Hadron Spectroscopy

Part II

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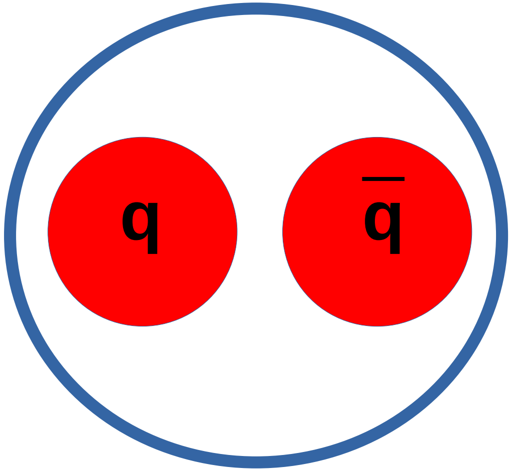
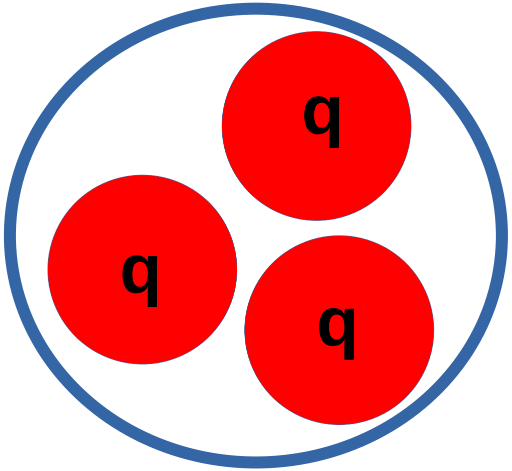
Outline

- Why do we call it spectroscopy?
- What are we really measuring?
- Conventional hadron spectra
- Light hadrons: hunt for glueballs, search for diquarks
- Heavy hadrons: multiquarks and other exotics

Quark model



mesons



baryons

More quarks per particle?

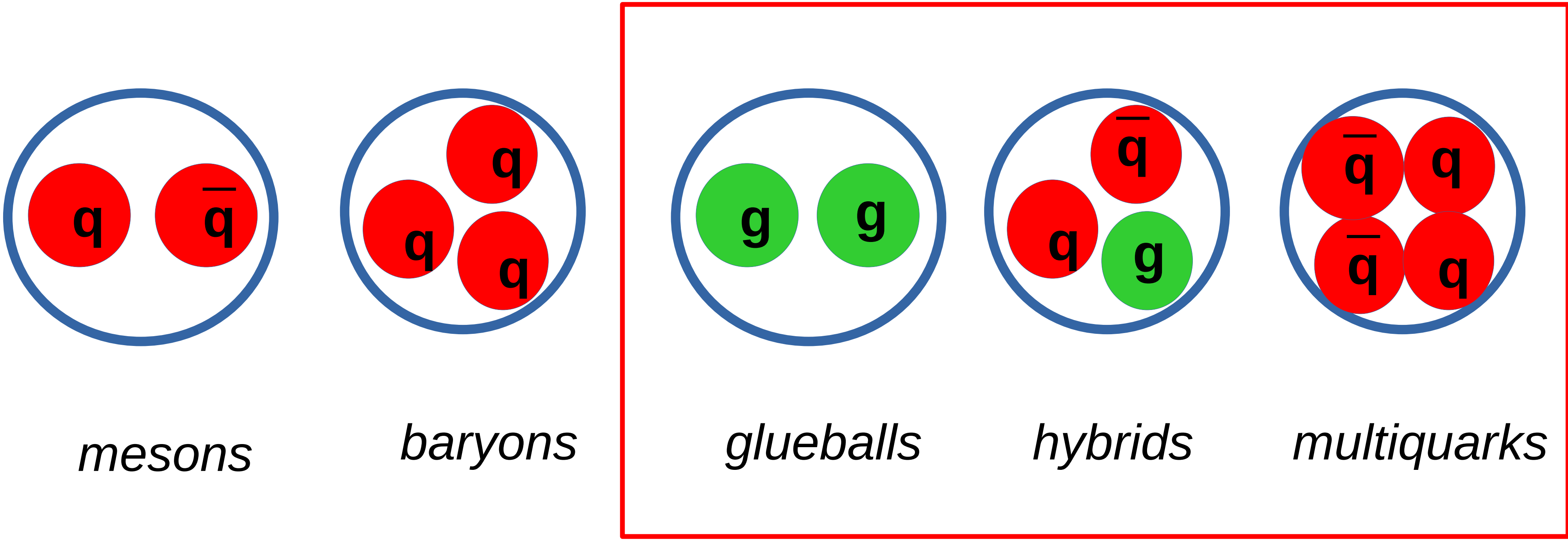
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

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 the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

Quark model


q $\bar{q}$
q q q
g g
$\bar{q}$ q g
$\bar{q}$ q $\bar{q}$ q
mesons
baryons
glueballs
hybrids
multiquarks

Question

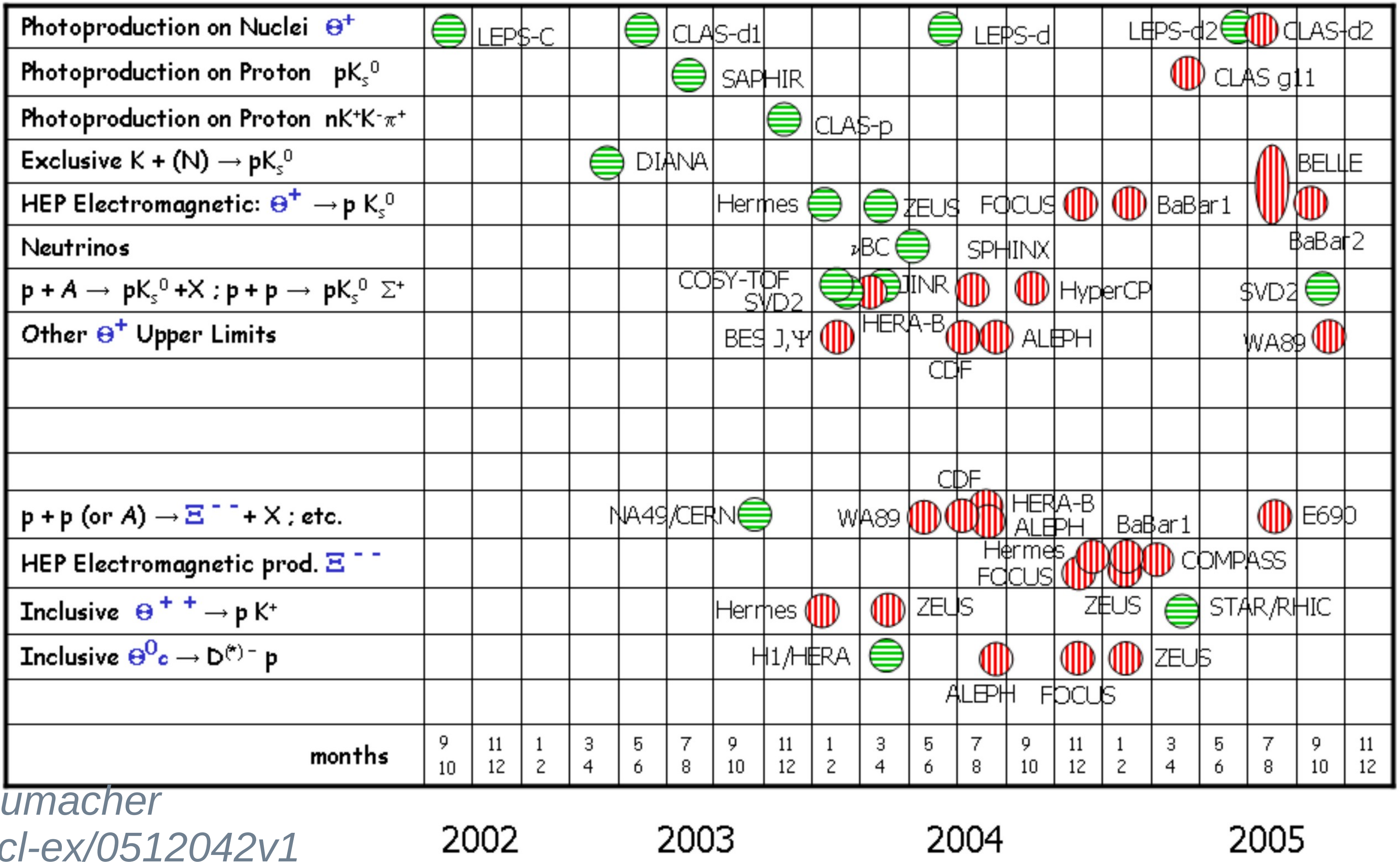
Can we call a deuteron a multiquark state?

How to identify exotic hadrons?

- Exotic quantum numbers:
  - e.g. $J^{pc} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$
- Surplus particles
- Unexpected decay patterns
  - e.g. $X^+ \rightarrow J/\psi\, \pi^+$

$\Theta^+ \rightarrow$ nK, pK

Θ^+(1530) story

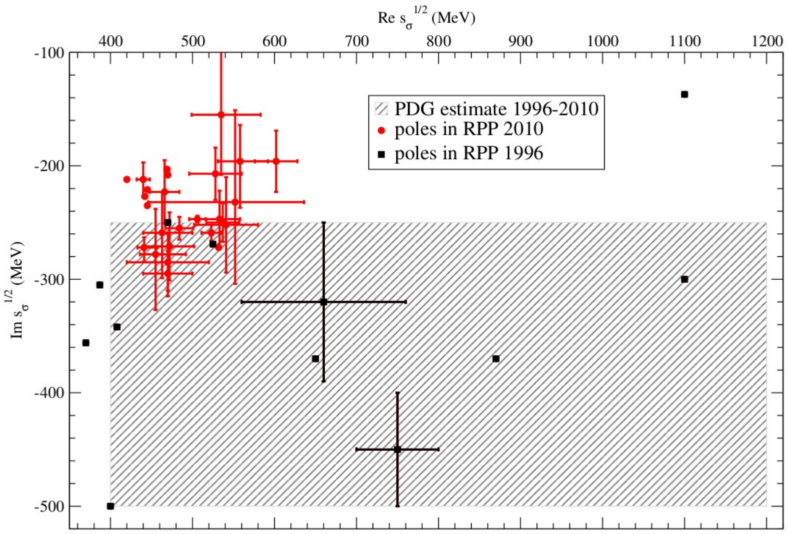


R.A.Schumacher
arXiv.nucl-ex/0512042v1

Light hadrons

$f_0(500)$ or σ

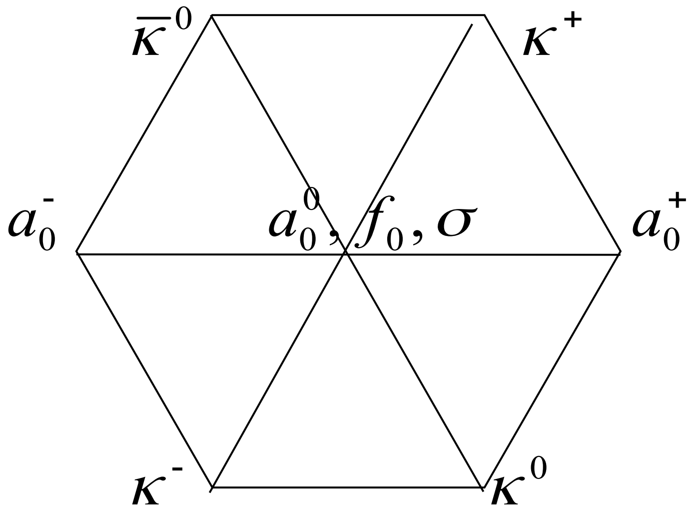
- ππ S wave
- Suggested in 1955 to explain short-range nucleon-nucleon interactions by two-pion exchange
- Controversial experimental status for about 40 years
- General agreement on the meson properties reached in mid-2000s after extensive theoretical and experimental efforts
- It is well established that it cannot be interpreted as predominantly made of a quark and an antiquark
  - Glueball?
  - Tetraquark?



J. Pelaez, arXiv:1510.00653v2

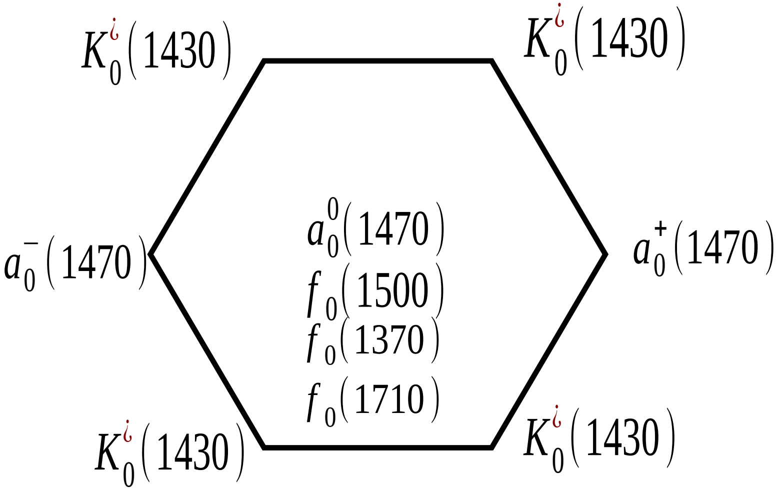
Other scalar mesons below 1 GeV

- K*(700) or κ: Kπ S wave similar to $f_0(500)$
- $a^0(980)$ and $f^0(980)$
  - Very close to KK threshold
  - Same mass
- Nonet: I=0: $f_0(500)$, $f_0(980)$, I=1/2: K*(700), I=1: $a_0(980)$?
- What is it? Meson-meson molecule, or diquark-antidiquark, or compact tetraquark, or what?

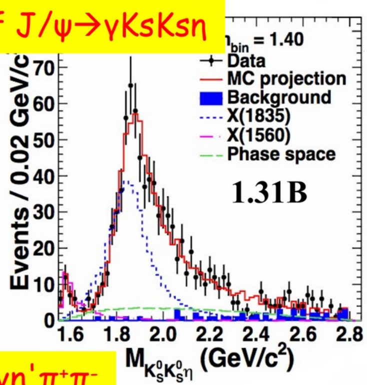


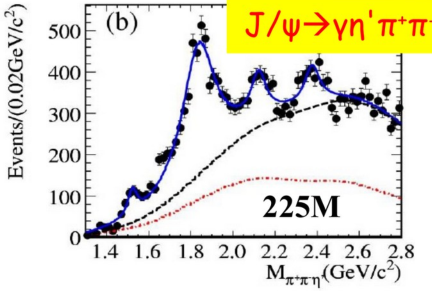
Scalar mesons above 1 GeV

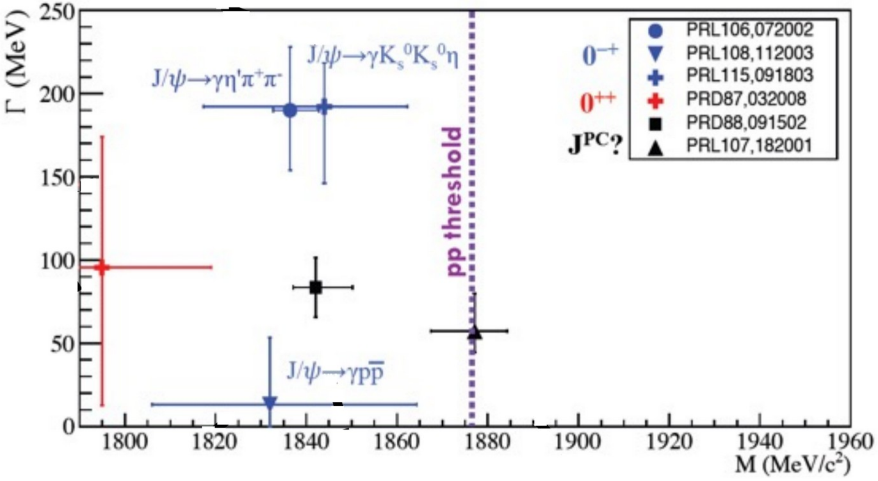
- Nonet: $K_0^*(1430)$, $a_0(1470)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
- Which of $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ is an extra state?

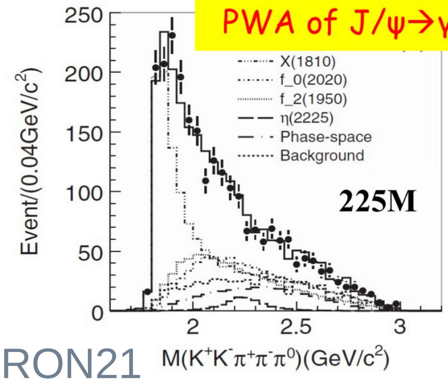


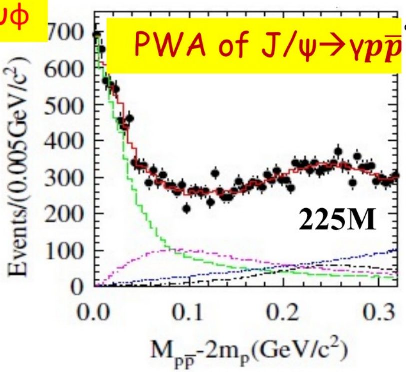
X(1835?) near the $p\bar{p}$ mass threshold

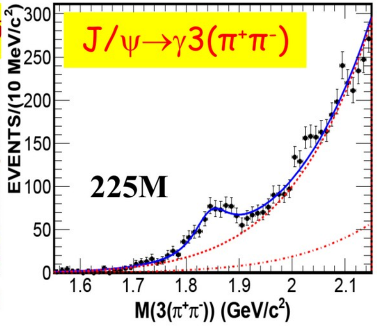


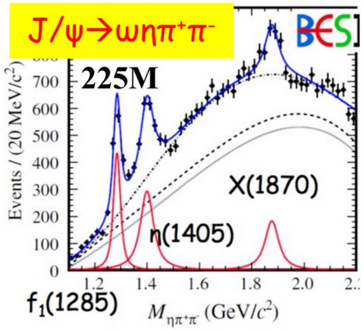






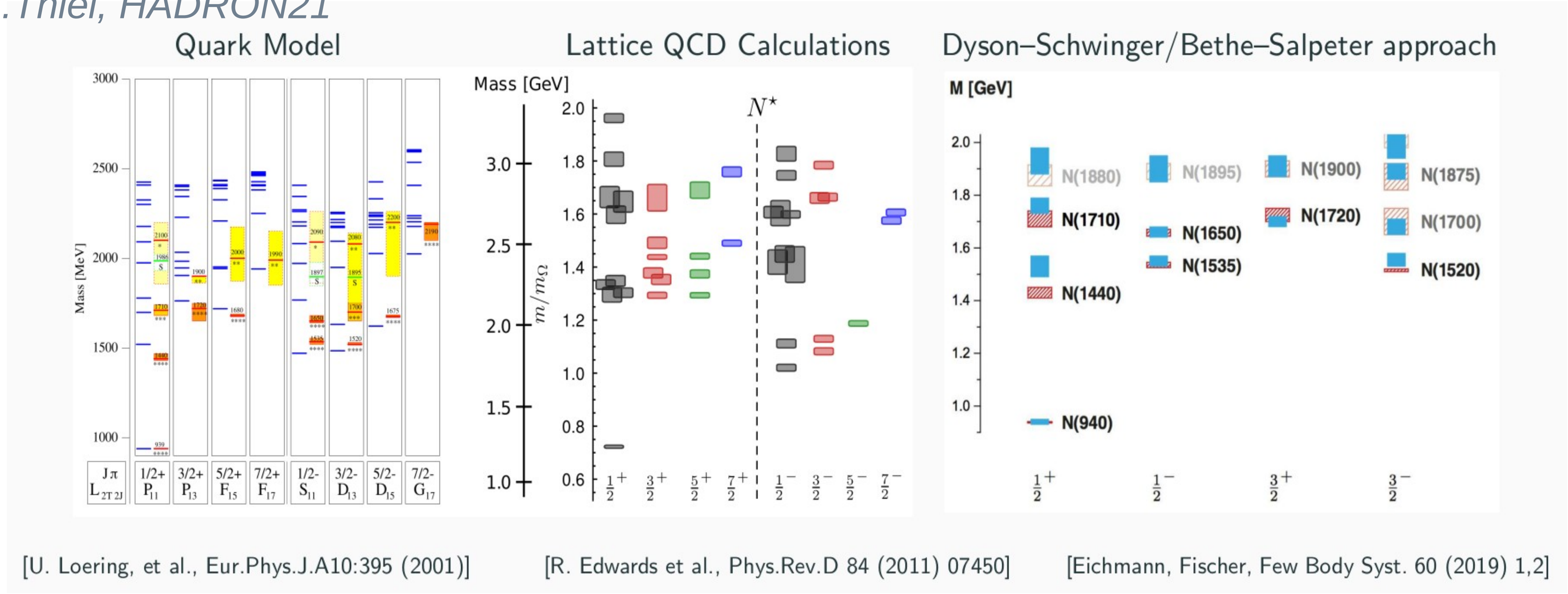






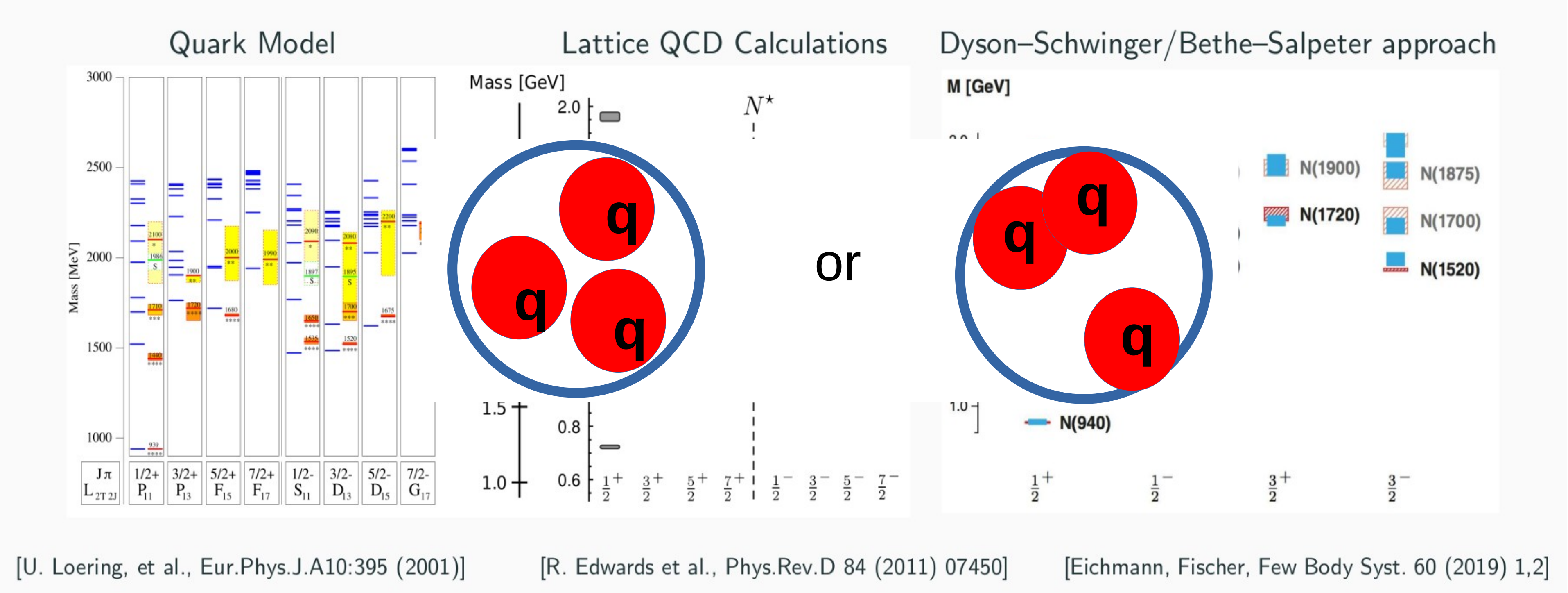
Missing light baryons

A.Thiel, HADRON21



- Large inconsistency between calculation and experiment
- Lack of experimental data or wrong theoretical assumptions?

Missing light baryons

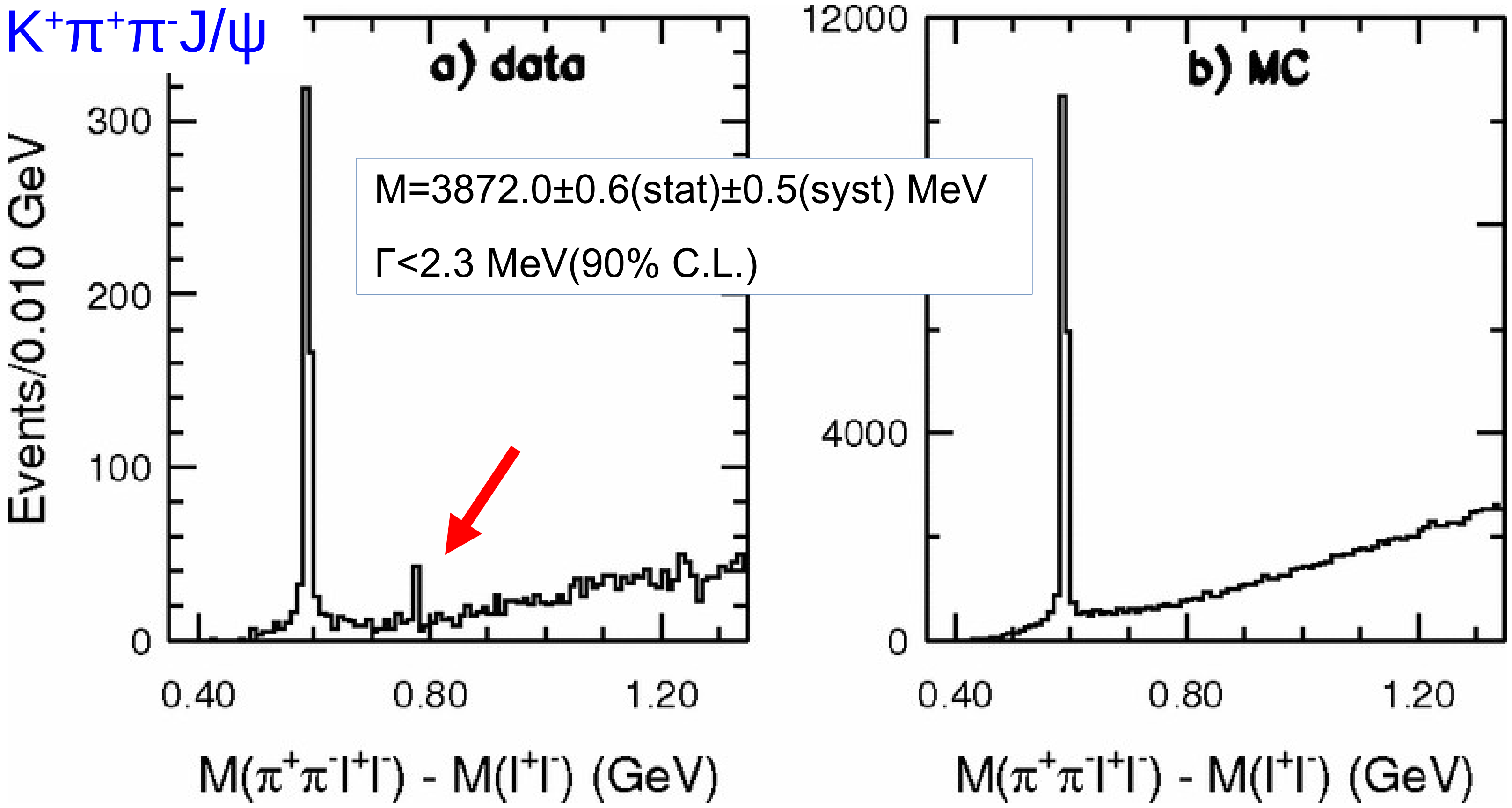


Since diquarks are not color singlets, they cannot exist as free particles. How to identify a diquark?

Heavy hadrons

First exotic heavy hadron - X(3872)

$B^+ \rightarrow K^+ \pi^+ \pi^- J/\psi$



M=3872.0±0.6(stat)±0.5(syst) MeV

Γ<2.3 MeV(90% C.L.)

S.-K. Choi et al. (Belle Collaboration)
Phys. Rev. Lett. 91 (2003) 262001

X(3872) two decades later

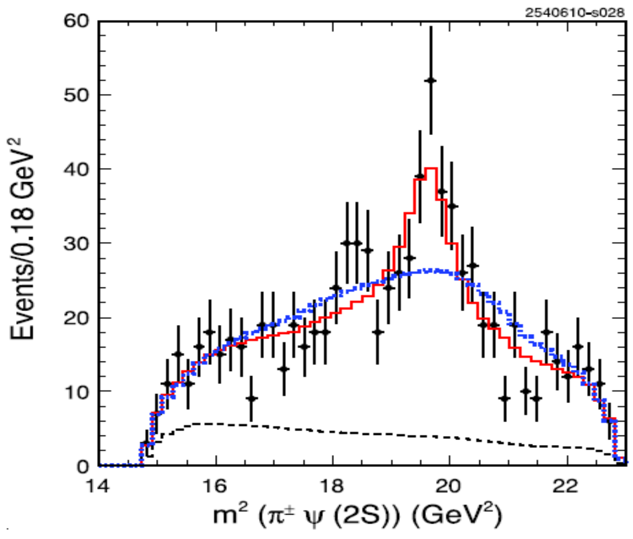
- $J^{pc} = 1^{++}$ (LHCb PRL 110, 222001 (2013))
- Mass is within 1 MeV with the mass of D*D
- Decay rate to ωJ/ψ and ρJ/ψ is approximately the same
- Comparable decay rate to D*D and γψ(3686): not a D*D bound state
- Charged partner is not found

Charged charmonium-like states $Z_c^{\pm}(4430)$, $Z_c^{\pm}(4050)$, $Z_c^{\pm}(4250)$

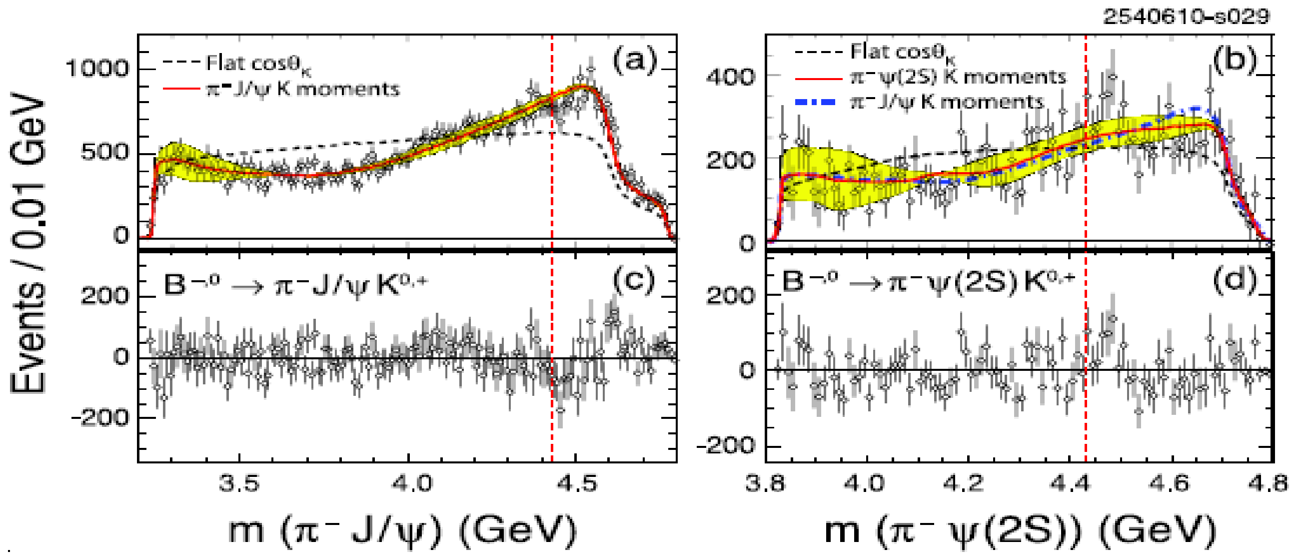
Observed by BELLE in $B \to K\pi\psi(2S)$, $B \to K\pi\chi_{c1}$

Not observed by BaBar in very similar conditions

BELLE



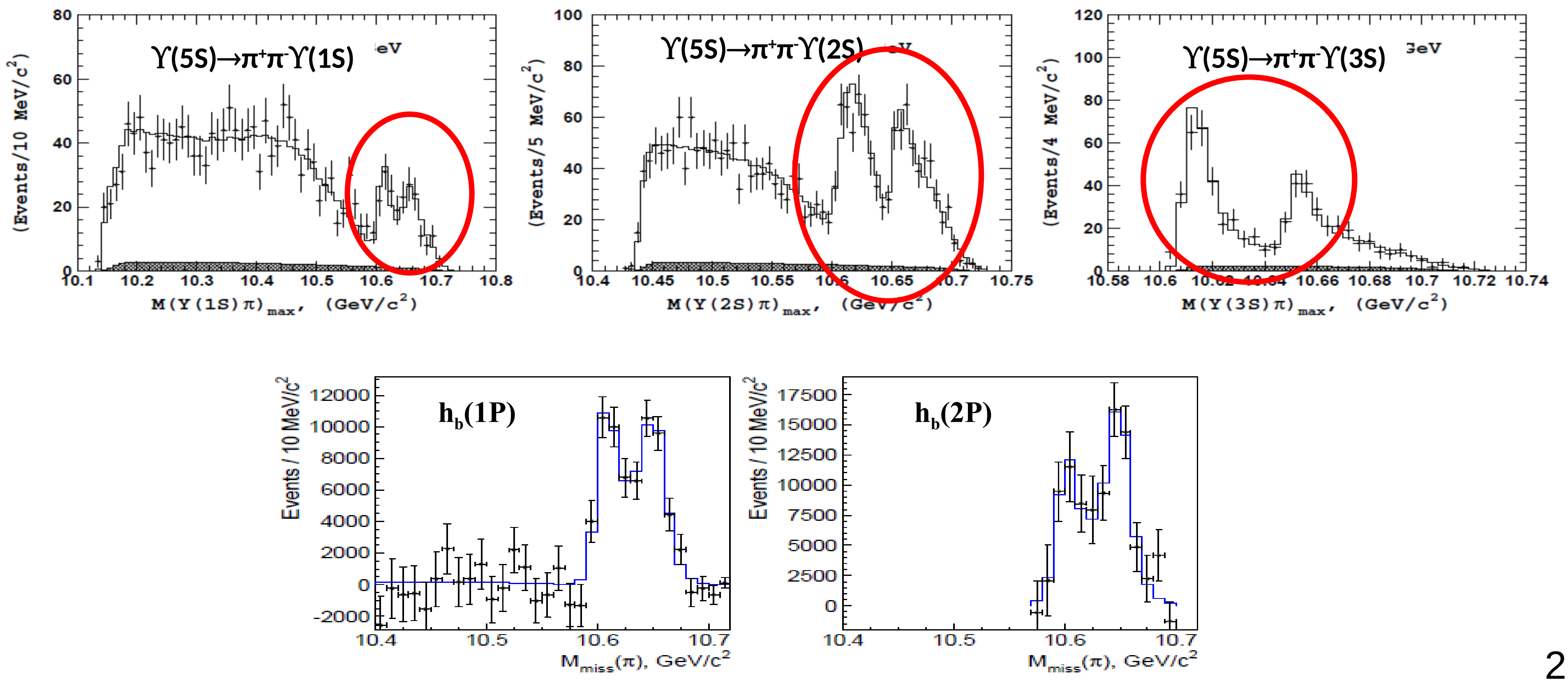
BaBar



Observation of charged bottomonium-like state Z_b(10610) and Z_b(10650)

$\Upsilon(5S)\to\pi^+\pi^-\Upsilon(nS)$, $\pi^+\pi^- h_b(nP)$

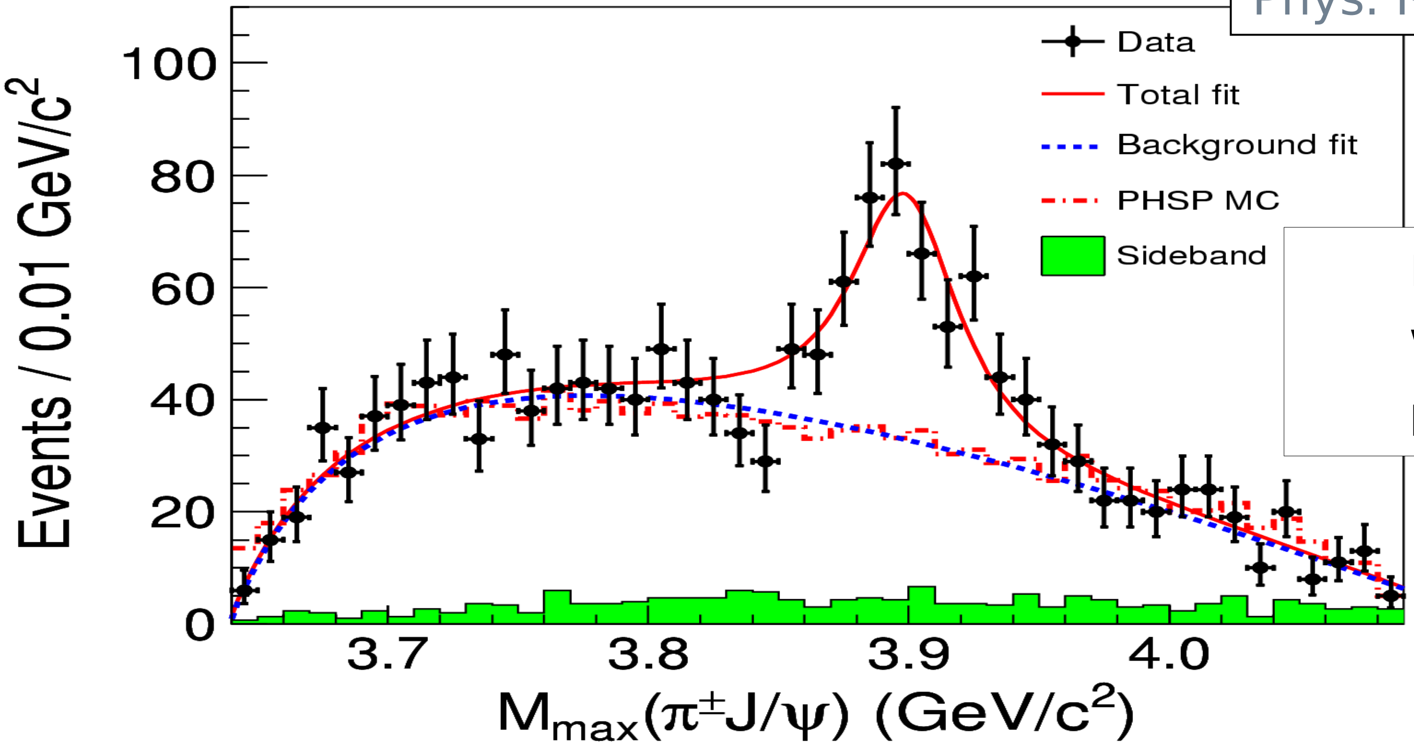
BELLE, PRL 108, 122001 (2012)



The $Z_c^{\pm}(3900)$ observaton @BESIII

$e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s}$=4260 MeV

BESIII: arXiv:1303.5949
Phys. Rev. Lett (2013) 252001



Mass = (3899.0±3.6±4.9) MeV

Width = (46±10±20) MeV

Fraction = (21.5±3.3±7.5)%

$Z_c(3900)^0$

Observation of neutral $Z(3900)^0$

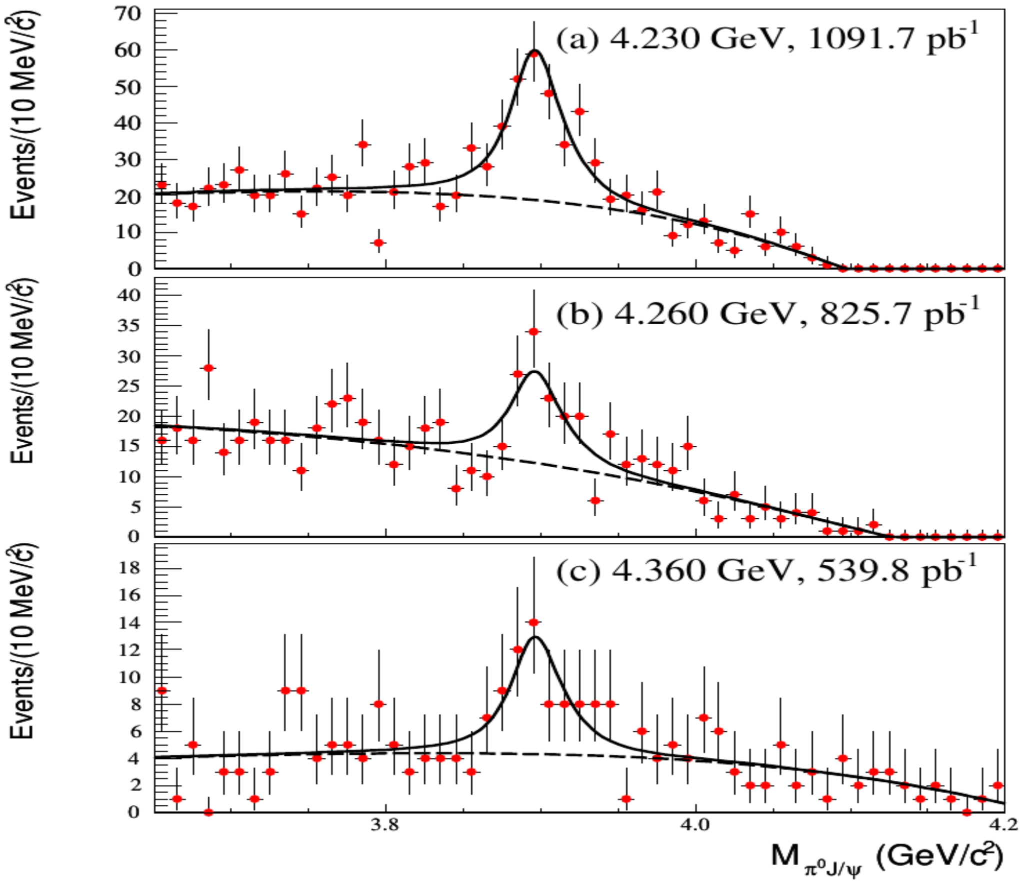
Phys. Rev. Lett. 115, 112003 (2015)

Process: e+e- → $\pi^0\pi^0 J/\psi$
@4.23 GeV (1 fb^{-1})
@4.26 GeV (0.8 fb^{-1})
@4.36 GeV (0.5fb^{-1})
+ 7 small samples 4.19 – 4.42 GeV

M = 3894.8 ± 2.3 ± 3.2 MeV/c^2
Γ = 29.6 ± 8.2 ± 8.2 MeV

Statistical significance: 10.4σ

Interpreted as isospin partner of $Z(3900)^{\pm}$



$Z_c(3885)^{\pm}$

Phys. Rev. Lett. 112, 022001 (2014)

$Z_c(3900)$ lies ~20 MeV above $D\bar{D}^*$ mass threshold.

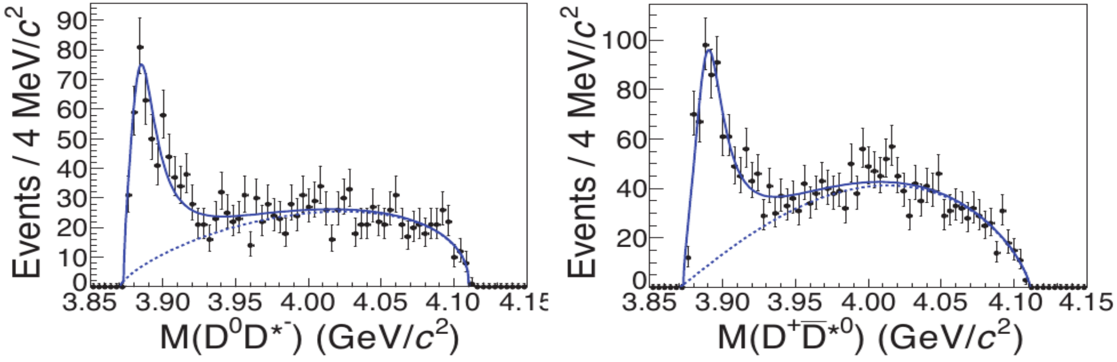
Process: $e^+e^- \to (D^0D^{*-})\pi^+ + (D^+\bar{D}^{*0})\pi^-$ @4.26 (0.5 fb^{-1})

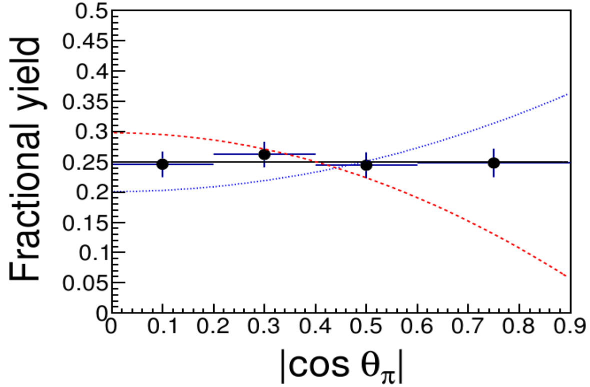
	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$	$3899 \pm 3.6 \pm 4.9$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$	$13.5 \pm 2.1 \pm 4.8$

Assuming $Z_c(3885)$ and $Z_c(3900)$ are one state

$$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

$$\frac{\mathcal{B}(\psi(3770) \to D\bar{D})}{\mathcal{B}(\psi(3770) \to J/\psi\pi^+\pi^-)} = 482 \pm 84$$





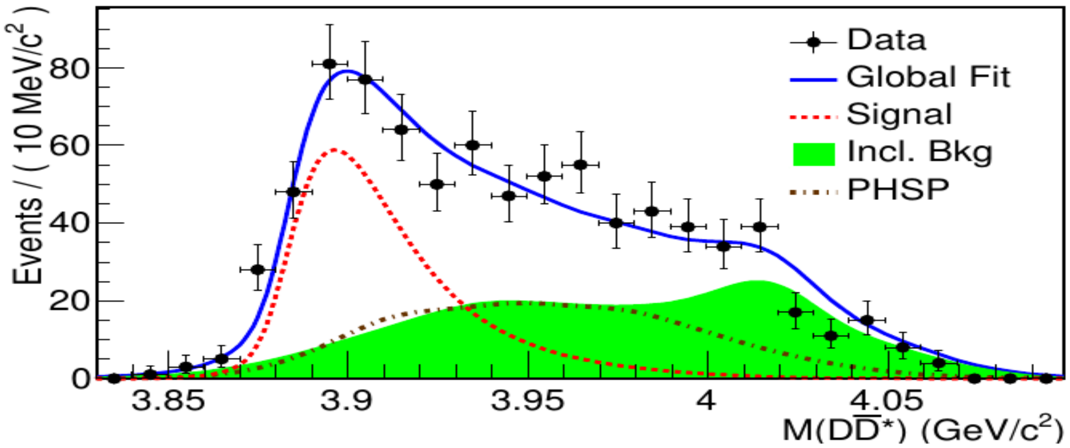
Black: 1^+
Red: 0^-
Blue: 1^-

$Z_c(3885)^0$

Phys. Rev. Lett. 115, 222002 (2015)

Process: $e^+e^- \rightarrow (D^+D^{*-})^0\pi^0 + (D^0\bar{D}^{*0})^0\pi^0$
@4.23 (1.1 fb^{-1})
@4.26 (0.8 fb^{-1})

$$M = 3885.7^{+4.3}_{-5.7} \pm 8.4\ MeV/c^2$$
$$\Gamma = 47 \pm 9 \pm 10\ MeV$$



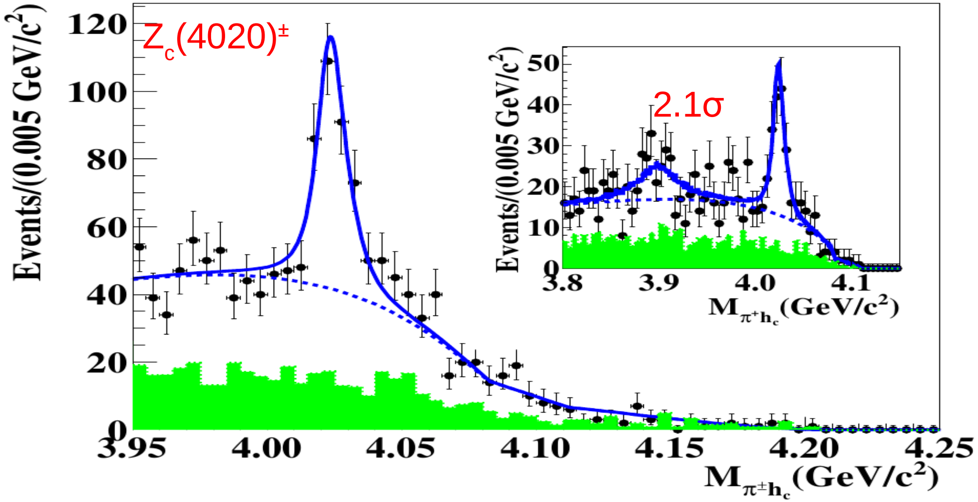
Born cross section consistent for
$e^+e^- \rightarrow Z_c\pi^0 \rightarrow (D\bar{D}^*)^0\pi^0$ + c.c.
is consistent with half of
$e^+e^- \rightarrow Z_c^+\pi^- \rightarrow (D\bar{D}^*)^+\pi^-$ + c.c.

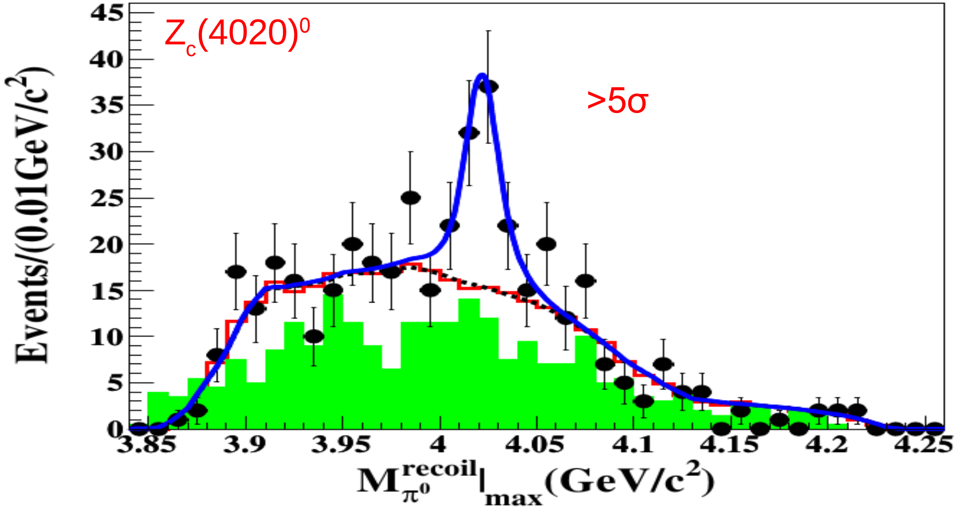
$Z_c(4020)^{\pm}$ and $Z_c(4020)^0$

$e^+e^- \to \pi^+\pi^- h_c$ and $\pi^0\pi^0 h_c$

h_c reconstructed through E1 transition $h_c \to \gamma\eta_c$, reconstructed from 16 exclusive hadronic modes.

$$\sqrt{s} = 4.23,\ 4.26,\ \text{and}\ 4.36\ \text{GeV}$$





Phys.Rev.Lett.111, 242001 (2013)

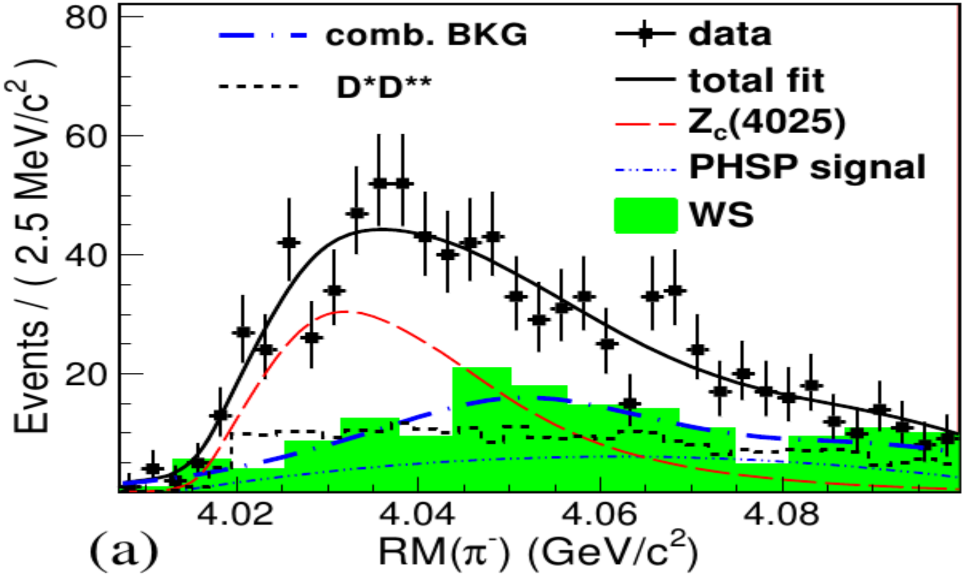
M=4022.9 ± 0.8 ± 2.7 MeV/c^2
Γ = 7.9 ± 2.7 ± 2.6 MeV

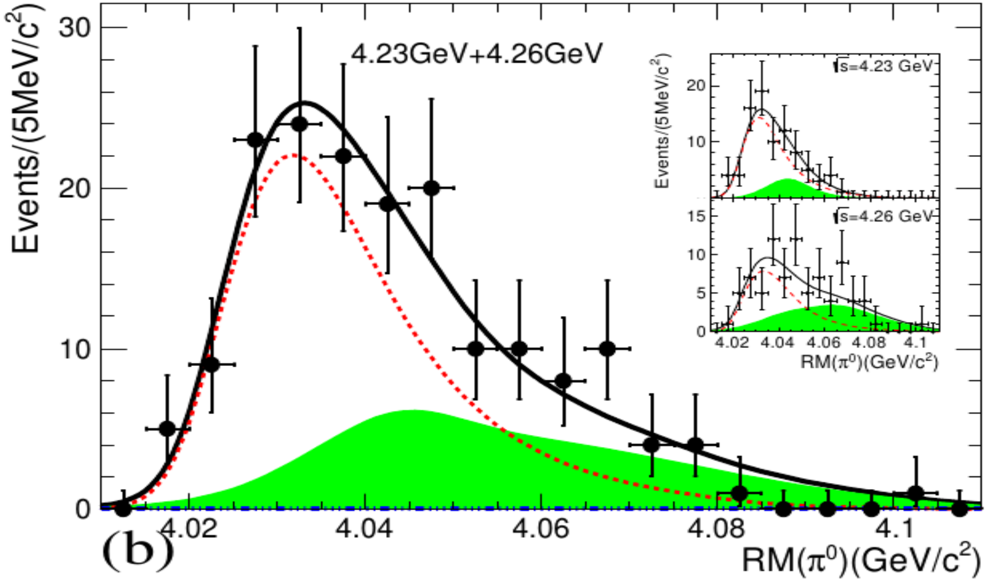
Phys.Rev.Lett.113.212002(2014)

M=4023.9 ± 2.2 ± 3.8 MeV/c^2
Fixed Γ

Close to $D^*\bar{D}^*$ threshold

$Z_c(4025)^{\pm}$ and $Z_c(4025)^0$





Phys. Rev. Lett. 112, 132001 (2014)

$e^+e^- \rightarrow (D^*\bar{D}^*)^+\pi^-$ + c.c.

0.8 fb^{-1} @ 4.26 GeV

Partial reconstruction technique

M = 4026.3 ± 2.6 ± 3.7 MeV/c^2

Γ = 24.8 ± 5.6 ± 7.7 MeV

Phys. Rev. Lett. 115, 182002 (2015)

$e^+e^- \rightarrow (D^*\bar{D}^*)^0\pi^0$

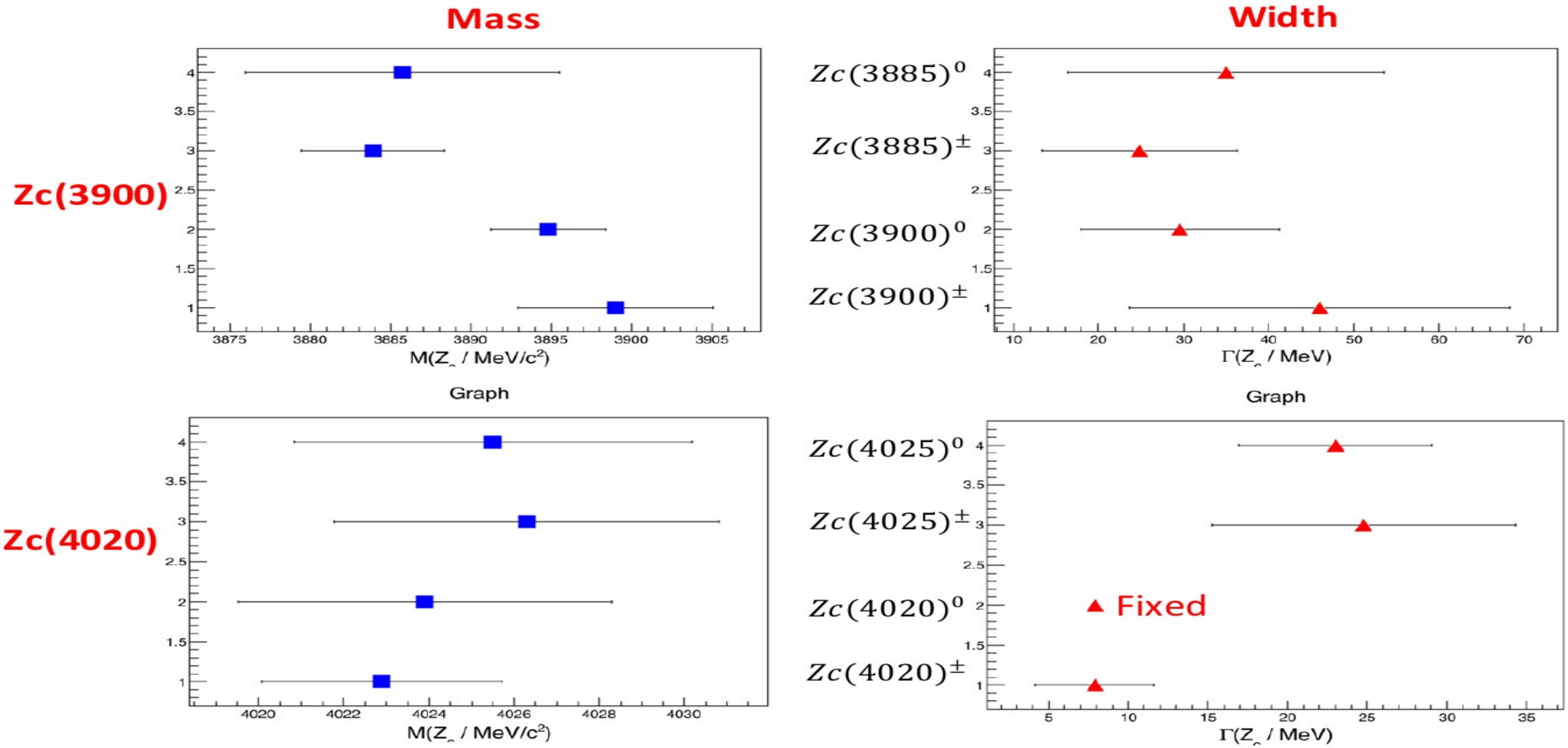
1.1 fb^{-1} @ 4.23 and 0.8 fb^{-1} @ 4.26 GeV

Parti $(4025.5^{+2.0}_{-4.7} \pm 3.1)\ \mathrm{MeV}/c^2$ e

M = $(23.0 \pm 6.0 \pm 1.0)\ \mathrm{MeV}$

Γ =

Summary on Z_c

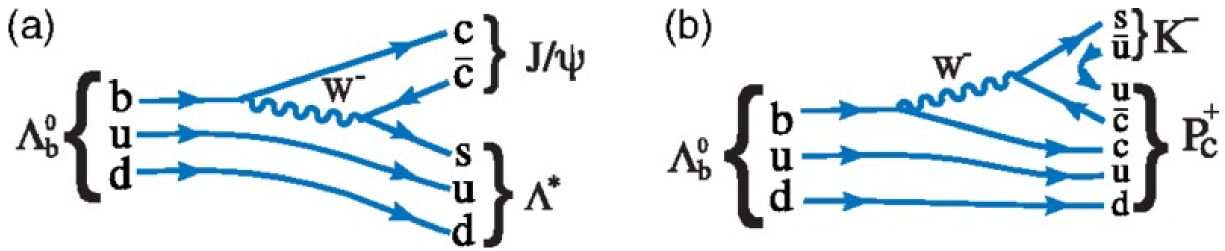


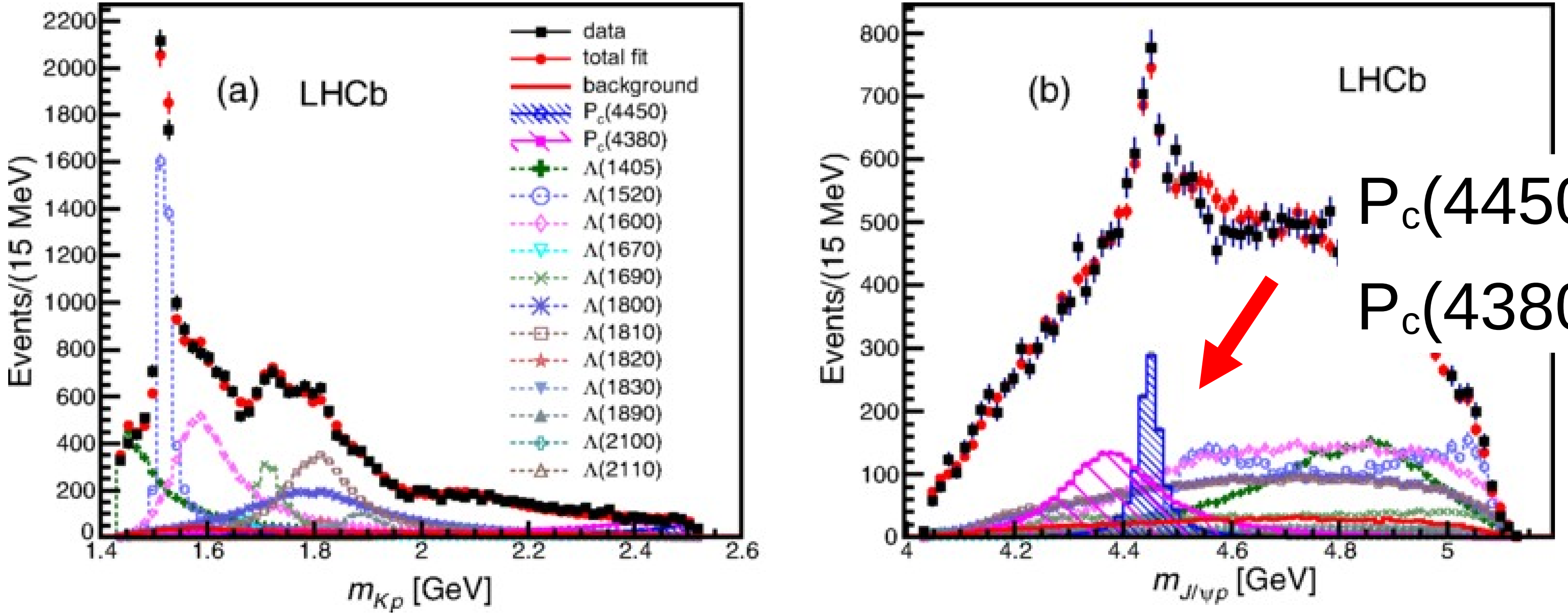
Question

Is it possible to look for a similar state with a strange quarkonium?

Pentaquarks at LHC

R. Aaij et al. (LHCb Coll.) Phys. Rev. Lett. 115 (2015) 072001

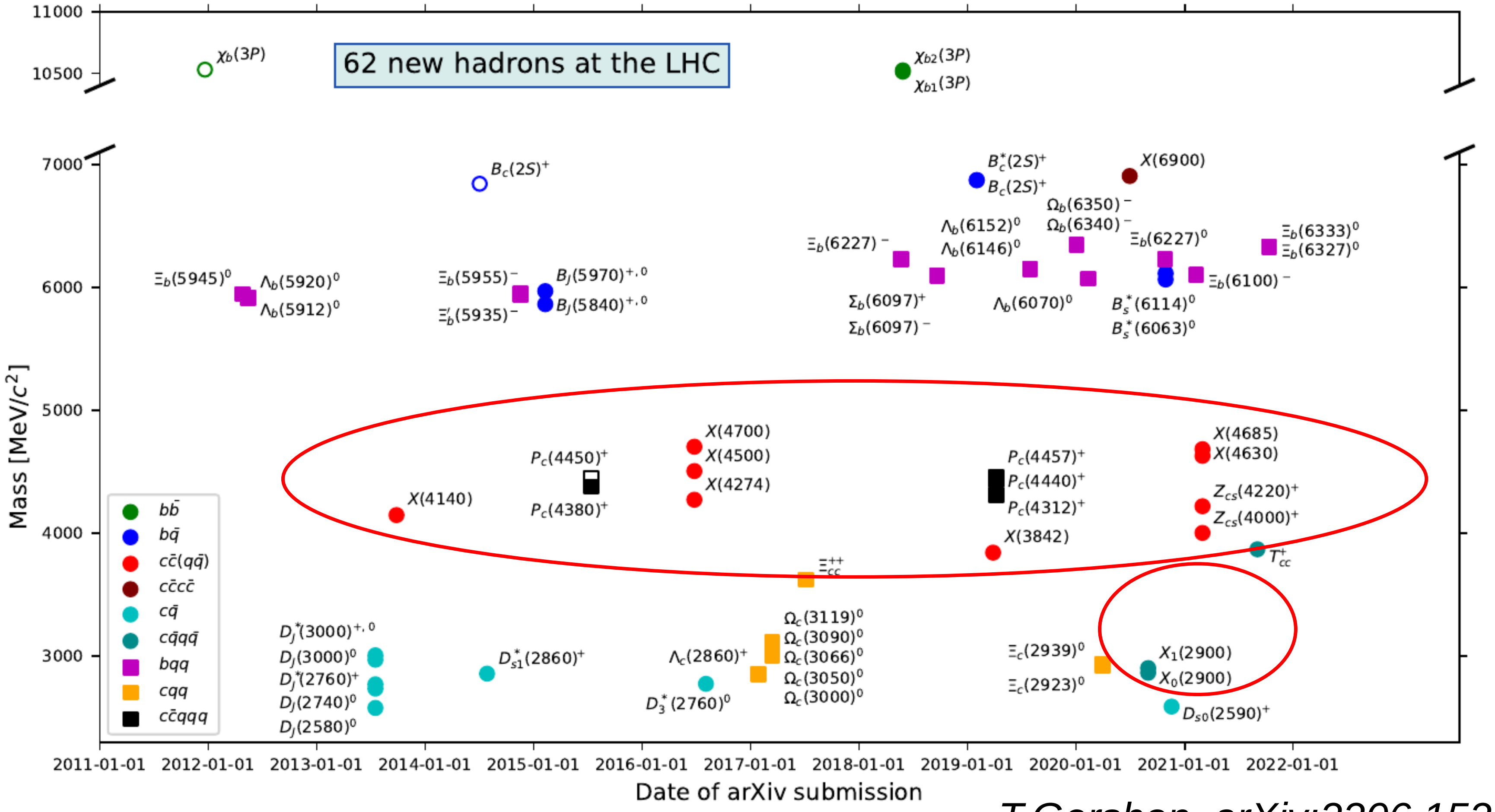




$P_c(4450)^+$

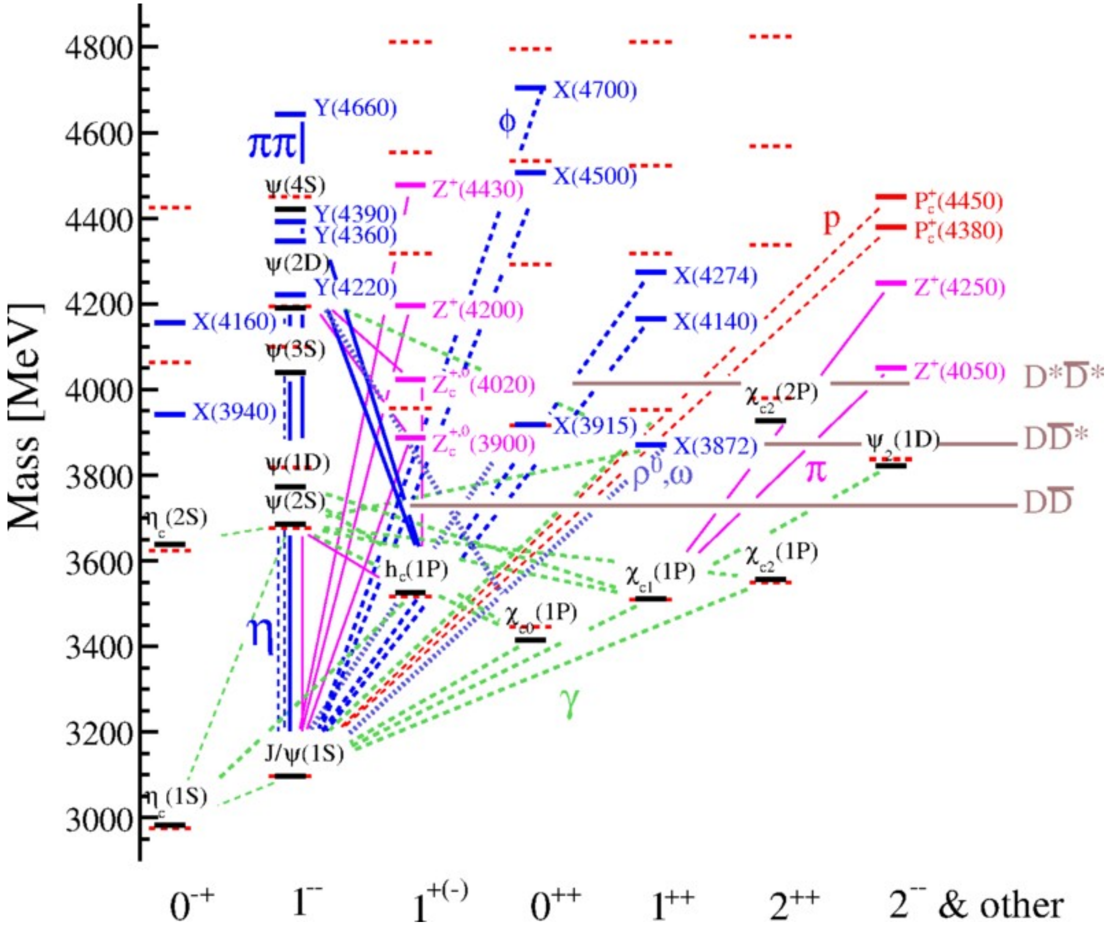
$P_c(4380)^+$

New hadrons at LHC



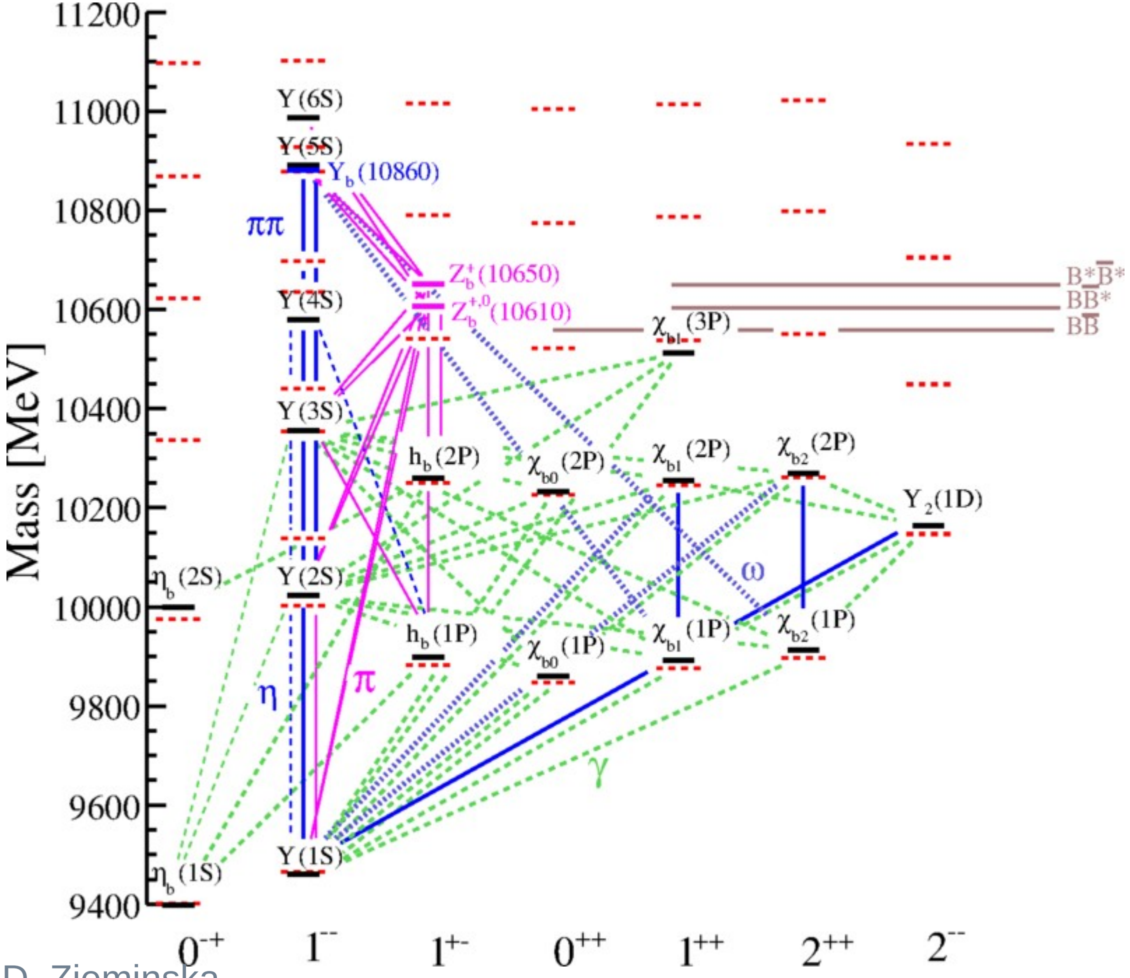
T.Gershon, arXiv:2206.15233

Modern charmonium-like spectrum



S. L. Olsen, T. Skwarnicki, D. Zieminska,
Rev. Mod. Phys. 90 (2018) 015003

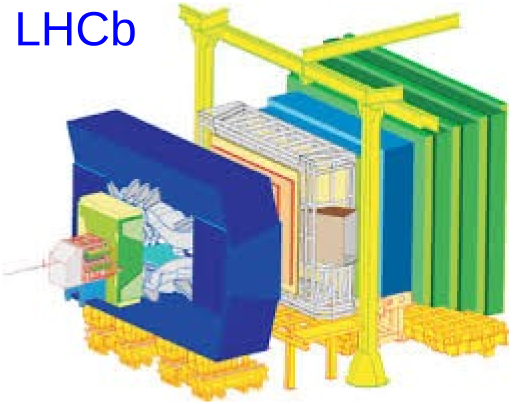
Modern bottomonium-like spectrum



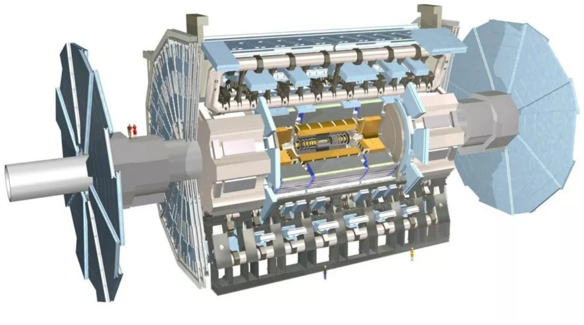
S. L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003

Experimental landscape

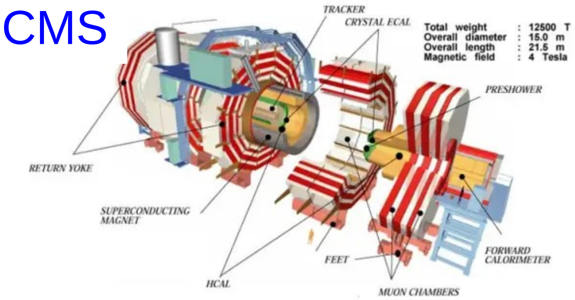
LHCb



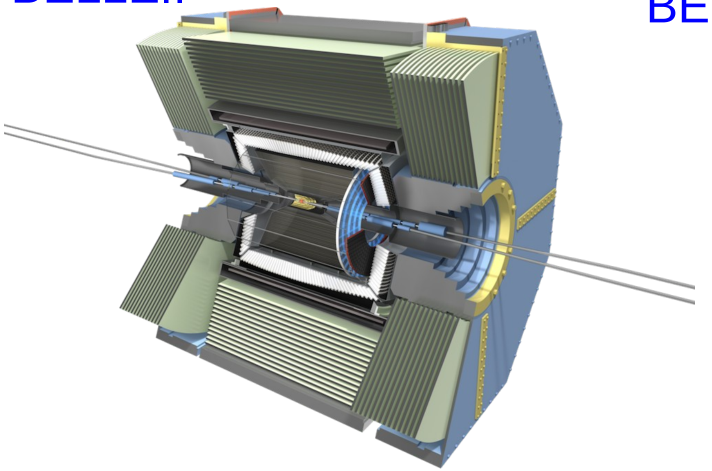
ATLAS



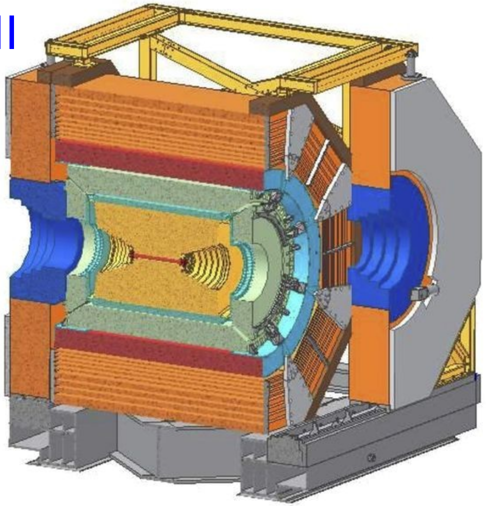
CMS

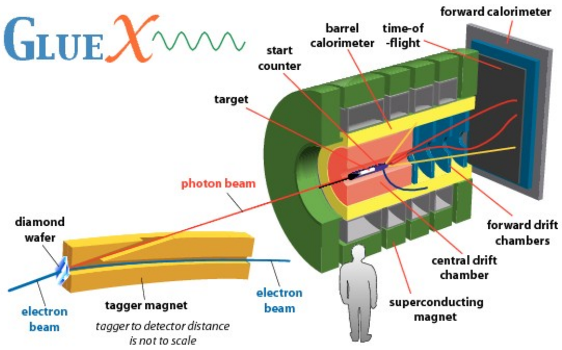


BELLEII



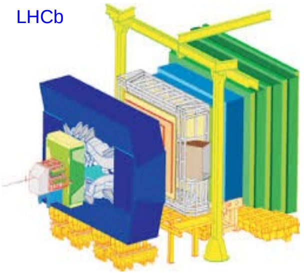
BESIII





Experimental landscape (near future)

LHCb



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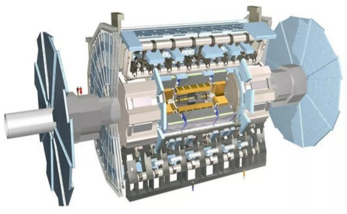
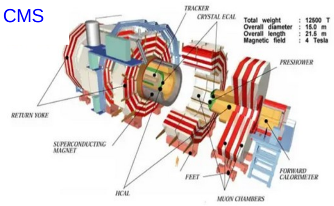


CMS



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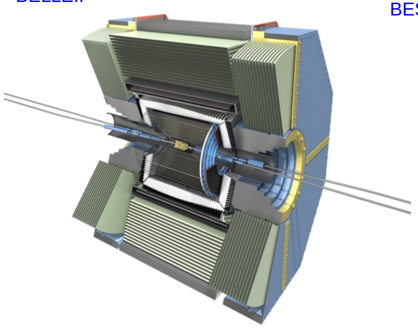
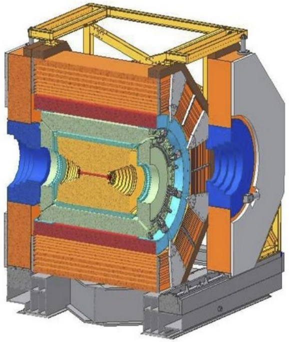
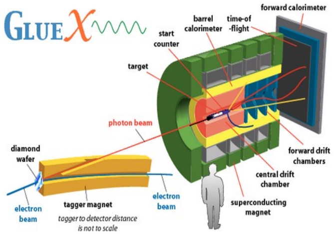


BESIII





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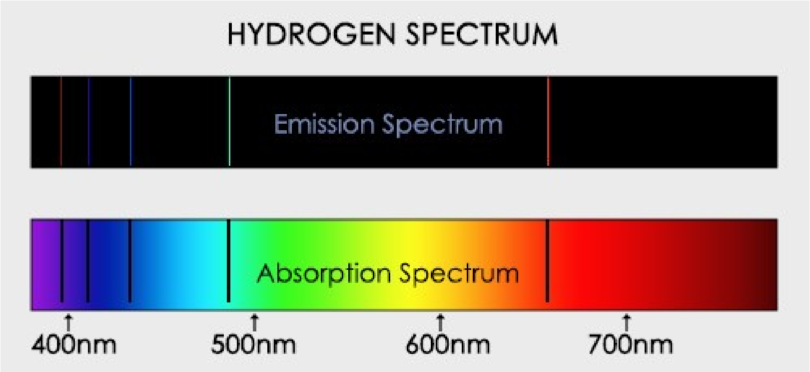
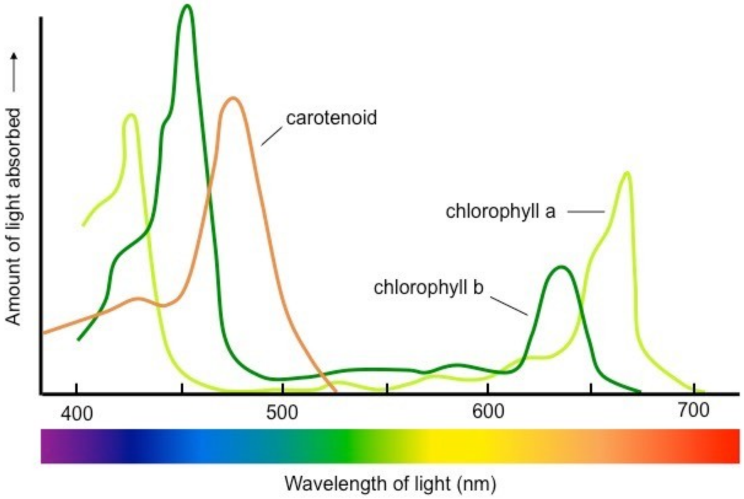
PANDA
AMBER
EIC
SCTF

Summary

- Hadron spectroscopy is a unique tool to gain knowledge about the intrinsic properties and the composition of hadrons
- Discovery of a large number of multiquark states is the most interesting event since J/ψ observation
- More precise experimental data are needed to understand XYZ states
- Surplus light mesons and missing light baryons are still there
- Lattice QCD is making a good progress, but theory describing all experimental findings is not yet built



A lot of exciting things ahead of us!



Thank you for your attention!