Сессия-конференция секции ЯФ ОФН РАН
"Физика фундаментальных взаимодействий“
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Новые результаты по тяжелому кварконию

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Contents

Last decade: high statistics of B- and c-factories allowed to study quarkonium states above open flavor thresholds $\Rightarrow$
properties are very different from the expectations for $b\bar{b}$ or $c\bar{c}$ states.

The only relatively well understood – near-threshold molecular states:

$X(3872)$, $Z_b(10610)^{\pm}$, $Z_b(10650)^{\pm}$

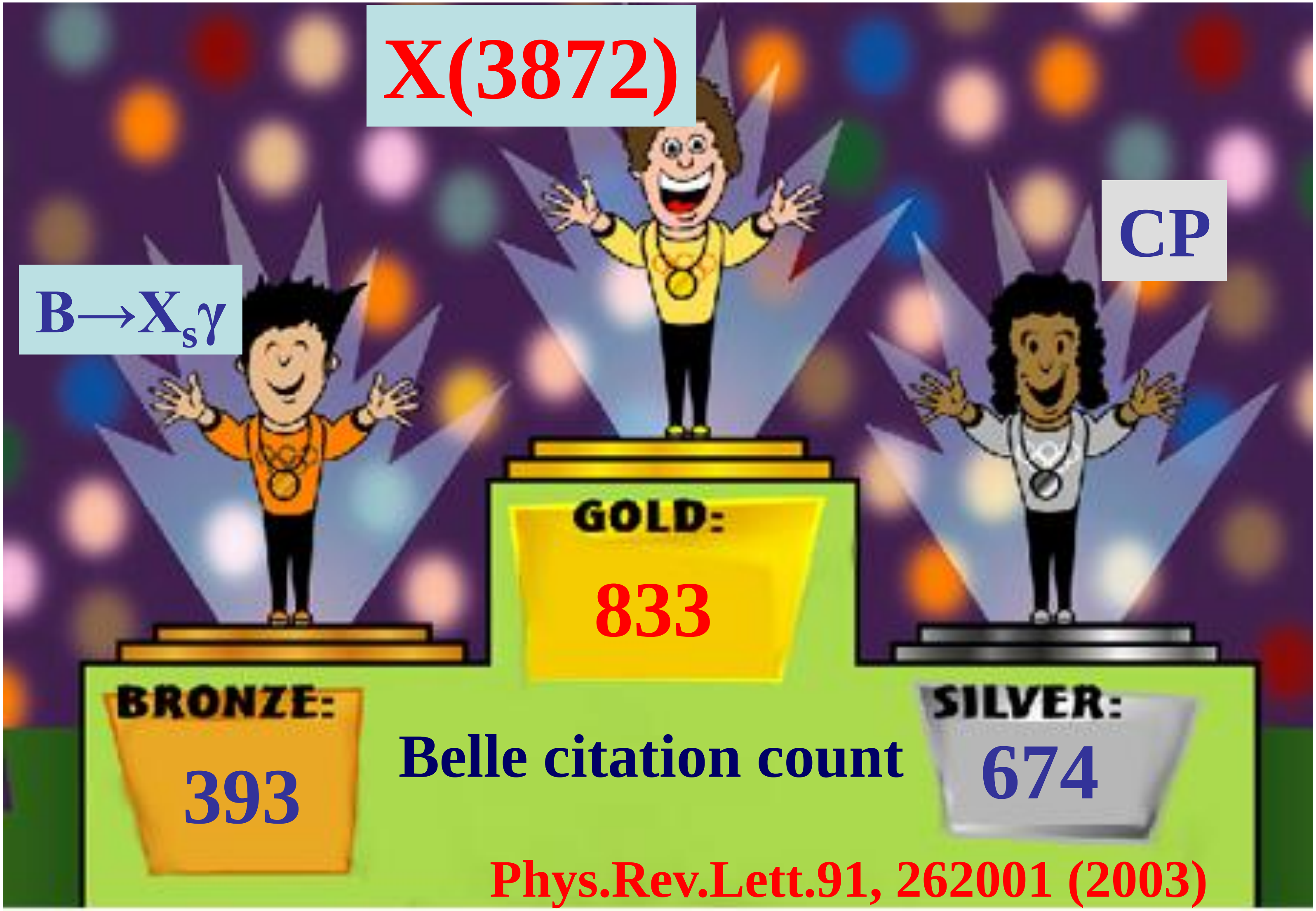
DD* BB* B*B*

BES-III (+ BELLE + CLEO-c) 2013:

$Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$, $Z_c(4025)^{\pm}$

DD* D*D*

Are these analogues of Z_b states, i.e. molecules?



10^{th} anniversary!

X(3872)

	Relative BF
$J/\psi\,\rho$	1
$J/\psi\,\omega$	0.8 ± 0.3
$J/\psi\,\gamma$	0.21 ± 0.06
$D^0\bar{D}^{*0}$	~ 10

isospin violation

WA

$$\boxed{M_{X(3872)} - (M_{D^0} + M_{D^{*0}}) = -0.09 \pm 0.28\ \text{MeV}}$$

$$\boxed{J^{PC} = 1^{++}}$$

LHCb: PRL110,222001(2013)

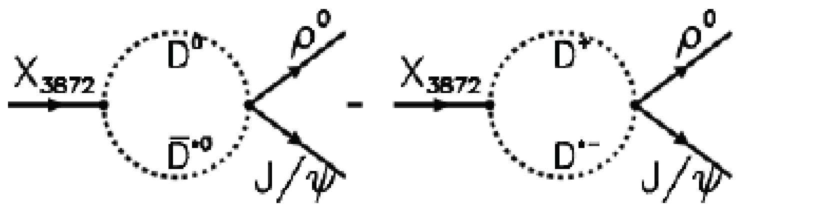
Most likely interpretation:

$D\bar{D}^*$ molecule with admixture of $\chi_{c1}(2P)$

isospin violation

production at high energy

Isospin Violation in X(3872) decay:



≈on mass shell ≈8 MeV off mass shell

Open questions:

- Bound or virtual?
- Fractions of admixtures?
- Dynamical model?

Experimental issues:

- δM (D^0 mass uncertainty dominates) LHCb
- line-shape in $D\bar{D}^*$ (statistics limited)
- absolute BF (inelastic channels?)
- $\psi(2S)\,\gamma$ (Belle/BaBar controversy)

Belle-II

$Z_b(10610)^+$, $Z_b(10650)^+$

Z_b prehistory

1. BaBar 2005: observation of peak in $\sigma(e^+e^- \to J/\psi\pi^+\pi^-) \Rightarrow Y(4260)$ state, $\Gamma \sim 100$MeV

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

No Y(4260) signal in $\sigma(e^+e^- \to \text{hadrons})$ $\Rightarrow$ $\Gamma\,[Y(4260) \to J/\psi\pi^+\pi^-] > 1$ MeV

$\Gamma\,[\psi'' \to J/\psi\pi^+\pi^-] \approx 0.04$ MeV

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2. Belle 2008: observation of anomalous $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ transitions

PRL100,112001(2008)

	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

Explanations:

Simonov JETP Lett 87,147(2008)

1. Rescattering $\Upsilon(5S) \to B\bar{B}\pi\pi \to \Upsilon(nS)\pi\pi$?

2. There exist Y_b – partner of Y(4260)

$\Upsilon(5S)$ – peak in $\sigma(e^+e^- \to \text{hadrons})$

Y_b – peak in $\sigma[e^+e^- \to \Upsilon(nS)\pi^+\pi^-]$

PRD82,091106R(2010)

To distinguish $\Upsilon(5S)$ and Y_b Belle performed energy scan

$\Rightarrow$ Shapes of R_b and $\sigma(\Upsilon\pi\pi)$ agree at 2σ level

Z_b prehistory (2)

3. CLEO-c 2010: observation of $e^+e^- \to h_c\pi^+\pi^-$ @ E=4170MeV

$$\sigma(h_c\,\pi^+\pi^-) \cong \sigma(J/\psi\,\pi^+\pi^-)$$

Hint of rise in $\sigma(h_c\pi^+\pi^-)$ @ Y(4260) ?

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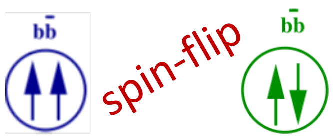
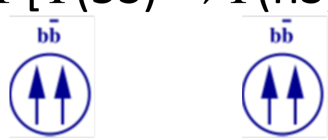
4. Belle 2011: observation of $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ transitions (m=1,2)



$$\frac{\Gamma[\Upsilon(5S) \to h_b(mP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-]} \sim 1$$



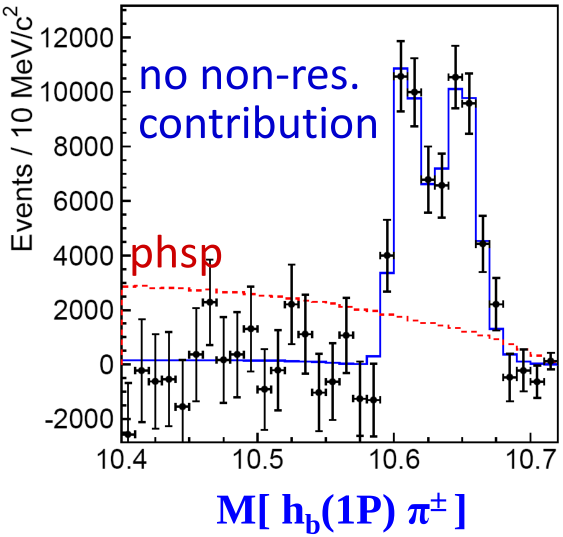
expect suppression
$(\Lambda_{QCD}/m_b)^2$

Mechanism of $\Upsilon(5S)$ decays ?

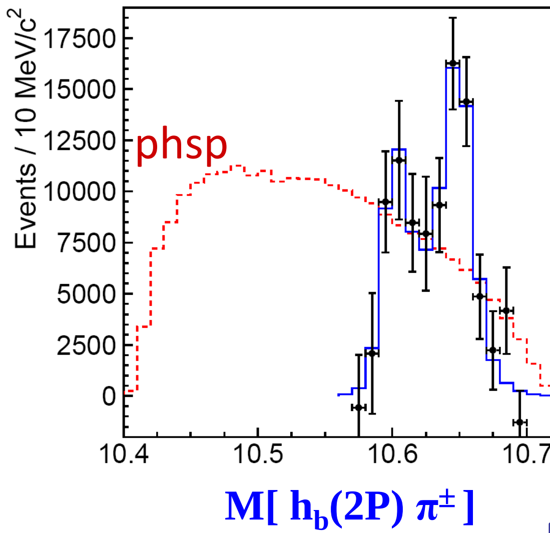
Resonant structure of $\Upsilon(5S) \to \Upsilon/h_b\ \pi^+\pi^-$

PRL108,122001(2012)

$\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$



$\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$



Two peaks in 5 modes

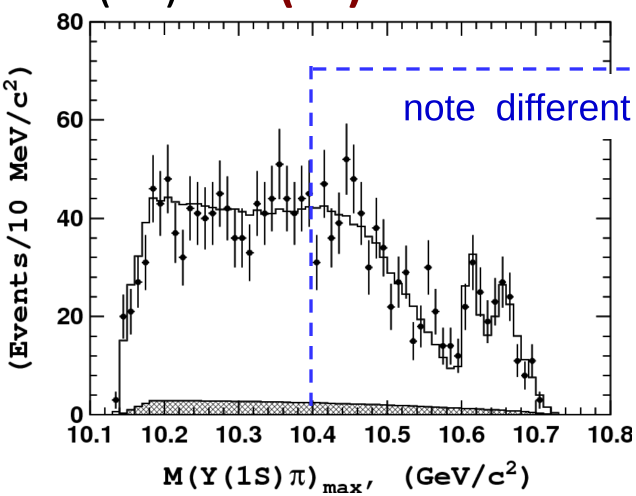
minimal quark content

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

flavor-exotic states

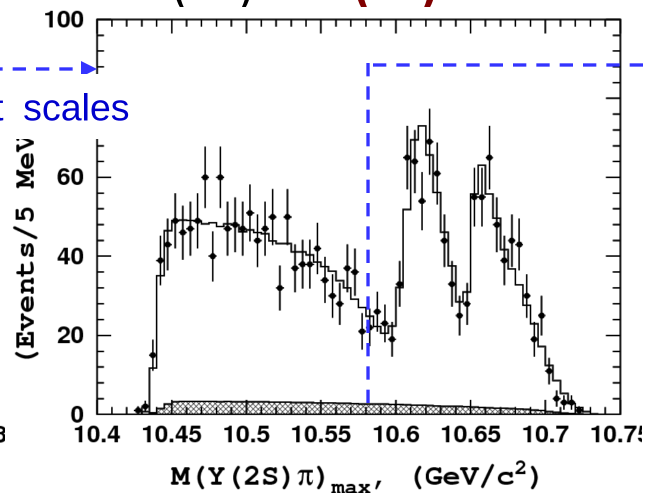
Parameters from amplitude analysis

$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$

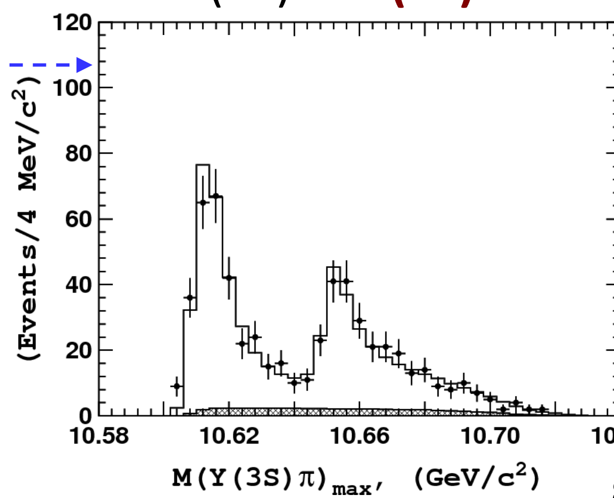


note different scales

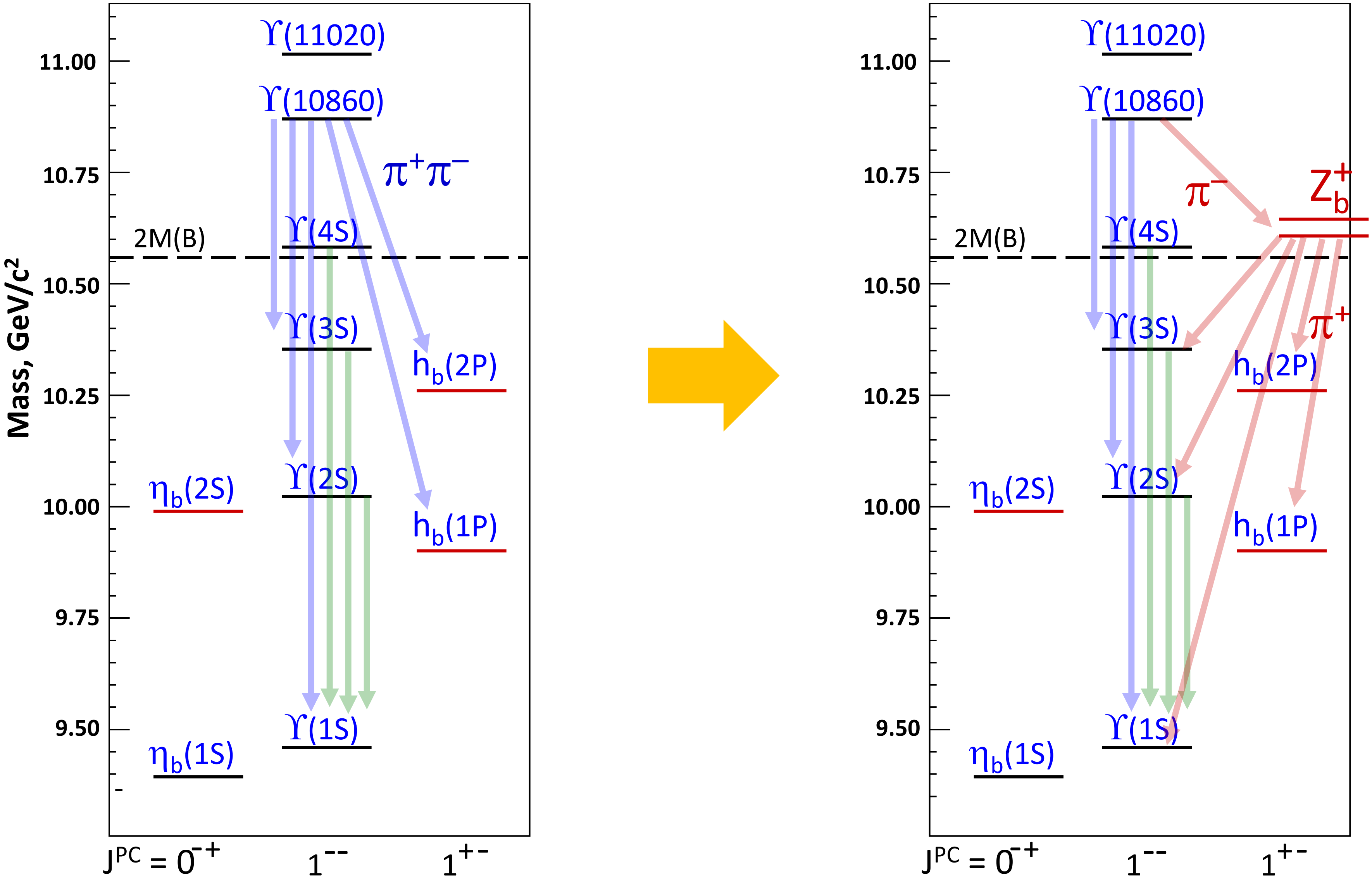
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$



$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$



Scheme of bottomonium transitions



Summary on Z_b^+

PRL108,122001(2012)

$Z_b(10610)$ $M_{Zb} - (M_B + M_{B*}) = +2.6 \pm 2.1$ MeV $\Gamma_{Zb} = 18.4 \pm 2.4$ MeV

$Z_b(10650)$ $M_{Zb'} - 2M_{B*} = +1.8 \pm 1.7$ MeV $\Gamma_{Zb'} = 11.5 \pm 2.2$ MeV

arxiv:1209.6450

Channel	$\mathcal{B}$ of $Z_b(10610)$	$\mathcal{B}$ of $Z_b(10650)$
$\pi^+\Upsilon(1S)$	$(0.32 \pm 0.09)\%$	$(0.18 \pm 0.05)\%$
$\pi^+\Upsilon(2S)$	$(4.38 \pm 1.21)\%$	$(1.80 \pm 0.47)\%$
$\pi^+\Upsilon(3S)$	$(2.15 \pm 0.56)\%$	$(1.23 \pm 0.30)\%$
$\pi^+h_b(1P)$	$(2.81 \pm 1.10)\%$	$(5.6 \pm 2.0)\%$
$\pi^+h_b(2P)$	$(4.34 \pm 2.07)\%$	$(11.1 \pm 4.7)\%$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$(86.0 \pm 3.6)\%$	$(25 \pm 10)\%$
$B^{*+}\bar{B}^{*0}$	–	$(55.1 \pm 5.3)\%$

dominant

suppressed

despite much larger PHSP

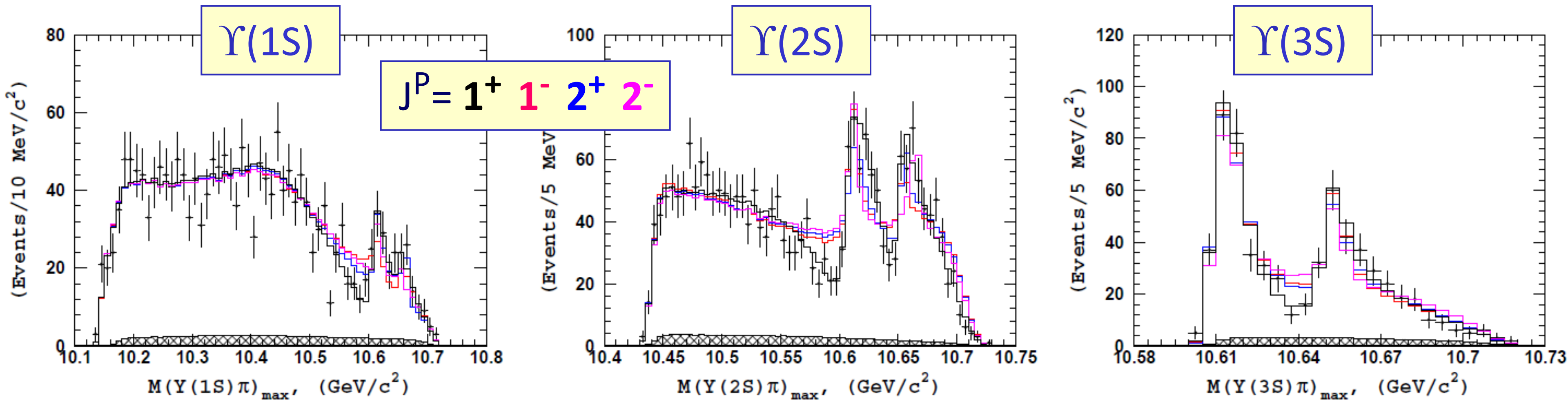
6D amplitude analysis : $J^P = 1^+$

Krokovny Moriond QCD 2013

$\Upsilon(5S) \to \Upsilon(nS)\,(\to \mu^+\mu^-)\,\pi^+\pi^-$ amplitude analysis

12 – 4 ($\underline{P}$ conservation) – 1 (Υ(nS) mass) – 1 (rotation around beam axis) = $\boxed{\text{6 d.o.f.}}$

$$S(s1,s2) = \underbrace{A(Z_{b1}) + A(Z_{b2})}_{\text{BW}} + \underbrace{A(f_0(980))}_{\text{Flatte}} + \underbrace{A(\sigma) + A(f_2(1275))}_{\text{BW}} + \underbrace{A_{NR}}_{C_1 + C_2\cdot m^2(\pi\pi)}$$



Spin-parity of Z_b(10610) and Z_b(10650) is $\mathbf{1^+}$.

All other $J \leq 2$ are excluded at $>5\sigma$ levels.

Structure of Z_b^+ : Molecule

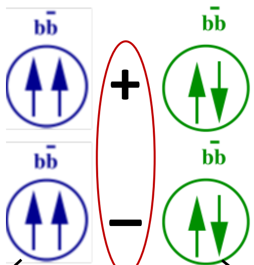
Proximity to BB* and B*B* thresholds suggests molecular structure. $J^P=1^+ \Rightarrow$ S-wave.

Decay into constituents (once kinematically allowed) is dominant.

Bondar et al, PRD84,054010(2011)

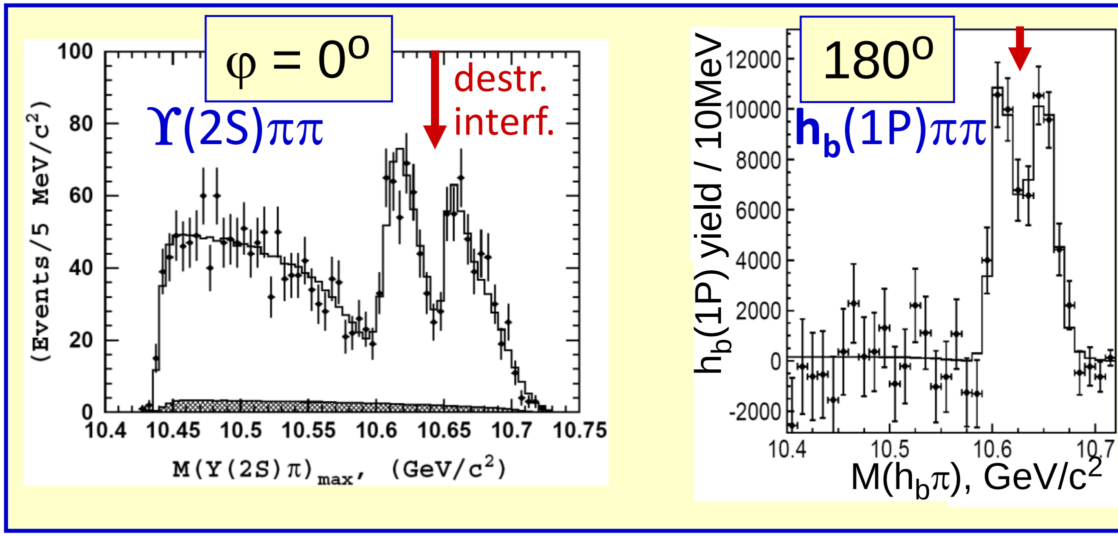
$Z_b \sim |B\bar{B}^*\rangle =$ +

$Z_b' \sim |B^*\bar{B}^*\rangle =$ −



$\Upsilon(nP)\pi$ $h_b(mP)\pi$

flip of phase



Assumption of molecular structure allows to explain all properties of Z_b

Structure of Z_b^+ : Diquark-antidiquark

Ali et al, PRD85,054011(2012)

$\Gamma(Z_b \to \Upsilon\pi) \sim \Gamma(Z_b \to B^{(*)}\bar{B}^*)$ $\Leftarrow$ diquark is broken in both cases

Masses are not bound to $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds

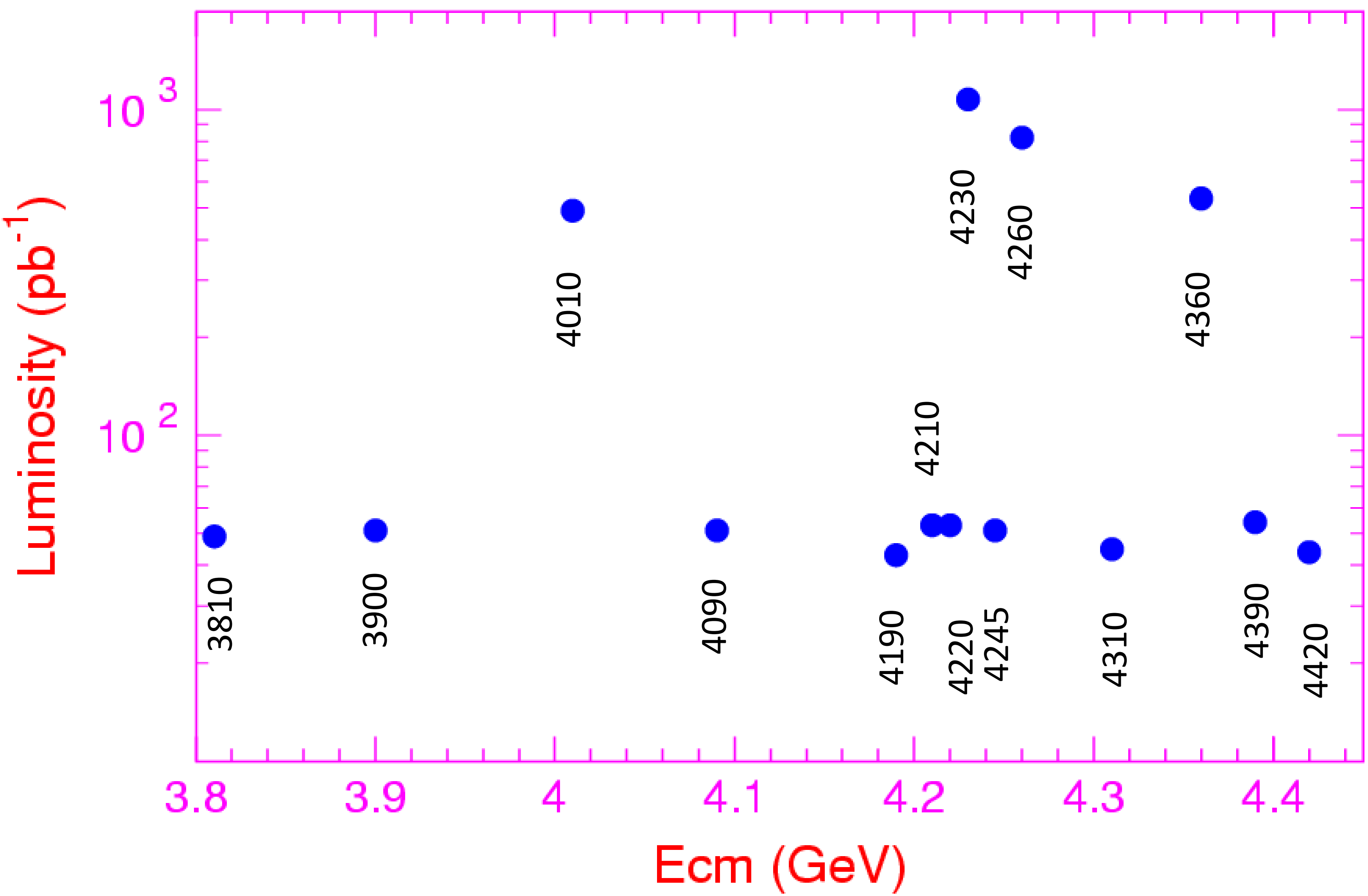
Lighter state is coupled to $B^*\bar{B}^*$ and heavier state is coupled to $B\bar{B}^*$

$\Rightarrow$ Expect $\boxed{\begin{array}{l} Z_b \to B^*\bar{B}^* \\ Z_b' \to B\ \bar{B}^* \end{array}}$

Decay pattern of the Z_b's excludes diquark-antidiquark hypothesis.

Z_c^+ states

BESIII collected 3.3/fb for XYZ study

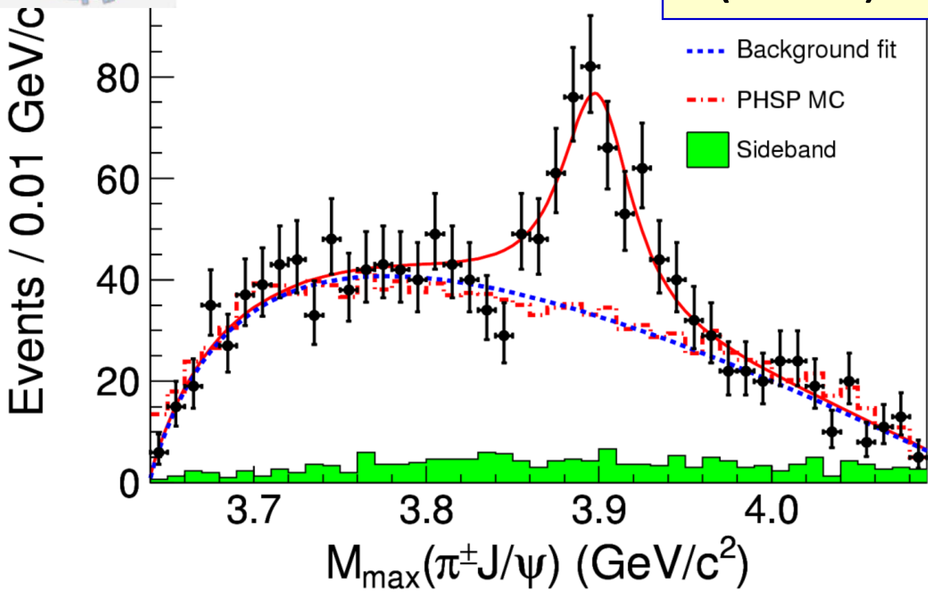


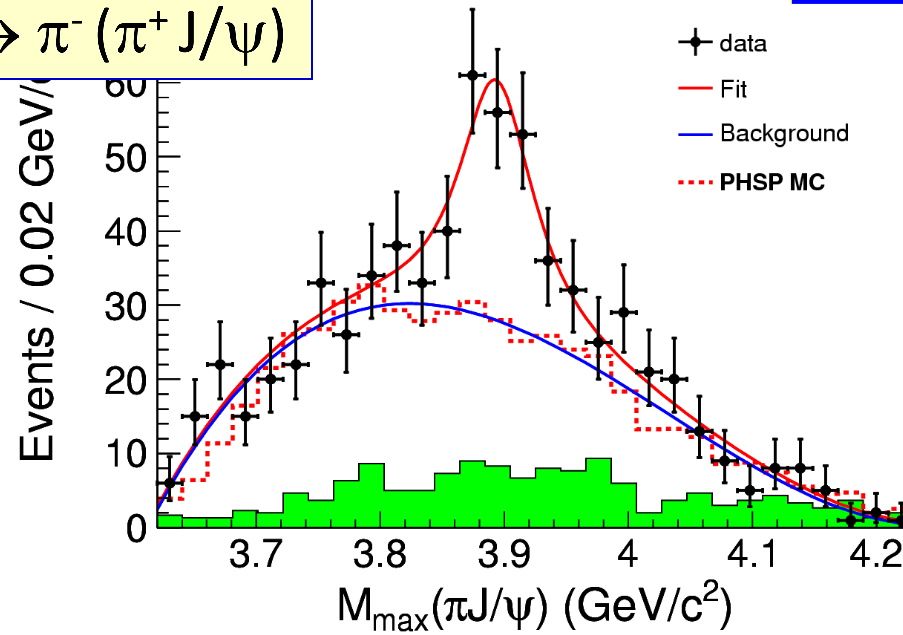
1303.5949

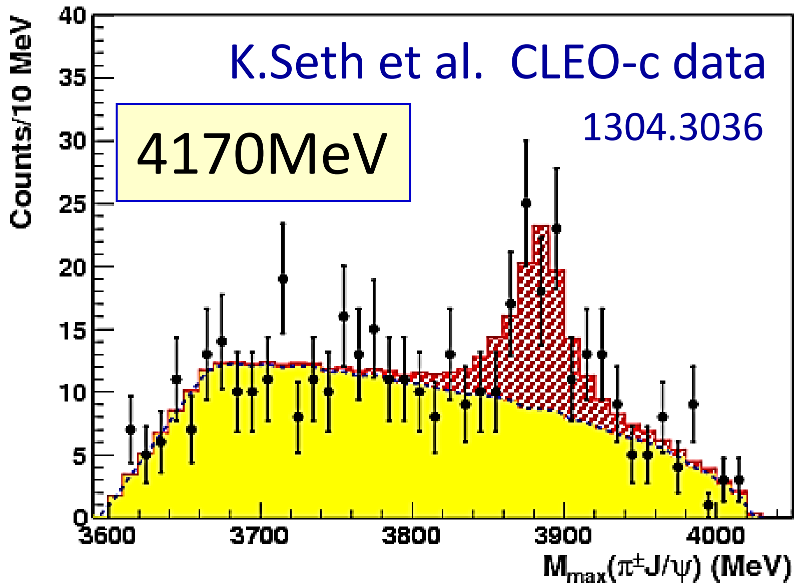
$Z_c(3900)^+$

1304.0121

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







$\langle M \rangle = 3891.5 \pm 3.5$ MeV

$\langle \Gamma \rangle = 40 \pm 11$ MeV

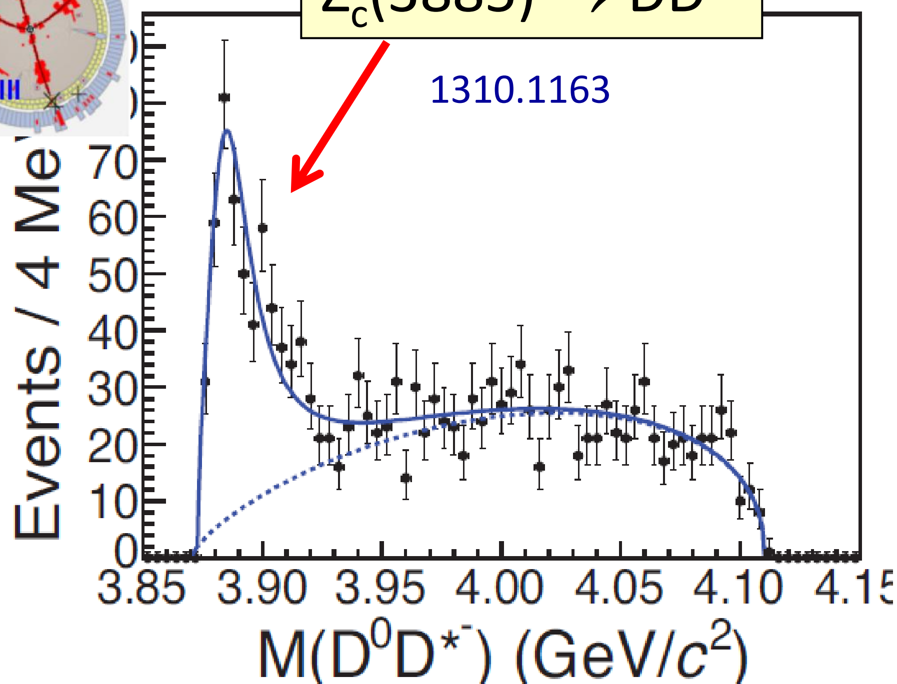
$M_{Zc} - M_{D*} - M_D \sim 16$ MeV

No interference !

Peak position can be shifted by $\leq \Gamma/2$.

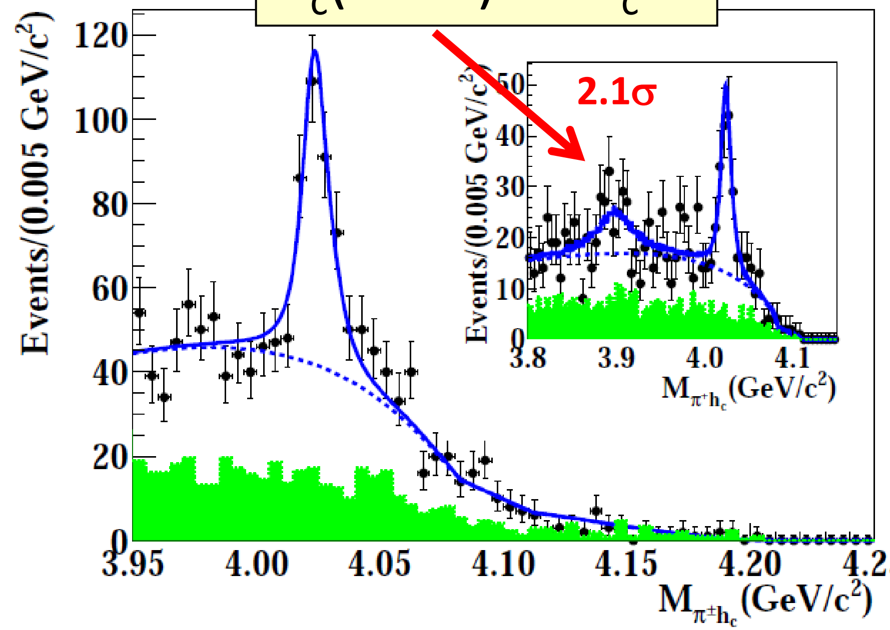
$Z_c(3885) \to D\bar{D}^*$

1310.1163



$Z_c(3900) \to h_c\,\pi$

1309.1896



No interference !

2σ

	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$	$Z_c(3900) \to \pi\, h_c$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$	$3899 \pm 3.6 \pm 4.9$	–
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$	$46 \pm 10 \pm 20$	–
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$	$13.5 \pm 2.1 \pm 4.8$	<11pb

$M_{Z_c} - M_{D^*} - M_D \sim 9$ MeV

PHSP suppression

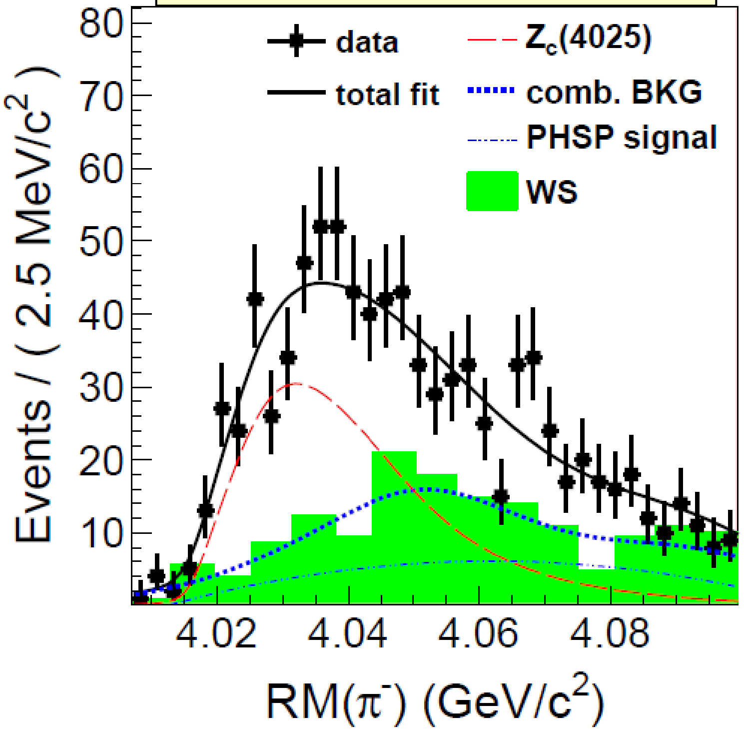
Angular analysis of $e^+e^- \to Z_c(3885)\pi \to D^*\bar{D}\,\pi \Rightarrow$ $J^P = 1^+$

$Z_c(3900)$ is a candidate for molecule [partner of $Z_b(10610)$].

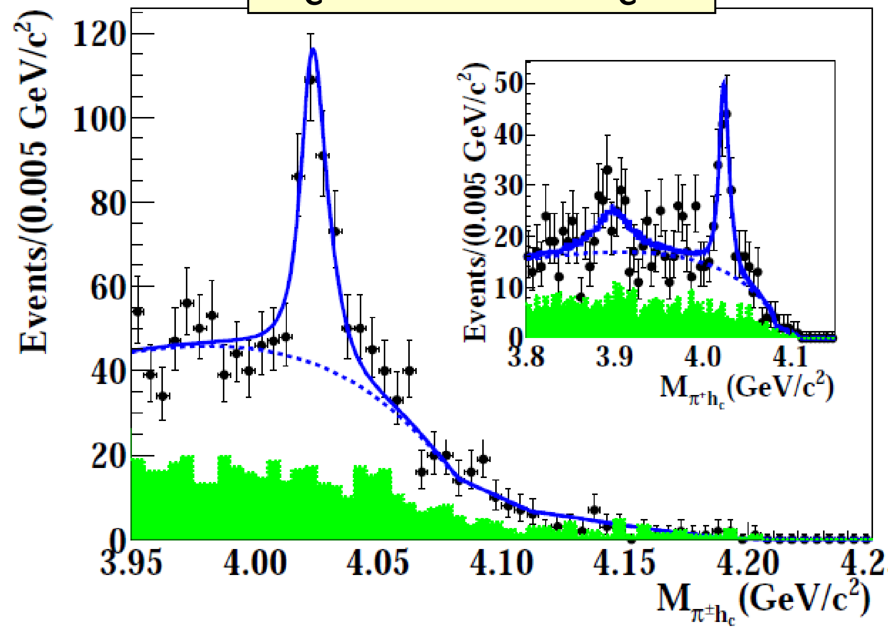
$Z_c(4020)^+$ / $Z_c(4025)^+$

arxiv:1308.2760
1309.1896

$Z_c(4025) \rightarrow (D^*D^*)^+$



$Z_c(4020) \rightarrow h_c\,\pi$



$$\left.\begin{array}{l} M = 4026.3 \pm 4.5\ \text{MeV} \\ \Gamma\ = 24.8 \pm 9.5\ \text{MeV} \end{array}\right\}\ \text{agree within } 1.1\sigma \left\{\begin{array}{l} M = 4022.9 \pm 2.8\ \text{MeV} \\ \Gamma\ = 7.9 \pm 3.8\ \text{MeV} \end{array}\right.$$

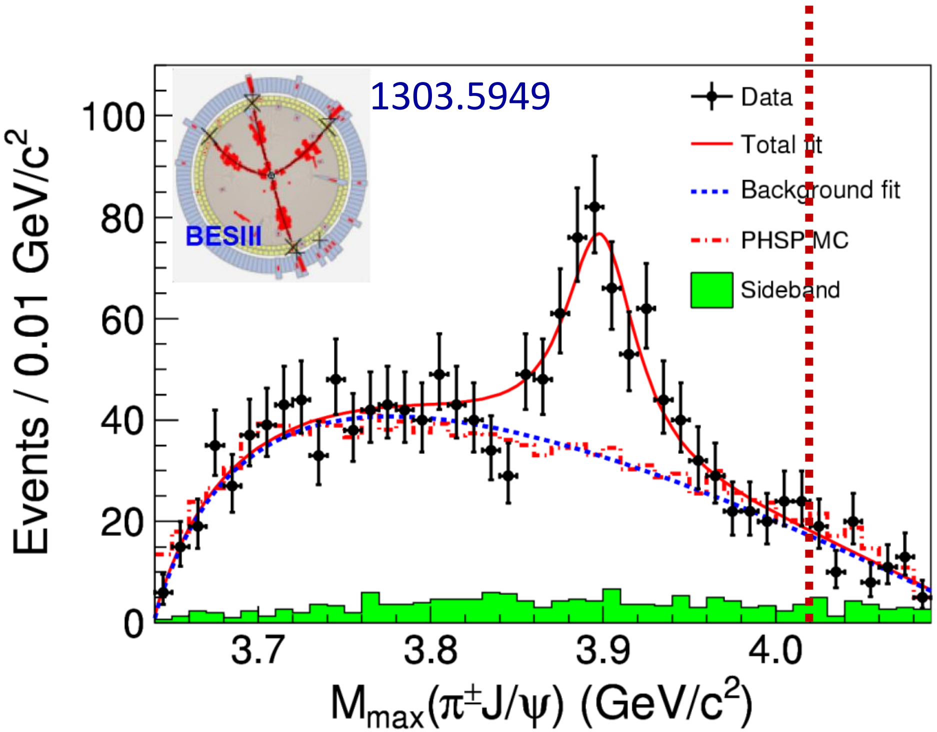
$\sigma \times BF = 89 \pm 19$ pb dominant

$\sigma \times BF = 7.4 \pm 3.0$ pb

$M_{Zc'} - M_{D*} - M_D \sim 6$ MeV

Where is $Z_c(4020,4025) \to J/\psi\ \pi$?

no sign



Molecule:

$c\bar{c}$ $c\bar{c}$

$Z_c \sim |D\ \bar{D}^*\rangle = (\uparrow\uparrow) + (\uparrow\downarrow)$

$Z_c' \sim |D^*\bar{D}^*\rangle = (\uparrow\uparrow) - (\uparrow\downarrow)$

$Z_c \to J/\psi\ \pi$

$Z_c' \not\to J/\psi\ \pi$

It is impossible that Z_c molecule decays to $J/\psi\ \pi$ while Z_c' does not.

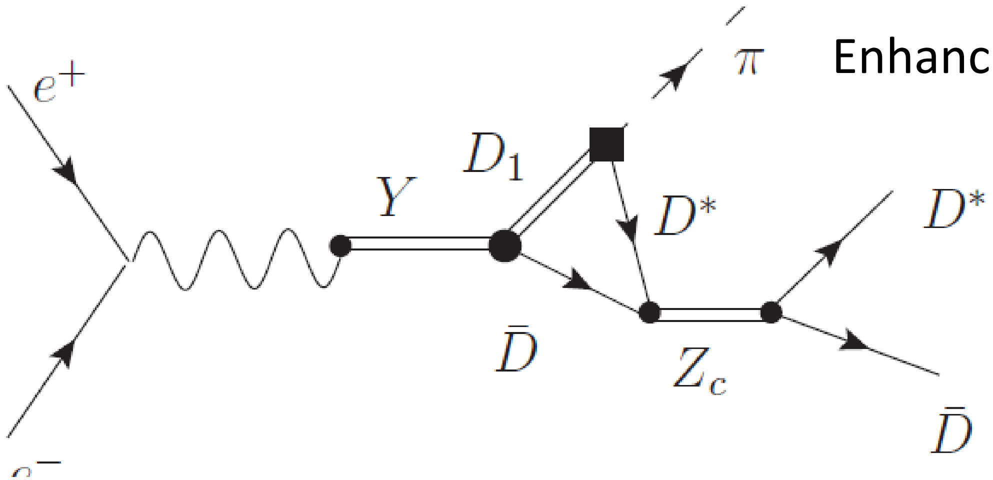
No $Z_c(4020,4025) \to J/\psi\ \pi \Rightarrow$ none is $Z_b(10650)$ partner

$\Rightarrow Z_c'$ is not produced at $Y(4260)$?

Y(4260) as $D_1(2420)\bar{D}$ molecule

Cleven, Wang, Guo, Hanhart, Meissner, Zhao
arxiv:1310.2190

M Y(4260) = 4250 $\pm$ 9 MeV
Γ Y(4260) = 108 $\pm$ 12 MeV
M D_1(2420) + M D = 4288 MeV



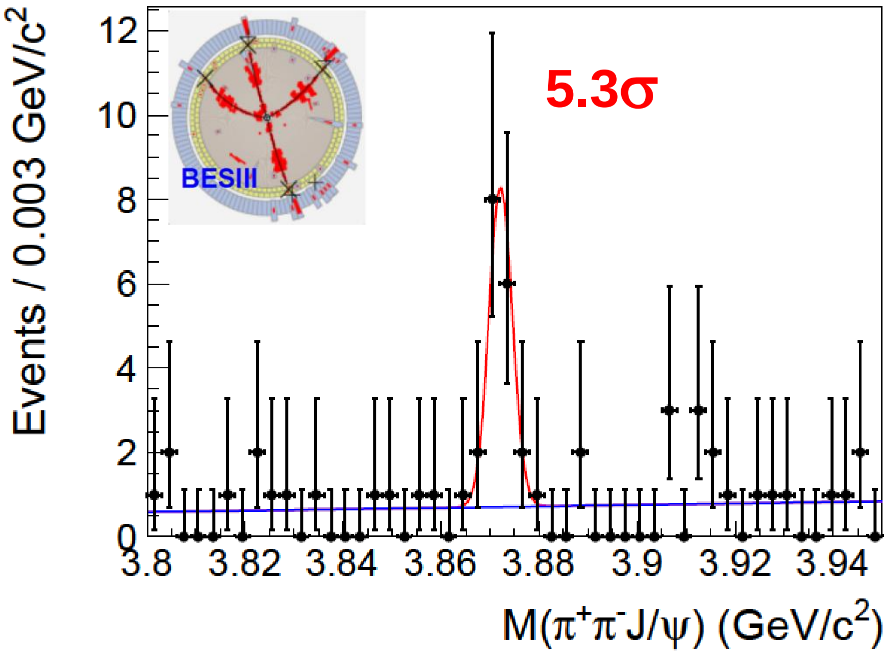
Enhanced by triangle singularity

$\rightarrow$Source of $D^*\bar{D}$ pairs with small relative momentum
$\rightarrow$ No $D^*\bar{D}^*$ pairs, **Z_c' are not produced at Y(4260)**

NB: "Υ(5S)" is not a $B_1\bar{B}$ molecule, since both Z_b and Z_b' are produced.

Observation of $Y(4260) \to \gamma\, X(3872)$

1310.4101



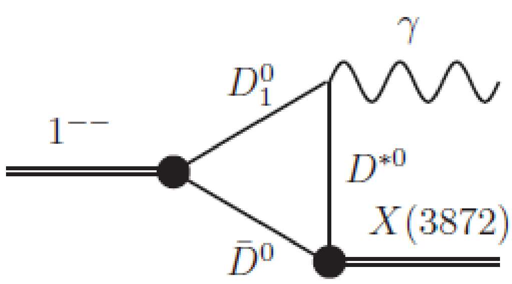
$$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 11.2\%$$

Large transition ratio !

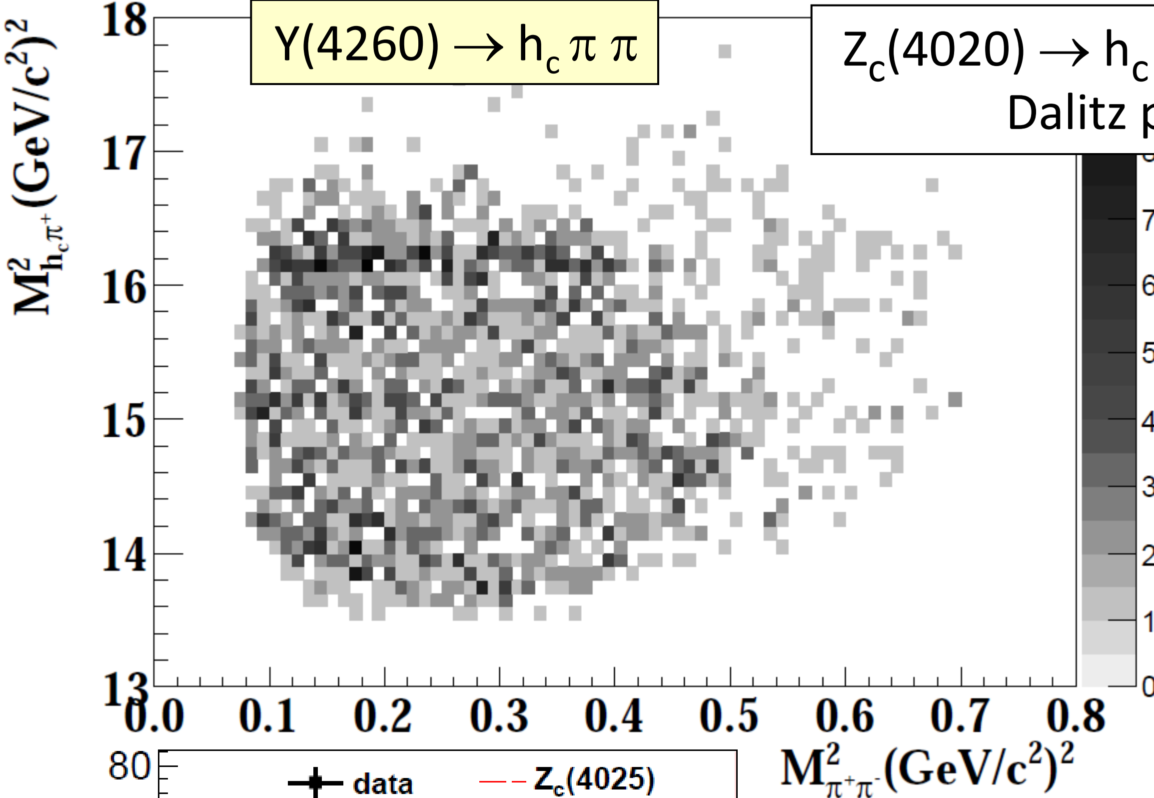
Looks breathtaking given that $\Gamma_{Y(4260)}$~100MeV

Was predicted !

Guo, Hanhart, Meissner, Wang, Zhao
PLB725,127 (2013)



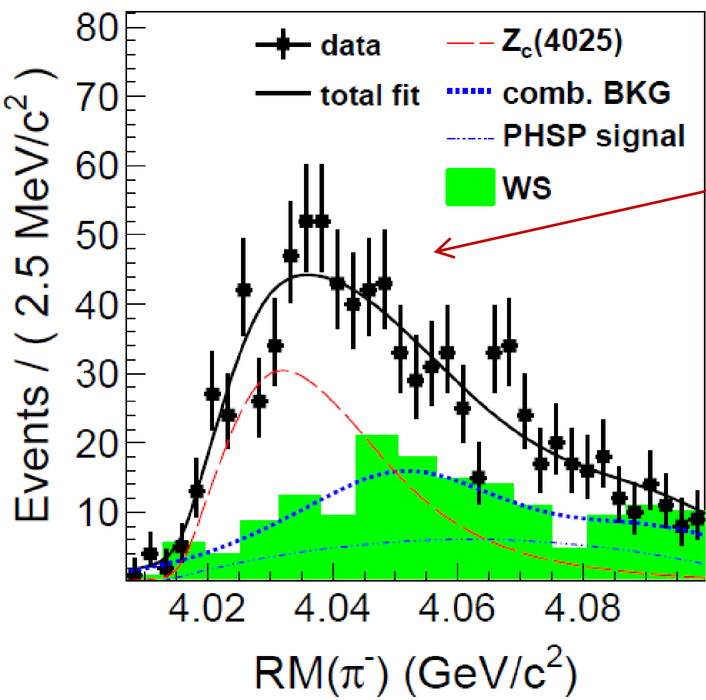
Support for molecular model of Y(4260).



$Z_c(4020) \to h_c \pi$ should be in P-wave.
Dalitz plot is strange ?

$\Rightarrow$ **$Z_c(4020)$** is not partner of $Z_b(10650)$ but smth **new**

Cross-check : measure J^P



$Z_c(4025)$ = non-resonant contribution?

Data could accommodate absence of Z_c' at $Y(4260)$?

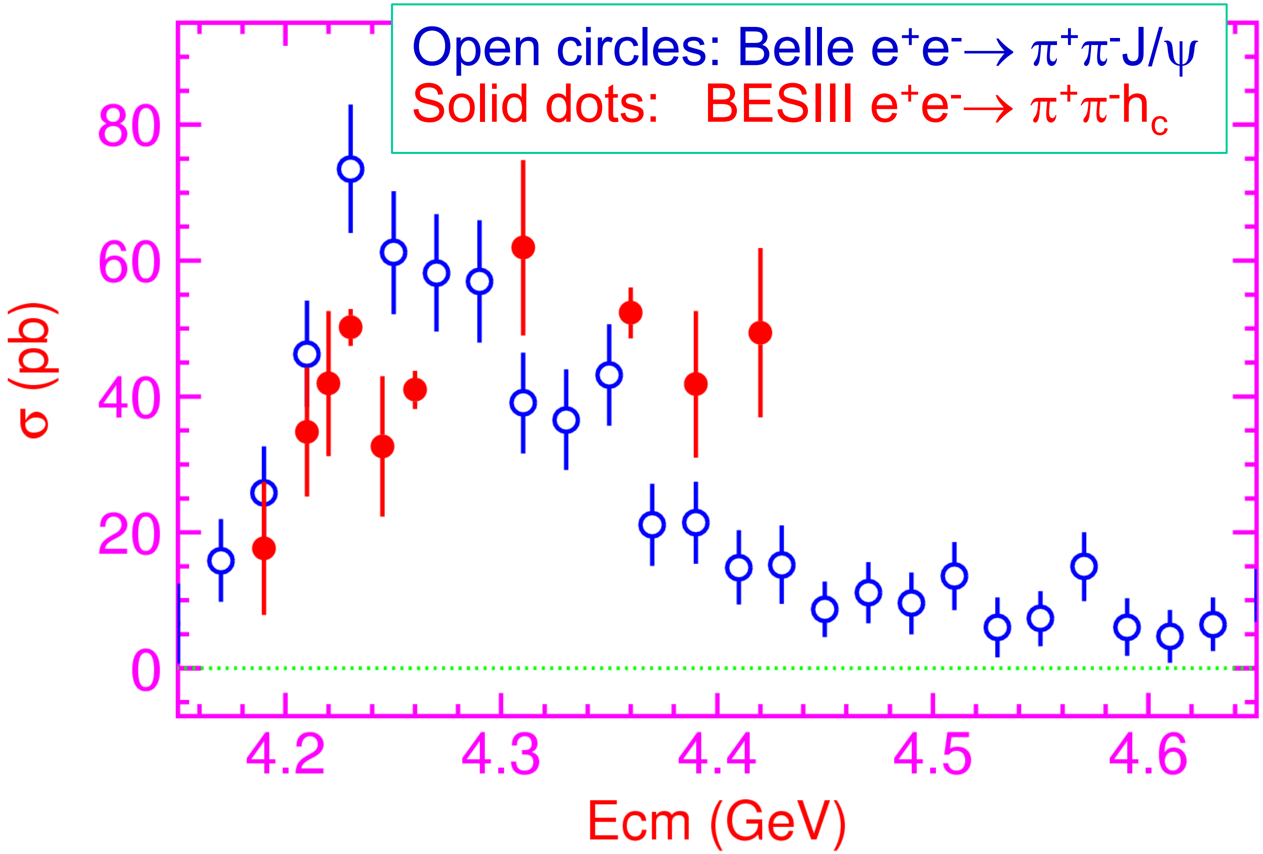
These are very bold guesses that will be checked by future BESIII analyses.

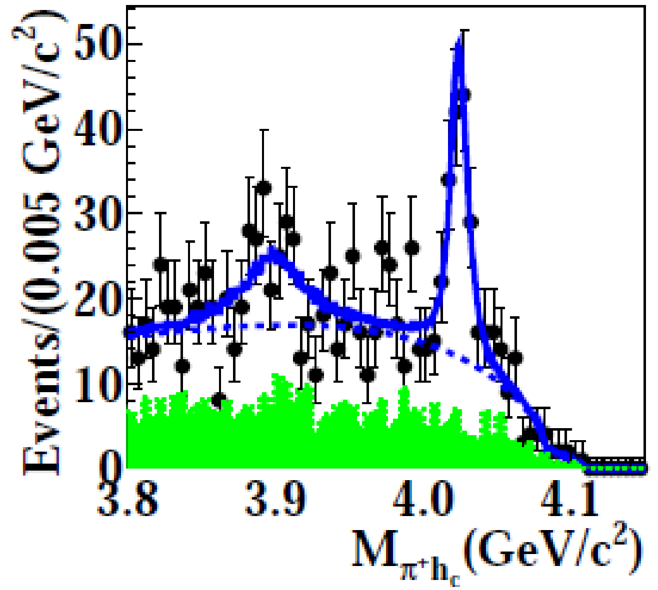
What next at BESIII?

Changzheng Yuan Charm2013

- Precise resonant parameters
- Spin-parity of Z_c and Z_c'
- More decay modes [$\pi\psi$', $\rho\eta_c$, open charm,…]
- Production mechanisms, production rates
- Test various theoretical models
- Neutral partners of Z_c and Z_c'
- Excited Z_c, Z_c' states? $Z_{cs} \rightarrow KJ/\psi$ states?
- Other XYZ states?
- More data at high energies

Comparison of $e^+e^- \to \pi^+\pi^- h_c$ and $\pi^+\pi^- J/\psi$

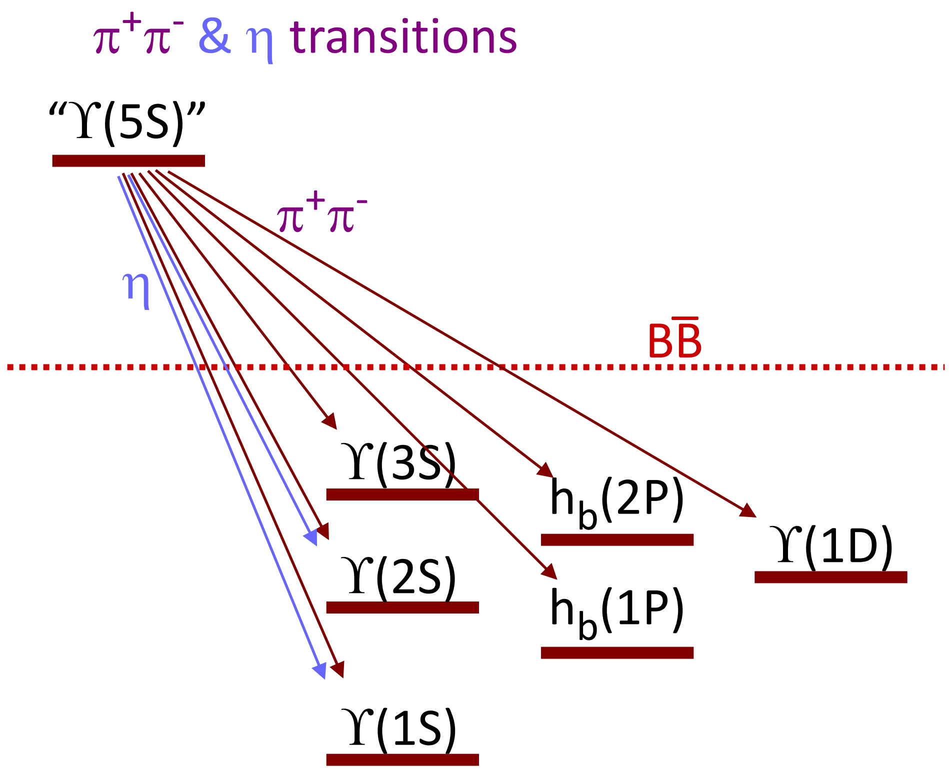




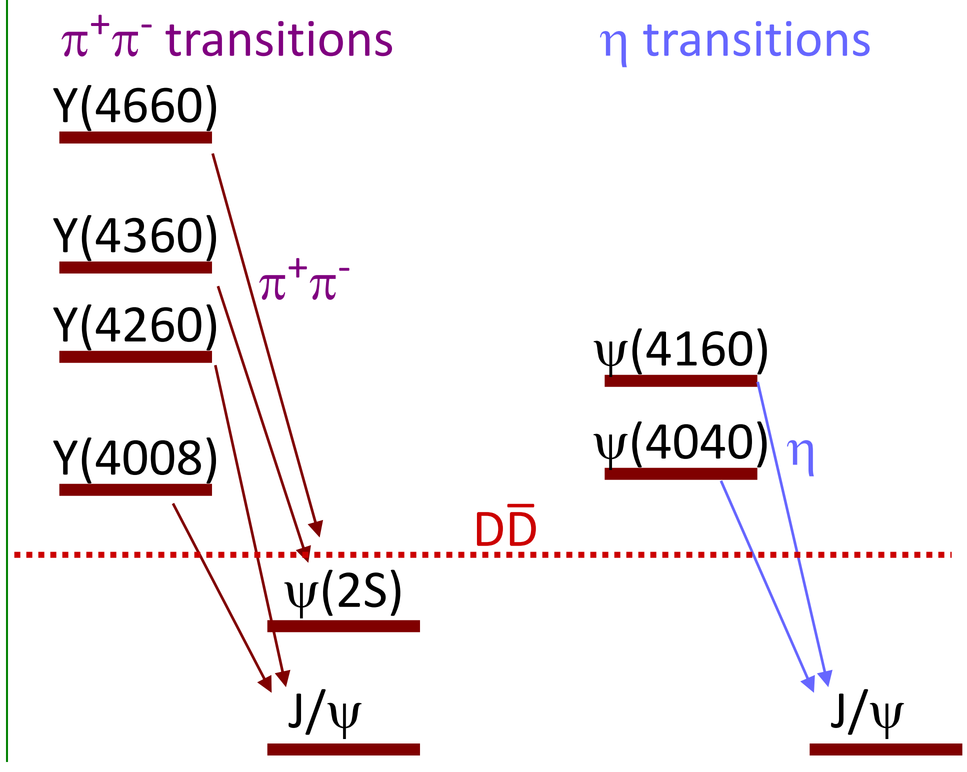
Non-resonant $e^+e^- \to \pi^+\pi^- h_c$ production violates HQSS.

If Y(4260) is a $D_1\bar{D}$ molecule $\Rightarrow$ mixture of ortho- and para-charmonium
$\Rightarrow$ mechanism for HQSS violation.

Bottomonium

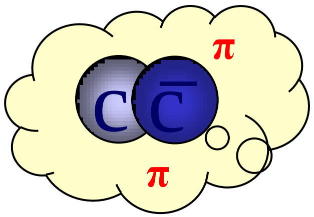


Charmonium



Γ["Υ(5S)" $\to$ ($b\bar{b}$) $\pi^+\pi^-$] ~ 1 MeV ⟷ similar ⟷ Γ[ψ/Y $\to$ ψ hadrons] ~ 1 MeV

Molecular models do not explain affinity to particular channels.



$\Leftarrow$ *Hadrocharmonium? Voloshin*

Also Z(4430)$^+ \to \psi'\pi^+$, Z(4050,4250)$^+ \to \chi_{c1}\pi^+$, Z_c(4020)$^+ \to h_c\pi^+$

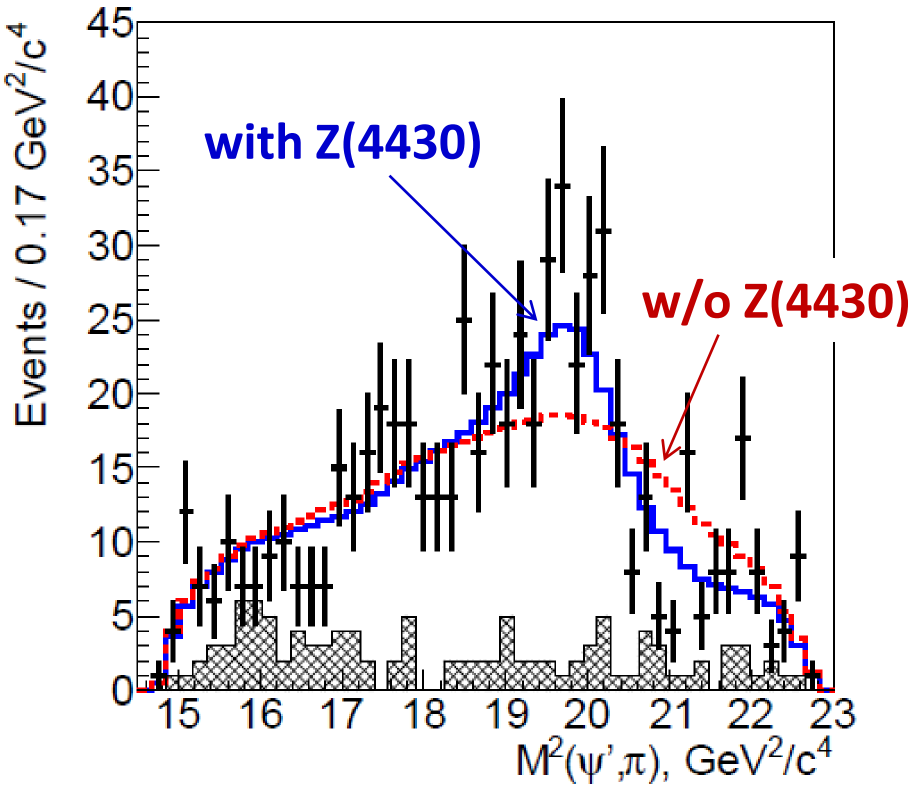
Z(4430) spin-parity

PRD88,074026

$B^0 \to (\psi'\pi^-) K^+$
$\quad\quad \hookrightarrow \mu^+\mu^-$

4D amplitude analysis

Model : $K_0^*(800)$, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$, Z(4430)



$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}$$
$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}.$$

$J^P = 1^+$ is favored

Exclusion levels: **0^-** (3.4σ)
1^- (3.7σ)
2^- (4.7σ)
2^+ (5.1σ)

$(\psi'\pi^-)$ are in S-wave

Z(4430) is not confirmed by BaBar and within the reach of LHCb

Conclusions

States with $\mathbf{c\bar{c}}$ or $\mathbf{b\bar{b}}$ pairs above open flavor thresholds are not $\mathbf{Q\bar{Q}}$ states.

BESIII : many interesting results

Interpretation is difficult
$\Rightarrow$ amplitude analyses are needed

Still no general model explaining all states.

Rich experimental material should be stimulating for theory.

Back-up

Y(4140) @ CMS & D0

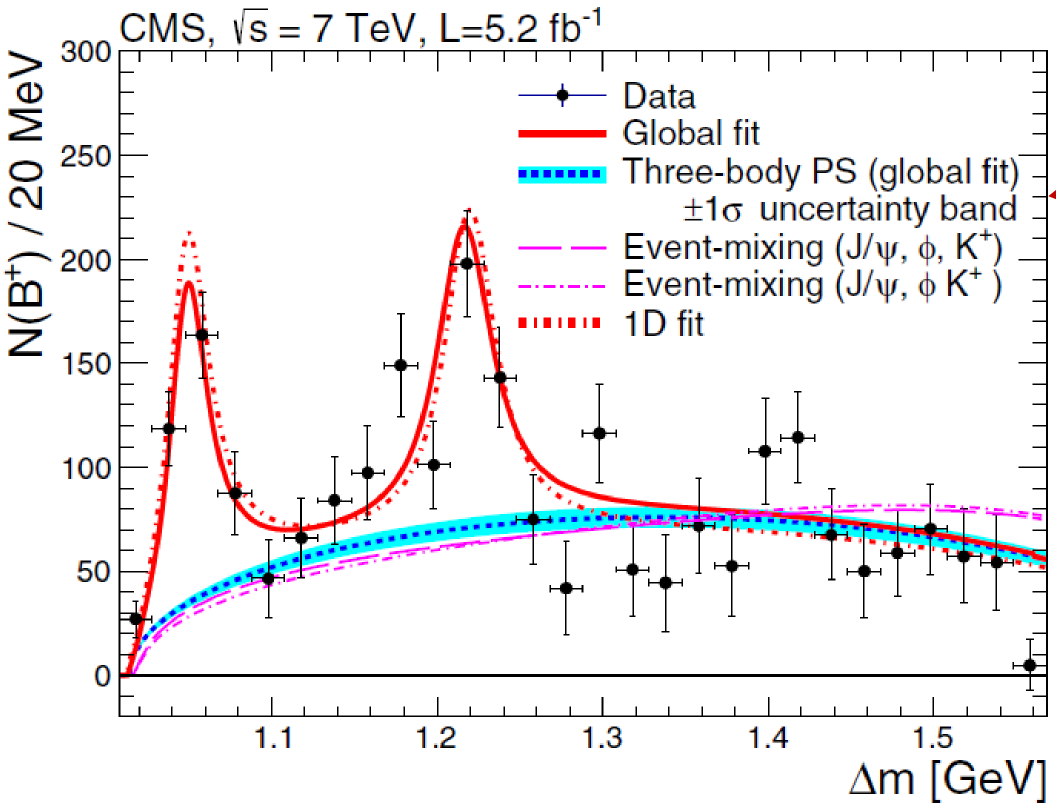
1101.6058

Y(4140) – CDF 2009: $B^+ \to (J/\psi\varphi) K^+$ Not confirmed by Belle & LHCb.

PRD85,091103

1309.6920

1309.6580



Confirmed by CMS & D0.

Parameters of Y(4140) agree among CDF, D0 and CMS.

2nd peak : Y(4274) seen by CDF, D0 and CMS.

Masses agree at 3σ level,

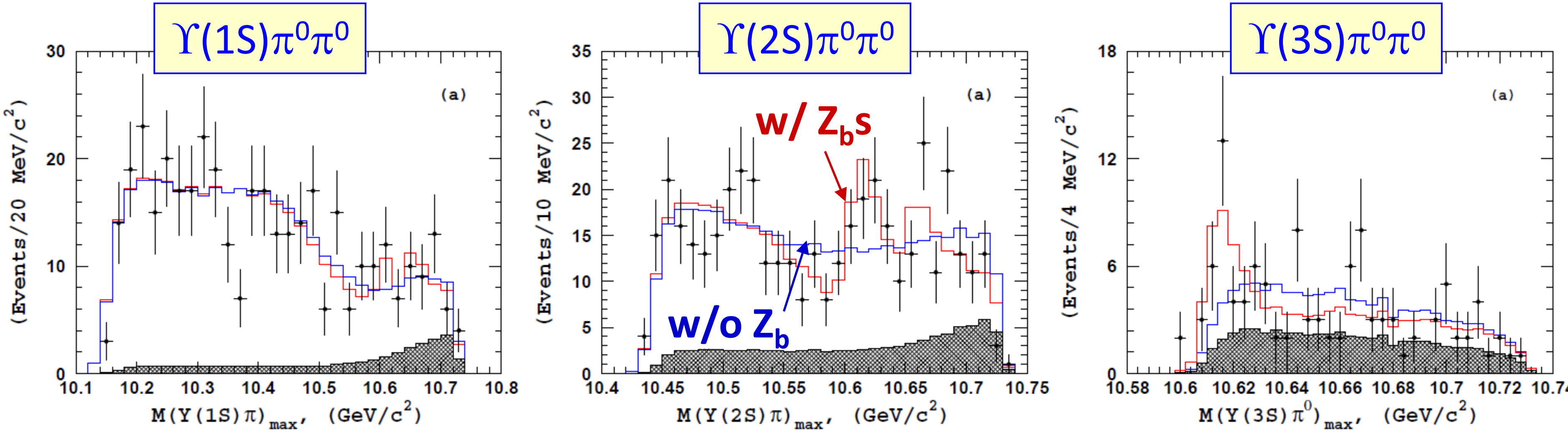
Region of $K^* \to \varphi K$ reflections.

Amplitude analyses are planned at CMS and LHCb.

Neutral Z_b

PRD88,052016(2013)

Dalitz analysis, the same as for charged states.



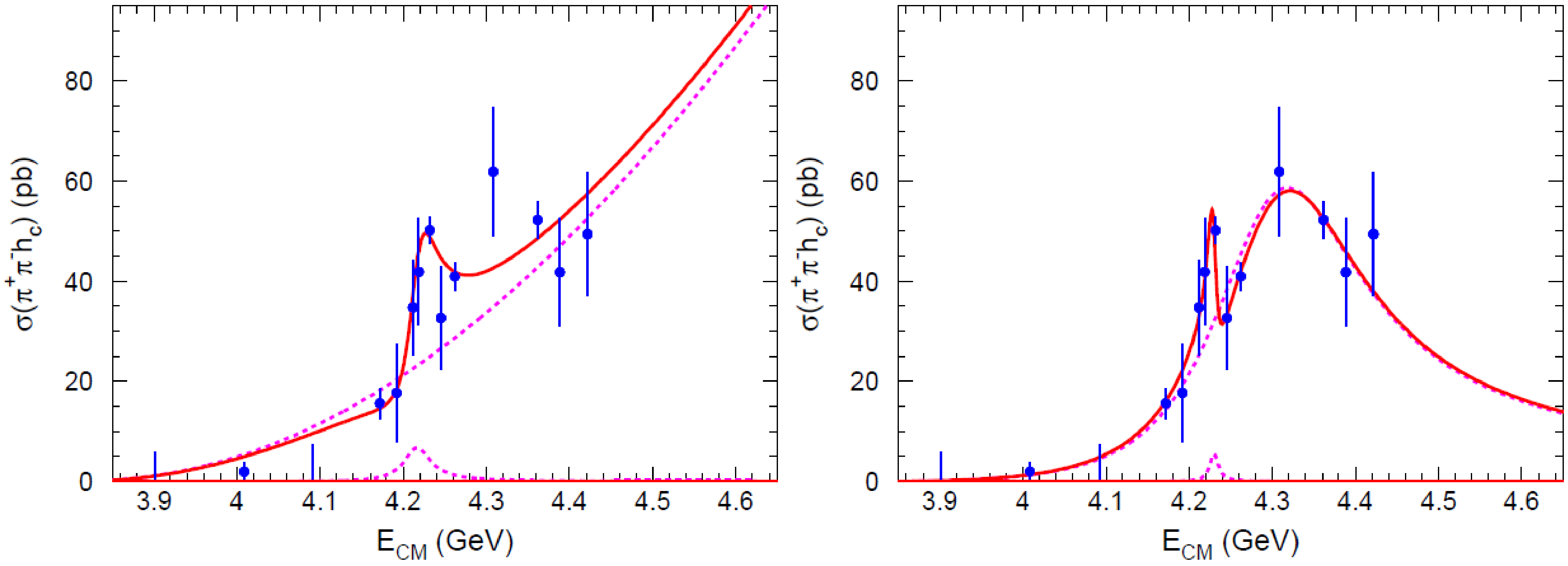
Fit fractions of neutral and charged Z_b's are consistent

	$\Upsilon(2S)\pi^0$	$\Upsilon(3S)\pi^0$	Combined
Significance of $Z_b(10610)$ *(including systematics)*	4.9σ	4.3σ	6.5σ

observation of $Z_b(10610)^0$

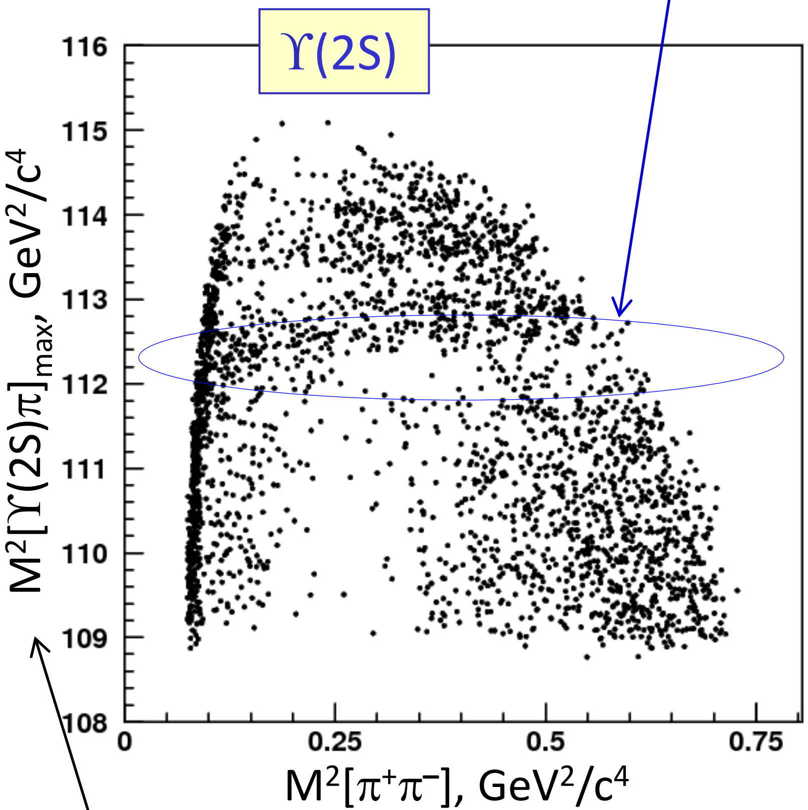
$\Upsilon(nS)\pi^0\pi^0$ channels are consistent with Z_b states being isotriplets

$e^+e^- \to h_c \pi^+\pi$: Y(4220)



Comparison of spin-parity hypotheses

Clear picture of interference between Z_b and non-resonant S-wave amplitude



Useful projection to explore "deficit" due to interference.

Z_b helicity angle $\sim M^2(\pi^+\pi^-)$

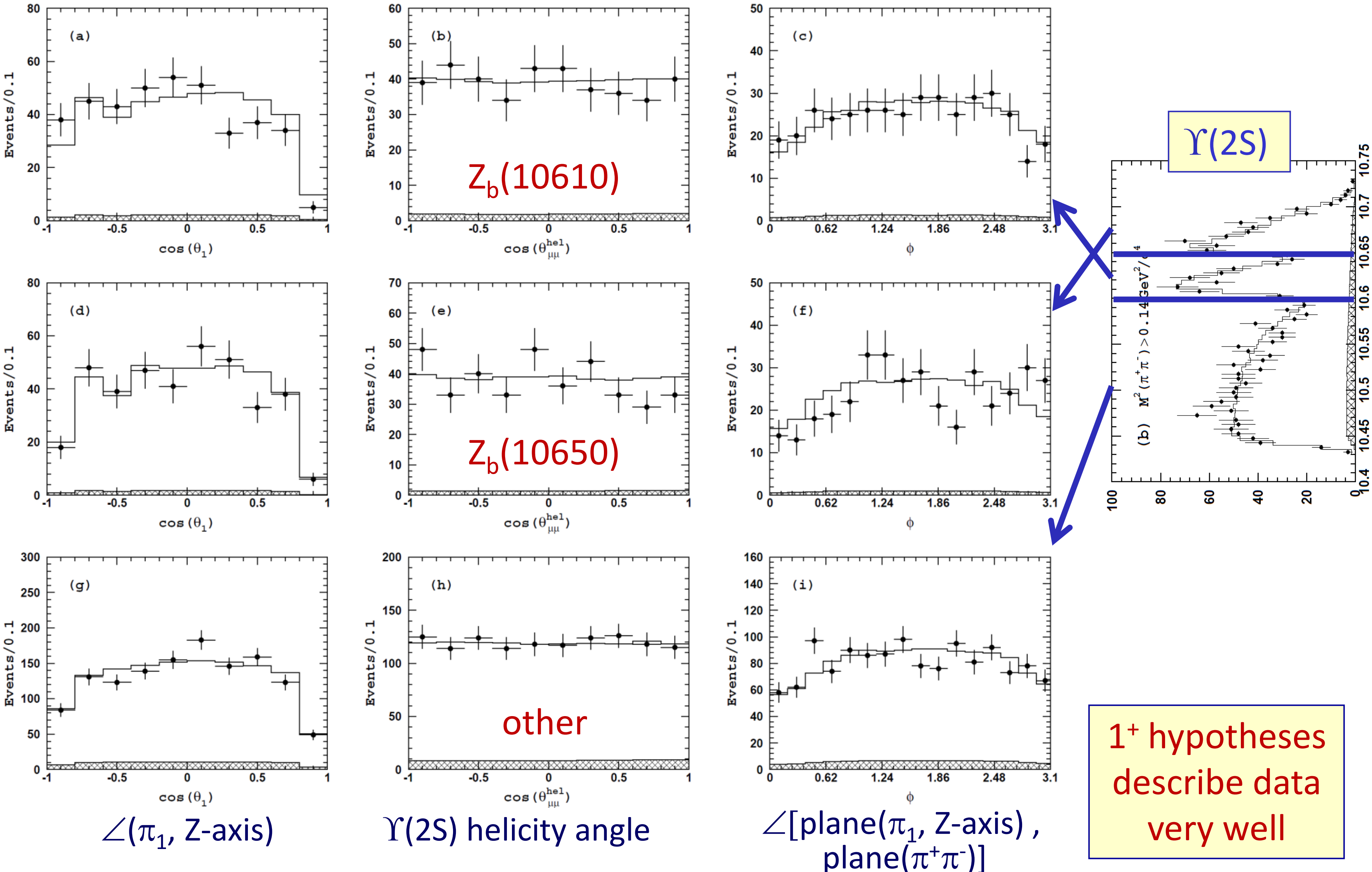
$$Z_b \to \Upsilon(nS)\pi \begin{cases} 1^+ & \text{S-wave} \\ 1^- & \text{P-wave} \\ 2^+ & \text{D-wave} \\ 2^- & \text{P-wave} \end{cases}$$

$\Rightarrow$ A_{Zb} is ~independent on $M^2(\pi^+\pi^-)$ for 1^+, other hypotheses change sign over $M^2(\pi^+\pi^-)$

Interference region has high sensitivity.

Angular projections of 6D fit

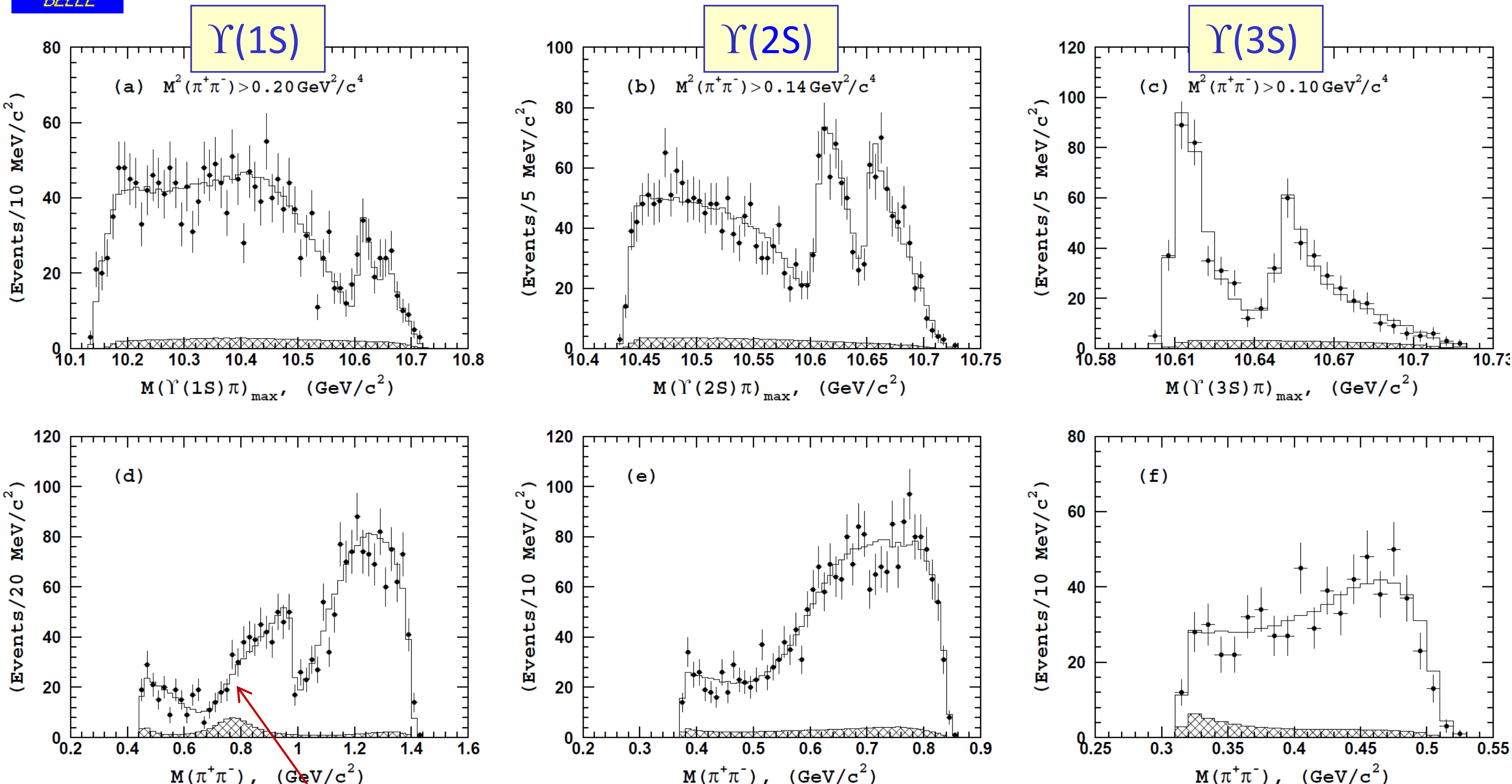
$J^P=1^+$



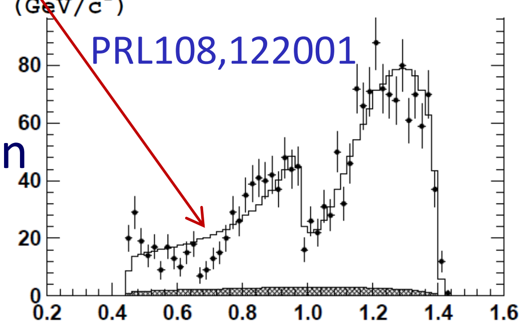
1^+ hypotheses describe data very well

Mass projections of 6D fit

$J^P=1^+$



Improvement due to inclusion of σ state

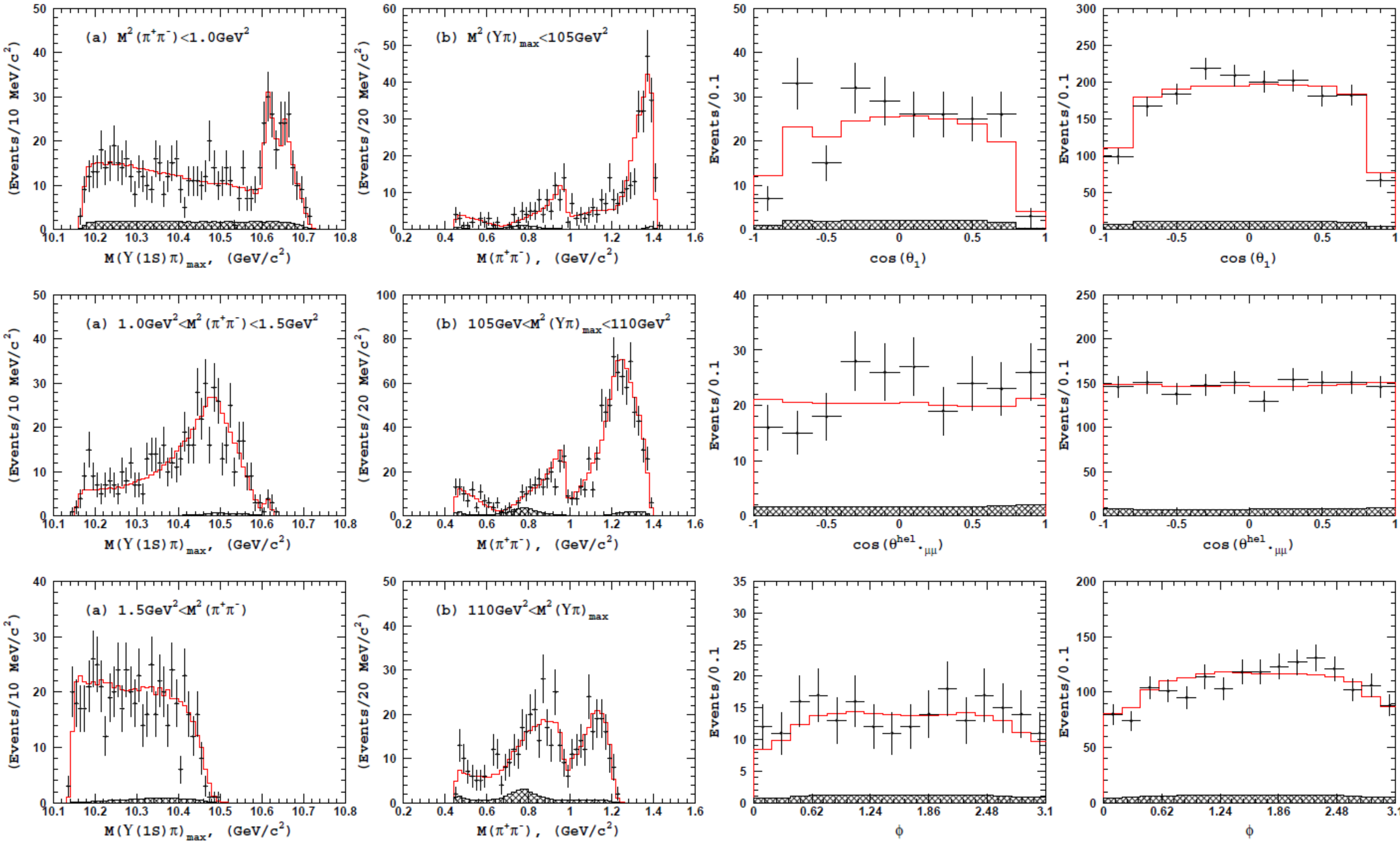


BW amplitudes describe Z_b states very well.

Resonant behavior of Z_b amplitudes (intensity & phase).

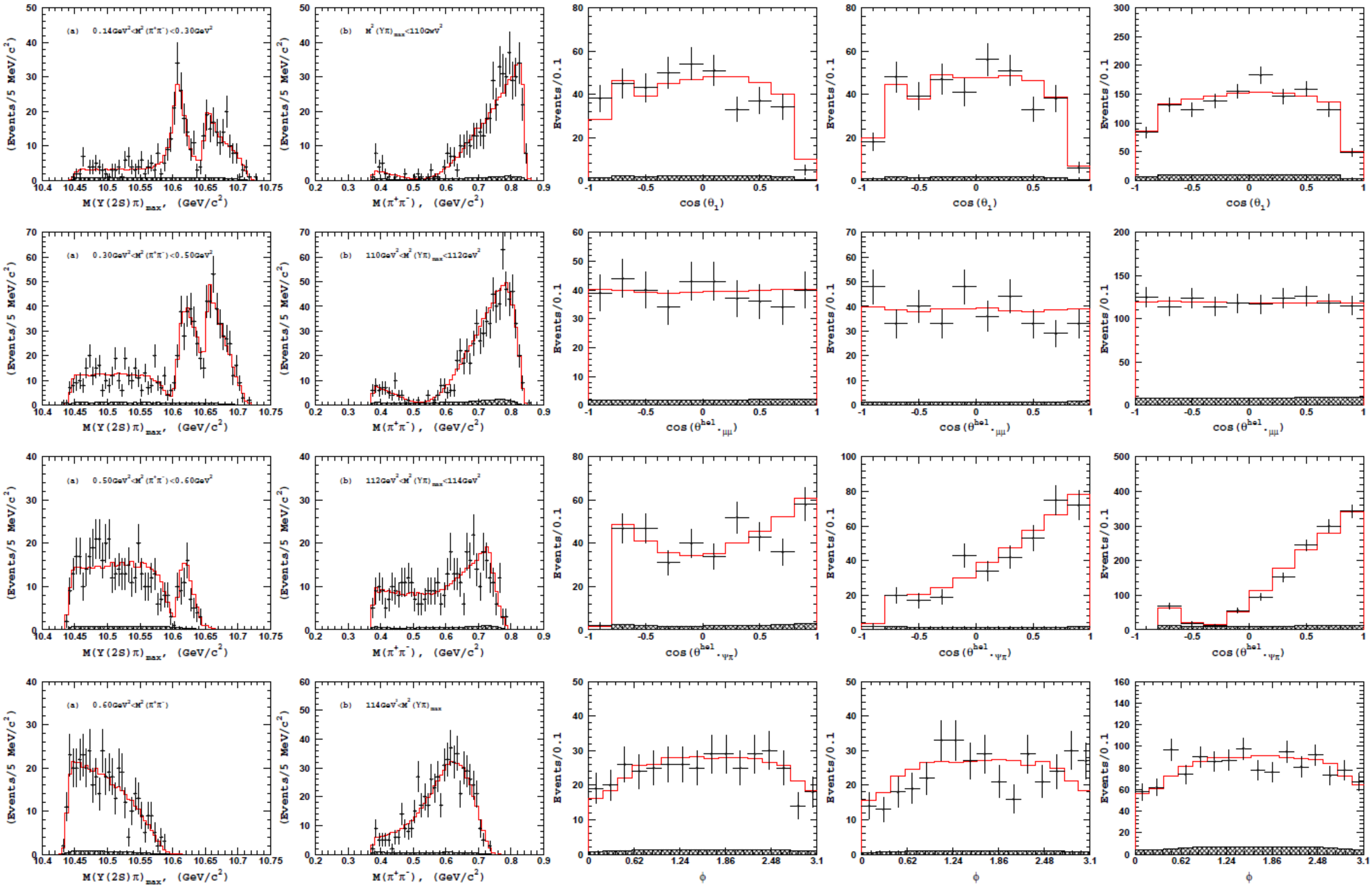
Fit projections for $\Upsilon(1S)\,\pi^+\pi^-$

$J^P=1^+$



Fit projections for $\Upsilon(2S)\,\pi^+\pi^-$

$J^P=1^+$



Fit projections for $\Upsilon(3S)\,\pi^+\pi^-$

$J^P=1^+$