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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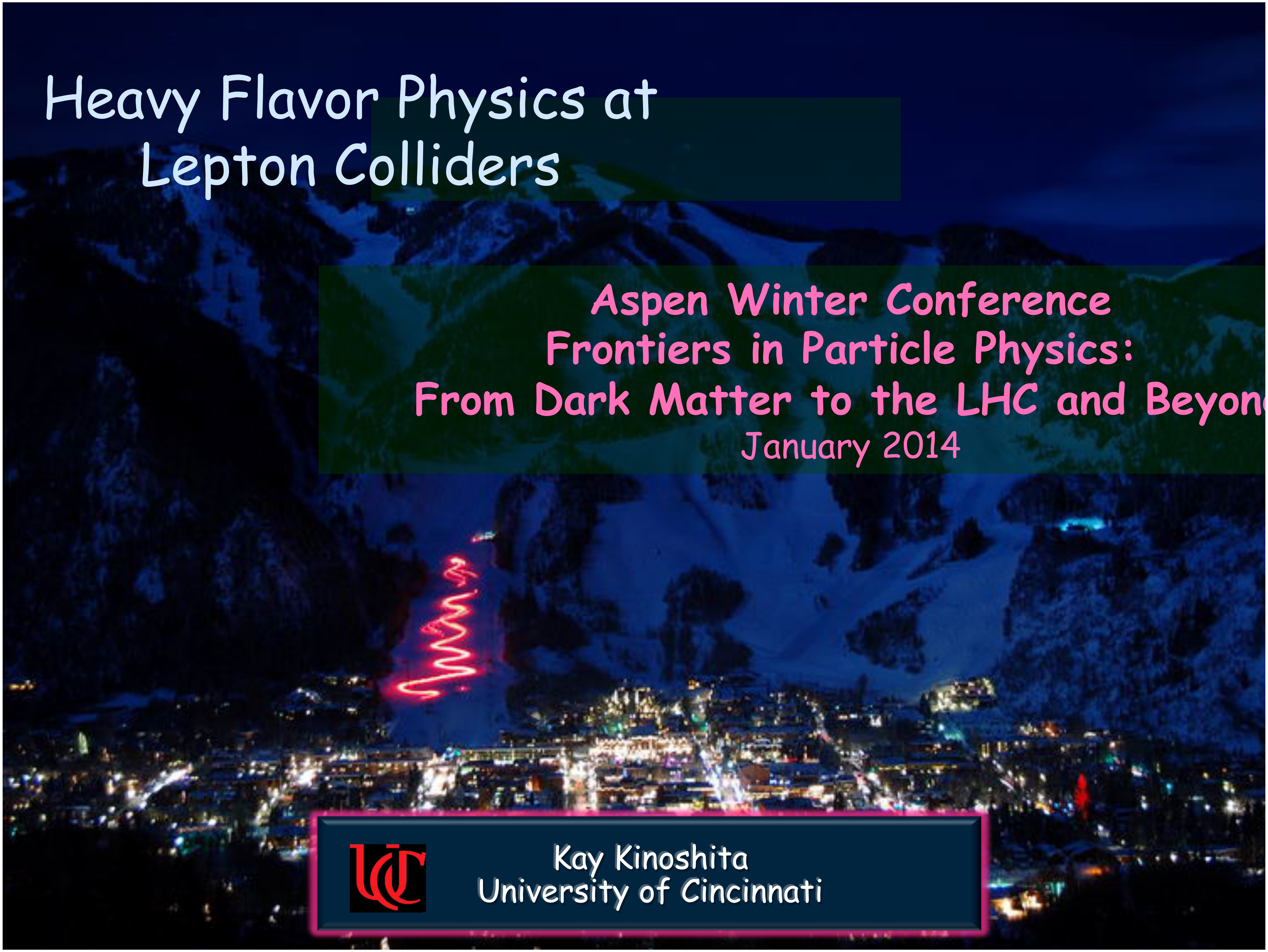
University of Cincinnati



e^+e^- collider experiments

NOW

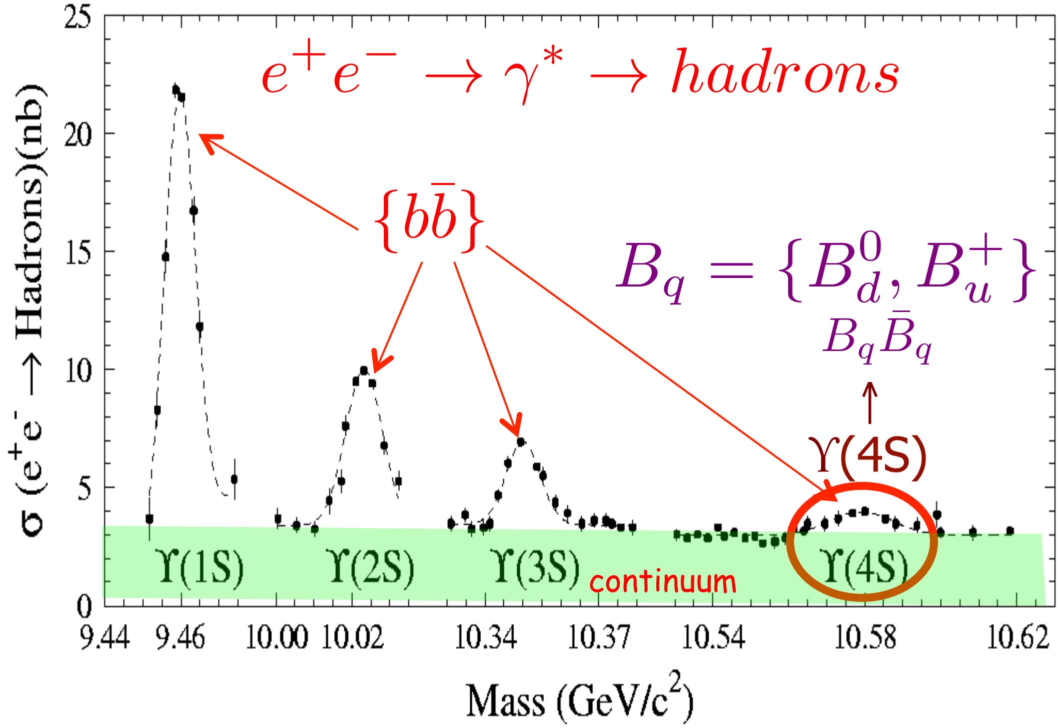
- BEPC II/BESIII
  - 2008- Symmetric
  - 1.3G J/ψ, 400M ψ′, 2.9 fb^{-1} ψ″, 3.3 fb^{-1} above 4 GeV
- PEP-II/Babar
  - 1999-2008 9 Gev e^- + 3 GeV e^+
  - 471M $\Upsilon(4S)$, ~500M charm pair
- KEKB/Belle
  - 1999-2010 8.5 GeV e^- + 3.5 GeV e^+
  - 772M $\Upsilon(4S)$ events(B pair), 10^9 charm pair, ~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

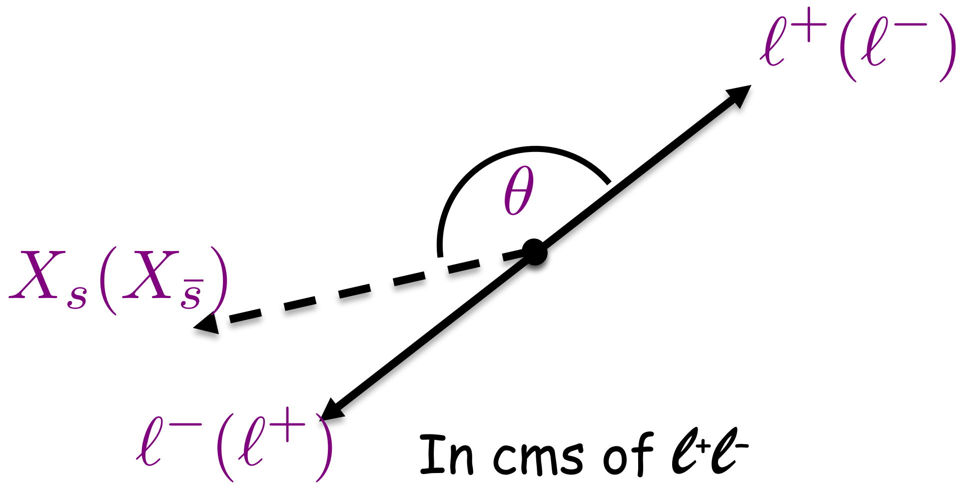
  - $b \to s l^+ l^-$ forward-backward asymmetry
  - $B^- \to \tau \nu$
  - $B \to D^{(*)} \tau \nu$
  - CP Asymmetries

  Charm

  - D^0 mixing
- QCD: Exotic heavy quarkonia

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

Belle



In cms of $\ell^+\ell^-$

Forward-backward Asymmetry

Belle

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

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

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

Wilson coefficients

- Previously measured in exclusive decays

  [PRL 103, 171801 (2009)]

- Inclusive A_{FB} has smaller theoretical uncertainty

A_{FB} semi-inclusive reconstruction

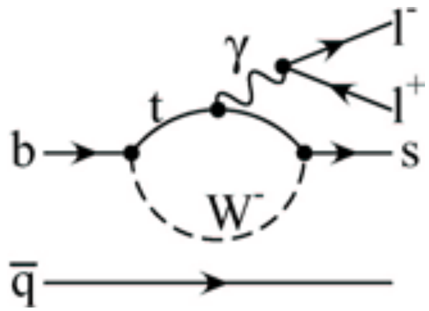
Belle

- 772×10^6 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

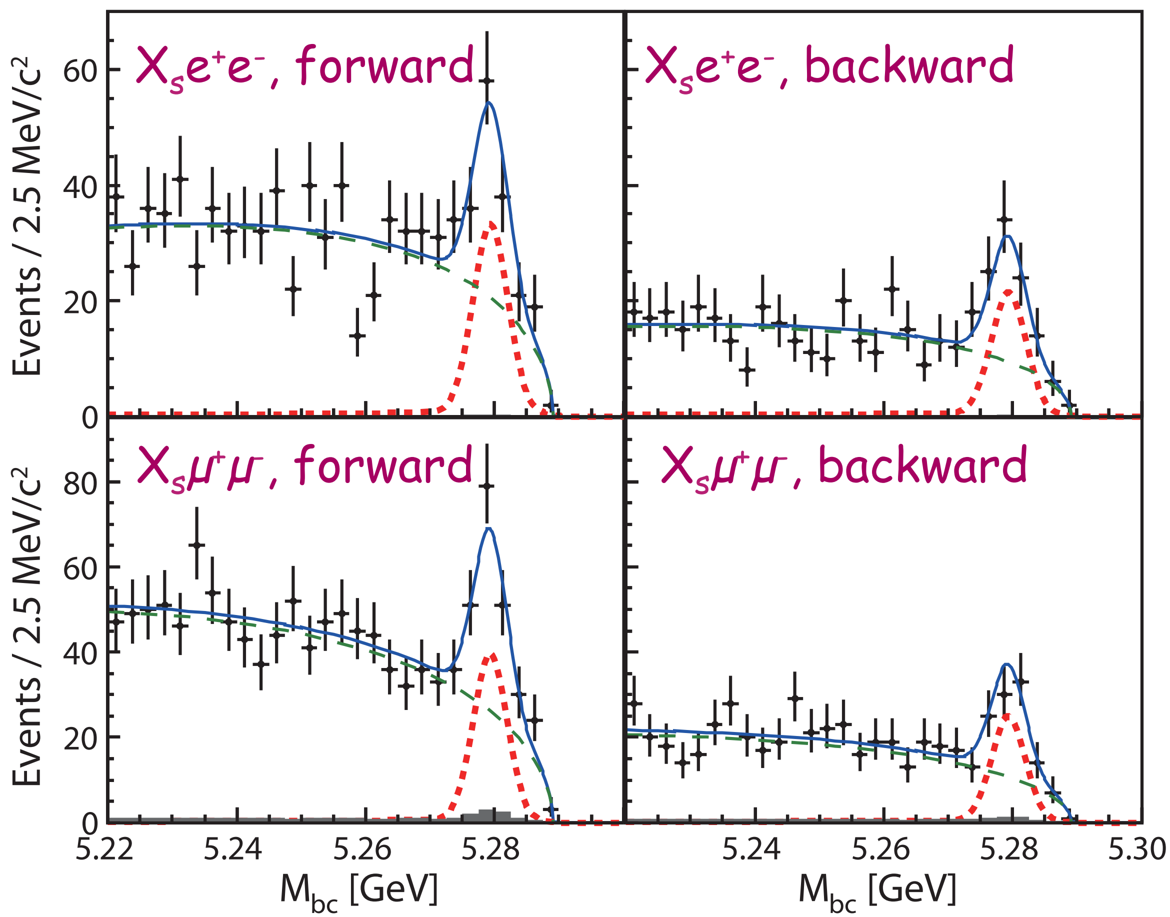
$$B \to X_s \ell^+ \ell^-$$



A_{FB} semi-inclusive

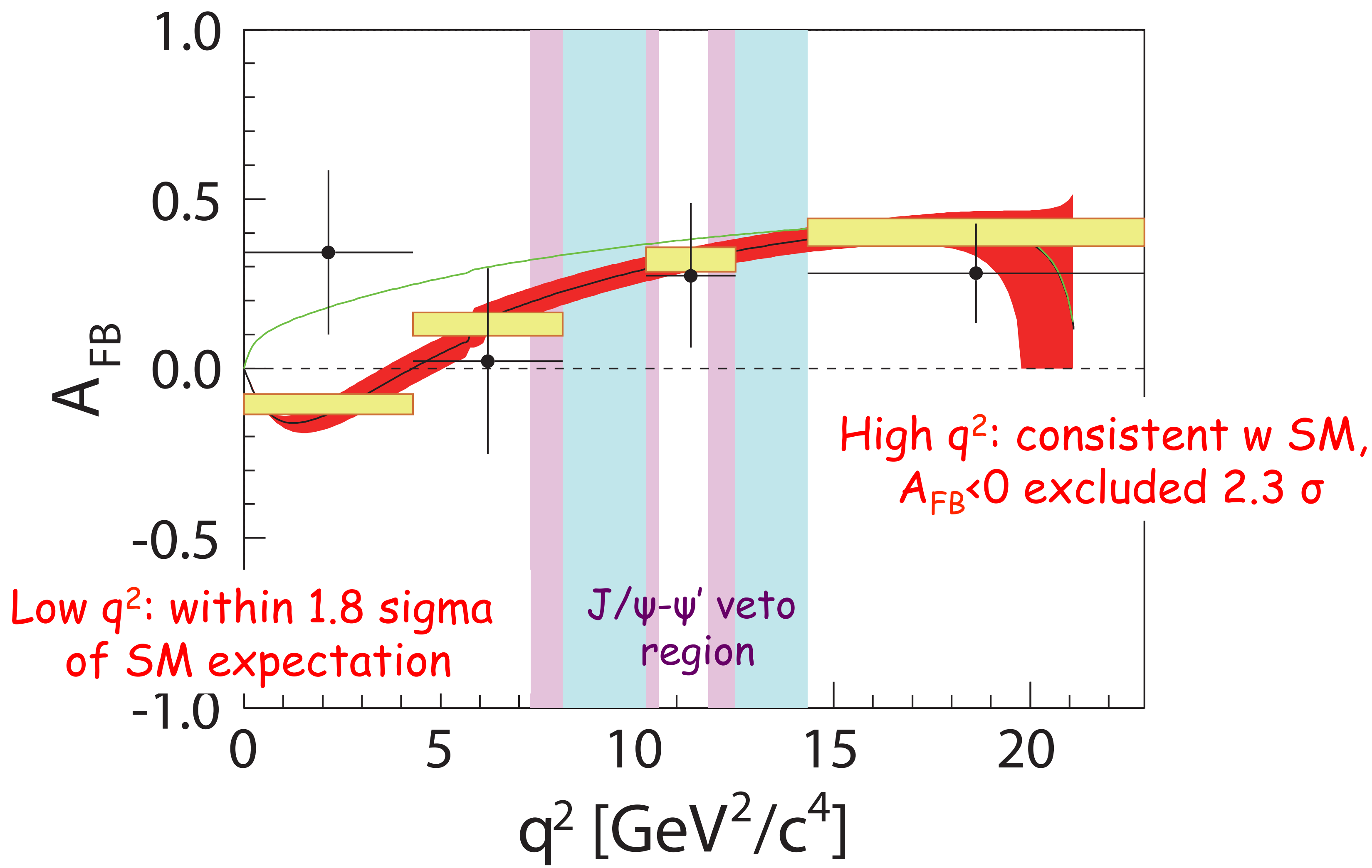
Belle

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



A_{FB} semi-inclusive: result

Belle Preliminary

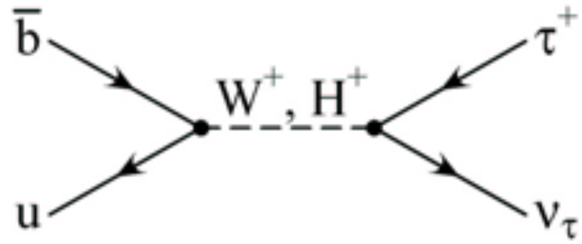


Lepton universality and New Physics

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

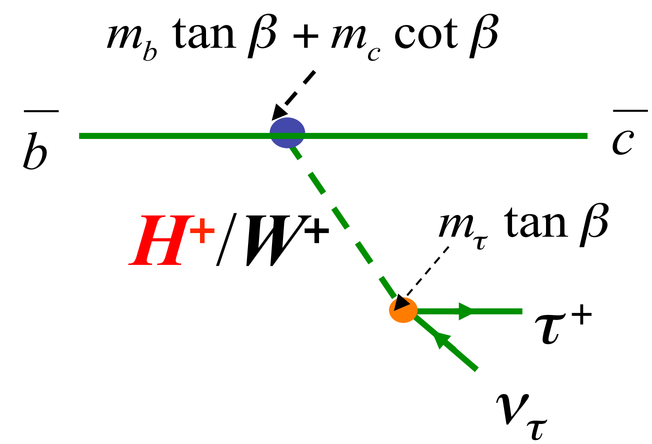
τ/μ (semi)leptonic decays

- 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

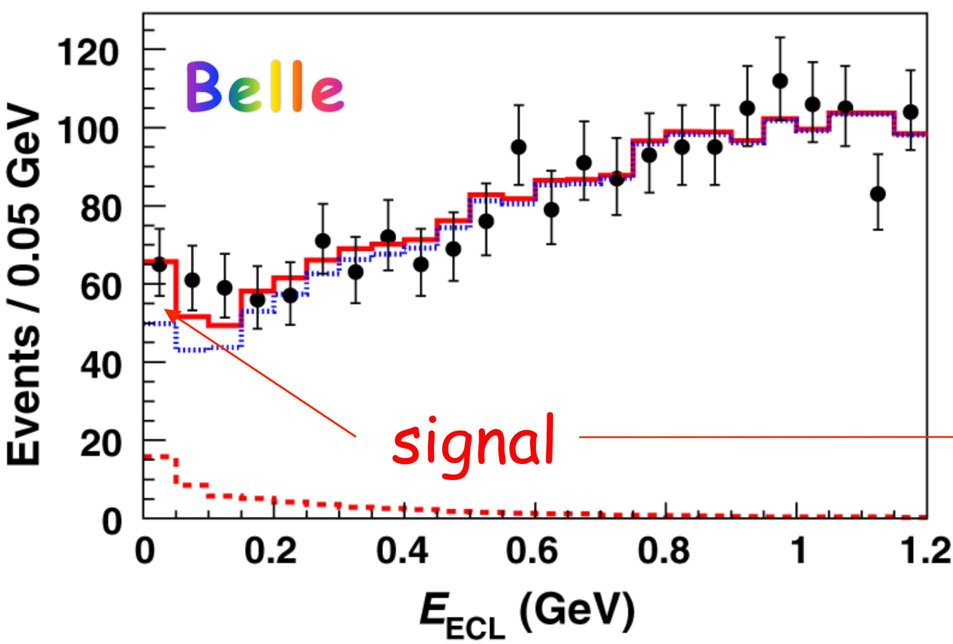
Belle & Babar

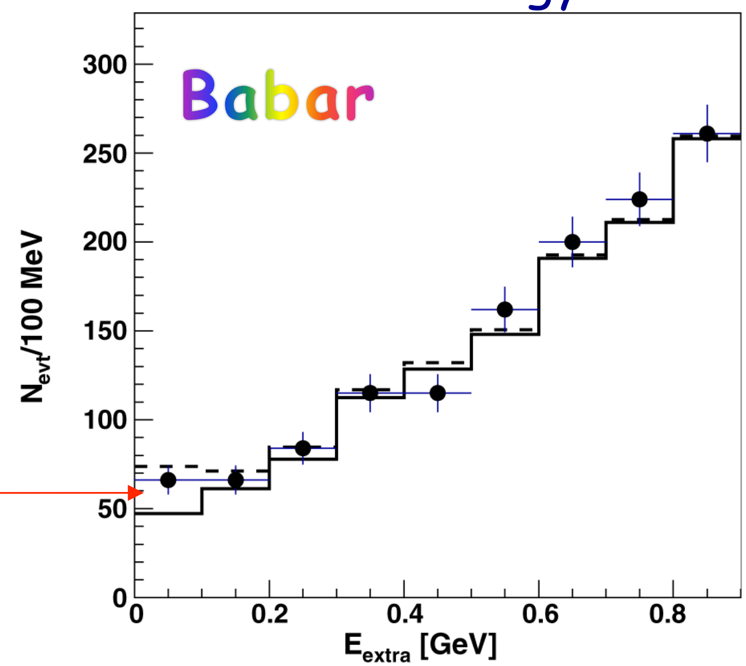
Belle $[0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$ PRL 110, 131801 (2013)

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





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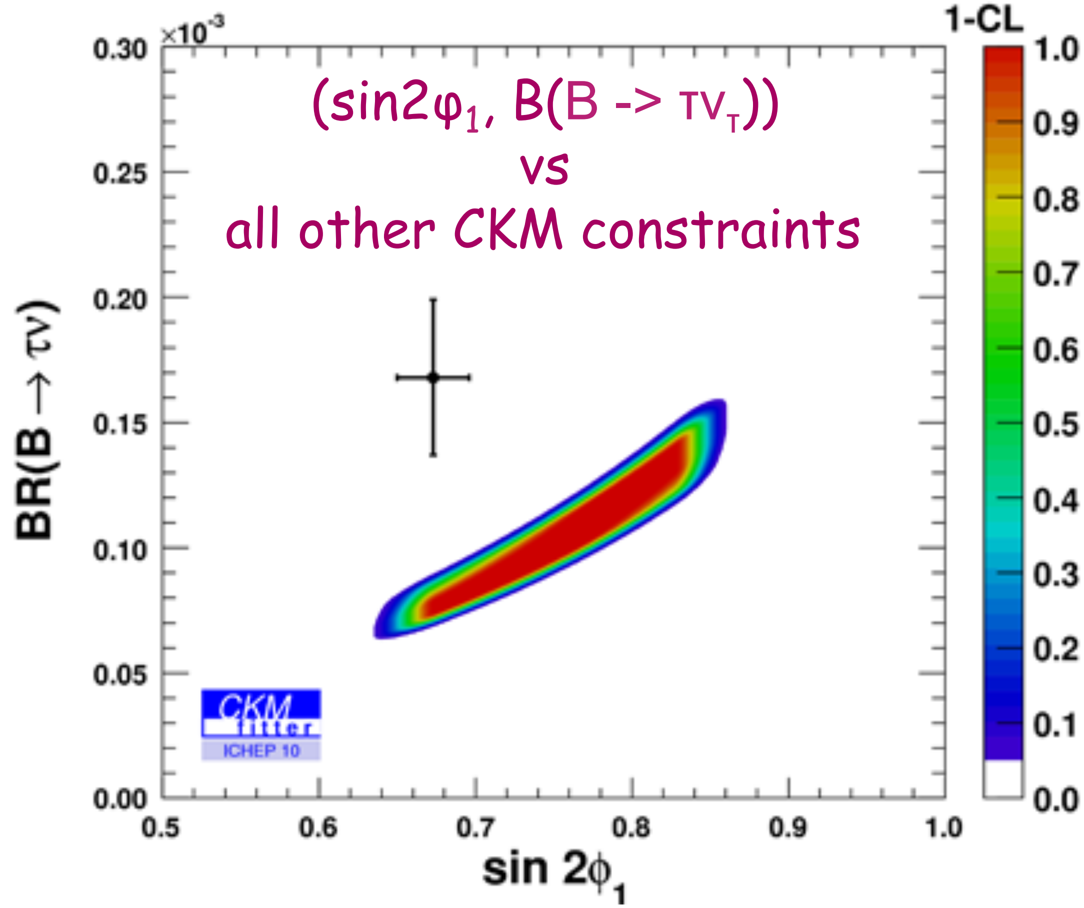
Previous results:
2.8σ "tension"



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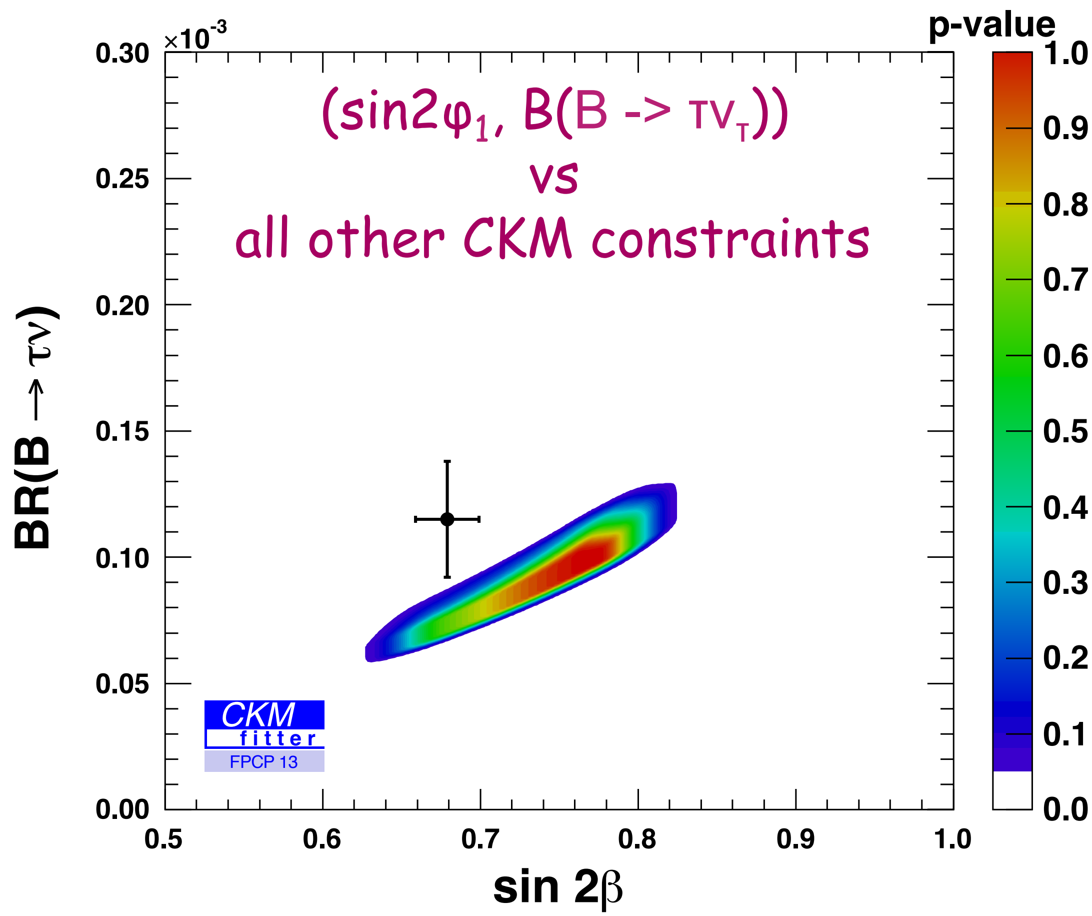
2014:
Not so tense

Precision will improve
in Belle II era



Future: leptonic τ/μ ratio

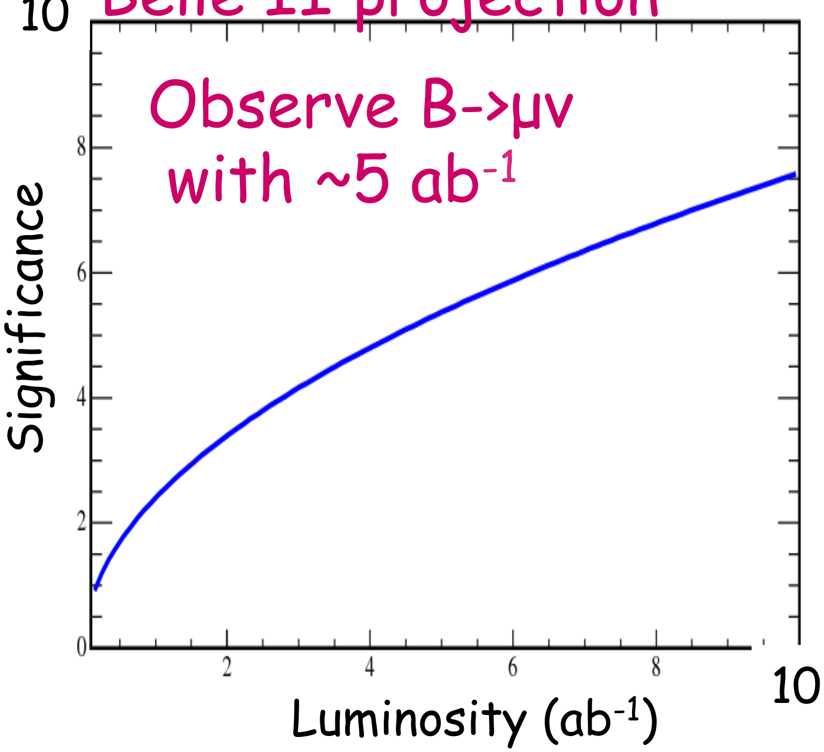
Belle II

SM:
B(B->τν) = 1.6x10^{-4}
B(B-> μν) = 7.1x10^{-7}
B(B-> eν) = 1.7x10^{-11}

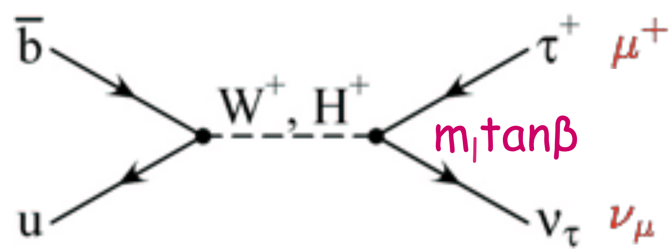
$$\mathcal{R}(\tau\bar{\nu}) \equiv \frac{\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to \ell^-\bar{\nu}_\ell)}$$

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

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

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

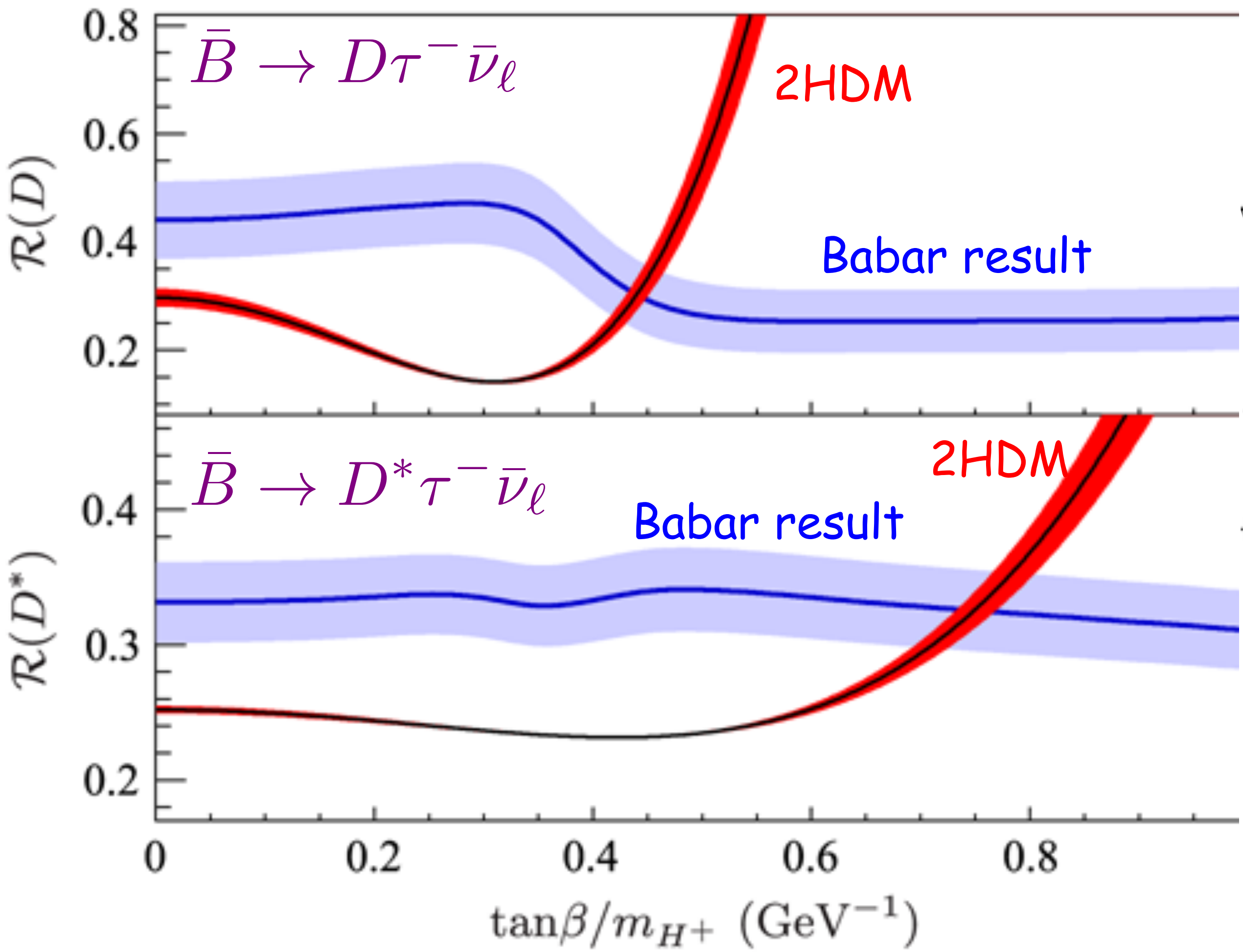
Not good agreement w SM

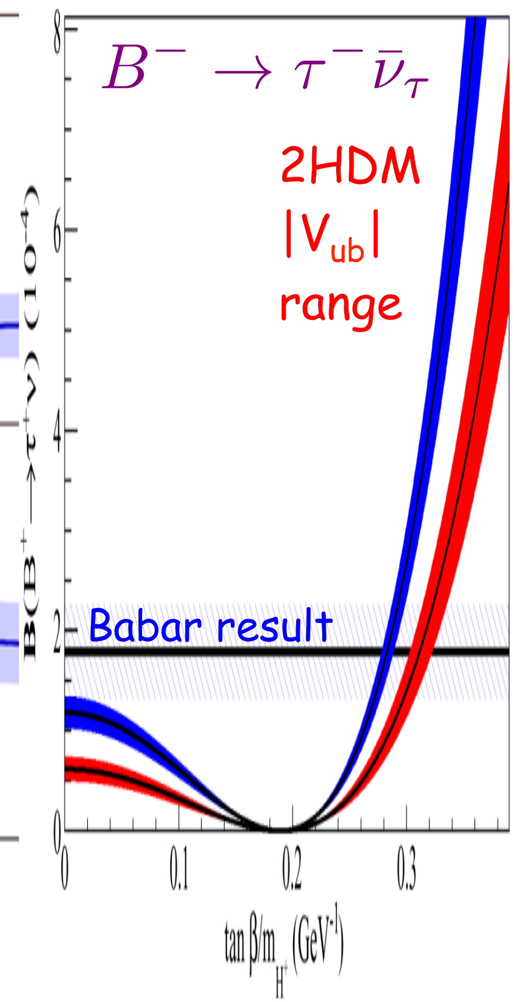
Test 2HDM type II

Babar

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

R vs tan β/m_H





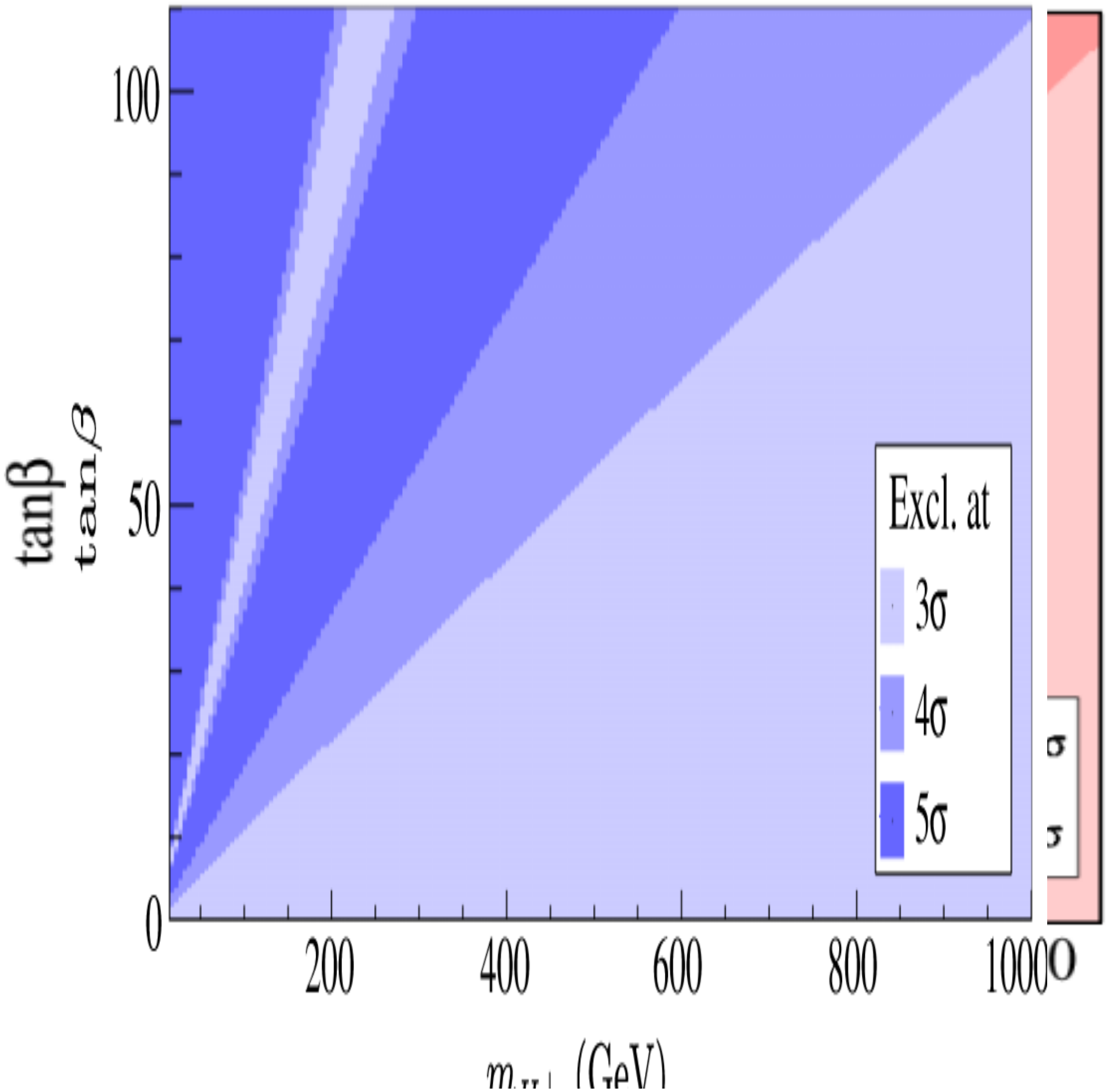
Test 2HDM type II

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
    - φ_1 (β), φ_2(α), φ_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 > φ_2, > 66.8°
- B->$\rho^0\rho^0$, isospin analysis — arXiv:1212.4015
  - φ_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 φ_3)

- First A_{CP}≠0 in a new penguin mode sensitive to φ_1

  $$B^0 \to \omega K_S^0$$ arXiv:1311.6666

- A_{CP} null searches

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

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

K. Kinoshita

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}

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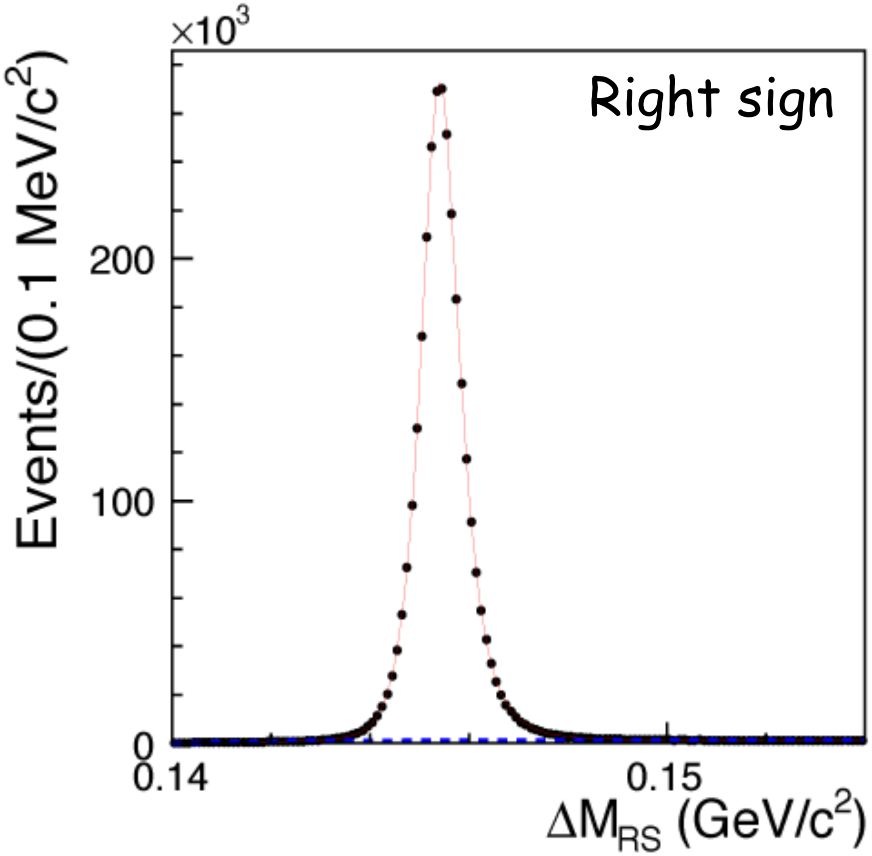

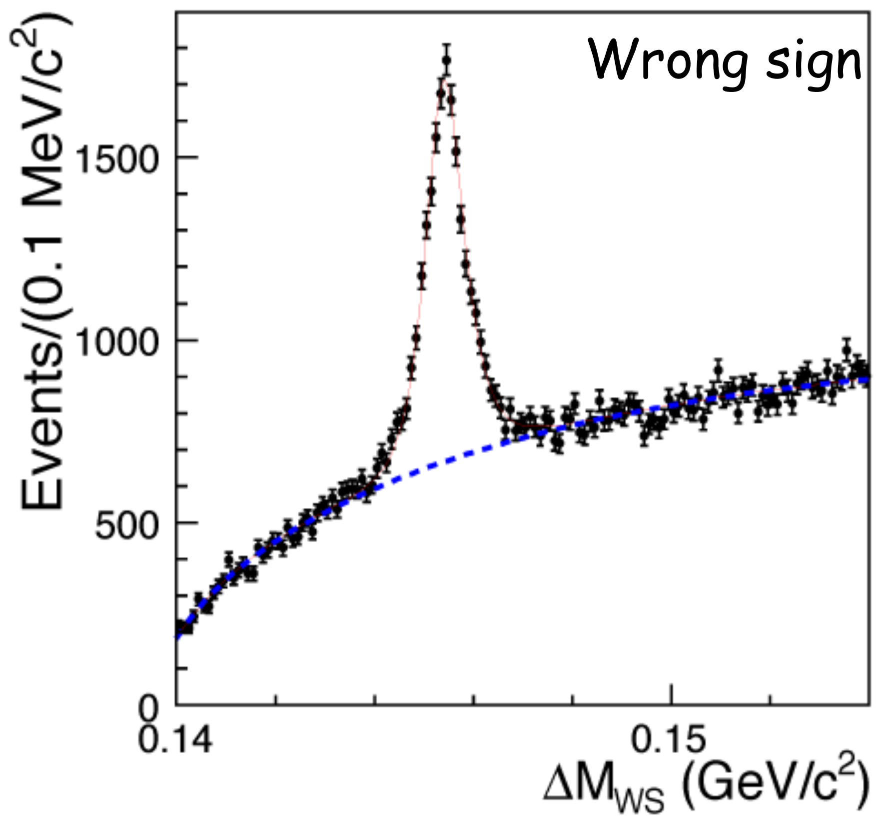

D^0 mixing

Belle arXiv:1401.3402

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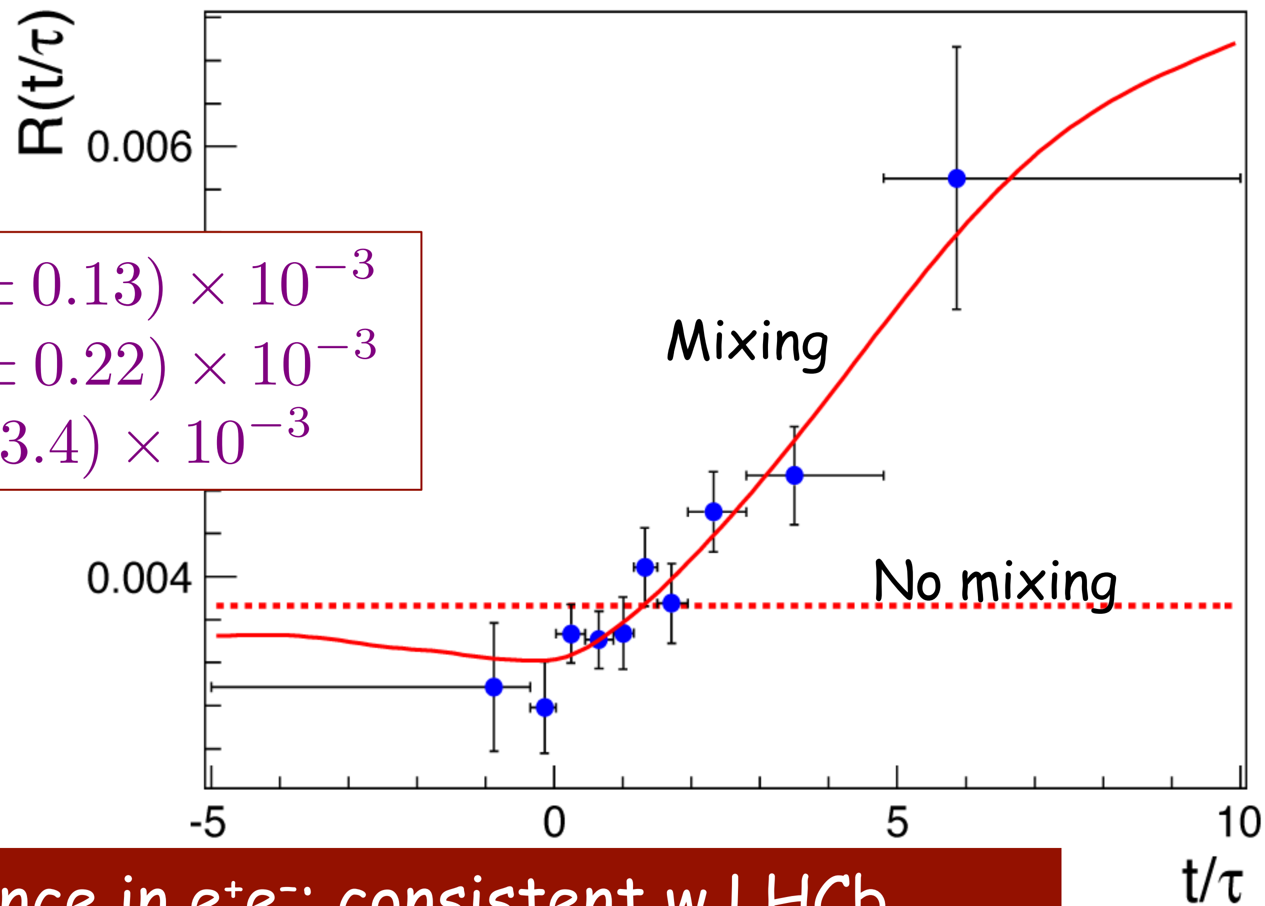
$$R(\tilde{t}/\tau) \equiv \frac{\Gamma_{\rm WS}(\tilde{t}/\tau)}{\Gamma_{\rm RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

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



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)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	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 ± 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 ± 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 ± 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)		
				$e^+e^-\to(\pi^0\pi^0J/\psi)$	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 ± 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!

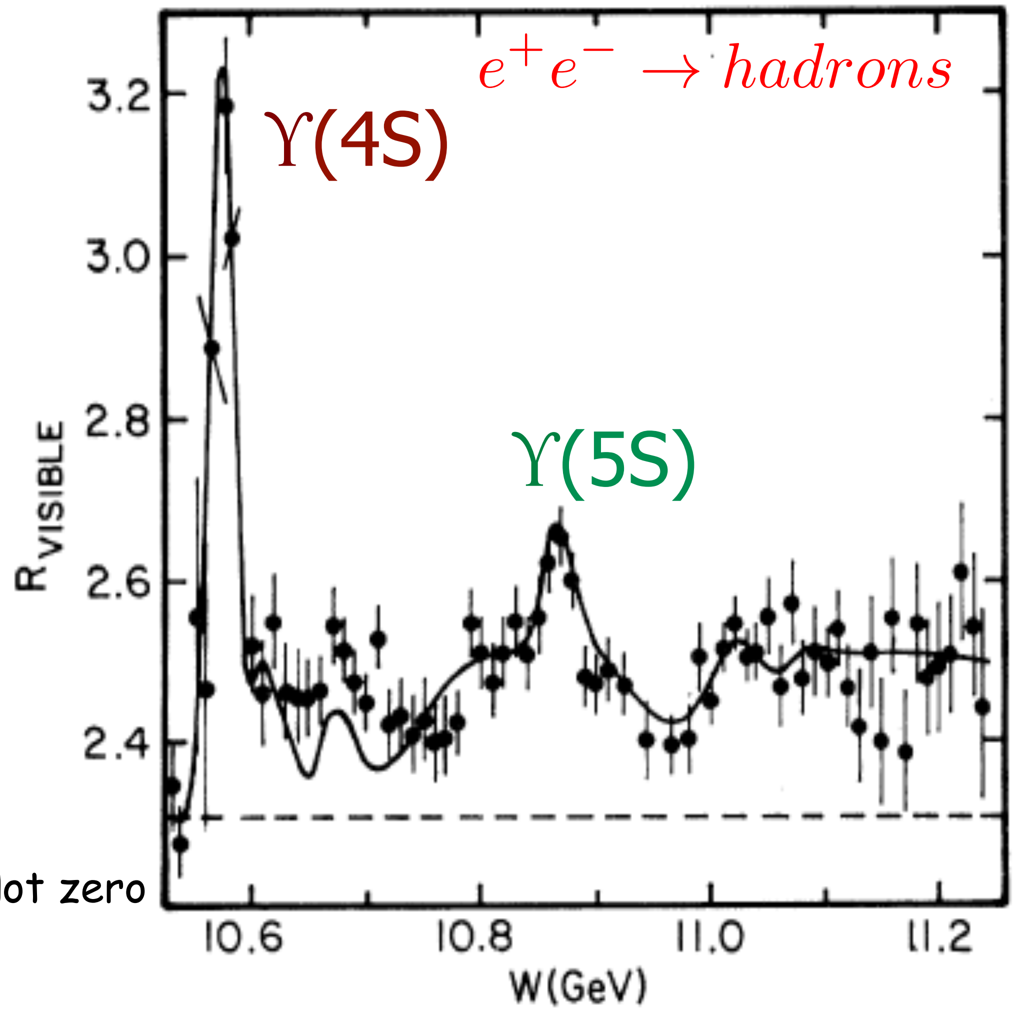
QCD

- 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 @ Υ(5S) (10860) [PRL 108, 122001 (2012)]

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

in events

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

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

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

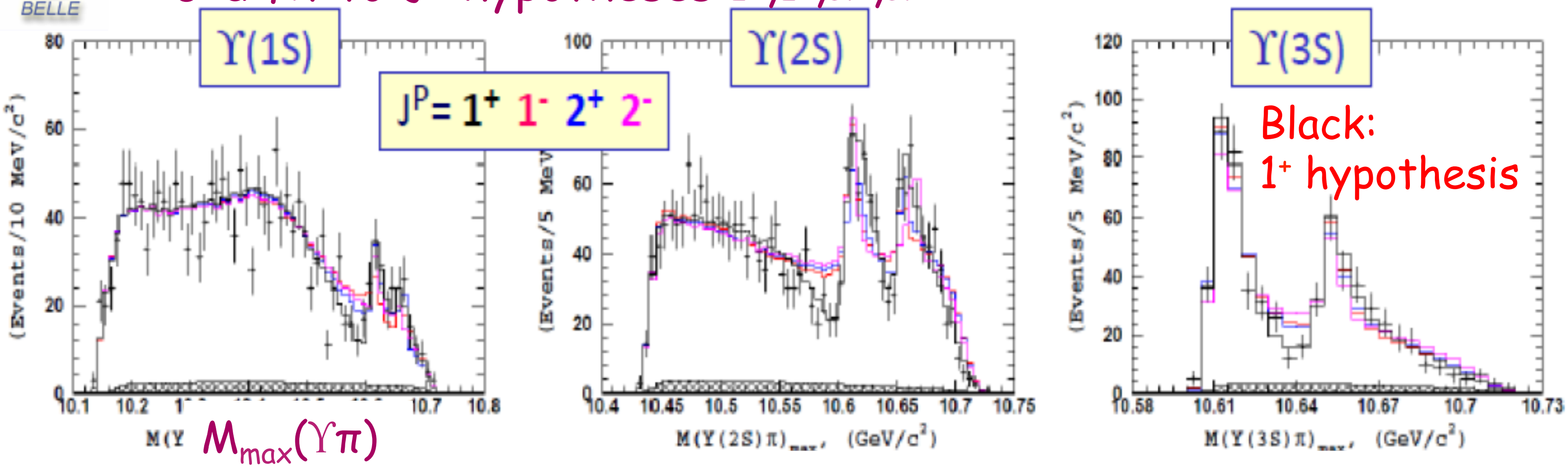
  - [PRD 88, 052016 (2013)] Observation of $Z_b^0(10610)$

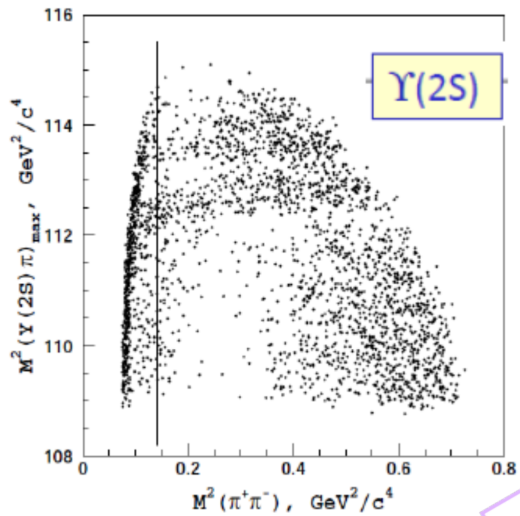
- Soon:
  - Scan of Υππ cross section, analysis of resonance/continuum b
    cf: PRD 82,091106(R) (2010)

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 $1^+, 1^-, 2^+, 2^-$





$Z_b(10610)$ \ $Z_b(10650)$	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)

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

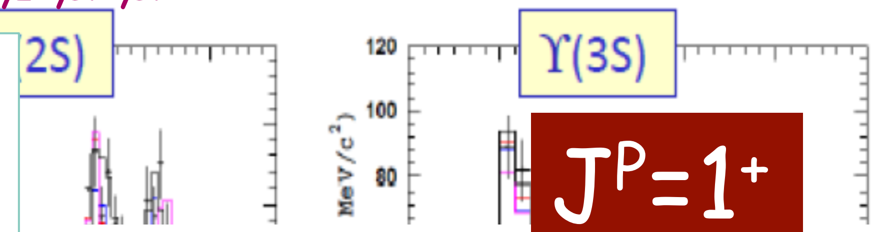
Belle

BELLE

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

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

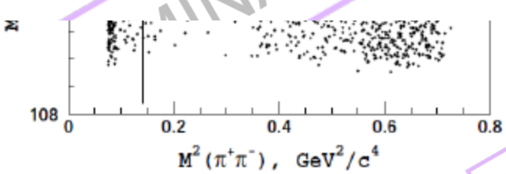
$$ln\mathcal{L}(1^+) - ln\mathcal{L}(J^P)$$



$J^P=1^+$

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

$Z_b(10610)$ \ $Z_b(10650)$	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)



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

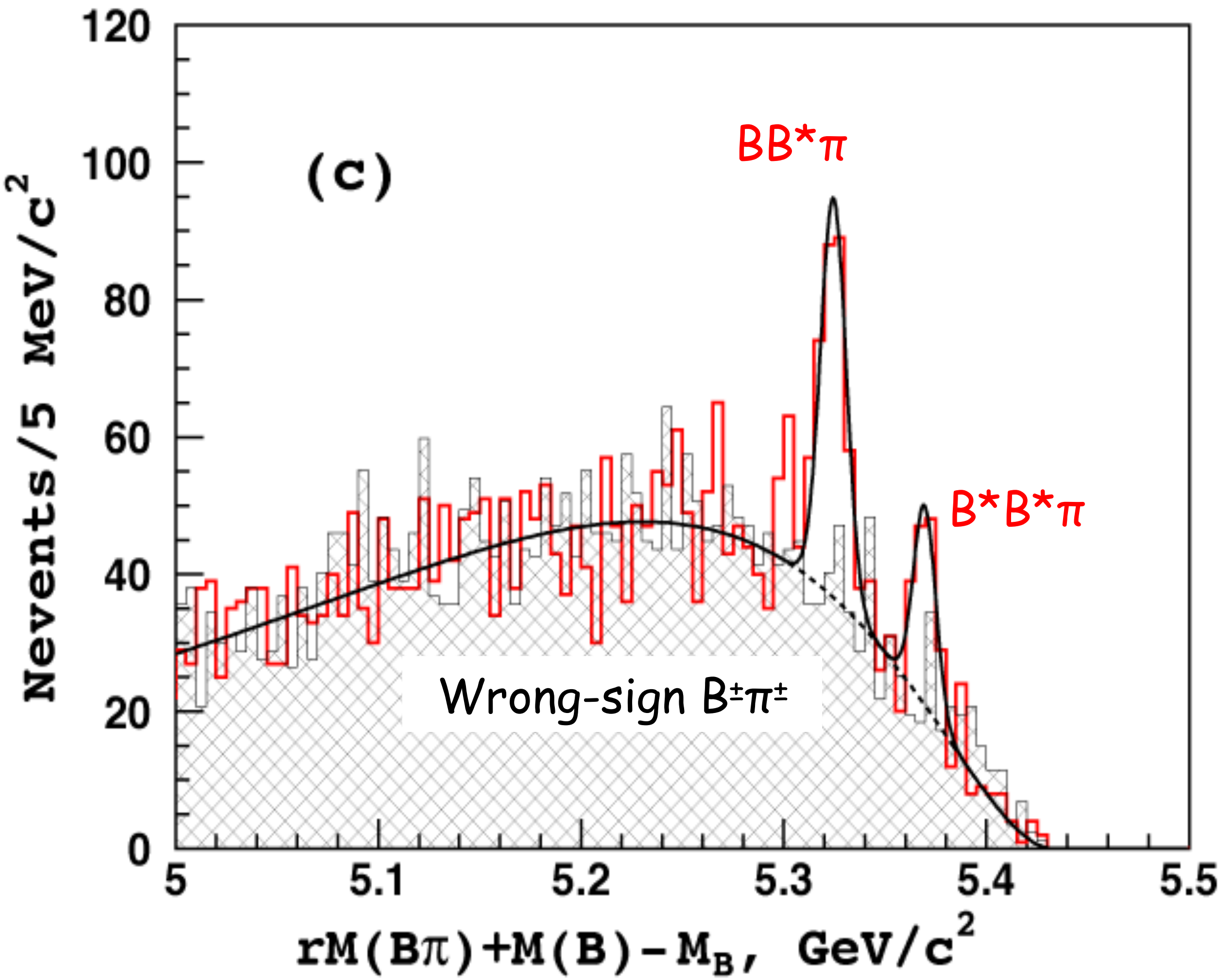
from A. Bondar, Hadrons from Quarks and Gluons 1/16/2014

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

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

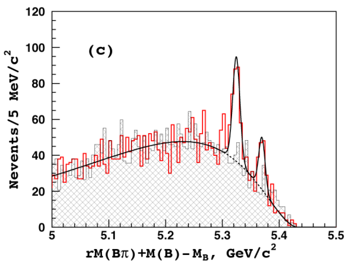


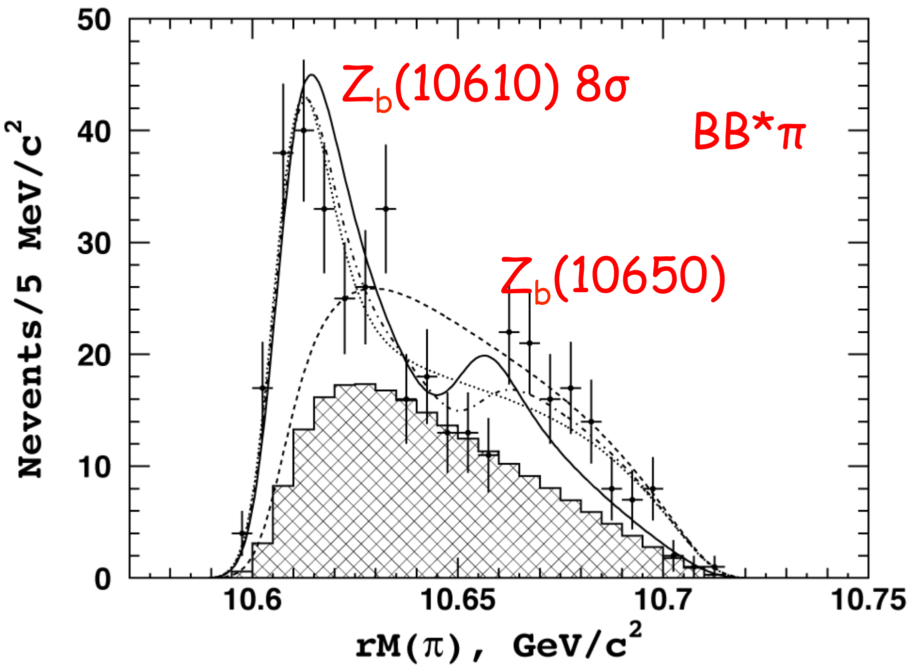
$Z_b^{\pm} \to [B^* \bar{B}^{(*)}, \bar{B}^* B^{(*)}]^{\pm}$

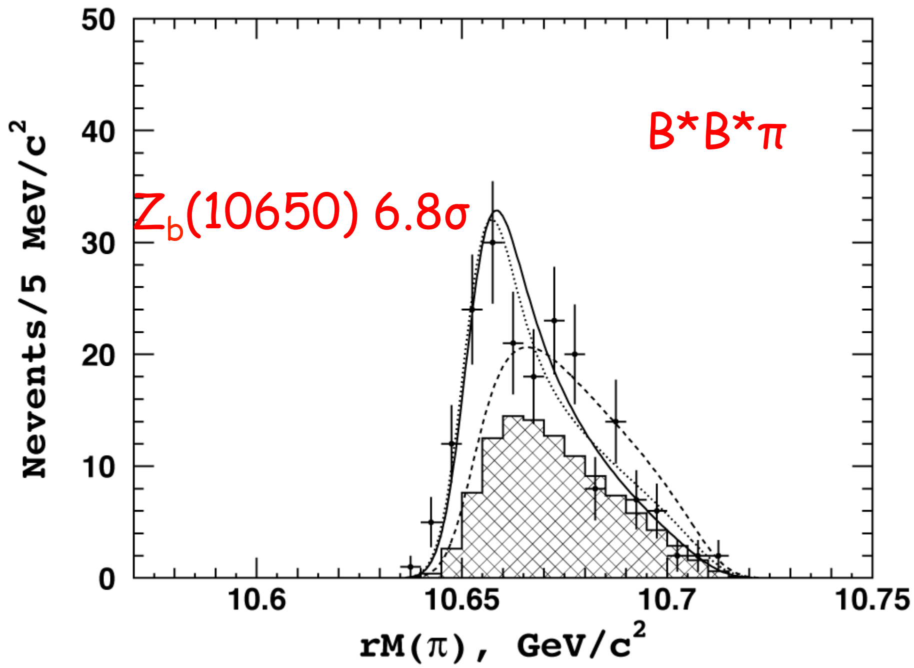
arXiv:1209.6450

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 ± 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

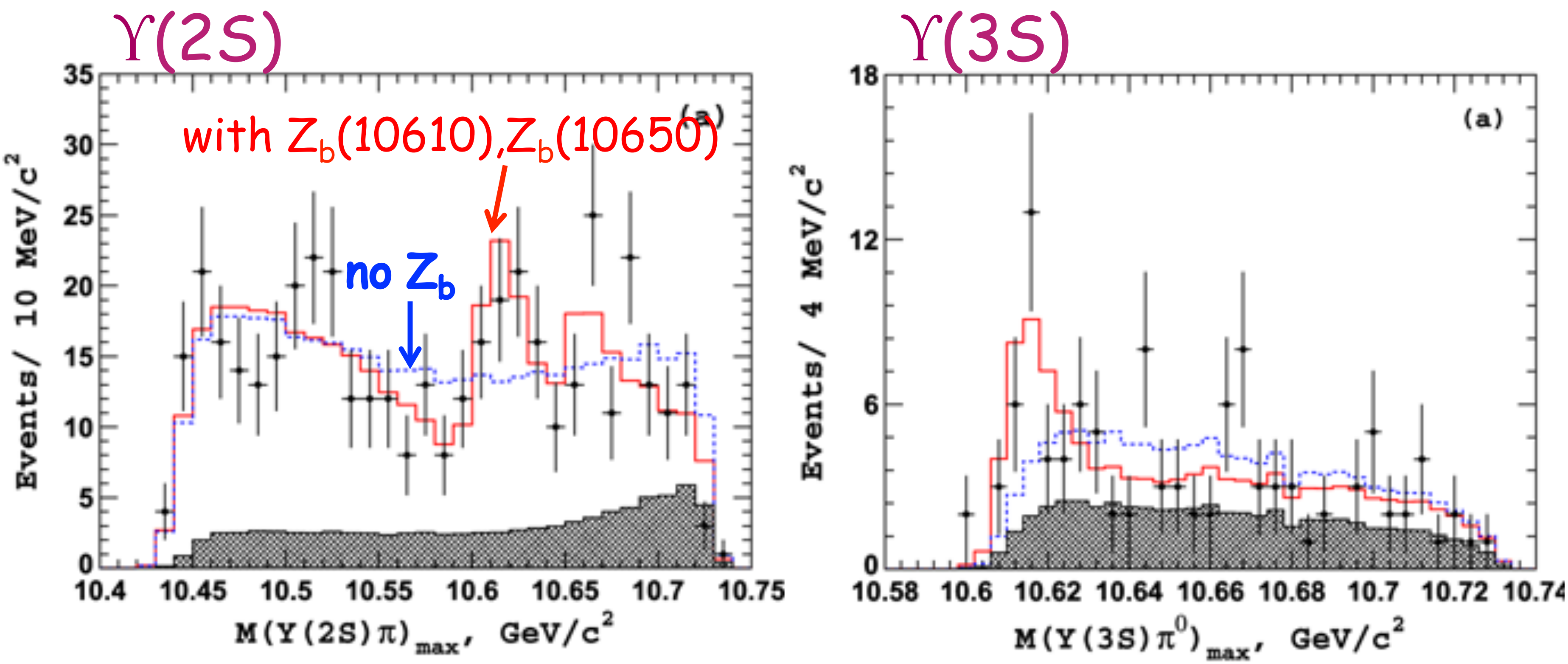
$B^*B^{(*)}$ Dominate

$Z_b^0(10610)$

PRD 88, 052016 (2013)

Belle

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

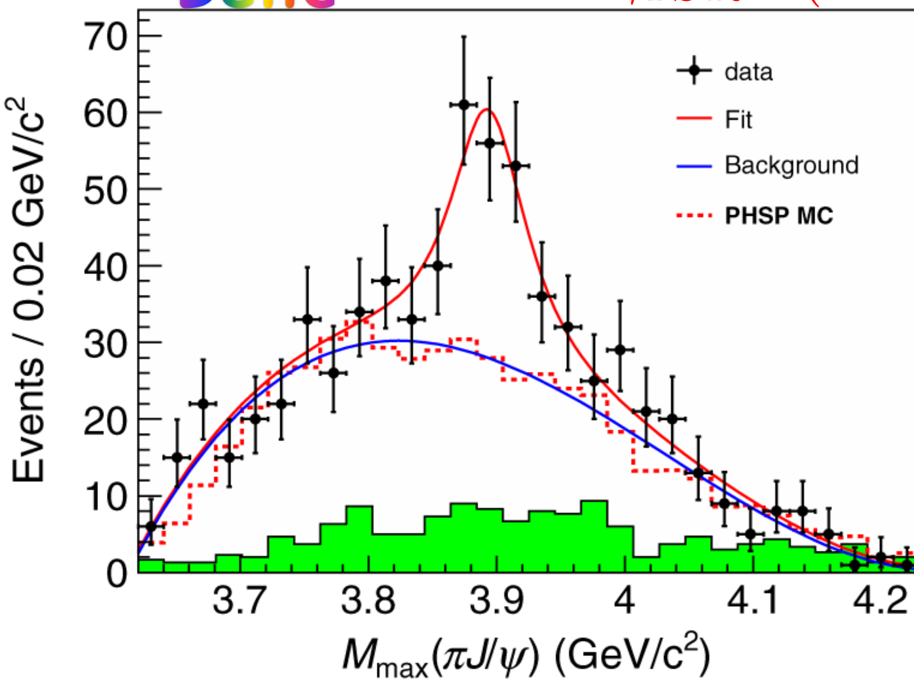


$Z_b^0(10610)$ observed with 6.5σ significance

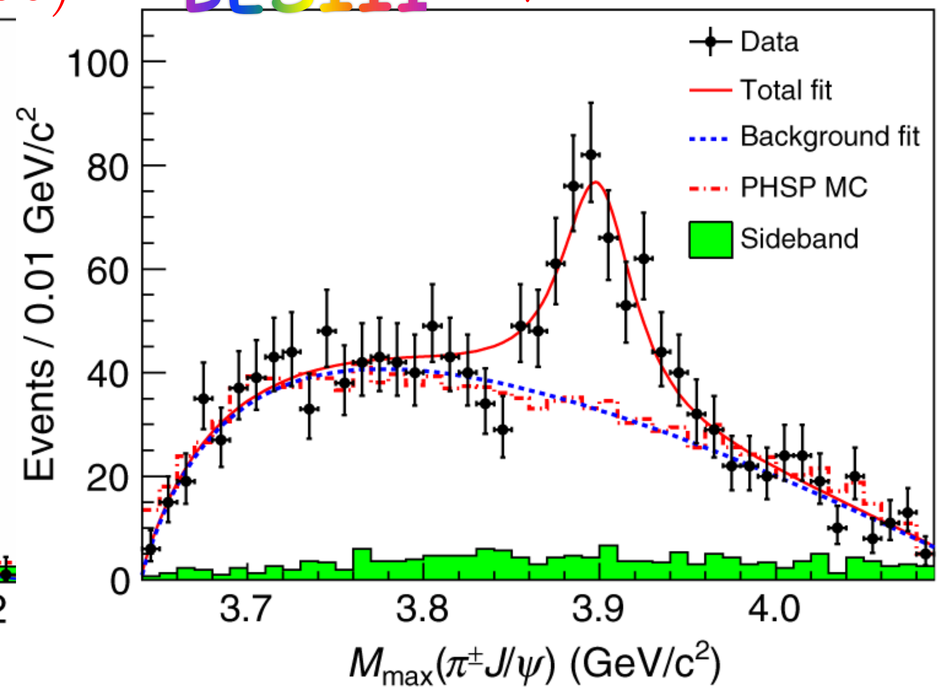
$Z_c^{\pm}(3900)$

- 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)

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

$$\Gamma = (63 \pm 24 \pm 26)\mathrm{MeV}$$

PRL 110, 252001 (2013)

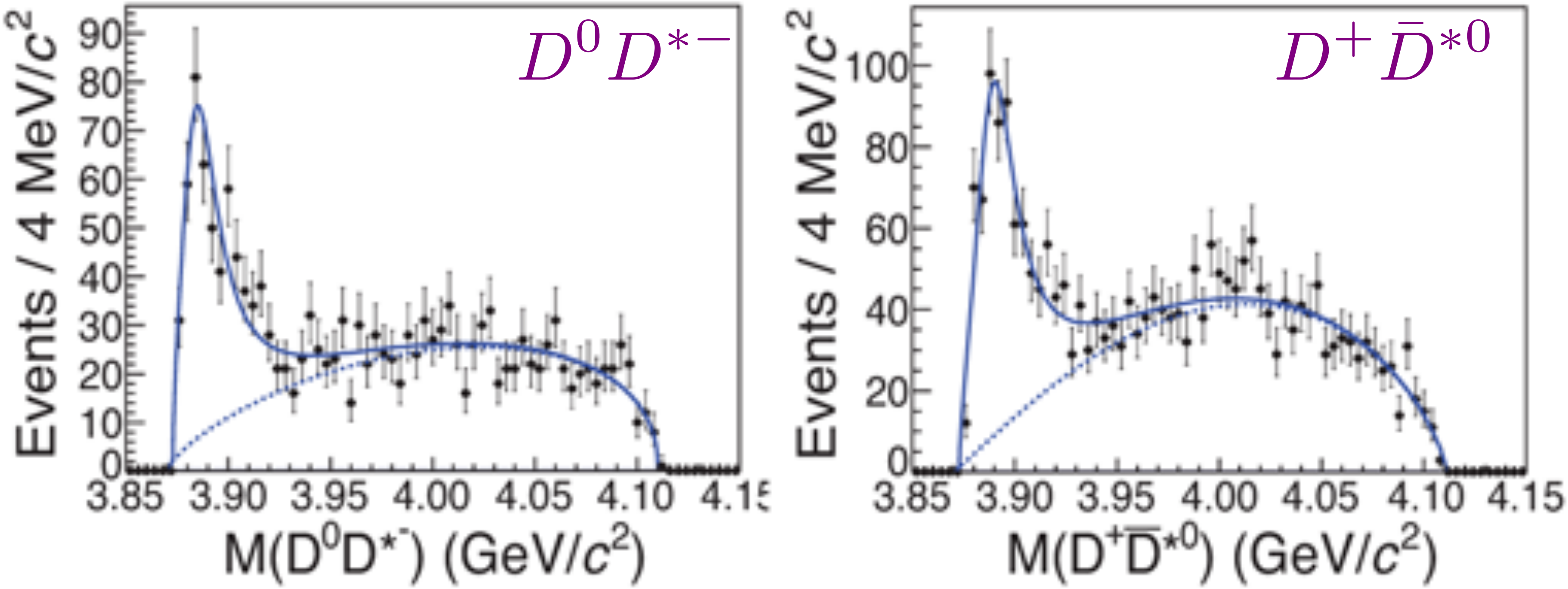
$$(3899.0 \pm 3.6 \pm 4.9)\mathrm{MeV}/c^2$$

$$(46 \pm 10 \pm 20)\mathrm{MeV}$$

"$Z_c(3885)$"

BESIII arXiv:1310.1163

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



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

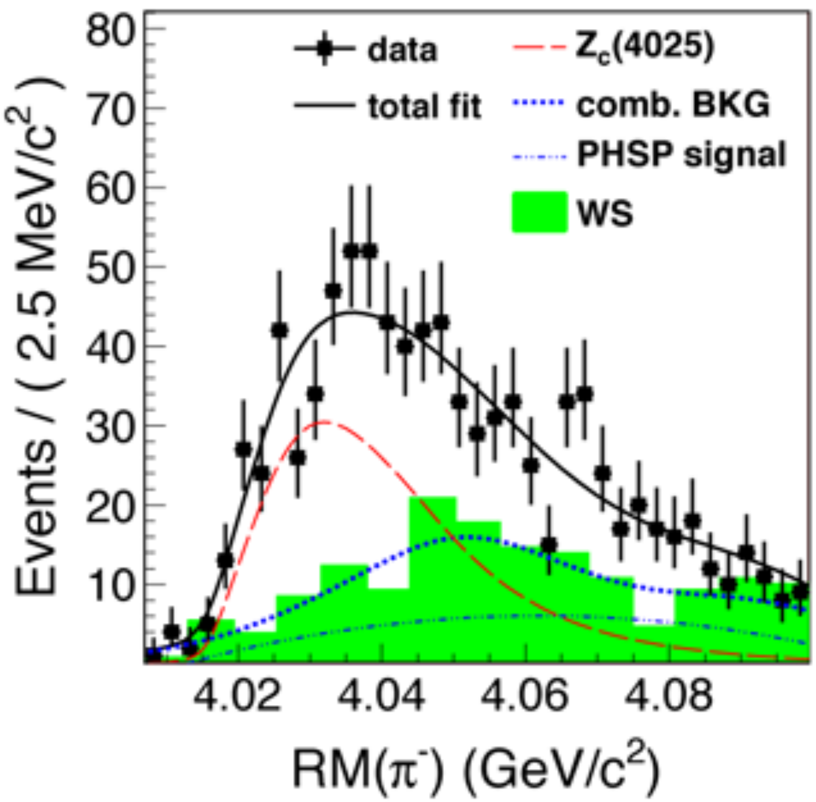
$$\Gamma = (24.8 \pm 3.3 \pm 11.0)\mathrm{MeV}$$

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

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



Reconstruct D^+, π^0

$M =$

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

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

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

$$= 0.65 \pm 0.09 \pm 0.06$$

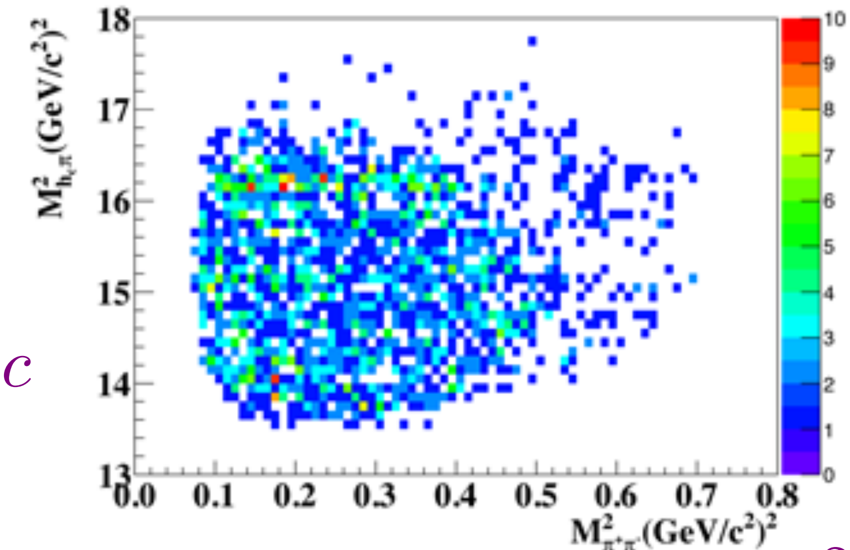
"$Z_c(4020)$"

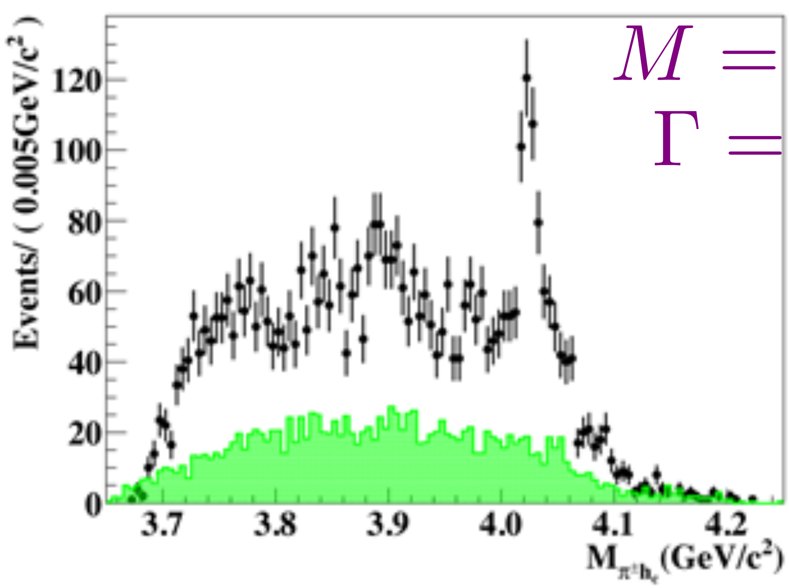
BESIII arXiv:1309.1896

- 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 π^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...

K. Kinoshita

to find the NEW… improve precision on the OLD

Still, not easy!

there IS a leopard