Physics in Collision 2019
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Review on Spectroscopy

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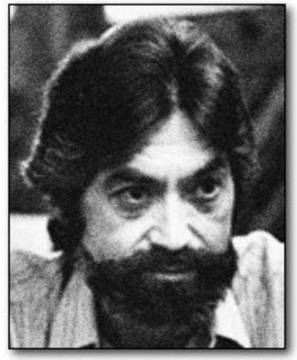
I apologize I can not cover all the results…

Outline

- Introduction: the success of Quark Model
- Charmonium Spectroscopy
- Tetraquak and Pentaquark
- Challenges and Perspectives
- Summary

Quark Model

1964



AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)

CERN - Geneva

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, 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".

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

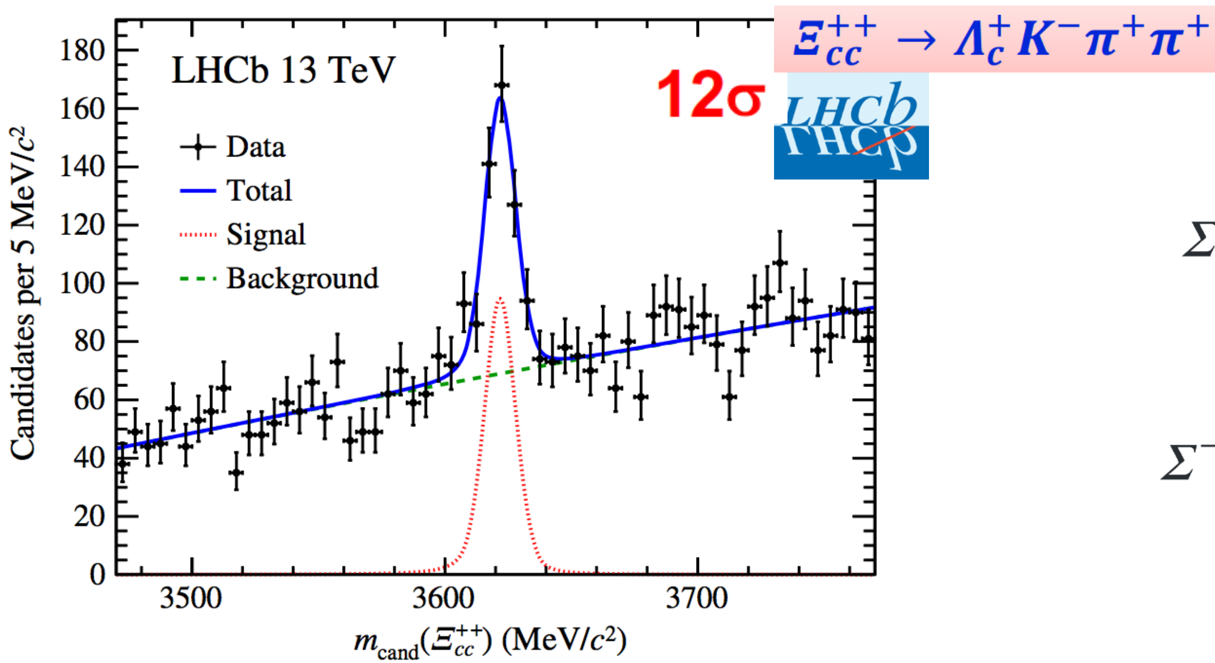
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

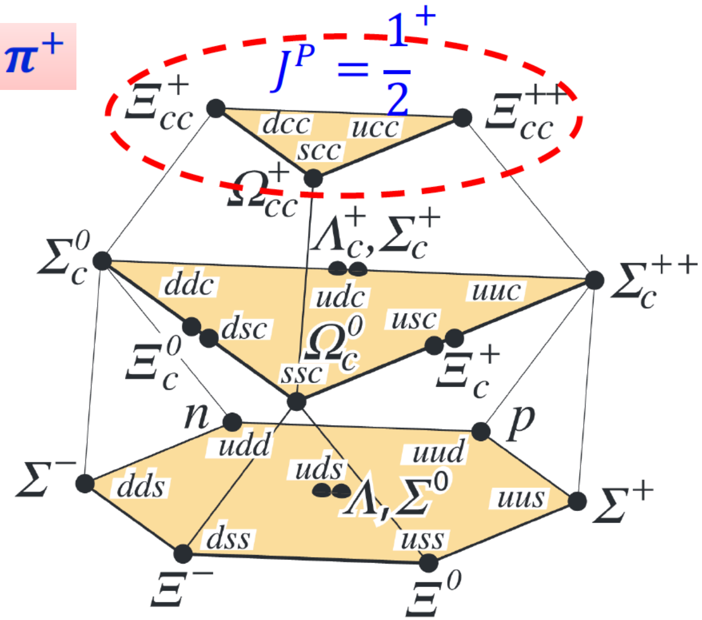
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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 (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**.

- Baryon (qqq) & meson ($q\bar{q}$)
- ($qq\bar{q}\bar{q}$) & ($qqqq\bar{q}$) etc. → Tetraquark & Pentaquark

Successful & Powerful

PRL 119, 112001 (2017)

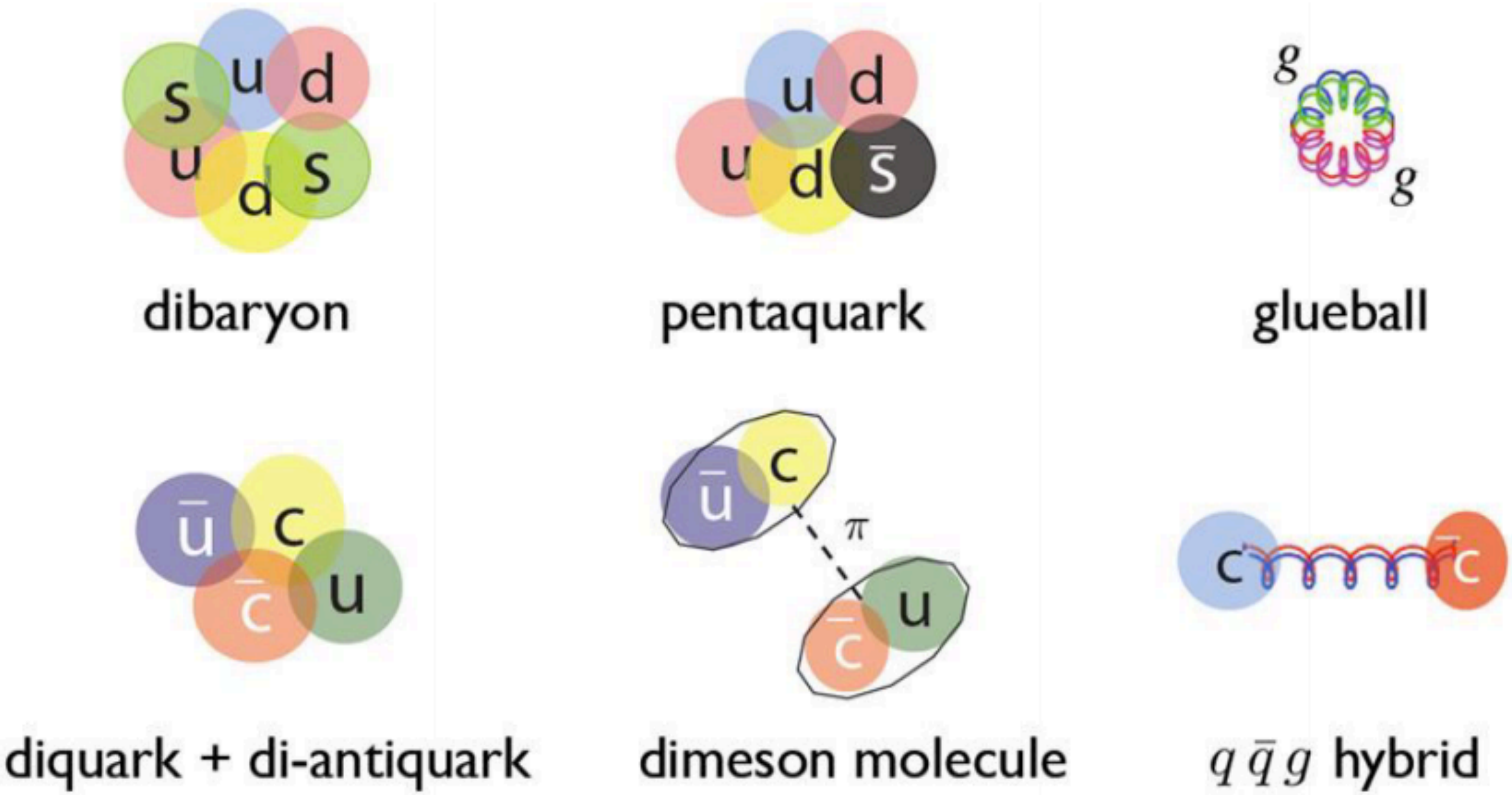




- Predicted the missing Ω^- baryon with m=1676 MeV, BNL discovered it (1964)
- In 2017, LHCb observed Ξ_{cc}^{++} with m=(3621.24 ± 0.65 ± 0.31) MeV, and life time $\tau=(256^{+24}_{-22} \pm 14)$ fs
- Consistent with Quark Model $J^p=1/2^+$ baryon (**ucc**)

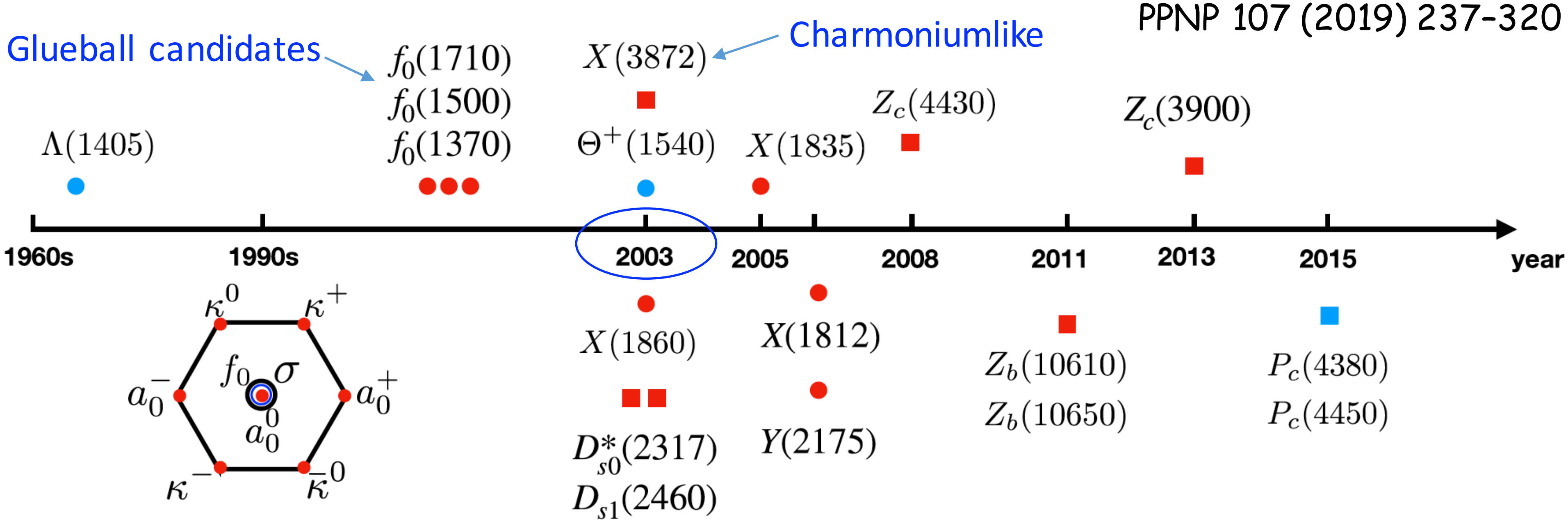
Exotic Hadron States

- The fundamental theory for strong interaction is QCD
- In QCD, hadrons beyond the (qqq) baryon and ($q\bar{q}$) meson exist!
- Difficulties, i.e. do not know how to calculate a confinement problem



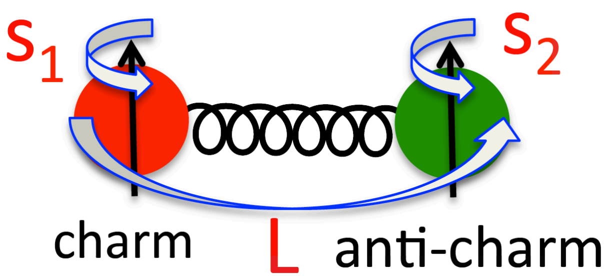
Experimental Search

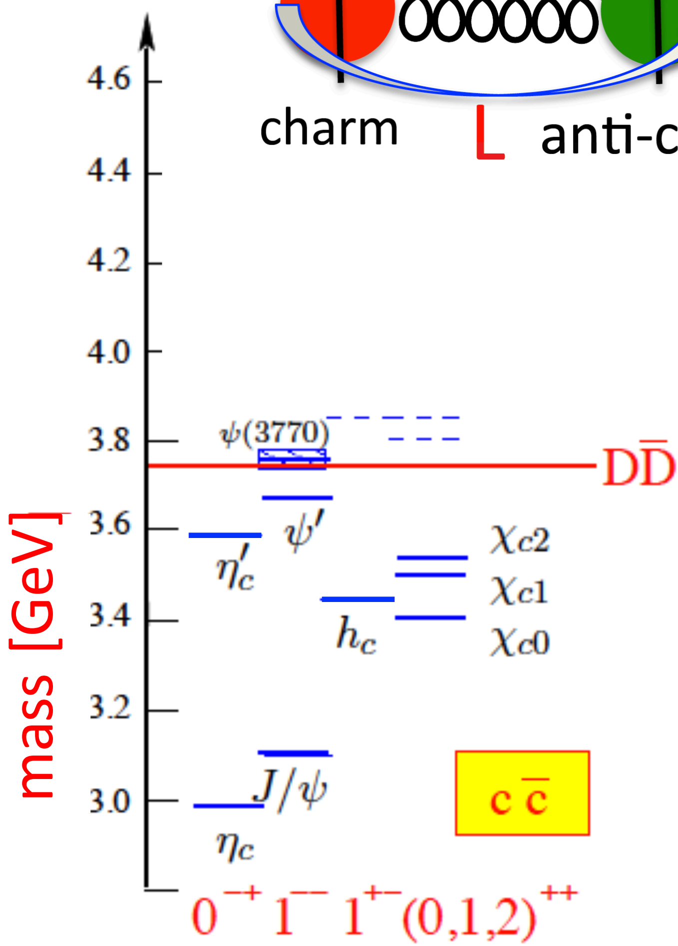
PPNP 107 (2019) 237-320



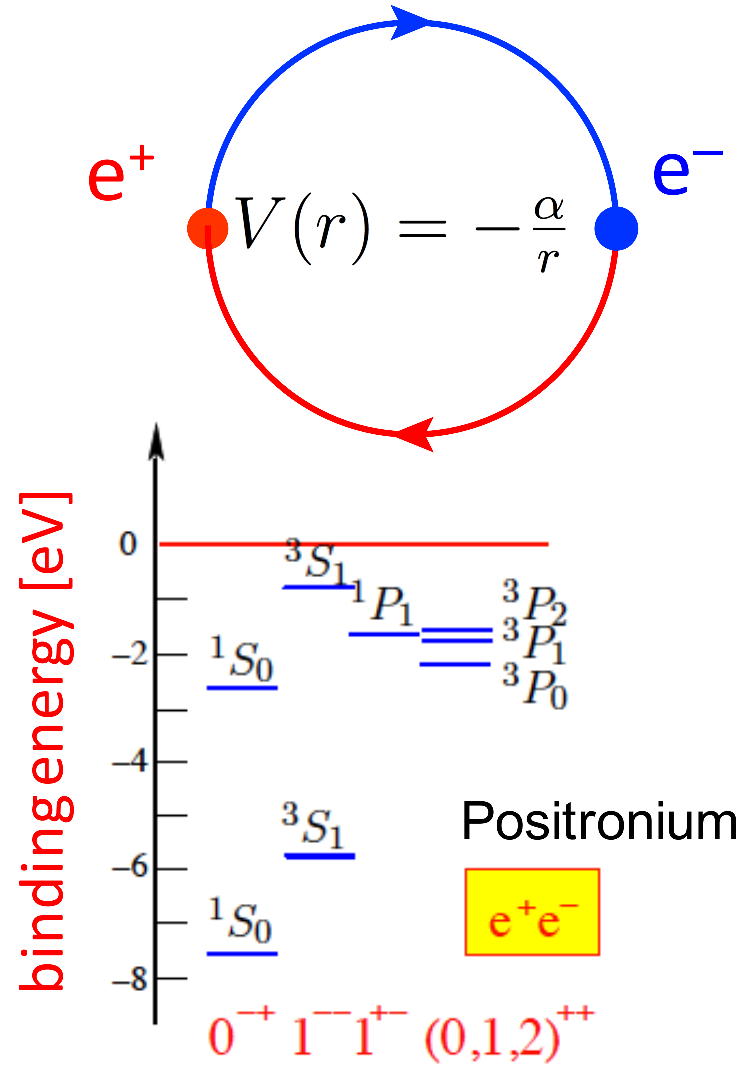
- In early years, Lattice QCD predicted lightest 0^{++} glueball mass 1.5 – 1.7 GeV
- Serious mixing with normal hadrons → Very challenging to identify them
- X(3872) in 2003 → Heavy quarkonium system is relatively easier to solve

Charmonium System

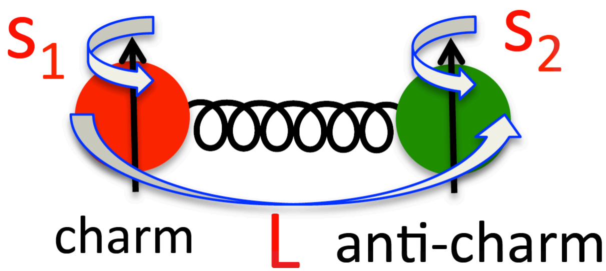


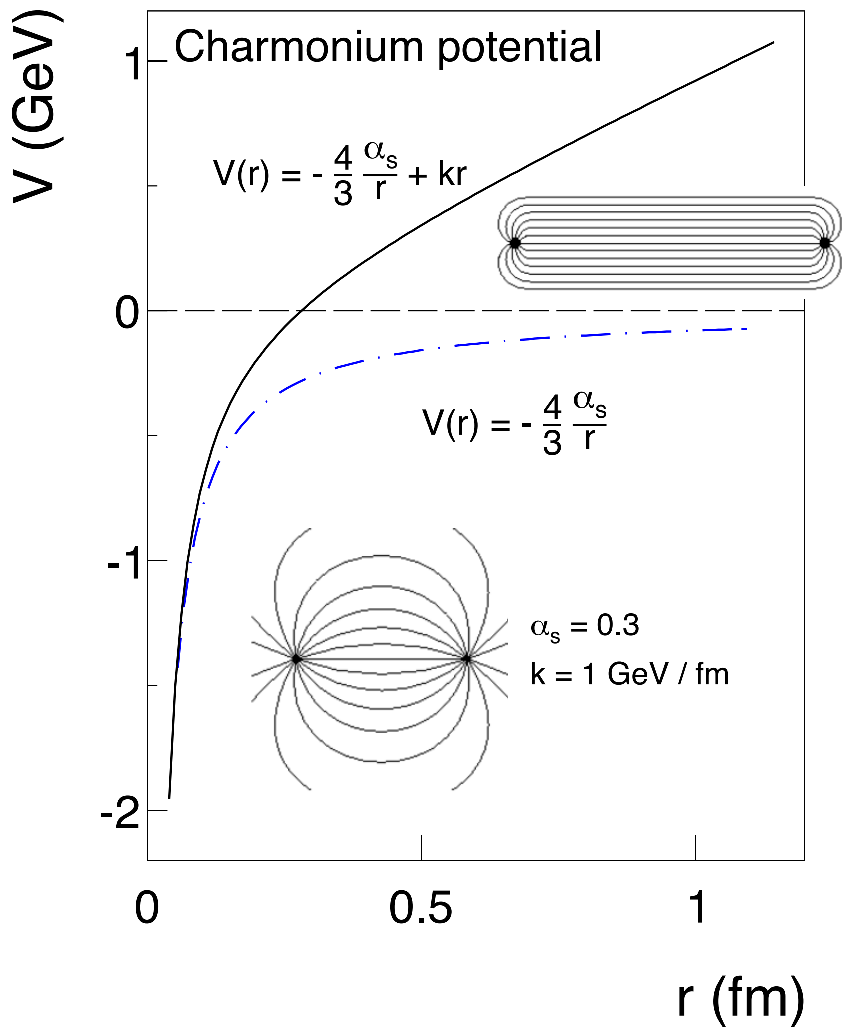


Potential



Nonrelativistic Potential





- **Coulomb + linear confinement**

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$
$$+ \; g_{ss}\vec{S}_c\vec{S}_c + g_{ls}\vec{L}\vec{S}$$

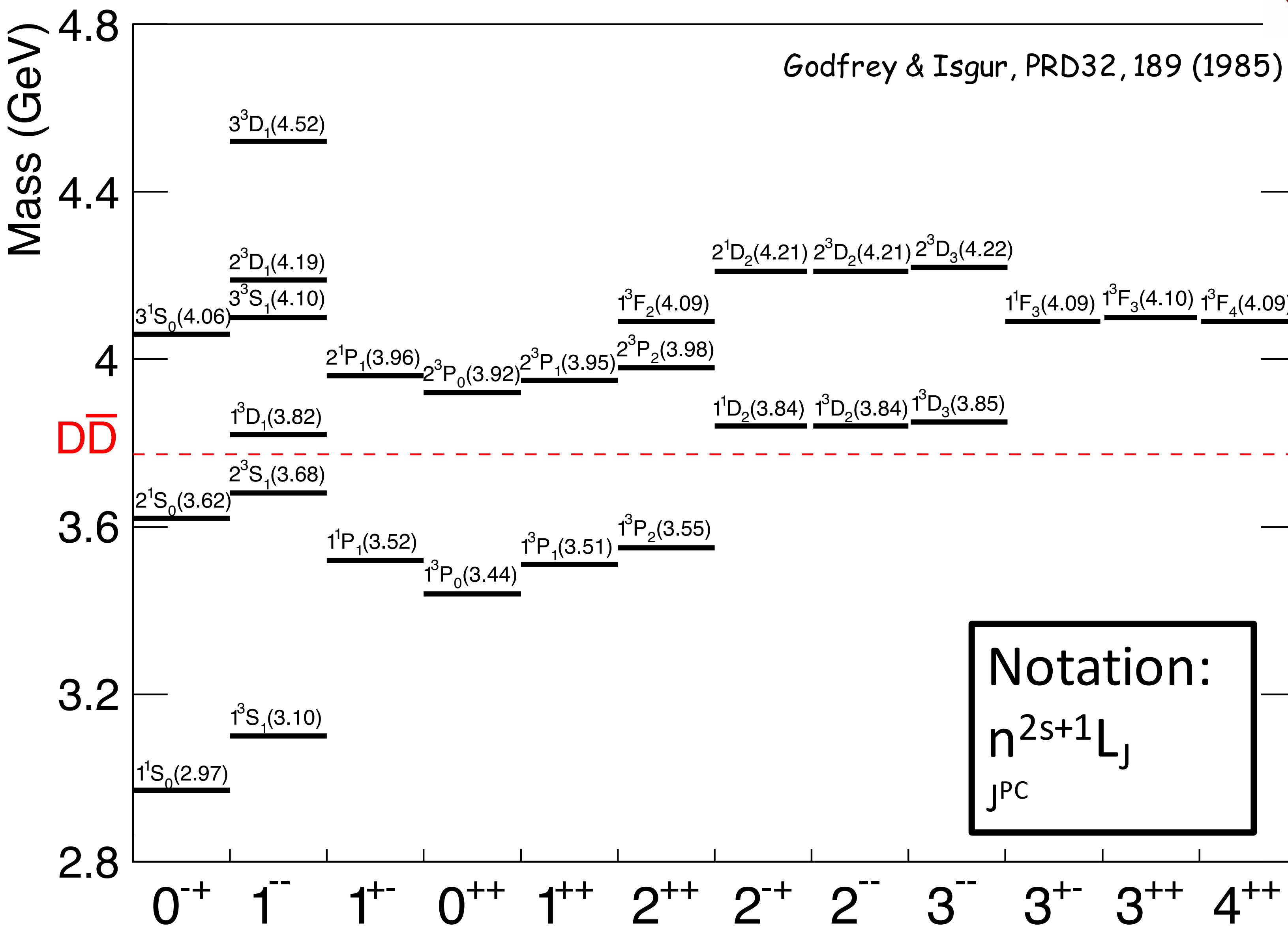
(Spin-spin) (Spin-orbit)

- **Solve Schrödinger equation**

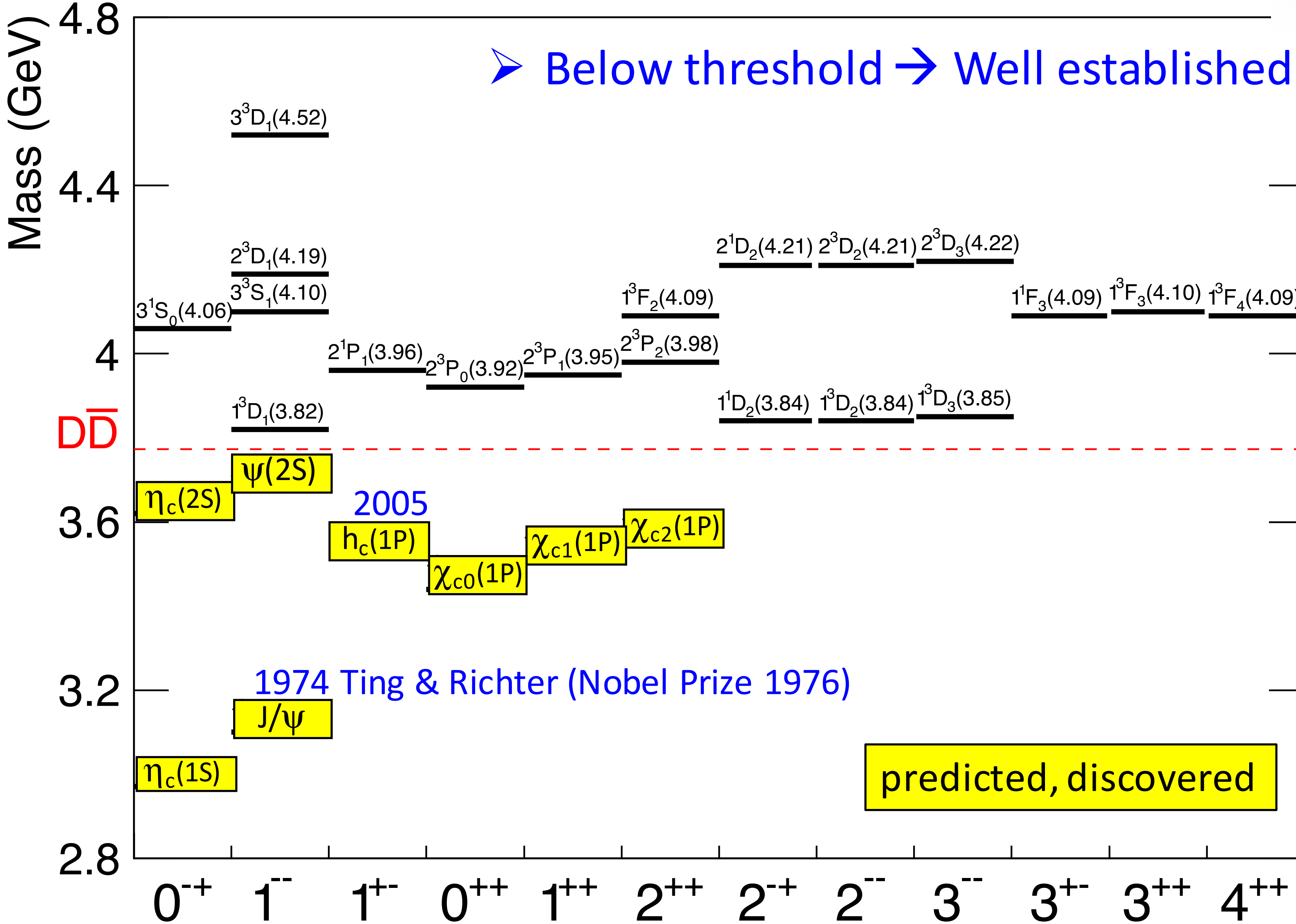
$$[\frac{-\hbar^2}{2m}\nabla^2 + V(r)]\psi(r,\theta,\phi) = E_{nl}\psi(r,\theta,\phi)$$

$$\psi(r,\theta,\phi) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

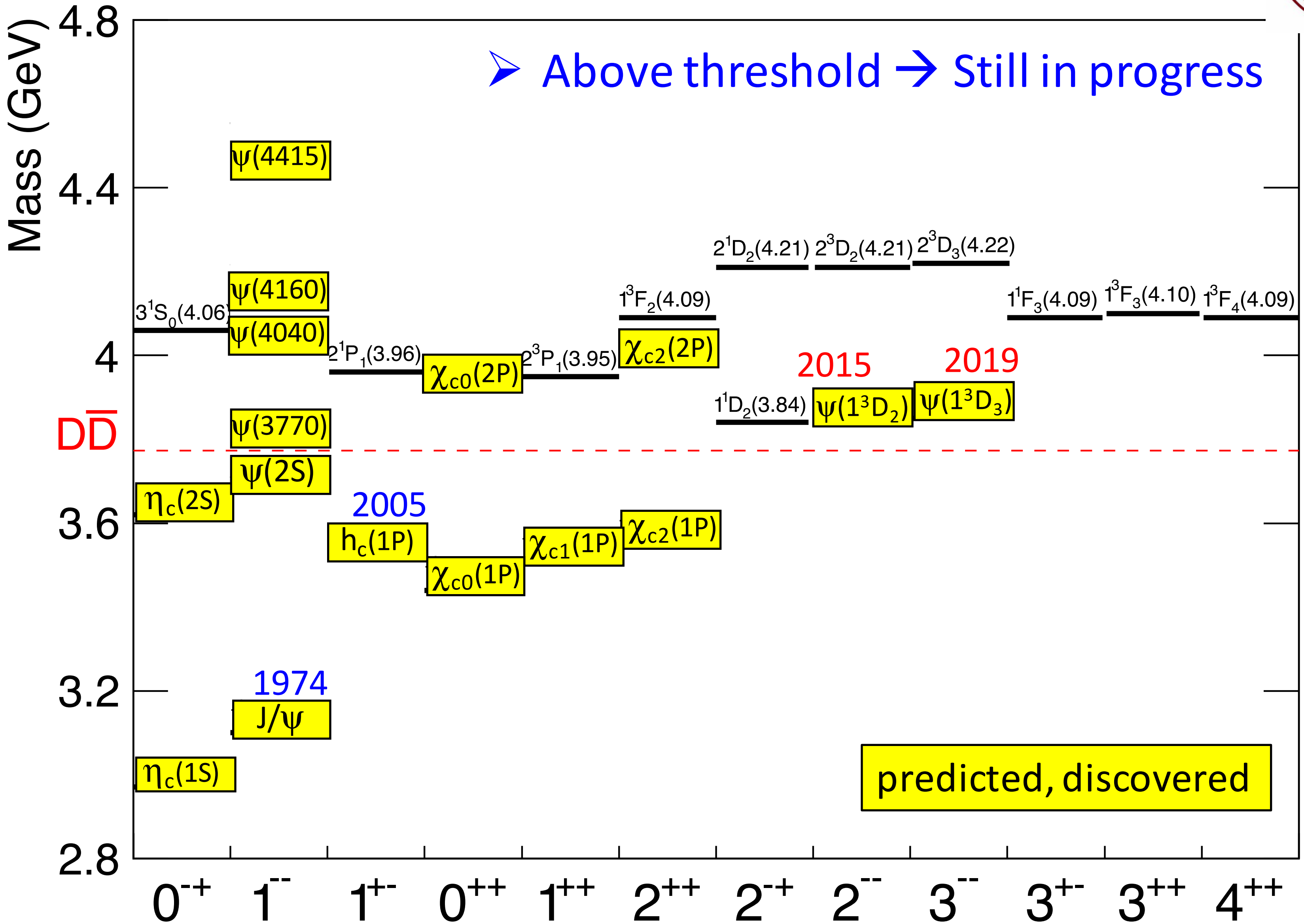
Charmonium Spectrum



Charmonium Spectrum

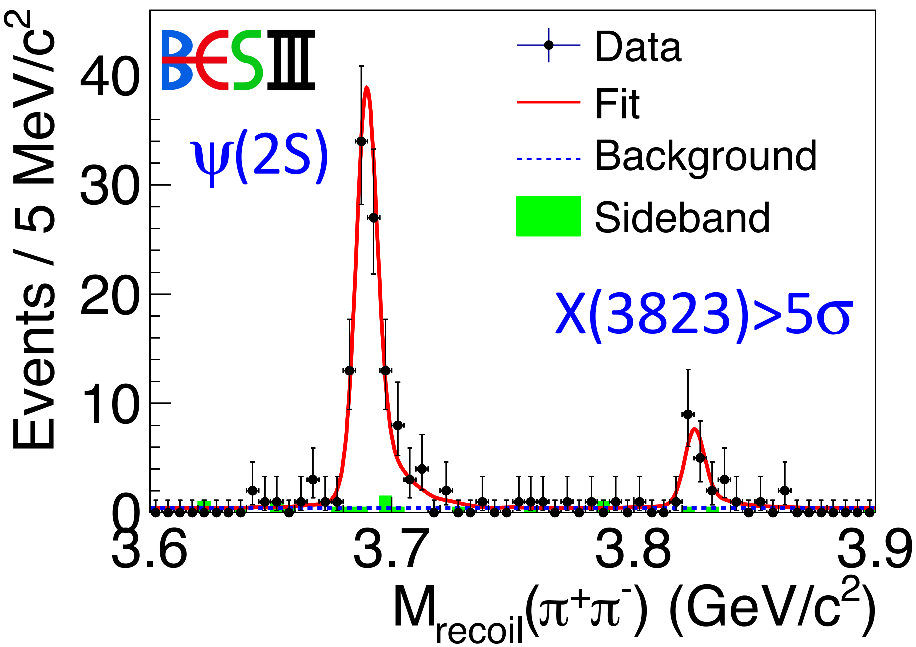


Charmonium Spectrum

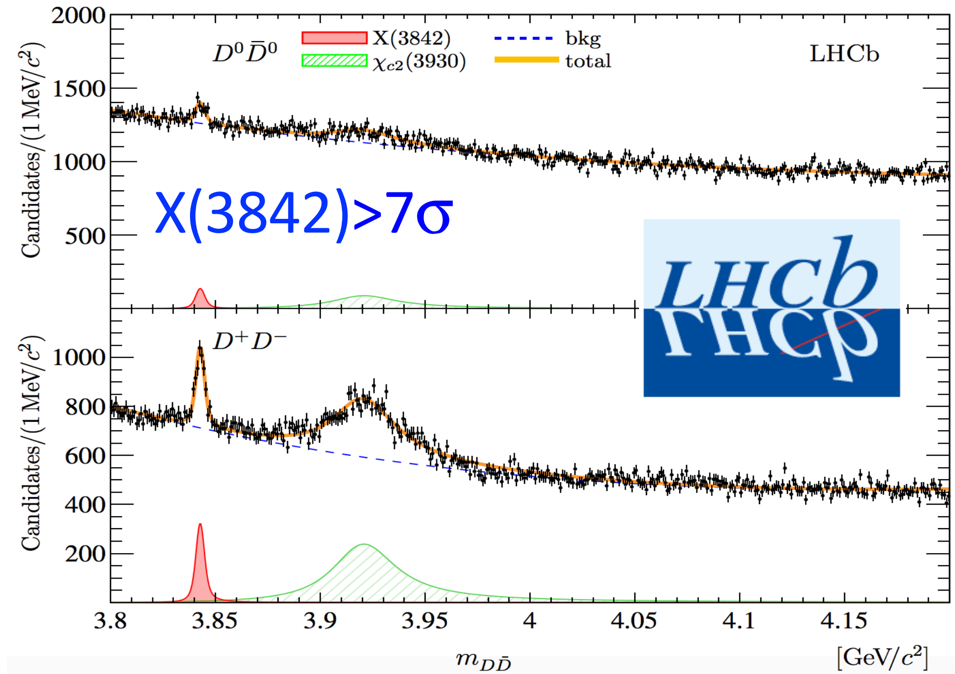


D-wave State $\psi(1^3D_2)$ & $\psi(1^3D_3)$

BESIII Collaboration, PRL115, 011803 (2015)



LHCb Collaboration, JHEP07(2019)035

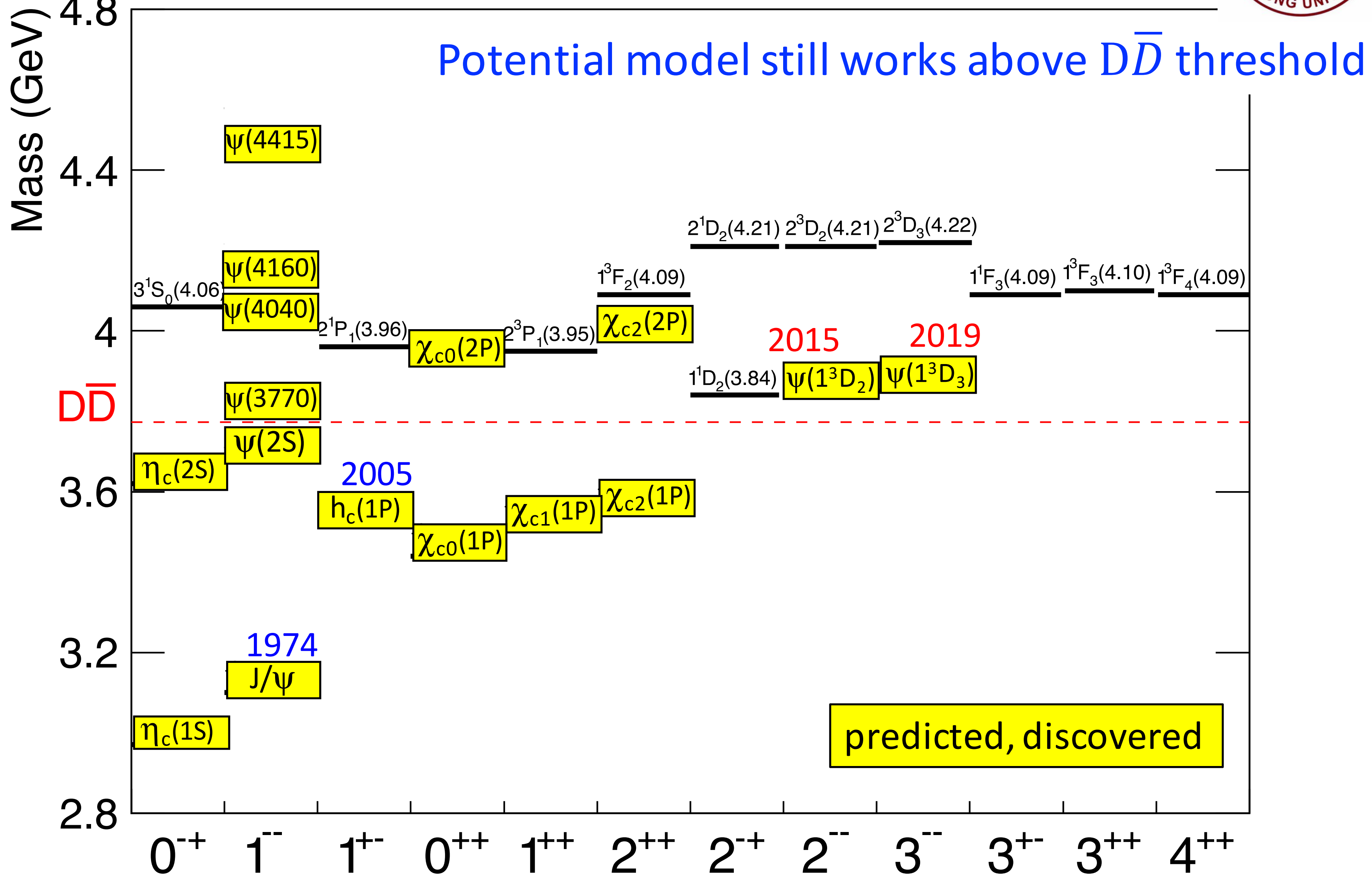


- Belle report evidence (PRL 111, 032001)
- BESIII study $e^+e^- \rightarrow \pi^+\pi^- X(3823) \rightarrow \pi^+\pi^-\gamma\chi_{c1}$
- $M=(3821.7\pm1.3\pm0.7)$ MeV, Γ is small

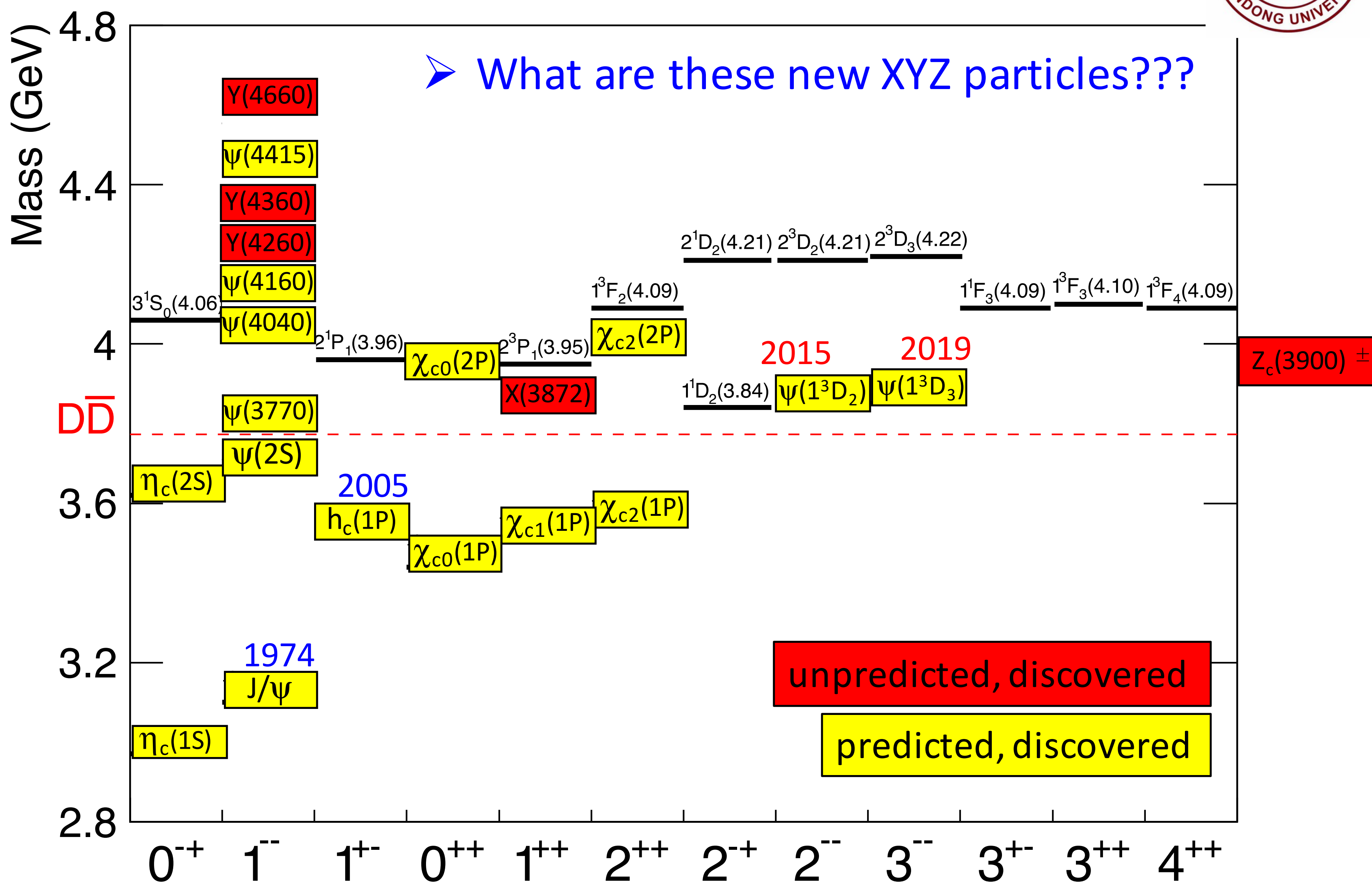
- $X(3842) \rightarrow D\bar{D}$
- $M=3842.71\pm0.16\pm0.12$ MeV, $\Gamma=2.79\pm0.51\pm0.35$ MeV

The X(3823) & X(3842) agree with predicted $\psi(1^3D_2)$ & $\psi(1^3D_3)$ well.

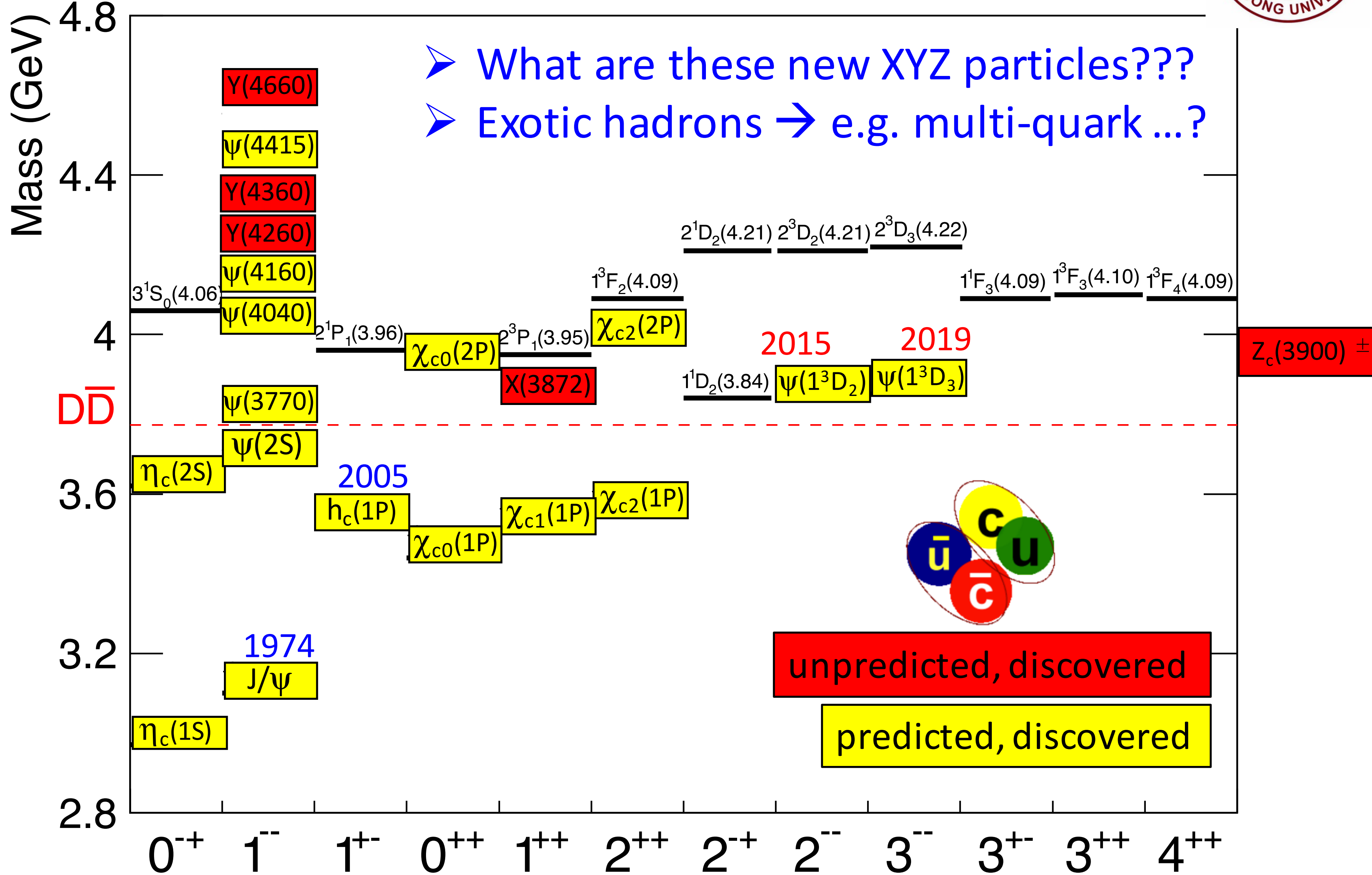
Charmonium Spectrum



Charmonium Spectrum



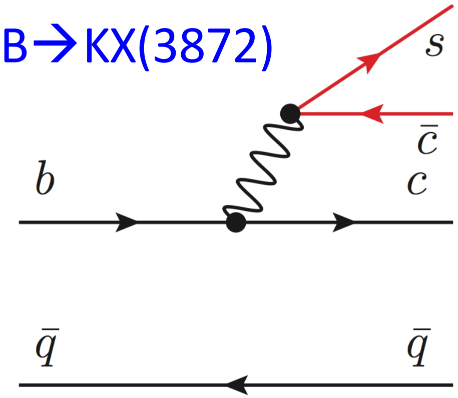
Charmonium Spectrum

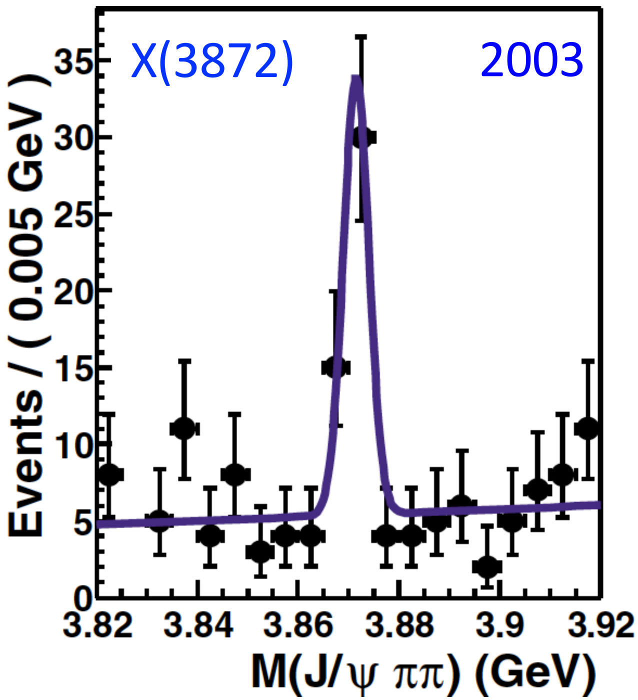


XYZ particles
fresh vista on new matter

X(3872)

B→KX(3872)

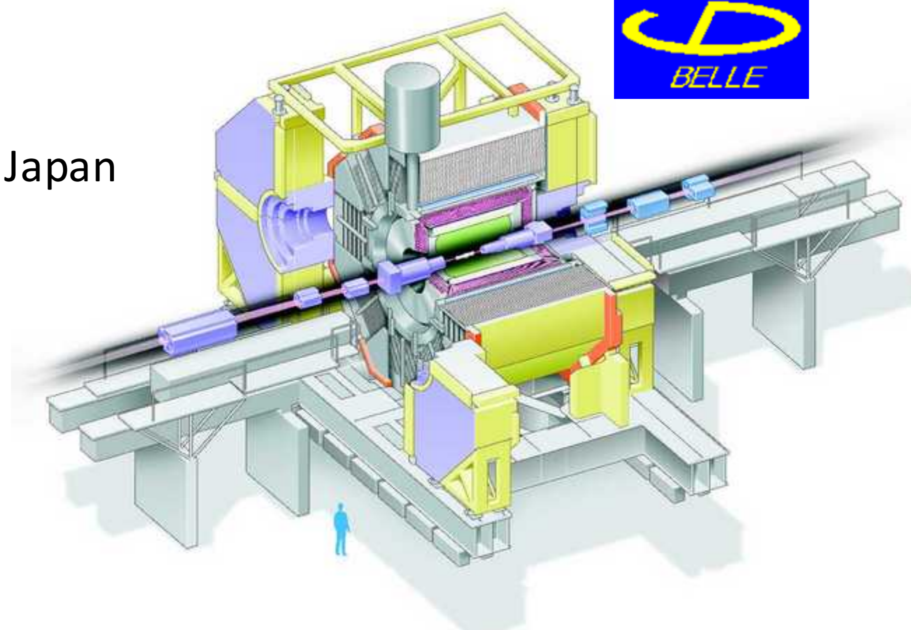




Confirmed by 7 independent experiments (BaBar, LHCb, CDF, D0, CMS, ATLAS, BESIII)

Solid signal !

KEK, Japan



PRL 91, 262001 (2003)

Mass and Quantum number

$\boxed{X(3872)}$ $I^G(J^{PC}) = 0^+(1^{++})$

M=3871.69±0.17 MeV (World average)

Γ[X(3872)]<1.2 MeV @ 90% CL.

No position in the potential model...

- 1^{++} $\chi_{c1}(2P)$ → M~3960 MeV, Γ~165 MeV

→Very different from X(3872)

Very Exotic !

- Isospin I=0 state, decay to $\rho J/\psi$, $\pi^0\chi_{c1}$ (I=1)

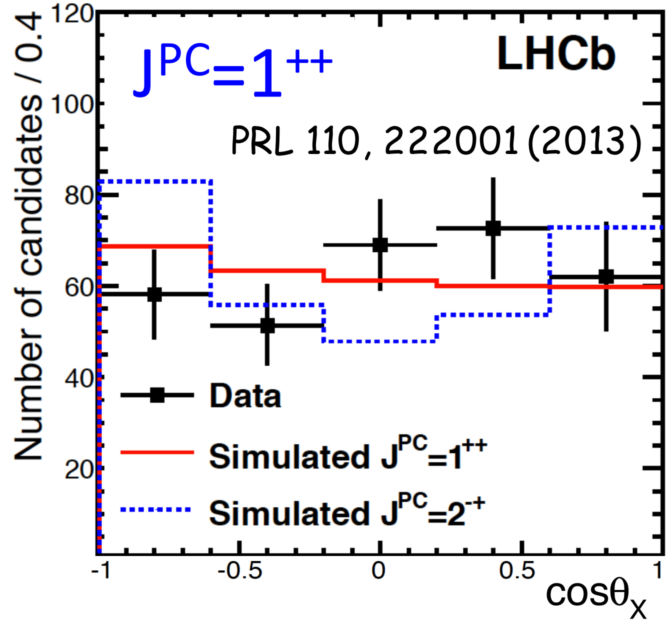
→B[X→ρJ/ψ]/B[X→ωJ/ψ]=$1.6^{+0.4}_{-0.3}\pm 0.2$ (BESIII)

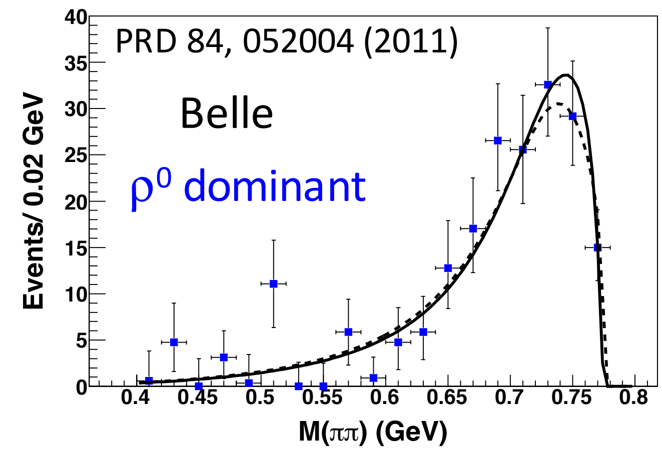
Isospin violation effect ! [PRL 122, 232002 (2019)]

→ 10 times larger than typical charmonium, e.g. ψ(2S)

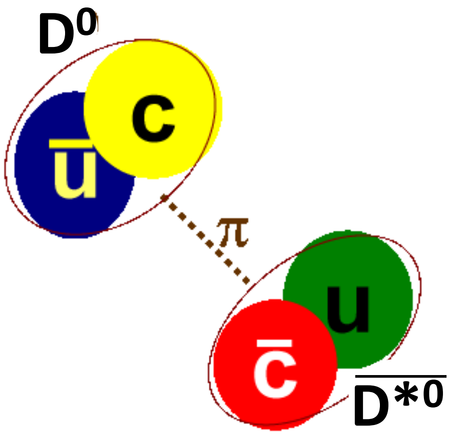
- $m(D^0)+m(\overline{D^{*0}})$=3871.684±0.08 MeV

→ Δ(E)~(0.0±0.28) MeV, bound state?

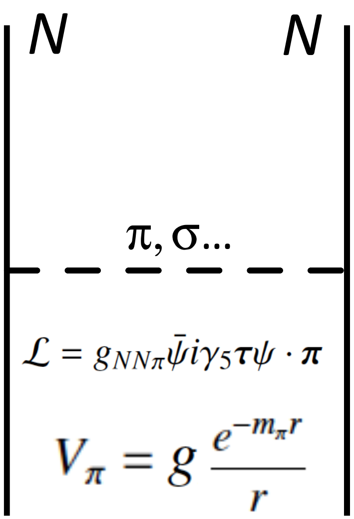




Interpretation (I)



$D^0 - \overline{D^{*0}}$ "molecule"



$$\mathcal{L} = g_{NN\pi}\bar{\psi} i\gamma_5 \tau\psi \cdot \pi$$

$$V_\pi = g\,\frac{e^{-m_\pi r}}{r}$$

Molecule-like bound state→ "Hadron Molecule"

- Long-range (π, σ…) exchange nuclear force
- Deuteron (p, n) → ΔE= 2.225 MeV
- X(3872) → Δ(E)= (0.0±0.28) MeV, loose (size ~8 fm)

- Explains:

  PRL 103, 162001

  Large decay width to $D^0\overline{D^{*0}}$ (~50%); isospin violation…
- Challenge: high production rate in $p\bar{p}$ collision @ 1.96 TeV

  Mixture: 5%$|c\bar{c}>$ + 95%$|D^0\overline{D^{*0}}>$? Wave overlap small?

  PTEP(2013),093D01

- Controversies:

  NPB 886(665)

  B[X→γψ(2S)]/B[X→γJ/ψ]~2.4 (BaBar, LHCb) → not welcome

  <0.59 (BESIII preliminary, Belle)

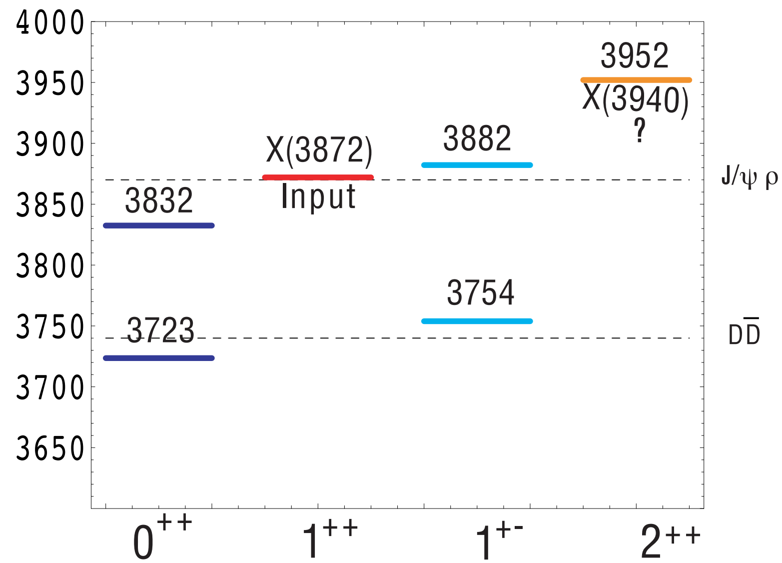
Interpretation (II)

diquark - diantiquark

Tetraquark - compact state

- Four quarks confined in a “bag”
- Diquark & diantiquark can be colored
- Explains: isospin violation …
- Prediction: partner particles

L. MAIANI et al. PRD 71, 014028 (2005)



CMI Phenomenological model

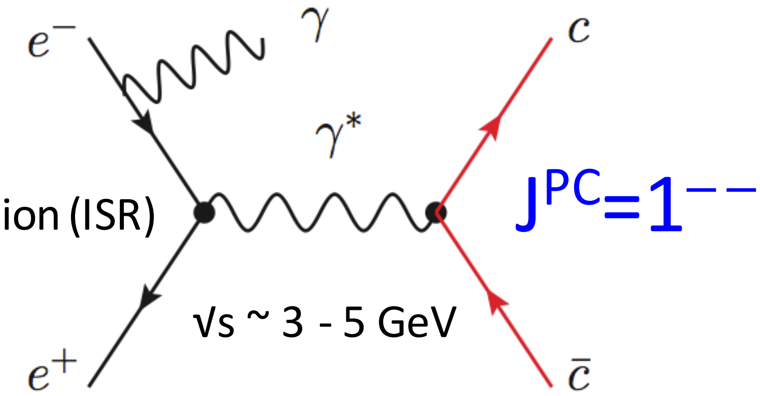
$$H = \sum_i m_i + \sum_{i<j} 2\kappa_{ij}(S_i \cdot S_j)$$

Partners not well established!

Vector Y(4260)

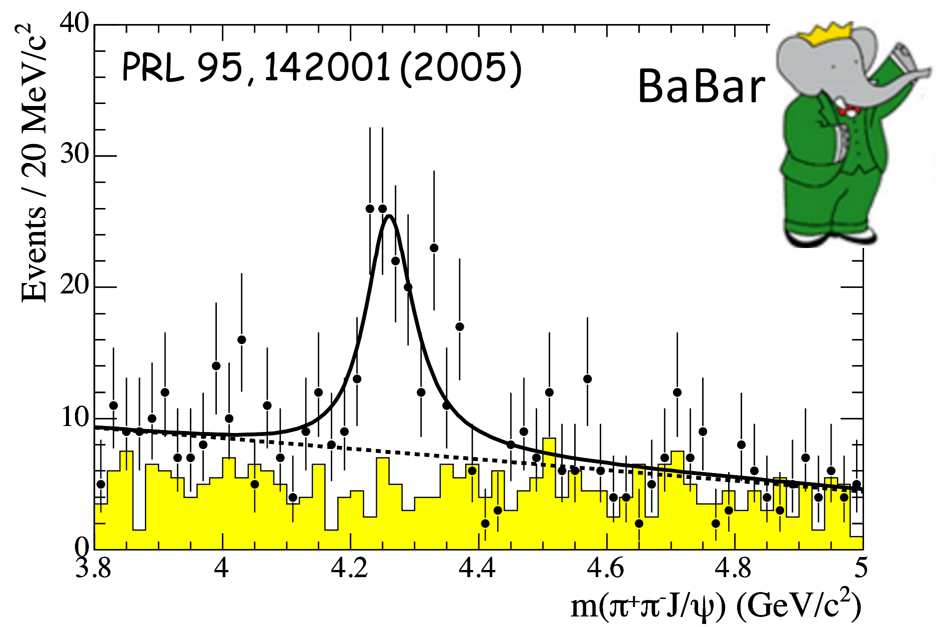
Y(4260) resonance

$\boxed{\psi(4260)}$ $I^G(J^{PC}) = 0^-(1^{--})$



- ➢ Mass ~4.26 GeV
- → Above $D^*\overline{D^*}$ threshold

Confirmed by Belle, CLEO and BESIII

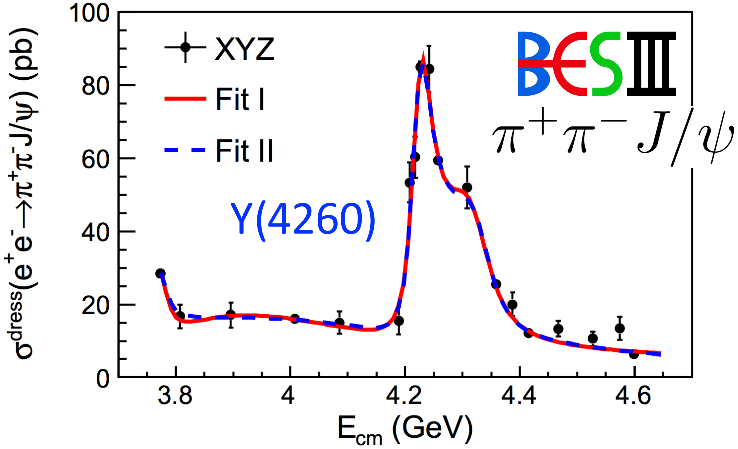


- ➢ Potential model prediction
- → Large decay width to $D^*\overline{D^*}$ for vector charmonium state

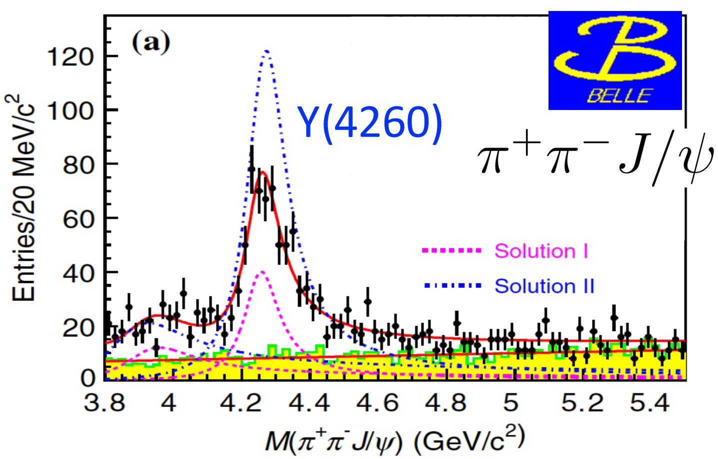
- ➢ Y(4260)→$D^*\overline{D^*}$
- → NOT seen, puzzling
- → Instead, tend to decay to hidden charmonium (J/ψ+ππ)

Vector Y-family

PRL**118**, 092001



PRL**110**, 252002



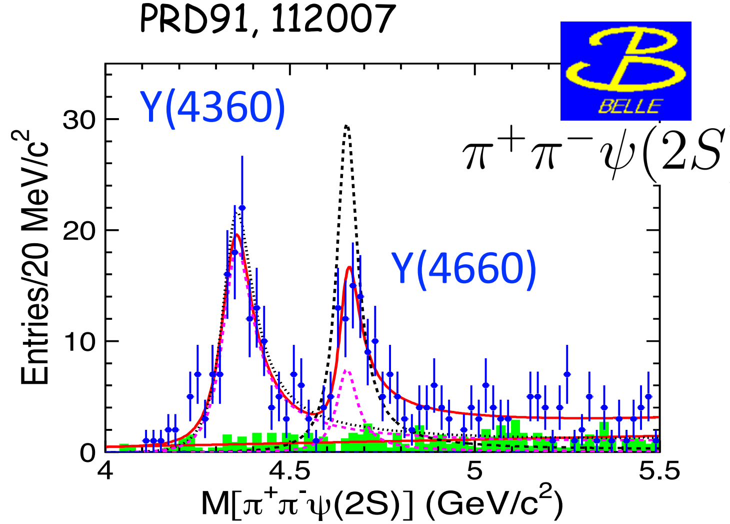
Y(4260)

Y(4360)

Y(4660)

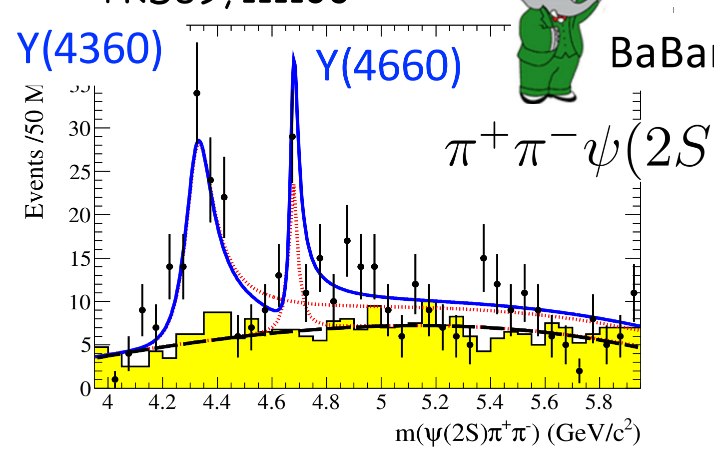
...

PRD91, 112007

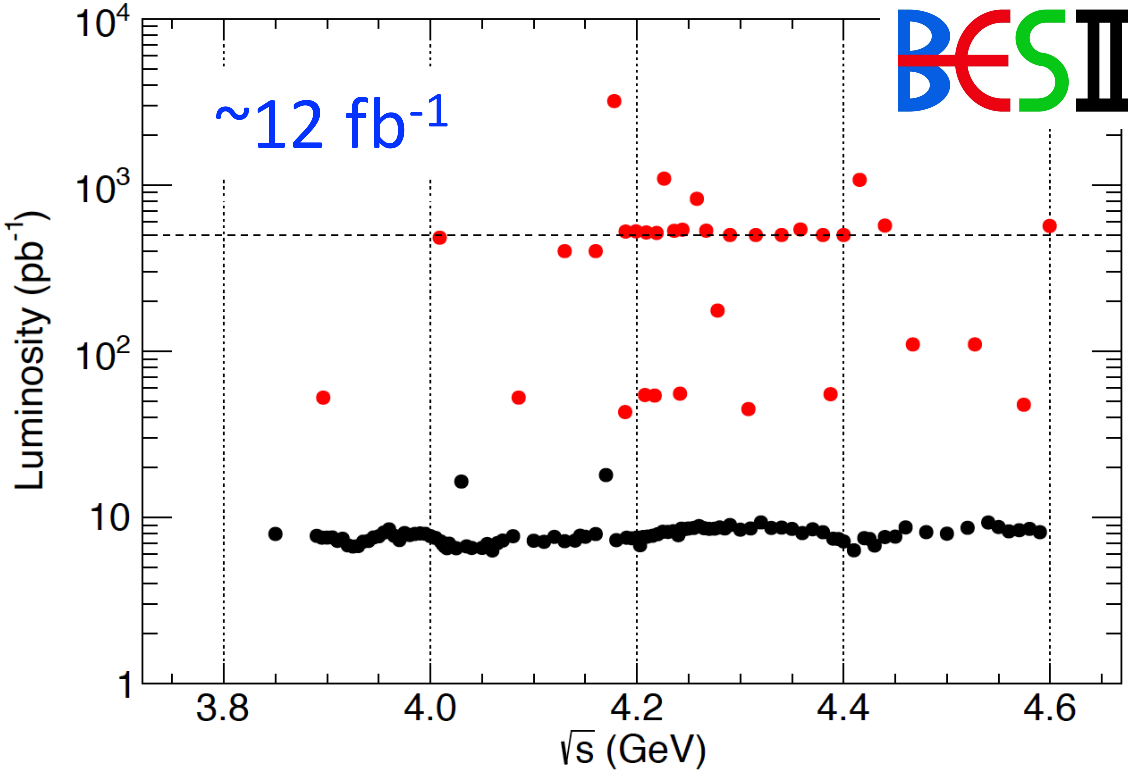


PRD89, 111103

BaBar



BESIII high luminosity scan



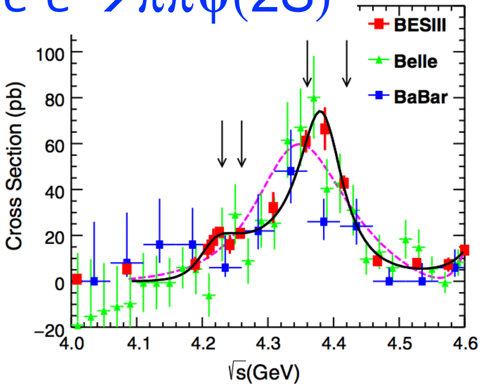
- An symmetric e+e- machine in Beijing, China
- $\sqrt{s}$ = 2 – 4.9 GeV
- Design L=1 × 10^{33} cm^{-1} s^{-1}

0.5 fb^{-1}/10 MeV scan from 4 – 4.6 GeV is ongoing

BESIII high luminosity scan

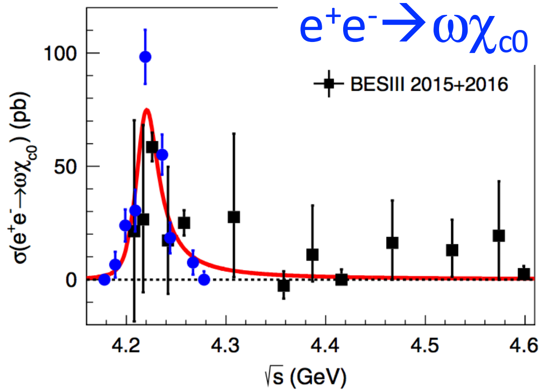
PRD 96, 032004

$e^+e^- \rightarrow \pi\pi\psi(2S)$

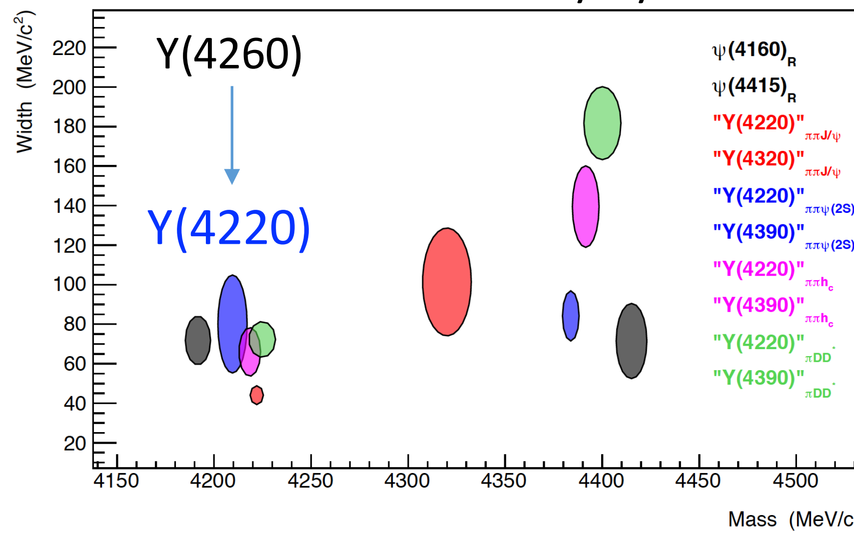


PRD 99, 091103

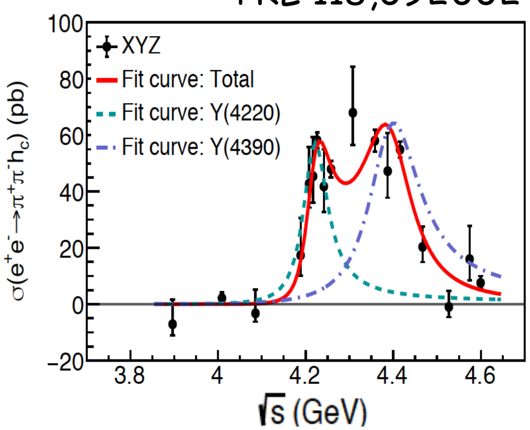
$e^+e^- \rightarrow \omega\chi_{c0}$



by Ryan Mitchell

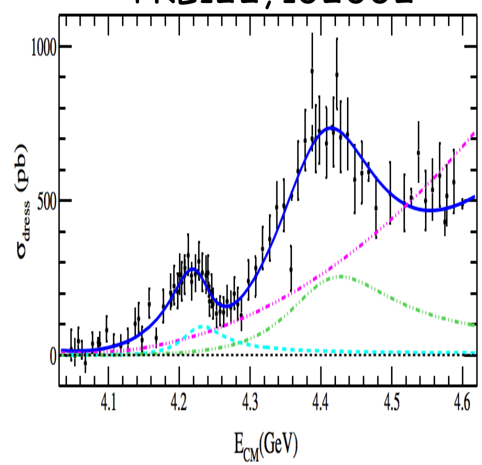


PRL 118, 092002



$e^+e^- \rightarrow \pi^+\pi^- h_c$

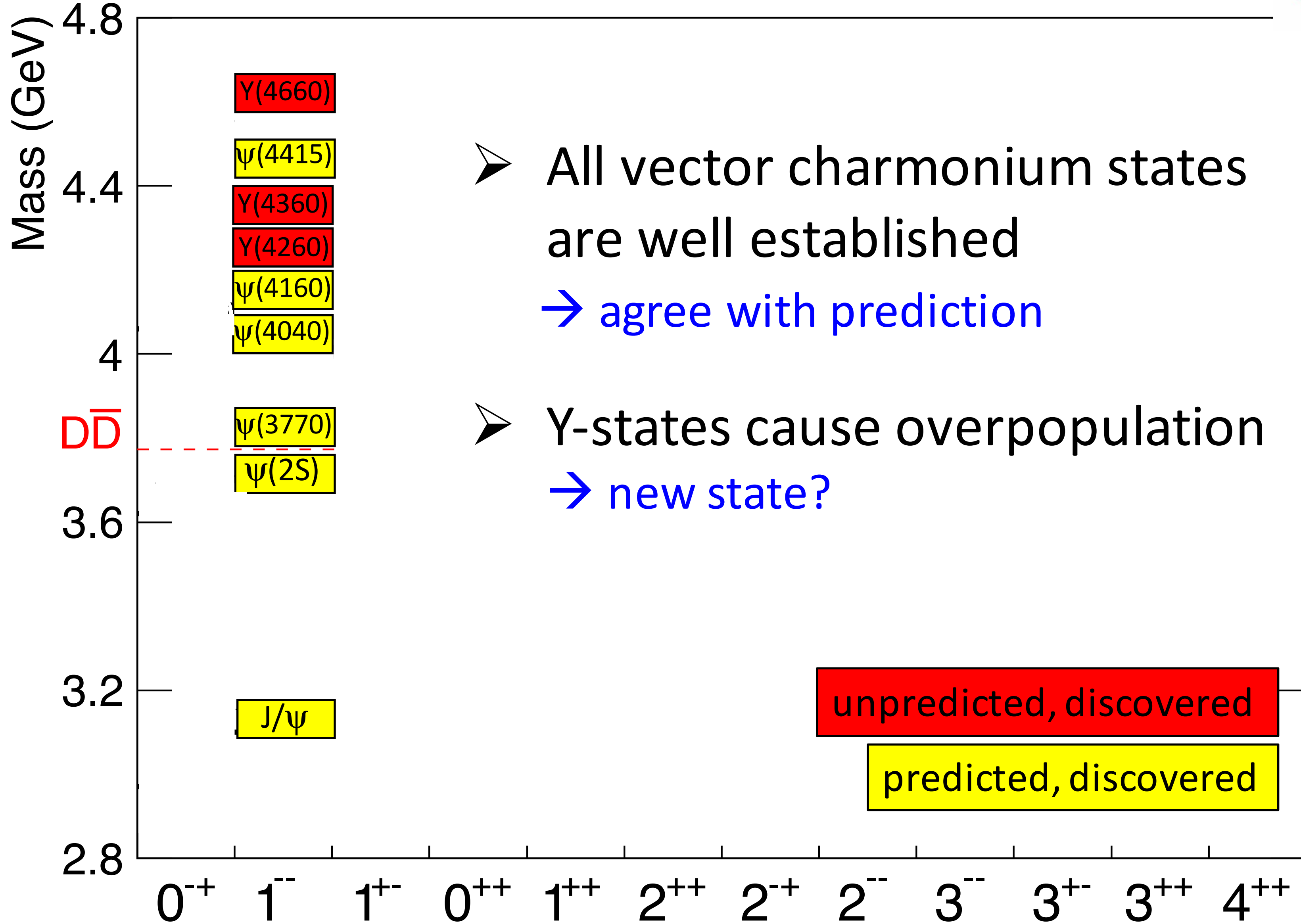
PRL122, 102002



$e^+e^- \rightarrow \pi^+ D^0 \overline{D^{*-}}$

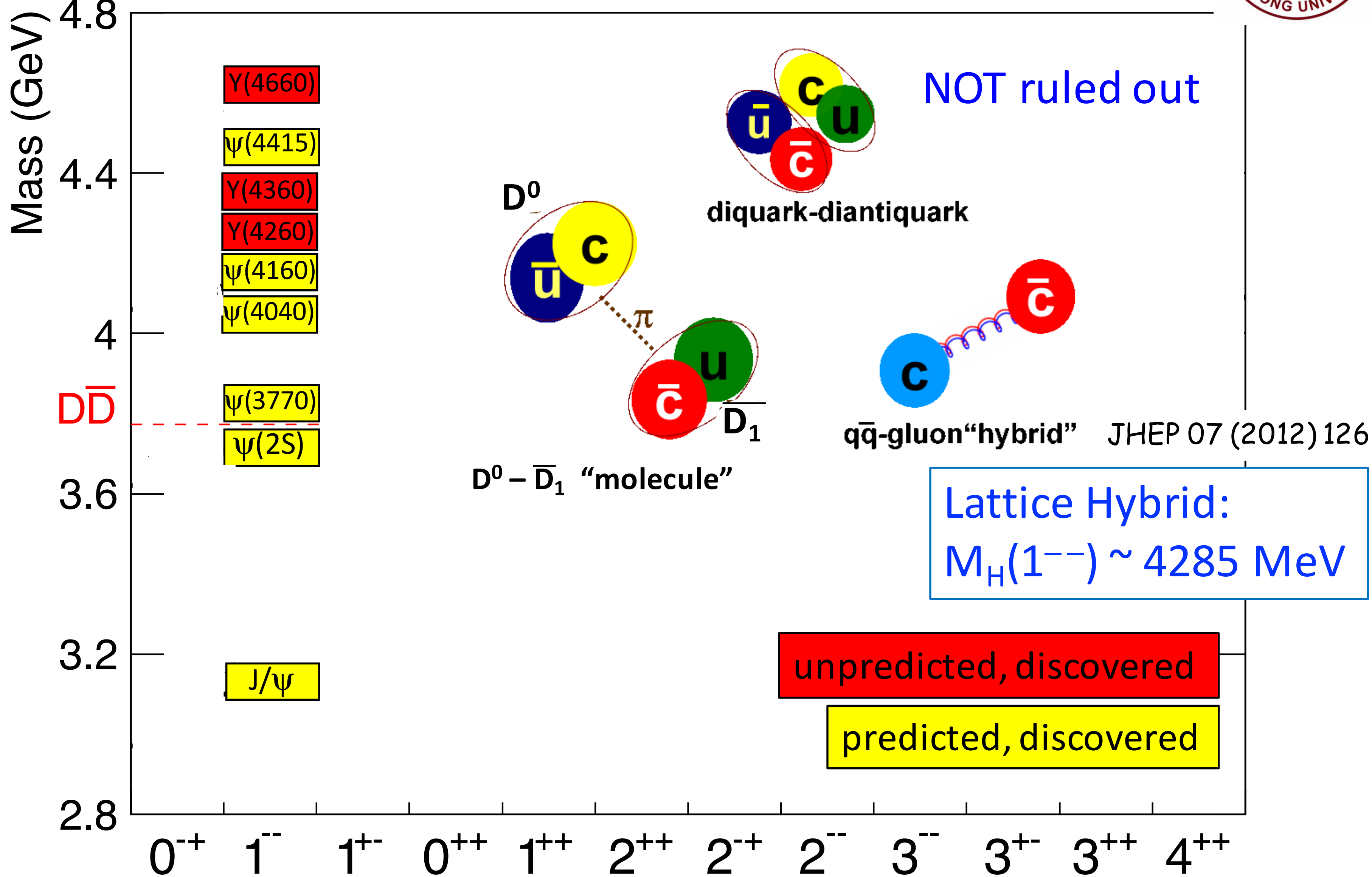
- Y(4260) mass lower to 4.22 GeV
- More vector states could exist
- Still need more efforts…

Overpopulation of vectors

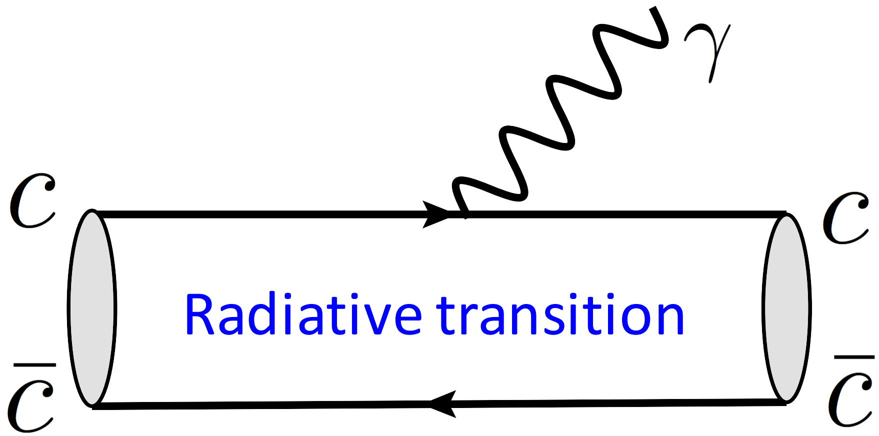


- All vector charmonium states are well established
  → agree with prediction
- Y-states cause overpopulation
  → new state?

Overpopulation of vectors

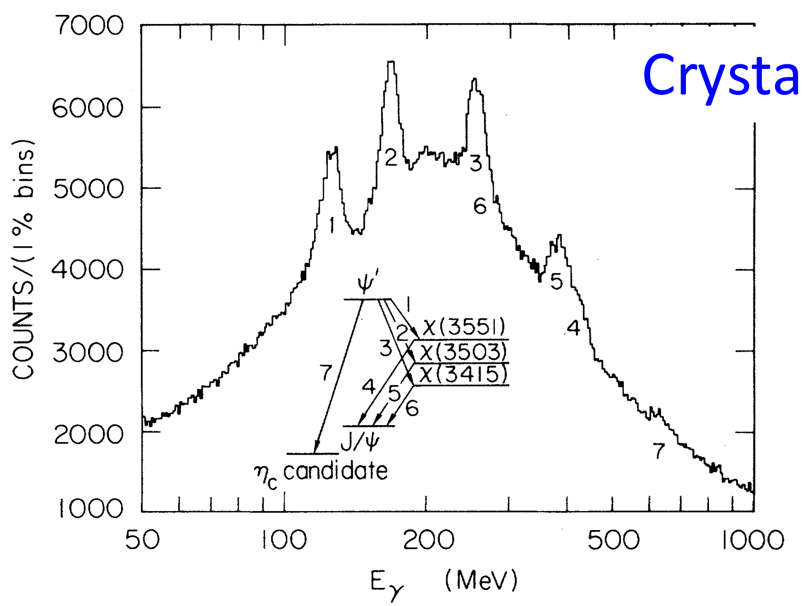


Y(4260) & X(3872)



Charmonium

Excited state → Ground state

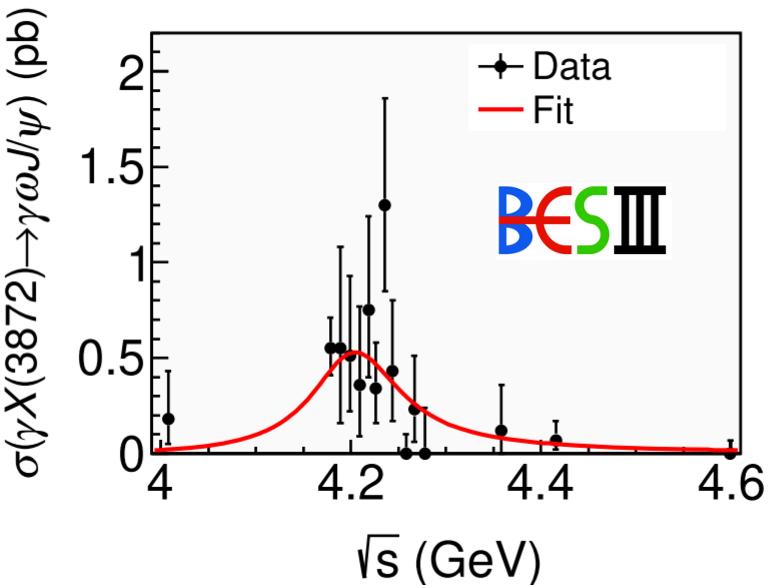


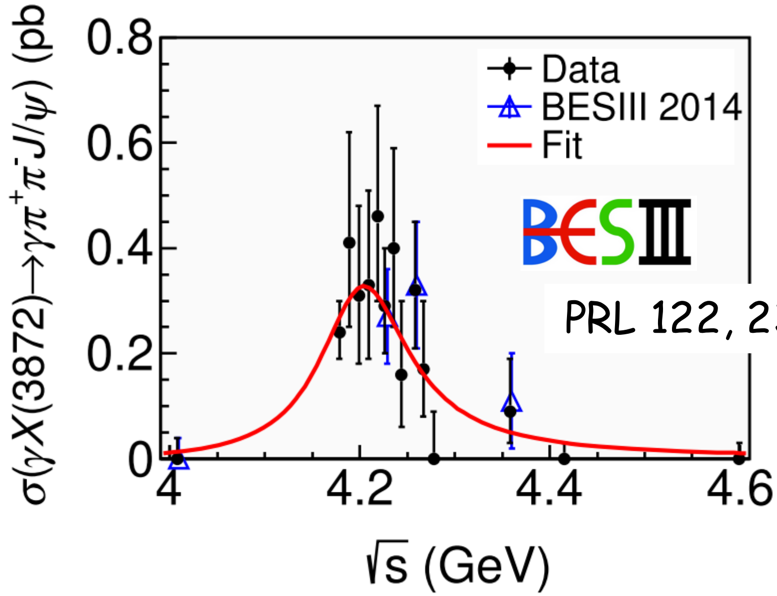
Crystal Ball

$\psi(2S) \rightarrow \gamma\chi_{c0,c1,c2}/\gamma\eta_c$

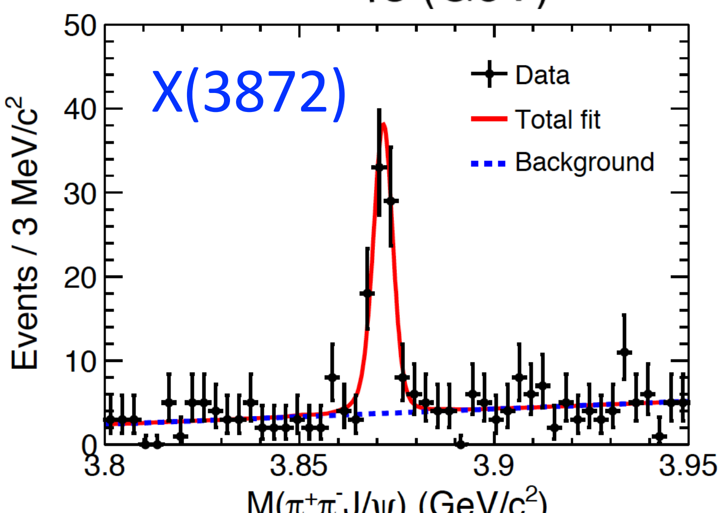
$\chi_{c0,c1,c2} \rightarrow \gamma J/\psi$

Y(4260) & X(3872)





PRL 122, 232002 (2019)



- $e^+e^-\to\gamma X(3872)$ cross section by BESIII
- $M=4200.6^{+7.9}_{-13.3}\pm3.0$ MeV, $\Gamma=115^{+38}_{-26}\pm12$ MeV
- Agree with the Y(4260) resonance

Commonality between Y & X?

$Z_c^{\pm}$ states

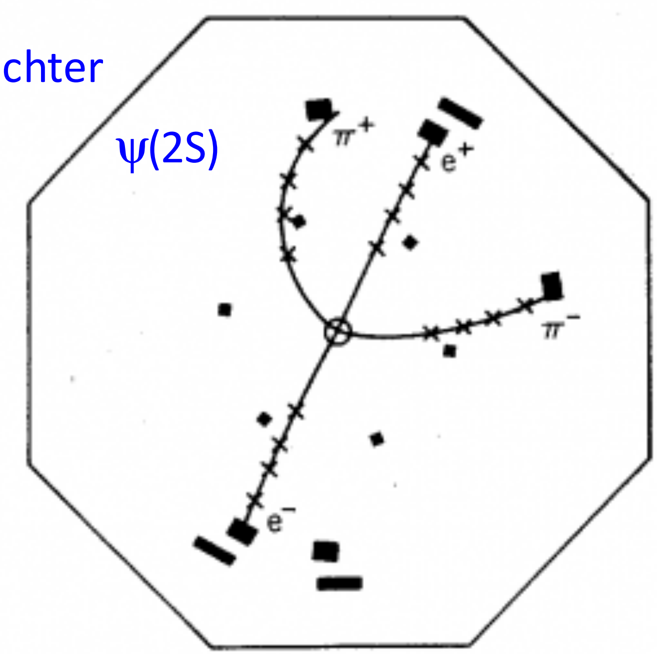
If the neutral state is too ambiguous,
a charged one should be NOT

Study Y(4260) at BESIII

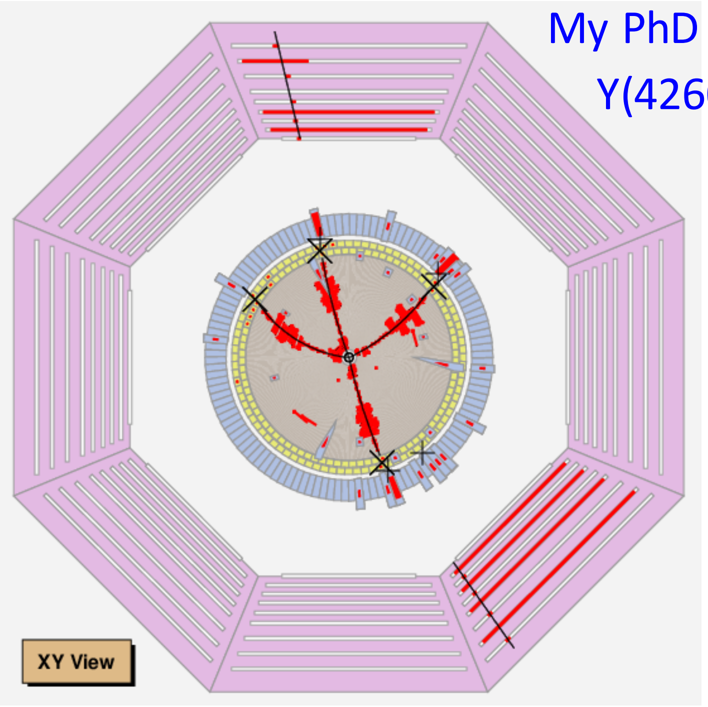
Mark-I (1977)
$e^+e^- \to \psi(2S) \to \pi^+\pi^- J/\psi$
at √s=3.686 GeV

BESIII (2013)
$e^+e^- \to \pi^+\pi^- J/\psi$
at √s=4.26 GeV

Richter

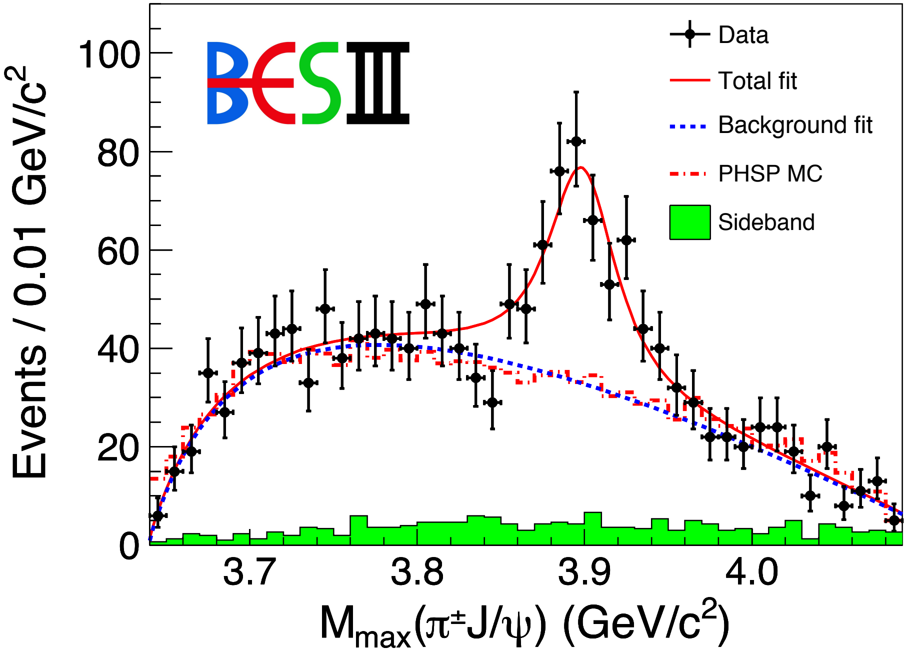


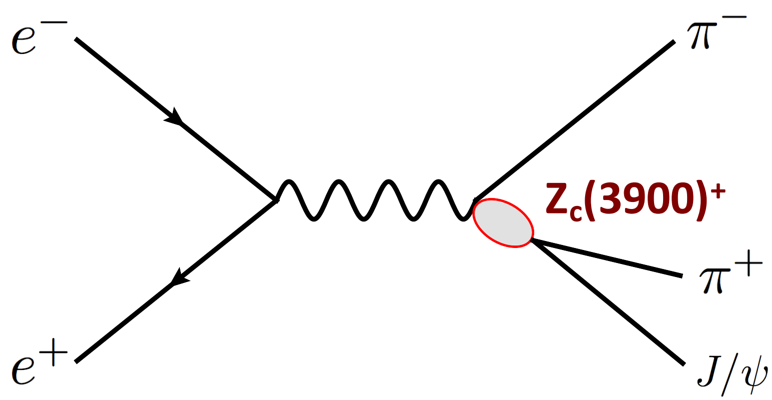
My PhD thesis
Y(4260)



$e^+e^- \to Y(4260) \to \pi^+ \pi^- J/\psi$

$Z_c(3900)^{\pm}$



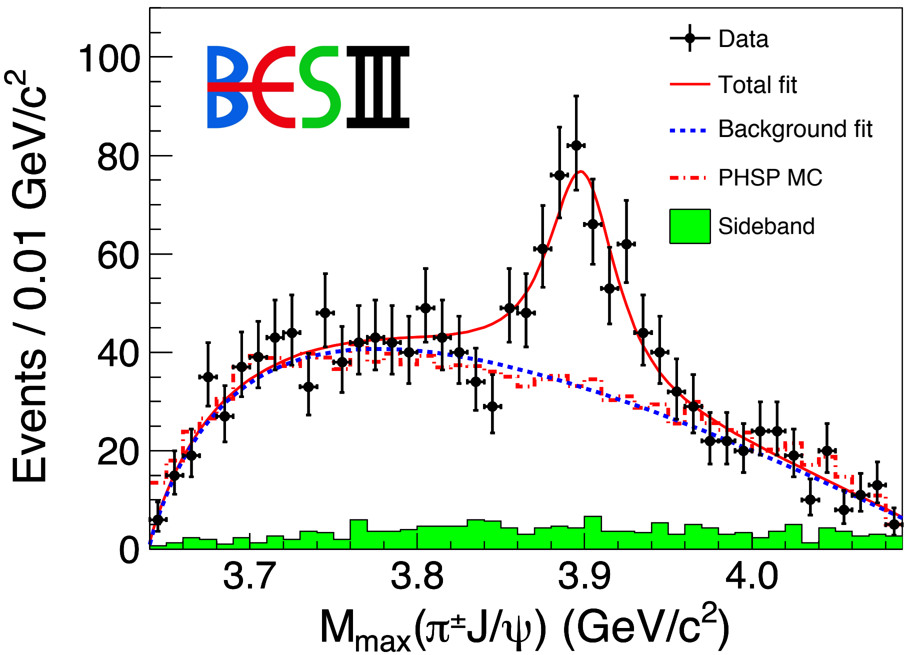


$M=(3899.0 \pm 3.6 \pm 4.9)$ MeV

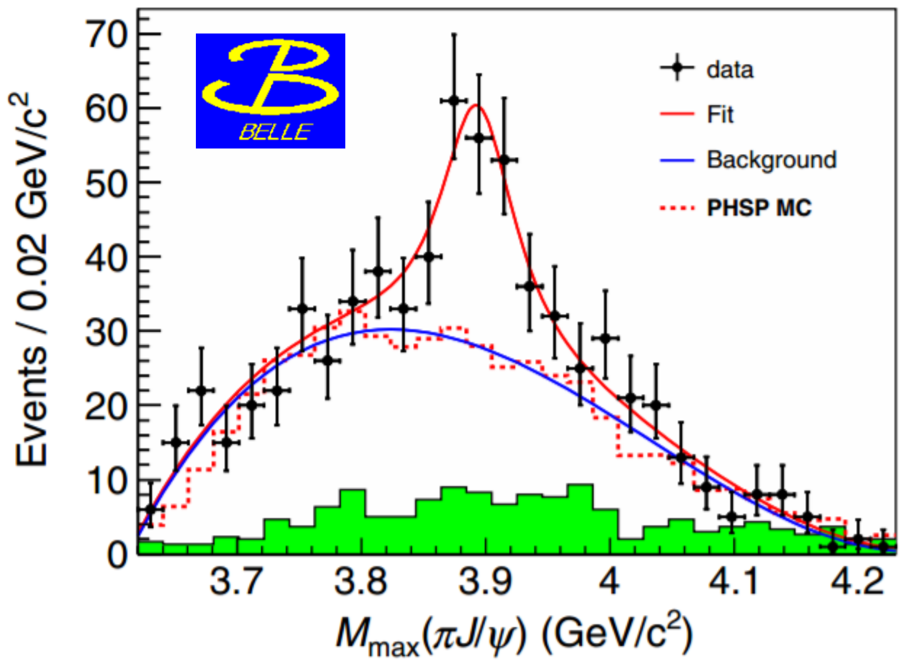
$\Gamma=(46 \pm 10 \pm 20)$MeV

Significance > 8σ, discovery !

$Z_c(3900)^{\pm}$



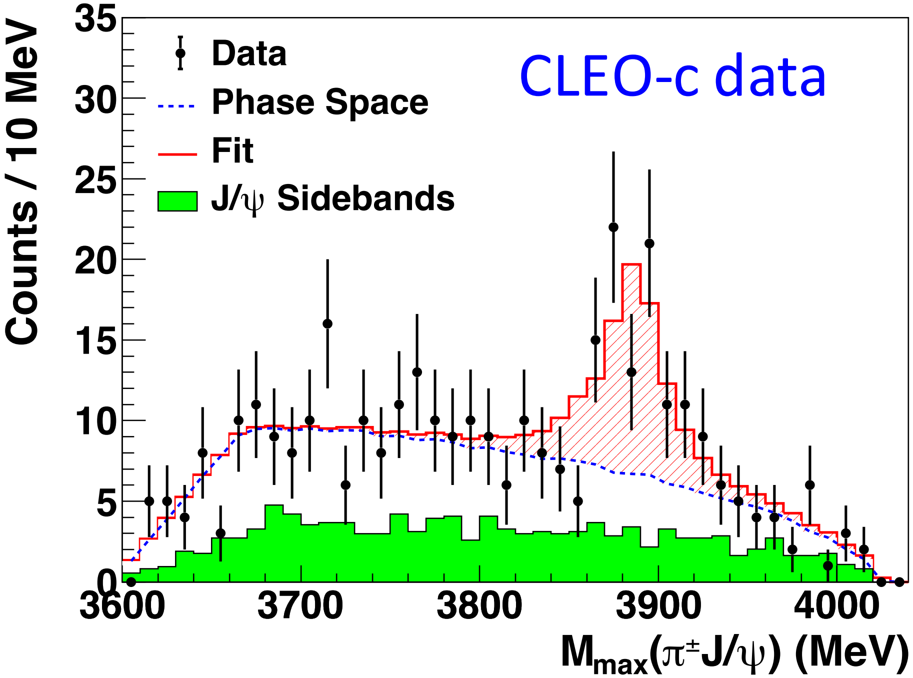
M=(3899.0±3.6±4.9) MeV
Γ=(46±10±20)MeV
Significance > 8σ, discovery !



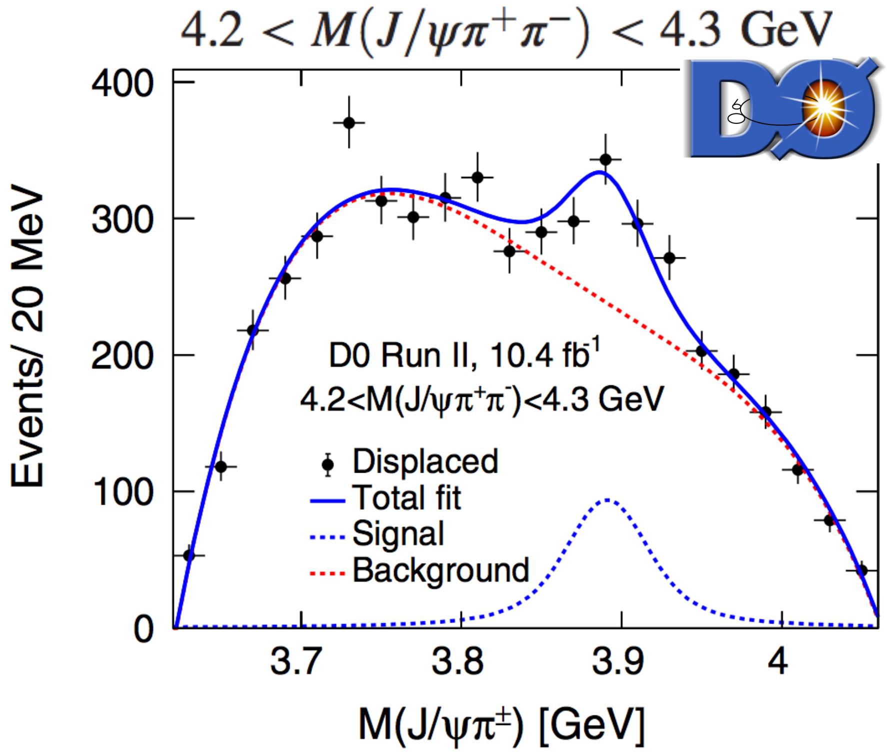
M=(3894.5±6.6±4.5) MeV
Γ=(63±24±26) MeV
Significance 5.2σ

M. Ablikim et al., Phys. Rev. Lett. 110, 252001 (2013);
Z. Q. Liu et al., Phys. Rev. Lett. 110, 252002 (2013).

$Z_c(3900)^{\pm}$ confirmed



PLB 727 (2013) 366



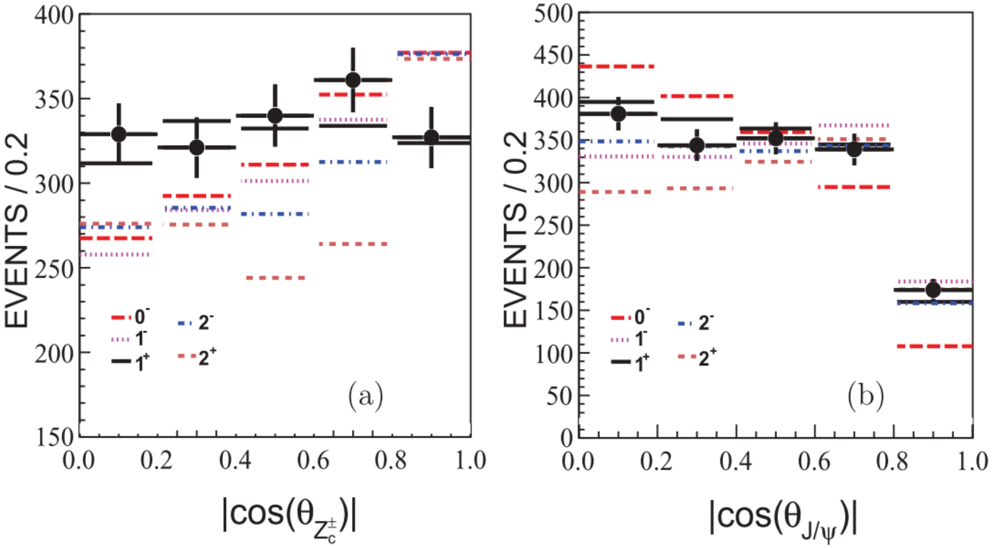
PRD 100, 012005 (2019)

$M=(3886\pm4\pm2)$ MeV
$\Gamma=(33\pm6\pm7)$ MeV
Significance 5.1σ

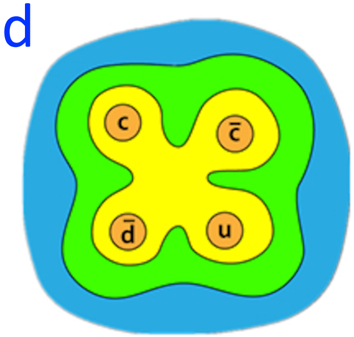
$M=(3902.6^{+5.2}_{-5.0}{}^{+3.3}_{-1.4})$ MeV
$\Gamma=(32^{+28}_{-21}{}^{+26}_{-7})$ MeV
Significance 5.4σ

$Z_c(3900)$ Structure

PRL 119, 072001 (2017)



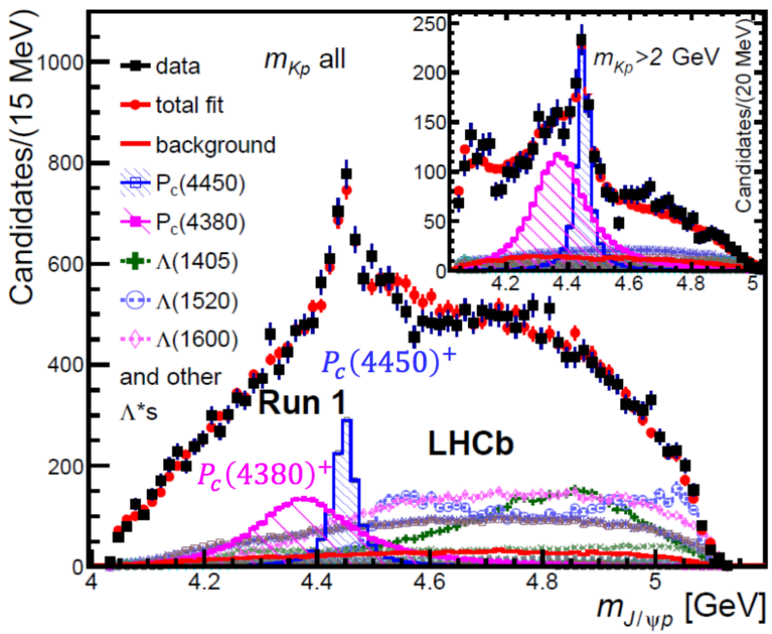
- $Z_c(3900)$ Spin Parity $J^P=1^+$
- Mass near $D\bar{D}^*$ threshold
- Molecule ?
- Tetraquark ?

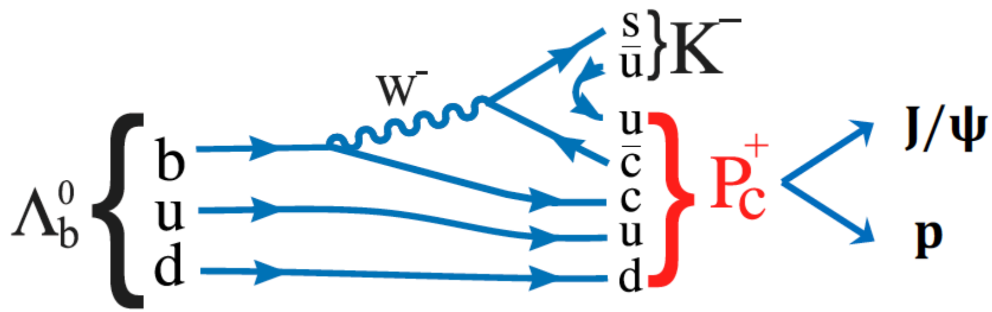


Charged state	Mass (MeV)	Observation
$Z_c(3900)^{(\pm,0)}$	3888.7	BESIII/Belle/CLEO-c/D0
$Z_c(4020)^{(\pm,0)}$	4023.9	BESIII
$Z_c(4050)^{\pm}$	4051	Belle
$Z_c(4100)^{\pm}$	4096	LHCb
$Z_c(4200)^{\pm}$	4196	Belle
$Z_c(4240)^{\pm}$	4239	LHCb
$Z_c(4250)^{\pm}$	4248	Belle
$Z_c(4430)^{\pm}$	4478	Belle/LHCb

Pentaquark

PRL 115 (2015) 072001





$P_c(4450)^+$ $M = 4450 \pm 2 \pm 3$ MeV

$\Gamma = 39 \pm 5 \pm 19$ MeV

$P_c(4380)^+$ $M = 4380 \pm 8 \pm 29$ MeV

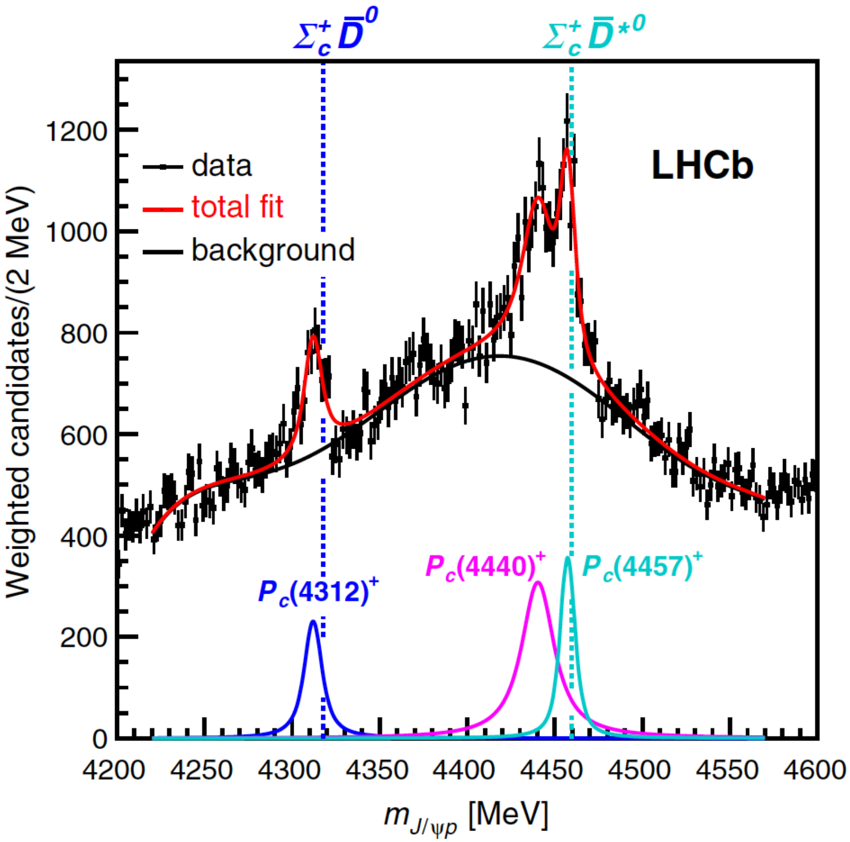
$\Gamma = 205 \pm 18 \pm 86$ MeV

$P_c(4380)/P_c(4450) \rightarrow pJ/\psi$

J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$

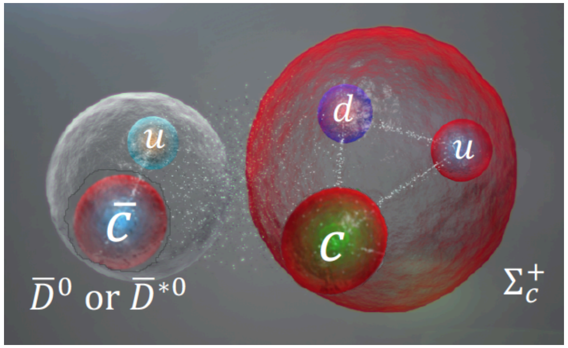
Pentaquark

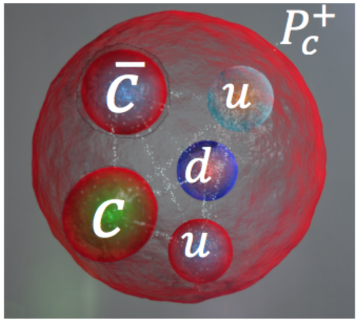
Updated with 10 × statistics in 2019



PRL 122, 222001 (2019)

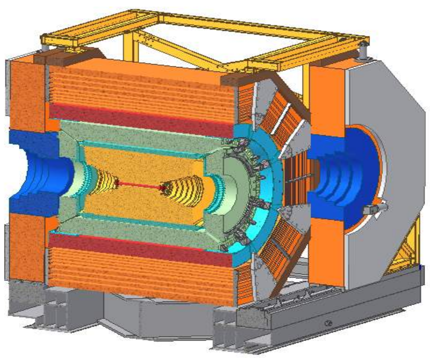
- Near threshold resonance
- Molecule? Pentaquark?
- Other special mechanics?



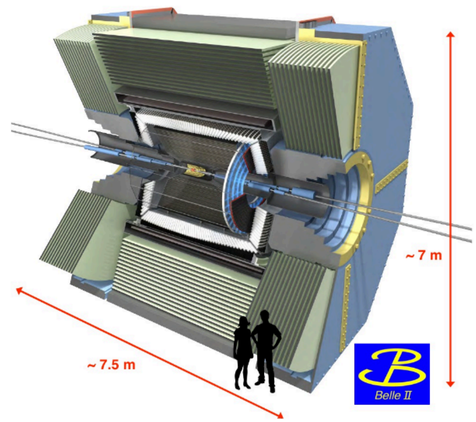


Challenges & Perspective

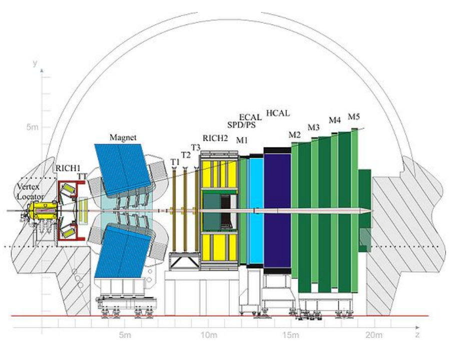
- A dozen of XYZ particles, but do not understand what they are.
- Currently depend on phenomenology models (QCD is difficult, lattice QCD?)
- Improvement from experiments still need (confirmation, precision…)



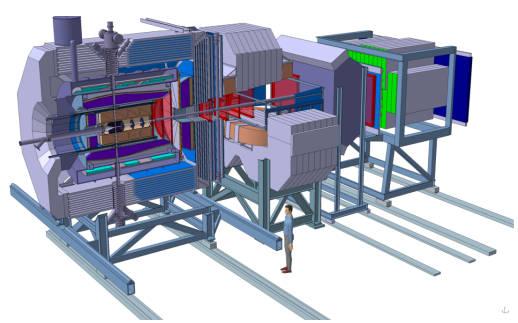
BESIII
- Upgrade
- continue >5 years?



Belle II
- Started in 2019
- Already ~6.5 fb^{-1}
- 50 ab^{-1} final



LHCb
- Upgrade now
- HL LHC
- 20 – 50 fb^{-1}



PANDA
- Start 2025
- Precise scan

Summary

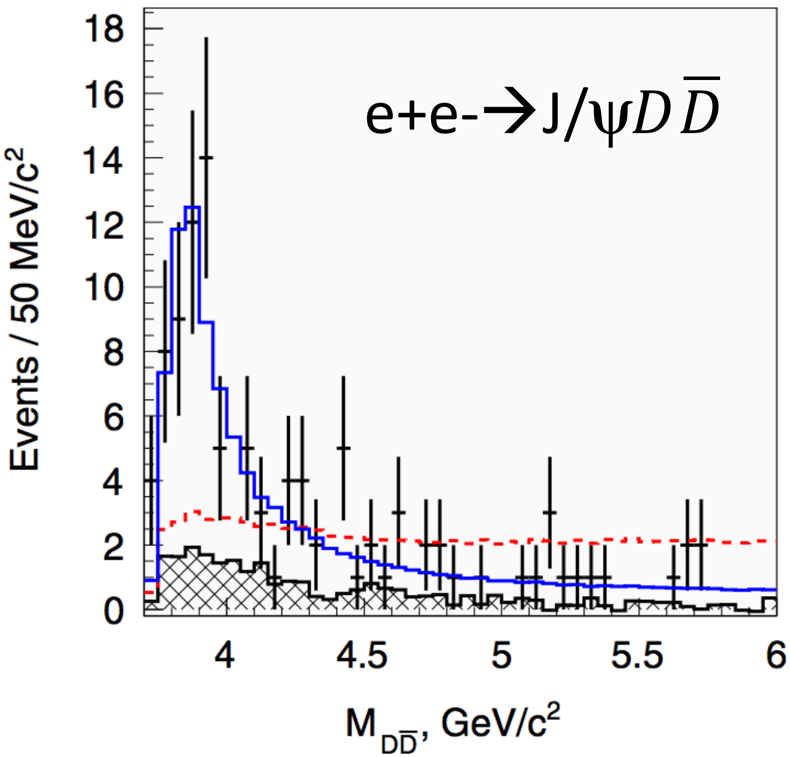
- Quark Model is a successful story for describe hadrons.
- The discovery of XYZ particles bring us new insight for hadronic matter (tetraquark, pentaquark, molecule…).
- To understand their structure is difficult, various models are proposed.
- More efforts are needed: theoretical side (e.g. lattice QCD…), experimental (BESIII, Belle II, LHCb, PANDA…).

Thank you!

Backup

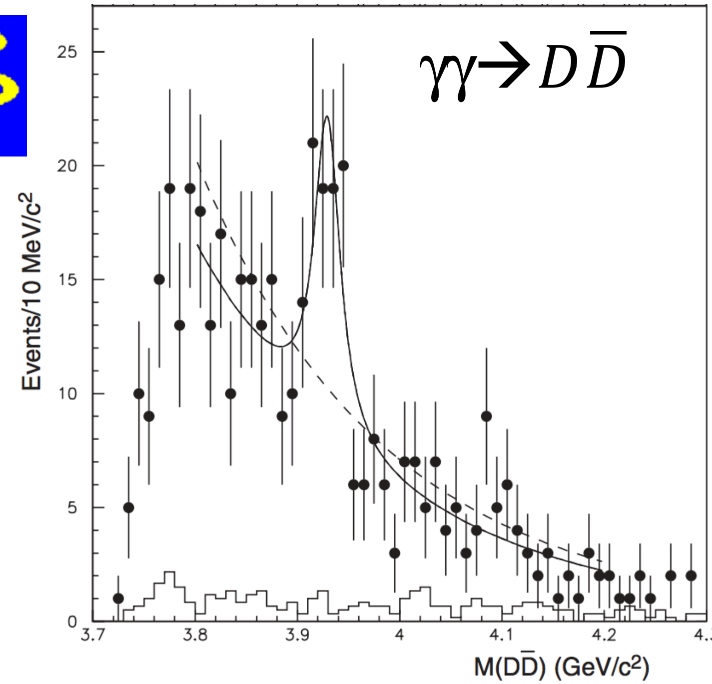
P-wave states $\chi_{c0}(2P)$ & $\chi_{c2}(2P)$

PRD 95, 112003 (2017)



- M=($3862^{+26}_{-32}{}^{+40}_{-13}$) MeV
- Γ=($201^{+154}_{-67}{}^{+88}_{-82}$) MeV
- $J^{PC}=0^{++}$ is favored

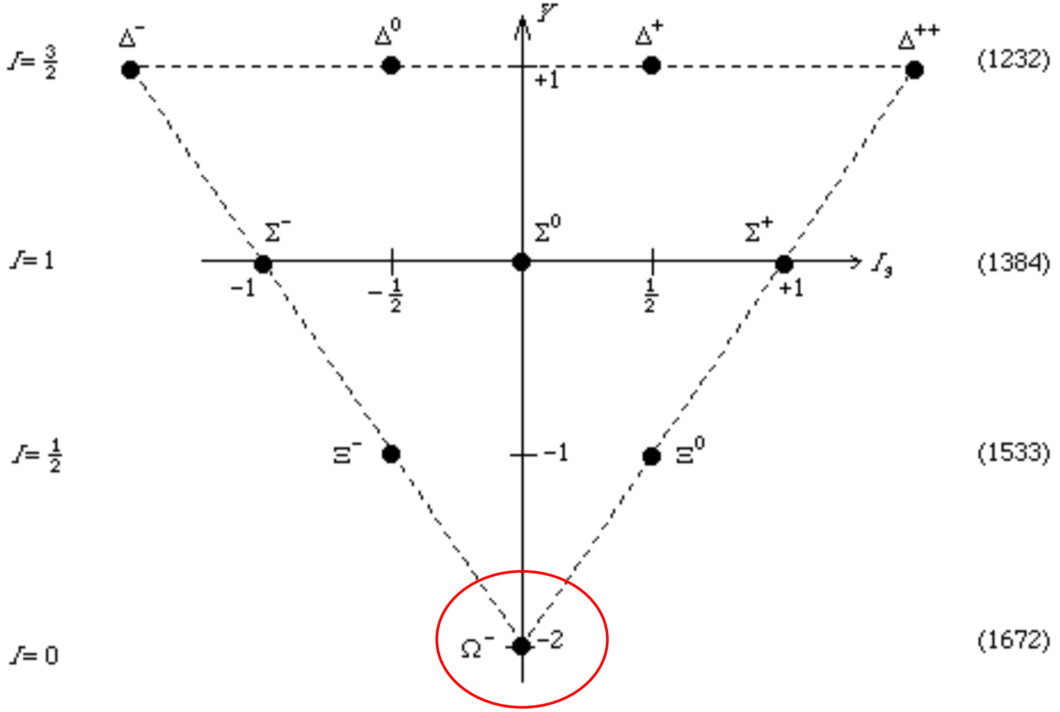
PRL 96, 082003 (2006)

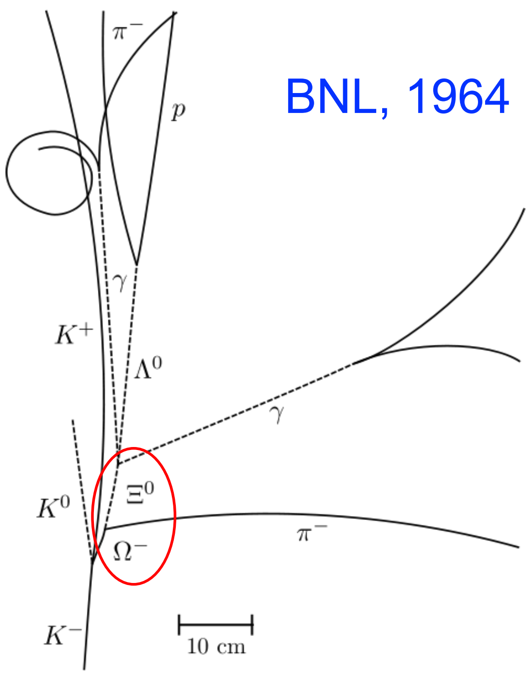


- M=($3929\pm5\pm2$) MeV
- Γ=($29\pm10\pm2$) MeV
- $J^{PC}=2^{++}$ is favored

Both candidates agree with the $\chi_{c0}(2P)$ & $\chi_{c2}(2P)$ charmonium state well

Success



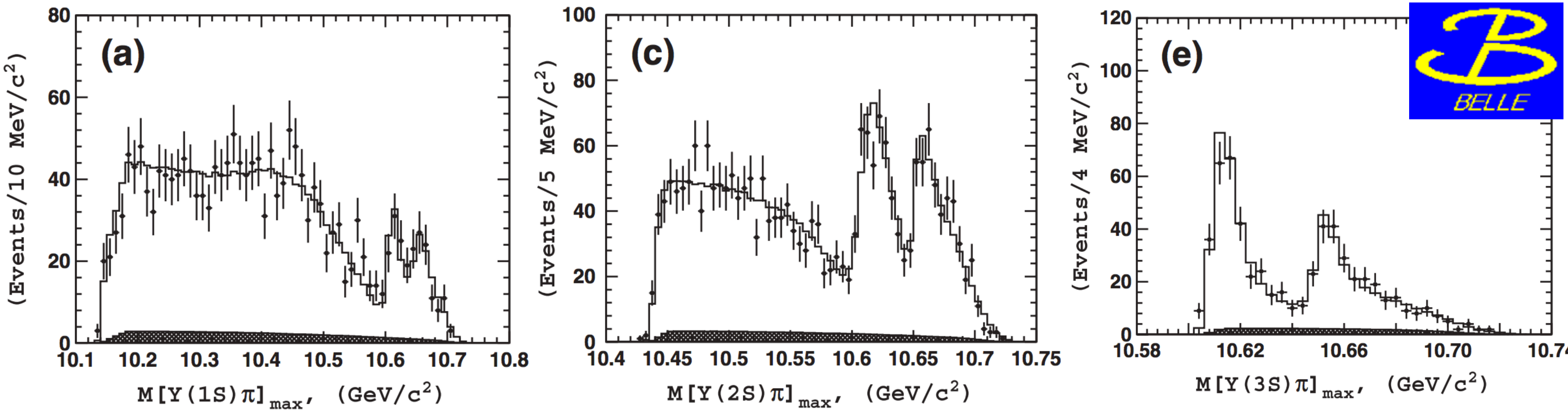


BNL, 1964

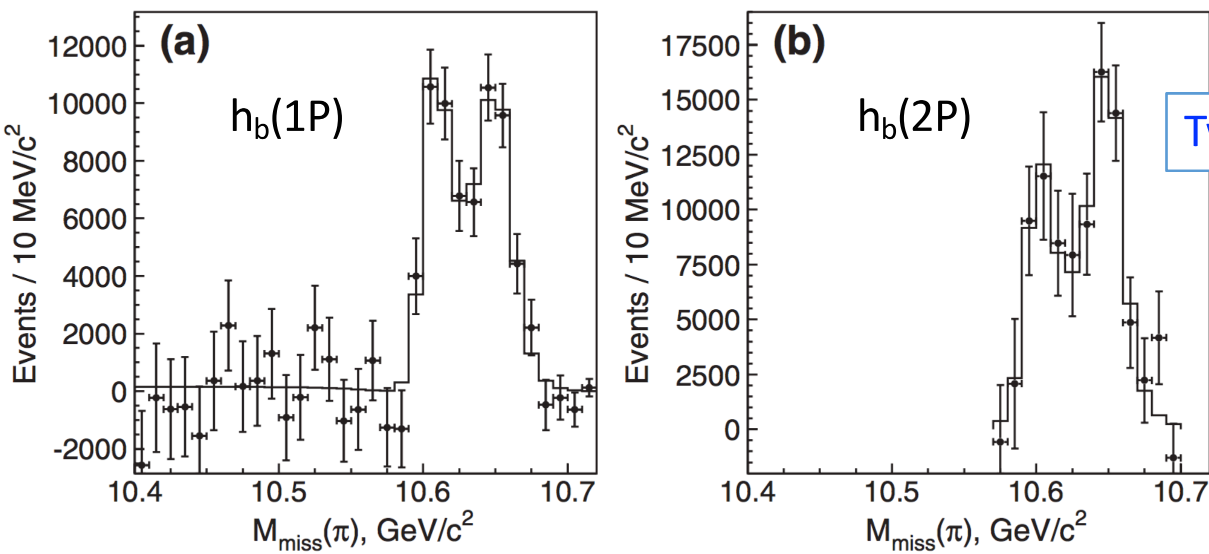
baryon decuplet

- Predict the missing Ω^- baryon with m=1676 MeV
- BNL discovered it with m=1672 MeV

$Z_b(10610)$ & $Z_b(10650)$



PRL 108, 122001 (2012)



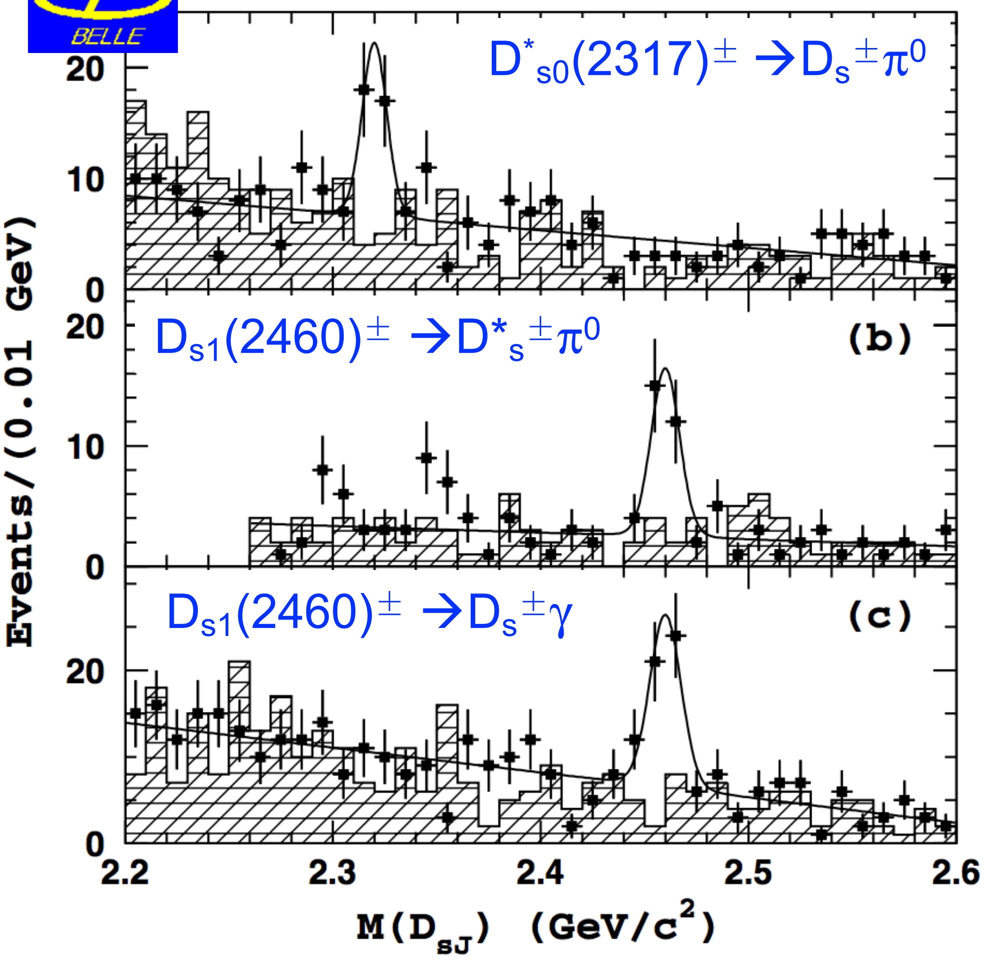
Two charged bottomoniumlike state

M_1=(10607.2 ± 2.0) MeV;
Γ_1=(18.4 ± 2.4) MeV

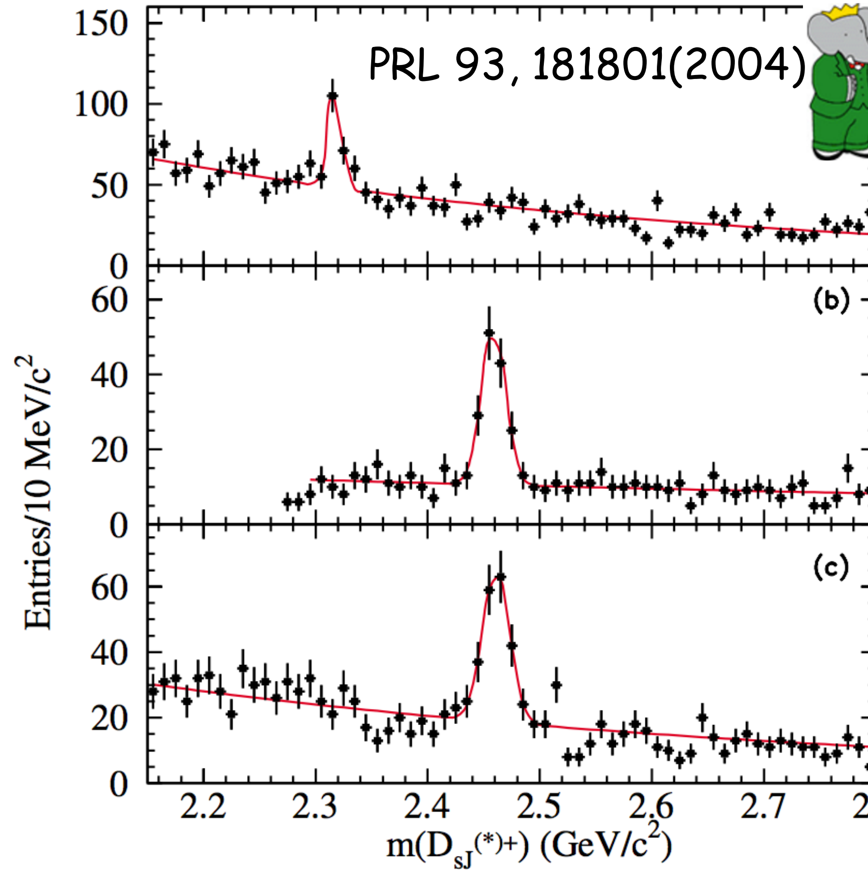
M_2=(10652.2 ± 1.5) MeV;
Γ_2=(11.5 ± 2.2) MeV

$D^{*}_{s0}(2317)^{\pm}$ & $D_{s1}(2460)^{\pm}$

PRL 91, 262002 (2003)



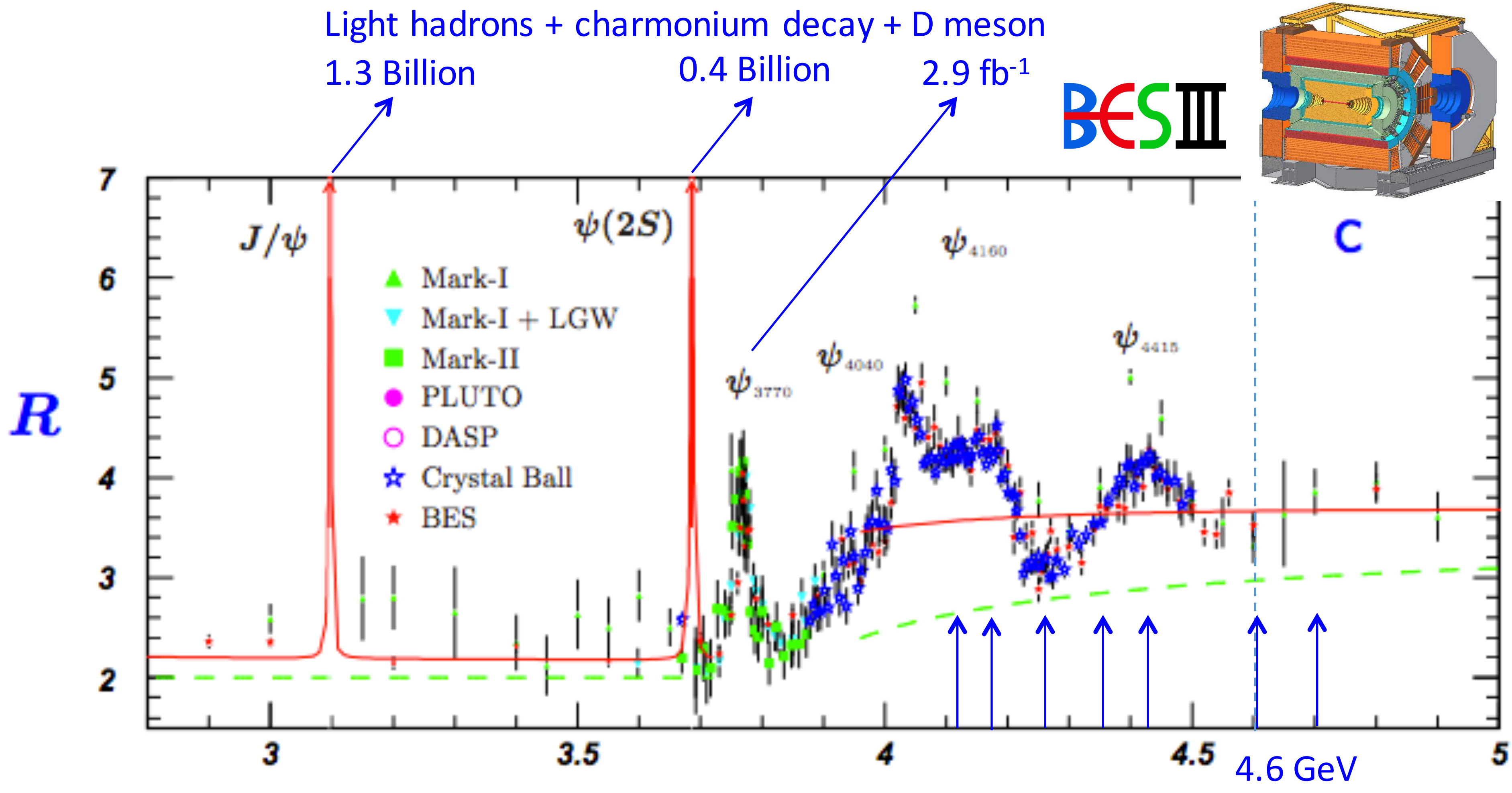
DK and D*K molecule?



$M[D^{*}_{s0}(2317)] = 2317.8 \pm 0.5$ MeV

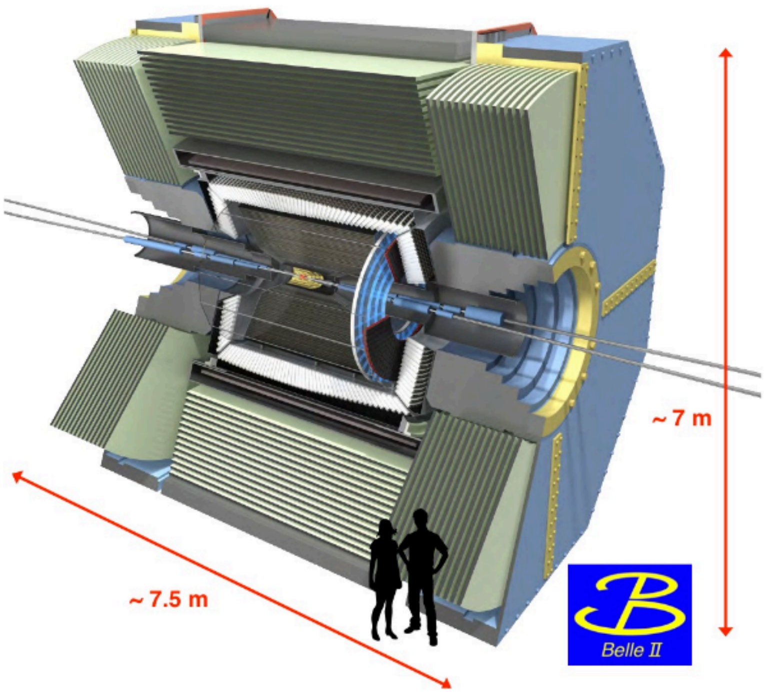
$M[D_{s1}(2460)] = 2459.5 \pm 0.6$ MeV

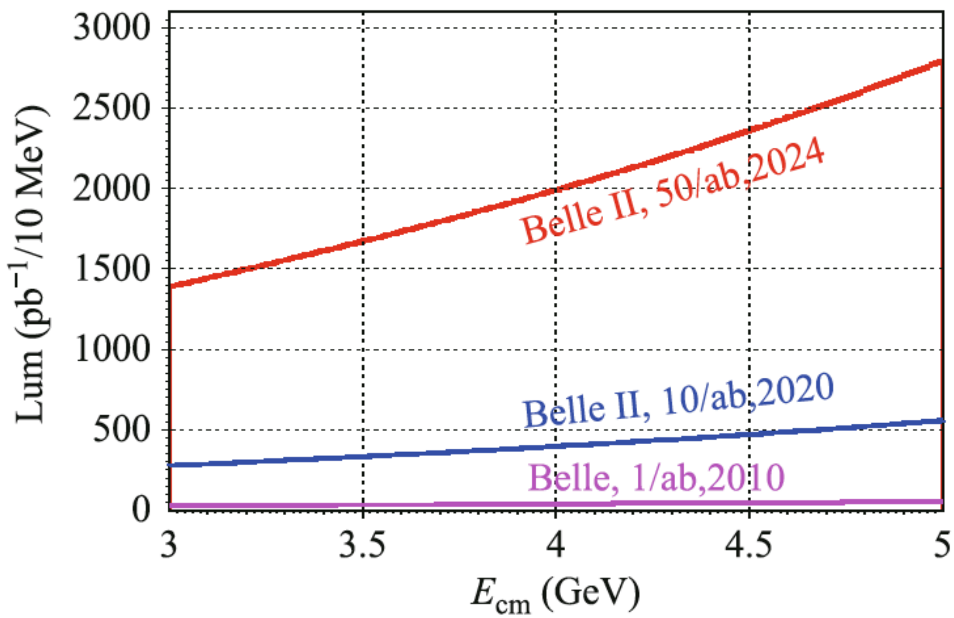
BESIII



Light hadrons + charmonium decay + D meson
1.3 Billion
0.4 Billion
2.9 fb-1
BESIII
R
J/ψ
ψ(2S)
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
ψ3770
ψ4040
ψ4160
ψ4415
C
4.6 GeV
2
3
4
5
6
7
3
3.5
4
4.5
5

Belle II



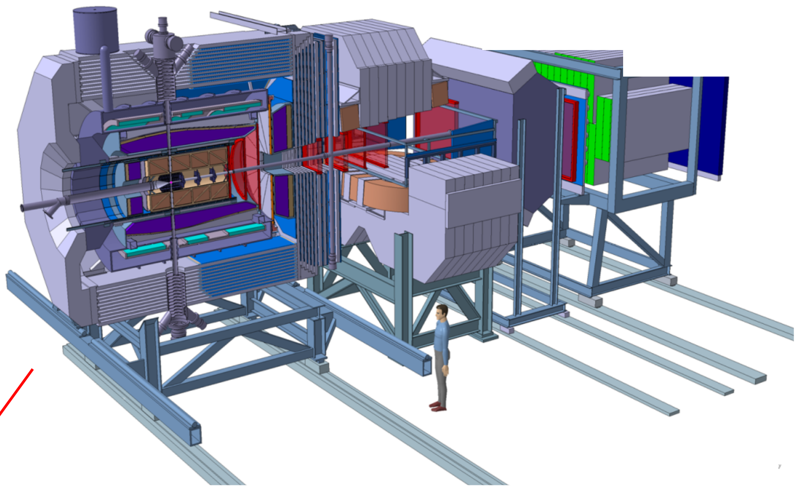


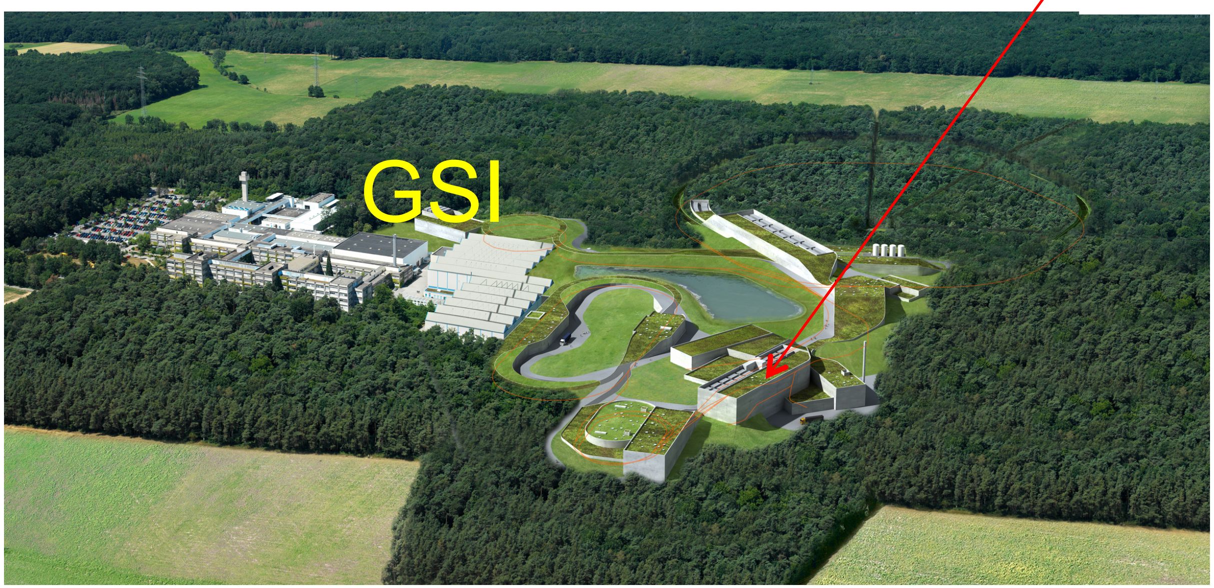
- L=8*10^{35} cm^{-2} s^{-1} ("nanobeam") → 40 times of Belle
- Data taken started in 2019, run 10 years…

PANDA

Antiproton beam,

$p_{beam} = 1.5 – 15$ GeV/c

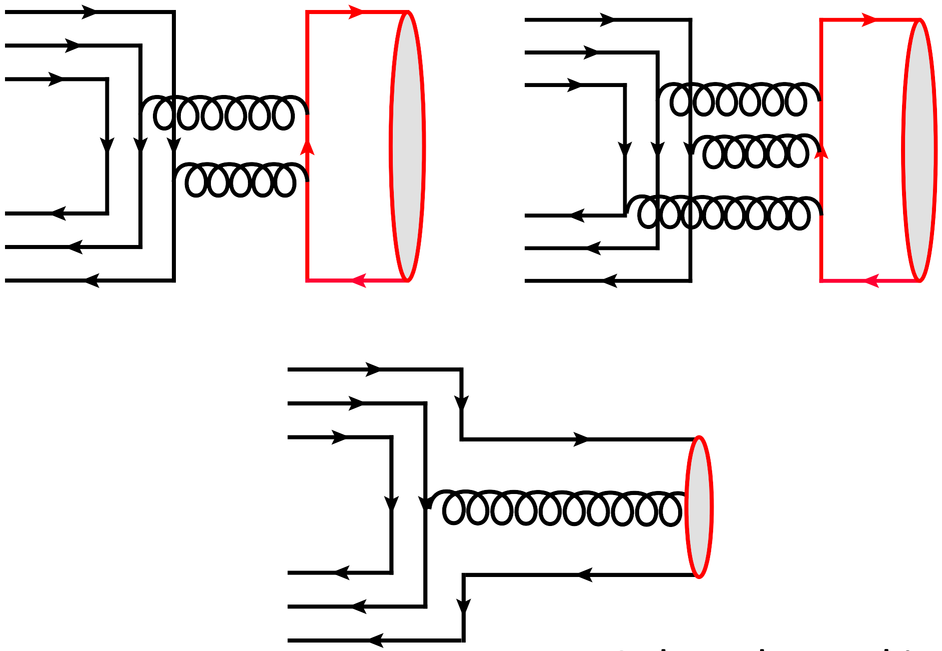




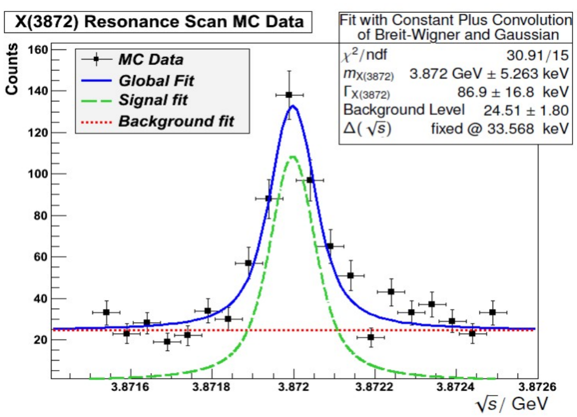
Under construction,
beam expected in 2022

PANDA

- Strong production
  → high production rate
- Various quantum numbers
  → high spin state
- Gluon rich environment
  → glueball & hybrid
- Beam cooling (50 – 200 keV)
  → fine scan of resonances

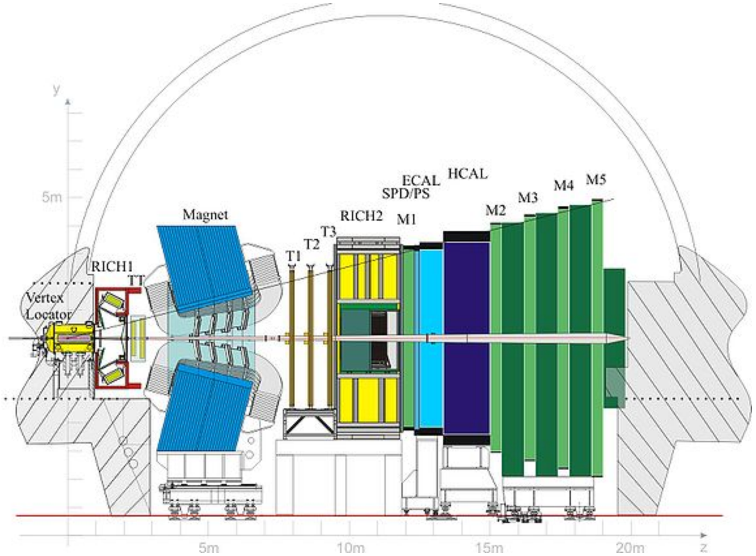


40 days data taking



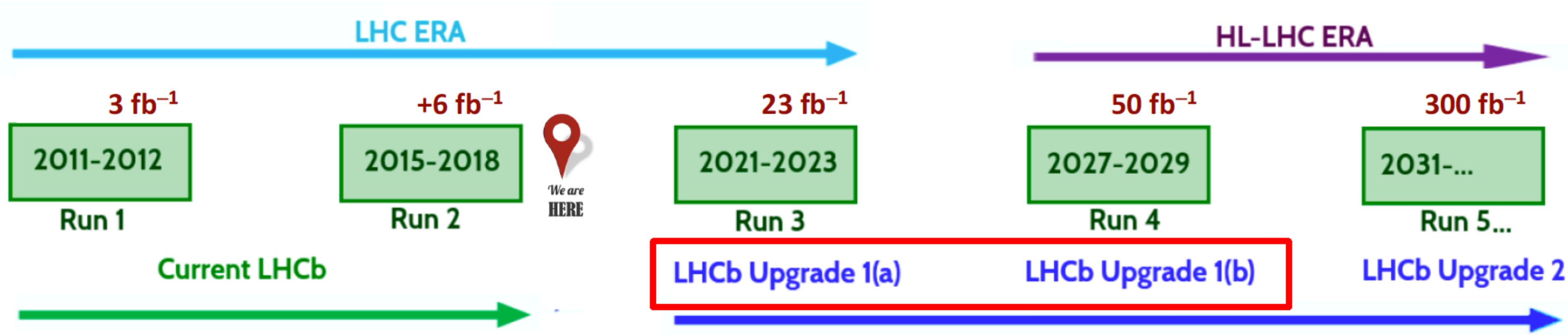
High resolution mode	High intensity mode
◉ $L = 2 \cdot 10^{31}\ cm^{-2}\ s^{-1}$	◉ $L = 2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$
◉ $\sigma_p/p < 5 \cdot 10^{-5}$	◉ $\sigma_p/p = 10^{-4}$

LHCb



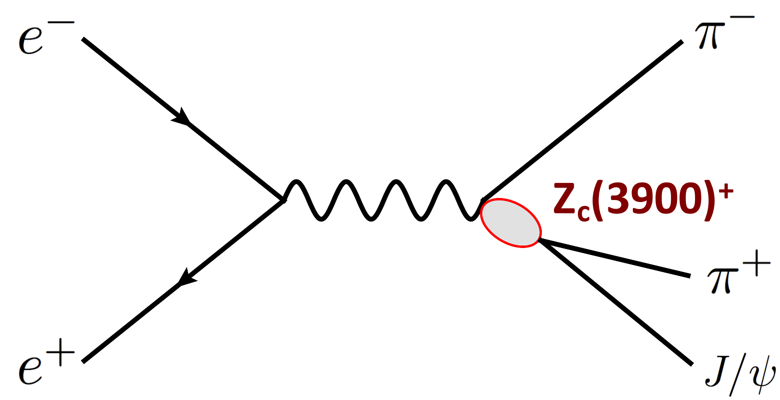
LHCb Upgrade I

From Zhang Liming



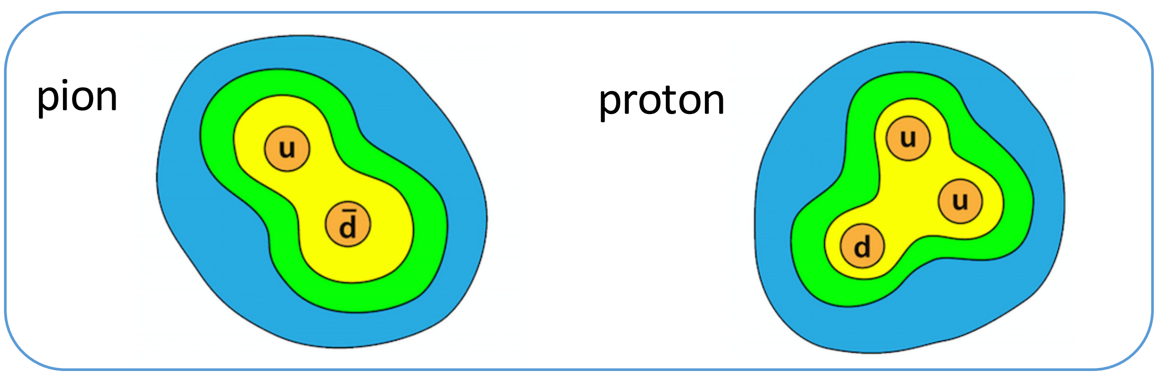
CERN-LHCC-2011-001

$Z_c(3900)^{\pm}$



- $Z_c(3900)^+$ decays to π^+ and J/ψ, carries electric charge!
- A charged state can not be charmonium → minimal four quarks

Naive Quark Model



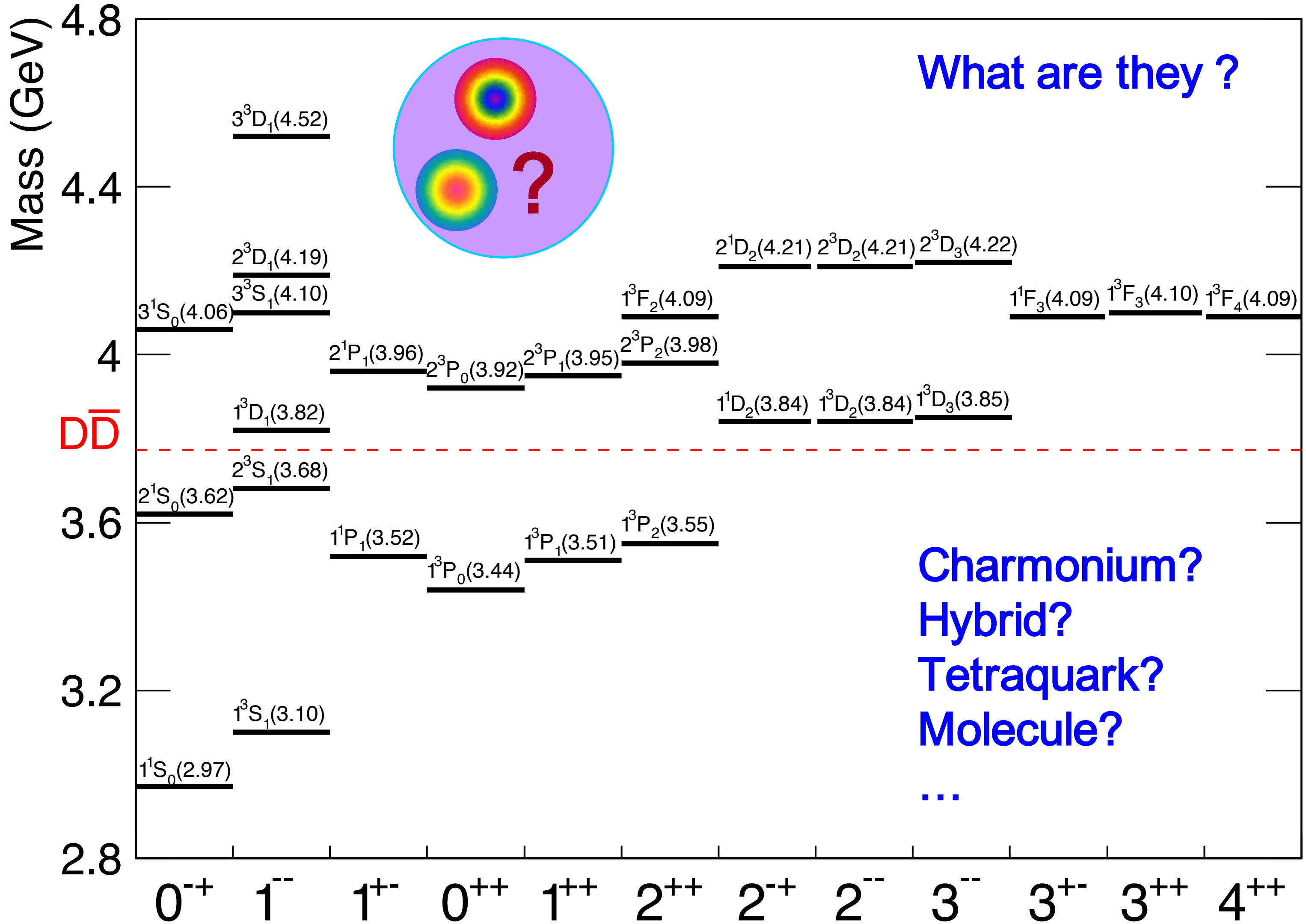
Neutral charmonium-like state

X(3872)

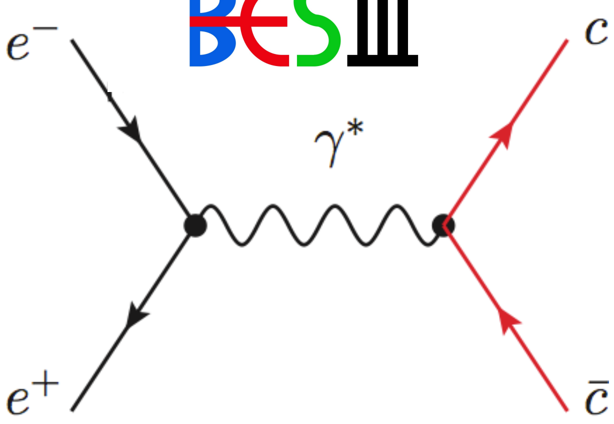
Y(4260)

.
.
.

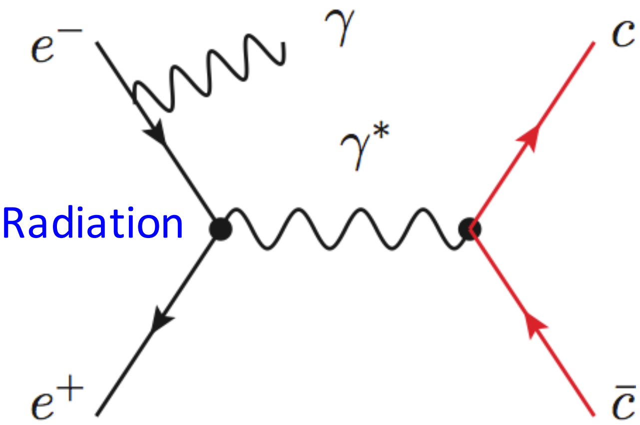
Y(4360)
X(3915)
X(4160)
Y(4008)
Y(4140)
X(4350)
Y(4660)
XYZ(3940)



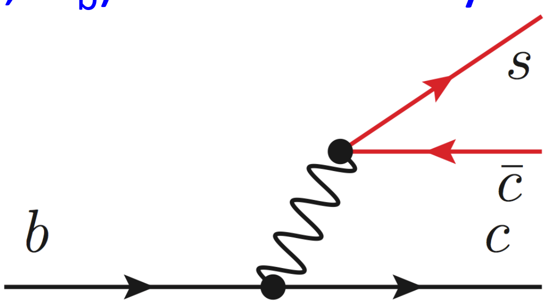
Charmonium production



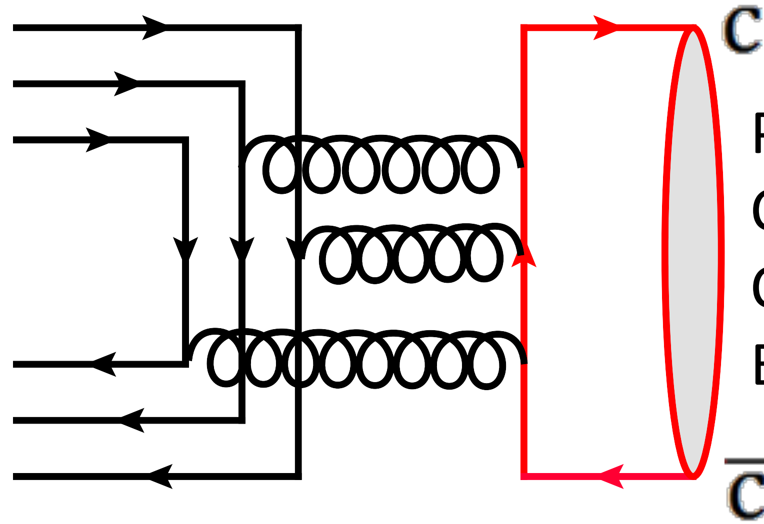
Initial-State-Radiation



(B, Λ_b) hadron decay



Quark-(gluon) annihilation/scattering



PANDA
CDF/D0
CMS
E705...