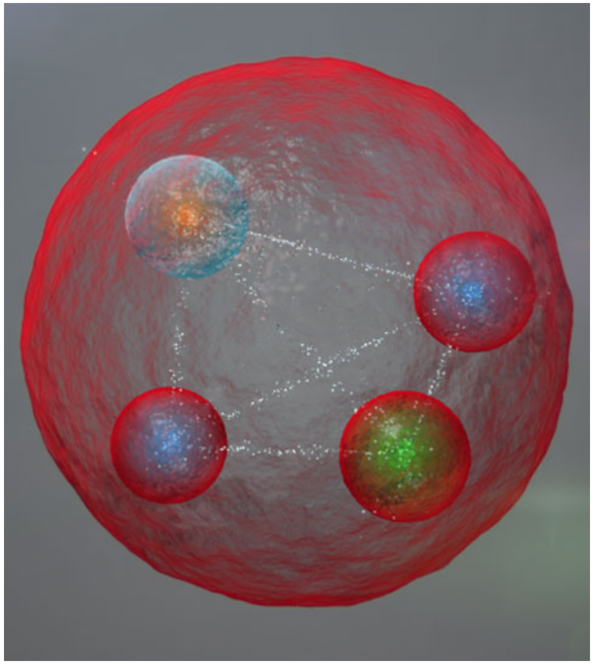
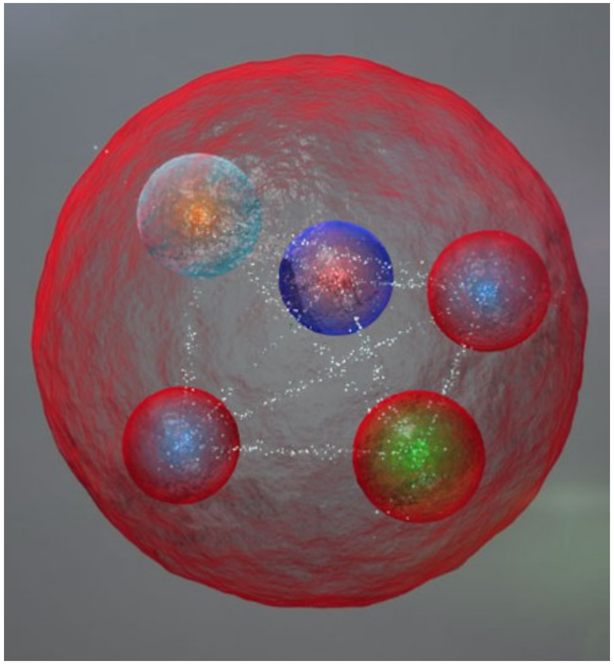
Tetraquarks and Pentaquarks

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

Tim Gershon
University of Warwick

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

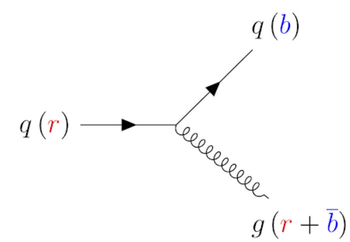
> Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**,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

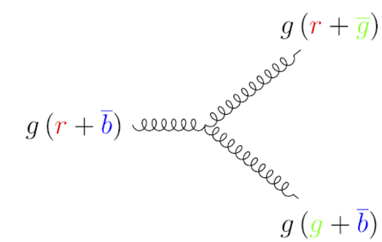
M. Gell-Mann, Phys. Lett. 8 (1964) 214

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

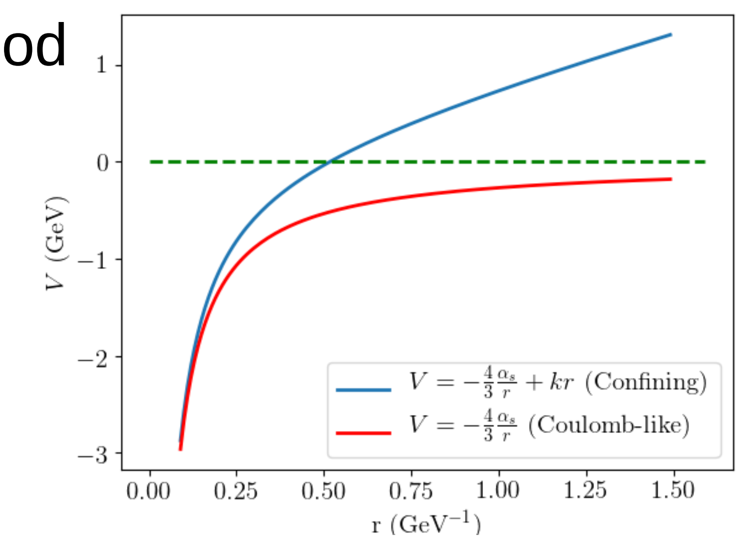
QCD basics

- 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



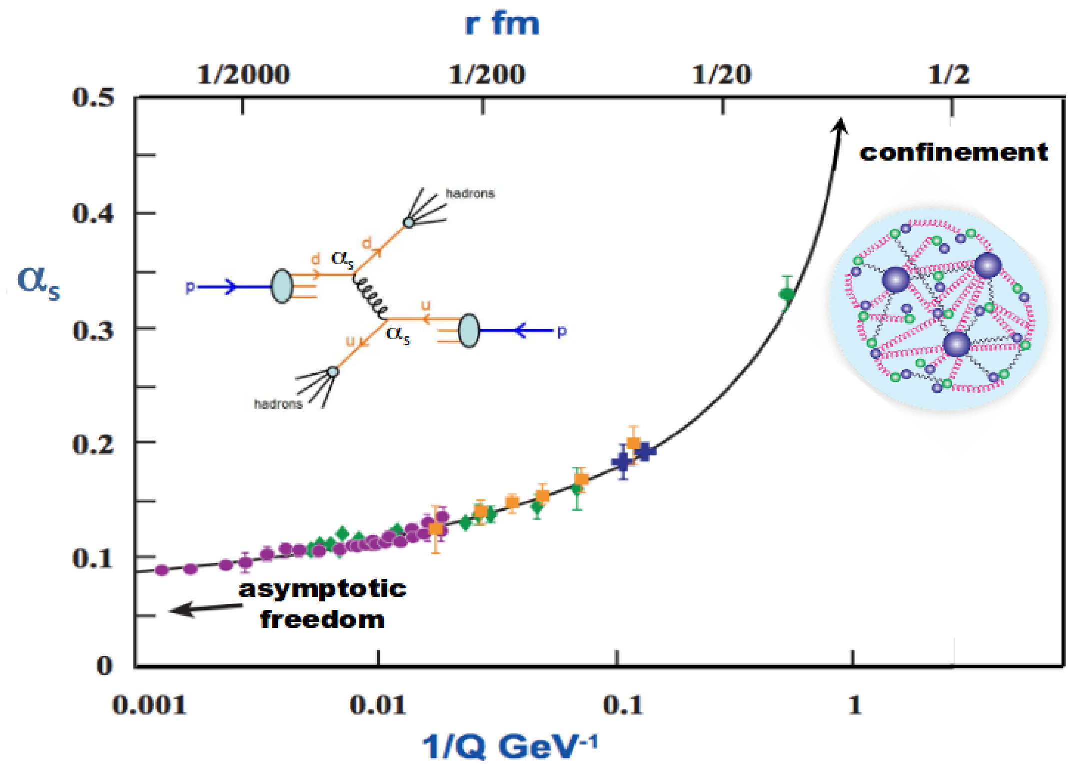
What do we learn from hadrons?

- 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

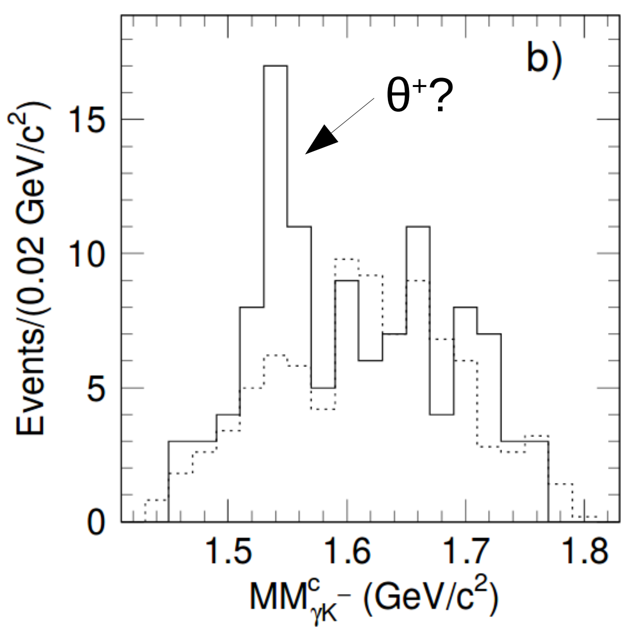
- The uuddss sexaquark S
  - with baryon number 2 (similar states sometimes called dibaryons)
  - has a totally symmetric wavefunction, hence large binding energy
  - if $m_S < m_d + m_e \sim 2(m_p + m_e)$ is completely stable
  - else if $m_S < m_p + m_e + m_\Lambda$ is effectively stable
  - could 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 now?

- 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)

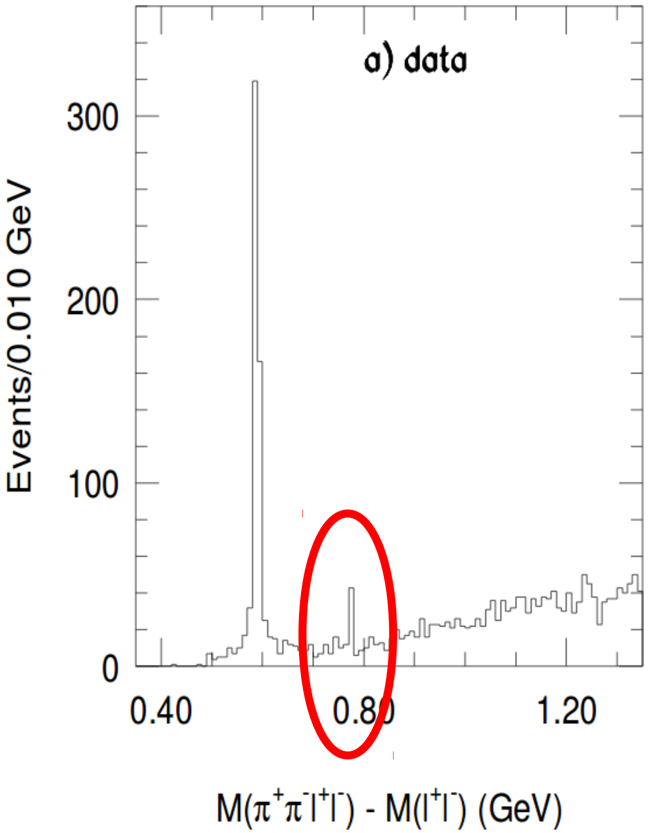


Why is this relevant now?

- 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)

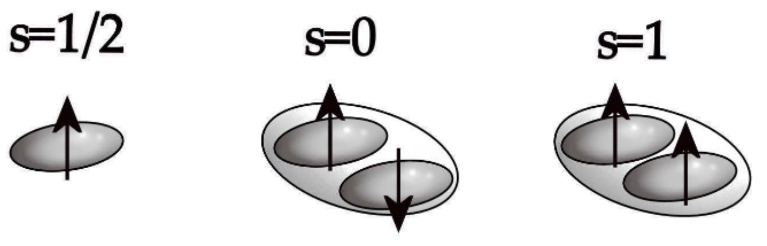
- Unexpected discovery by the Belle collaboration in 2003
  - $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$
  - Rapidly confirmed by
    - BaBar, CDF, D0
    - (later LHCb, CMS, ATLAS)
  - Produced in
    - B decay, pp & $p\bar{p}$ collisions
  - Decays to
    - $J/\psi\rho$, $J/\psi\omega$, $J/\psi\gamma$, $D\bar{D}^*$
- 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)



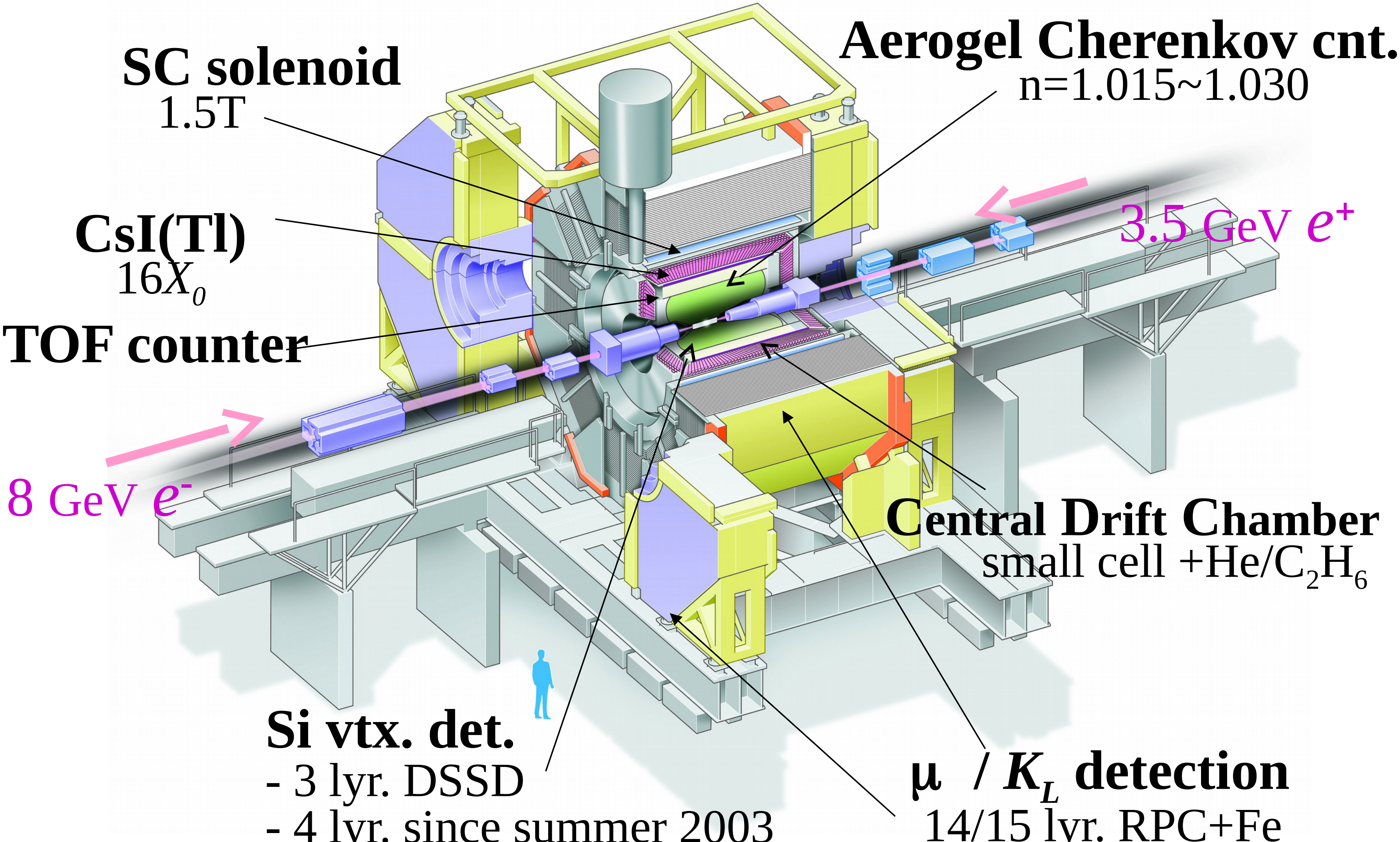
- For L=1, have $J^{PC} = 0^{++}$ (χ_{c0}), 1^{+-} (h_c), 1^{++} (χ_{c1}), 2^{++} (χ_{c2})
  - cannot get manifestly exotic quantum numbers (e.g. $J^{PC} = 0^{--}$, 0^{+-}, 1^{-+}) from $q\bar{q}$
- Other notations also used: $n^{2S+1}L_J$, ψ(2S), X(3872), ...
  - as usual in spectroscopy, L = 0,1,2,3 ... 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

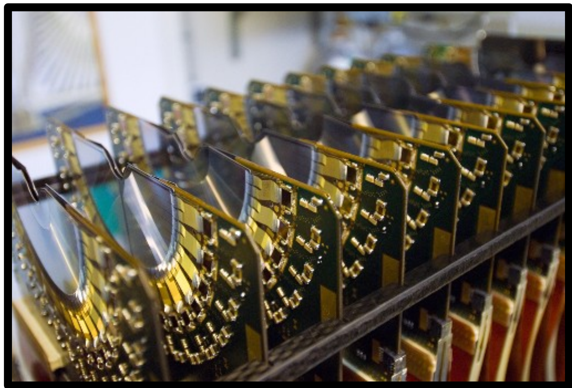
- Can be inferred from production or decay processes
  - all of J, P and C conserved in strong and electromagnetic processes
  - only J conserved in weak interactions (e.g. production in B decay)
- Production
  - in e^+e^- collisions then $J^{PC} = 1^{--}$
  - in hadron collisions → usually no information (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) → $J/\psi\gamma$ fixes C=+1)

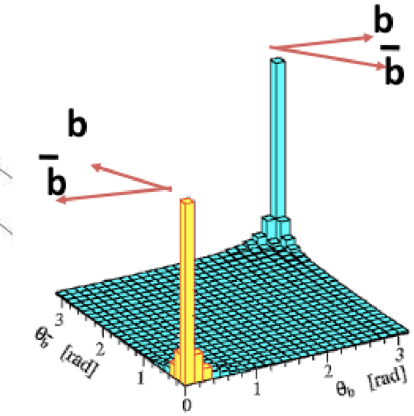
Large, clean samples of B decays at B factories and LHCb

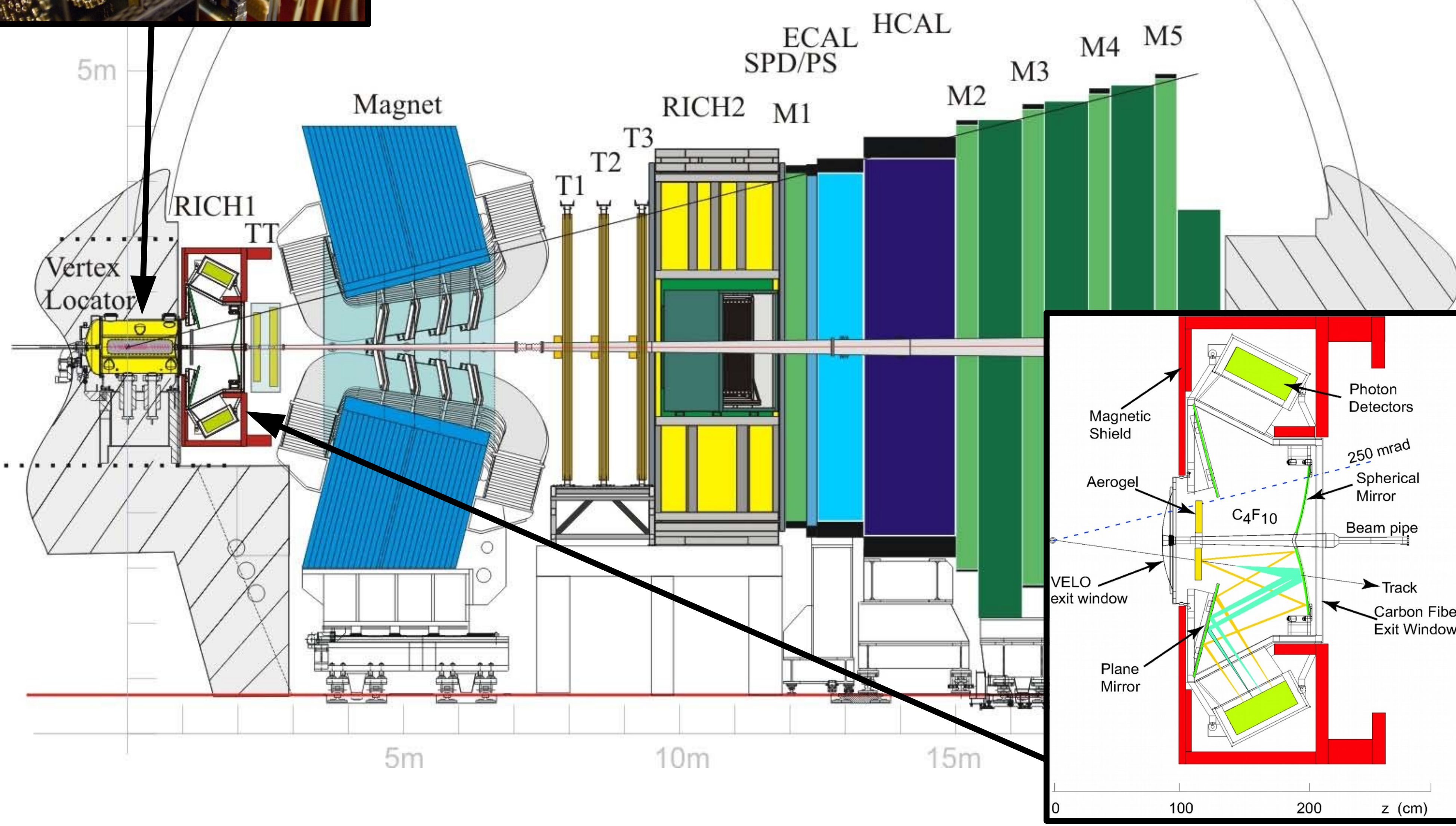
Belle Detector



LHCb detector





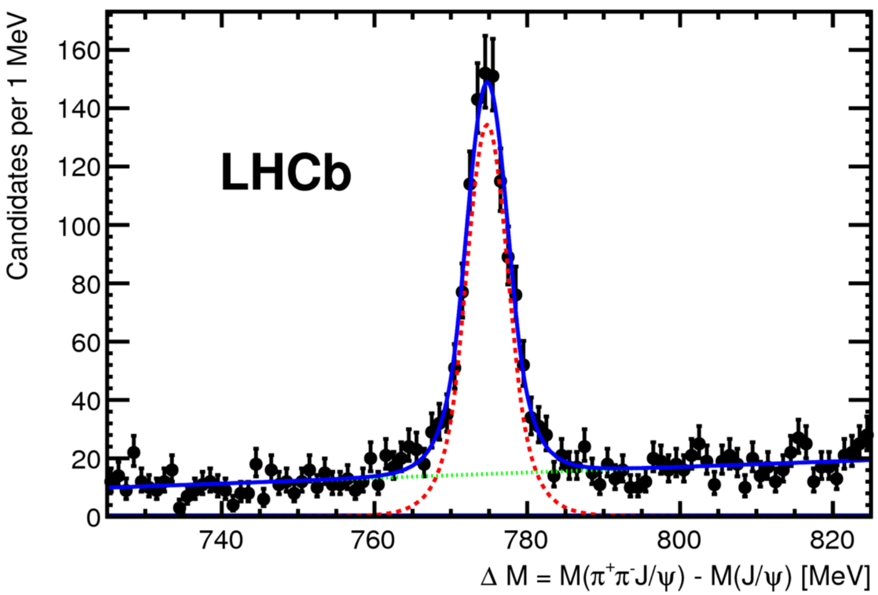


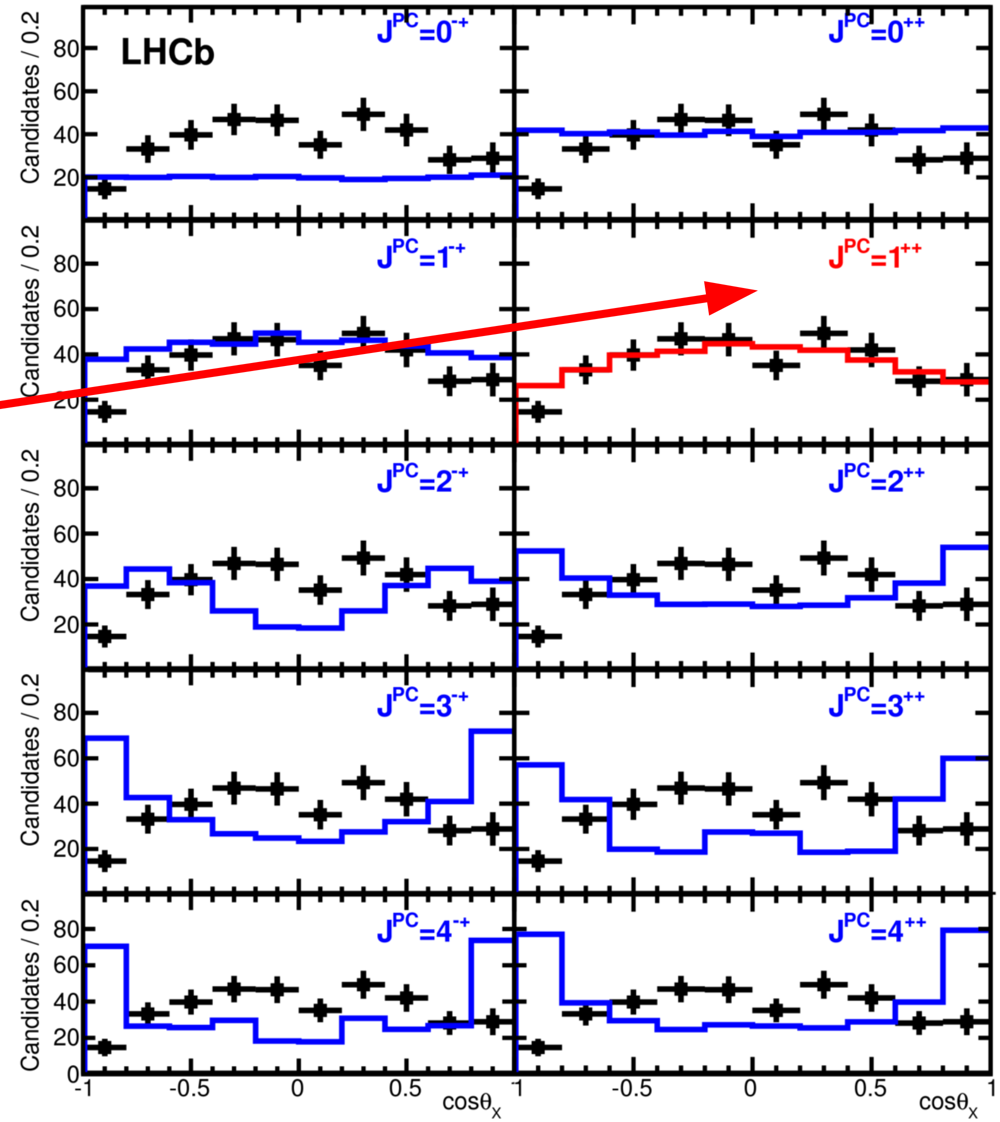
Measuring X(3872) quantum numbers

Phys. Rev. D92 (2015) 011102

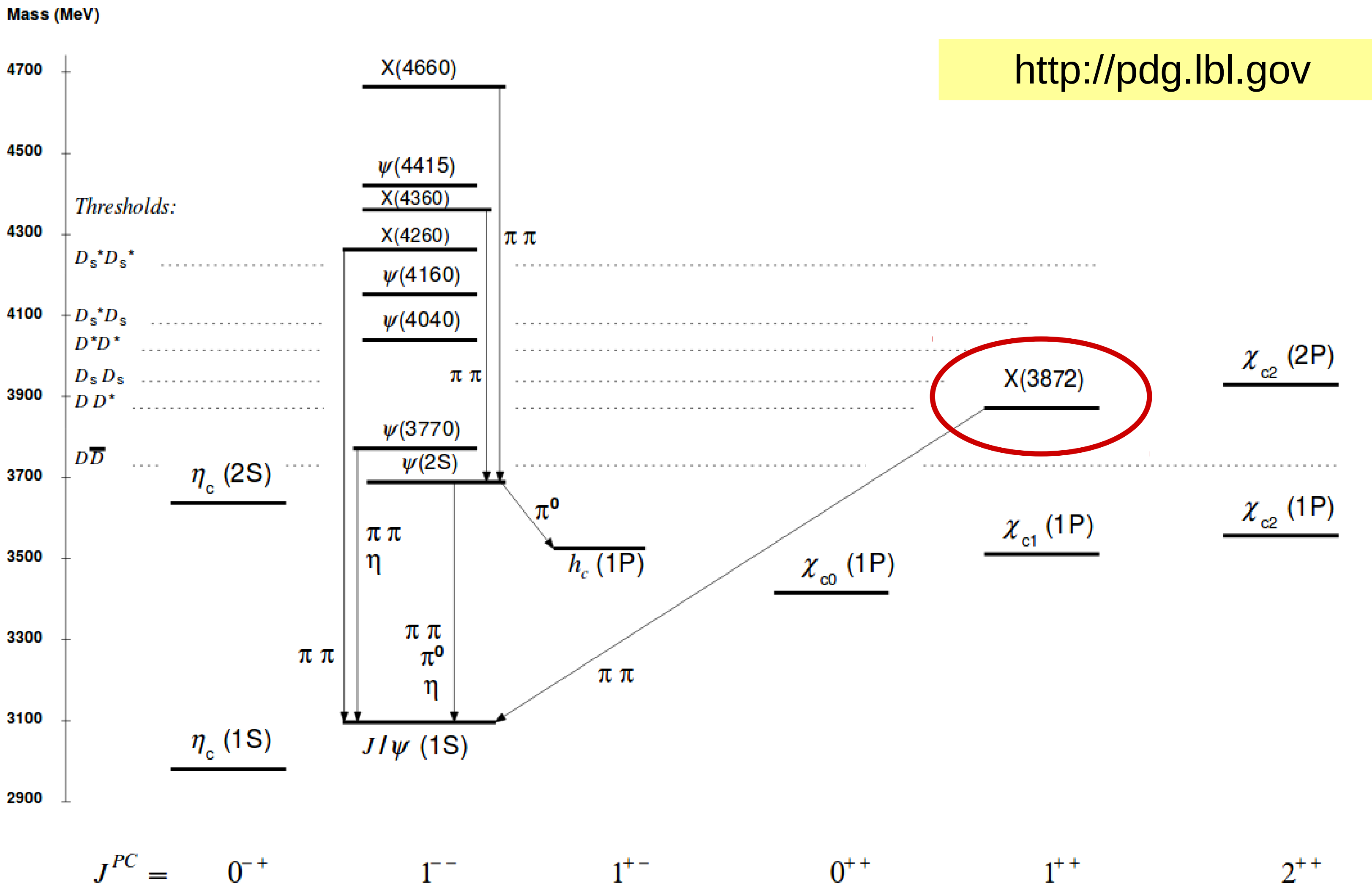
Example: angular distributions in
$B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\pi^+\pi^-$

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

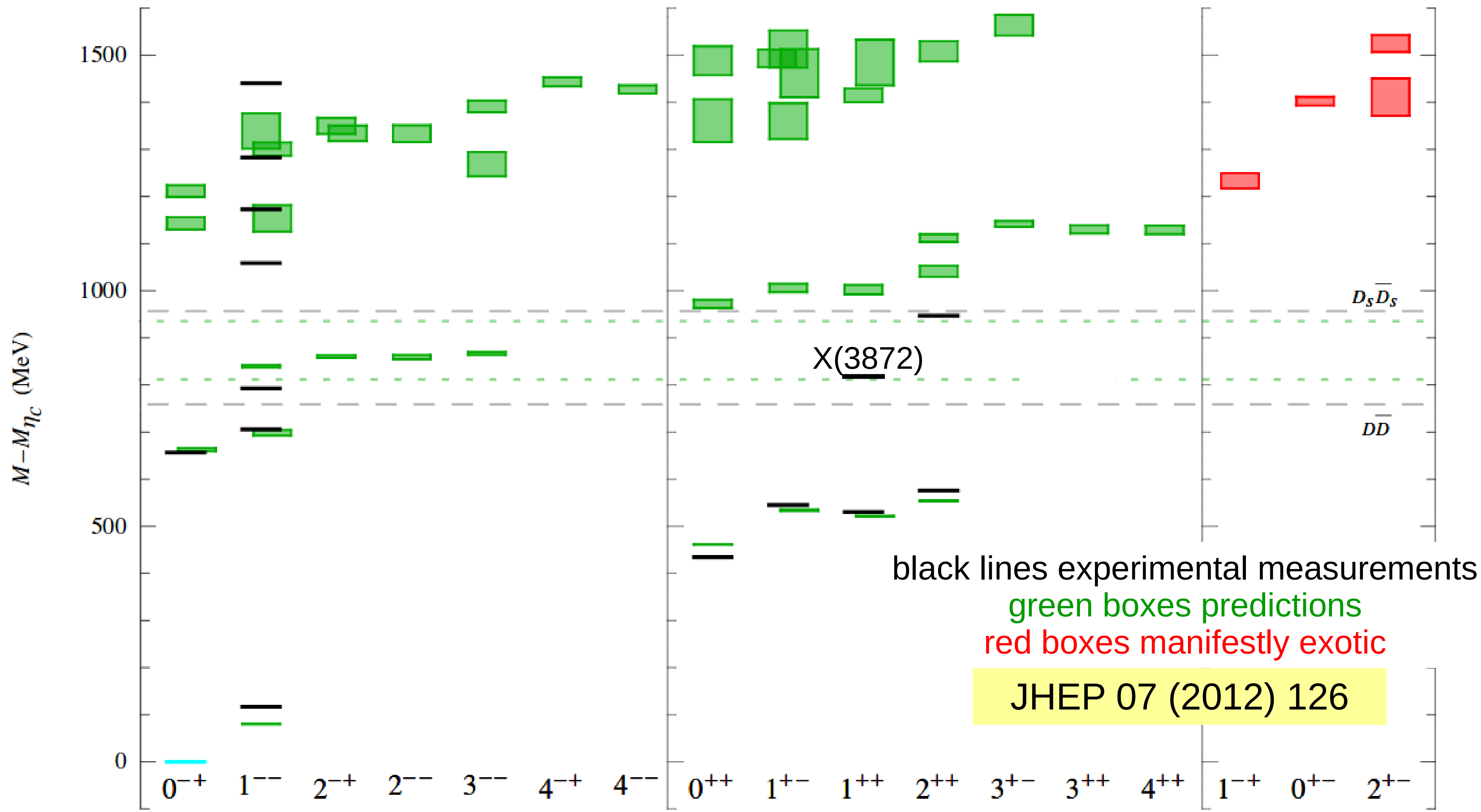




The $c\bar{c}$ spectrum



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



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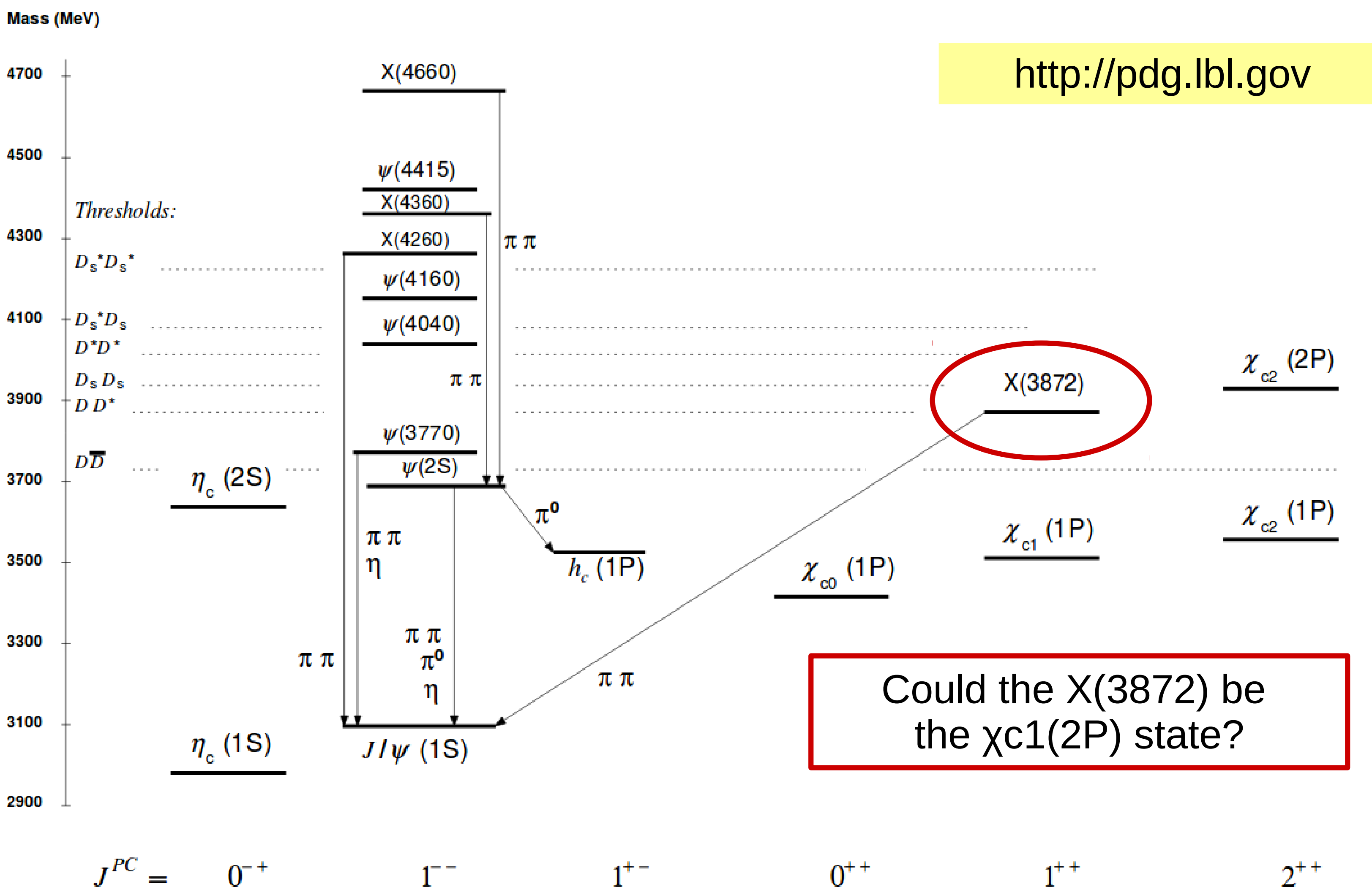
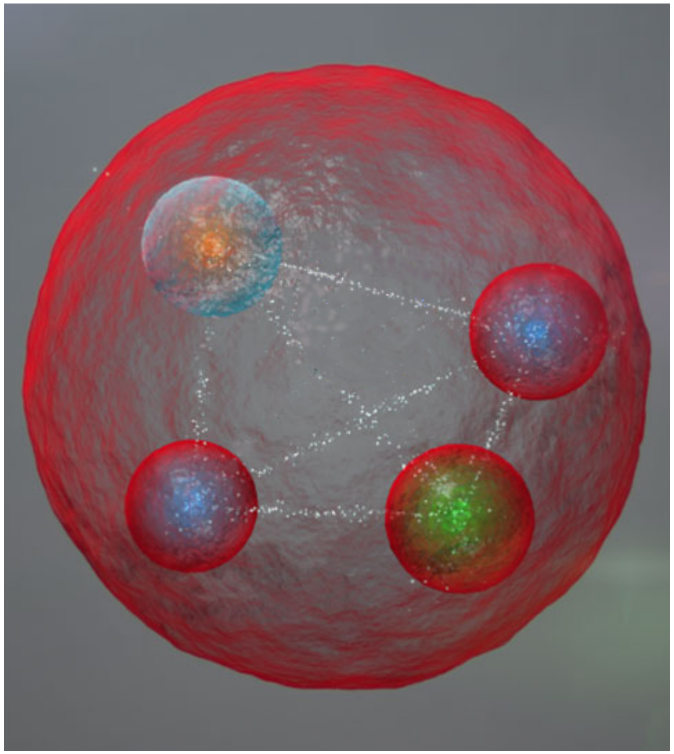


Could the X(3872) be the χc1(2P) state?

Could the X(3872) be the $\chi_{c1}(2P)$ state?

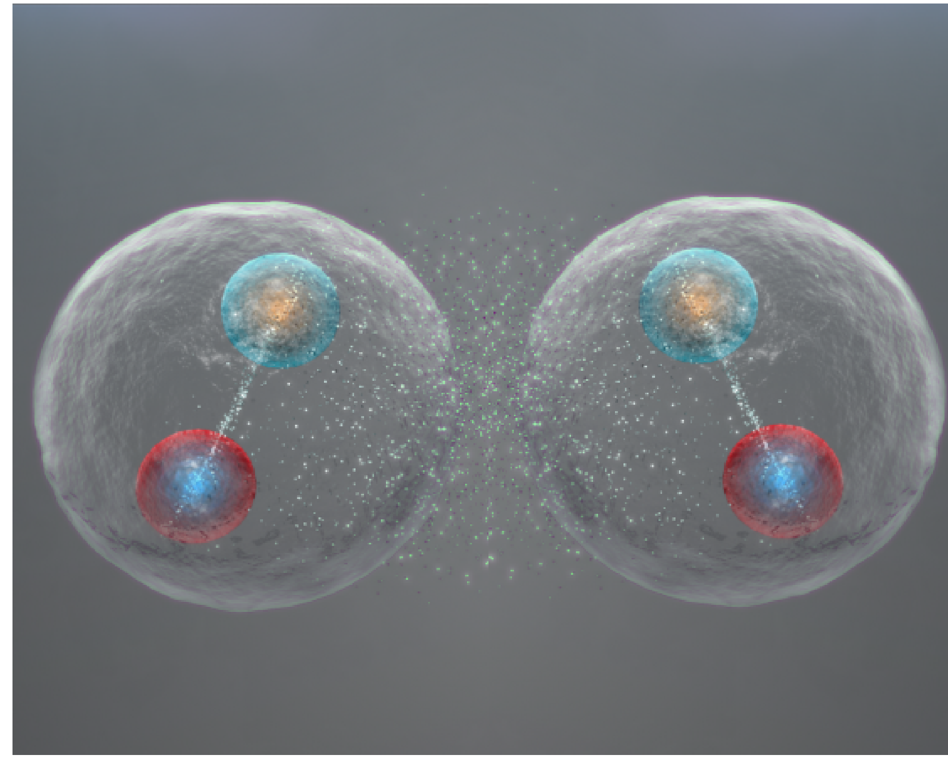
- Several strong arguments against:
  - isospin violation (decay to J/ψρ) not expected
    - near equality of branching fractions to J/ψρ & J/ψω
    - (isospin partners however not observed)
  - above threshold for decay to open charm but not significantly wider than $\chi_{c1}(1P)$
    - only upper limit on X(3872) width measured so far
  - mass splitting relative to $\chi_{c2}(2P)$ 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)

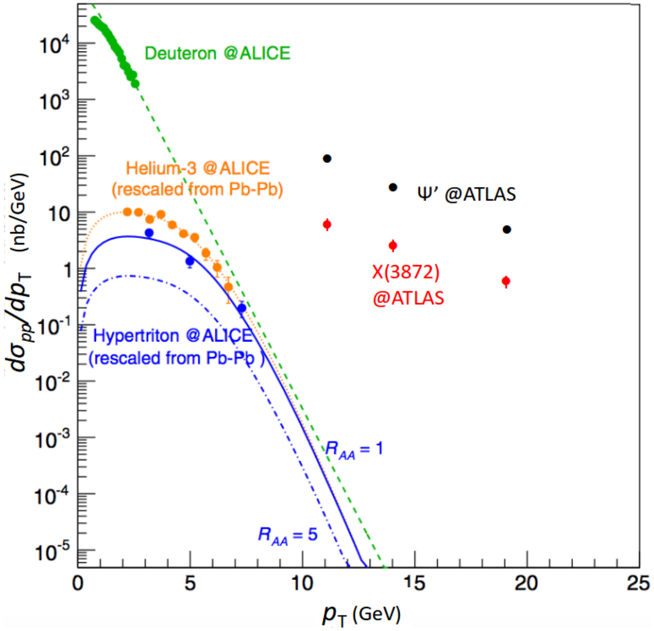


or some mixture with $c\bar{c}$,
or something else?

Simplified picture above:
most tightly bound models
involve diquarks

Molecular or tightly-bound?

- Molecular model ($D^0\overline{D}^{*0}$)
  - 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 χ_{c1}(2P)
    - lattice QCD calculations support this view (arXiv:1503.03257)



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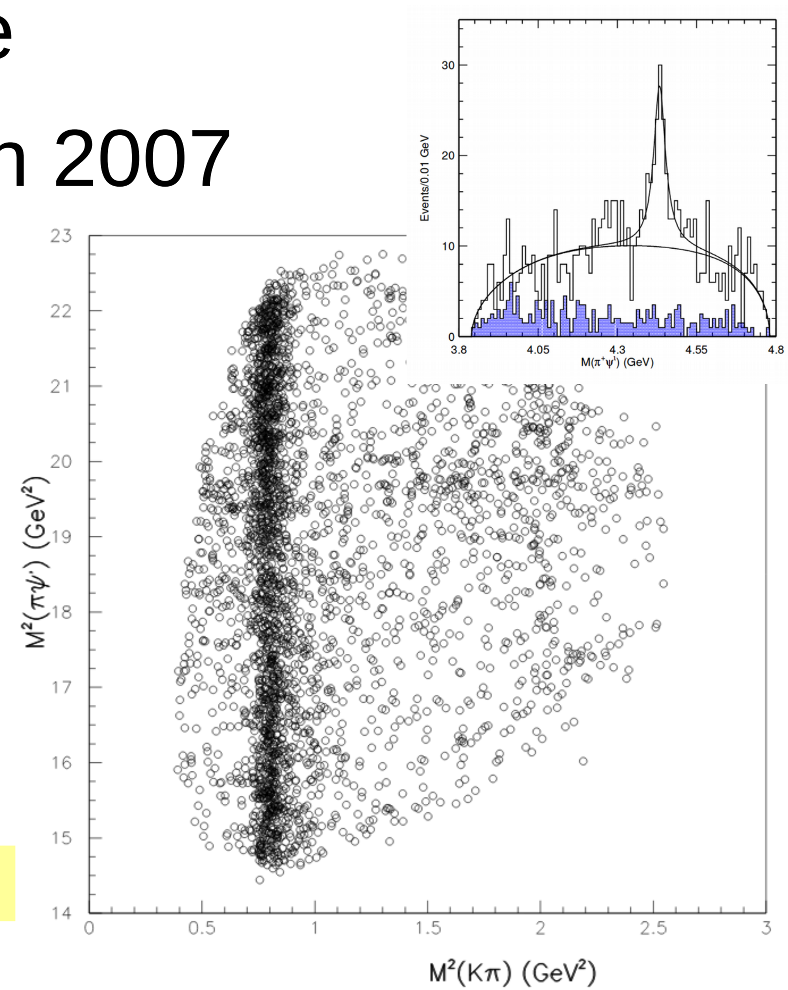
- Tightly bound diquarks ($[cu][\overline{cu}]$)
  - can explain isospin violation
  - predicts existence of isospin partners (not seen)

A smoking gun

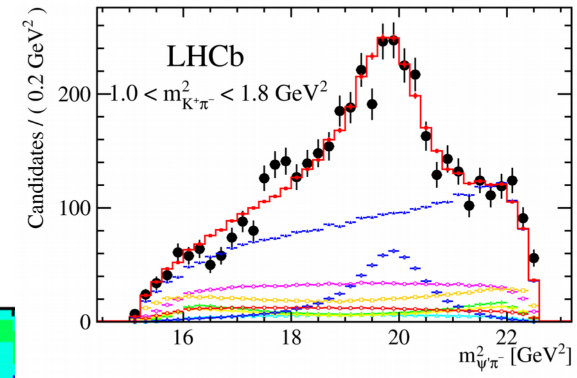
- An unambiguous signal for exotic hadrons is a charged charmonium-like state
- Belle discovered a candidate in 2007
  - $B^0 \rightarrow Z(4430)^- K^+$,
  - $Z(4430)^- \rightarrow \psi(2S)\pi^-$
- Not confirmed by BaBar
  - analysis method too simplistic?

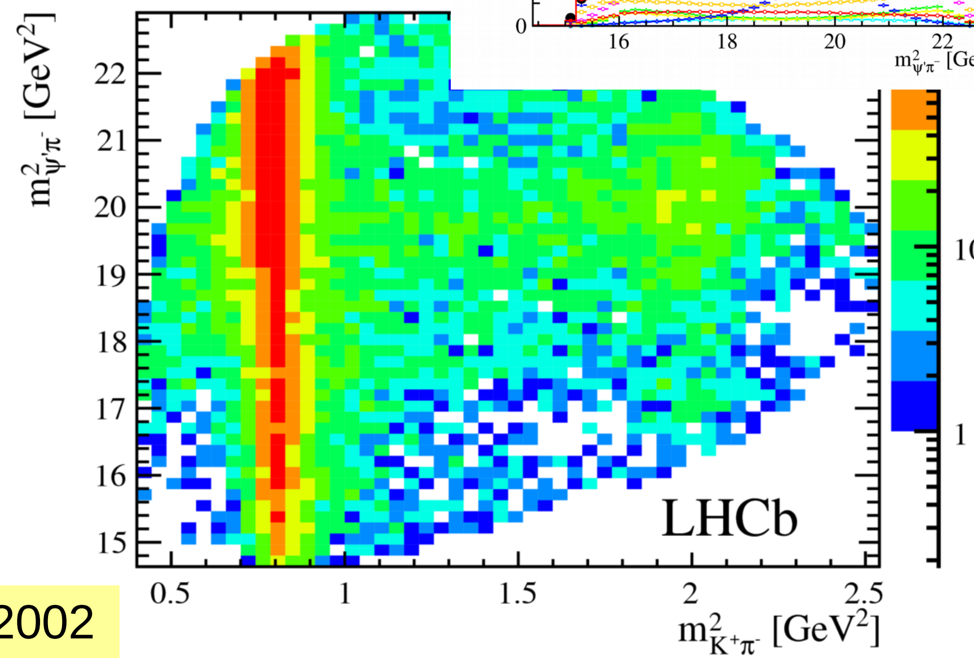


Phys.Rev.Lett. 100 (2008) 142001

Z(4430) confirmation by LHCb

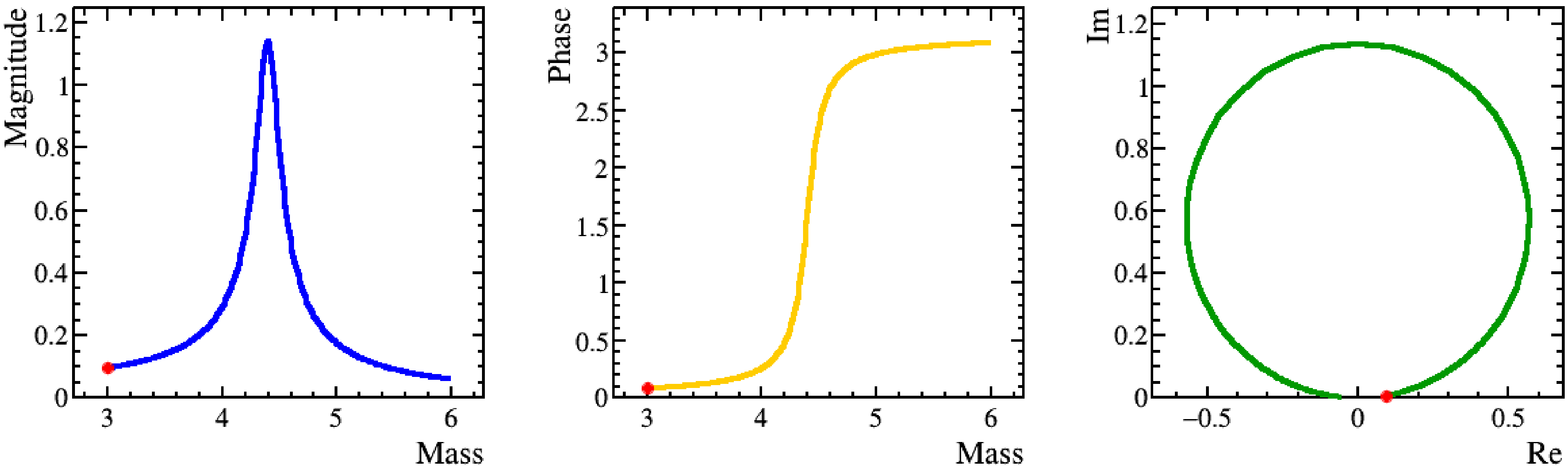
- An unambiguous signal for exotic hadrons is a charged charmonium-like state
- Belle discovered a candidate in 2007
  - $B^0 \rightarrow Z(4430)^- K^+$,
  - $Z(4430)^- \rightarrow \psi(2S)\pi^-$
- Confirmed by LHCb
  - Full 4D amplitude analysis
  - (necessary to determine parameters correctly)
  - Quantum numbers $J^P = 1^+$





Phys. Rev. Lett. 112 (2014) 222002

Resonant character of the Z(4430)



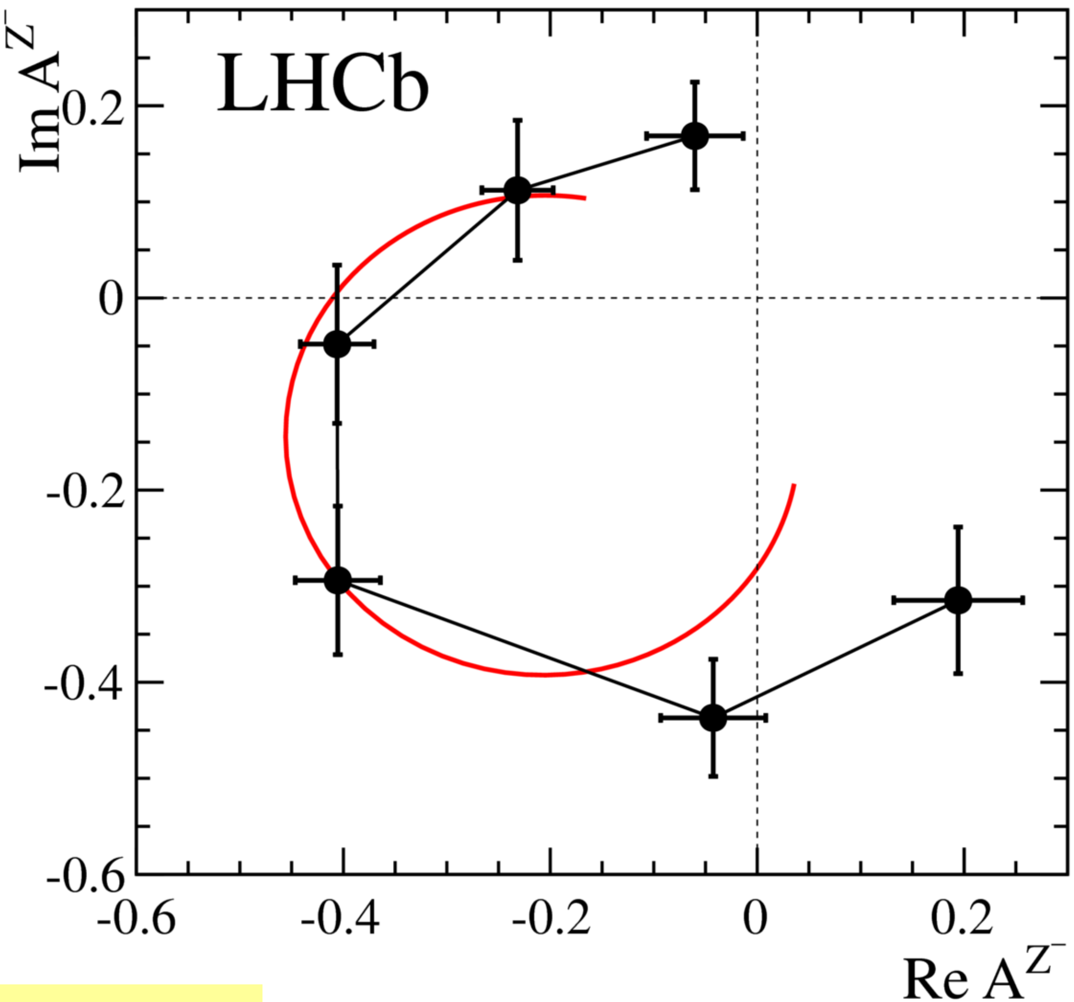
- A Breit-Wigner function has a characteristic rapid change of phase near the resonance peak

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

- 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

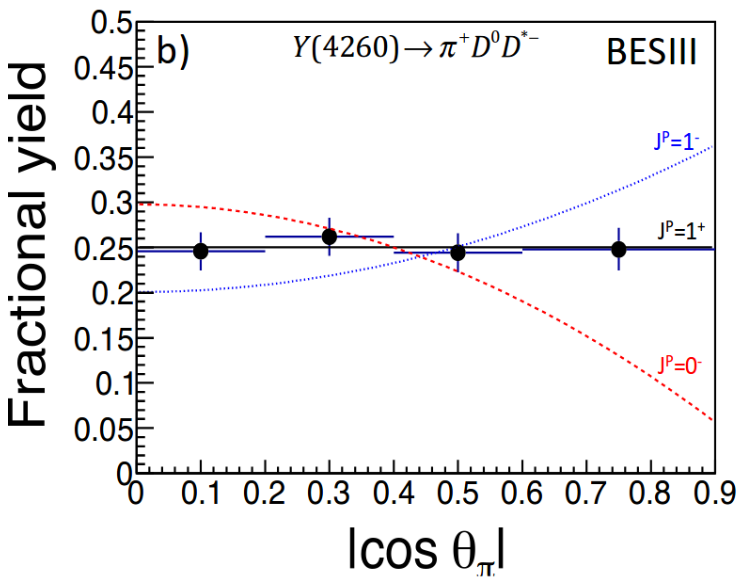


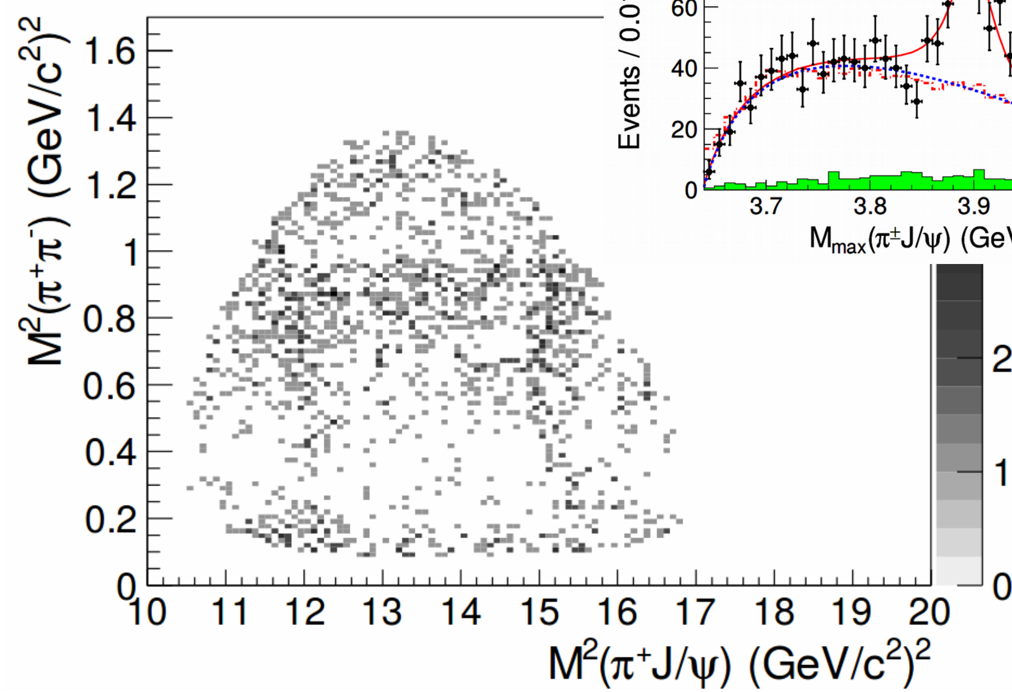
Phys. Rev. Lett. 112 (2014) 222002

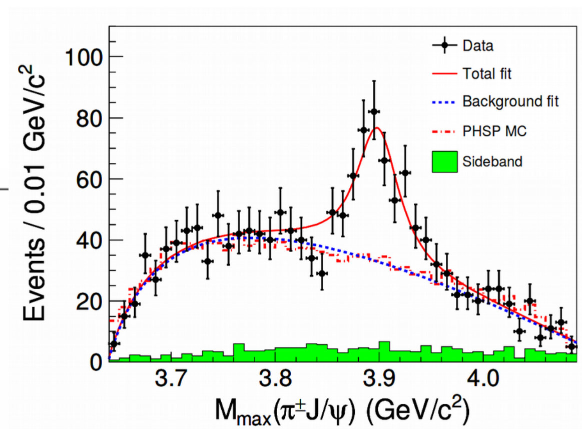
More smoking guns

- 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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- Isospin (neutral) partner observed
  - both $J/\psi\pi$ and $D\bar{D}^*$ ...
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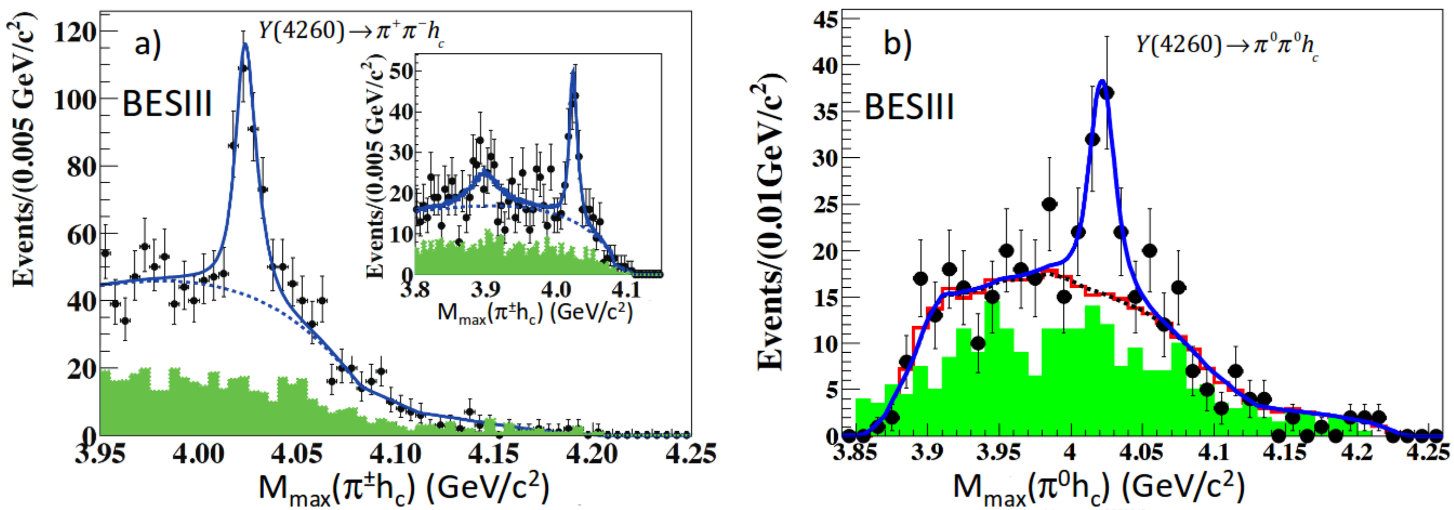
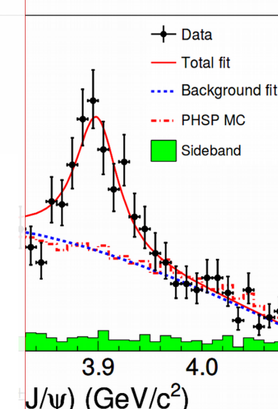
Phys. Rev. Lett. 110 (2013) 252001
Phys. Rev. Lett. 110 (2013) 252002

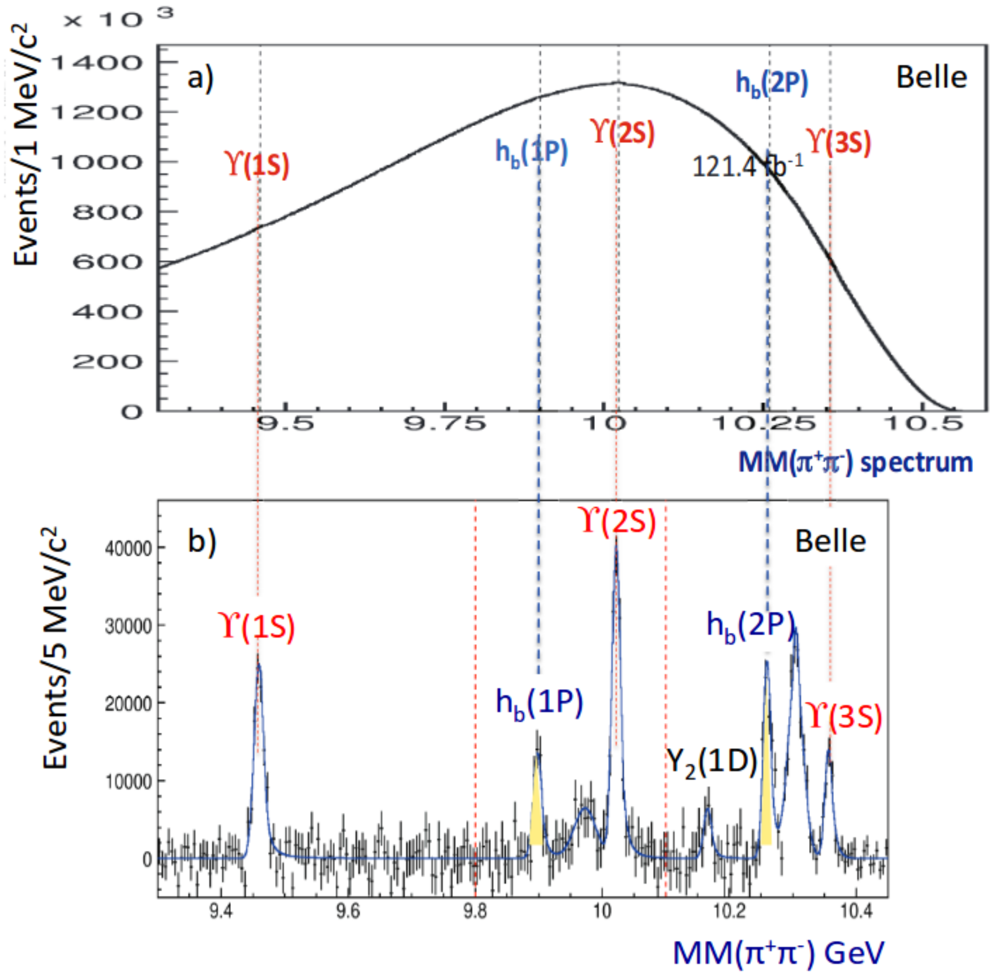
Similar isospin triplet Z(4020) seen decaying to $h_c\pi$ and $D^*\bar{D}^*$





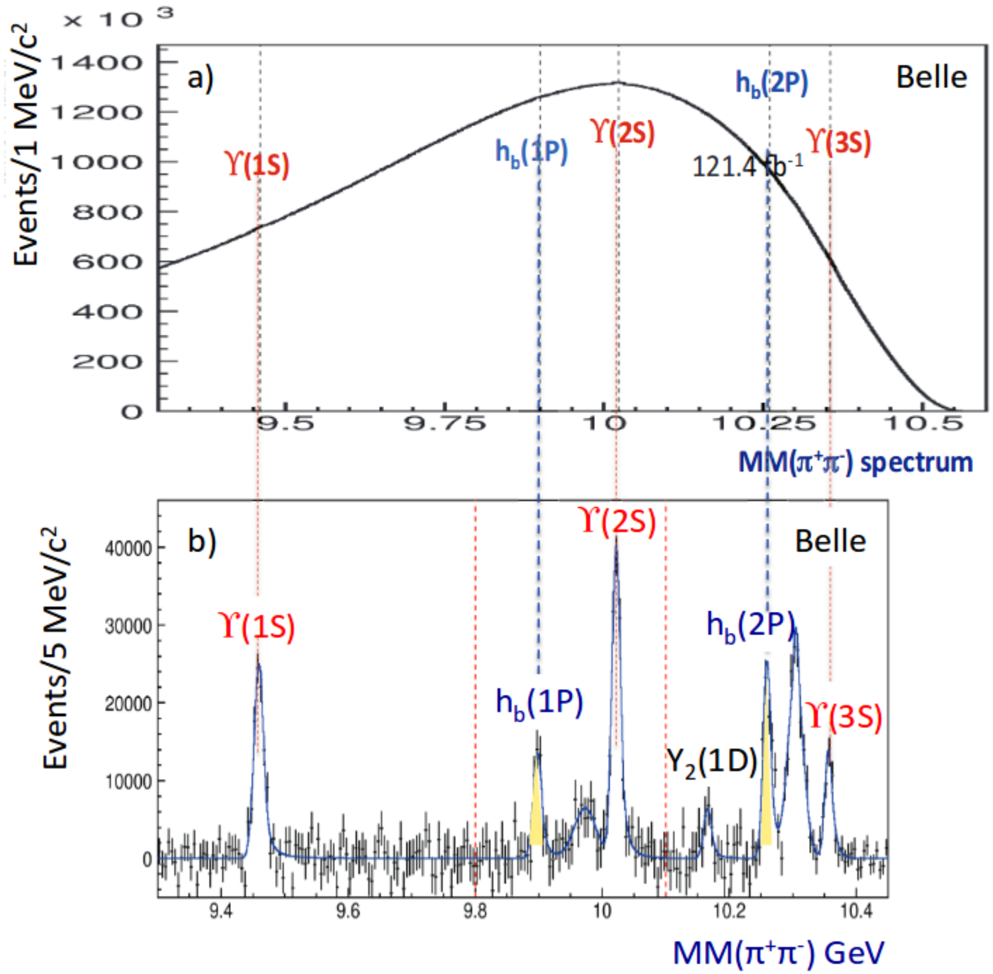
Phys. Rev. Lett. 112 (2014) 022001

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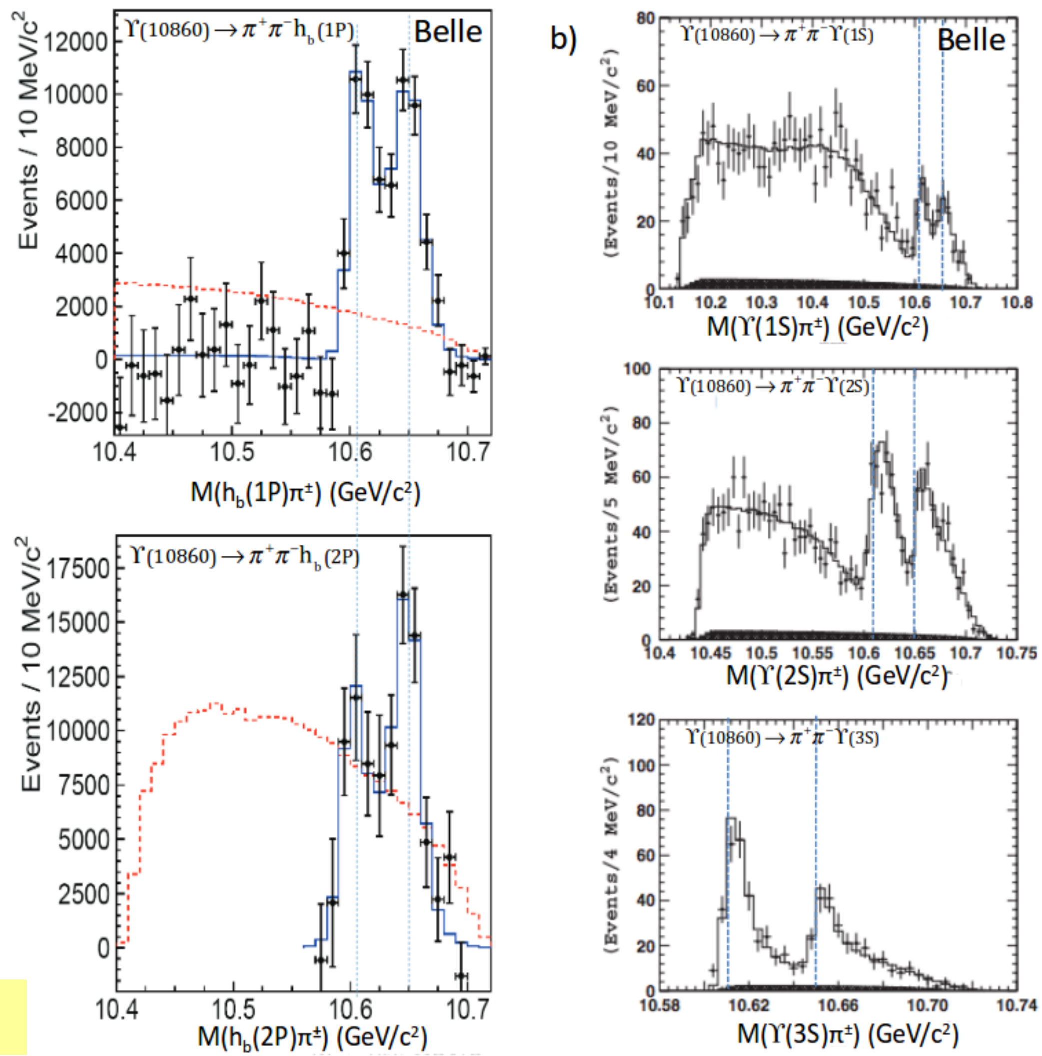
- Investigation of recoil mass revealed surprising presence of $h_b(1P)$ and $h_b(2P)$ states – first observations!
- Allows study of the $Y(nS)\pi$ and $h_b(nP)\pi$ mass distributions

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

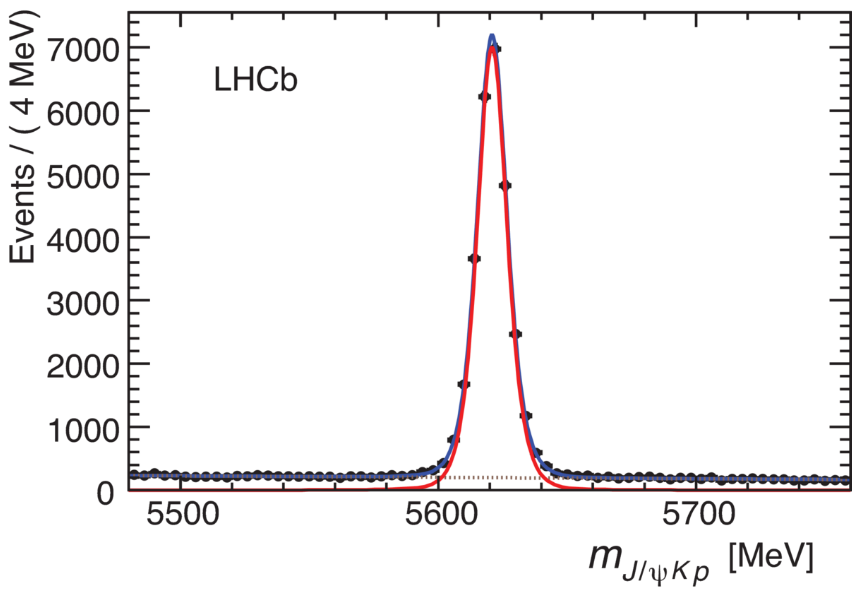


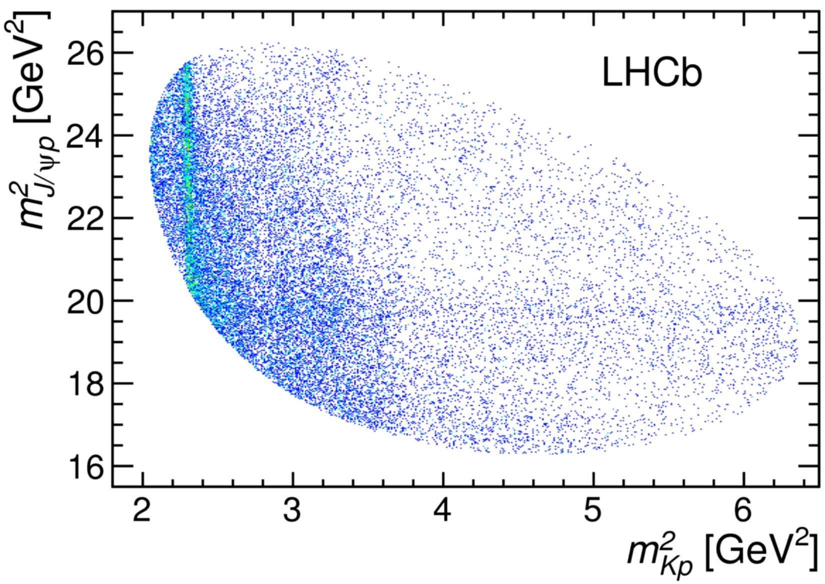
Phys.Rev.Lett. 108 (2012) 122001

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

Phys. Rev. Lett. 115 (2015) 072001

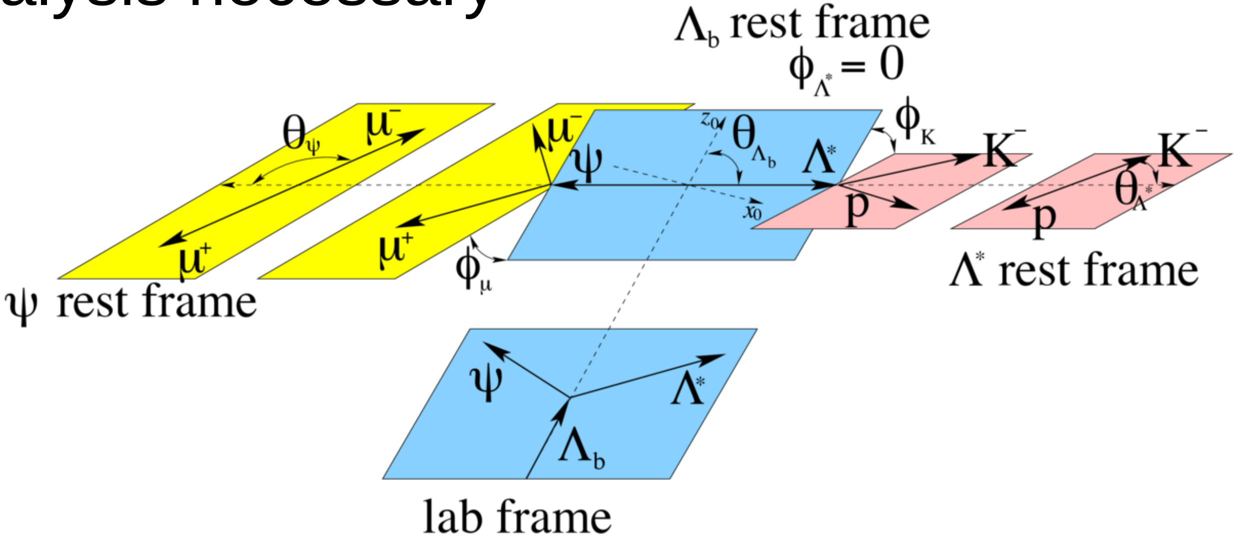




Amplitude analysis of baryon decay

Phys. Rev. Lett. 115 (2015) 072001

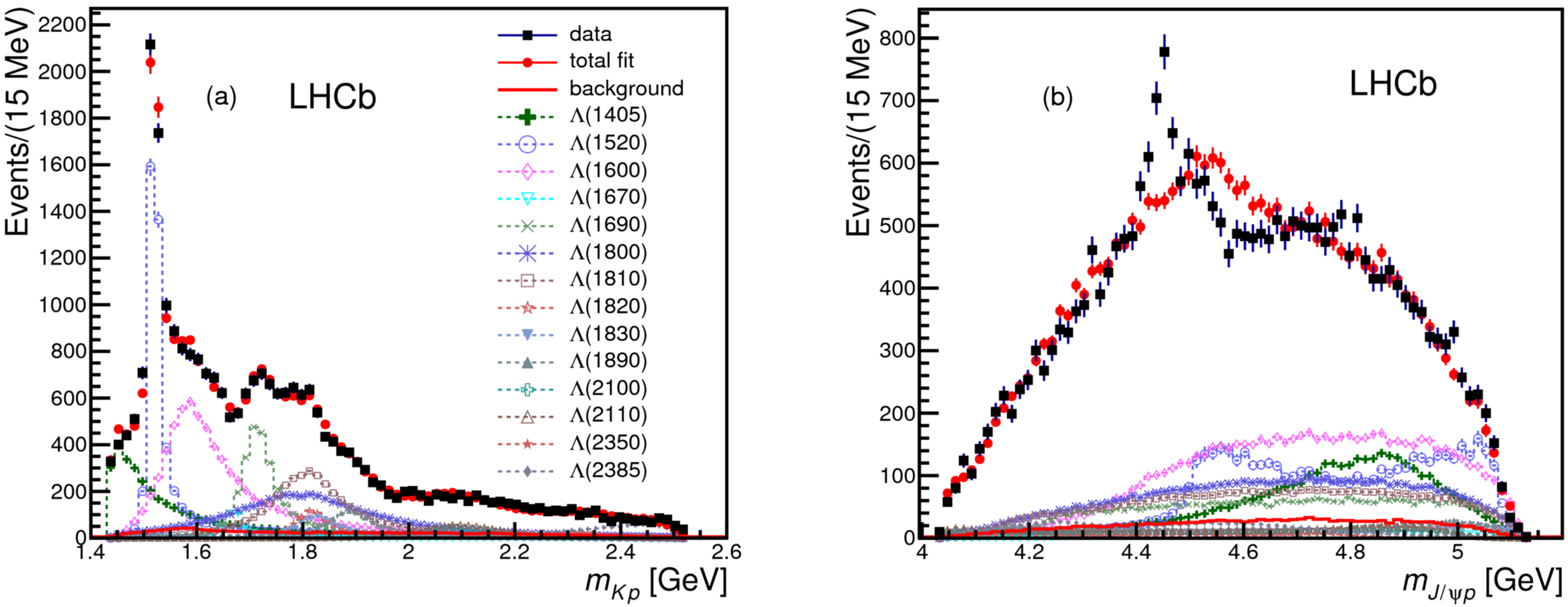
- Lesson from Z(4430)
  - full amplitude analysis is mandatory!
- Additional degrees of freedom for baryons
  - non-zero spin of initial and final state particles
  - 6D amplitude analysis necessary



Amplitude analysis of baryon decay

Phys. Rev. Lett. 115 (2015) 072001

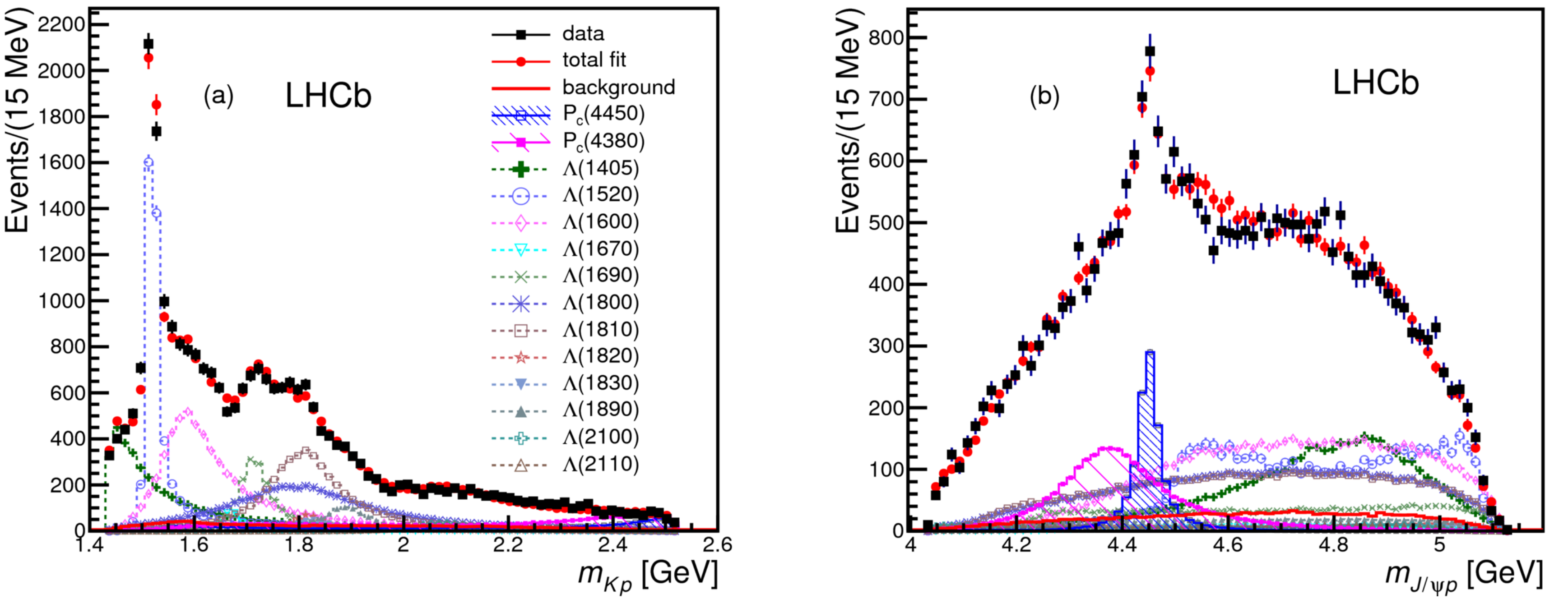
- Not possible to get good description of data including only Λ*→pK resonances



Amplitude analysis of baryon decay

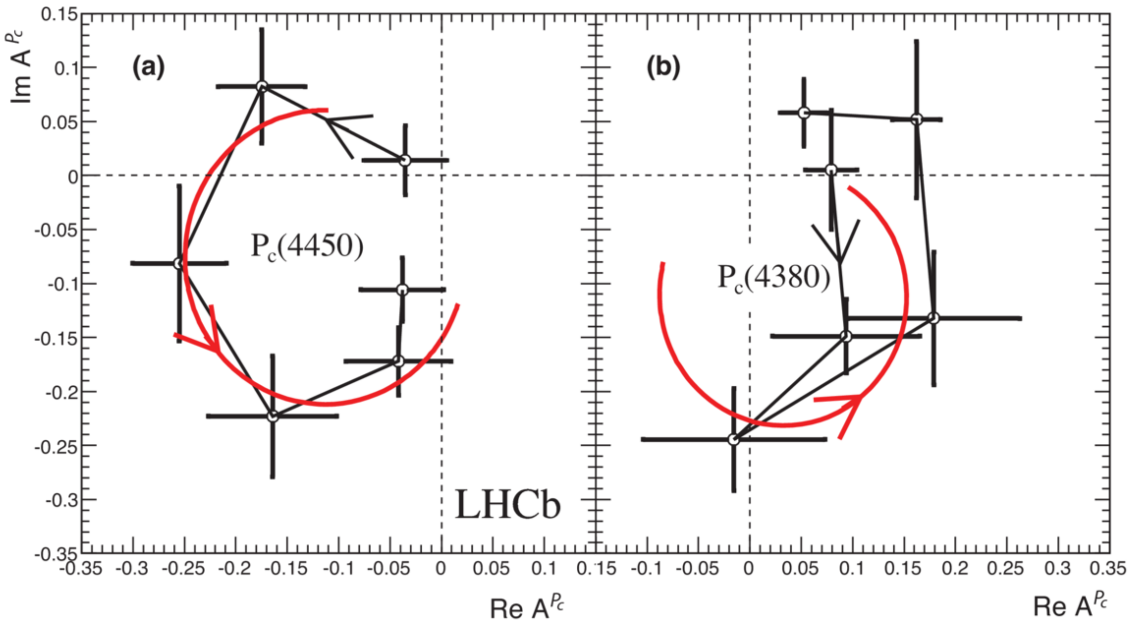
Phys. Rev. Lett. 115 (2015) 072001

- Not possible to get good description of data including only $\Lambda^* \to pK$ resonances
- Acceptable fit including two $P_c \to J\psi/p$ states



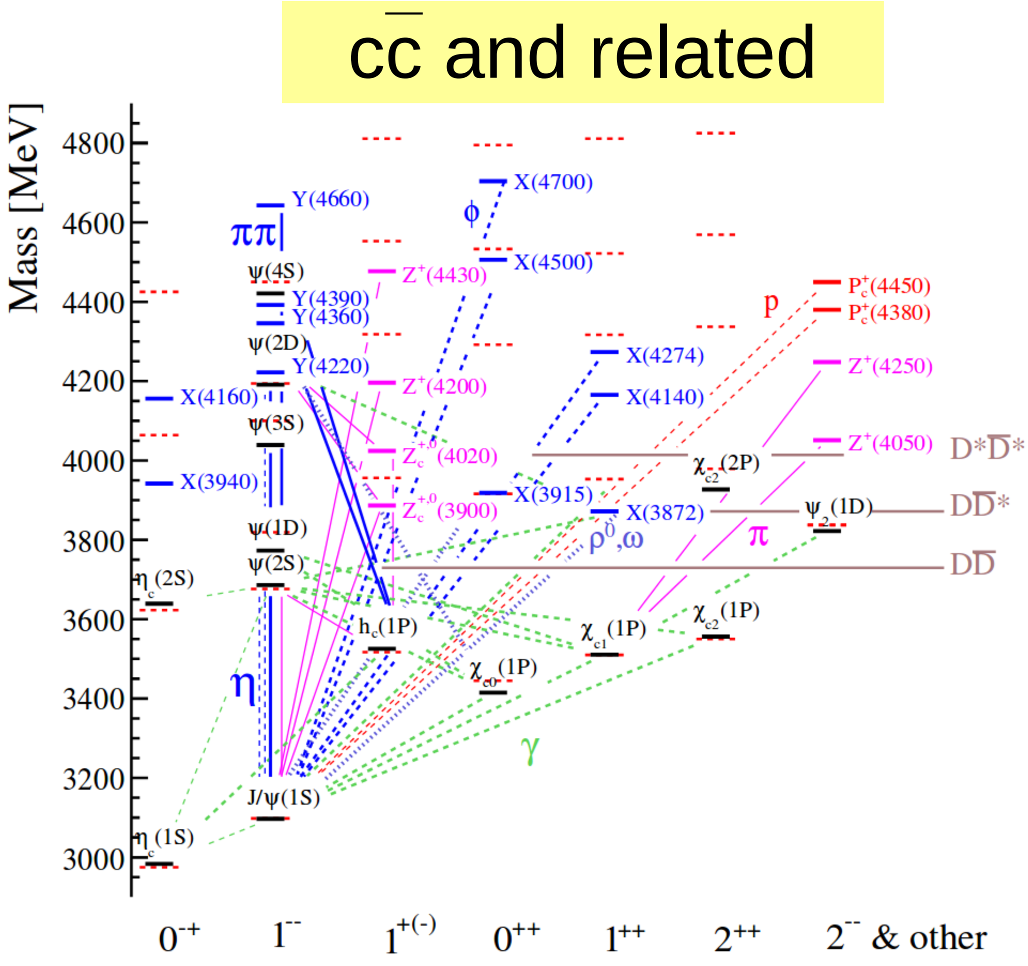
Resonant nature of the P_c states

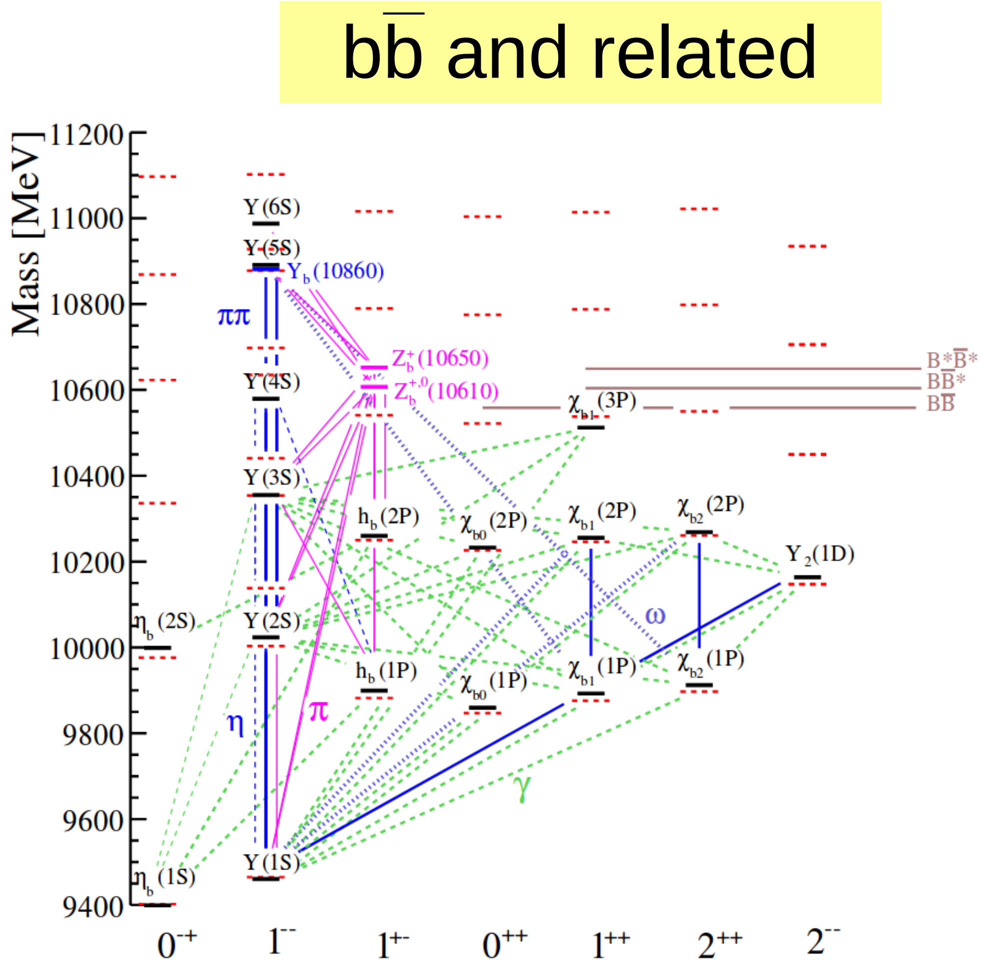
Phys. Rev. Lett. 115 (2015) 072001



- 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 ($P_c(4450)$, $P_c(4380)$) = $(3/2^{\pm},5/2^{\mp})$, $(5/2^{\pm},3/2^{\mp})$

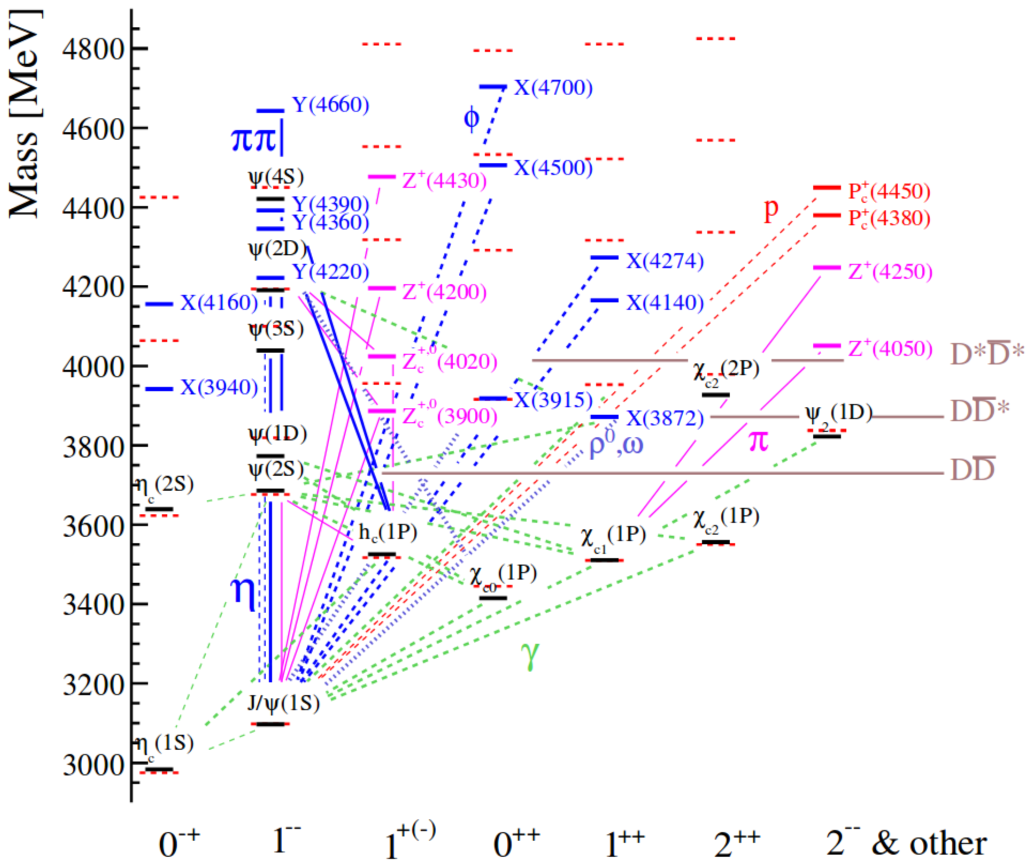
A new particle zoo





Rev. Mod. Phys. 90 (2018) 015003

A new particle zoo



Rev. Mod. Phys. 90 (2018) 015003

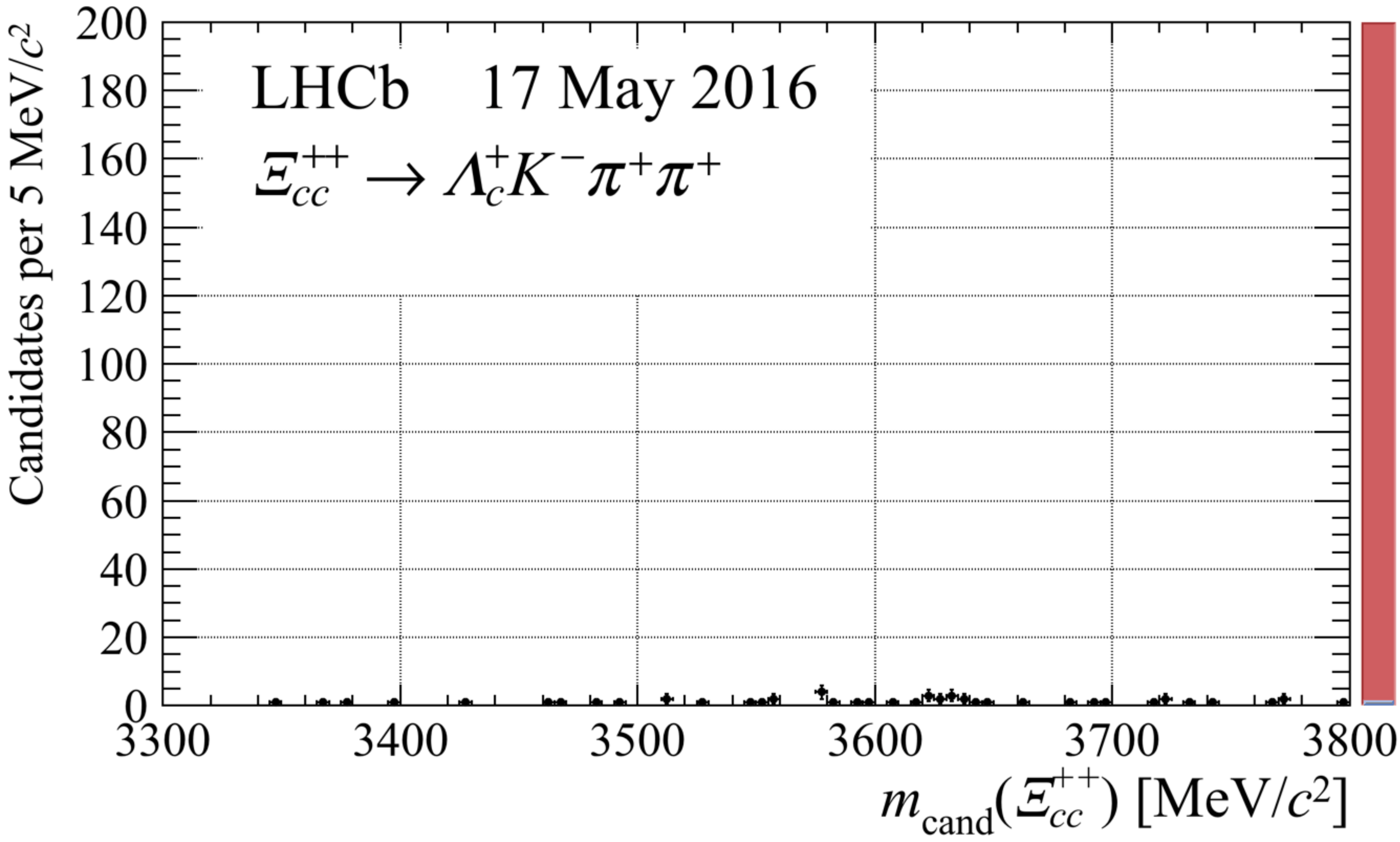
- Many new states found!
- Often by only one experiment &/or in only one channel
  - confirmations needed
- Colour code
  - conventional mesons
  - neutral states without charged partners
  - charged states (with or without neutral partners)
  - pentaquark states
- Many, but not all, states near thresholds, 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

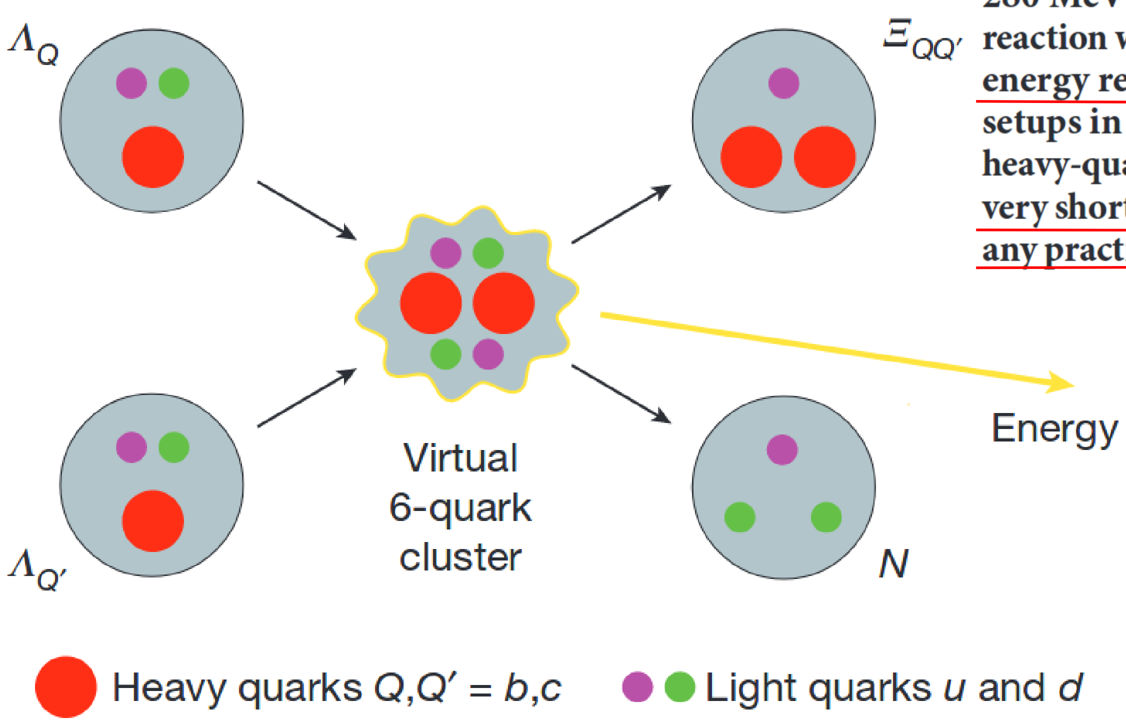
Observation of the Ξ_{cc}^{++}

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 ($\Lambda_c\Lambda_c \rightarrow \Xi_{cc}^{++}n$), resulting in an energy release of 12 MeV. This reaction is a quark-level analogue of the deuterium–tritium nuclear fusion reaction (DT $\rightarrow$ ^{4}He n). The much larger binding energy (approximately 280 MeV) between two bottom quarks (b) causes the analogous reaction with bottom quarks ($\Lambda_b\Lambda_b \rightarrow \Xi_{bb}^{0}n$) 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
  - A. Ali et al., Prog. Part. Nucl. Phys. 97 (2017) 123, https://arxiv.org/abs/1706.00610
  - R. Lebed et al., Prog. Part. Nucl. Phys. 93 (2017) 143, https://arxiv.org/abs/1610.04528