Unusual hadron states observed at B-factories

Miriam Fritsch
on behalf of the BaBar-Collaboration

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HI Mainz
Universität Mainz

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HELMHOLTZ GEMEINSCHAFT
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BaBar Detector

Asymmetric e^+e^- collider PEP-II, SLAC

$\sqrt{s}$=10.58 GeV, $\Upsilon(4S)$

1999-2008

Luminosity

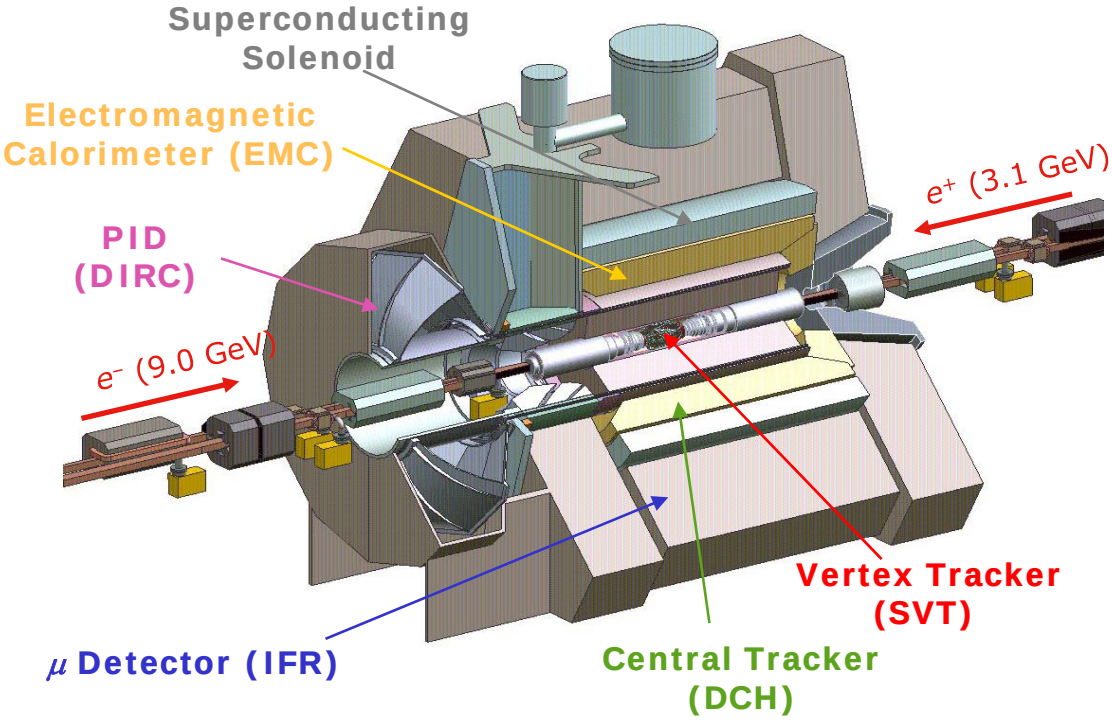
$\Upsilon(4S) \sim 432.9\ fb^{-1}$

- $\sim 450 \times 10^6\ B\bar{B}$ pairs
- $\sim 450 \times 10^6\ \tau$ pairs
- $\sim 650 \times 10^6$ Charm pairs

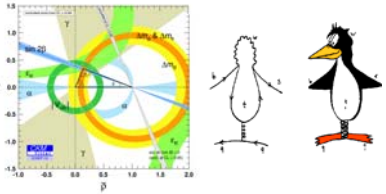
$\Upsilon(3S) \sim 30.2\ fb^{-1}$

$\Upsilon(2S) \sim 14.5\ fb^{-1}$

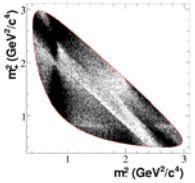
B-factory KEK-B
with BELLE (L_{int}> 1 ab^{-1})



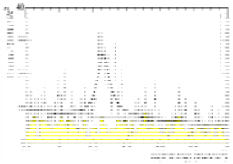
Physics topics at B-factories



B-Physics

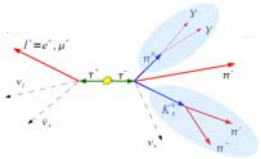


Charm-Physics

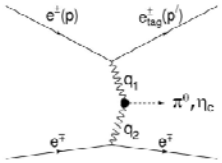


Charmonium

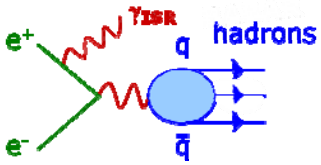
and more …



τ-Physics



γγ-Reactions



Initial State Radiation

Charmonium Spectroscopy

Potential

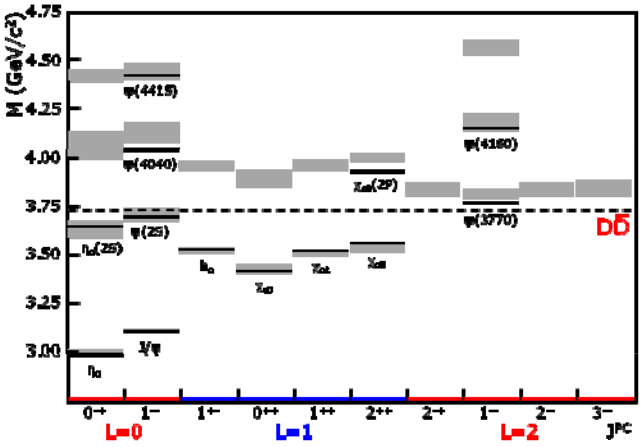
Structure

strong interaction

quark model

Detailed Measurement

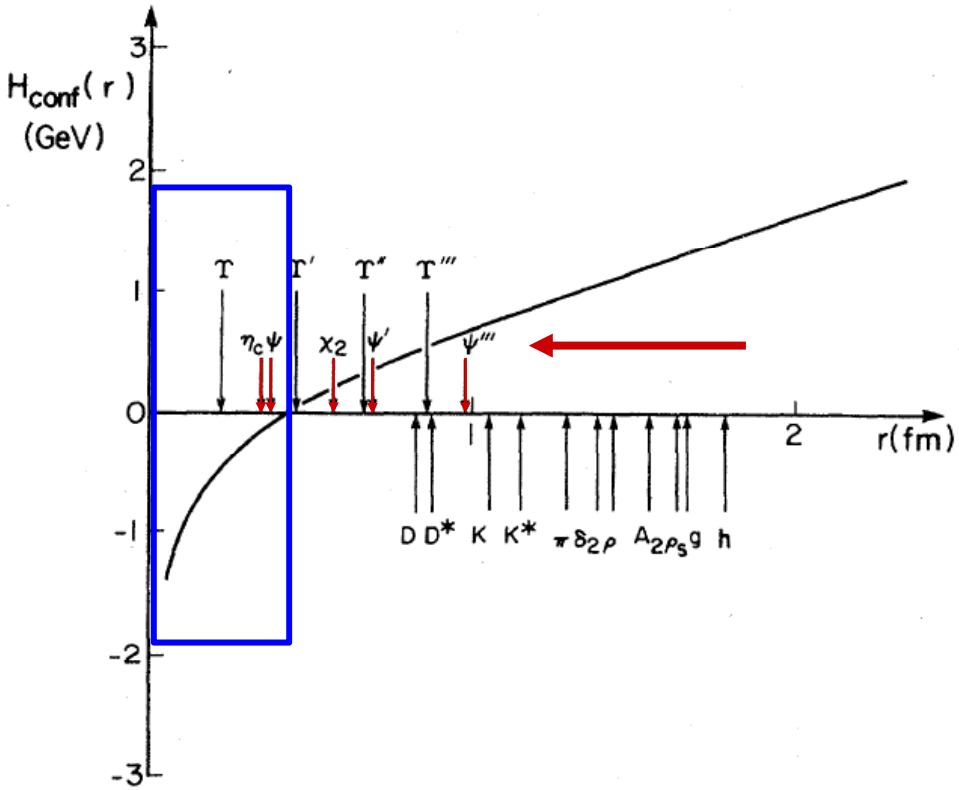
charmonium spectrum



Potential of the Strong Interaction

Perturbative QCD

small distances
Coulomb-like potential
one gluon exchange
asymptotic freedom



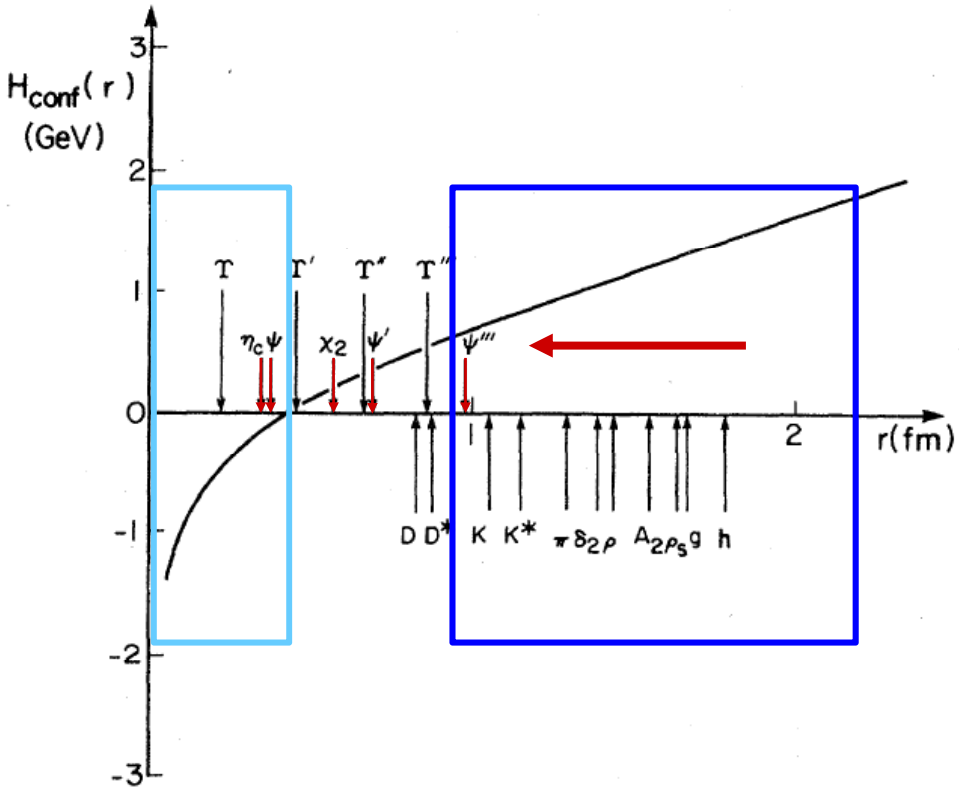
Potential of the Strong Interaction

Perturbative QCD

small distances
Coulomb-like potential
one gluon exchange
asymptotic freedom

Non-perturbative QCD

large distances
linear potential
confinement



Potential of the Strong Interaction

Perturbative QCD

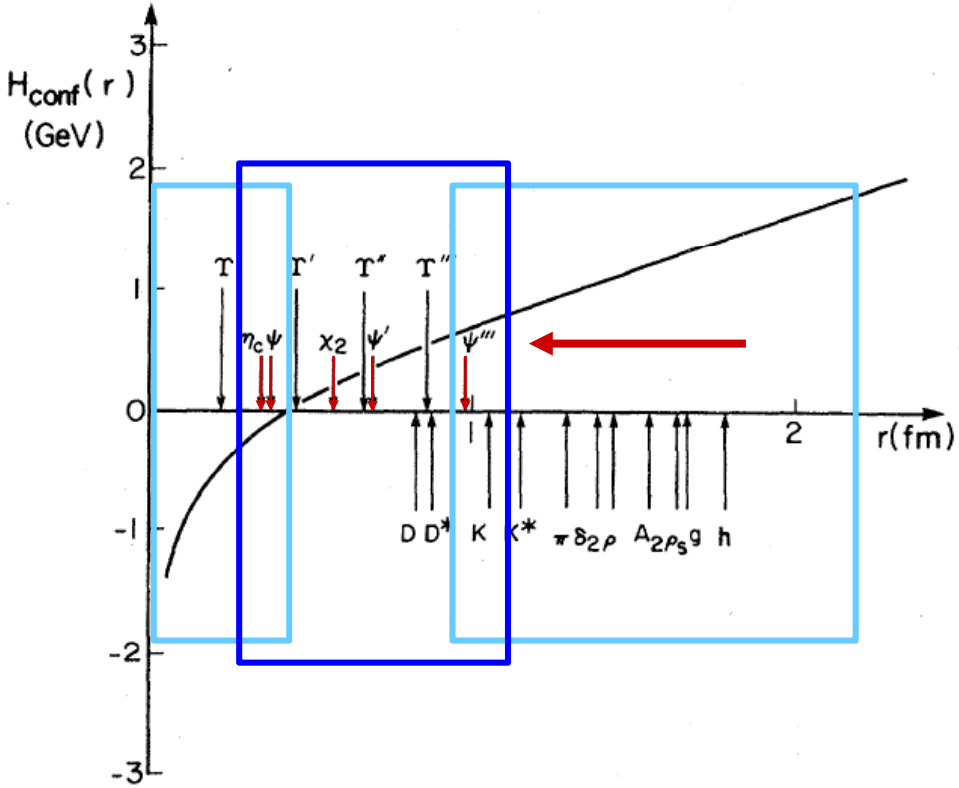
small distances
Coulomb-like potential
one gluon exchange
asymptotic freedom

Non-perturbative QCD

large distances
linear potential
confinement

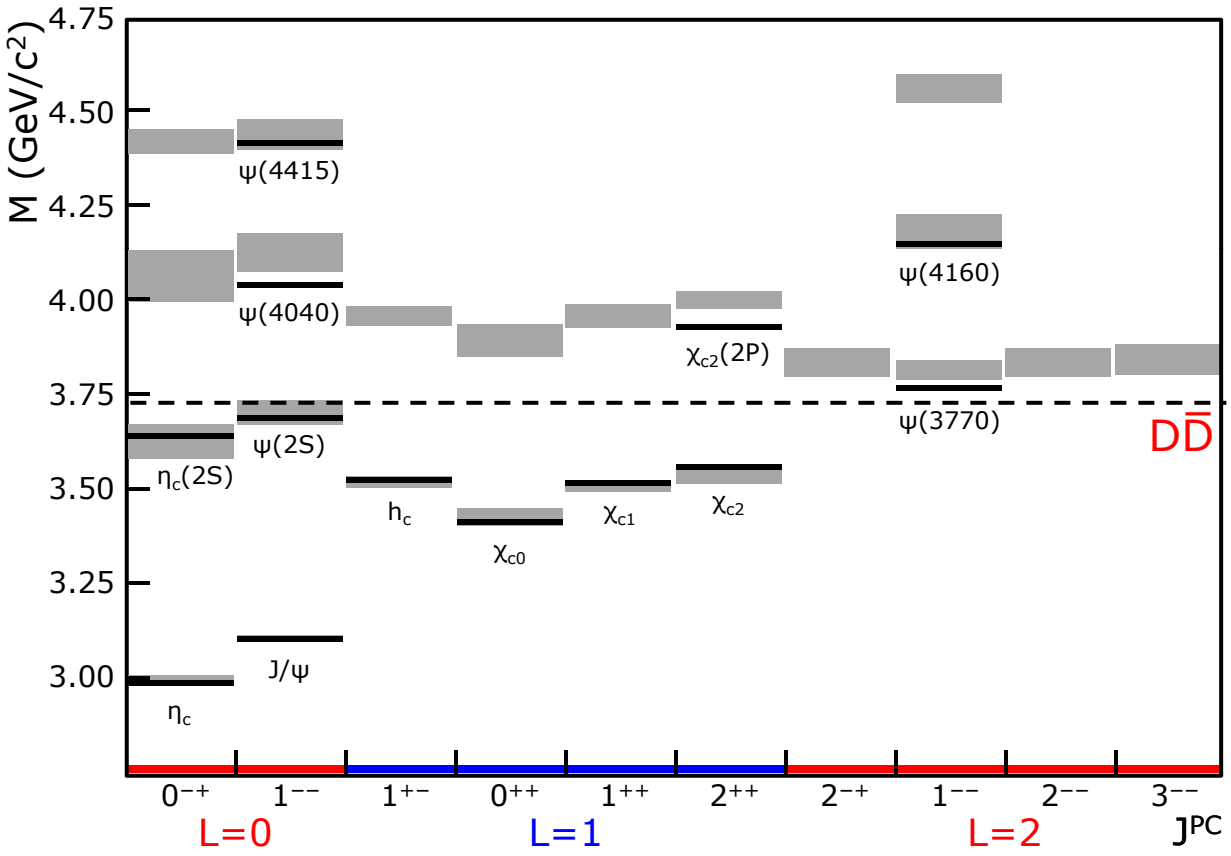
Charmonium Spectroscopy

transition region

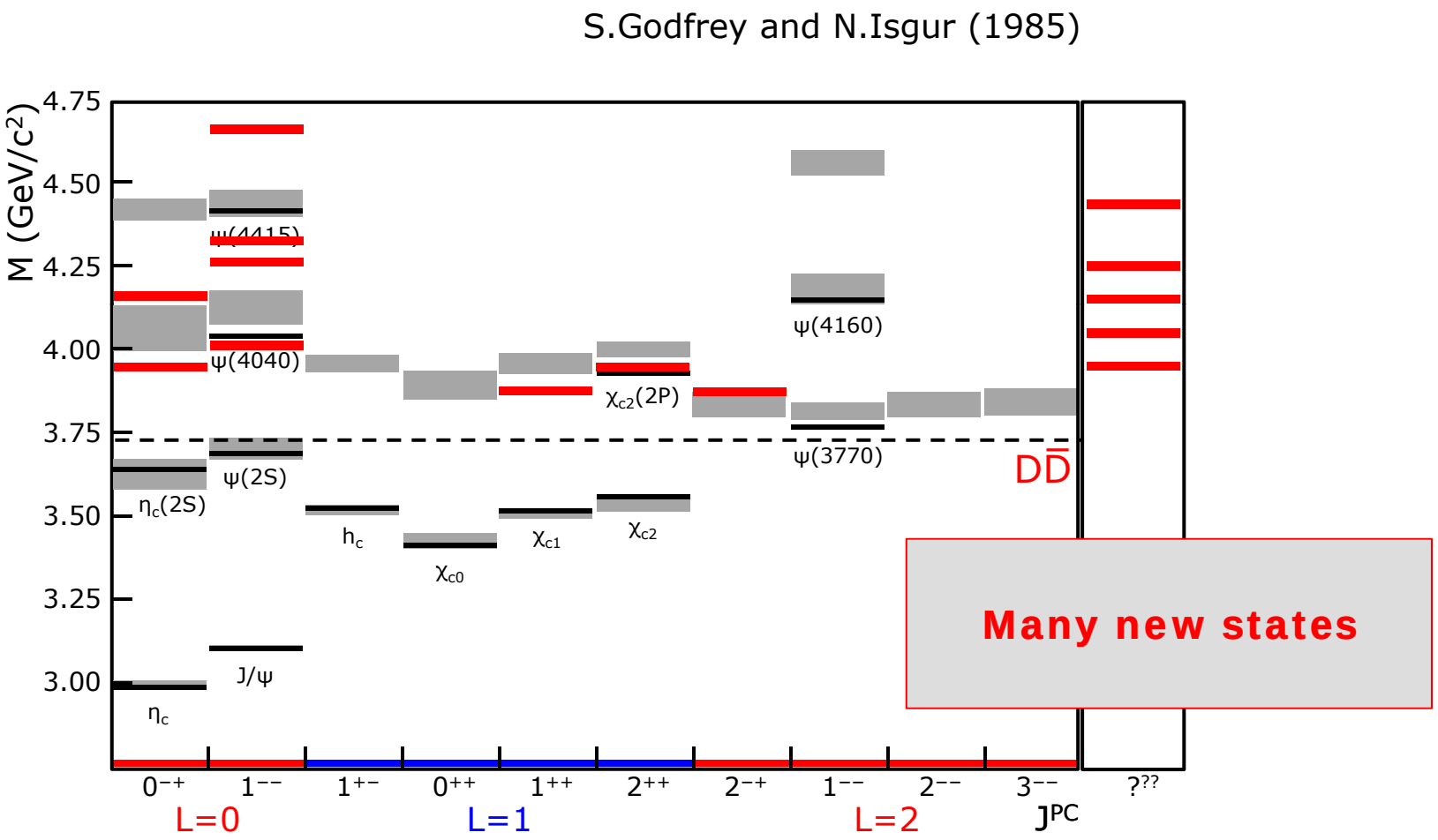


Charmonium Spectrum ($c\bar{c}$-Mesons)

S.Godfrey and N.Isgur (1985)



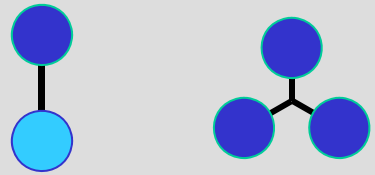
Charmonium Spectrum ($c\bar{c}$-Mesons)



Examples for allowed hadronic states

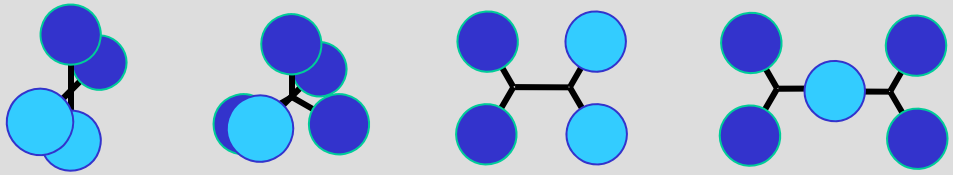
We know

mesons/baryons

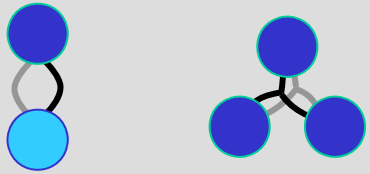


We presume

molecules/multi-quarks



hybrids

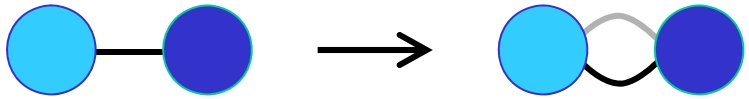


glueballs

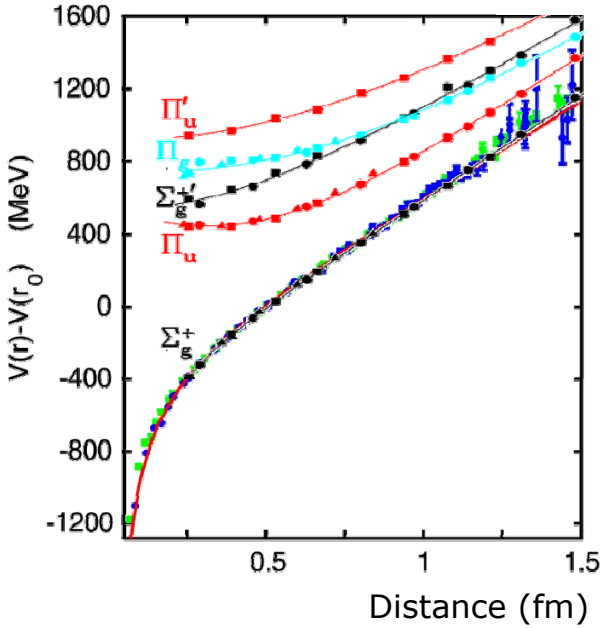
and more

Charmonium – different internal structure ?

different potential

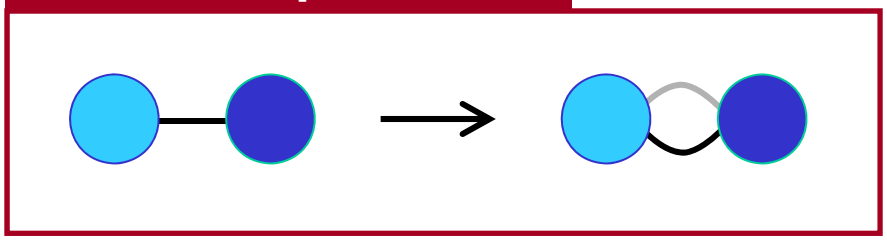


K.J. Juge, J. Kuti, C. Morningstar
hep/lat 9709131



Spectrum of Hybrids

different potential



K.J. Juge, J. Kuti, C. Morningstar
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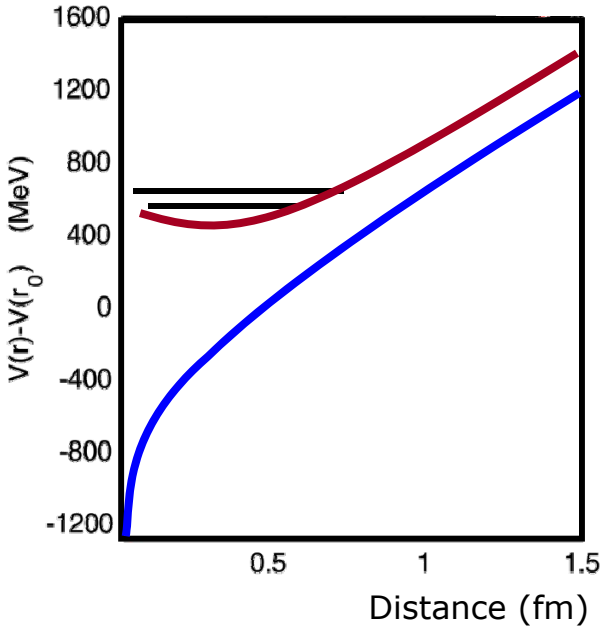
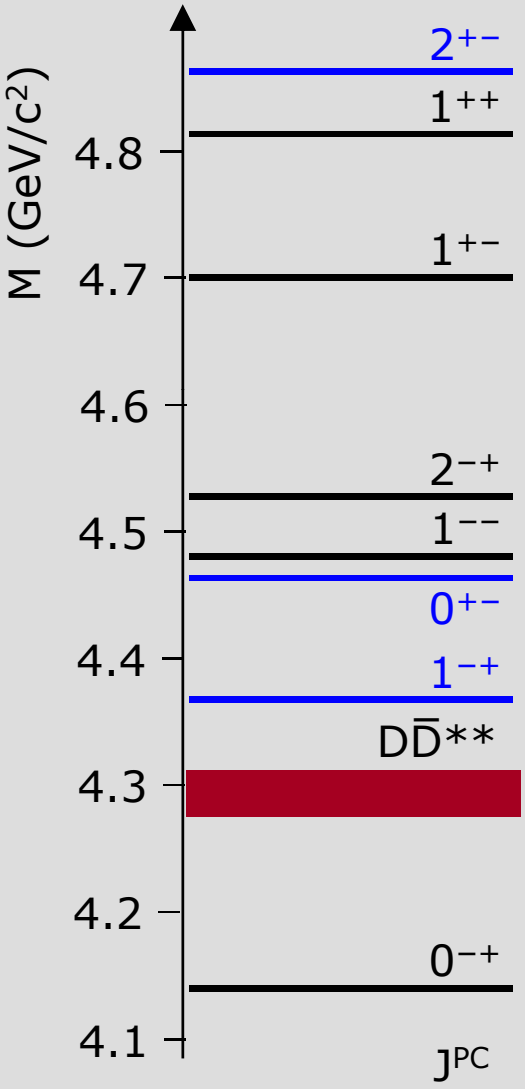




Begin of Charmonium Spectroscopy

1970

1974

J/ψ

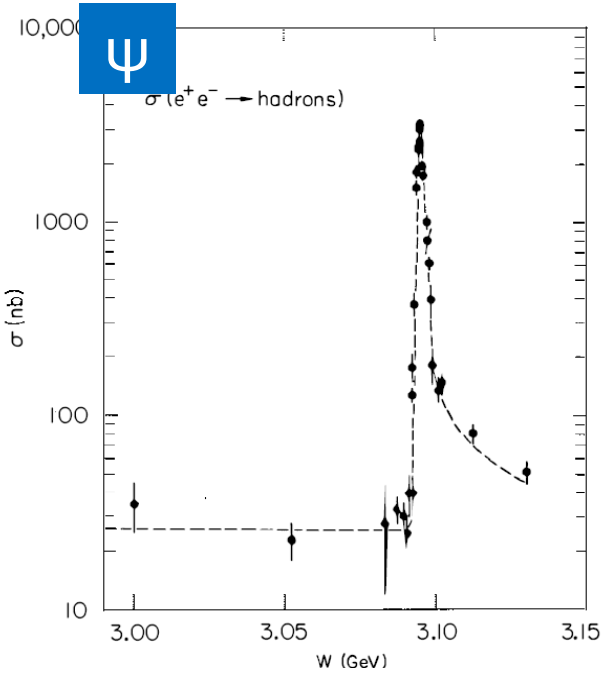
1980

1990

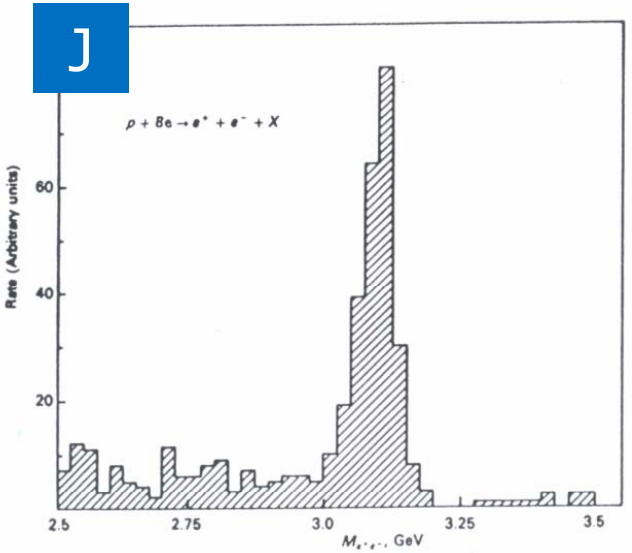
2000

2010

ψ



J

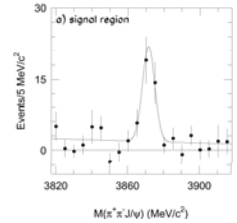
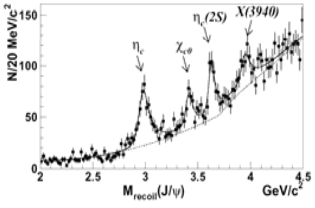
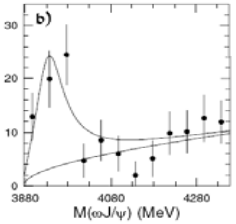
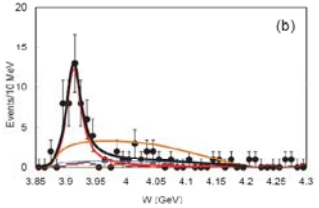
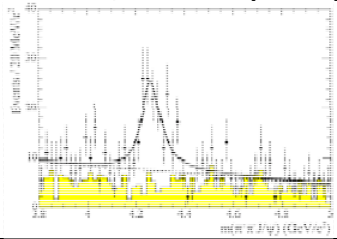
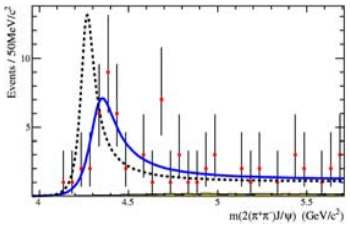
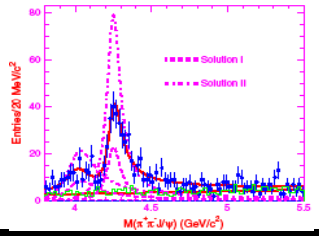
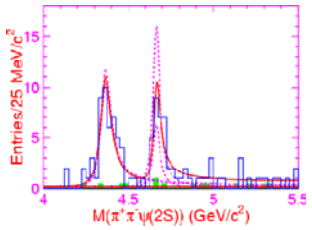
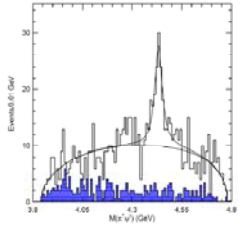
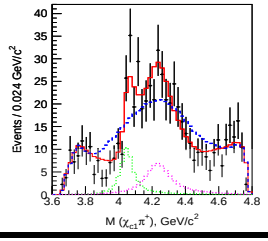
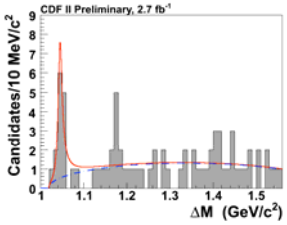
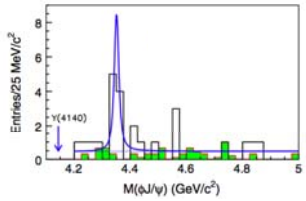


J.E. Augustin et al., MARK I, PRL 33, 1406 (ψ)
J.J. Aubert et al., BNL, PRL 33, 1404 (J)

$c\bar{c}$ vector ground state ($^3S_1$)

$J^{PC} = 1^{--}$

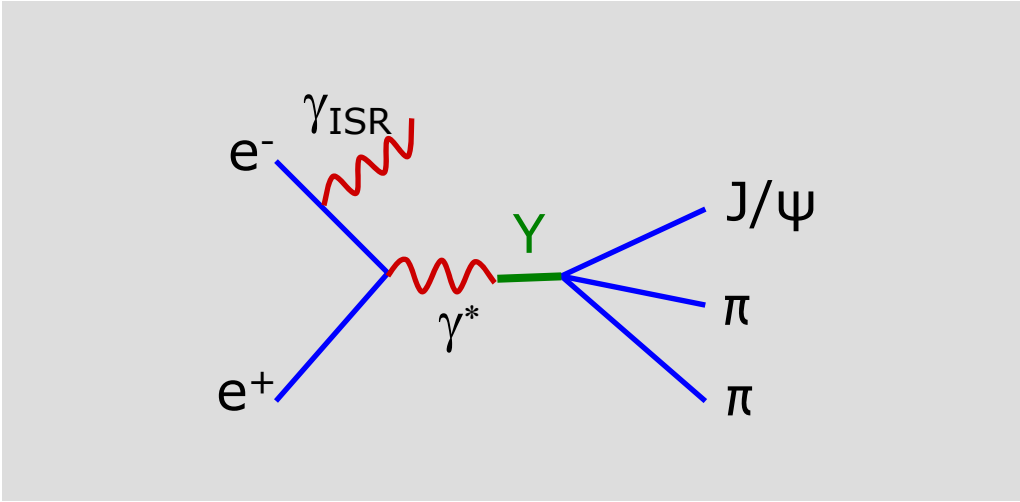
New Charmonium-like Discoveries

X(3872) PRL 91,262001 (2003) 	**X(3940)** PRL 98,082001 (2007) 	**Y(3940)** PRL 94,182002 (2005) 	**X(3915)** PRL 104,092001 (2010) 
Y(4260) PRL 95,142001 (2005) 	**Y(4350)** PRL 98,212001 (2007) 	**Y(4008)** PRL 99,182004 (2007) 	**Y(4660)** PRL 99,142002 (2007) 
$Z(4430)^-$ PRL 100,142001 (2008) 	**Z_1^- & Z_2^-** PRD 78,072004 (2008) 	**Y(4140)** PRL 102,242002 (2009) 	**X(4350)** PRL 104,112004 (2010) 

Spectroscopy at B-factories

Initial State Radiation

e.g. Y(4260)

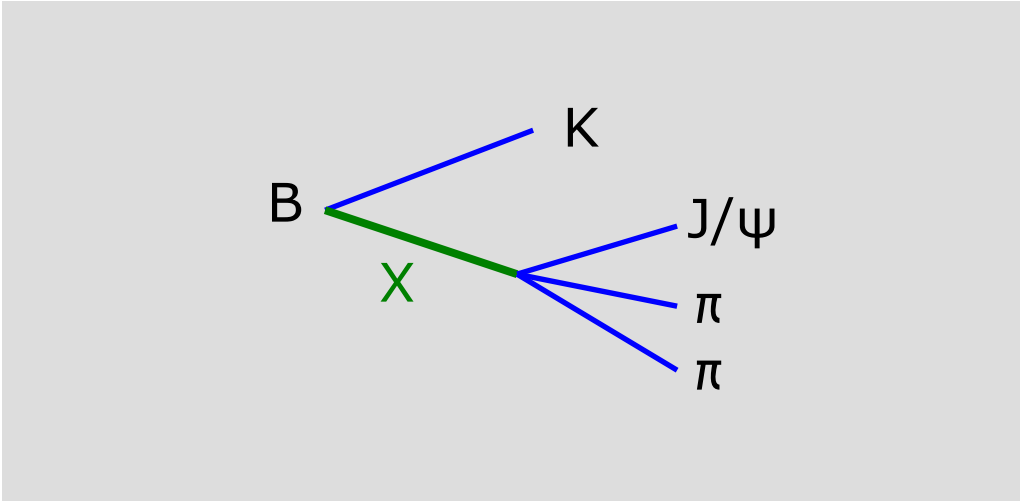


$J^{PC} = 1^{--}$

Spectroscopy at B-factories

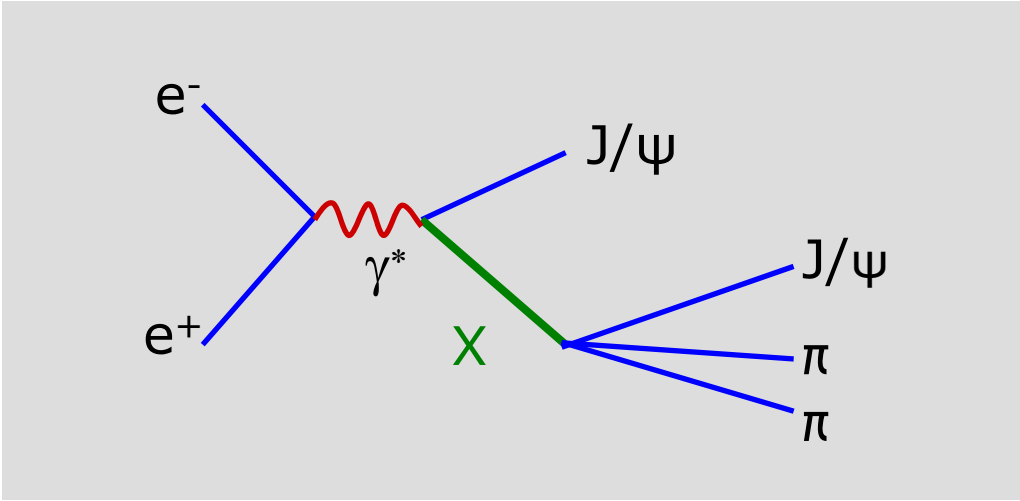
Initial State Radiation — e.g. Y(4260)

B-decay — e.g. X(3872), $Z(4430)^-$



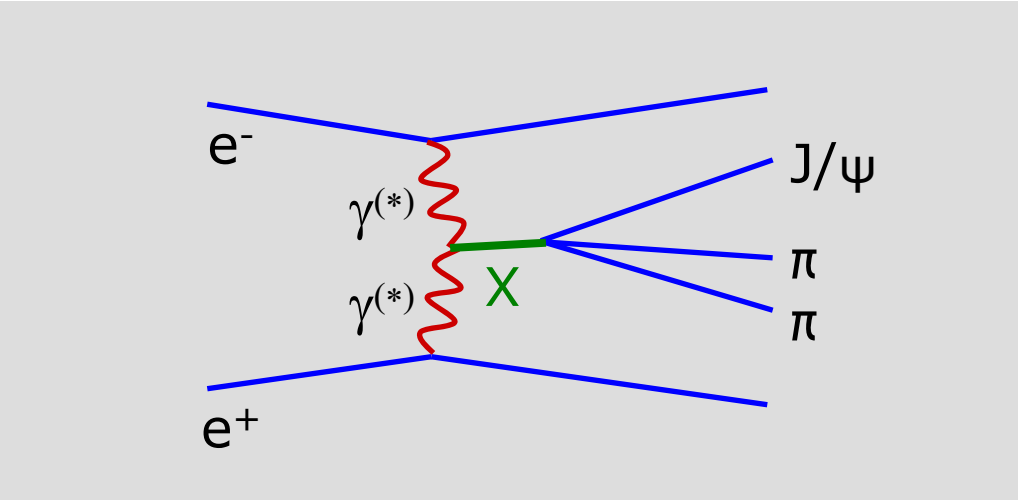
Spectroscopy at B-factories

Initial State Radiation	e.g. Y(4260)
B-decay	e.g. X(3872), $Z(4430)^-$
Double Charmonium Production	e.g. X(3940)



Spectroscopy at B-factories

Initial State Radiation	e.g. Y(4260)
B-decay	e.g. X(3872), $Z(4430)^-$
Double Charmonium Production	e.g. X(3940)
$\gamma\gamma$-Reaction	e.g. Z(3930), X(3915)

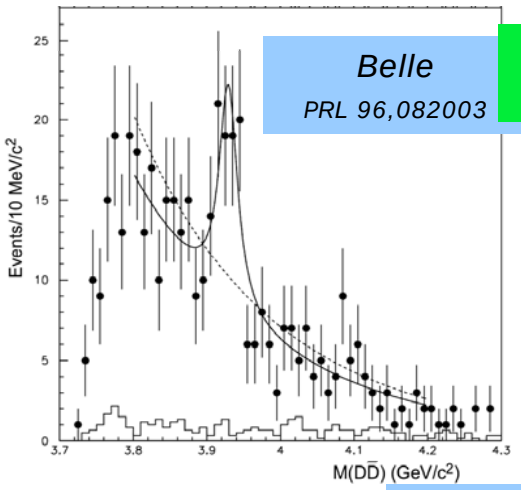


$J^{PC} = 0^{\pm+}, 2^{\pm+}$

Identified ?

$Z(3930) \rightarrow D\bar{D}$
in γγ-reactions

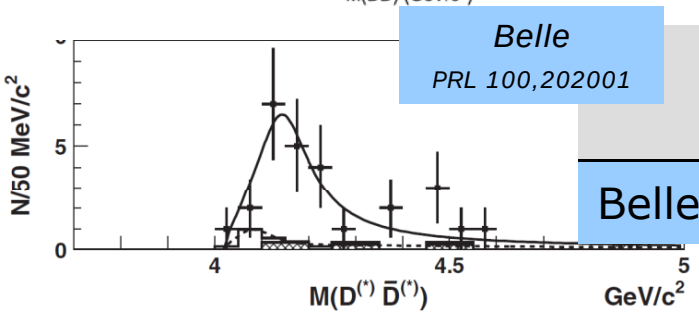
L=2 is favored
→ $\chi_{c2}(2P)$ with $J^{PC} = 2^{++}$



	Mass [MeV/c²]	Width [MeV]
Belle	3929 ± 5	29 ± 10
BaBar	3926.7 ± 2.7	21.3 ± 6.8

$X(4160) \rightarrow D^*\bar{D}^*$
in double charmonium

$J^{PC} = 0^{\pm+}, 2^{\pm+}$ possible
→ $\eta_c(3S)$ with $J^{PC} = 0^{-+}$

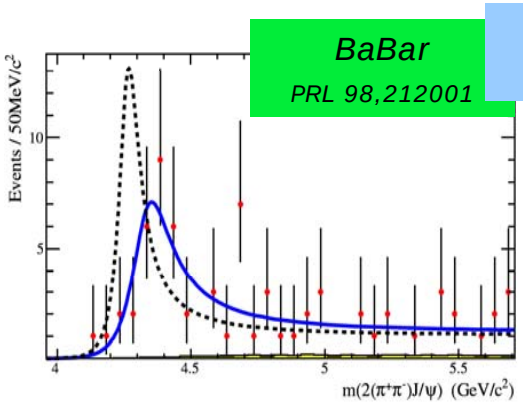


	Mass [MeV/c²]	Width [MeV]
Belle	4156^{+25}_{-20}	139^{+111}_{-61}

$Y(4350) \rightarrow \psi(2S)\,\pi\pi$
in ISR

$J^{PC} = 1^{--}$
→ ψ(4S) or ψ(3D)

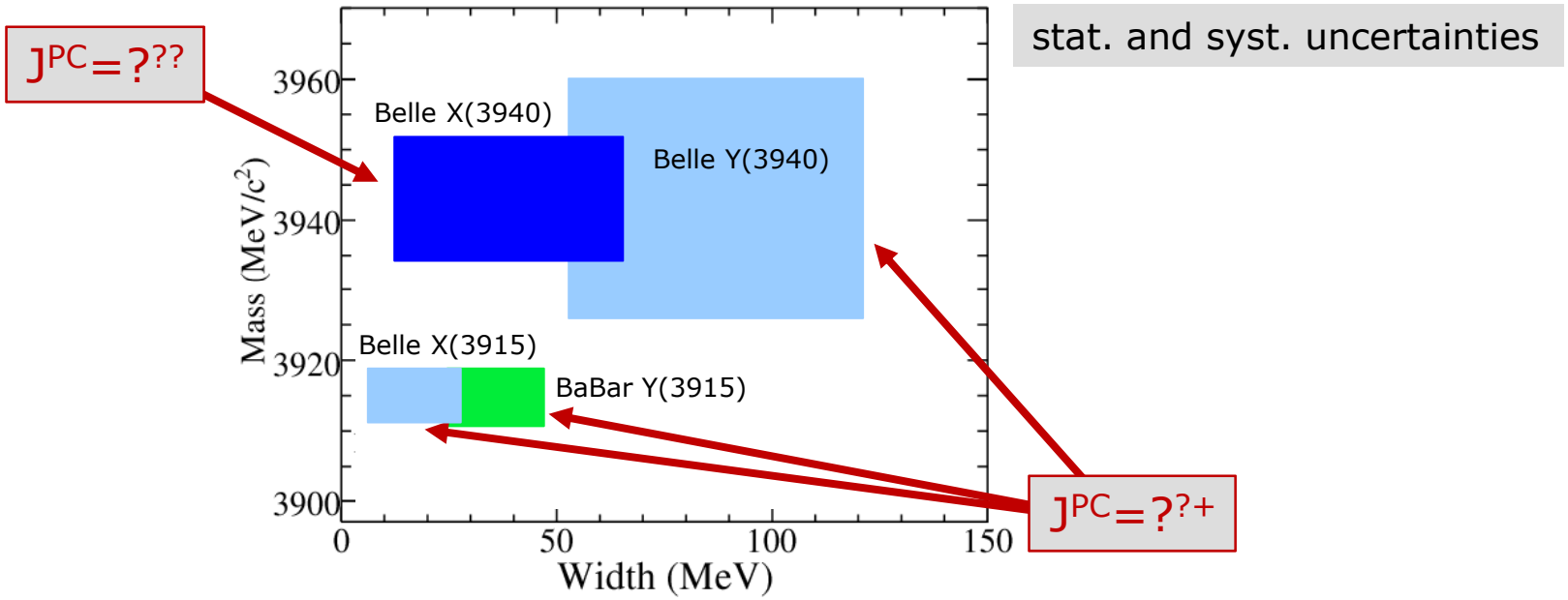
Eichten et al. RMP 80,1161



	Mass [MeV/c²]	Width [MeV]
BaBar	4324 ± 24	172 ± 33
Belle	4361 ± 9	74 ± 15

The 3940 family

State	Mass	Width	Production	Found	Not	J^{PC}	Exp.
X(3915)	3915 ± 3	17 ± 10	ϒϒ	J/ψ ω	-	$?^{?+}$	Belle PRL 104,092001
Y(3915)	3914.6 ± 3.6 3919.1 ± 3.6	34 ± 10 31 ± 9	B-decay	J/ψ ω	-	$?^{?+}$	BaBar PRL 101,082001 BaBar PRD 82, 011101(R)
Y(3940)	3943 ± 11	87 ± 22	B-decay	J/ψ ω	-	$?^{?+}$	Belle PRL 94,182002
X(3940)	3943 ± 6	39 ± 26	Double $c\bar{c}$	$D^*\bar{D}$	J/ψ ω	$?^{??}$	Belle PRL 98,082001



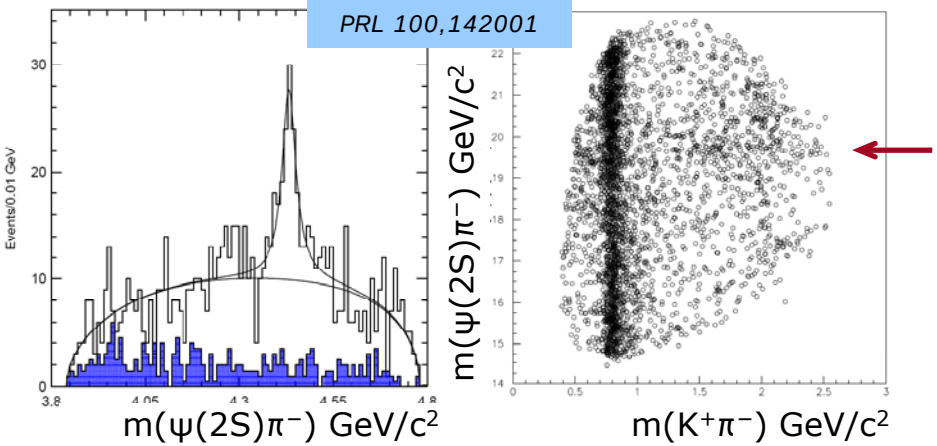
stat. and syst. uncertainties

Charged state $Z(4430)^-$

$Z(4430)^- \rightarrow \psi(2S)\,\pi^-$

in B−decays

Belle
PRL 100,142001



First time charge exchange
$B^0 \rightarrow K^+ Z^-$

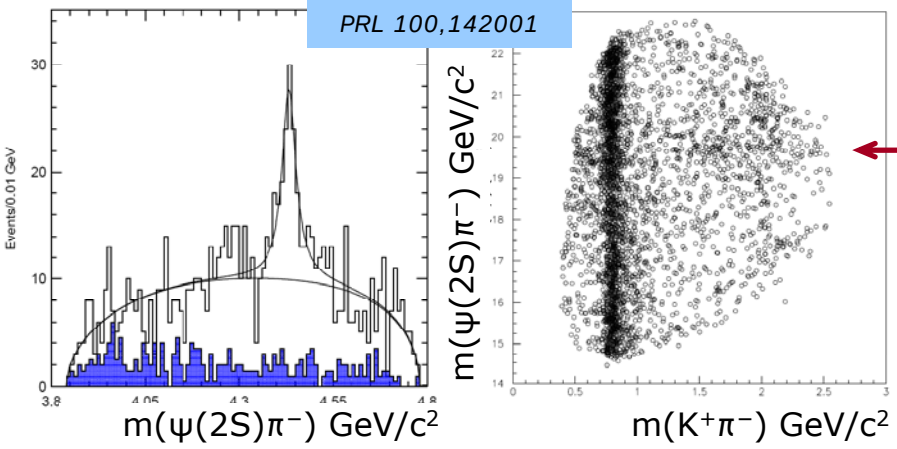
Significance
$\rightarrow$ 6.5σ

Charged state Z(4430)⁻

$Z(4430)^- \to \psi(2S)\,\pi^-$

in B−decays

Belle
PRL 100,142001



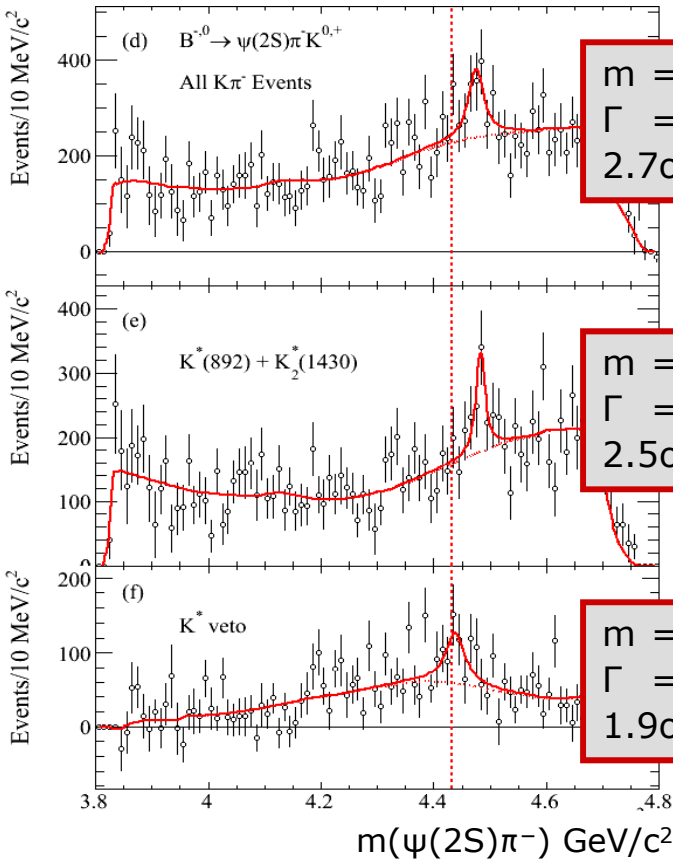
First time charge exchange
$B^0 \to K^+ Z^-$

Significance
$\to$ 6.5σ

BaBar
PRD 79,112001

Search for

$Z(4430)^- \to \psi(2S)\,\pi^-$



m = 4476±8 MeV
Γ = 32±16 MeV
2.7σ

m = 4483±3 MeV
Γ = 17±12 MeV
2.5σ

m = 4439±8 MeV
Γ = 41±33 MeV
1.9σ

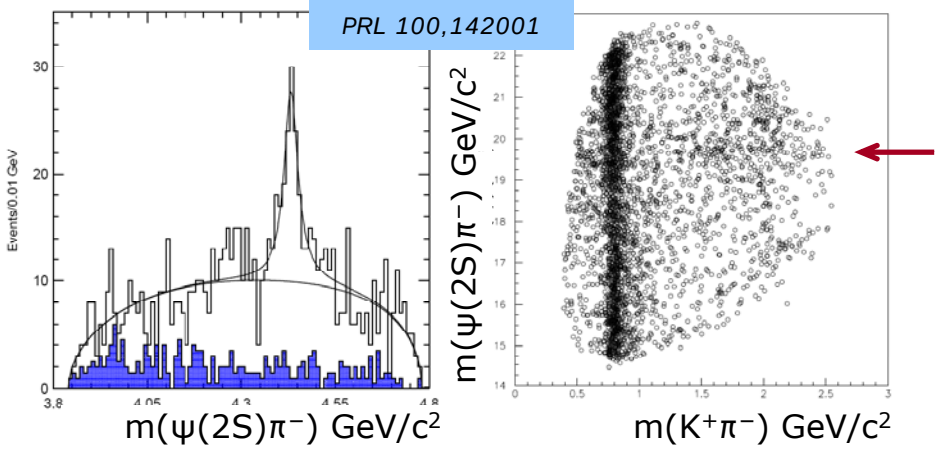
$\psi(2S)\,\pi^-$: 2-3σ
($J/\psi\,\pi^-$: No signal)

Charged state Z(4430)⁻

$Z(4430)^- \to \psi(2S)\,\pi^-$

in B−decays

Belle
PRL 100,142001



First time charge exchange
$B^0 \to K^+ Z^-$

Significance
$\to$ 6.5σ

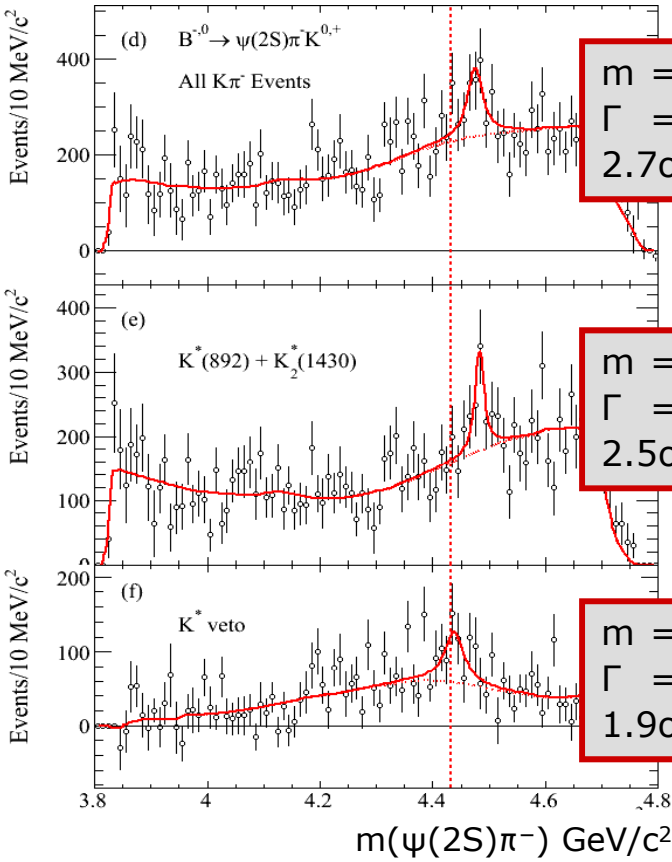
Dalitz plot analysis by Belle
$\to$ 6.4σ

Belle
PRD 80,031104

BaBar
PRD 79,112001

Search for

$Z(4430)^- \to \psi(2S)\,\pi^-$



m = 4476±8 MeV
Γ = 32±16 MeV
2.7σ

m = 4483±3 MeV
Γ = 17±12 MeV
2.5σ

m = 4439±8 MeV
Γ = 41±33 MeV
1.9σ

ψ(2S) π⁻: 2-3σ
(J/ψ π⁻: No signal)

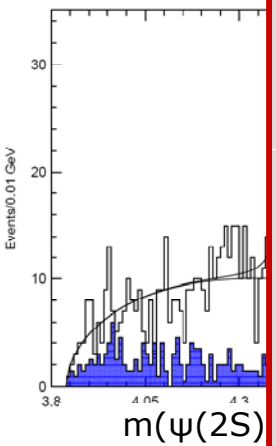
Charged state Z(4430)⁻

BaBar

Search for

Z(4430

in B–de



m(ψ(2S)

First tim

$B^0 \to K^+$

Signific

→ 6.5σ

Dalitz p

→ 6.4σ

Belle
PRD 80,031104

ψ(2S) π⁻ : 2-3σ
(J/ψ π⁻: No signal)

For Z(4430)⁻ still unclear:

→ existence ?

→ properties ?

→ more states ?

4476±8 MeV
32±16 MeV

First multiquark-state ?

4483±3 MeV
17±12 MeV

Two more resonances found by Belle

$Z_1(4050)^-$

$Z_2(4250)^-$

Analysis in BaBar still going on

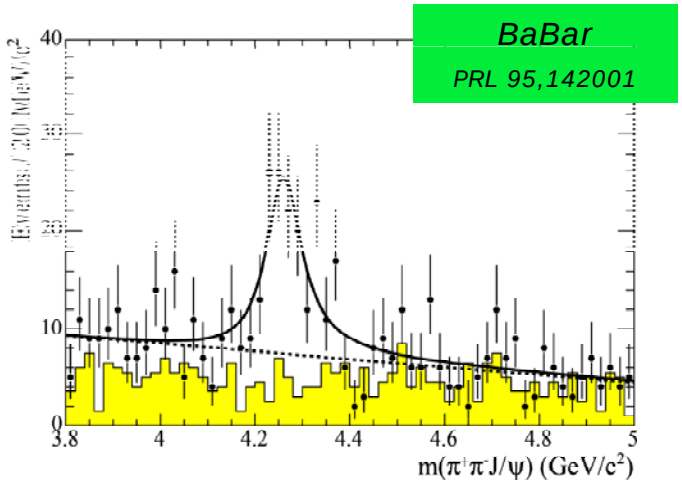
Belle
PRD 78,072004

4439±8 MeV
41±33 MeV

Hybrid Candidates with $J^{PC} = 1^{--}$

Y(4260)

Significance ~ 8σ



Confirmed
by Belle and Cleo-III
PRL 99,182004
PRL 96,162003

$e^+e^- \rightarrow J/\psi\ \pi\pi\ \gamma_{ISR}$

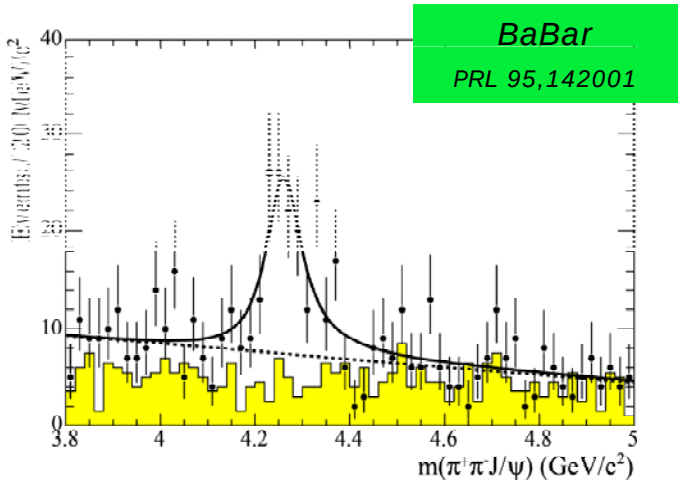
mass 4259 ± 8 MeV/c^2

width 88 ± 23 MeV

Hybrid Candidates with $J^{PC} = 1^{--}$

Y(4260)

Significance ~ 8σ



$e^+e^- \rightarrow J/\psi (\pi\pi) \gamma_{ISR}$

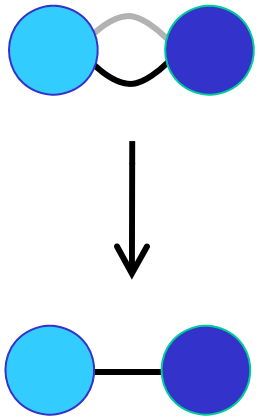
S–Wave

mass 4259 ± 8 MeV/c^2

width 88 ± 23 MeV

charmonium hybrid ?

hybrid properties



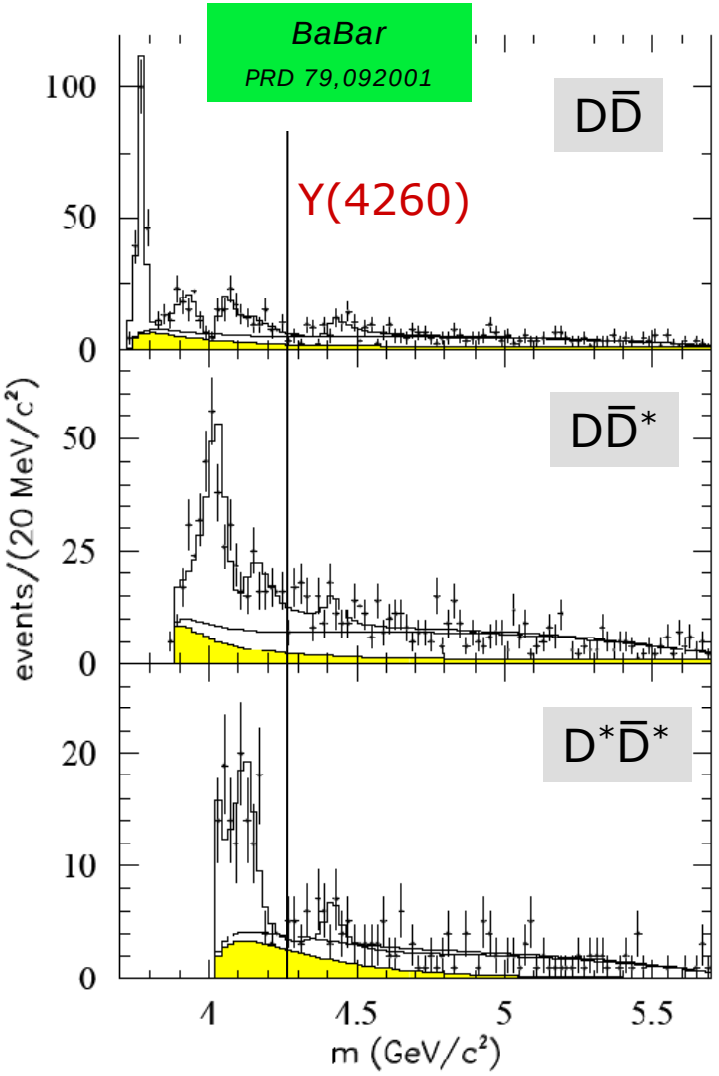
+

$(\pi\pi)$

S–Wave

L=0

Search for Y(4260) → $D^{(*)}\bar{D}^{(*)}$



Y(4260) above $D\bar{D}$-threshold:

→ Fit with Y(4260) and ψ's

- $D\bar{D}$: 0.2 ± 6.1 ± 2.8 Events
- $D\bar{D}^*$: 18 ± 24 ± 21 Events
- $D^*\bar{D}^*$: 9 ± 5 ± 10 Events

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 1.0$$

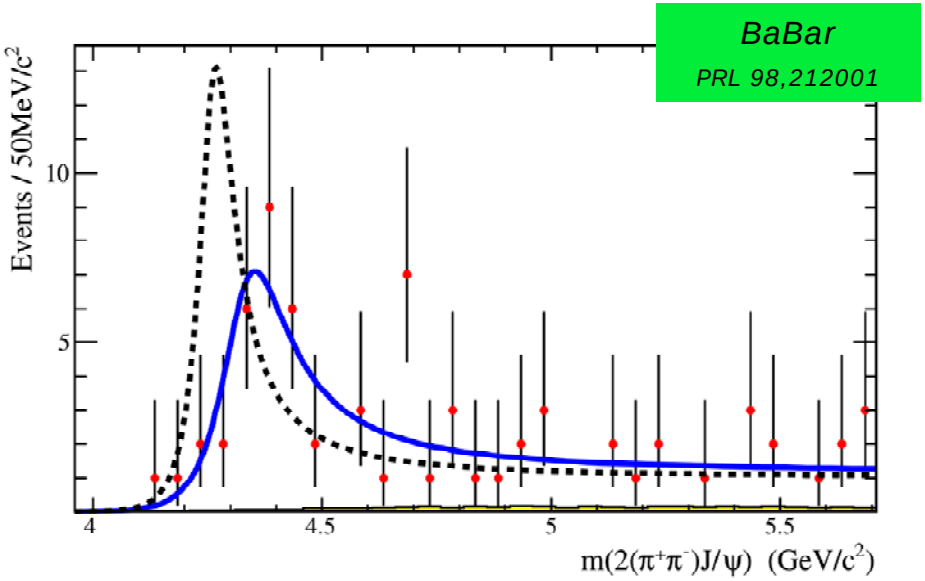
$$\frac{\mathcal{B}(Y(4260) \to D^*\bar{D})}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 34$$

$$\frac{\mathcal{B}(Y(4260) \to D^*\bar{D}^*)}{\mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-)} < 40$$

at 90% C.L.

No clear message yet !

Search for Y(4260) → ψ(2S)ππ



New resonance necessary

Mass 4324 ± 24 MeV/c^2

Width 172 ± 33 MeV

→ Y(4350)

Confirmed by Belle
PRL 99,142002

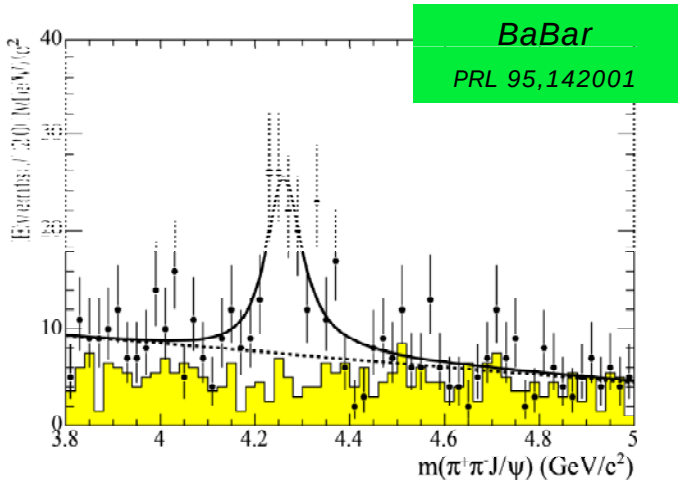
Two more resonances found by Belle
- Y(4008) PRL 99,182004
- Y(4660) PRL 99,142002

Analysis in BaBar still going on

Hybrid Candidates with $J^{PC} = 1^{--}$

Y(4260)

Significance ~ 8σ



$e^+e^- \to J/\psi (\pi\pi) \gamma_{ISR}$

S–Wave

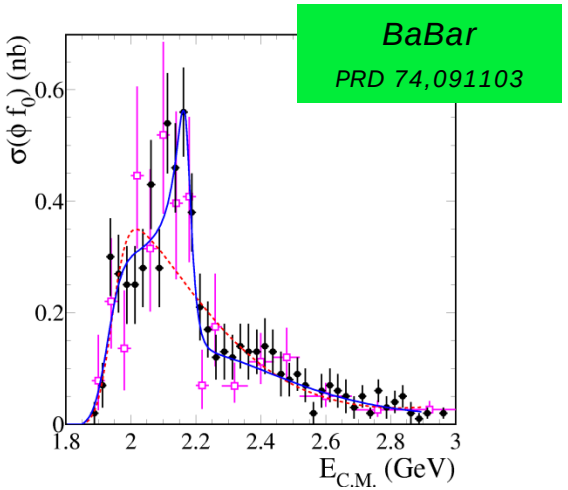
mass 4259 ± 8 MeV/c^2

width 88 ± 23 MeV

charmonium hybrid ?

Y(2175)

Significance ~ 5.8σ



$e^+e^- \to \phi (\pi\pi) \gamma_{ISR}$

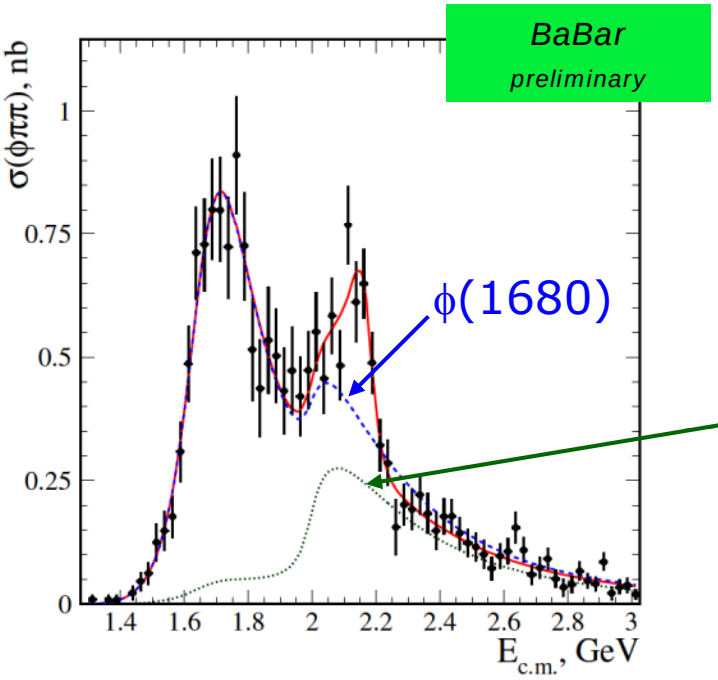
S–Wave

mass 2175 ± 10 MeV/c^2

width 58 ± 16 MeV

strangeonium hybrid ?

Hybrid Candidates with $J^{PC} = 1^{--}$



BaBar

$(\pi\pi)_S$-wave parametrization with BW for $f_0(600)$ and $f_0(980)$

$\phi(1680) \rightarrow \phi\, f_0(600)$
$\phi(1680) \rightarrow \phi\, f_0(980)$
$Y(2175) \rightarrow \phi\, f_0(980)$

With interference

Belle

2 incoherent BW

$\phi(1680) \rightarrow \phi\, \pi^+\pi^-$ without $f_0(980)$
$Y(2175) \rightarrow \phi\, f_0(980)$

	Mass [MeV/c²]	Width [MeV]	Channel
BaBar	2175 ± 10	58 ± 16	$\phi\, f_0(980)$
BES II	2186 ± 10	65 ± 23	$\phi\, f_0(980)$
Belle	2079 ± 13	192 ± 23	$\phi\pi^+\pi^-$
BES III	2177 ± 7	96 ± 28	$\phi\, f_0(980)$
BaBar	2179 ± 9	79 ± 17	$\phi\, f_0(980)$
BaBar	2175 ± 33	90 ± 24	$\phi\pi^+\pi^-$

preliminary

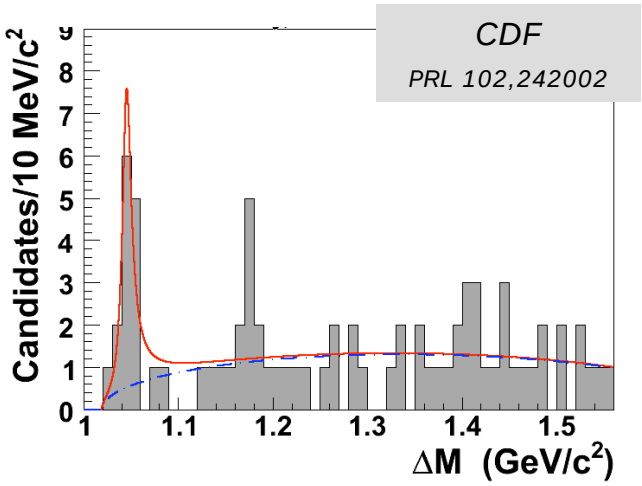
preliminary
L = 454 fb⁻¹

Exotic hybrid at CDF ?

$Y(4140) \rightarrow J/\psi\ \phi$ in B-decays

Decay unusal for $c\bar{c}$
Close to threshold
$J^{PC} = 0^{++}, 1^{-+}, 2^{++}$

Exotic hybrid ?



	Yield	Mass [MeV/c²]	Width [MeV/c²]	Sign.
Y(4140)	14 ± 5	4143.0 ± 2.9	$11.7_{-5.0}^{+8.3}$	3.8σ

Should be enhanced in γγ–reactions

Exotic hybrid at CDF ?

$Y(4140) \rightarrow J/\psi\ \phi$ in B-decays

Decay unusal for $c\bar{c}$
Close to threshold
$J^{PC} = 0^{++}, 1^{-+}, 2^{++}$

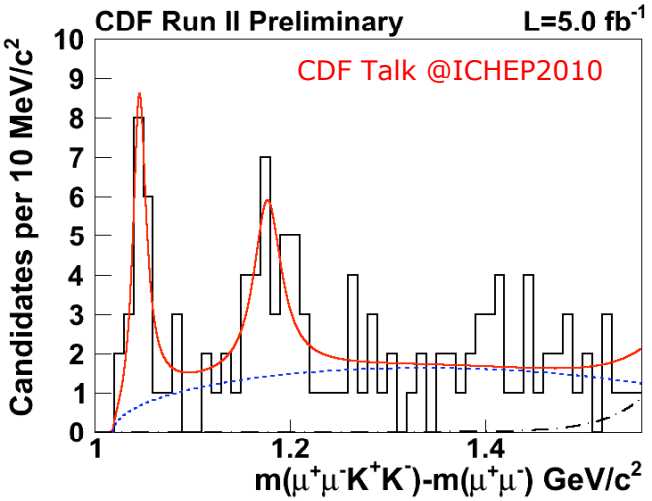
Exotic hybrid ?

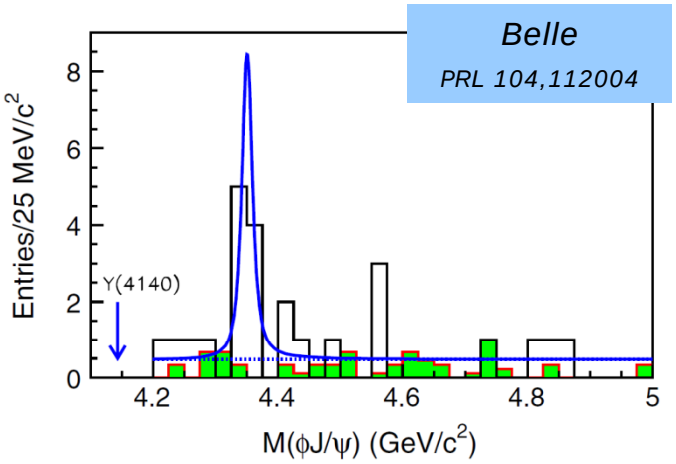
	Yield	Mass [MeV/c²]	Width [MeV/c²]	Sign.
Y(4140)	14 ± 5 19 ± 6	4143.0 ± 2.9 $4143.4_{-3.0}^{+2.9}$	$11.7_{-5.0}^{+8.3}$ $15.3_{-6.1}^{+10.4}$	3.8σ >5σ
Y(4300)	22 ± 8	$4274.4_{-6.7}^{+8.4}$	$32.3_{-15.3}^{+21.9}$	3.1σ
X(4350)	$8.8_{-3.2}^{+4.2}$	$4350.6_{-5.1}^{+4.6}$	13_{-9}^{+18}	3.9σ

Should be enhanced in γγ–reactions

→ No indication

→ But another resonance found, X(4350)

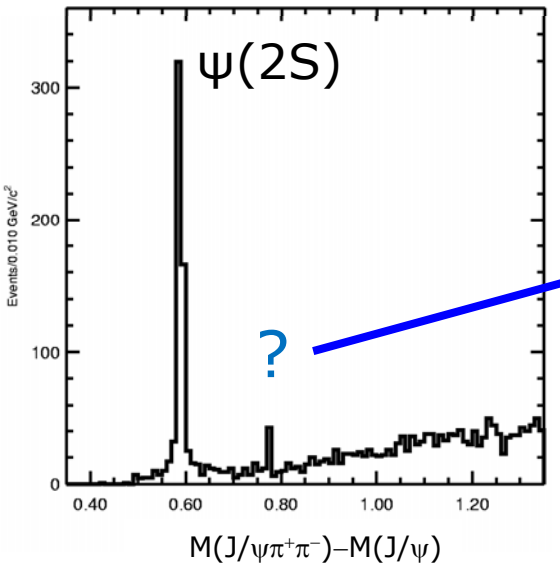


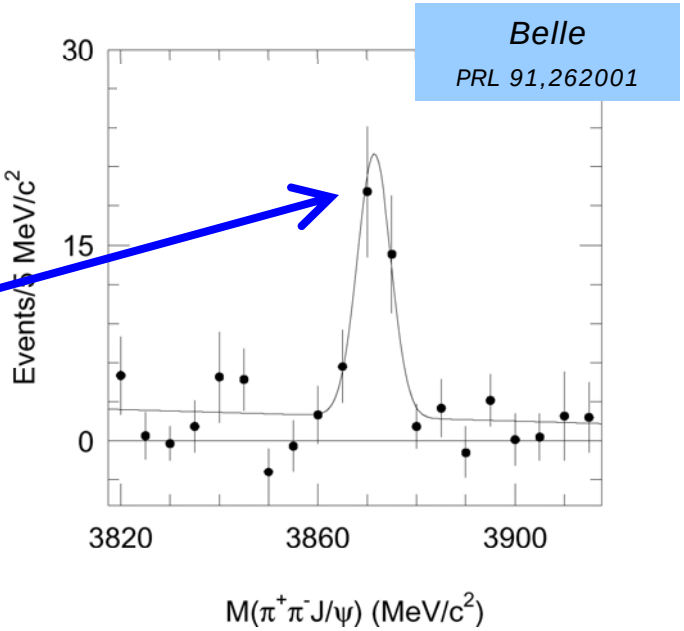


X(3872) Discovery

$X(3872) \rightarrow J/\psi\pi^+\pi^-$

in $B \rightarrow X\ K$



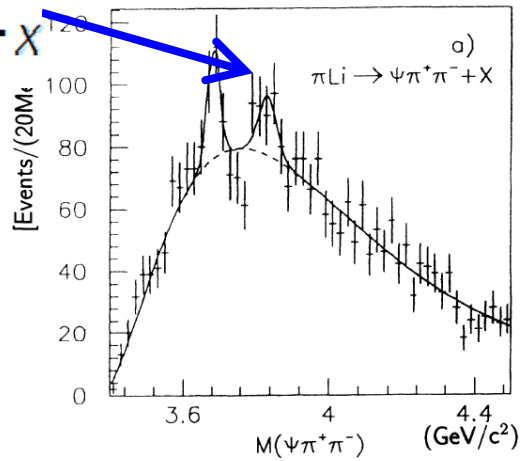


X(3872) - PDG

$X(3872)$ MASS FROM $J/\psi\pi\pi$ MODE

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3871.56± 0.22 OUR AVERAGE					
3871.61± 0.16±0.19	6k	[1,2] AALTONEN	09AU	CDF2	$p\overline{p} \to J/\psi\pi^+\pi^- X$
3871.4 ± 0.6 ±0.1	93.4	AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
3868.7 ± 1.5 ±0.4	9.4	AUBERT	08Y	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$
3871.8 ± 3.1 ±3.0	522	[2,3] ABAZOV	04F	D0	$p\overline{p} \to J/\psi\pi^+\pi^- X$
3872.0 ± 0.6 ±0.5	36	CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3868.6 ± 1.2 ±0.2	8	[4] AUBERT	06	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$
3871.3 ± 0.6 ±0.1	61	[4] AUBERT	06	BABR	$B^- \to K^- J/\psi\pi^+\pi^-$
3873.4 ± 1.4	25	[5] AUBERT	05R	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
3871.3 ± 0.7 ±0.4	730	[2,6] ACOSTA	04	CDF2	$p\overline{p} \to J/\psi\pi^+\pi^- X$
3836 ±13	58	[2,7] ANTONIAZZI	94	E705	300 $\pi^\pm$ Li $\to$ $J/\psi\pi^+\pi^- X$

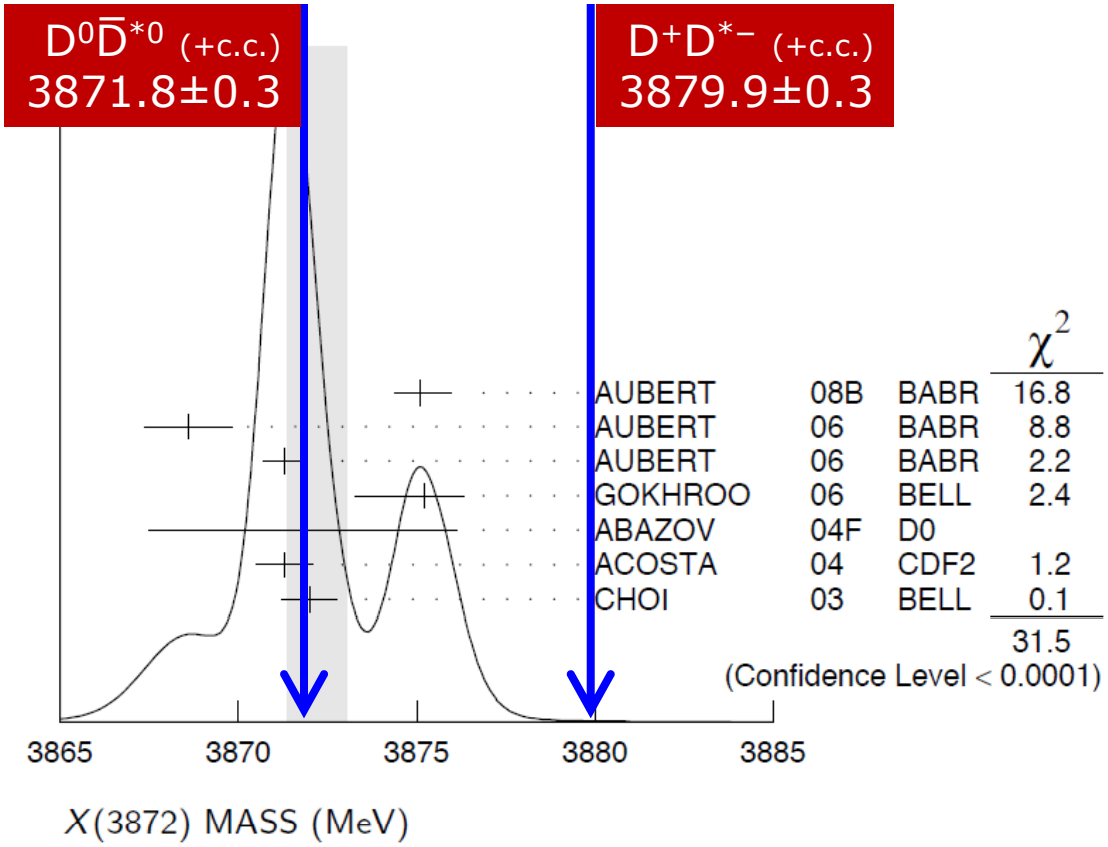
1994



Confirmed by BaBar, D0 and CDF

Width smaller than detector resolution
(< 2.3 MeV)

X(3872) Mass Measurements



Mass of X(3872) → $D^0\bar{D}^{*0}$ shifted by ~3 MeV/c^2
(last Belle result: no shift) PRD 81, 031103 (2010)

X(3872) Properties

Mass around $D^0\bar{D}^{*0}$-threshold (mass shift ?)

Width <2.3 MeV

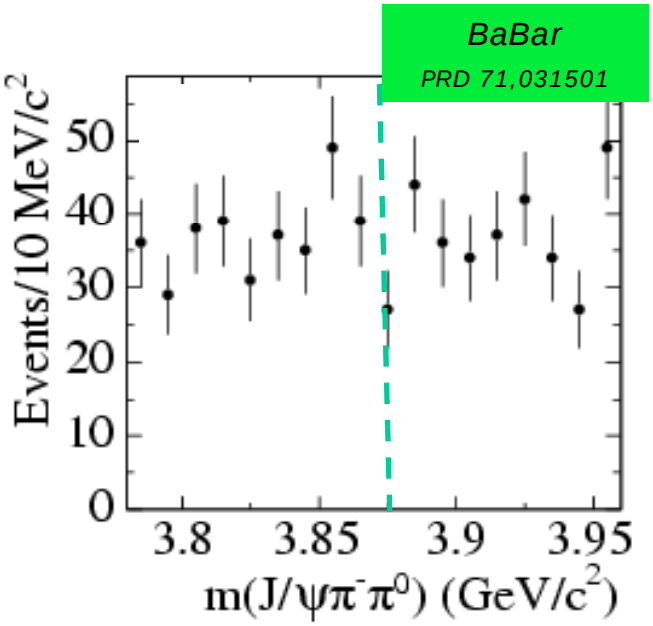
Not found in formation in e^+e^- collision
→ Not $J^{PC} = 1^{--}$

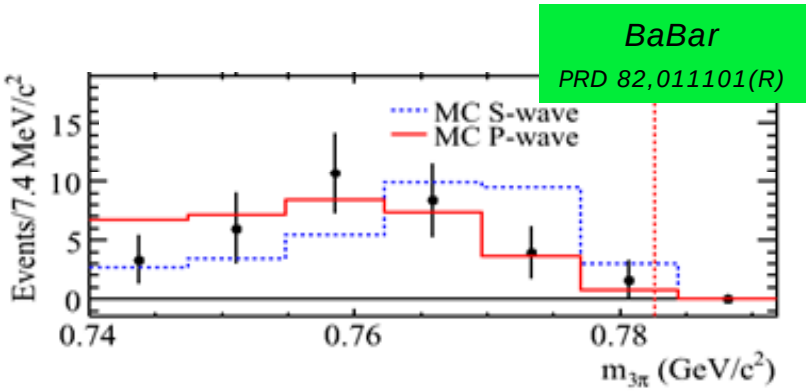
Observation of decay into $J/\psi\,\gamma$ → C=+1

All decay channels → $J^P = 1^+$ or 2^-
decay to $D\bar{D}$ forbidden,
D^+D^{*-} mass too high

No charged partner found → I=0

m(2π), m(3π) and angular analysis
→ more indication for $J^P = 2^-$





S−wave(1^+) P(χ^2/NDF)=7%
P−wave(2^-) P(χ^2/NDF)=62%

What could it not be?

Hybrid (m > 4.1 GeV/c^2)

Tetraquark (no charged partner was found)

X(3872) - Charmonium or Molecule ?

Charmonium?

Mass ok for 2^- (η_{c2}, $^1D_2$ $c\bar{c}$ ground state)

Large production rate in B-decays
and $\bar{p}p$-collisions

But:

Large isospin violation in $R_{\rho/\omega}=1$?

Molecule?

$m(D^0) + m(D^{0*}) = 3871.8 \pm 0.4$ MeV/c^2

Decay to $J/\psi\rho$, $J/\psi\omega$, $D^0\bar{D}^{0*}$ expected

Compatible with $J^P = 1^+$

Large isospin violation $R_{\rho/\omega}=1$

But:

$BF(X\rightarrow\psi(2S)\,\gamma)/BF(X\rightarrow J/\psi\,\gamma)= 3.4 \pm 1.4$

X(3872) - Charmonium or Molecule ?

Charmonium?

Mass ok for 2^- (η_{c2}, $^1D_2$ $c\bar{c}$ ground state)

Large production rate in B-decays and $\bar{p}p$-collisions

But:

Large isospin violation in $R_{\rho/\omega}=1$?

Molecule?

$m(D^0) + m(D^{0*}) = 3871.8 \pm 0.4$ MeV/c^2

Decay to $J/\psi\rho$, $J/\psi\omega$, $D^0\bar{D}^{0*}$ expected

Compatible with $J^P = 1^+$

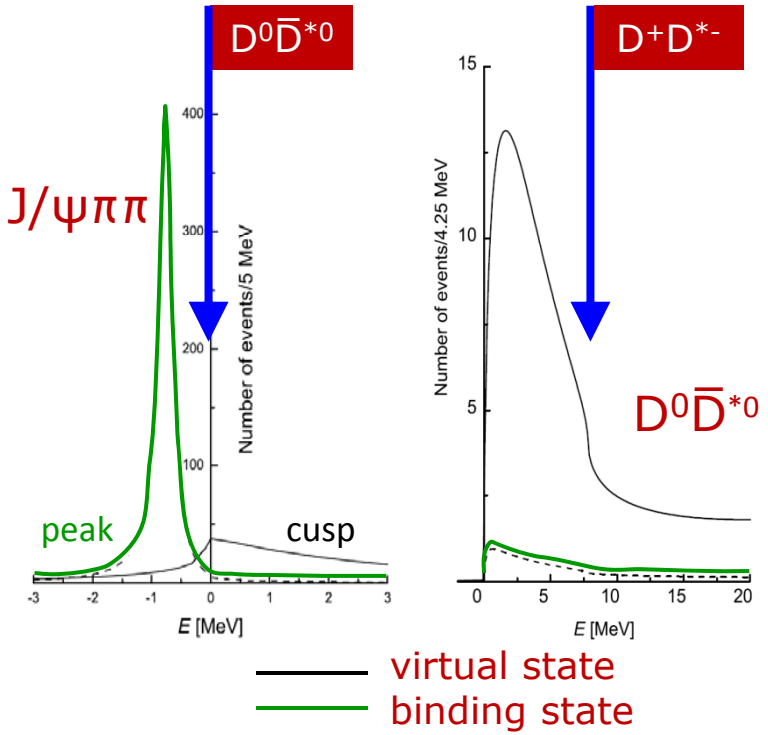
Large isospin violation $R_{\rho/\omega}=1$

But:

$BF(X\rightarrow\psi(2S)\,\gamma)/BF(X\rightarrow J/\psi\,\gamma)= 3.4 \pm 1.4$

Lineshape measurement …

C. Hanhart et al. (2007)



… of all final states with high resolution essential !

Summary

The binding among quarks is a long standing issue in hadron physics

Exotic and conventional states provide insight into the binding

Many new states found in charm sector, structure unknown

But: - Statistics small
- Detector resolution not sufficient

Next steps

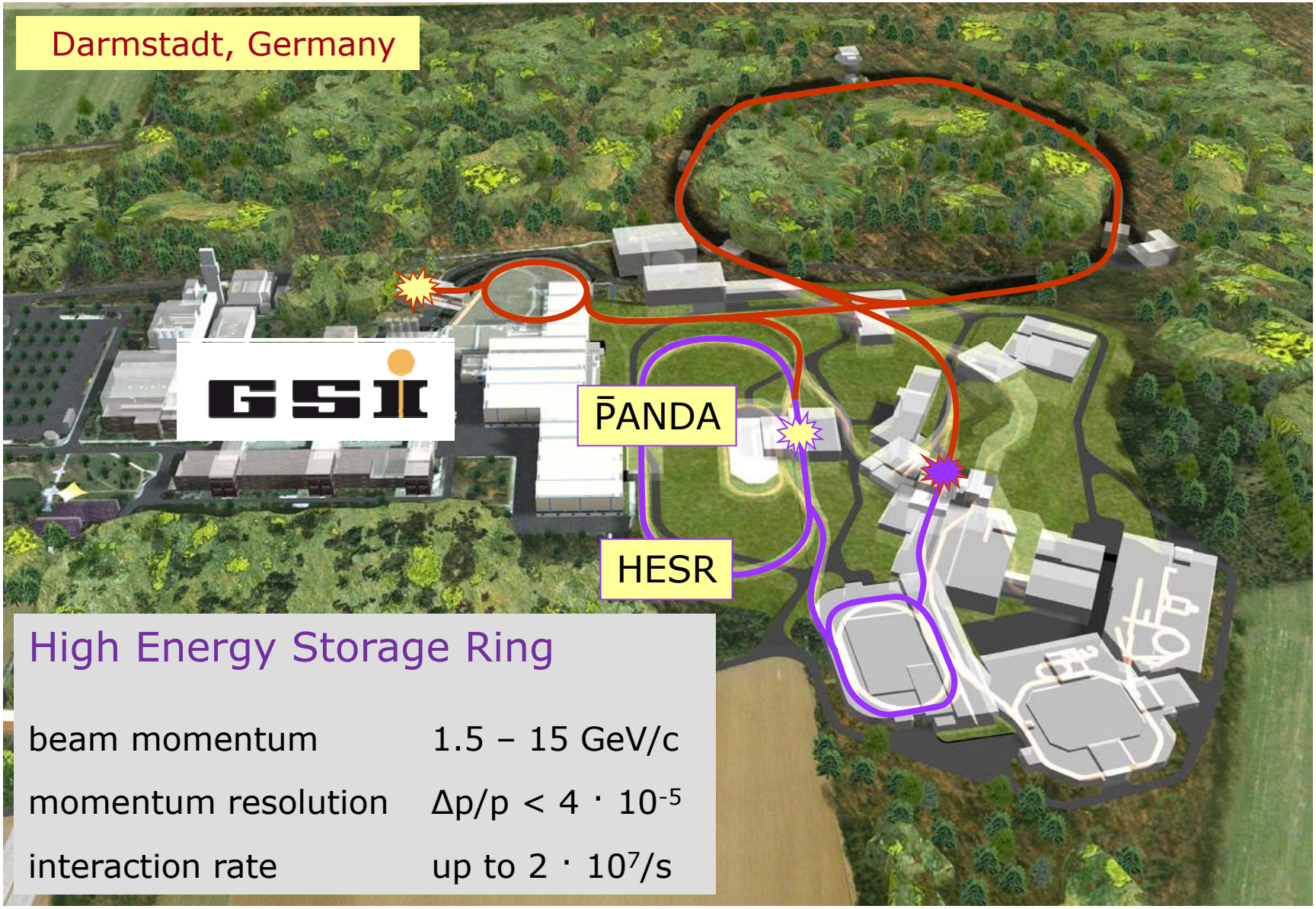
Ongoing analyses on BaBar and Belle

100 times more statistics on SuperB or Belle-2

Search for strangeonium resonances with BESIII

High precision measurement with PANDA ($\bar{p}p$-experiment)
- Energy scan experiments (resolution 50 keV/c^2)
- All quantum numbers accessible

FAIR

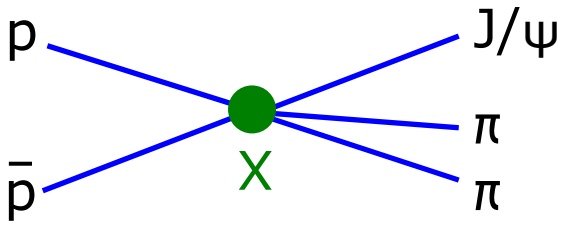


High Energy Storage Ring

beam momentum	1.5 – 15 GeV/c
momentum resolution	$\Delta p/p < 4 \cdot 10^{-5}$
interaction rate	up to $2 \cdot 10^{7}$/s

X(3872) at PANDA

Formation reaction



PDG

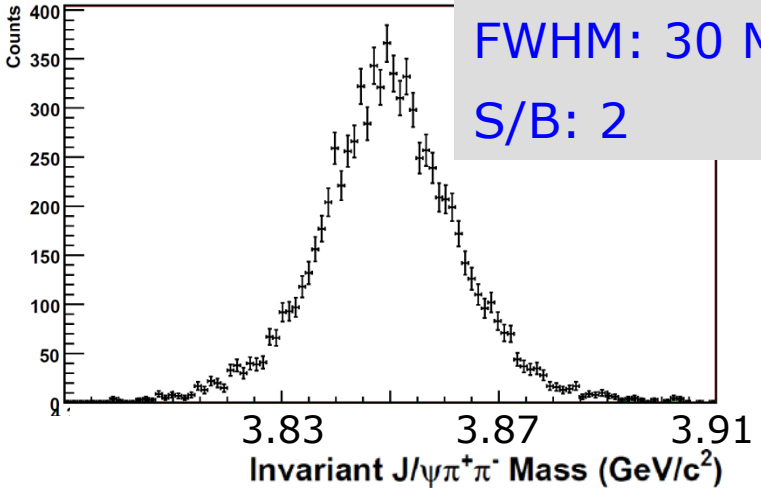
mass	3871.56 ± 0.22 MeV/c^2
width	< 2.3 MeV/c^2
	~ O(1 MeV/c^2)

Simulation at $\sqrt{\bar{s}}$ = 3872 MeV/c^2

Efficiency: 32%

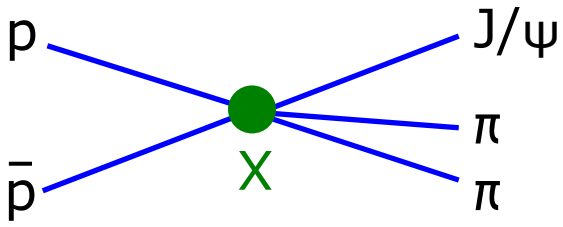
FWHM: 30 MeV/c^2

S/B: 2

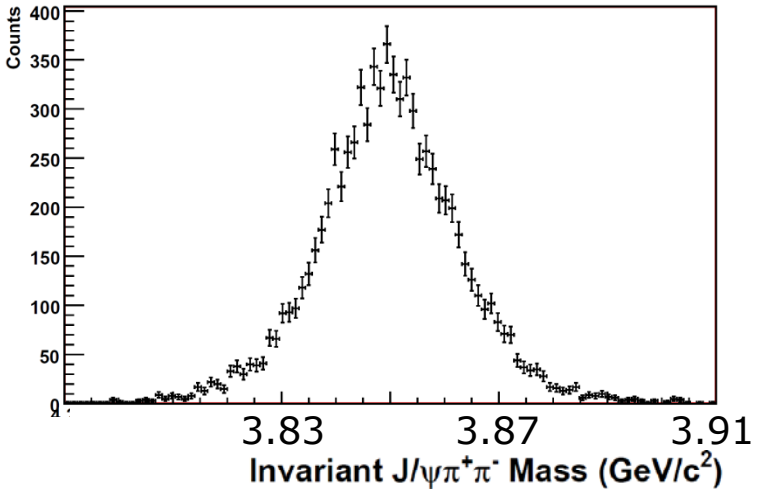


X(3872) at PANDA

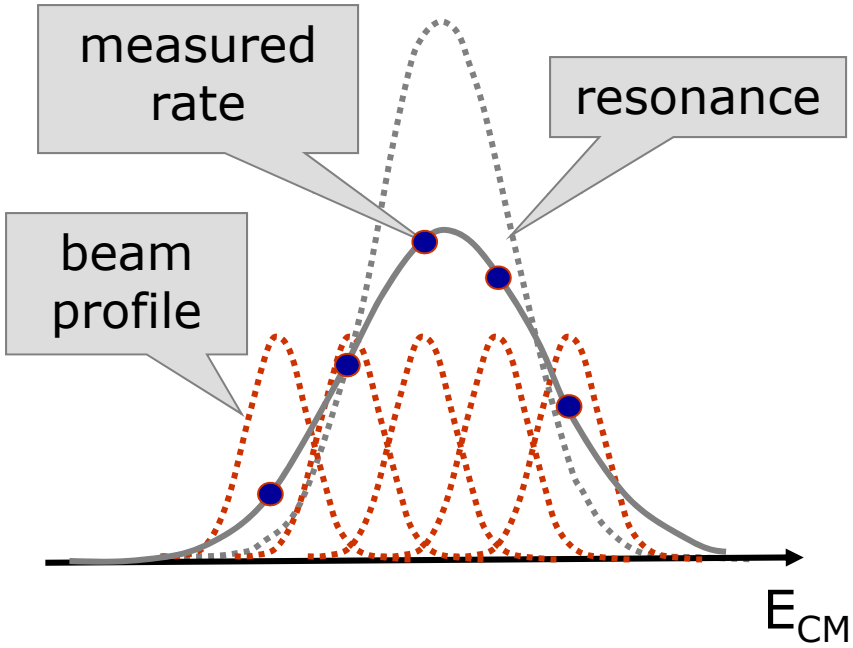
Formation reaction



Simulation at $\sqrt{\bar{s}}$ = 3872 MeV/c²



Lineshape measurement



Energy scan method

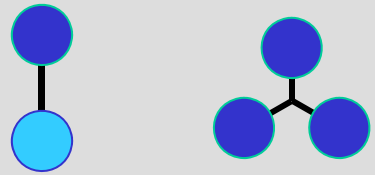
→ energy resolution ~ 50 keV

→ data taking ~ 40 days

Future ?

We know

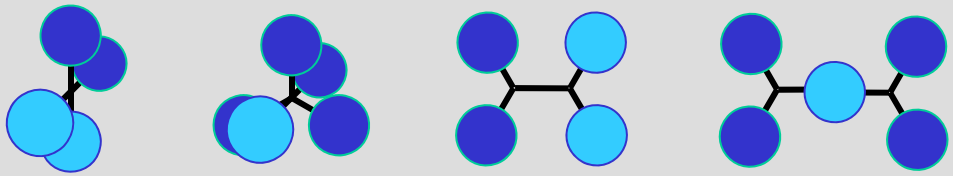
mesons/baryons



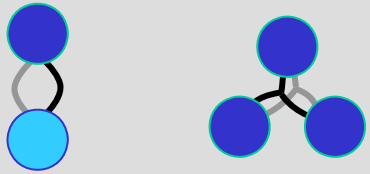
We presume

We know

molecules/multi-quarks



hybrids



glueballs

and more