The exciting physics with exotics

Ulrich Wiedner
(Ruhr-University Bochum)

SFAIR-Meeting Uppsala, 10.11.2014

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

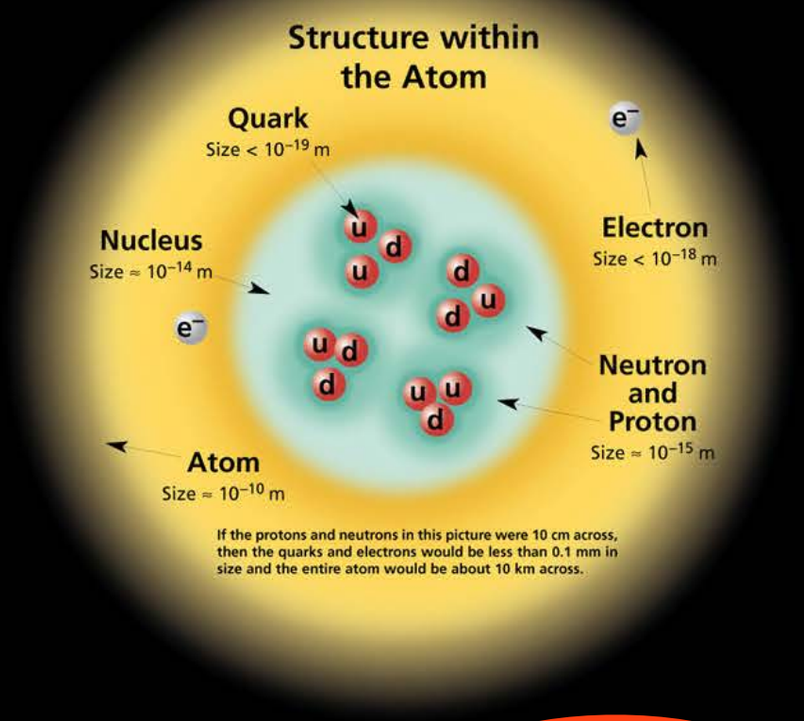
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

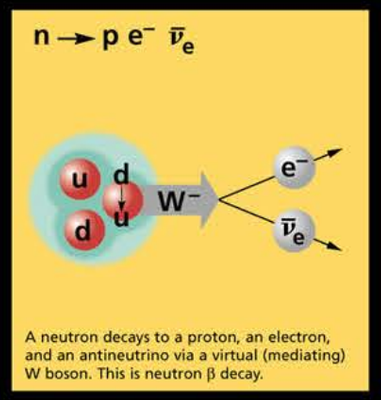
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

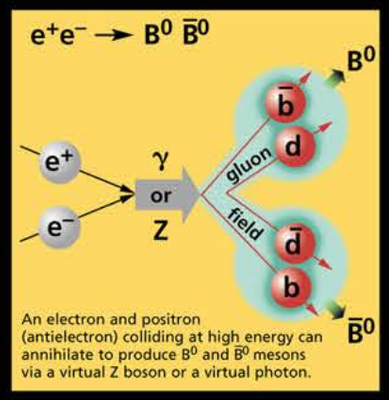
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

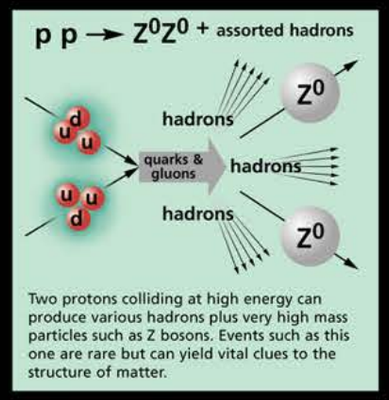
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

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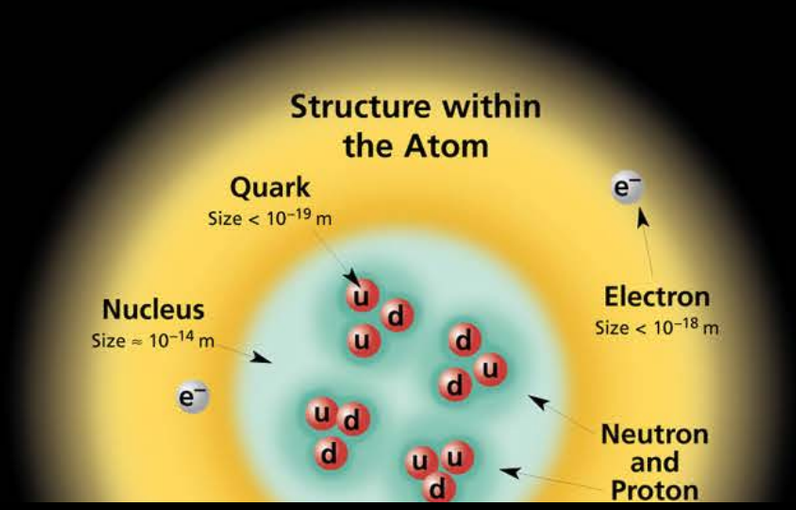

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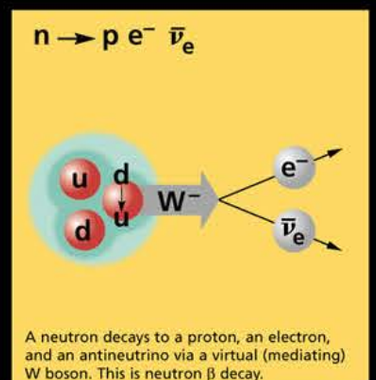

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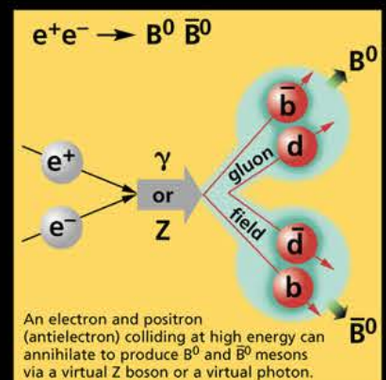

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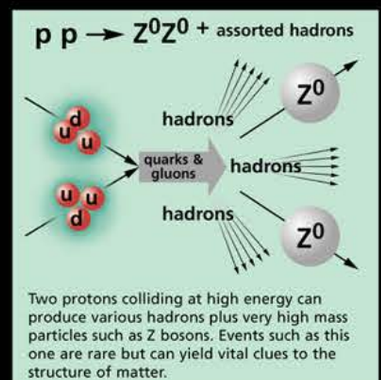

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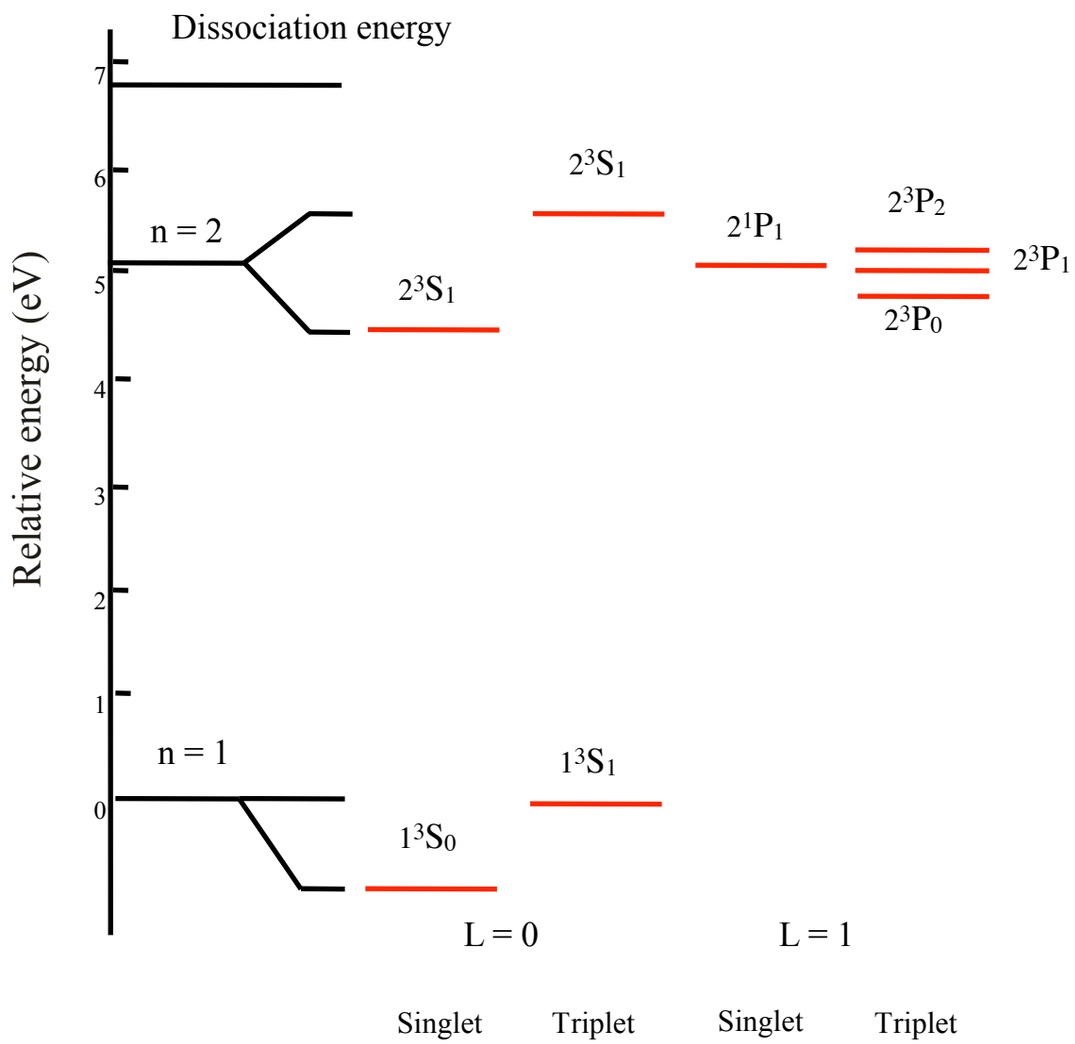
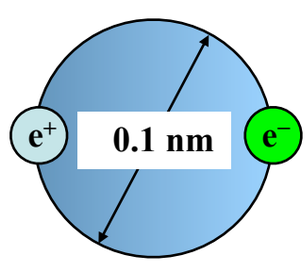
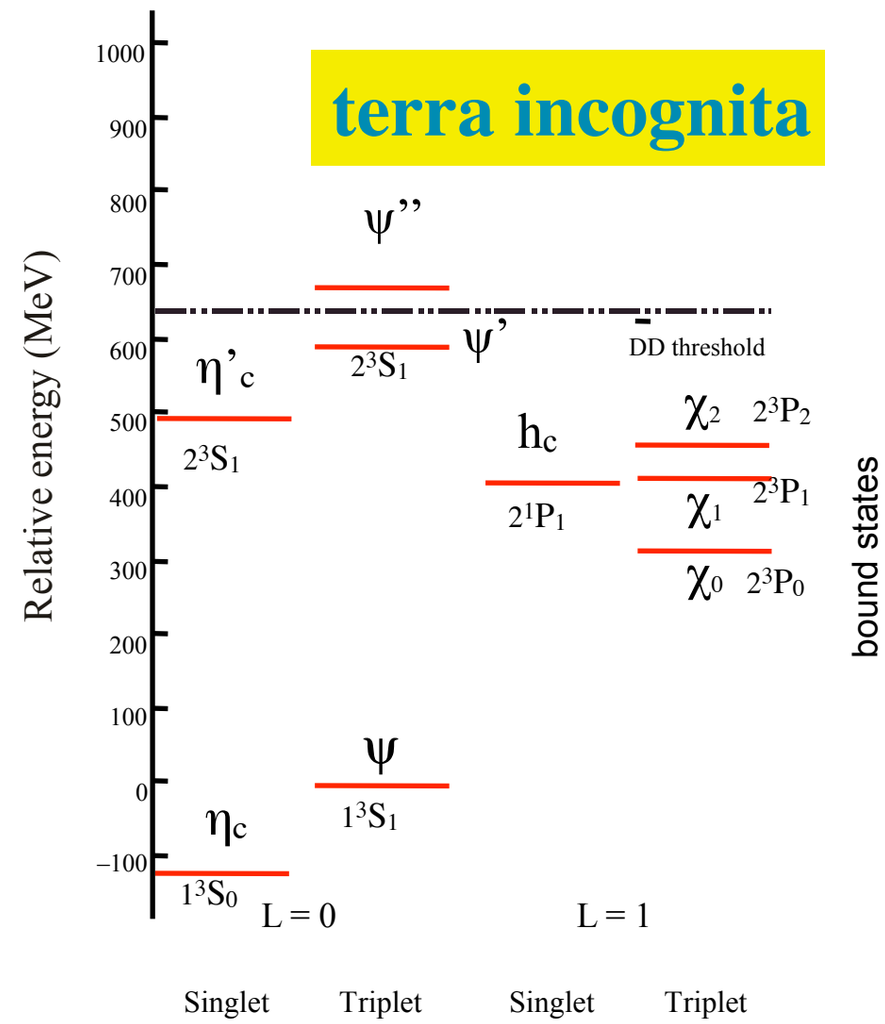
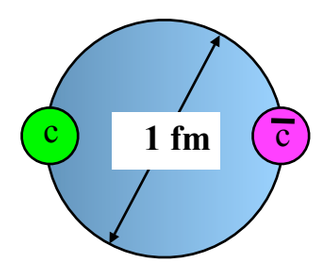
Positronium





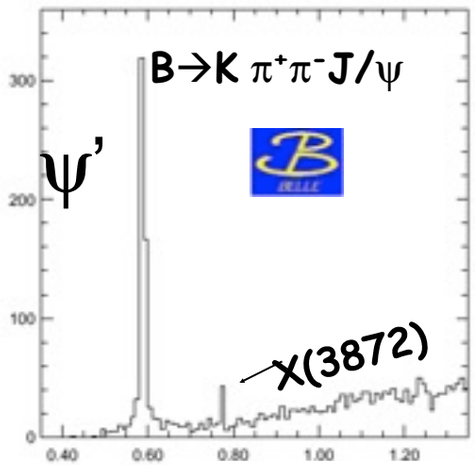
Charmonium





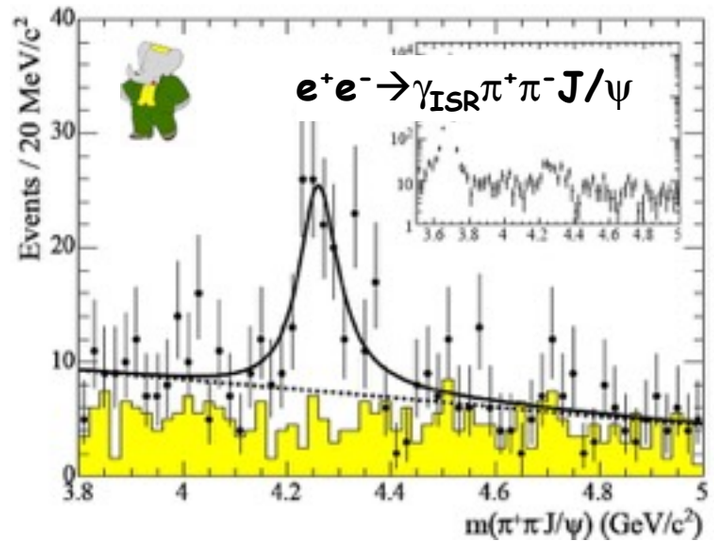
X and Y mesons

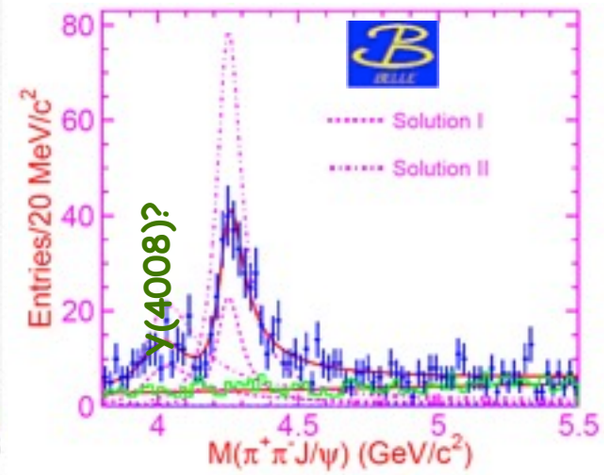
X(3872)



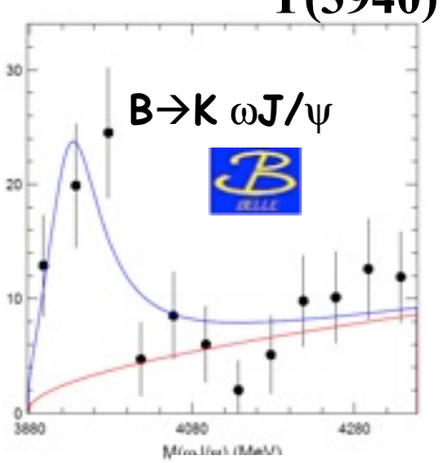
$M(\pi^+\pi^-J/\psi)-M(J/\psi)$

Y(4260)

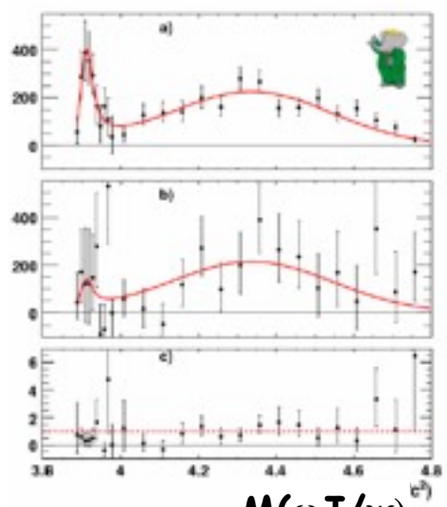




Y(3940)

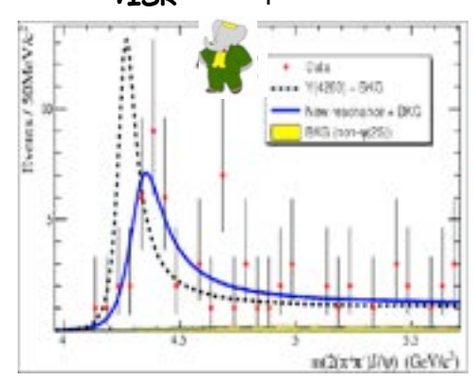


$M(\omega J/\psi)$



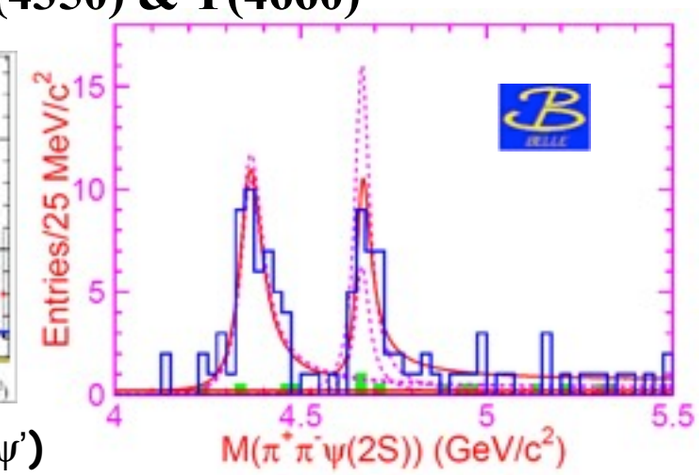
$M(\omega J/\psi)$

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

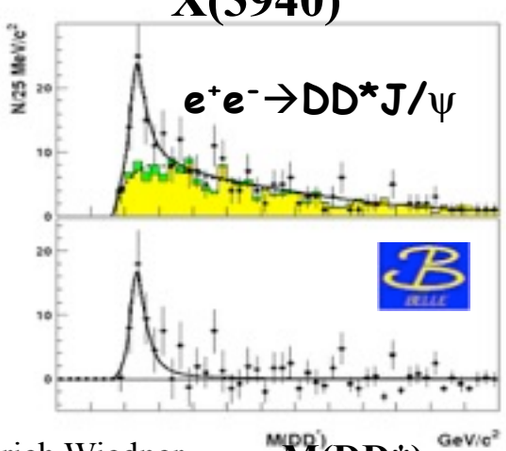


$M(\pi^+\pi^-\psi')$

Y(4350) & Y(4660)

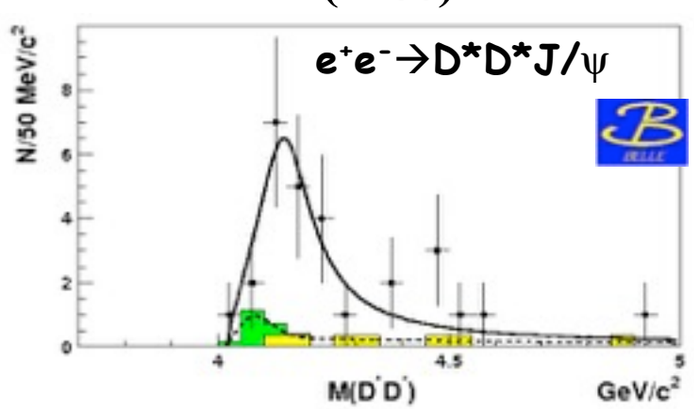


X(3940)



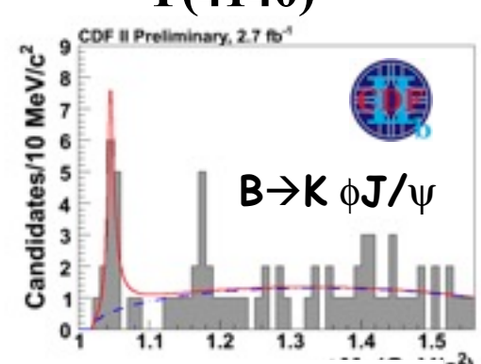
$M(DD^*)$

X(4160)



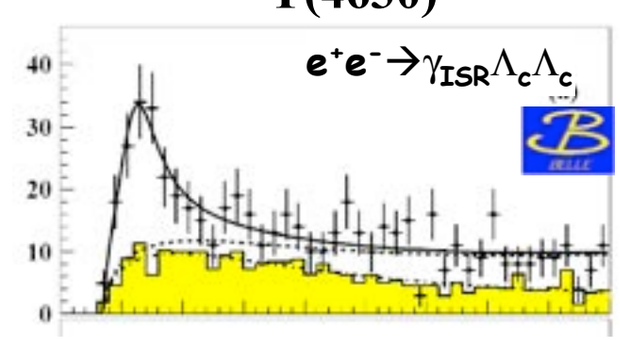
$M(D^*D^*)$

Y(4140)



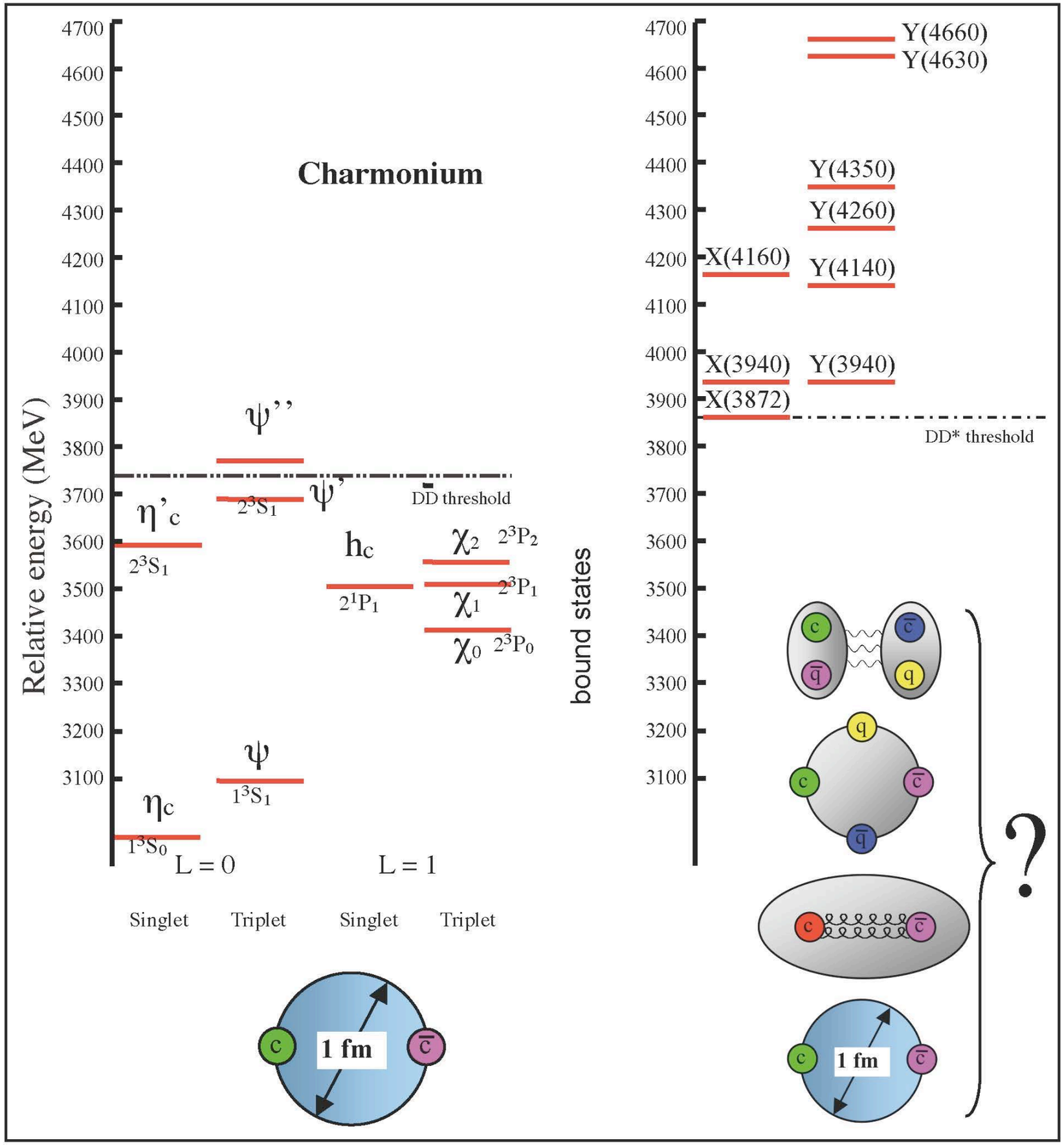
$M(\phi J/\psi)$

Y(4630)



$M(\Lambda_c\Lambda_c)$

Ulrich Wiedner


Charmonium
Relative energy (MeV)
4700
4600
4500
4400
4300
4200
4100
4000
3900
3800
3700
3600
3500
3400
3300
3200
3100
ψ''
ψ'
η'c
2³S₁
2³S₁
DD threshold
hc
χ2
2³P₂
2¹P₁
χ1
2³P₁
χ0
2³P₀
ψ
1³S₁
ηc
1³S₀
L = 0
L = 1
Singlet
Triplet
Singlet
Triplet
1 fm
c
c̄
bound states
Y(4660)
Y(4630)
Y(4350)
Y(4260)
X(4160)
Y(4140)
X(3940)
Y(3940)
X(3872)
DD* threshold
q
q̄
?

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x(3872) molecule

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Apr 15, 2004 – The **X**(**3872**) particle -- What is it? April 15 **...** Some theories have predicted that the **X**(**3872**) is a new type of particle called a meson-**molecule**.

[PDF] D (2700), D (2860) and the open-charm system **X**(**3872**): **molecu**…
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dorigo.wordpress.com/2006/06/.../spin-parity-analysis-of-the-**x3872**/
Jun 9, 2006 – Two possible spin-parity assignments of the **X**(**3872**) are equally probable: in particular, the X may be indeed a **molecular** bound state of two **...**

Phys. Rev. D 72, 114013 (2005): **X**(**3872**) boson: **Molecule** or **...**
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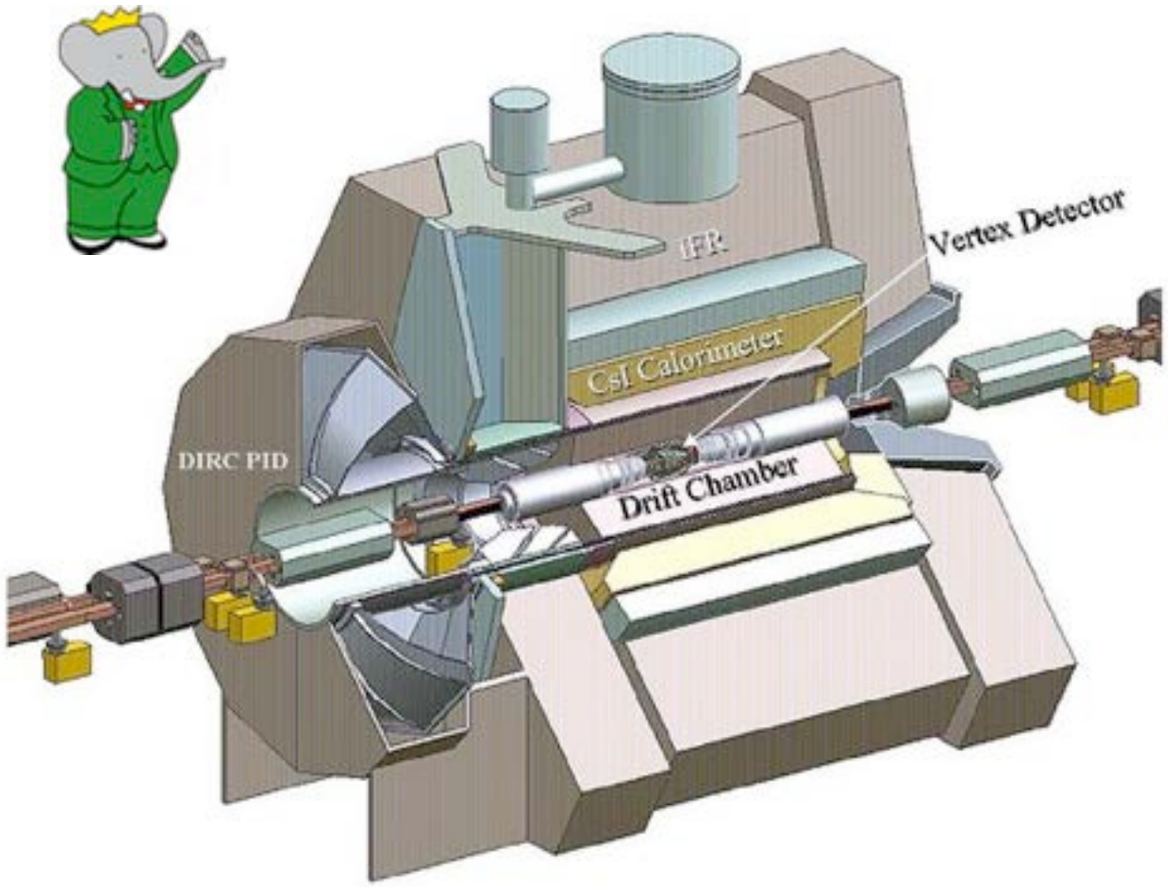
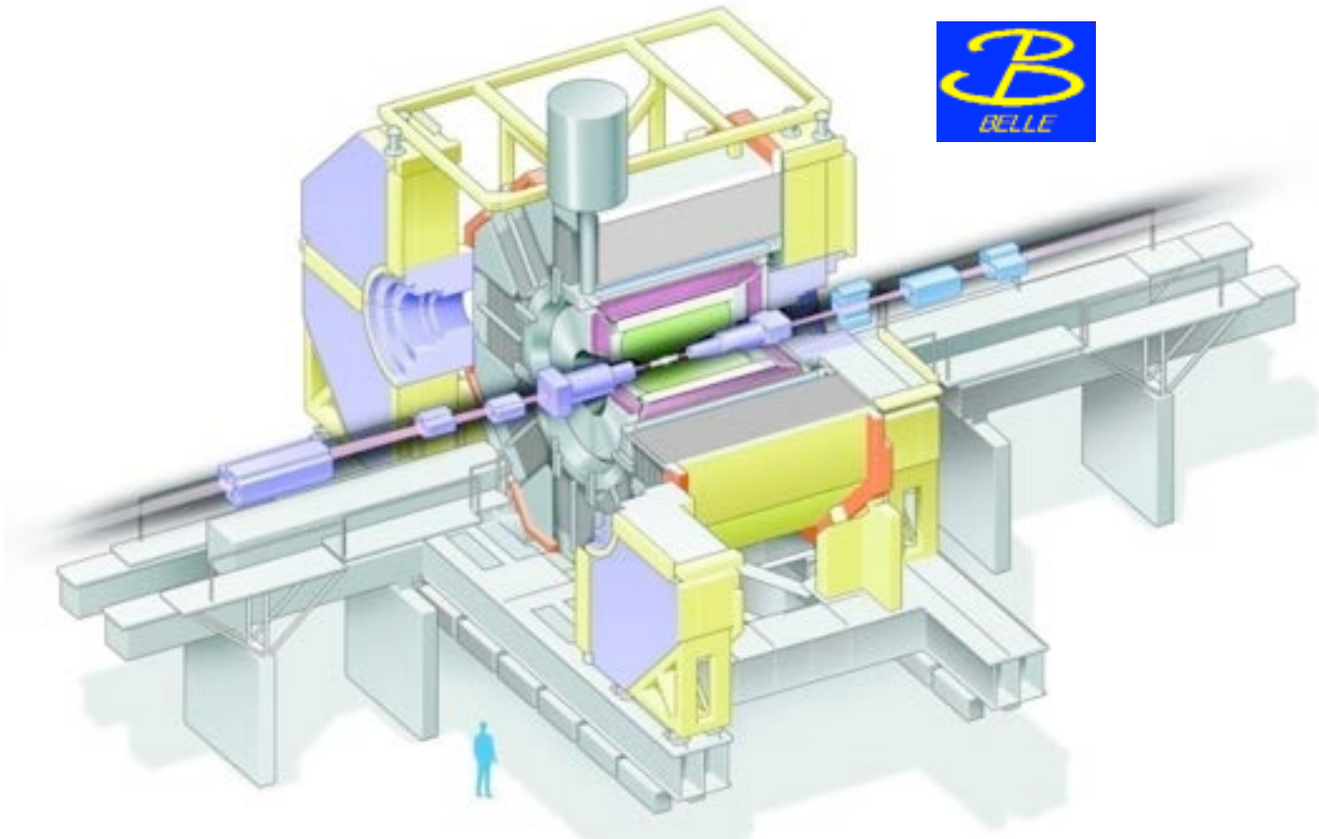
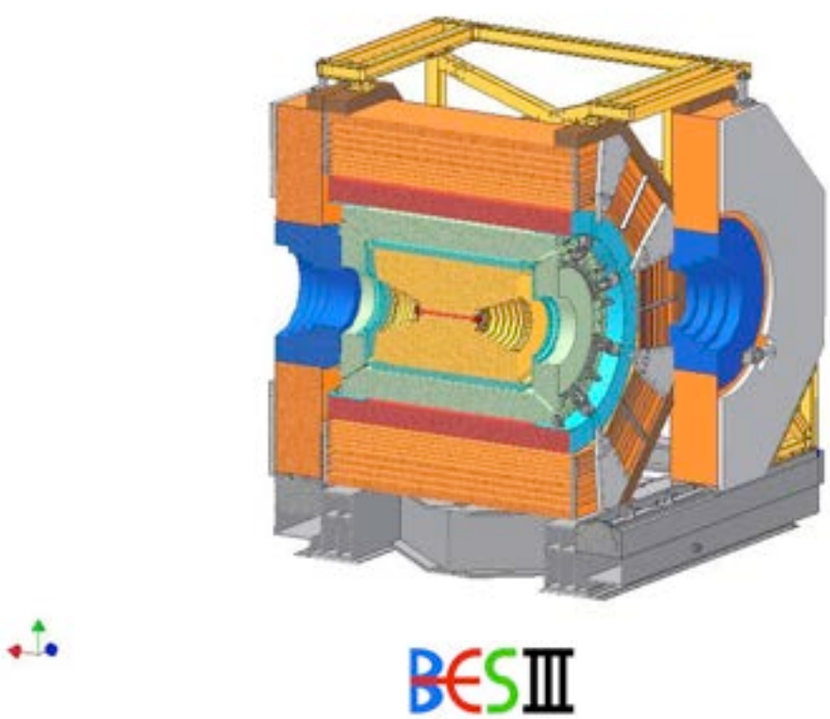
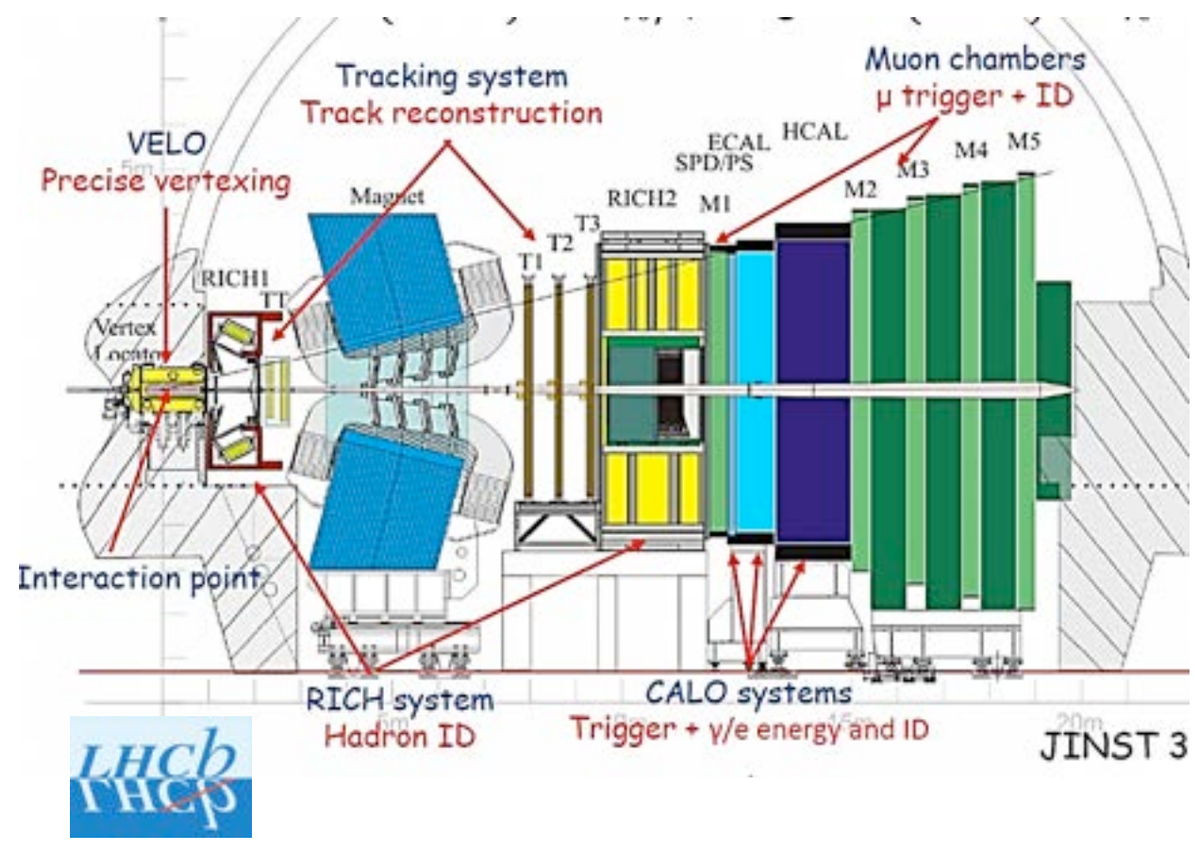
by M HARADA - Related articles
We discuss the possible interpretation of **X**(**3872**) as a DD̄ hadronic **molecule** with JP


IFR
Vertex Detector
CsI Calorimeter
DIRC PID
Drift Chamber

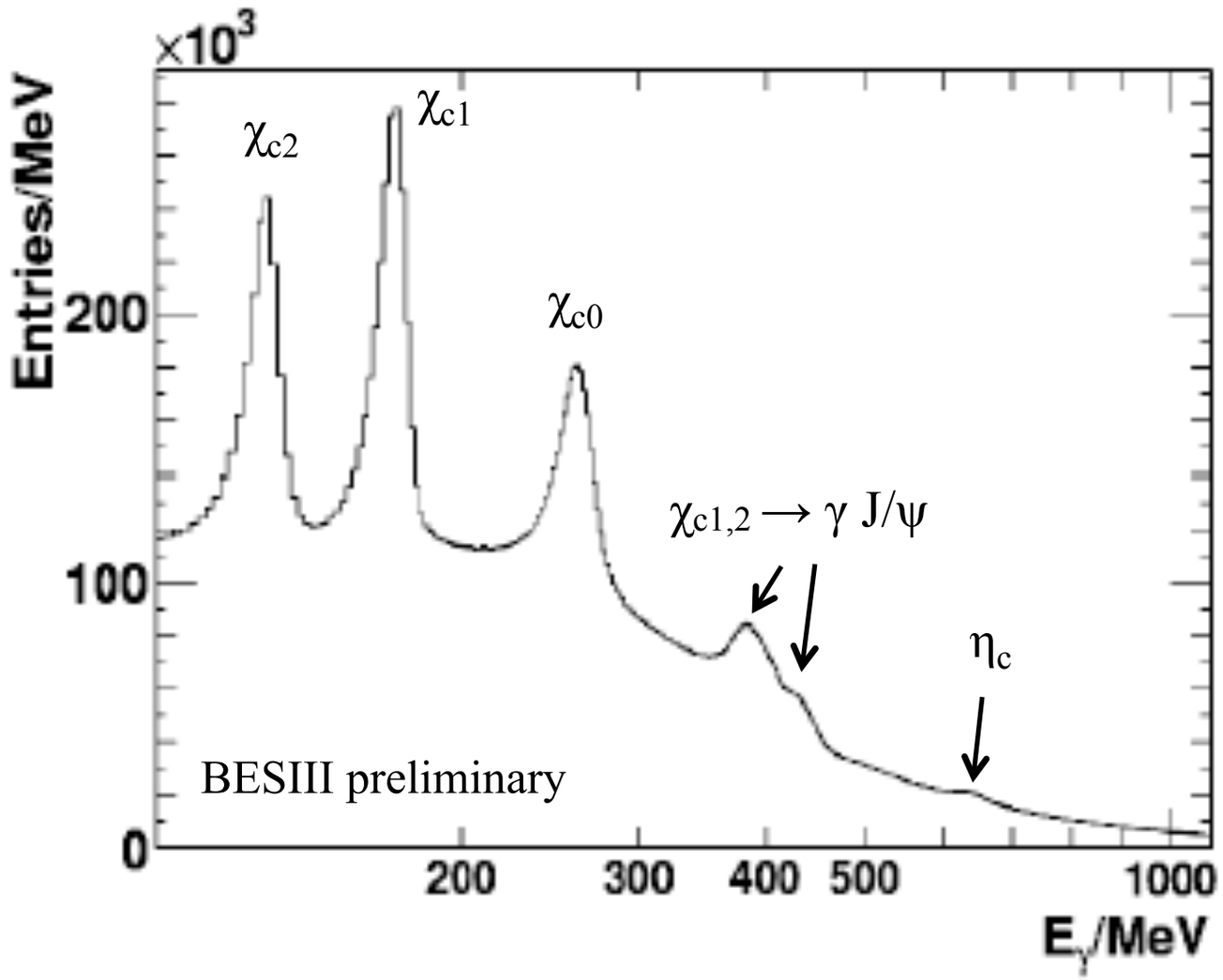

BELLE


BESIII


Tracking system
Track reconstruction
Muon chambers
μ trigger + ID
VELO
Precise vertexing
Magnet
RICH1
TT
Vertex Locator
T1
T2
T3
RICH2
M1
ECAL
SPD/PS
HCAL
M2
M3
M4
M5
Interaction point
RICH system
Hadron ID
CALO systems
Trigger + γ/e energy and ID
LHCb
JINST 3

BESIII data quality

$\psi' \rightarrow \gamma X$



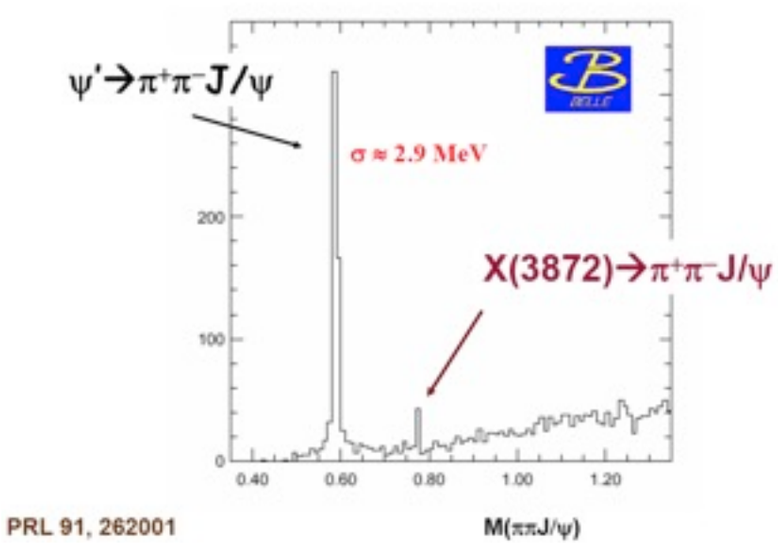
The X(3872)

Ulrich Wiedner

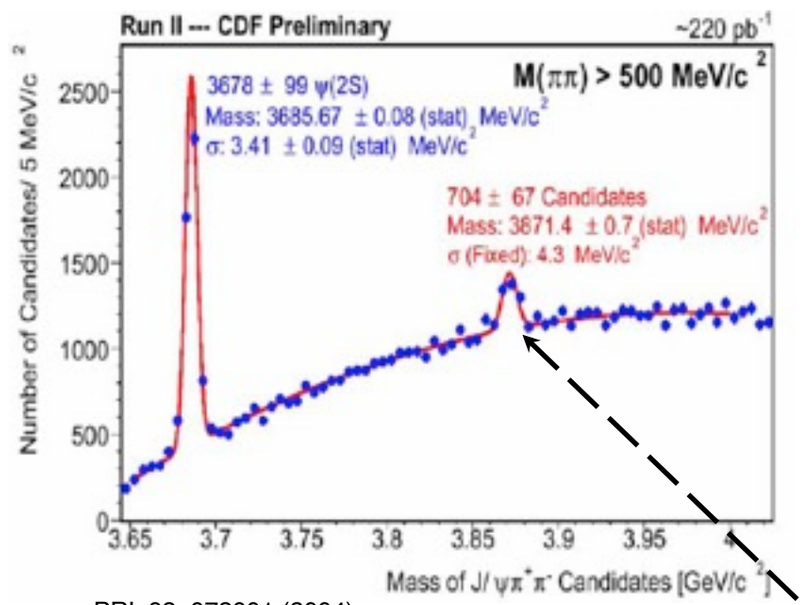
X(3872)

$B \to KX;\ p\bar{p}$
$X \to \pi^+\pi^- J/\psi$
$X \to \pi^+\pi^-\pi^0 J/\psi$
$X \to \gamma J/\psi;\ X \to \gamma\psi(2S)$
$X(3875) \to D^0\bar{D}^0\pi^0$

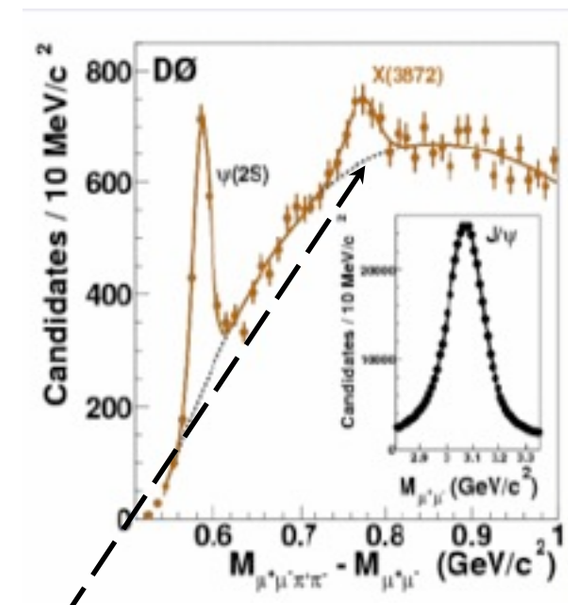
$J^{PC} = ?\ (1^{++})$
$M = 3871.68 \pm 0.17$ MeV
$\Gamma < 1.2$ MeV
$> 10\ \sigma$



PRL 91, 262001



PRL 93, 072001 (2004)



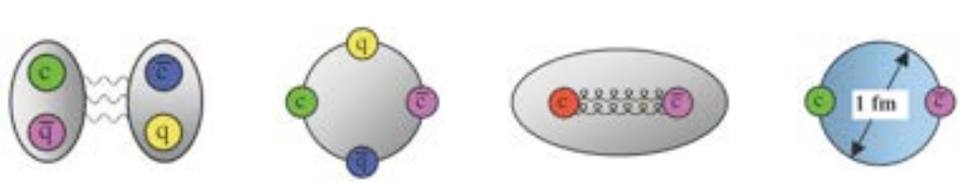
2003

X(3872)

2004

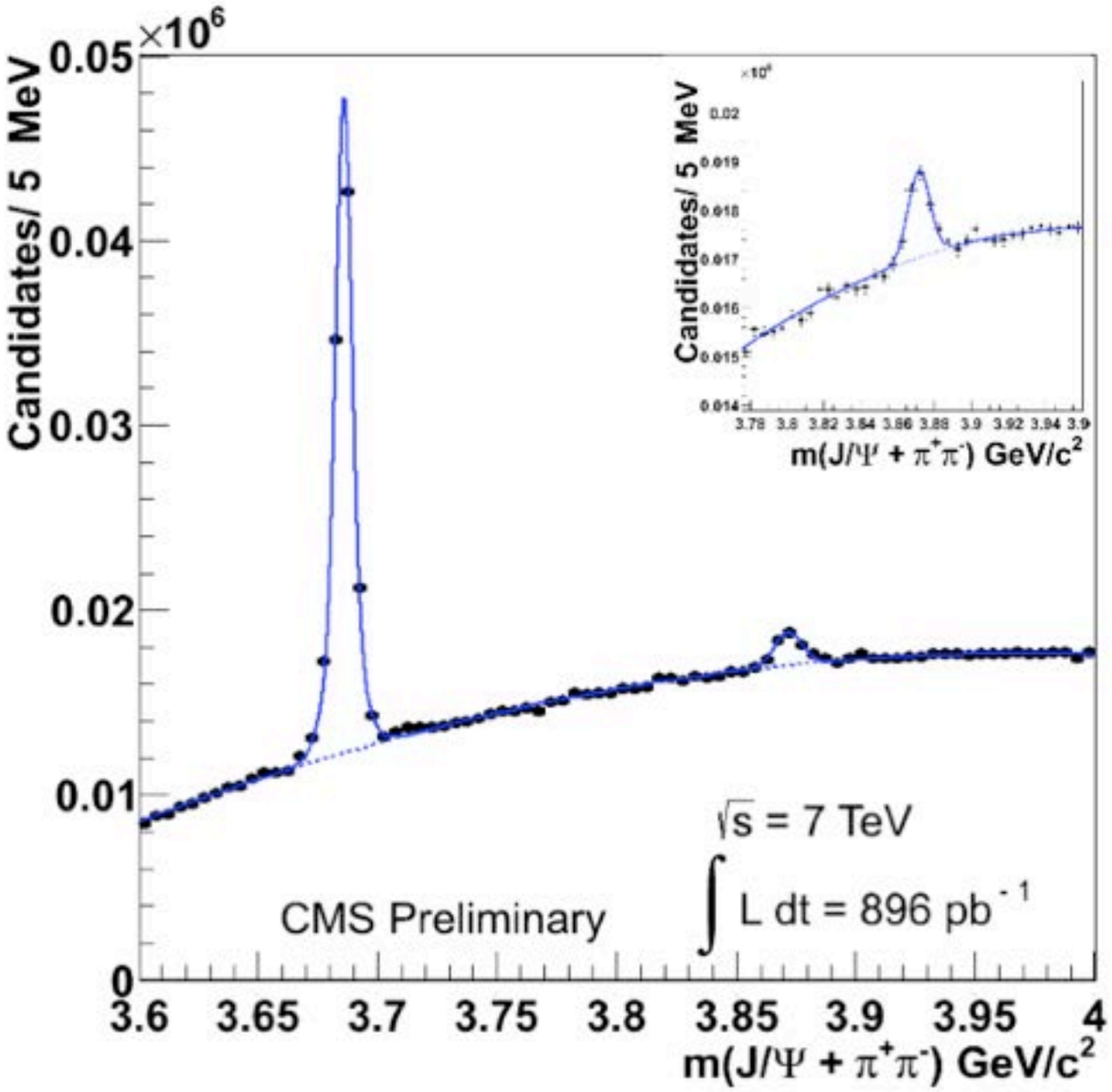
threshold effect ?

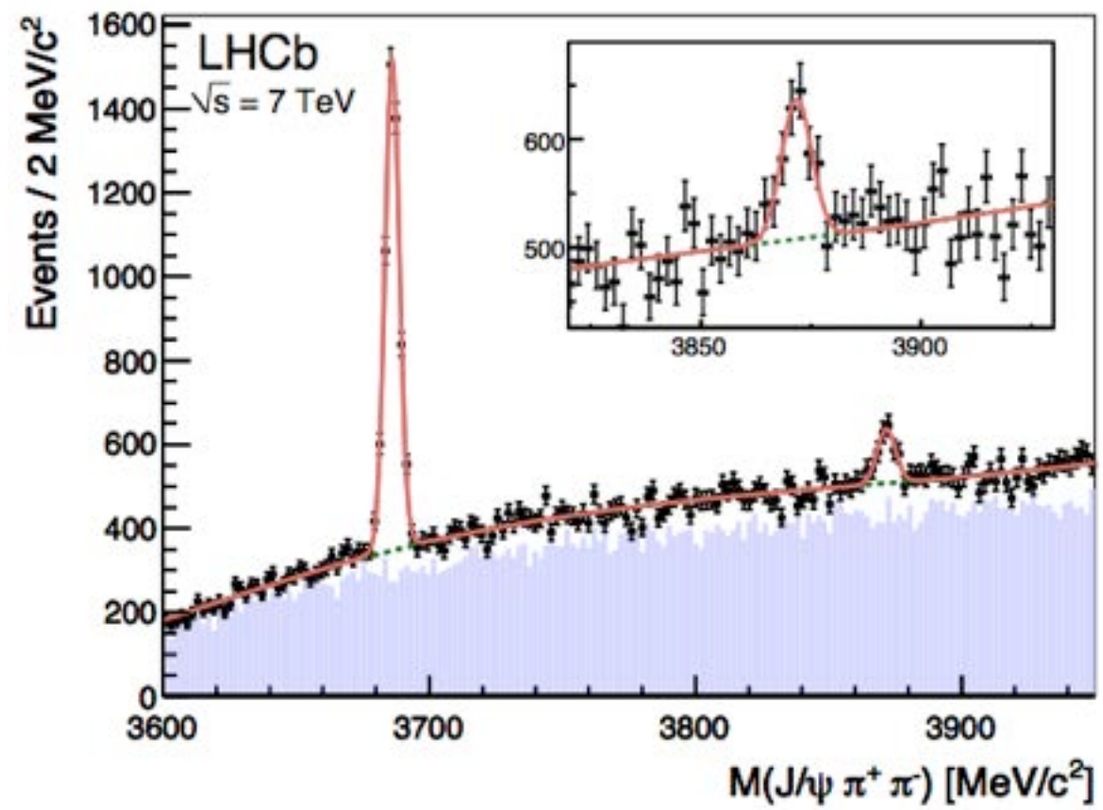
?



?

CMS: PoS EPS-HEP2011 (2011) 177

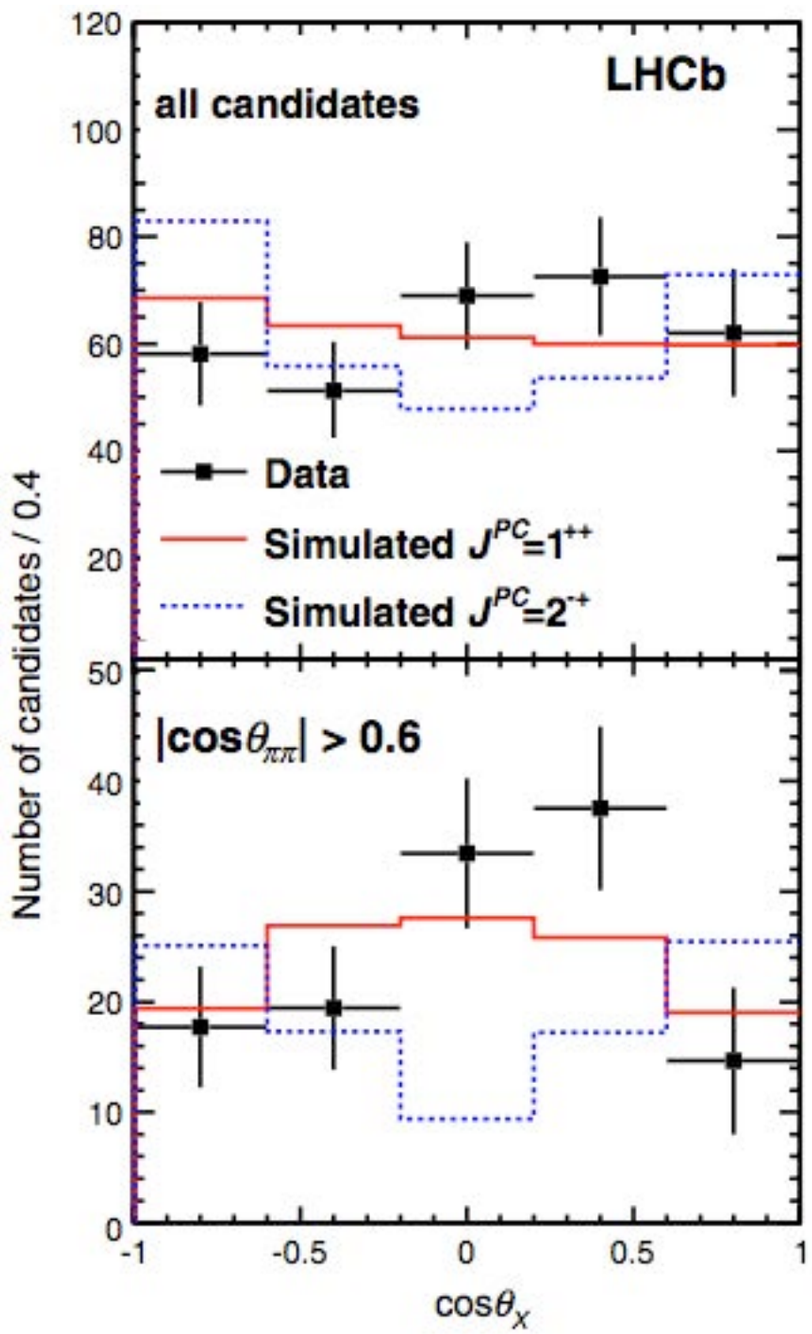


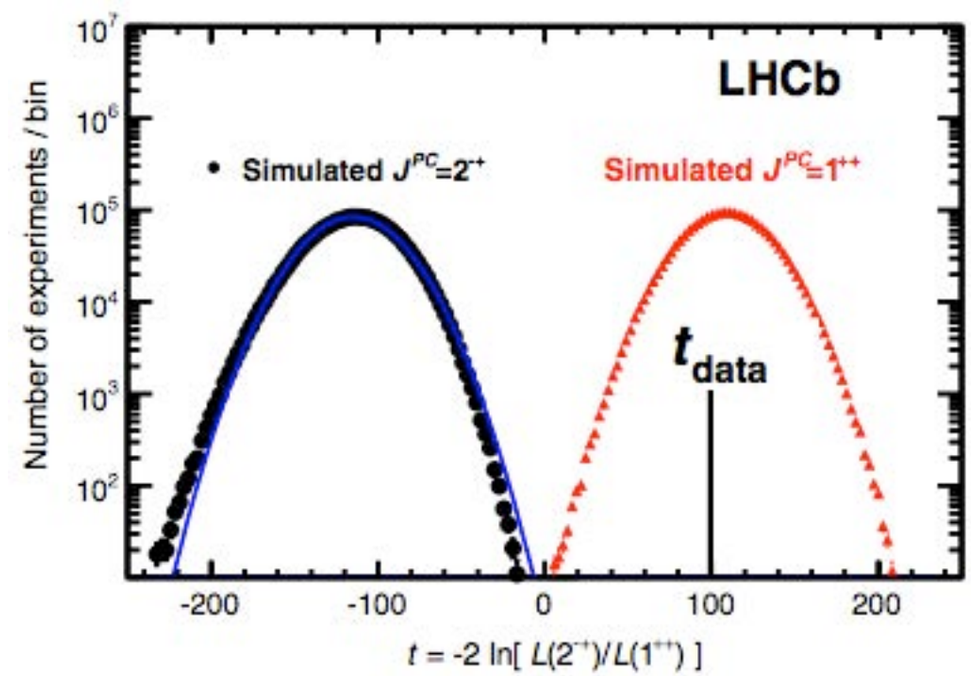


EPJC 72, 1972 (2012)

Observed decay X(3872) → γJ/ψ: ⇒ C=+

2013: LHCb

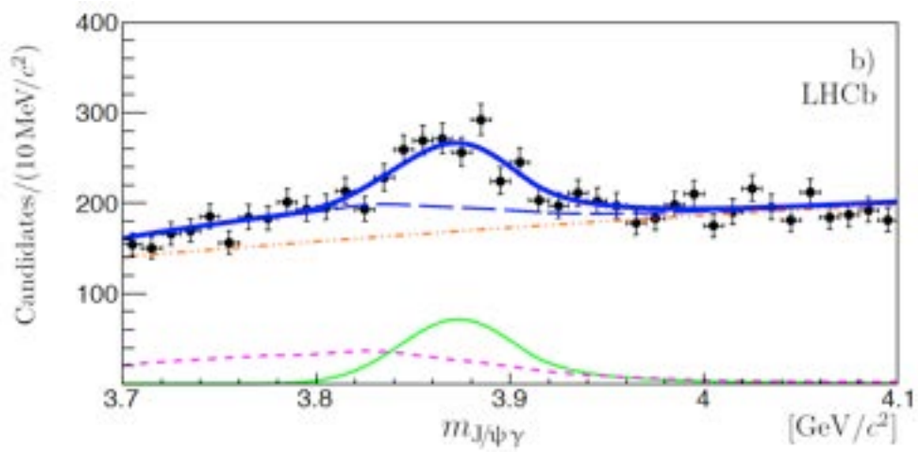


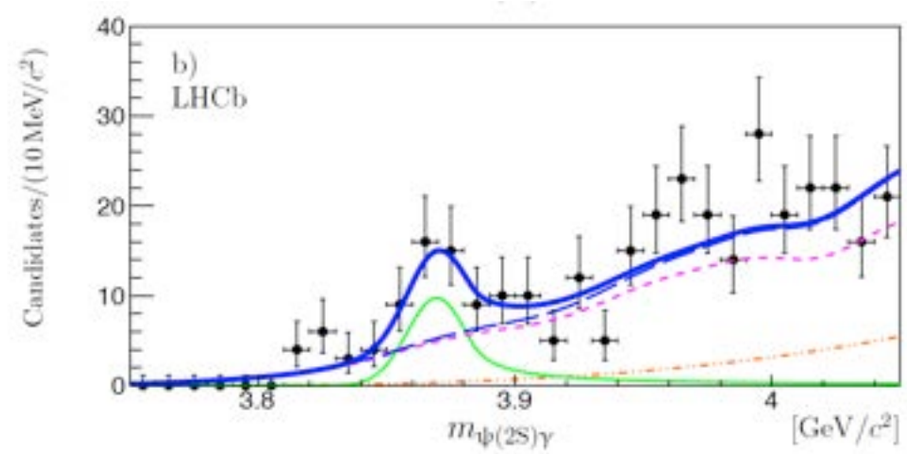


PRL 110 (2013) 222001

$J^{PC} = 1^{++}$ compatible
$J^{PC} = 2^{-+}$ rejected >8σ

What is the nature of the X(3872)?





arXiv:1404.0275 (2014)

$$R_{\gamma\psi} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

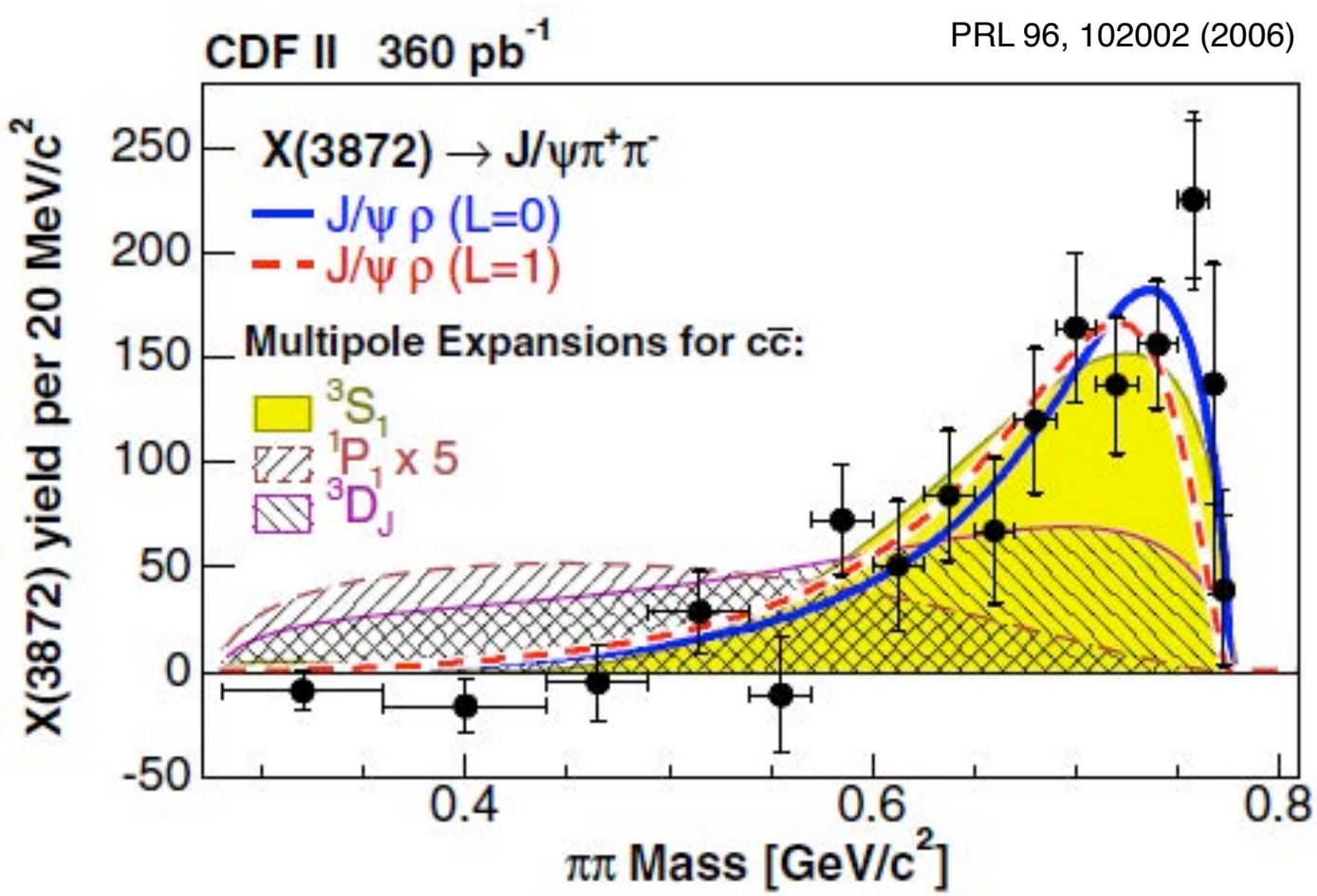
This agrees more with models favoring a charmonium state or a mixture of a charmonium/molecular state solutions than with a pure molecular interpretation.

... but still likely to be exotic:

Di-pion mass is dominated by the $\rho(770) \Rightarrow I=1$
BELLE and BaBar see decay $X(3872 \rightarrow J/\psi\omega$

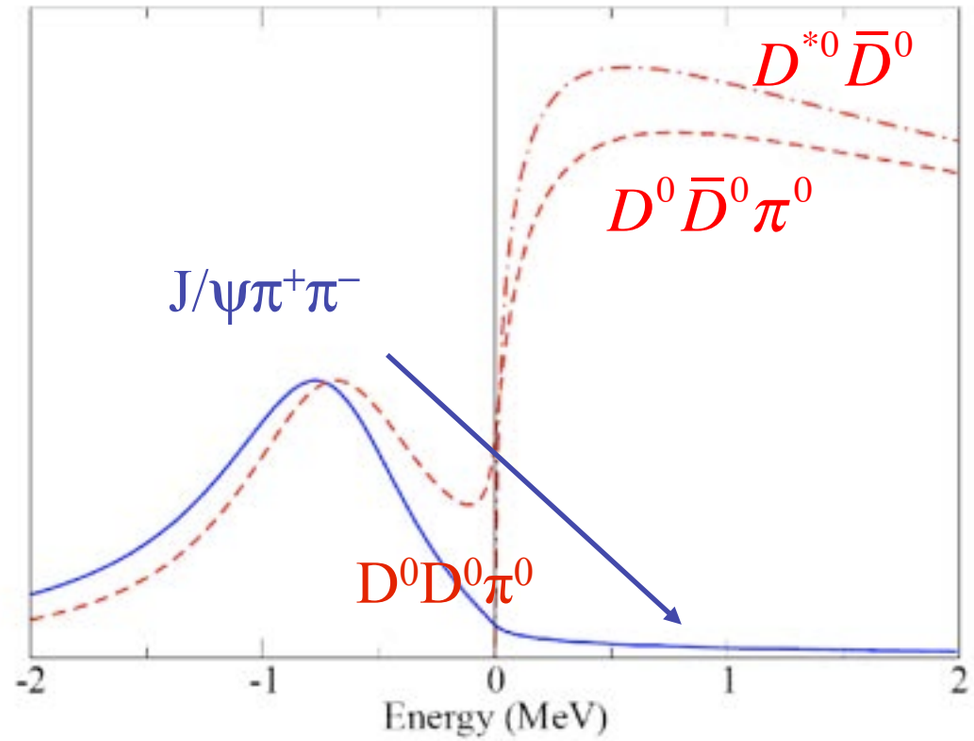
} Ratio ~ 1 ☛ huge isospin violation

PRL 96, 102002 (2006)



How to progress further in the understanding of the new states?

It is important to determine the resonance curve precisely ...



The line shapes for virtual state and bound state are the same *above* threshold but differ dramatically *below* threshold.

Analysis of $J/\psi\,\pi^+\pi^-$ and $D^0\bar{D}^0\pi^0$ Decays of the $X(3872)$

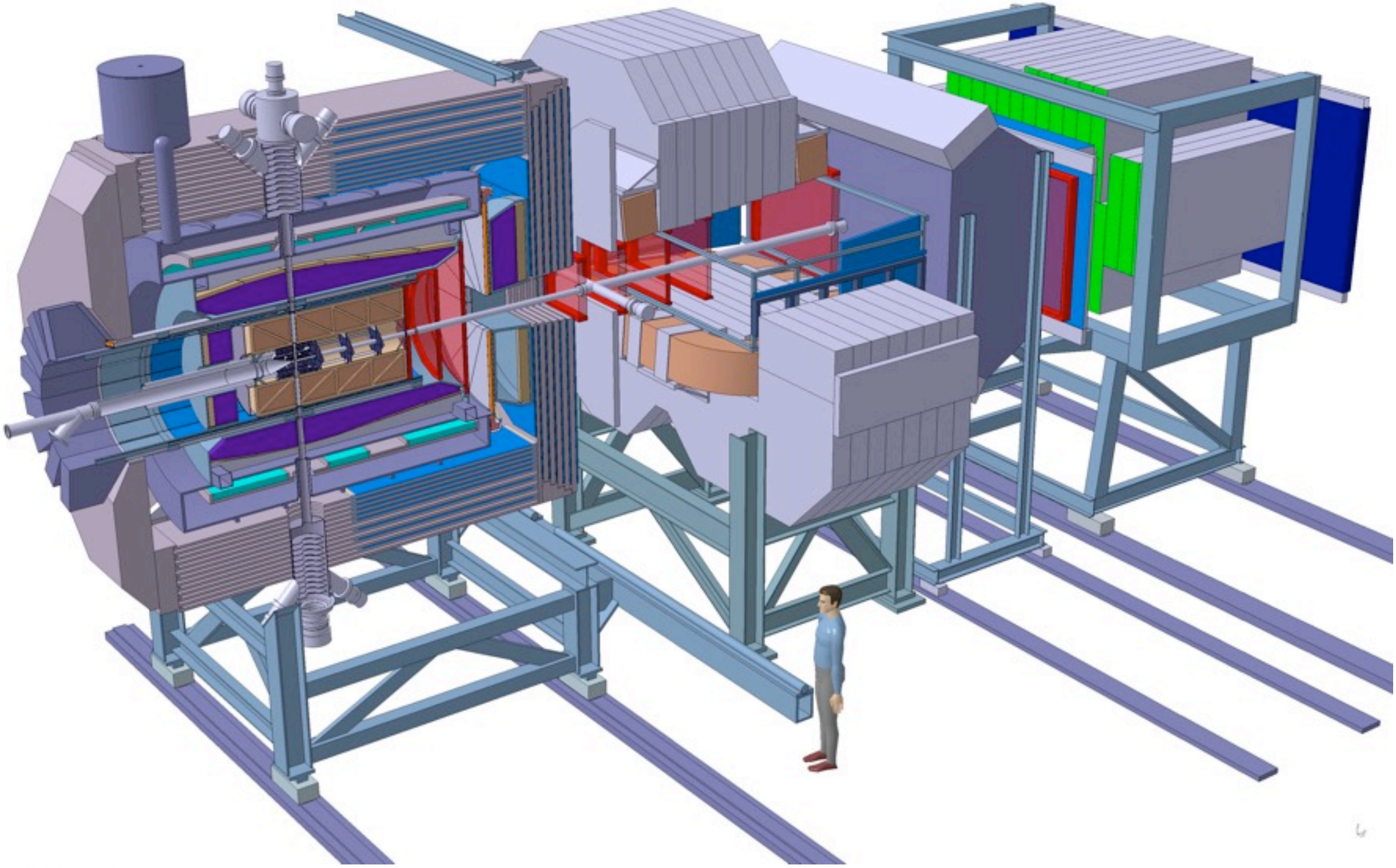
Eric Braaten and James Stapleton

Physics Department, Ohio State University, Columbus, Ohio 43210, USA

(Dated: July 17, 2009)

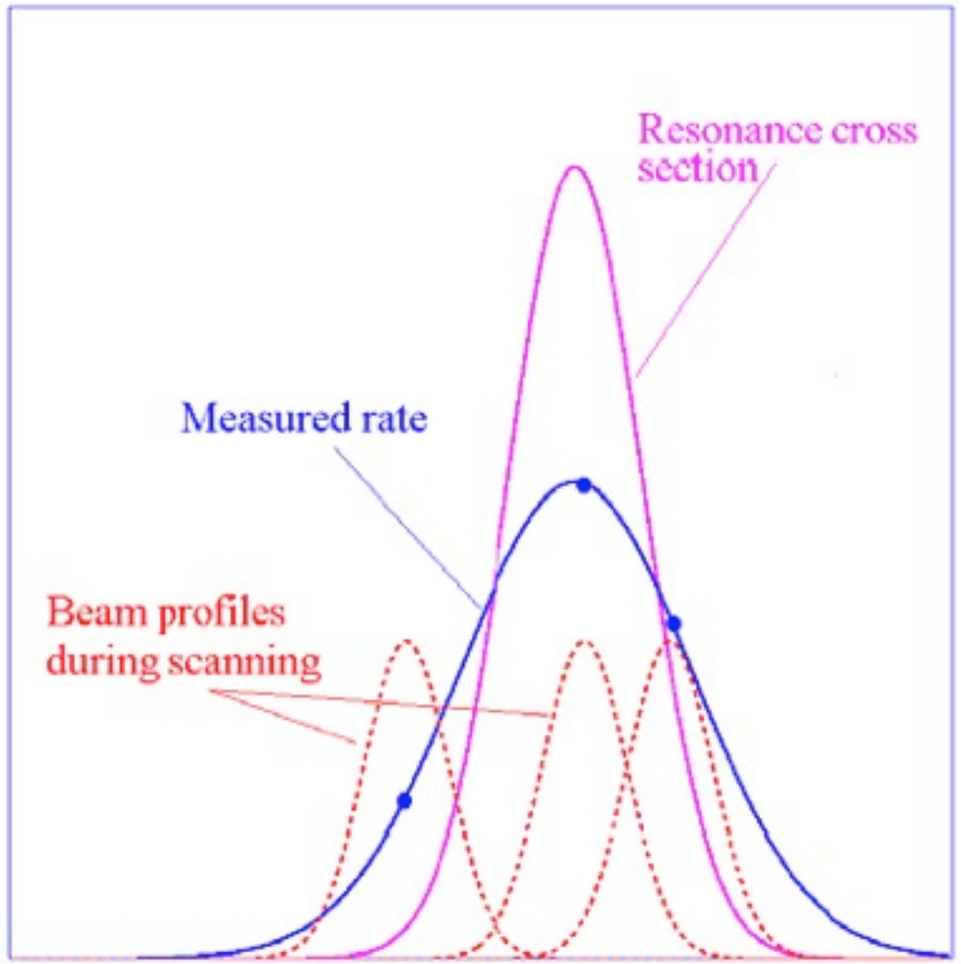
Phys.Rev. D81 (2010) 014019

The PANDA Detector



Resonance scan with varying $\bar{p}$ momentum at PANDA

(possible for states with all quantum numbers)

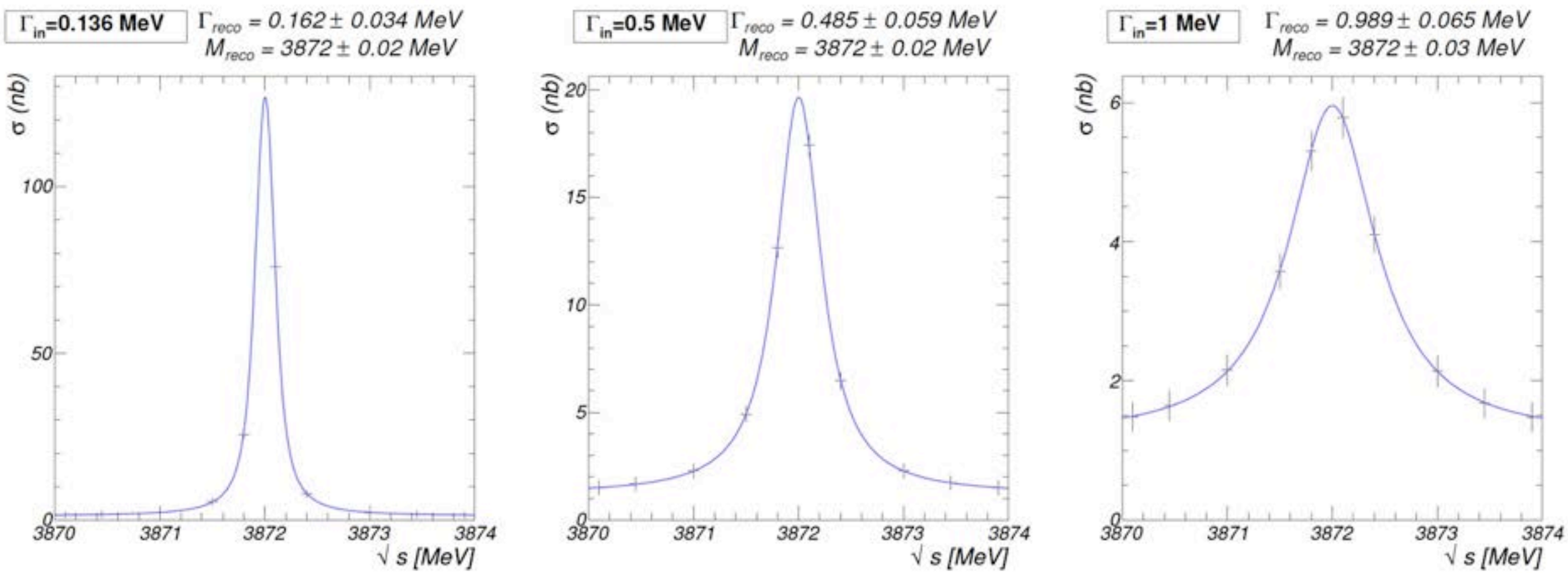


Measure rate of final state under study:

$$R_i = L_0 \bullet \sigma(p_i) \bullet K\,(\Delta p/p,\ |p_i - p_R|)$$

(K takes overlap between beam and resonance into account)

PANDA reconstruction of X(3872) mass and width



BELLE II:

An advanced width determination using measured masses, the beam energy and momentum of the B allowed BELLE to reduce the width determination from originally <2.4 GeV to <1.2 GeV in a 3-dimensional fit (Phys. Rev. D84(2011)052004).

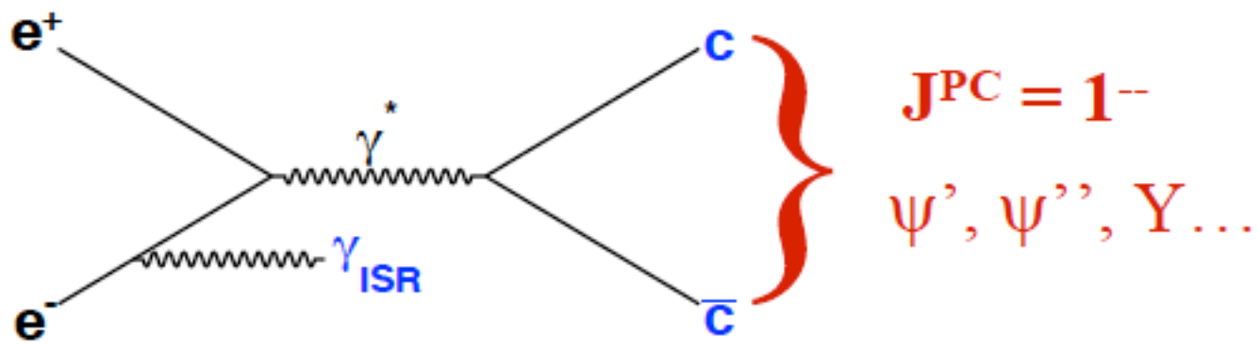
With the higher statistics (350 events expected for the X(3872) in 2020) in BELLE II Γ<110 keV might be achievable (S. Lange - FAIR conference Worms 2014).

A precise determination of the resonance curve form is not possible in BELLE.

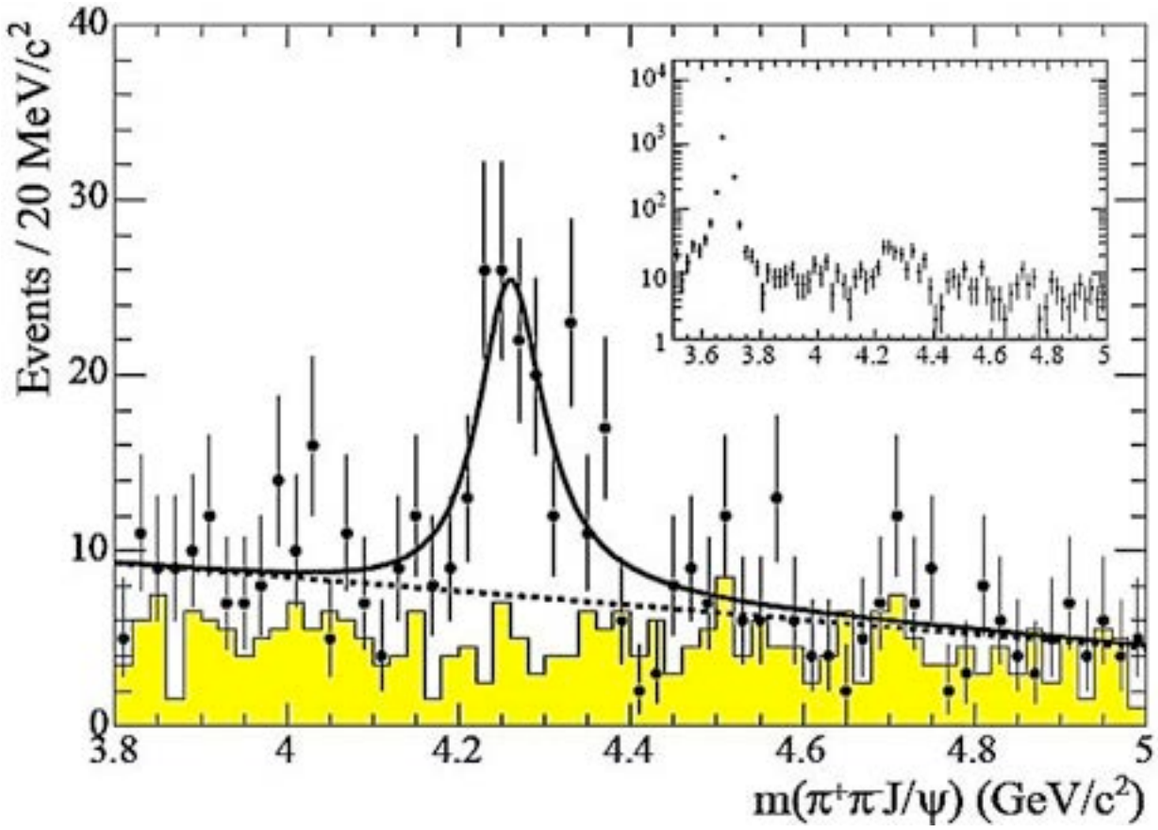
The Y story

Ulrich Wiedner

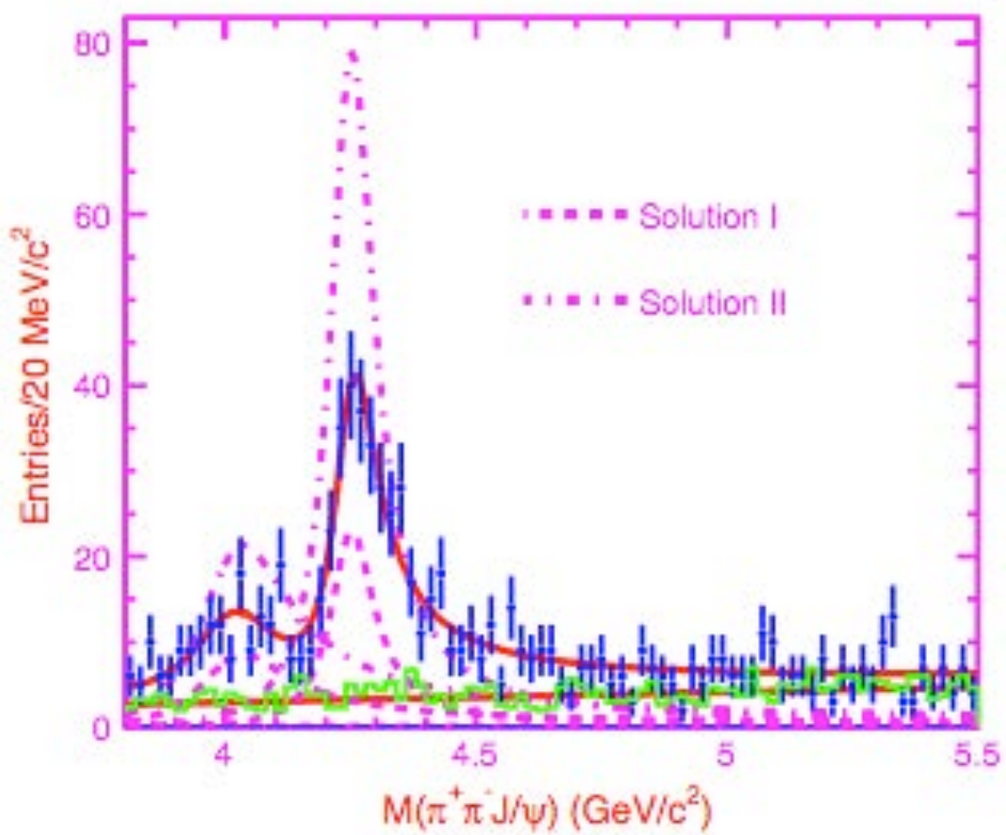
Using ISR (Initial State Radiation) to find states:



BaBar (initial results)

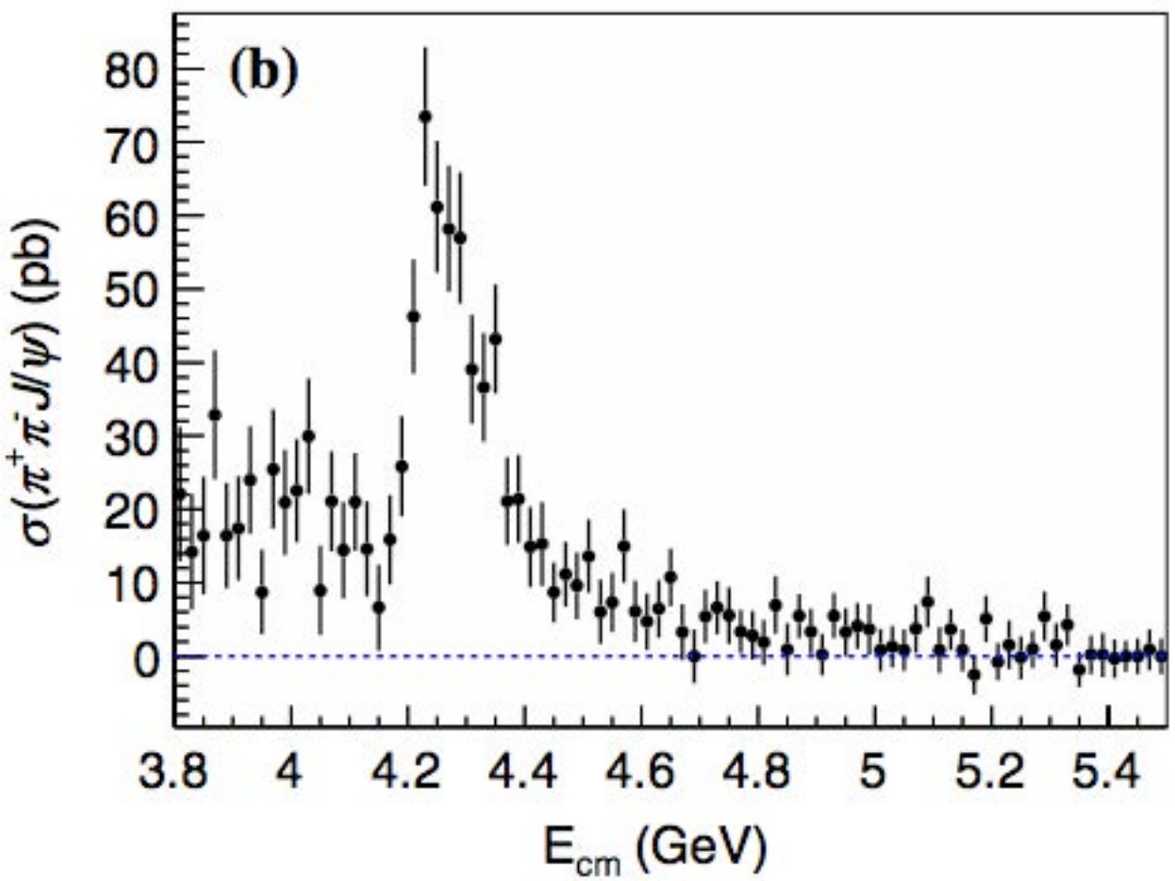


BELLE (initial results)

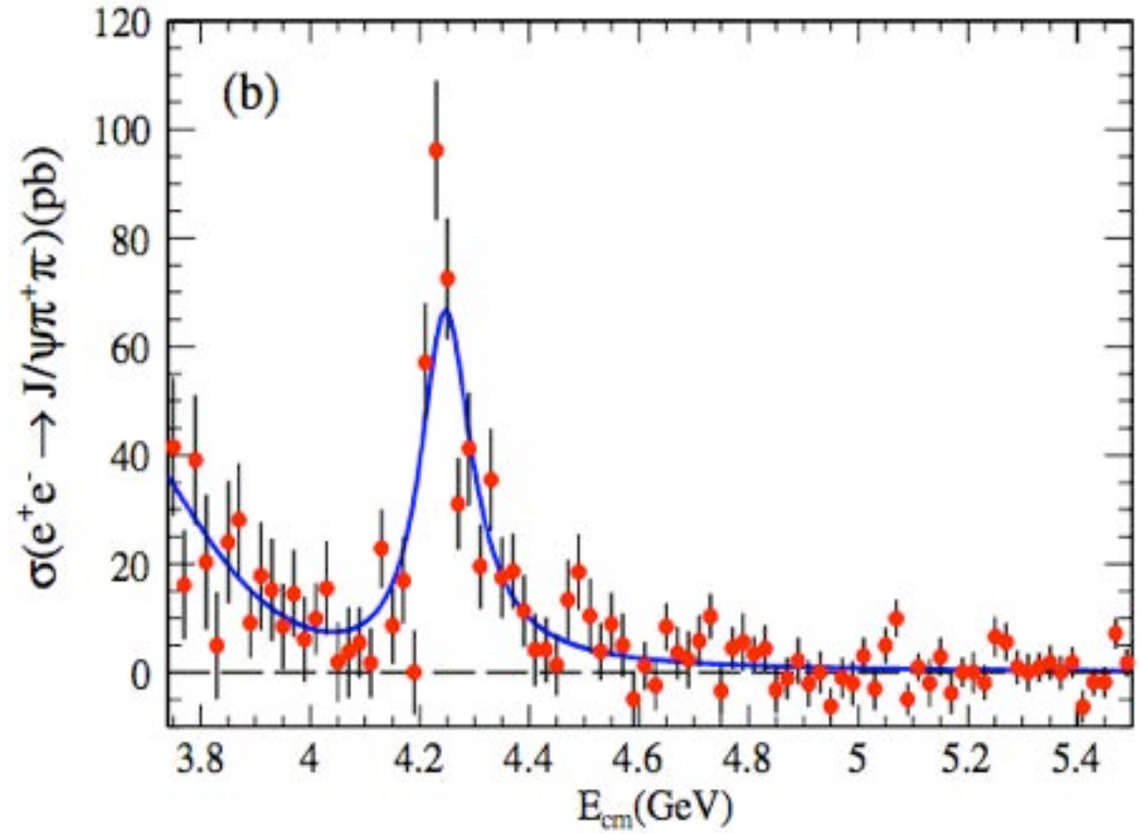


The respective cross sections:

BELLE: PRL110, 252002 (2013).



BaBar: PRD86, 051102 (2013).

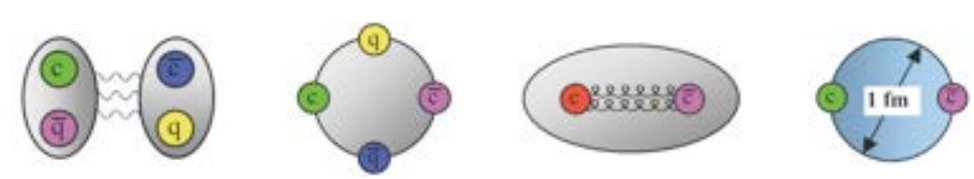


Y(4260): $M \approx 4260$ MeV, $\Gamma \approx 100$ MeV

Conventional wisdom and potential models: charmonia above threshold decay to open charm

$\psi(4040)$, $\psi(4160)$, $\psi(4415)$

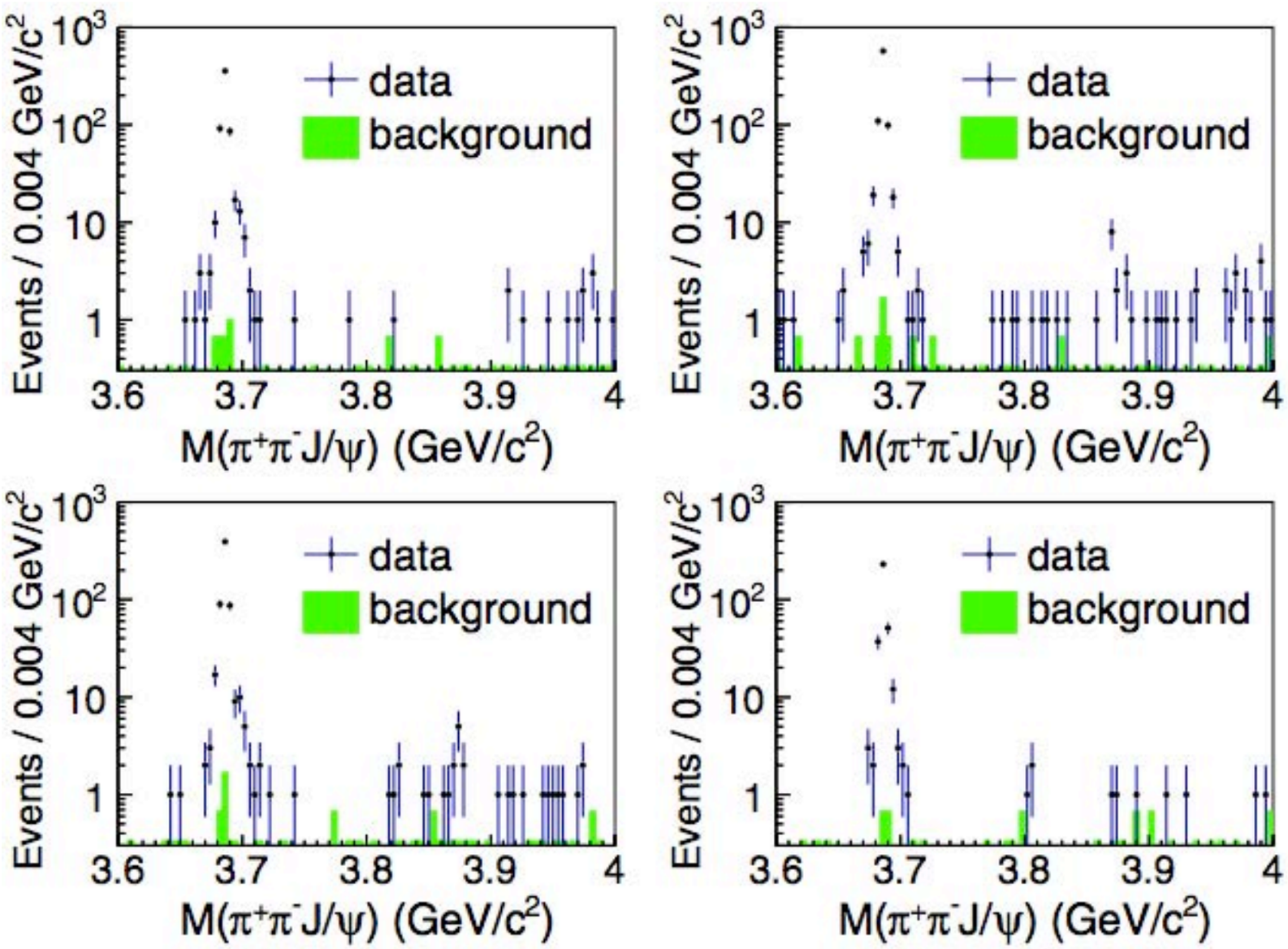
The Y(4260) has a large decay width to $\pi^+\pi^-$ J/ψ



Are there connections between X and Y particles?

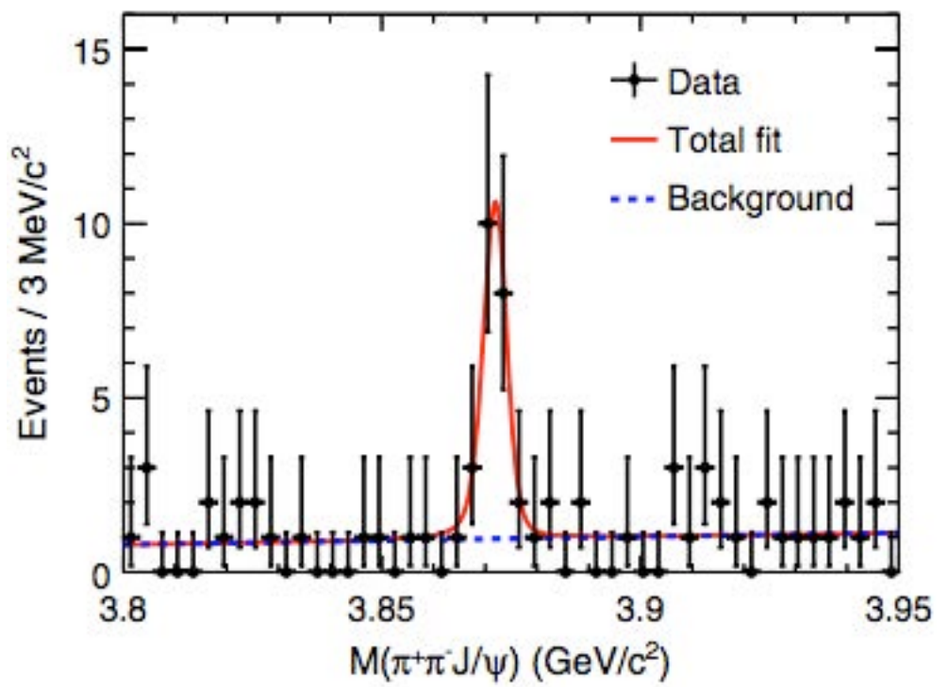
BESIII

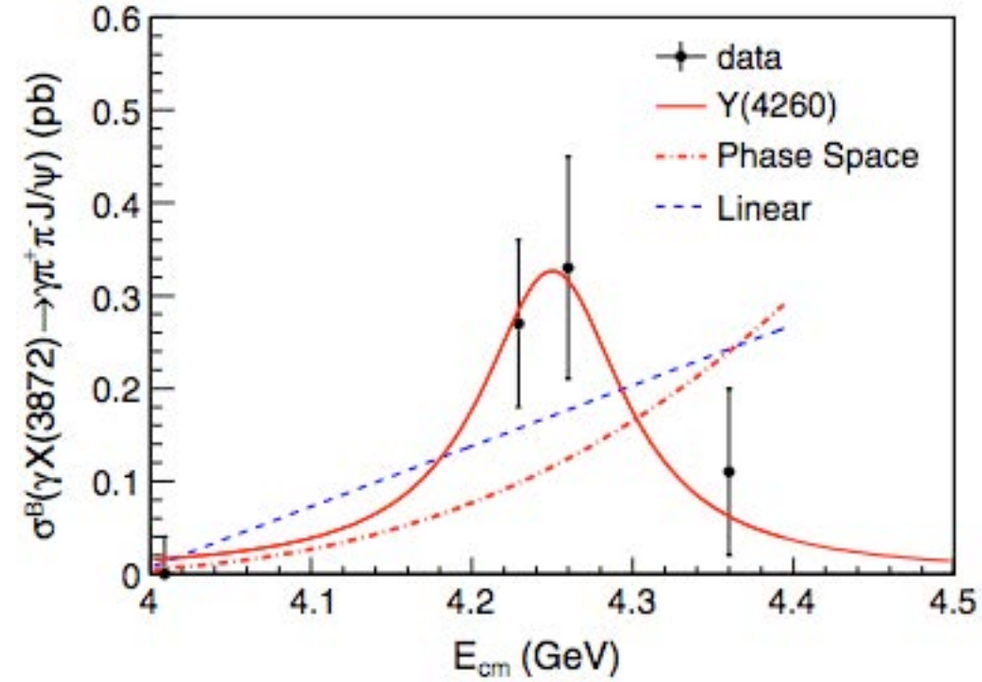
$e^+e^- \to \gamma\pi^+\pi^- J/\psi$



Observation of the X(3872) in the radiative decay of the Y(4260)

BESIII: PRL112, 092001 (2014).





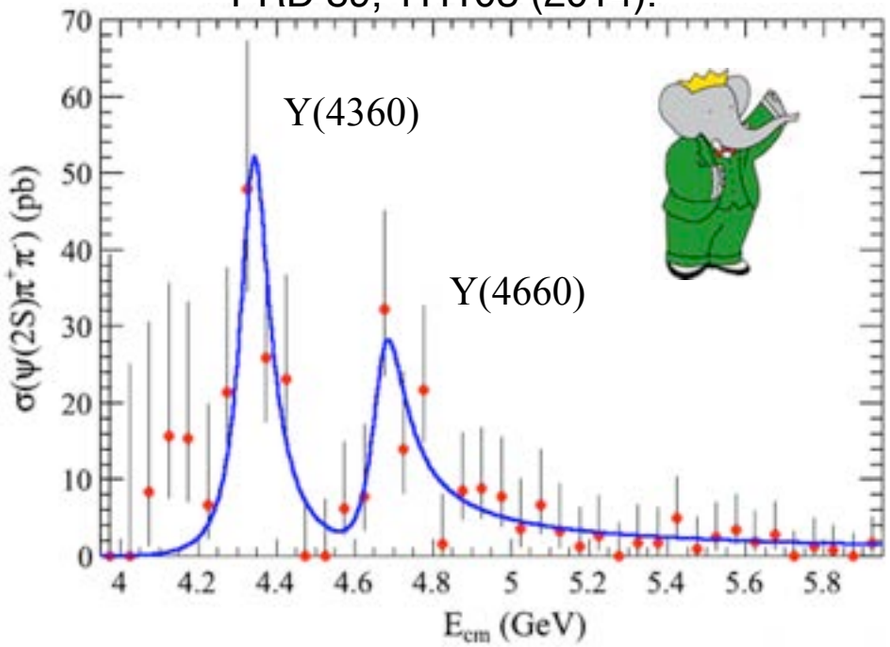
M = 3871.9 ± 0.7 MeV
Γ < 2.4 MeV @ 90% C.L.
Significance: 6.3 σ

Fit incl. the resonance,
an E1-transition phase space
and a linear background

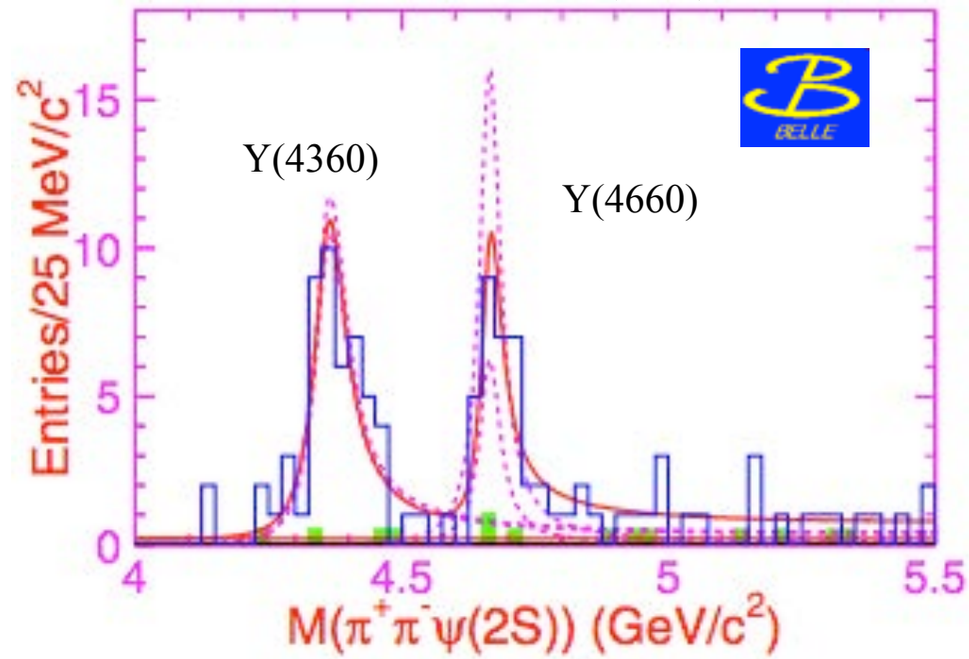
What does nature want to tell us?

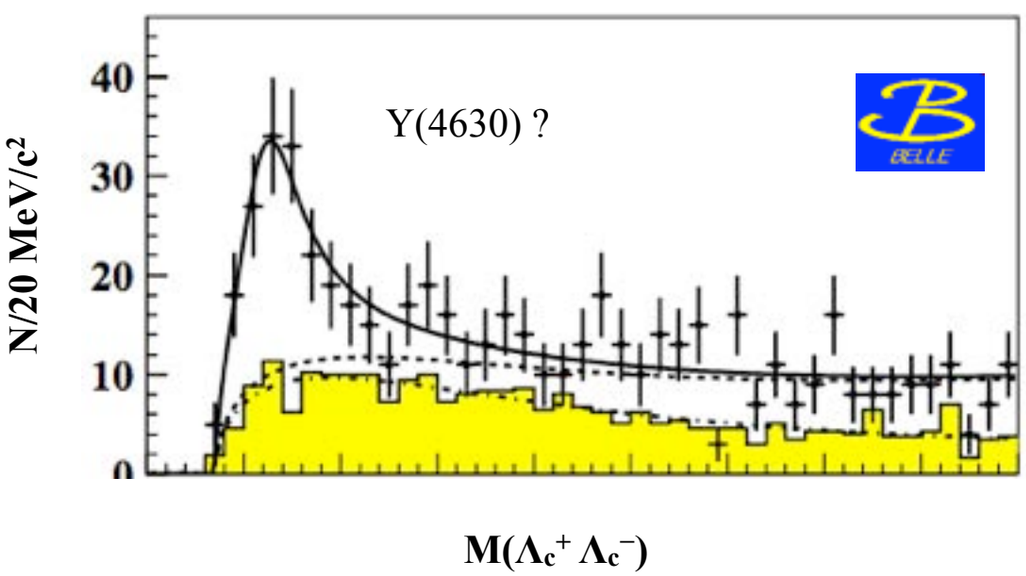
Additional members of the ISR Y family seen by BELLE and BaBar:

PRD 89, 111103 (2014).

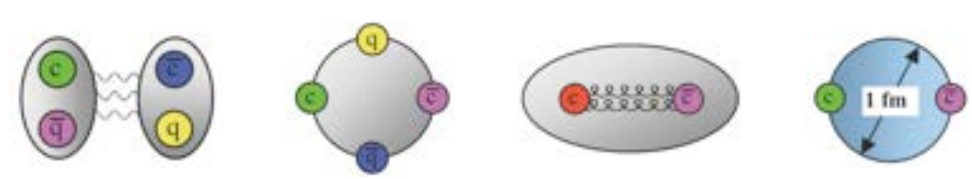


PRL 99, 142002 (2007).



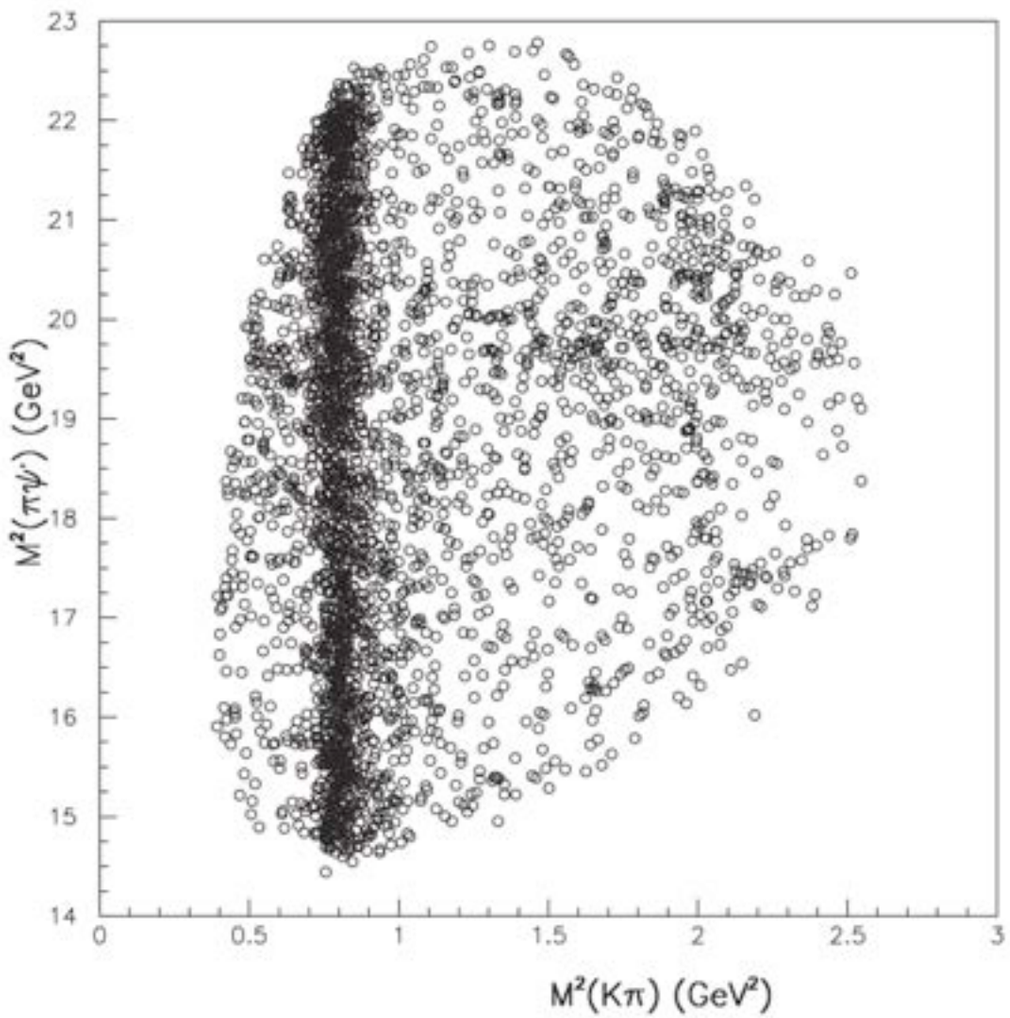


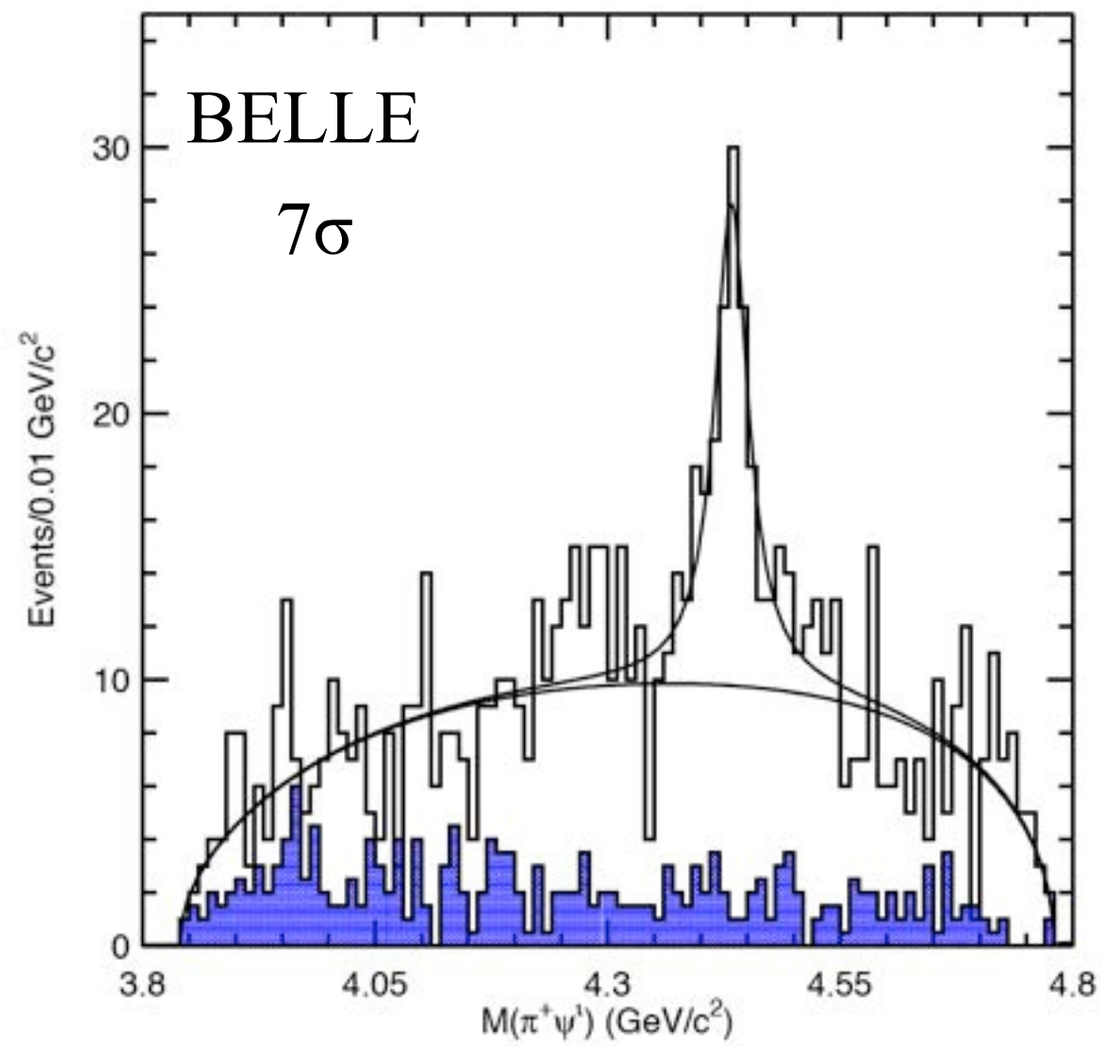
All states have $J^{PC} = 1^{--}$
Nature ???



The first obvious exotic: Z(4430)

Z^+ (4430) - a new state of matter (tetraquark) decaying into $\pi^+\psi'$





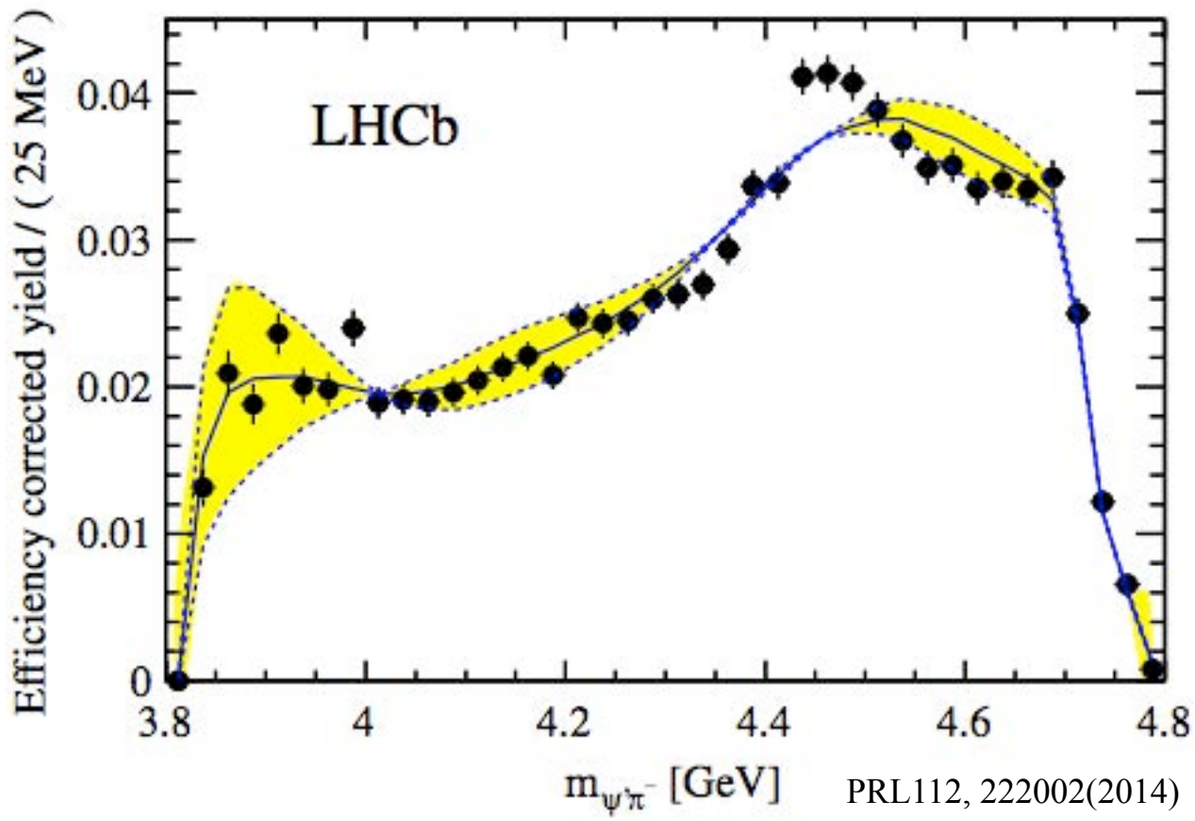
$$M = (4.433 \pm 0.004\ (\text{stat}) \pm 0.001\ (\text{syst}))\ \text{GeV}$$

$$\Gamma = (0.044^{+0.017}_{-0.011}(\text{stat})^{+0.030}_{-0.011}(\text{syst}))\ \text{GeV}$$

$$\mathcal{B}(B \to KZ(4430)) \times \mathcal{B}(Z \to \pi^+\psi') = (4.1 \pm 1.0\ (stat) \pm 1.3\ (syst)) \times 10^{-5}$$

PRL 100, 142001 (2008)
arXiv:0708.1790 [hep-ex]

Confirmation by LHCb



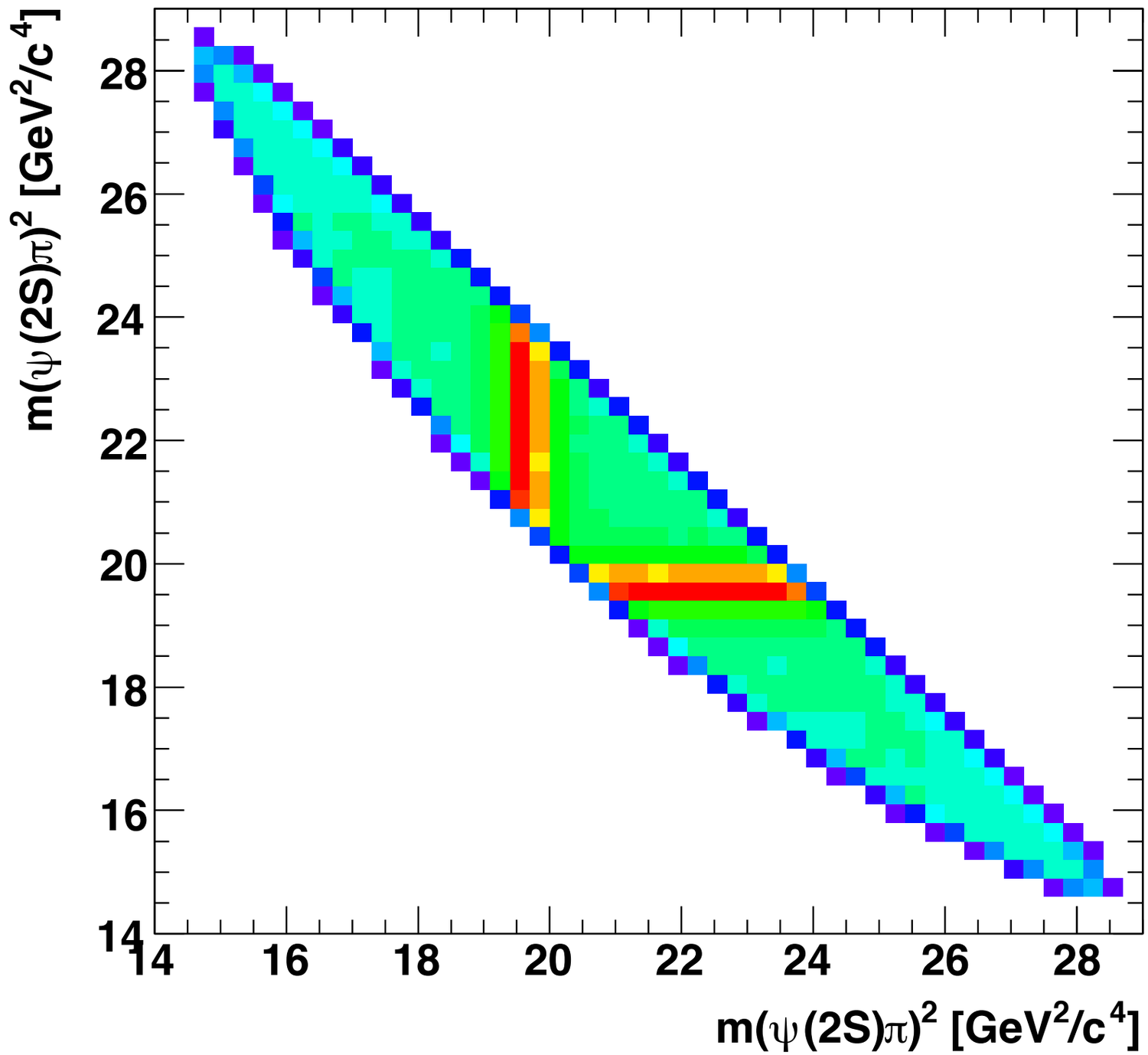
PRL112, 222002(2014)

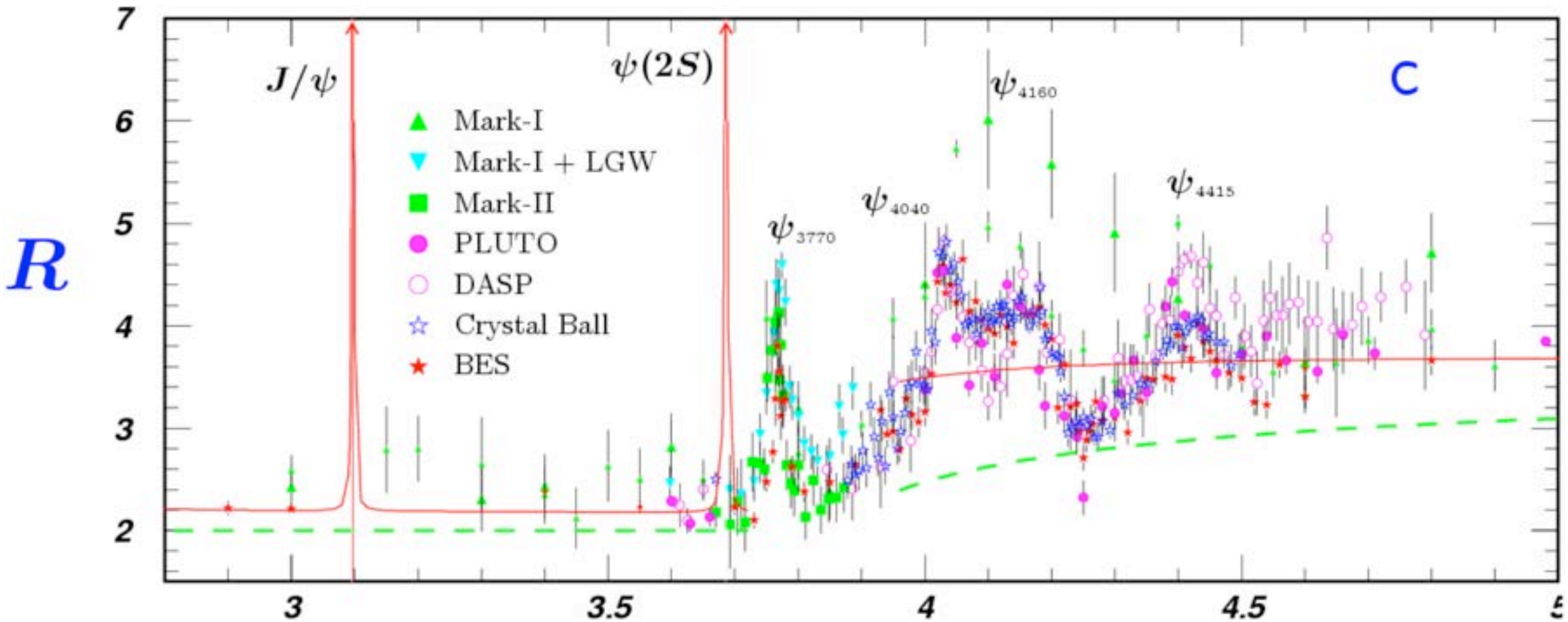
$$M = 4475 \pm 7^{+15}_{-25} \text{ MeV}$$

$$\Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV}$$

Significance: $>13.9\sigma$

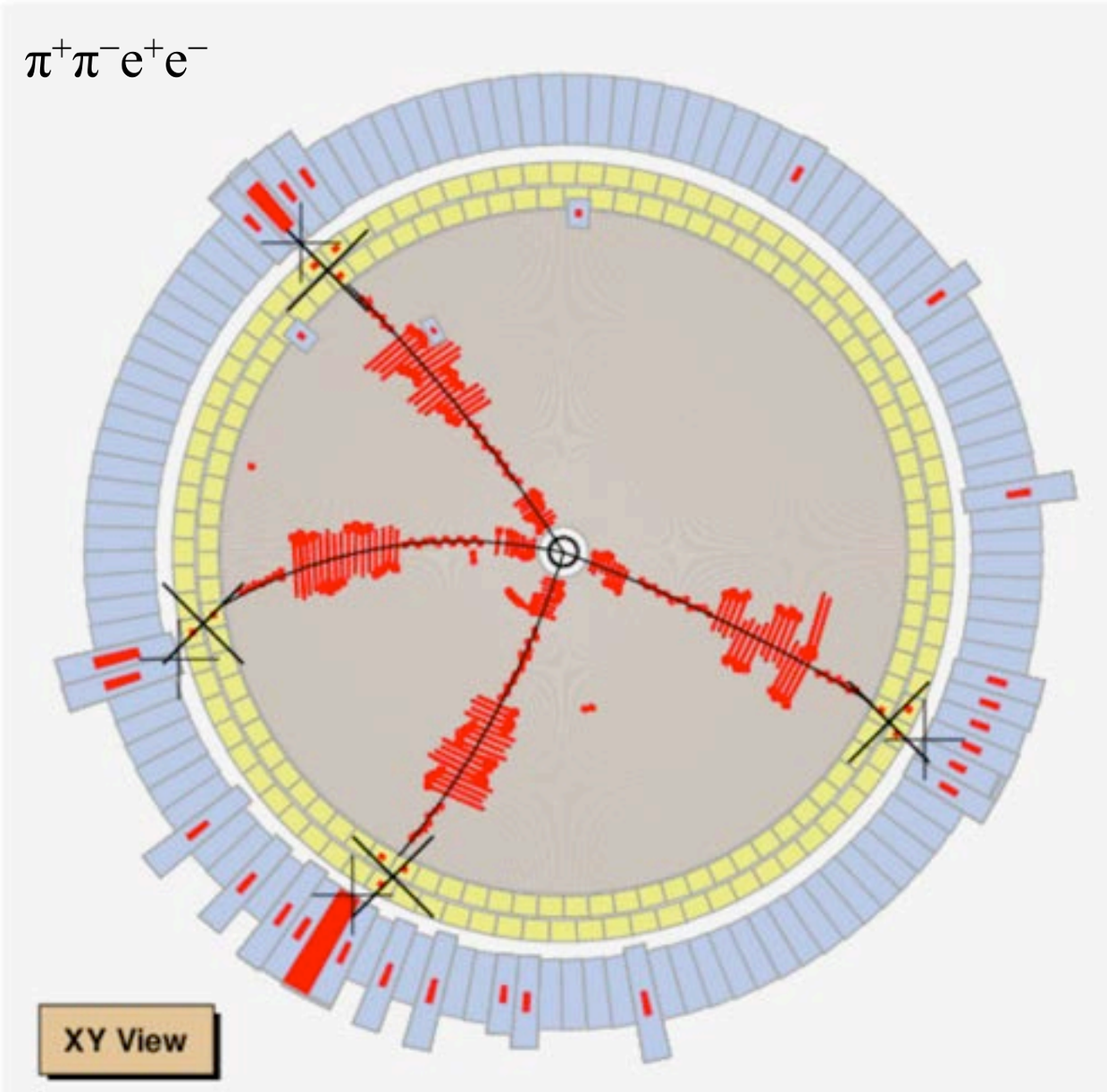
PANDA: $\bar{p}p \rightarrow Z^{+}(4430) + \pi^{-}$

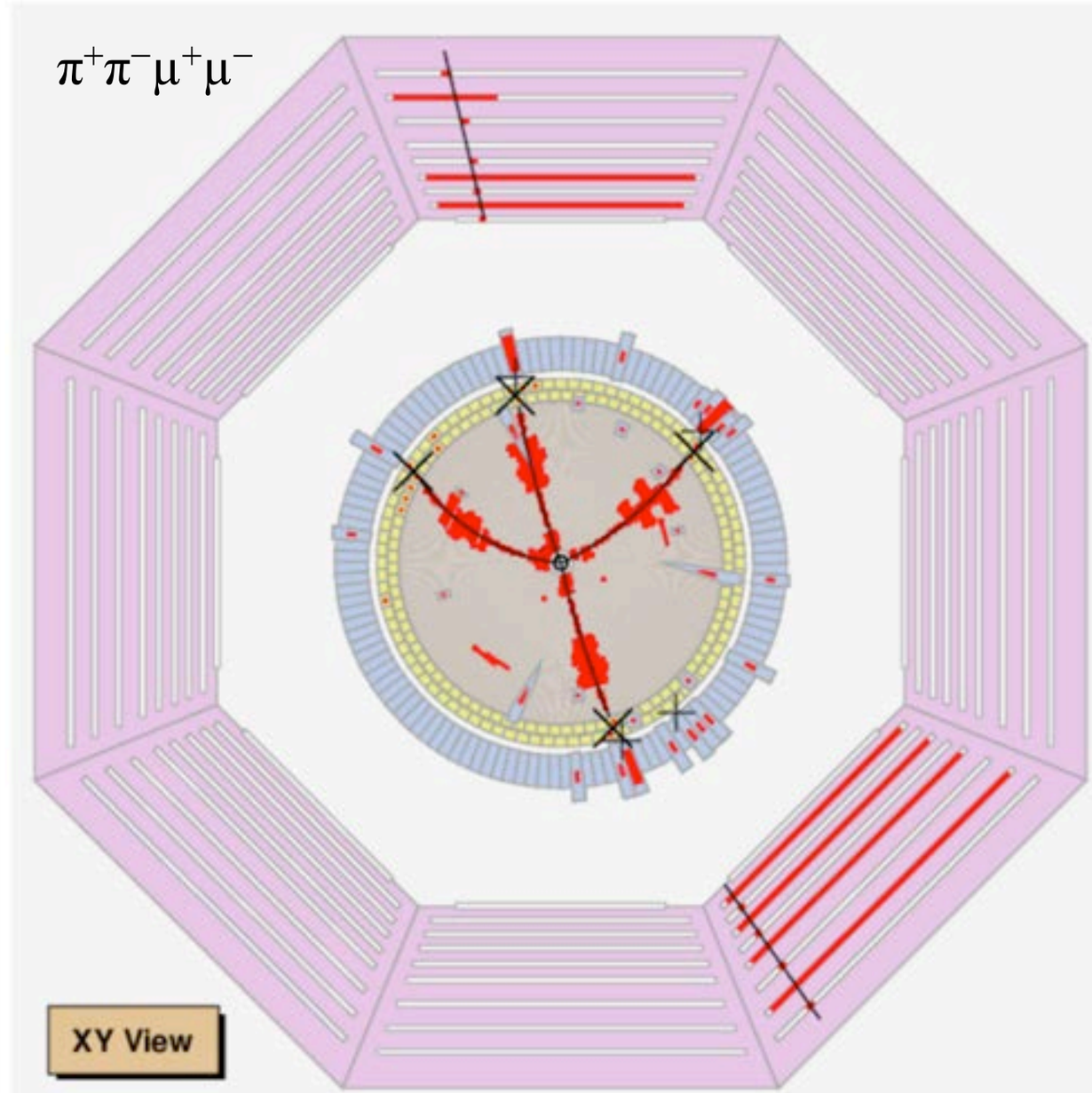




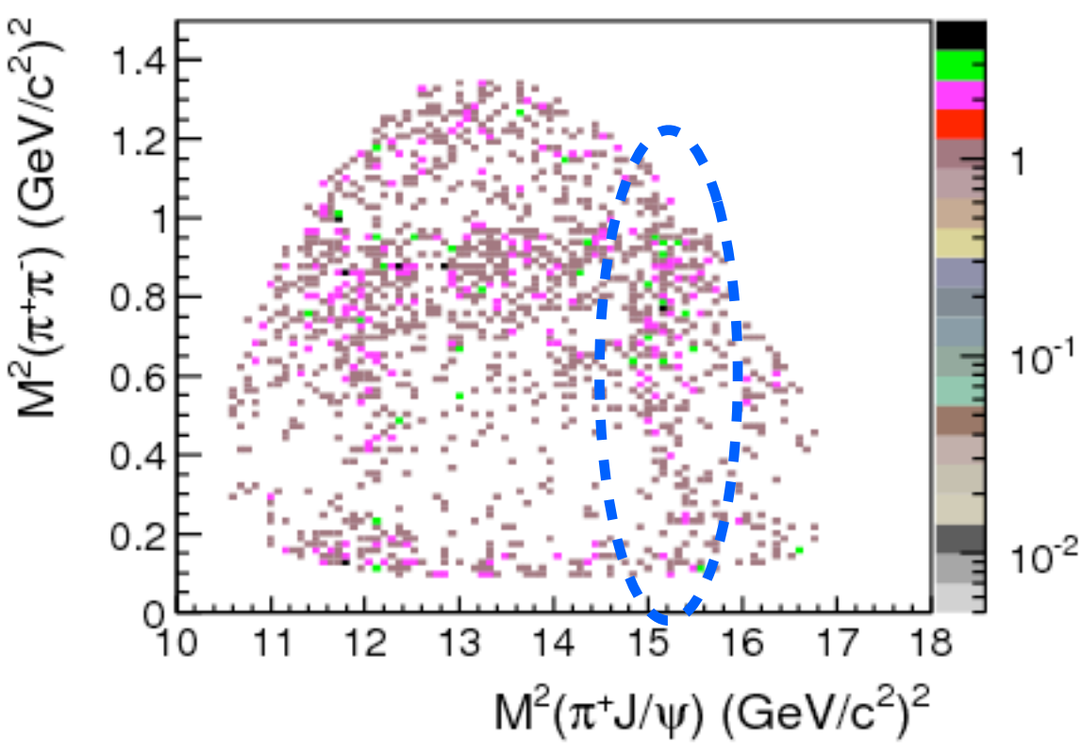
$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})
3.900	52.8
4.009	482.0
4.090	51.0
4.190	43.0
4.210	54.7
4.220	54.6
4.230	1090.0
4.245	56.0
4.260	826.8
4.310	44.9
4.360	544.5
4.390	55.1
4.420	44.7

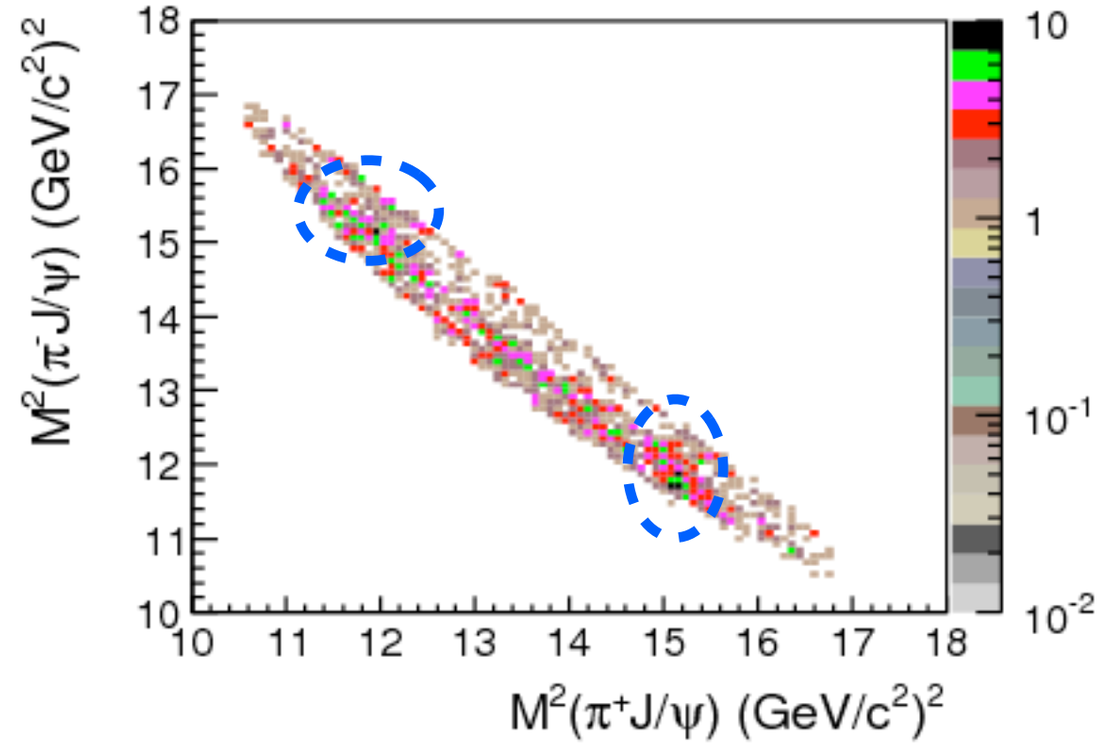
$Y(4260) \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^- e^+e^-$ ($\pi^+\pi^-\mu^+\mu^-$):
Straightforward analysis with 4 tracks

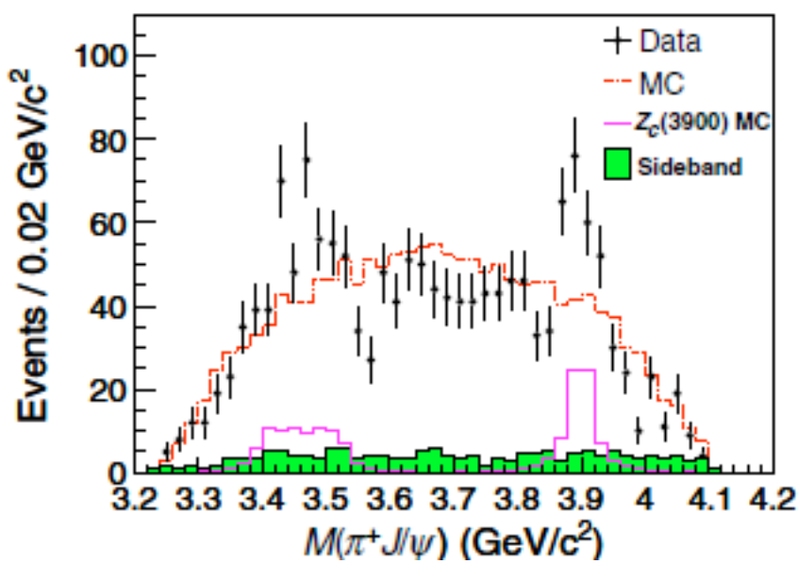


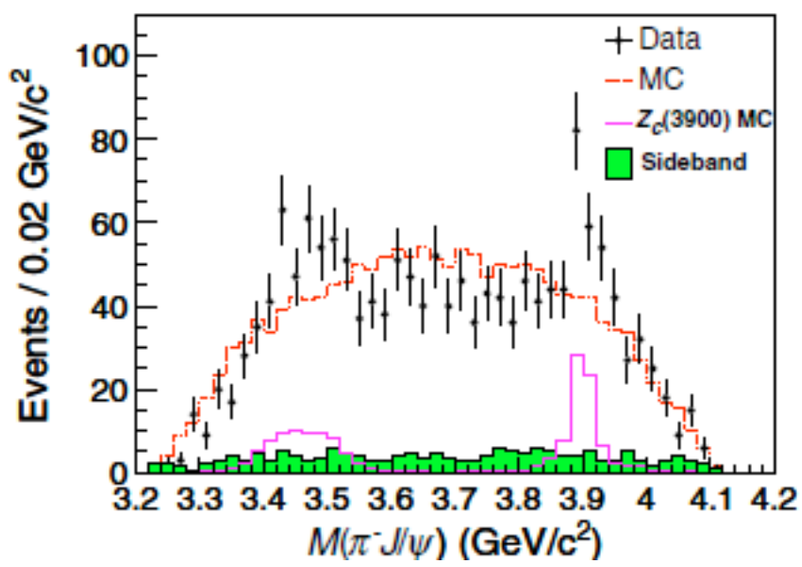


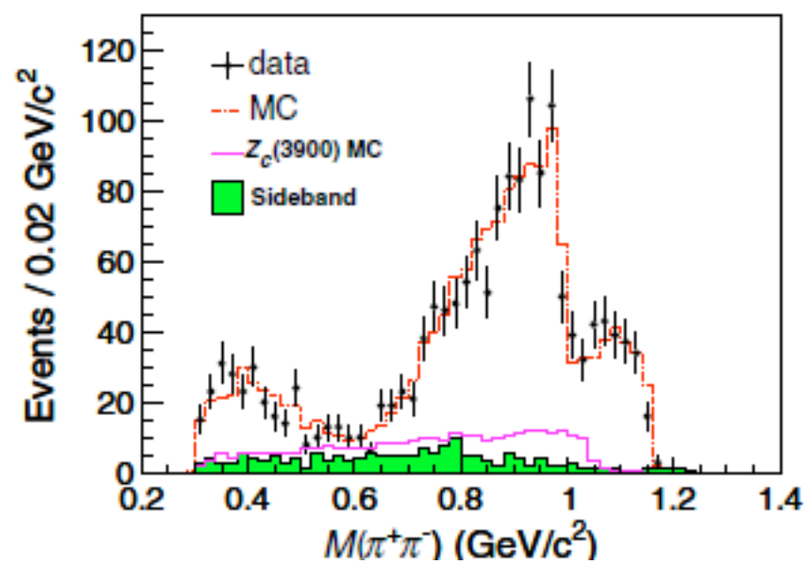
Observation of the $Z_c(3900)$ in BESIII



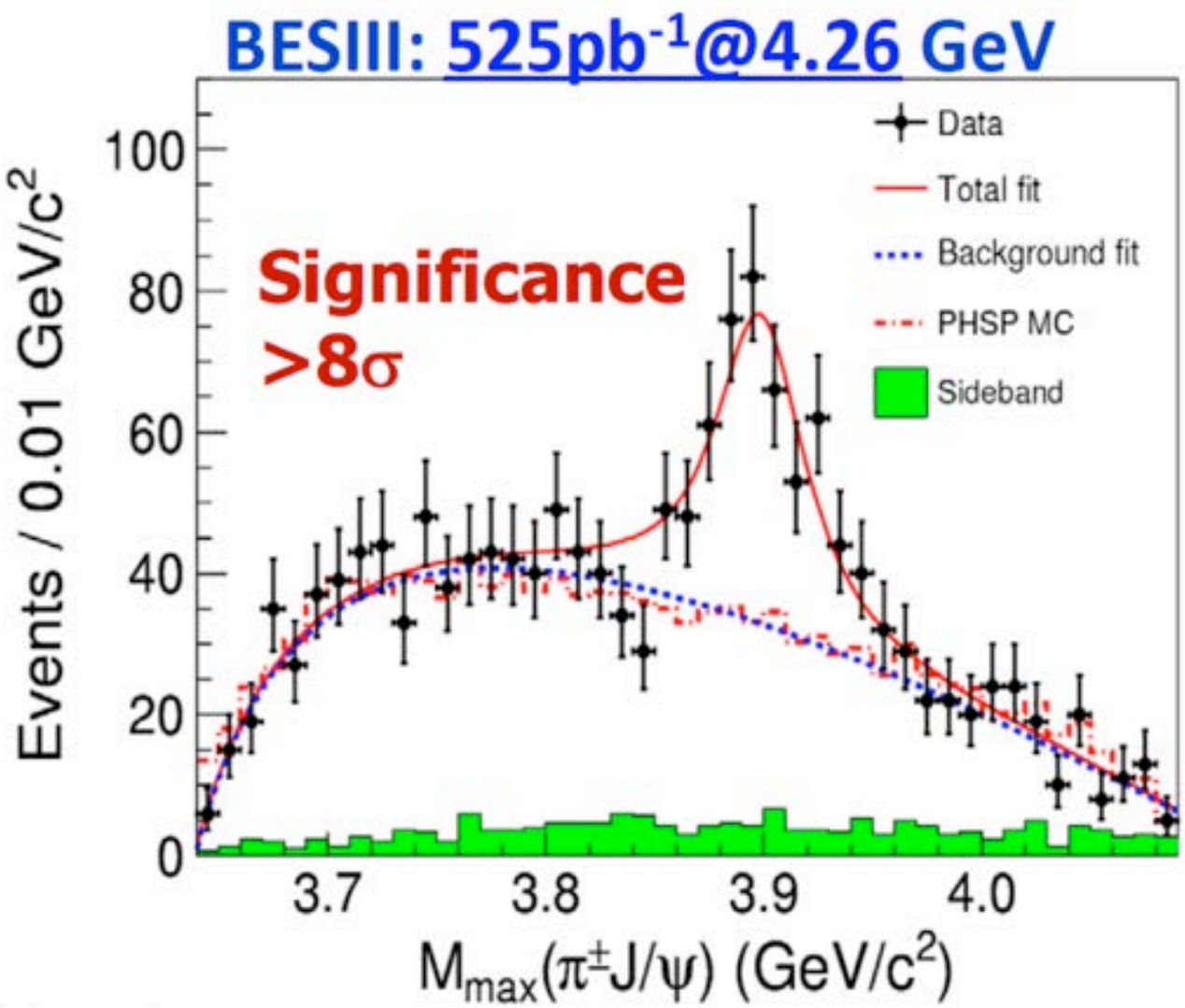








Observation of $Z_c(3900)$ at BESIII

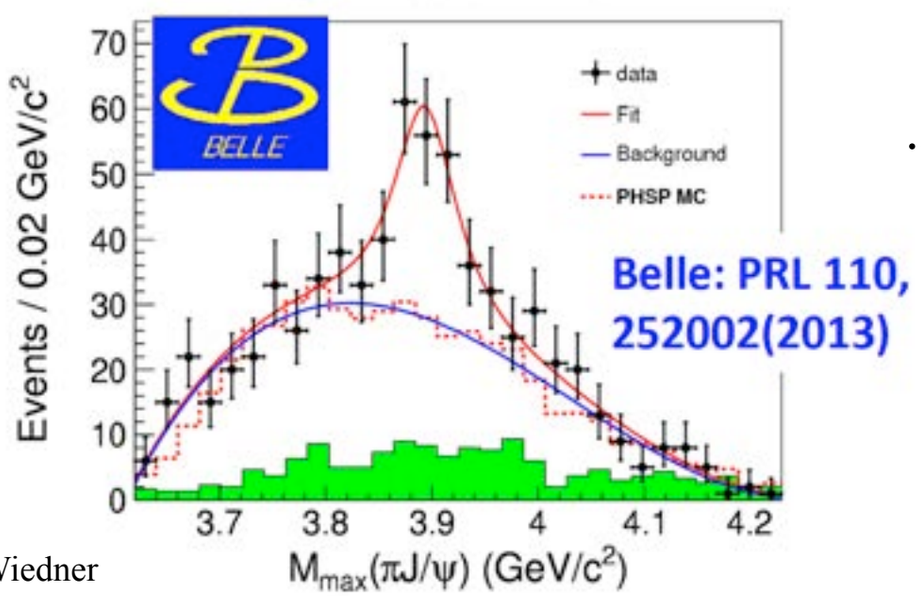


M = 3899.0±3.6±4.9 MeV

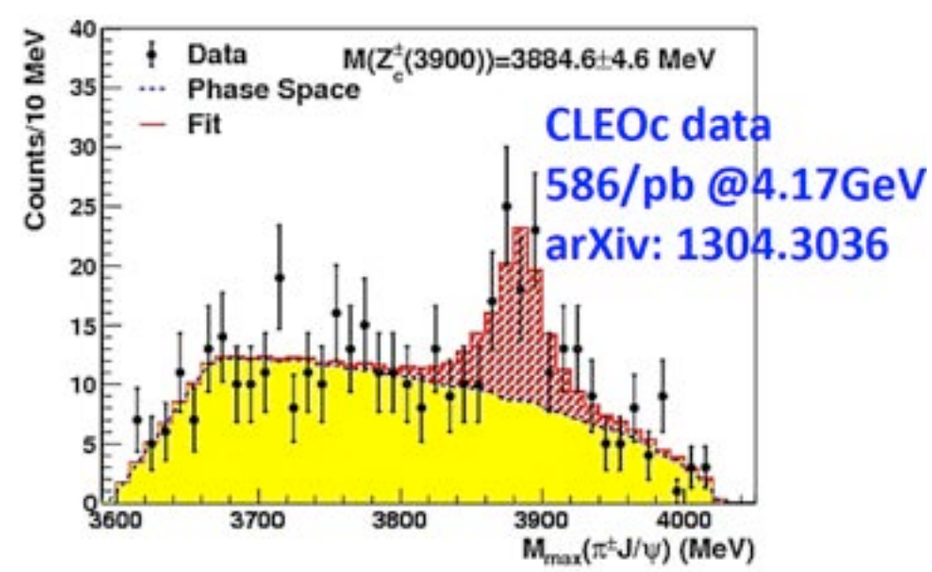
Γ = 46±10±20 MeV

307 ± 48 events

BESIII: PRL110, 252001 (2013)

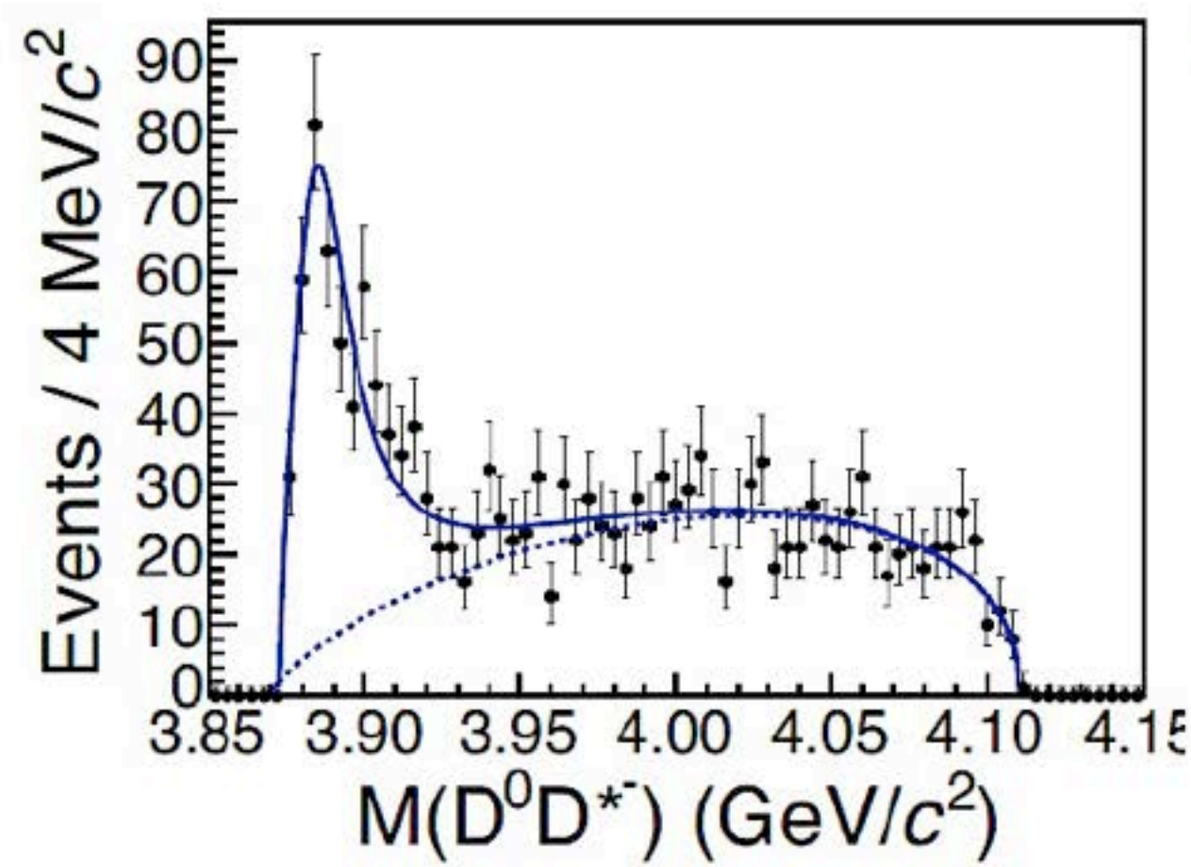


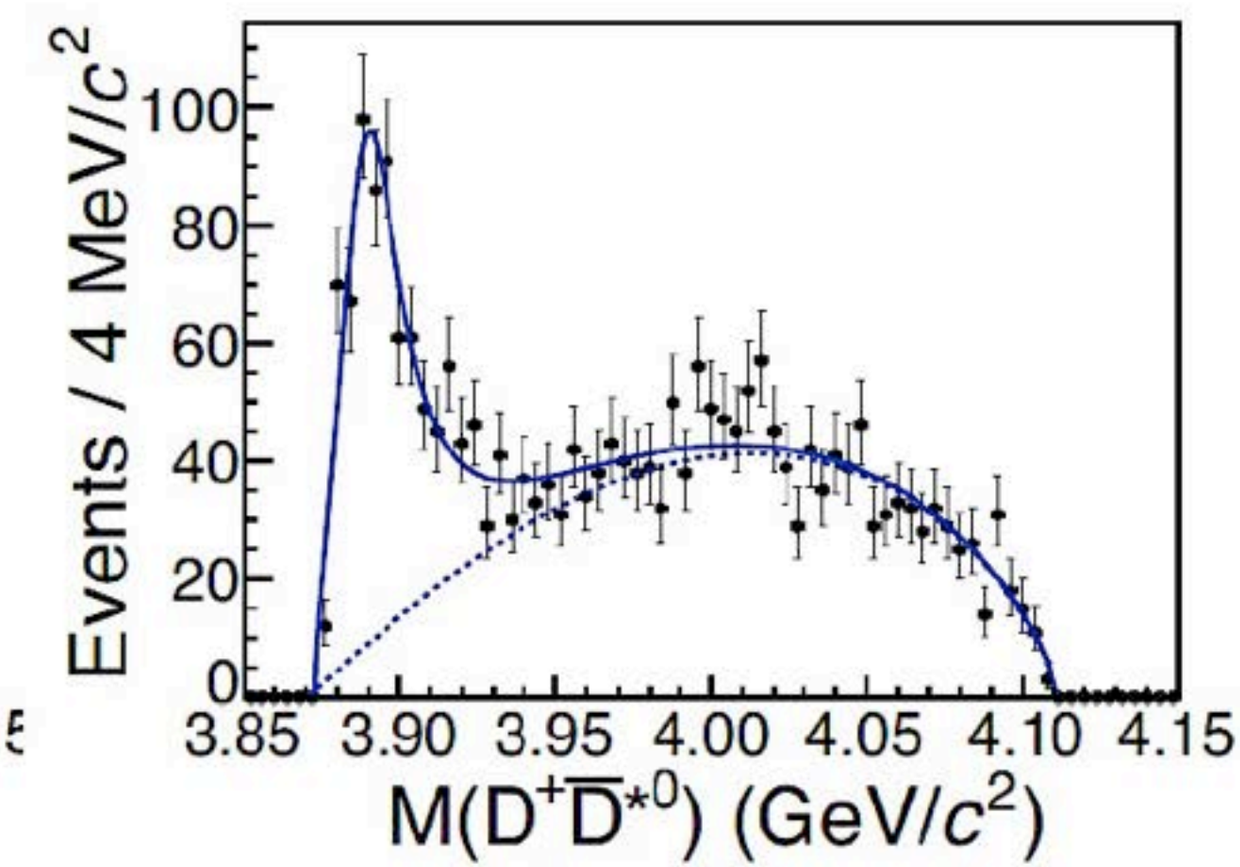
... quickly confirmed



Observation of $Z_c(3885)$ in $e^+e^- \to \pi^- (D^*D)^+$

525 pb-1 @ 4.260 GeV





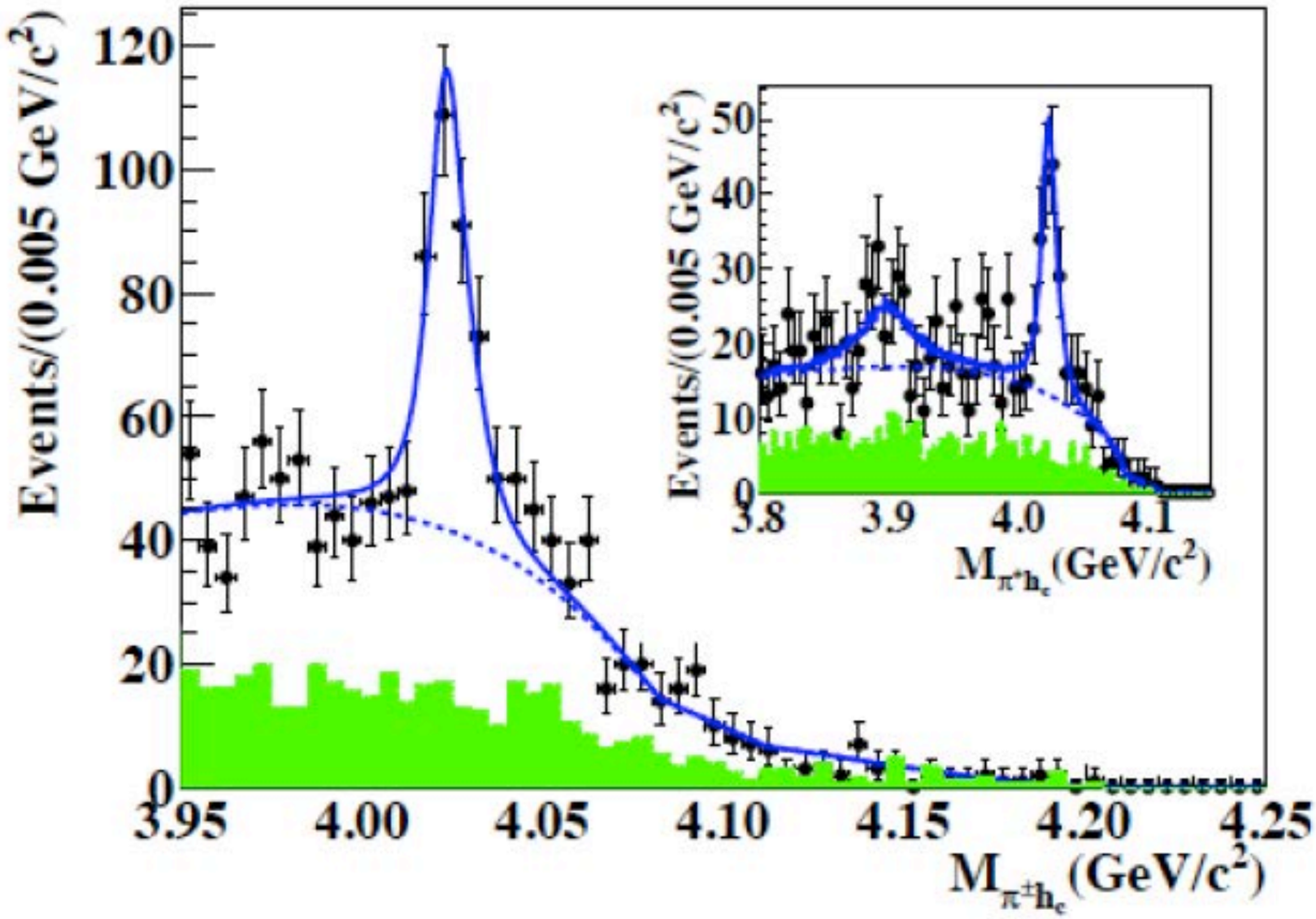
Phys. Rev. Lett 112, 022001 (2014) / 1310.1163

$M = 3883.9 \pm 1.5 \pm 4.2$ MeV; $\Gamma = 24.8 \pm 3.3 \pm 11.0$ MeV

$Z_c(3885) = Z_c(3900)$ but large yield of ~6 for $\dfrac{\Gamma(DD^*)}{\Gamma(\pi^\pm J/\psi)}$

$e^+e^- \to \pi Z_c(4020) \to \pi^+\pi^- h_c$

BESIII: 1309.1896

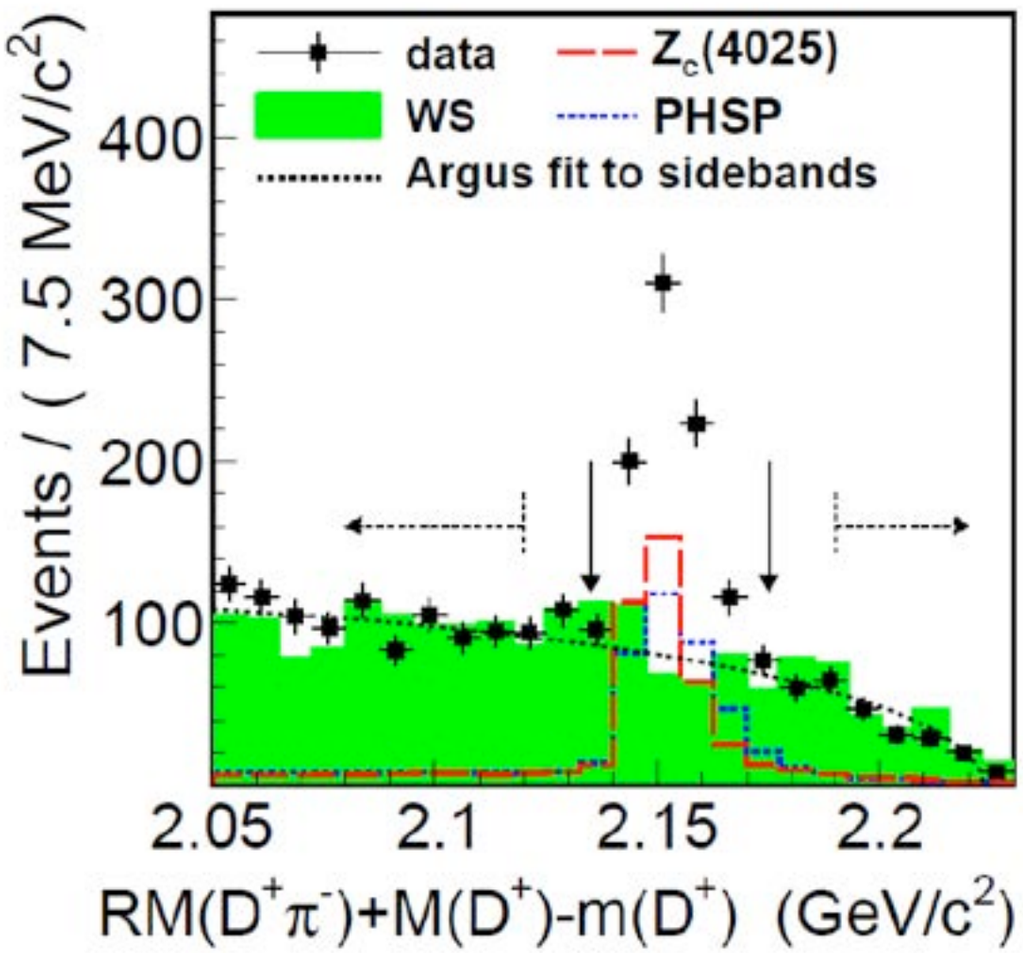


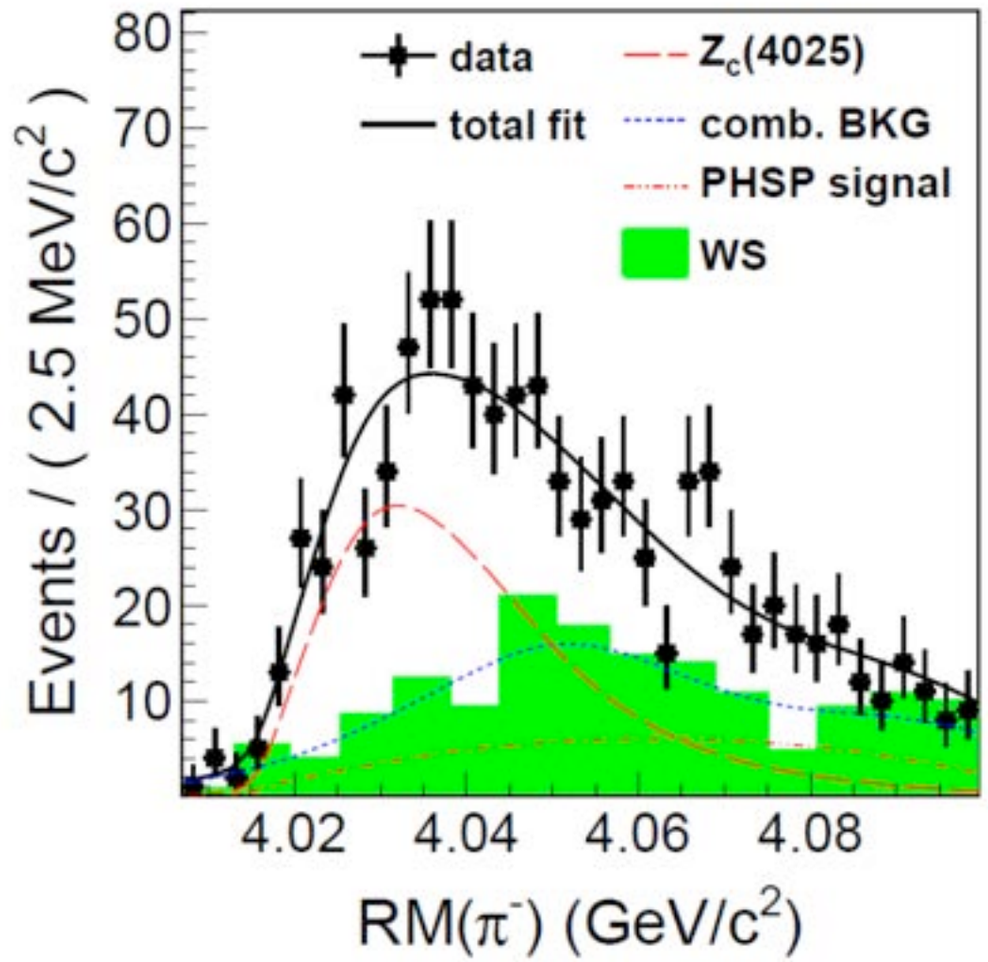
8.7±1.9±2.8±1.4 pb @ 4.230
7.4±1.7±2.1±1.2 pb @ 4.260
10.3±2.3±3.1±1.6 pb @ 4.360

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes:

$M = 4022.9 \pm 0.8 \pm 2.7$ MeV/c^2 $\quad \Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

$$e^+e^- \to \pi Z_c(4025) \to \pi^- (D^*\bar{D}^*)^+$$





BESIII: 1308.2760

Fit to $\pi^\pm$ recoil mass yields

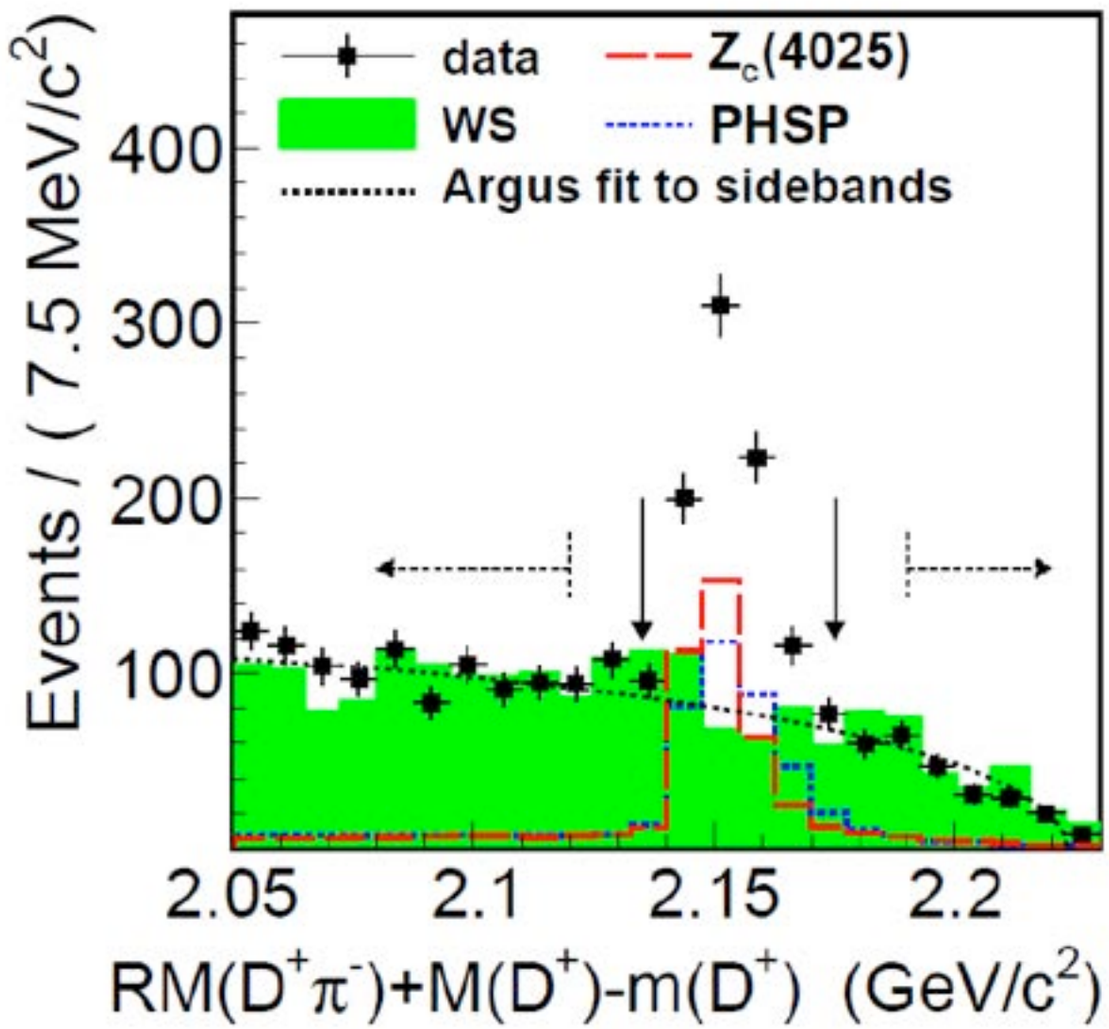
401±47 Zc(4025) events $\Rightarrow$ >10σ

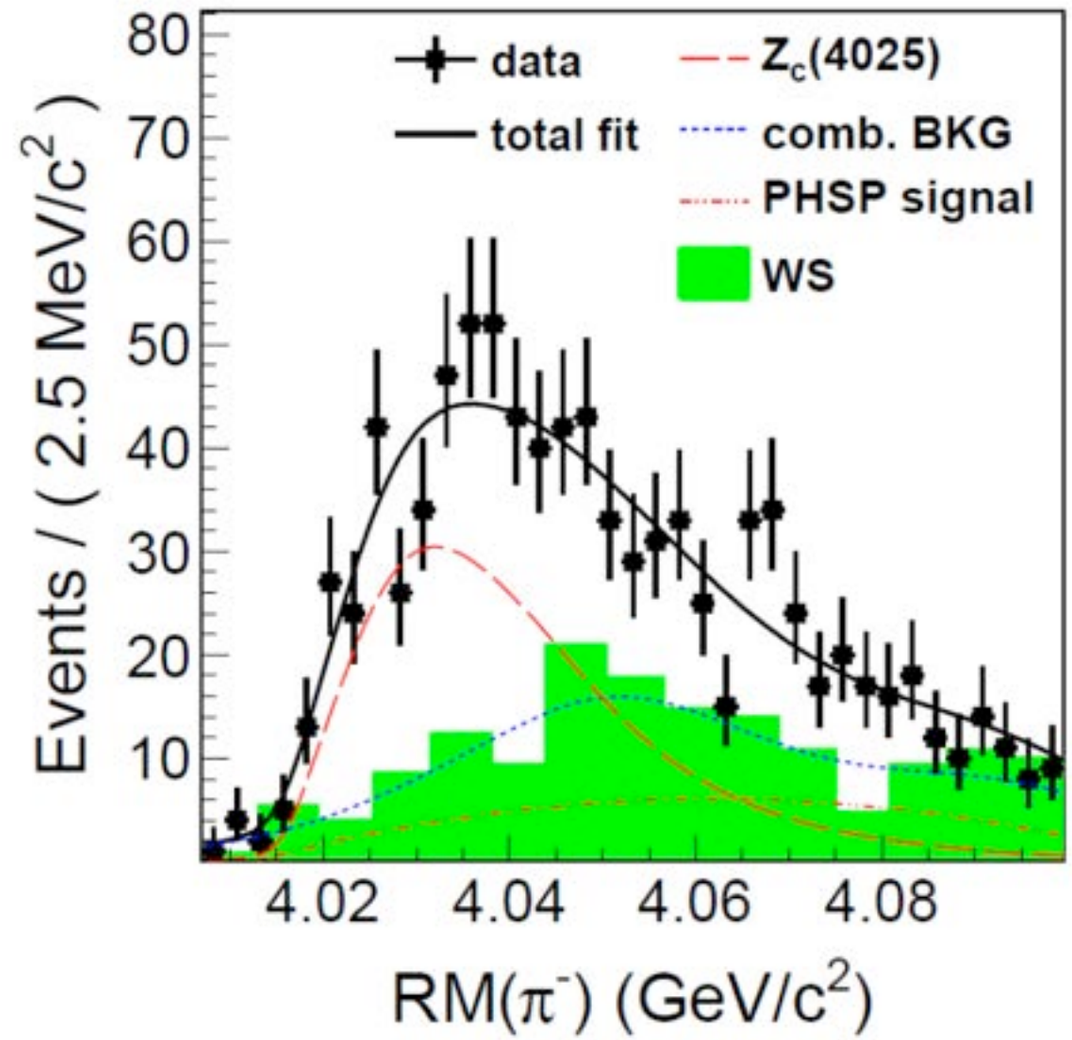
$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV

$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

$e^+e^- \to \pi Z_c(4025) \to \pi^- (D^*\bar{D}^*)^+$

BESIII: 1308.2760





Fit to $\pi^\pm$ recoil mass yields 401±47 Zc(4025) events $\Rightarrow$ >10σ

M(Z_c(4025)) = 4026.3±2.6±3.7 MeV; Γ(Z_c(4025)) = 24.8±5.6±7.7 MeV

$$R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp(4025) \to \pi^\pm (D*\bar{D}*)^\mp)}{e^+e^- \to \pi^\pm (D*\bar{D}*)^\mp} = (65 \pm 9 \pm 6)\%$$

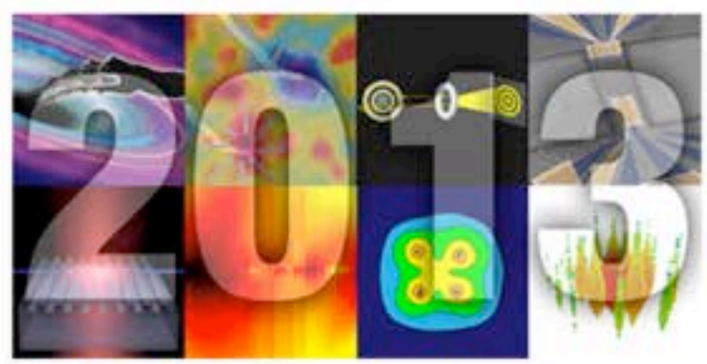
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

***Physics* looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas



Images from popular *Physics* stories in 2013.

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_c(3900)$, are possible, the "tetraquark" interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

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Synopsis | Jun 3, 2014

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Synopsis | Jun 2, 2014

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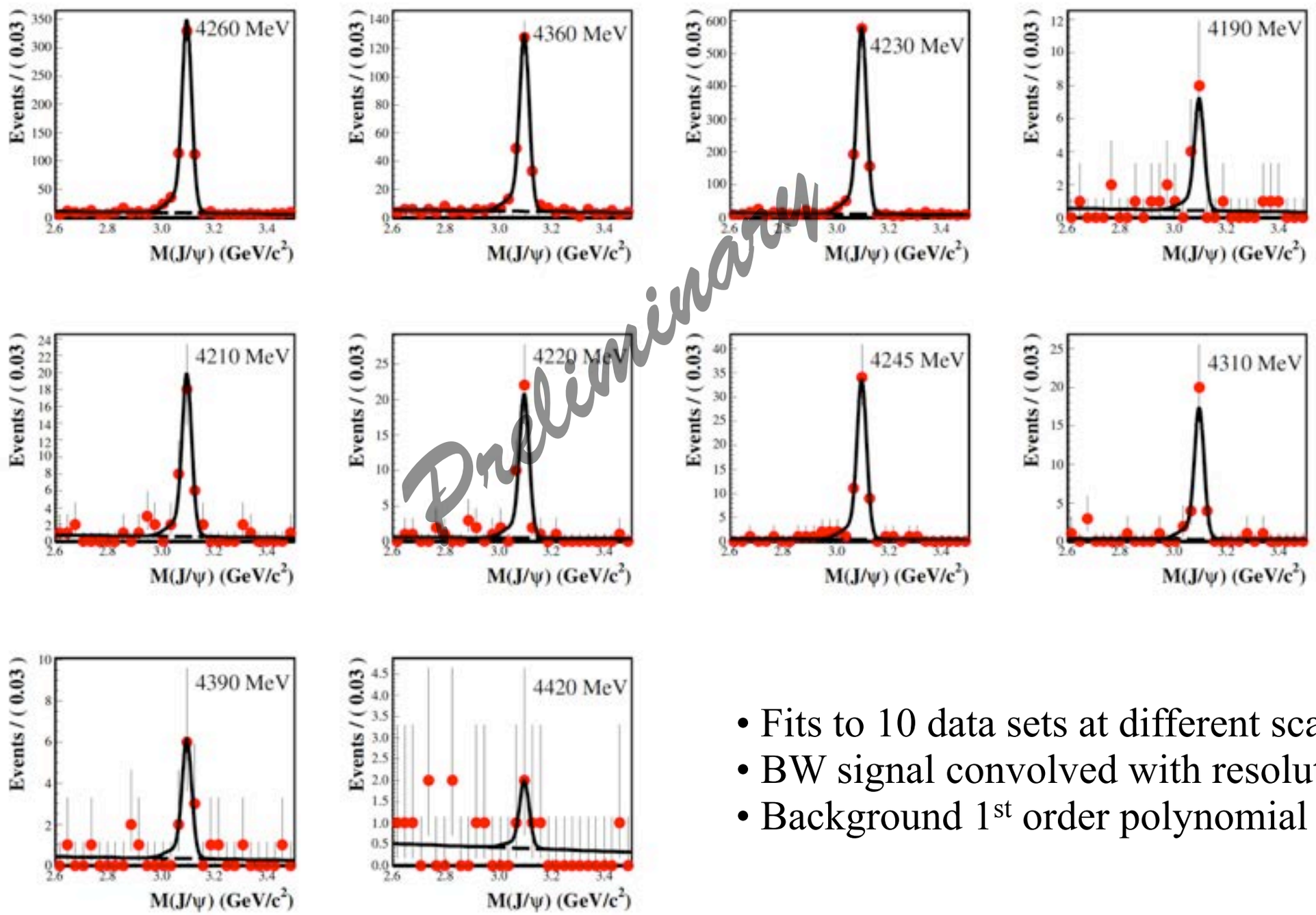
Viewpoint | Jun 2, 2014

Electrons Not the Cause of Charged Grains
Focus | May 30, 2014

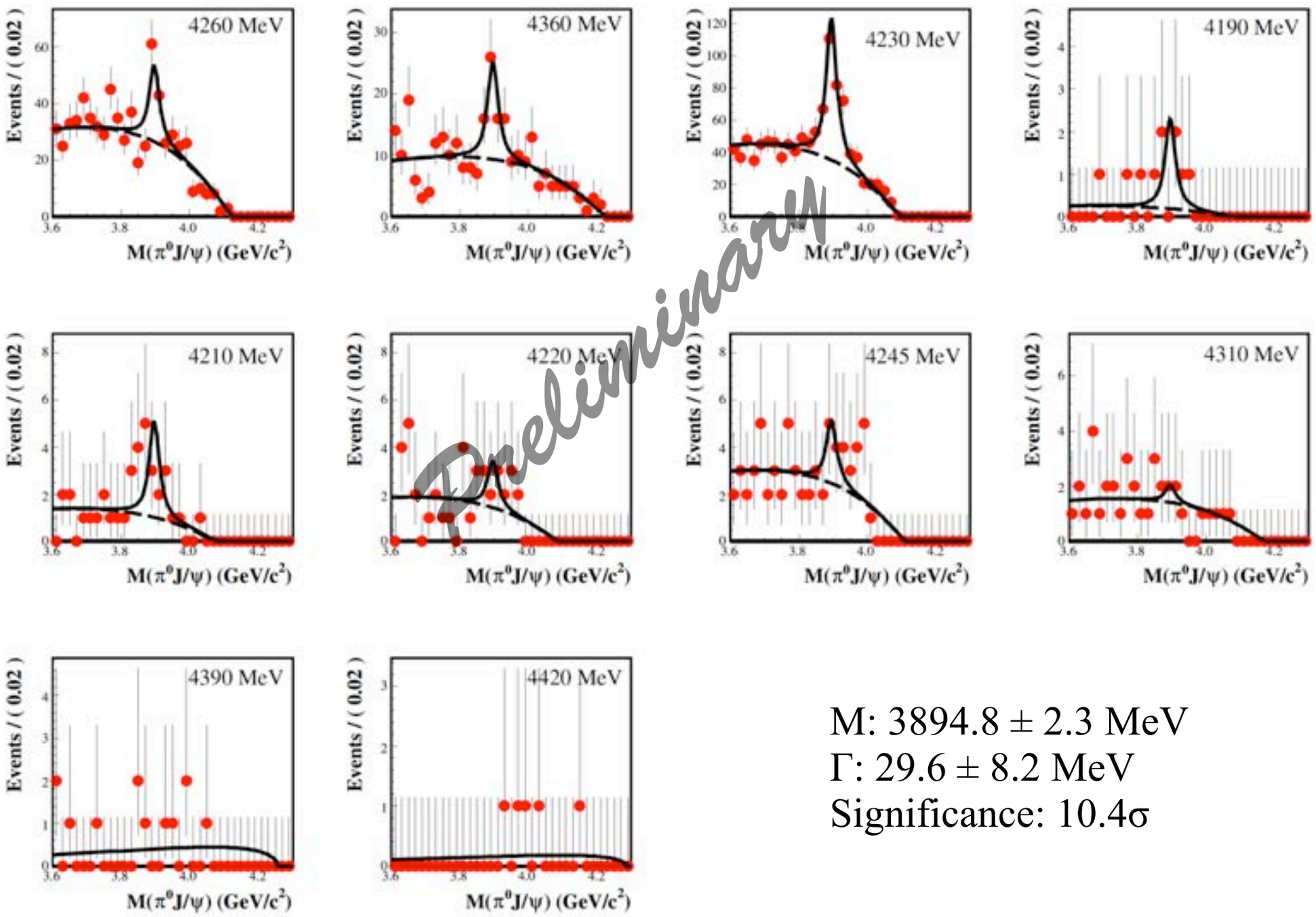
Seeing Just One Photon
Synopsis | May 29, 2014

Search for neutral partner of the $Z_c(3900)$: $e^+e^- \to \pi^0\pi^0 J/\psi$



- Fits to 10 data sets at different scan energies
- BW signal convolved with resolution
- Background 1st order polynomial

Search for neutral partner of the $Z_c(3900)$: $e^+e^- \to \pi^0\pi^0 J/\psi$



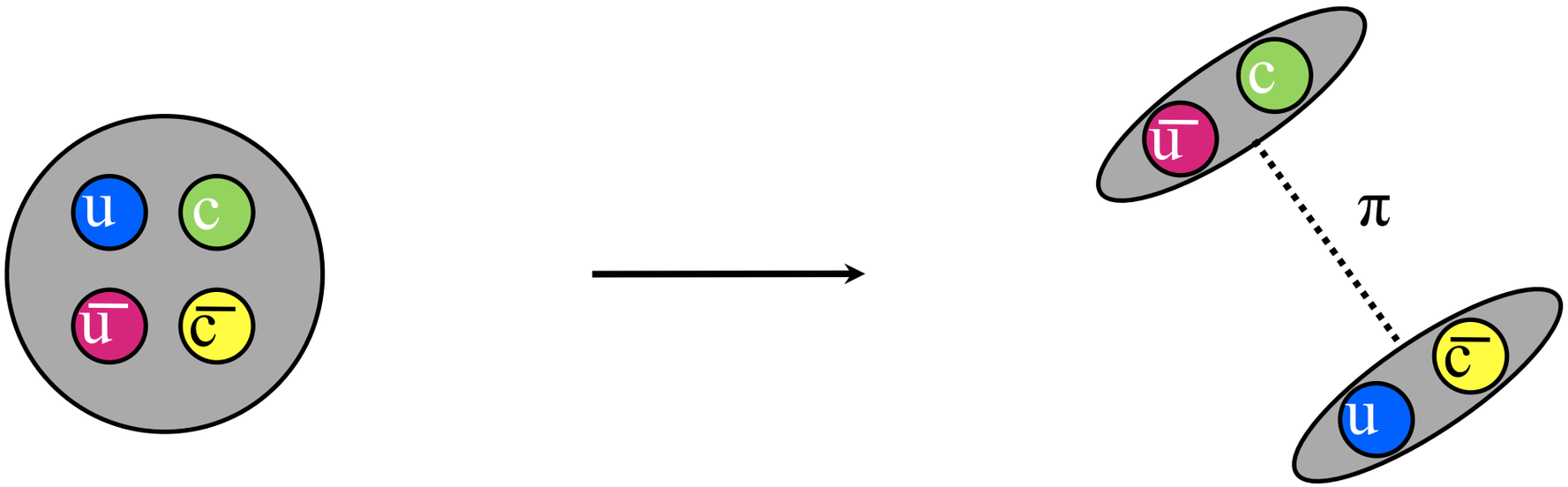
M: 3894.8 ± 2.3 MeV
Γ: 29.6 ± 8.2 MeV
Significance: 10.4σ

A new class of particles have been observed:

- At least 4-quarks
- Charged
- Close to DD thresholds
- They couple to DD final states larger than to charmonia

4-quark state

D-$\overline{\text{D}}$-“molecule”

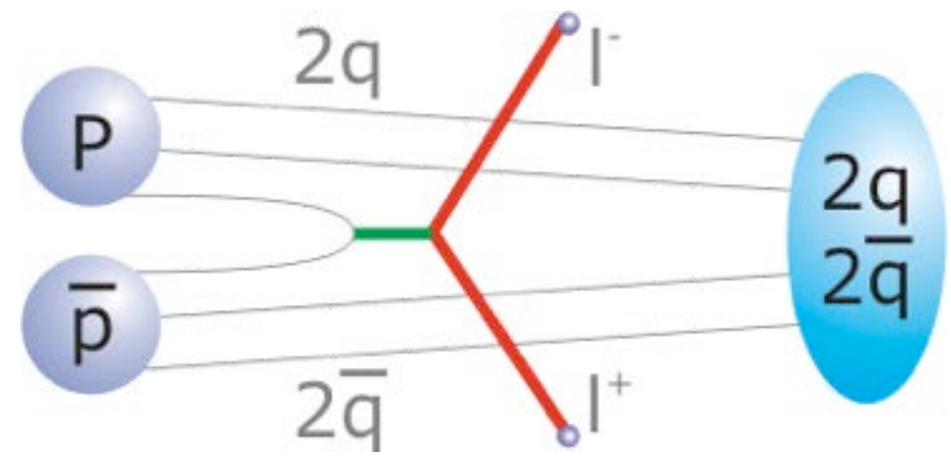


Transition from color forces to colorless nuclear forces ?

The future: PANDA

Proton-Antiproton contains already a 4-Quark-System

Idea: Dilepton-Tag from Drell-Yan-Production



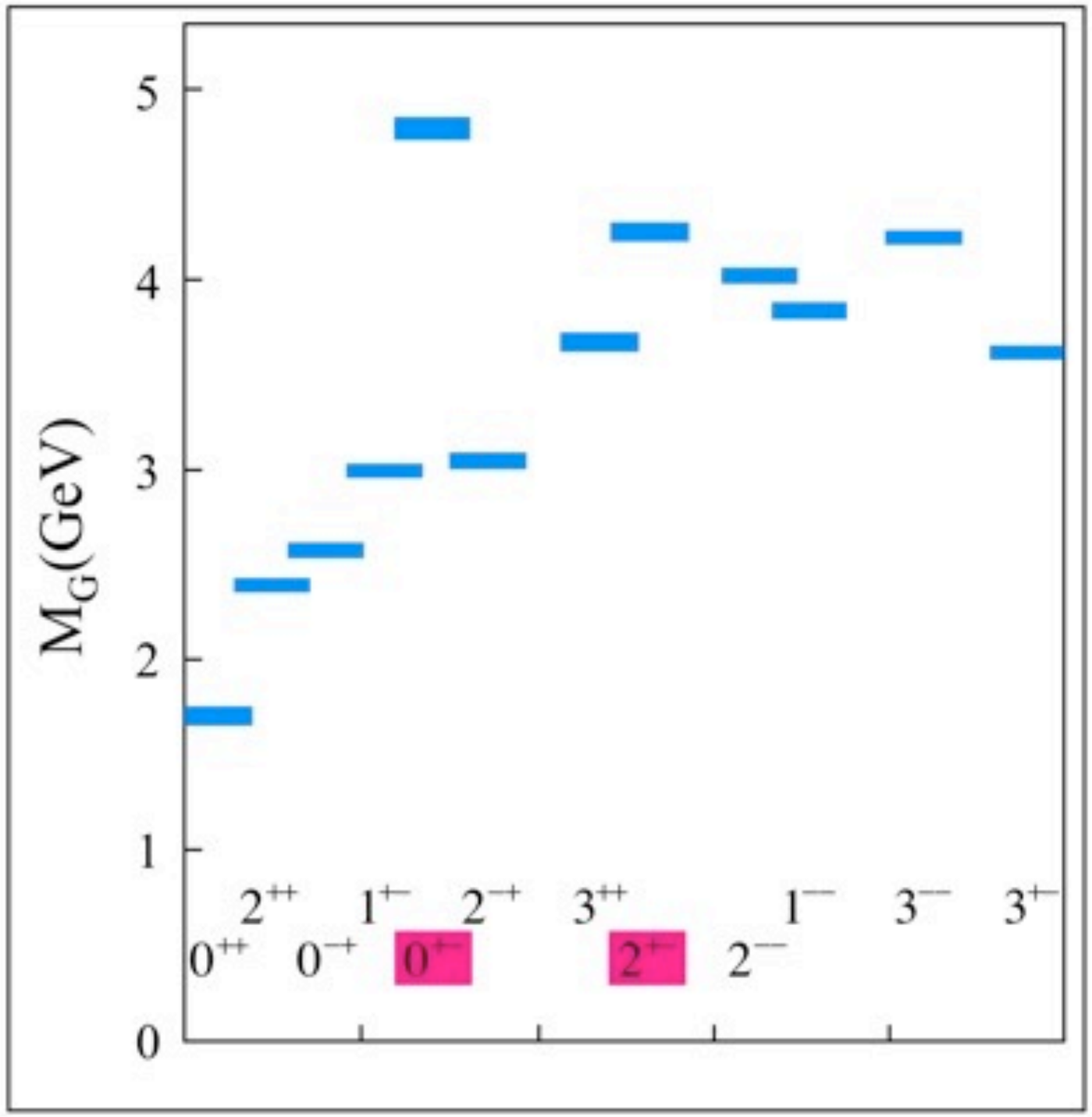
Bannikov, Gornuschkin, Kopeliovich, Krumshtein and Sapozhnikov, JINR E1-92-344 (1992)

Advantages

- Trigger
- less J^{PC}-Ambiguities
- 1200 E./day @ 12 GeV
- 300 E./day @ 5-8 GeV antiproton-Beam (for $L=10^{32}cm^{-2}s^{-1}$)

Other QCD states: Glueballs

A possible glueball spectrum



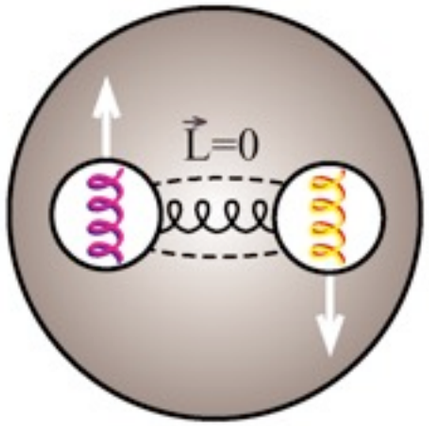
Glueballs $\rightarrow$ Creation of Mass

A few % of a hadron (proton) mass is generated due to the **Higgs mechanism**.

Most of the proton mass is created by the **strong interaction**.

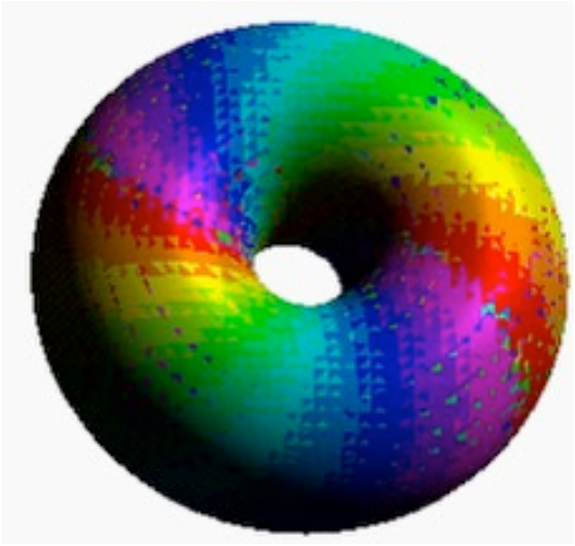
Glueballs gain their mass solely by the strong interaction and are therefore an unique approach to the mass creation by the strong interaction.

The structure of glueballs



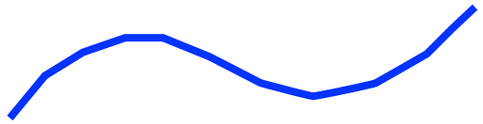
Glueball (gg)

Are glueballs configurations of twisted or knotted colored flux?

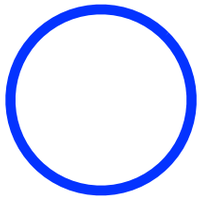


GLUEBALLS, FLUXTUBES AND η(1440).
L. Fadeev, A. Niemi and U. Wiedner Phys.Rev.D70:114033, 2004

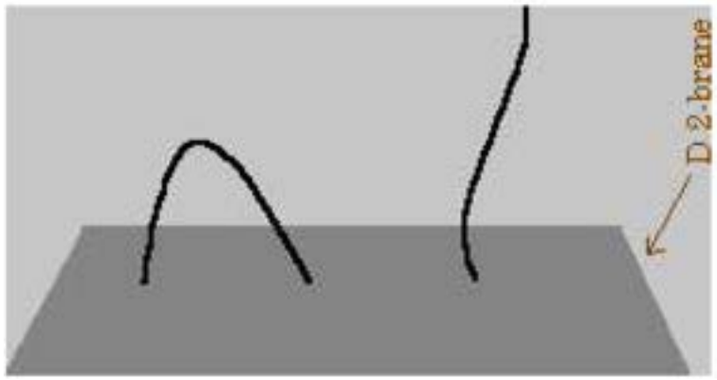
Open Strings



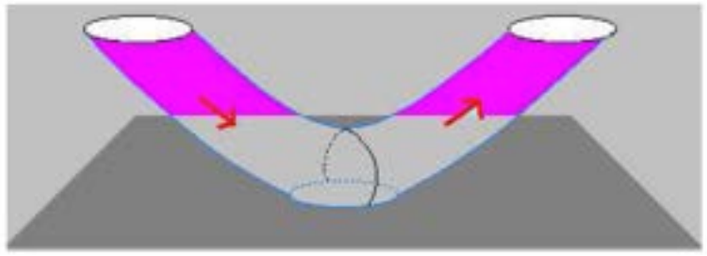
Closed Strings



String World

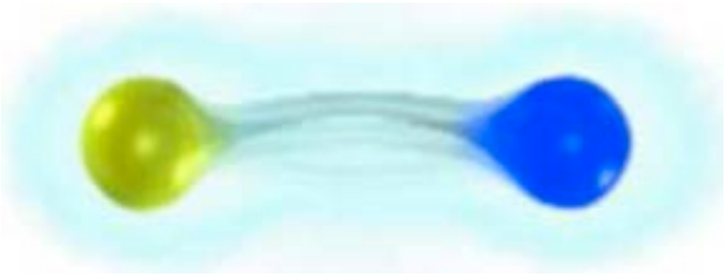


representing gauge theories

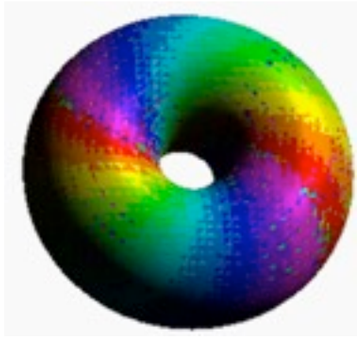


representing gravitation

Hadron World

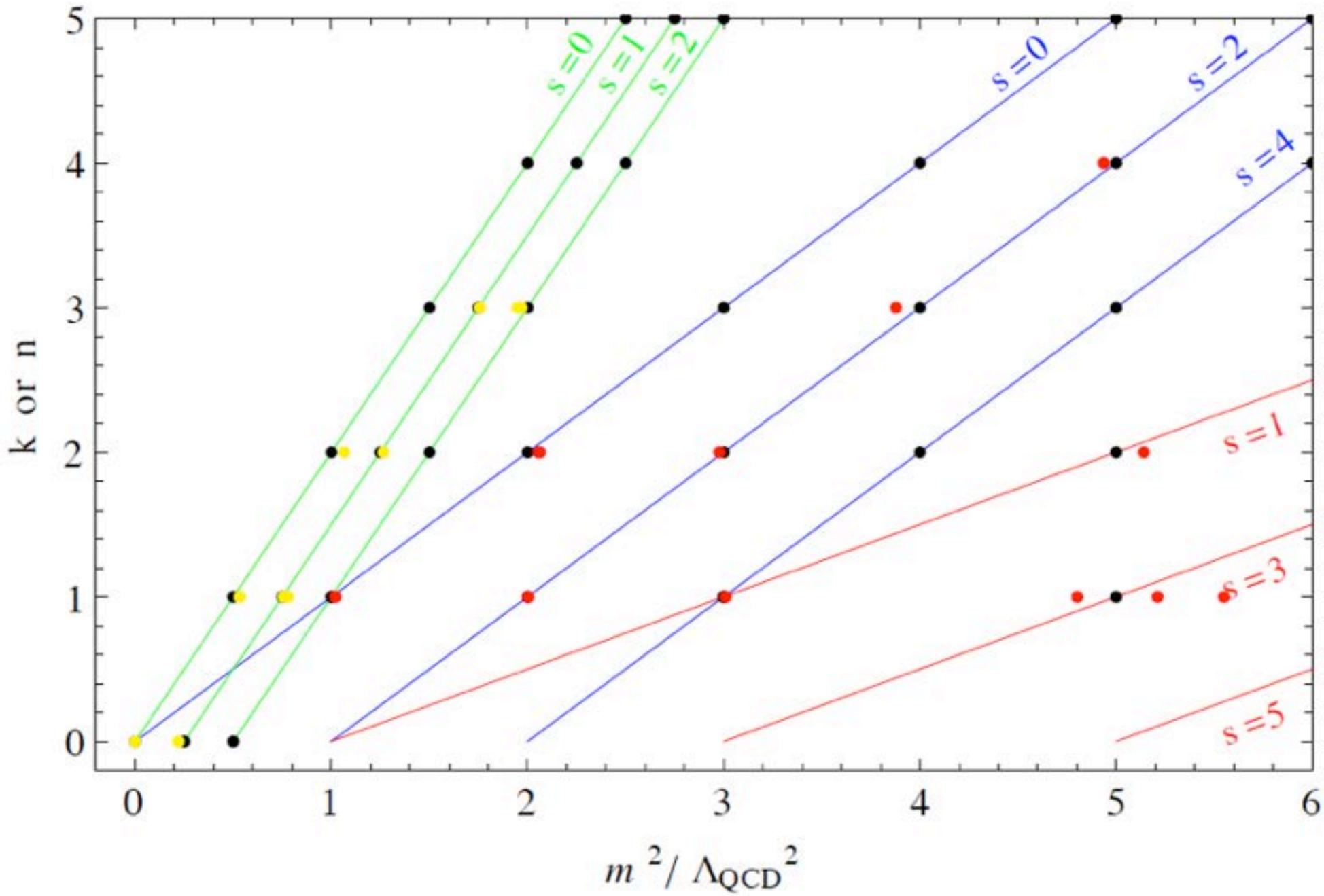


meson



glueball ?

Glueballs on Regge trajectories like mesons?



Marco Bochicchio; arXiv:1308.2925

Harvey B. Meyer, Michael J. Teper; Phys.Lett. B605 (2005) 344-354

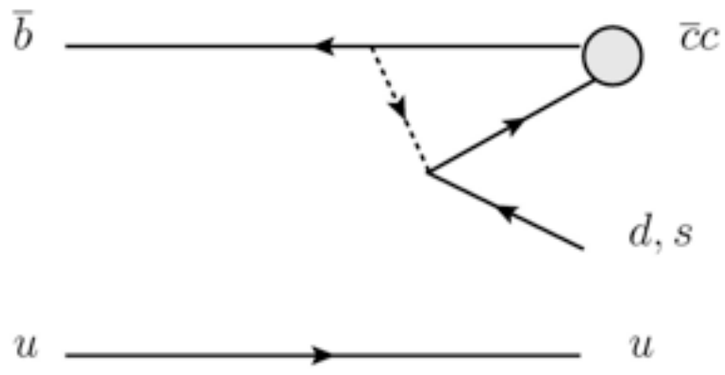
G. S. Bali et al.; arXiv:1302.1502

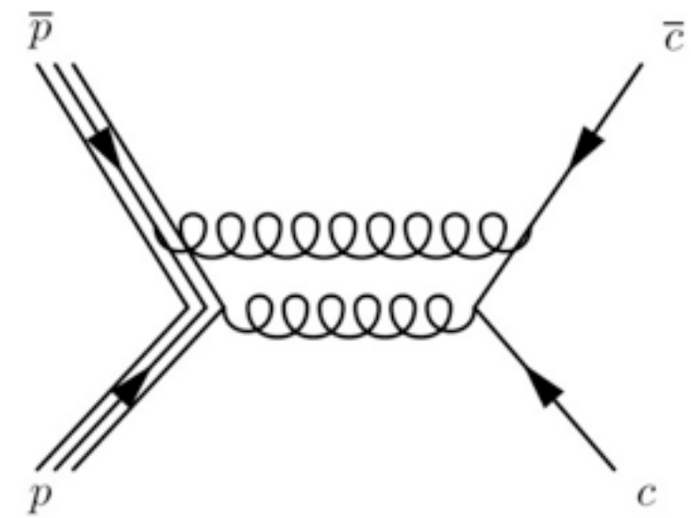
Hadron physics is the place on earth to study non-Abelian massless gauge boson - gauge boson interaction in a controlled manner.

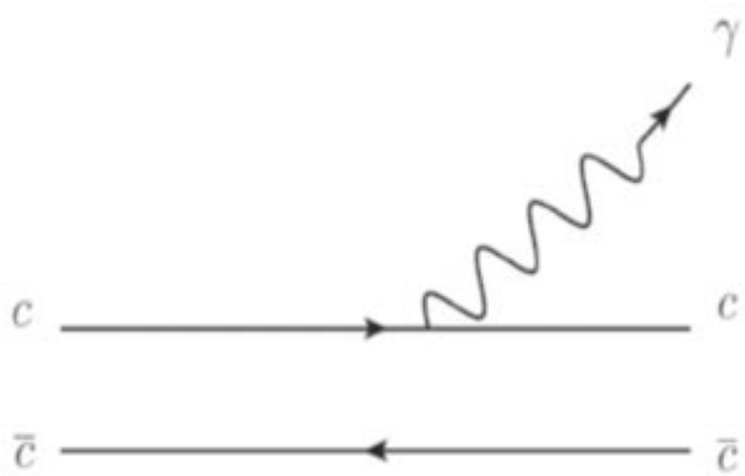
Feynman lectures on gravitation:

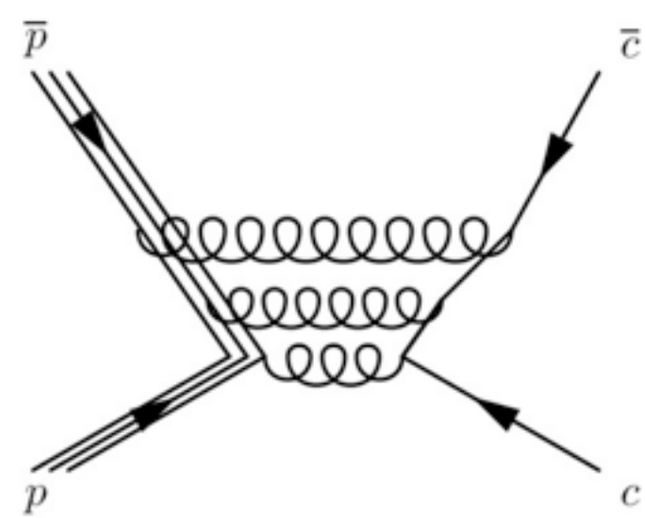
In fact, his work led to two sets of very useful results. The first, purely pedagogical, is embodied in the *Feynman Lectures on Gravitation* (publication [123]). In those lectures, Feynman develops the quantum field theory of a neutral massless spin 2 particle (the *graviton*), emphasizing the special features that arise, in comparison to theories of spin 0 and spin 1 particles, as well as the complications that result for a zero-mass particle in trying to create a self-consistent theory. As in the case of spin 1, masslessness results in redundant degrees of freedom, since Lorentz invariance requires that a *massless* particle can spin only along or opposite to its direction of momentum (positive or negative *chirality*), while a massive spin 2 particle may take up five different orientations relative to any arbitrary quantization direction. Eliminating the unwanted degrees of freedom is achieved by imposing certain "gauge conditions," which in the gravitational case brings about nonlinearity in the form of graviton–graviton interaction. Feynman shows that the classical limit of a properly gauged massless spin 2 theory is described by the Einstein gravitational field equations.[3]

The difference between e^+e^- colliders and PANDA





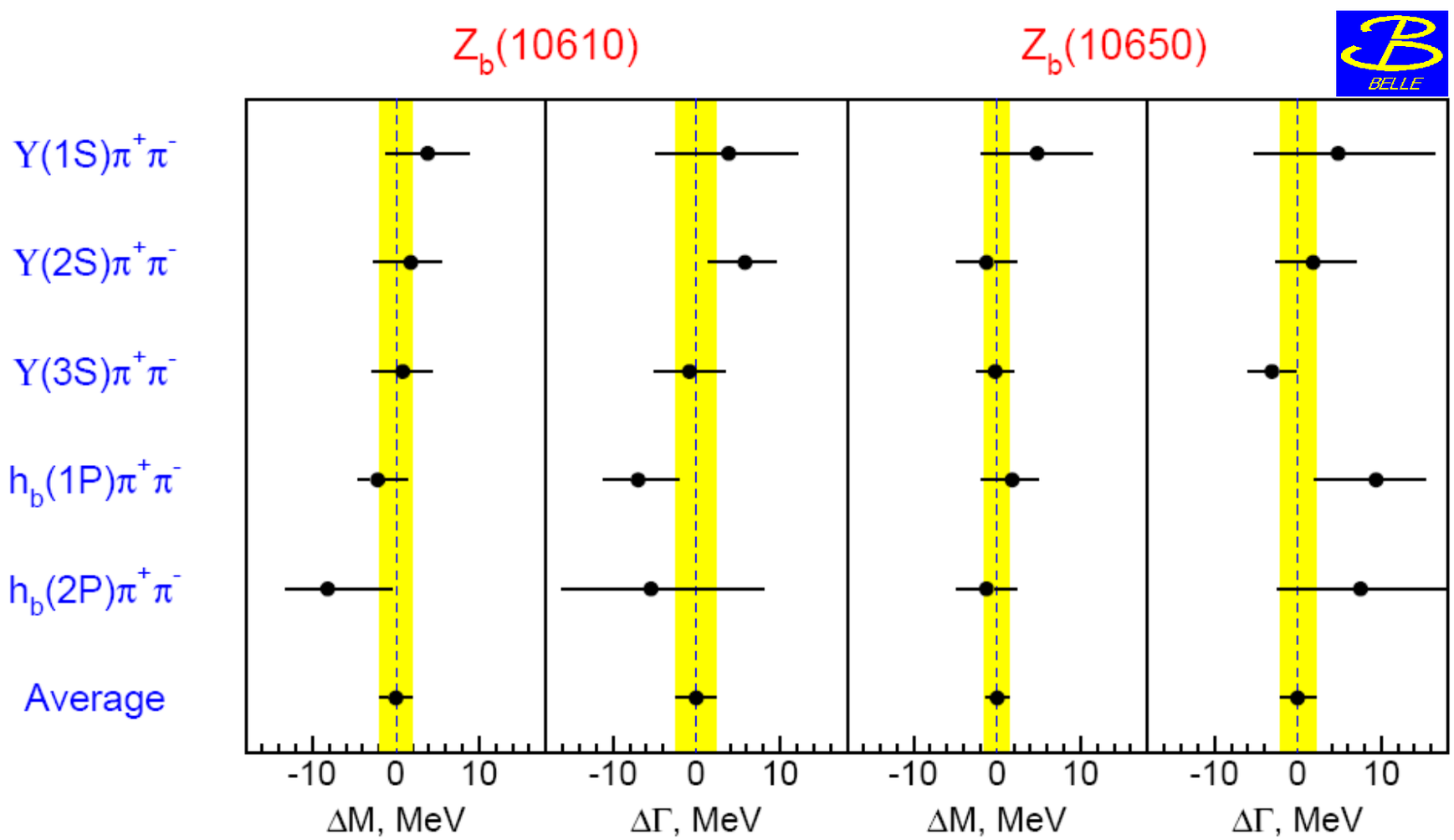




There exist also very narrow charged Z_b states

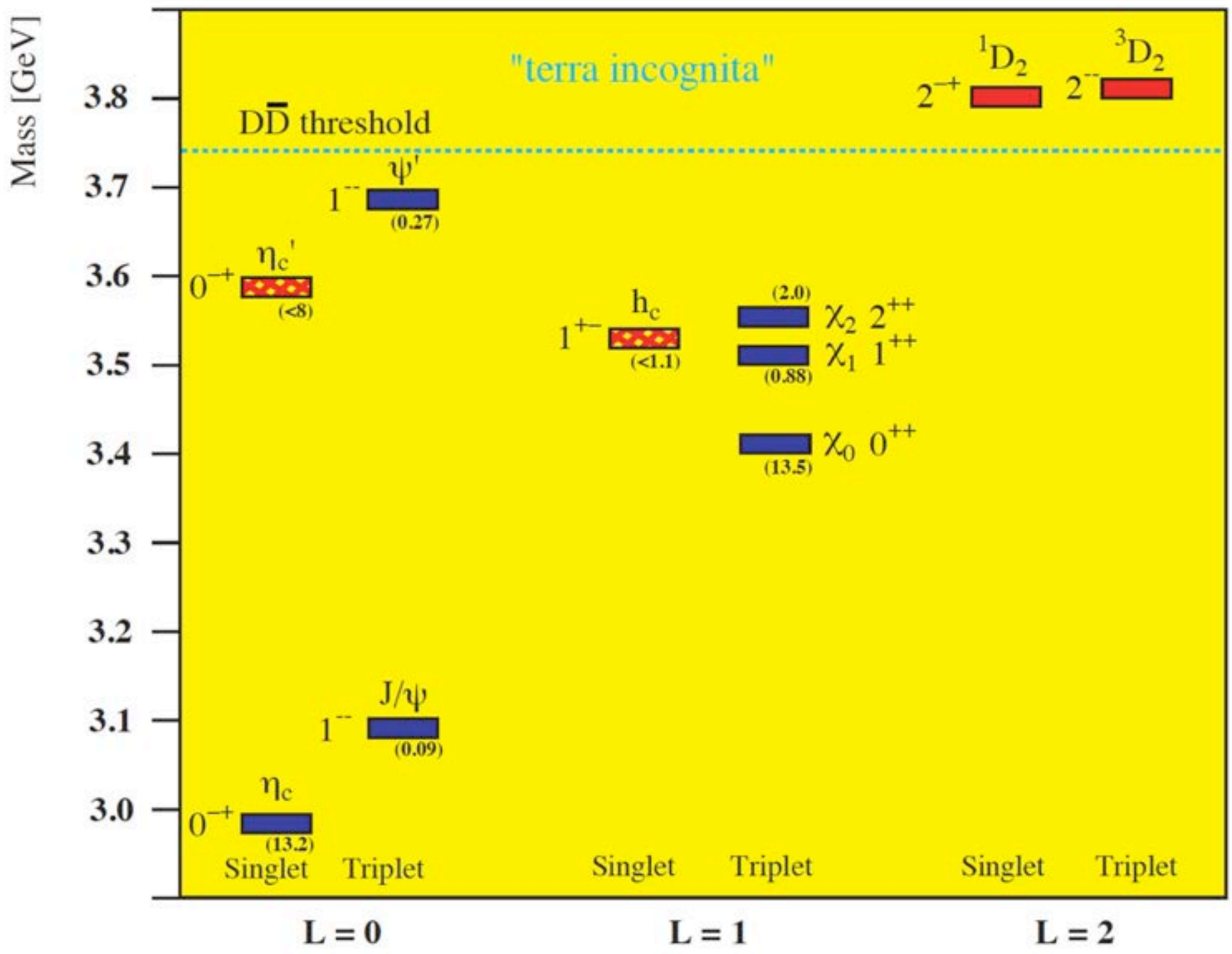
$M_1 = 10607.2 \pm 2.0$ MeV
$\Gamma_1 = 18.4 \pm 2.4$ MeV
$M_{Zb} - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV

$M_2 = 10652.2 \pm 1.5$ MeV
$\Gamma_2 = 11.5 \pm 2.2$ MeV
$M_{Zb} - (M_B + M_{B^*}) = +1.8 \pm 1.7$ MeV



Ulrich Wiedner

Ulrich Wiedner


Mass [GeV]
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3.0
"terra incognita"
DD̄ threshold
$^1D_2$
$^3D_2$
2^{-+}
2^{--}
ψ'
1^{--}
(0.27)
η_c'
0^{-+}
(<8)
h_c
1^{+-}
(<1.1)
(2.0)
χ_2 2^{++}
χ_1 1^{++}
(0.88)
χ_0 0^{++}
(13.5)
J/ψ
1^{--}
(0.09)
η_c
0^{-+}
(13.2)
Singlet
Triplet
Singlet
Triplet
Singlet
Triplet
L = 0
L = 1
L = 2

Thank you very much for your attention.