$ and $\chi_{c2}(3930)$
- R$_2$ matches none of the known states, (mass agrees with HQSS-predicted[1] 2^{++} partner of $X(3872)$, but width conflicts)

[1] F. K. Guo et al., PRD 88, 054007 (2013)
M. Albaladejo, et al., EPJC 75, 547 (2015).

X States: New States in $D_s^+ D_s^-$

- 9 fb^{-1} at LHCb, near threshold structure $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$, 12σ, $J^P = 0^{++}$
- X(4140) accounts for the dip around 4.14 GeV
- If $X(3960)$ and $X(3915)$ the same particle? More measurement needed.

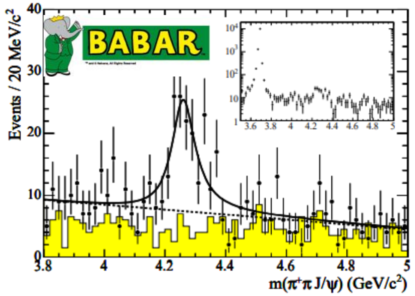
LHCb-PAPER-2022-018
LHCb-PAPER-2022-019

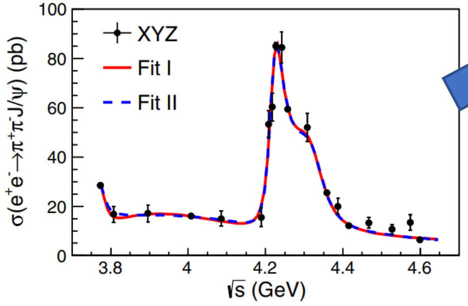


Component	J^{PC}	M_0 [MeV]	Γ_0 [MeV]	$\mathcal{F}$ [%]	$\mathcal{S}$ [σ]
$X(3960)$	0^{++}	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	$24.2 \pm 7.6 \pm 7.9$	12.6 (14.3)
$X_0(4140)$	0^{++}	$4133 \pm 7 \pm 11$	$69 \pm 17 \pm 7$	$17.7 \pm 4.9 \pm 7.7$	3.7 (3.9)
$\psi(4260)$	1^{--}	4230	55	$3.7 \pm 0.4 \pm 3.0$	3.1 (3.3)
$\psi(4660)$	1^{--}	4633	64	$2.2 \pm 0.2 \pm 0.5$	2.9 (3.2)
NR	S-wave	-	-	$46.6 \pm 13.3 \pm 11.3$	3.1 (3.4)

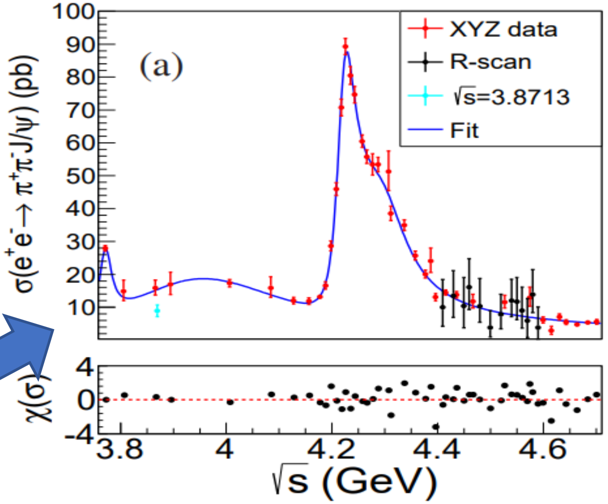
For details, see talk #4 in parallel session I(2)

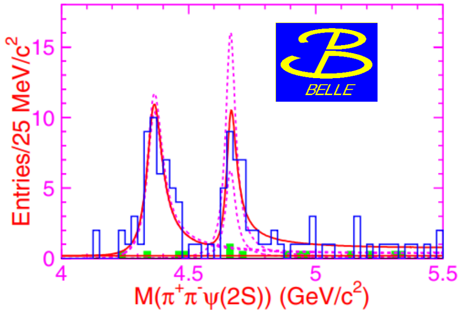
Y States: New Precise Measurements

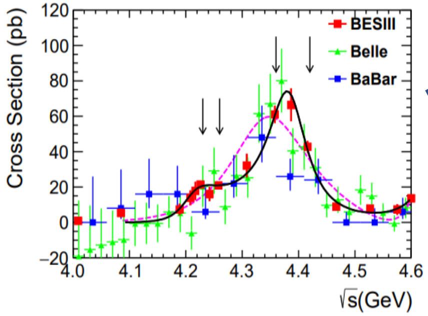




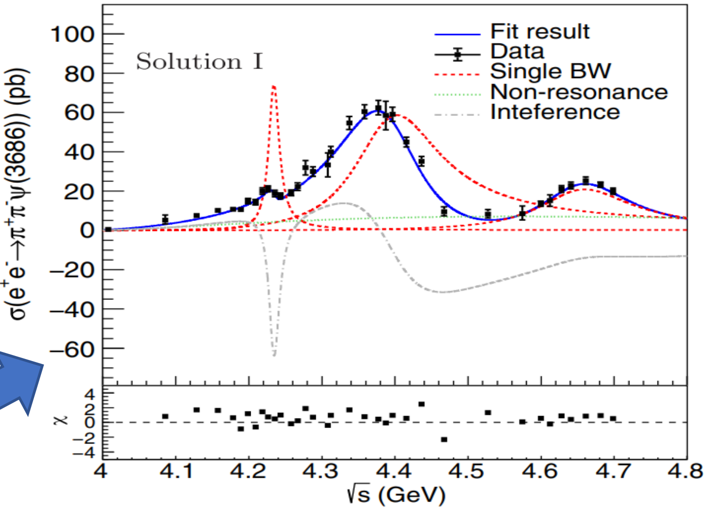
arXiv:2206.08554







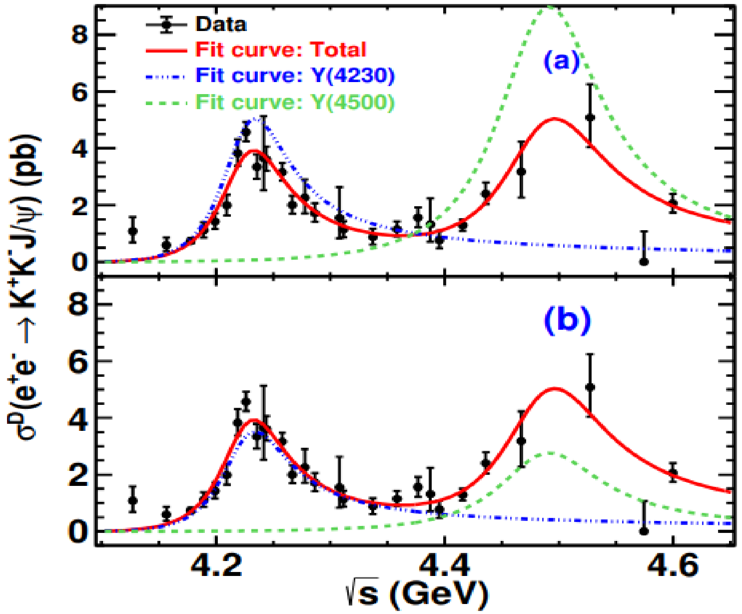
PRD 104, 052012 (2021)



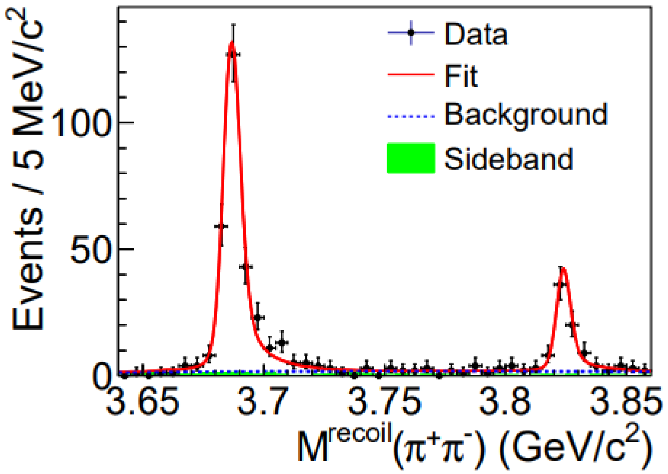
- $e^+e^- \to \pi^+\pi^- J/\psi$ from 3.773 to 4.700 GeV,~23 fb^{-1}
  - ➢ Structure close to 4.0 GeV is better described with a BW than Exp.
  - ➢ Enhancement around 4.5 GeV ~3σ, $\psi(4415)$ or $Y(4500)$?
- $e^+e^- \to \pi^+\pi^- \psi(3686)$ from 4.01 to 4.700 GeV
  - ➢ A continuous component is needed
  - ➢ First observation of $Y(4660)$ at BESIII

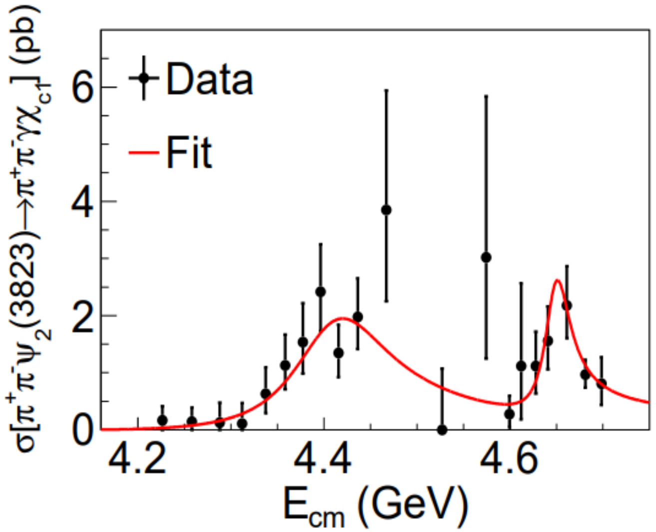
Y States: New States & Decay Modes

arXiv:2204.07800



arXiv:2203.05815





- Two resonances observed in $e^+e^- \to K^+K^-J/\psi$
  - ➢ Y(4230) firstly observed in K^+K^-J/ψ mode

$$0.02 < \frac{\mathcal{B}(Y(4230) \to K^+K^-J/\psi)}{\mathcal{B}(Y(4230) \to \pi^+\pi^-J/\psi)} < 0.26$$

  - ➢ Y(4500) not seen before (evidence in $e^+e^- \to \pi^+\pi^-J/\psi$)

  Cannot be assigned into any experimentally observed resonance

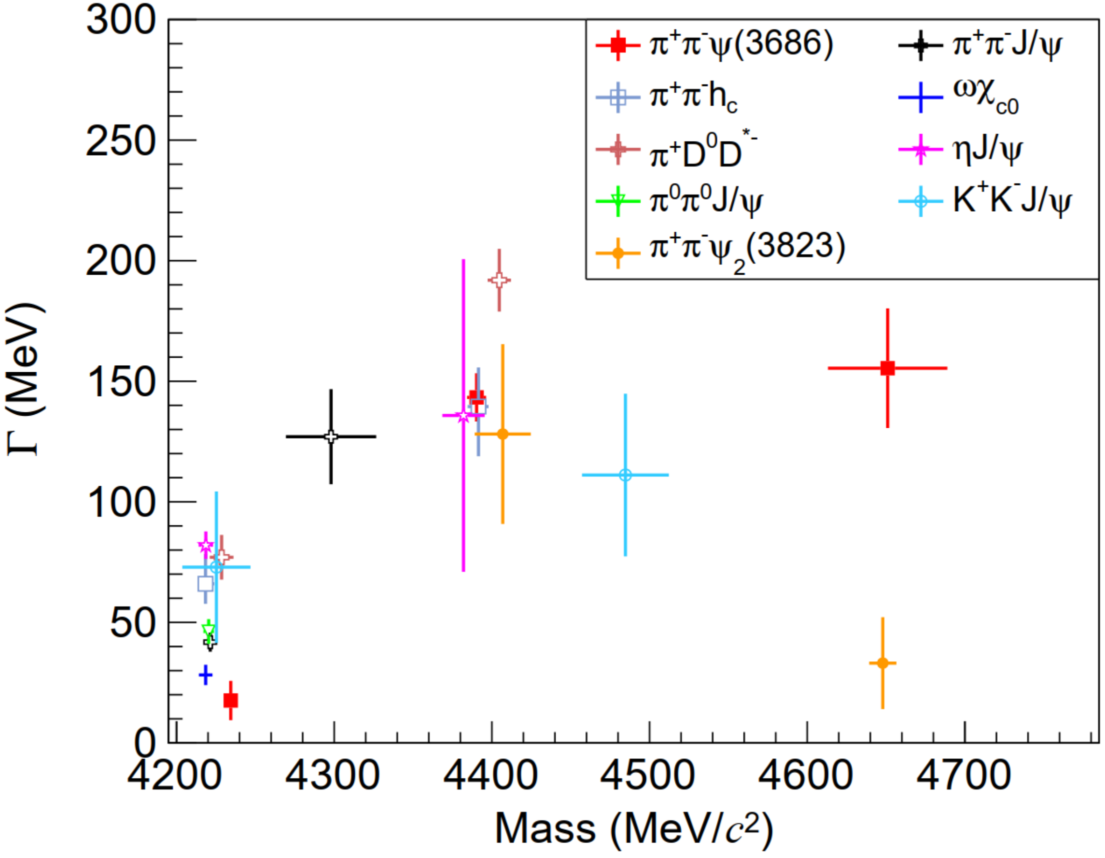
- Two resonances observed in $e^+e^- \to \pi^+\pi^-\psi_2(3823) \to \pi^+\pi^-\gamma\chi_{c1}$
  - ➢ Consistent with Y(4360) and Y(4660)
  - ➢ First observation of Y decaying to D-wave charmonium state

$$M[\psi_2(3823)] = 3823.12 \pm 0.43 \pm 0.13\ \mathrm{MeV}/c^2,$$

$$\Gamma[\psi_2(3823)] < 2.9\ \mathrm{MeV\ at\ 90\%\ C.L.}$$

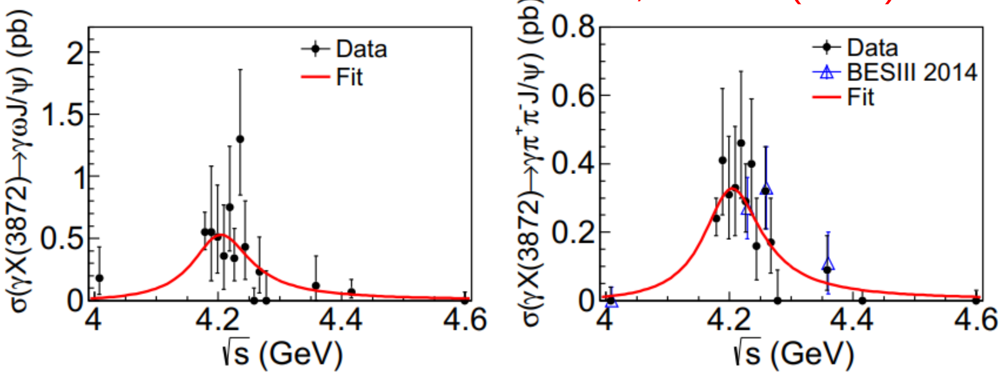
Y States: Y(4230)-Y(43xx)-Y(45xx)-Y(4660)

- Parameters of the peaks in e^+e^- cross sections

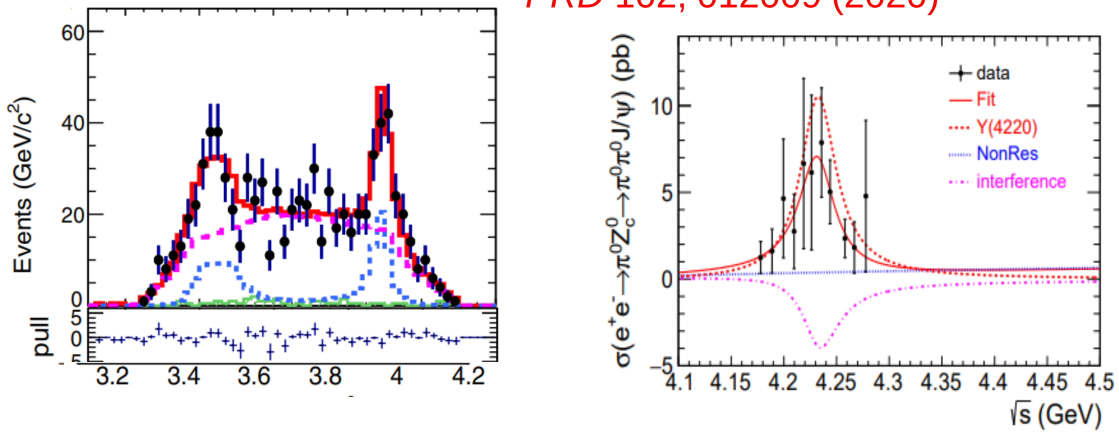


- Relations between $X(3872)-Y(4230)-Zc(3900)$ states

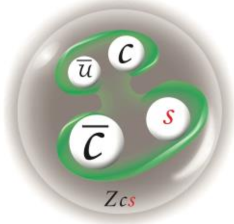
PRL 122, 232002 (2019)



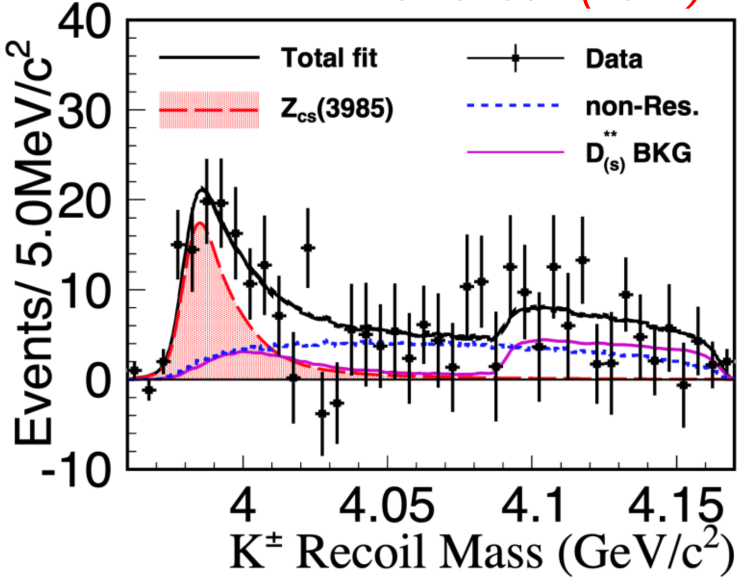
PRD 102, 012009 (2020)



Z States: Strange Partners

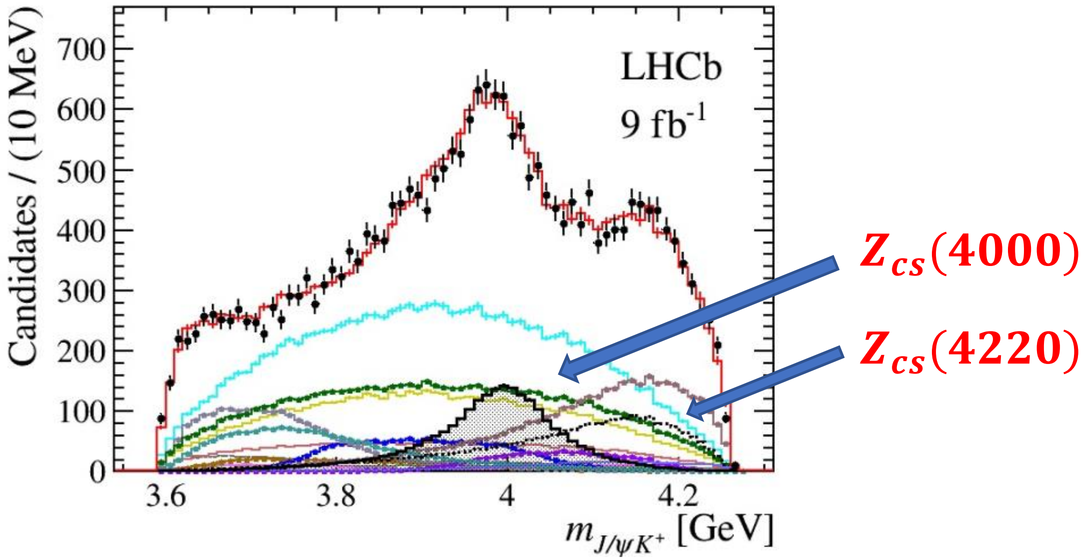


PRL 126.102001 (2021)



- $\boldsymbol{Z_{cs}(3985)^-}$ (aka $T_{\psi s1}(3985)^-$) in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
- Modeled by an S-wave Breit-Wigner function:
  - Mass: $(3985.2^{+2.1}_{-2.0} \pm 1.7)$ MeV/c^2
  - Width: $(13.8^{+8.1}_{-5.2} \pm 4.9)$ MeV

PRL 127, 082001 (2021)

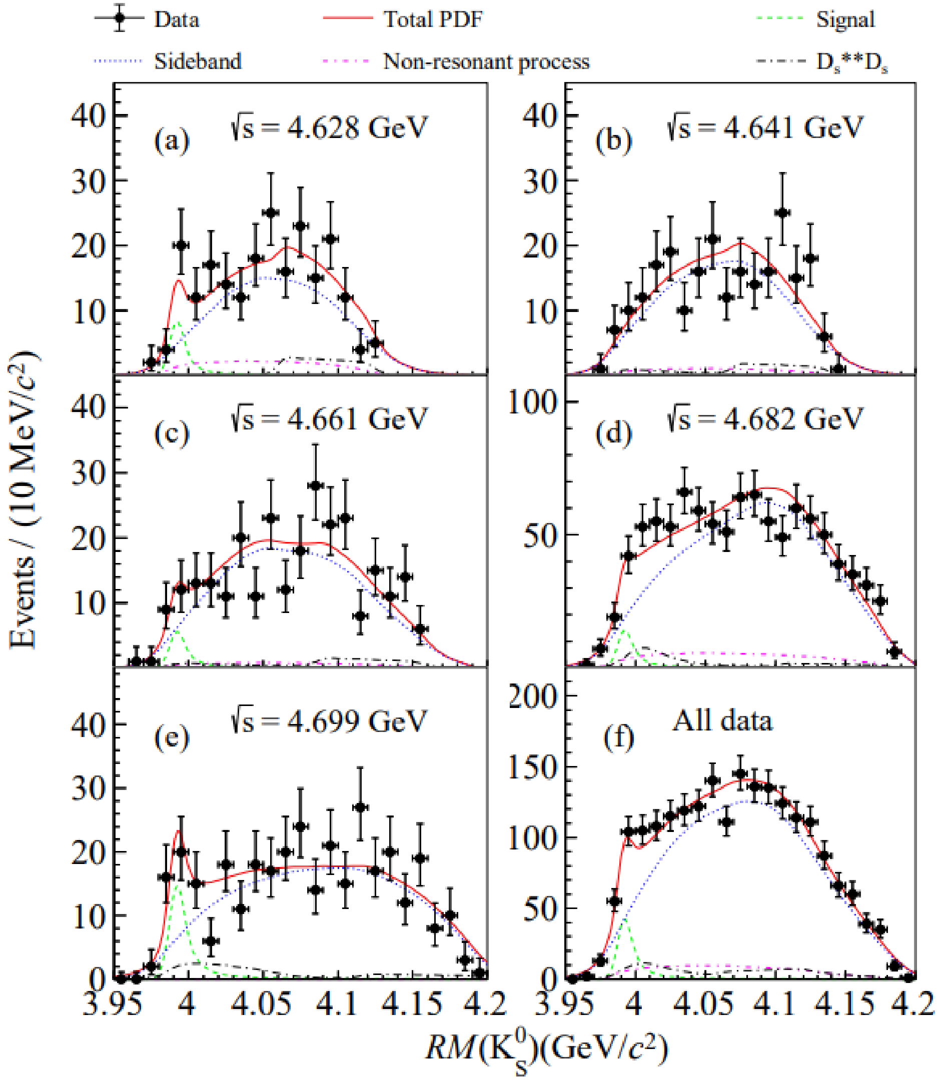


- Full amplitude analysis of $B^+ \to J/\psi \phi K^+$
  - $\boldsymbol{Z_{cs}(4000)^+}$ (aka $T^{\theta}_{\psi s1}(4000)^+$): $I = \frac{1}{2}$, $J^P = 1^+$
  - $\boldsymbol{Z_{cs}(4220)^+}$ (aka $T_{\psi s1}(4220)^+$) : $I = \frac{1}{2}$, $J^P = 1^?$

	$Z_{cs}(4000)^+$	$Z_{cs}(4220)^+$
Mass (MeV/c^2)	$4003 \pm 6^{+4}_{-14}$	$4216 \pm 24^{+43}_{-30}$
Width (MeV)	$131 \pm 15 \pm 26$	$233 \pm 52^{+97}_{-73}$

Z states: Strange Partners $c\bar{c}\bar{s}d$

arXiv:2204.13703



- $Z_{cs}(3985)^0$ (aka $T_{\psi s1}(3985)^0$) in $e^+e^- \to K_S^0\,(D_s^+D^{*-} + D_s^{*+}D^-) + c.c$ decay, 4.6σ
- Isospin partner of $Z_{cs}(3985)^+$

	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

- The slightly larger mass of $Z_{cs}(3985)^0$ consistent with theoretical predictions under molecular hypothesis or tetraquark hypothesis[1].

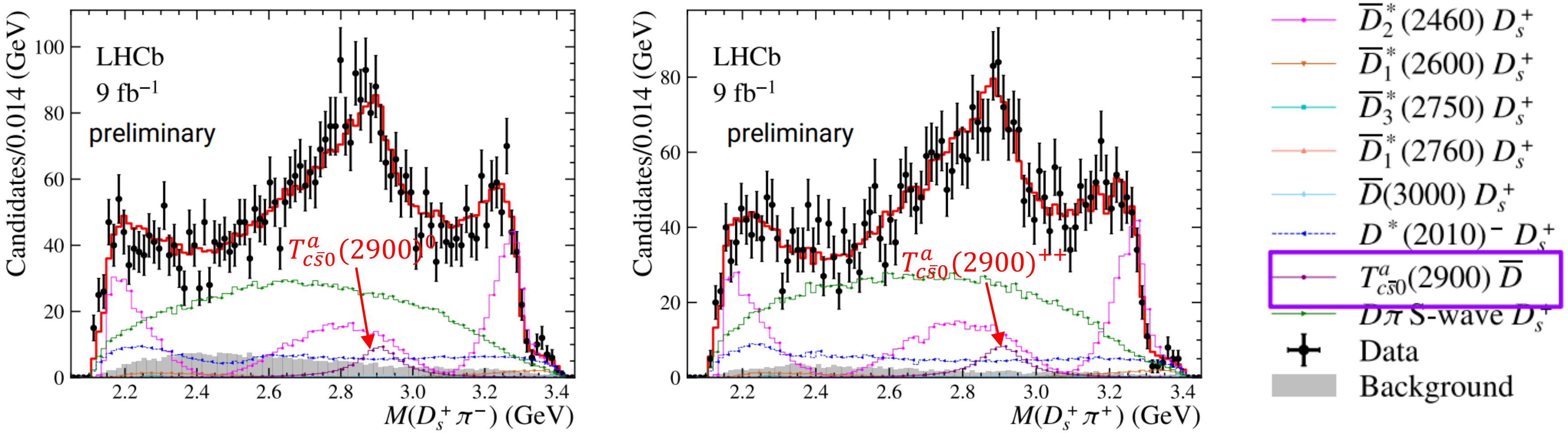
[1] B. D. Wan and C. F. Qiao, NPB 968, 115450 (2021).

Open Heavy-Flavor Tetraquark: $c\bar{s}u\bar{d}$ & $c\bar{s}\bar{u}d$

- $B \to D\bar{D}K$ decays is unique to study structures in $D\bar{D}$ and charm-strange systems. *PRD 102,112003 (2020)*
- $B^+ \to D^+D^-K^+$ show structures in D^-K^+ : $X_0(2900)$ aka $T_{cs0}(2900)^0$, $X_1(2900)$ aka $T_{cs1}(2900)^0$: $c\bar{d}s\bar{u}$

$B^0 \to \bar{D}^0 D_s^+ \pi^-$ $\quad$ $B^+ \to D^- D_s^+ \pi^+$

LHCb-PAPER-2022-026
LHCb-PAPER-2022-027



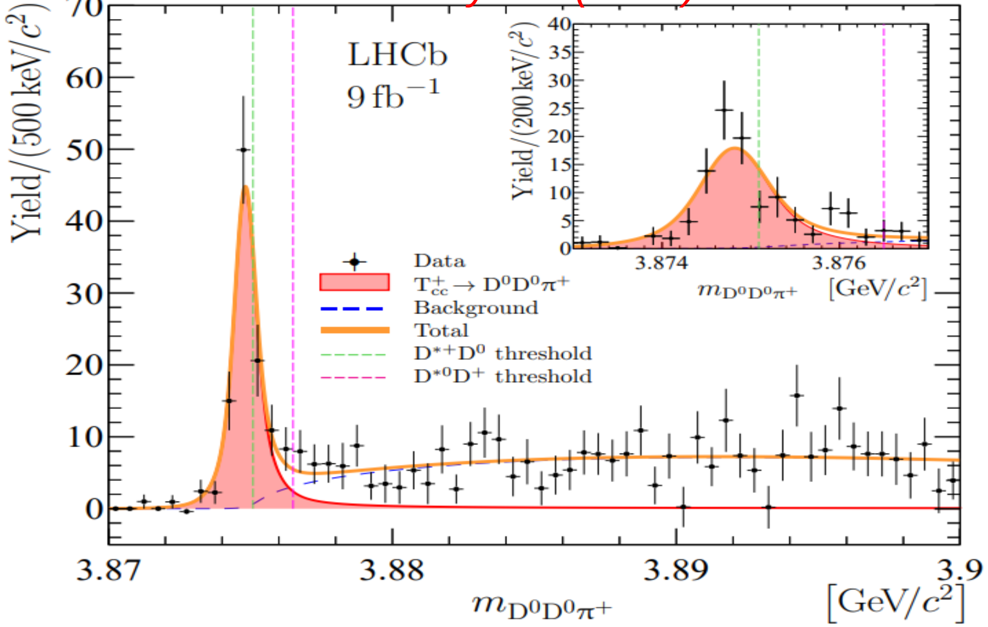
- First amplitude analysis of $B^+ \to D^- D_s^+ \pi^+$ & $B^0 \to \bar{D}^0 D_s^+ \pi^+$, at LHCb with 9 fb^{-1} data
- $D_s\pi$ well described by adding $J^P = 0^+$ $T^a_{c\bar{s}0}(2900)$
- Quark content: $c\bar{s}u\bar{d}$ and $c\bar{s}\bar{u}d$
- Isospin partner $T^a_{c\bar{s}0}(2900)^+$ will be searched with $D_s^+\pi^0$

$$M = 2.908 \pm 0.011 \pm 0.020\,\mathrm{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\mathrm{GeV}$$

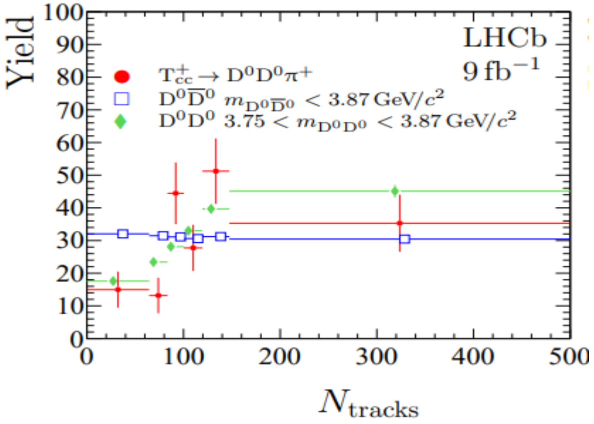
For details, see talk #1 in parallel session II (2)

Open Heavy-Flavor Tetraquark: $cc\bar{u}\bar{d}$

Nature Physics (2022)



Nature Comm., 13, 3351 (2022)

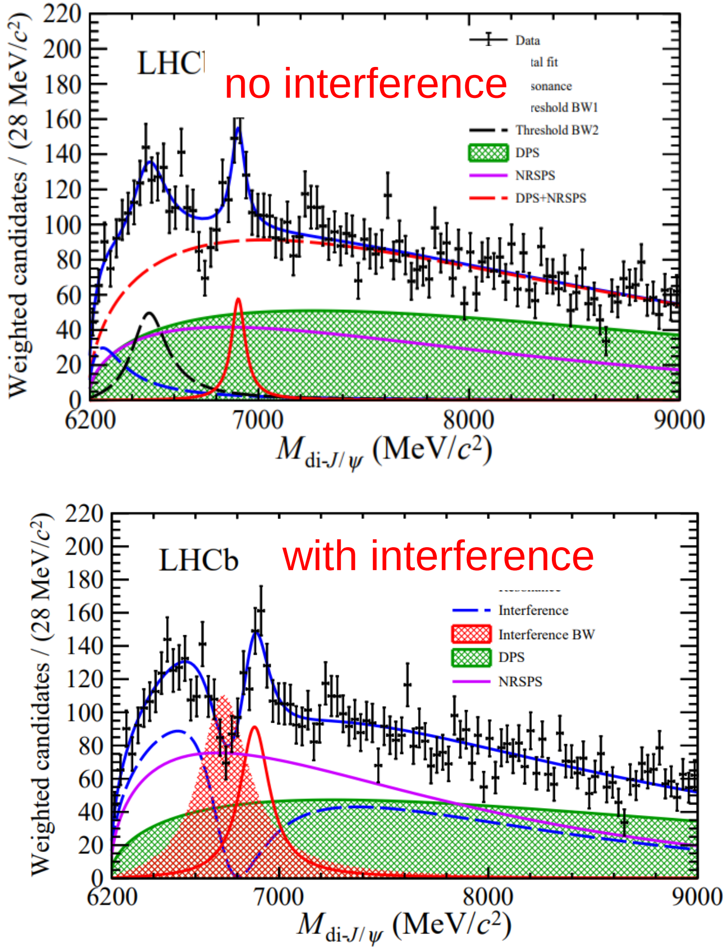


- A narrow state in $D^0D^0\pi^+$ mass spectrum promptly in pp collision with 9 fb^{-1} data, $T_{cc}(3875)^+$, 22σ
- The state just below $D^{*+}D^0$ mass threshold
- The structure is described by a relativistic P-wave two-body BW function => $J^P = 1^+$
  - ➢ $\delta m_{BW} = m_{BW} - (m_{D^{*+}} + m_{D^0}) = -273 \pm 61 \pm 5^{+11}_{-14}$ keV/c^2
  - ➢ $\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}$ keV

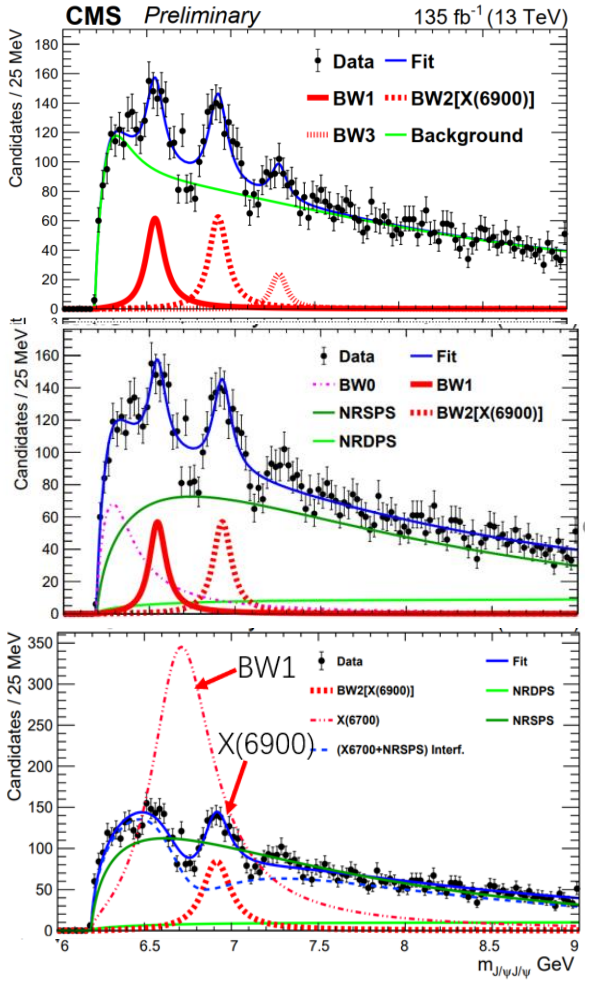
- More properties of $T_{cc}(3875)^+$ is discussed.
- Unlike in X(3872), no suppression of prompt $T_{cc}(3875)^+$ at high track multiplicities.

Fully Heavy System: $cc\bar{c}\bar{c}$

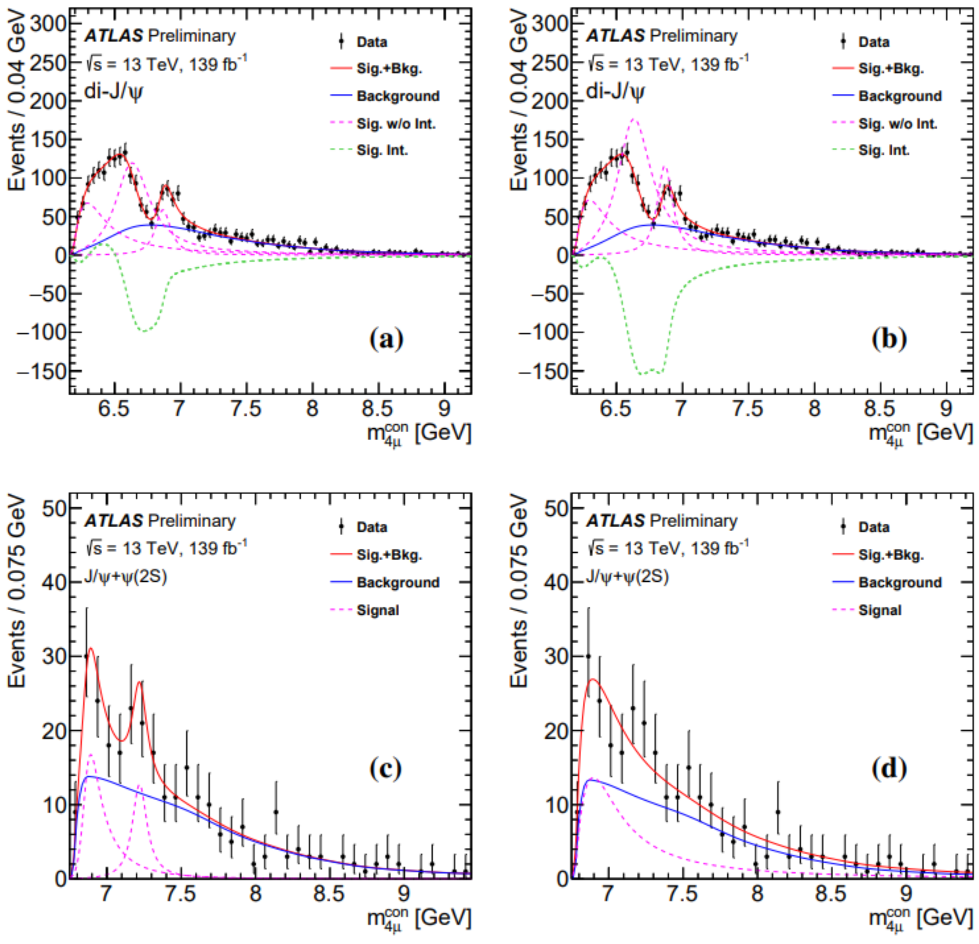
Science Bulletin 65,1983 (2020)



CMS-PAS-BPH-21-003



ATLAS-CONF-2022-040



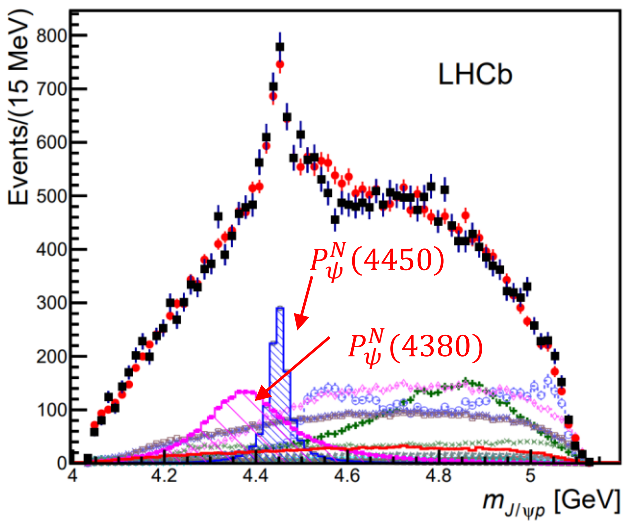
For details, see talk #2, #3 in parallel session I(2).

Hidden Charmonium Pentaquark: $c\bar{c}uud$

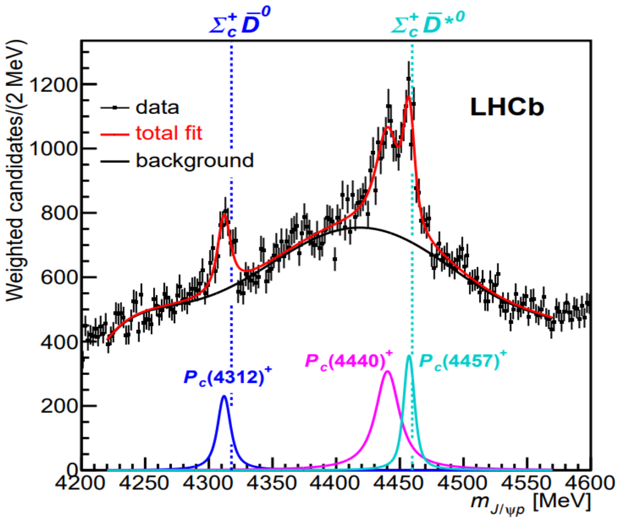
- $P_\psi^N(4450)$ and $P_\psi^N(4380)$ in $\Lambda_b^0 \to J/\psi p K^-$ decays, with 3 fb^{-1} LHCb data, >9σ
- 9 times decay events, $P_\psi^N(4450)$ =>$P_\psi^N(4440)$ and $P_\psi^N(4457)$, new state $P_\psi^N(4312)$ discovered.

- Evidence for $P_\psi^N(4337)$ in flavor-untagged $B_s^0 \to J/\psi p\bar{p}$ decays, with 9 fb^{-1} LHCb data, >3.1σ

PRL 115, 072001 (2015)

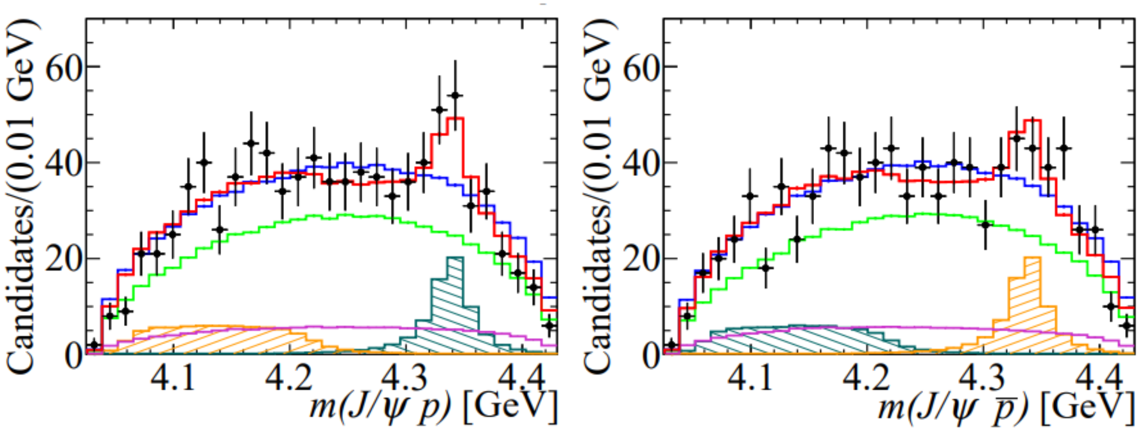


PRL 122, 222001(2019)



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(<20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

PRL 128, 062001 (2022)



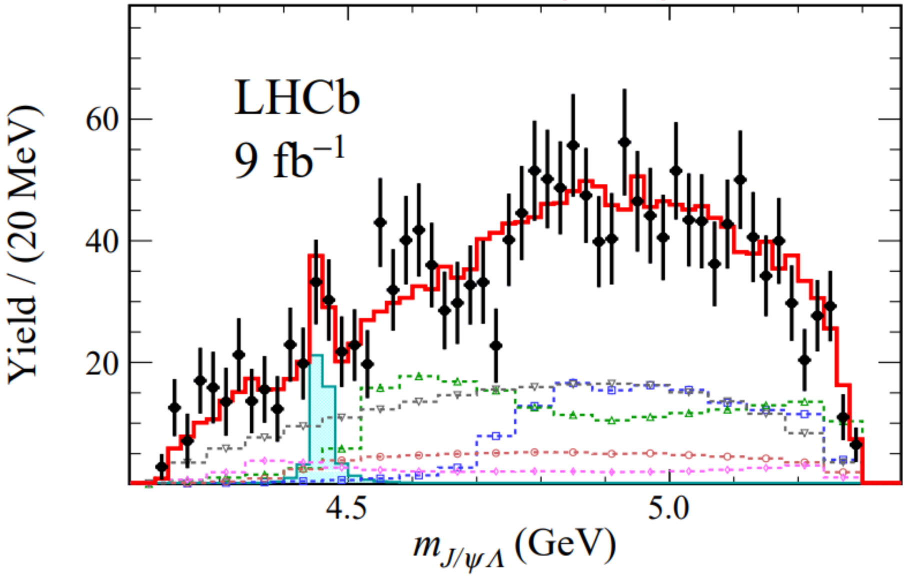
$$M_{P_c} = 4337\ ^{+7}_{-4}\ ^{+2}_{-2}\ \mathrm{MeV}$$
$$\Gamma_{P_c} = 29\ ^{+26}_{-12}\ ^{+14}_{-14}\ \mathrm{MeV}$$

For details, see talk #5, #6 in parallel session I(2)

Hidden Charmonium Pentaquark: $c\bar{c}uds$

- Evidence $P_{\psi}^{\Lambda}(4459))$ in $\Xi_b^- \to J/\psi\Lambda K^-$ decays, with 9 fb^{-1} LHCb data, 3.1σ
- Strange counterparts of P_{ψ}^{N}, at $\Xi_c^0 D^{*0}$ threshold

Science Bulletin 66 (2021) 1278-1287

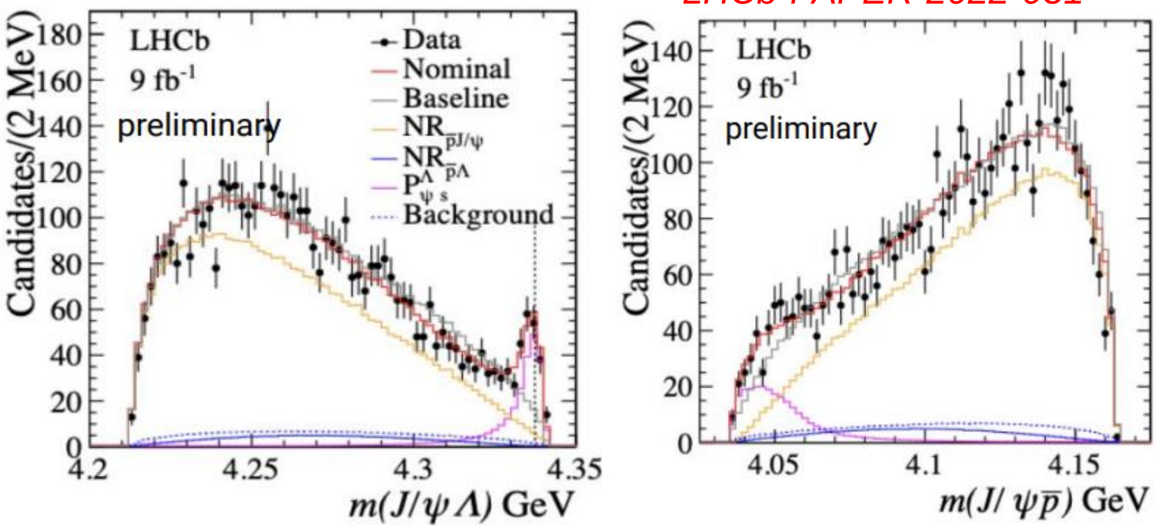


Mass: $4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV

Width: $17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

- $P_{\psi}^{\Lambda}(4338)$ in $B^- \to J/\psi\Lambda\bar{p}$ decays, with 9 fb^{-1} LHCb data, >10σ
- $J^P = \frac{1}{2}^-$ preferred, close to $\Xi_c^+ D^-$ threshold

LHCb-PAPER-2022-031



$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\text{MeV}$$

Summary

- Very active and fruitful results in hadron physics
  - Experiments are taking data: LHCb, BESIII, Belle II, …
  - Upgrade studies underway: BESIII: $\mathcal{L} \times 3$ above 4.6 GeV, LHCb: $\int \mathcal{L} \times 7$ after RUN4
- Various production accessible for hadron structure study
  - Direct production in e^+e^- collision, photon-photon scattering, prompt production…
  - New precision record, new production mechanism
- Solid experimental evidence of exotic states, in-depth property studies needed.
  - Last "hadronic zoo" was sixty years ago => established quark model
  - New "model" to order the "exotic hadronic zoo"?

谢谢！

感谢强子物理和味物理召集人、吕晓睿、何吉波、王小龙、李龙科等老师的帮助!

Heavy "Nonstandard" Hadrons Candidates

- New naming scheme arXiv: 2206.15233
  - T for tetra, P for penta
  - **Superscript**: based on existing symbols, to indicate isospin, parity and G-parity
  - **Subscript**: heavy quark content

2003-
$\chi_{c1}(3872)$

2005-
$\chi_{c1}(3915)$
$Y(4260)$
$Y_b(10860)$

2007-
$X(3940)$
$X(4160)$
$Y(4360)$
$Y(4660)$
$X(4050)$
$X(4250)$
$T_{\psi 1}^{b}(4430)^{+}$

2009-
$X(4140)$
$X(4350)$

2011-
$T_{\Upsilon 1}^{b}(10610)^{+}$
$T_{\Upsilon 1}^{b}(10650)^{+}$

2013-
$T_{\psi 1}^{b}(3900)$
$T_{\psi 1}^{b}(4020)$
$T_{\psi 1}^{b}(4200)$

2015-
$P_{\psi}^{N}(4380)$
$P_{\psi}^{N}(4450)$

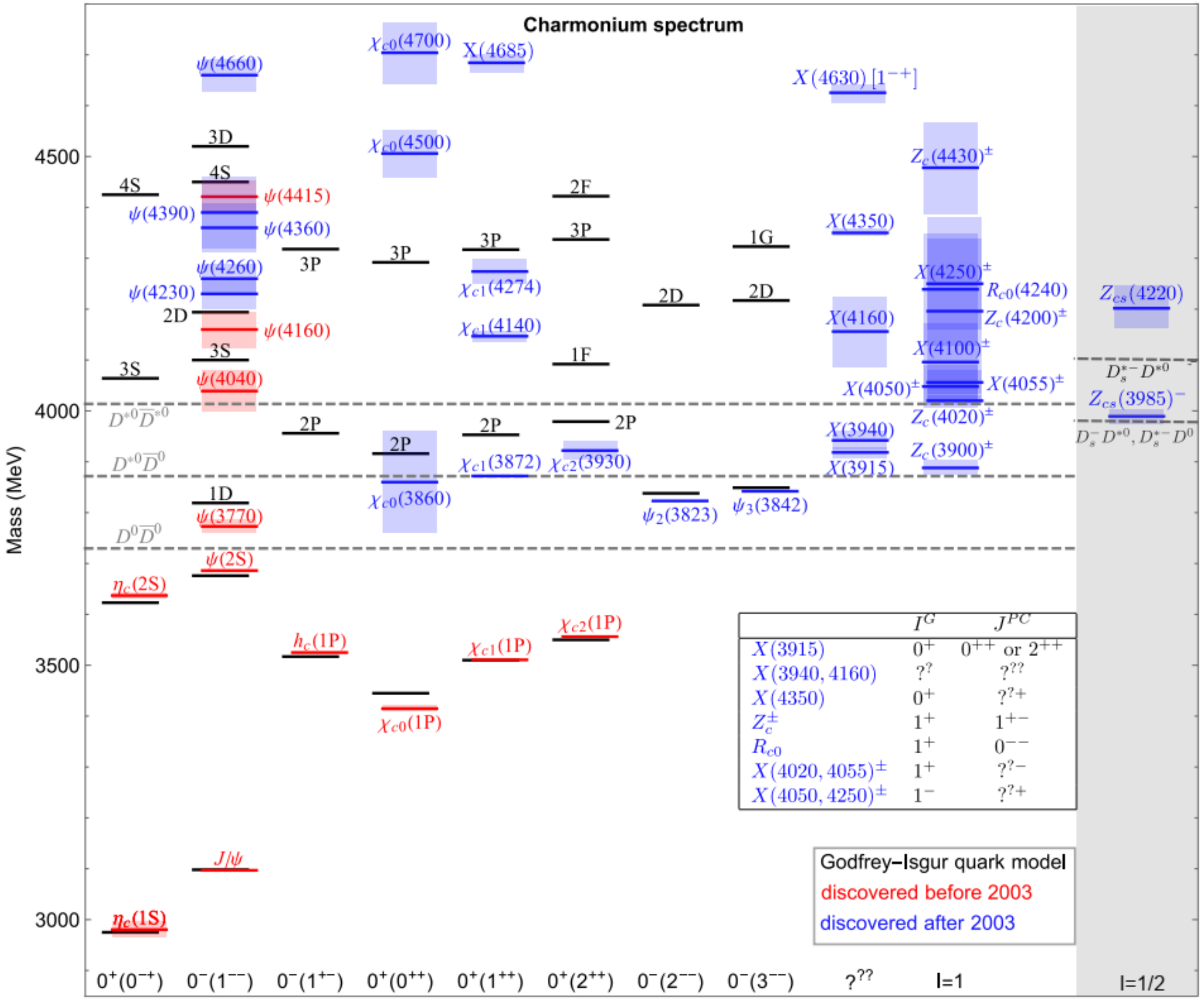
2017-
$X(4274)$
$X(4500)$
$X(4700)$
$Y(4220)$
$Y(4390)$

2019-
$P_{\psi}^{N}(4457)$
$P_{\psi}^{N}(4440)$
$P_{\psi}^{N}(4312)$
$T_{\psi\psi}(6900)$
$T_{cs1}(2900)^{0}$
$T_{cs0}(2900)^{0}$

2021-
$X(4685)$
$X(4630)$
$T_{\psi s1}(3985)^{+}$
$T_{\psi s1}(4220)^{+}$
$T_{\psi s1}^{\theta}(4000)^{+}$
$T_{cc}(3875)^{+}$
$T_{c\bar{s}0}^{a}(2900)^{0}$
$T_{c\bar{s}0}^{a}(2900)^{++}$
$T_{\psi\psi}(6600)$
$T_{\psi\psi}(7300)$
$P_{\psi s}^{\Lambda}(4459)$
$P_{\psi s}^{\Lambda}(4338)^{0}$

- Hidden heavy-flavor tetraquark
- Open heavy-flavor tetraquark
- Fully heavy system
- Hidden charmonium pentaquark

Charmonium (Like) spectroscopy



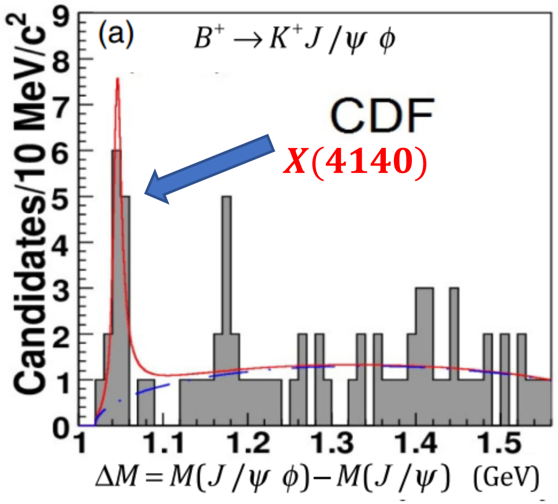
F.K. Guo, arXiv: 2203.07141

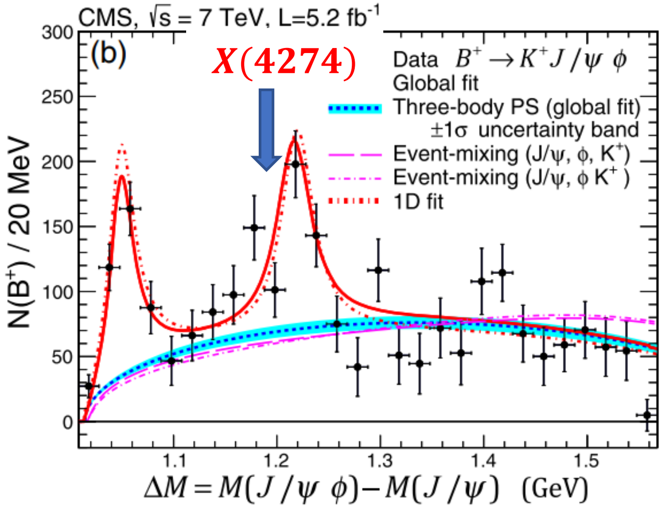
- Excellent platform to explore the QCD
- Fruitful results in past decade, a new territory to study exotic hadrons

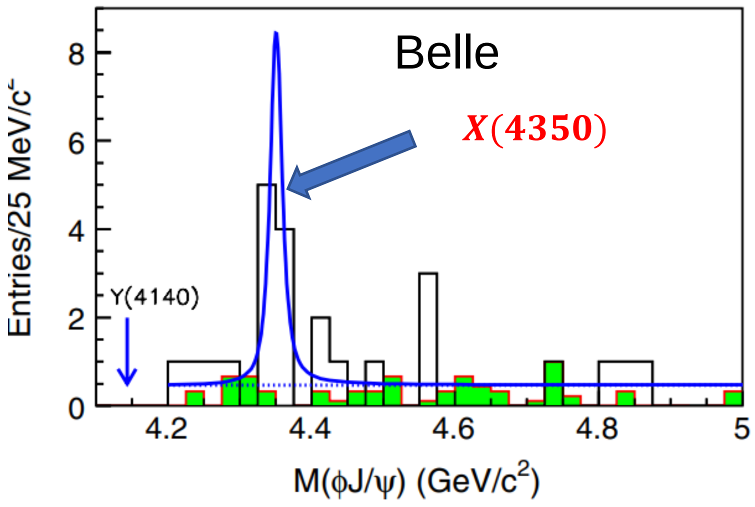
- Tasks :
  - ☐ Precisely measurement the transition
  - ☐ Search for the missing states
  - ☐ Search for the new exotic states
  - ☐ Determine J^{PC} for all known states

X States: New States in $J/\psi\phi$

- Rich structures in $J/\psi\phi$ mass spectrum
- In $B^+ \to K^+ J/\psi\ \phi$, $X(4140)$ observed in $J/\psi\ \phi$ in CDF[1], CMS[2] and D0[3], but not in Belle and BaBar[4]
- BESIII found no evidence of $X(4140) \to J/\psi\ \phi$ via $e^+e^- \to \gamma X(4140)$ [5]
- Belle observe $X(4350)$ in two-photon collision[6] , $J^{PC} = 0^{++}$ or 2^{++}



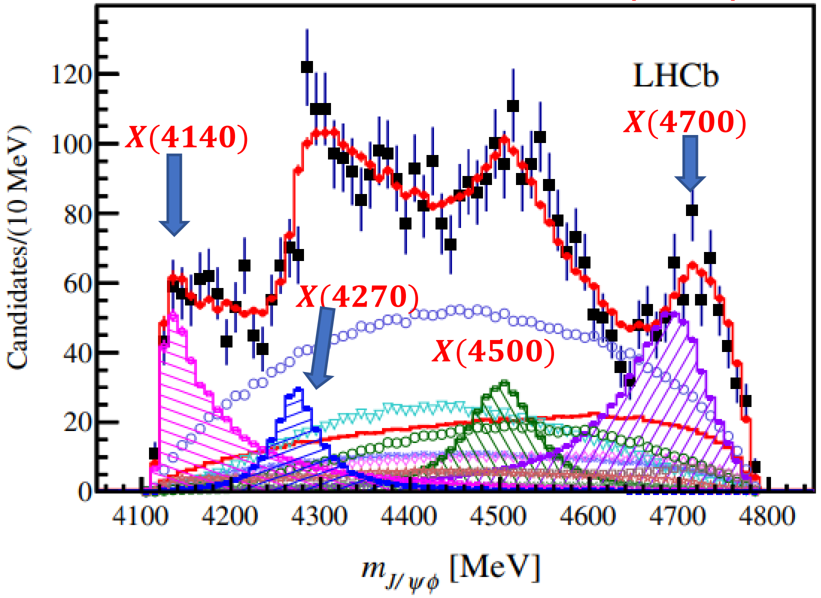




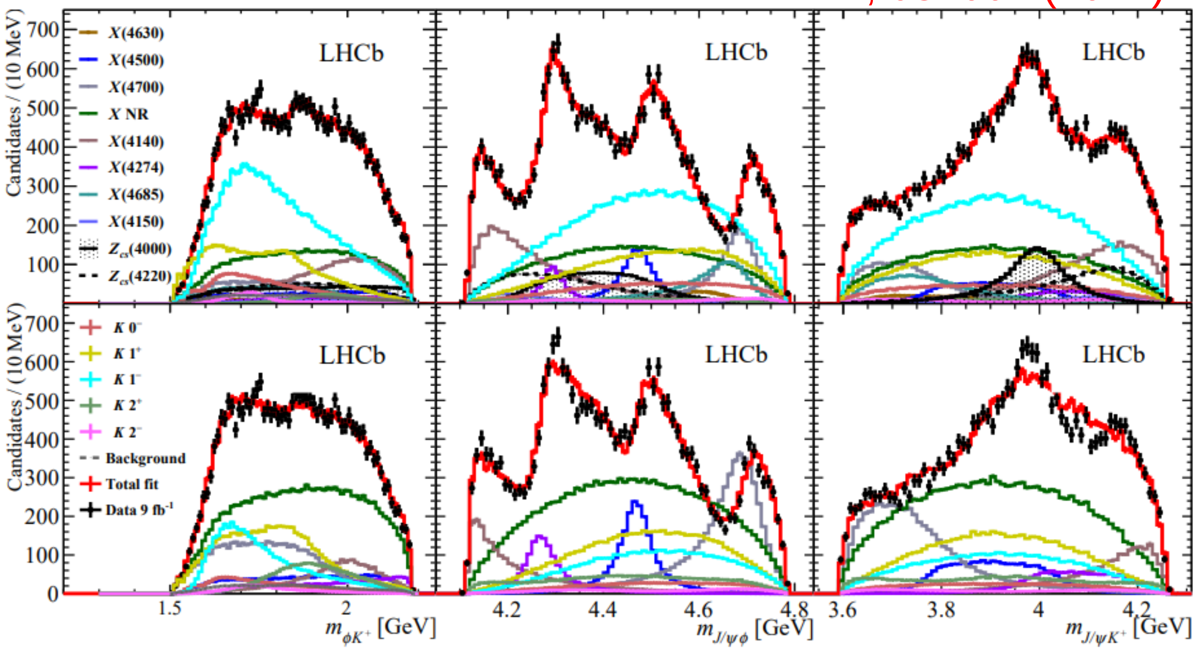
[1] PRL 102, 242002 (2009)
[2] PLB 734, 261 (2014)
[3] PRD 89, 012004 (2014)
[4] PRD 91, 012003 (2015)
[5] PRD 91, 032002 (2015)
[6] PRL 104, 112004 (2010)

X States: New States in $J/\psi\phi$

PRL 118.022003 (2017)



PRL127, 082001 (2021)



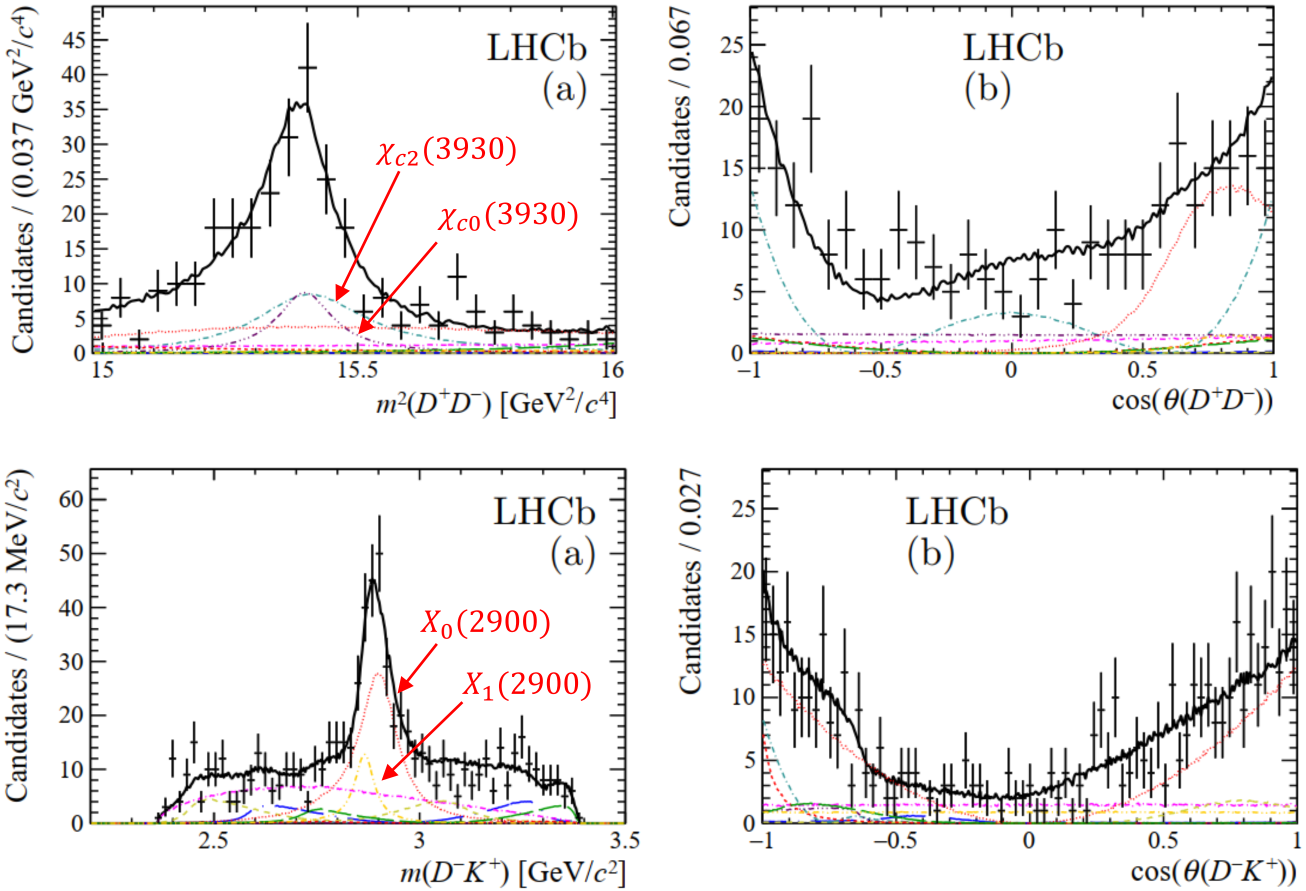
- 3 fb^{-1} data, six-dimensional amplitude analysis
- Four $J/\psi\ \phi$ structures observed:
  - ➢ Confirm $X(4140)$ and $X(4274), 1^{++}$
  - ➢ Two 0^{++} states: $X(4500), X(4700)$

- 9 fb^{-1}, six-dimensional amplitude analysis
- Confirmed four X states
- Two new states in $J/\psi\ \phi$
  - ➢ $X(4685)\ 1^{+}$
  - ➢ $X(4630)\ 1^{-}$ or 2^{-}
- Two new states in $J/\psi\ K$

Open Heavy-Flavor Tetraquark: $\bar{c}d\bar{s}u$

- $B \to D\bar{D}K$ decays is unique to study structures in $D\bar{D}$ and charm-strange systems.

PRD 102,112003 (2020)



- First amplitude analysis of $B^+ \to D^+D^-K^+$, at LHCb with 9 fb^{-1} data
- ➢ In $D\bar{D}$ structure:
  - Both spin-0 and spin-2 are needed
  - $\chi_{c0}(3930)$ consistent with $X(3915)$ observed in $J/\psi\omega$
- ➢ In D^-K^+ strucute:
  - Both spin-1 and spin-0 are needed
  - Quark content: $\bar{c}d\bar{s}u$

	Resonance	Mass (GeV/c^2)	Width (MeV)
	$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
	$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$
$T_{cs1}(2900)^0$	$X_0(2900)$	$2.866 \pm 0.007 \pm 0.002$	$57 \pm 12 \pm 4$
$T_{cs0}(2900)^0$	$X_1(2900)$	$2.904 \pm 0.005 \pm 0.001$	$110 \pm 11 \pm 4$