New results on the XYZ states and B-decays from Belle

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on behalf of the Belle Collaboration

Helmholts International Summer School – Dubna International Advanced School of Theoretical Physics "Quantum Field Theory at the Limits: from Strong Fields to Heavy Quarks"

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Outline

- Introduction of Belle experiment
- What are X, Y, Z's?
- New result on X(3872)
- Two new results on $Z_b(10610)$ and $Z_b(10650)$

Outline

- Summary of the Belle's results on Y's and Z_c's

- New result on angular analysis of $B \to K^* l^- l^+$
- New result on $\bar{B}^0 \to D^{*+} \tau \bar{\nu}_\tau$ with semileptonic tag

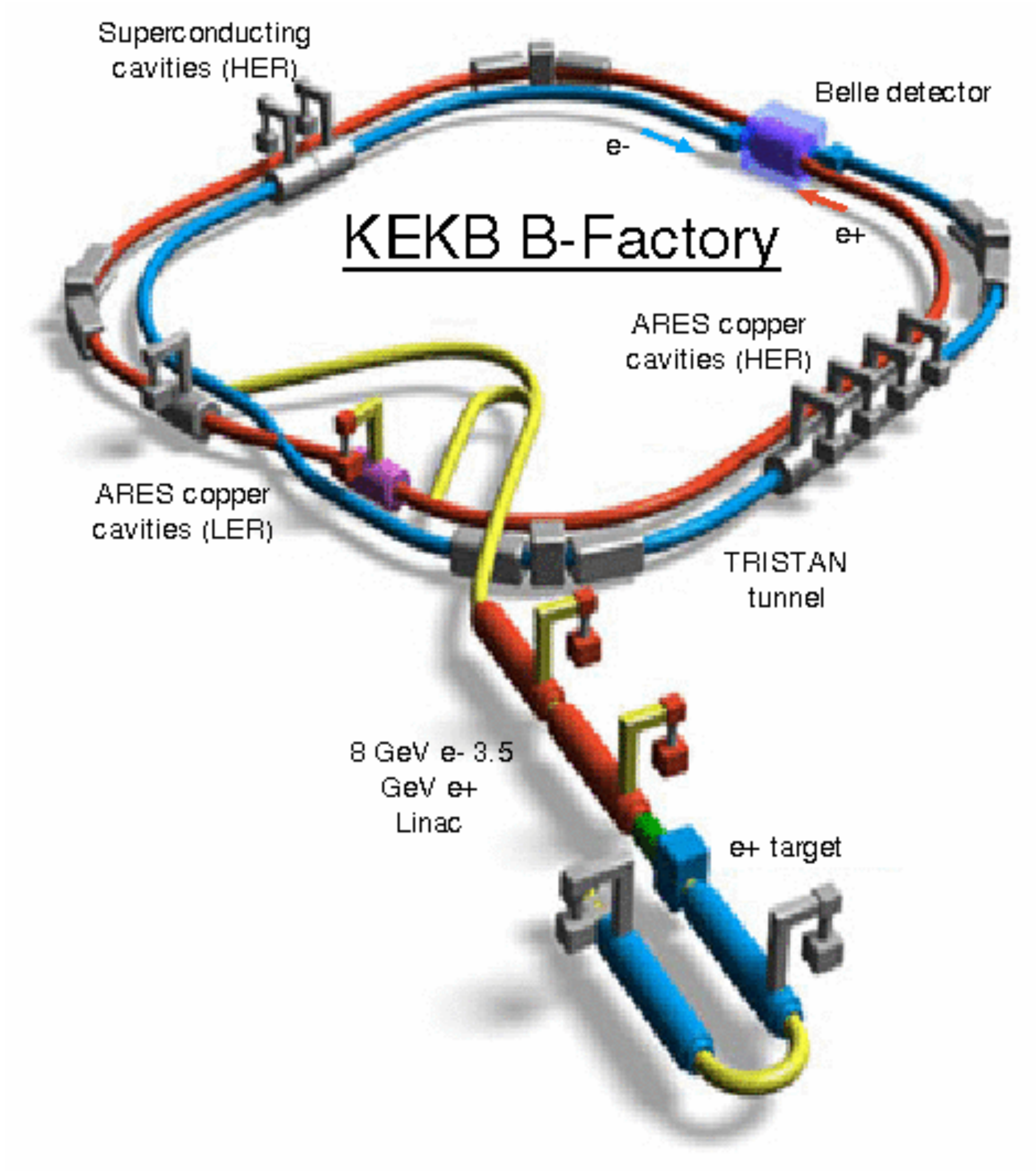
- Summary

Introduction of
Belle experiment

Belle experiment is the experiment at KEK B factory with Belle detector dedicated for the CP violation physics of B mesons

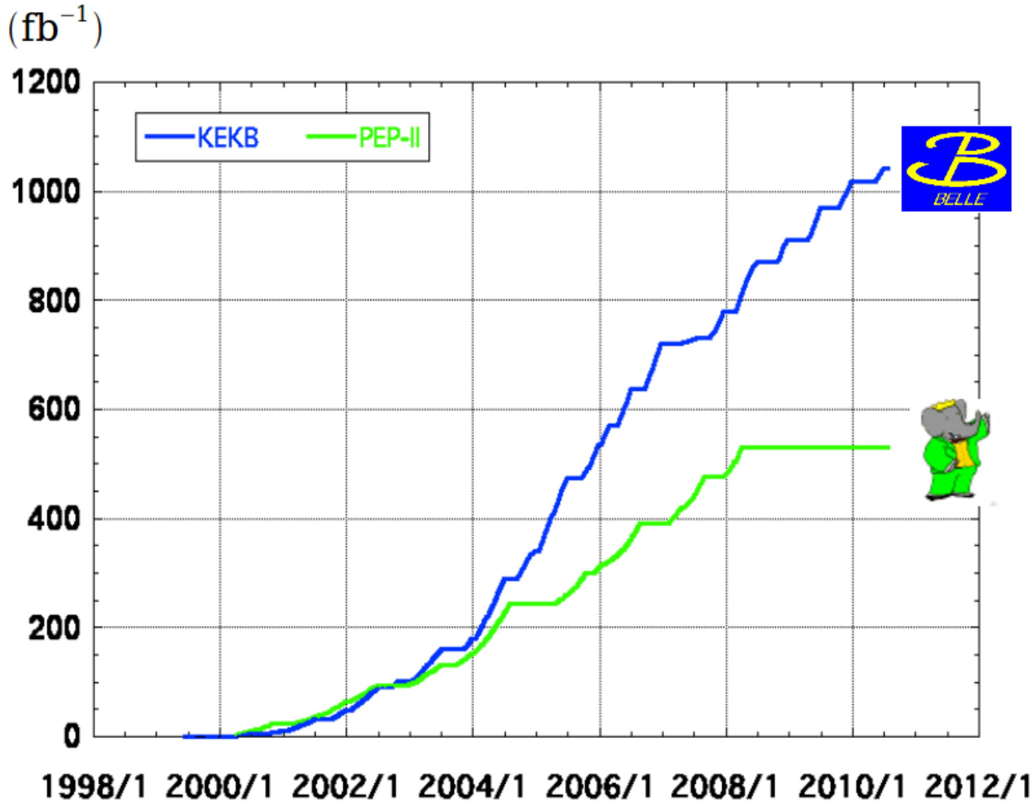
KEK B factory

KEK is located about 60km north east from Tokyo



- 8GeV(e^-) ×3.5GeV(e^+)
- Peak Luminosity 2.1×10^{34} cm^{-2} s^{-1}
- Integrated luminosity 1040 fb^{-1}

Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim$ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim$ 54 fb^{-1}

Cross section and luminosity

- Cross section , Unit: barn, symbol: b
  1 b = 10^{-24} cm^2
- Total cross section of $e^+e^- \to \mu^+\mu^-$

$$\sigma_{tot} = \int d\sigma = \frac{4\pi\alpha^2}{3E_{cm}^2}\sqrt{1-\frac{m_\mu^2}{E^2}}\left(1+\frac{1}{2}\frac{m_\mu^2}{E^2}\right) \cong \frac{87}{E_{cm}^2}\,nb \quad (E >> m_\mu)$$

  with E_{cm} in unit of GeV.
  (E is the electron energy in cm system.)
- Event rate = luminosity × cross section

- In the case of KEK B factory
  Event rate of $e^+e^- \to \mu^+\mu^-$
  $=87/(10.5)^2 \times 21 \sim 16.6$/sec

  Event number of $e^+e^- \to \mu^+\mu^-$
  $=87/(10.5)^2 \times$(nb/fb)$\times 1000 \sim 8\times 10^8$

- Event number of $e^+e^- \to c\bar{c}$
  =(2/3)^2×Nc×$87/(10.5)^2 \times$(nb/fb)$\times 1000 \sim$
  1.1×10^9
  Not only B factory, but also charm factory!
- 772×10^6 B Bbar pairs

Upsilon(4S) production rate

About Upsilon(4S)

- M = 10.5794 GeV
- $J^{PC} = 1^{--}$ same as photon!
- Width = 20.5 MeV
- $B^+ B^-$ & $B^0 B^{0bar}$ threshold = 10.559 GeV
- B B* threshold = 10.604 GeV
- Upsilon(4S) -> $e^+ e^-$ fraction = 1.57×10^{-5}
- Upsilon(4S) -> B B^{bar} fraction > 96%
  B meson production -> B factory!

$$\sigma(e^+e^- \to \Upsilon(4S)) = 64\pi^3\alpha^2 \frac{|\psi(0)|^2}{M^3} \delta(E_{cm}^2 - M^2)$$

$$\Gamma(\Upsilon(4S) \to e^+e^-) = \frac{16\pi\alpha^2}{3} \frac{|\psi(0)|^2}{M^2}$$

$$\sigma(e^+e^- \to \Upsilon(4S)) = 4\pi^2 \frac{3\Gamma(\Upsilon(4S) \to e^+e^-)}{M} \delta(E_{cm}^2 - M^2)$$

$$\delta(E_{cm}^2 - M^2) \sim \frac{1}{2\pi M \Gamma_{full}}$$

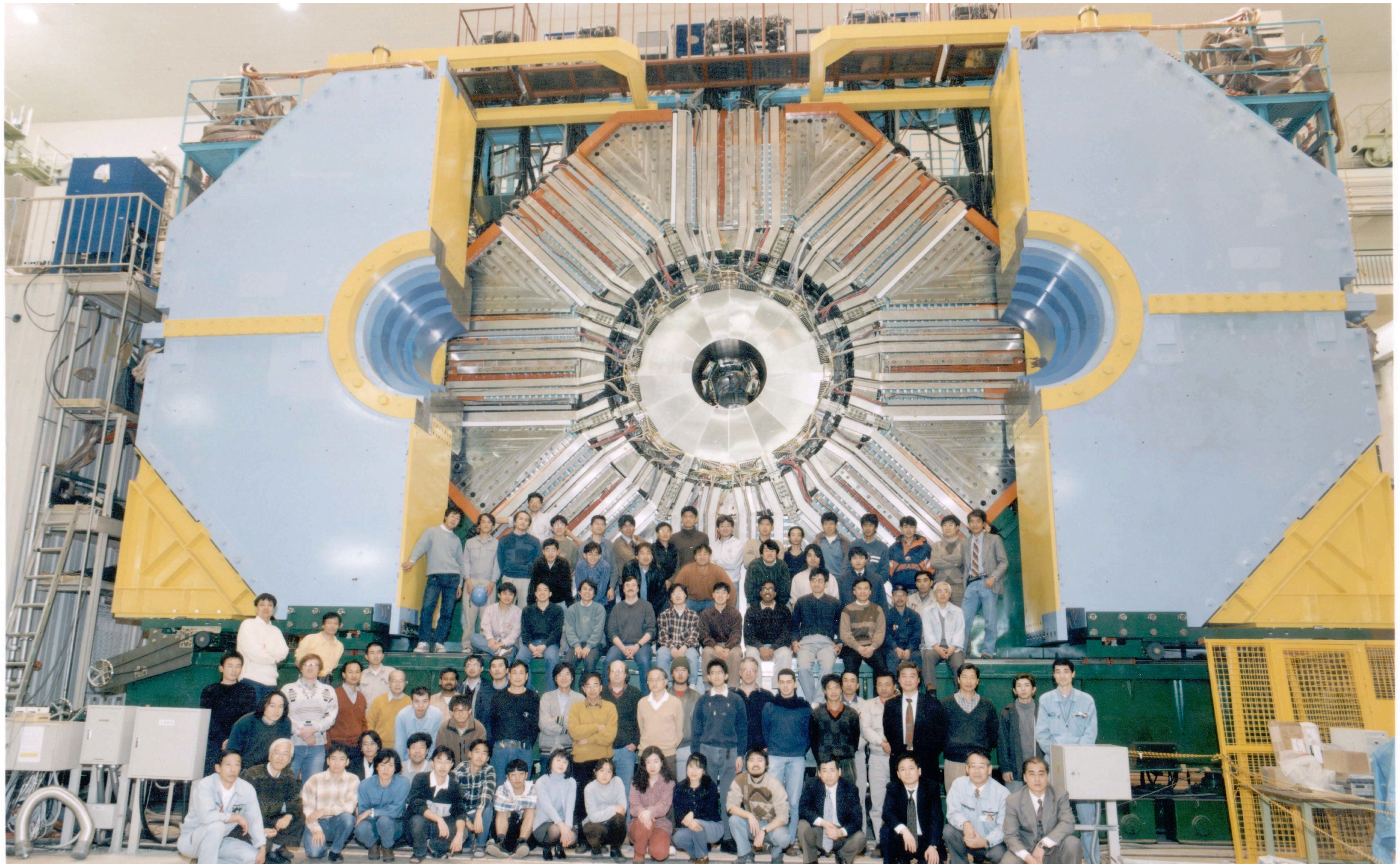
at E_{cm} = M with full width of Upsilon(4S)

$$\sigma\left(e^+e^- \to \Upsilon(4S)\right) = \frac{6\pi}{M^2}\,\frac{\Gamma\left(\Upsilon(4S) \to e^+e^-\right)}{\Gamma_{full}}$$

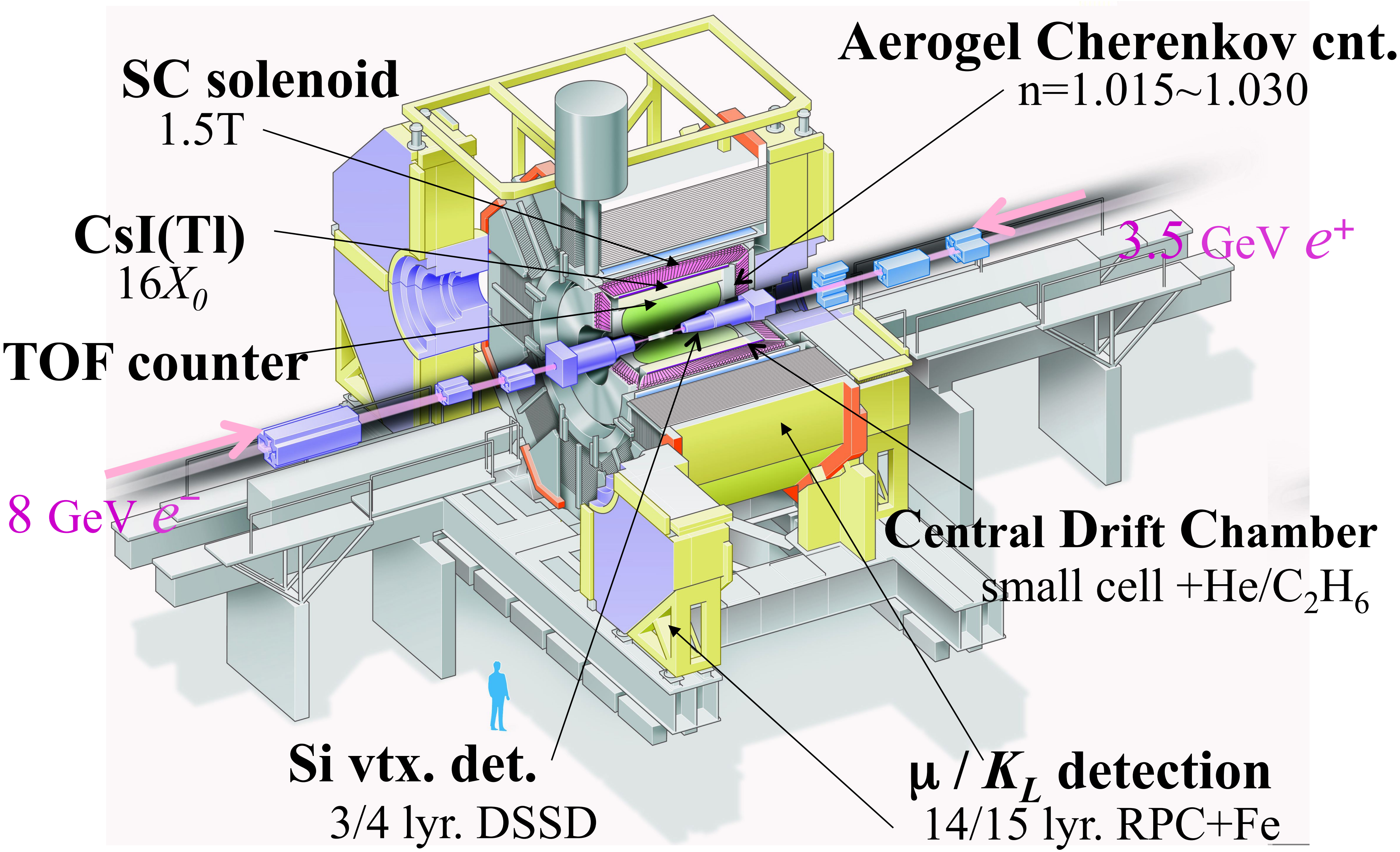
～1nb

Total number of Upsilon(4S)
～ 1.1nb/fb×700 = 770 M

Belle detector (already disassembled)



Belle Detector



- High resolution, multipurpose, good PID, 4π spectrometer

- Loose event selection

Data analyses at Belle

Detected particles

- photon
- electron, muon
- Charged hadrons:pion, kaon, proton
- Neutral hadrons:K_L
  π^0-> $\gamma\gamma$, eta-> $\gamma\gamma$, Ks -> $\pi\pi$, Λ-> pπ

  K_L is not used for hadron physics, but for cp violation physics.

Energy, momentum, track, vertex point
Combinations of these data are used for reconstruction of hadron resonances
For more detail, see PR D 67, 032003 (2003)

Physics runs

Table 1. Summary of the luminosity integrated by Belle, broken down by CM energy.

Resonance	On-peak luminosity (fb^{-1})	Off-peak luminosity (fb^{-1})	Number of resonances
$\Upsilon(1S)$	5.7	1.8	102×10^6
$\Upsilon(2S)$	24.9	1.7	158×10^6
$\Upsilon(3S)$	2.9	0.25	11×10^6
$\Upsilon(4S)$ SVD1	140.0	15.6	152×10^6 $B\bar{B}$
$\Upsilon(4S)$ SVD2	571.0	73.8	620×10^6 $B\bar{B}$
$\Upsilon(5S)$	121.4	1.7	7.1×10^6 $B_s\bar{B}_s$
Scan		27.6	

Reference: J. Brodzicka et. al., PTEP, 2012, 04D001

- Off-resonance data
  60MeV below the resonance peak in order to determine the non-BB^{bar} background

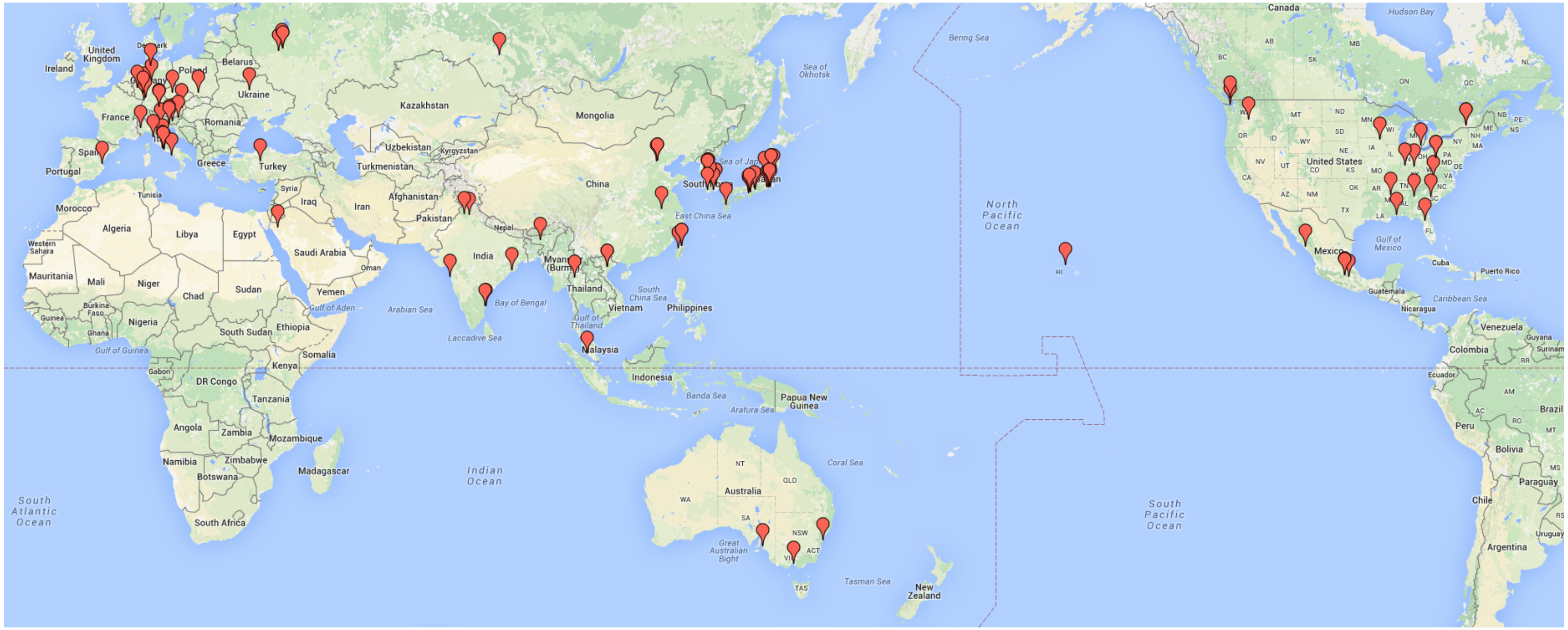
- Energy scan data
  between $\Upsilon(4S)$ (10.5794GeV) and $\Upsilon(6S)$ (11.019GeV)

Belle II Experiment

- Upgrade of Belle experiment
- KEK B-factory -> Super KEK B-factory
  40 times luminosity
- Belle detector -> Belle II detector
  More leyers of VXD, CDC,
  New Tech: TOP counter,
  High speed DAQ

Belle II collaboration

- 23 countries and regions
- 99 Institutes and Universities,
- Over 600 physicists



Belle II collaboration

Countries and Regions

AUSTRALIA	AUSTRIA	CANADA	CHINA	CZECH
GERMANY	INDIA	ITALY	JAPAN	KOREA
MALAYSIA	MEXICO	POLAND	RUSSIA	SAUDI ARABIA
SLOVENIA	SPAIN	TAIWAN	THAILAND	TURKEY
U.S.A.	UKRAINE	VIETNAM		

What are X, Y, Z's?

Y

- $J^{PC} = 1^{--}$
- Production: $e^+ e^- \to Y$
- Y has c and c^{bar} quarks
- But not the simple charmonium
- Examples:
  Y(4005), Y(4260), Y(4360), Y(4660)

Z (Z_c and Z_b)

- Z_c has c and c^{bar} quarks and a charge.
- So minimal quark content of Z_c^+ is c c^{bar} u d^{bar}. Exotic state!
- Usually the isospin of the Z is 1, so there exists neutral isospin partner. That is also called Z.
- Z_b has b and b^{bar} quarks and a charge.
- Examples: Z_b(10610), Z_b(10650), Z_c(4430), Z_c(3900), Z_c(4200) and more.

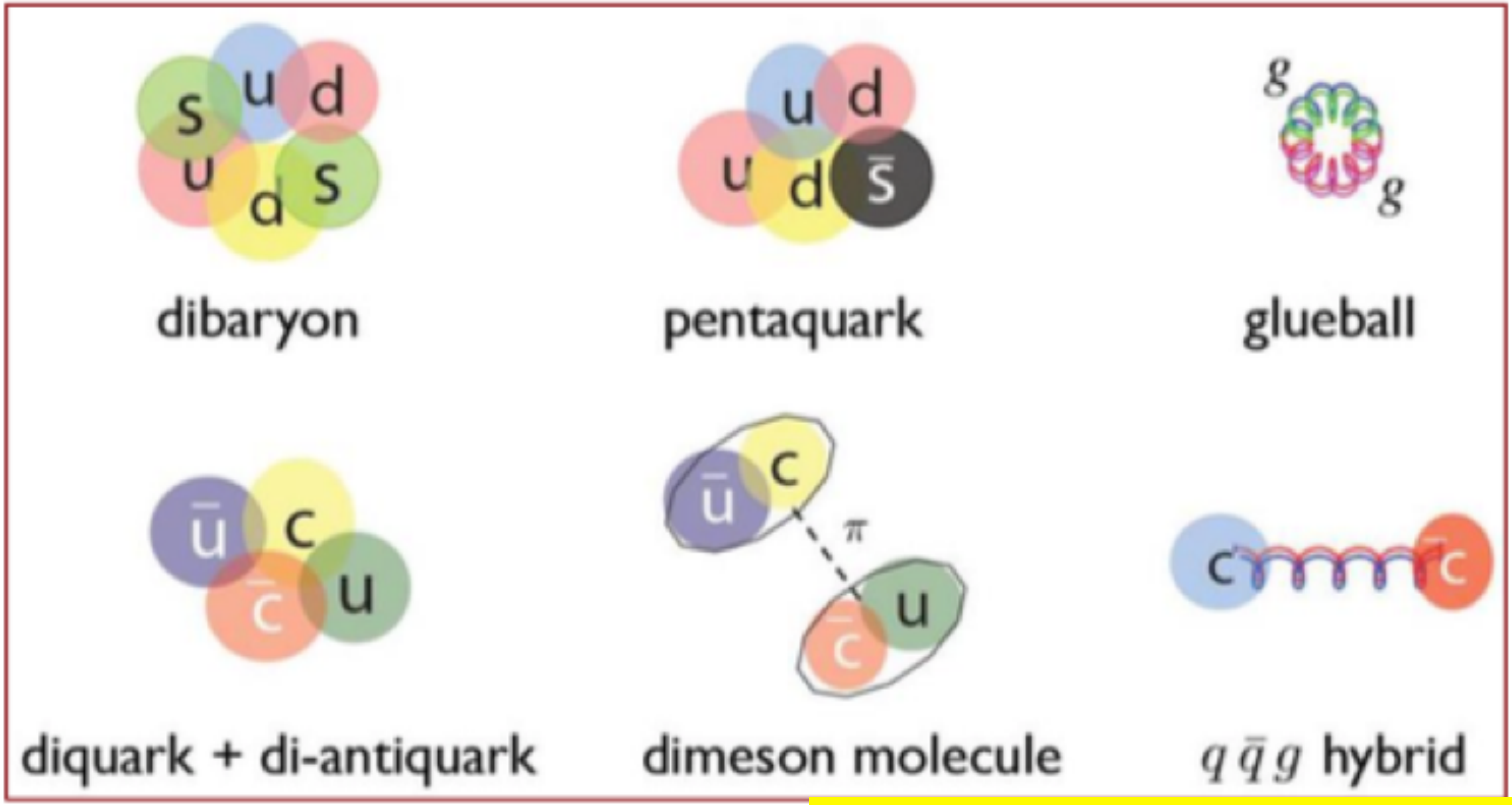
X

- X's are the non-qq^{bar} mesons other than Y's and Z's.
- Most famous one is X(3872).
- Example:
  X(3915), X(3940), X(4350)

Exotic Hadrons

- Normal hadorns:
  Meson: qq^{bar} structure
  Baryon: qqq structure

- Exotic hadrons:
  Glueball, qq^{bar} g hybrid,
  diquark + di-antiquark, dimeson molecule,
  pentaquark, dibaryon



Chengping Shen's slide for Meson 2016

Exotic Hadrons are not only these exotics but also the mixing of normal hadrons and these exotic hadrons

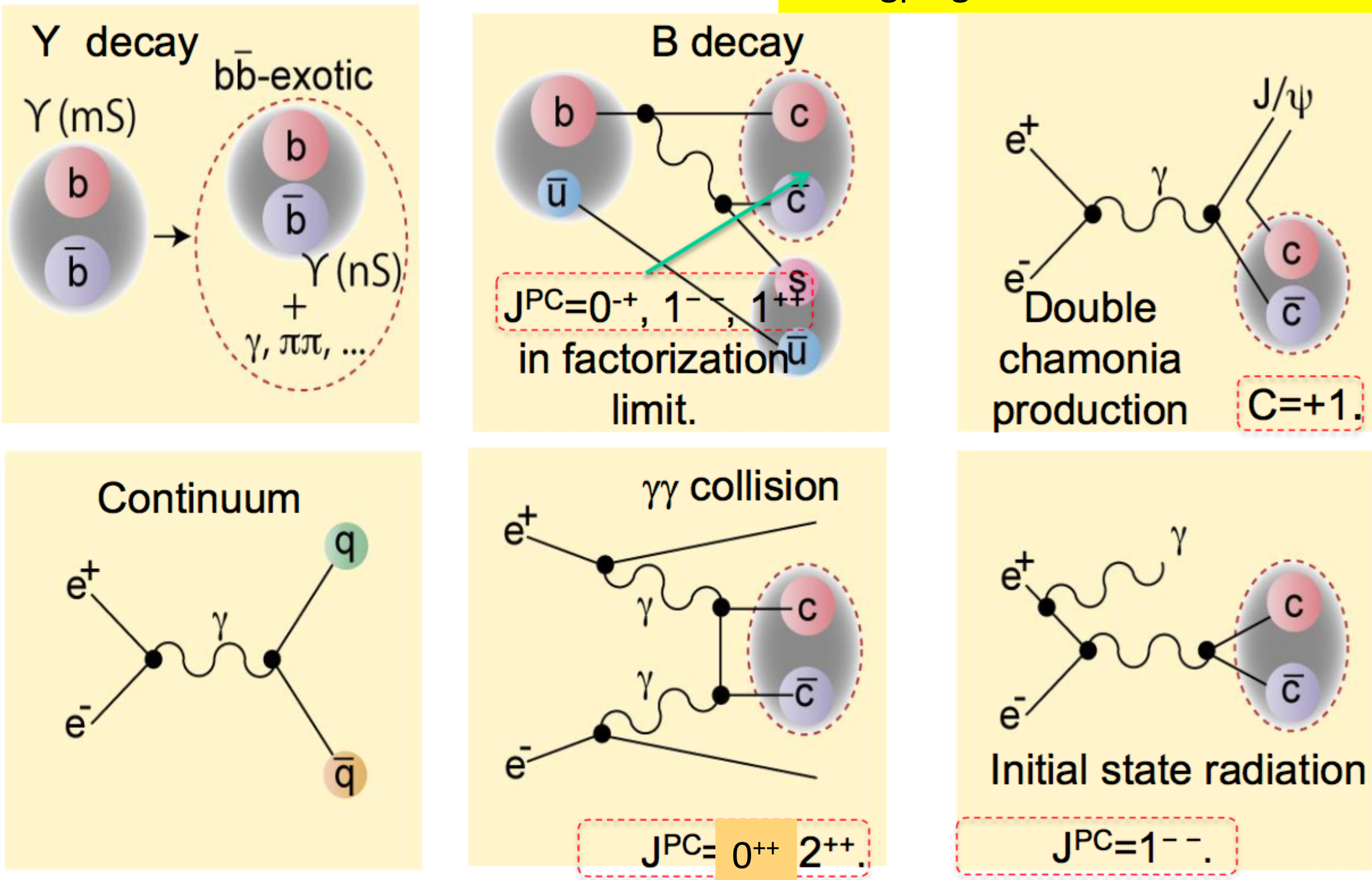
Why most of the exotics hadrons are charmonium-like or bottomonium-like states?

- Charm and Bottom quark masses are well above the QCD energy scale and the identities of c and b quarks are well established.

- Since the kinetic term of the heavy quark system is smaller than that of light quark system, it is easy to make the bound state for heavy quark system.

Production mechanism of the Exotic Hadrons

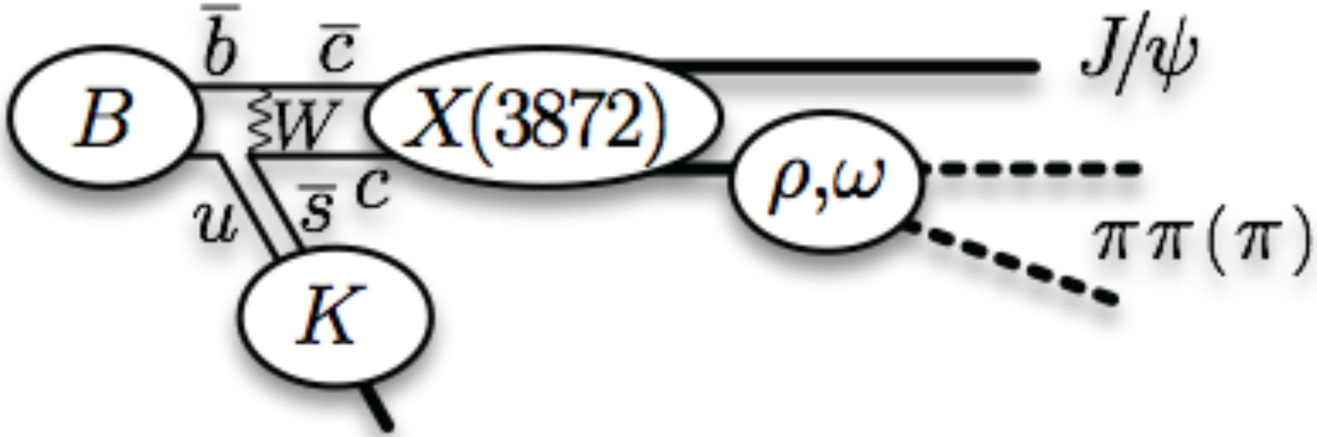
Chengping Shen's slide for Meson 2016



New result on X(3872)

X(3872)

- First observed from B decay by Belle on 2003.

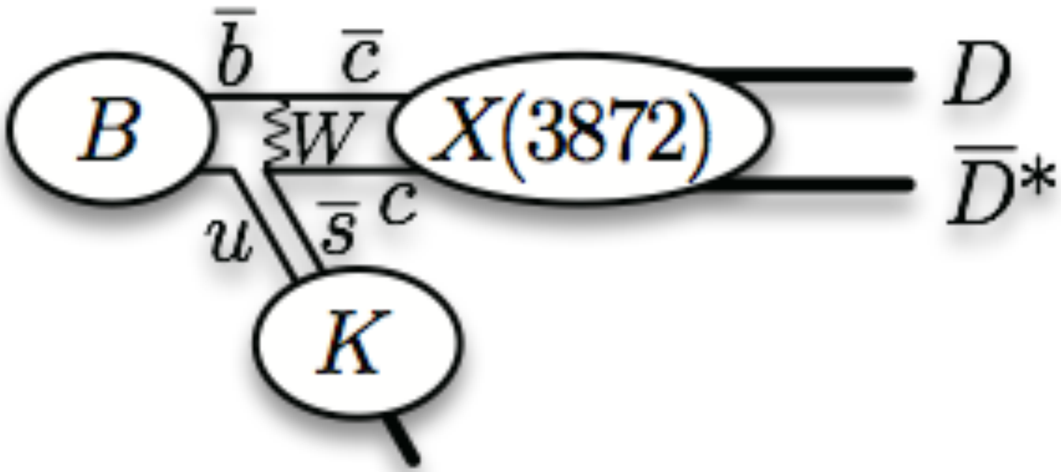


X(3872) should be Charmonium-like state.

J/ψ π^n Exp:
S.K.Choi et al. [Belle] PRL91, 262001 (2003)
B.Aubert et al. [BaBar] PRD71, 071103 (2005)

Belle paper was cited more than 1200 times.

X(3872)



X(3872) decays to DD^{*bar}

$Br(X \to D^0\bar{D}^{*0})/Br(X \to J/\psi\pi^2)$

$= 8.92 \pm 2.42, 19.9 \pm 8.05$ (calc from papers)

Belle BABAR

$D^0\bar{D}^{*0}$ exp
T.Aushev et al. [Belle] PRD81, 031103 (2010)
B.Aubert et al. [BaBar] PRD77, 011102 (2008)

Formation process of X(3872)

- X(3872) from
  - B^+ decay
  - B^0 decay
  - pp^{bar} collision
    - $Br(pp^{bar} \to X)/Br(pp^{bar} \to \psi(2S)) > 0.046$
  - pp collision
    - $J^{PC}=1^{++}$

p̄p exp
D.Acosta et al. [CDF] PRL93, 072001 (2004)
V.M.Abazov et al. [D0] PRL93, 162002 (2004)

C.Bignamini et al. PRL103, 162001 (2009)

pp exp
R.Aaij et al. [LHCb] EPJC72, 1972 (2012)

Decay process of X(3872)

- X(3872) decays into
  - $J/\psi\ \pi\pi$ [Belle][BaBar][CDF][D0][CMS]
  - $J/\psi\ \pi^3$ [BaBar]([Belle] not published)
  - $D^0\bar{D}^{*0}$ [Belle][BaBar]
  - $J/\psi\gamma$ [Belle][BaBar][LHCb]
  - $\psi(2S)\gamma$ [BaBar][LHCb]([Belle] not seen)

X(3872) facts

4 two-meson thresholds are nearby.

- $J^{PC}=1^{++}$
- X(3872) ($uc\bar{u}\bar{c}$, $dc\bar{d}\bar{c}$) thresholds
  - $D^{\pm}D^{*\mp}$ 3879.87±0.12 MeV
  - $J/\psi\omega$ 3879.57±0.12 MeV
  - $J/\psi\rho$ 3872.18±0.25 MeV
  - $D^0\bar{D}^{*0}$ 3871.80±0.12 MeV (Lowest threshold)

Mass and Decay to $J/\psi\ \pi^n$

- X(3872) decays into
  - ▷ $J/\psi\ \pi\pi$ isovector
    - mass 3871.69±0.17 MeV
      width < 1.2 MeV
  - ▷ $J/\psi\ \pi^3$ isoscalar
    - $Br(X \to J/\psi\pi^3)/Br(X \to J/\psi\pi^2)$ = 1.0±0.4±0.3, 0.8±0.3

      Belle BABAR

Binding energy is 0.11 MeV.

very narrow width

A large isospin symmetry breaking

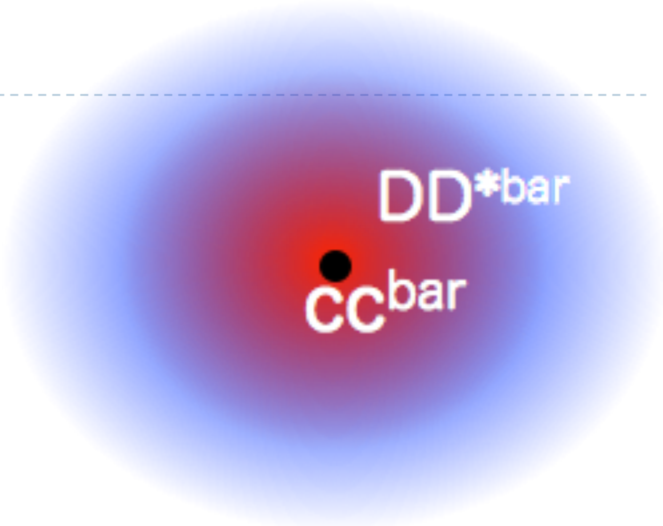
X(3872)

- Charmonium: 1^{++} corresponds $^3P_1$ state

$\chi_{c1}(1P)$ Mass: 3510.66 ± 0.07 MeV

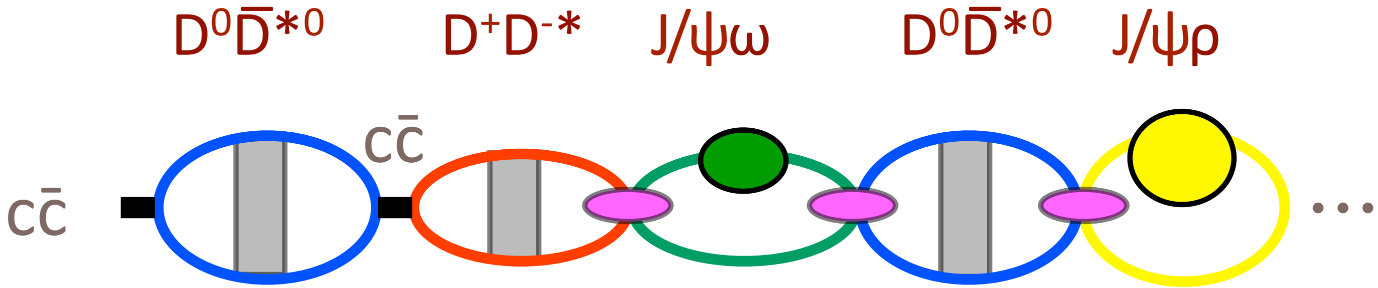
$\chi_{c1}(2P)$ Mass: Quark model prediction
NR: 3925 MeV
GI: 3953 MeV **Not observed**

X(3872) may be



Two-meson molecule with a cc^{bar} core:

- $c\bar{c}$ - $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ – $J/\psi\rho$



This is my personal opinion,
not the Belle opinion.

M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 0903D01
S.Takeuchi, K.Shimizu, and M.Takizawa, 2015, 079203

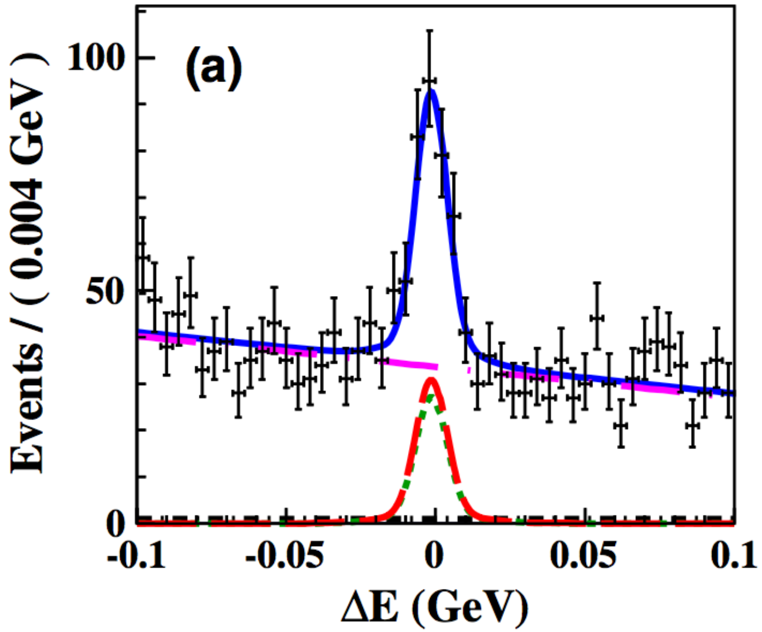
X(3872): new result from Belle

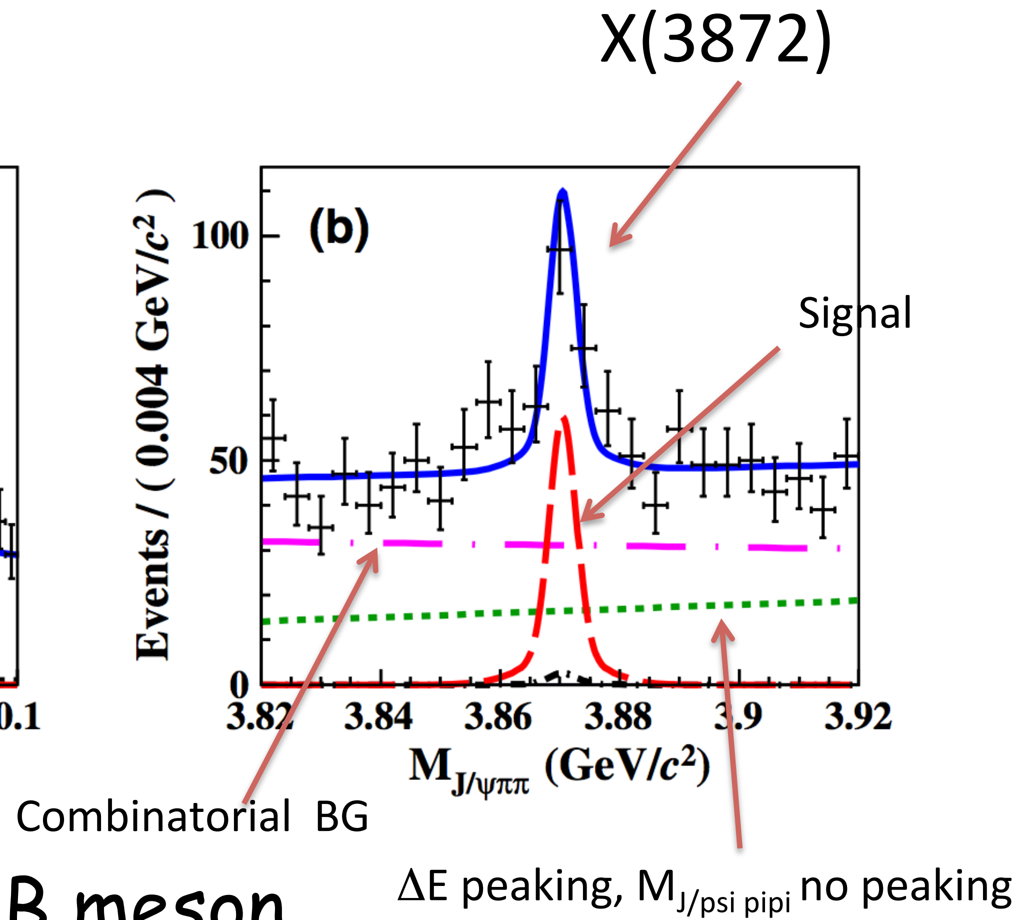
- Observation of X(3872) in B -> X(3872) K pi decays PRD 91, 051101(R) (2015)

- Observe: B^0 -> X(3872) K^+ pi^- decay
- Evidence: B^+ -> X(3872) K^0_s pi^+ decay

X(3872): new result from Belle

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

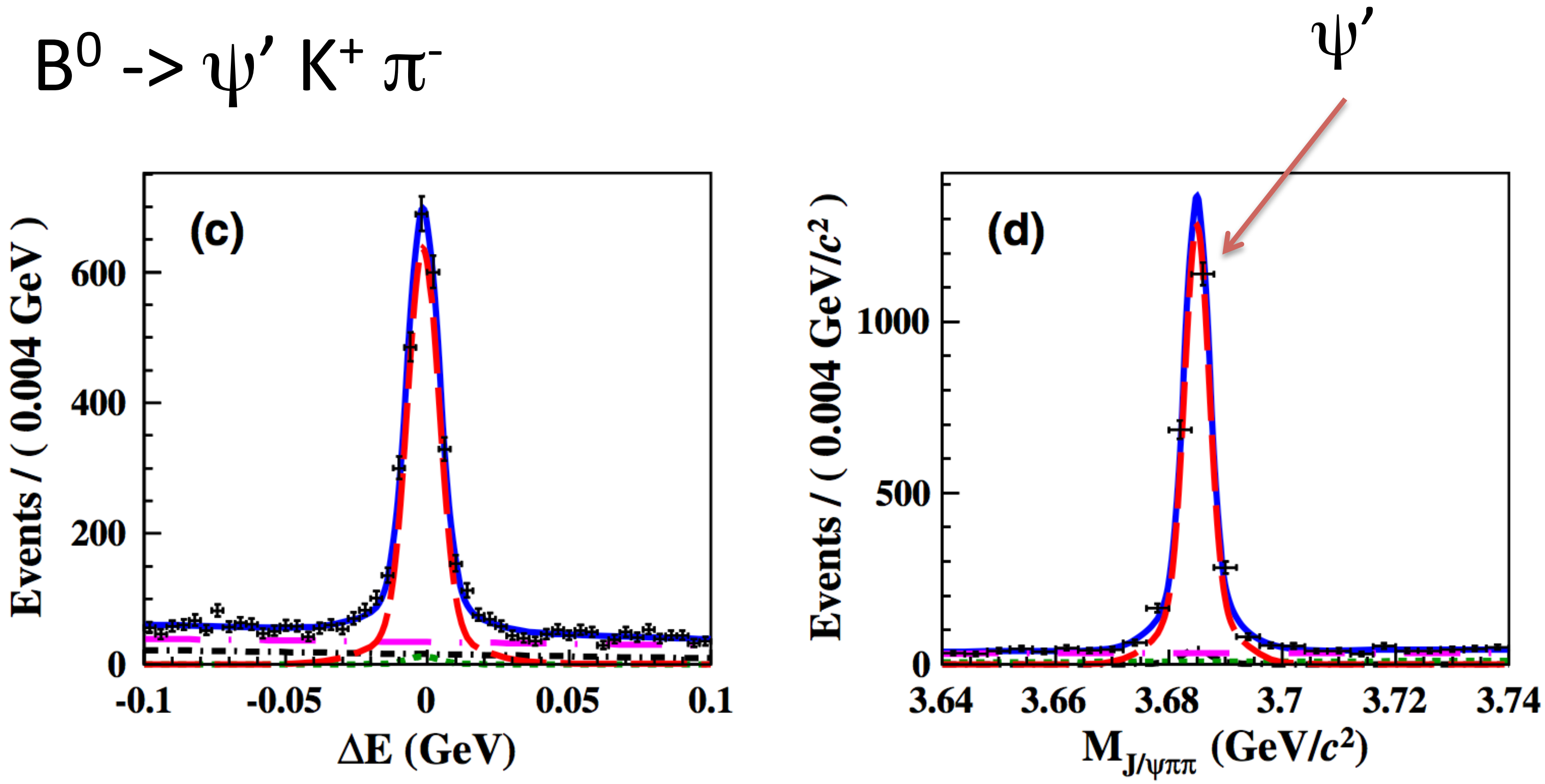




ΔE=0 means decay from B meson

X(3872): new result from Belle

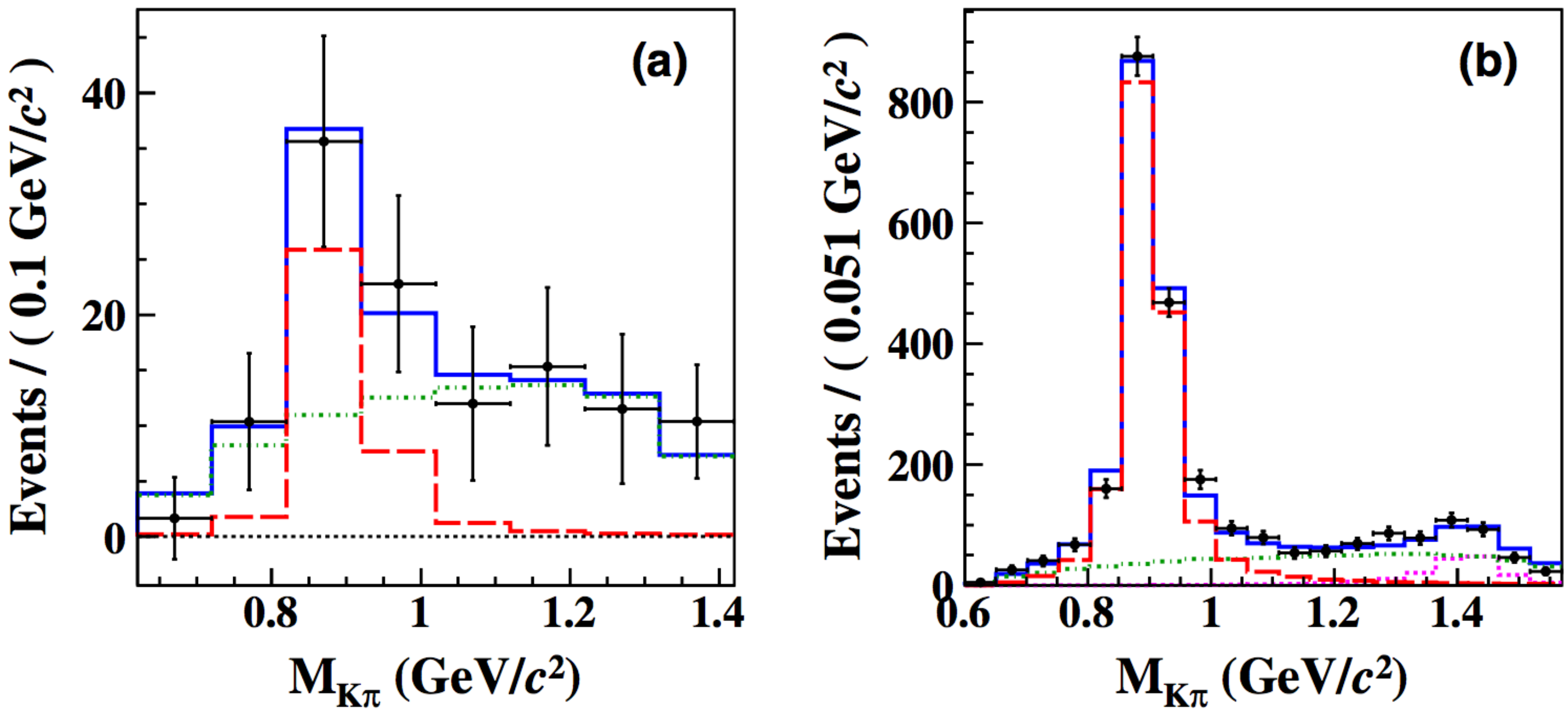
$B^0 \to \psi' K^+ \pi^-$



ΔE=0 means decay from B meson

X(3872): new result from Belle

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



Red :K* contributoin

Green: non-resonance contribution

$K^*(892)^0$ dominant

X(3872): new result from Belle

TABLE I. Signal yield (Y) from the fit, weighted efficiency (ϵ) after particle-identification correction, significance (Σ) and measured $\mathcal{B}$ for $B^0 \to X(3872)K^+\pi^-$ and $B^+ \to X(3872)K^0\pi^+$. The first (second) uncertainty represents a statistical (systematic) contribution.

Decay mode	Y	ϵ (%)	$\Sigma(\sigma)$	$\mathcal{B}(B \to X(3872)K\pi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$
$B^0 \to X(3872)K^+\pi^-$	116 ± 19	15.99	7.0	$(7.9 \pm 1.3 \pm 0.4) \times 10^{-6}$
$B^+ \to X(3872)K^0\pi^+$	35 ± 10	10.31	3.7	$(10.6 \pm 3.0 \pm 0.9) \times 10^{-6}$

Two new results on $Z_b(10610)$ and $Z_b(10650)$

$Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$

- First observation
  Phys. Rev. Lett. 108, 122001 (2012).

$$\Upsilon(5S) \to \Upsilon(1,2,3S)\pi^{\pm} \quad \pi^{\mp}$$
$$\Upsilon(5S) \to h_b(1,2P)\ \pi^{\pm} \quad \pi^{\mp}$$

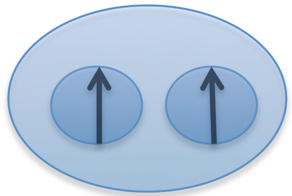
$$Z_b^{\pm}(10610),\ Z_b^{\pm}(10650)$$

$Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$

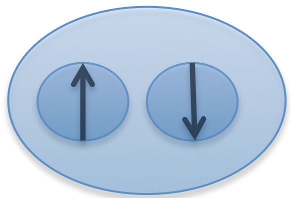
- Heavy quark spin flip transition

$$\Upsilon(5S) \to h_b(1,2P)\,\pi^{\pm} \quad \pi^{\mp}$$

Upsilon $^3S_1$ state =>



h_b $^1P_1$ state =>



- Why this transition is not suppressed?

Because Z_b is mixture of spin parallel and spin anti-parallel states.

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

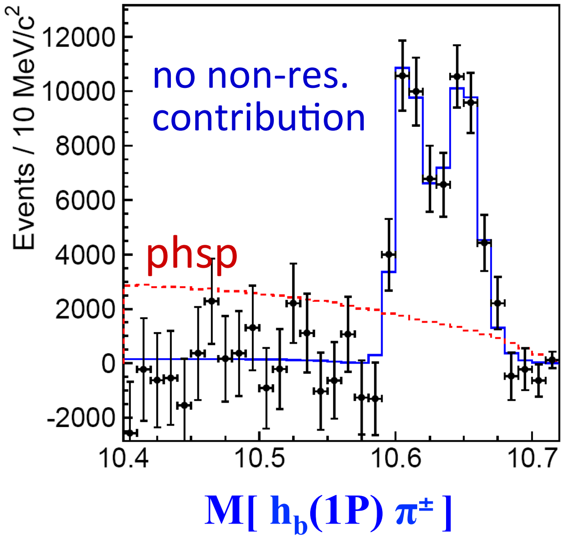
Alex Bondar's slide

Two peaks are observed in all modes!

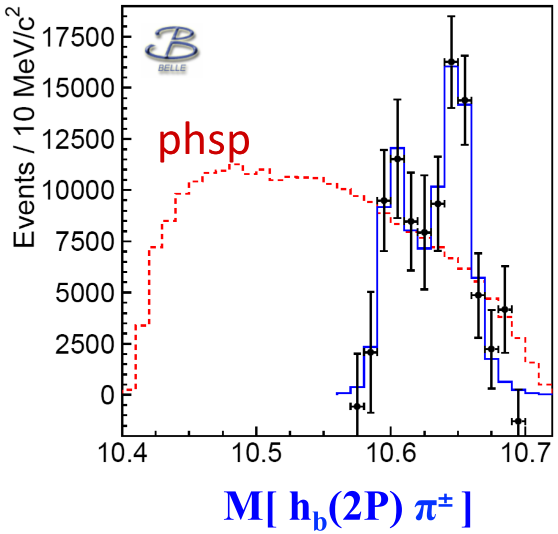
Belle: PRL108, 232001 (2012)

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

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

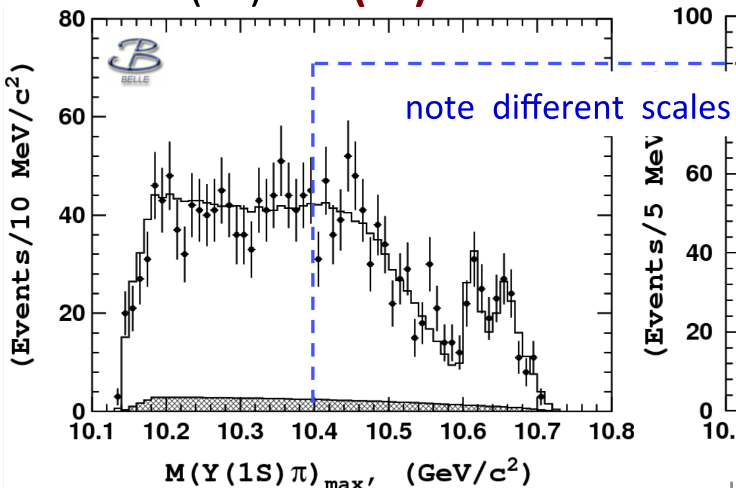


$\Upsilon(5S) \to$ **$h_b(2P)$**$\pi^+\pi^-$

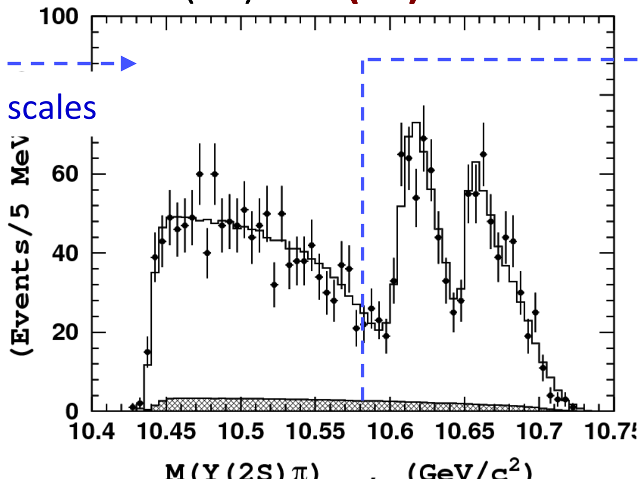


Dalitz plot analysis

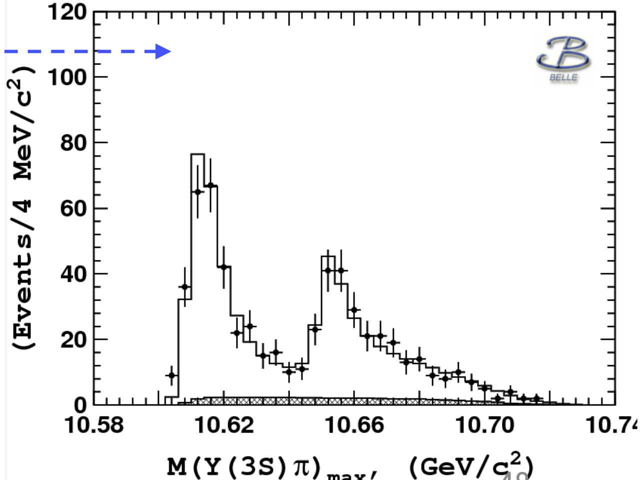
$\Upsilon(5S) \to$ **$\Upsilon(1S)$**$\pi^+\pi^-$



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

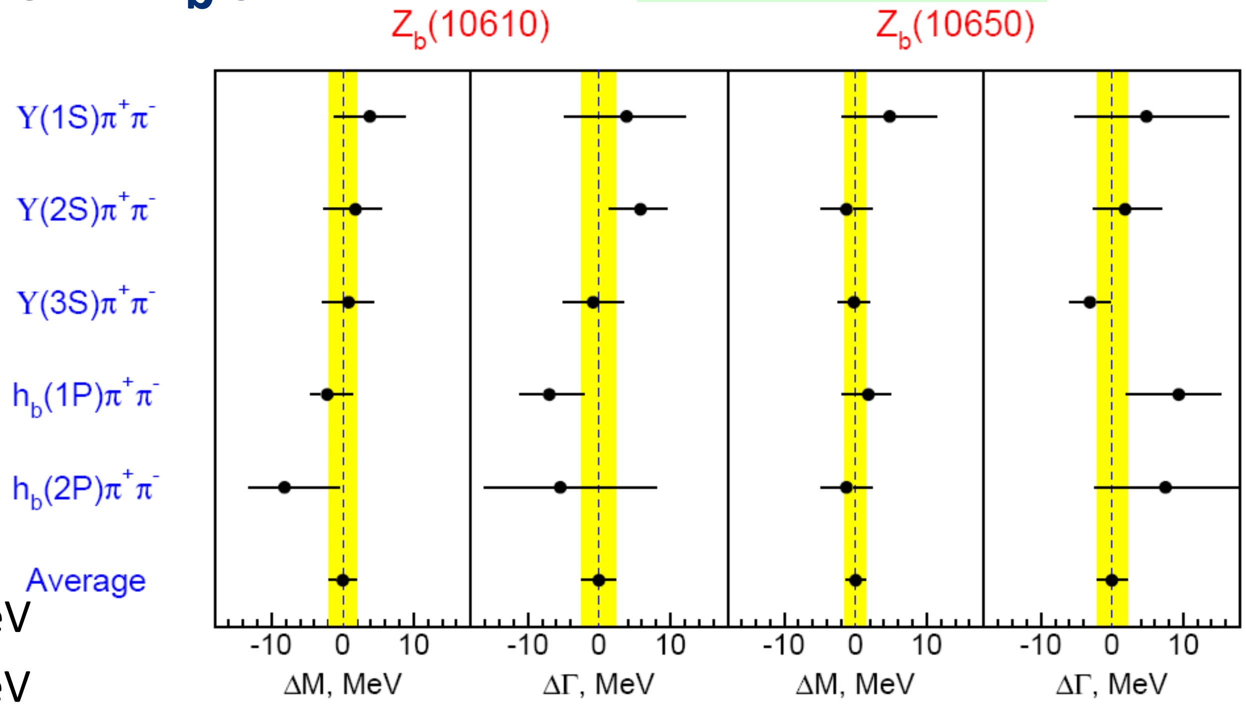


$\Upsilon(5S) \to$ **$\Upsilon(3S)$**$\pi^+\pi^-$



Summary of Z_b parameters

Alex Bondar's slide



Average over 5 channels

$$\langle M_1 \rangle = 10607.2 \pm 2.0 \text{ MeV}$$

$$\langle \Gamma_1 \rangle = 18.4 \pm 2.4 \text{ MeV}$$

$$\langle M_2 \rangle = 10652.2 \pm 1.5 \text{ MeV}$$

$$\langle \Gamma_2 \rangle = 11.5 \pm 2.2 \text{ MeV}$$

$M_1 - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV

$M_2 - 2M_{B^*} = +1.8 \pm 1.7$ MeV

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

$Z_b(10610)$ yield ~ $Z_b(10650)$ yield in every channel

Relative phases: 0^o for $\Upsilon\pi\pi$ and 180^o for $h_b\pi\pi$

$Z_b^0(10610)$

- How about the isospin partner of Z_b?
- Phys. Rev. D 88, 052016 (2013)

- Dalitz analysis of

$$\Upsilon(5S) \to \Upsilon(2,3S)\pi^0\pi^0$$

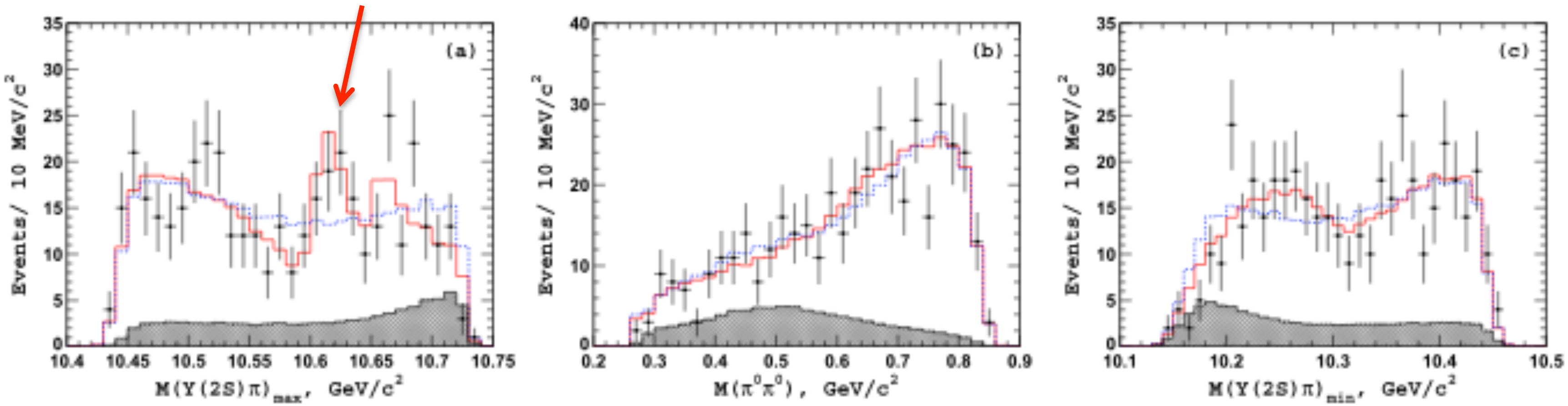


FIG. 4 (color online). Comparison of the (a) $M(\Upsilon(2S)\pi^0)_{max}$, (b) $M(\pi^0\pi^0)$, and (c) $M(\Upsilon(2S)\pi^0)_{min}$ distributions for the $\Upsilon(2S)\pi^0\pi^0$ events in the signal region (points with error bars) and results of the fit (open histograms). The legends are the same as in Fig. 3. Only solution A is shown. Both solutions give indistinguishable plots.

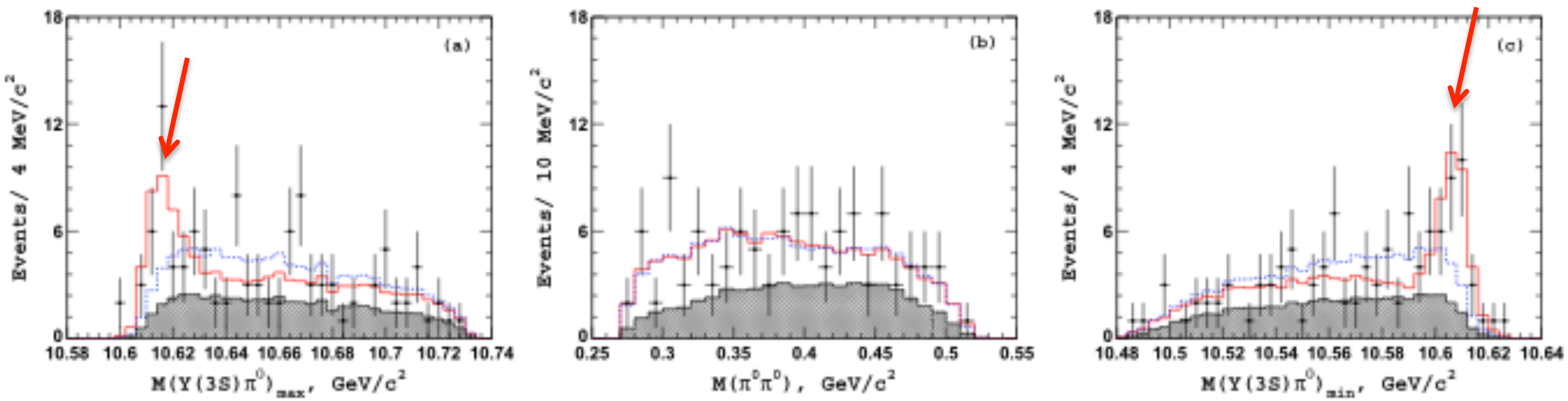


FIG. 5 (color online). Comparison of the (a) $M(\Upsilon(3S)\pi^0)_{max}$, (b) $M(\pi^0\pi^0)$, and (c) $M(\Upsilon(3S)\pi^0)_{min}$ distributions for the $\Upsilon(3S)\pi^0\pi^0$ events in the signal region (points with error bars) and results of the fit (open histograms). The legends are the same as in Fig. 3.

$Z_b^0(10610)$

- Mass: (10609±4±4) MeV
- Statistical significance is 6.5σ
- $Z_b^0(10650)$ signal is not significant.
- $Z_b^0(10610)$ and $Z_b^{\pm}(10610)$ may be same I=1 members
- Isospin symmetry breaking is small.

Z_b: new result (1)

- Full amplitude analysis of

$$e^+e^- \to \Upsilon(nS)\pi^+\pi^- \text{ at } \sqrt{s} = 10.866\text{GeV}$$

PRD 91, 072003 (2015)

- $J^P = 1^+$
- Update measurement of the cross sections.

Z_b: J^P assignment

TABLE III. Results of the fit to $\Upsilon(2S)\pi^+\pi^-$ [$\Upsilon(3S)\pi^+\pi^-$] events with different J^P values assigned to the $Z_b(10610)$ and $Z_b(10650)$ states. Shown in the table is the difference in $\mathcal{L}$ values for fits to an alternative model and the nominal one.

	$Z_b(10650)$			
$Z_b(10610)$	1^+	1^-	2^+	2^-
1^+	0(0)	60(33)	42(33)	77(63)
1^-	226(47)	264(73)	224(68)	277(106)
2^+	205(33)	235(104)	207(87)	223(128)
2^-	289(99)	319(111)	321(110)	304(125)

Z_b: J^P assignment

- Alternative $J^P = 1^-$ and $J^P = 2^+$, 2^- combinations are rejected at confidence levels exceeding 6 standard deviations.

Z_b: cross section measurement

TABLE IV. Results on cross sections for three-body $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ transitions. The first quoted error is statistical and the second is systematic. The last line quotes results from our previous publication for comparison.

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
Signal yield	2090 ± 115	2476 ± 97	628 ± 41
Efficiency, %	45.9	39.0	24.4
$\mathcal{B}_{\Upsilon(nS)\to\mu^+\mu^-}$, % [13]	2.48 ± 0.05	1.93 ± 0.17	2.18 ± 0.21
$\sigma^{\text{vis}}_{e^+e^-\to\Upsilon(nS)\pi^+\pi^-}$, pb	$1.51 \pm 0.08 \pm 0.09$	$2.71 \pm 0.11 \pm 0.30$	$0.97 \pm 0.06 \pm 0.11$
$\sigma_{e^+e^-\to\Upsilon(nS)\pi^+\pi^-}$, pb	$2.29 \pm 0.12 \pm 0.14$	$4.11 \pm 0.16 \pm 0.45$	$1.47 \pm 0.09 \pm 0.16$
$\sigma^{\text{vis}}_{e^+e^-\to\Upsilon(nS)\pi^+\pi^-}$, pb [1]	$1.61 \pm 0.10 \pm 0.12$	$2.35 \pm 0.19 \pm 0.32$	$1.44^{+0.55}_{-0.45} \pm 0.19$

Vis: visible cross section (before ISR correction)

Z_b: new result (2)

- Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B mesons
  PRL 116, 212001 (2016)

- First observation of the transitions

$$Z_b^{\pm}(10610) \to [B\bar{B}^* + \mathrm{c.c.}]^{\pm}$$

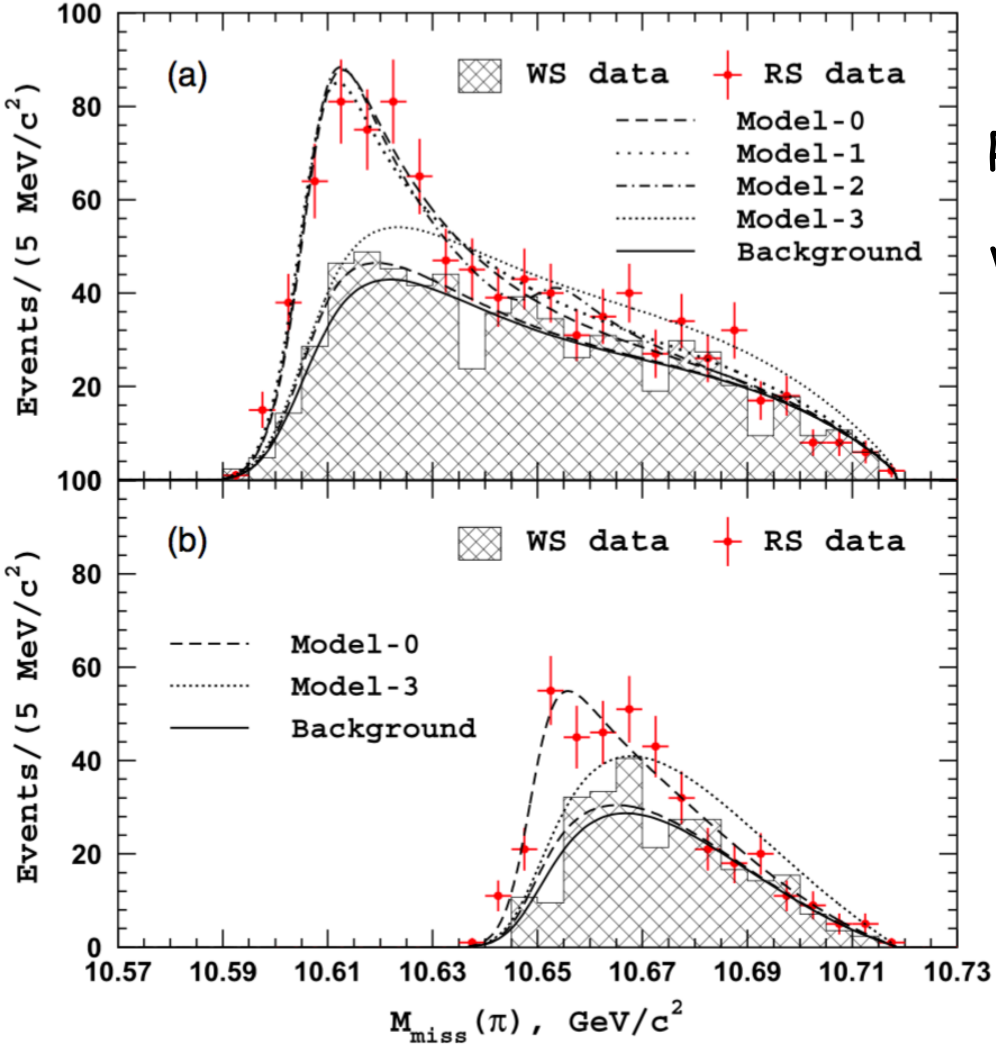
$$Z_b^{\pm}(10650) \to [B^*\bar{B}^*]^{\pm}$$

These modes dominate the final state.

Z_b: Decay modes

$B\bar{B}^*\pi$

$B^*\bar{B}^*\pi$



RS: Right Sign

WS: Wrong Sign

$e^+ e^- \to B^{(*)} B^{(*)} \pi$ Cross section

Parameter	$BB\pi$	$BB^*\pi$	$B^*B^*\pi$
N_f, events	13 ± 25	357 ± 30	161 ± 21
$\mathcal{B}_f$, 10^{-6}	293 ± 22	276 ± 21	223 ± 17
η	1.0	1.066	1.182
$1 + \delta_{\rm ISR}$	0.720 ± 0.017	0.598 ± 0.016	0.594 ± 0.016
σ, pb	< 2.9	$17.4 \pm 1.6 \pm 1.9$	$8.75 \pm 1.15 \pm 1.04$

Z_b: Branching Fraction

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	...
$B^{*+}\bar{B}^{*0}$	...	$73.7^{+3.4+2.7}_{-4.4-3.5}$

Z_b

- Z_b(10610) 's dominant structure may be BB^{*bar} hadronic molecule.

- Z_b(10650) 's dominant structure may be B^*B^{*bar} hadronic molecule.

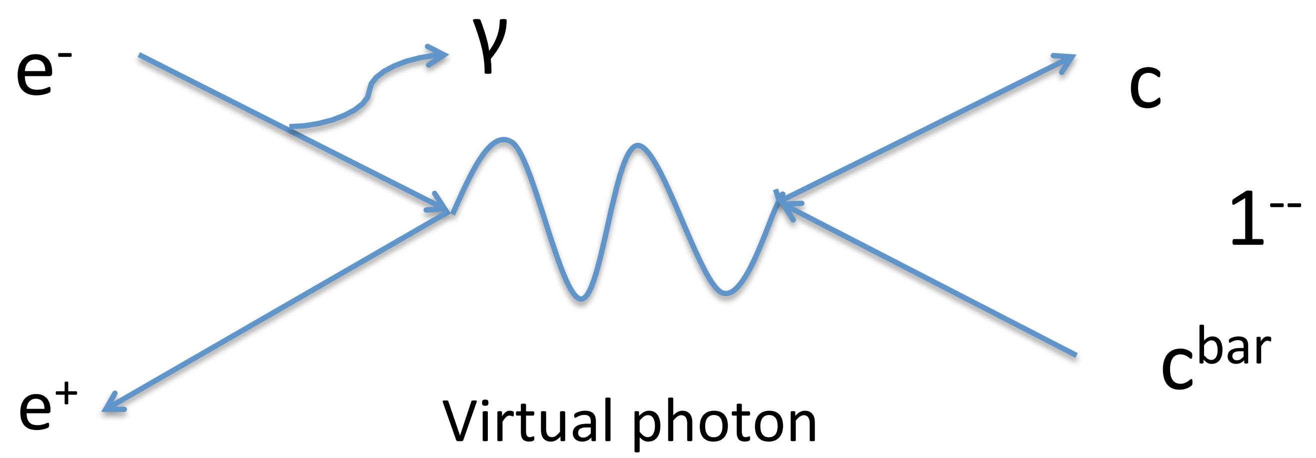
Summary of the Belle's results on Y's and Z_c's

Y(4260), Y(4360), Y(4660)

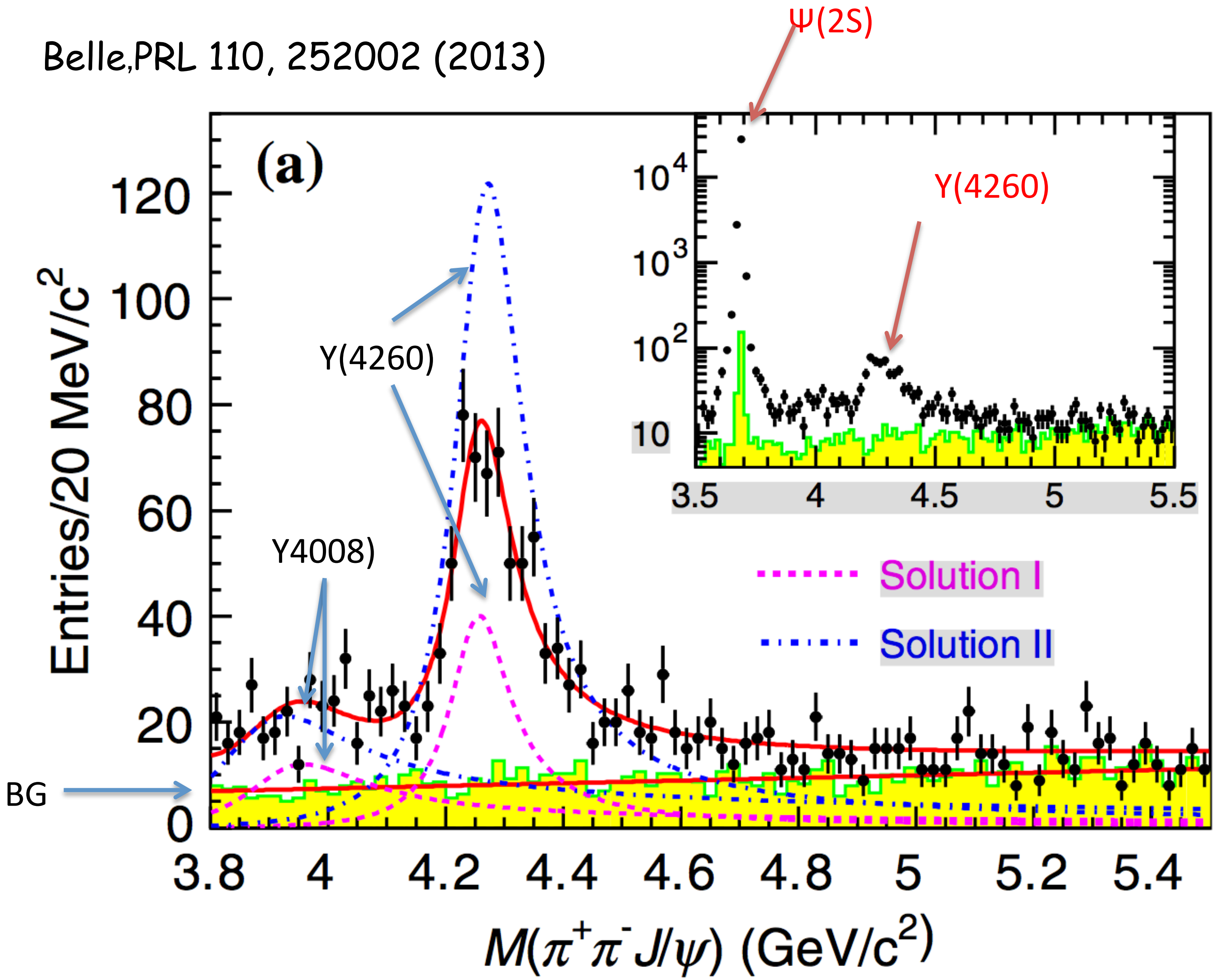
Y(4260)

- In 2005, BaBar: Initial-state-radiation process: PRL 95, 142001 (2005) $\pi^+ \pi^- J/\psi$ peak at 4260 MeV/c^2
- CLEO: PRD 74, 091104 (2006) and Belle: PRL 99, 182004 (2007) confirmed Full Data result: PRL 110, 252002 (2013)
- Not observed in DD^{bar} decay mode.

Near-threshold s-channel cc^{bar} production via initial-state radiation (ISR): 1^{--} state

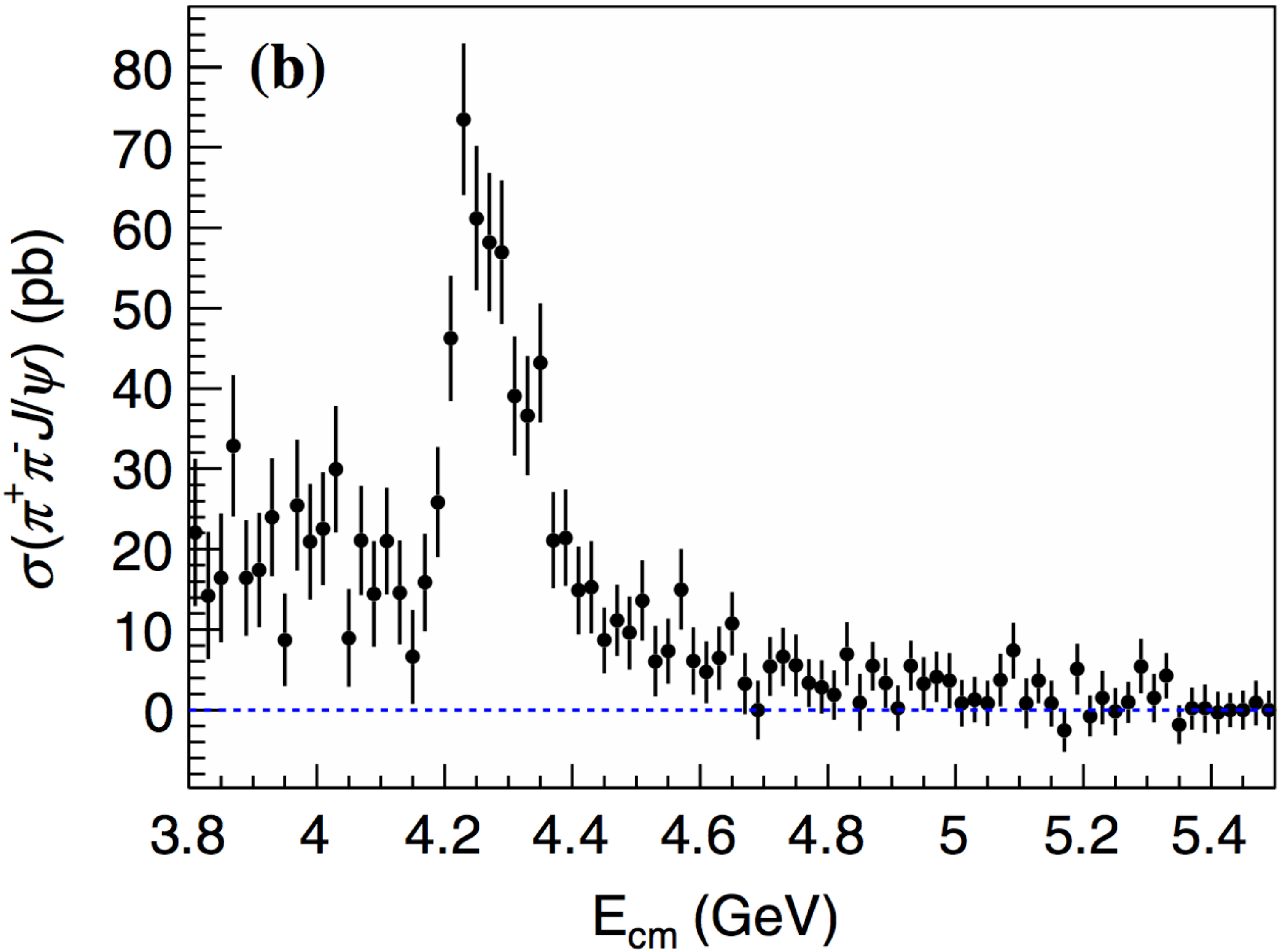


Belle,PRL 110, 252002 (2013)



Cross section

Belle, PRL 110, 252002 (2013)



Y(4260)

- Mass: 4251 ± 9 MeV (PDG)
- Width: 120 ± 12 MeV (PDG)
- 90% C.L. level lower limit on the pertial decay width

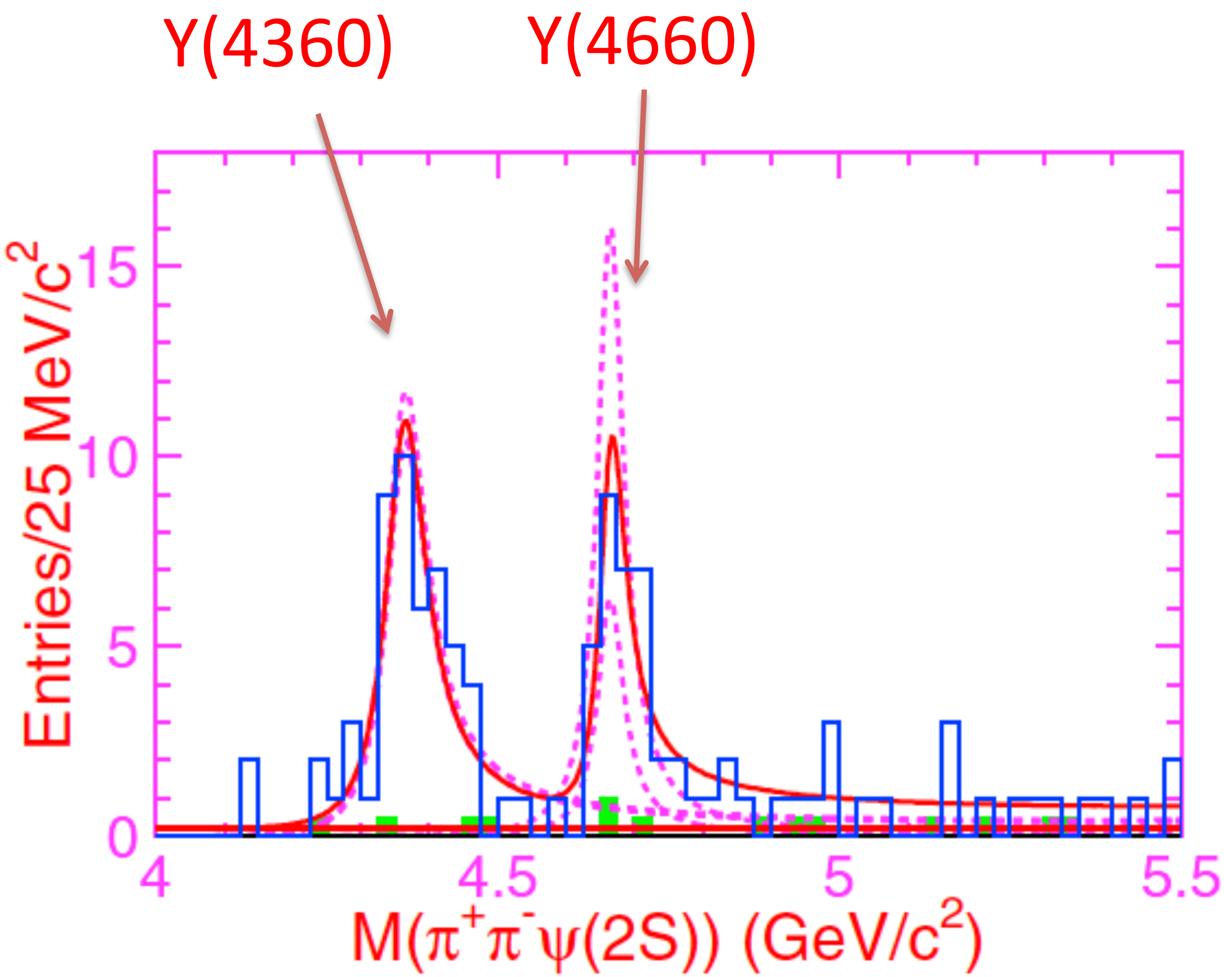
$$\Gamma\left(Y(4260) \to \pi^{+}\,\pi^{-}\,J/\psi\right) > 1.6\,MeV$$

much bigger than typical 1⁻⁻ charmonium e.g.

$$\Gamma\left(\psi(3770) \to \pi^{+}\,\pi^{-}\,J/\psi\right) = 53 \pm 8\,keV$$

Y(4360), Y(4660)

- In 2007, BaBar: Initial-state-radiation process: PRL 98, 212001 (2007) $\pi^+ \pi^- \psi(2S)$ peak at 4324 MeV/c^2
- Belle: PRL 99, 142002 (2007) confirmed
- Babar:PRD 89, 111103(R) (2014)
- Not observed in DD^{bar} and $\pi^+ \pi^- J/\psi$ decay modes.



Belle, PRL 99, 142002 (2007)

Belle, PRL 99, 142002 (2007)

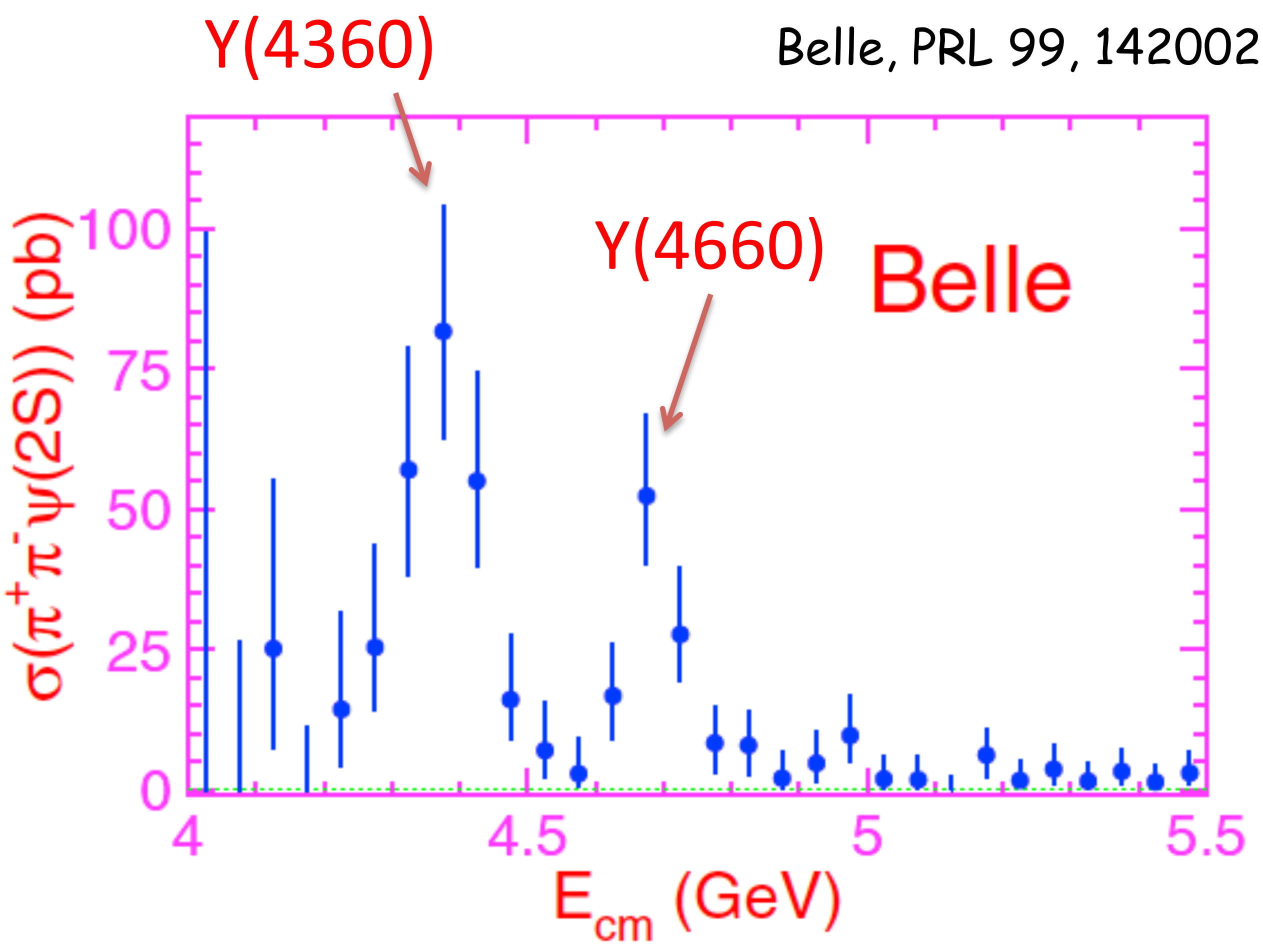


FIG. 5 (color online). The measured $e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section for $\sqrt{s} = 4.0$ GeV to 5.5 GeV. The errors are statistical only. Bins without entries have a central value of zero.

Y(4260), Y(4360), Y(4660)

- $e^+ e^-$ -> $D^{(*)} D^{(*)bar}$ dose not make peak structures at 4260, 4360, 4660 MeV
- The coupling to the open charmed meson pair seems to be very weak.
- No peak at 4260 MeV in π+ π- ψ(2S) channel
- No peaks at 4360 MeV and 4660 MeV in π+ π- J/ψ channel
- Not simple charmonia !

$Z_c(3900)$

$Z_c(3900)$ by Belle

- Reference: PRL 110, 252002 (2013) Observed by Belle and BESIII at the sametime

$e^+e^- \to \gamma(ISR)\pi^+\pi^- J/\psi$ Y(4260) 1^{--}

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

Large partial decay width: similar to $\Upsilon(5S)$

Charmed version of Z_b !

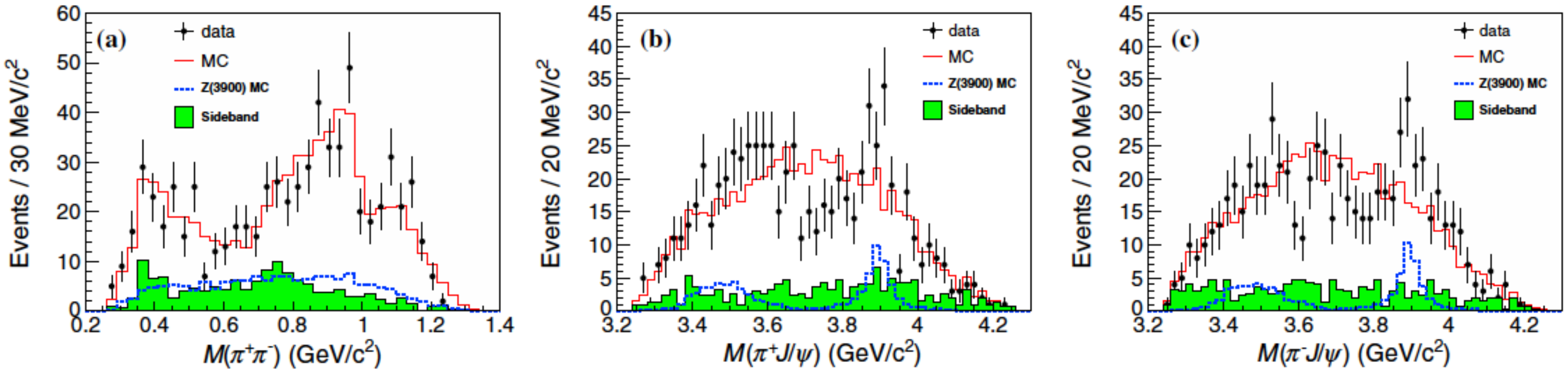


FIG. 3 (color online). Invariant mass distributions of (a) $\pi^+\pi^-$, (b) π^+J/ψ, and (c) π^-J/ψ for events in the $Y(4260)$ signal region. Points with error bars represent data, shaded histograms are normalized background estimates from the J/ψ-mass sidebands, solid histograms represent MC simulations of $\pi^+\pi^-$ amplitudes [22] (normalized J/ψ-mass sideband events added) and dashed histograms are MC simulation results for a $Z(3900)^{\pm}$ signal.

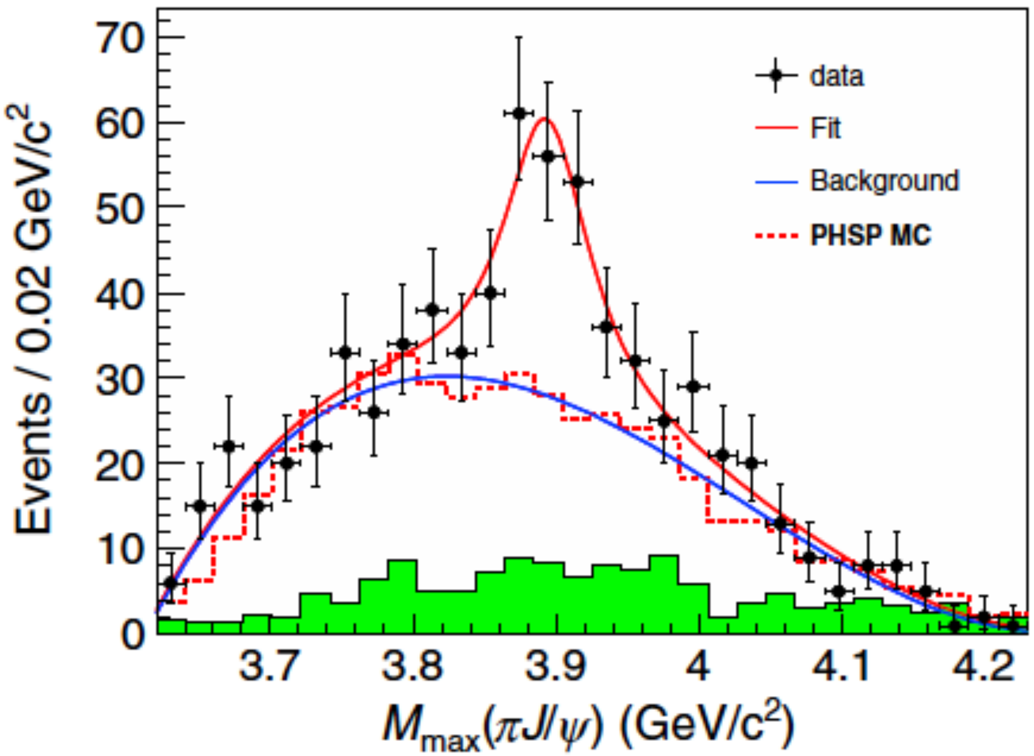


FIG. 4 (color online). Unbinned maximum likelihood fit to the distribution of the $M_{\max}(\pi J/\psi)$. Points with error bars are data, the curves are the best fit, the dashed histogram is the phase space (PHSP) distribution and the shaded histogram is the non-$\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands.

$Z_c(3900)^{\pm}$ (Belle's result)

- Mass: (3894.5±6.6±4.5) MeV
- Width: (63±24±26) MeV

- Consistent with BESIII result
  PRL 110, 252001 (2013)
  PRL 112, 022001 (2014)
- Explicitly exotic!

$Z_c(4200)$

$Z_c(4200)$

- Observed by Belle in 2014
- Reference: PRD 90, 112009 (2014)
- Amplitude analysis of $\bar{B}^0 \to J/\psi K^- \pi^+$
- Mass: 4196^{+31+17}_{-29-13} MeV
- Width: $370^{+70+70}_{-70-132}$ MeV
- $J^P = 1^+$

$Z_c(4200)$

All K^*'s contribution

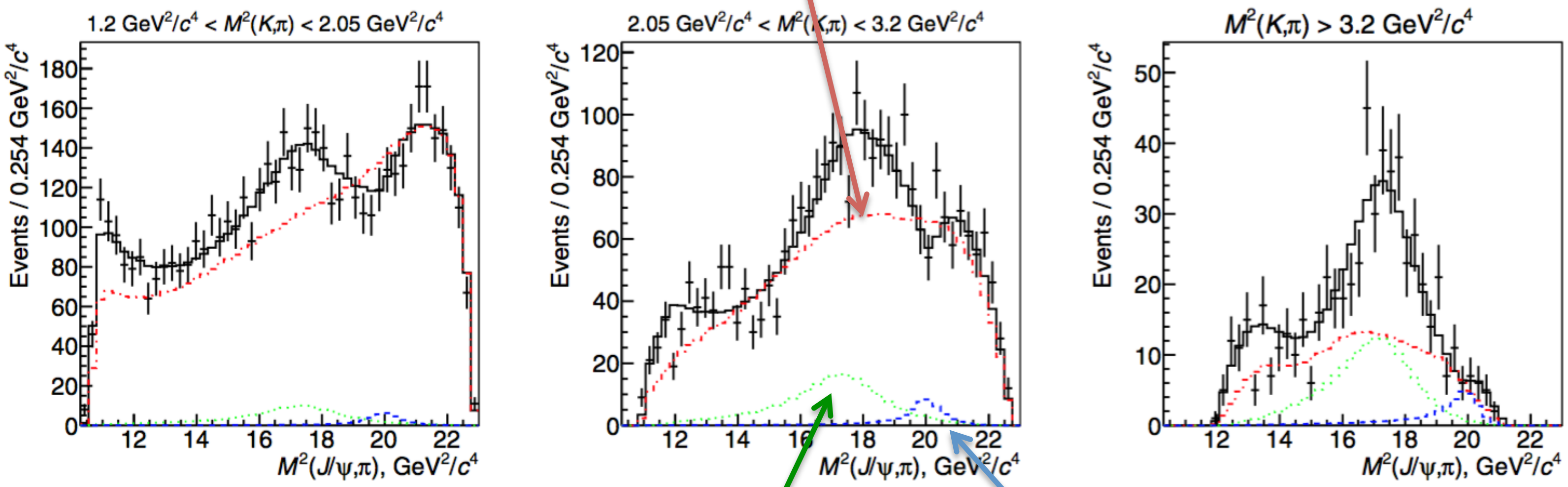
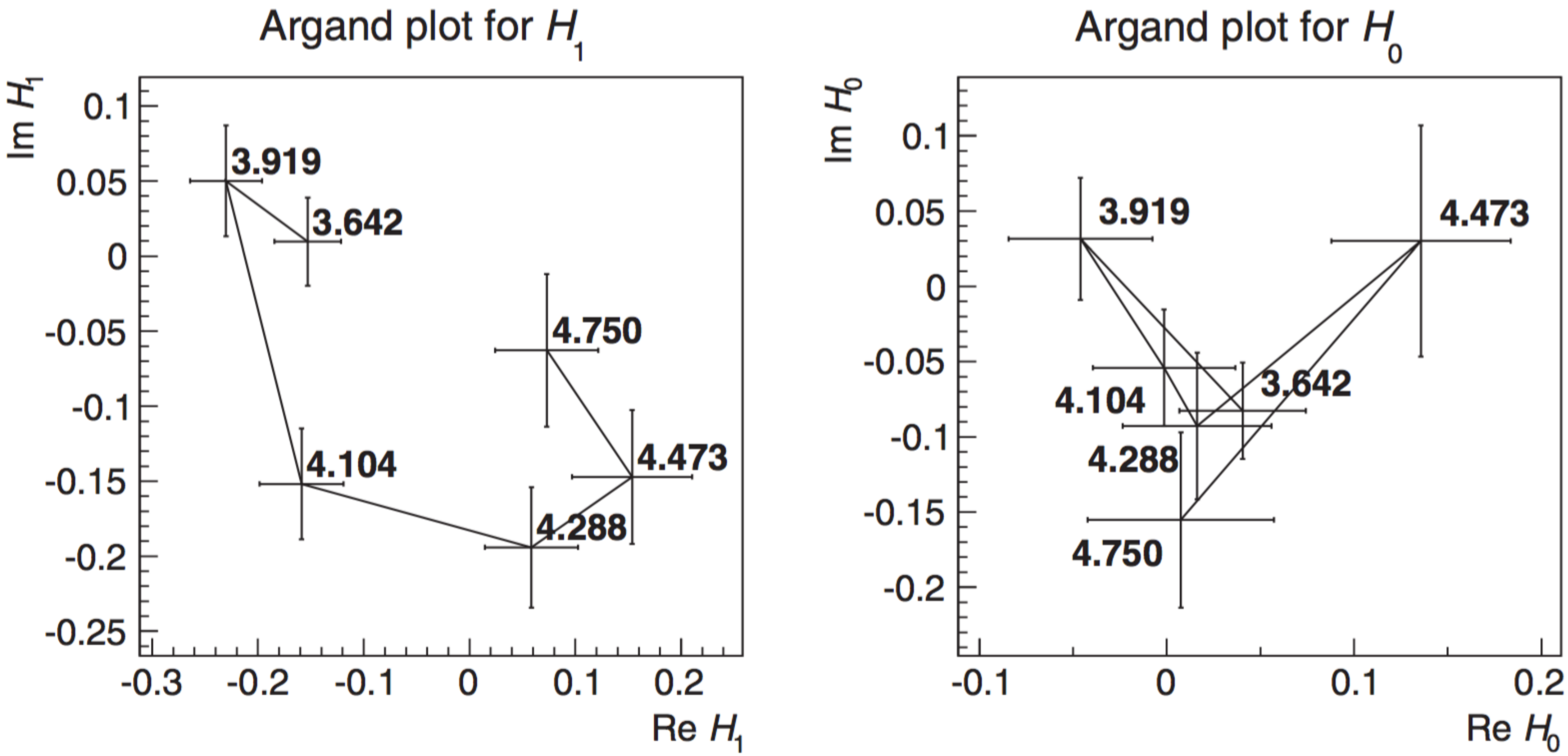


FIG. 8 (color online). The fit results with the $Z_c(4200)^+$ ($J^P = 1^+$) in the default model. The points with error bars are data; the solid histograms are fit results, the dashed histograms are the $Z_c(4430)^+$ contributions, the dotted histograms are the $Z_c(4200)^+$ contributions and the dash-dotted histograms are contributions of all K^* resonances. The slices are defined in Fig. 4.

$Z_c(4200)$ contribution

$Z_c(4430)$ contributoin

$Z_c(4200)$



Argand plot for H1
Im H1
Re H1
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.2
-0.1
0
0.1
0.2
3.919
3.642
4.750
4.104
4.473
4.288
Argand plot for H0
Im H0
Re H0
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.1
0
0.1
0.2
3.919
4.473
3.642
4.104
4.288
4.750

$Z_c(4200)$

- LHCb obtained the evidence of $Z_c(4200)$ in a full amplitude analysis of

$$\Lambda_b^0 \to J/\psi\, p\, \pi^-$$

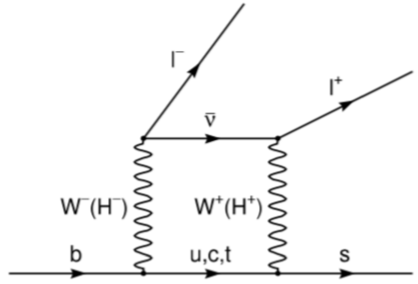
arXiv:1606.06999, 22 June 2016

New result on angular analysis of $B \to K^* l^- l^+$

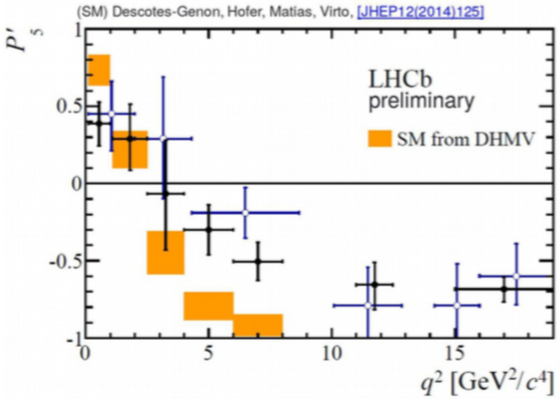
D. Liventsev's slide for Quarks 2016

Angular analysis of $B \to K^* \ell^+ \ell^-$

- The decay proceeds through $b \to s$ FCNC, forbidden at tree level in the SM.
- New Physics particles may contribute to loop and box diagrams and change BF and angular observables.
- Angular observables are less affected by the hadronic uncertainties.
- The decay and different subsets of angular observables were studied by BaBar, Belle, CDF and CMS – all in agreement with the SM.
- LHCb reported a 3.4σ deviation from the SM prediction using full set of angular observables.



Example of SM (NP) box diagram



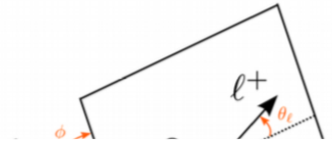
JHEP 02, 104 (2016)

D. Liventsev's slide for Quarks 2016

Angular analysis of $B \to K^* \ell^+ \ell^-$

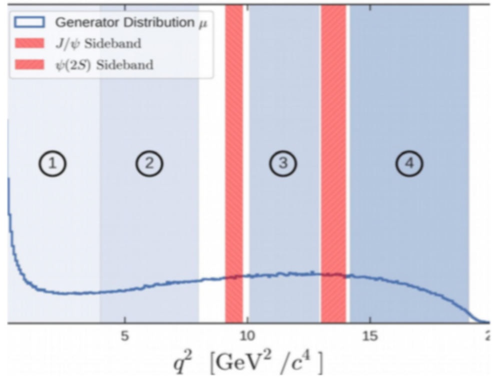
- The decay is completely described by θ_ℓ, θ_K, φ and $q^2 = M_{\ell\ell}^2$.

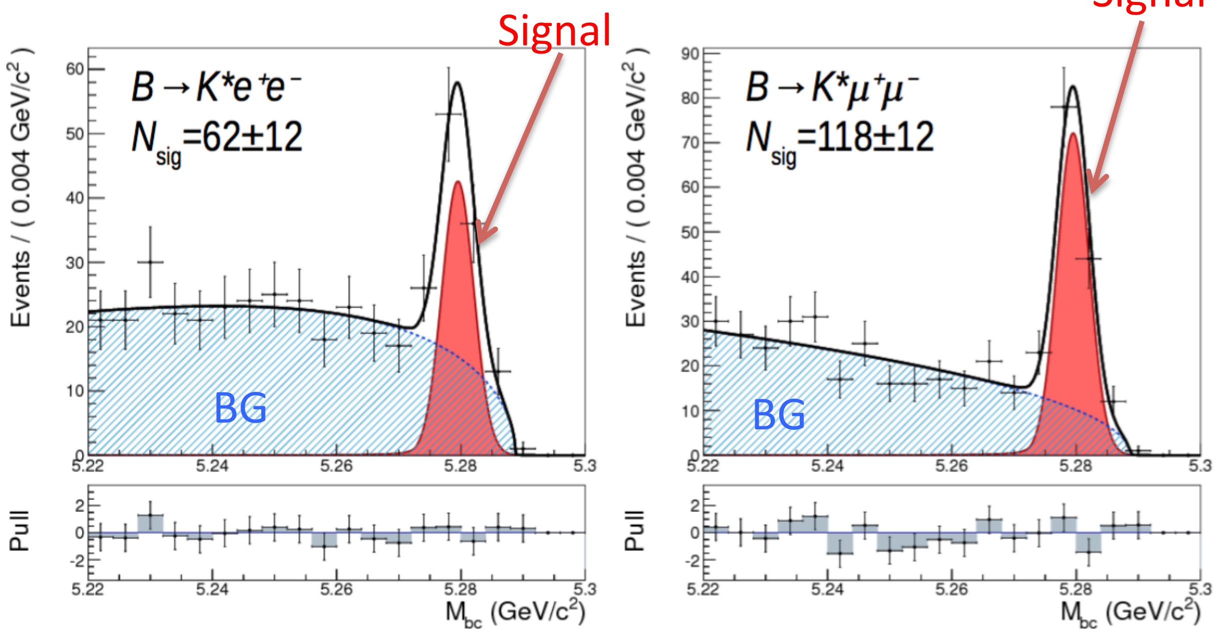
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2} \frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell \, \mathrm{d}\cos\theta_K \, \mathrm{d}\phi \, \mathrm{d}q^2} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K \right.$$



Angular analysis of $B \to K^* \ell^+ \ell^-$

- In Belle analysis arXiv: 1604.04042 both e^+e^- and $\mu^+\mu^-$ pairs are used.
- Irreducible background from $B \to K^{(*)} J/\psi$ and $B \to K^{(*)}\psi(2S)$ is vetoed.
- $M_{\rm bc} \equiv \sqrt{E^2_{\rm beam}/c^4 - |\vec{p}_B|^2/c^2}$

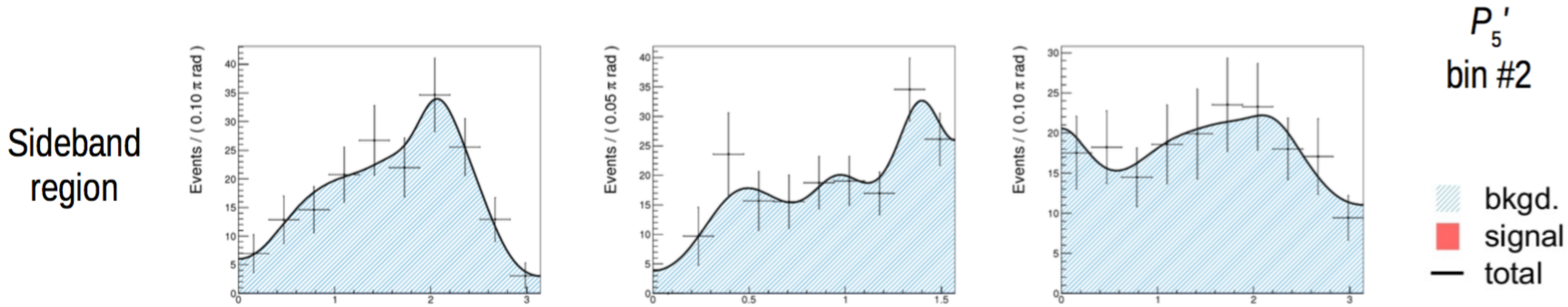




bin#	q^2	n_{sig}
1	0.1-4.0	30.9±7.4
2	4.0-8.0	49.8±9.3
3	10.09-12.90	39.6±8.0
4	14.18-19.00	56.5±8.7

Angular analysis of $B \to K^* \ell^+ \ell^-$

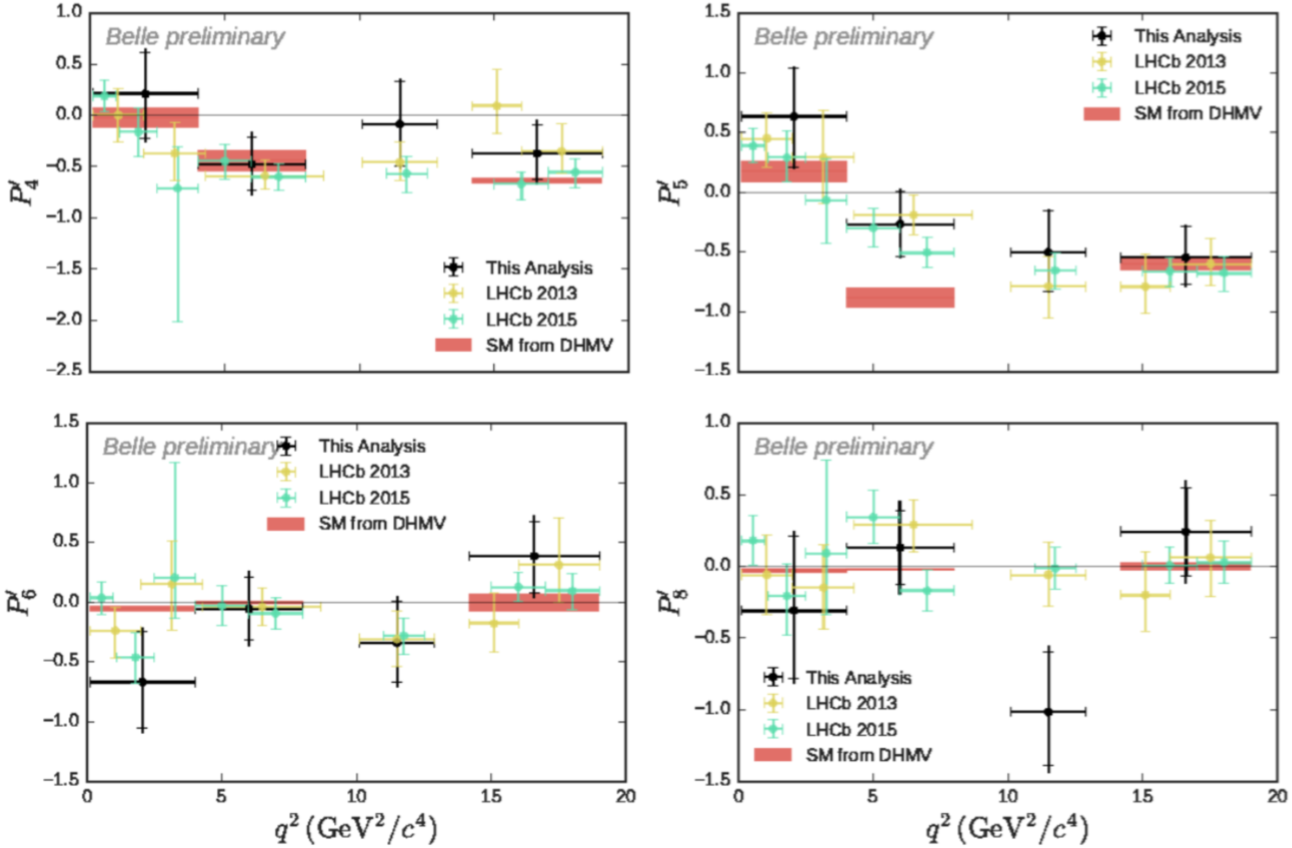
- P_i' are obtained by 3D fit to θ_ℓ, θ_K, φ in four bins of q^2.
- Signal and background normalization is defined from fit to M_{bc}.
- Background shape is defined from M_{bc} < 5.27 GeV/c^2 sideband.



D. Liventsev's slide for Quarks 2016

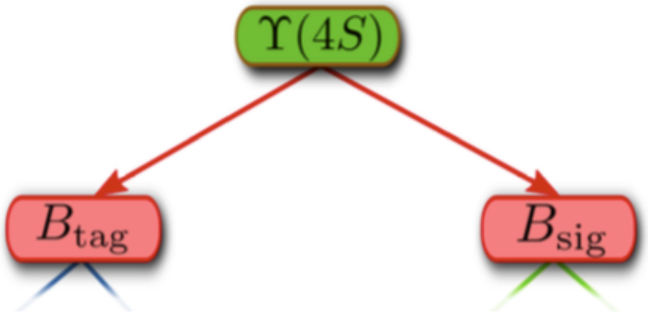
Angular analysis of $B \to K^* \ell^+ \ell^-$

- The results are compatible with SM and LHCb.
- One measurement is found to deviate by 2.1σ from the predicted value in the same direction and in the same q^2 region where the LHCb reported P_5' anomaly.



New result on $\bar{B}^0 \to D^{*+} \tau \bar{\nu}_\tau$ with semileptonic tag

Tagging techniques for Υ(4S) events



- Tagging provides:
  - Background suppression
  - Information on B_{sig} (4-momentum)

Untagged
- No requirement on B_{tag}
- High efficiency, low purity

Semileptonic tag
- $B_{tag} \rightarrow D^* l\nu$
- Efficiency ~O(0.2%)

Hadronic tag
- $B_{tag} \rightarrow$ hadrons
- Efficiency ~O(0.1%)

C. Schwanda's slide for HQL2016

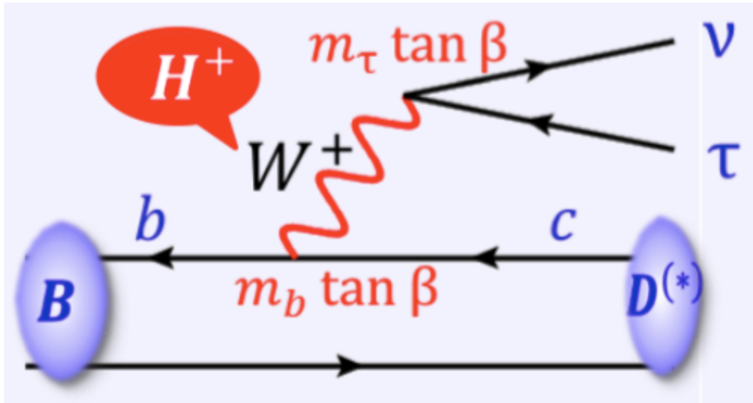
New Physics in $B \to D^{*}\tau\nu$

Semitauonic B decays of type $b \to c\tau\nu$ are sensitive probes to search for New Physics. NP can change the branching ratio and the D^*/τ polarization.

C. Schwanda's slide for HQL2016

Type II 2HDM

- A charged Higgs of spin 0 mediates the decay instead of the W
- Can enhance or decrease the BR of $B \to D^*\tau\nu$



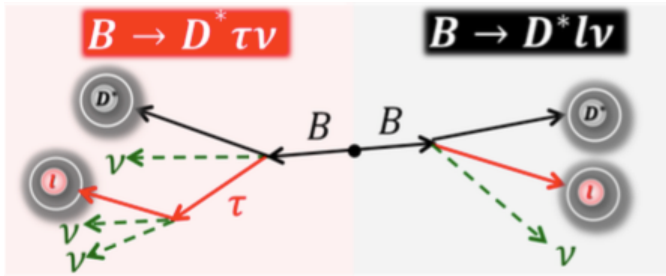
Leptoquark models

- LQs are bosons which couple to a lepton-quark pair
- Carry color and electric charge, baryon and lepton number
- LQ models which generate an effective tensor operator lead to an effect in $B \to D^{*}\tau\nu$

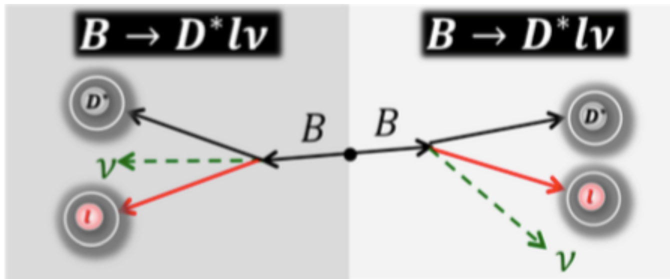
Principle of the measurement

- Simultaneously reconstruct signal and normalization events
- D^* reconstruction: $D^{*+} \to D^0\pi^+, D^+\pi^0$ (~100%)
  - 10 D^0 modes (~37%)
  - 5 D^+ modes (~22%)
- Semileptonic tag: combine D^{*+} with an oppositely charged lepton, calculate cos theta$_{B,D^*l}$
- Require two tagged B candidates per event of opposite charge

Signal event



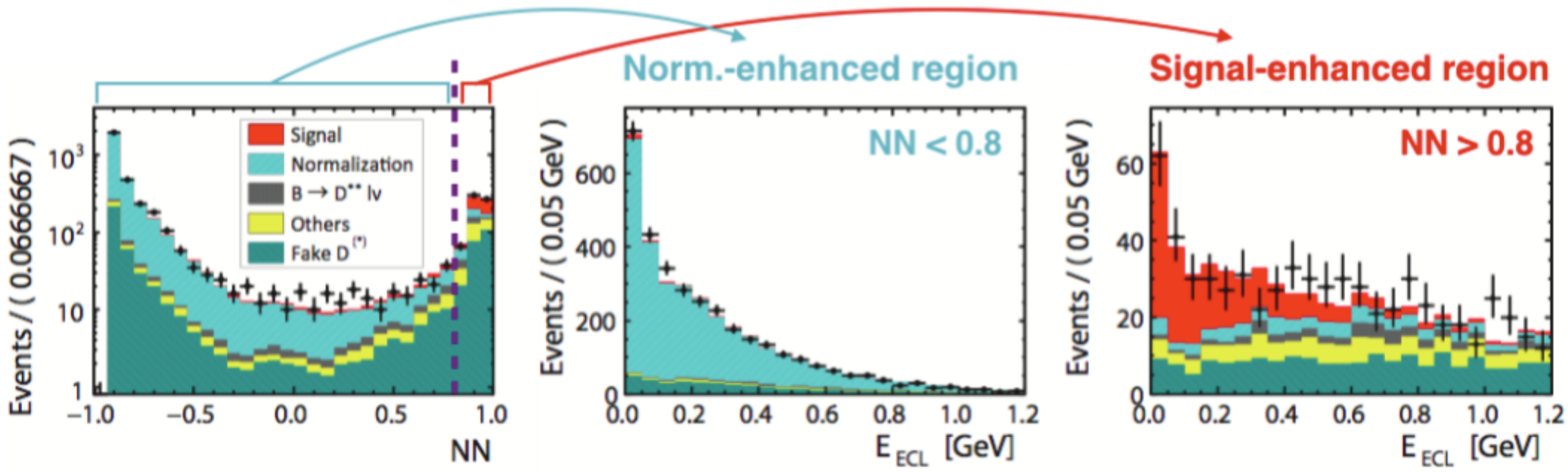
Normalization event



$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\mathrm{beam}}E_{D^*\ell} - m_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B| \cdot |\vec{p}_{D^*\ell}|}$$

C. Schwanda's slide for HQL2016

Fit result



$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)}$$

$$\mathcal{R}(D^*) = \frac{1}{\mathcal{B}(\tau^- \to l^-\bar{\nu}_l\nu_\tau)} \cdot \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \cdot \frac{N_{\text{sig}}}{N_{\text{norm}}}$$

$$\mathcal{R}(D^*) = 0.302 \pm 0.030(\text{stat}) \pm 0.011(\text{syst}) \quad (13.8\sigma)$$

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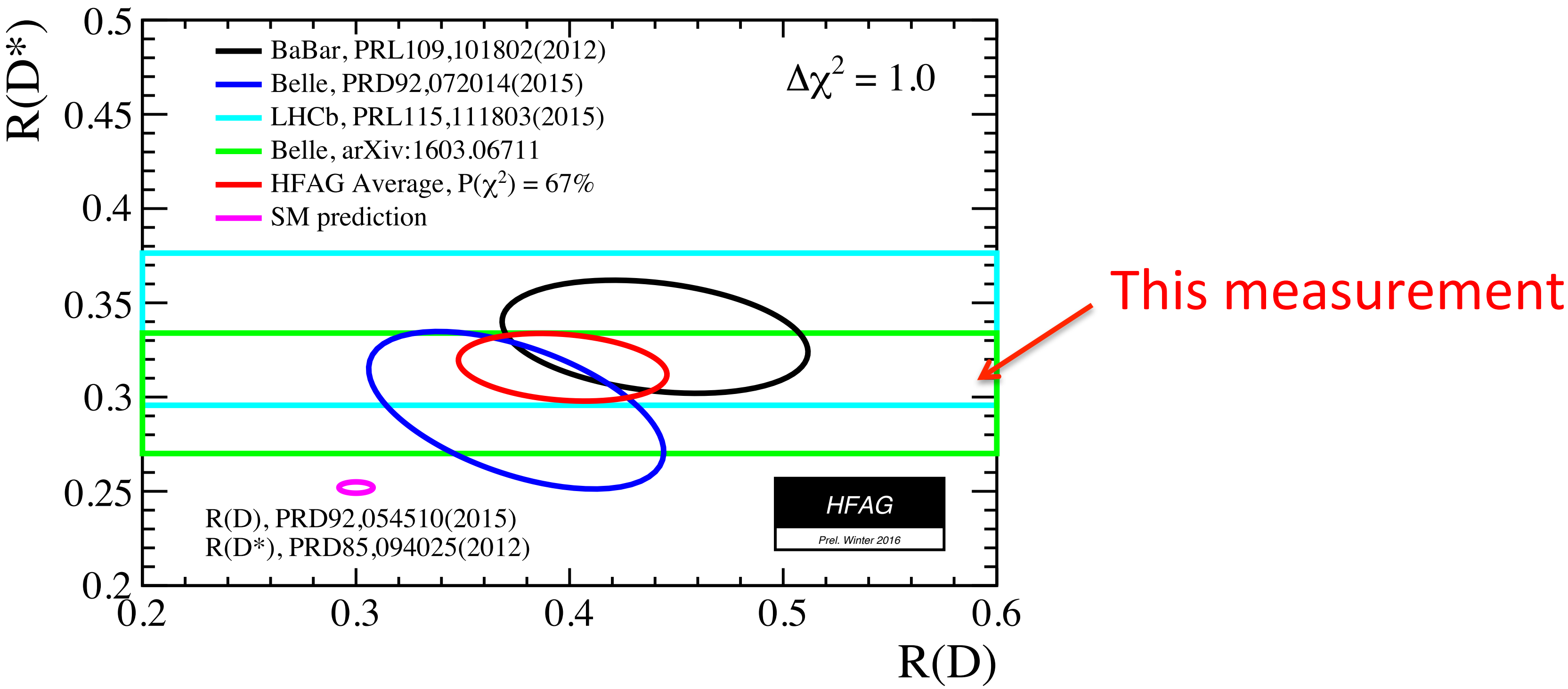
Comparison to other measurements



- The difference with the SM prediction is at the level of 4.0 sigma for all four measurements combined

C. Schwanda's slide for HQL2016

Summary

- Although the data taking was finished on June 30, 2010, there may be rich physics to be analyzed in Belle data.

Summary: X(3872)

- B^0 -> X(3872) K^+ pi^- decay is observed and evidence of B^+ -> X(3872) K^0_s pi^+ decay is found.

- In B^0 -> psi' K^+ pi^- decay, $K^*(892)^0$ dominates K^+ pi^- channel, but in B^0 -> X(3872) K^+ pi^- decay, there is non-resonance contribution.

Summary: $Z_b(10610)$, $Z_b(10650)$

- Full amplitude analysis of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ at $\sqrt{\mathrm{s}} = 10.866\mathrm{GeV}$ determines $Z_b(10610)$ and $Z_b(10650)$'s J^P are both 1^+.
- First observation of the transitions

$$Z_b^{\pm}(10610) \to [B\bar{B}^* + \mathrm{c.c.}]^{\pm}$$
$$Z_b^{\pm}(10650) \to [B^*\bar{B}^*]^{\pm}$$

Strong evidence of the hadronic molecule structure of Z_b

Summary: B decays

- Angular analysis of $B \to K^* l^- l^+$ supports LHCb result of P'_5 deviation from Standard model.

- R(D*) determined from $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$ is consistent with other results. Combined result of R(D*) by HFAG deviates from Standard Model by 4.0 sigma.

- Belle II will start data taking from 2017!!

- Belle II welcomes young physicists!