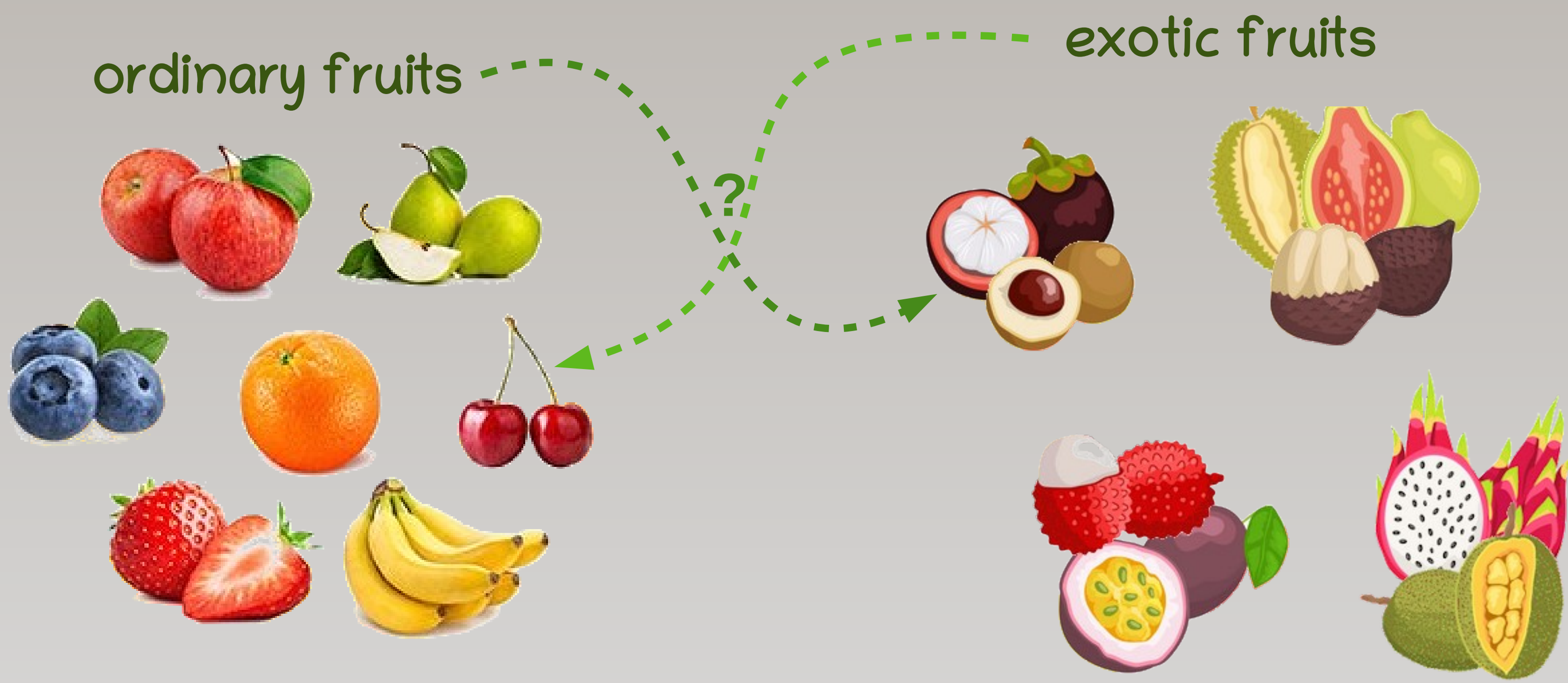
Exotic Spectroscopy

present status and prospects

* Exotic hadrons – everything beyond $q\bar{q}$ / qqq



Ivan Polyakov, CERN

30th Rencontres du Vietnam
9 August 2023

Outline

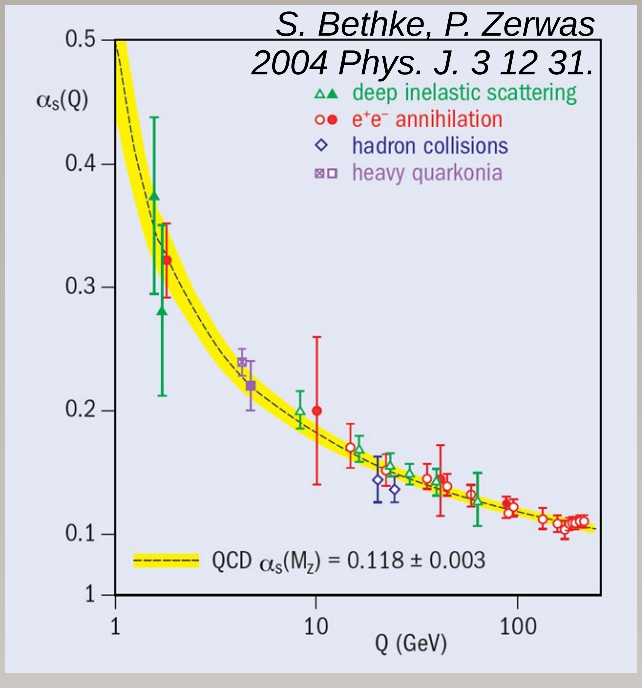
- Broad review of the field

- New results

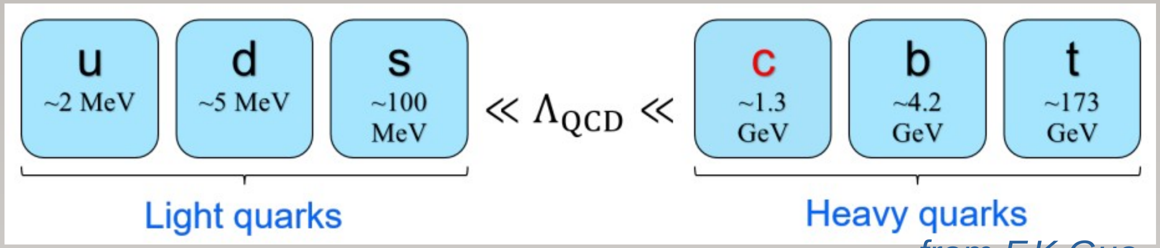
- Future prospects

Meaning for QCD

- QCD – perfect at high energies,
  but not that successful at nuclei/hadron energies

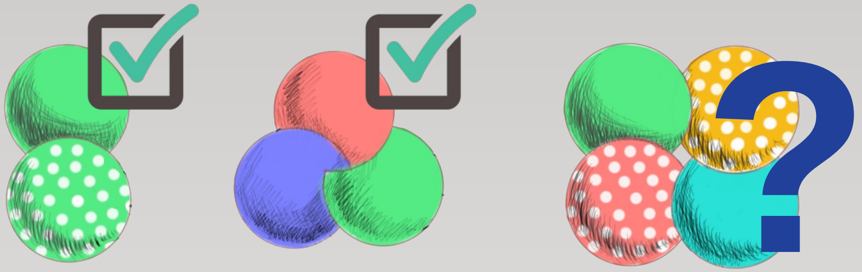


- Spectroscopy – the main tool for understanding QCD at this energy regime
  → great advance from heavy quarks



from F.K.Guo

- All mesons $(q_1\bar{q}_2)$ and baryons $(q_1q_2q_3)$ are discovered except for bcq & QQ'Q''



...

  - Progress limited by quark configurations studied

First exotic hadrons

- Were anticipated since 60's

- No success in light sector
  - First candidates for tetraquarks in 90's: $f_0(500)$, $K^*_0(800)$, … later $D^*_{sJ}(2317)$, ...
  - Pentaquark Θ^+ [$uudd\bar{s}$] in 2003

no clear conclusion reached due to large widths & theoretical ambiguities

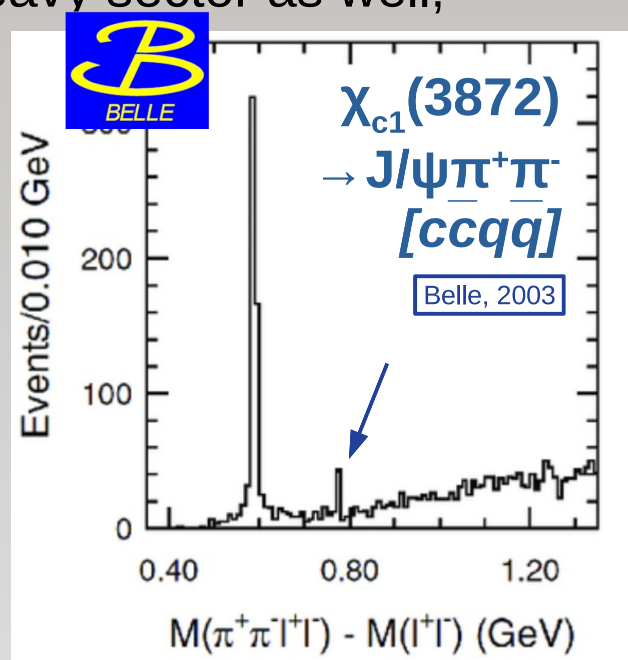
Fazio, 2004 | Eidelman, Gutsche, Hanhart, Mitchell, Spanier, 2020 (PDG)

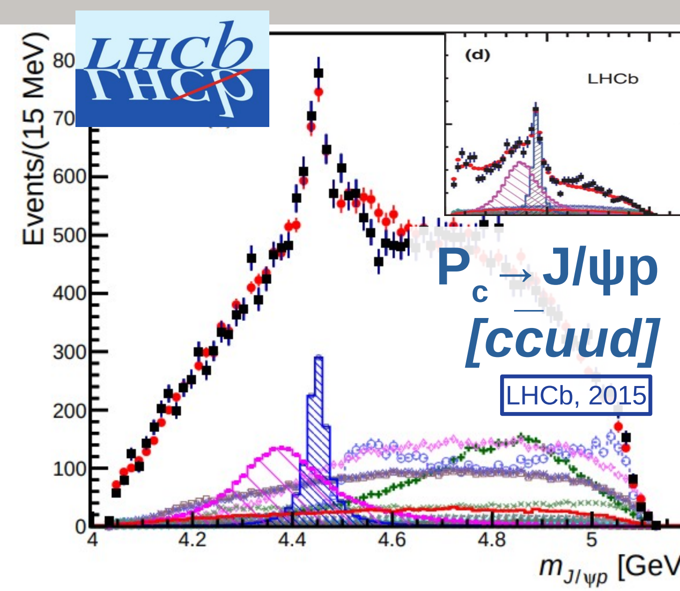
later shown to be false

Trilling, 2006 (PDG)

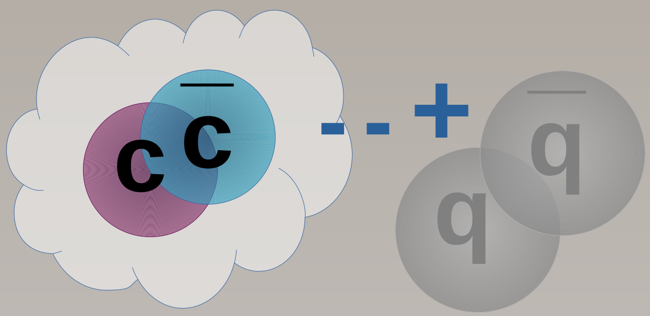
- First one uniquely identified as exotic was $\chi_{c1}(3872)$ discovered in heavy sector in 2003;
  First pentaquark in 2015 in heavy sector as well;

much smaller widths and clearer understanding of $c\bar{c}$ allowed to exclude conventional interpretations

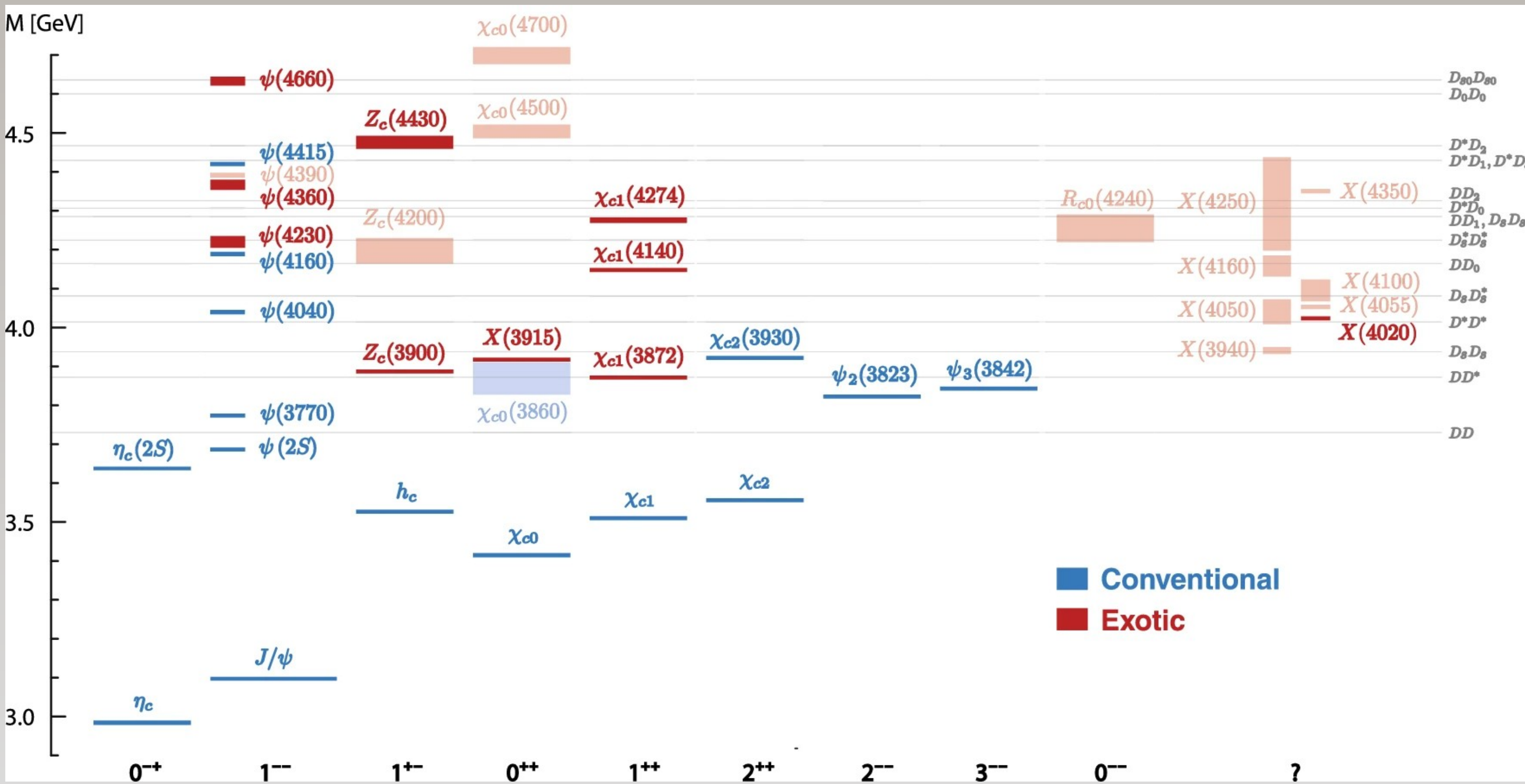




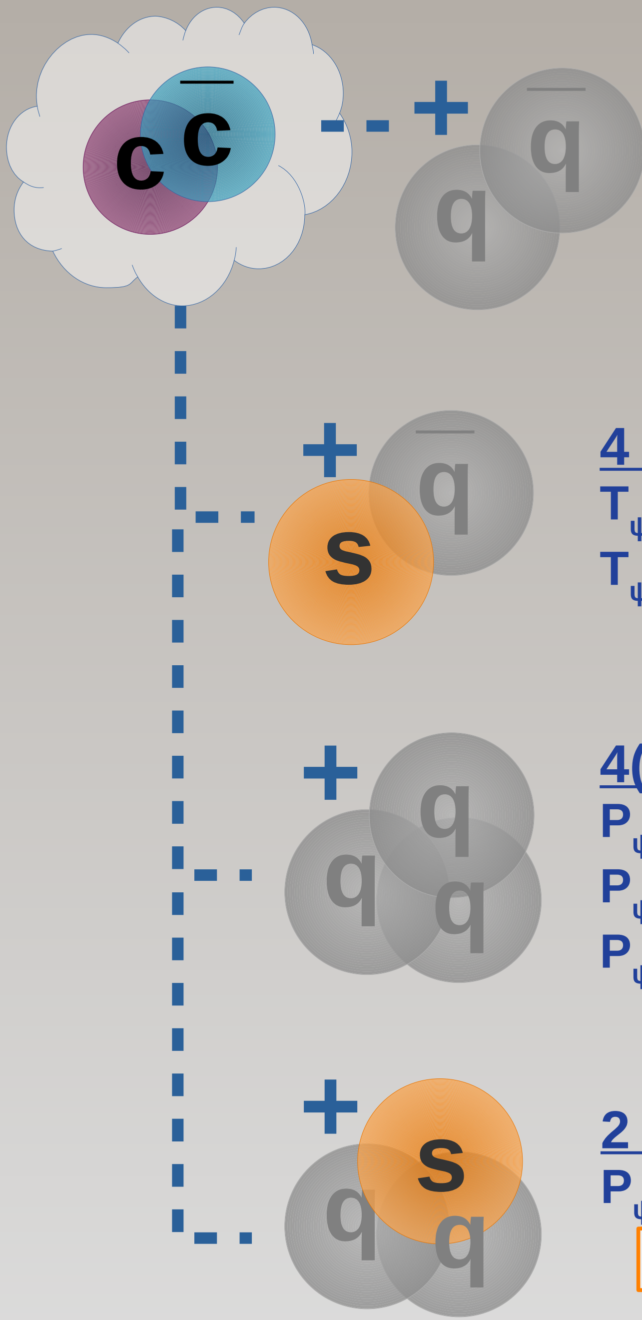
Hidden charmonium



<u>17 states</u>: $\chi_{c1}(3872)$,
$T_{\psi 1}(3900)^+$, $T_{\psi}(4020)^+$, $T_{\psi}(4050)^+$, $T_{\psi}(4100)^+$, $T_{\psi}(4200)^+$,
$T_{\psi 1}(4430)^+$, $T_{\psi}(4240)^+$,
$\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$,
$X(4630)$, $X(4150)$, $X(4740)$, $X(3960)$



Hidden charmonium



17 states: $\chi_{c1}(3872)$,
$T_{\psi 1}(3900)^{+}$, $T_{\psi}(4020)^{+}$, $T_{\psi}(4050)^{+}$, $T_{\psi}(4100)^{+}$, $T_{\psi}(4200)^{+}$,
$T_{\psi 1}(4430)^{+}$, $T_{\psi}(4240)^{+}$,
$\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$,
$X(4630)$, $X(4150)$, $X(4740)$, $X(3960)$

4 states: NEW
$T_{\psi s}(3985)^{+}$, $T_{\psi s}(4000)^{+}$, $T_{\psi s}(4000)^{0}$,
$T_{\psi s1}(4220)^{+}$

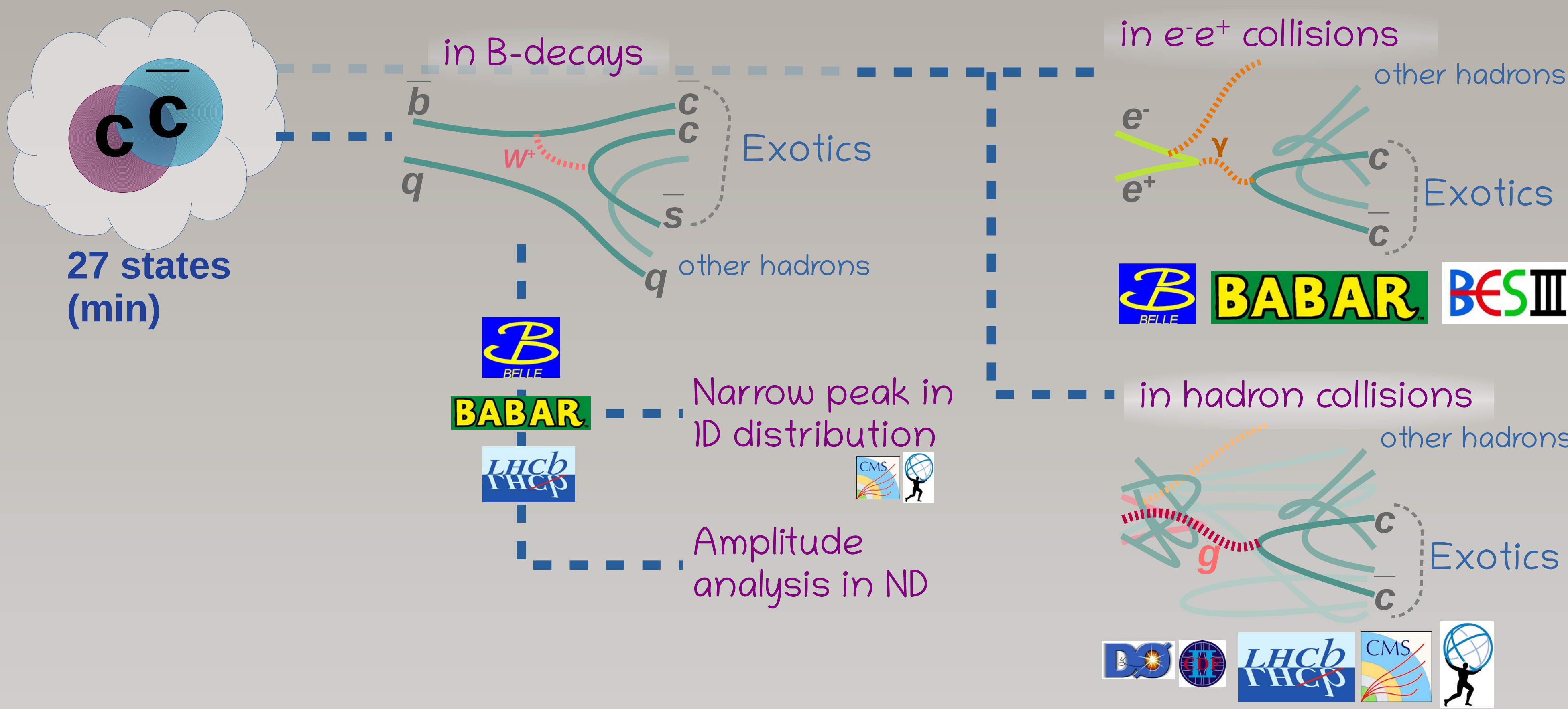
9 states from
5D analysis of
$B^{+} \to J/\psi \phi K^{+}$

4(5) states:
$P_{\psi}(4312)$, $P_{\psi}(4337)$,
$P_{\psi}(4440)$, $P_{\psi}(4457)$,
$P_{\psi}(4380)$?

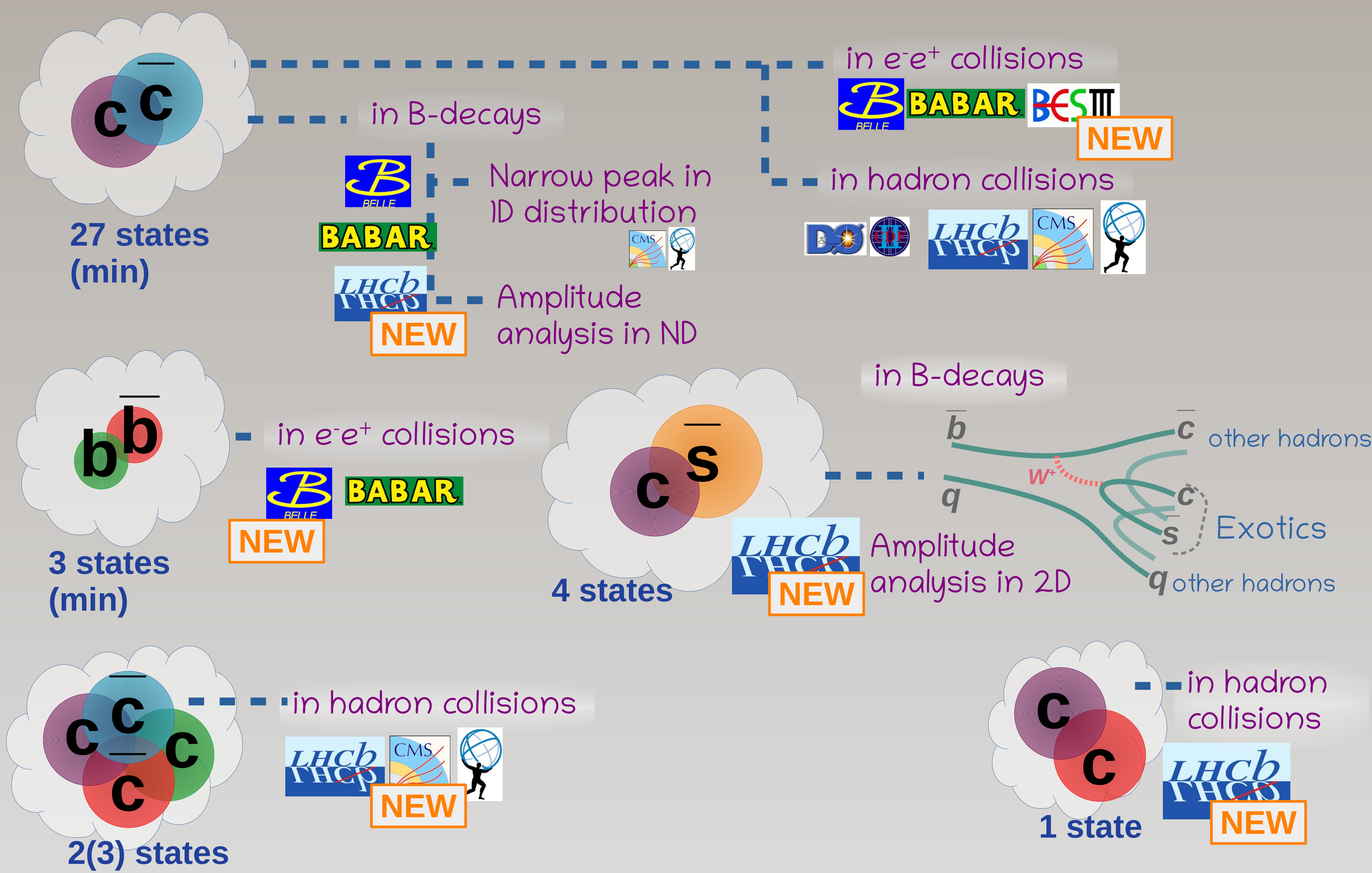
2 states:
$P_{\psi s}(4338)$, $P_{\psi s}(4459)$
NEW

27 states in total (min)

Discovering more exotics ...



Summary of all exotics … 37 states

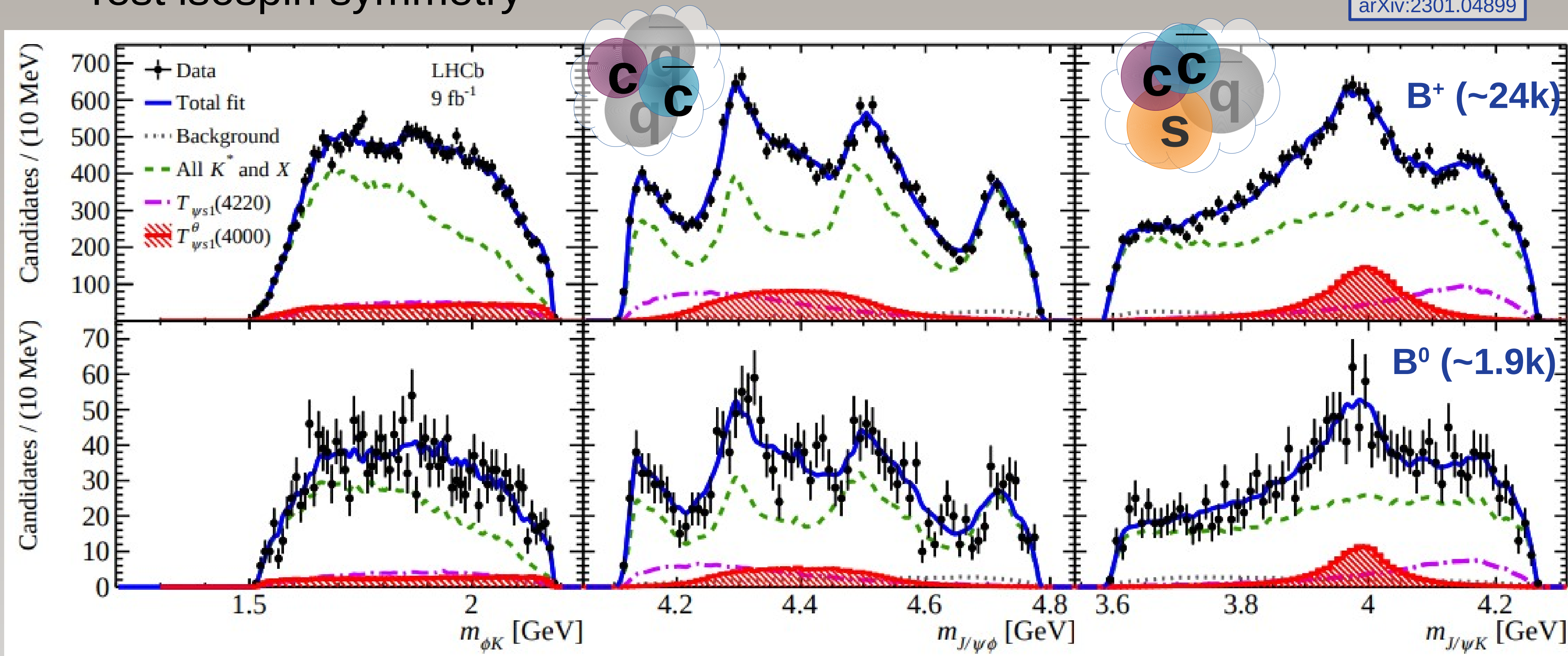


$B^0 \to J/\psi\phi K_s$

NEW

- Compare $B^0 \to J/\psi\phi K_s^0$ decays to $B^+ \to J/\psi\phi K^+$ (10x larger statistics)
- Test isospin symmetry

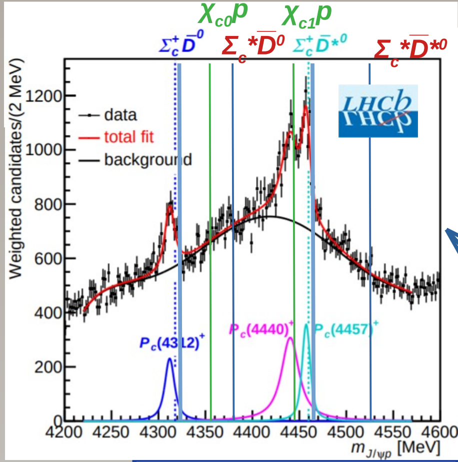
arXiv:2301.04899



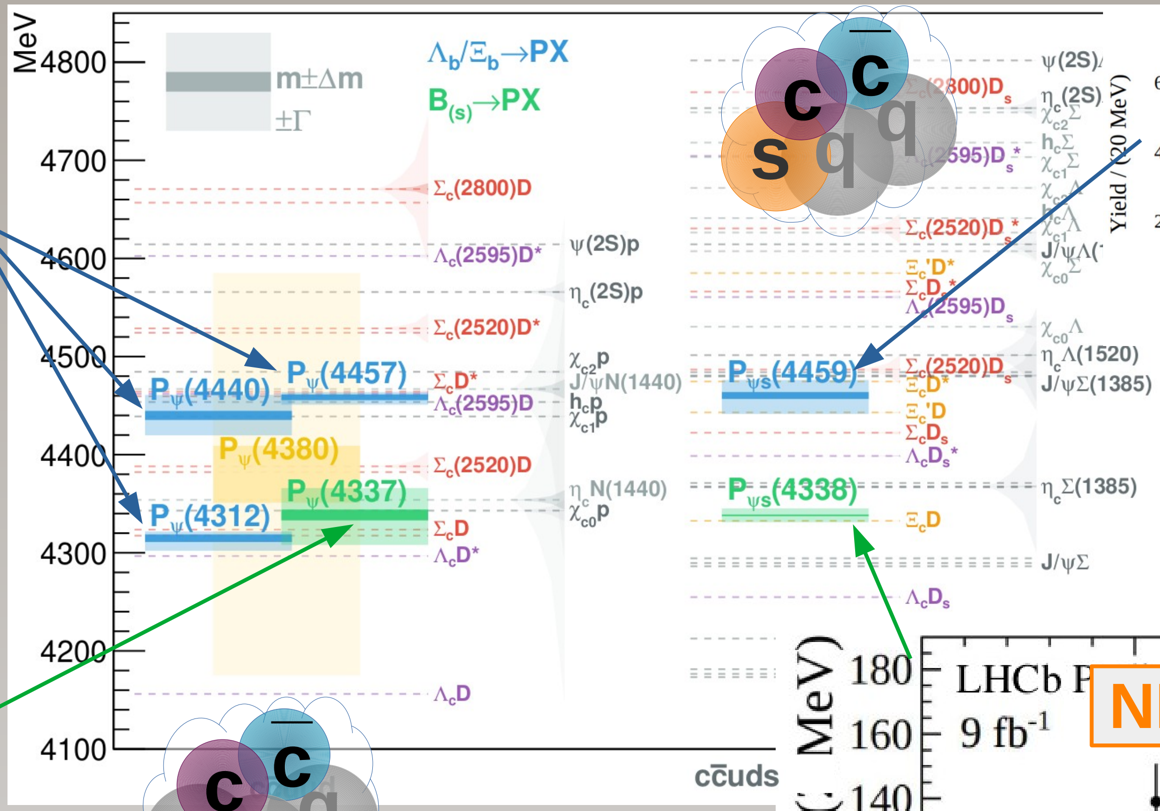
- Share parameters for all $K^* \to \phi K$ and $X \to J/\psi\phi$ components with B^+ mode
- $T_{\psi s1}(4000)^0$ seen with >4σ significance – isospin partner of $T_{\psi s1}(4000)^+$

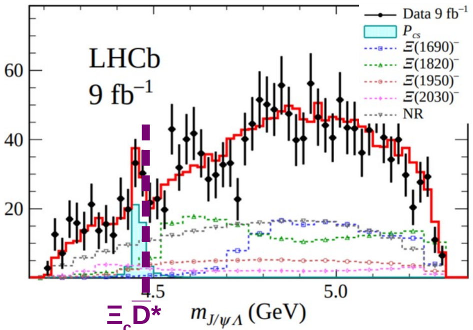
$$\Delta M = -12\,^{+11}_{-10}\,^{+6}_{-4}\ \text{MeV}$$

Pentaquarks at LHCb

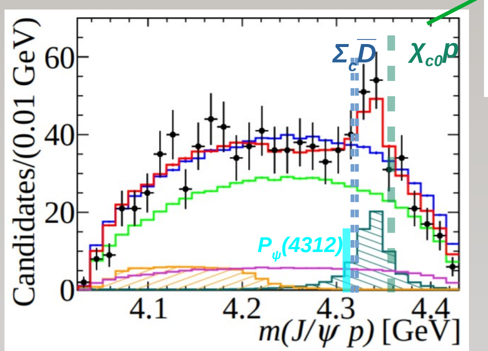


PRL 115 (2015) 072001,
PRL 122 (2019) 222001



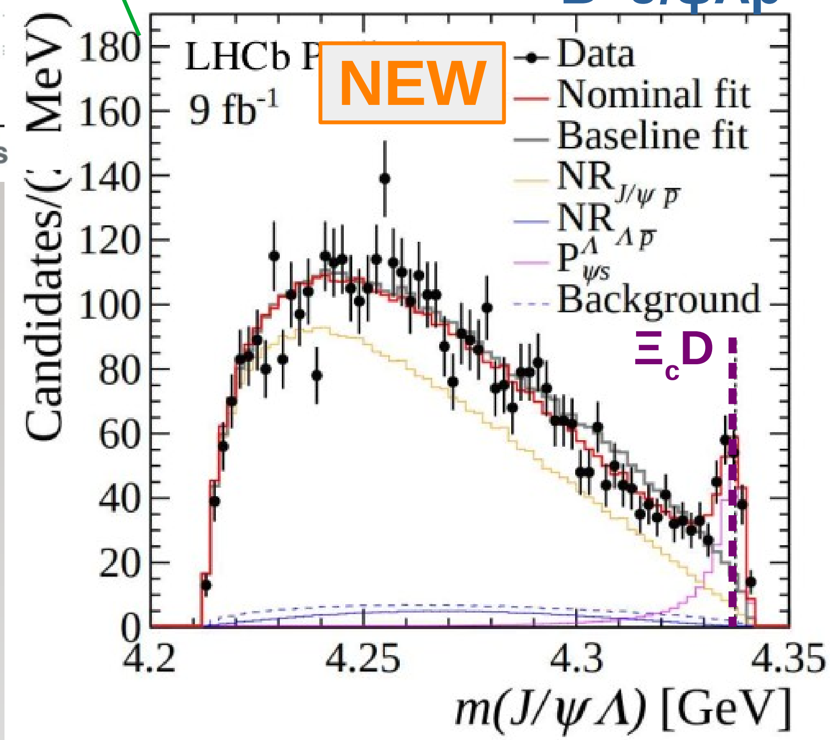


Science Bulletin 66 (2021) 1278

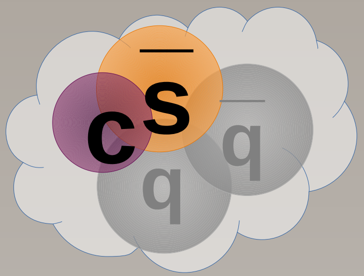


Phys. Rev. Lett. 128 (2022) 062001

$B^- \to J/\psi \Lambda \bar{p}$



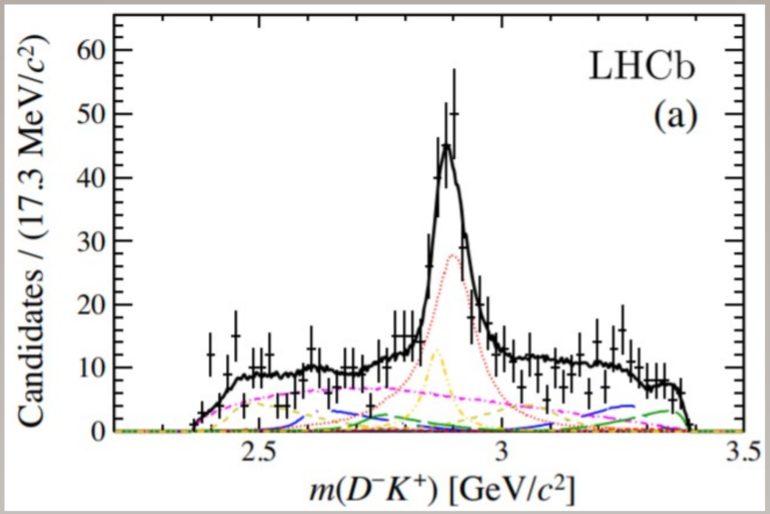
PRL 131 (2023) 031901



T_{cs} at LHCb

- First $[cs\bar{u}\bar{d}]$ state observed in $B^+ \to D^+ D^- K^+$: $T_{cs0}(2900)^0$, $T_{cs1}(2900)^0$

PRD 102 (2020) 112003

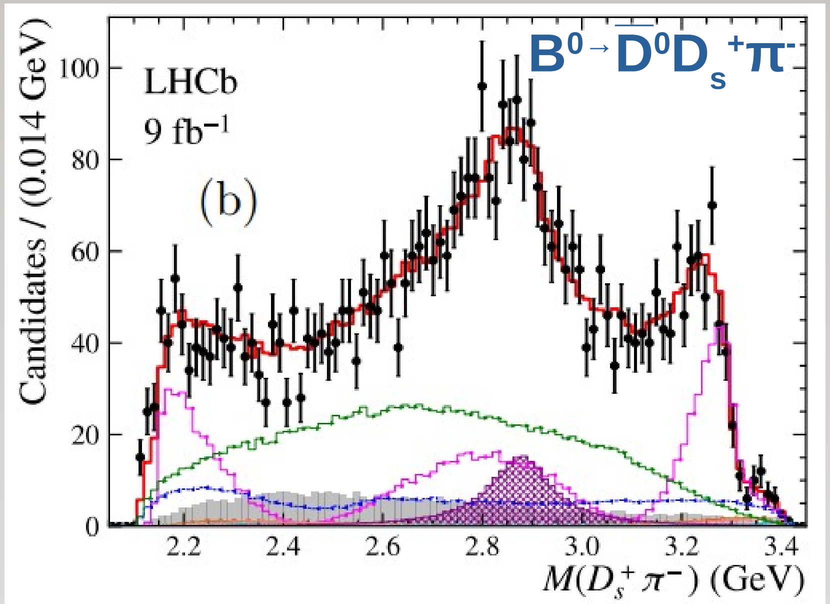


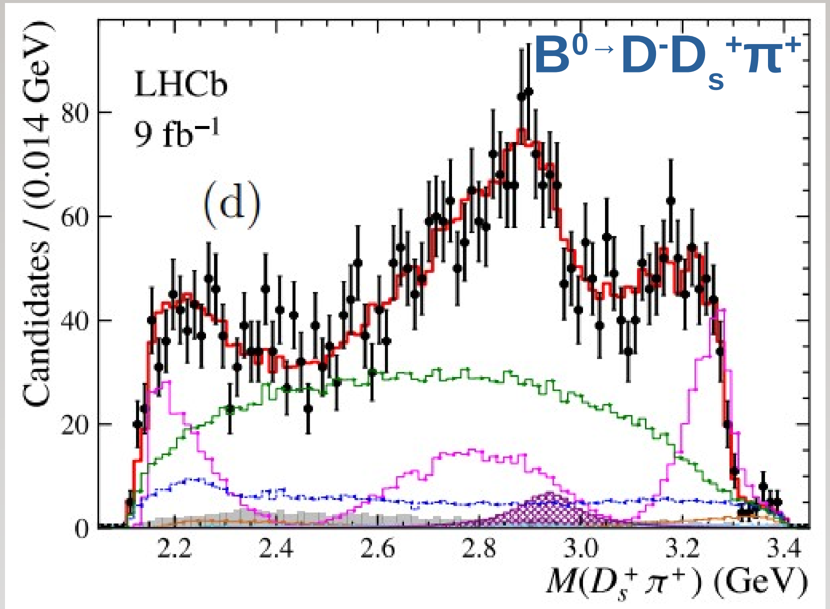
- Search for $[c\bar{s}q\bar{q}]$ partners in $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^0 \to D^- D_s^+ \pi^+$

NEW

- Observed $T_{c\bar{s}0}(2900)^0$, $T_{c\bar{s}0}(2900)^{++}$

arXiv:2212.02716 arXiv:2212.02717



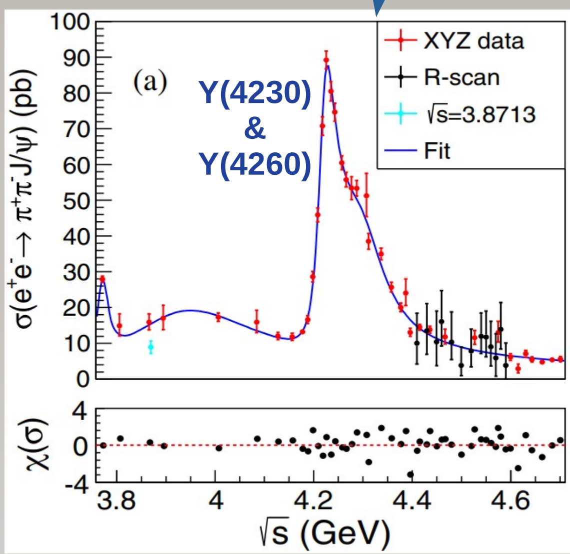


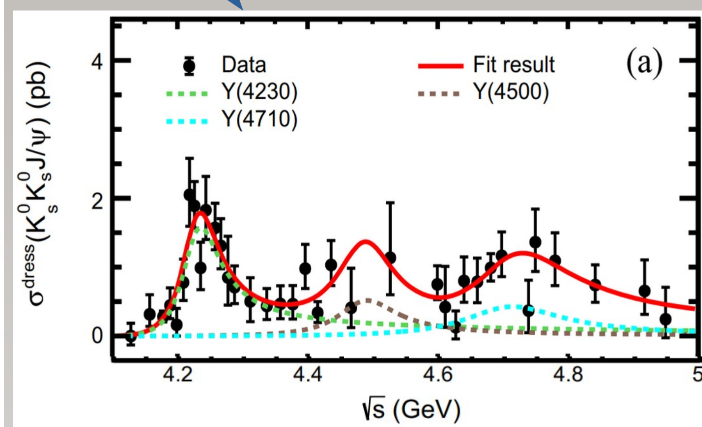
New results from BESIII

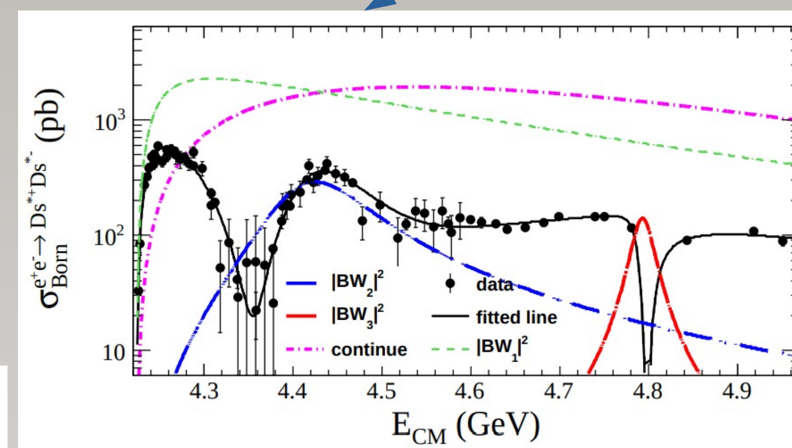
NEW

- Exclusive $e^-e^+ \to X$ cross-section in number of channels:

- $J/\psi\pi^+\pi^-$ PRD 106 (2022) 072001
- $J/\psi K^+K^-$ CPC 46 (2022) 111002
- $J/\psi K_S K_S$ PRD 107 (2023) 092005
- $\psi_2(3823)\pi^+\pi^-$ PRL 129 (2022) 102003
- $\psi_2(3823)\pi^0\pi^0$ JHEP 02 (2023) 171
- $\chi_{cJ}\phi$ JHEP 01 (2023) 132
- $D^{*+}D^{(*)-}$ JHEP 05 (2022) 155
- $D^{*0}D^{*-}\pi^+$ PRL 130 (2023) 121901
- $D^+D^-\pi^+\pi^-$ PRD 106 (2022) 052012
- $D_s^{*+}D_s^{*-}$ arXiv:2305.10789







- Probing same poles, hope to fit them all with common K-matrix in future

- Different from those seen by LHCb ($J^P=1^-$ vs. $0^+/1^+/2^-$)

New results from BESIII

NEW

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  - $J/\psi\pi^+\pi^-$ PRD 106 (2022) 072001
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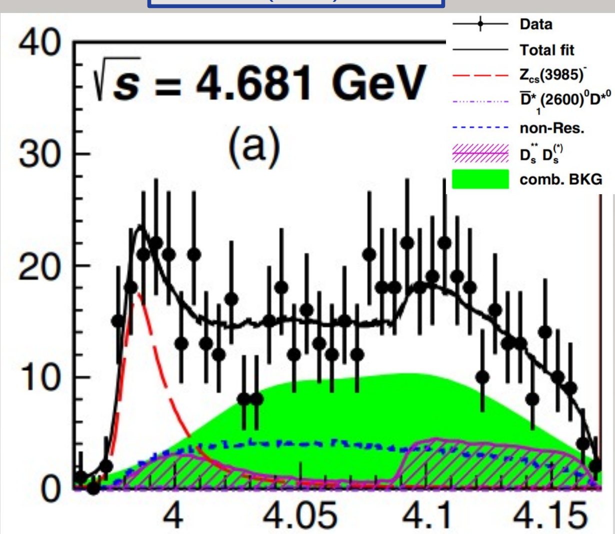
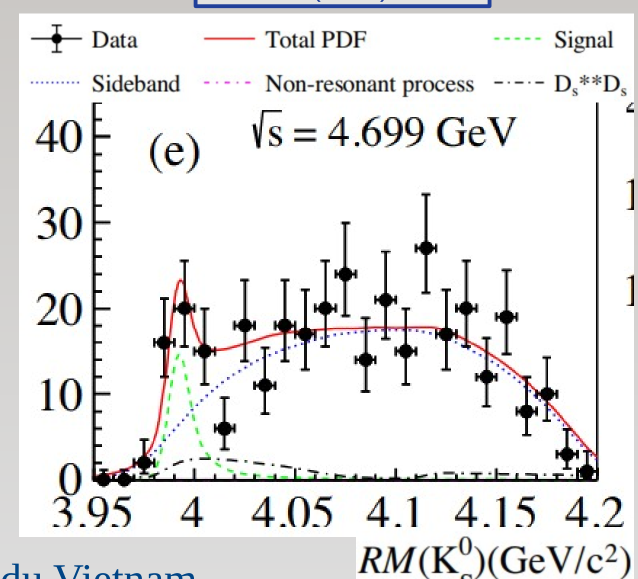
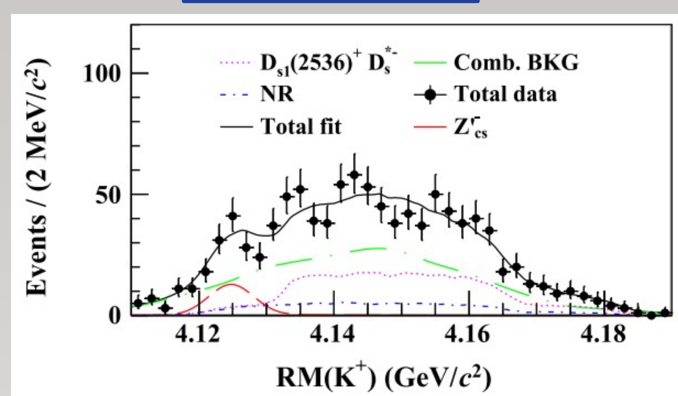
  - $D^+D^-\pi^+\pi^-$ PRD 106 (2022) 052012
  - $D_s^{*+}D_s^{*-}$ arXiv:2305.10789

- $T_{\psi s}$ states via $e^-e^+ \to K(D_s^-D^*)$

- $K^+(D_s^-D^{*0} + D_s^{*-}D^0)$ PRL 126 (2021) 102001
- $K_S(D_s^-D^{*+} + D_s^{*-}D^+)$ PRL 129 (2022) 112003
- $K_S(D_s^{*-}D^{*0})$ CPC 47 (2023) 033001

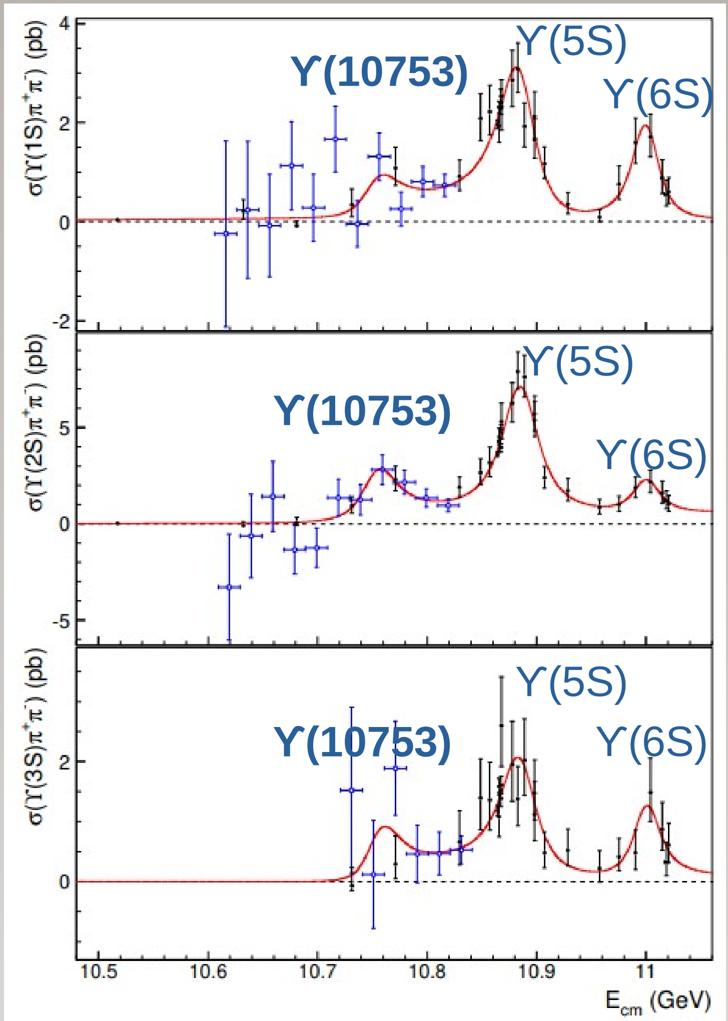




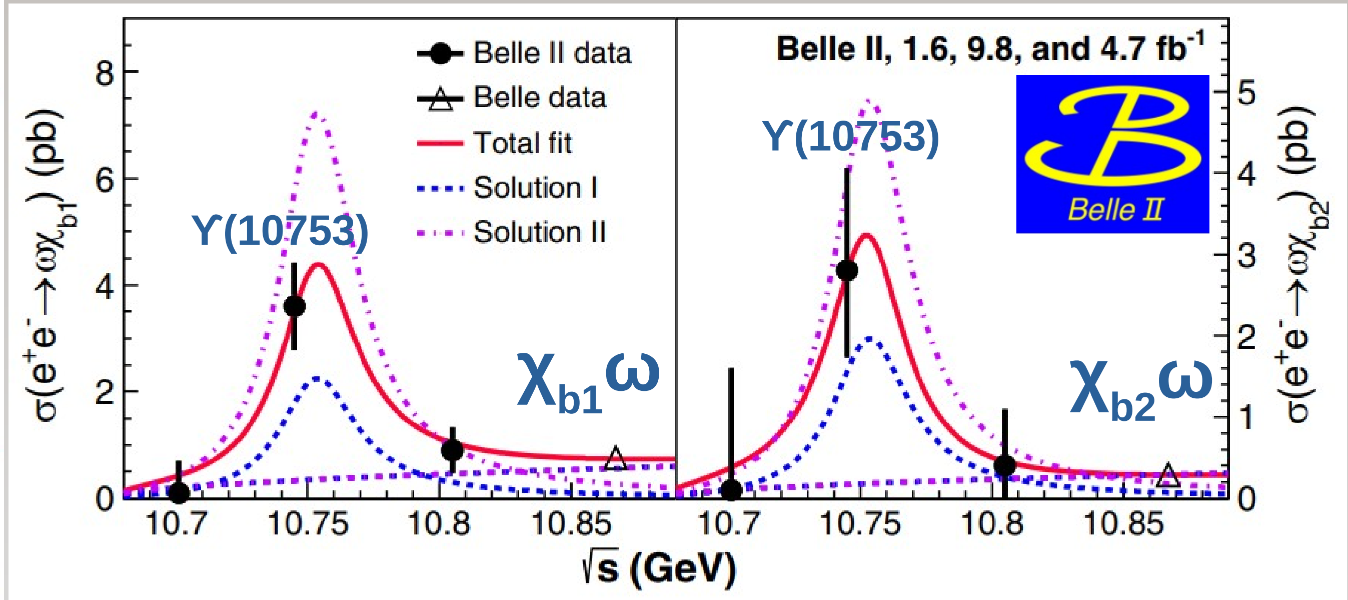


$b\bar{b}$ on Υ(10753) from Belle(II)

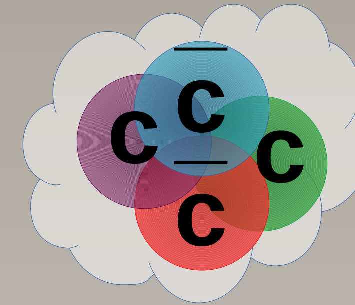
- Structure in Υ(1/2/3S)$\pi^+\pi^-$ → Υ(3D) or exotics JHEP 10 (2019) 220
- Not seen in $B^{(*)}\bar{B}^{(*)}$



- Now observed in $\chi_{b1,2}\omega$ PRL 130 (2023) 091902 **NEW**

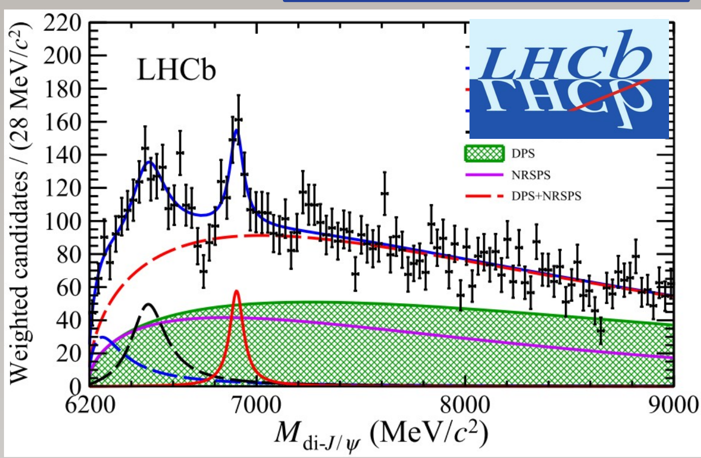


4c-tetraquark

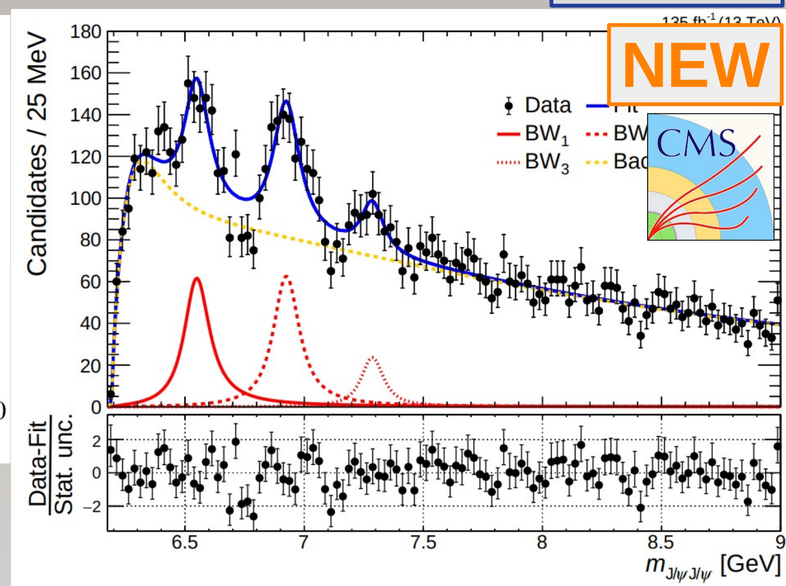


- In 2020 LHCb observed structures in J/ψJ/ψ mass spectrum → clear peak at 6900 MeV with >5σ significance
- CMS and ATLAS confirm the $T_{\psi\psi}$(6900) state
- Confirm hints seen at 6600 (7200) MeV as peaks with 10(4)σ significance

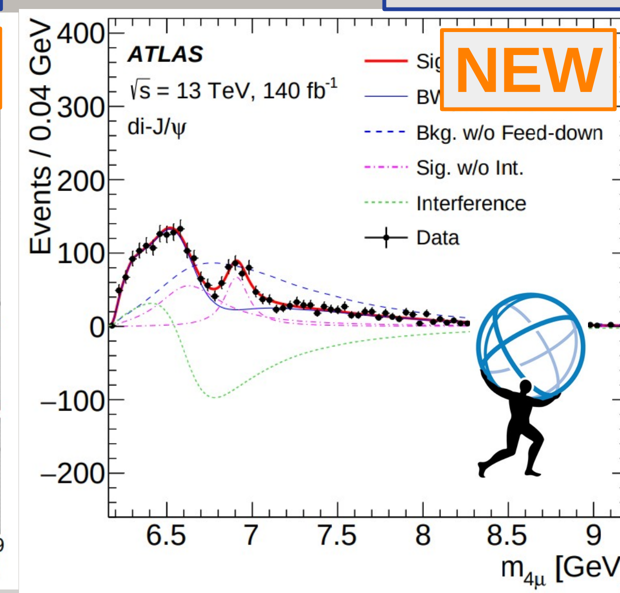
Science Bulletin 65 (2020) 1983



arXiv:2306.07164



arXiv:2304.08962



Scenario I

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV}$$

Scenario II

$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}$$

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

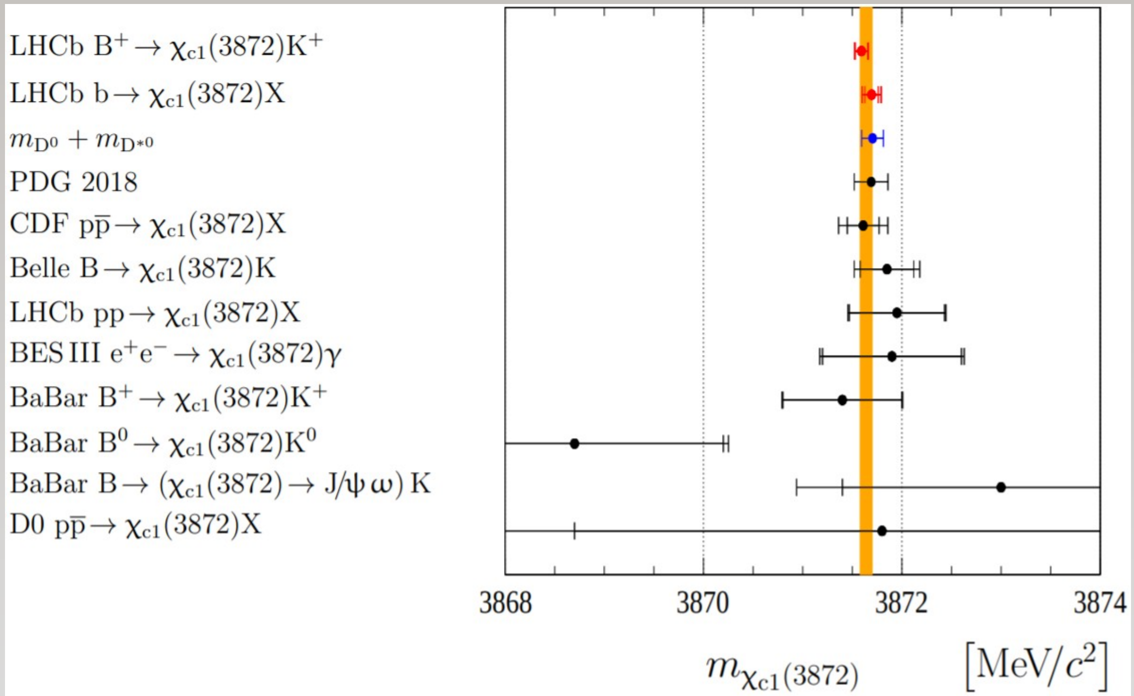
di-J/ψ	model A	model B
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$

$\chi_{c1}(3872)$ – most studied one

- Quantum numbers measured to be 1^{++}
- Various production channels: B/Λ_b-decays, $pp(\bar{p},Pb)$, PbPb, e^+e^-
- Various decay modes: $J/\psi\pi^+\pi^-(\rho^0)$, $J/\psi\omega$, $D^0\bar{D}^{*0}$, $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_{c1}\pi^0$, …
- Mass & width measurement drastically improved

$M(\chi_{c1}(3872)) - M(D^0\bar{D}^{*0}) =$
$= -0.04 \pm 0.12$ MeV
$\Gamma = 1.19 \pm 0.21$ MeV *[in $J/\psi\pi^+\pi^-$]*

though still indistinguishable from $D^0\bar{D}^{*0}$ threshold



χ_{c1}(3872) – new measurements

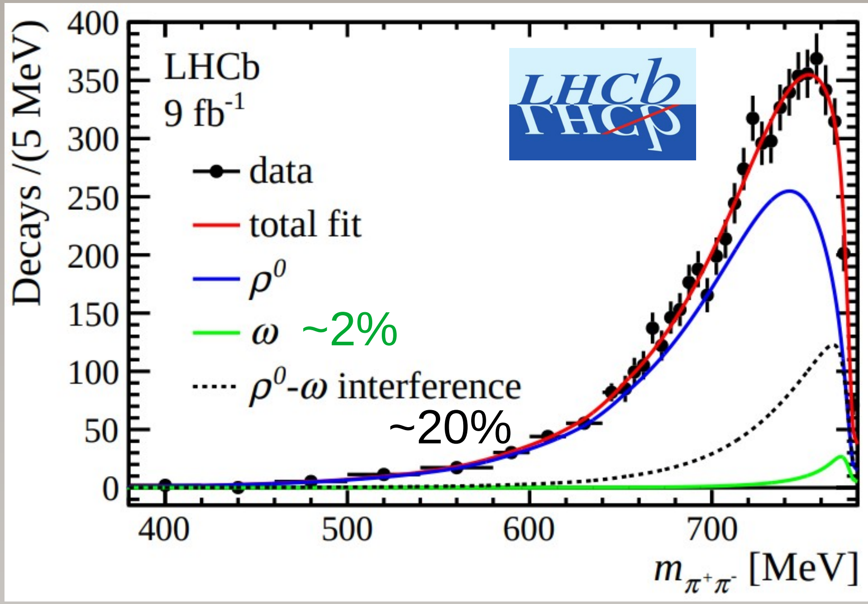
NEW

- BR($J/\psi\omega$) wrt BR($J/\psi\rho^0$) PRD 108 (2023) 011103
  via $\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-$
  - isospin violation 5x larger than typical for charmonia:

$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04$$

vs.

$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$



- Decays to $\bar{D}^0D^{*0}[\rightarrow D^0\gamma/\pi^0]$
  - χ_{c1}(3872) lineshape

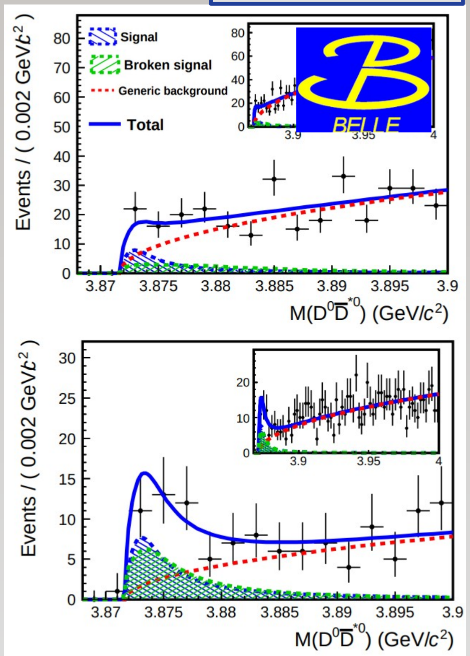
$$m_{\mathrm{BW}} - (m_{D^0} + m_{D^{*0}}) = 2.02^{+0.56}_{-0.50}(\mathrm{stat}) \pm 0.08(\mathrm{syst})\ \mathrm{MeV}/c^2$$

$$\Gamma_{\mathrm{BW}} = 5.2^{+2.2}_{-1.5}(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{MeV}$$

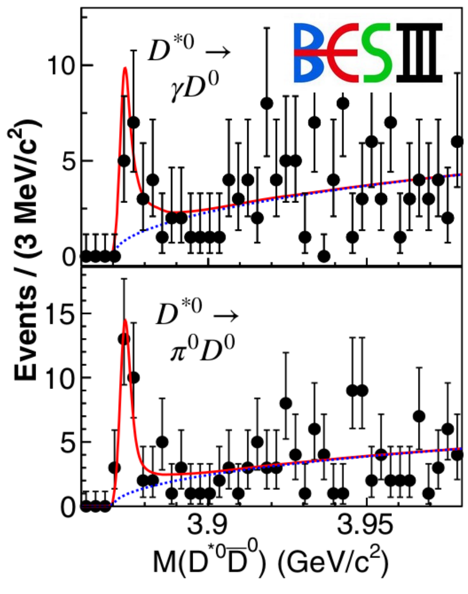
- BRs wrt $J/\psi\pi^+\pi^-$

Mode	Ratio	UL
$\gamma J/\psi$	0.79 ± 0.28	...
$\gamma\psi'$	-0.03 ± 0.22	< 0.42
$\gamma D^0\bar{D}^0$	0.54 ± 0.48	< 1.58
$\pi^0 D^0\bar{D}^0$	-0.13 ± 0.47	< 1.16
$D^{*0}\bar{D}^0$ + c.c.	11.77 ± 3.09	...
γD^+D^-	$0.00^{+0.48}_{-0.00}$	< 0.99
$\omega J/\psi$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	...
$\pi^0\chi_{c1}$	$0.88^{+0.33}_{-0.27} \pm 0.10$ [27]	...

arXiv:2302.02127



PRL 124 (2020) 242001

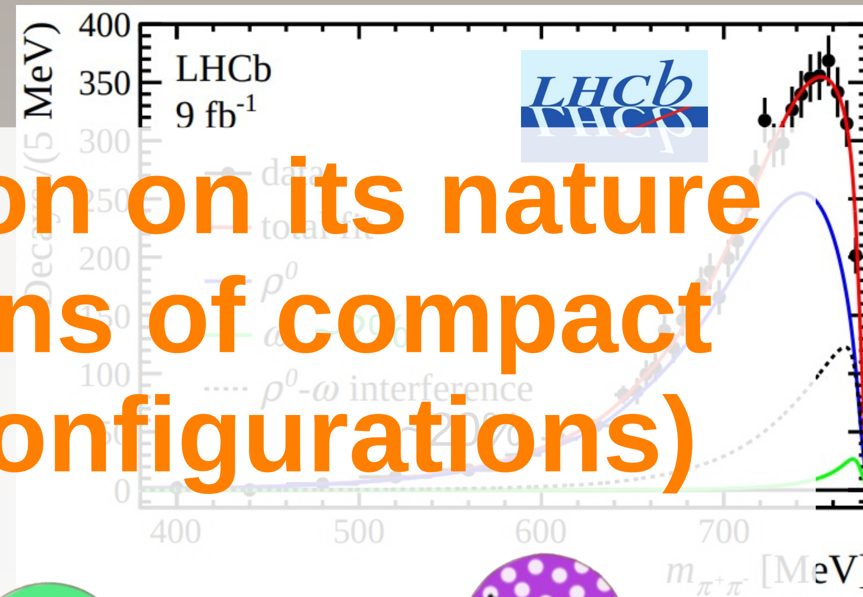


$\chi_{c1}(3872)$ – new measurements

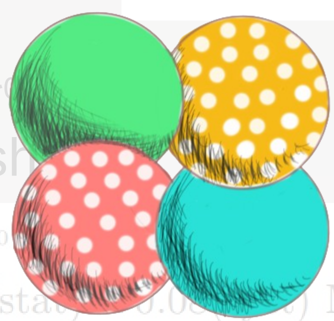
NEW

- BR($J/\psi\omega$) wrt BR($J/\psi\rho^0$) arXiv:2204.12597
  via $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$
  - isospin violation larger than typical for charmonia:

$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04 \quad \text{vs.} \quad \frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$



Still no conclusion on its nature (relative fractions of compact and molecula configurations)



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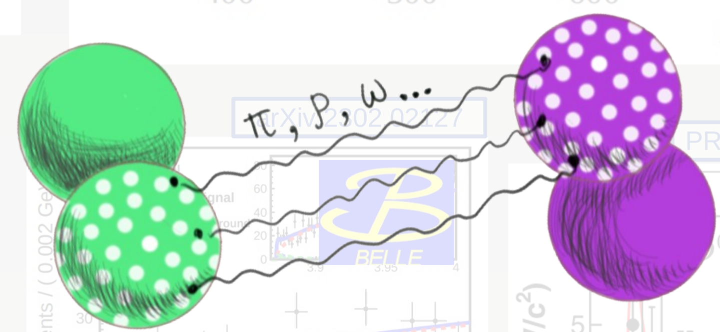

- Decays to $\bar{D}^0 D^{*0}$ arXiv:2202.02227 PRL 124 (2020) 242001
  - $\chi_{c1}(3872)$ lineshape

$$m_{\rm BW} - (m_{D^0} + m_{D^{*0}}) = 2.02^{+0.56}_{-0.50}(\text{stat}) \pm 0.0?(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma_{\rm BW} = 5.2^{+2.2}_{-1.5}(\text{stat}) \pm 0.4(\text{syst})\ \text{MeV}$$

  - BRs wrt $J/\psi\pi^+\pi^-$

Mode	Ratio	UL
$\gamma J/\psi$	…	…
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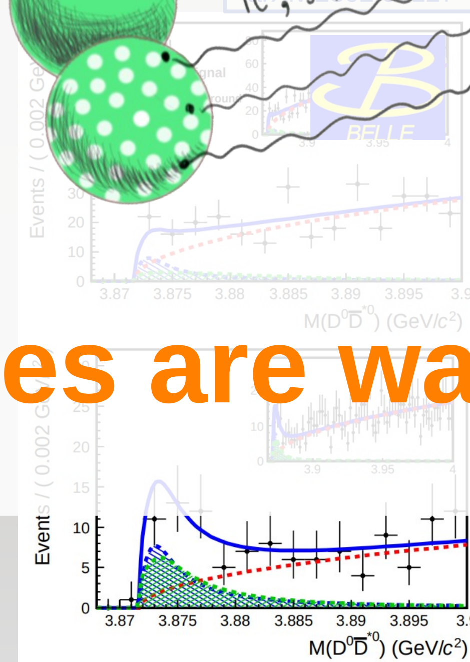
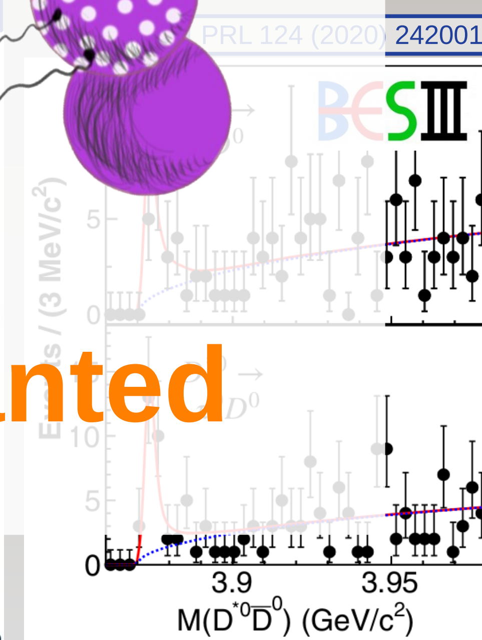
$\pi^0 D^0\bar{D}^0$	-0.13 ± 0.47	< 1.16
$D^{*0}\bar{D}^0$ + c.c.	11.77 ± 3.09	…
γD^+D^-	$0.00^{+0.48}_{-0.00}$	< 0.99
$\omega J/\psi$	$1.6^{+0.4}_{-0.3} \pm 0.2$ [18]	…
$\pi^0\chi_{c1}$	$0.88^{+0.33}_{-0.27} \pm 0.10$ [27]	…





narrower states are wanted

The narrowest one - T_{cc} $[cc\bar{u}\bar{d}]$

- 2021: signal in $D^0D^0\pi^+$ just below D^0D^{*+} threshold

- Model as $T_{cc}^+ \rightarrow D^0D^{*+}(\rightarrow D\pi)$ for $I(J^P)$ of T_{cc} as $0(1^+)$

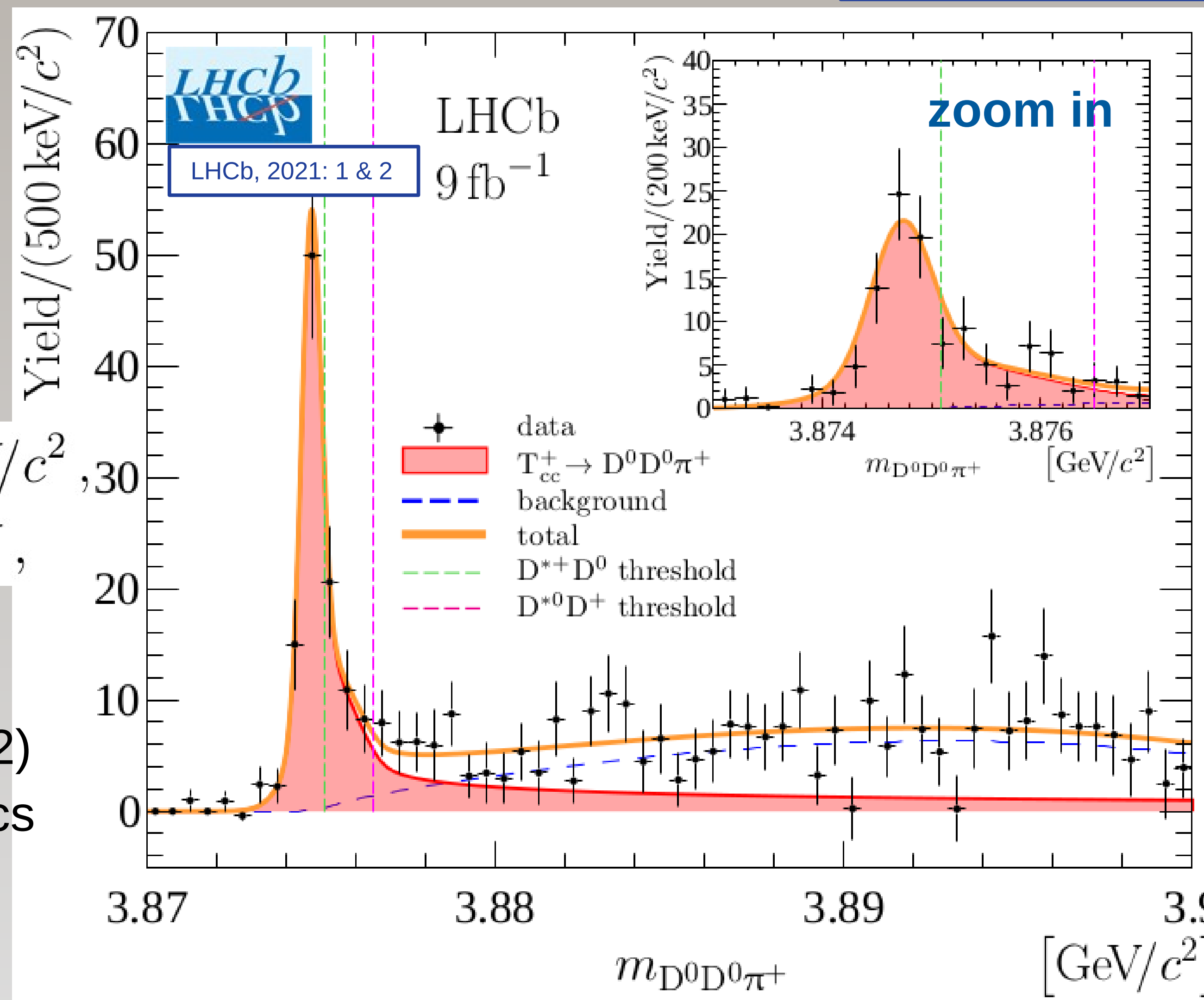
  in this model width defined by $\Gamma(D^{*+})$ and δm

Nature Phys. 18 (2022) 751
Nature Commun. 13 (2022) 3351

- Results:

$$\delta m_{\rm pole} = -360 \pm 40\,^{+\,4}_{-\,0}\ {\rm keV}/c^2\,,$$
$$\Gamma_{\rm pole} = 48 \pm\ 2\,^{+\,0}_{-\,14}\,{\rm keV}\,,$$

- 20x more narrow than $\chi_{c1}(3872)$ and 1000x than all other exotics

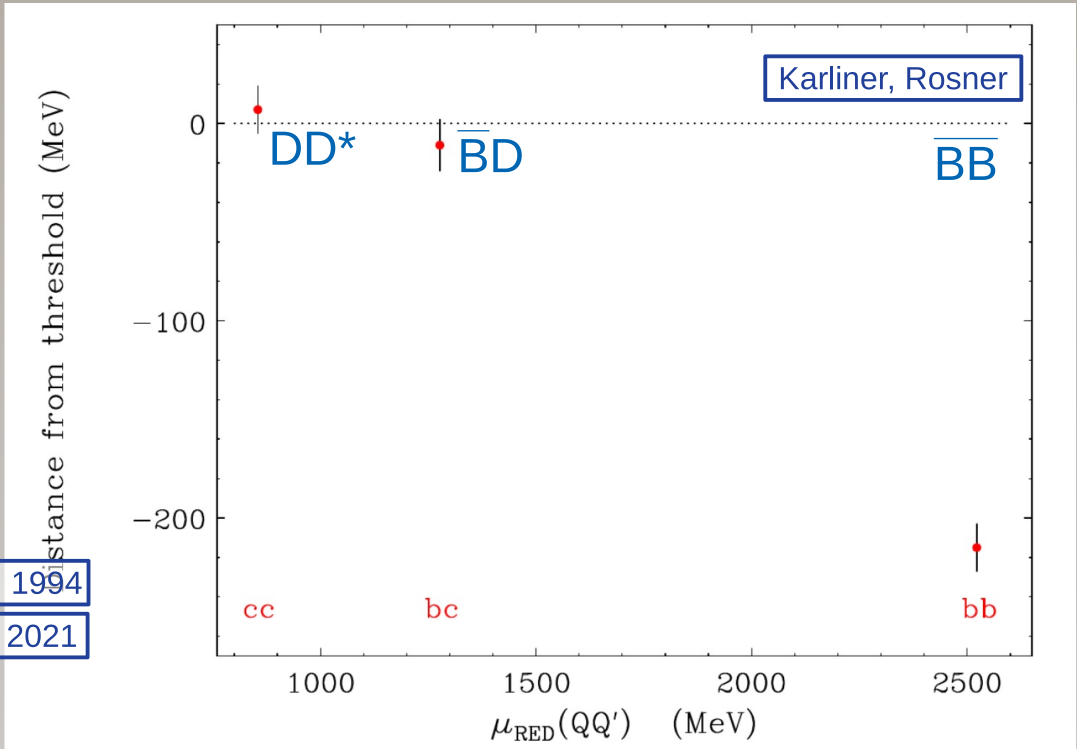


Other doubly-heavy states, $[QQ\overline{ud}]$

- The T_{bb} ***[bb][$\overline{ud}$]*** is likely long-lived...
… but expected yields are only ~10^{-4}
(see backup)

- T_{bc} ***[bc][$\overline{ud}$]*** may be below $\overline{B}D$ threshold by O(10) MeV

Karliner, Rosner, 2017 | Semay, SIlvestre-Brac, 1994
Liu et al., 2019 | Carames, Vijande, Valcarce, 2019 | Meng et al., 2021



  - Opposite expectations in some molecular models Li, Sun, Liu, Zhu, 2012 | Hudspith et al., 2020
  what your model predicts?

Much more interesting!

- Prospects for searches at pp (LHC/LHCb) :
1-10 events per mode in Run3.
real chances to find (if combining several modes)

Long-lived 5/6-quark states

- Qqqqq and Qqqqqq are candidates for stable compact multiquarks since 1980s

  Dover, Kahana, 1977 | Gignoux, Silvestre-Brac, Richard, 1987 | Lipkin, 1987

- Arguments for both ***instability*** and ***stability*** can be found

  Pepin, Stancu, 1998 | Park, Park, Lee, 2015 | Leandri, Silvestre-Brac, 1993, 1995

  Vijande et al., 2016 | Wang et al., 1995 | Stancu, 1999 | Chow, 1995

  Huang, Ping, Wang, 2014 | Park, Cho, Lee, 2018 | Meng, Wang, Zhu, 2020

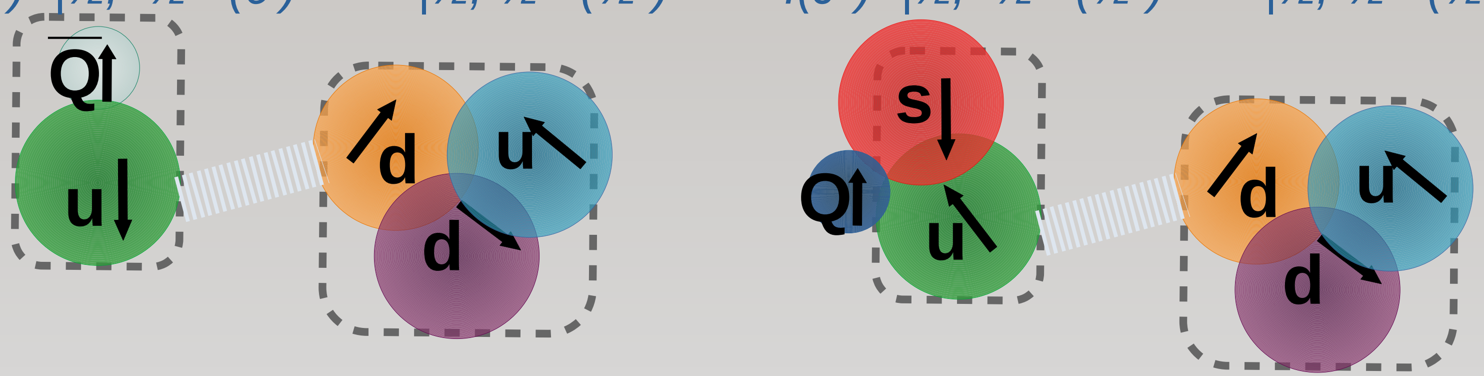
Instability of compact-state → short-range repulsion for molecula?

- Molecule configurations may give ~2-20 MeV binding (2.2 MeV in deuteron) → long-lived states

  Yamaguchi et al., 2011 | Huang, Ping, Wang, 2014

- Deuteron-like baryon-meson/di-baryon moleculas with c/b-quark

$I(J^P)=|½;+½> (0^-)$ *$|½;-½> (½^+)$* *$I(J^P)=|½;+½> (½^+)$* *$|½;-½> (½^+)$*

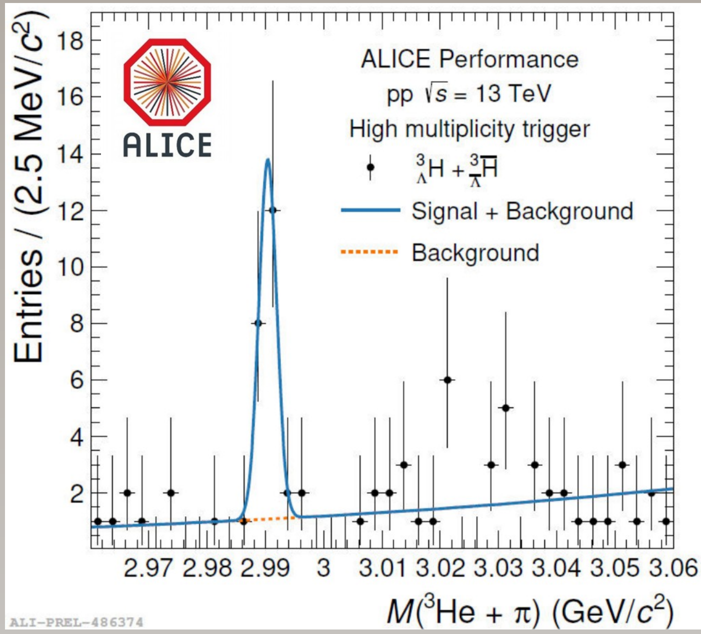


… meeting hypernuclei physics.

Will inclusion of heavy quarks be as fruitful as it was in hadron spectroscopy?

Experimental feasibility

- ALICE observed hypertriton
  in both PbPb, pPb and pp collisions
  ALICE, 2021



- LHCb has x50-100 larger statistics of pp-collisions
  than ALICE

- LHCb has searched for long-lived ***[$\bar{b}$udud] & [$\bar{b}$sudu]***
  in J/ψpKπ & J/ψpϕ channels

  $\sigma*BR(pp\rightarrow P_bX)/\sigma*BR(pp\rightarrow \Lambda_b) <\sim 2 \times 10^{-3}$

  compare to σ(d)/σ(p)~2 x 10^{-3} LHCb, 2018

- Even more perspectives with charm / double-charm
  → my estimates for LHCb:
  O(10^5) candidates for $H_{c(s)}$, O(10^3-10^4) for $H_{b(s)}$ and O(10-100) for H_{cc}
  → O(10^4) H_c for ALICE J. Stachel, talk

Conclusion

- Exotic Spectroscopy is the main tool to study quark interaction at hadron level
- Huge experimental progress in last 20 years,
  … more than 36 states established … a lot of hopes attached
- Now need to start new “precise” phase
  - Accounting for coupled-channels in analyses of wide exotic states (produced in both B-decays and e^-e^+)
- Hunt for new narrow states
  - T_{bc} $\boldsymbol{[bc\overline{ud}]}$ likely be most important measurement of next 5-10 years in the field
  - Deuteron-like states with b/c quarks