# Heavy Flavor Physics at Lepton Colliders

**Aspen Winter Conference**
**Frontiers in Particle Physics:**
**From Dark Matter to the LHC and Beyond**
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# $e^+e^-$ collider experiments



**NOW**

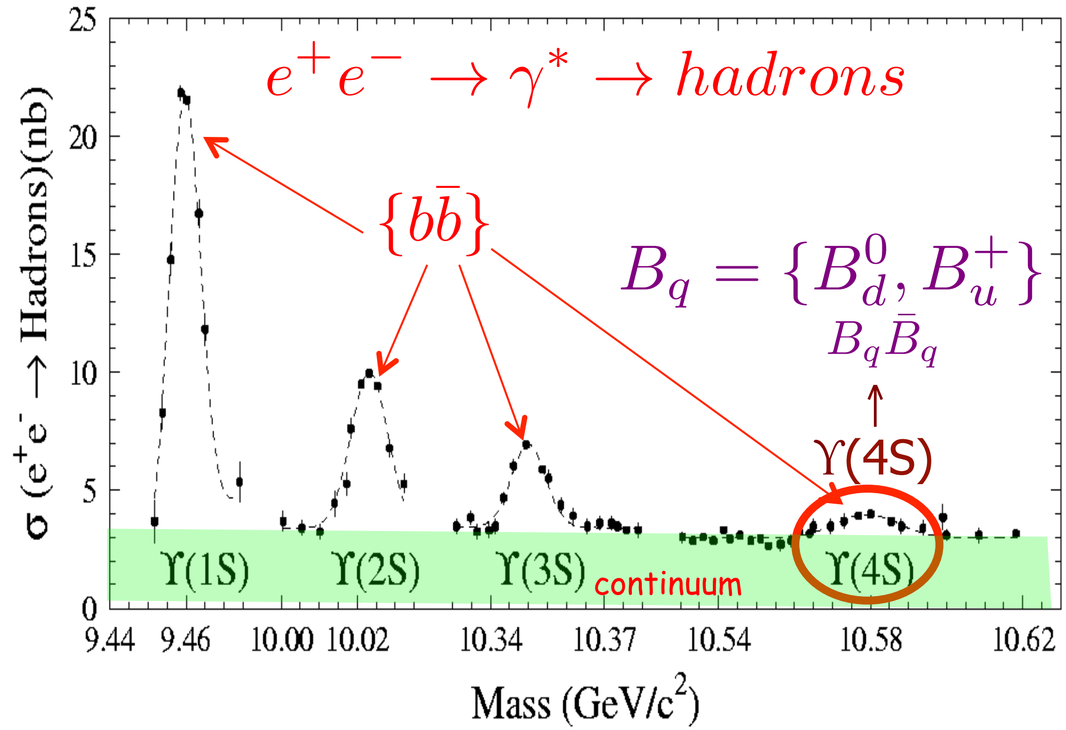
- BEPC II/BESIII
  - 2008- Symmetric
  - 1.3G $J/\psi$, 400M $\psi'$, 2.9 $fb^{-1}$ $\psi''$, 3.3 $fb^{-1}$ above 4 GeV
- PEP-II/Babar
  - 1999-2008 9 Gev $e^-$ + 3 GeV $e^+$
  - 471M $\Upsilon(4S)$, ~500M charm pair
- KEKB/Belle
  - 1999-2010 8.5 GeV $e^-$ + 3.5 GeV $e^+$
  - 772M $\Upsilon(4S)$ events(B pair), $10^9$ charm pair, ~37M b-pair@$\Upsilon(5S)$, ~31 $fb^{-1}$ $\Upsilon(5S)$ scan, 34 $fb^{-1}$ $\Upsilon(1/2/3S)$

**FUTURE**

- SuperKEKB/Belle II under construction
  - 2016-
  - 50 $ab^{-1}$ ~ 5 x $10^{10}$ B pairs, etc.

# $e^+e^-$ annihilation

For example, Upsilon region ~10 GeV (similar in J/ψ region ~3-4 GeV)




- Event CM energy = $e^+e^-$ CM energy ± few MeV
- "Hermetic" detector measures nearly all final particles exc. $K_L$, n, ν
  => "neutrals reconstruction" is possible
- Average multiplicity (chg+neutral) ~15-20
- Near-threshold @ ϒ(4S), ϒ(5S) [ψ″] exclusive B [D] pair events – full reconstruction tagging and other tricks

# Outline

- CKM/New Physics

  Beauty

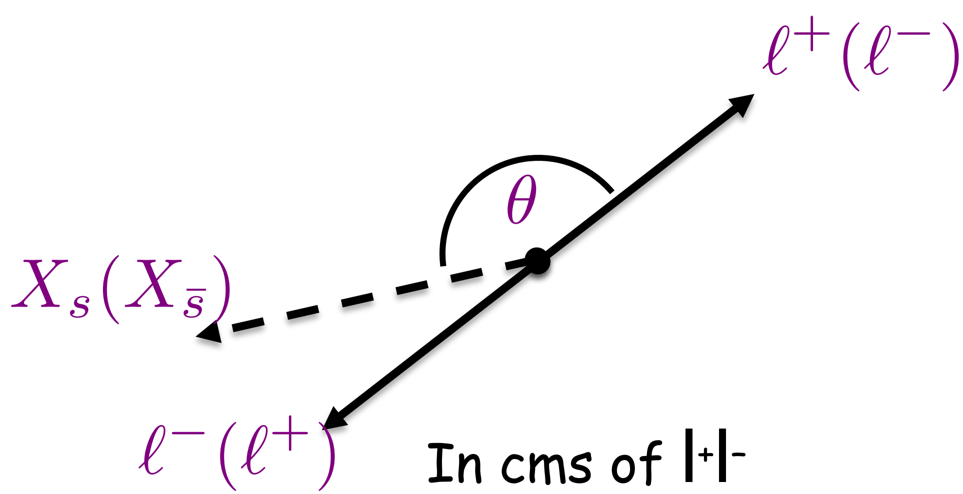
  - $b \to s l^+ l^-$ forward-backward asymmetry
  - $B^- \to \tau \nu$
  - $B \to D^{(*)} \tau \nu$
  - CP Asymmetries

  Charm

  - $D^0$ mixing
- QCD: Exotic heavy quarkonia

# Lepton Forward-Backward Asymmetry in Inclusive $B \to X_s \ell^+ \ell^-$

**Belle**



# Forward-backward Asymmetry

Belle

$$\mathcal{A}_{\rm FB} \equiv \frac{\Gamma(b \to s\ell^+\ell^-; \cos\theta > 0) - \Gamma(b \to s\ell^+\ell^-; \cos\theta < 0)}{\Gamma(b \to s\ell^+\ell^-; \cos\theta > 0) + \Gamma(b \to s\ell^+\ell^-; \cos\theta < 0)}$$

- Theory: contributions from EM penguin, EW vector, axial vector

$$\frac{d\mathcal{A}_{\rm FB}}{dq^2} = -3\Gamma_0 m_b^3 (1 - \frac{q^2}{m_b^2})^2 \frac{q^2}{m_b^2} C_{10} Re(C_9 + \frac{2m_b^2}{q^2} C_7)$$

Wilson coefficients

- Previously measured in exclusive decays

  [PRL 103, 171801 (2009)]

- Inclusive $A_{FB}$ has smaller theoretical uncertainty

# $A_{FB}$ semi-inclusive reconstruction

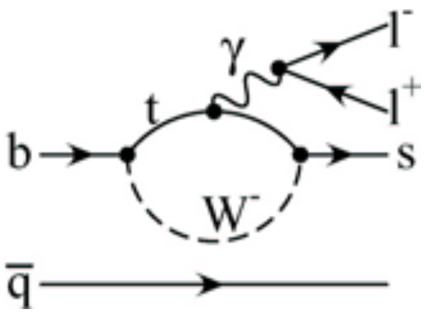
Belle

- $772 \times 10^6$ B pairs
- 18 exclusive hadronic final states
  - $X_s$={K}{nπ}, n=1,2,3,4
- Full reconstruction
  - $M_{bc}$, ΔE
- Leptons: $e^+e^-$ or $\mu^+\mu^-$
  - J/ψ, ψ(2S) veto
- Neurobayes neural network background suppression
- Select one candidate per event
- Use
  - 10 hadronic final states:

    No K+4π modes

    $B^0$ – self-tag ($K^\pm$) modes only

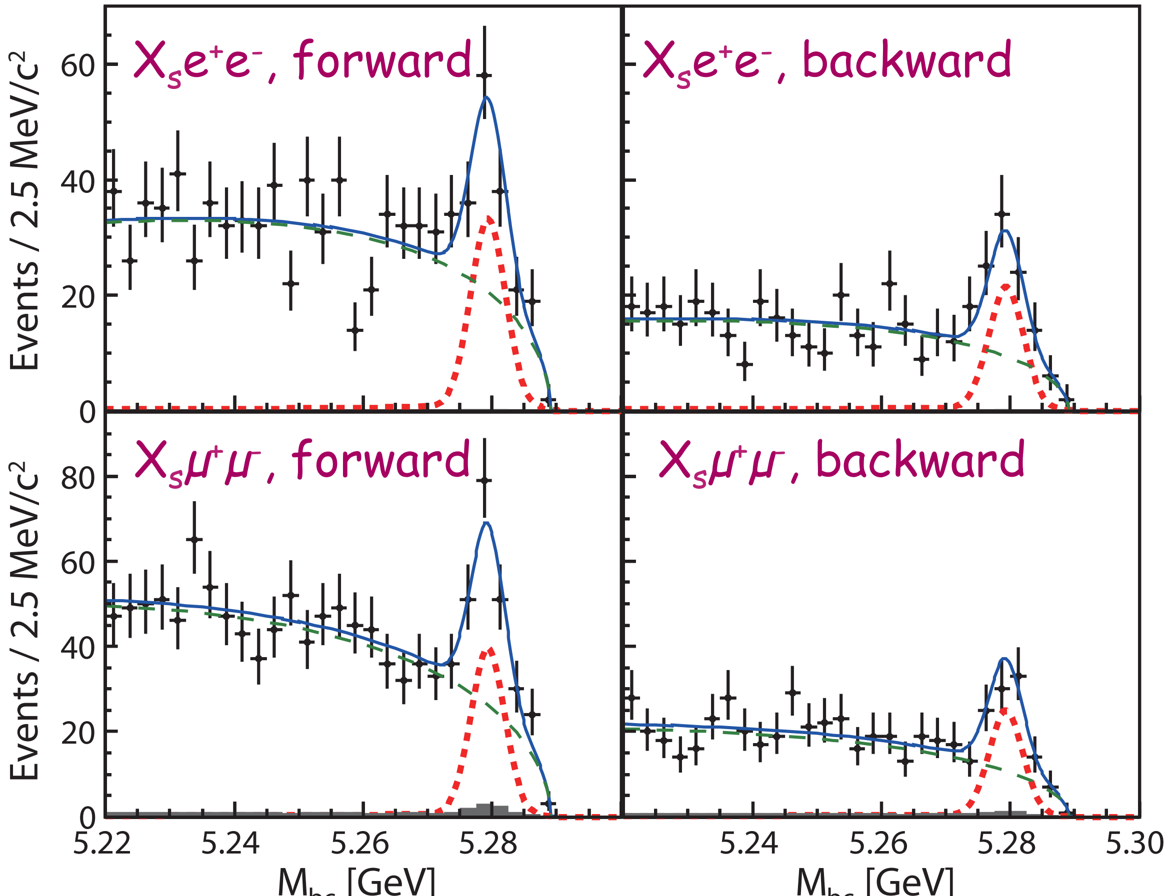
$$B \to X_s \ell^+ \ell^-$$



# $A_{FB}$ semi-inclusive

Belle

- 4 bins of $q^2$
- Simultaneous fit in $M_{bc}$, {F,B} incl. efficiency
- Correct raw $A_{FB}$ via MC

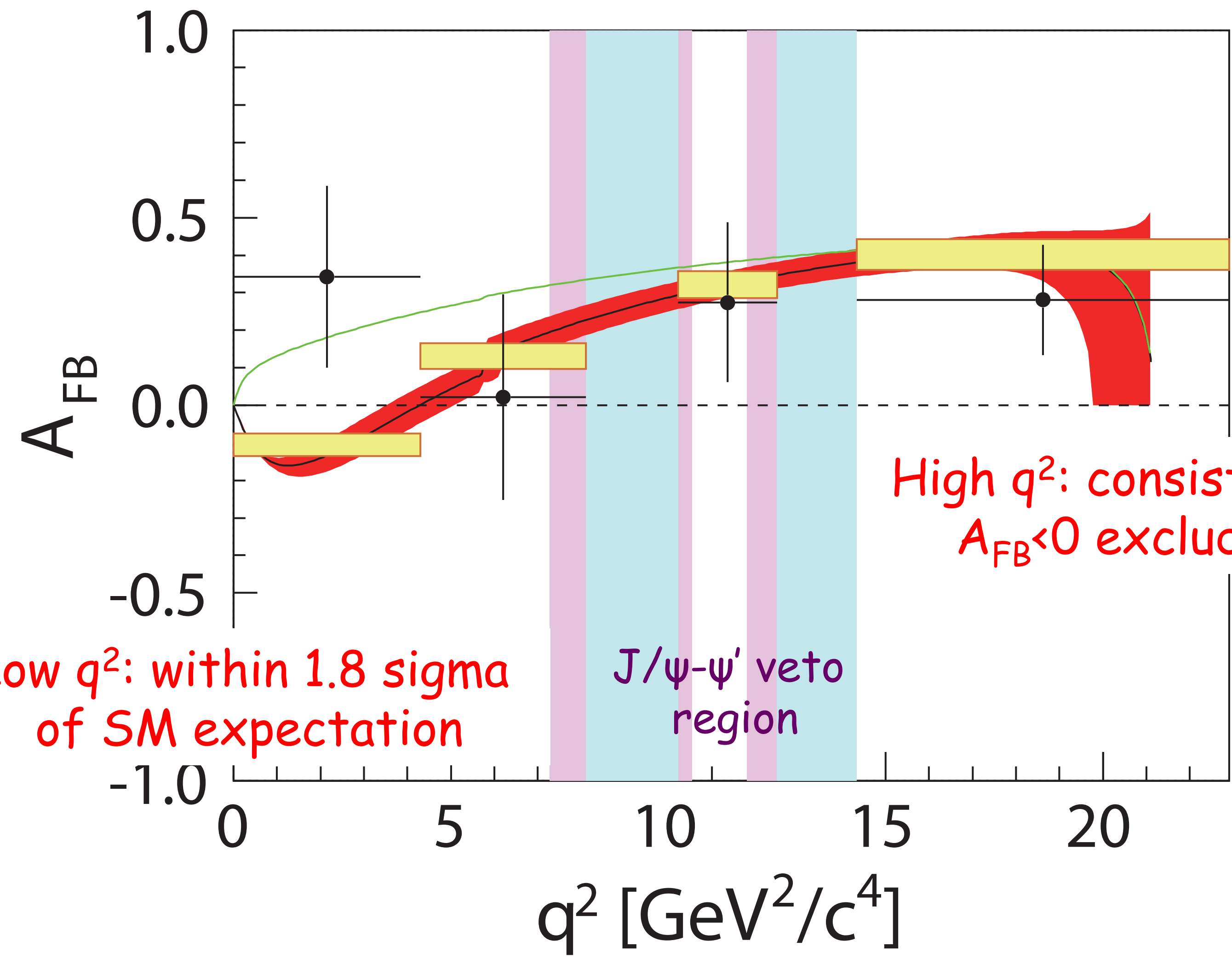





K. Kinoshita

# $A_{FB}$ semi-inclusive: result

Belle Preliminary




High $q^2$: consistent w SM, $A_{FB}$<0 excluded 2.3 σ

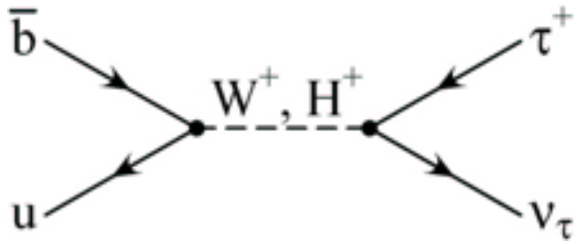
Low $q^2$: within 1.8 sigma of SM expectation

# Lepton universality and New Physics

neutrino "reconstruction" in $e^+e^-$ events

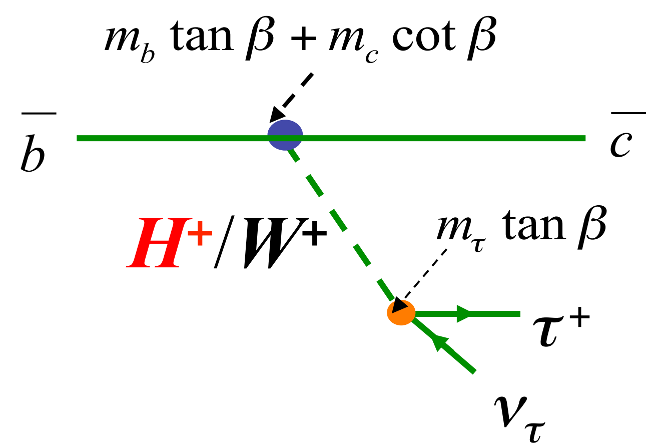
# τ/μ (semi)leptonic decays

- Leptonic




$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Semileptonic




- **Ratio** (τ/μ) is sensitive to charged Higgs
- B->τ ν probes leptonic + H-b-u vertices
- B->D$^{(*)}$τ ν probes leptonic + H-b-c vertex

# $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ with hadronic tagging

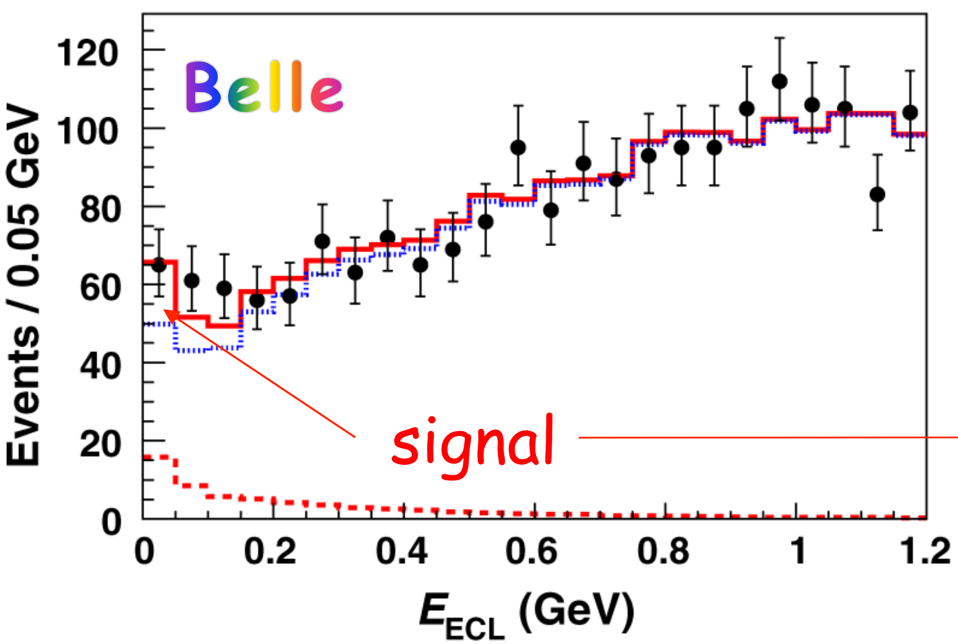
**Belle & Babar**

Belle $[0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$ PRL 110, 131801 (2013)

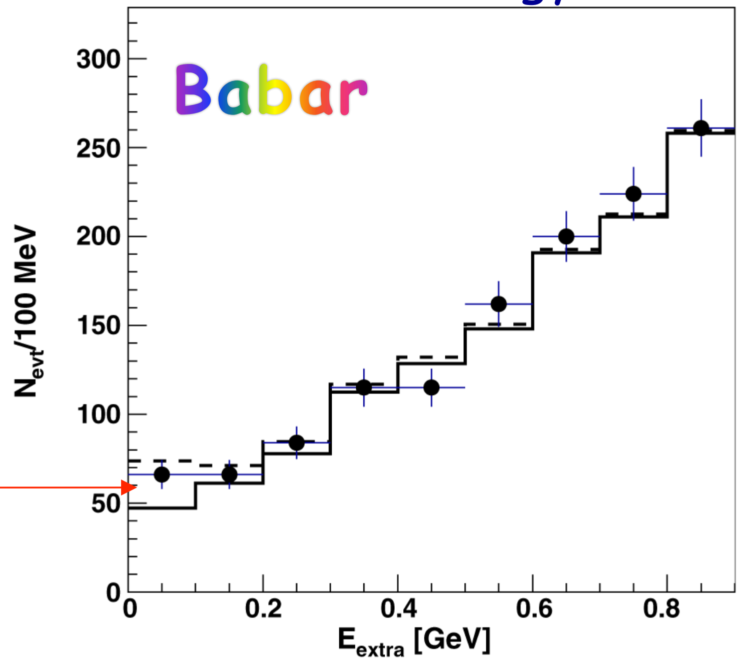
Babar $[1.83^{+0.53}_{-0.49} \pm 0.24] \times 10^{-4}$ PRD(RC) 88, 031102 (2013)

Combined w previous results: $= [1.14 \pm 0.22] \times 10^{-4}$

- full reconstruction of B on one side; examine residual particles
- partial reconstruction of tau, plot residual detected energy




signal



$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ with hadronic tagging **Belle & Babar**



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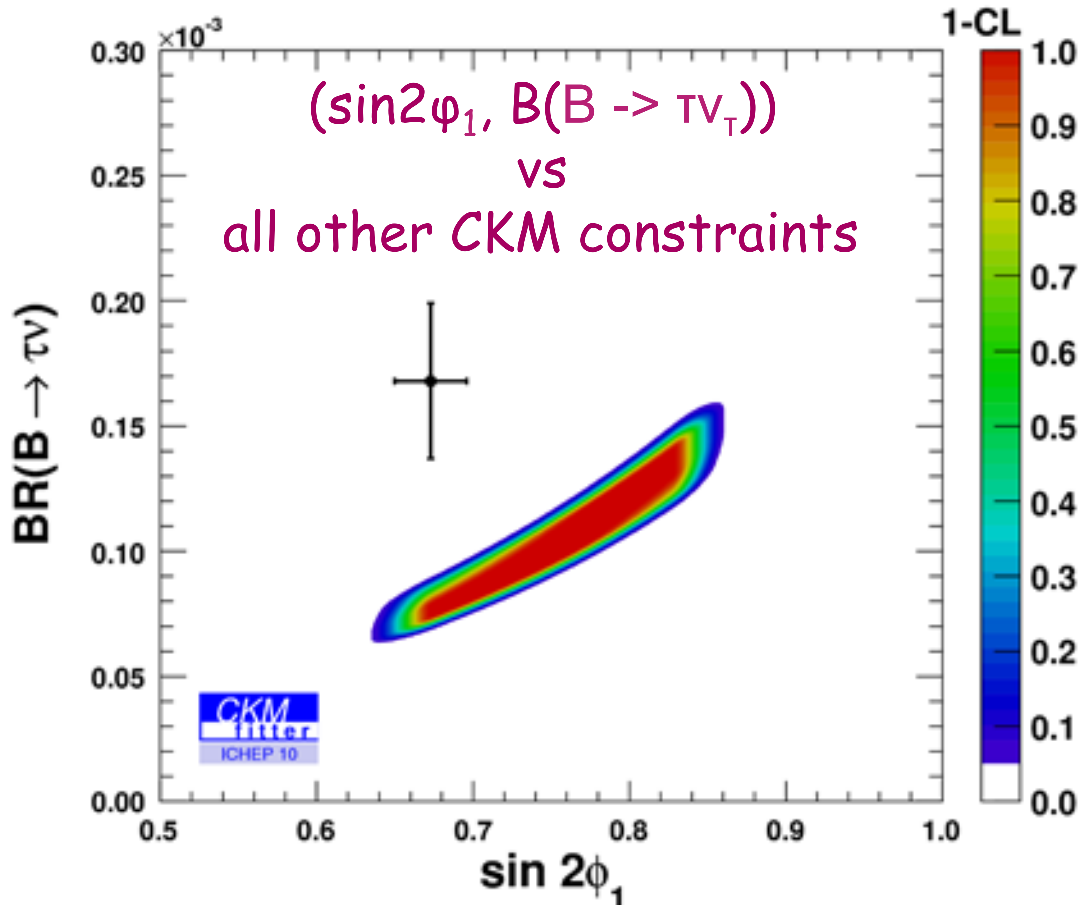
Previous results:
2.8σ "tension"



# $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ with hadronic tagging

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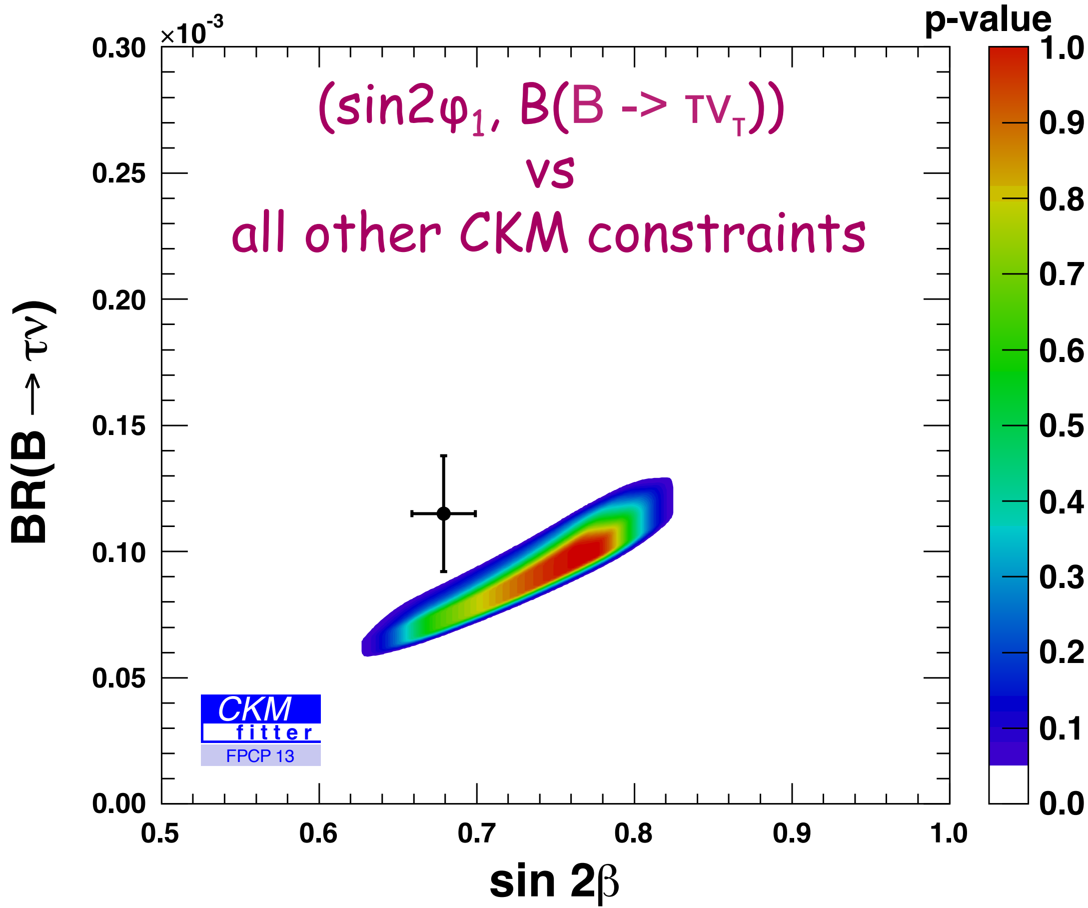
2014:
Not so tense

Precision will improve
in Belle II era



# Future: leptonic τ/μ ratio

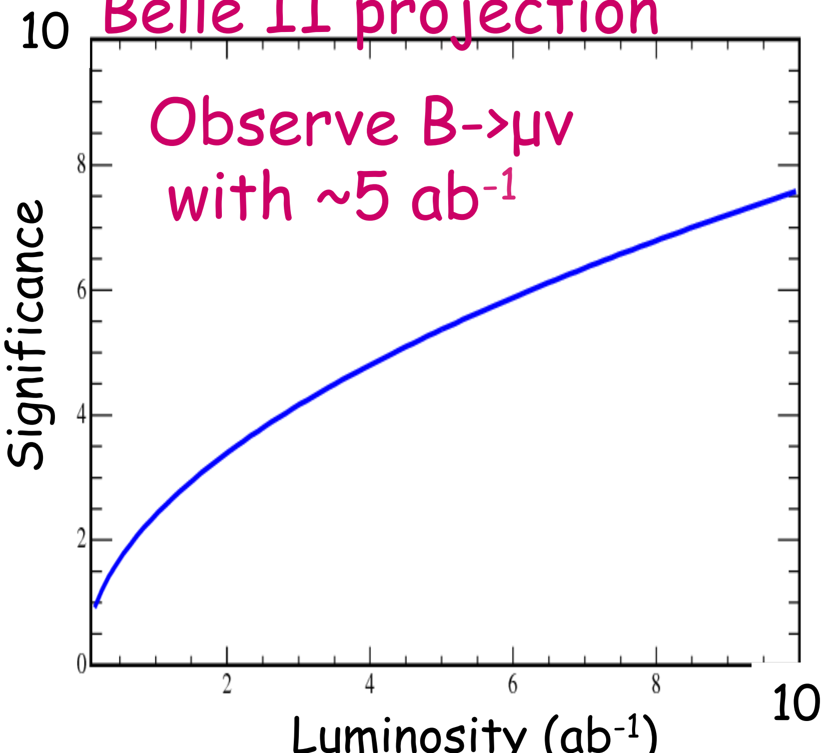
Belle II

SM:
$B(B\to\tau\nu) = 1.6\times10^{-4}$
$B(B\to\mu\nu) = 7.1\times10^{-7}$
$B(B\to e\nu) = 1.7\times10^{-11}$

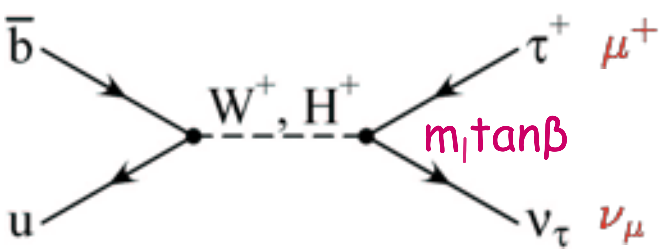
$$\mathcal{R}(\tau\bar{\nu}) \equiv \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)}$$

systematics cancel in ratio
-> strong test of universality

Belle II projection




Potential deviations, e.g.
2-Higgs doublet Model




$$\mathcal{R}(\tau\nu)_{\rm 2HDM} = \mathcal{R}(\tau\nu)_{\rm SM}\left[1 - \frac{m_B^2 \tan^2\beta}{m_H^2}\right]^2$$

# $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$

PRL 109, 101802; PRD 88, 072012 (2013)

Babar

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

- In SM, $\mathcal{R}(D) = 0.297 \pm 0.017$ $\mathcal{R}(D^*) = 0.252 \pm 0.003$
- e.g., in Type II 2HDM:

$$\mathcal{R}(D^{(*)})_{\mathrm{2HDM}} = \mathcal{R}(D^{(*)})_{\mathrm{SM}} + A_{D^{(*)}}\frac{\tan^2\beta}{m_{H^+}^2} + B_{D^{(*)}}\frac{\tan^4\beta}{m_{H^+}^4}$$

Babar

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$$

$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$$

Not good agreement w SM

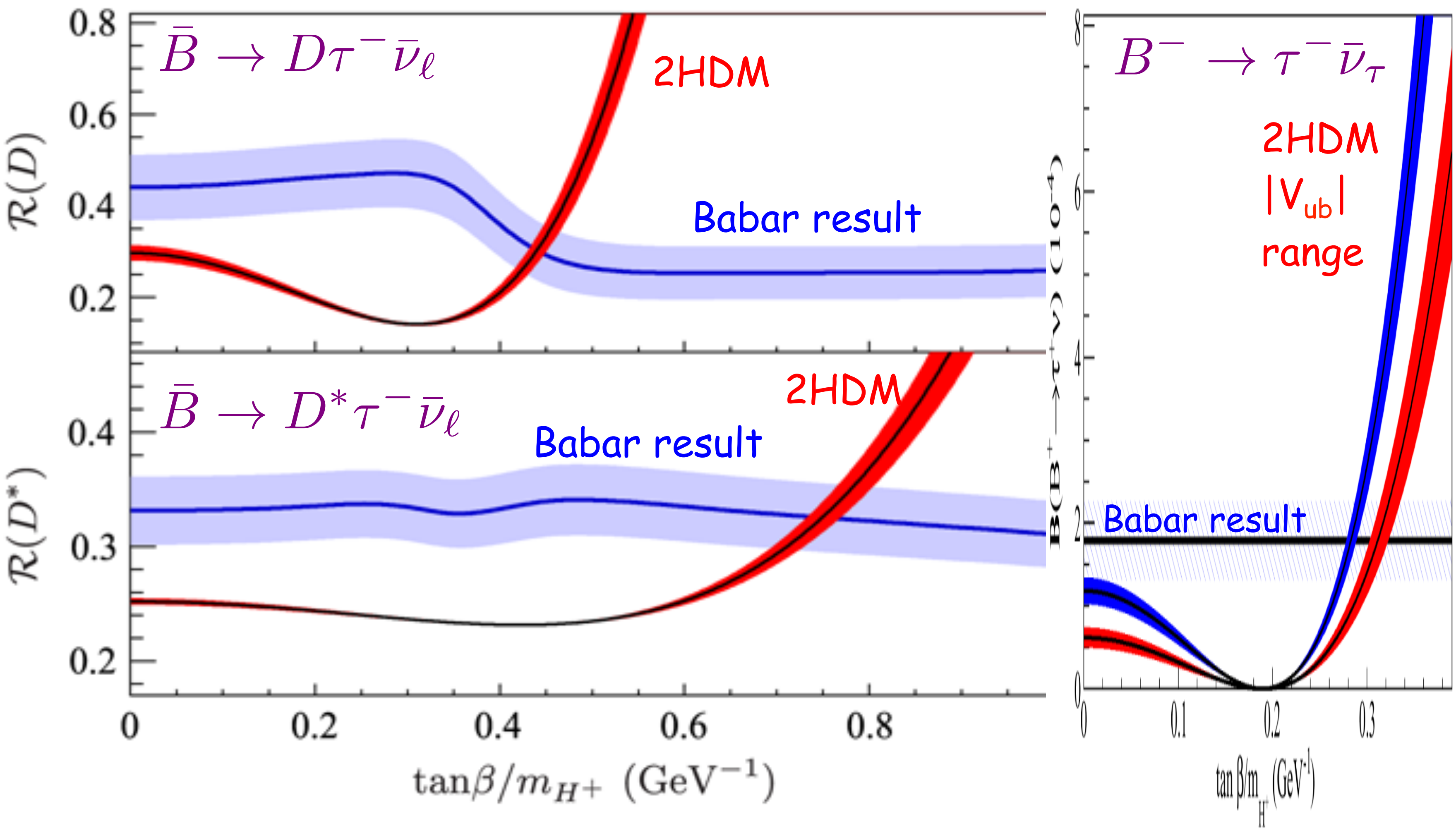
# Test 2HDM type II

Babar

PRL 109, 101802; PRD 88, 072012 (2013)

PRD(RC) 88, 031102 (2013)

R vs tan β/$m_H$

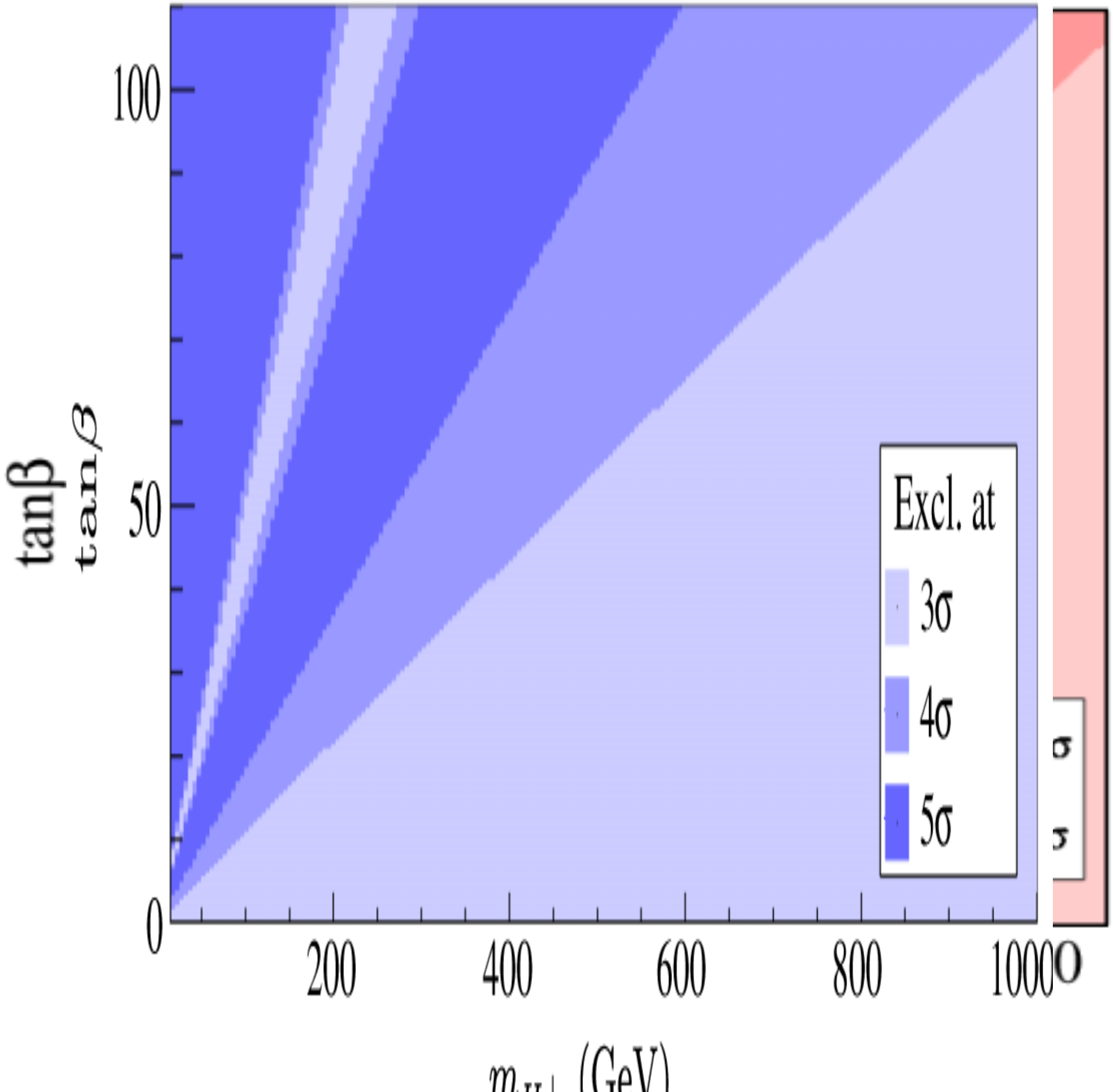


# Test 2HDM type II

Babar

PRL 109, 101802; PRD 88, 072012 (2013)
PRD(RC) 88, 031102 (2013)

tan β vs $m_H$




$\bar{B} \to D^* \tau^- \bar{\nu}_\ell$

Most of parameter space excluded at 2σ

$B^- \to \tau^- \bar{\nu}_\tau$

Most of parameter space excluded at 3σ

**Tension!**

# CP Asymmetries

- The Universe is CP-asymmetric – what is the origin?
- The only known source of CP asym. (CKM) is insufficient
  - ➔ There must be another source
- To find new sources, we need to understand old ones
    - $\varphi_1$ (β), $\varphi_2$(α), $\varphi_3$(γ)
- Analysis at Belle, Babar continues, look forward to Belle II

# Recent results

Belle

- B->ππ, $A_{CP}$, isospin analysis — PRD 88, 092003 (2013)
  - 23.8 > $\varphi_2$, > 66.8°
- B->$\rho^0\rho^0$, isospin analysis — arXiv:1212.4015
  - $\varphi_2$ = 84.9±12.9
- Evidence for suppressed — PRD 88, 091104(R) (2013)

  $B^- \to DK^-\{D \to K^+\pi^-\pi^0\}\ D = D^0 \text{ or } \bar{D}^0$ (sensitive to $\varphi_3$)
- First $A_{CP}$≠0 in a new penguin mode sensitive to $\varphi_1$ — arXiv:1311.6666

  $B^0 \to \omega K_S^0$
- $A_{CP}$ null searches

  $B^+ \to \omega K^+$ — arXiv:1311.6666

  $B^0 \to \phi K^*$ — PRD 88, 072004 (2013)

# Charm

# $D^0$ mixing

Belle arXiv:1401.3402

976 fb$^{-1}$

"Wrong-sign" $D^{*+} \to D^0\pi^+,\, D^0 \to K^+\pi^-$

interference: mixing, double Cabibbo-suppression (DCS)

$$R(\tilde{t}/\tau) \equiv \frac{\Gamma_{\rm WS}(\tilde{t}/\tau)}{\Gamma_{\rm RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

Mixing

$$x \equiv \Delta m/\Gamma \quad x' \equiv x\cos\delta + y\sin\delta$$
$$y \equiv \Delta\Gamma/2\Gamma \quad y' \equiv y\cos\delta - x\sin\delta$$

δ = relative phase

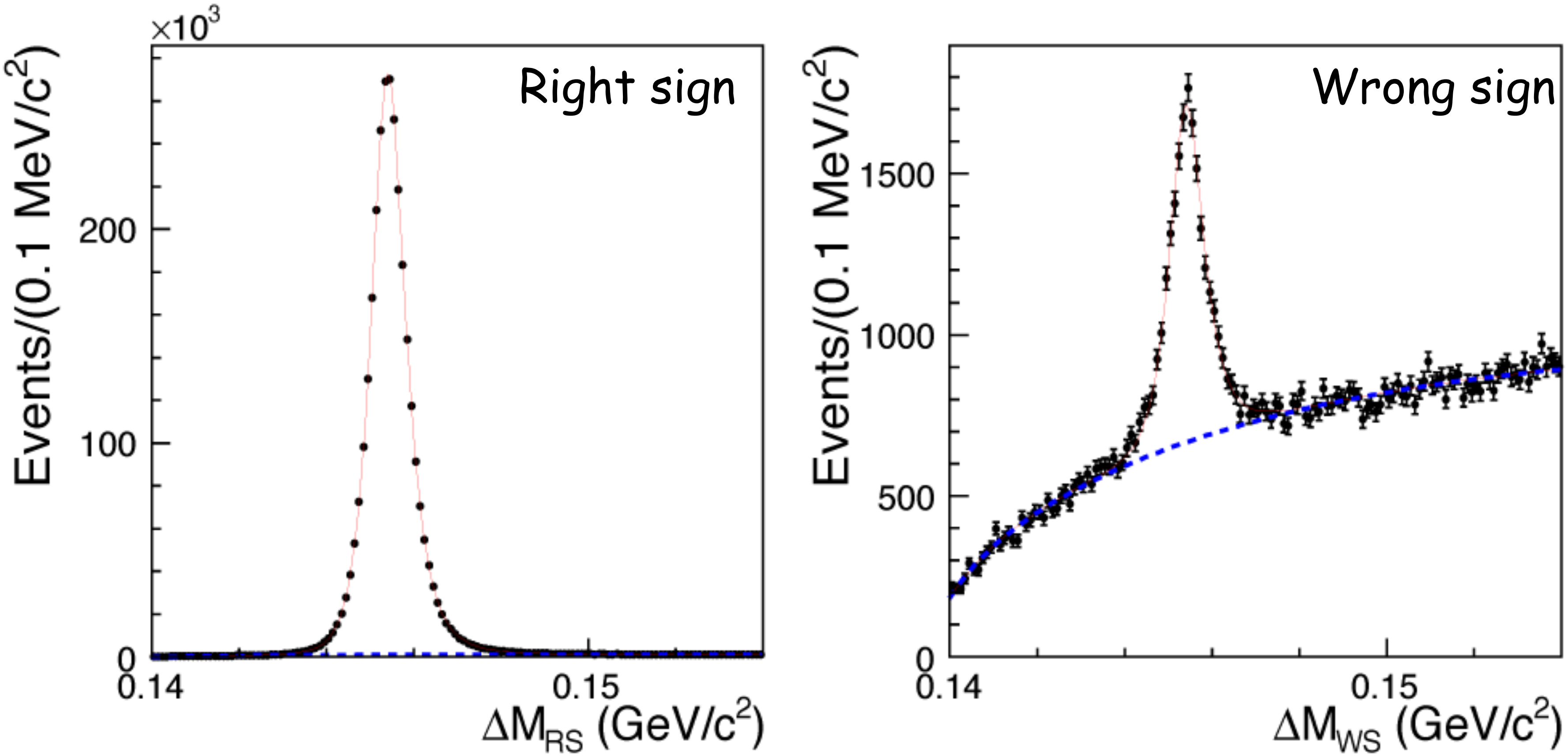
DCS $R_D \equiv \Delta\Gamma(DCS)/\Delta\Gamma(CF)$

# $D^0$ mixing

Belle arXiv:1401.3402

976 $fb^{-1}$

"Wrong-sign" $D^{*+} \to D^0\pi^+, D^0 \to K^+\pi^-$

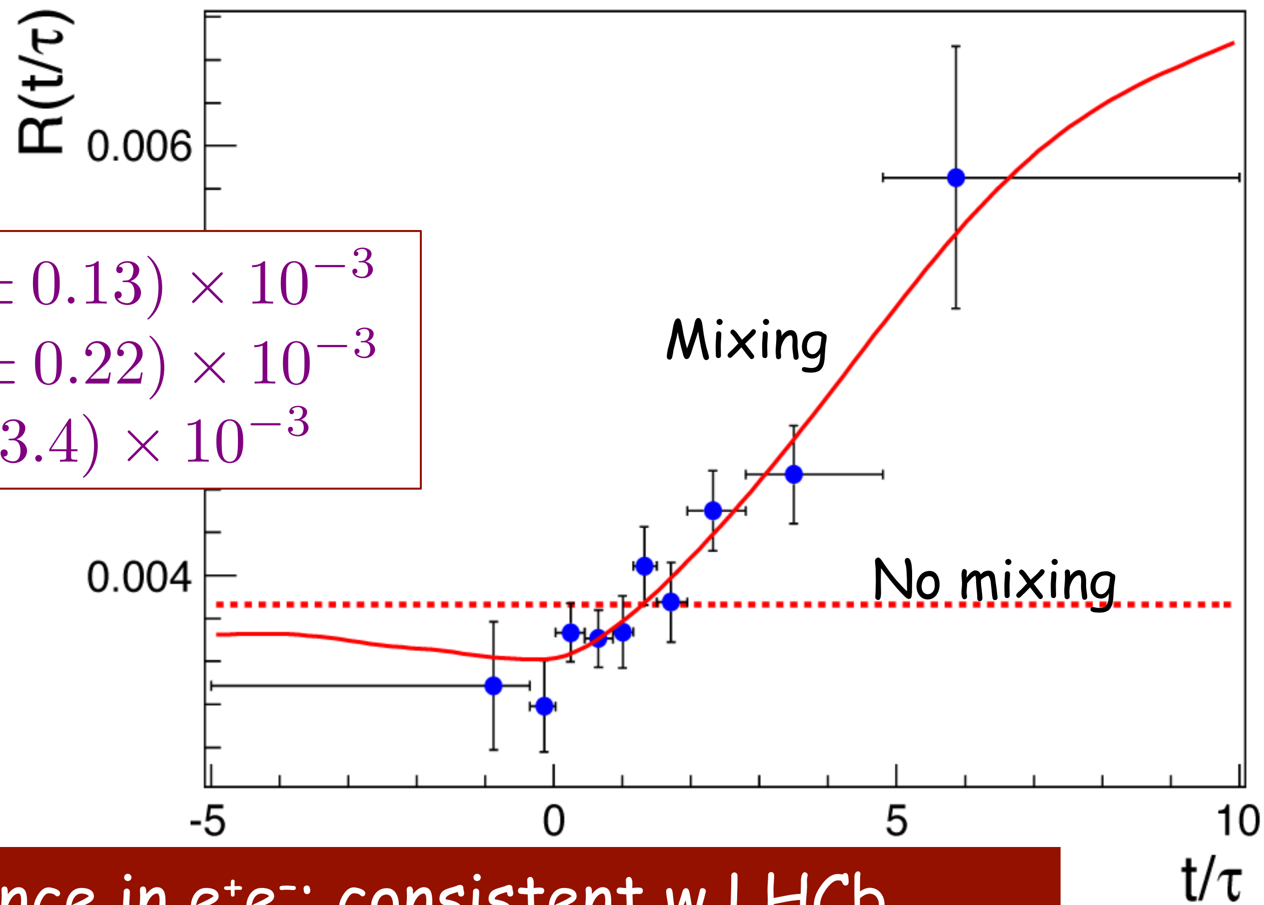


# $D^0$ mixing

Belle arXiv:1401.3402

976 fb$^{-1}$

$$R(\tilde{t}/\tau) \equiv \frac{\Gamma_{WS}(\tilde{t}/\tau)}{\Gamma_{RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$




$$R_D = (3.53 \pm 0.13) \times 10^{-3}$$
$$x'^2 = (0.09 \pm 0.22) \times 10^{-3}$$
$$y' = (4.6 \pm 3.4) \times 10^{-3}$$

First evidence in $e^+e^-$; consistent w LHCb

# QCD
# Exotic quarkonium-like states

(conventional quarkonium results
not included here)

# History of heavy quark exotica

PDG13

Many are unconfirmed
Primary characteristic:
high rate to quarkonia

Charmonium-like

Z(3900)

Z(3885)

Z(4025)

Z(4020)

Bottomonium-like

$Z_b^0(10610)$

| State | $m$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode) | Experiment ($\#\sigma$) | Year | Status |
|---|---|---|---|---|---|---|---|
| $X(3872)$ | 3871.68±0.17 | $< 1.2$ | $1^{++}/2^{-+}$ | $B \to K(\pi^+\pi^- J/\psi)$ | Belle [36,37] (12.8), BABAR [38] (8.6) | 2003 | OK |
| | | | | $p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$ | CDF [39–41] (np), D0 [42] (5.2) | | |
| | | | | $B \to K(\omega J/\psi)$ | Belle [43] (4.3), BABAR [23] (4.0) | | |
| | | | | $B \to K(D^{*0}\overline{D}^0)$ | Belle [44,45] (6.4), BABAR [46] (4.9) | | |
| | | | | $B \to K(\gamma J/\psi)$ | Belle [47] (4.0), BABAR [48,49] (3.6) | | |
| | | | | $B \to K(\gamma\psi(2S))$ | BABAR [49] (3.5), Belle [47] (0.4) | | |
| | | | | $pp \to (\pi^+\pi^- J/\psi) + ...$ | LHCb [50] (np) | | |
| $X(3915)$ | $3917.4 \pm 2.7$ | $28^{+10}_{-\ 9}$ | $0/2^{?+}$ | $B \to K(\omega J/\psi)$ | Belle [51] (8.1), BABAR [52] (19) | 2004 | OK |
| | | | | $e^+e^- \to e^+e^-(\omega J/\psi)$ | Belle [53] (7.7), BABAR [23] (np) | | |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $e^+e^- \to J/\psi(D\overline{D}^*)$ | Belle [54] (6.0) | 2007 | NC! |
| | | | | $e^+e^- \to J/\psi(...)$ | Belle [20] (5.0) | | |
| $G(3900)$ | $3943 \pm 21$ | 52±11 | $1^{--}$ | $e^+e^- \to \gamma(D\overline{D})$ | BABAR [55] (np), Belle [56] (np) | 2007 | OK |
| $Y(4008)$ | $4008^{+121}_{-\ 49}$ | 226±97 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ | Belle [57] (7.4) | 2007 | NC! |
| $Z_1(4050)^+$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | ? | $B \to K(\pi^+\chi_{c1}(1P))$ | Belle [58] (5.0), BABAR [59] (1.1) | 2008 | NC! |
| $Y(4140)$ | $4143.4 \pm 3.0$ | $15^{+11}_{-\ 7}$ | $?^{?+}$ | $B \to K(\phi J/\psi)$ | CDF [60,61] (5.0) | 2009 | NC! |
| $X(4160)$ | $4156^{+29}_{-25}$ | $139^{+113}_{-65}$ | $?^{?+}$ | $e^+e^- \to J/\psi(D\overline{D}^*)$ | Belle [54] (5.5) | 2007 | NC! |
| $Z_2(4250)^+$ | $4248^{+185}_{-\ 45}$ | $177^{+321}_{-\ 72}$ | ? | $B \to K(\pi^+\chi_{c1}(1P))$ | Belle [58] (5.0), BABAR [59] (2.0) | 2008 | NC! |
| $Y(4260)$ | $4263^{+8}_{-9}$ | 95±14 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ | BABAR [62,63] (8.0) | 2005 | OK |
| | | | | | CLEO [64] (5.4), Belle [57] (15) | | |
| | | | | $e^+e^- \to (\pi^+\pi^- J/\psi)$ | CLEO [65] (11) | | |
| | | | | $e^+e^- \to (\pi^0\pi^0 J/\psi)$ | CLEO [65] (5.1) | | |
| $Y(4274)$ | $4274.4^{+8.4}_{-6.7}$ | $32^{+22}_{-15}$ | $?^{?+}$ | $B \to K(\phi J/\psi)$ | CDF [61] (3.1) | 2010 | NC! |
| $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0/2^{++}$ | $e^+e^- \to e^+e^-(\phi J/\psi)$ | Belle [66] (3.2) | 2009 | NC! |
| $Y(4360)$ | $4361 \pm 13$ | 74±18 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$ | BABAR [67] (np), Belle [68] (8.0) | 2007 | OK |
| $Z(4430)^+$ | $4443^{+24}_{-18}$ | $107^{+113}_{-\ 71}$ | ? | $B \to K(\pi^+\psi(2S))$ | Belle [69,70] (6.4), BABAR [71] (2.4) | 2007 | NC! |
| $X(4630)$ | $4634^{+\ 9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$ | Belle [72] (8.2) | 2007 | NC! |
| $Y(4660)$ | 4664±12 | 48±15 | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$ | Belle [68] (5.8) | 2007 | NC! |
| $Z_b(10610)^+$ | 10607.2±2.0 | 18.4±2.4 | $1^+$ | $\Upsilon(5S) \to \pi^-(\pi^+[b\bar{b}])$ | Belle [73,74] (16) | 2011 | NC! |
| $Z_b(10650)^+$ | 10652.2±1.5 | 11.5±2.2 | $1^+$ | $\Upsilon(5S) \to \pi^-(\pi^+[b\bar{b}])$ | Belle [73,74] (16) | 2011 | NC! |
| $Y_b(10888)$ | 10888.4±3.0 | $30.7^{+8.9}_{-7.7}$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$ | Belle [75,76] (2.0) | 2010 | NC! |

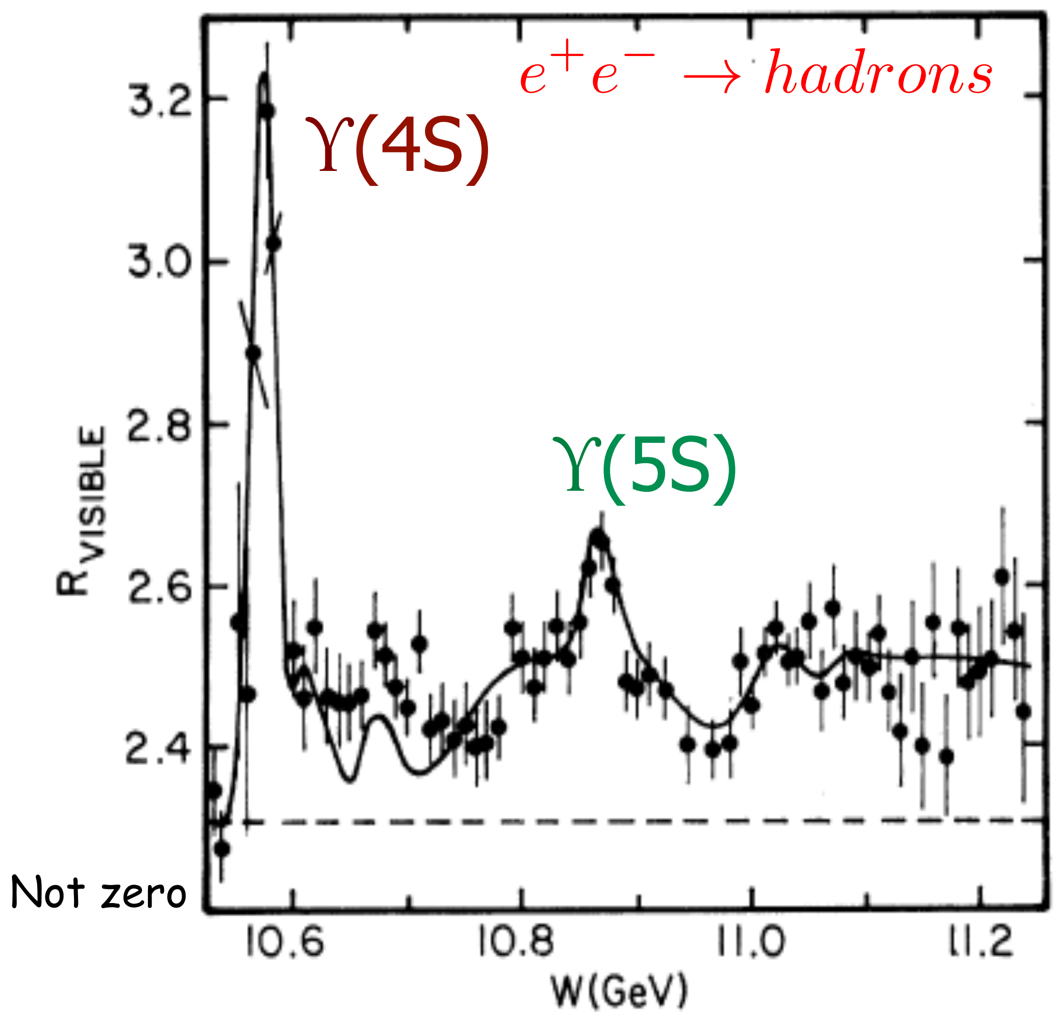
# QCD

- Observable states ⇔ color singlet
  - Mesons, baryons $\{q\bar{q}\},\ \{qqq\}$
  - Other possible color singlet combinations
    - Pentaquark $\{qqqq\bar{q}\}$
    - H-dibaryon $\{qqqqqq\}$
    - Glueball $\{gg\}$
    - Tetraquark $\{q\bar{q}\}\{q\bar{q}\}\ \{qq\}\{\bar{q}\bar{q}\}$
    - Quark-gluon hybrid $\{qqg\}$

# Upsilon region

Belle

- Bottomonium-like, found mainly in region above $\Upsilon(4S)$



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

Belle

- Observed in 121 fb−1 @ $\Upsilon$(5S) (10860) [PRL 108, 122001 (2012)]

$$Z_b^{\pm}(xx) \to \{b\bar{b}\}\pi^{\pm}$$

in events

$$e^+e^- \to \{\Upsilon(1\text{S}), \Upsilon(2\text{S}), \Upsilon(3\text{S}), h_b(1\text{P}), h_b(2\text{P})\}\pi^+\pi^-$$

- Since observation:
  - NEW: Measurement of $J^P$
  - [arXiV:1209.6450] Observation of

$$e^+e^- \to Z_b^{\pm}\pi^{\mp}\{Z_b^{\pm} \to [\{B^*\bar{B}^{(*)}\}^{\pm}, \bar{B}^*B^{(*)}\}^{\pm}]\}$$

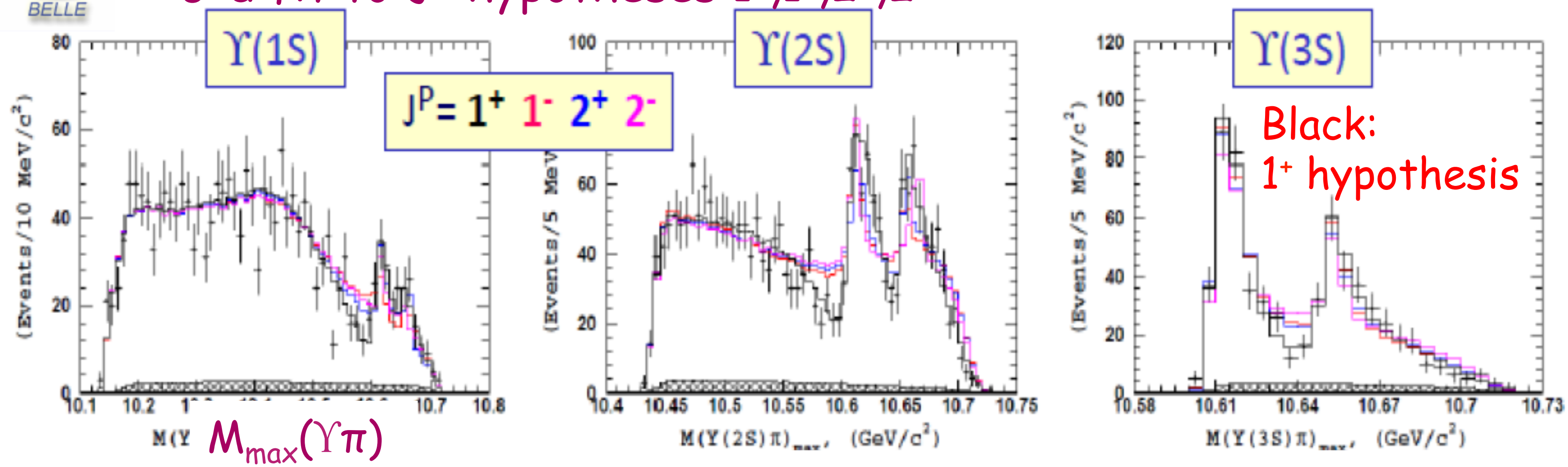
  - [PRD 88, 052016 (2013)] Observation of $Z_b^0(10610)$

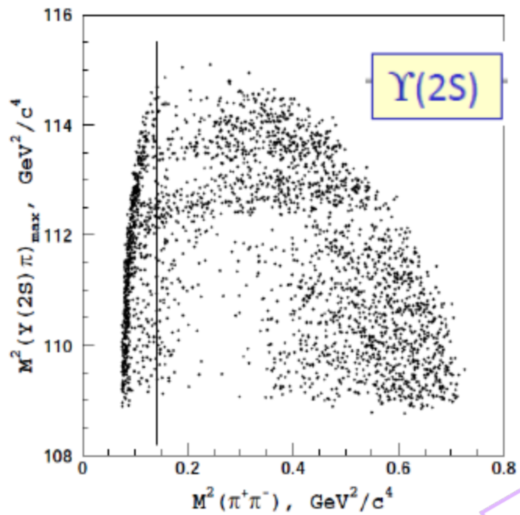
- Soon:
  - Scan of $\Upsilon\pi\pi$ cross section, analysis of resonance/continuum b
    cf: PRD 82,091106(R) (2010)

# Measurement of $J^P$ $Z_b^{\pm}(10610)$, $Z_b^{\pm}(10650)$ Belle

$$e^+e^- \to \Upsilon(nS)\pi^+\pi^- \{\Upsilon(nS) \to \mu^+\mu^-\}$$

6-d fit to $J^P$ hypotheses $1^+, 1^-, 2^+, 2^-$




| $Z_b(10650)$ / $Z_b(10610)$ | $1^+$ | $1^-$ | $2^+$ | $2^-$ |
|---|---|---|---|---|
| $1^+$ | 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) |



**Spin parity of Zb(10610) and Zb(10650) is $1^+$.**
**All other $J^P$<3 are excluded.**

from A. Bondar, Hadrons from Quarks and Gluons 1/16/2014

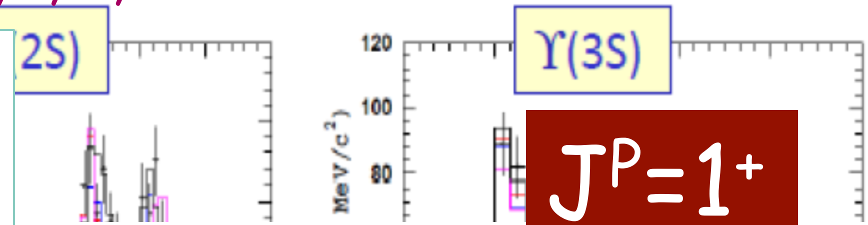
# Measurement of $J^P$ $Z_b^{\pm}(10610)$, $Z_b^{\pm}(10650)$

Belle

$$e^+e^- \to \Upsilon(nS)\pi^+\pi^- \{\Upsilon(nS) \to \mu^+\mu^-\}$$

6-d fit to $J^P$ hypotheses $1^+, 1^-, 2^+, 2^-$

$$ln\mathcal{L}(1^+) - ln\mathcal{L}(J^P)$$

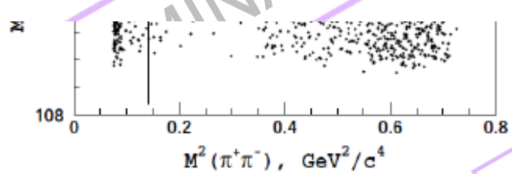



$J^P = 1^+$

| $Z_b(10610)$ \ $Z_b(10650)$ | $1^+$ | $1^-$ | $2^+$ | $2^-$ |
|---|---|---|---|---|
| $1^+$ | 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) |

$\Upsilon(2S)\pi\pi$ ($\Upsilon(3S)\pi\pi$)

PRELIMINARY




Belle PRELIMINARY

**Spin parity of Zb(10610) and Zb(10650) is $1^+$.**
**All other $J^P<3$ are excluded.**

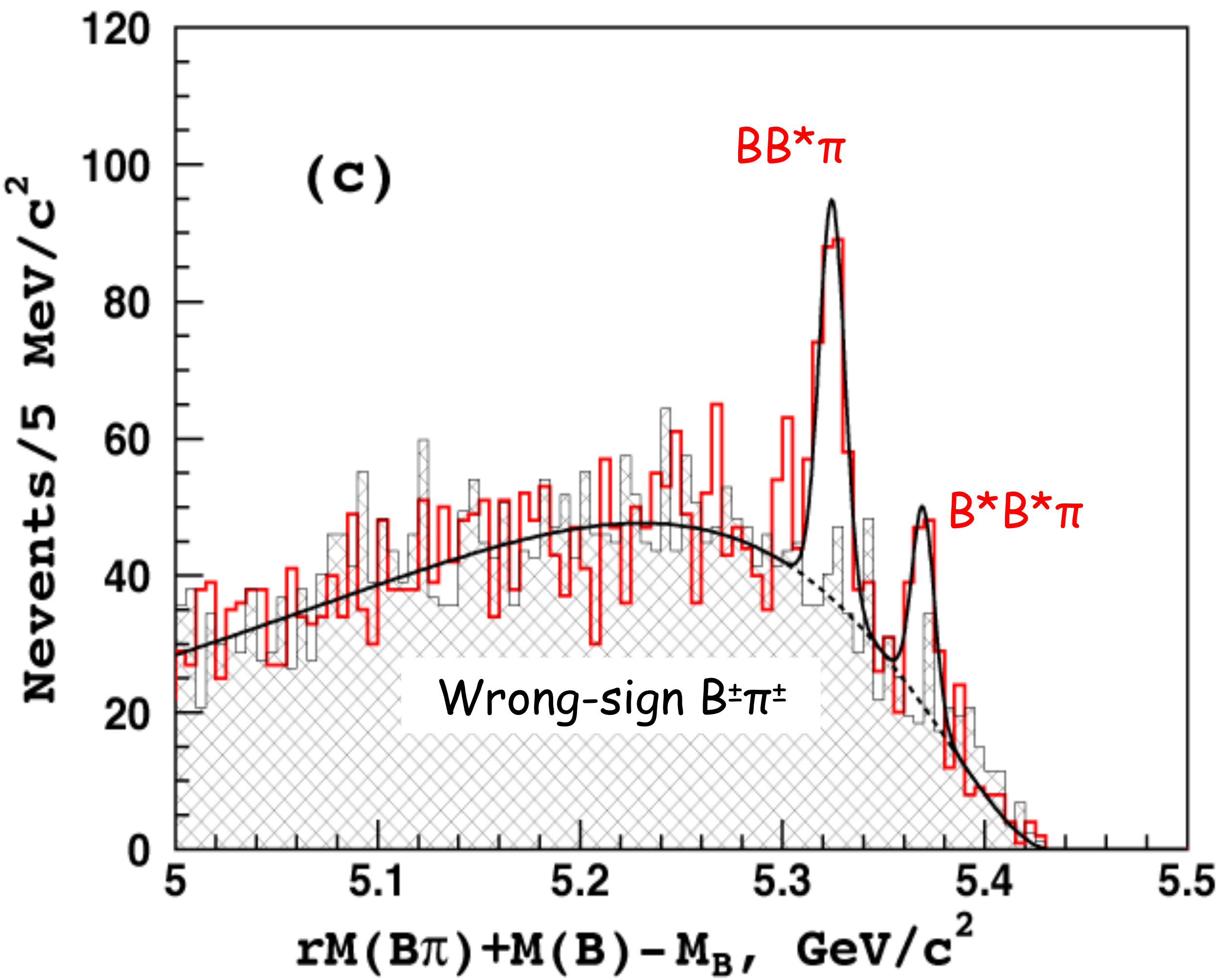
from A. Bondar, Hadrons from Quarks and Gluons 1/16/2014

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

arXiv:1209.6450

Belle

- Events $e^+e^- \to [B^* \bar{B}^{(*)}, \bar{B}^* B^{(*)}]^{\pm} \pi^{\mp}$
- Select (fully reconstructed B,π), examine recoiling mass

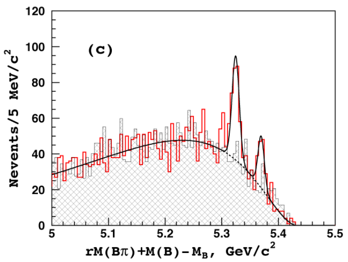


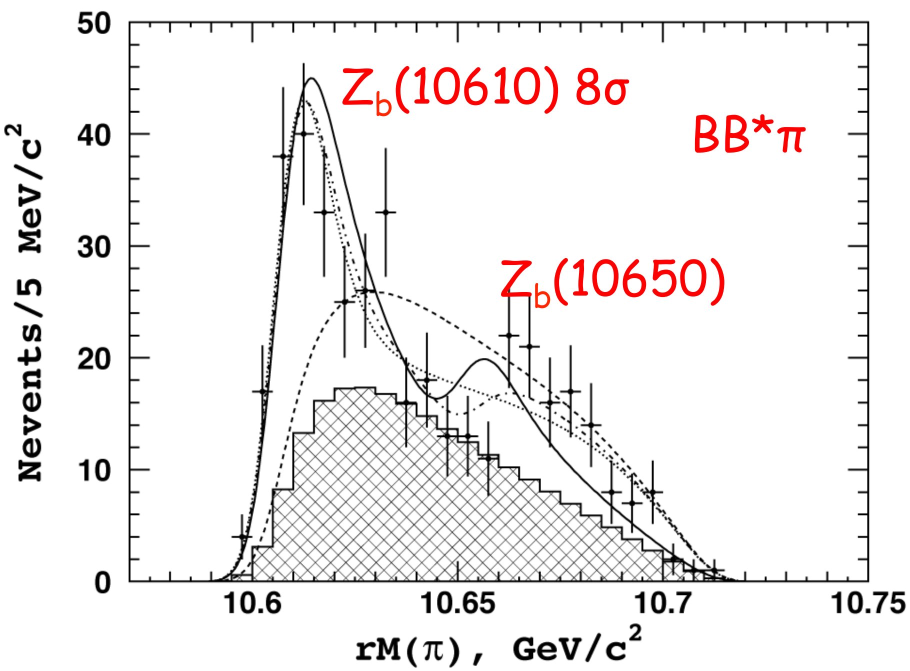
# $Z_b^{\pm} \rightarrow [B^* \bar{B}^{(*)}, \bar{B}^* B^{(*)}]^{\pm}$

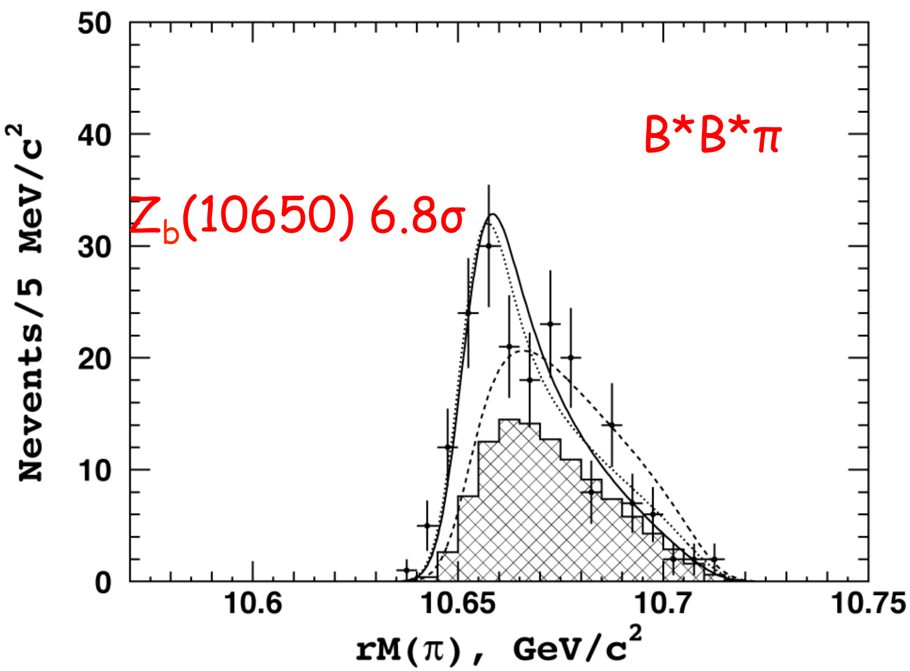
arXiv:1209.6450

Belle

- Select candidate events, plot mass recoiling against π




good fit to $Z_b(10610)$+$Z_b(10650)$ or $Z_b(10610)$+non-resonant.

good fit to $Z_b(10650)$

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

arXiv:1209.6450

Belle

- Assuming observed modes saturate $Z_b^{\pm}$, calculate branchings

PRELIMINARY

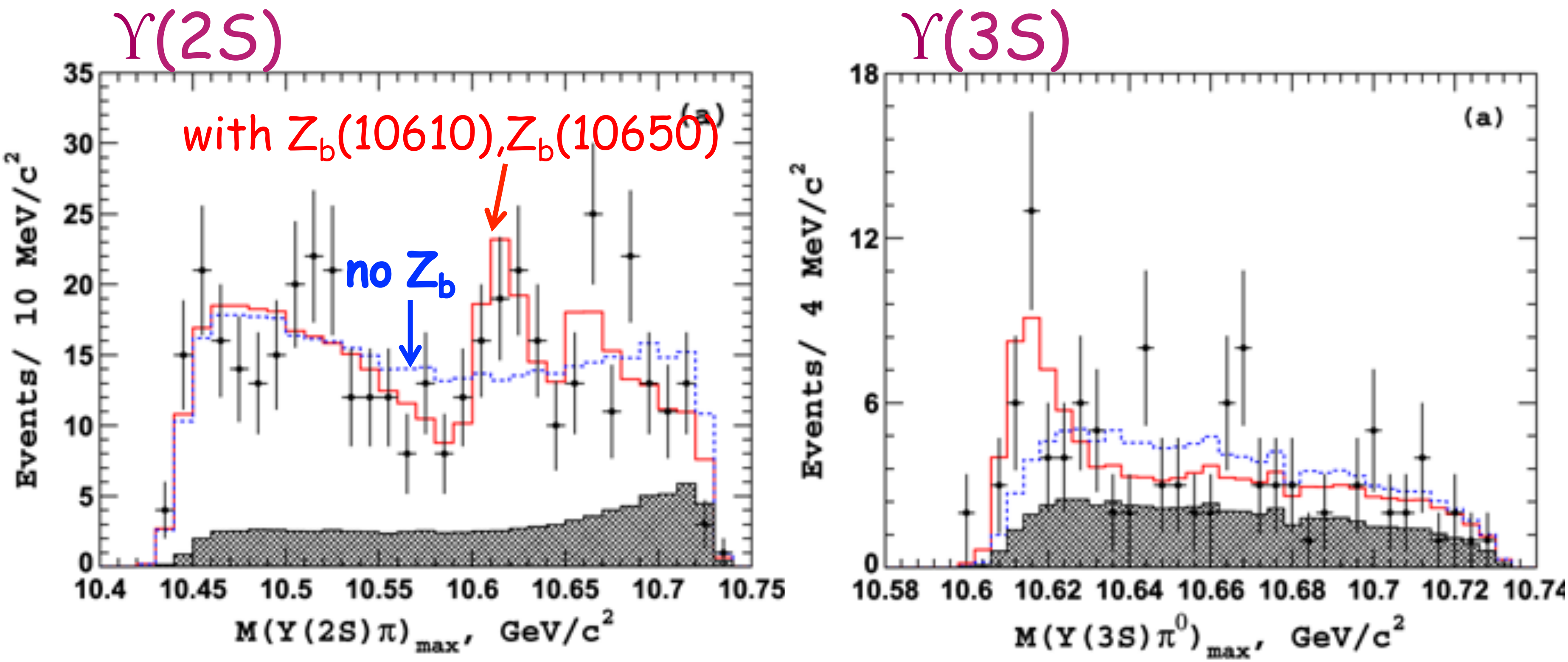
| Channel | Fraction, % | |
|---|---|---|
| | $Z_b(10610)$ | $Z_b(10650)$ |
| $\Upsilon(1S)\pi^+$ | $0.32 \pm 0.09$ | $0.24 \pm 0.07$ |
| $\Upsilon(2S)\pi^+$ | $4.38 \pm 1.21$ | $2.40 \pm 0.63$ |
| $\Upsilon(3S)\pi^+$ | $2.15 \pm 0.56$ | $1.64 \pm 0.40$ |
| $h_b(1P)\pi^+$ | $2.81 \pm 1.10$ | $7.43 \pm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

$B^*B^{(*)}$ Dominate

# $Z_b^0$(10610)

PRD 88, 052016 (2013) Belle

$$\Upsilon(1S, 2S, 3S)\pi^0\pi^0 \quad \{\Upsilon \to e^+e^-, \mu^+\mu^-\}$$



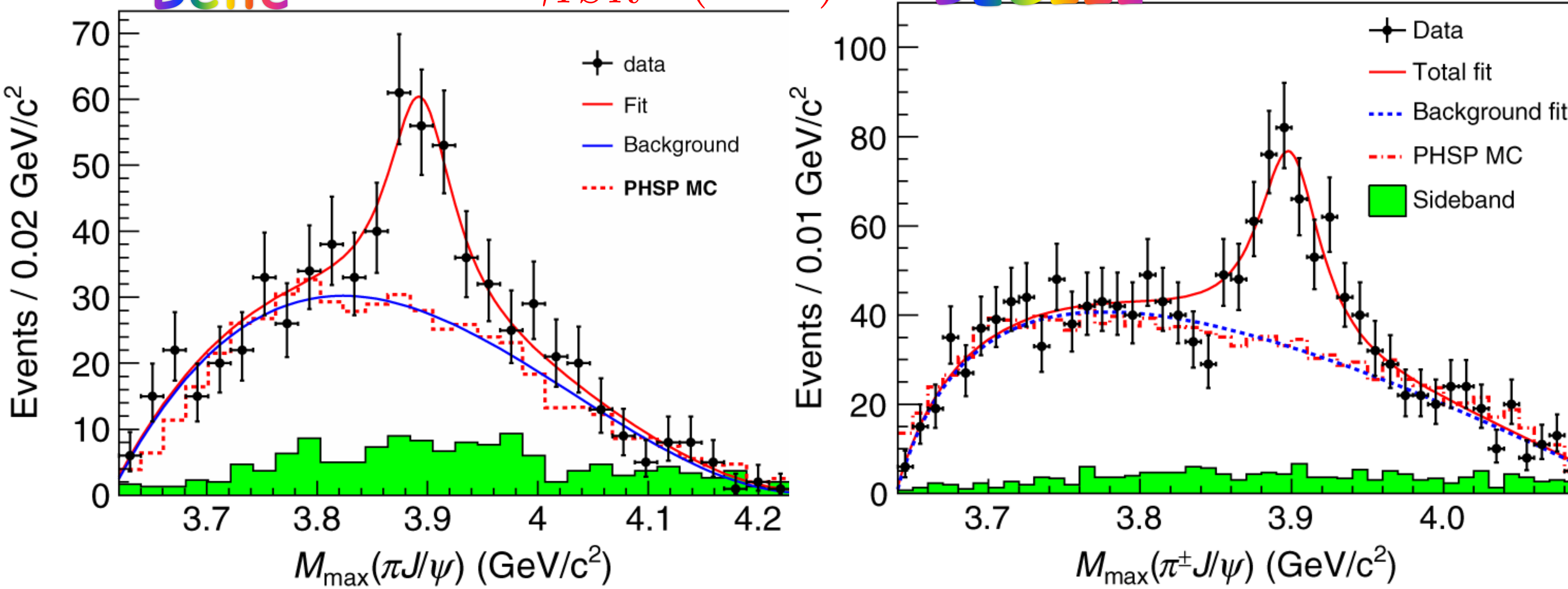

$Z_b^0$(10610) observed with 6.5σ significance

# $Z_c^{\pm}(3900)$

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

Belle $e^+e^- \to \gamma_{ISR}Y(4260)$

BESIII $\sqrt{s} = 4.26$ GeV




PRL 110, 252002 (2013)

PRL 110, 252001 (2013)

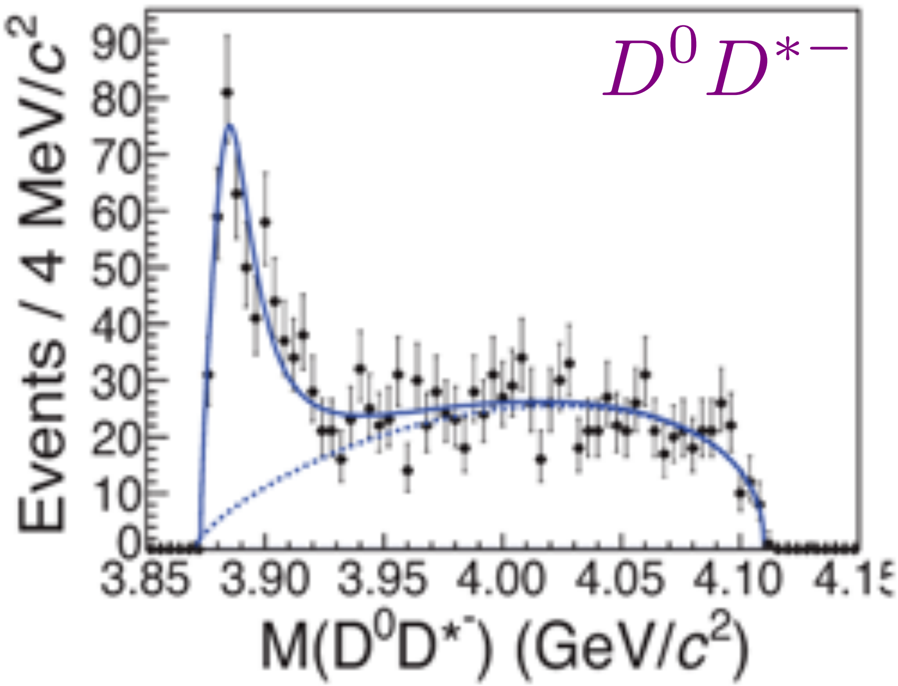
$M = (3894.5 \pm 6.6 \pm 4.5)\mathrm{MeV}/c^2$ $\quad (3899.0 \pm 3.6 \pm 4.9)\mathrm{MeV}/c^2$

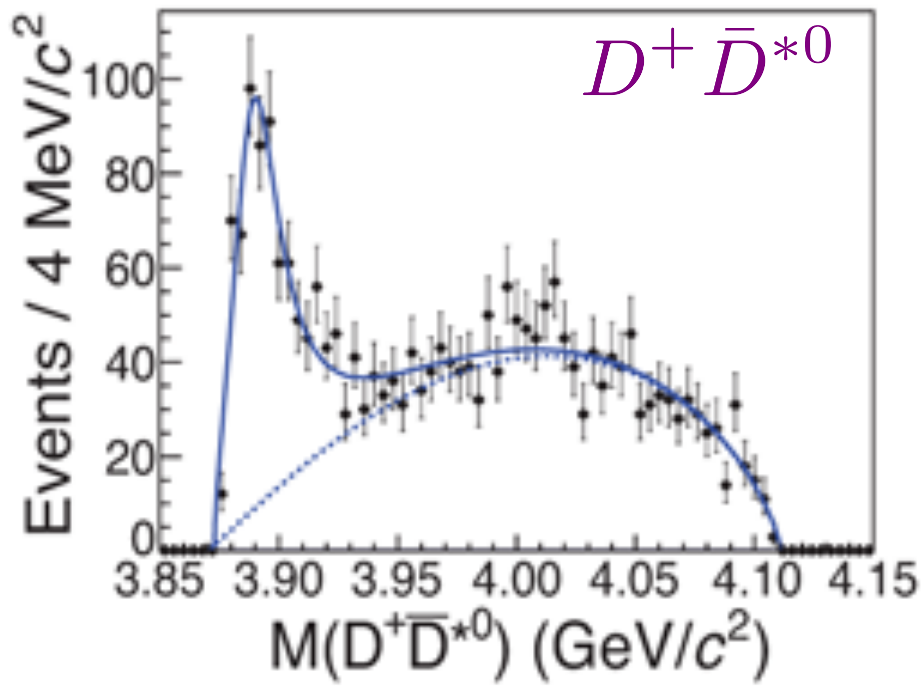
$\Gamma = (63 \pm 24 \pm 26)\mathrm{MeV}$ $\quad (46 \pm 10 \pm 20)\mathrm{MeV}$

# "$Z_c$(3885)"

BESIII arXiv:1310.1163

$$e^+e^- \to [D\bar{D}^*]^\pm \pi^\mp \qquad \sqrt{s} = 4.26\ \mathrm{GeV}$$




$$M = (3883.9 \pm 1.5 \pm 4.2)\mathrm{MeV}/c^2$$

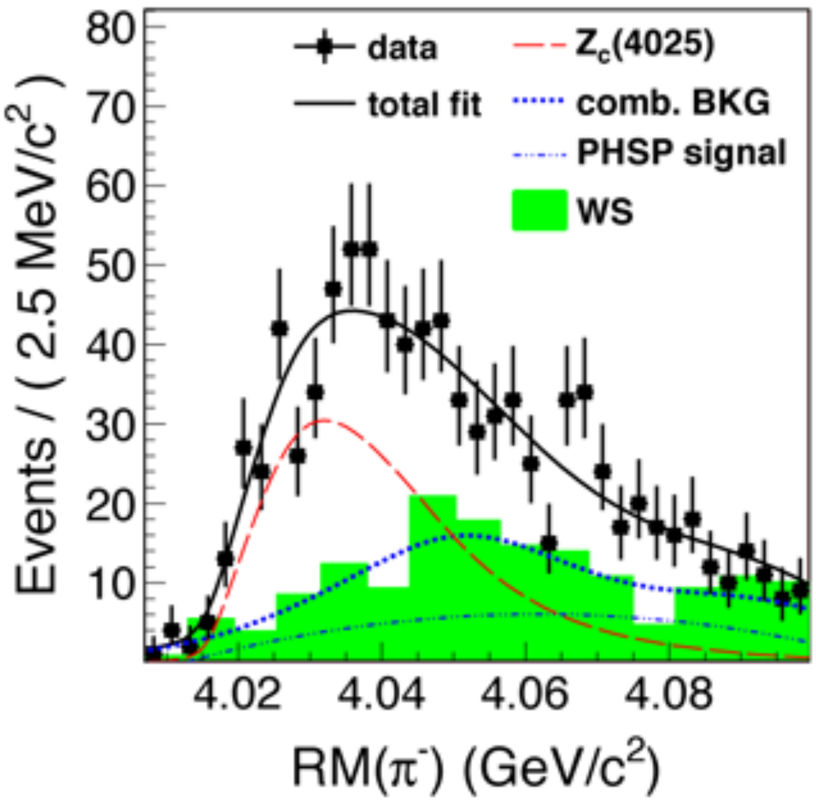
$$\Gamma = (24.8 \pm 3.3 \pm 11.0)\mathrm{MeV}$$

If we assume Z(3900) & Z(3885) are the same, $\frac{\Gamma(Z(3885) \to DD^*)}{\Gamma(Z(3900) \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$

# "$Z_c(4025)^\pm$"

BESIII arXiv:1308.2760

$$e^+e^- \to [D^*\bar{D}^*]^\pm\pi^\mp \qquad \sqrt{s} = 4.26\ \mathrm{GeV}$$




Reconstruct $D^+$, $\pi^0$

$$M = (4026.3 \pm 2.6 \pm 3.7)\mathrm{MeV}/c^2$$

$$\Gamma = (24.8 \pm 5.6 \pm 7.7)\mathrm{MeV}$$

$$\frac{\sigma(e^+e^- \to Z_c(4025)^\pm\pi^\mp \to [D^*\bar{D}^*]^\pm\pi^\mp)}{\sigma(e^+e^- \to [D^*\bar{D}^*]^\pm\pi^\mp)} = 0.65 \pm 0.09 \pm 0.06$$

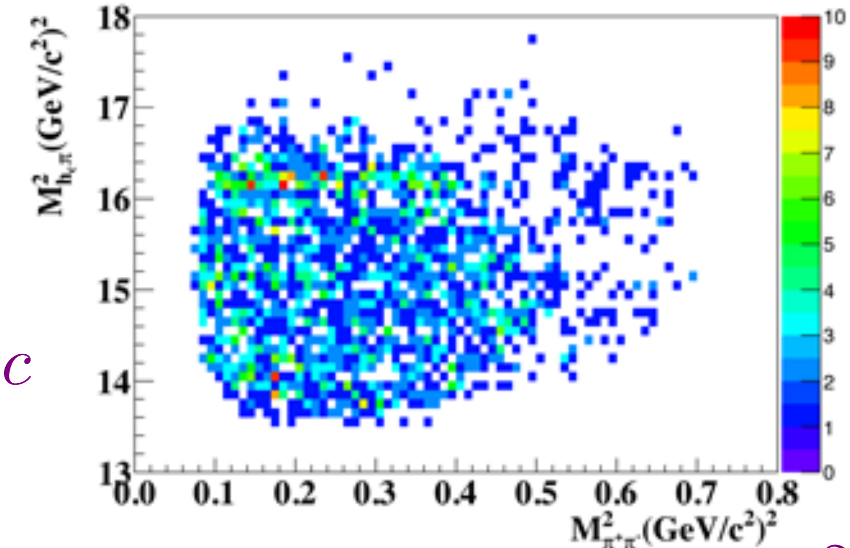
# "$Z_c(4020)$"

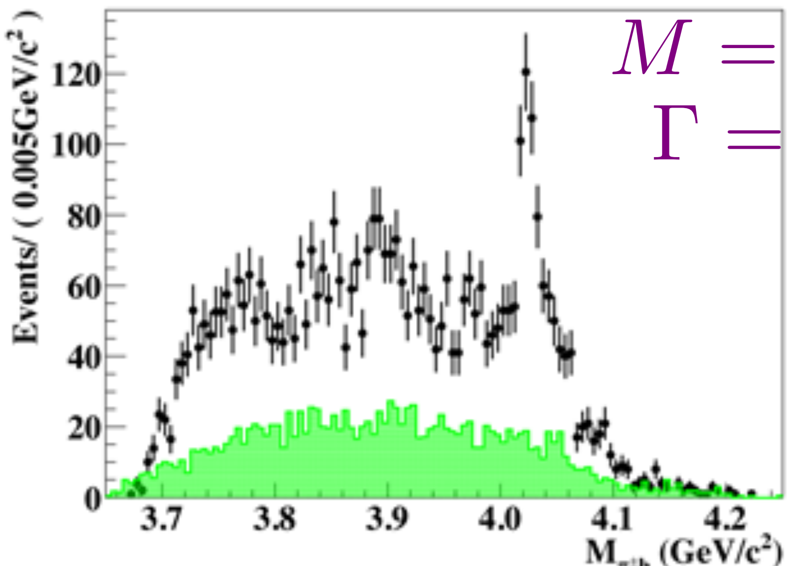
BESIII arXiv:1309.1896

- 13 cms energy points 3.90-4.42 GeV

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

$$h_c \rightarrow \gamma\eta_c$$
$$\eta_c \rightarrow 16\ exclusive\ hadronic$$




$$M = (4022.9 \pm 0.8 \pm 2.7)\mathrm{MeV}/c^2$$
$$\Gamma = (7.9 \pm 2.7 \pm 2.6)\mathrm{MeV}$$

Agreement w $Z_c(4025)$: 1.5σ

No significant $Z_c(3900)$

# Emerging dualities

**Bottomonium-like & Charmonium-like**

- charged -onium-like structures $Z_1$, $Z_2$
- Z's are very close to open flavor thresholds: QQ*, Q*Q* (Q=B,D)
- $I^G J^{PC}=1^+1^{+-}$
- Observed in both hidden-flavor and open-flavor modes
- Open-flavor modes dominate but not overwhelmingly

**What are they??**

# Emerging dualities

**What are they??** many theories

- Meson molecule

  [A.Bondar, et al., PRD 84, 054010 (2011)]
- Coupled channel resonances

  [I.V.Danilkin et al, arXiv:1106.1552]
- Cusp

  [D.Bugg, Europhys.Lett. 96, 11002 (2011)]
- Tetraquark

  [M.Karliner & H.Lipkin, arXiv:0802.0649]

**Much still remains to be explored**

- Belle final set, BESIII still running
- Belle II to come

# Summary

$e^+e^-$ colliders

- complementary role to the Energy Frontier
  - "inclusive" studies
  - Modes that include $\pi^0$, ν
  - Clean data, low systematics
- Recent results
  - b -> $sl^+l^-$ $A_{FB}$ by semi-inclusive method
  - Leptonic & semileptonic decays – tension on 2HDM
  - CP, CKM
  - $D^0$ mixing
  - Rich spectroscopy of quarkonium-like particles
- Looking to the future – probe TeV mass scales via Intensity …

# to find the NEW…

# to find the NEW… improve precision on the OLD

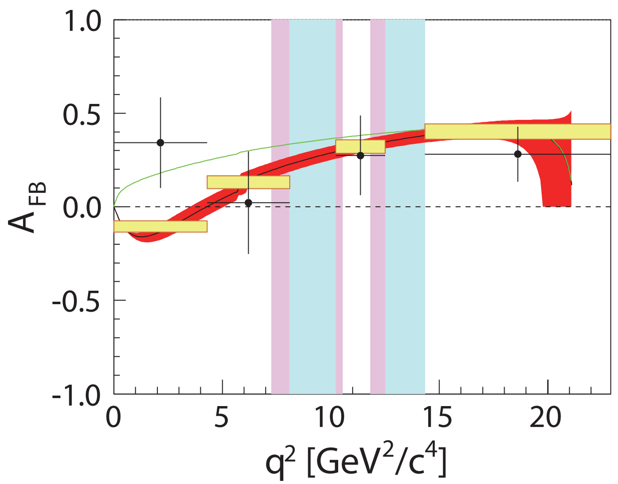
Still, not easy!

there IS a leopard

# Backup

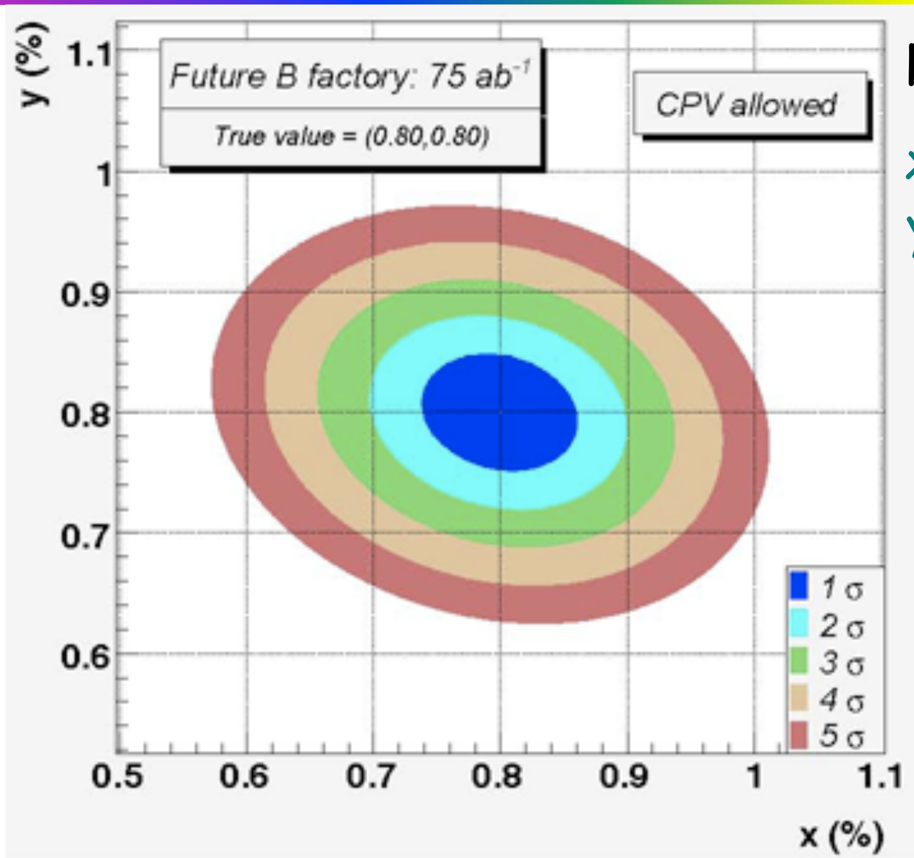
# Result $A_{FB}$

Belle




| | | 1st bin | 2nd bin | 3rd bin | 4th bin |
|---|---|---|---|---|---|
| $q^2$ range $[\mathrm{GeV}^2/c^4]$ | $(B \to X_s e^+ e^-)$ | [0.2,4.3] | [4.3,7.3] | [10.5,11.8] | [14.3, 25.0] |
| | $(B \to X_s \mu^+ \mu^-)$ | | [4.3,8.1] | [10.2,12.5] | |
| $\mathcal{A}_{\mathrm{FB}}$ | | 0.34 ± 0.24 ± 0.02 | 0.04 ± 0.31 ± 0.05 | 0.28 ± 0.21 ± 0.01 | 0.28 ± 0.15 ± 0.01 |
| $\mathcal{A}_{\mathrm{FB}}$ (theory) | | -0.11 ± 0.03 | 0.13 ± 0.03 | 0.32 ± 0.04 | 0.40 ± 0.04 |
| $N_{\mathrm{sig}}^{ee}$ | | 45.6 ± 10.9 | 30.0 ± 9.2 | 25.0 ± 7.0 | 39.2 ± 9.6 |
| $N_{\mathrm{sig}}^{\mu\mu}$ | | 43.4 ± 9.2 | 23.9 ± 10.4 | 30.7 ± 9.9 | 62.8 ± 10.4 |
| $\alpha^{ee}$ | | 1.289 ± 0.004 | 1.139 ± 0.003 | 1.063 ± 0.003 | 1.121 ± 0.003 |
| $\alpha^{\mu\mu}$ | | 2.082 ± 0.010 | 1.375 ± 0.003 | 1.033 ± 0.003 | 1.082 ± 0.003 |
| $\beta$ | | 1.000 | 1.019 ± 0.003 | 1.003 ± 0.000 | 1.000 |

# D mixing/CP violation




For 75 ab$^{-1}$

x=0.8 >4σ significance on x

y=0.8 >5σ significance on y

|q/p|=0.9

~4σ significance on 1-|q/p|