QCD studies and discoveries with e^+e^- colliders and future perspectives

(mainly Belle, Belle II and PANDA)

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5th International Symposium on Symmetries in Subatomic Physics
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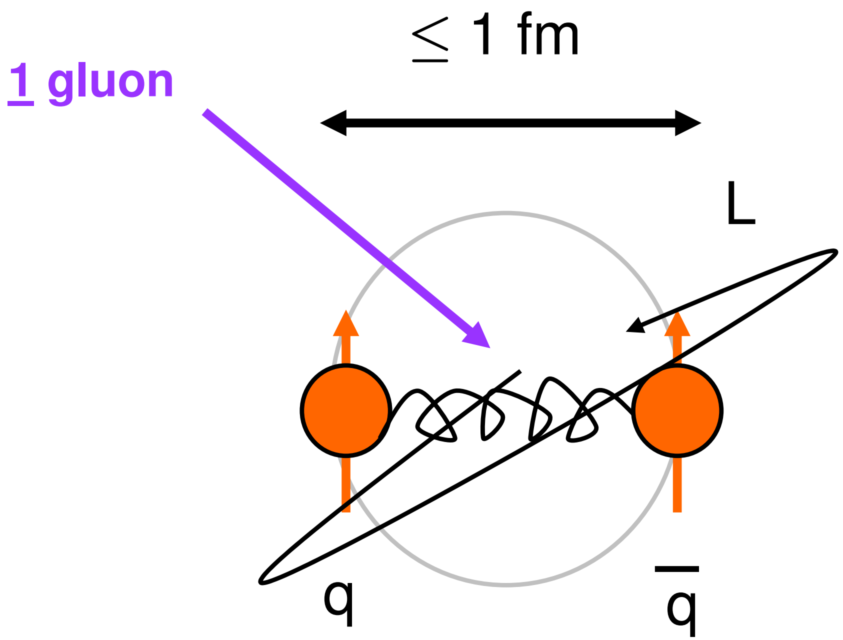
KVI Groningen, the Netherlands

One of the simplest QCD problems

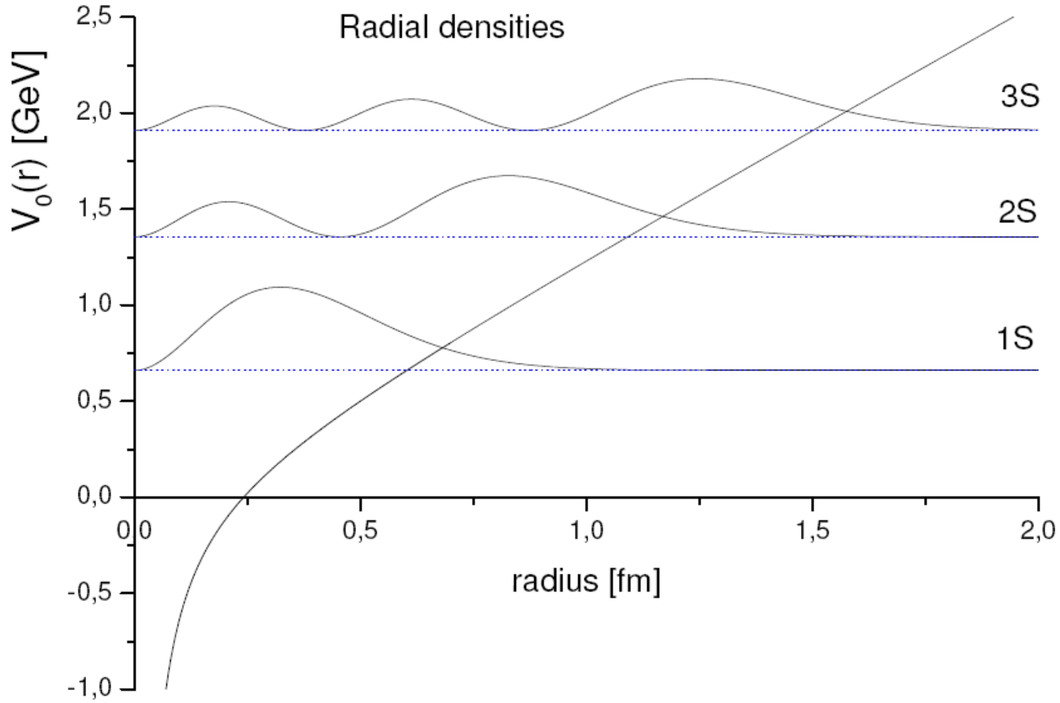


- heavy quarks (c,b) $\rightarrow$ non-relativistic
- α_S constant

A large part of the experimental program
at Belle (KEKB), BaBar (SLAC),
BESIII (BEPCII), KEDR (VEPP), CLEO (CESR), …

Static Quark Anti-Quark Potential

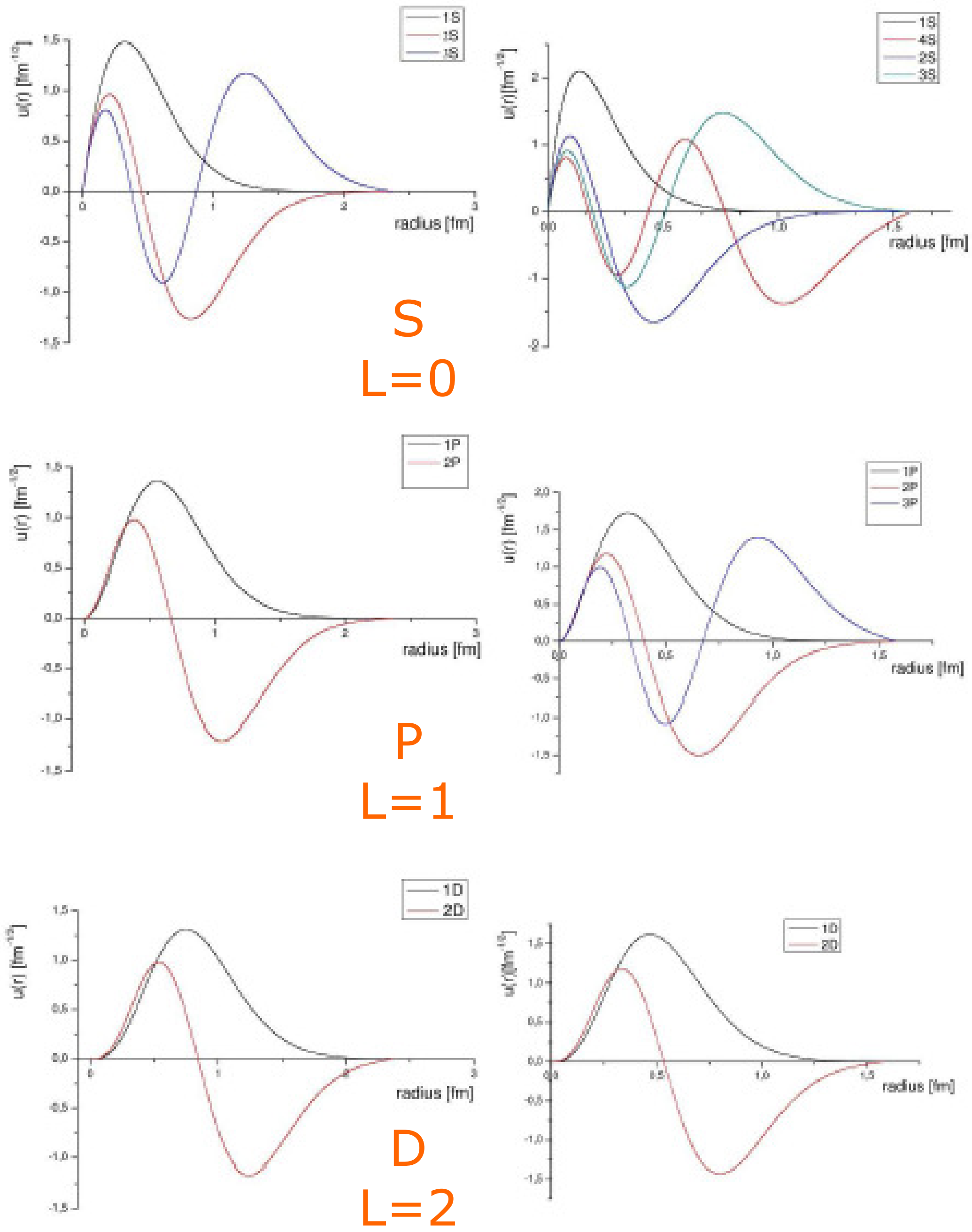
„linear" term
(QCD confinement)



„Coulomb" term
(due to vector nature of the gluon)

Wavefunctions

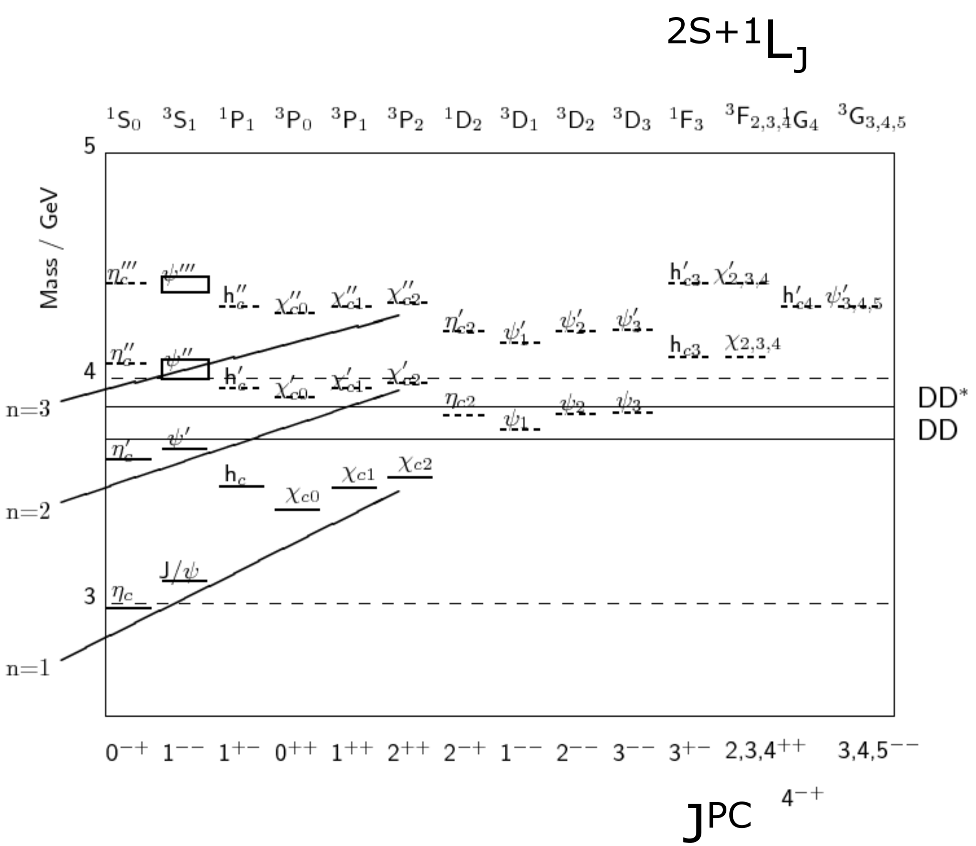
Charmonium



Bottomonium

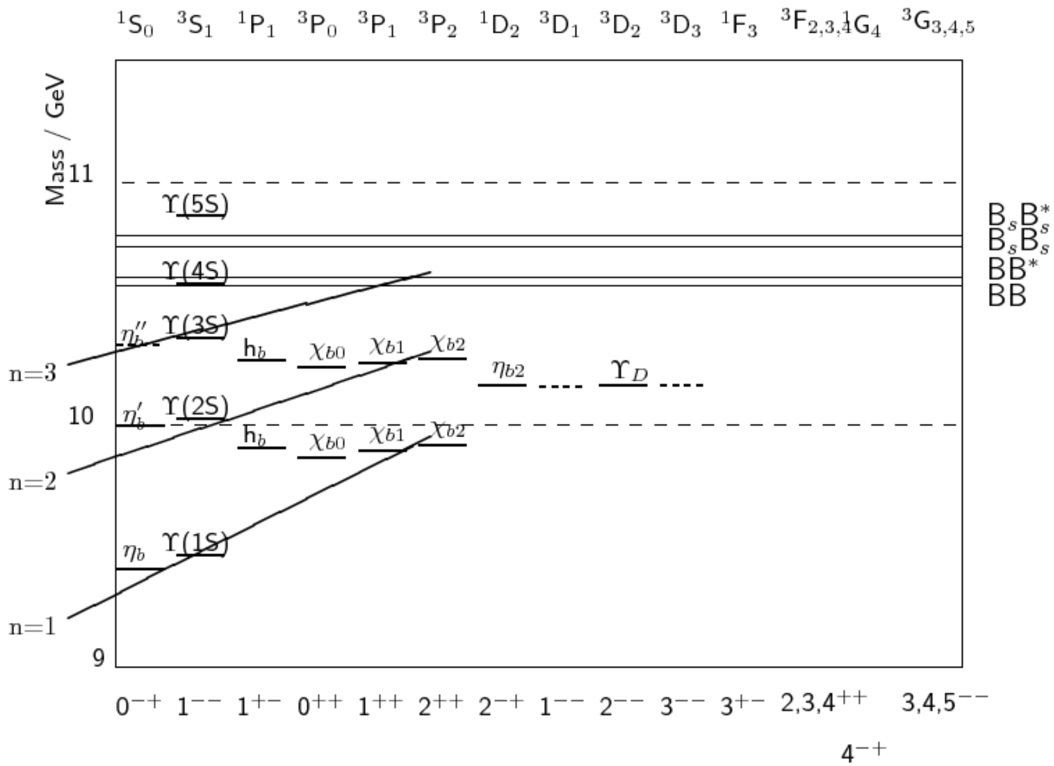
Levels

Charmonium



Two L=2 states
above $\bar{D}D$ threshold
→ broad (>20 MeV)

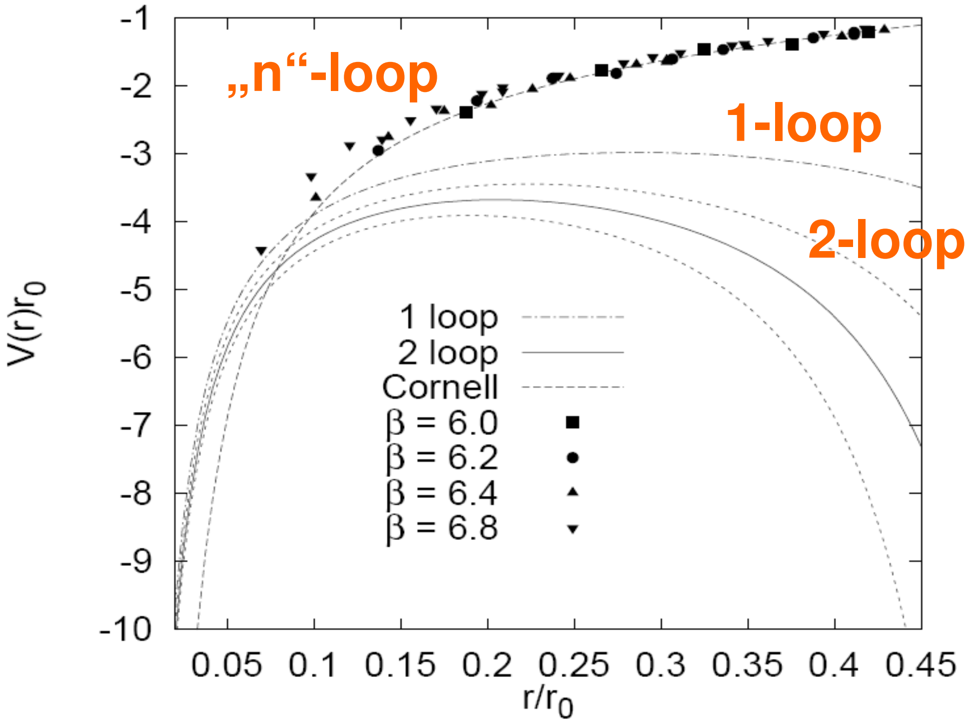
Bottomonium



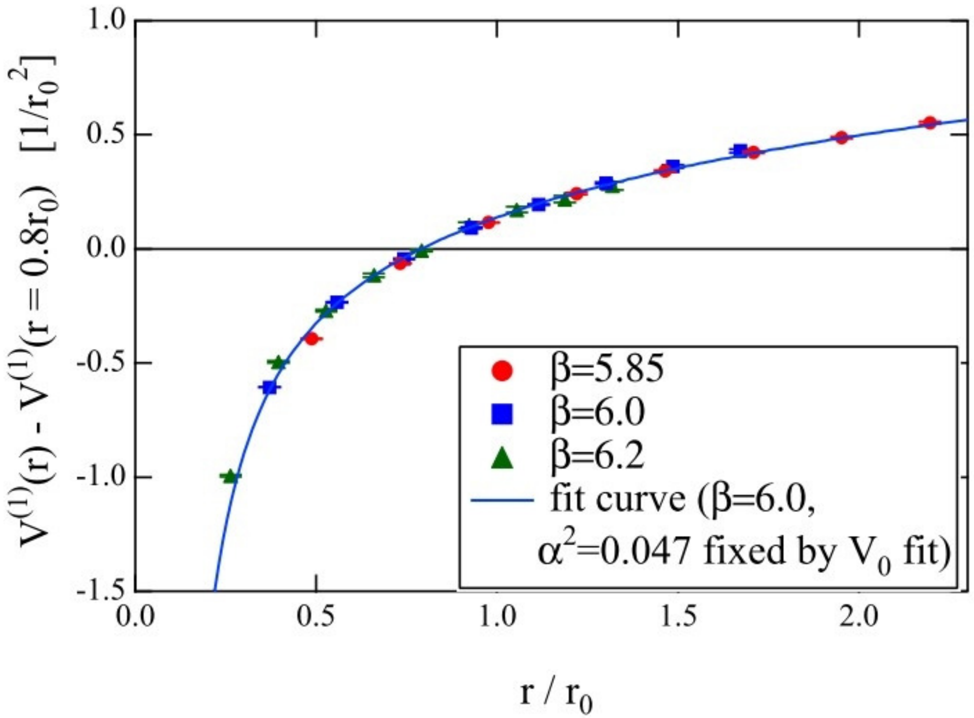
Two L=2 states
below $\bar{B}B$ threshold
→ narrow (~30 keV expected)

Not so simple potential at all: Lattice QCD results

G. Bali, hep-ph/9905387



Y. Koma, M. Koma, H. Wittig, Phys. Rev. Lett. 97(2006)122003; Y. Koma, M. Koma, arXiv:0911.3204[hep-lat]

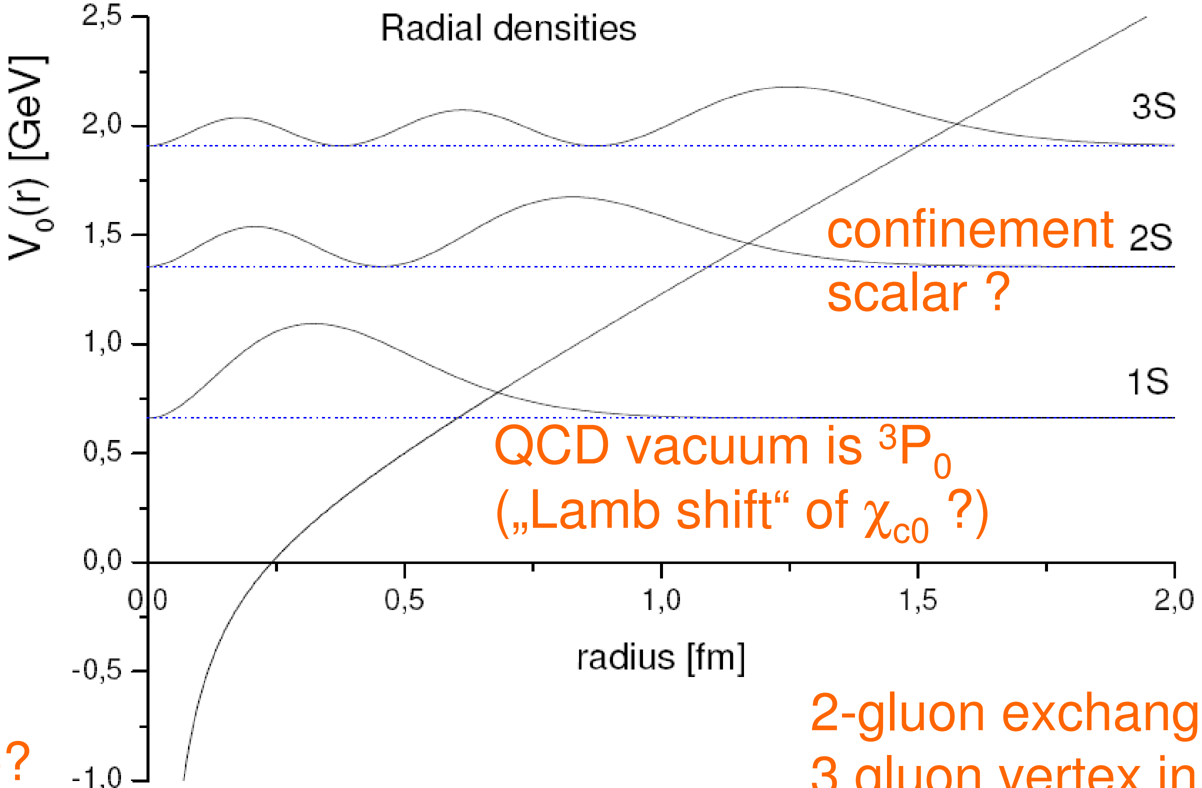


Relativistic corrections at order $1/m^2$ indicate logarithmic long-range behaviour ~17% shift for charmonium

Not so simple potential at all: a closer look

$\alpha_S > 1$ at large radius
non-perturbative?

string breaking regime
„bound" states?



confinement
scalar ?

QCD vacuum is $^3P_0$
(„Lamb shift" of χ_{c0} ?)

asymptotic free?
(why annihilation branching so high?)
contact term (spin-spin)

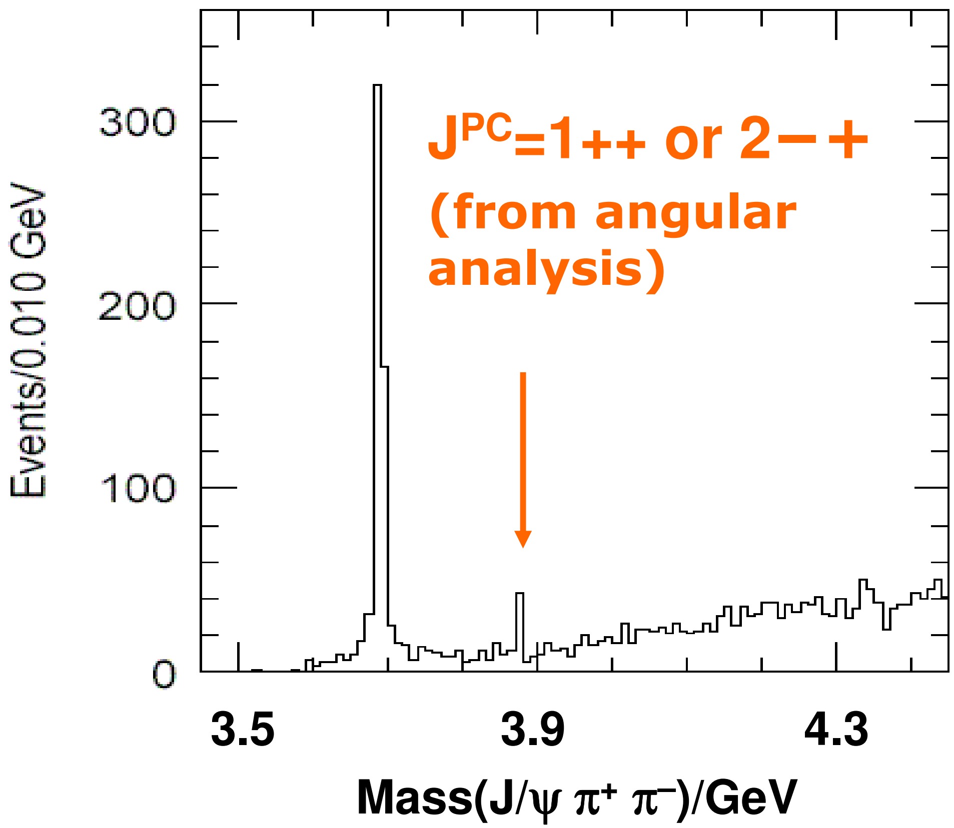
2-gluon exchange?
3 gluon vertex in hadronic decays?
molecular potential?
$[c\ \bar{c}]_8$ + gluon hybrid?
(color octet)

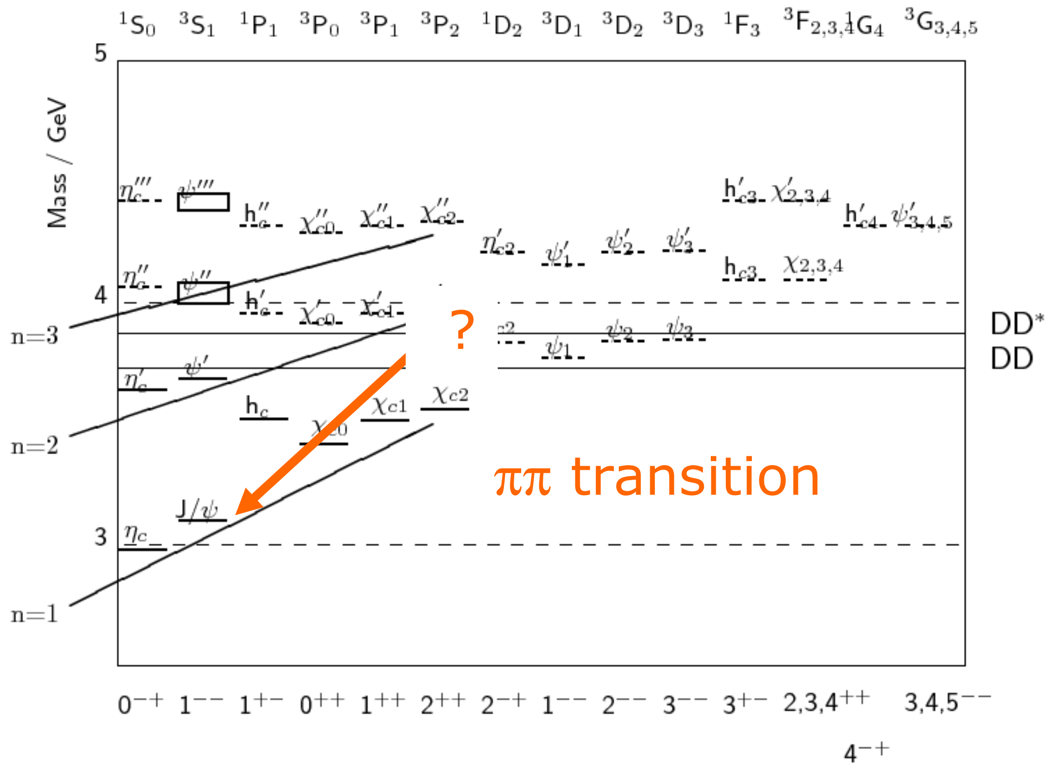
Experimental Results: Charmonium

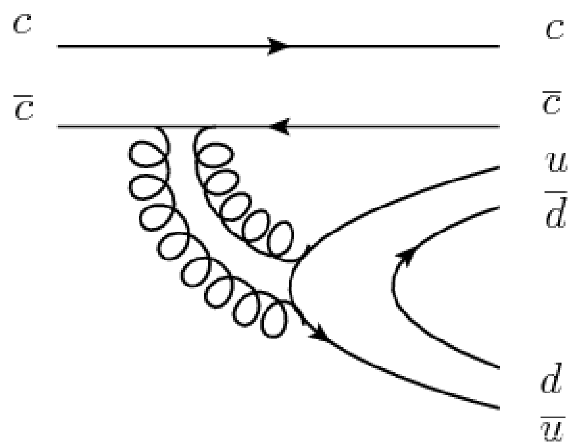
The X(3872) State

Belle, Phys. Rev. Lett. 91(2003)262001
138 fb^{-1}

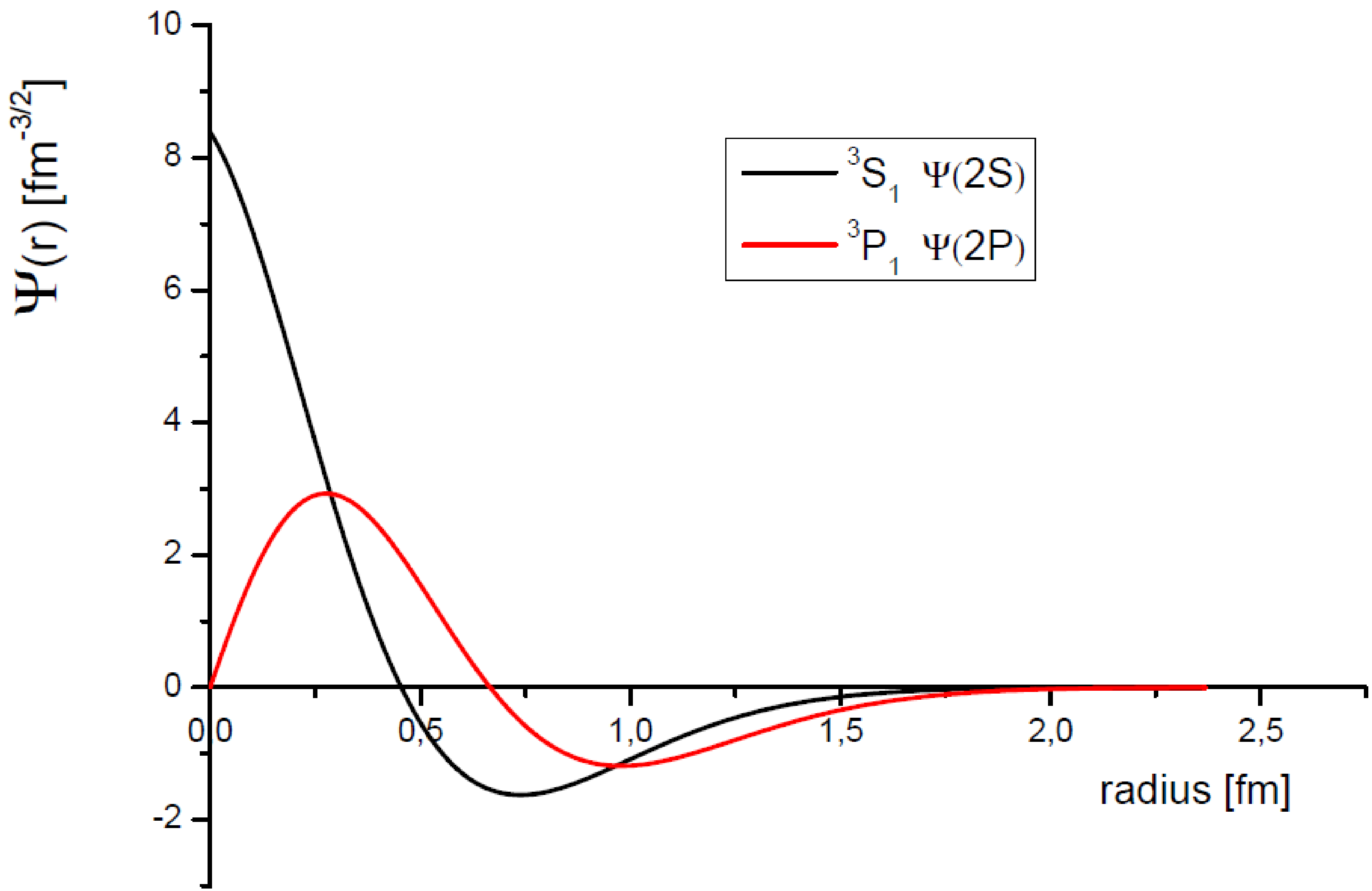
$\psi'(3686)$, $J^{PC}=1^{--}$







$J^{PC}=1^{++}$ vs. 1^{--}

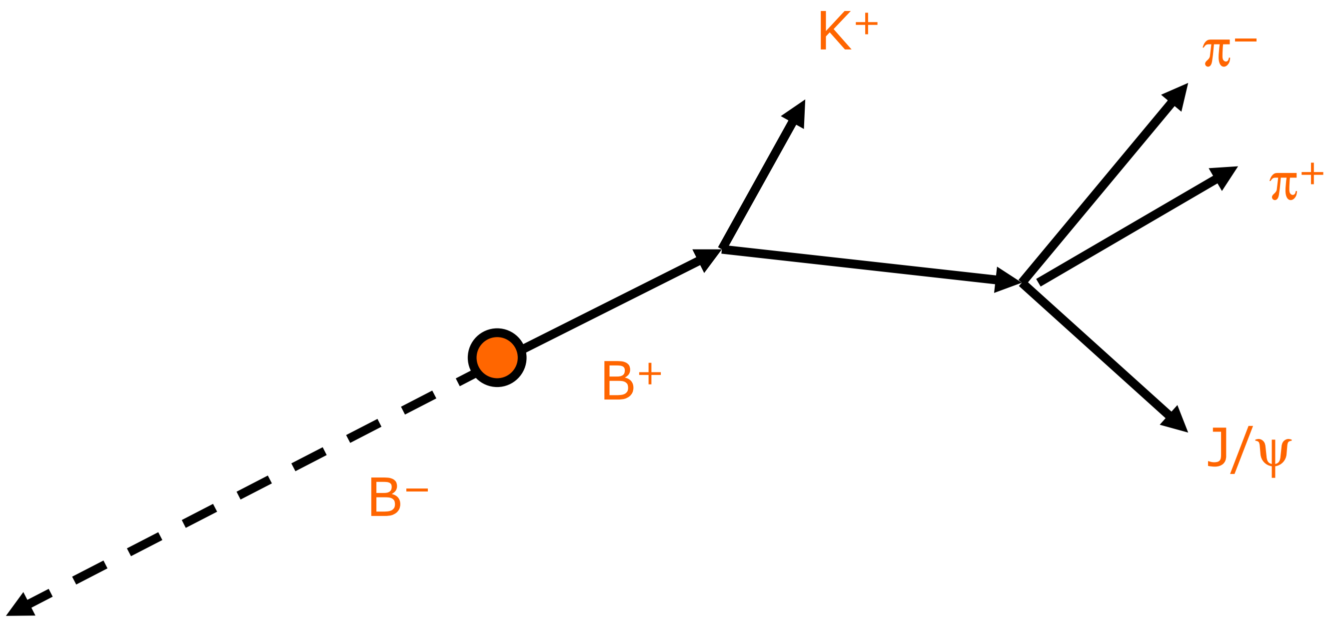


$$e^+ e^- \to \Upsilon(4S) \;@\; \sqrt{s}=10.58\ \text{GeV}$$

$$\Upsilon(4S) \to B^+ B^-$$

$$B^+ \to K^+ X(3872)$$

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



Why the X(3872) has not seen before?

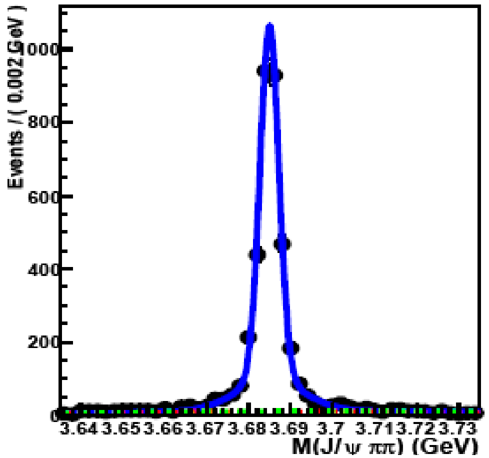
$B \to K\ X(3872)$
$0- \to 0-\ 1+$
parity $(-1) \to$ parity $(-1) \times (+1) \times (-1)^L$

We need L=1 to create J=1,
but this violates parity.
$\to$ rare process

$B(B \to KX(3872)) \times B(X(3872) \to J/\psi\pi^+\pi^-) = (9.5 \pm 1.9) \times 10^{-6}$

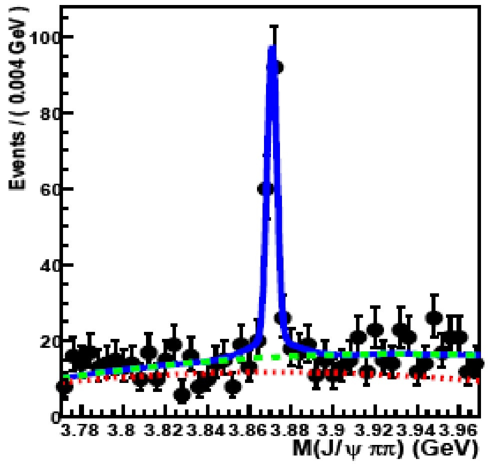
Analysis of X(3872) → J/ψ π+π−
with final Belle data set, 711 fb^{-1}

Belle
Phys. Rev. D84(2011)052004
arXiv:1107.0163 [hep-ex]



M(J/ψ π^+ π^-)/GeV

Control Signal
ψ´



M(J/ψ π^+ π^-)/GeV

X(3872)
151±15 events

fixed resolution parameters from ψ´
Mass MC/data shift +0.92±0.06 MeV, measured and fixed from ψ´ mass

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

Belle result contains MC/data shift 0.92 ± 0.006 MeV, fixed from reference channel ψ'

Experiment	
CDF 2	3871.61 ± 0.16 ± 0.19 MeV
BaBar (B^+)	3871.4 ± 0.6 ± 0.1 MeV
BaBar (B^0)	3868.7 ± 1.5 ± 0.4 MeV
D0	3871.8 ± 3.1 ± 3.0 MeV
Belle	3871.84 ± 0.27 ± 0.19 MeV
LHCb	3871.96 ± 0.46 ± 0.10 MeV
World Average	**3871.67 ± 0.17 MeV**
$M(D^0)+M(D^{*0})$ PDG2010	3871.79 ± 0.30 MeV

"Binding Energy"

$$m(X) - m(D^{*0}) - m(D^0)$$

$$\Delta m = -0.12 \pm 0.35 \text{ MeV}$$

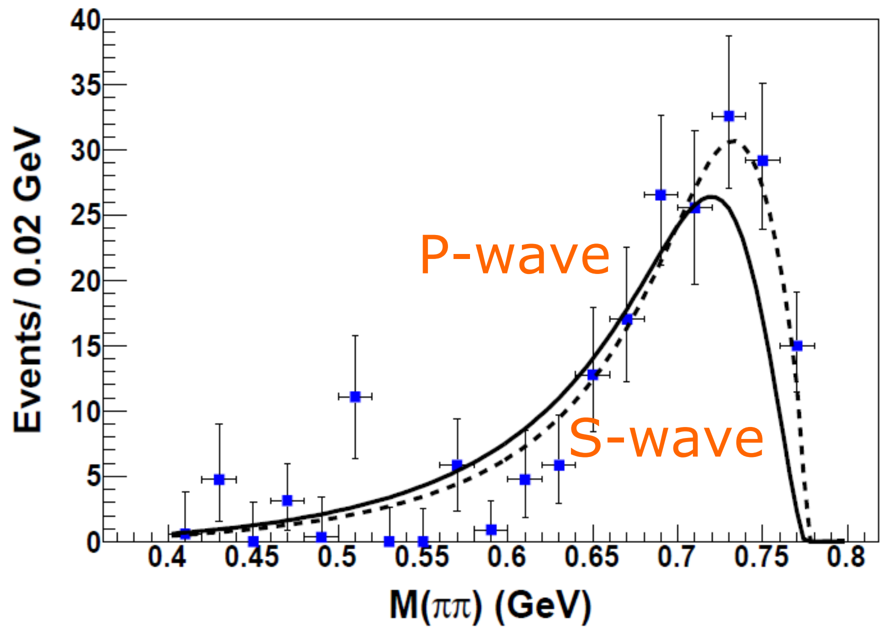
Only 120 keV below threshold

$\rightarrow$ S-wave $\bar{D}D^*$ molecular state?

Reminder: Δm(deuteron) = –2.2 MeV

Isospin Violation

- $X(3872) \rightarrow J/\psi\ \pi^+ \pi^-$
  observation: $\pi^+\pi^-$ invariant mass peaks at ρ^0
- $X(3872)\rightarrow J/\psi\rho(I=1)$
  violates isospin
- Reason ρ/ω mixing ?
  Terasaki, Prog. Theor. Phys. 122(2010)1285



ψ'

Isospin violating Charmonium Transistions

Only two decays known (measured).

Decays into $J/\psi(1S)$ and anything

$J/\psi(1S)$anything		(59.5 ± 0.8) %		–
$J/\psi(1S)$neutrals		(24.6 ± 0.4) %		–
$J/\psi(1S)\pi^+\pi^-$		(33.6 ± 0.4) %		477
$J/\psi(1S)\pi^0\pi^0$		(17.76 ± 0.34) %		481
$J/\psi(1S)\eta$		(3.28 ± 0.07) %		199
$J/\psi(1S)\pi^0$	CLEO	$(1.30 \pm 0.10) \times 10^{-3}$	S=1.4	528

Hadronic decays

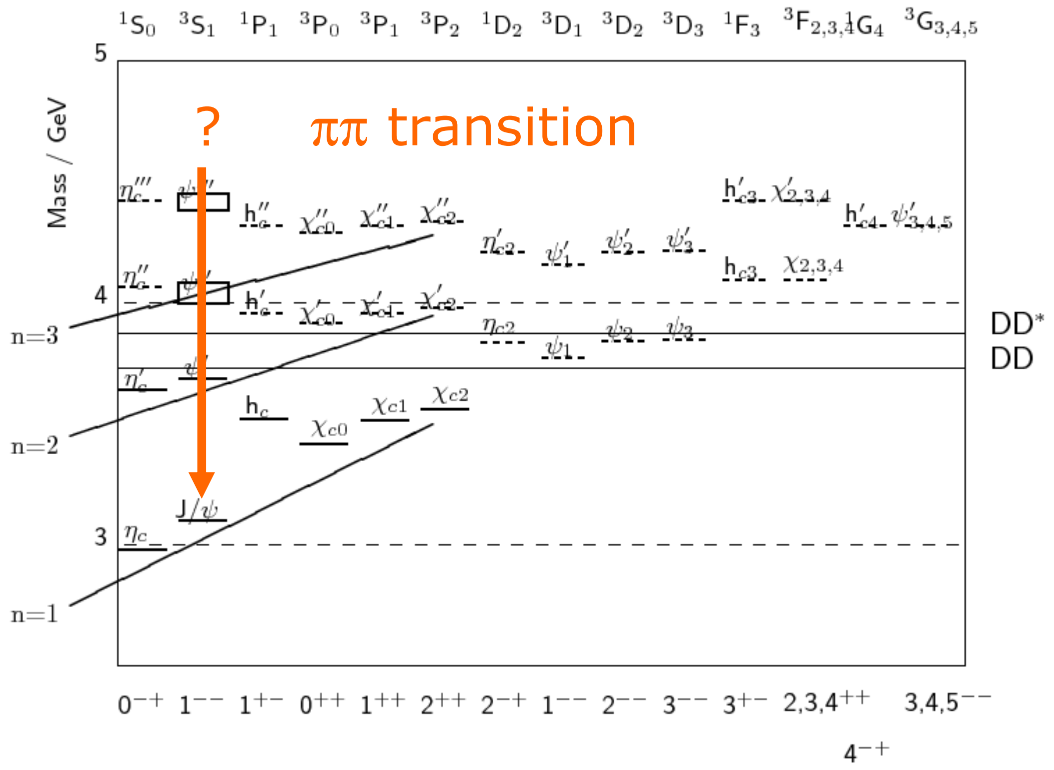
$\pi^0 h_c(1P)$	CLEO, Bes3	$(8.4 \pm 1.6) \times 10^{-4}$		85

For the X(3872) the BR of isospin violating transistion is (among the known decays) oder of ~10%
$\rightarrow$ largely enhanced

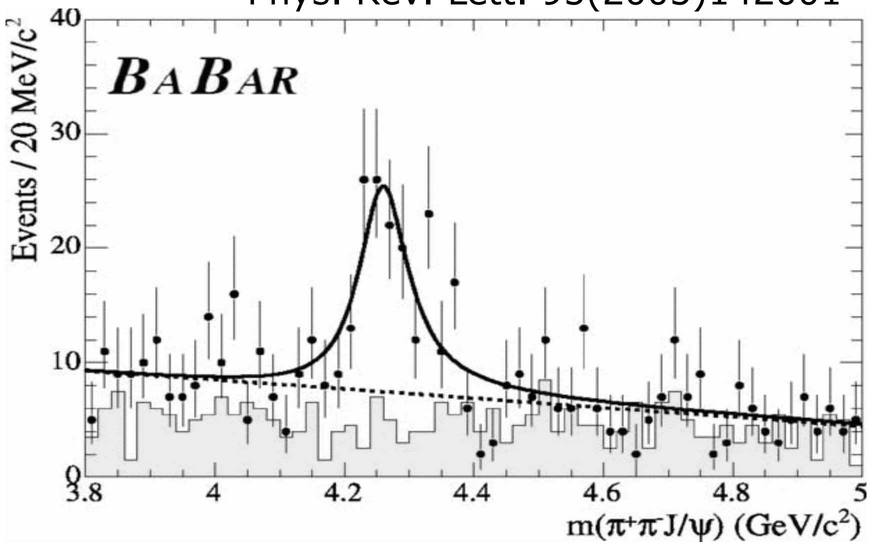
The Y(4260) State

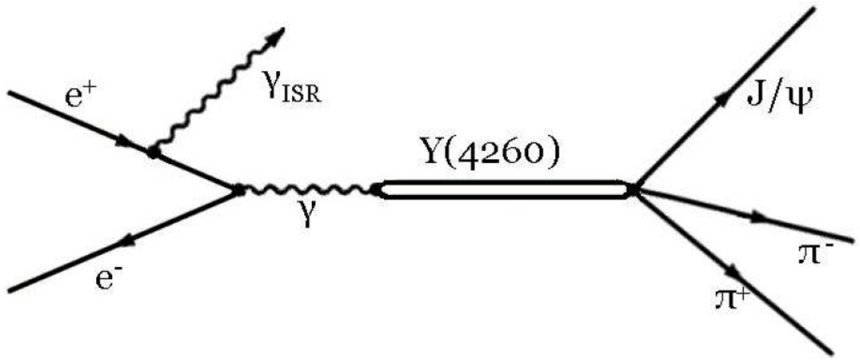
- mass >4 GeV
  far above $\bar{D}D^{(*)}$ threshold
- width < 100 MeV
  quite narrow
- quantum numbers must be (based upon production mechanism)

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



Phys. Rev. Lett. 95(2005)142001





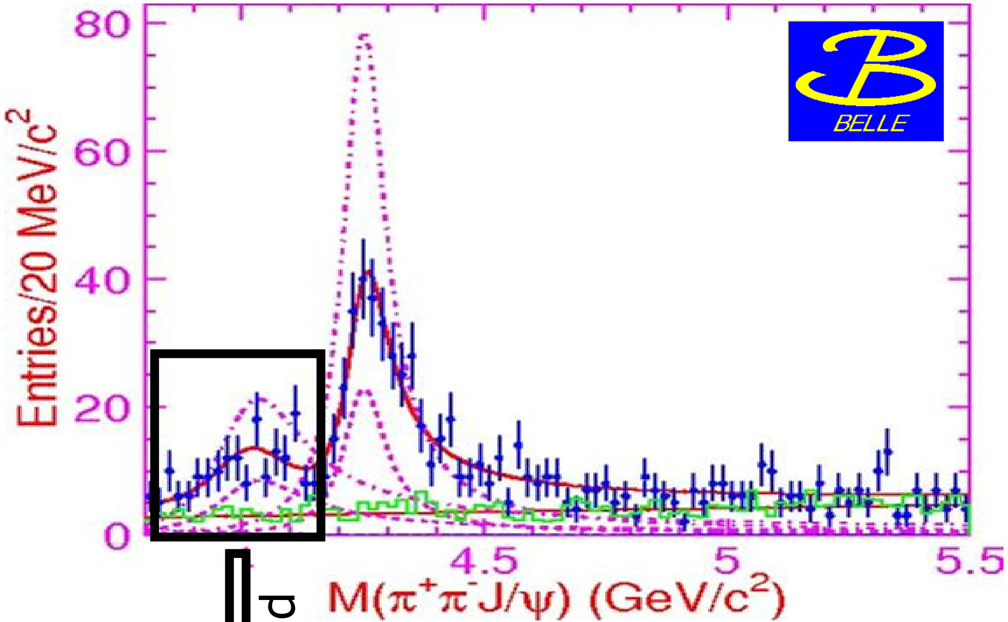
Y(4260) Parameters

	BaBar [1]	CLEO-III [2]	Belle [3]	Belle [4]	BaBar [5]
	211 fb^{-1}	13.3 fb^{-1}	553 fb^{-1}	548 fb^{-1}	454 fb^{-1}
N	125±23	$14.1^{+5.2}_{-4.2}$	165±24	324±21	344±39
Significance	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	–
m / MeV	$4259\pm8^{+2}_{-6}$	$4283^{+17}_{-16}\pm4$	$4295\pm10^{+10}_{-3}$	$4247\pm12^{+17}_{-32}$	$4252\pm6^{+2}_{-3}$
Γ / MeV	$88\pm23^{+6}_{-4}$	70^{+40}_{-25}	$133\pm26^{+13}_{-6}$	108±19±10	$105\pm18^{+4}_{-6}$

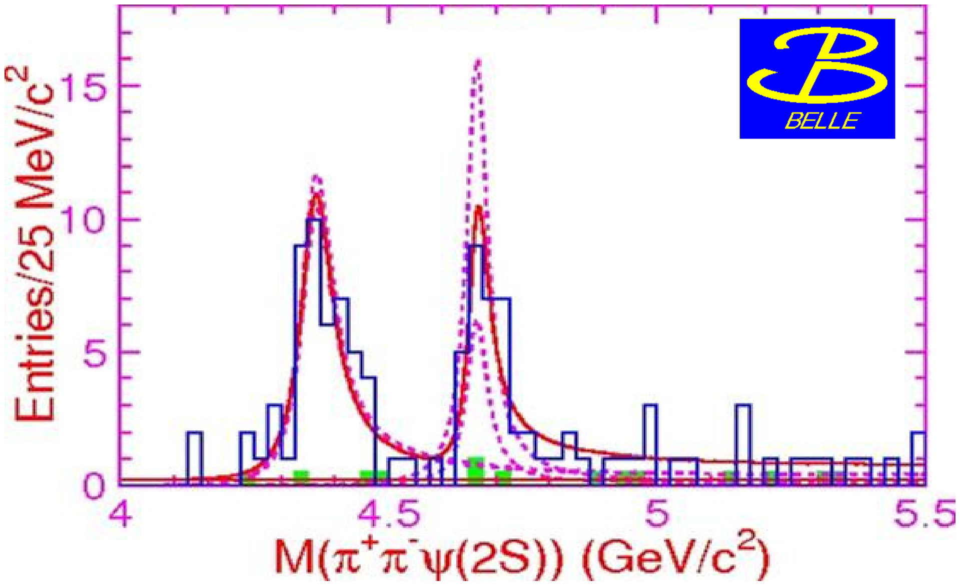
[1] Phys. Rev. Lett. 95(2005)142001
[2] Phys. Rev. Lett. 96(2006)162003
[3] arXiv:hep-ex/0612006
[4] Phys. Rev. Lett. 99(2007)182004
[5] arXiv:0808.1543[hep-ex]

$e^+e^- \rightarrow \gamma_{ISR}\ J/\psi\ (\psi')\ \pi^+\pi^-$ Y(4008,4260,4350,4660)

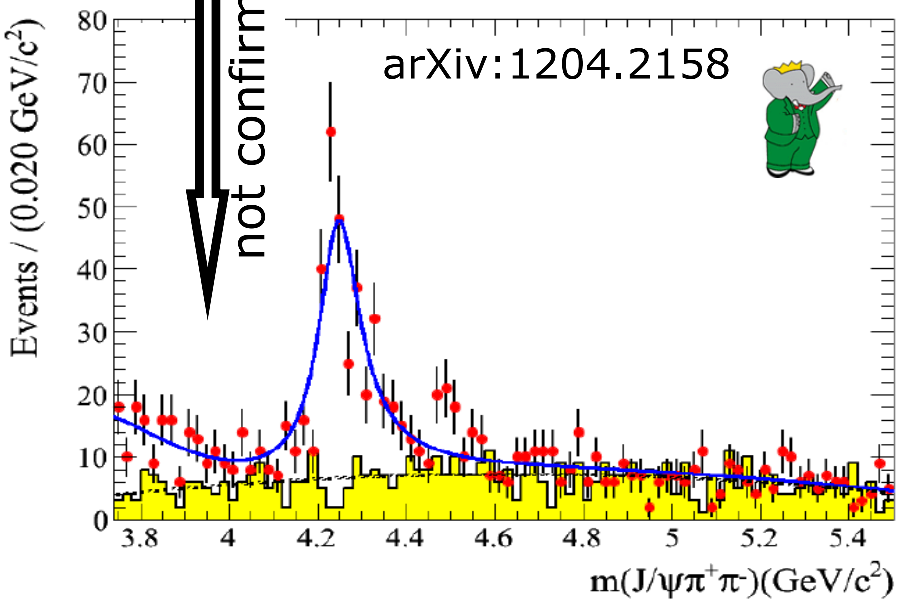
Phys. Rev. Lett. 99(2007)182004, 550/fb

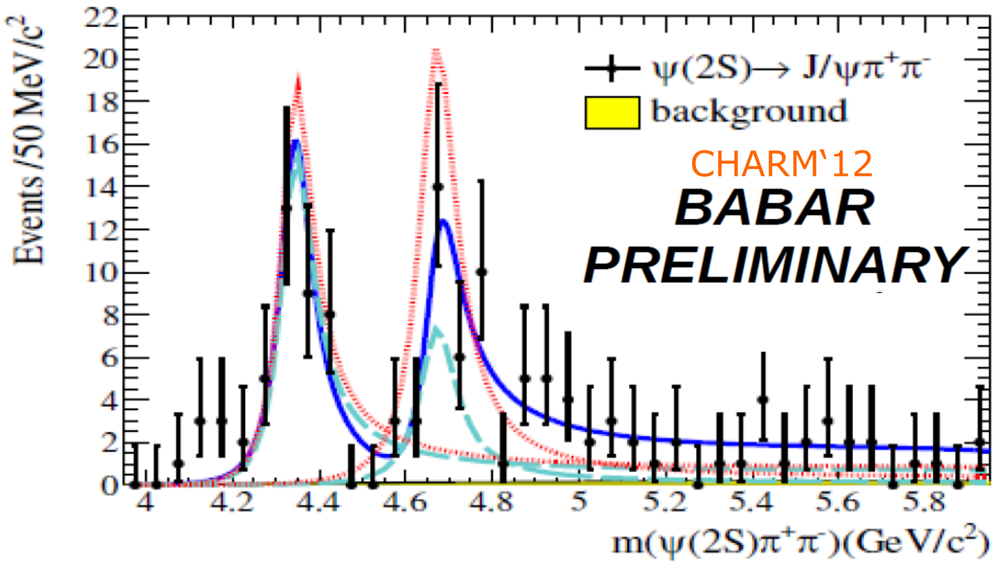


Phys. Rev. Lett. 99(2007)142002, 670/fb

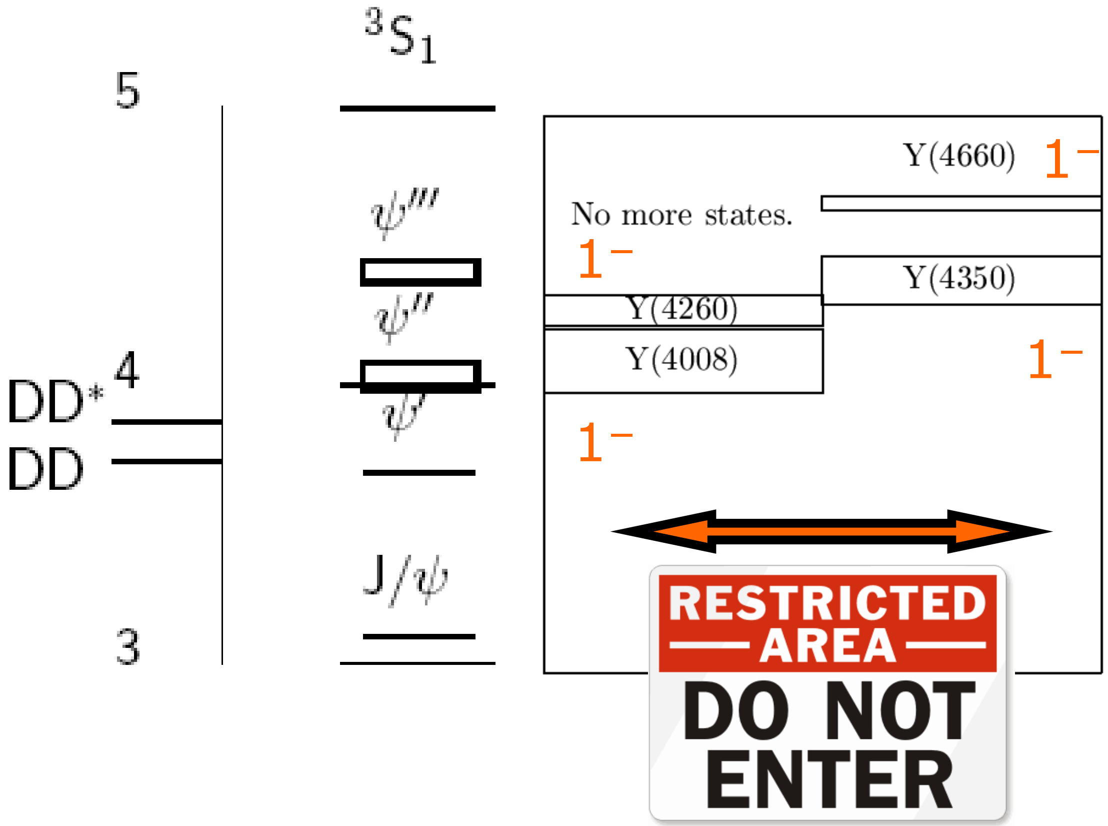


not confirmed





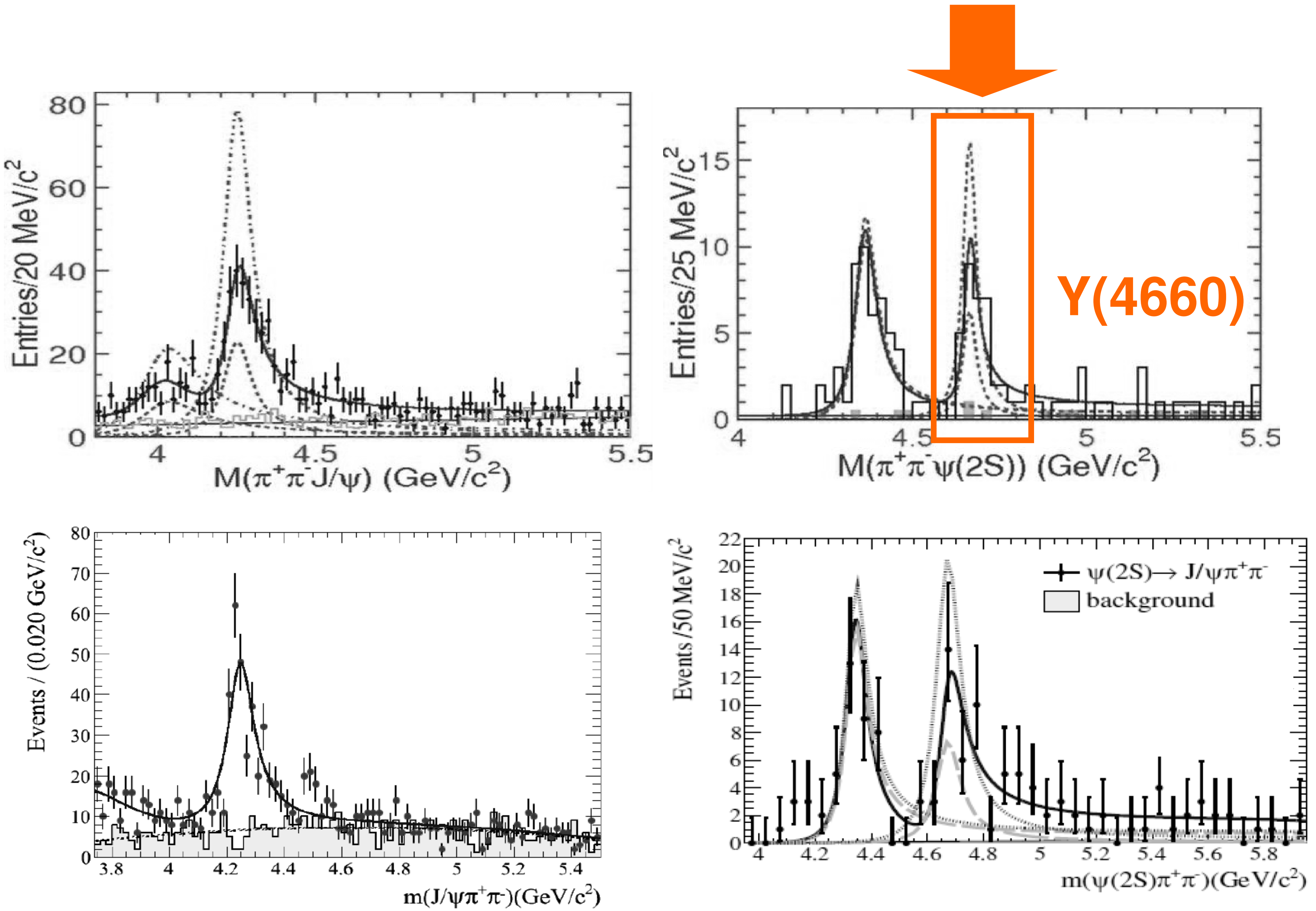
Y States : Overpopulation of $J^{PC}=1^{--}$



Pattern completely non-understood:

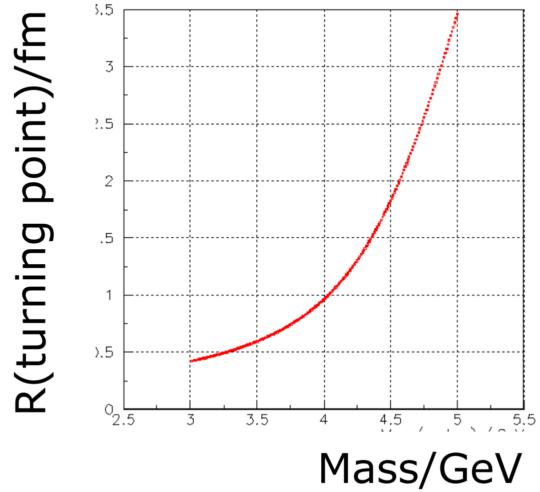
2 non-mixing doublets, no parity flip, no charge flip

What is the underlying symmetry?

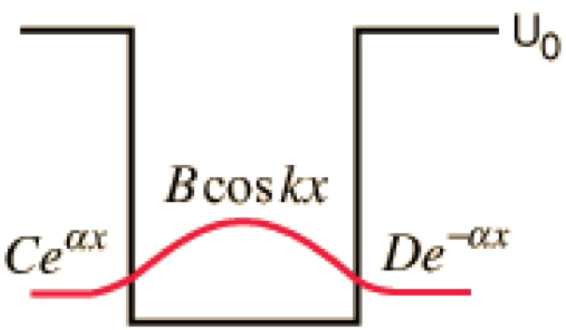

Y(4660)
Entries/20 MeV/c^2
M($\pi^+\pi^-$J/ψ) (GeV/c^2)
Entries/25 MeV/c^2
M($\pi^+\pi^-\psi$(2S)) (GeV/c^2)
Events / (0.020 GeV/c^2)
m(J/$\psi\pi^+\pi^-$)(GeV/c^2)
Events /50 MeV/c^2
m(ψ(2S)$\pi^+\pi^-$)(GeV/c^2)
ψ(2S)$\to$ J/$\psi\pi^+\pi^-$
background

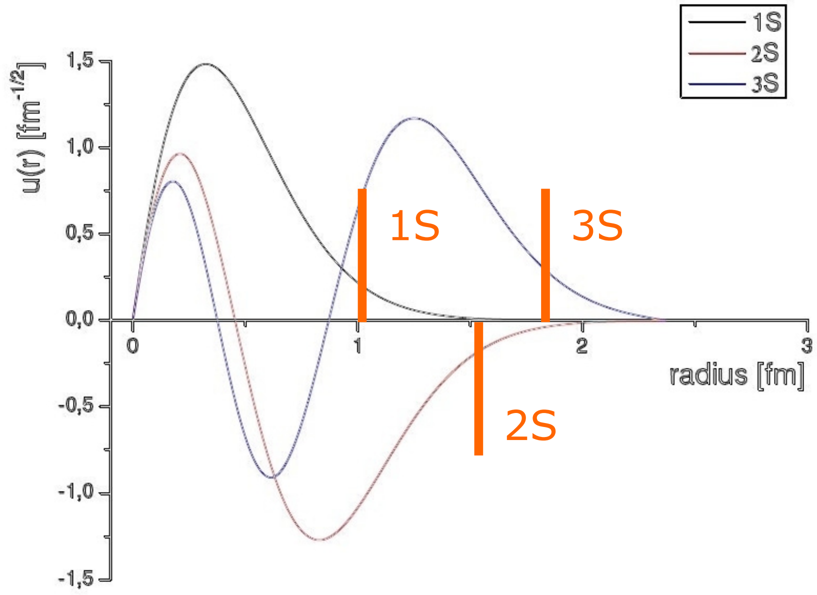
$\bar{q}q$ Potential model boundary condition: Wronski-Determinant must be zero at turning point

$$r_{\text{turning point}} = \frac{E-2m}{2\sigma} + \sqrt{\frac{4m^2-4mE+E^2}{4\sigma^2}+\frac{4\alpha_s}{3\sigma}}$$

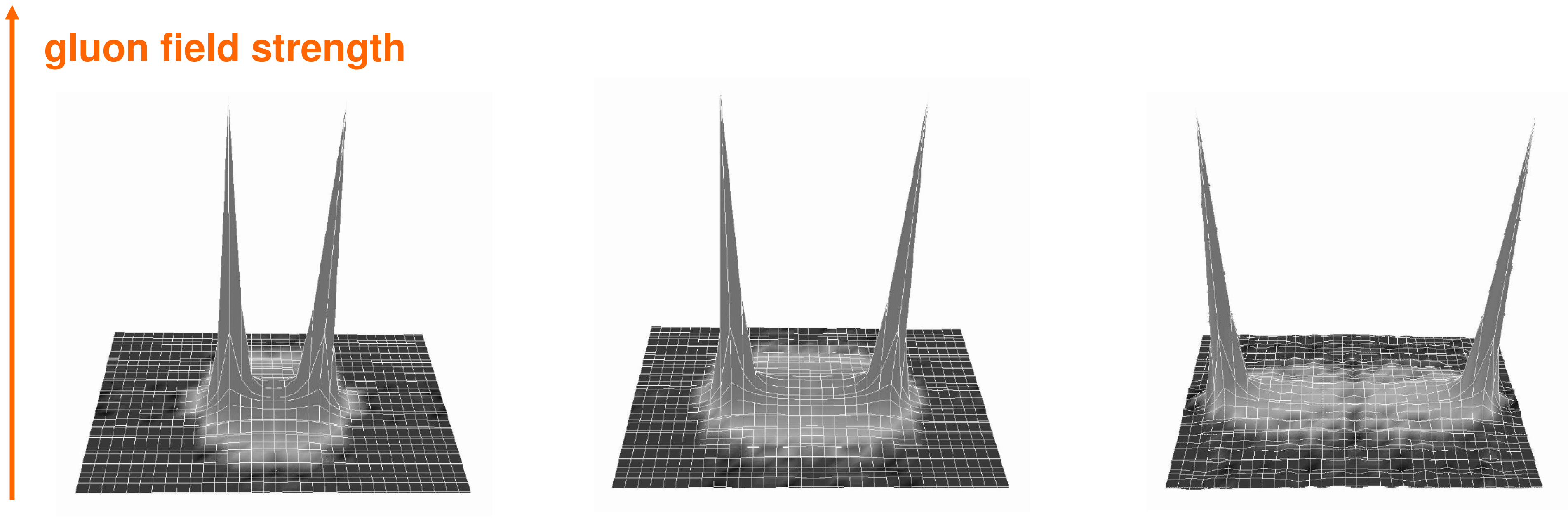


- at m=4.660 GeV, the turning point of the wave function is at r>2.2 fm!
- large fraction of wave function is in string breaking regime r>1.35 fm





The QCD String



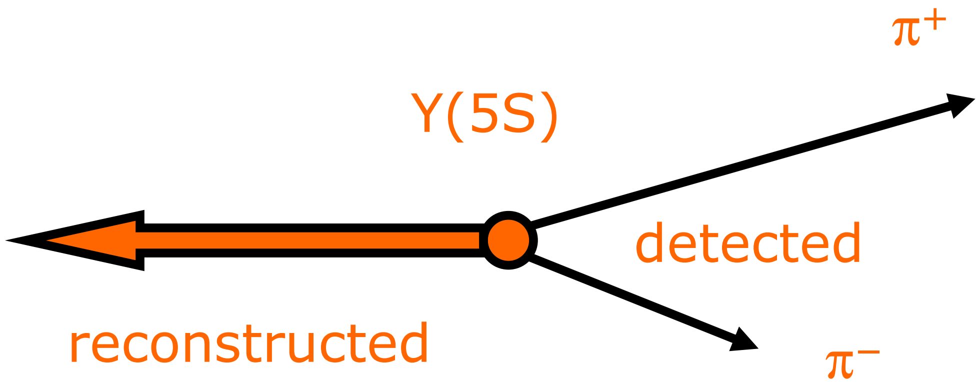
r=0.7 fm r=1.0 fm r=1.35 fm

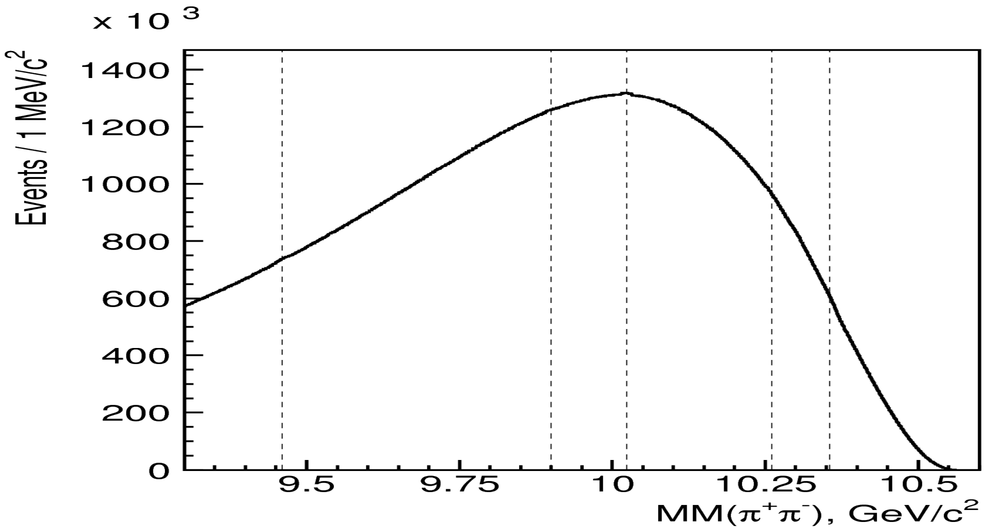
string breaking regime

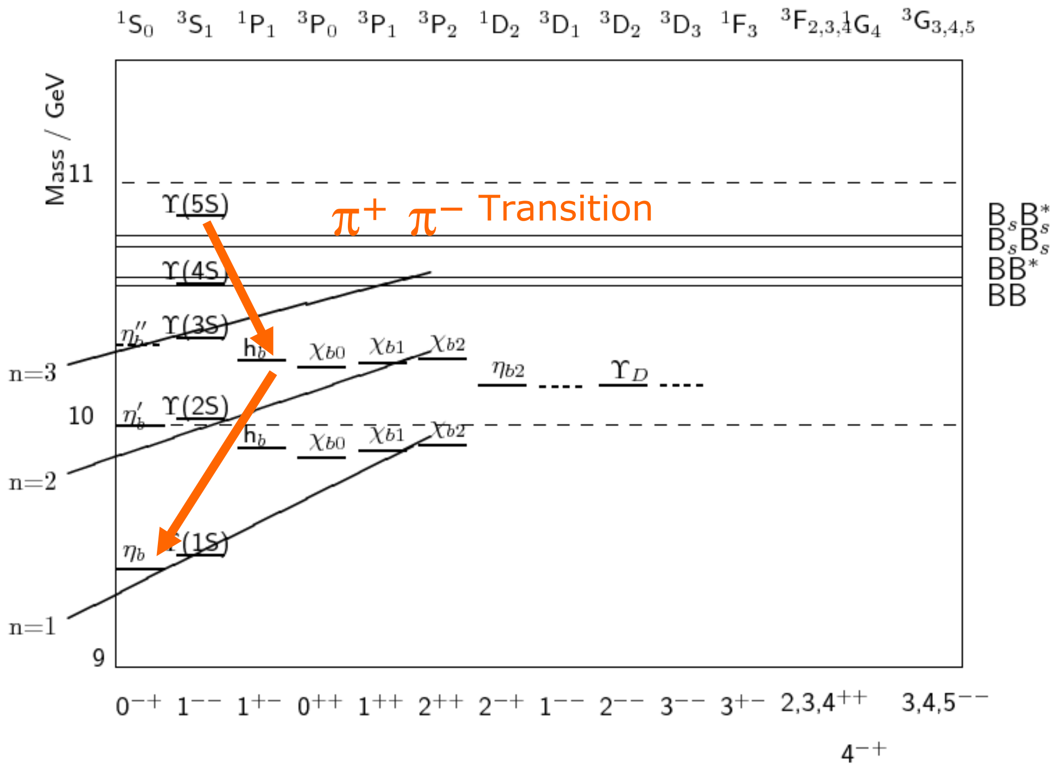
Lattice QCD, G. Bali, hep-lat/9409005

Experimental Results: Bottomonium

$\Upsilon(5S) \to X\, \pi^+\pi^-$ reconstruction







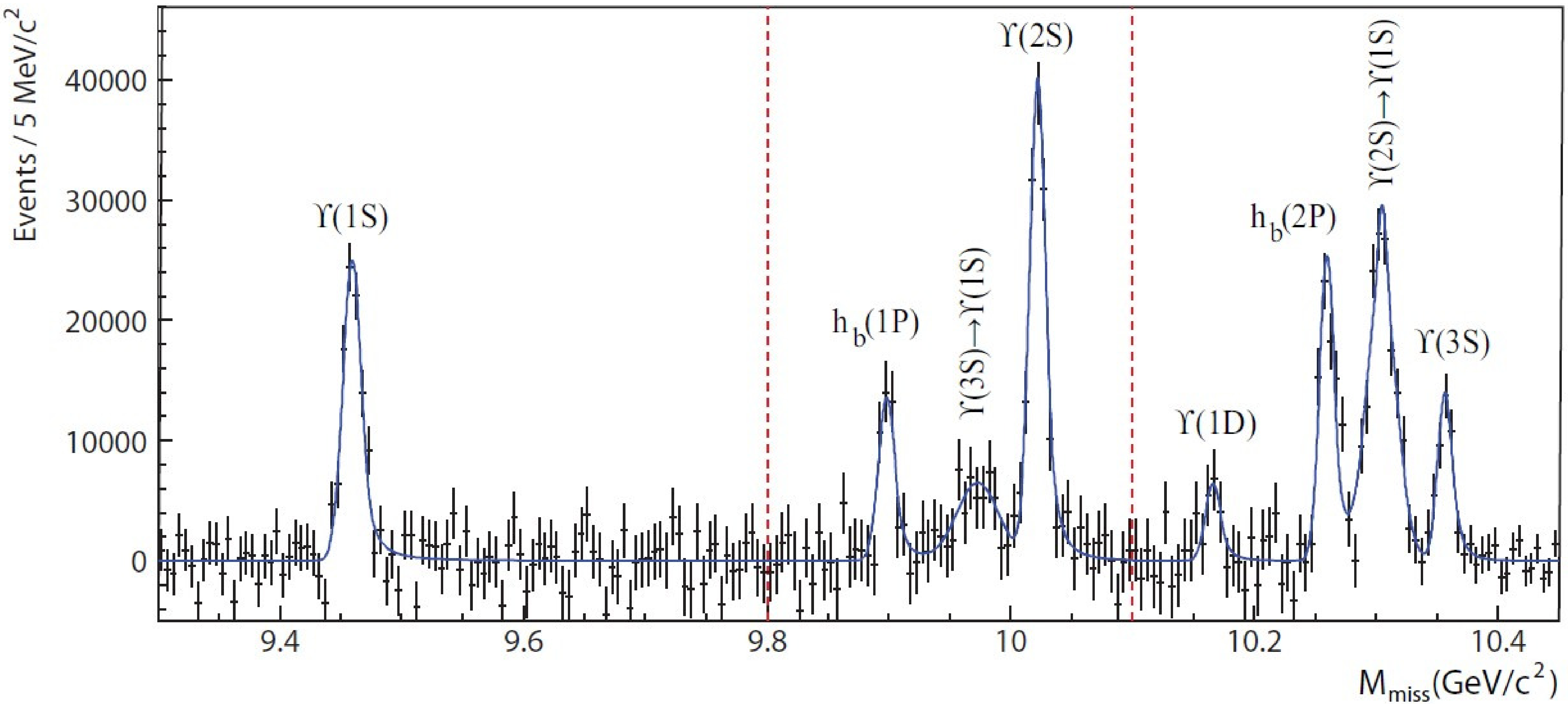
$$M_{\mathrm{miss}}(X) = \sqrt{(E_{\mathrm{c.m.}} - E_X^*)^2 - p_X^{*2}}$$

Υ(5S) Decays

$\pi^+ \pi^-$ missing mass

First observation of $h_b(1P)$ and $h_b(2P)$

Belle, 121.4 fb^{-1}
Phys. Rev. Lett 108(2011)032001
arXiv:1103.3419



Precision Test of Tensor Term in $\bar{q}q$ Potential

$$m(h_c) \stackrel{?}{=} \frac{m(\chi_{c0}) + 3 \cdot m(\chi_{c1}) + 5 \cdot m(\chi_{c2})}{9}$$

and analogue for h_b

- Test of hyperfine splitting
  $\Delta m_{HF} = < m(n^3P_J) >_{\text{spin-averaged}} - m(n^1P_1)$
- For the 1st time possible in the bottomonium system
- For the 1st time possible for n=1 and n=2
  as $h_c(2P)$ not observed yet

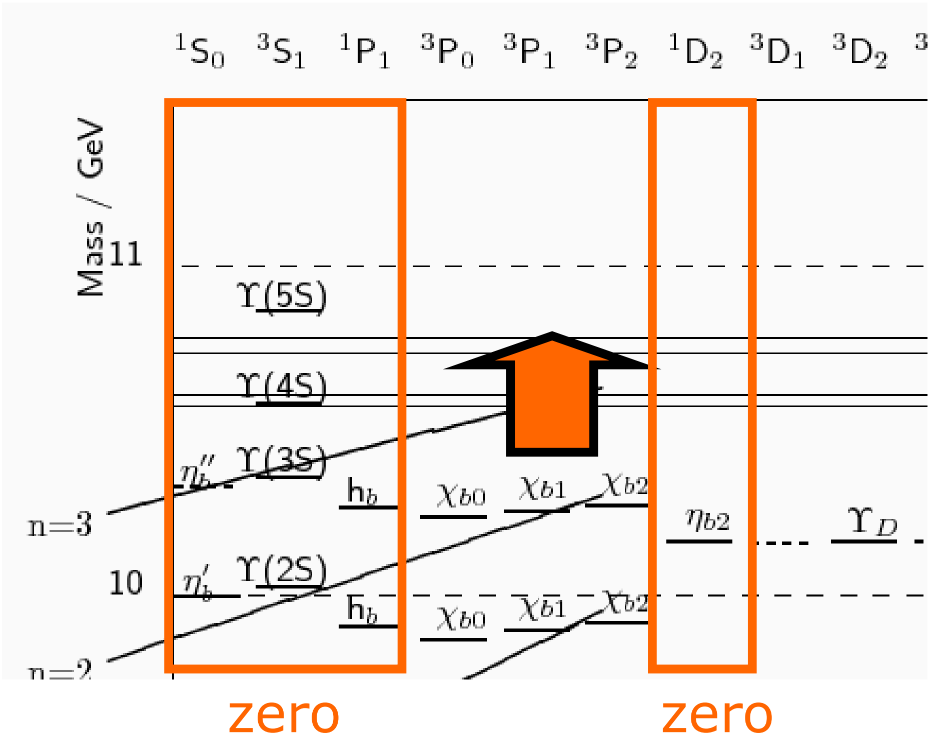
$\bar{q}q$ Potential
with fine structure and hyperfine structure

$$
\begin{aligned}
V(r) \;=\; & -\frac{4}{3}\frac{\alpha_s}{r} + kr \\
& + \frac{32\pi\alpha_s}{9m_c^2}\delta_r \vec{S}_c \vec{S}_{\overline{c}} \\
& + \frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S} \\
& + \frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\overline{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\overline{c}}\right)
\end{aligned}
$$

tensor term

Precision Test #1: Tensor Term in $\bar{q}q$ Potential

- treated as perturbation
- vanishes for
  S=0 (η_b, Y, h_b, ...)
  L=0 ($^1D_2$,...)
- sign of potential term is positive
  $\rightarrow$ masses should be shifted up
- Simplified view:
  wavefunction of h_c (h_b) at r=0
  is not vanishing



Result:

State	$h_b(1P)$	$h_b(2P)$
$\Delta M_{\rm HF}$, MeV	1.7 ± 1.5	$+0.5^{+1.6}_{-1.2}$

compared to 0.00 ± 0.15 MeV for the $h_c(1P)$

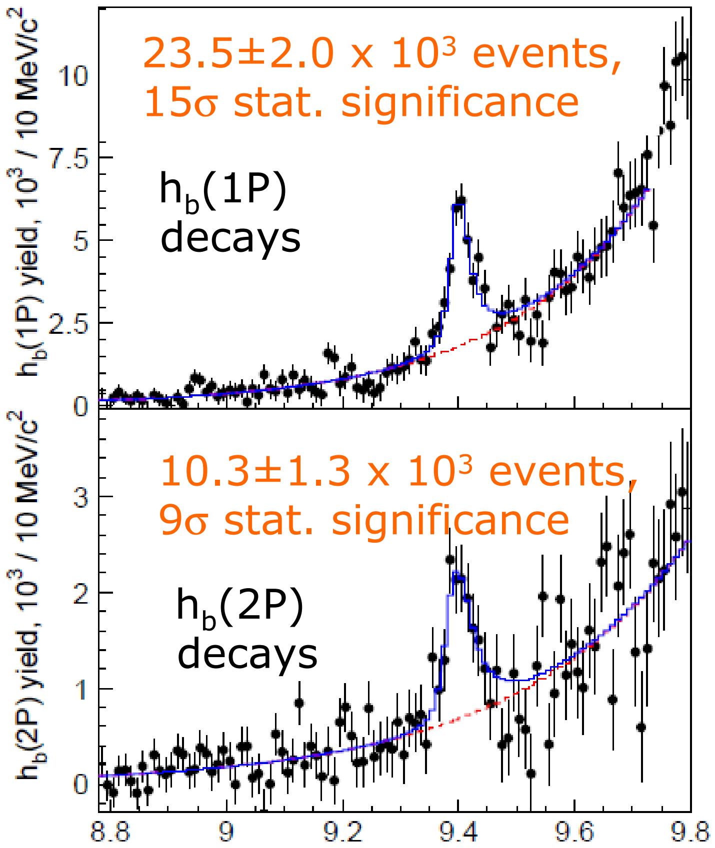
One step further:

$$h_b \to \eta_b \, \gamma$$

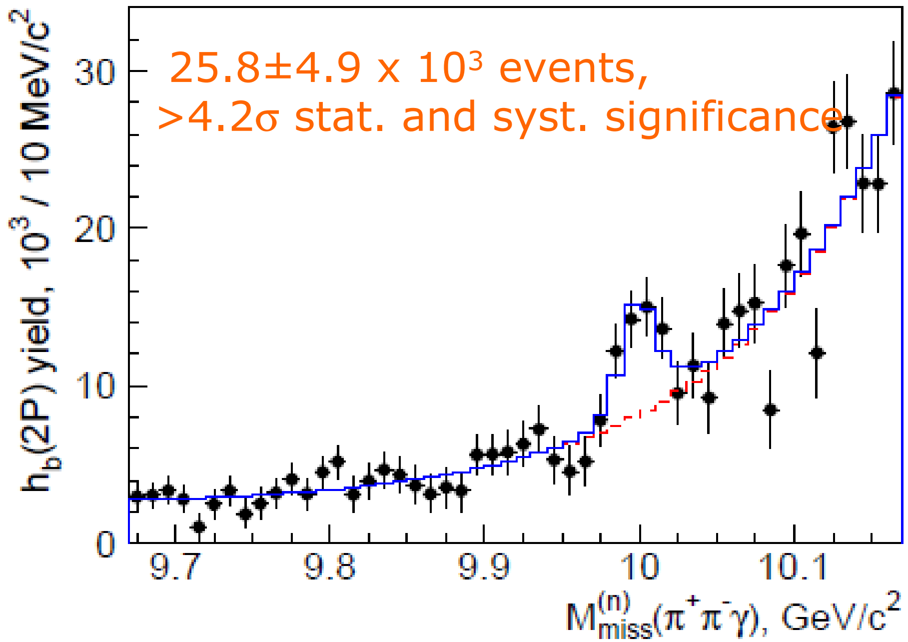
- With 50k events of $h_b(1P)$ and 84k of $h_b(2P)$
- Reminder: $\eta_b(1S)$ only known for 3 years
  First observations by BaBar (2008, 2009) and CLEO (2010)
- In addition, search for $\eta_b(2S)$

$\eta_b(1S)$ and evidence for $\eta_b(2S)$

State	Mass, MeV	Width, MeV
$\eta_b(1S)$	$9402.4 \pm 1.5 \pm 1.8$	$10.8^{+4.0+4.5}_{-3.7-2.0}$
$\eta_b(2S)$	$9999.0 \pm 3.5^{+2.8}_{-1.9}$	< 24

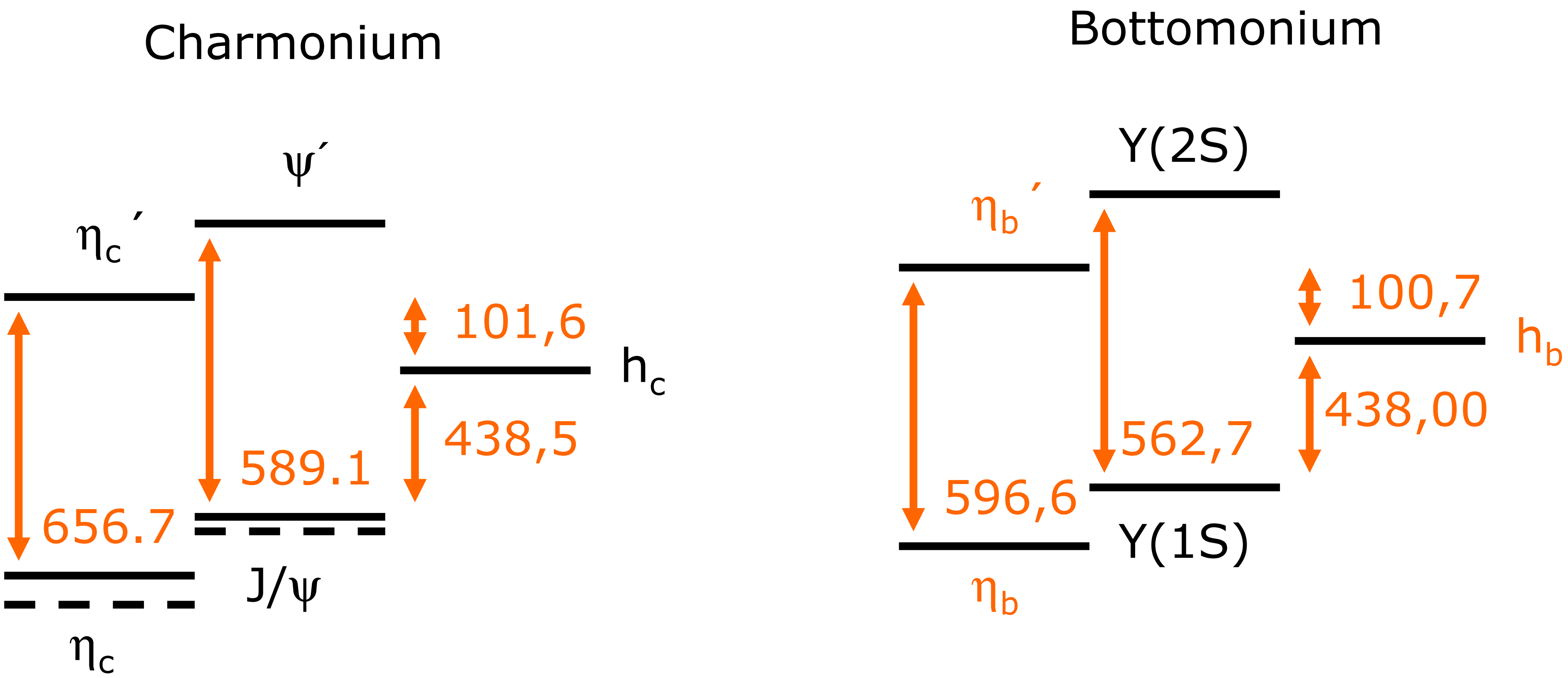


Belle, arXiv:1205.6351
subm. Phys. Rev. Lett.
133.4 fb^{-1}



Precision Test #2:
Flavour Independance of $\bar{q}q$ Potential
Are the level spacings the same?

e.g. C. Quigg, hep-ph/9707493



Excellent agreement for h states (S=0,L=1)
Poor agreement for the ground states (S=0, L=0)
Mixing η, η', η_c ? Gluonic component?

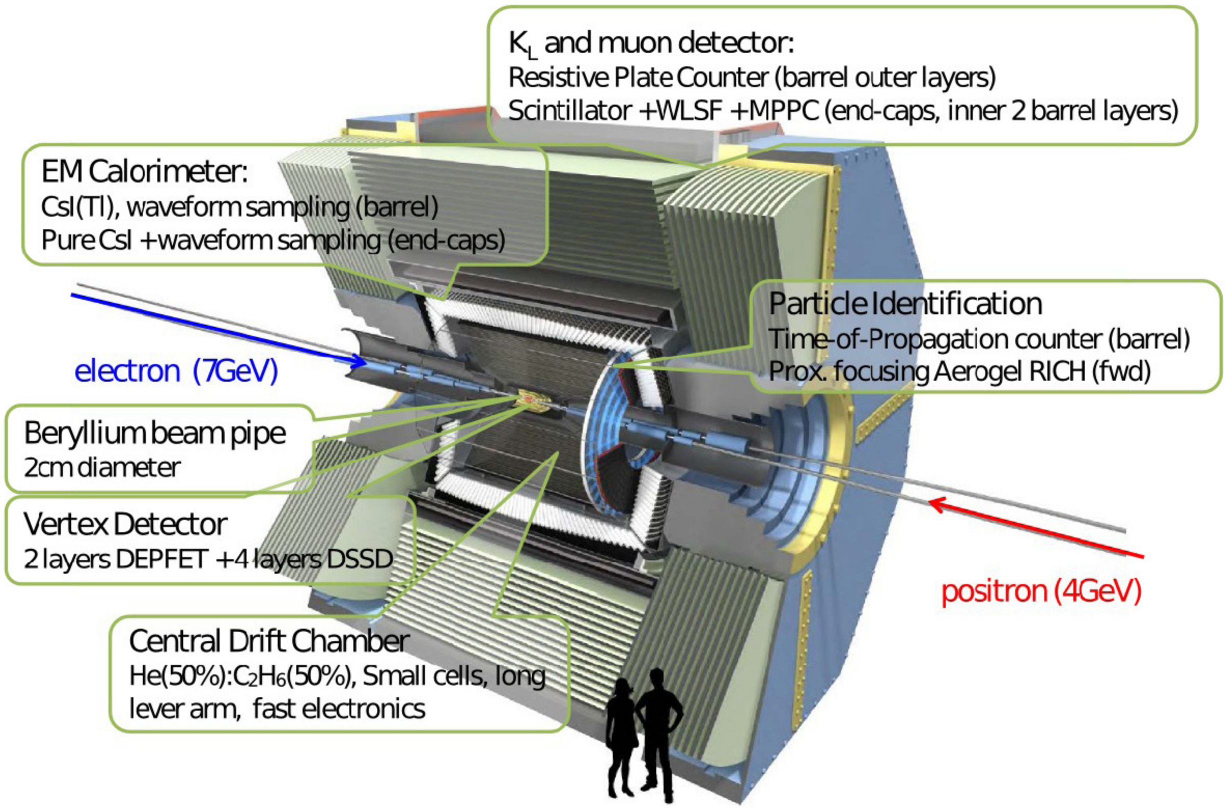
The Future:
Measurement of Widths in Sub-MeV Region

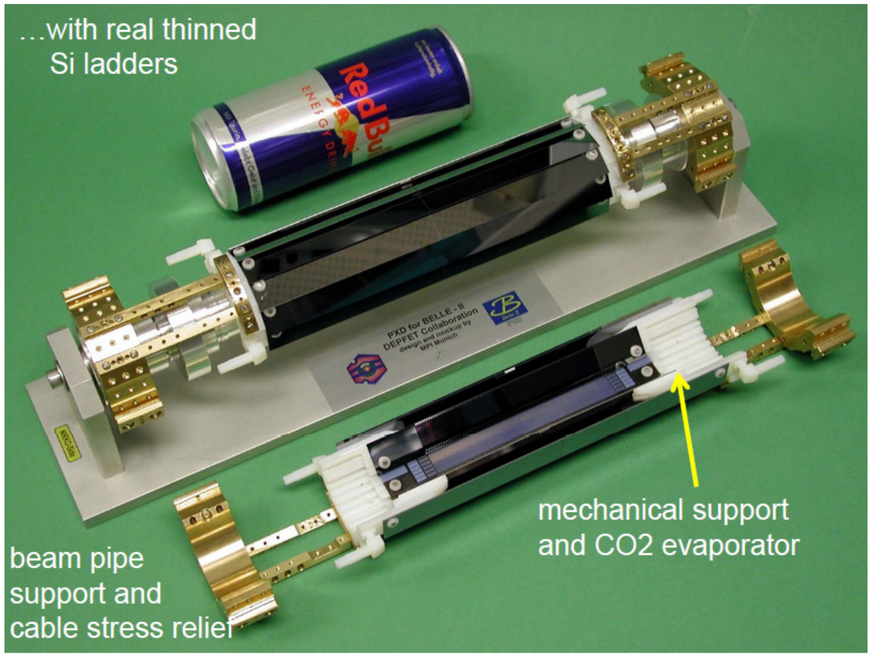
Belle II, first beams planned 2015
(SuperB Italy $\rightarrow$ see talk by K. Flood, TUE 15:10)

PANDA, first beams planned 2018

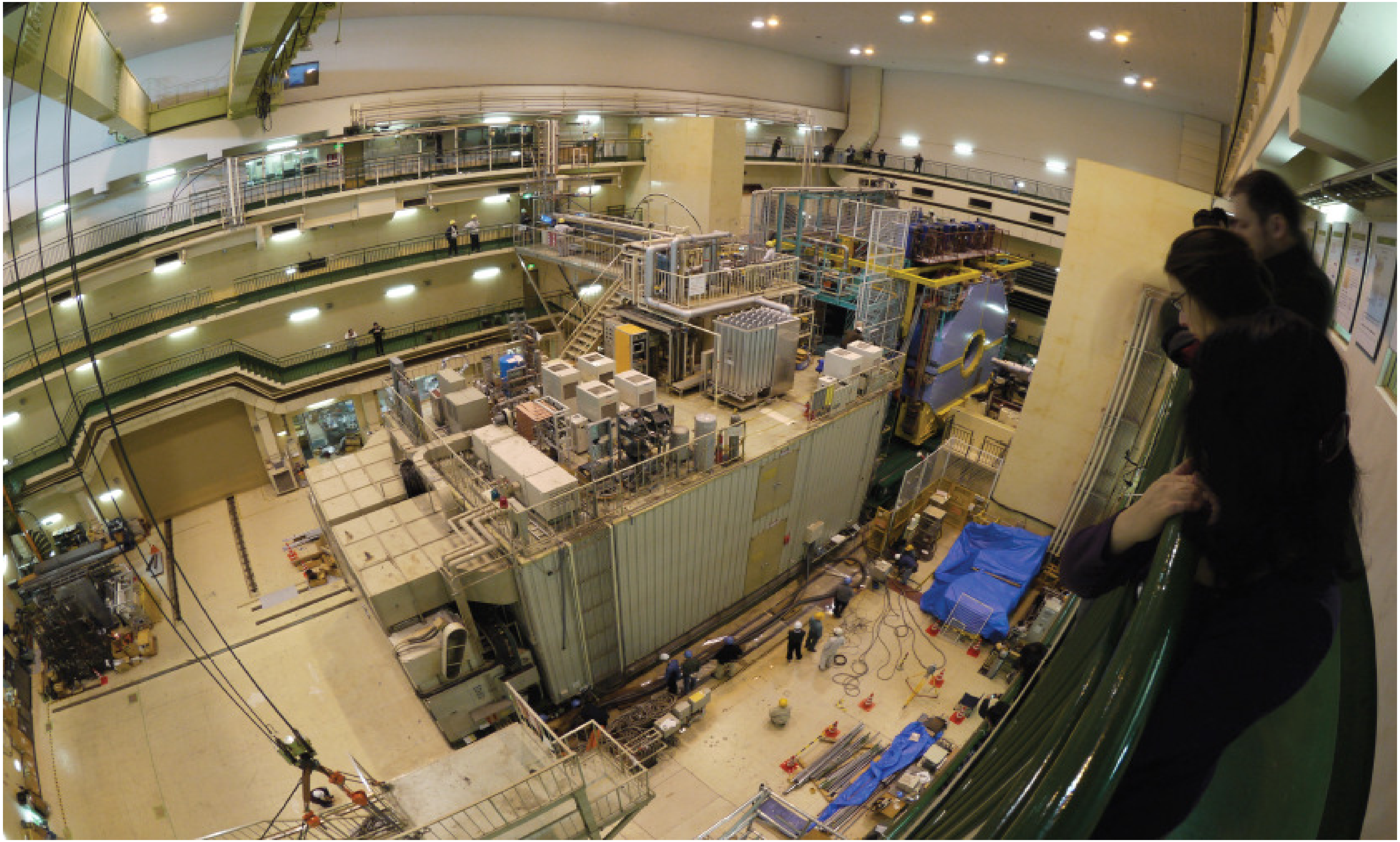
Belle-II and Super-KEKB

- Luminosity x 40 ($8x10^{35}$ cm^{-2} s^{-1})
- Data Set x 50 (plan 50 ab^{-1} by ·2021)
- Groundbreaking Ceremony: Nov 18, 2011
- Technical Design Report, arXiv:1011.0352
- Several new detectors, e.g. 2-layer DEPFET Pixel Detector
  vertex resolution $\Delta z \geq 20\ \mu m$ for p>1 GeV/c

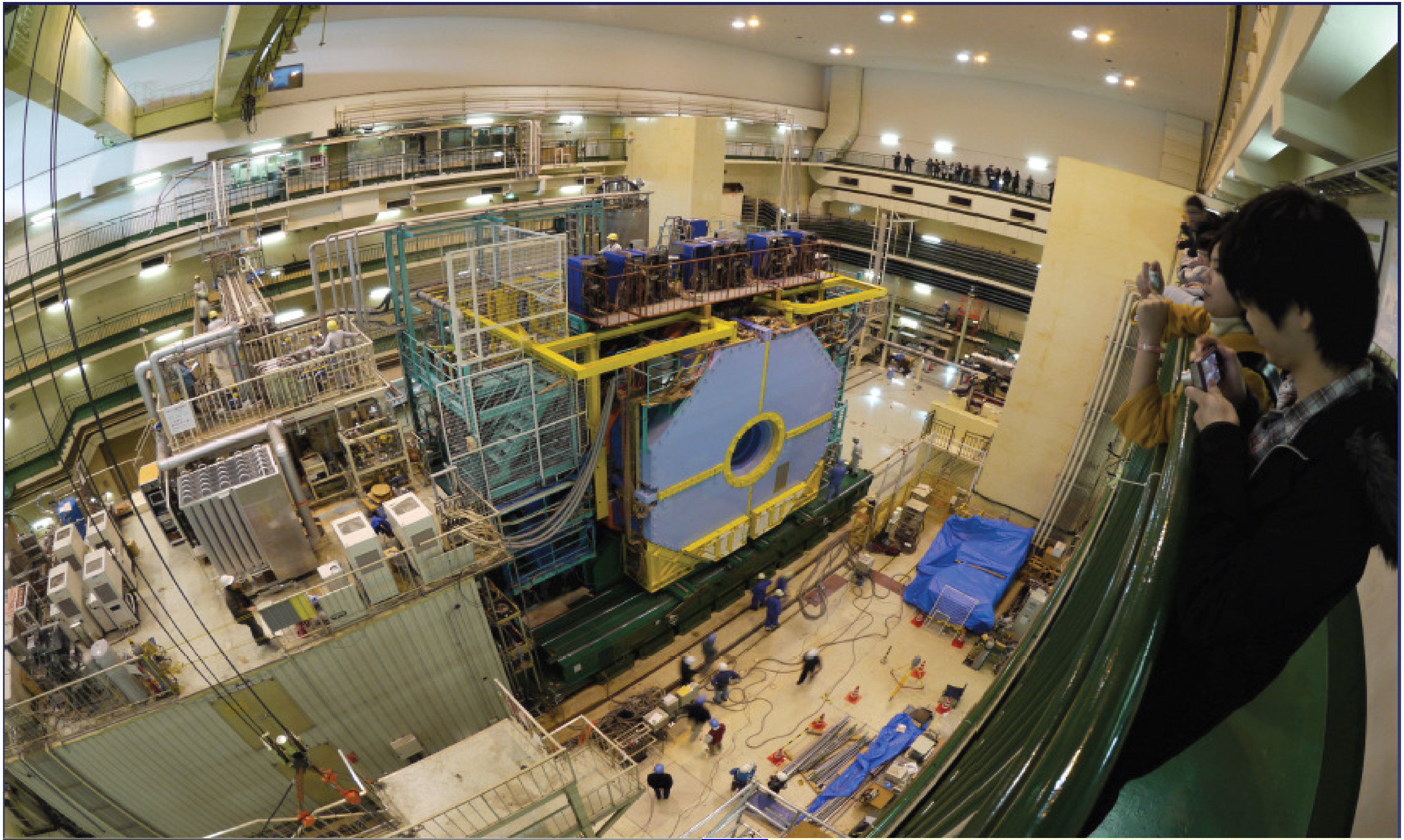




Belle Rollout, 09.12.2010

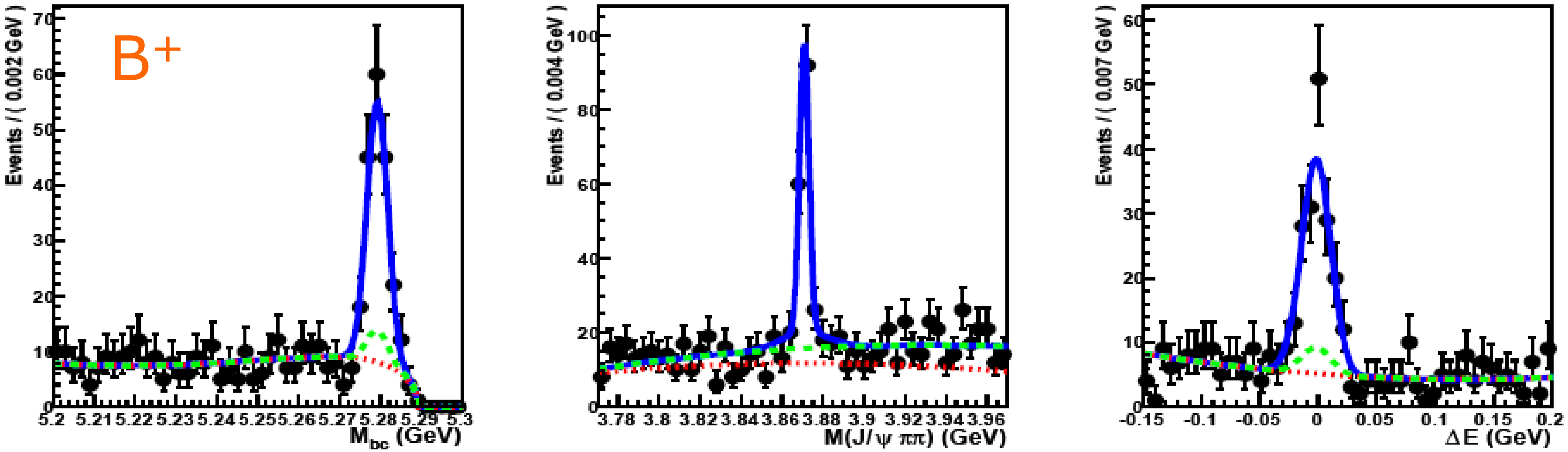


Belle Rollout, 09.12.2010



X(3872) Width Measurement at Belle

$M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$ X(3872) $\to J/\psi\, \pi^+ \pi^-$ $\Delta E \equiv E_B^{cms} - E_{beam}^{cms}$

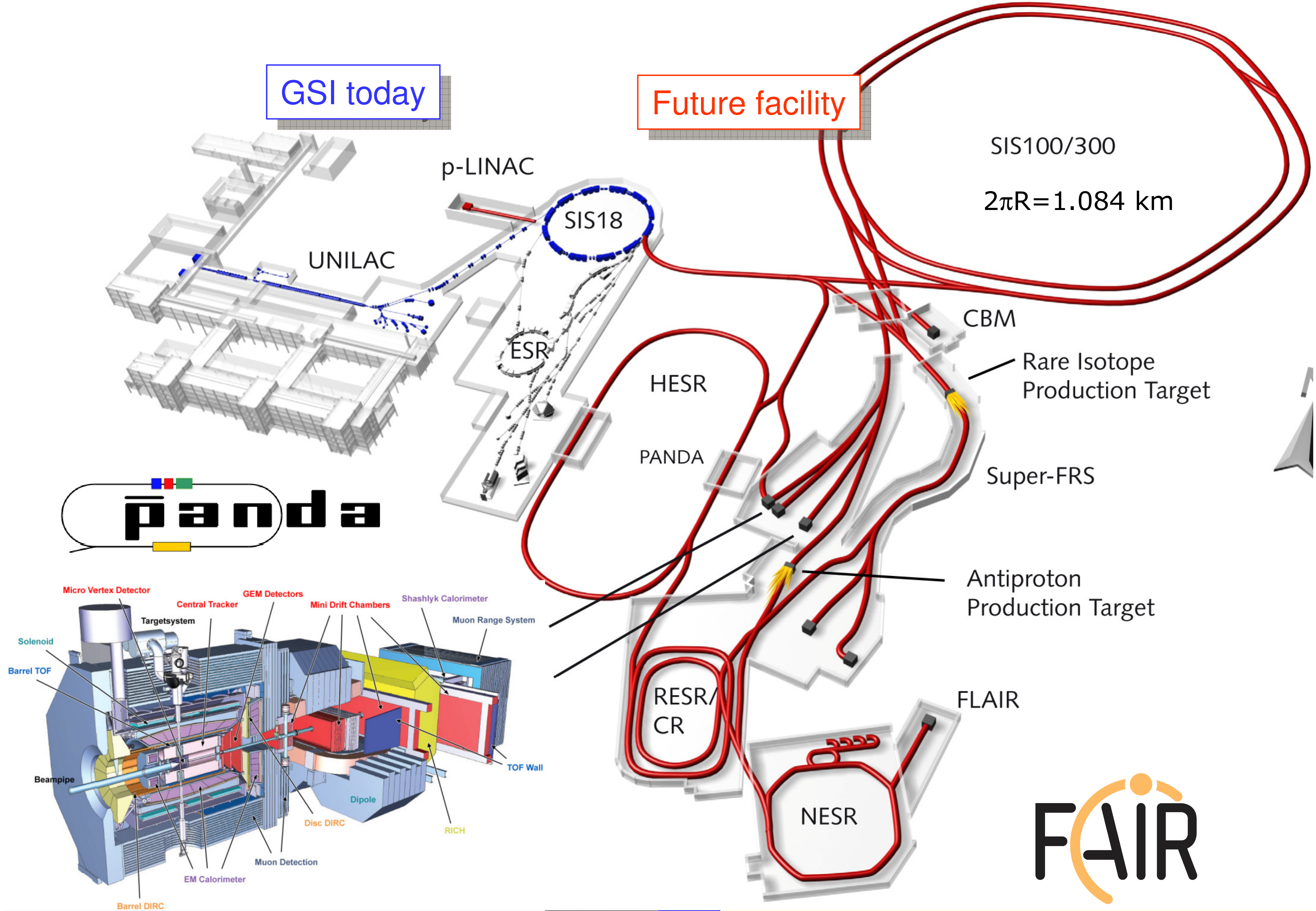


M_{BC} /GeV M($J/\psi\, \pi^+ \pi^-$)/GeV ΔE/GeV

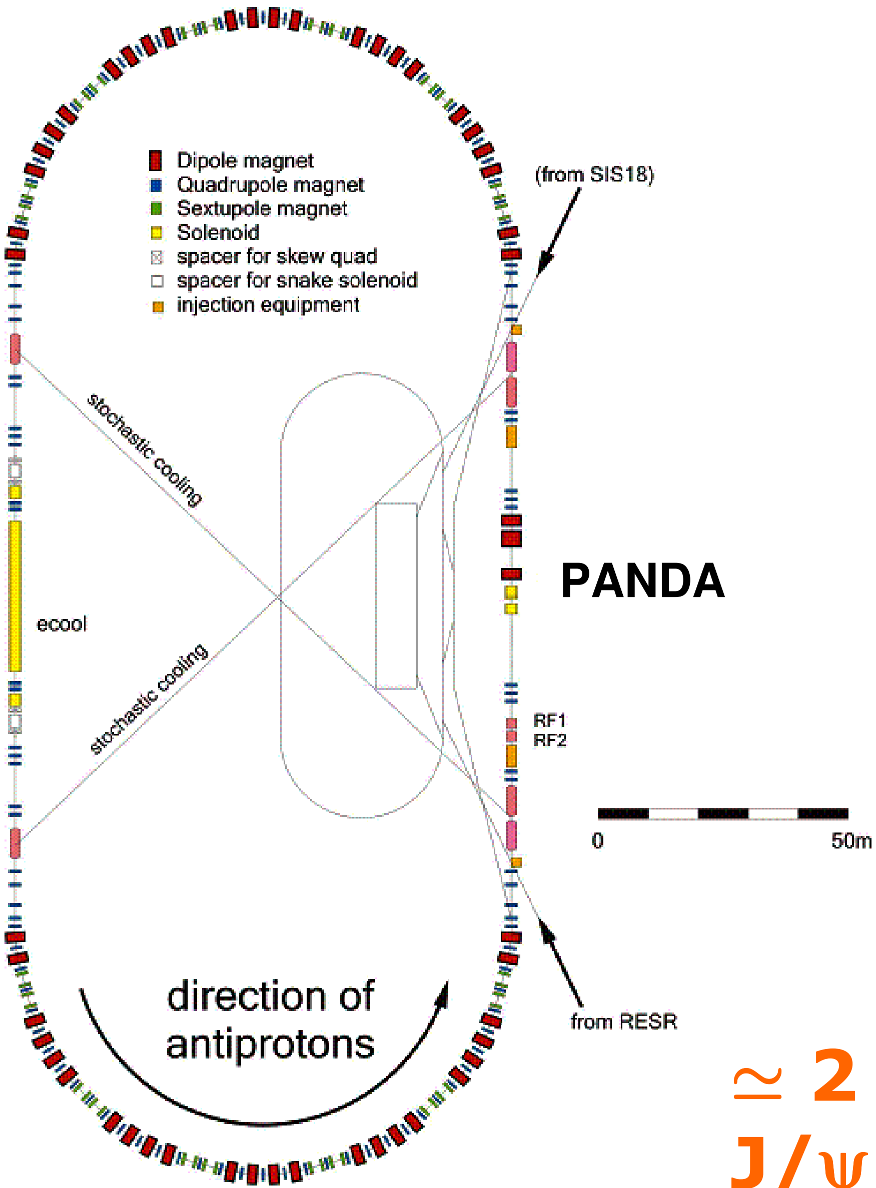
3-dim fit → kinematical over-constraint provides access to observables smaller than detector resolution

upper limit on width $\Gamma_{X(3872)} < 1.2$ MeV (90% C.L.)

Belle II: width measurement in X(3872) $\to J/\psi\gamma$
expected yield N $\simeq$ 1750
monoenergetic photon provides additional constraint
$\Gamma < 1$ MeV might be feasible


GSI today
Future facility
p-LINAC
SIS18
UNILAC
ESR
SIS100/300
2πR=1.084 km
CBM
Rare Isotope Production Target
HESR
PANDA
Super-FRS
Antiproton Production Target
RESR/ CR
FLAIR
NESR
FAIR
p̄anda
Micro Vertex Detector
Central Tracker
GEM Detectors
Mini Drift Chambers
Shashlyk Calorimeter
Targetsystem
Muon Range System
Solenoid
Barrel TOF
Beampipe
TOF Wall
Dipole
Disc DIRC
RICH
Muon Detection
EM Calorimeter
Barrel DIRC

Width measurement even smaller as 1 MeV?
HESR (High Energy Storage Ring)



Cooled Anti-Protons

High intensity mode

- $10^{11}\ \bar{p}$
- $\delta p/p \approx 10^{-4}$ (stochastic cooling)

High resolution mode

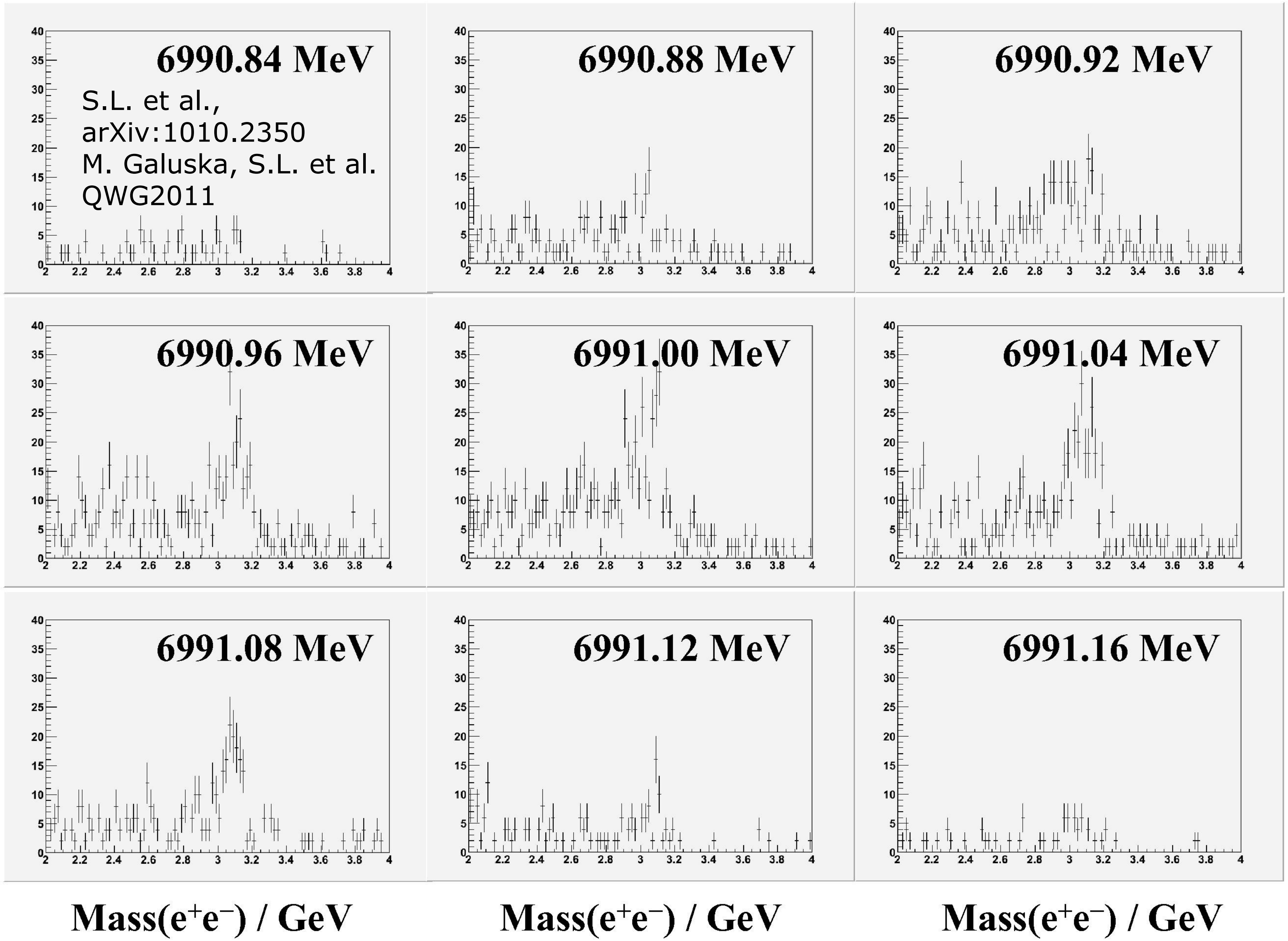
- $10^{10}\ \bar{p}$
- $\delta p/p \approx 10^{-5}$ (e^- cooling)

Internal targets

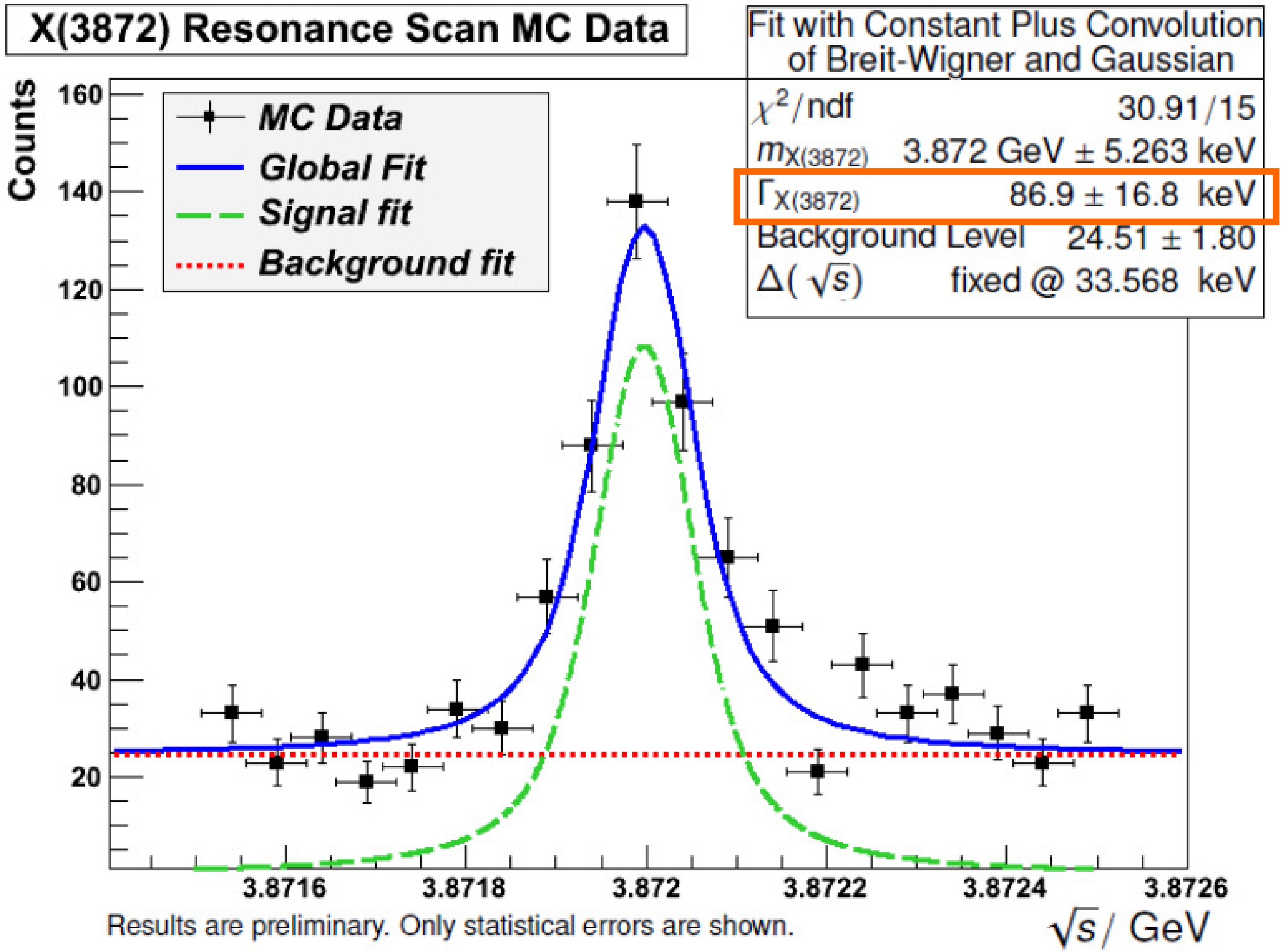
- $\mathcal{L} = 2 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Pellets
- Cluster jet
- Nuclei: Be, C, Si, Al

$\simeq$ 2 x 10^9 J/ψ per year

PANDA: detailed MC Simulation of X(3872) scan
Tagged J/ψ signal from $X(3872) \rightarrow J/\psi\, \pi^+ \pi^-$ decays



Input Width $\Gamma_{X(3872)}$=100 keV

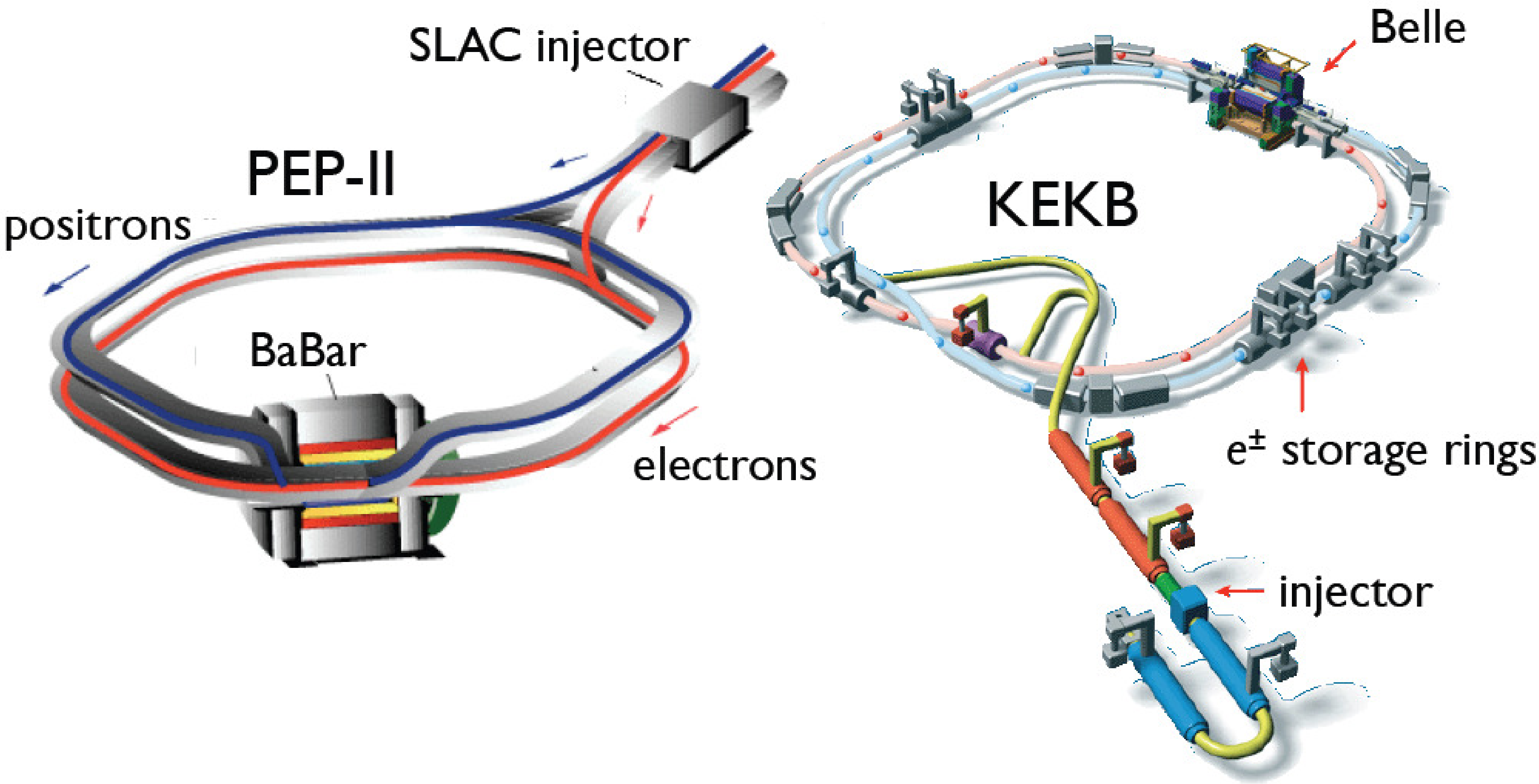


Summary

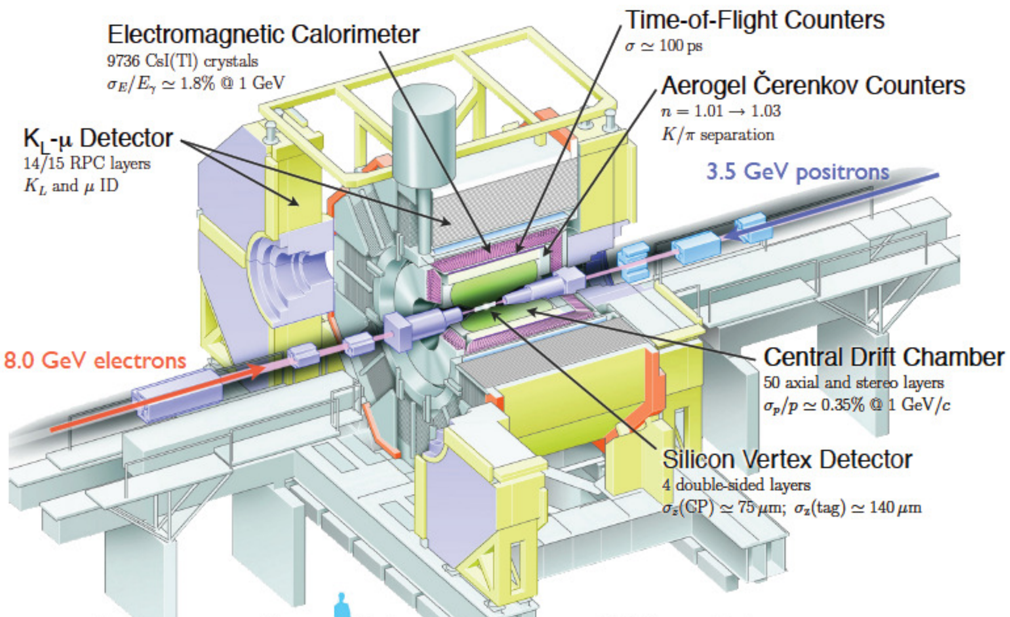
- $e^+ e^-$ colliders enable unique precision tests of the $\bar{q}q$ potential
- „simple“ potential model fails for many observations
  $\rightarrow$ clear indication of non-$\bar{q}q$ phenomena
- Future facilities (Belle II, PANDA) will provide precision tests not only of masses, but also widths (in sub-MeV region)

BACKUP

B Factories

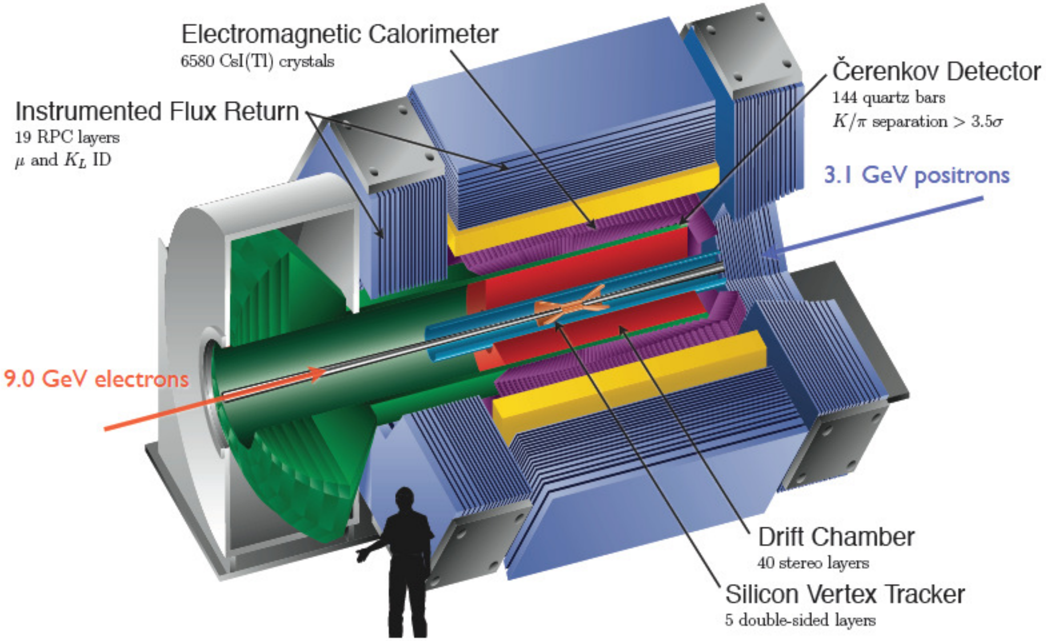

SLAC injector
PEP-II
positrons
BaBar
electrons
Belle
KEKB
e± storage rings
injector

Belle at KEKB



14 countries, 55 institutes, ~400 collaborators

BaBar at PEP-II

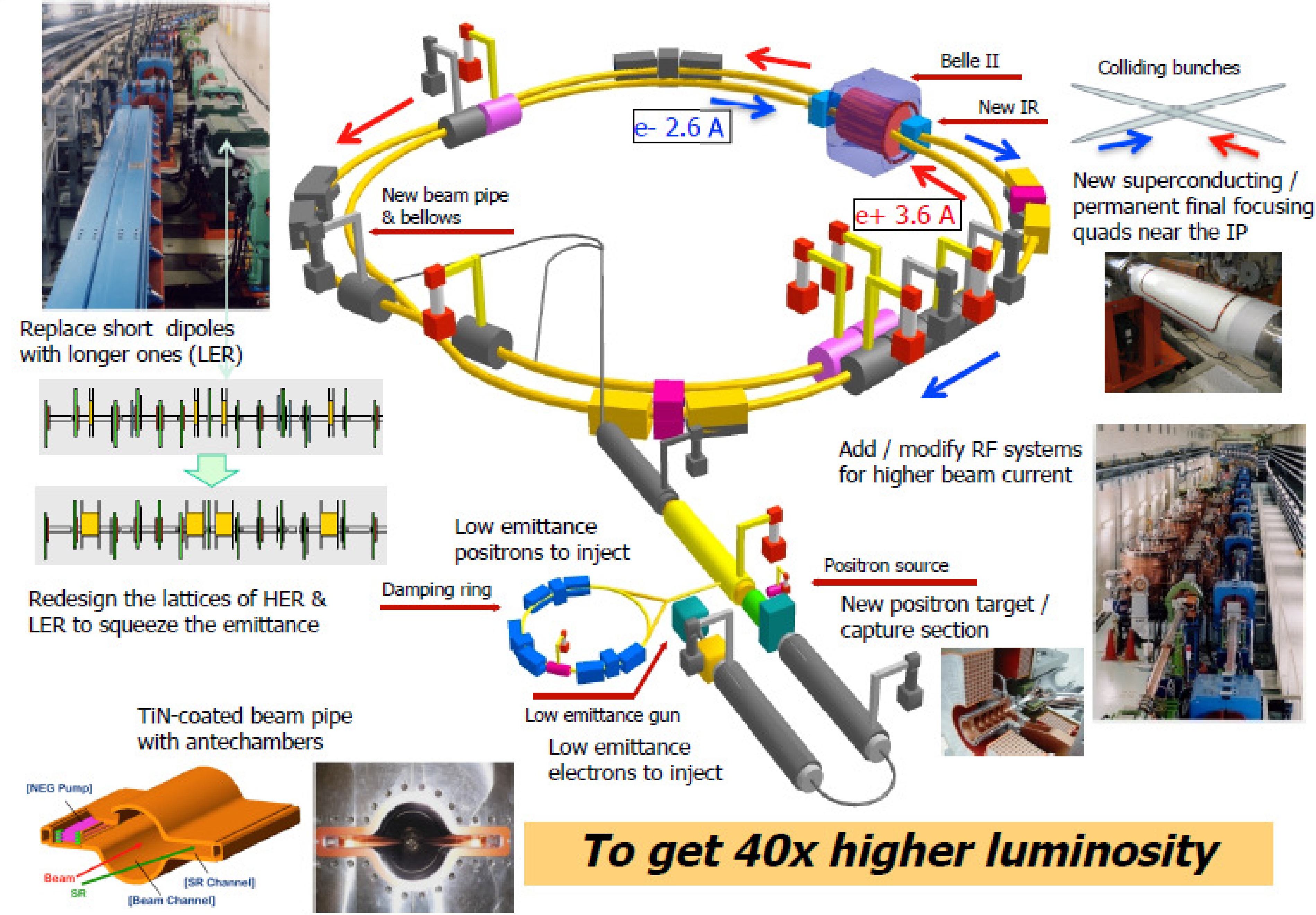


11 countries, 80 institutes, ~600 collaborators

$\geq$ **1000 /fb**
On-resonance samples:
Υ(4S): 711 /fb
Υ(5S): 121 /fb
Υ(3S): 3.0 /fb
Υ(2S): 24 /fb
Υ(1S): 5.7 /fb
Off-resonance: 87 /fb

~553 /fb
On-resonance samples:
Υ(4S): 433 /fb
Υ(3S): 30 /fb
Υ(2S): 14 /fb
Off-resonance: 54 /fb

KEKB → SuperKEKB (nano-beam)



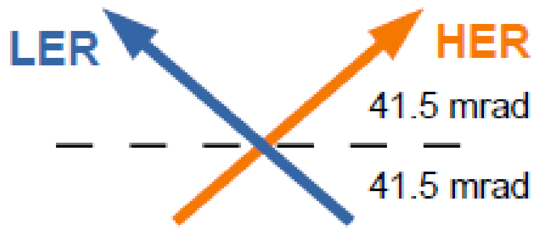
	KEKB Design	KEKB Achieved	SuperKEKB	
β^*_y [mm] (LER/HER)	10 / 10	5.9 / 5.9	0.27 / 0.3	x 20
ξ_y	0.052	0.129 / 0.090	0.0881 / 0.0807	
I_{beam} [A] (LER/HER)	2.6 / 1.1	1.64 / 1.19	3.6 / 2.6	x 2
$N_{bunches}$	5000	1585	2500	
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	80	x 40
σ^*_y [μm] (LER / HER)	1.9	0.84	0.048 / 0.059	
σ^*_z [mm] (LER / HER)	4	~7	6 / 5	

KEKB LER 3.5 GeV → **SuperKEKB** LER 4 GeV

KEKB HER 8 GeV → **SuperKEKB** HER 7 GeV

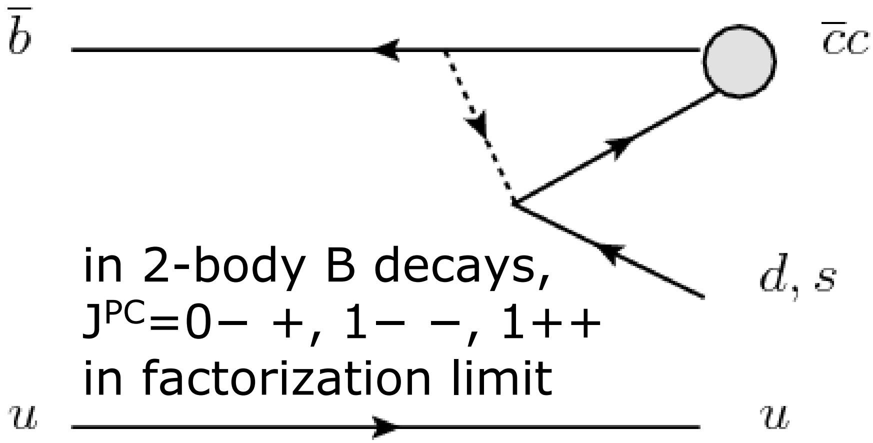
Center of Mass energy of 10.58 GeV stays the same

Crossing angle is increased to 83 mrad



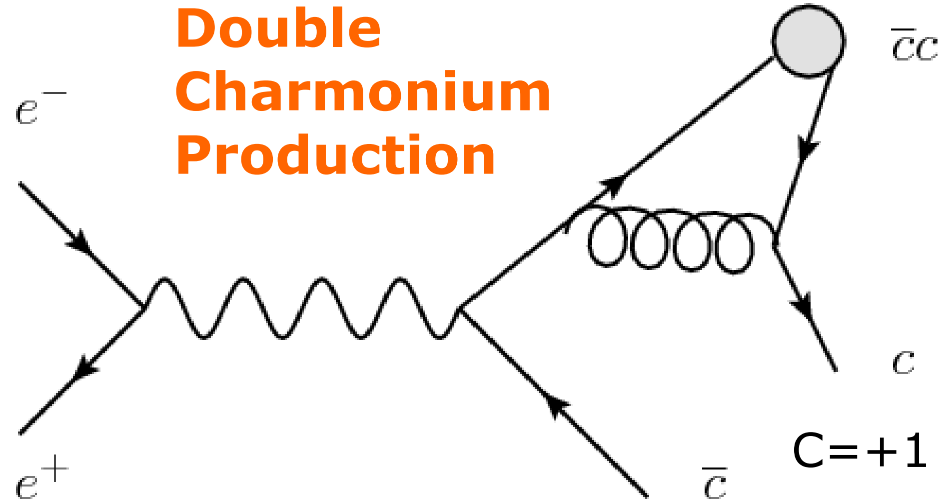
Production of Charmonium

B Decays



in 2-body B decays,
J^{PC}=0− +, 1− −, 1++
in factorization limit

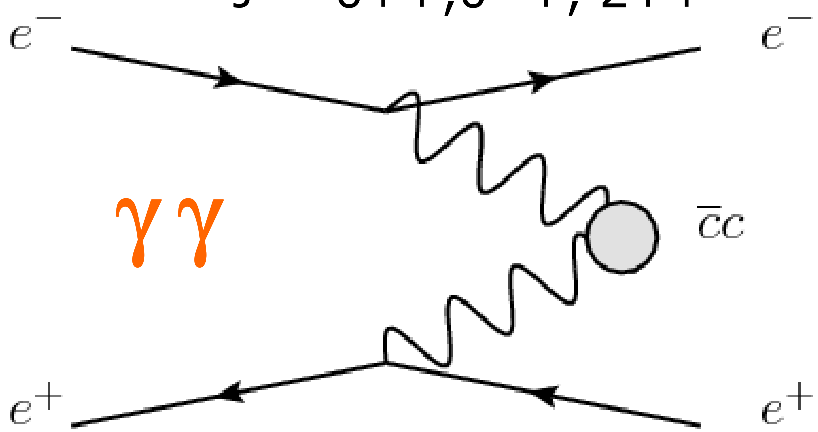
Double Charmonium Production



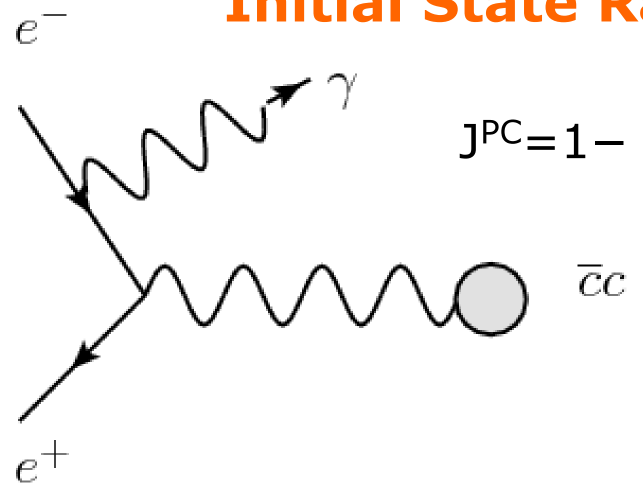
C=+1

γγ

J^{PC}=0++,0−+, 2++

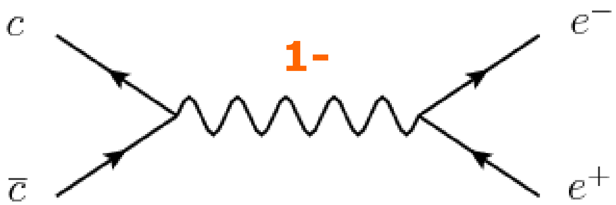


Initial State Radiation



J^{PC}=1− −

Decays of Charmonium States



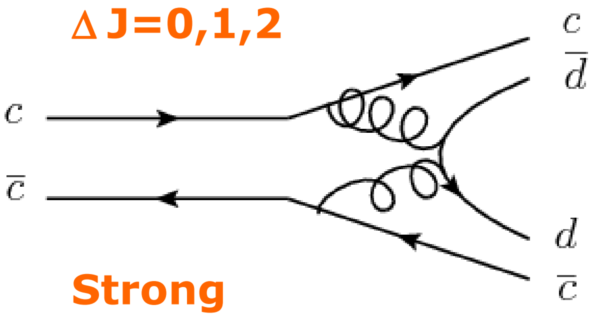
1-

EM

Annihilation

e.g. $J/\psi \to \pi^+ \pi^- \pi^0$
OZI suppressed

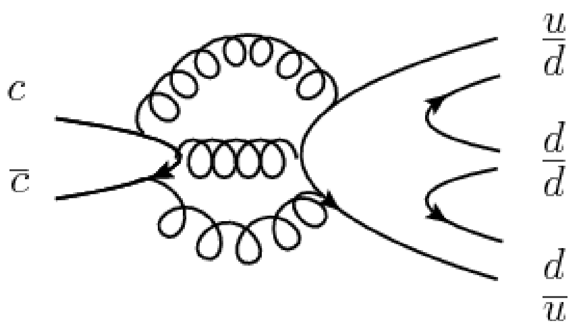
Δ J=0,1,2



$D^{o(*)}$

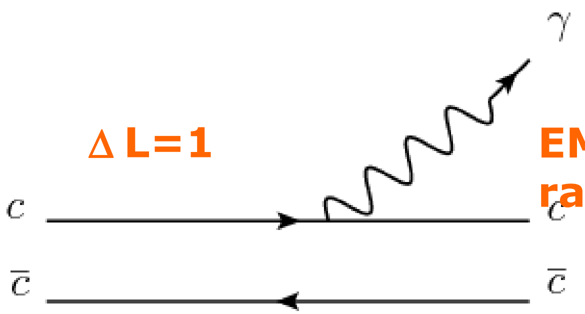
$\bar{D}^{o(*)}$

Strong



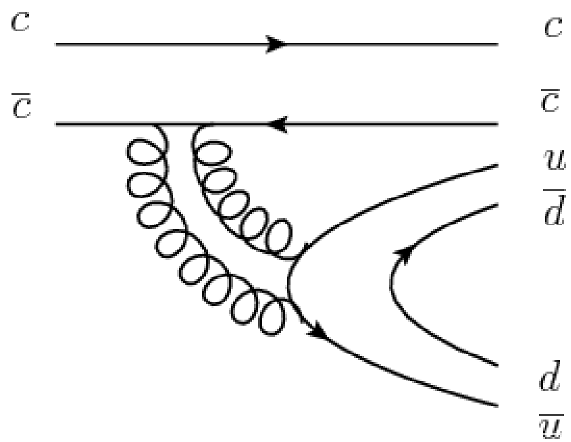
Strong
$\sim 1/\alpha_s^2$

Δ L=1



EM
radiative

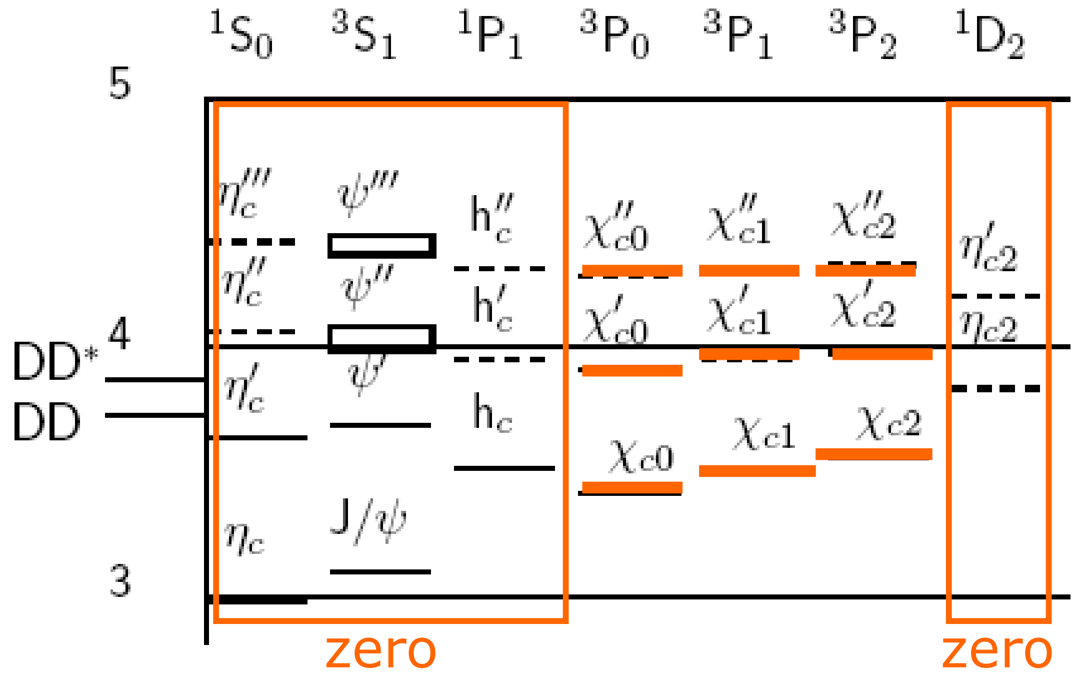
e.g. $\psi' \to \chi_{cJ}\, \gamma$



Strong
spectator
isospin
transition ?
(if $(\pi\pi)=\rho$)
$\sim 1/\alpha_s^2$
e.g. $\psi' \to J/\psi\, \pi^+ \pi^-$

	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

Tensor Term



- treated as perturbation
- has diagonal and non-diagonal elements
- vanishes for S=0
- vanishes for L=0
- same order of magnitude and same range as LS term

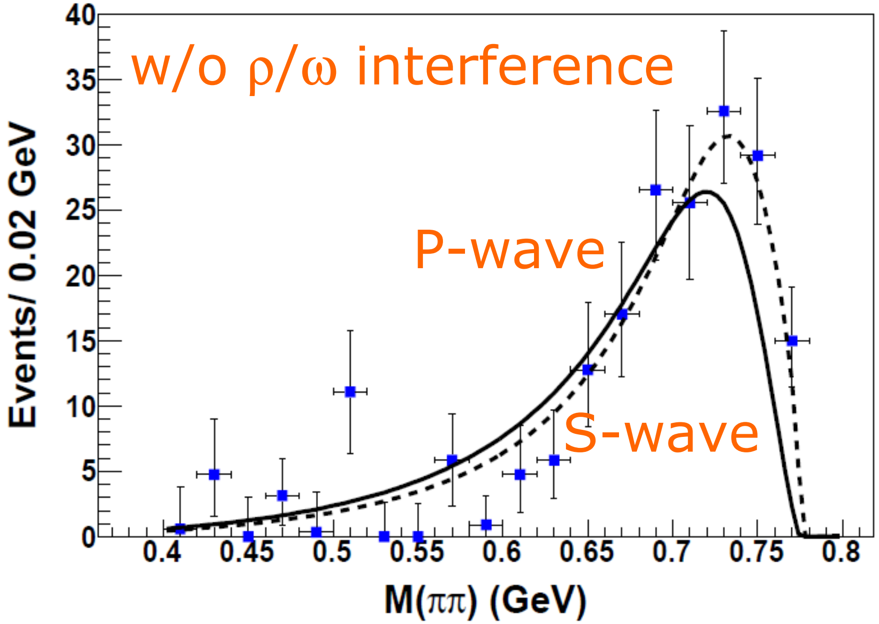
$$+\alpha_s \frac{j(j+1)-l(l+1)-S(S+1)}{m_q^2}\left\langle\frac{1}{r^3}\right\rangle+\alpha_s\frac{S_{12}}{3m_q^2}\left\langle\frac{1}{r^3}\right\rangle$$

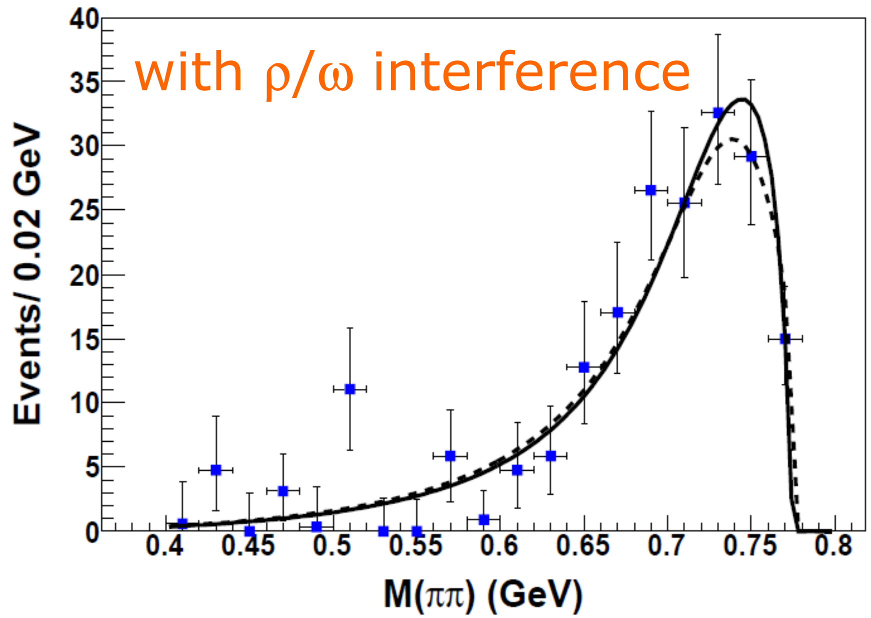
Among all the states used as input for potential model fit, only χ_{cJ} are shifted by tensor term.

j	l-1	l	l+1
S_{12}	$-\frac{2l+2}{2l-1}$	2	$-\frac{2l}{2l+3}$

Isospin Violation

- $X(3872) \to J/\psi\, \pi^+ \pi^-$ observation: $\pi^+\pi^-$ invariant mass peaks at ρ^0
- $X(3872) \to J/\psi \rho$ *(I=1)* violates isospin
- Reason?
  - mixing (ρ/ω) ?
  - u-d mass difference X(3872) can decay only into $\bar{D}^{0*}D^0$, [c$\bar{u}$] not in $D^{+*}D^-$, [c$\bar{d}$] (threshold is 8 MeV higher)
  - decay might be EM (photon $\to \pi^+ \pi^-$), not strong (2 gluon $\to \pi^+ \pi^-$) but should be suppressed

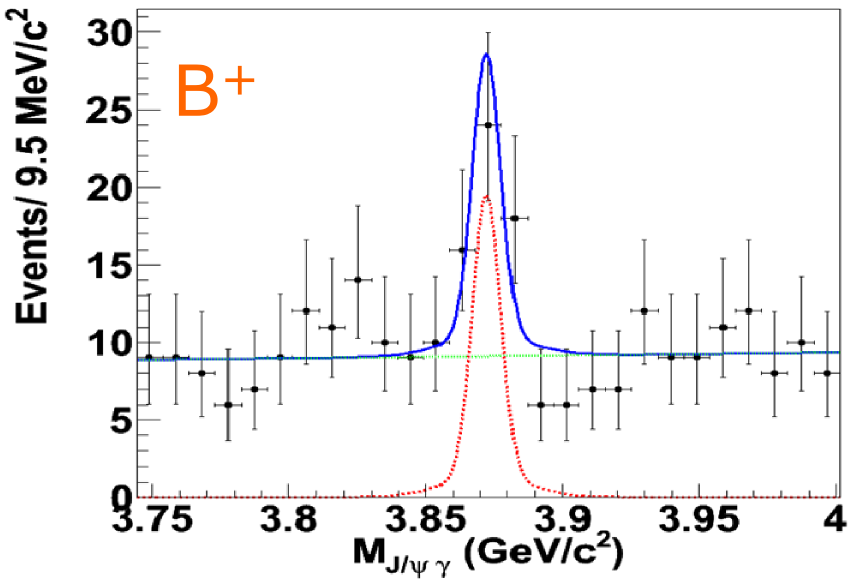


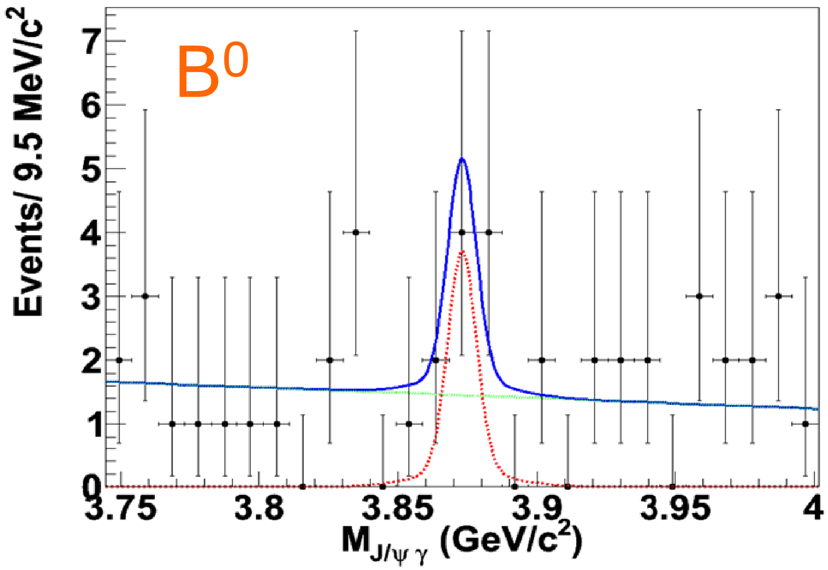


Charge Conjugation in radiative decays X(3872)→J/ψγ

Belle, Phys. Rev. Lett. 107(2011)091803

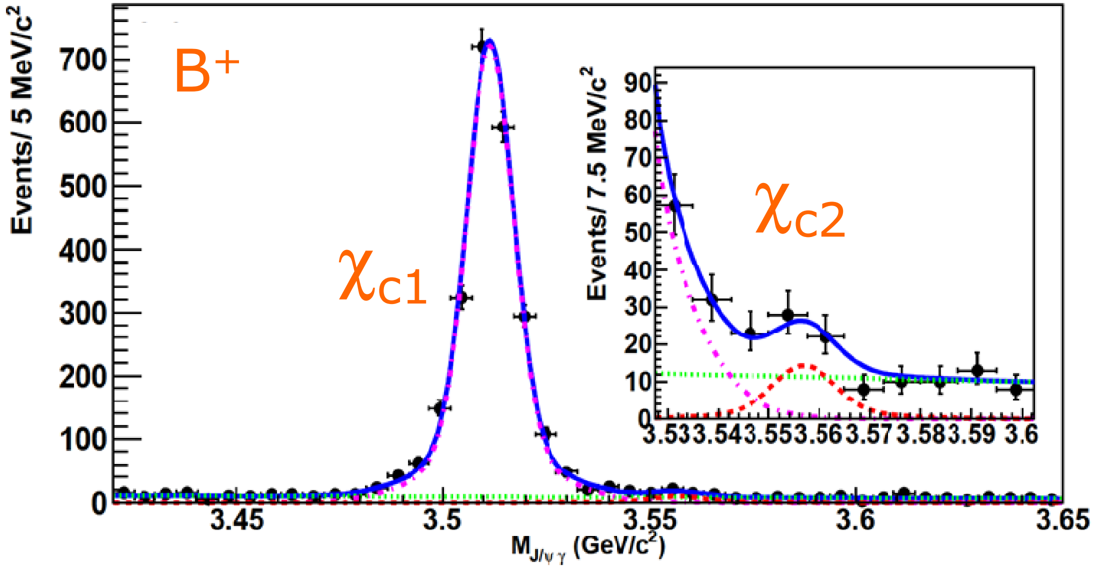
- $B^+ \to K^+ X(3872)$
  $30.0^{+8.2}_{-7.4}$ events (4.9σ)
  $B^0 \to K^0 X(3872)$
  $5.7^{+3.5}_{-2.8}$ (2.4σ)
- BR is factor 10 smaller than $X(3872) \to J/\psi\, \pi^+ \pi^-$
- small signal, but large implication: decay into two particles, which are identical with their anti-particles
- C=+1

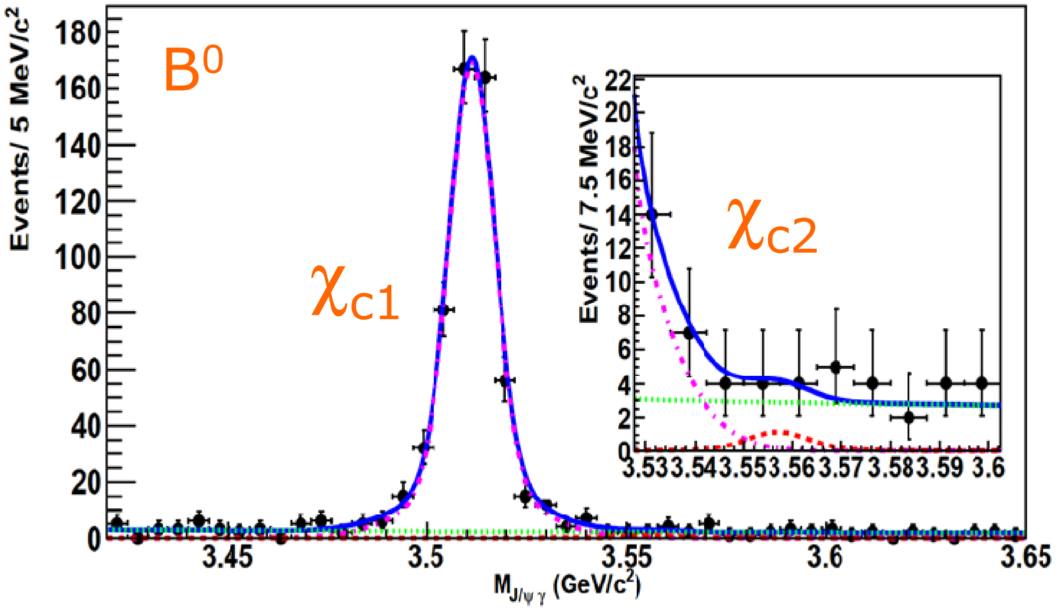




Control signal for X(3872) → $J/\psi\ \gamma$, Belle, arXiv:1105.0177 [hep-ex], subm. PRL

$B^{\pm} \rightarrow K^{\pm}\ \chi_{c1,2}$ with $\chi_{c1,2} \rightarrow J/\psi\ \gamma$





First Evidence for $B^{\pm} \rightarrow \chi_{c2}\ K^{\pm}$

$B^{+} \rightarrow K^{+}\ \chi_{c2}$

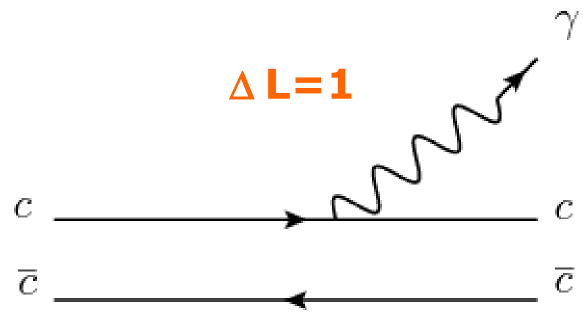
$32.8^{+10.9}_{-10.2}$ events

3.6σ (stat. and syst.)

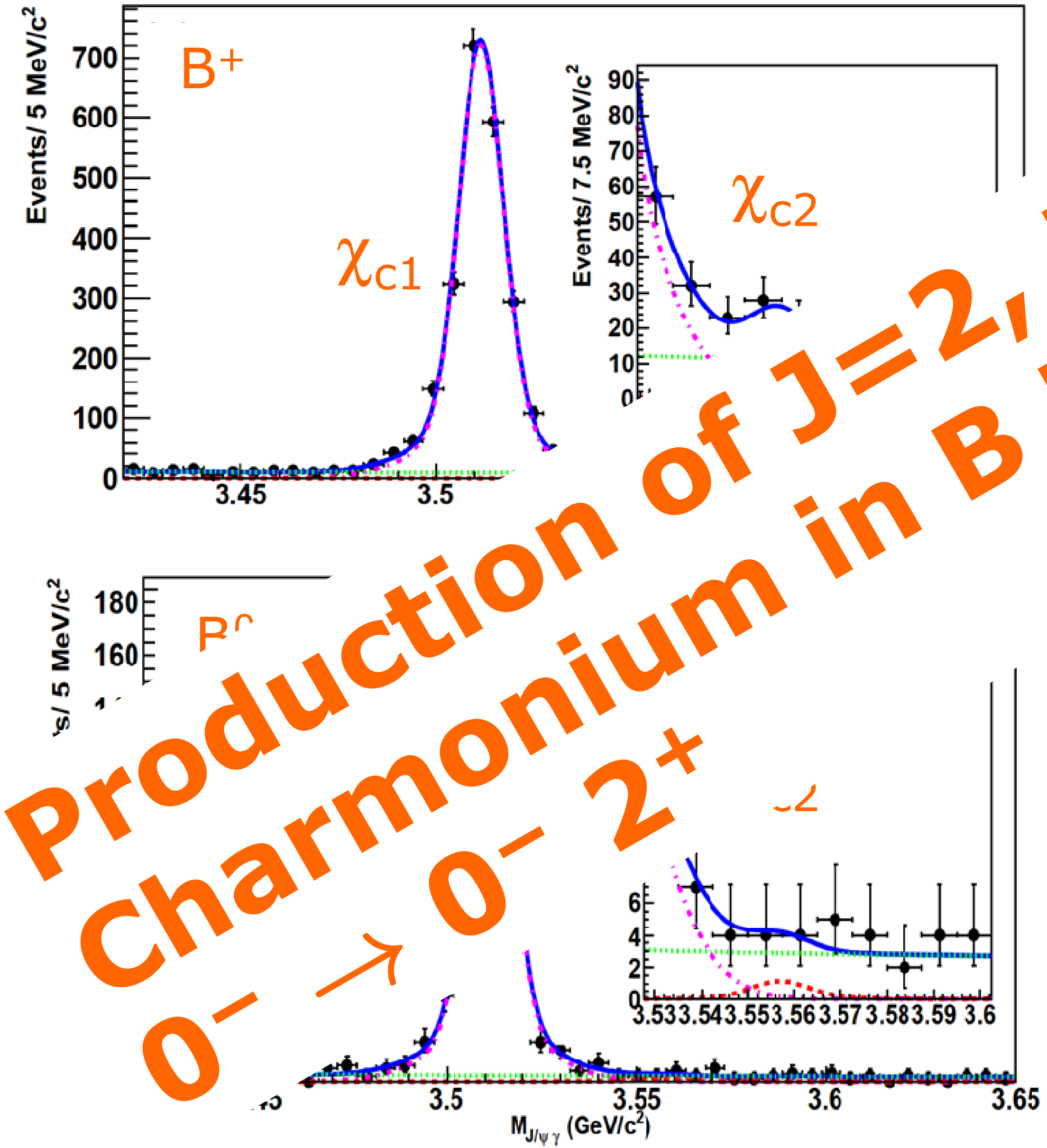
$B^{0} \rightarrow K^{0}\ \chi_{c2}$

$2.8^{+4.7}_{-3.9}$ events

0.7σ (stat. and syst.)



Same Analysis, but reference signal … ψγ



Production of J=2, Parity=+ Charmonium in B Meson Decays

$0^- \to 0^-\ 2^+$

Fi…

… events

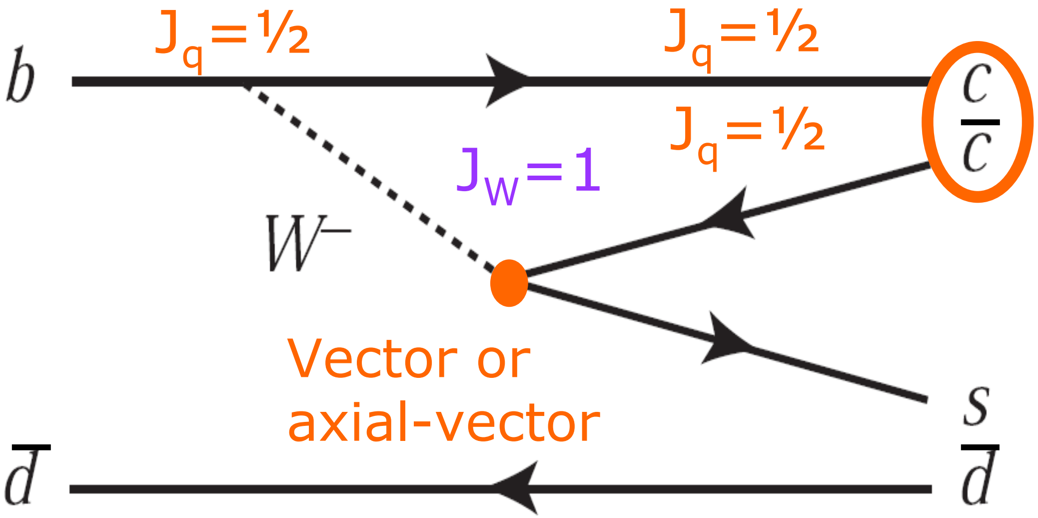
… and syst.)

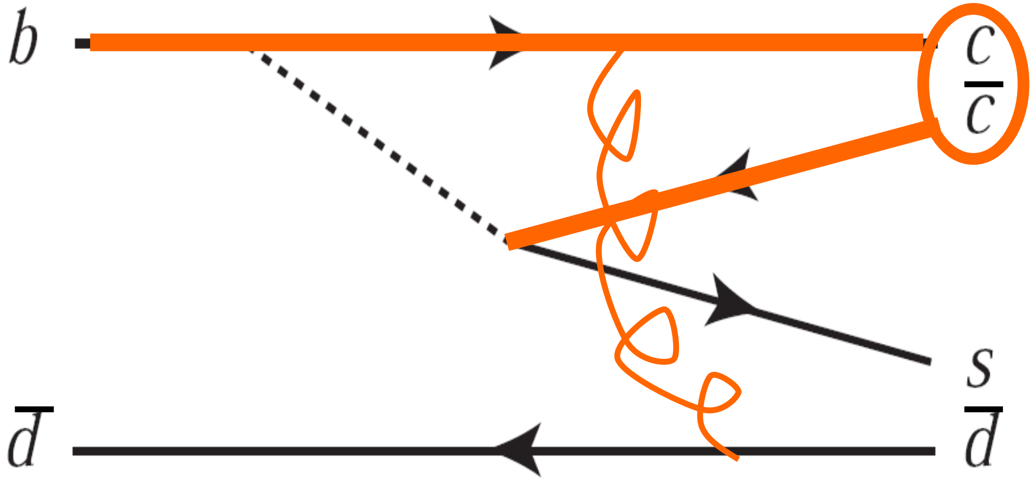
$B^0 \to K^0\ \chi_{c2}$

$2.8^{+4.7}_{-3.9}$ events

0.7σ (stat. and syst.)

$B^{\pm} \to K^{\pm} \chi_{c2}$





J=0 or J=1 preferred
J=2 difficult to be generated

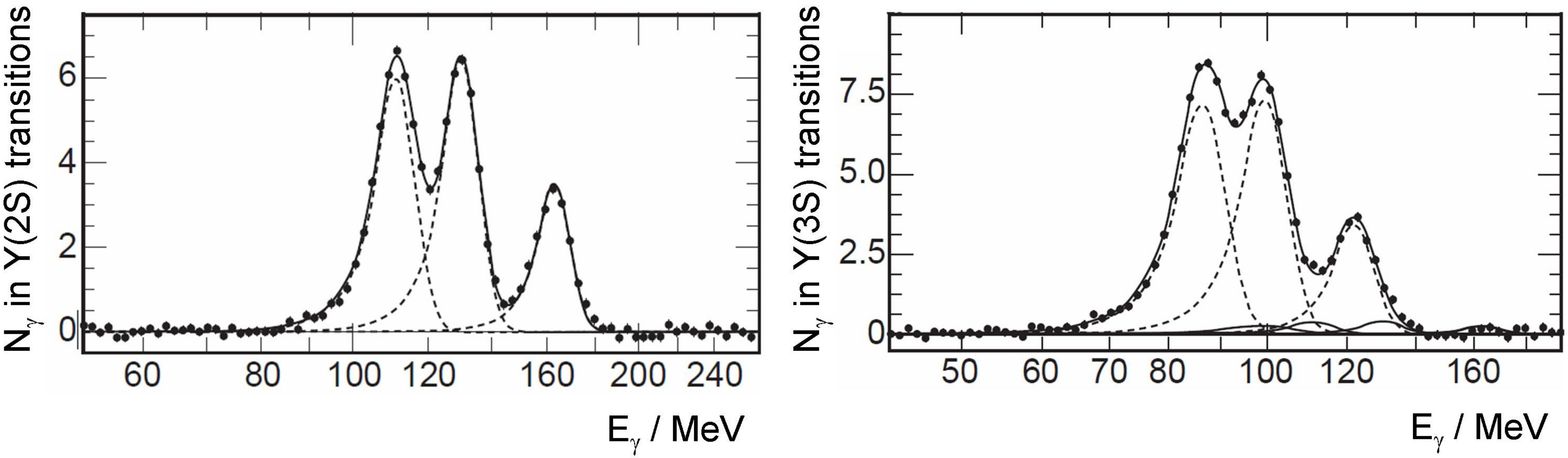
Parity + or parity − allowed

But parity +
forbidden in naïve factorization
additional soft gluon required

Bauer, Stech, Wirbel
Z. Phys. C34(1987)103

χ_b States, n=1 and n=2

CLEO Collaboration
Phys. Rev. Lett. 94(2005)032001

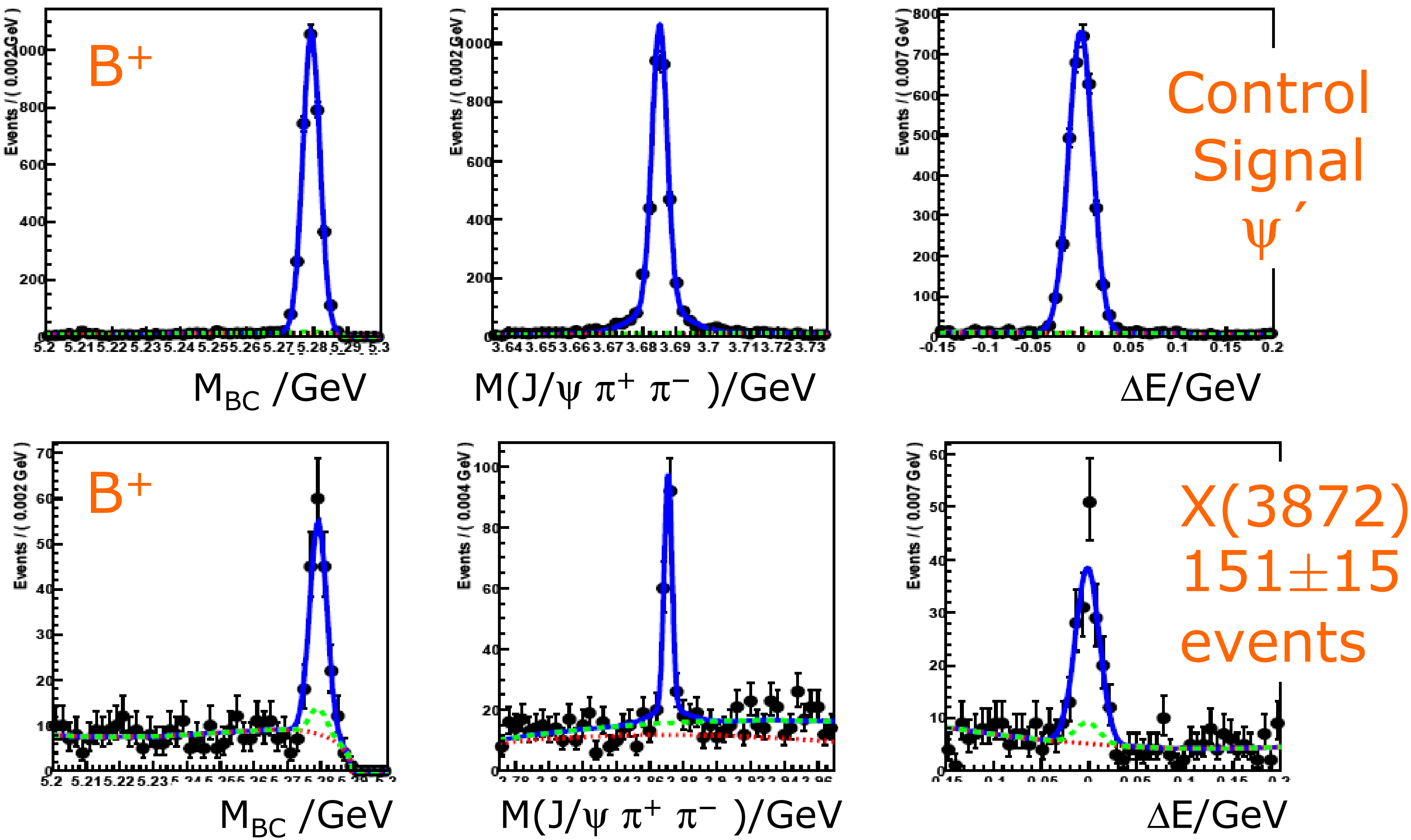


Analysis of X(3872) → J/ψ π+π− with final Belle Data Set, 711 fb^{-1}

Belle, Phys. Rev. D 84(2011)052004
arXiv:1107.0163 [hep-ex]

$$M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$$

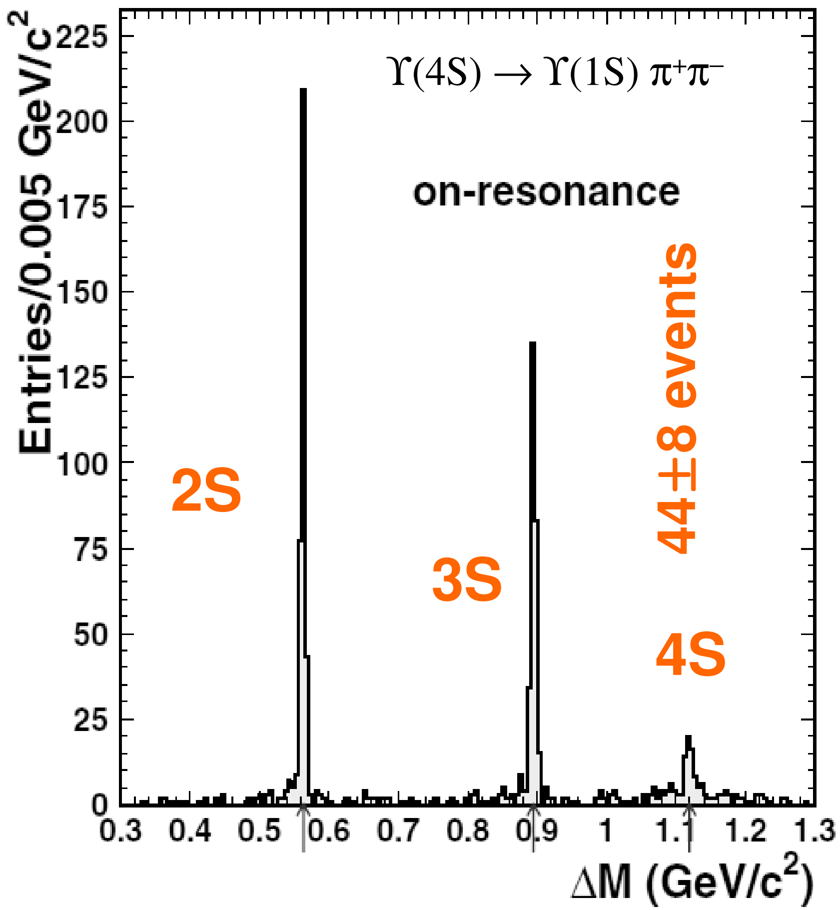
$$\Delta E \equiv E_B^{cms} - E_{beam}^{cms}$$



3-dim fit
with fixed resolution parameters from ψ´
Mass MC/data shift +0.92±0.06 MeV, measured and fixed from ψ´ mass

Γ[Υ(5S)→ππΥ(nS)] is huge

Υ(4S)→ππΥ(1S)
477 fb^{-1}

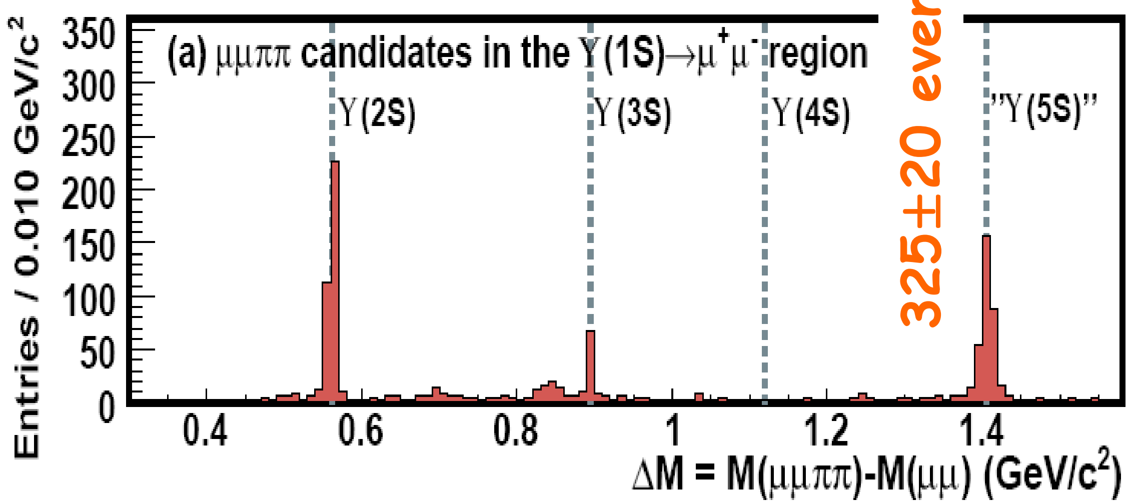


Phys. Rev. D75(2007)071103

8 times as many events integrated for Υ(nS)

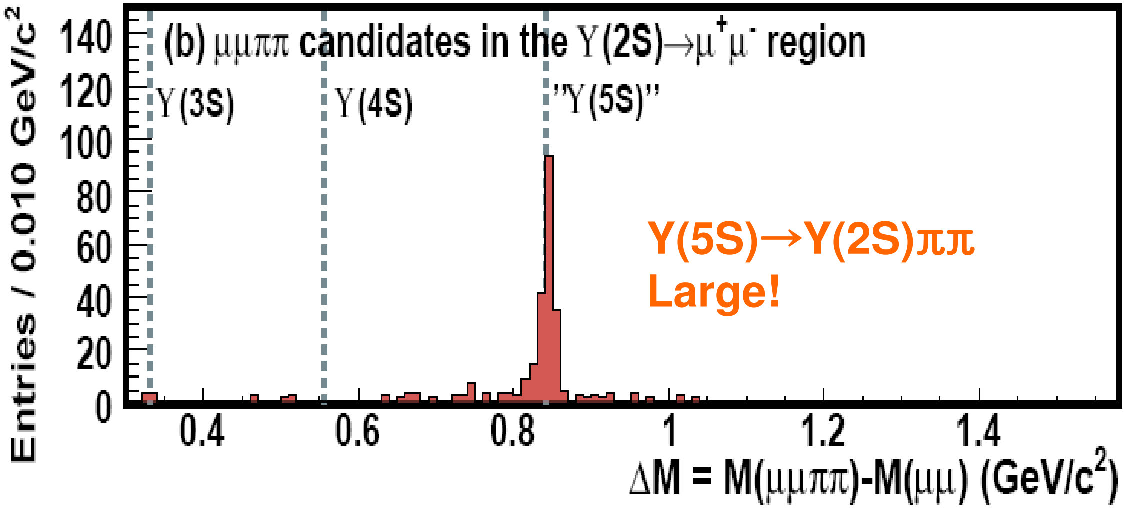
1/20 times the data & ~1/10th the crosssection

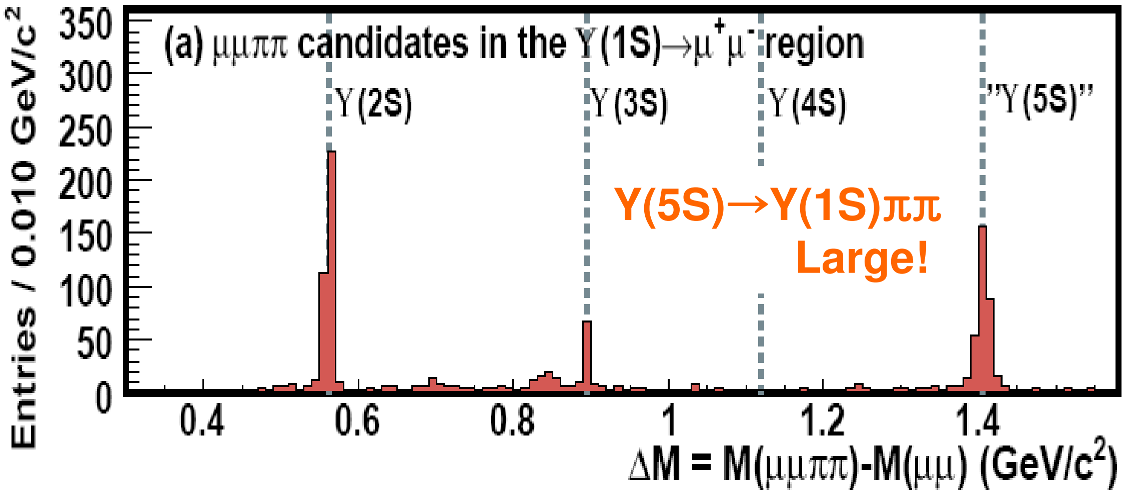
Υ(5S)→ππΥ(1S)
21.7 fb^{-1}



Belle Phys. Rev. Lett. 100, 112001 (2008)

Not only Υ(5S)→ Υ(1S)ππ is large, but also Υ(5S)→ Υ(2S)ππ





Is there a non-expected state near the Υ(5S) contributing to Υ(nS)ππ?

→ beam energy scan!

Beam Energy Scan, Dec 2007

Target Ecm [relative to 5S]	KEKB Ecm*	$\mathcal{L}$ (RunInfo)
10800[−69] MeV	10798.5 MeV	30.71/pb
10824[−45] MeV	10824.0 MeV	
10829[−40] MeV	10827.5 MeV	1615.22/pb
10844[−25] MeV	10844.0 MeV	
10854[−15] MeV	10852.5 MeV	30.70/pb
10844[−5] MeV	10864.0 MeV	
10869 MeV	10869.0 MeV	
10869 MeV	10871.0 MeV†	
10884[+15] MeV	10882.5 MeV	1745.28/pb
10884[+15] MeV	10884.0 MeV	
10891.5[+22.5] MeV	10889.5 MeV	30.76/pb
10899[+30] MeV	10897.5 MeV	1339.23/pb
10904[+35] MeV	10904.0 MeV	
10929[+60] MeV	10927.5 MeV	1074.67/pb
10959[+90] MeV	10957.5 MeV	945.84/pb
10989[+120] MeV	10987.5 MeV	30.53/pb
11019[+150] MeV	11017.5 MeV	792.04/pb

Υ(1S)$\pi^+\pi^-$

Υ(2S)$\pi^+\pi^-$

$\sqrt{s}$=10.8275 GeV

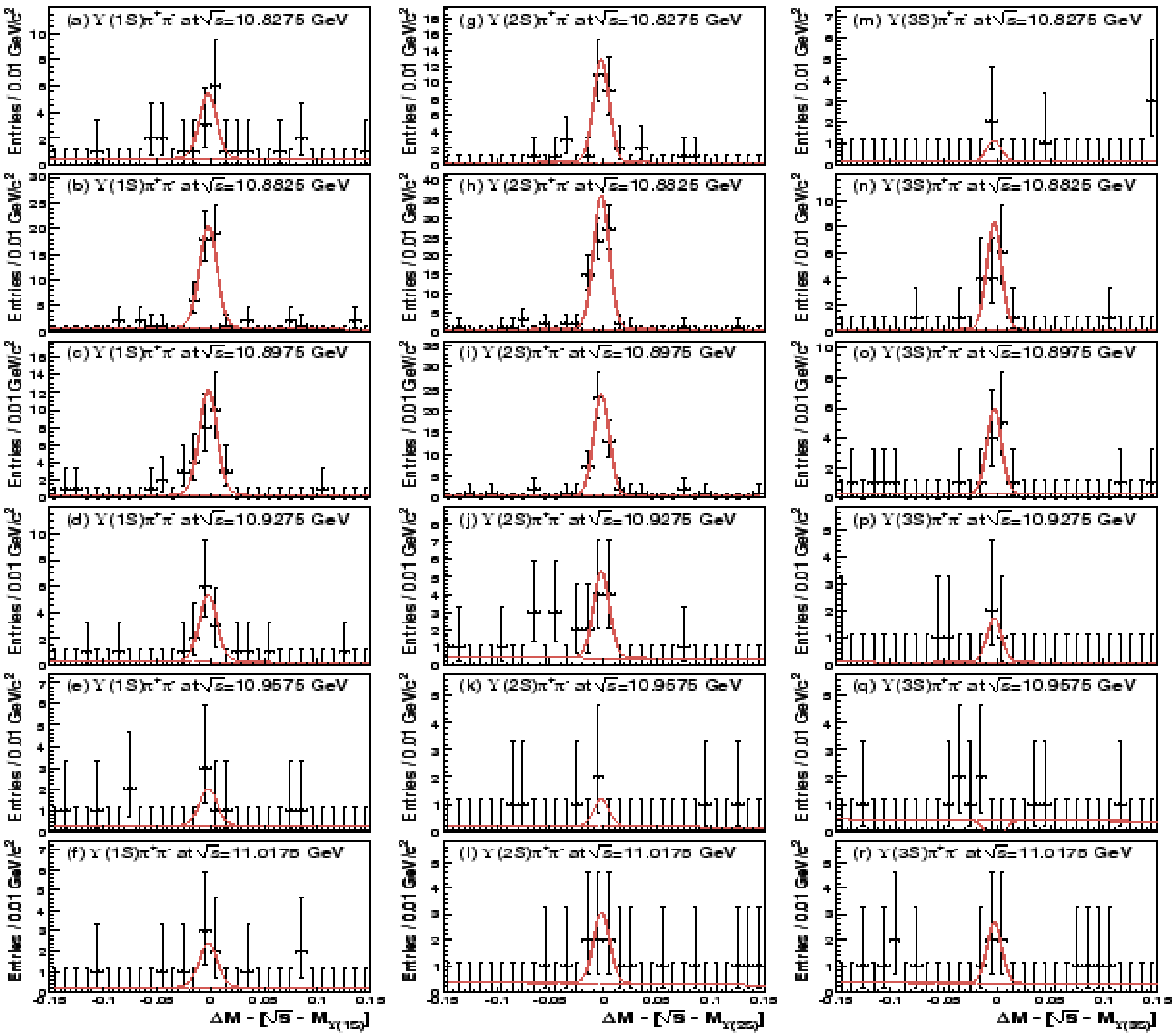
$\sqrt{s}$=10.8825 GeV

$\sqrt{s}$=10.8975 GeV

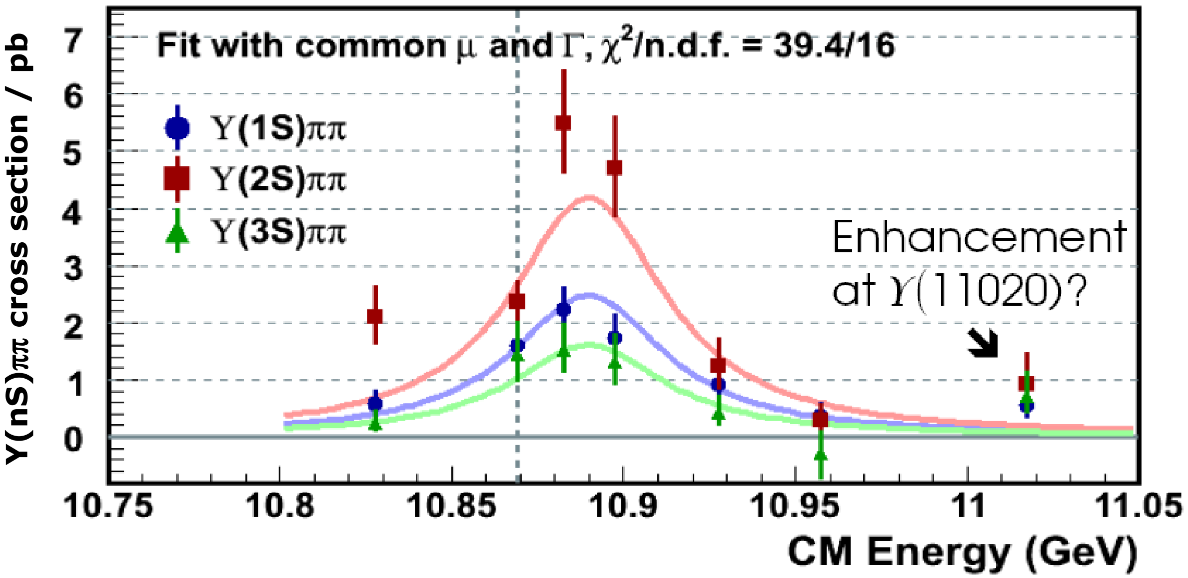
$\sqrt{s}$=10.9275 GeV

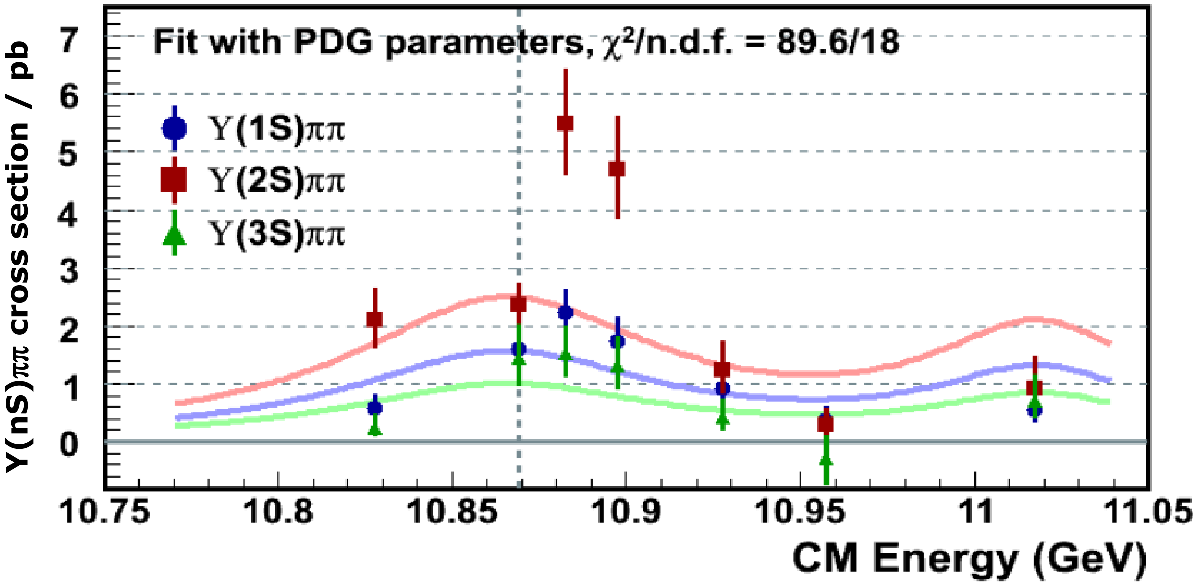
$\sqrt{s}$=10.9575 GeV

$\sqrt{s}$=11.0175 GeV



The Y_b(10889)





- Fit with 1 Breit-Wigner (floated mean and width) with 3 floated normalizations (for 1S, 2S and 3S)
- Comparison Y_b vs. Y(5S): mean ~20 MeV higher width around ½

- Fit with 2 Breit-Wigners fixed to Y(10860) = Y(5S) Y(11020) = Y(6S) PDG parameters

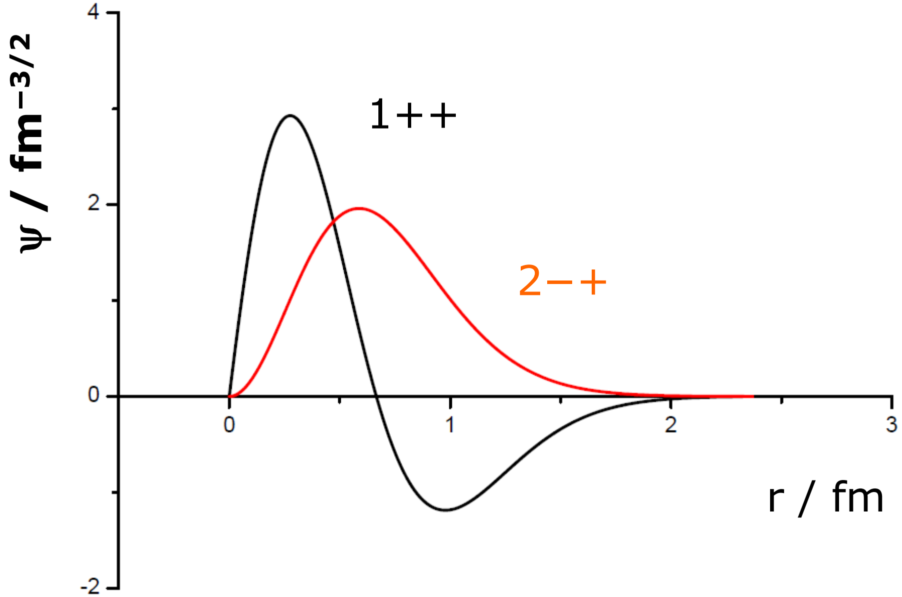
- Final state interaction or a new state?

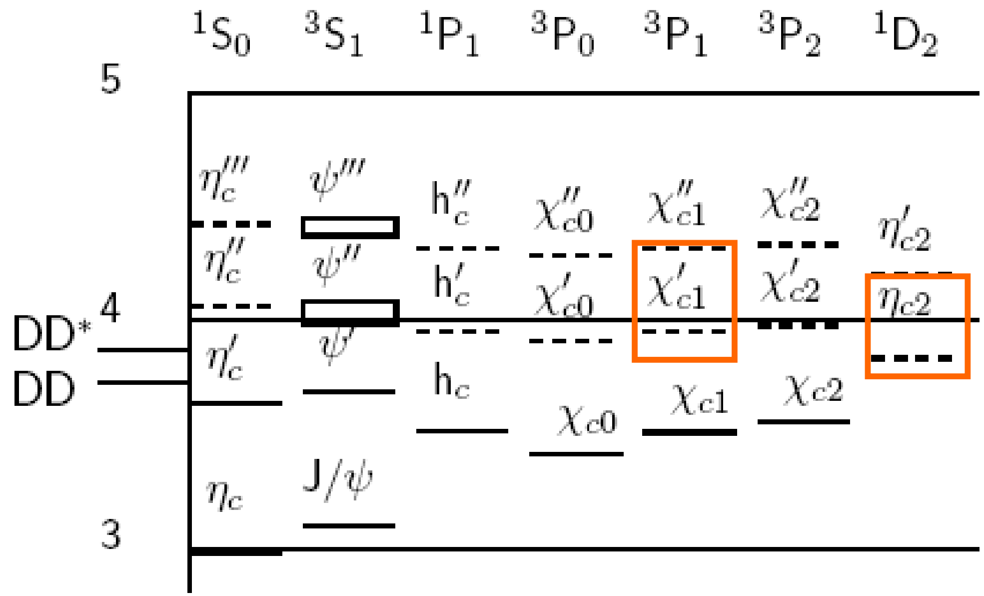
X(3872) Possible Charmonium Assignment

- Case $2\pi \rightarrow P=+$
  1++
  $\chi_{c1}{}'$ $^3P_1$
  predicted mass 3953 MeV
  n=2
  supported by angular analysis
  CDF-II, PRL98(2007)132002
  Belle, hep-ex/0505037

- Case $3\pi \rightarrow P=-$
  2−+
  η_{c2} $^1D_2$
  $\lesssim$ 100 MeV lower than $\chi_{c1}{}'$
  predicted mass 3837 MeV
  n=1
  (would be a L=2 meson)

Mass predictions by
Barnes, Godfrey, Swanson
Phys. Rev. D72(2005)054026

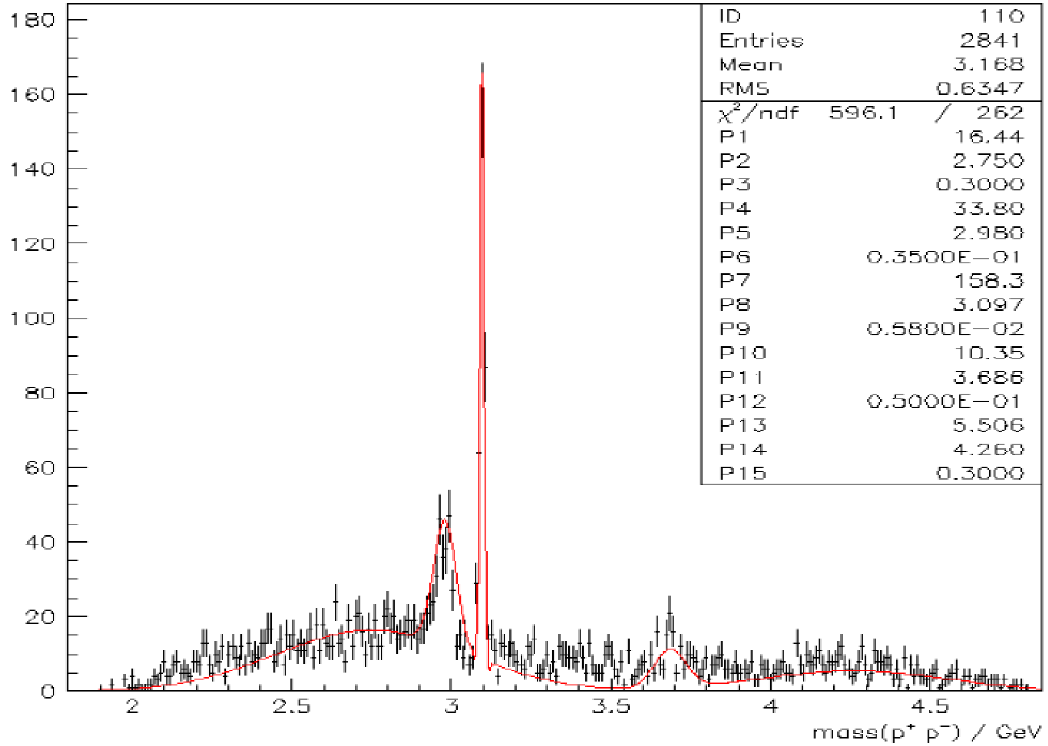




How do we know the $\bar{p}p$ cross sections?

- From $(\bar{c}c) \rightarrow \bar{p}p$ decays
- Time-reversal symmetry between decay and production („detailed balance")

Bachelor Thesis, M. Wagner, Giessen 2010



XYZ State
Here: charmonium mass region only

	prod.	J^{PC}	width	decay		
X(3872)	B decays	$1++$	<2.3	$J/\psi\pi^+\pi^-$, $J/\psi\omega$, DD^*	Belle, BaBar, CDF, D0	$(D^0\overline{D}^{*0})$ Molecule?
X(3940)	$e^+e^-\to c\bar{c}c\bar{c}$	0?+	$\simeq 37$	DD^* (not DD, $J/\psi\omega$	Belle	η_c''?
Y(3920)	B decays	??+	$\simeq 30$	$J/\psi\omega$ (not DD^*)	Belle, BaBar	?
Y(4140)	B decays	??+	$\simeq 11$	$J/\psi\omega$	CDF	$c\bar{c}s\bar{s}$
X(4160)	$e^+e^-\to c\bar{c}c\bar{c}$	0?+	$\simeq 140$	D^*D^* (not DD, $DD*$)	Belle	η_c''?
Y(4008)	ISR	1–	$\simeq 220$	$J/\psi\pi^+\pi^-$	Belle (not BaBar)	?
Y(4260)	ISR	1–	$\simeq 80$	$J/\psi\pi^+\pi^-$	BaBar, CLEO, Belle	$c\bar{c}g$ hybrid?
X(4350)	$\gamma\gamma$	??+	$\simeq 13$	$J/\psi\phi$	Belle	$c\bar{c}s\bar{s}$
Y(4350)	ISR	1–	$\simeq 75$	$\psi'\pi^+\pi^-$	BaBar, Belle	?
Y(4660)	ISR	1–	$\simeq 50$	$\psi'\pi^+\pi^-$, $\Lambda_c\overline{\Lambda}_c$ (?)	Belle	?
$Z^{\pm}$(4430)	B decays	???	$\simeq 100$	$\psi'\pi^{\pm}$	Belle (not BaBar)	4-quark?
$Z^{\pm}$(4050)	B decays	???	$\simeq 80$	$\chi\_c1\pi^{\pm}$	Belle	4-quark?
$Z^{\pm}$(4250)	B decays	???	$\simeq 180$	$\chi\_c1\pi^{\pm}$	Belle	4-quark?

X(4630)

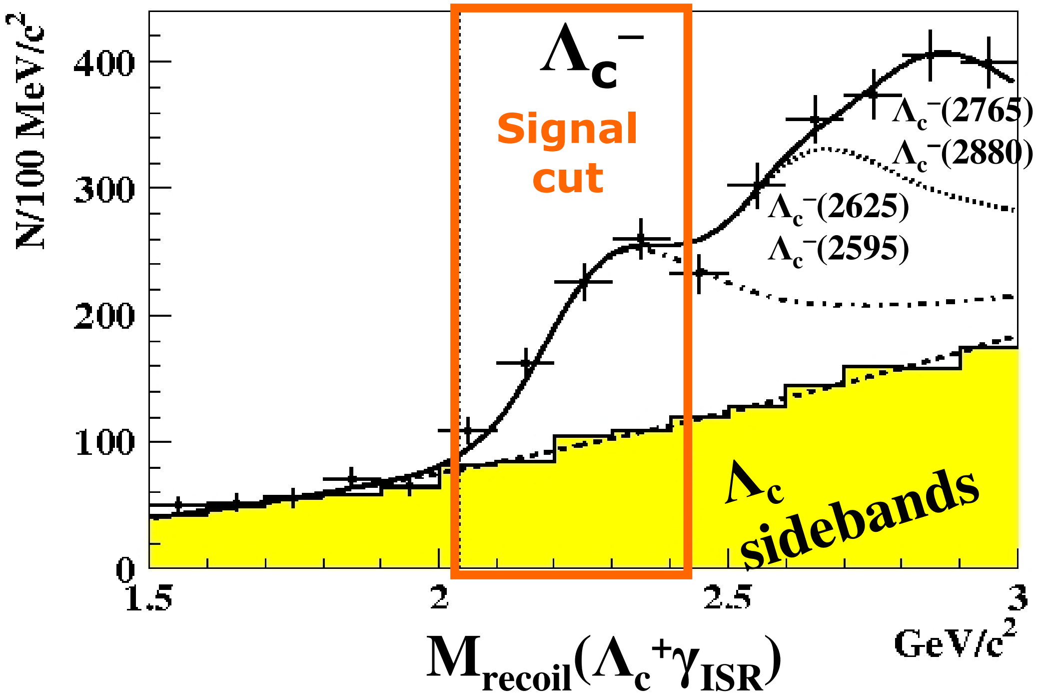
highest charmonium(-like) state observed so far
only new state with decay to <u>baryons</u> seen

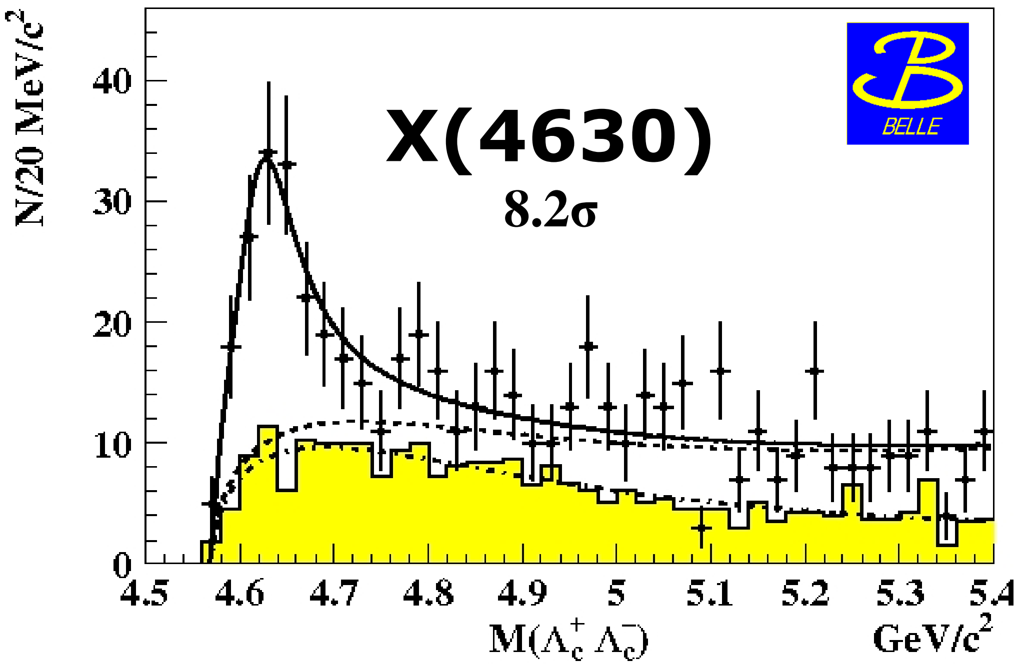
$e^+e^- \to \Lambda_c^+ \Lambda_c^- \gamma_{ISR}$

$\Lambda_c \to pK_s^0$, $pK^-\pi^+$, $\Lambda\pi^+$
Λ_c^- is tagged by anti-proton,
(partial reconstruction,
recoil mass)

- 5^3S_1 or 4^3D_1 ?
  Segovia, Yasser, Entem, Fernandez
- 6^3S_1 ?
  Li, Chao
- 2-baryon threshold effect?
  as seen in B decays, J/ψ decays

Phys. Rev. Lett. 101(2008)172001, 670/fb





Static Quark-Antiquark Potential for Charmonium

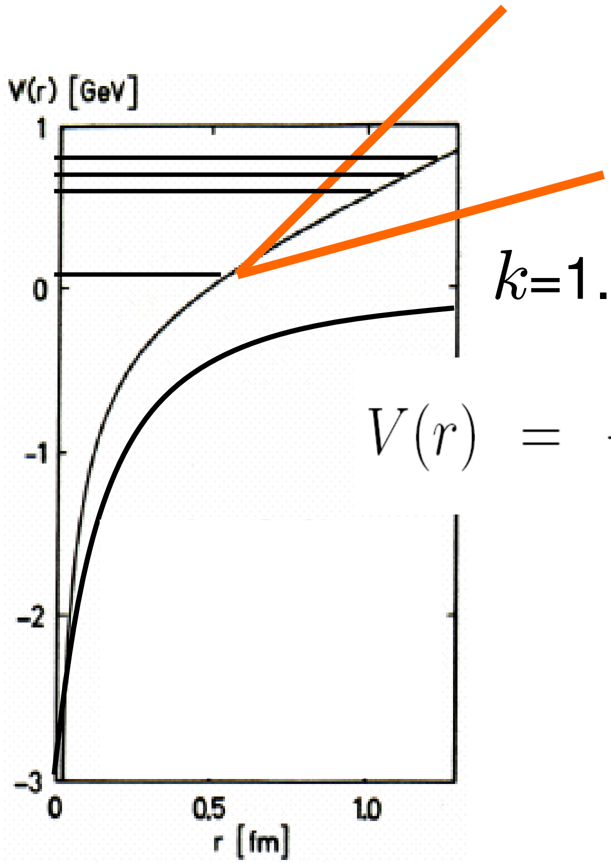
- Coulomb-Potential
  + Confinement-Term

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

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

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

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



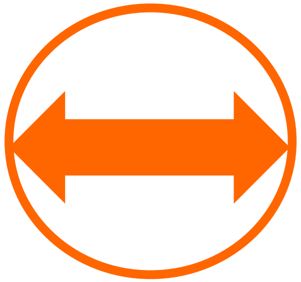
- solve Schrödinger equation
  (m_c heavy $\rightarrow$ non-relativistic)
  $\rightarrow$ states

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

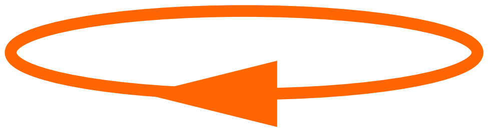
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right] R_{nl}(r) = E_{nl}R_{nl}(r)$$

Charmonium States

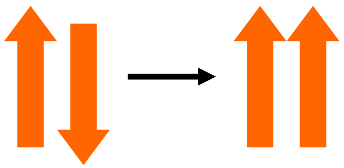
radial
n



orbital
L



spin
S

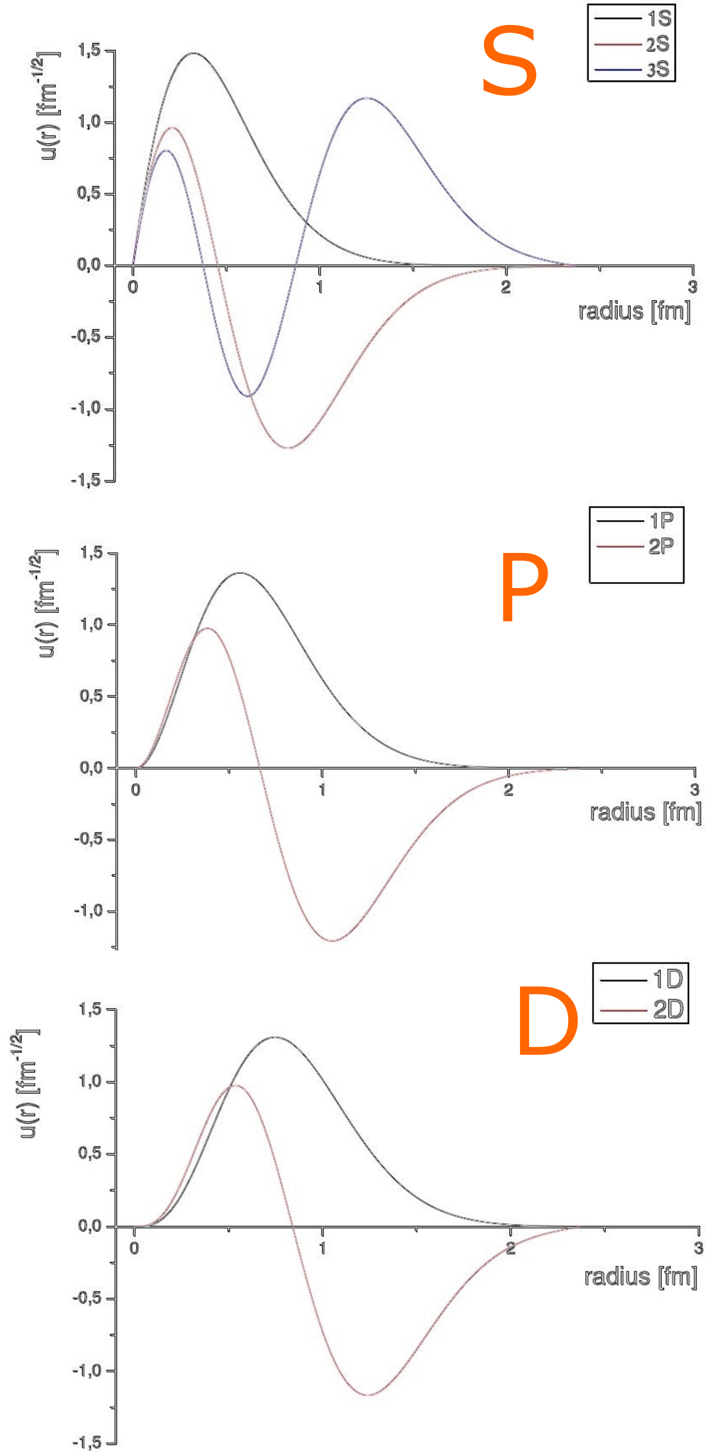


spectroscopic
notations

$n^{2S+1}L_J$

J^{PC}

radial
wavefunction



Master thesis
M. Ullrich, Gießen, 2010
Master thesis
M. Werner, Gießen, 2010

$$\vec{J} = \vec{L} + \vec{S}$$
$$P = (-1)^{L+1} \quad \text{parity}$$
$$C = (-1)^{L+S} \quad \text{charge conjugation}$$

Mass of a Charmonium State

(Potential Model)

n dependant term

$$M(n^{2S+1}l_j) = E_{nl} + 2m_q + \frac{2\alpha_s}{3m_q^2}\int d^3r\Psi^*(\vec{r})\left(\frac{1}{r}\vec{\nabla}^2 + \frac{1}{r}\frac{\partial^2}{\partial r^2}\right)\Psi(\vec{r})$$

$$+ \frac{4\pi\alpha_s}{3m_q^2}|\Psi(0)|^2 + \frac{32\pi\alpha_s}{9m_q^2}\left(\frac{1}{2}S(S+1) - \frac{3}{4}\right)|\Psi(0)|^2$$

spin-spin

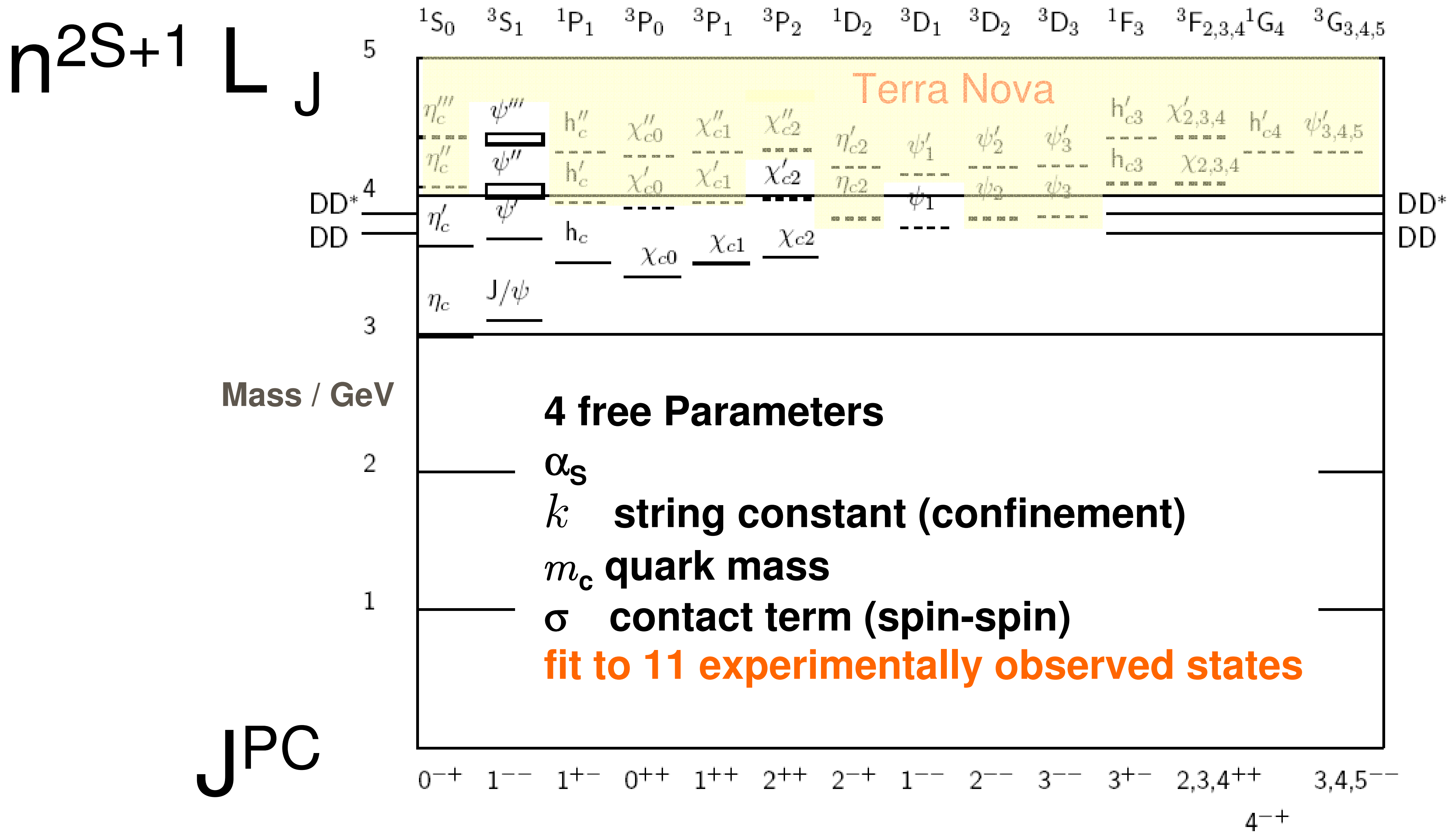
$$+ \alpha_s\frac{j(j+1) - l(l+1) - S(S+1)}{m_q^2}\left\langle\frac{1}{r^3}\right\rangle + \alpha_s\frac{S_{12}}{3m_q^2}\left\langle\frac{1}{r^3}\right\rangle$$

spin-orbit

tensor

Master thesis
M. Ullrich, Gießen, 2010
Master thesis
M. Werner, Gießen, 2010

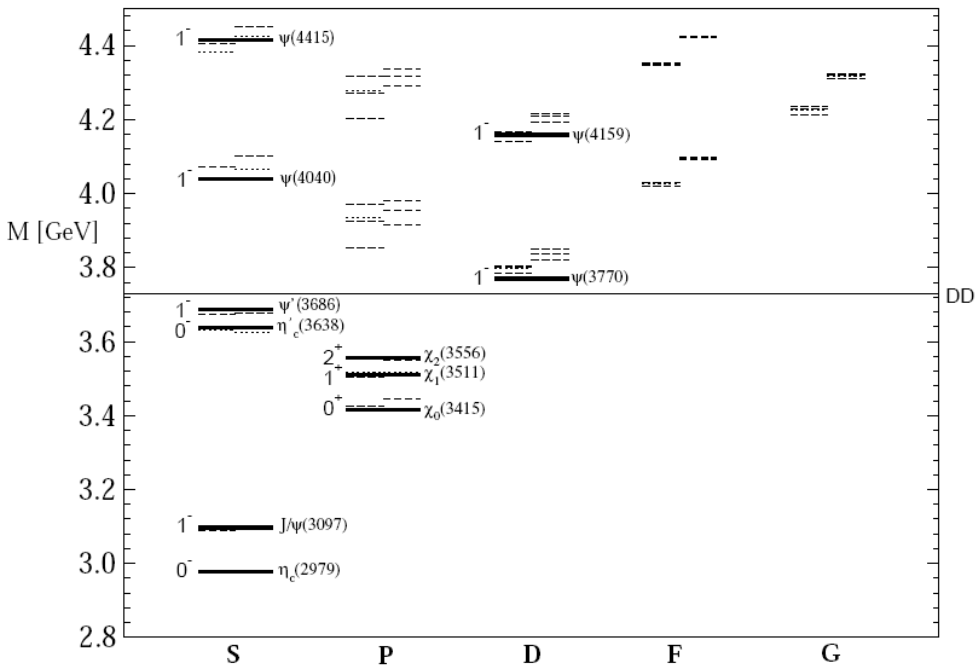
Charmonium Excited States n ≤ 3, L ≤ 4

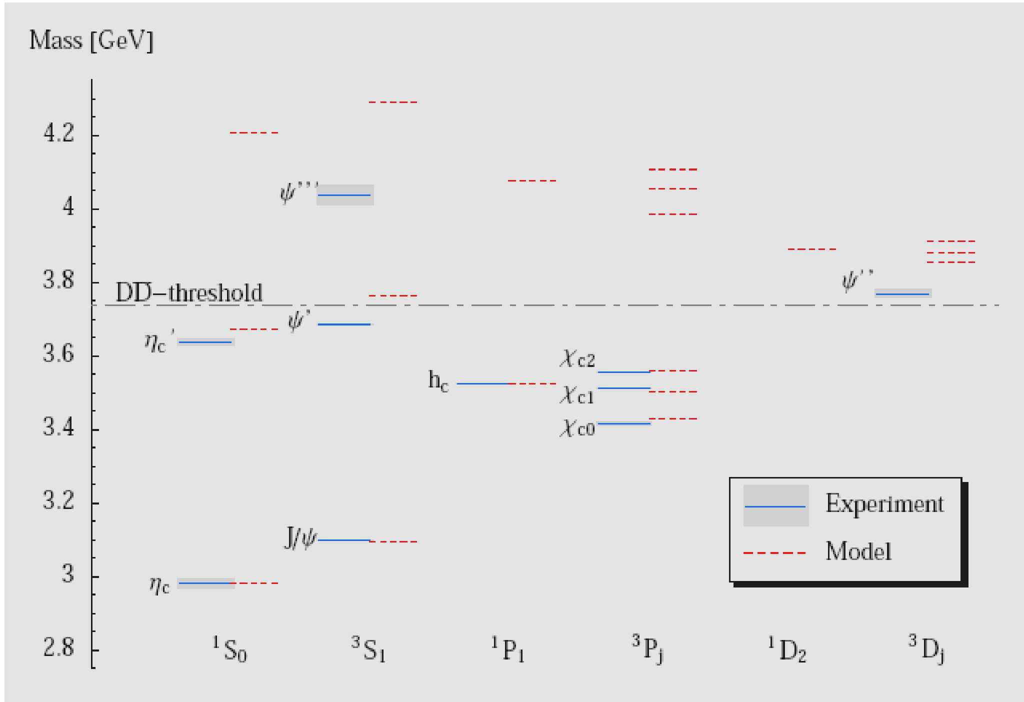


4 free Parameters

- α_s
- k **string constant (confinement)**
- m_c **quark mass**
- σ **contact term (spin-spin)**

fit to 11 experimentally observed states





Barnes, Godfrey, Swanson
Phys. Rev. D72(2005)054026

α_S = 0.55
k = 0.723 GeV/fm
m_c = 1.4794 GeV

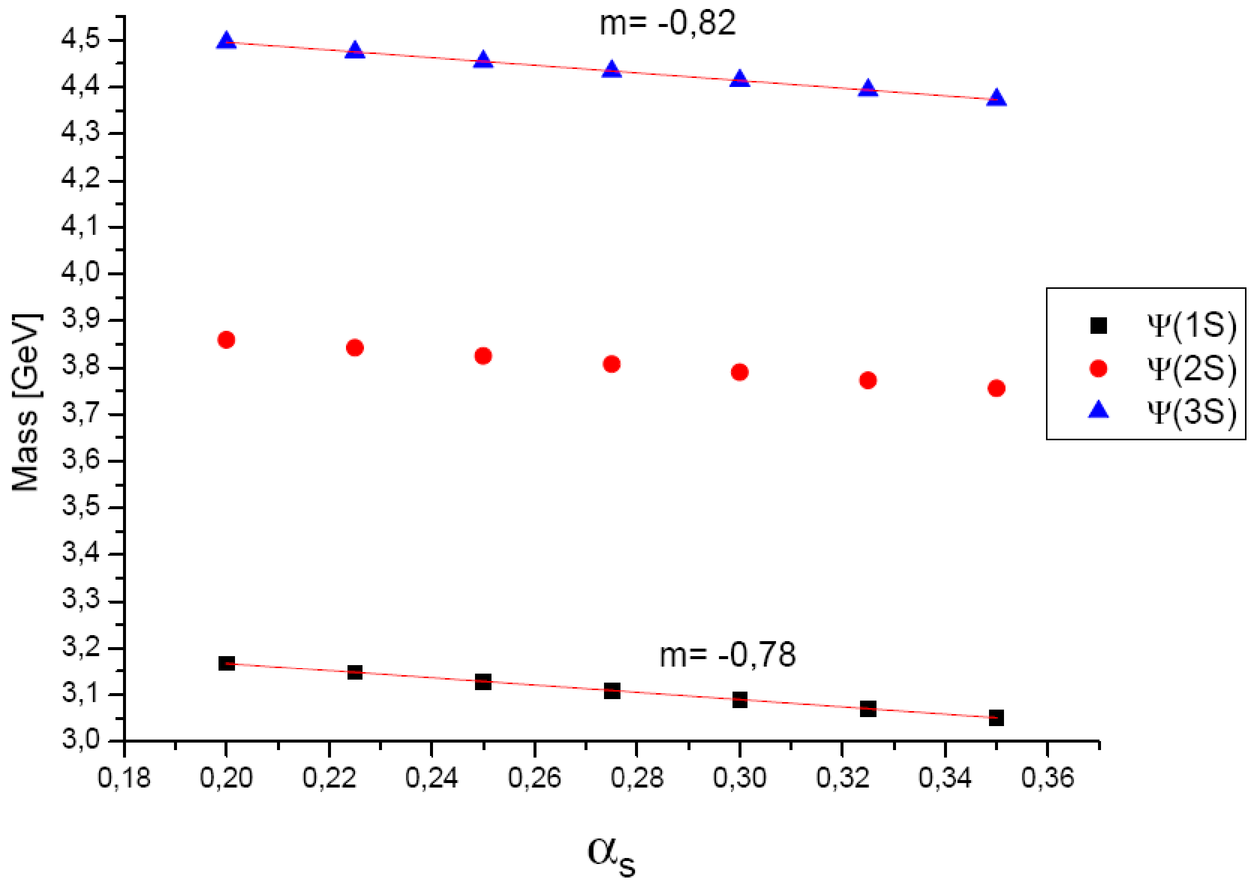
Eiglsperger
arXiv:0707.1269[hep-ph]
Weise, HIRSCHEGG 2007

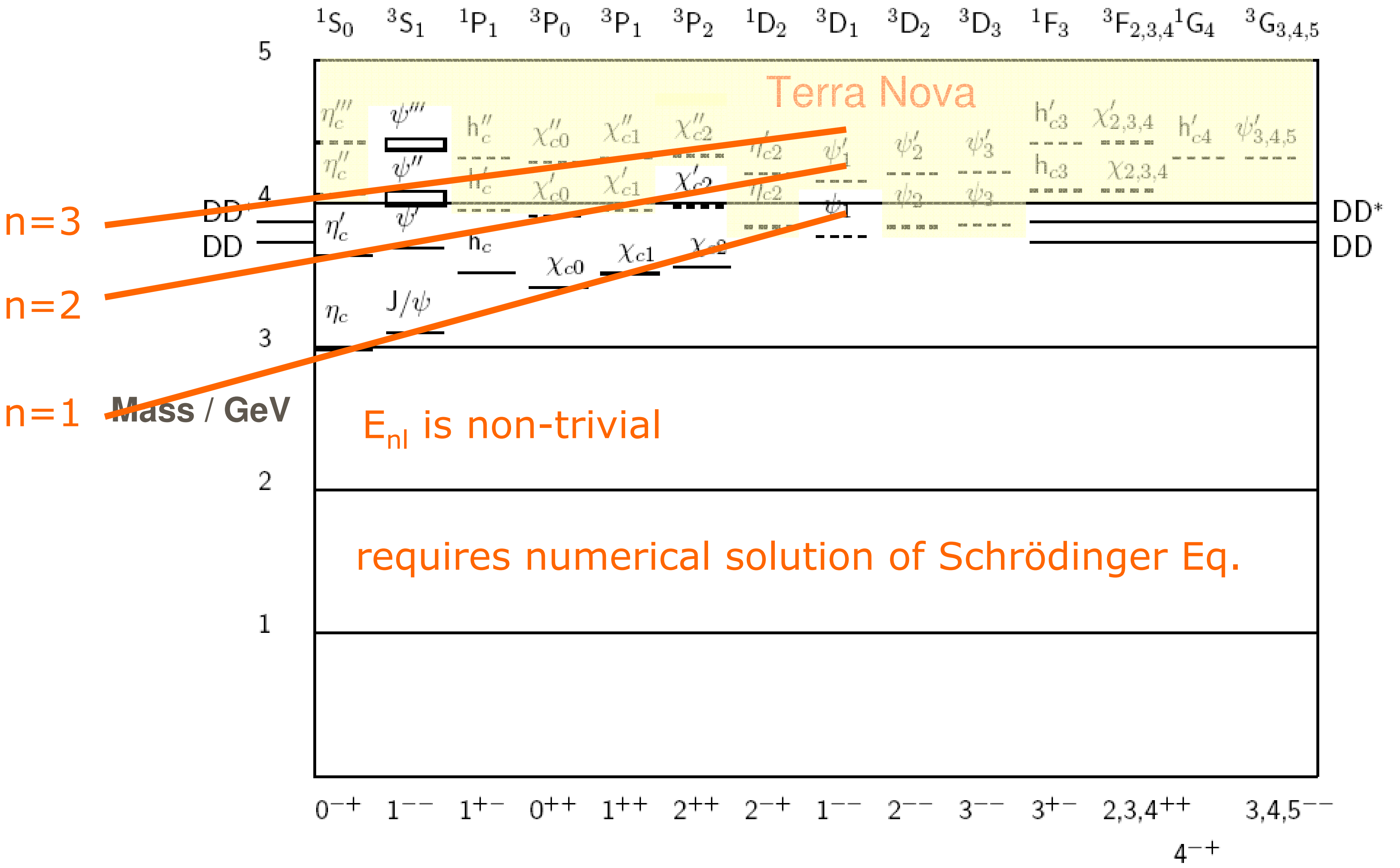
α_S = 0.29
k = 1.306 GeV/fm
m_c = 1.2185 GeV

Note: string tension from Lattice QCD k$\simeq$1 GeV/fm

α_s

- Strong coupling is assumed constant for $0 \leq r \leq \infty$
- Mass solutions depend on α_s with $\Delta m \leq 100$ MeV for $\Delta\alpha_s \leq 0.1$

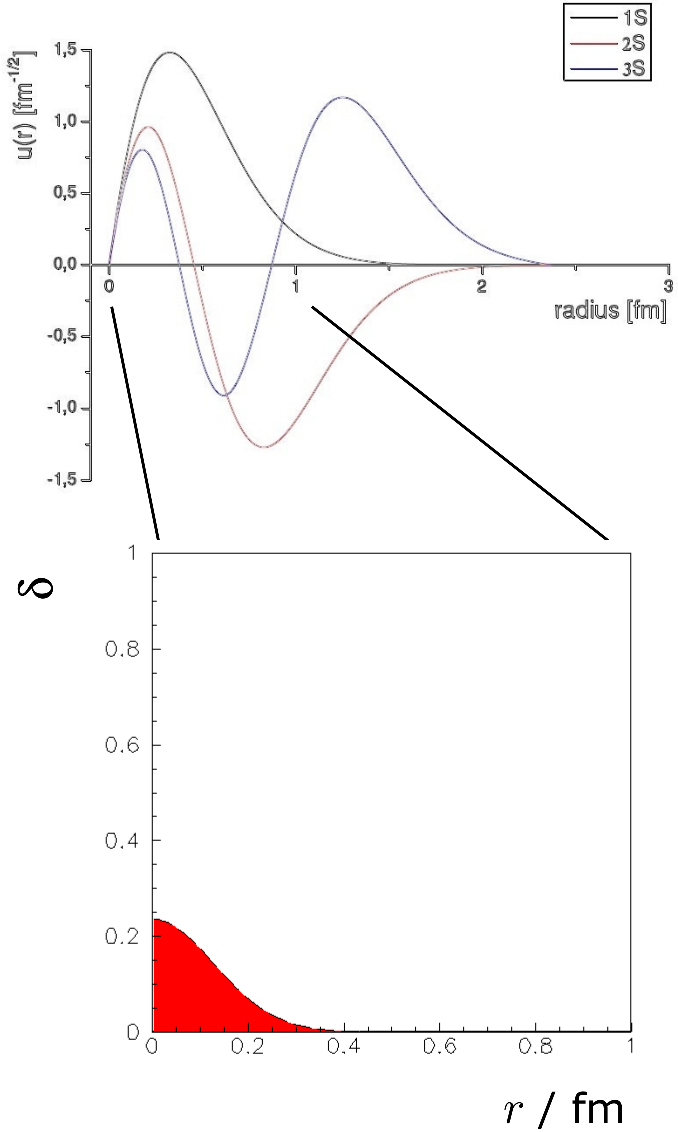


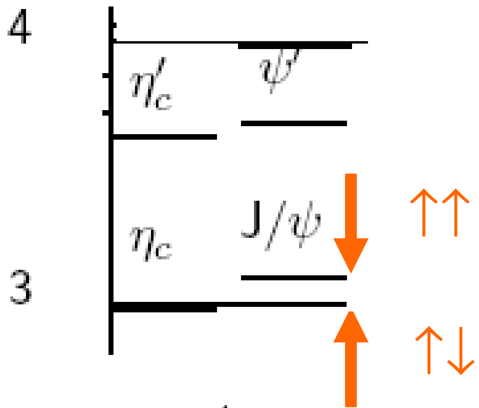


Terra Nova
n=3
n=2
n=1
Mass / GeV
E_nl is non-trivial
requires numerical solution of Schrödinger Eq.
1S0 3S1 1P1 3P0 3P1 3P2 1D2 3D1 3D2 3D3 1F3 3F2,3,4 1G4 3G3,4,5
0−+ 1−− 1+− 0++ 1++ 2++ 2−+ 1−− 2−− 3−− 3+− 2,3,4++ 3,4,5−−
4−+
DD*
DD
5
4
3
2
1
ηc J/ψ hc χc0 χc1 χc2

Short-range Forces: Spin-Spin Term

- consequence of one-gluon exchange
- spin-spin term is put into the potential, i.e. not treated as a mass shift
- radial only
- „contact term", Gaussian
- fit to experimental data gives $\sigma \simeq 1$ GeV





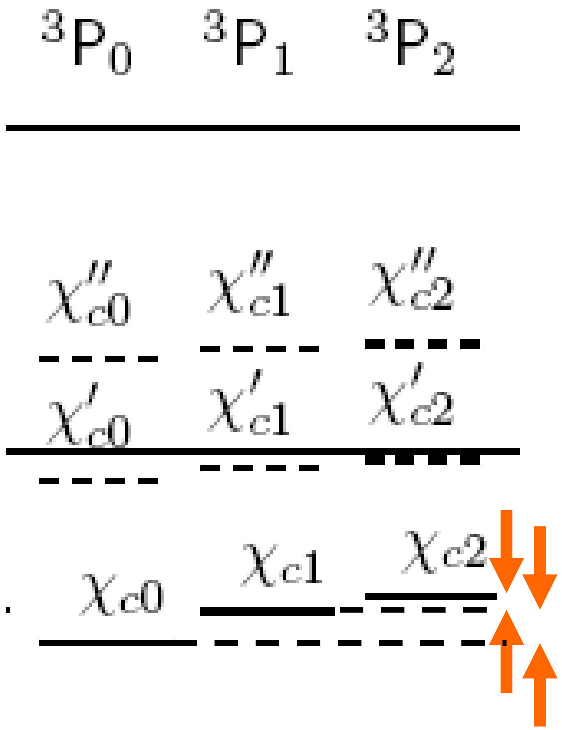
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\,\tilde{\delta}_\sigma(r)\,\vec{S}_c\cdot\vec{S}_{\bar{c}}$$

$$\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3\, e^{-\sigma^2 r^2}$$

Long-range forces: Testing Confinement

- Testing e.g. mass splitting of P-wave states $\langle r \rangle \simeq 0.7$ fm
  - Coulomb term transforms as Lorentz vector (photon = vector)
  - Linear term transforms as Lorentz scalar
  - Scalar implies: >=2 gluons needed

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



$$R = \frac{m(^3P_2) - m(^3P_1)}{m(^3P_1) - m(^3P_0)}$$

$R_{exp} = 0.48 \pm 0.01$

$R_{vector} \geq 0.8$

$\rightarrow$ Confinement term is needed.
$\rightarrow$ Confinement is scalar.

X(3872)

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

- observed
  in more than one
  decay channel

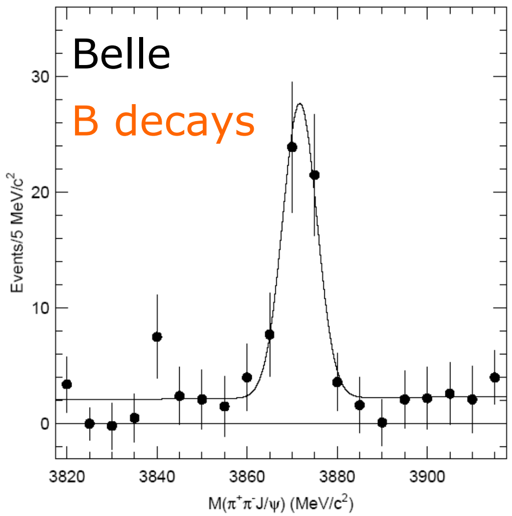
$$X(3872) \rightarrow J/\psi\pi^+\pi^-$$
$$X(3872) \rightarrow J/\psi\gamma$$
$$X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0$$
$$X(3872) \rightarrow D^0\overline{D}^0\pi^0$$
$$X(3872) \rightarrow D^0\overline{D}^0\gamma$$
$$X(3872) \rightarrow \psi'\gamma$$

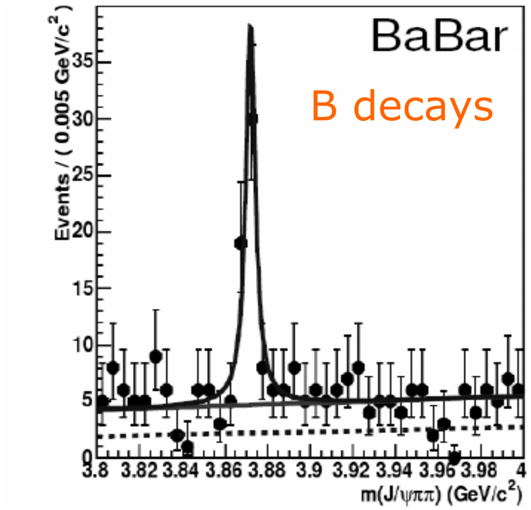
- narrow width
  Γ<2.3 MeV (90% CL)

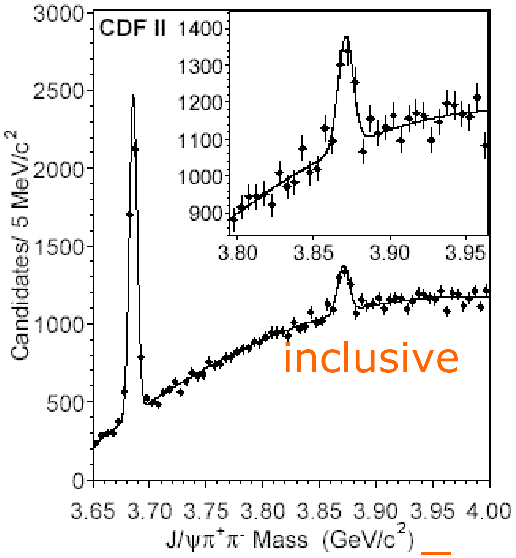
- Mass 3871.46±0.19 MeV
  very close to threshold

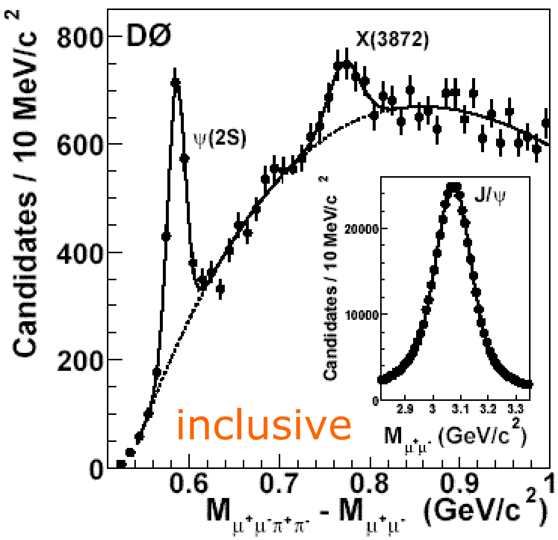
$$M_X - (m_{D^*} + m_{\bar{D}^0}) =$$
–0.32±0.35 MeV

S-wave molecular state?





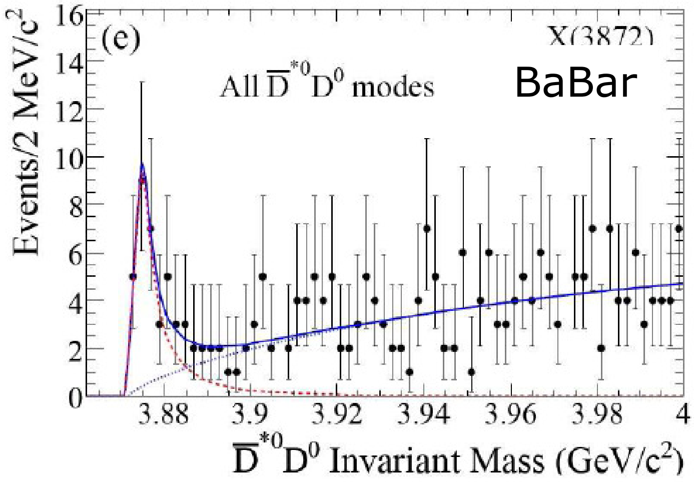


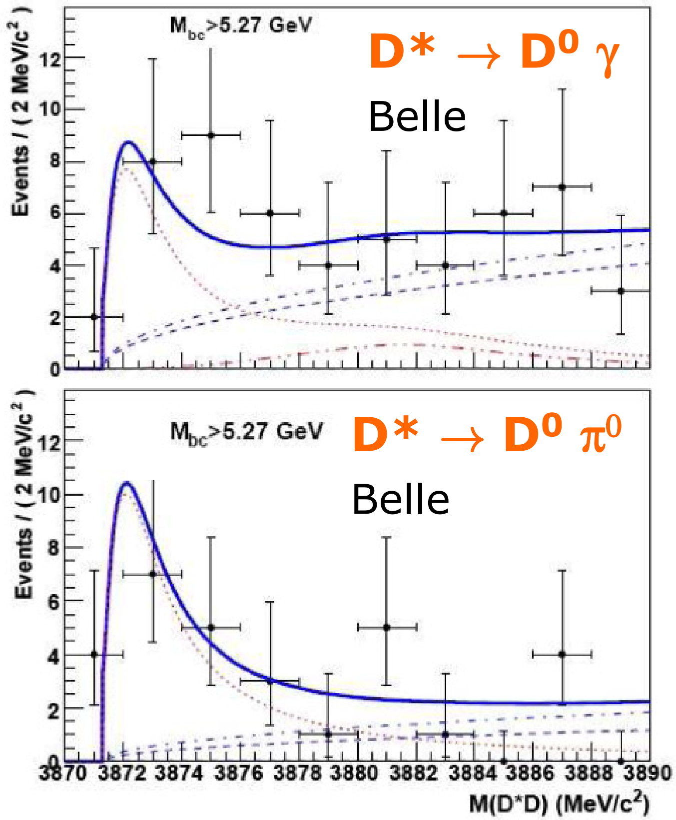


$p\bar{p}$, $\sqrt{s}$=1.8 TeV

Strong Decay X(3872) → $\bar{D}D^*$

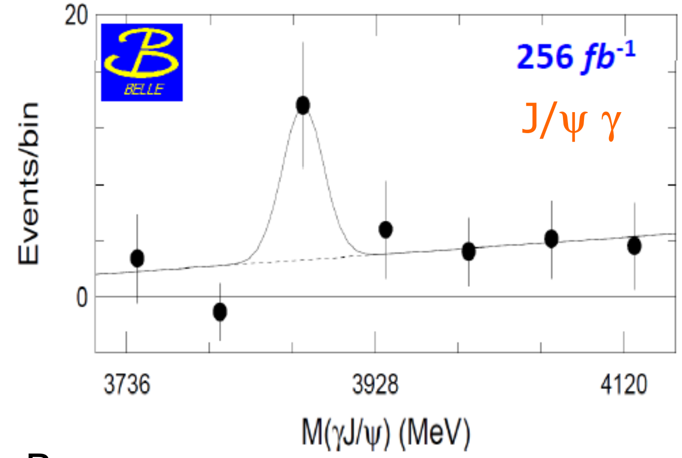
- Decay into $\bar{D}D^*$ is dominant
  BR is factor $9.4^{+3.6}_{-4.3}$
  higher than for $J/\psi\ \pi^+\ \pi^-$
- BaBar, Phys. Rev. D77(2008)011102(R)
  m=$3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV
  - binned maximum likelihood fit
  - 1-dim fit, M(D*D)
  - signal pdf from MC
  - exponential function background
- Belle, Phys. Rev. D81(2010)031103
  m=$3872.9^{+0.6}_{-0.4}\,{}^{+0.4}_{-0.5}$ MeV
  - unbinned maximum likelihood fit
  - 2-dim fit
    - beam constraint mass
      Gaussian signal
      Argus function for background
    - M(D*D)
      Breit-Wigner signal
      square root for background



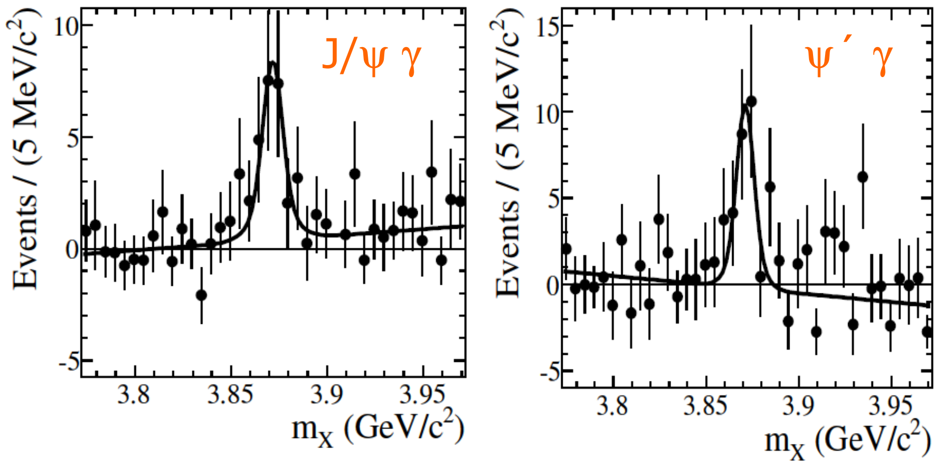


Radiative Decay X(3872) → J/ψ γ, ψ´γ

- Rare Decay
  BR is factor ~6
  smaller than BR(X→ J/ψ $\pi^+ \pi^-$)
  Combined branching fraction
  BR(B decay) × BR(X decay) ≃ 10^{-6}
- Evidence for X(3872)→ J/ψ γ by Belle
  256/fb
  13.6±4.4 events
  arXiv:hep-ex/0505037
- Confirmed by BaBar
  424/fb
  23.0±6.4 events
  Phys. Rev. D 74(2006)071101
- Proof for positive C parity J^{P+}
- BaBar found evidence
  for X(3872)→ψ´γ
  424/fb
  25.4±7.4 events
  Phys. Rev. Lett. 102(2009)132001



BaBar

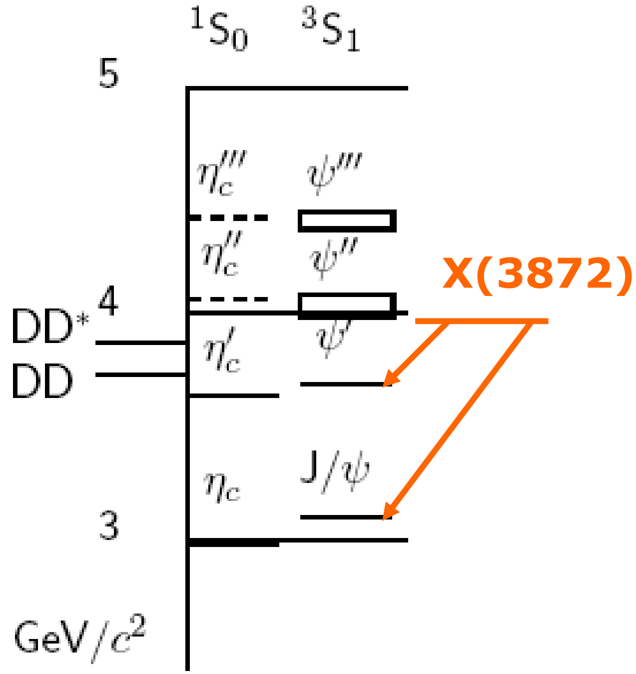


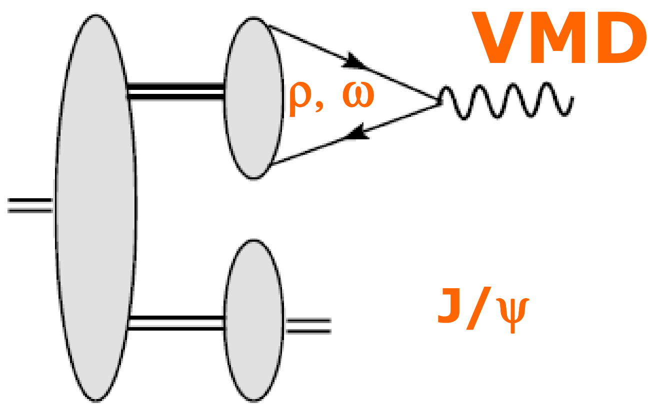
$$\frac{\mathcal{B}(X(3872) \to \psi'\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4$$

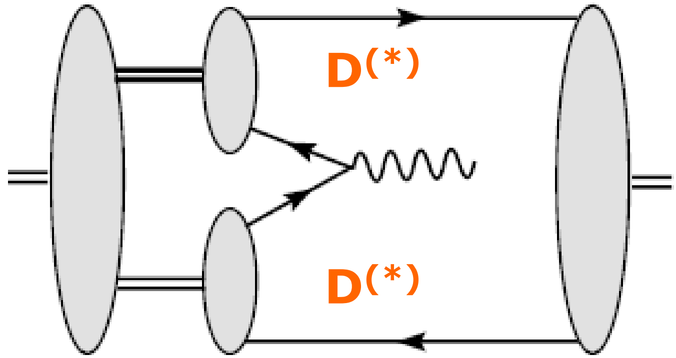
(large)

Radiative Decay X(3872) $\rightarrow$ J/ψ γ, ψ´γ

- X(3872) → J/ψ γ, E_γ=775 MeV
  VMD contributes (ρ, ω)
- X(3872) → ψ´γ, E_γ=186 MeV
  can only proceed through
  light quark annihilation
  → expected small
  → BaBar measurement surprising
- New measurement by Belle
  Preliminary, QWG10, 711/fb





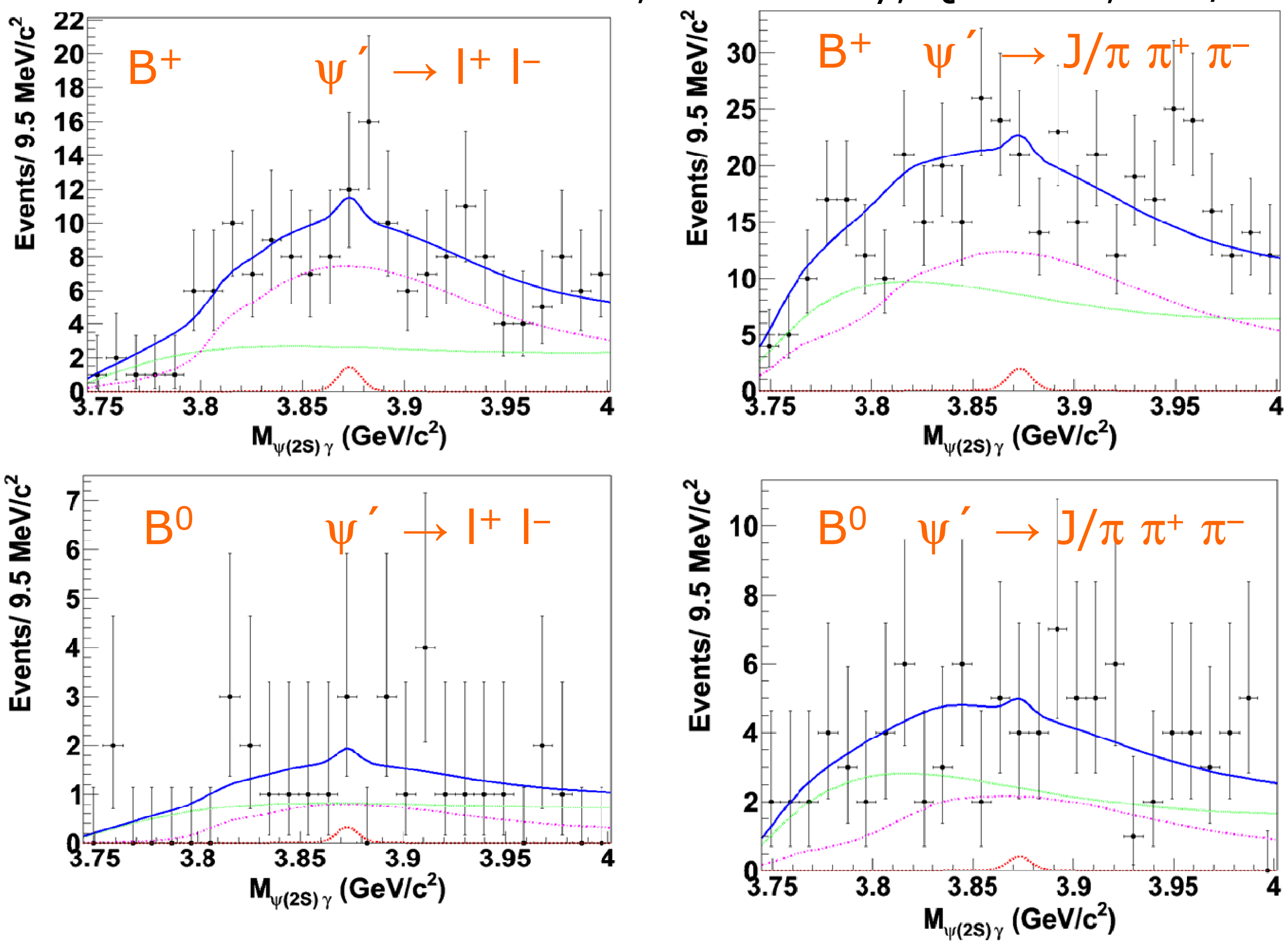


Swanson, Phys. Rept. 429(2006)243

New Measurement of X(3872) Radiative Decays
X(3872)→ψ´γ

ψ´K and ψ´K* background is different for ll and J/ψ ππ
→ simultaneous fit, 2nd order Chebyshev polynom
Combinatorial Background

Belle, Preliminary, QWG´10, 711/fb



$B^+ \to K^+$ X(3872)
$5.0^{+11.9}_{-11.0}$ events
(0.4σ)
BR<3.4 x 10^{-6} (90% CL)

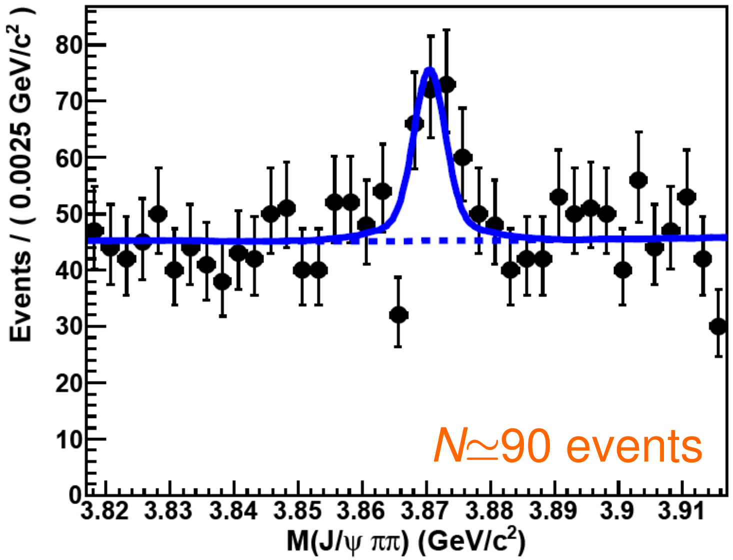
$B^0 \to K^0$ X(3872)
$1.5^{+4.8}_{-3.9}$
(0.2σ)
BR<6.6 x 10^{-6} (90% CL)

No signal observed

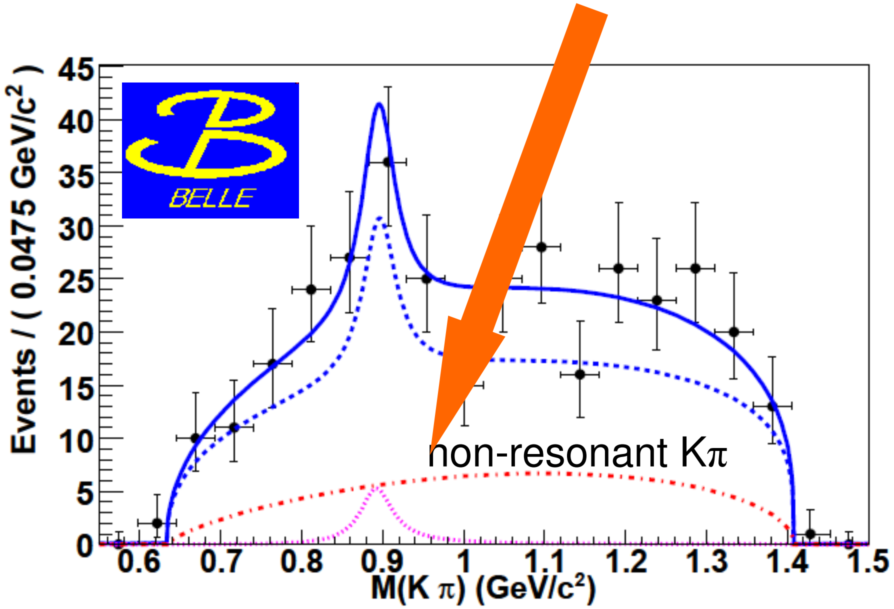
No indication, that X→(n=2) charmonium is stronger than X→(n=1) charmonium

B → X(3872) K π

Belle, arXiv:0809.1224, 605/fb



small K*(892) signal



$$BR(B^0 \to X[K^+\pi^-]_{non-res} \quad \times BR(X \to J/\psi\pi^+\pi^-) = \quad (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

$$BR(B^0 \to X K^{*0} \times \quad BR(X \to J/\psi\pi^+\pi^-) < \quad 3.4 \times 10^{-6} \quad \text{at } 90\% \text{ C.L.}$$

$$BR(B^+ \to X K+) \times \quad BR(X \to J/\psi\pi^+\pi^-) = \quad (8.10 \pm 0.92 \pm 0.66) \times 10^{-6}$$

Belle, arXiv:0809.1224

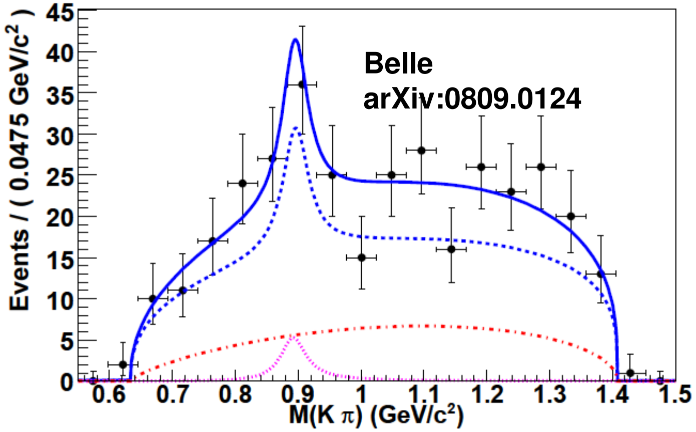
$$(8.4 \pm 1.5 \pm 0.7) \times 10^{-6}$$

BaBar, Phys. Rev. D77(2008)111101

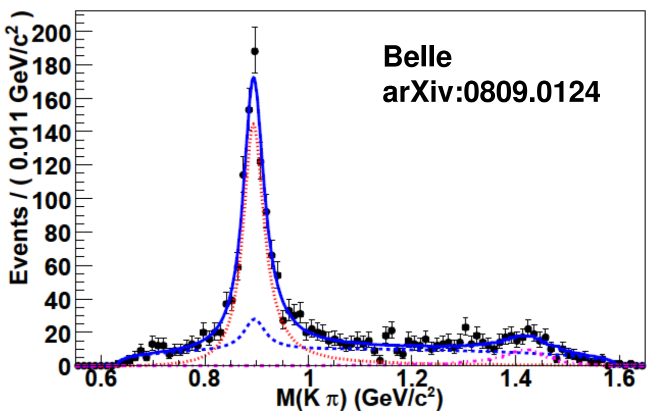
BR(B→ K X) ≃ BR(B → K π X)
non-resonant Kπ as strong as resonant K
(although phasespace smaller)

$B \to K\pi X(3872)$ is very different from other $B \to K\pi$ Charmonium

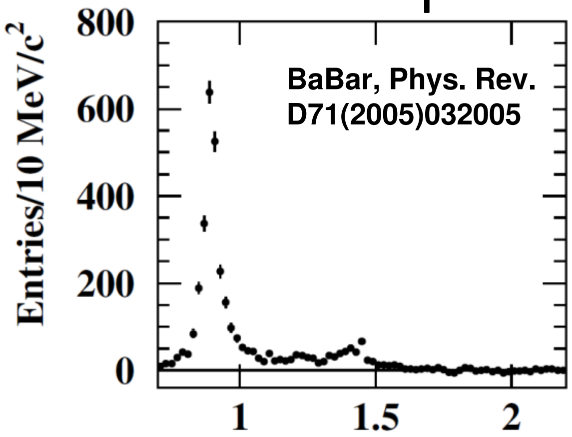
$K\pi X(3872)$



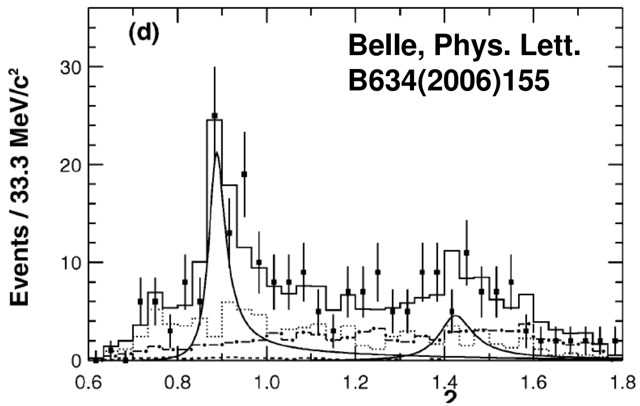
$K\pi\psi'$



$K\pi J/\psi$

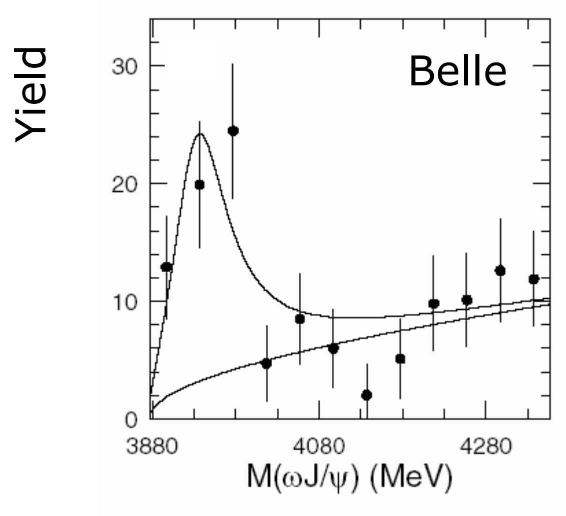


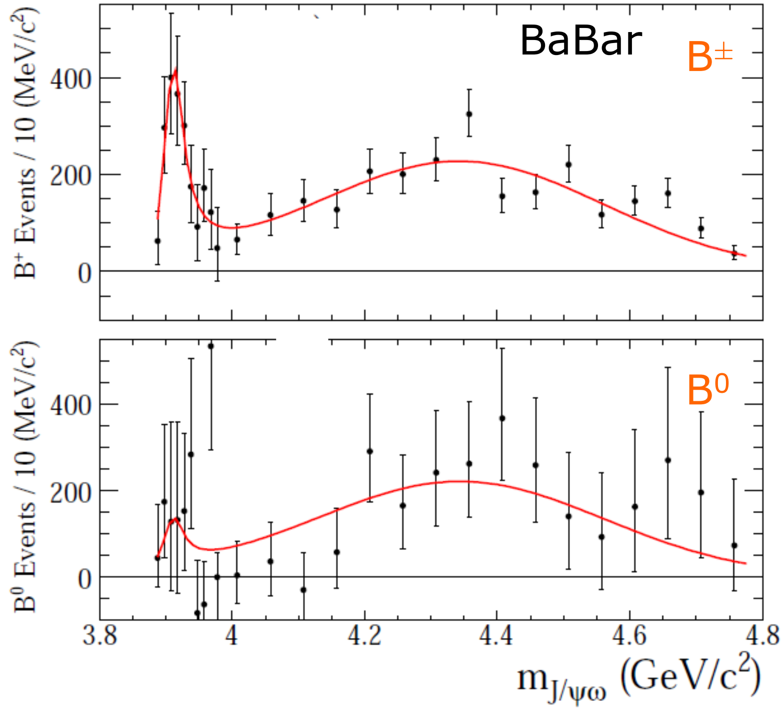
$K\pi\chi_{c1}$



Y(3940)

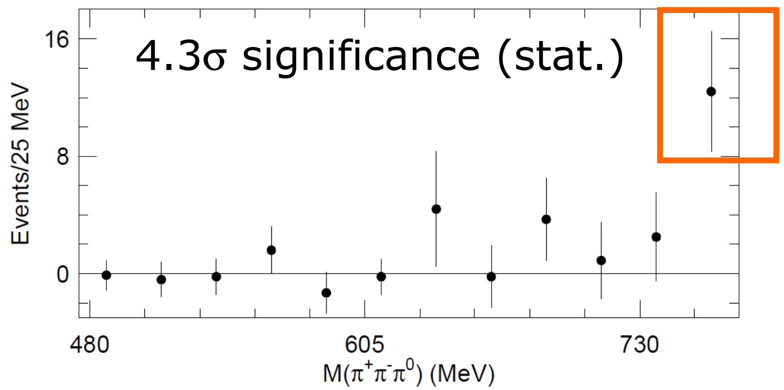
- only decay seen so far: $J/\psi\omega$
- quite narrow
  radially excited P wave state?
  $n \geq 2$ has nodes in wave function
  $\rightarrow$ width narrower
- Belle, Phys. Rev. Lett. 94(2005)182002
  275×10^6 B meson pairs
  mass 3943±11(stat.)±13(syst.) MeV
  width 87±22(stat.)±26(syst.) MeV
  - BG ~ q*(m)
    momentum of particles in $J/\psi\omega$ restframe
  - mass resolution fixed $\Delta m(J/\psi\omega) \simeq 6$ MeV
    factor >10 narrower than Breit-Wigner
- BaBar, Phys. Rev. D82(2010)011101
  467×10^6 B meson pairs
  mass $3919.1^{+3.8}_{-3.4}$ (stat.)±2.0 (syst.) MeV
  width 31^{+10}_{-8}(stat.)±5(syst.) MeV
  - BG Gaussian
  - mass dependant resolution





Observation of X(3872) $\rightarrow J/\psi\ \omega(\rightarrow \pi^+ \pi^- \pi^0)$

- Belle, arXiv:hep-ex/0505037
  256/fb



- Isospin violation
  (additional π^0)
  seems large
- → BaBar
  re-analysis of Phys. Rev. Lett.101(2008)082001
  with new ω mass cut
  BaBar, Phys. Rev. D82(2010)011101, 433/fb

$$\frac{\mathcal{B}(X \rightarrow \pi^+\pi^-\pi^0 J/\psi)}{\mathcal{B}(X \rightarrow \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})$$

Belle
MC efficiency corrected

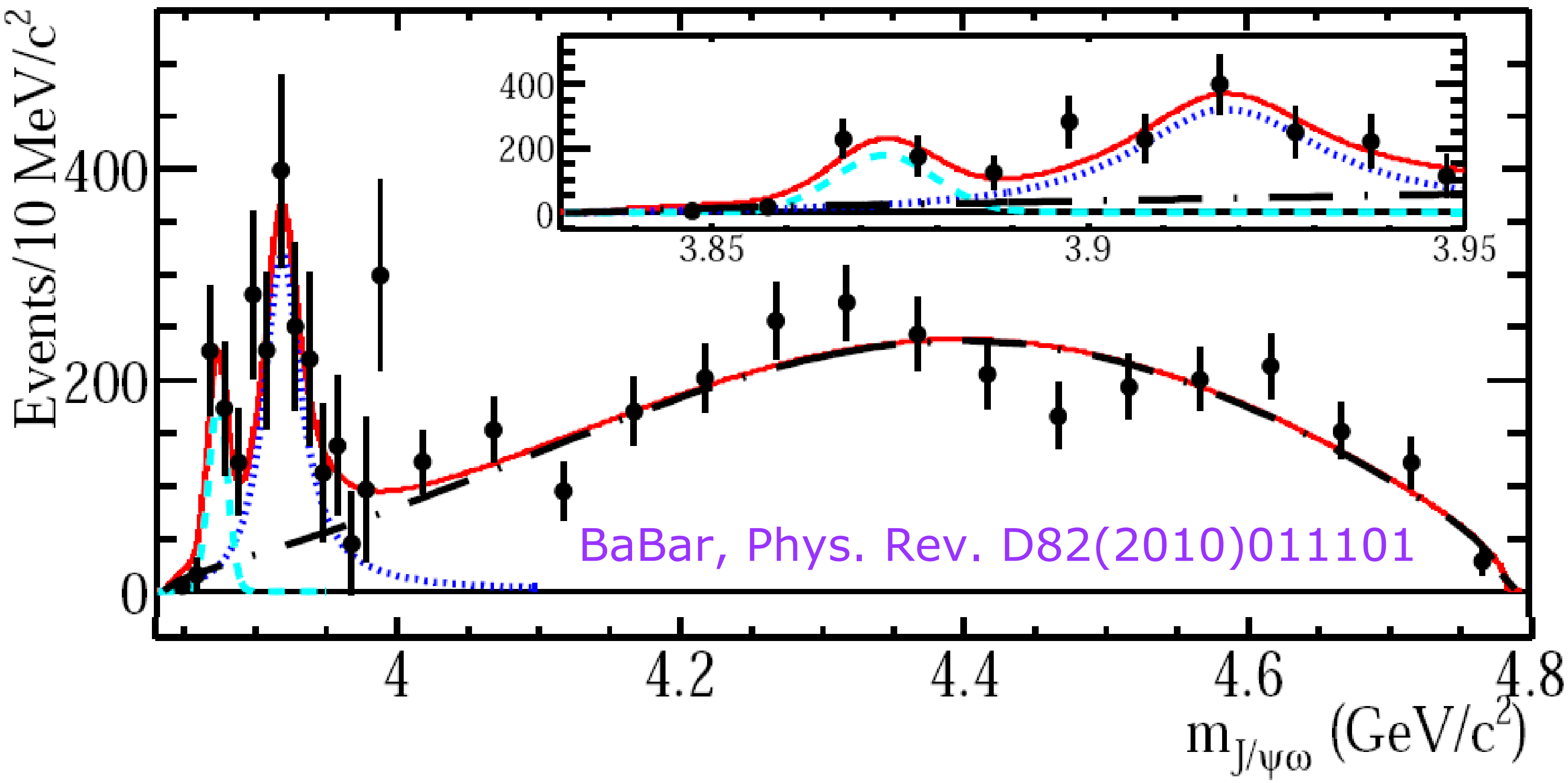
BaBar, Phys. Rev. D82(2010)011101, 433/fb

	Belle hep-ex/0505037	BaBar Phys. Rev. Lett.101(2008)082001	BaBar QWG10
Cut on ΔE $=\sqrt{(E_B^{cms})^2 - (p_B^{cms})^2}$	±35 MeV (charged only)	±20 MeV (B^+) ±15 MeV (B^0)	±20 MeV (B^+) ±15 MeV (B^0)
Cut on $m(3\pi)$	≥0.7500 GeV (charged only)	0.7695-0.7965 GeV (B^+) 0.7605-0.8055 GeV (B^0)	0.7400-0.7965 GeV (B^+) 0.7400-0.8055 GeV (B^0)

PDG2008 $m(\omega)$=0.78265±0.00012 MeV

$B^+ \to K^+ X(3872)(\to J/\psi\ \omega(\to \pi^+ \pi^- \pi^0))$

X(3872)   Y(3940)



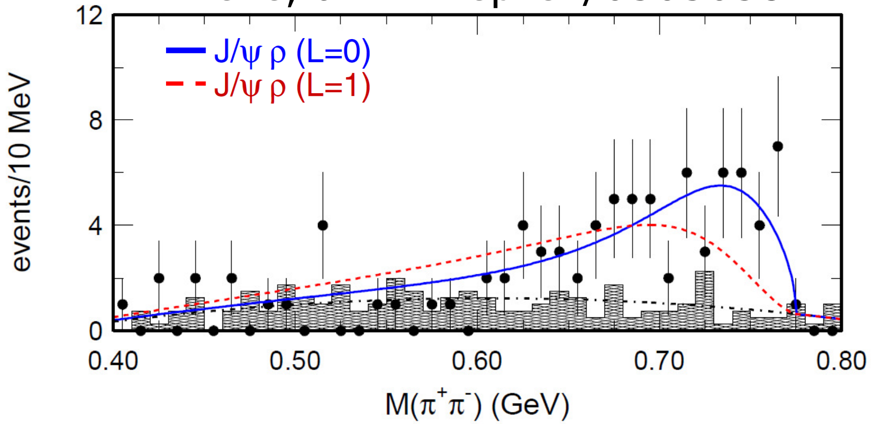
$$\frac{\mathcal{B}(X(3872) \to J/\psi\omega)}{\mathcal{B}(X(3872) \to J/\psi\pi\pi)} = 0.7 \pm 0.3$$

Large isospin violation confirmed

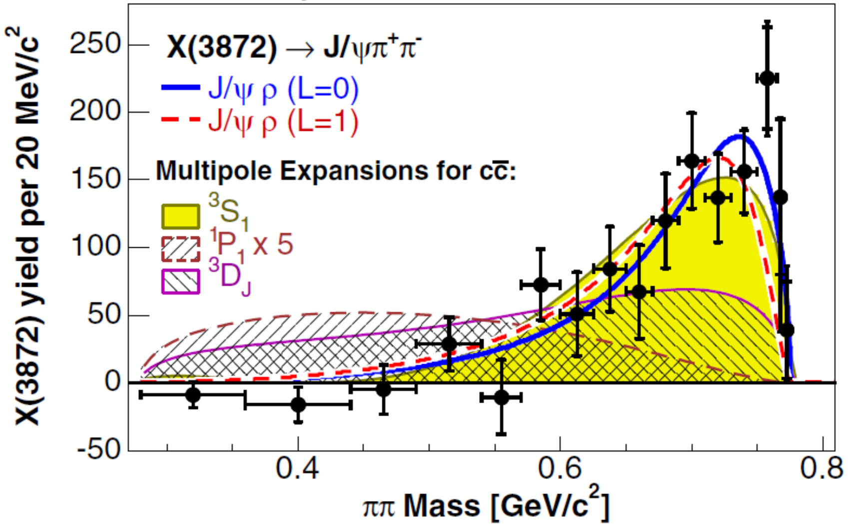
Testing the Quantum Numbers of the X(3872)

$X(3872) \to J/\psi\ 2\pi$
S-wave preferred

Belle, arXiv:hep-ex/0505038

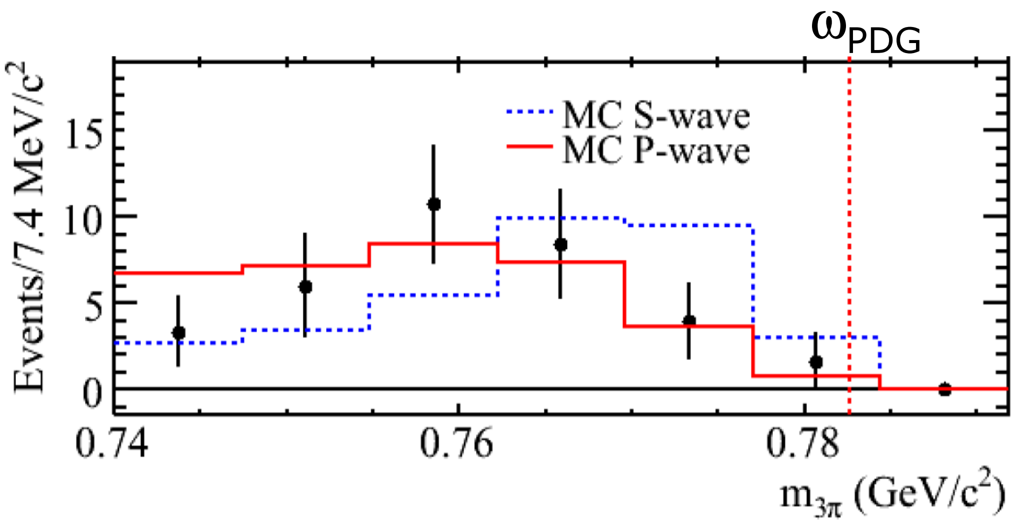


CDF-II, PRL 96(2006)102002



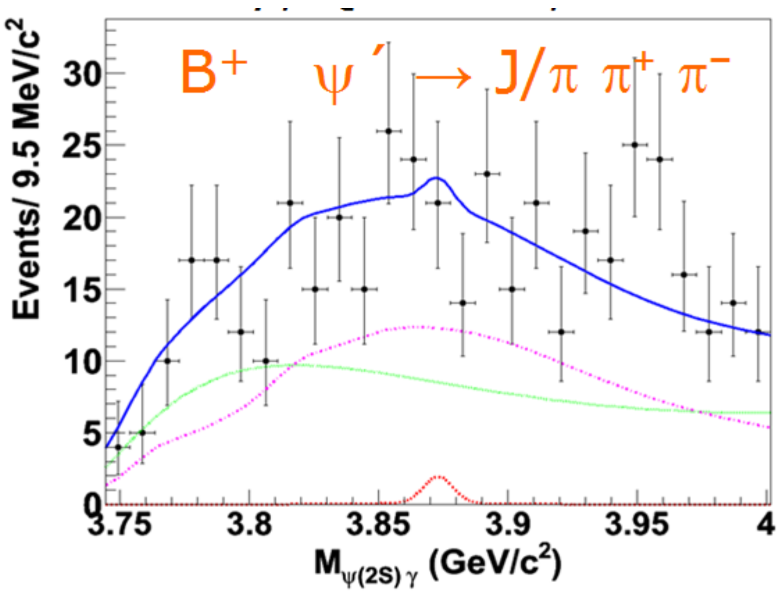
$X(3872) \to J/\psi\ 3\pi$
P-wave preferred

BaBar, arXiv:1005.5190, 433/fb



X(3872): Notes

- If X(3872) is $^1D_2$
  then it is S=0
  transition to J/ψ = spin-flip!
  M1 transition. Must be suppressed.
  Example:
  E1 $\psi' \to \gamma\, \chi_{c1}$ BR=9.2±0.4 %
  M1 $\psi' \to \gamma\, \eta_c$ BR=0.34±0.05 %
  (although phasespace larger)



-

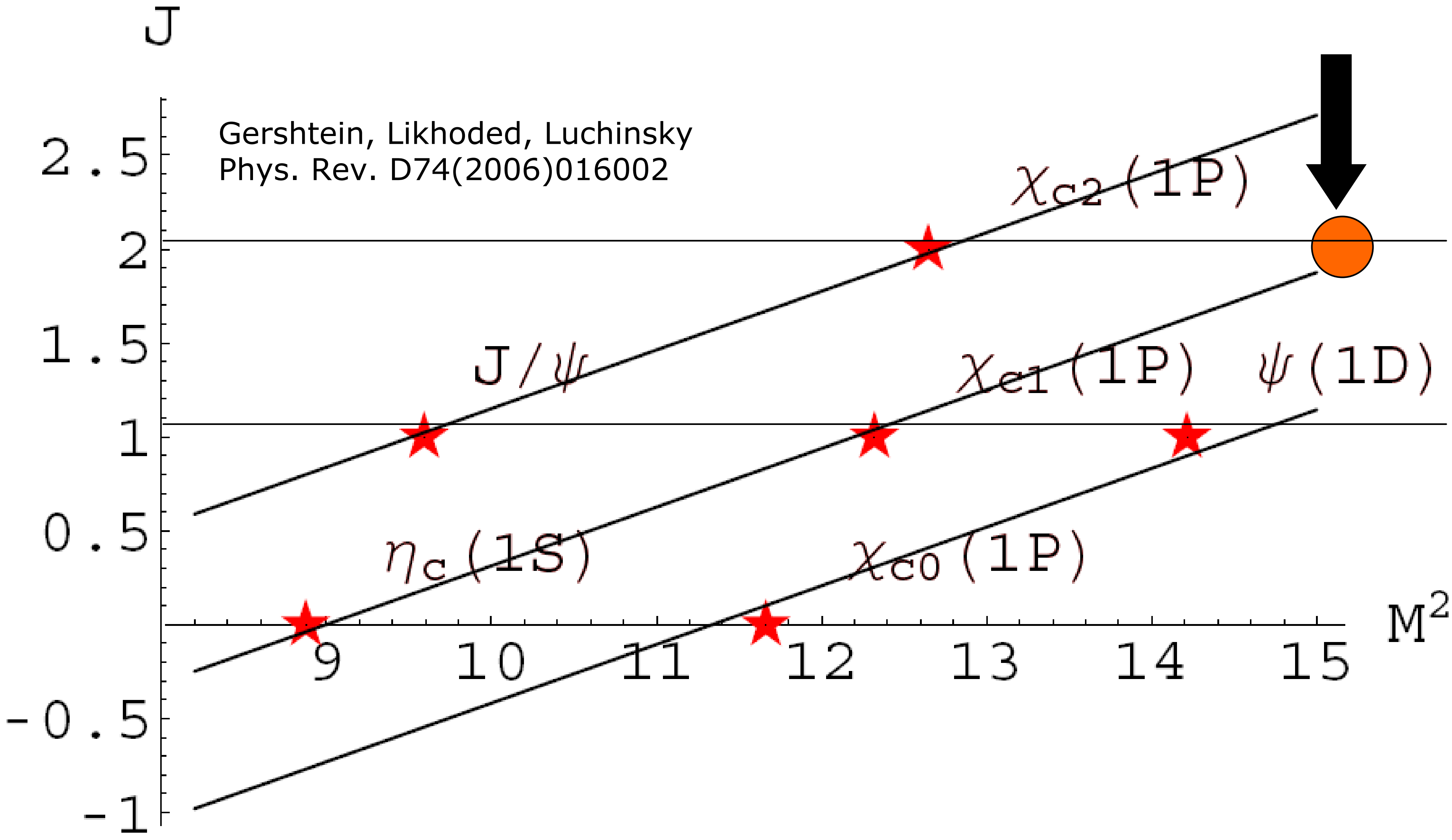
	$^3P_1$	$^1D_2$
LS term	−2	zero
Tensor term	+2/3	+2/3

$$+\alpha_s \frac{j(j+1)-l(l+1)-S(S+1)}{m_q^2}\left\langle\frac{1}{r^3}\right\rangle + \alpha_s \frac{S_{12}}{3m_q^2}\left\langle\frac{1}{r^3}\right\rangle$$

$^1D_2$ mass prediction ~50 MeV too low
Barnes, Godfrey, Swanson, Phys. Rev. D72(2005)054026

Regge Trajectories

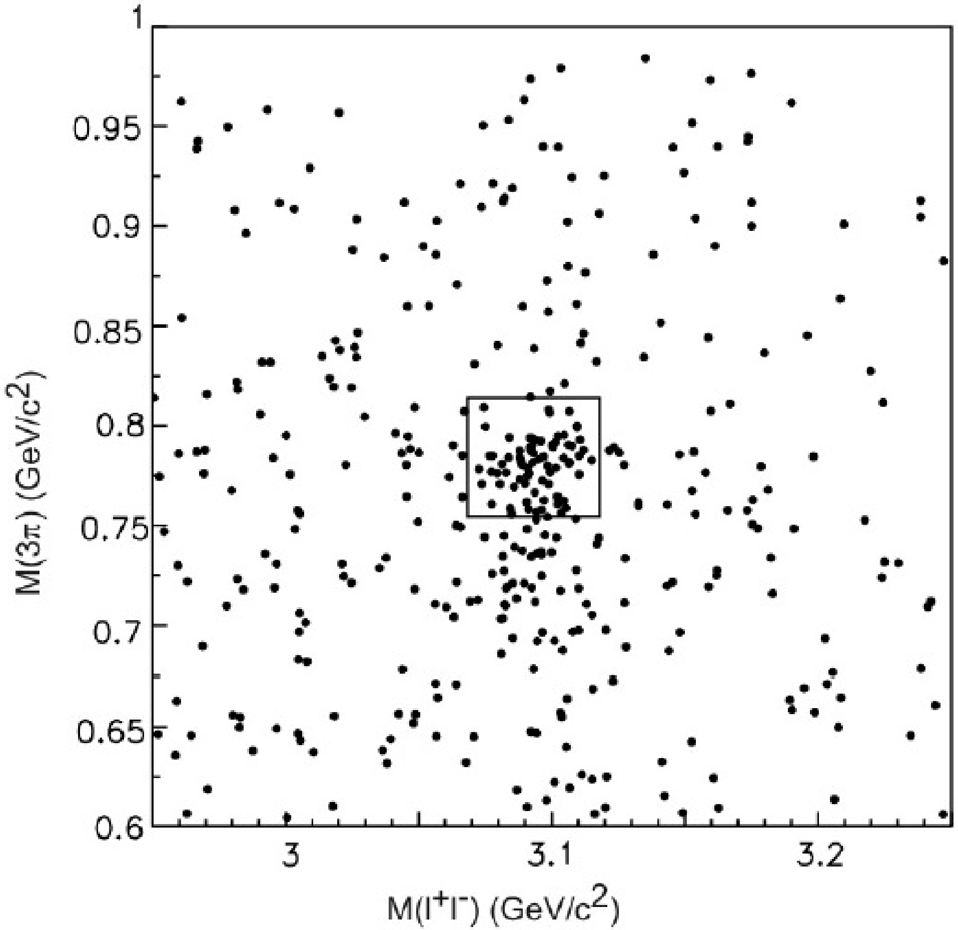
if X(3872) is J=2

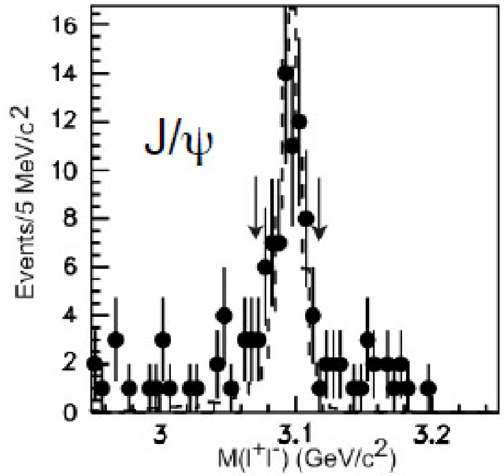


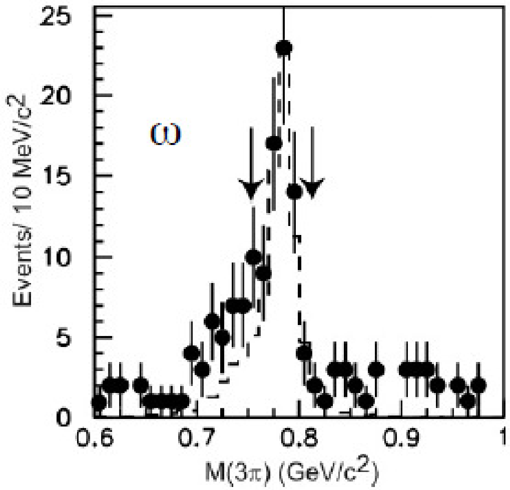
$\gamma\gamma \rightarrow J/\psi\ \omega$

694/fb
includes Y(3S) and Y(5S) data

- Belle, Phys. Rev. Lett. 104(2010)092001
- Final state 2 vector mesons with I=0





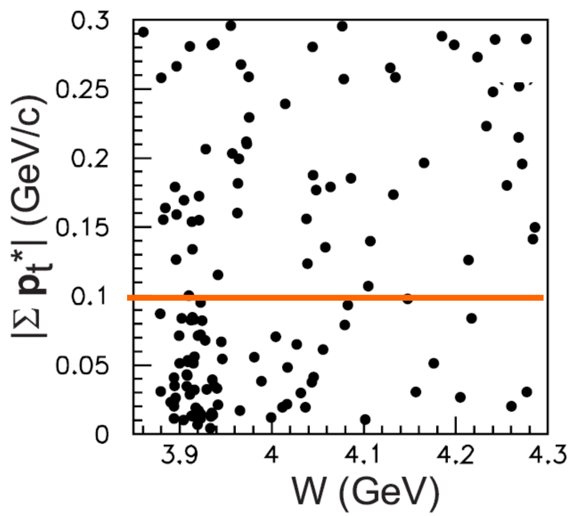


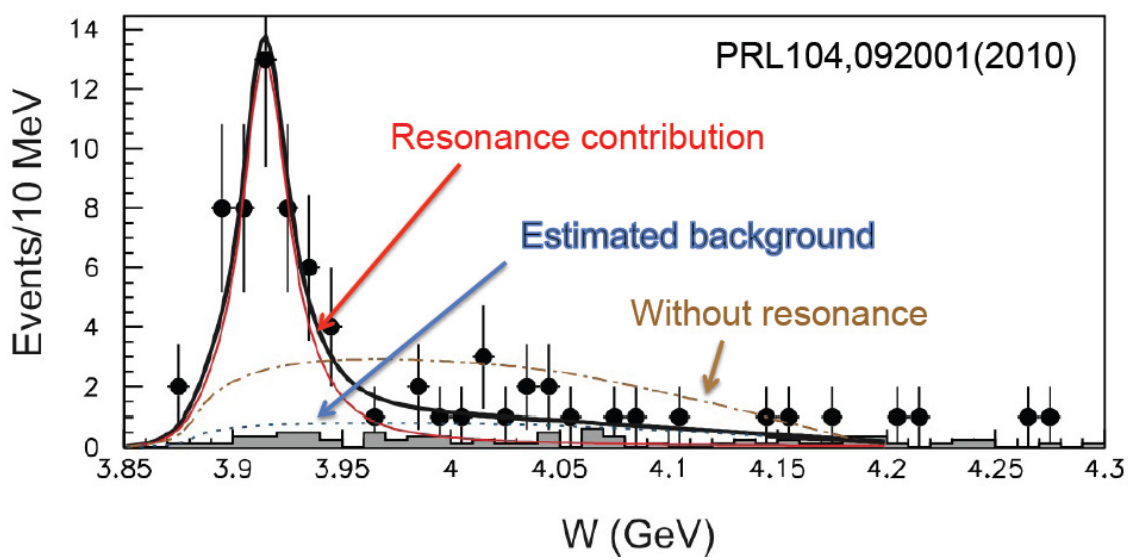
Event selection:
4 tracks
Net charge=0
π^0 candidate
Lepton ID
K rejection
P_T balance

$\gamma\gamma \to J/\psi\ \omega$

- $\gamma\gamma$ collision signal region (P_T < 0.1 GeV)
- Clear enhancement seen just above J/ψ ω threshold
- 7.7σ (stat.)
  49±14(stat.)±4(syst.) events
- M=3915±3(stat.)±2(syst.) MeV
- Γ=17±10(stat.)±3(syst.) MeV
- C=even, but J^P not yet determined (need much more statistics)
- Is this the Y(3940)? (in a 2nd production mode)

Belle





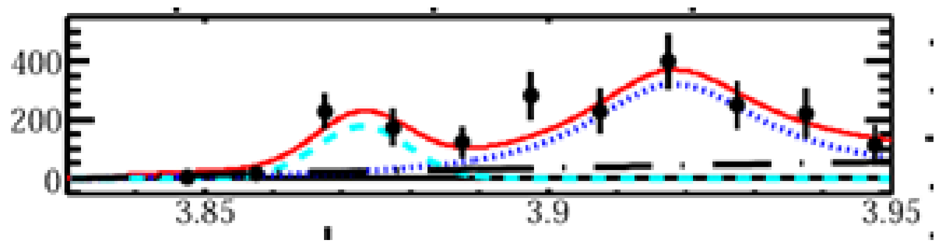
If this state is the Y(3940), it implies:

in $\gamma\gamma$ collisions $J^{PC}=1^{++}$ or 2^{-+} can not be produced

(only 0^{++}, 0^{-+}, 2^{++})

X(3872) and Y(3940) would have different J^{PC}

$\rightarrow$ mixing forbidden (in B decays)



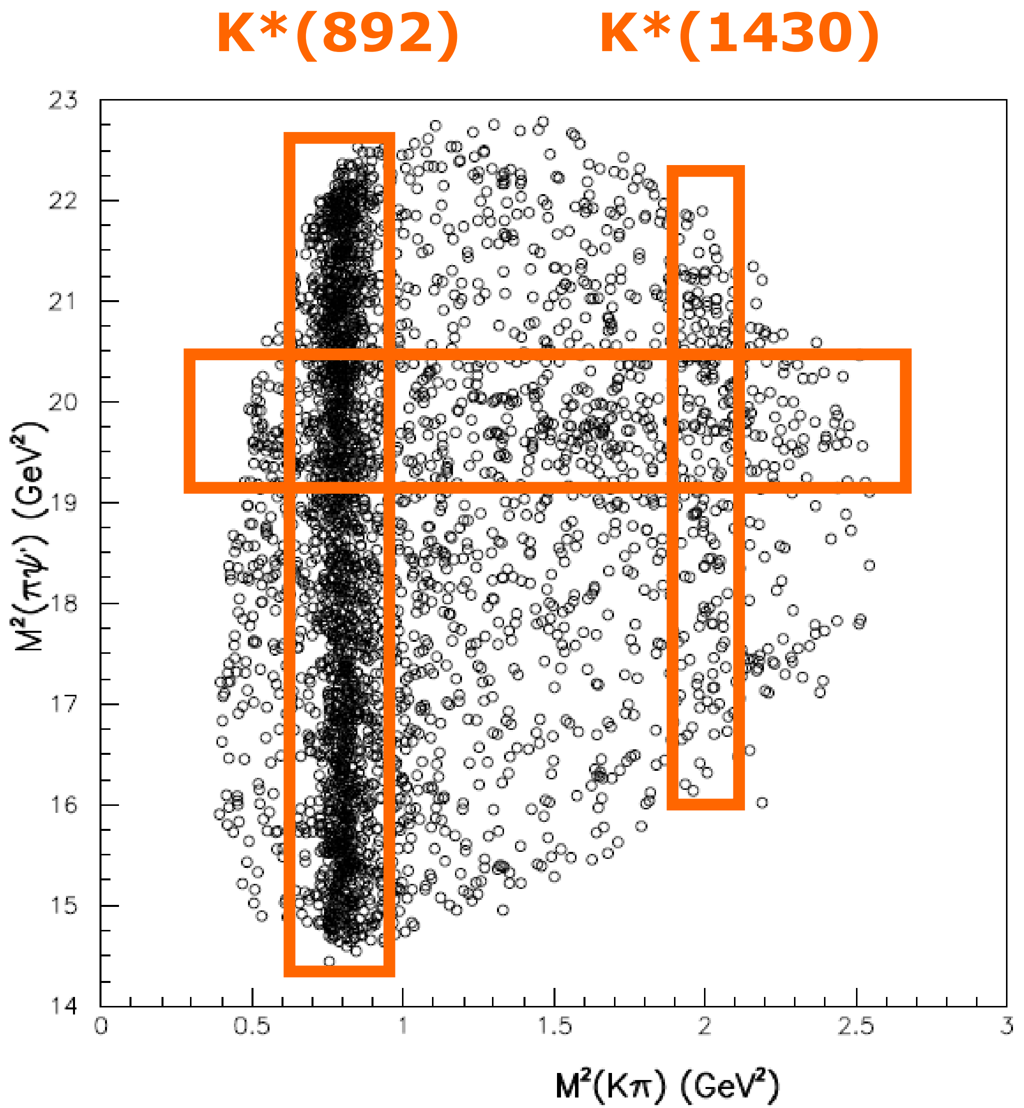
M(J/ψω) / GeV

(see p. 29)

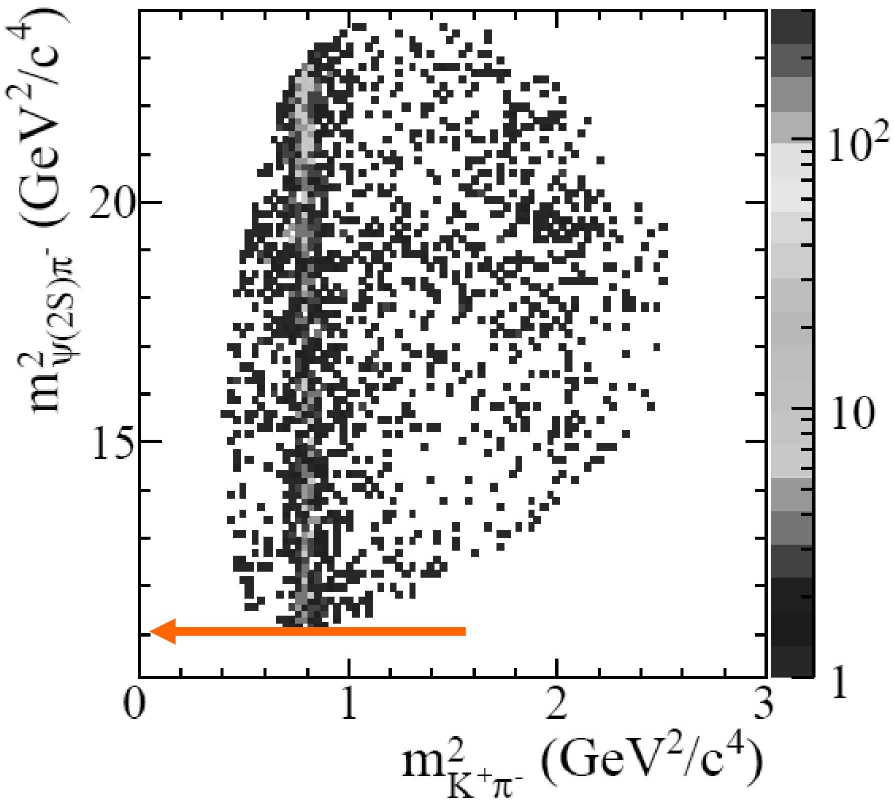
$Z(4430)^+$

A charged charmonium(-like) state.

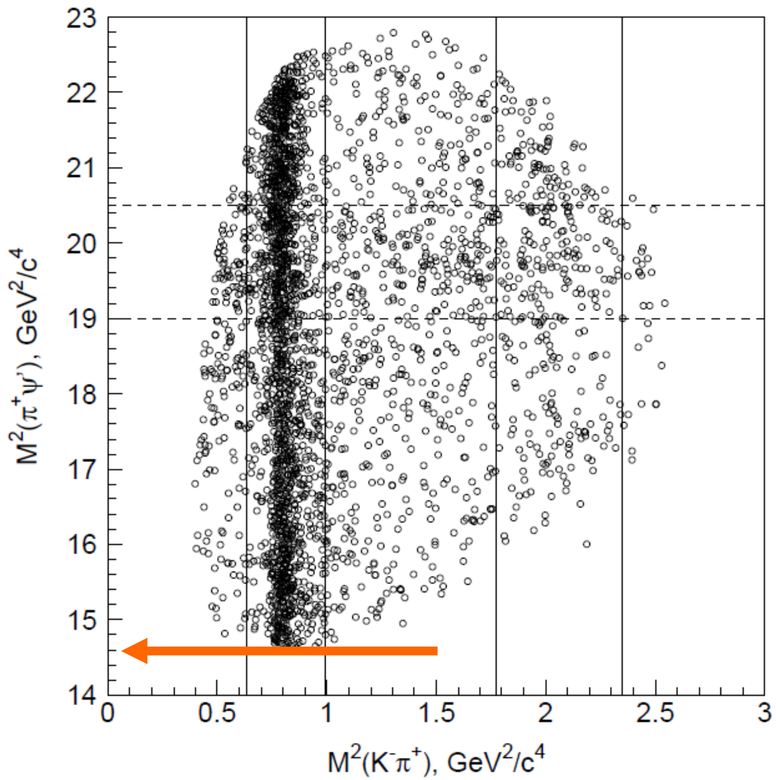
$B^0 \to K^+ \psi' \pi^-$



Z(4430)+



BaBar
Phys. Rev. D79(2008)112001
413/fb

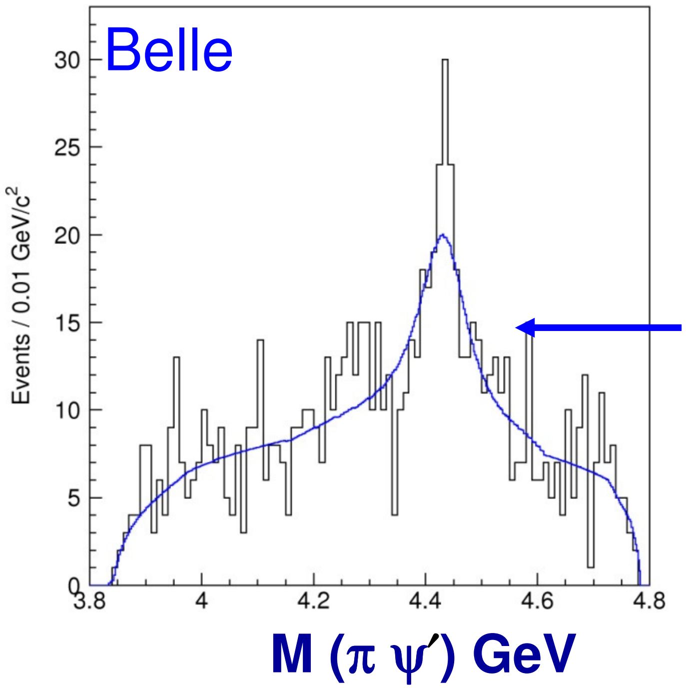


Belle
Phys. Rev. D80(2009)031104
605/fb

Dalitz plot shows same features, although different range.

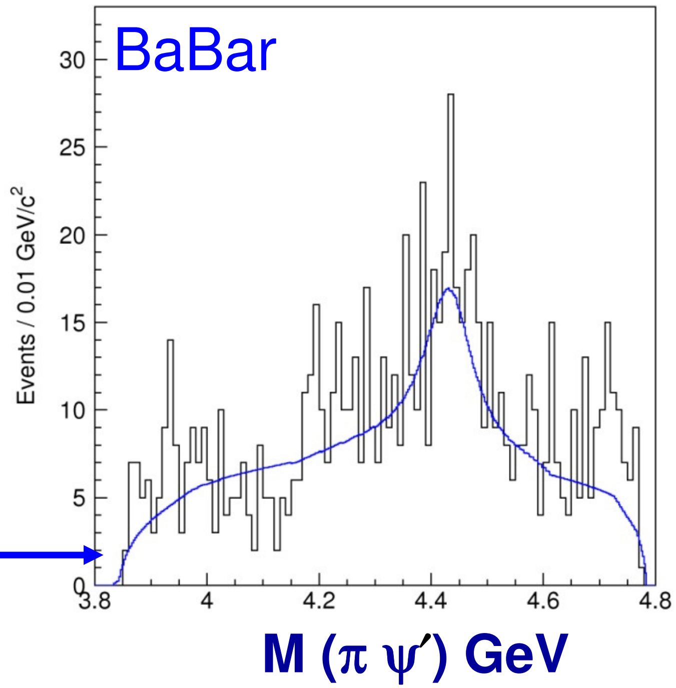
Belle and BaBar data look similar.

with K* veto



Result of Belle Dalitz fit analysis.

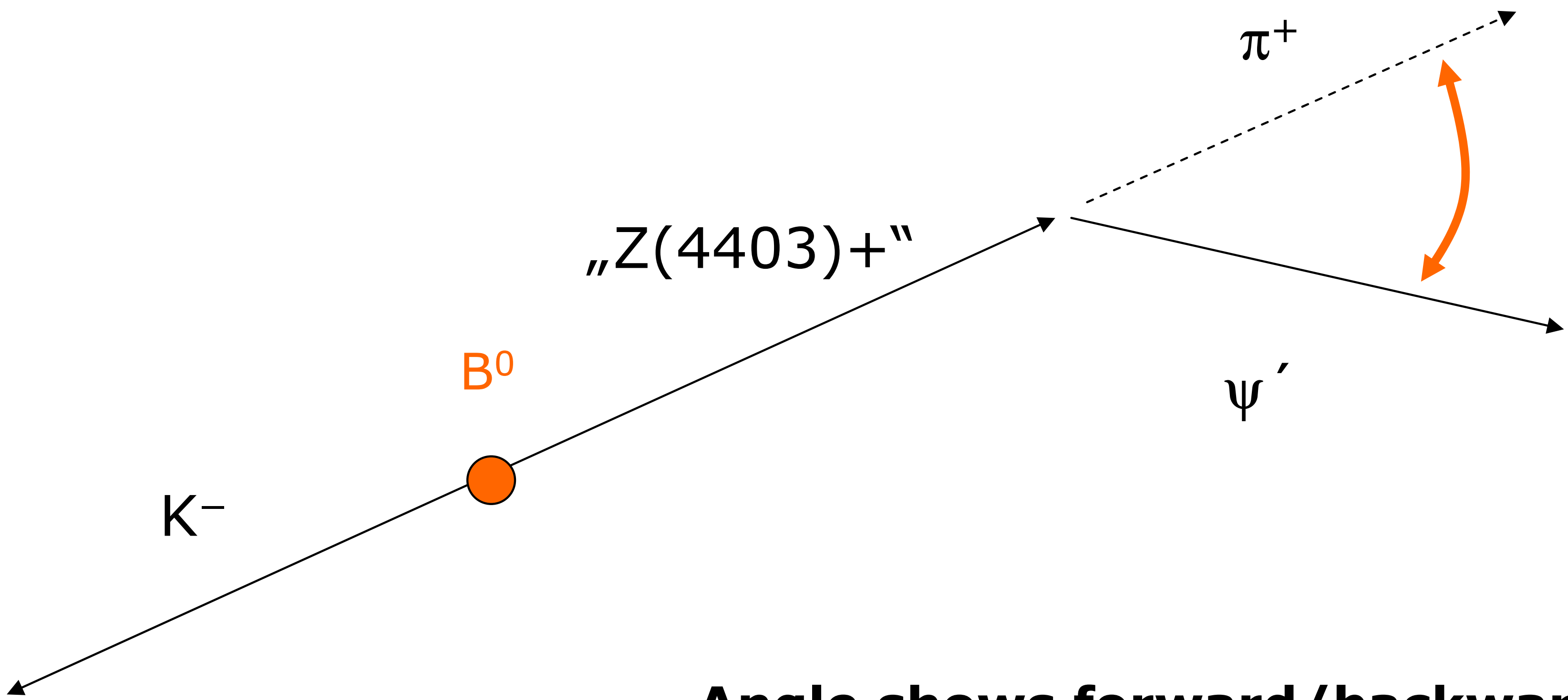
The same curve divided by 1.18 (scaled with Integrated luminosity)



Enhancement in **Mass(πψ′)** is seen in both data samples, only interpretation is different.

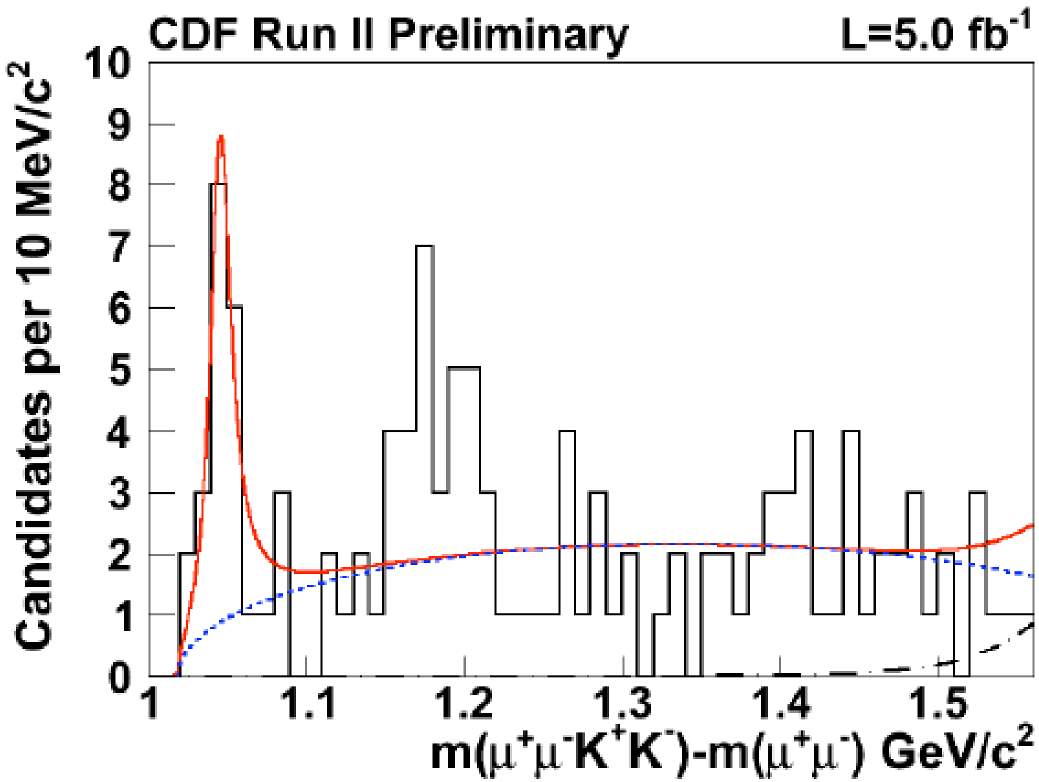
K* is peaking with respect to this angle

in B meson rest frame



Angle shows forward/backward asymmetry for K*
(because of P-wave ?)

$B^+ \to K^+\, Y(4140)(\to J/\psi\phi)$



Signal PDF: S-wave BW convoluted with resolution (1.7 MeV)

Background PDF: 3-body phase space (blue dot)

Fixed component for Bs component (black dot dash)

Δm, Γ consistent with previous result, yield is increased

Result w/ 5.0 fb^{-1}:

Yield = 19 ± 6

Δm = $1046.7^{+2.9}_{-3.0}$ MeV/c^2

Γ = $15.3^{+10.4}_{-6.1}$ (stat) MeV/c^2

$\sqrt{(-2\log(L_{max})/L_0)}$ = 5.91

Result w/ 2.7 fb^{-1}:

Yield = 14 ± 5

Δm = 1046.3 ± 2.9 (stat) MeV/c^2

Γ = $11.7^{+8.3}_{-5.0}$ (stat) MeV

8

Kai Yi et al., ICHEP 2010

Analysis with 2.7/fb in Phys. Rev. Lett. 102(2009)242002

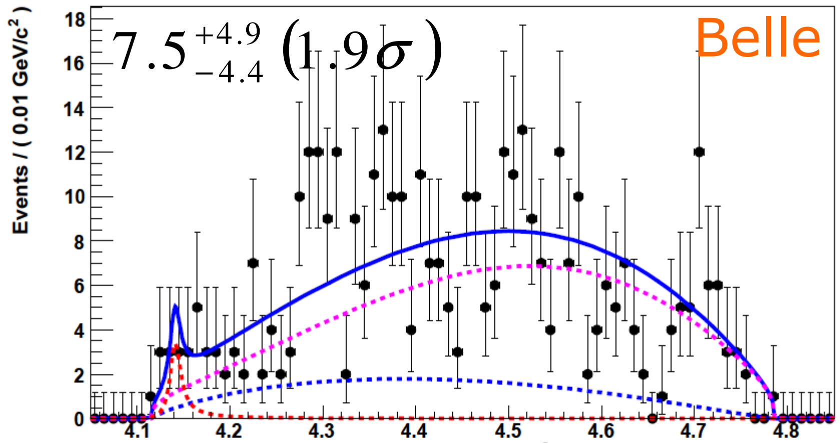
$B^+ \to K^+\ Y(4140)(\to J/\psi\phi)$

- $D_s^{0*}\ D_s$ molecule?
  - Beware:
    there is no neutral $D_s^{(*)}$ meson.
  - $m(D_s^+) + m(D_s^+) = 3937$ MeV
    $\to$ too low.
  - $m(D_s^{+*}) + m(D_s^+) = 4286$ MeV
    $\to$ too high
- $J/\psi\ \phi$ molecule?
  - both neutral and heavy
  - $m(J/\psi) + m(\phi) = 4116$ MeV
  - close, but positive „binding energy"
    (would be a virtual state)

$Br(B^+ \to Y(4140)K^+)\ \times Br(Y \to J/\psi\phi)$

CDF $(9.0 \pm 3.4 \pm 2.9) \times 10^{-6}$

Belle $< 6 \times 10^{-6}$ at 90% CL

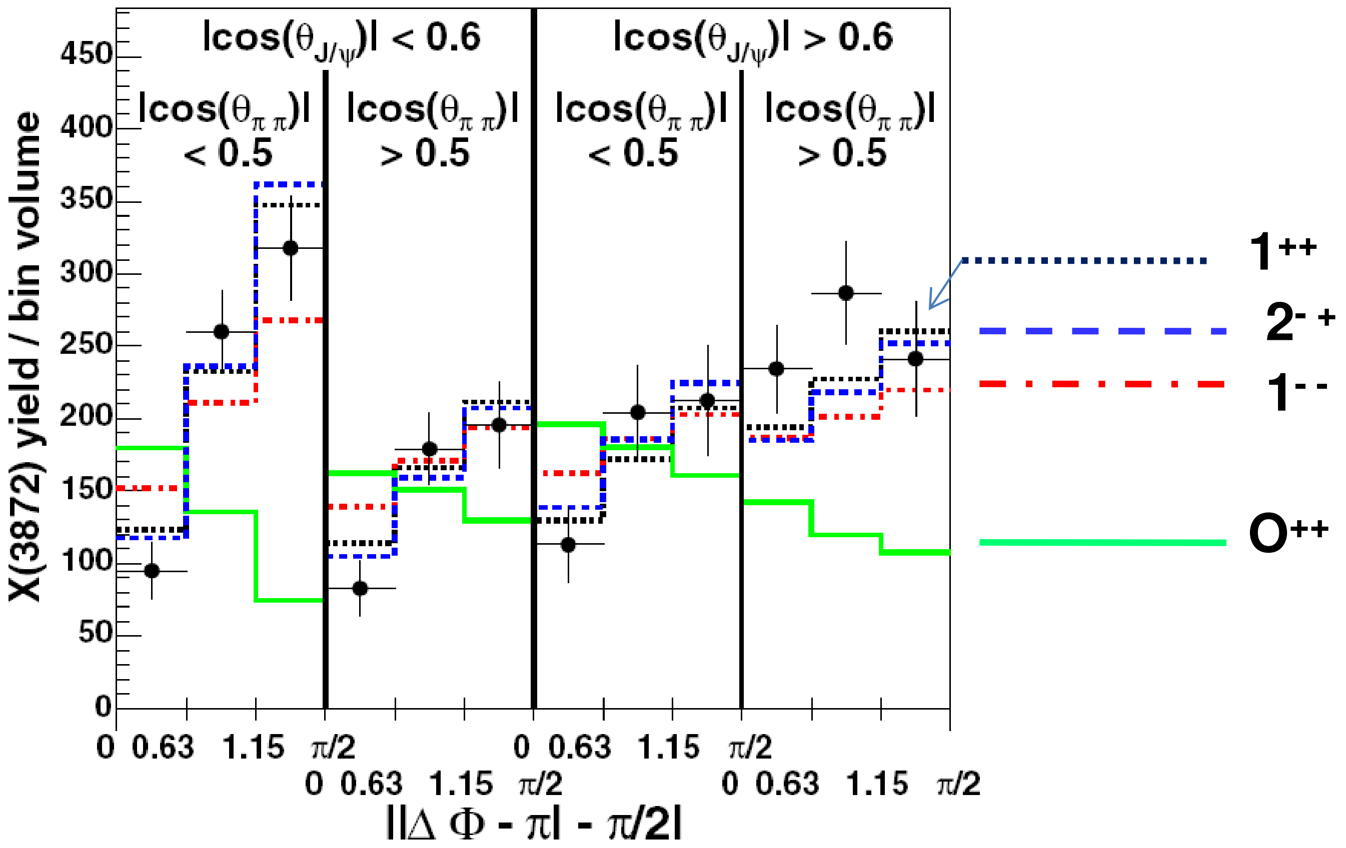


$M(J/\psi\phi)$ / GeV

Belle, Lepton-Photon-09
771/fb

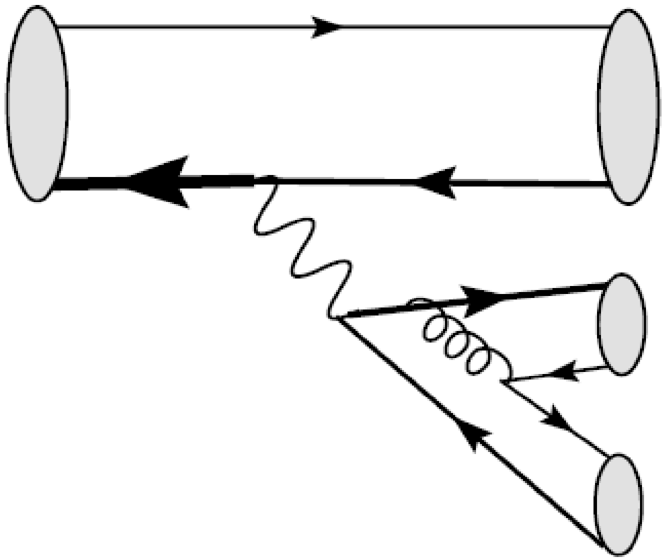
All J^{PC} values other than 1^{++} or 2^{-+} are ruled out with high confidence

CDF: PRL 98 132002

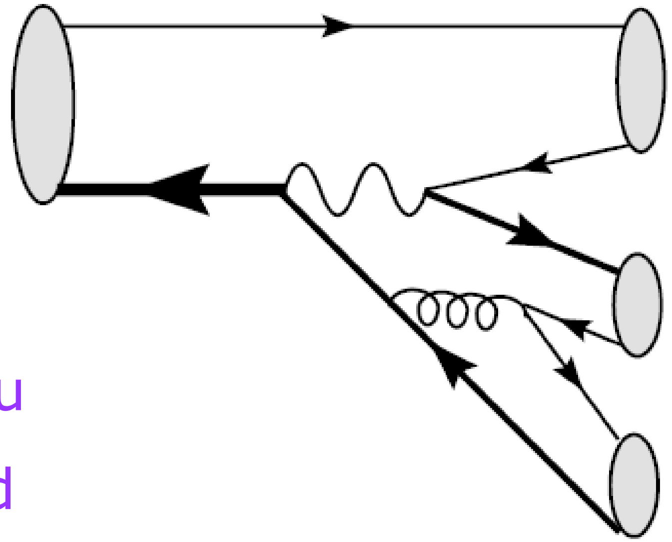


B^+ and B^0 decays are quite different.

Swanson, Phys. Rept. 429(2006)243



$B^+ = B_u$
$B^0 = B_d$



$B^0 \to K^+$
$B^0 \to K^0$
$B^+ \to K^+$
$B^+ \to K^0$
any combination possible

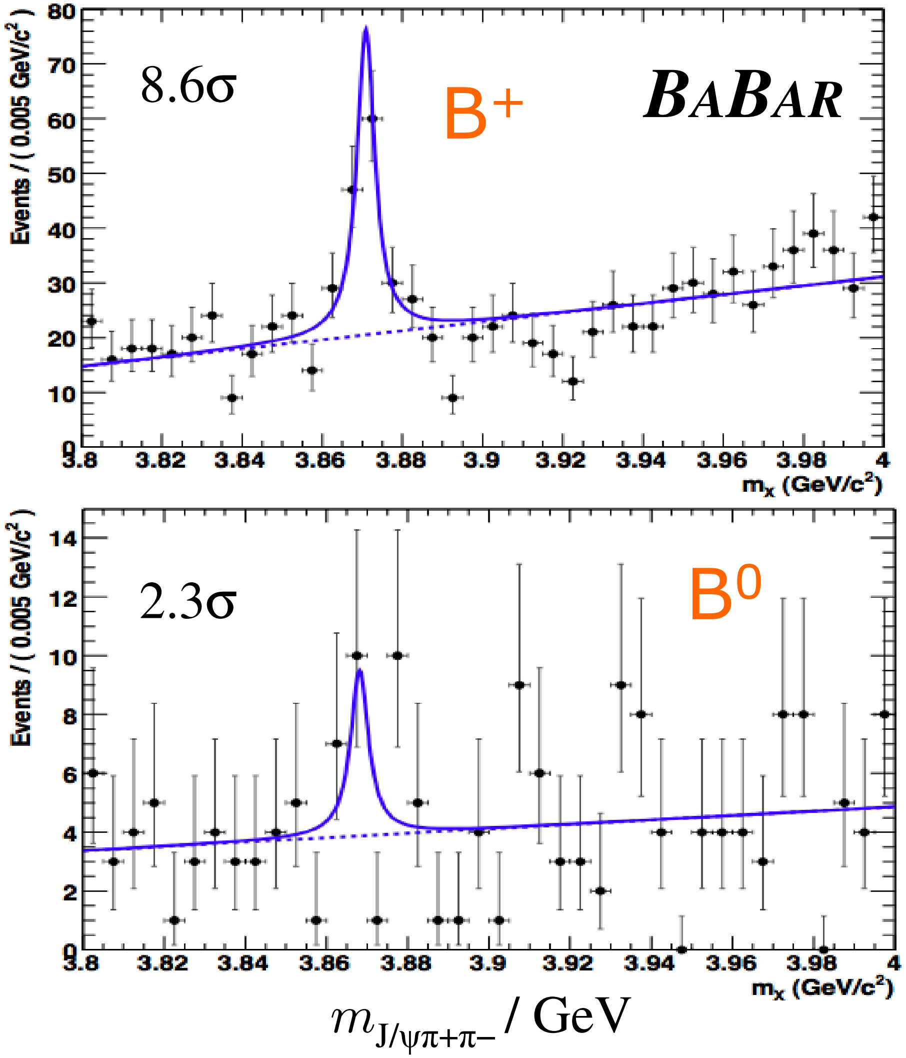
color enhanced

$B^+ \to K^+$
$B^0 \to K^0$
(charge sign changes by $W^\pm$,
and changes back,
$\to$ same charge for B and K)

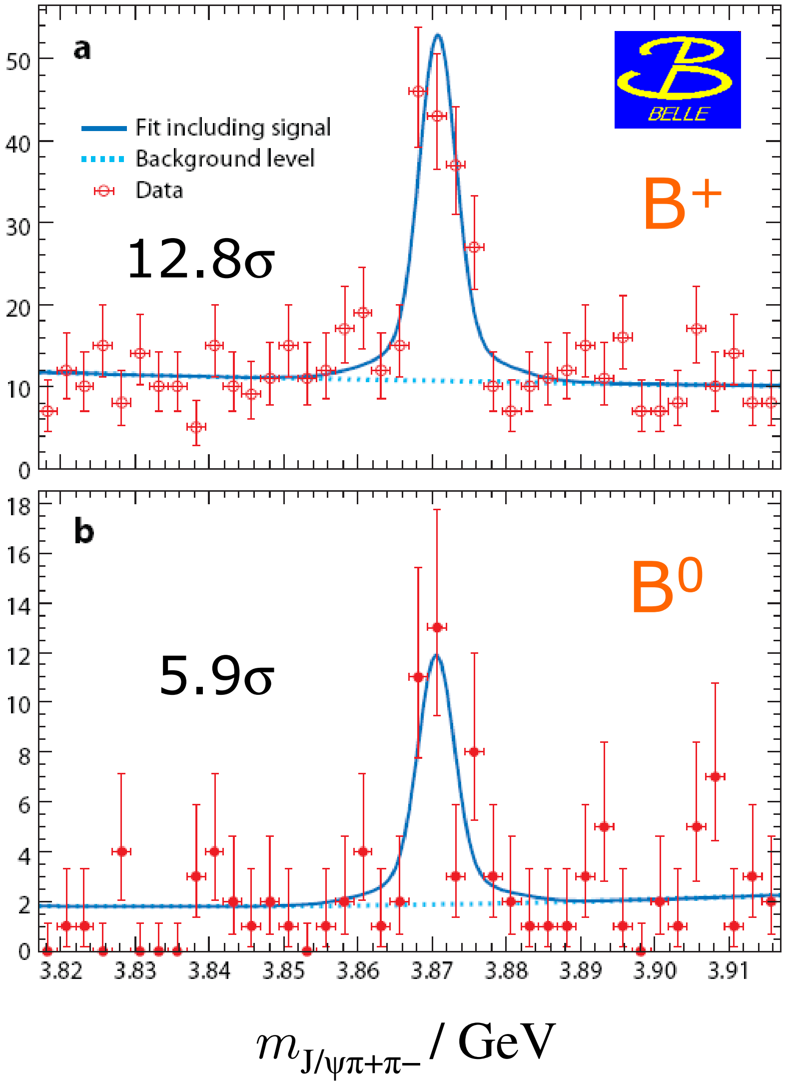
color suppressed
(color is locked by spectator quark)

X(3872)→J/ψπ⁺π⁻ in B⁺ and B⁰

Phys. Rev. D 77(2008)111101, 413/fb



arXiv:0809.1224, 605/fb



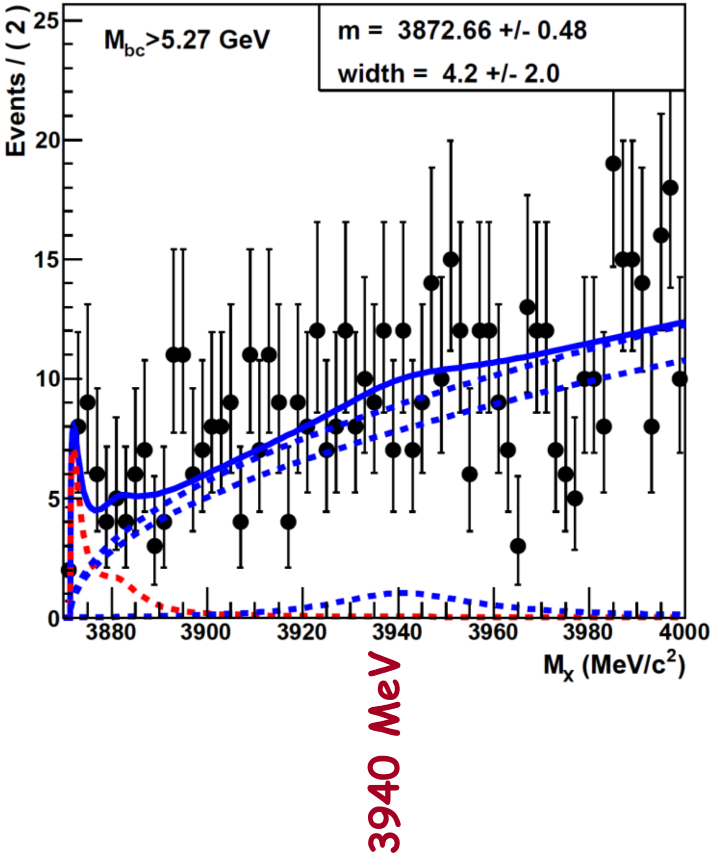
Ratio B^0/B^* = 0.82±0.22±0.05 (Belle)   0.41±0.24±0.05 (BaBar)

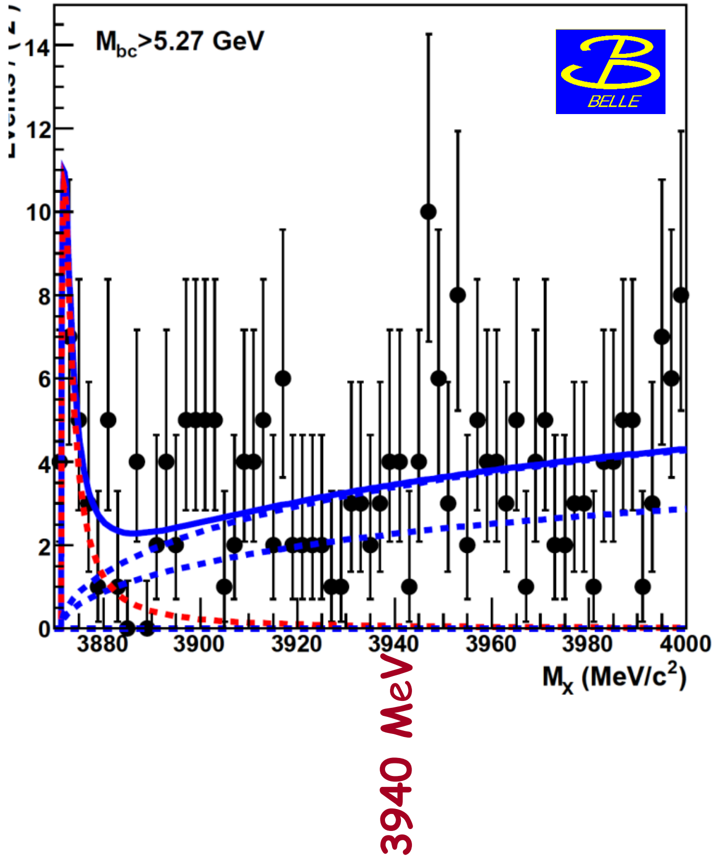
Predictions for molecule
e.g. Braaten, Lu,
Phys. Rev. D 77(2008)014029

Y(3940) → DD* ?

B→KDD*

ArXiv:0810.0358

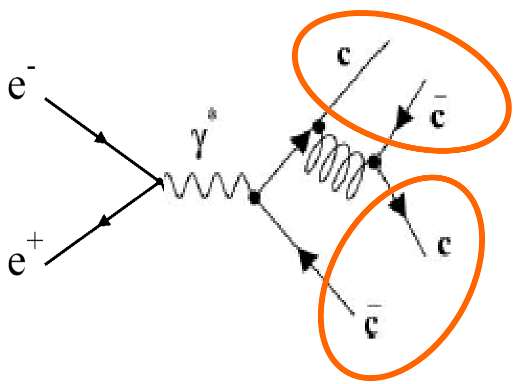




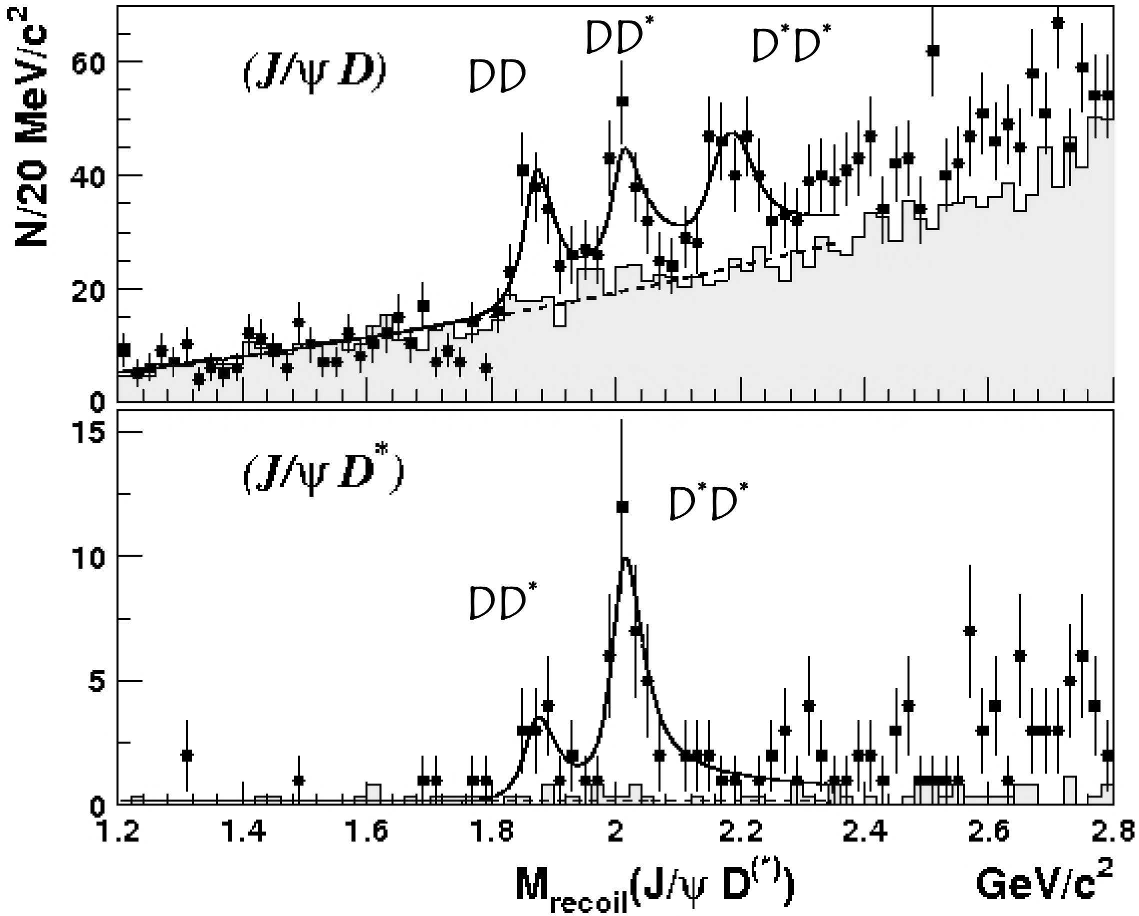
$$\frac{\mathcal{B}(Y(3940) \to \omega\, J/\psi)}{\mathcal{B}(Y(3940) \to D^{*0}\bar{D}^0)} > 0.75$$

C=+ States

Double charmonium production
Recoil mass
(direct production in continuum)



Belle, 693/fb, arXiv:0708.3812

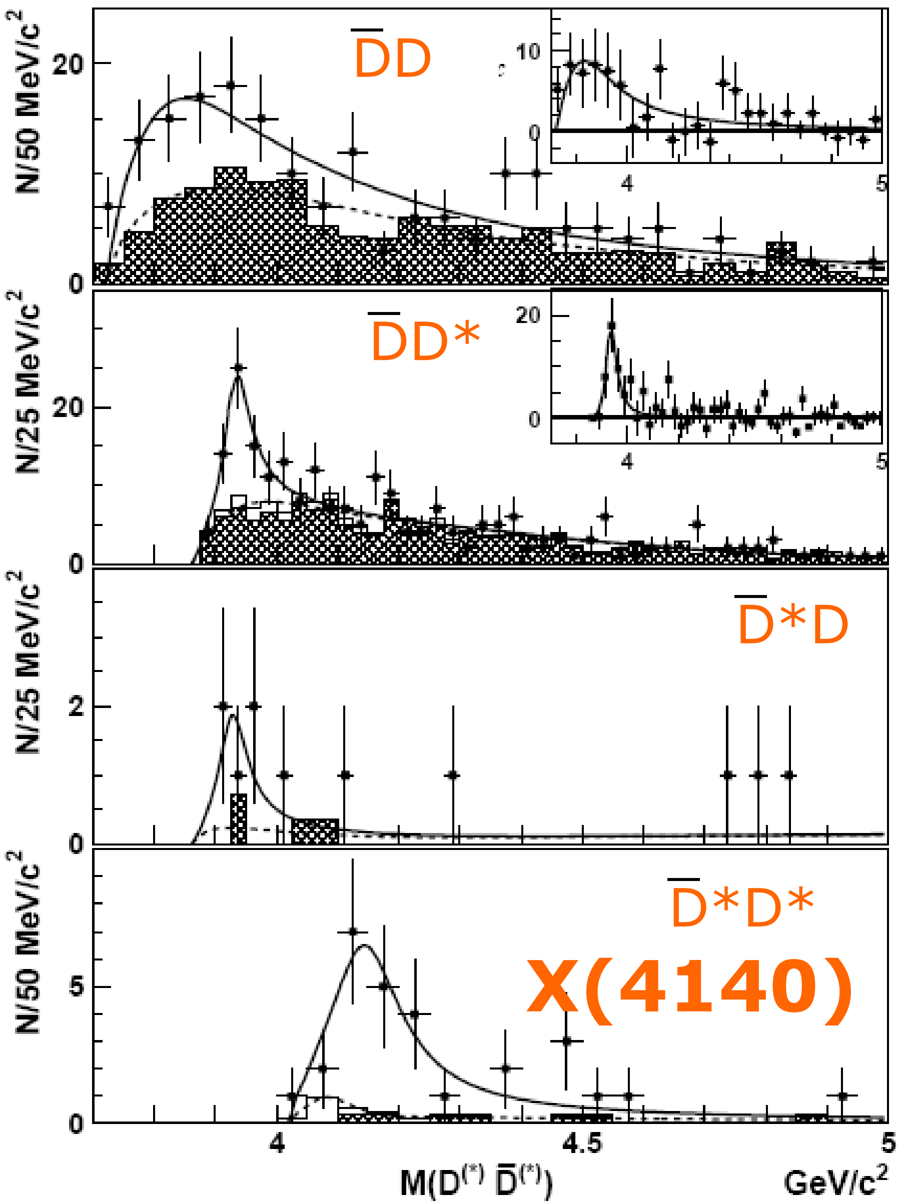


recoil = $D^{(*)}D^{(*)}$

C=+ preferred

High branching fraction
for this process unexplained
(probably non-pertubative QCD)

Any of the D(*)D(*) seems to indicate S-wave enhancement



Too high
for molecular
Hypothesis.

Constituents	J^{PC}	Mass [MeV]
$D\bar{D}^*$	0^{-+}	≈ 3870
$D\bar{D}^*$	1^{++}	≈ 3870
$D^*\bar{D}^*$	0^{++}	≈ 4015
$D^*\bar{D}^*$	0^{-+}	≈ 4015
$D^*\bar{D}^*$	1^{+-}	≈ 4015
$D^*\bar{D}^*$	2^{++}	≈ 4015

Predictions of molecular states
one-pion exchange model
Törnqvist
Phys. Lett. B590(2004)209
Phys. Rev. Lett. 67(1991)556

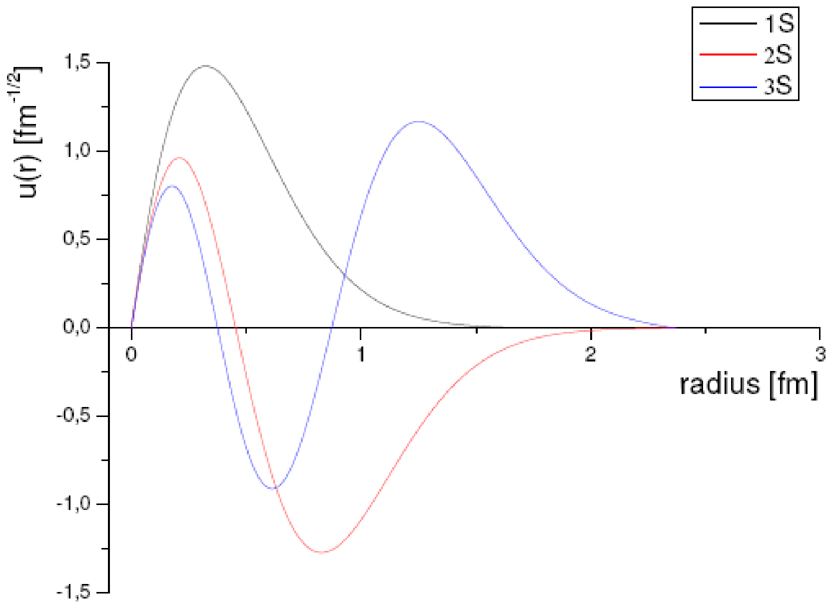
C=+ states

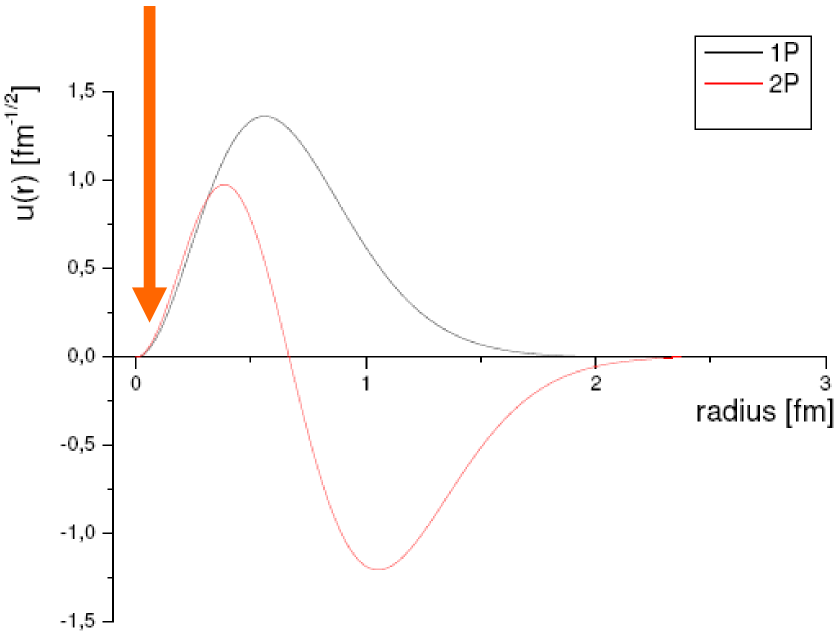
- Cannot annihilate to γ ($e^+ e^-$)
- only decay to γγ or gluon gluon

$$\Gamma(^3S_1 \to \gamma) = \frac{65\pi}{9}\frac{\alpha_{em}}{m_c^2}|\psi(r=0)|^2$$

$$\Gamma(^3P_0 \to \gamma\gamma) = \frac{256}{3}\frac{\alpha_{em}^2}{m_c^4}|\frac{\partial\psi}{\partial r}(r=0)|^2$$

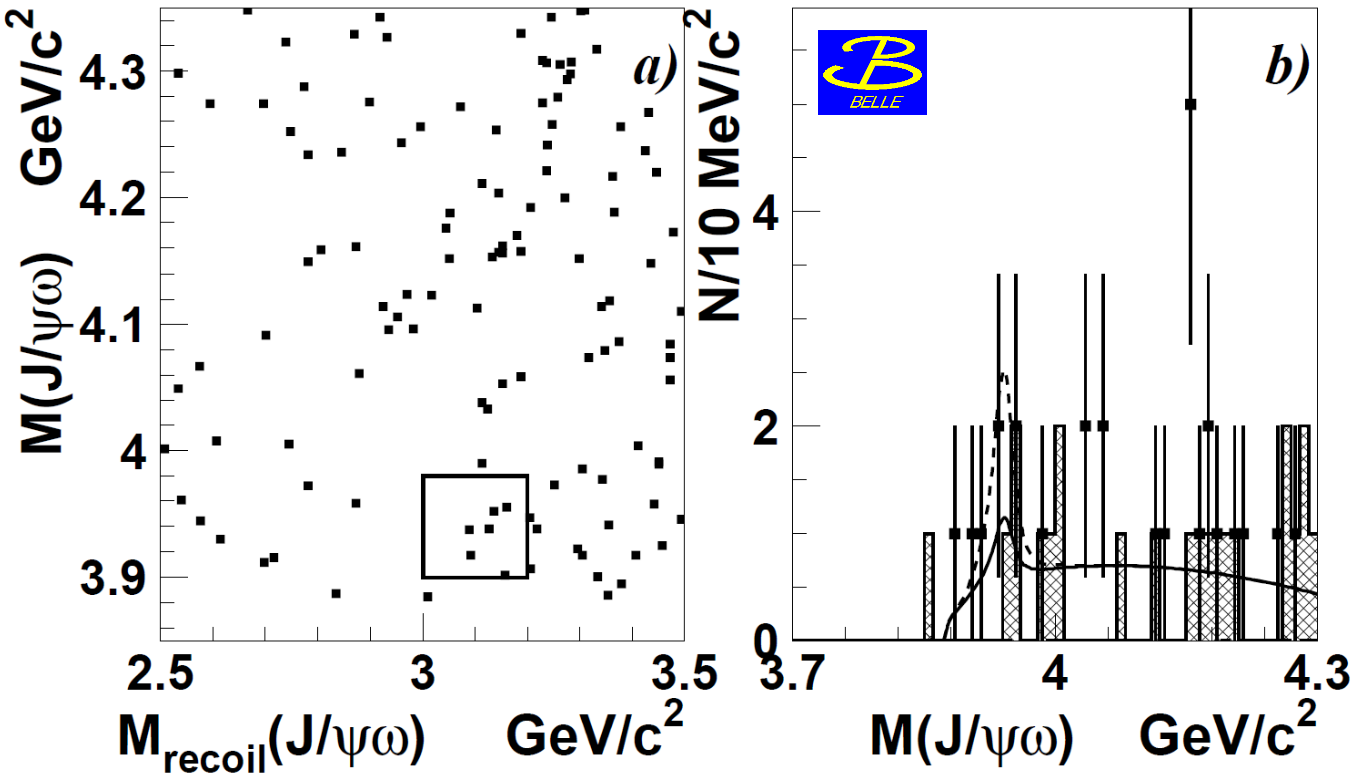
sensitive to derivative of wavefunction





[ωJ/ψ] in double charmonium production?

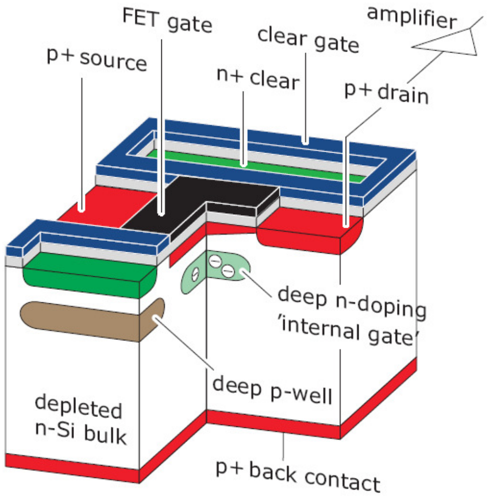
$e^+e^- \rightarrow J/\psi + (\omega\ J/\psi)$



Phys. Rev. Lett. 98(2007)082001

$$\frac{\mathcal{B}(X(3940) \rightarrow \omega\, J/\psi)}{\mathcal{B}(X(3940) \rightarrow D^{*0}\bar{D}^0)} < 0.6$$

A cross section through the device is shown in Fig. 4.3. A p-channel MOSFET or JFET (junction field effect transistor) is integrated onto a silicon detector substrate, which becomes fully depleted by a sufficiently high negative voltage to a p^+ contact on the back side. A potential minimum is formed by sideward depletion [4], which is shifted directly underneath the transistor channel at a depth of about $1\,\mu$m by an additional phosphorus implantation underneath the external gate. Incident particles generate electron-hole pairs within the fully depleted bulk. While the holes drift to the back contact, electrons are accumulated in the potential minimum, called the "Internal Gate". When the transistor is switched on, the electrons modulate the channel current. The readout is non-destructive and can be repeated many times.



The removal of the signal charge and thermally generated electrons from the internal gate is called "Clear". A neighboring n^+ contact is pulsed at a positive voltage providing a punch-through into the internal gate. Any reset noise is avoided if the entire charge is removed. An advantage of the DEPFET device is the amplification of the signal charge just above the position of its generation, thus avoiding any lateral charge transfer where losses could occur. The most important feature of the DEPFET is the very small capacitance of the internal gate, resulting in a very low noise performance even at room temperature.