Heavy-flavor exotic hadrons: selected experimental highlights

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Status of our understanding of hadron spectroscopy

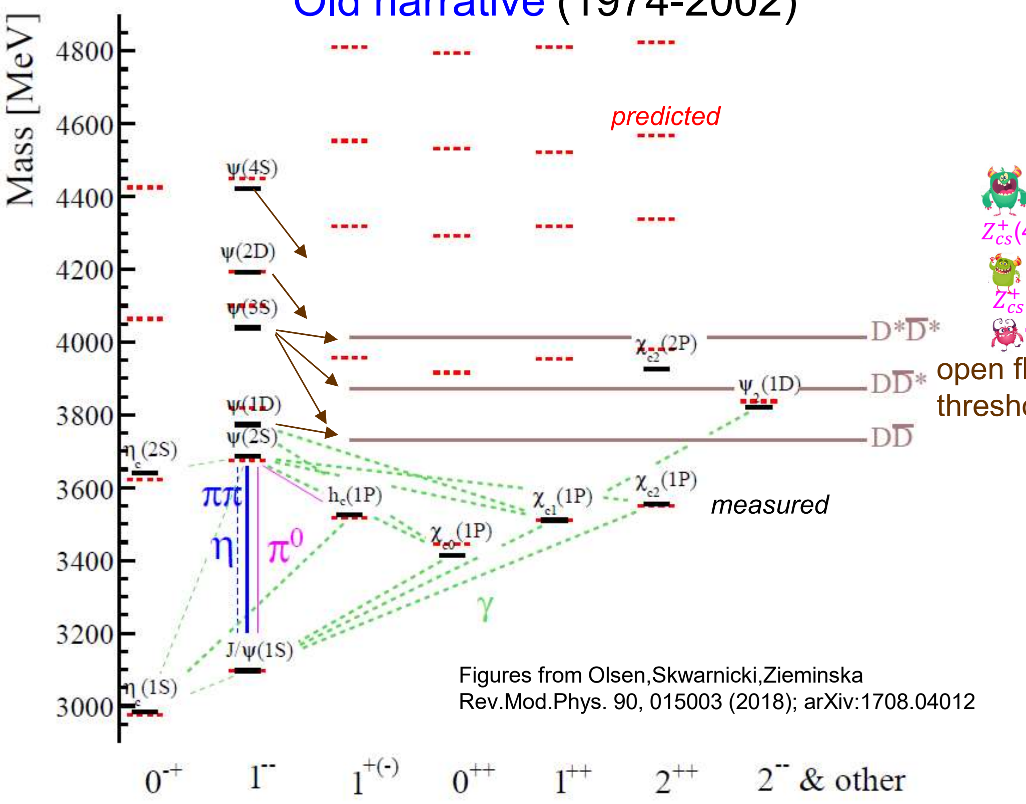
- We know the lightest hadrons in each quark configuration are predominantly bound states of $q\bar{q}$ or qqq
- We don't know if diquarks, strongly motivated by QCD, are good building blocks for more complex quark structures: $(qq)(\bar{q}\bar{q})$?, $(qq)(qq)\bar{q}$?, …
- We are not even sure about 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 $gq\bar{q}$?, $gqqq$?
- We are not sure if nuclear-type forces can bind mesons to other mesons or baryons ("molecular" states)

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 $bb\bar{u}\bar{d}$)

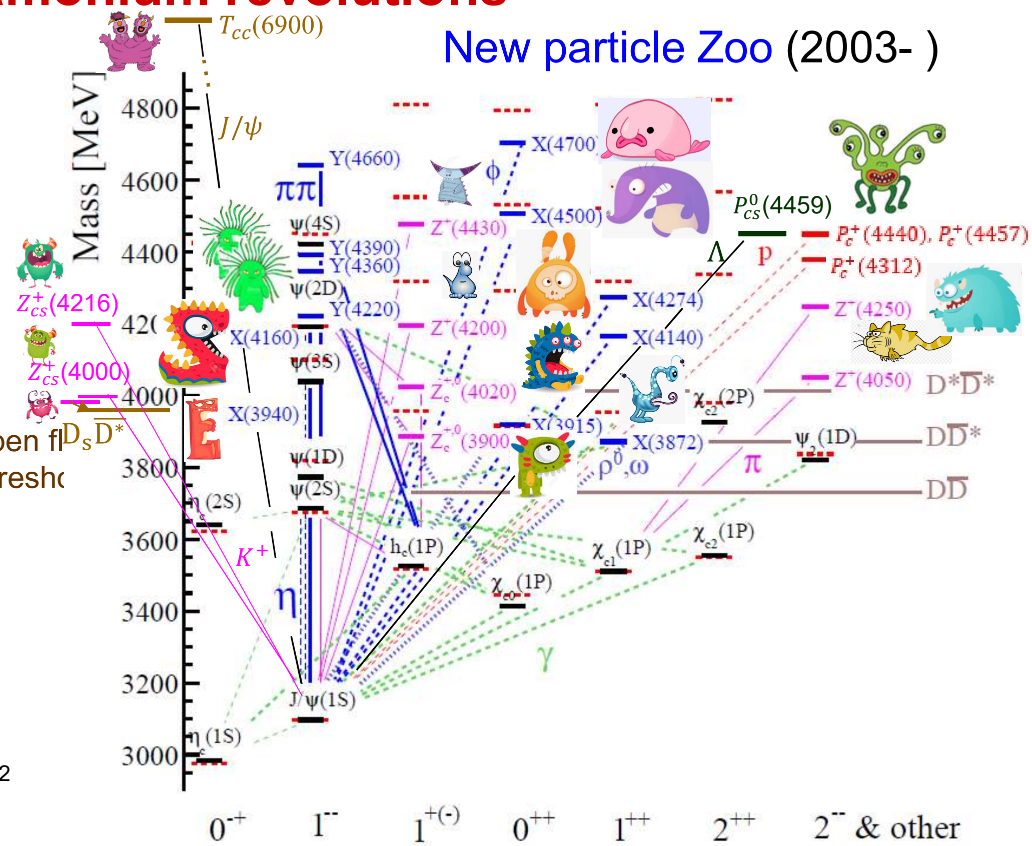
Why heavy flavor hadrons: two chamonium revolutions

Old narrative (1974-2002)



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

New particle Zoo (2003-)



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

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.

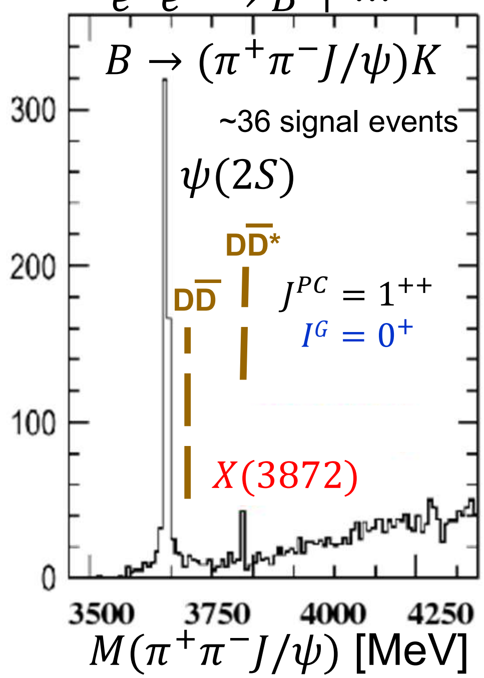
- Almost all excited states for light hadrons are above "open flavor threshold"

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 ? ($c\bar{c}$)

D^0 $\bar{D}^{*0}$? ($c\bar{u}$, $u\bar{c}$)

? diquark tetraquark (cu, $\overline{cu}$)
(narrow width hard to explain)

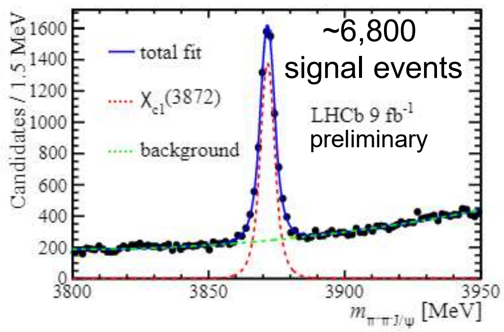
Large isospin violation rules out pure $c\bar{c}$ interpretation

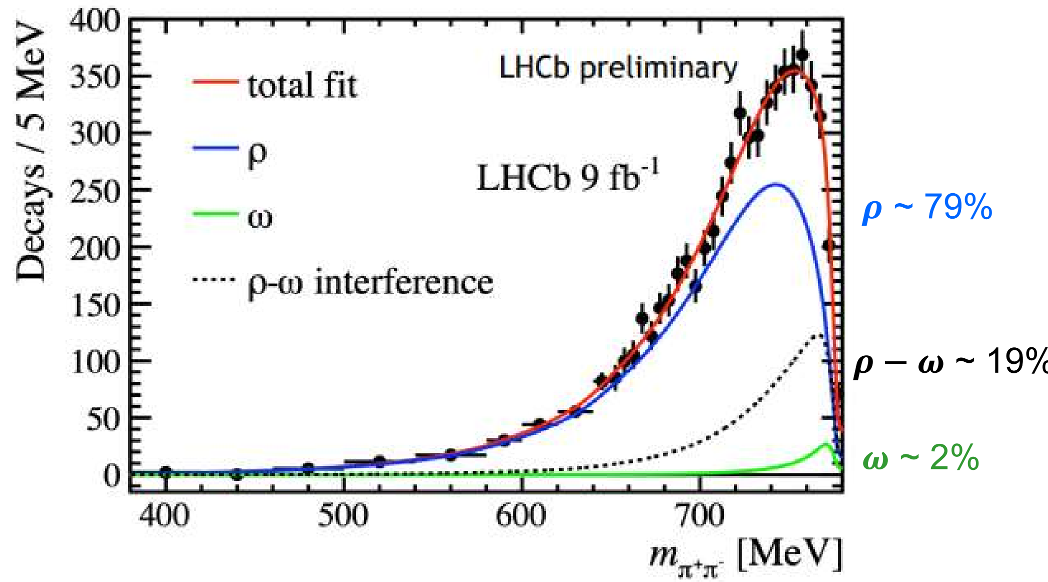
LHCb-PAPER-2021-045 in preparation (B. Batsukh Ph.D. thesis, Syracuse 2021)

see Chen Chen's talk at LP2021 Jan 11,22 for more details

$pp \to B^+ + \cdots$

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



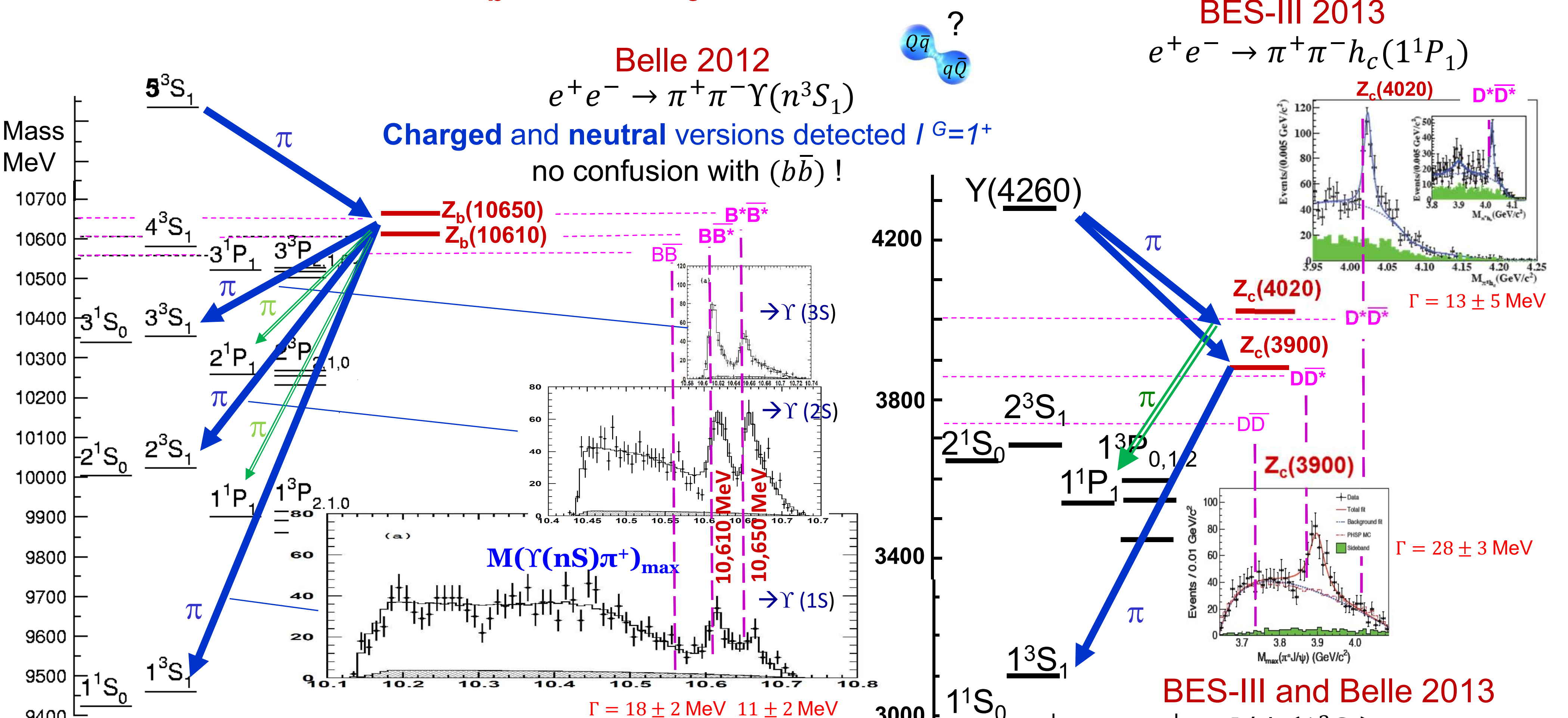


Isospin-violating / Isospin-conserving couplings

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

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

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



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.

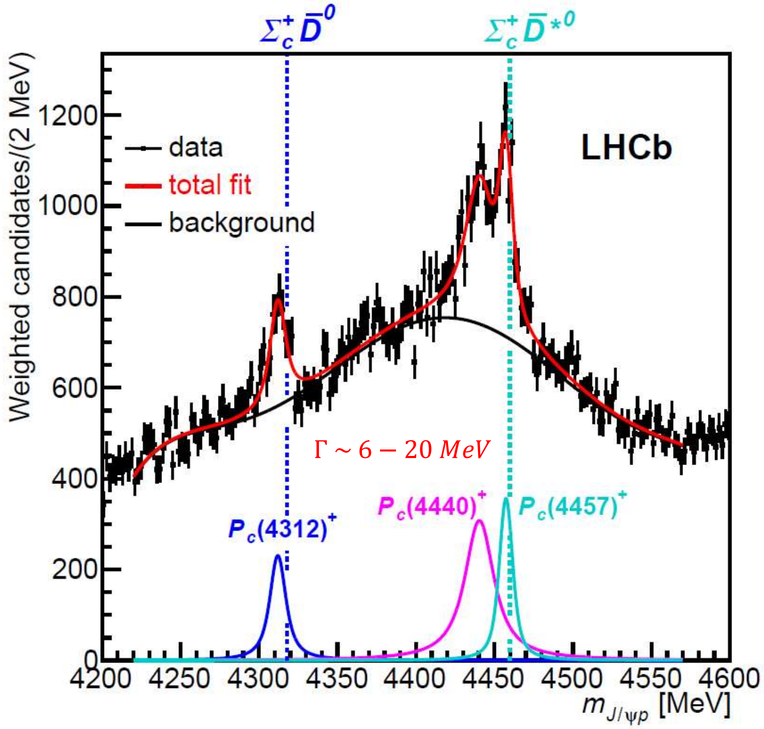
Coupled-channel fit (with $D\bar{D}^*$data) for $Z_c(3900)^+$, gives its pole mass slightly below the threshold.

Narrow P_c^+ states

LHCb 2019 PRL **122**, 222001

$pp \to \Lambda_b + \cdots$

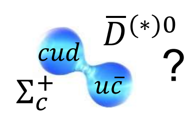
$\Lambda_b \to (p\, J/\psi)K^+$



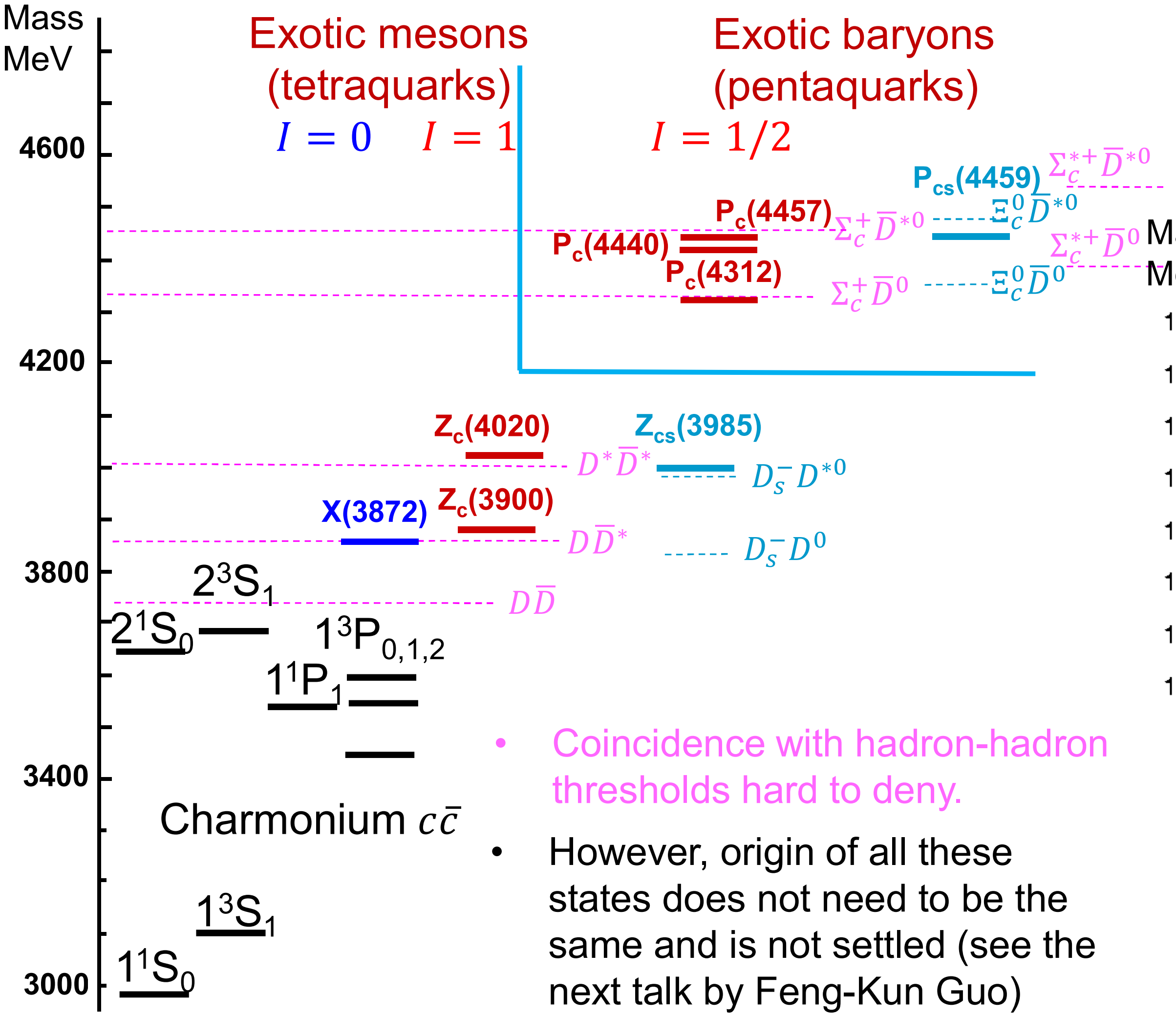
Expected in molecular model:

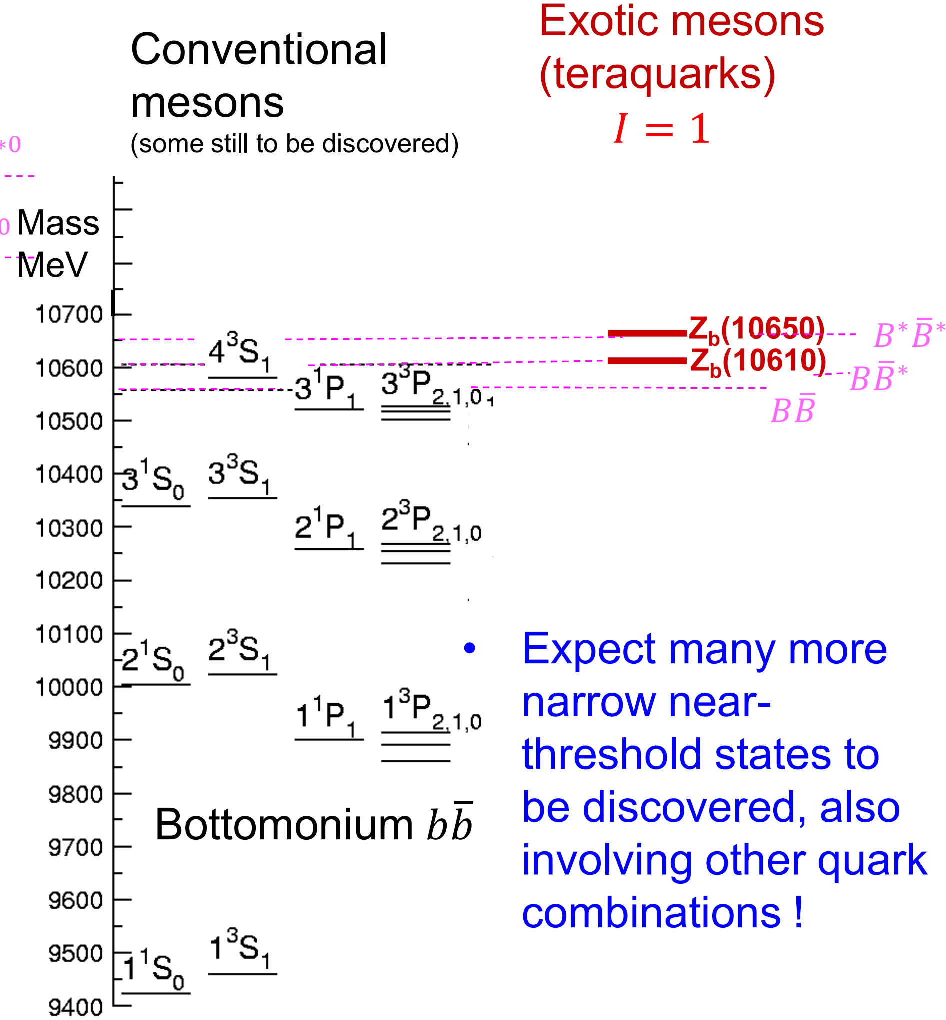
$J^P = \frac{1}{2}^-$ for $\Sigma_c^+ \bar{D}^0$ $(J^P_{\Sigma_c^+} = \frac{1}{2}^+, J^P_{D^0} = 0^-)$

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



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 (see the next talk by Feng-Kun Guo)

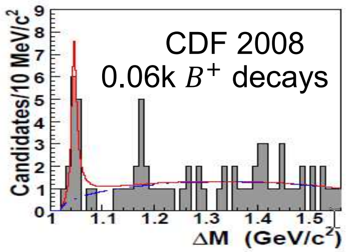
- Expect many more narrow near-threshold states to be discovered, also involving other quark combinations !

Many broader exotic states not near thresholds

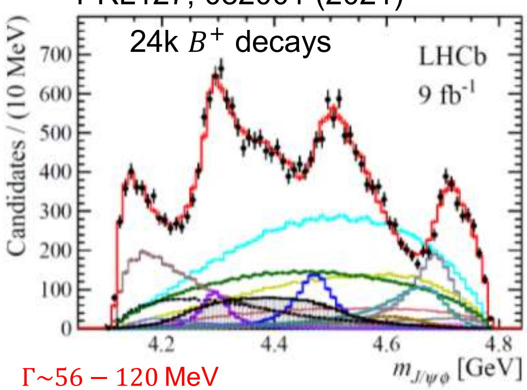
$B^+ \to (J/\psi\phi)K^+$

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

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



PRL127, 082001 (2021)

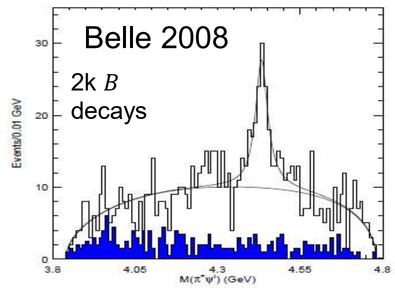


$\Gamma \sim 56 - 120$ MeV

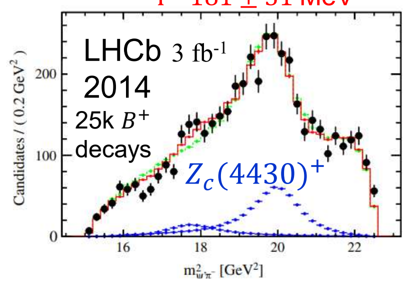
Amplitude analysis reveals large number of $J/\psi\phi$ states, and two $J/\psi K^+$ states ($Z_{cs}^+(4000)$, $Z_{cs}^+(4216)$)

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

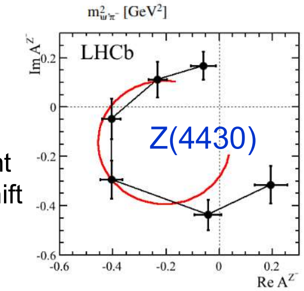
$(cu)(\bar{c}\bar{d})$ tetraquark?



$\Gamma \sim 181 \pm 31$ MeV

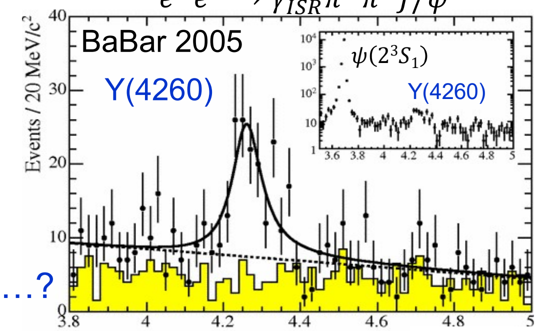


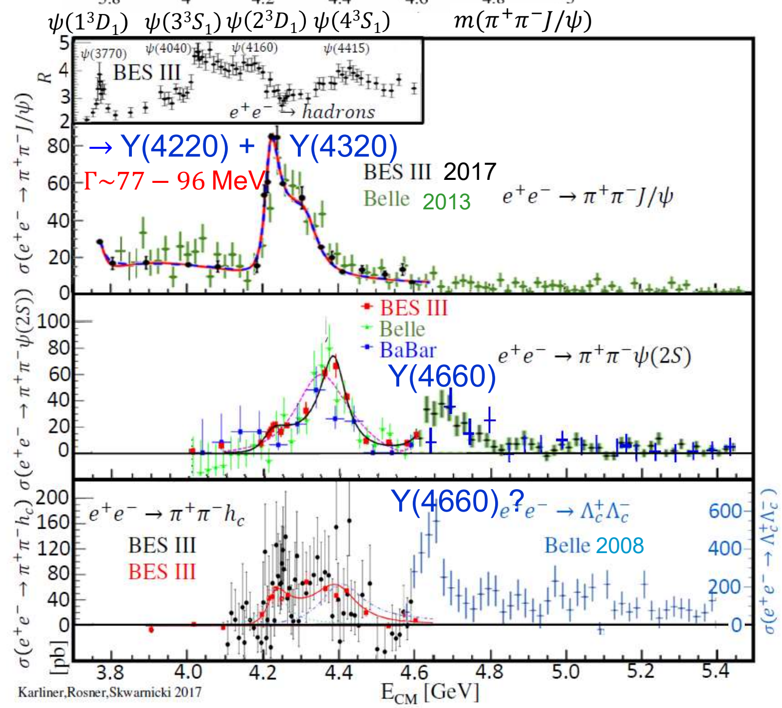
Resonant phase-shift



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

$e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$

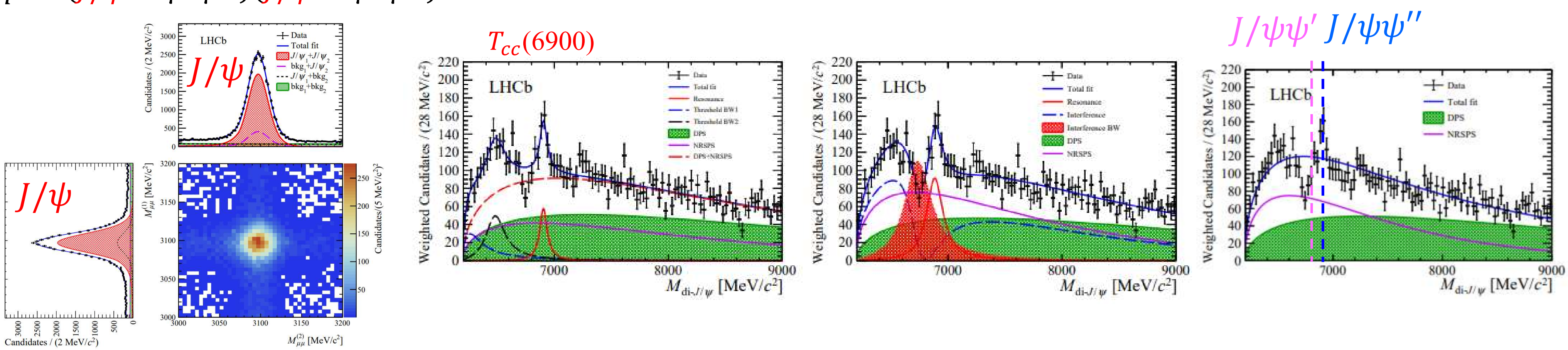




A lot of $c\bar{c}q\bar{q}$ structures. Amplitude analyses very complex, but still naïve, since coupled-channels $(D_{(s)}^{(*)}\bar{D}_{(s)}^{(*)})$ neglected.

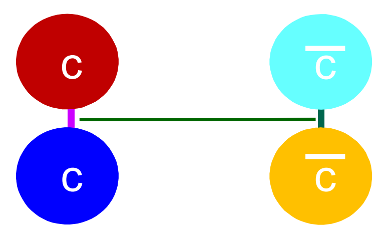
Hidden double-charm tetraquarks ?

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

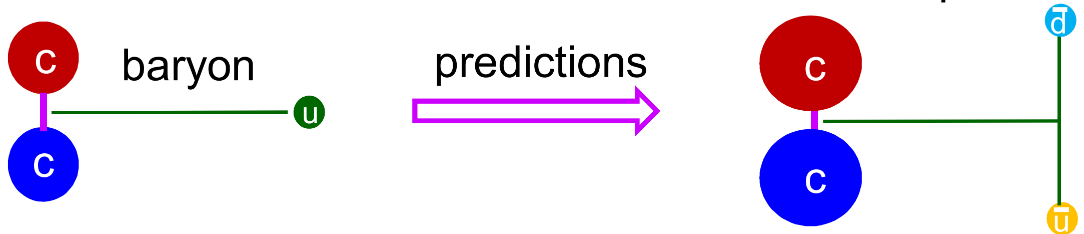


- Very significant structure in J/ψJ/ψ mass
- Interpretation of data is not clear:
  - One, or more (interfering?) resonances
  - X(6900) peak seems too wide to be loosely-bound (Γ~80 MeV or more), tightly-bound tetraquark state?
  - Possible effects due to nearby $J/\psi\psi'$, $J/\psi\psi''$ thresholds 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 ?

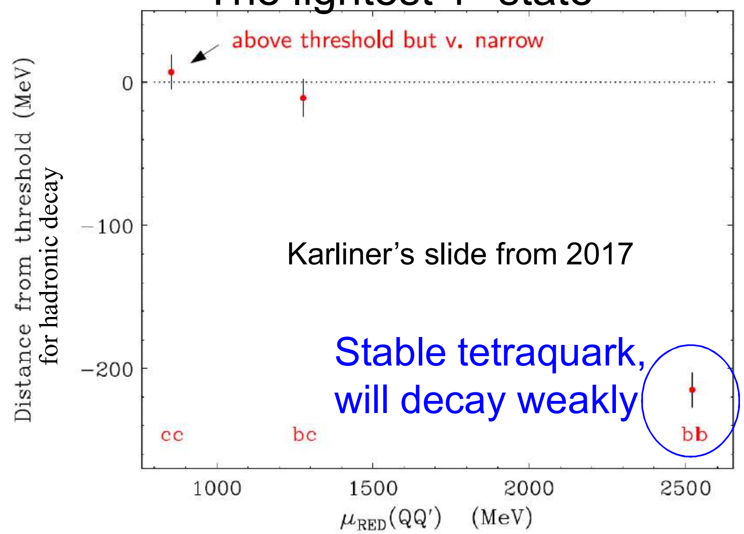


Stable tightly-bound $(bb)(\bar{u}\bar{d})$ teraquark?



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

The lightest 1+ state



Karliner,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)

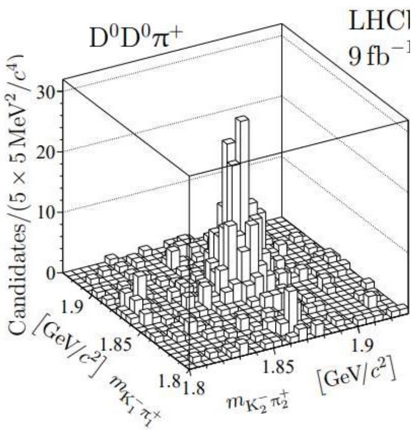
consistent results predicted by LQCD:
Francis,Hudspith,Lewis,Maltman
PRL 1118,142001 (2017)

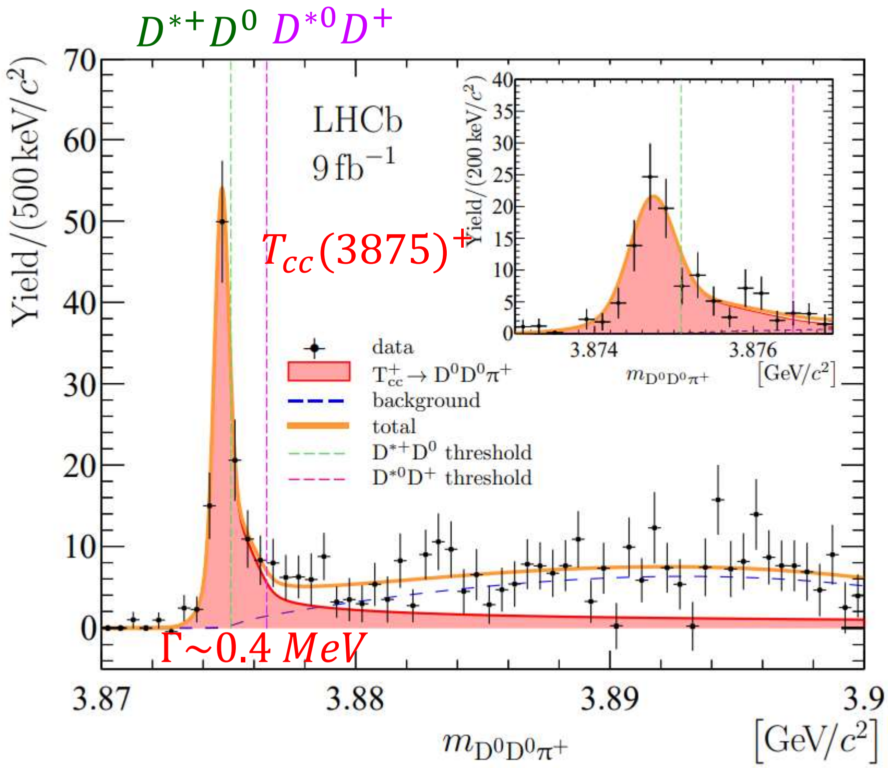
See the talk by Atsushi Hosaka yesterday!

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





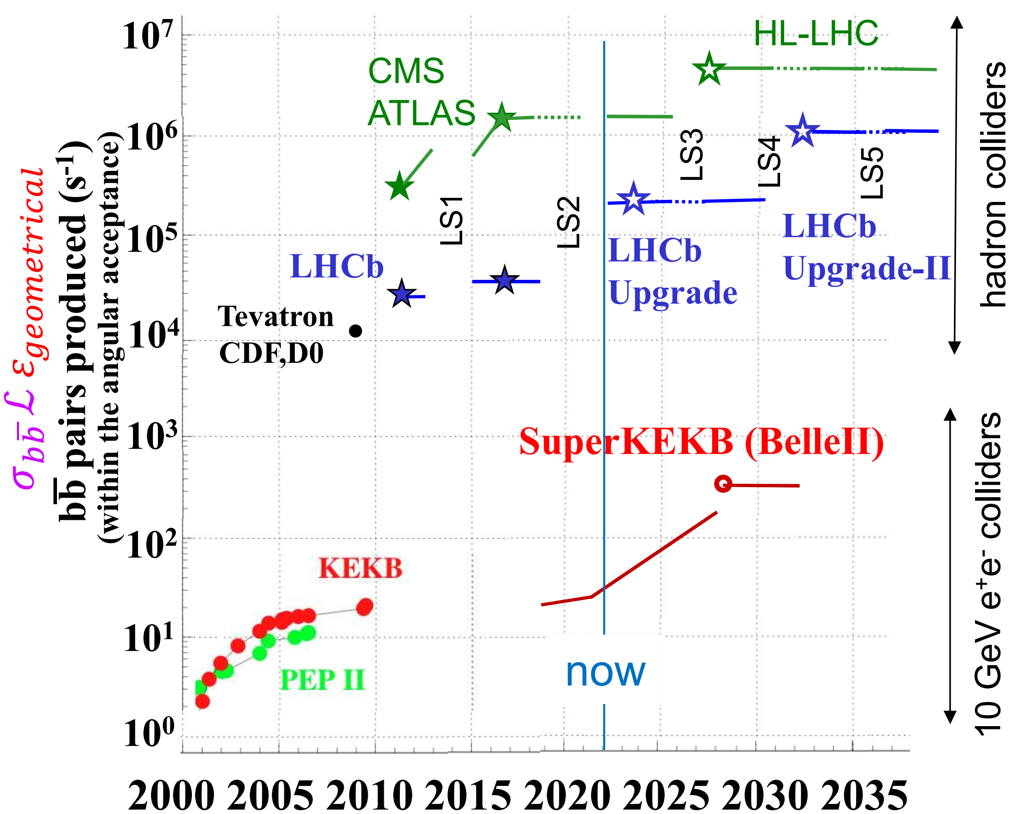
I=0 favored

$M_{T_{cc}^+} = 2M_{D^0} + M_{\pi^+} + \sim$6MeV
Very small phase-space for $D^0D^0\pi^+$, or any other strong decay

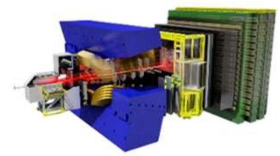
- Very narrow state, very close to the meson-meson threshold. It could be a loosely-bound $D^{*+/0}D^{0/+}$ state.
- Very little phase-space for any strong decay! It could also be a tightly-bound $(cc)(\bar{u}\bar{d})$ diquark state!
- Detecting $bb\bar{u}\bar{d}$ can separate these two mechanisms (Hosaka's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

Experimental prospects for the next decade

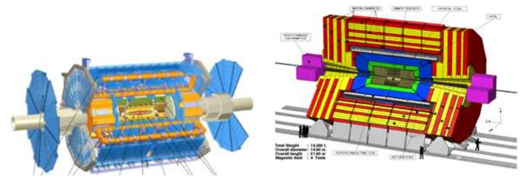
$b \to c$ major source of spectroscopic data on charm



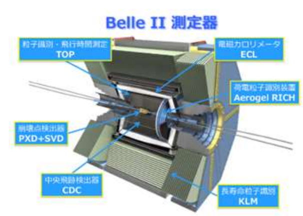
- Unique features of LHC:
  - enormous production rates (before trigger)
  - access to b-baryons (also serves pathway to charm pentaquarks)
  - access to doubly-flavored states ($b\bar{c}, ccq, cc\bar{c}\bar{c}, \ldots$)
- Expect many new measurements/discoveries from LHCb
  - triggering optimized to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

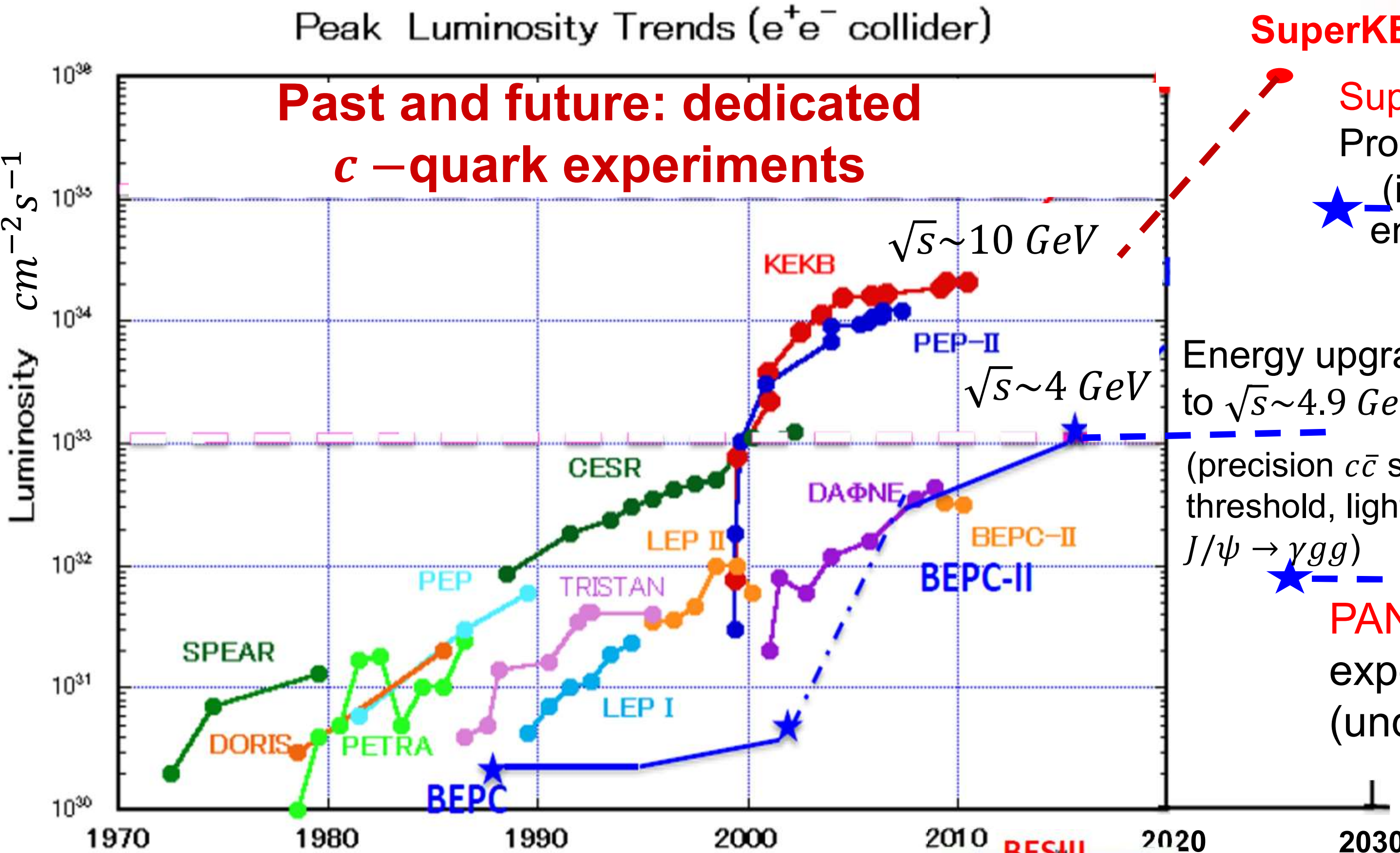


- ATLAS/CMS potential:
  - best flavor rates, but triggering on them is a challenge, no hadron ID
  - can be competitive in certain channels ($\mu^+\mu^-\mu^+\mu^-$?)
  - the only experiments which may have a chance to confirm some of LHCb claims



- 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





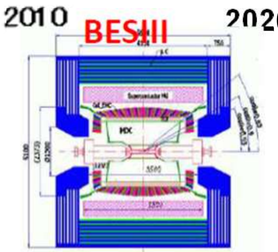
Super Tau-Charm Factory
Proposed at Hefei and Novosibirsk
(in R&D phase)
energy up to $\sqrt{s}$~7 GeV

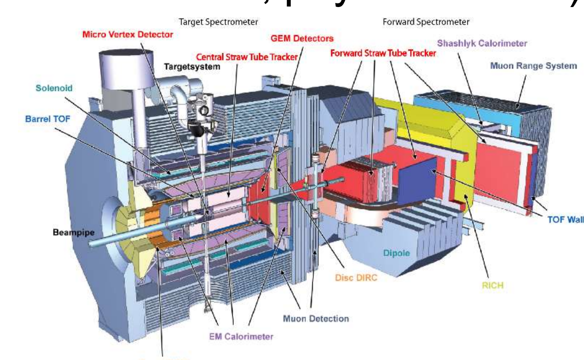
Energy upgrade to $\sqrt{s}$~4.9 GeV

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

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

PANDA: highest luminosity $p\bar{p} \to c\bar{c}$ experiment near the charm threshold
(under construction; physics 2025-)

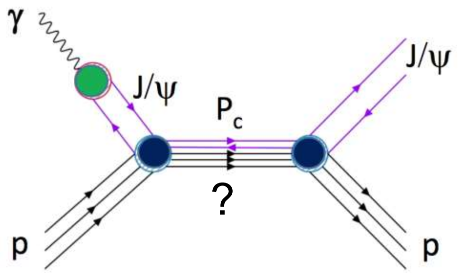




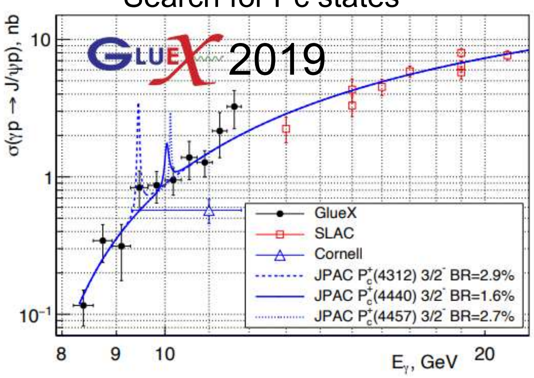
Experimental prospects at JLab and EIC

JLab: 12 GeV e^- beam (2017-…)

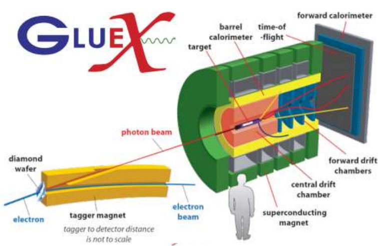
Photoproduction of charm



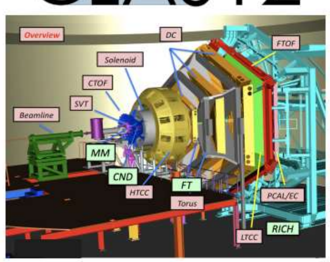
Search for Pc states



Statistical errors will be improved

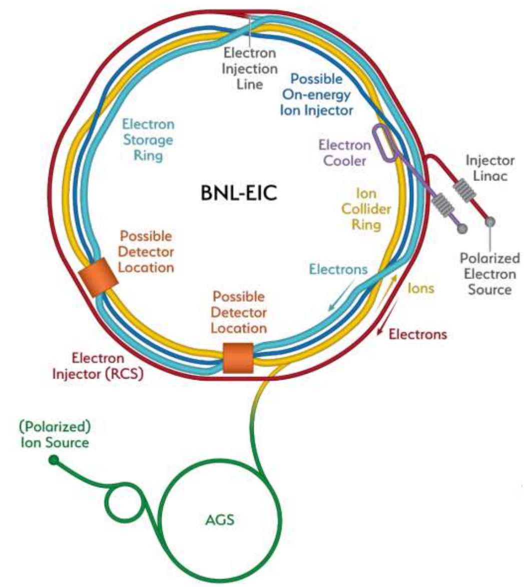


CLAS12



Search for light hybrid mesons

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