Hidden and open charm at Belle [and elsewhere]

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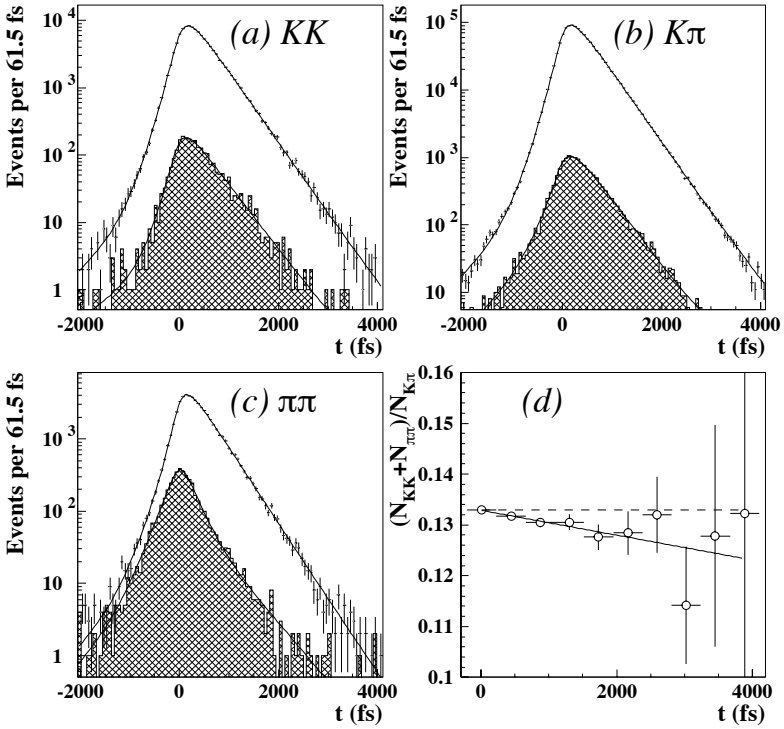
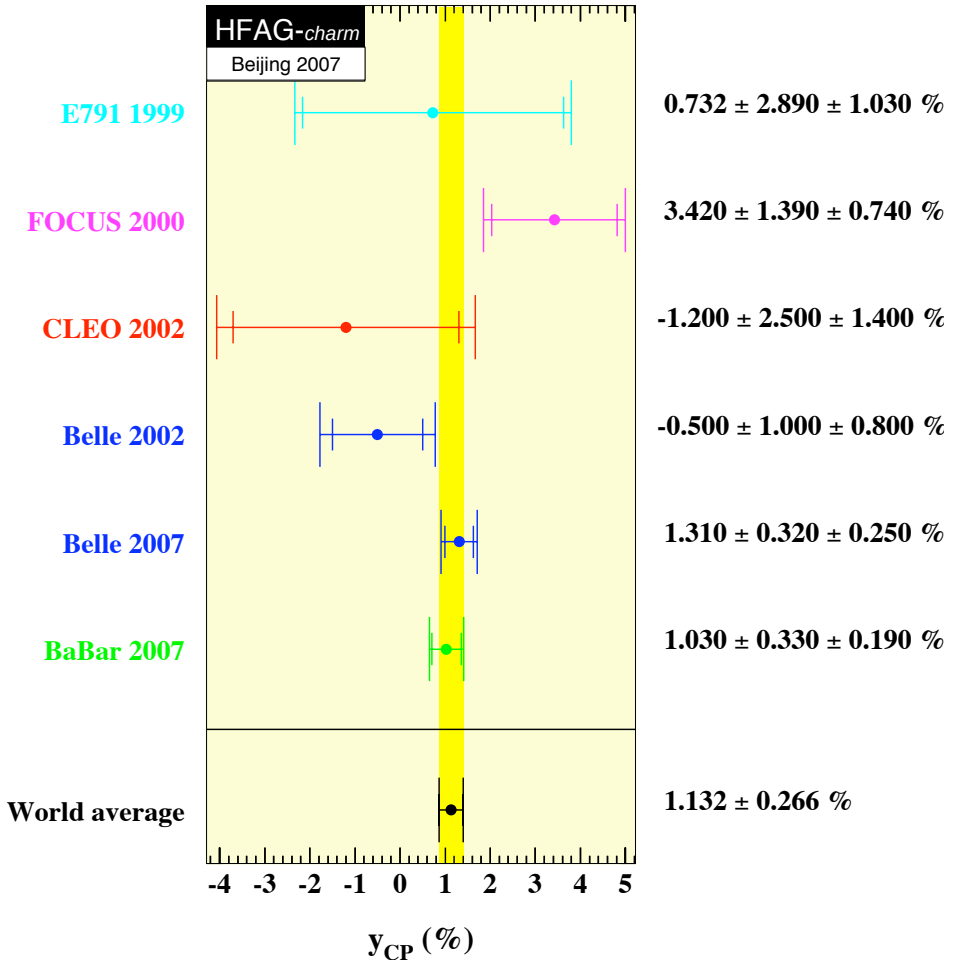
Belle collaboration / University of Sydney High Energy Physics group

BEACH 2008, University of South Carolina, 26th June 2008

Mixing since 2006: (1) y_{CP} via $D^0 \to K^+K^-, \pi^+\pi^-$

M. Starič, B. Golob et al, Phys. Rev. Lett. 98, 211803 (2007)



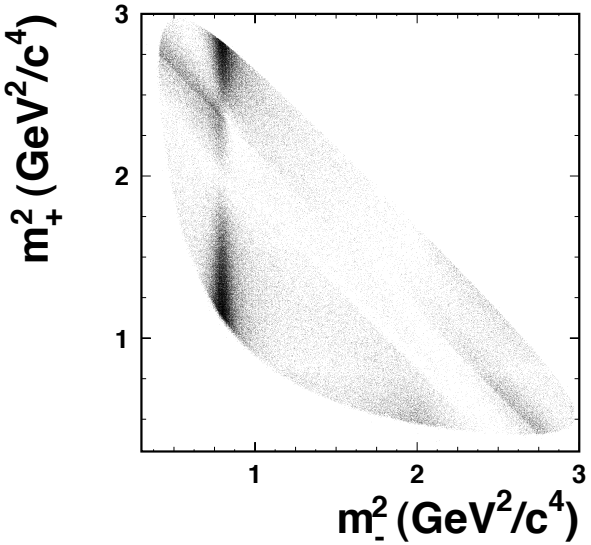


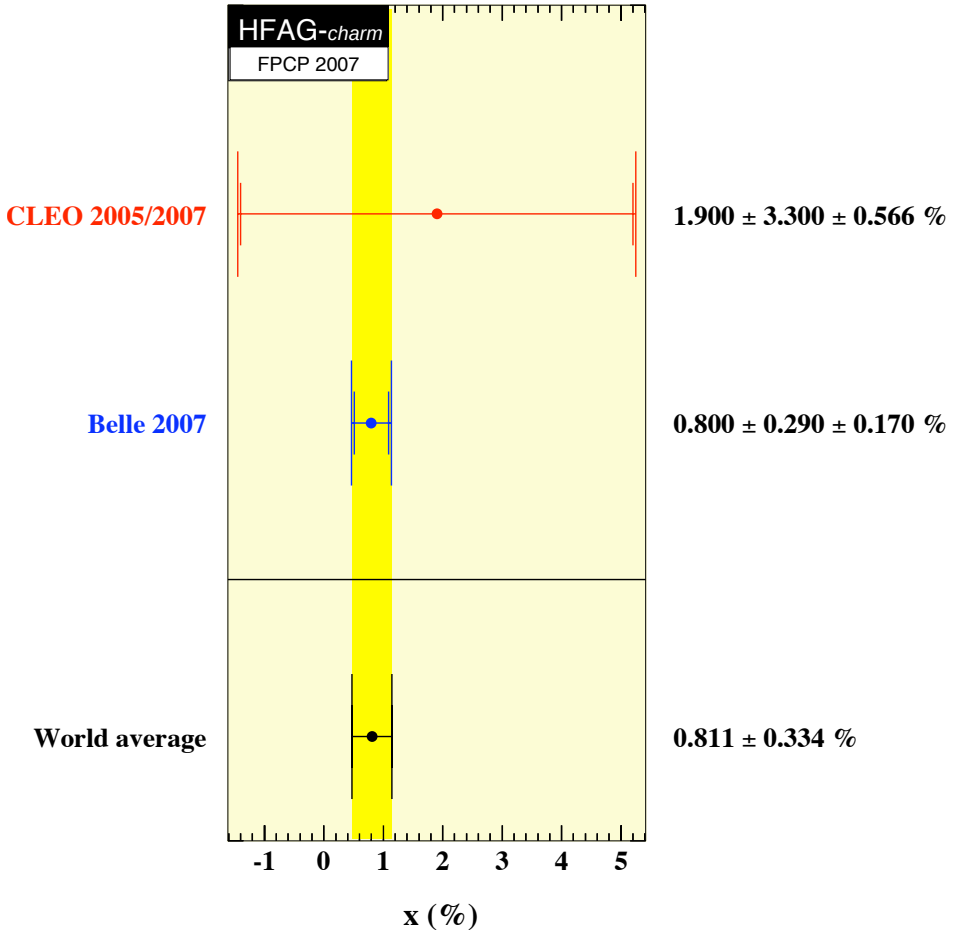
very robust evidence for mixing:

- strongly data-driven $R(t-t')$
- result tracks run periods, τ_{D^0}
- binned fits, good $P(\chi^2, n_{dof})$ throughout

Mixing since 2006: (2) $K^0_S\pi\pi$ t-dependent Dalitz

L.-M. Zhang et al, Phys. Rev. Lett. 99, 131803 (2007)





sub-%-level access to (x, y)

[CLEO method; CLEO stats $\times 60$]:

$$\mathcal{M}(m_-^2, m_+^2, t) = \mathcal{A}(m_-^2, m_+^2)\frac{1}{2}[e_1(t) + e_2(t)] + \frac{q}{p}\overline{\mathcal{A}}(m_-^2, m_+^2)\frac{1}{2}[e_1(t) - e_2(t)]$$

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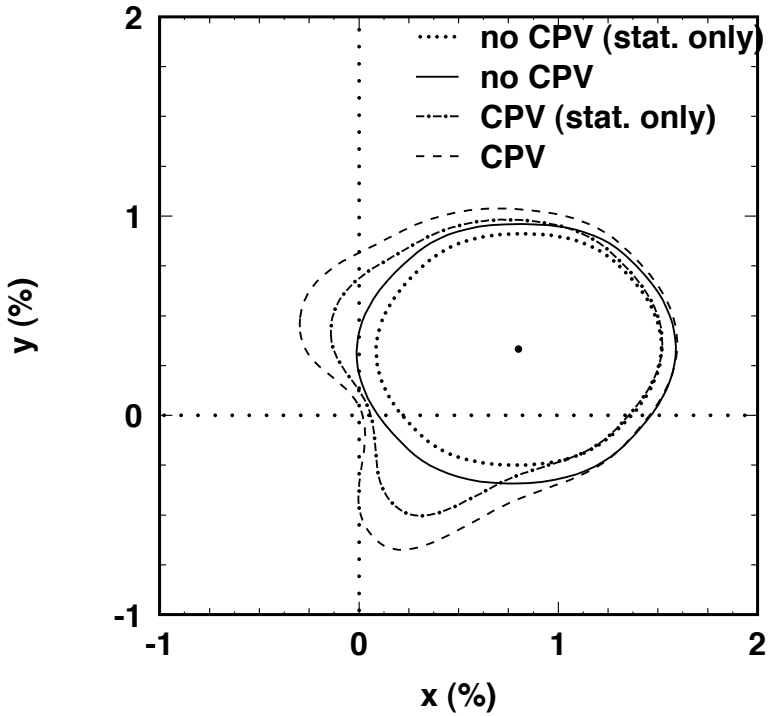
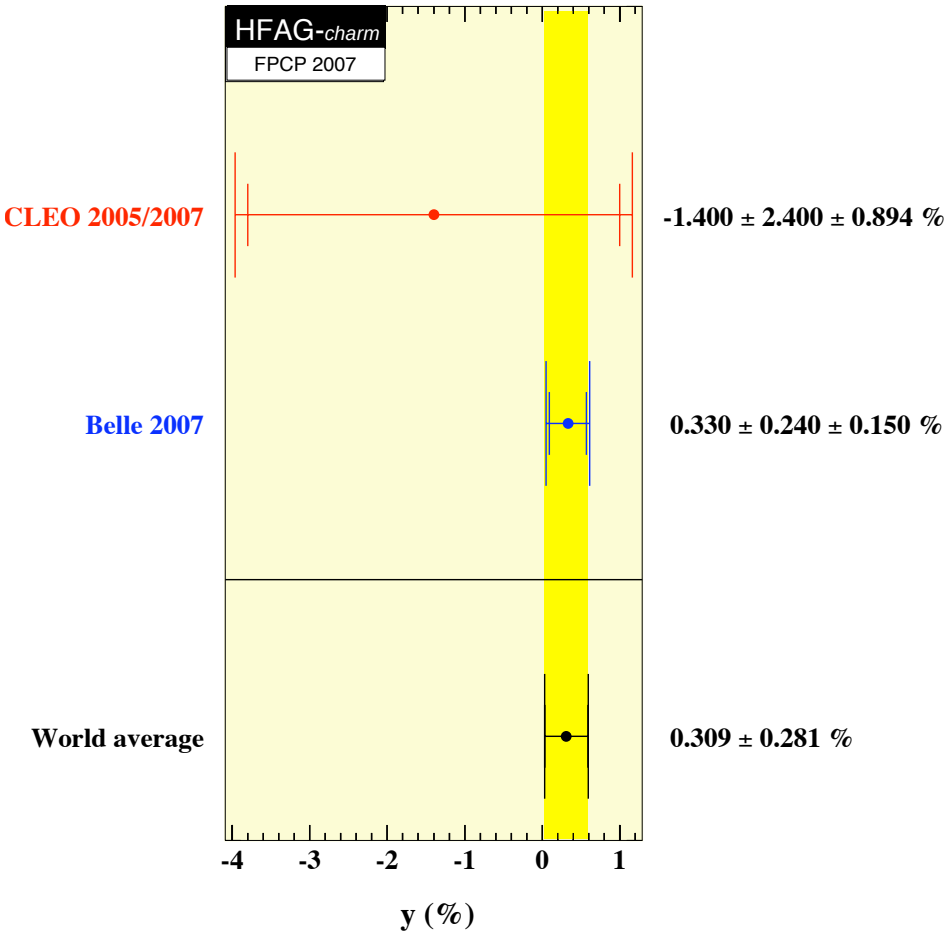




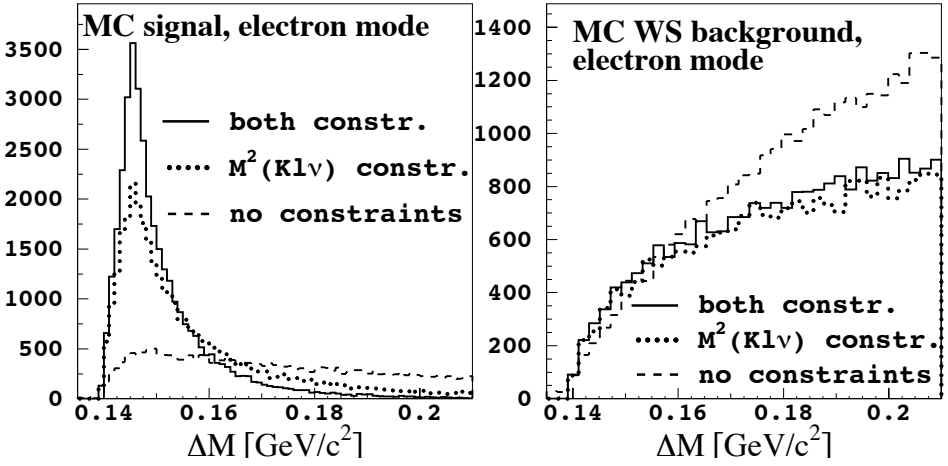
only 2.2σ signif. in isolation <u>but</u>

gives standalone 2D anchor in (x, y)

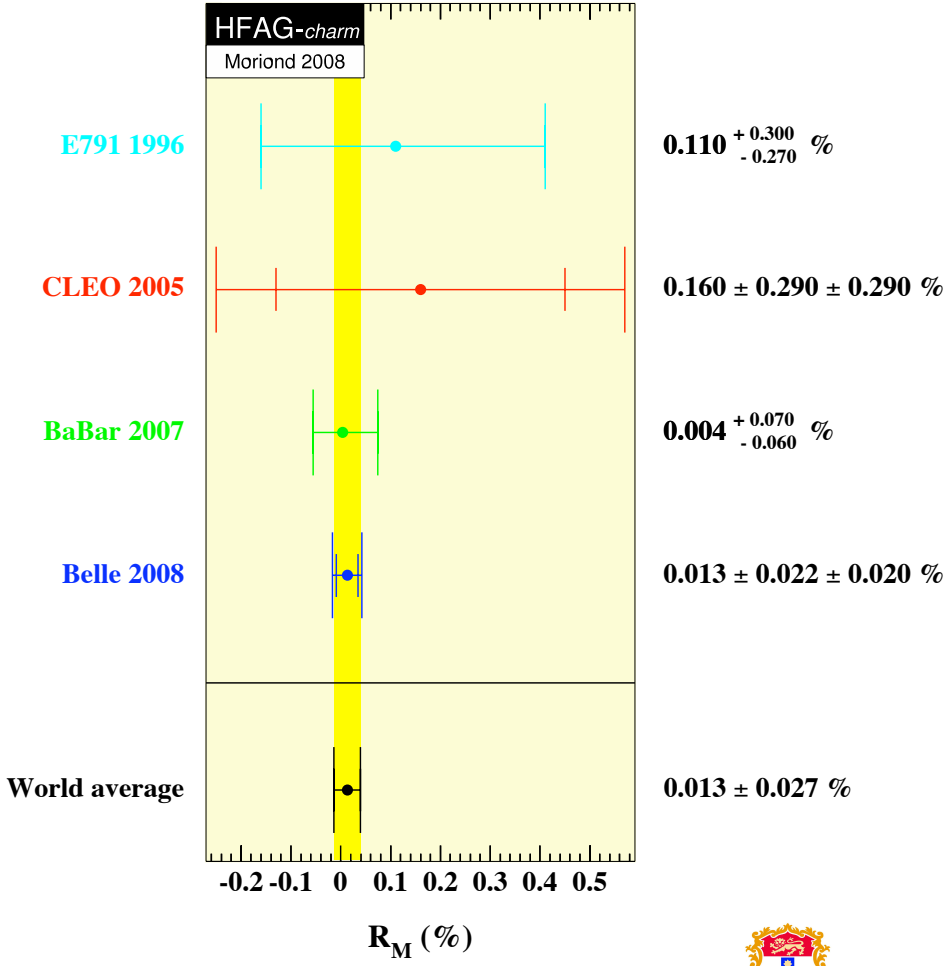
[favours lower y than y_{CP} results . . .]

Mixing since 2006: (3) $D^0 \to K^{(*)+}\ell^-\overline{\nu}$

U. Bitenc et al, Phys. Rev. D 77, 112003 (2008)



- (2005 result + stats + μ) $\otimes$ method improvement
- $R_M < 6.1 \times 10^{-4}$ (90% limit) *cf.* $R_M \sim 5.9 \times 10^{-4}$ from FOCUS y_{CP} value



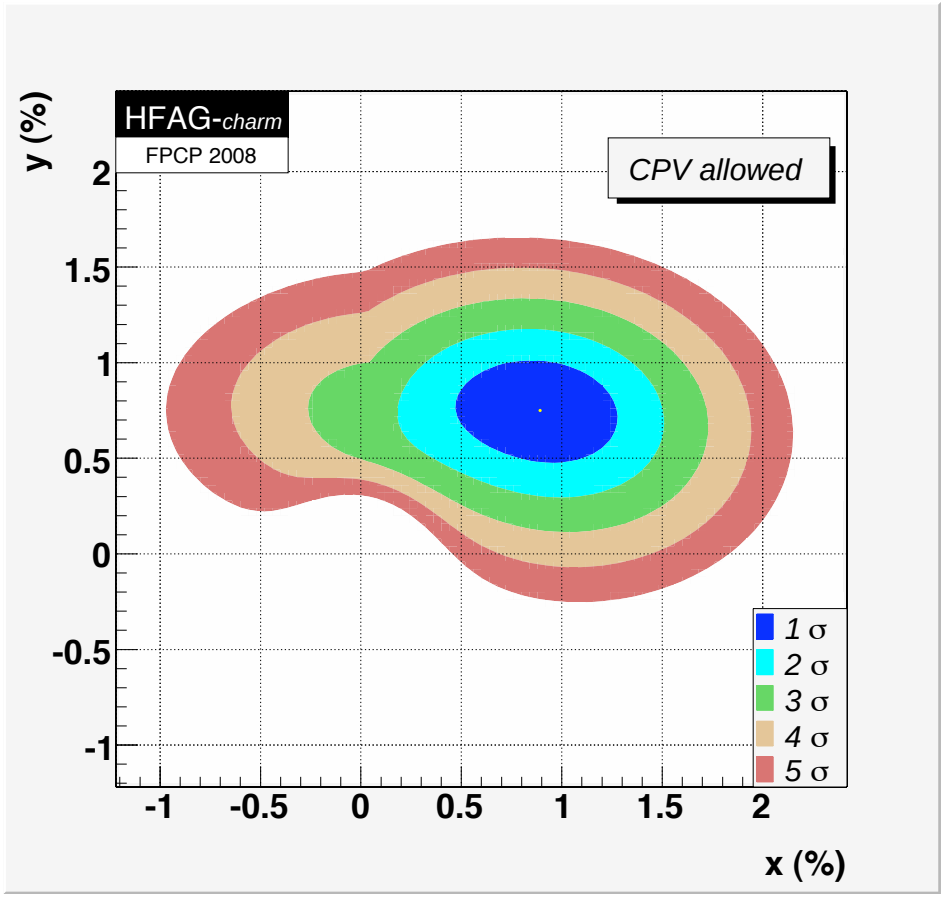
Mixing since 2006: (4) grand average

HFAG-Charm, current at FPCP08/Taipei (May 2008)

- other evidence: $D^0 \to K^+\pi^-$
  - BaBar 3.9σ PRL 98, 211802
  - Belle'06: $\begin{cases} \simeq \text{sensitivity} \\ \text{lower signif.} \end{cases}$
  - CDF 3.8σ compatible result arXiv:0712.1567 [hep-ex] $\to$ PRL
- also $K^+\pi^-\pi^0$ & $K^+\pi^-\pi^+\pi^-$: [see V.Santoro talk for mixing/BaBar]
- global fit driven by:

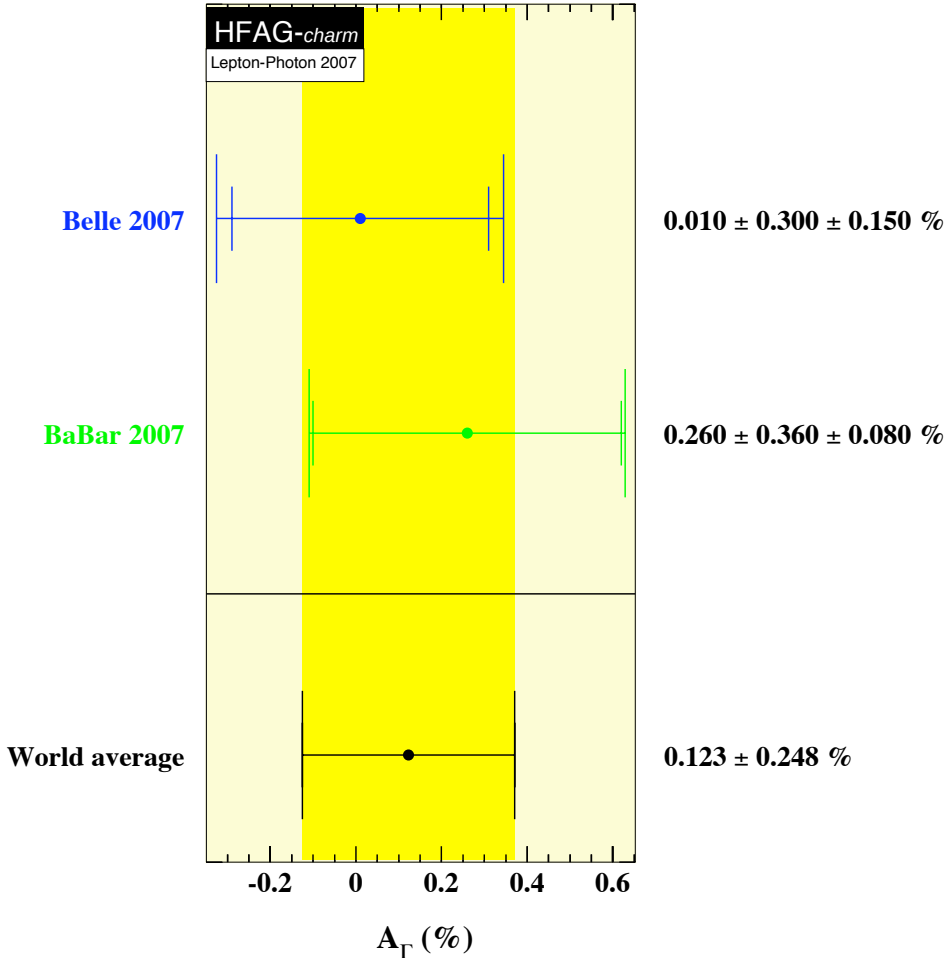
$$\begin{cases} x: & K^0_S\pi^+\pi^- \\ y: & y_{CP},\ K^0_S\pi^+\pi^- \\ \ni?(0,0): & y_{CP},\ K^+\pi^- \text{ (and } K^0_S\pi^+\pi^-,\ K^+\pi^-\pi^0) \end{cases}$$

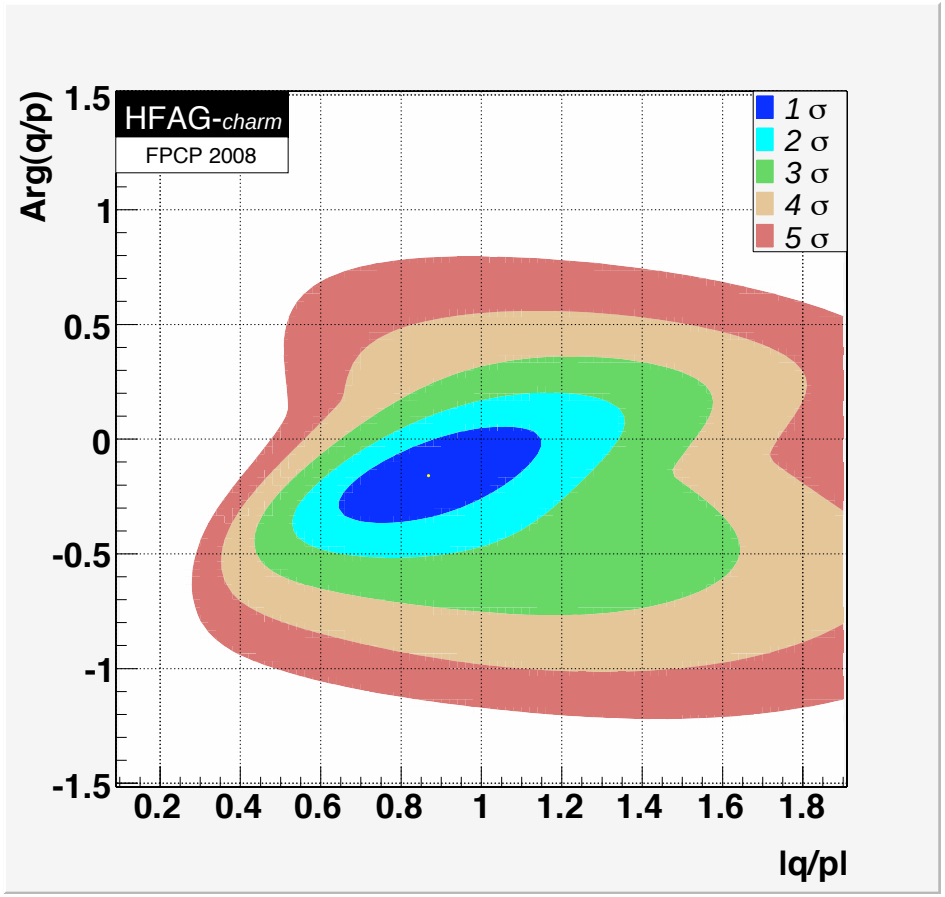
- CLEO-c $(|D^0\rangle|\overline{D}^0\rangle - |\overline{D}^0\rangle|D^0\rangle)$+ WA y: $\delta_{K\pi}$ constraint



Mixing since 2006: (5) CPV in our future?

HFAG-Charm, current at FPCP08/Taipei (May 2008)





also: A_{CP}^{KK}, $A_{CP}^{\pi\pi}$: BaBar [PRL 100, 061803]; Belle [→ PLB ∼ now]

X(3872): state of play in 2006

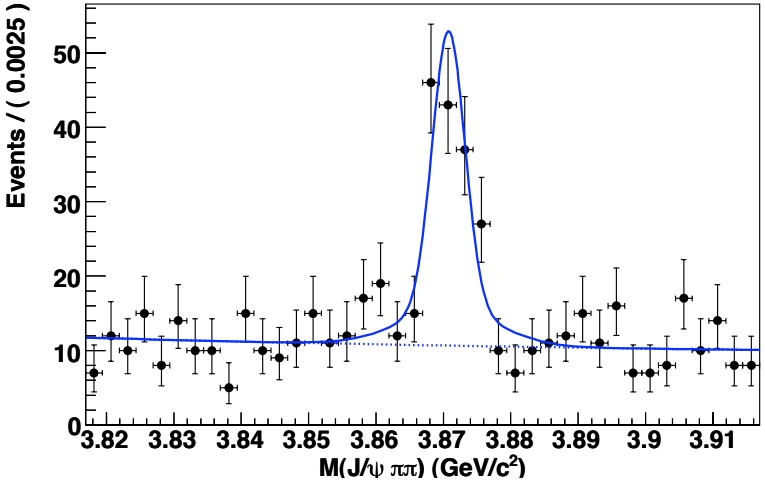
adapted from B.D. Yabsley, Beauty 2006 review; `arXiv:hep-ex/0702012`

- narrow; prominent $\pi^+\pi^-\psi$ decay [Belle discovery; CDF, D0, BaBar]
  - $\mathcal{B}(X \to \pi^+\pi^- J/\psi) > 4.2\%$ [BaBar inclusive, *PRD* **71**, 031501]
  - $\Gamma < 2.3\,\mathrm{MeV}$ (90% C.L.) [Belle discovery]
- $M = (3871.2 \pm 0.5)\,\mathrm{MeV} \lesssim (m_{\mathrm{D}^0} + m_{\mathrm{D}^*})$ by 1σ [WA; CLEO]
- $\mathrm{p\bar{p}}$ prod^n: $(16 \pm 5 \pm 2)\%$ b-decay, rest prompt; "ψ'-like" [CDF]
- $X^\pm$ not seen: not an isovector [BaBar *PRD* **71**, 031501]
- C-even, from $X \to \gamma\psi$ [Belle, BaBar] and $\pi^+\pi^-\pi^0\psi$ [Belle]
  - $X \to \rho\psi$ dominates, $L = 0, 1$ [CDF $M(\pi^+\pi^-)$ *PRL* **96**, 102002]
  - $J^{PC} = 1^{++}$ or 2^{-+} [CDF angular *PRL* **98**, 132002]
- B^+ *vs* $\mathrm{B}^0 \to \mathrm{K}\,X$ "needs more data" *TM* [BaBar *PRD* **73**, 011101(R)]
- X peak in $\mathrm{B} \to \mathrm{K}\mathrm{D}^0\overline{\mathrm{D}}^0\pi^0$ needs confirm^n [Belle *PRL* **97**, 162002]
- experimental loose ends: $\pi^0\pi^0 J/\psi$, $\gamma\psi'$, $\pi^+\pi^-\eta_c$, $\mathrm{D}\overline{\mathrm{D}}\gamma$

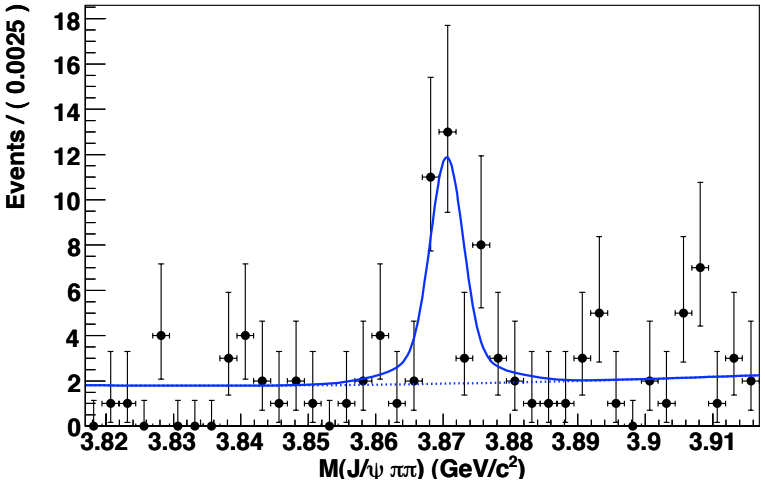
X(3872): loose ends that have been addressed

Belle 2007 conf. prelim.; cf. BaBar PRD 77, 111101 (2008); and others

$\mathrm{B}^+ \to \mathrm{K}^+ X[\to \pi^+\pi^-\psi]$: 12σ



$\mathrm{B}^0 \to \mathrm{K}^0_S X$: 6.5σ "first obs^n



$R = \mathcal{B}_{\mathrm{K}^0 X}/\mathcal{B}_{\mathrm{K}^+ X}$	$0.94 \pm 0.24 \pm 0.10$	*cf.*	$0.41 \pm 0.24 \pm 0.05$
$\delta m = M_{\mathrm{K}^+ X} - M_{\mathrm{K}^0_S X}$	$(+0.22 \pm 0.90 \pm 0.27)\,\mathrm{MeV}$	BaBar:	$(+2.7 \pm 1.6 \pm 0.4)\,\mathrm{MeV}$

[note withdrawal of molecule $\to$ low-R claim: Braaten & Lu, PRD 77, 014029 (2008)]

BaBar [PRD 77, 01102 (2008)] confirms large $\mathcal{B}(X \to \mathrm{D}^0\overline{\mathrm{D}}^0\pi^0)$

- $X \to \mathrm{D}^{*0}\overline{\mathrm{D}}^0$ or $\mathrm{D}^0\overline{\mathrm{D}}^0\pi^0$? [nontrivial lineshape; discriminating]
- $M = (3875.1^{+0.7}_{-0.5} \pm 0.5)\,\mathrm{MeV}$ (Belle 3875.4); two states? dynamics?

$e^+e^- \to \psi\, D^{(*)}\overline{D}^{(*)}$: states above threshold

P. Pakhlov et al, Phys. Rev. Lett. 100, 202001 (2008)

refinement of $M_{\text{recoil}}(\psi)$ method:

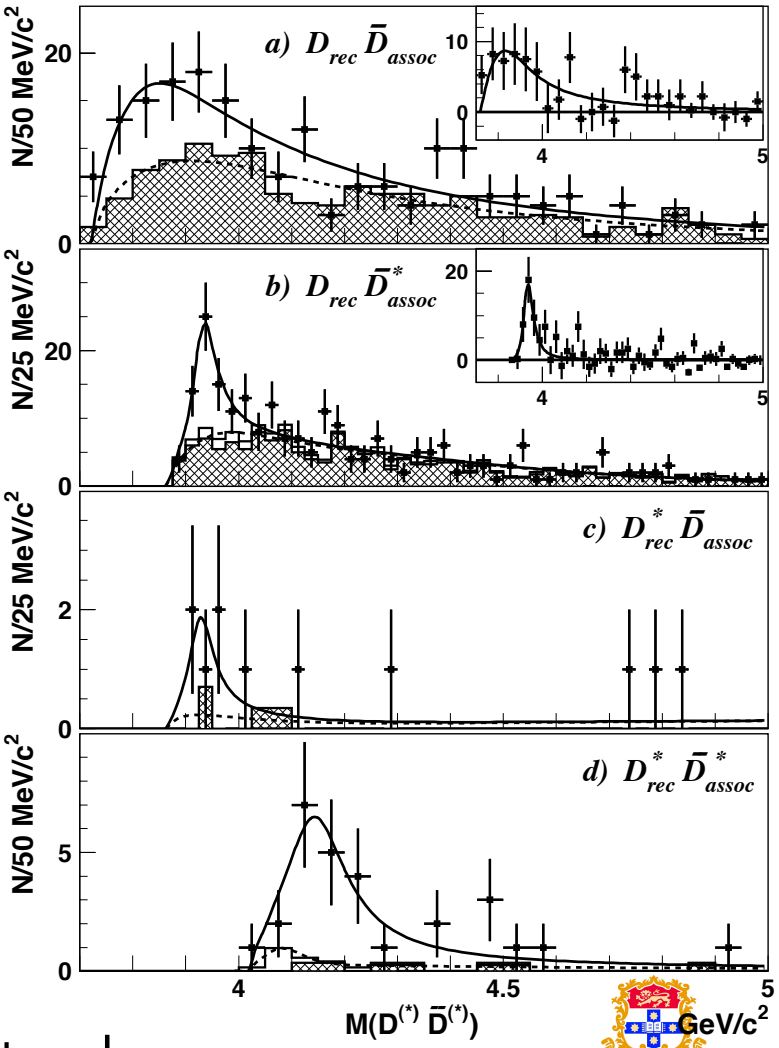
- D reconstruction; refit $\to m_{\mathrm{D}}$
- tag: $|M_{\text{recoil}}(\psi \mathrm{D}^{(*)} - m_{\text{tag}})| < 70\,\mathrm{MeV}$ and constrain $\to m_{\text{tag}} = m_{\mathrm{D}^{(*)}}$
- fit $M(\mathrm{D}^{(*)}\overline{\mathrm{D}}^{(*)})$: bkgd (sideband) + x-feed + threshold f^n + rel. S-wave B-W

$\sigma(e^+e^- \to \psi X) \times \mathcal{B}(X \to \mathrm{D}^{(*)}\overline{\mathrm{D}}^*)$

$X(3940)$	$\mathrm{D}\overline{\mathrm{D}}^*$	$(13.9^{+6.4}_{-4.1})\,\mathrm{fb}$	$[6.0\sigma]$
$X(4160)$	$\mathrm{D}^*\overline{\mathrm{D}}^*$	$(24.7^{+12.8}_{-8.3})\,\mathrm{fb}$	$[5.5\sigma]$

cf. $\psi(nS)\,\eta_c(mS)$: $\sim 20\,\mathrm{fb}$ for $m, n \in \{1, 2\}$:

- consistent with X as $c\bar{c}$ states?
- production mechanism still not understood



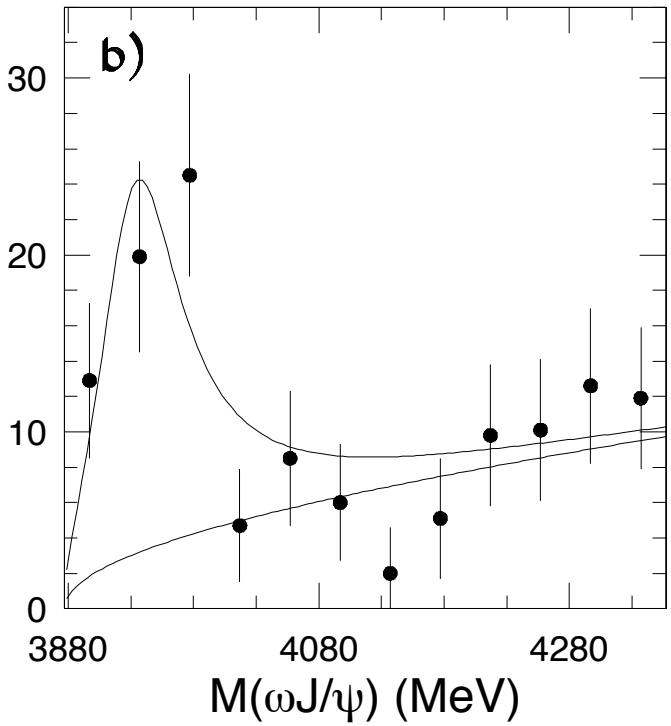
the Y(3940) threshold enhancement and BaBar

Belle PRL 94, 182002 (2005); BaBar `arXiv:0711.2047 [hep-ex]` → **PRL**

$\mathrm{B} \to \mathrm{K}\omega\psi$ sample: enhancement "$Y(3940)$" at $\omega\psi$ threshold:

- *cf.* $\begin{cases} X(3940)\ [??\eta_c(3S)] & \mathrm{e^+e^-} \to \psi X \\ Z(3930)\ [?\chi_{c2}(2P)] & \gamma\gamma \to \mathrm{D\overline{D}} \end{cases}$

  Y hardest to understand as $(c\overline{c})_{res}$
- even non-$(c\overline{c})_{res}$ (*e.g.* hybrid) hard $\Longrightarrow$ least-believed of "XYZ" states



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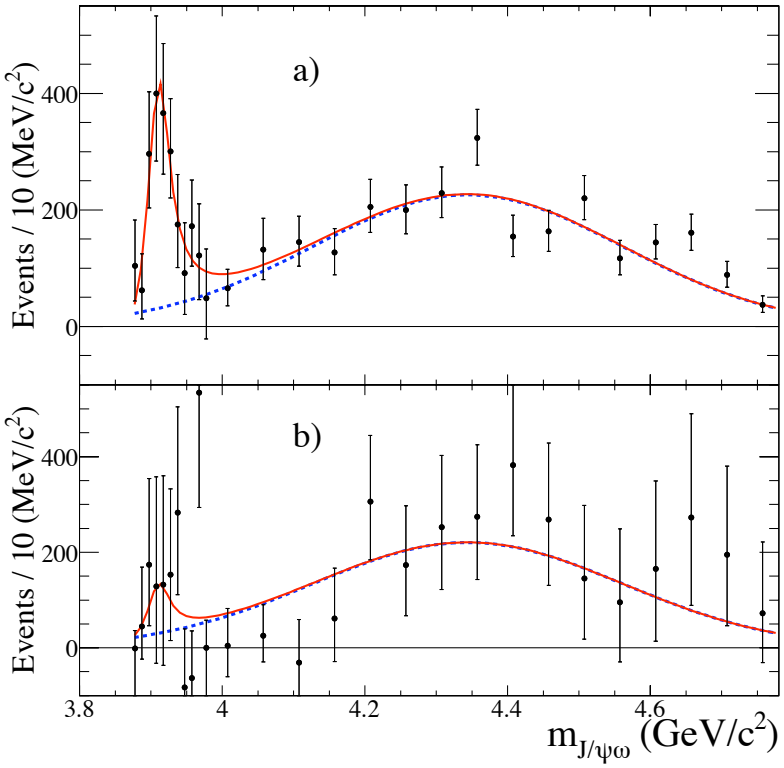
  Y hardest to understand as $(c\overline{c})_{res}$
- even non-$(c\overline{c})_{res}$ (*e.g.* hybrid) hard $\Longrightarrow$ least-believed of "XYZ" states
- spectacular confirmation by BaBar:
  - M-dependent {resolution, ϵ} corr^n
  - simultaneous B^+ & B^0 fit; R floats
  - Gaussian bkgd + S-wave B-W signal

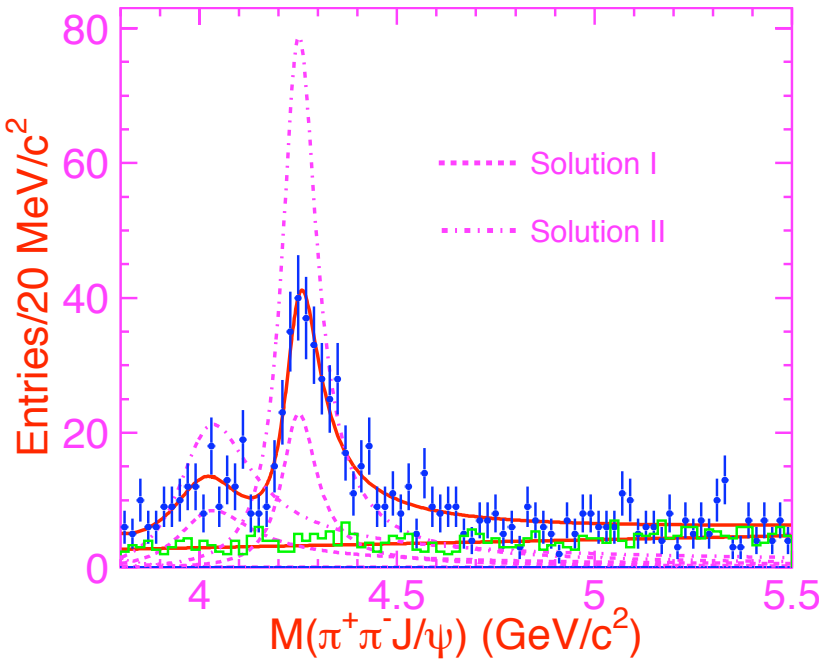
  cf. Belle threshold $q^*(M)$+ S-wave B-W

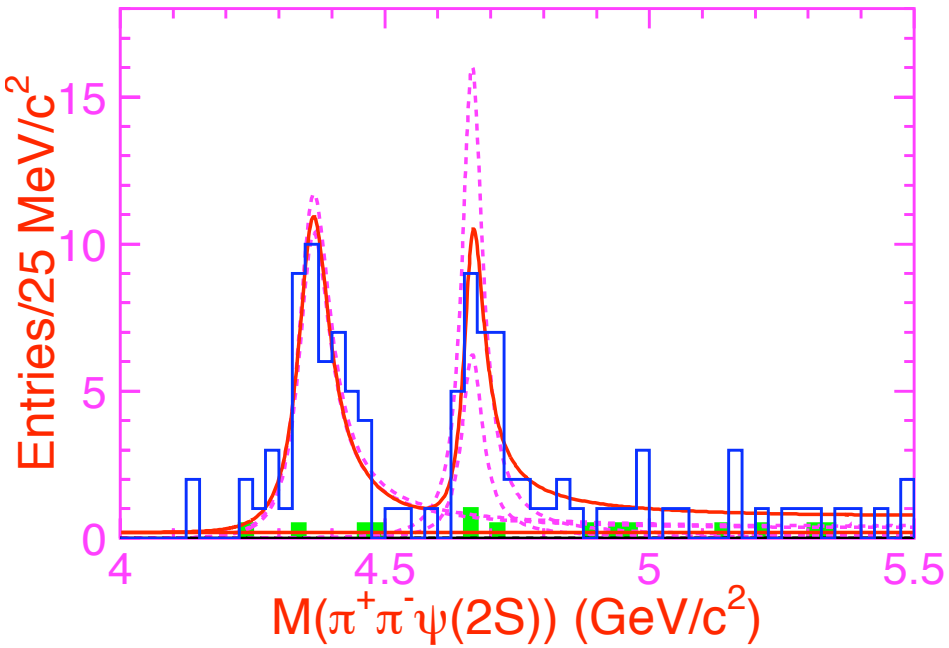


- $M = (3914.6^{+3.8}_{-3.4} \pm 1.9)\,\mathrm{MeV}$, $\Gamma = (34^{+12}_{-8} \pm 5)\,\mathrm{MeV}$ [both < Belle]
- $R_Y = \mathcal{B}_{\mathrm{B}^0}/\mathcal{B}_{\mathrm{B}^+} = 0.27^{+0.28+0.04}_{-0.23-0.01}$; *cf.* $R_{\text{non-res}} = 0.97^{+0.23+0.03}_{-0.22-0.02}$

The 1^{--} states seen in ISR (following BaBar)

C.Z. Yuan et al, PRL 99, 182004; X.L. Wang et al, PRL 99, 142002 (2007);





- confirms $Y(4260)$ [also CLEO]
- amplitude nontrivial near 4050 MeV

- confirms $\pi^+\pi^-\psi'$ signal
- splits "$Y(4360)$" peak $\rightarrow$ two

none seen in ISR $\mathrm{D}^{(*)}\overline{\mathrm{D}}^{(*)}$: *e.g.* explicit BaBar $Y(4260)$ limit $\mathcal{B}_{\mathrm{D}\overline{\mathrm{D}}}/\mathcal{B}_{\pi^+\pi^-\psi} < 1.0$ at 90% C.L. [arXiv:0710.1371 $\rightarrow$ PRD]

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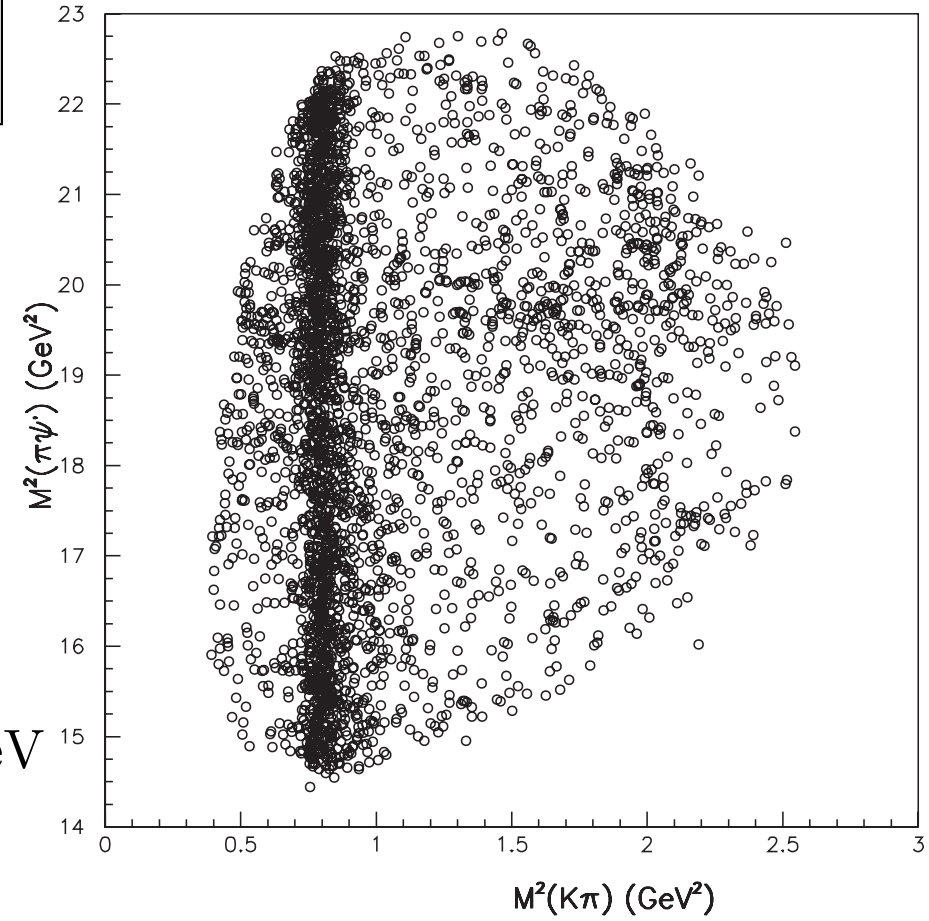
- phenomenology demands *some* non-$(c\overline{c})_{res}$ structure(s), BUT
  - not every peak is necessarily a state [Charm 2007: `arXiv:0711.1636`]
  - the implied spectrum must not be *too* rich: we do not see a forest

$Z(4430)^+$: a charged [?state?] with hidden charm

S.-K. Choi, S.L. Olsen et al, Phys. Rev. Lett. 100, 142001 (2007)

some structures allow manifestly exotic states with Q and/or $S \neq 0$:

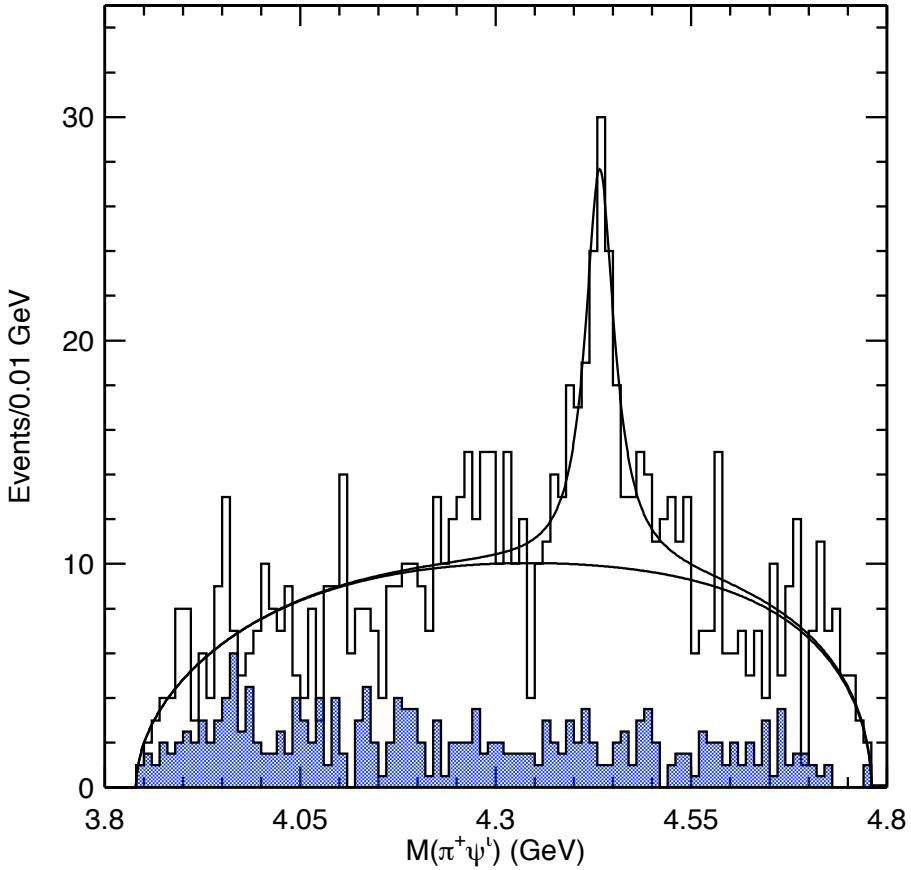
- Belle looked in $\mathrm{B} \to \mathrm{K}\pi^{\pm}\psi'$,
  $$\psi' \to \begin{cases} \pi^+\pi^-\psi & \psi \to \ell^+\ell^- \\ \ell^+\ell^- & (\ell = \mathrm{e}, \mu) \end{cases}$$
- standard B recon, $q\overline{q}$ supp^n
- 2.5K B signal, $\approx$ 90% purity
- Dalitz ($M^2(\mathrm{K}\pi^+)$, $M^2(\pi^+\psi')$):
  - vertical: $\mathrm{K}^*\psi'$, $\mathrm{K}_2^*(1430)\psi'$
  - horizontal: $M^2(\pi^+\chi_{c1}) \simeq 20\,\mathrm{GeV}$
- veto $\mathrm{K}^*(892)$, $\mathrm{K}_2^*(1430)$
- study in $\Delta E = E_{\mathrm{B}} - E_{\mathrm{beam}}$ ...



$Z(4430)^+$: a charged [?state?] with hidden charm

S.-K. Choi, S.L. Olsen et al, Phys. Rev. Lett. 100, 142001 (2007)

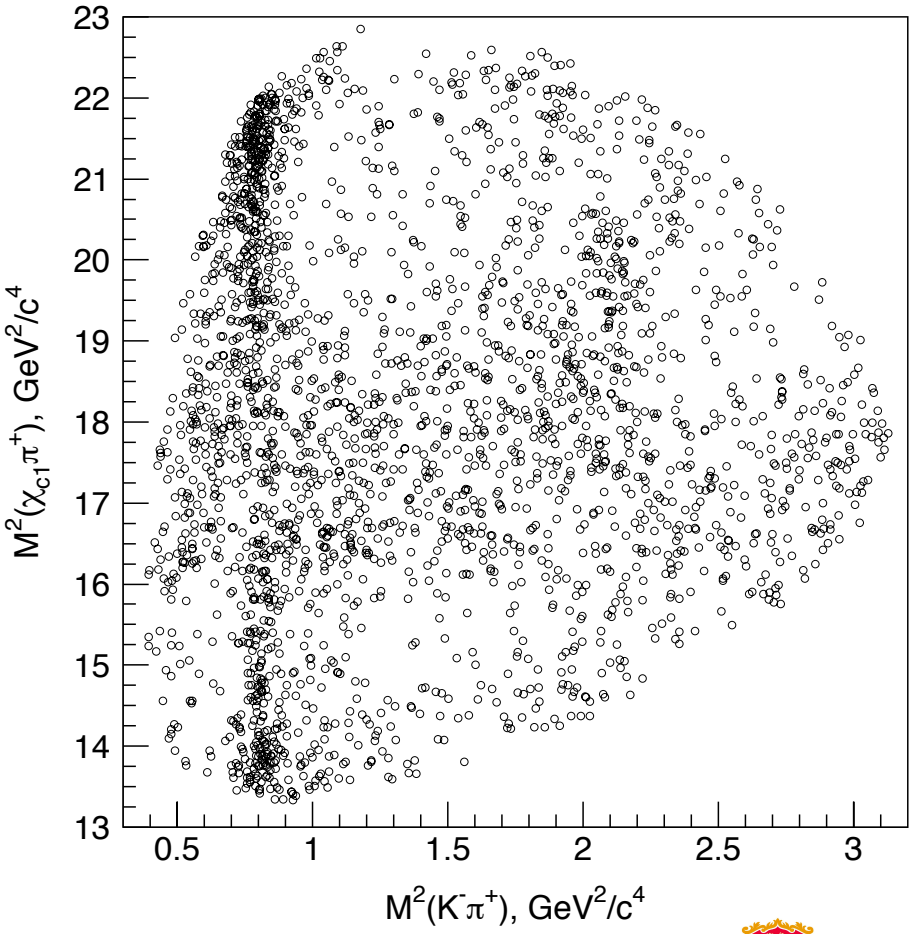
- signal; scaled δE sideband
- fit S-wave B-W signal + bkgd $q^*(Q^{1/2} + A_1 Q^{3/2} + A_2 Q^{5/2})$
  - q^*: $p(\pi^+)$ in $\pi^+\psi'$ rest
  - $Q = M_{\rm max} - M(\pi^+\psi')$
    $[M(\pi^+\psi') < 4.78\,\mathrm{GeV} = M_{\rm max}]$
- 6.5σ peak; $\chi^2/n_{dof} = 80.2/94$
- subsample fits performed:
  - signals; consistent M
  - width discrep^y betw. $\pi\pi\psi$, $\ell\ell$
- not $\mathrm{K}\pi$ $\{S, P, D\}$ interference
  [too narrow: gives other structures]
- $M = (4433 \pm 4 \pm 2)\,\mathrm{MeV}$, $\Gamma = (45^{+18+30}_{-13-13})\,\mathrm{MeV}$



$\overline{\mathrm{B}}^0 \to \mathrm{K}^-\pi^+\chi_{c1}$: (1) basics

BELLE–CONF–0848/arXiv:0806.4098 [hep-ex] **available now**

- $605\,\mathrm{fb}^{-1}$: 657×10^6 $\mathrm{B}\overline{\mathrm{B}}$
- recon $\overline{\mathrm{B}}^0 \to \mathrm{K}^-\pi^+\chi_{c1}+$ c.c.
  - $\chi_{c1} \to \gamma\psi$
  - $\psi \to \ell^+\ell^-$, $\mu^+\mu^-$
  - mass-constrained fit to both
- $\mathrm{B}\overline{\mathrm{B}}$ sel^n: $\begin{cases} M_{bc} & \in [5275, 5287]\,\mathrm{MeV} \\ |\Delta E| & < 12\,\mathrm{MeV} \end{cases}$
  - $2126 \pm 56 \pm 42$ candidates
  - $\epsilon = (20.0 \pm 1.4)\%$
  - ΔE sidebands for bkgd estim^n
  - constrained fit to m_{B}
- Dalitz ($M^2(\mathrm{K}^-\pi^+)$, $M^2(\pi^+\chi_{c1})$):
  - vertical band for $\mathrm{K}^*(892)^+\chi_{c1}$
  - horizontal band $M^2(\pi^+\chi_{c1}) \simeq 17\,\mathrm{GeV}$ ...



$\overline{\mathrm{B}}^0 \to \mathrm{K}^-\pi^+\chi_{c1}$: (2) fit details

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- integration over angular quantities $\cos\theta_{\chi_{c1}}$, $\phi_{\chi_{c1}}$, $\cos\theta_\psi$, ϕ_ψ:
  - efficiency almost uniform ...
  - distributions studied as cross-check after the fit
- binned likelihood fit (small bins: fully-contained subset of 400×400)
- $F(s_x, s_y) = S(s_x, s_y) \times \epsilon(s_x, s_y) + B(s_x, s_y)$
  [bkgd $B(s_x, s_y)$ from ΔE sidebands; eff^y ϵ from MC; both smoothed]
- isobar model: $\pi^+\chi_{c1}$ exotic resonance + known $\mathrm{K}^-\pi^+$
  $\{\kappa, \mathrm{K}^*(892), \mathrm{K}^*(1410), \mathrm{K}_0^*(1430), \mathrm{K}_2^*(1430), \mathrm{K}^*(1680), \mathrm{K}_3^*(1780)\}$
  - Blatt-Weisskopf form factors
  - energy-dependent widths
  - angular terms from helicity formalism
    [$\lambda_{\chi_{c1}}$ subtlety: different ref. axes for $\mathrm{K}^*(\to \mathrm{K}\pi)\chi_{c1}$ and $\mathrm{K}Z(\to \pi\chi_{c1})$]
  - (m_i, Γ_i) fixed to PDG averages save κ and $\pi^+\chi_{c1}$ exotic

$\overline{B}^0 \to K^-\pi^+\chi_{c1}$: (3) fit with known K^* states

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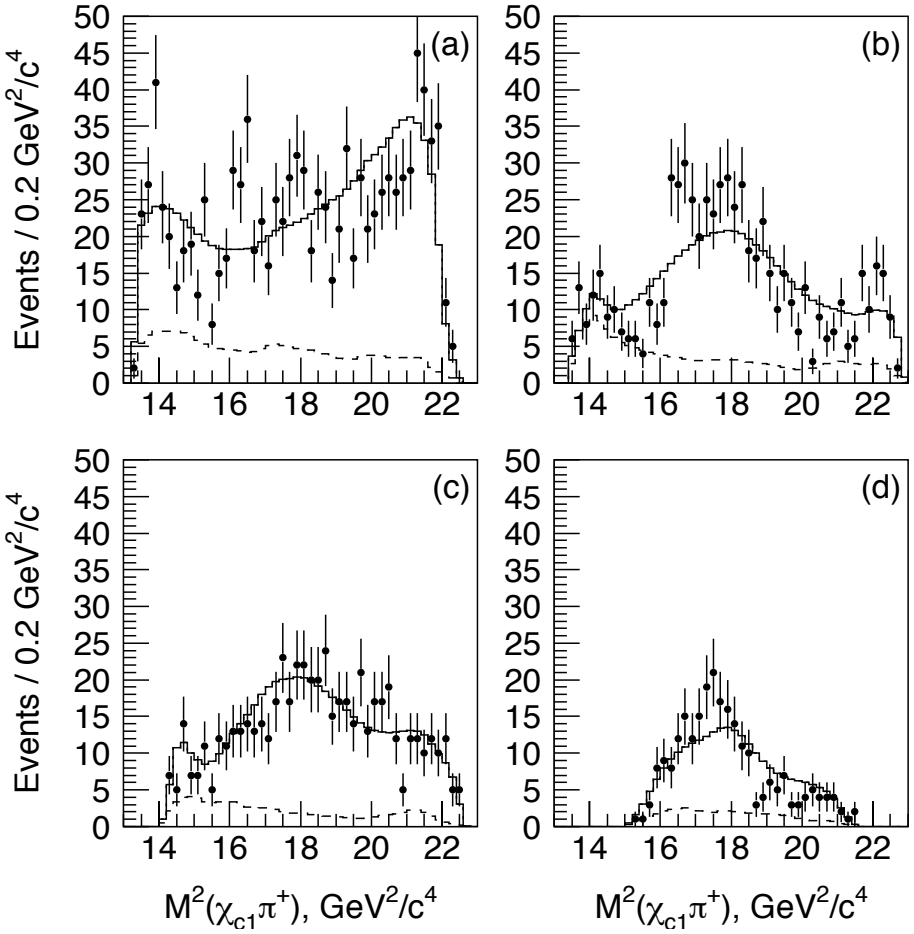
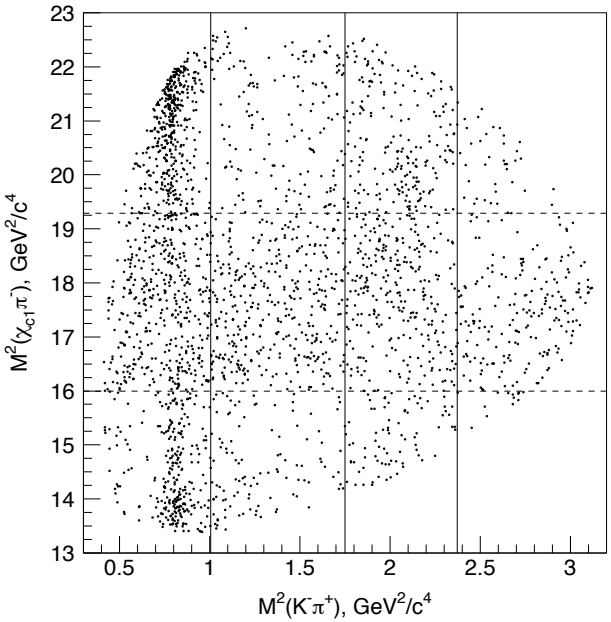


proj^{ns} to Dalitz slices:



- v.poor fit quality; unresolved:
  - $M \sim 4150\,\mathrm{MeV}$ enhancement
  - troughs
- only 1 of 4 slices plausible

$\overline{B}^0 \to K^-\pi^+\chi_{c1}$: (4) known $K^* + K_2^*$, $\chi_{c1}K$ NR

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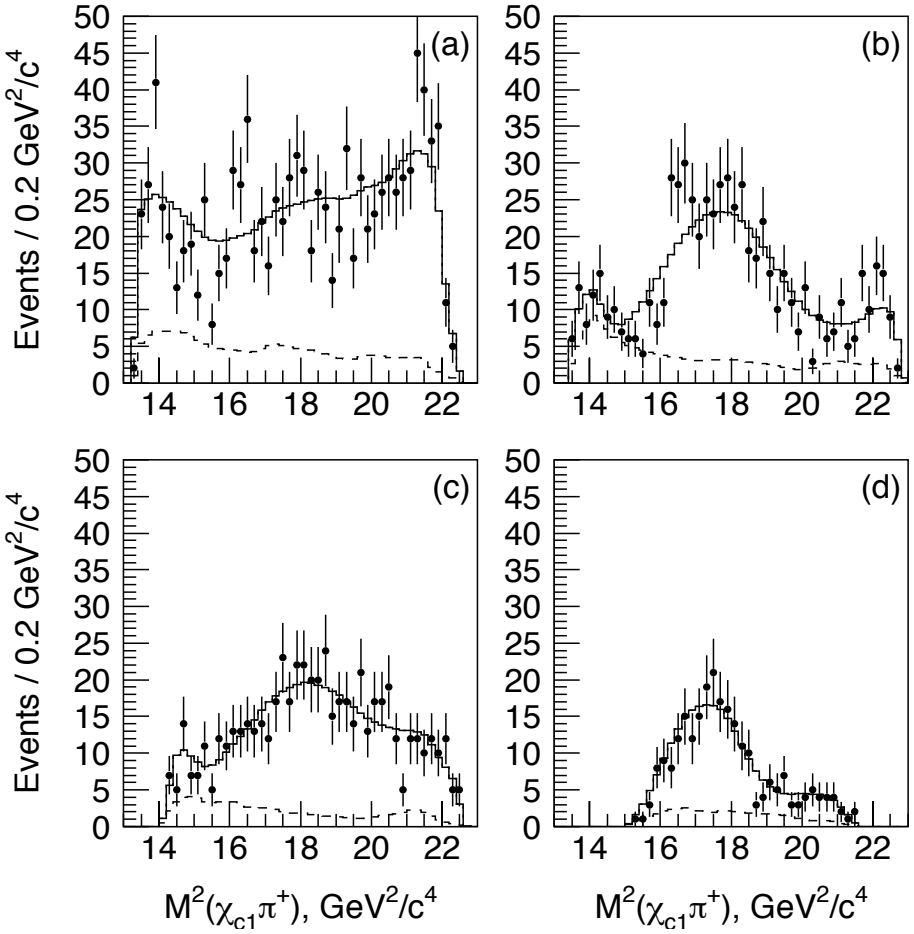
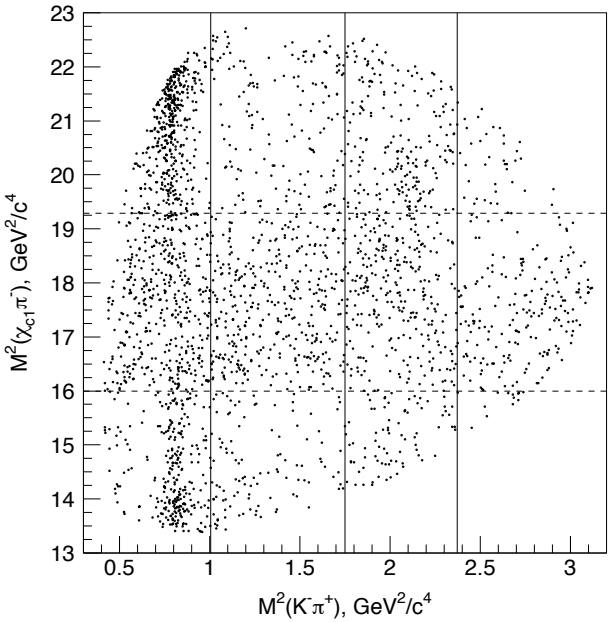


proj^{ns} to Dalitz slices:



- improvements:
  - troughs $\approx$ reproduced
  - 2 of 4 slices $\approx$ OK
- peak still poorly matched

$\overline{B}^0 \to K^-\pi^+\chi_{c1}$: (5) fit with $Z^+ \to \pi^+\chi_{c1}$ added

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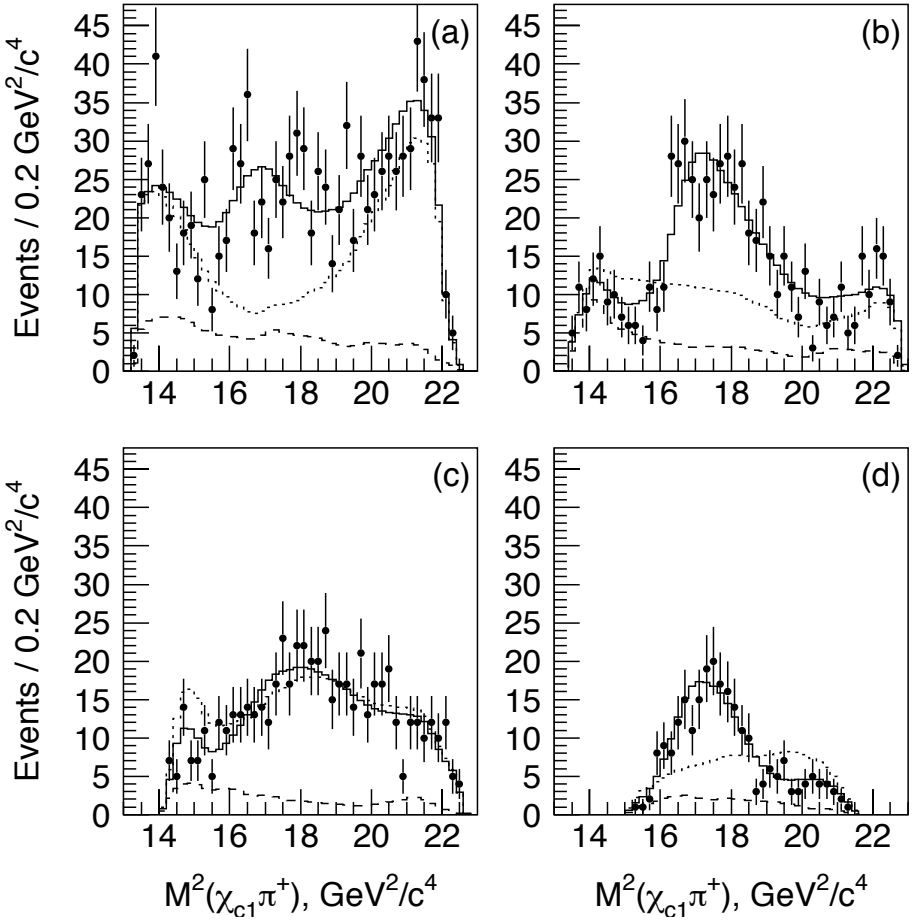
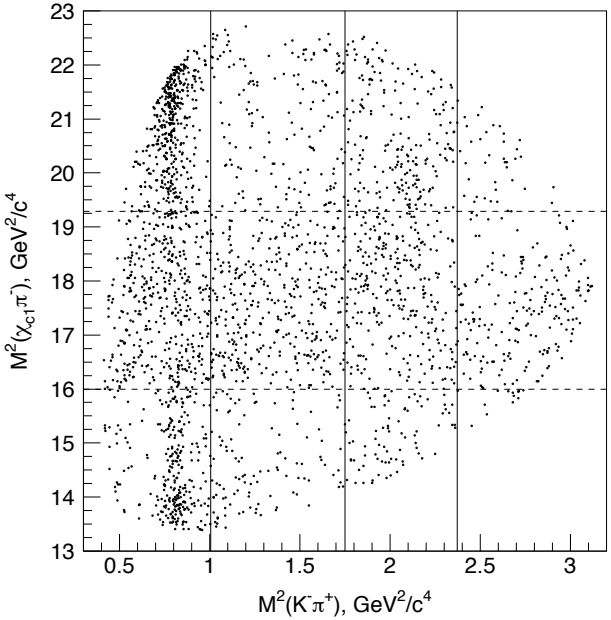


proj^{ns} to Dalitz slices:



- significant ($> 10\sigma$) Z term:
  - general agreement throughout
  - peak fine structure poor
- 92-bin χ^2_P fit: 0.1% C.L.

$\overline{B}^0 \to K^-\pi^+\chi_{c1}$: (6) with two $Z^+ \to \pi^+\chi_{c1}$ terms

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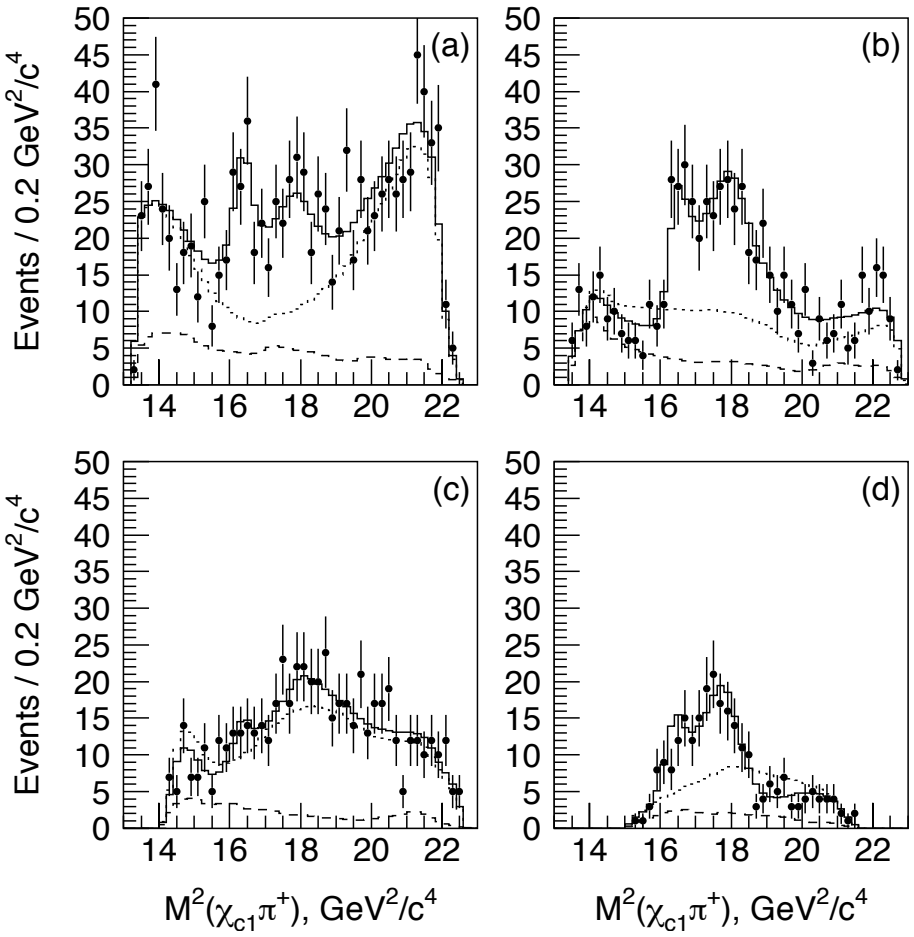
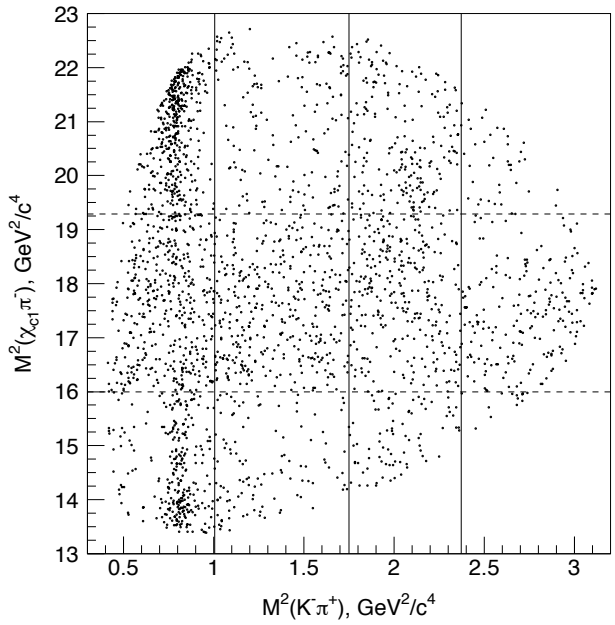


proj^{ns} to Dalitz slices:



- two-*vs*-one Z favoured:
  - matches peak fine structure
  - $> 5\sigma$ improvement
- good total fit quality: 40% C.L.

$\overline{B}^0 \to K^- \pi^+ \chi_{c1}$: (7) fit contributions

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	One Z^+		Two Z^+	
Contribution	Fit fraction	Signif.	Fit fraction	Signif.
$Z^+_{(1)}$	$(33.1^{+8.7}_{-5.8})\%$	$10.7\,\sigma$	$(8.0^{+3.8}_{-2.2})\%$	$5.7\,\sigma$
Z^+_2	–	–	$(10.4^{+6.1}_{-2.3})\%$	$5.7\,\sigma$
κ	$(1.9 \pm 1.8)\%$	$2.1\,\sigma$	$(3.6 \pm 2.6)\%$	$3.5\,\sigma$
$K^*(892)$	$(28.5 \pm 2.1)\%$	$10.6\,\sigma$	$(30.1 \pm 2.3)\%$	$9.8\,\sigma$
$K^*(1410)$	$(3.6 \pm 4.4)\%$	$1.3\,\sigma$	$(4.4 \pm 4.3)\%$	$2.0\,\sigma$
$K^*_0(1430)$	$(22.4 \pm 5.8)\%$	$3.4\,\sigma$	$(18.6 \pm 5.0)\%$	$4.5\,\sigma$
$K^*_2(1430)$	$(8.4 \pm 2.7)\%$	$5.2\,\sigma$	$(6.1 \pm 2.9)\%$	$5.4\,\sigma$
$K^*(1680)$	$(5.2 \pm 3.7)\%$	$2.2\,\sigma$	$(4.4 \pm 3.1)\%$	$2.4\,\sigma$
$K^*_3(1780)$	$(7.4 \pm 3.0)\%$	$3.6\,\sigma$	$(7.2 \pm 2.9)\%$	$3.8\,\sigma$
	110.5%		92.8%	

$\overline{\mathrm{B}}^0 \to \mathrm{K}^-\pi^+\chi_{c1}$: (8) systematics

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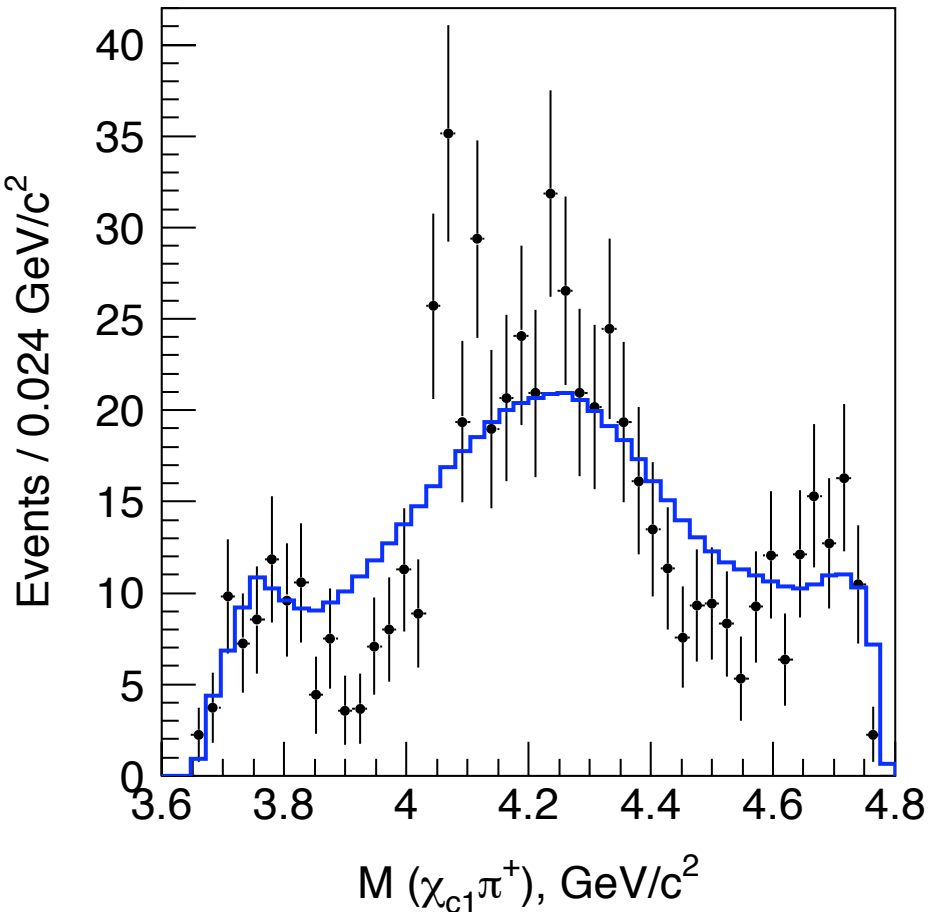
	Model	One Z^+	2-vs-1 Z^+	Two Z^+
1	default model	$10.7\,\sigma$	$5.7\,\sigma$	$13.2\,\sigma$
2	no κ	$15.6\,\sigma$	$5.0\,\sigma$	$16.6\,\sigma$
3	no $K^*(1410)$	$13.4\,\sigma$	$5.4\,\sigma$	$14.8\,\sigma$
4	no $K_0^*(1430)$	$10.4\,\sigma$	$5.2\,\sigma$	$14.4\,\sigma$
5	no $K^*(1680)$	$13.3\,\sigma$	$5.6\,\sigma$	$14.8\,\sigma$
6	no $K_3^*(1780)$	$12.9\,\sigma$	$5.6\,\sigma$	$14.4\,\sigma$
7	add $\chi_{c1}\mathrm{K}^-$ non-res.	$9.0\,\sigma$	$5.3\,\sigma$	$10.3\,\sigma$
8	add $\chi_{c1}\mathrm{K}^-$ non-res., no $K^*(1410)$	$11.3\,\sigma$	$5.1\,\sigma$	$13.5\,\sigma$
9	add $\chi_{c1}\mathrm{K}^-$ non-res., no $K^*(1680)$	$11.4\,\sigma$	$5.3\,\sigma$	$13.7\,\sigma$
10	add $\chi_{c1}\mathrm{K}^-$ non-res., no $K_3^*(1780)$	$10.8\,\sigma$	$5.4\,\sigma$	$13.2\,\sigma$
11	add $\chi_{c1}\mathrm{K}^-$ non-res., release κ constraints	$9.5\,\sigma$	$5.3\,\sigma$	$10.7\,\sigma$
12	add $\chi_{c1}\mathrm{K}^-$ non-res., new K^* (J=1)	$7.7\,\sigma$	$5.4\,\sigma$	$9.2\,\sigma$
13	add $\chi_{c1}\mathrm{K}^-$ non-res., new K^* (J=2)	$6.2\,\sigma$	$5.6\,\sigma$	$8.1\,\sigma$
14	LASS parametrization of S-wave	$13.1\,\sigma$	$5.7\,\sigma$	$14.6\,\sigma$

$\overline{B}^0 \to K^-\pi^+\chi_{c1}$: (9) summary of Dalitz analysis

BELLE–CONF–0848/arXiv:0806.4098 [hep-ex] **available now**

- very poor fit using known states



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BELLE–CONF–0848/arXiv:0806.4098 [hep-ex] **available now**

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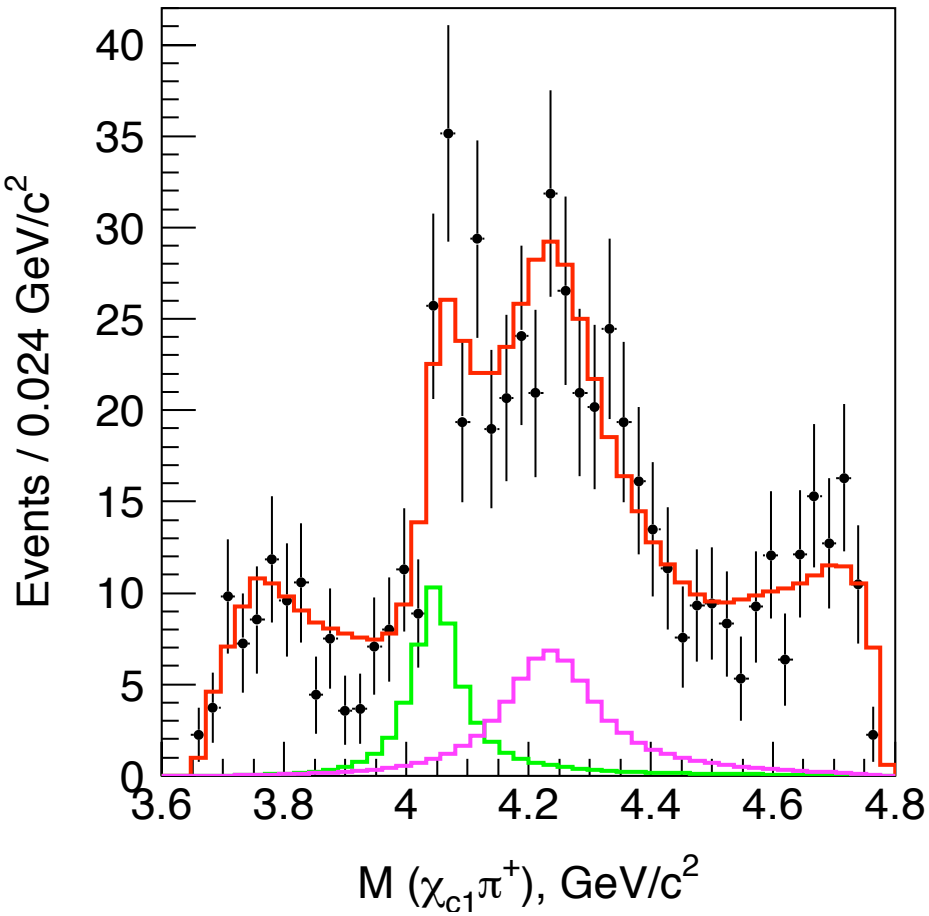
- exotic $Z^+ \to \pi^+\chi_{c1}$ needed



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BELLE–CONF–0848/arXiv:0806.4098 [hep-ex] **available now**

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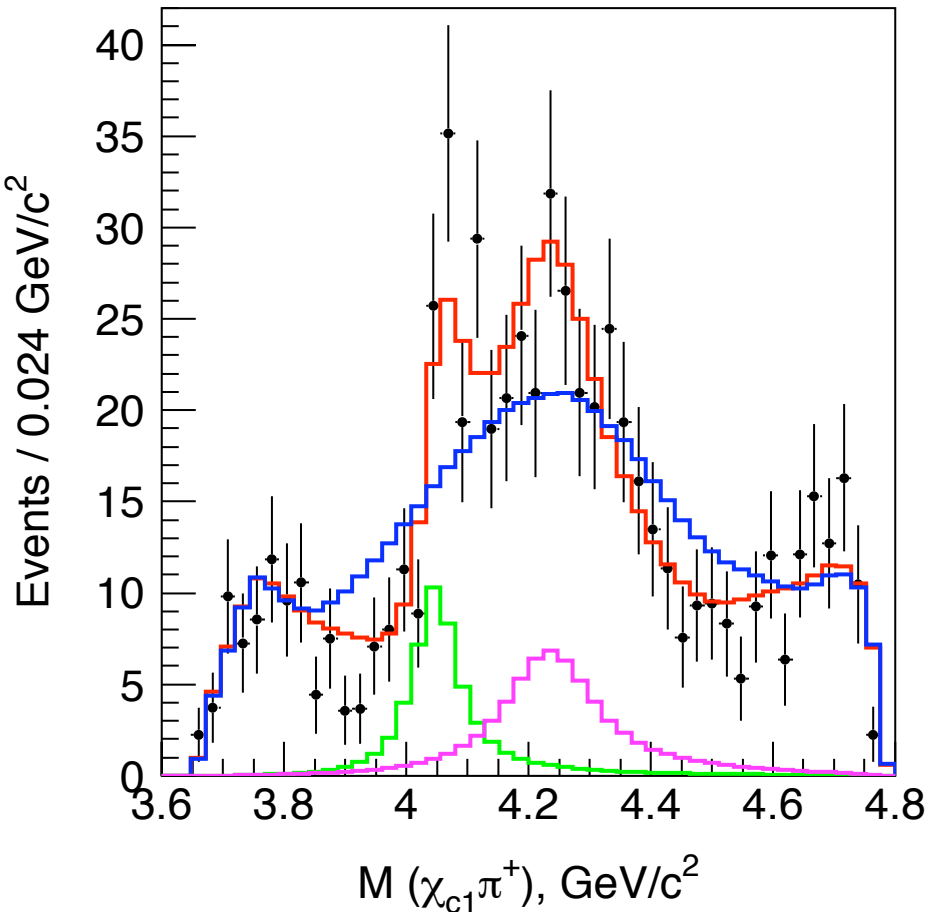
- $> 6\sigma$ even under speculative changes to the fitting model



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BELLE–CONF–0848/arXiv:0806.4098 [hep-ex] **available now**

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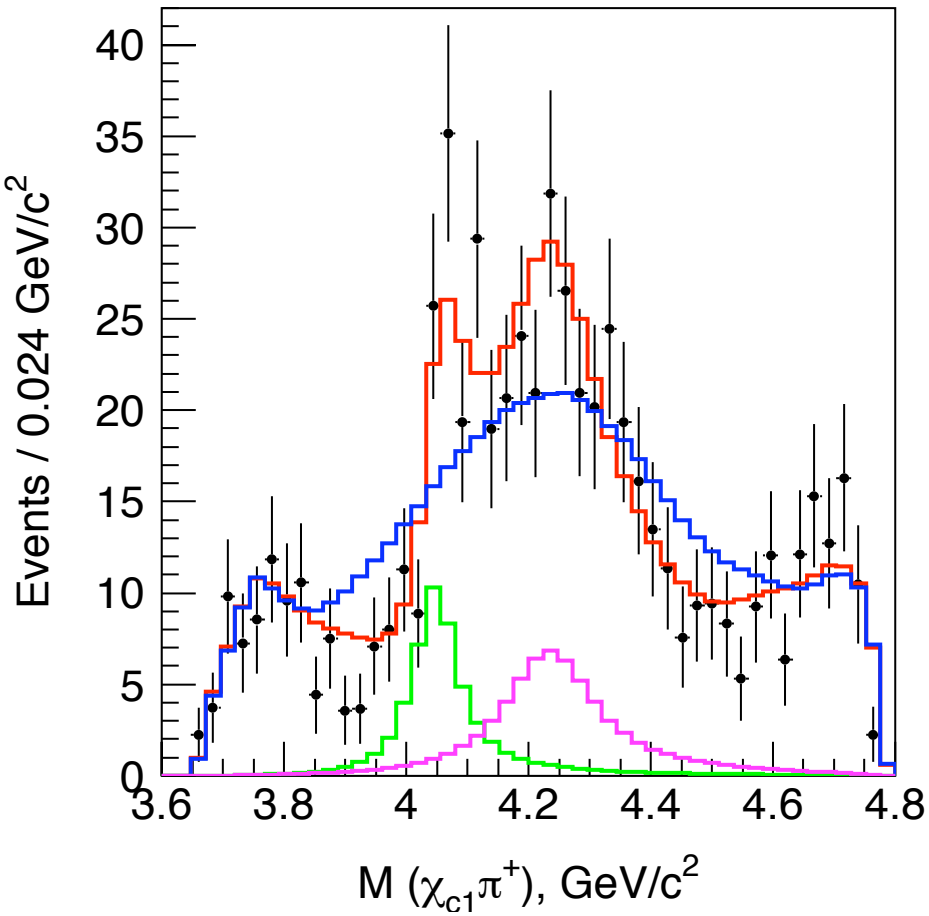
- $> 6\sigma$ even under speculative changes to the fitting model
- *two* terms preferred at $> 5\sigma$

	Z_1^+	Z_2^+
M/MeV	$4051 \pm 14^{+20}_{-41}$	$4248^{+44\,+180}_{-29\,-35}$
Γ/MeV	$82^{+21\,+47}_{-17\,-22}$	$177^{+54\,+316}_{-39\,-61}$
$\mathcal{B}_{\overline{\mathrm{B}}^0} \times \mathcal{B}_{Z^+}$	$(3.1^{+1.5\,+3.7}_{-0.9\,-1.7})$ $\times 10^{-5}$	$(4.0^{+2.3\,+19.7}_{-0.9\,-0.5})$ $\times 10^{-5}$

[*cf.* $\mathcal{B} \times \mathcal{B}$ with $X(3872)$, $Y(3940)$, $Z(4430)^+$]



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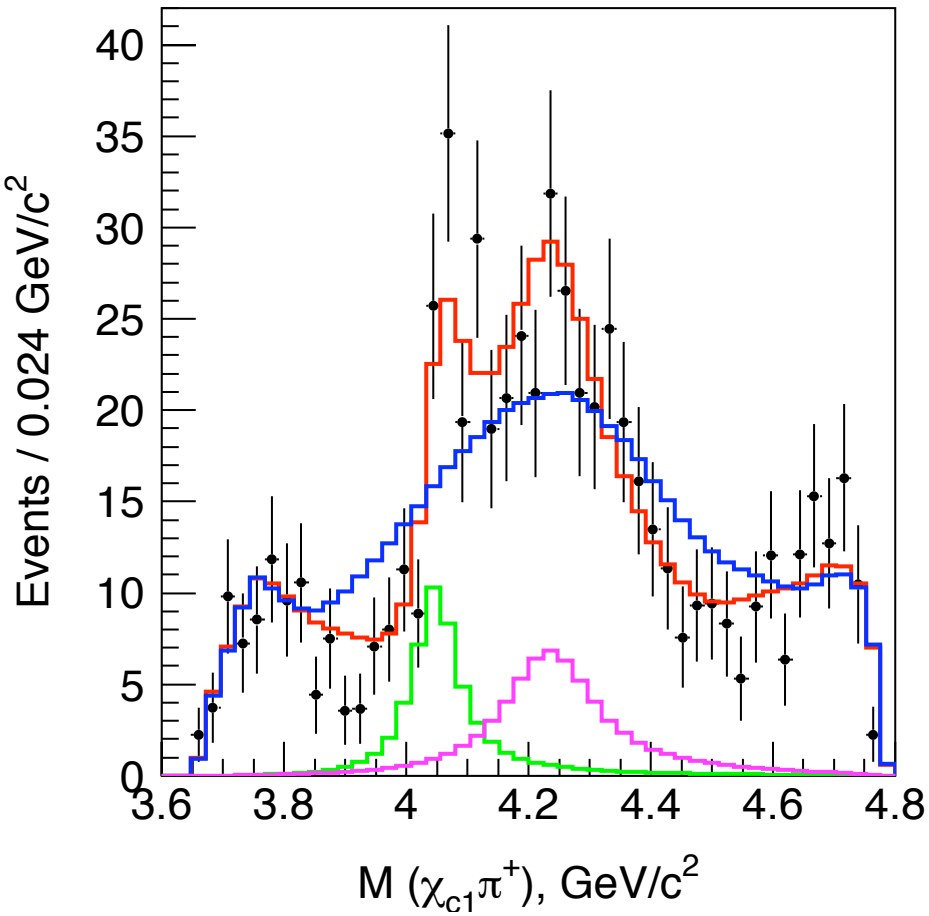

- Z_1^+, Z_2^+ join $Z(4430)^+$ as candidate hidden-charm exotics