CHARMONIUM AND CHARMONIUM-LIKE STATES AT BABAR

Vincent Poireau

CNRS-IN2P3, LAPP Annecy, Université de Savoie Mont Blanc, France

On behalf of the BaBar collaboration

Jinan

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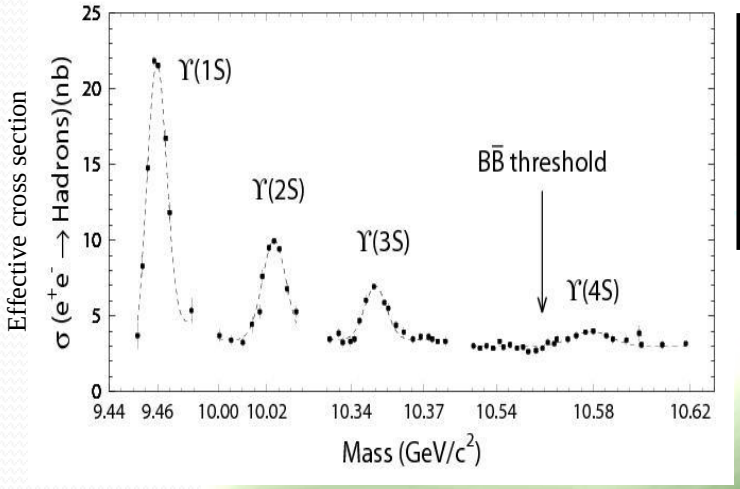
PEP-II AND BABAR



Energy in the centre-of-mass frame: 10.58 GeV

$e^+ e^- \rightarrow \Upsilon(4S)\ (b\bar{b}) \rightarrow B\bar{B}$

Ran also at Υ(2S), Υ(3S)

Luminosity:

$\mathcal{L} = 12.1\ 10^{33}\ cm^{-2}s^{-1}$

BABAR EXPERIMENT

Silicon vertex detector
Precise reconstruction of vertex, dE/dx

Solenoid 1.5 T

Drift chamber
Momentum, dE/dx

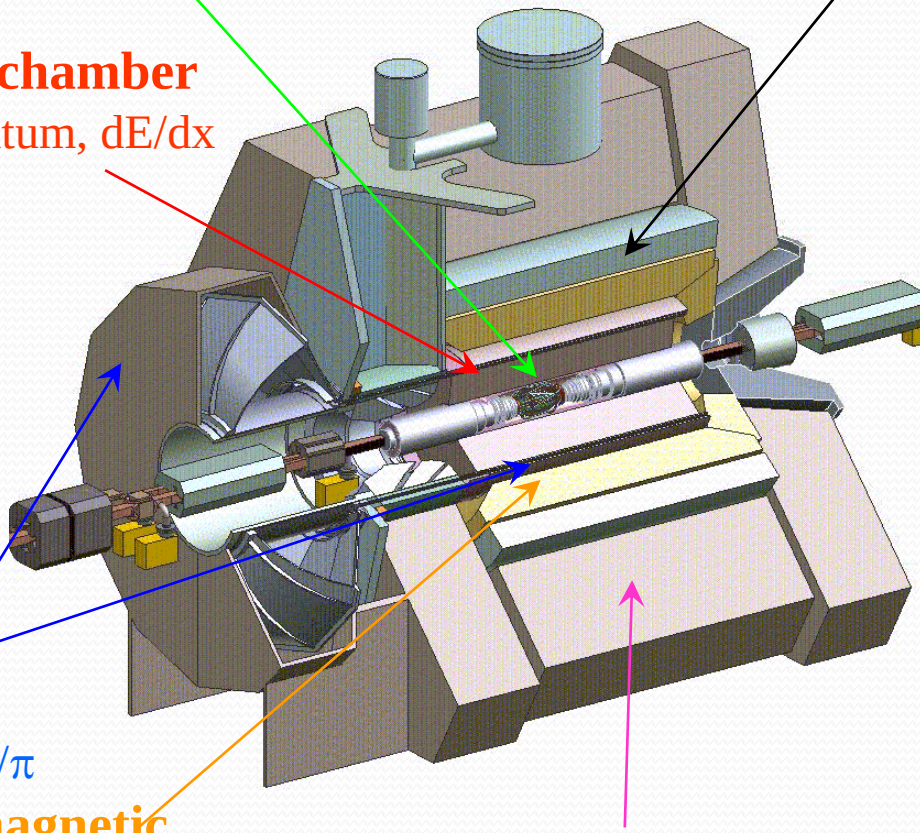
3.1 GeV e^+

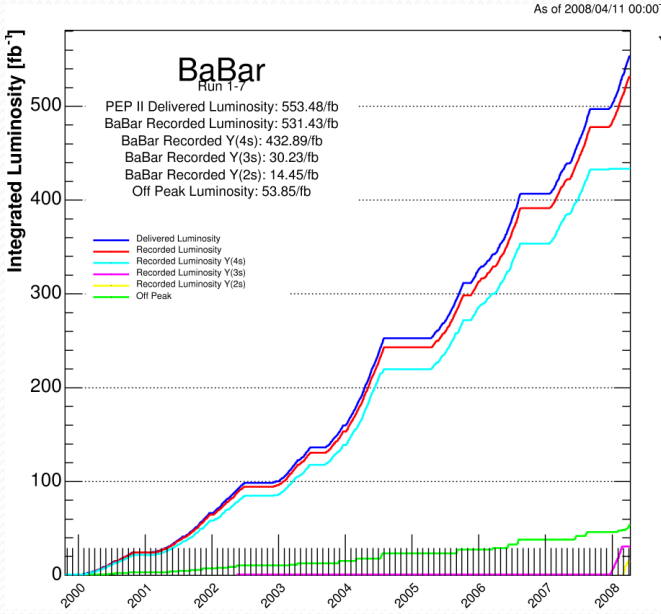
9 GeV e^-

Cherenkov detector
Identification, K/π

Electromagnetic calorimeter
Identification of π^0, γ, e^-, detection of neutral hadrons

Instrumented flux return
Identification μ, detection of neutral hadrons





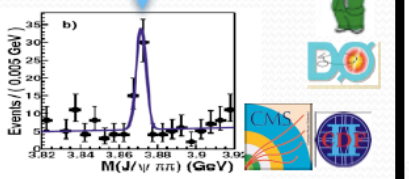
BABAR EXPERIMENT

- BaBar recorded 531 fb^{-1} in total
  - $\Upsilon(4S)$: 433 fb^{-1}
  - $\Upsilon(3S)$: 30 fb^{-1}
  - $\Upsilon(2S)$: 14 fb^{-1}
  - Off-peak: 54 fb^{-1}
- Cross sections at $\sqrt{s} = 10.58$ GeV
  - $\sigma(e^+e^- \to b\bar{b}) =$ **1.1 nb** $\to 475.10^6$ $B\bar{B}$ pairs
  - $\sigma(e^+e^- \to c\bar{c}) =$ **1.3 nb** $\to 633.10^6$ $c\bar{c}$ pairs
- BaBar is a B factory… but BaBar is also a charm factory!

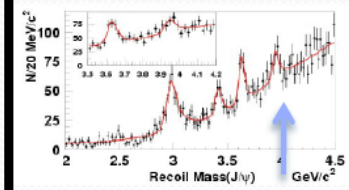
- The BaBar experiment switched off in 2008, but still produces many interesting results!
  - **551** papers in total
  - > **350** PhD thesis!
  - **26** papers in **2013**
  - **14** papers in **2014**
  - And **more** to come!

NEW STATE OVERVIEW

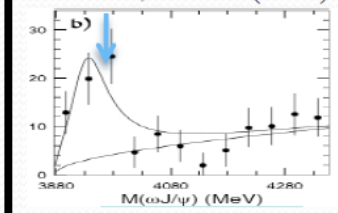
X(3872)
PRL 91, 262001 (2003)



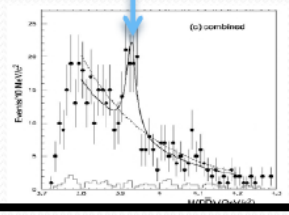
X(3940)
PRL 98, 082001 (2007)



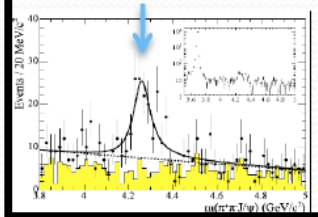
Y(3940)
PRL 94, 182002 (2005)



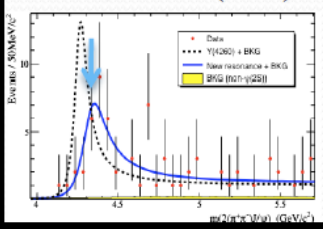
$\chi_{c2}(2P)$
PRL 96, 082003 (2006)



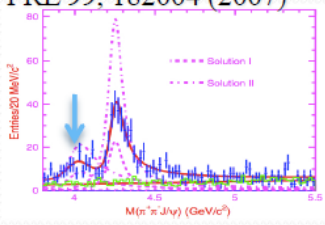
Y(4260)
PRL 95, 142001 (2005)



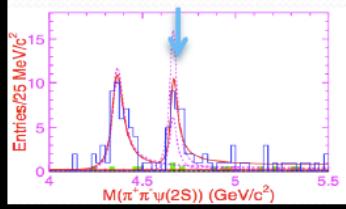
Y(4350)
PRL 98, 212001 (2007)



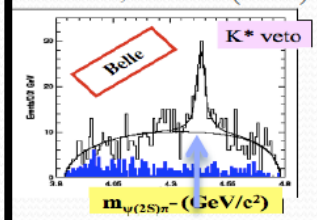
Y(4008)
PRL 99, 182004 (2007)



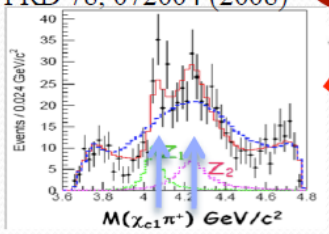
Y(4660)
PRL 99, 142002 (2007)



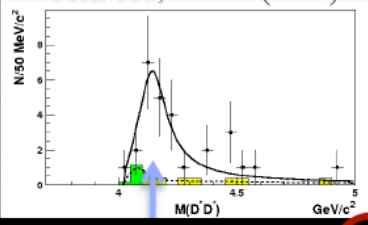
$Z(4430)^+$
PRL 100, 142001 (2008)



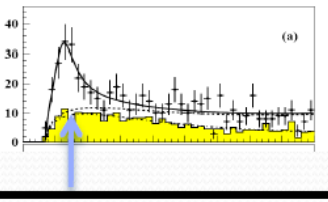
Z_1^+ and Z_2^+
PRD 78, 072004 (2008)



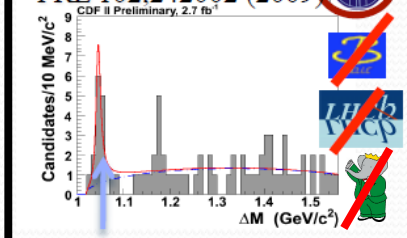
X(4160)
PRL 100,202001 (2008)



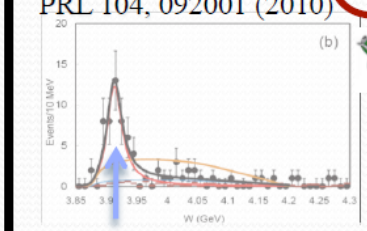
X(4630)
PRL 101, 172001 (2008)



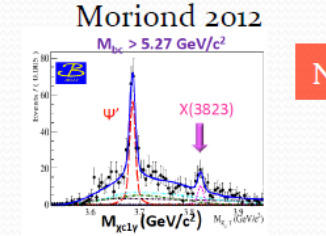
Y(4140)
PRL 102,242002 (2009)



X(3915)
PRL 104, 092001 (2010)



X(3832)
Moriond 2012



NEW

TOPICS

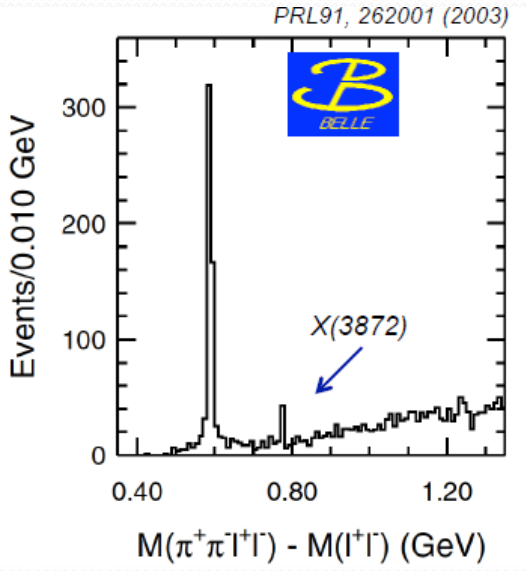
I will mainly focus on the charmonium-like states

- X(3872)
- X(3915)
- Inclusive charmonium production in $B^{\pm}$ decays and search for exotic states
- The Y family: Y(4260), Y(4008), Y(4350), Y(4660)
- Y(4140)
- $Z(4430)^{-}$
- $Z_1(4050)^{+}$ and $Z_2(4250)^{+}$

X(3872): WHERE IT ALL BEGAN

X(3872) DISCOVERY

- First observation in 2003 by Belle in B decays $B^{\pm} \to X(3872)K^{\pm}$ with $X(3872) \to J/\psi\pi^+\pi^-$
  - **First indication** of an exotic charmonium state!

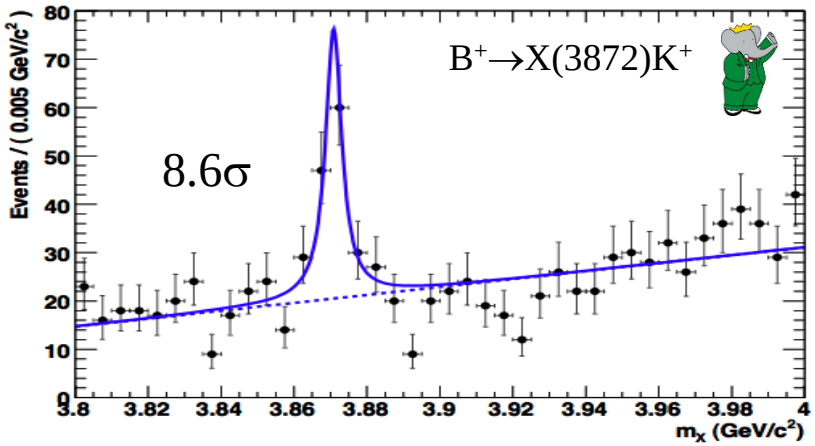


- Properties
  - $M = (3871.69 \pm 0.17)$ MeV/c^2
  - $\Gamma < 1.2$ MeV at 90% CL
  - $J^{PC} = 1^{++}$
- This state is above $D\bar{D}$ threshold
  - Should have **large** width! (if natural parity)
- This state is very close to the $D^{*0}\bar{D}^0$ threshold (affects width if unnatural parity)
  - $m(D^0) + m(\bar{D}^{0*}) = (3871.8 \pm 0.12)$ MeV/c^2
  - Is this a **coincidence**?
- BaBar: search for a charged partner (decaying to $J/\psi\pi^0\pi^-$) **Phys. Rev. D71, 031501 (2005)**
  - **No signal**

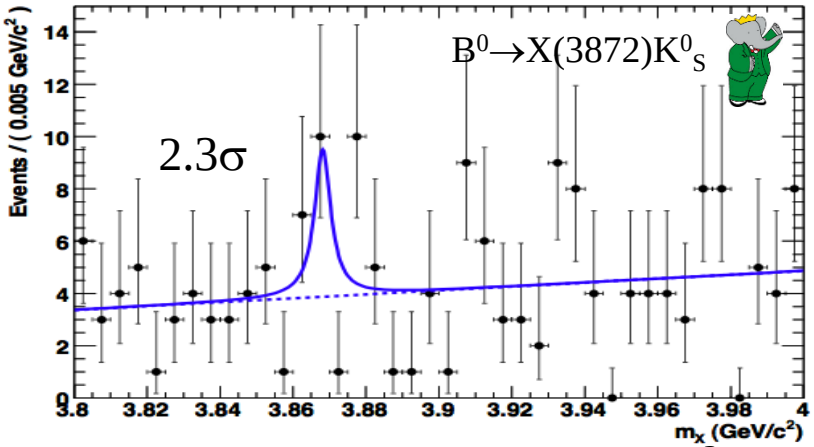
X(3872) → J/ψπ⁺π⁻

413 fb^{-1}

- BaBar results for X(3872) → J/ψπ⁺π⁻



$M_{J/\psi\pi^+\pi^-}$ (GeV/c^2)



$M_{J/\psi\pi^+\pi^-}$ (GeV/c^2)

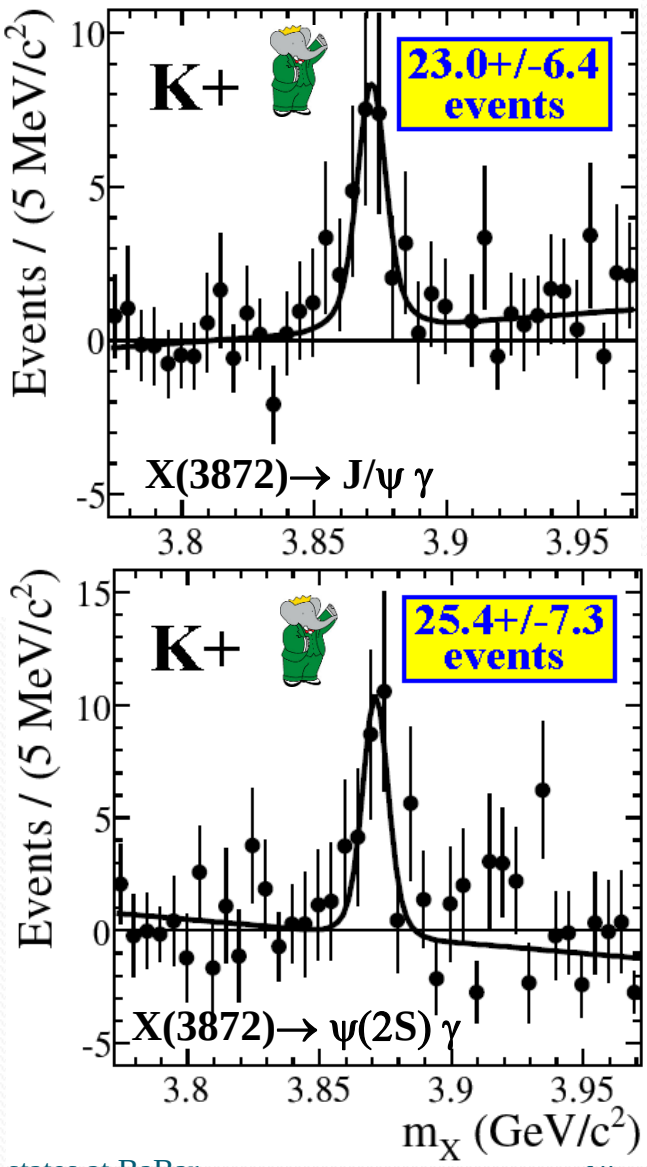
- Main results
  - BF($B^+ \to XK^+$, $X \to J/\psi\pi^+\pi^-$) = (8.4±1.5±0.7) x 10^{-6}
  - BF($B^0 \to XK^0$, $X \to J/\psi\pi^+\pi^-$) = (3.5±1.9±0.4) x 10^{-6}, <6.0x10^{-6} @ 90% C.L.
  - $R(X) = BF(B^0)/BF(B^+) = 0.41 \pm 0.24 \pm 0.05$
  - Γ(X)<3.3 MeV @ 90% CL

PRD 77,111101 (2008)

X(3872) → J/ψ γ, ψ(2S) γ

424 fb^{-1}

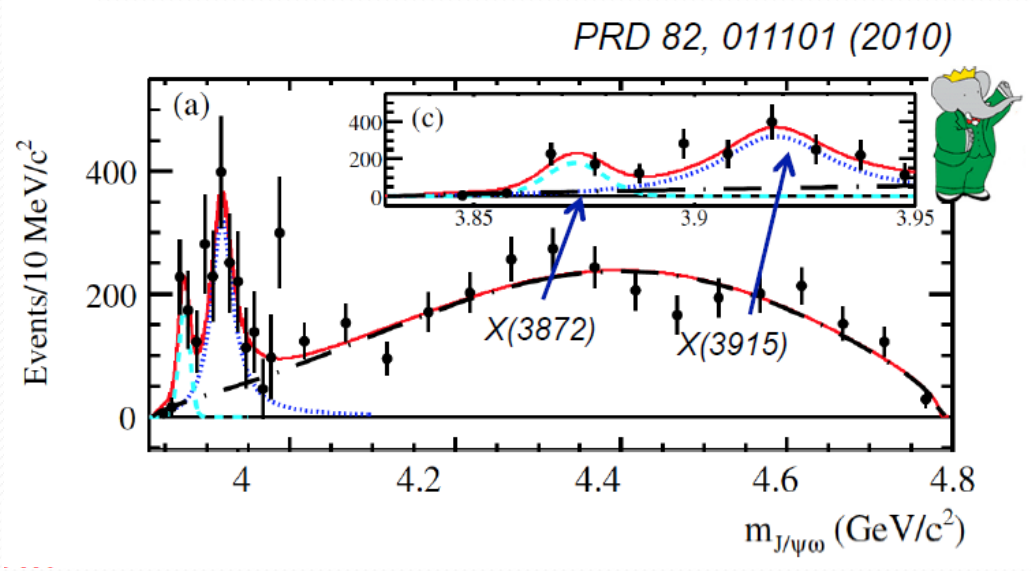
- Find 3.6σ evidence for $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\,\gamma$ **PRL 102, 132001 (2009)**
  - $BF(B^+ \to X(3872)K^+) \times (X(3872) \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$
- First evidence for $B^+ \to X(3872)K^+$, $X(3872) \to \psi(2S)\,\gamma$
  - **3.5σ** significance
  - $BF(B^+ \to X(3872)\,K^+) \times (X(3872) \to \psi(2S)\gamma) = (9.5 \pm 2.7 \pm 0.9) \times 10^{-6}$
- $BF(X(3872) \to \psi(2S)\,\gamma) / BF(X(3872) \to J/\psi\,\gamma) = 3.4 \pm 1.4$
  - Inconsistent with a **pure** $D^{*0}\bar{D}^0$ **molecule**, but consistent with $c\bar{c}$-$D^{*0}\bar{D}^0$ **admixture**
- No Signal seen by Belle in $X(3872) \to \psi(2S)\,\gamma$
  - Upper limit compatible with BaBar BF **PRL 107, 091803 (2011)**
- But signal confirmed by LHCb **NPB 886, 665 (2014)**



X(3872) → J/ψ ω

- Study the decay $B^{0,+} \to J/\psi\, \pi^+\pi^-\pi^0\, K^{0,+}$ $(\omega \to \pi^+\pi^-\pi^0)$

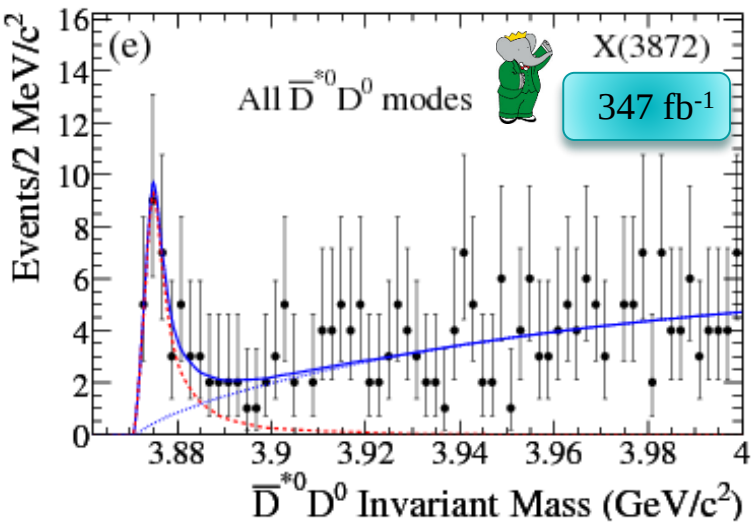
- Clear signal (4σ) for the X(3873) → J/ψ ω
  - 26.7 ± 7.6 events



- BF(X → J/ψ ω) / BF(X → J/ψ $\pi^+\pi^-$) = 0.8 ± 0.3

THE X(3872)→$D^0\bar{D}^{*0}$ SAGA

- Belle in 2006: excess in the $\bar{D}^0D^0\pi^0$ invariant mass in $B \to \bar{D}^0D^0\pi^0K$, with a shifted mass with respect to $X(3872) \to J/\psi\pi^+\pi^-$
  - $M = (3875.2 \pm 0.7^{+1.2}_{-2.0})$ MeV/c²
  - **2σ away** from the $X(3872) \to J/\psi\pi^+\pi^-$
- BaBar in 2008: study of $X(3872)\to D^0\bar{D}^{*0}$
  - Confirms X(3872) signal (**4.9σ**)
  - $M = (3875.1^{+0.7}_{-0.5} \pm 0.5)$ MeV/c²
  - **4.5σ away** from the $X(3872) \to J/\psi\pi^+\pi^-$
  - Measurement of the **width**
    - $\Gamma = 3.0\ ^{+1.9}_{-1.4} \pm 0.9$ MeV
  - **Angular** study inconclusive



- In 2010, Belle redid the mass measurement for $D^0\bar{D}^{*0}$ with more statistics
  - $M = (3872.9\ ^{+0.6}_{-0.4}\ ^{+0.4}_{-0.5})$ MeV/c²
  - In better **agreement** with $X(3872) \to J/\psi\pi^+\pi^-$
    - However **width** still in disagreement $\Gamma = (3.9\ ^{+2.8}_{-1.4}\ ^{+0.2}_{-1.1})$ MeV
  - In **disagreement** with BaBar result

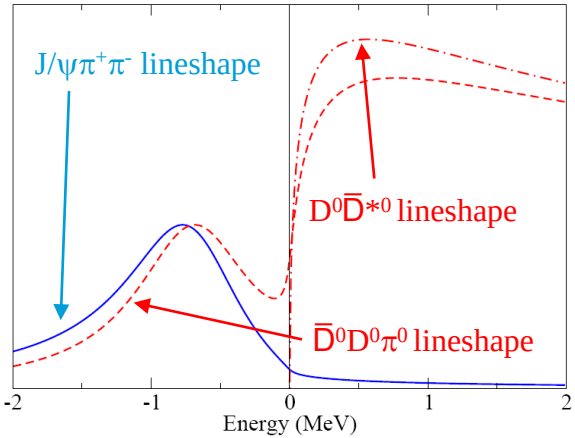
Belle: PRL 97, 162002 (2006)
BaBar: PRD77, 011102 (2008)
Belle: PRD 81, 031103 (2010)

THE X(3872)→$D^0\bar{D}^{*0}$ SAGA

- Saga summary

Year	Collaboration	Channel	Mass measurement
2003-2015	World average	$J/\psi\ \pi^+\ \pi^-$	$M = (3871.69 \pm 0.17)$ MeV/c²
2006	Belle	$\bar{D}^0 D^0 \pi^0$	$M = (3875.2 \pm 0.7^{+1.2}_{-2.0})$ MeV/c²
2008	BaBar	$D^0\bar{D}^{*0}$	$M = (3875.1^{+0.7}_{-0.5} \pm 0.5)$ MeV/c²
2008	Belle	$D^0\bar{D}^{*0}$	$M = (3872.9\ ^{+0.6}_{-0.4}\ ^{+0.4}_{-0.5})$ MeV/c²

- One possible explanation for the mass shift in X(3872)→$D^0\bar{D}^{*0}$
  - **No proximity of the threshold** for $J/\psi\pi^+\pi^-$
    - Mass and width measurement **correspond** to the real particle
  - **Proximity of the threshold** for $D^0\bar{D}^{*0}$
    - If particle just below threshold, we see a peak above threshold **NOT corresponding** to the real particle

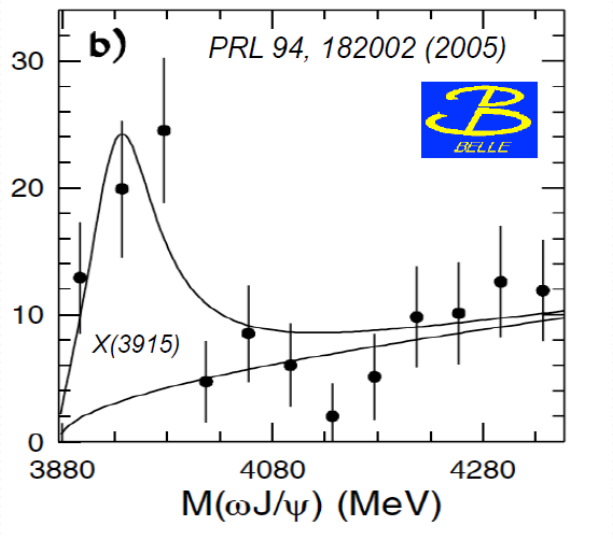


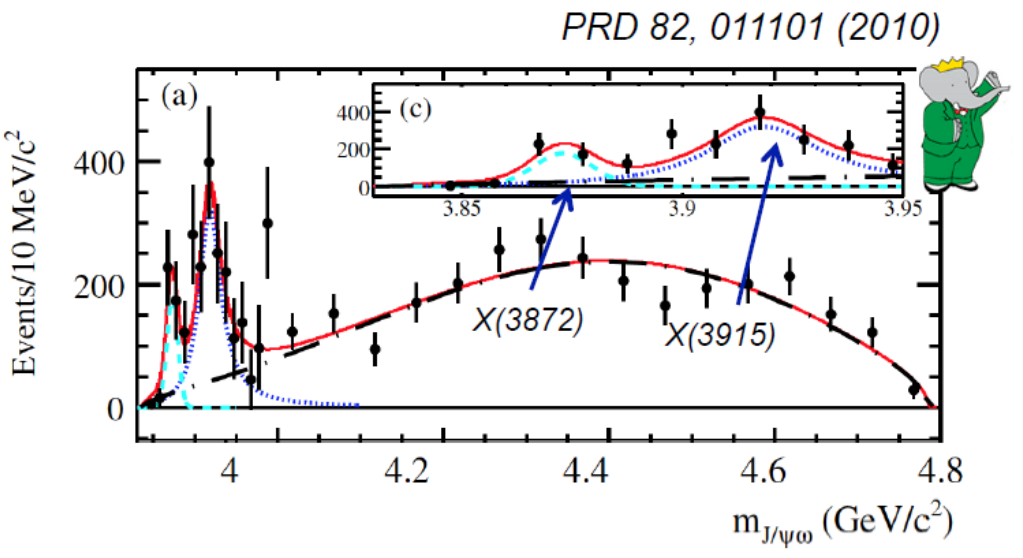
Braaten, Stapleton,PRD 81, 014019 (2010)

X(3915)

X(3915) DISCOVERY

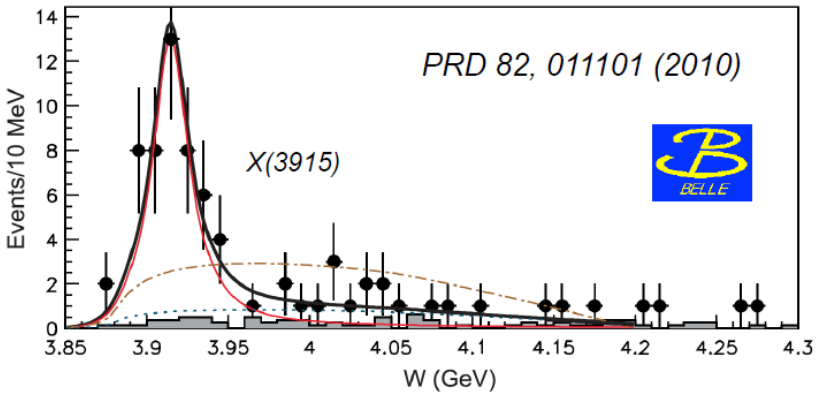
- First observation by Belle in B→X K, X → J/ψω decays (called Y(3940) then) and confirmed later by BaBar





- Belle also observed X(3915) in two-photon production

$\gamma\gamma \rightarrow X(3915) \rightarrow J/\psi\omega$

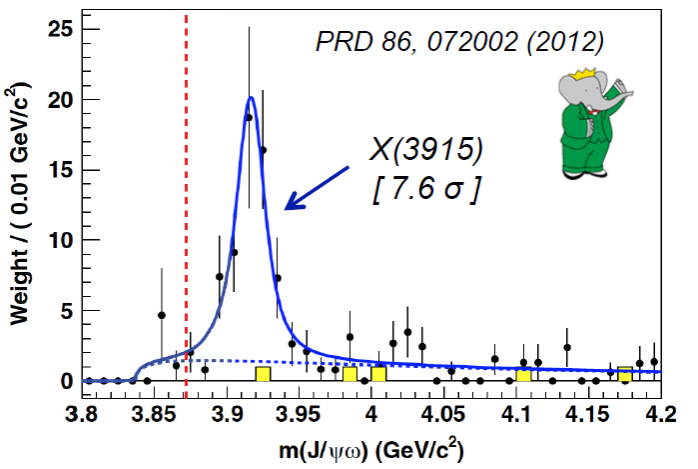


X(3915) IN BABAR

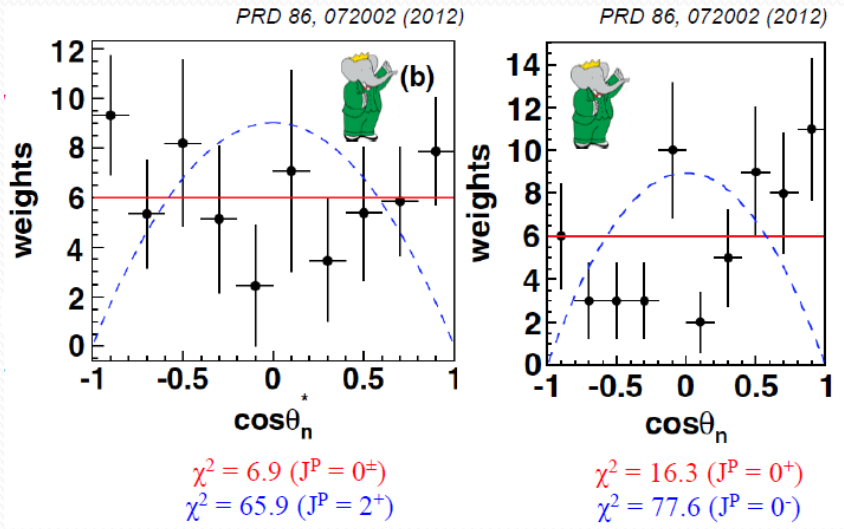
519 fb^{-1}

- BaBar also studied X(3915) → J/ψω in two-photon production
- Good agreement between BaBar and Belle measurements

	BABAR	Belle
Mass (MeV/c^2)	$3919.4 \pm 2.2 \pm 1.6$	$3915 \pm 3 \pm 2$
Width (MeV)	$13 \pm 6 \pm 3$	$17 \pm 10 \pm 3$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=0) (eV)	$52 \pm 10 \pm 3$	$61 \pm 17 \pm 8$
$\Gamma_{\gamma\gamma} \times \mathcal{B}$ (J=2) (eV)	$10.5 \pm 1.9 \pm 0.6$	$18 \pm 5 \pm 2$



- Discriminate between $J^P = 0^{\pm}$ and $J^P = 2^+$ with angular analysis
  - **0^+ strongly preferred** in distribution of all variables
  - Consistent with the X(3915) being the **χ_{c0}(2P) state**



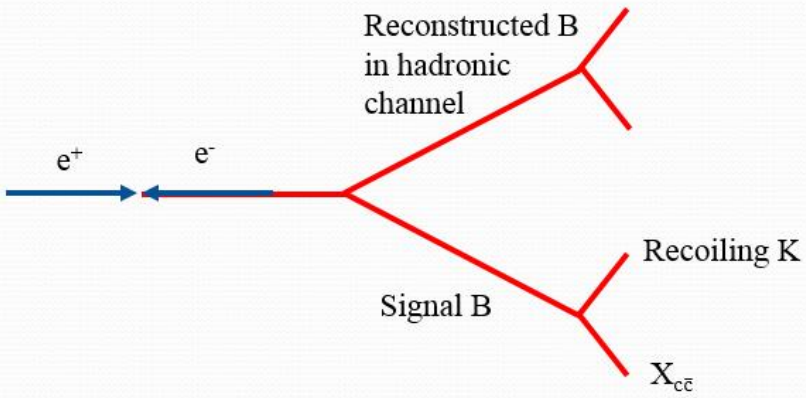
INCLUSIVE CHARMONIUM PRODUCTION IN $B^{\pm}$ DECAYS

Preliminary result

PRINCIPLES

- Study of the two-body decays $B^{\pm} \rightarrow K^{\pm} X_{c\bar{c}}$
  - Update of Phys. Rev. Lett. 96, 052002 (2006) with **full data sample**

- With the full reconstruction of one B meson, one can look at the momentum of a Kaon in its B center of mass



- Will exhibit a peak each time there is a two body decay $B \rightarrow K\ X$

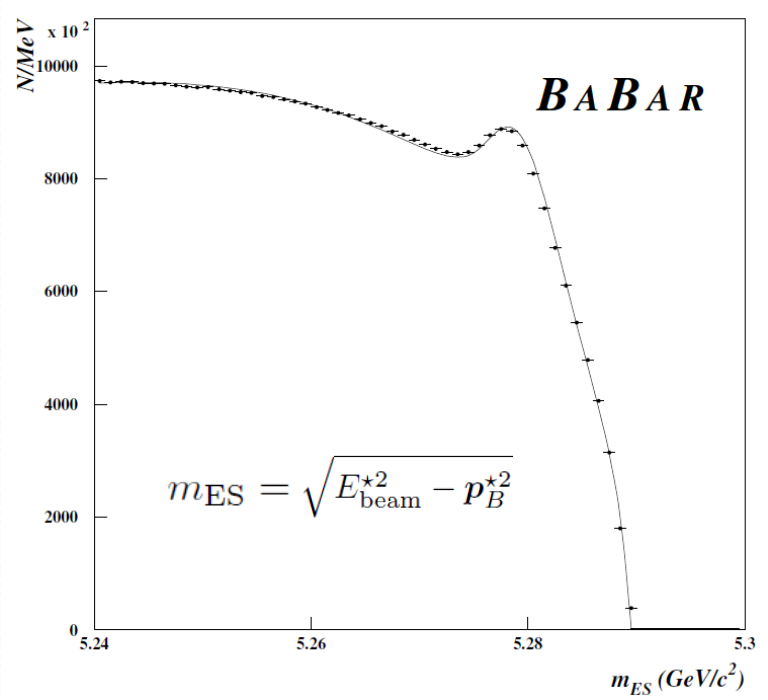
$$m_X = \sqrt{m_B^2 + m_K^2 - 2E_K m_B}$$

PRINCIPLES

- Allows to measure absolute BR for the normal charmonium spectrum and to search for the exotic charm mesons
  - **Independent** from the $X_{c\bar{c}}$ decay channel

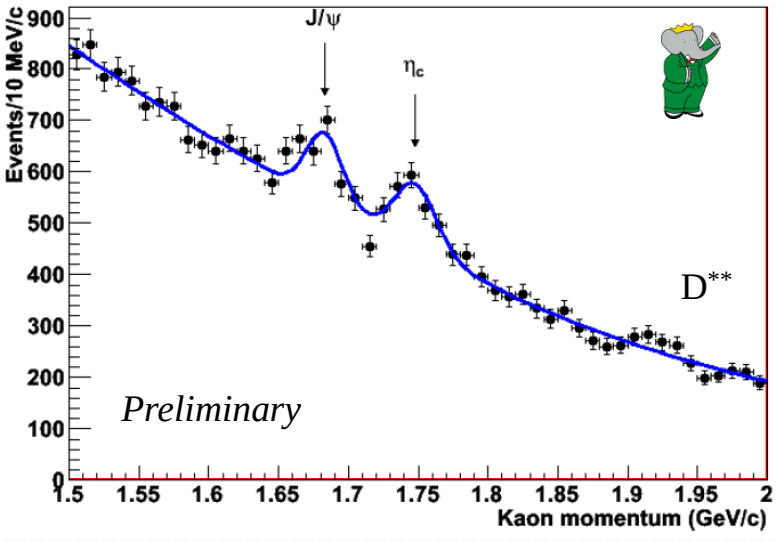
- Sensitivity : BR of a few 10^{-4}

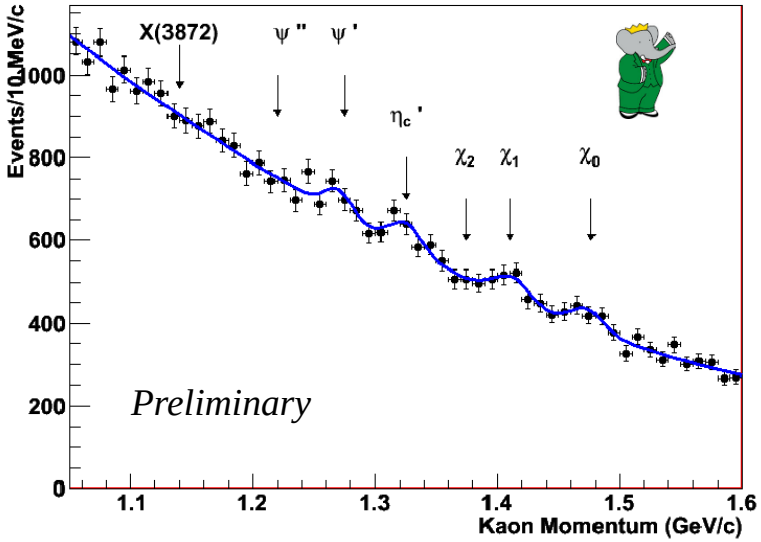
- m_{ES} distribution of all the exclusively reconstructed $B^{\pm}$ meson

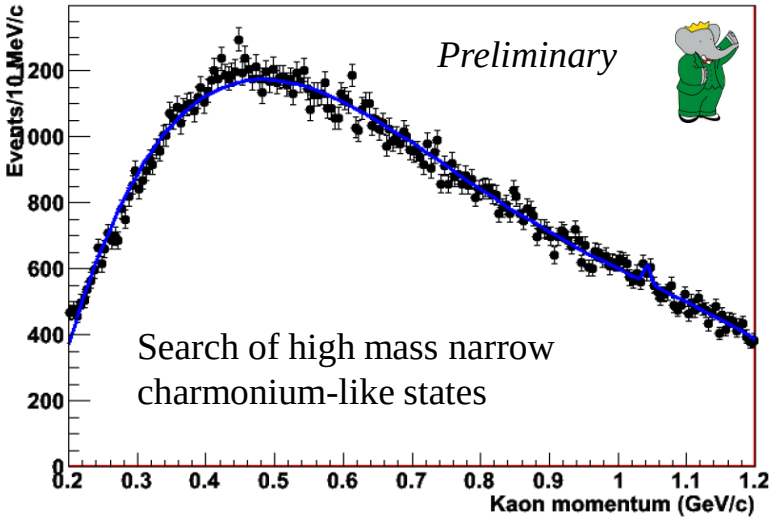


SPECTRA

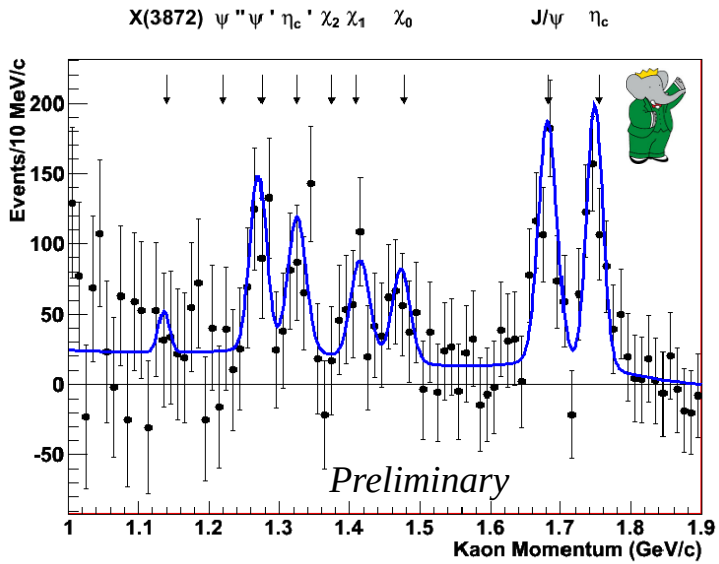
424 fb^{-1}







4.75 GeV



RESULTS

- Improvements in BR($B^{\pm} \to K^{\pm} X_{c\bar{c}}$) for all channels

Particle	Yield	Peak Position	Width	BF(10^{-4})
J/ψ	516±67			9.6±1.2(sta)±0.8(sys)
η_c	655±77	2982±5	<43	13.3±1.8(stat)±0.4(sys)±0.3(ref)
χ_{c0}	218±76			4.4±0.9
χ_{c1}	192±35			7.0±1.3(stat)±1.0(sys)
χ_{c2}	0±32			<1.2
η_c (2S)	283±94	3632±0.007	<33	6.0±2.1(stat)±0.4(sys)
ψ'	293±90			6.2±2(stat)±0.6(sys)
$\psi(3770)$	0±49			<2.0
X(3872)	75±81			1.4±1.5 or < 4.4

($B^+ \to XK^+$, $X \to J/\psi\pi^+\pi^-$) ~ 0.1

- Analysis extended to D mass region

Particle	Yield	Peak Position	BF(10^{-4})	PDG 2014
D^0	126±20		3.5±0.5(sta)±0.3(sys)	3.7±0.17
D^{*0}	126±21		3.5±0.5(stat)±0.3(sys)	4.2±0.34
$D_1(2420)^0$	97±25		2.1±0.5(stat))±0.3(sys)	-
$D^{**0}(2680)$	95±29	2.68±0.003	2.1±0.6(stat)±0.3(sys)	-
$D^{\pm}$	44±10		3.3±0.8(sta)±0.3(sys)	2.0±0.21
$D^{*\pm}$	40±10		3.0±0.8(stat)±0.3(sys)	2.1±0.16
$D^*(2420)^{\pm}$	52±13		3.9±1.0(stat))±0.3(sys)	-

- Charged kaon recoiling against a neutral B: no signal for charged $X_{c\bar{c}}$ states

THE Y FAMILY

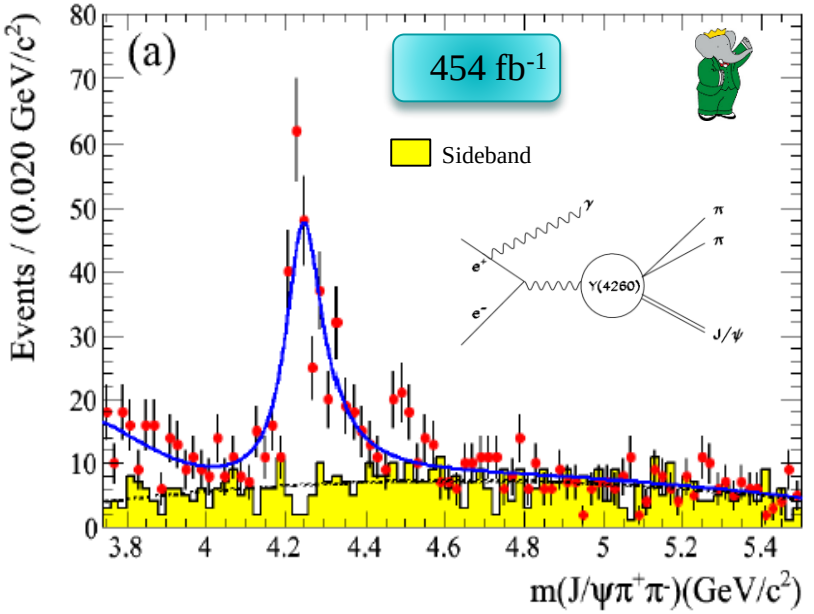
Y(4260)

- Resonance discovered in $e^+e^- \to \gamma_{ISR}(J/\psi\pi^+\pi^-)$ by BaBar in 2005
- Confirmation by CLEO-c, CLEO-III, and Belle with some spread in the resonance parameters

- Belle result suggested the existence of another broad structure: the Y(4008)

- BaBar updated the measurement in 2012
  - $M = (4244 \pm 5 \pm 4)$ MeV/c^2
  - $\Gamma = (114\ ^{+16}_{-17} \pm 7)$ MeV

- Excess at low mass: might result from the $\psi(2S)$ tail and a possible $e^+e^- \to J/\psi\pi^+\pi^-$ continuum contribution
- No evidence for the Y(4008) state

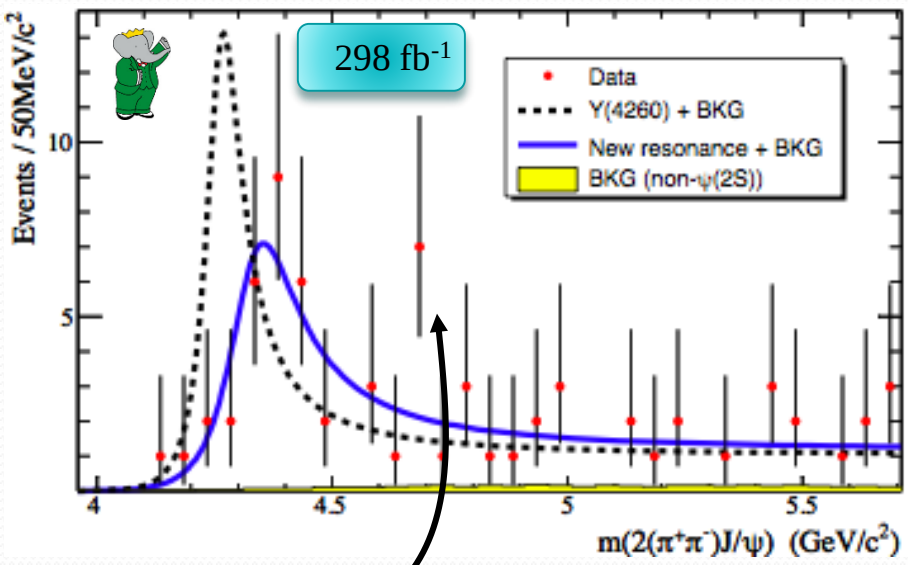


PRD 86, 051102 (2012)

Y(4260)... AND Y(4350)

- Natural to study of Y(4260) → $\psi(2S)\pi^+\pi^-$ in ISR production

- Peak found… but not at the expected position!
  - **New resonance**: the **Y(4350)**
  - M = (4324 ± 24) MeV/c^2
  - Γ = (172 ± 33) MeV



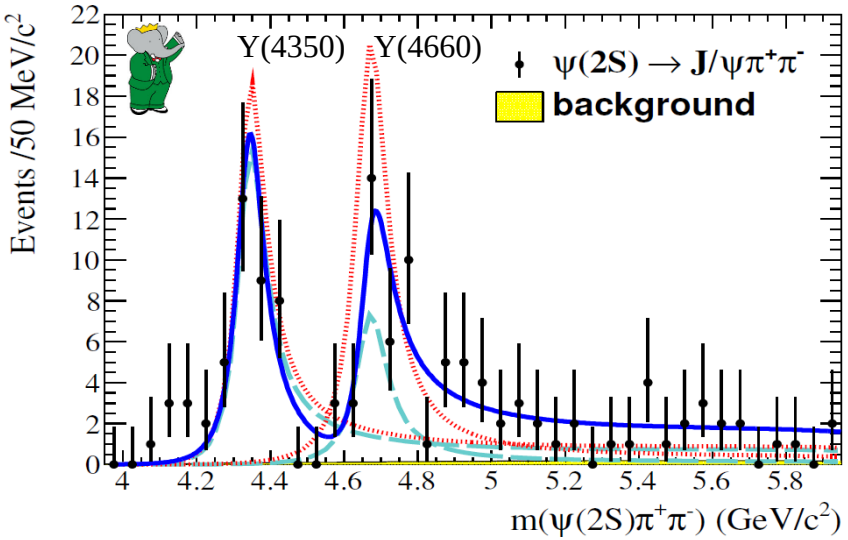
- Confirmed by Belle
  - M = (4361 ± 9 ± 9) MeV/c^2
  - Γ = (74 ± 15 ± 15) MeV
- Belle also reports another state: Y(4660)
  - M = (4664±11±5) MeV/c^2, Γ = (48±15±3) MeV

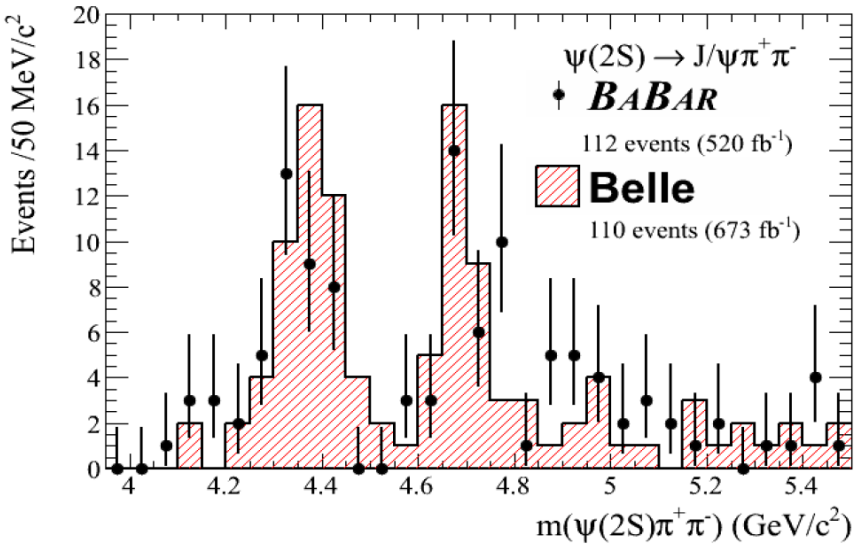
BaBar: PRL 98, 212001 (2007)
Belle: PRL 99, 142002 (2007)

UPDATED RESULT

520 fb^{-1}

- Update of BaBar analysis with the full dataset





- BaBar confirms the Y(4660)
- Parameters for both Y(4350) and Y(4660) are consistent with the Belle measurements

Parameters	First Solution (constructive interference)	Second Solution (destructive interference)
Mass Y(4360) (MeV/c^2)	$4340 \pm 16 \pm 9$	
Width Y(4360) (MeV)	$94 \pm 32 \pm 13$	
$\mathcal{B} \times \Gamma_{ee}(Y(4360))$ (eV)	$6.0 \pm 1.0 \pm 0.5$	$7.2 \pm 1.0 \pm 0.6$
Mass Y(4660) (MeV/c^2)	$4669 \pm 21 \pm 3$	
Width Y(4660) (MeV)	$104 \pm 48 \pm 10$	
$\mathcal{B} \times \Gamma_{ee}(Y(4660))$ (eV)	$2.7 \pm 1.3 \pm 0.5$	$7.5 \pm 1.7 \pm 0.7$
ϕ (°)	$12 \pm 27 \pm 4$	$-78 \pm 12 \pm 3$

Y(4140)

Phys. Rev. D 91, 012003 (2015)

MOTIVATION

- 2009 + 2011

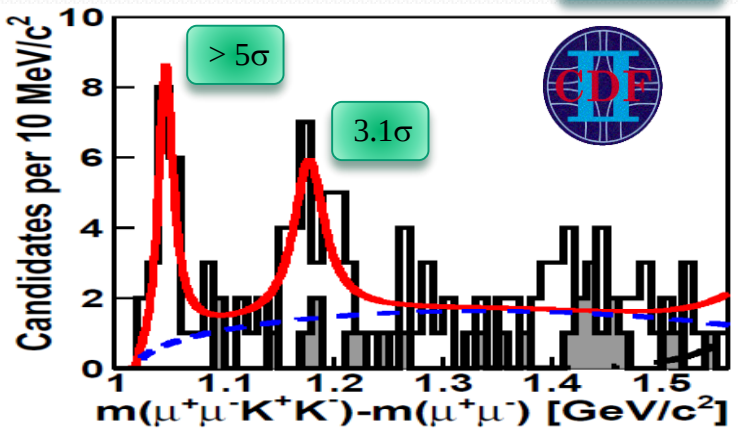
CDF studied the decay mode

$B^+ \to J/\psi\, \phi\, K^+$, $\phi \to K^+ K^-$, $J/\psi \to \mu^+\mu^-$

- Looked at **J/ψ ϕ invariant mass**
- Observed **two narrow peaks**, named **X(4140)** and **X(4270)**

PRL102, 242002 (2009)
arXiv:1101.6058 (2011)

6.0 fb^{-1}



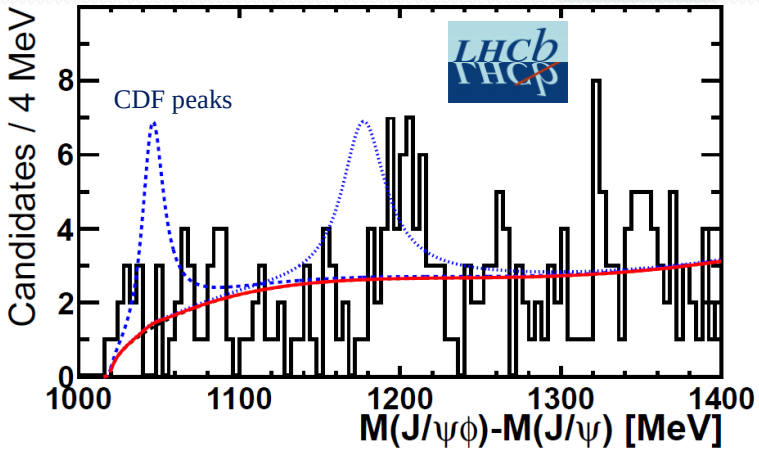
- 2012

LHCb did not confirm these peaks

- **2.4σ disagreement** with CDF

PRD85, 091103 (2012)

0.37 fb^{-1}

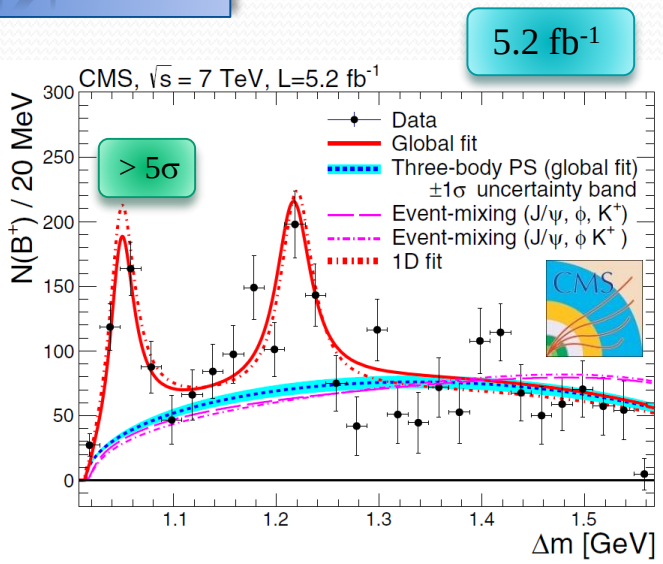


MOTIVATION

- 2013

CMS confirmed the presence of the two resonances

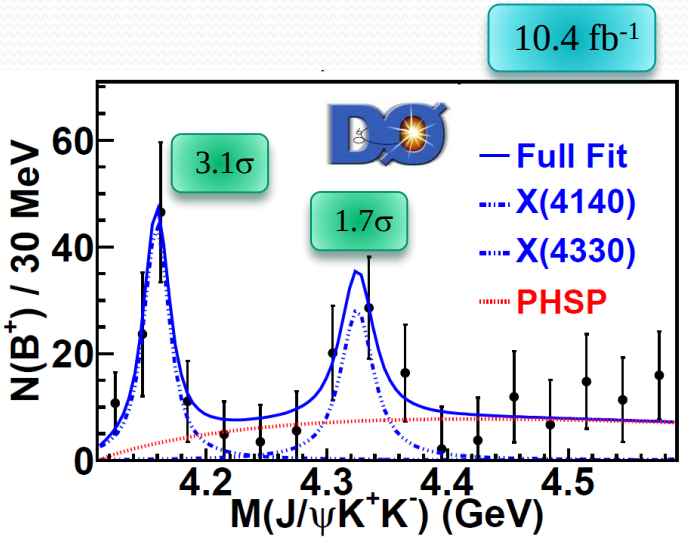
Physics Letter B 734, 261 (2014)



- 2014

D0 saw evidence for the two resonances

PRD89, 012004 (2014)

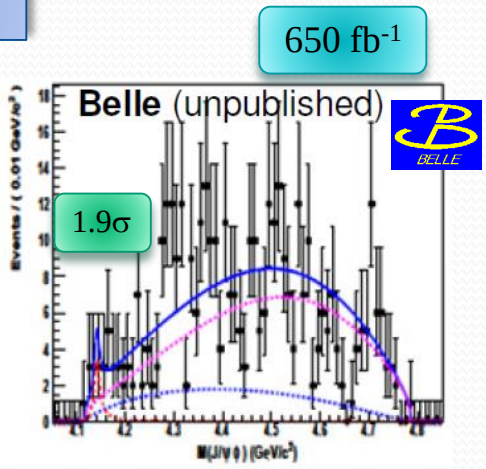


MOTIVATION

- Nota: 2009

Belle did the study (unpublished) Lepton-Photon conference 2009

  - Unable to conclude due to **low efficiency** at threshold



- Summary of the previous results

	X(4140)		X(4270)	
Reference	Mass (MeV/c^2)	Width (MeV)	Mass (MeV/c^2)	Width (MeV)
CDF PRL102,242002(2009)	$4143 \pm 2.9 \pm 1.2$	$11.7\ ^{+8.3}_{-5.0} \pm 3.7$	Possible signal	
CDF arXiv:1101.6058	$4143.4\ ^{+2.9}_{-3.0} \pm 0.6$	$15.3\ ^{+10.4}_{-6.1} \pm 2.5$	$4274.4\ ^{+8.4}_{-6.7} \pm 1.9$	$32.3\ ^{+21.9}_{-15.3} \pm 7.6$
LHCb PRD85,091103(R) (2012)	No signal		No signal; excess at ~ 4.3 GeV/c^2	
D0 PRD89,012004(2014)	$4159 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6\ ^{+3.0}_{-8.0}$	~ 4360	30.0 (fixed)
CMS arXiv:1309.6920	$4148.0 \pm 2.4 \pm 6.3$	$28\ ^{+15}_{-11} \pm 19$	$4313.8 \pm 5.3 \pm 7.3$	$38\ ^{+30}_{-15} \pm 16$

BABAR ANALYSIS

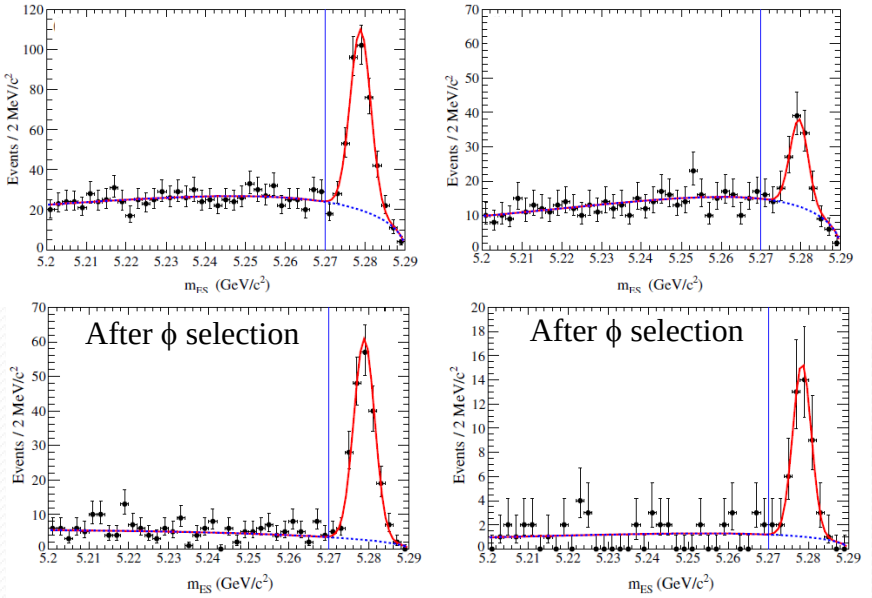
424 fb^{-1}

- Study of the processes $B^+ \to J/\psi\, K^+ K^- K^+$, $B^0 \to J/\psi\, K^+ K^- K^0_S$
  - $J/\psi \to e^+e^-, \mu^+\mu^-$ $\quad \phi \to K^+ K^-$
  - Perform the **branching fraction** measurements
  - Search for the **resonances** X(4140) and X(4270)

- Branching fraction measurement
  - Fit to the **m_{ES} distributions**

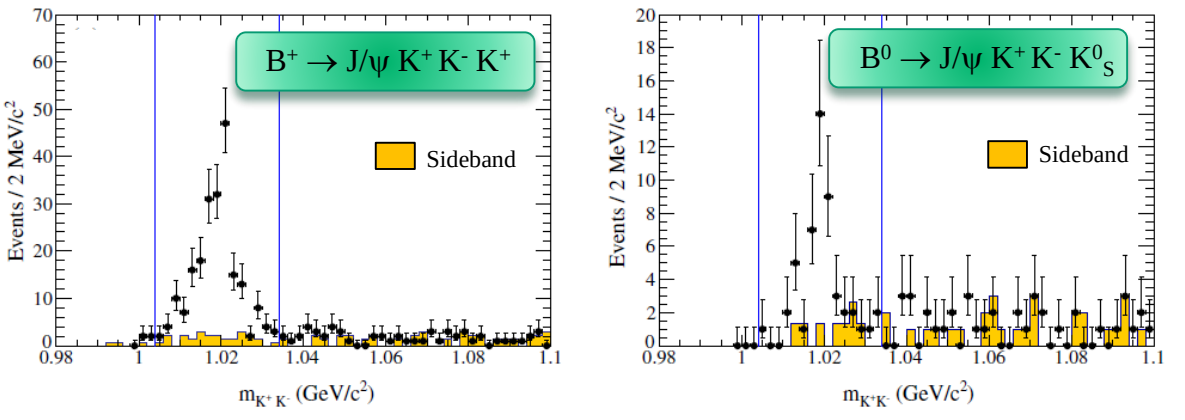
$$m_{\mathrm{ES}} = \sqrt{E^{\star 2}_{\mathrm{beam}} - p^{\star 2}_{B}}$$

$B^+ \to J/\psi\, K^+ K^- K^+$ $\qquad$ $B^0 \to J/\psi\, K^+ K^- K^0_S$



BRANCHING FRACTIONS

- Observation of a clear $\phi \rightarrow K^+ K^-$ signal



- Yields and branching fractions

B channel	Event yield	ϵ (%)	Corrected yield	$\mathcal{B}$ ($\times 10^{-5}$)
$B^+ \rightarrow J/\psi K^+ K^- K^+$	290 ± 22	15.08 ± 0.04	1923 ± 146	$3.37 \pm 0.25 \pm 0.14$
$B^+ \rightarrow J/\psi \phi K^+$	189 ± 14	13.54 ± 0.04	1396 ± 103	$5.00 \pm 0.37 \pm 0.15$
$B^0 \rightarrow J/\psi K^+ K^- K^0$	68 ± 13	10.35 ± 0.04	657 ± 126	$3.49 \pm 0.67 \pm 0.15$
$B^0 \rightarrow J/\psi \phi K^0$	41 ± 7	10.10 ± 0.04	406 ± 69	$4.43 \pm 0.76 \pm 0.19$

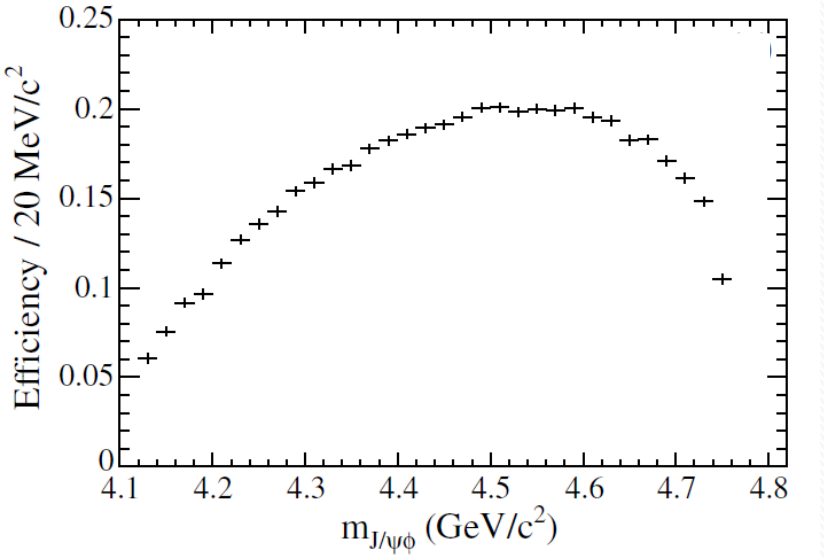
- Values in agreement with previous BaBar measurement and with other experiments (CLEO, LHCb)
- Ratio of the resonant and nonresonant BF in agreement with predictions from spectator quark model

SEARCH FOR RESONANCES

- Study of the J/ψ ϕ mass spectrum in B → J/ψ ϕ K

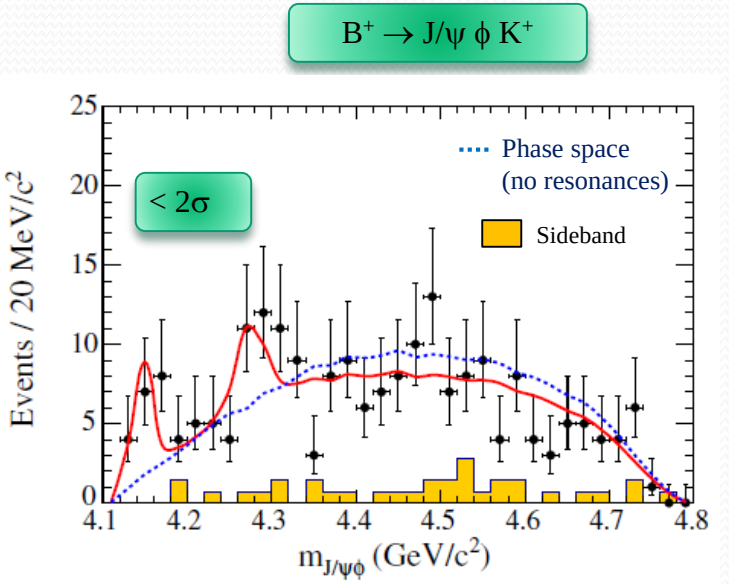
- Ingredients
  - **Signal**: two incoherent Breit-Wigner distributions with parameters fixed to CDF values arXiv:1101.6058 (2011)
    - **2D efficiency map** taken into account in the fit
  - **Background**: uniform distribution (phase space)

- Efficiency in the J/ψ ϕ invariant mass:

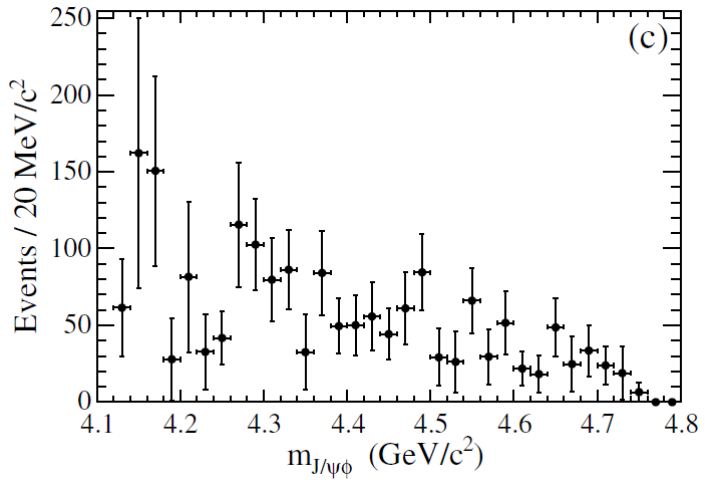


SEARCH FOR RESONANCES

- Result of the fit
  - Fit with the **two CDF resonances**
    - χ^2/NDF = 12.7/12
  - Fit with **no resonances**
    - χ^2/NDF = 26.4/14



- Efficiency-corrected and background-subtracted J/ψ φ mass spectrum for the combined B^0 and B^+ samples



SEARCH FOR RESONANCES

- Fit fractions with the assumption of two resonances
  - f(4140) = (9.2 ± 3.3 ± 4.7)%; UL(90% CL) = 13.3%
  - f(4270) = (10.6 ± 4.8 ± 7.1)%; UL(90% CL) = 18.1%

- Comparison to other experiments

Experiments	f (4140) [%]	f (4270) [%]
CDF	$14.9 \pm 2.9 \pm 2.4$	-
LHCb	<7	< 8
D0	$19 \pm 7 \pm 4$	-
CMS	10 ± 3	18.0 ± 7.3 (*)

(*) Estimated from number of signal events quoted

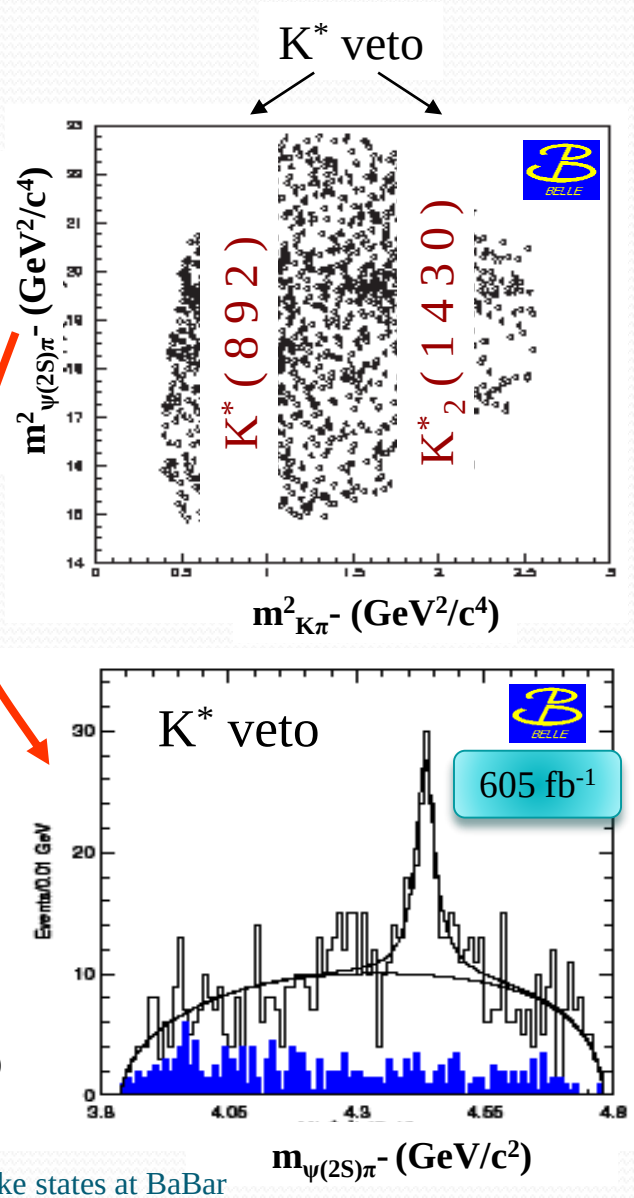
- No clear conclusion from BaBar on these resonances
  - Significance **below 2σ** for both X(4140) and X(4270)
  - Hypothesis that events are distributed uniformly on the Dalitz plot gives a **poorer description of the data**

$Z(4430)^-$: FIRST CHARGED STATE?

Phys. Rev. D 79, 112001 (2009)

$Z(4430)^-$ DISCOVERY

- Belle has reported a new charged charmonium-like state in the decay $B \to Z^- K$, $Z^- \to \psi(2S)\pi^-$
- The reported mass and width are:
  - $M = (4433 \pm 4 \pm 2)$ MeV/c^2
  - $\Gamma = (45^{+18}_{-13}{}^{+30}_{-13})$ MeV
- Significance: 6.5σ
  - 121 ± 30 events
- If this result is confirmed
  - **First observation** of a $c\bar{c}u\bar{d}$ tetraquark state, since it is charged and carries hidden charm
- Belle confirmed this result with a Dalitz plot analysis
  - $M = (4485^{+22}_{-22}{}^{+28}_{-11})$ MeV/c^2
  - $\Gamma = (200^{+41}_{-46}{}^{+26}_{-35})$ MeV



Belle: PRL 100, 142001 (2008)
Belle: PRD 80, 031104 (2009)
Belle: PRD 88, 074026 (2013)

BABAR SEARCH FOR Z(4430)$^-$

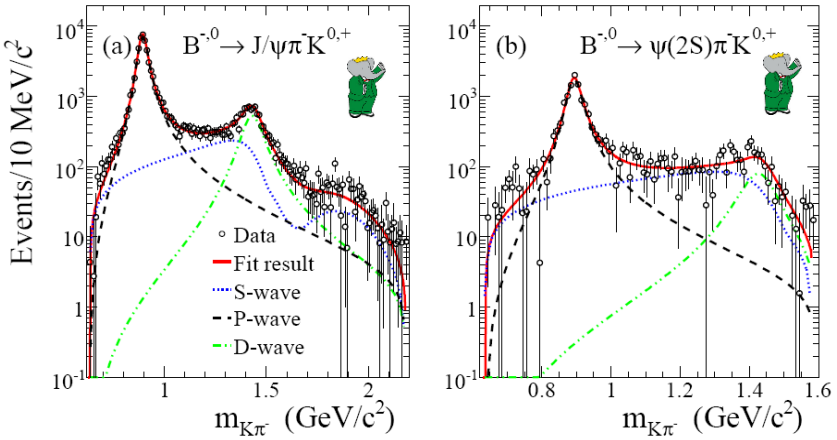
- Search for the $Z(4430)^-$ with 413 fb^{-1} in the decay modes
  - $B^- \to J/\psi \pi^- K^0$
  - $B^0 \to J/\psi \pi^- K^+$
  - $B^- \to \psi(2S) \pi^- K^0$
  - $B^0 \to \psi(2S) \pi^- K^+$

In the following, using "ψ" to denote J/ψ or $\psi(2S)$

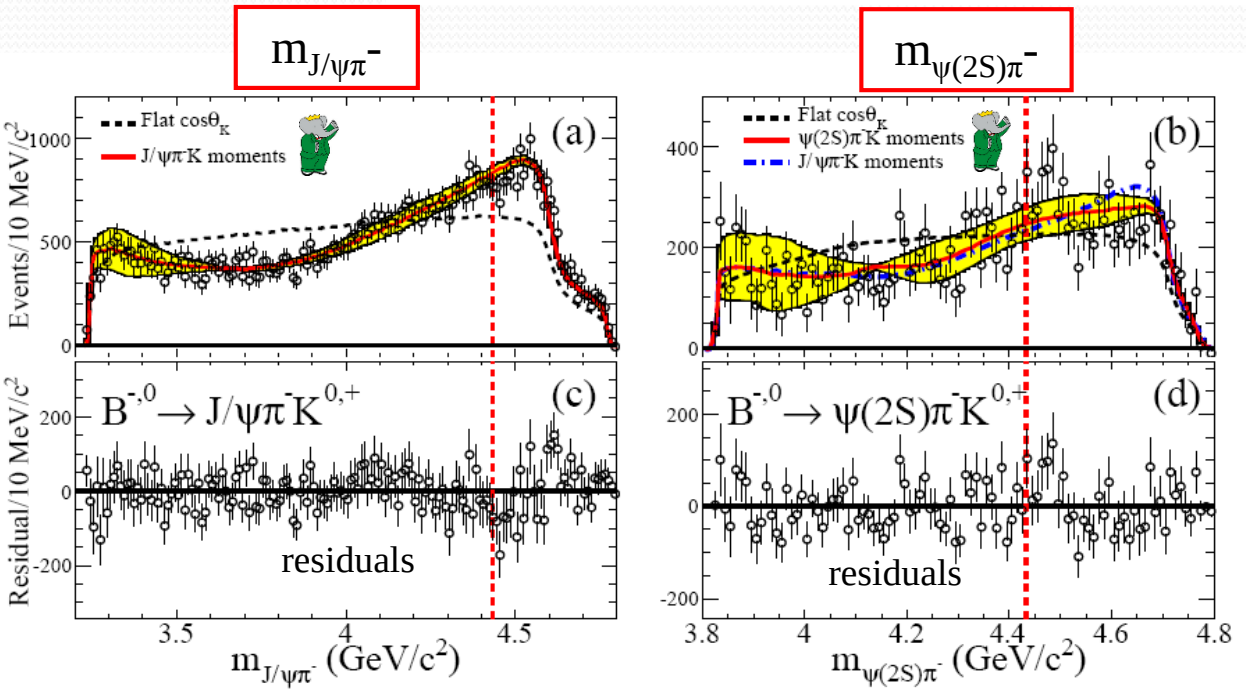
- Describe the $K\pi^-$ system in detail, since structure in the $K\pi^-$ mass and angular distributions dominates each Dalitz plot
- Correct the data for efficiency event-by-event across the Dalitz plot, and describe using only $K\pi^-$ S-, P-, and D-wave intensity contributions
- Project each $K\pi^-$ description onto the relevant $\psi\pi^-$ mass distribution to investigate the need for $Z(4430)^-$ signal above this "$K\pi^-$ background"

CORRECTED DISTRIBUTIONS

- Good descriptions of the m(Kπ^-) distributions are obtained



- The Kπ- reflections reproduce the data
  - no **evidence** for additional structure

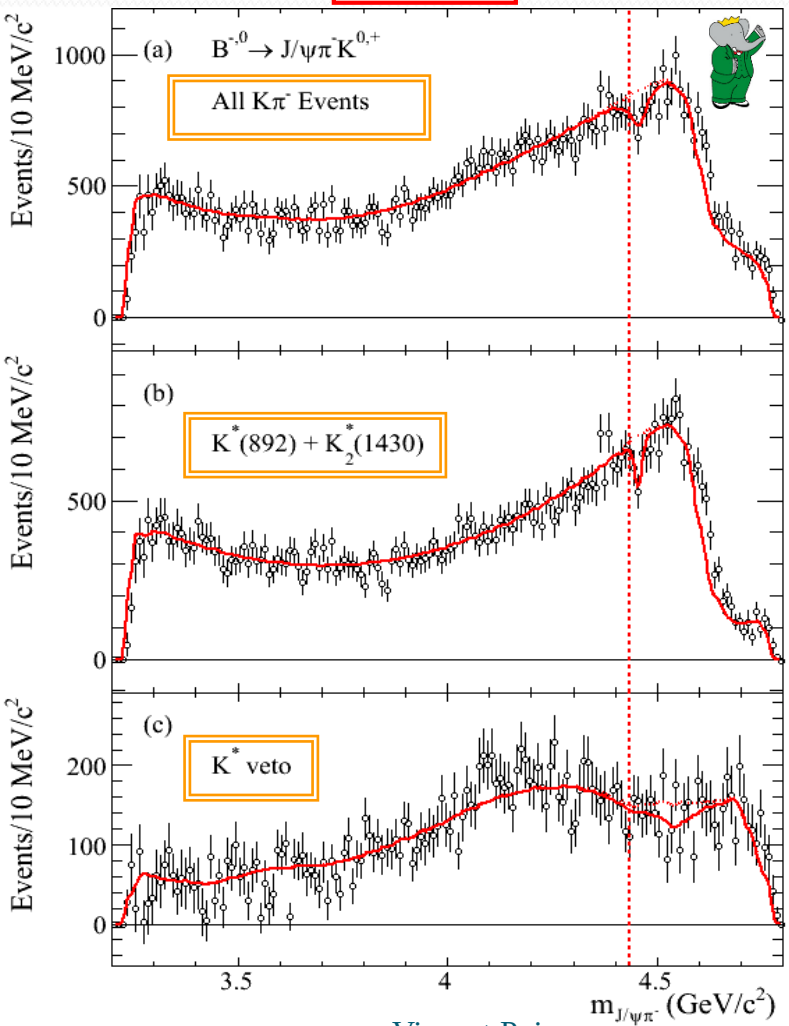


FITS TO THE CORRECTED $M_{\psi\pi^-}$ DISTRIBUTIONS

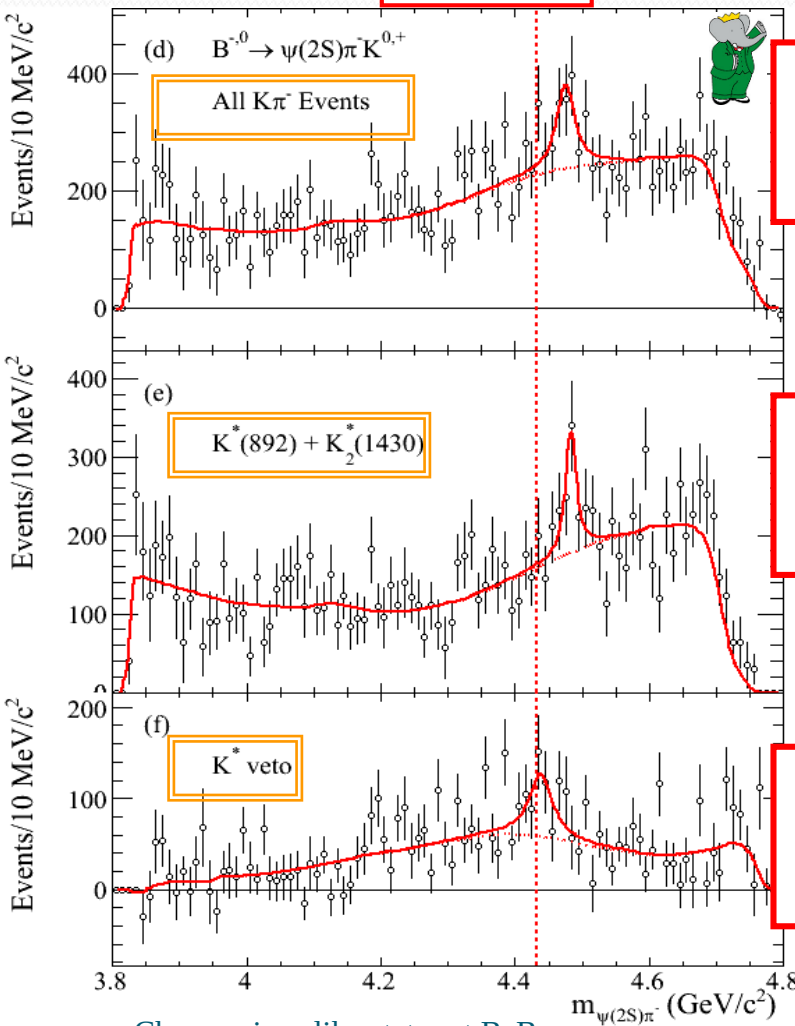
413 fb^{-1}

- No significant Z(4430)$^-$ signal in BaBar

$m_{J/\psi\pi^-}$



$m_{\psi(2S)\pi^-}$



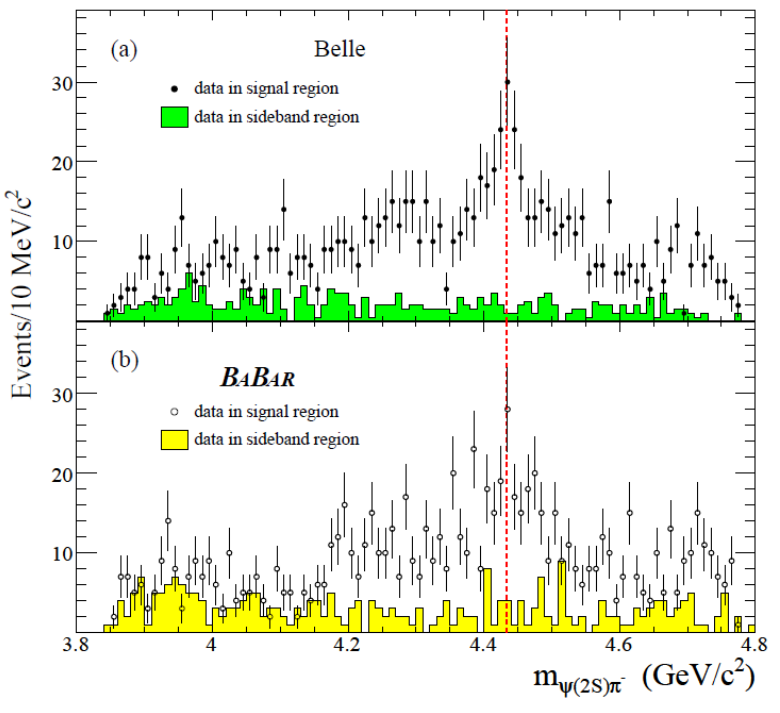
M=4476±8
Γ=32±16
2.7σ

M=4483±3
Γ=17±12
2.5σ

M=4439±8
Γ=41±33
1.9σ

BABAR SEARCH FOR Z(4430)$^-$

- BaBar – Belle comparison
  - BaBar and Belle distributions statistically **consistent**



- No need for the Z(4430)$^-$ in the BaBar data

- LHCb did confirm the existence of Z(4430)$^-$ with large significance

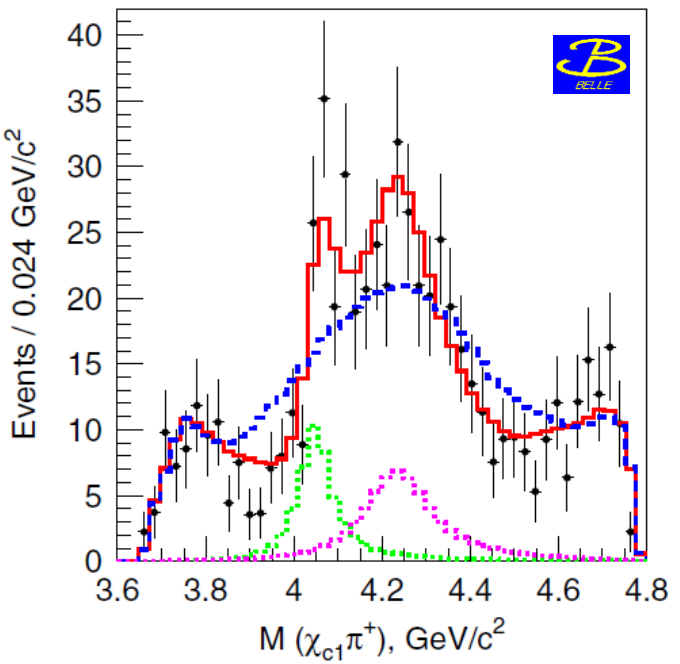
PRL 112, 222002 (2014)

$Z_1(4050)^+$ AND $Z_2(4250)^+$

Phys. Rev. D 85, 052003 (2012)

MOTIVATIONS

- Belle observed charged charmonium-like states $Z_1(4050)^+$ and $Z_2(4250)^+$ in $\bar{B}^0 \to \chi_{c1} K^- \pi$
  - $M_{Z1} = (4051 \pm 14\ ^{+20}_{-41})$ MeV/c^2
  - $\Gamma_{Z1} = (82^{+21}_{-17}\ ^{+47}_{-22})$ MeV
  - $M_{Z2} = (4248\ ^{+44}_{-29}\ ^{+180}_{-35})$ MeV/c^2
  - $\Gamma_{Z2} = (177^{+54}_{-39}\ ^{+316}_{-61})$ MeV



PRD78, 072004 (2008)

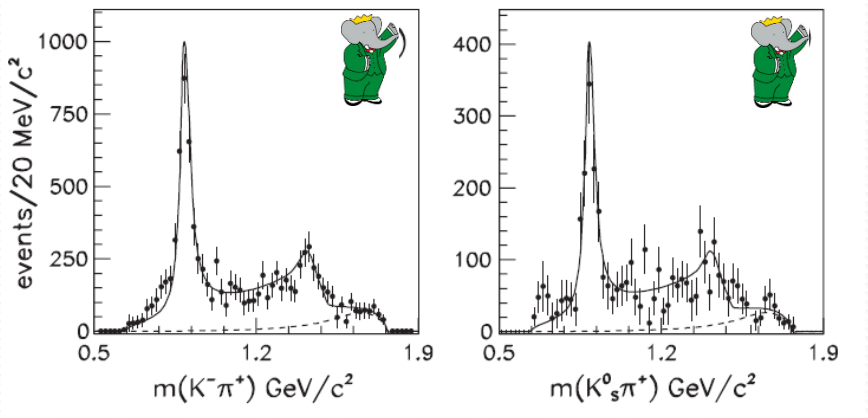
- BaBar studied the processes

$\bar{B}^0 \to \chi_{c1} K^- \pi^+$ and $B^+ \to \chi_{c1} K^0_S \pi^+$ to search for these states (where $\chi_{c1} \to J/\psi\gamma$)

ANALYSIS PROCEDURE

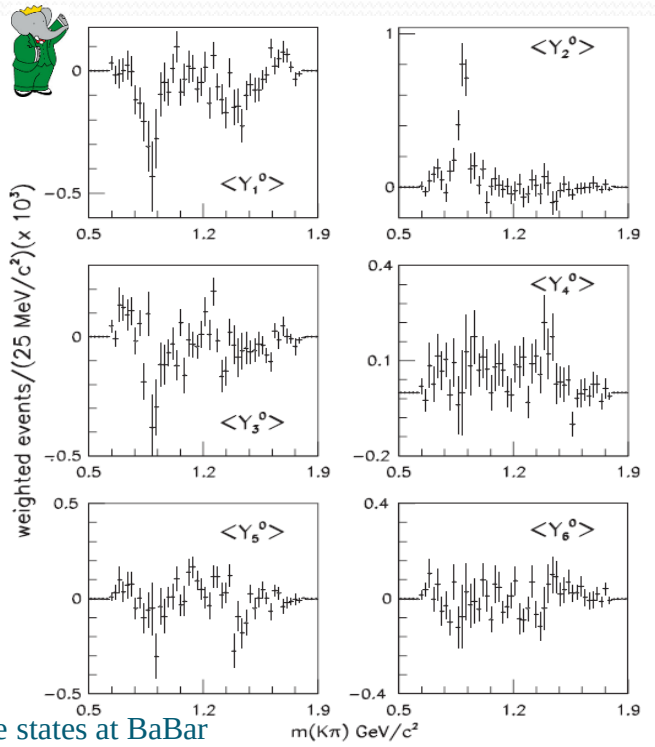
429 fb^{-1}

- Binned χ^2 fits to the background-subtracted and efficiency-corrected Kπ mass spectra in terms of S, P, and D waves amplitudes



Channel	S wave	P wave	D wave	χ^2/NDF
$\bar{B}^0 \to \chi_{c1} K^- \pi^+$	40.4 ± 2.2	37.9 ± 1.3 10.3 ± 1.5	11.4 ± 2.0	58/54
$B^+ \to \chi_{c1} K^0_S \pi^+$	42.4 ± 3.5	37.1 ± 3.2 10.4 ± 2.5	10.1 ± 3.1	55/54

- To represent the angular structure, we compute the efficiency-corrected Legendre polynomial moments $\langle Y_L^0 \rangle$ in each Kπ mass interval by correcting for efficiency and then weighting each event by the $Y_L^0(\cos\theta)$ functions

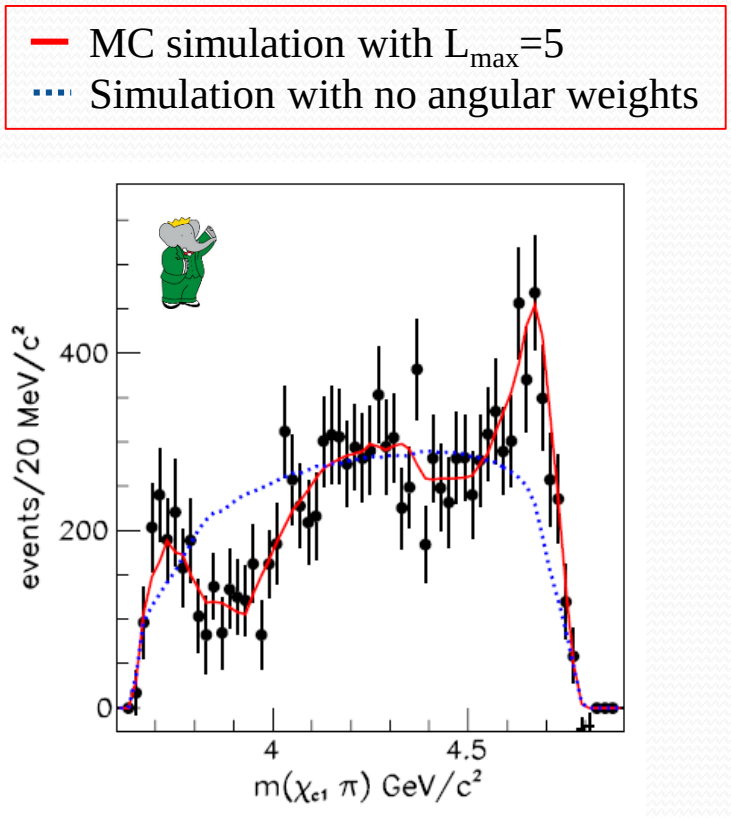


ANALYSIS PROCEDURE

- We generate high-statistics MC $m(\chi_{c1}\pi^+)$ distribution based on angular structure in $K\pi$ system using $\langle Y_L^0 \rangle$ in $K\pi$ mass interval

- Best result for $L_{max}=5$
- The excellent description of the data indicates that the angular information from the $K\pi$ channel with $L_{max}=5$ is able to account for the structures observed in the $\chi_{c1}\pi^+$ projection

- No need for additional structures in the mass distribution



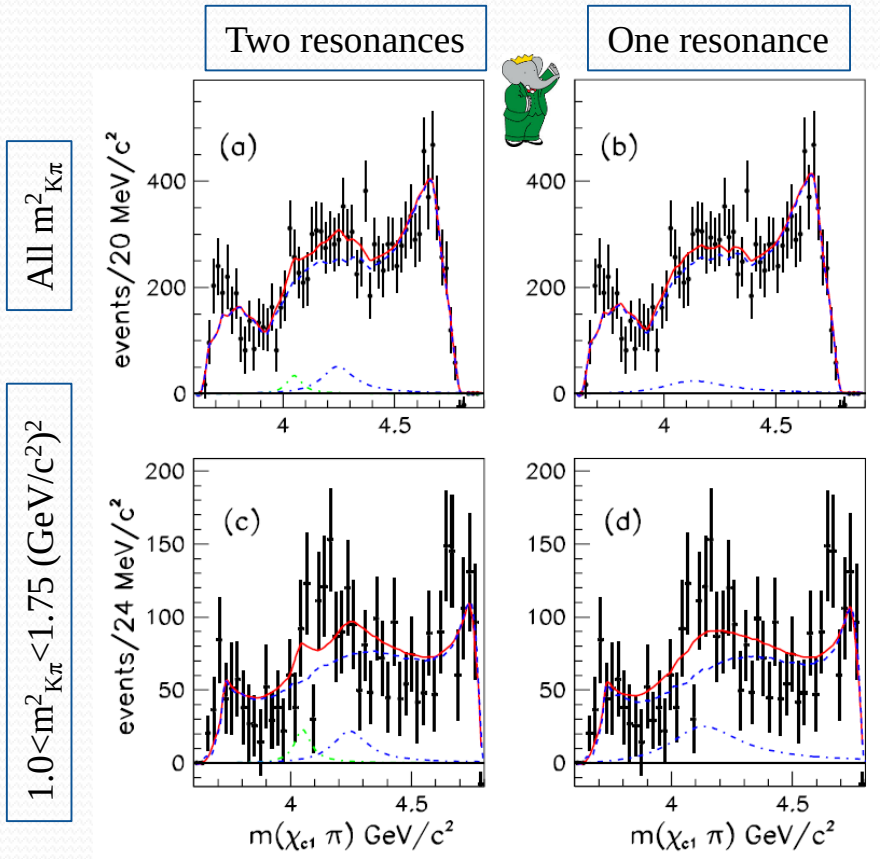
FITS OF THE DISTRIBUTIONS

- Fit the $\chi_{c1}\pi^+$ mass spectrum using two scalar Breit-Wigner with parameters fixed to the Belle measurement

- Less than 2σ in any distribution
- No significant excess for a single resonance either
- Limits on BF not inconsistent with Belle results due to Belle uncertainties

$$\mathcal{B}(\bar{B}^0 \to Z_1(4050)^+ K^-) \times \mathcal{B}(Z_1(4050)^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5},$$

$$\mathcal{B}(\bar{B}^0 \to Z_2(4250)^+ K^-) \times \mathcal{B}(Z_2(4250)^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5},$$



- Z_1 and Z_2 still need confirmation!

CONCLUSIONS

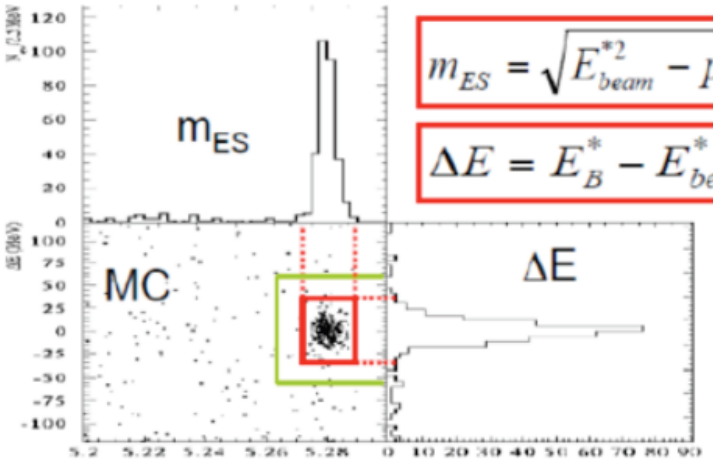
SUMMARY AND OUTLOOK

- Many results given by BaBar on charmonium and charmonium-like states
- Some states are in agreement among the different experiments
  - X(3872), X(3915), Y(4260), Y(4350)
- But some states are not confirmed by BaBar
  - Y(4008), Y(4140), $Z(4430)^+$, $Z(4050)^+$, $Z(4250)^+$
- This situation should be clarified with more statistics thanks to LHCb and Belle II

ADDITIONAL SLIDES

Common analysis techniques

Kinematics of fully reconstructed B

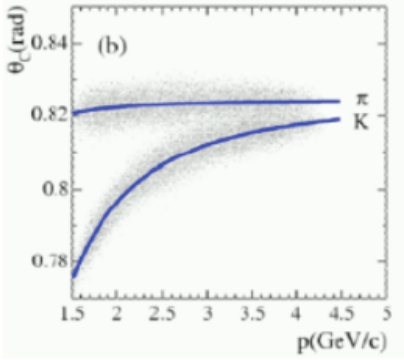


$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

K/π separation

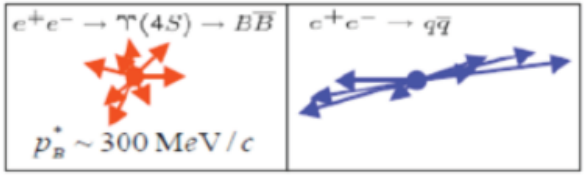
Very good **particle ID** between 1.5 and 4 GeV/c



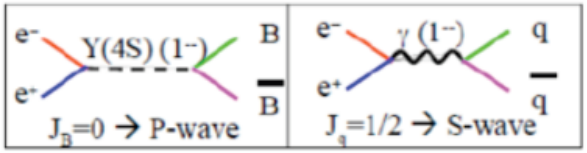
Background discrimination

Suppression by **multi-variable classifiers** based on **event-shape variables**: Fisher discriminant, Boosted Decision Trees (BTD)...

Topology:



Angular distribution:

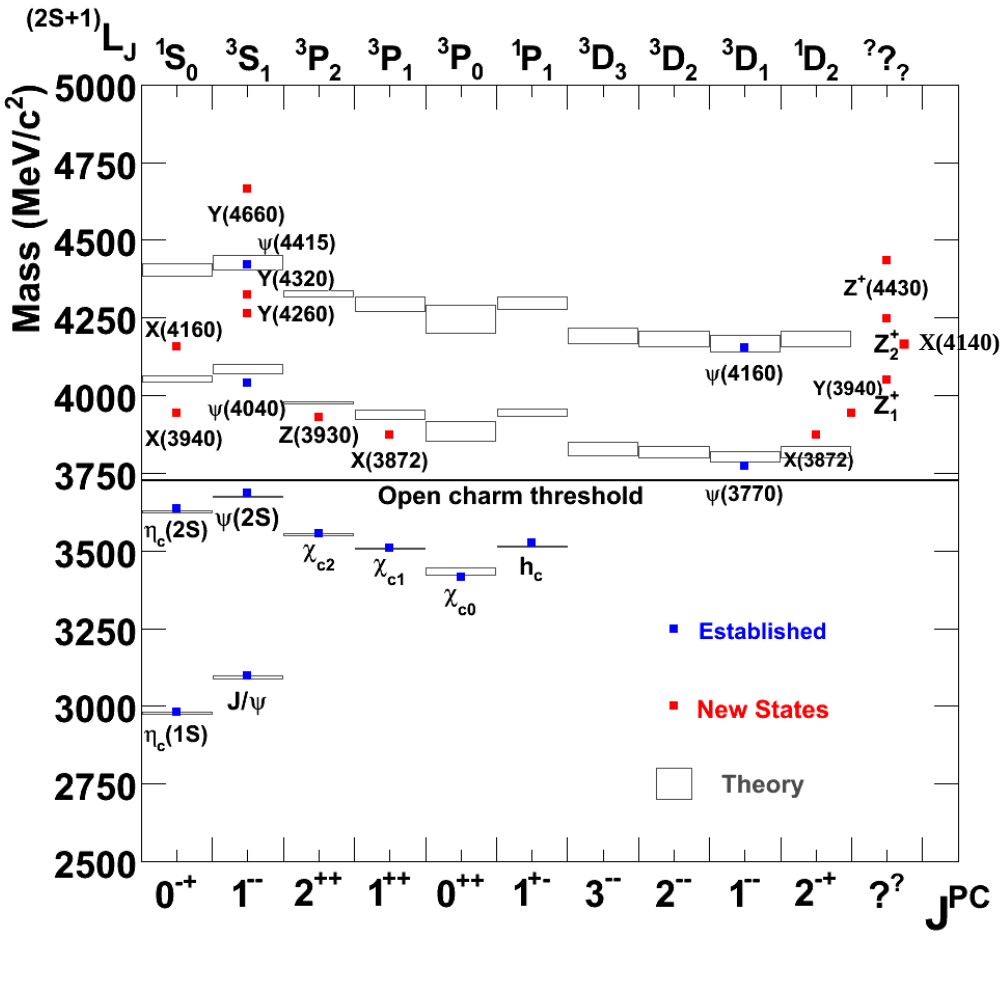


- Strongly discriminate continuum events ($e^+e^- \to q\bar{q}$ (q = u,d,s,c)
- Background from B decays

Variables are often combined to a likelihood function, used in a maximum likelihood fit for signal/background separation and to measure parameters of interest

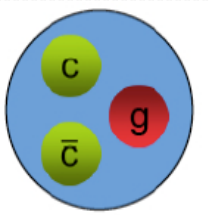
CHARMONIUM

- Charmonium: $c\bar{c}$ or $c\bar{c}$-like
- Below the $D^{(*)}\bar{D}^{(*)}$ threshold
  - **Narrow** width
  - All states are **observed** and **explained**
- Above the $D^{(*)}\bar{D}^{(*)}$ threshold
  - **Large** width expected
  - Many **unexpected states** reported since 2003!
    - Some of them narrow
- Several exotic hypothesis
  - Tetraquarks
  - Hadronic molecules
  - Hybrids
  - Glueball
  - …

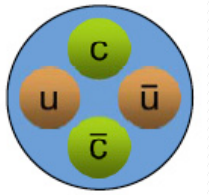


BEYOND CHARMONIUM

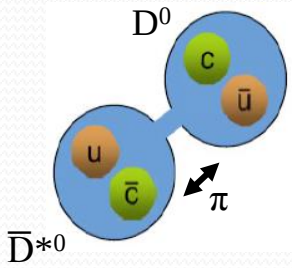
- Hybrids
  - States with **excited gluonic** degrees of freedom
  - Lattice and model predictions for the **lowest-mass** hybrid
    - M ~ **4.2 GeV/c^2**



- Tetraquarks
  - Bound states of **4 quarks**
  - **Large number** of states expected
  - **Small widths** above threshold



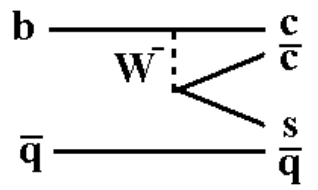
- Molecular states
  - Loosely bound states of a **pair of mesons**
  - **Small number** of states
  - **Small widths** above threshold



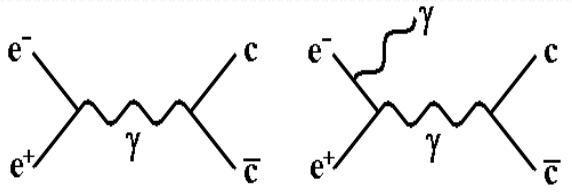
- Other possibilities
  - **Threshold**, **cusp**, or **coupled-channel** effect
  - Give a **cross section enhancement** which may not correspond to resonance production at all

CHARMONIUM PRODUCTION

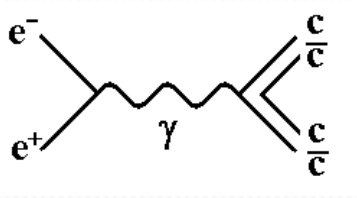
- B-meson decay
  - Color-suppressed b→c decay
  - Penguin diagram also possible



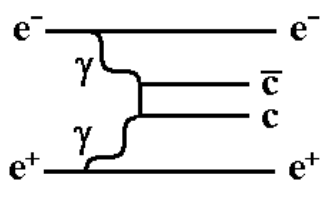
- e^+e^- Initial State Radiation (ISR)
  - e^+e^- collision below nominal c.m. energy
  - $J^{PC} = 1^{--}$



- Double charmonium production
  - Typically one J/ψ or ψ, plus second $c\bar{c}$ state



- Two-photon production
  - Access to C=+1 states



X(3872): INTERPRETATION

- X(3872) likely not a charmonium state
  - Radial excitation of χ_{c1} **($J^{PC} = 1^{++}$)** expected at 3950 MeV/c^2
  - η_{c2} **($J^{PC} = 2^{-+}$)** should have X $\rightarrow$ J/$\psi\gamma$ suppressed
  - **No satisfactory $c\bar{c}$ assignment**

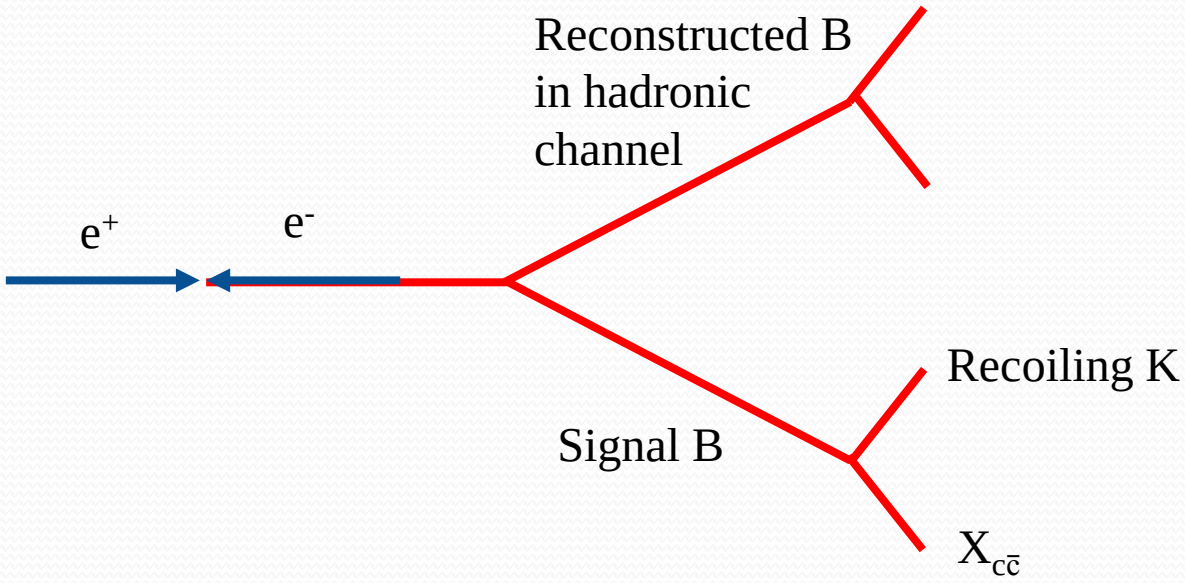
- $\bar{D}^0D^{*0}$ molecule? Phys. Rev. D71, 074005 (2005)
  - Would explain proximity of the **$\bar{D}^0D^{*0}$ threshold**
  - favors $D\bar{D}^*$ decay over J/$\psi\pi\pi$ over J/$\psi\gamma$ (as observed)
  - Expect X $\rightarrow$ ψ(2S)γ to be suppressed (in **contradiction** with observation)

- tetraquark state? Phys. Rev. D71, 014028 (2005)
  - Predict **2 neutral states** and **2 charged states**
    - Neutral states produced in B^0 and B^+ decays: **$\Delta m \approx (7 \pm 2)$ MeV/c^2**
  - **Measurements**:
    - $\Delta m = (2.7 \pm 1.6 \pm 0.4)$ MeV/c^2 in B $\rightarrow$ J/$\psi\pi^+\pi^-$
  - No **evidence** for charged partners

- Mixing of $\bar{D}^0D^{*0}$ and χ_{c1}? Something else?...

Y(4260): INTERPRETATION

- No $c\bar{c}$ assignment for 1^{--} state
- Probably not a glueball — Phys. Lett. B625, 212 (2005)
  - No evidence for $Y(4260) \rightarrow \phi\pi\pi$
- tetraquark state $[cs][\bar{c}\bar{s}]$? — Phys. Rev. D72, 031502 (2005)
  - Should decay dominantly to $\bar{D}_s D_s$
- Hybrid meson?
  - $\bar{D}D$, $\bar{D}^*D^*$, $\bar{D}D^*$ decays suppressed
  - $\bar{D}D_1(2420)$ decays should dominate
- hybrid + quenched lattice QCD predicts, for 1^{--}
  - $M = 4380 \pm 150$ MeV/c^2 — Phys. Rev. D74, 034502 (2006)
- $\omega\chi_{c1}$ molecule? — Phys. Lett. B634, 399 (2006)


Reconstructed B
in hadronic
channel
e+
e-
Recoiling K
Signal B
Xcc̄