Experimental Review of Heavy Exotic Hadrons

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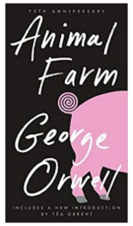
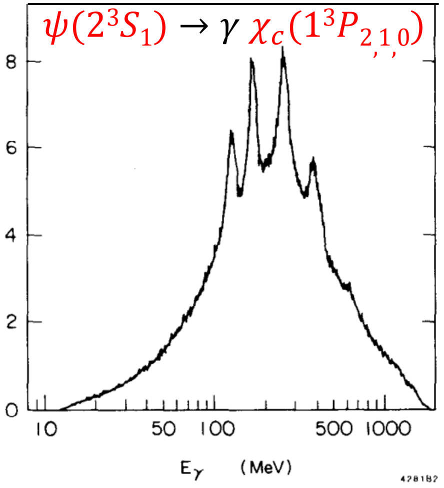
20th Conference on Flavor Physics and CP violation, May 23-27, 2022

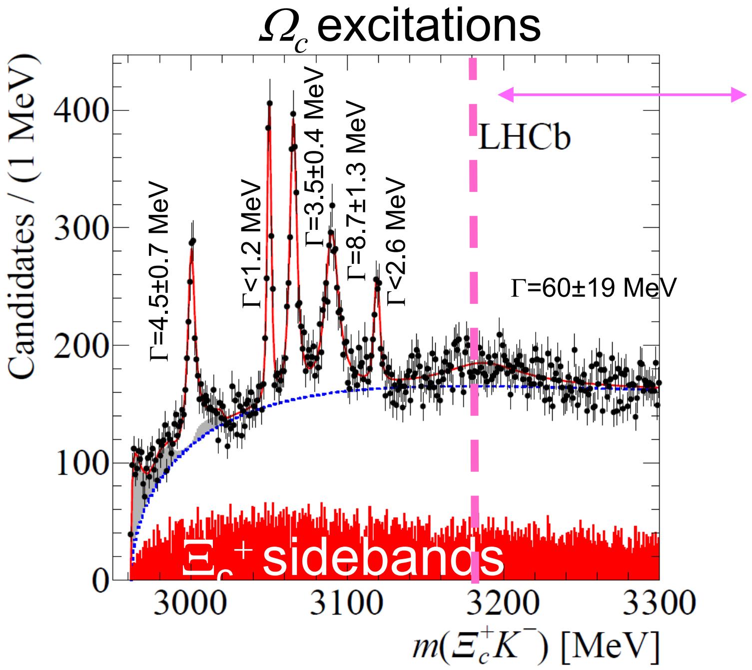
Heavy-flavor hadrons are special



- Strong interactions are flavor independent ($SU(3)_f \rightarrow QCD$), thus why?
- Marek Karliner: “all quarks are created equal, but heavy quarks are more equal than others”
  - $m_Q/\Lambda_{QCD} \gg 1 \rightarrow$ decreased kinetic energy of heavy quarks, increased binding energy ($V_{Q\bar{Q}} \sim m_Q$)
  - quark velocity v_Q/c becomes an expansion parameters in effective theories (potential models, NRQCD,…)
  - heavy quark content self-evident from hadron masses; no mixing with different flavor hadrons
  - many lower excitations forced below threshold for OZI favored decays making them narrow (long-lived)



Crystal Ball SLAC-PUB-2887 (1982)

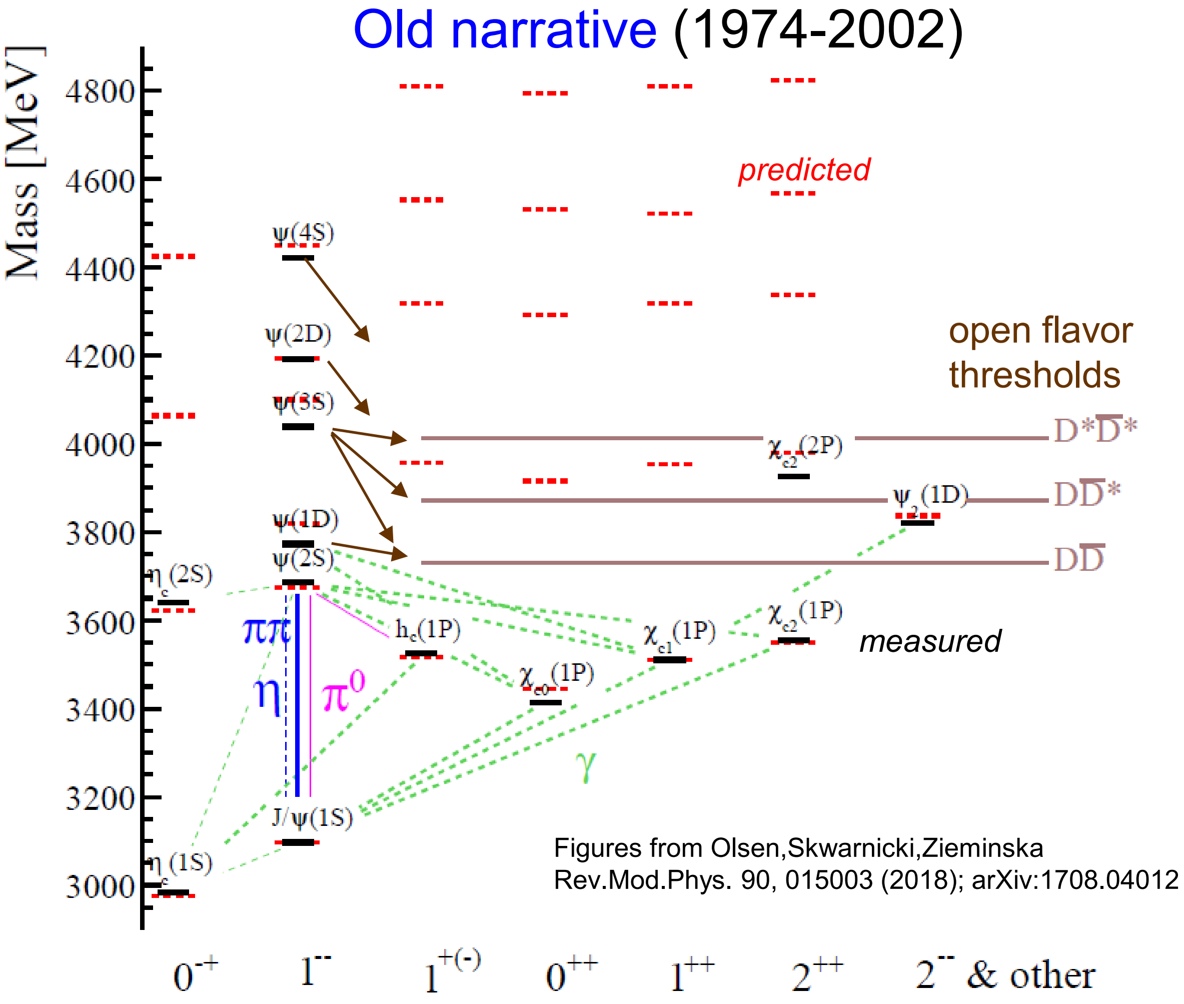


$c(ss) \rightarrow q(ss) + \bar{q}c$

threshold

The narrow states are likely 1P and 2S of c-(ss diquark)

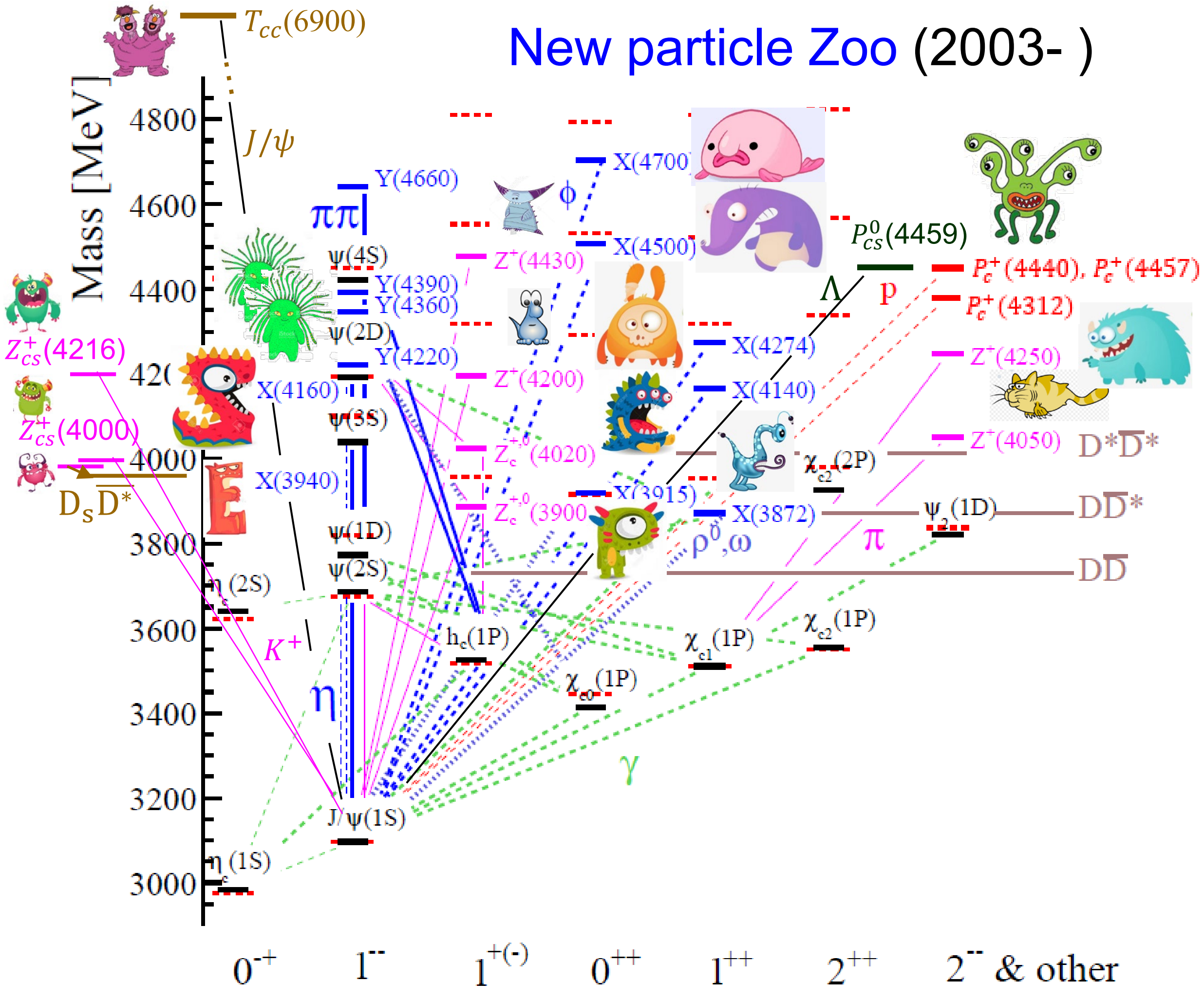
Why heavy flavor hadrons: two chamonium revolutions



Figures from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

Mesons are simple $(q\bar{q})$ bound states.

- Almost all excited states for light hadrons are above "open flavor threshold"



Mesons/baryons are **predominantly** $(q\bar{q}/qqq)$ bound states below the open flavor threshold. **They are more complex structures above it,** and we have not yet understood them.

Don’t we need to revisit our concept of light hadrons?

S. Godfrey, N. Isgur
PR,D32,189 (1985)
Mesons in a relativized quark model with chromodynamics

Excited kaons $q\bar{s}$

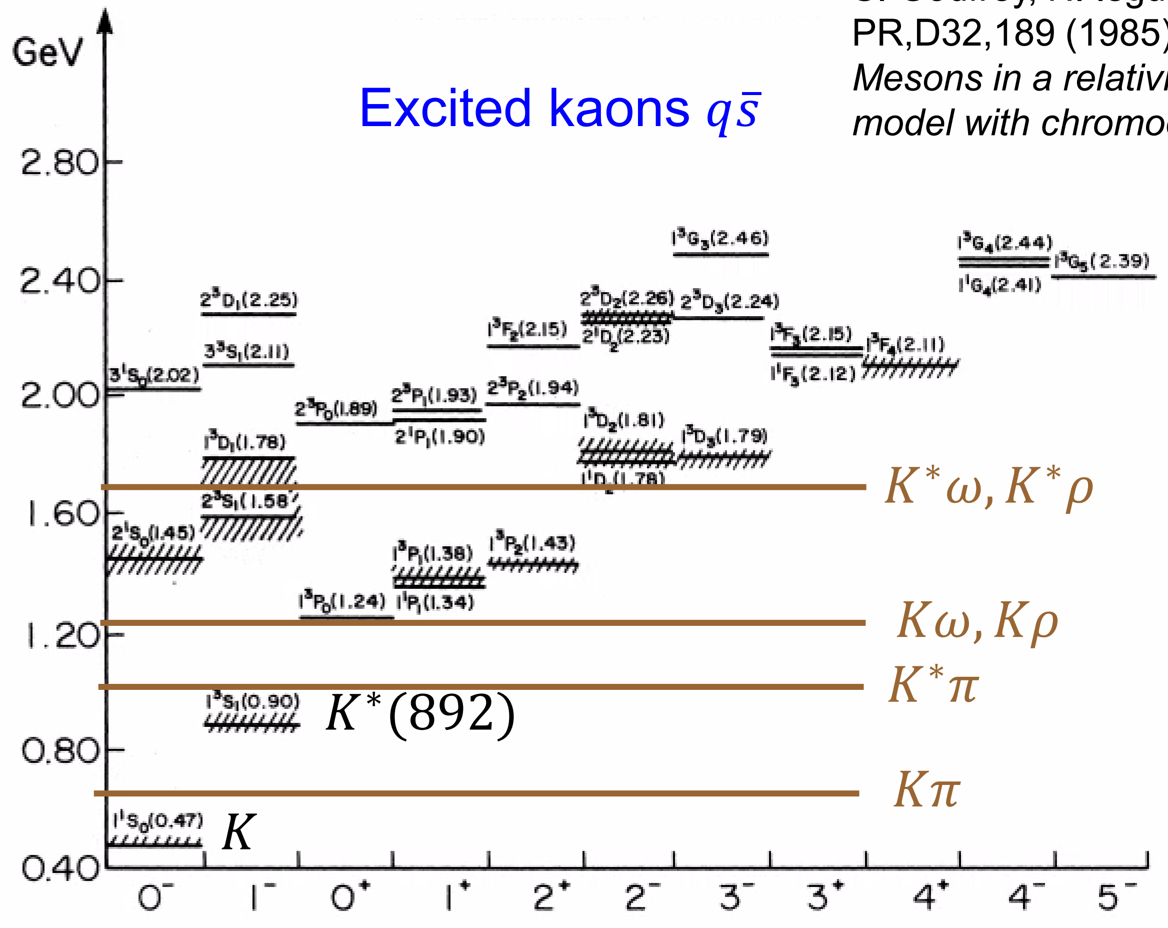


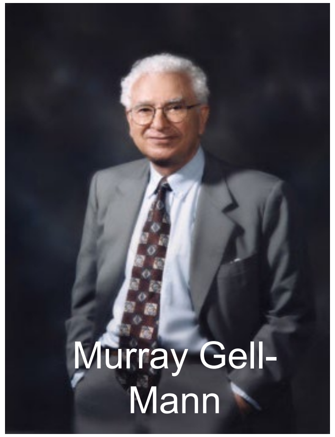
FIG. 4. The strange mesons ($-u\bar{s}$, $-d\bar{s}$). The legend is as for Fig. 3. Significant spectroscopic mixing in this sector:

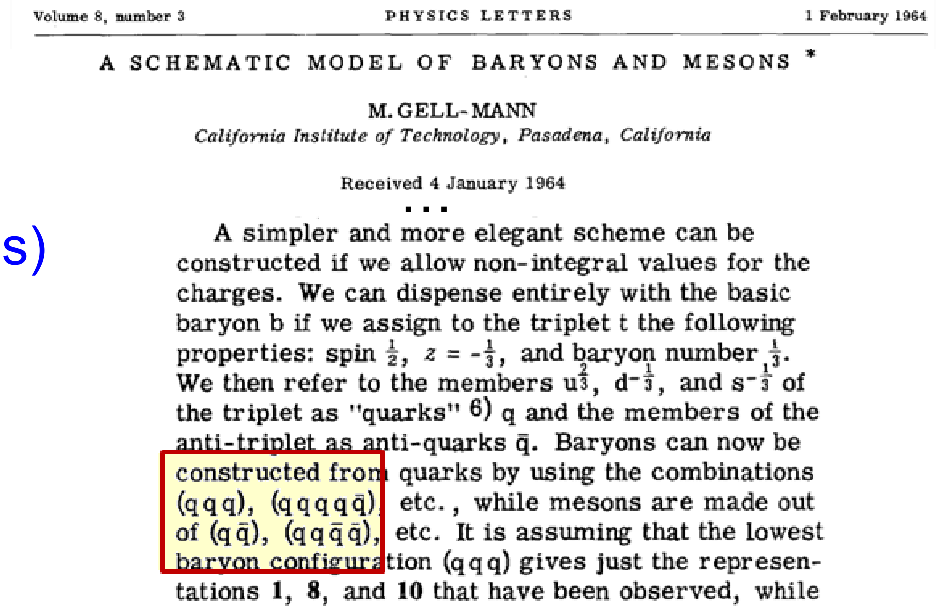
(a) With $\begin{bmatrix} Q_{\rm low} \\ Q_{\rm high} \end{bmatrix} \simeq \begin{bmatrix} \cos\theta_{nL} & \sin\theta_{nL} \\ -\sin\theta_{nL} & \cos\theta_{nL} \end{bmatrix} \begin{bmatrix} n\,{}^1L_L \\ n\,{}^3L_L \end{bmatrix}$ we find $\theta_{1P} \simeq 34^0$, $\theta_{1D} \simeq 33^0$, $\theta_{2P} \simeq 15^0$, $\theta_{1F} \simeq 32^0$, $\theta_{2D} \simeq 25^0$, $\theta_{1G} \simeq 33^0$;

New Zoo is likely also here!

($q\bar{s}q\bar{q}$ states)

Didn’t
Gell-Mann
tell us so?


Murray Gell-Mann


Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

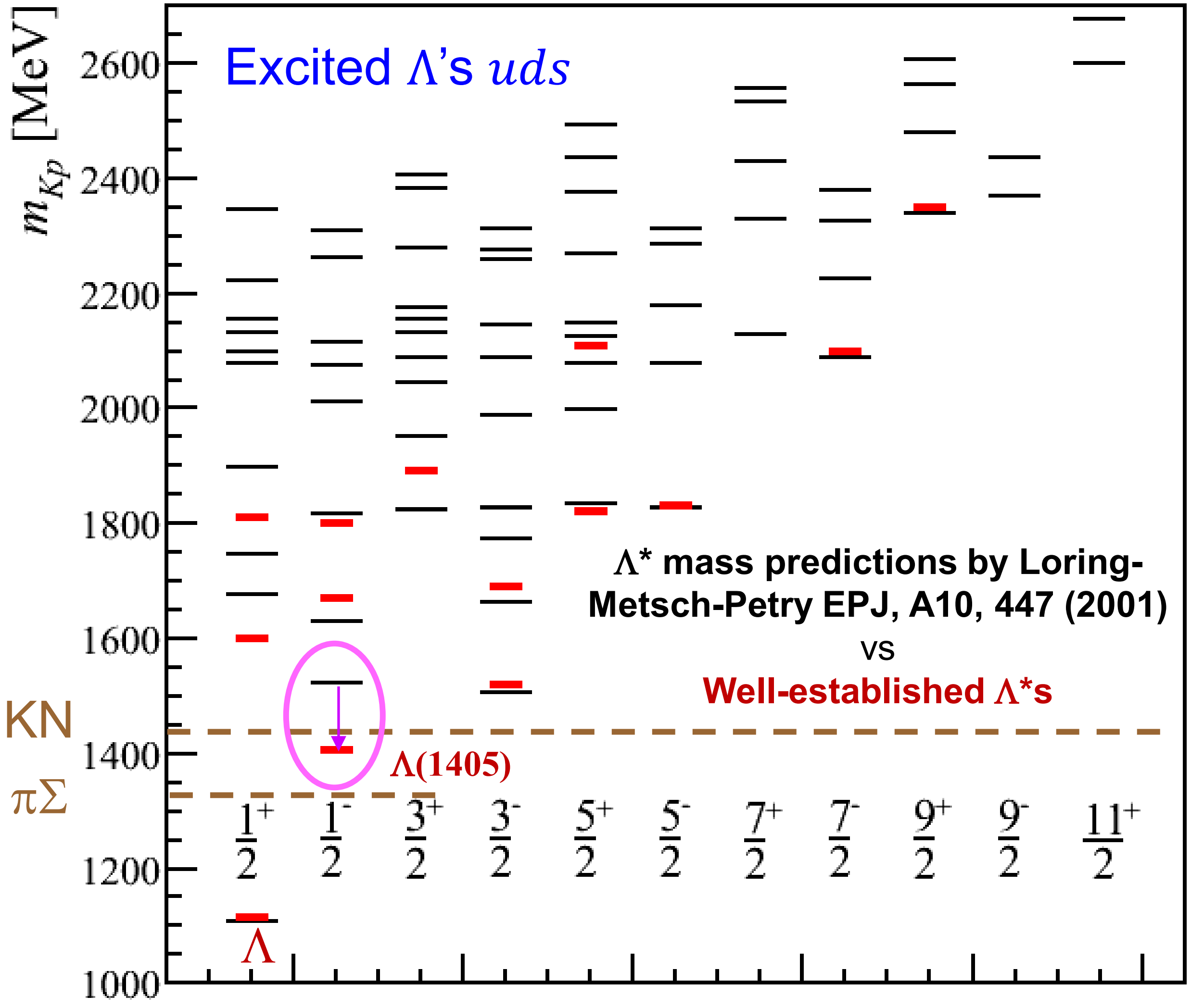
Received 4 January 1964

. . .

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while

LQCD is only learning now how to simulate strongly decaying hadrons

Don’t we need to revisit our concept of light hadrons?



Λ* mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

vs

Well-established Λ*s

New Zoo is likely also here!

($udsq\bar{q}$ states)

In fact, we do find evidence for multiquark effects among excited hadrons!

- Mass of **Λ(1405)** significantly shifted relative the expectations to below the KN threshold. Molecular components? Compact pentaquark component?

Status of our understanding of hadron spectroscopy

- We know the lightest hadrons in each quark configuration are predominantly bound states of $q\bar{q}$ or qqq
- We are not sure if nuclear-type forces can bind mesons to other mesons or baryons (loosely bound “molecular” states)
- We don’t know if diquarks, strongly motivated by QCD, are good building blocks for more complex quark structures (tightly bound multiquark states), and in which situations: $(qq)(\bar{q}\bar{q})$?, $(qq)(qq)\bar{q}$?, …
- We are not even sure about the role of diquarks in baryons $q(qq)$?
- We don’t know if gluon can be among dominant hadron constituents, as motivated by QCD: glueballs gg? hybrids $gq\bar{q}$?, $gqqq$?

Scandalous situation!

Present limitations in understanding are both of theoretical (e.g. difficult to simulate in LQCD full dynamics of multiquark or unstable states) or experimental nature (e.g. insufficient sensitivity to all possible decay modes, difficulty in producing and reconstruction of hadrons with key quark content like $bb\bar{u}\bar{d}$)

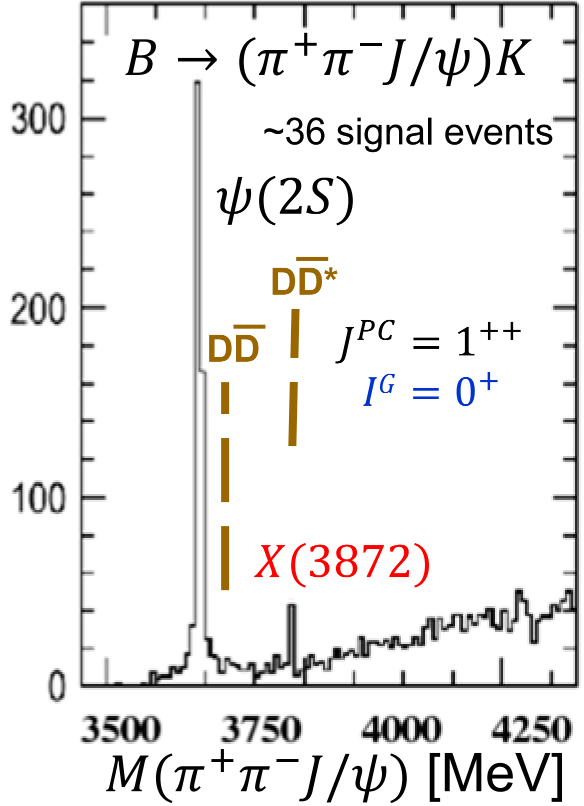
The first and most experimentally studied state – X(3872) aka $\chi_{c1}(3872)$

- Experimentally accessible via $b \to c(\bar{c}s), gg \to c\bar{c}, \ldots$

Belle 2003: discovery of X(3872)

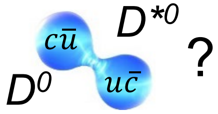
PRL 91, 262001 (2003)

$e^+e^- \to B + \cdots$



$\Gamma = 1.2 \pm 0.2\ MeV\ (PDG\ 2021)$

2^3P_1 ?



?

? diquark tetraquark

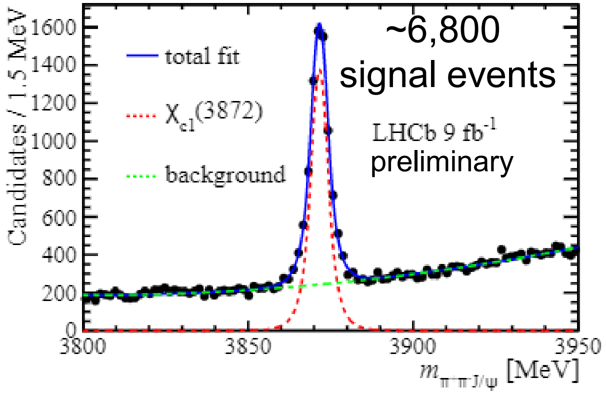
(coincidence with threshold and narrow width hard to explain)

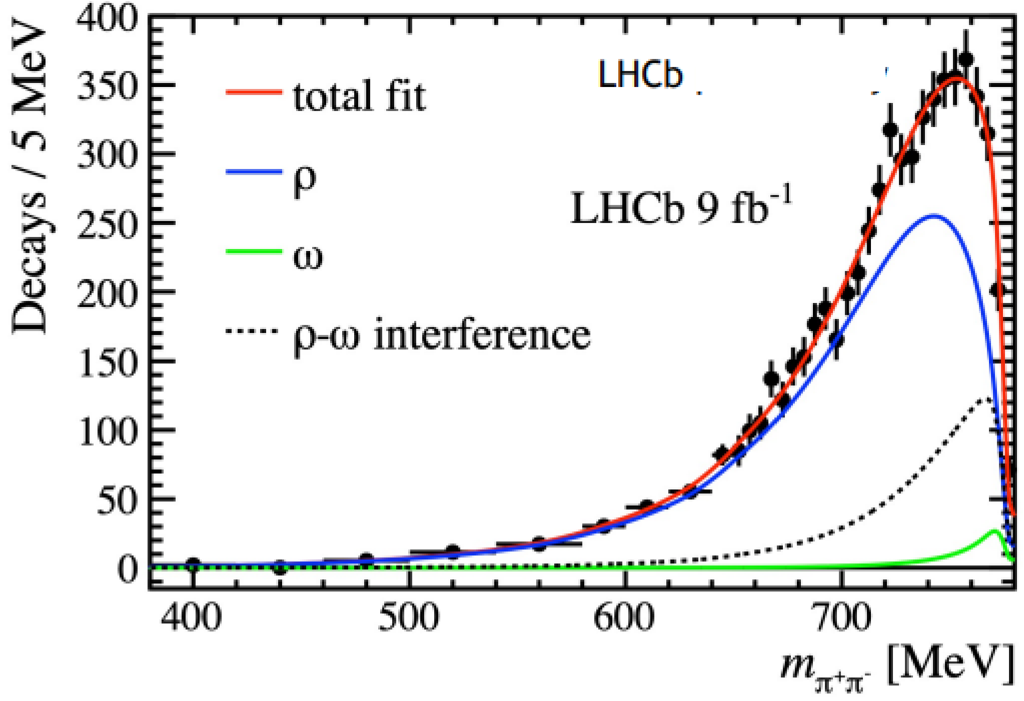
Large isospin violation rules out pure $c\bar{c}$ interpretation

LHCb-PAPER-2021-045 arXiv:2204.12597 (B. Batsukh Ph.D. thesis, Syracuse 2021)

$pp \to B^+ + \cdots$

$B^+ \to (\pi^+\pi^- J/\psi)K^+$





ρ ~ 79%

$\rho - \omega$ ~ 19%

ω ~ 2%

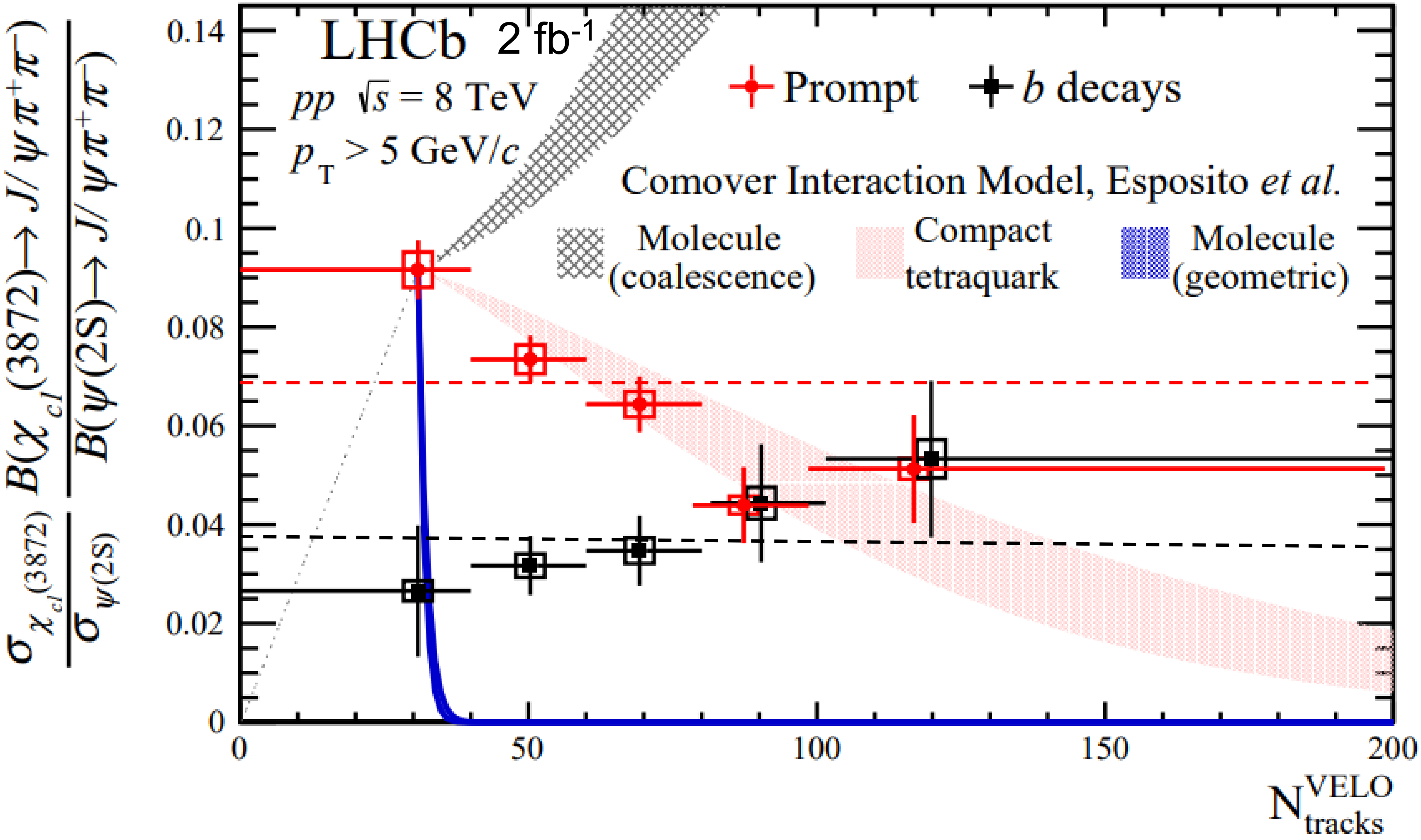
Isospin-violating / Isospin-conserving couplings

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

Natural explanation via large $D^0\bar{D}^{*0}$ component (the mass 8 MeV below $D^+\bar{D}^{*-}$)

Event multiplicity dependence of prompt production of X(3872)

PRL126 (2021) 092001



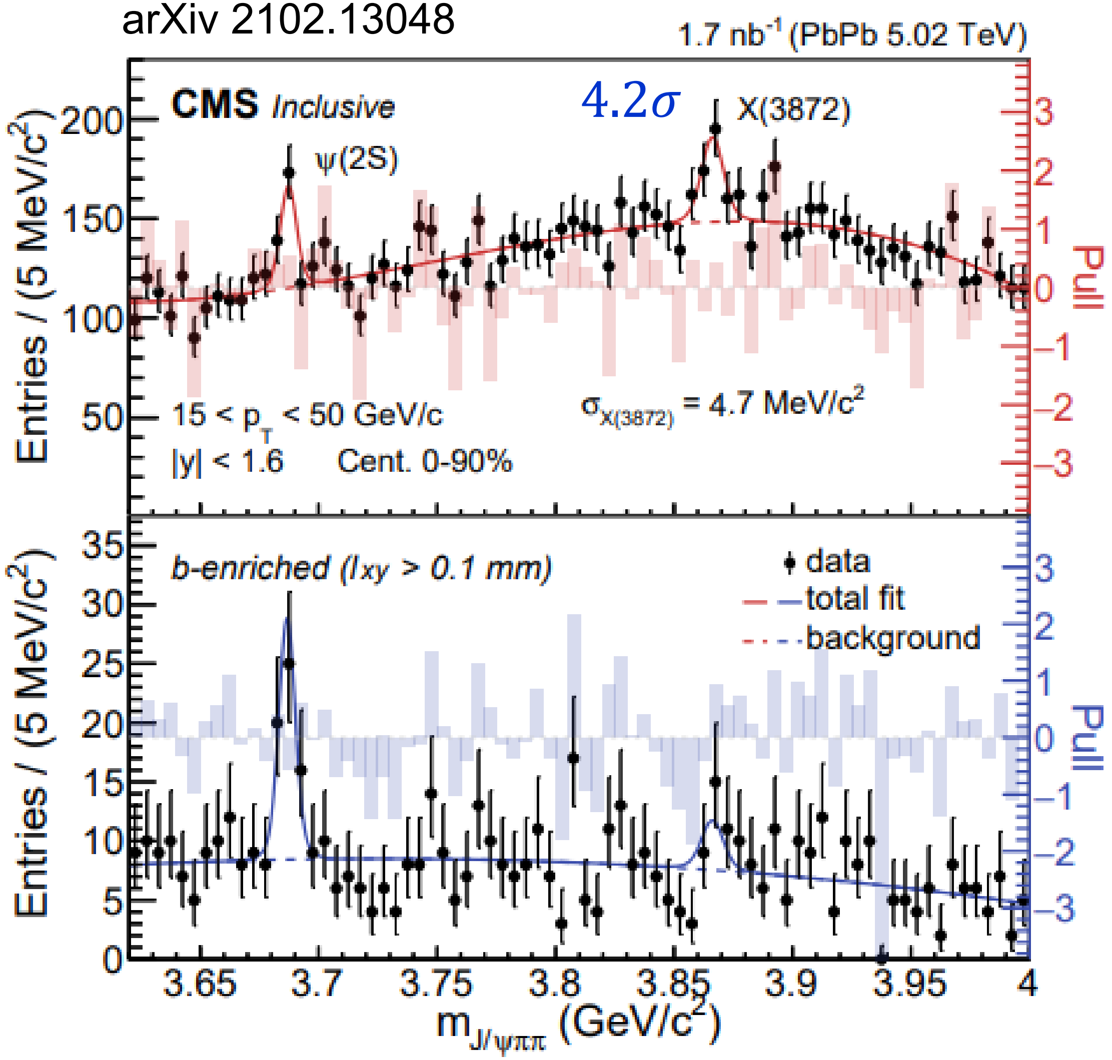
- Dependence of X(3872) prompt production cross-section on event multiplicity is significantly different (5σ) then the one for $\psi(2S)$

How $\chi_{c1}(2P) - D^0\overline{D}^{*0}$ mixture model would look like on this plot?

∝ number of particles produced in pp collision

Evidence for X(3872) production in Pb-Pb collisions

PRL 128, 032001 (2022)
arXiv 2102.13048



$$\frac{\sigma(PbPb \to (X(3872) \to \pi^+\pi^- J/\psi)) + \cdots)}{\sigma(PbPb \to (\psi(2S) \to \pi^+\pi^- J/\psi)) + \cdots)}$$
$$= 1.08 \pm 0.49 \pm 0.52$$

vs ~0.1 in pp collisions

Very consequential if the central value persists with more data

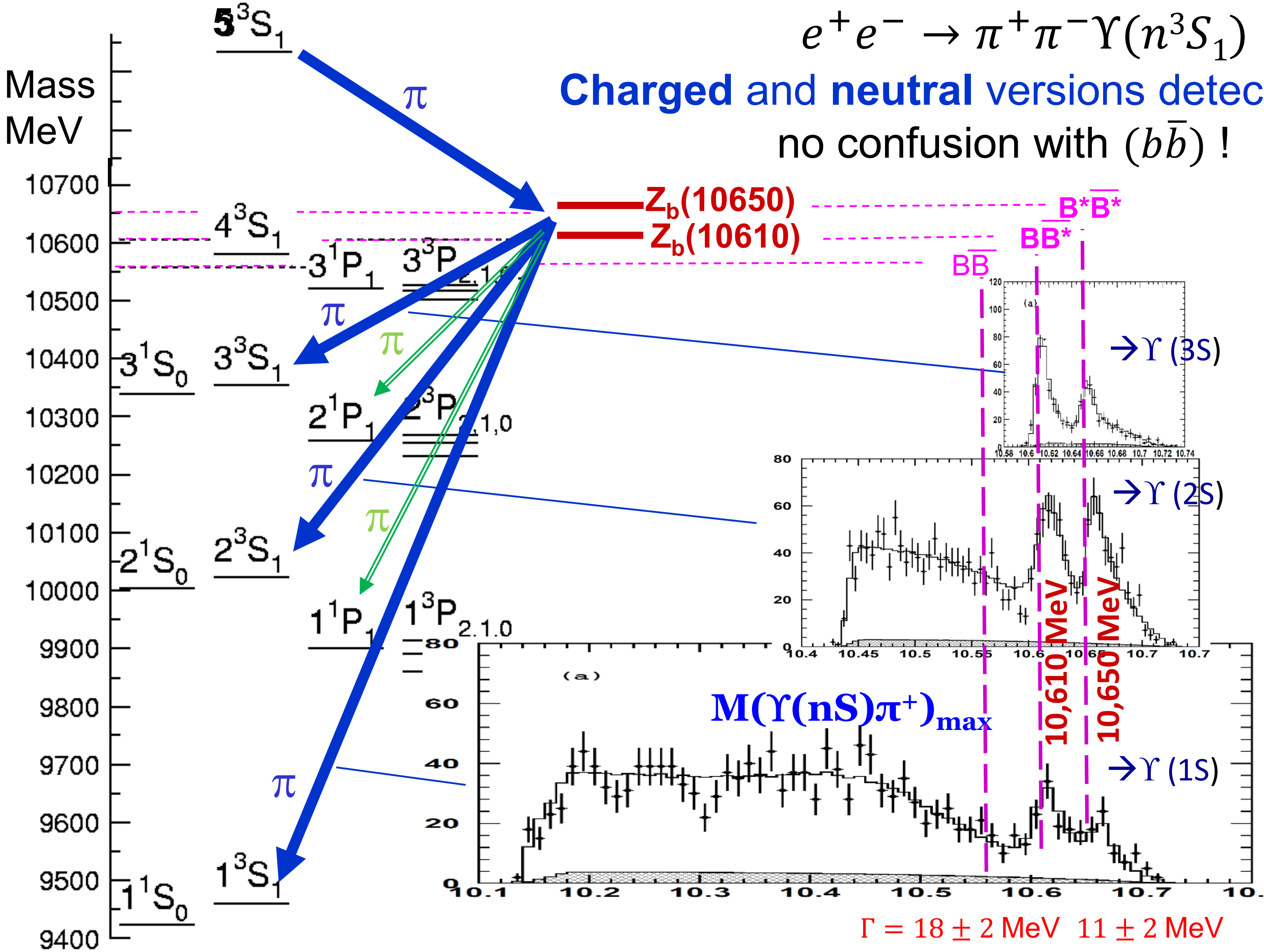
Narrow $Z_b^{+,0}$ and $Z_c^{+,0}$ states

Belle 2012

$e^+e^- \to \pi^+\pi^-\Upsilon(n^3S_1)$

Charged and **neutral** versions detected / $I^G=1^+$

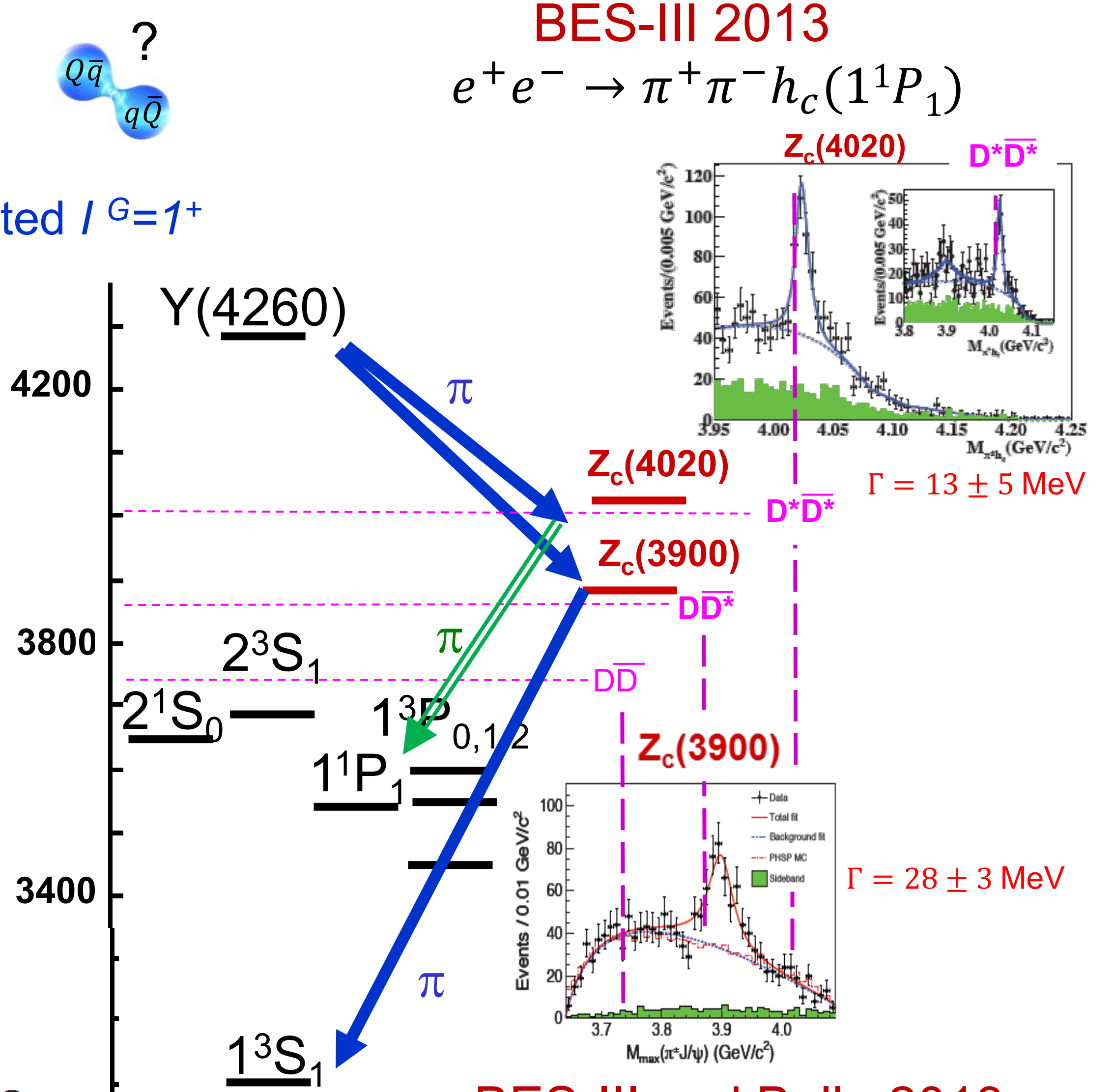
no confusion with $(b\bar{b})$!



Γ = 18 ± 2 MeV 11 ± 2 MeV

BES-III 2013

$e^+e^- \to \pi^+\pi^- h_c(1^1P_1)$



Γ = 13 ± 5 MeV

Γ = 28 ± 3 MeV

BES-III and Belle 2013

$e^+e^- \to \pi^+\pi^- J/\psi\ (1^3S_1)$

$e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi\ (1^3S_1)$

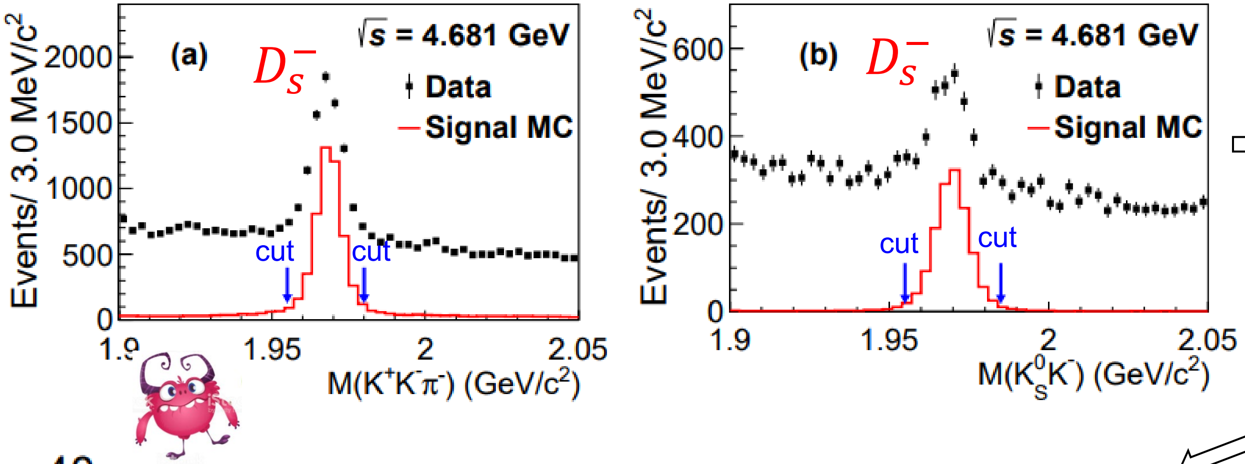
Narrow! Masses peak slightly above thresholds.

Coupled-channel fits (with $D\bar{D}^*$data) for $Z_c(3900)^+$, give its pole mass slightly below the threshold.

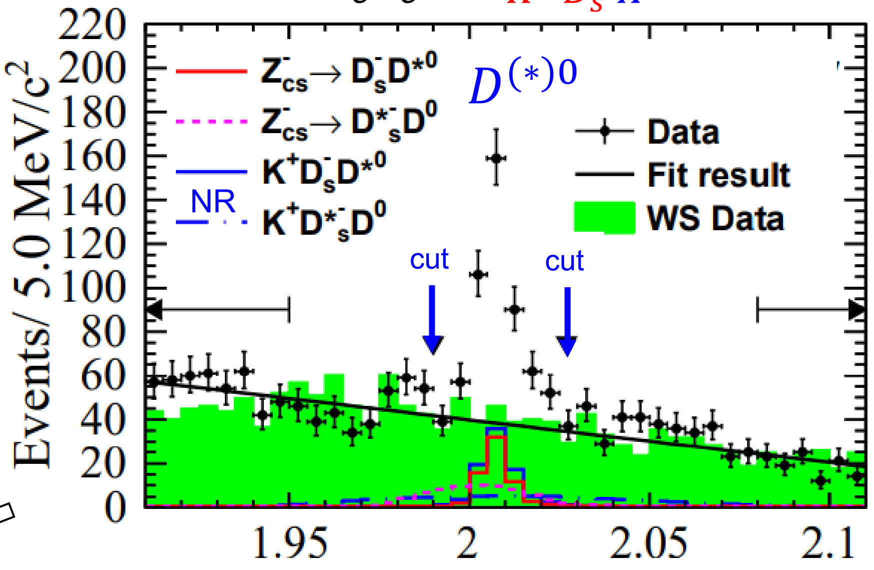
Observation of narrow $Z_{cs}^- \to D_s^- D^{*0}, D_s^{*-} D^0$ state by BESIII

Clever partial reconstruction technique

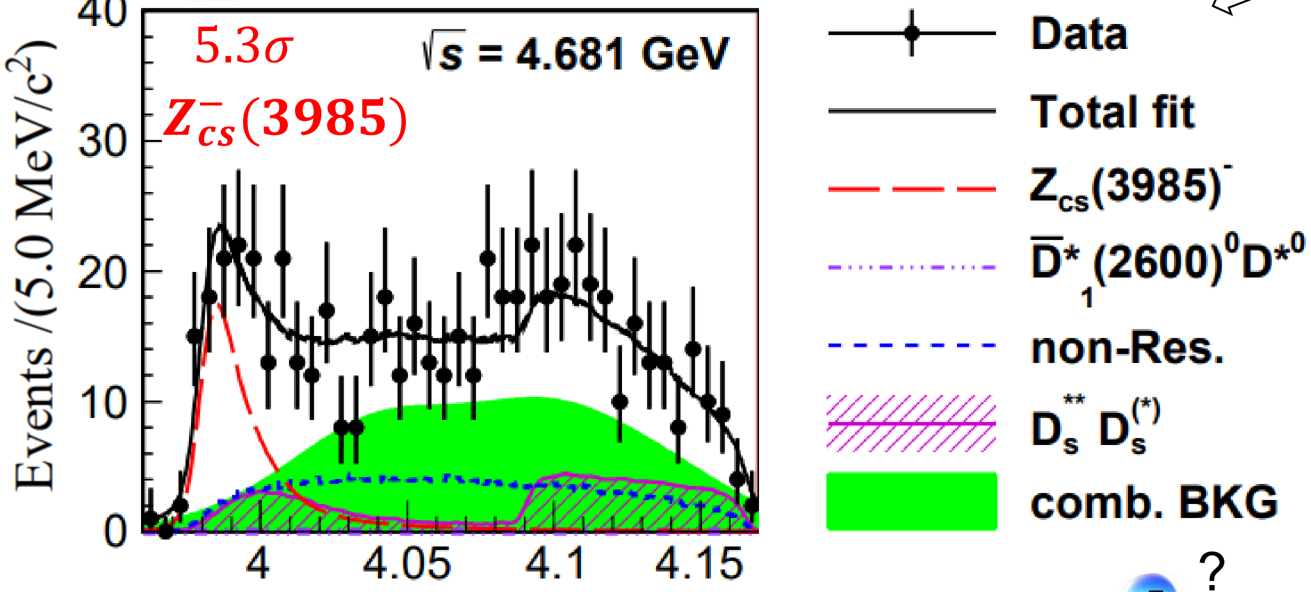
BESIII PRL 126, 102001 (2021)



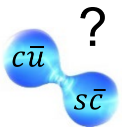
$e^+e^- \to K^+ D_s^- X$



$M(X)$ via Recoil Mass against $K^+ D_s^-$



$M(D_s^- D^{(*)0})$ via Recoil Mass against K^+



$$m_{Z_{cs}(3985)} = 3982.5^{+1.8}_{-2.6} \pm 2.1 \ MeV$$

$$m_{D_s^-} + m_{D^{*0}} = 3975.2 \pm 0.1 \ MeV$$

$$m_{D_s^{*-}} + m_{D^0} = 3977.0 \pm 0.4 \ MeV$$

$$\Gamma_{Z_{cs}(3985)} = 12.8^{+5.3}_{-4.4} \pm 3.0 \ MeV$$

Narrow, a few MeV above the threshold

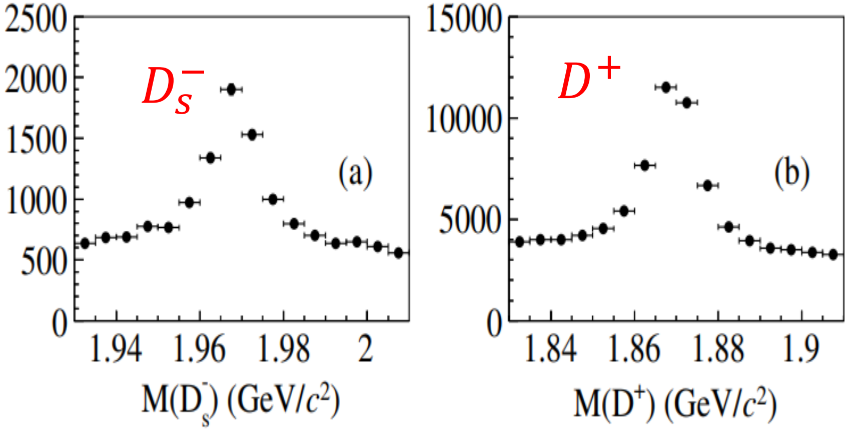
SU(3)$_f$ partner of $Z_c^{\pm,0}(3900)$?

Evidence for narrow $Z_{cs}^0 \to D_s^- D^{*+}, D_s^{*-} D^+$ state by BESIII

Similar technique to the last year paper $K^+ \to K_S^0$

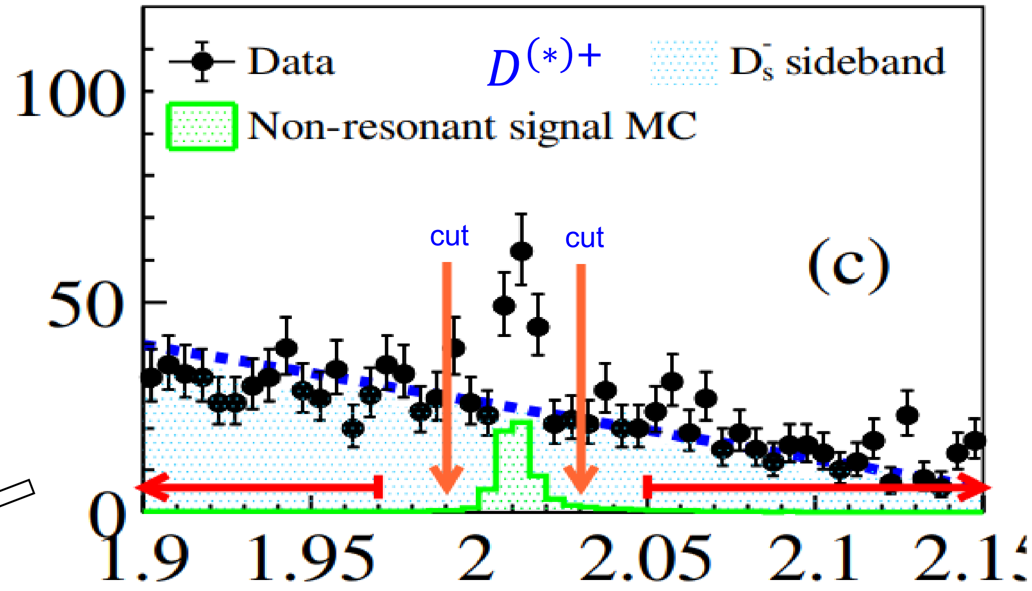
Use even more D_s^- decay modes.

Reconstruct also D^+ in several modes.

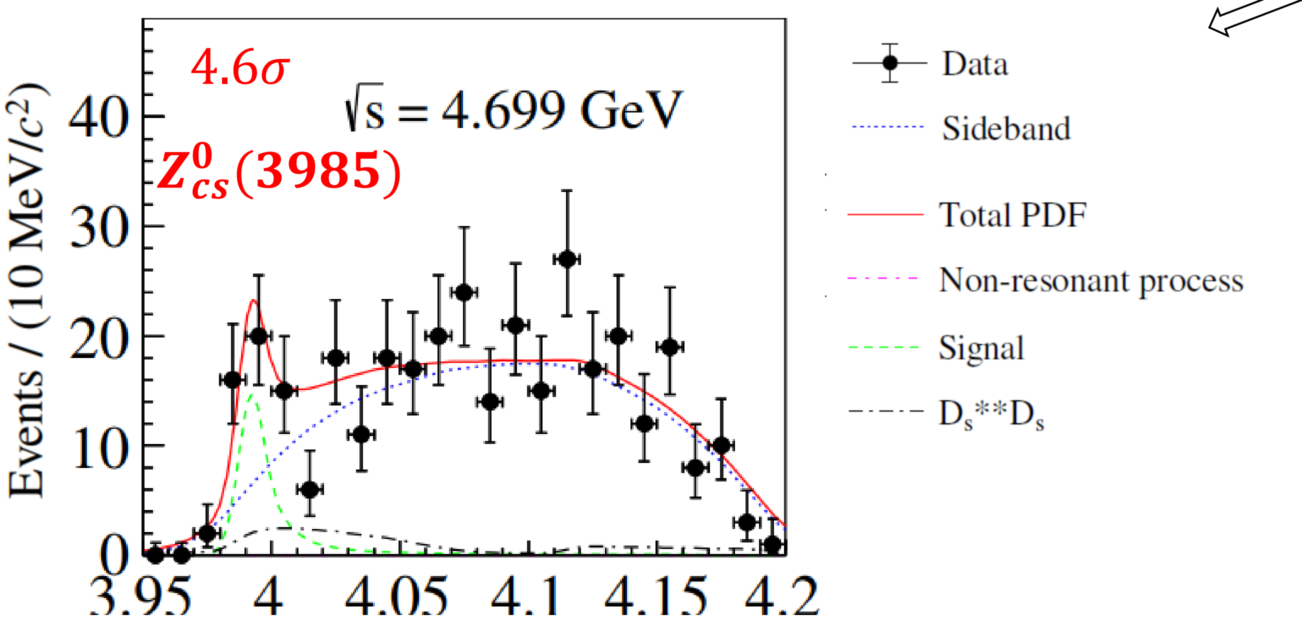


BESIII arXiv:2204.13703

$e^+e^- \to K_S^0 D_s^- X$



$M(X)$ via Recoil Mass against $K_S^0 D_s^-$



$M(D_s^- D^{(*)+}, D_s^{(*)-} D^+)$ via Recoil Mass against K_S^0

$$m_{Z_{cs}^0} = 3902.2 \pm 1.7 \pm 1.6 \ MeV$$

$$m_{Z_{cs}^-} = 3982.5^{+1.8}_{-2.6} \pm 2.1 \ MeV$$

$$\Gamma_{Z_{cs}^0} = 7.7^{+4.1}_{-3.8} \pm 4.3 \ MeV$$

$$\Gamma_{Z_{cs}^-} = 12.8^{+5.3}_{-4.4} \pm 3.0 \ MeV$$

Clearly isospin partners

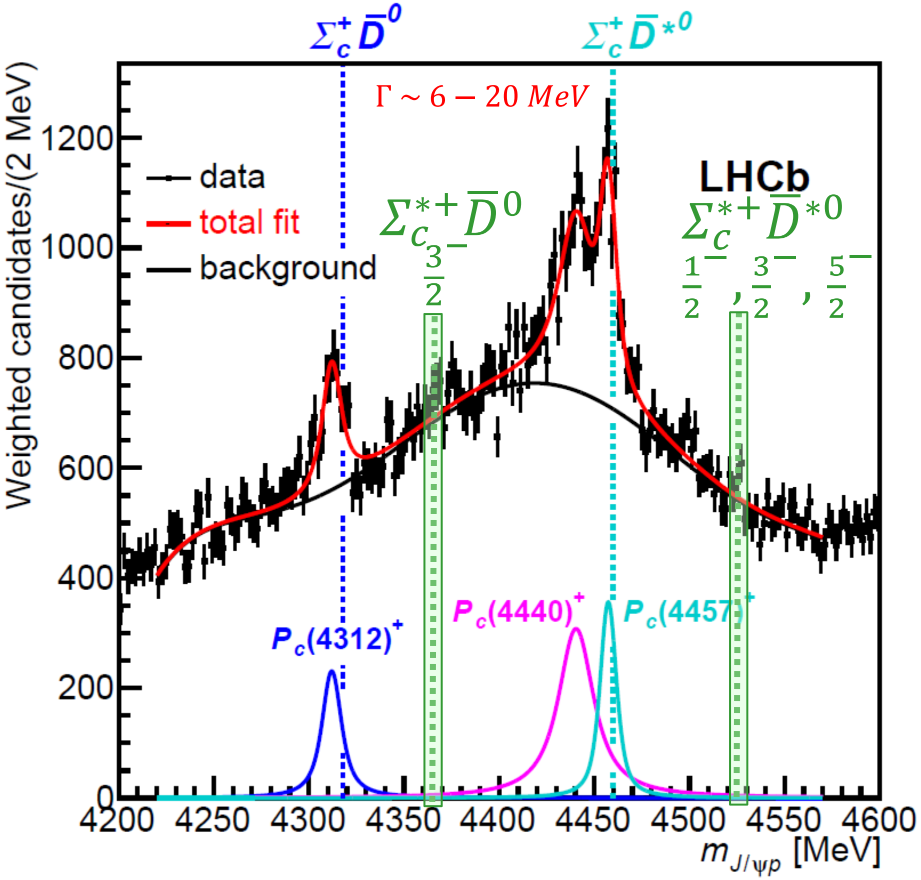
Narrow $P_{c(s)}^{+}$ states

LHCb 2019 PRL **122**, 222001

$pp \to \Lambda_b + \cdots$

$\Lambda_b \to (J/\psi p)K^+$

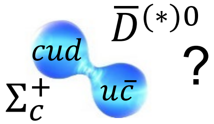
$246k\ \Lambda_b \to J/\psi p K^-$



Expected in molecular model:

$J^P = \frac{1}{2}^-$ for $\Sigma_c^+\bar{D}^0$ $(J^P_{\Sigma_c^+} = \frac{1}{2}^+, J^P_{D^0} = 0^-)$

$J^P = \frac{1}{2}^-, \frac{3}{2}^-$ for $\Sigma_c^+\bar{D}^{*0}$ $(J^P_{\Sigma_c^+} = \frac{1}{2}^+, J^P_{D^{*0}} = 1^-)$



Also expect 4 relatively narrow states $\Sigma_c^{*+}\bar{D}^{(*)0}$

?compact pentaquark

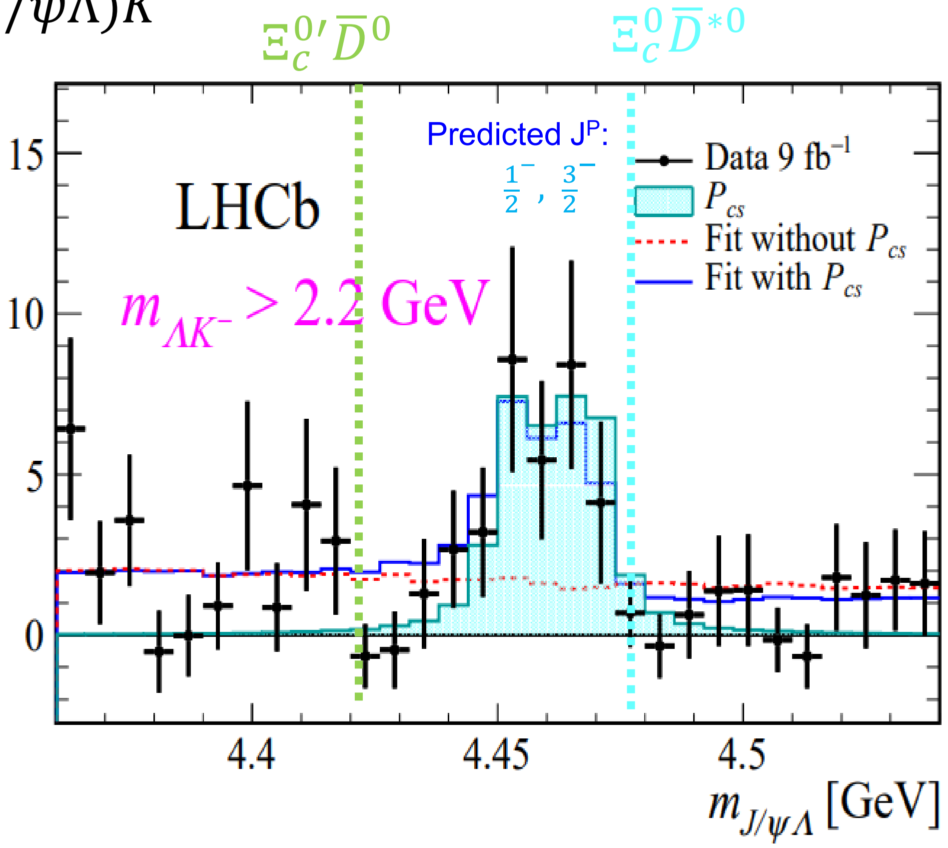
(mass spacing and narrow widths hard to explain)

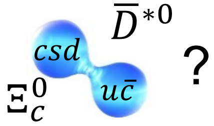
LHCb 2021 Science Bulletin 66, 1278 (2021)

$pp \to \Xi_b^- + \cdots$

$\Xi_b^- \to (J/\psi\Lambda)K^-$

$1.8k\ \Xi_b^- \to J/\psi\Lambda K^-$



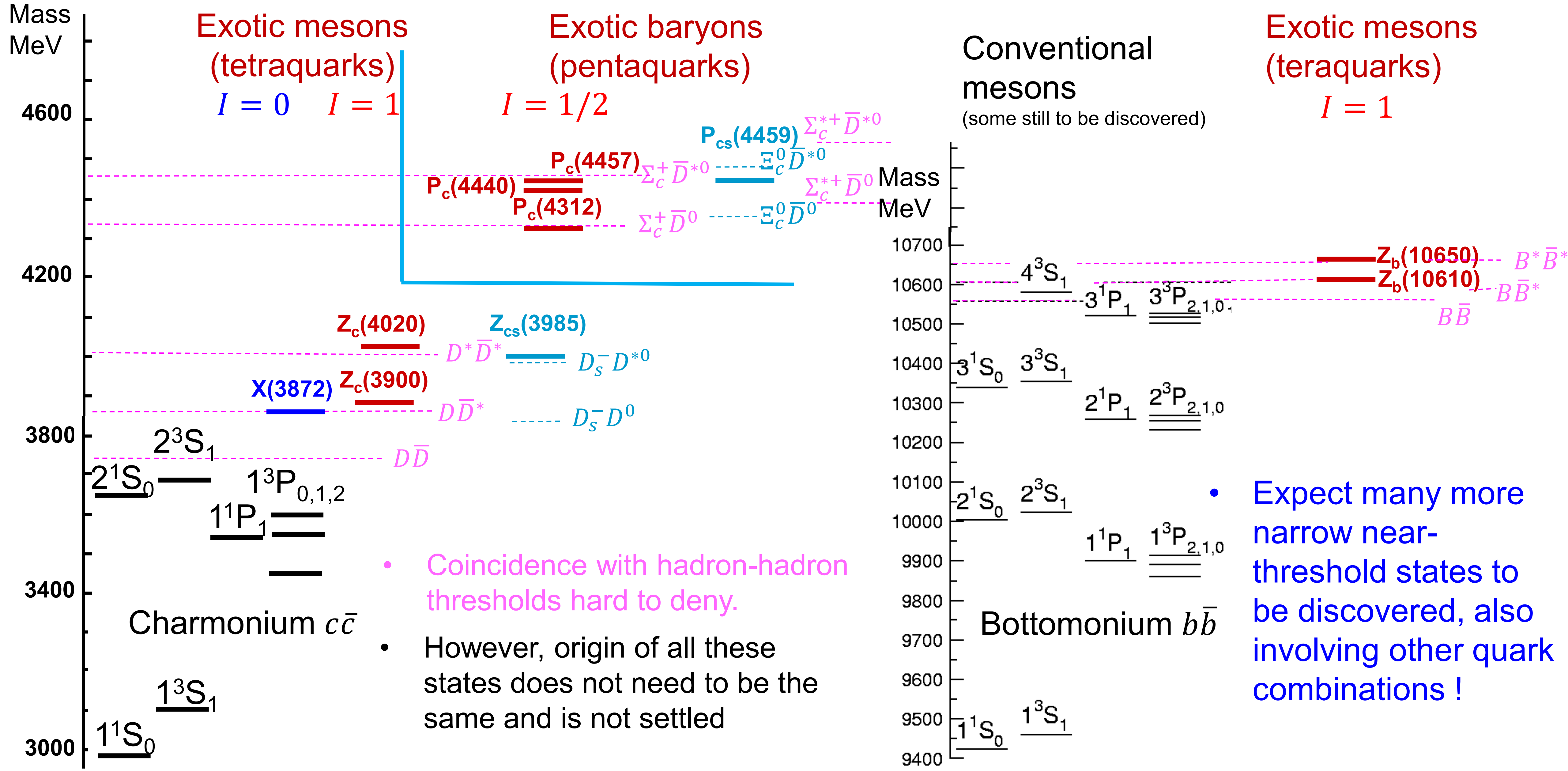


3σ evidence for a $J/\psi\Lambda$ mass structure

one or two states?

Need more data!

Narrow states near hadron-hadron thresholds



- Coincidence with hadron-hadron thresholds hard to deny.
- However, origin of all these states does not need to be the same and is not settled

- Expect many more narrow near-threshold states to be discovered, also involving other quark combinations !

Not all heavy exotic hadrons are near hadron-hadron thresholds

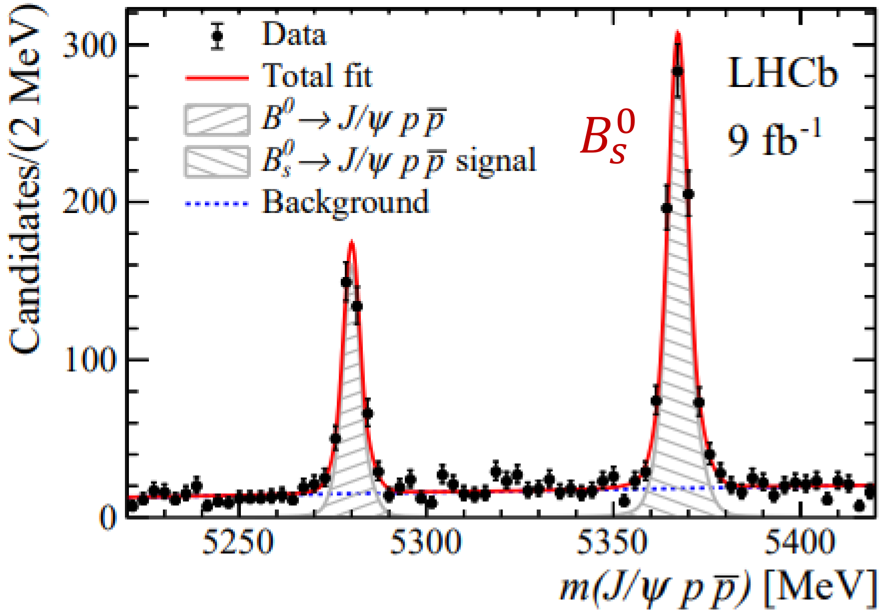
LHCb 2022 PRL **128**, 062001

$pp \rightarrow B_s^0 + \cdots$

$B_s^0 \rightarrow J/\psi p\bar{p}$

$0.8k\ B_s^0 \rightarrow J/\psi p\bar{p}$

4D amplitude analysis



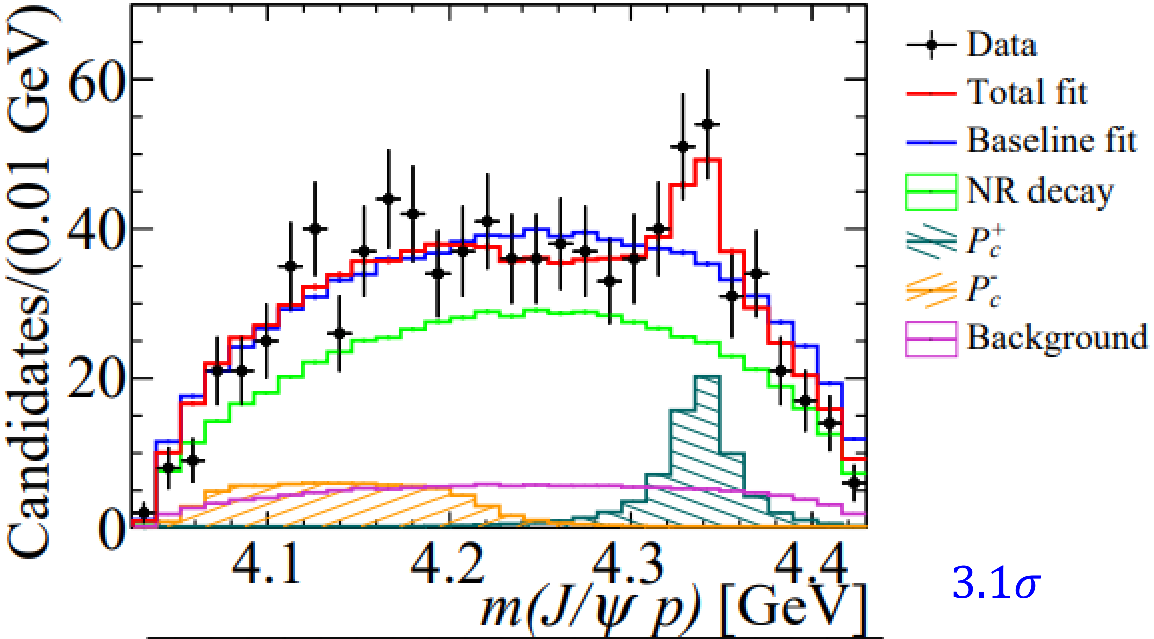
$$m_{P_c^+} = 4337^{+7}_{-4} \pm 2\ MeV$$

$$\Gamma_{P_c^+} = 29^{+26}_{-12}{}^{+14}_{-14}\ MeV$$

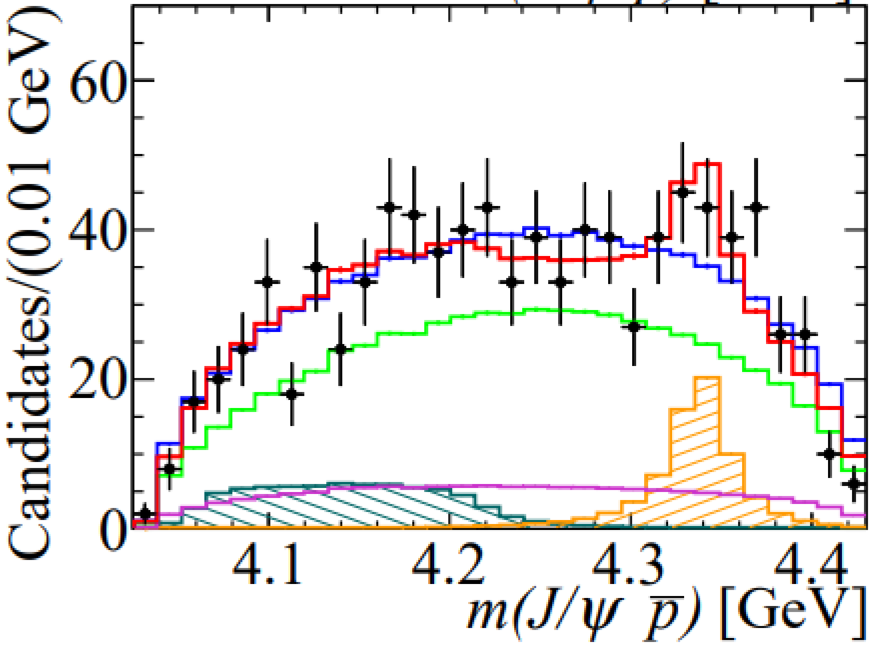
Not near any baryon-meson threshold

More than one mechanism to bind pentaquarks?

Need more data!



3.1σ

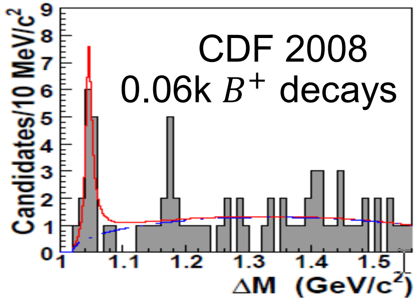


Many broader exotic states not near thresholds

$B^+ \to (J/\psi\phi)K^+$

$(cs)(\bar{c}\bar{s})$ tetraquarks?

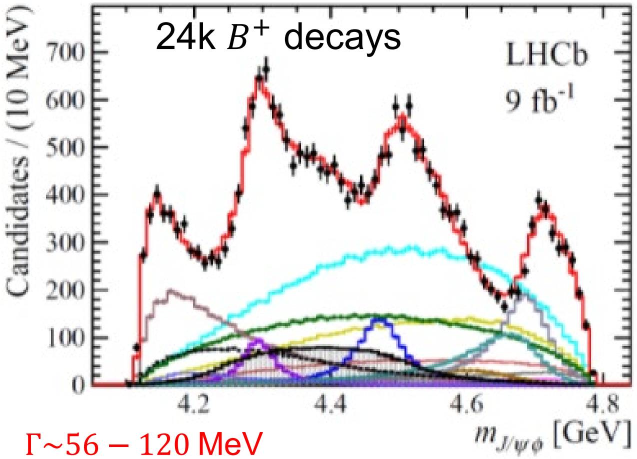
$3,4\,^3P_{1,0}$ $(c\bar{c})$ in the mix?



CDF 2008

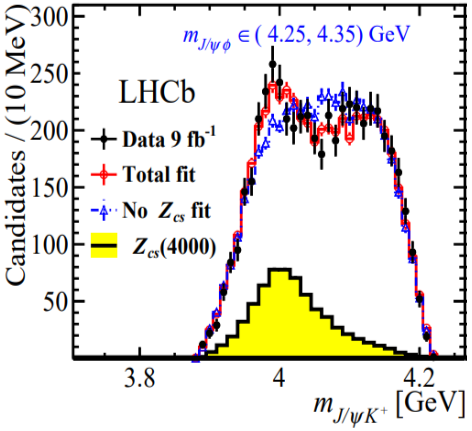
0.06k B^+ decays

PRL127, 082001 (2021)



24k B^+ decays

Γ~56 – 120 MeV



$Z_{cs}(4000)^+$ significantly wider than $Z_{cs}(3985)^+$ from BESIII.

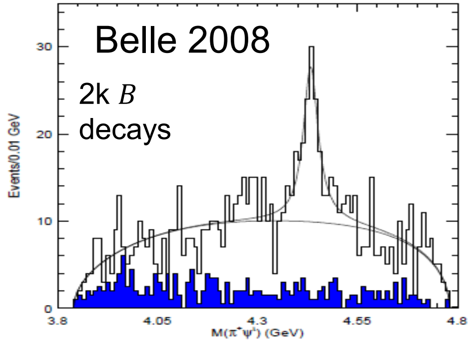
Likely different states with different dynamics.

Amplitude analysis reveals large number of $J/\psi\phi$ states, and two $J/\psi K^+$ states ($Z_{cs}^+(4000)$, $Z_{cs}^+(4216)$)

A lot of $c\bar{c}q\bar{q}$ structures. Amplitude analyses very complex, but still naïve, since coupled-channels ($D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)}$) neglected.

$B \to (\psi(2S)\pi^+)K$

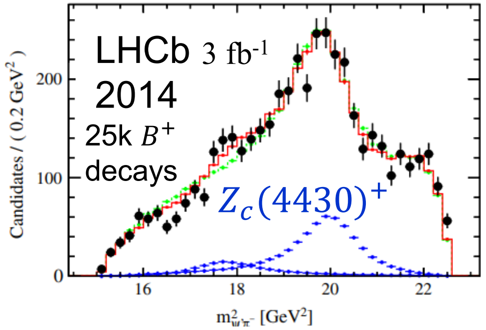
$(cu)(\bar{c}\bar{d})$ tetraquark?



Belle 2008

2k B decays

Γ~181 ± 31 MeV

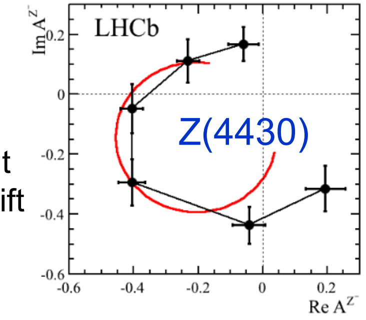


LHCb 3 fb^{-1} 2014

25k B^+ decays

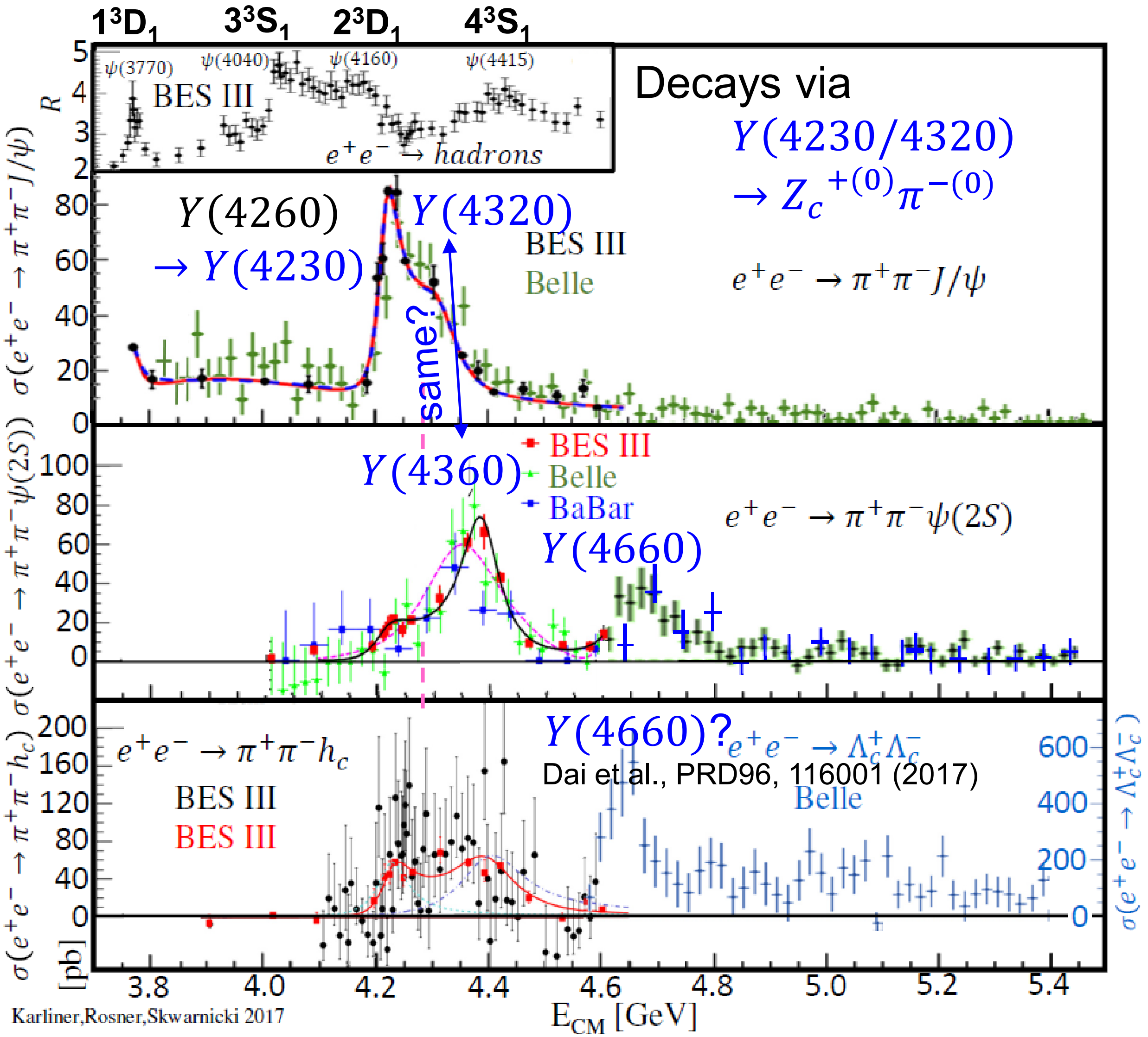
$Z_c(4430)^+$

Resonant phase-shift



Z(4430)

Anomalous charmonium-like vector states



Decays via $Y(4230/4320)$ $\to Z_c{}^{+(0)}\pi^{-(0)}$

$Y(4260)$ $\to Y(4230)$

$Y(4320)$

same?

$Y(4360)$

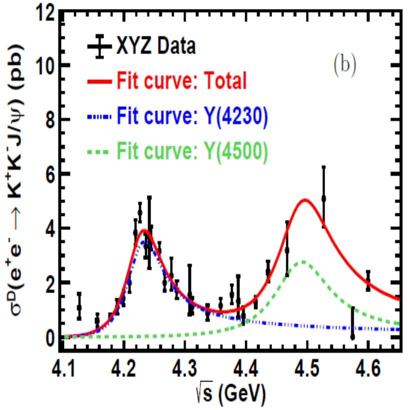
$Y(4660)$

$Y(4660)$?

Dai et al., PRD96, 116001 (2017)

Karliner,Rosner,Skwarnicki 2017

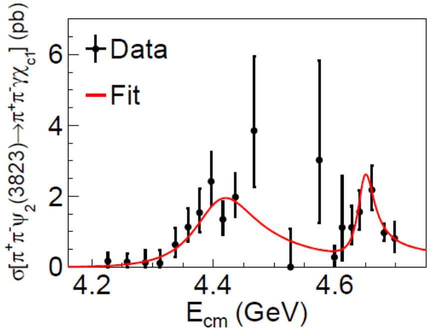
$e^+e^- \to K^+K^-J/\psi$



BESIII arXiv:2204.07800

$$4225.3 \pm 2.3 \pm 21.5\ \ MeV$$
$$\Gamma = 72.9 \pm 6.1 \pm 30.8\ \ MeV$$
$$4484.7 \pm\ \ 13.3 \pm 24.1\ \ MeV$$
$$\Gamma = 111.1 \pm 30.1 \pm 15.2\ \ MeV$$

$e^+e^- \to \pi^+\pi^-\psi_2(3823)$



BESIII arXiv:2203.05815

$$4406.9 \pm 17.2 \pm 4.5\ \ MeV$$
$$\Gamma = 128.1 \pm 37.2 \pm 2.3\ \ MeV$$
$$4647.9 \pm\ \ 8.6 \pm 0.8\ \ MeV$$
$$\Gamma = 33.1 \pm 18.6 \pm 4.1\ \ MeV$$

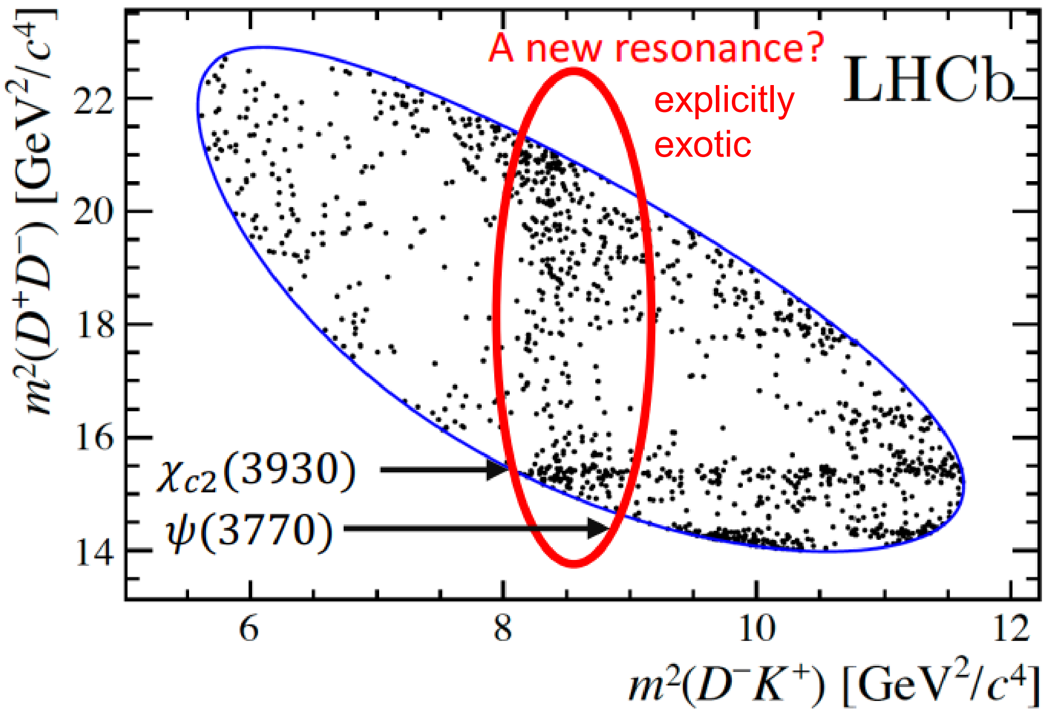
$gc\bar{c}$ hybrid states?,
$(cd)(\bar{c}\bar{d})$ tetraquarks,…?

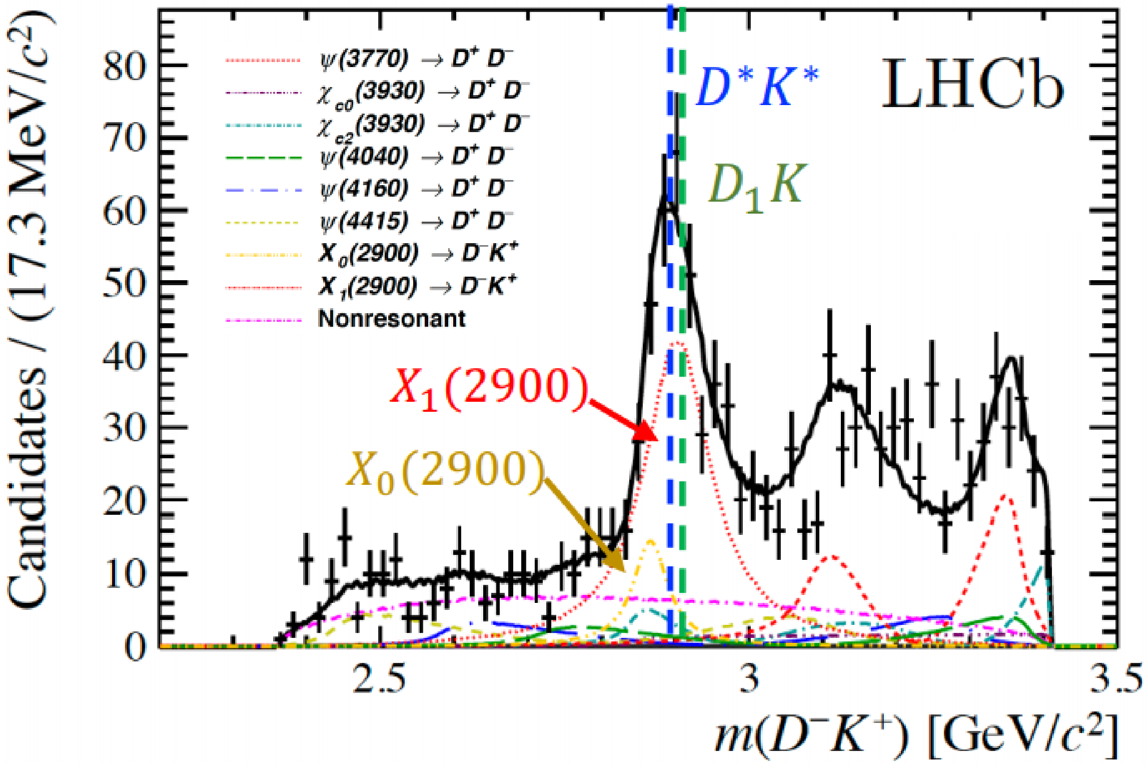
Charming and strange exotic states

LHCb 9 fb^{-1} PRD102, 112003 (2020) amplitude analysis
PRL 125, 242001 (2020) model-independent

1.3k $B^+ \to D^+D^-K^+$

Amplitude analysis

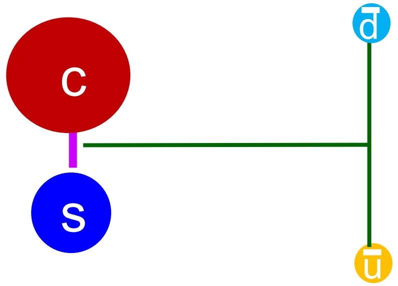




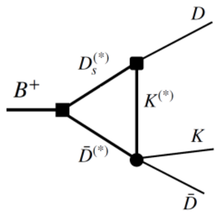
$X_0(2900):\quad M = 2.866 \pm 0.007 \pm 0.002\,\mathrm{GeV}/c^2,\quad \Gamma = 57 \pm 12 \pm 4\,\mathrm{MeV}$

$X_1(2900):\quad M = 2.904 \pm 0.005 \pm 0.001\,\mathrm{GeV}/c^2,\quad \Gamma = 110 \pm 11 \pm 4\,\mathrm{MeV}$

- The 0^+ $X_0(2900)$ state is a good candidate for a “nearly”-doubly-heavy tetraquark

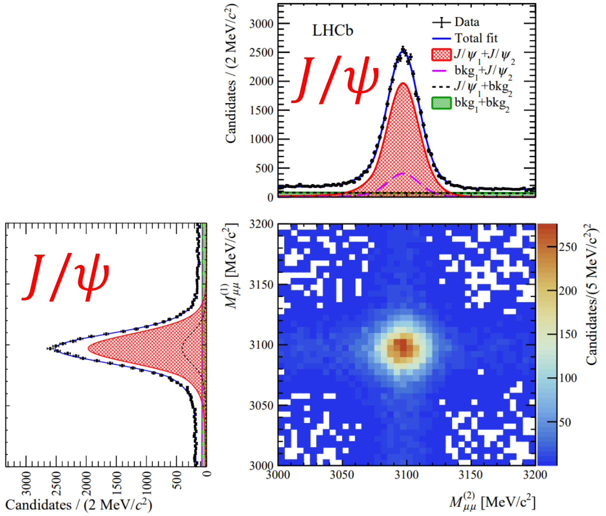


Proximity of the thresholds motivates other explanations - molecular or triangle diagrams

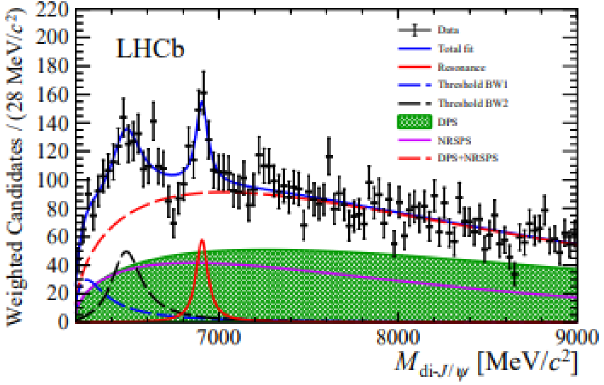


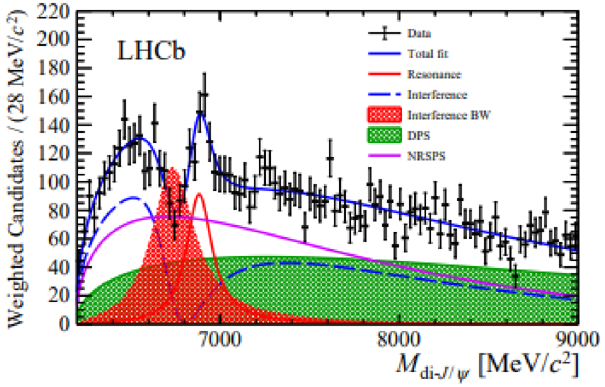
Hidden double-charm tetraquarks ?

$pp \to (J/\psi \to \mu^+\mu^-)(J/\psi \to \mu^+\mu^-) + \cdots$ Science Bulletin 65, 1983 (2020), arXiv:2006.16957 9 fb^{-1}

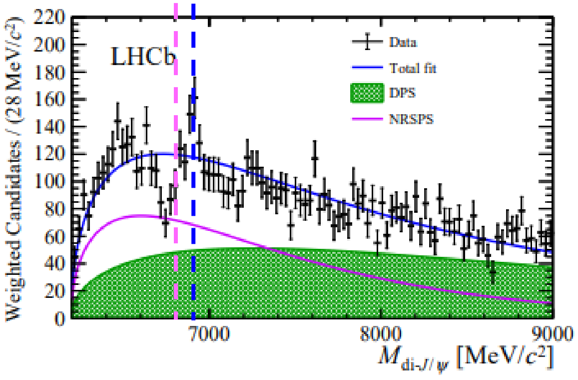


$T_{cc}(6900)$



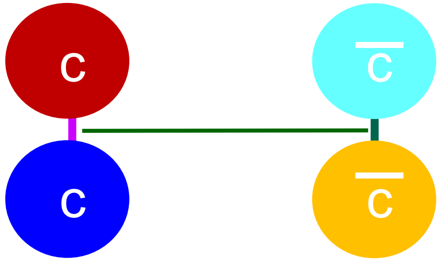


$J/\psi\psi'$ $J/\psi\psi''$

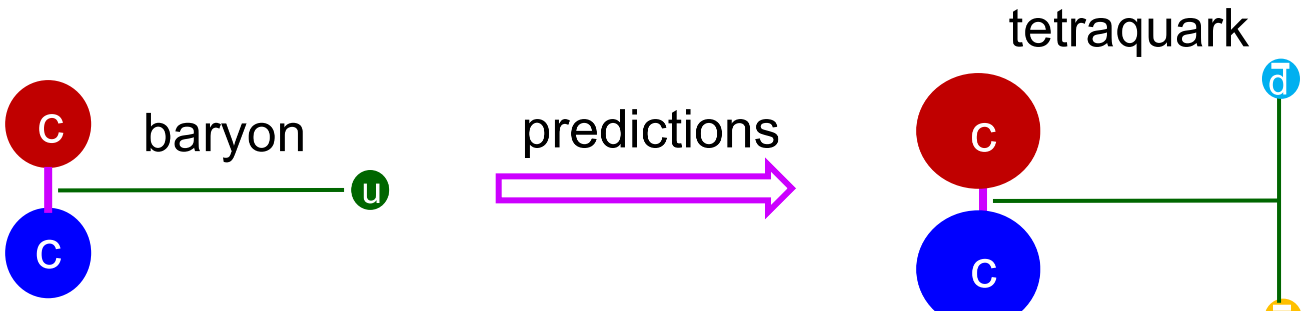


- Very significant structure in J/ψJ/ψ mass
- Interpretation of data is not clear:
  - One, or more (interfering?) resonances
  - X(6900) peak seems too wide to be loosely-bound (Γ~80 MeV or more), tightly-bound tetraquark state?
  - Possible effects due to nearby $J/\psi\psi'$, $J/\psi\psi''$ thresholds via coupled channel effects, see Dong,Baru,Fen-Kun Guo,Hanhart,Nefediev PRL 126,132001 (2021)
- Likely theoretical interpretation: $(cc)(\bar{c}\bar{c})$ tetraquark state(s), but the coupled channel effects may be important in shaping the mass spectrum

Tetraquark ?

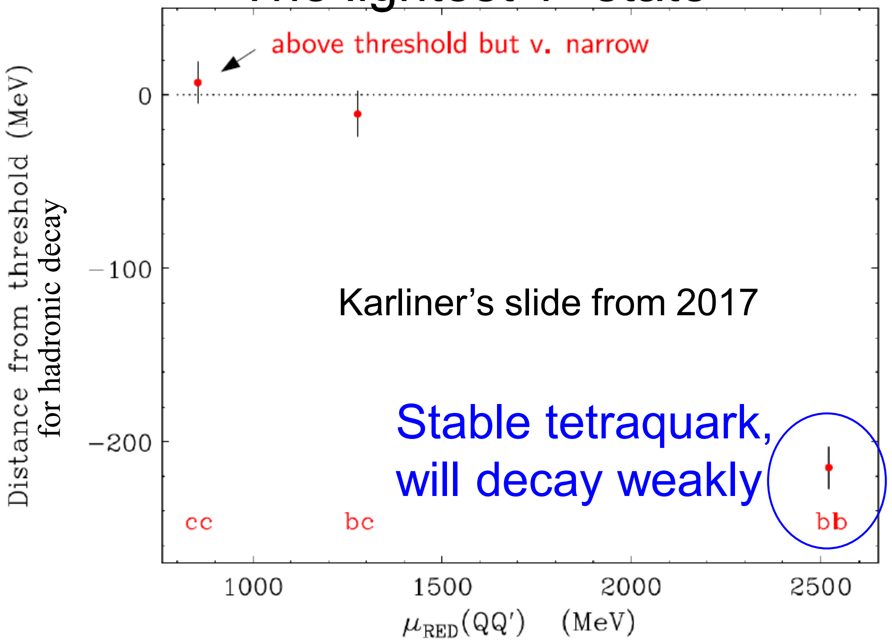


Stable tightly-bound $(bb)(\bar{u}\bar{d})$ teraquark?



Ξ_{cc}^{++} baryon observed by LHCb in 2017

The lightest 1⁺ state



Karliner's slide from 2017

Stable tetraquark, will decay weakly

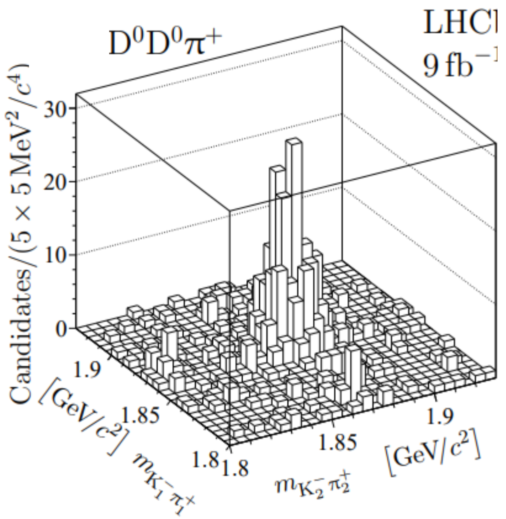
Karliner,Rosner PRL 119, 202001 (2017)
See also
Eighten, Quigg PRL 119, 202002 (2017)
Czarnecki, Leng, Voloshin PLB 778, 233 (2018)
Meng,Hiyama,Hosaka,Oka,Guber,Can,Takahashi,Zong PLB 814, 136095 (2021)

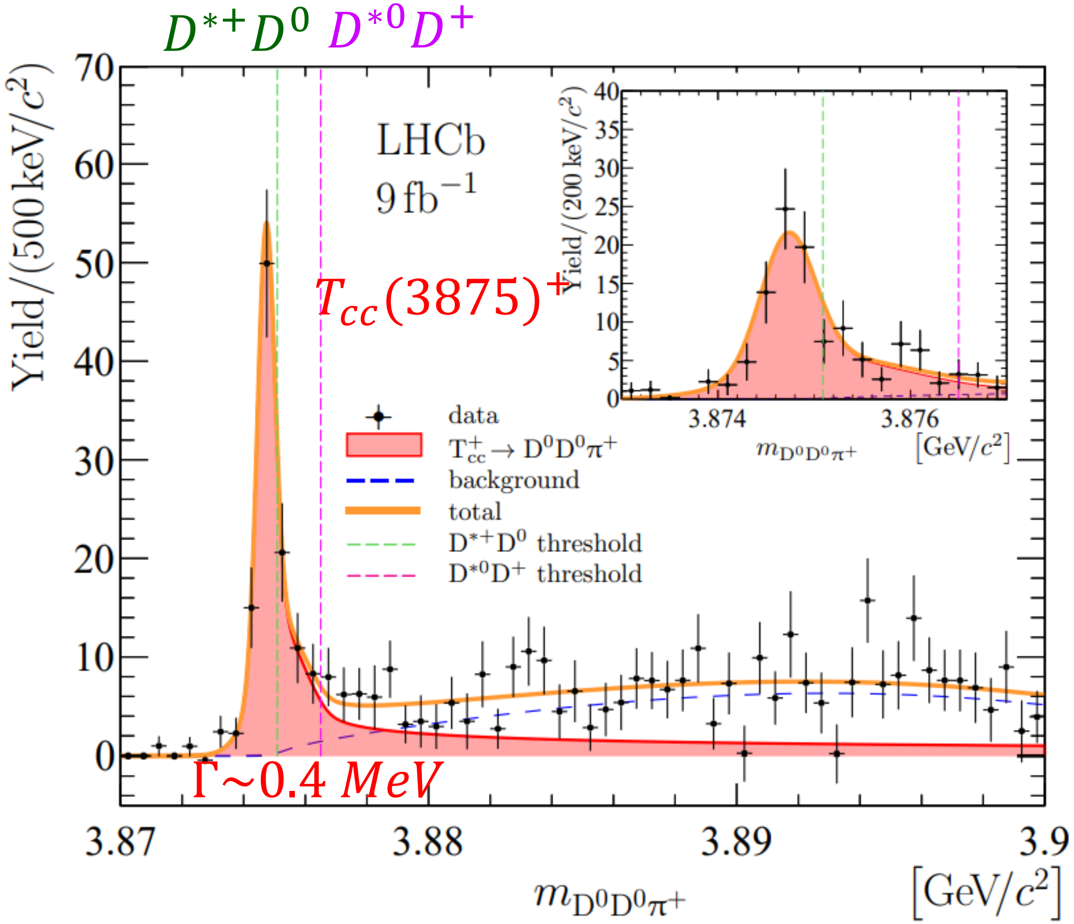
consistent results predicted by LQCD:
Francis,Hudspith,Lewis,Maltman
PRL 1118,142001 (2017)

Double-charm tetraquark

$$pp \to D^0(\to K^-\pi^+)D^0(\to K^-\pi^+)\pi^+ + \cdots$$

LHCb-PAPER-2021-031,-032
arXiv:2109.01038,2109.01113
Sept. 02, 2021





$M_{T_{cc}^+} = 2M_{D^0} + M_{\pi^+} + \sim$6MeV

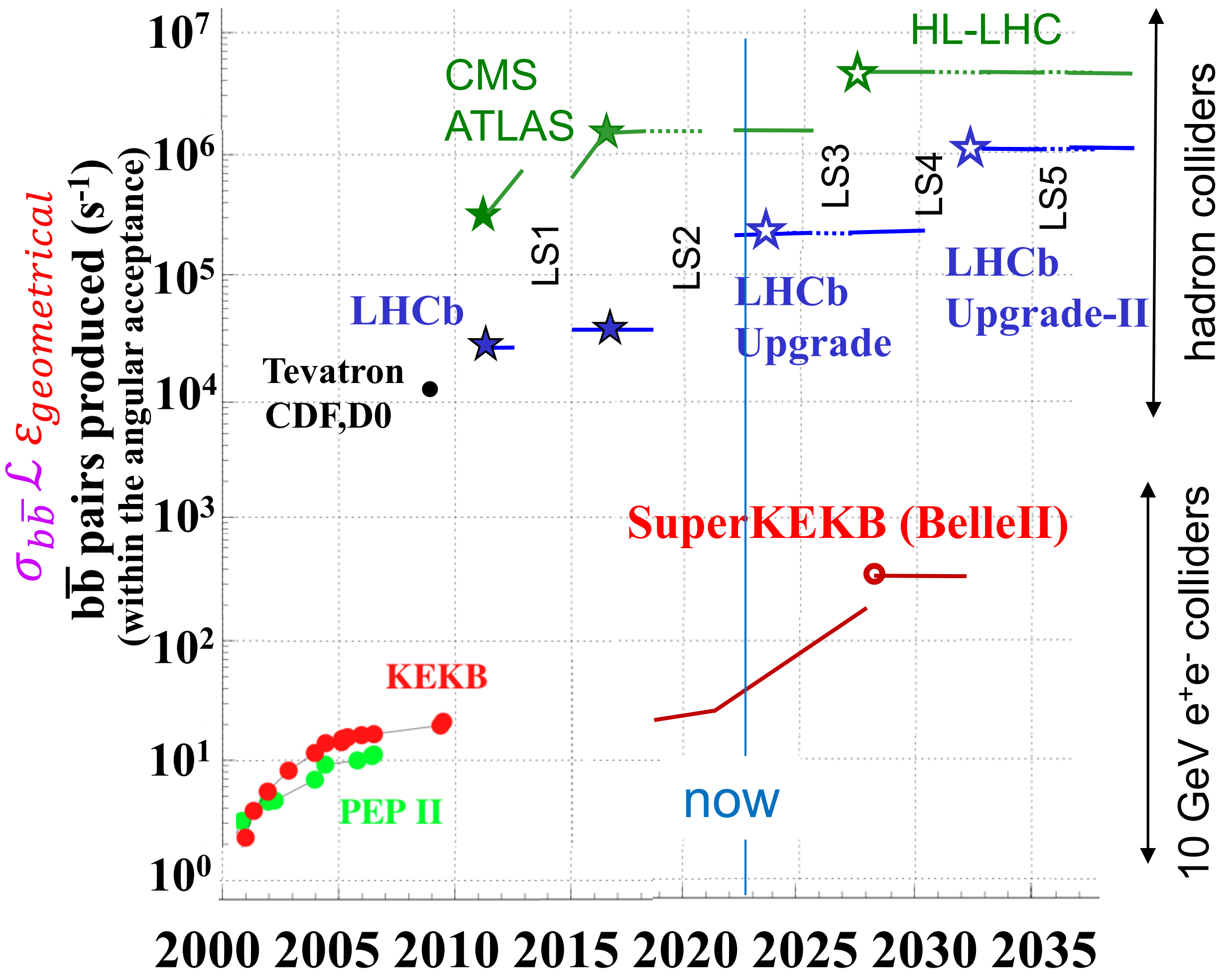
Very small phase-space for $D^0D^0\pi^+$, or any other strong decay

I=0 favored

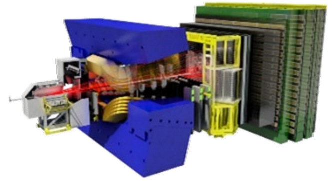
- Very narrow state, very close to the meson-meson threshold. It could be a loosely-bound $D^{*+/0}D^{0/+}$ state.
- Very little phase-space for any strong decay! It could also be a tightly-bound $(cc)(\bar{u}\bar{d})$ diquark state!
- Detecting $bb\bar{u}\bar{d}$ can separate these two mechanisms, but it will be very challenging experimentally. $bc\bar{u}\bar{d}$ easier?

Experimental prospects for the next decade

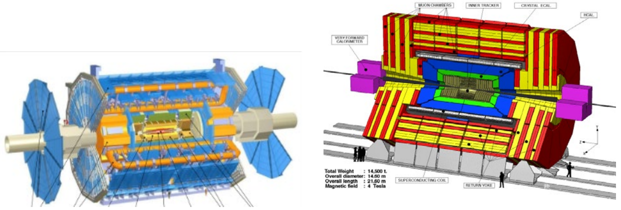
$b \rightarrow c$ major source of spectroscopic data on charm



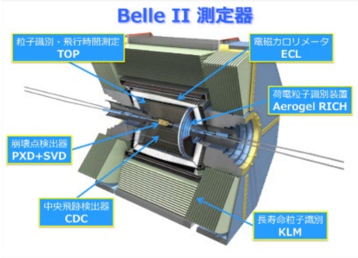
- Unique features of LHC:
  - enormous strong production rates (before trigger)
  - access to b-baryons (also serves pathway to charm pentaquarks)
  - access to doubly-flavored states ($b\bar{c}, ccq, cc\overline{qq}, cc\bar{c}\bar{c}$, …)
- Expect many new measurements/discoveries from LHCb
  - triggering optimized to flavor physics
  - good hadrons ID (π/K/p separation)



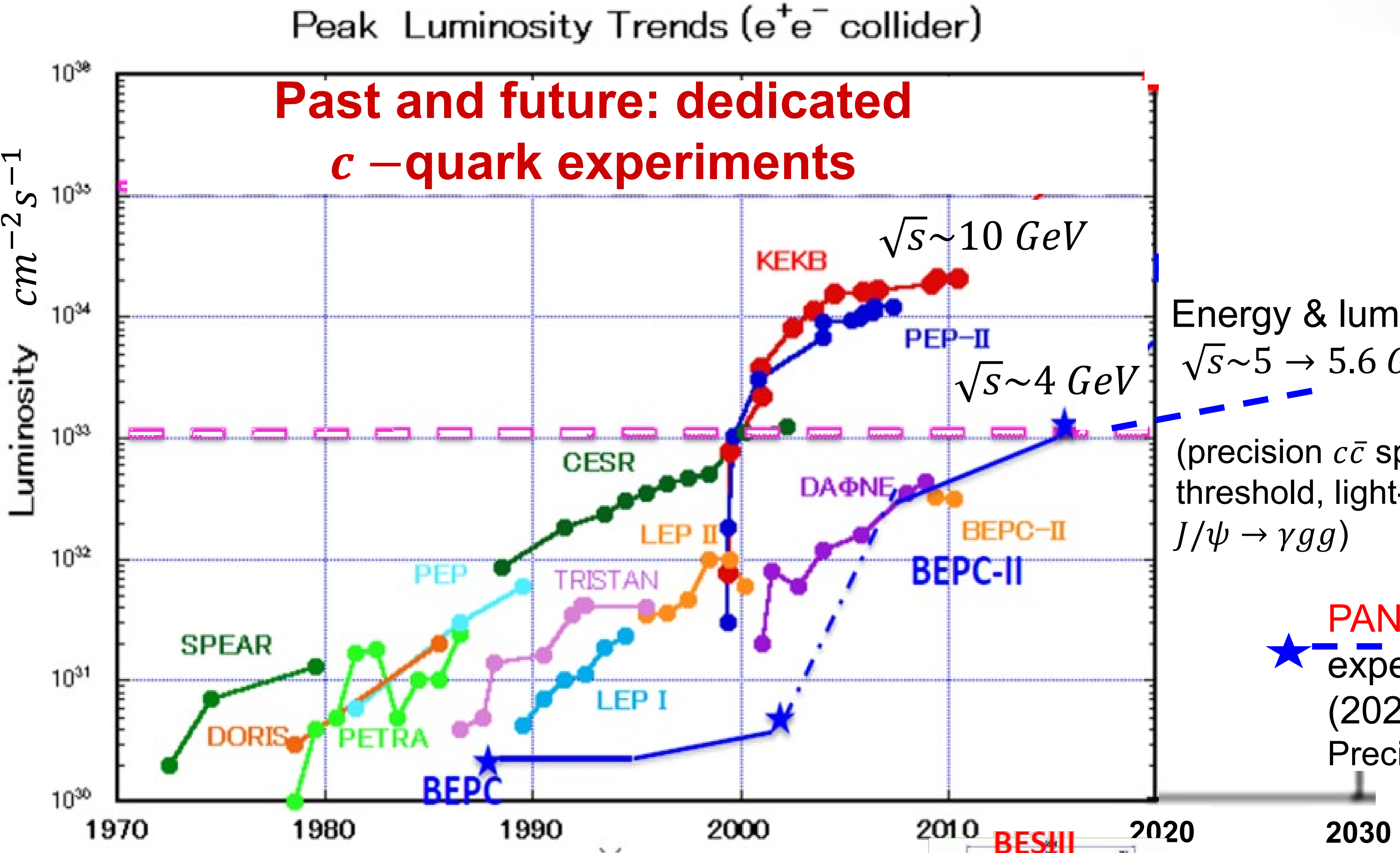
- ATLAS/CMS potential:
  - best flavor rates, but triggering on them is a challenge, no hadron ID
  - can be competitive in certain channels ($\mu^+\mu^-\mu^+\mu^-$?)
  - the only experiments which may have a chance to confirm some of LHCb claims



- Expect many new measurements/discoveries from Belle II. Unique features:
  - good γ, π^0, η detection
  - access to precision $b\bar{b}$ spectroscopy below and above $B\bar{B}$ threshold (via dedicated runs)
  - production also via $\gamma\gamma$ collisions, and $e^+e^- \rightarrow c\bar{c}c\bar{c}$



Past and future: dedicated c −quark experiments



Super Tau-Charm Factory
Proposed at Hefei and Novosibirsk
(in R&D phase)
energy up to $\sqrt{s}\sim 7\ GeV$

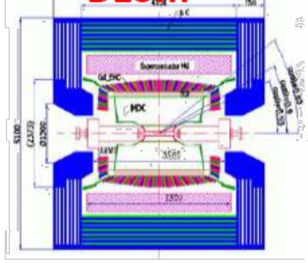
Energy & lumi upgrade
$\sqrt{s}\sim 5 \rightarrow 5.6\ GeV$

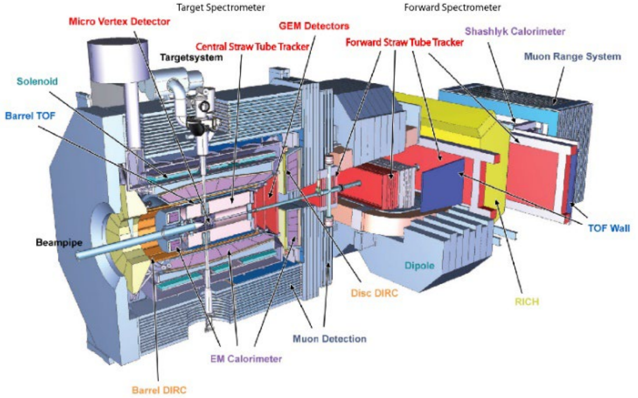
BES-III: highest luminosity $e^+e^- \rightarrow c\bar{c}$ experiment near the charm threshold

(precision $c\bar{c}$ spectroscopy below and above $D\bar{D}$ threshold, light-hadron spectroscopy including glue-rich $J/\psi \rightarrow \gamma gg$)

PANDA: highest luminosity $p\bar{p} \rightarrow c\bar{c}$ experiment near the charm threshold
(2025- ?)
Precision scans of charmonium-like states?

BESIII



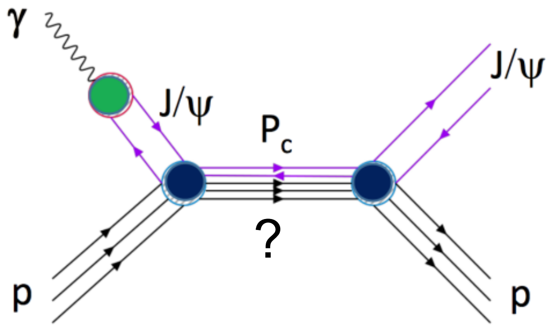


Experimental prospects at JLab and EIC

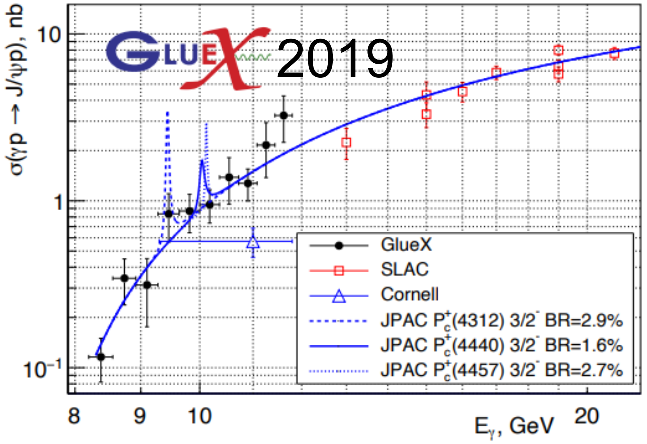
JLab: 12 GeV e$^-$ beam (2017-…)

Photoproduction of charmonium(-like) states

If detected offers a good insight into their substructure



Search for Pc states

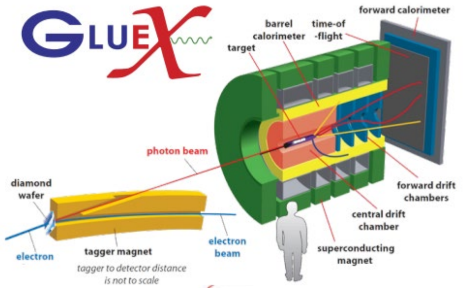


Statistical errors will be improved

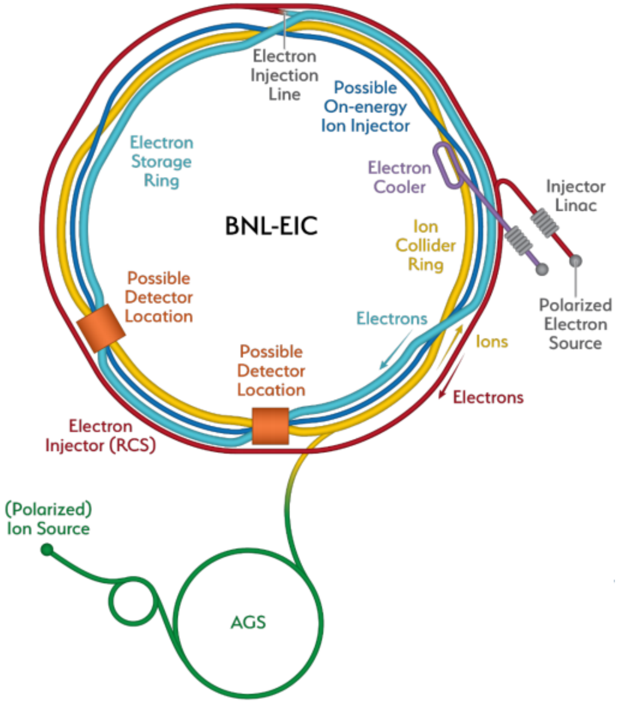
Search for light hybrid mesons

JLab upgrade to 20-24 GeV e$^-$ beam?

Would greatly increase a chance to detect charmonium-like states



Electron Ion Collider e$^-$p, e$^-$A (2030-…)



$$\sqrt{s} = 20 - 141\ \mathrm{GeV}$$

$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Photoproduction of charmonium exotics possible

Summary

- The experimental discoveries in the last two decades in the heavy flavor sector showed us that we understand very little from hadron spectroscopy.
- Many heavy hadron exotics are narrow, and near hadron-hadron thresholds, pointing to hadron-hadron interactions playing an important role in their creation (molecular states?)
- There are also many exotic hadron candidates not fitting this pattern, leaving room for tetraquark and pentaquark state tightly bound directly by color interactions (diquarks or other color schemes?)
- The states of mixed nature, certainly must exist too
- We need a broad spectroscopy program to continue:
  - in the coming decade LHCb upgrades are likely to produce the largest amount of experimental information in the biggest variety of heavy quark configurations
  - the BESIII, and later new tau-charm factory, have their own variety of charmonium-like states to study above the open charm threshold. They also have unique access to light hadron spectroscopy, including glueballs.
  - Belle II has similar unique access to bottomonium-like states
  - Photoproduction of charmonium-like states at JLab or EIC can play an important role, if such states are produced with sufficient rates