New XYZ results from B-factories

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X(3872)

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Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

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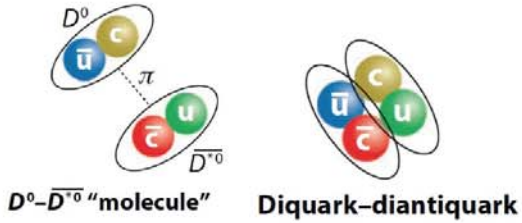
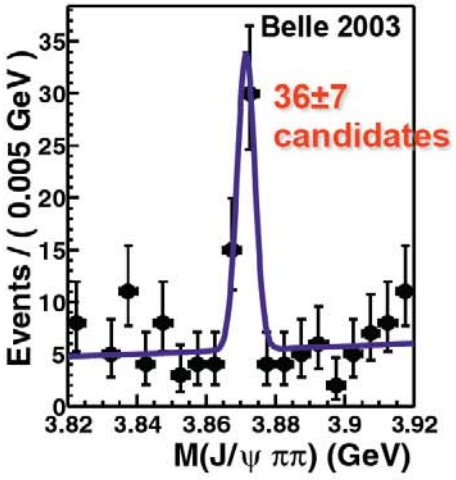
(Belle Collaboration)

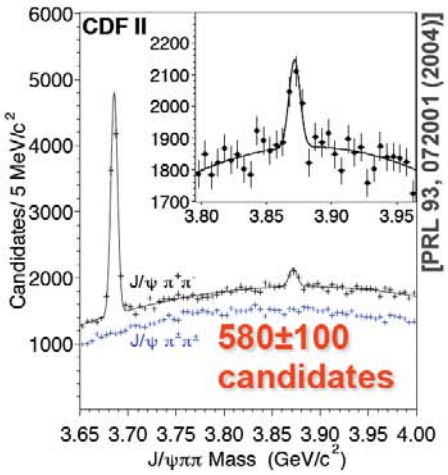
(Received 8 September 2003; published 23 December 2003)

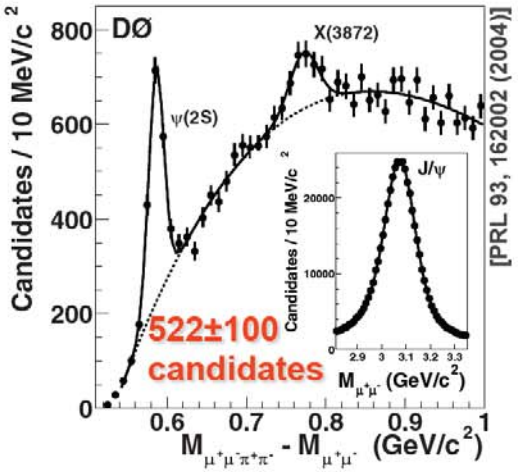
X(3872): properties

- **First exotic meson candidate found**
  - Discovered by Belle in 2003 with $B^+ \to K^+ X(3872) \to K^+ J/\psi \pi^+ \pi^-$ decays [PRL 92, 262001 (2003)]
  - Later confirmed by CDF (2004), D0 (2004) and Babar (2005)
- **Abundant and well studied exotic state**
  - Di-pion mass spectrum studied by CDF [PRL 96, 102002 (2006)]
  - Quantum numbers constrained to $J^{PC}=1^{++}$ or 2^{-+} [PRL 98, 132002 (2007)]
- **Nature still uncertain, possible models:**
  - Tetraquark, $D^0\bar{D}^{0*}$ molecular state ($J^{PC}=1^{++}$)
  - Conventional charmonium
- **More measurements required:**
  - Quantum numbers, decay modes, possible charged partners



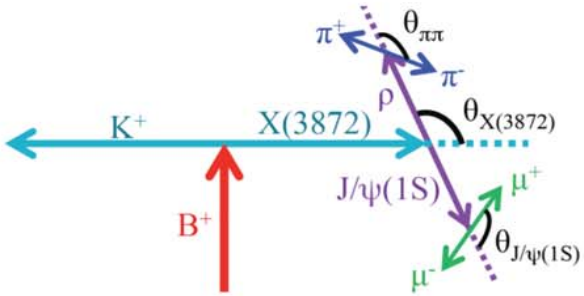


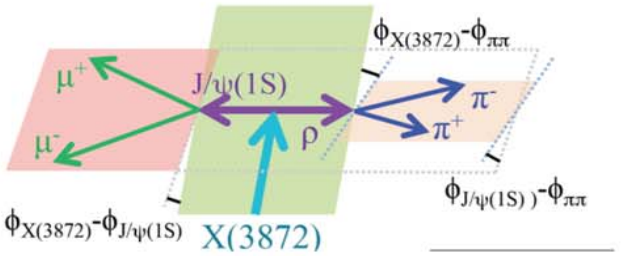


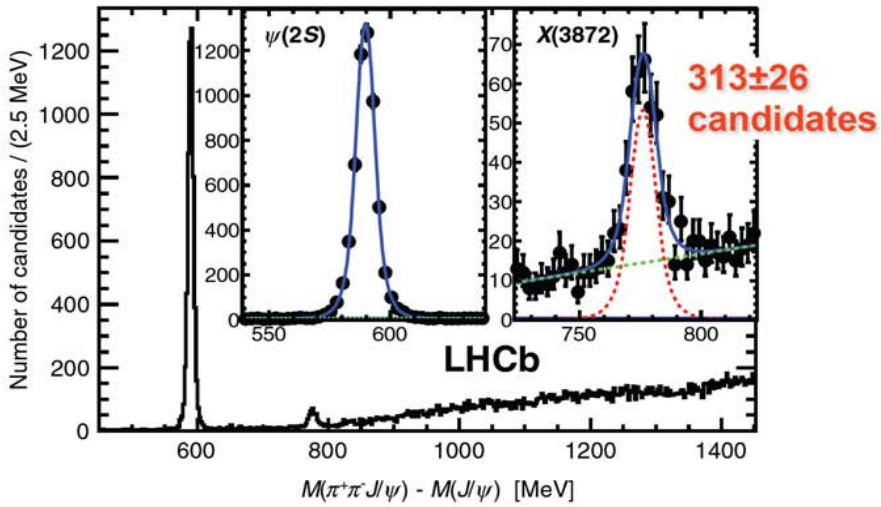


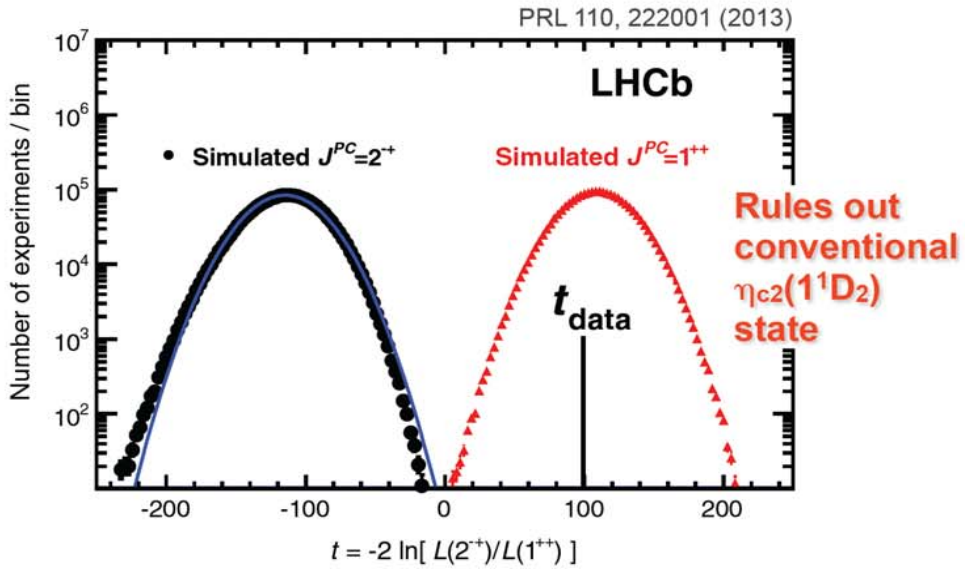
X(3872): J^{PC}

- **Recently determined by LHCb using $B^+ \to X(3872)K^+$, with $X(3872) \to J/\psi(\mu\mu)\pi^+\pi^-$**
  - **Five-dimensional angular analysis based on 1 fb^{-1} and assuming $X(3872) \to \rho(770)J/\psi$**
  - **X(3872) decay angles: $\cos\theta_X$, $\cos\theta_{\pi\pi}$, $\cos\theta_{J/\psi}$ - decay planes: $\Delta\phi_{X,\pi\pi}$, $\Delta\phi_{X,J/\psi}$**
  - **Test statistics built from likelihood ratio of 2^{-+} over 1^{++} hypotheses**
  - **1^{++} assignment preferred to 2^{-+} with significance larger than 8σ**









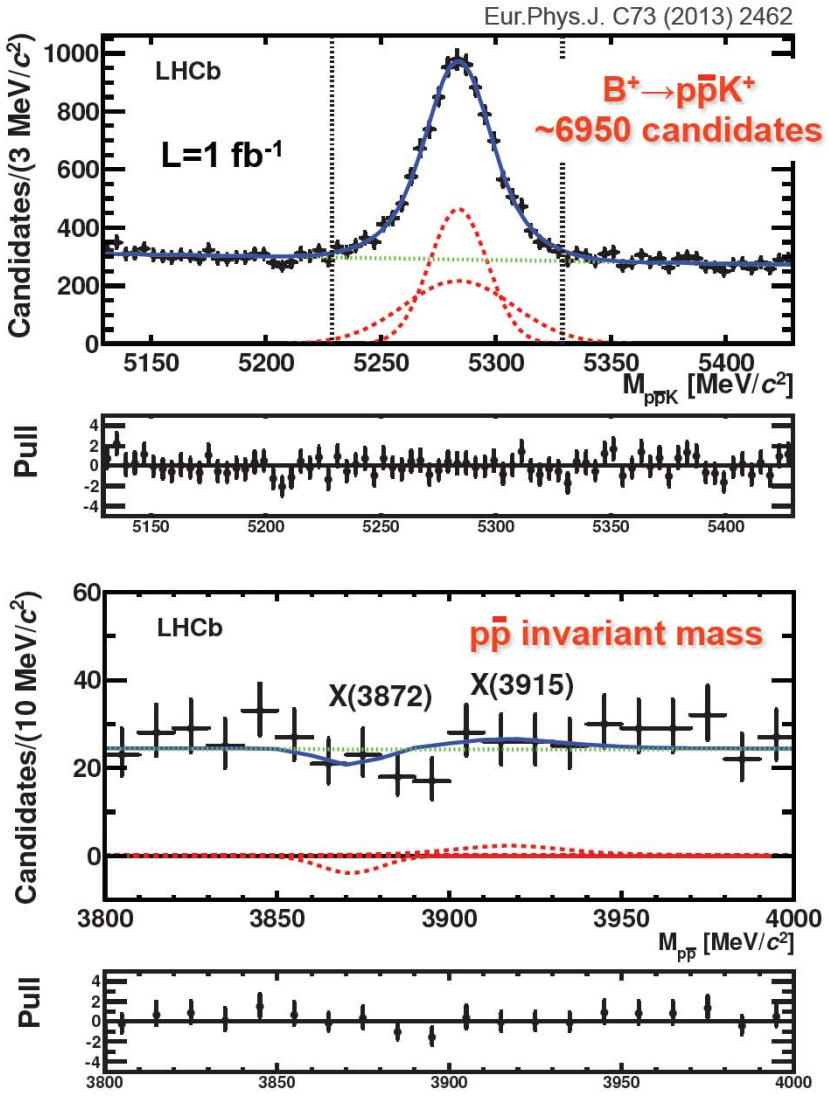
Search for X(3872)→p $\bar{p}$

- Search of X decays to p$\bar{p}$ using inclusive $B^+ \to p\bar{p}K^+$ decays
- Three-track final state selected with Boosted Decision Tree based on 12 kinematic variables
- p$\bar{p}$ invariant mass shows no signal in the X(3872) mass window
- 95% CL exclusion limit on the ratio of BR:

$$\frac{\mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)} < 2.0 \times 10^{-3}$$

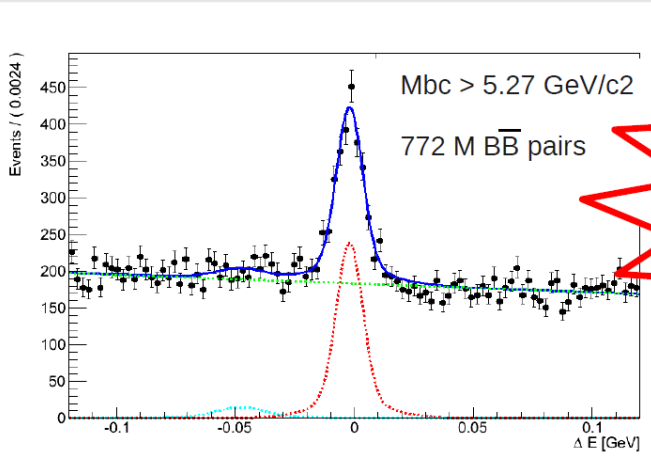
- Challenges some of the predictions for the molecular interpretation

[PRD 77 (2008) 097501, PRD 77, 034019 (2008)]



Search for X(3872)→ $\pi^+\pi^-\chi_{c1}$

If X(3872)= χ_{c1}', we may observe it decaying to $\pi^+\pi^-\chi_{c1}$

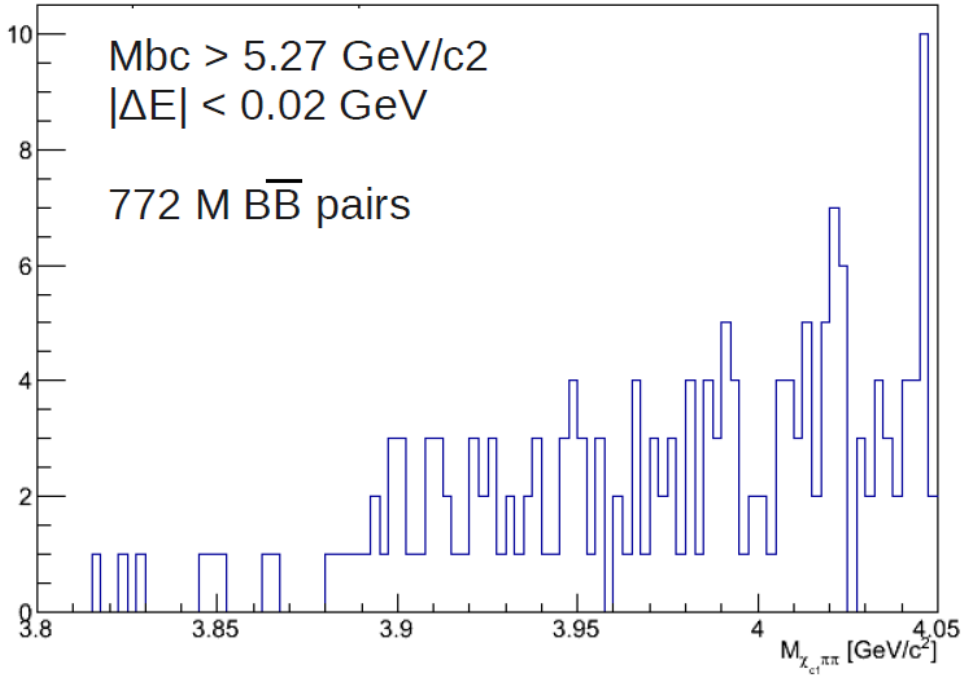


First Observation ! of $B^\pm \to \chi_{c1}\pi^+\pi^- K^\pm$

preliminary

1597 ± 76 events

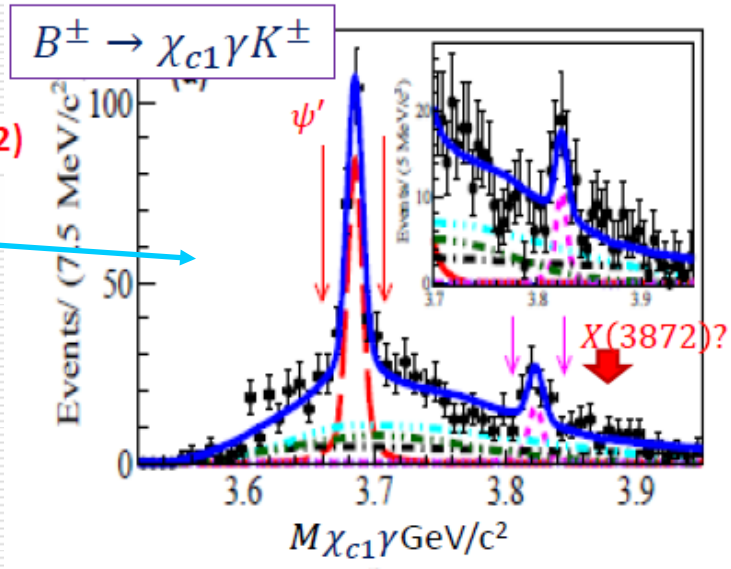
No peaking structure could Be observed !



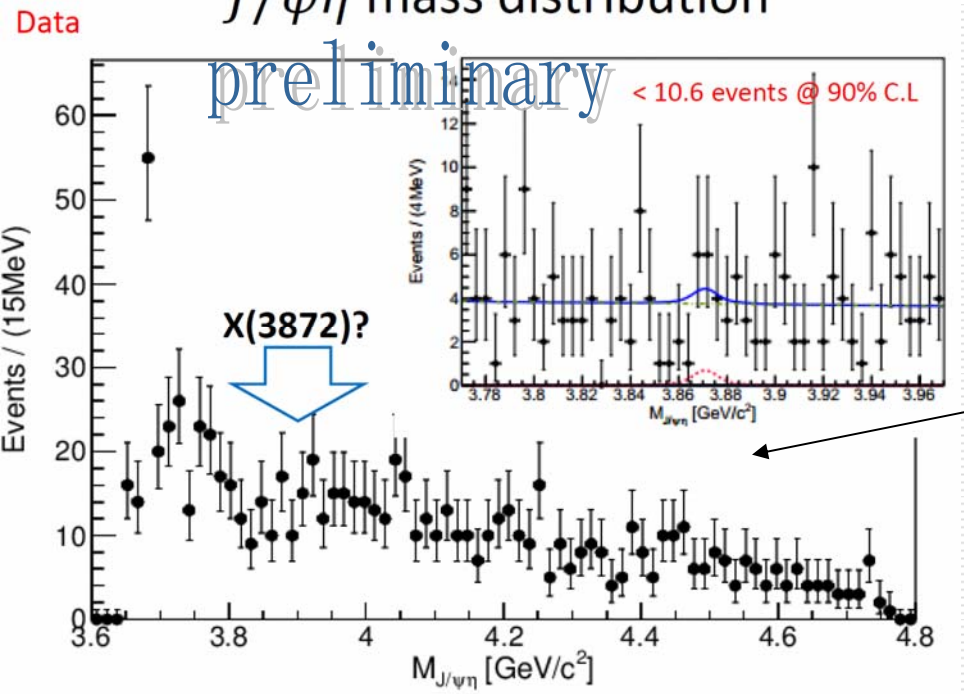
Search for C-odd X(3872) partner

In either tetraquark or molecule pictures, X(3872) can have C-odd partner which may decay into

- ✓$X(3872)^{C-} \rightarrow J/\Psi\eta$ K. Terasaki, PTEP 127, 577 (2012)
- ✓$X(3872)^{C-} \rightarrow \chi_{c1}\gamma$



$J/\psi\eta$ mass distribution



With all of current Belle data:
No clear Ψ(4040) and Ψ(4160).
No evidence for C-odd partner of X(3872) and other state.

$Br(B^{\pm} \rightarrow X(3872)K^{\pm}) \cdot Br(X(3872) \rightarrow J/\psi\eta) < 3.8 \times 10^{-6}$ @ 90% C.L.

(PDG $< 7.7 \times 10^{-6}$)

$B^0 \to X(3872) K^+ \pi^-$

Belle observed $B^0 \to X(3872) K^+ \pi^-$ with smaller data sample (605 fb^{-1})

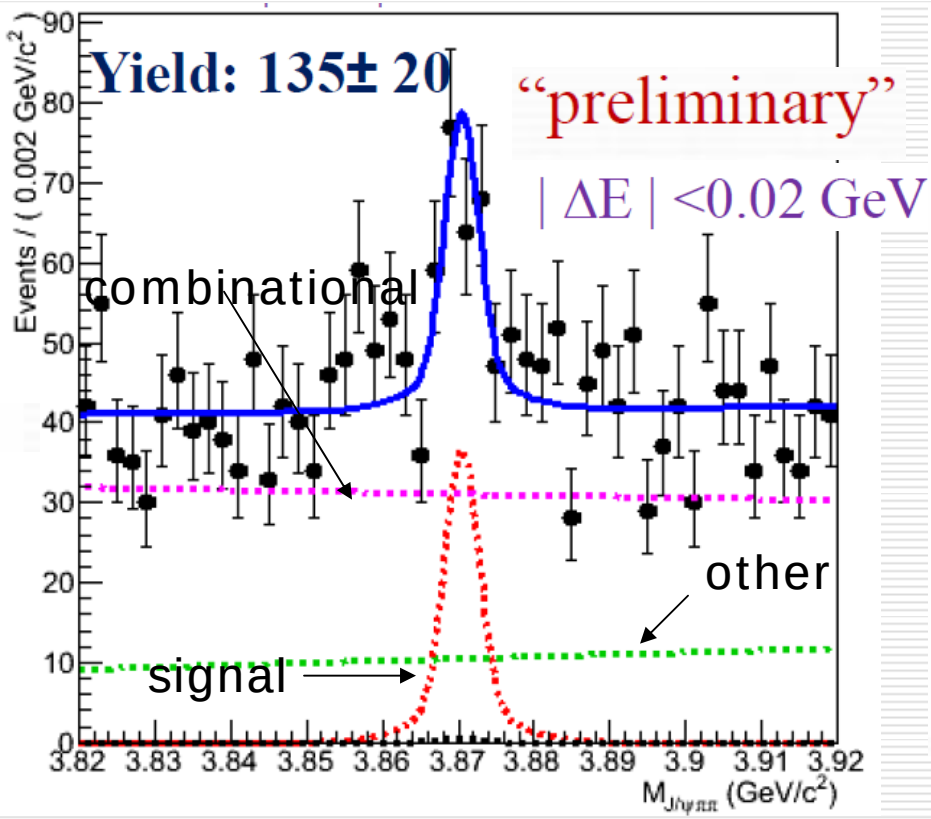
BELLE-CONF-0849

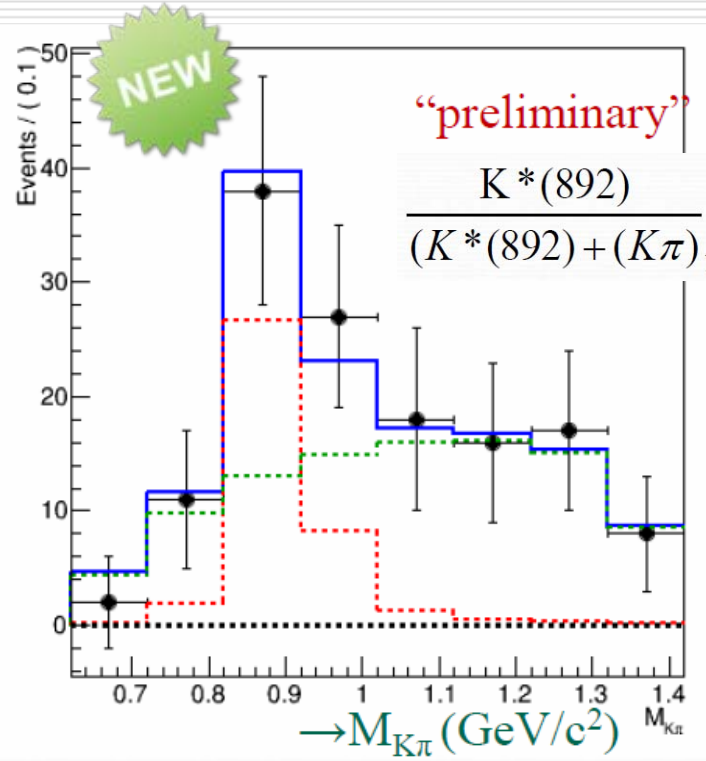
arXiv:0809.1224

$$BR(B^0 \to X(K^+\pi^-)_{non\_res})\, BR(X \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

dominates ! unlike $B \to (c\bar{c})K\pi$

$$BR(B^0 \to XK^{*0}) BR(X \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}\ 90\%\ CL$$





$$\frac{K^*(892)}{(K^*(892)+(K\pi)_{NR})} = 0.29 \pm 0.08$$

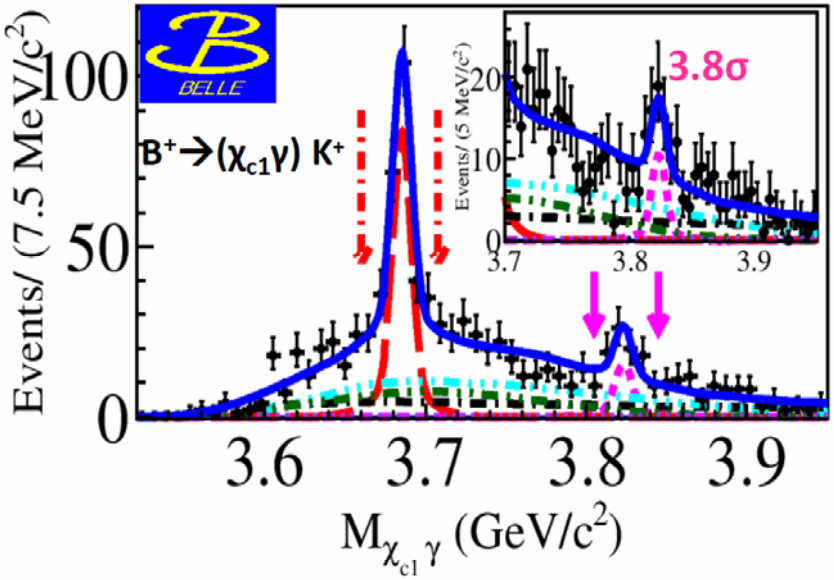
$$BR(B^0 \to X(3872)K^+\pi^-) \times BR(X(3872) \to J/\psi\pi^+\pi^-) = (8.55 \pm 1.31\ (+0.48-0.76)) \times 10^{-6}$$

Search for X(3823) in more channels

Belle found a narrow peak at $X(3823) \rightarrow \chi_{c1}\gamma$ in $B^+ \rightarrow (\chi_{c1}\gamma)\, K^+$

Its narrow width and properties suggest, it to be Ψ_{2D} (2^{--}) charmonium state.

Belle, PRL 111, 032001 (2013)



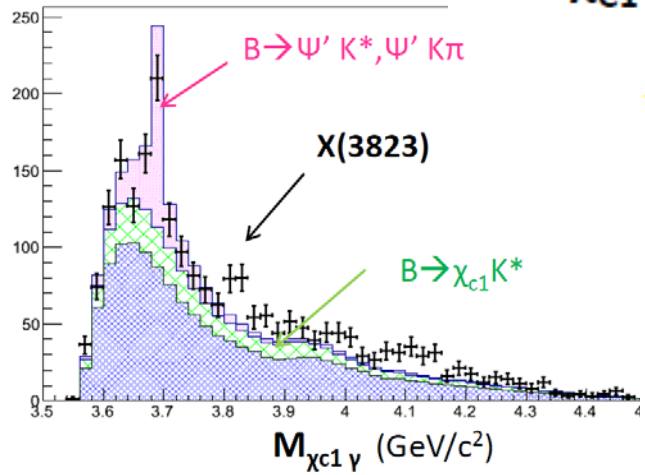
If so, it is suppressed in $B^+ \rightarrow \Psi_{2D}\, K^+$.
But one can expect it to have reasonable $BR(B^+ \rightarrow \Psi_{2D}\, K^+\, \pi^-)$

$B^0 \rightarrow \chi_{cJ}\gamma K^+\pi^-$ can be useful mode to search for X(3823) .

- **-25 MeV < ΔE<20 MeV**
- **E_γ scaled (ΔE=0) to improve the resolution of $M_{\chi c1,c2\gamma}$.**
- **Search for X(3823) and other new state in $M_{\chi c1,c2\gamma}$**

X(3823) in $B^0 \to \gamma\, \chi_{c1/c2} K^+ \pi^-$

$B^0 \to \chi_{c1}\, \gamma\, K^+\pi^-$

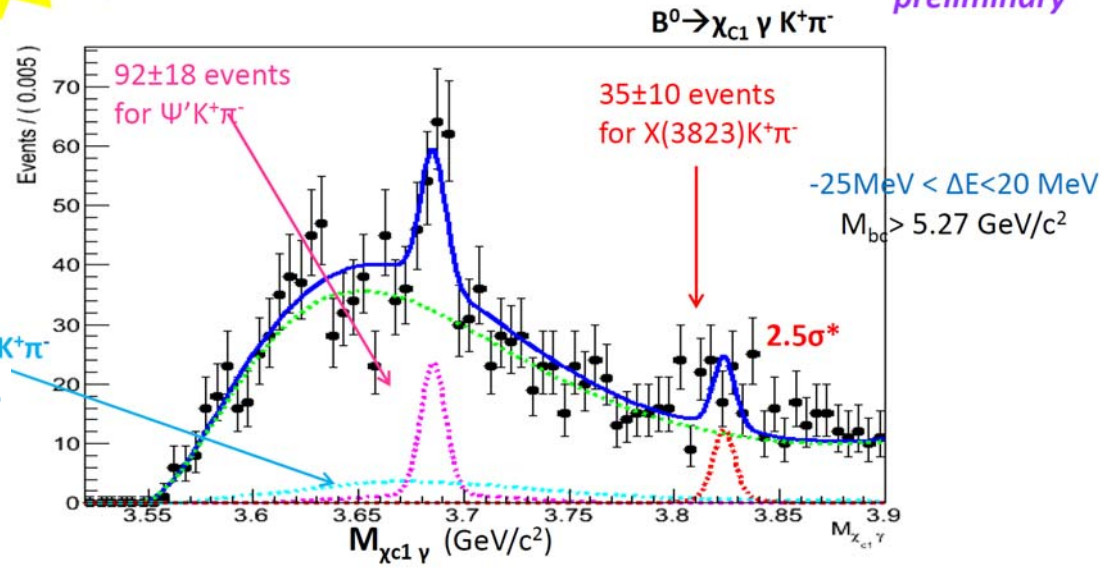


NEW

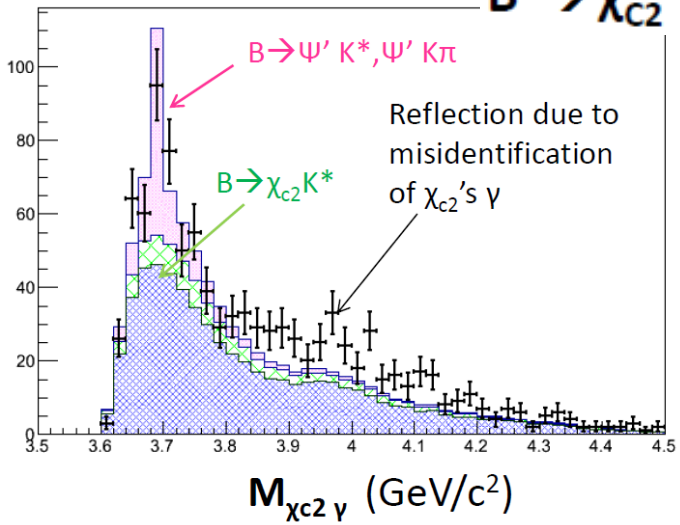
Fit to X(3823)

772 x 10^6 $N_{B\bar{B}}$

preliminary



$B^0 \to \chi_{c2}\, \gamma\, K^+\pi^-$



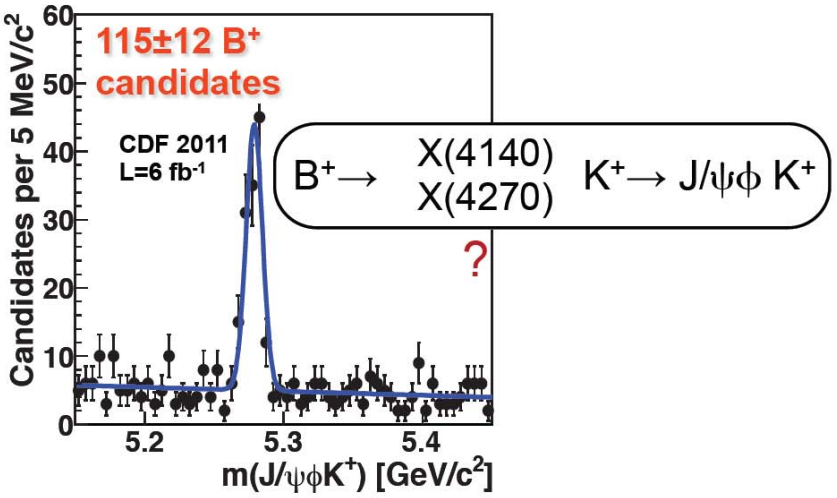
preliminary

Resolution fixed from Belle previous study of $B^+ \to (\chi_{c1}\gamma)K^+$ study

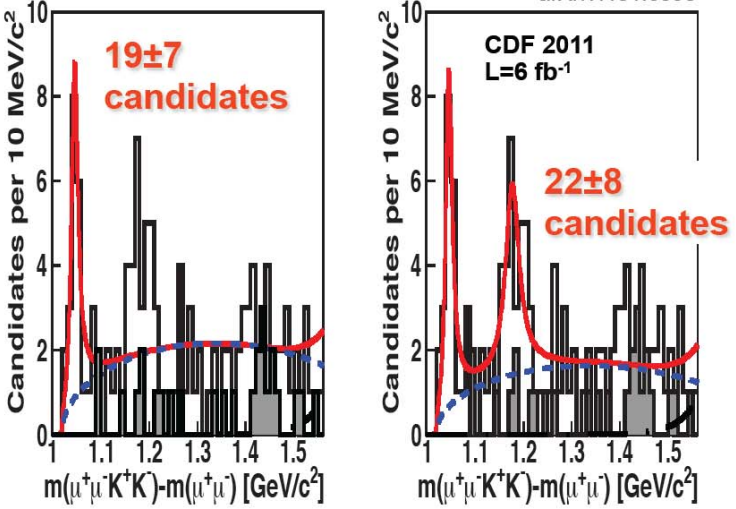
$$\frac{BR^{\dagger}(B^0 \to X(3823)K^+\pi^-)}{BR(B^+ \to X(3823)K^+)} = 2.5 \pm 1.0(\text{stat. only})$$

X(4140) and X(4270)

- First evidence (3.8σ) for a near-threshold narrow peak in the J/ψφ system, reported by CDF in $B^+ \to J/\psi(\mu\mu)\phi(KK)K^+$ decays in 2009, based on 2.7 fb^{-1}.
- Result updated in 2011 with 6 fb^{-1}, significance over 5σ. Assuming relativistic BW:
  - $M_1 = 4143.0^{+2.9}_{-3.0}(stat) \pm 0.6(syst)$ MeV
  - $\Gamma_1 = 15.3^{+10.4}_{-6.1}(stat) \pm 2.5(syst)$ MeV
- Evidence (3.1σ) for a second structure:
  - $M_2 = 4274.4^{+8.4}_{-6.7}(stat) \pm 1.9(syst)$ MeV
  - $\Gamma_2 = 32.3 + 21.9(stat) \pm 7.6(syst)$ MeV
- Could be $c\bar{c}$ bound state but well above open-charm threshold (3740 MeV). Some models:
  - Molecular ($D_s \bar{D}_s$) state
  - Hybrid particle ($q\bar{q}g$)
  - Four-quark combination ($c\bar{c}s\bar{s}$)
- No significant first structure from Belle in exclusive B decays. 3.2σ evidence for second structure at 4350 MeV in $\gamma\gamma \to J/\psi\phi$
  - Exclusion limits on partial width disfavor molecular scenarios with 0^{++}, 2^{++}

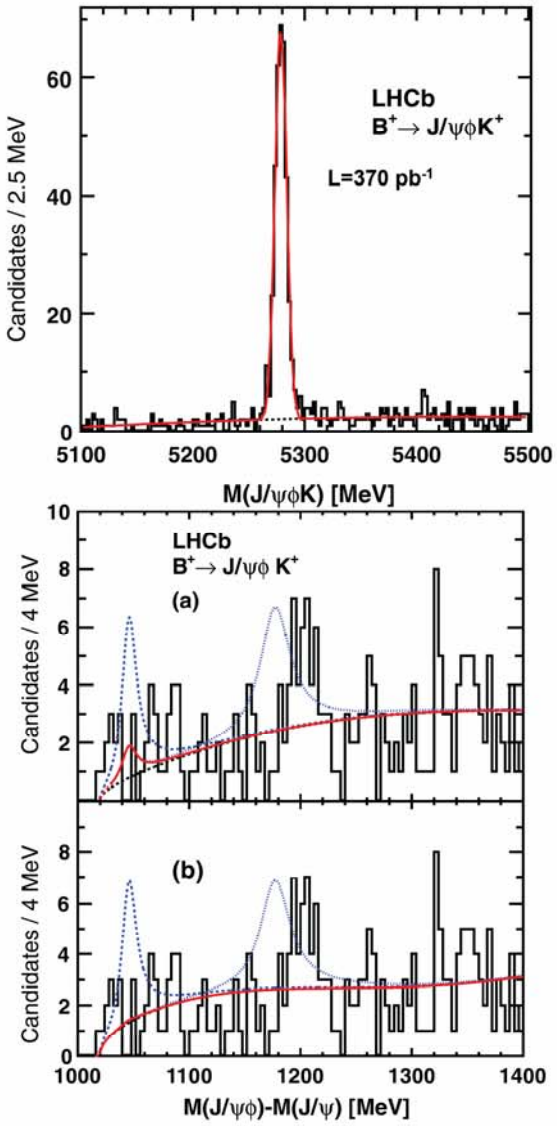


PRL 102, 242002 (2009)
arXiv:1101.6058



Searches at LHCb

PRD 85, 091103 (2012)

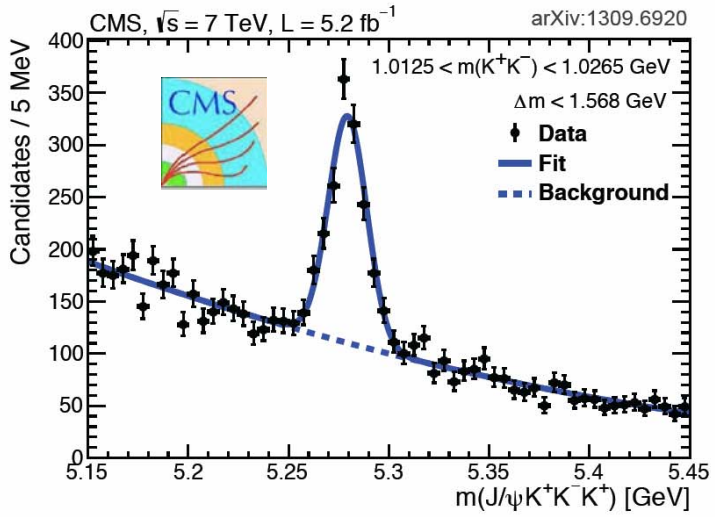


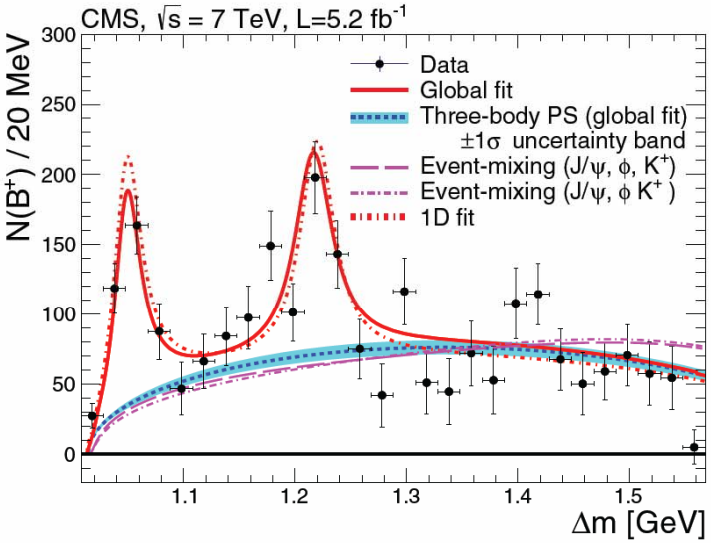
- **Search based on 370 pb^{-1} in $B^+ \to J/\psi\phi K^+$ decays:**
  - **382±22** B^+ candidate decays observed
  - CDF fit model used to quantify X(4140) and X(4270) yields
  - No significant signal observed in either case. 2.4σ tension with CDF
  - 90% CL exclusion limits on ratios of branching fractions

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.07.$$

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.08$$

Searches at CMS

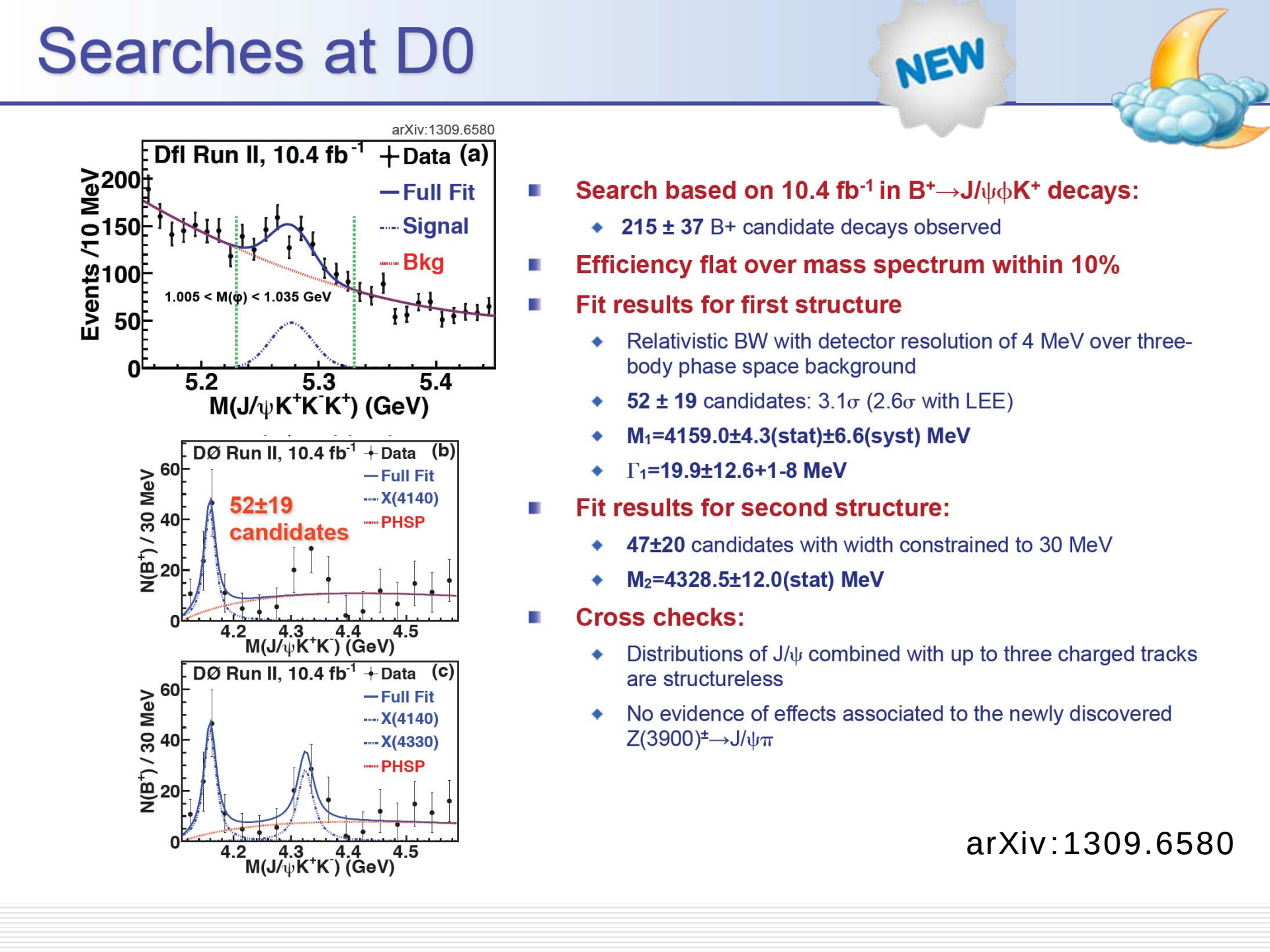




- **Search based on 5.2 fb^{-1} in $B^+ \to J/\psi\phi K^+$ decays:**
  - Largest sample so far: **2480±160** B^+ candidates
- **Fitted Δm distribution corrected for detector efficiency**
  - Efficiency fairly uniform over mass spectrum (<20%)
- **Fit model: S-wave relativistic BW for signal, and three-body phase space**
  - Event mixing used as cross check
- **First peak observed with significance exceeding 5σ**
  - **M_1 =4148.0±2.4(stat.)±6.3(syst.) MeV**
  - **$\Gamma_1 = 28^{+15}_{-11}$(stat.)±19(syst.) MeV**
- **Evidence for a second peak:**
  - **M_2 =4313.8±5.3(stat.)±7.3(syst.) MeV**
  - **$\Gamma_2 = 38^{+30}_{-16}$(stat.) ± 16 (syst.) MeV**
- **Parameters of the second structure my be affected by ϕK^+ reflections**
- **Analysis performed with tighter B^+ signal selection gives consistent results**

arXiv:1309.6920

Searches at D0



arXiv:1309.6580

- **Search based on 10.4 fb^{-1} in $B^+ \to J/\psi\phi K^+$ decays:**
  - **215 ± 37** B+ candidate decays observed
- **Efficiency flat over mass spectrum within 10%**
- **Fit results for first structure**
  - Relativistic BW with detector resolution of 4 MeV over three-body phase space background
  - **52 ± 19** candidates: 3.1σ (2.6σ with LEE)
  - **M_1=4159.0±4.3(stat)±6.6(syst) MeV**
  - **Γ_1=19.9±12.6+1-8 MeV**
- **Fit results for second structure:**
  - **47±20** candidates with width constrained to 30 MeV
  - **M_2=4328.5±12.0(stat) MeV**
- **Cross checks:**
  - Distributions of J/ψ combined with up to three charged tracks are structureless
  - No evidence of effects associated to the newly discovered $Z(3900)^{\pm} \to J/\psi\pi$

arXiv:1309.6580

Summary of searches

	M_1 (MeV)	Γ_1 (MeV)	M_2 (MeV)	Γ_2 (MeV)
Belle	-	-	$4350^{+4.6}_{-5.1}\pm0.7$	$13^{+18}_{-9}\pm4$
CDF	$4143.0^{+2.9}_{-3.0}\pm0.6$	$15.3^{+10.4}_{-6.1}\pm2.5$	$4274.4^{+8.4}_{-6.7}\pm1.9$	$32.3+21.9\pm7.6$
CMS	$4148.0\pm2.4\pm6.3$	$28^{+15}_{-11}\pm19$	$4313.8\pm5.3\pm7.3$	$38^{+30}_{-16}\pm16$
D0	$4159.0\pm4.3\pm6.6$	$19.9\pm12.6^{+1.0}_{-8.0}$	4328.5 ± 12.0	30 (constrained)
LHCb	-	-	-	-

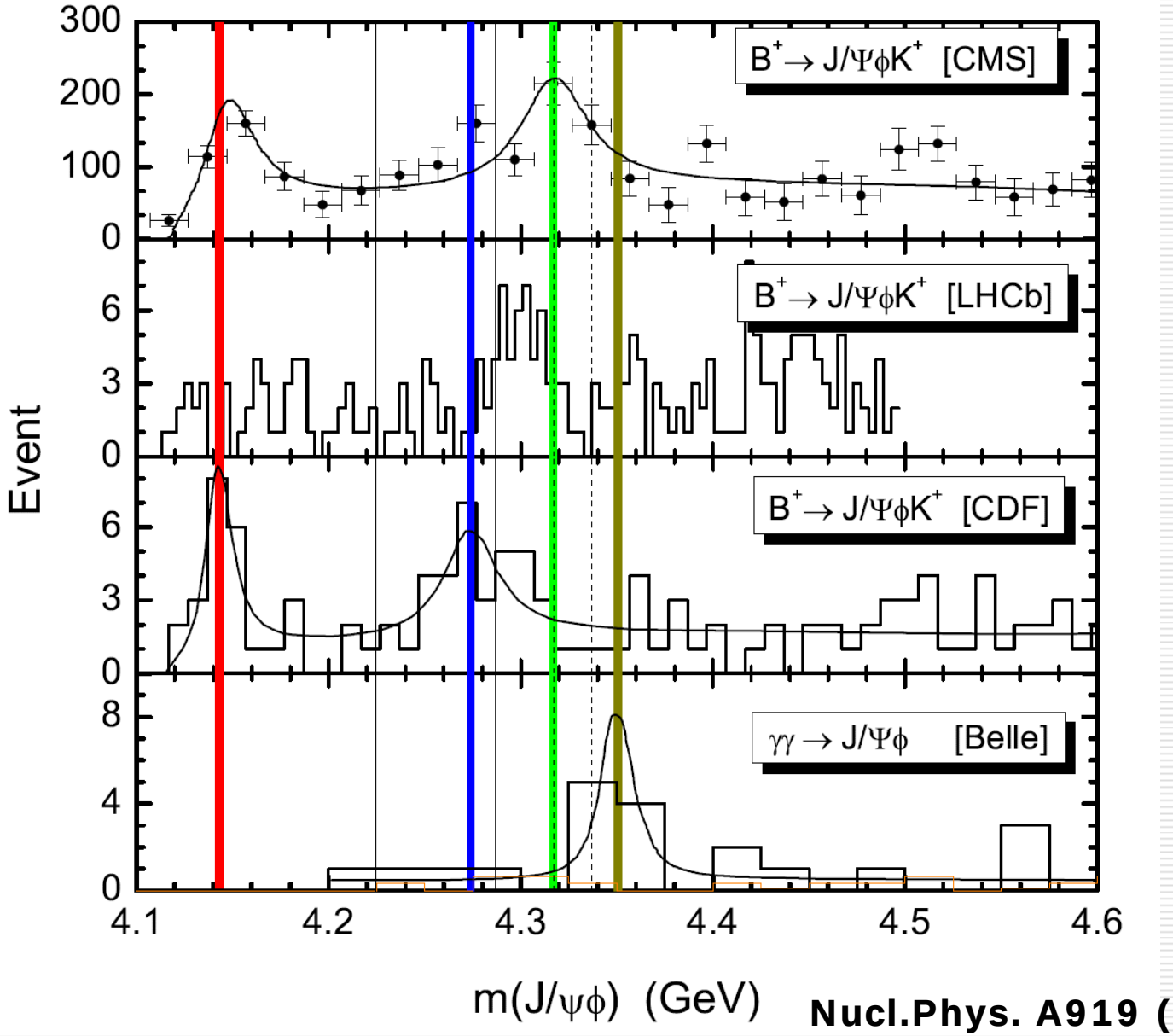
>5σ

>3σ

N.A.

Not very consistent each other.

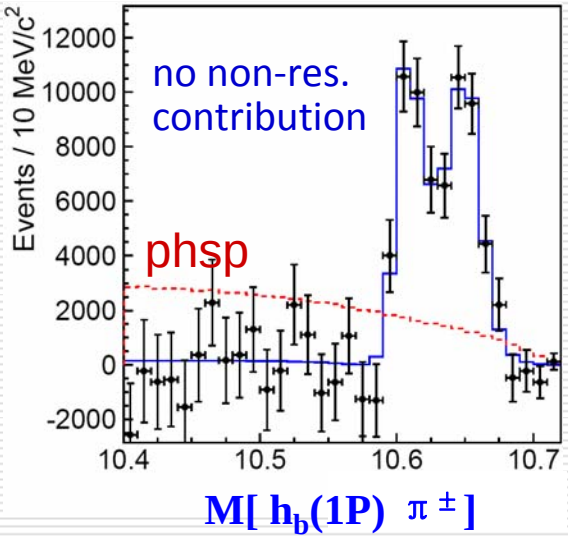
Four resonances ?!



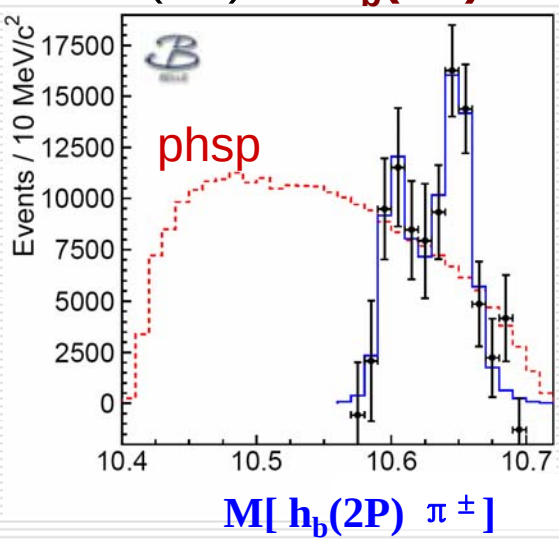
Nucl.Phys. A919 (2013) 1-14

Resonant structure of $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$

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



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



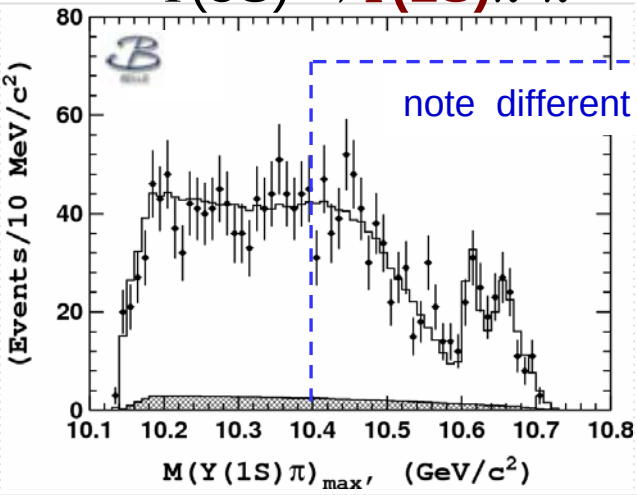
Two peaks are observed in all modes!

Belle: PRL108, 232001 (2012)

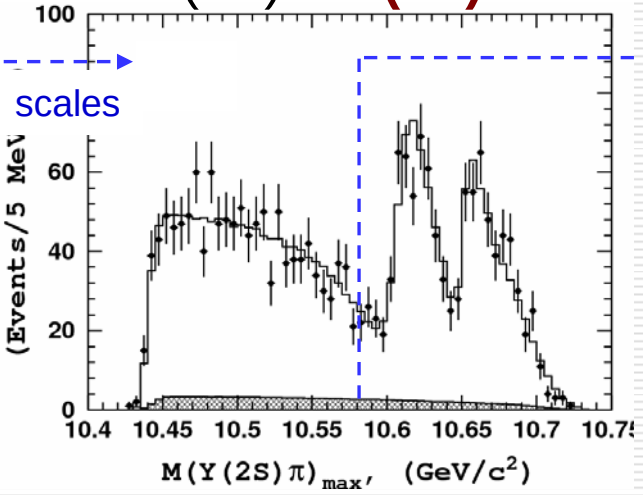
$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states

Dalitz plot analysis

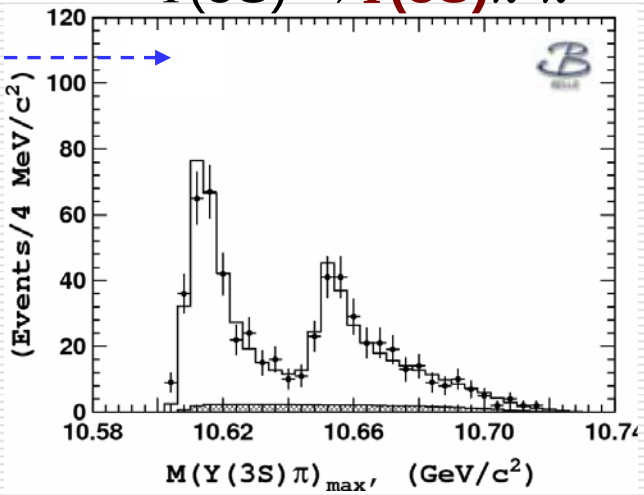
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$



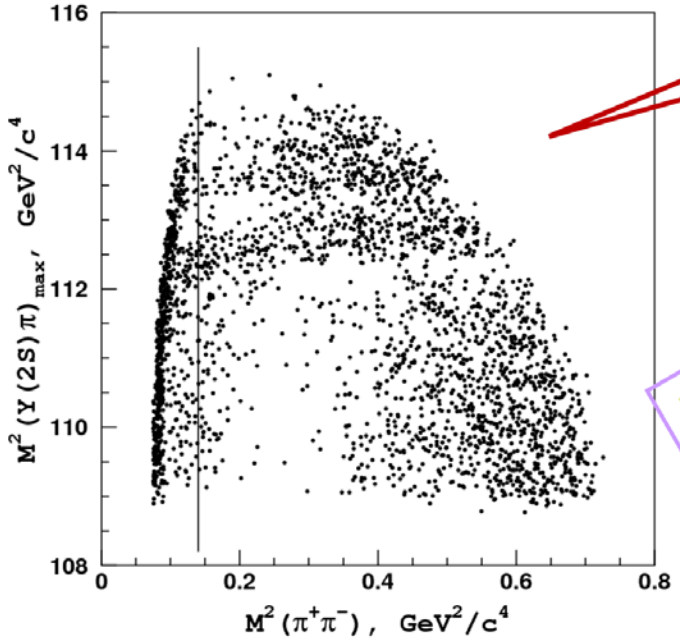
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$



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

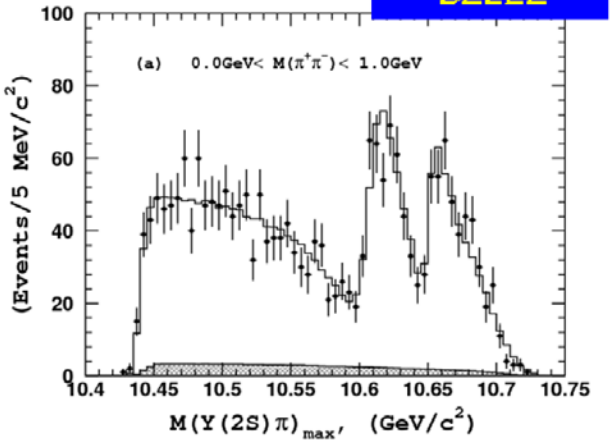


$\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-$: J^P Analysis

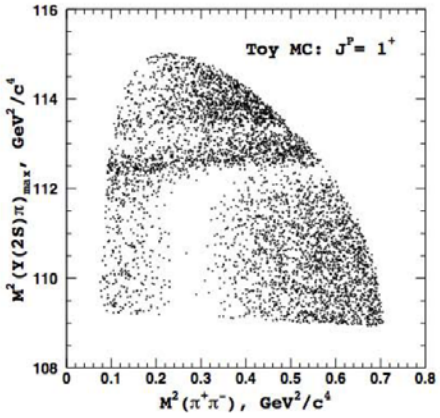


$\Upsilon(2S)\pi^+\pi$ Data

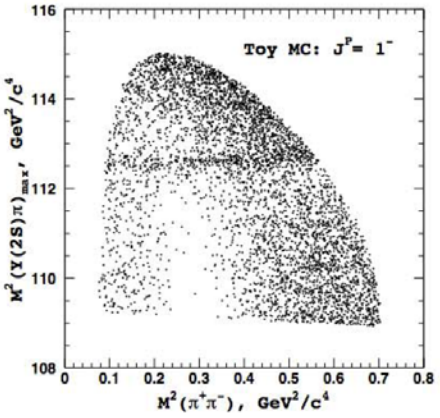
Belle PRELIMINARY



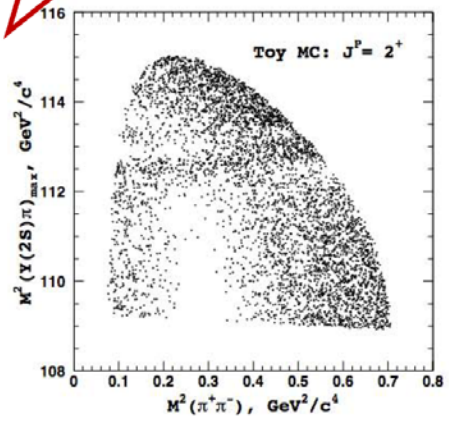
Toy MC with various J^P



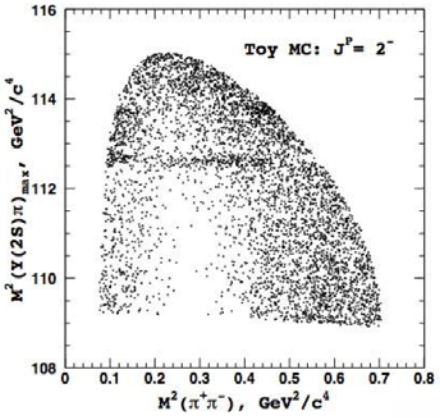
$J^P = 1^+$



$J^P = 1^-$

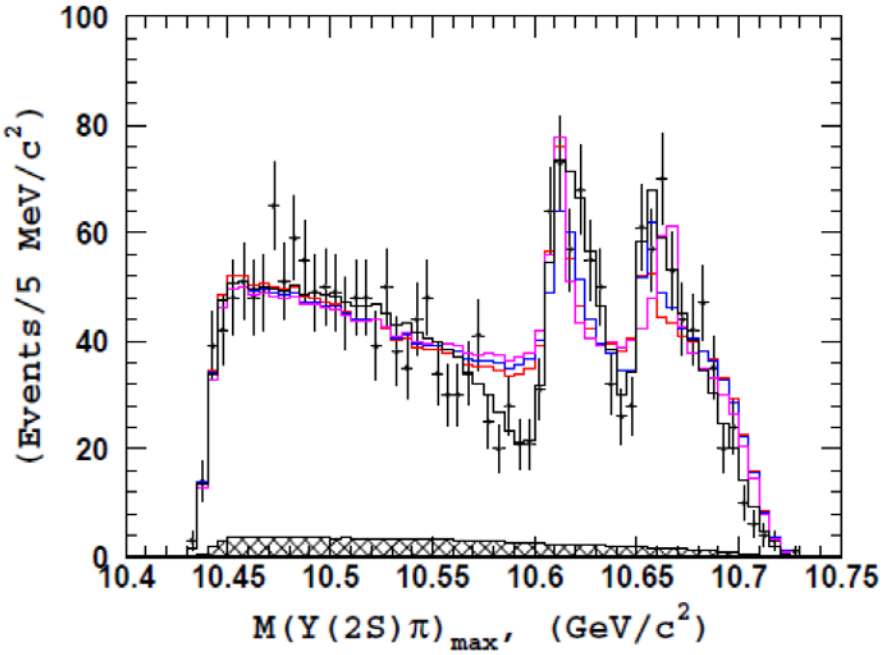


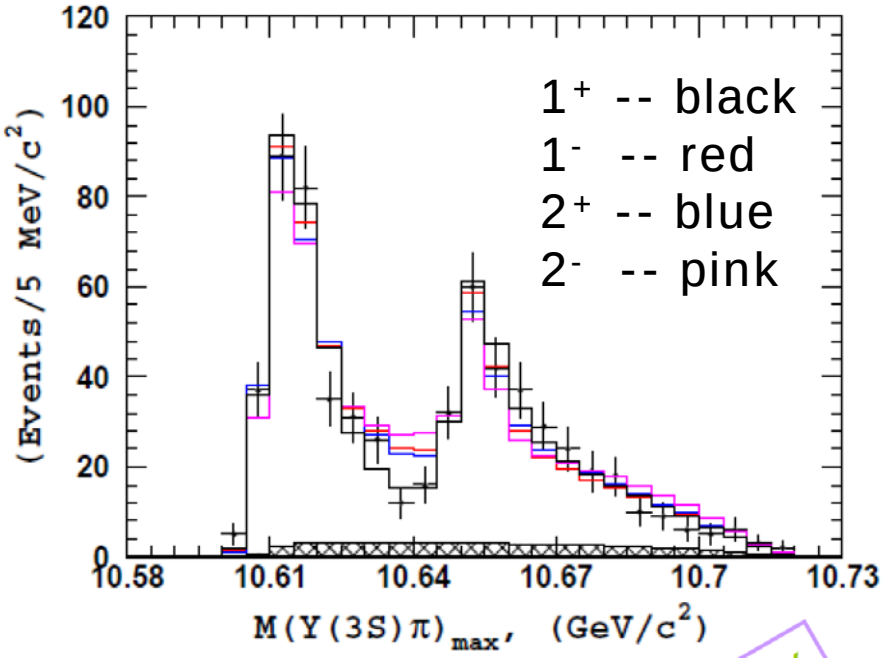
$J^P = 2^+$



$J^P = 2^-$

$\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-$: J^P Results





6D amplitude analysis of decays $\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-$

L values for fits to corresponding models:

J^P \ Mode	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
1^+	0	0	0
1^-	64	264	73
2^+	41	207	87
2^-	59	304	125

Belle PRELIMINARY

Spin parity of both Zb is $J^P=1^+$

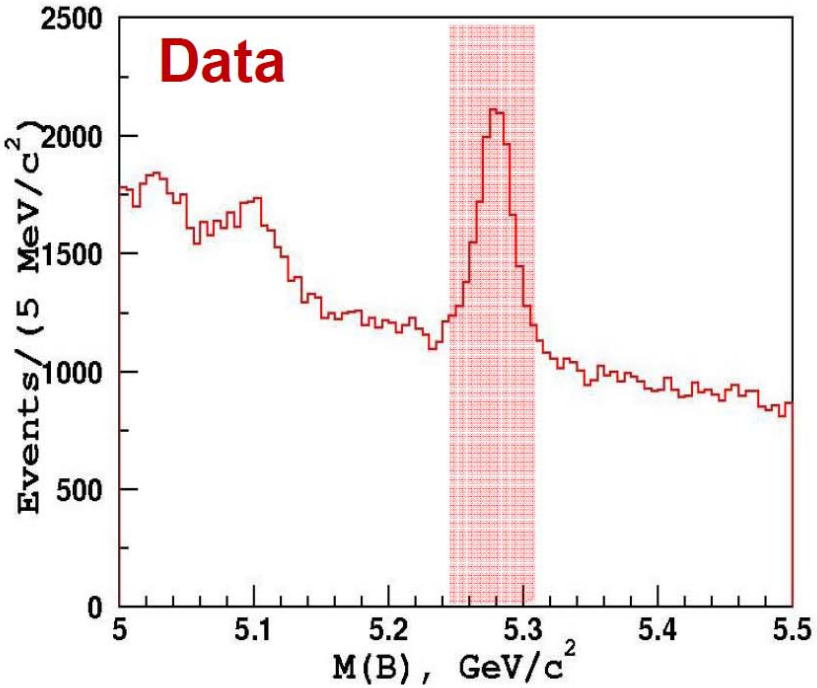
All other J^P are excluded

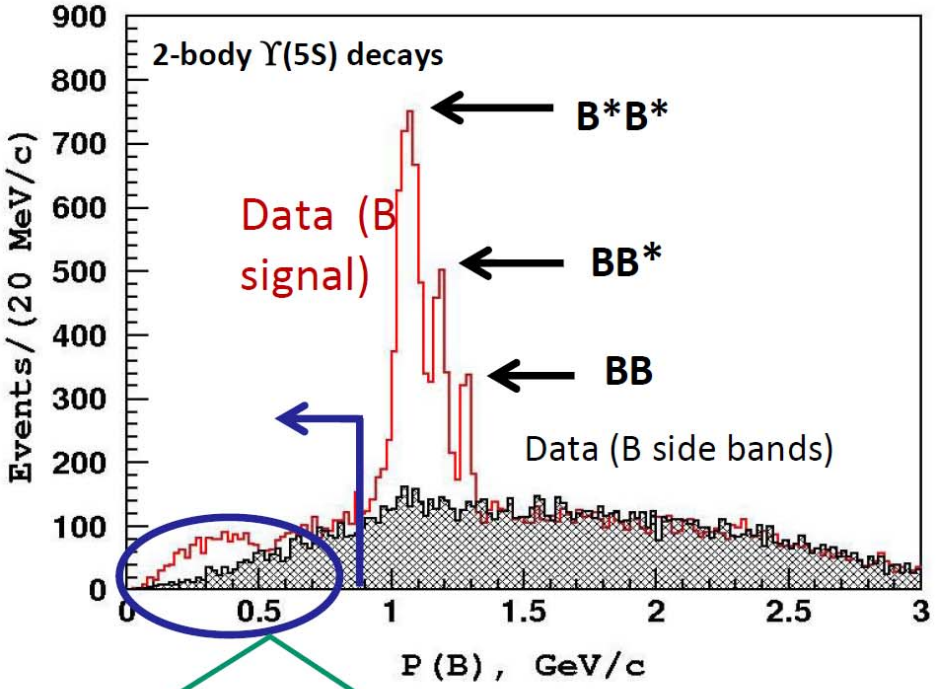
$\Upsilon(5S) \to Z_b^-(10610)\pi^+ \to BB^*\,\pi^+$

$Z_b^-(10650)\pi^+ \to B^*B^*\pi^+$

Masses of $Z_b(10610)$ and $Z_b(10650)$ are close to BB^* and B^*B^* threshold.

Search for $\Upsilon(5S) \to Z_b\pi$ decay with $Z_b \to B^{(*)}B^*$; reconstruct only one B and prompt pion





Effective B fraction:
$Br[B \to f] = 1.4 \times 10^{-3}$

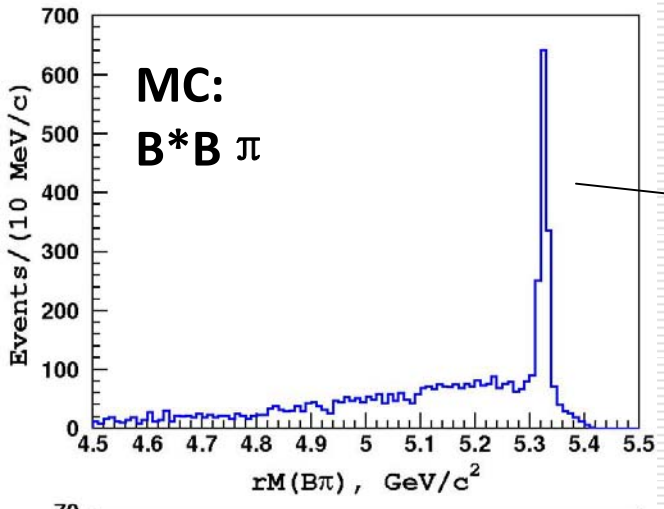
3-body $\Upsilon(5S) \to B^{(*)}B^{(*)}\pi$ decays & ISR to $\Upsilon(4S)$: $P(B) < 0.9$ GeV/c

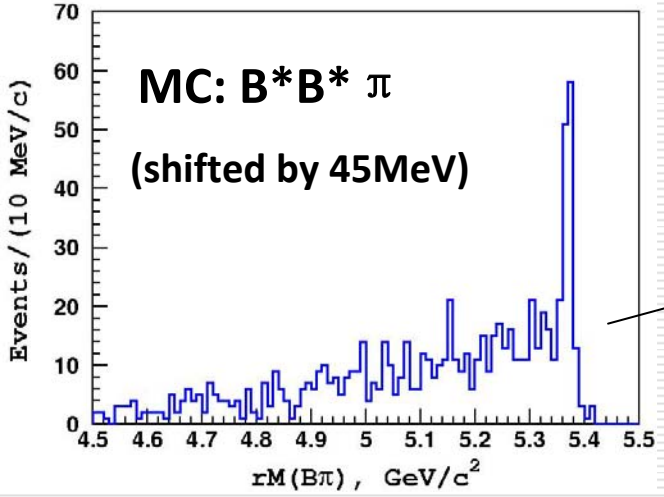
Charged B: $D^0[K\pi, K\pi\pi\pi]\pi^-$, $J/\psi[\mu\mu]\,K^-$

Neutral B: $D^+[K\pi\pi]\pi^-$, $J/\psi[\mu\mu]\,K^{*0}$, $D^{*+}[K\pi, K\pi\pi^0, K\pi\pi\pi]\pi^-$

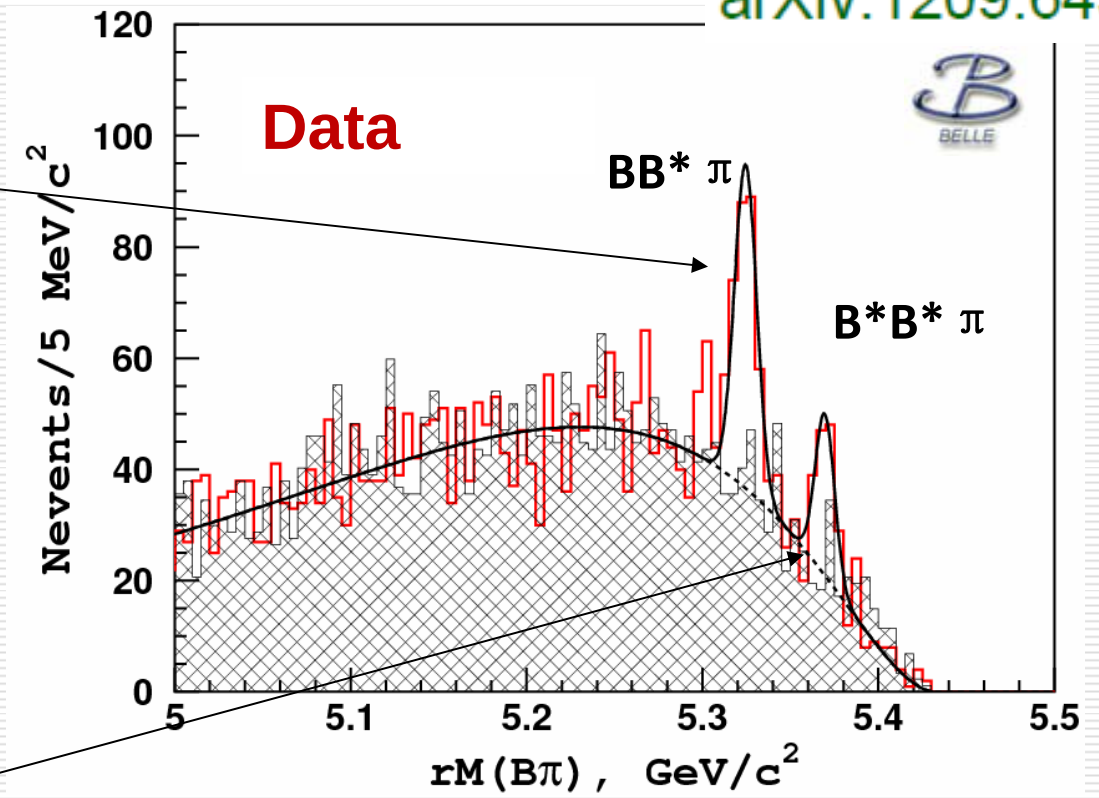
Belle PRELIMINARY

$\Upsilon(5S) \to B^* B^{(*)} \pi$: Fit





arXiv:1209.6450



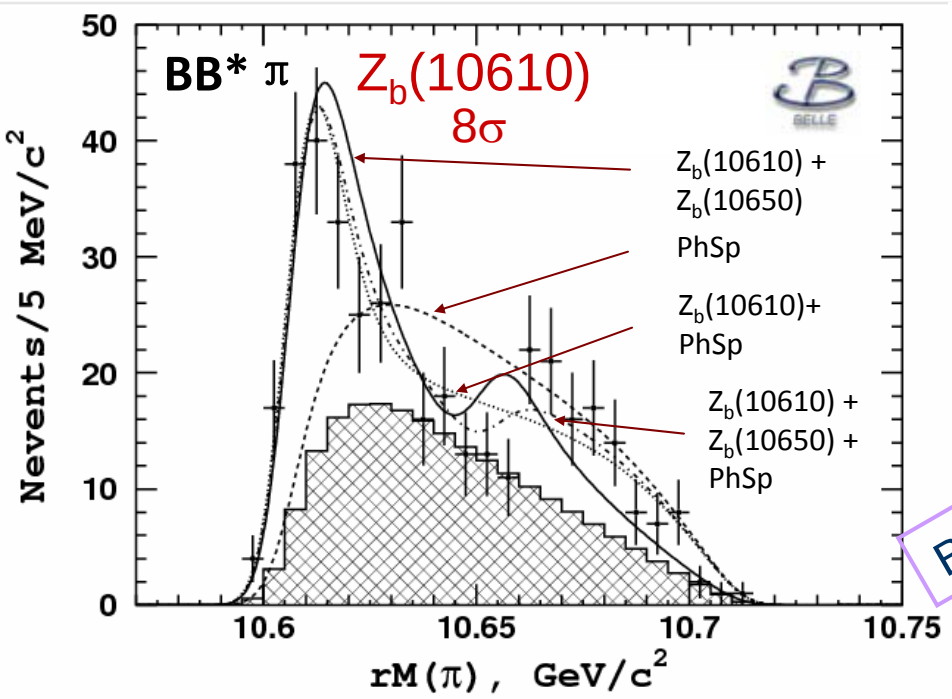
Red histogram – right sign B π combinations;
Hatched histogram – wrong sign B π combinations;
Solid line – fit to right sign data.

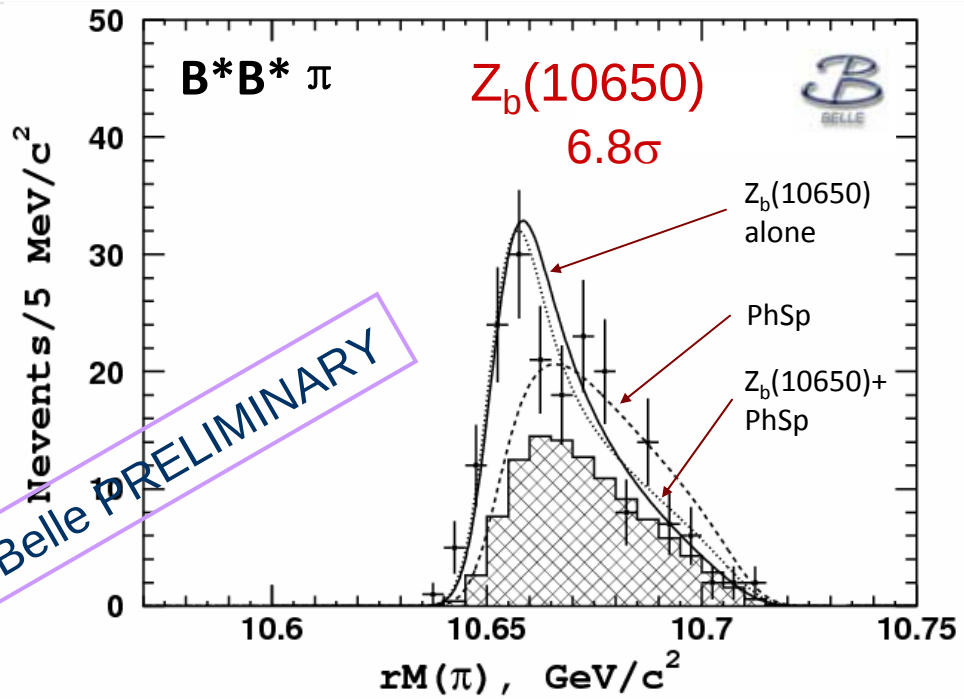
Belle PRELIMINARY

Fit yields: $N(B\bar{B}\pi) = 0.3 \pm 14$

$N(B\bar{B}^*\pi) = 184 \pm 19$ (9.3 σ) $\quad N(B^*\bar{B}^*\pi) = 82 \pm 11$ (5.7 σ)

$\Upsilon(5S) \to B^{*}B^{(*)}\pi$: Search for Z_b





points – right sign B π combinations (data);

lines – fit to data with various models (times PHSP, convolved with resolution function = Gaussian with σ =6MeV).

hatched histogram – background component

B*B*π candidates are well described by $Z_b(10650)$ only contribution.

BB*π can be described by two models:

$Z_b(10610) + Z_b(10650)$;

$Z_b(10610)$ + non-resonant amplitude.

Z_b branching fractions

Υ(5S) Brs:

BBπ < 0.60% (90%CL)

BB*π = (4.25 $\pm$ 0.44 $\pm$ 0.69)%

B*B*π = (2.12 $\pm$ 0.29 $\pm$ 0.36)%

arXiv:1209.6450

To be compared with PRD 81 (2010)

f(BB*π) = (7.3±2.2±0.8)%

f(B*B*π) = (1.0±1.4±0.4)%

Assuming Z_b decaying to Υ(nS) π , h_b(mP) π and B(*)B* only:

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

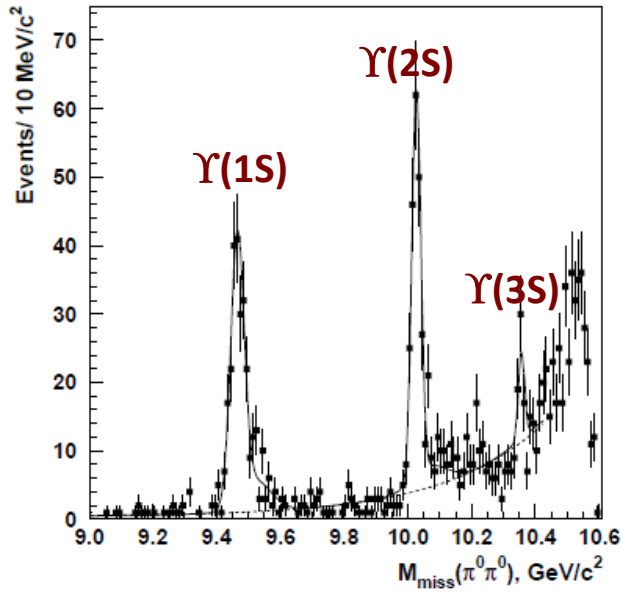
Belle PRELIMINARY

B(*)B* channels dominate Z_b decays !

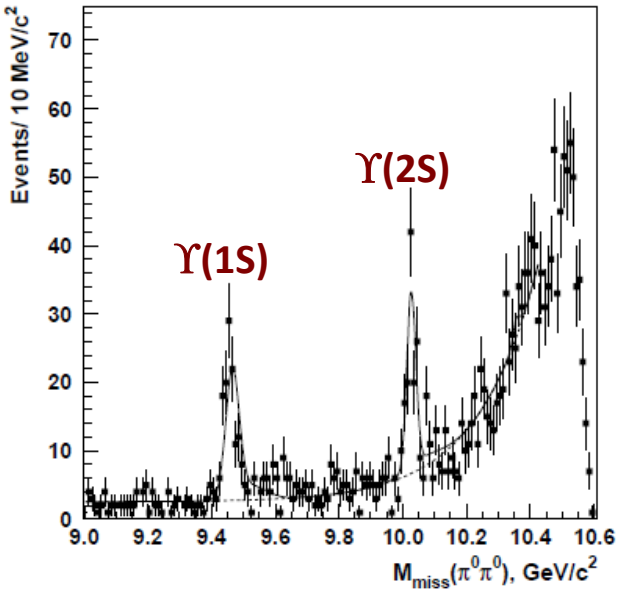
$\Upsilon(5S)\to\Upsilon(nS)\pi^0\pi^0$

$\Upsilon(1,2,3S)\to\mu^+\mu^-$, e^+e^-, $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$

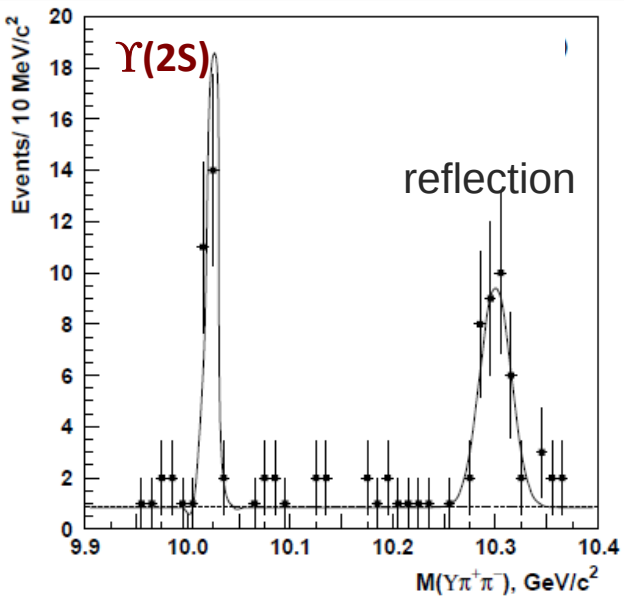
$\mu^+\mu^-\pi^0\pi^0$



$e^+e^-\pi^0\pi^0$



$Y(1S)[l^+l^-]\,\pi^+\pi^-\,\pi^0\pi^0$



$\sigma[e^+e^-\to\Upsilon(5S)\to\Upsilon(1S)\pi^0\pi^0] = (1.16\pm0.06\pm0.10)$ pb

$\sigma[e^+e^-\to\Upsilon(5S)\to\Upsilon(2S)\pi^0\pi^0] = (1.87\pm0.11\pm0.23)$ pb

$\sigma[e^+e^-\to\Upsilon(5S)\to\Upsilon(3S)\pi^0\pi^0] = (0.98\pm0.24\pm0.19)$ pb

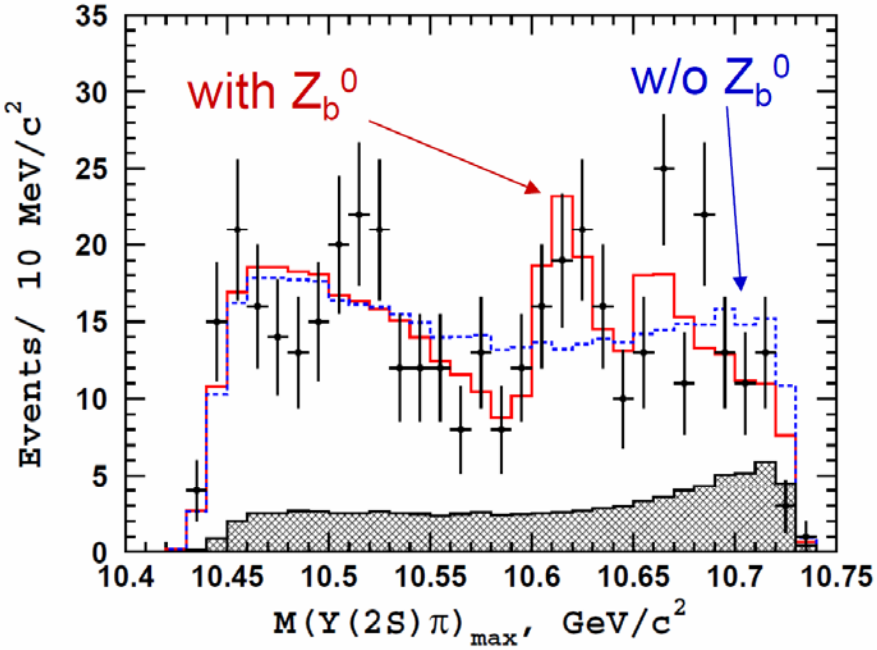
Consistent with ½ of $Y(nS)\pi^+\pi^-$

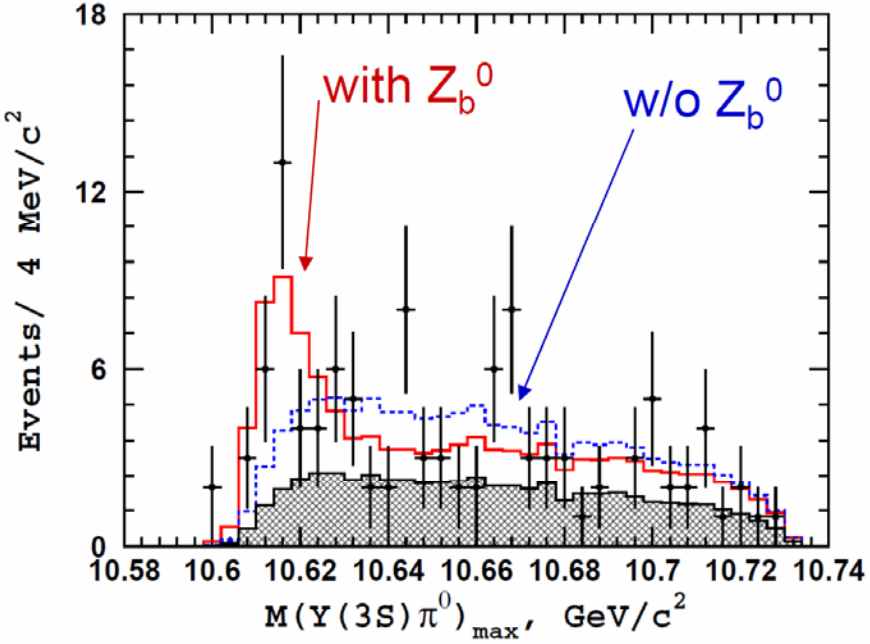
Phys. Rev. D 88, 052016 (2013)

$\Upsilon(2,3S)\pi^0\pi^0$ Dalitz analysis

$$M(s_1, s_2) = A_{Z1} + A_{Z2} + A_{f_0} + A_{f_2} + A_{NR}$$

Phys. Rev. D88, 052016

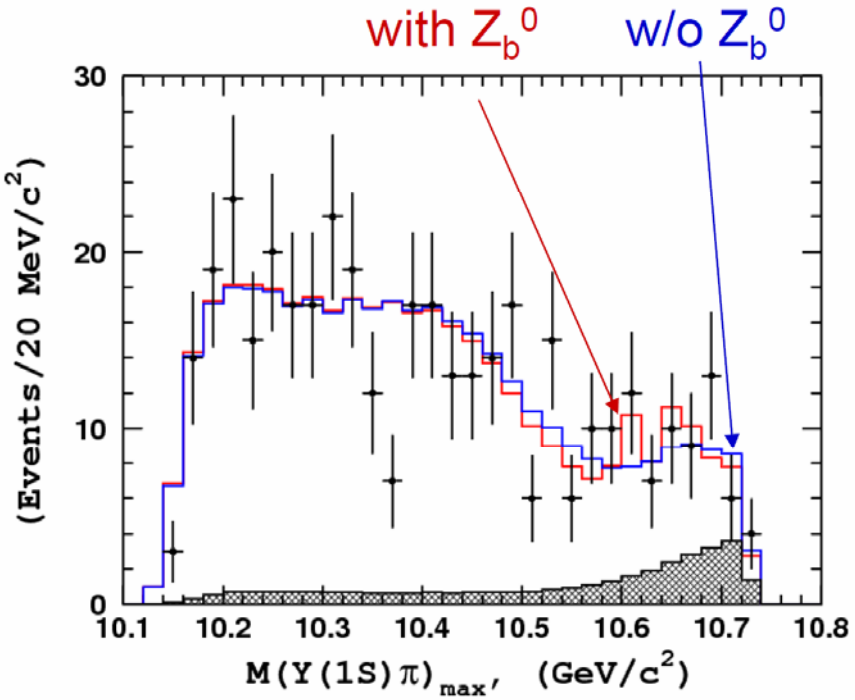


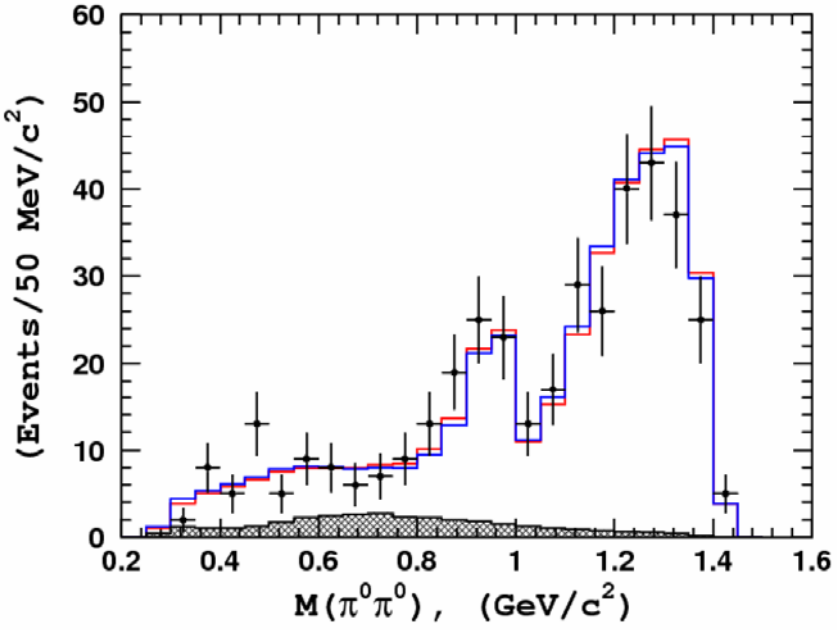


- Z_b^0 resonant structure has been observed in $\Upsilon(2S)\pi^0\pi^0$ and $\Upsilon(3S)\pi^0\pi^0$
- Statistical significance of $Z_b^0(10610)$ signal is 6.5σ including systematics
- $Z_b^0(10650)$ signal is not significant (~2σ), not contradicting with its existence
- $Z_b^0(10610)$ mass from the fit $M=10609 \pm 4 \pm 4$ MeV/c^2 $M(Z_b^+)=10607\pm2$ MeV/c^2

$\Upsilon(1S)\pi^0\pi^0$ Dalitz analysis

Dalitz analysis $$M(s_1, s_2) = A_{Z1} + A_{Z2} + A_{f_0} + A_{f_2} + A_{NR}$$



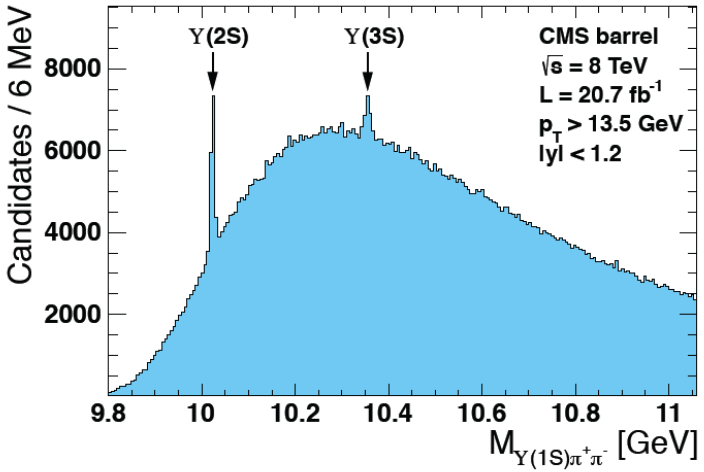


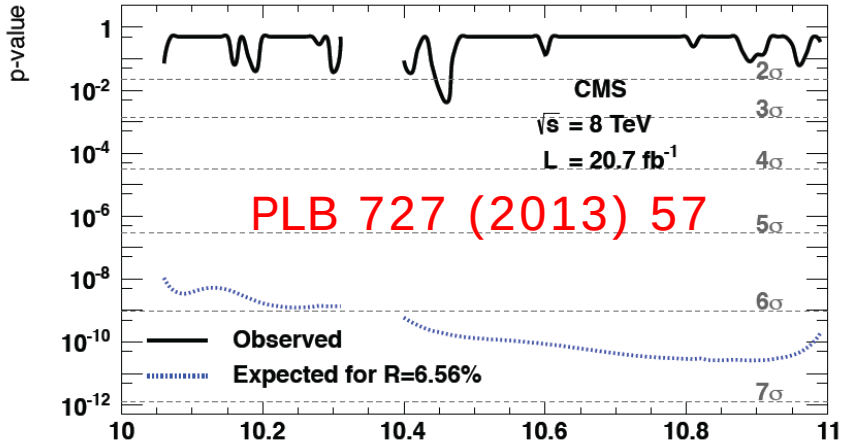
Phys. Rev. D88, 052016 (2013)

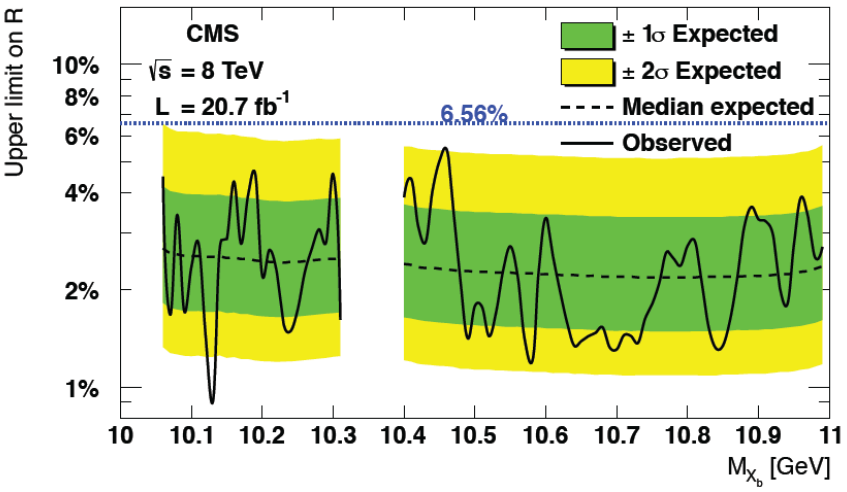
Signals of both Z_b^0 are not significant. Data is not contradicting with their existence.

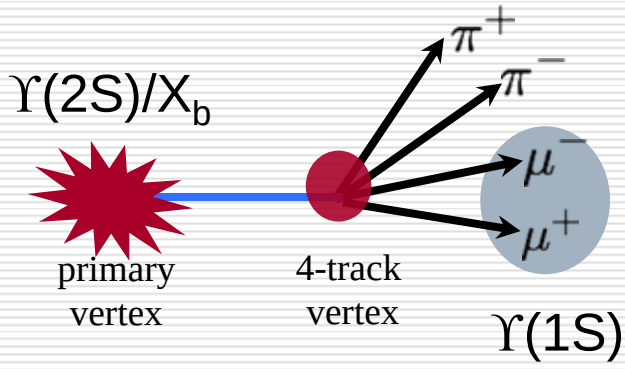
Searches for X_b

- **Search for the X(3872) counterpart in the bottomonium sector - called here X_b**
  - Decay channel $\Upsilon(1S)\pi^+\pi^-$
  - Mass predicted close to the BB or BB* threshold. Search scans 10-11 GeV mass range
  - Search in two rapidity regions due to different mass resolution
  - Dipion mass distribution assumed to be as for Y(2S) and similar to X(3872)
- **"R" ratio of observed X_b and Y(2S) candidates corrected for detector efficiency**
  - R=6.56% motivated by X(3872) case would yield >5σ observation over the full mass range
- **No excess observed. 95% CL upper bounds on R within (0.9 - 5.4)%.**
  - First upper limit on possible X_b state at hadron collider









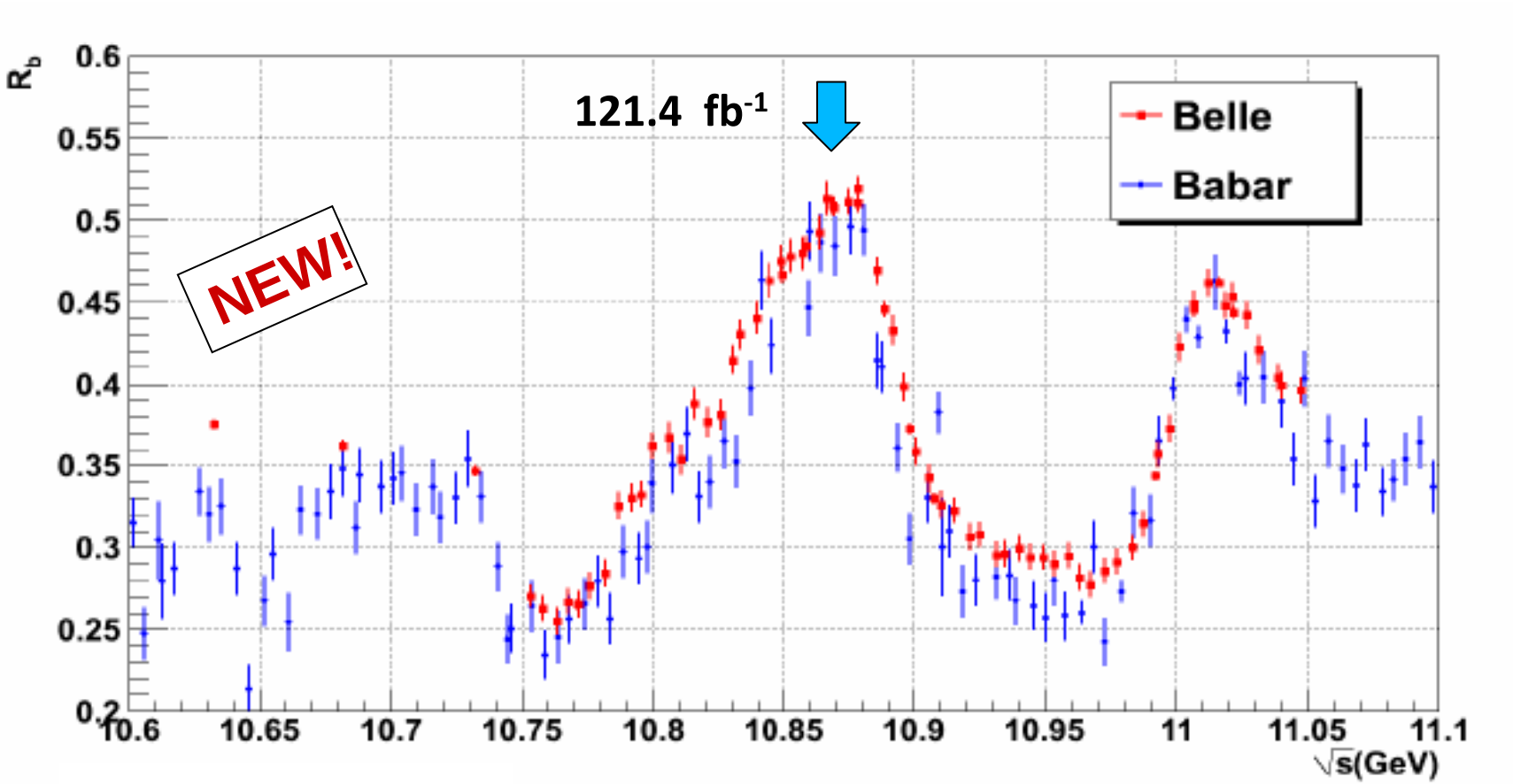
Summary of this talk

- Low energy QCD is one of the least understood area of the SM.
- B factories have brought many discoveries of new states, especially the quarkonium-like exotics “XYZ”.
- More recently, discoveries are extended to the bottomonium region.
- Need more studies to investigate their nature.
- More data are expected from existing Belle data and from Super-KEKB/Belle II.

Thanks!

Stay Tuned !

R_b Measurements



- Better statistic errors, but covers a smaller energy range compared to Babar
- R_b is slightly higher by 0.0185
- No Ali's $\Upsilon_b(10900)$ (Phys.Lett. B 684, 28-39 2010) Γ_{ee}<36eV