Recent Belle results

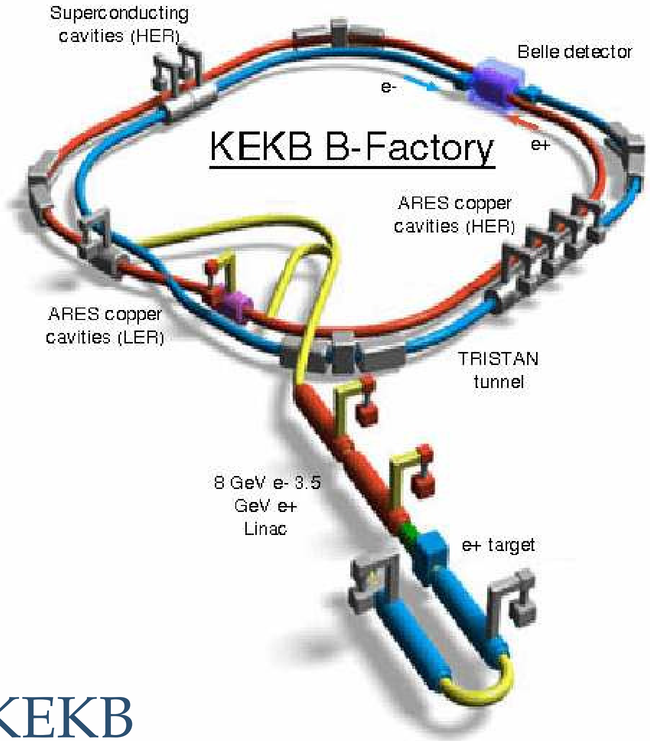
Dmitri Liventsev (KEK)

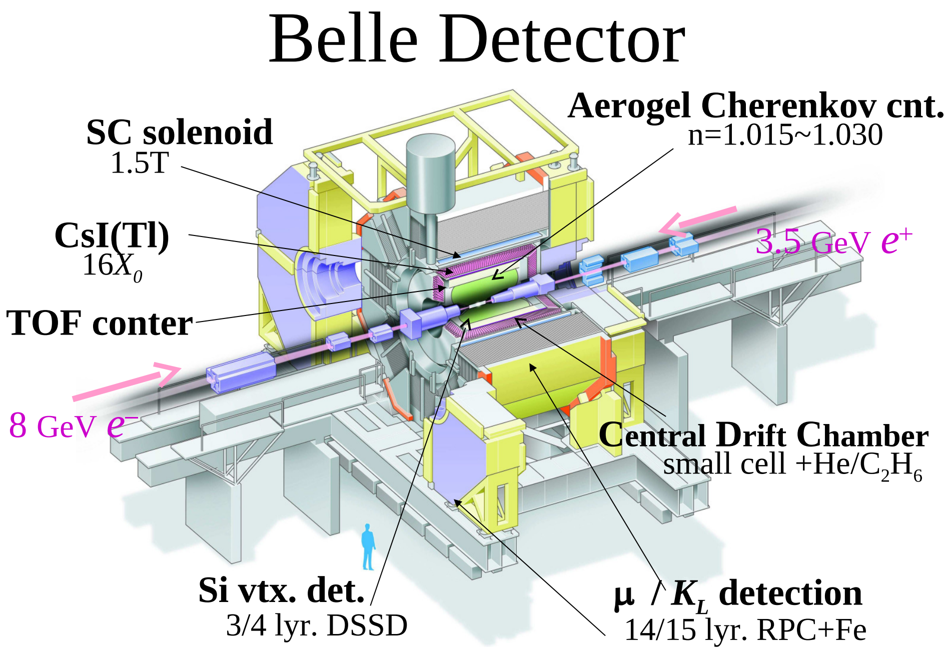
on behalf of the Belle collaboration

Physics of Heavy Quarks and Hadrons 2013,
Dubna, Russia, July 22, 2013

Belle experiment

$$c\bar{c}, q\bar{q}, \ell\ell \leftarrow e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$





- KEKB
  - Asymmetric-energy e^+e^- collider: $3.5\text{GeV} \times 8\text{GeV}$
  - Record luminosity $L = 2.1 \times 10^{34} cm^{-2} s^{-1}$
- Belle
  - Designed for CP violation study in B decays
  - Suitable for many other studies: quarkonium, charm, τ etc.

The *Belle* Collaboration

BINP
Bonn U.
Charles U.
Chiba U.
U. of Cincinnati
Fu-Jen C.U.
Giessen U.
Gyeongsang Nat'l U.
Goethingen
Hanyang U.
U. of Hawaii
Hiroshima Tech.
IHEP, Beijing
IHEP, Moscow
IHEP, Vienna

Indiana U.
ITEP
Kanagawa U.
KEK
Karlsruhe U.
KISTI
Korea U.
Krakow Inst. of Nucl. Phys.
Kyungpook Nat'l U.
EPF Lausanne
Jozef Stefan Inst. / U. of Ljubljana / U. of Maribor
Luther
U. of Melbourne
MPI

Nagoya U.
Nara Women's U.
National Central U.
National Taiwan U.
National United U.
Nihon Dental College
Niigata U.
Osaka RCNP
Osaka City U.
Panjab U.
Peking U.
PNNL
Riken
Saga U.
USTC
Seoul National U.

Shinshu U.
Sungkyunkwan U.
U. of Sydney
Tata Institute
Toho U.
Tohoku U.
Tohuku Gakuin U.
U. of Tokyo
Tokyo Inst. of Tech.
Tokyo Metropolitan U.
Tokyo U. of Agri. and Tech.
Toyama Nat'l College
Torino
Wayne S.U.
VPI
Yonsei U.

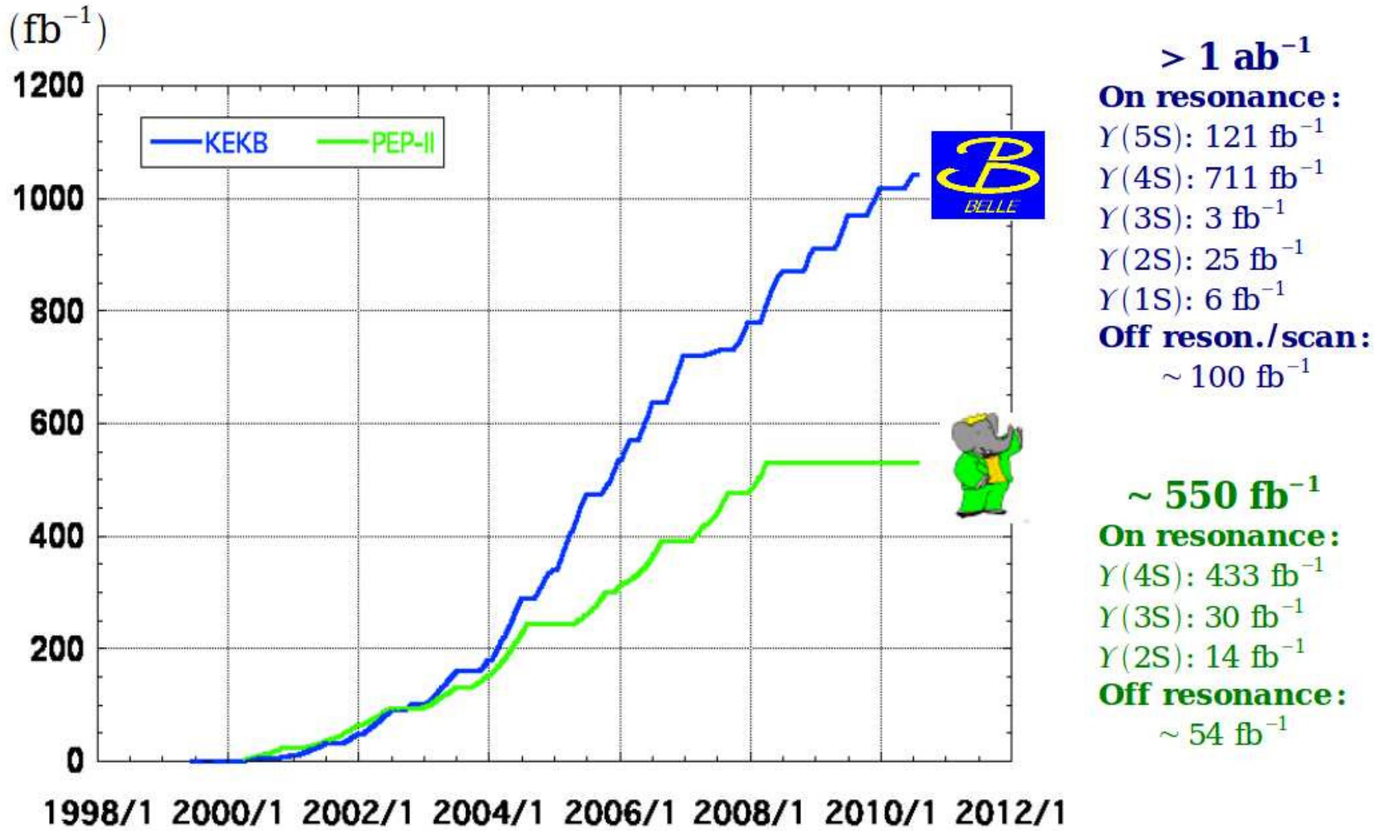
15 countries, 64 institutes, ~400 collaborators

(as of Aug. 2011)

1

Integrated luminosity

- Data was taken in 1999 – 2010
- World largest accumulated luminosity $> 1ab^{-1}$
- $711fb^{-1}$ on $\Upsilon(4S)$ resonance correspond to 772×10^6 $B\bar{B}$ pairs

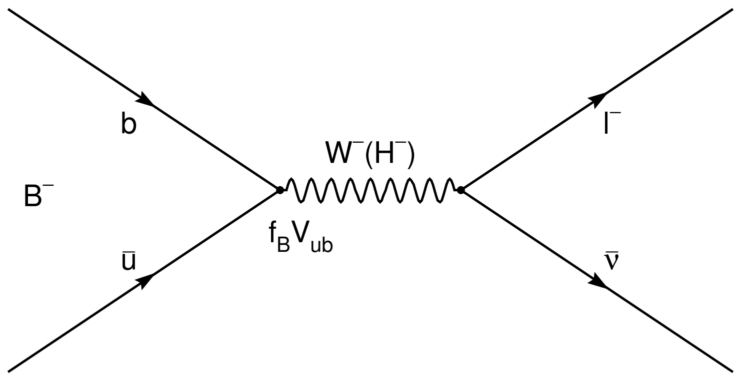


- $B \to \tau\nu_\tau$ and related results.
- Bottomonium study.
- CKM measurements.

Standard Model and New Physics

- The Standard Model describes known processes very well;
- However, there are indications, that the Standard Model is not complete:
  - neutrino oscillations, baryon asymmetry, dark matter;
  - too many parameters, hierarchy problem;
- There should be something beyond the Standard Model — New Physics.
- New Physics effects are expected to be small, therefore the best way to look is to study rare decays.

New Physics and $B \to \ell\nu$



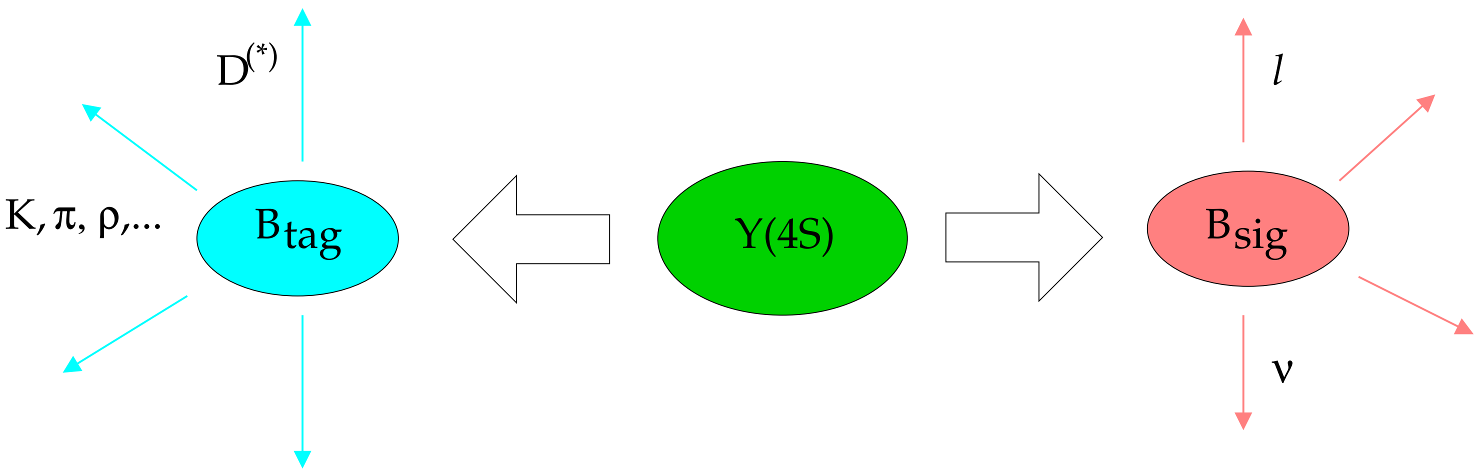
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}(1 - \frac{m_\ell^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Leptonic B decays are clean since there are no hadronic uncertainties.
- Leptonic decays are helicity-suppressed: $\mathcal{B}(B^- \to e^- \bar{\nu}_e) \ll \mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) \ll \mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$.
- Good place to look for New Physics, *e.g.* charged Higgs exchange: $\mathcal{B}_{NP}(B^- \to \ell^- \bar{\nu}_\ell) = \mathcal{B}_{SM}(B^- \to \ell^- \bar{\nu}_\ell) \times r_H$, where r_H depends on the Higgs model, but not on the mode. In Type II 2HDM (W. S. Hou, PRD 48, 2342 (1993)) $r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2 \beta)^2$.

Full reconstruction tagging

- At B factory events are clearly separated;
- $\Upsilon(4S)$ decays into two B mesons;
- All particles (but neutrinos) are detected;
- Initial energy is known.

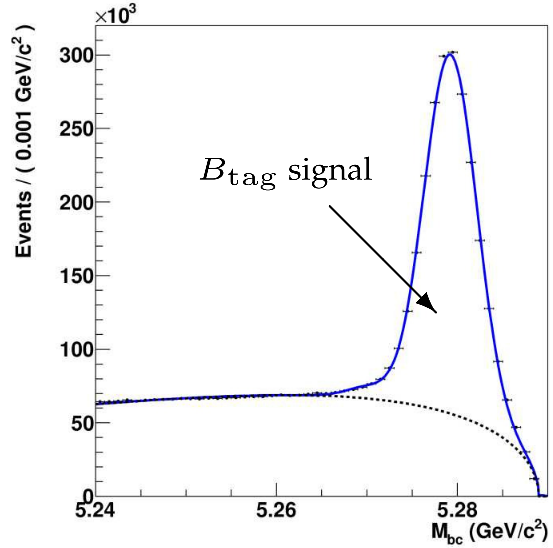
We can reconstruct one B meson in hadronic or semileptonic mode (B_{tag}), reconstruct some particles from the other B meson (B_{sig}), and restrict unreconstructed part from the information about the whole event.



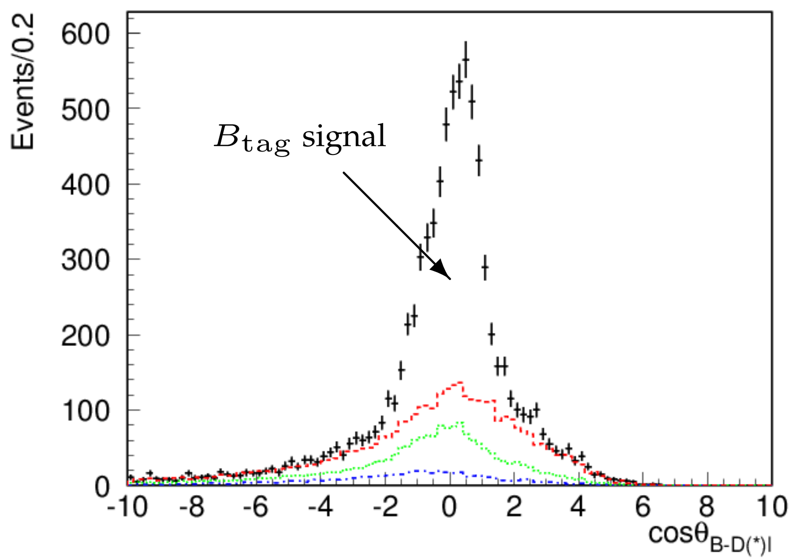
Full reconstruction types

- Hadronic tagging
  - Exclusive tagging:
    - $B_{\rm tag}$ is reconstructed as $D^{(*)}X$ combination;
    - $B_{\rm sig}$ is reconstructed;
  - Inclusive tagging:
    - $B_{\rm sig}$ is reconstructed;
    - The rest of the event is combined into $B_{\rm tag}$ and checked if it is consistent with B meson hypothesis;
  - Efficiency $\sim 0.2\%$;
- Semileptonic tagging
  - B meson is reconstructed as $D^{(*)}\ell$;
  - Efficiency $\sim 0.7\%$, but more background;

$$\Delta E = E_B - E_{beam}, M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$



$$\cos\theta_{B,D\ell} = \frac{2E_{beam}E_{D\ell} - m_B^2 - M_{D\ell}^2}{2P_B P_{D\ell}}$$



Existing experimental results

- Belle

Hadronic tagging, 449M $\mathcal{B} = [1.79^{+0.56}_{-0.49}{}^{+0.46}_{-0.51}] \times 10^{-4}$

Semileptonic tagging, 657M $\mathcal{B} = [1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}] \times 10^{-4}$

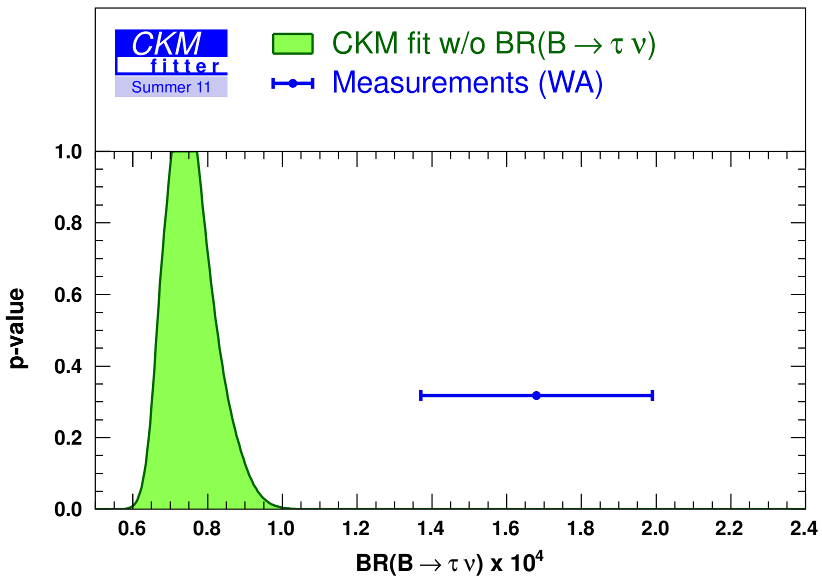
- BaBar

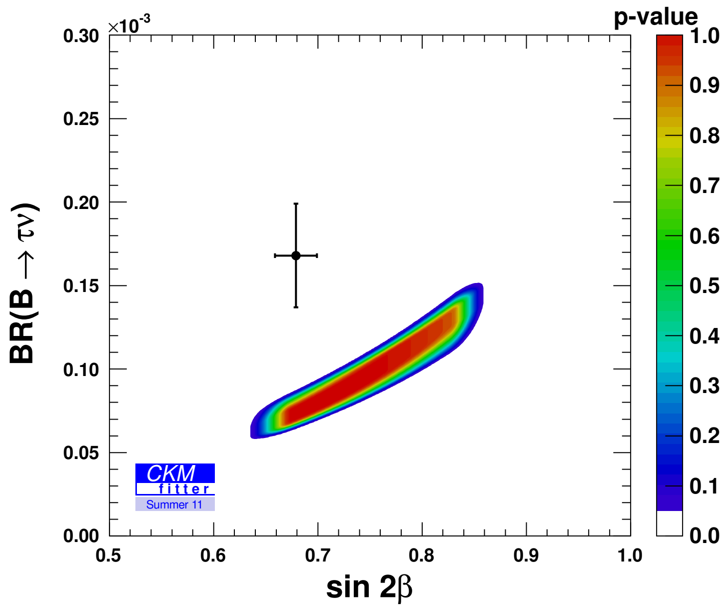
Hadronic tagging, 468M $\mathcal{B} = [1.80^{+0.57}_{-0.54} \pm 0.24] \times 10^{-4}$

Semileptonic tagging, 459M $\mathcal{B} = [1.7 \pm 0.8 \pm 0.2] \times 10^{-4}$

2.8σ deviation

“Tension” in CKM global fit?





Improvement in hadronic tagging

Analysis of $B \to \tau \nu_\tau$ with hadronic tag was already made by Belle at smaller data sample (PRL 97, 251802 (2006)).
What is new in this analysis?

- All data reprocessed; better efficiency of low p_T tracks and neutrals reconstruction;
- Increased data sample 449M $\Rightarrow$ 772M (factor of 1.7);
- Improved hadronic tagging efficiency due to new algorithm (factor of 2.2);

NIM A654, 432 (2011)

- Improved signal efficiency due to less restrictive requirements (factor of 1.8);
- 2D fit (residual calorimeter energy E_{ECL} vs missing mass M_{miss}) instead of 1D fit (residual energy only);
- Background rejection with reconstructed K_L.

Analysis procedure

772M $B\bar{B}$

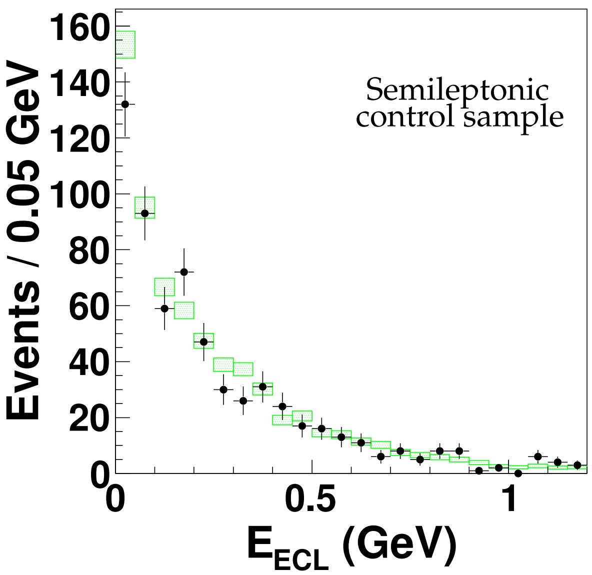
PRL 110, 131801 (2013)

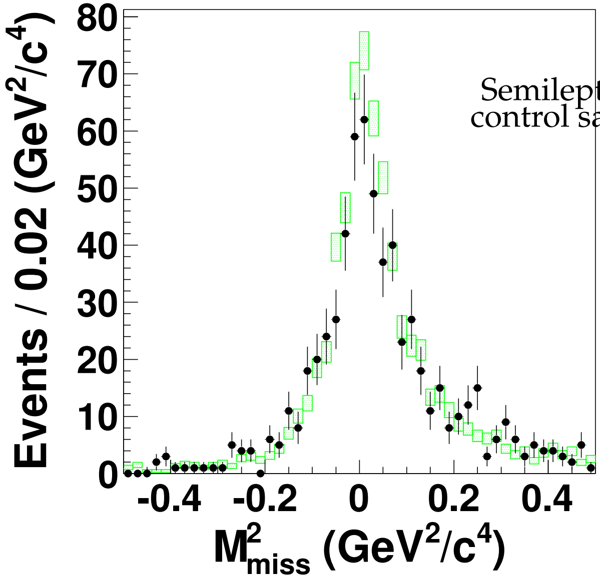
- τ^- is identified in the $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, and $\pi^-\pi^0\nu_\tau$ decay channels;
- No tracks, π^0, K_L left in the event after $B_{\rm tag}$, $B_{\rm sig}$ reconstruction;
  - K_L efficiency checked in $D^0 \to \phi K_S$, $\phi \to K_L K_S$ vs $\phi \to K^+K^-$;
- Backgrounds were simulated by MC;
- E_{ECL}, M^2_{miss} distributions were validated in number of samples: sidebands, B^0 sample, $B^-_{\rm sig} \to D^{*0}\ell^-\bar{\nu}_\ell$.

E_{ECL} and M^2_{miss} for $B^-_{\rm sig} \to D^{*0}\ell^-\bar{\nu}_\ell$

Dots with error bars — data

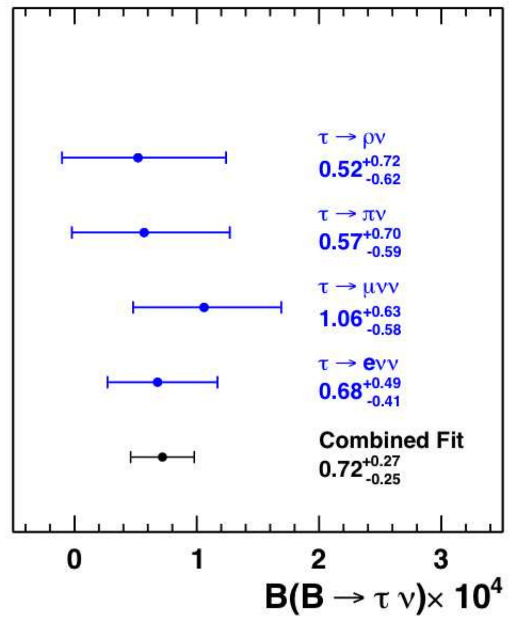
Rectangles — normalized MC

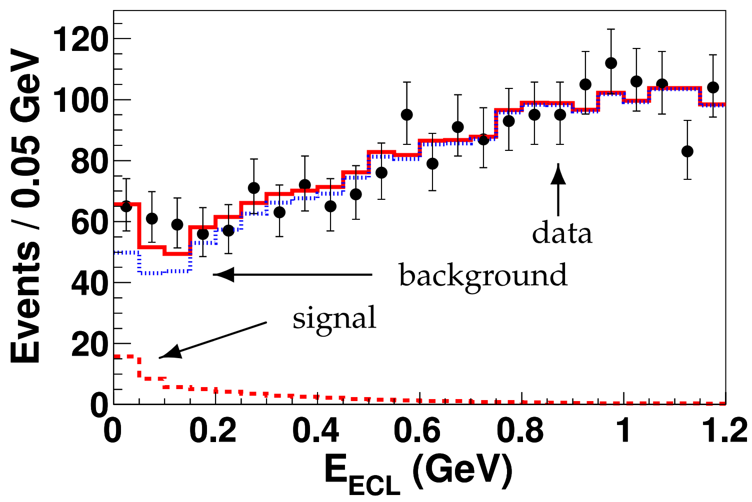


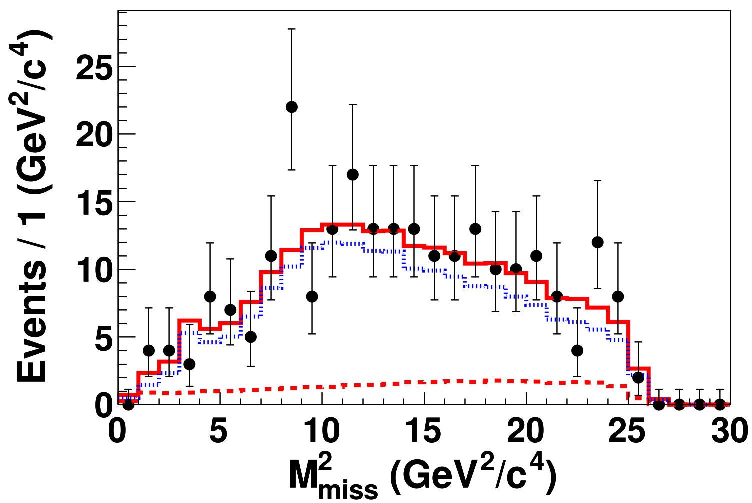


New $B \to \tau\nu_\tau$ study results

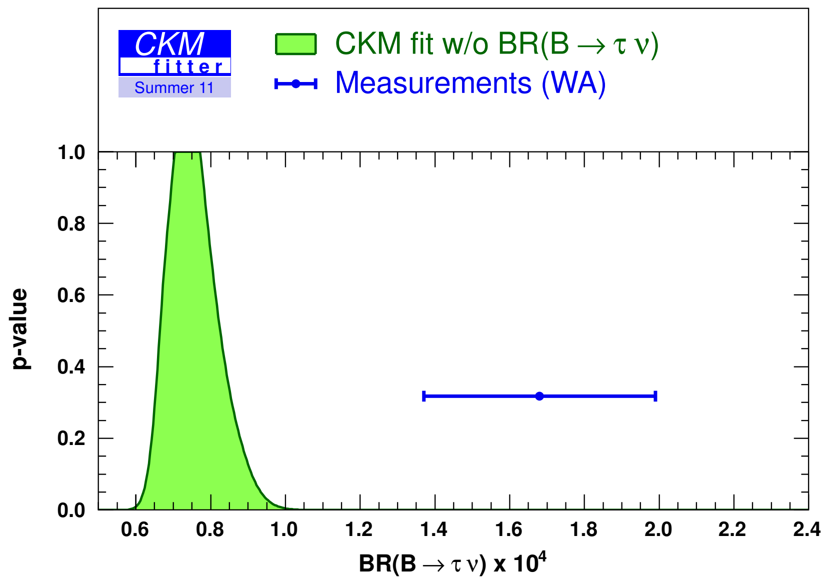
- Simultaneous fit to different τ decay modes.
- Signal yield $N = 62^{+23}_{-22} \pm 6$
- $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$
- Significance = 3.0σ including systematic error
- Results for individual decay modes are consistent.
- Result at the data sample used earlier is consistent with the previous result.

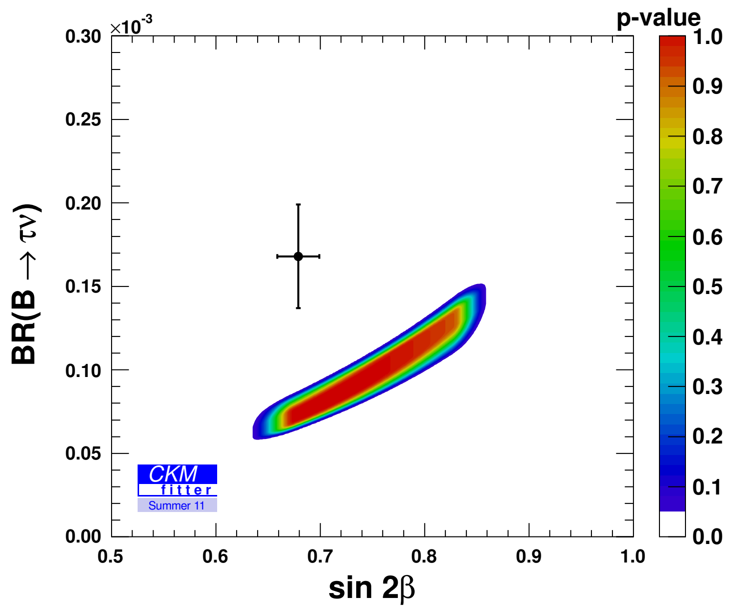






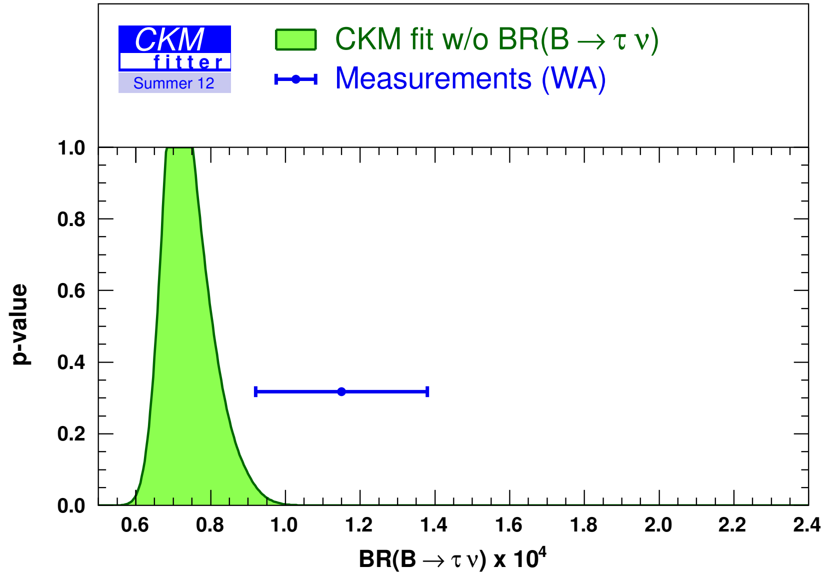
Latest Belle result	$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$
Latest Belle average	$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.96 \pm 0.26] \times 10^{-4}$
Measured world average	$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [1.15 \pm 0.23] \times 10^{-4}$
CKM global fit	$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.73^{+0.12}_{-0.07}] \times 10^{-4}$

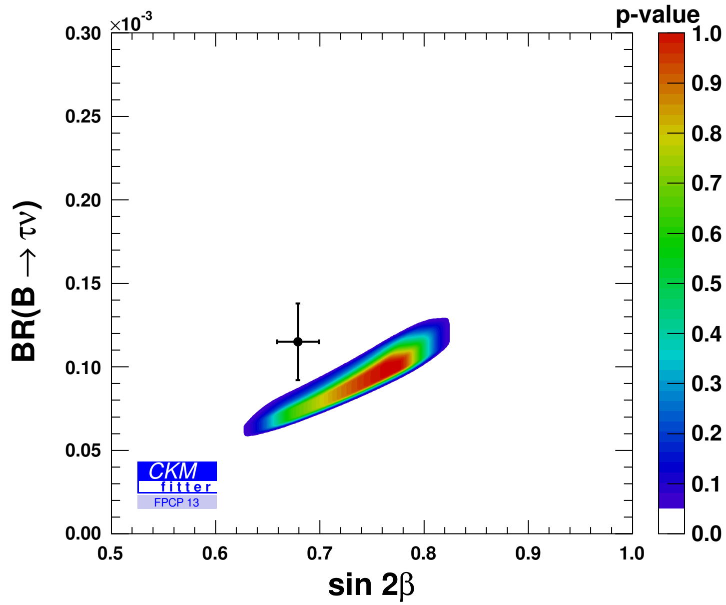




Comparison of the $B \to \tau\nu_\tau$ results

Latest Belle result	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$
Latest Belle average	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.96 \pm 0.26] \times 10^{-4}$
Measured world average	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [1.15 \pm 0.23] \times 10^{-4}$
CKM global fit	$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.73^{+0.12}_{-0.07}] \times 10^{-4}$





"Tension" in CKM global fit is reduced (1.6σ).

$B \to \ell\nu$ with hadronic tagging

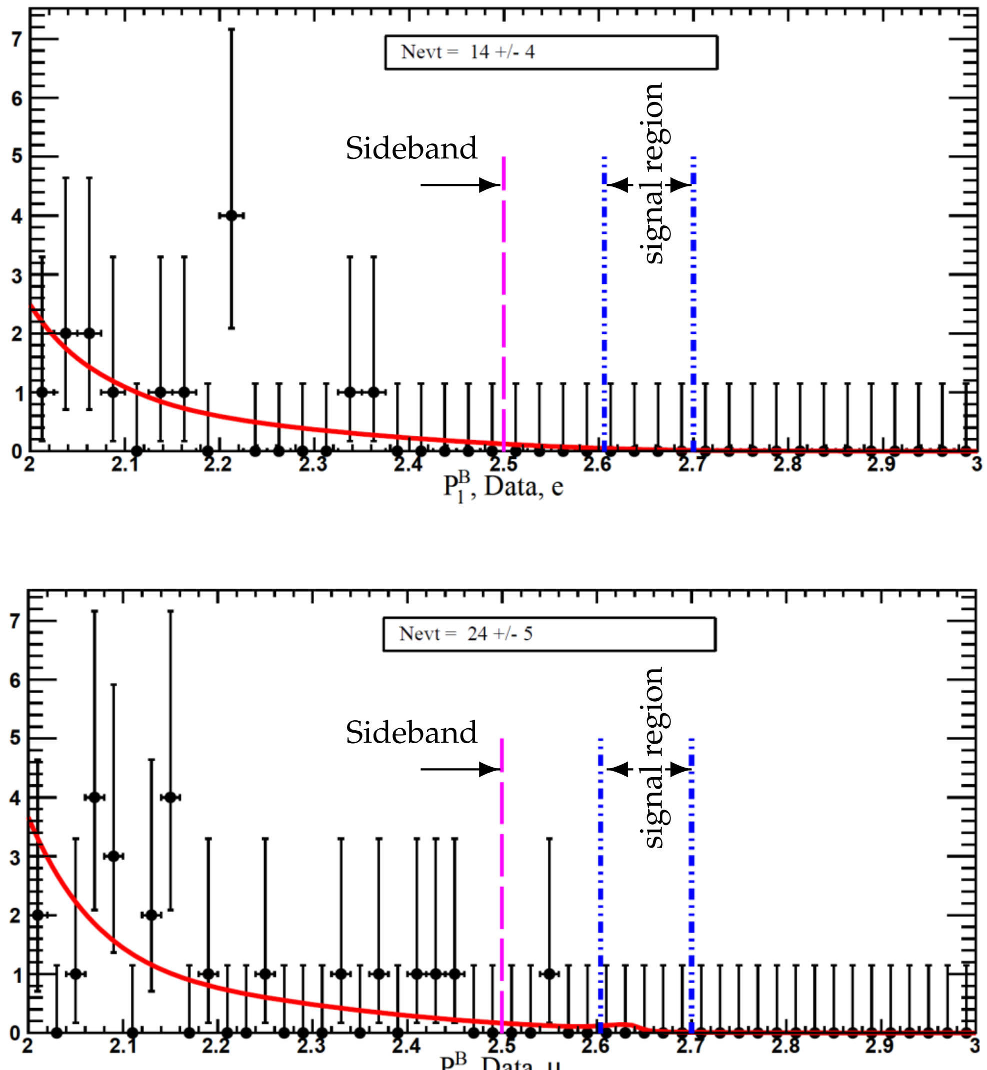
772M $B\bar{B}$

ICHEP2012

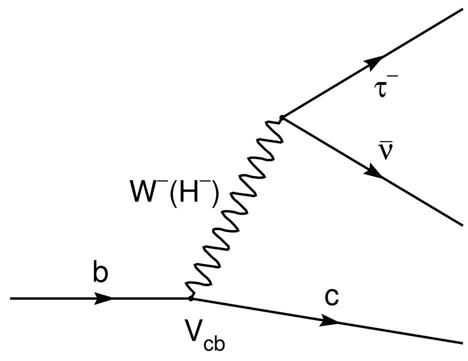
- SM expectation:
  $\mathcal{B}(B \to e\nu_e) \sim 1 \times 10^{-11}$
  $\mathcal{B}(B \to \mu\nu_\mu) \sim 5 \times 10^{-7}$

- Exclusive hadronic tagging
- Zero events observed
- $\mathcal{B}(B \to e\nu_e) < 3.5 \times 10^{-6}$
  $\mathcal{B}(B \to \mu\nu_\mu) < 2.5 \times 10^{-6}$

- Inclusive tag with 277M $B\bar{B}$
  (PLB 647, 67 (2007))
  $\mathcal{B}(B \to e\nu_e) < 1.7 \times 10^{-6}$
  $\mathcal{B}(B \to \mu\nu_\mu) < 0.98 \times 10^{-6}$



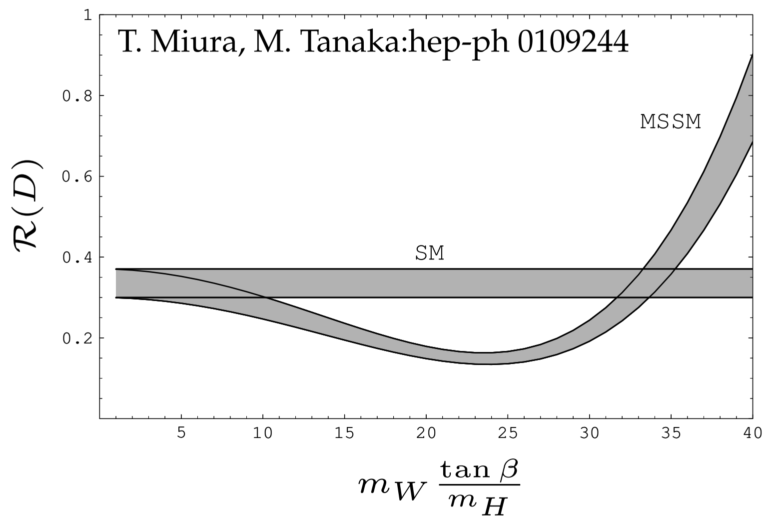
Semileptonic $B \to \bar{D}^{(*)}\tau\nu_\tau$ decays
are sensitive to charged Higgs and
are complementary to leptonic $B \to \tau\nu$ decay.



To reduce experimental and theoretical uncertainties we use ratio

$$\mathcal{R}(D) \equiv \frac{\mathcal{B}(B \to \bar{D}\tau\nu_\tau)}{\mathcal{B}(B \to \bar{D}\ell\nu_\ell)}$$

SM expected values:
$\mathcal{B}(B \to \bar{D}\tau\nu_\tau) \sim 0.7\%$
$\mathcal{B}(B \to \bar{D}^*\tau\nu_\tau) \sim 1.4\%$



$B^0 \to D^{*-}\tau^+\nu_\tau$ *with inclusive tagging*

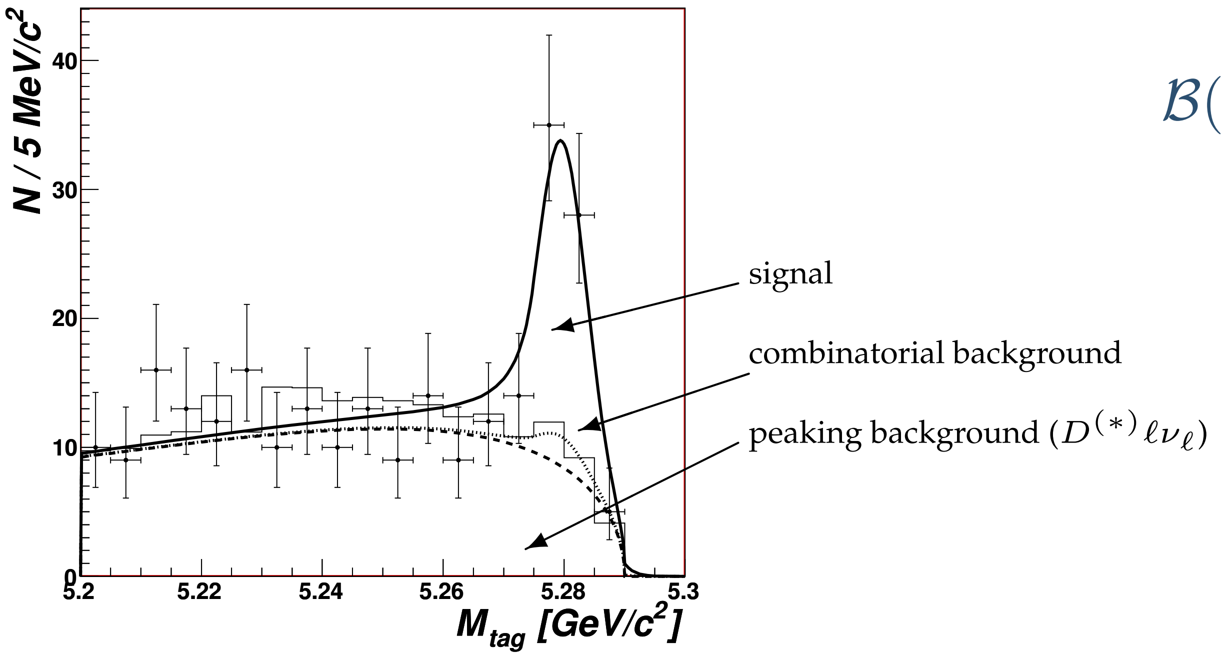
535M $B\bar{B}$

PRL 99, 191807 (2007)

Inclusive tagging is a variant of "full reconstruction" tagging:

- $B_{\rm sig}$ is reconstructed as $D^{*-}\tau^+$;
- The rest of the event is checked to be consistent with B hypothesis.

The first observation of exclusive B decay due to $b \to c\tau\nu_\tau$ transition.



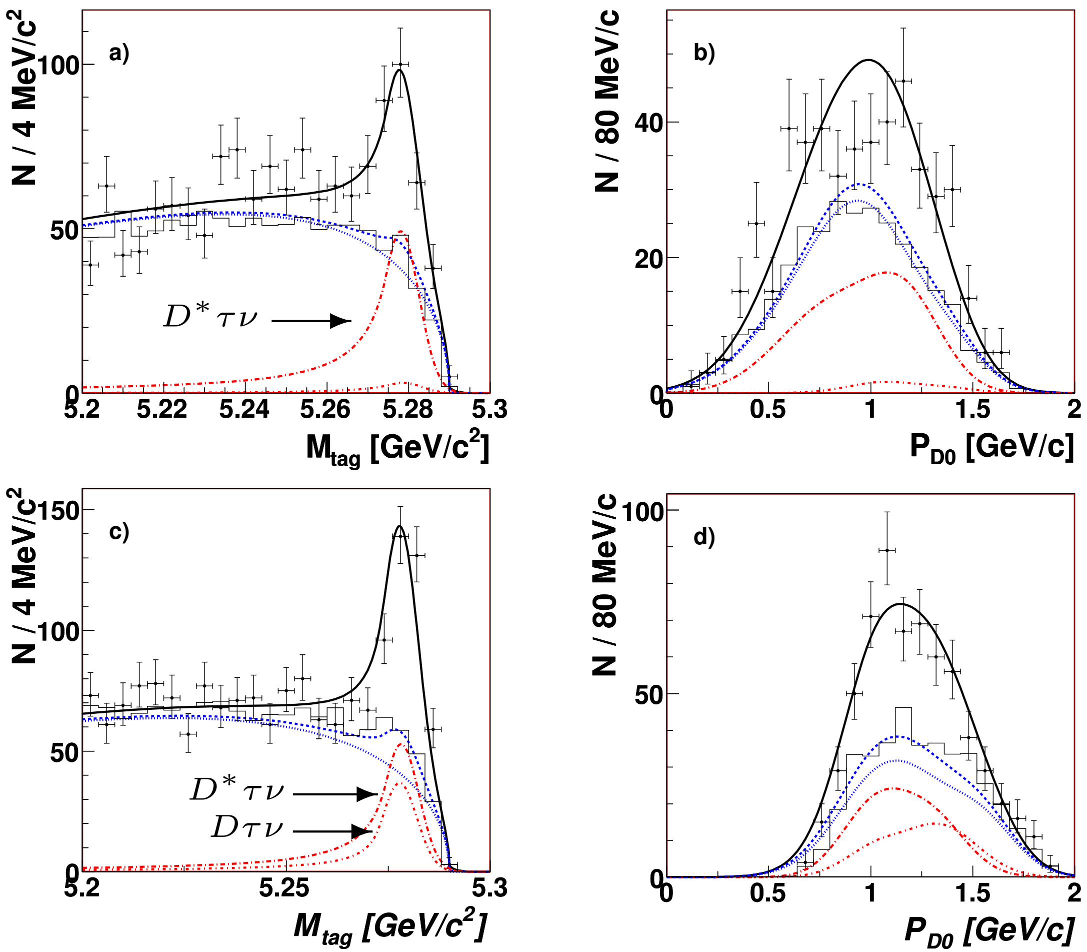
$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) =$
$(2.02^{+0.40}_{-0.37} \pm 0.37)\%$,
5.2σ significance

$B^+ \to \bar{D}^{(*)0}\tau^+\nu_\tau$ with inclusive tagging

657M $B\bar{B}$

PRD 82, 072005(2010)

- Simultaneous extraction of D and D^* yields;
- 2D fit to $M_{\rm tag}$ and P_D.



$$\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = (2.12^{+0.28}_{-0.27} \pm 0.29)\%,$$
8.1σ significance

$$\mathcal{B}(B^+ \to \bar{D}^{0}\tau^+\nu_\tau) = (0.77 \pm 0.22 \pm 0.12)\%,$$
3.5σ significance

a), b) $D^{*0}\tau\nu_\tau$

c), d) $D^{0}\tau\nu_\tau$

$B^0 \to D^{(*)-}\tau^+\nu_\tau$ with exclusive tagging

657M $B\bar{B}$

arXiv:0910.4301

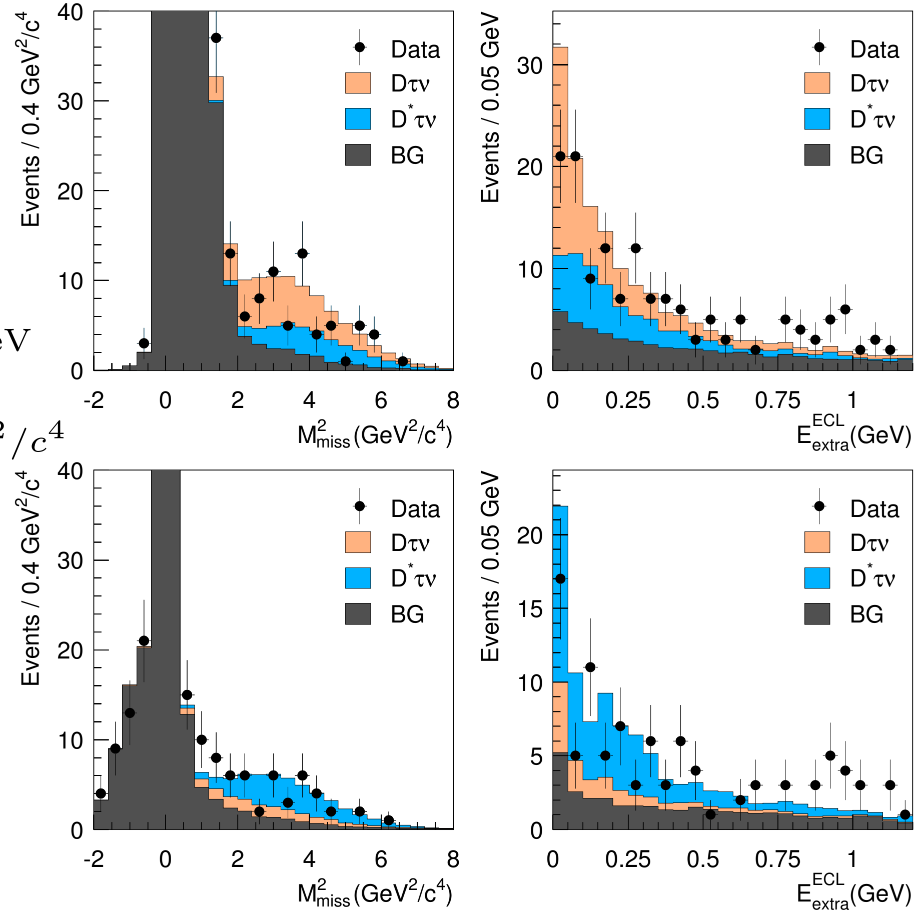
- Exclusive hadronic tagging method;
- Simultaneous extraction of D and D^* yields;
- 2D fit to M^2_{miss} and E_{ECL}.

$B^0 \to D\tau\nu$

M^2_{miss} : $E_{ECL} < 0.2\text{GeV}$

E_{ECL} : $M^2_{miss} > 2.0\text{GeV}^2/c^4$

$B^0 \to D^*\tau\nu$



$$\mathcal{B}(B^0 \to D^-\tau^+\nu_\tau) = (1.01^{+0.46}_{-0.41}{}^{+0.13}_{-0.11} \pm 0.10)\%,$$

2.6σ significance

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (2.56^{+0.75}_{-0.66}{}^{+0.31}_{-0.22} \pm 0.10)\%$$

4.7σ significance

$$\mathcal{R}(D^0) = 0.70^{+0.19}_{-0.18}{}^{+0.11}_{-0.09}$$
$$\mathcal{R}(D^{*0}) = 0.47^{+0.11}_{-0.10}{}^{+0.06}_{-0.07}$$

$B^+ \to \bar{D}^{(*)0}\tau^+\nu_\tau$ *with exclusive tagging*

657M $B\bar{B}$

arXiv:0910.4301

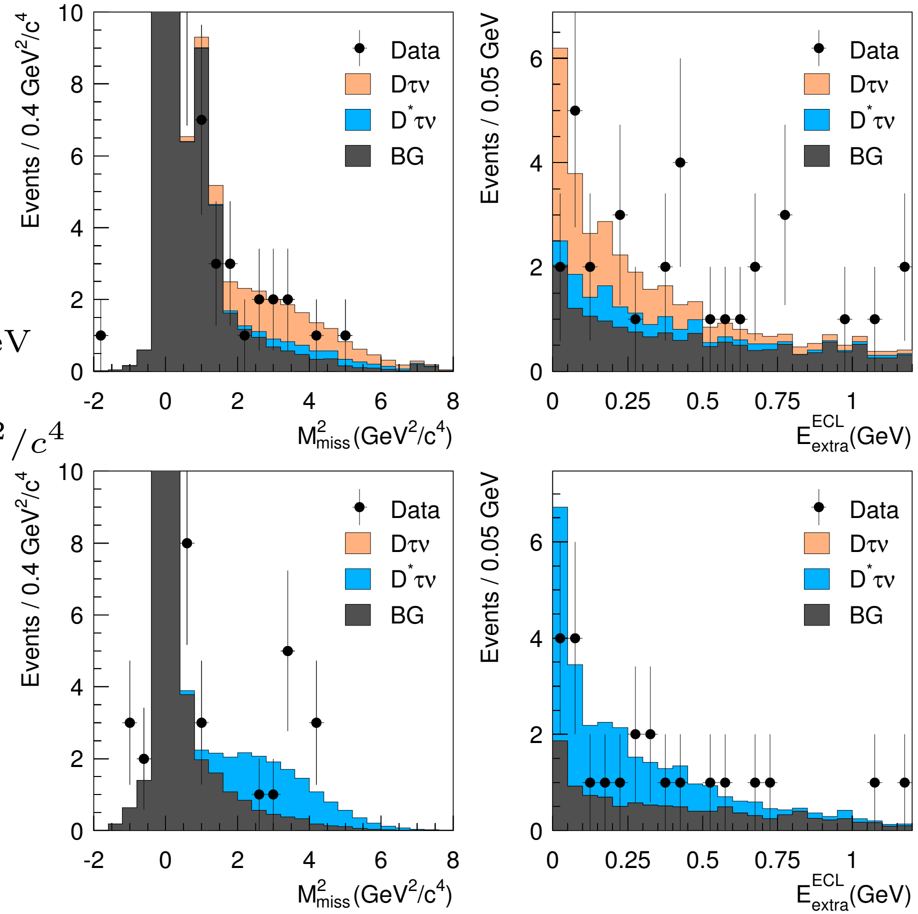
- Exclusive hadronic tagging method;
- Simultaneous extraction of D and D^* yields;
- 2D fit to M^2_{miss} and E_{ECL}.

$B^+ \to \bar{D}\tau\nu$

M^2_{miss} : $E_{ECL} < 0.2\text{GeV}$

E_{ECL} : $M^2_{miss} > 2.0\text{GeV}^2/c^4$

$B^+ \to \bar{D}^*\tau\nu$



$$\mathcal{B}(B^+ \to \bar{D}^0\tau^+\nu_\tau) = (1.51^{+0.41}_{-0.39}{}^{+0.24}_{-0.19} \pm 0.15)\%,$$
3.8σ significance

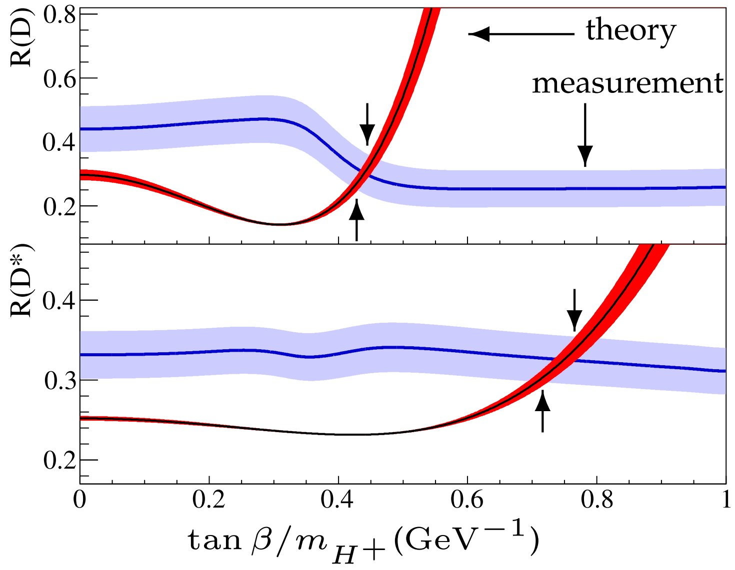
$$\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = (3.04^{+0.69}_{-0.66}{}^{+0.40}_{-0.47} \pm 0.22)\%,$$
3.9σ significance

$$\mathcal{R}(D^-) = 0.48^{+0.22}_{-0.19}{}^{+0.06}_{-0.05}$$
$$\mathcal{R}(D^{*-}) = 0.48^{+0.14}_{-0.12}{}^{+0.06}_{-0.04}$$

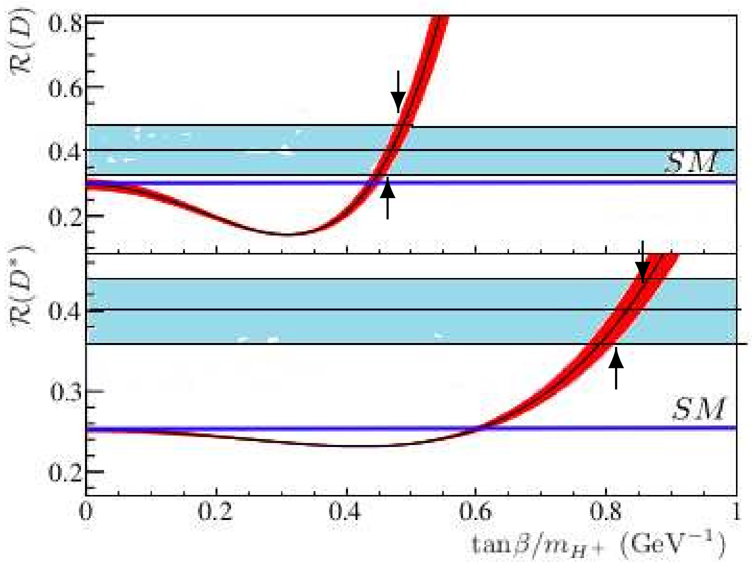
Constraint for 2HDM type II

- Combining results from $B \to \tau\nu_\tau$ and $B \to \bar{D}^{(*)}\tau\nu_\tau$ we can constrain charged Higgs model 2HDM type II.
- On all figures preferred regions are different.
- 2HDM type II is excluded?

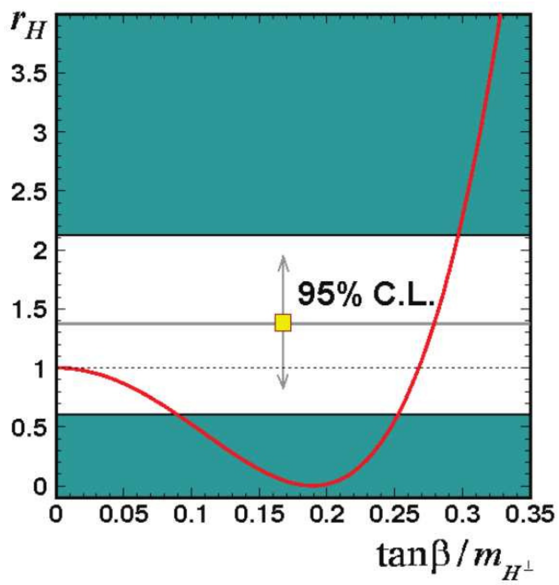
BaBar $B \to \bar{D}^{*()}\tau\nu_\tau$



Belle $B \to \bar{D}^{*()}\tau\nu_\tau$



Belle $B \to \tau\nu_\tau$



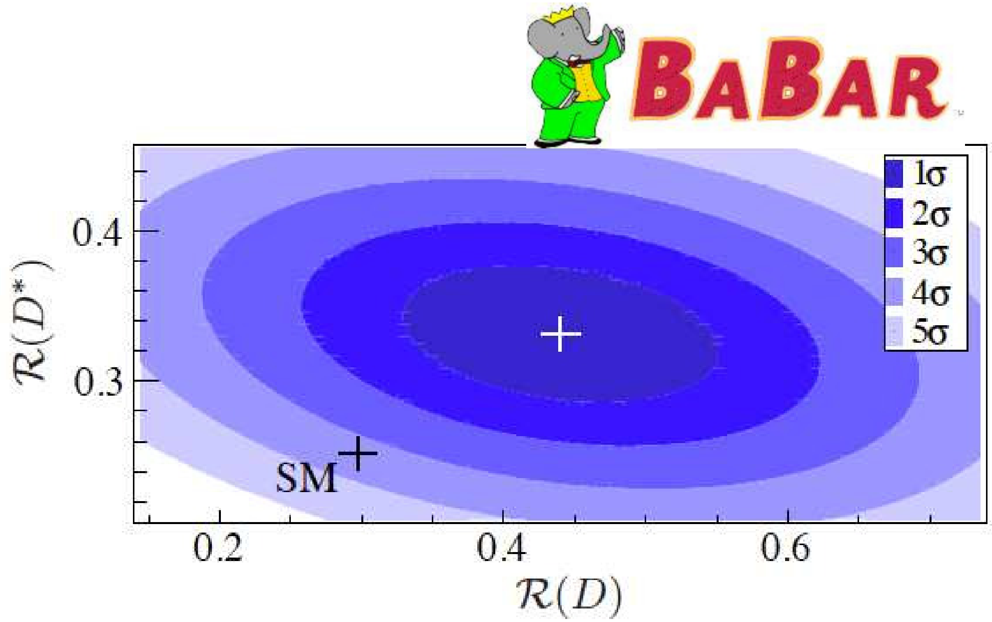
$B \to \bar{D}^{(*)}\tau\nu_\tau$ and SM

PRD 85, 094025 (2012)

SM	Belle	Deviation
$\mathcal{R}(D) = 0.297 \pm 0.017$	$\mathcal{R}(D) = 0.430 \pm 0.091$	1.4σ
$\mathcal{R}(D^*) = 0.252 \pm 0.003$	$\mathcal{R}(D^*) = 0.405 \pm 0.047$	3.0σ
	Combined	3.3σ

PRL 109, 101802 (2012)

BaBar	Deviation
$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$	2.0σ
$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$	2.7σ
Combined	3.4σ



Belle & BaBar	Deviation
$\mathcal{R}(D)$	2.4σ
$\mathcal{R}(D^*)$	3.8σ
Combined	4.8σ

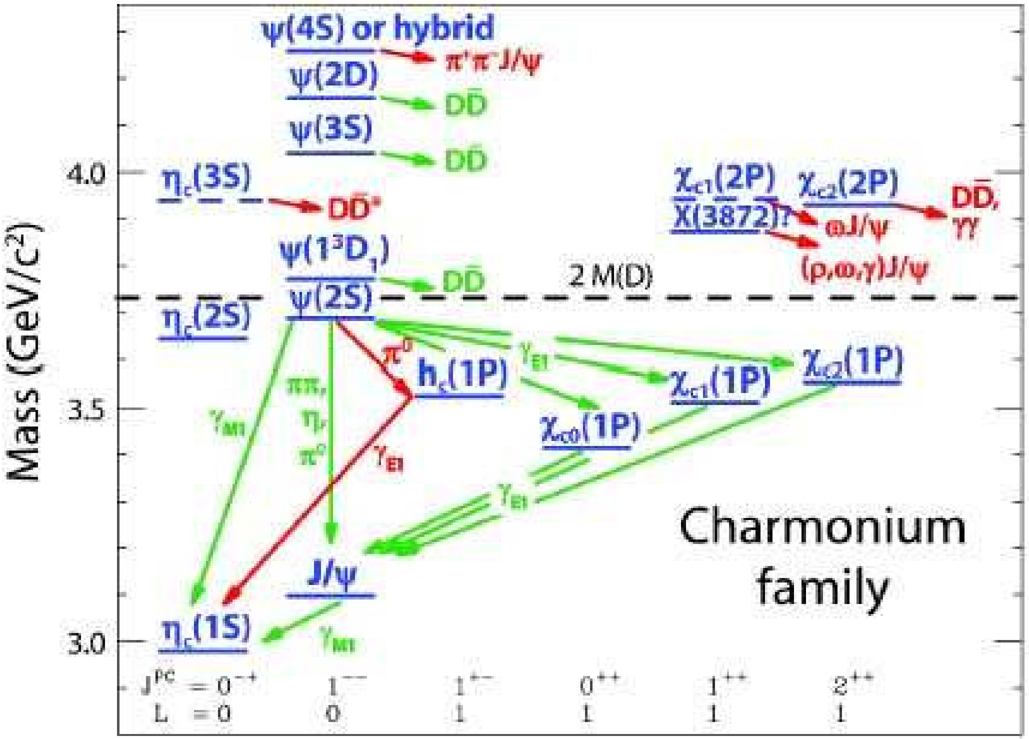
$B \to \tau\nu_\tau$ summary

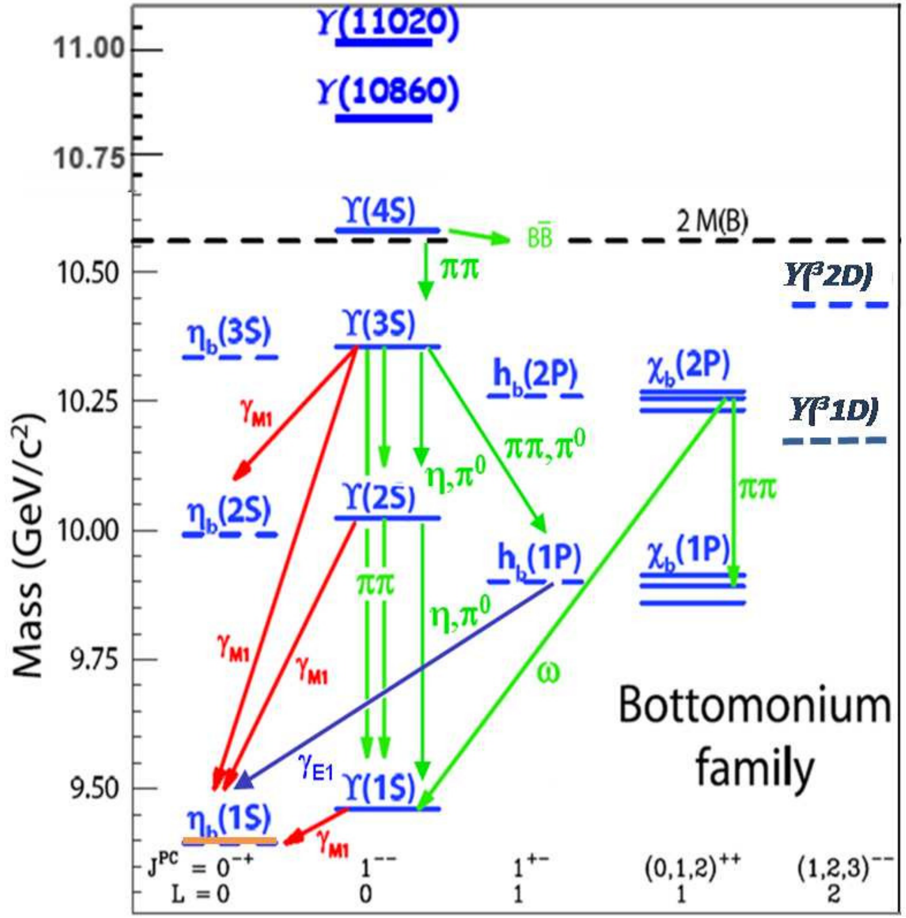
- $B \to \tau\nu_\tau$ decay was studied at Belle with different tagging. Results are consistent with each other and BaBar result;
- Recent result is much closer to SM prediction, "tension" in CKM global fit is reduced;
- Results for $B \to \bar{D}^{(*)}\tau\nu_\tau$ are consistent between tagging types and experiments;
- 2HDM type II seems to be excluded by combination of $B \to \tau\nu_\tau$ and $B \to \bar{D}\tau\nu_\tau$ results;
- Results for $\mathcal{R}(D^{(*)})$ are different from SM at 4.8σ for combination of Belle and BaBar results.

- $B \to \tau\nu_\tau$ and related results.
- Bottomonium.
- CKM measurements.

Bottomonium spectroscopy

Heavy Quarkonia is an ideal tool for testing QCD





Anomalous production of $\Upsilon(nS)$

PRL100,112001(2008)

Process	$\Gamma(\mathrm{MeV}/c^2)$
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

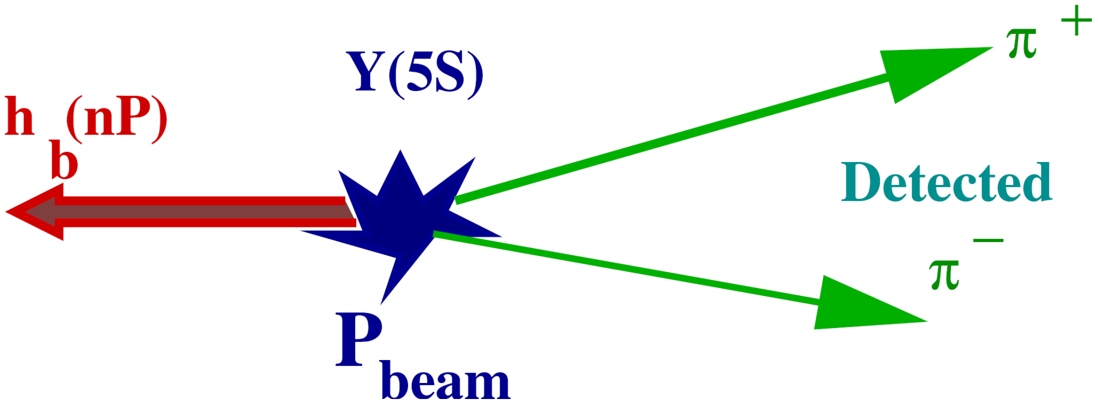
100 times difference!

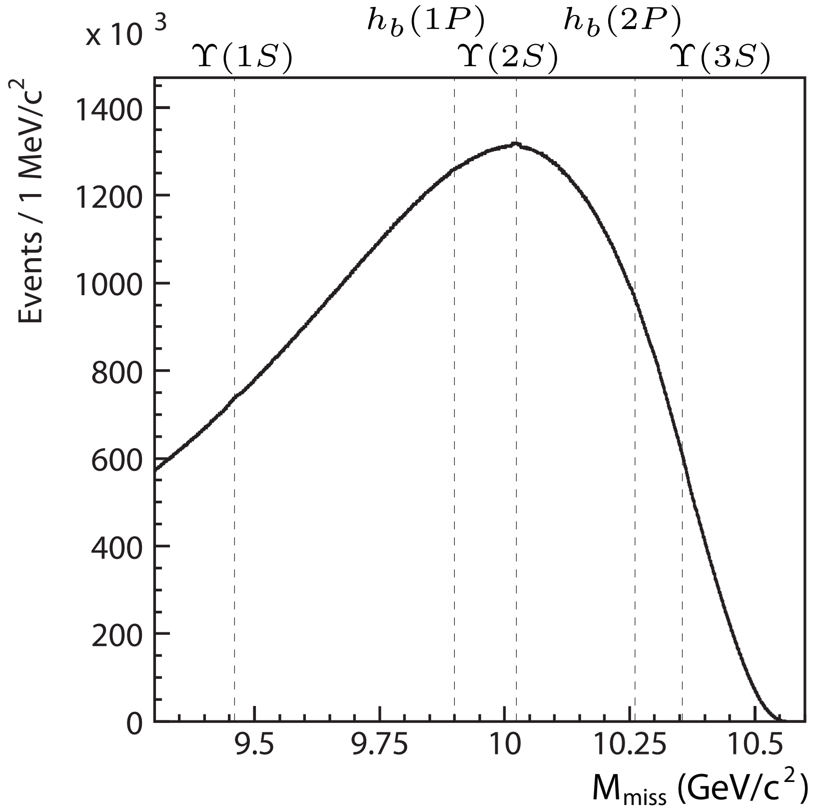
Observation of $h_b(1P)$ and $h_b(2P)$

PRL108,032001(2012)

h_b has no good exclusive final states. h_b is observed in the missing mass

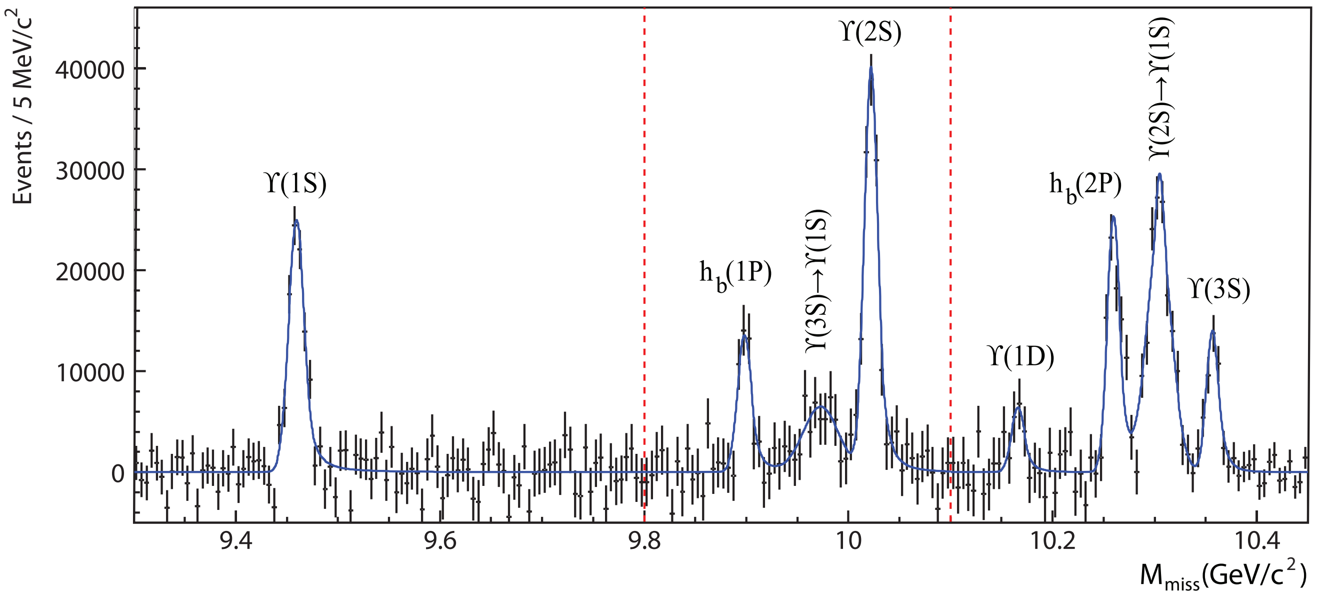
$$M_{miss} = \sqrt{(E_{cm} - E^*_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}} = M(h_b)$$





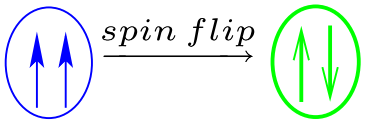
Observation of $h_b(1P)$ and $h_b(2P)$

After background subtraction

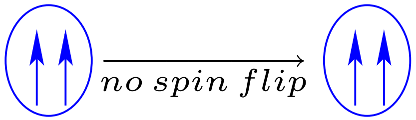


	Yield, 10^3	Mass, MeV$/c^2$	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

Ratio of production rates



$$\frac{\Gamma(\Upsilon(5S)\to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S)\to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

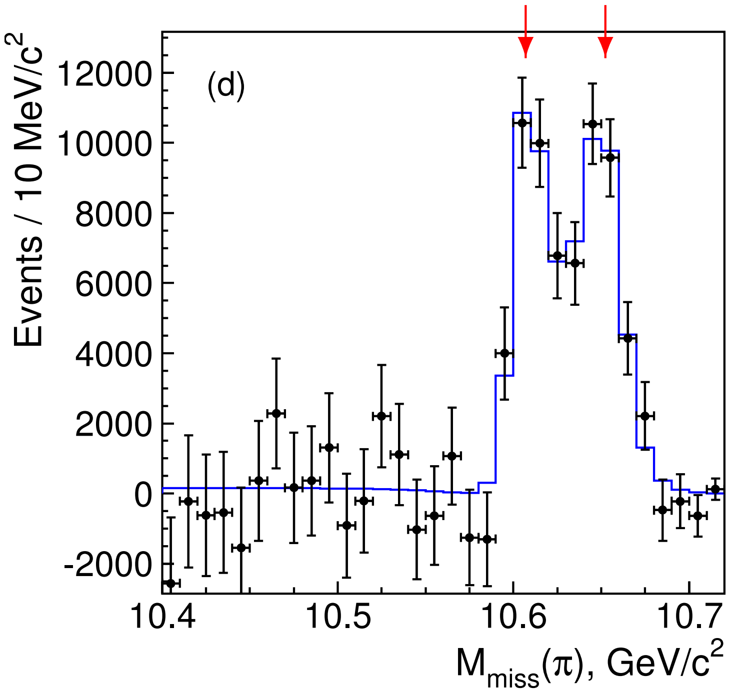


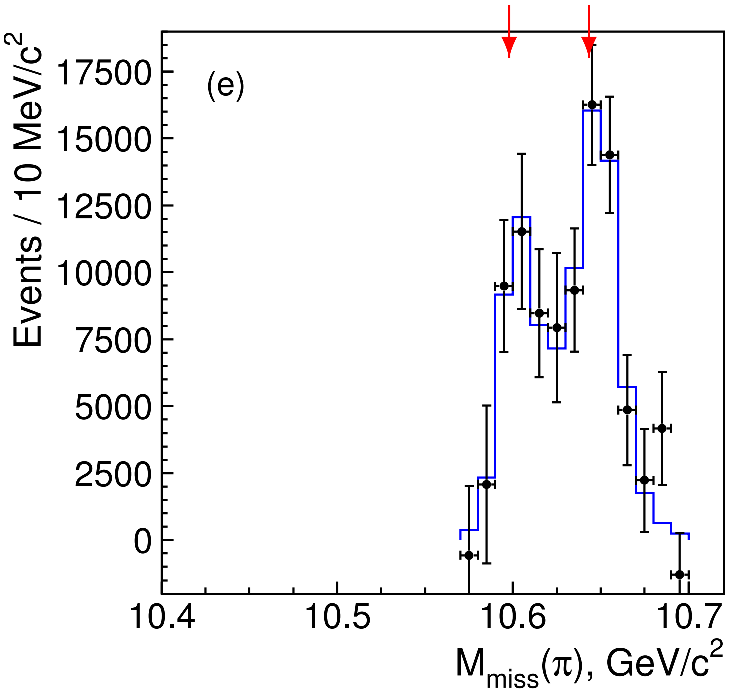
Process with spin-flip of heavy quark is not suppressed!
(should be suppressed as $(\Lambda_{QCD}/m_b)^2$)

Resonant structure of $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$

PRL 108, 122001 (2012)

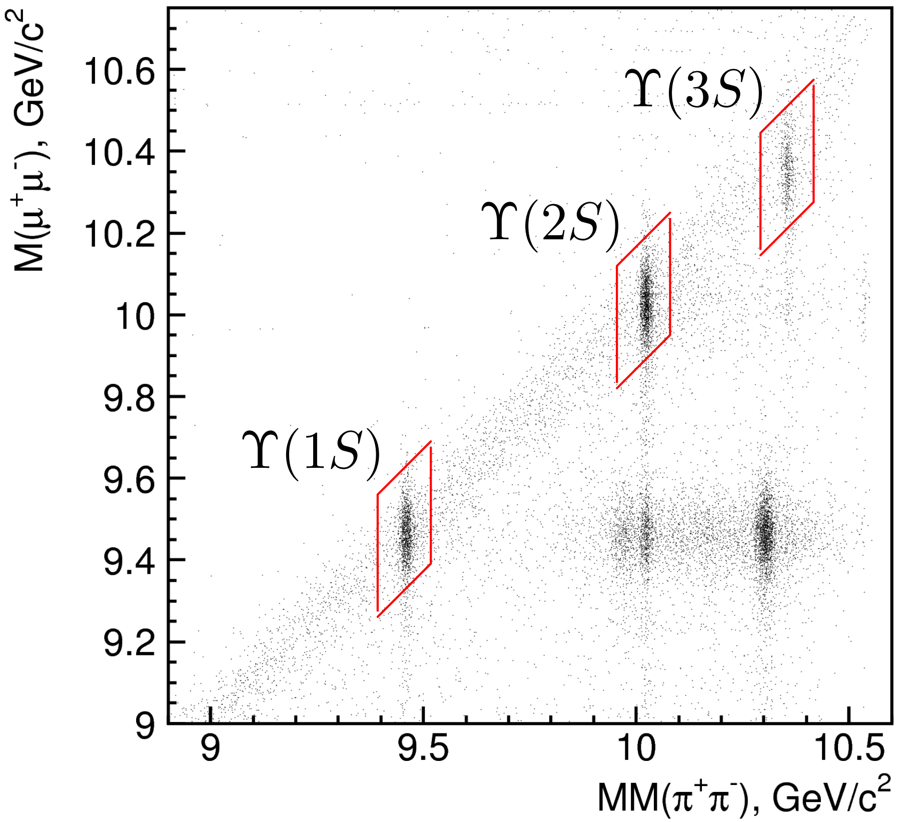
1D fit to $M_{miss}(\pi^+\pi^-)$ in $M(h_b\pi)$ bins (non-resonant contribution is negligible).





	(d)	(e)
$M_1 =$	$10605 \pm 2^{+3}_{-1}$ MeV$/c^2$	$10599^{+6}_{-3}\,^{+5}_{-4}$ MeV$/c^2$
$\Gamma_1 =$	$11.4^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$ MeV	$13^{+10}_{-8}\,^{+9}_{-7}$ MeV
$M_2 =$	$10654 \pm 3^{+1}_{-2}$ MeV$/c^2$	$10651^{+2}_{-3}\,^{+3}_{-2}$ MeV$/c^2$
$\Gamma_2 =$	$20.9^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$ MeV	$19 \pm 7^{+11}_{-7}$ MeV

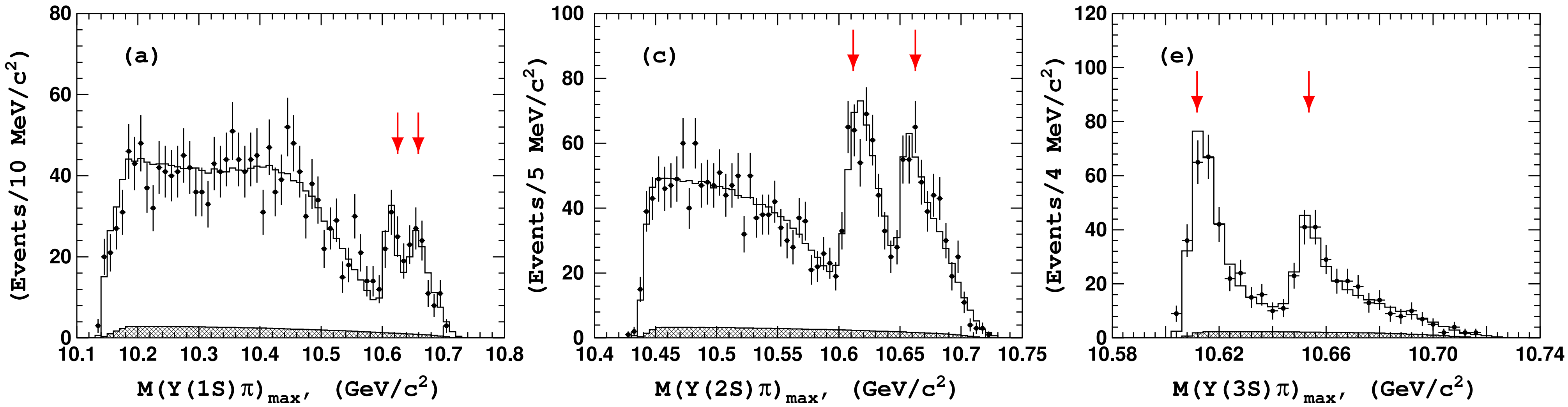
$$\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$$
$$\Upsilon(nS) \to \mu^+\mu^-$$



Resonant structure of $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

PRL 108, 122001 (2012)

Projections of the fit to Dalitz plot

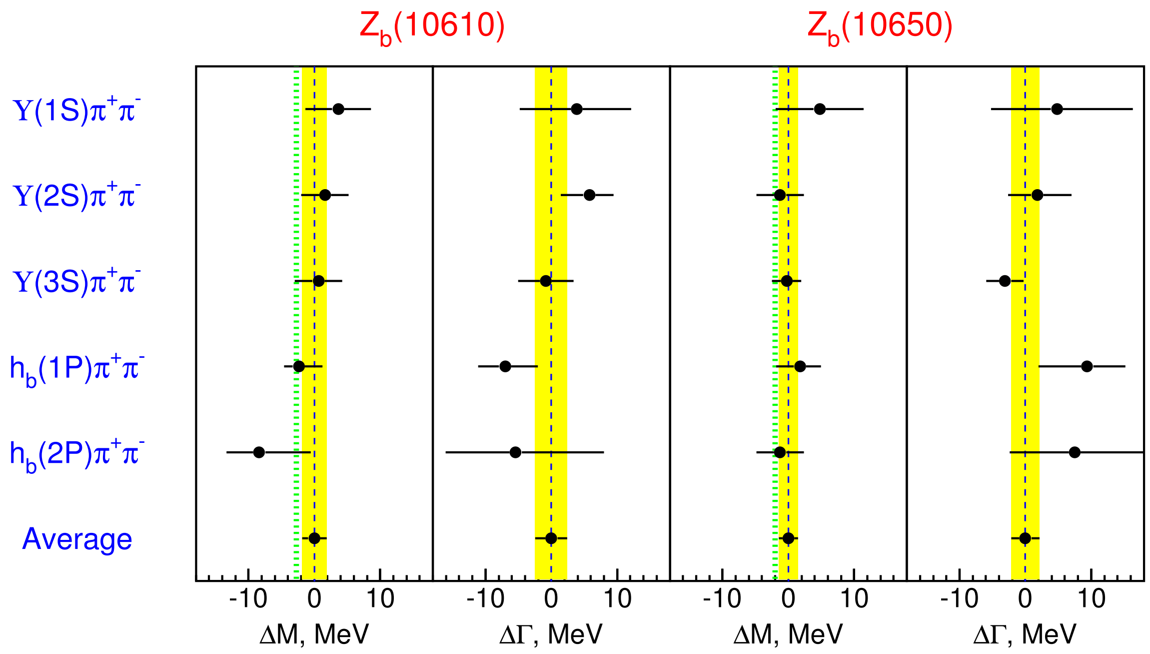


Summary of Z_b parameters

Averaging over five decay channels we get

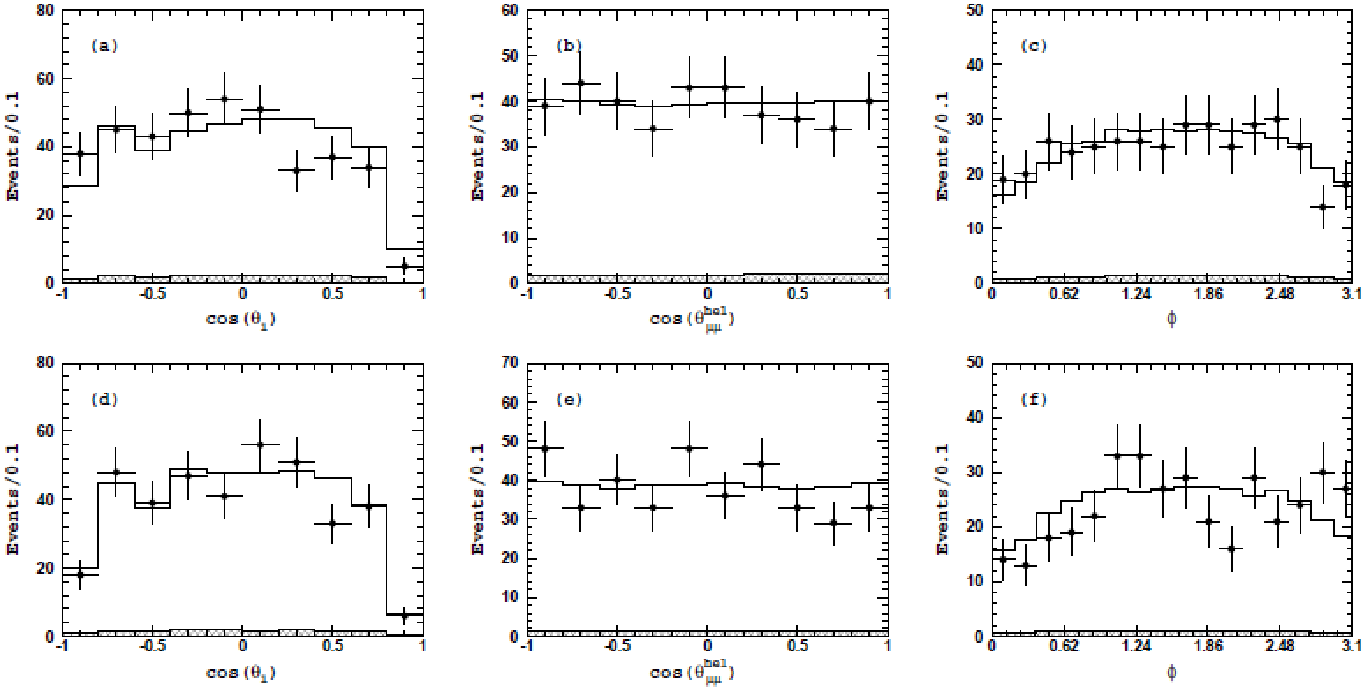
$M_1 = 10607.2 \pm 2.0\ \mathrm{MeV}/c^2$
$\Gamma_1 = 18.4 \pm 2.4\ \mathrm{MeV}$
$M(BB^*) = 10604.8 \pm 0.4\ \mathrm{MeV}/c^2$

$M_2 = 10652.2 \pm 1.5\ \mathrm{MeV}/c^2$
$\Gamma_2 = 11.5 \pm 2.2\ \mathrm{MeV}$
$M(BB^*) = 10650.4 \pm 0.8\ \mathrm{MeV}/c^2$



Z_b angular analysis

arXiv:1105.4583



$Z_b(10610)$

$Z_b(10650)$

Angle between prompt pion and beam axis

$\Upsilon \to \mu^+\mu^-$ helicity angle

Angle between planes formed by $\pi^+\pi^-$ and Υ, beam axis

The probabilities at which different J^P hypotheses are disfavored compared to the 1^+

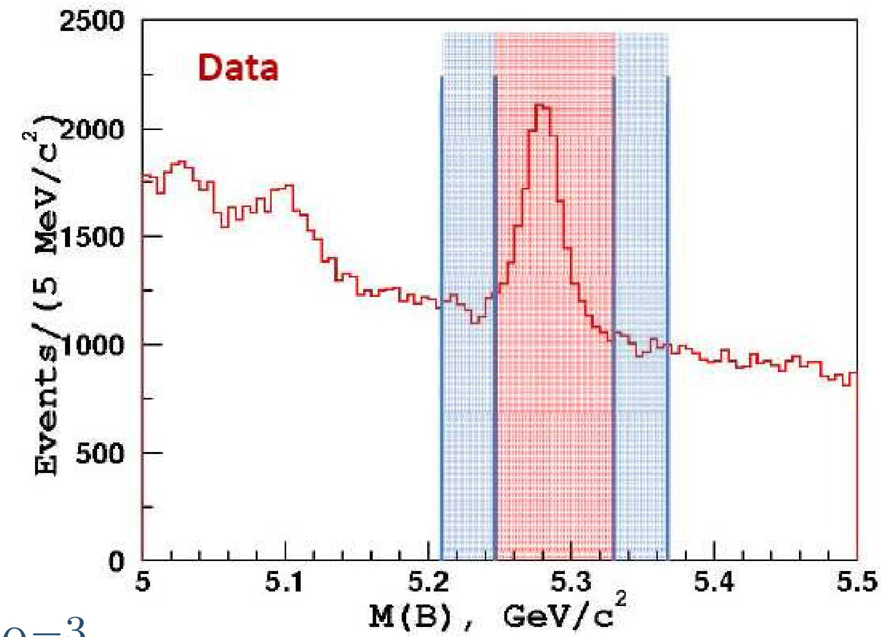
J^P	$Z_b(10610)$			$Z_b(10650)$		
	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$
1^-	$3.6\,\sigma$	$0.3\,\sigma$	$0.3\,\sigma$	$3.7\,\sigma$	$2.6\,\sigma$	$2.7\,\sigma$
2^+	$4.3\,\sigma$	$3.5\,\sigma$	$4.3\,\sigma$	$4.4\,\sigma$	$2.7\,\sigma$	$2.1\,\sigma$
2^-	$2.7\,\sigma$	$2.8\,\sigma$		$2.9\,\sigma$	$2.6\,\sigma$	

Study of $\Upsilon(5S) \to B^{(*)}B^{(*)}\pi$: Selection

arXiv:1209.6450

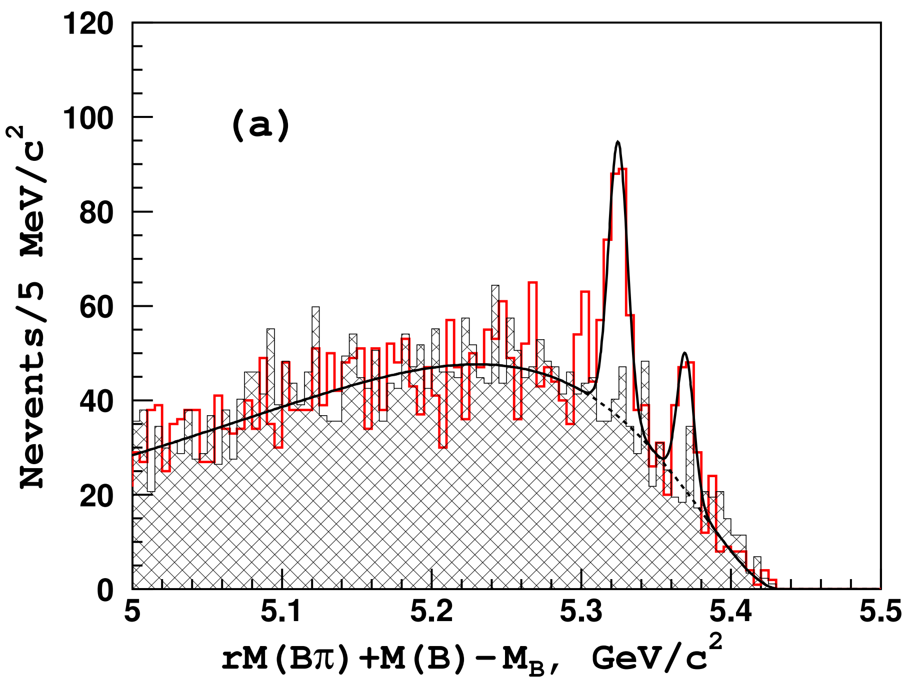
Mass of $Z_b(10610)$ $[Z_b(10650)]$ is close to BB^* $[B^*B^*]$ threshold.
It is interesting to search for $\Upsilon(5S) \to Z_b\pi$ decay with $Z_b \to B^{(*)}B^*$;
reconstruct only one B and prompt pion.

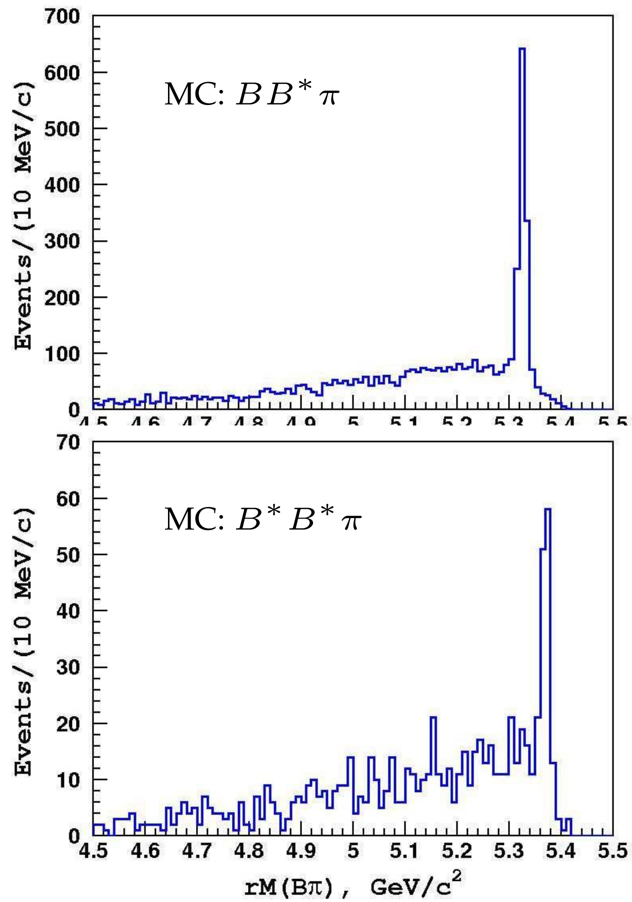
- Charged B
  - $D^0[K\pi, K\pi\pi\pi]\pi^-$
  - $J/\psi[\mu\mu]K^-$
- Neutral B
  - $D^+[K\pi\pi]\pi^-$
  - $D^{*+}[K\pi, K\pi\pi^0, K\pi\pi\pi]\pi^-$
  - $J/\psi[\mu\mu]K^{*0}$



Effective B fraction: $\mathcal{B}(B \to f) = 1.4 \times 10^{-3}$

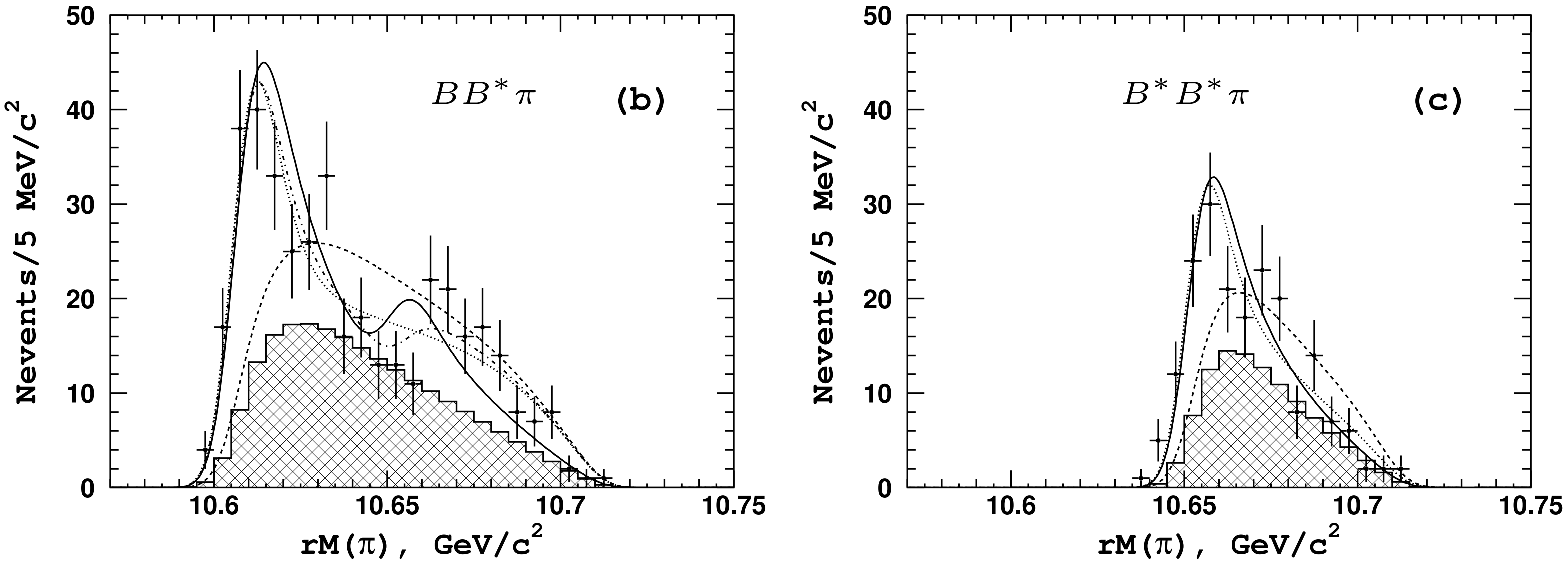
Study of $\Upsilon(5S) \to B^{(*)}B^{(*)}\pi$: Fit





Recoil mass to $B\pi$.
Red histogram: right charge combination;
hatched histogram: wrong charge combination
$N(BB\pi) = 0.3 \pm 14$
$N(BB^*\pi) = 184 \pm 19\ (9.3\sigma)$
$N(B^*B^*\pi) = 82 \pm 11\ (5.7\sigma)$

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



$B^*B^*\pi$ candidates are described well by $Z_b(10650)$ only contribution.
$BB^*\pi$ can be described by two models:
$Z_b(10610) + Z_b(10650)$;
$Z_b(10610)$ + non-resonant amplitude

Z_b branching fractions

Assuming Z_b decays to $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ only:

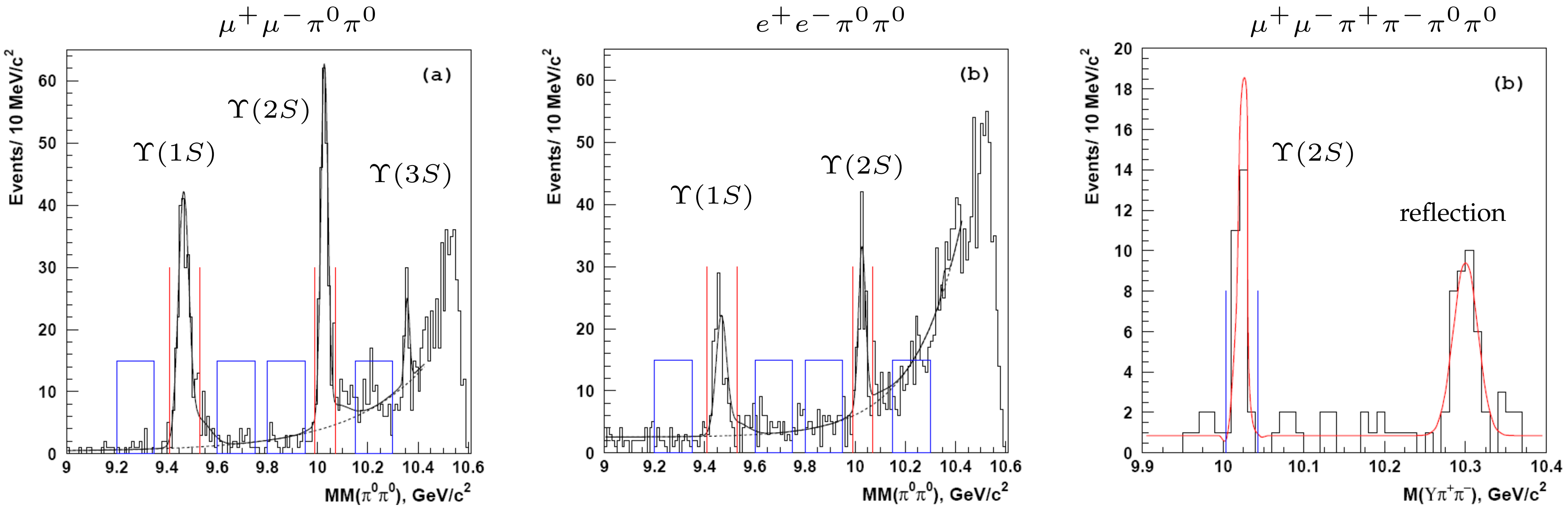
Channel	$\mathcal{B}$ of $Z_b(10610)$, %	$\mathcal{B}$ of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0}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

$B^{(*)}B^*$ — is the dominant mode of Z_b decays!

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

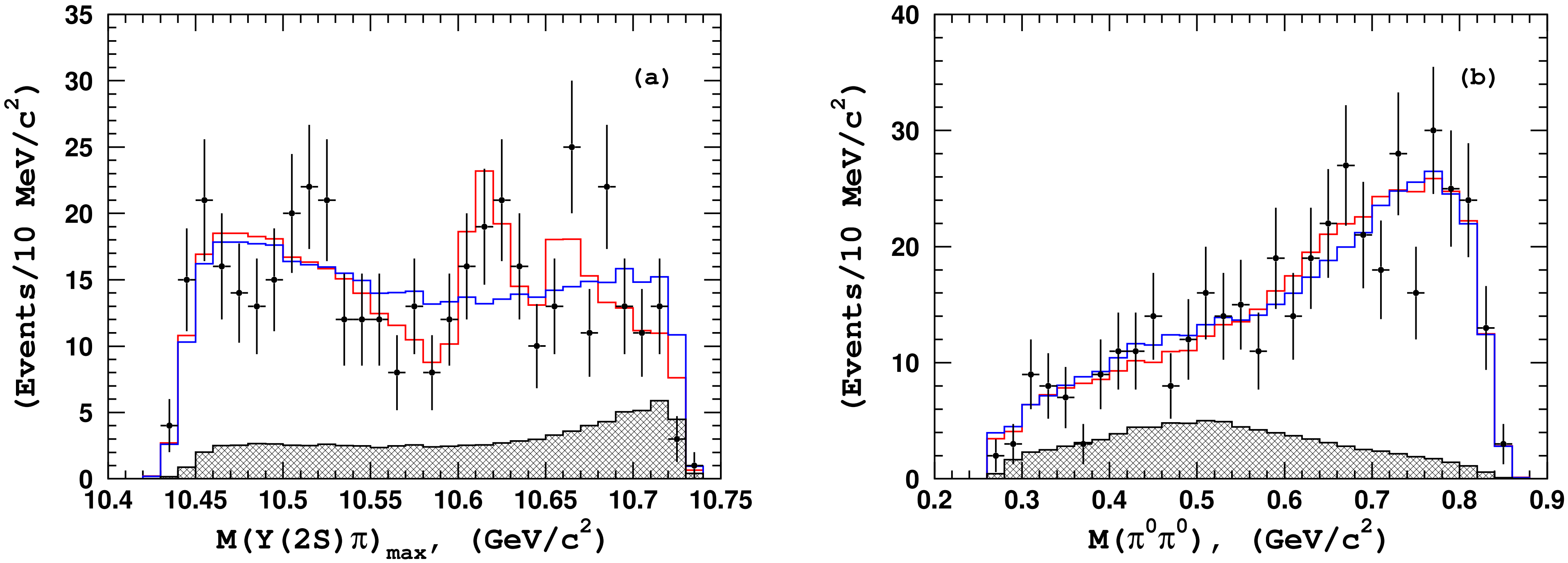
arXiv:1207.4345

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



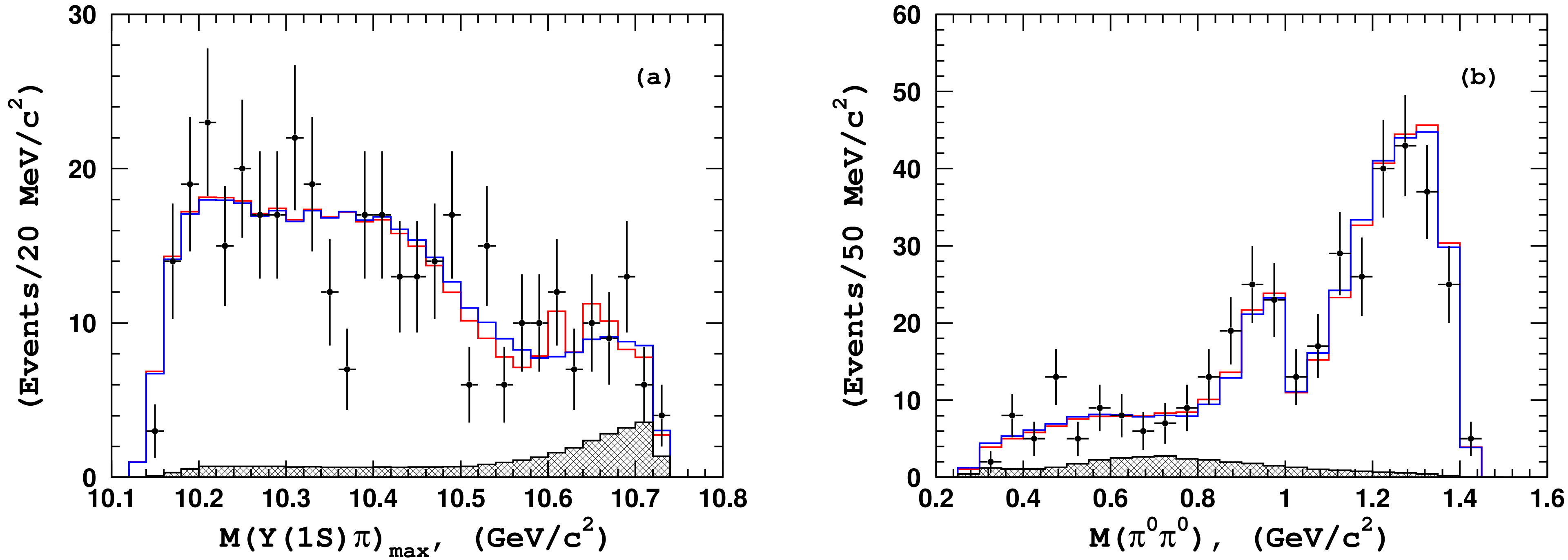
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^0\pi^0) = (2.25 \pm 0.11 \pm 0.20) \times 10^{-3}$
$\mathcal{B}(\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0) = (3.79 \pm 0.24 \pm 0.49) \times 10^{-3}$
Consistent with $\frac{1}{2}$ of $\Upsilon(nS)\pi^+\pi^-$

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



- Z_b^0 resonant structure is observed in $\Upsilon(2S)\pi^0\pi^0$
- Statistical significance of $Z_b^0(10610)$ signal is 5.3σ (4.9σ with systematics)
- $Z_b^0(10650)$ signal is not significant ($\sim 2\sigma$), not contradicting with its existence
- $M(Z_b^0(10610)) = 10609 \pm 8 \pm 6\text{MeV}/c^2$ ($M(Z_b^+) = 10607 \pm 2\text{MeV}/c^2$)

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



Signals of both Z_b^0 are not significant. Data does not contradict with their existence.

Z_b summary

- Charged bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ were observed by Belle in $\Upsilon(5S)$ decays;
- Their masses are close to BB^* and B^*B^* thresholds, respectively;
- Z_bs decays to BB^* and B^*B^* have large branching fractions;
- Angle analysis favors 1^+ for J^P;
- Evidence of neutral partner Z_b^0 was found.

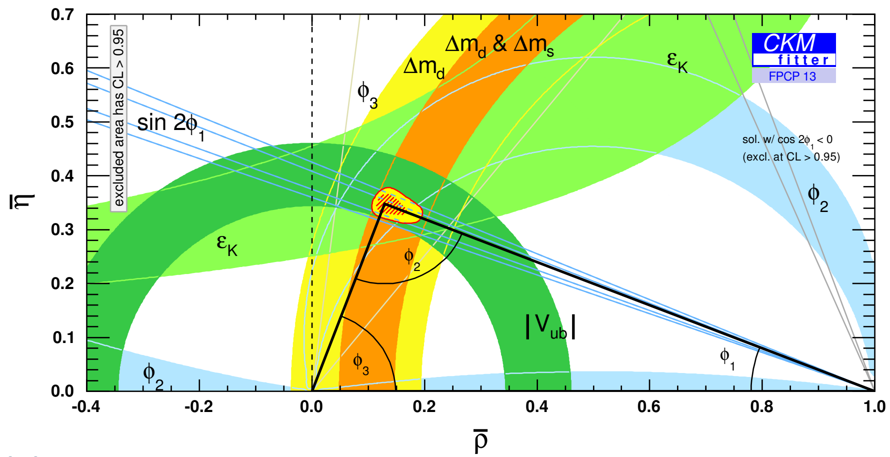
- $B \to \tau\nu_\tau$ and related results.
- Bottomonium study.
- CKM measurements.

CKM measurements

- Over-constrain unitarity triangle to test CKM mechanism: 2 sides, 3 angles.
- Time-dependent decay rate of B or $\bar{B}$ meson decaying into common CP eigenstate

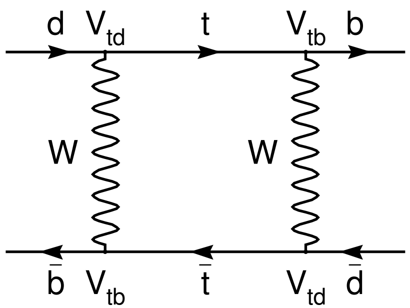
$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{1 + q\left[\mathcal{A}_{CP}\cos\Delta m_d\Delta t + \mathcal{S}_{CP}\sin\Delta m_d\Delta t\right]\right\}.$$

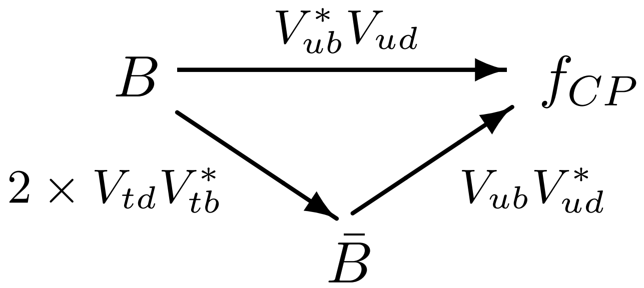
- $\mathcal{A}_{CP}$ — direct CP violation ($= -\mathcal{C}_{CP}$)
- $\mathcal{S}_{CP}$ — mixing induced CP violation
- q: flavor of B_{tag}
- τ_{B^0}: B life time
- Δm_d: mass difference of B_H and B_L
- Δt: decay time difference of B_{CP} and B_{tag}



Mixing induced CP violation

$\phi_2 = arg(\frac{V_{td}V_{tb}^*}{V_{ub}V_{ud}^*})$ is accessible through mixing-induced CP violation in $b \to u$ transitions, e.g. interference between $B \to \pi^+\pi^-$ and $B \to \bar{B} \to \pi^+\pi^-$

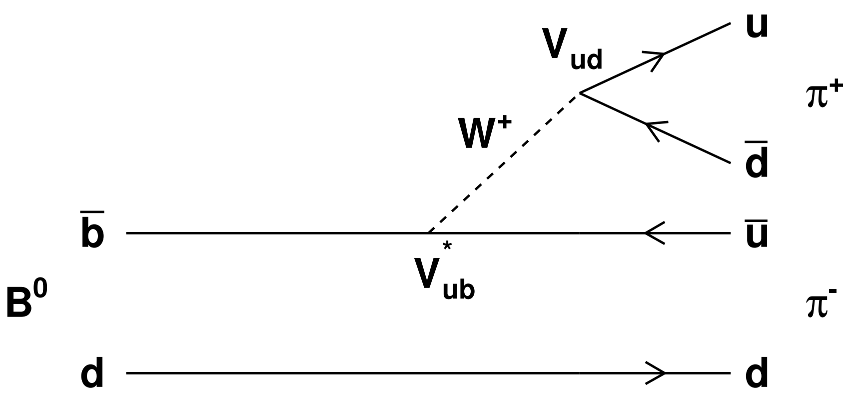


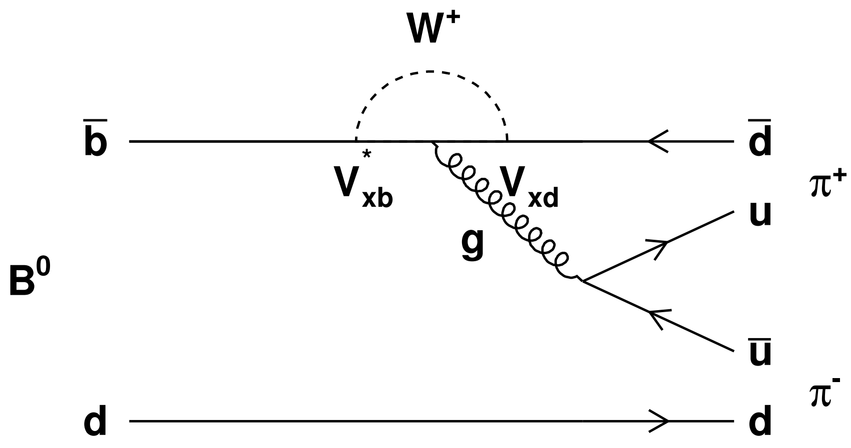


At tree level $\mathcal{S}_{CP} = \sin(2\phi_2)$, $\mathcal{A}_{CP} = 0$

Mixing induced CP violation

But more amplitudes may contribute (penguin) with different weak/strong phases:





$\Rightarrow \phi_2$ penguin pollution $\Rightarrow \Delta\phi_2, \mathcal{A}_{CP} \neq 0$

Measured observable $\phi_2^{eff} = \phi_2 + \Delta\phi_2$

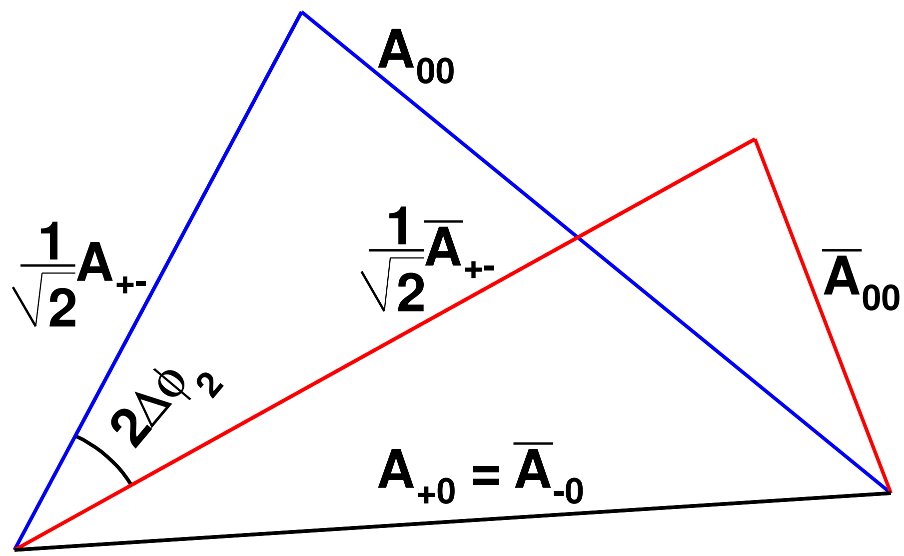
$$\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}^2} \sin(2\phi_2^{eff})$$

It is possible to determine $\Delta\phi_2 = \phi_2^{eff} - \phi_2$ with $SU(2)$ isospin analysis considering different charge combinations of $B \to \pi\pi$

$$A_{+0} = \frac{1}{\sqrt{2}} A_{+-} + A_{00},$$

$$\bar{A}_{-0} = \frac{1}{\sqrt{2}} \bar{A}_{+-} + \bar{A}_{00},$$

$$A_{+0} = A_{-0} \text{ (no penguin)}$$



M. Gronau and D. London, PRL 65 3381 (1990)

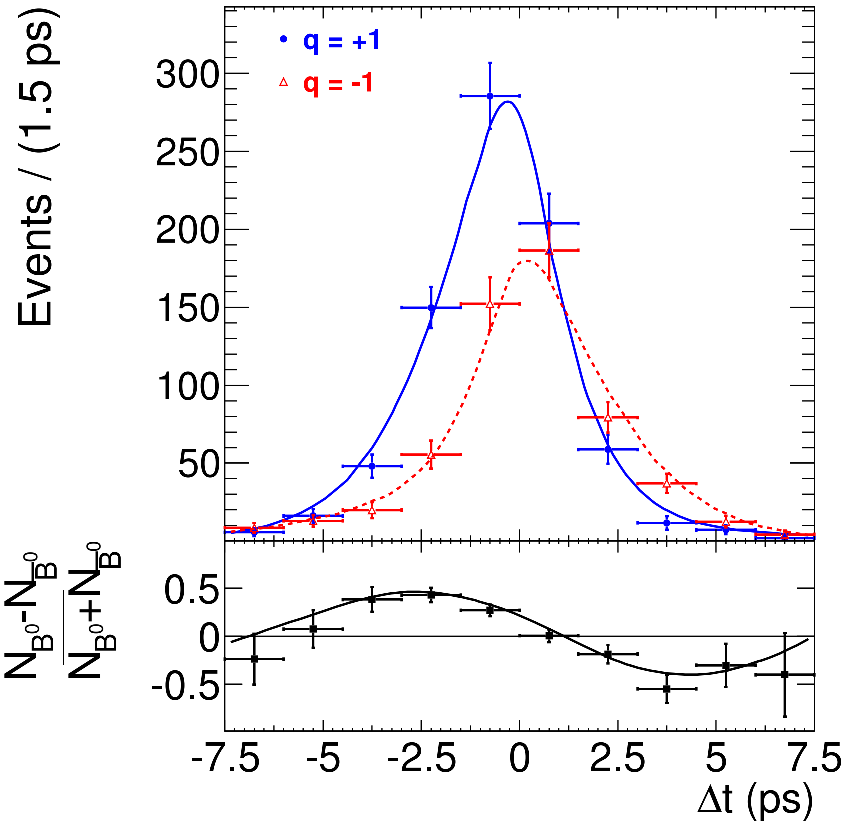
$B \to \pi^+\pi^-$ ***study***

arXiv:1302.0551

$$\mathcal{S}_{CP}^{\pi^+\pi^-} = -0.636 \pm 0.082 \pm 0.027$$

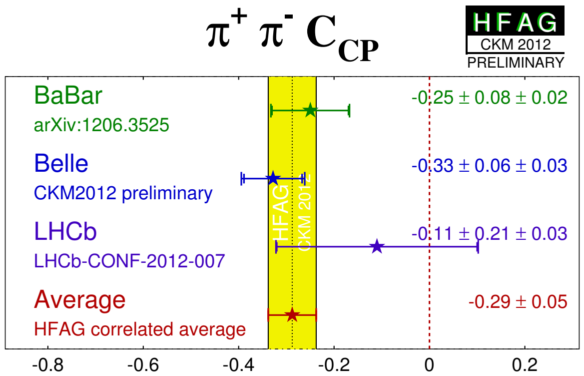
$$\mathcal{A}_{CP}^{\pi^+\pi^-} = +0.328 \pm 0.061 \pm 0.027$$

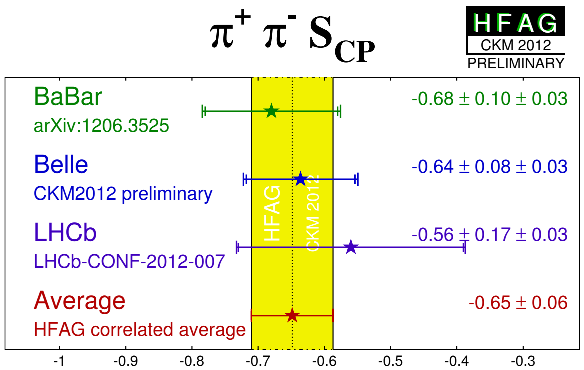
Clear mixing induced CP violation and presence of penguins!

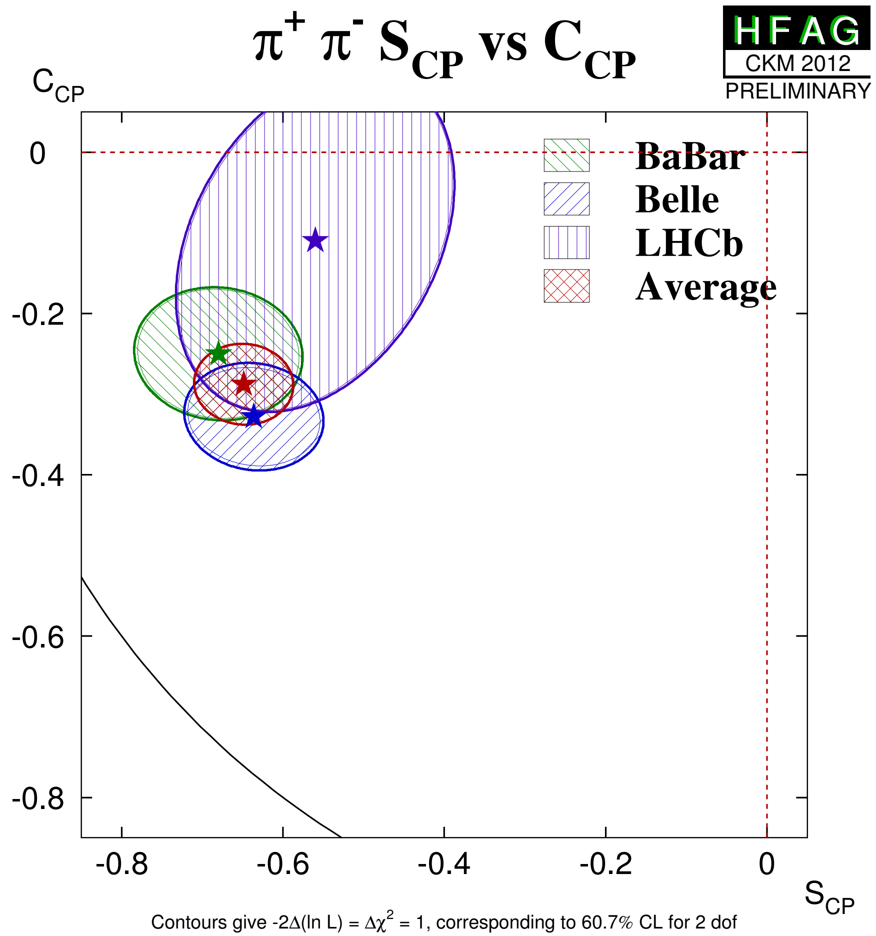


World averages show good agreement between experiments

$$\mathcal{C}_{CP} = -\mathcal{A}_{CP}$$

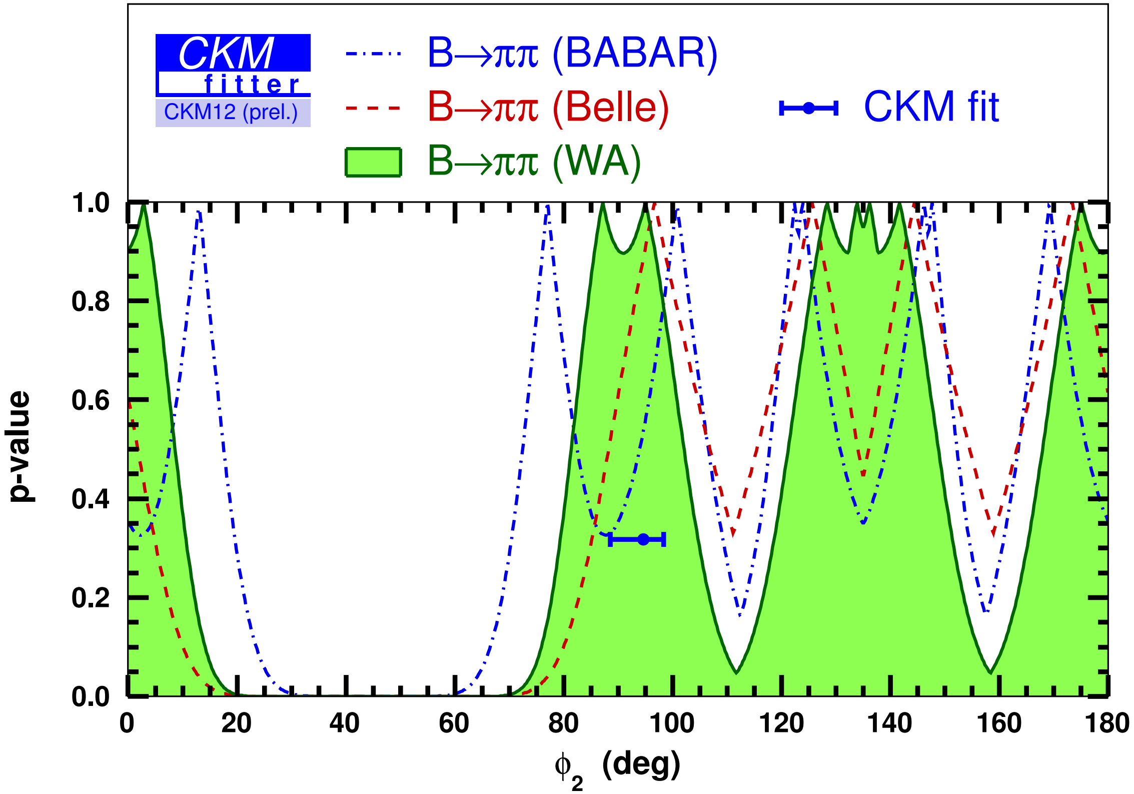


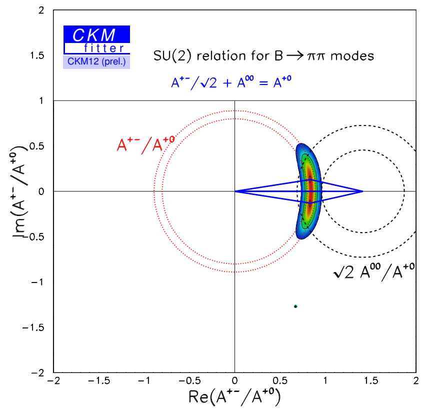


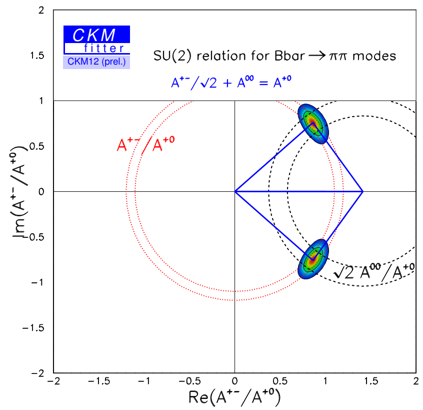


ϕ_2 from $B \to \pi\pi$

ϕ_2/α constraints







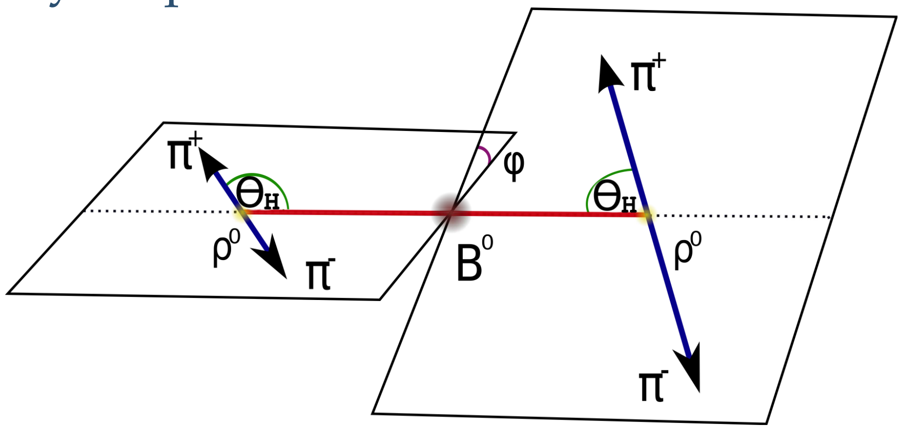
Belle: $\phi_2 \in [85.0^\circ, 148.0^\circ]$, BaBar: $\alpha \in [71^\circ, 109^\circ]$, WA: $\phi_2/\alpha = (87.1^{+17.5}_{-7.8})^\circ$

$B \to \rho\rho$

- $B \to \rho\rho$, $\rho \to \pi\pi$
- Superposition of CP even and odd states
- Separation through helicity analysis
-

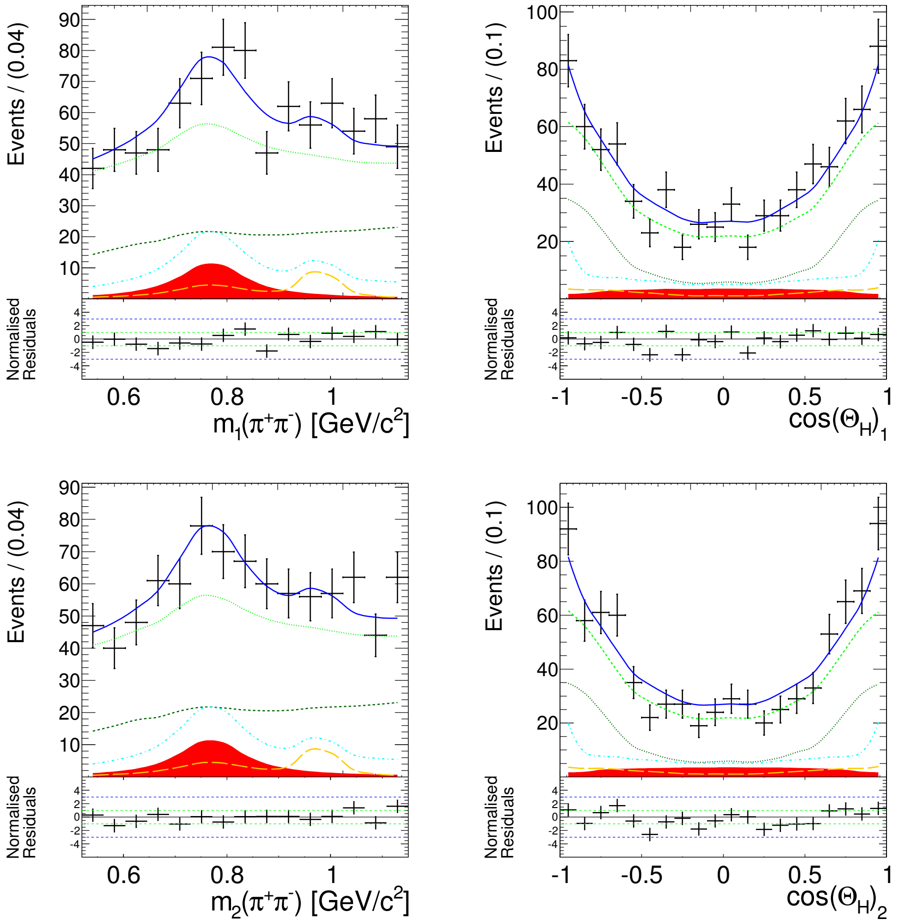
$$\frac{d^2\Gamma}{\Gamma d\cos\theta_{H1} d\cos\theta_{H2}} = \frac{9}{4}\left[\frac{1}{4}(1-f_L)\sin^2\theta_{H1}\sin^2\theta_{H2} + f_L\cos^2\theta_{H1}\cos^2\theta_{H2}\right]$$

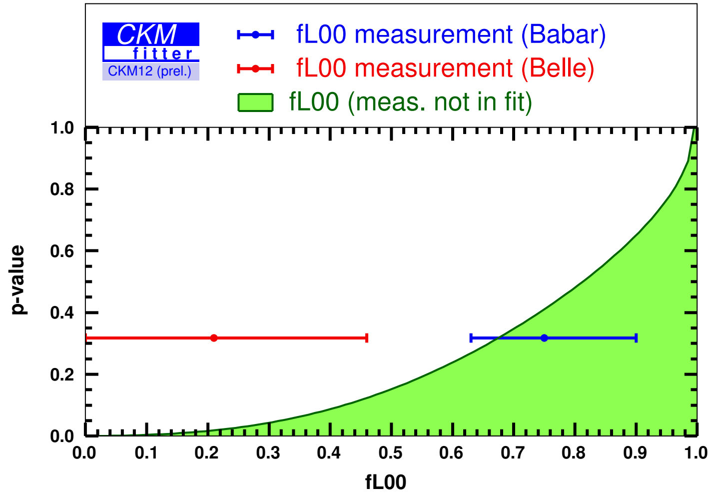
where $f_L = |A_0|^2/\sum|A_i|^2$ is the fraction of longitudinal polarization (pure CP eigenstate); A_0, A_{+1} and A_{-1} are the helicity amplitudes.



arXiv:1212.4015

6D fit to data





2.1σ tension

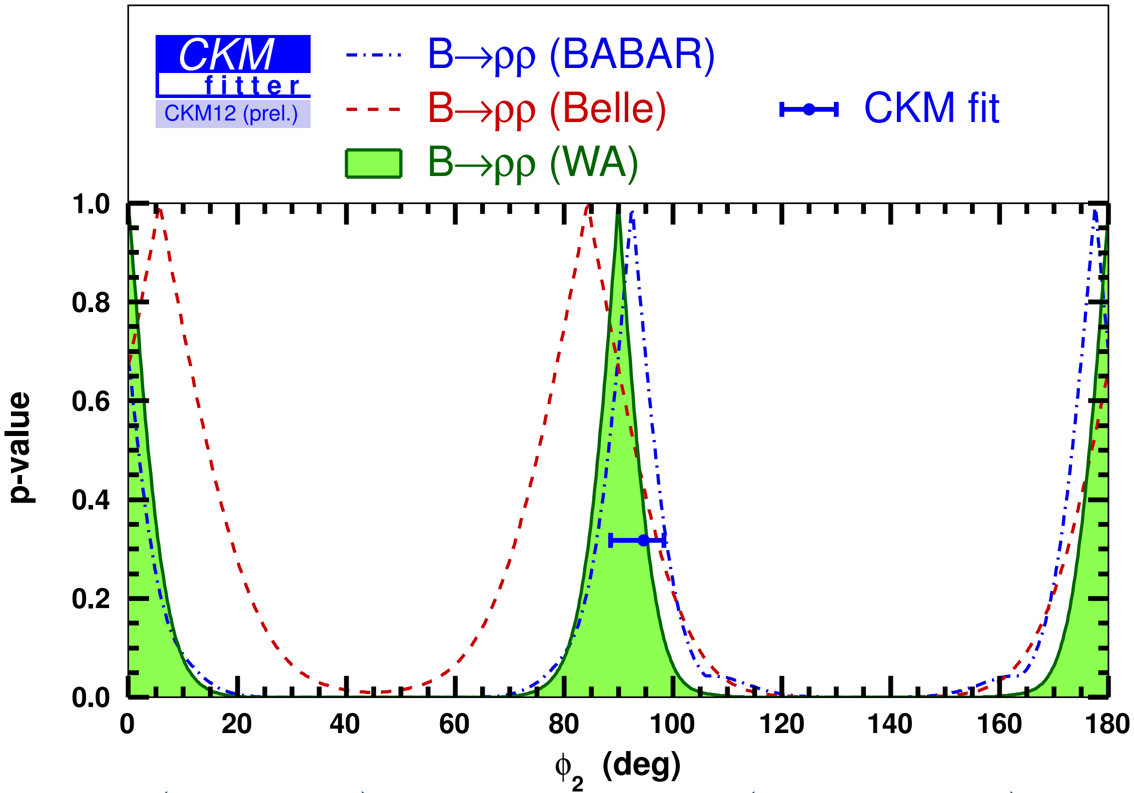
$$\mathcal{B}(B \to \rho^0 \rho^0) = (1.02 \pm 0.30 \pm 0.22) \times 10^{-6}$$

$$f_L = 0.21^{+0.18}_{-0.22} \pm 0.11$$

ϕ_2 from $B \to \rho\rho$

ϕ_2/α constraints

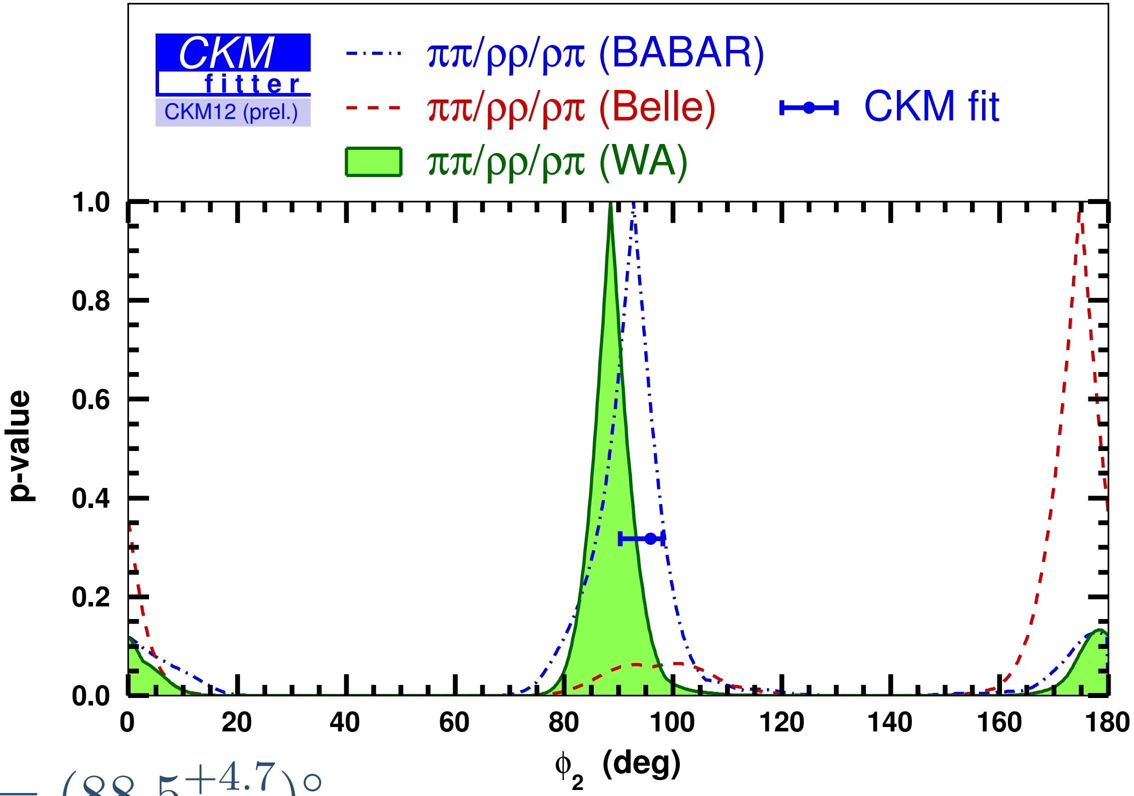
- small penguin contribution
- best environment for constraining ϕ_2 with 1st generation B-factories



Belle: $\phi_2 = (84 \pm 13)^\circ$, BaBar: $\alpha = (92.4 \pm 6.4)^\circ$, WA: $\phi_2/\alpha = (89.9^{+5.4}_{-5.3})^\circ$

Summary of $B \to \pi\pi, \rho\rho$

- Belle updated results on $B \to \pi^+\pi^-$, $B \to \rho^0\rho^0$
- Best constraint on ϕ_2/α comes from $B \to \rho\rho$

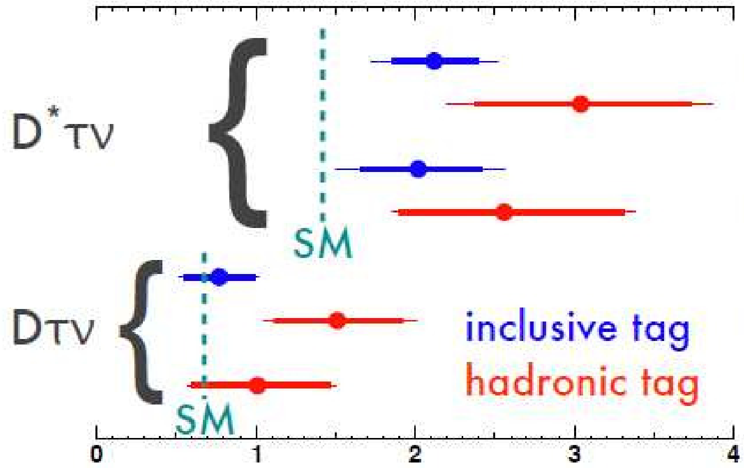


$$\phi_2/\alpha = (88.5^{+4.7}_{-4.4})^\circ$$

Stay tuned for updated results and upcoming Belle II results.

Thank you!

Comparison of the $B \to \bar{D}^{(*)}\tau\nu_\tau$ results



$\mathcal{B}(D^{*0}\tau^-\bar{\nu}_\tau) = [2.12^{+0.28}_{-0.27}(\text{stat}) \pm 0.29(\text{syst})]\%$

$\mathcal{B}(D^{*0}\tau^-\bar{\nu}_\tau) = [3.04^{+0.69}_{-0.66}(\text{stat})^{+0.40}_{-0.47}(\text{syst}) \pm 0.22(\text{norm})]\%$

$\mathcal{B}(D^{*+}\tau^-\bar{\nu}_\tau) = [2.02^{+0.40}_{-0.37}(\text{stat}) \pm 0.37(\text{syst})]\%$

$\mathcal{B}(D^{*+}\tau^-\bar{\nu}_\tau) = [2.56^{+0.75}_{-0.66}(\text{stat})^{+0.31}_{-0.22}(\text{syst}) \pm 0.10(\text{norm})]\%$

$\mathcal{B}(D^{0}\tau^-\bar{\nu}_\tau) = [0.77 \pm 0.22(\text{stat}) \pm 0.12(\text{syst})]\%$

$\mathcal{B}(D^{0}\tau^-\bar{\nu}_\tau) = [1.51^{+0.41}_{-0.39}(\text{stat})^{+0.24}_{-0.19}(\text{syst}) \pm 0.15(\text{norm})]\%$

$\mathcal{B}(D^{+}\tau^-\bar{\nu}_\tau) = [1.01^{+0.46}_{-0.41}(\text{stat})^{+0.13}_{-0.11}(\text{syst}) \pm 0.10(\text{norm})]\%$

- Good agreement between different tagging;
- Good agreement with BaBar:
  $\mathcal{B}(B \to \bar{D}^*\tau\nu_\tau) = [1.76 \pm 0.13 \pm 0.12]\%$
  $\mathcal{B}(B \to \bar{D}\tau\nu_\tau) = [1.02 \pm 0.13 \pm 0.11]\%$;
- All results are slightly larger than SM predictions.