Review on Spectroscopy

Frank Nerling
HFHF, GSI Darmstadt

Physics in Collision, 40th International Symposium,
RWTH Aachen, Germany, Sep 14th - 17th 2021

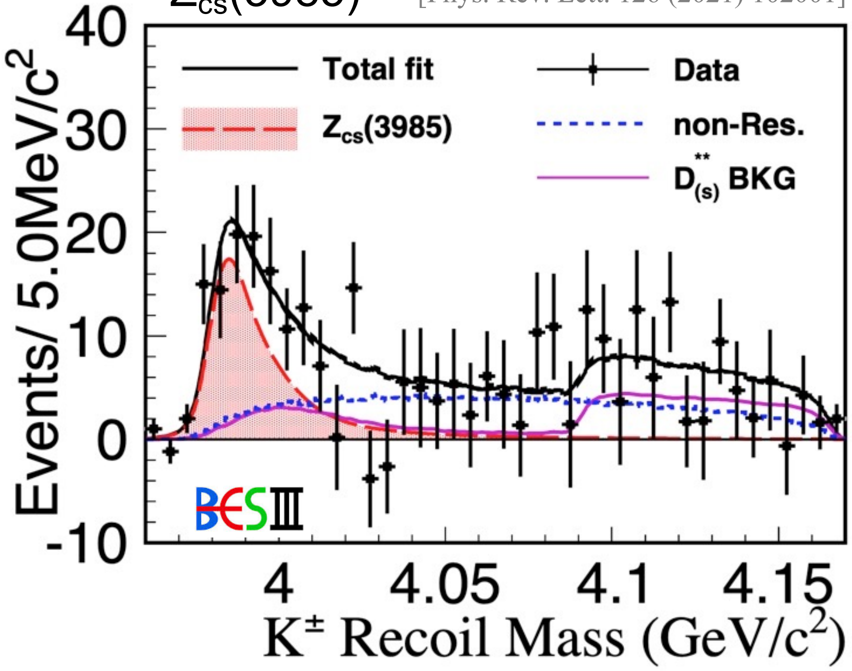
Outline

- **Introduction: From cosmic rays to hadrons**
- **The powerful Quark Model and QCD**
- **Charmonium (-like exotic) spectroscopy**
- **A selection of recent results**
  - Supernumerary vector Y states
  - Manifestly exotic Z_c states
  - The X(3872) and other X states
- **Summary & prospectives**

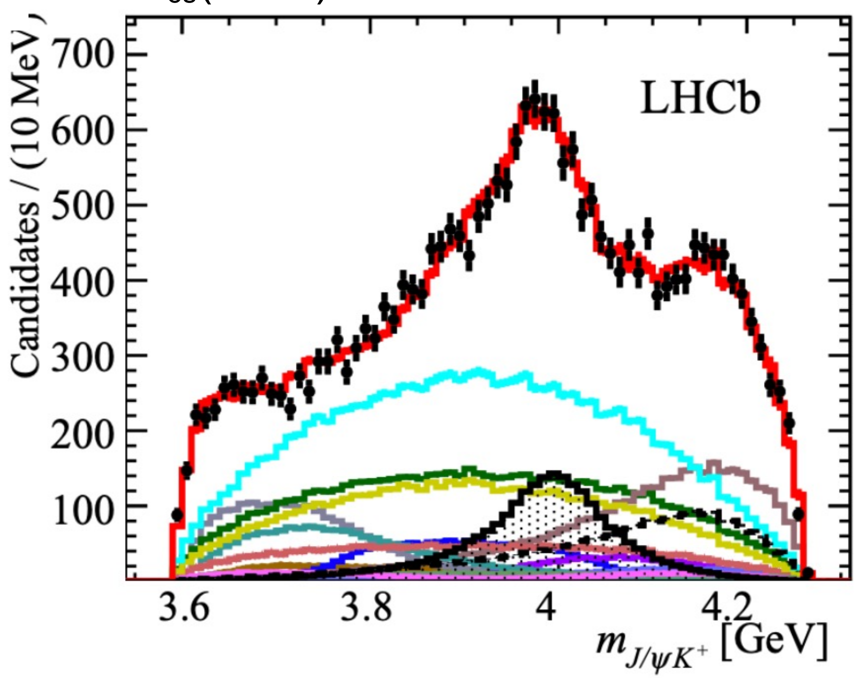
Recent hot topics

Hadron Spectroscopy

$Z_{cs}(3985)$ [Phys. Rev. Lett. 126 (2021) 102001]



$Z_{cs}(4000)$ [LHCb, arXiv:2103.01803]



Strange partner of the famous,
unexpected, manifestly exotic $Z_c(3900)$?

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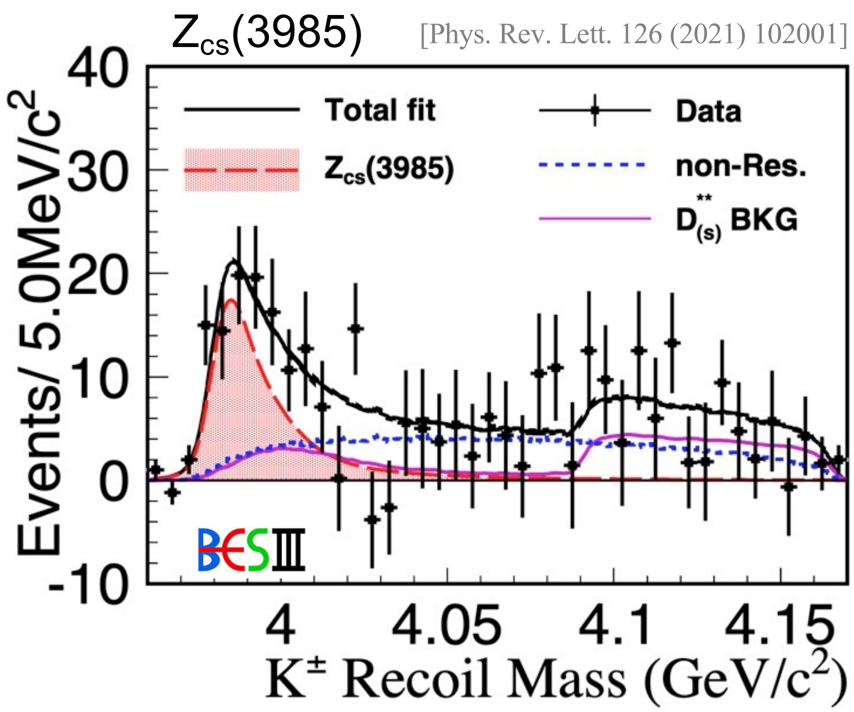

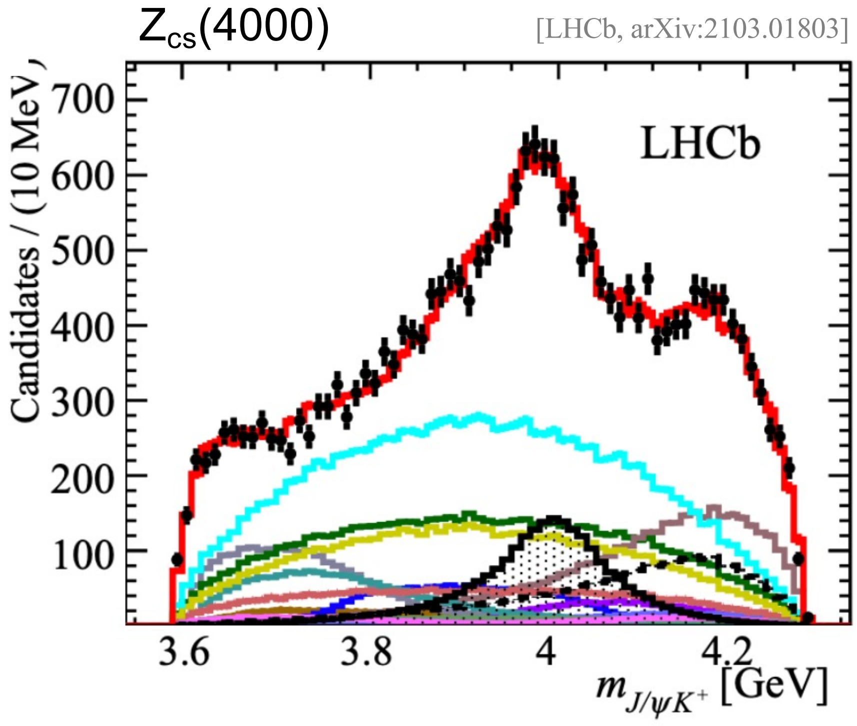

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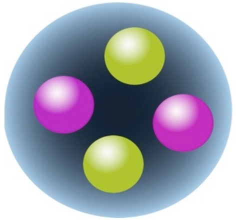
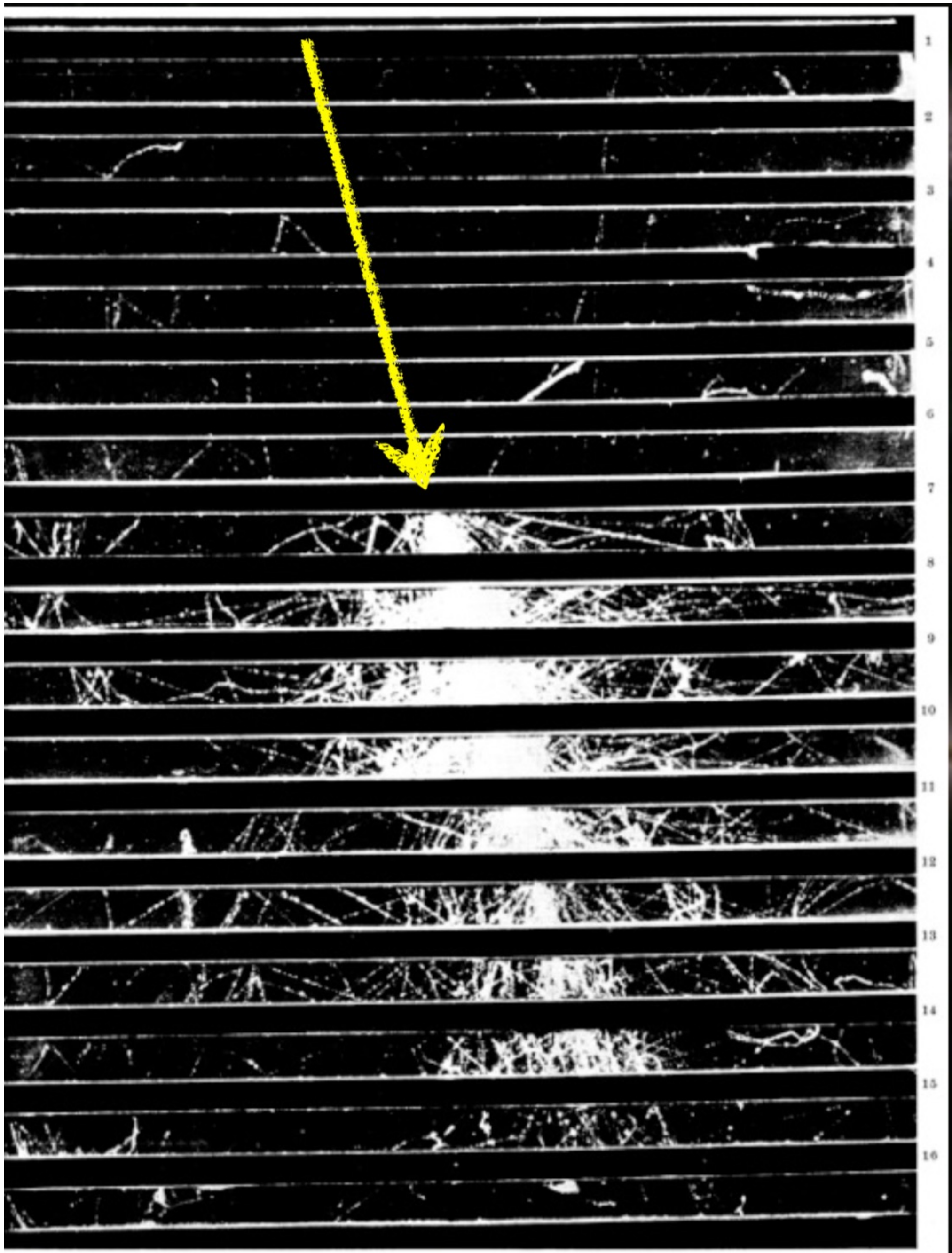
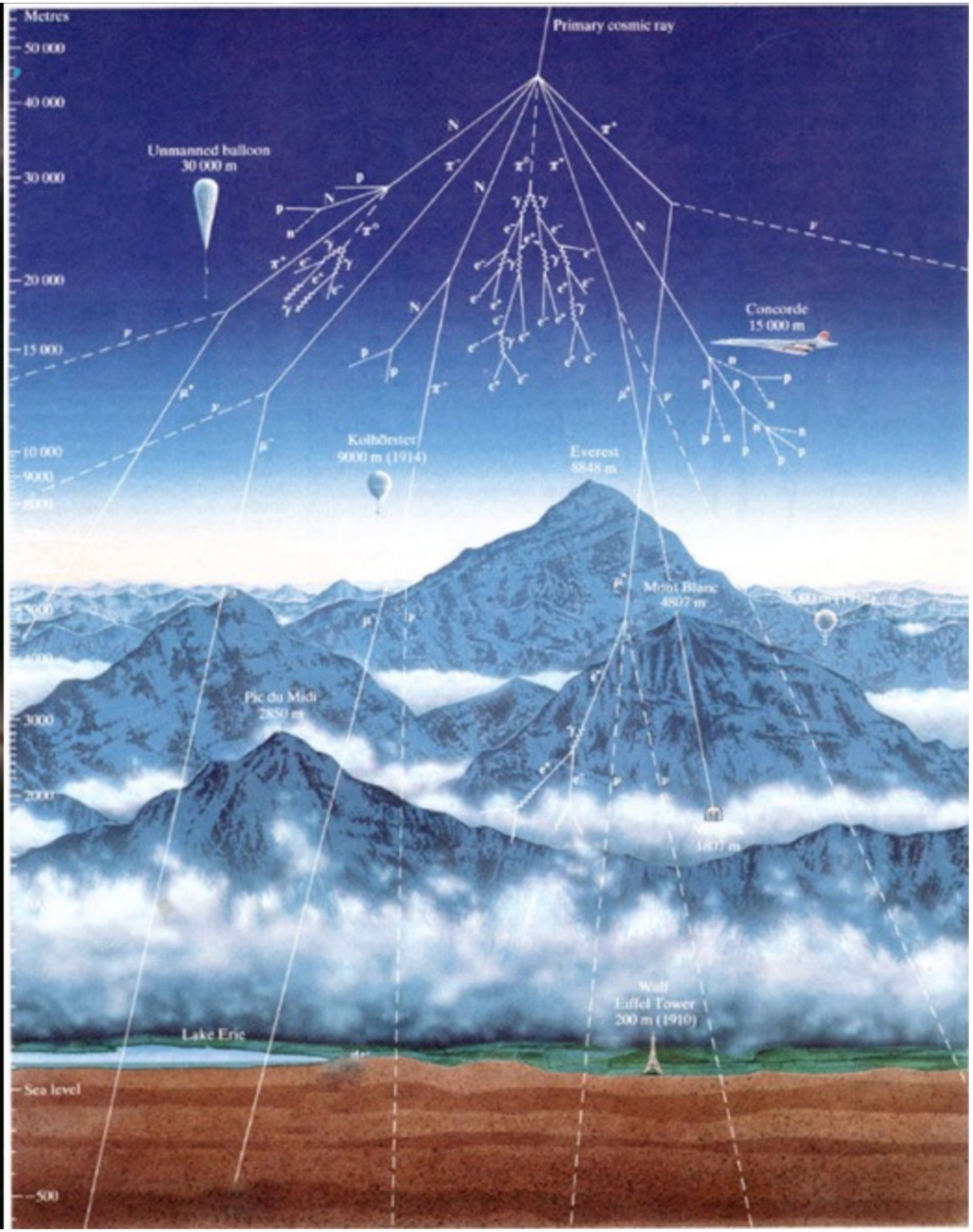


Extensive air showers (1938)





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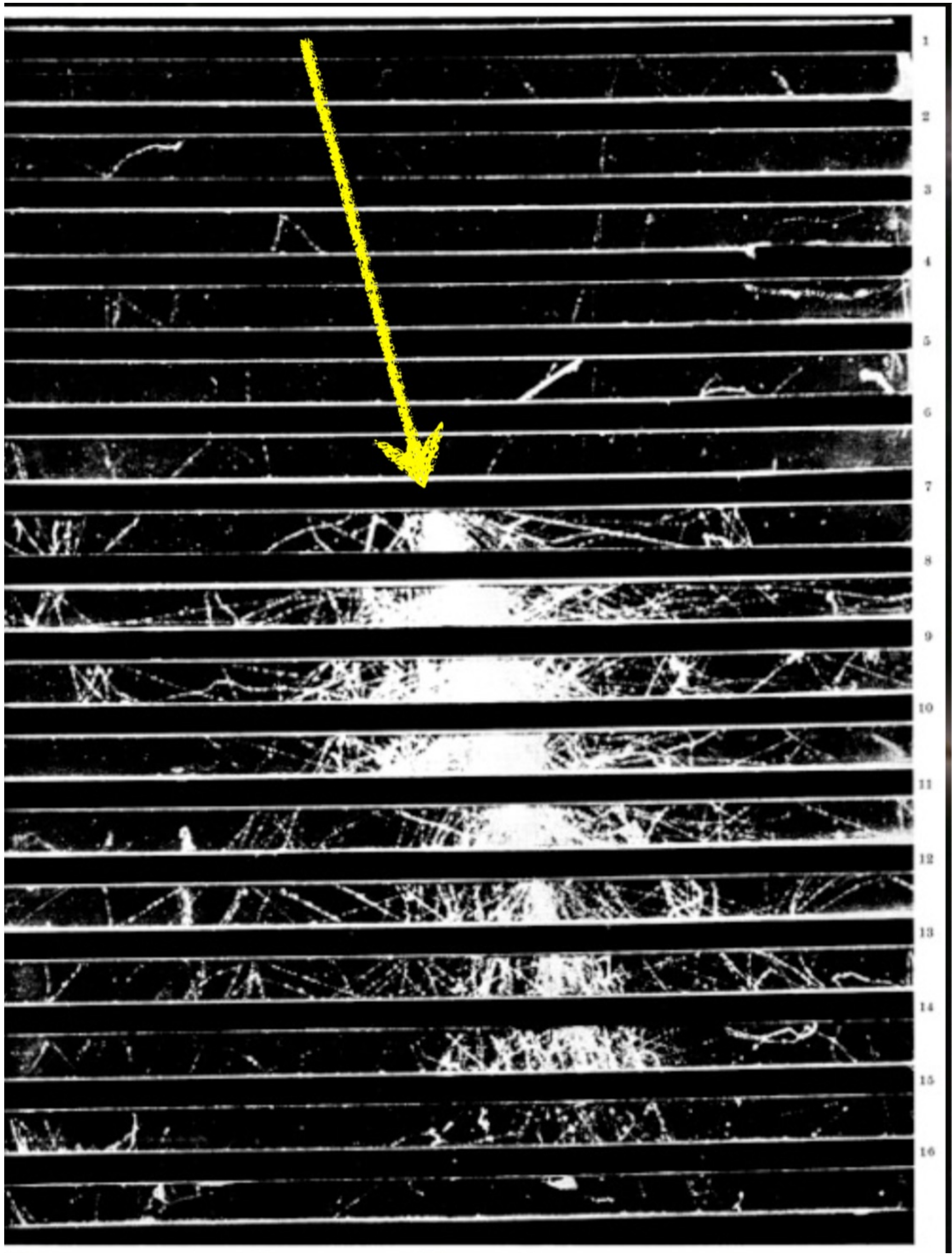

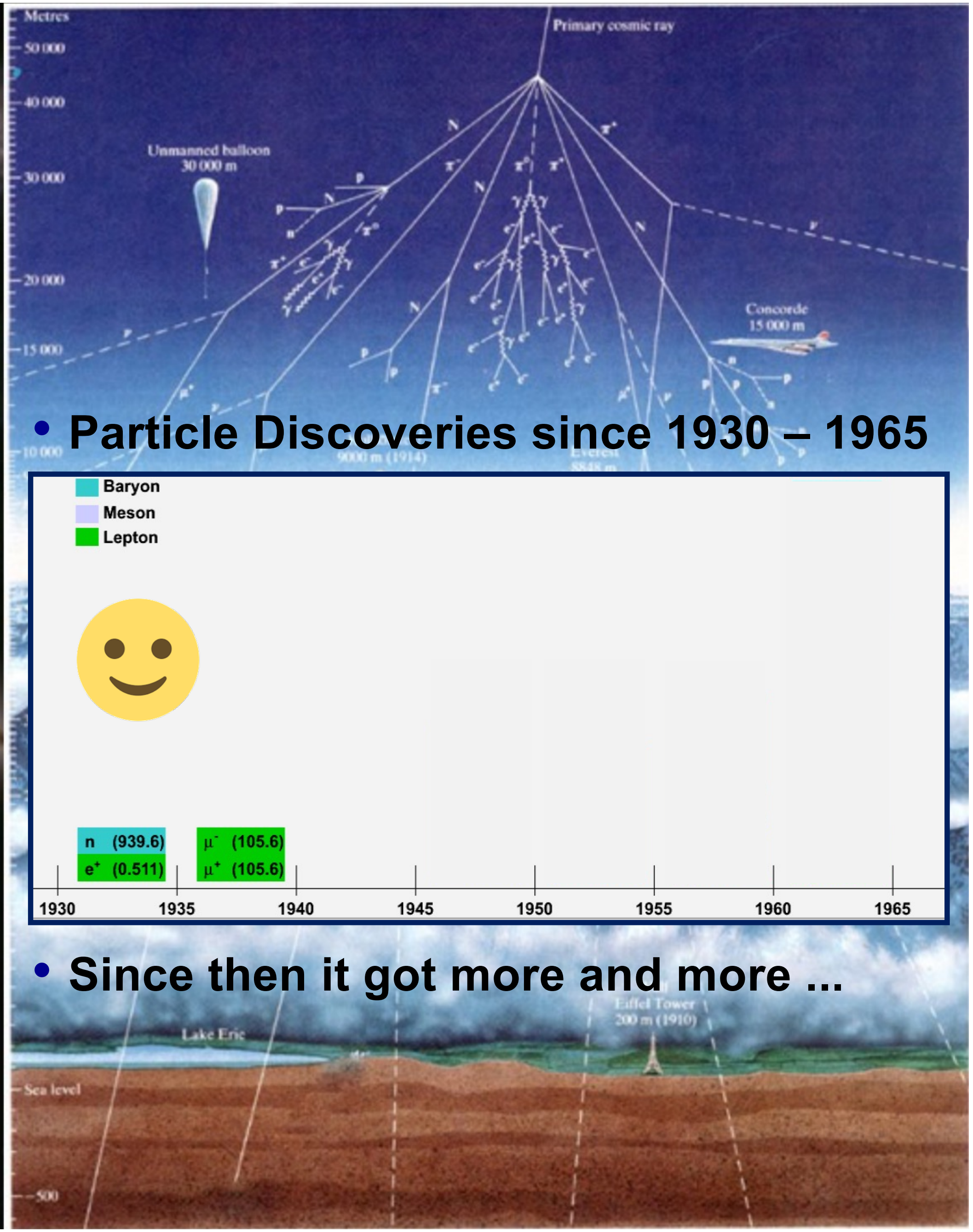

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- Since then it got more and more ...

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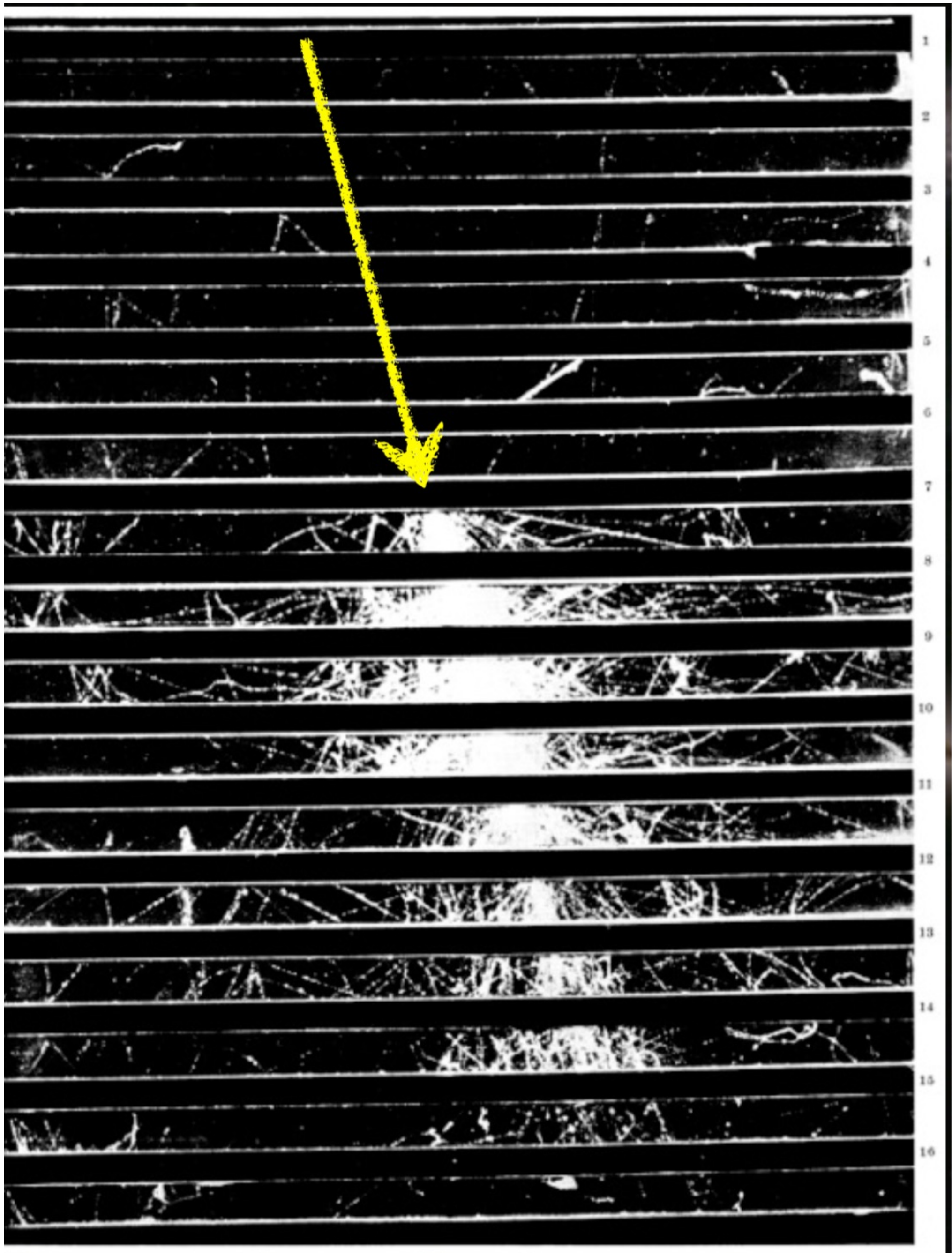

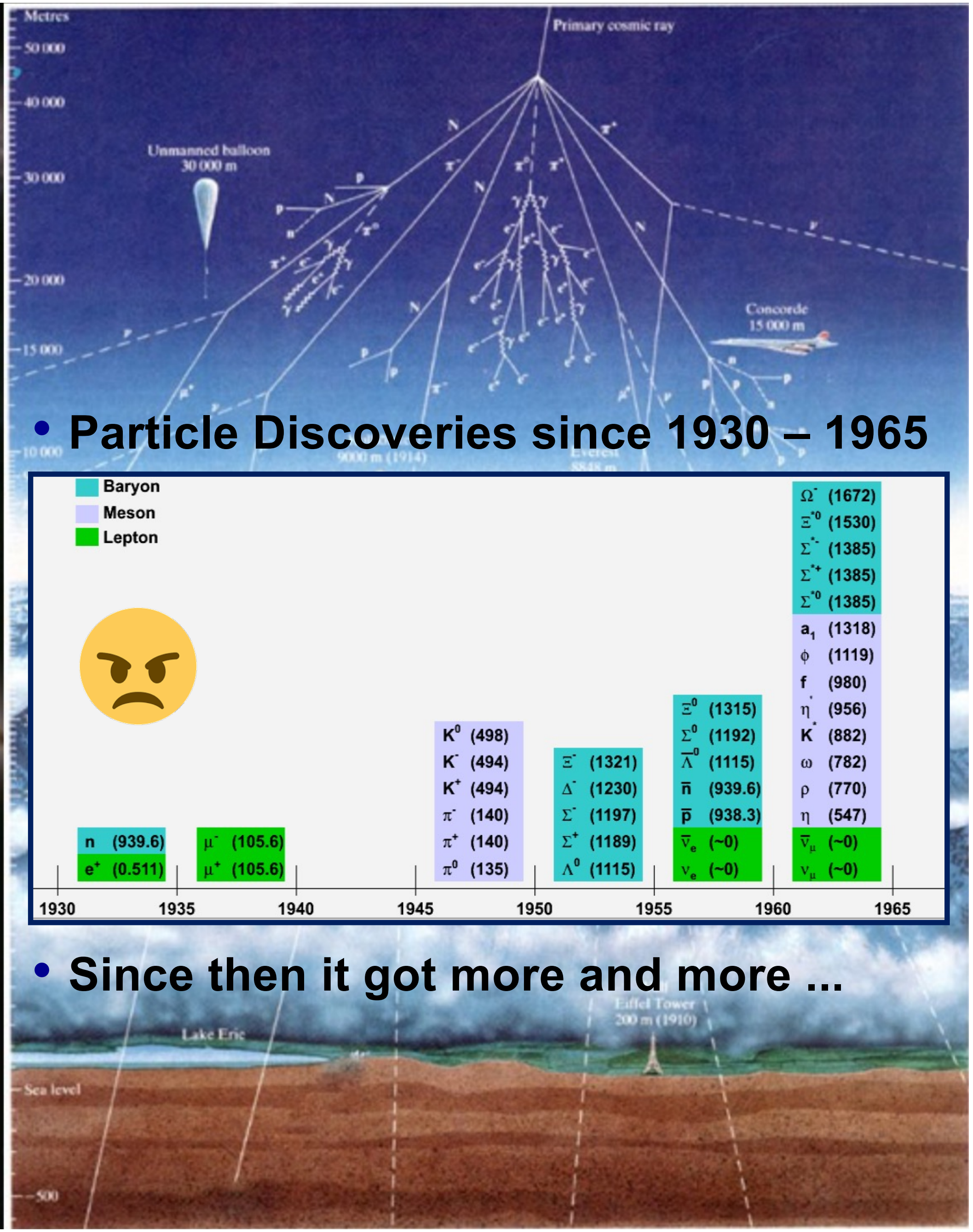

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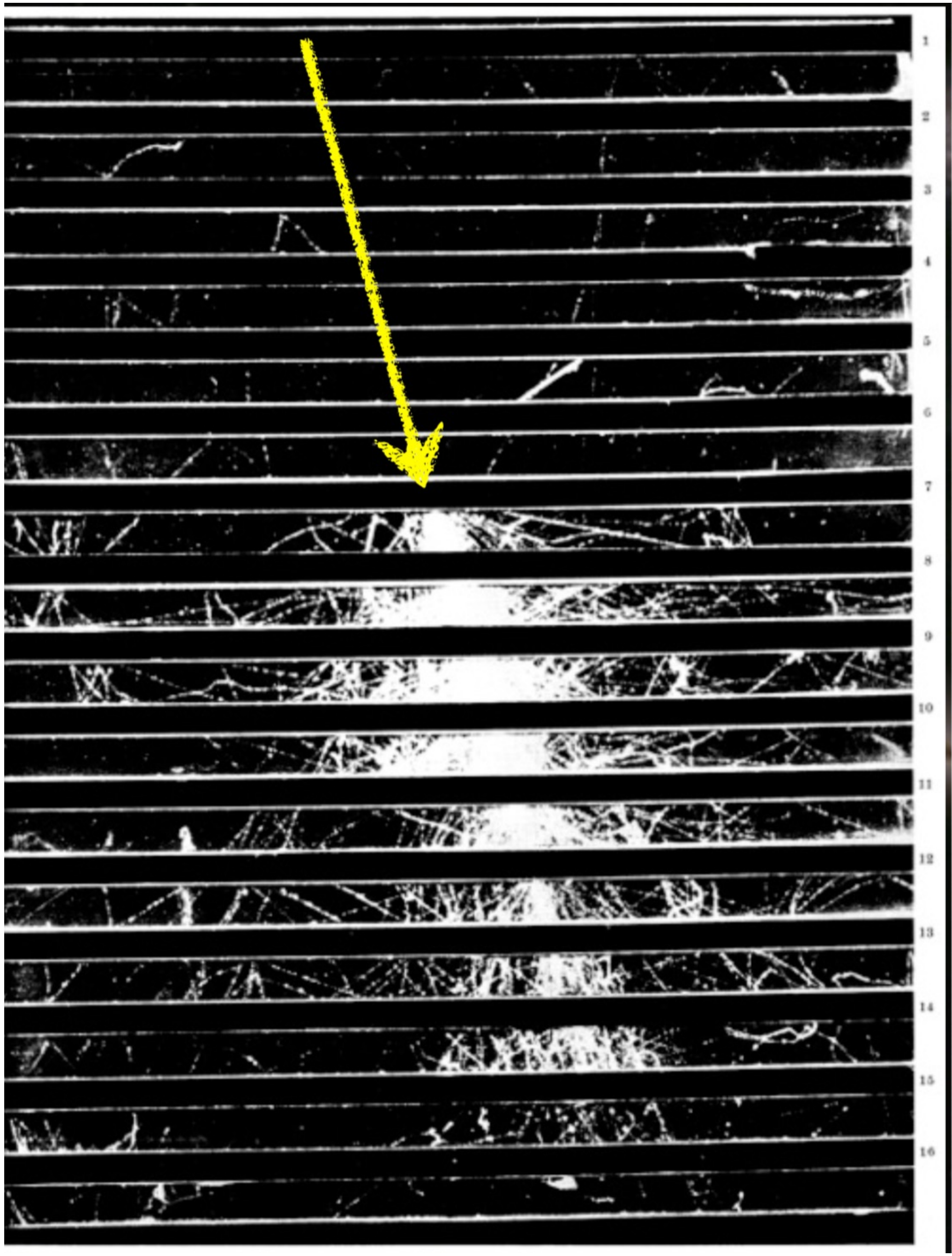

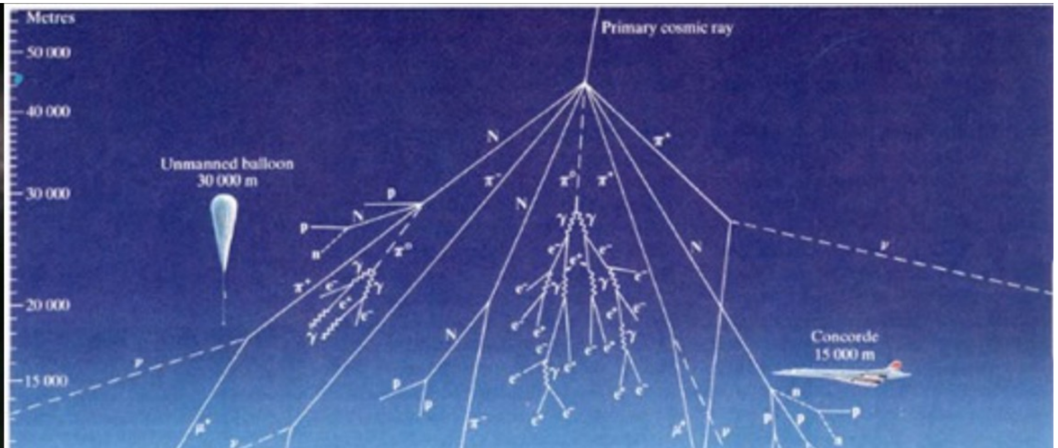

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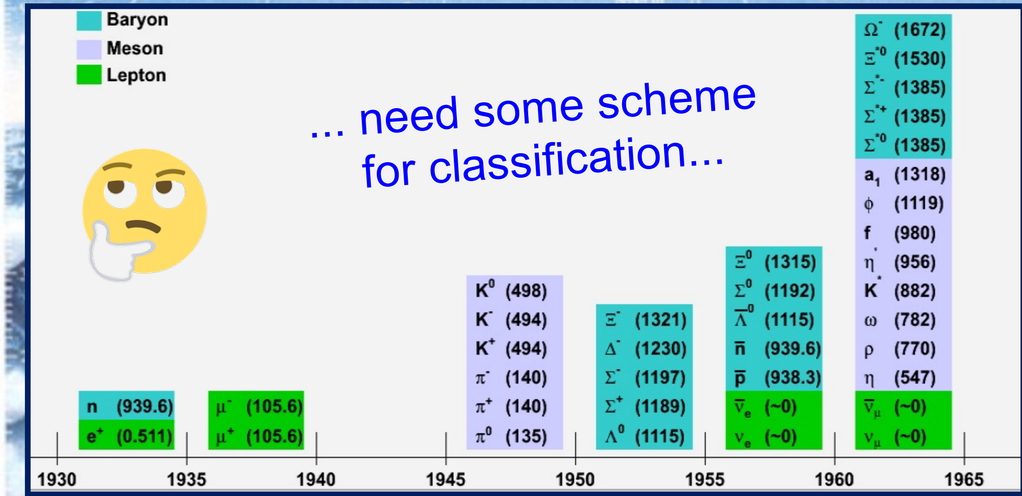

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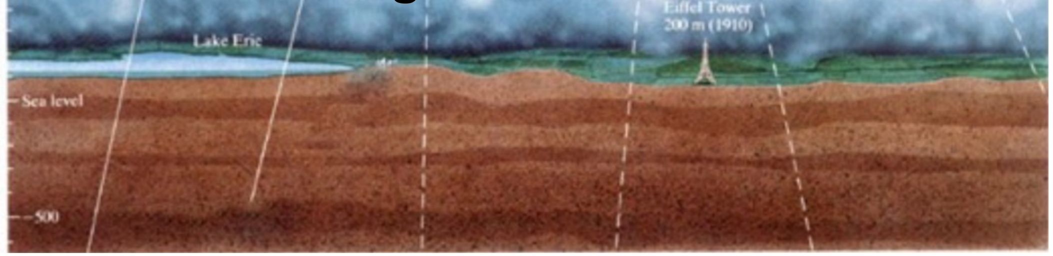
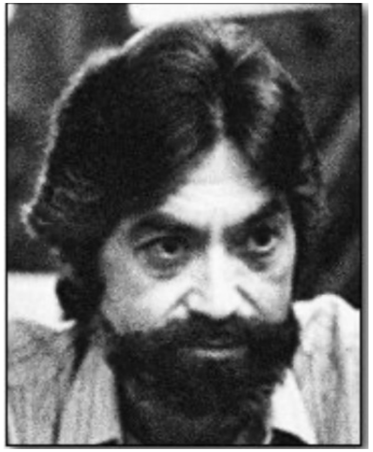


The successful Quark Model

1964



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

Received 4 January 1964

. . .

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

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

. . .

6) 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".

Geburt der Teilchen- und Hadronenphysik

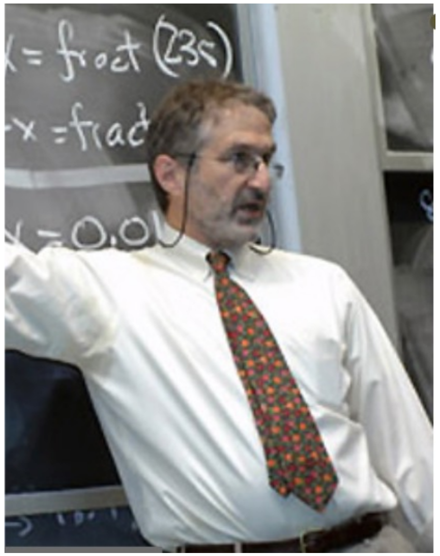
PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

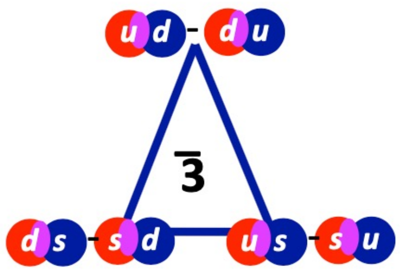
Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

R. J. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [ϵ(700), S^*,δ,κ] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L=1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.



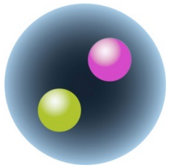


Antisymmetric in:
color
flavor
spin (S=0)

Mesons and exotic states

Simple Quark model

- Mesons: Color neutral $q\bar{q}$ systems

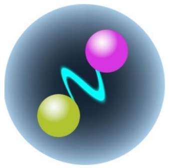


Conventional ($q\bar{q}$)

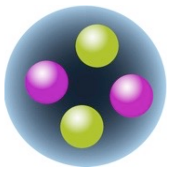
QCD

- Meson states beyond $q\bar{q}$

Alternative 4-quark configurations:

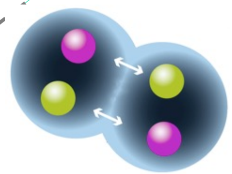


Hybrid ($q\bar{q}$) g

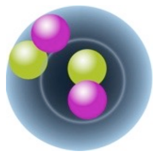


Tetraquark ($q\bar{q}q\bar{q}$)

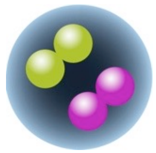
Glue-ball (gg) or (ggg)



Molecule ($q\bar{q}$)($q\bar{q}$)



Hadro-quarkonium ($Q\bar{Q}$)($q\bar{q}$)



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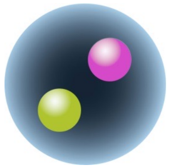

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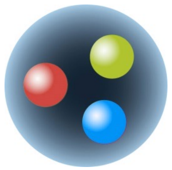

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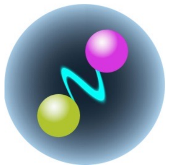

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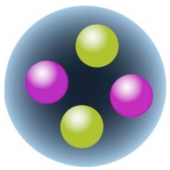

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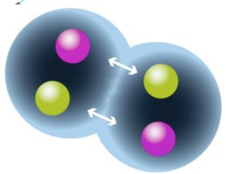

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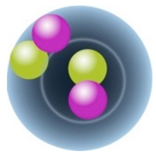

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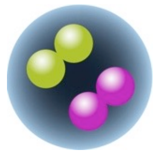

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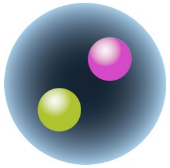

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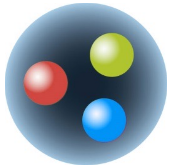
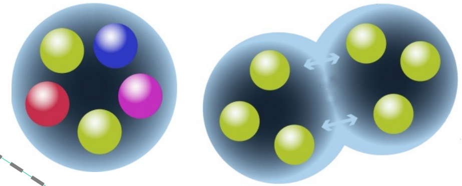


Lead to further alternative multi-quark configurations:



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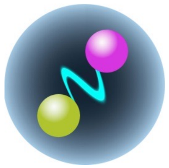

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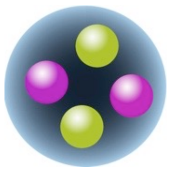

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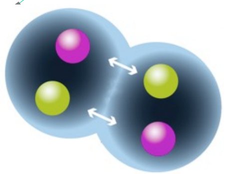

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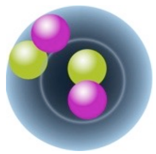

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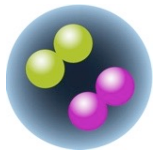

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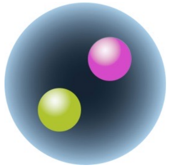

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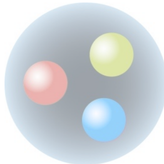

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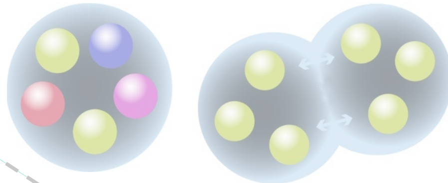

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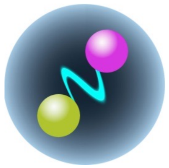

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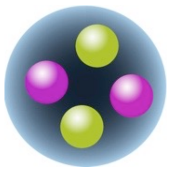

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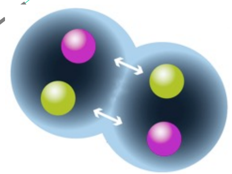

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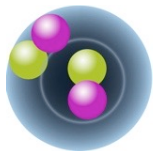

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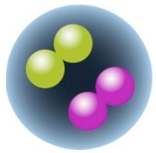
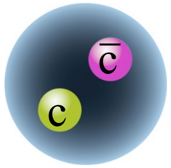
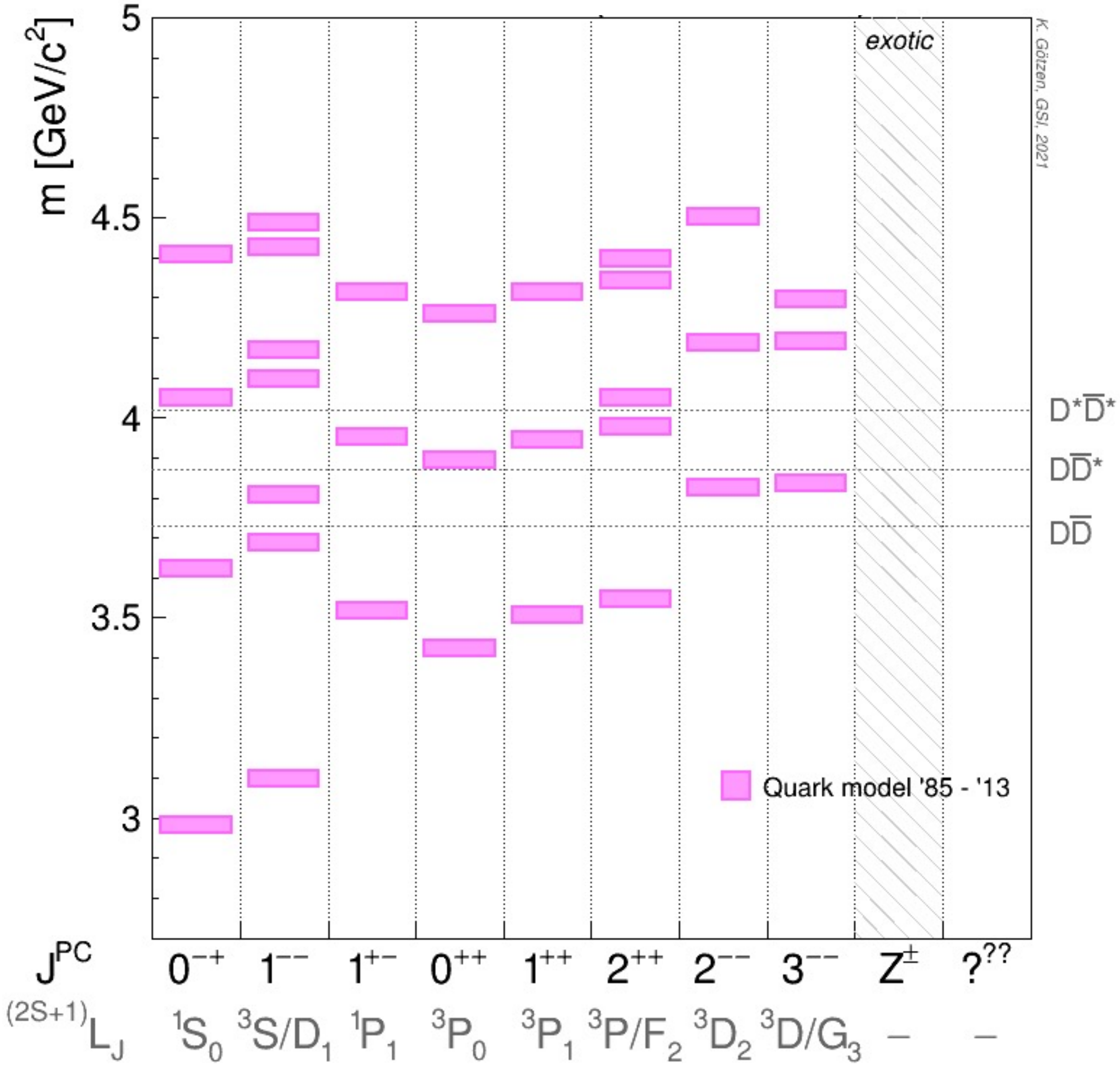


Di-quarkonium $(qq)(\bar{q}\bar{q})$

Charmonium spectrum ($c\bar{c}$)





Potential model:

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

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+ relativistic corrections!

[Godfrey & Isgur, PRD 32 (1985) 189]

[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]

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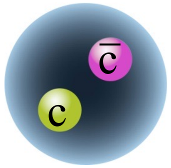

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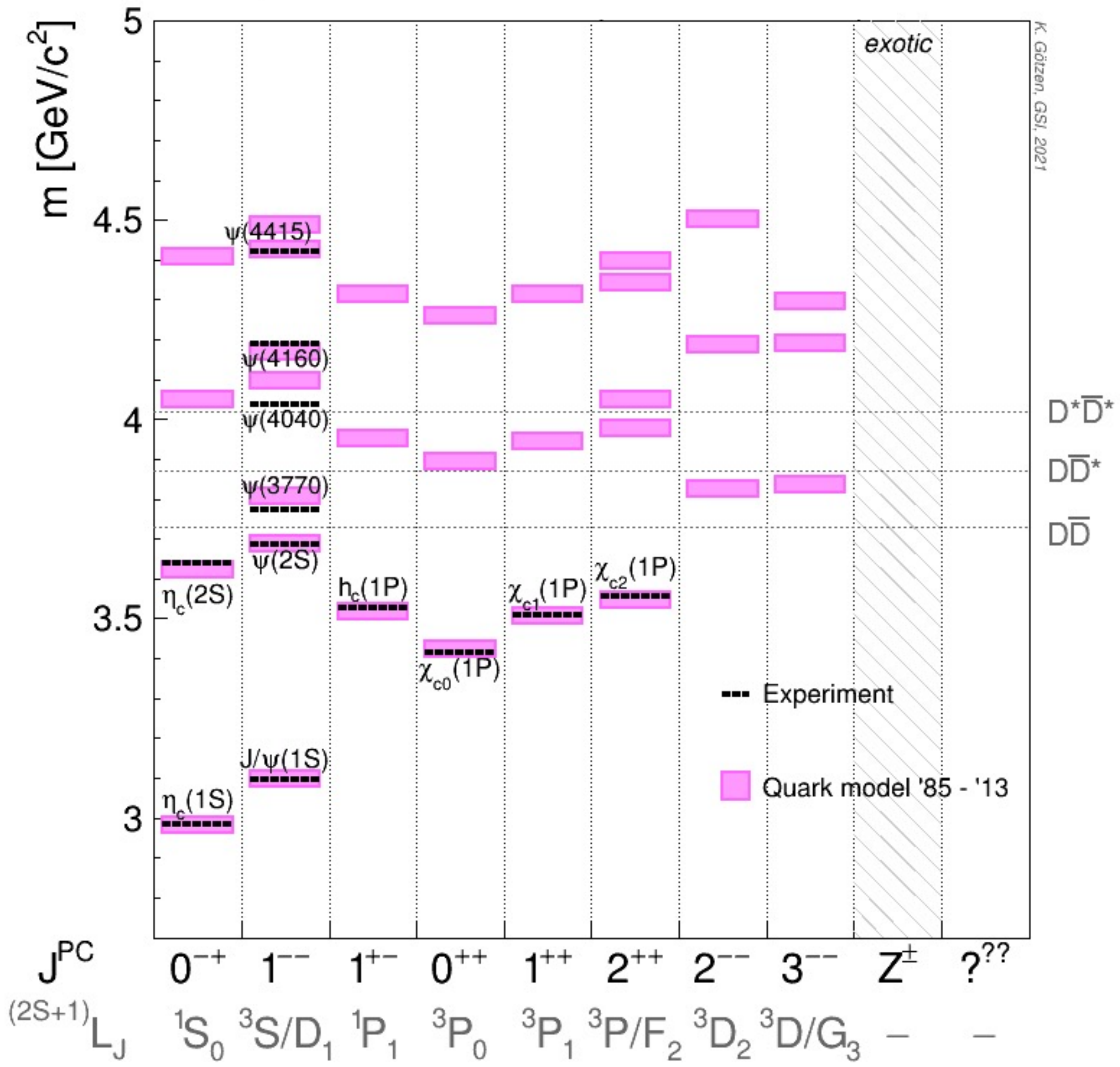

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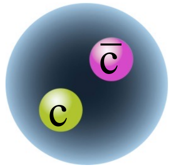

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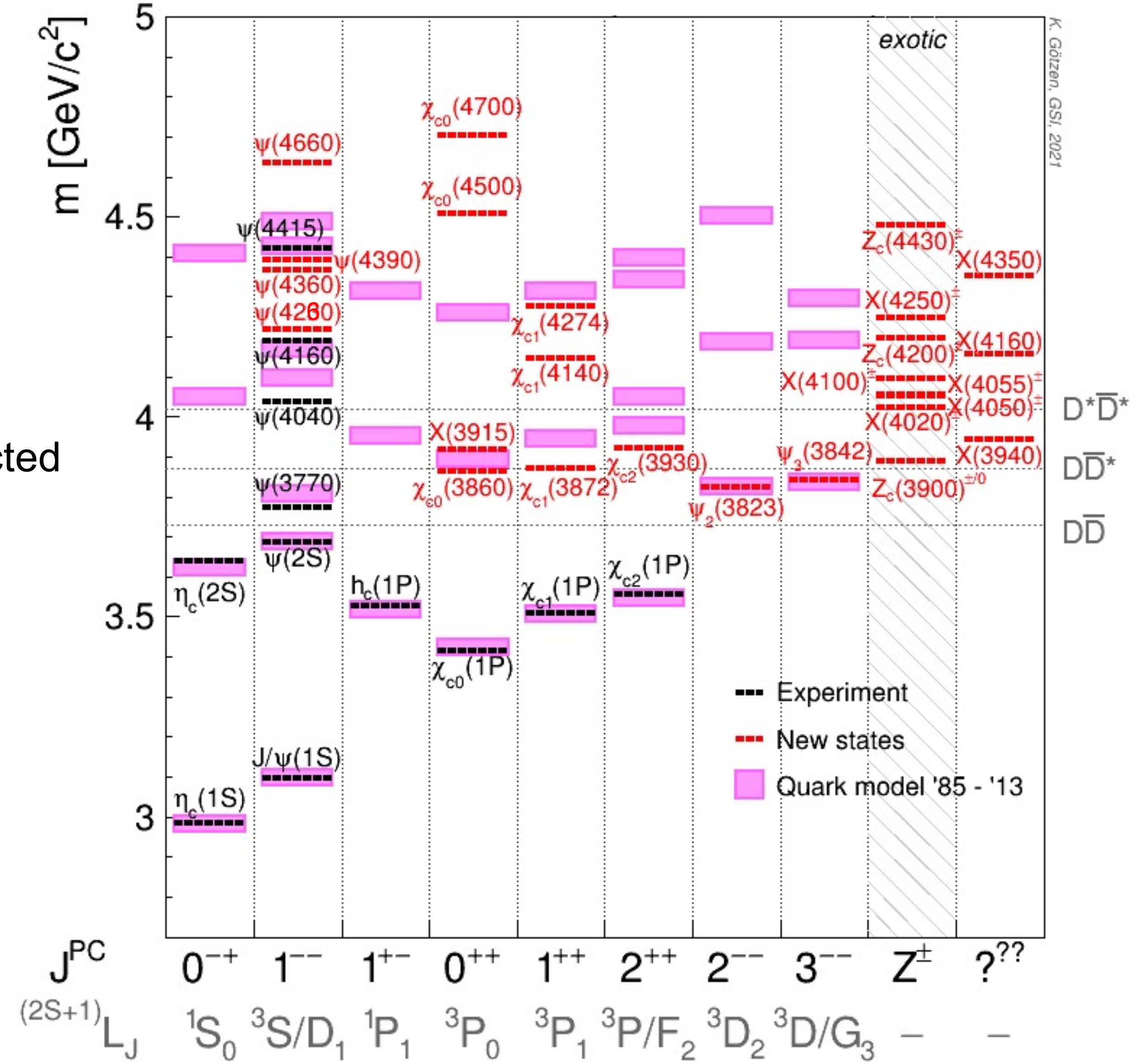
- After 2003:
  - ➢ Severe mismatch between predicted and observed spectrum



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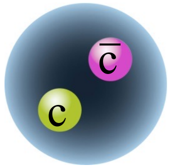
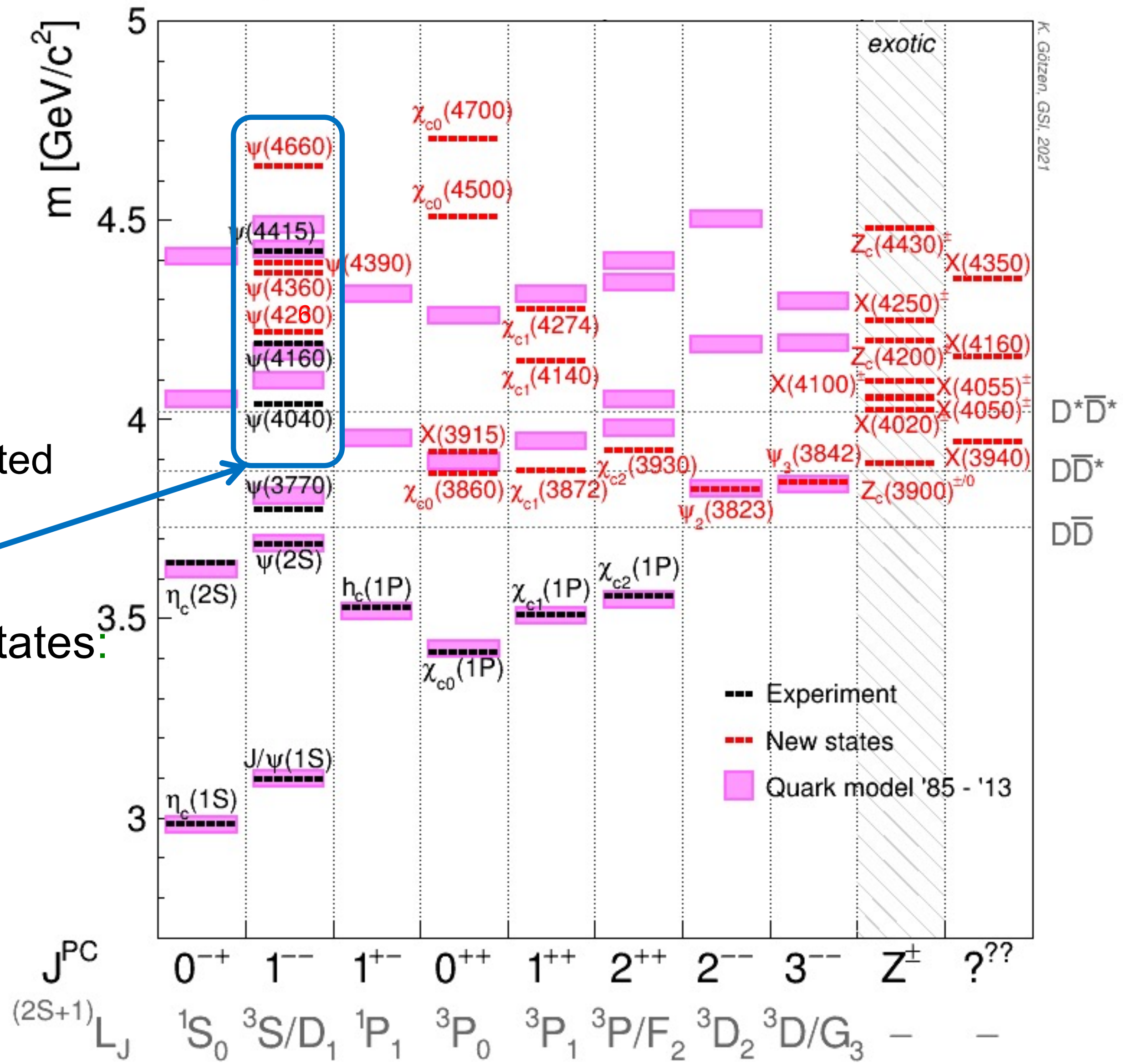
[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]

Charmonium spectrum ($c\bar{c}$)



- Before 2003:
  - ➢ Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - ➢ Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: Y(4260), ..., Y(4660)



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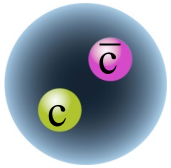

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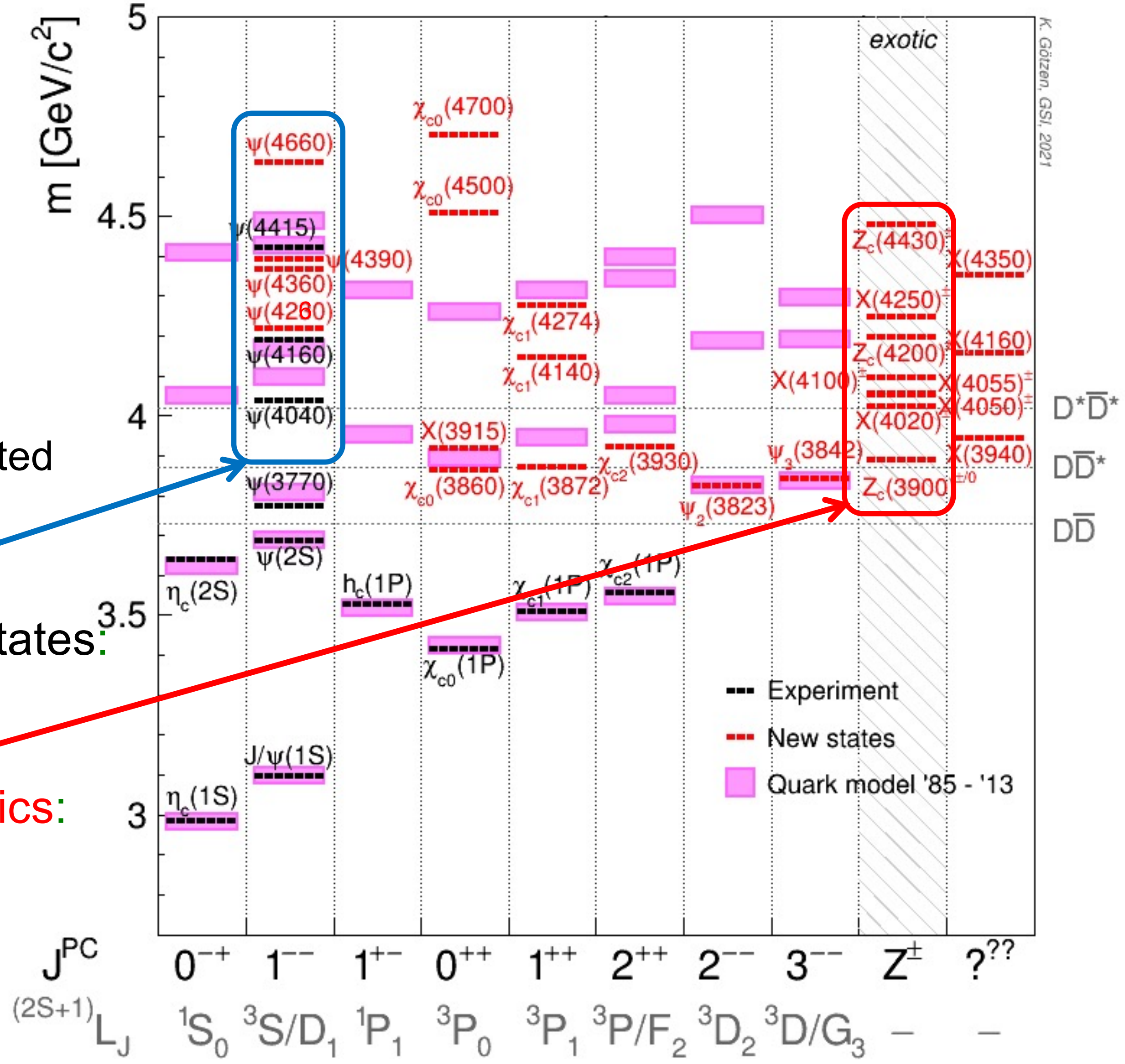
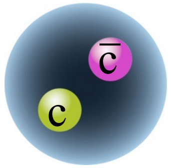


Charmonium spectrum ($c\bar{c}$)



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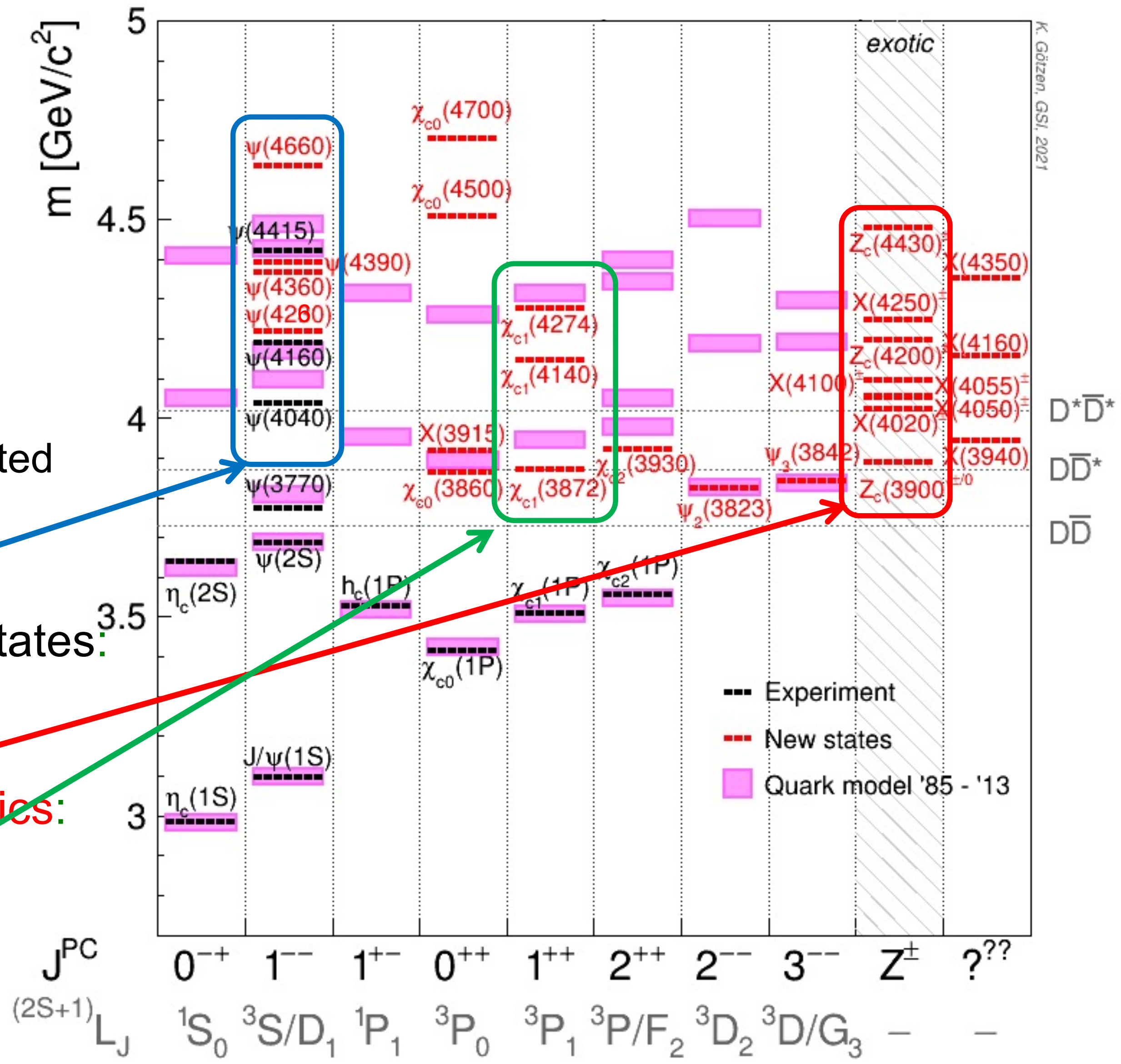
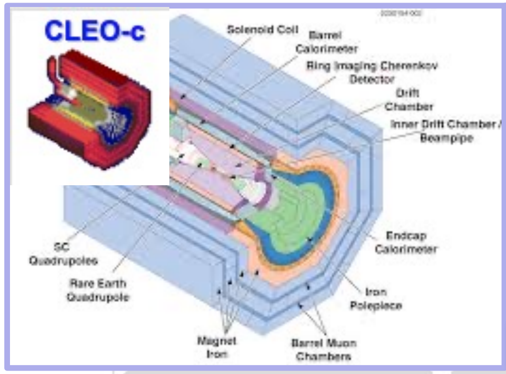
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$
- The X states – the $\chi_{c1}(3872)$ was the first observed in 2003



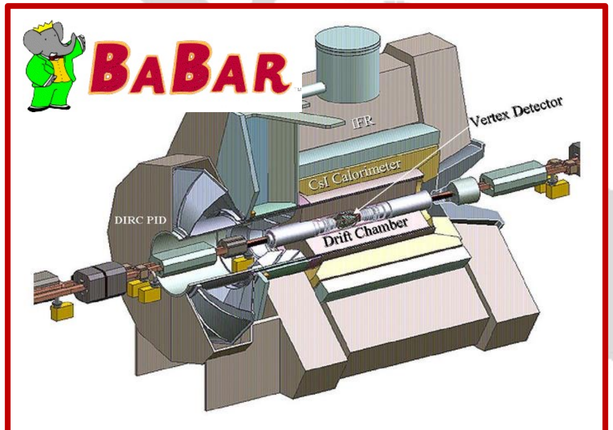
Major labs and past experiments



- Data taking 1980 – 2000 (2002 – 2008)
- e^+e^- collider, $E_{cms} \leq 3$ -12 GeV

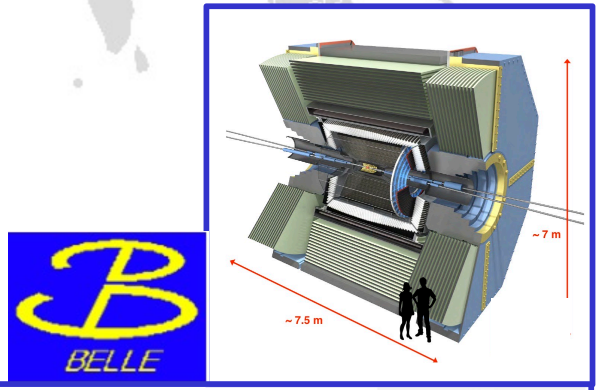
Cornell University (CESR)

SLAC Stanford (PEP-II)



- Data taking 1999 – 2008
- e^+e^- collider, $E_{cms} \leq 10.58$ GeV

KEKB Tsukuba



- Data taking 1999 – 2010
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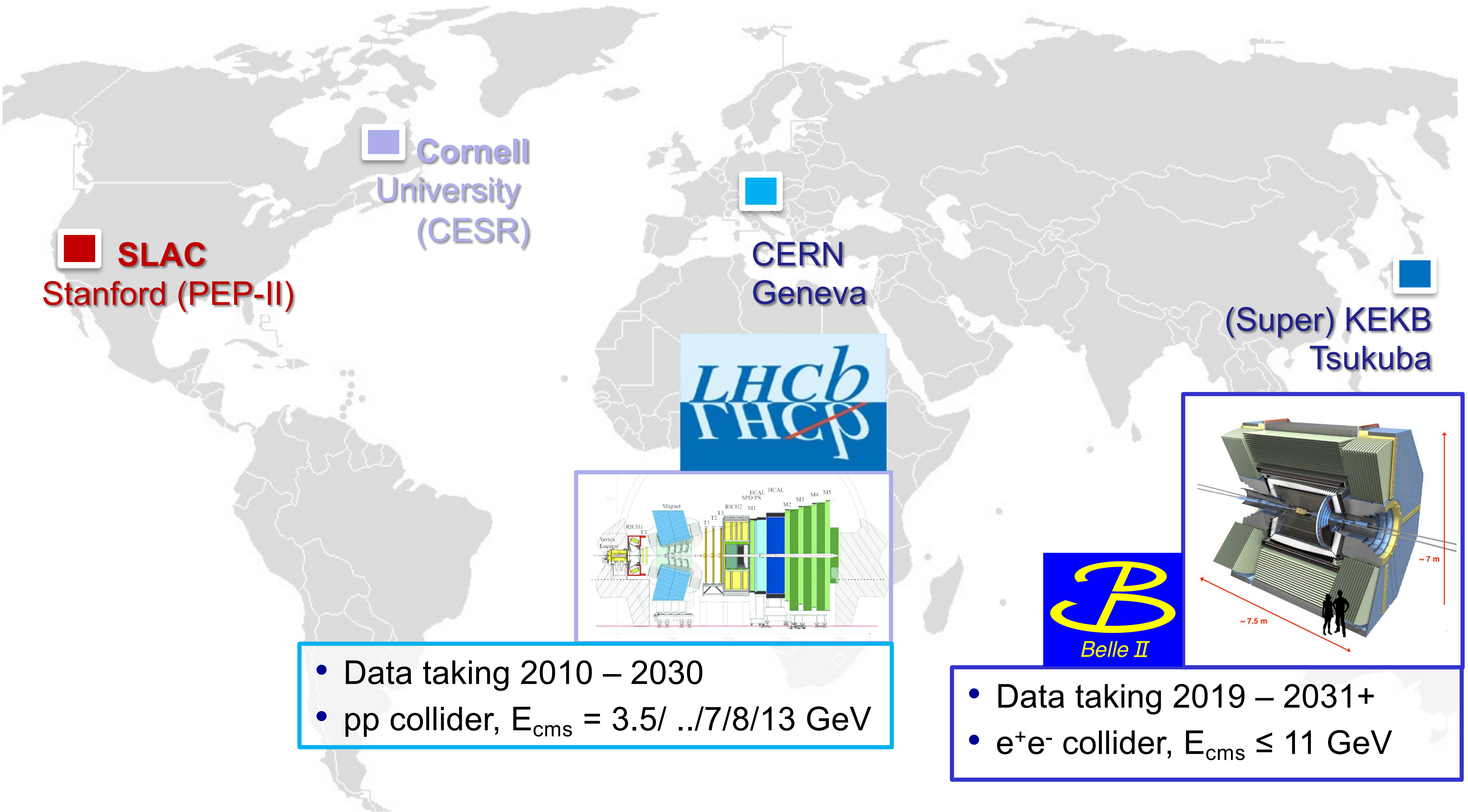
Major labs and running experiments



- Data taking 2010 – 2030
- pp collider, E_{cms} = 3.5/ ../7/8/13 GeV

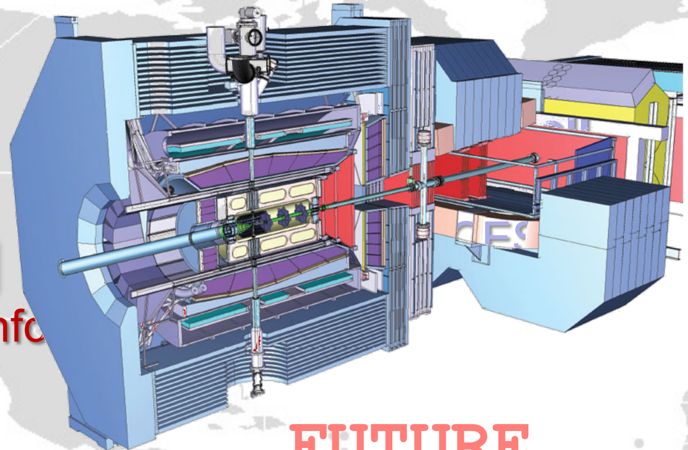
- Data taking 2019 – 2031+
- e^+e^- collider, $E_{cms} \leq 11$ GeV

Major labs and running experiments

- Data taking 2008 – 2030
- e^+e^- collider, $E_{cms} \leq 4.6$ / 4.9 GeV

BESIII

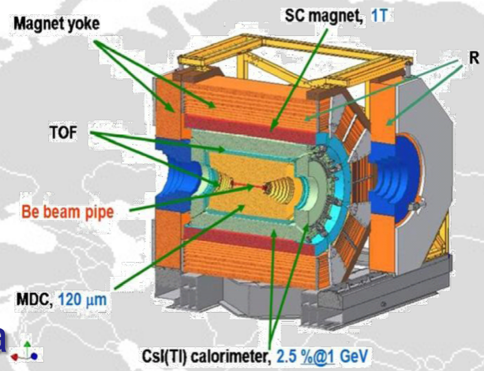
IHEP Beijing (BEPC-II)



FAIR / GSI Darmstadt

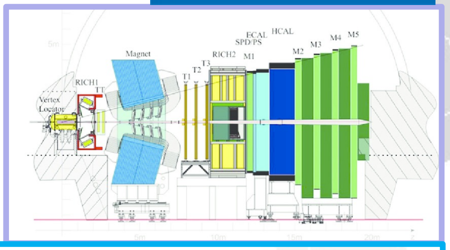
FUTURE

- Data taking starts 2025
- $p\bar{p}$ annihilation, $E_{cms} \leq 5.5$ GeV



CERN Geneva

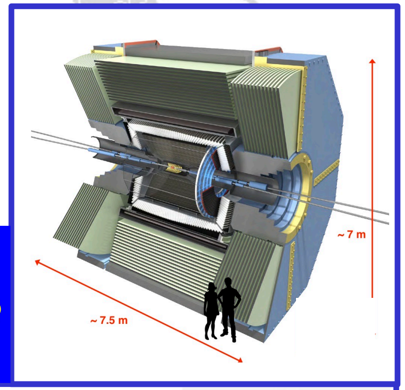
LHCb



- Data taking 2010 – 2030
- pp collider, E_{cms} = 3.5/ ../7/8/13 GeV

(Super) KEKB Tsukuba

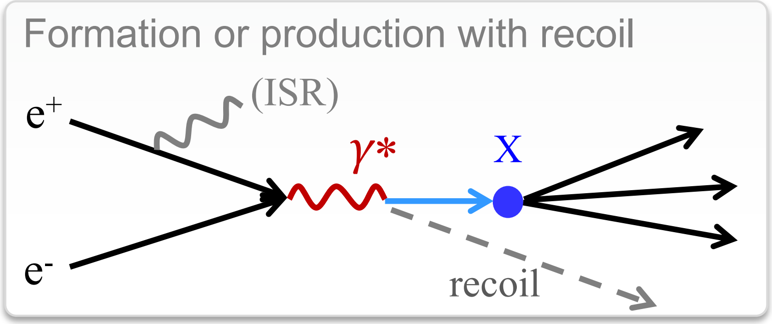
Belle II



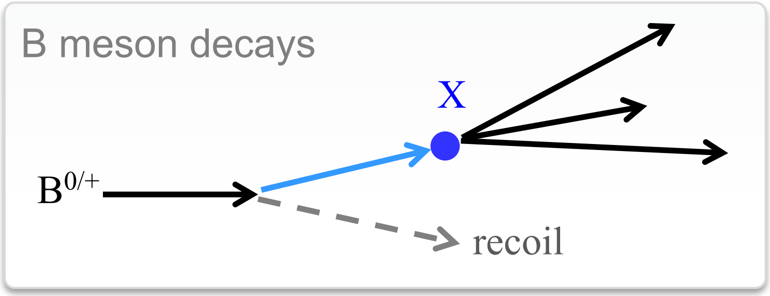
- Data taking 2019 – 2031+
- e^+e^- collider, $E_{cms} \leq 11$ GeV

Stanford

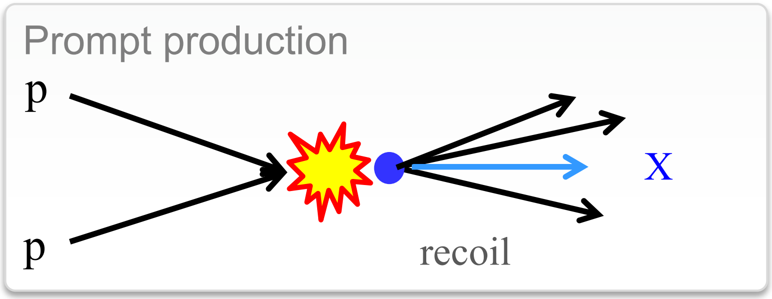
Production mechanisms of hadrons



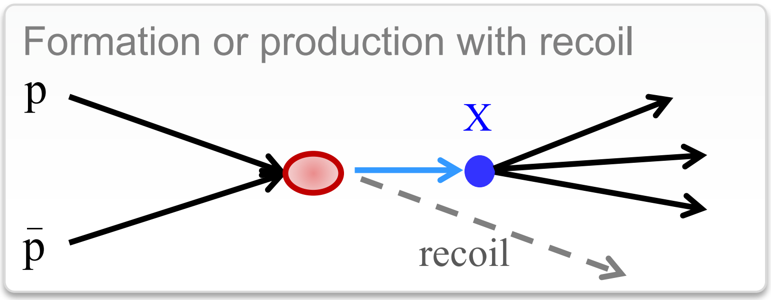
- Formation & Production with recoil particle(s)
  - CLEO(-c), BaBar, Belle(II) ($E_{cms} \leq 12$ GeV)
  - BESI-III ($E_{cms} \leq 4.9$ GeV)



- B meson decays
  - CLEO, BaBar, Belle(II) ($E_{cms} \leq 12$ GeV)
  - LHCb: pp (7 TeV/c)



- Prompt production
  - LHCb: pp (7 TeV/c),
  - also CDF, ATLAS, CMS ...



- Formation & Production with recoil particle(s)
  - E760/E835, PANDA ($E_{cms} \leq 5.5$ GeV)
  - No running experiment presently

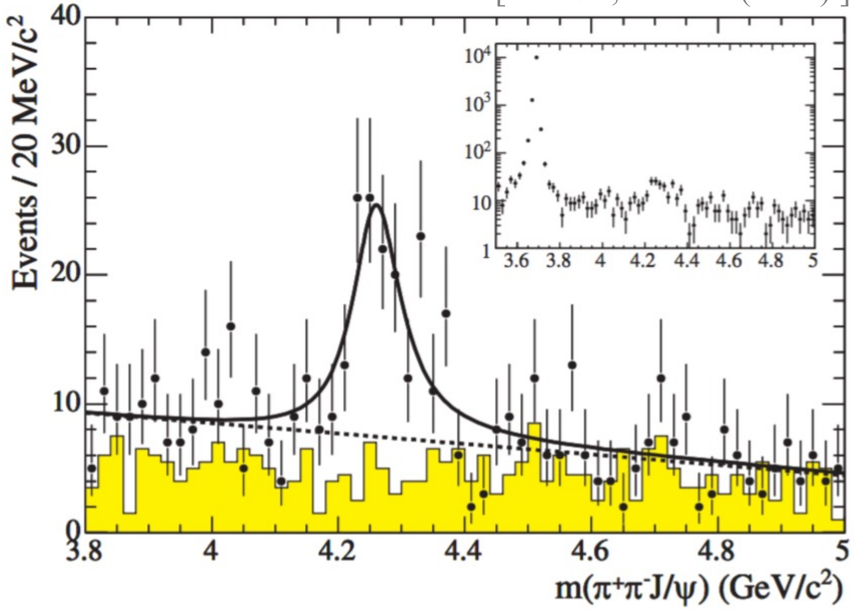
The Y(4260) and further supernumerary vector states

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

Some history:

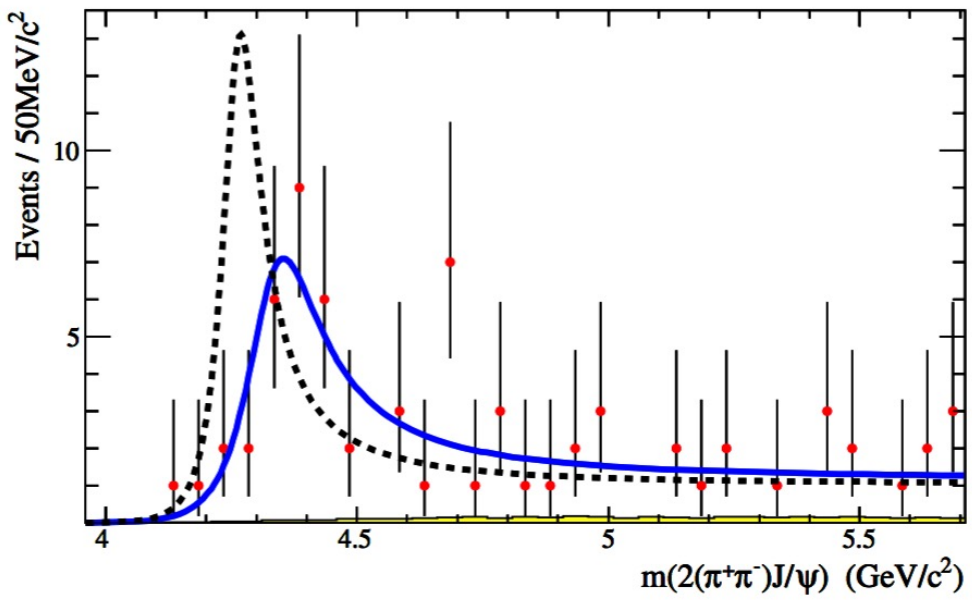
$e^+e^- \to J/\psi\pi^+\pi^-$

[PRL 95, 142001 (2005)]



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

[PRL 98, 212001 (2007)]



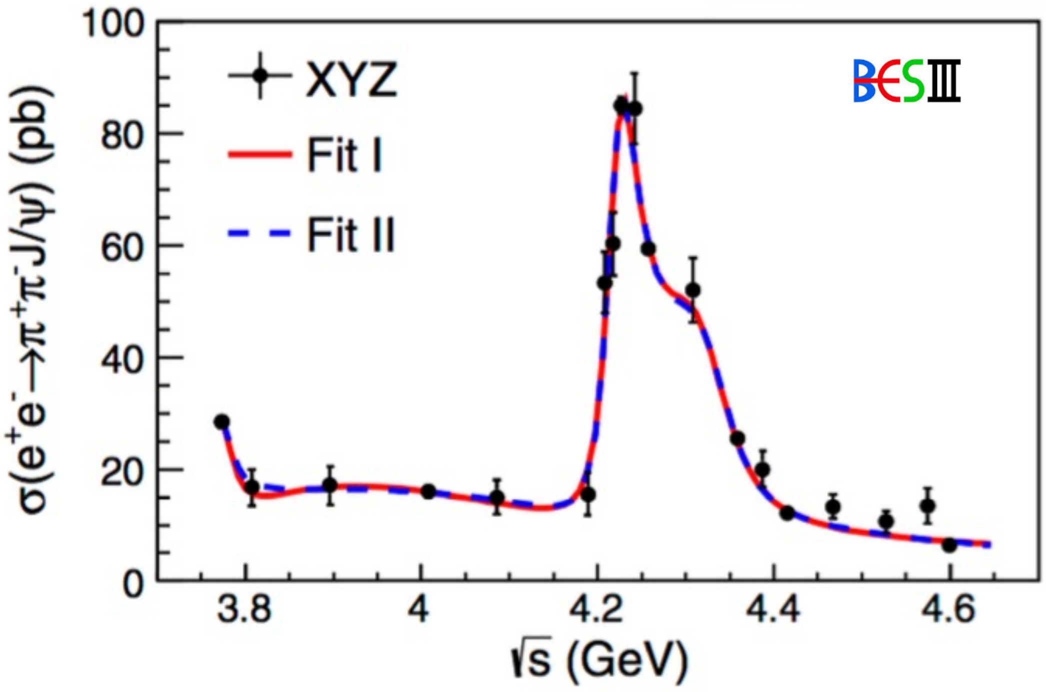
- Discovery of the Y(4260) using ISR by BaBar in $J/\psi\pi^+\pi^-$
- Discovery of the Y(4360) using ISR by BaBar in $\psi(2S)\pi^+\pi^-$

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

BESIII result, published

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

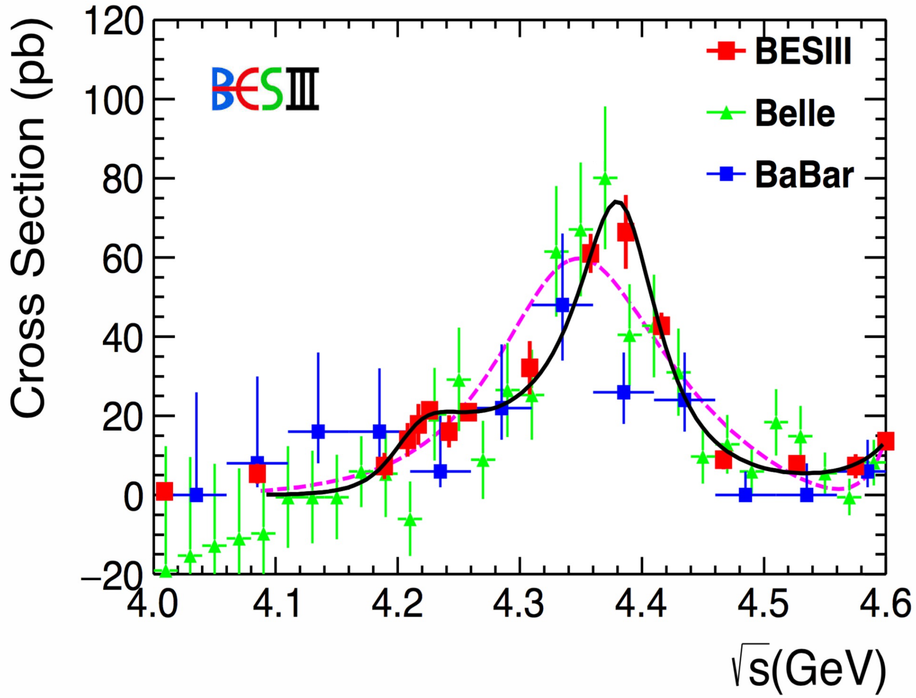
[PRL 118, 092001 (2017)]



- Cross-section inconsistent with the single resonance Y(4260)!
  - ➢ Two favoured over one by >7σ

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

[Phys. Rev. D 96, 032004 (2017)]

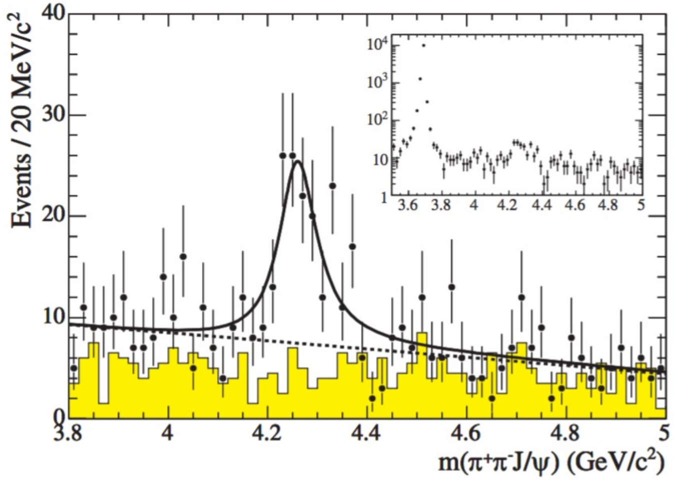


- BESIII: Much higher precision (5.8σ)
- Coherent BW fit: Y(4220) and Y(4390)

What happened to the Y states?

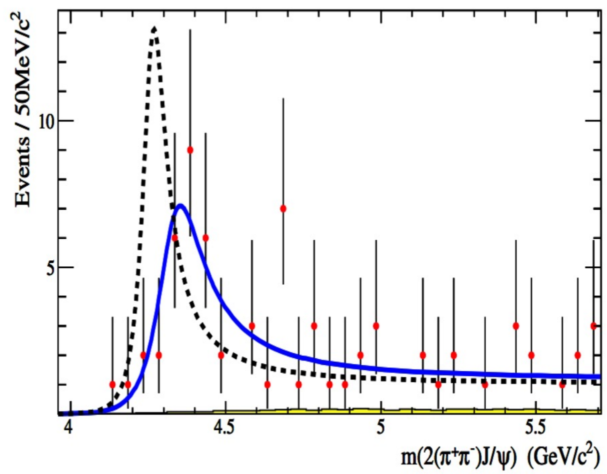
$e^+e^- \to J/\psi\pi^+\pi^-$

[BaBar, PRL 95, 142001 (2005)]

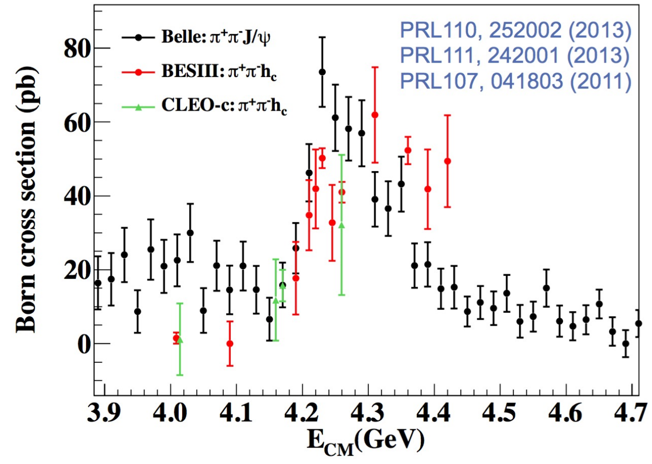


$e^+e^- \to \psi(2S)\pi^+\pi^-$

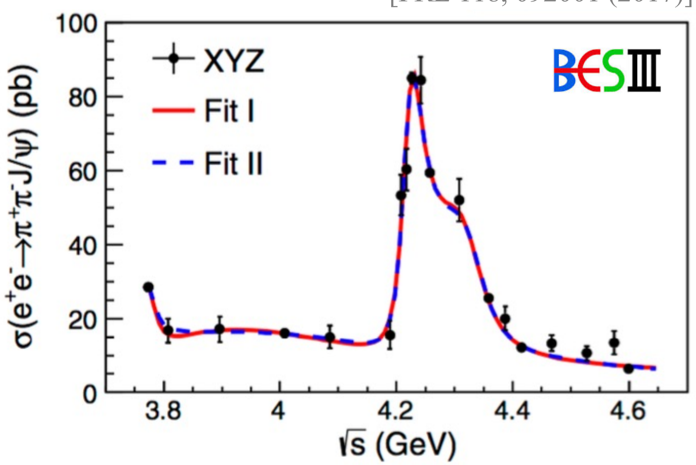
[BaBar, PRL 98, 212001 (2007)]



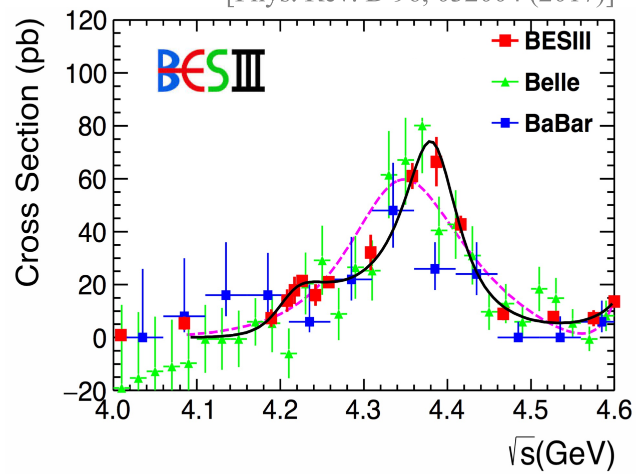
$e^+e^- \to h_c\pi^+\pi^-$



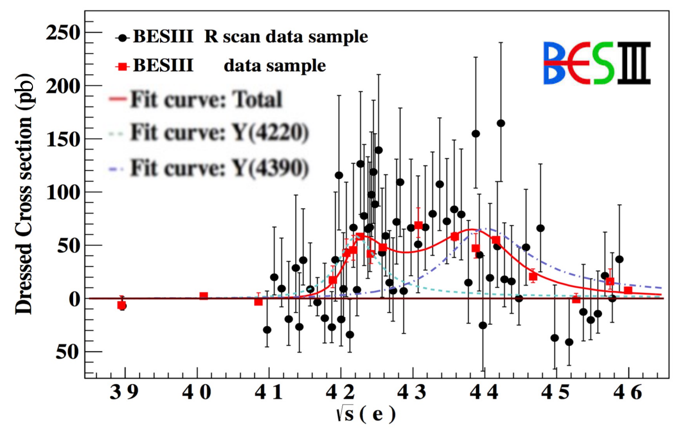
[PRL 118, 092001 (2017)]



[Phys. Rev. D 96, 032004 (2017)]



[Phys. Rev. Lett. 118 092002 (2017)]

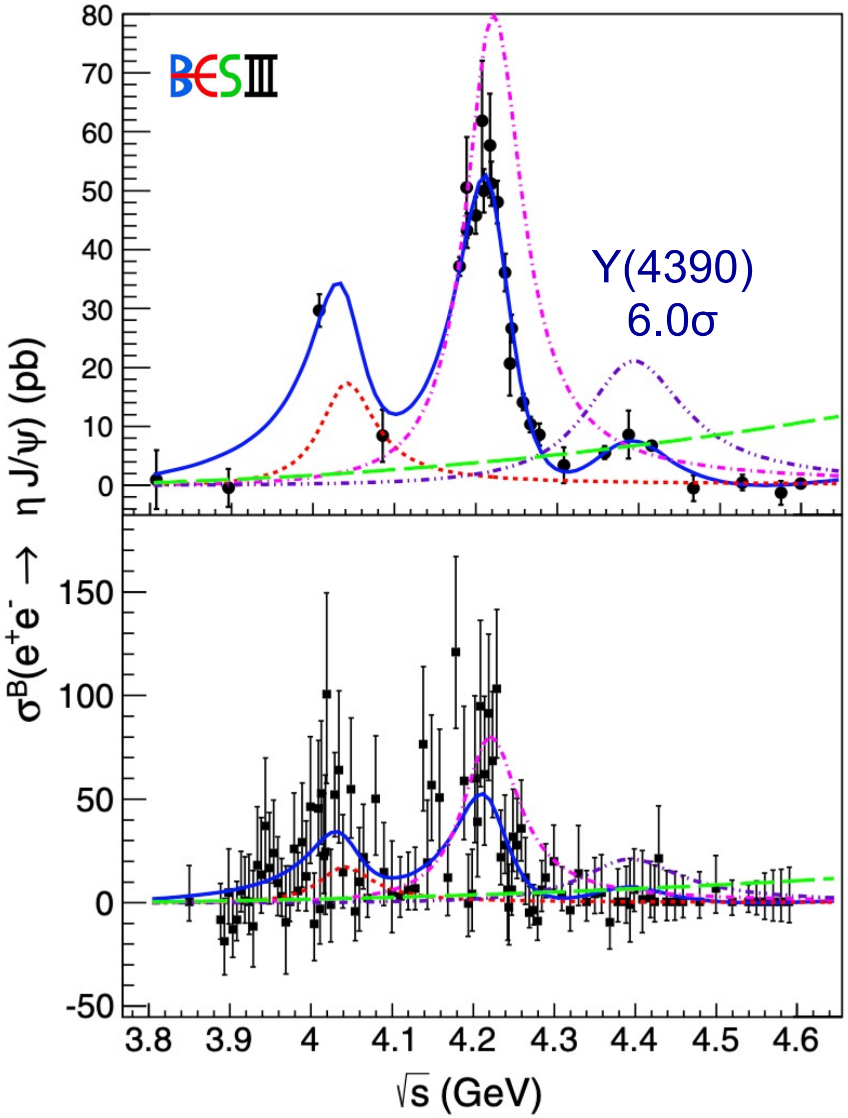


Two structures now resolved: Y(4260) → Y(4220) , Y(4360) → Y(4390)

Further decays of Y(4260)

$e^+e^- \to J/\psi\ \eta$

[Phys. Rev. D 102, 031101 (2020)]

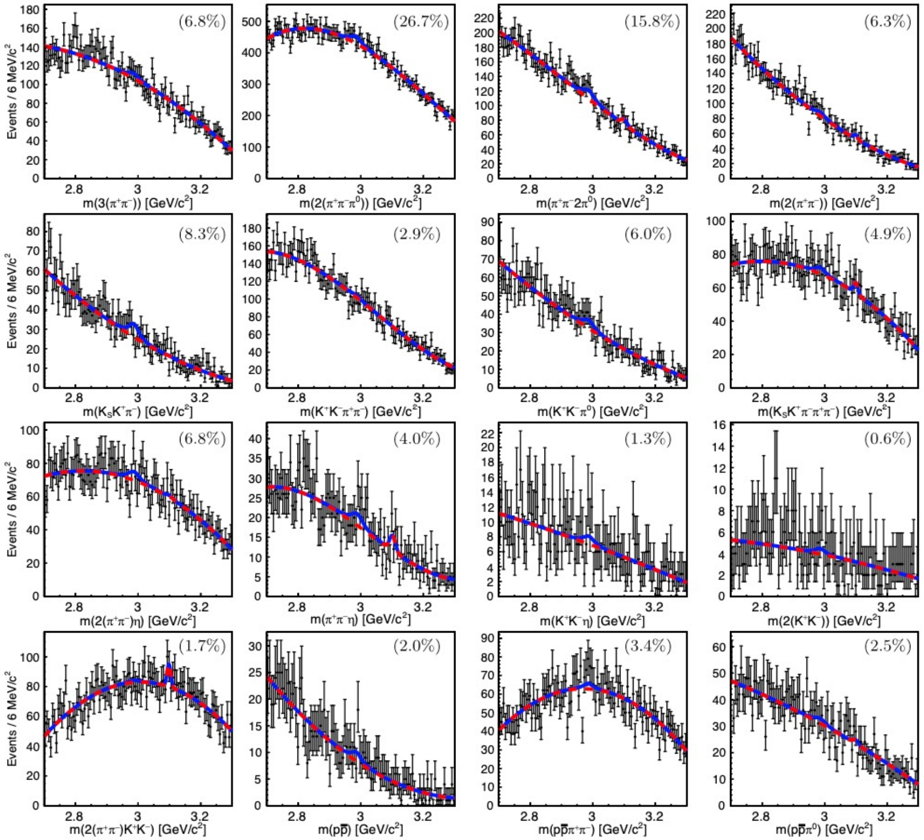


- Simultaneous maximum-likelihood fit (*Top: High stat. XYZ data, Bottom: Scan data)*
- ψ(4040) assumed, Y(4220), Y(4390) ?
- Significance of Y(4390) = 6.0 σ

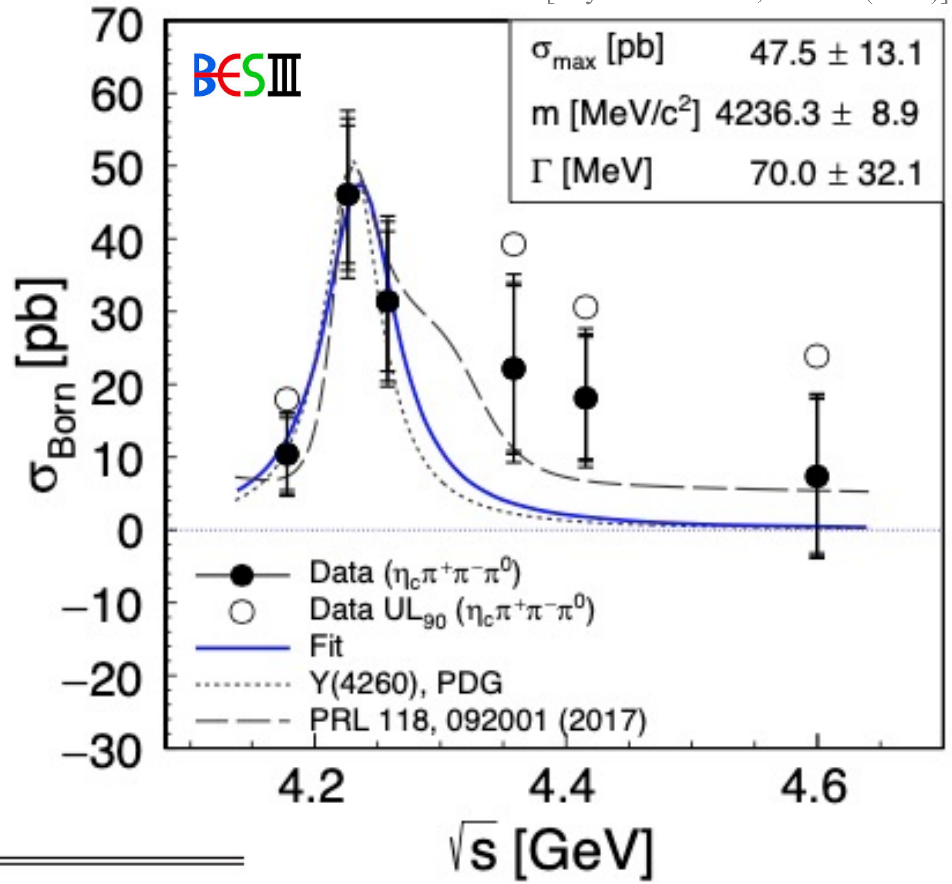
Parameters	Solution 1	Solution 2	Solution 3
$M_1(\mathrm{MeV}/c^2)$		4039(fixed)	
$\Gamma_1(\mathrm{MeV})$		80(fixed)	
$\Gamma_1^{e^+e^-}\mathcal{B}r_1$ (eV)	1.5 ± 0.3	1.4 ± 0.3	7.0 ± 0.6
ϕ_1 (rad)	3.3 ± 0.3	3.1 ± 0.3	4.5 ± 0.2
$M_2(\mathrm{MeV}/c^2)$		4218.6 ± 3.8	
$\Gamma_2(\mathrm{MeV})$		82.0 ± 5.7	
$\Gamma_2^{e^+e^-}\mathcal{B}r_2$ (eV)	8.0 ± 1.7	4.8 ± 1.0	7.0 ± 1.5
ϕ_2 (rad)	4.2 ± 0.4	3.6 ± 0.3	2.9 ± 0.3
$M_3(\mathrm{MeV}/c^2)$		4382.0 ± 13.3	
$\Gamma_3(\mathrm{MeV})$		135.8 ± 60.8	
$\Gamma_3^{e^+e^-}\mathcal{B}r_3$ (eV)	3.4 ± 2.2	1.5 ± 1.0	1.7 ± 1.1
ϕ_3 (rad)	2.8 ± 0.4	3.3 ± 0.4	3.0 ± 0.4

Further decays of Y(4260)

$e^+e^- \to \eta_c \pi^+\pi^-\pi^0$



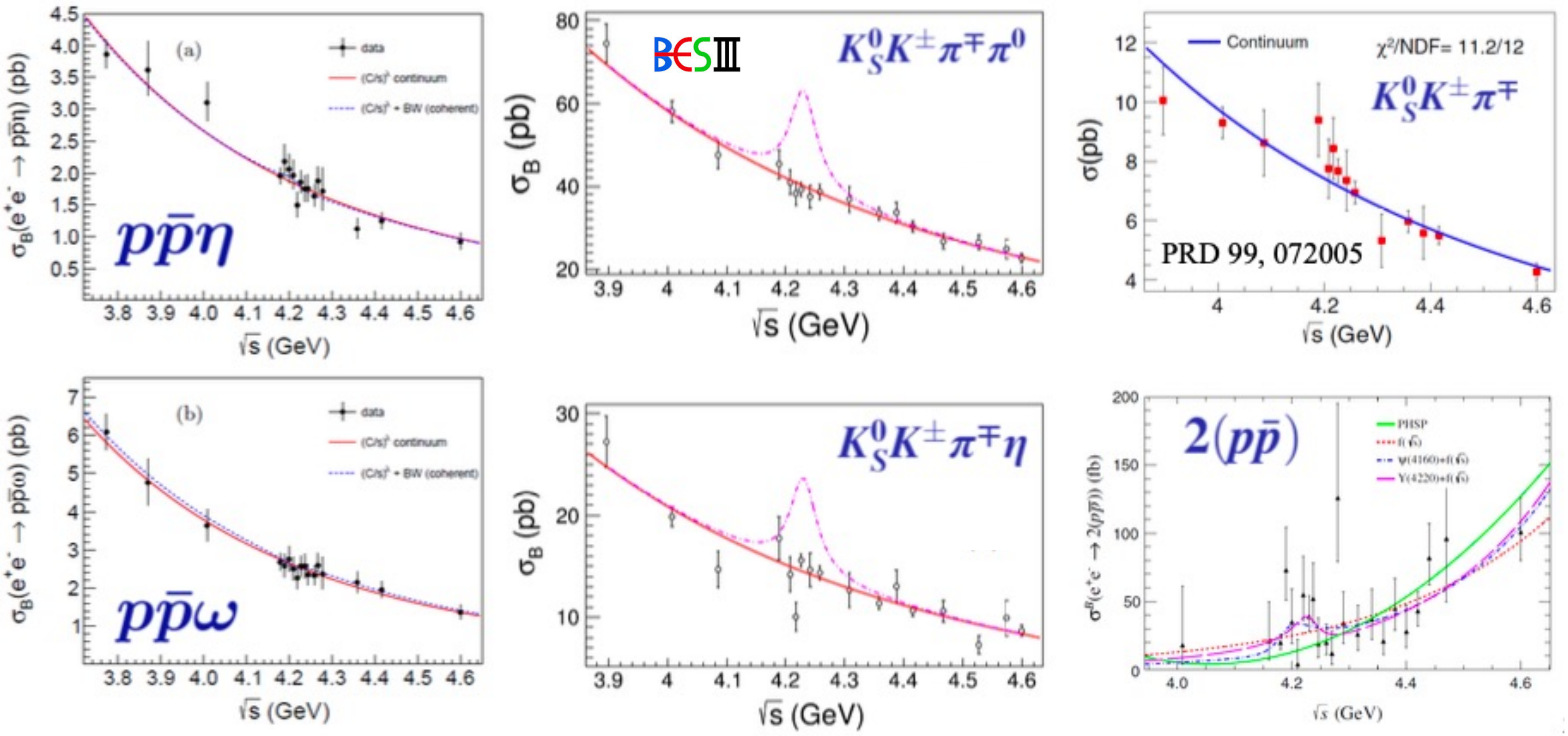
[Phys. Rev. D 103, 032006 (2021)]



				$e^+e^- \to \eta_c\pi^+\pi^-\pi^0$				
$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	$N_{\rm obs}$	κ	$f_{\rm VP}$	$\sum \epsilon_i \mathcal{B}_i$ [%]	$\sigma_{\rm Born}$ [pb]	UL$_{90}$ [pb]	$\mathcal{S}_{\rm stat}/\mathcal{S}_{\rm tot}$ [σ]
4.1780	3189.0	530 ± 246	[0.720, 0.734]	1.056	2.0	$10.4^{+5.0}_{-4.9} \pm 2.9$	17.9	2.2/1.9
4.2263	1091.7	786 ± 159	[0.716, 0.731]	1.056	2.0	$46.1^{+9.5}_{-9.4} \pm 6.6$	61.0	5.1/4.6
4.2580	825.7	465 ± 134	[0.786, 0.824]	1.054	2.0	$31.4^{+9.6}_{-9.6} \pm 6.7$	46.6	3.5/3.2
4.3583	539.8	242 ± 115	[0.802, 0.880]	1.051	2.1	$22.2^{+11.4}_{-11.3} \pm 6.2$	39.2	2.2/1.9
4.4156	1073.6	379 ± 165	[0.780, 0.850]	1.053	2.2	$18.1^{+8.4}_{-8.4} \pm 4.5$	30.6	2.3/2.1
4.5995	566.9	79 ± 102	[0.763, 0.807]	1.055	2.0	$7.4^{+10.6}_{-10.5} \pm 3.9$	23.9	0.8/0.7

=> Clear evidence for
$Y(4220) \to \eta_c \pi^+\pi^-\pi^0$

Decays of Y(4260) to light hadrons



arXiv:2102.04268 arXiv:1810.09395 PRD 103, 052003

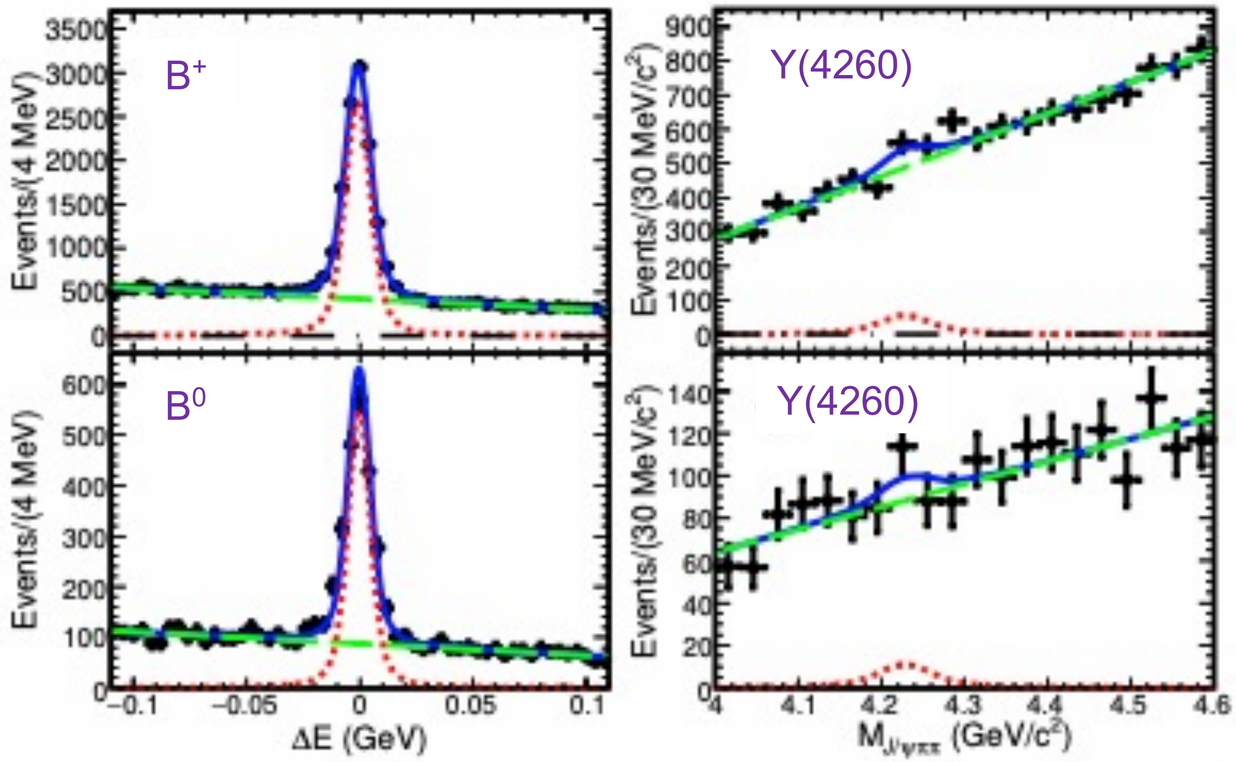
- More and more possible decay channels to light hadrons investigated
- Still no clear evidence ...

The Y(4260) in B decays

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

$$B^0 \to Y(4260)K^0_S \to J/\psi\pi^+\pi^-K^0_S$$

[Phys. Rev. D 99, 071102 (2019)]

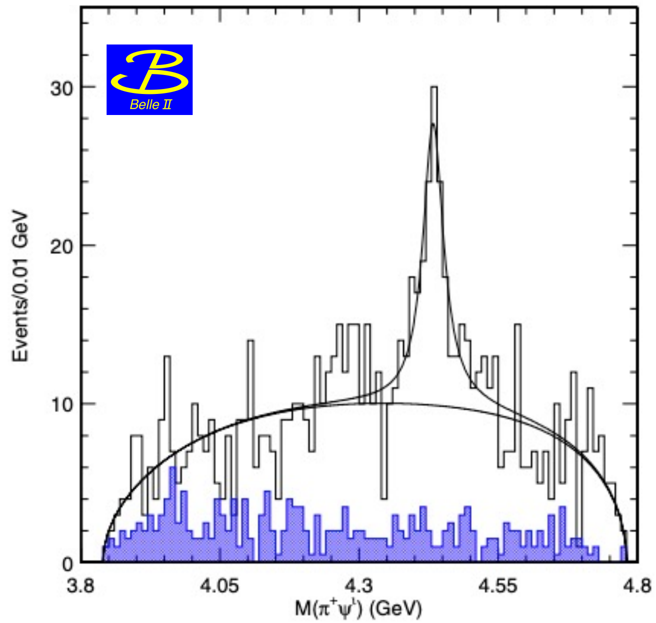


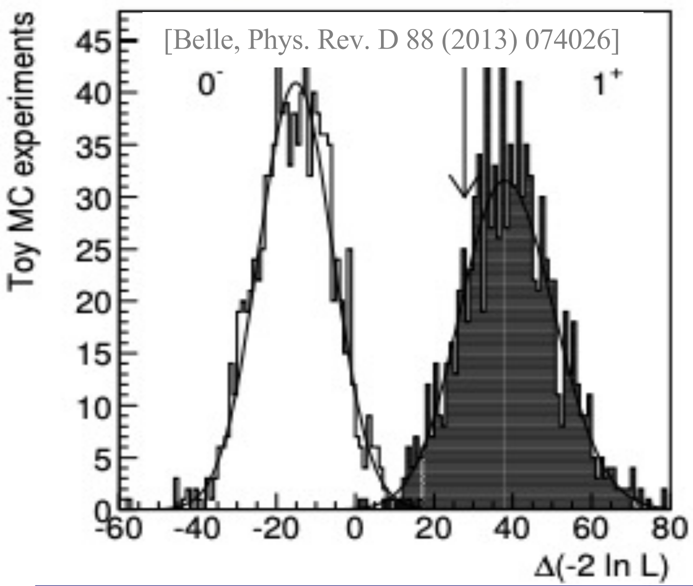
- Search for the Y(4260) in $B^{+/0}$ decays
- BaBar reported 3.1σ for B^+ [PRD 73, 011101 (2006)]
- No significant evidence (2.1σ/0.9σ), for B^0 first result
- Upper limits (CL90) on branching fractions
  - $\mathcal{B}(B^+ \to Y(4260)(\to J/\psi\pi^+\pi^-)K^+) < 1.4 \times 10^{-5}$
  - $\mathcal{B}(B^0 \to Y(4260)(\to J/\psi\pi^+\pi^-)K^0_S) < 1.7 \times 10^{-5}$

The Z(4430) and further (charged) Z_c states

Experimental review of the Z(4430)

[Belle, Phys. Rev. Lett., 100 (2008) 142001]





- First observed by Belle in 2008
  - $B \to K^{\mp} Z(4430)^{\pm} \to K^{\mp}\pi^{\pm}\psi'$
  - relatively narrow state, 6.5 σ
  - first charmonium-like state with a non-zero electric charge

=> Minimal quark content [$c\bar{c}u\bar{d}$] = manifestly exotic

- BaBar searched for it, however, does not confirm [PRD 79, 112001 (2009)]

- Decay to J/ψ/π seen in B decays by Belle [PRD 90, 112009 (2014)], and not seen by BaBar [PRD 79, 112001 (2009)]

- LHCb confirms and showed resonant behavior in argand plot [PRL 112, 222002 (2014)]

- Spin-parity constrained by Belle: $J^P = 1^+$, confirmed by LHCb [PRL 112, 222002 & PRD 92, 112009 (2015)]

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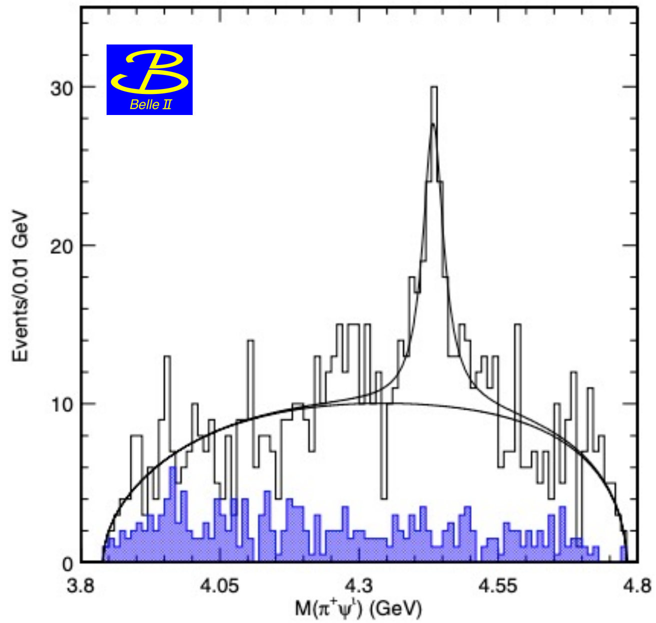

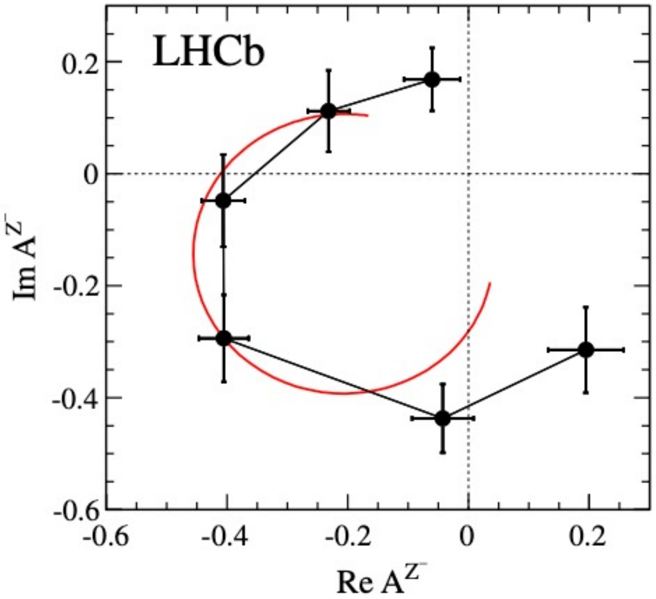

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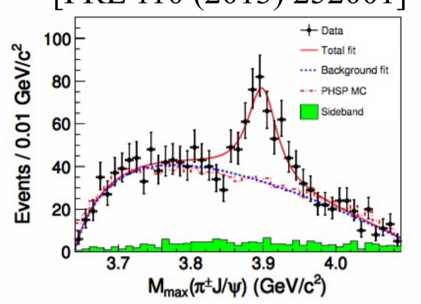
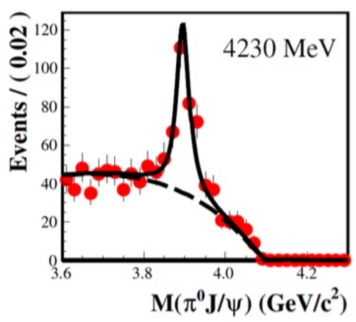
Two Z_c triplets established at BESIII

[PRL 110 (2013) 252001]



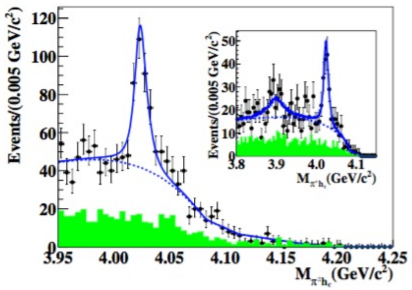
$e^+e^- \to \pi^-\pi^+J/\psi$

[PRL 115 (2015) 112003]



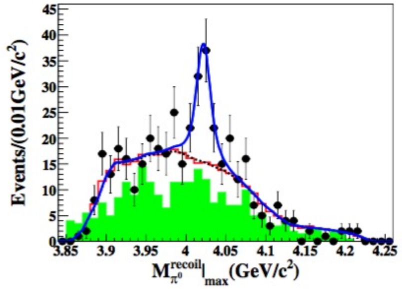
$e^+e^- \to \pi^0\pi^0J/\psi$

[PRL 111 (2013) 242002]



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

[PRL 113 (2014) 212002]



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

Charged **Neutral**

$Z_c(3900)^{\pm,0}$?

Charged **Neutral**

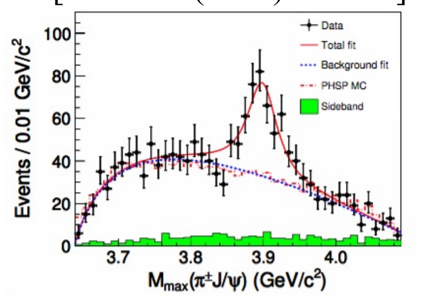
$Z_c(4020)^{\pm,0}$?

- Two isospin triplets of charmonium-like exotic states established

Two Z_c triplets established at BESIII

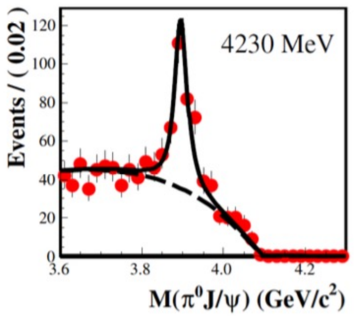
Hidden Charm

[PRL 110 (2013) 252001]



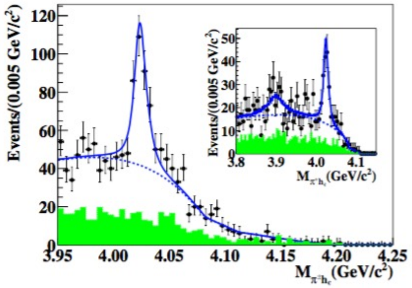
$e^+e^- \to \pi^-\pi^+ J/\psi$

[PRL 115 (2015) 112003]



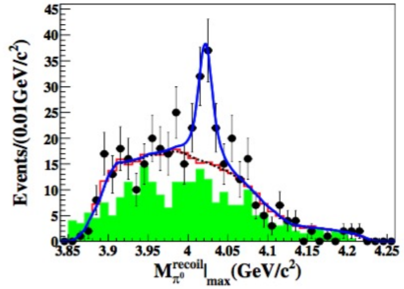
$e^+e^- \to \pi^0\pi^0 J/\psi$

[PRL 111 (2013) 242002]



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

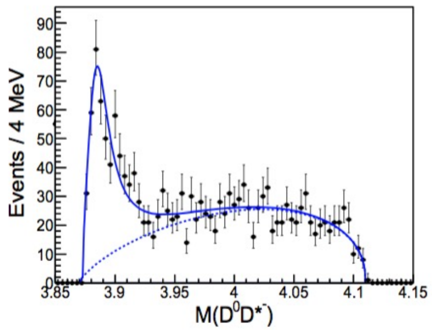
[PRL 113 (2014) 212002]



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

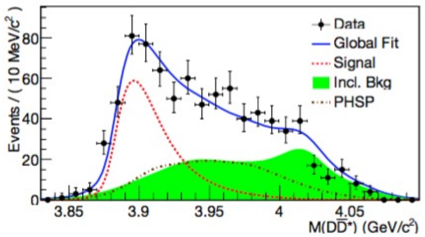
Open Charm

[PRL 112 (2014) 022001]

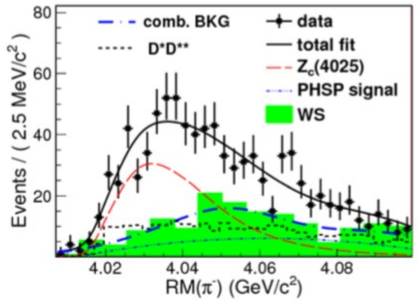


$e^+e^- \to \pi^-(D\bar{D}^*)^+$

[PRL 115 (2015) 222002]

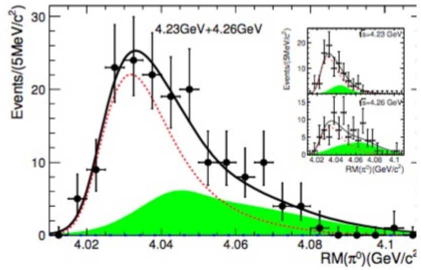


[PRL 112 (2013) 132001]



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

[PRL 115 (2015) 182002]



Charged **Neutral** — $Z_c(3900)^{\pm,0}$?

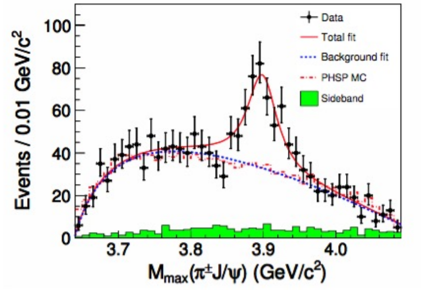
Charged **Neutral** — $Z_c(4020)^{\pm,0}$?

- Two isospin triplets of charmonium-like exotic states established
- Different decay *(hidden vs. open charm)* of same state observed?

Two Z_c triplets established at BESIII

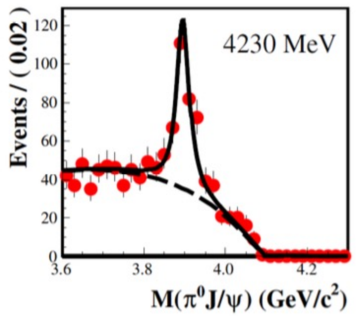
Hidden Charm

[PRL 110 (2013) 252001]



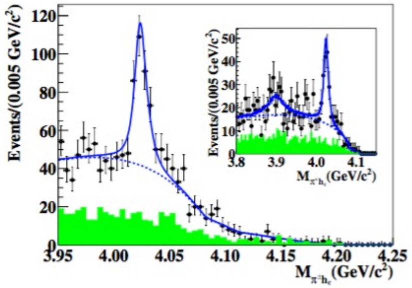
$e^+e^- \to \pi^-\pi^+ J/\psi$

[PRL 115 (2015) 112003]



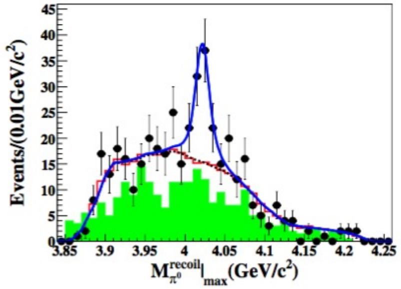
$e^+e^- \to \pi^0\pi^0 J/\psi$

[PRL 111 (2013) 242002]



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

[PRL 113 (2014) 212002]



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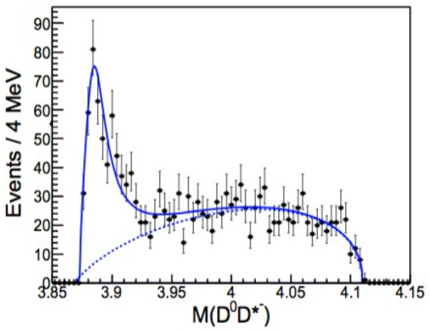
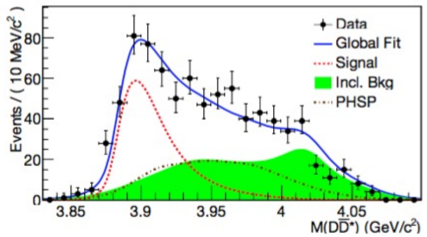
Open Charm

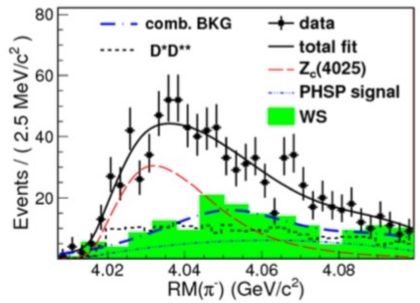
[PRL 112 (2014) 022001]



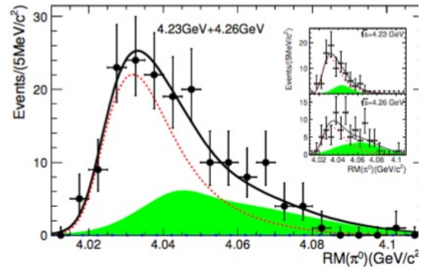
[PRL 115 (2015) 222002]



[PRL 112 (2013) 132001]

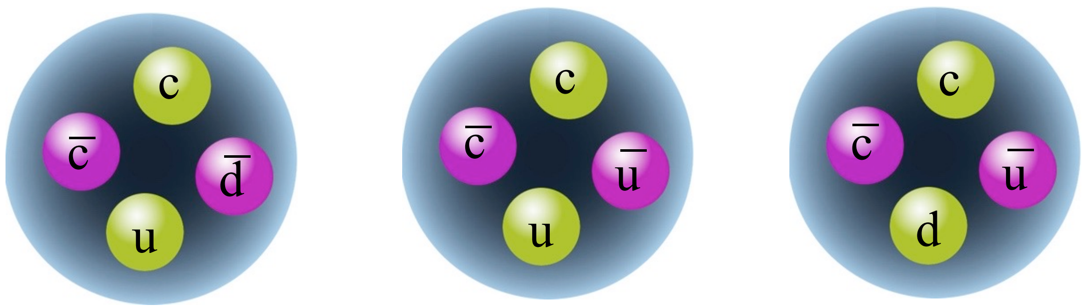


[PRL 115 (2015) 182002]



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

$Z_c(3900)^+$ $Z_c(3900)^0$ $Z_c(3900)^-$



harged Neutral

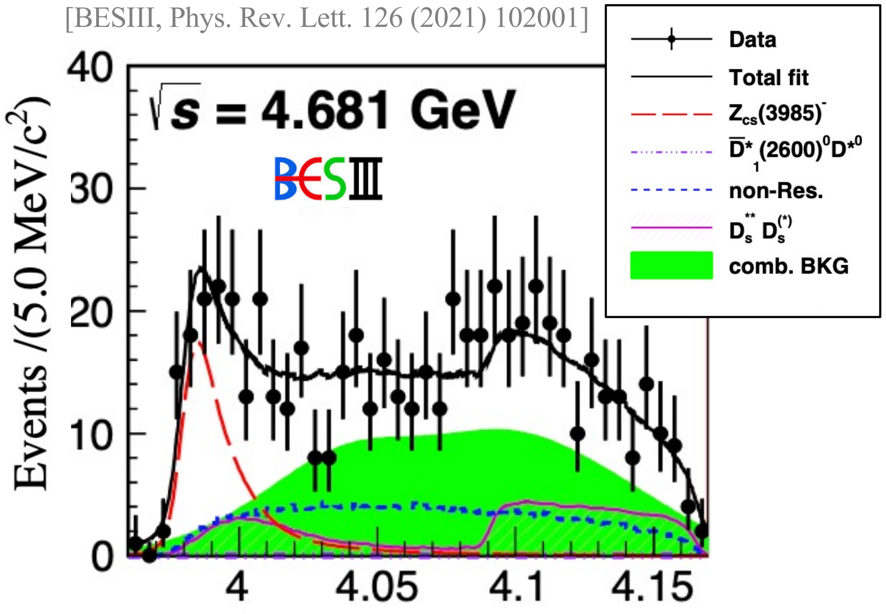
$Z_c(4020)^{\pm,0}$?

tes established

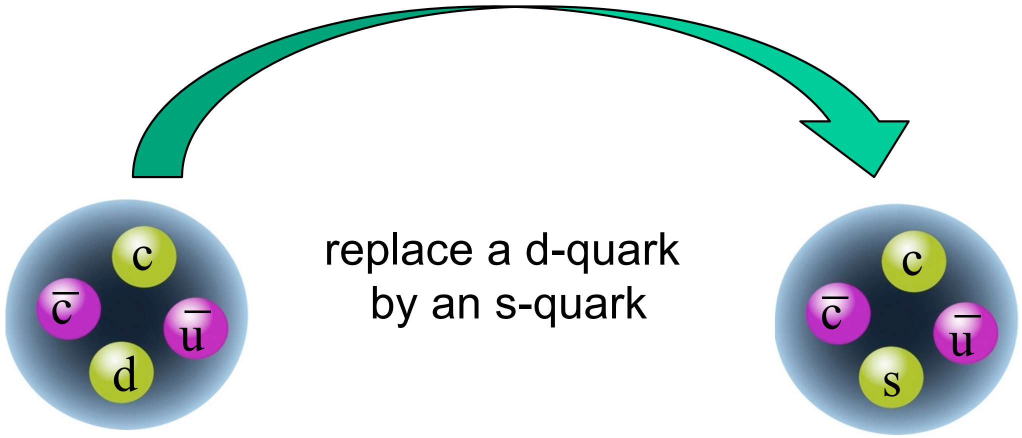
state observed?

First Z_{cs} candidates Z(3985) reported

[BESIII, Phys. Rev. Lett. 126 (2021) 102001]



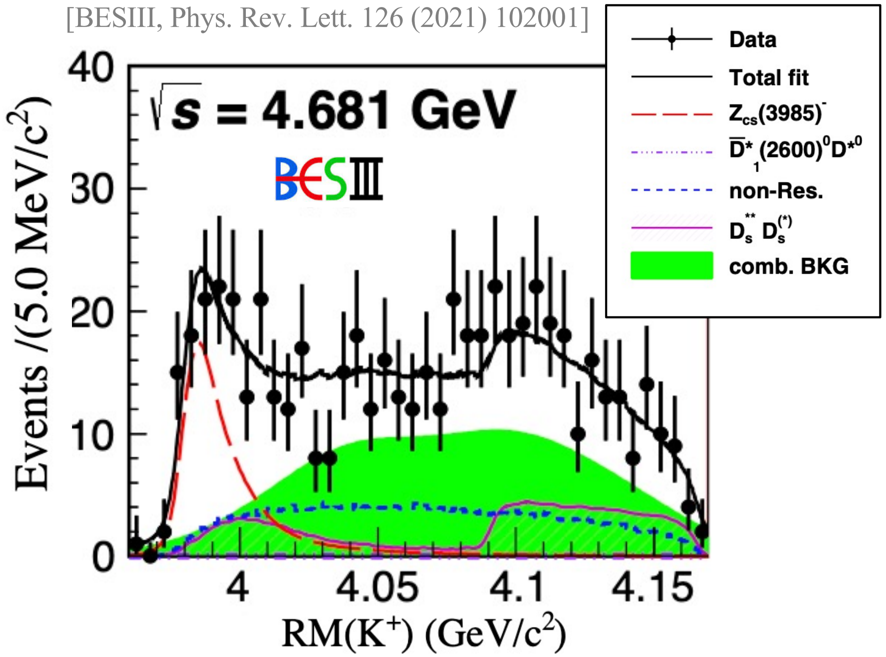
- Search for strange partner of $Z_c(3900)$
  - Containing s quark in open charm decay
  - $e^+e^- \to K^+(D_sD^*/D_s^*D)^-$
  - Narrow threshold enhancement (5.3σ)
  - $M = (3982.5^{+1.8}_{-2.6} \pm 2.1)\text{MeV}/c^2,$
    $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0)\text{MeV}$
- Manifestly exotic charged hidden-charm tetraquark candidate with strangeness
  - With a non-zero electric charge
  - Thus, minimal quark content => [$c\bar{c}s\bar{u}$]



$Z_c(3900)$ $Z_{cs}(3985)$

First Z_{cs} candidates Z(3985) reported

[BESIII, Phys. Rev. Lett. 126 (2021) 102001]



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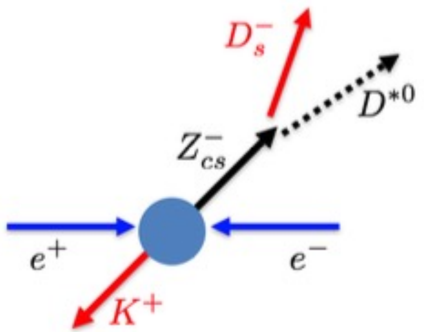
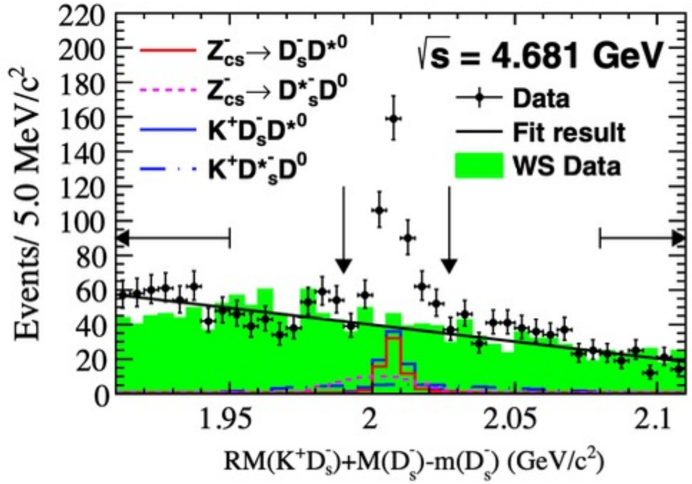
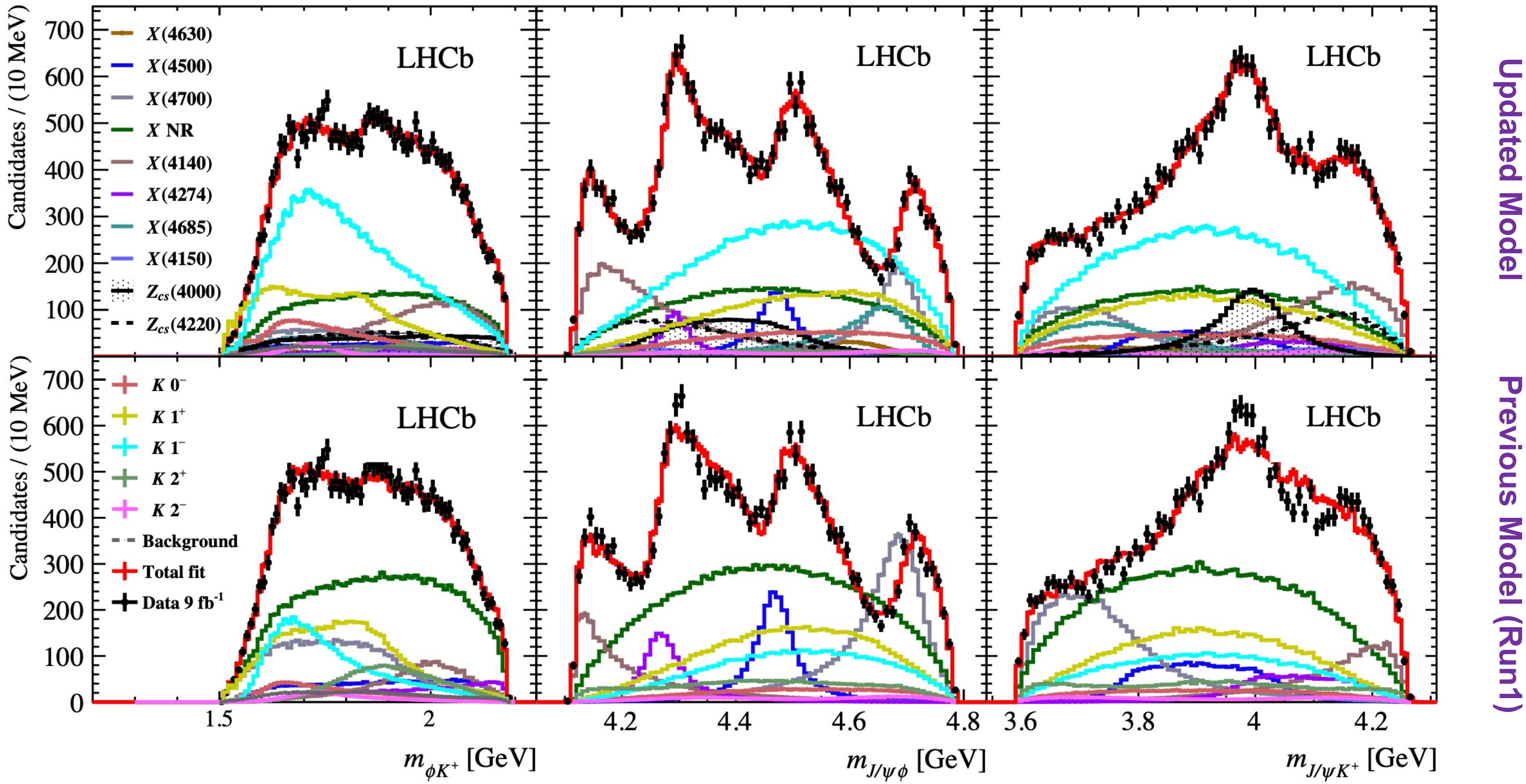
Missing Mass Technique:





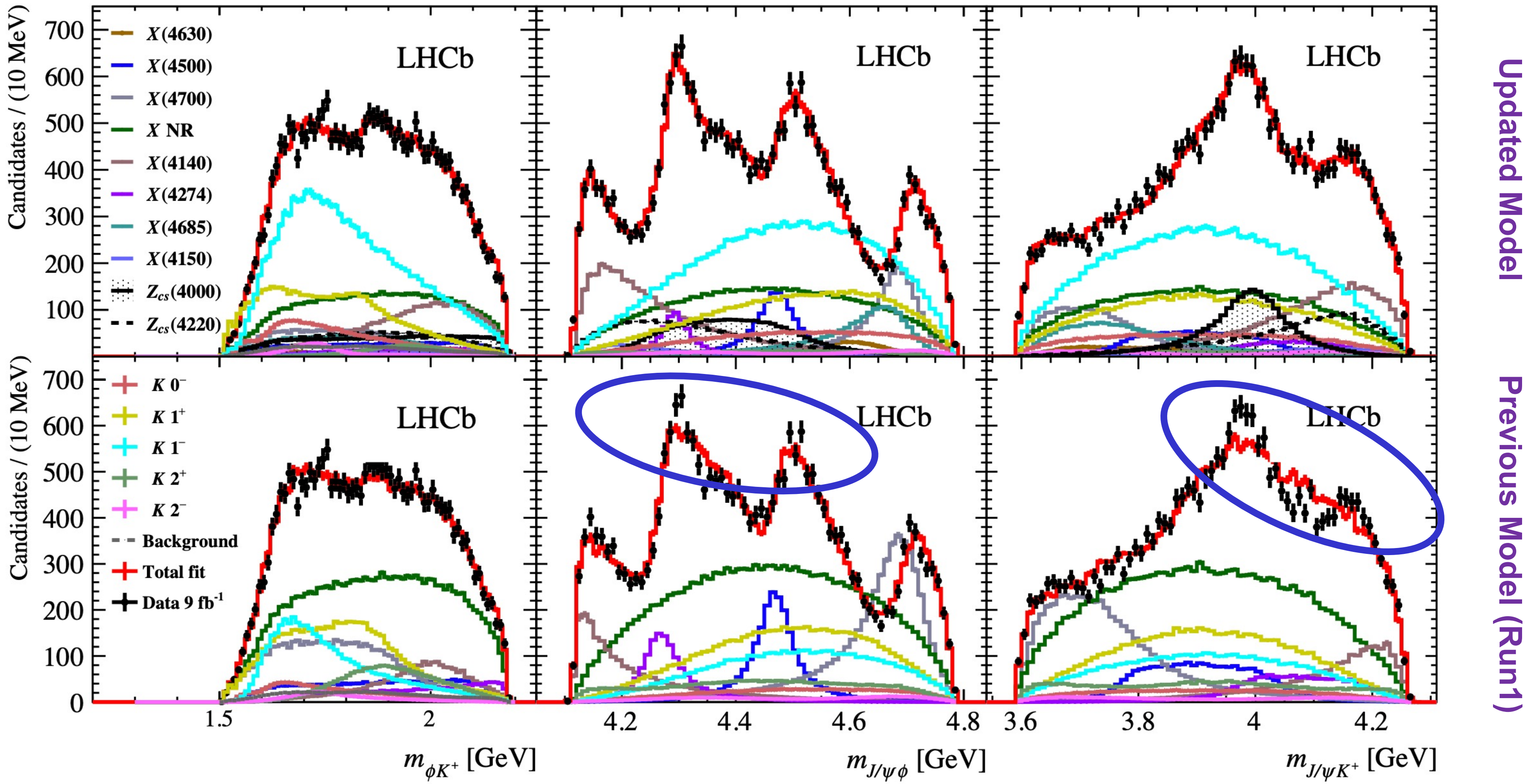
First Z_{cs} candidates Z(3985) reported



- LHCb reports two Z_{cs} candidates in $B \rightarrow \phi(J/\psi K^+)$
  - ➢ $Z_{cs}(4000)$, $J^P = 1^+$, hidden charm final state (15σ)
  - ➢ $Z_{cs}(4220)$, $J^P = 1^+$ or 1^-, hidden charm final state, broader (5.9σ)

[LHCb, PRL 127, 082001 (2021)]

First Z_{cs} candidates Z(3985) reported



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[LHCb, PRL 127, 082001 (2021)]

First Z_{cs} candidates Z(3985) reported

J^P	Contribution		Significance (σ)	M_0 (MeV)	Γ_0 (MeV)	FF (%)
1^+	2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10^{+16}_{-46}$	$149 \pm 41^{+231}_{-23}$	
	2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37^{+124}_{-48}$	$276 \pm 50^{+319}_{-159}$	
	1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3^{+3}_{-11}$
2^-	1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
	1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2^{+35}$[illegible]
	2^3S_1	$K^*(1410)$	7.7 (15)	1414	[illegible]	[illegible]
2^-	2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22^{+194}_{-31}$	[illegible]	[illegible]
0^-	2^1S_0	$K(1460)$	12 (13)	1483	[illegible]	[illegible]
2^-		$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 3$[illegible]	[illegible]	[illegible]
1^-		$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	[illegible]	[illegible]
0^+		$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
		$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
		$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
1^+		$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
		$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
		$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
1^+		$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
		$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

Updated model extended by:
- 2 Z_{cs} states, $J/\psi K$ resonances
- 2 $J/\psi\phi$ resonances
- 4 $J/\psi\phi$ resonances already previously included confirmed

Updated Model

Previous Model (Run1)

- LHCb reports two Z_{cs} candidates in $B \to \phi(J/\psi K^+)$
  - $Z_{cs}(4000)$, $J^P = 1^+$, hidden charm final state (15σ) → *10x broader than BESIII cand.*
  - [illegible] ...der (5.9σ)

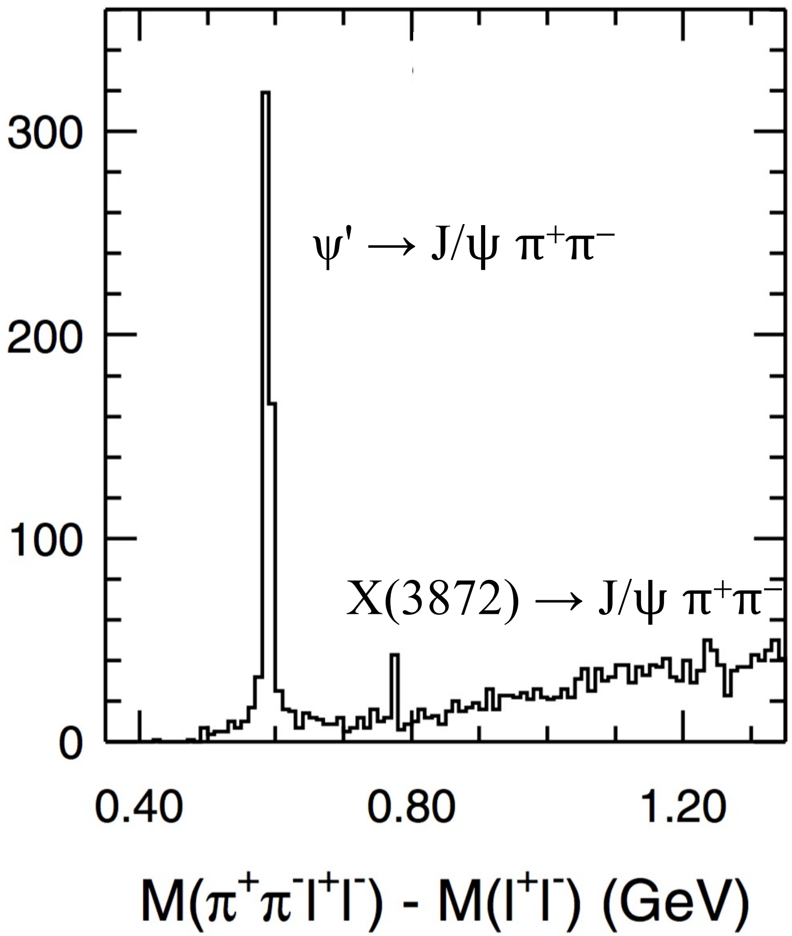
=> Same state observed in different decays (open/hidden charm) at two experiments?

[LHCb, PRL 127, 082001 (2021)]

The X(3872)
and further X states

Experimental review of the X(3872)

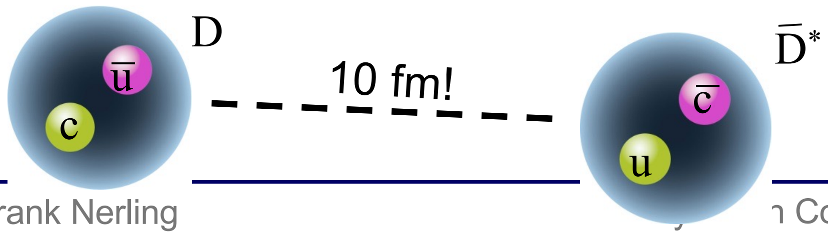
[Belle Collab., PRL 91 (2003) 262001]



- First observed by Belle in 2003
  - $X(3872) \to J/\psi\pi^+\pi^-$
  - very narrow state with $J^{PC} = 1^{++}$
- Belle & BaBar report signal in
  - $X(3872) \to D^0\bar{D}^{*0}$
- Mass $m[X(3872)] - m[D^{*0}] - m[D^0]$

  $= (-0.07 \pm 0.12)$ MeV/c² (LHCb 2020)
- Width measurement:
  - $\Gamma_{X(3872)} < 1.2$ MeV (2011, Belle)
  - $\Gamma_{X(3872)} = 1.39$ MeV (2020, LHCb)

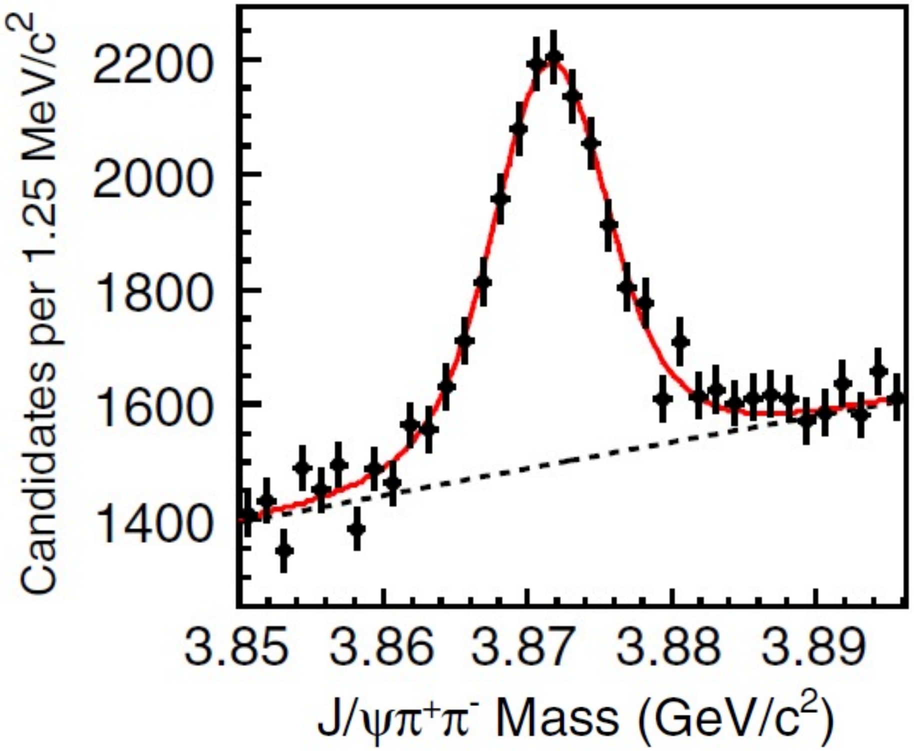
Analogy to deuteron:

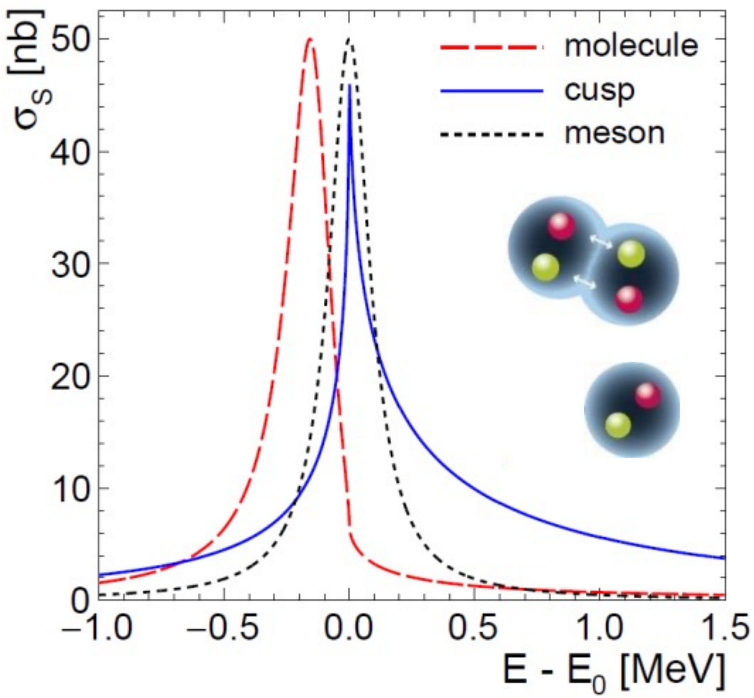


For clarification:
=> Precision measurement with
sub-MeV resolution needed!

Experimental review of the X(3872)

[CDF, Phys. Rev. Lett., 103 (2009) 152001]





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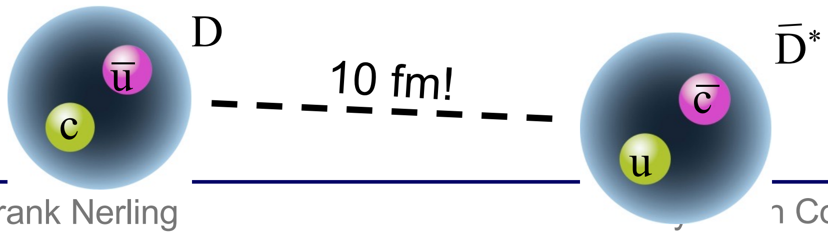

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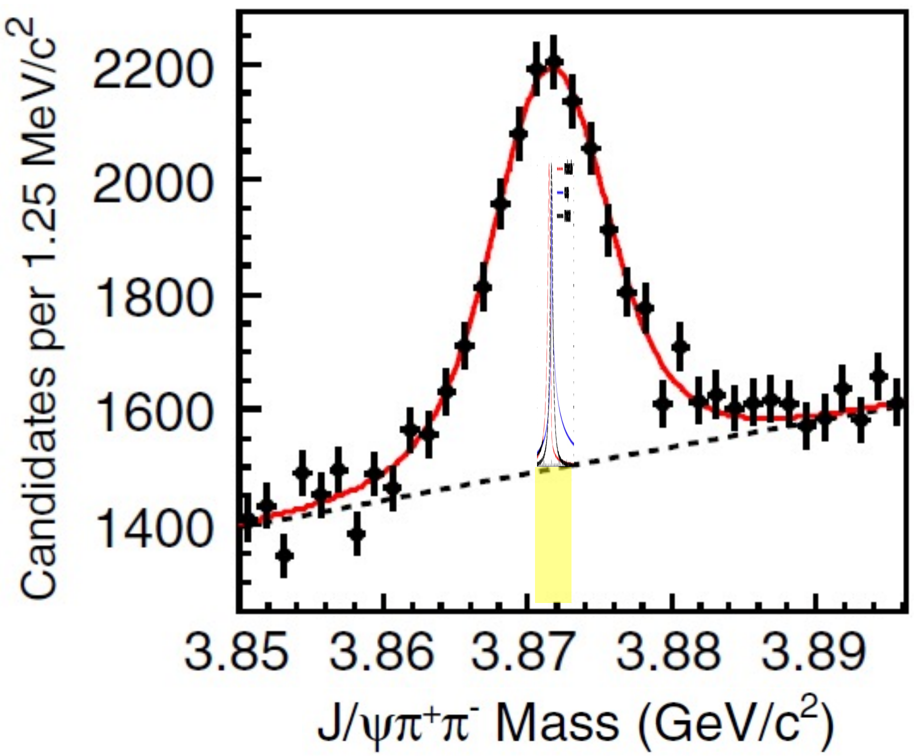

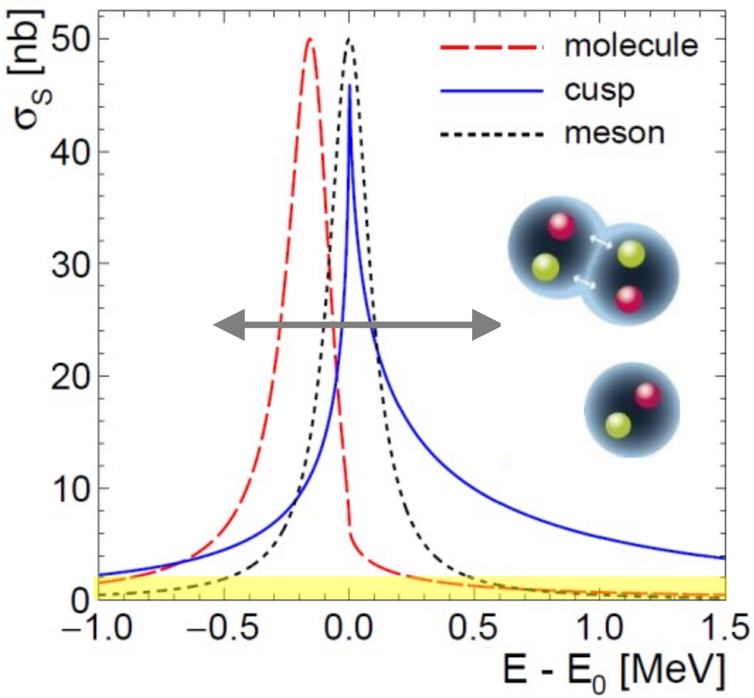

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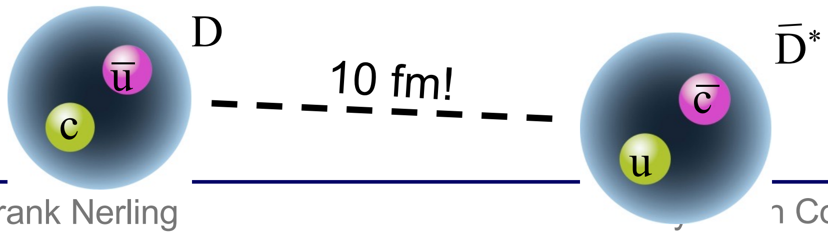

For clarification:
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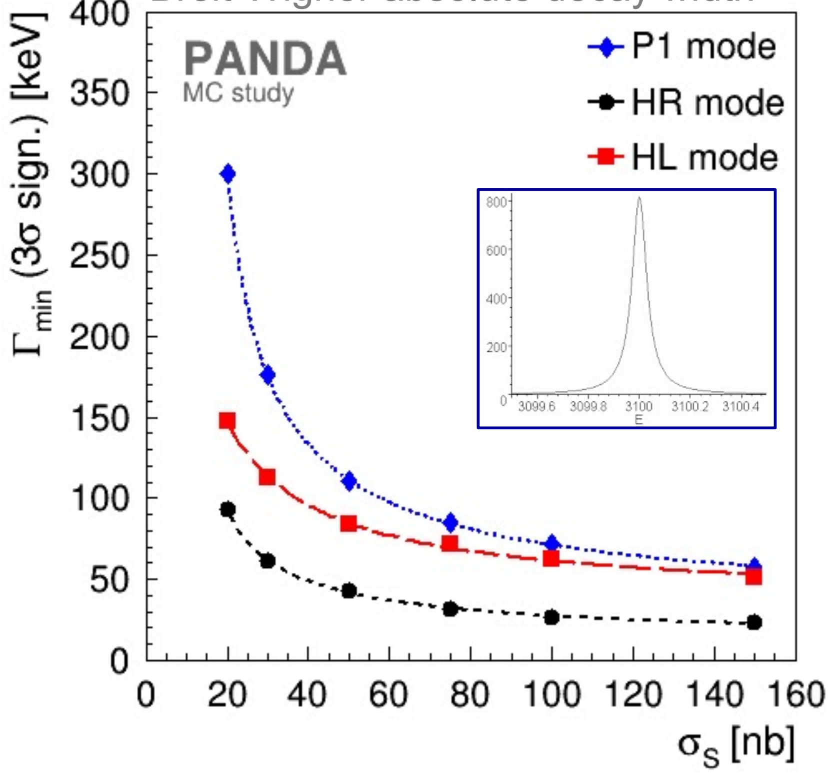
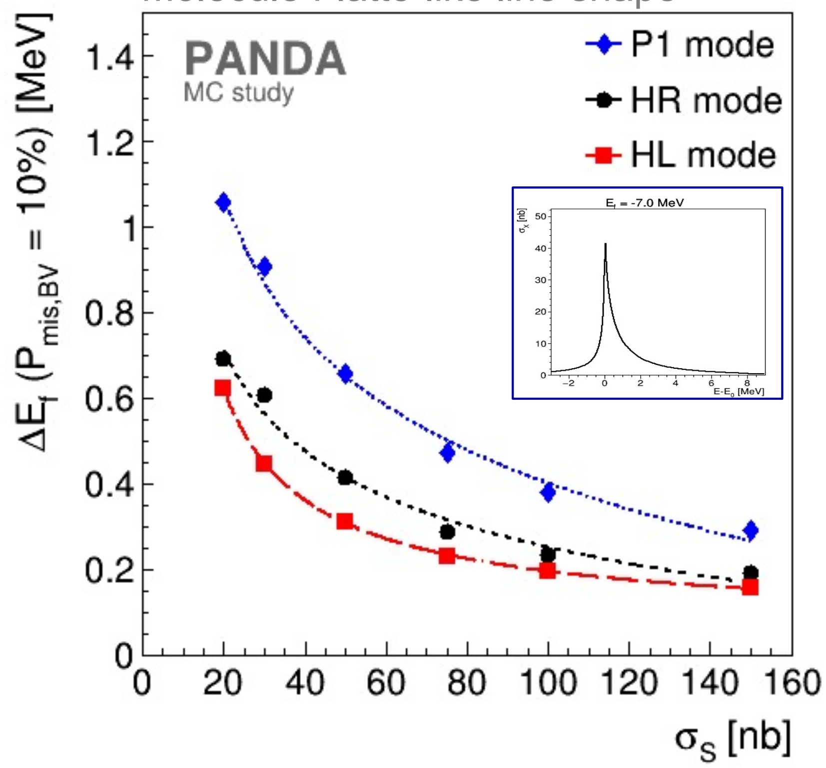
Sensitivity for resonance energy scans

(comprehensive MC simulation study)

Sensitivity:
Breit-Wigner absolute decay width



Sensitivity:
Molecule Flatte-like line shape

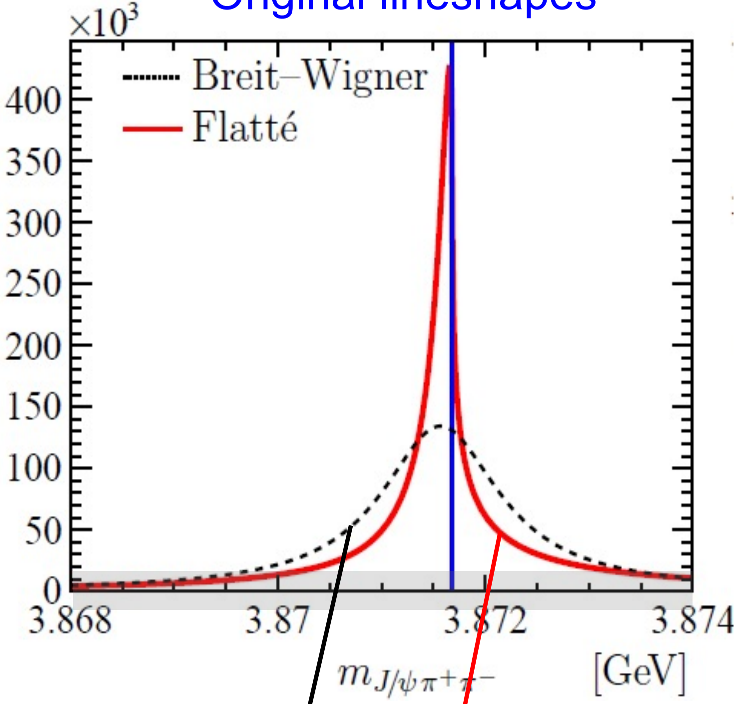


- Sub-MeV resolution well feasible for
  - absolute Breit-Wigner decay width
- Sub-MeV resolution well feasible for
  - molecule Flatte-like line shape

[PANDA, Eur. Phys. J. A 55 (2019) 42]

LHCb lineshapes (incl. resolution)

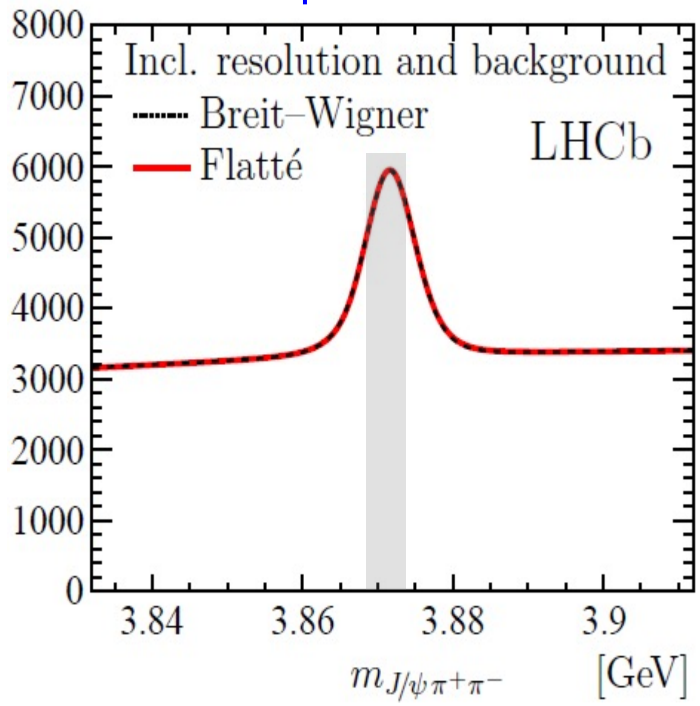
Original lineshapes



$m_{\chi_{c1}(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010$ MeV
$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10$ MeV

Mode [MeV]	Mean [MeV]	FWHM [MeV]
$3871.69^{+0.00+0.05}_{-0.04-0.13}$	$3871.66^{+0.07+0.11}_{-0.06-0.13}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$

Lineshapes with resolution



7.3 Comparison between Breit–Wigner and Flatté lineshapes

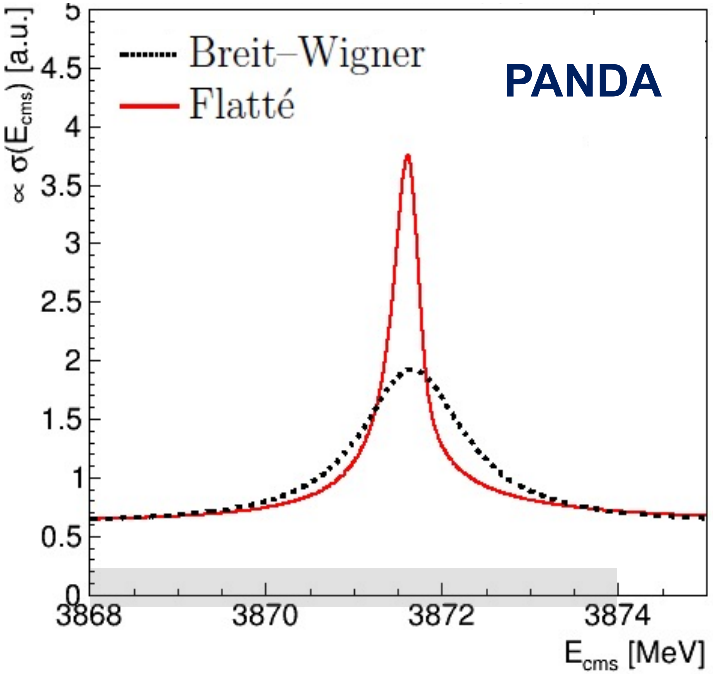
Figure 4 shows the comparison between the Breit–Wigner and the Flatté lineshapes. While in both cases the signal peaks at the same mass, the Flatté model results in a signifcantly narrower lineshape. However, after folding with the resolution function and adding the background, the observable distributions are indistinguishable.

- Due to detector resolution both models cannot be distinguished
  - 1.39 MeV (BW) vs. 0.22 MeV (Flatté) => factor of ~5

[Phys.Rev.D 102 (2020) 9, 092005]

PANDA lineshapes (incl. resolution)

Lineshapes with resolution (P1)



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Mode [MeV]	Mean [MeV]	FWHM [MeV]
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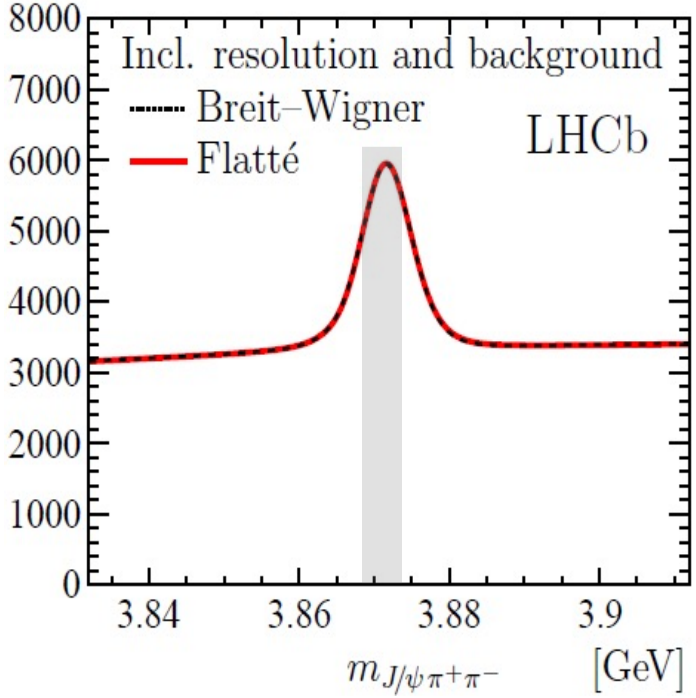
Lineshapes with resolution



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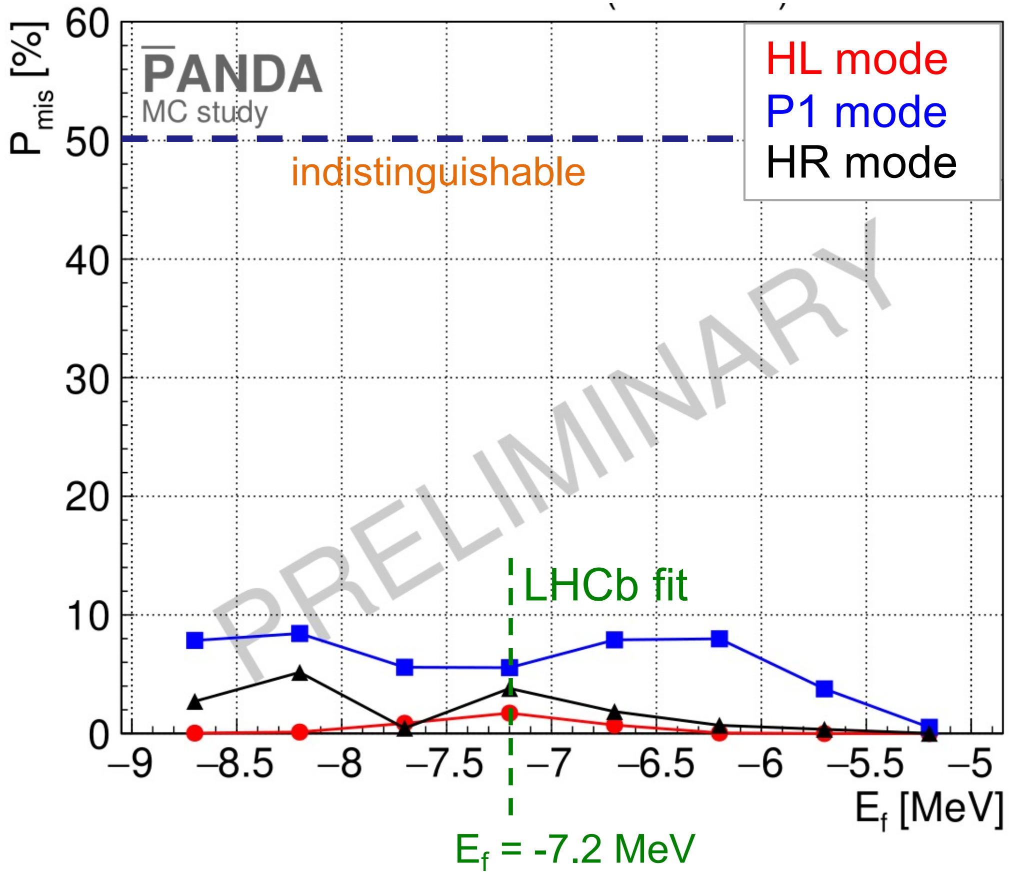
- Thanks to the beam resolution both models can be distinguished at PANDA
  - ➢ 1.39 MeV (BW) vs. 0.22 MeV (Flatté) => factor of ~5

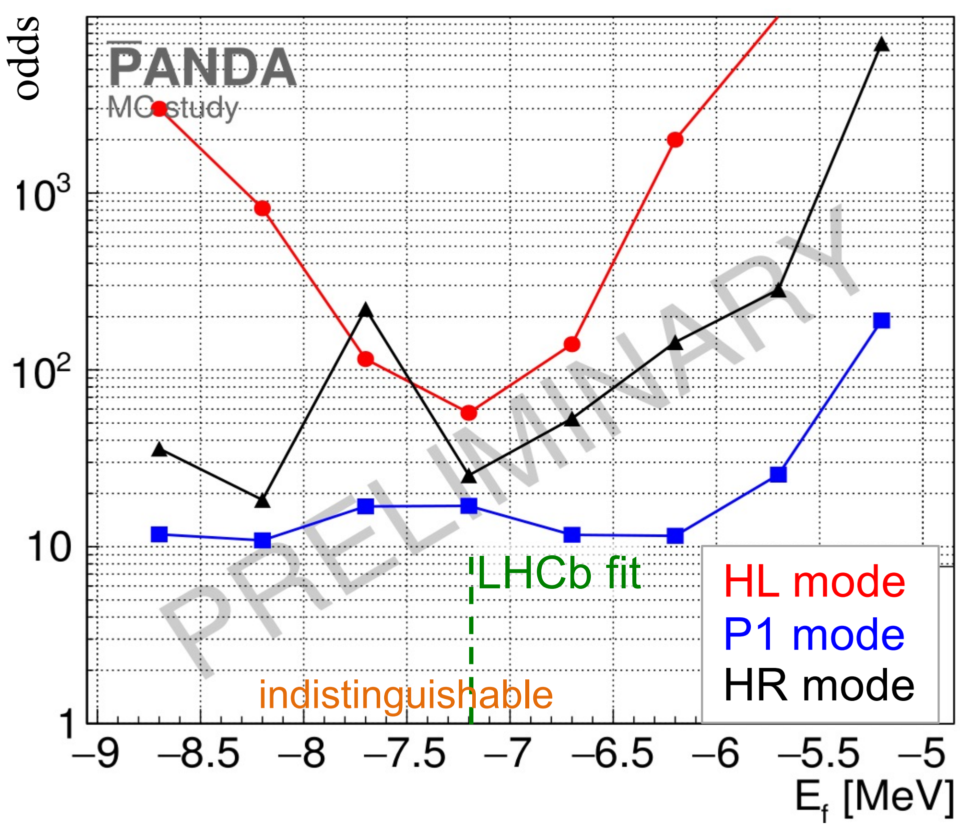
[Phys.Rev.D 102 (2020) 9, 092005]

Sensitivity: Distinguish line shapes

How much better are we than than "indistinguishable“?

Idea: Consider so-called odds := correct identifications per wrong one





$$odds = (1 - P_{mis}) / P_{mis}$$

[K.Götzen and F.Nerling, for the PANDA Collab., QWG2021]

Sensitivity: Distinguish line shapes

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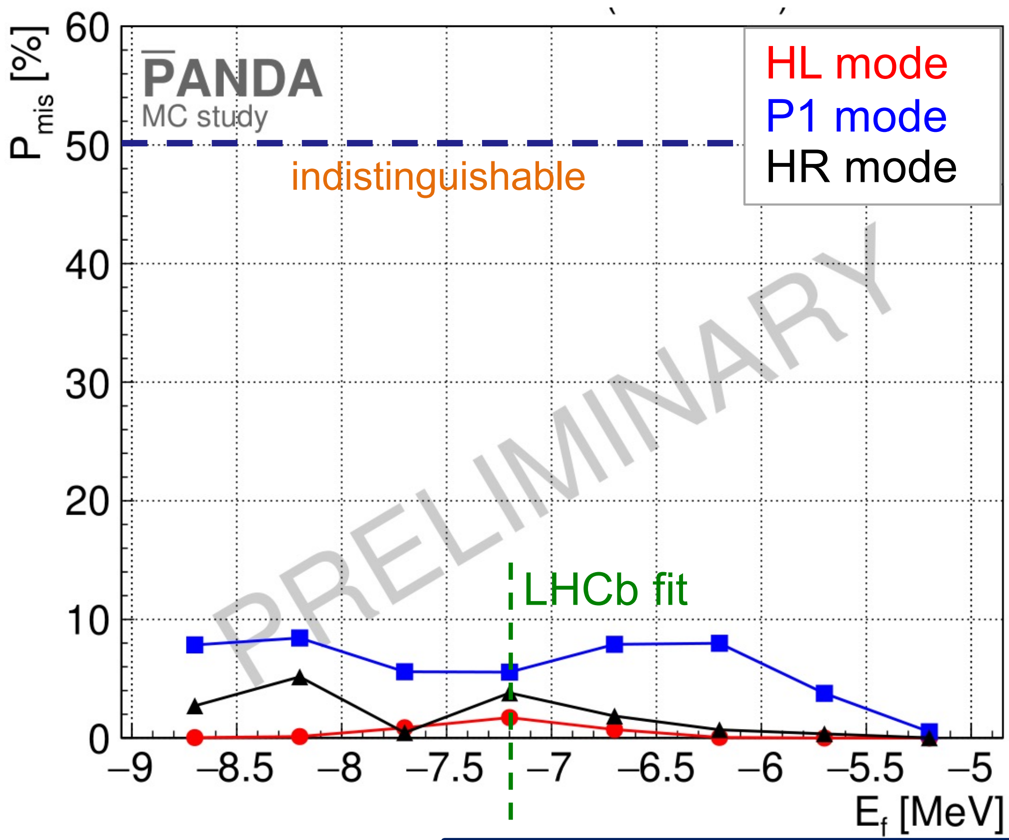
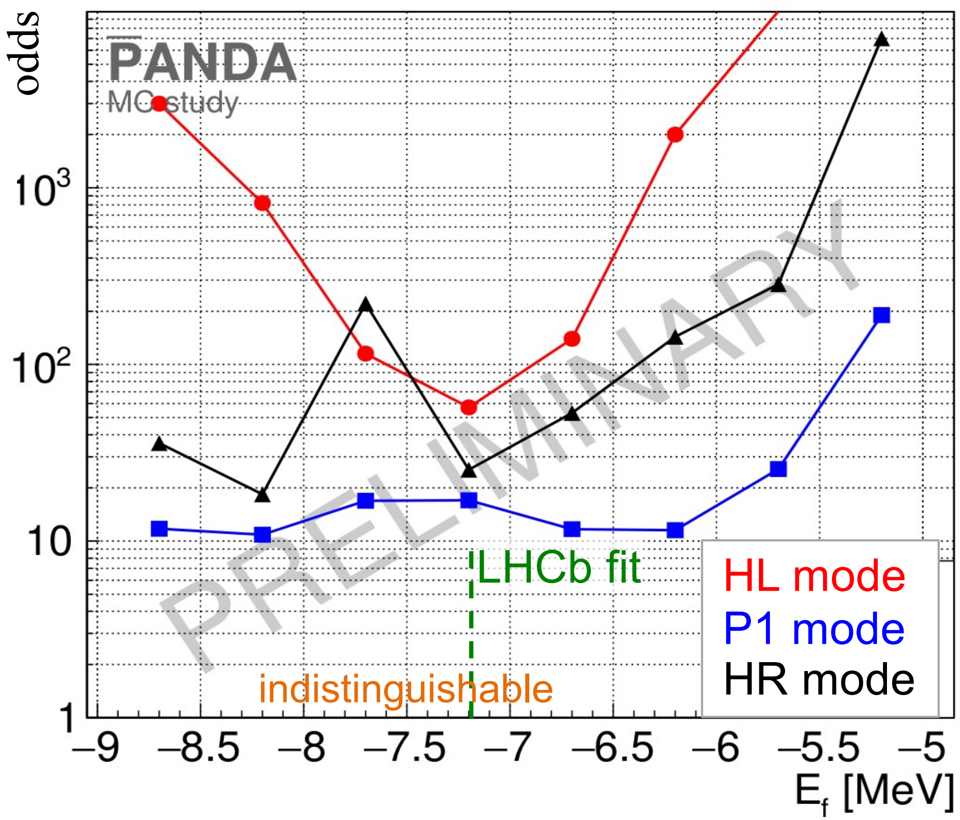
Flatté → BW





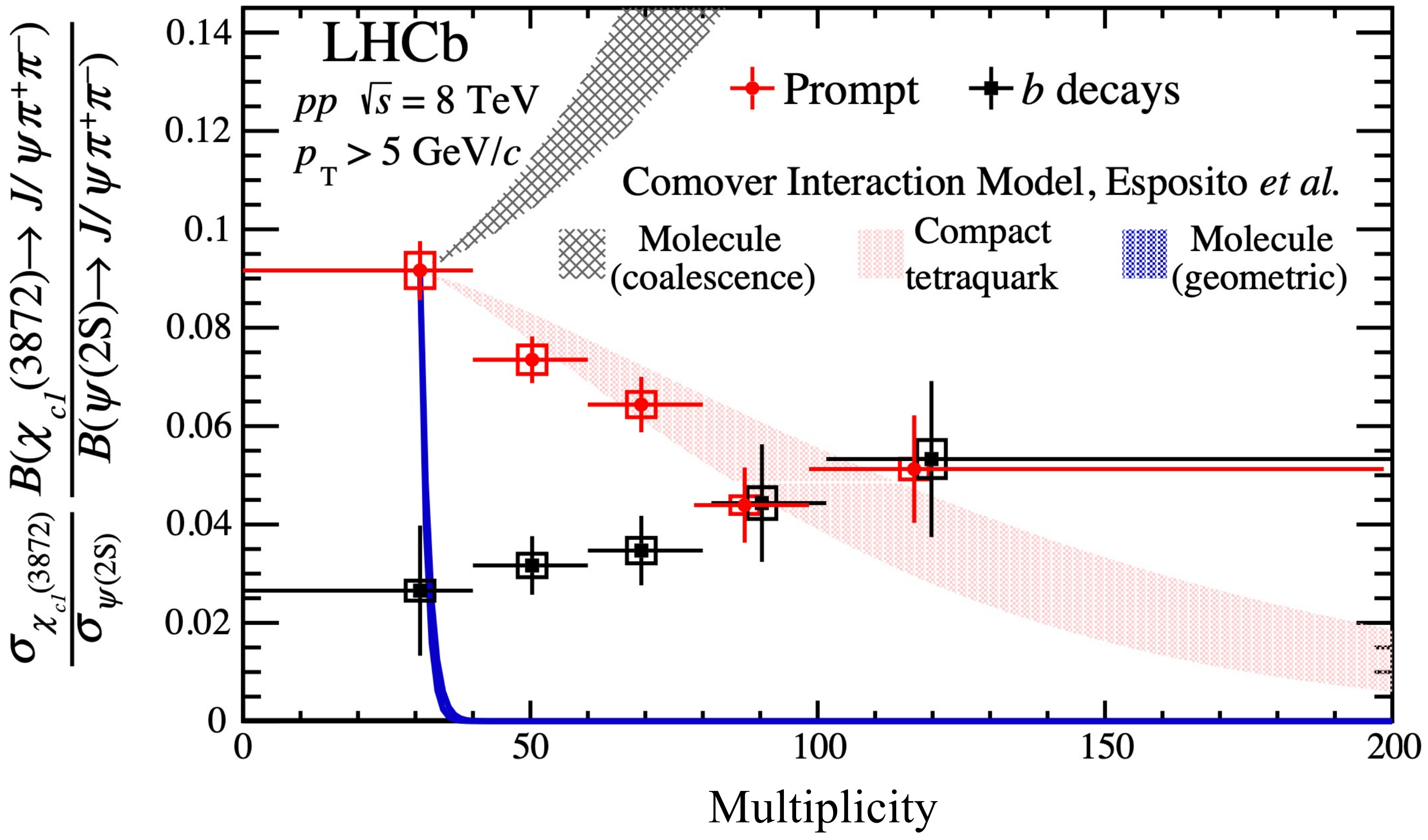
At least ~10x better than indistinguishable *(full range)*

$$odds = (1 - P_{mis}) / P_{mis}$$

[K.Götzen and F.Nerling, for the PANDA Collab., QWG2021]

Prompt production of the X(3872)

Alternatively: Ratio of cross sections x BRs for X(3872) vs. ordinary charmonium in prompt production provides handle to sort out models ...



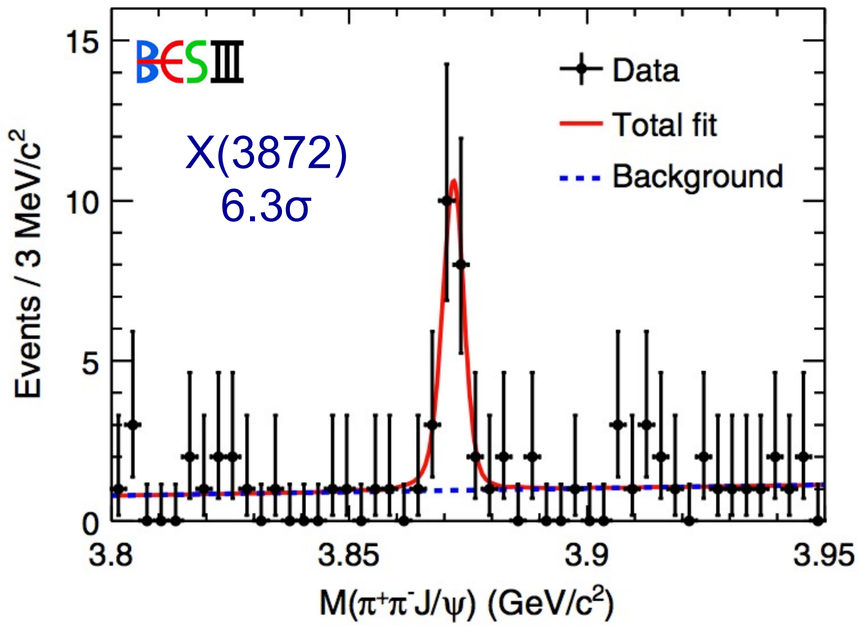
=> Compact tetraquark preferred, others not yet excluded ... *(model dependency)*

[LHCb, PRL 126, 092001 (2021)]

First observation of $e^+e^- \to \gamma X(3872)$

BESIII: First observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$

[Phys. Rev. Lett. 112 (2014) 092001]



- $m = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$
- $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)

First observation of $e^+e^- \to \gamma X(3872)$

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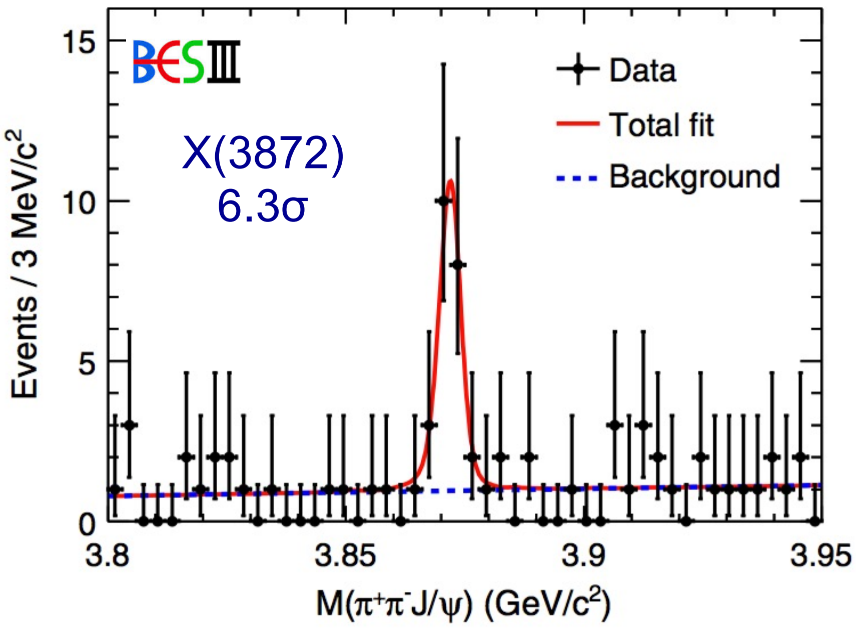
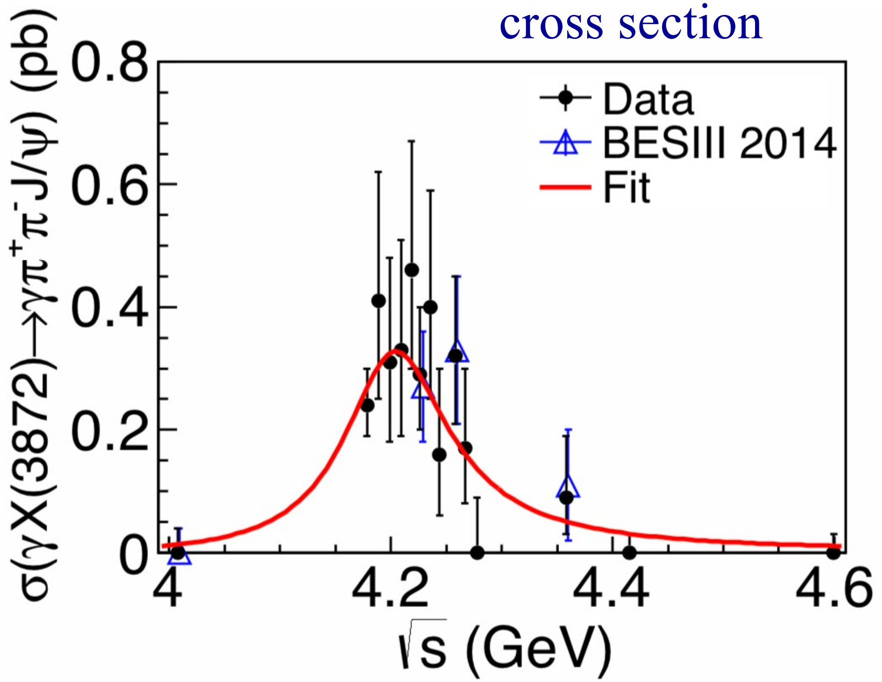
$$e^+e^- \to Y(4260) \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi \quad ?$$

[Phys. Rev. Lett. 112 (2014) 092001]



cross section



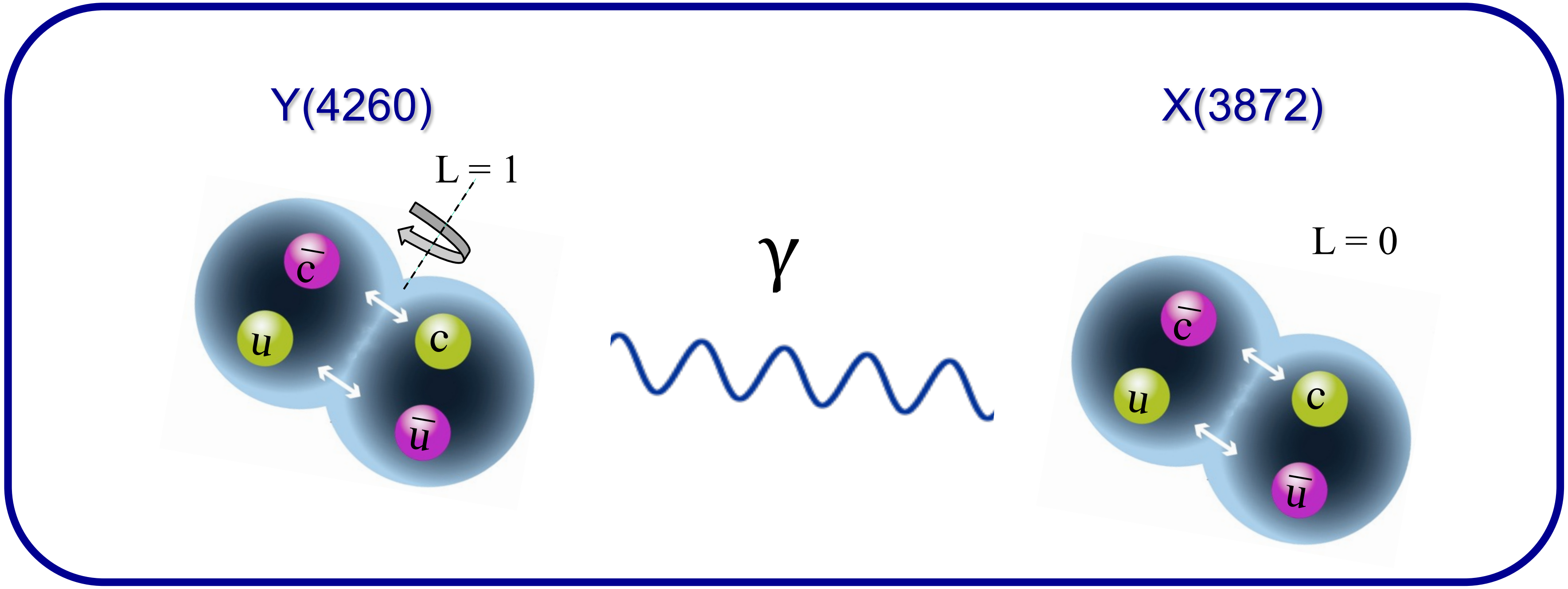
- $m = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$
- $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)

- Shape consistent with production via a $\Upsilon(4260)$ state

[Subm. to Phys. Rev. Lett., arXiv:1903.04695 [hep-ex]]

If X(3872) is a molecule ...

- Radiative decay observed $Y(4260) \to \gamma X(3872)$
  - ➢ de-excitation via gamma emission
  - ➢ quark flavour conserved, spin flip



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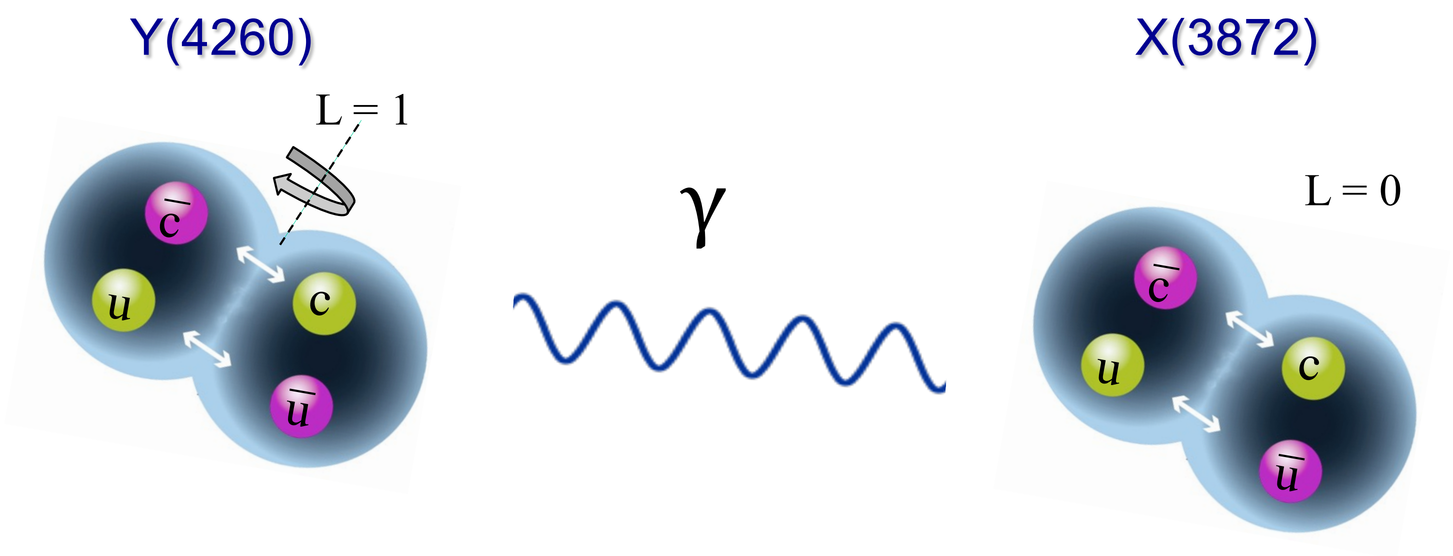


- If X(3872) is a molecule (or a compact tetraquark)
  => **Y(4260) is also a molecule** (or a compact tetraquark)

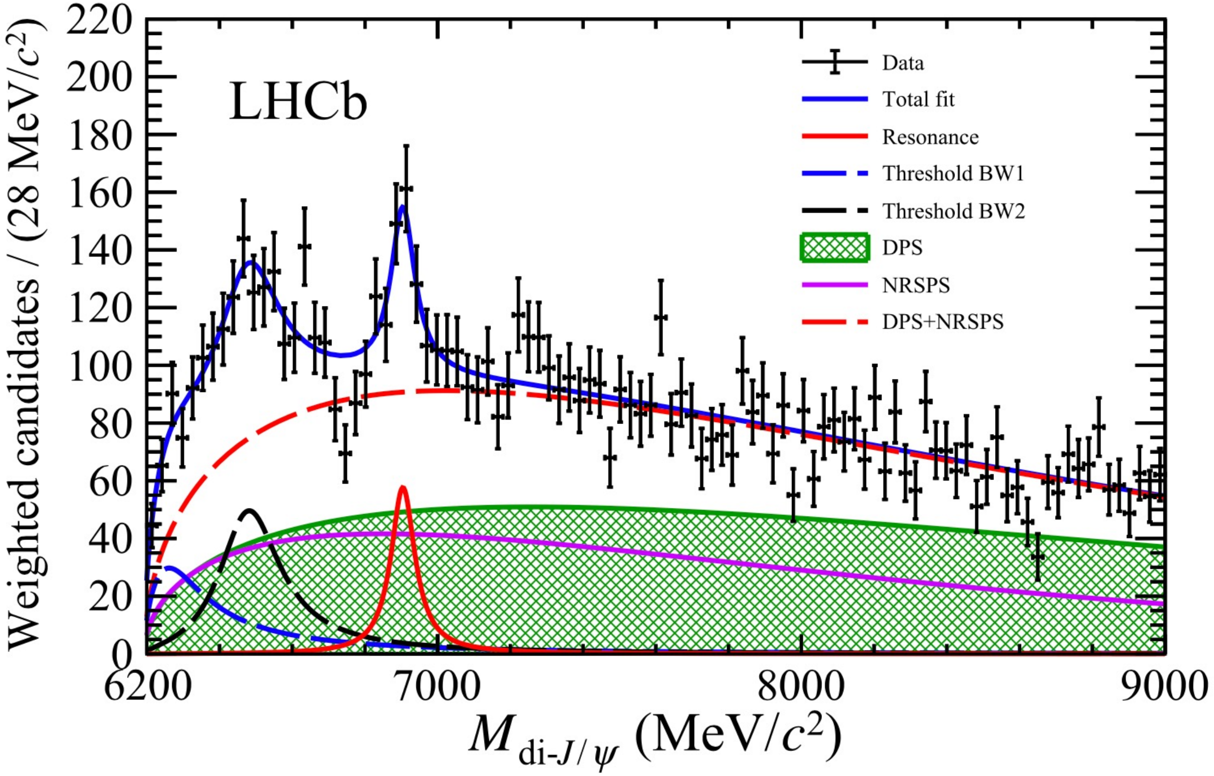
... and a couple of further, newly discovered states ...

First observation of X(6900)

LHCb: First observation of a hidden doubly charmed tetraquark candidate

$T_{cc\bar{c}\bar{c}}$: X(6900) > 5σ

[Science Bulletin 65 (2020) 1983]



Model I

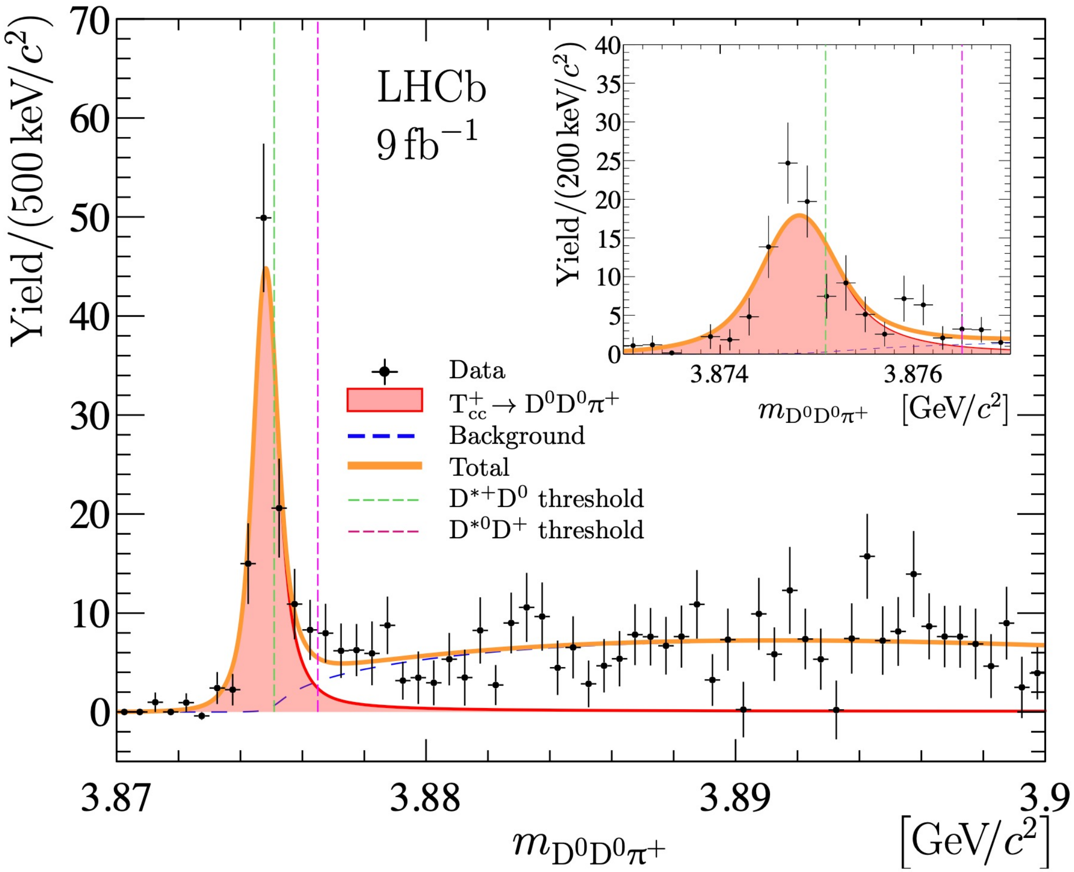
- $m = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$
- $\Gamma = 80 \pm 19 \pm 33\,\text{MeV}$

First observation of a T_{cc}^{+} state

LHCb: First observation of a same signed doubly charmed tetraquark candidate

T_{cc}^{+} > 22σ

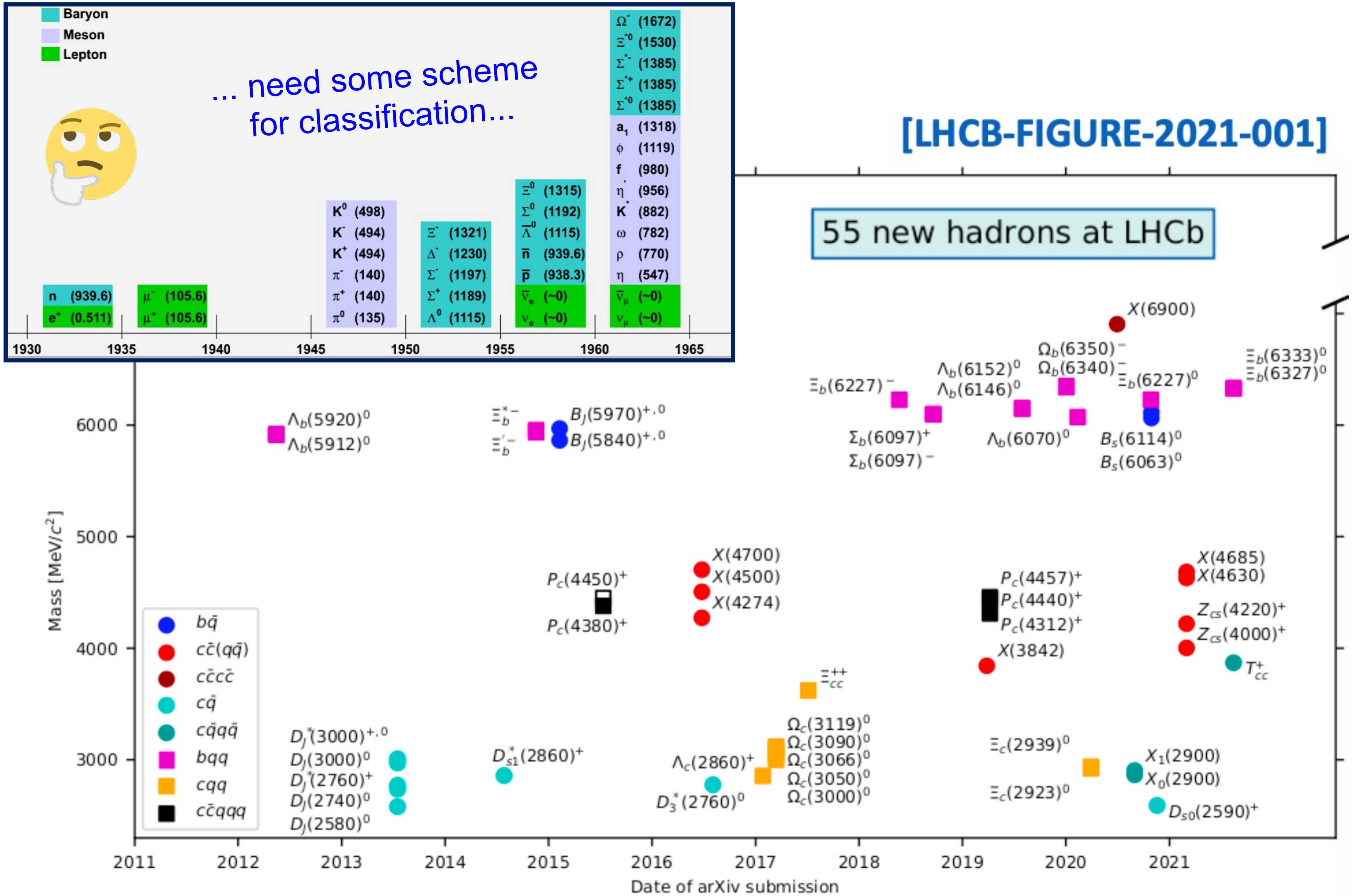
[LHCb-Paper-2021-032 (2021)]



$$T_{cc}^{+} \rightarrow D^0 D^0 \pi^+$$

- Minimal quark content => $[cc\bar{u}\bar{d}]$
- $\delta m_{BW} = m_{BW} - (m_{D^{*+}} + m_{D^0})$
- $m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14}\,\mathrm{keV}/c^2$
- $\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}\,\mathrm{keV}$

Again a Zoo of (exotic) hadrons ...



[Polyakov, EPS-HEP-2021]

Summary and Prospectives

- New era of charmonium-like exotic states started two decades ago, and more than 20 unexpected XYZ states have been discovered

  - Supernumerary vector Y states consistently resolved (statistics)
    - *Y(4260) and Y(3360) → Y(4220), Y(4390)?*
    - *First decays to open charm, further new decay modes to $c\bar{c}$ and/or light hadrons investigated*

  - Charged Z_c states are manifestly exotic states
    - *First complete isospin triplets established*
    - *First strange partner(s) reported*

  - The first of the XYZ states discovered, the X(3872), still not understood
    - *Consistent picture in B decays and e^+e^- production*
    - *Line shape to be measured precisely*

  - New exciting doubly charmed states discovered in prompt production ...

- Puzzling: Different states observed in B decays vs. e^+e^- annihilation

Summary and Prospectives

- The B factories CLEO(-c) and BarBar have run for one / two decades
- Belle has run a decade, meanwhile upgraded to BelleII
  - ➢ Comissioned, first physics run last year
  - ➢ Looking forward to new results

- BESIII successfully operating since 2008
  - ➢ World largest data sets in tau-charm mass region, unique XYZ data
  - ➢ Machine upgrade allows to extend studies up to E_{cms} = 5 GeV
- LHCb successfully operating since 2011
  - ➢ Unprecedented high statitics and energy
  - ➢ Turns out to be a factory of new discoveries

- Upcoming and future experiments
  - ➢ PANDA/FAIR as complementary and unique $\bar{p}p$ experiment
  - ➢ Super tau-charm factory in China and/or Russia

Outlook: Completion of the exotic multiplets

→ *High statistics and precision, in combination with different probes*

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- The B factories CLEO(-c)
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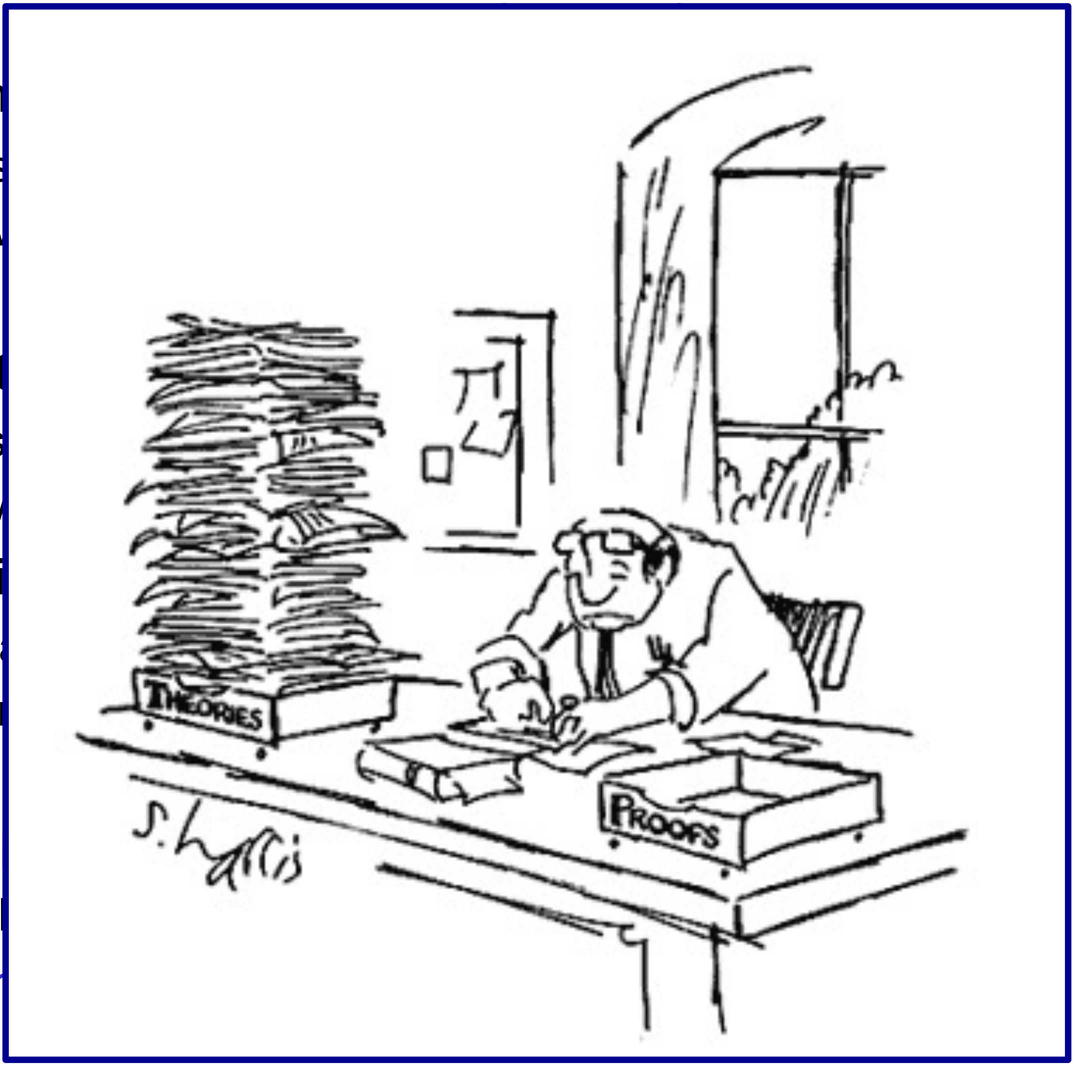

Outlook: Completion of the exotic multiplets

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Back-up

First observation of X(6900)

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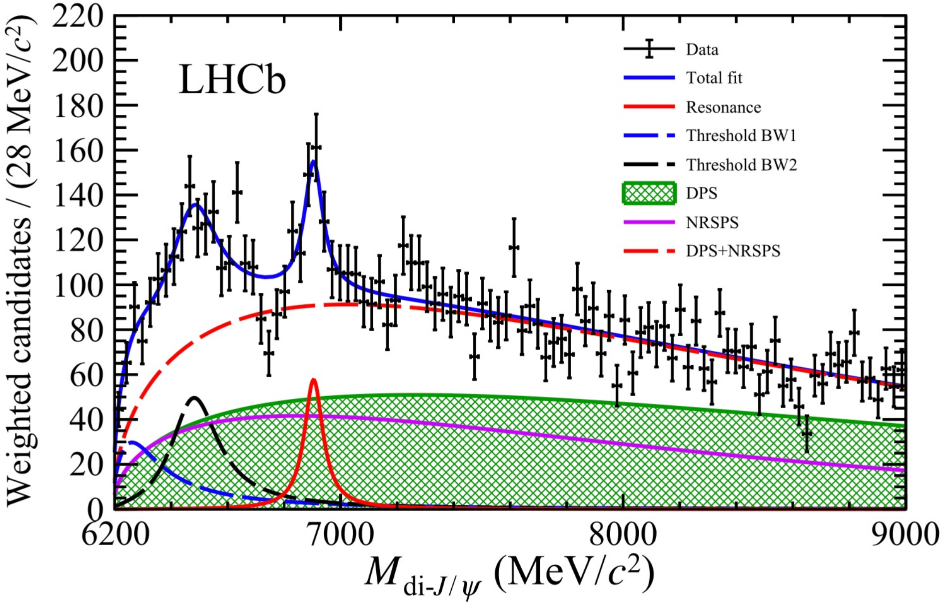
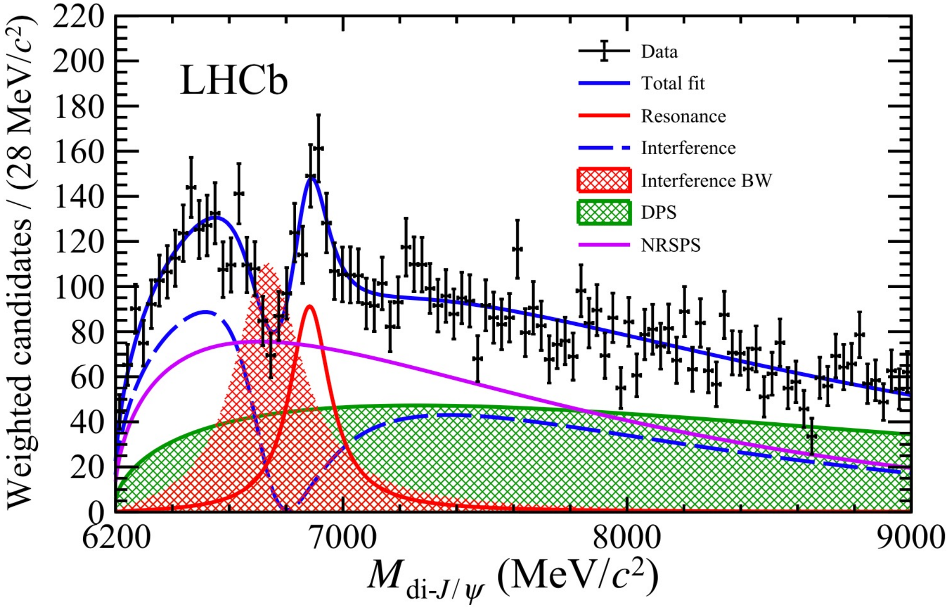


$T_{cc\bar{c}\bar{c}}$: X(6900) > 5σ [Science Bulletin 65 (2020) 1983]



Model I

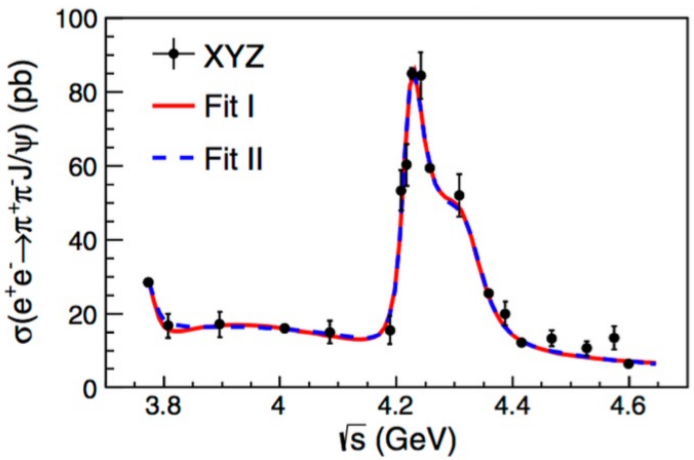
- $m = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$
- $\Gamma = 80 \pm 19 \pm 33\,\text{MeV}$

Model II

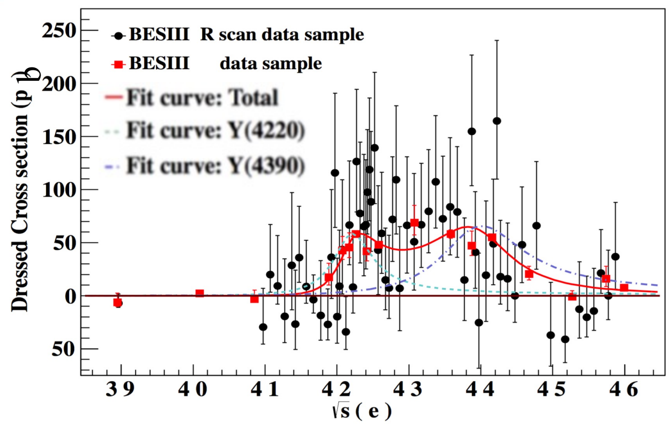
- $m = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$
- $\Gamma = 168 \pm 33 \pm 69\,\text{MeV}$

What happened to the Y states?

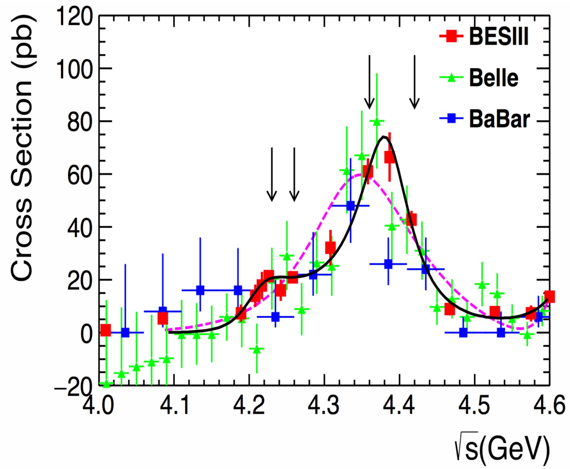
$e^+e^- \rightarrow J/\psi\pi^+\pi^-$



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

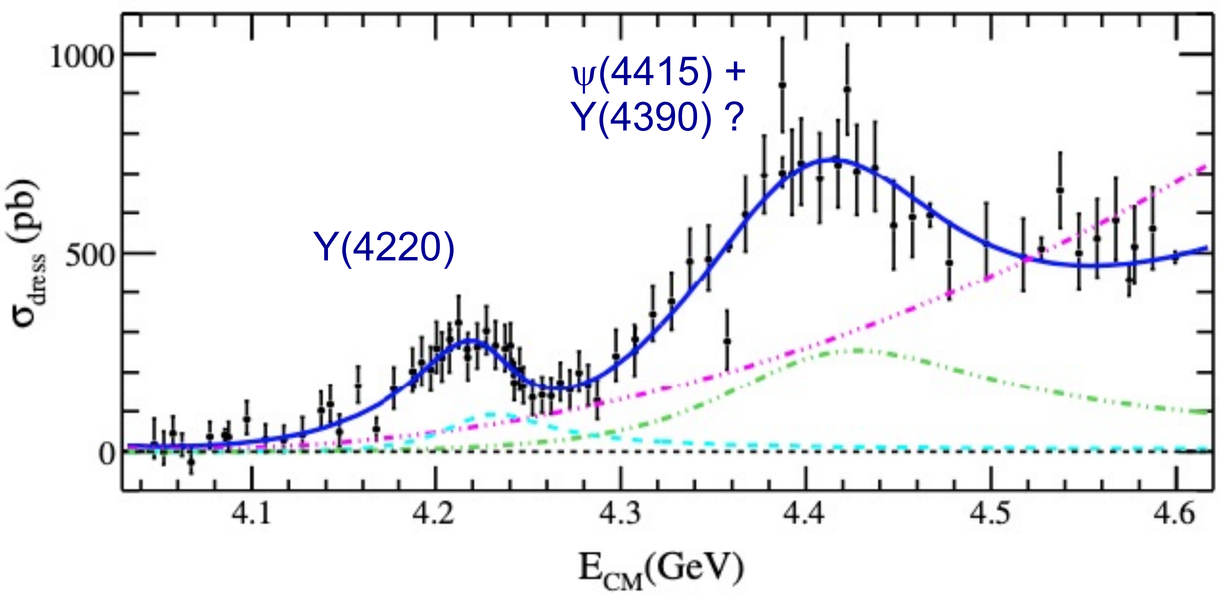


$e^+e^- \rightarrow h_c\pi^+\pi^-$



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

[PRL 122, 102002 (2019)]



Y(4220):

- M = (4228.6 ± 4.1 ± 6.3) MeV/c^2
- Γ = (77.0 ± 6.8 ± 6.3) MeV/c^2

Y state at about 4.40 GeV:

- strongly model dependent

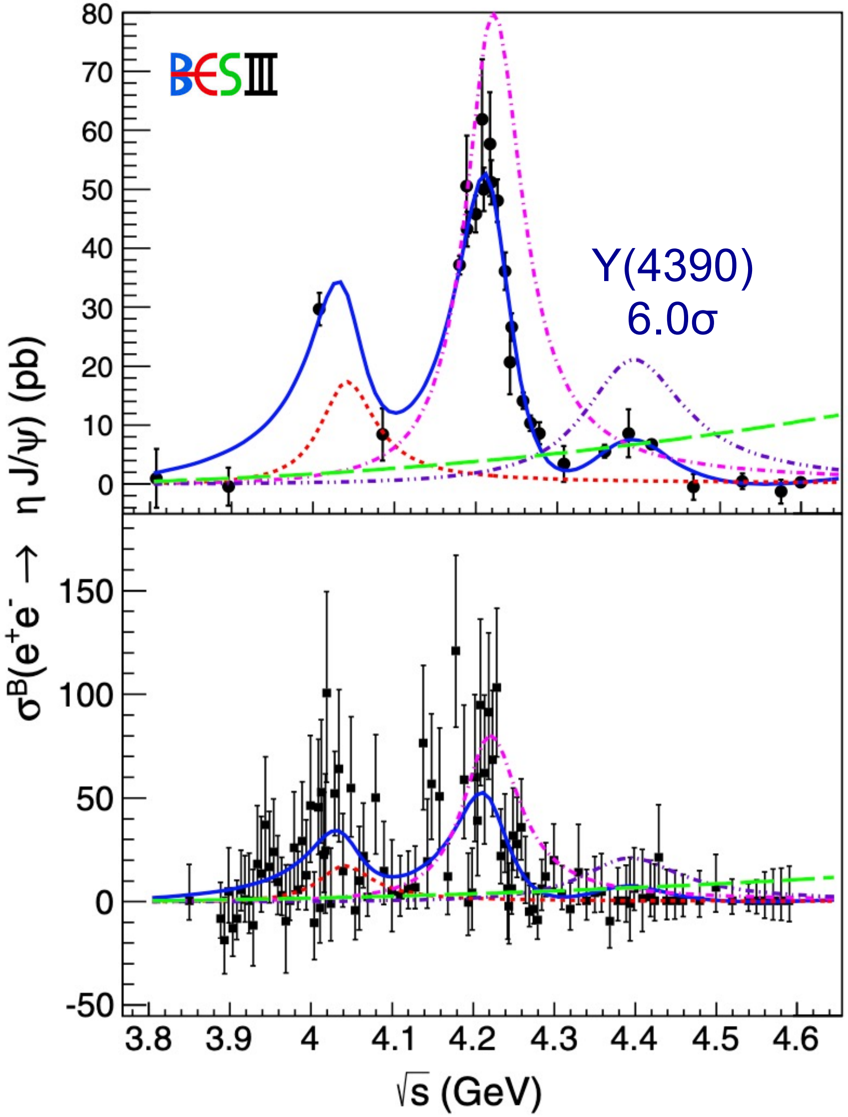
=> First Y decays to open-charm

=> Consistency with structures in J/ψ / h_c / $\psi(2S)\ \pi\pi$

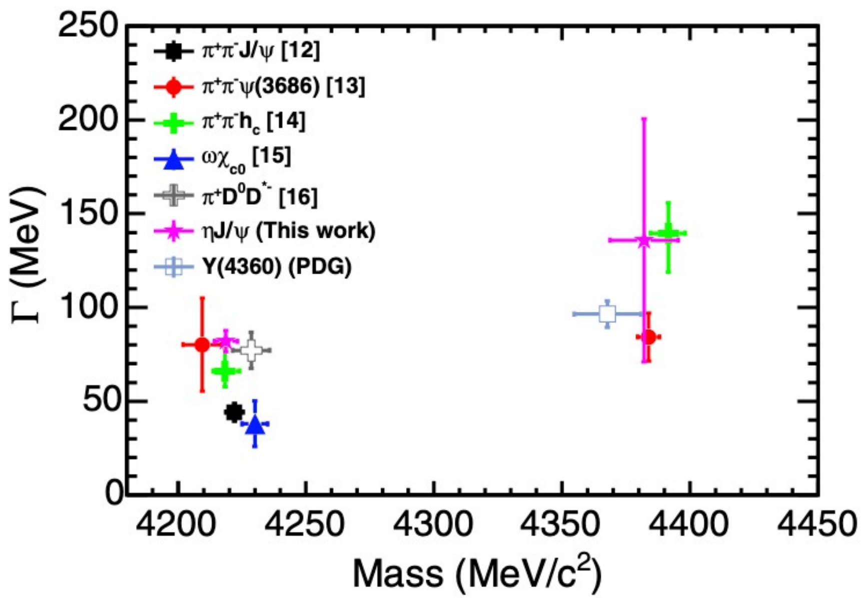
Further decays of Y(4260)

$e^+e^- \rightarrow J/\psi\ \eta$

[Phys. Rev. D 102, 031101 (2020)]



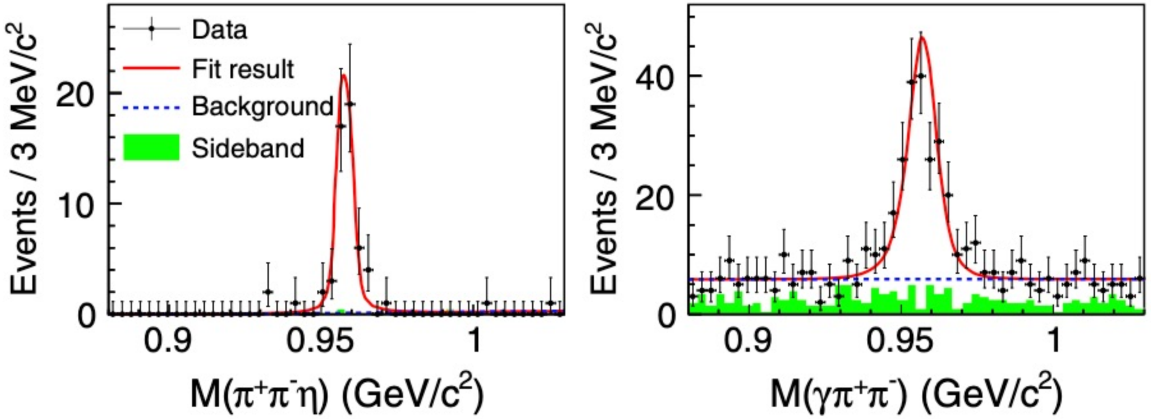
- Simultaneous maximum-likelihood fit
  (*Top: High stat. XYZ data, Bottom: Scan data)*
- ψ(4040) assumed, Y(4220), Y(4390) ?
- Significance of Y(4390) = 6.0 σ
- Y(4220) & Y(4390) mass and width compilation vs. Y(4360) from PDG:

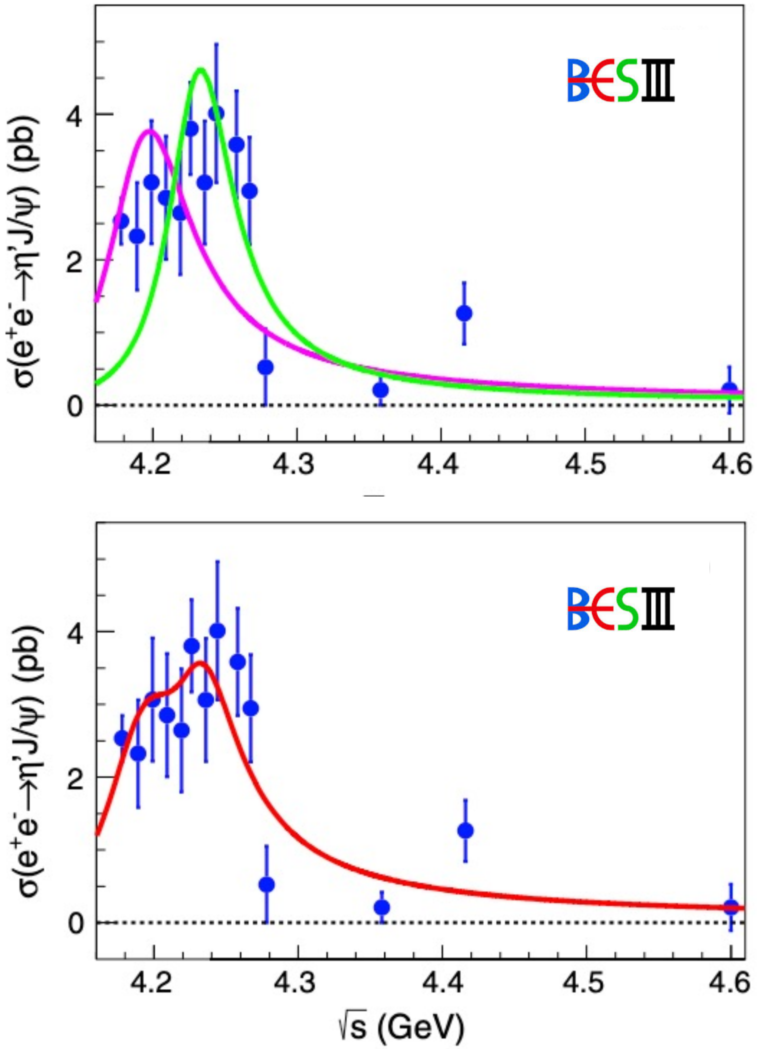


Further decays of Y(4260)

$e^+e^- \to J/\psi\ \eta'$

[Phys. Rev. D 101, 012008 (2020)]



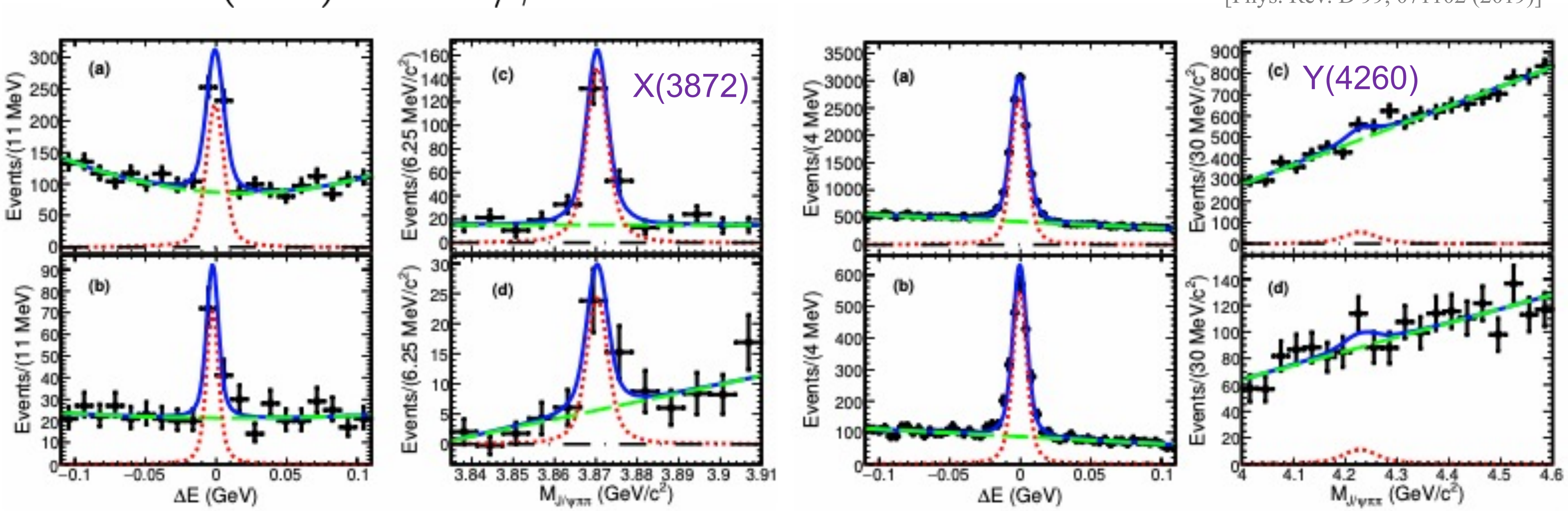


- Simultaneous maximum-likelihood fit
  (*to the two η' decay modes*)
- Fit to cross section σ [(m,Γ) fixed to PDG]
  - ➢ Single $\psi(4160)$ or Y(4260)
  - ➢ Coherent sum of $\psi(4160)$ and Y(4260)
- Coherent sum preferred by data
  - ➢ 4.0σ and 6.3σ, respectively
  - ➢ Xsec σ an order of magnitude smaller than the one for $J/\psi\ \eta$
- Higher statistics needed ...

The Y(4260) in B decays

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

[Phys. Rev. D 99, 071102 (2019)]



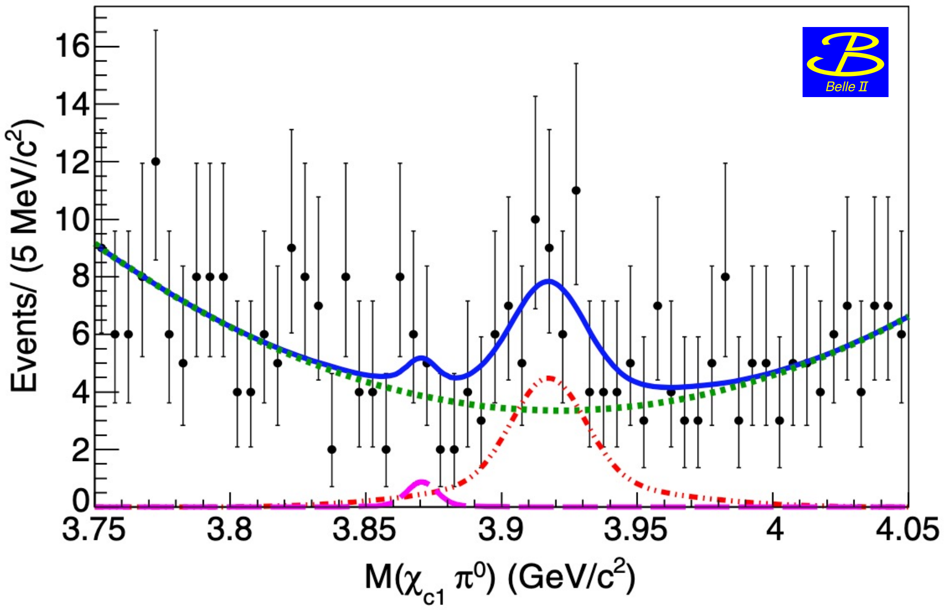
$B^0 \to Y(4260)K^0_S \to J/\psi\pi^+\pi^-K^0_S$

Belle II

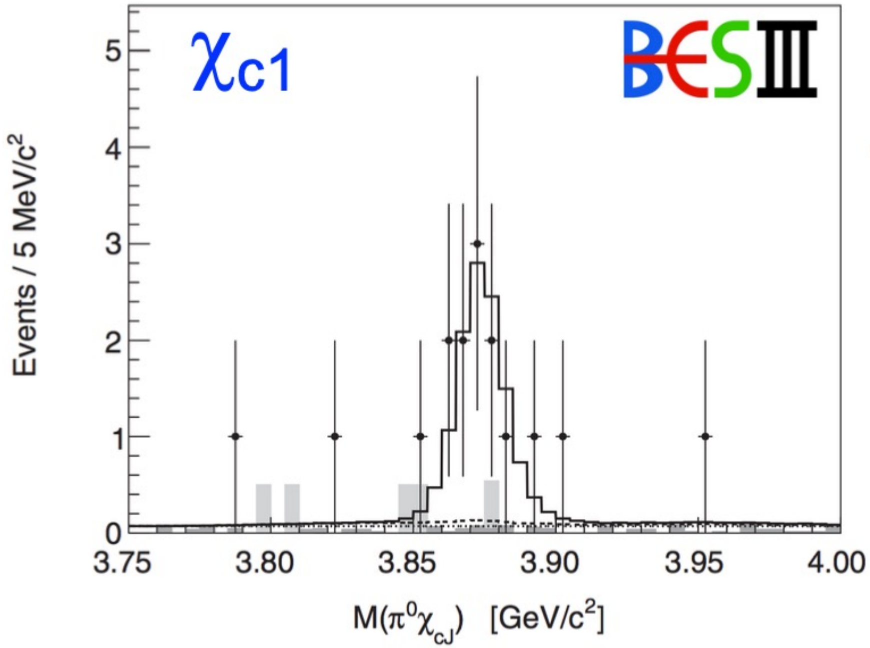
- Search for the Y(4260) in $B^{+/0}$ decays
- BaBar reported 3.1σ for B^+ [PRD 73, 011101 (2006)]
- No significant evidence (2.1σ/0.9σ), for B^0 first result
- Upper limits (CL90) on branching fractions
  - $\mathcal{B}(B^+ \to Y(4260)(\to J/\psi\pi^+\pi^-)K^+) < 1.4 \times 10^{-5}$
  - $\mathcal{B}(B^0 \to Y(4260)(\to J/\psi\pi^+\pi^-)K^0_S) < 1.7 \times 10^{-5}$

First observation of $X(3872) \rightarrow \chi_{c1}\pi^0$

[Belle, Phys. Rev. D 99 111101 (2019)]



[BESIII, Phys. Rev. Lett., 122 (2019) 202001]



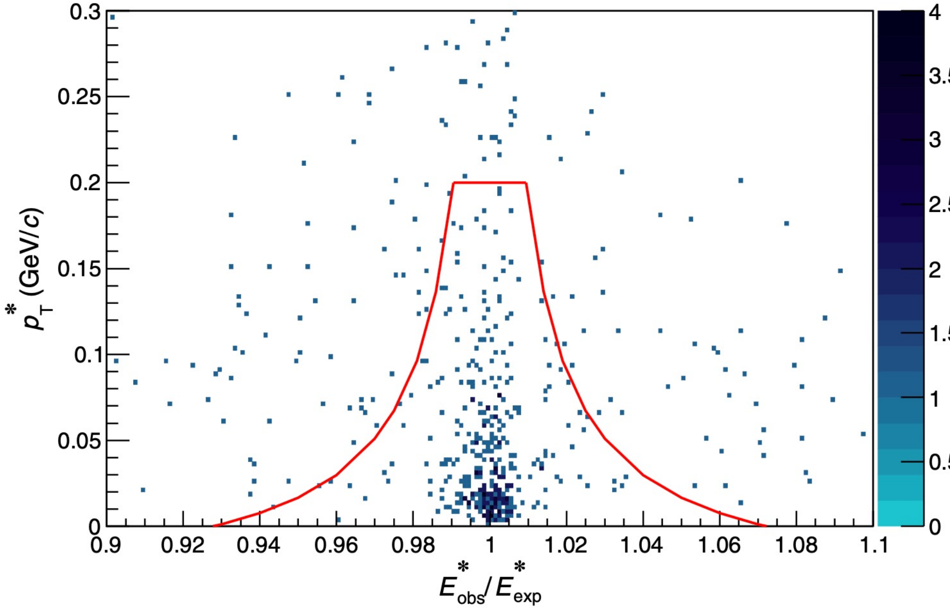
- No significant signals were found by Belle in search for X(3872) and X(3915) to $\chi_{c0}\,\pi^0$ (0.3σ / 2.3σ)
  - $\mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.)
- BESIII observes now X(3872) decay to $\chi_{c0}\,\pi^0$ (> 5σ)
  - $\mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = 0.88^{+0.33}_{-0.27} \pm 0.10$

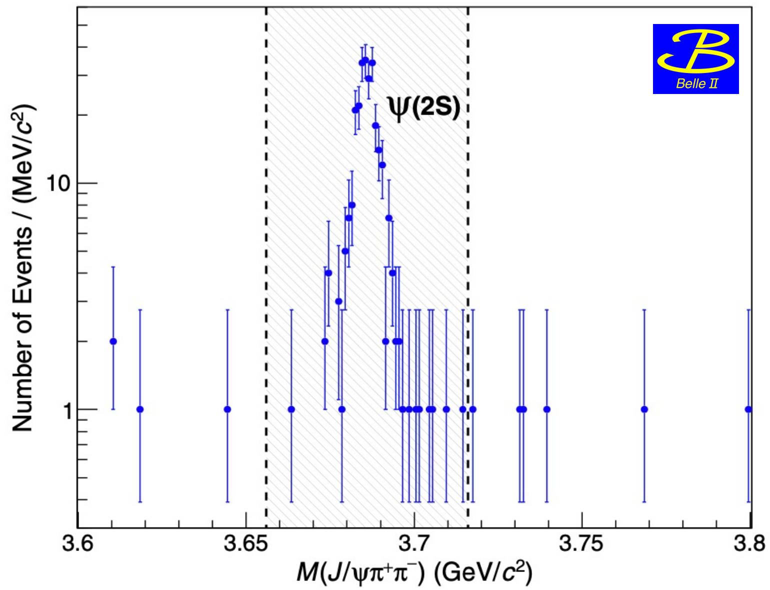
Isospin violation, comparable decay rate to J/ψρ

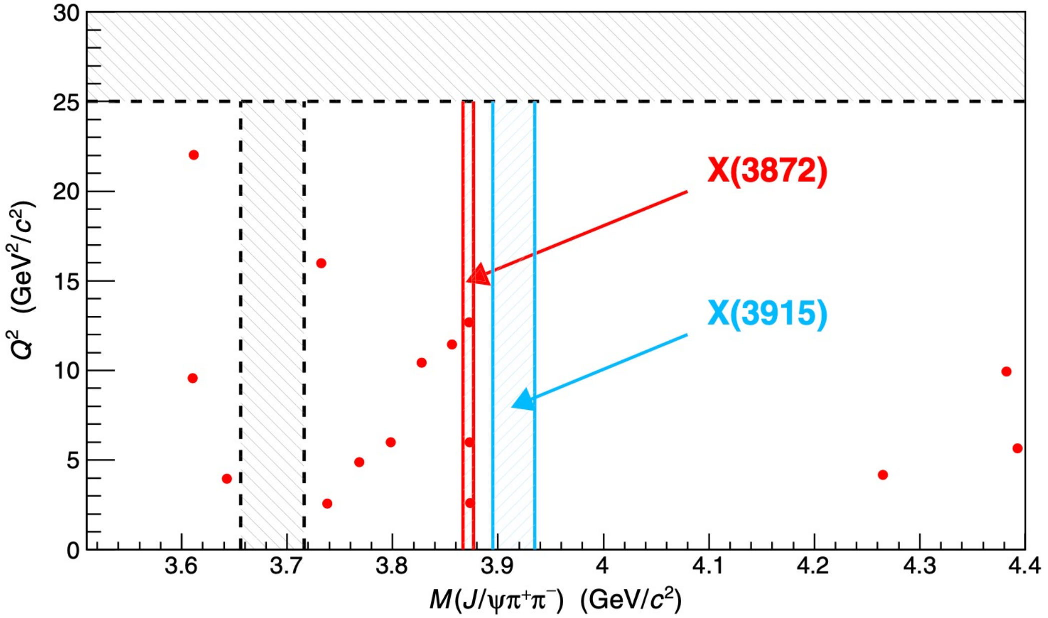
=> Disfavours χ_{c1}(2P)

First evidence for $\gamma\gamma \rightarrow X(3872)$

[Belle, PRL 126, 122001 (2021)]







- Data set of 825 fb^{-1}
- Kinematic cuts applied
- No events in X(3915) band
- 3 events survived in X(3872) band
  - 3.2σ significance
  - $\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)$
    $= 5.5^{+4.1}_{-3.8}(\text{stat}) \pm 0.7(\text{syst})$ eV