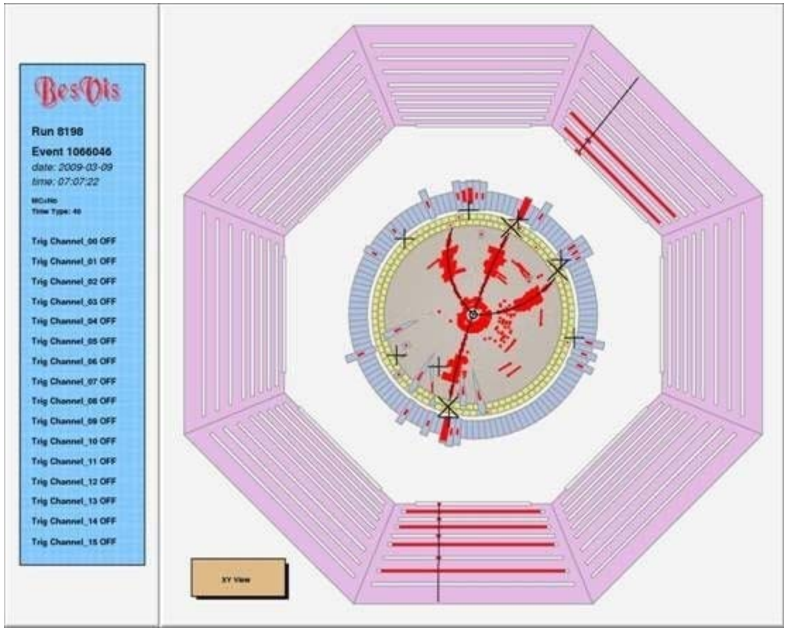
Charmonium
experimental overview

Stephen Lars Olsen
Seoul National University



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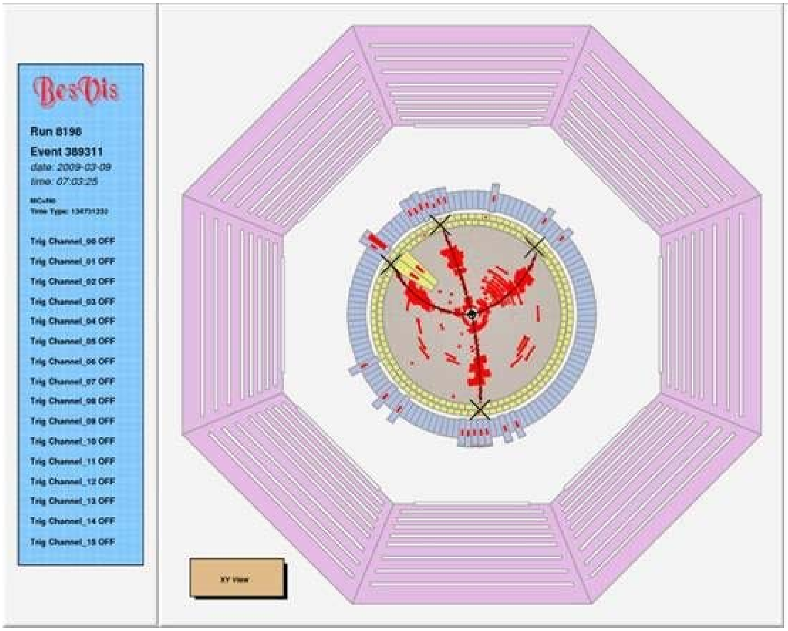

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Trig Channel_15 OFF

Topical Seminar on Frontier of Particle Physics
Hu Yu Village, Beijing CHINA
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outline

Lecture1: ~~History & the discovery of the bound charmonium states~~

Yesterday

Lecture 2: The non-charmonium, charmonium-like states & the future

Today

Summary (lecture 1)

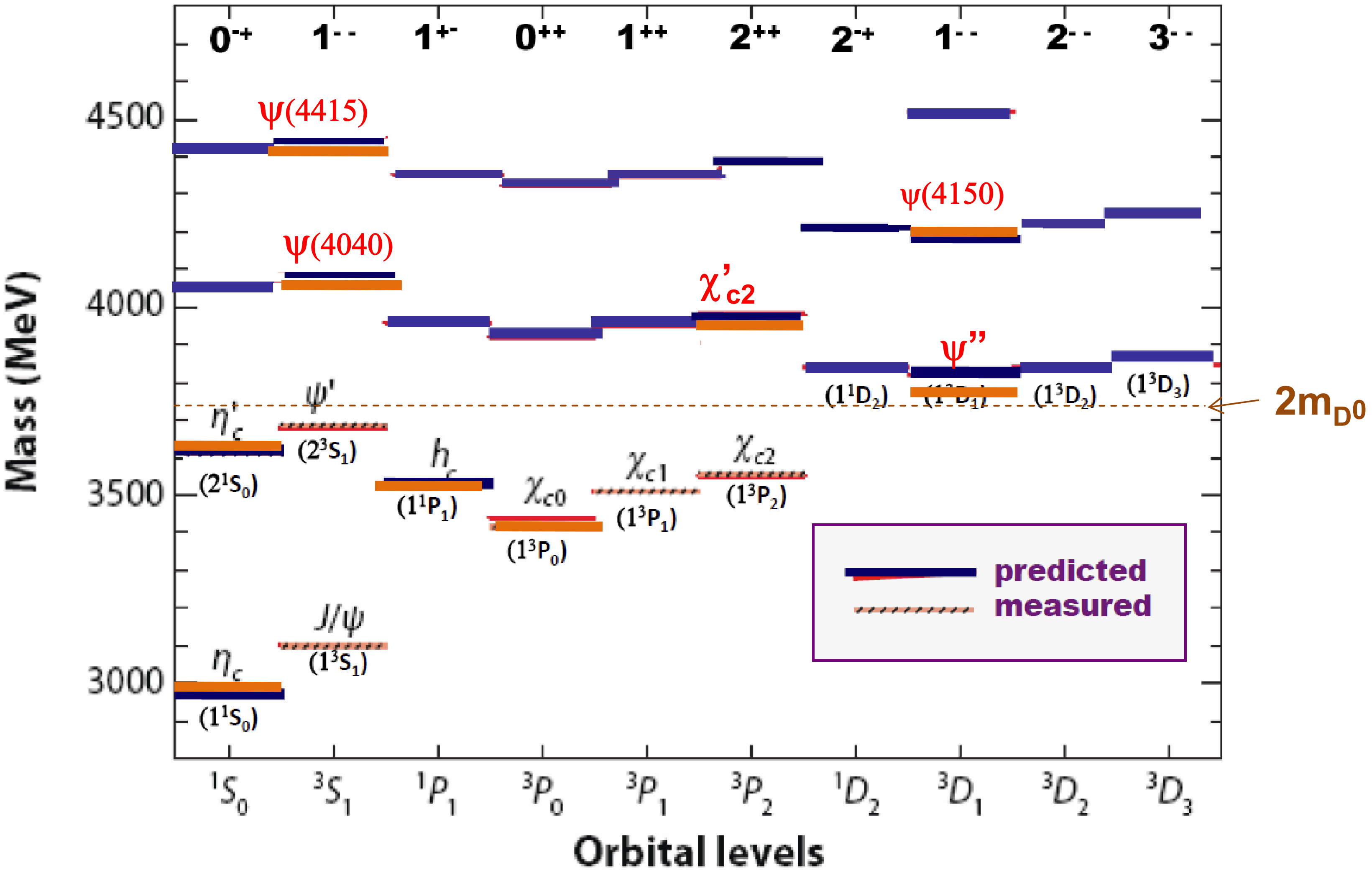
- The charmonium spectrum is strong evidence that hadrons are composed of spin=1/2 constituent particles

- All of the charmonium states below the $M=2m_D$ "open charm" threshold have been found

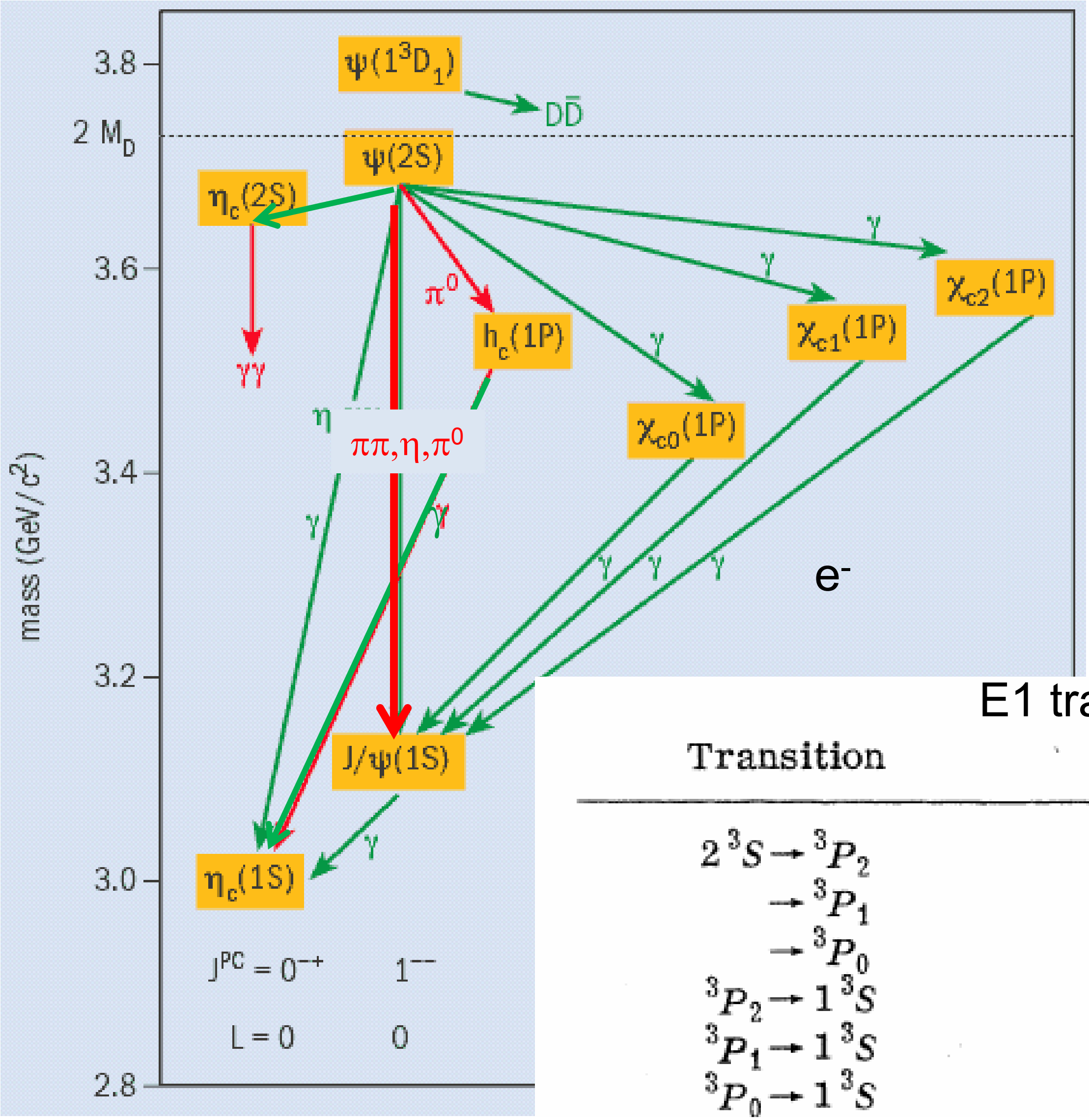
- Most of the above-threshold 1^{--} states & the χ_{c2}' have been identified

- The masses of the assigned states match theory predictions
  - variations are less than ~50 MeV

- Transitions between charmonium states are in reasonably good agreement with theoretical expectations


0-+
1--
1+-
0++
1++
2++
2-+
1--
2--
3--
Mass (MeV)
4500
4000
3500
3000
ψ(4415)
ψ(4040)
ψ(4150)
χ'c2
ψ''
2mD0
η'c
ψ'
(2¹S₀)
(2³S₁)
hc
(1¹P₁)
χc0
(1³P₀)
χc1
(1³P₁)
χc2
(1³P₂)
(1¹D₂)
(1³D₁)
(1³D₂)
(1³D₃)
J/ψ
(1³S₁)
ηc
(1¹S₀)
predicted
measured
¹S₀
³S₁
¹P₁
³P₀
³P₁
³P₂
¹D₂
³D₁
³D₂
³D₃
Orbital levels

γ Transitions



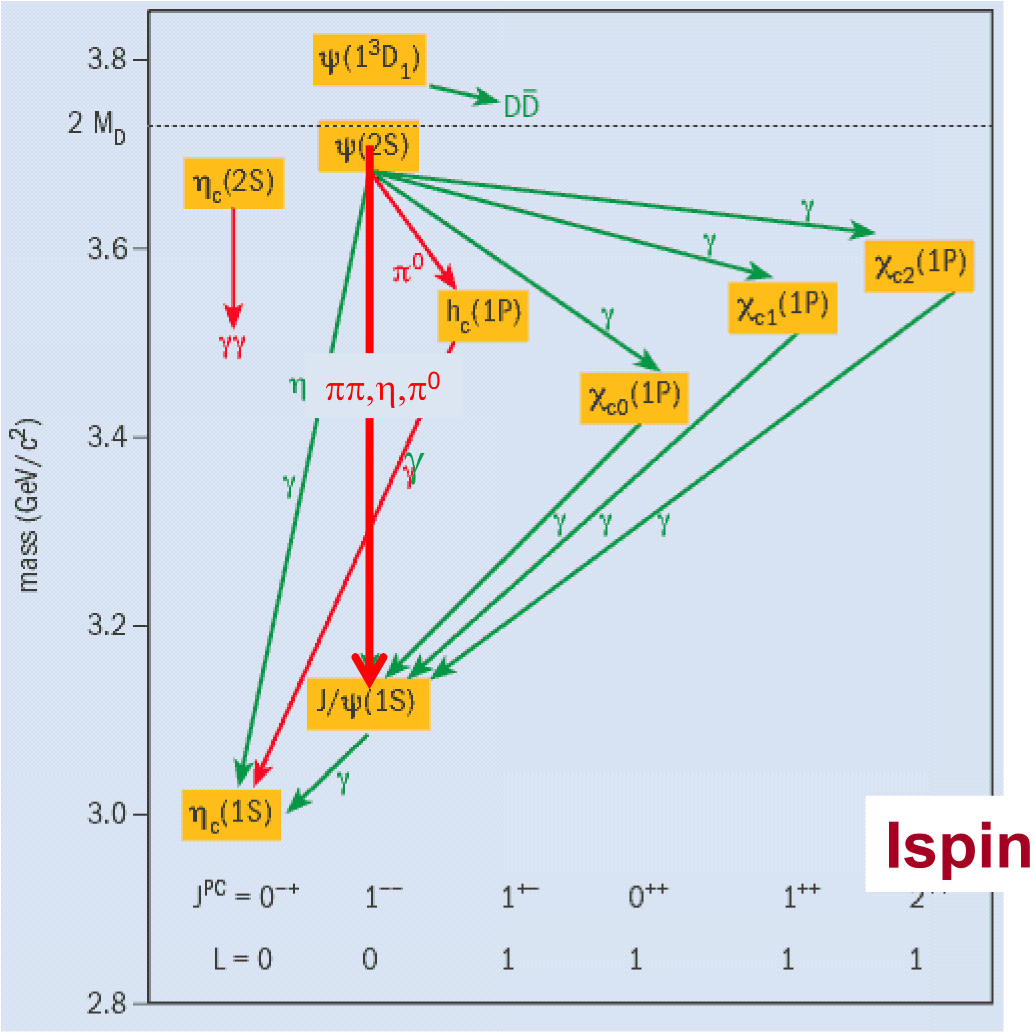
M1 transitions (Γ(keV))

	Th.	*Expt*
$J/\psi \rightarrow \gamma\, \eta_c$	*2.4*	*1.6 ± 0.4*
$\psi' \rightarrow \gamma\, \eta_c$	*4.6*	*1.1 ± 0.2*

E1 transitions

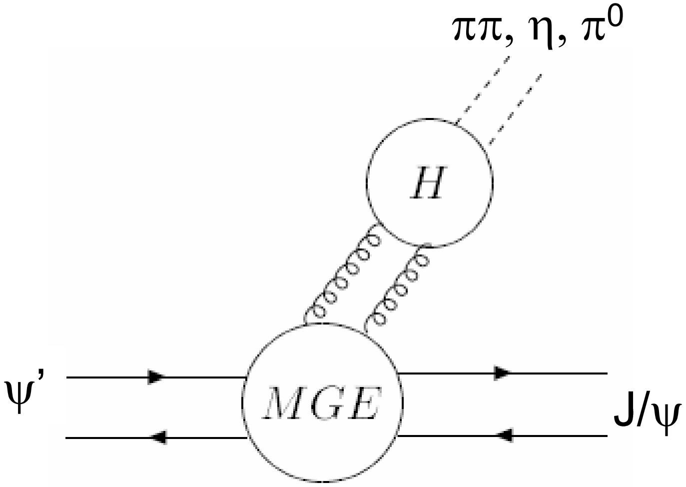
Transition	Γ_γ	Γ_γ (keV) *Th.*	*Expt*
$2\,^3S \rightarrow {}^3P_2$	$5 I_1 \alpha k^3$	*24*	*27 ± 4*
$\rightarrow {}^3P_1$	$3 I_1 \alpha k^3$	*29*	*27 ± 3*
$\rightarrow {}^3P_0$	$1 I_1 \alpha k^3$	*26*	*27 ± 3*
${}^3P_2 \rightarrow 1\,^3S$	$I_2 \alpha k^3$	*313*	*426 ± 51*
${}^3P_1 \rightarrow 1\,^3S$	$I_2 \alpha k^3$	*239*	*291 ± 48*
${}^3P_0 \rightarrow 1\,^3S$	$I_2 \alpha k^3$	*114*	*110 + 19*

Hadronic transitions



$\psi' \rightarrow J/\psi$ +hadrons

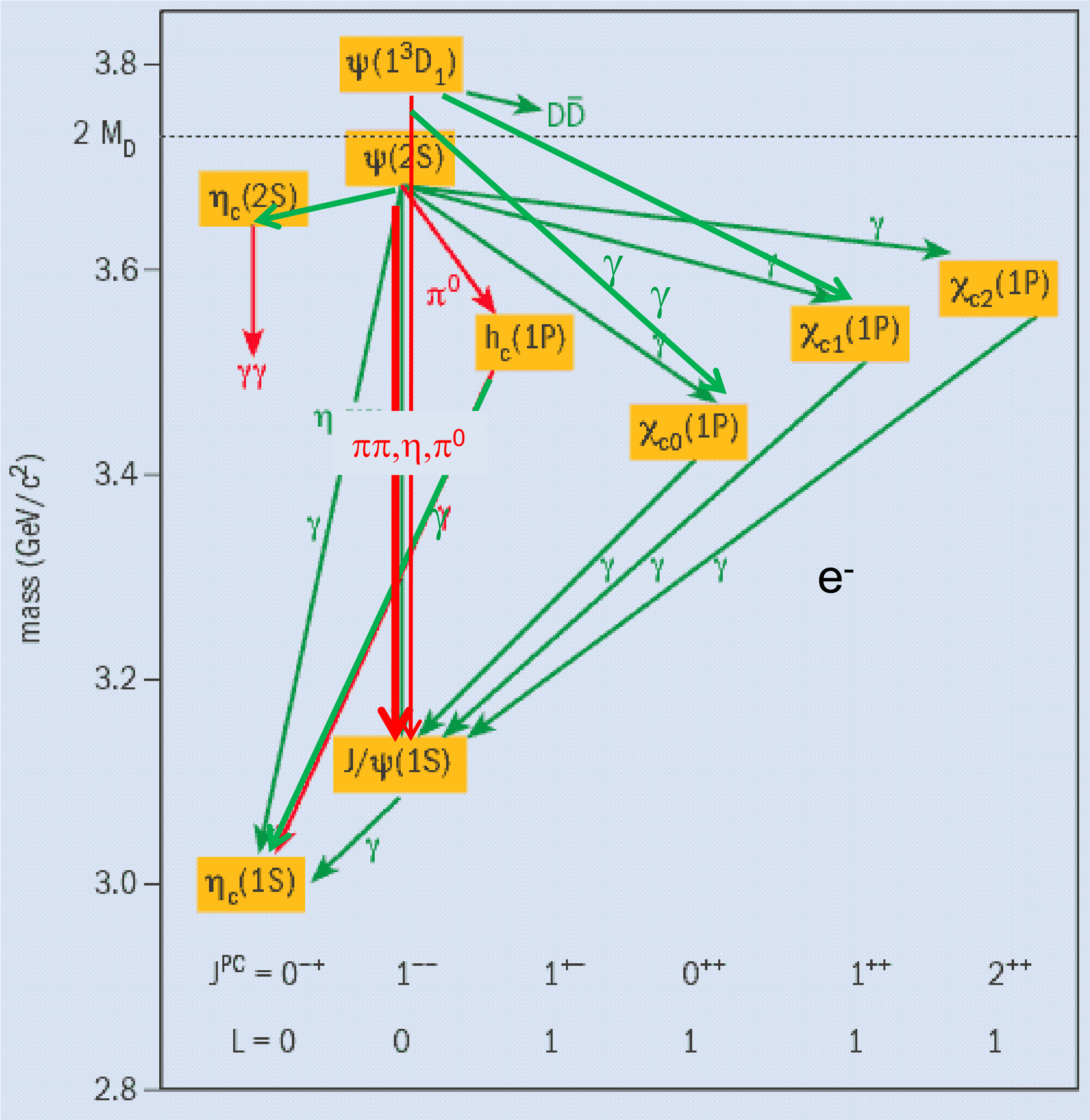
	Γ_{exp}(keV)
$\psi' \rightarrow \pi^+\pi^- J/\psi$	*88 ± 7*
$\psi' \rightarrow \eta J/\psi$	*9 ± 1*
$\psi' \rightarrow \pi^0 J/\psi$	*0.4±0.1*



Ispin violation:

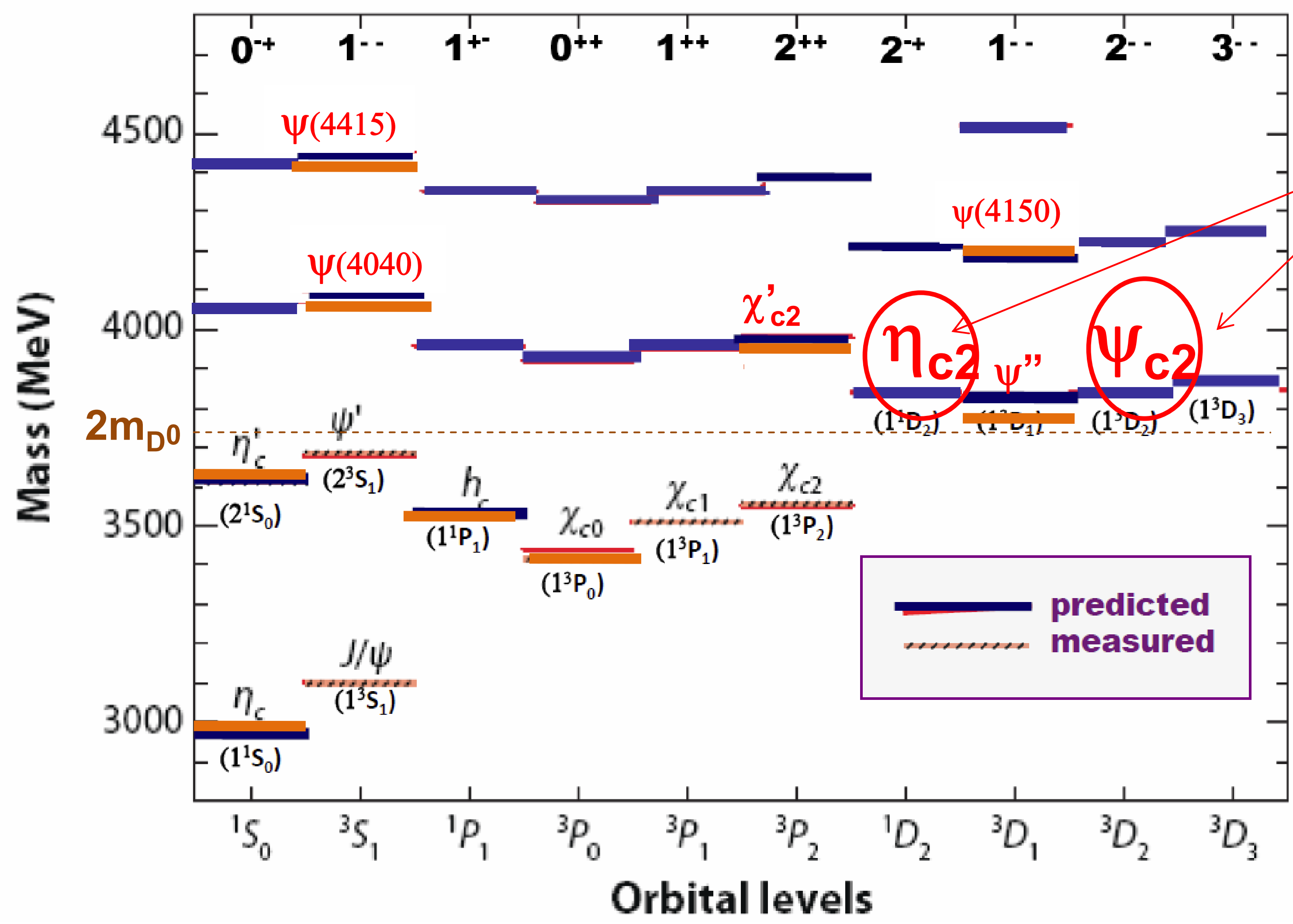
$$\frac{\psi' \rightarrow \pi^0 J/\psi}{\psi' \rightarrow \pi\pi J/\psi} \sim 1/200$$

Predictions for the ψ”



	Γ_{exp}(keV)	
	th.	*Expt*
ψ”→$\pi^+\pi^-$ J/ψ	*~80*	*55 ± 15*
ψ” →γ χ_{c1}	*77*	*70 ± 17*
ψ”→ γχ_{c0}	*213*	*172 ±30*

Can we find other above-threshold states?

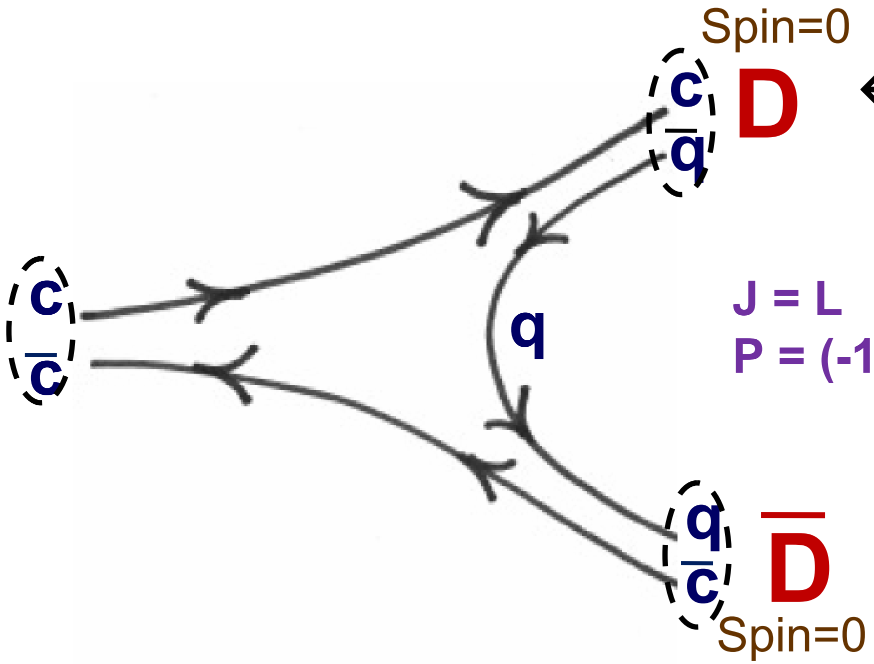


These 2 may be simpler

2^{-+} & 2^{--} → $D\bar{D}$ not allowed

η_{c2} ψ_{c2}

J = 2
P=-1



ψ_{c2} (or η_{c2})

←D^0 or D^+

←$\bar{D}^0$ or D^-

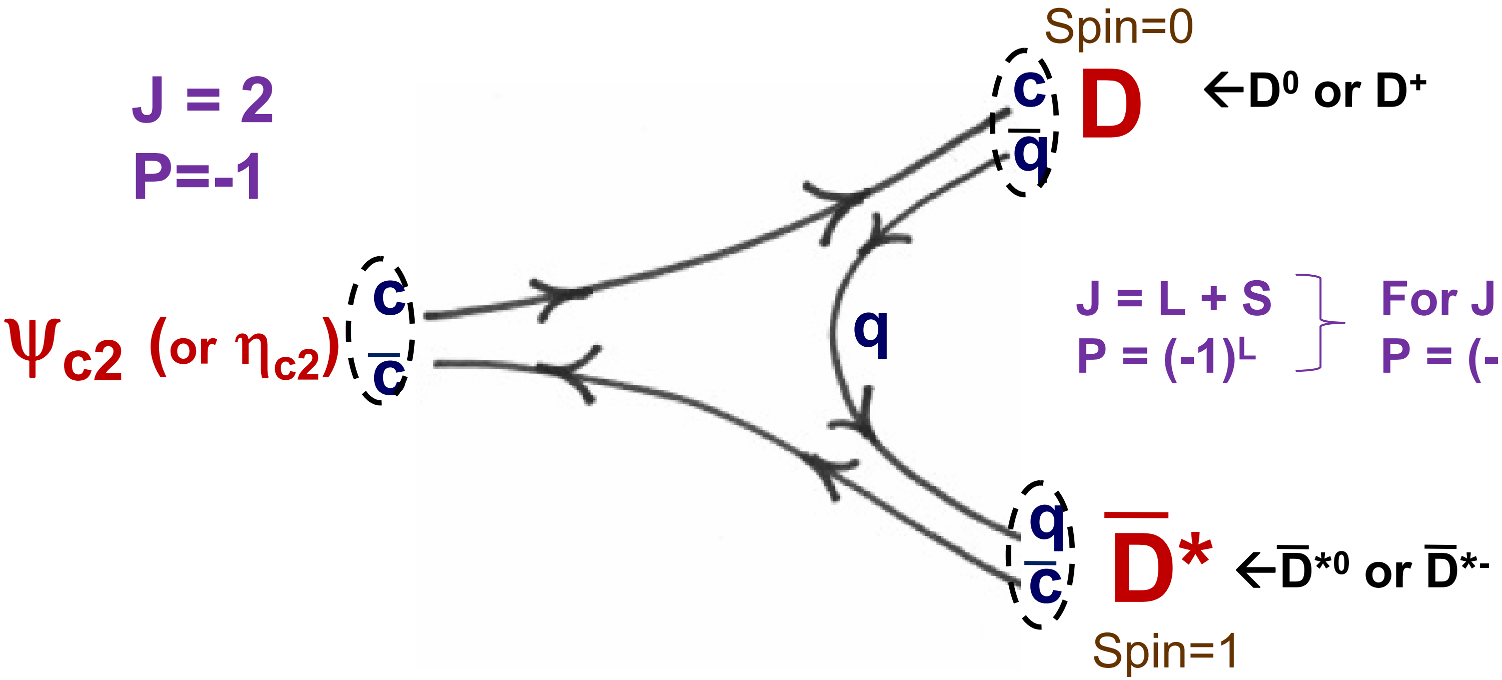
J = L
P = $(-1)^L$

For J = 2
P = $(-1)^2$ = +1

ψ_{c2} (η_{c2})→$D\bar{D}$ violates parity

Lowest possibility is $D\bar{D}^*$ (or $D^*\bar{D}$)

J = 2
P=-1

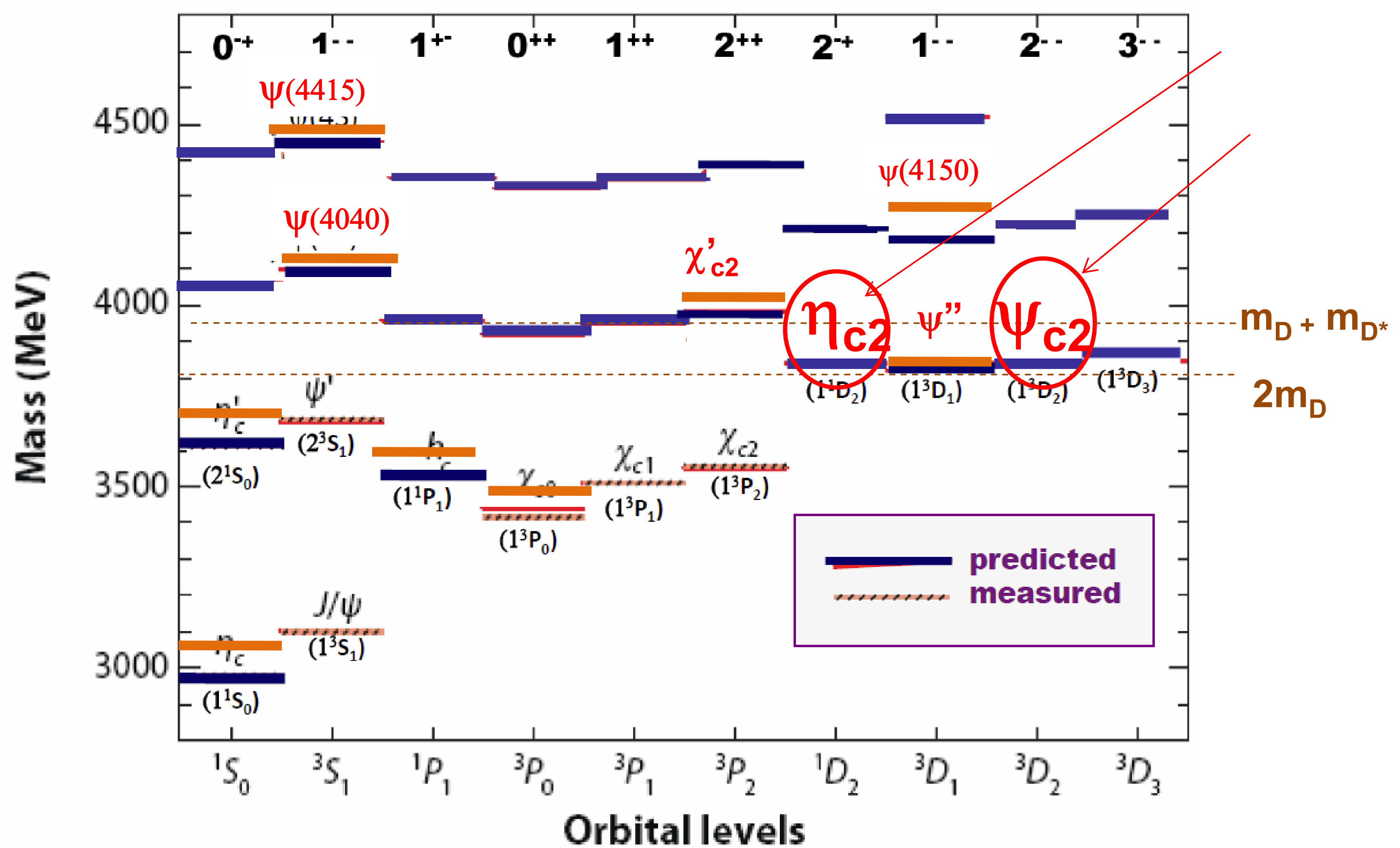


J = L + S
P = $(-1)^L$

For J = 2, L=1 is OK
P = $(-1)^1$ = -1

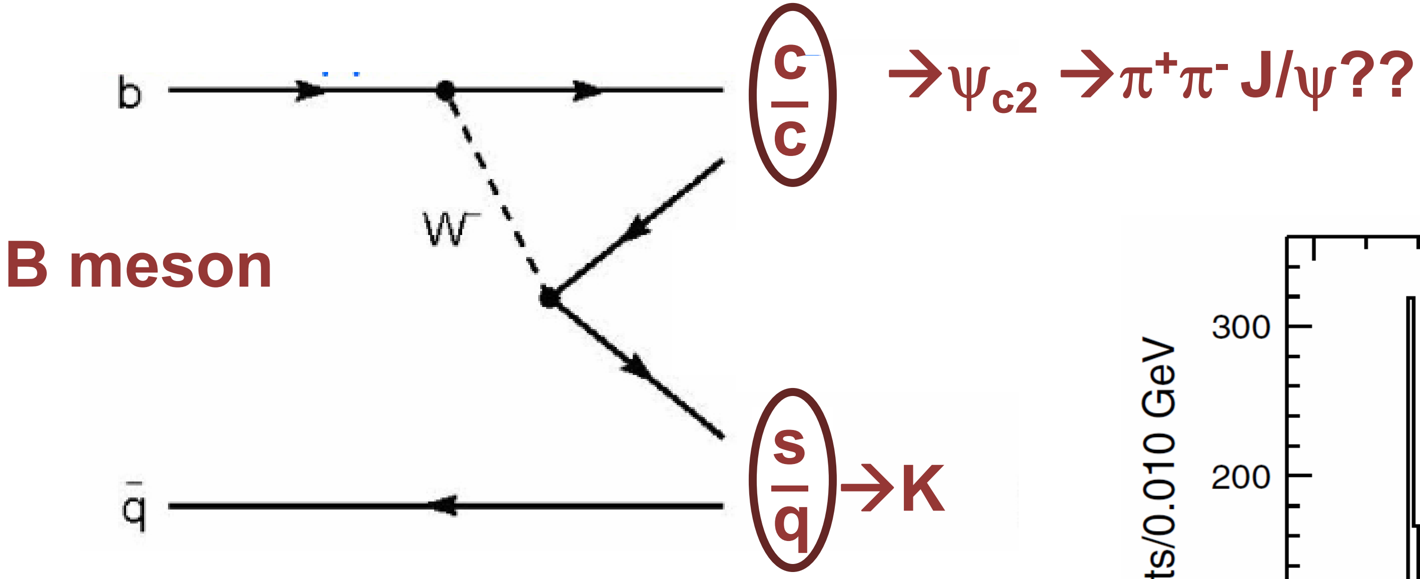
ψ_{c2} (η_{c2})→$D\bar{D}^*$ doesn't violate parity

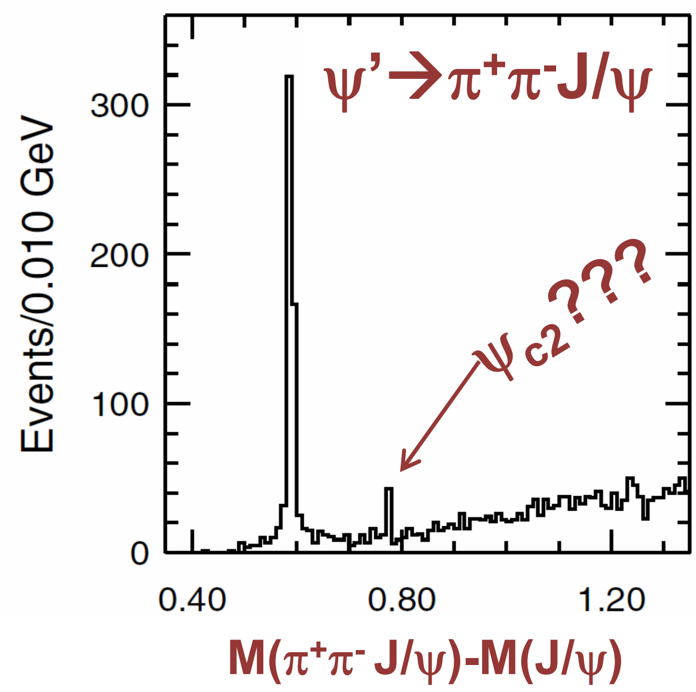
ψ_{c2} & η_{c2} are expected to be below $m_D+m_{D^*}$ threshold



Belle: search for ψ_{c2} in $B \to K\psi_{c2} \to K(\pi^+\pi^- J/\psi)$

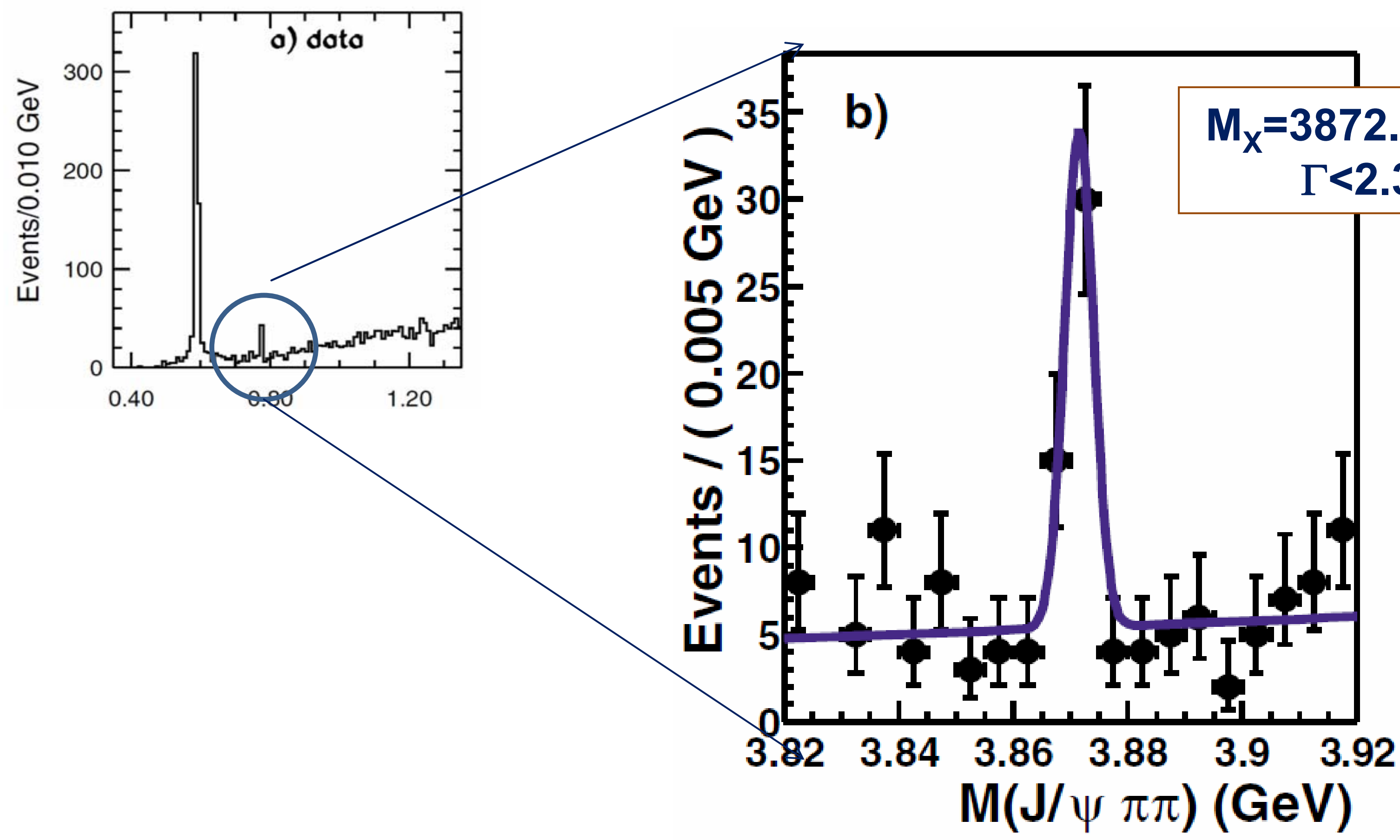
Eichten et al:
PRL 98, 162002 (2002)





Belle PRL **91**, 262001 (2003)

X(3872)

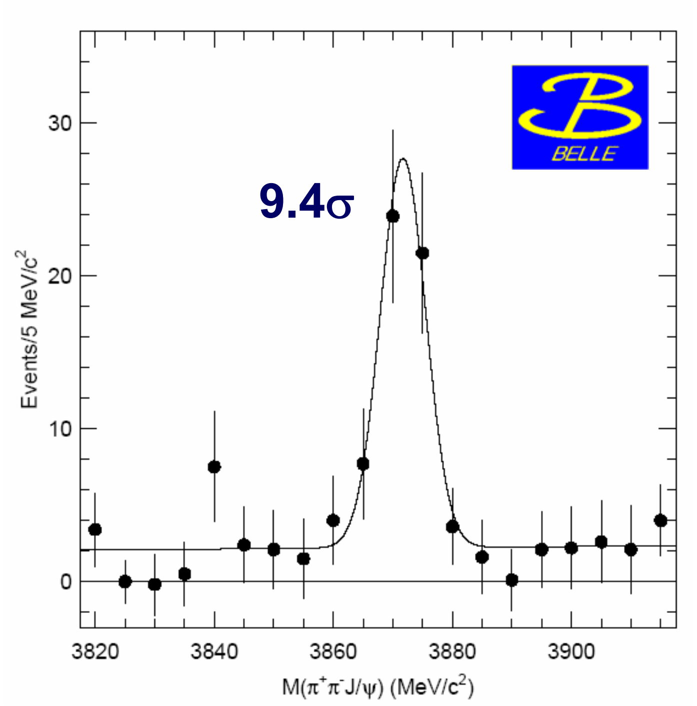


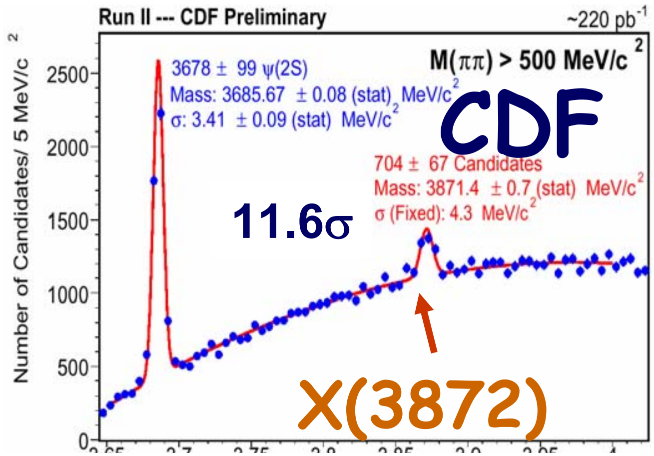
M_X=3872.0±0.6 MeV
Γ<2.3 MeV

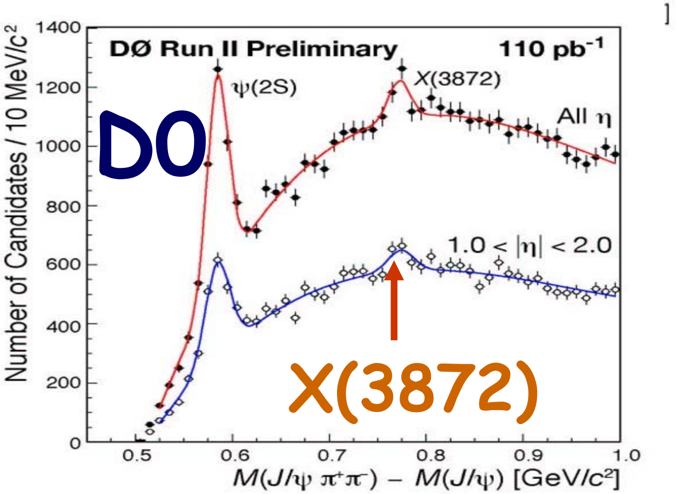
Belle PRL **91**, 262001 (2003)

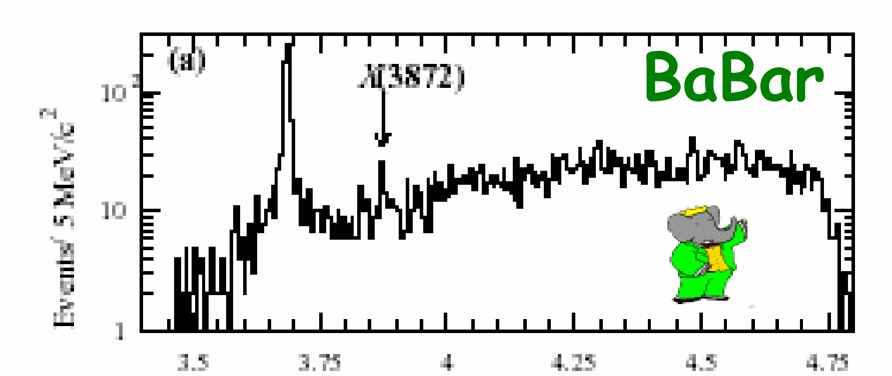
X_{3872} is well established

seen in 4 experiments









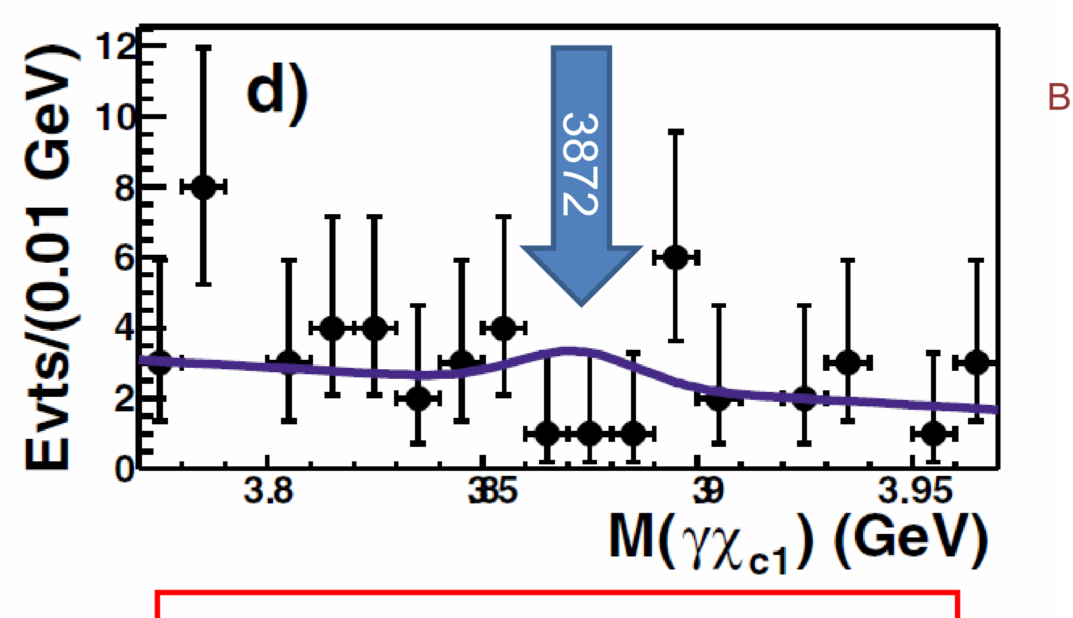
Is the X(3872) the ψ_{c2}?

Eichten et al:
PRL 98, 162002 (2002)

$$\frac{Bf(\psi_{c2}\rightarrow\gamma\,\chi_{c1})}{Bf(\psi_{c2}\rightarrow\pi^+\pi^- J/\psi)} > 5$$

“Look for X→γ χ_{c1}, you should be flooded by events”

Belle search for X(3872)→$\gamma\chi_{c1}$



Belle PRL **91**, 262001 (2003)

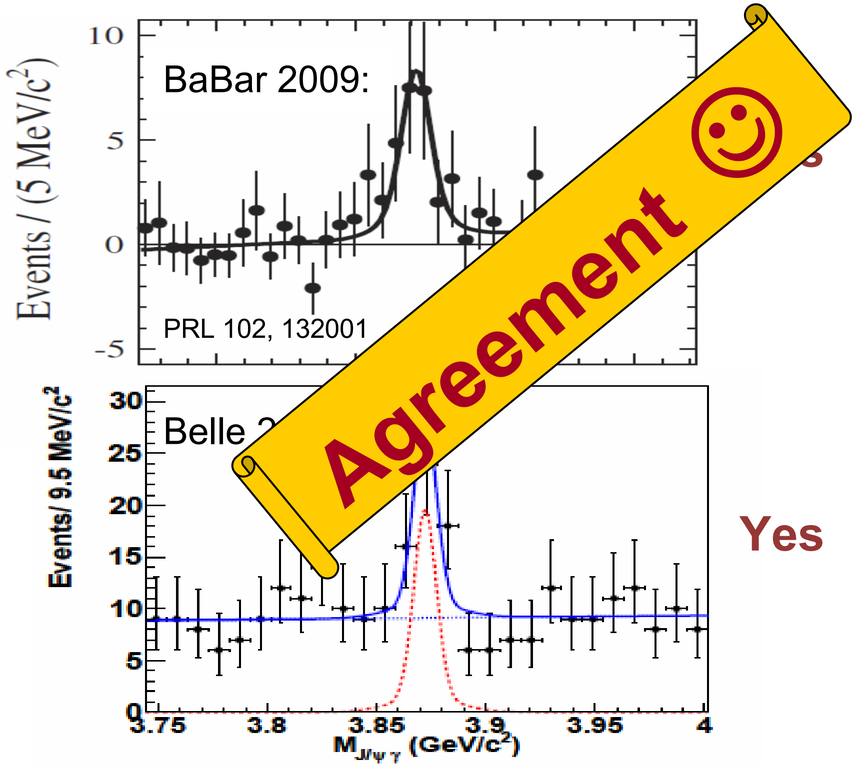
$$\frac{\mathbf{Bf}(\psi_{c2}\rightarrow\gamma\,\chi_{c1})}{\mathbf{Bf}(\psi_{c2}\rightarrow\pi^+\pi^-J/\psi)} < 0.9$$

The X(3872) is not the ψ_{c2}!!

If not ψ_{c2}, what???

Look for other decay modes:

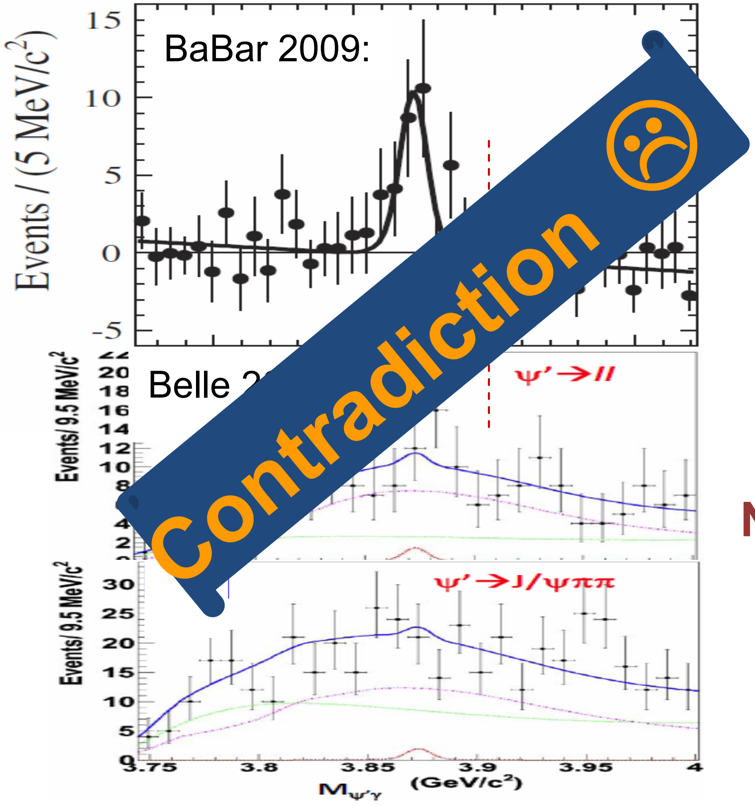
X(3872)→ γ J/ψ ?



Yes

V. Bhardwaj QWG 2010

X(3872)→ γ ψ'?



Yes

No

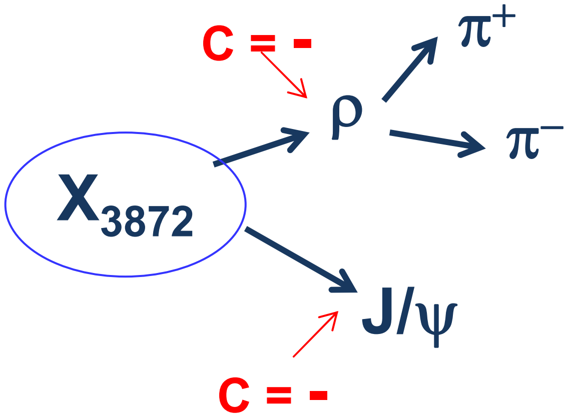
$C(X_{3872}) = +$

$X_{3872} \rightarrow \gamma\ J/\psi$ ➡ $C(X_{3872})$ **must be (-)×(-) = +**

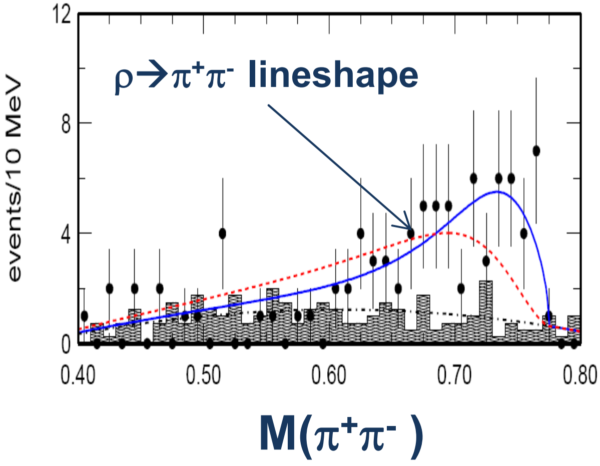
C = - **C = -**

if $C(X_{3872})$ is + :

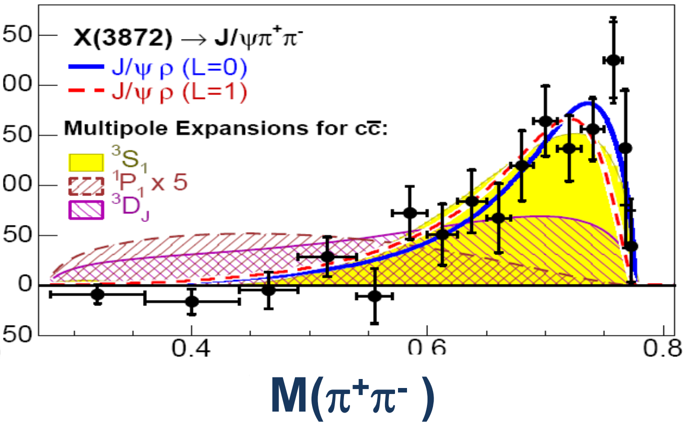
$\pi^+\pi^-$ system in $X_{3872} \rightarrow \pi^+\pi^-\ J/\psi$ must come from $\rho \rightarrow \pi^+\pi^-$



Belle agrees

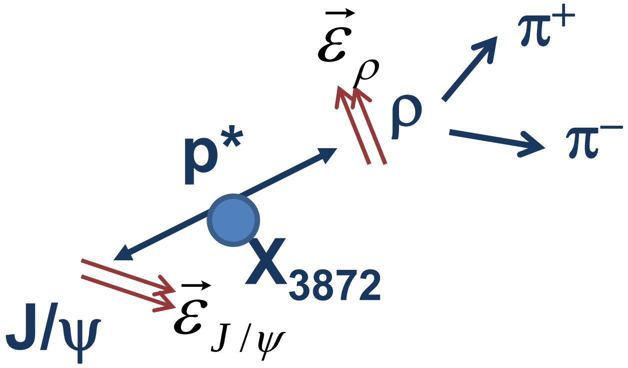


CDF agrees



J^{PC} of X_{3872}

0^{-+} ??



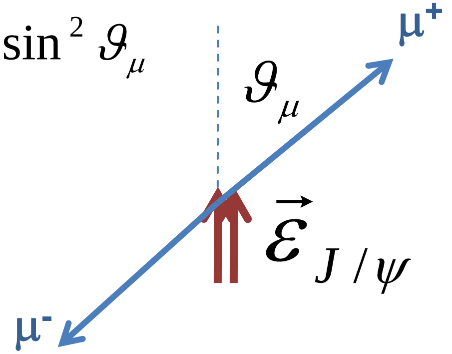
spin polarization vectors

$$L_{\text{int}} \propto \underbrace{\left(\vec{\varepsilon}_\rho \times \vec{\varepsilon}_{J/\psi}\right) \bullet \vec{p}\,^*}_{\Big\Downarrow}$$

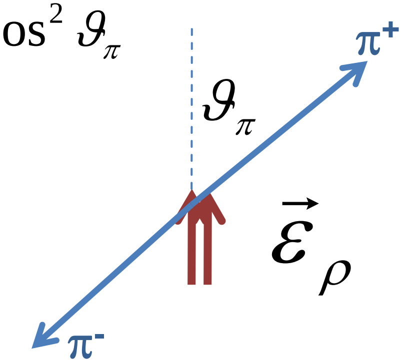
$$\vec{p}\,^* \qquad \vec{\varepsilon}_\rho \qquad \vec{\varepsilon}_{J/\psi}$$

mutually perpendicular

$$\frac{d\Gamma}{d\cos\vartheta_\mu} \propto \sin^2\vartheta_\mu$$

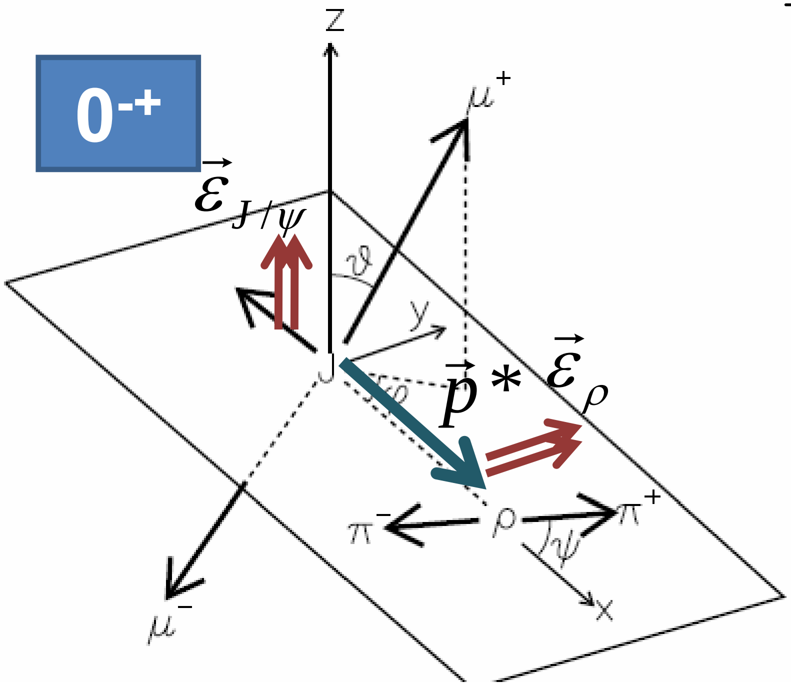


$$\frac{d\Gamma}{d\cos\vartheta_\pi} \propto \cos^2\vartheta_\pi$$

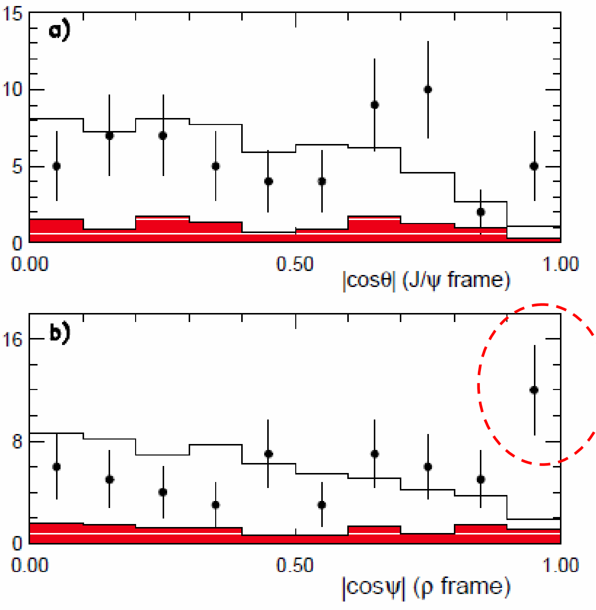


Does the X(3872) $J^{PC} = 0^{-+}$??

0^{-+}



$$\frac{d\Gamma}{d\cos\psi d\cos\vartheta} \propto \sin^2\psi \sin^2\vartheta$$



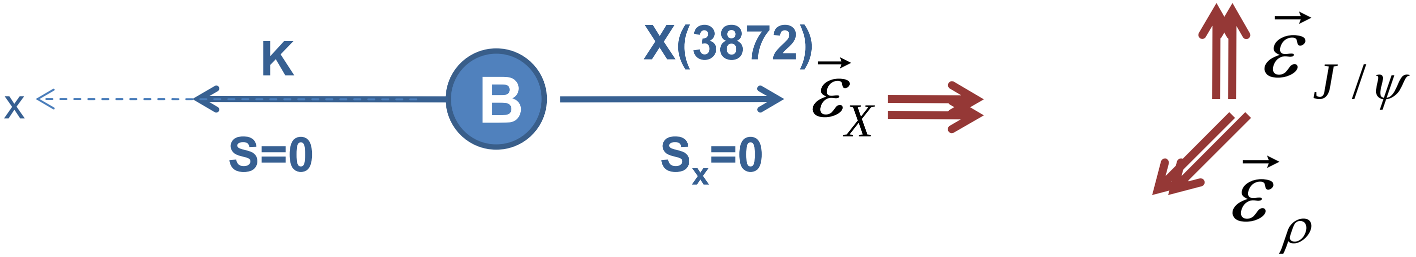
!!!

No, the X(3872) cannot be 0^{-+}

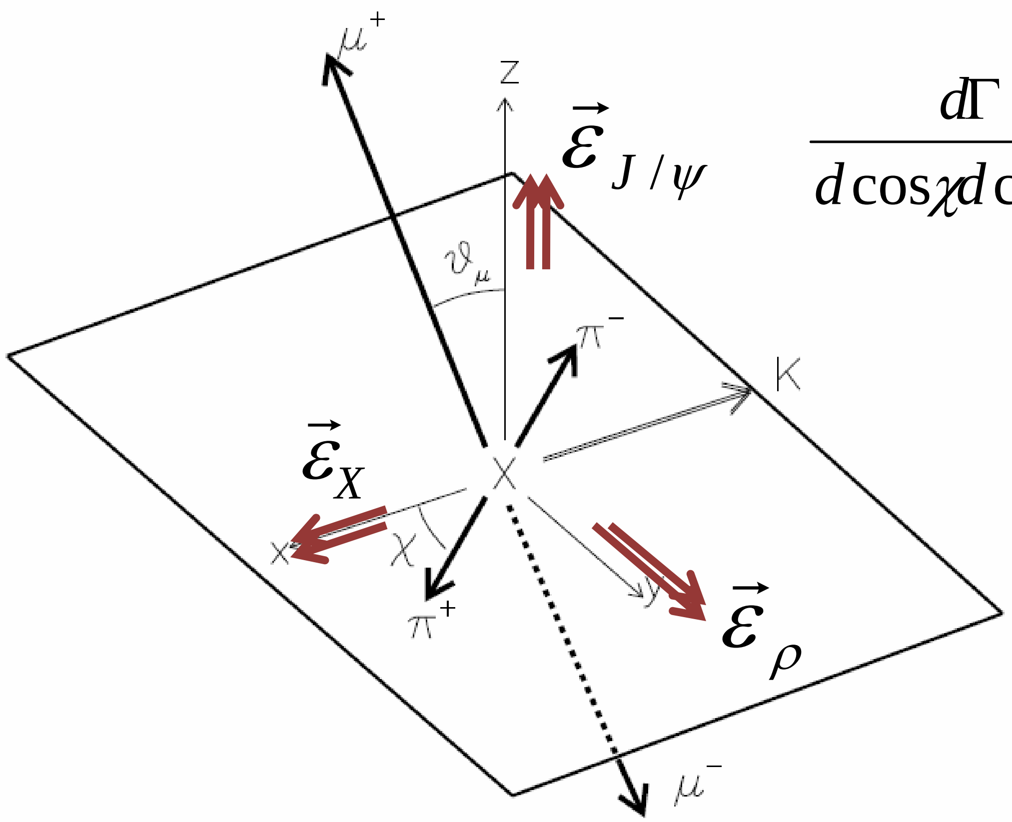
Does the X(3872) J^{PC} = 1^{++} ??

$$L_{\text{int}} \propto \underbrace{\left(\vec{\varepsilon}_{\rho} \times \vec{\varepsilon}_{J/\psi}\right) \bullet \vec{\varepsilon}_{X}}_{\Downarrow}$$

$\vec{\varepsilon}_{X}$ $\vec{\varepsilon}_{\rho}$ $\vec{\varepsilon}_{J/\psi}$ mutually perpendicular

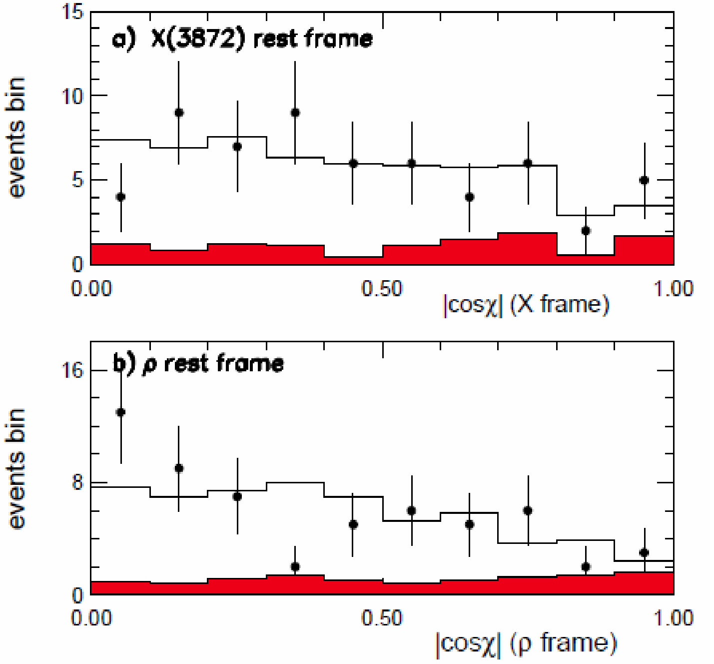


1^{++} fits well



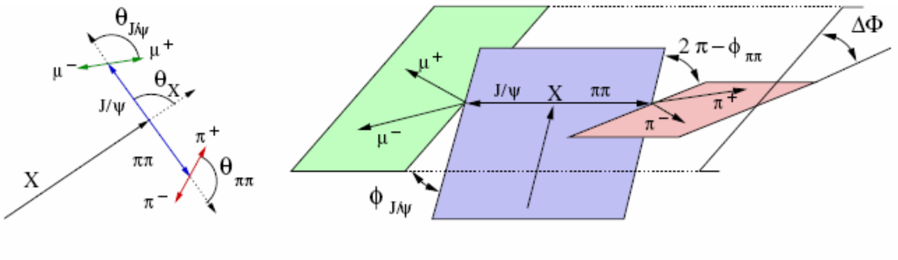
$$\frac{d\Gamma}{d\cos\chi\, d\cos\vartheta_\mu} \propto \sin^2\chi \sin^2\vartheta_\mu$$

Belle Data



CDF angular correlation analysis

Only 1^{++} or 2^{-+} fit data



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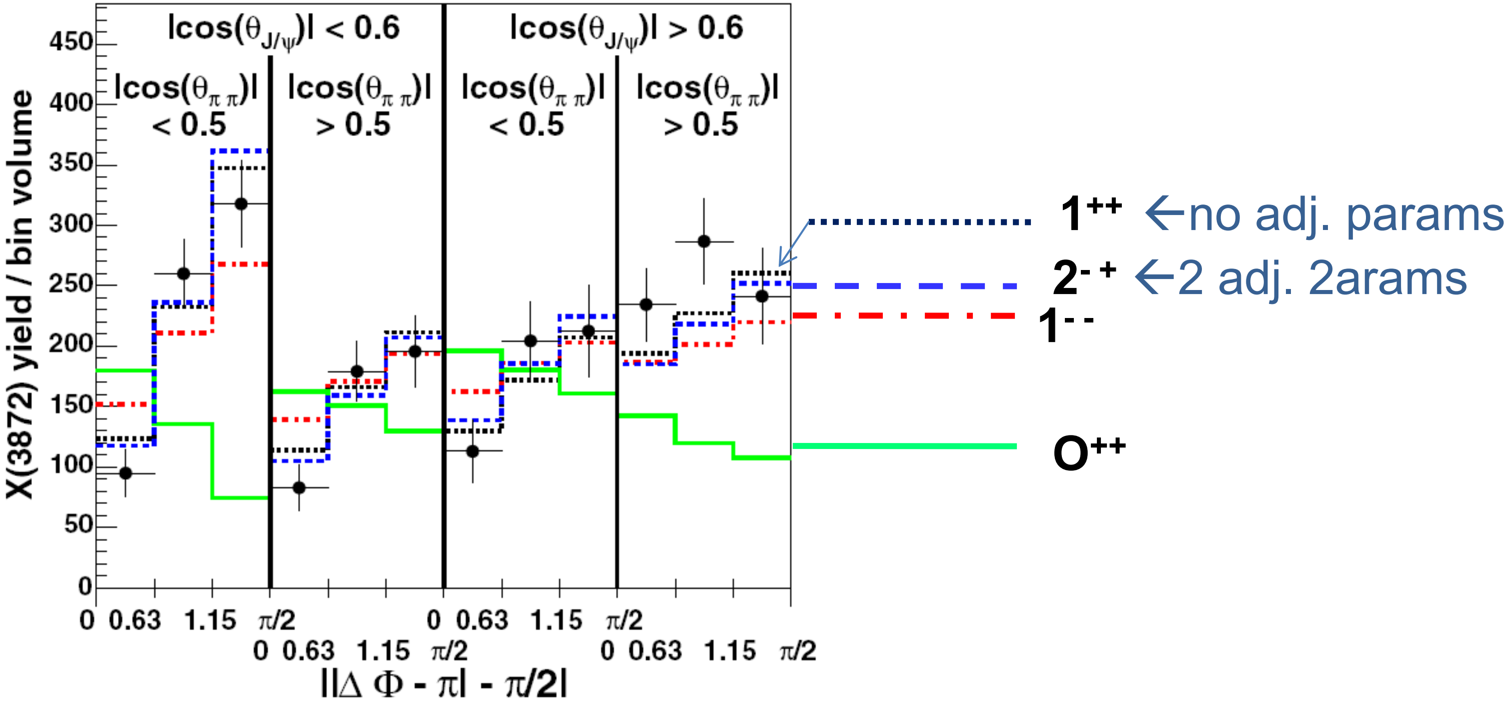
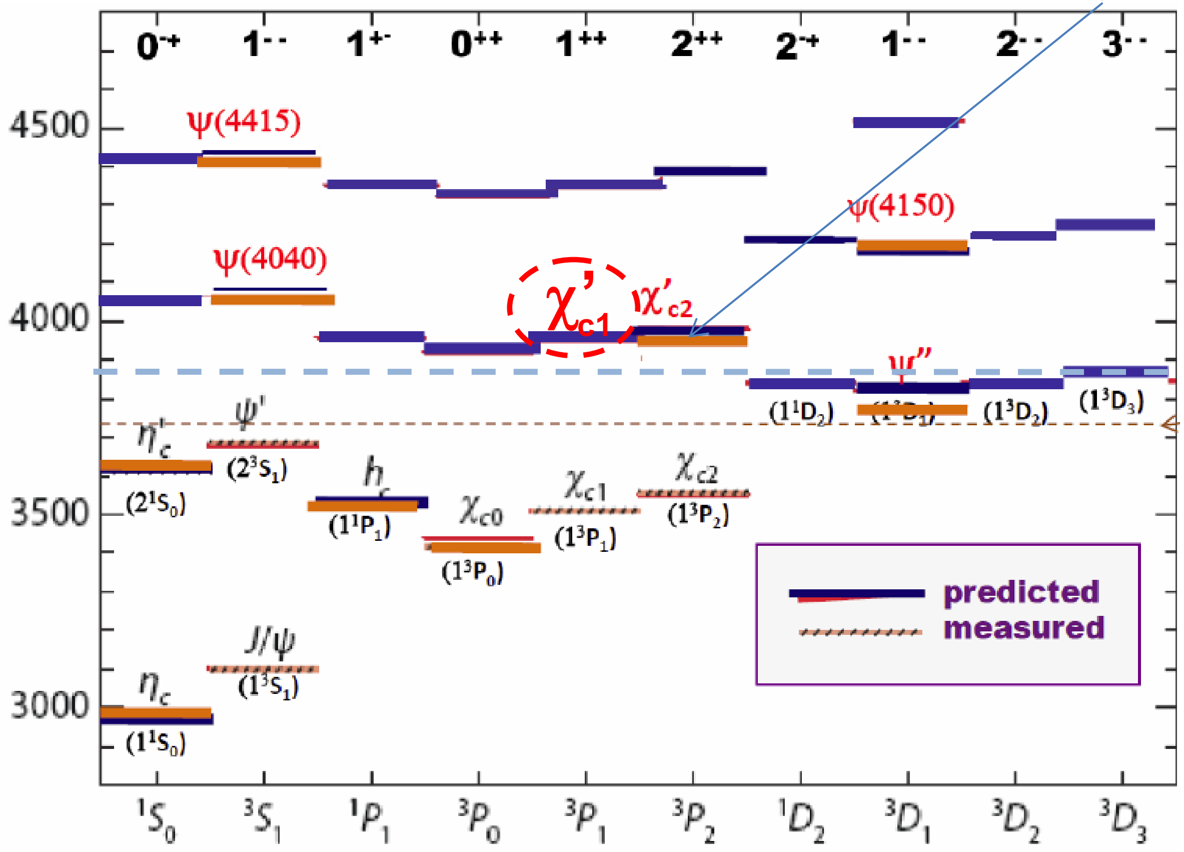


1^{++} fits well with no adjustable parameters

2^{-+} looks like 1^{++} for $\alpha \approx 0.6e^{i20^o}$, at least with current statistics

a 1^{++} $c\bar{c}$ state for the X_{3872}?



set by:
$M\chi'_{c2}$=3930 MeV

- Mass is too low?
  - 3872 *vs* 3905 MeV

- $\Gamma(\chi'_{c1} \rightarrow \gamma\ \psi')$ ~180 keV
- $\Gamma(\chi'_{c1} \rightarrow \gamma\ J/\psi)$ ~14 keV

T.Barnes *et al* PRD 72, 054026

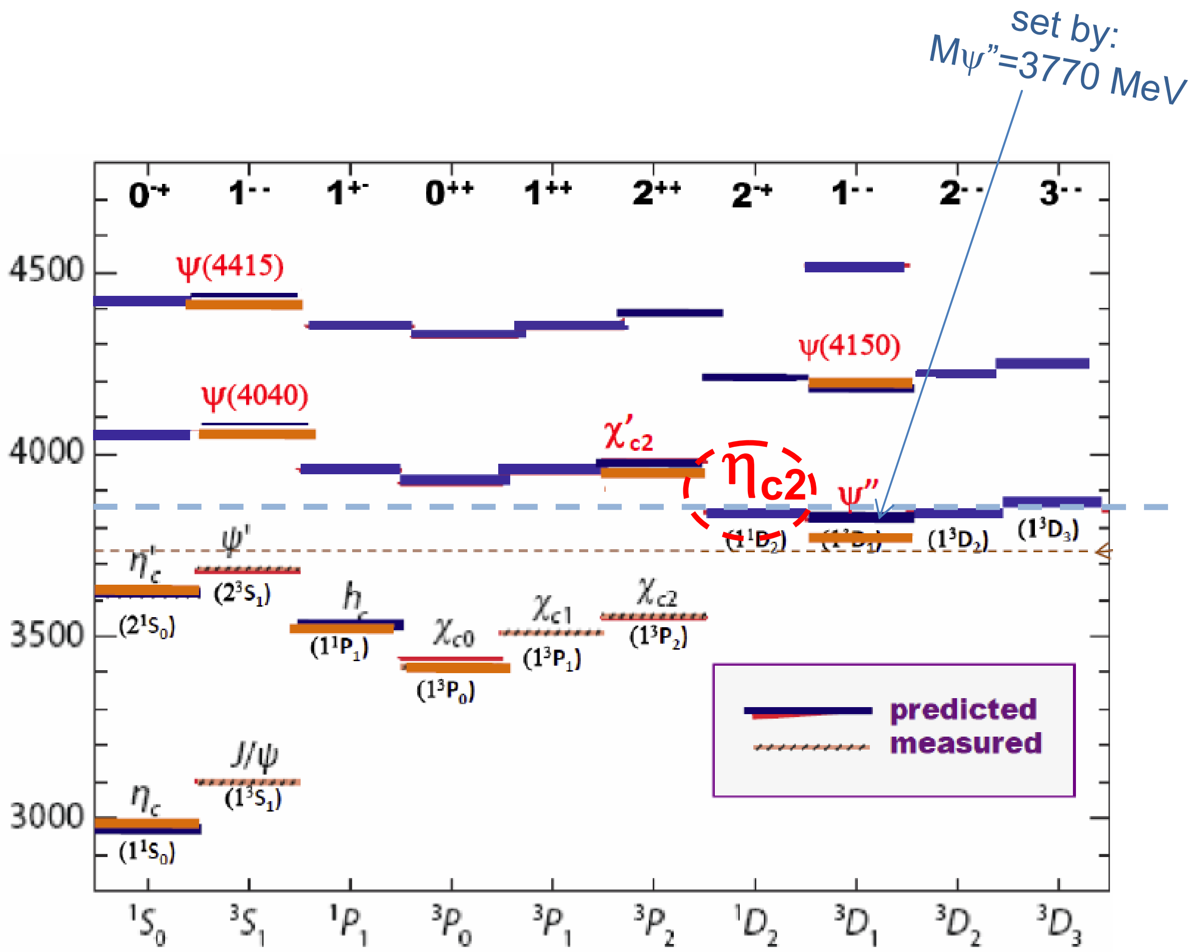
$\Gamma(\gamma\ \psi')/\Gamma(\gamma\ J/\psi)>>1$

- $\Gamma_{\pi+\pi-\ J/\psi}$ =(3.4±1.2) $\Gamma_{\gamma J/\psi}$~45 keV

huge for Isospin-violating dec

c.f.: $\Gamma(\psi'\rightarrow\pi^0 J/\psi)\approx 0.4$ keV

a 2^{-+} $c\bar{c}$ state for the X_{3872}?



- Mass is too high?
  - 3872 *vs* 3837 MeV

T.J. Burns *et al* arXiv:1008.0018

- $\Gamma(\eta_{c2} \rightarrow \gamma\, \psi') \sim 0.4$ keV
- $\Gamma(\eta_{c2} \rightarrow \gamma\, J/\psi) \sim 9$ keV

Y. Jia *et al* arXiv:1007.4541

- $\Gamma(\eta_{c2} \rightarrow \gamma\, \psi')/\Gamma(\eta_{c2} \rightarrow \gamma\, J/\psi) << 1$

- $\Gamma_{\pi+\pi-\, J/\psi} = (3.4 \pm 1.2)\, \Gamma_{\gamma J/\psi} \sim 30$ keV
  - huge for Ispin-violating decay
    c.f.: $\Gamma(\psi' \rightarrow \pi^0 J/\psi) \approx 0.4$ keV

- $B \rightarrow K\eta_{c2}$ violates factorization
  - $B \rightarrow Kh_c$ not seen
  - $B \rightarrow K\chi_{c2}$ barely seen

- $\eta_{c2} \rightarrow DD^*$ expected to be tiny

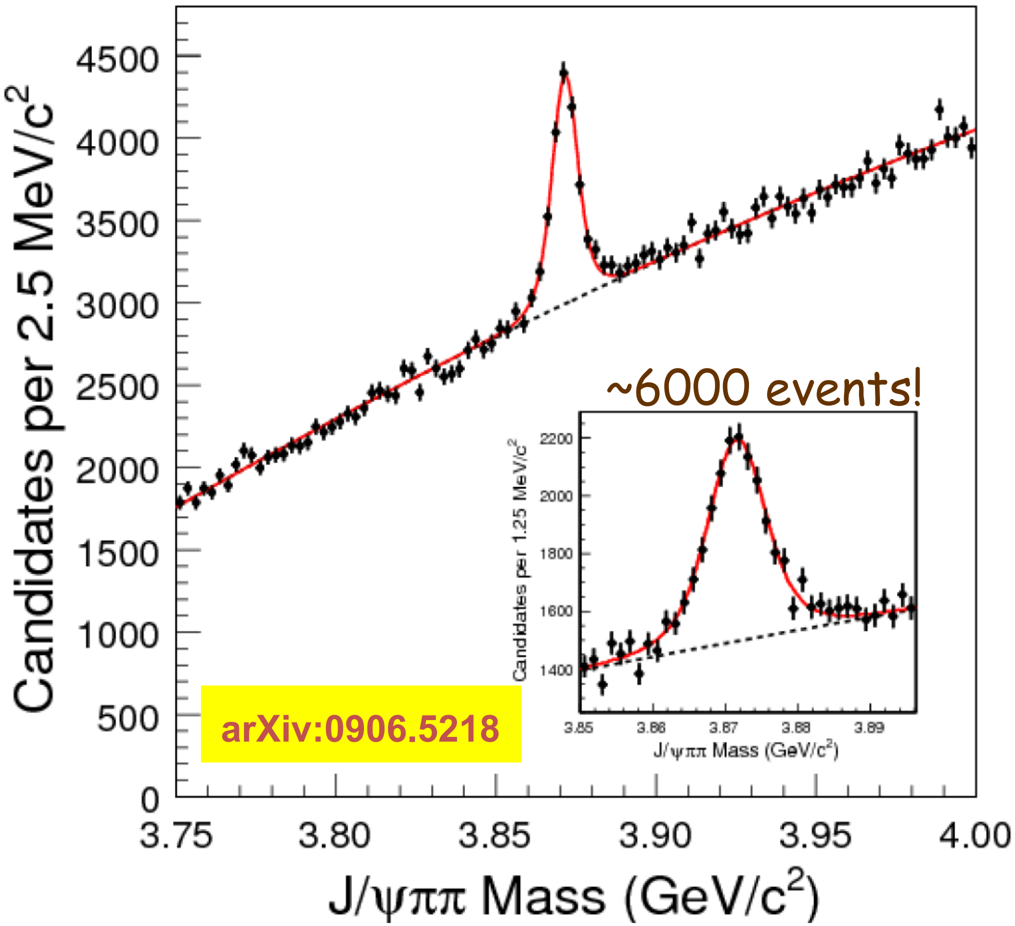
Y. Kalasnakova *et al* arXiv:1008.2895

Belle & BaBar:
$\Gamma(\mathbf{X \rightarrow DD^*})/\Gamma(\mathbf{X \rightarrow \pi\pi J/\psi}) = 9.5 \pm 3.1$

If not charmonium, what is it?

CDF X(3872)→$\pi^+\pi^-$ J/ψ Mass

recent results



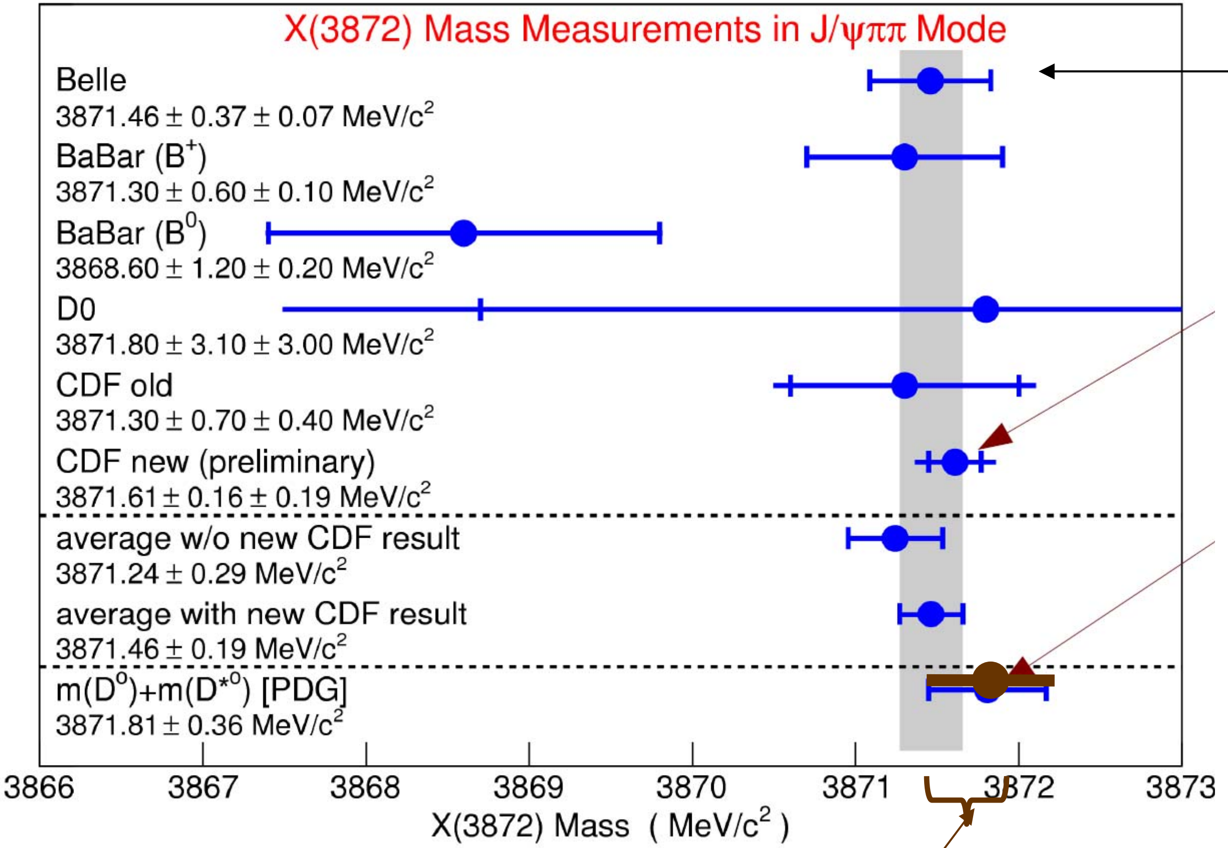
~6000 events!

arXiv:0906.5218

$$M_X = 3871.61 \pm 0.16 \pm 0.19 \text{ MeV}$$

$M_{X(3872)} \approx M_{D^0} + M_{D^{*0}}$

$<M_X>= 3871.46 \pm 0.19$ MeV



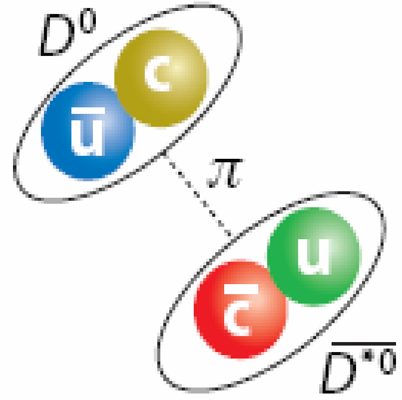
new Belle meas.

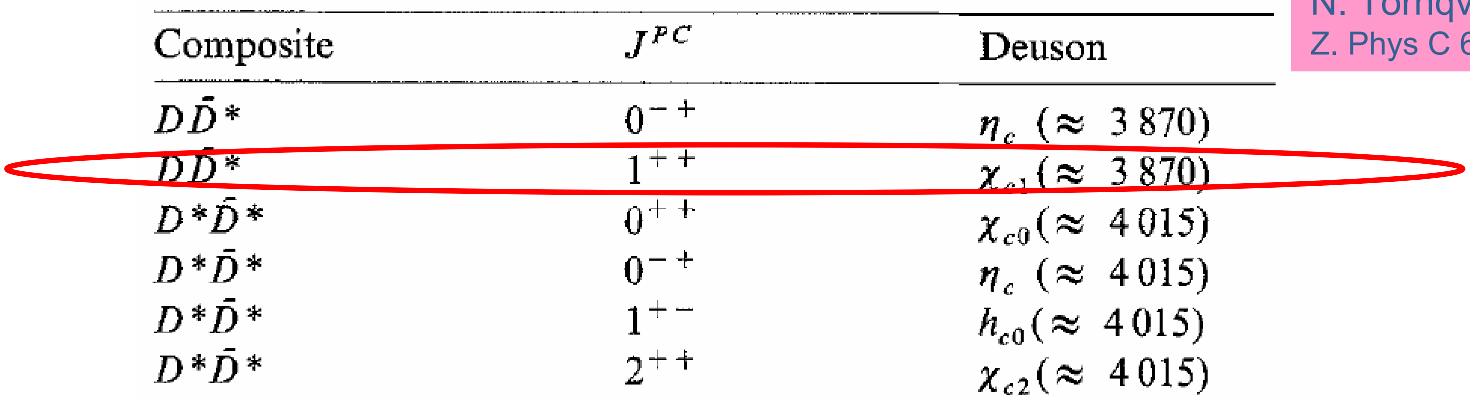
new CDF meas.

$M_{D0} + M_{D*0}$
3871.8±0.4 MeV

$\delta m = -0.35 \pm 0.41$ MeV

X(3872) looks like a $D^0\bar{D}^{*0}$ "molecule"





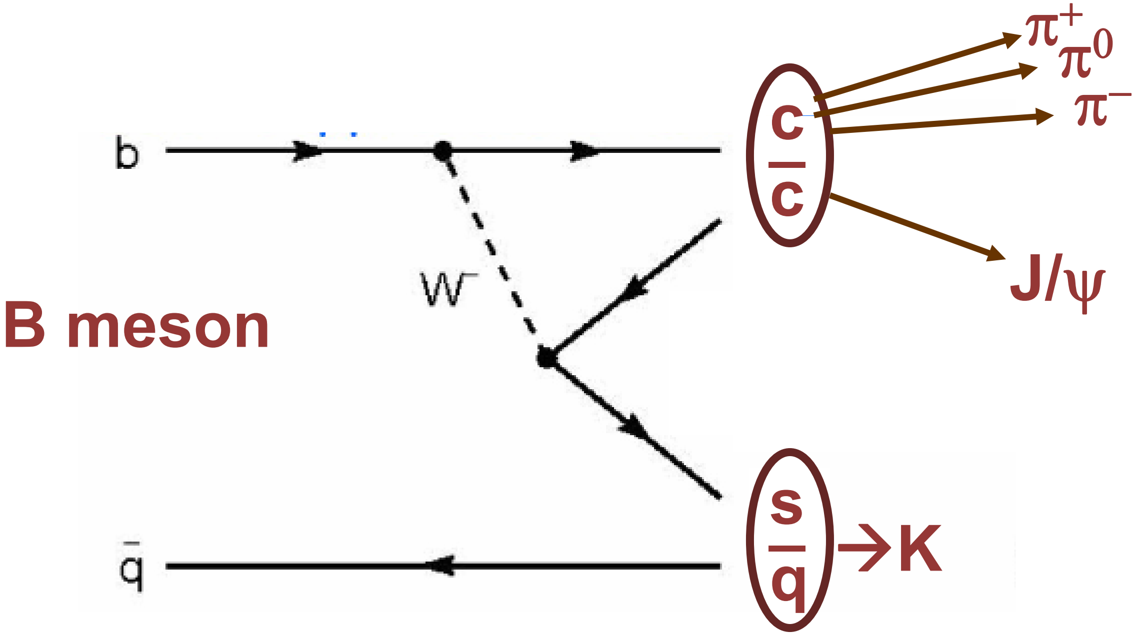
Composite	J^{PC}	Deuson
$D\bar{D}^*$	0^{-+}	η_c (≈ 3 870)
$D\bar{D}^*$	1^{++}	χ_{c1}(≈ 3 870)
$D^*\bar{D}^*$	0^{++}	χ_{c0}(≈ 4 015)
$D^*\bar{D}^*$	0^{-+}	η_c (≈ 4 015)
$D^*\bar{D}^*$	1^{+-}	h_{c0}(≈ 4 015)
$D^*\bar{D}^*$	2^{++}	χ_{c2}(≈ 4 015)

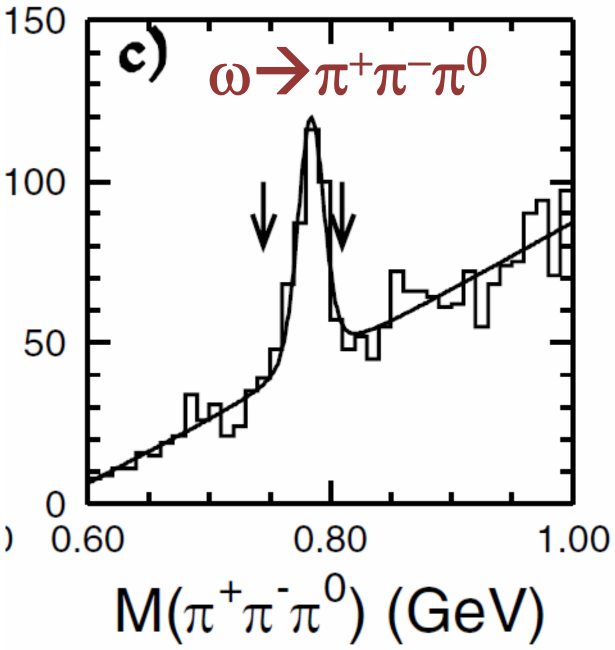
N. Tornqvist
Z. Phys C 61, 525 (1994)

predicted by Tornqvist in 1994, requires: $J^{PC} = 1^{++}$ or 0^{-+}

States near 3940 MeV

Search for other states in $B \rightarrow K\ \pi^+\pi^-\pi^0\ J/\psi$ decays

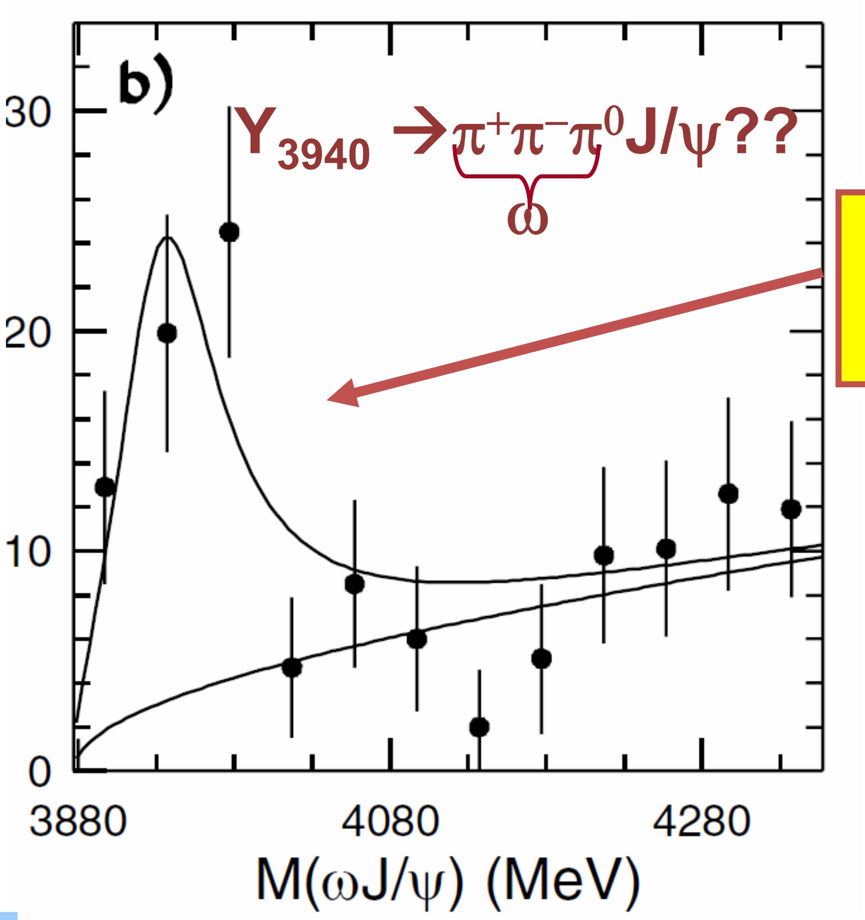




M(ω J/ψ)

Y(3940)

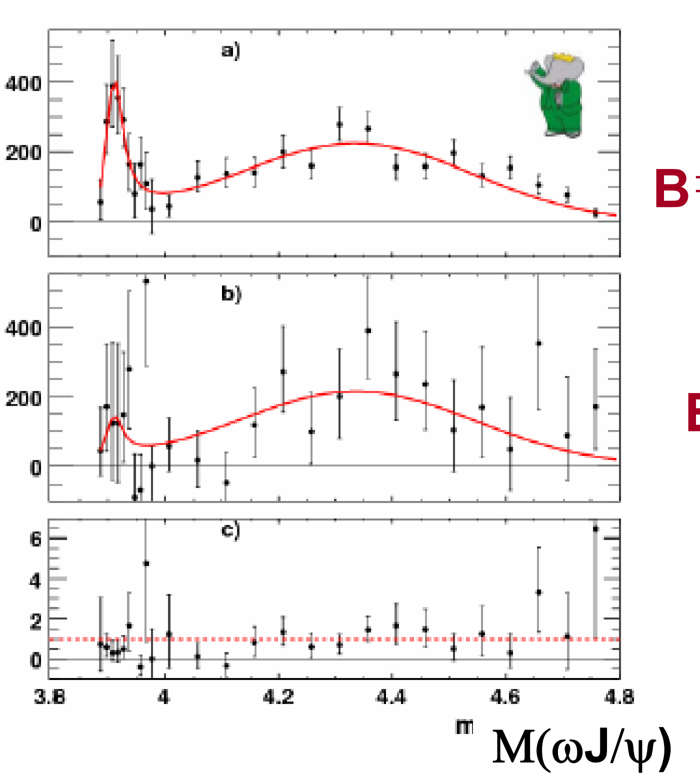
unexpected peak at 3940 MeV



M=3940 ± 11 MeV
Γ= 92 ± 24 MeV

S.-K. Choi et al (Belle)
PRL94, 182002 (2005)

Y(3940) confirmed by BaBar



$B^{\pm} \rightarrow K^{\pm}\omega J/\psi$

$B^0 \rightarrow K_S\omega J/\psi$

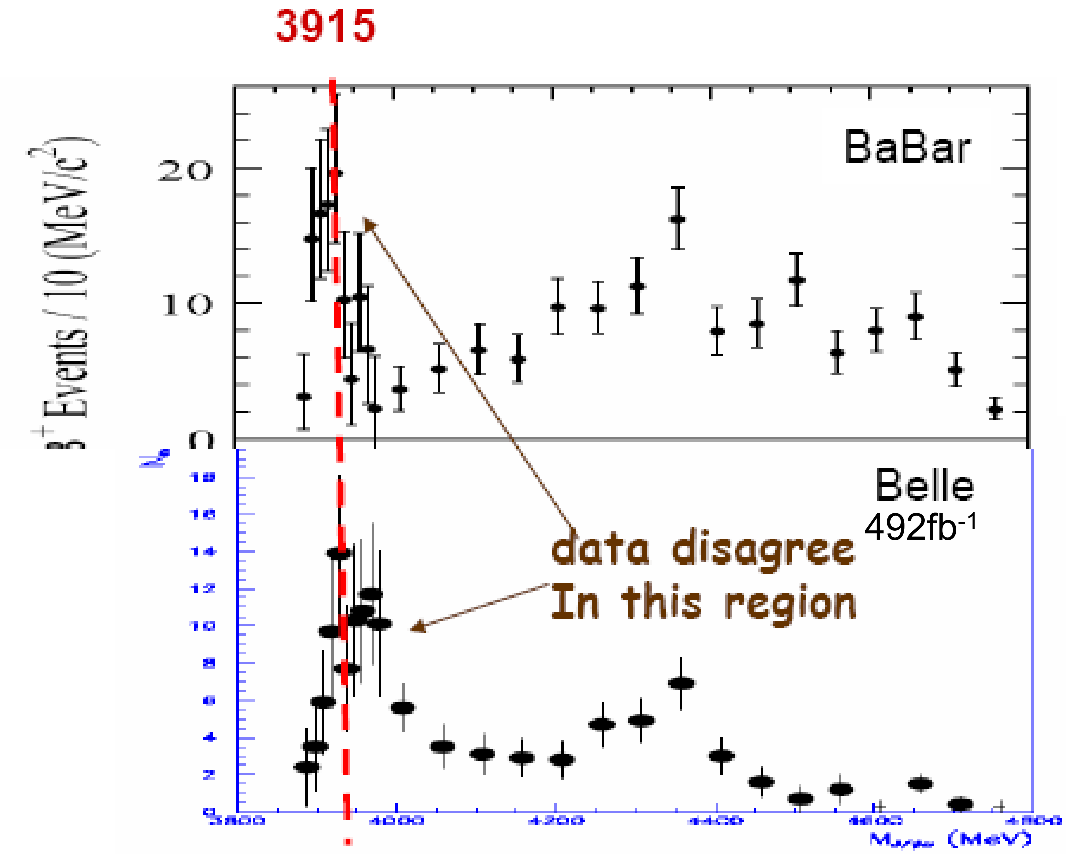
ratio

	Mass (MeV)	Γ (MeV)
Belle 253 fb^{-1}	$3943 \pm 11(stat) \pm 13(syst)$	$87 \pm 22(stat) \pm 26(syst)$
BaBar 350 fb^{-1}	$3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst)$	$33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst)$

PRL 101, 082001

Some discrepancy in M & Γ; general features agree

Belle-BaBar direct comparison



data disagree
In this region

Same binning

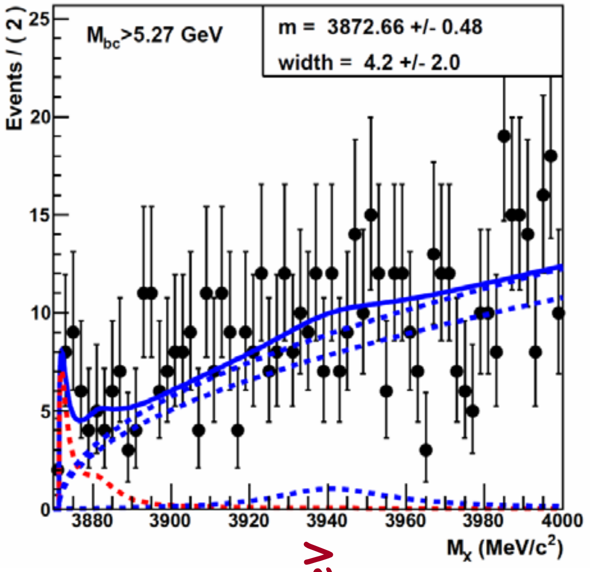
(Belle published
result : 253 fb^{-1})

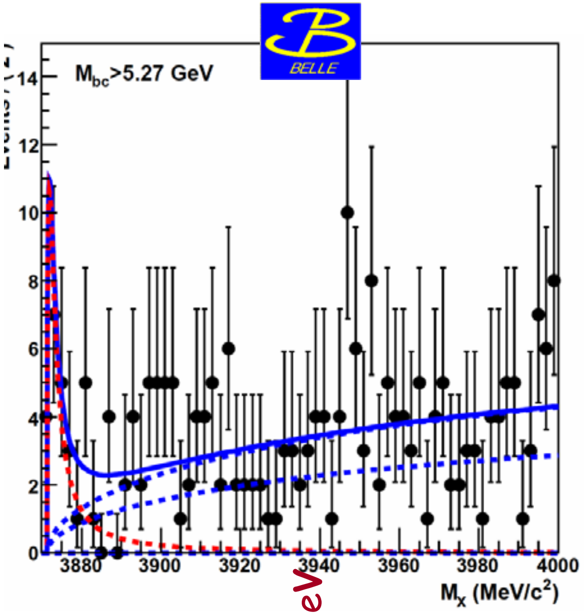
Belle will update with the complete Υ(4S) date set later this Fall

Does Y(3940) → D$\bar{D}$* ?

B→KD$\bar{D}$*

ArXiv:0810.0358





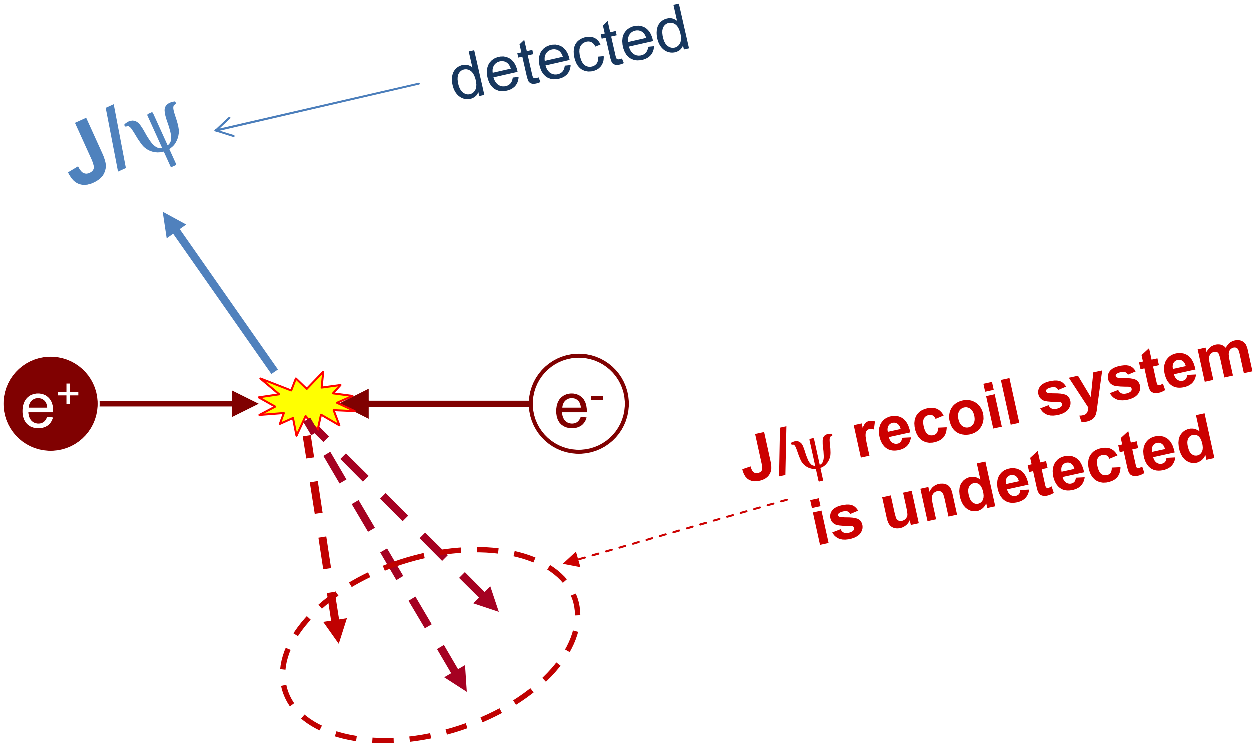
3940 MeV

3940 MeV

No signal:

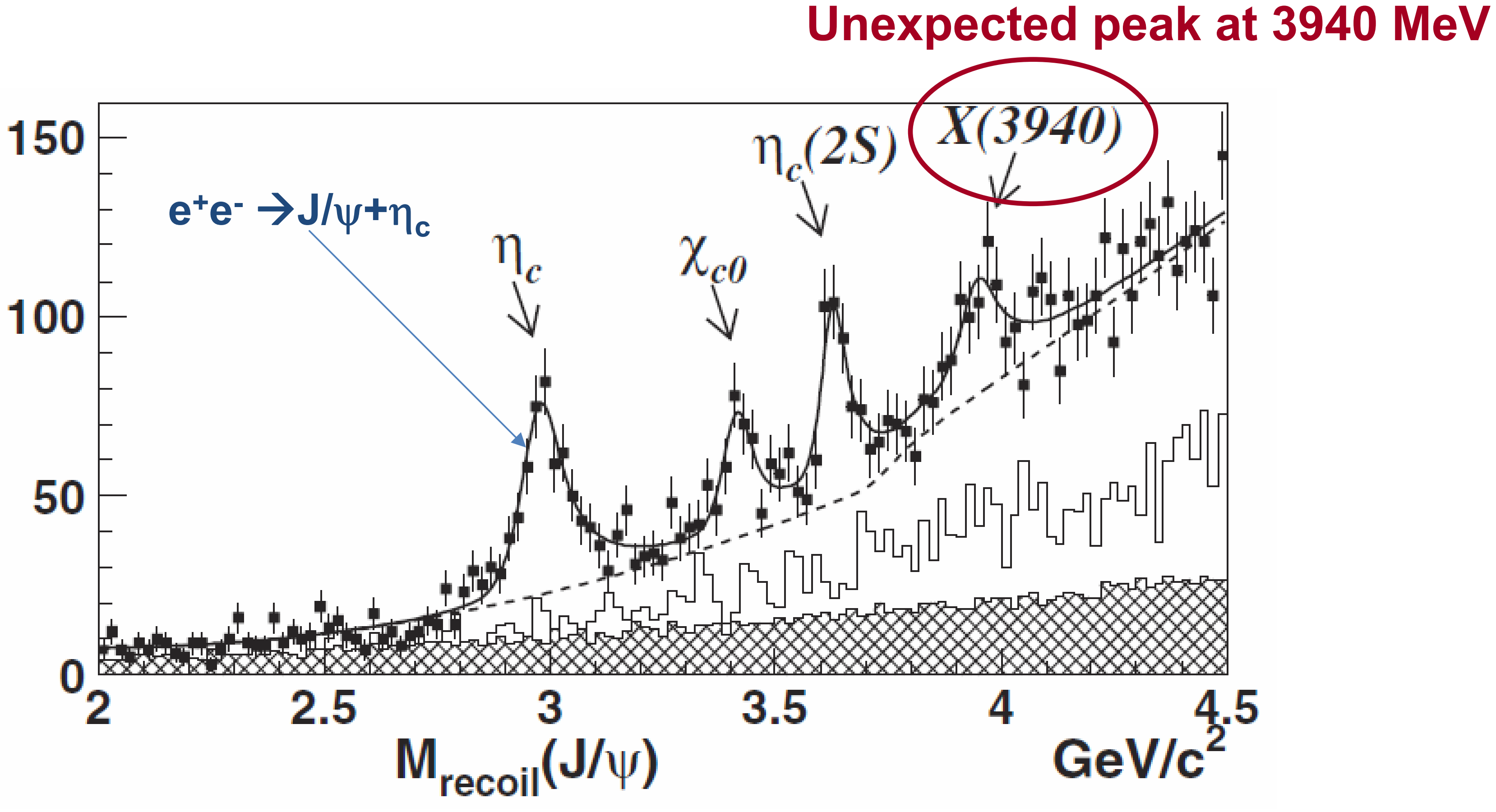
$$\frac{\mathcal{B}(Y(3940) \to \omega\, J/\psi)}{\mathcal{B}(Y(3940) \to D^{*0}\bar{D}^{0})} > 0.75$$

Study $e^+e^- \rightarrow J/\psi$ + anything

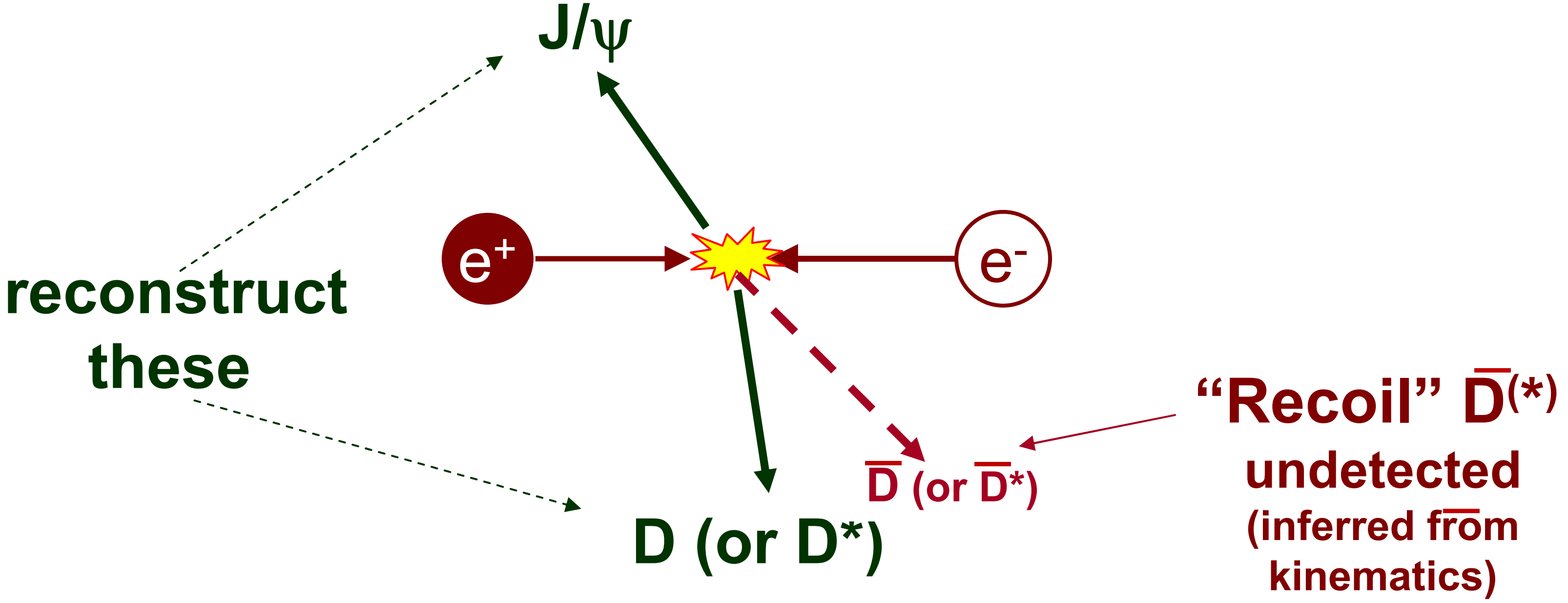


Recoil Mass: $M_{recoil} = \sqrt{(E_{cm} - E_{J/\psi})^2 - (-\vec{p}_{J/\psi})^2}$

$\sigma(e^+e^- \rightarrow J/\psi + c\bar{c})$ unexpectedly big



Use “partial reconstruction” to study X_{3940}→ $D\bar{D}$ or $D\bar{D}^*$



J/ψ

e^+

e^-

reconstruct these

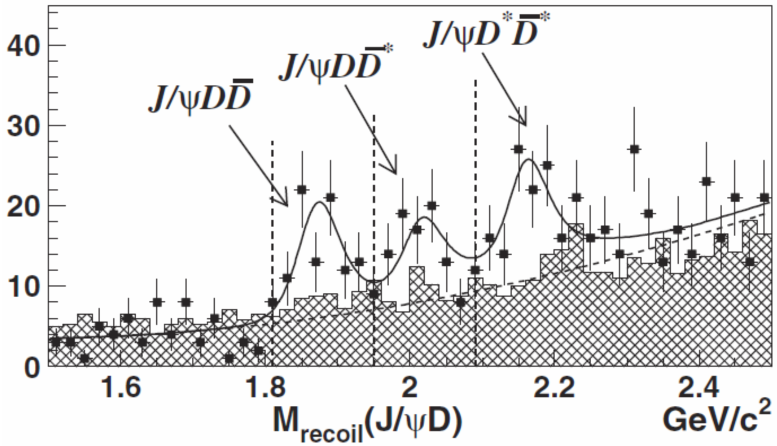
D (or D*)

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

“Recoil” $\bar{D}^{(*)}$

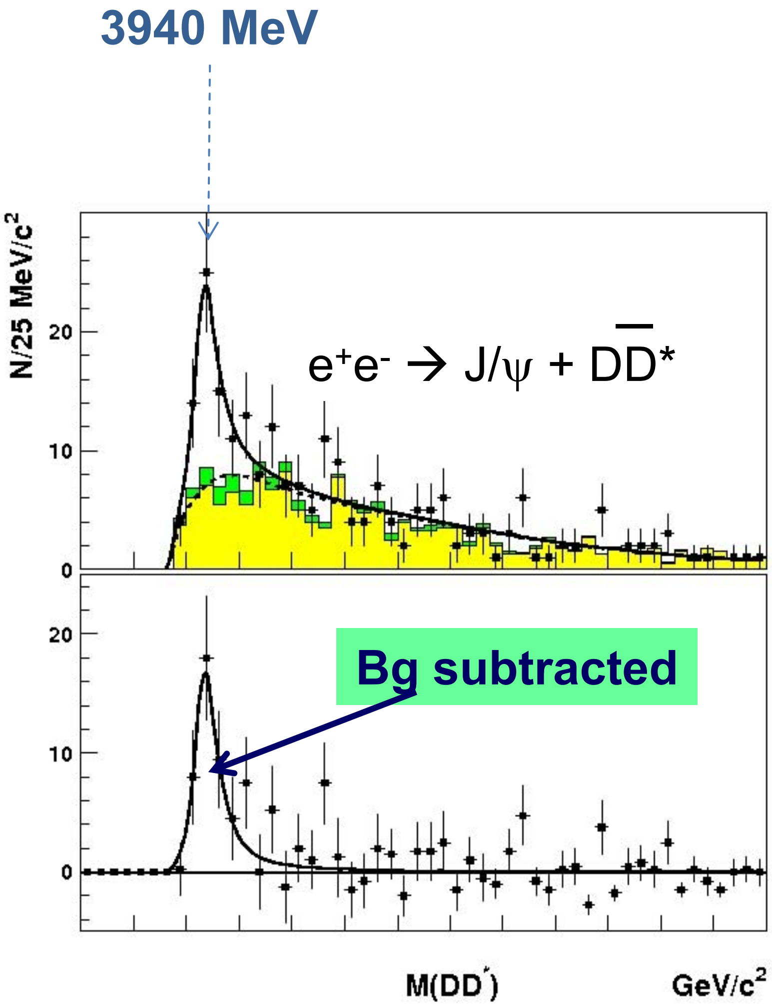
undetected

(inferred from kinematics)



$$M_{D^{(*)}} = \sqrt{(E_{cm} - E_{J/\psi} - E_{D^{(*)}})^2 - (\vec{p}_{J/\psi} + \vec{p}_{D^{(*)}})^2}$$

$X(3940) \to D\bar{D}^*$ is large



$M = 3942\ ^{+7}_{-6} \pm 6$ MeV

$\Gamma_{tot} = 37\ ^{+26}_{-15} \pm 12$ MeV

Nsig $= 52\ ^{+24}_{-16}\ \pm$

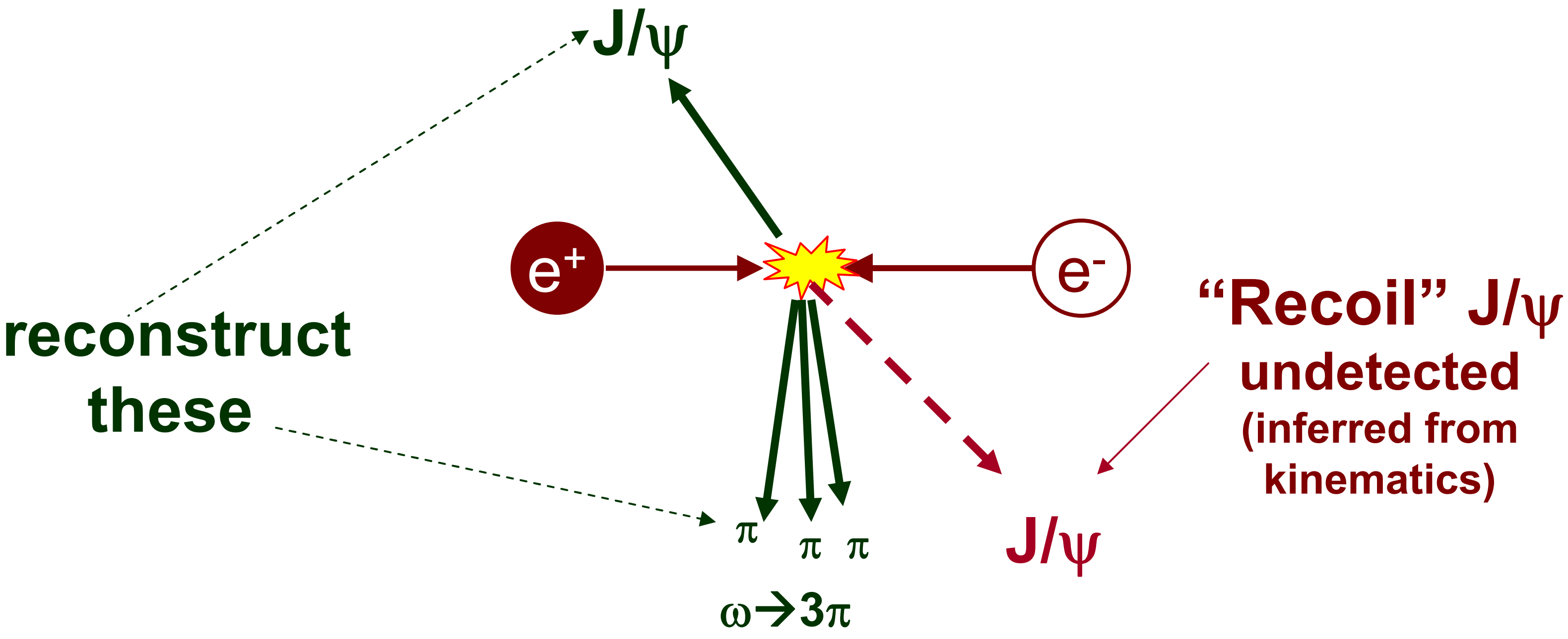
arXiv:0708.3812

PRL 98, 802001 (2007)

$$\mathcal{B}_{>2}(X(3940) \to D^*\bar{D}) = (96^{+45}_{-32} \pm 22)\%$$

($>$45% at 90% C.L.)

Use “partial reconstruction” to search for X(3940)→ωJ/ψ



J/ψ

e^+

e^-

reconstruct these

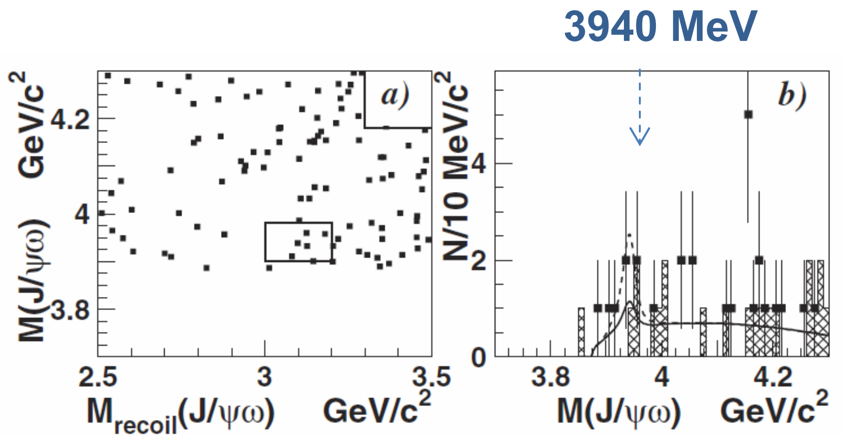
π π π

ω→3π

“Recoil” J/ψ undetected

(inferred from kinematics)

J/ψ



no signal:

$\mathcal{B}(X(3940) \to J/\psi\omega) < 26\%$ at 90% C.L.

X_{3940} & Y_{3940} are not the same

from:
$e^+e^- \rightarrow J/\psi\ D\bar{D}^*$ & $J/\psi\ \omega J/\psi$

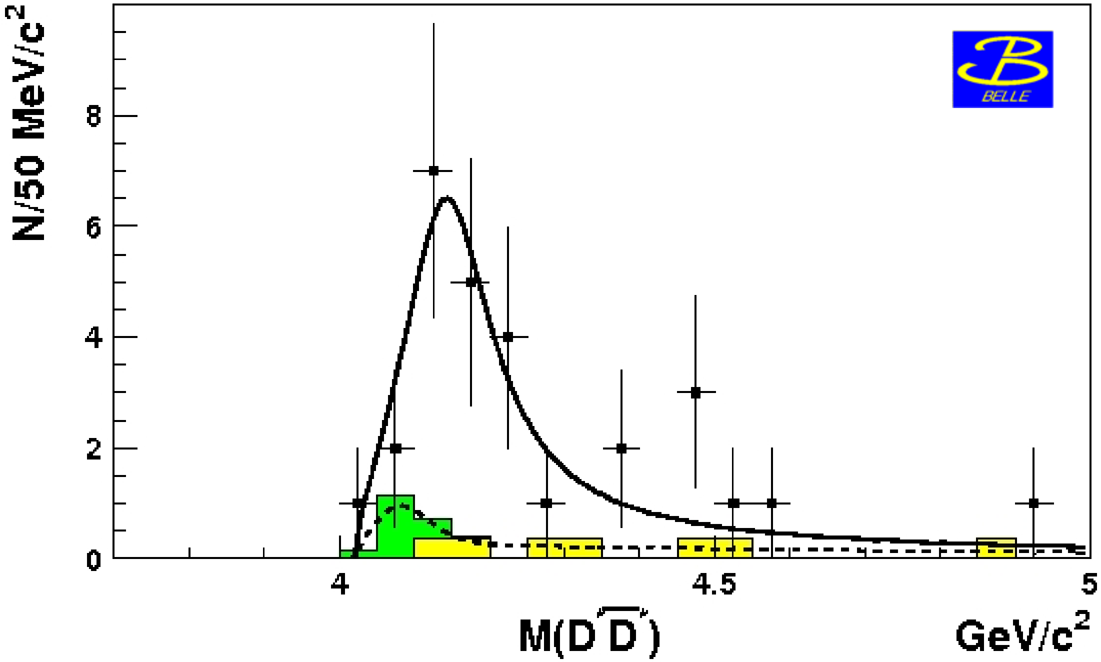
$$\frac{\mathcal{B}(X(3940) \to \omega\, J/\psi)}{\mathcal{B}(X(3940) \to D^{*0}\bar{D}^0)} < 0.6$$

from:
$B \rightarrow K\ \omega J/\psi$ & $KD\bar{D}^*$

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

$M(D^*\bar{D}^*)$ has a peak too

$e^+e^- \rightarrow J/\psi\, D^*\bar{D}^*$



$M = 4156\ ^{+25}_{-20} \pm 15$ MeV

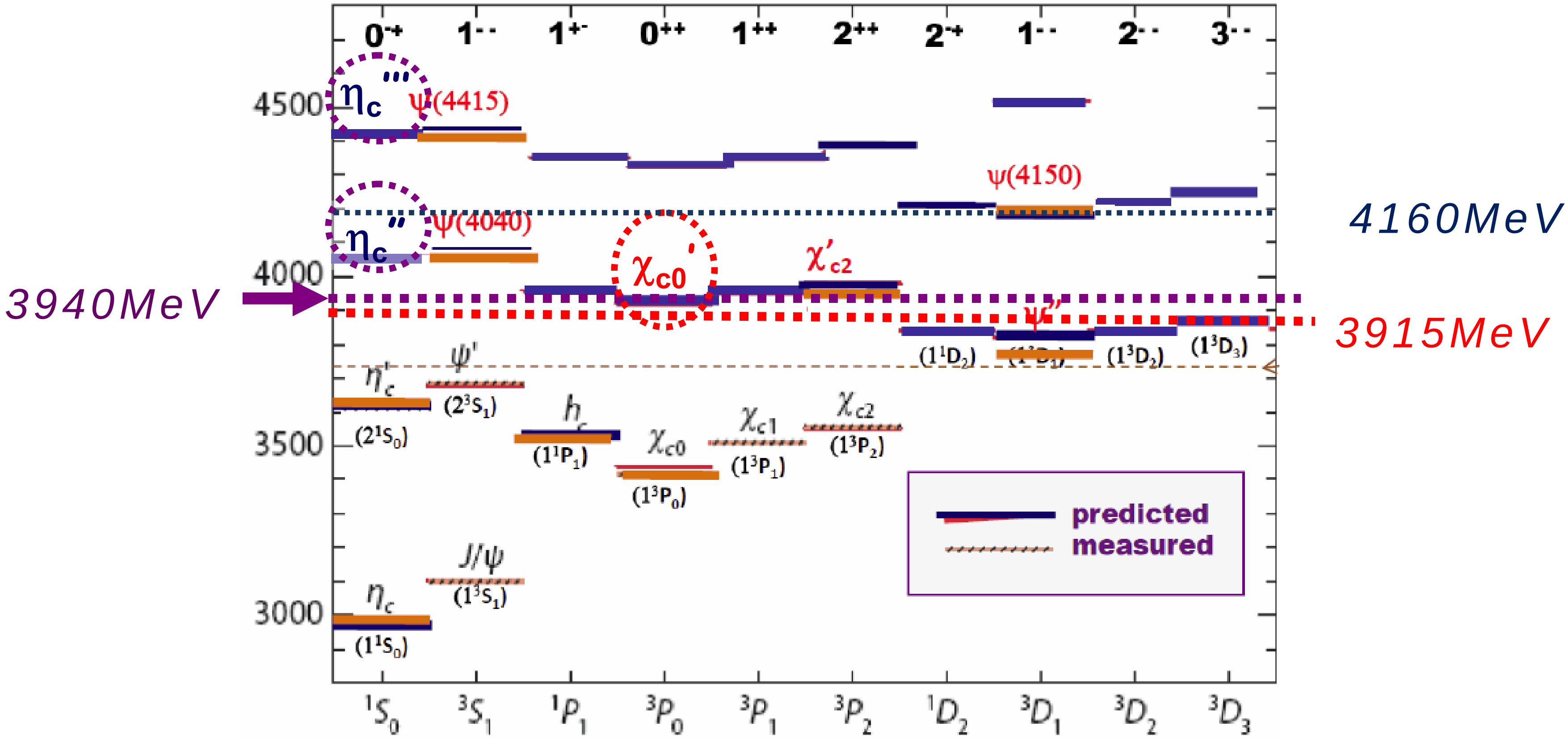
$\Gamma_{tot} = 139\ ^{+111}_{-61} \pm$

$Nsig = 24\ ^{+12}_{-8} \pm 11$evts

arXiv:0708.3812

It has to have $C=+$; most likely 0^{-+}

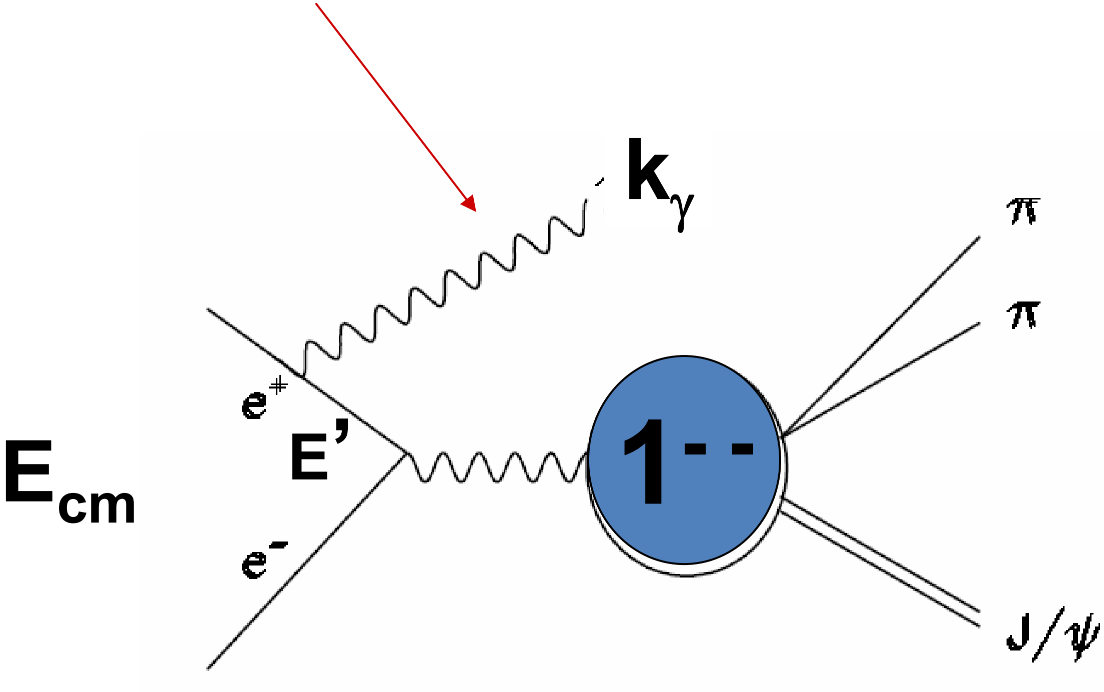
$c\bar{c}$ assignments for X(3940), Y(3915) & X(4160)?



- Y(3915) = χ_{co}'? ← $\Gamma(\omega J/\psi)$ too large?
- X(3940) = η_c''? ← mass too low?
- X(4160) = η_c''? ← mass too high?
- X(4160) = η_c'''? ← mass much too low?

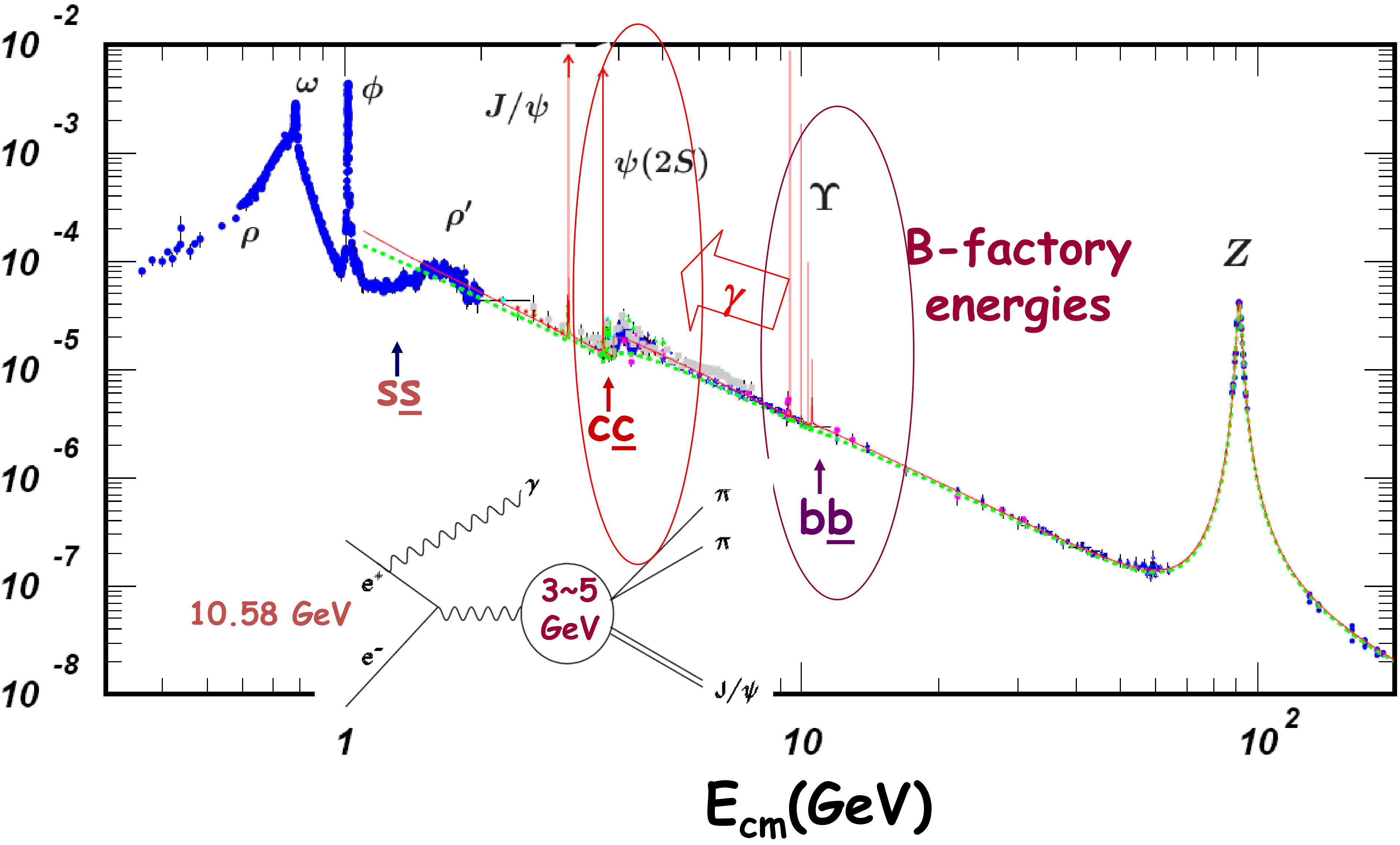
1^{--} states seen via "radiative return"

"initial-state-radiation" photon: γ_{ISR}



if $k_\gamma = 3.8 \sim 4.5$ GeV, E' = 3~5GeV

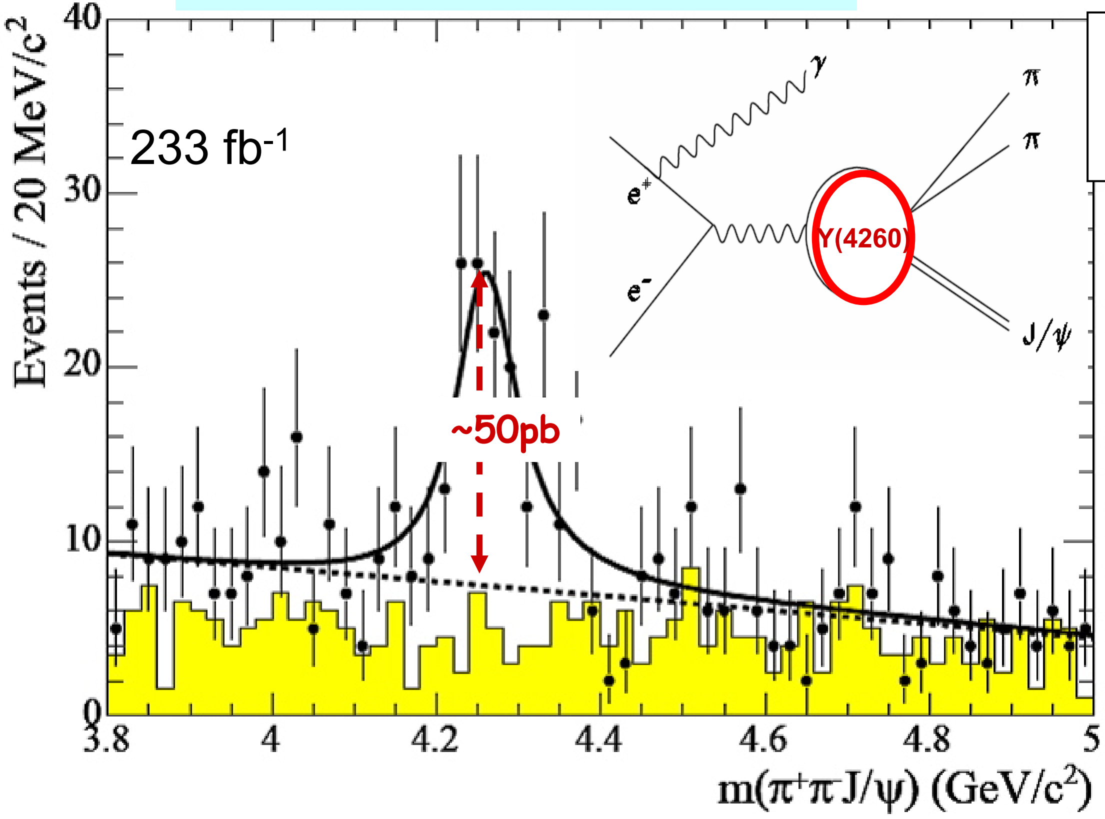
Radiative return



$e^+e^- \to \gamma_{isr}$ Y(4260) at BaBar

$\hookrightarrow \pi^+\pi^-$ J/ψ

BaBar PRL95, 142001 (2005)



fitted values:

M=4259 ± 8 $^{+2}_{-6}$ MeV

Γ = 88 ± 23 $^{+6}_{-9}$ MeV

“(4260) confirmed by Belle

M=4247 ± 12 $^{+17}_{-32}$ MeV

Γ = 108 ± 19 ±10 MeV

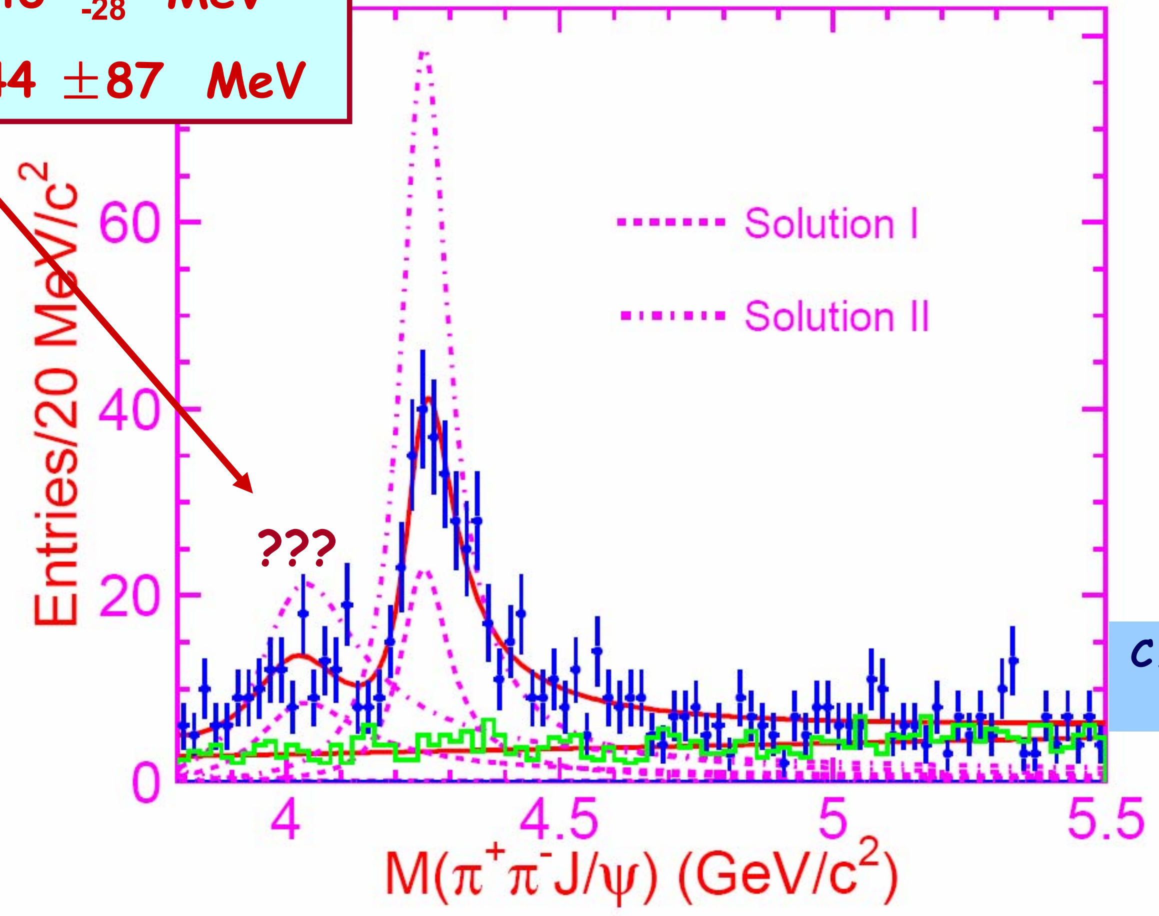
BaBar values:

M=4259 ± 8 $^{+2}_{-6}$ MeV

Γ = 88 ± 23 $^{+6}_{-9}$ MeV

M=4008 ± 40 $^{+114}_{-28}$ MeV

Γ = 226 ± 44 ±87 MeV

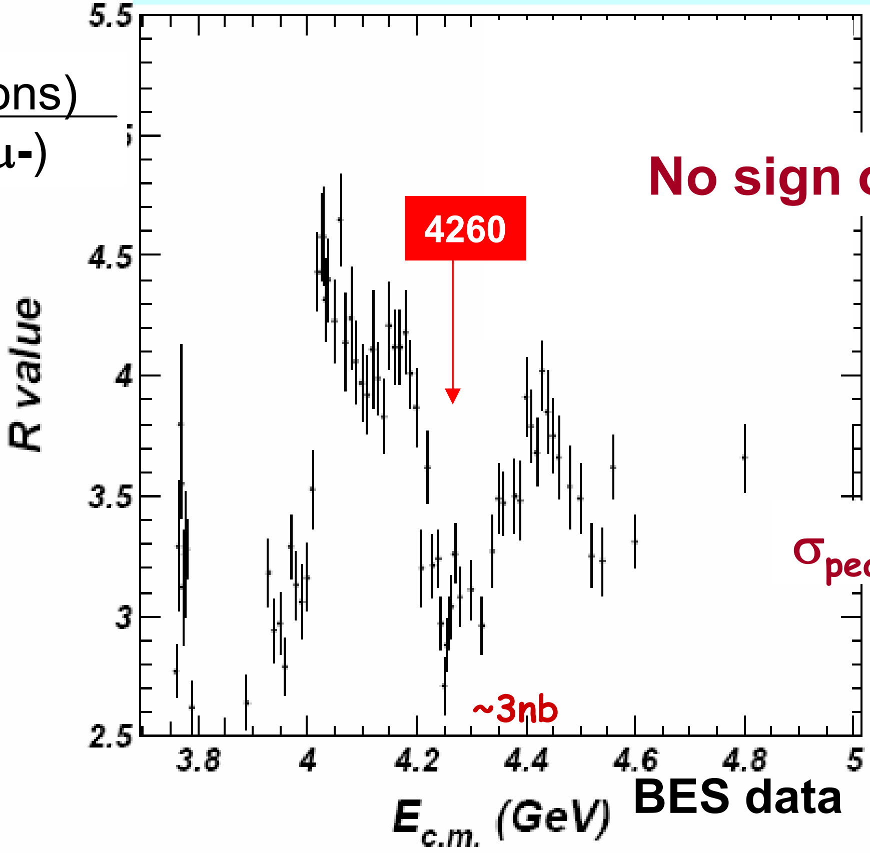


C.Z Yuan et al (Belle) PRL 99, 182004

Not seen in e^+e^- → hadrons

J.Z.Bai *et al* (BES), PRL 88, 101802 (2006)

$$\frac{\sigma(e+e- \to hadrons)}{\sigma(e+e- \to \mu+\mu-)}$$



4260

~3nb

BES data

No sign of $Y(4260) \to D^{(*)}D^{(*)}$

$\sigma_{peak}(Y(4260) \to \pi^+\pi^- J/\psi) \sim 50$ pb

Huge by charmonium standards

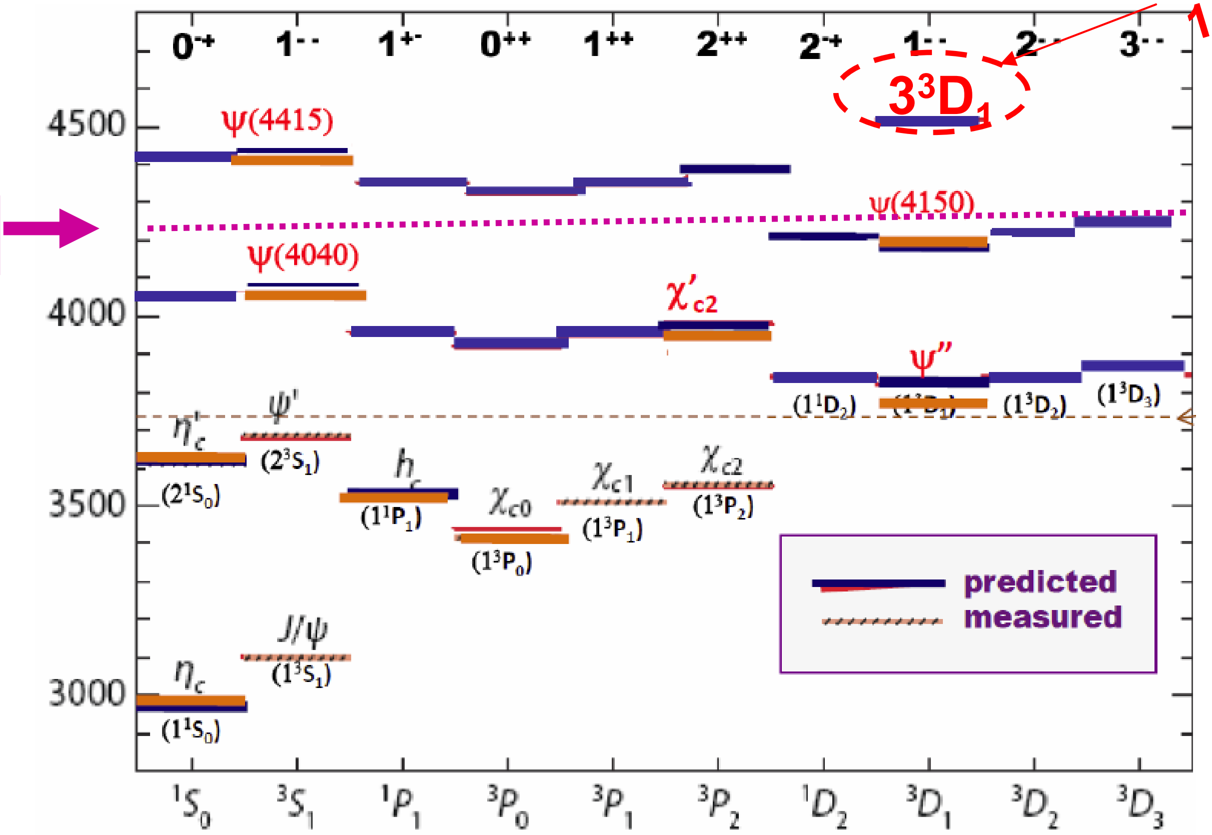
$\Gamma(Y_{4260} \to \pi^+\pi^- J/\psi) > 1.6$MeV @ 90% CL

X.H. Mo *et al*, PL B640, 182 (2006)

cc assignment for the Y(4260)??

4260MeV

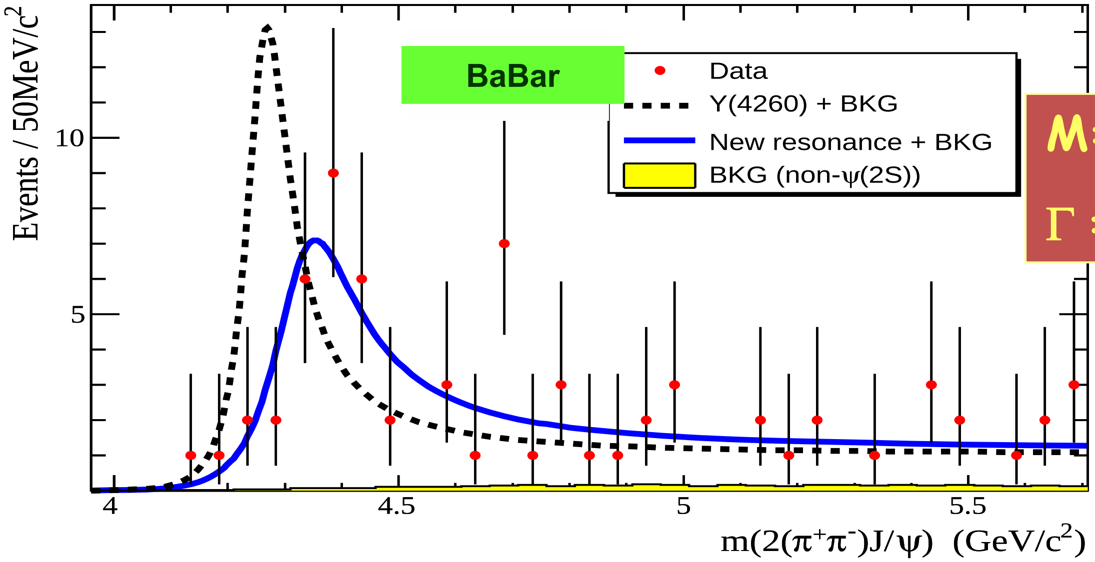
only unfilled 1⁻⁻ state left



Y(4260) = 3^3D_1? ← mass too low & $\Gamma(\pi^+\pi^- J/\psi)$ too large

another peak in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\psi'$

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



M=4324 ± 24 MeV

Γ = 172 ± 33 MeV

Peak is 4324 MeV, distinct from 4260 MeV

4325 MeV $\pi^+\pi^-\psi'$ peak in Belle

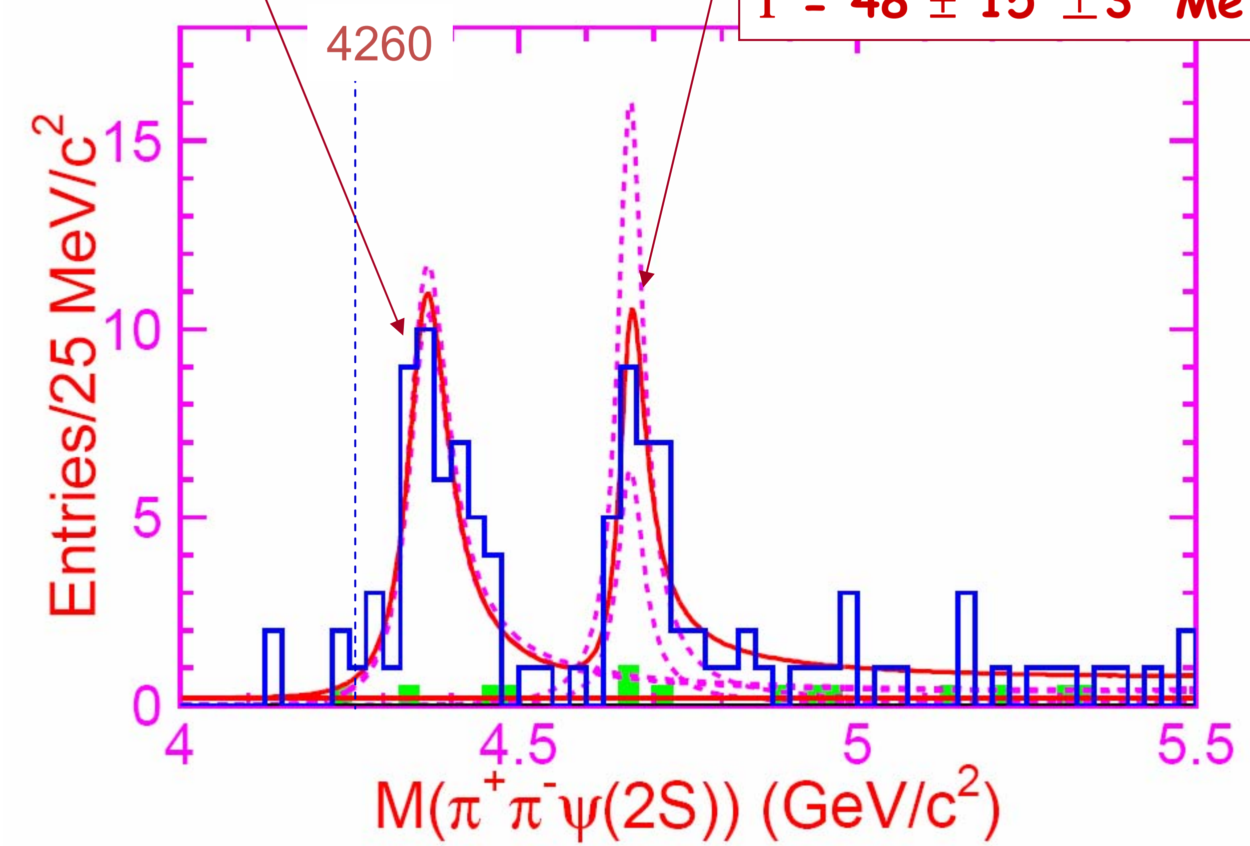
Two peaks! (both relatively narrow)
(& neither consistent with 4260)

M=4361 ± 9 ±9 MeV

Γ = 74 ± 15 ±10 MeV

M=4664 ± 11 ±5 MeV

Γ = 48 ± 15 ±3 MeV



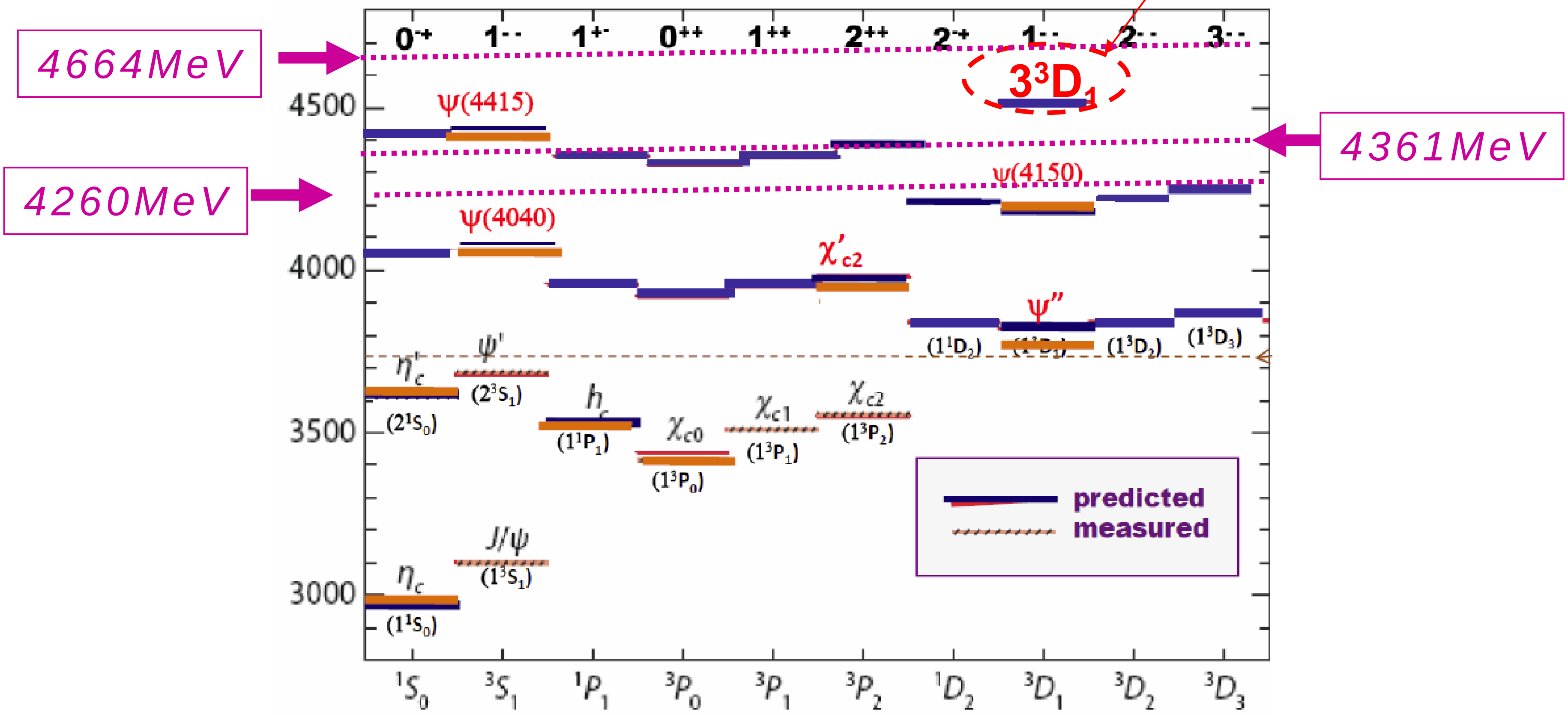
BaBar values

M=4324 ± 24 MeV

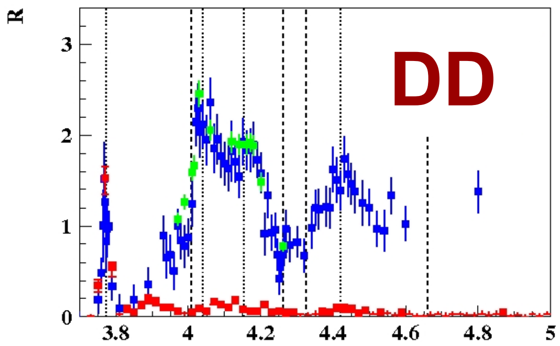
Γ = 172 ± 33 MeV

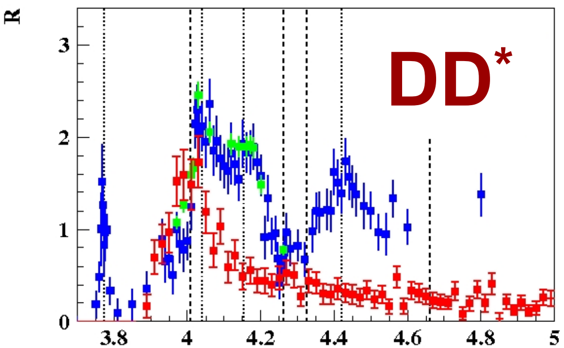
X.L. Wang et al (Belle)
PRL 99, 142002 (2007)

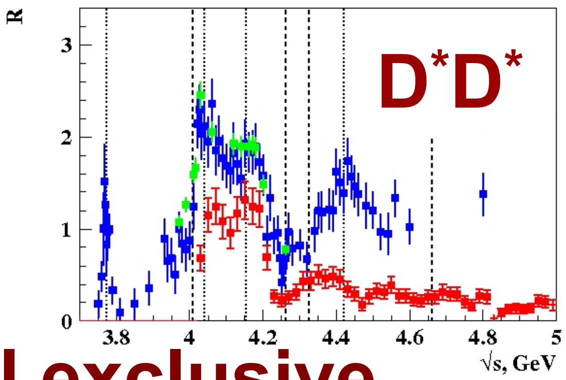
At least three peaks for only one empty level

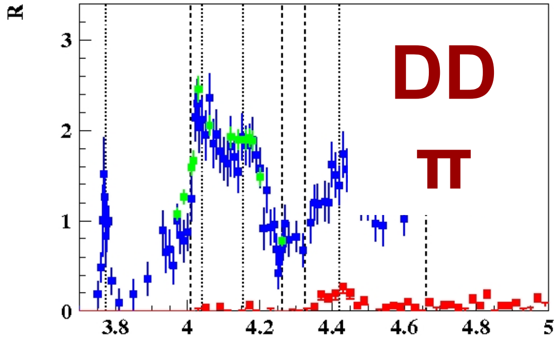


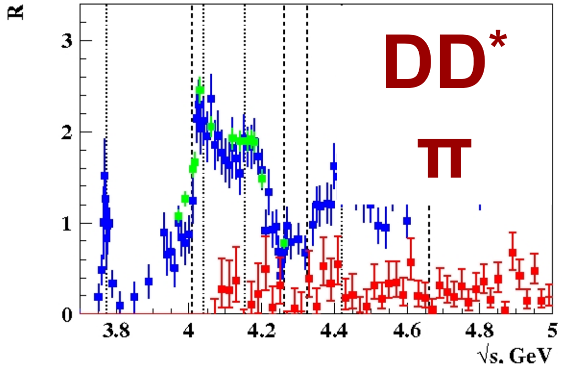
exclusive $e^+e^- \rightarrow \gamma_{ISR} D^{(*)} D^{(*)}$ channels

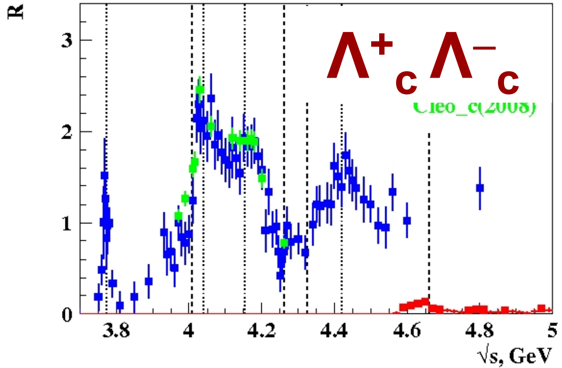




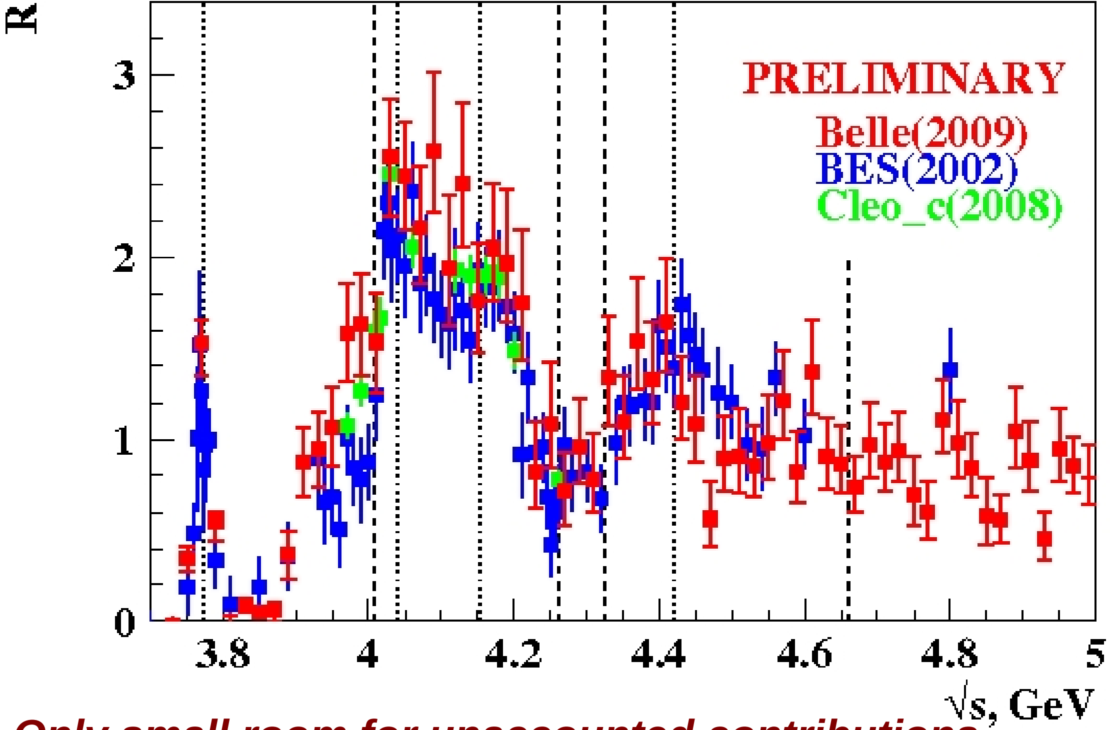








Sum of all exclusive contributions



Only small room for unaccounted contributions

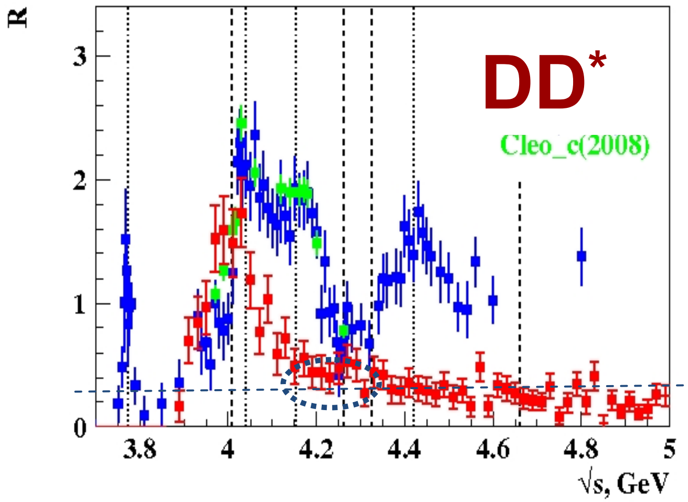
- Charm strange final states

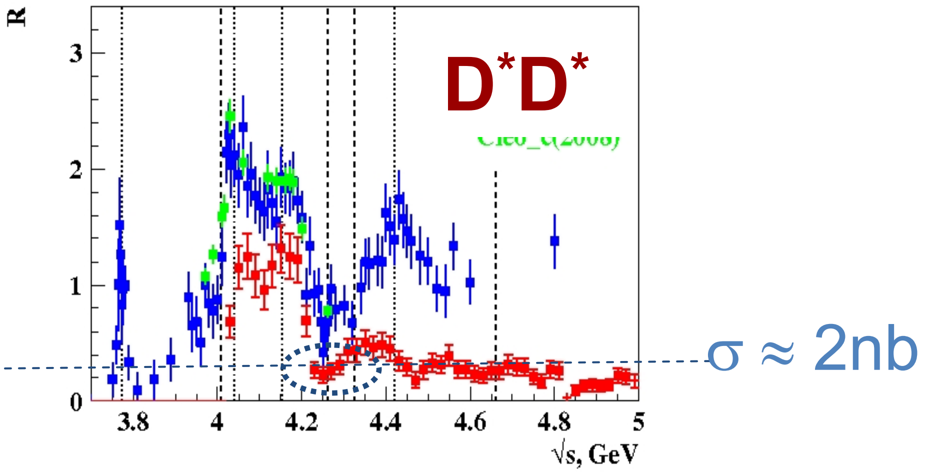
Limited inclusive data above 4.5 GeV

- Charm baryons final states

Experiment for BES III?: Search for other Y(4260) modes

Scan the 4260 ± 100 MeV region & measure dominant channels to ± 1%



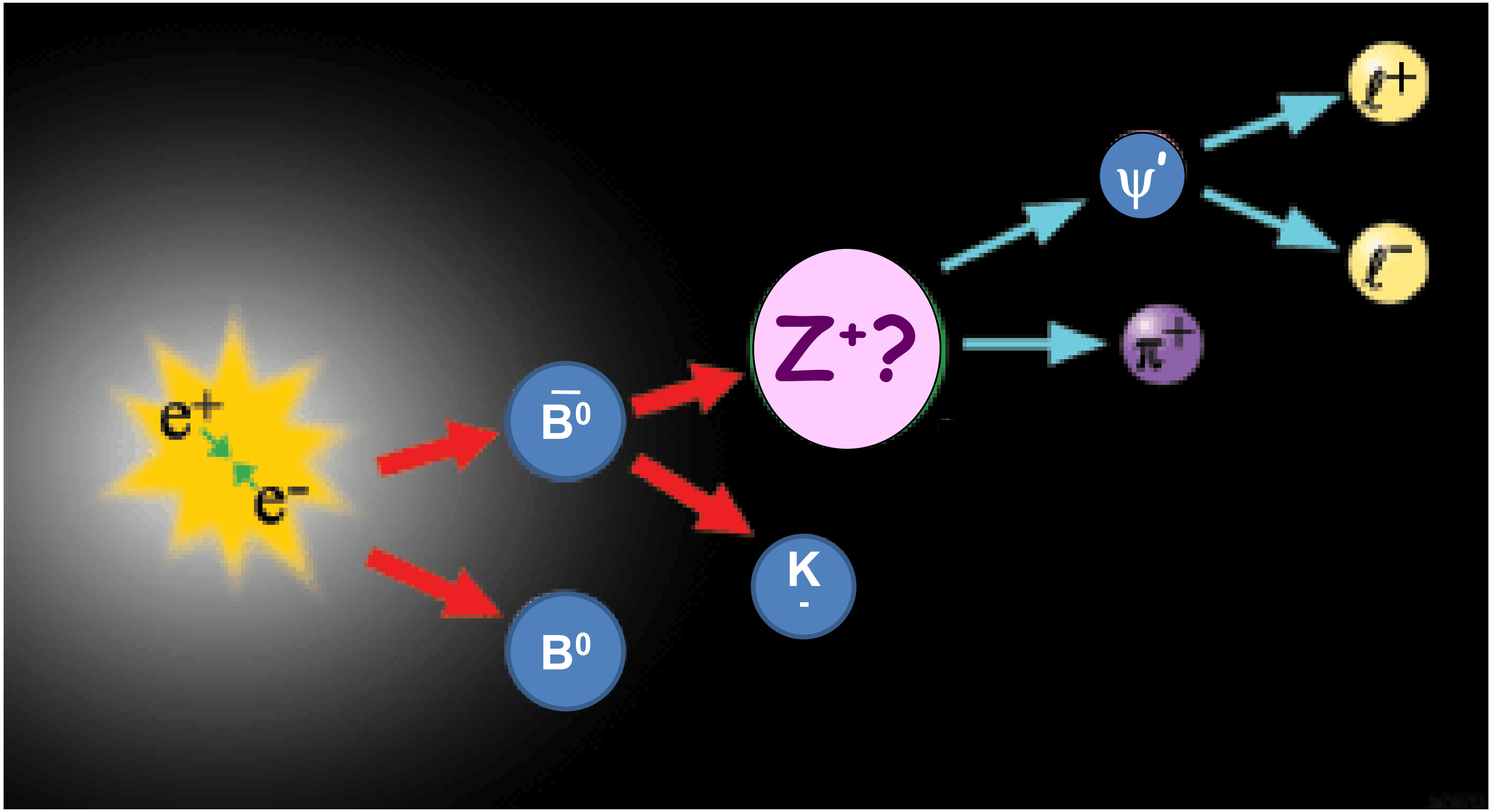


$$\int dtLum = \frac{N_{evts}}{s \times effic} \approx \frac{10^4}{2\times 10^3\, pb \times 0.1} = 50\, pb^{-1} / pt$$

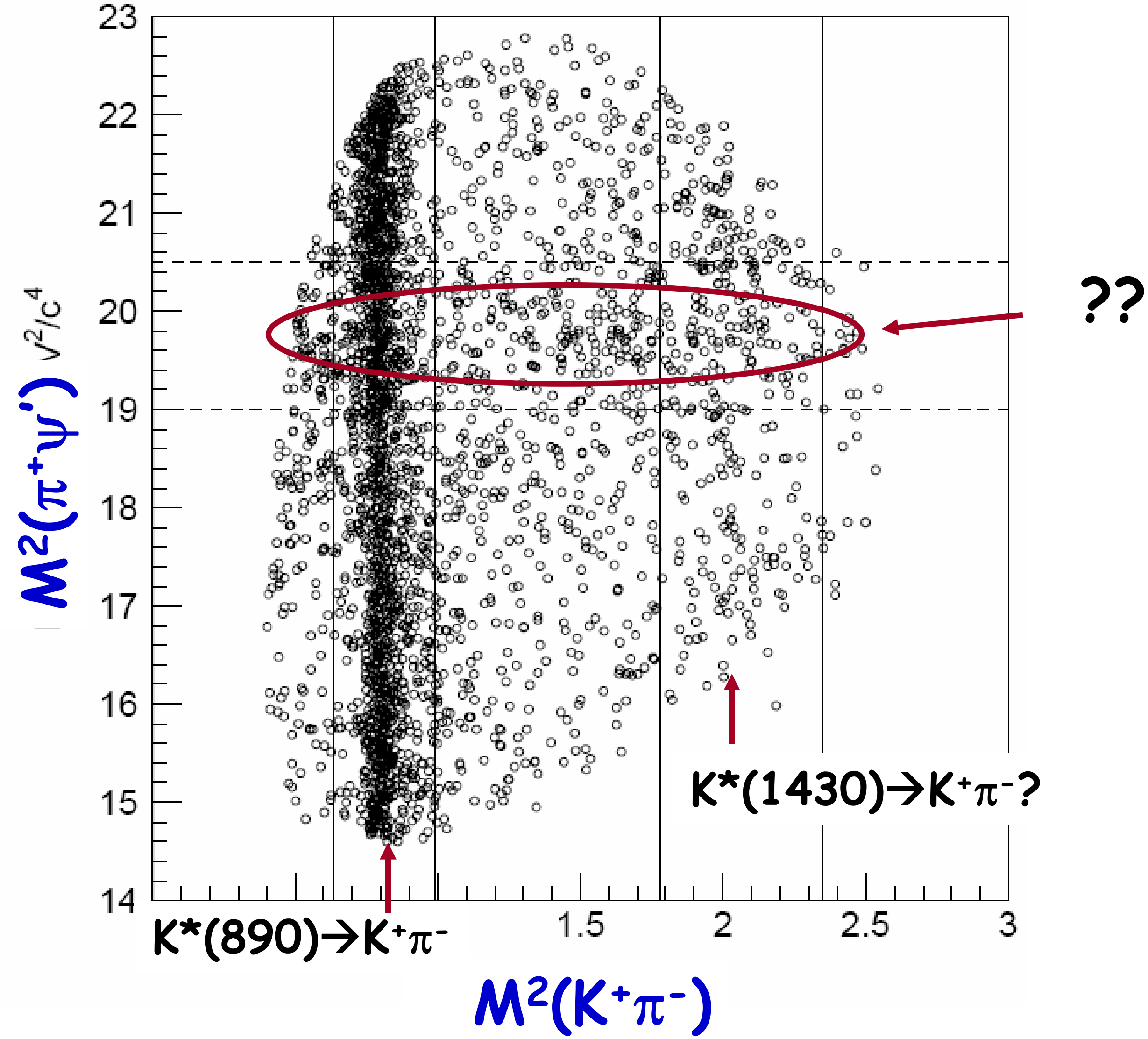
20 points ➔ ~1 year of BES III data taking

The Z(4430)$^+$ → $\pi^+\psi'$

"smoking gun" for a four quark meson?



B→$K^{\pm}\pi^{\mp}\psi'$ (in Belle)



??

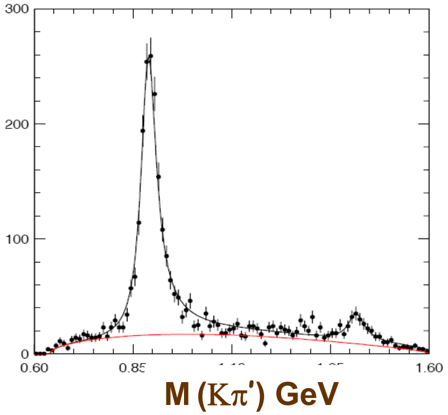
$K^*(1430)\rightarrow K^+\pi^-$?

$K^*(890)\rightarrow K^+\pi^-$

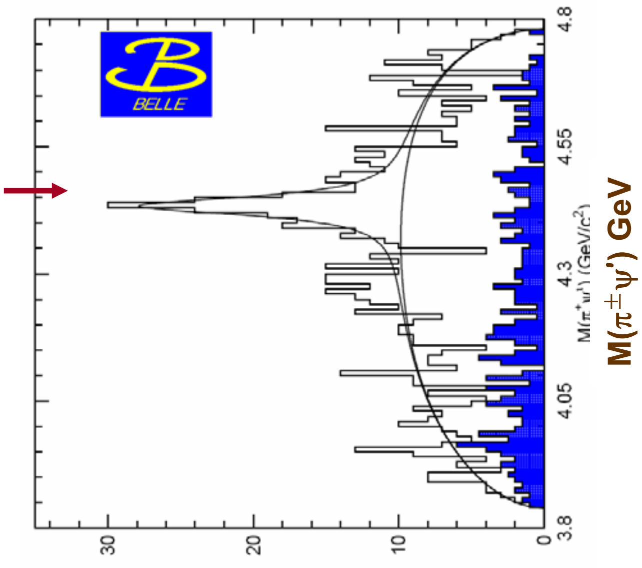
The Z(4430)$^\pm$ →$\pi^\pm\psi'$ peak

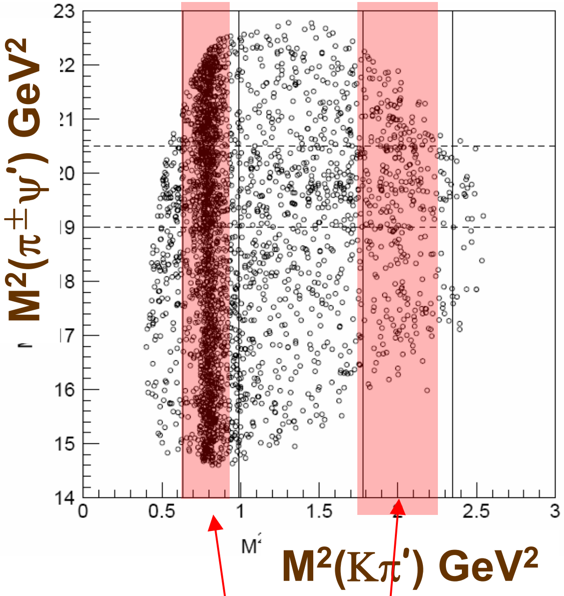
B→K $\pi^+\psi'$

M = 4433 ±4 ±2 MeV/c^2
Γ_{tot} = 45 $^{+18}_{-13}$ $^{+30}_{-13}$ MeV
Nsig =121 ± 30 evts
χ^2/dof = 80.2/94.0   6.5 σ



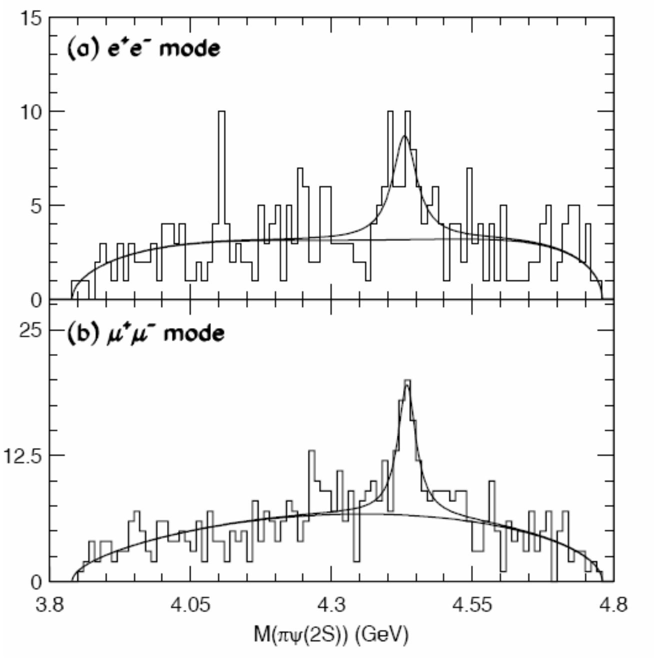
Z(4430) →

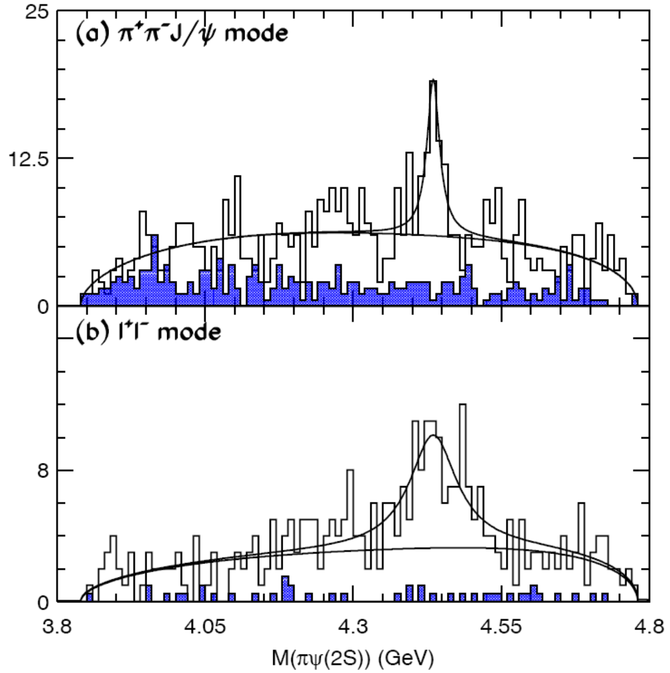


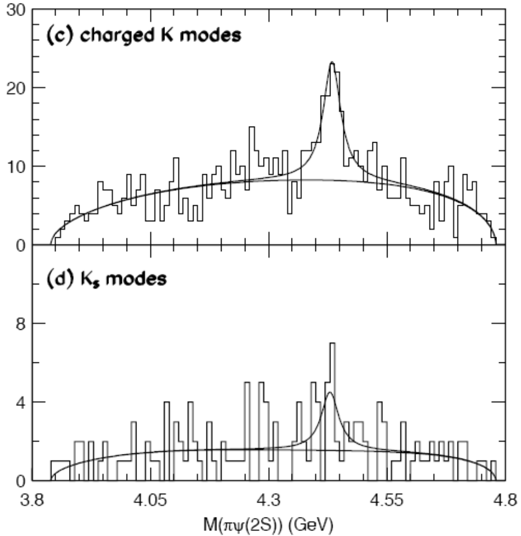


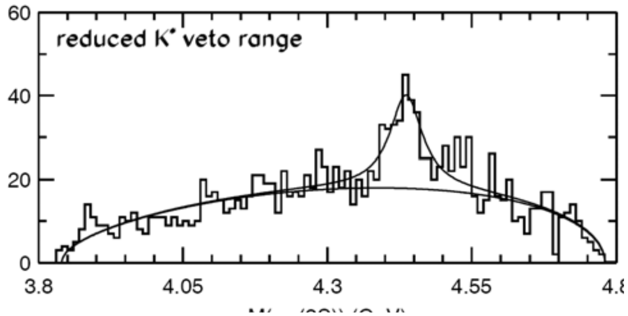
“K* Veto”

Shows up in all data subsamples



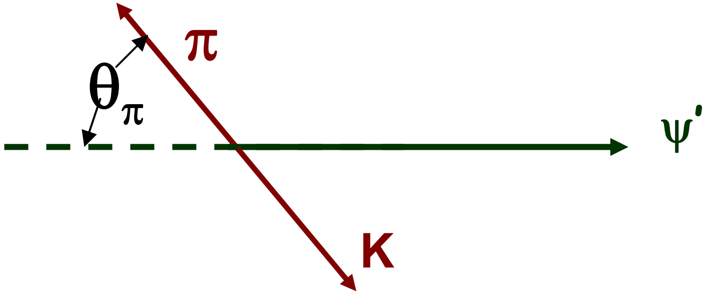


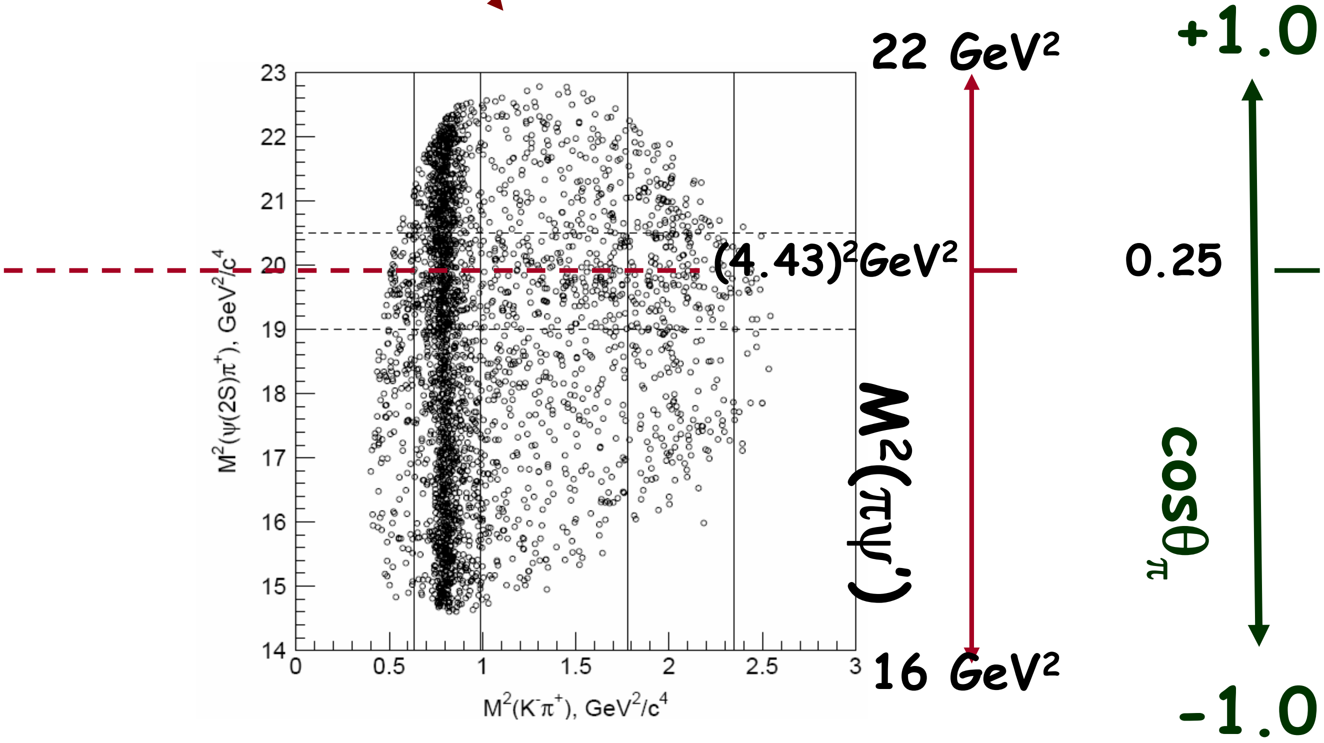




Could the Z^+(4430) be due to a reflection from the $K\pi$ channel?

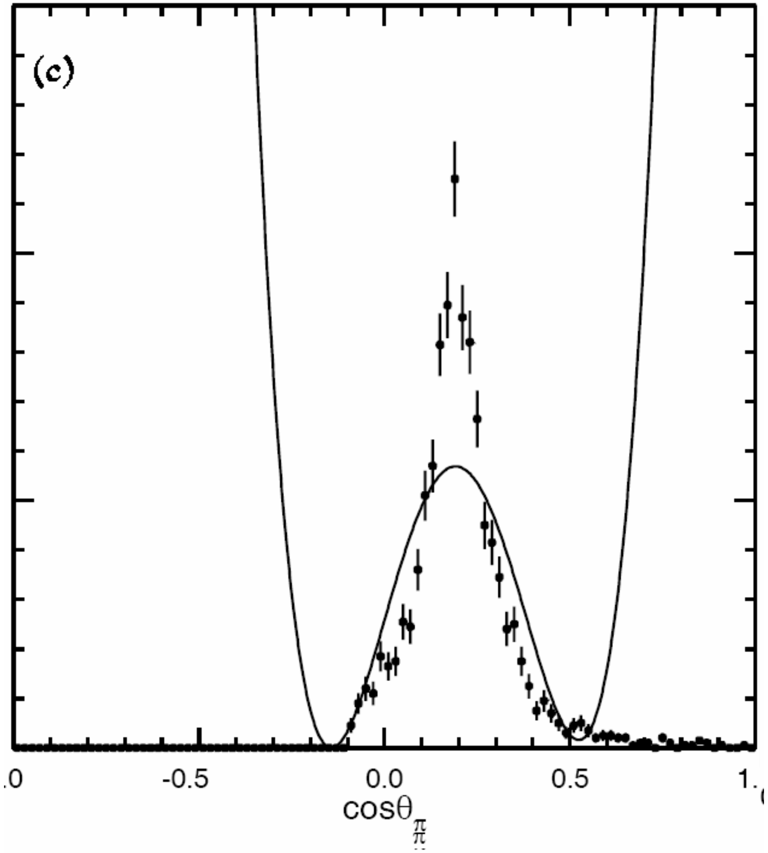
Cos θ_π vs $M^2(\pi\psi')$





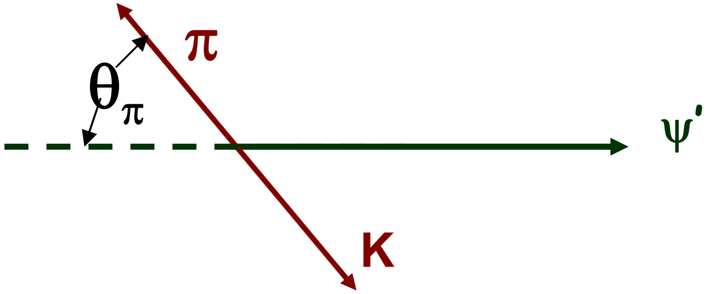
M ($\pi\psi'$) & cosθ_π are tightly correlated;
a peak in cosθ_π ➔ peak in M($\pi\psi'$)

S- P- & D-waves cannot make a peak (+ nothing else) at $\cos\theta_{\pi} \approx 0.25$



not without introducing other, even more dramatic features at other $\cos\theta_{\pi}$ (i.e., other $M_{\pi\psi'}$) values.

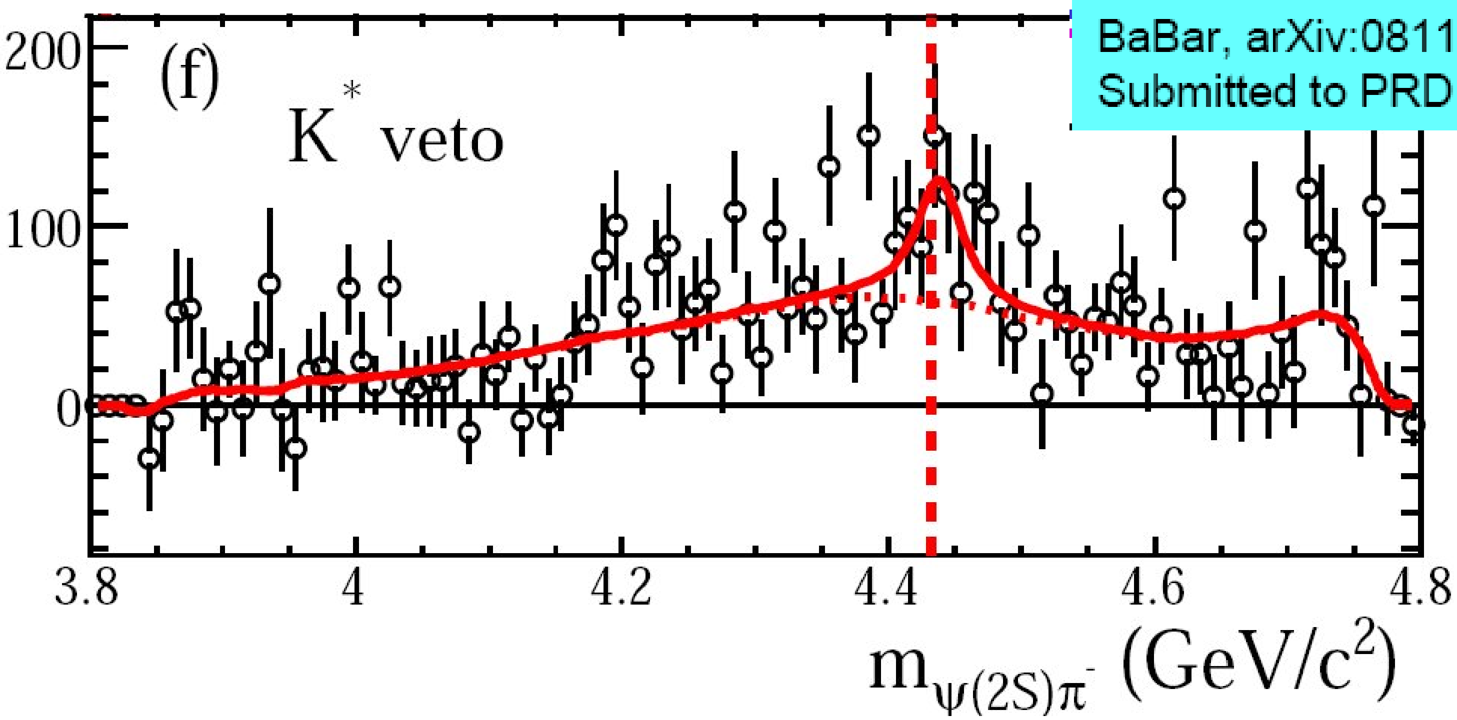
HW



Compute the relation between $\cos\theta_\pi$ and $M^2(\pi\psi')$

But…

BaBar doesn't see a significant Z(4430)$^+$



BaBar, arXiv:0811.0564
Submitted to PRD

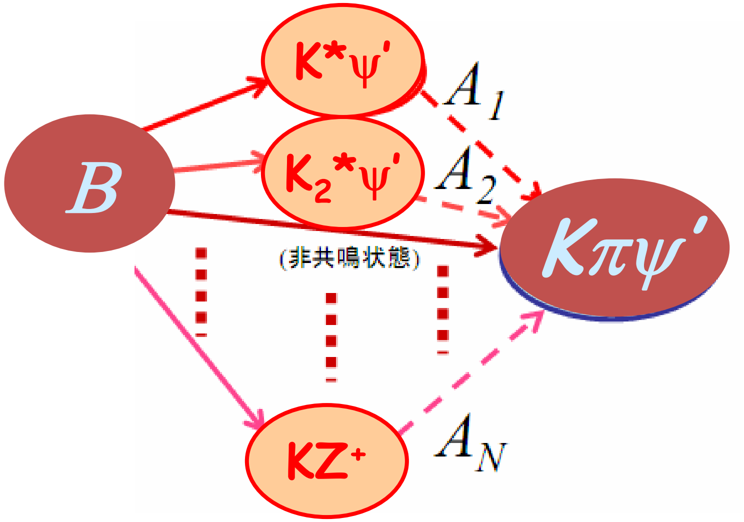
"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

$$BF(B^0 \rightarrow Z^+K) \times BF(Z^+ \rightarrow \psi(2S)\pi^+) < 3.1 \times 10^{-5}$$

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

Reanalysis of Belle's B→K$\pi\psi'$ data using Dalitz Plot techniques

2-body isobar model for $\rightarrow K\pi\psi'$



Our default model

$\kappa\psi'$

$K^*(890)\psi'$

$K^*(1410)\psi'$

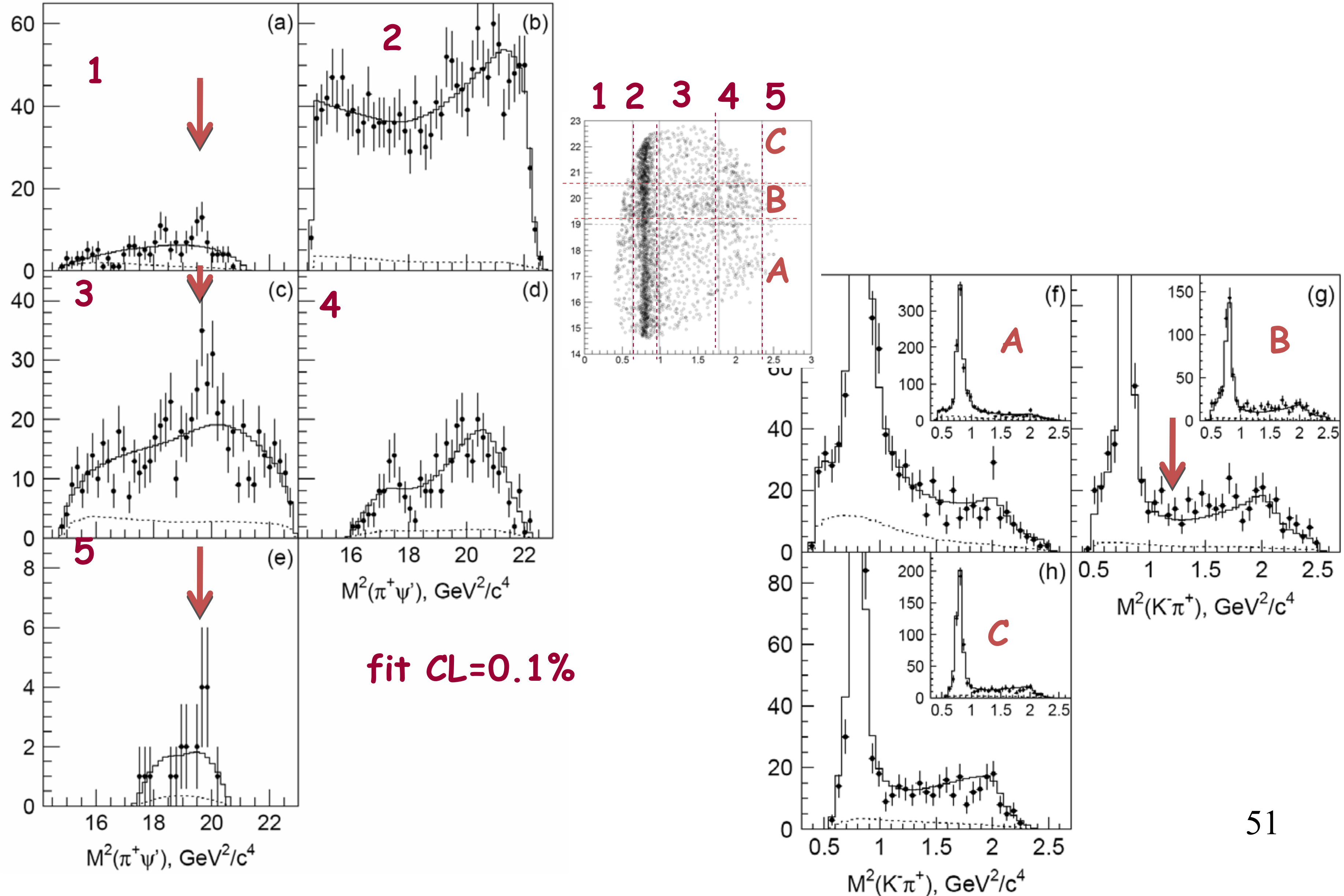
$K_0^*(1430)\psi'$

$K_2^*(1430)\psi'$

$K^*(1680)\psi'$

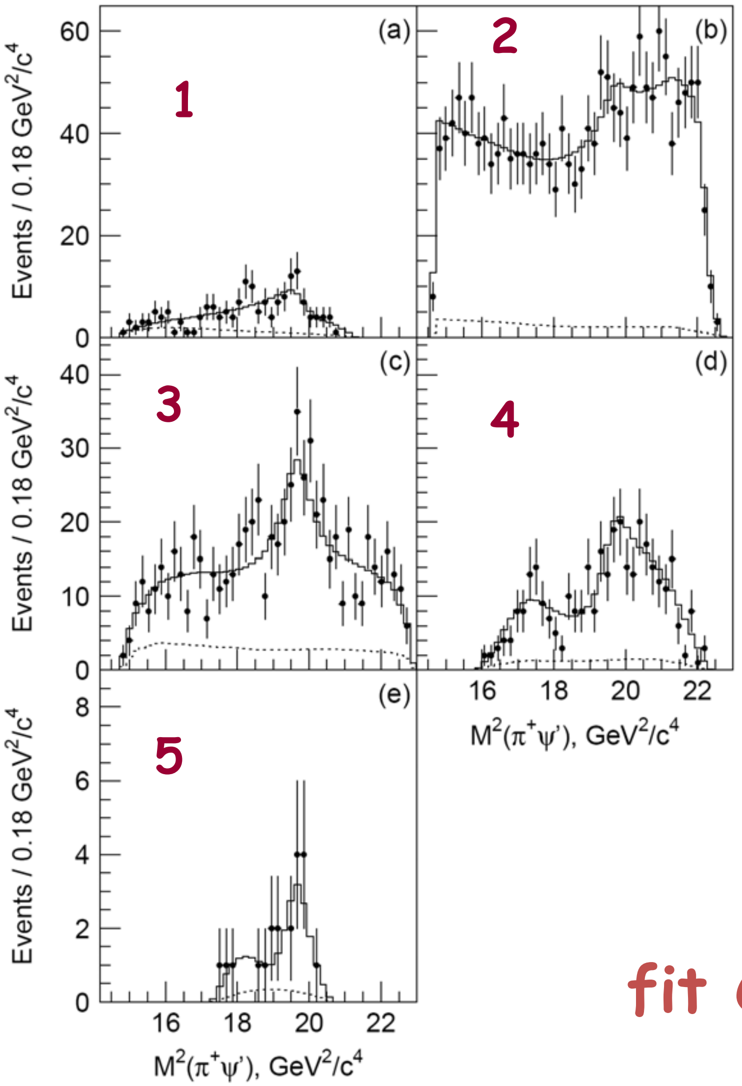
KZ^+

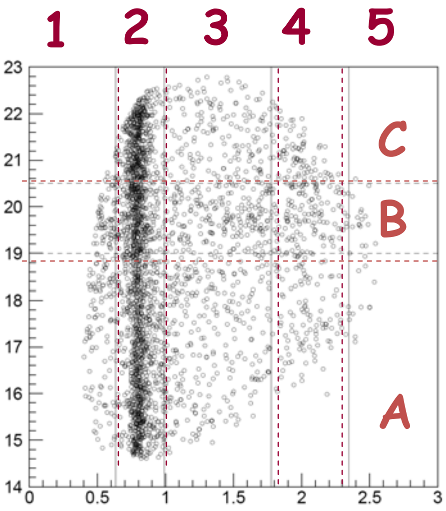
Results with no KZ^+ term

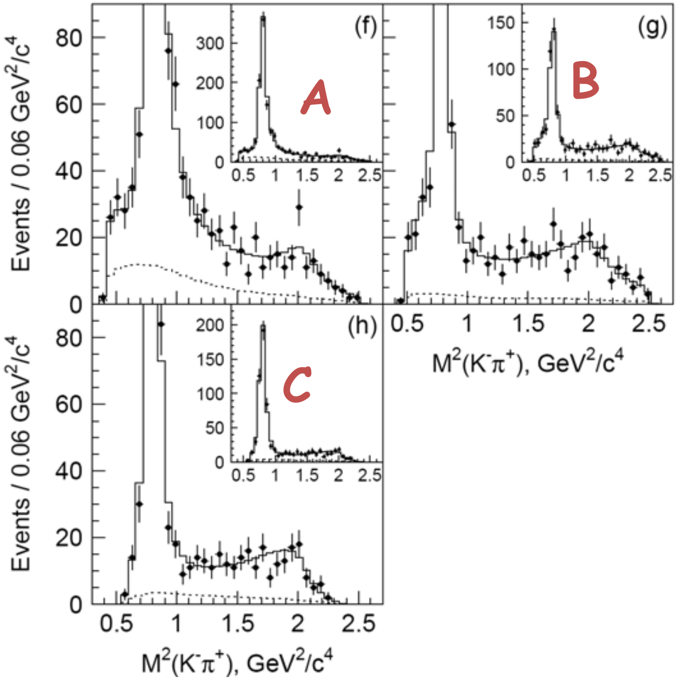


fit CL=0.1%

Results with a KZ$^+$ term



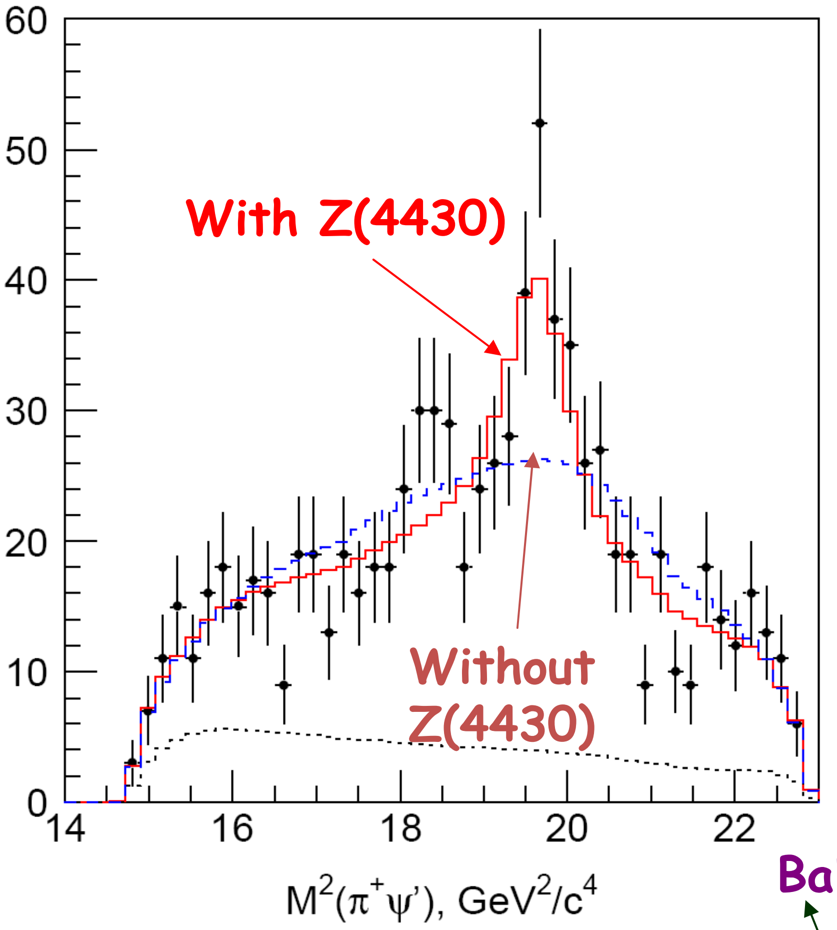




fit CL=36%

Compare with PRL results

K* veto applied



$M = 4443^{+15}_{-12}{}^{+17}_{-13}$ MeV/c^2

$\Gamma = 109^{+86}_{-43}{}^{+57}_{-52}$ MeV

Signif: 6.4σ

Published results

$M = 4433 \pm 4 \pm 2$ MeV/c^2
$\Gamma_{tot} = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV
Nsig = 121 ± 30 evts
$\chi^2/dof = 80.2/94.0$ 6.5 σ

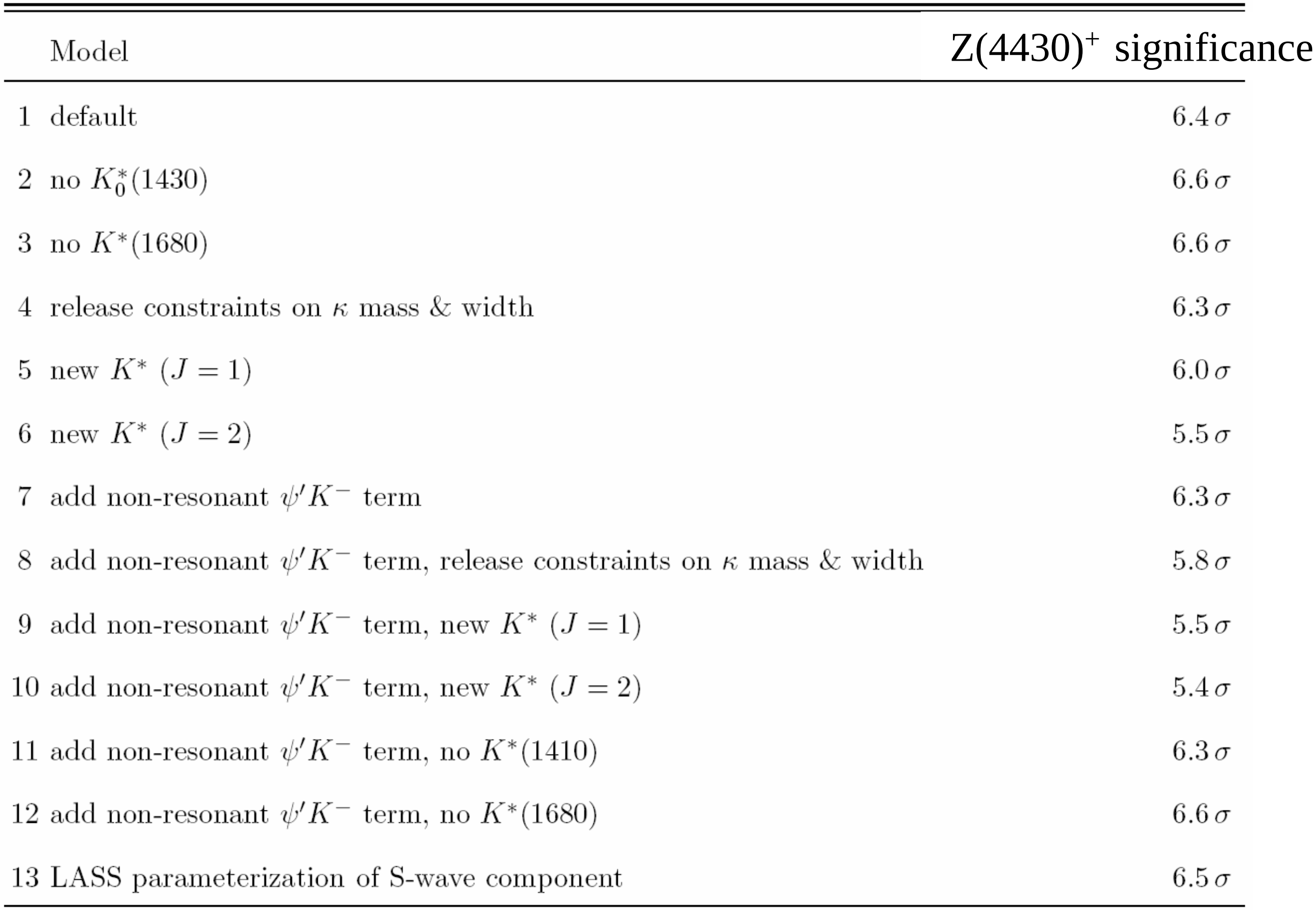
Mass & significance similar, width & errors are larger

BaBar: $BF(B^0 \rightarrow Z^+K) \times BF(Z^+ \rightarrow \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

Belle: $= (3.2^{+1.8+9.6}_{0.9-1.6}) \times 10^{-5}$

No big contradiction

Variations of the model

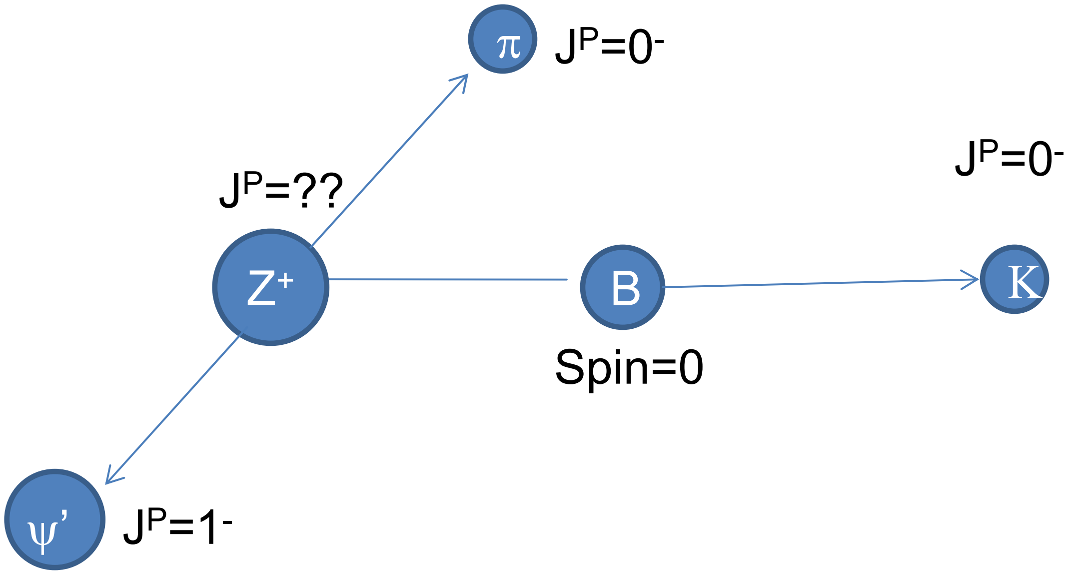


	Model	$Z(4430)^+$ significance
1	default	$6.4\,\sigma$
2	no $K_0^*(1430)$	$6.6\,\sigma$
3	no $K^*(1680)$	$6.6\,\sigma$
4	release constraints on κ mass & width	$6.3\,\sigma$
5	new K^* $(J=1)$	$6.0\,\sigma$
6	new K^* $(J=2)$	$5.5\,\sigma$
7	add non-resonant $\psi' K^-$ term	$6.3\,\sigma$
8	add non-resonant $\psi' K^-$ term, release constraints on κ mass & width	$5.8\,\sigma$
9	add non-resonant $\psi' K^-$ term, new K^* $(J=1)$	$5.5\,\sigma$
10	add non-resonant $\psi' K^-$ term, new K^* $(J=2)$	$5.4\,\sigma$
11	add non-resonant $\psi' K^-$ term, no $K^*(1410)$	$6.3\,\sigma$
12	add non-resonant $\psi' K^-$ term, no $K^*(1680)$	$6.6\,\sigma$
13	LASS parameterization of S-wave component	$6.5\,\sigma$

Others: Blatt f-f term 0←r=1.6fm→4fm; Z^+ spin J=0→J=1; incl K* in the bkg fcn

HW

Devise strategies to determine J^P of the $Z(4430)^+$

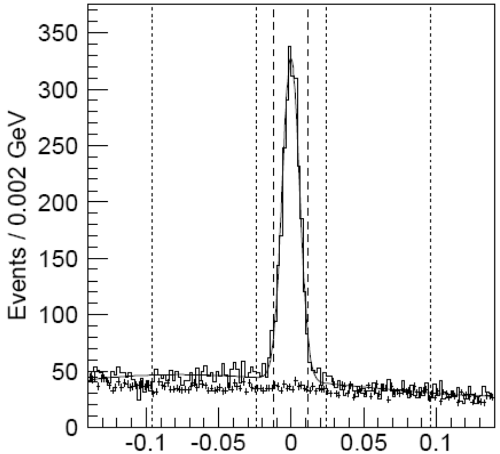


Are any J^P values immediately ruled out?
Can we use parity conservation? For which decays?

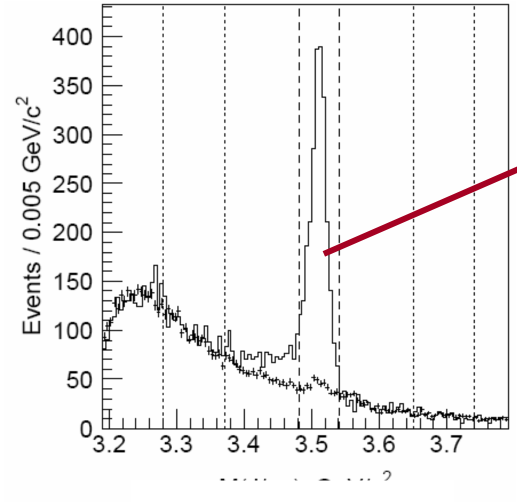
The $Z_1(4050)^+$ & $Z_2(4250)^+$ $\rightarrow \pi^+\chi_{c1}$ peaks

R. Mizuk et al (Belle), PRD 78,072004 (2008)

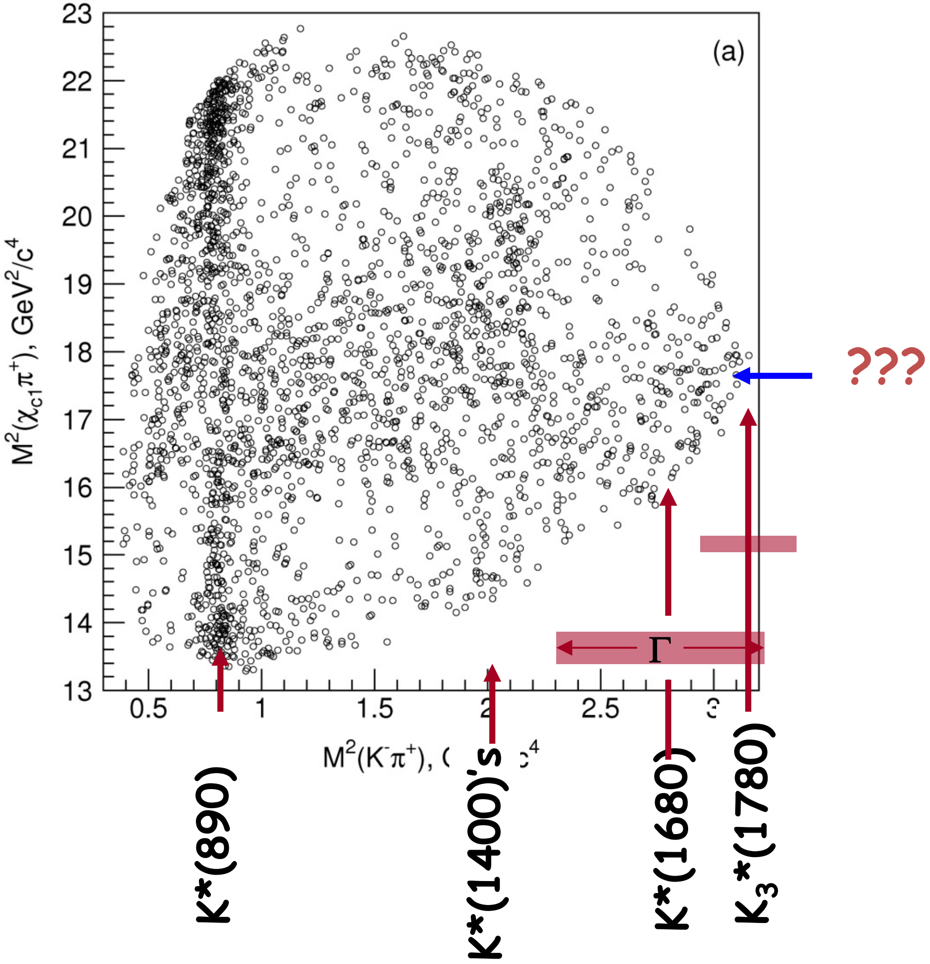
Dalitz analysis of $\bar{B}^0 \rightarrow K^-\pi^+\chi_{c1}$



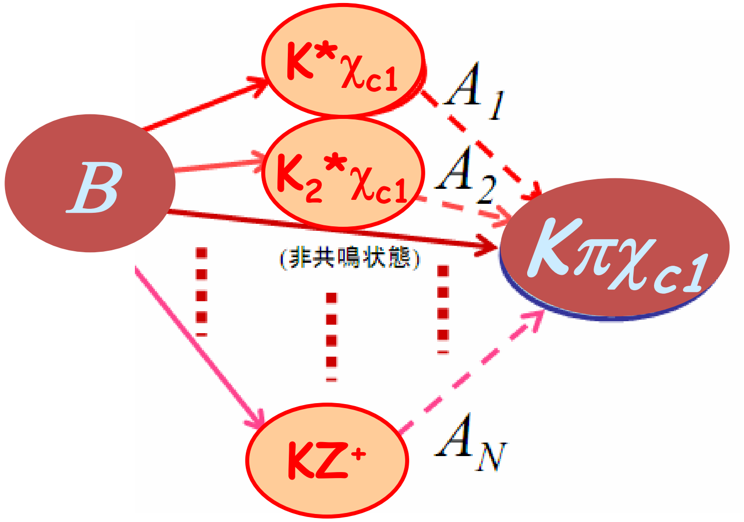
ΔE GeV



M (J/ψγ) GeV



$B \to K\pi\chi_{c1}$ Dalitz-plot analyses



Default Model

$K\chi_{c1}$

$K^*(890)\chi_{c1}$

$K^*(1410)\chi_{c1}$

$K_0{}^*(1430)\chi_{c1}$

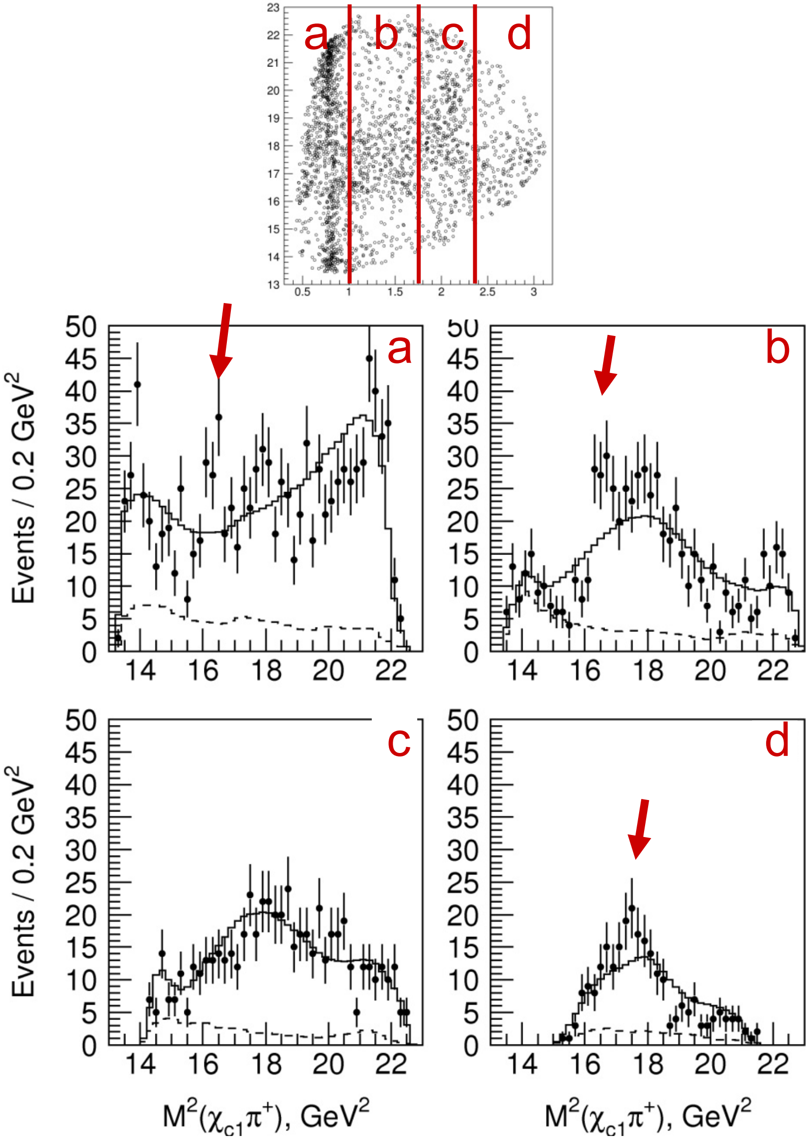
$K_2{}^*(1430)\chi_{c1}$

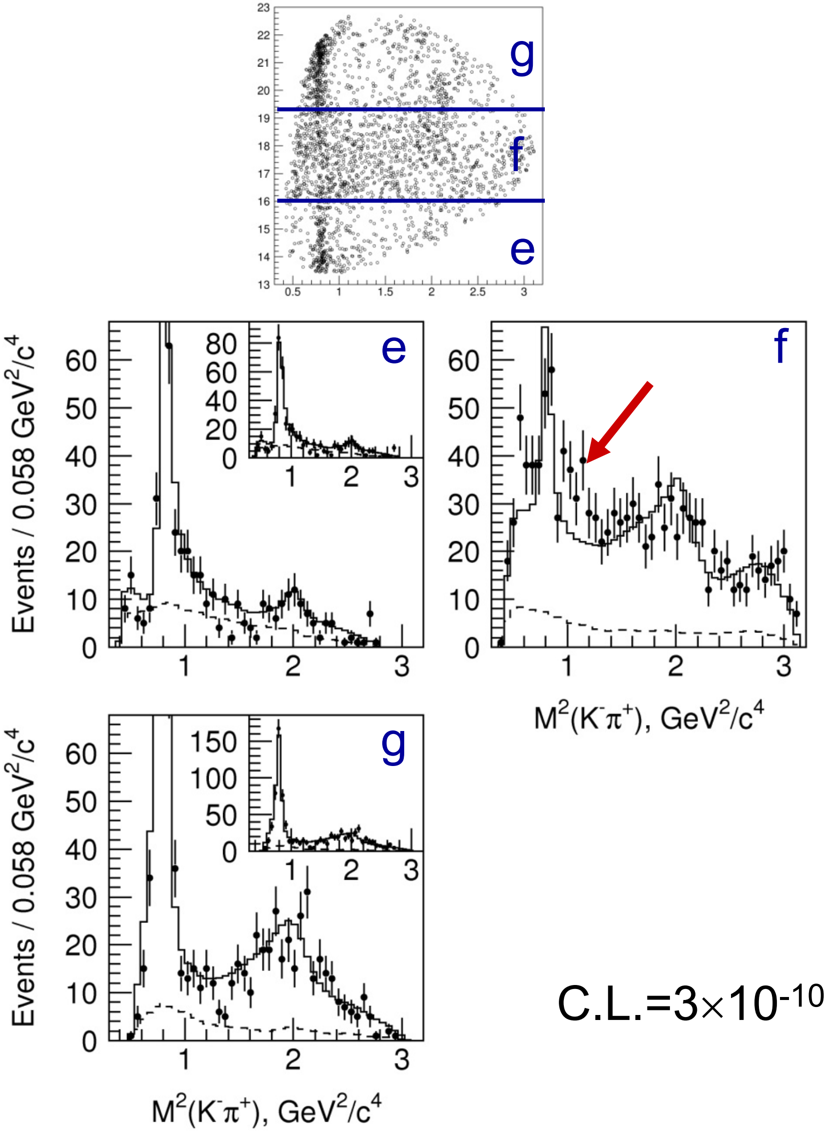
$K^*(1680)\chi_{c1}$

$K_3{}^*(1780)\chi_{c1}$

KZ^+

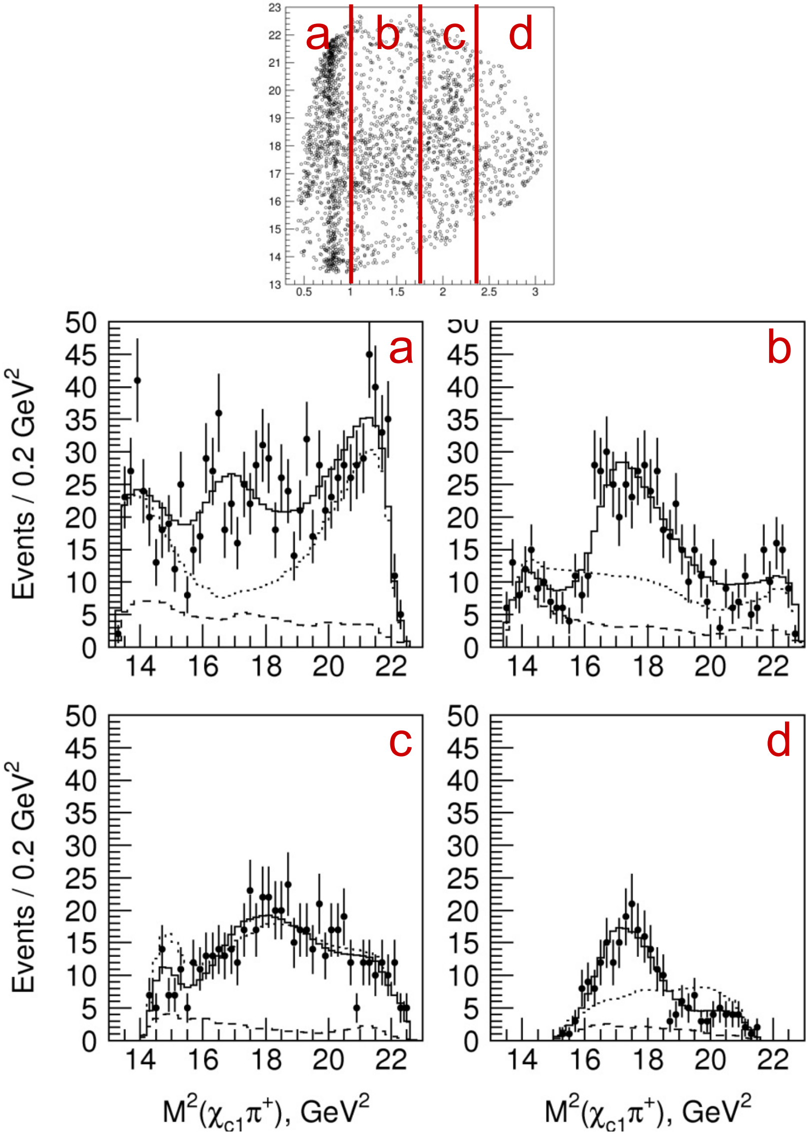
Fit model: all low-lying K*'s (no **Z+** state)

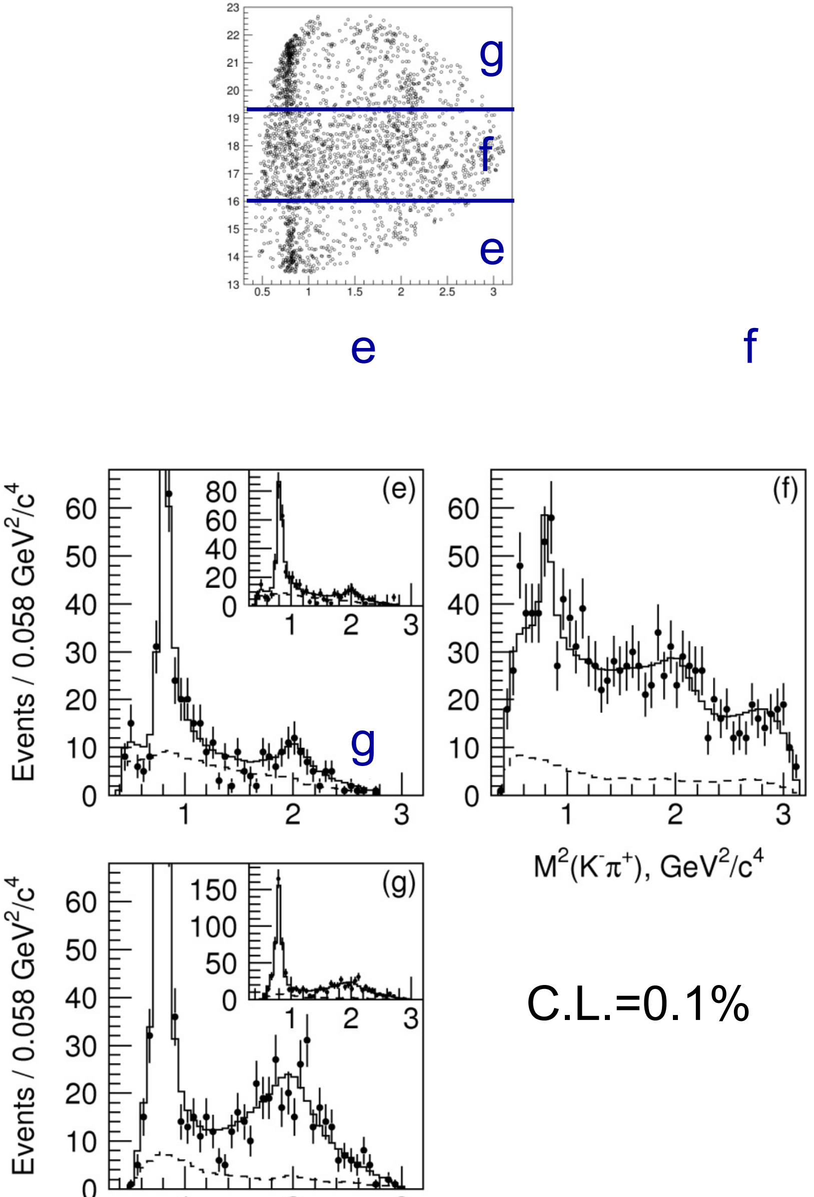




C.L.=3×10^{-10}

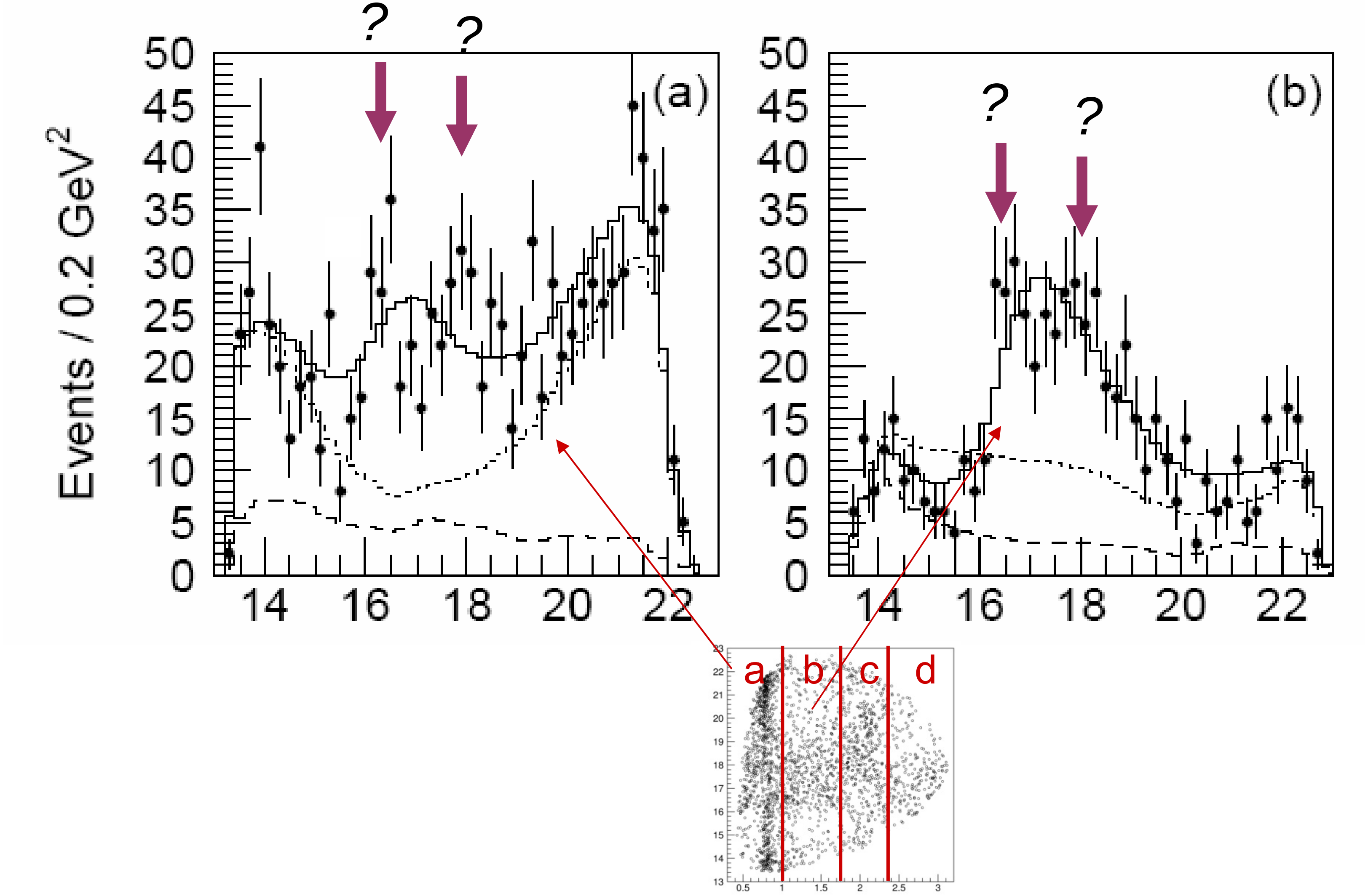
Fit model: all K*'s + one Z⁺ state



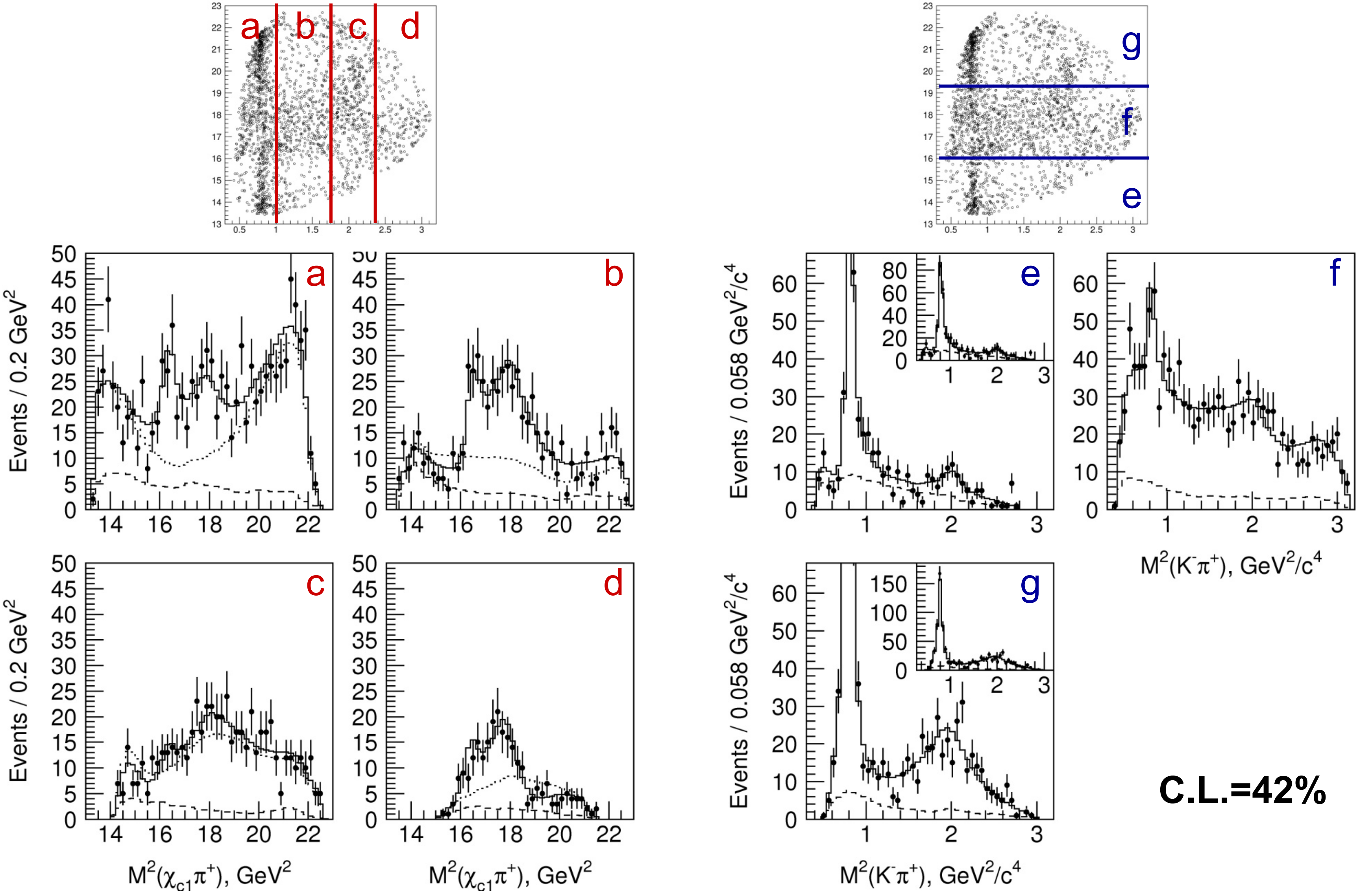


C.L.=0.1%

Are there two?

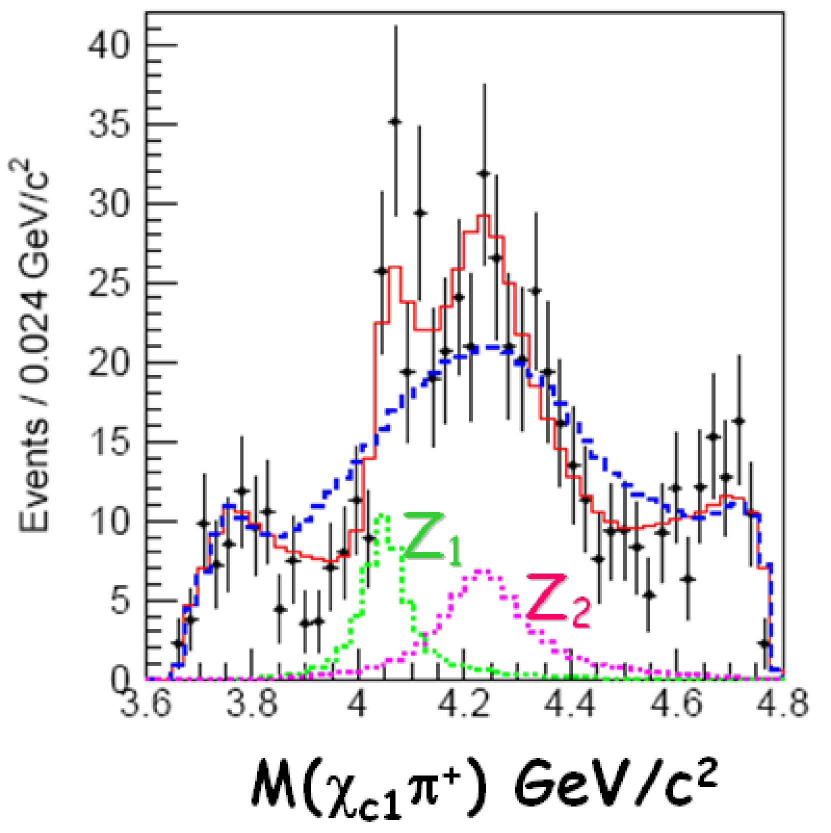


Fit model: all K*'s + two **Z⁺** states



C.L.=42%

Two Z-states give best fit


Projection with K* veto

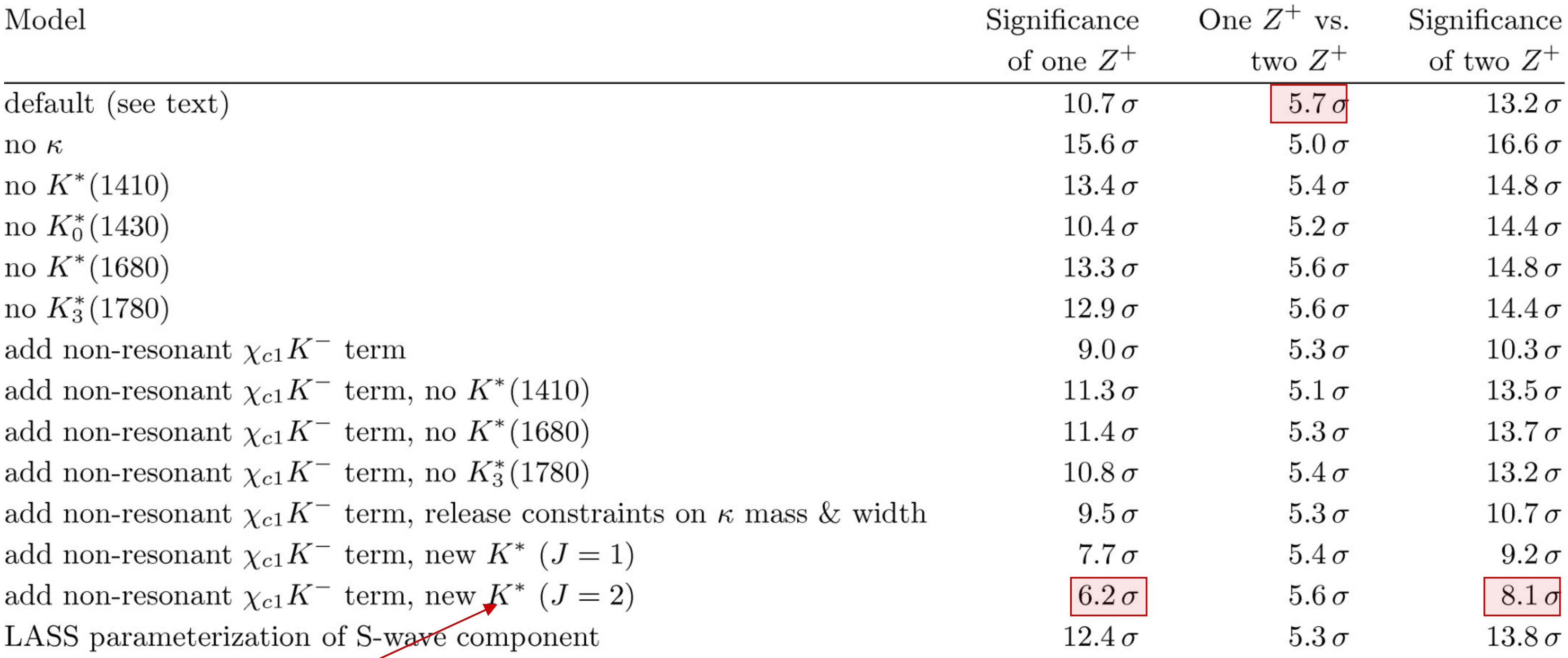
$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-\ 35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-\ 61})\ \mathrm{MeV},$$

$$f_1 = (8.0^{+3.8+9.5}_{-2.2-4.2})\%$$
$$f_2 = (10.4^{+6.1+51.5}_{-2.3-\ 0.7})\%$$

Significance: 5.7σ
(difference of -2lnL for double and single Z models)
Fit CL: 40%
(from Toy MC study)

$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+\chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$
$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+\chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-\ 0.5}) \times 10^{-5}.$$

Systematics of $\overline{B}^0 \to K^- \pi^+ \chi_{c1}$ fit



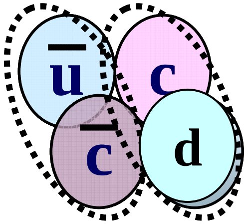
Model	Significance of one Z^+	One Z^+ vs. two Z^+	Significance of two Z^+
default (see text)	$10.7\,\sigma$	$5.7\,\sigma$	$13.2\,\sigma$
no κ	$15.6\,\sigma$	$5.0\,\sigma$	$16.6\,\sigma$
no $K^*(1410)$	$13.4\,\sigma$	$5.4\,\sigma$	$14.8\,\sigma$
no $K_0^*(1430)$	$10.4\,\sigma$	$5.2\,\sigma$	$14.4\,\sigma$
no $K^*(1680)$	$13.3\,\sigma$	$5.6\,\sigma$	$14.8\,\sigma$
no $K_3^*(1780)$	$12.9\,\sigma$	$5.6\,\sigma$	$14.4\,\sigma$
add non-resonant $\chi_{c1}K^-$ term	$9.0\,\sigma$	$5.3\,\sigma$	$10.3\,\sigma$
add non-resonant $\chi_{c1}K^-$ term, no $K^*(1410)$	$11.3\,\sigma$	$5.1\,\sigma$	$13.5\,\sigma$
add non-resonant $\chi_{c1}K^-$ term, no $K^*(1680)$	$11.4\,\sigma$	$5.3\,\sigma$	$13.7\,\sigma$
add non-resonant $\chi_{c1}K^-$ term, no $K_3^*(1780)$	$10.8\,\sigma$	$5.4\,\sigma$	$13.2\,\sigma$
add non-resonant $\chi_{c1}K^-$ term, release constraints on κ mass & width	$9.5\,\sigma$	$5.3\,\sigma$	$10.7\,\sigma$
add non-resonant $\chi_{c1}K^-$ term, new K^* $(J=1)$	$7.7\,\sigma$	$5.4\,\sigma$	$9.2\,\sigma$
add non-resonant $\chi_{c1}K^-$ term, new K^* $(J=2)$	$6.2\,\sigma$	$5.6\,\sigma$	$8.1\,\sigma$
LASS parameterization of S-wave component	$12.4\,\sigma$	$5.3\,\sigma$	$13.8\,\sigma$

M=1.04 GeV; G=0.26 GeV

Significance of $Z_1(4050)^+$ and $Z_2(4250)^+$ is high.

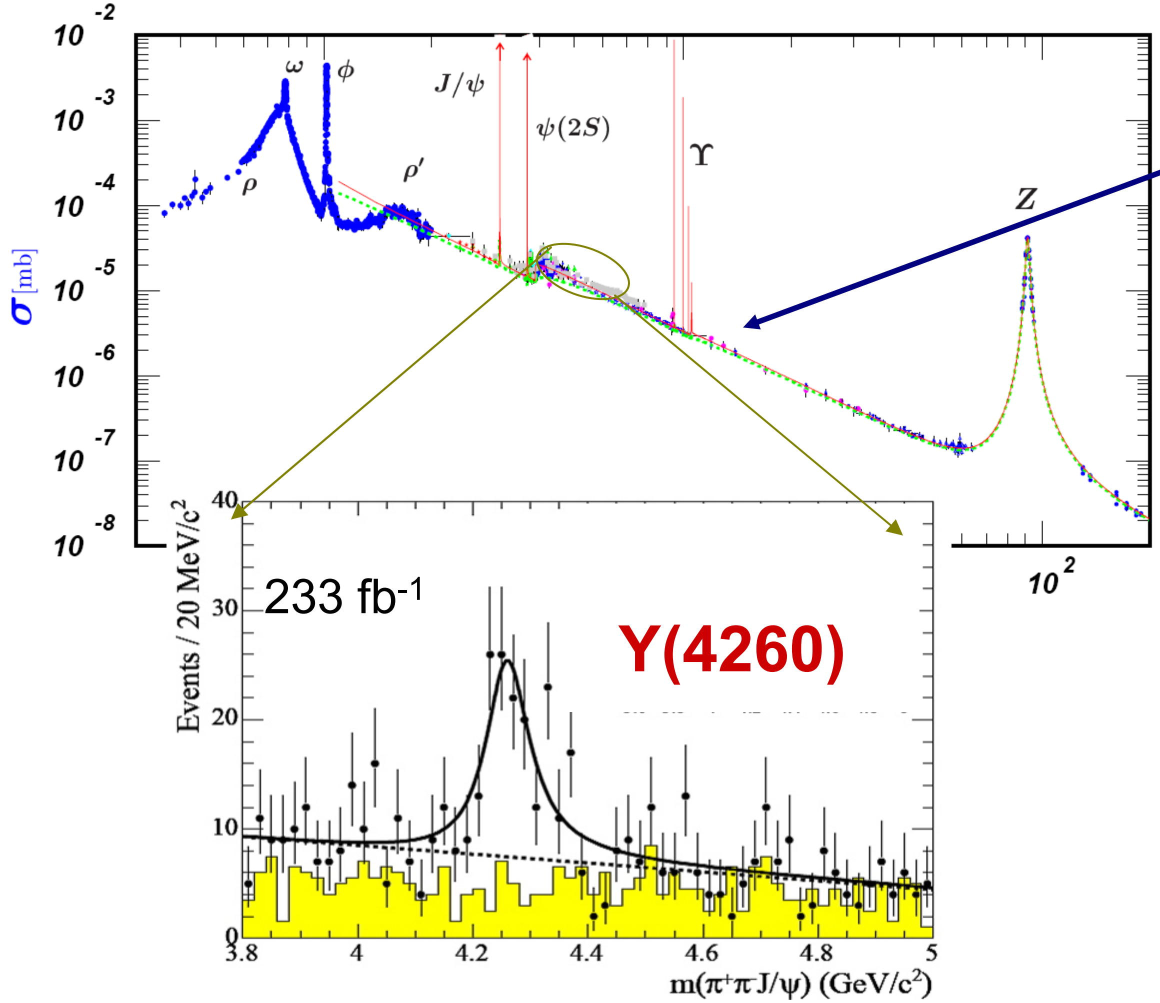
Fit assumes $J_{Z1}=0$, $J_{Z2}=0$; no signif. improvement for $J_{Z1}=1$ &/or $J_{Z2}=1$.

Z states cannot be charmonium



Need confirmation from other experiments (CDF? … D0?)

Are there XYZ counterparts in the b- and s-quark sectors?

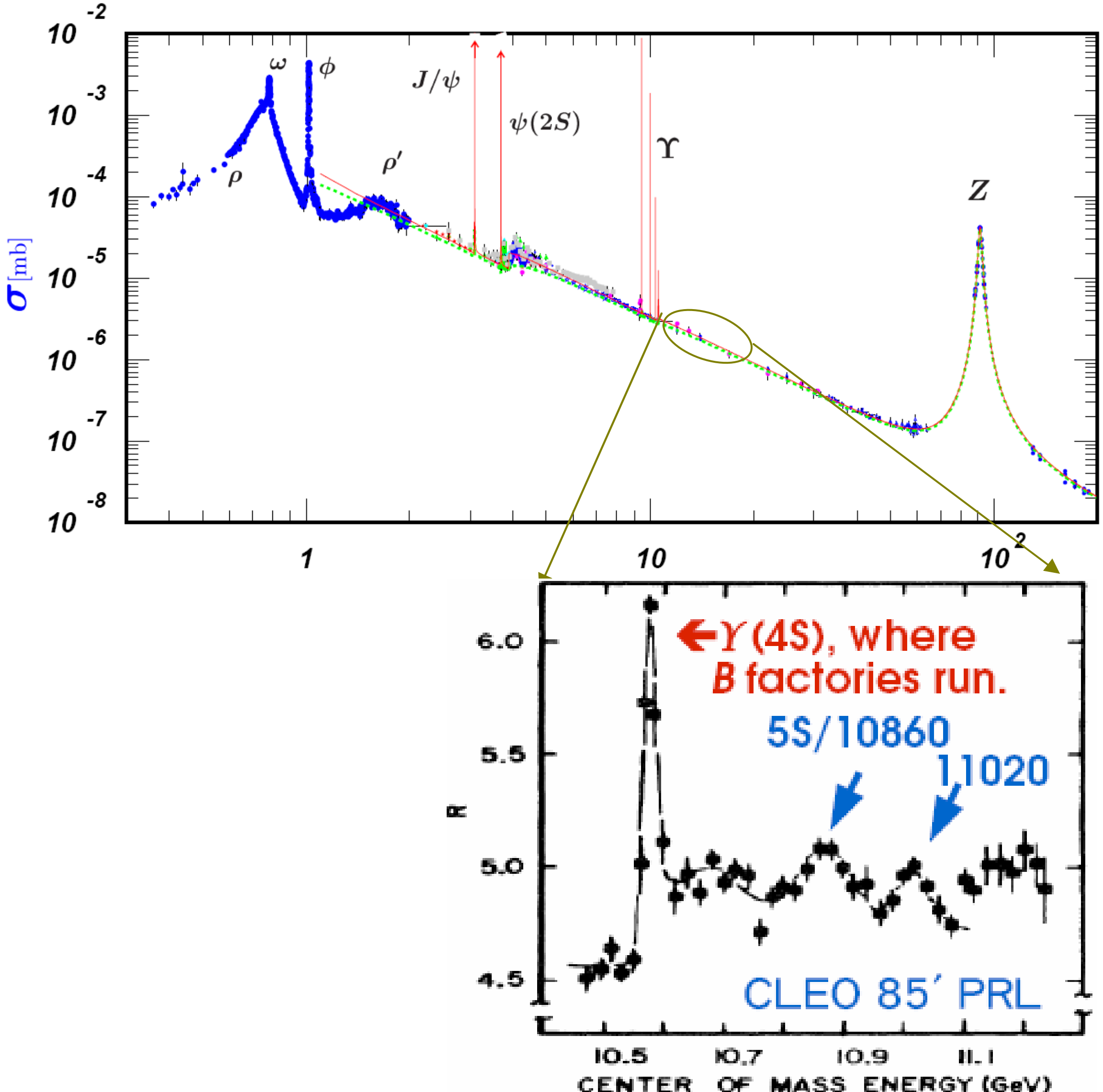


233 fb^{-1}

Y(4260)

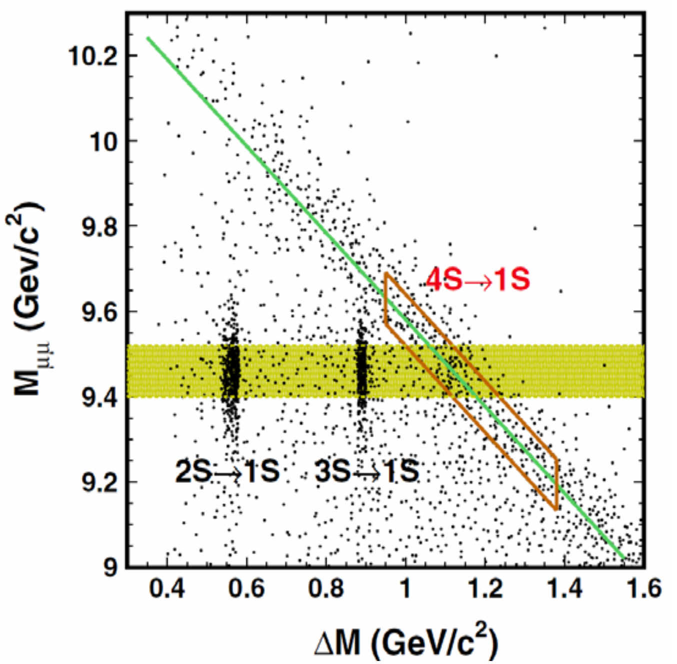
What about here?

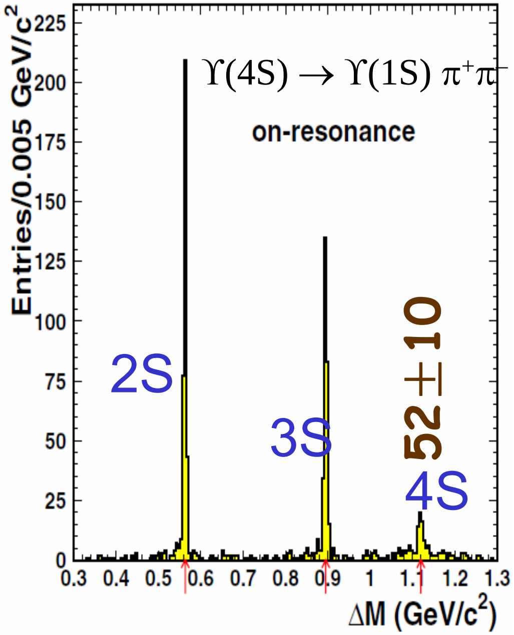
b-quark threshold region



Belle: $\Gamma(\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S))$

477 fb^{-1}

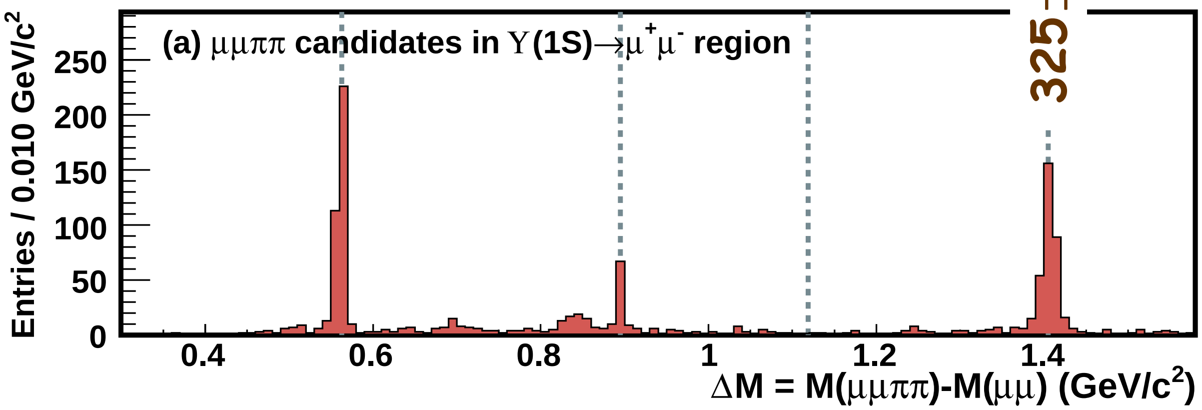




$N(\Upsilon_{4S})$	$N(\pi^+\pi^-\Upsilon_{1S})$	$B(Y_{4S}\rightarrow\pi\pi\Upsilon_{1S})$	$\Gamma(Y_{4S}\rightarrow\pi\pi\Upsilon_{1S})$	Γ_{theory}
535×10^6	52±10	$9 \pm 2 \times10^{-5}$	1.75 ± 0.35 keV	1.47±0.03 keV

Belle: $\Gamma(\Upsilon_{5S} \rightarrow \pi^+\pi^-\Upsilon_{1S})$

23.6 fb^{-1}



325±20 evts!

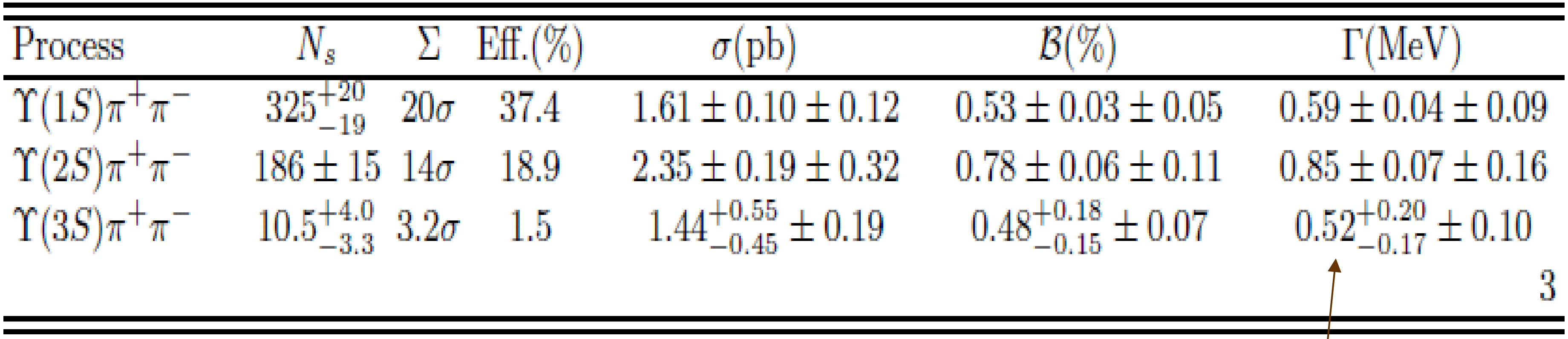
1/20th the data &
1/10th the cross-section
>6 times as many events!!

K.F. Chen et al (Belle)
PRL 100, 112001 (2008)

Partial Widths

Assuming the source is the Υ(5S)

PDG value taken for Υ(nS) properties



Process	N_s	Σ	Eff.(%)	σ(pb)	$\mathcal{B}$(%)	Γ(MeV)
$\Upsilon(1S)\pi^+\pi^-$	325^{+20}_{-19}	20σ	37.4	$1.61 \pm 0.10 \pm 0.12$	$0.53 \pm 0.03 \pm 0.05$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	186 ± 15	14σ	18.9	$2.35 \pm 0.19 \pm 0.32$	$0.78 \pm 0.06 \pm 0.11$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$10.5^{+4.0}_{-3.3}$	3.2σ	1.5	$1.44^{+0.55}_{-0.45} \pm 0.19$	$0.48^{+0.18}_{-0.15} \pm 0.07$	$0.52^{+0.20}_{-0.17} \pm 0.10$

3

N.B. Resonance cross section 0.302 ± 0.015 nb at 10.87 GeV

PRD **98,** 052001 (2007) [Belle]

>300 times bigger than that for the Υ_{4S}!!

c.f.

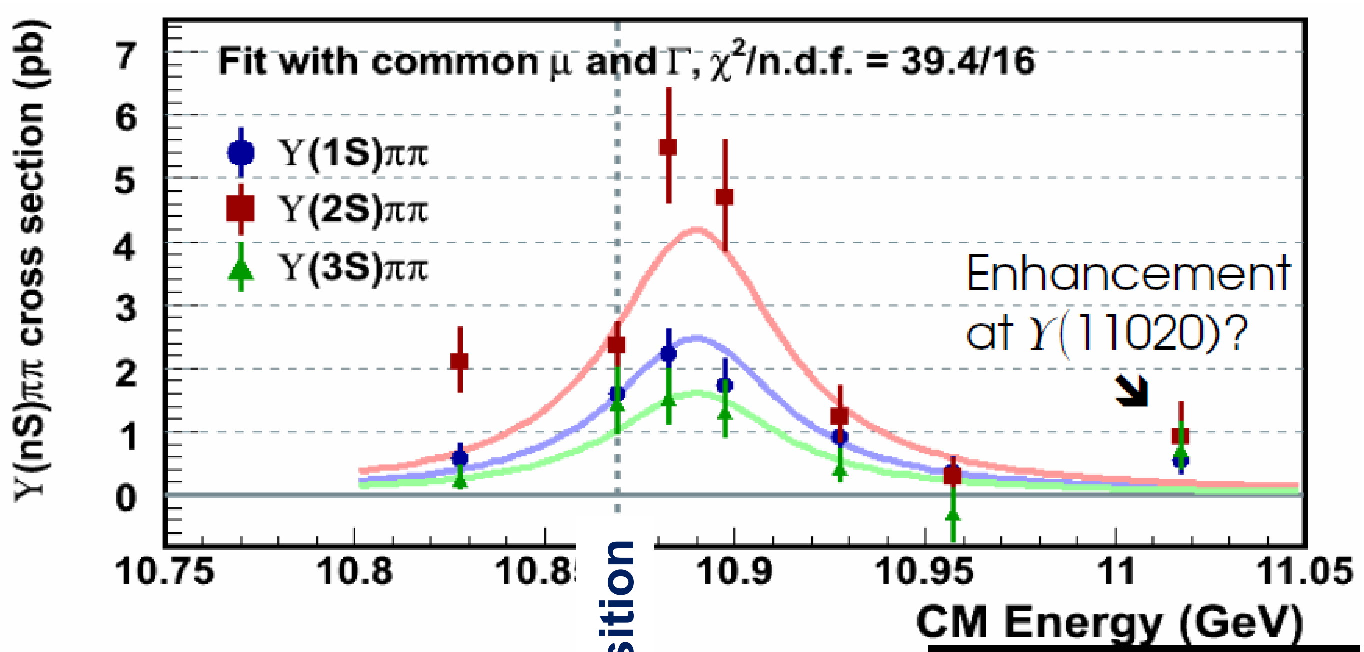
Υ(2S) → Υ(1S)$\pi^+\pi^-$ ~ 6 keV

Υ(3S) 0.9 keV

Υ(4S) 1.8 keV

Are these events from the Υ_{5S}?

$\sigma(e+e- \rightarrow \pi^+\pi^-\Upsilon_{nS})$ from a cm energy scan



Enhancement at Υ(11020)?

Υ_{5S} **peak position**

Fitted parameters

10889.6 ±1.8 ±1.5 MeV

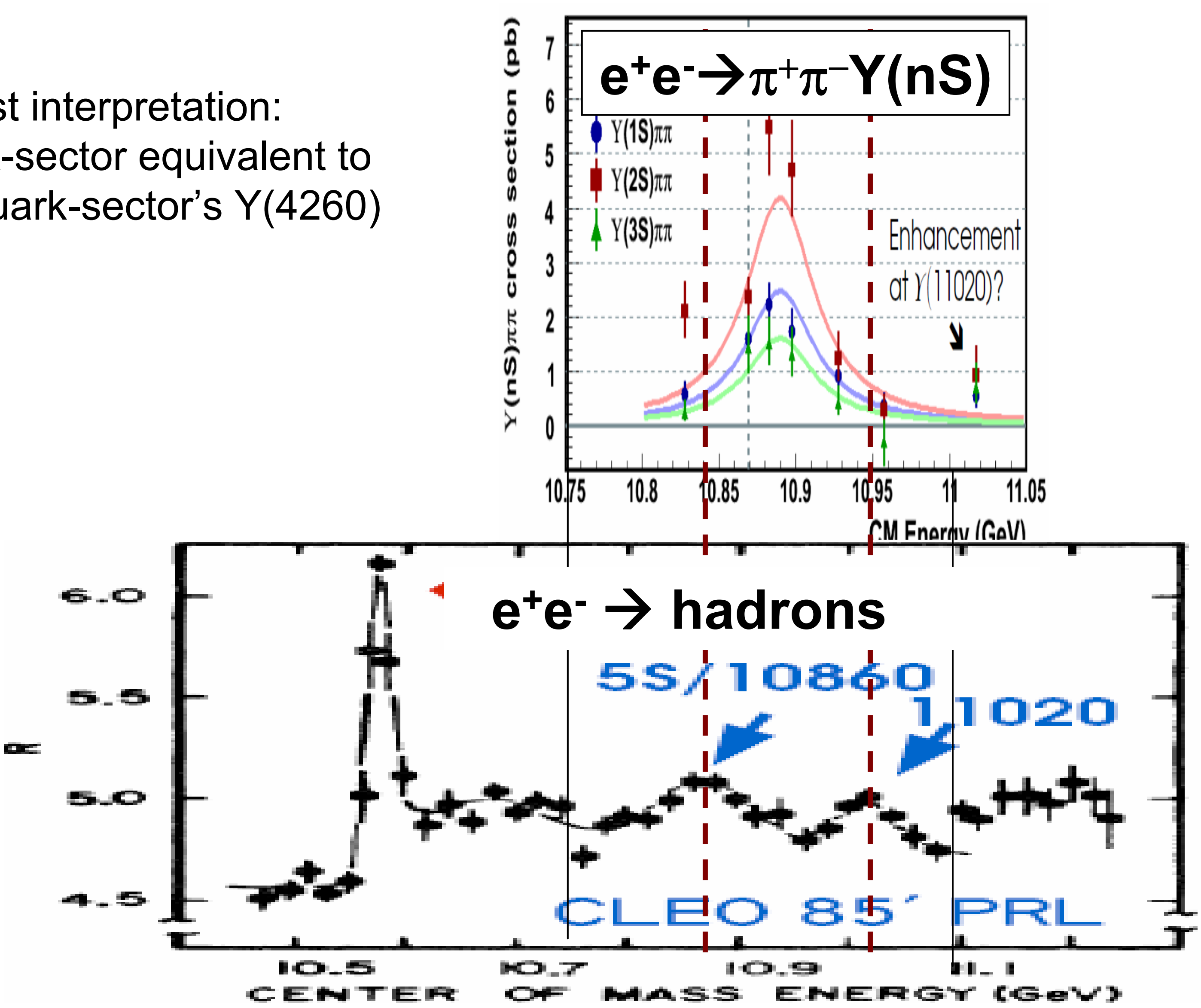
$54.7^{+8.5}_{-7.2}$±2.5 MeV

PDG(Υ_{5S}): μ = 10865 ± 8 MeV
Γ = 110 ±13 MeV

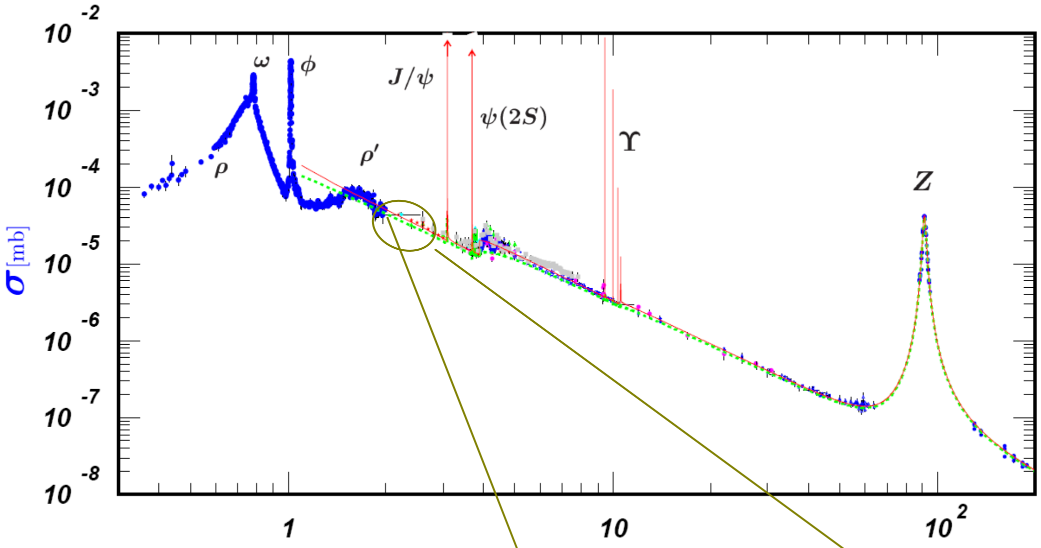
K.F. Chen et al (Belle)
arXiv: 0810.3829

Peak & width in $\pi^+\pi^-\Upsilon(nS)$ different from $\Upsilon(5S)$ &$\Upsilon(6S)$

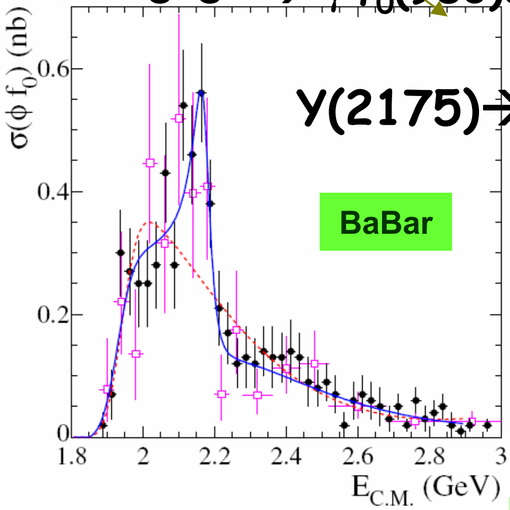
Simplest interpretation:
b-quark-sector equivalent to
the c-quark-sector’s Y(4260)



Y(4260) equivalent with s-quarks?



e+e- → γ f$_0$(980)φ



Y(2175)→f$_0$(980)φ

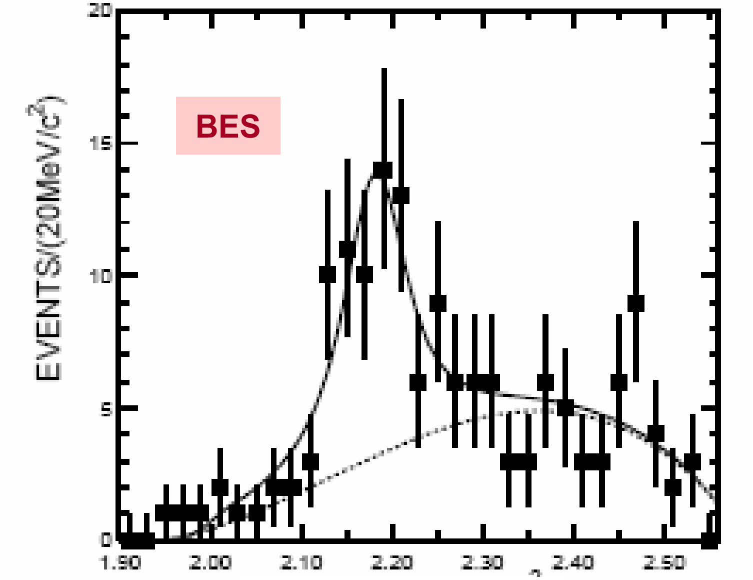
$\sigma(e^+e^- \rightarrow \underbrace{\pi^+\pi^-}_{f_0(980)\rightarrow\pi^+\pi^-}\phi(1020))$

M(f$_0$(980)φ)

BaBar, PRD 74, 091103

Confirmed by BES & Belle

confirmed by BESII
in J/ψ → η φ f_0(980)



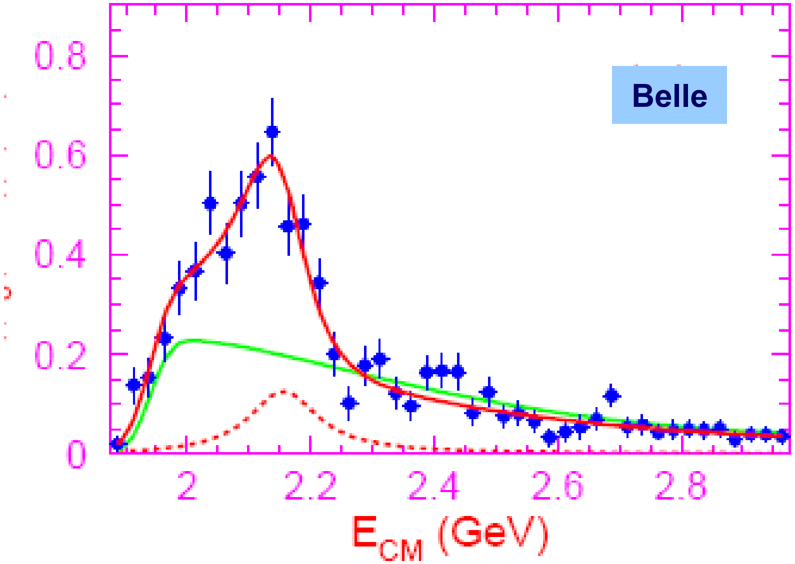
M(f_0(980)φ GeV

$J/\psi \to \eta\phi f_0(980)$

X. Wan X.Y. Shen F. Liu

M.Ablikim et al (BES)
PRL 100, 102003 (2008)

σ(e^+e^- → f_0(980)φ(1020))



C.P.Shen et al (Belle) arXiv: 0808.0006

The “XYZ” mesons

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi$, $D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^-(ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^-(ISR)
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^-(ISR)
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$

Concluding remarks

- Charmonium mesons are strong evidence for quarks
  - All the lowest-lying charmonium states have been found
  - Good agreement between their measured properties & theory
  - Charmonium is the “best understood” hadronic system

- Higher-mass charmonium meson searches have produced surprizes
  - A number of non-charmonium meson candidates have been found.
  - They have strong transitions to ordinary charmonium states
  - Corresponding states sem to exist in the b-qyark & s-quark sectors

- Most of the new states are in the BEPC-II E_{cm} range
  - We have to figure out how to access them (& find new ones)
  - So far only final states with a J/ψ or ψ' have been studied
  - *e.g.,* final states with an η_c or a h_c may be interesting

- Lots of opportunities for BES III
  - Need creativity and new ideas

Thank You

謝謝

감사합니다