HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

JÜLICH FORSCHUNGSZENTRUM

X, Y, Z AND MORE *EXOTIC BEASTS*

WHAT DID WE UNDERSTAND AFTER 14 YEARS?

Program: **MATTER AND UNIVERSE**

Topic: Hadron spetroscopy

Research Unit: **IKP-1**

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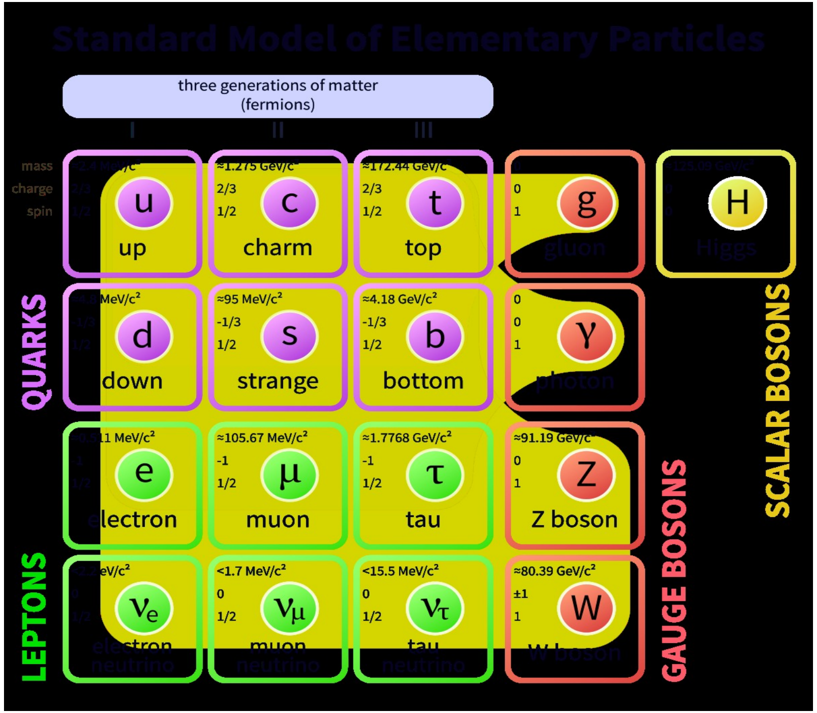
PHYSICS AT THE TERASCALE – DESY – 27-29.11.2017

OUTLINE

- Introduction
- Main achievements in spectroscopy at e^+e^- colliders
- States with hidden strange quark content
- Open questions
- Interpretation
- Looking forward to new experiments
- Summary

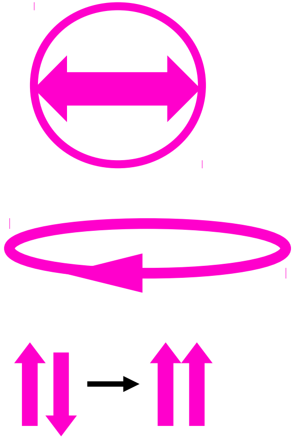
INTRODUCTION

- Standard model of particles physics:
  - Elementary particles
  - Mesons (quark + anti-quark)
  - Baryons (3 quarks)
- Other possibilities considered, nowadays. Why?
- Since 2003 several observations not fitting the potential models
- New possibilities:
  - tetraquarks
  - hybrids
  - molecular states
  - hadrocharmonium
  - pentaquarks
  - hexaquarks.....



QUANTUM NUMBERS

Spectroscopy notations



$n^{2S+1} L_J$ L=S,P,D,...

J^{PC}

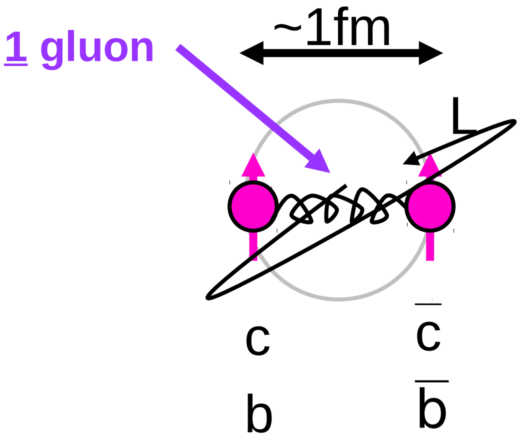
$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$ parity

$$C = (-1)^{L+S}$$ charge conjugation

QUARKONIA

u	c	t
d	s	b



Charm-onium: $c\bar{c}$+...
Bottom-onium: $b\bar{b}$+....

STATIC $Q\bar{Q}$ POTENTIAL FOR CHARMONIUM

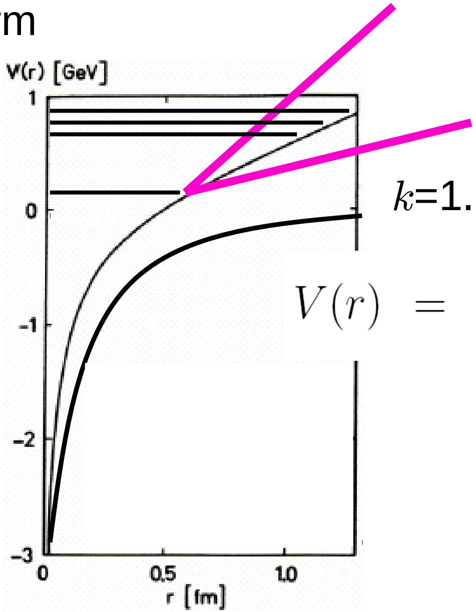
- Coulomb-Potential + Confinement term

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

spin-spin $+\frac{32\pi\alpha_s}{9m_c^2}\delta_r\vec{S}_c\vec{S}_{\bar{c}}$

spin-orbit $+\frac{1}{m_c^2}(\frac{2\alpha_s}{r^3} - \frac{k}{2r})\vec{L}\vec{S}$

tensor $+\frac{1}{m_c^2}\frac{4\alpha_s}{r^3}(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\bar{c}})$



k=1.5 GeV/fm

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r}$$

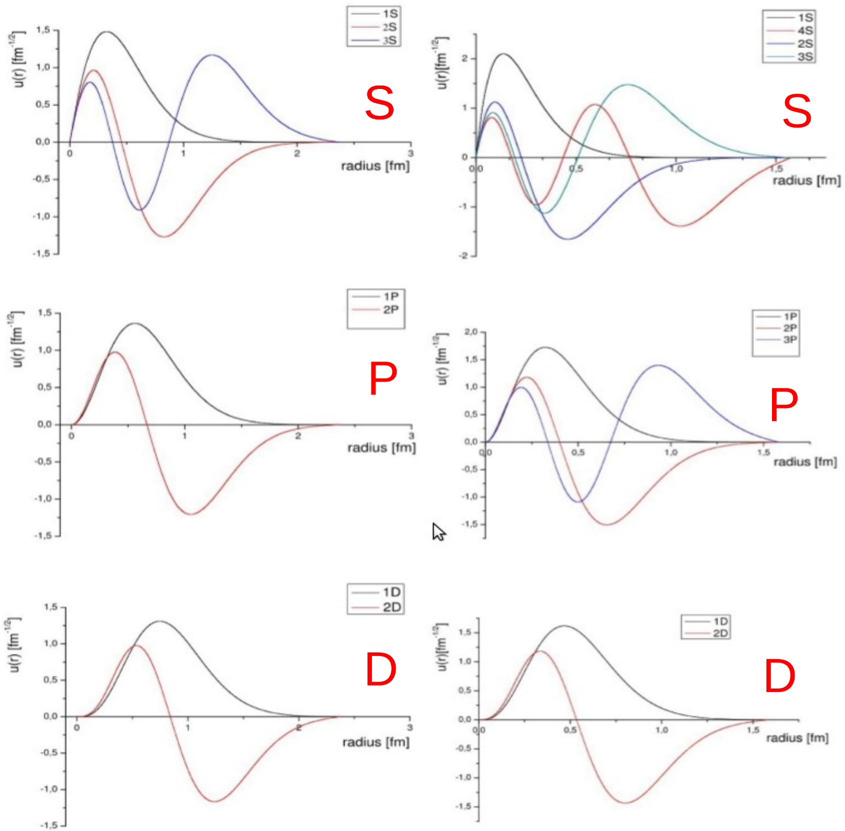
- Solve Schrödinger equation (quark mass heavy → non-relativistic) → **states**

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

$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

RADIAL WAVE FUNCTION

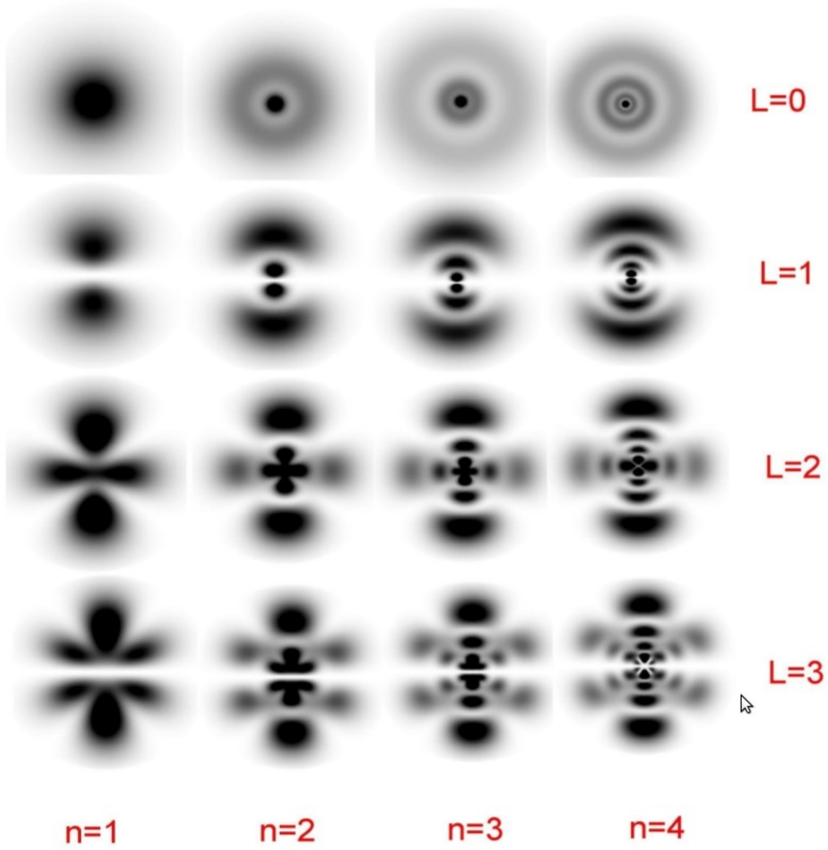
Charmonium



Bottomonium

courtesy of S. Lange, habil. thesis

ANGULAR PART OF THE WAVE FUNCTION



courtesy of S. Lange, habil. thesis

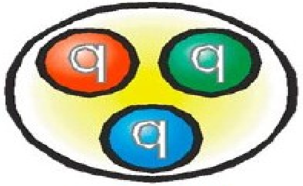
WHY CHARMONIUM?

- Gell-Mann Zweig idea: Constituent Quark Model (CQM). Still valid since half century
  →it classifies all known hadrons
- QCD describes the force binding quarks into hadrons
- Perturbation theory: limited applicability at scale corresponding to the separation between quarks inside hadrons
- Many models available to describe spectra and properties of hadrons: those incorporating features of the QCD are the most useful
- QCD-motivated models predict the existence of hadrons with more complex structures than simple $q\bar{q}$ or *qqq*.
- **Lot of experimental effort to prove it**!
- No unambiguous evidence for hadrons with non-CQM like structure has been found, but indeed....
- The study of Charmonium(-like) spectrum (e.g., $c\bar{c}$ + xx) have uncovered a number of candidates that not seem to conform CQM expectations
- *Exotic states* are predicted to exist in the light meson spectrum
  →difficult to disentangle from the dense background of conventional states
- Charmonium spectrum provide a cleaner environment: $c\bar{c}$ + xx exotics easier to identify

QUARK BOUND STATES

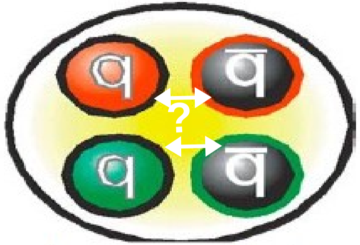
Meson

Lifetime:
< 10^{-8} s



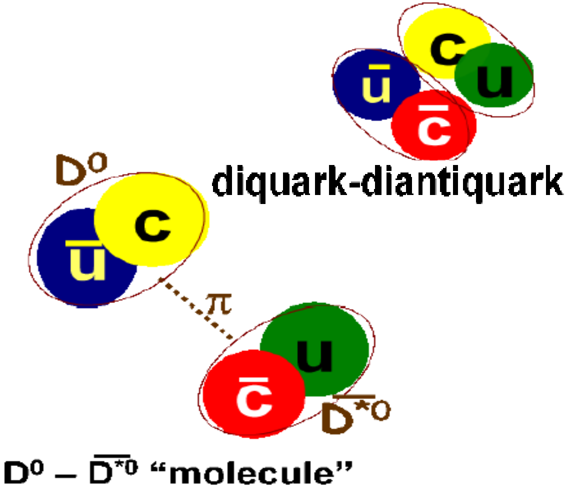
Baryon

Lifetime:
> 10^{30} (proton)
~ 10 min (neutron)
< 10^{-10} s (others)

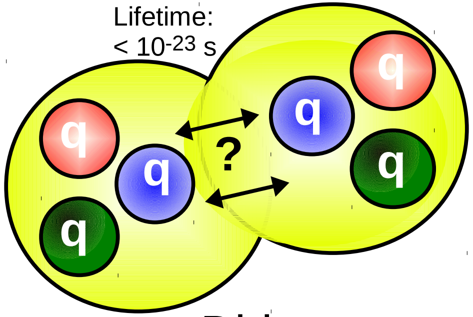


Tetraquark

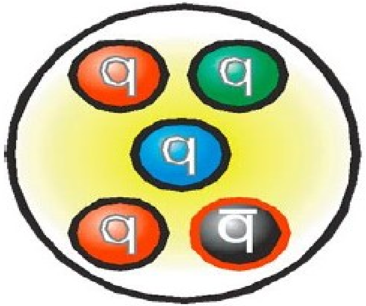
Lifetime:
< 10^{-23} s



Lifetime:
< 10^{-23} s



Di-baryon



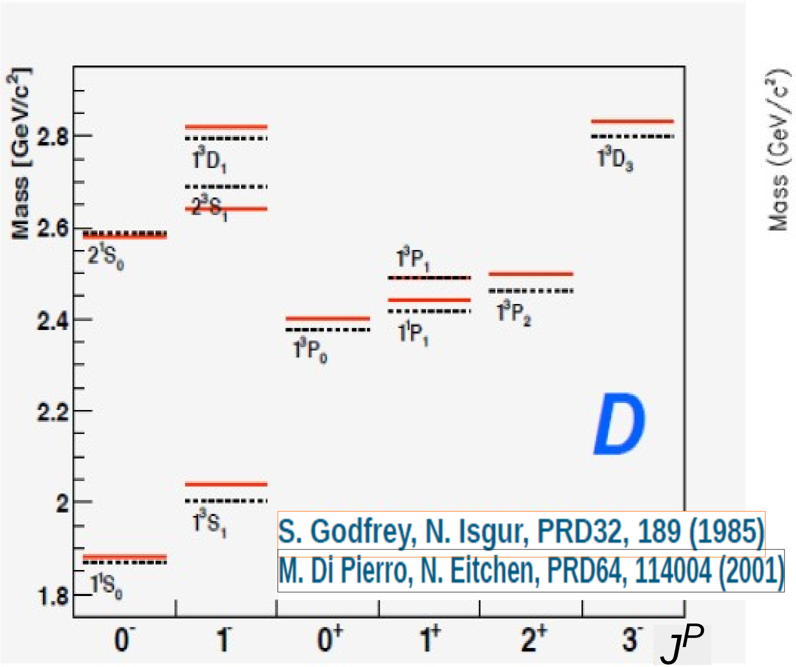
Pentaquark

Lifetime:
< 10^{-20} s

Hybrid meson

Glueball

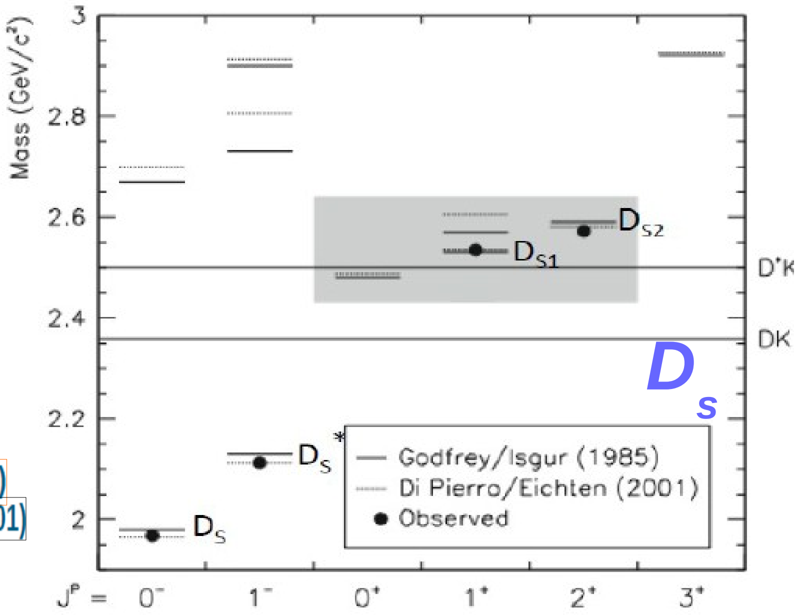
CHARM- AND CHARM-STRANGE SPECRUM



$|c\bar{u}\rangle$ $|c\bar{d}\rangle$

$\overline{M}_D = (1864.91 \pm 0.17)$ MeV/c²

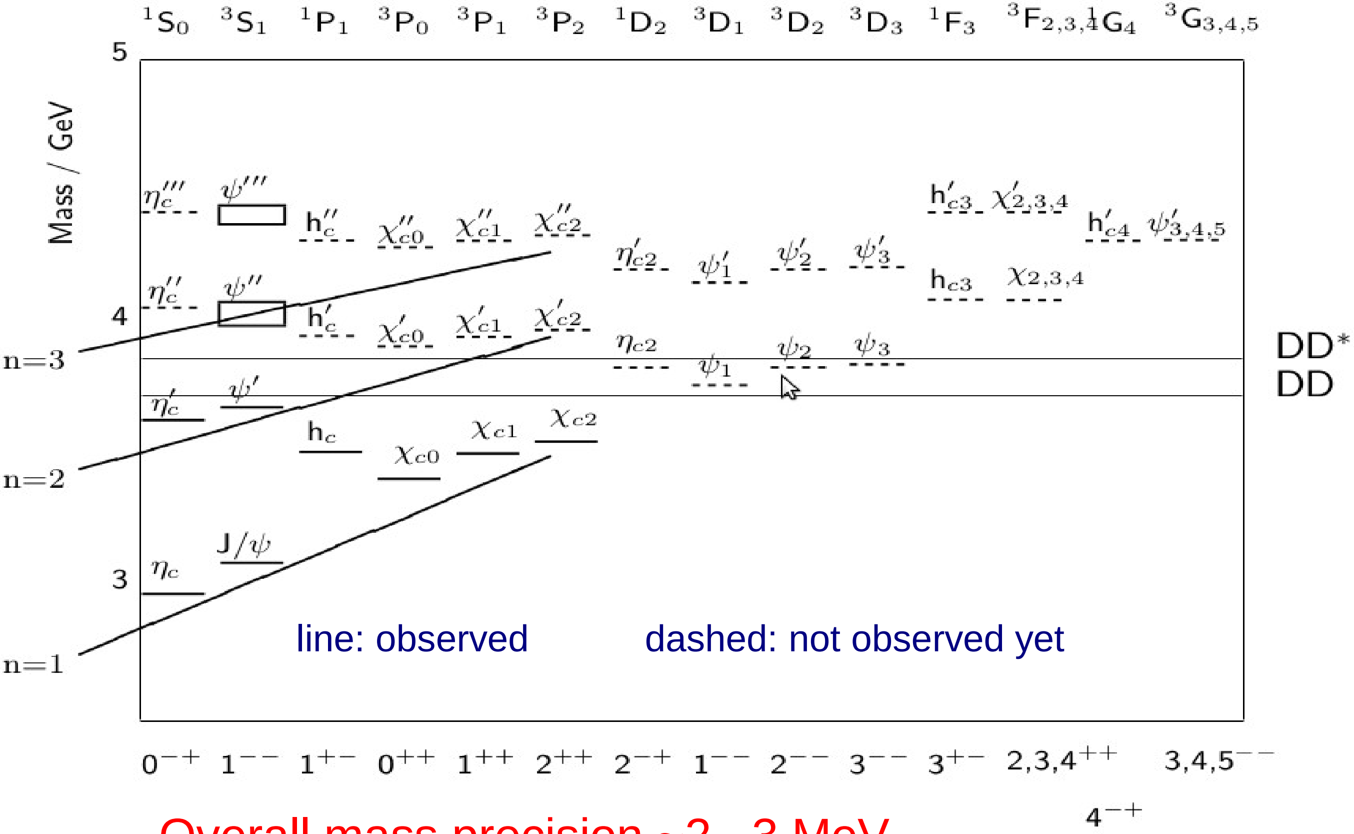
$M_\pm - M_0 = (4.74 \pm 0.28)$ MeV/c²



$|c\bar{s}\rangle$

Theoretical prediction have been in qualitative agreement with experimental results...until 2003!

CHARMONIUM SPECTRUM



Overall mass precision ~2−3 MeV

For >30 years theory and experiments agreed.
Then something happened.

How has the story begun?

2003: DISCOVERY OF THE X(3872)

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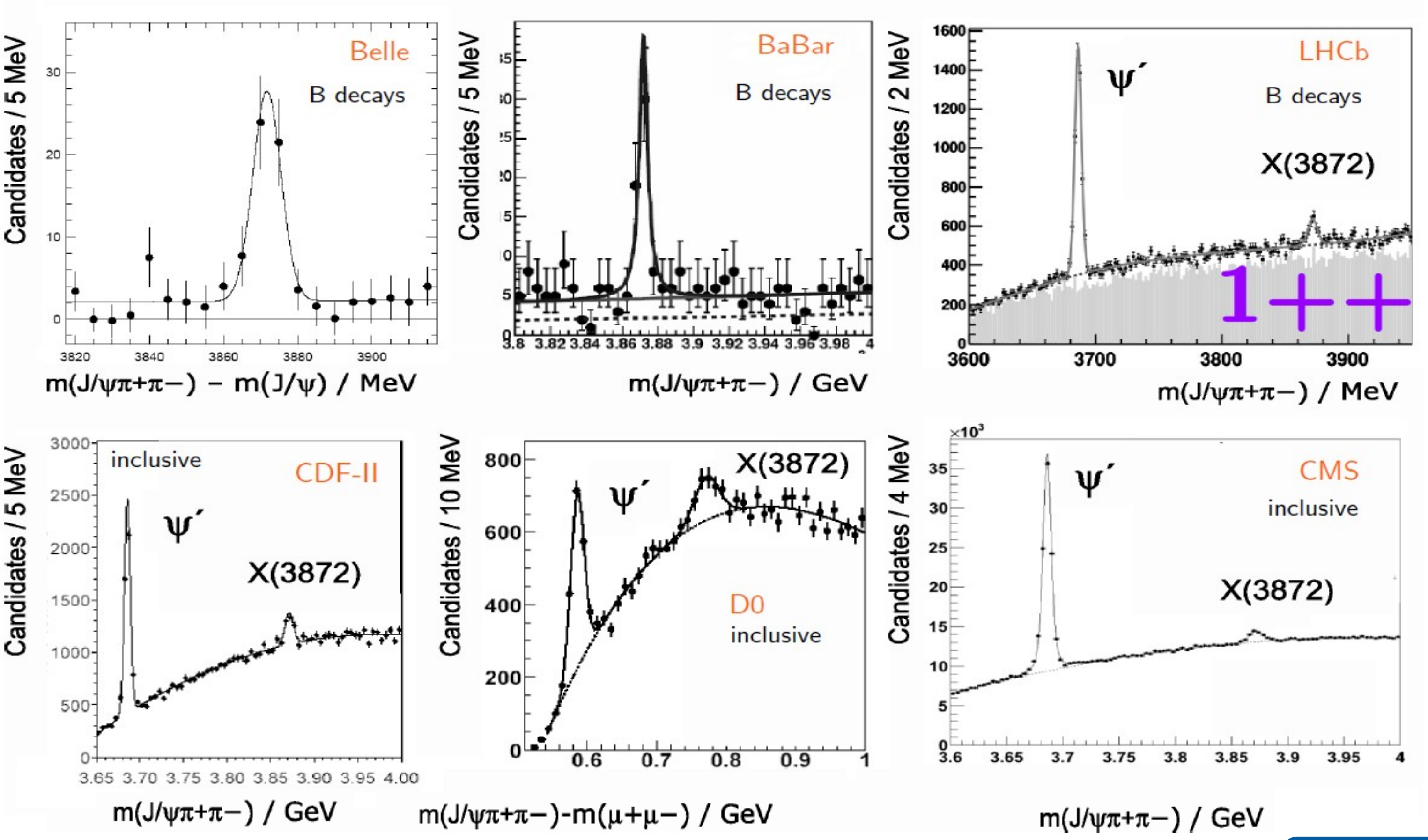


X(3872): CONFIRMED IN SEVERAL DECAY MODES

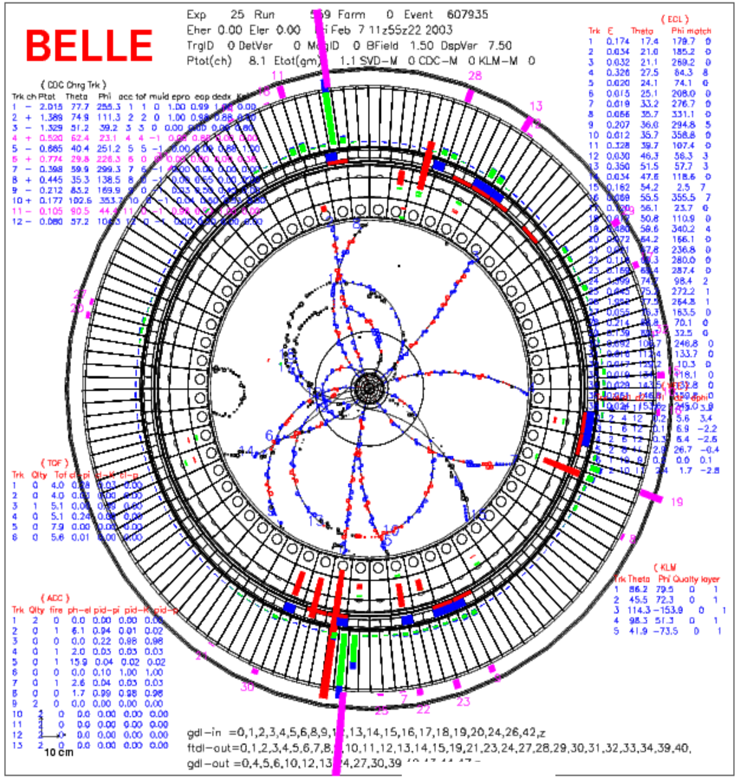
- Observed in more than one decay channel

$$X(3872) \rightarrow J/\psi\pi^+\pi^-$$
$$X(3872) \rightarrow J/\psi\gamma$$
$$X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0$$
$$X(3872) \rightarrow D^0\overline{D}^0\pi^0$$
$$X(3872) \rightarrow D^0\overline{D}^0\gamma$$
$$X(3872) \rightarrow \psi'\gamma$$

- Very narrow width
  Γ<1.2 MeV (90% CL)

Too narrow:
Need to measure
the width and line shape
to understand its nature

- Mass very close to $\overline{D}D^*$ threshold



Belle, Phys. Rev. Lett.91 (2003) 262001

CDF-II, Phys. Rev. Lett.93 (2004) 072001

D0, Phys. Rev. Lett.93 (2004) 162002

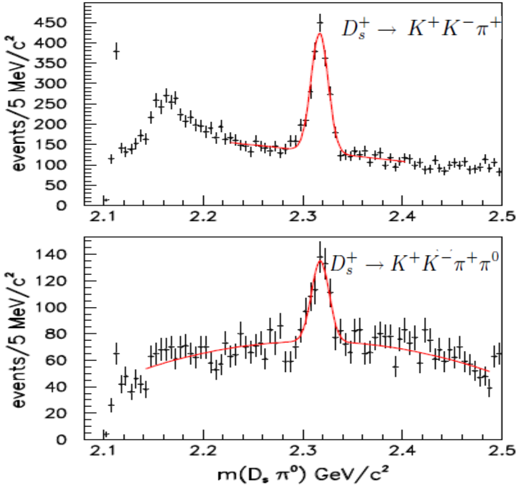
BaBar, Phys. Rev. D71 (2005) 071103

LHCb, Eur. Phys. J. C72 (2012) 1972

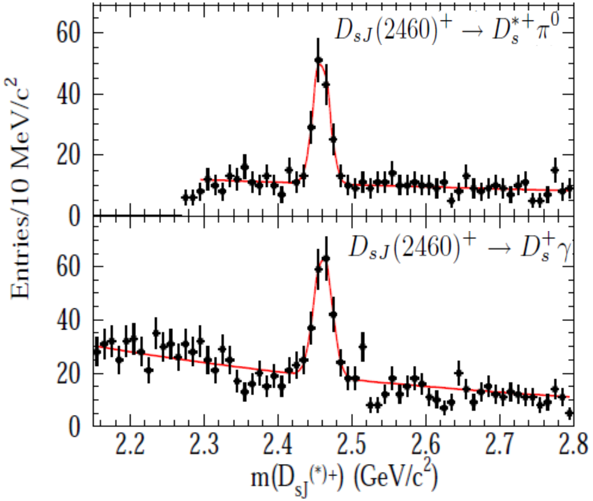
CMS, JHEP 04 (2013) 154

2003: DISCOVERY OF THE $D_{s0}^*(2317)^+$

BABAR, PRL 90 (2003) 242001



BABAR, PRL 93 (2004) 181801



$m(D_{s0}^*(2317)^+) = (2317.7\pm0.6)$ MeV/c²

$m(D_{s0}^*(2317)^+ - m(Ds^+)) = (349.4\pm0.6)$ MeV/c²

$\Gamma < 3.8$ MeV CL=95.0%

$m(D_{s1}(2460)^+) = (2459.5\pm0.6)$ MeV/c²

$m(D_{s1}(2460)^+ - m(D_s^{*+})) = (347.3\pm0.7)$ MeV/c²

$m(D_{s1}(2460)^+ - m(D_s^+)) = (491.2\pm0.6)$ MeV/c²

$\Gamma < 3.5$ MeV CL=95.0%

THE PUZZLING CASE OF $D_{s0}{}^*(2317)^+$ AND $D_{s1}(2460)^+$

Decay Channel	$D_{sJ}^*(2317)^+$	$D_{sJ}(2460)^+$
$D_s^+\pi^0$	Seen	Forbidden
$D_s^+\gamma$	Forbidden	Seen
$D_s^+\pi^0\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\pi^0$	Forbidden	Seen
$D_{sJ}^*(2317)^+\gamma$	—	Seen
$D_s^+\pi^0\pi^0$	Forbidden	Allowed
$D_s^+\gamma\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\gamma$	Allowed	Allowed
$D_s^+\pi^+\pi^-$	Forbidden	Seen

(a) Non-resonant only

- $D_{s0}{}^*(2317)^+$ is found below the DK threshold:
- $D_{s0}{}^*(2317)^+$ can in principle decay
  - electromagnetically (no exp. evidence); or
  - through isospin-violation $D_s{}^+\pi^0$ strong decay

Is $D_{s0}{}^*$ the missing 0^+ state of the *cs-spectrum*?

- Most of theoretical works treat *cs-systems* as the hydrogen atom (potential models, *c* = heavy quark):
- $D_{s1}(2317)^+$ and $D_{s2}(2460)^+$ are predicted, found with good accuracy <u>but</u>:

m($D_{s0}{}^*(2317)^+$) found 160 MeV/c^2 lower

m($D_{s1}(2460)^+$) found 120 MeV/c^2 lower

than predicted by potential models

- $D_{s1}(2460)^+$ is found in the inv. mass $D_s{}^+\gamma$
- Spin <u>at least</u> 1
- We can exclude the hypothesis 0^+, because $D_{s1}(2460)^+ \to D_s{}^+\gamma$

Is D_{s1} the missing 1^+ of the *cs-spectrum*?

THE PUZZLING CASE OF $D_{s0}^*(2317)^+$ AND $D_{s1}(2460)^+$

Decay Channel	$D_{sJ}^*(2317)^+$	$D_{sJ}(2460)^+$
$D_s^+\pi^0$	Seen	Forbidden
$D_s^+\gamma$	Forbidden	Seen
$D_s^+\pi^0\gamma$ (a)	Allowed	All[illegible]
$D_s^*(2112)^+\pi^0$	Forbidden	[illegible]
$D_{sJ}^*(2317)^+\gamma$	—	[illegible]
$D_s^+\pi^0\pi^0$	Forbid[illegible]	[illegible]
$D_s^+\gamma\gamma$ (a)	A[illegible]	[illegible]
$D_s^*(2112)^+\gamma$	[illegible]	[illegible]
$D_s^+\pi^+\pi^-$	[illegible]	[illegible]een

(a) Non-resonant only

Too narrow:
need to measure its width
to disclose its nature:
UL(Γ)<3.8 MeV@90% CL

- $D_{s0}^*(2317)^+$ is found bel[illegible] [illegible]hreshold:
- $D_{s0}^*(2317)^+$ can in princip[illegible] decay
  - electromagnetically (no exp. evidence); or
  - through isospin-violation $D_s^+\pi^0$ strong decay

Is D_{s0}^* the missing 0^+ state of the *cs-spectrum*?

- Most of theoretical works treat *cs-systems* as the hydrogen atom (potential models, *c* = heavy quark):
- $D_{s1}(2317)^+$ and $D_{s2}(2460)^+$ are predicted, found with good accuracy

<u>but</u>:

m(D_{s0}*(2317)$^+$) found 160 MeV/c^2 lower

m($D_{s1}(2460)^+$) found 120 MeV/c^2 lower

than predicted by potential models

- $D_{s1}(2460)^+$ is found in the inv. mass $D_s^+\gamma$
- Spin <u>at least</u> 1
- We can exclude the hypothesis 0^+, because $D_{s1}(2460)^+ \to D_s^+\gamma$

Is D_{s1} the missing 1^+ of the *cs-spectrum*?

Different theoretical approaches, different interpretations	$\Gamma(D_{s0}^*(2317)^+ \to D_s\pi^0)$ (keV)
M. Nielsen, Phys. Lett. B 634, 35 (2006)	6 ± 2
P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003)	7 ± 1
S. Godfrey, Phys. Lett. B 568, 254 (2003)	10 Pure $\bar{c}s$ state
Fayyazuddin and Riazuddin, Phys. Rev. D 69, 114008 (2004)	16
W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003)	21.5
J. Lu, X. L. Chen, W. Z. Deng and S. L. Zhu, Phys. Rev. D 73, 054012 (2006)	32
W. Wei, P. Z. Huang and S. L. Zhu, Phys. Rev. D 73, 034004 (2006)	39 ± 5
S. Ishida, M. Ishida, T. Komada, T. Maeda, M. Oda, K. Yamada and I. Yamauchi, AIP Conf. Proc. 717, 716 (2004)	15 - 70
H. Y. Cheng and W. S. Hou, Phys. Lett. B 566, 193 (2003)	10 - 100 Tetraquark state
A. Faessler, T. Gutsche, V.E. Lyubovitskij, Y.L. Ma, Phys. Rev. D 76 (2007) 133	79.3 ± 32.6 DK had. molecule
M.F.M. Lutz, M. Soyeaur, Nucl. Phys. A 813, 14 (2008)	140 Dynamically gen. resonance
L. Liu, K. Orginos, F. K. Guo, C. Hanhart, Ulf-G. Meißner Phys. Rev. D 87, 014508 (2013)	133 ± 22 DK had. molecule
M. Cleven, H. W. Giesshammer, F. K. Guo, C. Hanhart, Ulf-G. Meißner Eur. Phys. J A (2014) 50 -149	Strong and radiative decays of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

- The measurement of the **narrow width** plays a leading role in the interpretation of D_s^*

...and it was just the beginning!

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How does the spectrum look like, nowadays?

CHARM SPECTRUM, TODAY

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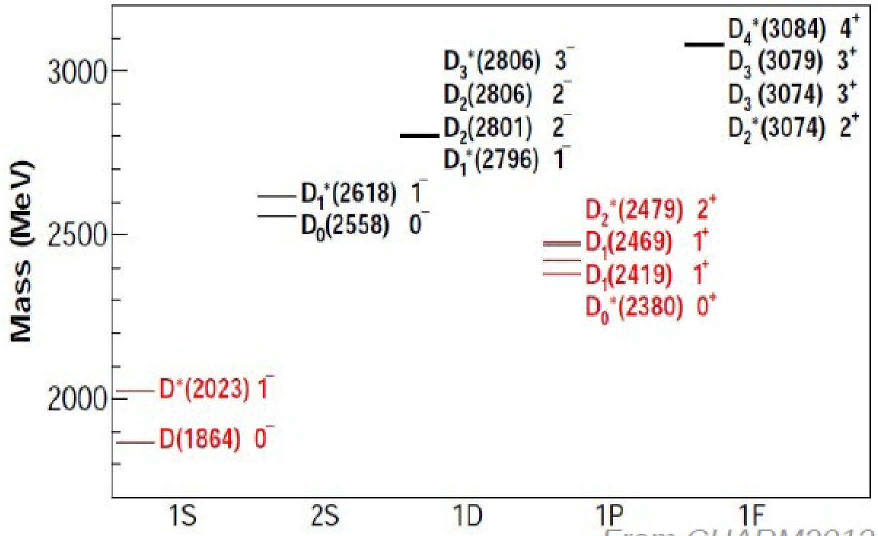
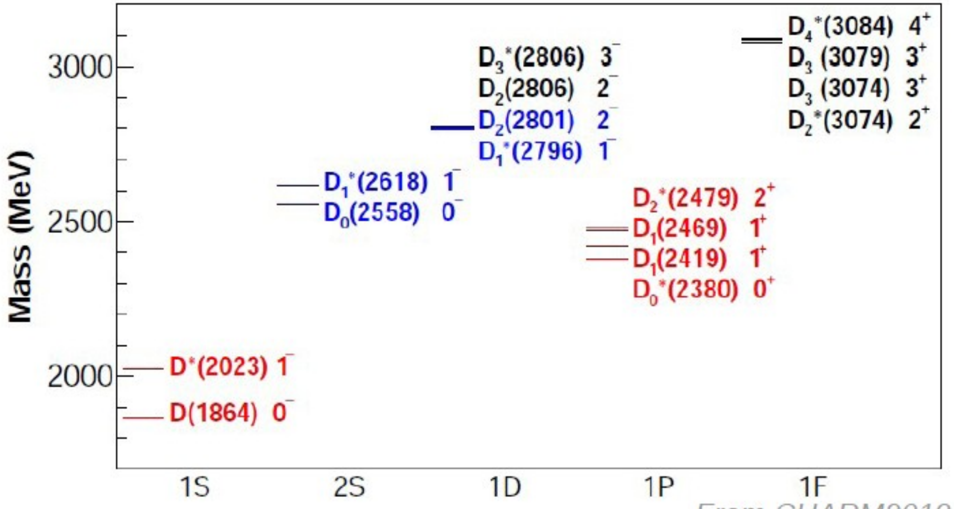


From CHARM2013

- Ground states (D, D*), and two of *1P* states (D_1(2420) and D_2(2460)*) experimentally well established: relatively small width (~30 MeV)
- Broad states with *L=1* (D^*_0(2400) and D'_1(2430)) are well established from BaBar and Belle in exclusive B decays
- BaBar → found new states: D_0(2550), D_0(2560), D_0(2750) and D_0(2760)

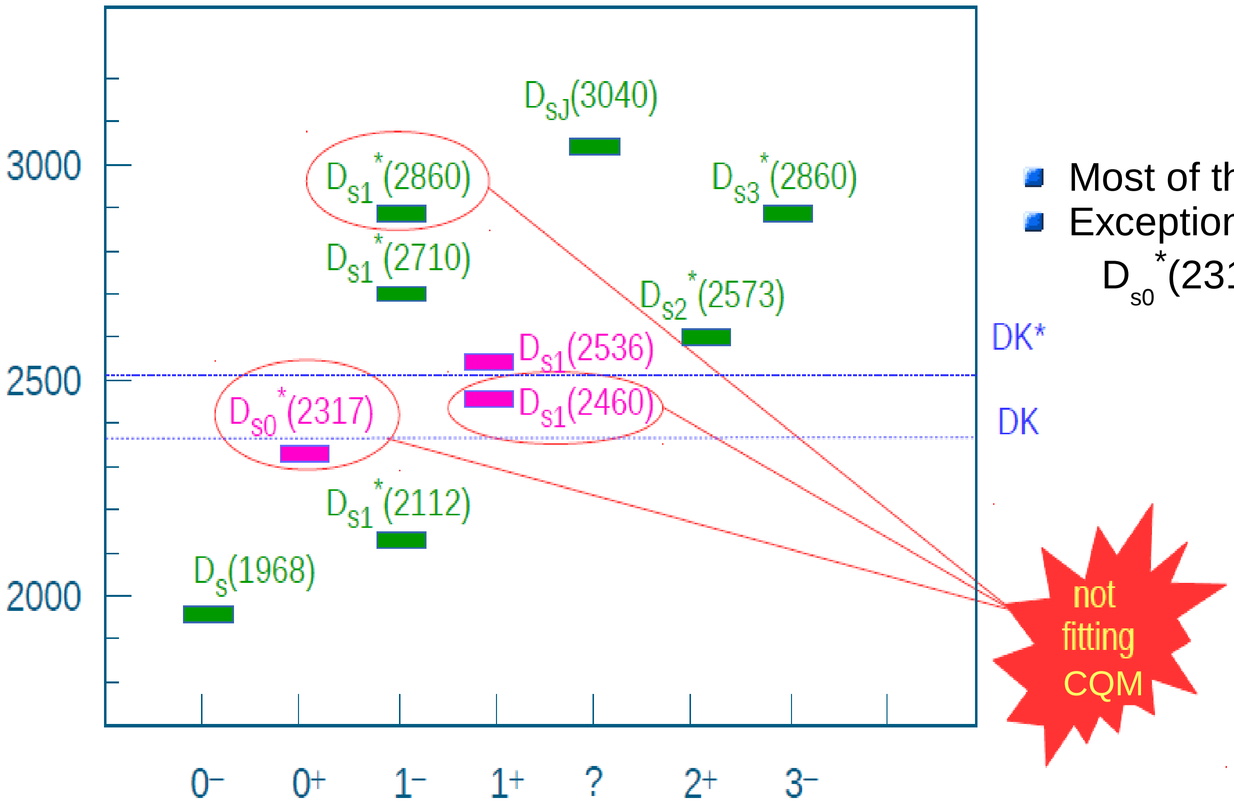
INTERPRETATION OF THE CHARM SPECTRUM



From CHARM2013

- The $D^*_J(2650)^0$ resonance could be identified as $J^P=1^-$ state (2S $D^*_1(2618)$)
- The $D^*_J(2760)^0$ could be identified as $J^P=1^-$ state (1D $D_1^*(2796)$)
- The $D_J(2580)^0$ could be identified with (2S $D^0(2558)$) state, although $J^P=0^-$ does not fit well the data
- The $D_J(2740)^0$ could be identified as $J^P=2^-$ (1D D2(2801) resonance
- Broad structures observed at 3.0 GeV in $D^{*+}\pi^-$ and $D\pi$ mass spectra. Are them superimposition of several other states?

CHARM-STRANGE SPECTRUM, TODAY



- Most of the states fit the potential models
- Exceptions:
  $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$ and $D_{s1\text{-}3}'(2860)^+$

What about the Charmonium spectrum?

EXPERIMENTAL TECHNIQUES

e^+e^- colliders

- Direct formation
- Two photon production
- Initial state radiation (ISR)
- B meson decays

(BaBar, Belle(II), BES, Cleo(-c), CESR, LEP...)

Low hadronic background
High discovery potential

BUT

Direct formation limited to vector states
Limited mass and width resolution
for non vector states

$p\bar{p}$ annihilation

(LEAR, Fermilab E 760/835, $\overline{P}$ANDA)

Hadron production

(CDF, D0, LHC)

Electro/photon production

(HERA, JLAB)

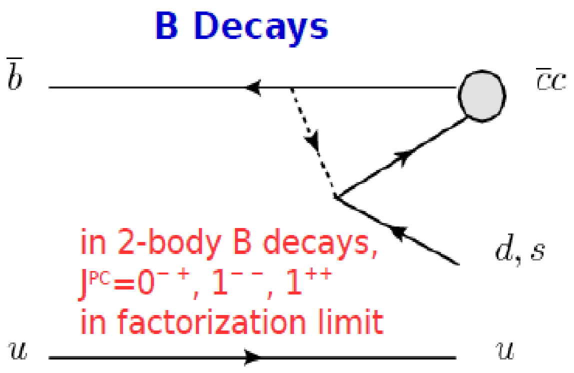
High hadronic background

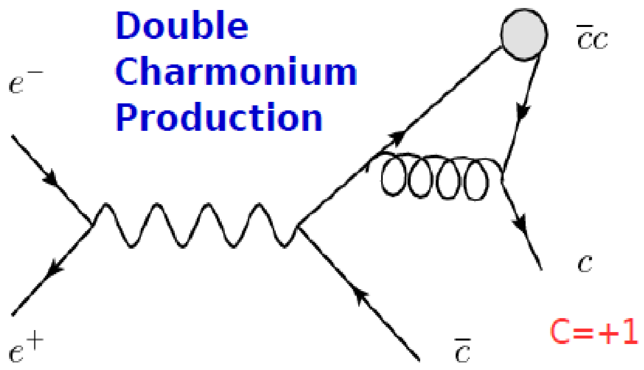
BUT

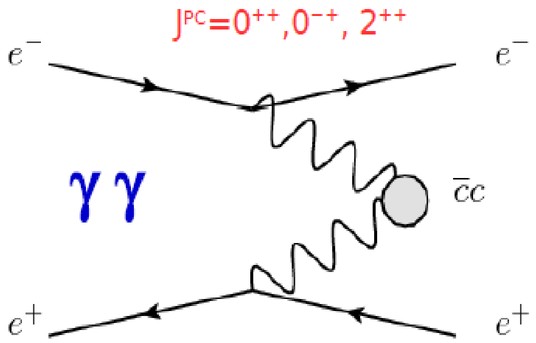
High discovery potential
Direct formation for all (non exotic) states
Excellent mass and width resolution
for all states

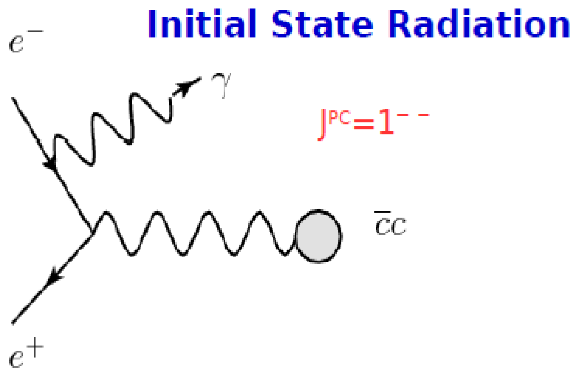
7

CHARMONIUM PRODUCTION @ e^+e^-









SEARCH FOR *CHARMONIUM-LIKE EXOTICS*

- J/ψ + vector mesons: reach environment for *new exotics*

B decays

$J/\psi\pi^+\pi^-$, $\rho\to\pi^+\pi^-$	X(3872)
$J/\psi KK$, $\phi\to KK$	X(4140), X(4274), X(4500), X(4700)
$J/\psi\omega$, $\omega\to\pi^+\pi^-\pi^0$	X(3872), X(3915)
$J/\psi\eta$, $\eta\to\pi^+\pi^-\pi^0$	–
$D^{(*)}\overline{D}^{(*)}(\pi)$	X(3872), X(3940), X(4020)

ISR

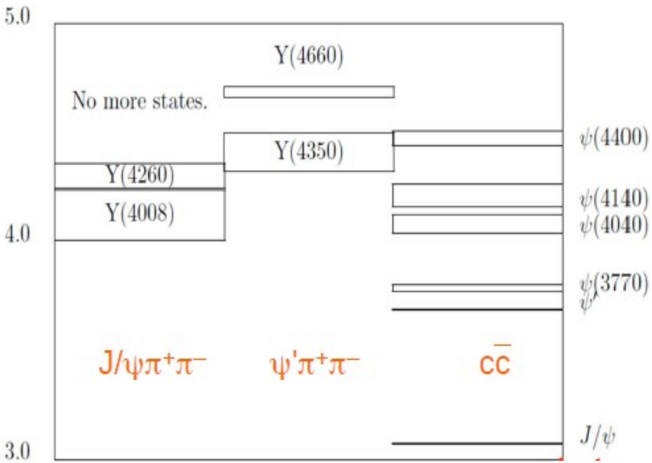
$J/\psi\pi\pi$	X(4260)
$\psi(2s)\pi\pi$	X(4360), X(4660)

$\gamma\gamma$ interactions

$J/\psi\omega$	X(3940), X(4350)
$J/\psi\phi$	X(4350)

e^+e^- directly

X(3820), X(3900), X(4020), X(4230)....



- Only neutral states, here
- Y-states not possible at LHCb: observed via ISR, only

Y(4260): IS THAT A TETRAQUARK?

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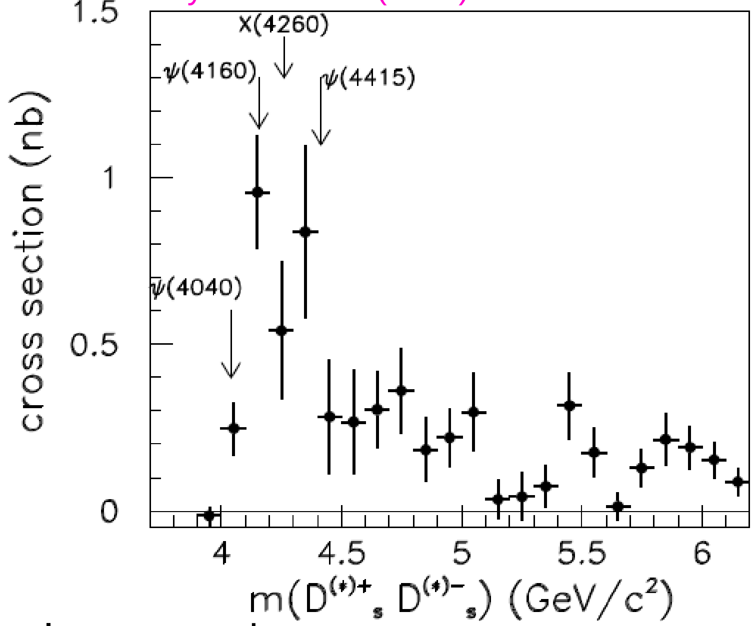
- Analyzing $e^+e^- \to D_s^+ D_s^-$, $e^+e^- \to D_s^{*+} D_s^-$, $e^+e^- \to D_s^{*+} D_s^{*-}$ via ISR

$$\frac{\mathcal{B}(X(4260) \to D_s^+ D_s^-)}{\mathcal{B}(X(4260) \to J/\psi \pi^+ \pi^-)} < 0.7,$$

$$\frac{\mathcal{B}(X(4260) \to D_s^{*+} D_s^-)}{\mathcal{B}(X(4260) \to J/\psi \pi^+ \pi^-)} < 44,$$

$$\frac{\mathcal{B}(X(4260) \to D_s^{*+} D_s^{*-})}{\mathcal{B}(X(4260) \to J/\psi \pi^+ \pi^-)} < 30$$

Phys .Rev. D82 (2010) 052004



- If Y(4260) is 1^{--} **charmonium state**, it should decay mostly to open charm
- If Y(4260) is a **tetraquark**, it should decay to $D_s^- D_s^+$
  it does not happen @95%c.l. with 525 fb^{-1} (BaBar data set)!

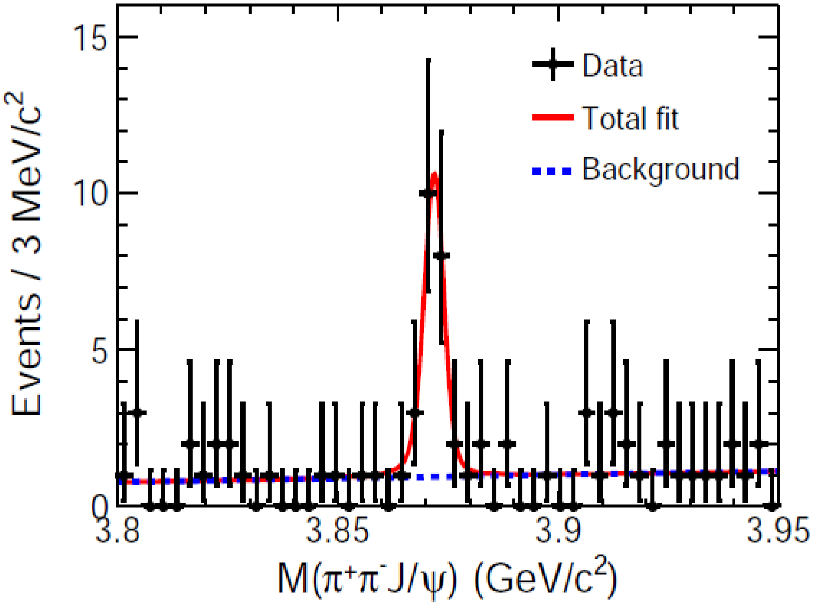
Y(4260): IS THAT A CHARMONIUM STATE?

Y↔X connection: radiative decay

- Observed Y(4260)→γX(3872) at BES III

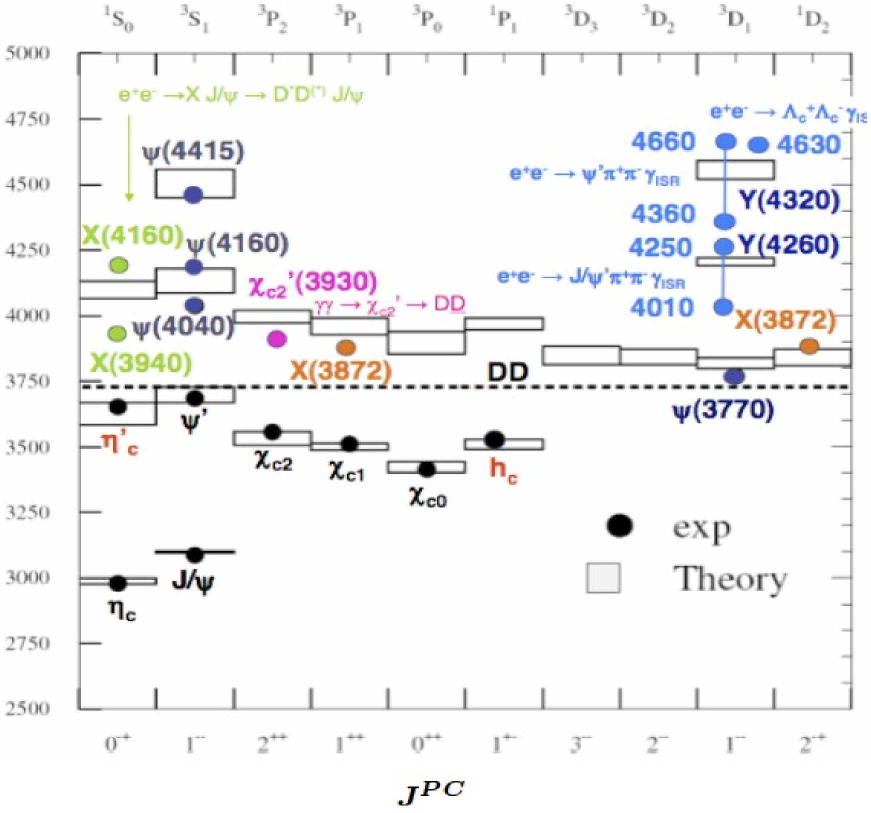
$$\frac{\sigma(e^+e^- \to \gamma X(3872))\mathcal{B}(X(3872) \to \pi\pi J/\psi)}{\sigma(e^+e^- \to J/\psi\pi^+\pi^-)} = 0.52\%$$

BES III. Phys. Rev. Lett.112 (2014) 092001



- Radiative decay of Y(4260) to X(3872):
- Not possible if Y(4260) is charmonium
- Predicted if Y(4260) is likely a **molecular state**
  →strong indication in favor of the molecular interpretation of the Y(4260)

CHARMONIUM SPECTRUM, TODAY

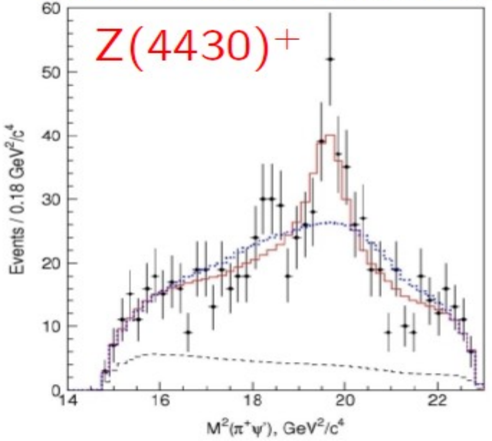


2009: CHARGED CHARMONIUM STATES

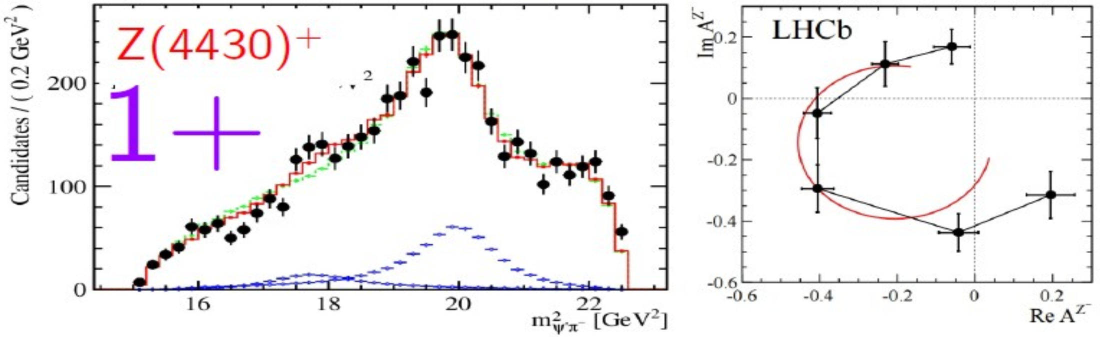
Search for exotic charged states

- New revolution!
- The $Z(4430)^+$ announced by Belle
- Not confirmed by BaBar (less statistics, but data sets consistent)
- Confirmed by LHCb

Belle, Phys. Rev D80(2009)031104



LHCb, Phys. Rev. Lett. 112(2014)222002



$B^0 \rightarrow K^{\mp} \psi(2s) \pi^{\pm}$

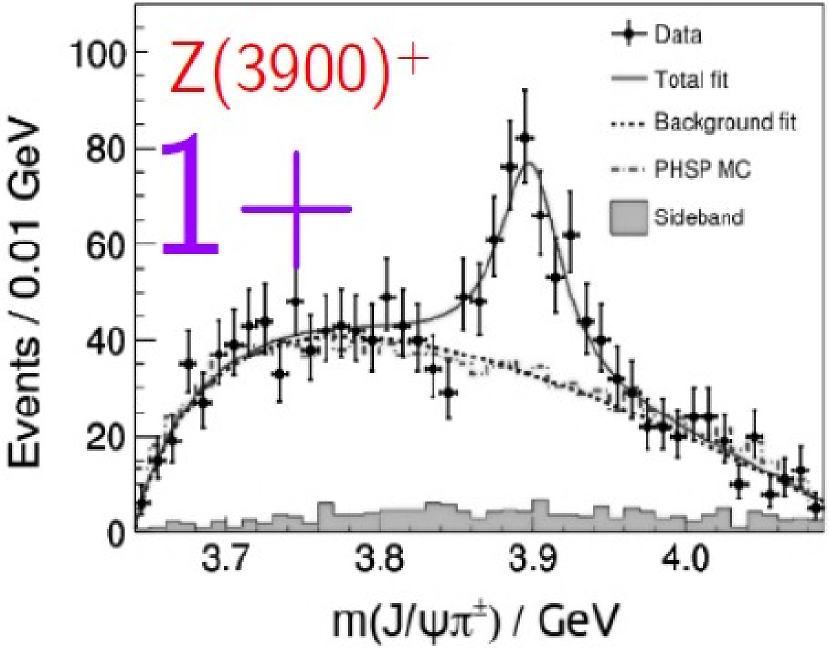
THE $Z_c(3900)^+$

Y↔Z Transition

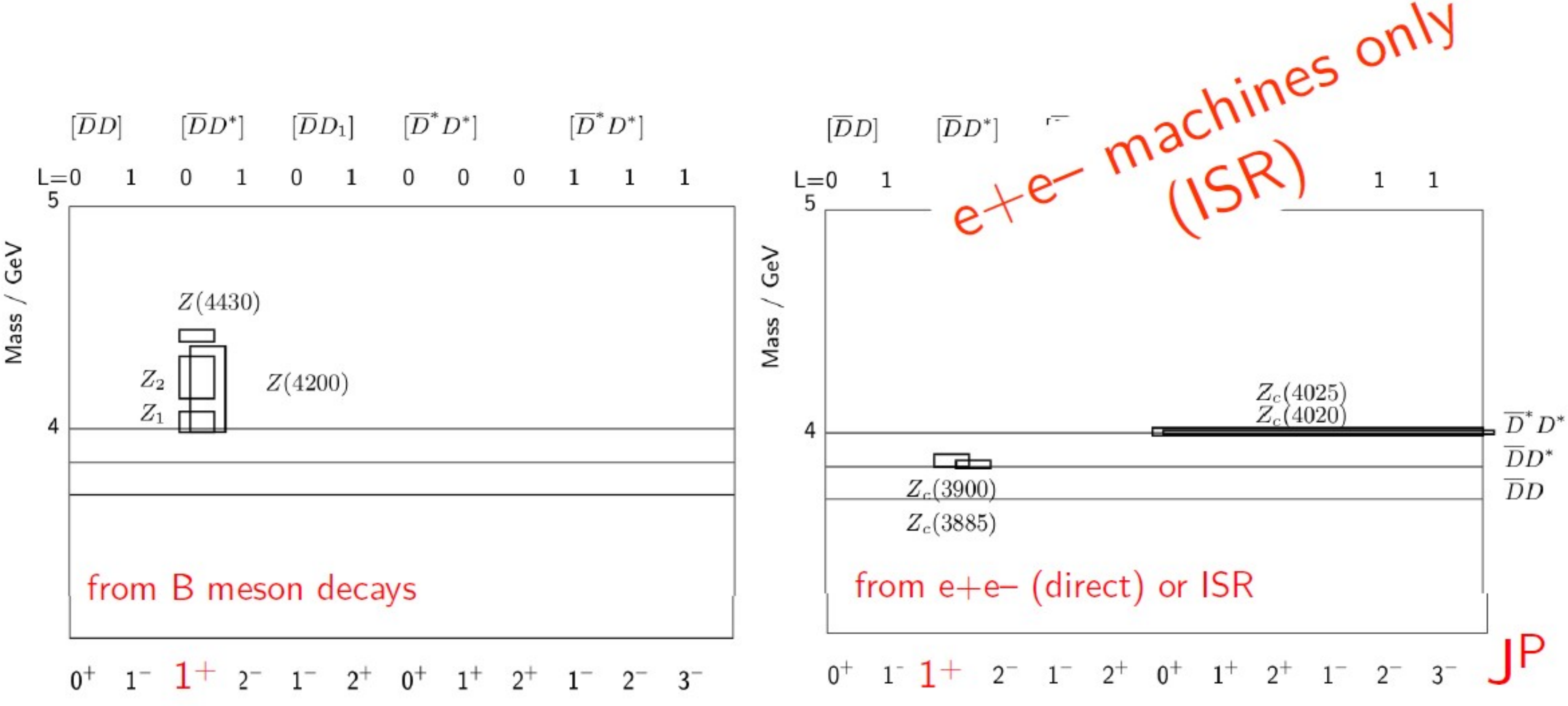
$$e^+e^- \rightarrow Y(4260) \rightarrow J/\psi\pi^+\pi^-$$

- Believed to be the first observed **tetraquark**
- Observed at Belle, then at BES III
- Establish a connection between Y and Z states:
  decay with emission of a charged pion
- A neutral partned observed 2 years later:
  decay with emission of neutral π^0
- Z-triplet

BES III. Phys. Rev. Lett.110 (2013) 252001



TWO DIFFERENT CLASSES OF Z STATES?



– large widths
– not connected to thresholds?

– narrow widths
– near thresholds

Z CHARGED STATES, TODAY

- All measured masses above the threshold

State	m/MeV	Threshold	Δm/MeV
$Z_c(3900)$	$3899.0 \pm 3.6 \pm 4.9$	$D^+ \overline{D}^{0*}$	$+22.4$
$Z_c(3900)$	$3899.0 \pm 3.6 \pm 4.9$	$D^0 \overline{D}^{+*}$	$+23.9$
$Z_c(3900)$	$3894.5 \pm 6.6 \pm 4.5$	$D^+ \overline{D}^{0*}$	$+17.9$
$Z_c(3900)$	$3894.5 \pm 6.6 \pm 4.5$	$D^0 \overline{D}^{+*}$	$+19.4$
$Z_c(3900)$	$3885 \pm 5 \pm 1$	$D^+ \overline{D}^{0*}$	$+8.4$
$Z_c(3900)$	$3885 \pm 5 \pm 1$ MeV	$D^0 \overline{D}^{+*}$	$+9.9$
$Z_c(3885)$	$3883.9 \pm 1.5 \pm 4.2$	$D^+ \overline{D}^{0*}$	$+7.4$
$Z_c(3885)$	$3883.9 \pm 1.5 \pm 4.2$	$D^0 \overline{D}^{+*}$	$+8.8$
$Z_c(4020)$	$4022.9 \pm 0.8 \pm 2.7$	$D^{0*} \overline{D}^{\pm *}$	$+5.6$
$Z_c(4025)$	$4026.3 \pm 2.6 \pm 3.7$	$D^{0*} \overline{D}^{\pm *}$	$+9.0$

$J/\psi\pi^+$

$h_c\pi^+$

	possible?
threshold	yes (by loops)
tetraquark	yes (spin–spin forces)
molecules	no, if bound state (pole below threshold, $E_B>0$)

Z CHARGED & NEUTRAL STATES, TODAY

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State	m [MeV]	Width [MeV]	Decay
$Z_c(3900)^+$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$J/\psi\pi^+$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$J/\psi\pi^0$
$Z_c(3885)^+$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 1.0$	$(DD^*)^+$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(DD^*)^0$
$Z_c(4020)^+$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$h_c\pi^+$
$Z_c(4020)^0$	$4023.8 \pm 2.2 \pm 3.8$	Fixed to 7.9	$h_c\pi^0$
$Z_c(4025)^+$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$(D^*D^*)^+$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$(D^*D^*)^0$

Z at $\bar{D}D$ threshold:
still missing....
Advantage at $\bar{p}p$ machine

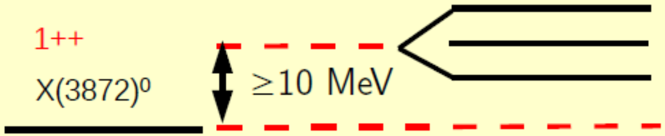
BESIII, Phys. Rev. Lett. 110 (2013) 252001
BESIII, Phys. Rev. Lett. 115 (2015) 112003
BESIII, Phys. Rev. Lett. 112 (2014) 022001
BESIII, Phys. Rev. Lett. 115 (2015) 222002
BESIII, Phys. Rev. Lett. 111 (2013) 242001
BESIII, Phys. Rev. Lett. 113 (2014) 212002
BESIII, Phys. Rev. Lett. 112 (2014) 13200
BESIII, Phys. Rev. Lett. 115 (2015) 182002

4-quark content:
charged Z $[c\bar{c}u\bar{d}]$, neutral Z $[c\bar{c}u\bar{u}]$,$[c\bar{c}d\bar{d}]$
$\rightarrow$ masses may be different

X(3872) AND Z(3900) ISOSPIN TRIPLET?

for parity assume L=0
(close to threshold)

mass degenerate



$Z(3900)^+$	1+
$Z(3900)^0$	1+ −
$Z(3900)^-$	1+

$\Gamma \leq 1.2$ MeV

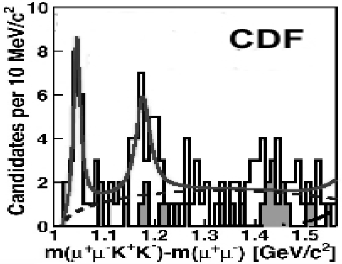
$\Gamma \simeq 50$ MeV

Is the $Z(3900)^{+,0,-}$ the isospin partner to the X(3872)?
No!
Wrong G-parity.

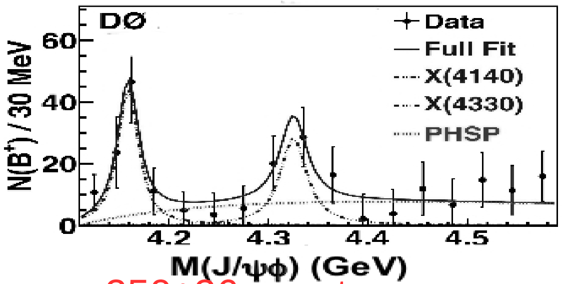
G PARITY =
generalization of C-parity
C-parity: only neutral
G-parity: whole multiplet

THE X(3872) AND THE X(4140)

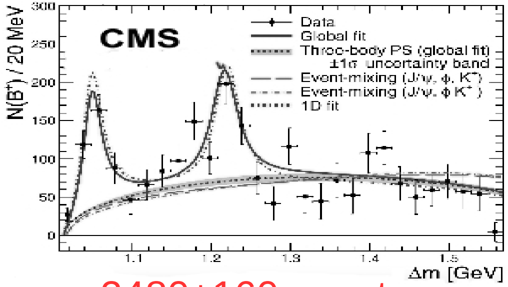
- The X(4140) was observed in the invariant mass system of J/ψKK (φ→K⁺K⁻)
- The X(4140) can be considered the *strange* counterpart of the X(3872)
- Is the X(4140) a real particle?



75±10 events

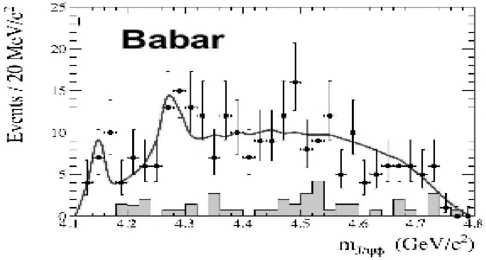


250±36 events

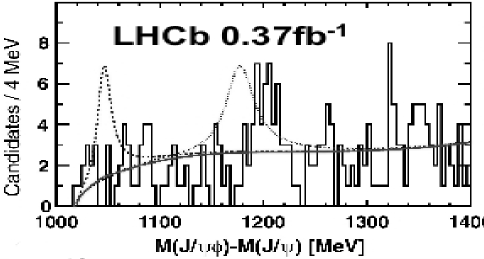


2480±160 events

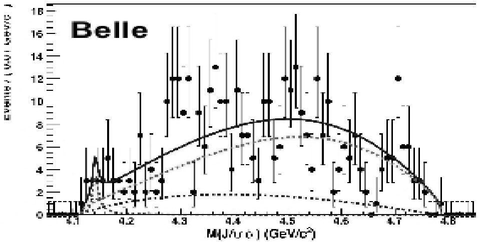
(2010)



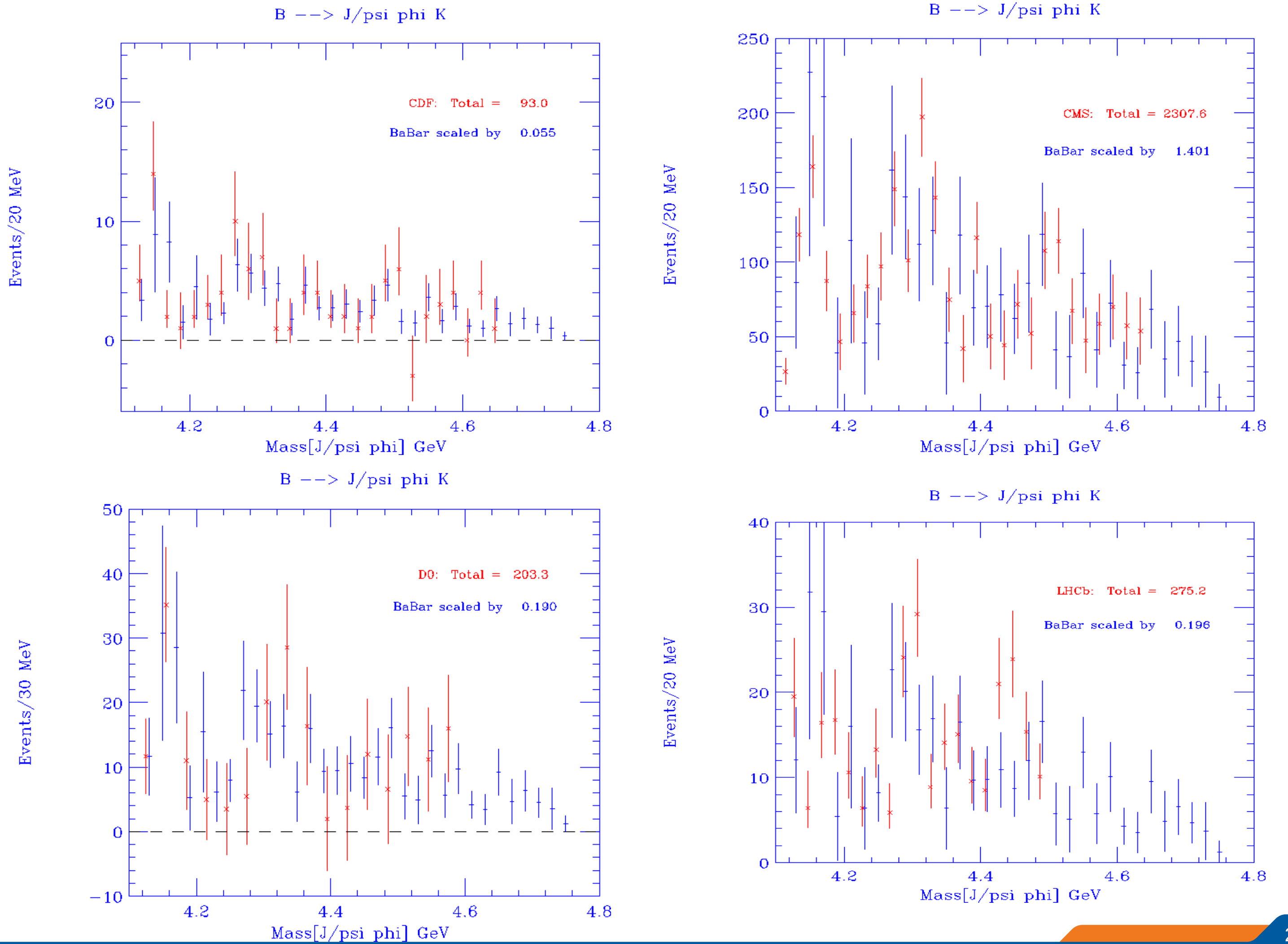
189±14 events



346±20 events



325±21 events



- Exercise:
data comparison (2015) does not show big disagreement!

E.P, EPJ Web Conf 95 (2015) 05012

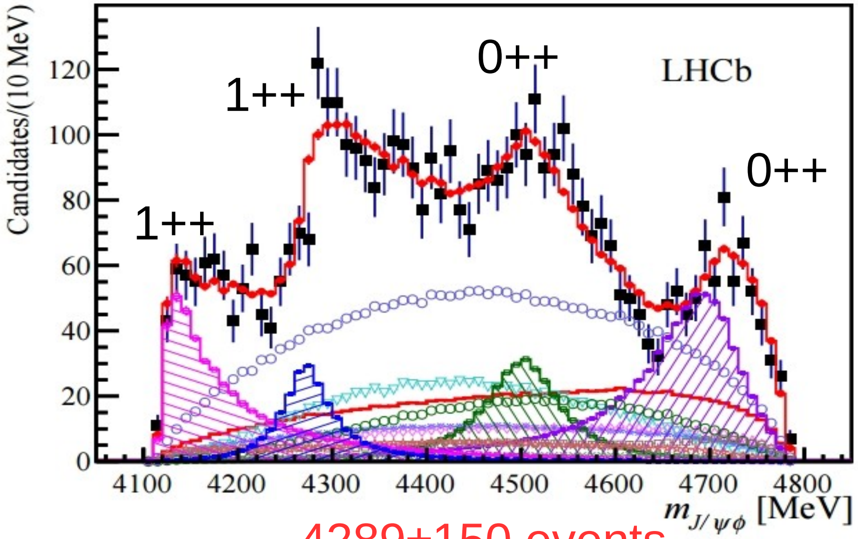
X(4140): INTERPRETATION

- In 2015 a new publication from LHCb (larger x10 data)
- 1^{++} doublet → problem for diquark anti-diquark tetraquarks
- Solution: interpret X(4140) as threshold effect
- $J/\psi\phi$ hadro–charmonium: doublet o.k., but:
  - sequence should be 0++, 1++, 0++, 1++
  - $m(J/\psi)+m(\phi)$= 4116 MeV

  → <u>positive</u> „binding energy“ (~20 MeV)
- molecules ? → no isospin! → η exchange

  Karliner, Rosner, Nucl. Phys. A 954(2016)365

Phys. Rev. Lett. 118 (2016) 022003



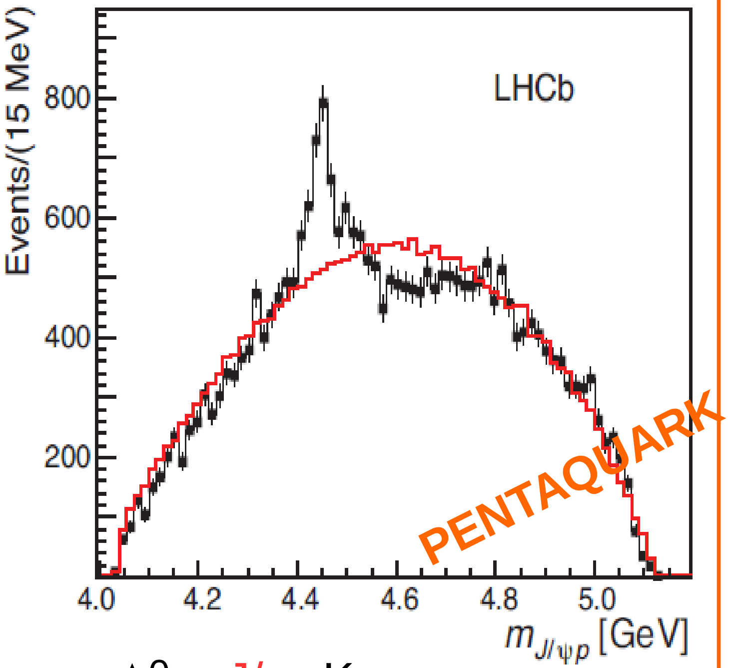
4289±150 events

$c\bar{c}s\bar{s}$ bound states: it wold be interesting to look for those in $D_s^{(*)}D_s^{(*)}$ systems: C=1⁻ not seen here!

Remember: J/ψ is a “*nice*” object to reconstruct; $D_s^{(*)}$ can be “*nasty*”: too many low momentum photons

PENTAQUARKS, HEXAQUARKS AND CUSPS

Phys. Rev. Lett. 115 (2015) 072001



- $\Lambda^0_b \to J/\psi pK$
  $P_c(4380)$, $P_c(4450)$

- Di-baryon search
  - R.L. Jaffe (1977) predictions (udsuds)
  - d*(2380) observed at WASA-at-COSY (2014) in np scattering fits the theoretical prediction.
  - Candidate for di-baryon (**hexaquak**)

Phys. Rev. Lett 112 (2014) 202301

- **Cusps** = kinks in the amplitude of an observable
- Where to looks for those?
  - at the opening of the S-wave threshold
  - narrow peaks at the threshold are good candidates
  - kinematic threshold cusp cannot produce narrow peak in the invariant mass distributions in elastic scattering processes
  - cusps seen mostly in low mass meson spectrum

- Is the X(4140) a cusp effect? Look for it into $D_s^{(*)}D_s^{(*)}$:
  →a signal would exclude the cusp hypothesis

Future perspectives

SuperKEKB asymmetric B meson factory, e+ e– → $B\bar{B}$
adjusted to Υ(4S) resonance, $\sqrt{s}$=10.6 GeV
different beam energies
8 GeV → 7 GeV (lower emittance)
3.5 GeV → 4 GeV (Touschek lifetime)
Upgrade: luminosity peak x40, integrated x50

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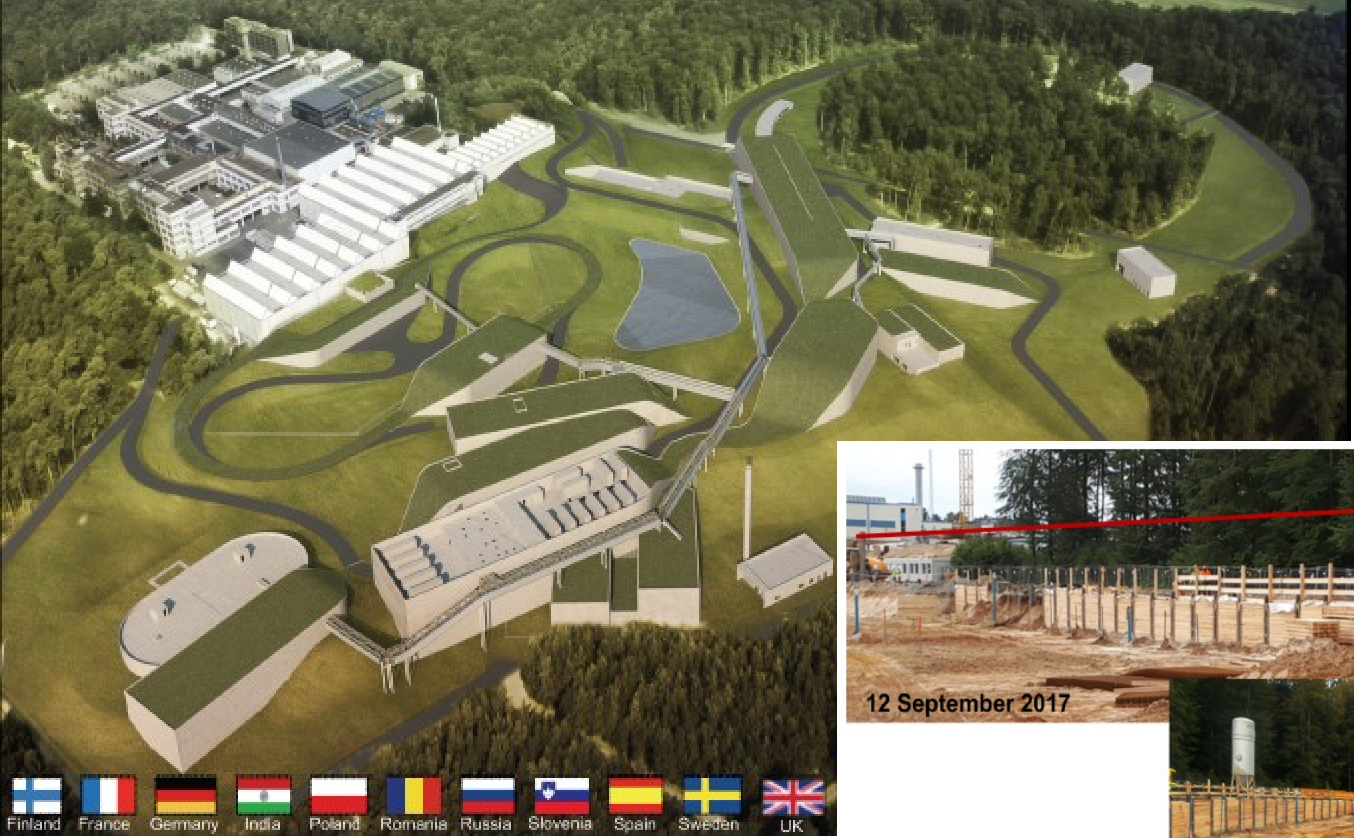
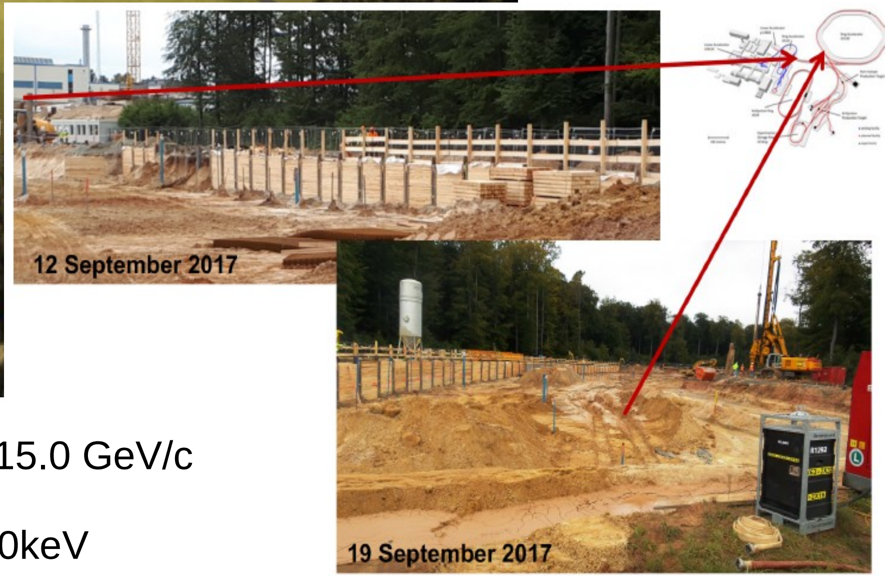
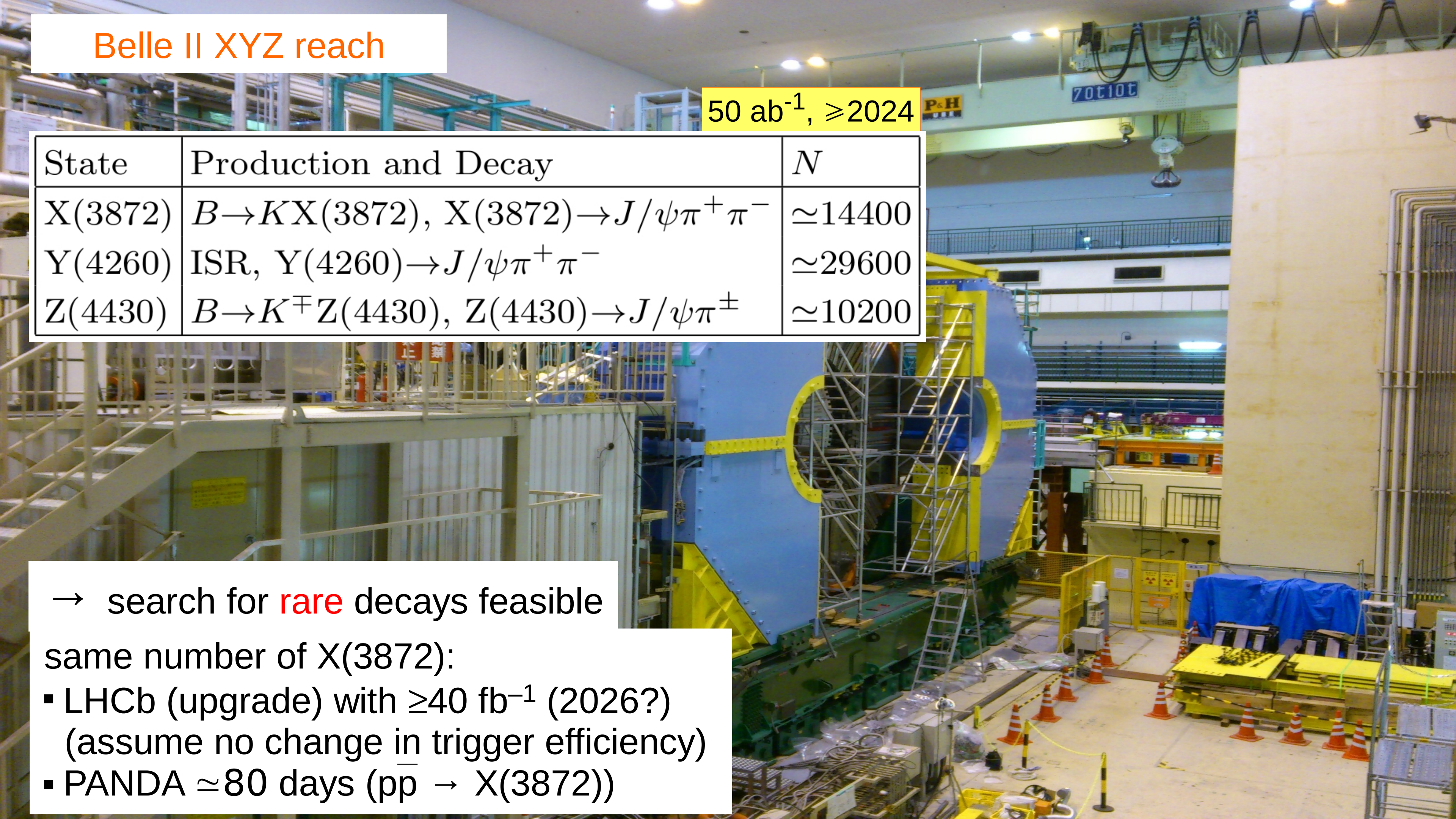


GSI, Darmstadt (DE)



- $\bar{p}p$ interaction, antiproton beam up to 15.0 GeV/c
- Direct access to all quantum number
- High precision: will measure width ⩾50keV

Belle II XYZ reach



50 ab^{-1}, ⩾2024

State	Production and Decay	N
X(3872)	$B \to K X(3872)$, $X(3872) \to J/\psi \pi^+ \pi^-$	$\simeq$14400
Y(4260)	ISR, $Y(4260) \to J/\psi \pi^+ \pi^-$	$\simeq$29600
Z(4430)	$B \to K^{\mp} Z(4430)$, $Z(4430) \to J/\psi \pi^{\pm}$	$\simeq$10200

→ search for rare decays feasible

same number of X(3872):

- LHCb (upgrade) with ≥40 fb^{-1} (2026?) (assume no change in trigger efficiency)
- PANDA $\simeq$80 days ($p\bar{p} \to X(3872)$)

EXTRAPOLATIONS (1 day of data taking)

	BESIII	BELLE II (scaled from Belle, assume 40 fb^{-1} per day)
X(3872	0.7 (radiative)	8.5 (Belle was 0.2)
Y(4260)	50	23.6
Z(3900)	10	5.0
Z(4430)	–	8.3
	LHCb (assume 2 fb–1/year)	PANDA (startup, $L=1 \times 10^{31}$ cm^{-2} s^{-1})
X(3872)	1.7 (trigger)	65 (50 nb, B=5%)
Y(4260)	–	1900 (<67) (2 nb, B=100%)
Z(3900)	–	405 (<14)
Z(4430)	4.7	–

HADRON2015 Proc, AIP 1735 (2016) 060011

SUMMARY

- Increasing evidence that this world is more than *mesons & baryons*
- Confirmed observations of several new bound states with >3-quark content
- Thresholds play a role in the interpretation of these exotic states
- Which mechanism does it fit all observed states?

  maybe not only one model can fit all of them!
- Experiments with better precision and higher statistics are needed:

  →they will guide our search to new unexplored territories

Thank you
for your
kind attention!

e.prencipe@fz-juelich.de

"The greatest danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieve our mark." (Michelangelo, 1475 - 1564)