Cusps and Exotic Charmonia

Eric Swanson

Filling out the CKM matrix has been very good for spectroscopy!

Focus on Charged & Heavy States [hence four-quark states(?)]

$\pi\pi J/\psi$ $\pi D\bar{D}^*$	$\pi\pi h_c$ $\pi D^*\bar{D}^*$	$K\pi\chi_{cJ}$	$K\pi J/\psi$	$\pi K\psi'$	$\pi\pi\Upsilon(nS)$ $\pi\pi h_b(nP)$ $\pi B\bar{B}^*$
$Z_c(3900)$	$Z_c(4025)$	$Z_1(4050)$ $Z_2(4250)$	$Z_c(4200)$	$Z_c(4475)$	$Z_b(10610)$ $Z_b(10650)$
BELLE, BESIII, CESR CLEO	BELLE, BESIII	BELLE, ~~BABAR~~	BELLE	BELLE, LHCb, ~~BABAR~~, CDF, ~~CDF~~	BELLE

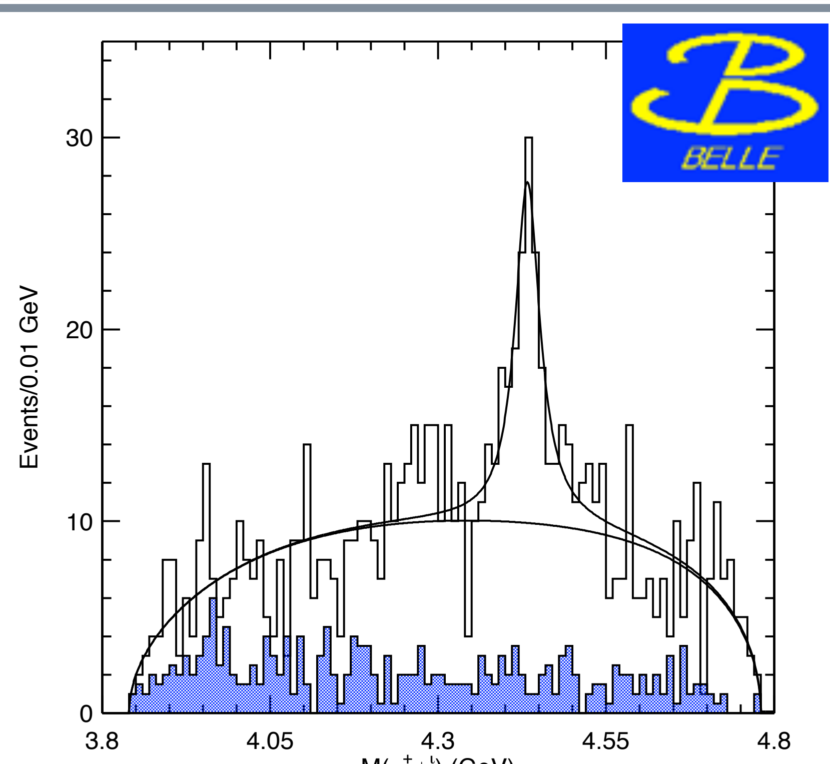
Z(4430)|Z(4475)/ Z(4200)

$Z^+(4430)$

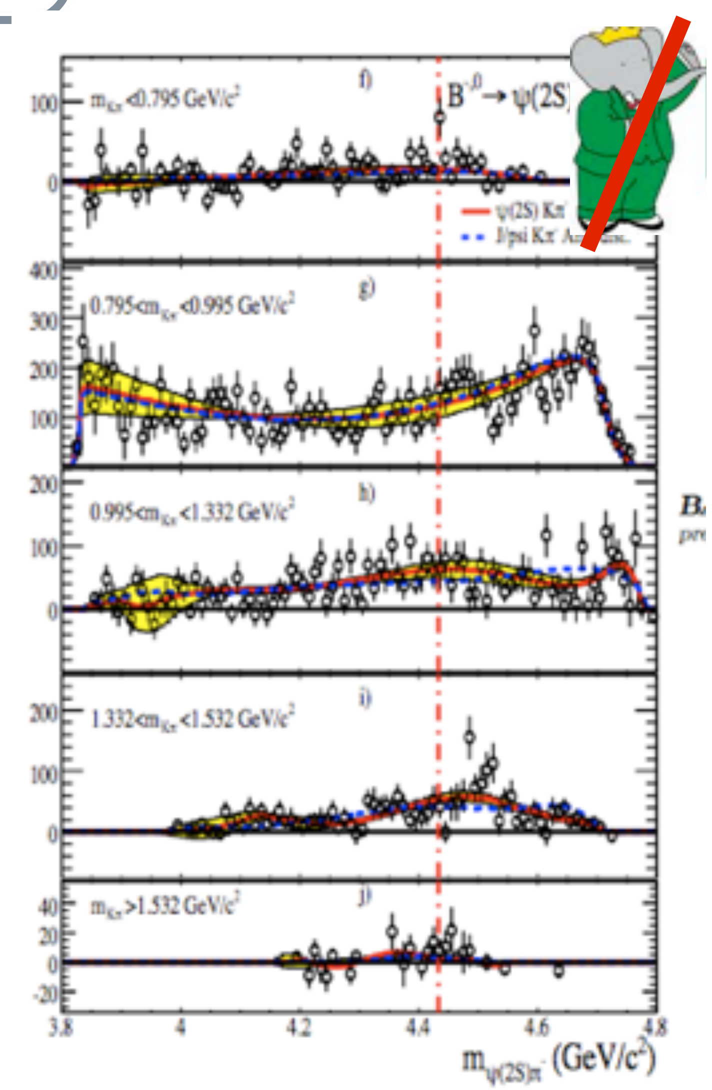
$B \to K\pi^+\psi'$

$$M = 4443^{+24}_{-18}$$
$$\Gamma = 107^{+113}_{-71}$$
$$J^{PC} = ?$$

.manifestly exotic
.not confirmed by BaBar



S.-K Choi et al. [Belle] 0708.1790

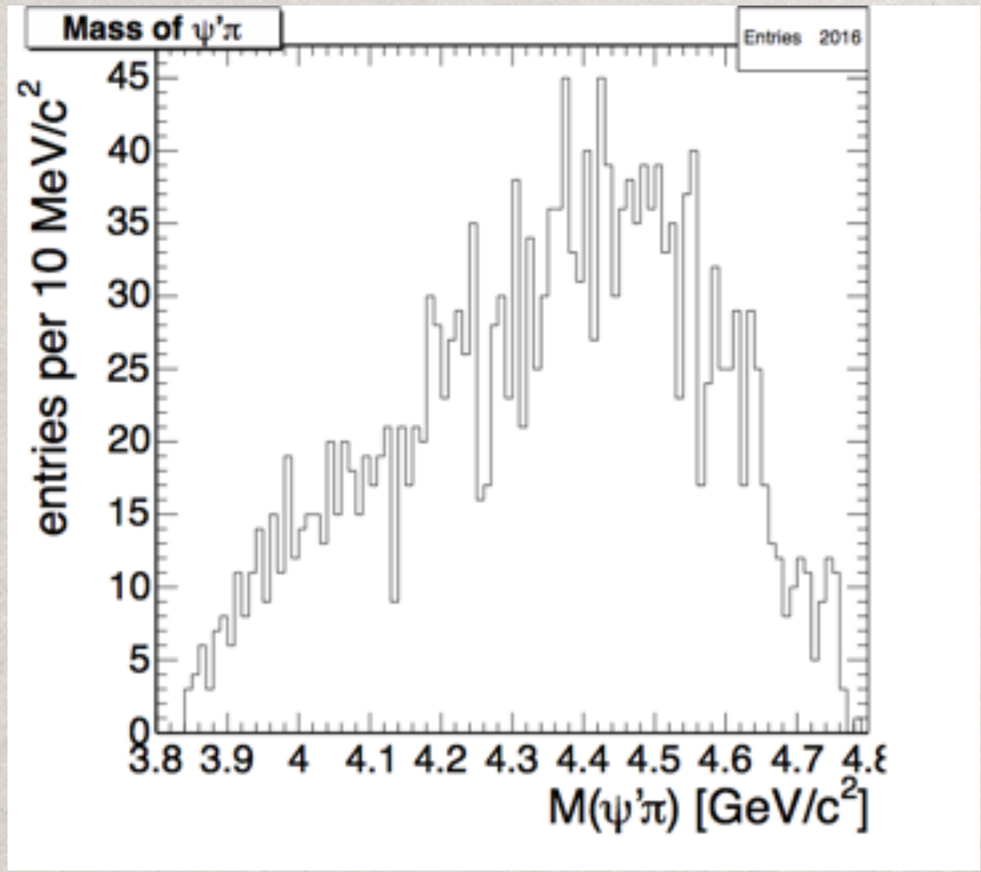


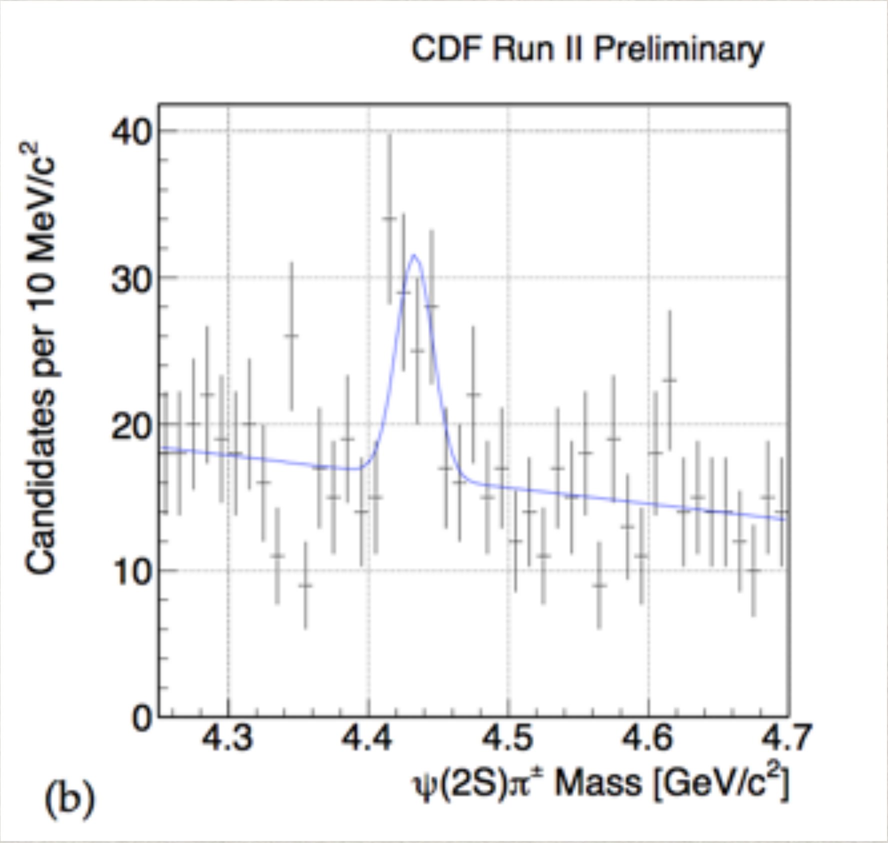
Mokhtar. 0810.1073

$Z^+(4430)$

pp -> B B(pi K psi')

prompt production



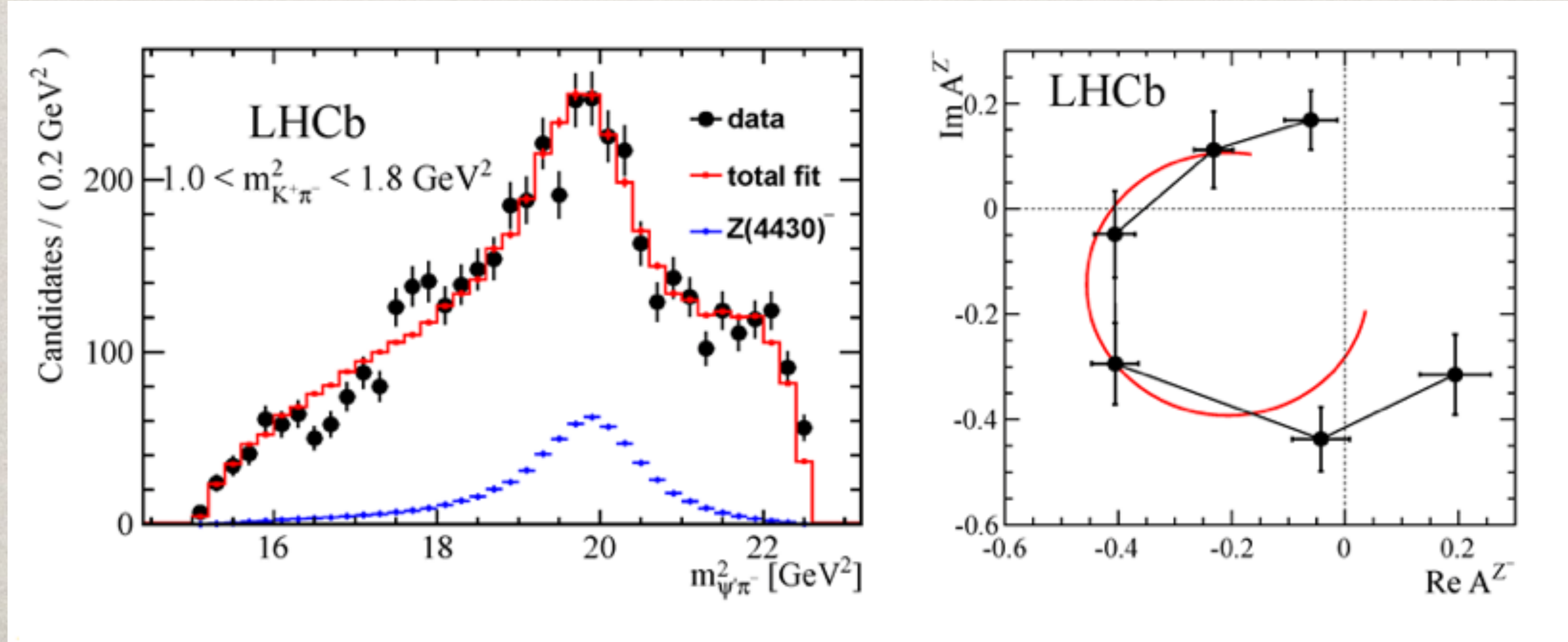


F. Rubbo, Torino thesis

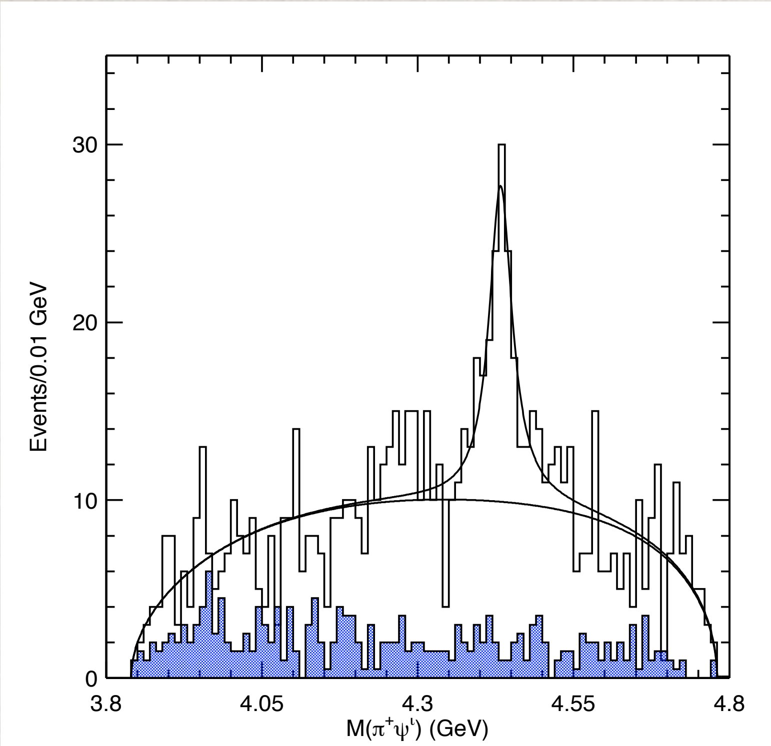
$Z^+(4430)$

.confirmed by LHCb

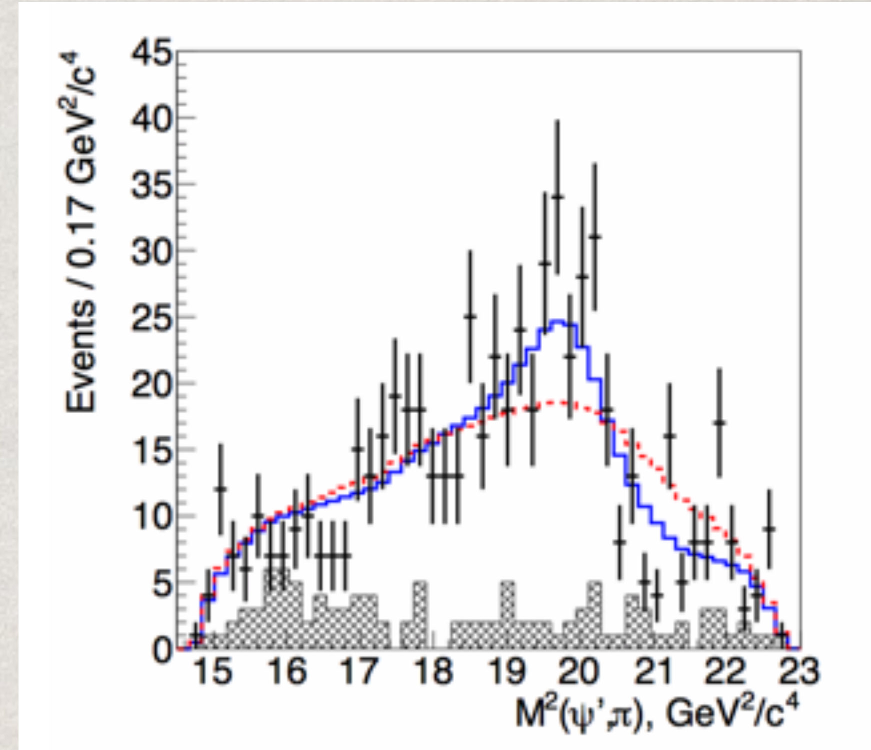
$J^P = 1^+$



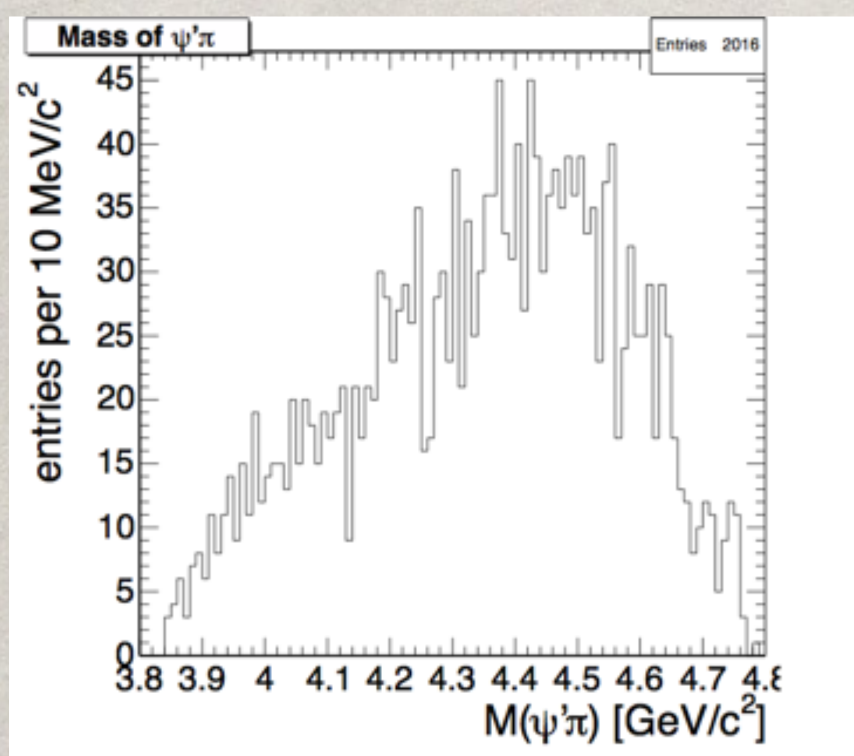
$Z^+(4430)$



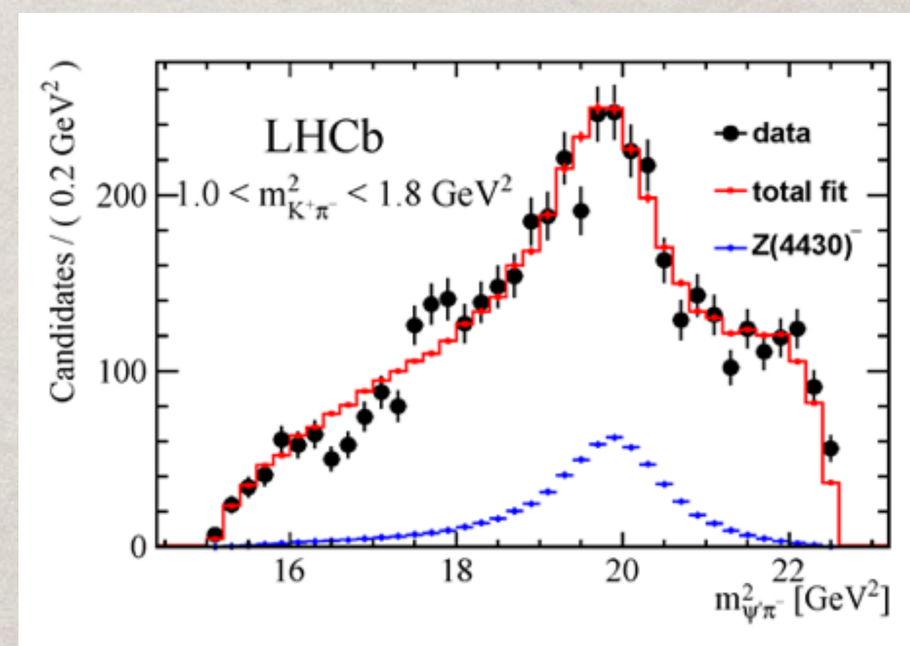
Belle original



Belle re-analysis
1306.4894



CDF



LHCb

Systematics: second exotic Z?

- Fit confidence level increases to 26% with a second exotic ($J^P=0^-$) component, but…
  - No evidence for Z_0 in model independent approach.
  - Argand diagram for Z_0 is inconclusive.
- Need larger samples to characterise this state.

Significance from

$$\Delta(-2\ln L)$$

$$6\sigma$$

Fitted parameters

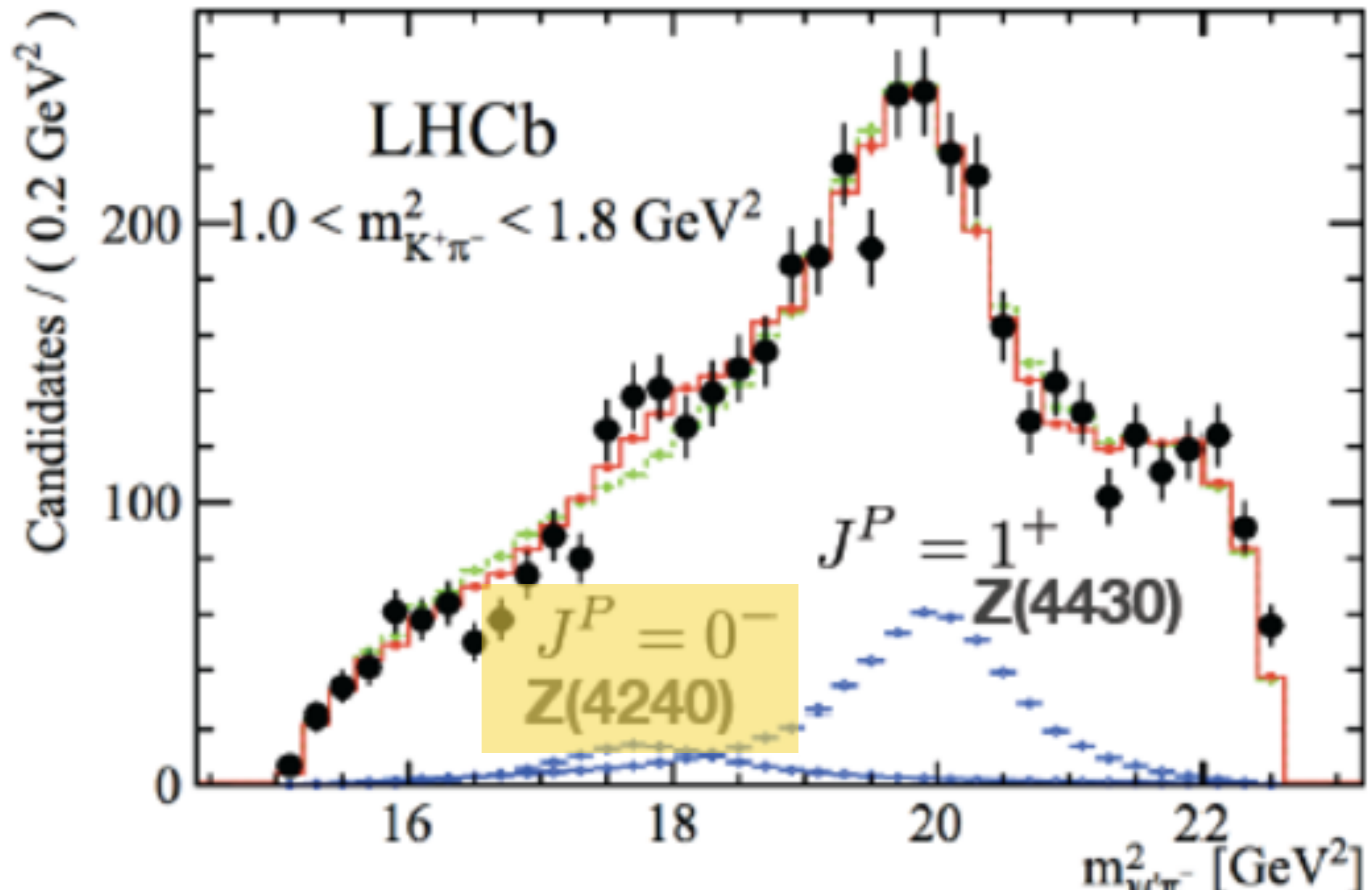
$$M_{Z_0} = 4239 \pm 18\ ^{+45}_{-10}\ \mathrm{MeV}$$

$$\Gamma_{Z_0} = 220 \pm 47\ ^{+108}_{-\ 74}\ \mathrm{MeV}$$

$$f_{Z_0} = (1.6 \pm 0.5\ ^{+1.9}_{-0.4})\%$$

Same mass, width as $Z^- \to \chi_{c1}\pi^-$ seen by Belle, but $J^P=0^-$ can't decay strongly to $\chi_{c1}\pi^-$

[PRD 78 (2008) 072004]



- Many checks performed to determine stability of the result and evaluate systematic errors on m_Z, Γ_Z, f_Z.
- Main systematics come from assumption on $K^+\pi^-$ Isobar model, efficiency

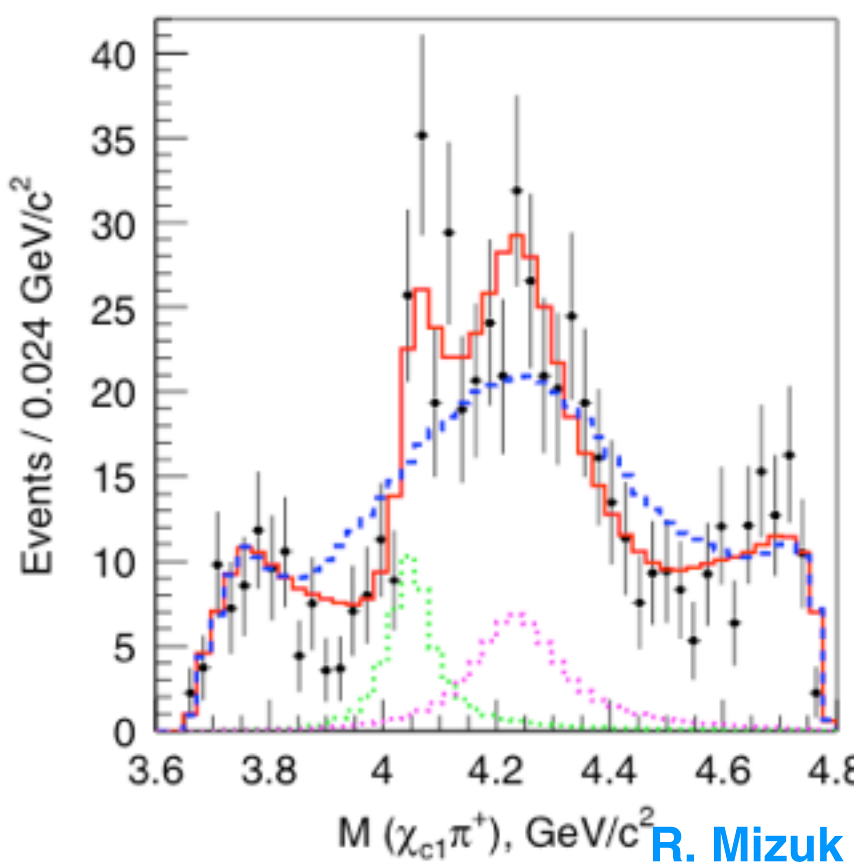
Z_1 & Z_2

$$Z_1(4050)$$
$$Z_2(4250)$$

$$B \to ZK \to \chi_{c1}\pi K$$

$$M = 4051(30)$$
$$\Gamma = 82(51)$$
$$M = 4248^{+185}_{-45}$$
$$\Gamma = 177^{+113}_{-72}$$
$$J^{PC} = ?$$

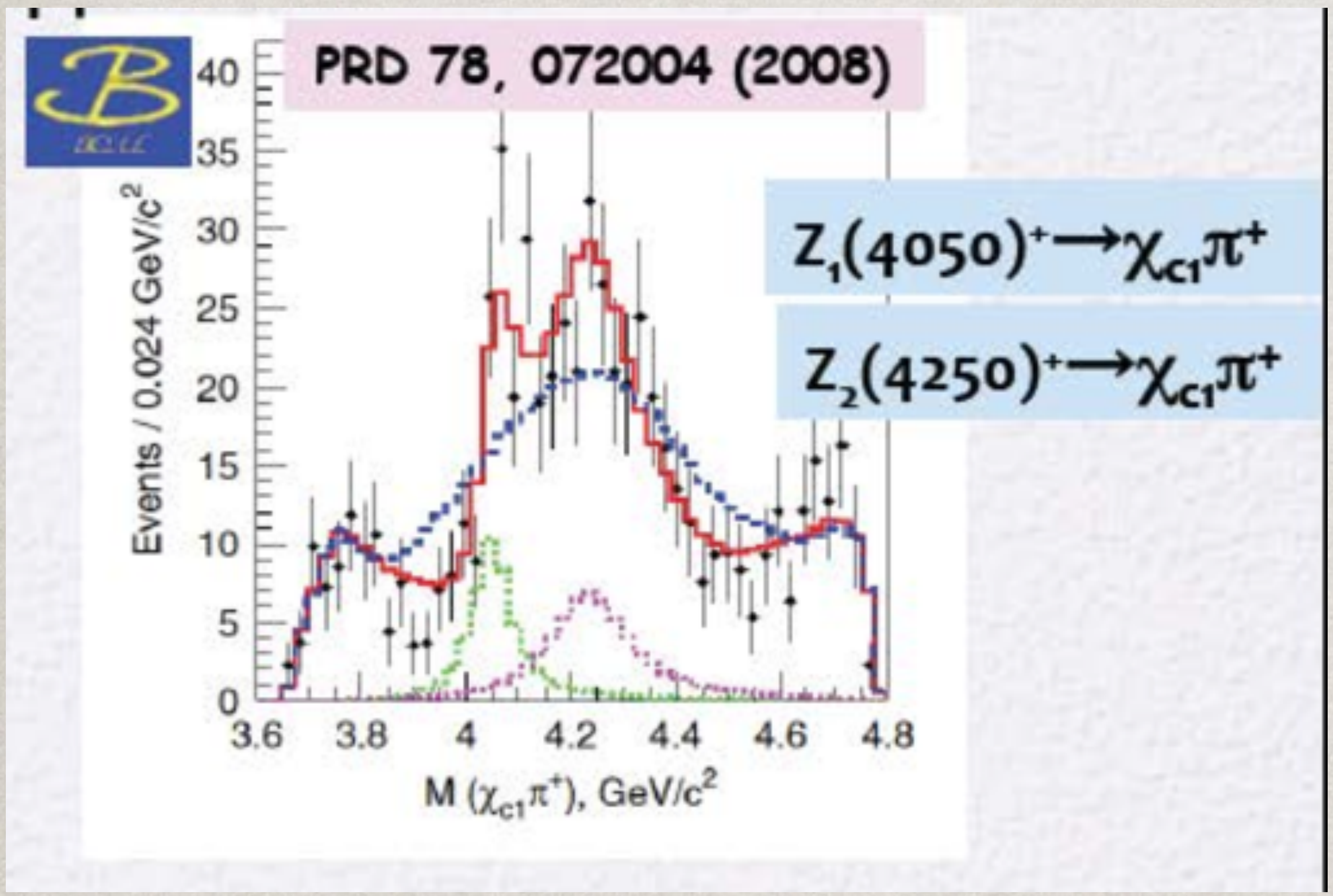
.manifestly exotic
.dubious

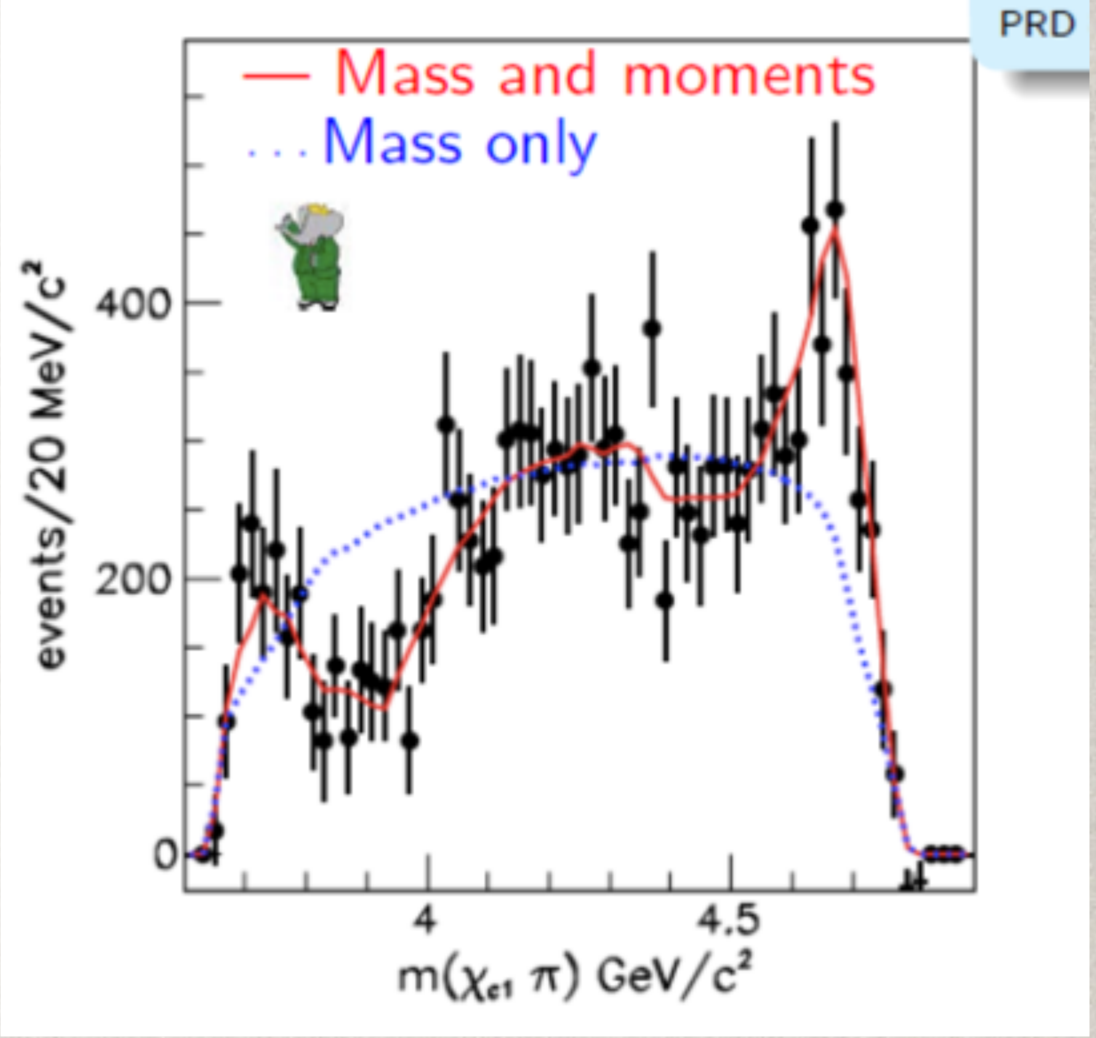


BELLE

R. Mizuk et al. [Belle], PRD76, 072004 (08)

$$Z_1(4050)$$
$$Z_2(4250)$$



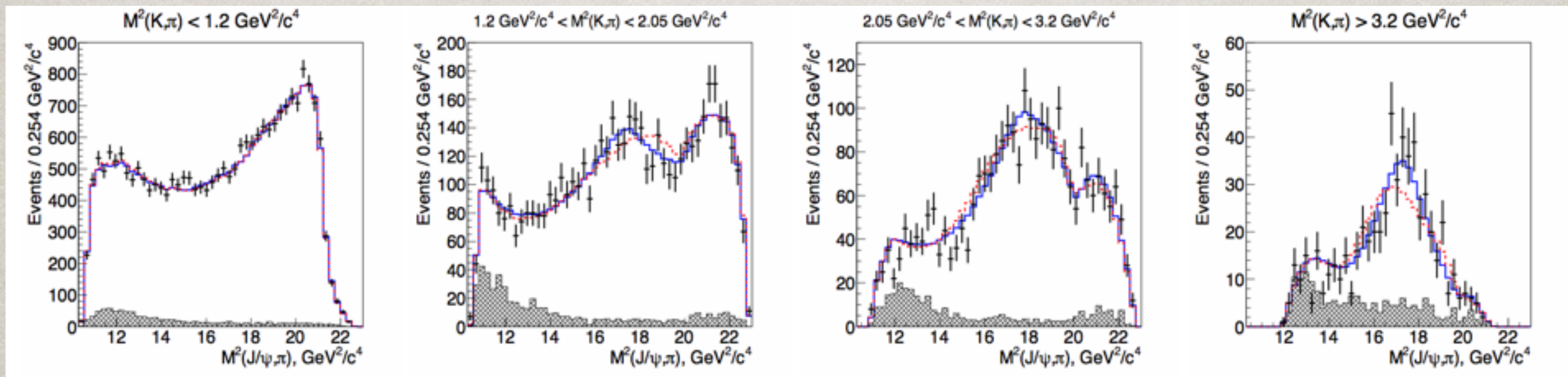


good fit with only K resonances!

Zc(4200)

$Z_c(4200)$

$$B \to K\pi J/\psi$$



dotted: without Zc(4200)

K. Chilikin et al. [Belle] 1408.6457

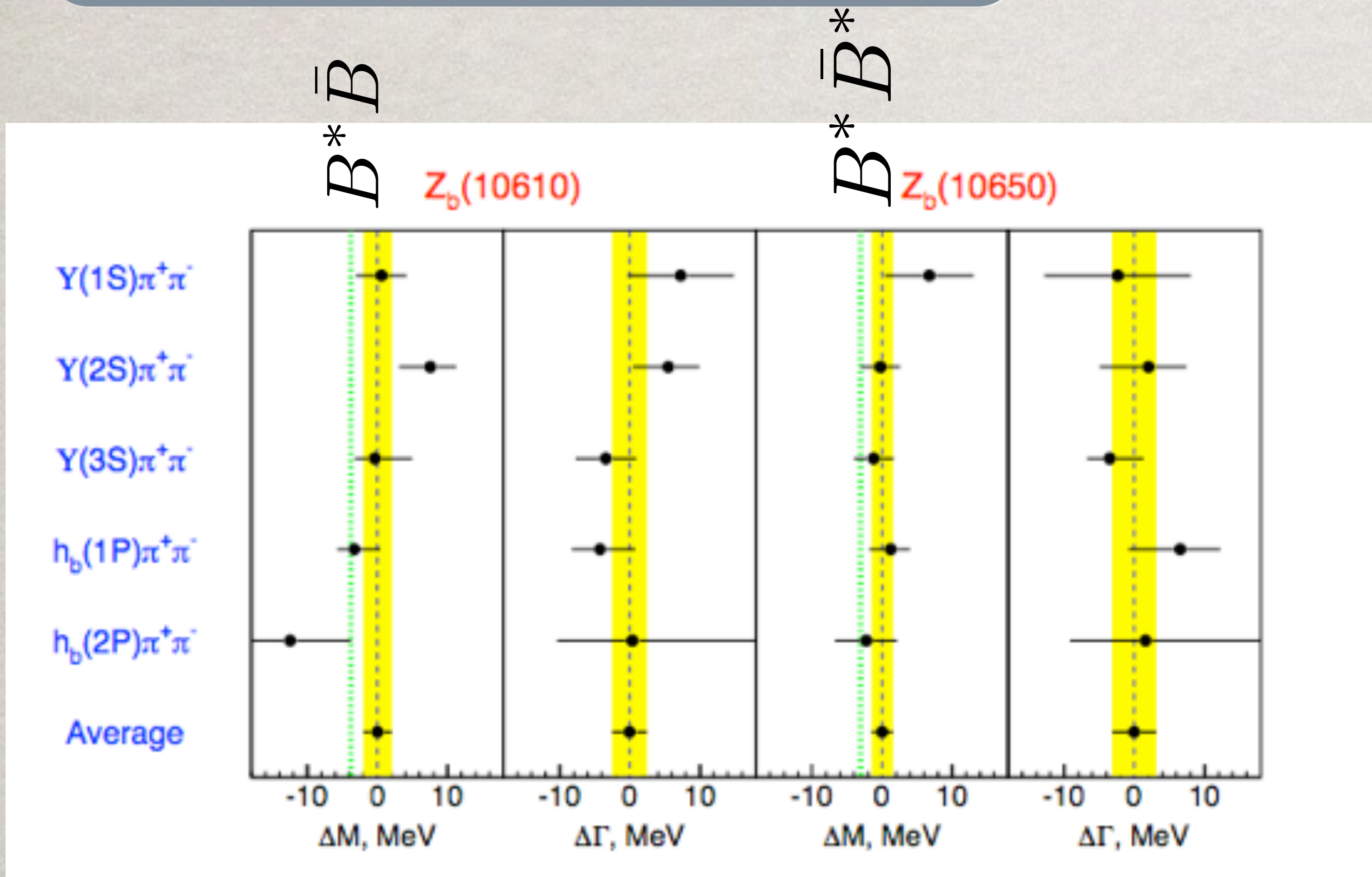
Cusp States

Bottom Zs

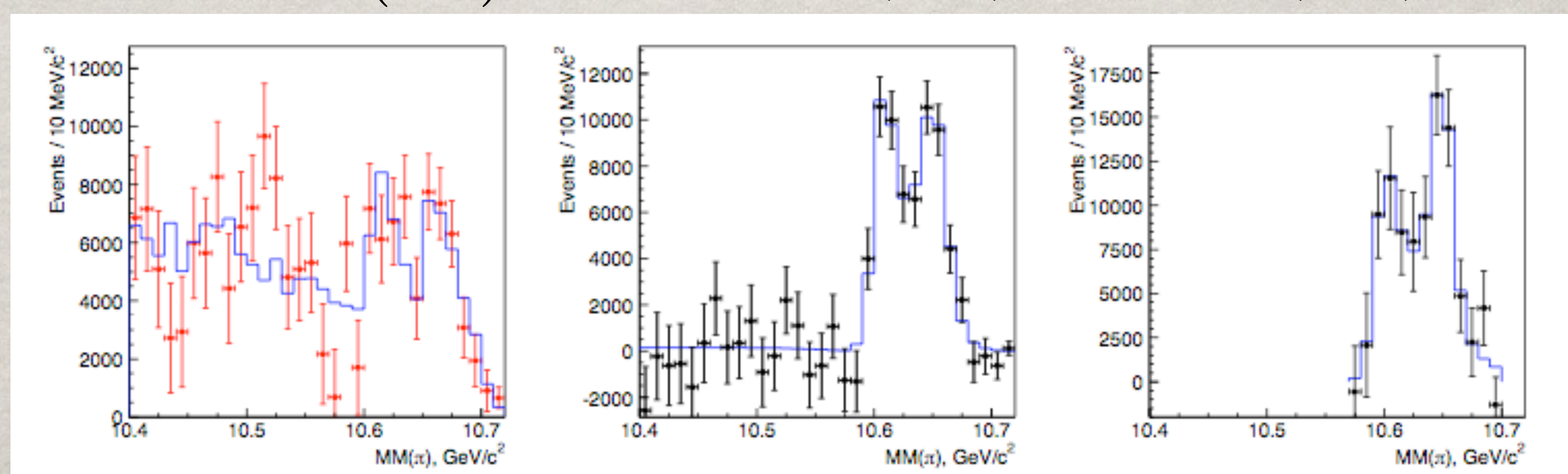
$Z_b^+(10610) \quad Z_b^+(10650)$

Adachi et al. [Belle] 1105.4583

$$I^G J^P = 1^+ 1^+$$



$\Upsilon(2S)$ $h_b(1P)$ $h_b(2P)$



Charm Zs

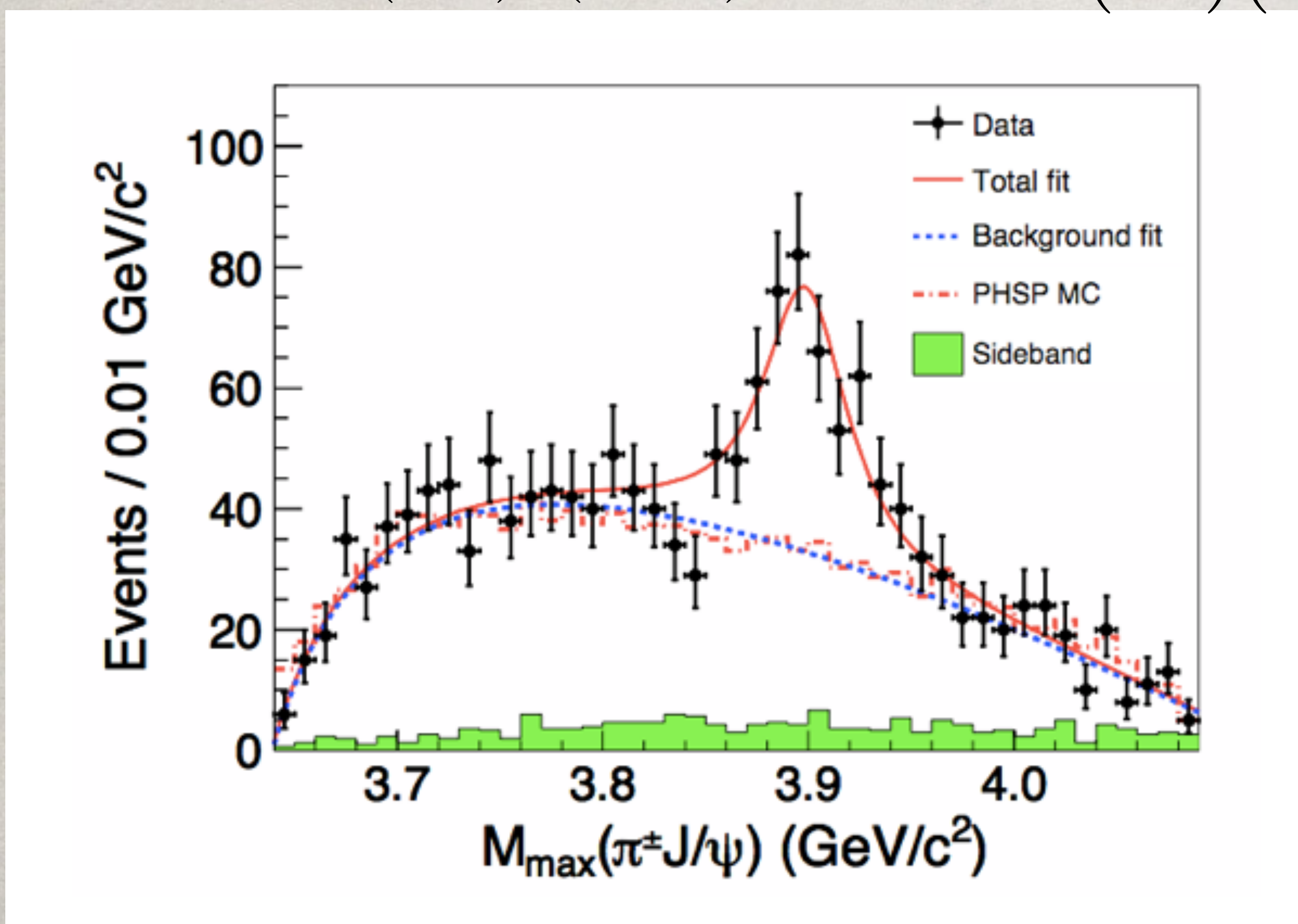
Zc(3900)

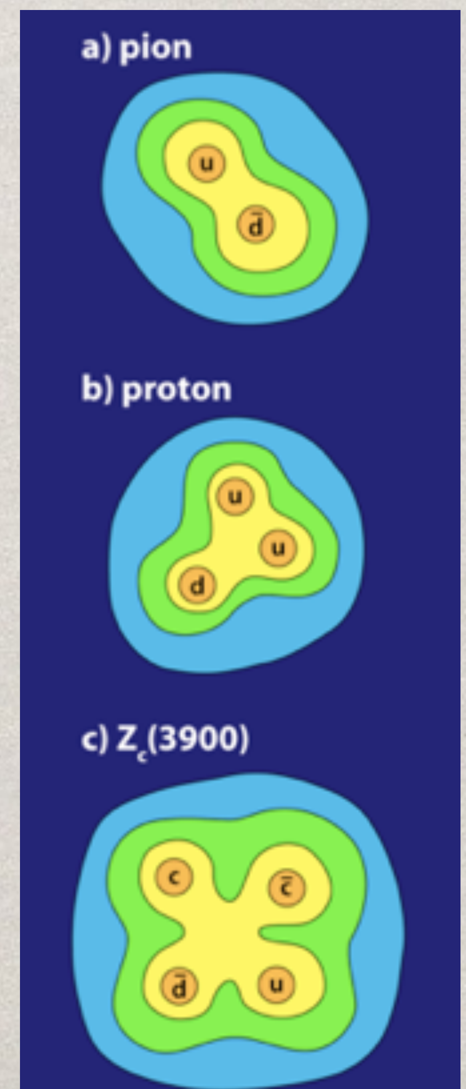
M. Ablikim et al. [BESIII], PRL (13)

A.Q. Lin et al. [Belle], PRL (13)

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

M = 3899 (3.6) (4.98) $\Gamma = 46(10)(20)$



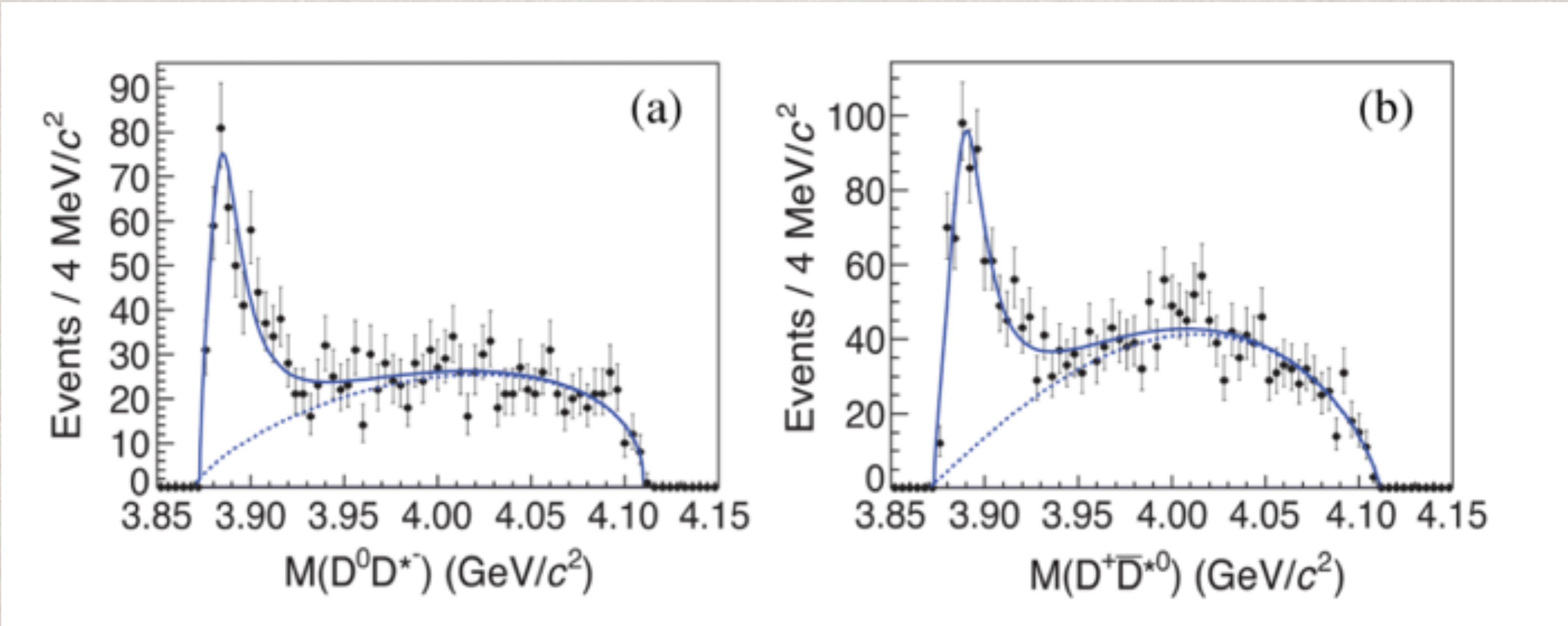


Zc(3900)

$$e^+e^- \to \pi D\bar{D}^* \qquad \sqrt{s} = 4.26$$

$$M = 3883.9 \pm 1.5 \pm 4.2$$

$$\Gamma = 24.8 \pm 3.3 \pm 11.0$$



BESIII PRL112 022001 (14)

$Z_c(4025)$

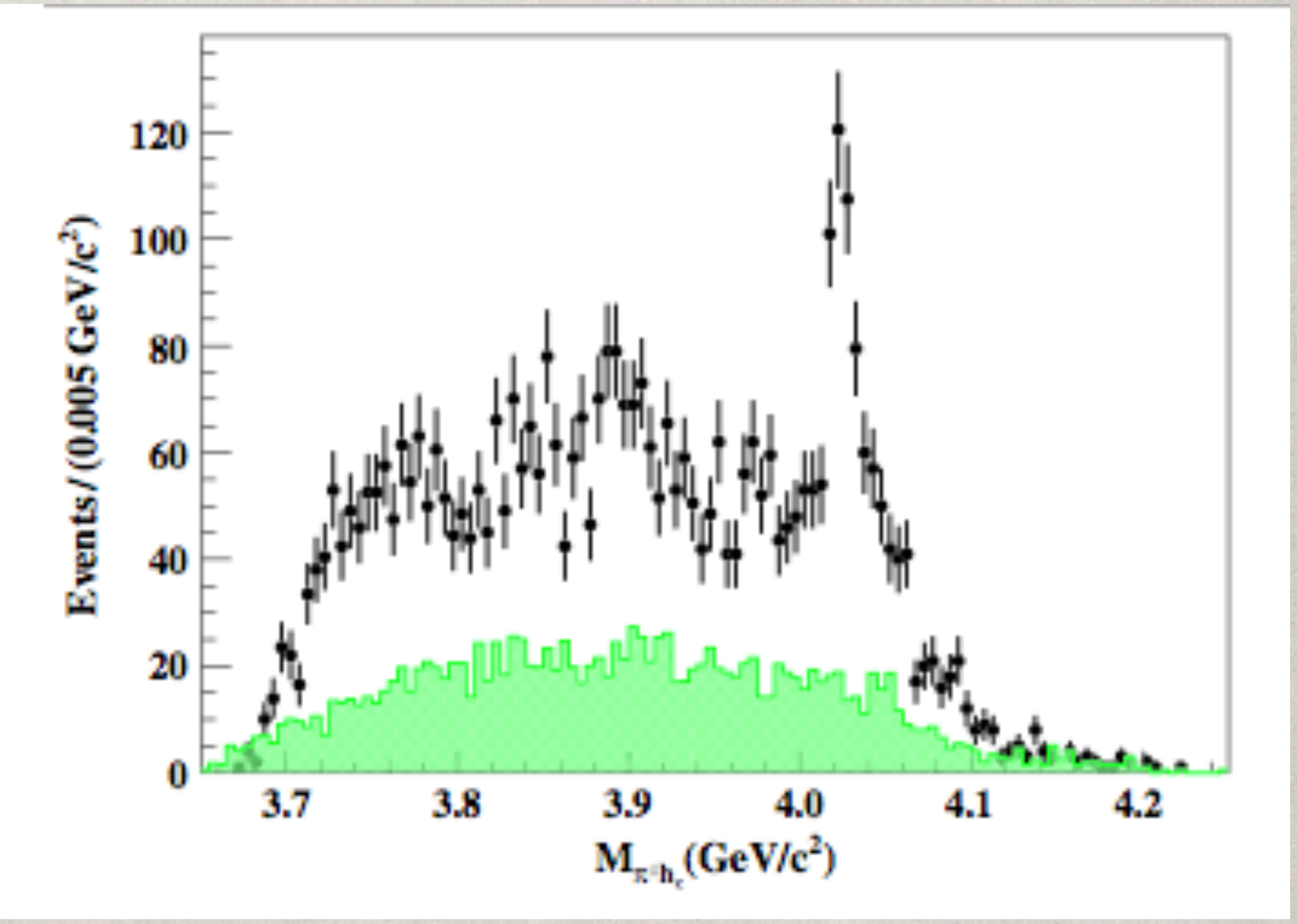
$$e^+e^- \to \pi^+\pi^- h_c$$

sums 13 different ee energy values

"no significant Zc(3900) observed"

$$M = 4022.9 \pm 0.8 \pm 2.7$$

$$\Gamma = 7.9 \pm 2.7 \pm 2.6$$



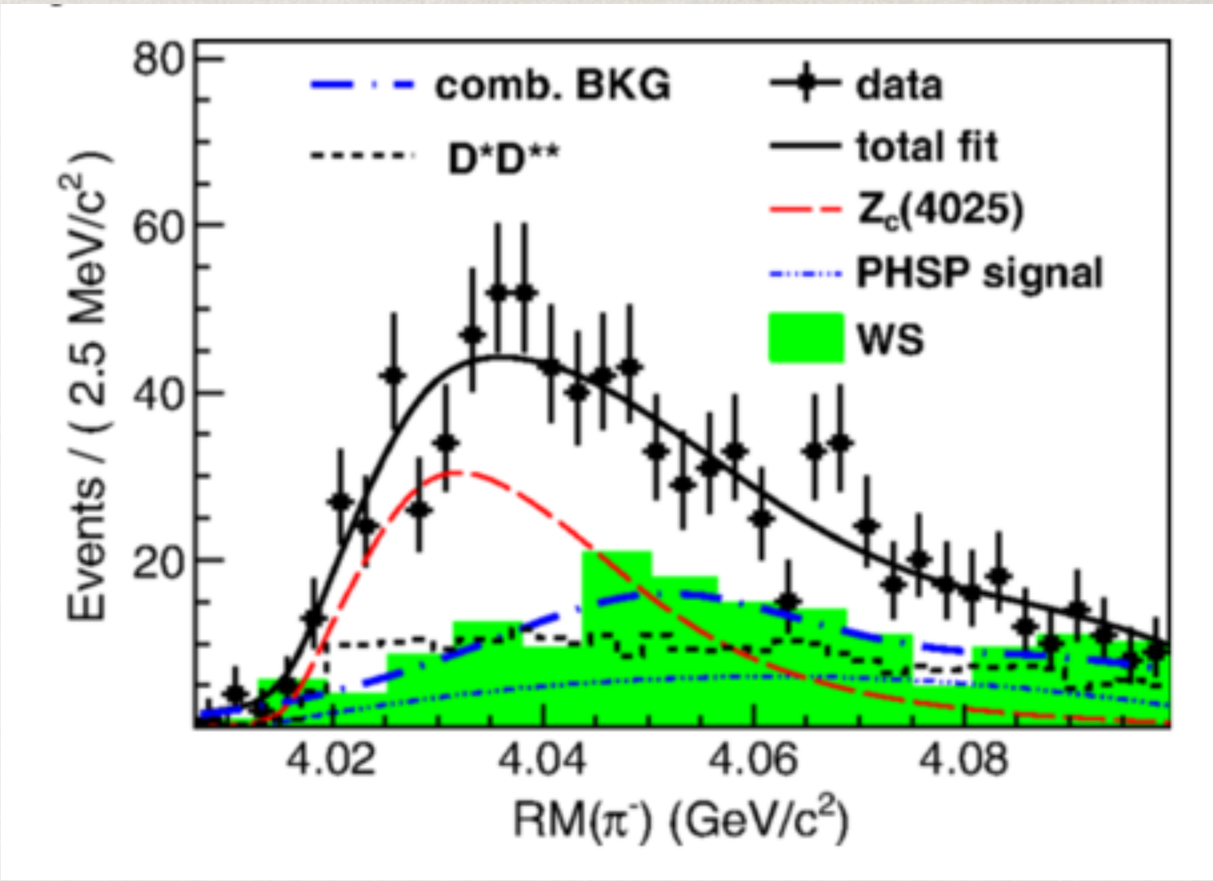
BESIII Phys. Rev. Lett. 111, 242001 (2013).

$Z_c(4025)$

$$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$$

$$M = 4026.3 \pm 2.6 \pm 3.7$$

$$\Gamma = 24.8 \pm 5.6 \pm 7.7$$



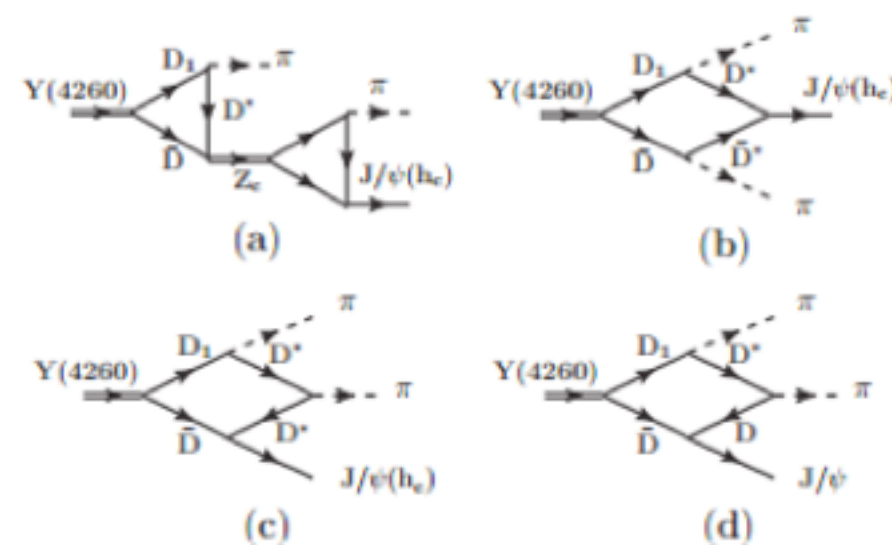
BESIII Phys. Rev. Lett. 112, 132001 (2014)

Zc(3900)
Zc(4025)

Theory

From SPIRE HEP Database (21st, Apr):

1. Tetraquarks
   - arXiv:1110.1333, 1303.6857
   - arXiv:1304.0345, 1304.1301
2. Hadronic molecules
   - arXiv:1303.6608, 1304.2882, 1304.1850
3. Four quark state (1 or 2)
   - arXiv:1304.0380
4. Meson loop
   - arXiv:1303.6355
   - arXiv:1304.4458
5. ISPE model
   - arXiv:1303.6842
6. ...



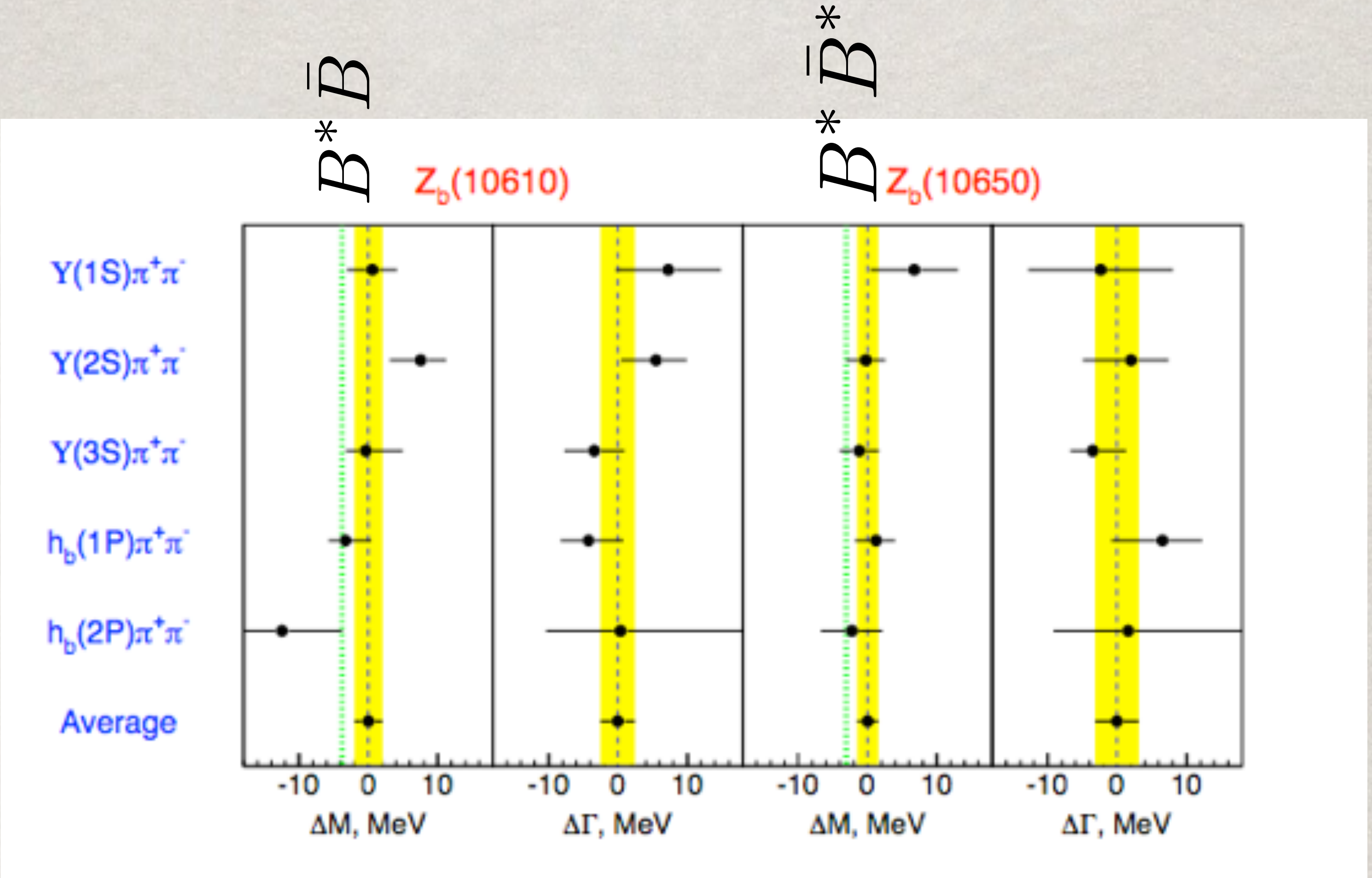
Meson loop

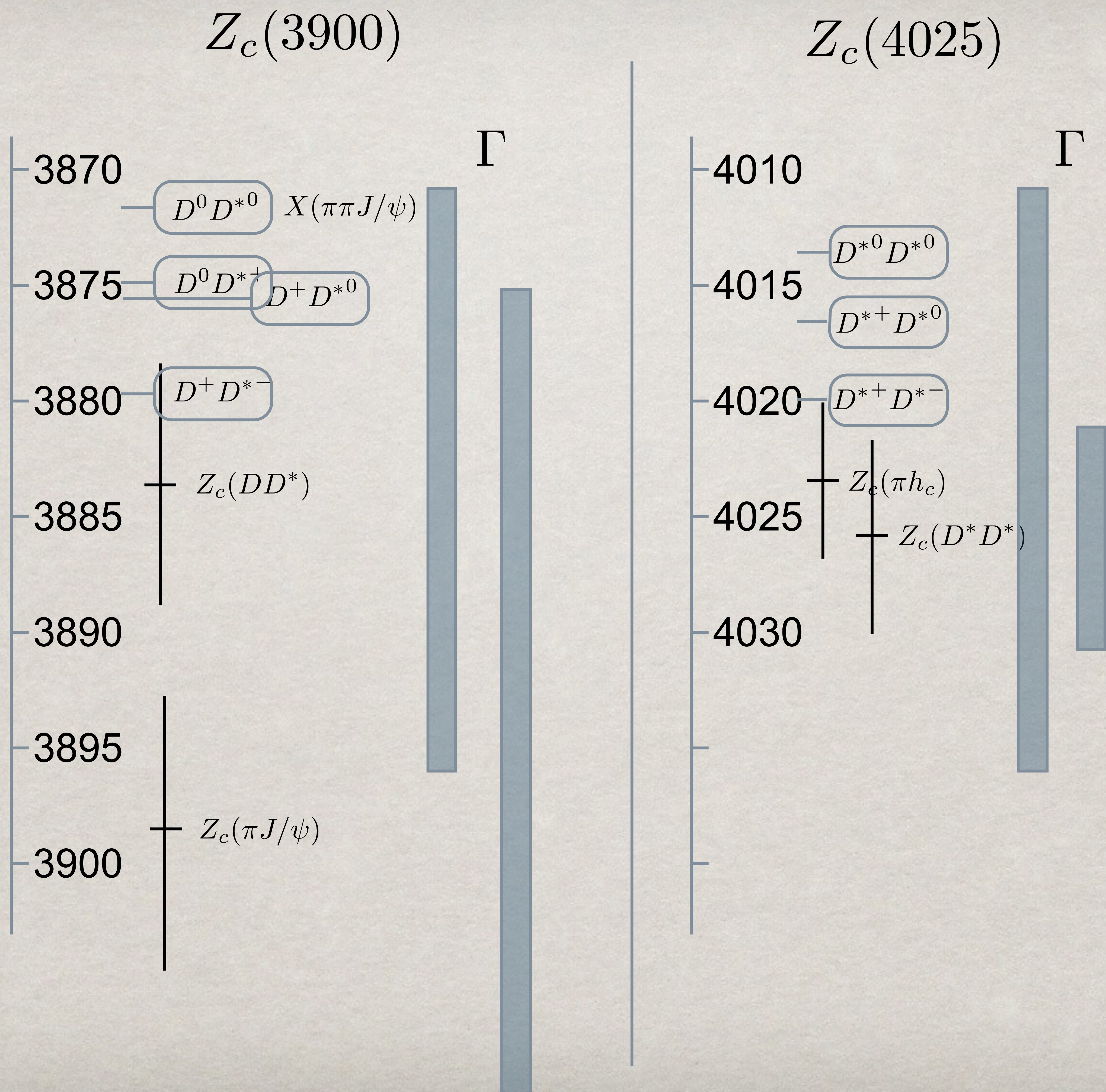
A Cusp Model

E.S. Swanson, arXiv:1409.3291; v2 to appear

Charged Exotics as Threshold Cusps

It seems foolish to ignore that many of these states are just above open charm/bottom thresholds.

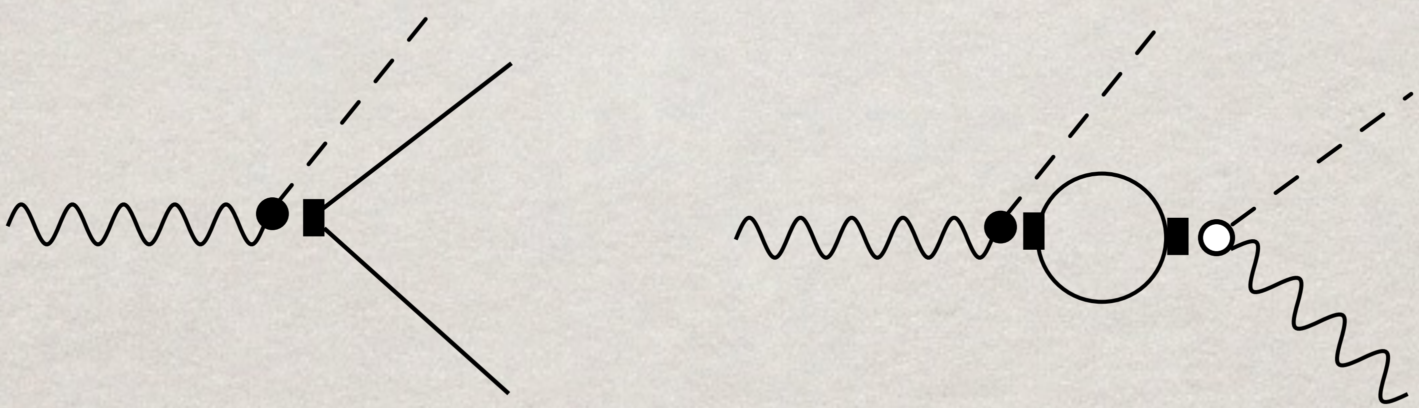




$Z_c(3900)$
$Z_c(4025)$
Γ
Γ
3870
3875
3880
3885
3890
3895
3900
$D^0 D^{*0}$
$X(\pi\pi J/\psi)$
$D^0 D^{*+}$
$D^+ D^{*0}$
$D^+ D^{*-}$
$Z_c(DD^*)$
$Z_c(\pi J/\psi)$
4010
4015
4020
4025
4030
$D^{*0} D^{*0}$
$D^{*+} D^{*0}$
$D^{*+} D^{*-}$
$Z_c(\pi h_c)$
$Z_c(D^* D^*)$

Cusp Model

Attempt a "microscopic" cusp model.
[separable nonrelativistic model; solve exactly]

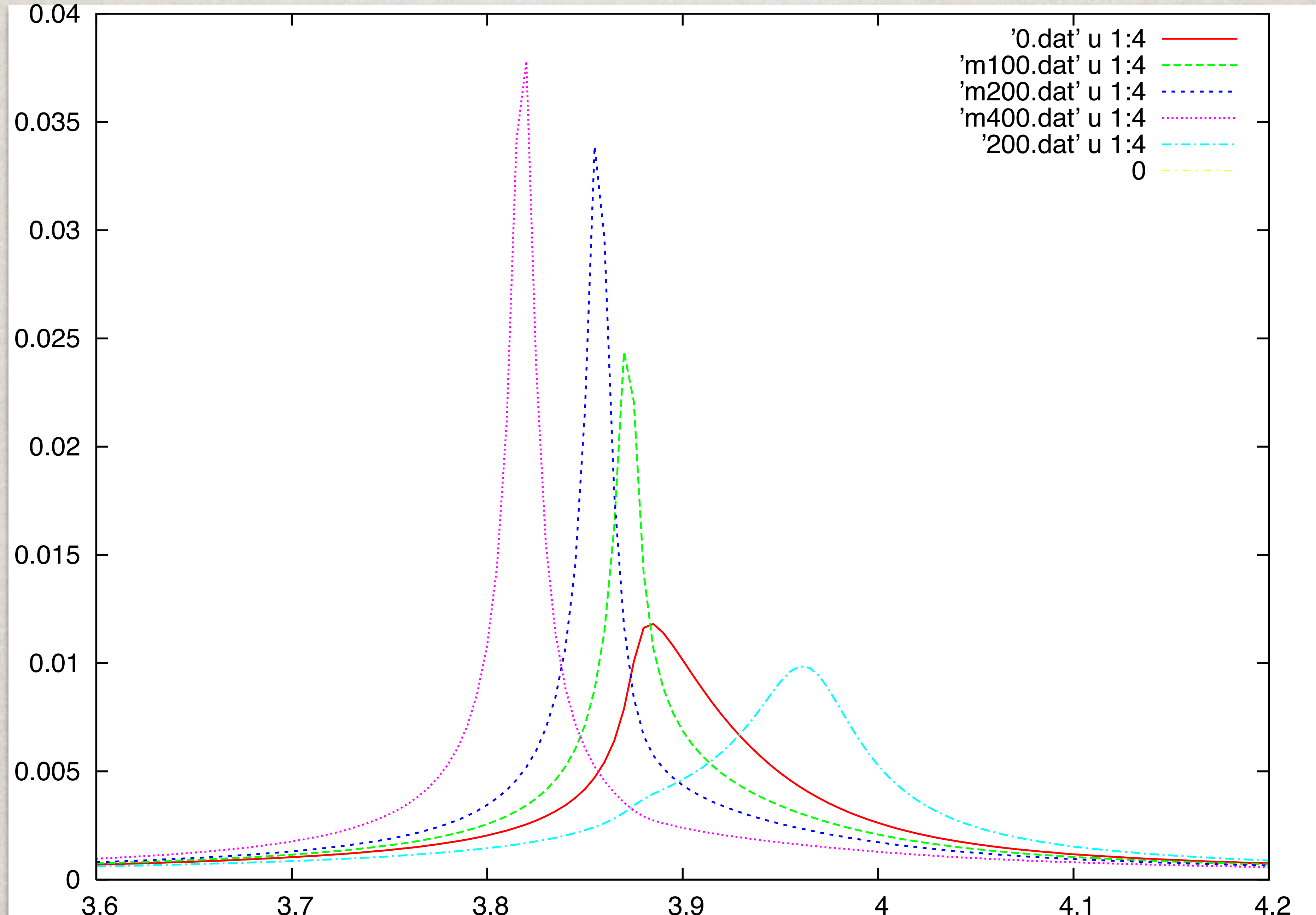


$Y(4260) \to \pi D\bar{D}^*$ $\qquad$ $Y(4260) \to \pi\pi J/\psi$

$$g_{DD^*} \cdot \exp(-\lambda(s_{\pi Y})/\beta^2_{\pi Y}) \exp(-\lambda(s_{DD^*})/\beta^2_{DD^*})$$

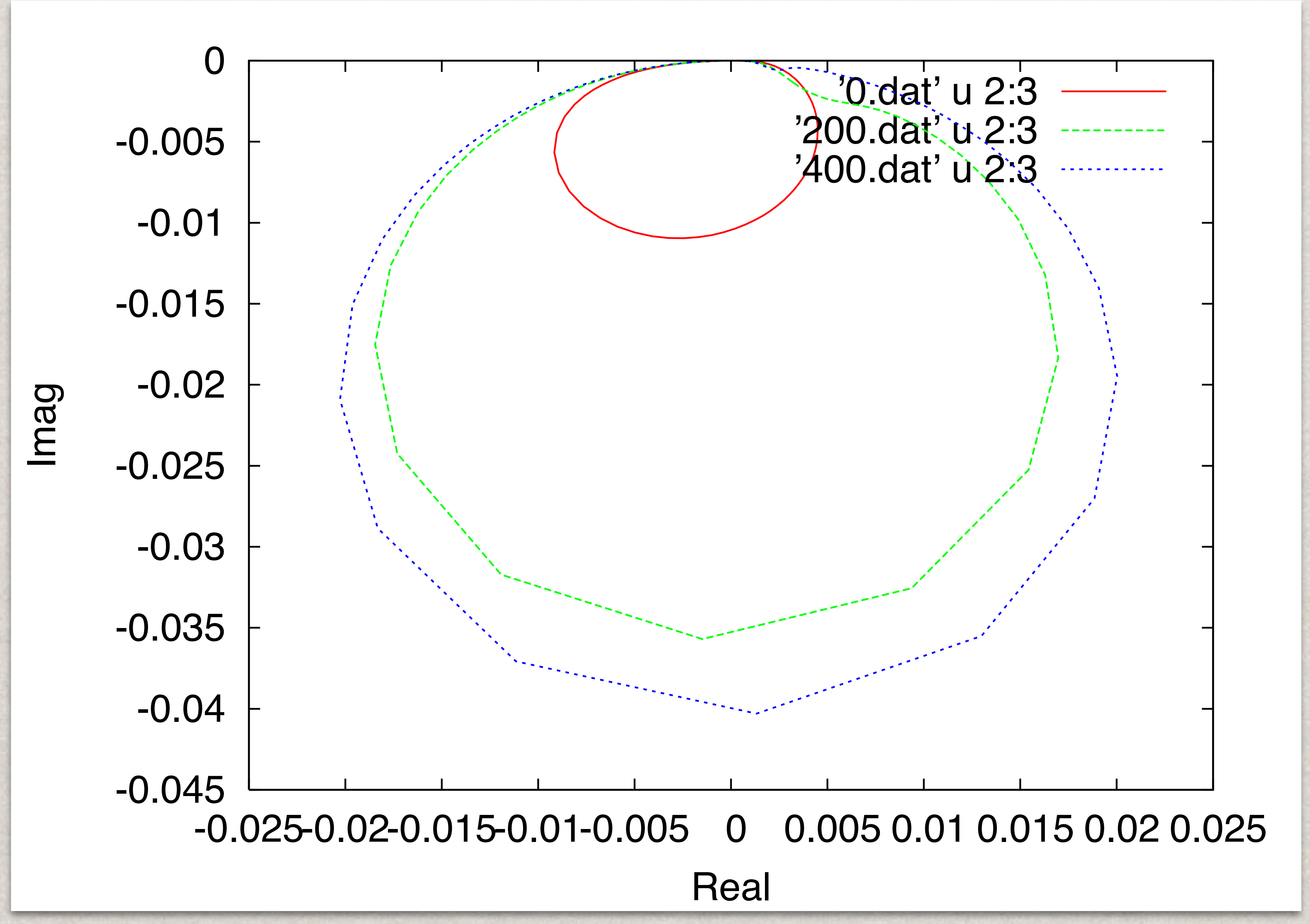
Cusp Model

effect of the bubble sum



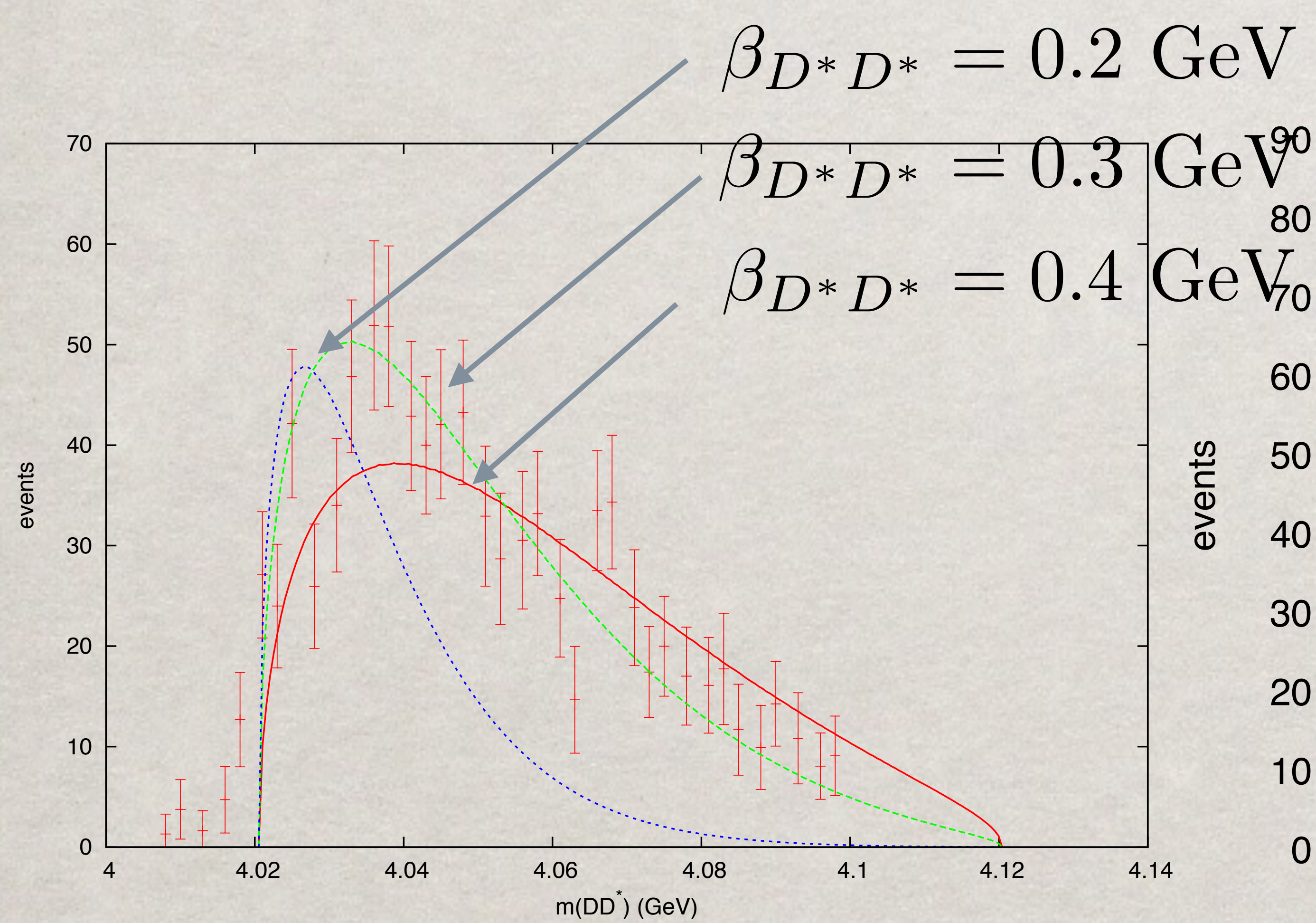
Cusp Model

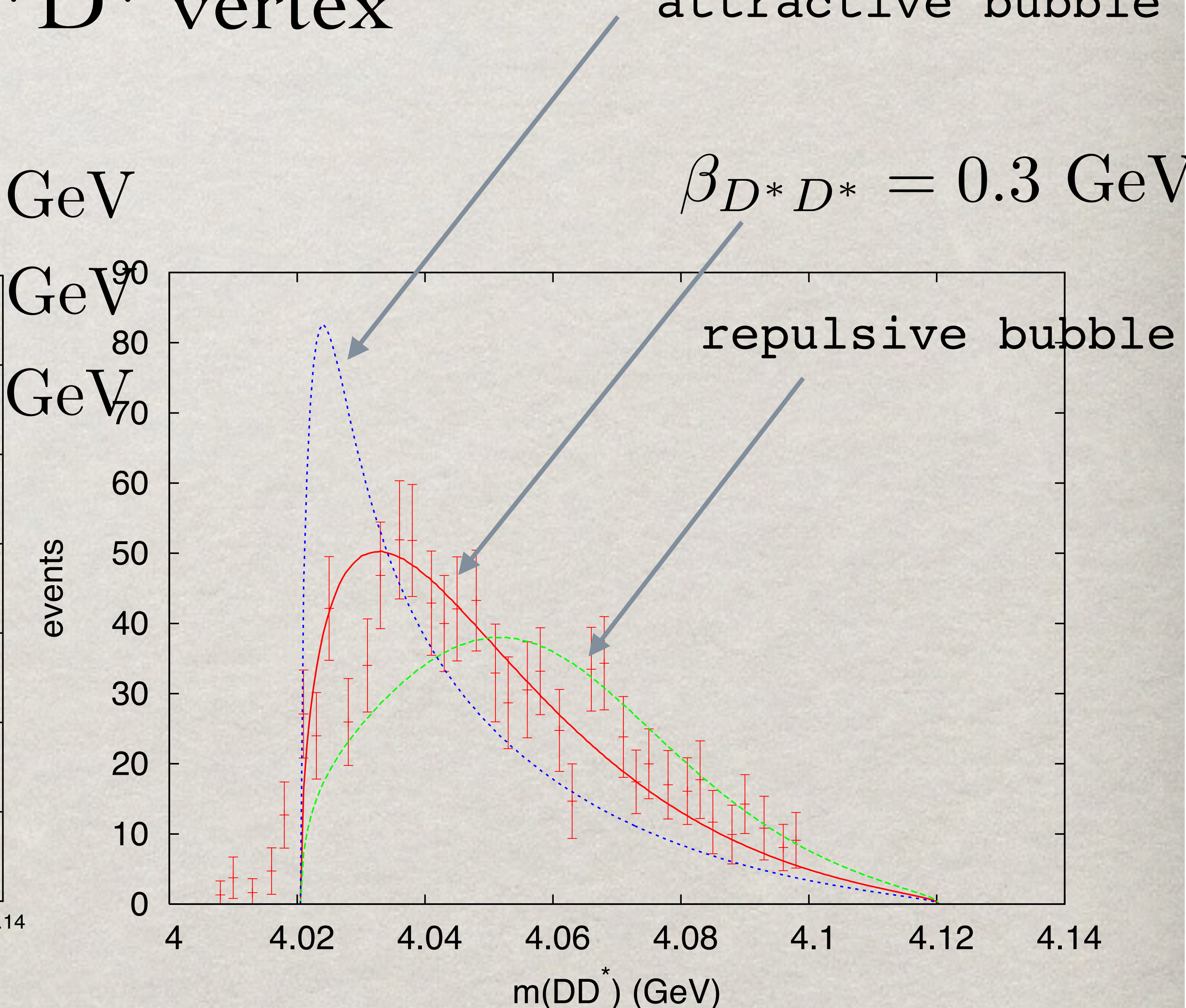
effect of the bubble sum



Fit D*D* Vertex

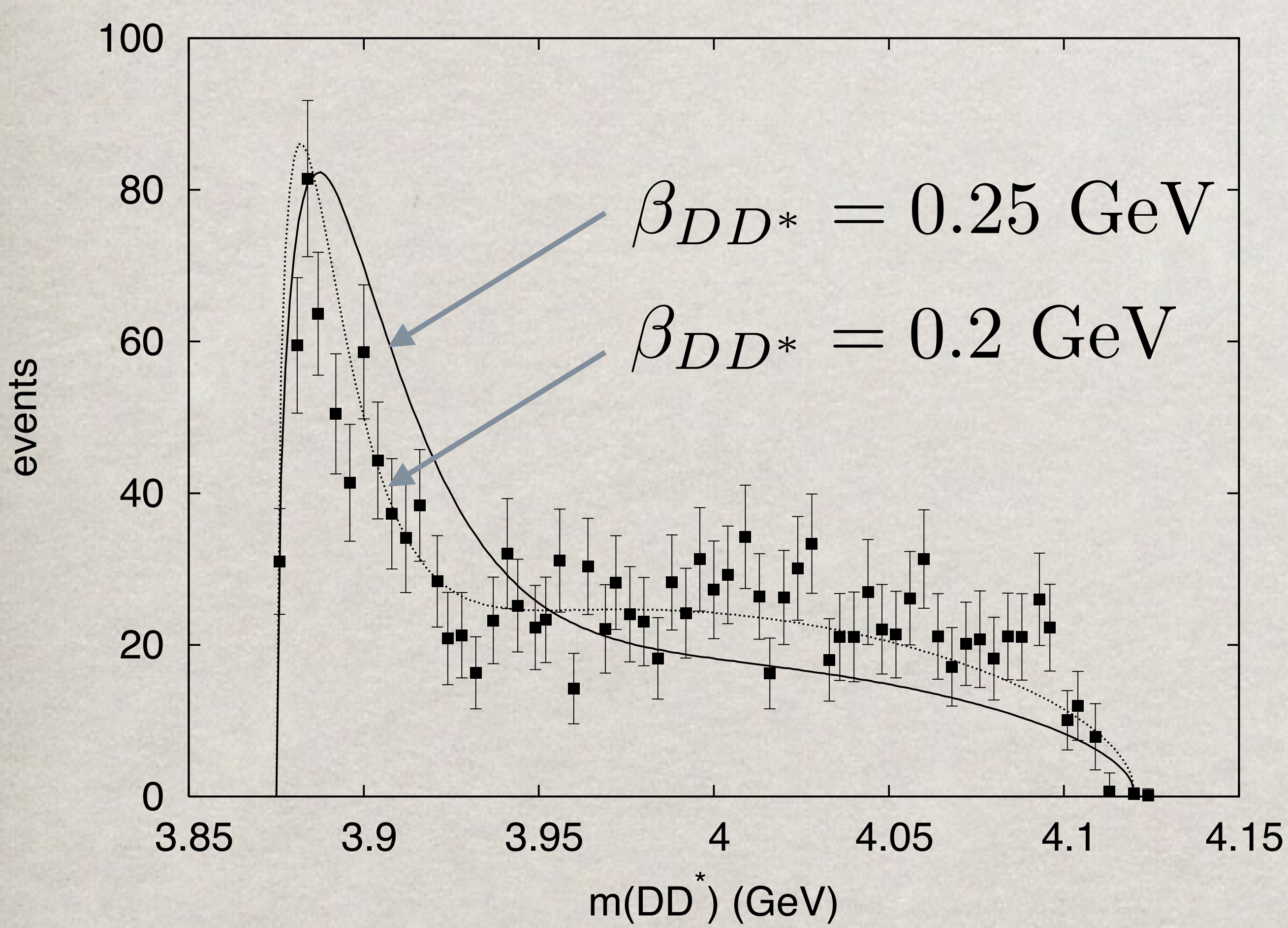
fit the pi Y: D*D* vertex

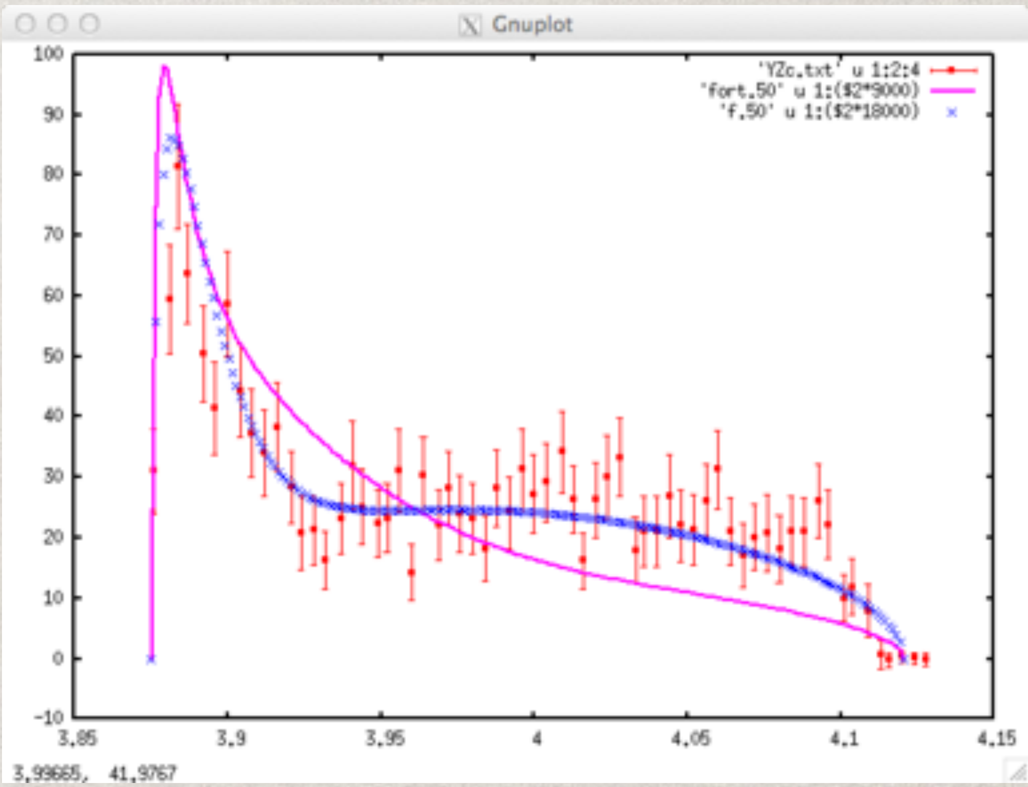




no evidence for π D* dynamics, background, or bubble

Fit DD* Vertex

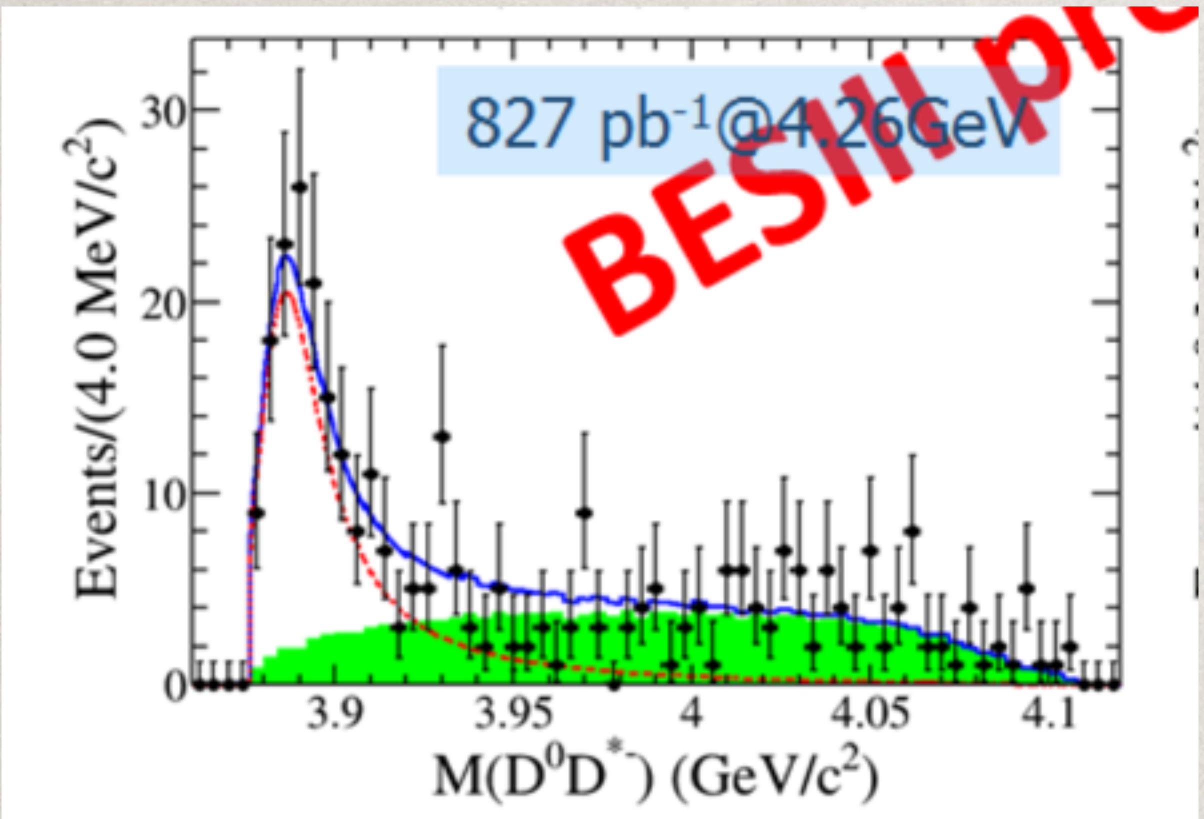


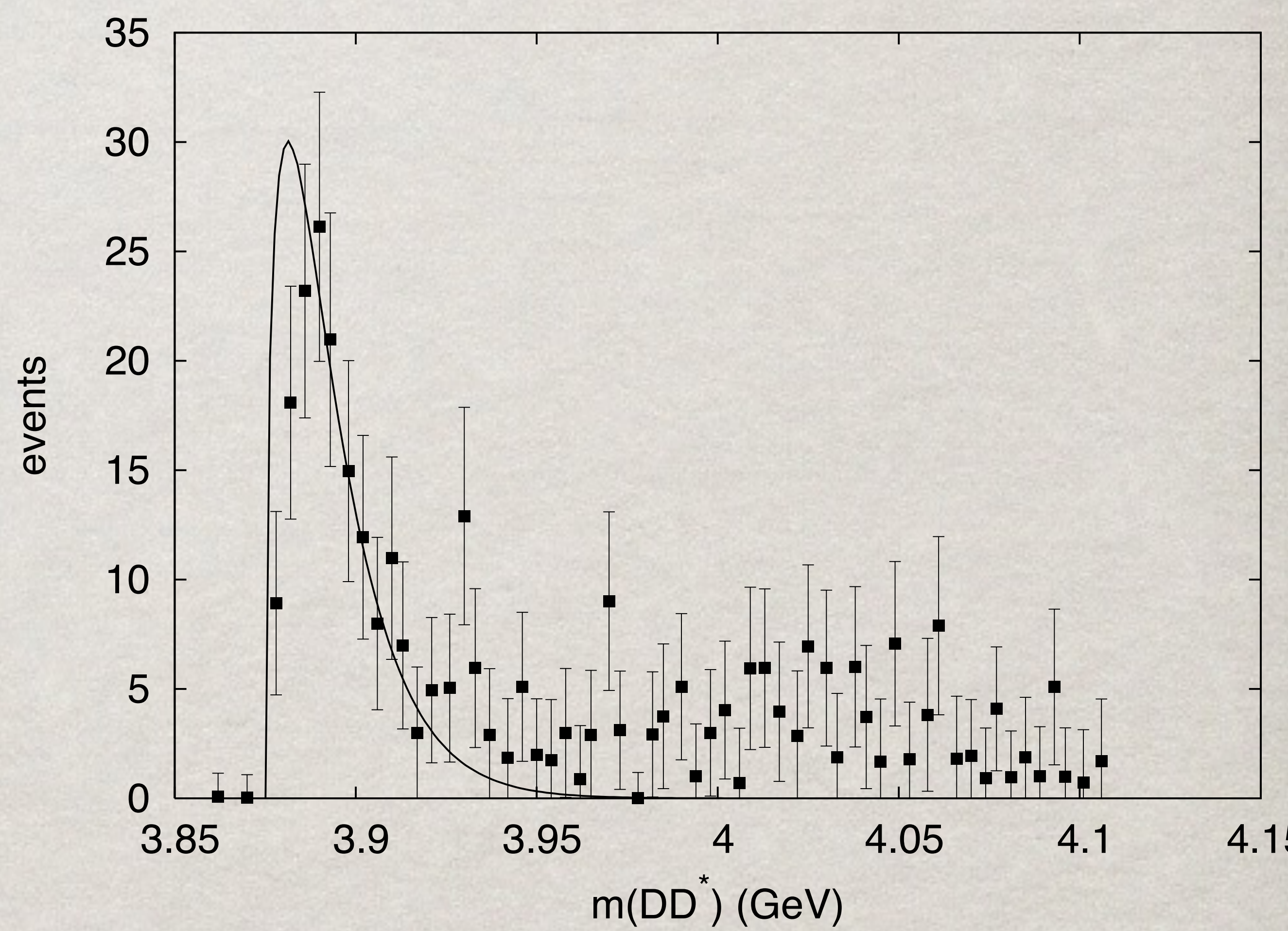


no evidence for bubble

evidence for incoherent background

Fit DD* Vertex



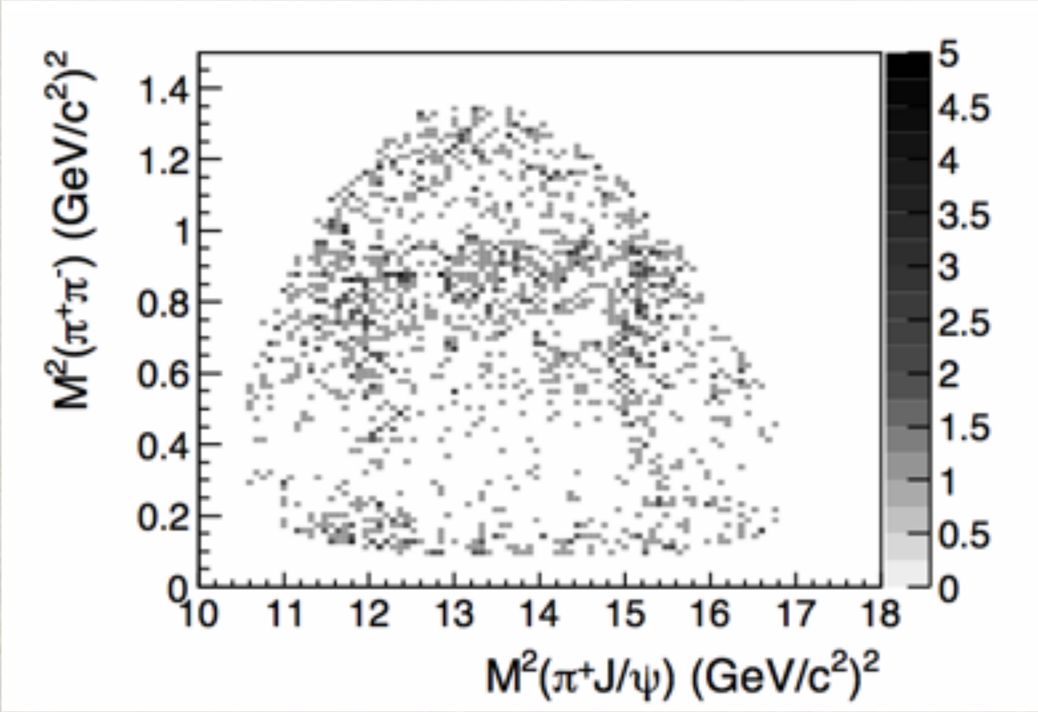


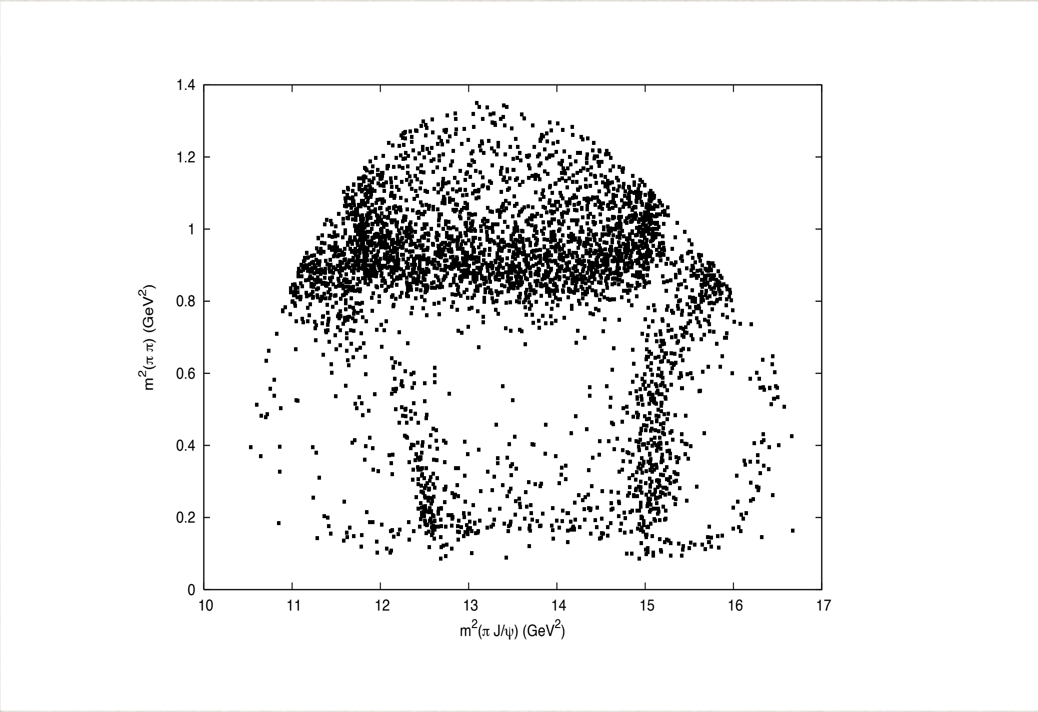
Wolfgang Gradl, "Bound States in QCD", St Goar, Mar 24-27, 2015

New BESIII result with all three particles identified.
As hoped, background is diminished.

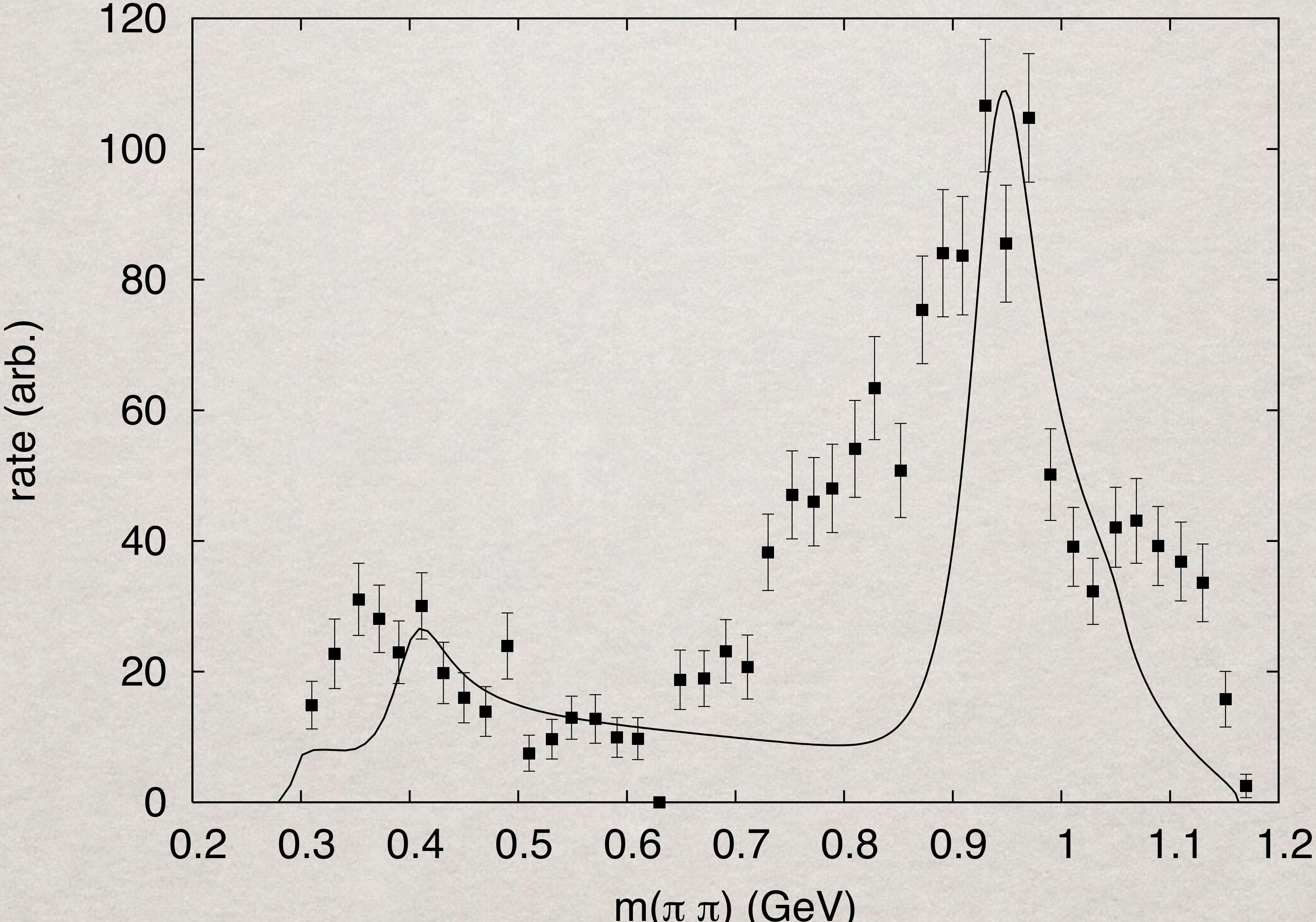
Obtain pi pi J/psi

Now pi pi dynamics is important





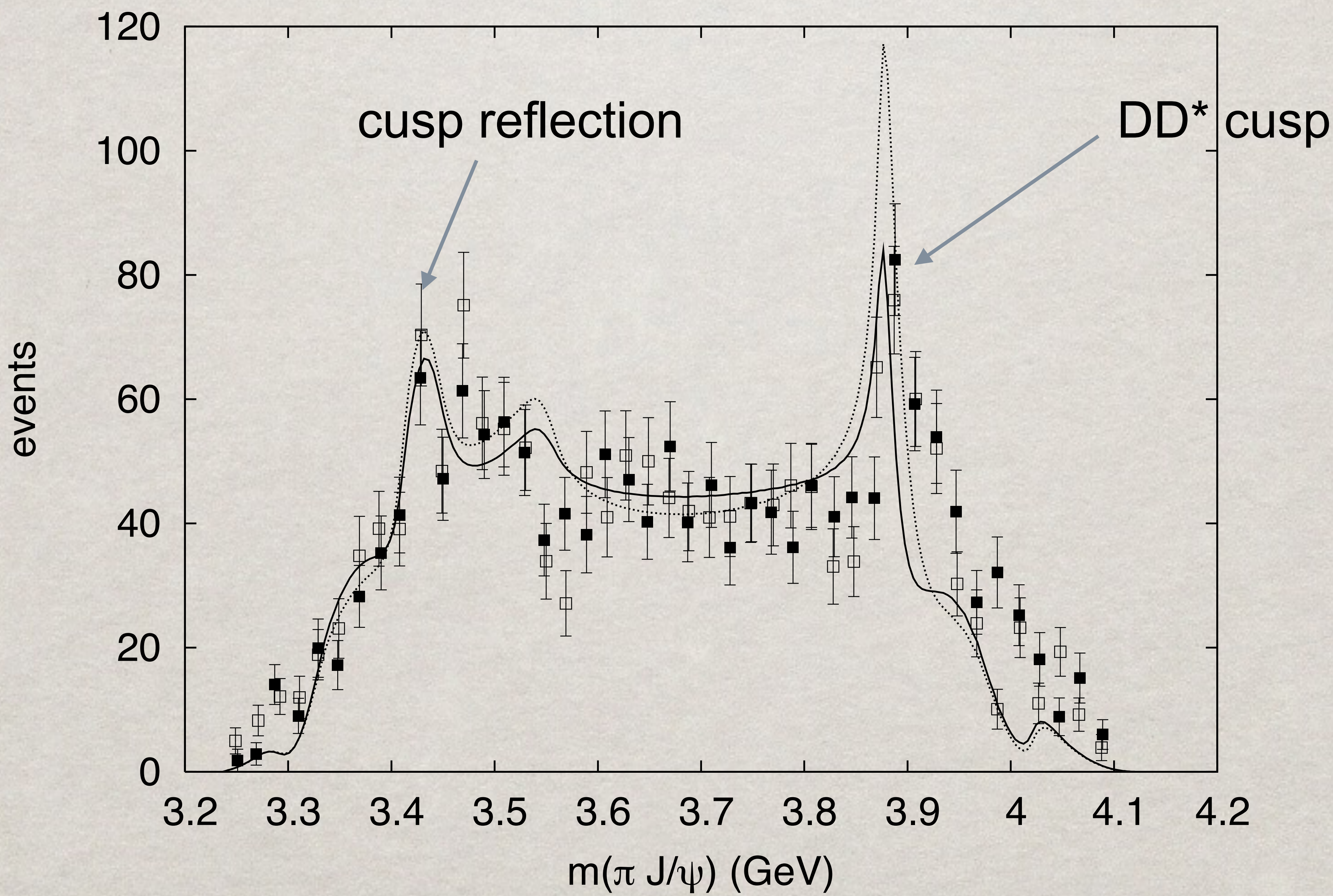
Obtain pi pi J/psi



BESIII

BW(0.4,60) + BW(0.94,80), betas=0.3, gamma=0

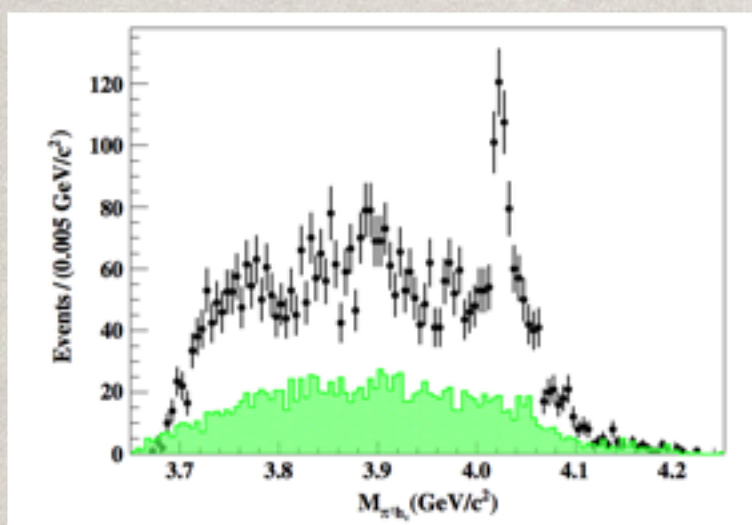
Obtain pi pi J/psi

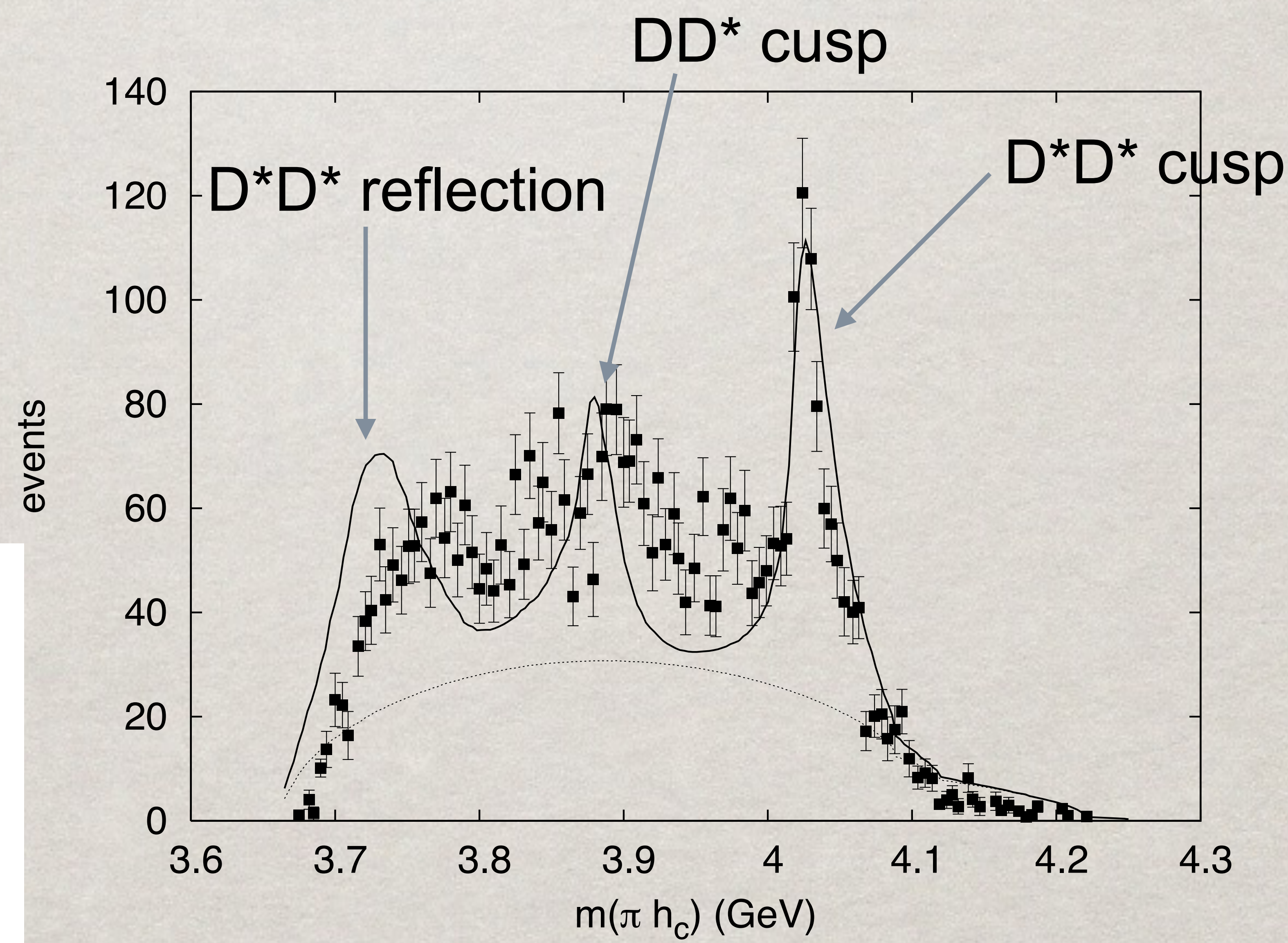


BESIII

Obtain pi pi h_c

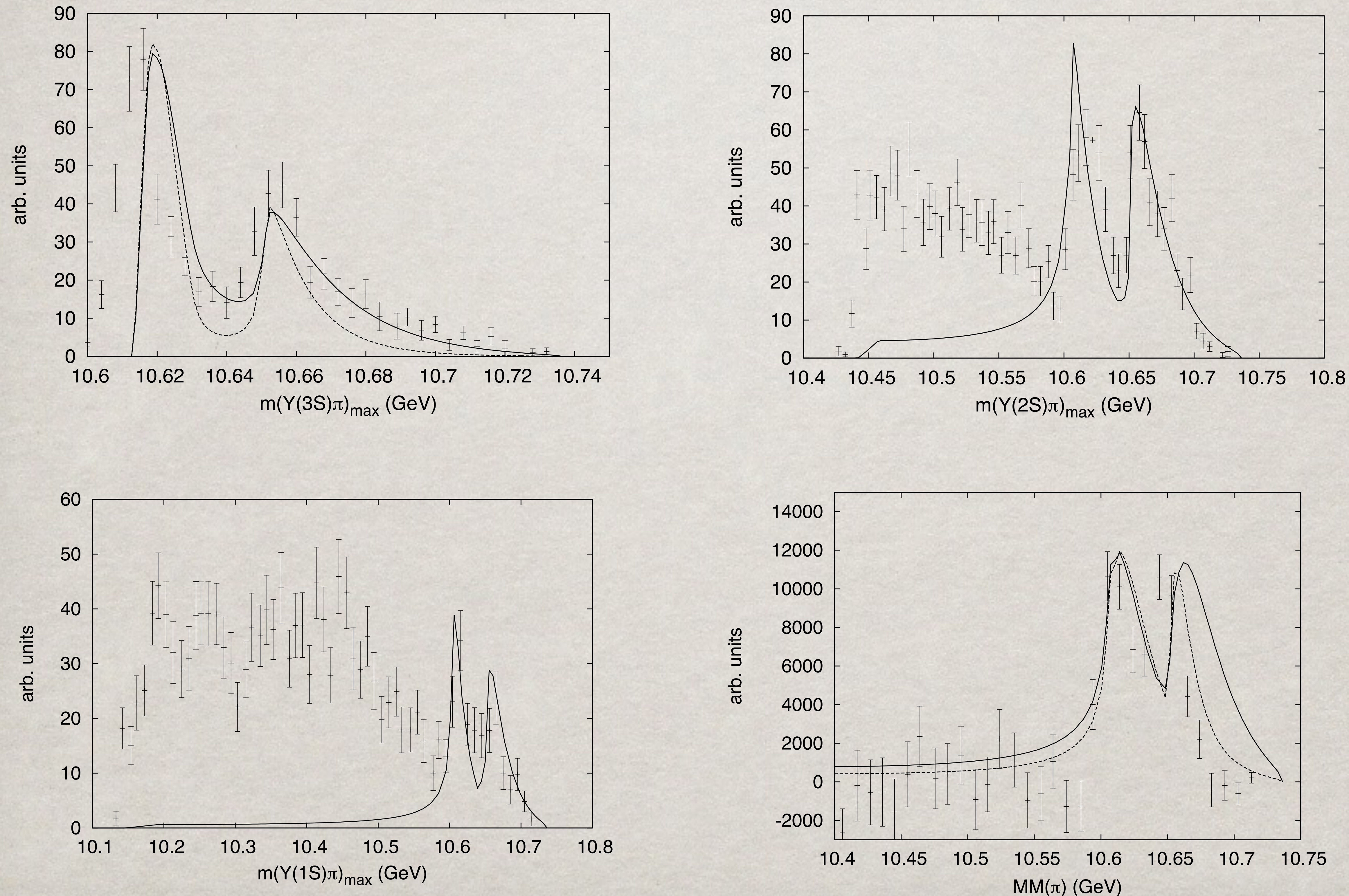
[incoherent background only]





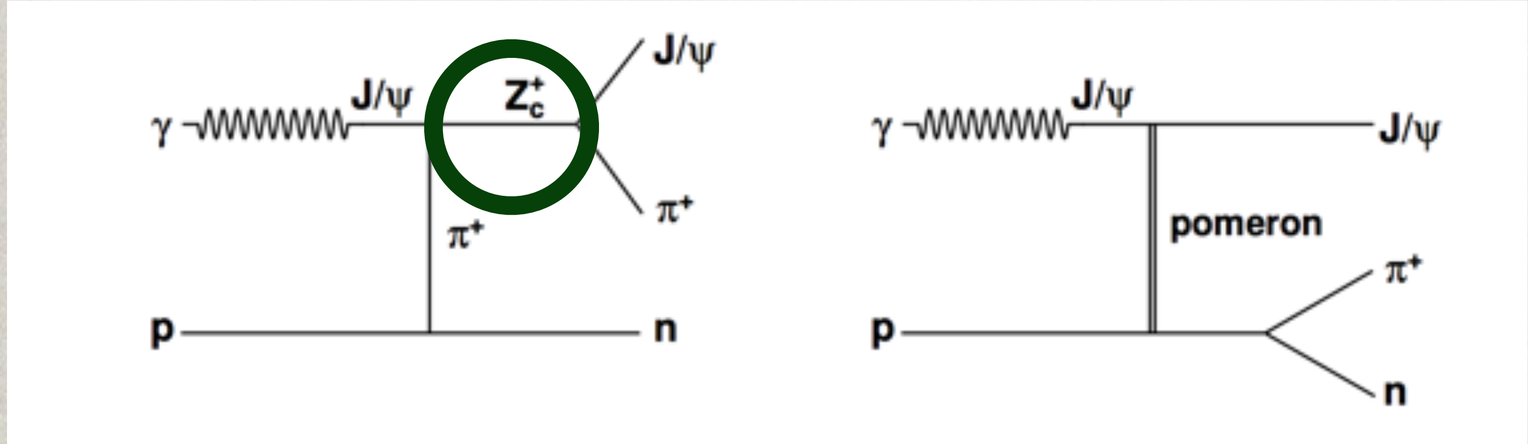
M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 111, 242001 (2013).

$$\Upsilon(5S) \to \Upsilon(nS)\pi\pi$$



Missing Exotics

COMPASS

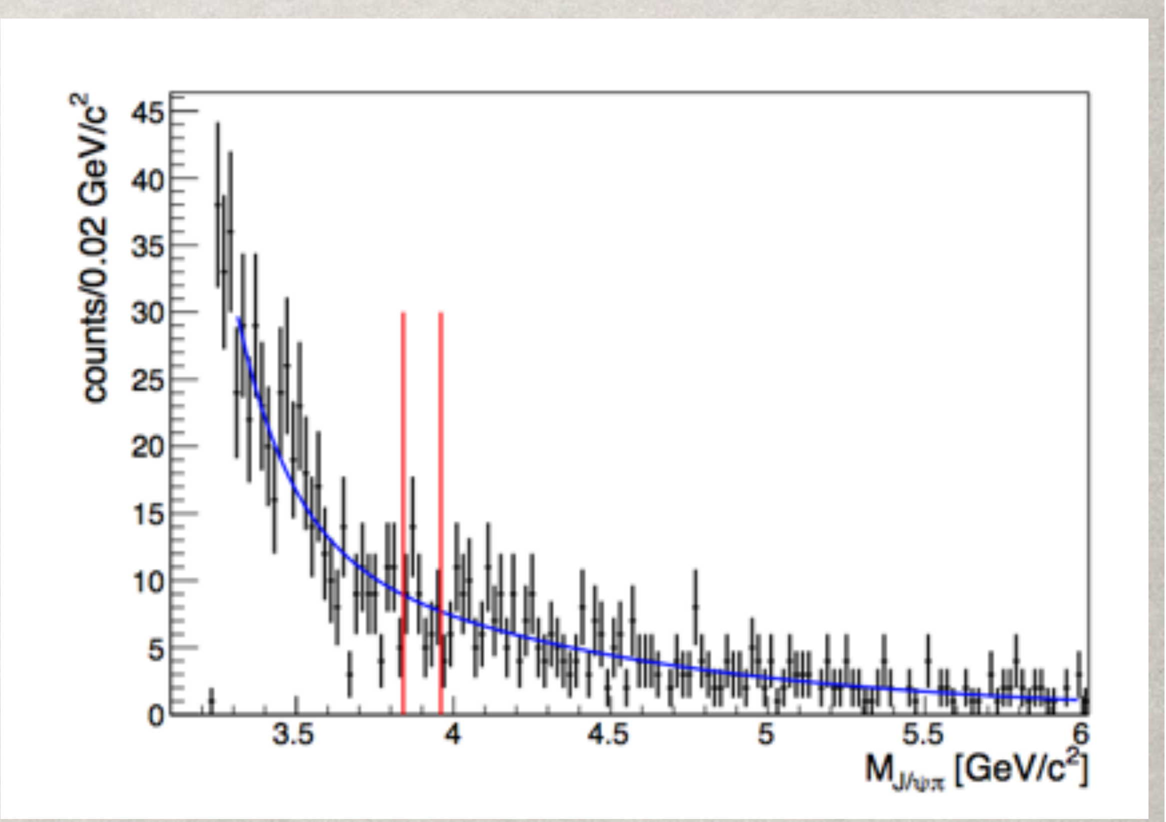


$$\sqrt{s_{\gamma N}} = 7 \text{ GeV}$$

$$\exp(-\lambda(s_{\gamma N}, m_\psi^2, m_\pi^2)/(4 s_{\gamma N}\beta^2) \approx$$

$$\exp(-(s_{\gamma N} - m_\psi^2)^2/(4 s_{\gamma N}\beta^2) \quad \approx$$

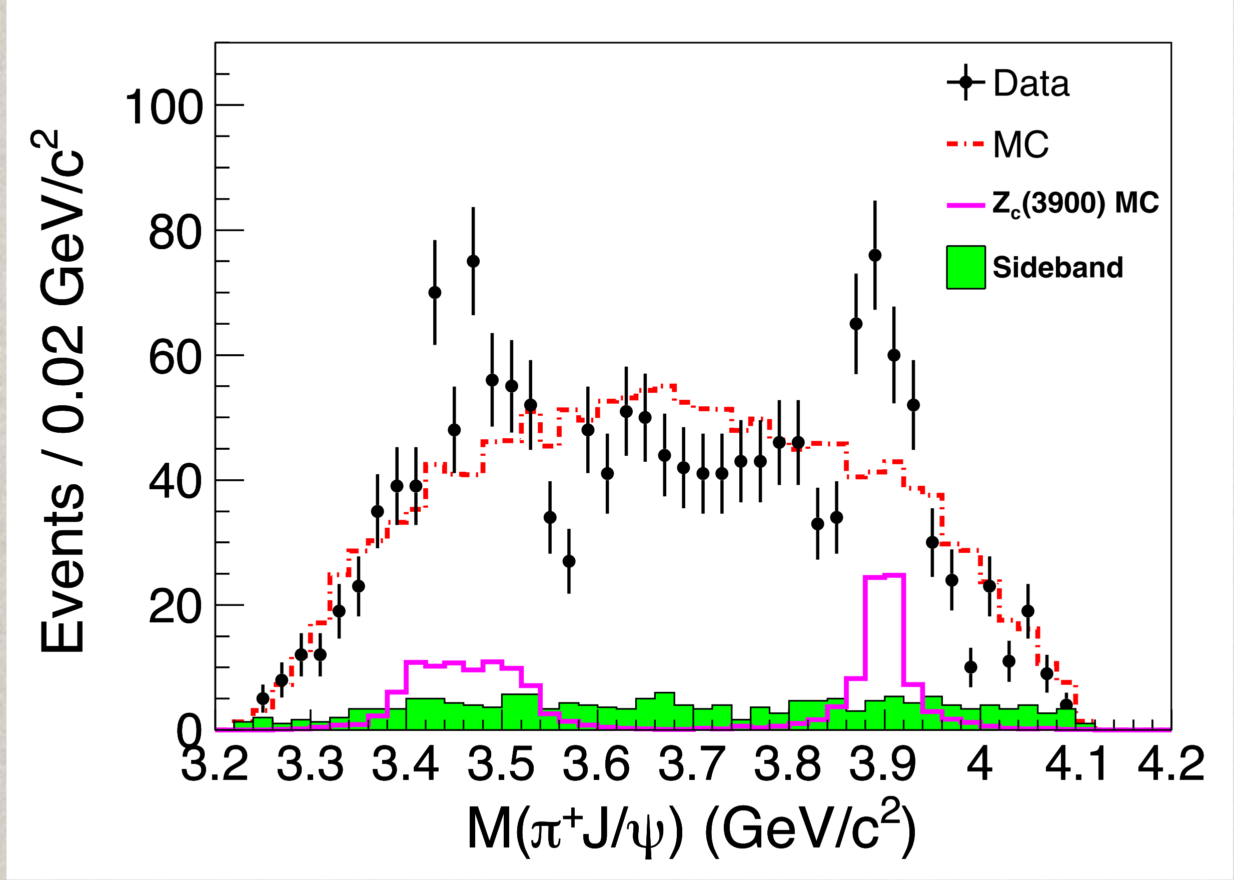
$$\exp(-88)$$



C. Adolph et al. [COMPASS] arXiv:1407.6186v1

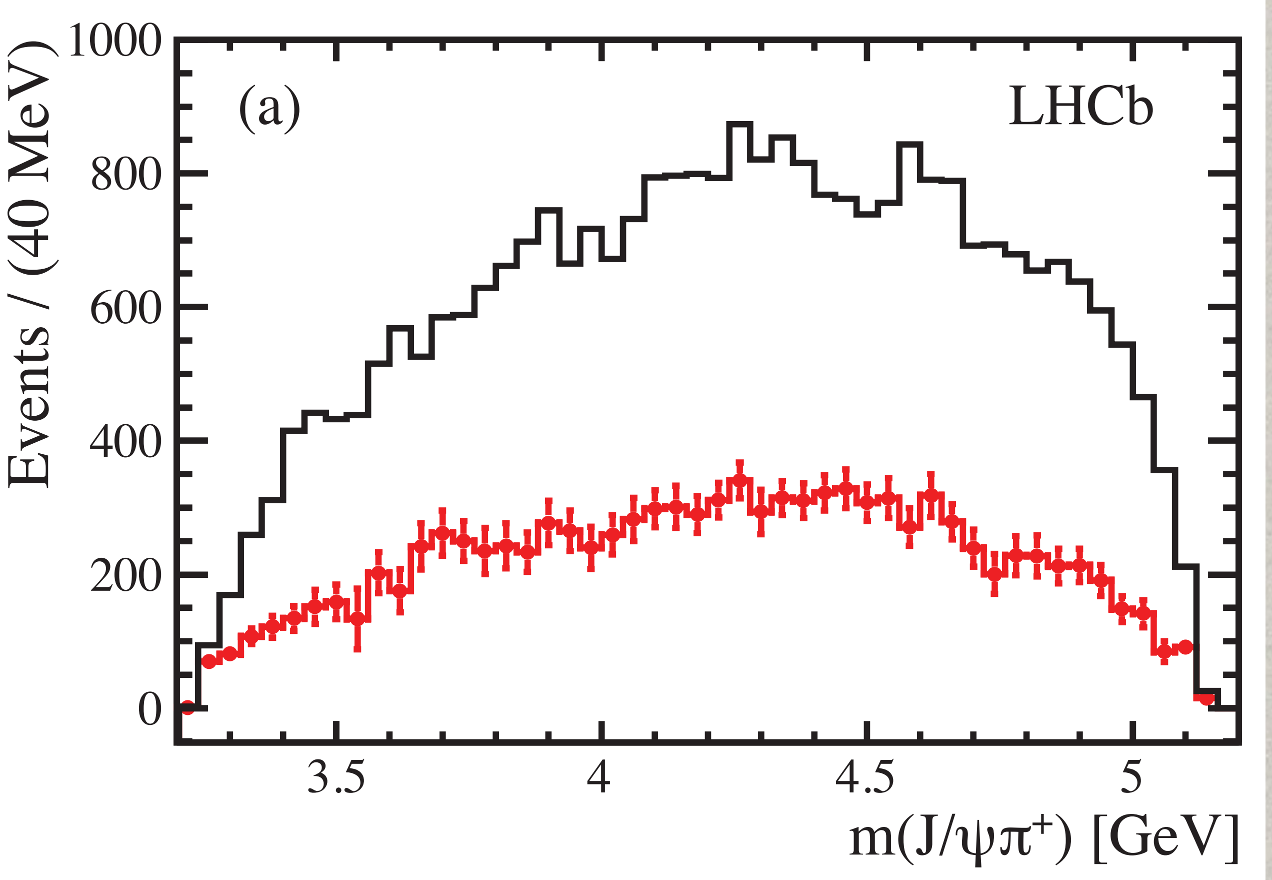
Missing Exotics

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



BESIII

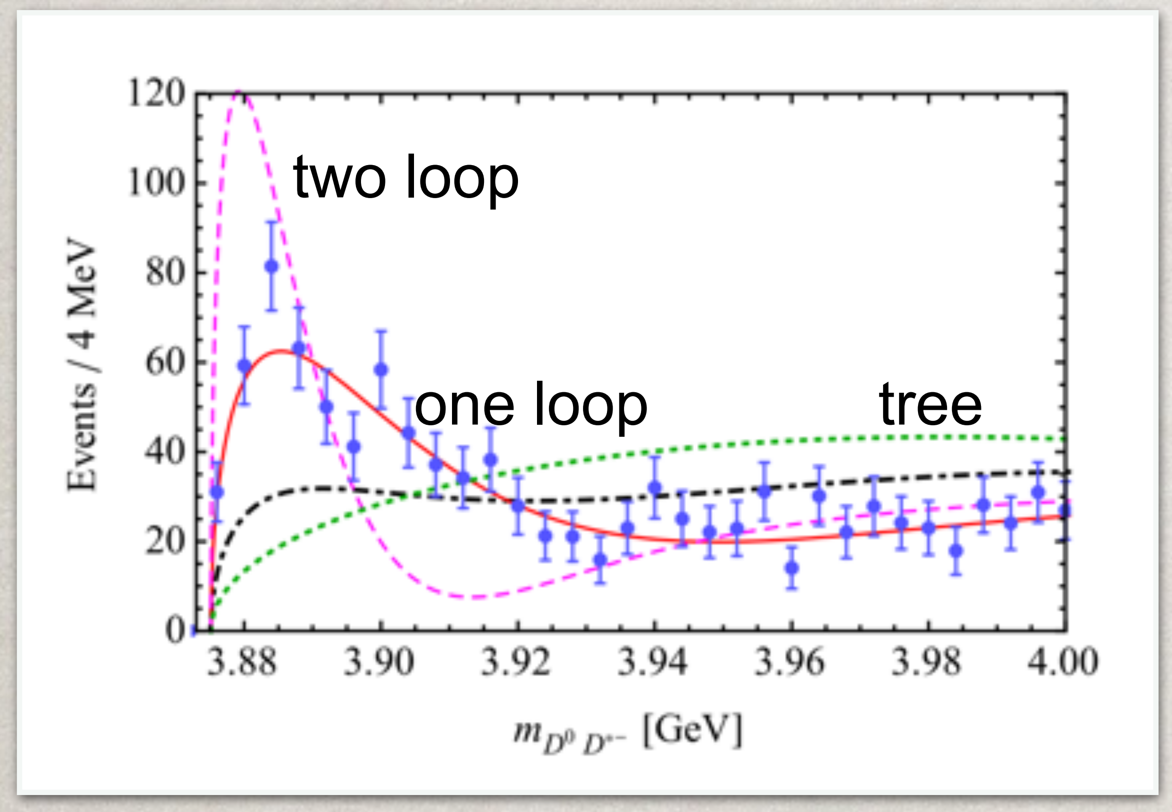
$B_0 \to \pi^+\pi^- J/\psi$

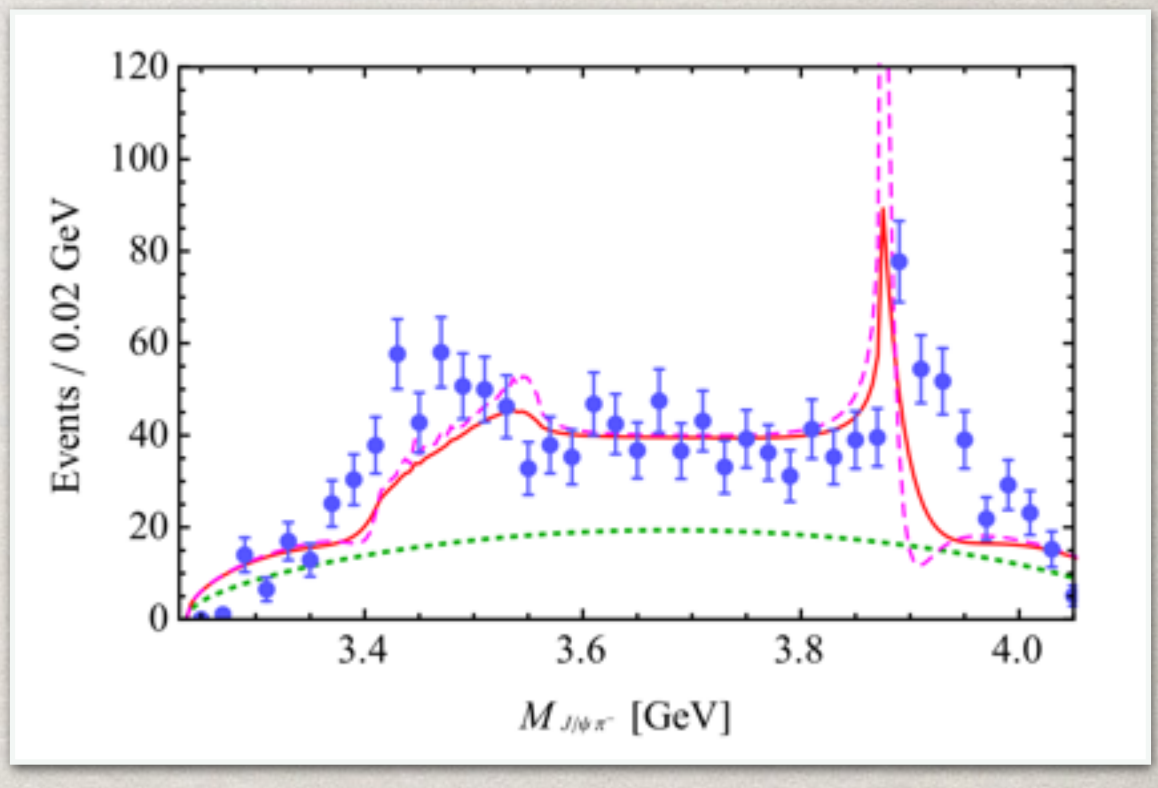


LHCb

R. Aaij et al. [LHCb Collaboration], Phys. Rev. D 90, 012003 (2014).

Hanhart Model



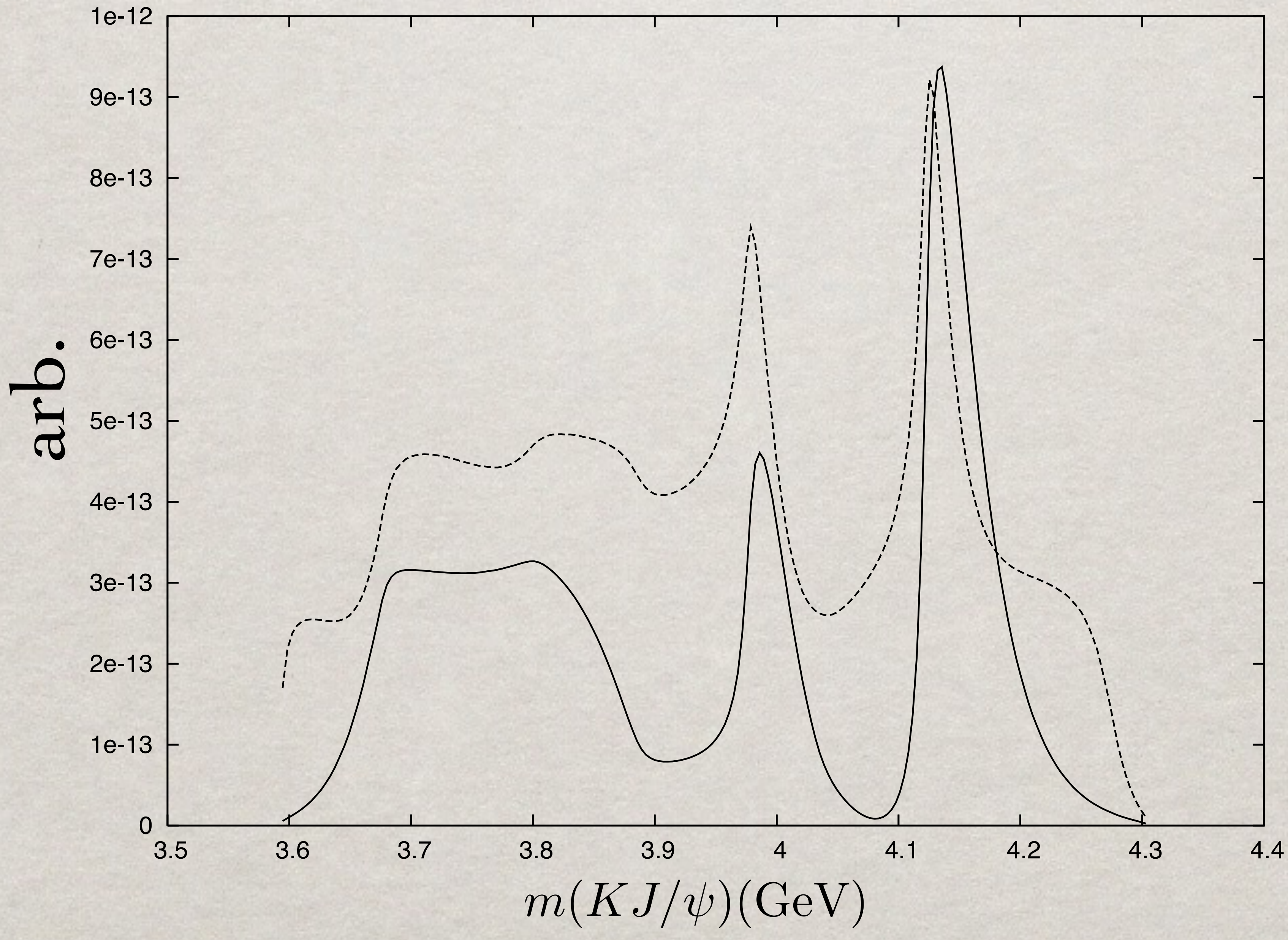


Hanhart *et al.* claim that the strength of the vertex requires bubble summation, which generates a pole.

F.-K. Guo et al. arXiv: 1411.5584

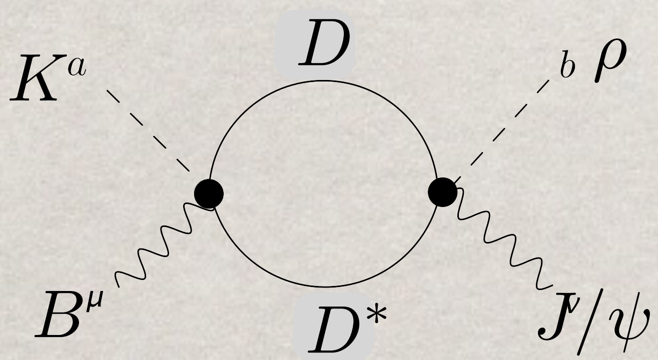
Other Exotics?

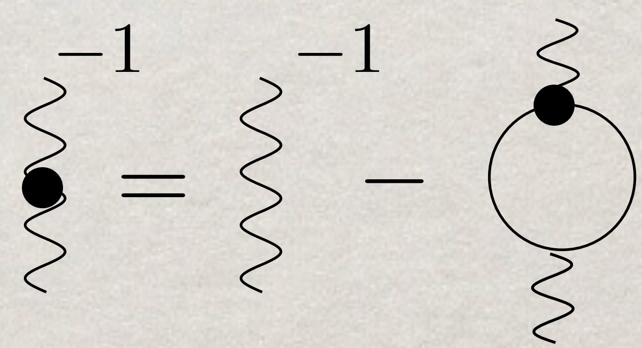
$$e^+e^-(\sqrt{s} = 4.8) \to K^+K^-J/\psi$$

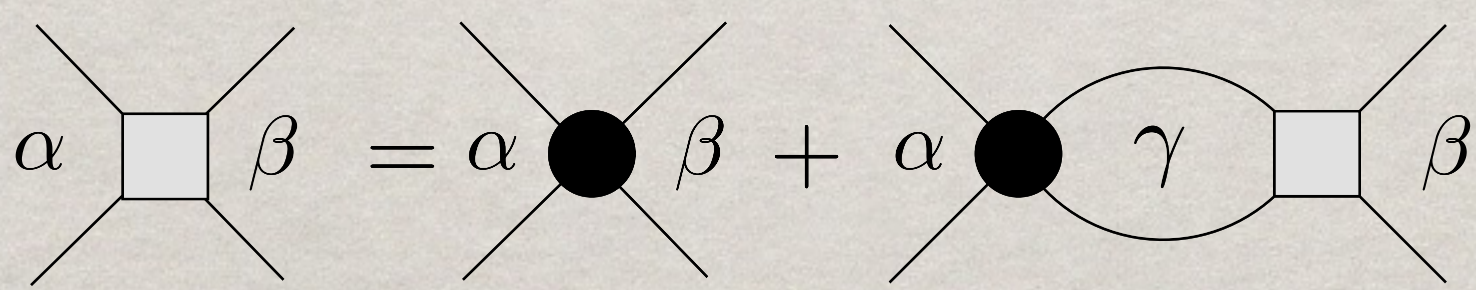


Cusp Model — to do

- examine the X(3872): interplay of cusp, possible bound state dynamics, and mixing with cc states

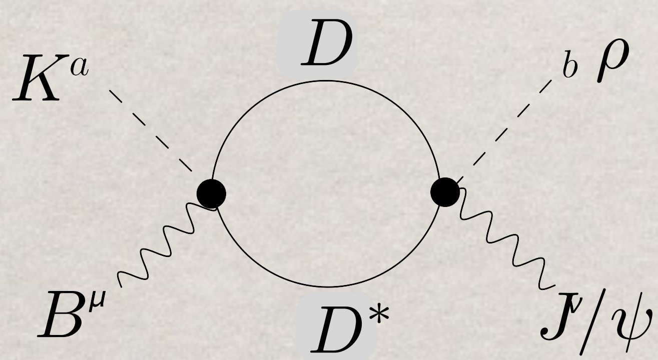


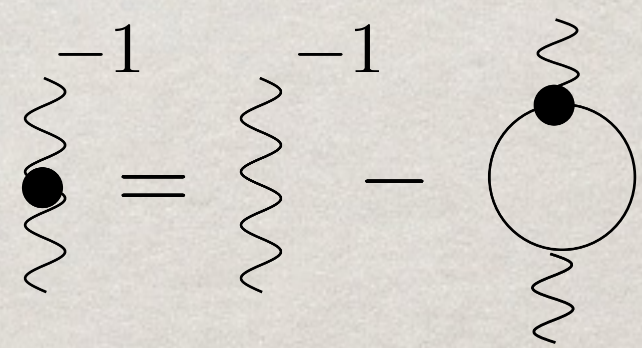


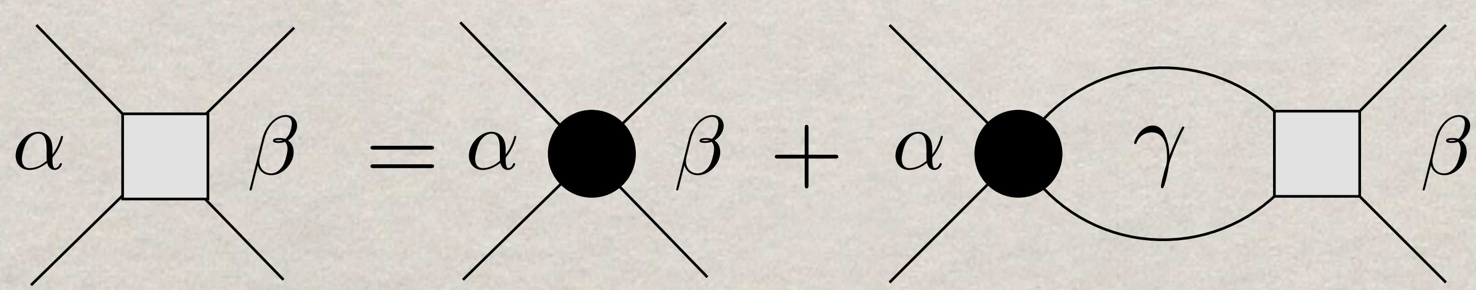


Cusp Model — to do

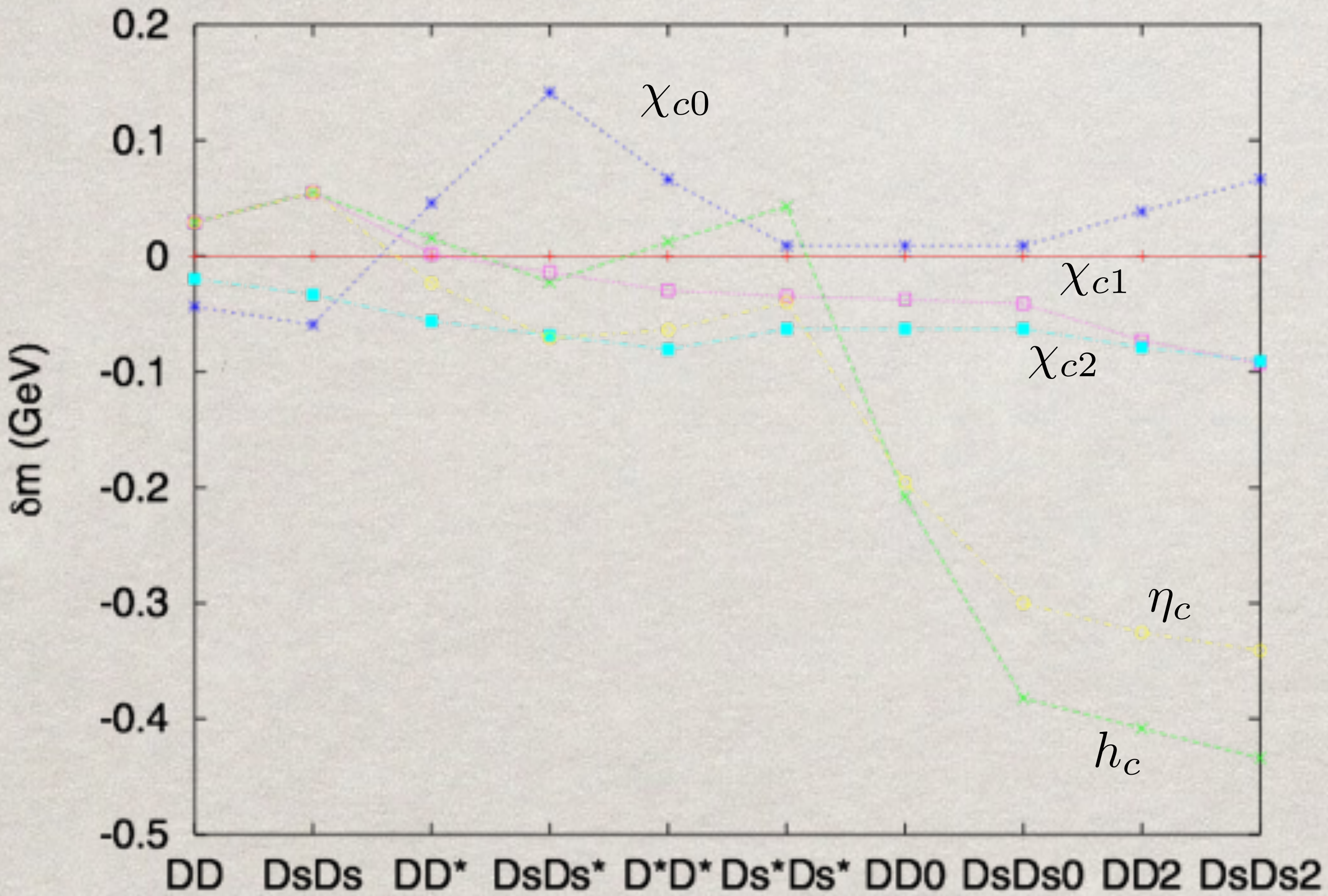
- model vertices in a reasonable way and perform bubble sums
- compare to D D* pi and pi pi J/psi
- examine the X(3872): interplay of cusp, possible bound state dynamics, and mixing with cc states







Cusp Model — to do



Need to correctly renormalise the bare model (in this case, the constituent quark model)

Conclusions

- there are a lot of new states, not all of them are 'real'!
- X(3872) appears to be a likely cusp/molecule/ charmonium mixture supernumerary state
- cusp effects can be important and should be accounted for when modelling
- it appears likely (?) that the Z_b and Z_c states are not associated with S-matrix poles
- analogue states will appear in many places, but must not be swamped in the production

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