RF7: Hadron Spectroscopy

Conveners:

Richard Lebed, *Arizona State University,* Richard.Lebed@asu.edu

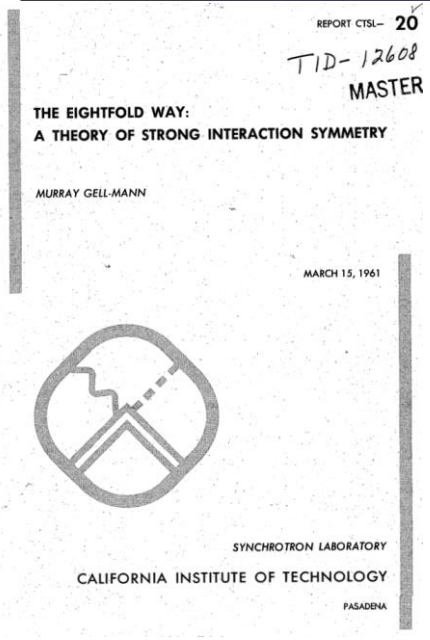
Tomasz Skwarnicki, *Syracuse University,* tskwarni@syr.edu

Rare Processes and Precision Frontier Kick-off Workshop, July 27, 2020

Organizational issues

- RF7 subgroup has been created only last week
  - We are in the process of organizing ourselves.
  - Stay tuned for details of the group structure and schedule. Please subscribe to our mailing list (blank-subject-line E-mail to listserv@fnal.gov with SUBSCRIBE SNOWMASS-RPF-07-HADR-SPECT FIRSTNAME LASTNAME in the body text)
- Hadron spectroscopy is a very broad subject crossing particle and nuclear physics communities. We will focus on heavy-quark conventional hadron ($q\bar{q}$, qqq) spectroscopy (charm and bottom), and on "exotic" hadron (multiquark or with valence gluons) spectroscopy (heavy and light)
- Previously, we have been active under EF06 subgroup (QCD and strong interactions: hadronic structure and forward QCD):
  - **A meeting dedicated to hadron spectroscopy took place on June 24. See 6 introductory talks at: https://indico.fnal.gov/event/43796/**
  - Summary of that meeting was given by Bryan Fulsom on July 8
- Broad participation in RF7 is welcome. Consider submitting LoI.

Why bother?



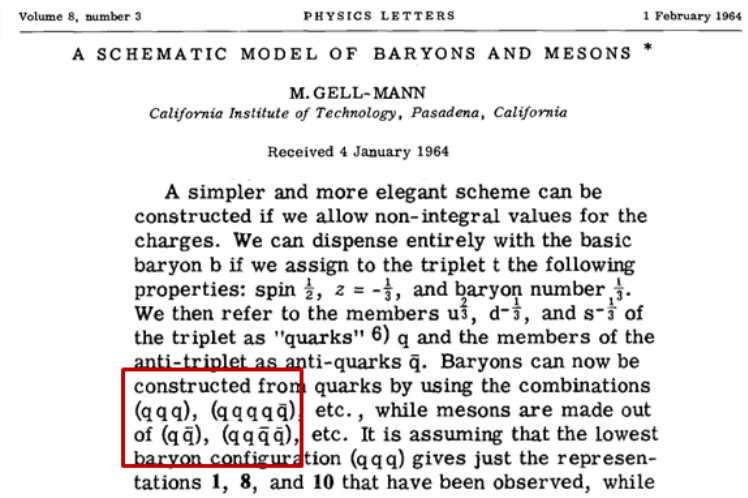
REPORT CTSL- 20
TID-12608
MASTER

THE EIGHTFOLD WAY:
A THEORY OF STRONG INTERACTION SYMMETRY

MURRAY GELL-MANN

MARCH 15, 1961

SYNCHROTRON LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA



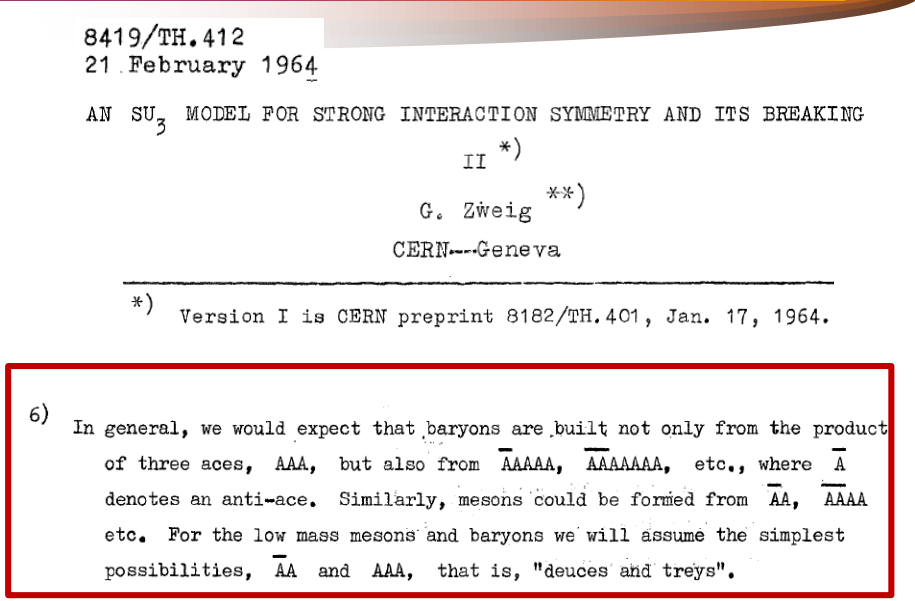
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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 (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig **)

CERN--Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

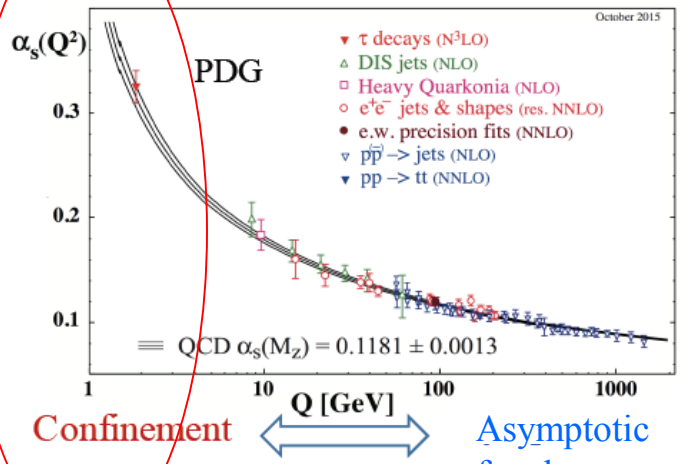
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

- Don't we know about quarks from mid 1960s?
- …and don't we have exact theory of strong interactions since early 1970s?

$$\mathcal{L}_{QCD} = \sum \bar{q}\,(i\gamma_\mu D^\mu - m_q)\,q \;-\; \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}$$

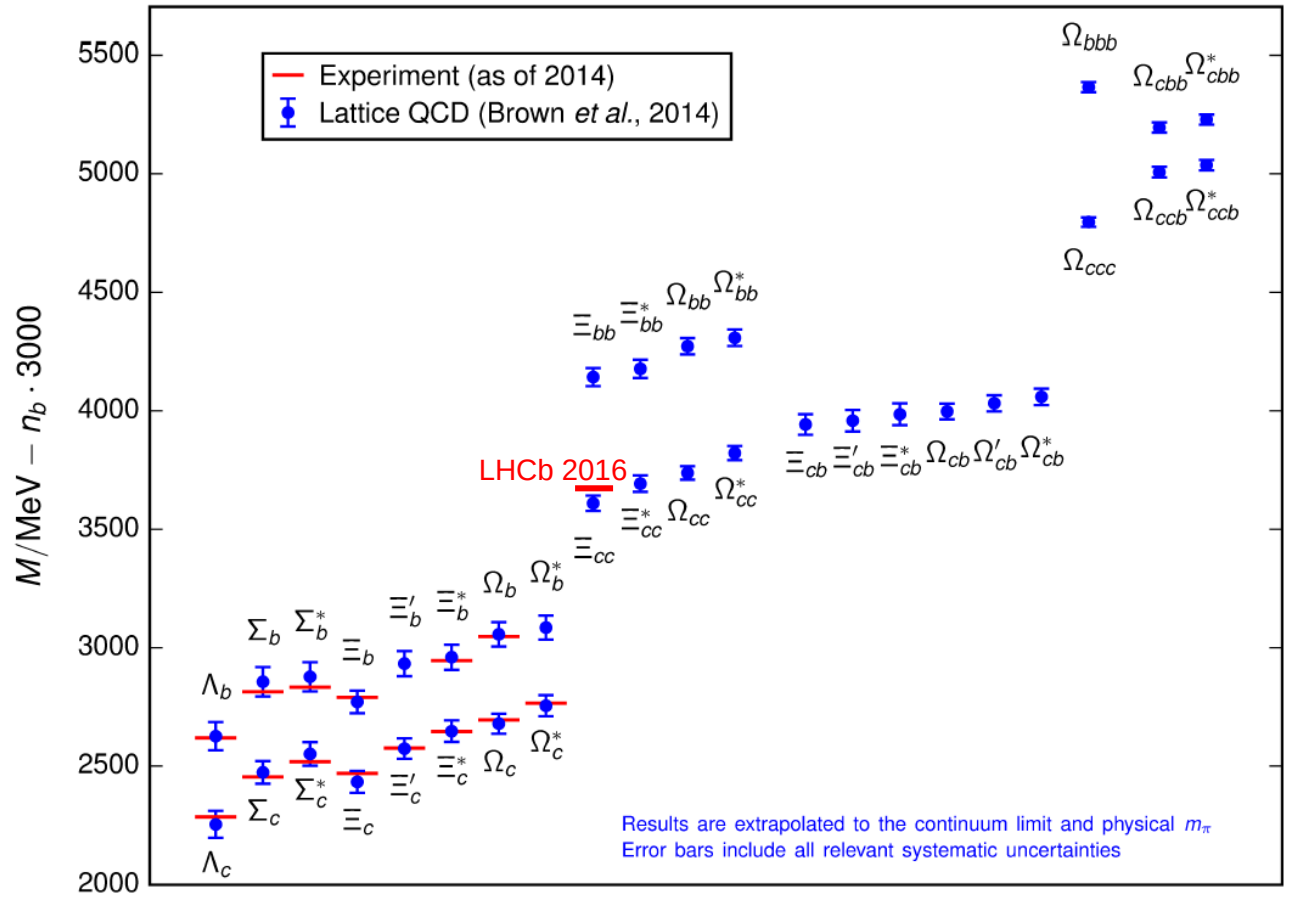
Strongly coupled theory

Hadron spectroscopy



- Lattice QCD is doing very well for lower excitations of $q\bar{q}$ and qqq hadrons
- Still in its infancy when dealing with unstable and multiquark states $qq\bar{q}\bar{q}$, $qqqq\bar{q}$, …

PRD90,094507 (2014)



- QCD-motivated phenomenology, with uncontrollable errors due to model assumptions

See next talk by Richard Lebed

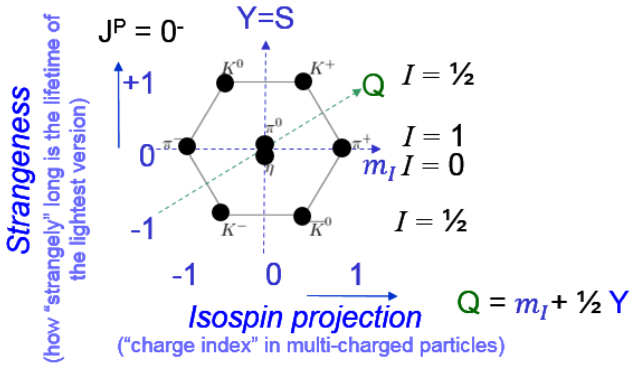
Status of our understanding of hadron spectroscopy

- 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)

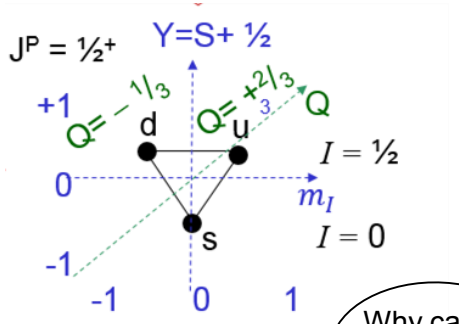
Scandalous situation!

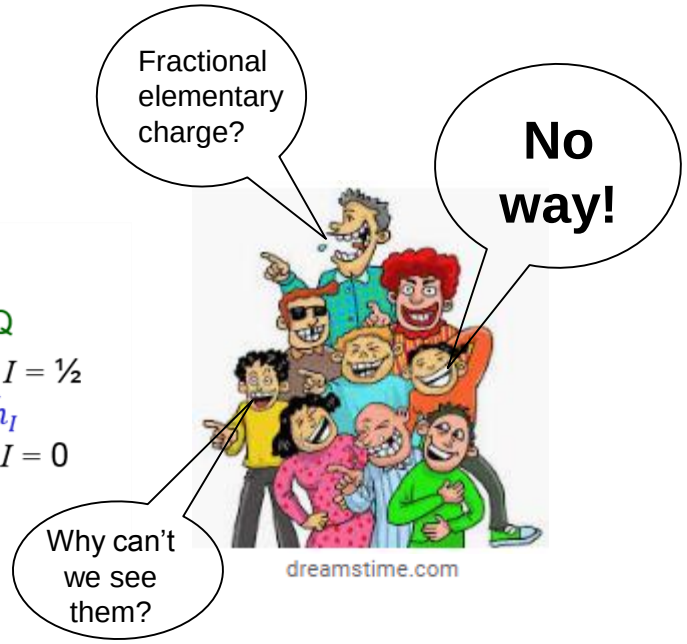
Heavy hadrons often lead the way

"Eightfold Way" symmetry – Gell-Mann 1961



Meson
octet

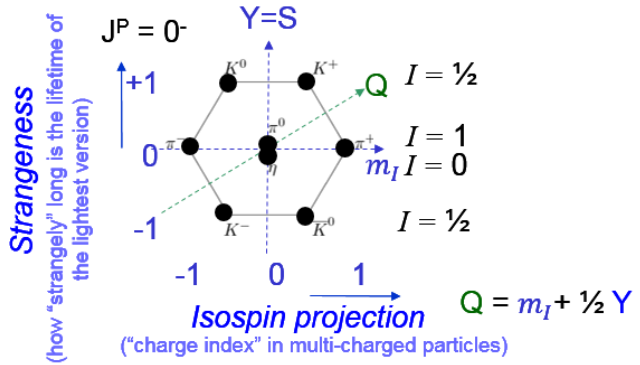




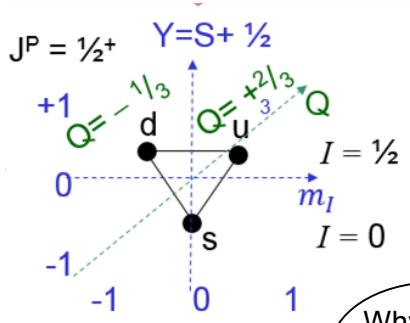
Heavy hadrons often lead the way

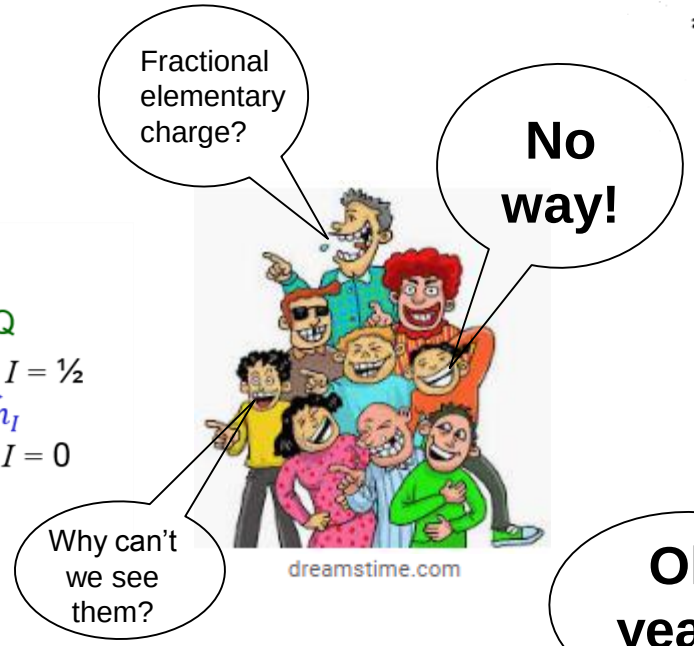
November revolution of 1974

"Eightfold Way" symmetry – Gell-Mann 1961

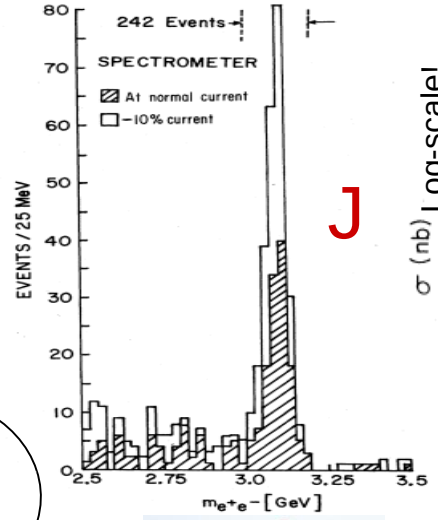


Meson octet





$pBe \rightarrow e^+e^- X$



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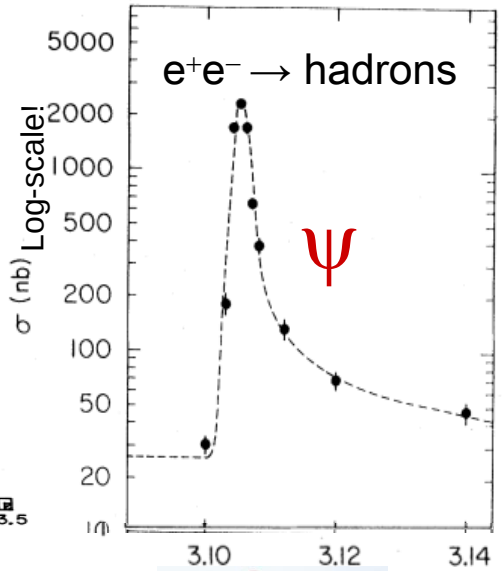
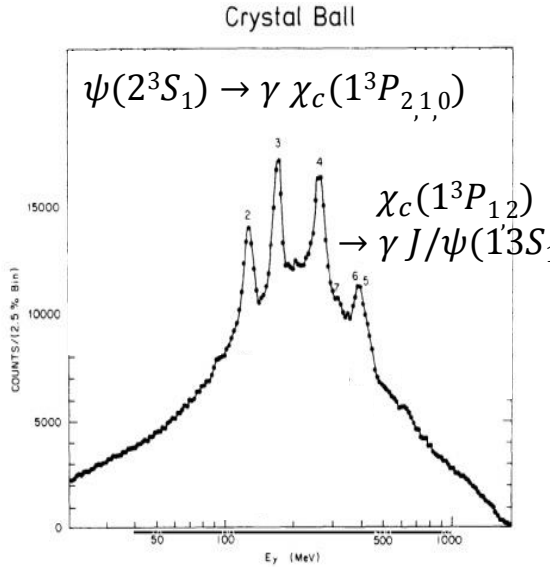
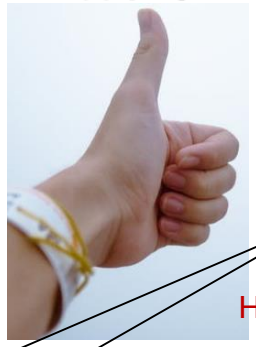
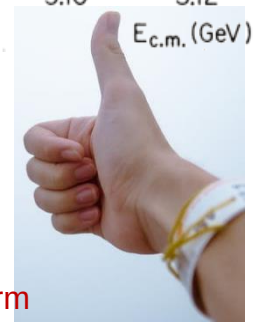








Hidden charm

Non-relativistic bound states of heavy fermion pair $(c\bar{c})$
carrying new quantum number (charm)
conserved in strong interactions

Separation of interaction energies and the masses of constituents helps!
Source of effective theories. ⇒ Rich's talk

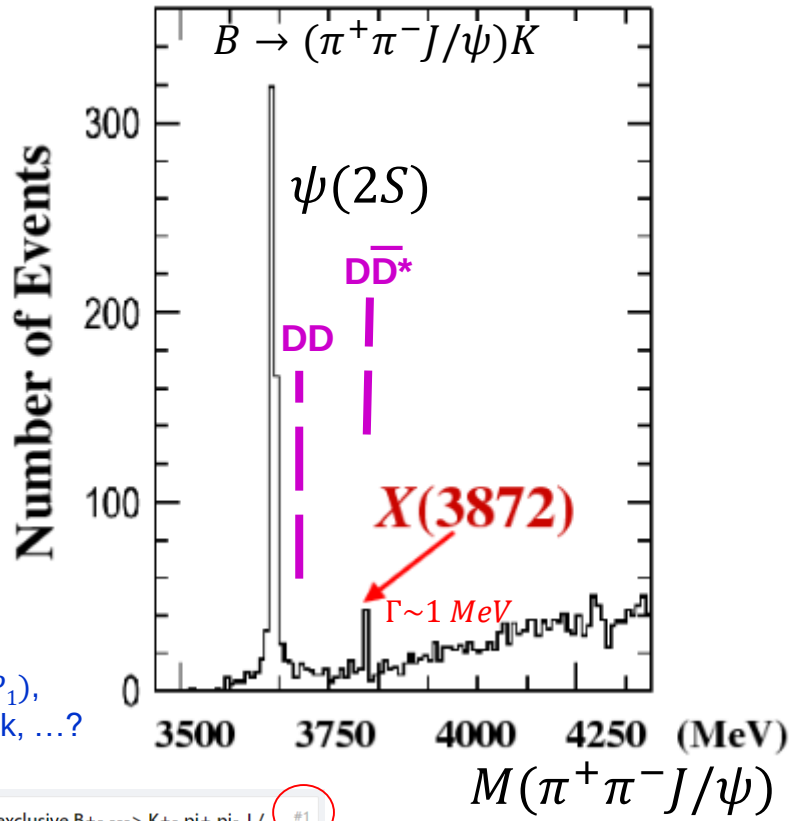
Heavy hadrons often lead the way

XYZ Revolution

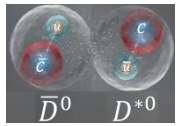
Belle 2003

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$,

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



not all mesons are simple $q\bar{q}$!



?

$D^0\bar{D}^{*0}$ molecule, $\chi_c(2^3P_1)$, $(cu)(\bar{c}\bar{u})$ diquark tetraquark, …?

Dispute ranges on!

Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays #1

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep 10, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]

pdf links DOI cite 1,797 citations

Observation of large CP violation in the neutral B meson system #2

Belle Collaboration • Kazuo Abe (KEK, Tsukuba) et al. (Jul 24, 2001)

Published in: *Phys.Rev.Lett.* 87 (2001) 091802 • e-Print: hep-ex/0107061 [hep-ex]

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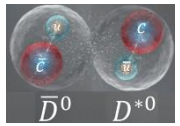

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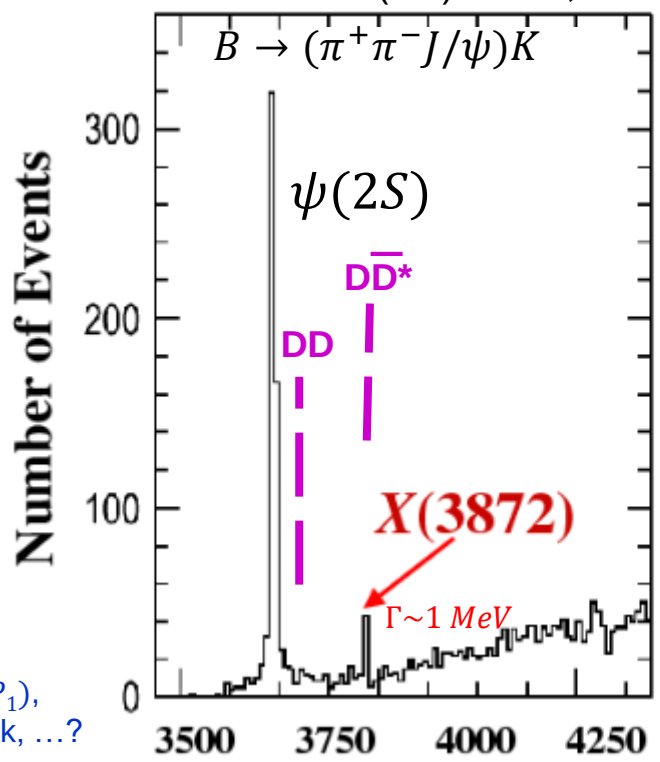
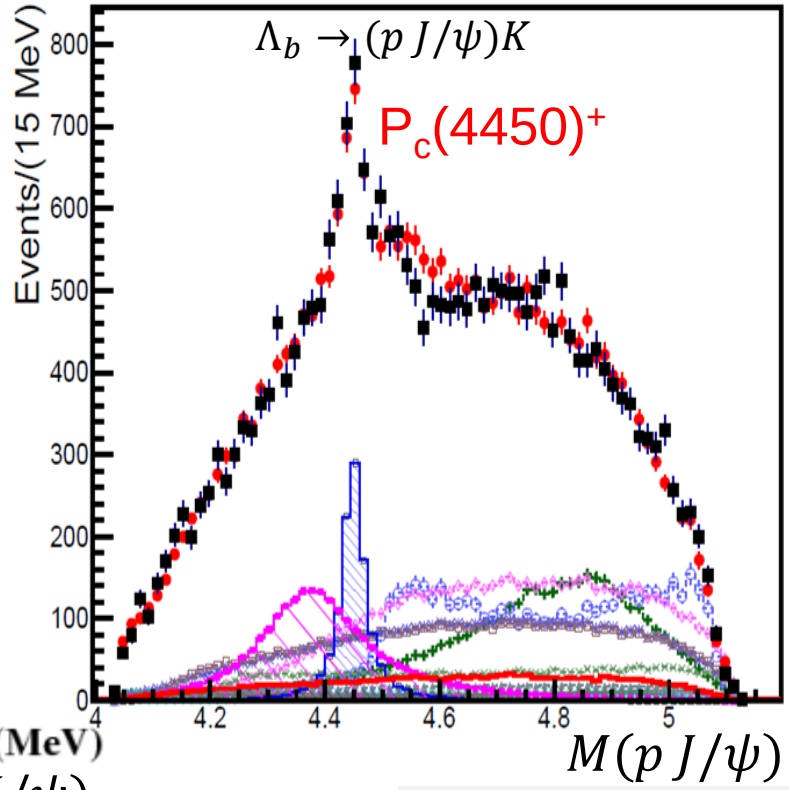


$M(\pi^+\pi^- J/\psi)$

LHCb 2015 run 1

$pp \to \Lambda_b + \cdots$

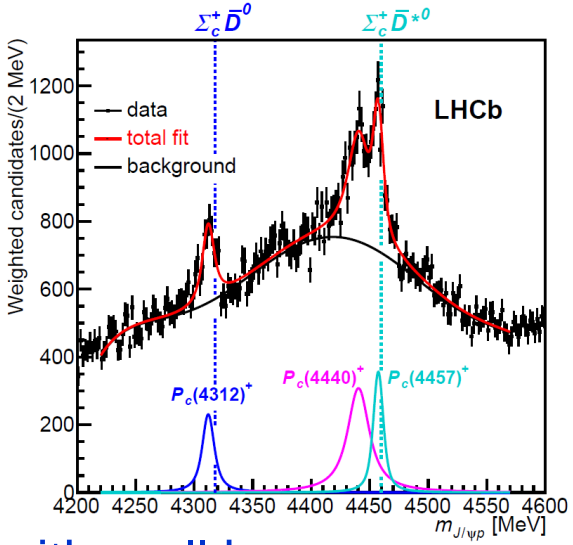
$\Lambda_b \to (p\,J/\psi)K$



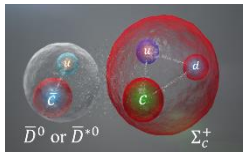
$M(p\,J/\psi)$

LHCb 2019 run 1 & 2

$\Gamma \sim 6 - 20\ MeV$



neither all baryons are simple qqq states!



?

$\bar{D}^{(*)0}\Sigma_c^+$ molecules, $(cu)(ud)\bar{c}$ pentaquarks,… ?

Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays #1
Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep 10, 2003)
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pdf DOI cite 1,012 citations

Hidden charm

Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays #1
LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 25, 2014)
Published in: *Phys.Rev.Lett.* 113 (2014) 151601 • e-Print: 1406.6482 [hep-ex]
pdf DOI cite 1,001 citations

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays #2
LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)
Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]
pdf links DOI cite 1,000 citations

Among enduring legacies of the heavy flavor experiments

Reflects a large community of physicists working on hadron spectroscopy

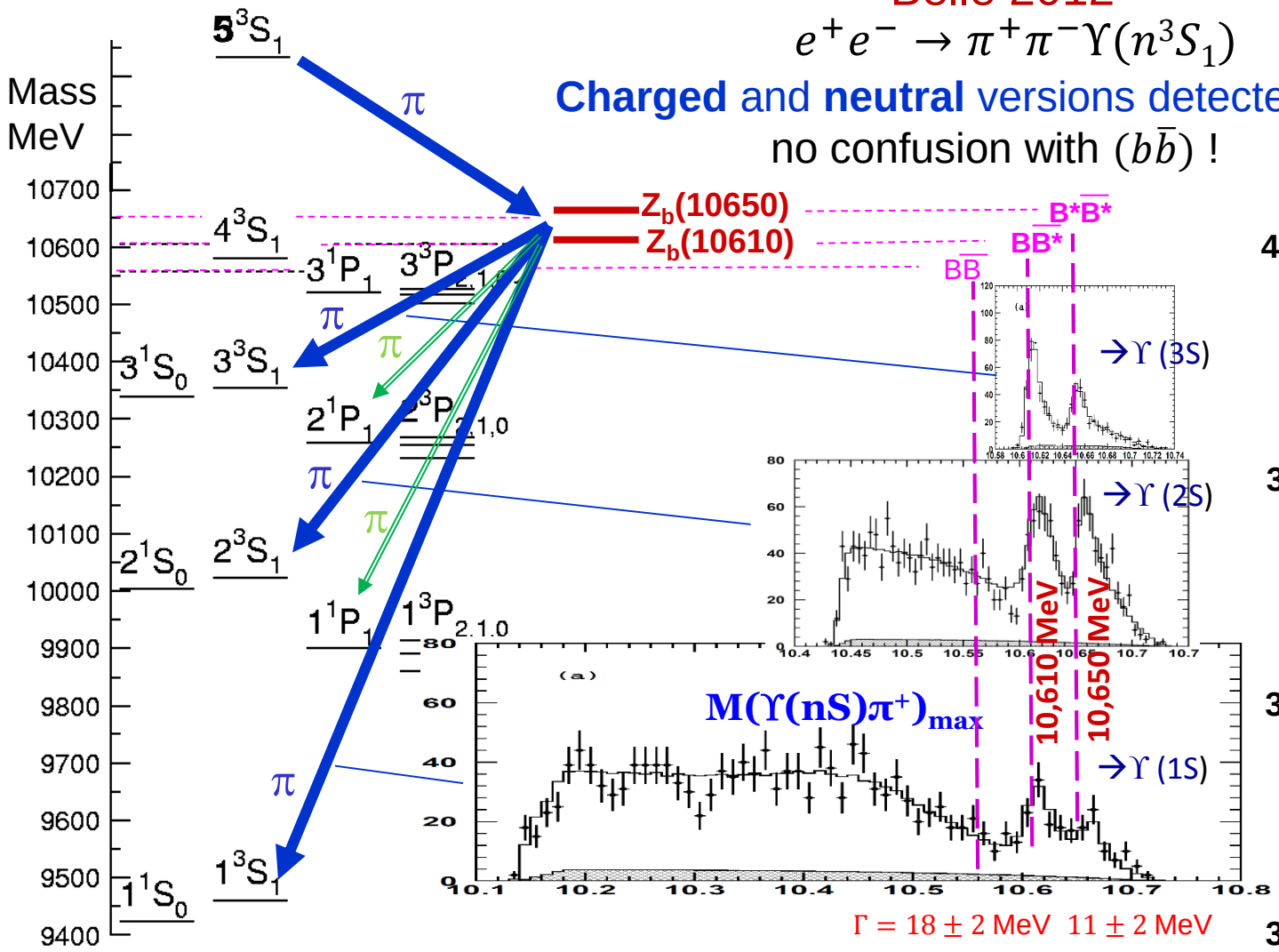
Narrow $Z_b^{+,0}$ and $Z_c^{+,0}$ states

Belle 2012

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

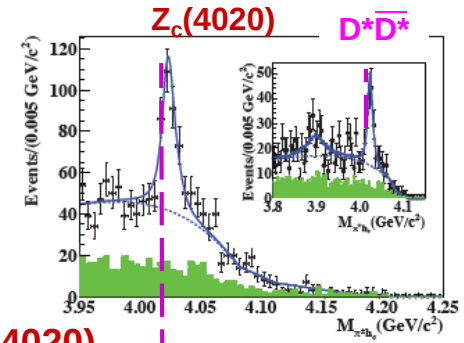
Charged and **neutral** versions detected $I^G=1^+$

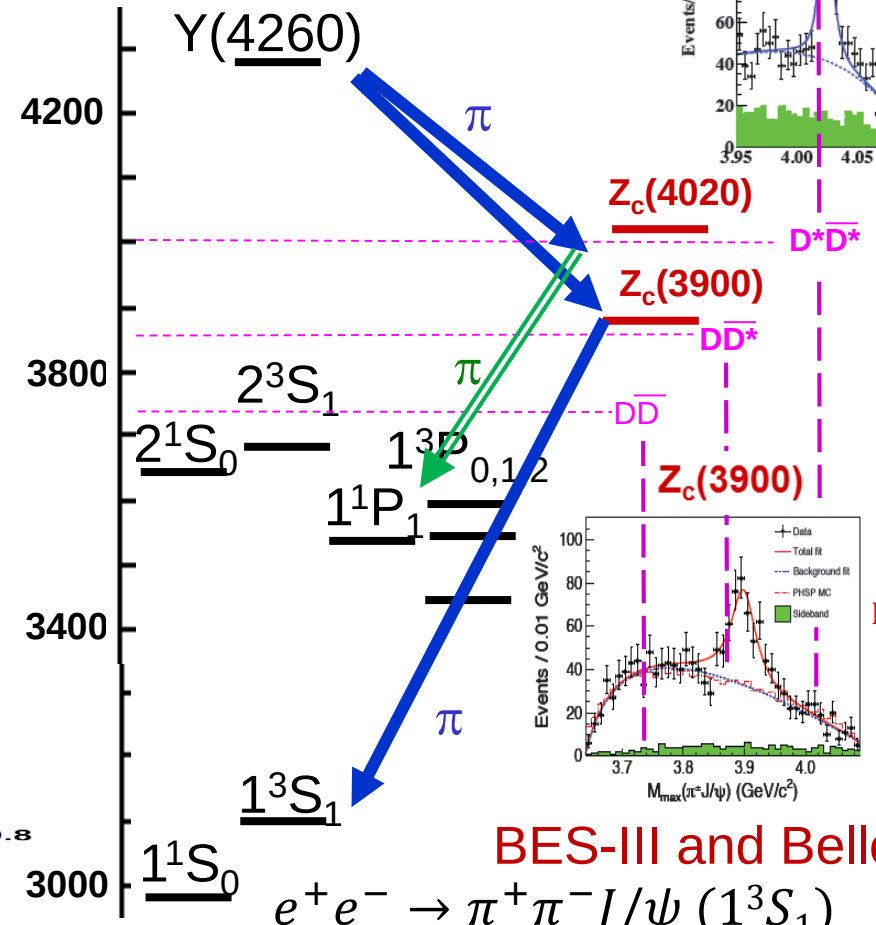
no confusion with $(b\bar{b})$!



BES-III 2013

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





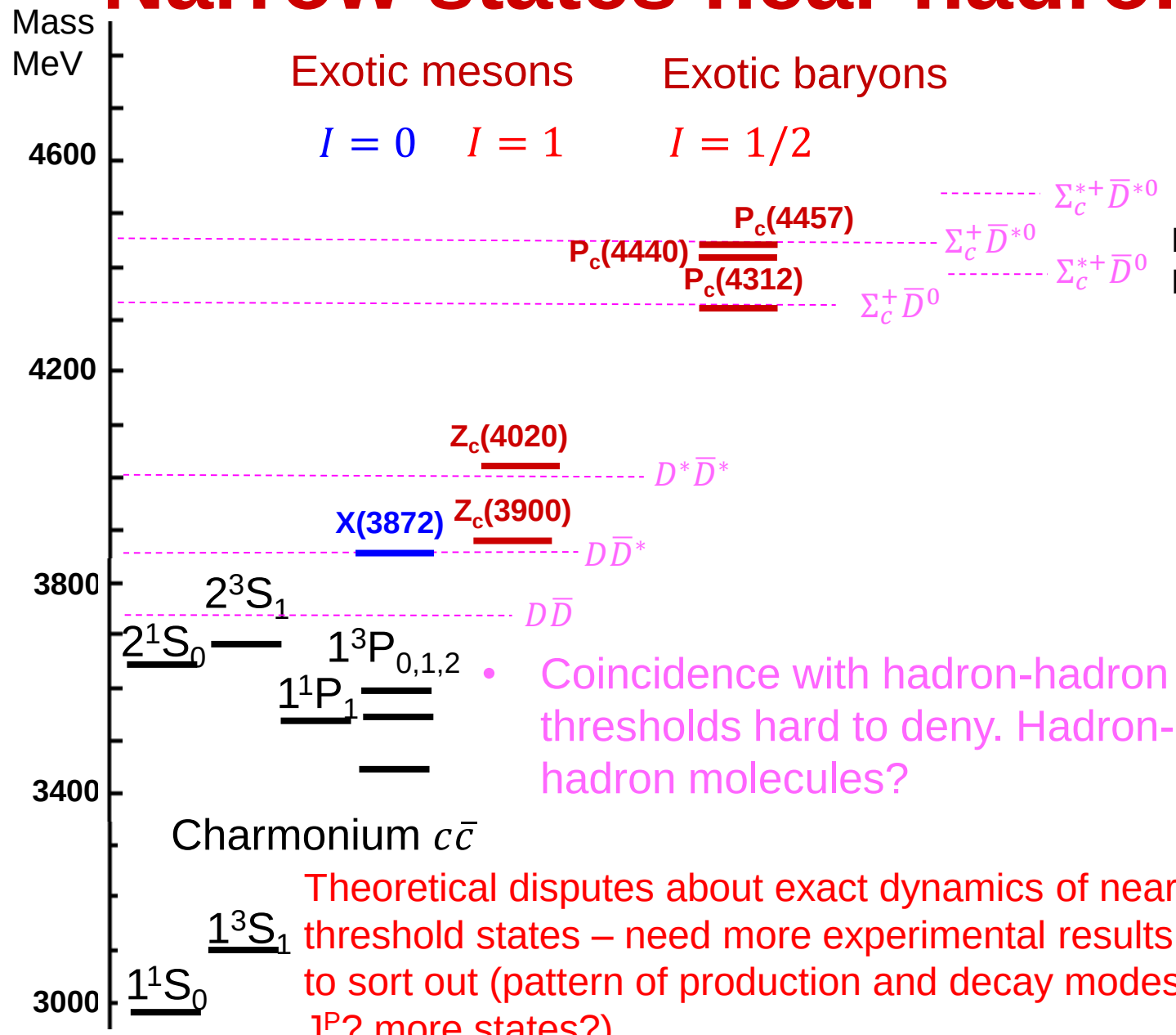
BES-III and Belle 2013

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

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

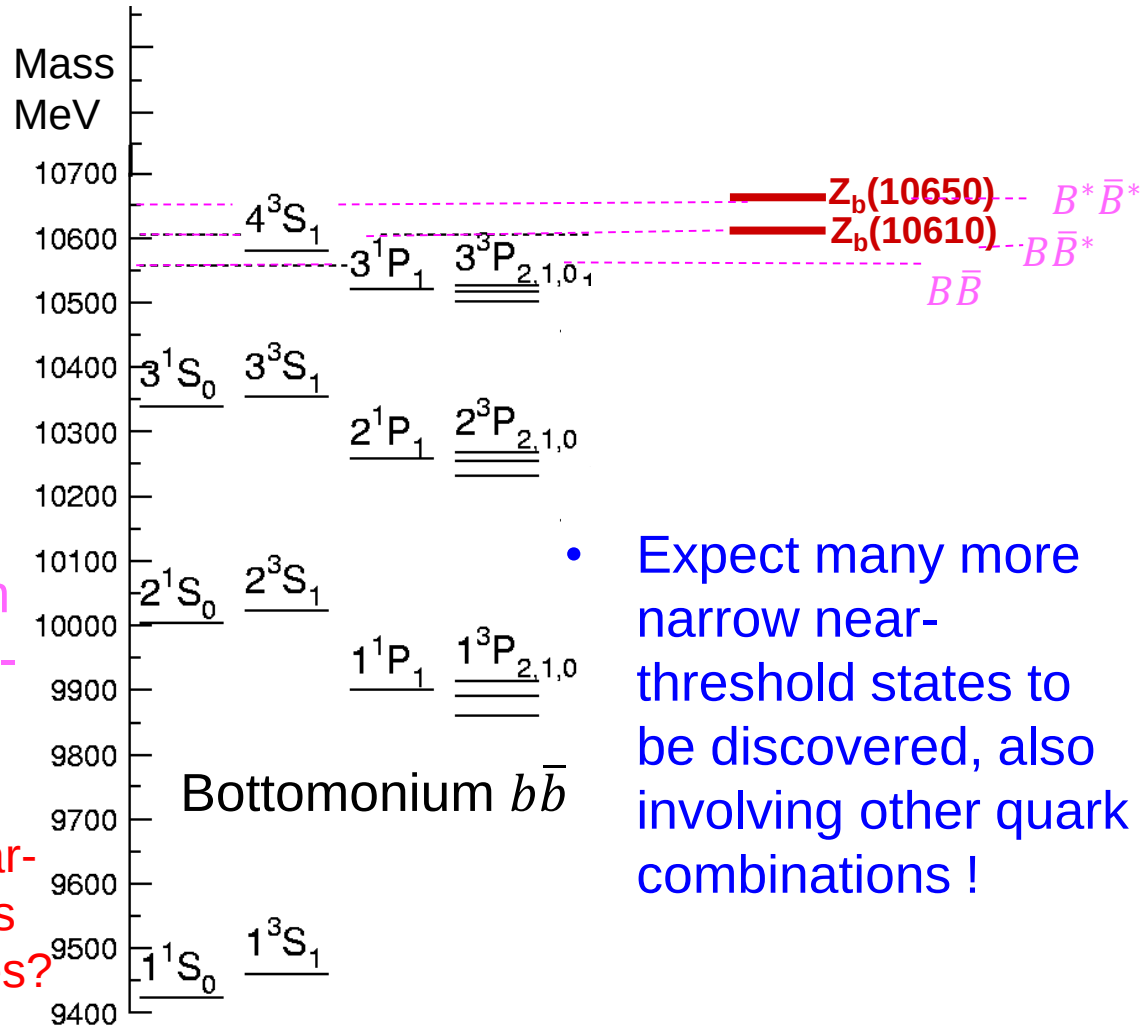
Narrow! Masses slightly above thresholds?

Narrow states near hadron-hadron thresholds



- Coincidence with hadron-hadron thresholds hard to deny. Hadron-hadron molecules?

Theoretical disputes about exact dynamics of near-threshold states – need more experimental results to sort out (pattern of production and decay modes? J^P? more states?)



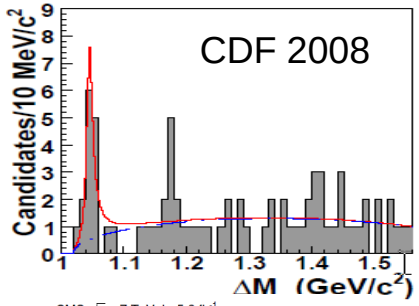
- Expect many more narrow near-threshold states to be discovered, also involving other quark combinations !

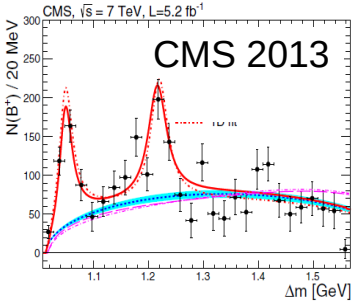
Many exotic broader states not near thresholds

$B \to XK, X \to J/\psi\phi$

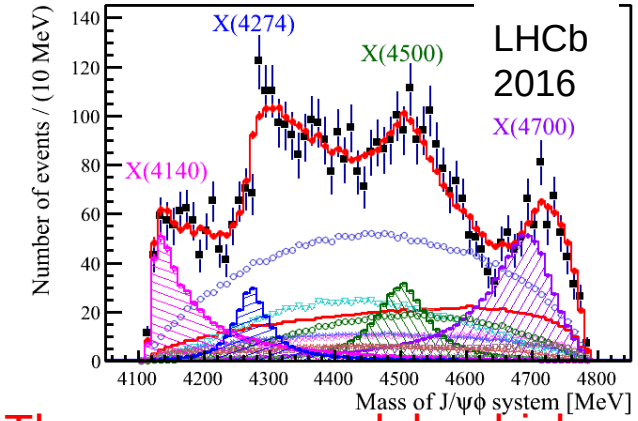
$(cs)(\bar{c}\bar{s})$ tetraquarks?

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



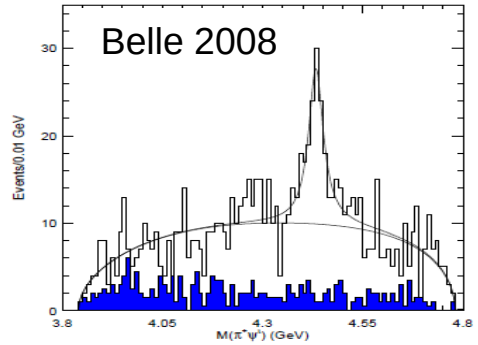


Γ~56 – 120 MeV

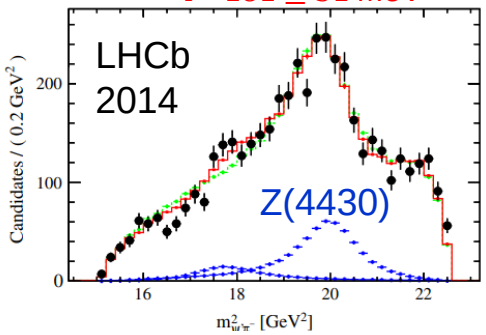


$B \to ZK, Z \to \psi(2S)\pi^{\pm}$

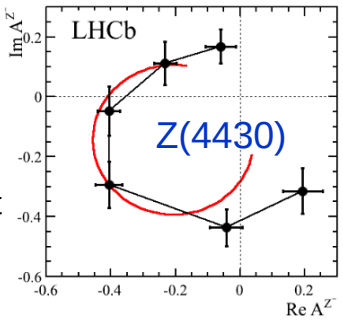
$(cu)(\bar{c}\bar{d})$ tetraquark?



Γ~181 ± 31 MeV



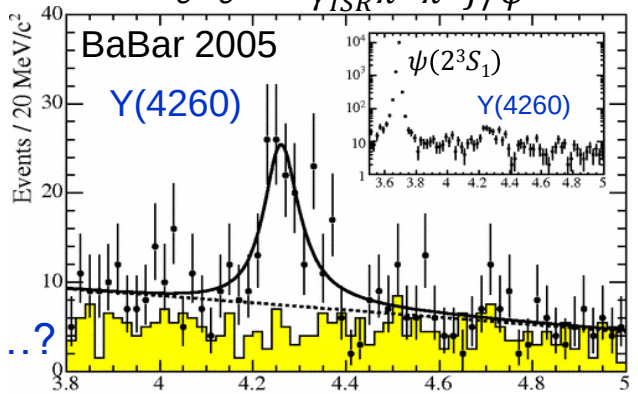
Resonant phase-shift



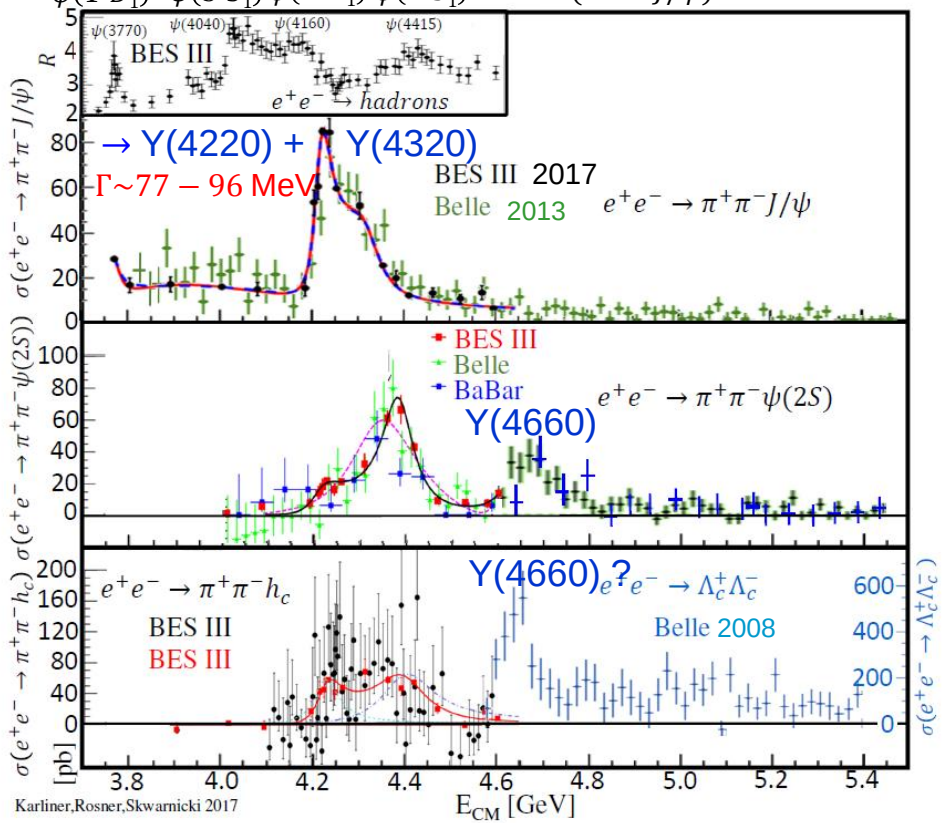
$gc\bar{c}$ hybrid states?,

$(cd)(\bar{c}\bar{d})$ tetraquarks,…?

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



$\psi(1^3D_1)$ $\psi(3^3S_1)$ $\psi(2^3D_1)$ $\psi(4^3S_1)$ $m(\pi^+\pi^- J/\psi)$

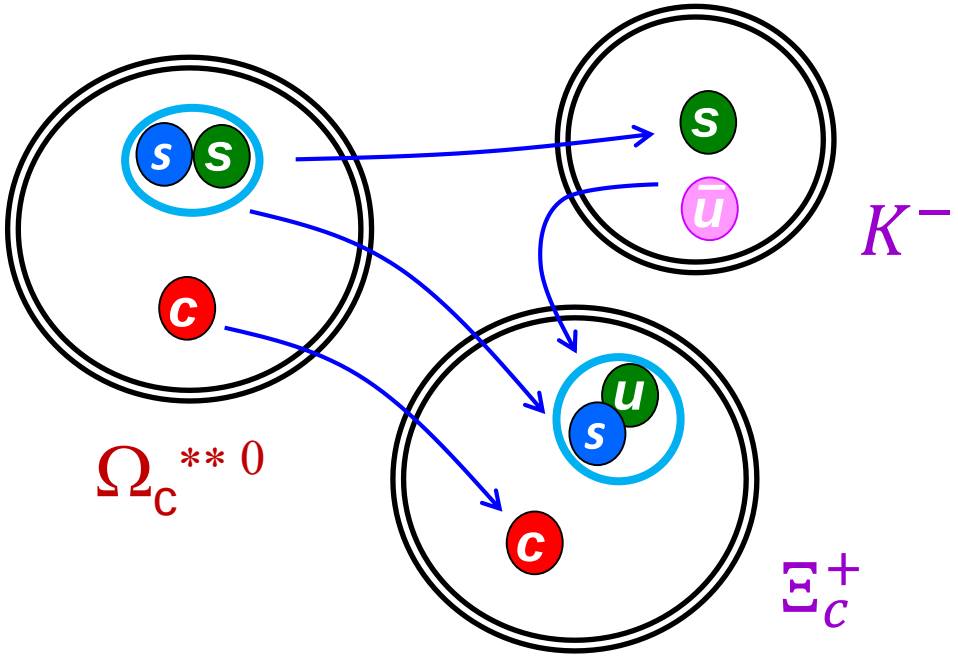


There are no models which can explain all these effects at the same time

Conventional heavy baryons

- A lots of new states are being discovered. Many contain nice evidence for diquark substructure e.g.

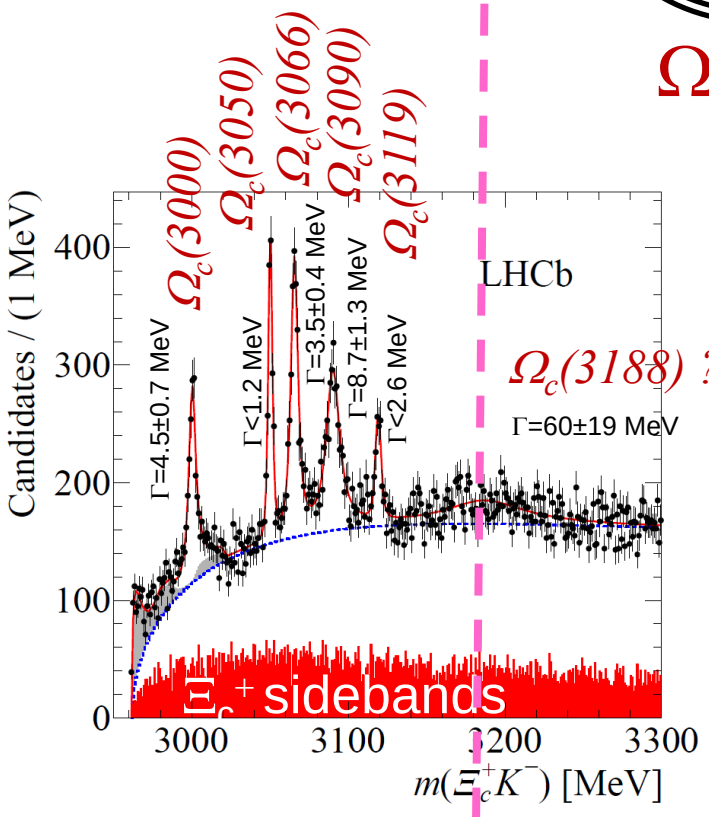
LHCb-PAPER-2017-002, PRL 118 (2017) 182001; 3.3 fb^{-1} $\Omega_c^{**\,0} \to \Xi_c^+ K^-$, $\Xi_c^+ \to pK^-\pi^+$

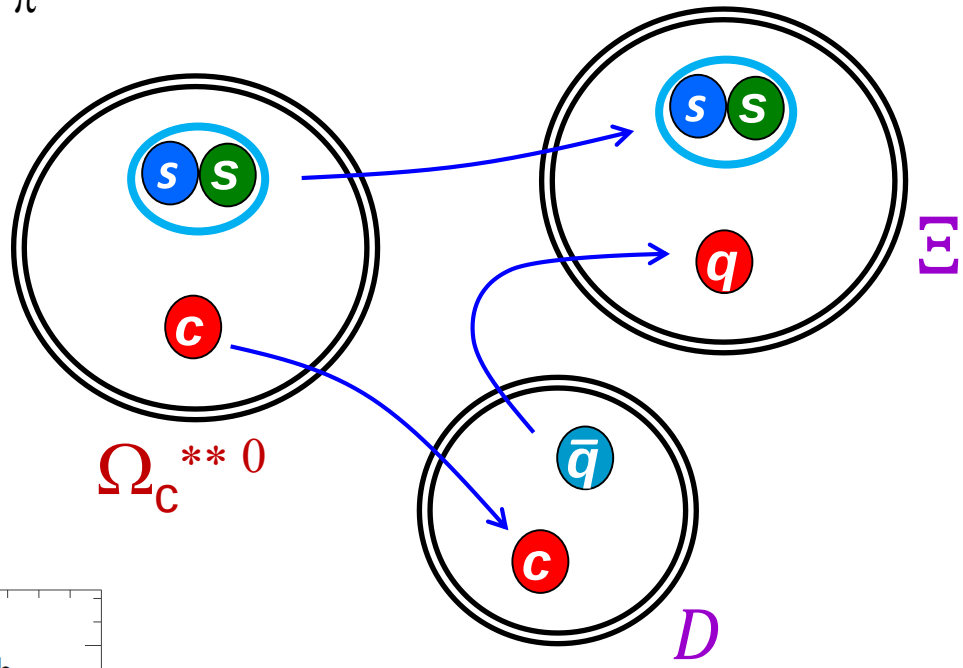


OZI allowed but rips the diquark apart
– suppressed (narrow states)

ΞD threshold

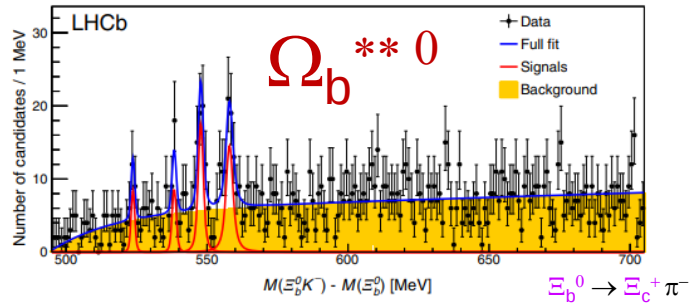
The narrow states are likely 1P and 2S of c-(ss diquark)





the diquark survives
– fast fall apart (wide states)

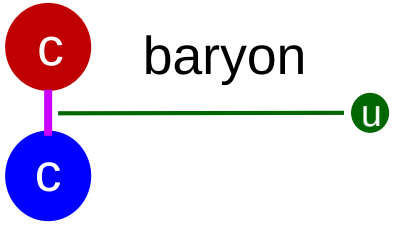
LHCb-PAPER-2019-042, PRL 124 (2020) 082002; 9 fb^{-1}



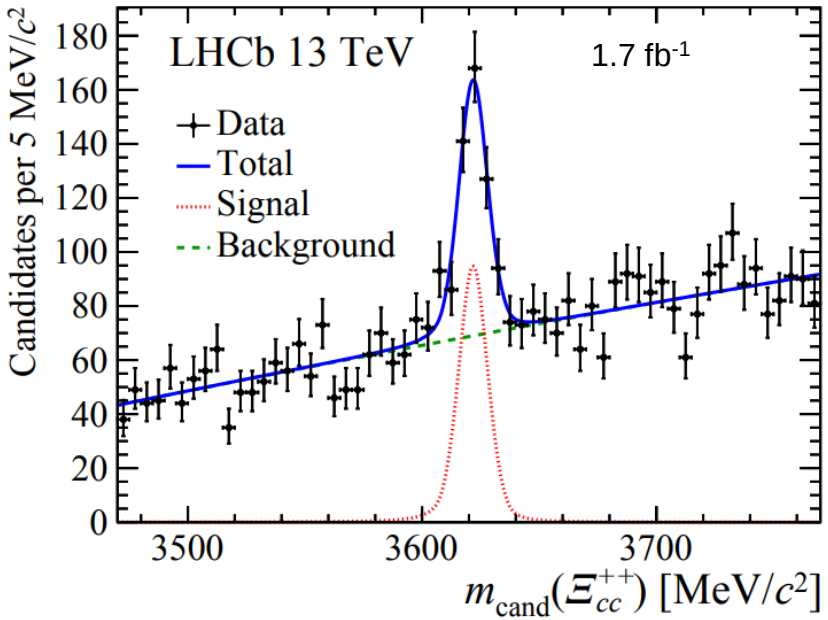
Future:

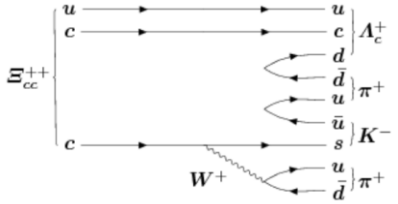
Many more charm and beauty baryons to discover
Study different decay modes of known baryons

Doubly flavored baryons and stable (?) tetraquarks



LHCb-PAPER-2017-018, LHCb PRL 119 (2017) 112001





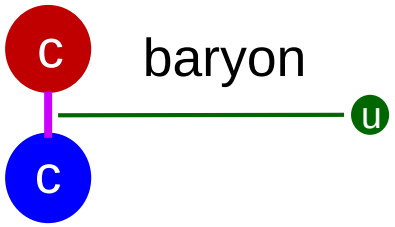
$\Lambda_c^+ \to pK^-\pi^+$

Karliner,Rosner PRD90,094007 (2014)

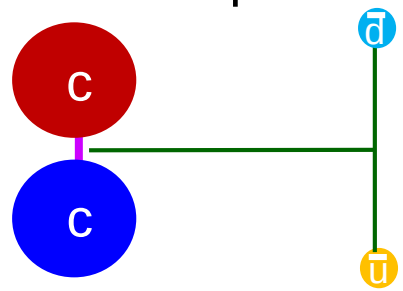
State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

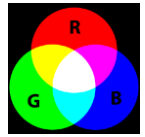
Doubly flavored baryons and stable (?) tetraquarks



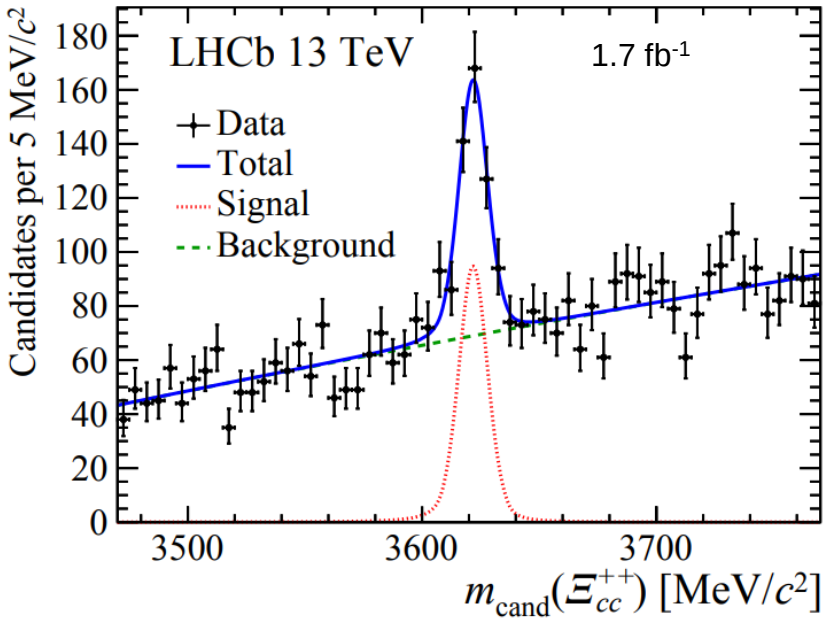
baryon

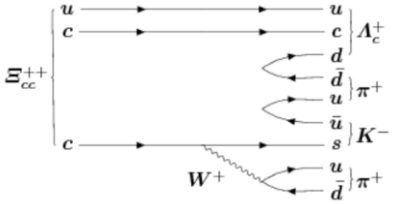


tetraquark



LHCb-PAPER-2017-018, LHCb PRL 119 (2017) 112001

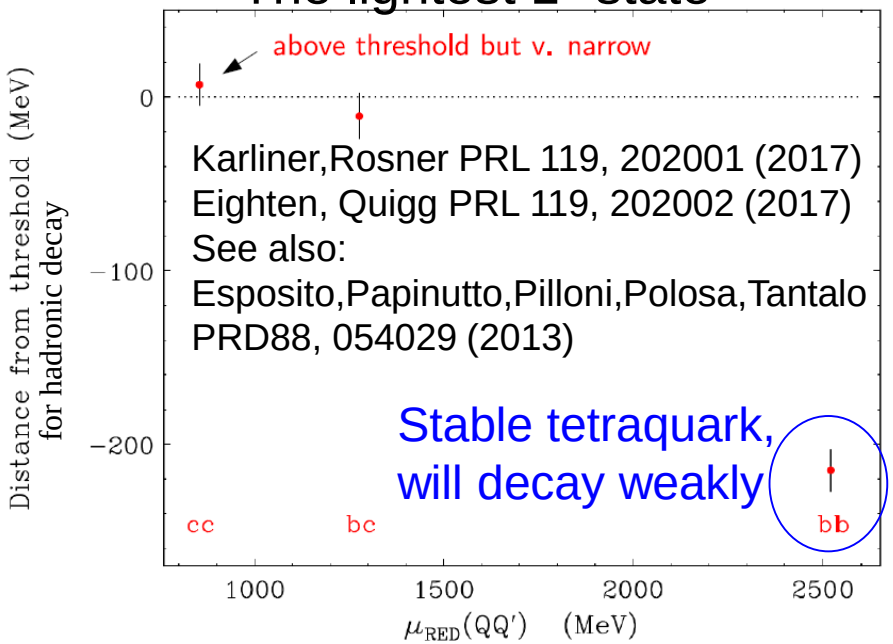




$\Lambda_c^+ \to pK^-\pi^+$

the same toolkit

The lightest 1^+ state



Karliner,Rosner PRD88, 054029 (2013)

Stable tetraquark, will decay weakly

Karliner,Rosner PRD90,094007 (2014)

State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

55

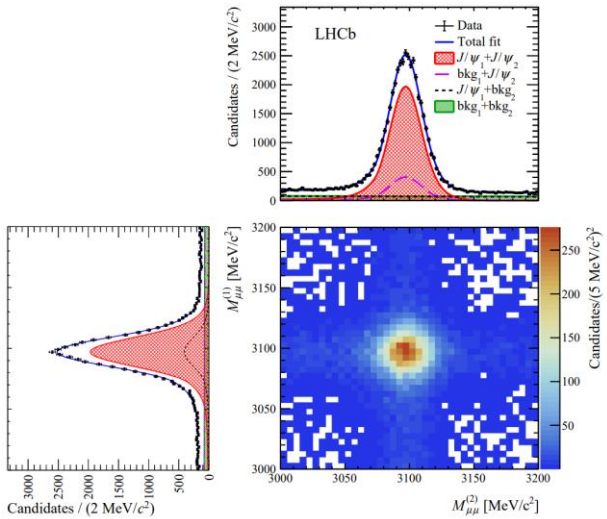
Consistent results predicted by LQCD: Francis,Hudspith,Lewis,Maltman PRL 1118,142001 (2017)

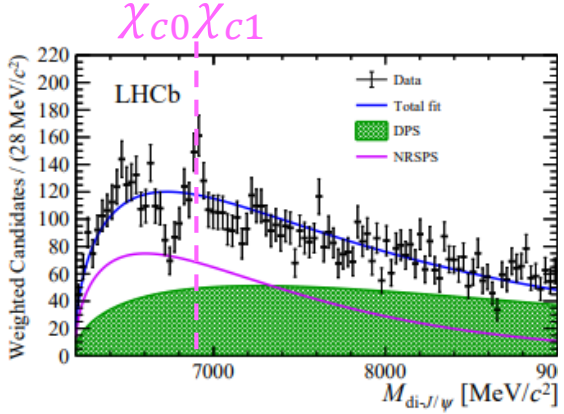
Future searches for such states above or below the $(Q\bar{q})(Q\bar{q})$ threshold will be very exciting

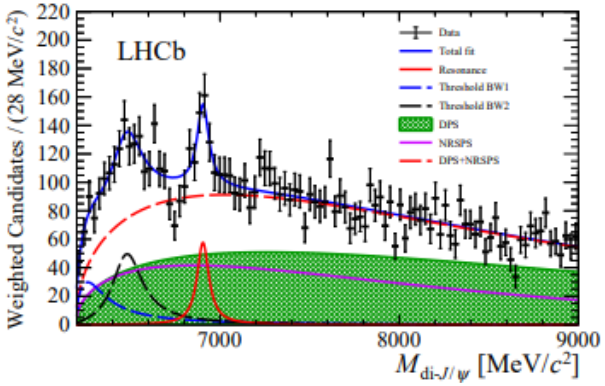
Hidden double charm tetraquarks ?

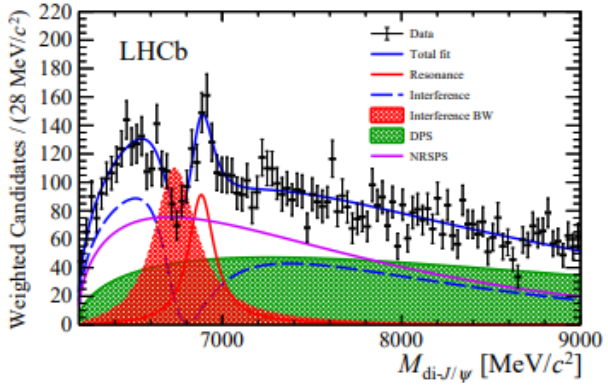
$pp \to (J/\psi \to \mu^+\mu^-)(J/\psi \to \mu^+\mu^-) + \cdots$

LHCb June 2020



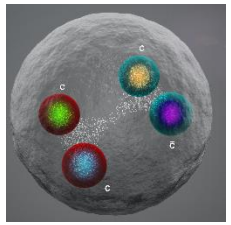






Structure	Significance $p_T^{\text{di-}J/\psi}$-threshold	Significance $p_T^{\text{di-}J/\psi}$-binned
Any structure beyond NRSPS plus DPS	$3.4\,\sigma$	$6.0\,\sigma$
Threshold enhancement plus $X(6900)$	$6.4\,\sigma$	$6.9\,\sigma$
Threshold enhancement	$6.0\,\sigma$	$6.5\,\sigma$
$X(6900)$	$5.1\,\sigma$	$5.4\,\sigma$

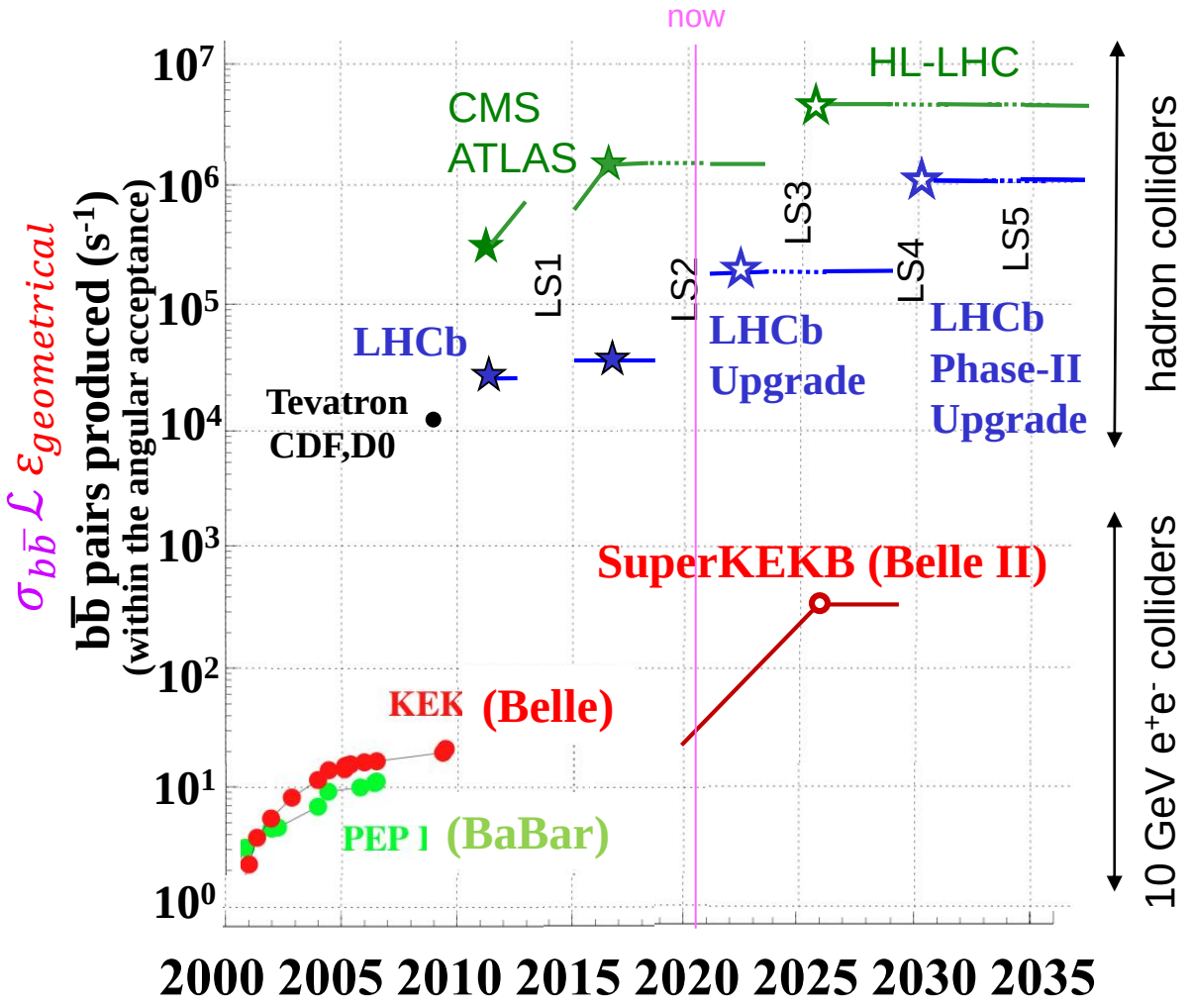
- Very significant structure in J/ψJ/ψ mass
- Interpretation of data is not clear:
  - One, or more (interfering?) resonances
  - possible effects due to nearby $\chi_{c0}\chi_{c0,1}$ thresholds, however, there are no known mechanism for binding forces between two charmonium states, and the X(6900) peak seems too wide to be a molecule (Γ~80 MeV or more)
  - likely theoretical interpretation: $(cc)(\bar{c}\bar{c})$ tetraquark state(s)
- Experimental questions to answer in the future:
  - How many states? J^Ps? Other decay modes e.g. $J/\psi\eta_c$



?

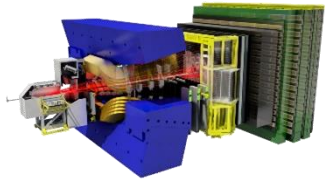
Experimental prospects for the next decade

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



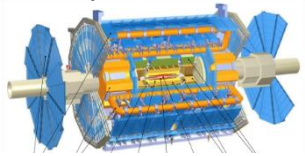
- Unique features of LHC:
  - enormous production rates (before trigger)
  - access to b-baryons (also serves pathway to charm pentaquarks)
  - access to doubly-flavored states ($b\bar{c}, ccq, cc\bar{c}\bar{c}, \ldots$)
- Expect many new measurements/discoveries from LHCb
  - triggering optimized to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

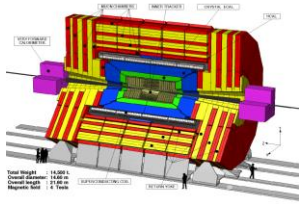
    (see talk by T.S. on June 24)



- 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 chase to confirm some of LHCb claims

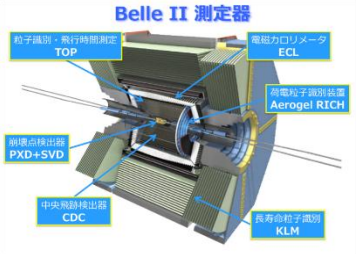
    (see talk by Alexis Pompili on June 24)

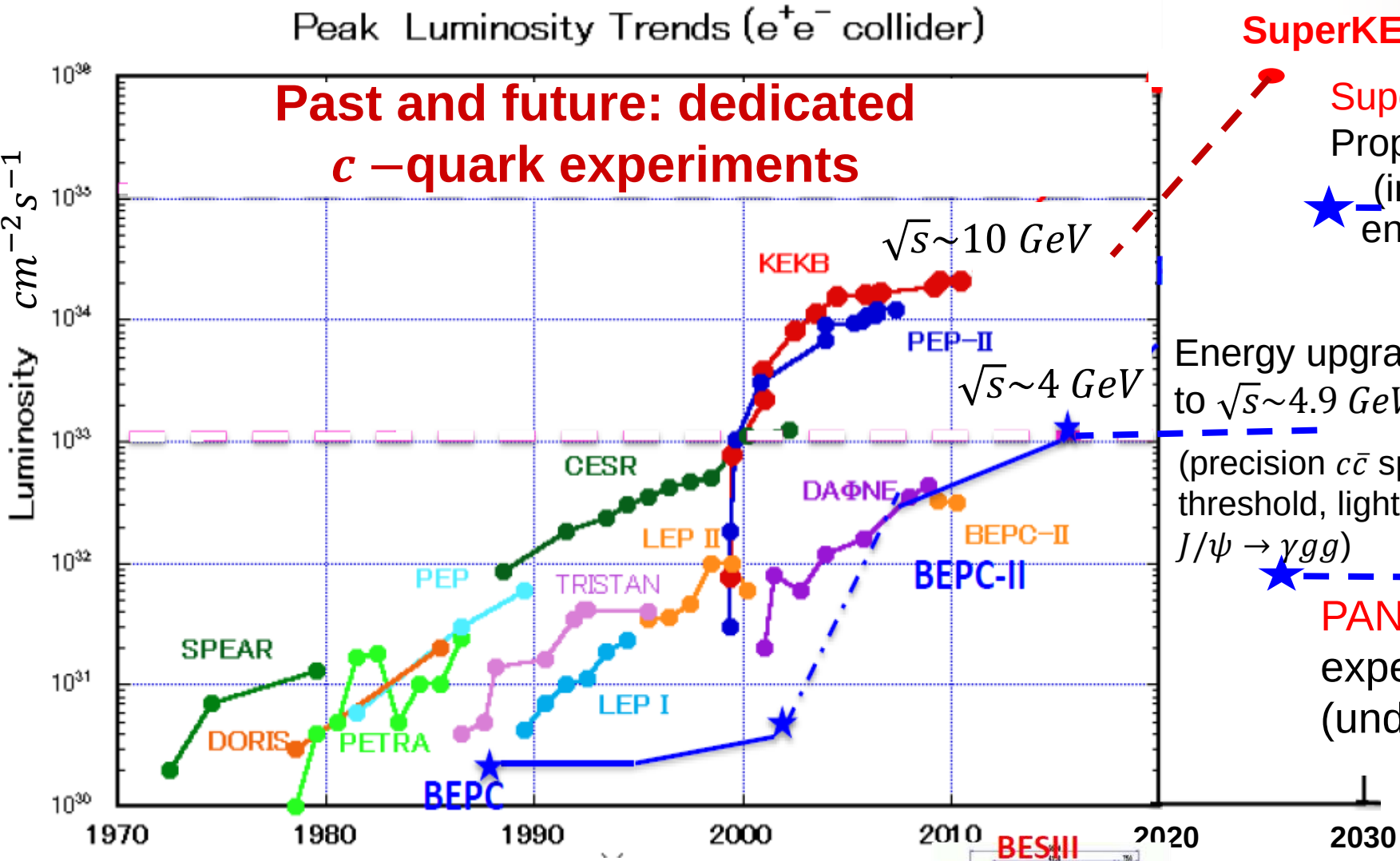




- Expect many new measurements/discoveries from Belle II. Unique features:
  - good γ, π^0, η detection
  - access to precision $b\bar{b}$ spectroscopy below and above $B\bar{B}$ threshold (via dedicated runs)
  - production also via $\gamma\gamma$ collisions

    (see talk by Bryan Fulsom on June 24)





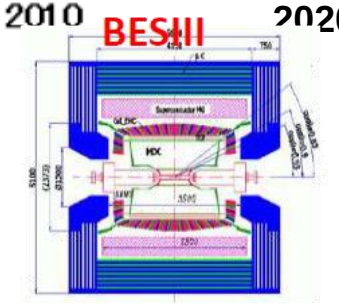
SuperKEKB

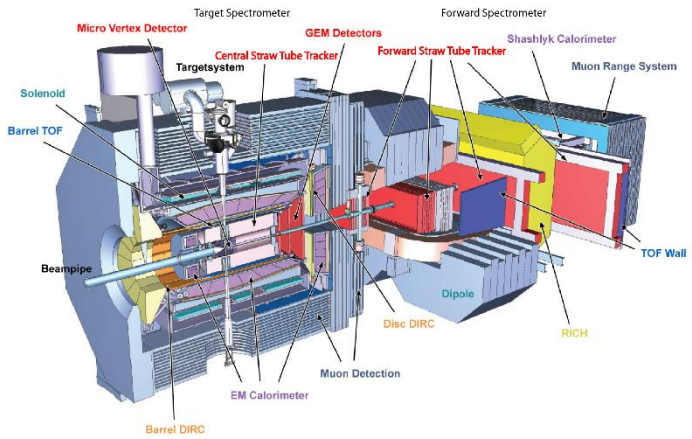
Super Tau-Charm Factory
Proposed at Hefei and Novosibirsk
(in R&D phase)
★ energy up to $\sqrt{s}$~7 GeV

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 $J/\psi \to \gamma gg$)
(see talk by Ryan Mitchell on June 24)
★

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

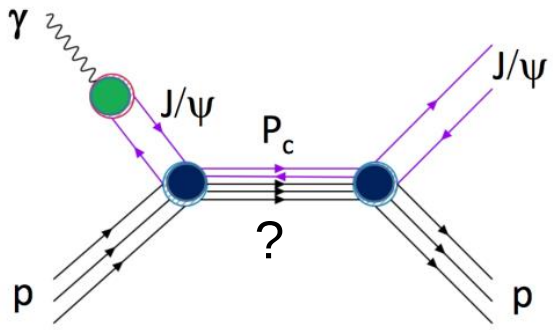




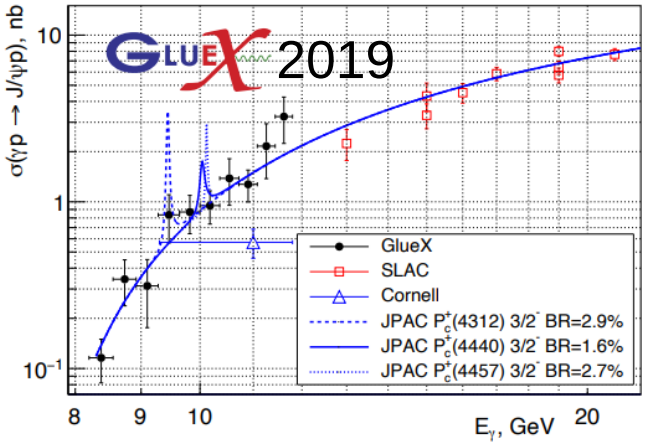
Experimental prospects at JLab and EIC

JLab: 12 GeV e^- beam (2017-…)

Photoproduction of charm

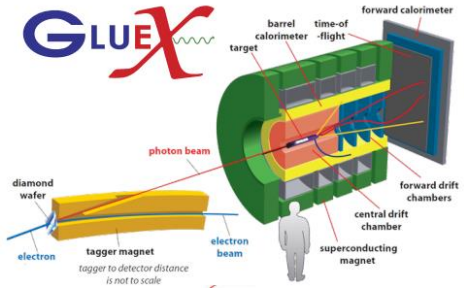


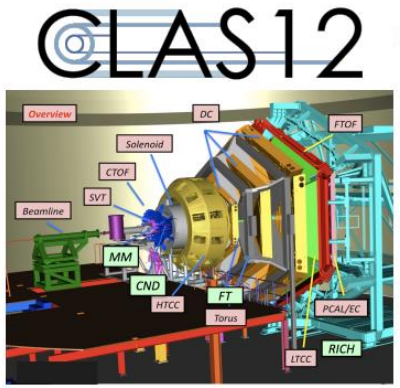
Search for Pc states



Statistical errors will be improved

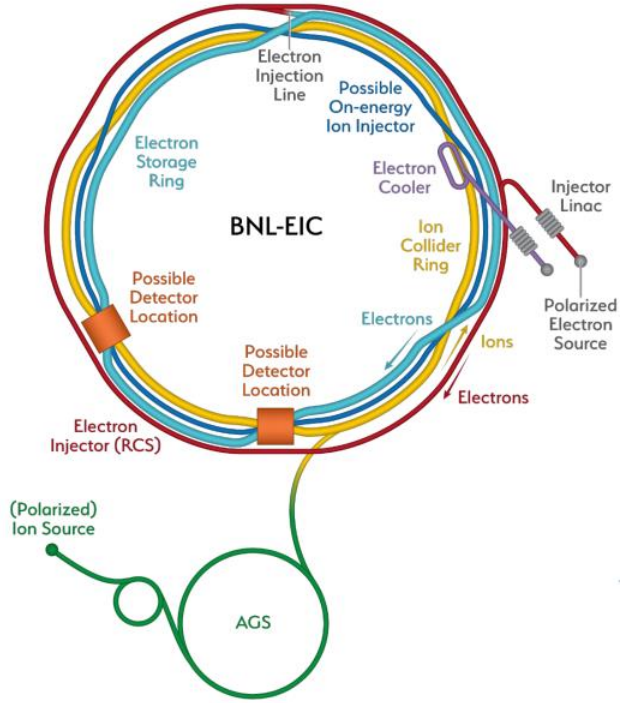
(see talk by Justin Stevens on June 24)





Search for light hybrid mesons

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



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

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

Photoproduction of charmonium exotics possible

Summary and outlook

- It is a jungle out there! Renewed experimental and theoretical (see next talk) efforts are needed
  - States at hadron-hadron thresholds must be better understood (bound “molecular” states or something more complicated)
  - Can we definitely establish diaquark substructures? In baryons? In tetra- or penta-quarks? Stable tetraquarks?
  - Still looking for definite experimental proofs of bound states with valence gluons: hybrids and glueballs
  - Do conventional $q\bar{q}$, qqq states get modified by multiquark effects? Precision studies of conventional mesons and baryons
- Tentative goals for Snowmass21:
  - Identify opportunities offered by facilities available in the next decade or two,
  - … and identify work which needs to be done to take the best advantage of them:
    - e.g. triggering in ATLAS,CMS; data mining triggers in LHCb; better EM calo in LHCb; dedicated runs of Belle II for $b\bar{b}$ spectroscopy, use of central collisions at LHC (glueballs?), exotic hadrons in heavy-ion program, …
- Other experimental projects, which have not been mentioned are welcome to contribute

Charmonium above the flavor threshold: more exotic states than $c\bar{c}$ states!