Tetraquarks and Pentaquarks

based in part on forthcoming IoP eBook by TG and Greig Cowan
also drawing extensively on Rev. Mod. Phys. 90 (2018) 015003

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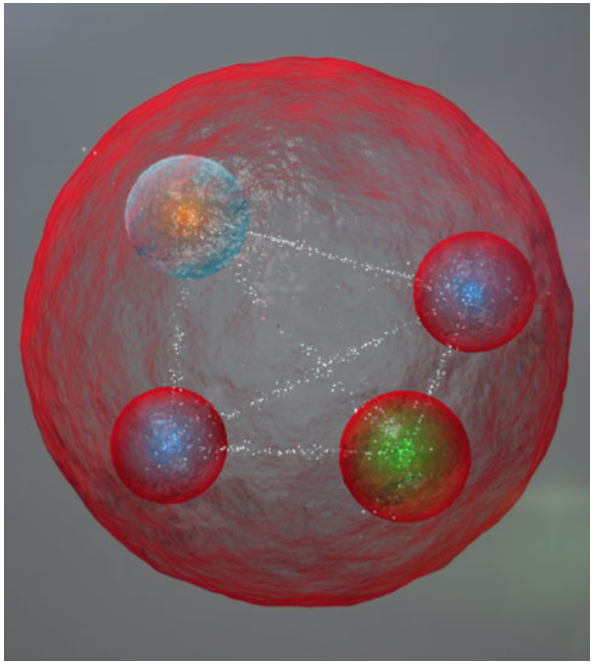
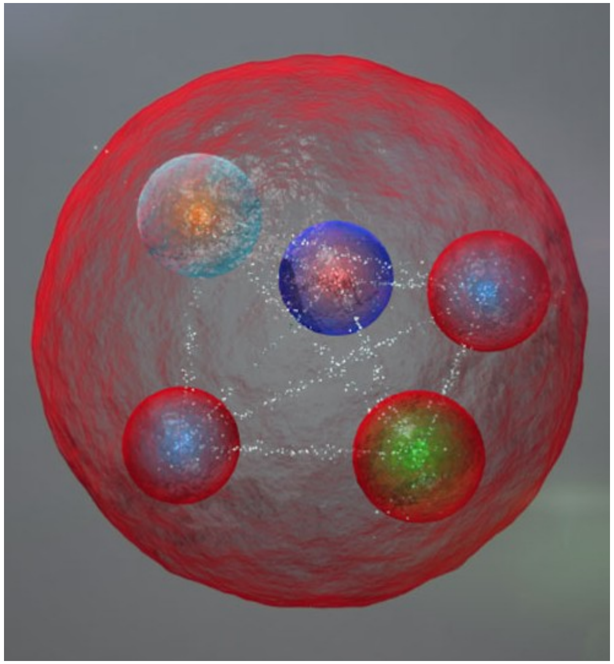
Seminar at University of Birmingham
2nd May 2018





The birth of the quark model

- Nowadays, usual to think of hadrons as being either
  - $q\bar{q}$ mesons or qqq baryons ($\overline{qqq}$ antibaryons)
- But these are not the only options, as has been known since the start of the quark model

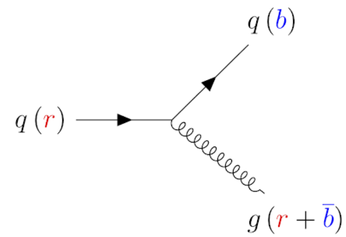
> Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

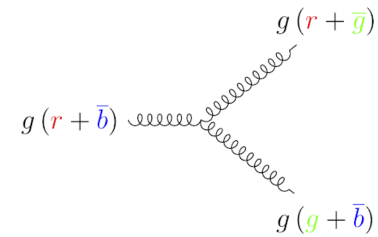
M. Gell-Mann, Phys. Lett. 8 (1964) 214

- Where are the $qq\overline{qq}$ tetraquarks and $qqqq\bar{q}$ pentaquarks?

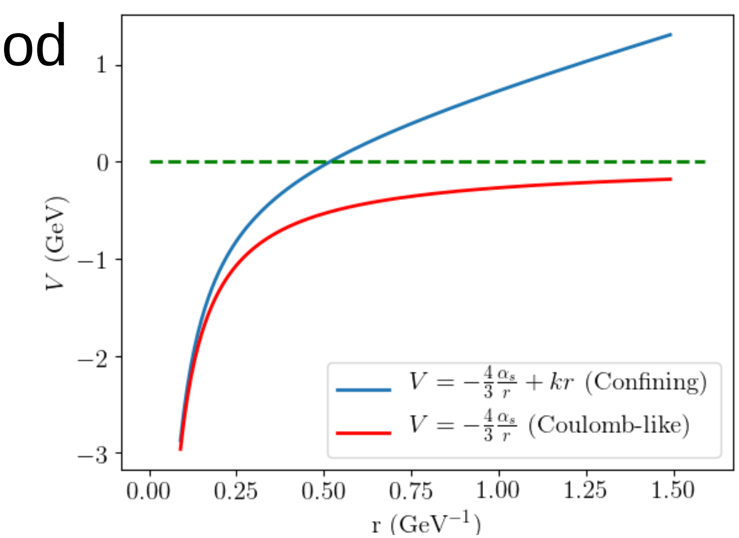
QCD basics

- Due to confinement, bound states must be colourless
  - rgb (baryons) or r$\bar{r}$+g$\bar{g}$+b$\bar{b}$ (mesons)
  - thus, $\bar{r}$ ≡ gb, etc., as regards SU(3)
  - important for diquark model
    - baryons can be modelled as quark-diquark mesons





- Perturbative methods do not work at low energies
  - can use NRQCD based on an effective potential
  - lattice QCD important & predictive method
    - limited by available computing power
    - not a silver bullet to understand hadrons



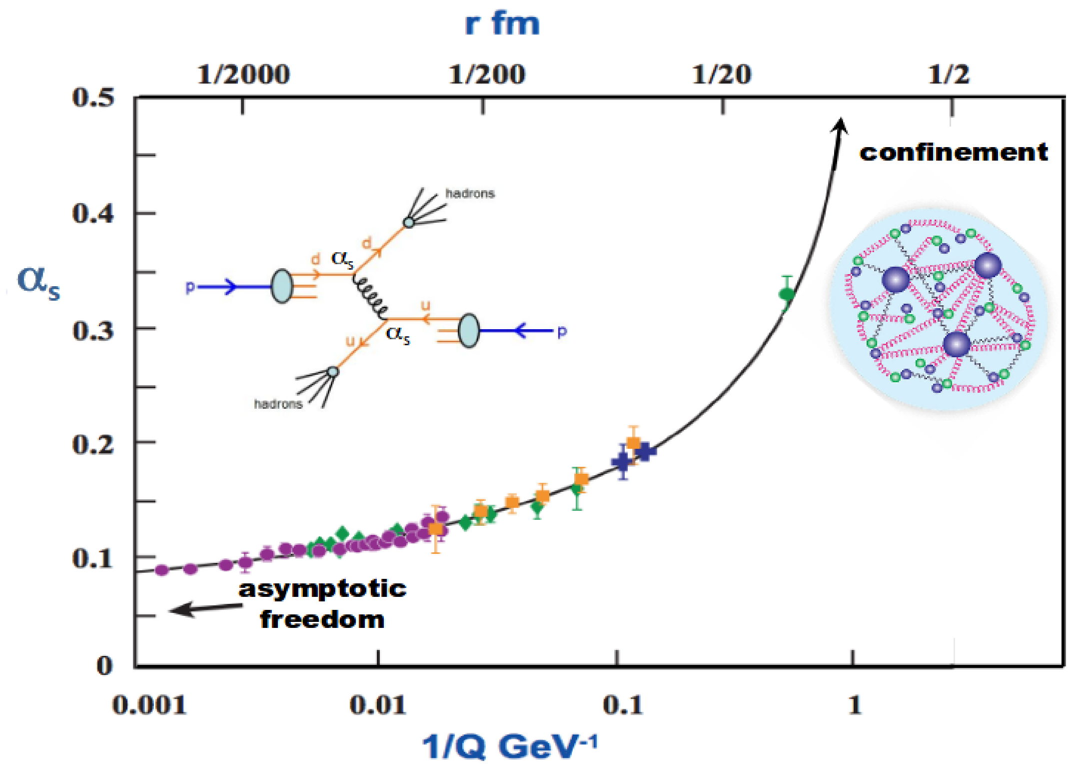
What do we learn from hadrons?

- New states, bound by QCD, do not test the SM per se
- Yet they do provide insight into a murky corner of the SM, namely confinement

Think you understand confinement?

Solve the Millenium prize!

http://www.claymath.org/millennium-problems/yang--mills-and-mass-gap



Rev. Mod. Phys. 90 (2018) 015003

What do we learn from hadrons?

- New states, bound by QCD, do not test the SM per se
- Yet they do provide insight into a murky corner of the SM, namely confinement
- Understanding strong interactions could be important for new high energy phenomena
  - Higgs boson as a composite state
  - Strong interactions in a dark sector (e.g. arXiv:1602.00714)
  - Hadronic dark matter?
- Exotic spectroscopy is an open and fast moving field – exciting and fun to be involved
  - n.b. will use “exotic” to refer to anything that is not “conventional”

A stable sexaquark?

arXiv:1708.08951

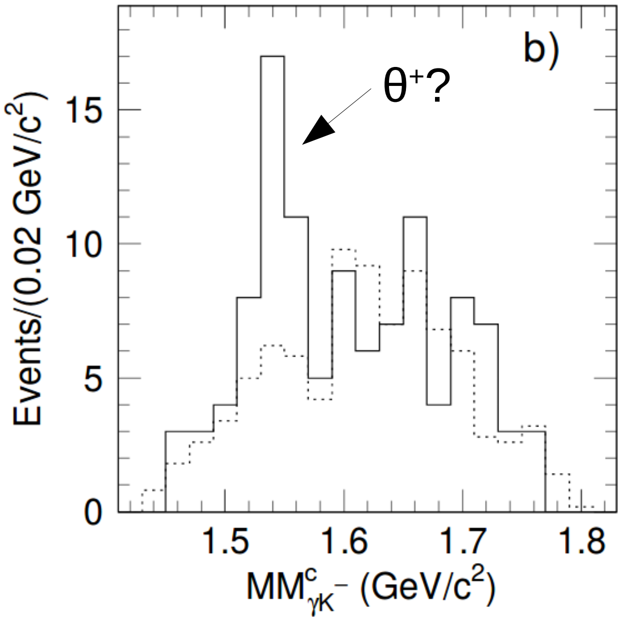
- The uuddss sexaquark S
  - with baryon number 2 (similar states sometimes called dibaryons)
  - has a totally symmetric wavefunction, hence large binding energy
  - if $m_S < m_d + m_e \sim 2(m_p + m_e)$ is completely stable
  - else if $m_S < m_p + m_e + m_\Lambda$ is effectively stable
  - could be a dark matter candidate
- This model has issues, but still interesting
  - Oxygen decay through $NN \rightarrow SX$ not seen in Super Kamiokande (arXiv:1803.10242)
- Dedicated searches possible (e.g. in Y decay at B factories)

Why is this relevant <u>now</u>?

- Searches for exotic hadrons have been ongoing for ~50 years *with light quarks*
  - some claimed signals for pentaquarks which led to nothing …

LEPS collaboration
Phys.Rev.Lett. 91 (2003) 012002

- See also DIANA, CLAS, SAPHIR, NA49, HERMES, SVD, COSY-TOF, ZEUS, H1, …
- Many peaks disappeared with more data and more careful analyses
- Non-observations in other experiments
- See hep-ph/0703004 for a review
- (Not all claims completely disproved yet)

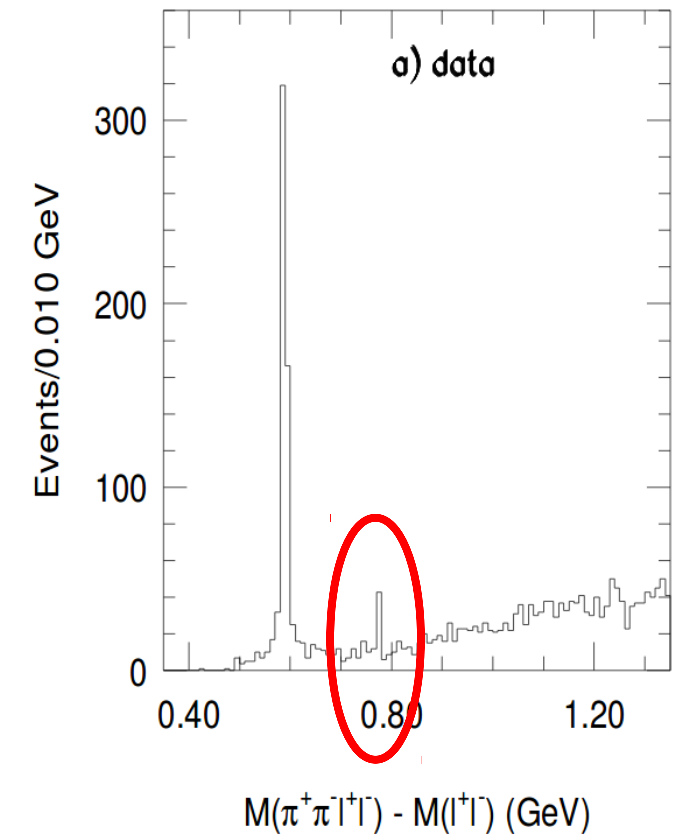


Why is this relevant <u>now</u>?

- Searches for exotic hadrons have been ongoing for ~50 years *with light quarks*
  - some claimed signals for pentaquarks which led to nothing …
  - too many scalar states
    - with an unexpected pattern of masses ($K\bar{K}$ threshold effect?)
    - $\pi_1(1400)$, $\pi_1(1600)$ states with $J^{PC} = 1^{-+}$
      - i.e. manifestly exotic quantum numbers
  - difficult to make definitive claims in light hadron sector
    - states broad and overlapping
- New possibilities in latest generations of heavy flavour experiments, especially for $c\bar{c}$ (and related) states

X(3872)

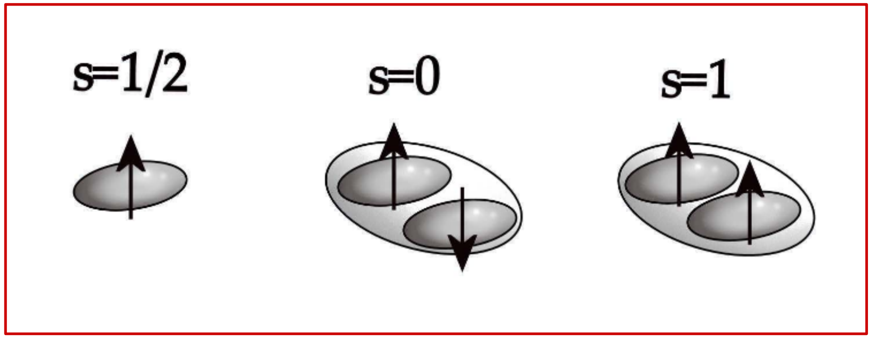
- Unexpected discovery by the Belle collaboration in 2003
  - $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$
  - Rapidly confirmed by
    - BaBar, CDF, D0
    - (later LHCb, CMS, ATLAS)
  - Produced in
    - B decay, pp & $p\bar{p}$ collisions
  - Decays to
    - $J/\psi\rho$, $J/\psi\omega$, $J/\psi\gamma$, $D\bar{D}^*$
- Does not fit conventional $c\bar{c}$ spectrum



Phys.Rev.Lett. 91 (2003) 262001

Conventional $q\bar{q}$ spectroscopy

- Define, as usual, intrinsic spin S, orbital angular momentum L, total angular momentum ("spin") $J = L \oplus S$
- q & $\bar{q}$ have opposite parity: $P = -1^{L+1}$
- charge conjugation: $C = (-1^{S})(-1^{L})$
- For L=0, have $J^{PC} = 0^{-+}$ (η_c), 1^{--} (J/ψ)



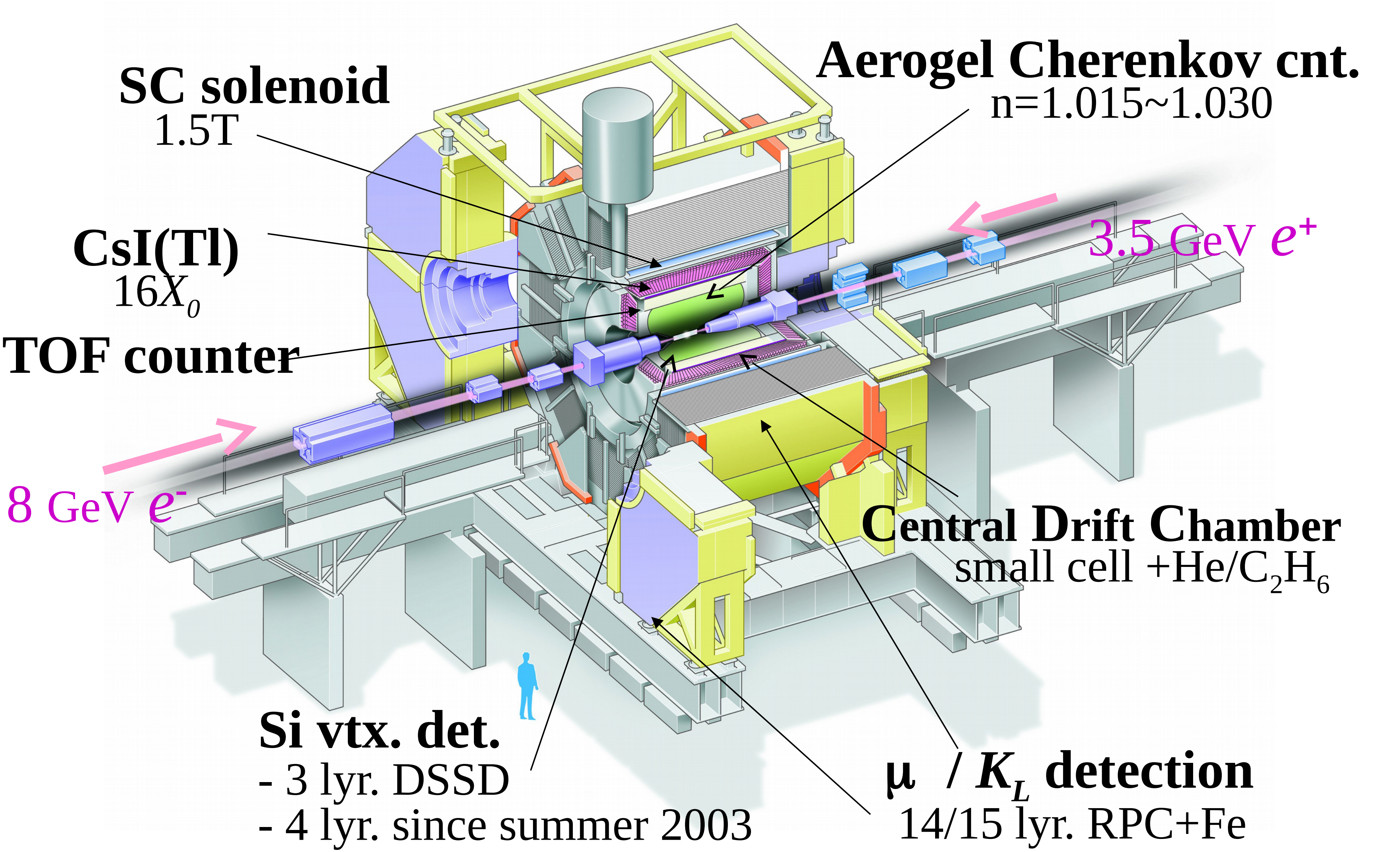
- For L=1, have $J^{PC} = 0^{++}$ (χ_{c0}), 1^{+-} (h_c), 1^{++} (χ_{c1}), 2^{++} (χ_{c2})
  - cannot get manifestly exotic quantum numbers (e.g. $J^{PC} = 0^{--}$, 0^{+-}, 1^{-+}) from $q\bar{q}$
- Other notations also used: $n^{2S+1}L_J$, $\psi(2S)$, X(3872), ...
  - as usual in spectroscopy, L = 0,1,2,3 ... denoted S,P,D,F ...
- Simple prediction for pattern of masses and quantum numbers
  - need to measure both, as well as total widths, branching fractions, ...

Measuring quantum numbers

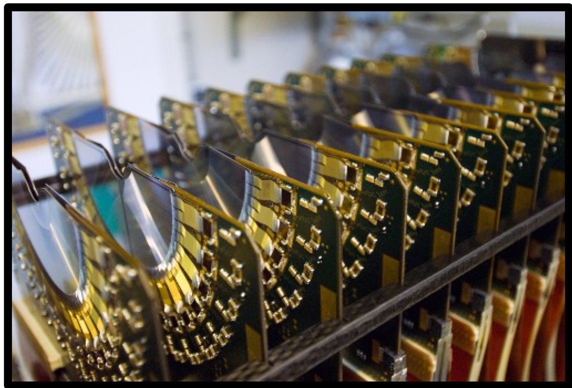
- Can be inferred from production or decay processes
  - both P and C conserved, since strong or electromagnetic processes
- Production
  - in e^+e^- collisions then $J^{PC} = 1^{--}$
  - in hadron collisions → usually no information (unknown additional particles)
  - in B decay → initial state constrained
- Decay
  - need to measure angular momentum between final state particles
    - require constrained initial and final states – B decay chain ideal
  - (some exceptions, e.g. $X(3872) \to J/\psi\gamma$ fixes C=+1)

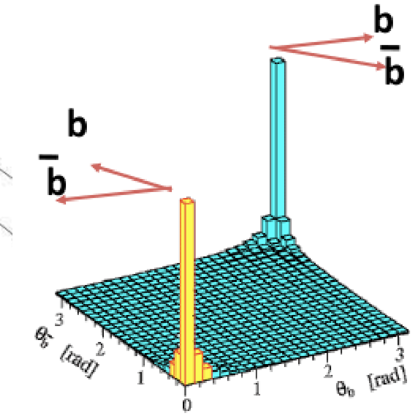
Large, clean samples of B decays at B factories and LHCb

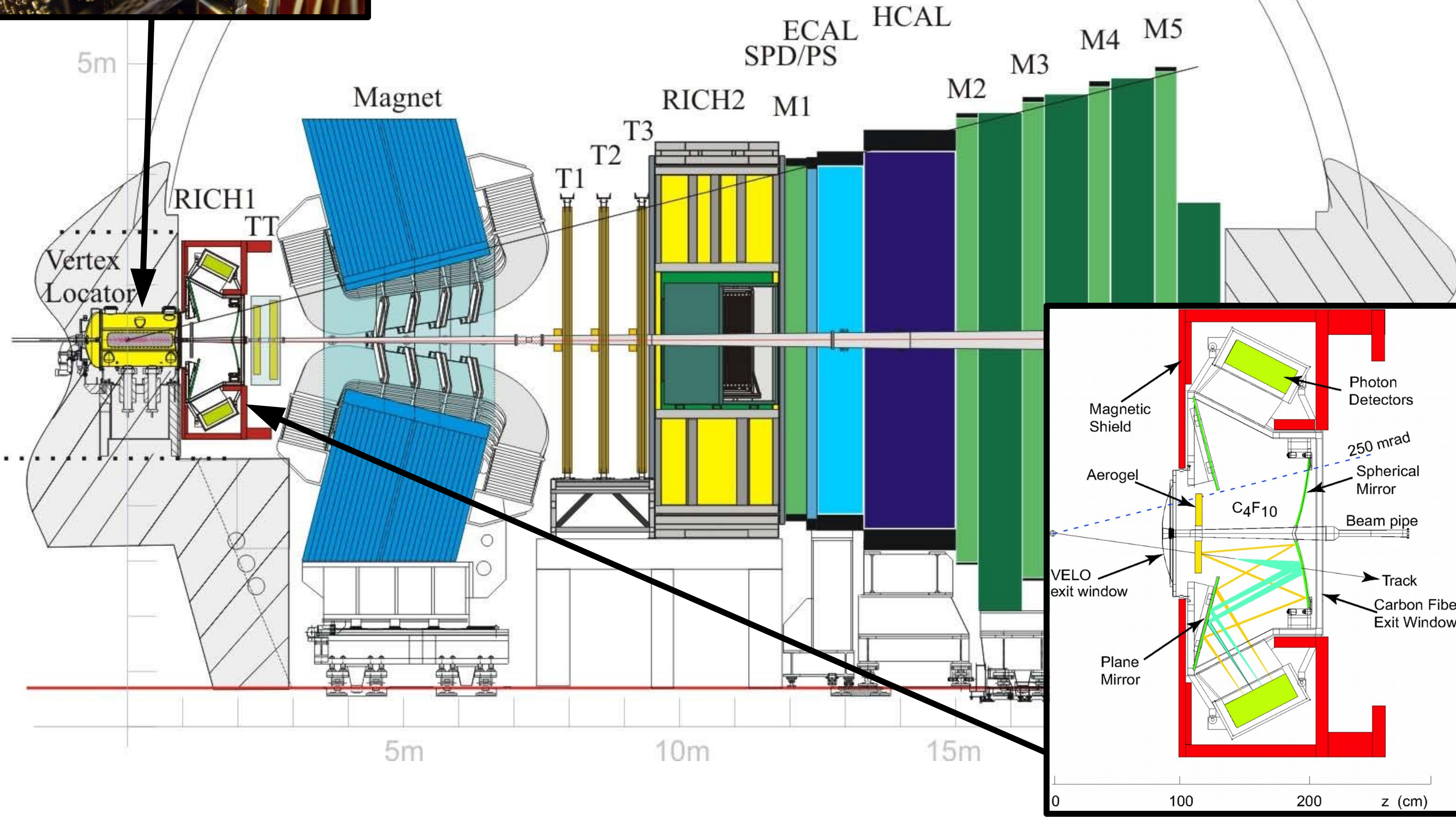
Belle Detector



LHCb detector





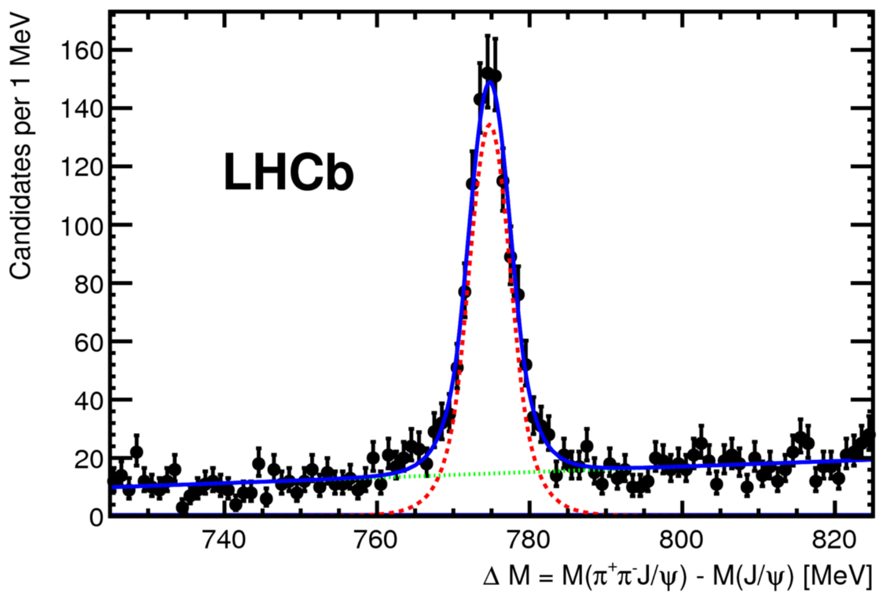


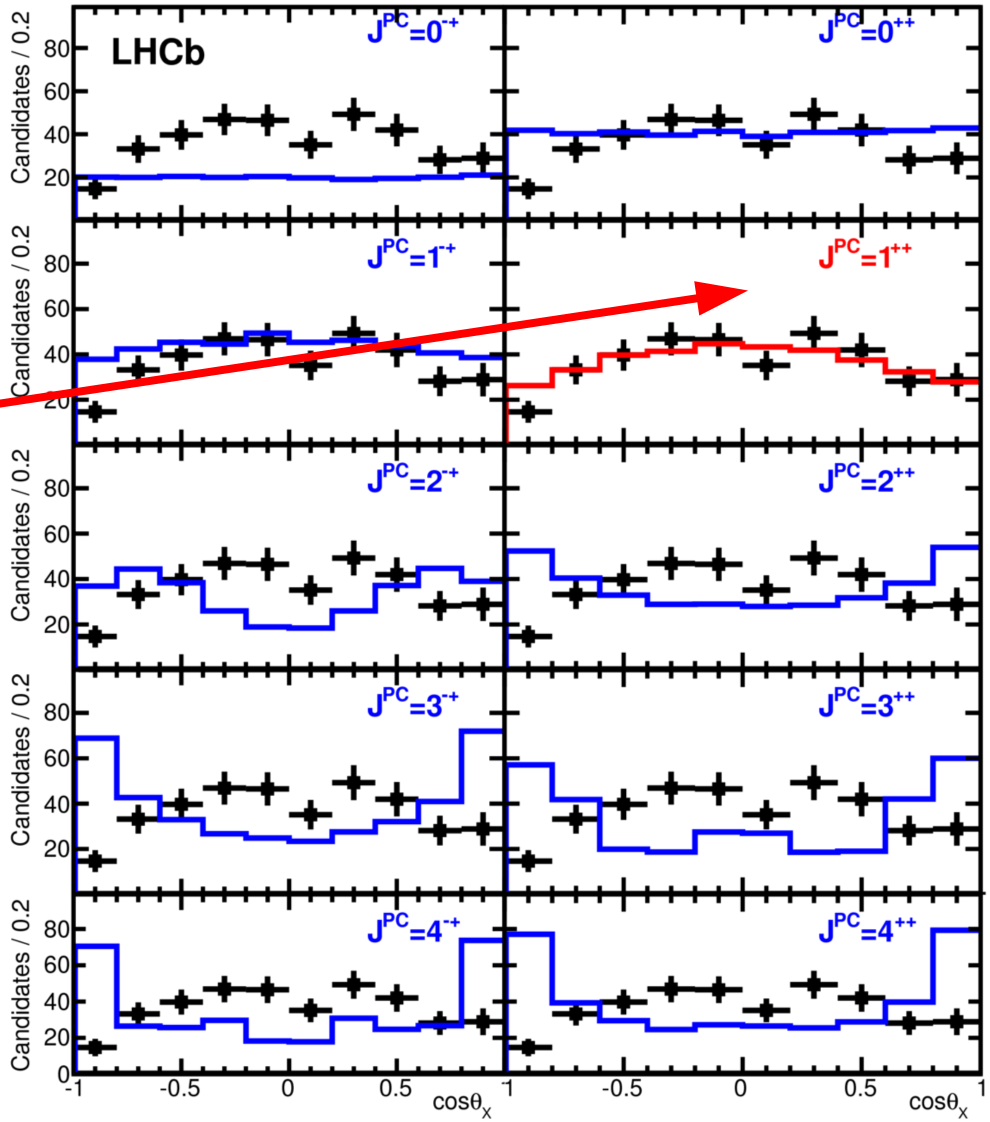
Measuring X(3872) quantum numbers

Phys. Rev. D92 (2015) 011102

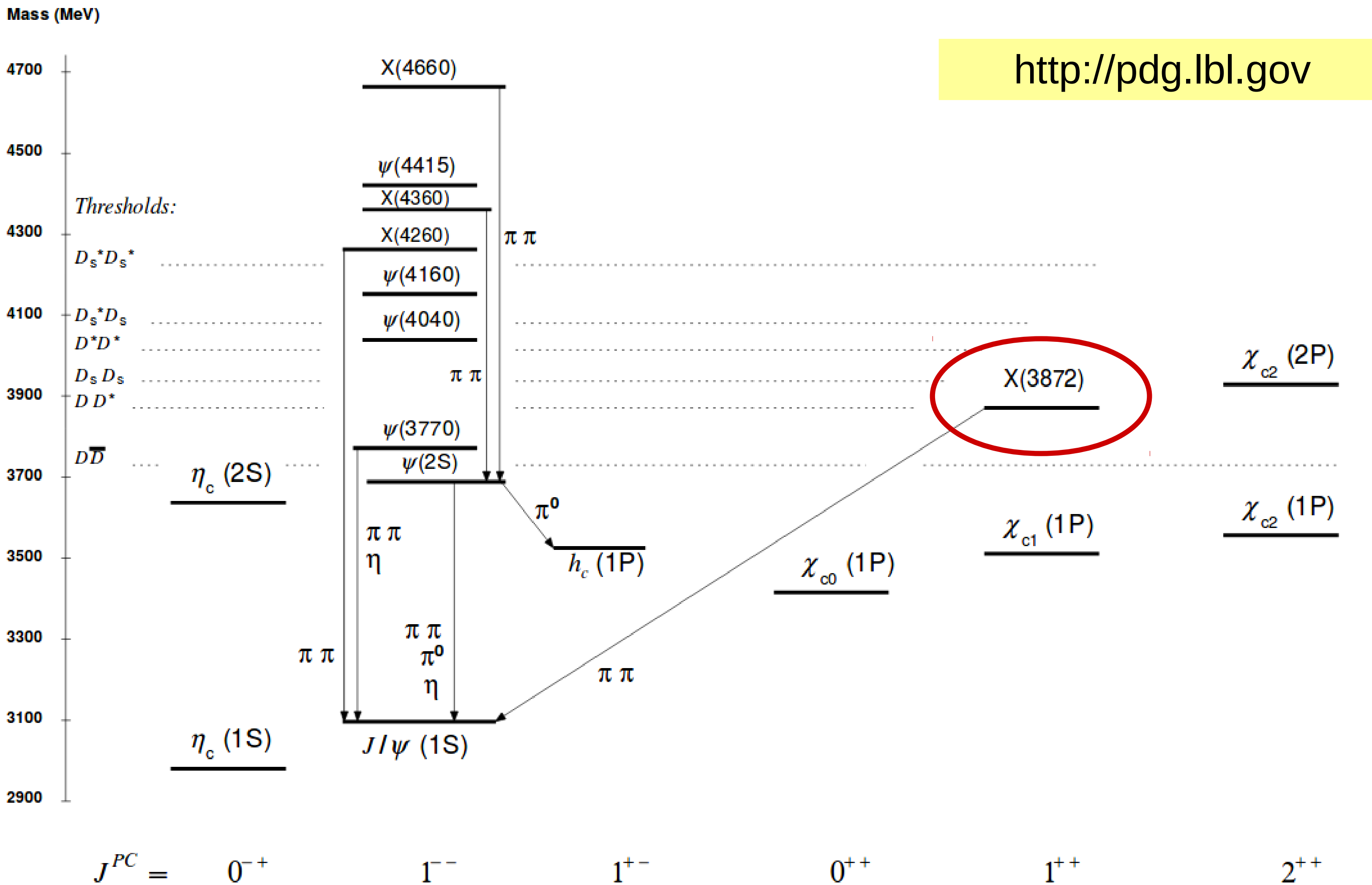
Example: angular distributions in
$B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$

Unambiguously determines $J^{PC} = 1^{++}$
(projections in plots do not carry all information)

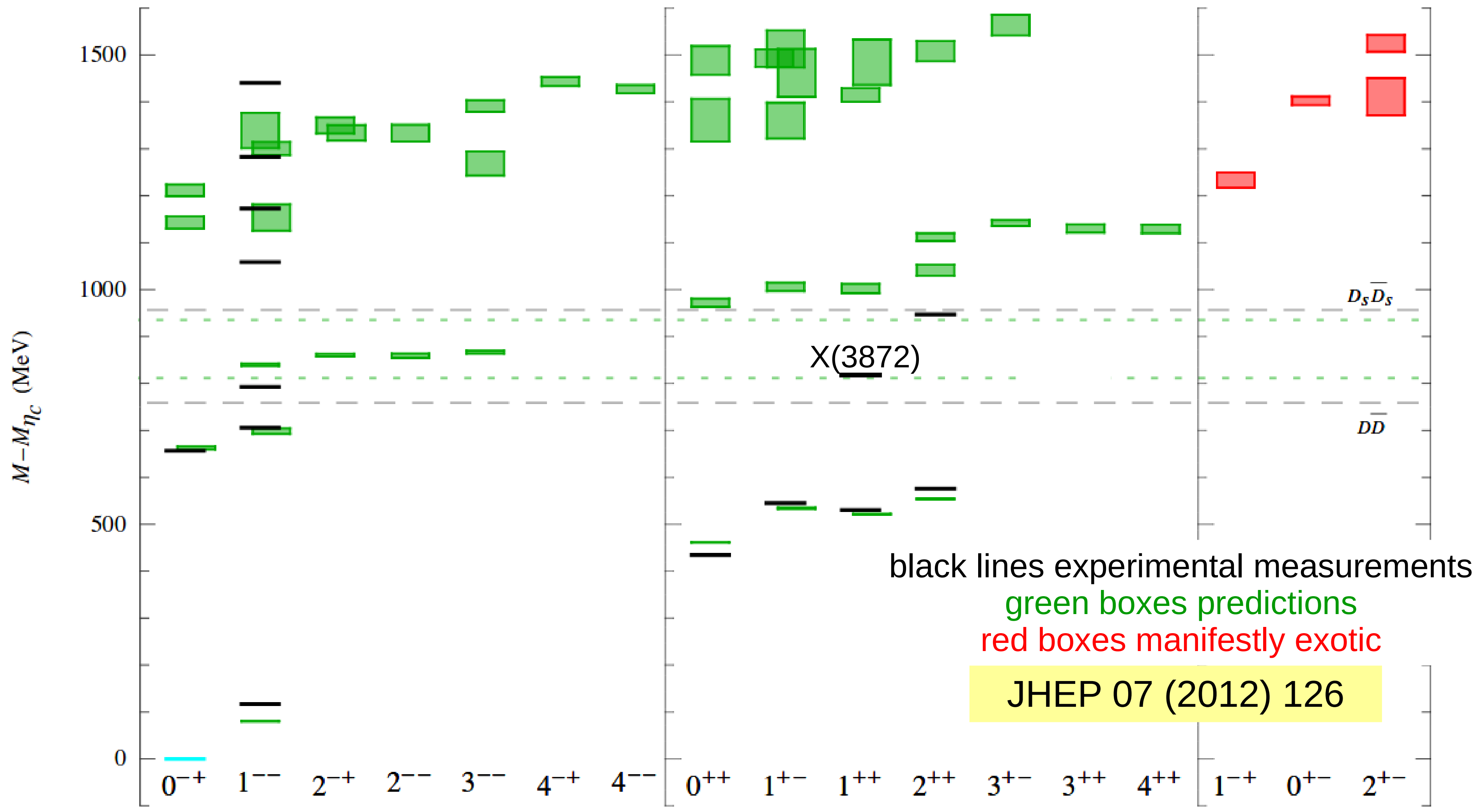




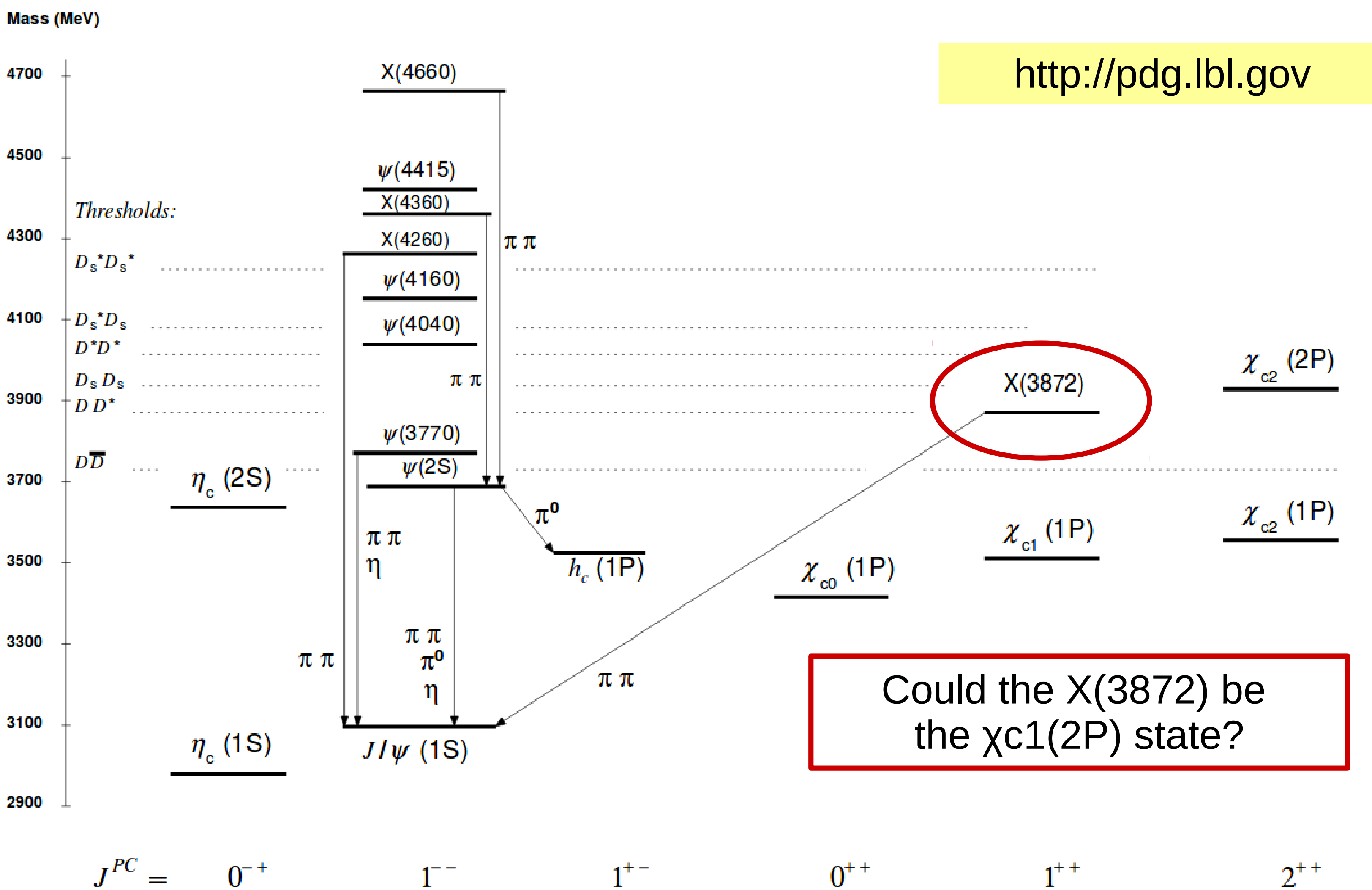
The $c\bar{c}$ spectrum



The $c\bar{c}$ spectrum from lattice QCD



The $c\bar{c}$ spectrum

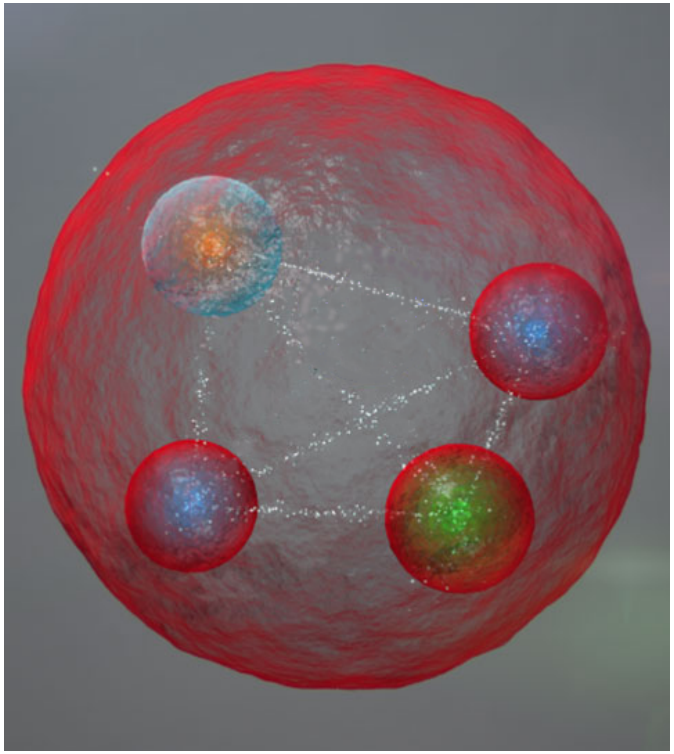


Could the X(3872) be the χc1(2P) state?

Could the X(3872) be the χ_{c1}(2P) state?

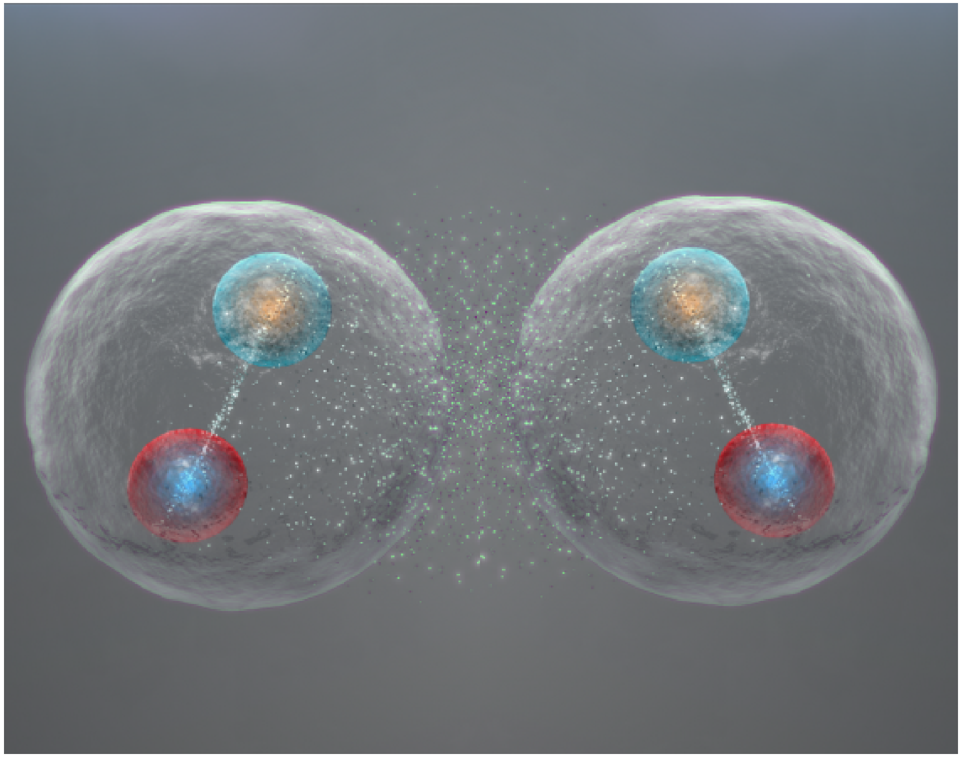
- Several strong arguments against:
  - isospin violation (decay to J/ψρ) not expected
    - near equality of branching fractions to J/ψρ & J/ψω
    - (isospin partners however not observed)
  - above threshold for decay to open charm but not significantly wider than χ_{c1}(1P)
    - only upper limit on X(3872) width measured so far
  - mass splitting relative to χ_{c2}(2P) state less than expected
    - mass suspiciously close to $D\bar{D}^*$ threshold
- If not, what is it?

Tightly bound tetraquark
(all quarks bound by gluons)



or

Meson-meson molecule
(bound by pion exchange)

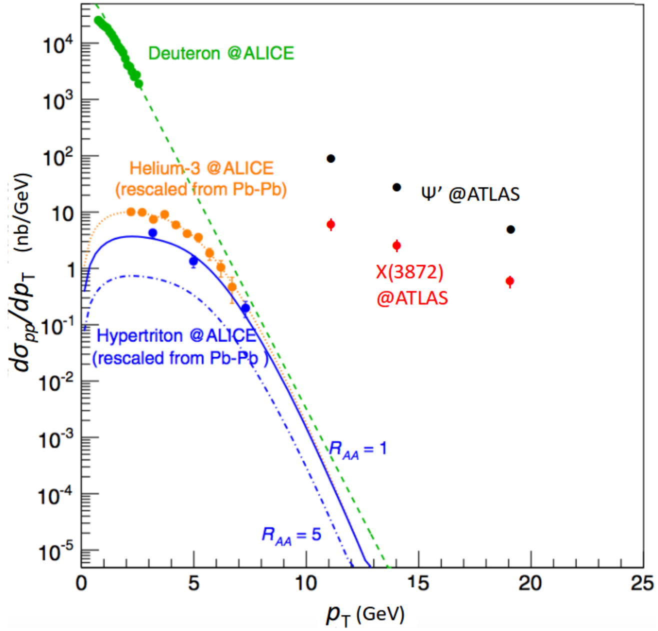


or some mixture with $c\bar{c}$,
or something else?

Simplified picture above:
most tightly bound models
involve diquarks

Molecular or tightly-bound?

- Molecular model ($D^0\bar{D}^{*0}$)
  - natural explanation for mass being near threshold
  - natural explanation for isospin violation
    - amplification of $D^{(*)+}$–$D^{(*)0}$ mass difference
  - production in pp ($p\bar{p}$) not as expected
    - could be explained by admixture with $\chi_{c1}(2P)$
    - lattice QCD calculations support this view (arXiv:1503.03257)



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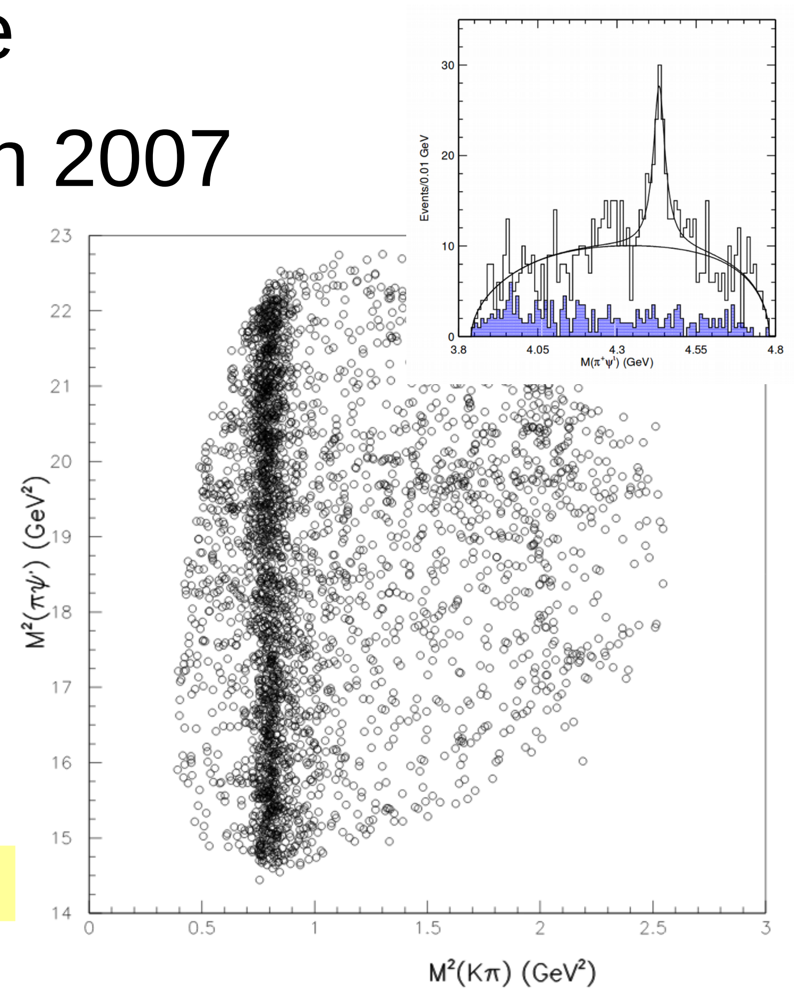
- Tightly bound diquarks ($[cu][\overline{cu}]$)
  - can explain isospin violation
  - predicts existence of isospin partners (not seen)

A smoking gun

- An unambiguous signal for exotic hadrons is a charged charmonium-like state
- Belle discovered a candidate in 2007
  - $B^0 \rightarrow Z(4430)^- K^+$,
  - $Z(4430)^- \rightarrow \psi(2S)\pi^-$
- Not confirmed by BaBar
  - analysis method too simplistic?



Phys.Rev.Lett. 100 (2008) 142001

Z(4430) confirmation by LHCb

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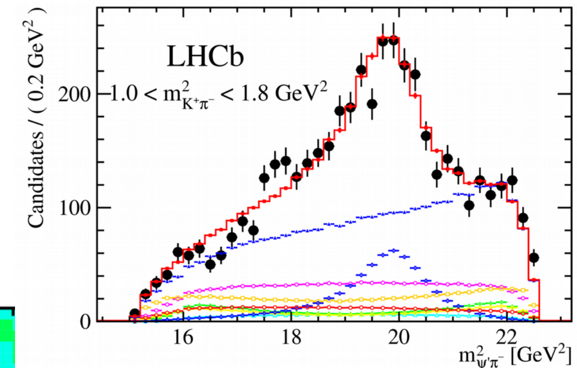
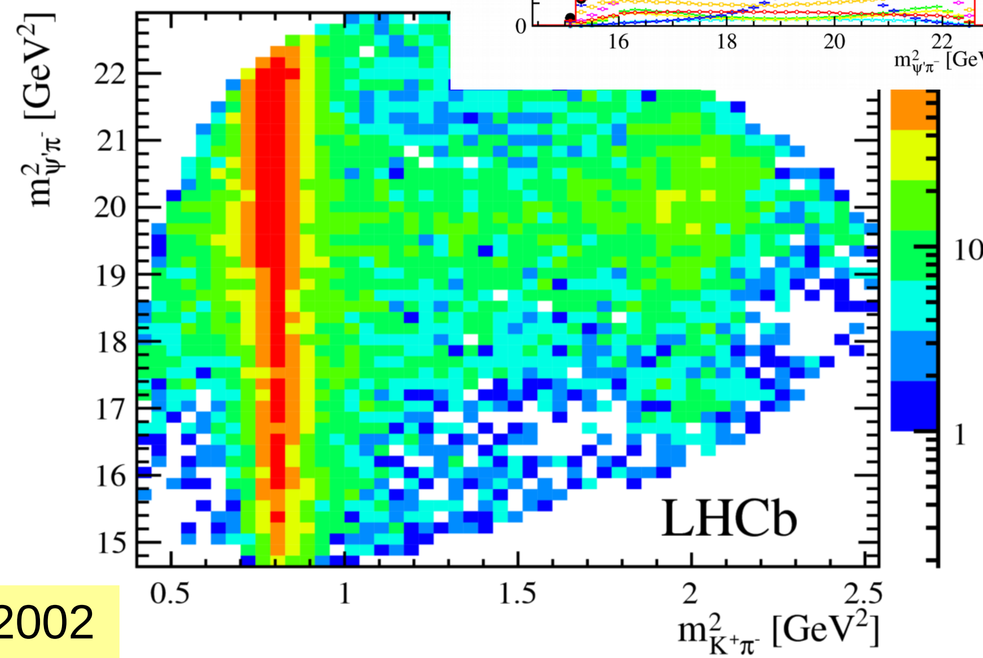
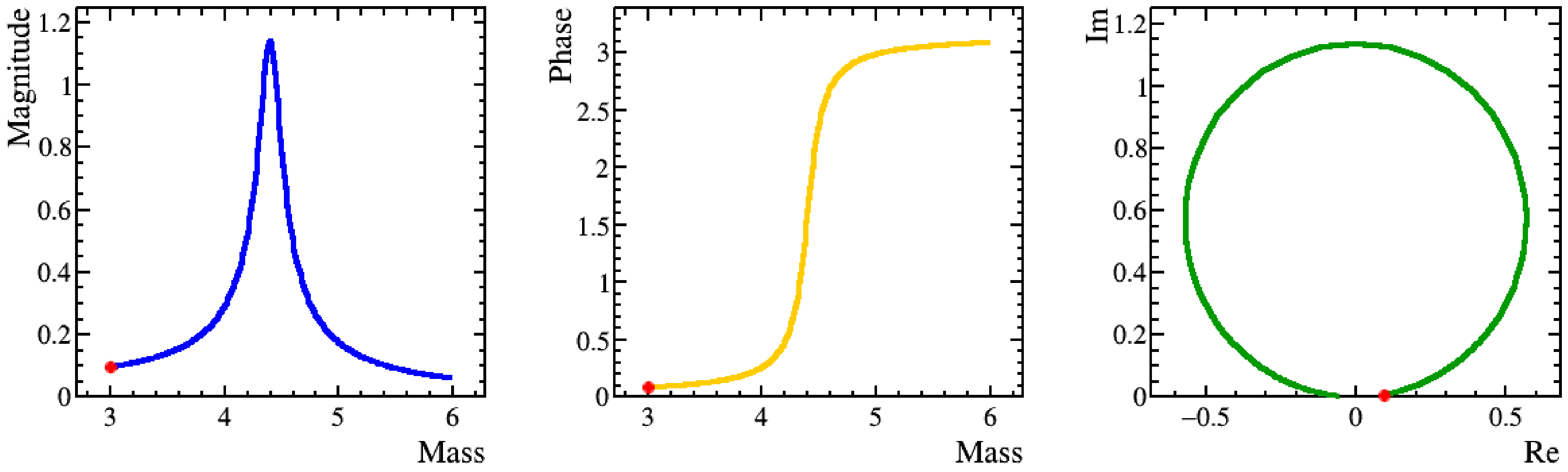
- Belle discovered a candidate in 2007
  - $B^0 \to Z(4430)^- K^+$,
  - $Z(4430)^- \to \psi(2S)\pi^-$
- Confirmed by LHCb
  - Full 4D amplitude analysis
  - (necessary to determine parameters correctly)
  - Quantum numbers $J^P = 1^+$





Phys. Rev. Lett. 112 (2014) 222002

Resonant character of the Z(4430)



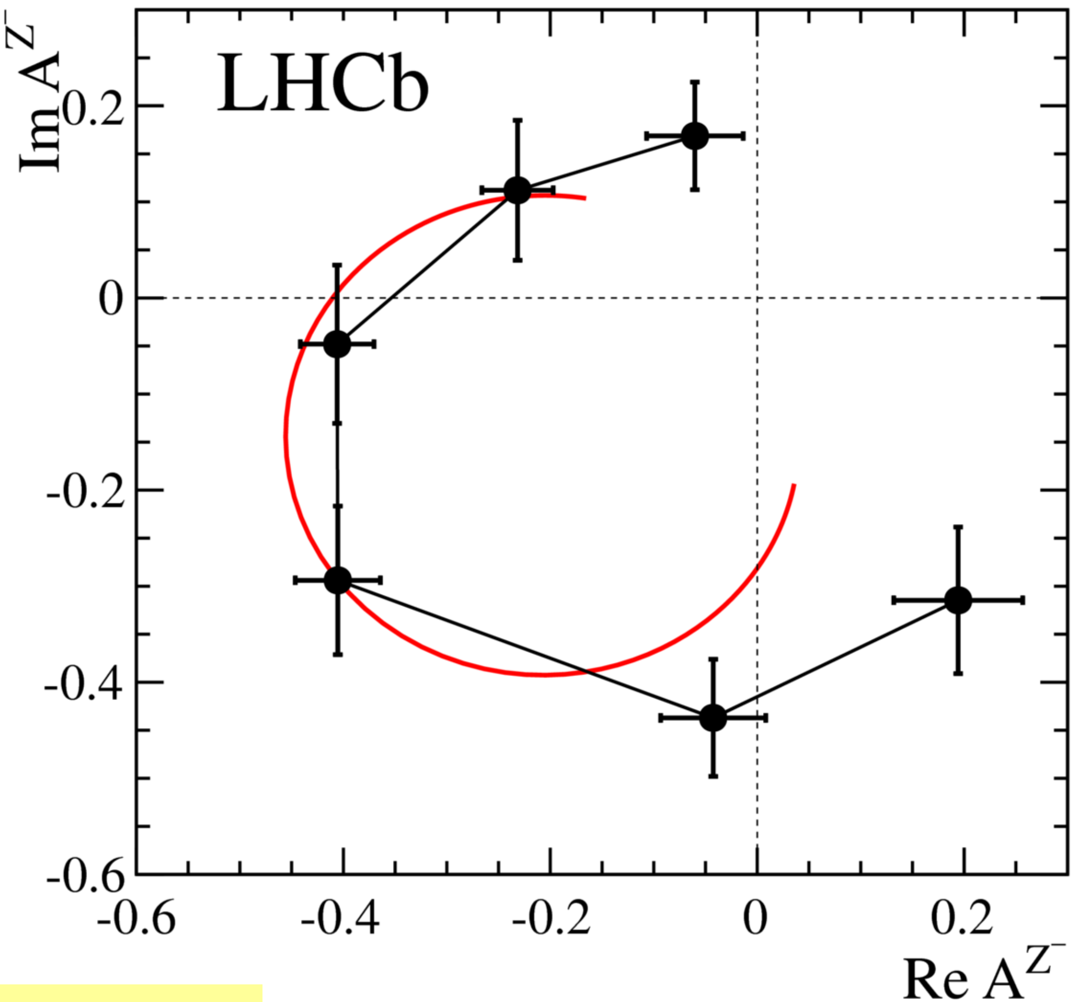
- A Breit-Wigner function has a characteristic rapid change of phase near the resonance peak

$$A(s) \propto \frac{1}{m^2 - s^2 + im\Gamma(s)}$$

- Plotting the amplitude in the Argand plane, the lineshape maps out a circle (anticlockwise, as mass increases)
- Can be measured in an amplitude analysis

Resonant character of the Z(4430)

- Complex amplitude measured in 6 bins of m(ψ(2S)π⁻)
- Found to follow expected anticlockwise trajectory in Argand plan
- Rules out models where Z(4430) arises due to kinematic effects

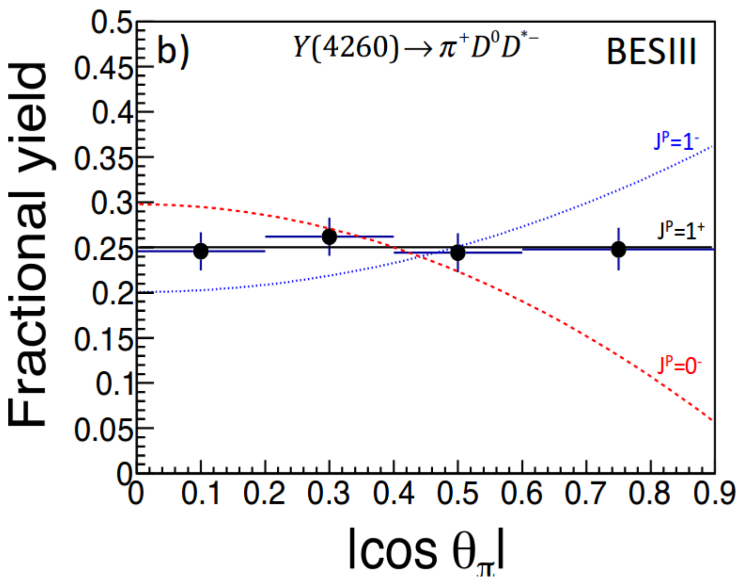


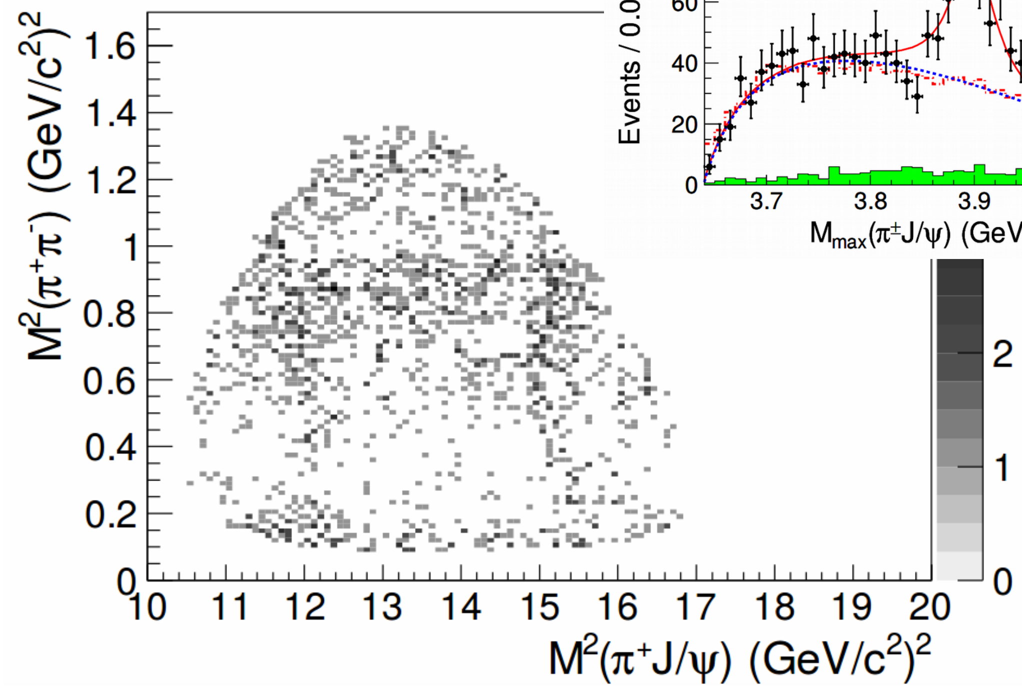
Phys. Rev. Lett. 112 (2014) 222002

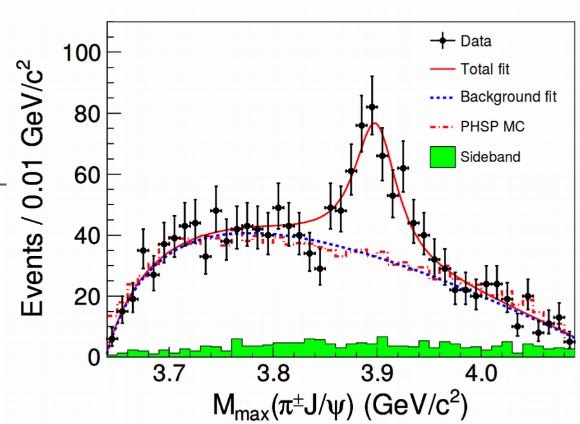
More smoking guns

- BESIII and Belle both reported $Y(4260) \rightarrow Z(3900)\pi$, $Z(3900) \rightarrow J/\psi\pi$
- Later seen in $D\overline{D}^*$ decay mode
- Isospin (neutral) partner observed
  - both $J/\psi\pi$ and $D\overline{D}^*$ modes
- Quantum numbers $J^P = 1^+$

Phys. Rev. Lett. 110 (2013) 252001
Phys. Rev. Lett. 110 (2013) 252002







Phys. Rev. Lett. 112 (2014) 022001

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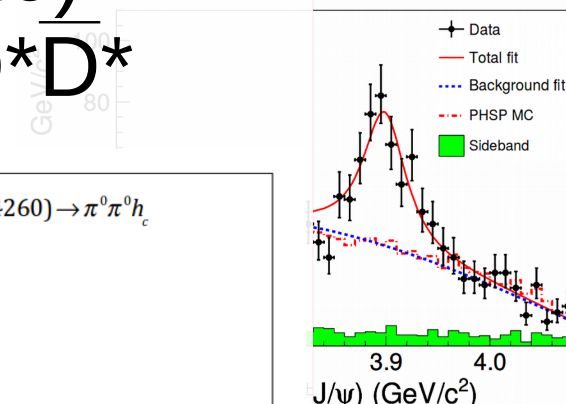
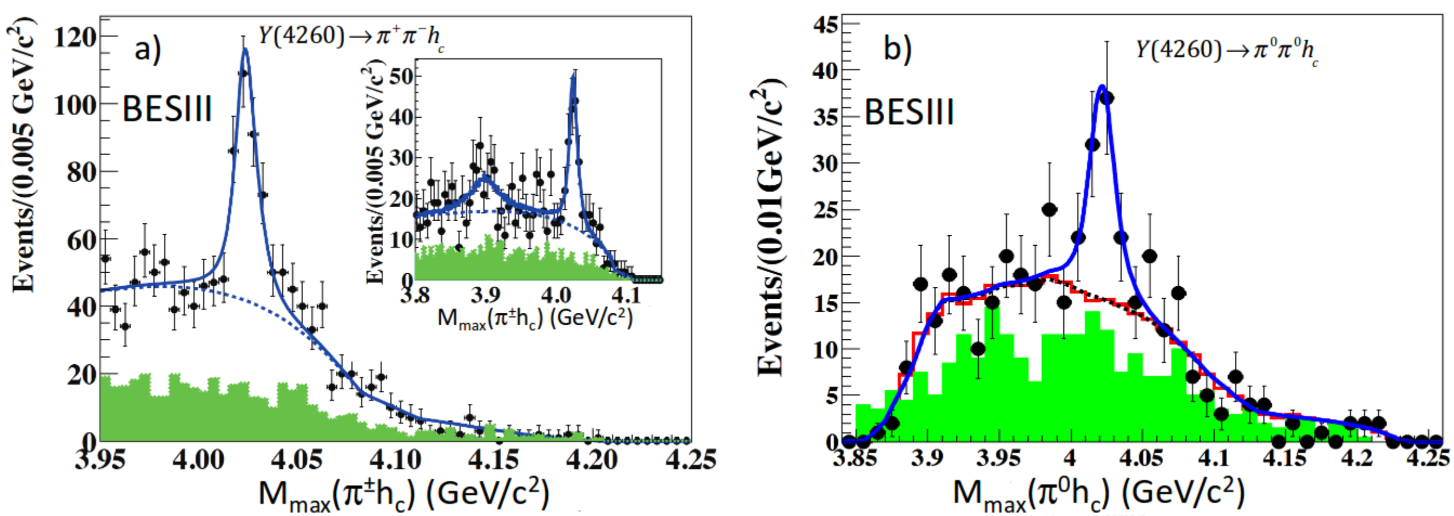
Phys. Rev. Lett. 110 (2013) 252002

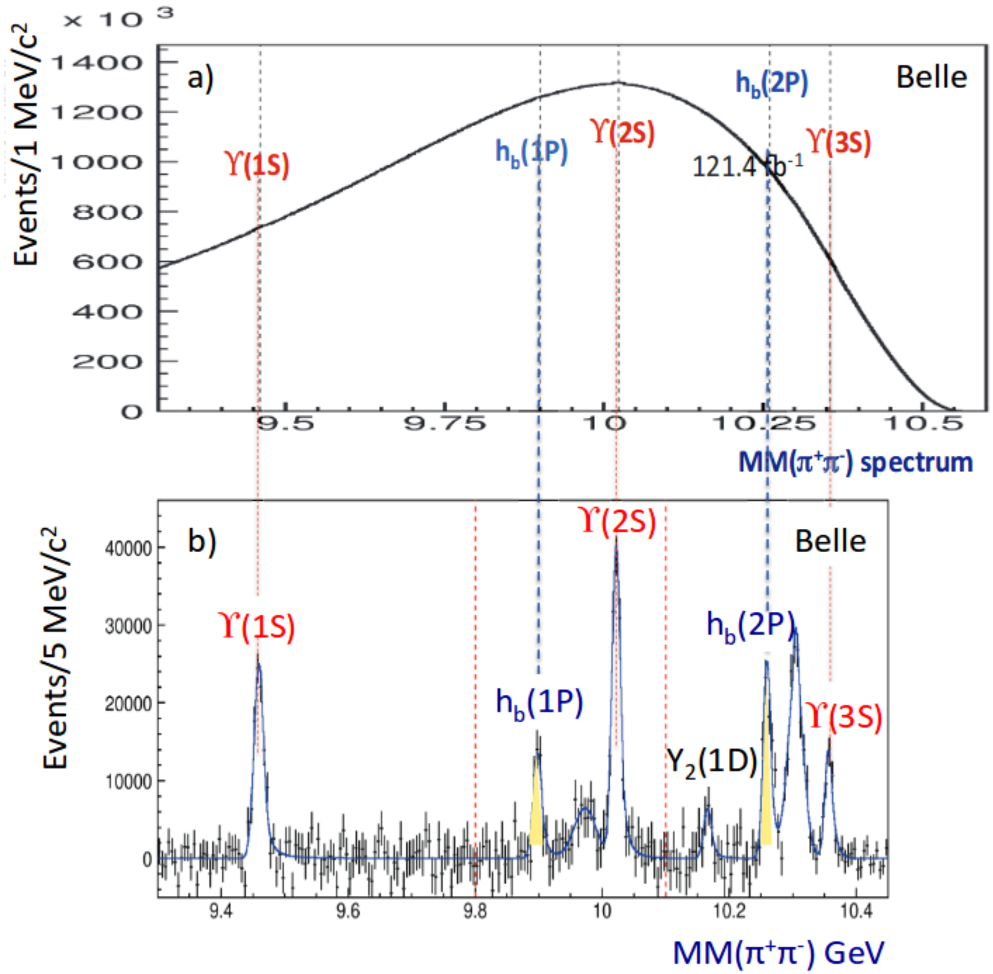


Similar isospin triplet Z(4020) seen decaying to $h_c\pi$ and $D^*\bar{D}^*$



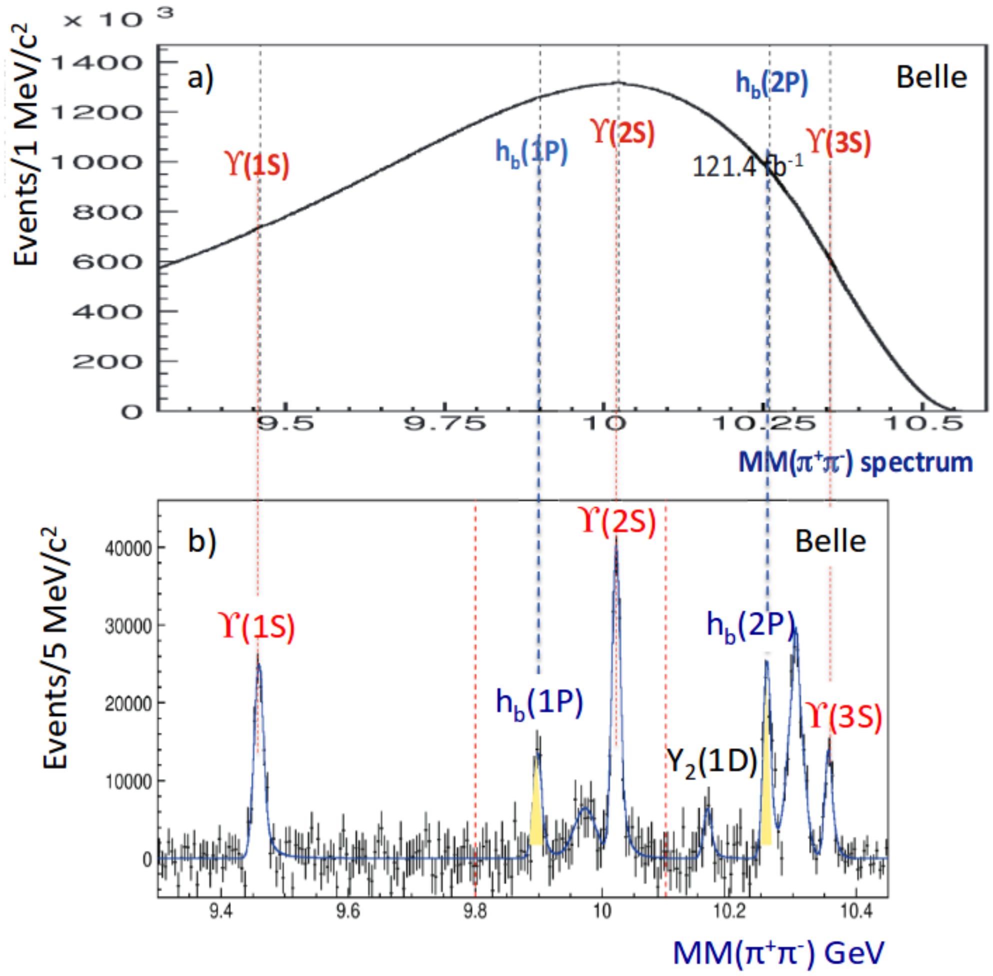
Phys. Rev. Lett. 112 (2014) 022001

Smoking guns in the $b\bar{b}$ system



- Belle observed anomalously high rate of $e^+e^- \rightarrow Y(10860) \rightarrow Y(nS)\pi^+\pi^-$
- Investigation of recoil mass revealed surprising presence of $h_b(1P)$ and $h_b(2P)$ states – first observations!

Smoking guns in the $b\bar{b}$ system



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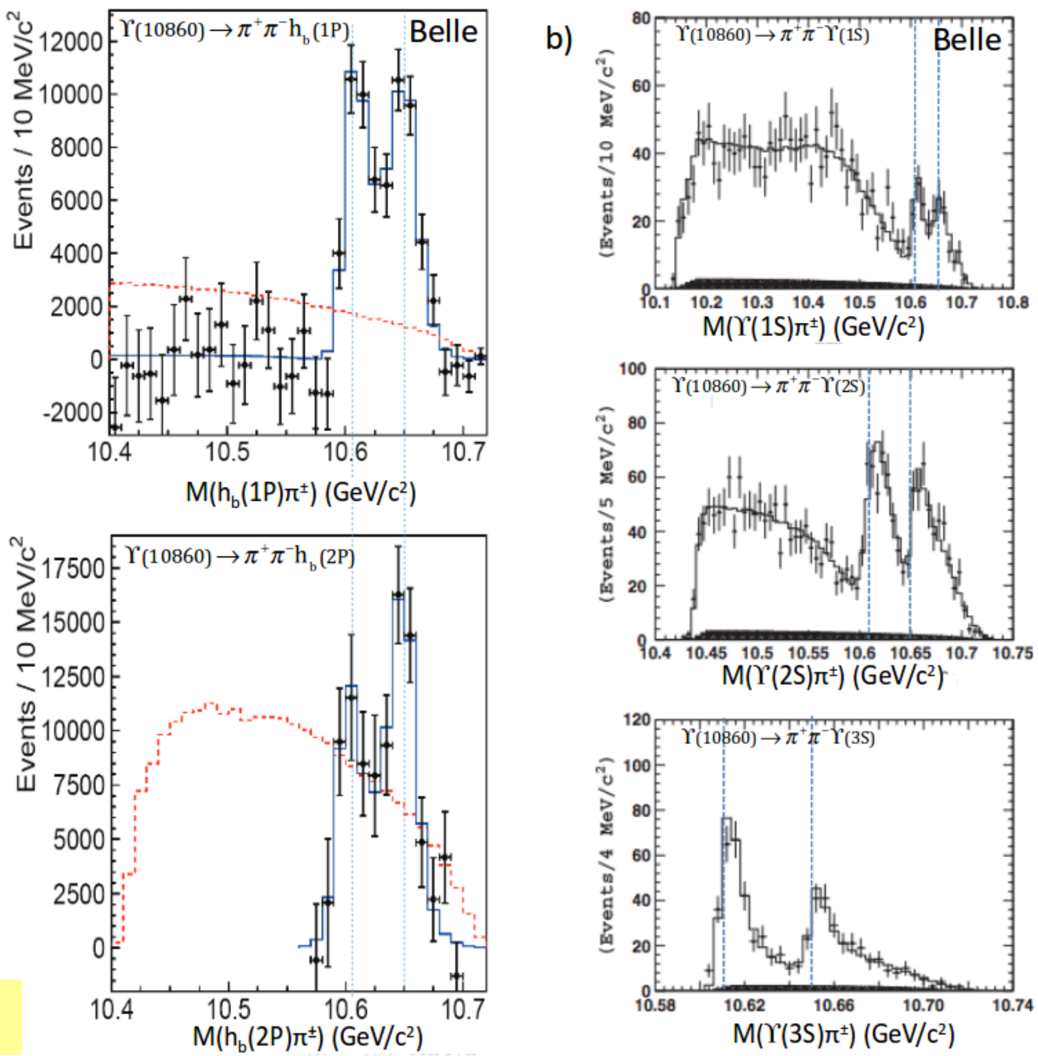
- Investigation of recoil mass revealed surprising presence of $h_b(1P)$ and $h_b(2P)$ states – first observations!
- Allows study of the $Y(nS)\pi$ and $h_b(nP)\pi$ mass distributions

Phys. Rev. Lett. 100 (2008) 112001
Phys. Rev. Lett. 108 (2012) 032001

Smoking guns in the $b\bar{b}$ system

- Two peaks, $Z_b(10610)$ and $Z_b(10650)$ seen with consistent properties in five different decay modes!
- Quantum numbers $J^P = 1^+$
- Masses near to $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds
  - decays to $B\bar{B}^*$ and $B^*\bar{B}^*$ also seen
- Isospin partners observed

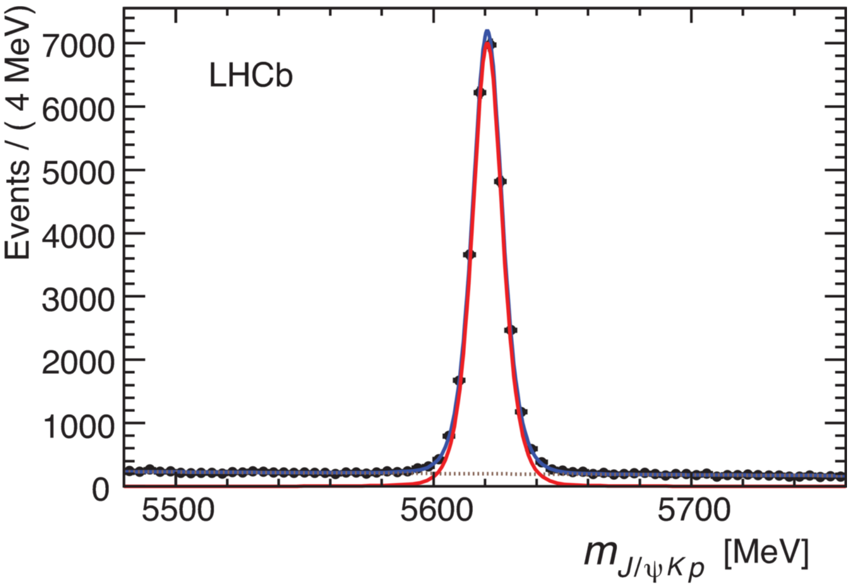


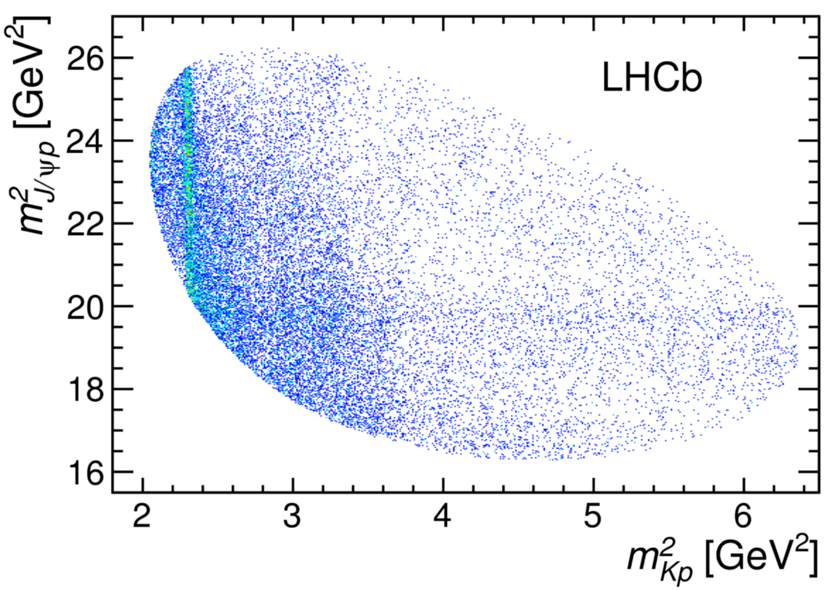
Phys.Rev.Lett. 108 (2012) 122001

Pentaquarks

- Large samples of b baryons produced at LHC
- Ideal to search for pentaquarks containing $c\bar{c}$
  - Particle identification important to reject B meson decay backgrounds
  - Strong advantage of LHCb (but hope ATLAS+CMS can contribute)
- Study of $\Lambda_b \rightarrow J/\psi p K^-$

Phys. Rev. Lett. 115 (2015) 072001

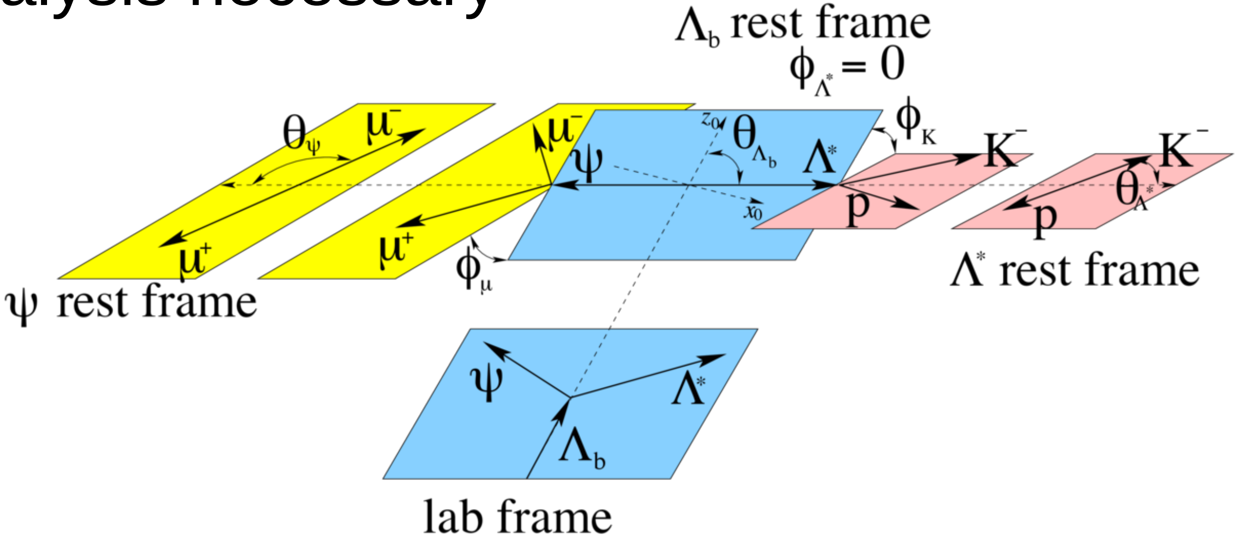




Amplitude analysis of baryon decay

Phys. Rev. Lett. 115 (2015) 072001

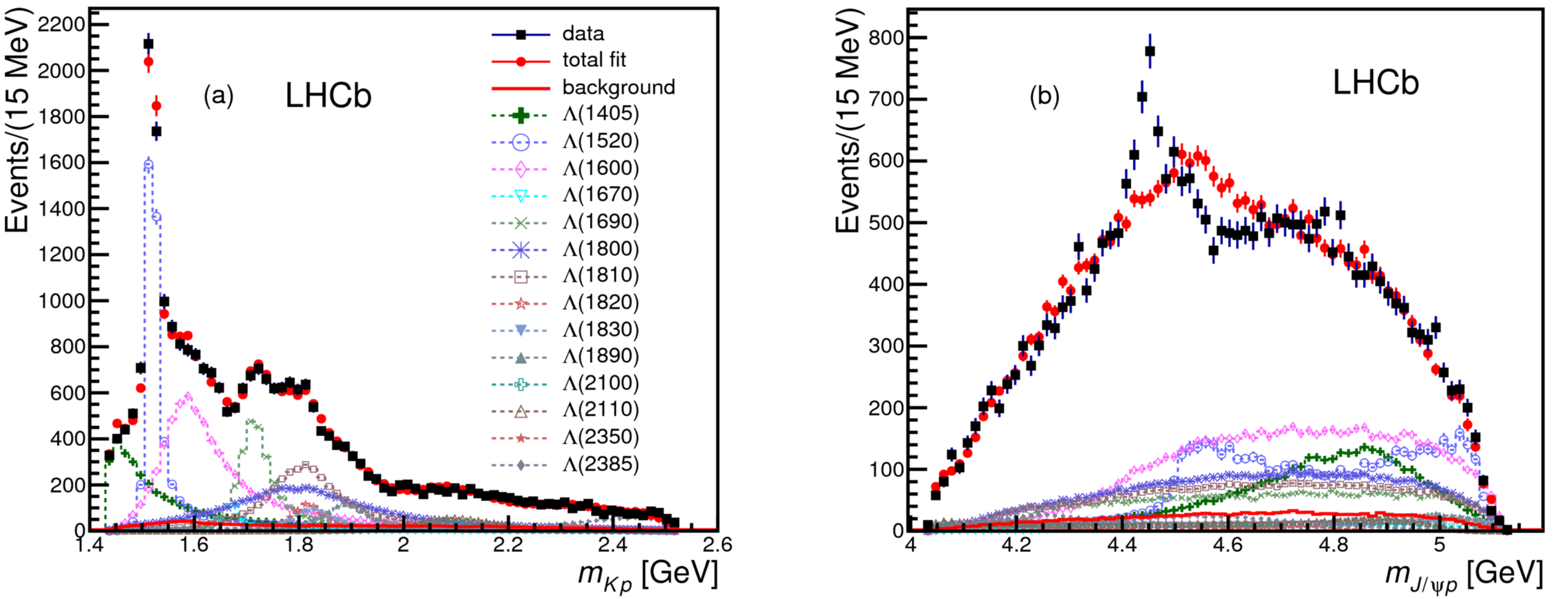
- Lesson from Z(4430)
  - full amplitude analysis is mandatory!
- Additional degrees of freedom for baryons
  - non-zero spin of initial and final state particles
  - 6D amplitude analysis necessary



Amplitude analysis of baryon decay

Phys. Rev. Lett. 115 (2015) 072001

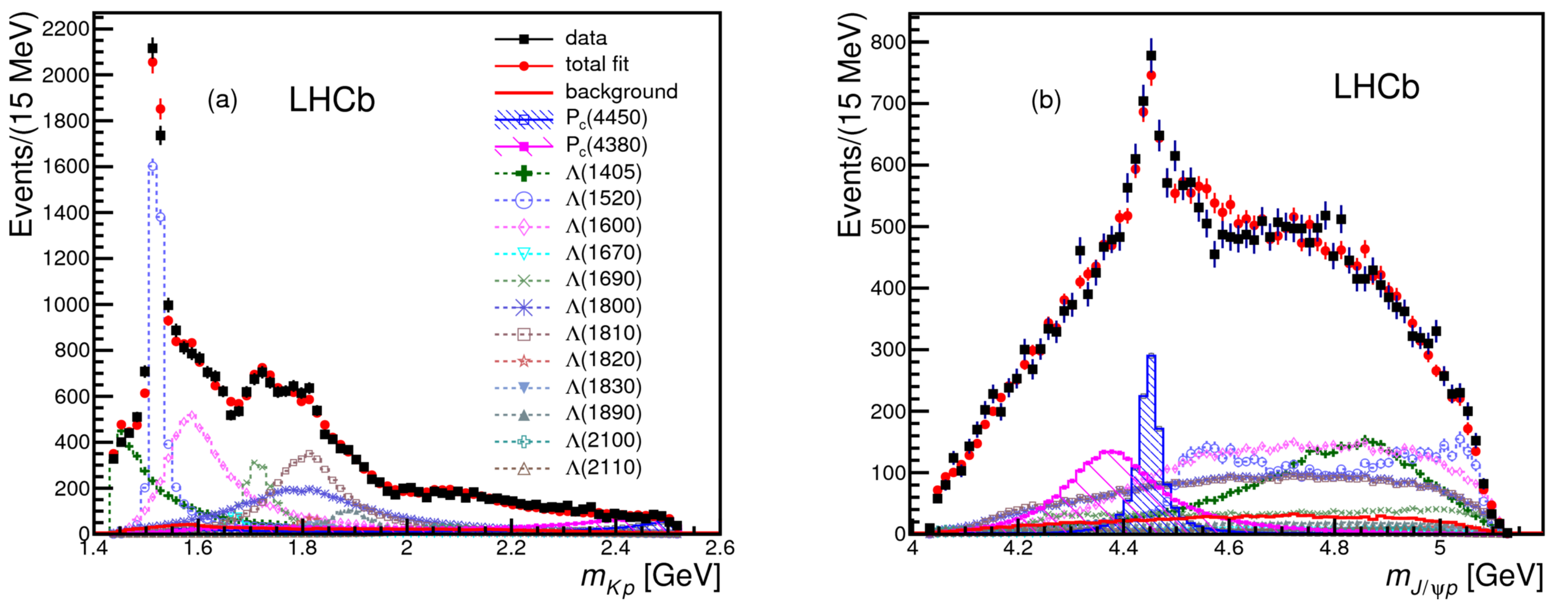
- Not possible to get good description of data including only Λ*→pK resonances



Amplitude analysis of baryon decay

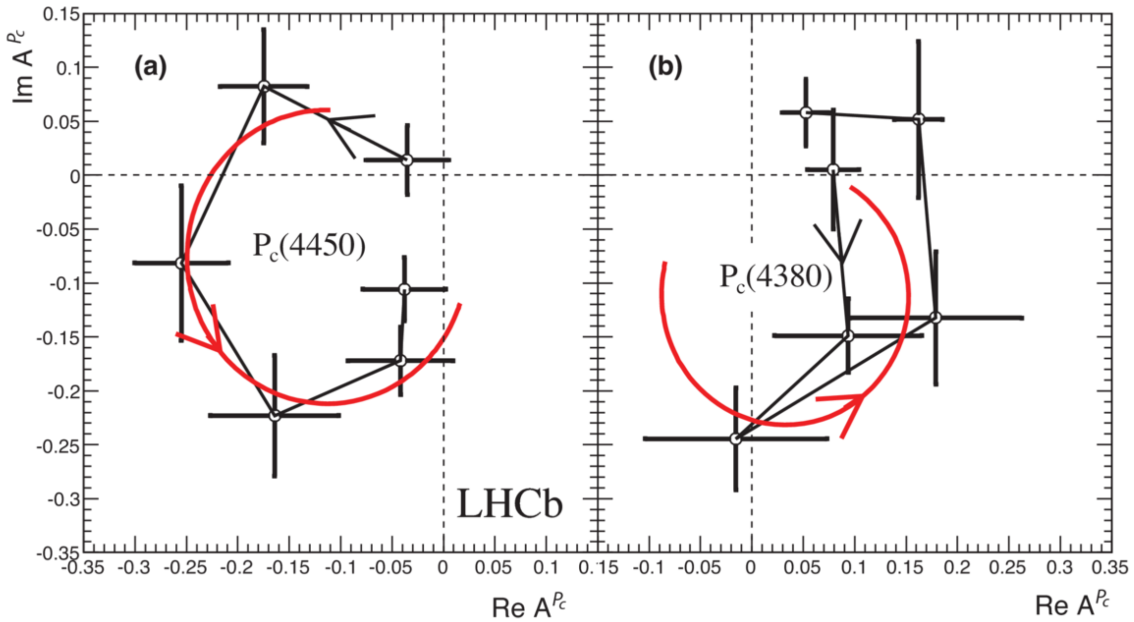
Phys. Rev. Lett. 115 (2015) 072001

- Not possible to get good description of data including only Λ*→pK resonances
- Acceptable fit including two P_c→Jψ/p states



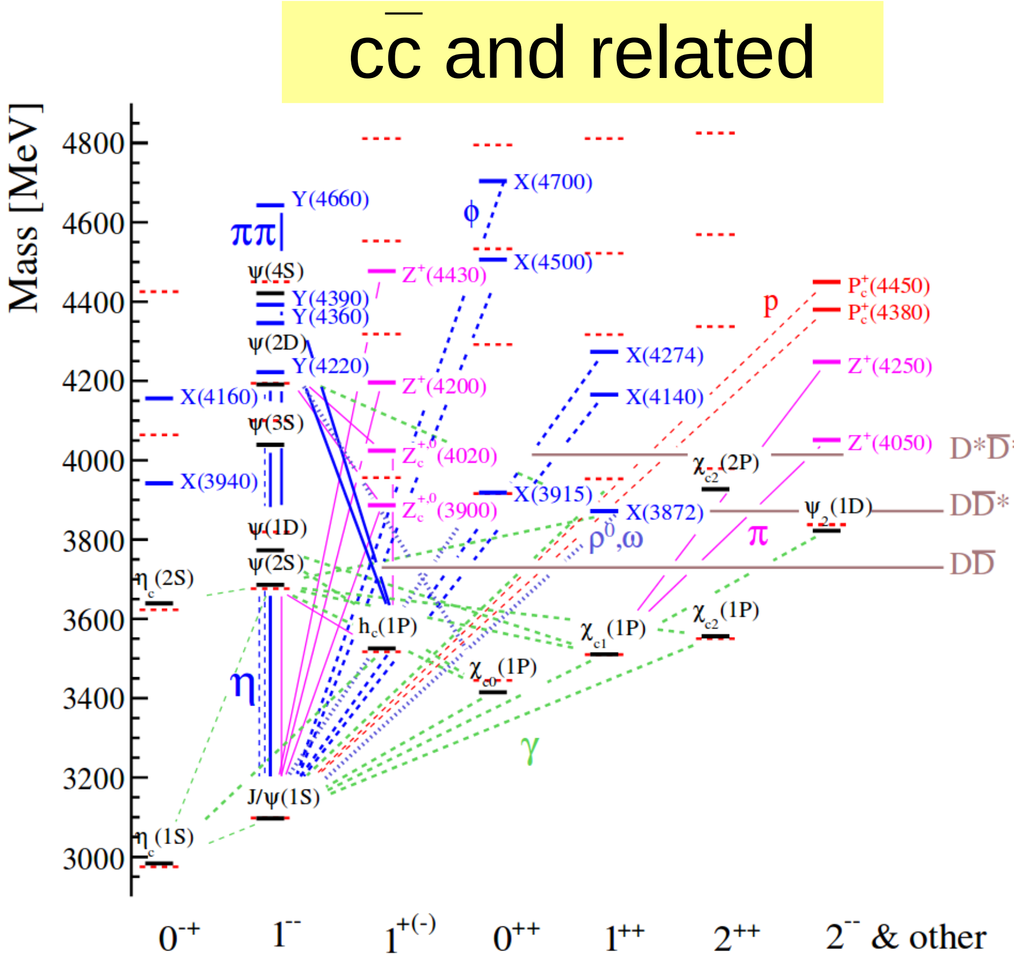
Resonant nature of the P_c states

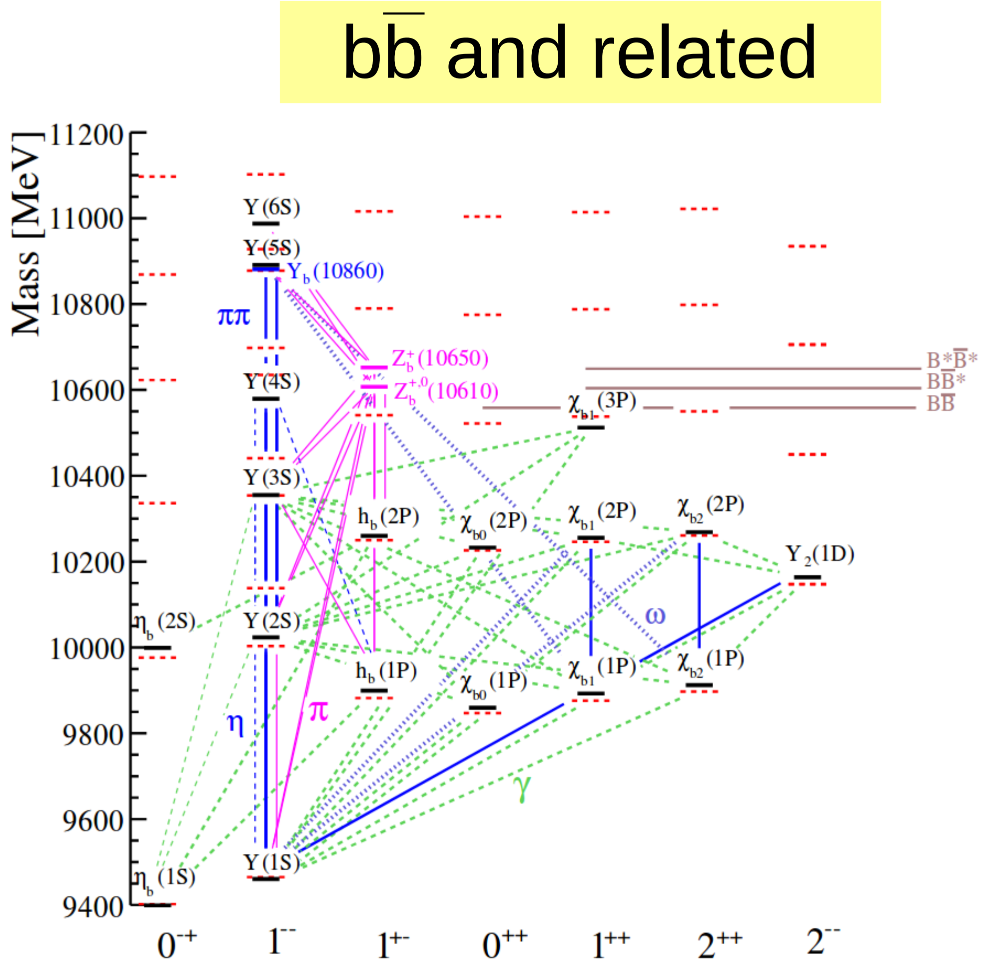
Phys. Rev. Lett. 115 (2015) 072001



- Phase rotation as expected for $P_c(4450)$
- Situation less clear for $P_c(4380)$ – update with more data needed
- Not possible to unambiguously assign quantum numbers
  - Four possibilities: J^P ($P_c(4450)$, $P_c(4380)$) = $(3/2^{\pm},5/2^{\mp})$, $(5/2^{\pm},3/2^{\mp})$

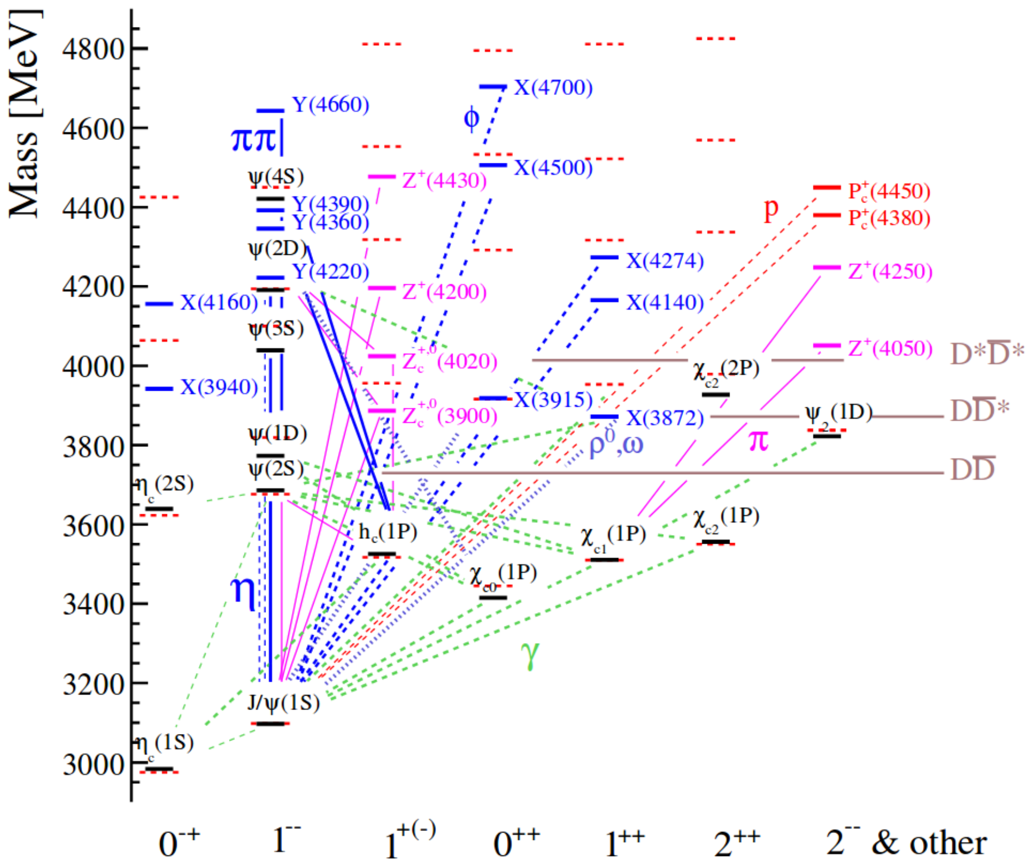
A new particle zoo





Rev. Mod. Phys. 90 (2018) 015003

A new particle zoo



Rev. Mod. Phys. 90 (2018) 015003

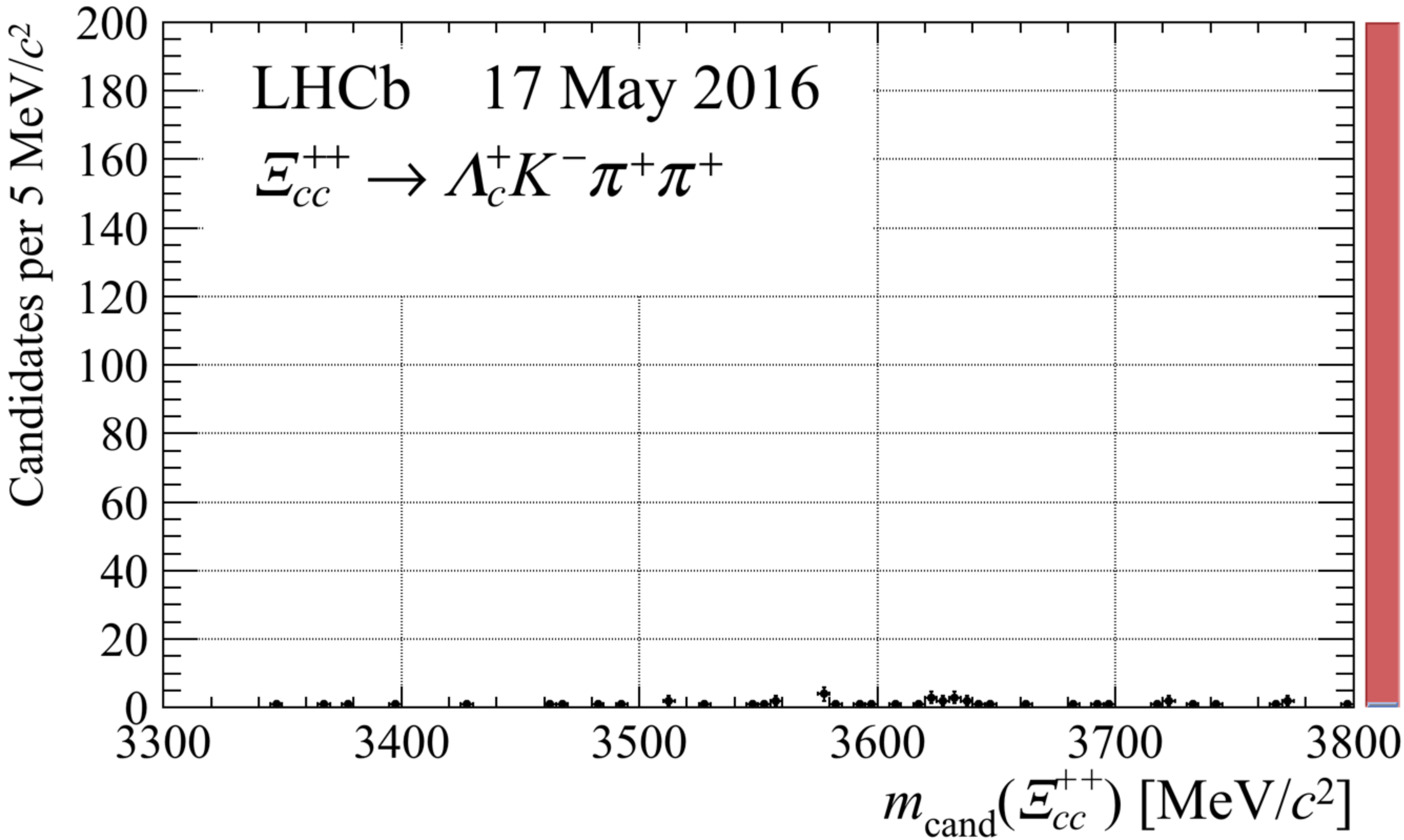
- Many new states found!
- Often by only one experiment &/or in only one channel
  - confirmations needed
- Colour code
  - conventional mesons
  - neutral states without charged partners
  - charged states (with or without neutral partners)
  - pentaquark states
- Many, but not all, states near thresholds, e.g. $D^{(*)}\overline{D}^{(*)}$
  - more than one effect at play?

How to make sense of it all?

- We will need
  - better data
    - more measurements inspired by better predictions
    - excellent prospects with LHCb, Belle II and LHCb upgrades
  - better predictions
    - can be made by benefitting from better data
    - including results on conventional hadrons
- Excellent example: doubly heavy baryons
  - ideal testing ground for QCD potential in diquark models

Observation of the Ξ_{cc}^{++}

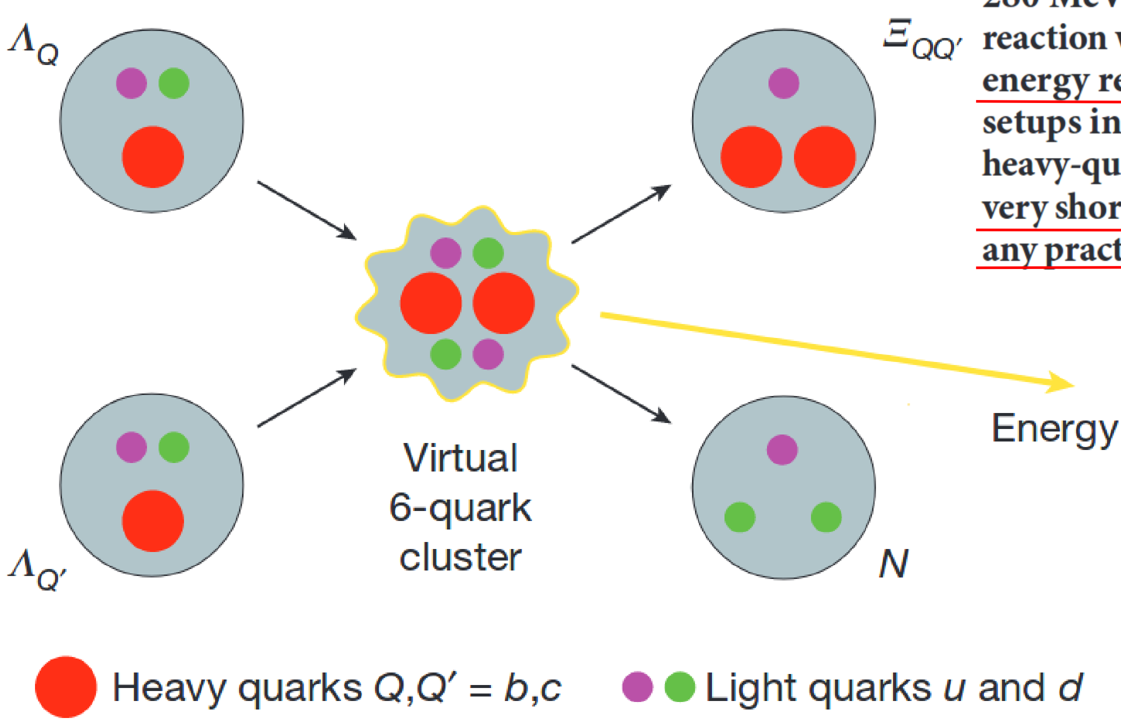
Phys. Rev. Lett. 119 (2017) 112001



Practical applications?

Nature 551 (2017) 89

nuclei. The recent discovery[1] of the first doubly charmed baryon Ξ_{cc}^{++}, which contains two charm quarks (c) and one up quark (u) and has a mass of about 3,621 megaelectronvolts (MeV) (the mass of the proton is 938 MeV) also revealed a large binding energy of about 130 MeV between the two charm quarks. Here we report that this strong binding enables a quark-rearrangement, exothermic reaction in which two heavy baryons (Λ_c) undergo fusion to produce the doubly charmed baryon Ξ_{cc}^{++} and a neutron n ($\Lambda_c\Lambda_c \to \Xi_{cc}^{++}n$), resulting in an energy release of 12 MeV. This reaction is a quark-level analogue of the deuterium–tritium nuclear fusion reaction (DT $\to$ ^{4}He n). The much larger binding energy (approximately 280 MeV) between two bottom quarks (b) causes the analogous reaction with bottom quarks ($\Lambda_b\Lambda_b \to \Xi_{bb}^{0}n$) to have a much larger energy release of about 138 MeV. We suggest some experimental setups in which the highly exothermic nature of the fusion of two heavy-quark baryons might manifest itself. At present, however, the very short lifetimes of the heavy bottom and charm quarks preclude any practical applications of such reactions.



Roadmap for double heavies

- The observation of the Ξ_{cc}^{++} (ccu) baryon is the start of a programme
- Crucial to measure properties of isospin partner Ξ_{cc}^{+} (ccd) and of their excited states
  - (also lifetime, production rate and other decay modes)
- Studies of Ξ_{bc} states also essential
- Will allow precise predictions of [bb][$\overline{ud}$], [bc][$\overline{ud}$], and [cc][$\overline{ud}$] tetraquarks

Summary

- No longer any doubt that exotic hadrons exist
  - question is now over their binding mechanism
- Situation currently rather cloudy
  - some models explain some of the data well
    - threshold effects, molecules, tightly bound tetraquarks, hadrocharmonium, ...
  - no model explains all of the data by itself
    - more than one effect contributing?
- Good reasons for optimism about progress in coming years
  - quite likely that major discoveries are waiting to be made

Bibliography

- Several excellent recent review articles

  - M. Karliner et al., to appear in Ann. Rev. Nucl. Part. Sci., https://arxiv.org/abs/1711.10626
  - S. Olsen et al., Rev. Mod. Phys. 90 (2018) 015003, https://arxiv.org/abs/1708.04012
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  - R. Lebed et al., Prog. Part. Nucl. Phys. 93 (2017) 143, https://arxiv.org/abs/1610.04528