Une Belle histoire

(recent results)

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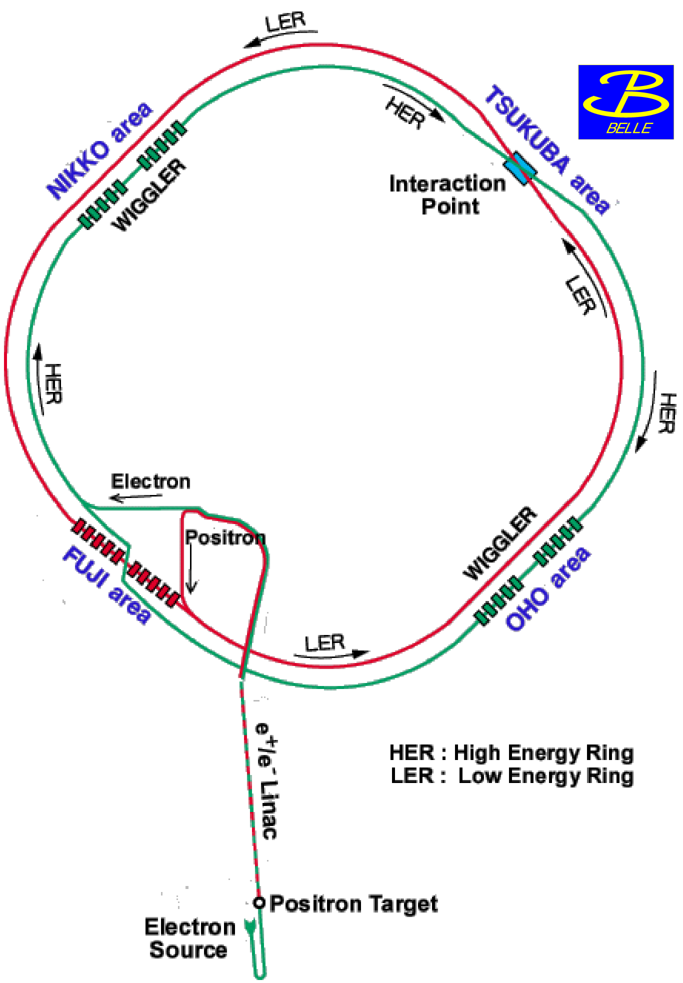
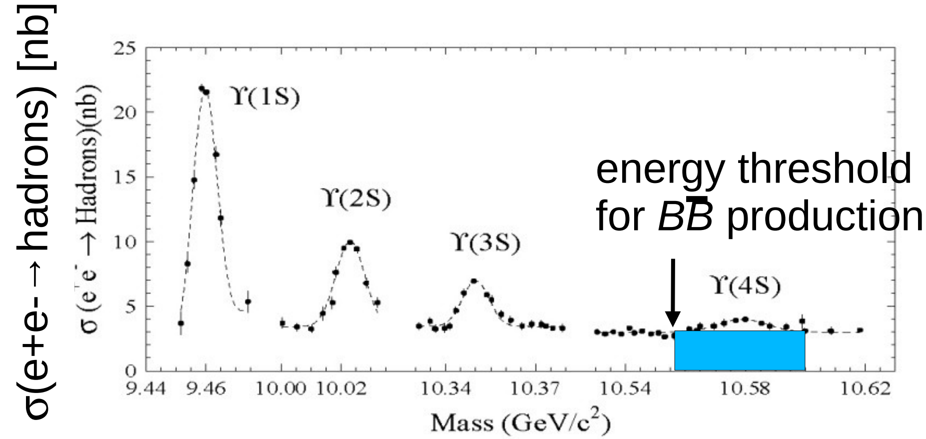
LPNHE, Oct 3, 2013

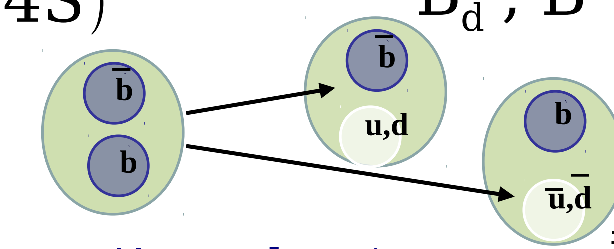
Belle = Υ(4S) B-factory

Belle is an international collaboration
18 countries, 80 institutes
448 members





Υ(4S) B_d^0, B^+



$\bar{B}_d^0$, B^-

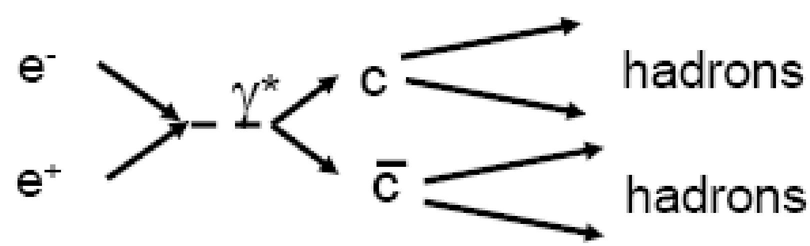
''on resonance'' production

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0\bar{B}_d^0$, B^+B^-

- 2 B's and nothing else !
- 2 B mesons are created simultaneously in a L=1 coherent state
  ⇒ before first decay, the final states contains a B and a $\bar{B}$

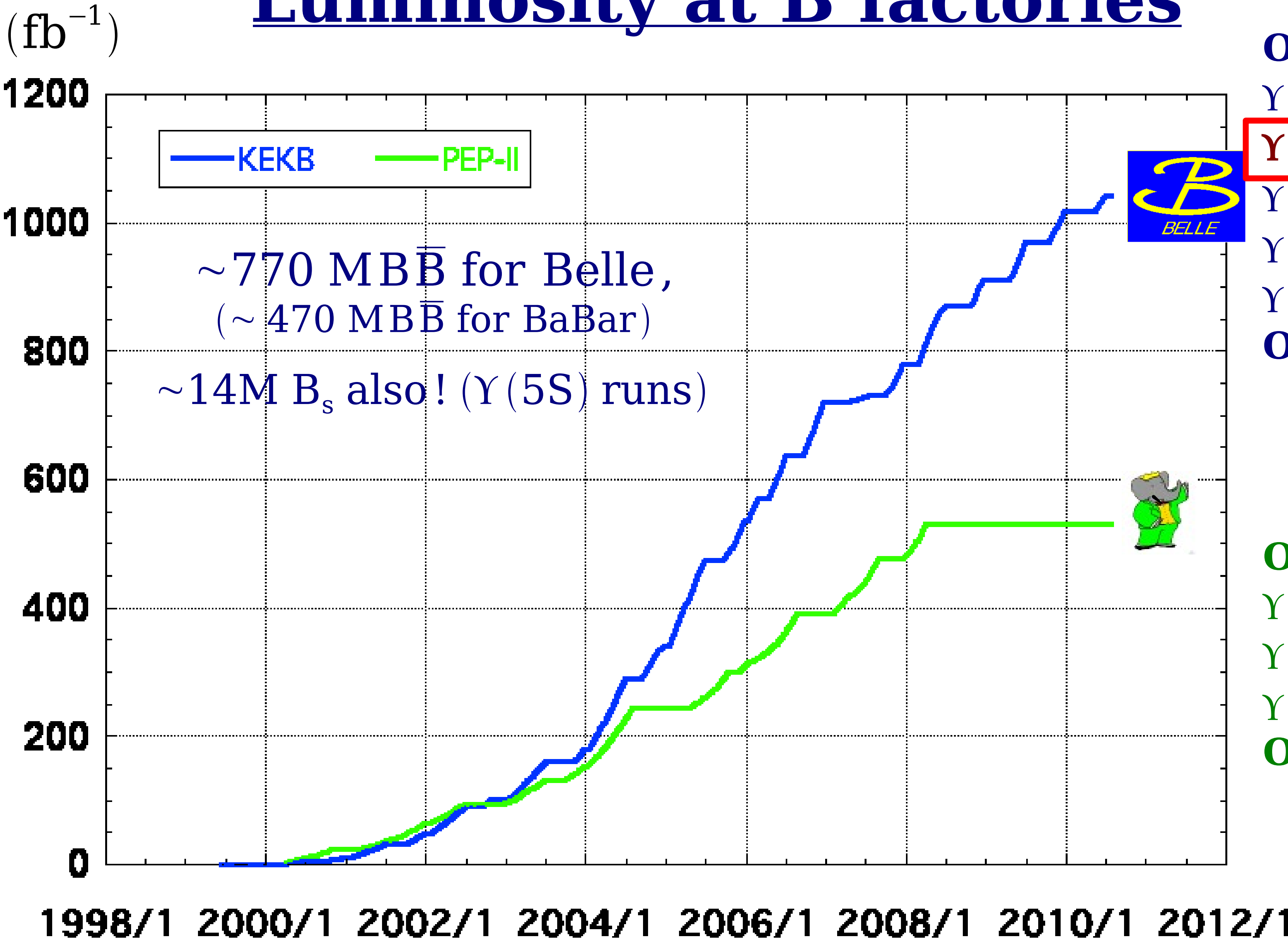
''continuum'' production

$\sigma(e^+e^- \rightarrow c\bar{c}) \simeq 1.3$ nb ($\sim 1.3\times10^9$ $X_c\bar{Y}_c$ pairs)



ττ production also !

Luminosity at B factories



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

Υ(2S): 24 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan:

$\sim$ 100 fb^{-1}

$\sim$ 550 fb^{-1}

On resonance:

Υ(4S): 433 fb^{-1}

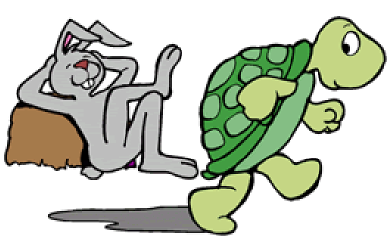
Υ(3S): 30 fb^{-1}

Υ(2S): 14 fb^{-1}

Off resonance:

$\sim$ 54 fb^{-1}

Rien ne sert de courir ; il faut partir a point.
Le Lievre et la Tortue en sont un temoignage.
Gageons, dit celle-ci, que vous n'atteindrez point
Si tot que moi ce but. Si tot ? Etes-vous sage ?
Repartit l'Animal leger...



Belle in a nutshell

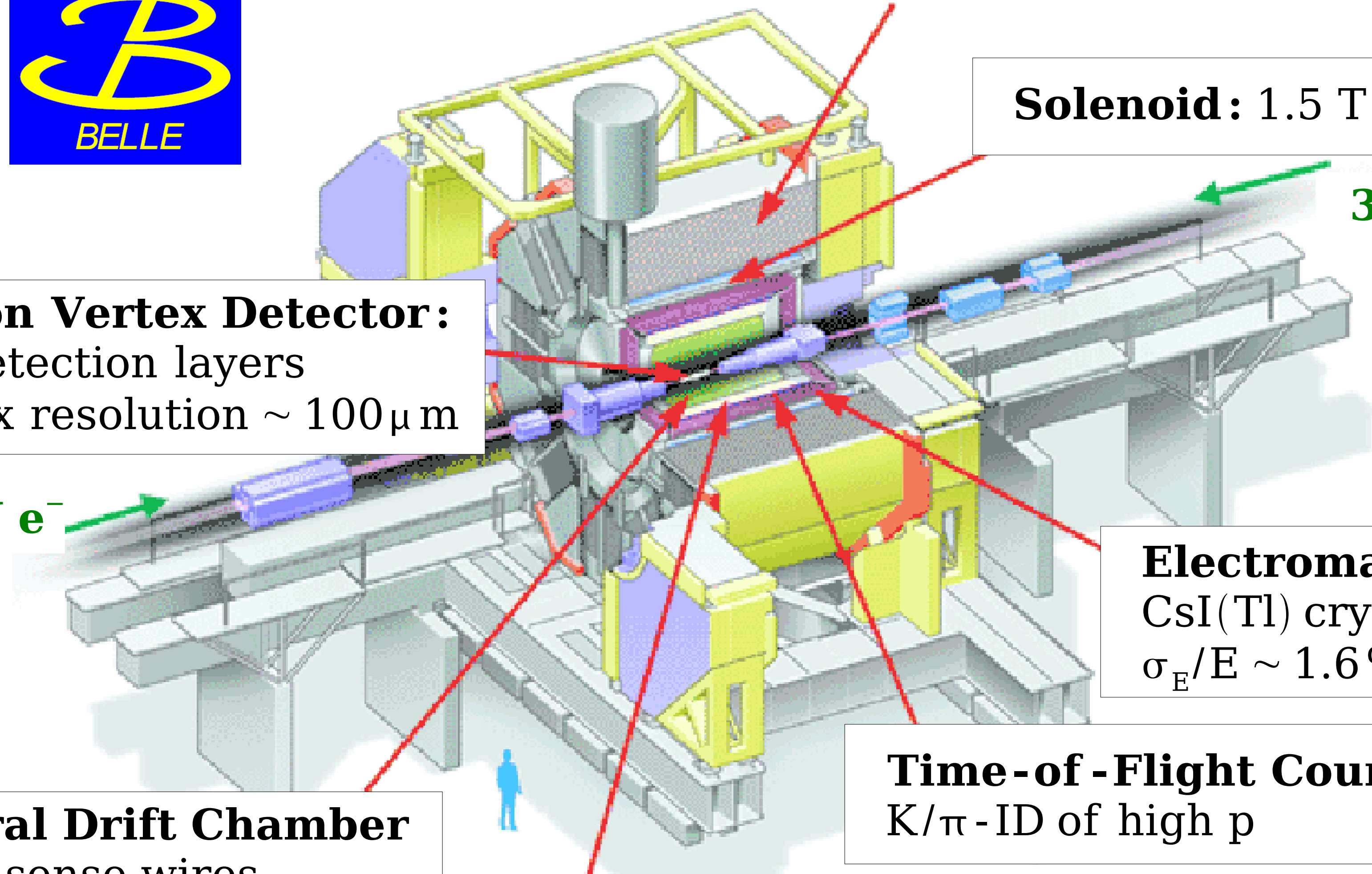
KLM ($K_L\mu$) Detector: Sandwich of 14 RPCs and 15 iron plates

Solenoid: 1.5 T

3.5 GeV e^+

Silicon Vertex Detector:
3/4 detection layers
Vertex resolution ~ 100 μm

8.0 GeV e^-



Electromagnetic Cal:
CsI(Tl) crystal
$\sigma_E/E \sim 1.6\%$ @ 1 GeV

Time-of-Flight Counter:
K/π-ID of high p

Central Drift Chamber
8,400 sense wires
PID with dE/dx

Aerogel Cerenkov Counter:
Refractive index n=1.01-1.03
K/π of middle p

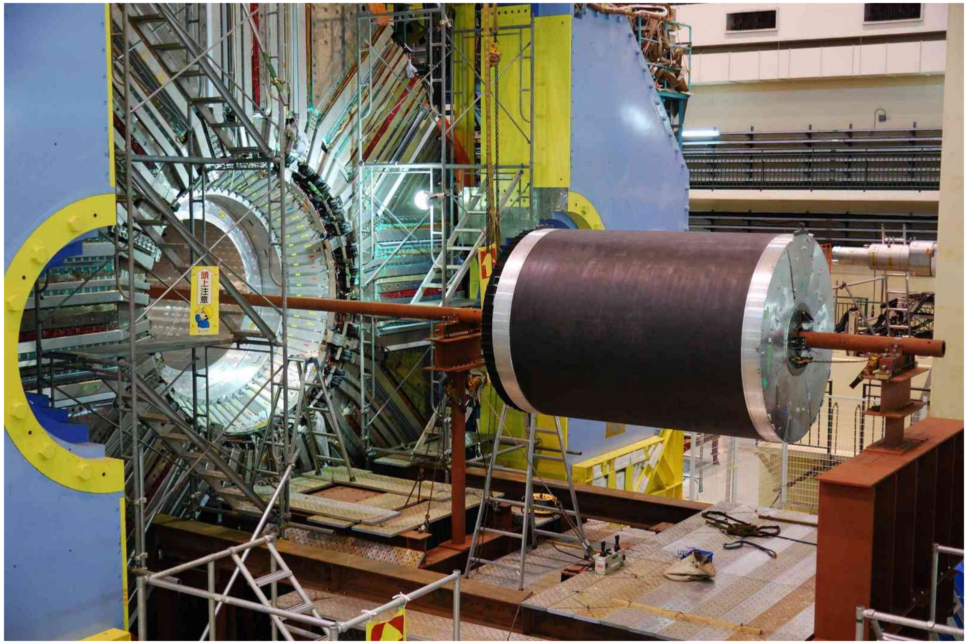
very stable detector, good particle identification, (kaon, pion, electron, muon),

e^+e^- is a clean environment: excellent tracking, triggering, tagging...

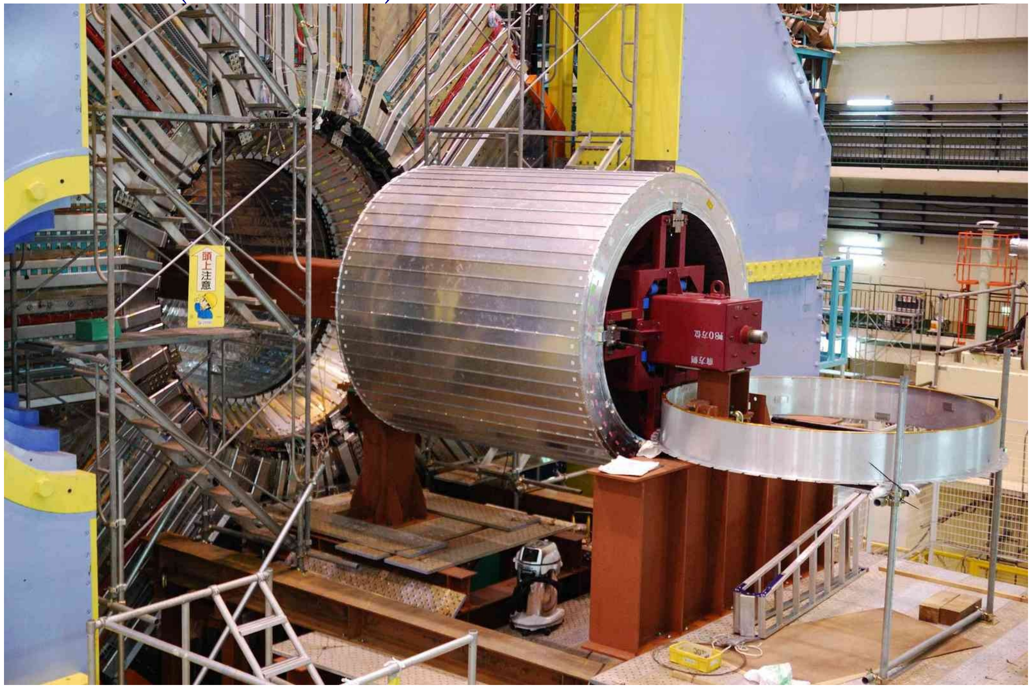
Belle soon after 2010 shutdown...

CDC

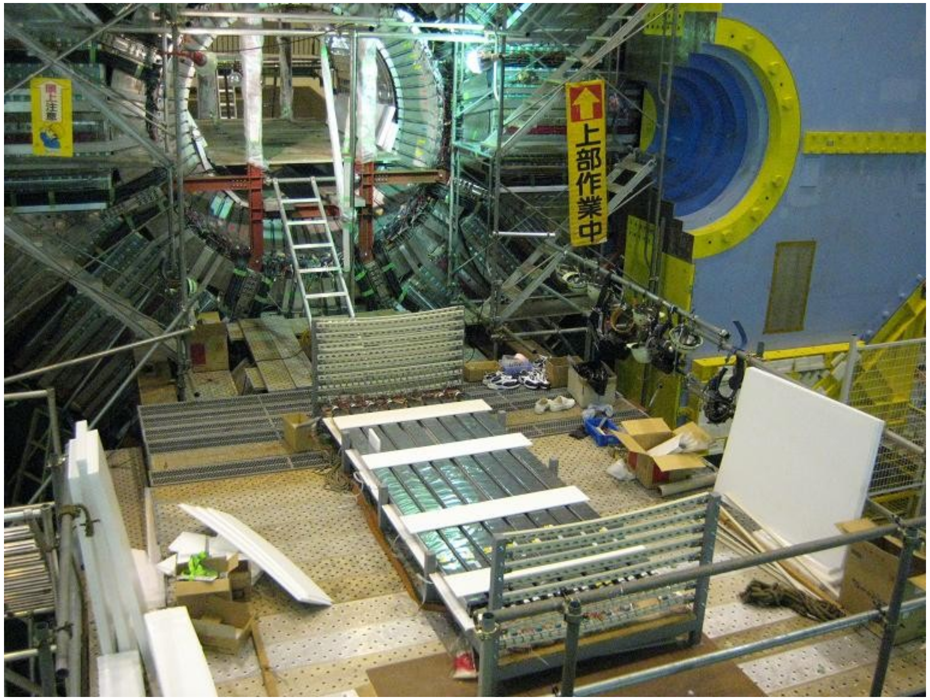
ECL (backward endcap)



ACC (barrel)



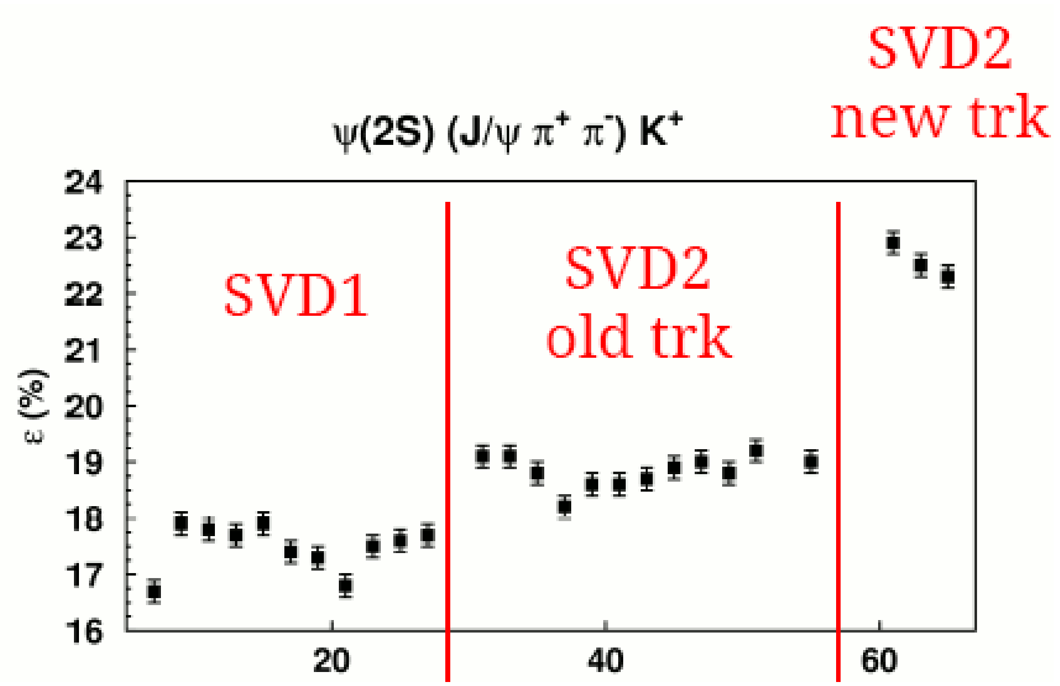
TOF



Toward the final Belle results...

- include the last part of the data (> 200 fb^{-1}, often much more...)
- reprocessed data (~ 3/4 of the data, tracking efficiency increase > 20%)
- significant improvements on the hadronic tag

Efficiency for $B^+ \to \psi(2S)\,(J/\psi\,\pi\pi)\,K^+$



reconstruction systematics improved:

tracking efficiency systematics at high P_t

1.2% → 0.35% (update)

K_S: 4.5% → 2%

π^0: 4% → ??

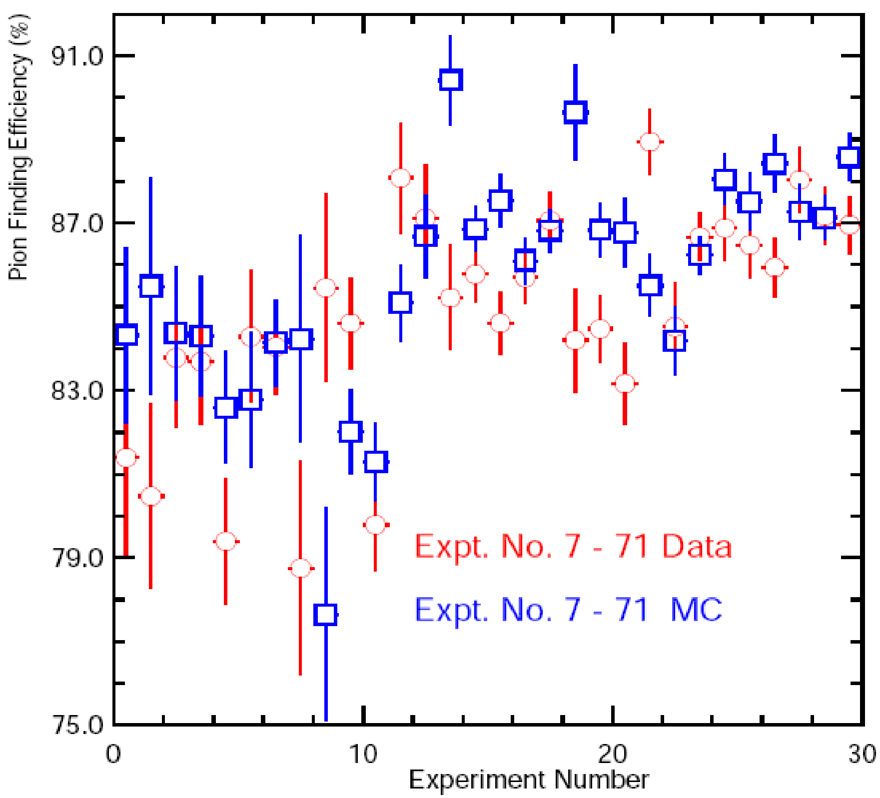
Example of $D \to K_S\pi\pi$

0.5M signal candidates in 540 fb^{-1}

PRL 99, 131803 (2007)

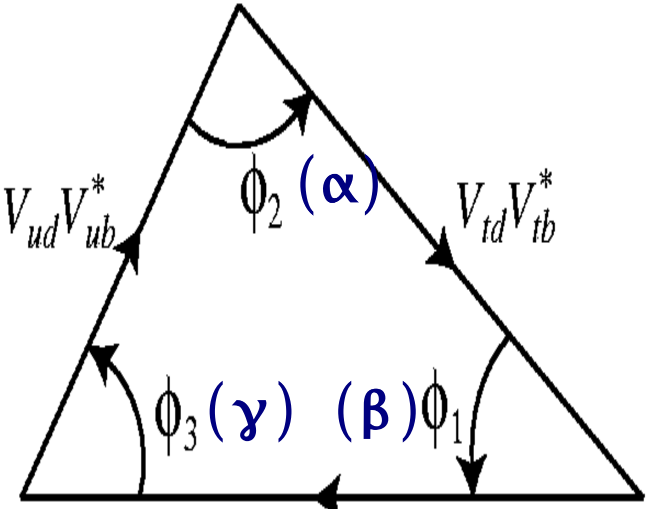
status of the update:

1.1M signal candidates in 790 fb^{-1}

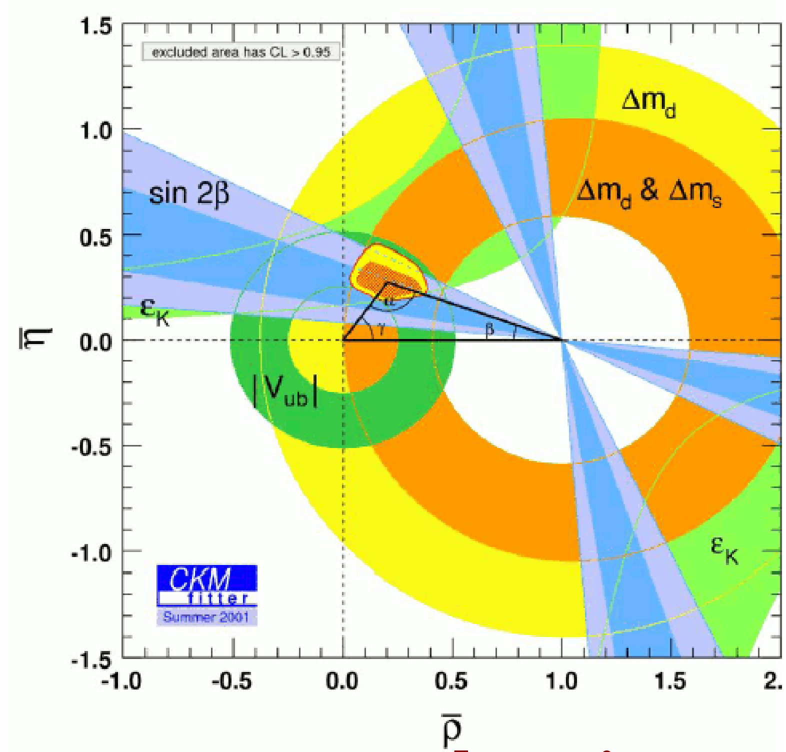


First motivation of Belle

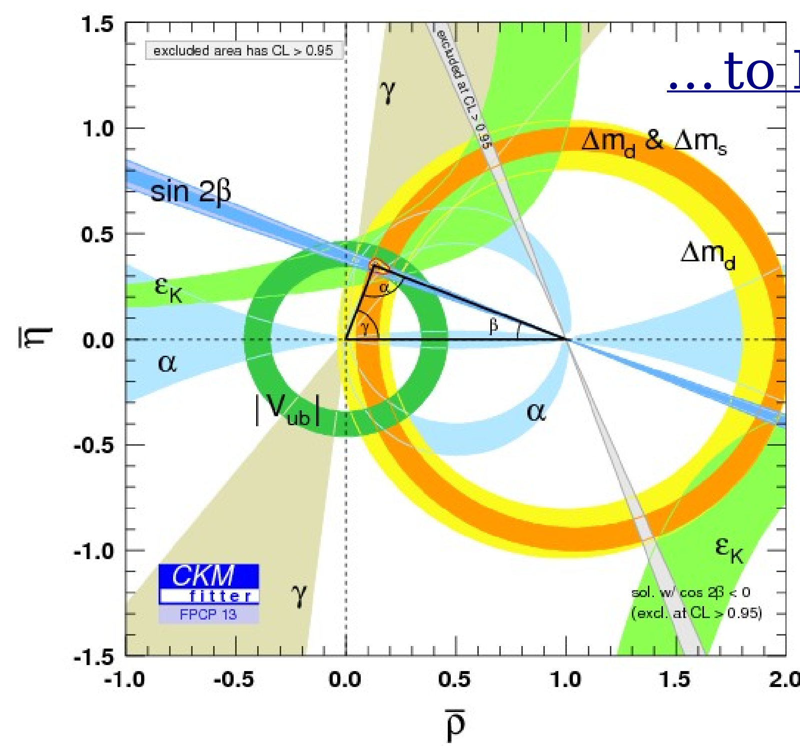
- Overconstrain the CKM matrix: measure fundamental parameters, constrain new physics effects
- Measure the 4 free parameters in various ways:
  - CP conserving $\{|V_{us}|, |V_{cb}|, |V_{td}|, |V_{ub}|\}$
  - CP violating $\{\epsilon_K, \varphi_s, \beta, \gamma\}$
  - Tree level $\{\dots, \dots, |V_{ub}|, \gamma\}$
  - Loop level $\{\dots, \dots, |V_{td}|, \beta\}$
  - ...



from EPS 2001...



...to FPCP 2013



⇒ **clear impact on B-factories (angles and sides) !**

Outline

Recent updates for UT:

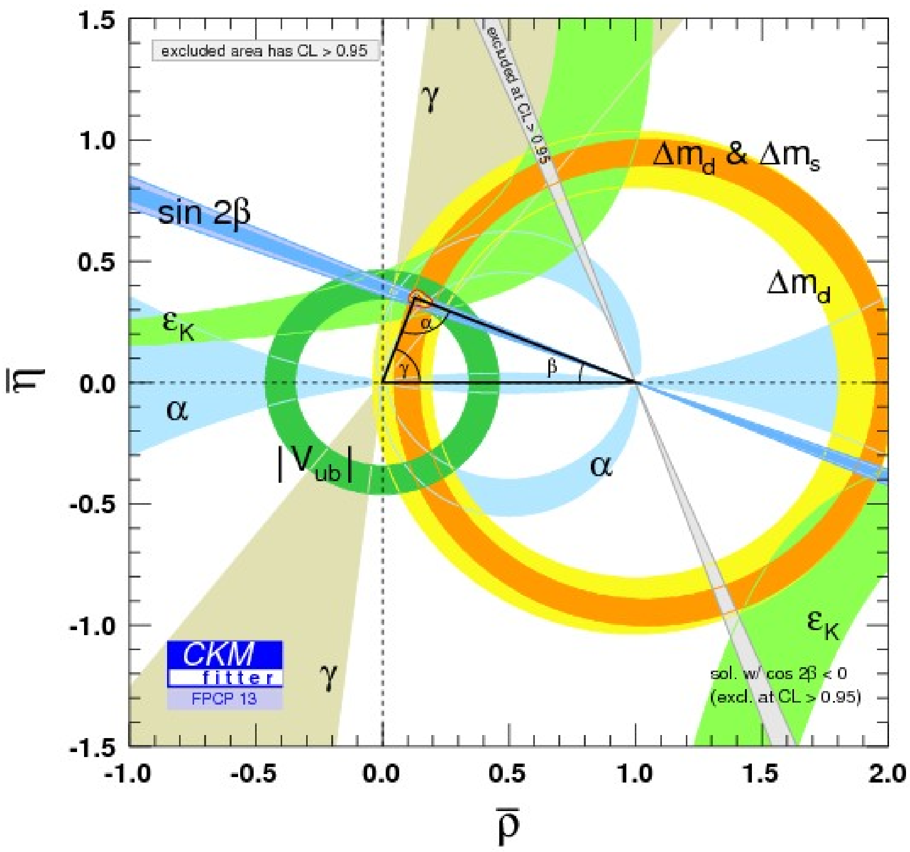
β: $b \to c\bar{c}d$, $b \to c\bar{c}s$ processes

γ: $B^+ \to D^{(*)}K^+$

$B \to \tau\nu$

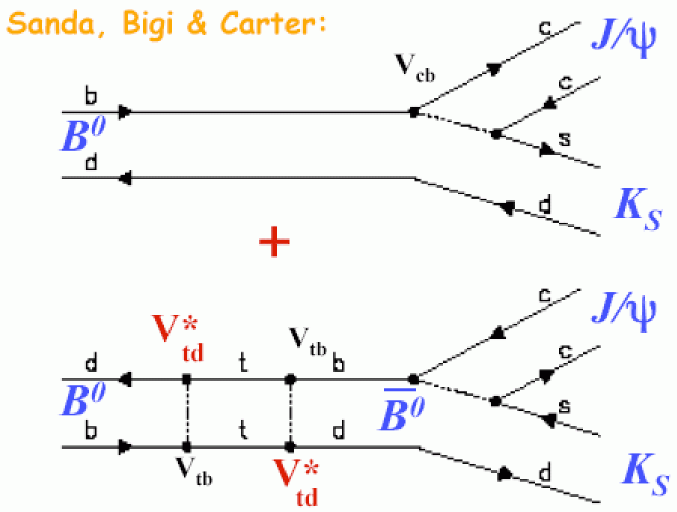
(and modes with missing energy)

Physics at $\Upsilon(5S)$: B_s and bottomomium



Time−dependent CP asymmetries in decays to CP eigenstates

Sanda, Bigi & Carter:



$\propto V_{td}^{*2}$

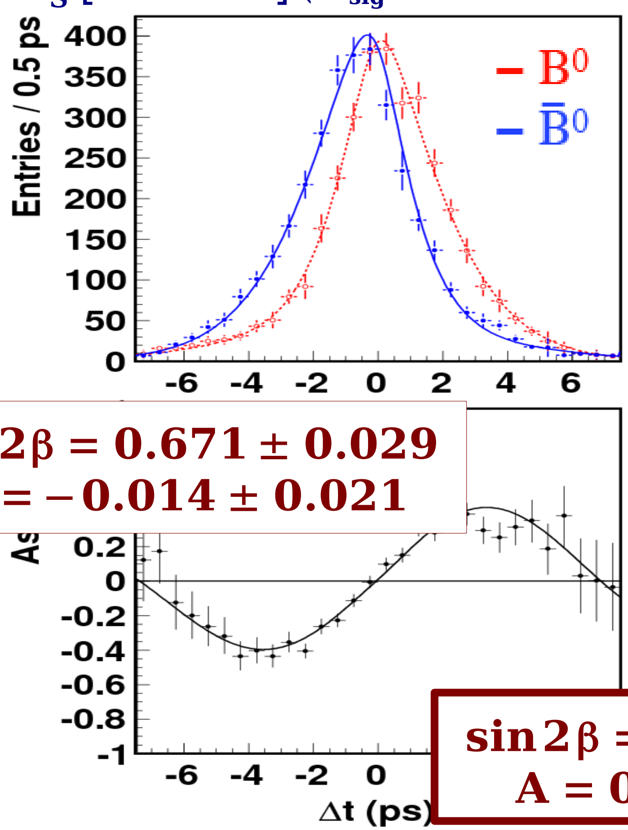
$$A_{CP}(f;t) = \frac{N(\overline{B}^0(t)\to f) - N(B^0(t)\to f)}{N(\overline{B}^0(t)\to f) + N(B^0(t)\to f)} = \mathbf{S}\sin\Delta m_d t + \mathbf{A}\cos\Delta m_d t$$

$$= \frac{2\,\mathrm{Im}\,\lambda}{|\lambda|^2+1}\sin\Delta m_d t + \frac{|\lambda|^2-1}{|\lambda|^2+1}\cos\Delta m_d t$$

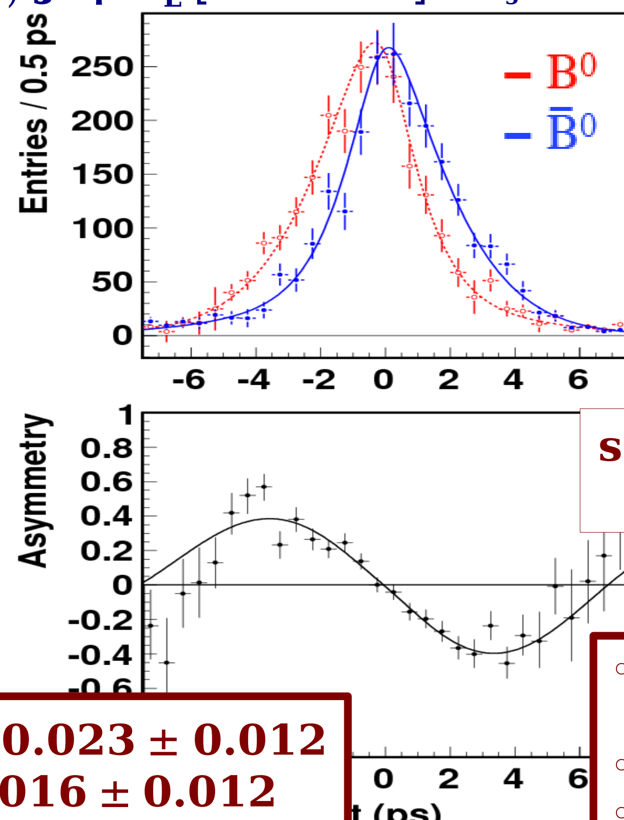
$$\lambda = \frac{q}{p}\,\frac{A(\overline{B}^0\to f)}{A(B^0\to f)} = e^{-i2\varphi_i}\frac{\overline{A}_f}{A_f}$$

$\mathbf{A} = 0$ and $\mathbf{S} = -\xi_f \sin 2\beta$ for $(c\bar{c})K_{S/L}$ $(\xi_f = \mp 1)$

$(c\bar{c})K_S$ [CP odd] (N_{sig} = 15600, Purity = 96%) **$J/\psi K_L$ [CP even] (N_{sig} = 10041, Purity = 63%)**



sin 2β = 0.671 ± 0.029
A = −0.014 ± 0.021



sin 2β = 0.642 ± 0.047
A = 0.019 ± 0.026

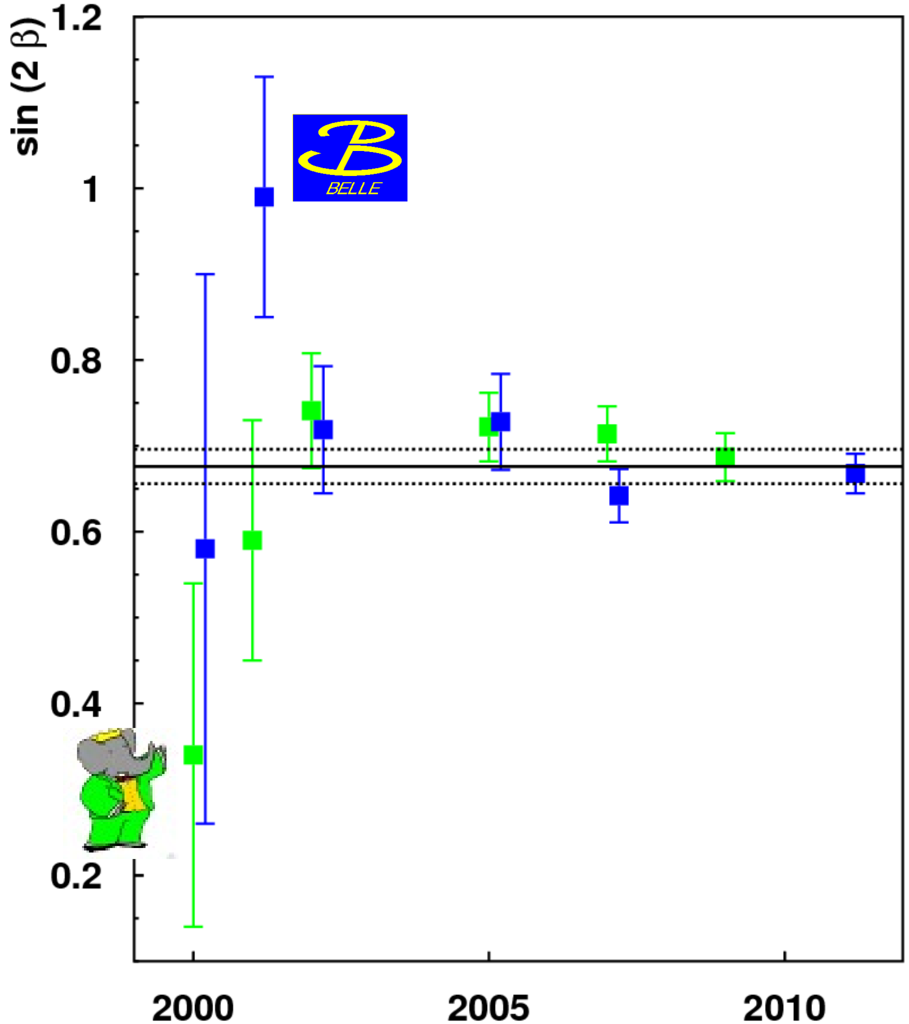
772×10^6 $B\overline{B}$ pairs
[PRL 108 (2012) 171802]

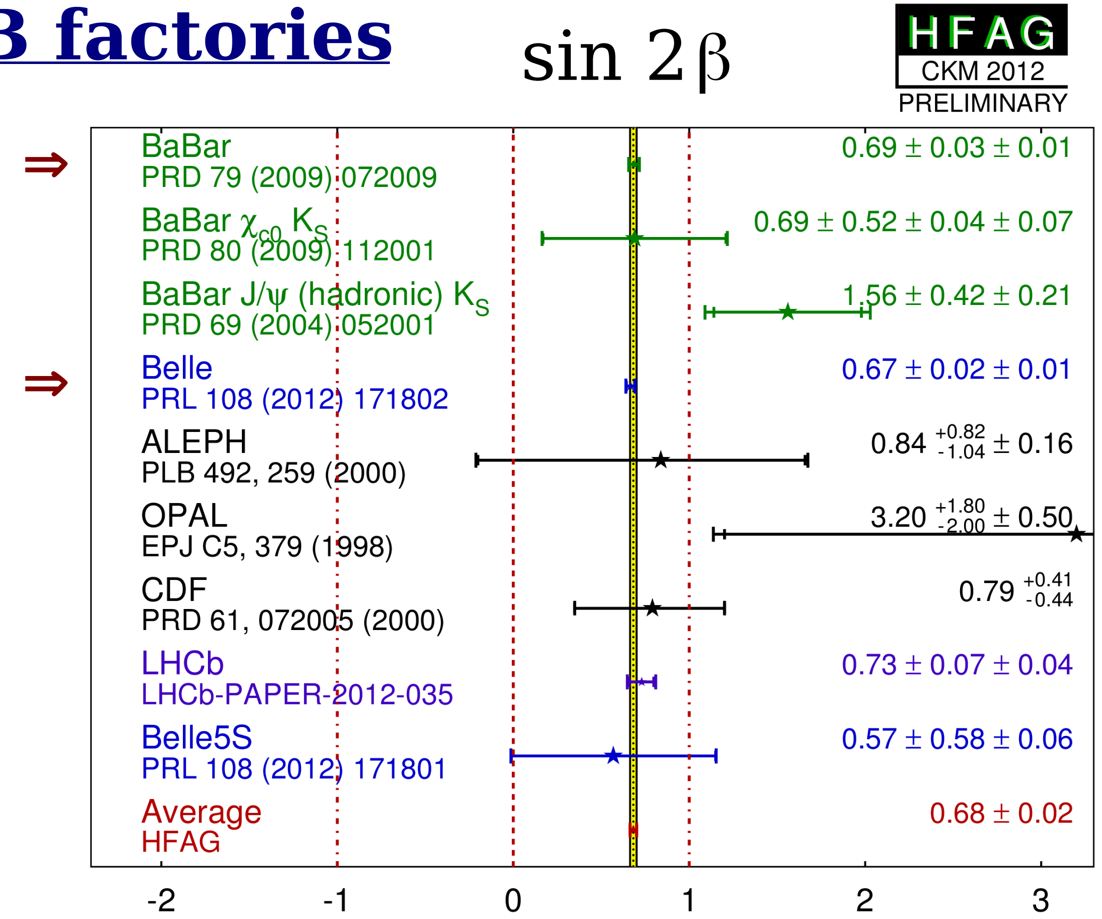
background subtracted
good tagged only

sin 2β = 0.667 ± 0.023 ± 0.012
A = 0.006 ± 0.016 ± 0.012

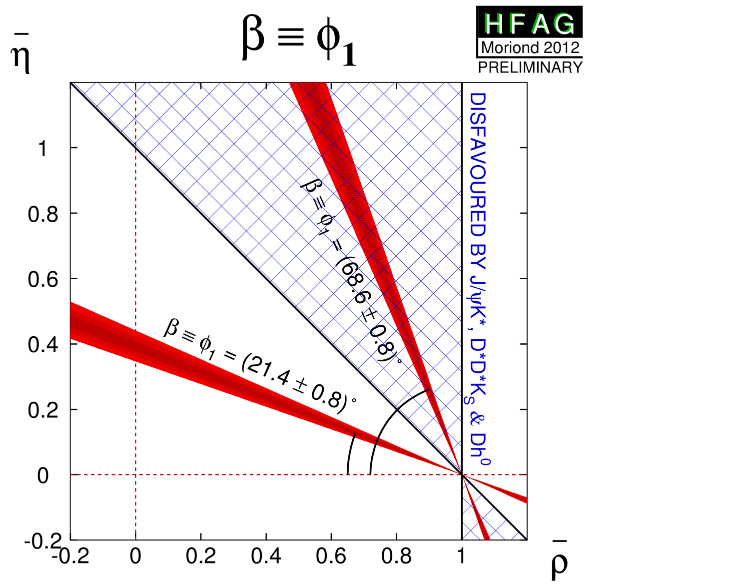
- World's most precise measurements
- anchor point of the SM
- still statistically limited !

La raison d'être of the B factories





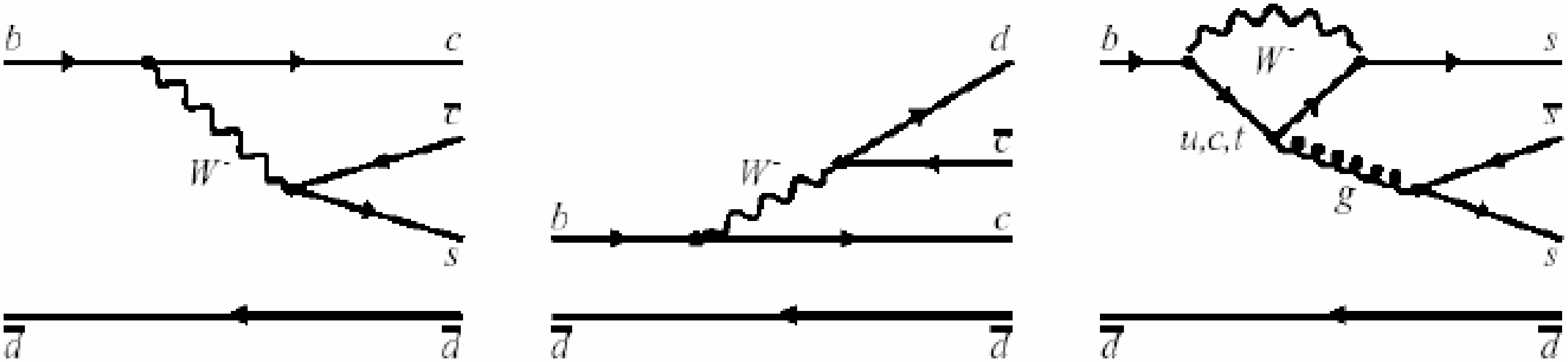
$$\beta = (21.5 \pm 0.8)^\circ$$



what is the source of CP violation ?

the **Kobayashi-Maskawa phase** is the source

β in other modes



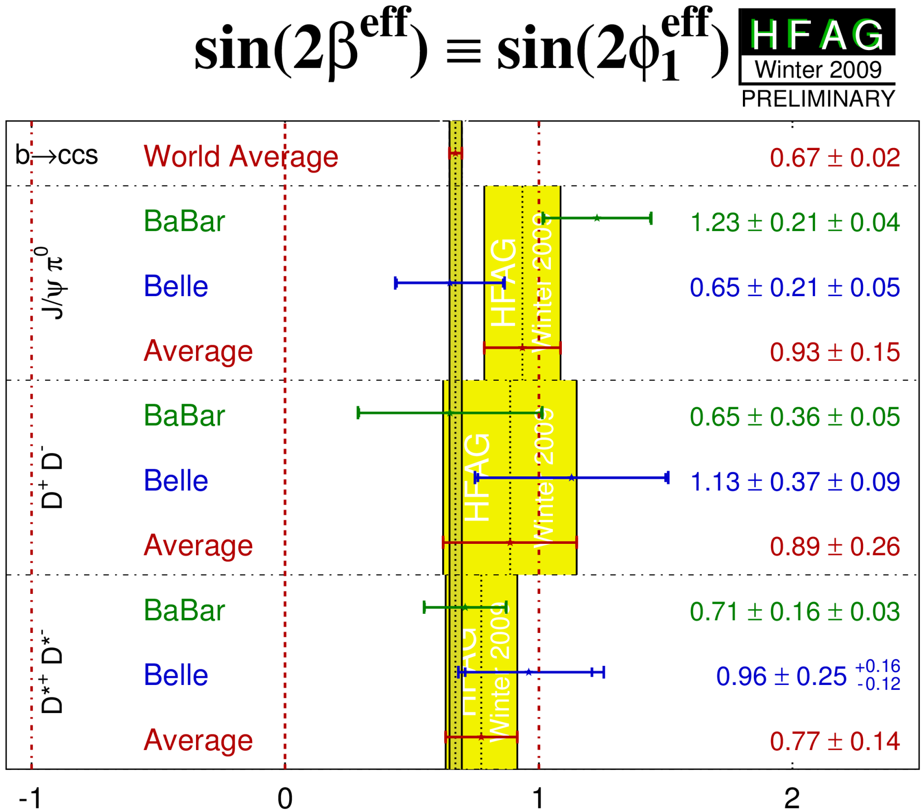
$J/\psi K^0_S, \psi(2S)K^0_S, \chi_{c1}K^0_S,$ $\eta_c K^0_S, J/\psi K^0_L,$ $J/\psi K^{*0}(K^{*0} \to K^0_S \pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K^0_S,$ $K^0_S K^0_S K^0_S, \eta' K^0, K^0_S \pi^0,$ $\omega K^0_S, f_0(980)K^0_S$

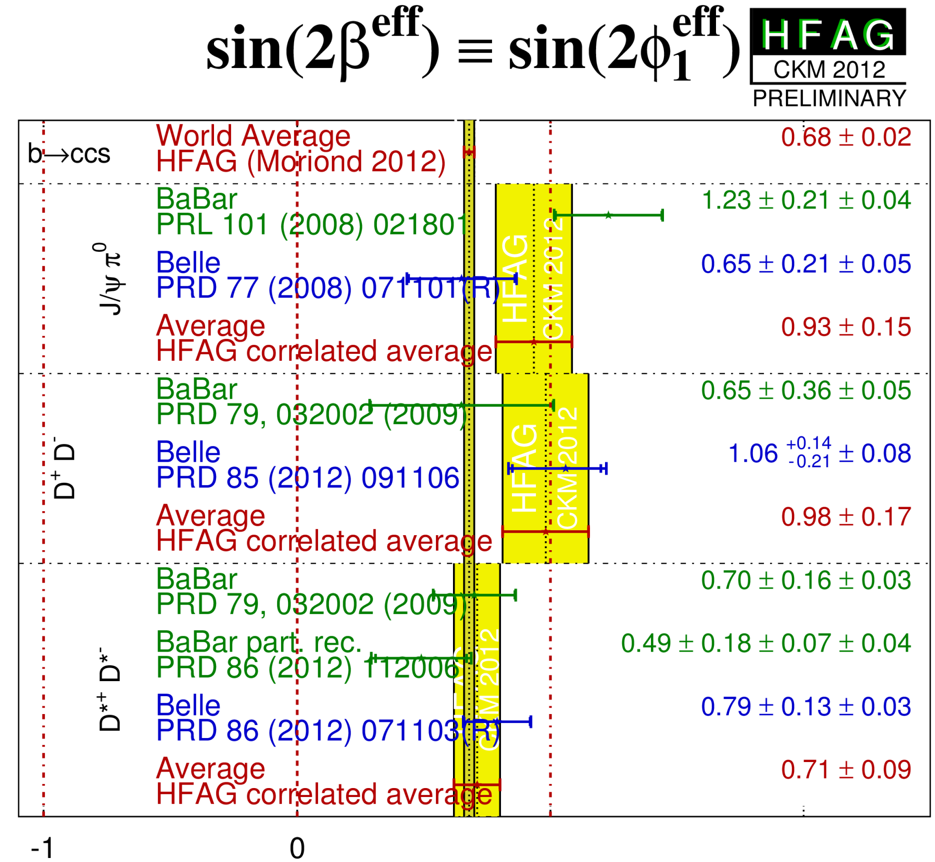
increasing tree diagram amplitude ←

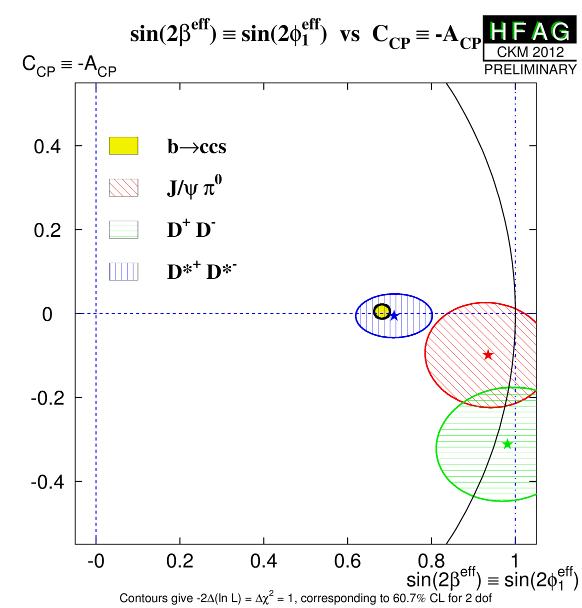
increasing sensitivity to new physics →

possible new sources of CPV ?

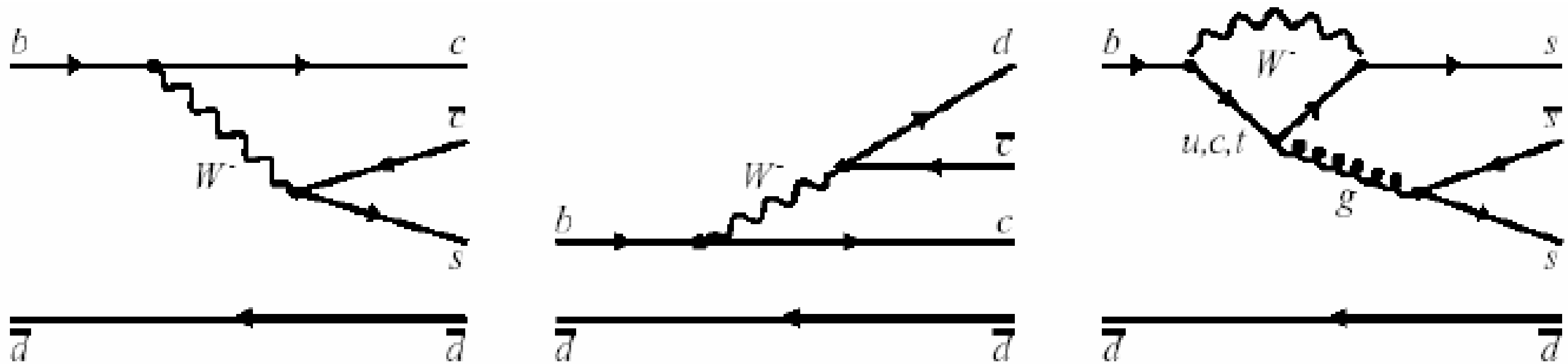
S and A in b→c$\bar{c}$d modes







good agreement with b→c$\bar{c}$s modes result
$S=-\sin 2\beta,\ A=0$



$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0, \eta_c K_S^0, J/\psi K_L^0, J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$, $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0, K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0, \omega K_S^0, f_0(980)K_S^0$

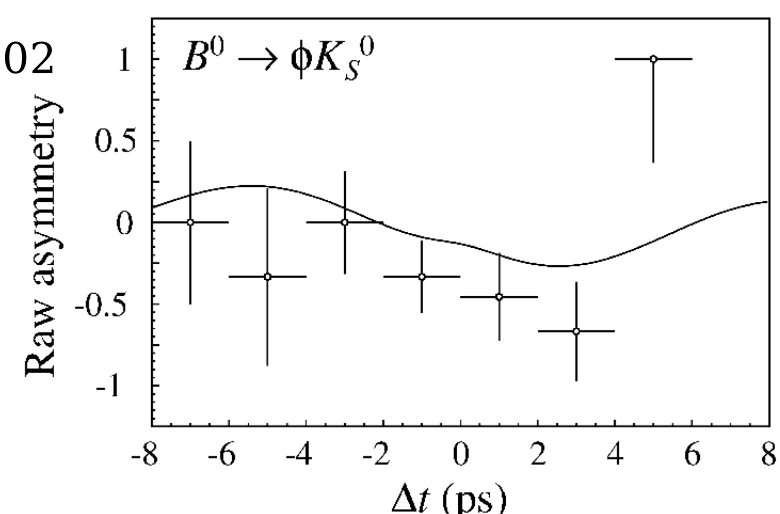
increasing tree diagram amplitude ←

increasing sensitivity to new physics →

first reported in Moriond EW 2002

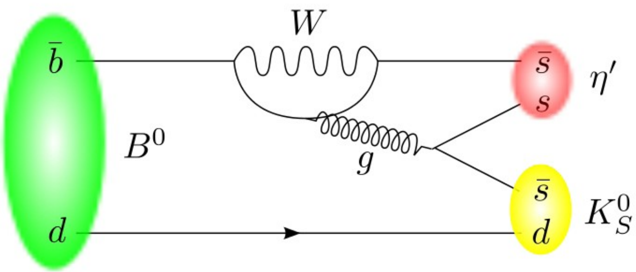
$''\sin 2\beta'' = -0.73 \pm 0.64 \pm 0.22$

[PRD 67, 031102 (2003)]



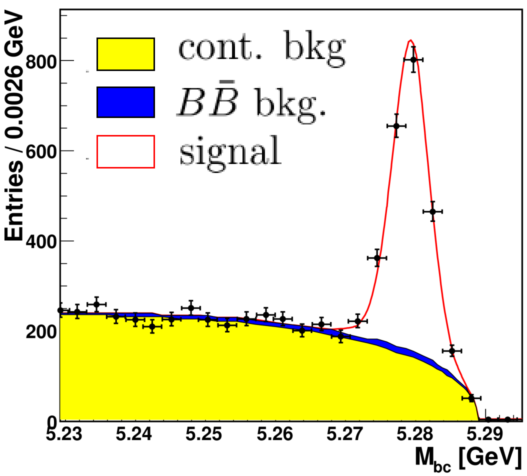
CPV in $b \to s\bar{q}q$ decays

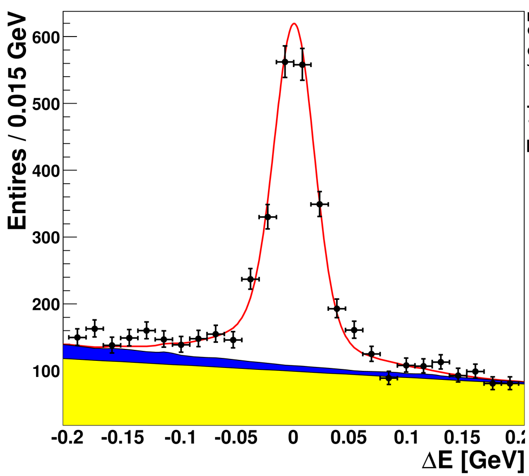
Observing $|S_{s\bar{q}q} - S_{J/\psi K^0}|$ to be large → sign of new physics

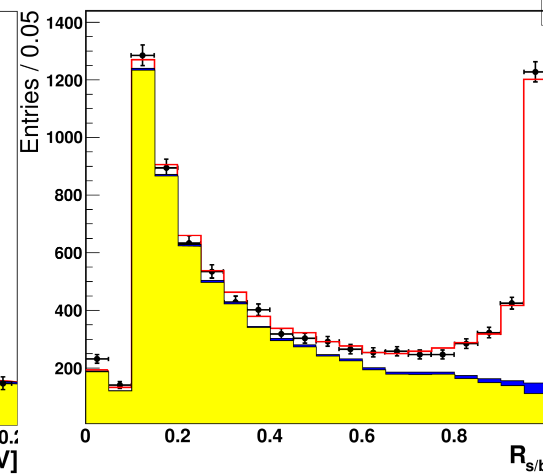


Mode	Events	Purity (%)
$\eta' \to \rho\gamma$	1411 ± 49	59
$\eta' \to \eta(\gamma\gamma)\pi\pi$	648 ± 28	89
$\eta' \to \eta(\pi\pi\pi^0)\pi\pi$	174 ± 14	94

$\eta' K_S^0$: M_{bc}, ΔE, $R_{s/b}$



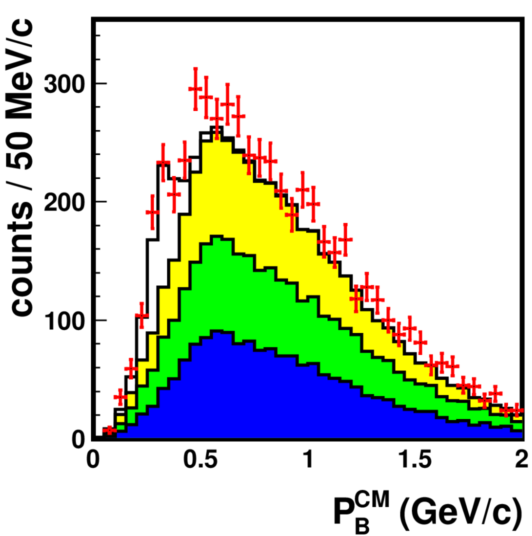


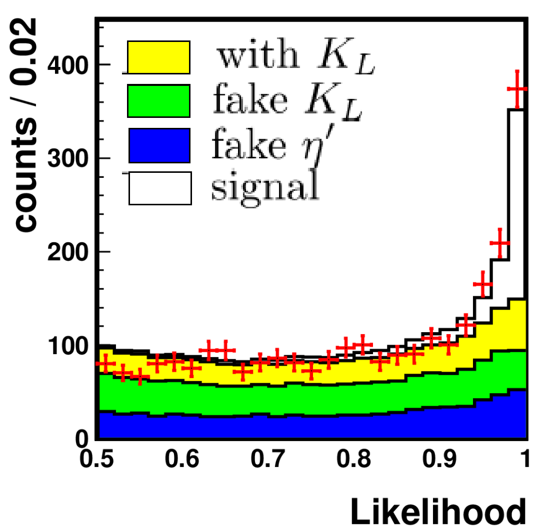


$R_{s/b}$ – likelihood ratio
event shape variables

To separate signal and main background, $e^+e^- \to q\bar{q}$ $(q = u, d, s \text{ and } c)$

$\eta' K_L^0$: p_B^{cms}, $R_{s/b}$, r





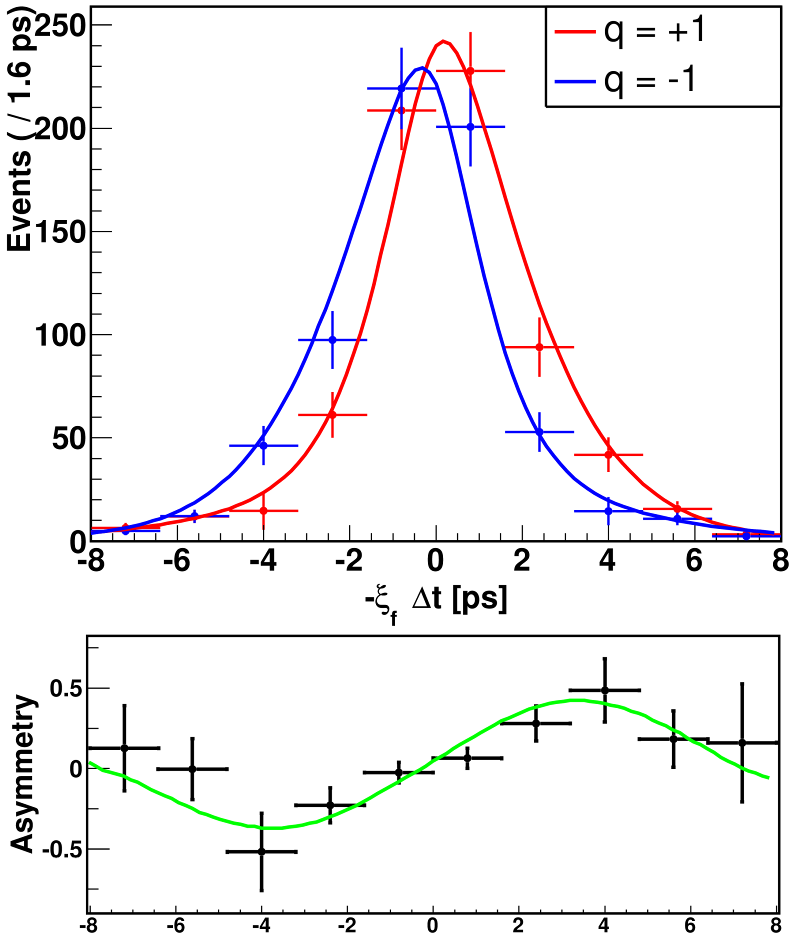
	This analysis 772 M $B\bar{B}$	2007 analysis 534 M $B\bar{B}$
mode	N_{sig}	N_{sig}
$\eta' K_S$	2506.3 ± 63.1	1256.6 ± 42.1
$\eta' K_L$	1041.7 ± 41.1	478.8 ± 41.1

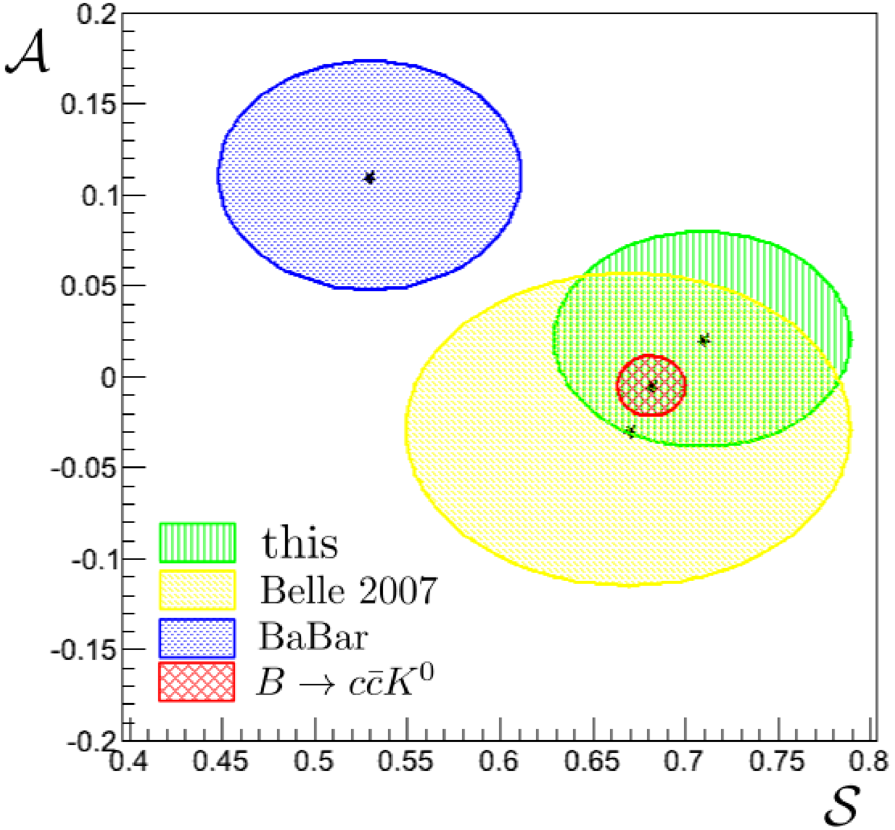
Beside additional data,
~ 25 % improvement
in reconstruction efficiency

$B^0 \to \eta' K^0$ analysis

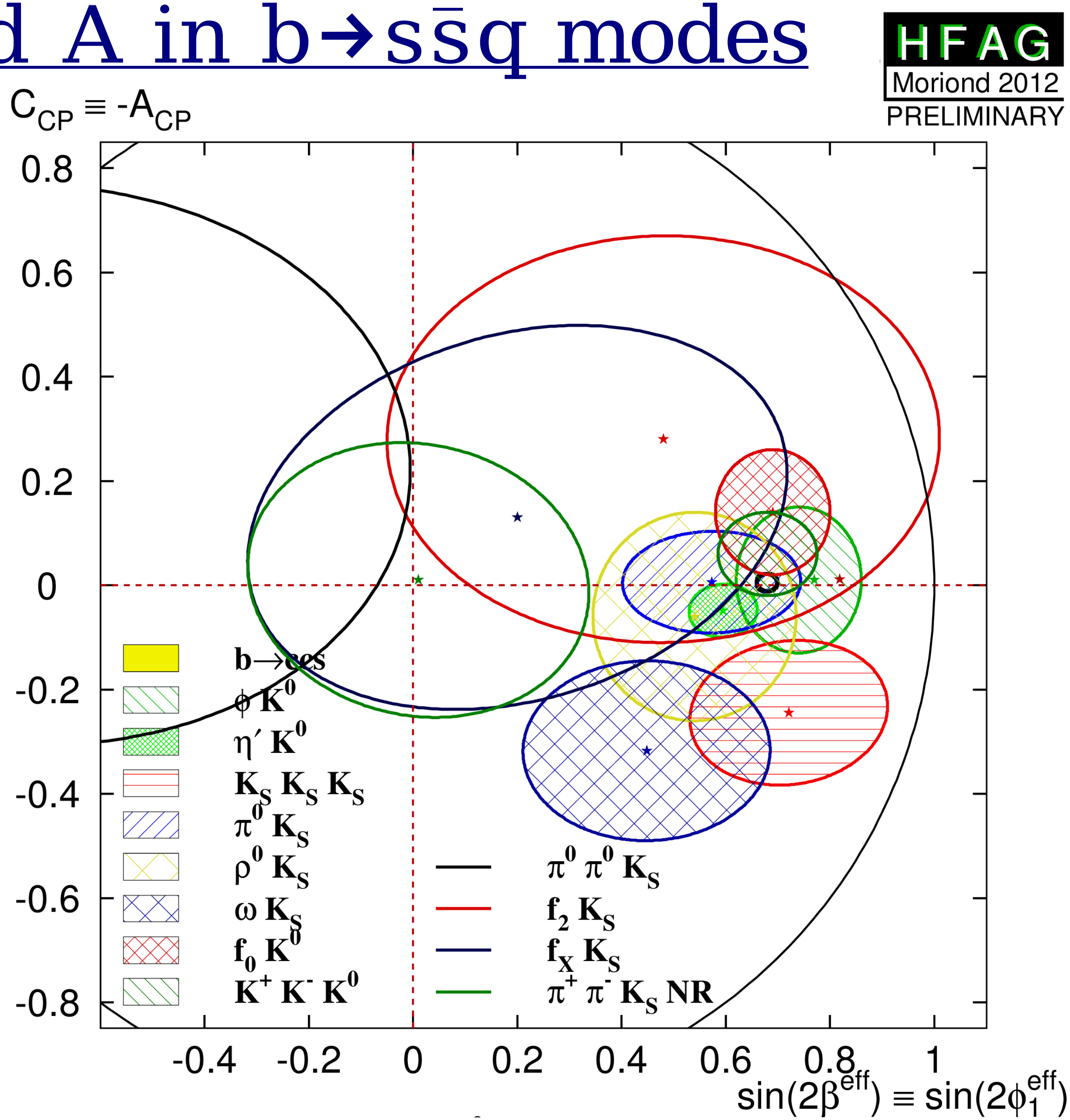
	772 M $B\bar{B}$	
mode	$-\xi_f \mathcal{S}$	$\mathcal{A}$
$\eta' K^0_S$	0.71 ± 0.07	0.02 ± 0.05
$\eta' K^0_L$	0.46 ± 0.21	0.09 ± 0.14

$\eta' K^0$ $0.68 \pm 0.07 \pm 0.03$ $0.03 \pm 0.05 \pm 0.03$





S and A in $b \to s\bar{s}q$ modes



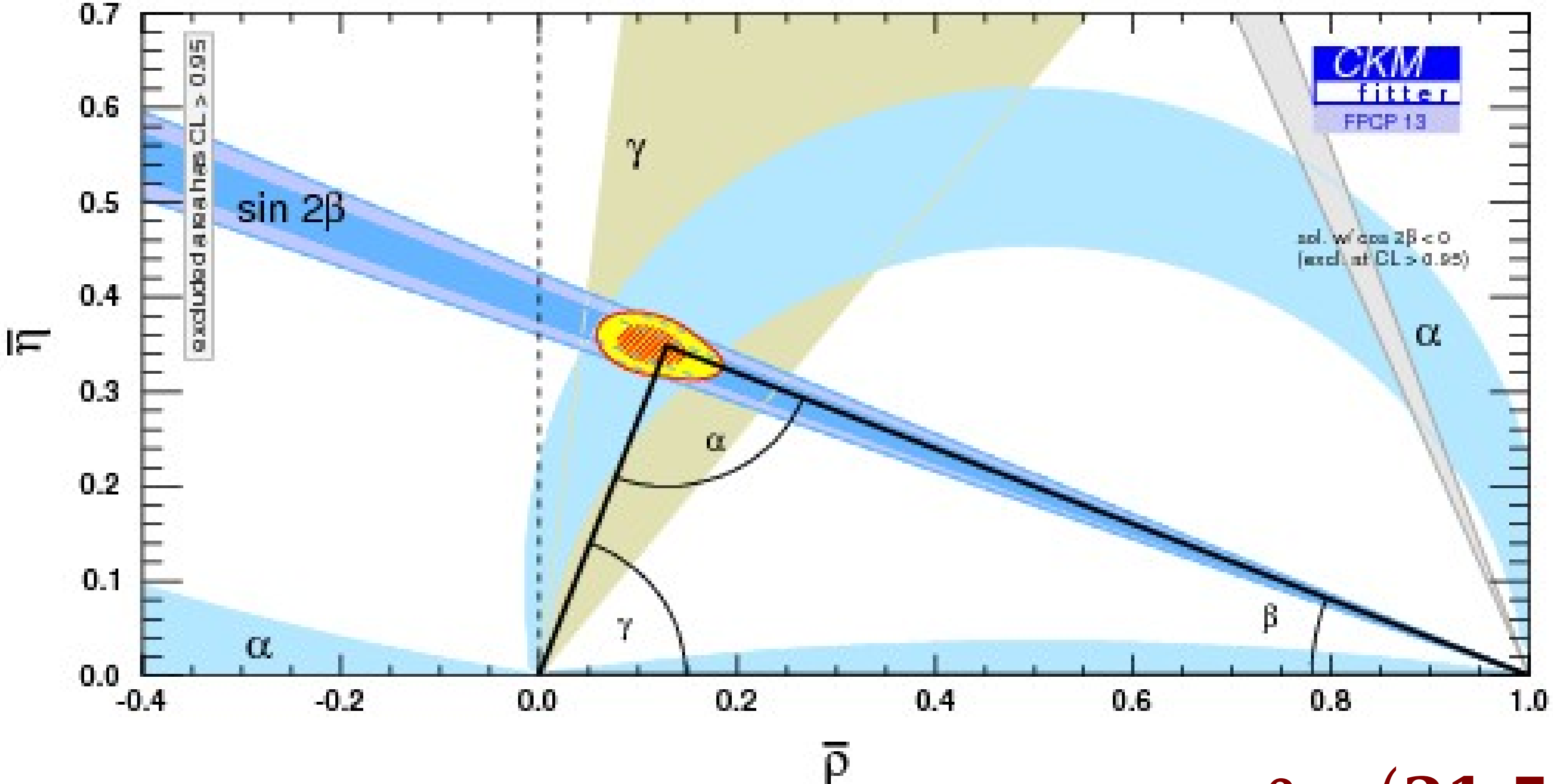
good agreement with $b \to c\bar{c}s$ modes result

$S = -\sin 2\beta, \quad A = 0$

UT angles

not only CP parameters of $\pi^+\pi^-$, $\rho^+\rho^-$ ...
but also BF and A of other modes (isospin)

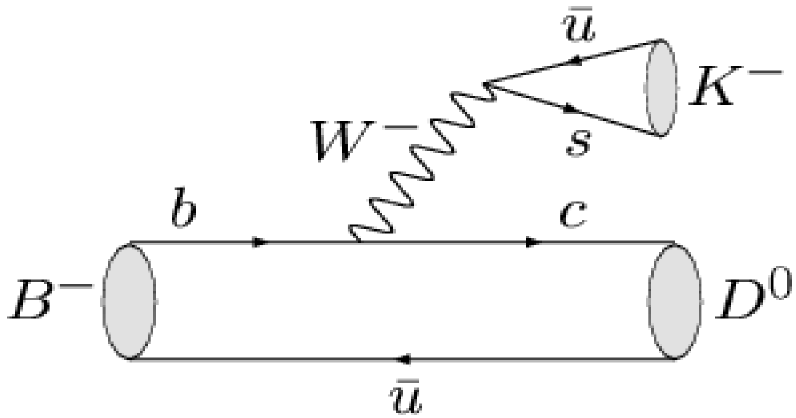
$$\alpha = (85.4^{+4.0}_{-3.8})^\circ$$



$$\beta = (21.5^{+0.8}_{-0.7})^\circ$$

γ measurements from $B^{\pm} \to DK^{\pm}$

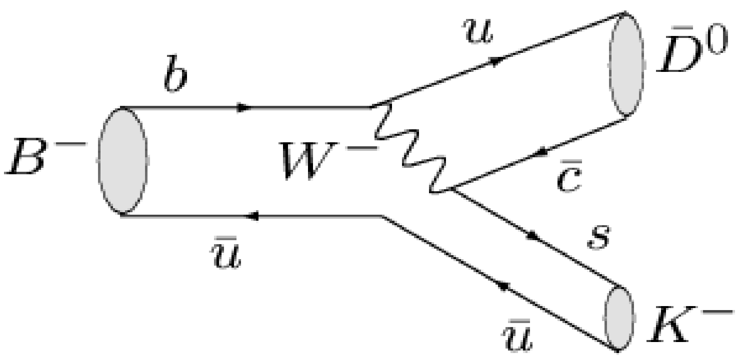
- Theoretically pristine $B \to DK$ approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$



color allowed

$B^- \to D^0 K^- \sim V_{cb} V_{us}^*$

$\sim A\lambda^3$



color suppressed

$B^- \to \bar{D}^0 K^- \sim V_{ub} V_{cs}^*$

$\sim A\lambda^3(\rho + i\eta)$

relative magnitude of suppressed amplitude is r_B

$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times [\text{color supp}] = 0.1\text{-}0.2$$

relative weak phase is γ, relative strong phase is δ_B

γ measurements from $B^{\pm} \to DK^{\pm}$

- Reconstruct D in final states accessible to both D^0 and $\overline{D}^0$
  - $D = D_{CP}$, CP eigenstates as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$

    GLW method (Gronau-London-Wyler)
  - $D = D_{sup}$, Doubly-Cabbibo suppressed decays as $K\pi$

    ADS method (Atwood-Dunietz-Soni)
  - Three-body decays as $D \to K_S\pi^+\pi^-$, $K_S K^+ K^-$

    GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)

- Largest effects due to
  - charm mixing
  - charm CP violation

  } small

  Y.Grossman, A.Soffer, J.Zupan [PRD 72, 031501 (2005)]

- **Different B decays (DK, D^*K, ...)**
  - **different hadronic factors (r_B, δ_B) for each**

$B \to D^{(*)} K^{(*)}$ Dalitz analysis

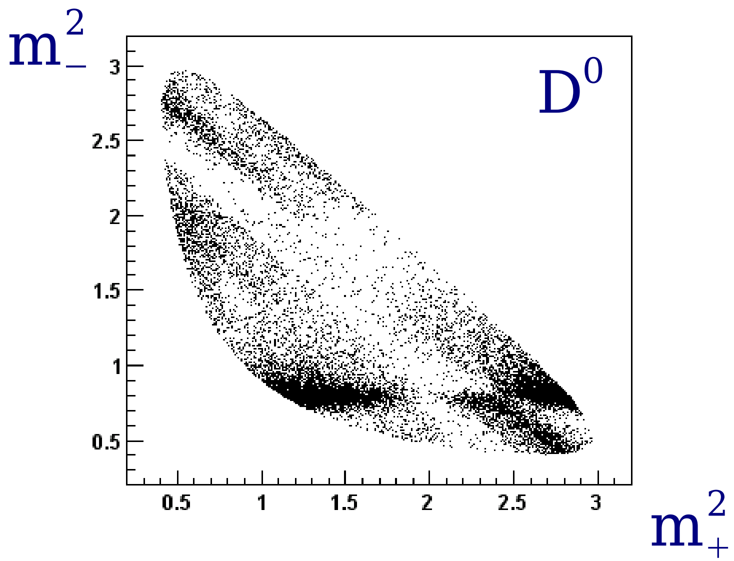
Reconstruction of three−body final states $D^0, \overline{D}^0 \to K_S \pi^+ \pi^-$

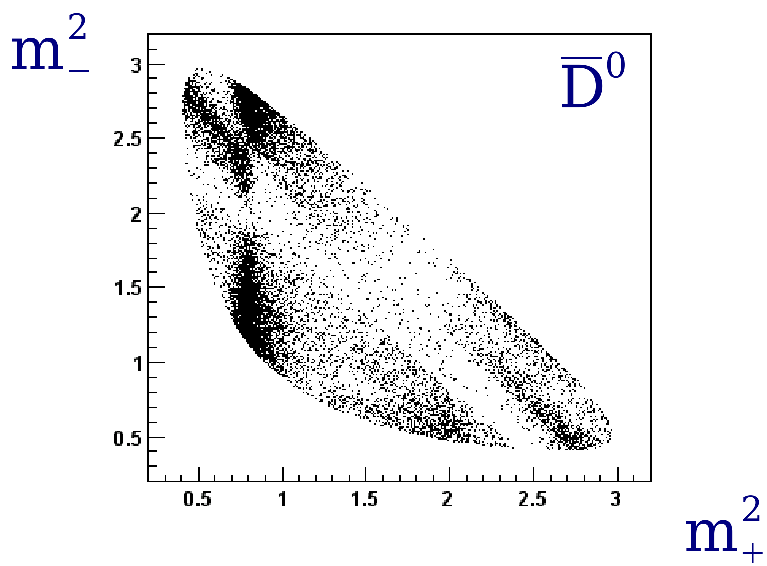
Amplitude for each Dalitz point is described as:

$$\overline{D}^0 \to K_S \pi^+ \pi^- \sim f(m_+^2, m_-^2)$$
$$D^0 \to K_S \pi^+ \pi^- \sim f(m_-^2, m_+^2)$$

$$B^+ \to (K_S \pi^+ \pi^-)_D K^+ : f(m_+^2, m_-^2) + r e^{i(\delta_B + \gamma)} f(m_-^2, m_+^2)$$

$m_- = M(K_S \pi^-)$
$m_+ = M(K_S \pi^+)$





$$B^- \to (K_S \pi^+ \pi^-)_D K^- : f(m_-^2, m_+^2) + r e^{i(\delta - \gamma)} f(m_+^2, m_-^2)$$

Simultaneous fit of B^+ and B^- to extract parameters r_B, ϕ_3 and δ_B

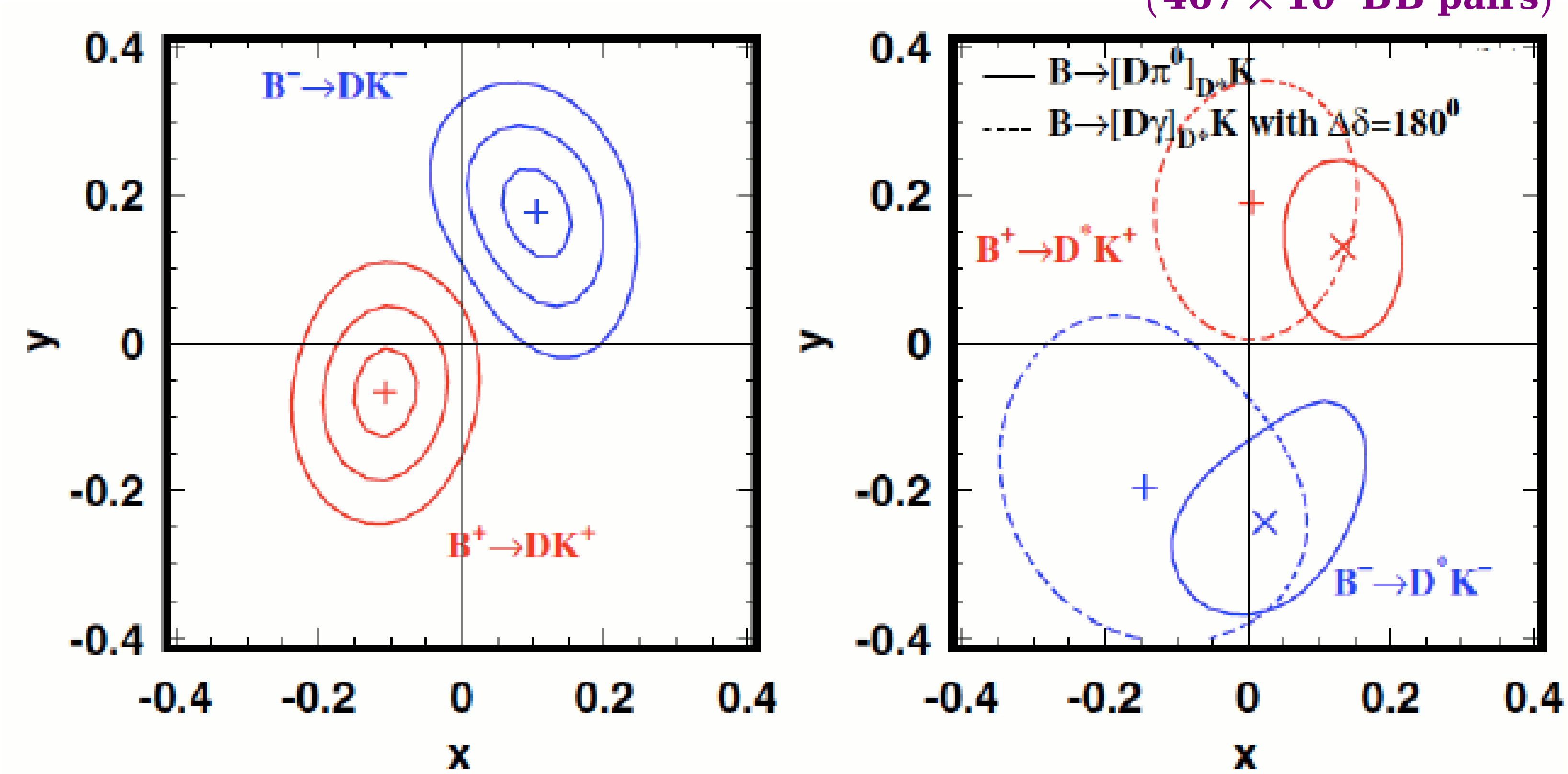
Note: 2 fold ambiguity on γ: $(\gamma, \delta_B) \to (\gamma + \pi, \delta_B + \pi)$

γ measurement with $B \to D(K_S\pi\pi)K$

PRD 81, 112002 (2010)
657×10^6 $B\bar{B}$ pairs

$x_\pm = r_B \cos(\delta_B \pm \gamma)$, $y_\pm = r_B \sin(\delta_B \pm \gamma)$

(similarly PRL 105 (2010) 121801)
(467×10^6 $B\bar{B}$ pairs)



$\gamma = (80.8\,^{+13.1}_{-14.8} \pm 5.0 \pm 8.9)^\circ$
$r_B = 0.161\,^{+0.040}_{-0.038} \pm 0.011\,^{+0.050}_{-0.010}$
$\delta_B = (137.4\,^{+13.0}_{-15.7} \pm 4.0 \pm 22.9)^\circ$

$\gamma = (73.9\,^{+18.9}_{-20.2} \pm 4.2 \pm 8.9)^\circ$
$r_B = 0.196\,^{+0.073}_{-0.072} \pm 0.013\,^{+0.062}_{-0.012}$
$\delta_B = (341.7\,^{+18.6}_{-20.9} \pm 3.2 \pm 22.9)^\circ$

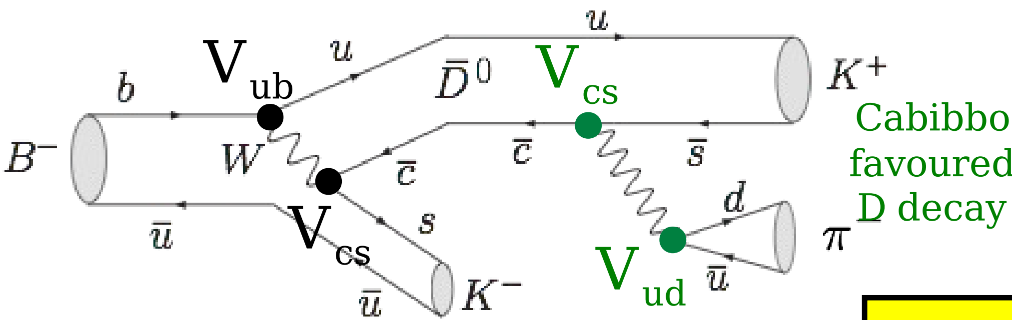
combining both B modes (Dalitz): $\boldsymbol{\gamma = (78.4\,^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ}$

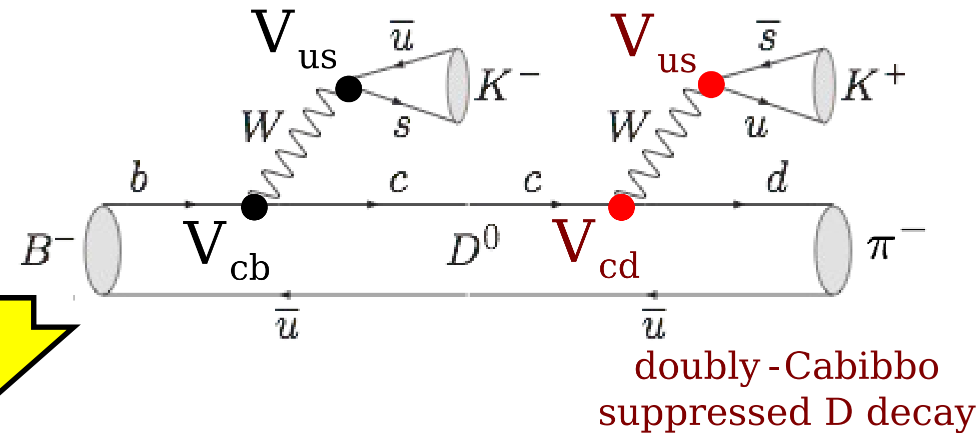
CPV significance is 3.5 standard deviations

(model-dependent error will limit viability of this approach)

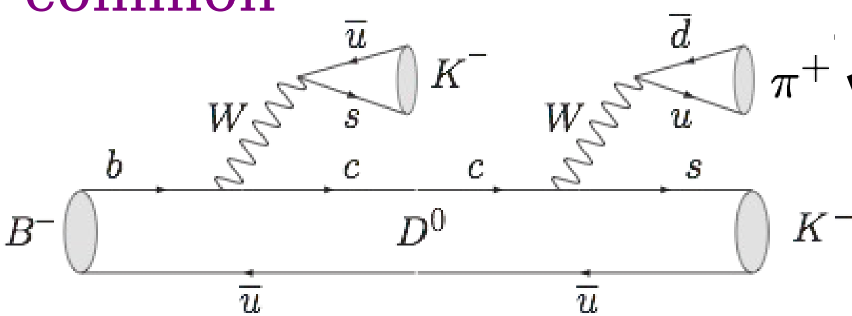
ADS method: γ via the interference in rare $B^- \to [K^+\pi^-]_D K^-$ decays

rate and asymmetry (relative to the common decay):





common



$$\mathcal{R}_{DK} = \frac{\Gamma([K^+\pi^-]K^-) + \Gamma([K^-\pi^+]K^+)}{\Gamma([K^-\pi^+]K^-) + \Gamma([K^+\pi^-]K^+)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

$$\mathcal{A}_{DK} = \frac{\Gamma([K^+\pi^-]K^-) - \Gamma([K^-\pi^+]K^+)}{\Gamma([K^-\pi^+]K^-) + \Gamma([K^+\pi^-]K^+)}$$

$$= 2 r_B r_D \sin(\delta_B + \delta_D)\sin\gamma \;/\; \mathcal{R}_{DK}$$

where $r_D = \left| \frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(\bar{D}^0 \to K^+\pi^-)} \right| = 0.0613 \pm 0.0010$

$B^- \to DK^-$, $D \to K^+\pi^-$ ADS

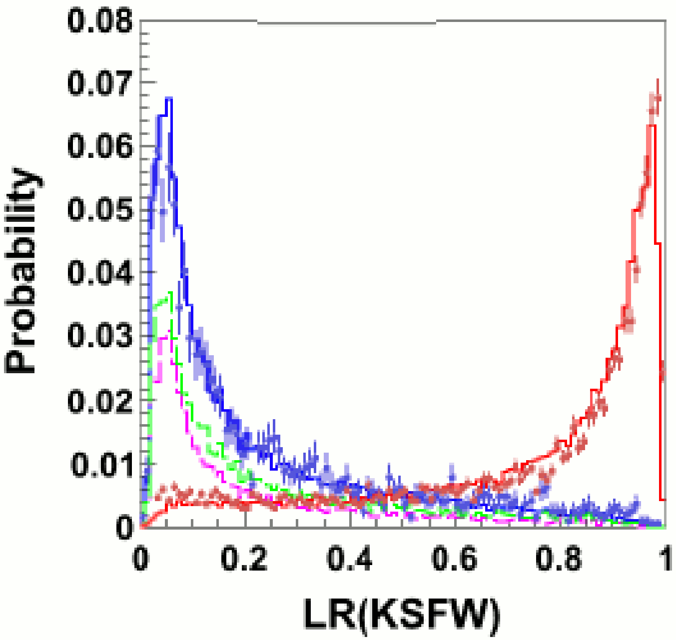
Main background is $e^+e^- \to q\bar{q}$ ($q=u, d, s, c$) continuum

combine 10 variables with neural network:

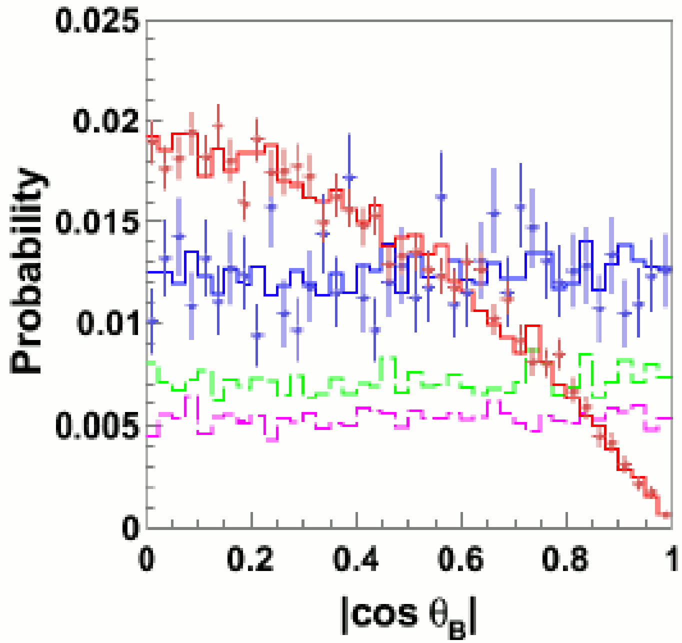
$B^- \to D\pi^-$
$\to K^-\pi^+$
M_{bc}-sideband

- Variables which have different distributions for signal and $q\bar{q}$ background are used.

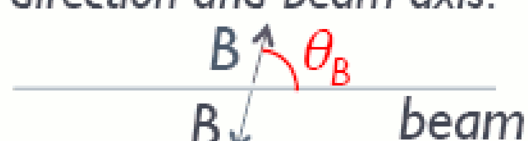
histogram: MC, dots: data
signal
qq = charm + uds

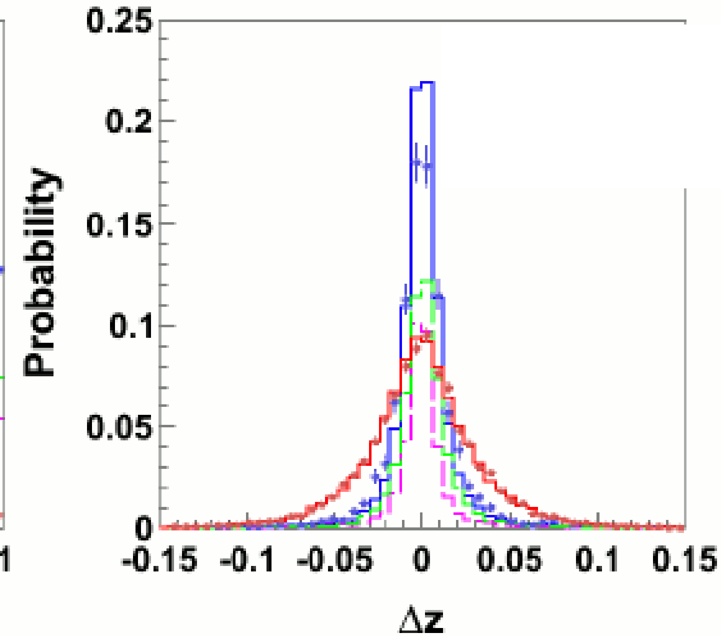


Likelihood ratio for KSFW.

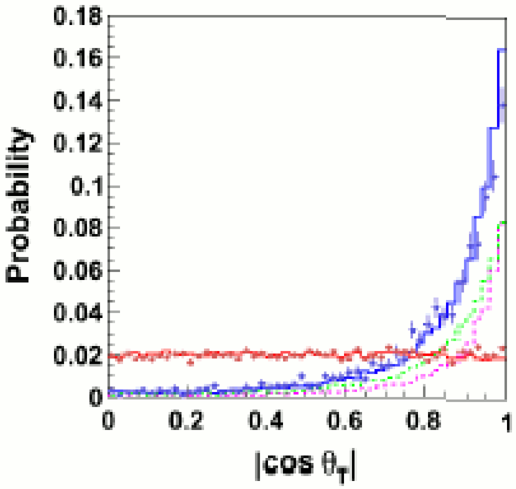


θ_B is angle between B-flight direction and beam axis.

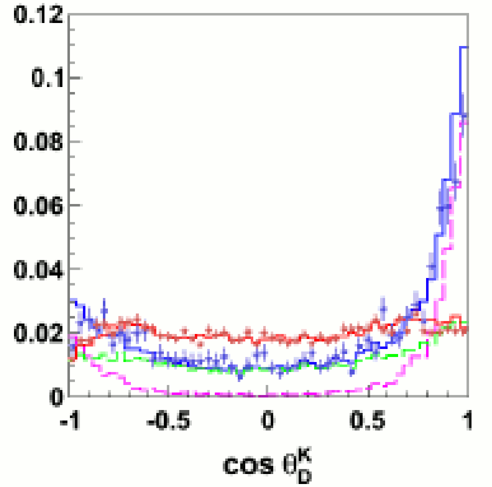




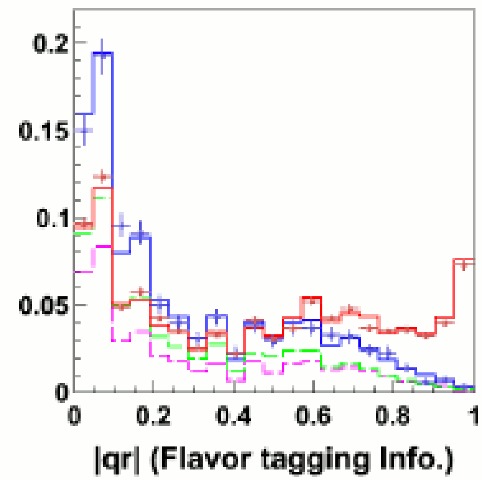
Vertex separation between reconstructed B and the other B.



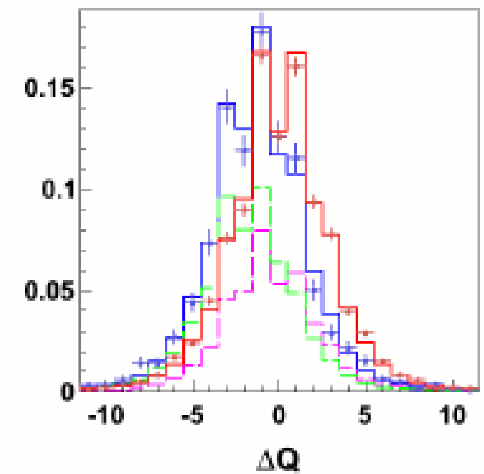
Angle between thrust axes of B decay and remainder.
No full correlation to LR(KSFW).



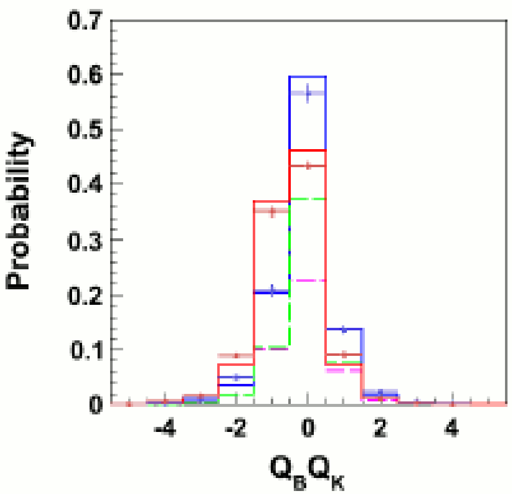
Decay angle of D → kπ.



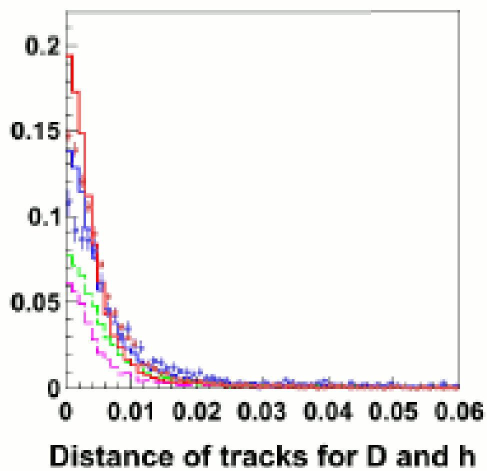
Flavor tagging Info. by MDLH. (NB possible.)



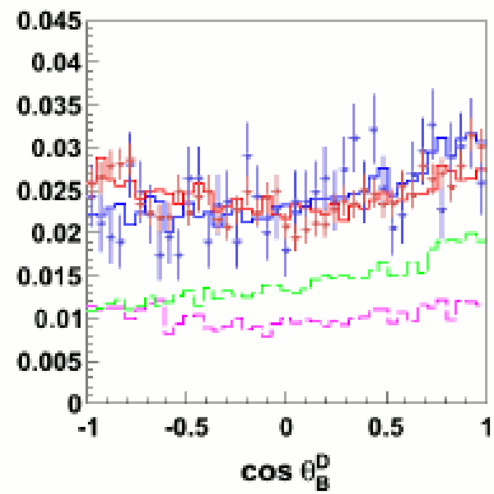
Difference of charges in D hemisphere and opposite hemisphere.



Product of charge of B and sum of charges for K not used in B reconstruction.



Distance of tracks for D and K.



Decay angle of B → DK.

10 variables combined to obtain a single NN output (NB)

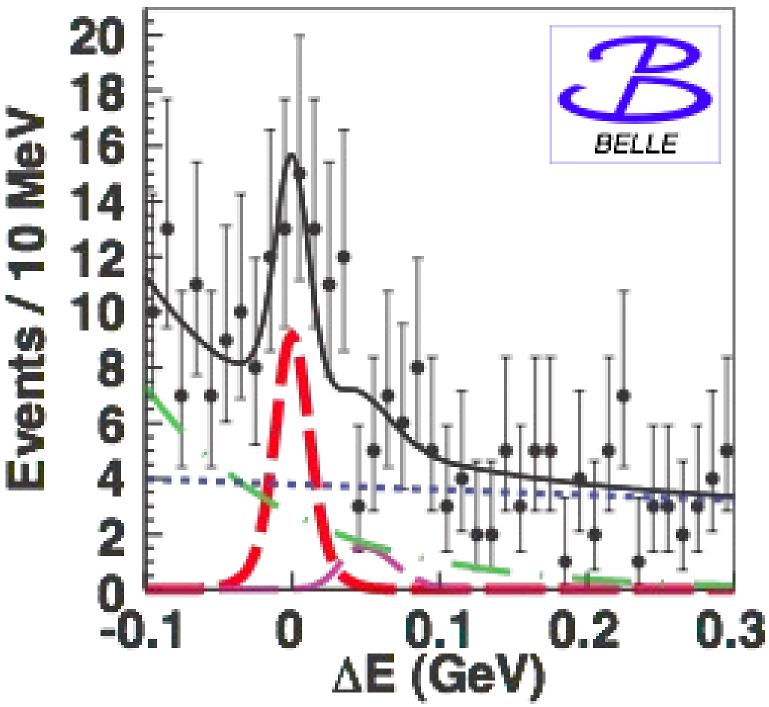
for example, at 99% bckg rej. signal eff. = 42% now becomes 60%

Yields for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\overline{B}$ events

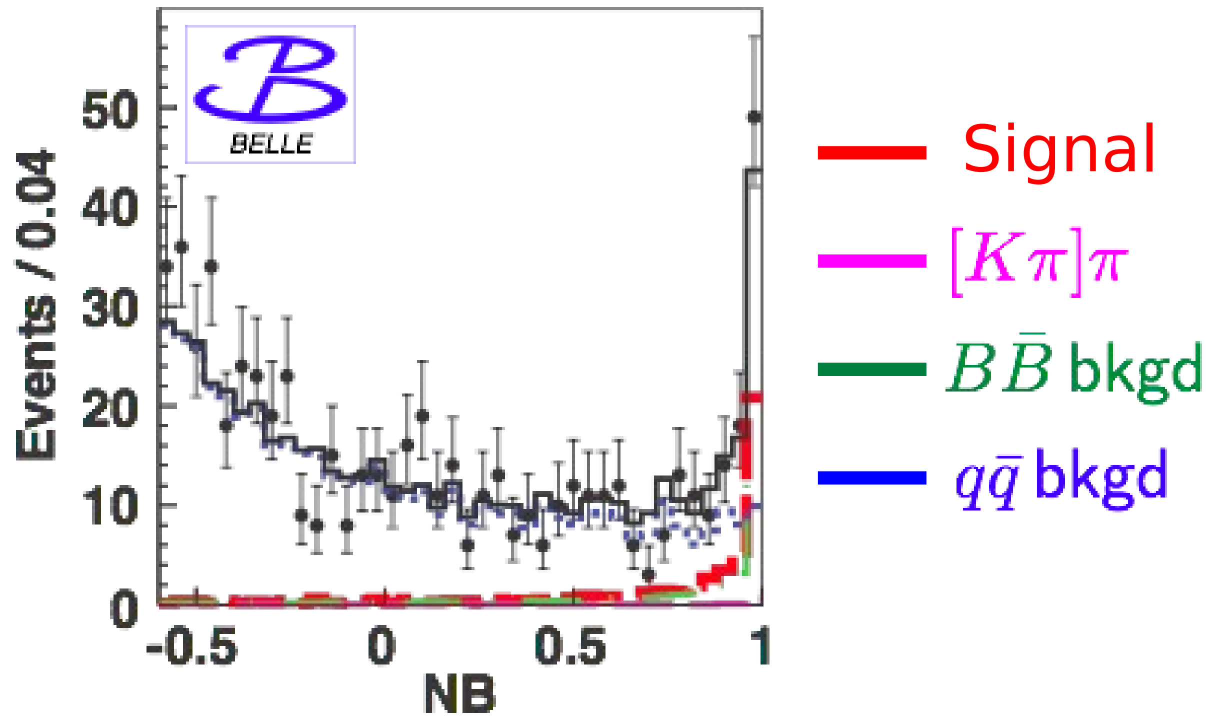
PRL 106, 231803 (2011)

Fit ΔE and NB distributions together to extract signal

for NB > 0.9



for $|\Delta E| < 0.03$ GeV



$56.0^{+15.1}_{-14.2}$ events

$$\mathbf{R_{DK} = (1.63\,^{+0.44}_{-0.41}\,^{+0.07}_{-0.13}) \times 10^{-2}}$$

$$\mathbf{A_{DK} = -0.39\,^{+0.26}_{-0.28}\,^{+0.04}_{-0.03}}$$

First evidence obtained with a significance of 4.1σ (including syst.)

First evidence for the ADS mode $B^- \to [K^+\pi^-]_{D^*}K^-$

Preliminary

study both modes: $D^* \to D\pi^0$, $D\gamma$:

[see ''On φ_3 Measurements Using $B \to D^* K^-$ Decays'', arXiv:hep-ph/0409281]

$B \to D\pi$
$B \to DK$
$B\bar{B}$
continuum

Signal seen
with a significance of 3.5σ
for $D^* \to D\gamma$ mode

Ratio to favored mode:

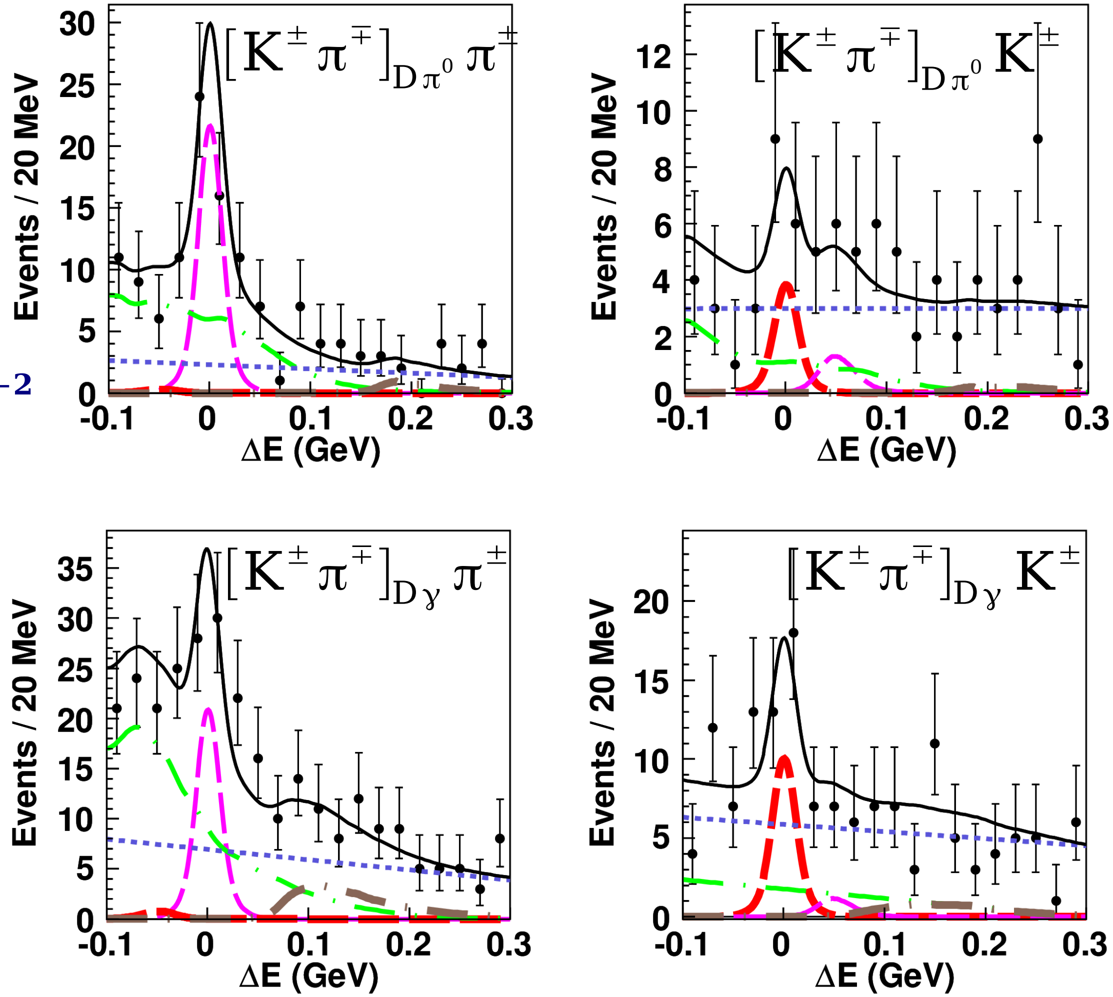
$$R_{D\pi^0} = (1.0\,^{+0.8}_{-0.7}(\mathrm{stat})\,^{+0.1}_{-0.2}(\mathrm{syst})) \times 10^{-2}$$

$$R_{D\gamma} = (3.6\,^{+1.4}_{-1.2}(\mathrm{stat}) \pm 0.2(\mathrm{syst})) \times 10^{-2}$$

asymmetry:

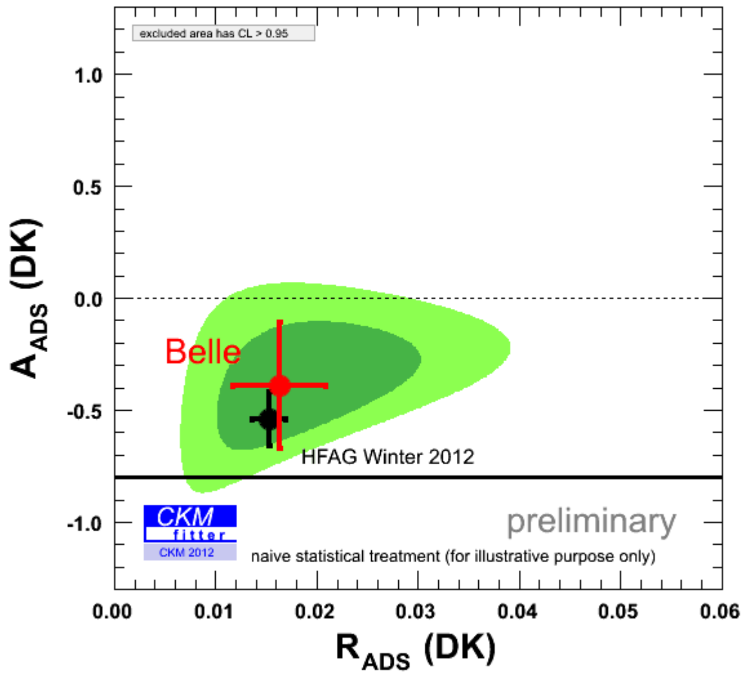
$$A_{D\pi^0} = 0.4\,^{+1.1}_{-0.7}(\mathrm{stat})\,^{+0.2}_{-0.1}(\mathrm{syst})$$

$$A_{D\gamma} = -0.51\,^{+0.33}_{-0.29}(\mathrm{stat}) \pm 0.08(\mathrm{syst})$$



Comparison of the results obtained for $D^{(*)}K$ with expectations

where ''expectations'' are derived from the GGSZ observables (W.A.), δ_D and γ_{UT}

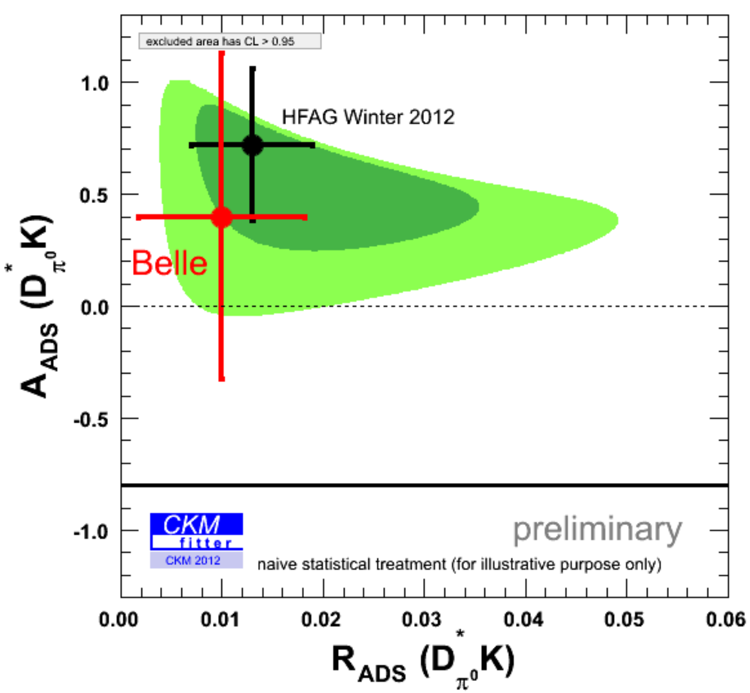


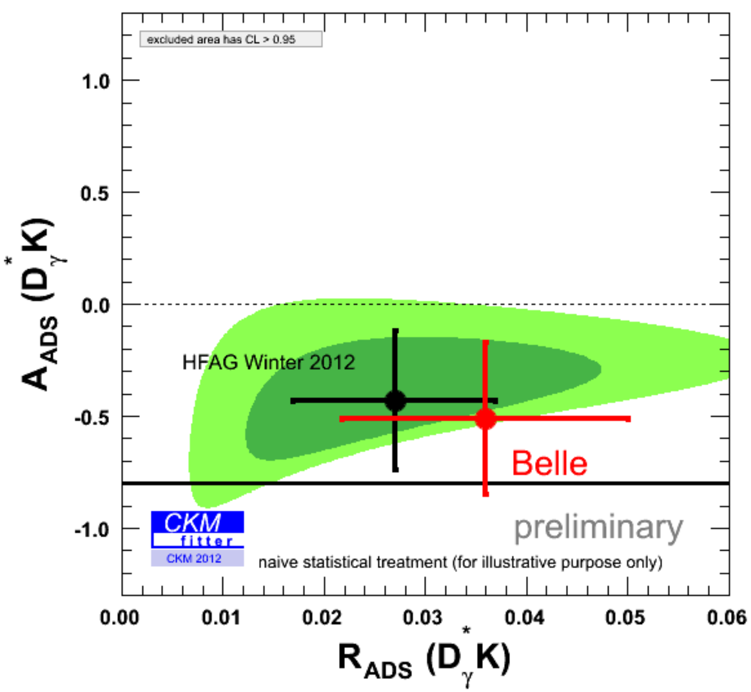
$$R_{ADS}(DK) = r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B + \delta_D)\cos\gamma$$
$$A_{ADS}(DK) = 2r_Br_D\sin(\delta_B + \delta_D)\sin\gamma / R_{ADS}(DK)$$

$$R_{ADS}(D^*_{\pi^0}K) = r_B^{*2} + r_D^2 + 2r_B^*r_D\cos(\delta_B^* + \delta_D)\cos\gamma$$
$$A_{ADS}(D^*_{\pi^0}K) = 2r_B^*r_D\sin(\delta_B^* + \delta_D)\sin\gamma / R_{ADS}(D^*_{\pi^0}K)$$

$$R_{ADS}(D^*_{\gamma}K) = r_B^{*2} + r_D^2 - 2r_B^*r_D\cos(\delta_B^* + \delta_D)\cos\gamma$$
$$A_{ADS}(D^*_{\gamma}K) = -2r_B^*r_D\sin(\delta_B^* + \delta_D)\sin\gamma / R_{ADS}(D^*_{\gamma}K)$$

(HFAG winter 2012 includes Belle results)

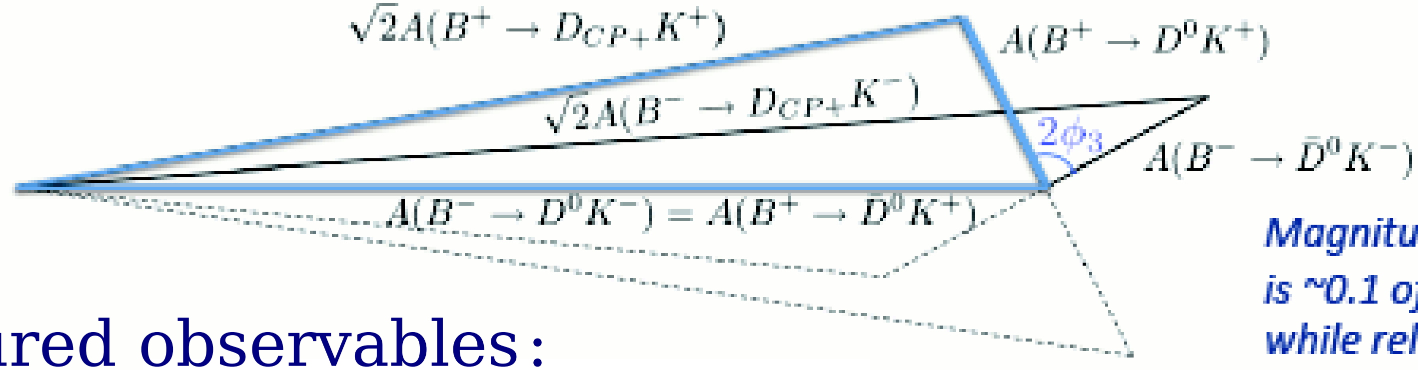




GLW with $D^{(*)}_{CP}K$

D decays to CP eigenstates

- Amplitude triangle:



Magnitude of one side is ~0.1 of the others while relative magnitude of the others help ϕ_3 constraint.

measured observables:

$$R_{CP\pm} \equiv \frac{Br(B^- \to D_{CP\pm}K^-) + Br(B^+ \to D_{CP\pm}K^+)}{Br(B^- \to D^0K^-) + Br(B^+ \to \bar{D}^0K^+)}$$

$$A_{CP\pm} \equiv \frac{Br(B^- \to D_{CP\pm}K^-) - Br(B^+ \to D_{CP\pm}K^+)}{Br(B^- \to D_{CP\pm}K^-) + Br(B^+ \to D_{CP\pm}K^+)}$$

Relation between $(A_{CP+}, A_{CP-}, R_{CP+}, R_{CP-})$ and (γ, r_B, δ_B)

$$A_{CP+} = \frac{+2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2r_B\cos\delta_B\cos\gamma} \qquad A_{CP-} = \frac{-2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 - 2r_B\cos\delta_B\cos\gamma}$$

$$R_{CP+} = 1 + r_B^2 + 2r_B\cos\delta_B\cos\gamma \qquad R_{CP-} = 1 + r_B^2 - 2r_B\cos\delta_B\cos\gamma$$

$\Rightarrow$ look for $R_{CP\pm} \neq 1$ and $A_{CP\pm} \neq 0$

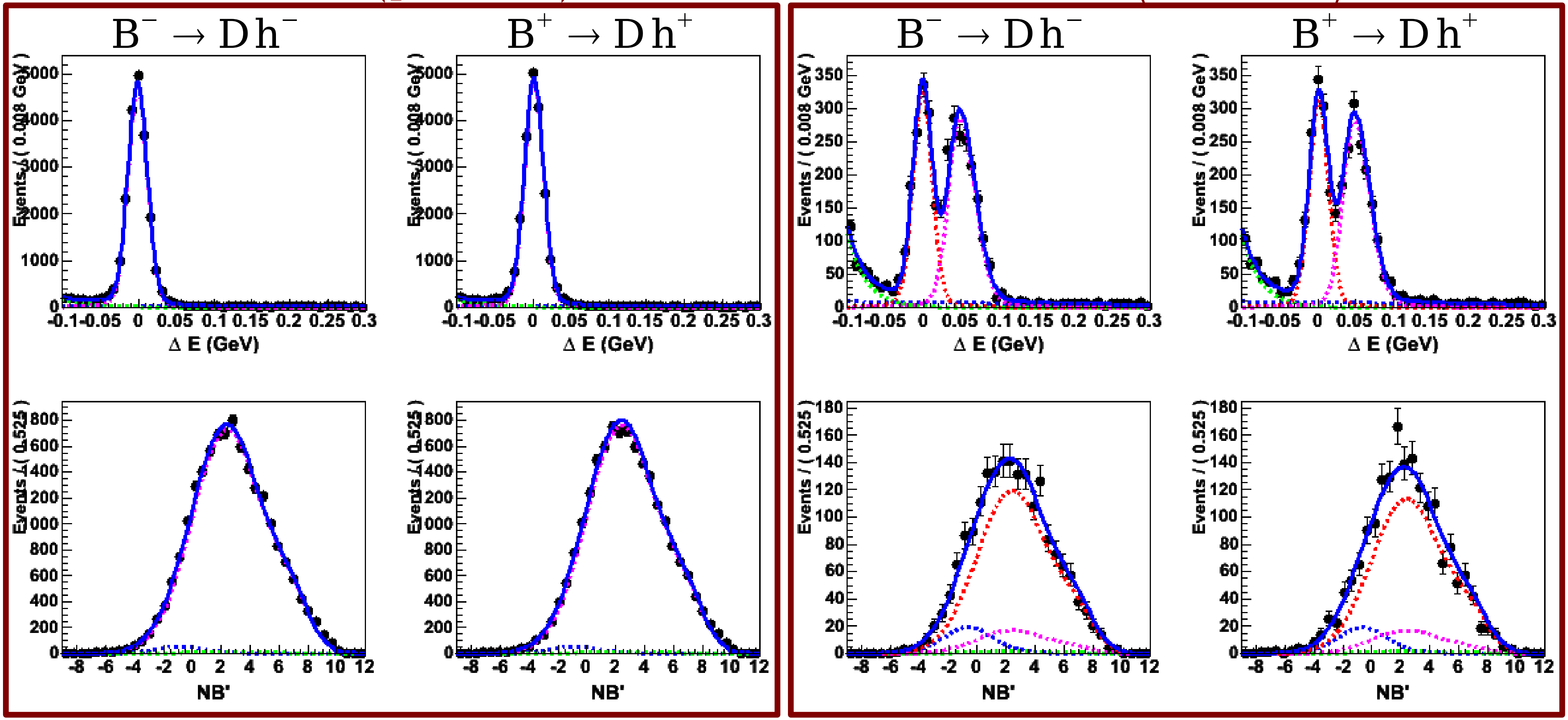
$\Rightarrow$ $\neq$ CP, $\neq$ sign of asymmetry

Fit for GLW Dh , D→Kπ → $R_{D_{fav}}$

B → Dπ
B → DK
$B\bar{B}$
continuum

KID< 0.6 (pion-like)

KID> 0.6 (kaon-like)



$$N^{DK}_{\eta,\,KID>0.6} = \frac{1}{2}\left(1-\eta A^{DK}\right) N^{D\pi}_{tot}\ R_{K/\pi}\ \epsilon$$

$$N^{DK}_{\eta,\,KID<0.6} = \frac{1}{2}\left(1-\eta A^{DK}\right) N^{D\pi}_{tot}\ R_{K/\pi}\ (1-\epsilon)$$

$$N^{D\pi}_{\eta,KID>0.6} = \frac{1}{2}\left(1-\eta A^{D\pi}\right) N^{D\pi}_{tot}\ \kappa$$

$$N^{D\pi}_{\eta,KID<0.6} = \frac{1}{2}\left(1-\eta A^{D\pi}\right) N^{D\pi}_{tot}\ (1-\kappa)$$

$B \to Dh$, $D \to K^+K^-, \pi^+\pi^- \to R_+$

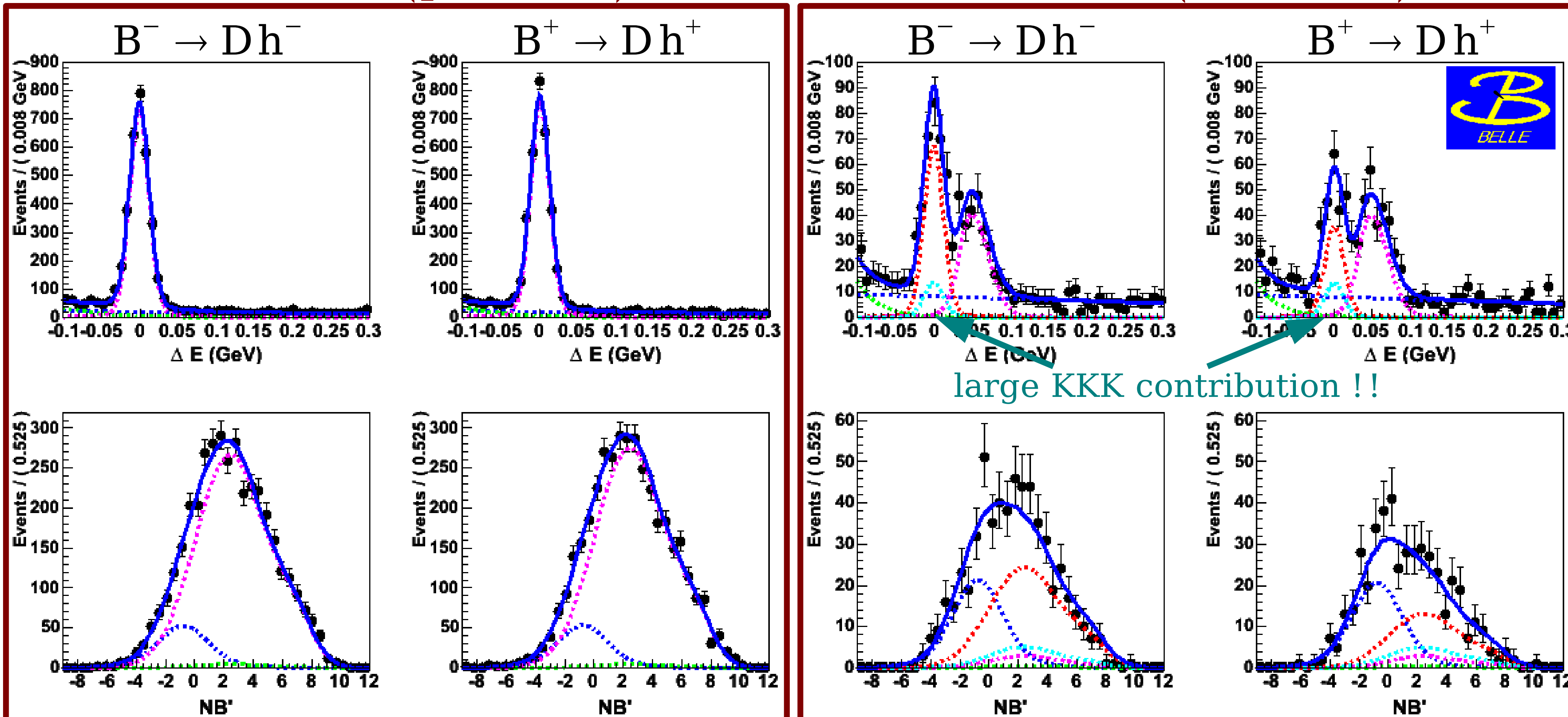
Preliminary
(772 M $B\bar{B}$)
$B \to D\pi$
$B \to DK$
$B\bar{B}$
continuum

Yields	**$B \to D\pi$**	**$B \to DK$**
$D \to K\pi$	50432 ± 243	3692 ± 83
$D \to KK, \pi\pi$	7696 ± 106	582 ± 40

$\Rightarrow R_{D_{fav}} = (7.32 \pm 0.16)\%$

$A(DK) = (1.4 \pm 2.0)\%$

KID< 0.6 (pion-like) **KID> 0.6 (kaon-like)**



$$\Rightarrow R_{D_{CP+}} = (7.56 \pm 0.51)\%, \quad A_{D_{CP+}} = (28.7 \pm 6.0)\%$$

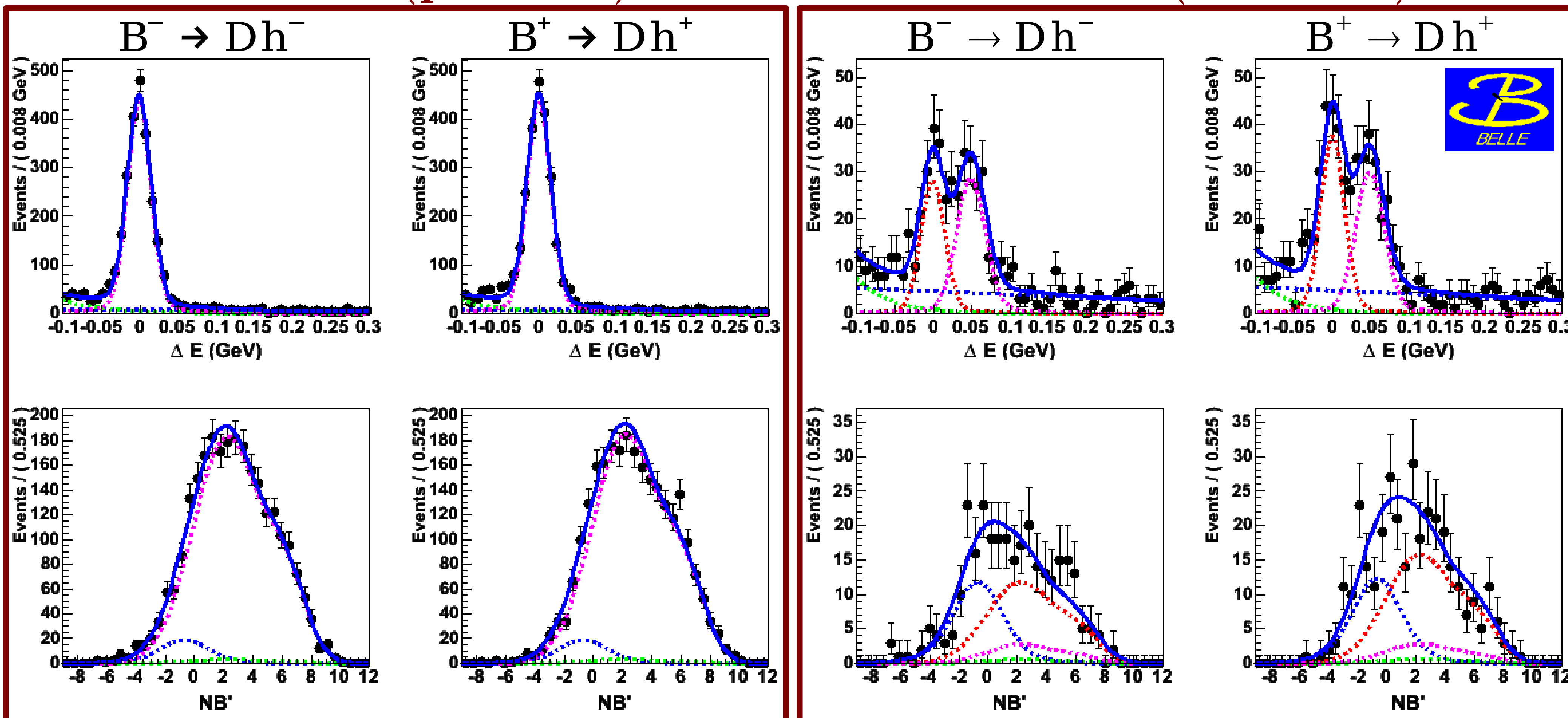
large asymmetry !!

$B \to Dh,\ D \to K_S\pi^0,\ K_S\eta \to R_-$

Preliminary
(772 M$B\bar{B}$)
$B \to D\pi$
$B \to DK$
$B\bar{B}$
continuum

Yields	$B \to D\pi$	$B \to DK$
$D \to K_S\pi^0,\ K_S\eta$	5745 ± 91	476 ± 37

KID< 0.6 (pion-like) **KID> 0.6 (kaon-like)**



$$\Rightarrow\ R_{D_{CP-}} = (8.29 \pm 0.63)\%,\ \ A_{D_{CP-}} = (-12.4 \pm 6.4)\%$$

opposite asymmetry !!

GLW Results

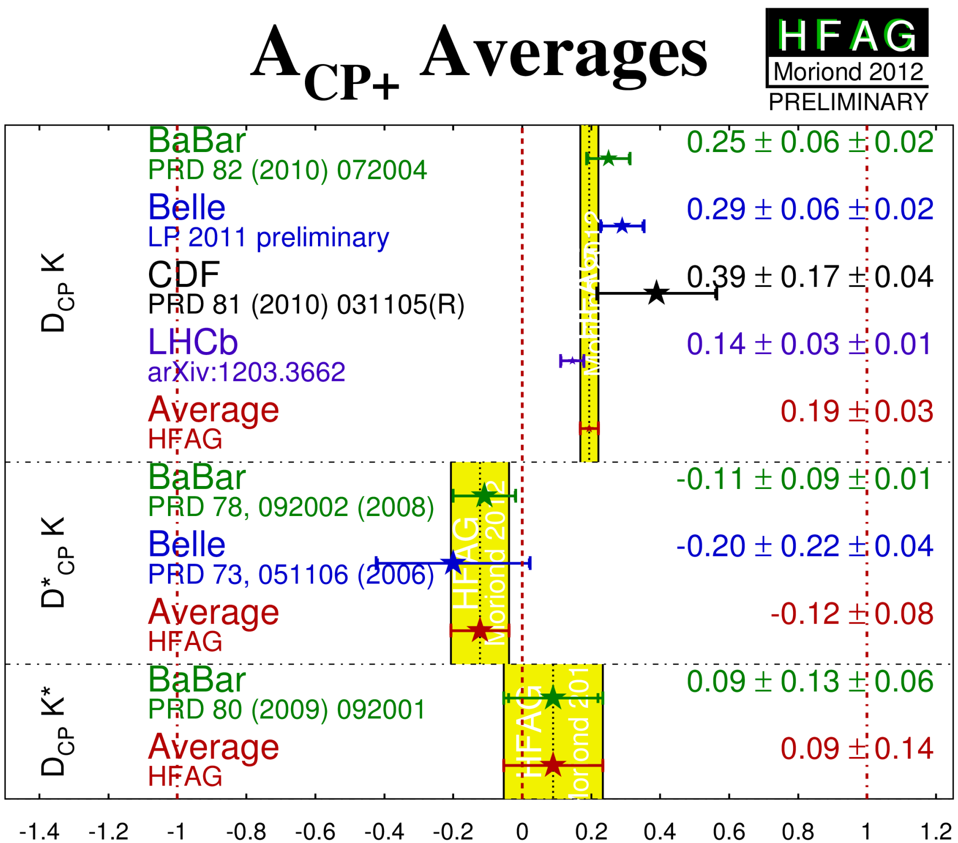
Preliminary

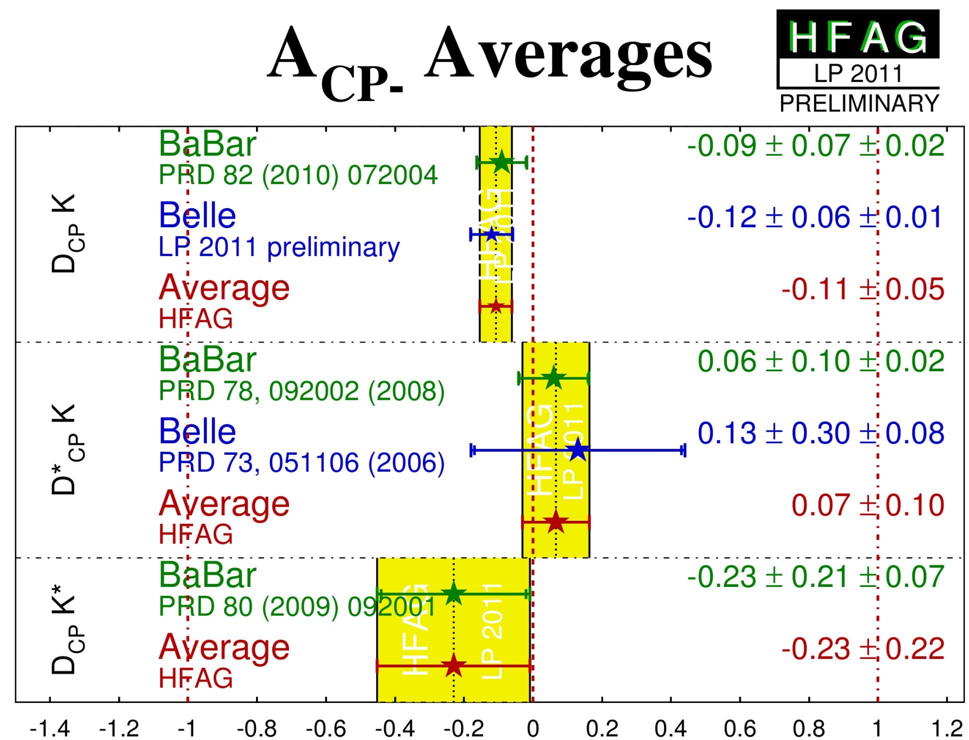
$$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$$
$$R_{CP-} = 1.13 \pm 0.09 \pm 0.05$$

$$A_{CP+} = +0.29 \pm 0.06 \pm 0.02$$
$$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$$

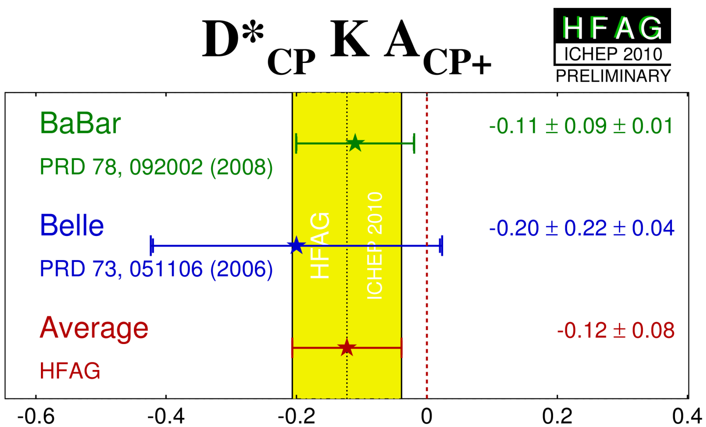
CP-odd observables
only available at B-factories

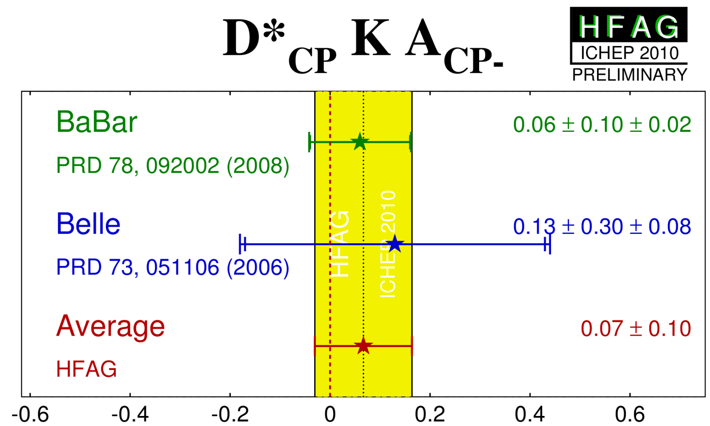
(systematics dominated by peaking background, double ratio approximation)





Status and motivation for GLW in $B \to D^{*0} K$





Mode	Experiment	A_{CP+}	A_{CP-}	R_{CP+}	R_{CP-}	Reference
$D^*_{CP}K^-$	BaBar N(BB)=383M	−0.11 ± 0.09 ± 0.01	0.06 ± 0.10 ± 0.02	1.31 ± 0.13 ± 0.03	1.09 ± 0.12 ± 0.04	PRD 78, 092002 (2008)
	Belle N(BB)=275M	−0.20 ± 0.22 ± 0.04	0.13 ± 0.30 ± 0.08	1.41 ± 0.25 ± 0.06	1.15 ± 0.31 ± 0.12	PRD 73, 051106 (2006)
	Average	−0.12 ± 0.08 χ^2 = 0.14 (CL=0.71 ⇒ 0.4σ)	0.07 ± 0.10 χ^2 = 0.05 (CL=0.83 ⇒ 0.2σ)	1.33 ± 0.12 χ^2 = 0.12 (CL=0.73 ⇒ 0.4σ)	1.10 ± 0.12 χ^2 = 0.03 (CL=0.87 ⇒ 0.2σ)	HFAG

[Belle previous result: 1/3 of the full data sample, only $D^* \to D\pi^0$]

- compared to DK, the D^{*0} constraint suppresses the peaking multi-body charmless decays
- $D^{*0} \to D\pi^0$, $D\gamma$: effective strong phase shift of π between two cases (sign swap in asymmetries between $D\pi^0$ and $D\gamma$ cases)
- available only (in principle) at B-factories (independent observables)
- D^{*0} selection is same than ADS case, D selection same than GLW case

$B \to D^{*0} K, D^{*0} \to D\pi^0$

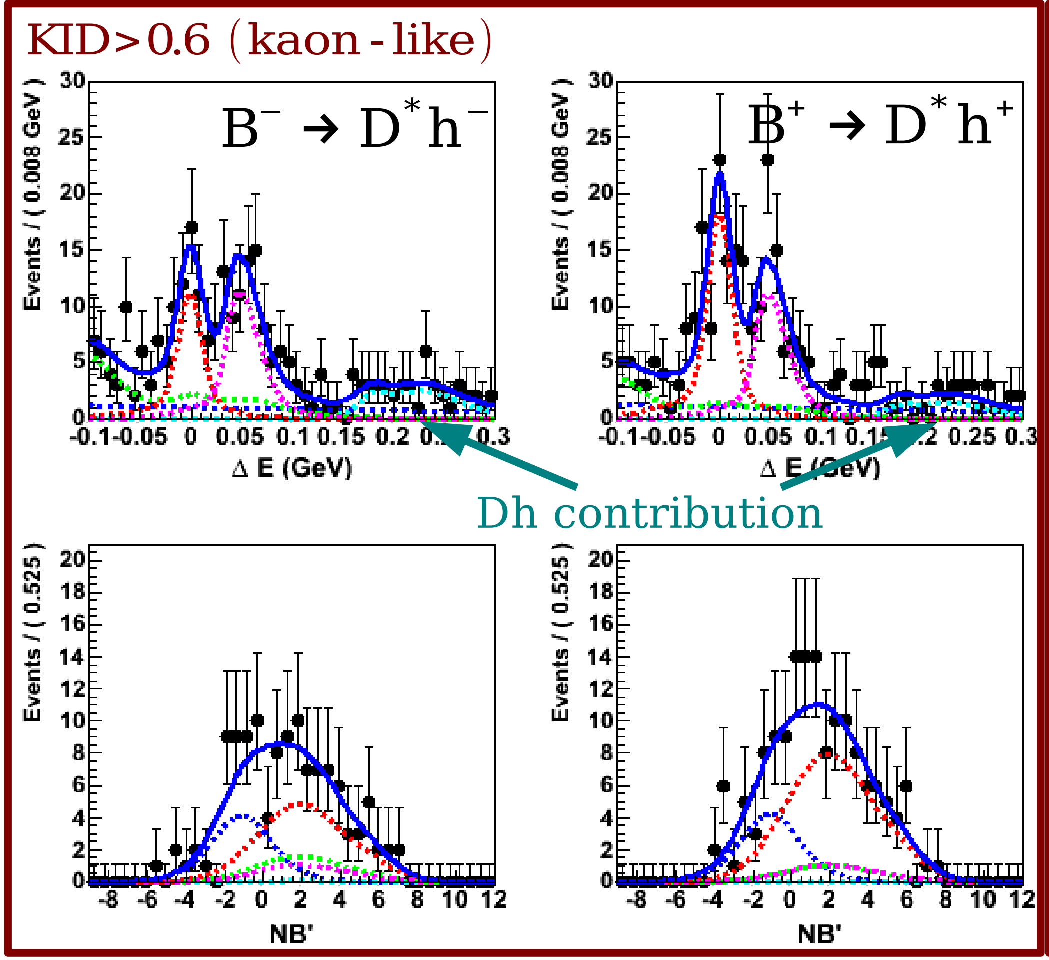
preliminary ($772\ M B\bar{B}$)

Yields	$B \to D^* \pi$	$B \to D^* K$
$D \to K\pi$	$(14.4 \pm 0.2) \times 10^3$	1074 ± 52
$D \to KK, \pi\pi$	$(2.14 \pm 0.07) \times 10^3$	195 ± 20
$D \to K_S\pi^0, K_S\eta$	$(1.67 \pm 0.07) \times 10^3$	156 ± 21

$\Rightarrow R_{D_{fav}} = (7.46 \pm 0.36)\%$

$A(D^*_{fav} K) = (3.2 \pm 4.4)\%$

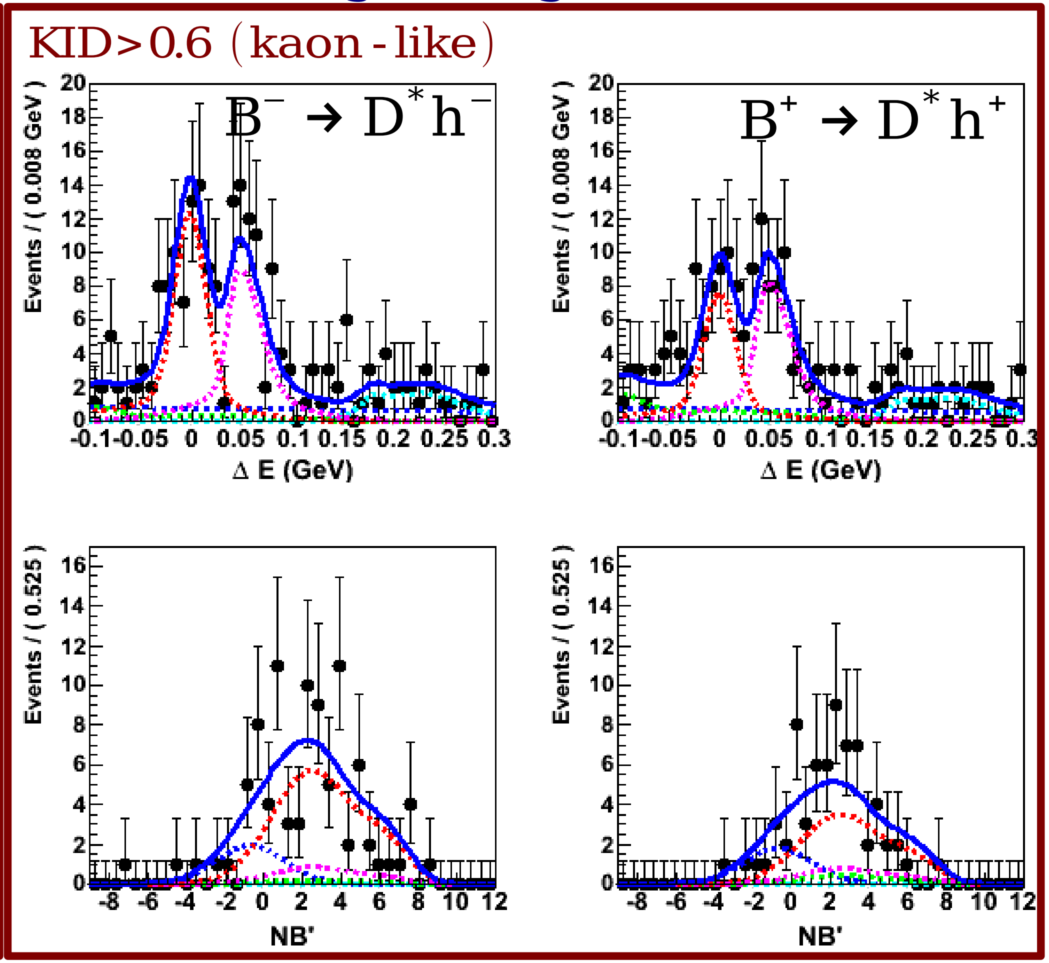
$D \to K^+K^-, \pi^+\pi^- \to CP+$



$R_{CP+} = 1.25 \pm 0.16$

$A_{CP+} = -0.23 \pm 0.11$

$D \to K_S\pi^0, K_S\eta \to CP-$



$R_{CP-} = 1.26 \pm 0.18$

$A_{CP-} = +0.20 \pm 0.13$

$B \to D^{*0} K,\ D^{*0} \to D\gamma$

preliminary

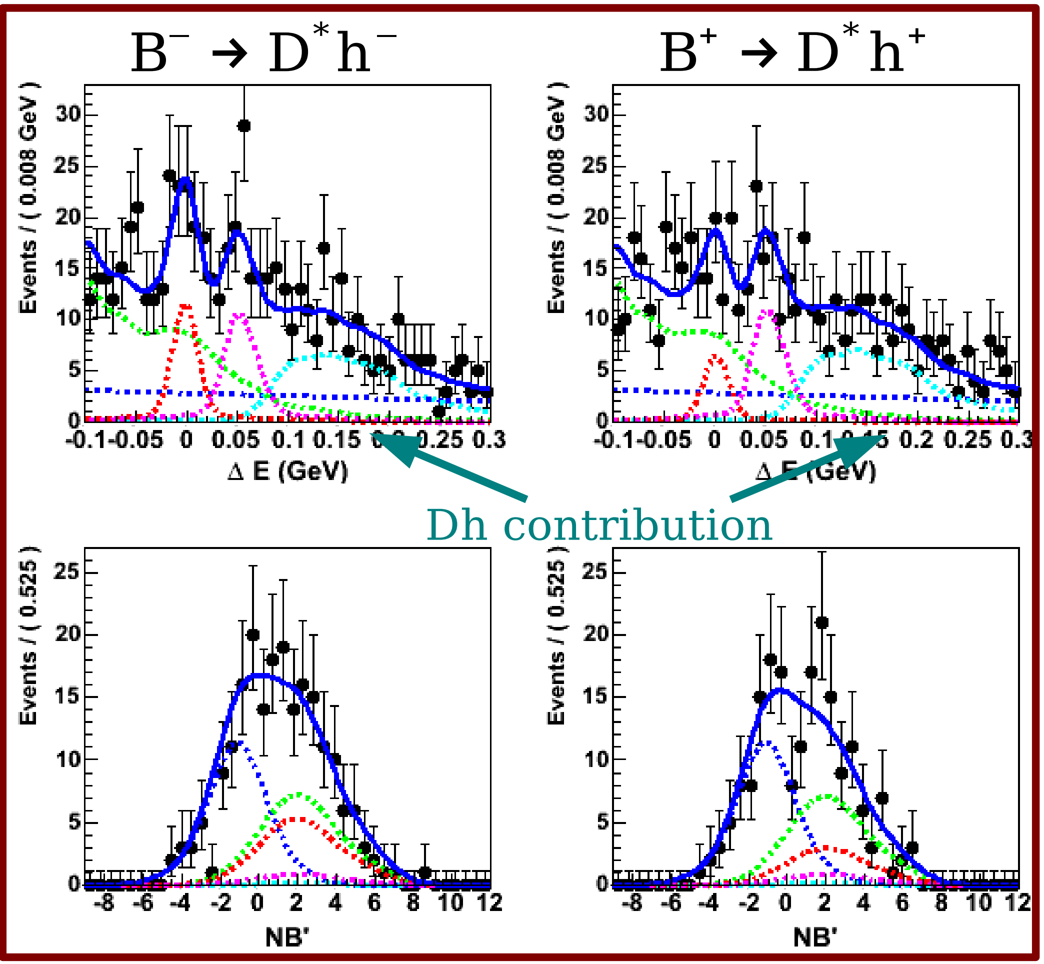
($772\ \mathrm{M} B\bar{B}$)

Yields	$B \to D^{*}\pi$	$B \to D^{*}K$
$D \to K\pi$	$(13.3 \pm 0.2) \times 10^{3}$	979 ± 59

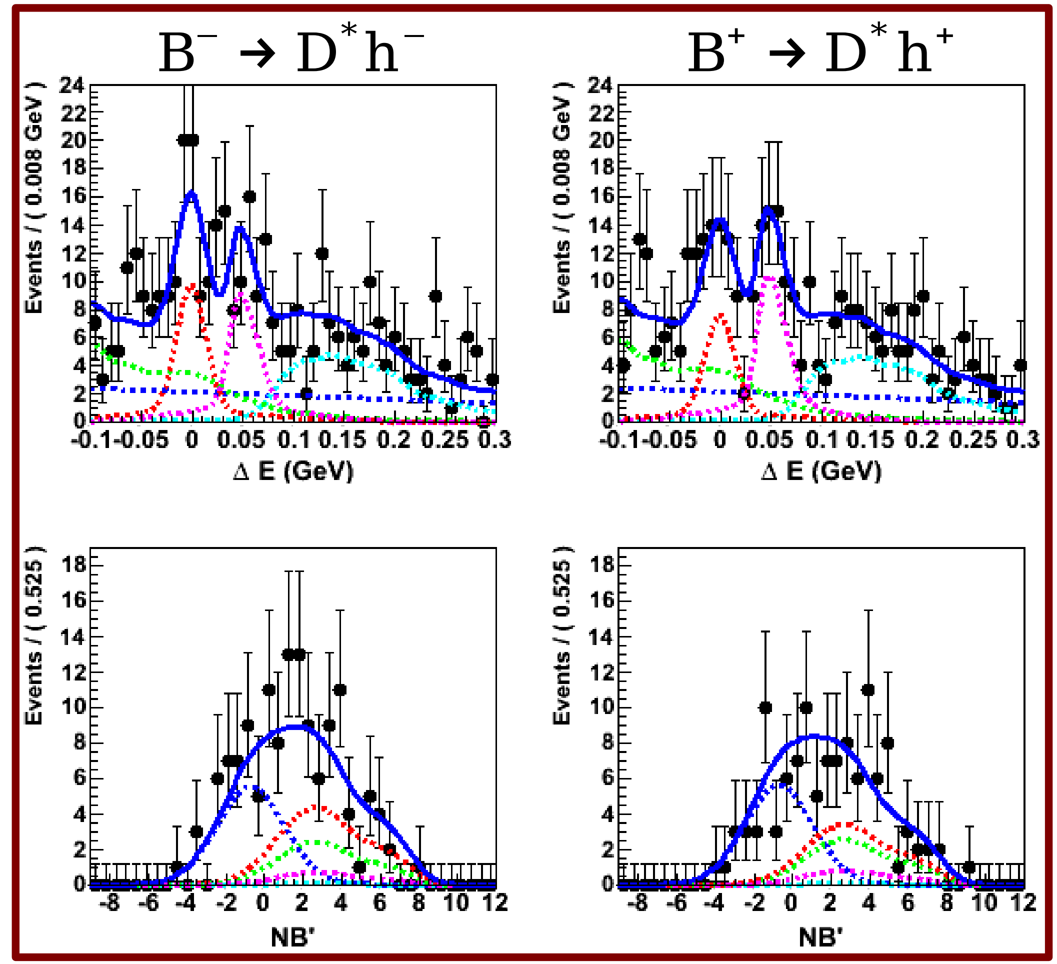
$\Rightarrow R_{D_{fav}} = (7.36 \pm 0.44)\%$

$A(D^{*}_{fav}K) = (-1.93 \pm 5.8)\%$

$D \to K^{+}K^{-},\ \pi^{+}\pi^{-} \to CP-$



$D \to K_S\pi^{0},\ K_S\eta \to CP+$



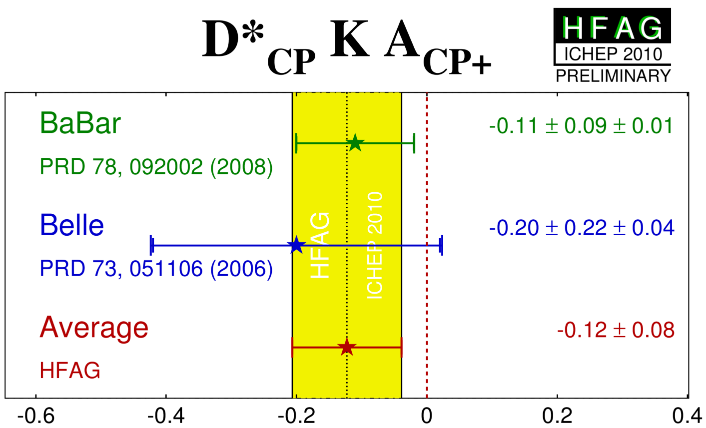
$R_{CP-} = 0.77 \pm 0.19$

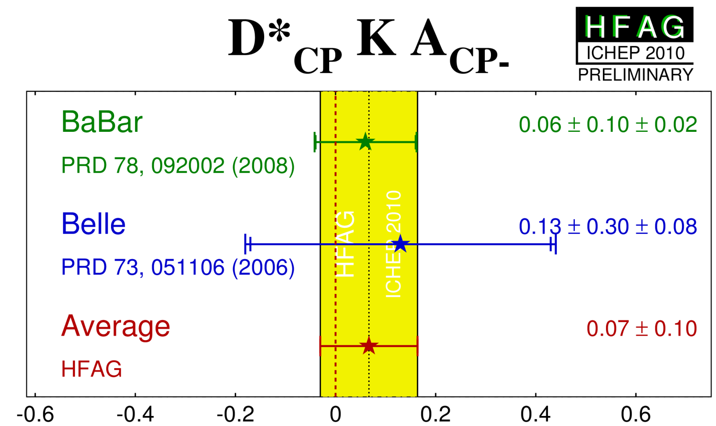
$A_{CP-} = +0.28 \pm 0.23$

$R_{CP+} = 1.07 \pm 0.22$

$A_{CP+} = +0.13 \pm 0.19$

Status and motivation for GLW in $B \to D^{*0}K$





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$D^*_{CP}K^-$	BaBar N(BB)=383M	−0.11 ± 0.09 ± 0.01	0.06 ± 0.10 ± 0.02	1.31 ± 0.13 ± 0.03	1.09 ± 0.12 ± 0.04	PRD 78, 092002 (2008)
	Belle N(BB)=275M	−0.20 ± 0.22 ± 0.04	0.13 ± 0.30 ± 0.08	1.41 ± 0.25 ± 0.06	1.15 ± 0.31 ± 0.12	PRD 73, 051106 (2006)
	Average	−0.12 ± 0.08 χ^2 = 0.14 (CL=0.71 ⇒ 0.4σ)	0.07 ± 0.10 χ^2 = 0.05 (CL=0.83 ⇒ 0.2σ)	1.33 ± 0.12 χ^2 = 0.12 (CL=0.73 ⇒ 0.4σ)	1.10 ± 0.12 χ^2 = 0.03 (CL=0.87 ⇒ 0.2σ)	HFAG

[Belle previous result: 1/3 of the full data sample, only $D^* \to D\pi^0$]

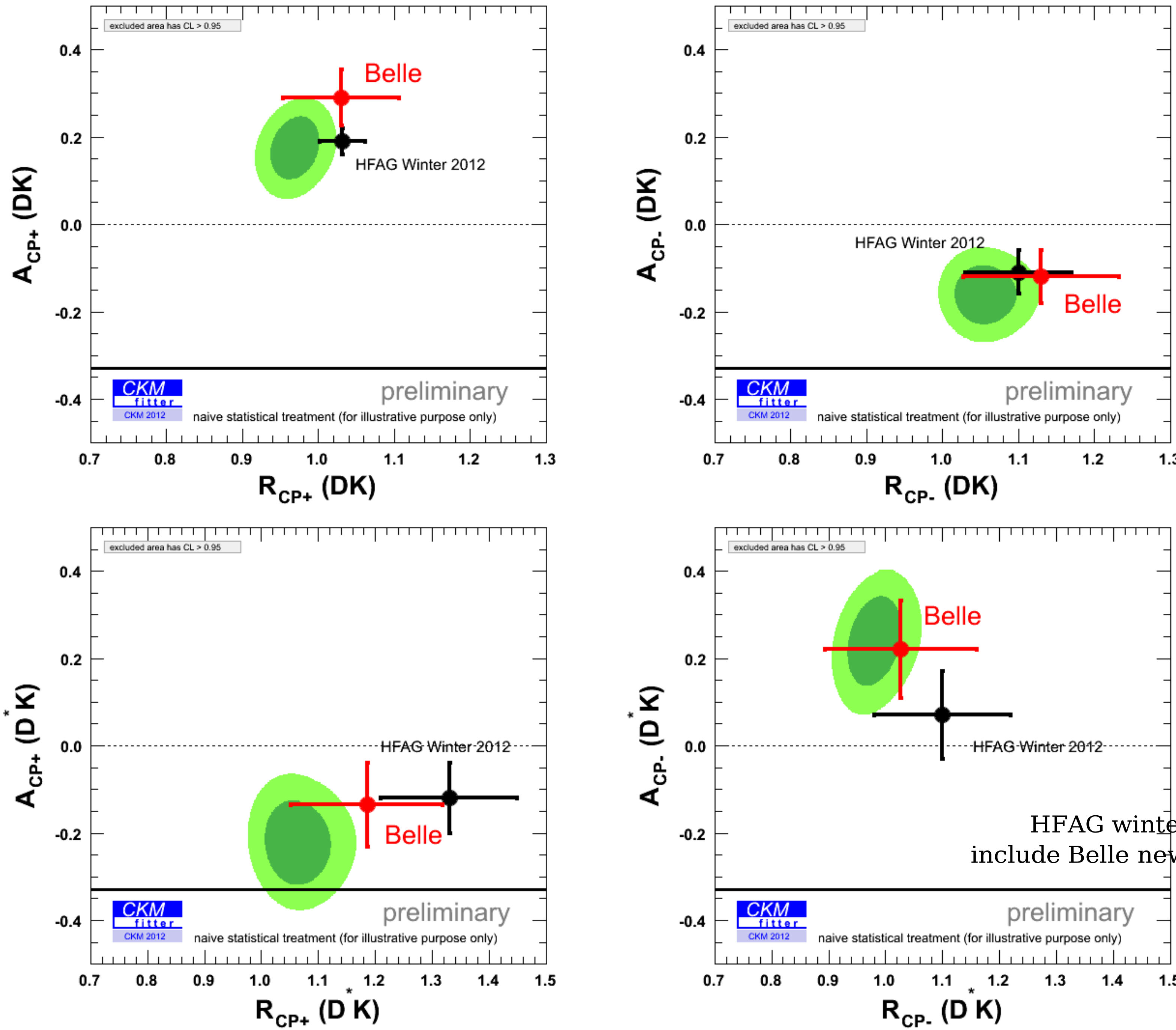
Combining the results of $D^* \to D\pi^0$, $D\gamma$:

$$R_{CP+} = 1.19 \pm 0.13 \pm 0.03$$
$$R_{CP-} = 1.03 \pm 0.13 \pm 0.03$$
$$A_{CP+} = -0.14 \pm 0.10 \pm 0.01$$
$$A_{CP-} = +0.22 \pm 0.11 \pm 0.01$$

significant improvement, consistent with expected pattern

Comparison of the results obtained for GLW $D^{(*)}K$ with expectations

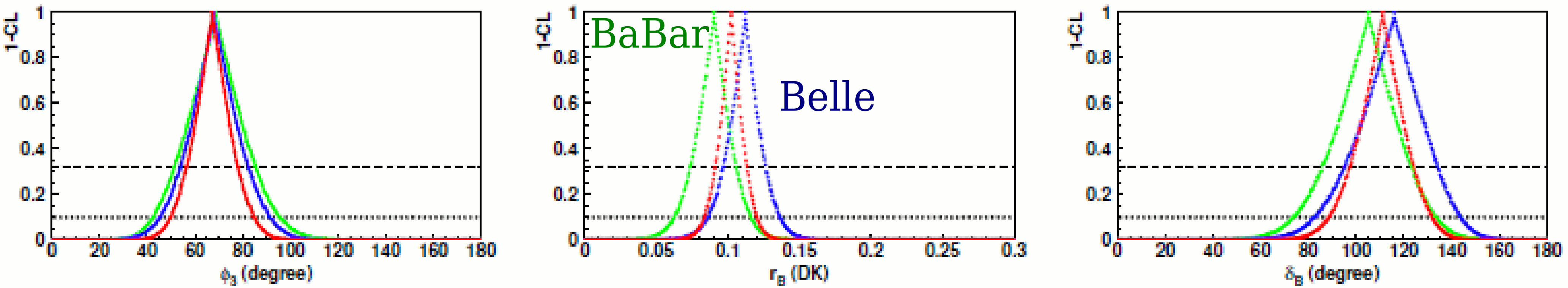
where ''expectations'' are derived from the GGSZ observables (W.A.), δ_D and γ_{UT}



HFAG winter 2012 doesn't include Belle new (GLW D^*K) results

Combined measurements for γ from all methods

γ, from B-factories

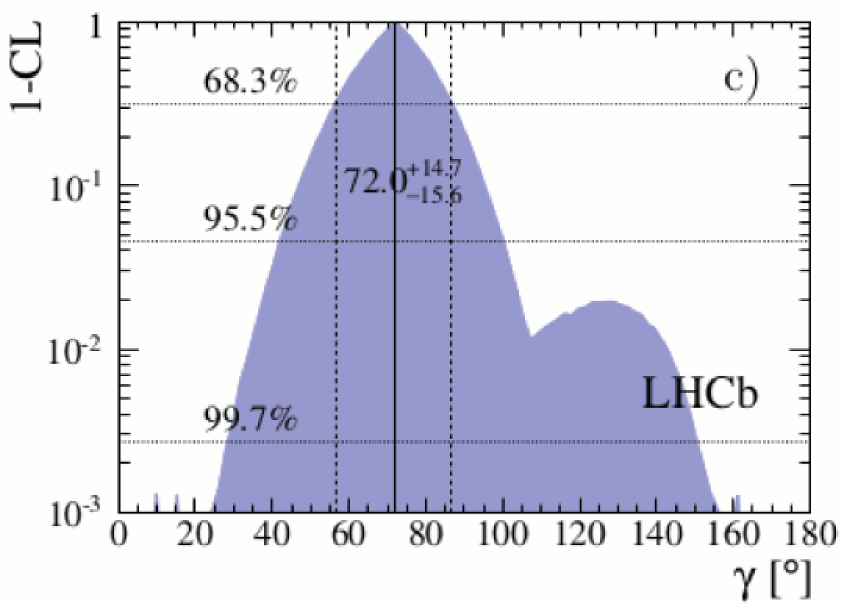


	ϕ_3 (°)	$r_B(DK)$	$\delta_B(DK)$ (°)
BaBar	69 ± 17	$0.090^{+0.016}_{-0.017}$	105 ± 19
Belle	68 ± 14	0.112 ± 0.015	116^{+19}_{-21}
B factories	67 ± 11	0.102 ± 0.011	111^{+13}_{-14}

[see also 1301.1029]

γ, from LHCb [combination DK, GGSZ, ADS ($K\pi$, $K3\pi$), GLW (KK, $\pi\pi$)]

[arXiv:1305.2050v2]

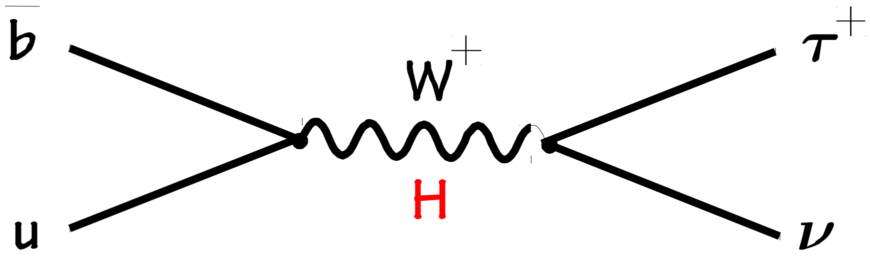


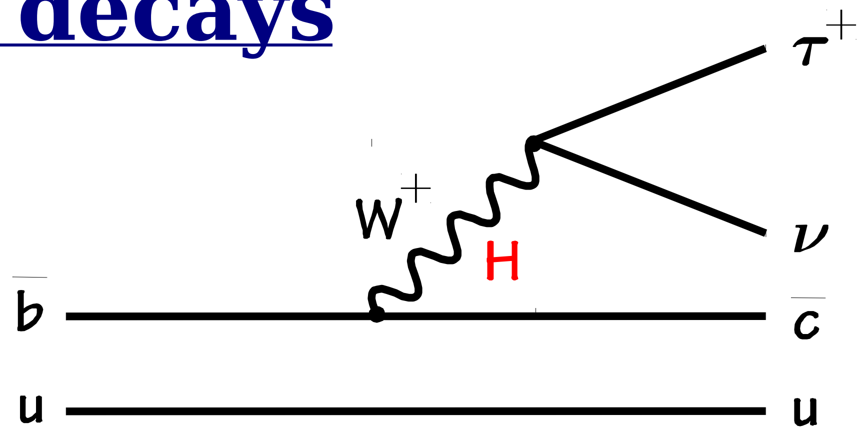
$$\gamma = (72.0^{+14.7}_{-15.6})^\circ$$

$$\delta_B = (112^{+14}_{-16})^\circ$$

$$r_B = 0.089 \pm 0.009$$

Tauonic B decays





$B \to \tau\nu$

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

$$\text{2HDM (type II)}: \mathcal{B}(B^+ \to \tau^+\nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$

uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B and other CKM uncertainties by combining with precise Δm_d

$B \to D^{(*)}\tau\nu$

$$\text{2HDM (type II)}: \mathcal{B}(B \to D\tau^+\nu) = G_F^2 \tau_B |V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$$

uncertainties from form factors F_V and F_S can be studied with $B \to D l \nu$ (more form factors in $B \to D^* \tau\nu$)

$B^+ \to \tau^+ \nu$ results (before summer 2012)

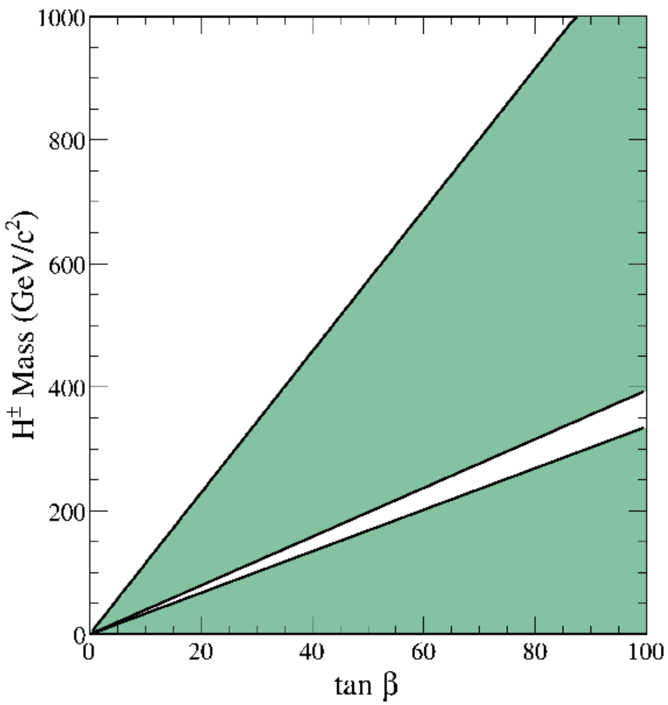
World average: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.68 \pm 0.31) \times 10^{-4}$

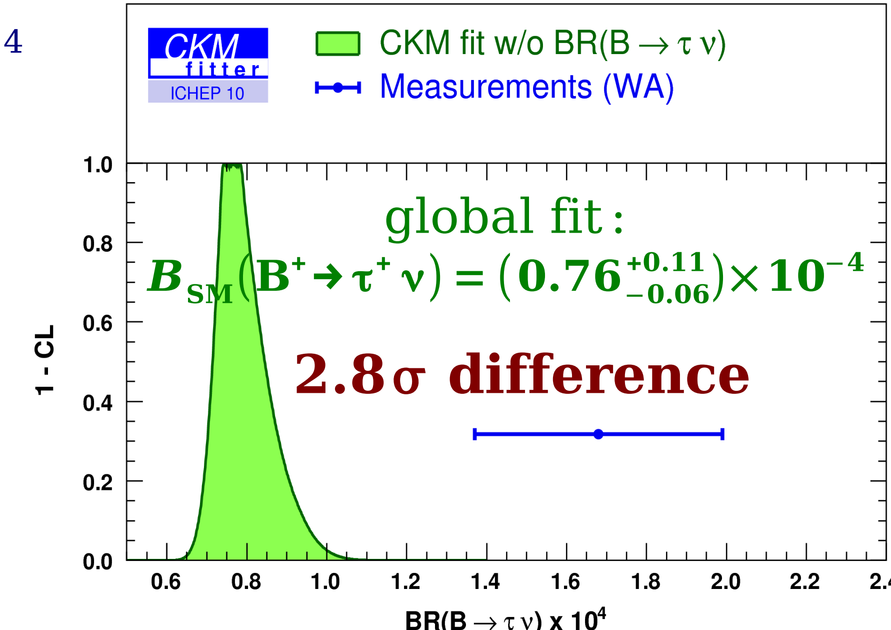
$$\mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4}$$

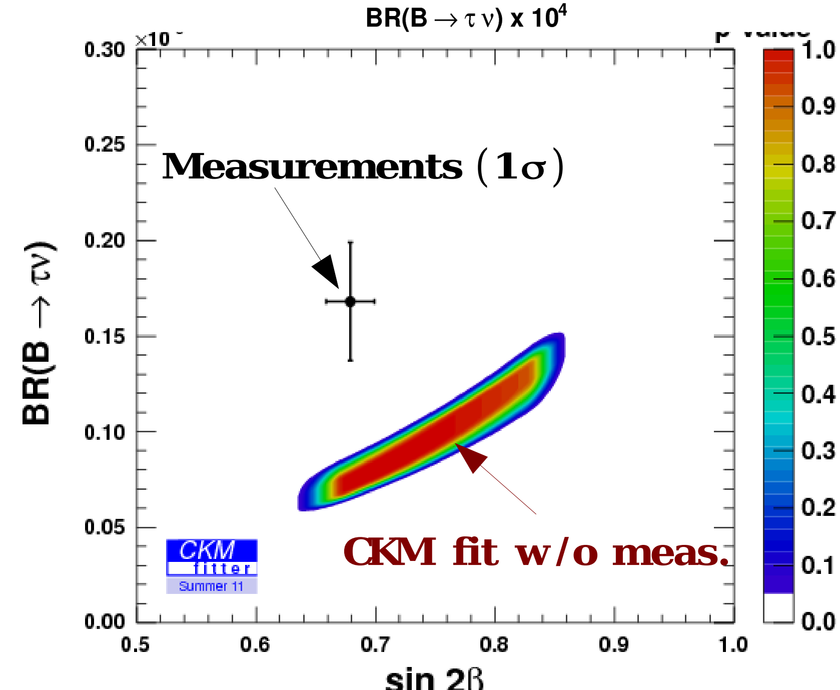
using f_B (HPQCD), $|V_{ub}|$ (HFAG)

2HDM (type II):

$$\mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$







⇒ within the SM, either the observed BR[$B \to \tau\nu$] is too high, either $\sin 2\beta_{cc}$ is too low

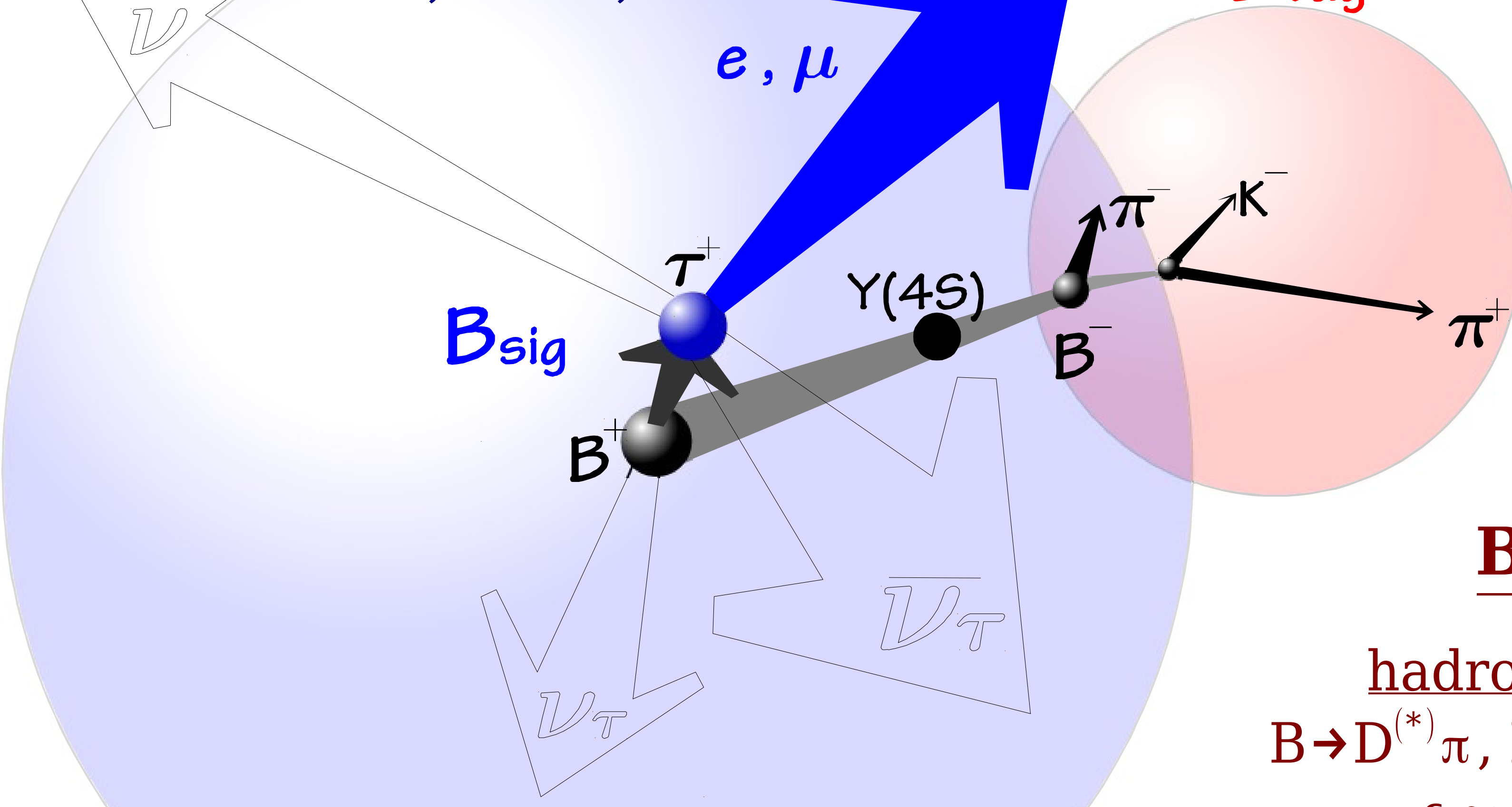
Event reconstruction in $B \to \tau \nu$

$B_{sig} \to \tau \nu$

(70 % of all τ decays)

$\tau \to e \nu \nu$, $\mu \nu \nu$,

$\tau \to \pi \nu$, $\pi \pi^0 \nu$, $3 \pi \nu$



Require no particle
and no energy left
after removing B_{tag}
and visible particles of B_{sig}

B_{tag}

hadronic tag

$B \to D^{(*)}\pi$, $D^{(*)}$%rho....

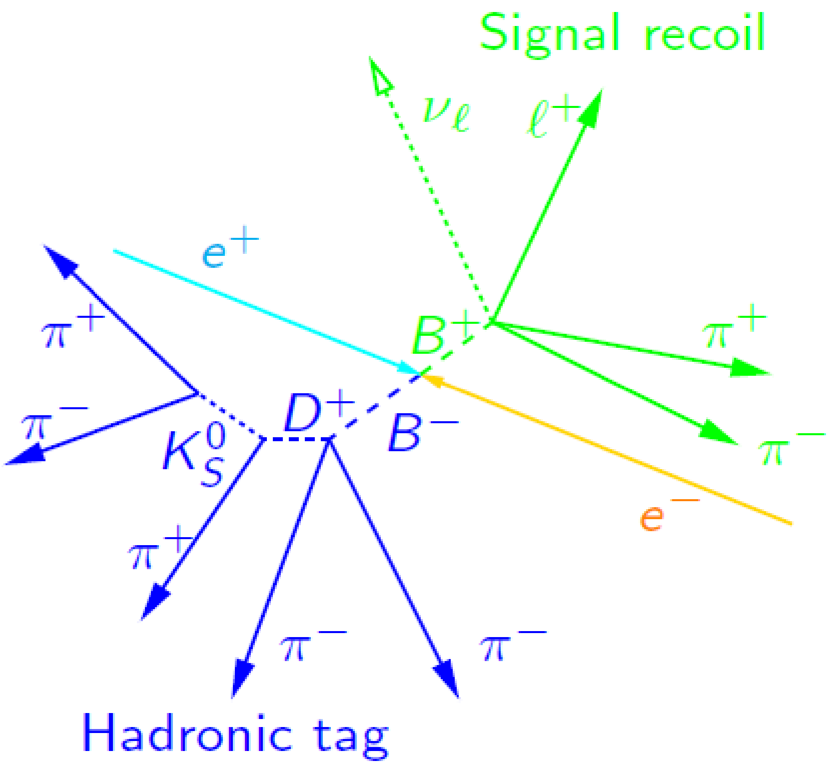
$\epsilon \sim 0.3\,\%$

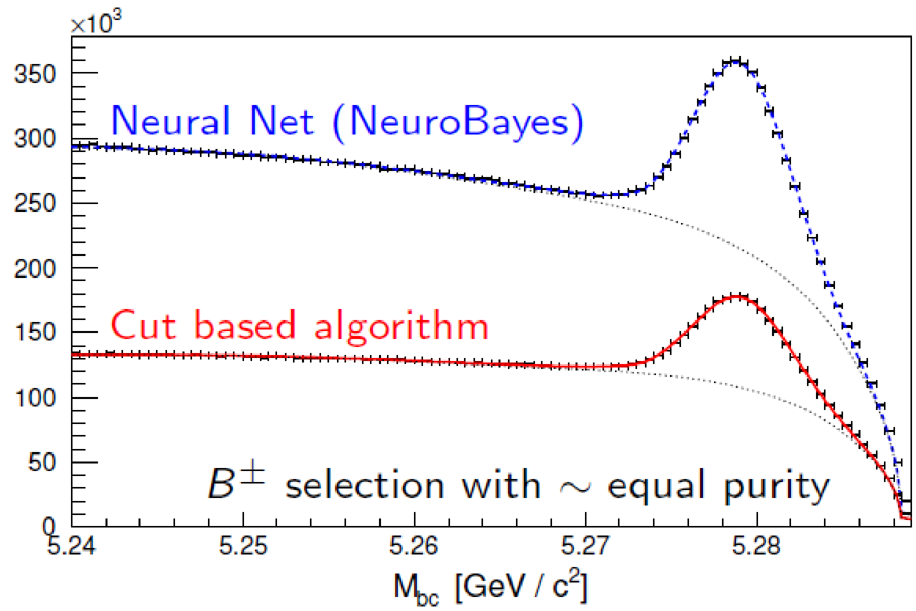
semileptonic tag

$B \to D^{(*)} l \nu \, X$

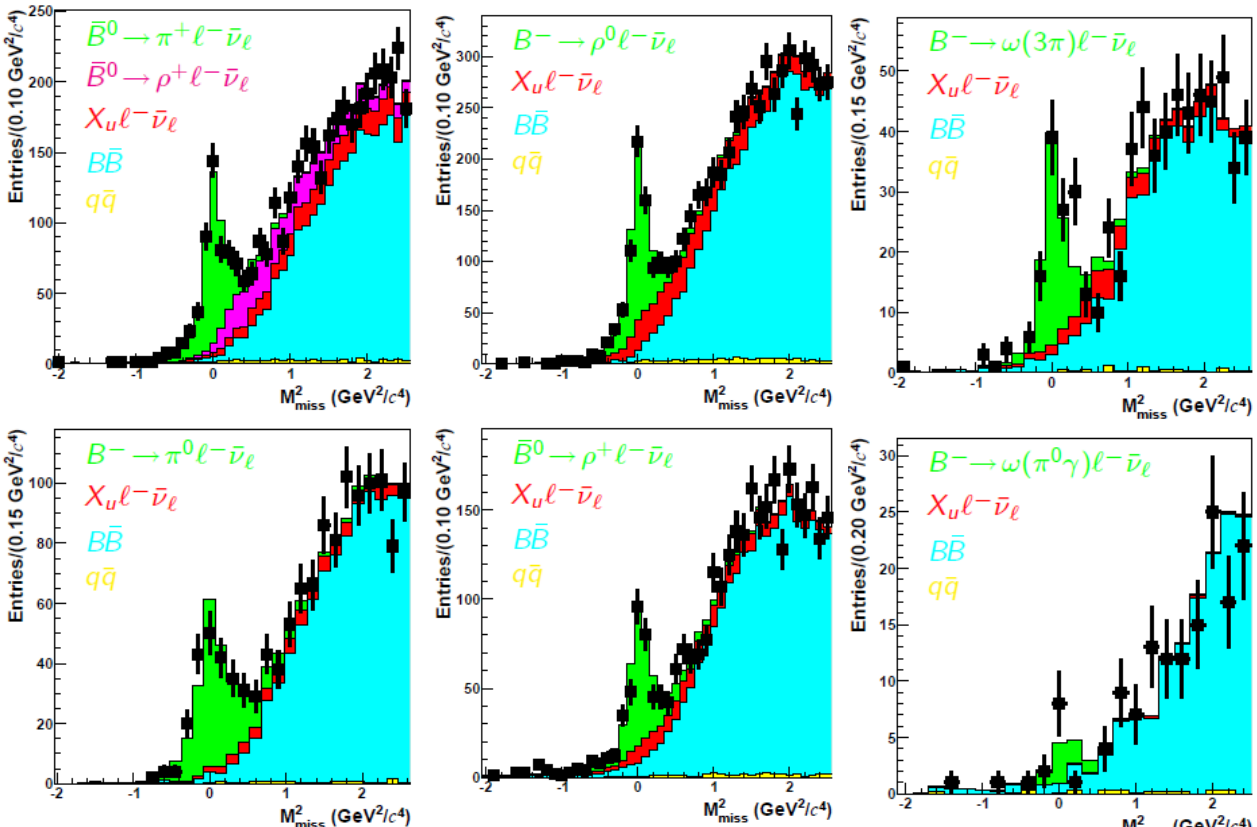
Exclusive (Semi)leptonic Decays

- Recent improvements to Belle hadronic tagging ([NIM A654, 432 (2011)])
  - Based on NeuroBayes package
  - Reconstructs tag-side B meson in > 1100 exclusive hadronic decay modes
  - Calibrated with charm semileptonic decays
  - Gives ~ 2 × more efficiency than previous cut-based tagging method





B → (π, ρ, ω) l ν as an illustration [PRD 88, 032005 (2013)]



- π and ρ measurements allow tests of isospin symmetry:

$$2 \times \frac{\mathcal{B}(B^- \to \pi^0\ell^-\bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.00 \pm 0.13_{\rm tot}$$

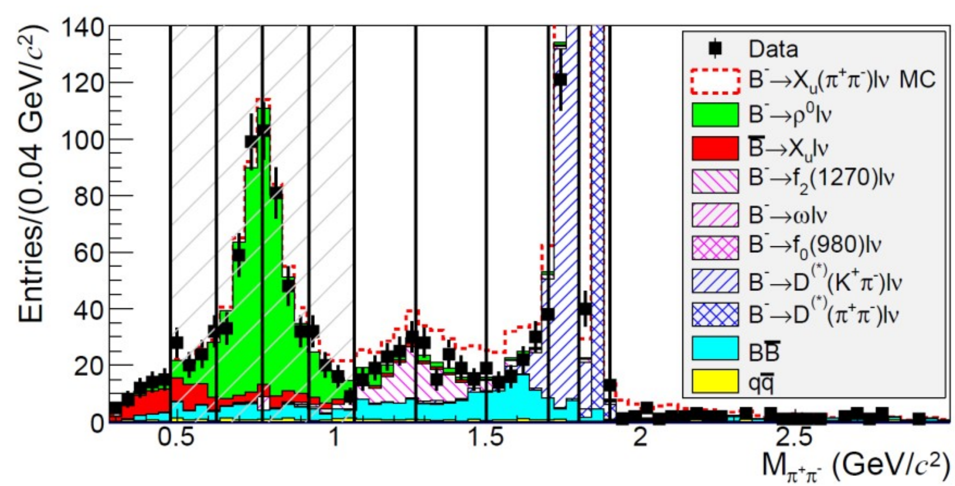
$$2 \times \frac{\mathcal{B}(B^- \to \rho^0\ell^-\bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \rho^+\ell^-\bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.06 \times (1 \pm 0.13_{\rm tot})$$

both consistent with SM (= 1)

- B→ρ l ν:
  - Deficit of nonresonant ππ predicted by PYTHIA
  - ~3 × higher f_2 contribution than ISGW2

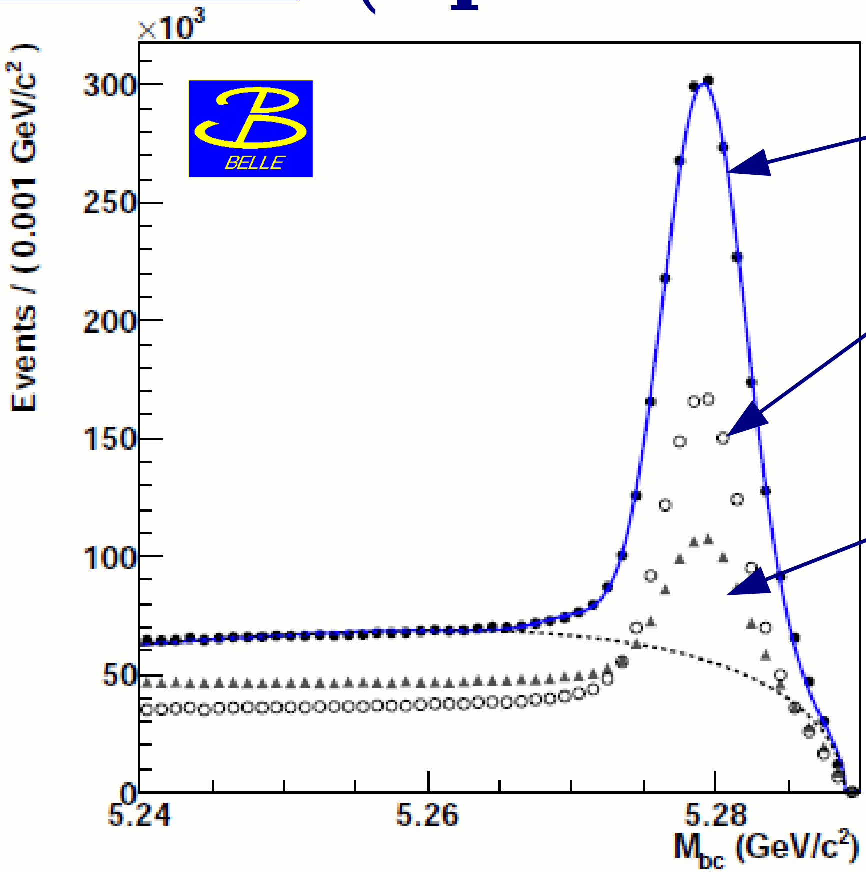
→ Potentially impacts inclusive $|V_{ub}|$ through improvements to MC

X_u	$N^{\rm fit}$	$\mathcal{B}$ (x10⁴)
π^0	232.2 ± 22.6	$0.80 \pm 0.08 \pm 0.04$
π^+	462.6 ± 27.7	$1.49 \pm 0.09 \pm 0.07$
ρ^0	621.7 ± 35.0	$1.83 \pm 0.10 \pm 0.10$
ρ^+	343.3 ± 28.3	$3.22 \pm 0.27 \pm 0.24$
$\omega(3\pi)$	96.7 ± 14.5	$1.07 \pm 0.16 \pm 0.07$
$\omega(\pi^0\gamma)$	9.0 ± 4.0	$1.06 \pm 0.47 \pm 0.07$
ω(average)		$1.07 \pm 0.15 \pm 0.07$



$B^+ \to \tau^+ \nu$ (update hadronic tag)

[PRL 110, 131801 (2013)]
[arXiv:1208.4678]



new tag algorithm on full data
(reprocessed)

new tag algorithm on previous data

based on neural network & more exclusive hadronic decay modes (>1100)
NIM A654, 432 (2011)

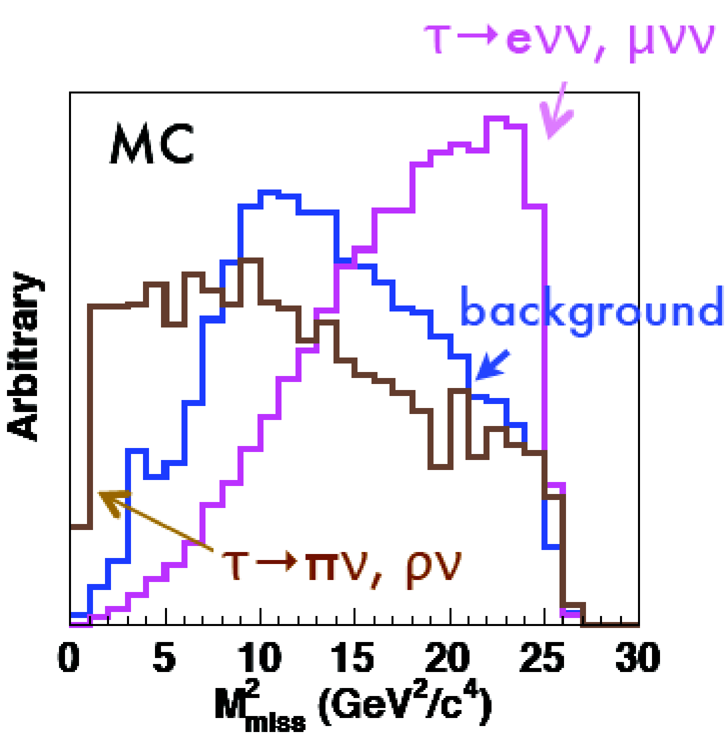
previous tag algorithm on previous data

× 3 B_{tag} sample size

[purity also improved]

Signal extraction based on two variables:

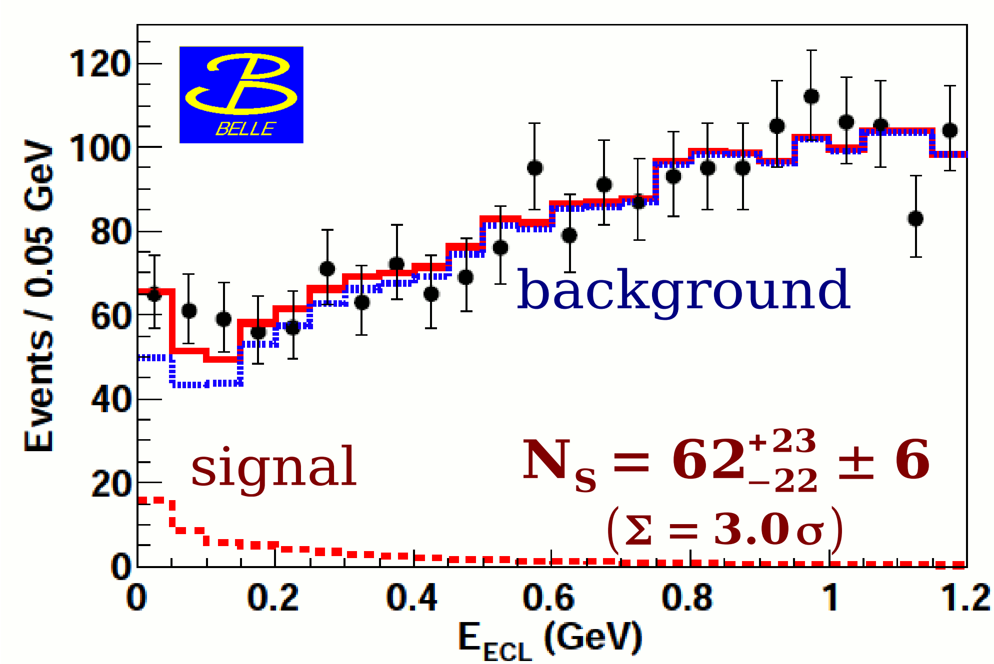
- E_{ECL}: remaining energy in electromagnetic calorimeter (peak at $E_{ECL} = 0$ GeV for signal)
- M^2_{miss}: missing mass squared (larger for $e\nu\nu/\mu\nu\nu$, smaller for $\pi\nu/\rho\nu$)

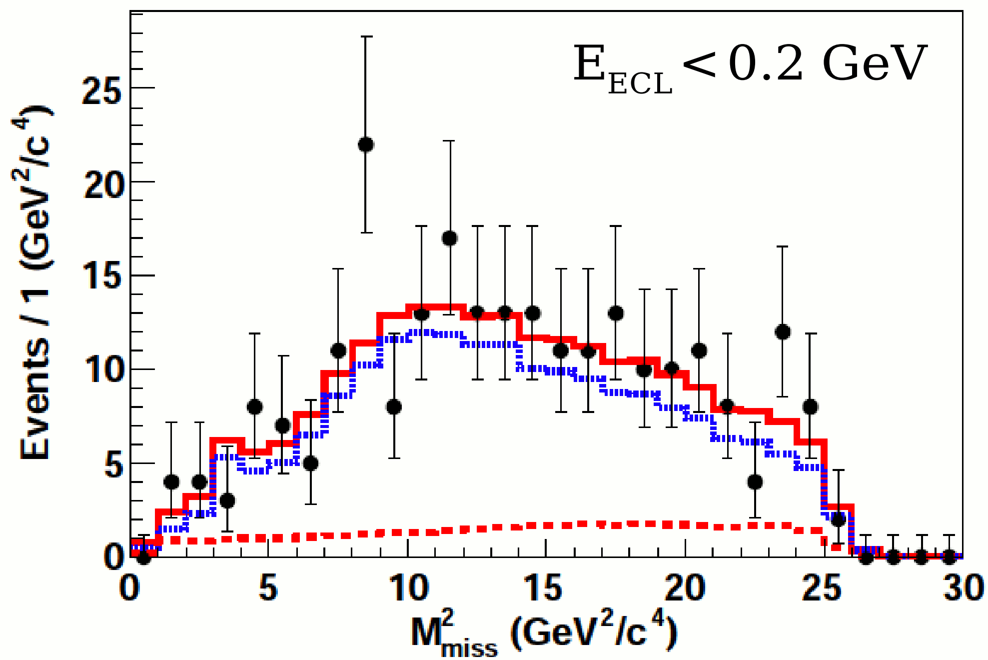


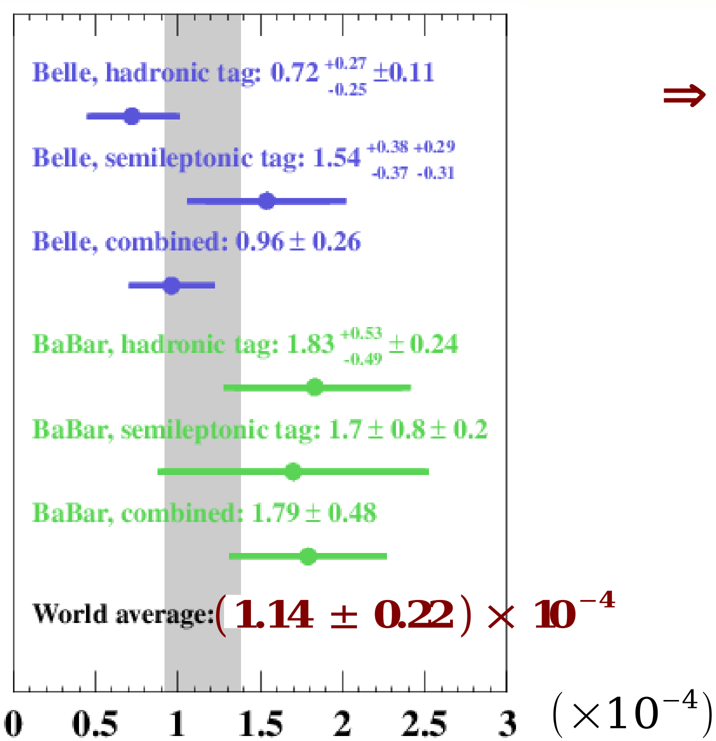
$B^+ \to \tau^+ \nu$ (update hadronic tag)

[PRL 110, 131801 (2013)]
[arXiv:1208.4678]

simultaneous fit to the different τ reconstruction modes ($\tau \to e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$)





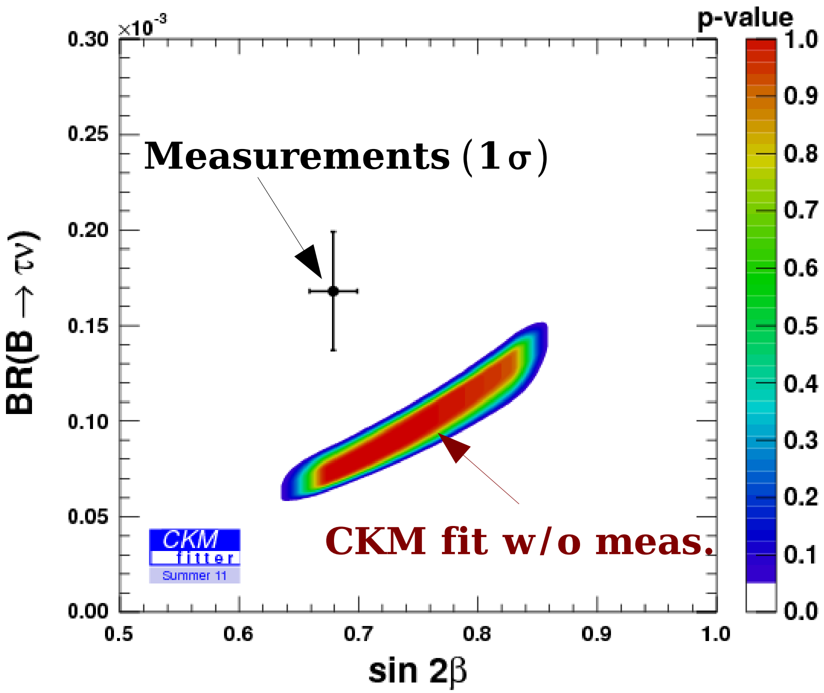


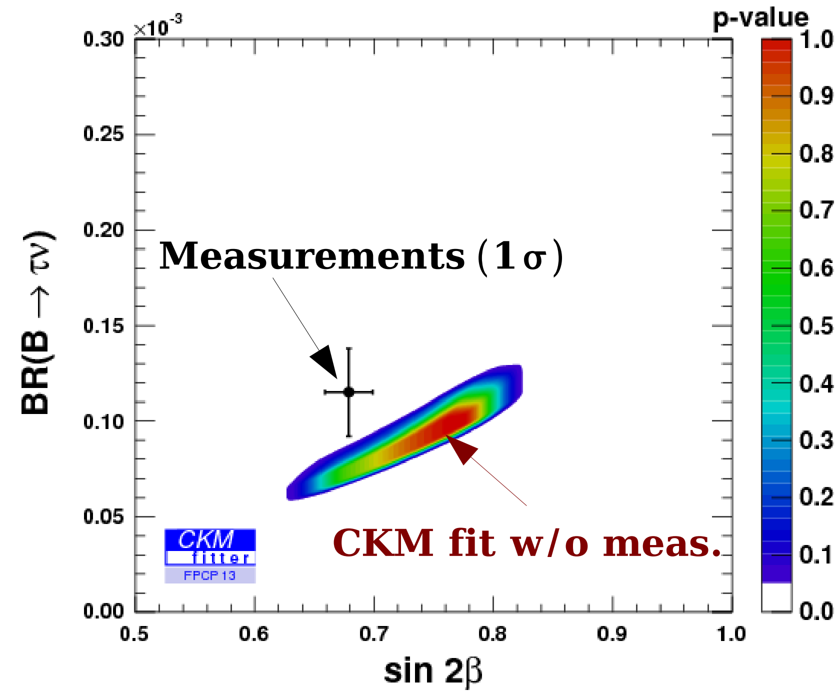
$$\Rightarrow \mathcal{B}(B^+ \to \tau^+ \nu) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$$

Significance of 3.0σ

Sub-mode	N_{sig}	ϵ (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	16^{+11}_{-9}	3.0	$0.68^{+0.49}_{-0.41}$
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	26^{+15}_{-14}	3.1	$1.06^{+0.63}_{-0.58}$
$\tau^- \to \pi^- \nu_\tau$	8^{+10}_{-8}	1.8	$0.57^{+0.70}_{-0.59}$
$\tau^- \to \pi^- \pi^0 \nu_\tau$	14^{+19}_{-16}	3.4	$0.52^{+0.72}_{-0.62}$
Combined	62^{+23}_{-22}	11.2	$0.72^{+0.27}_{-0.25}$

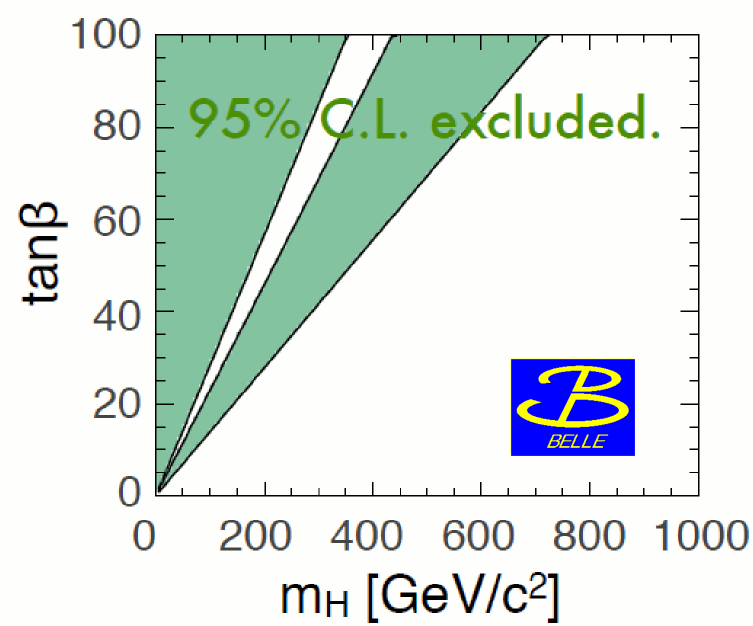
$B^+ \to \tau^+ \nu$ vs $\sin 2\beta$





⇒ Tension in global fit significantly easy : now reduced to ~ 1.6 σ

⇒ Set very powerful constraints on $\tan\beta$, m_H parameter space



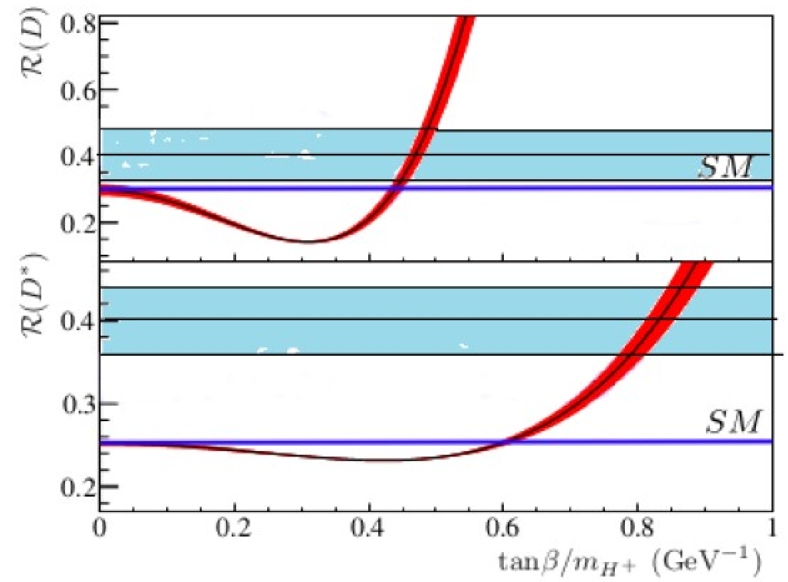
Results on $B \to D^{(*)} \tau \nu$

- Also sensitive to charged Higgs:
  - uncertainties related to $|V_{cb}|$ and hadronic effects cancel in ratios:

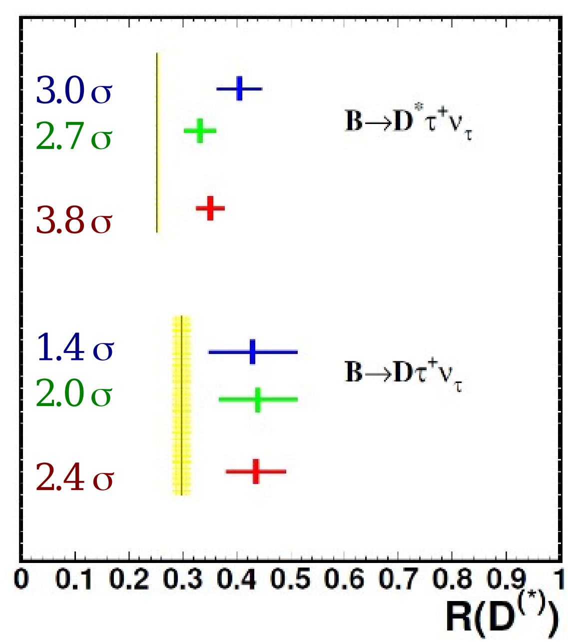
$$\mathcal{R}(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^- \bar{\nu}_\ell)} \qquad \mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^- \bar{\nu}_\ell)}$$

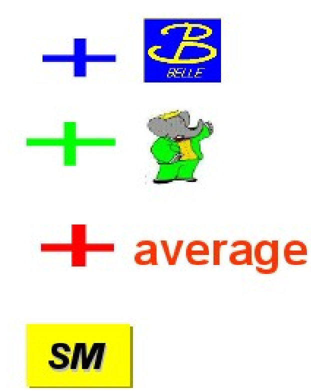
  - Standard Model expectations:

$$\mathcal{R}(D) \sim 0.3 \qquad \mathcal{R}(D^*) \sim 0.25$$



- Previous Belle measurements:
  - Inclusive tagging:
    - $B^0 \to D^{*-} \tau^+ \nu$ [PRL 99, 191807 (2007)]
    - $B^+ \to D^{(*)0} \tau^+ \nu$ [PRD 82, 072005 (2010)]
  - Exclusive tagging:
    - $B^0 \to D^{(*)-} \tau^+ \nu$
    - $B^+ \to D^{(*)0} \tau^+ \nu$ [arXiv:0910/4301]



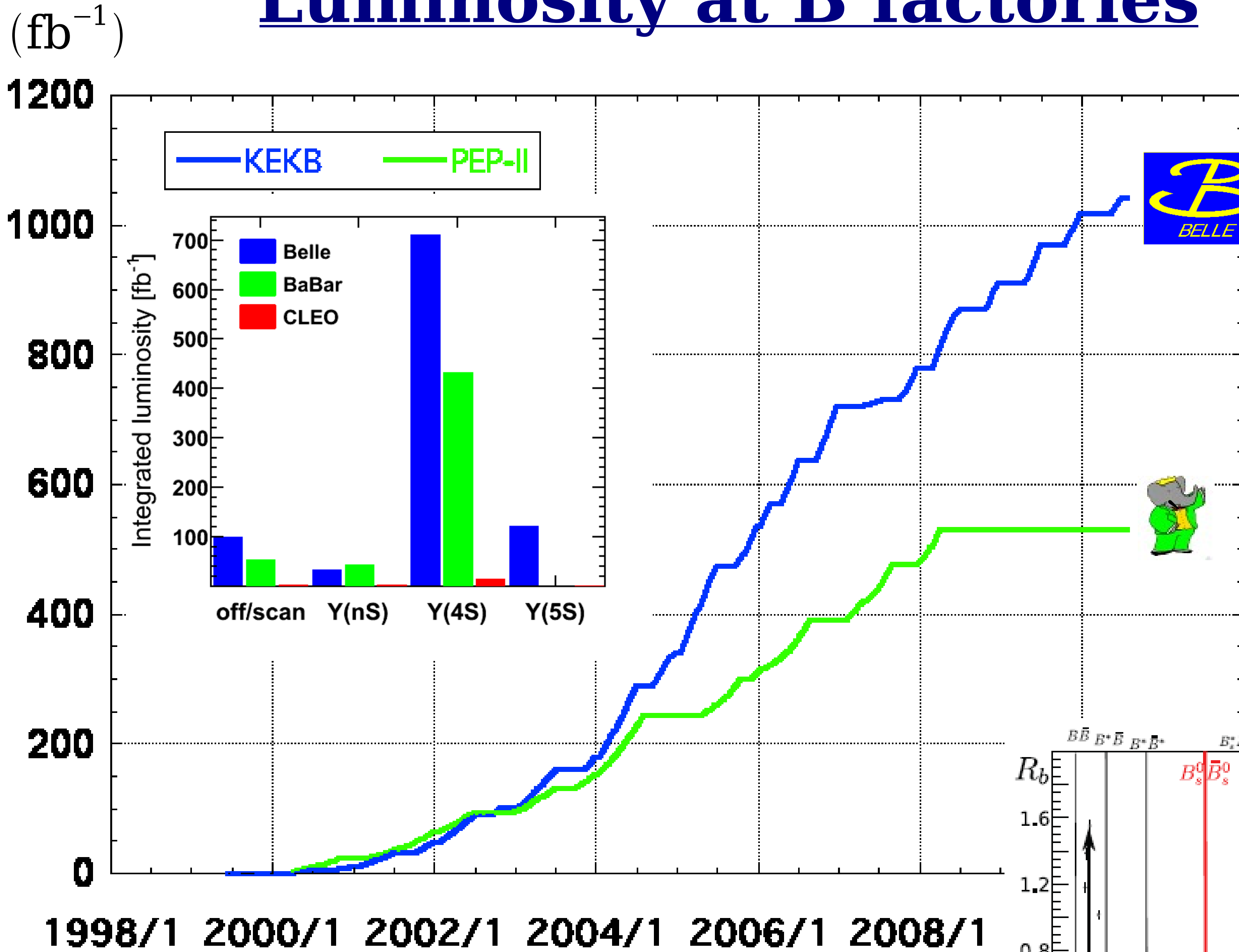


PRD 85, 094025 (2012)

Combined for Belle/BaBar $R(D^{(*)})$: 4.8 σ

⇒ $R(D^{(*)})$ analysis for final Belle data set (had tag) underway

Luminosity at B factories



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

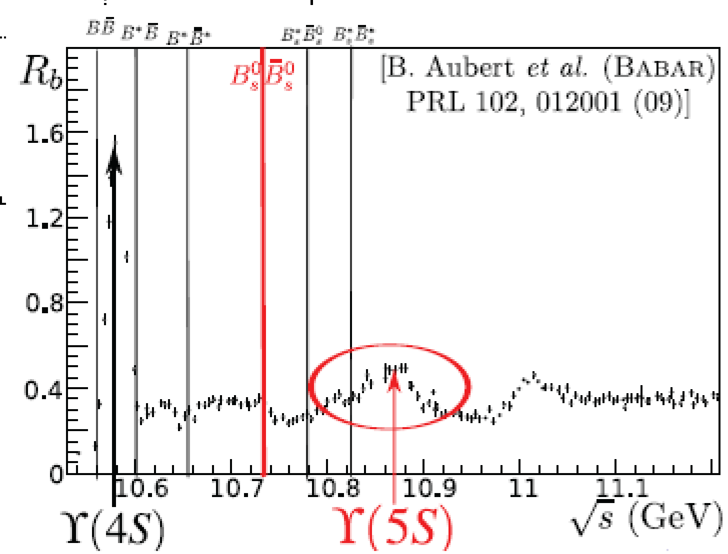
Υ(2S): 24 fb^{-1}

Υ(1S): 6 fb^{-1}

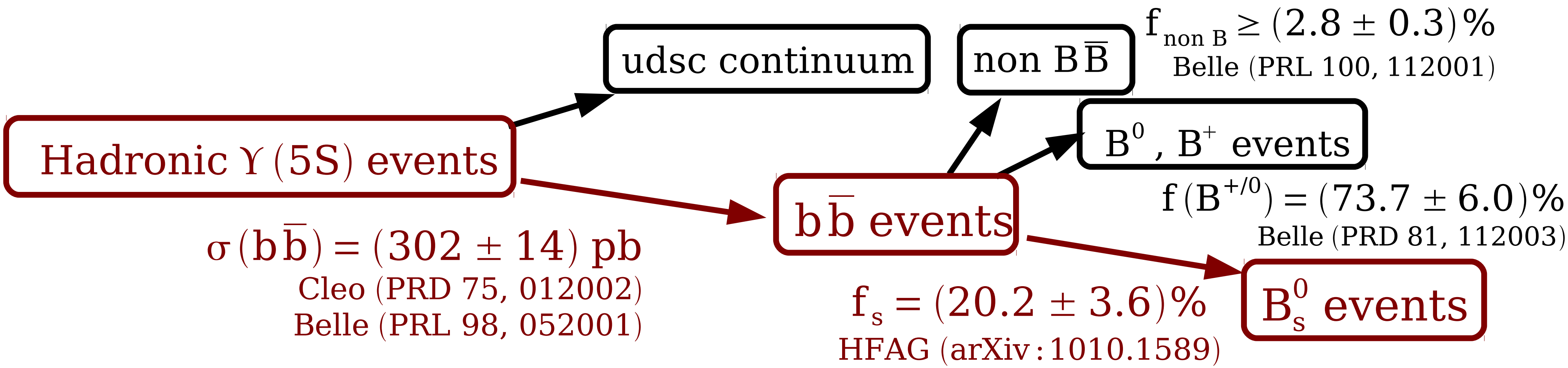
Off reson./scan:

~ 100 fb^{-1}

Data taken at Υ(5S) ($\sqrt{s}$ = 10867 ± 1 MeV)



B_s production at $\Upsilon(5S)$



f_s = fraction of B_s. Inclusive measurements:

$$\underbrace{\frac{1}{2}\mathcal{B}(\Upsilon(5S) \to D_s X)}_{\Upsilon(5S)\ \text{data}} = f_s \times \underbrace{\mathcal{B}(B_s \to D_s X)}_{\text{model-dependent estimate}} + (1-f_s) \times \underbrace{\mathcal{B}(B \to D_s X)}_{\Upsilon(4S)\ \text{data}}$$

15% uncertainty, mainly due to model-dependent estimate

$\Rightarrow$ dominant systematics for Belle branching fractions

$$\textbf{In 121 fb}^{-1}: N_{B_s^0} = 2\, L_{int} \cdot \sigma(b\bar{b}) \cdot f_s \approx 14 \times 10^6$$

for ~ 90%, they are $B_s^* \bar{B}_s^*$ events

$B_s \to$ CP eigenstates decays and more…

- CP eigenstates:
  - $B_s \to J/\psi\,\varphi$ (especially BR)
  - $B_s \to J/\psi\, f_0(980)$ (silver mode at LHCb to measure β_s)
  - $B_s \to J/\psi\,\eta$, $J/\psi\,\eta'$, KK, …

$\Rightarrow$ **the first step is to establish these modes !**

- $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ dominates $\Delta\Gamma_s$

$$\Delta\Gamma^{CP} = \Gamma(\text{CP-even}) - \Gamma(\text{CP-odd}) \approx \Gamma(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$$

CKM-favored and CP-even eigenstate (in heavy-quark limit)

Dominates $\Delta\Gamma$ (this relation has few % theoretical uncertainty)

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \approx \frac{2 \times \mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})}{1 - \mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})}$$

R.Aleksan et al., Phys. Lett. B 316, 567 (1993)

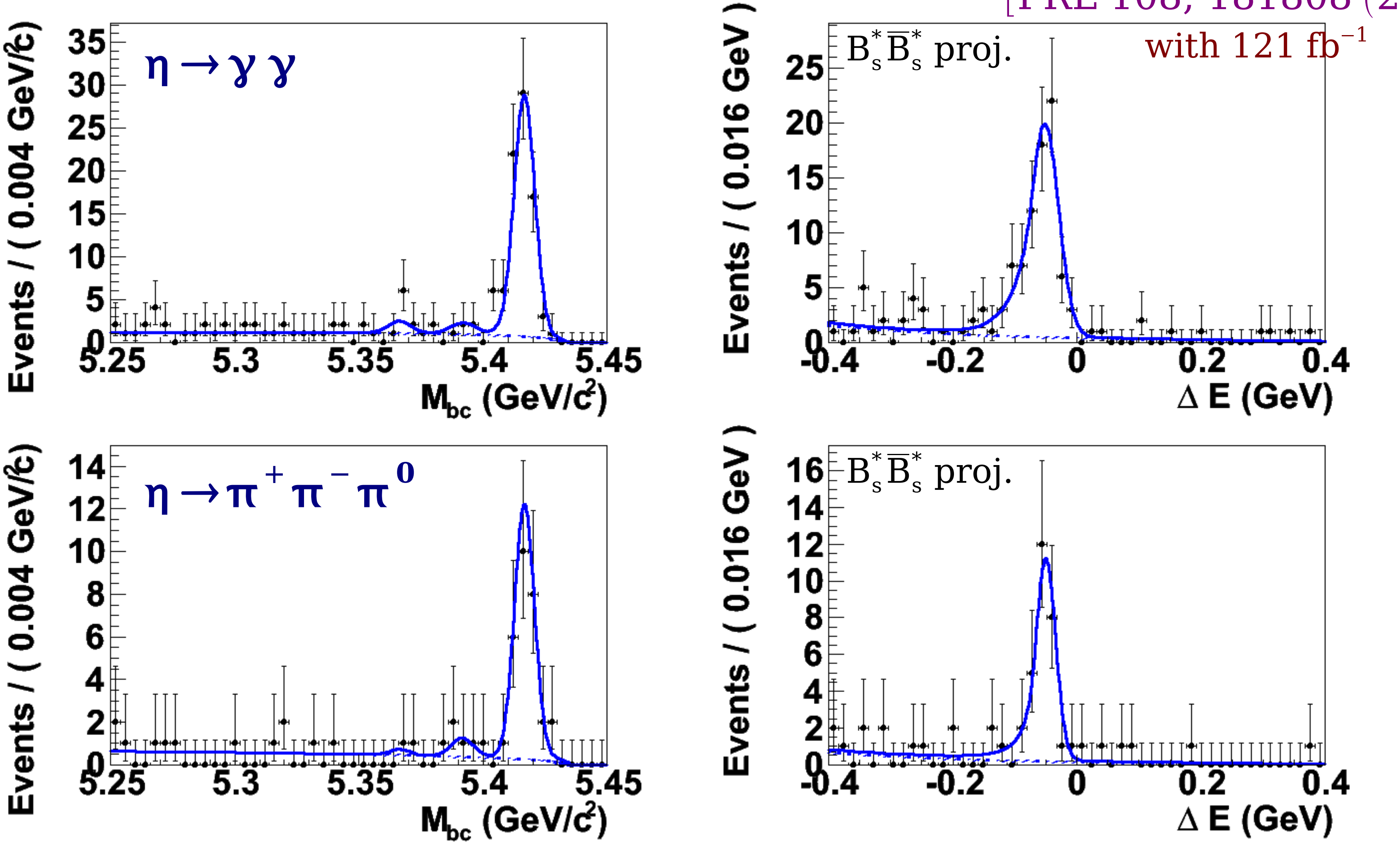
- Rare B_s decays: radiative decays…

$\Rightarrow$ **decays with π^0 and/or γ are difficult for hadron-collider experiments**

$B_s^0 \rightarrow$ CP-eigenstate Decay Modes

- Precise measurements of exclusive modes, including CP modes
  for example, ''Observation of $B_S^0 \rightarrow J/\psi f_0(980)$...'', PRL 106, 121802 (2011)
- **$B_s \rightarrow J/\psi\,\eta$ in $\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^+\pi^-\pi^0$ channels**

[PRL 108, 181808 (2012)]

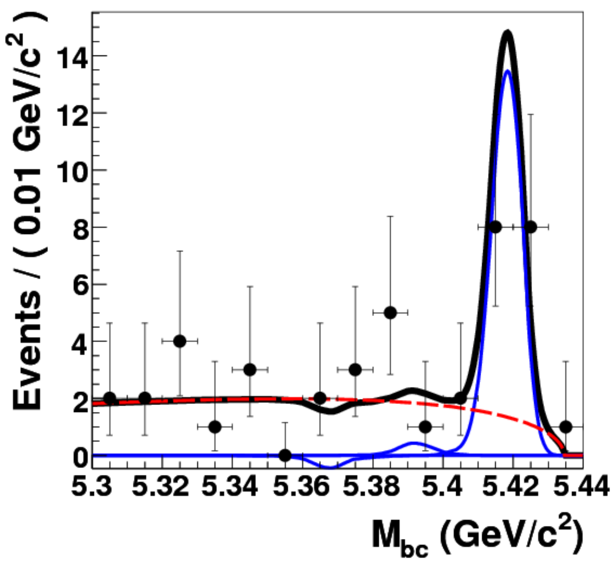


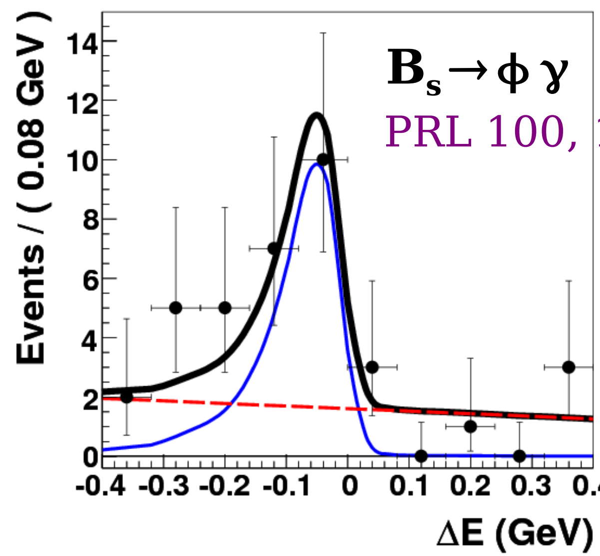
$$\mathbf{Br(B_s \rightarrow J/\psi\,\eta) = (5.10 \pm 0.50\,(stat) \pm 0.25\,(syst)\,^{+1.14}_{-0.79}\,(f_s)) \times 10^{-4}}$$

soon after confirmed by LHCb with 1 fb^{-1} [arXiv:1210.2631], similarly for $J/\psi\,\eta'$

$B_s \to \varphi\gamma$, $\gamma\gamma$

using only 23 fb^{-1}

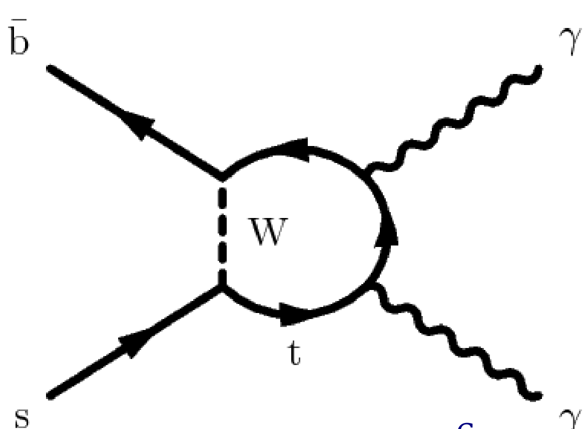




PRL 100, 121801 (2008)

$$\mathcal{B}(B_s \to \varphi\gamma) = (57^{+18}_{-15}(\text{stat})^{+12}_{-11}(\text{syst})) \times 10^{-6}$$

$$\mathcal{B}(B_s \to \gamma\gamma) < 8.7 \times 10^{-6} \text{ @ 90\% C.L.}$$

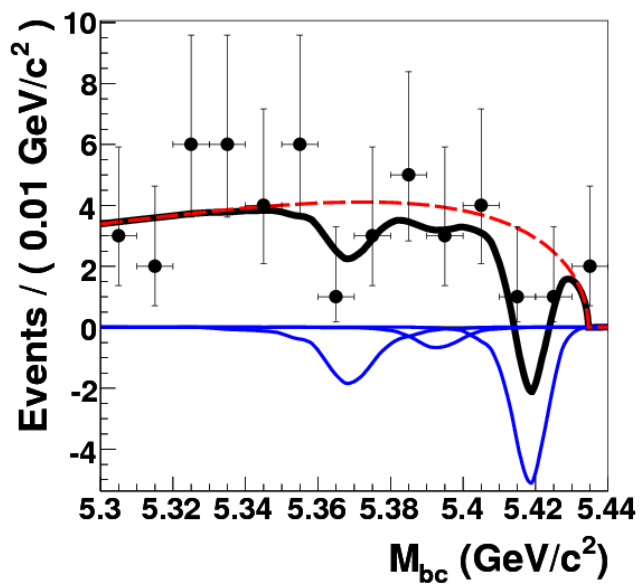


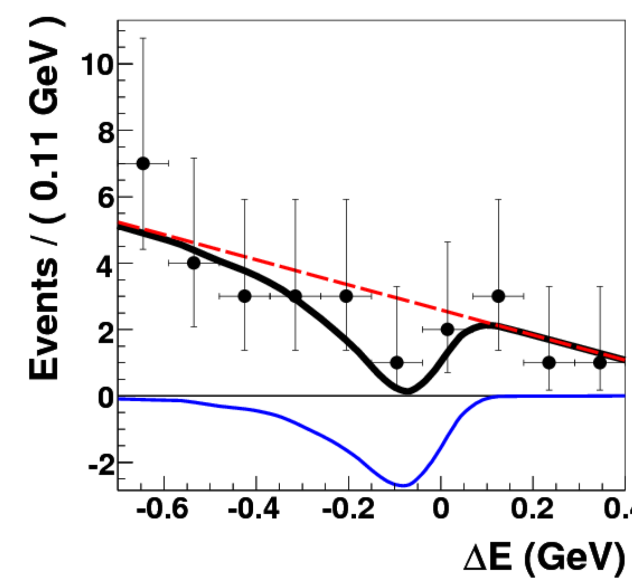
$\mathcal{B}_{SM} \sim 1 \times 10^{-6}$

Bosch and Buchalla

JHEP 0208:054 (2002)

$(\mathcal{B}_{SM}(B_d \to \gamma\gamma) \sim 3 \times 10^{-8})$



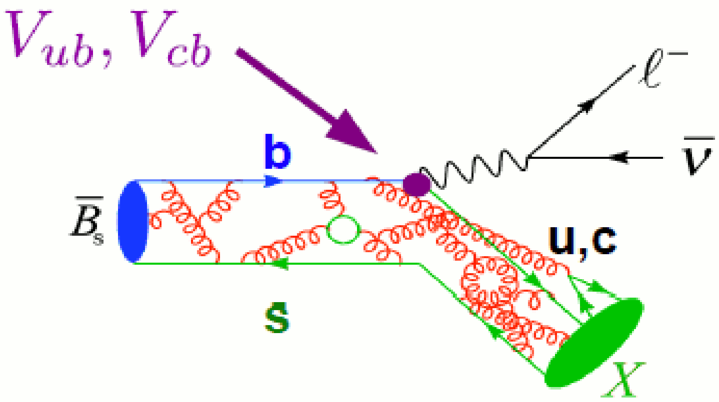


Using full Belle sample ($\times$ 5) and improved procedure

$\Rightarrow$ getting close to observation

$B_s \to X l \nu$

[arXiv:1212.6400]
to appear in PRD

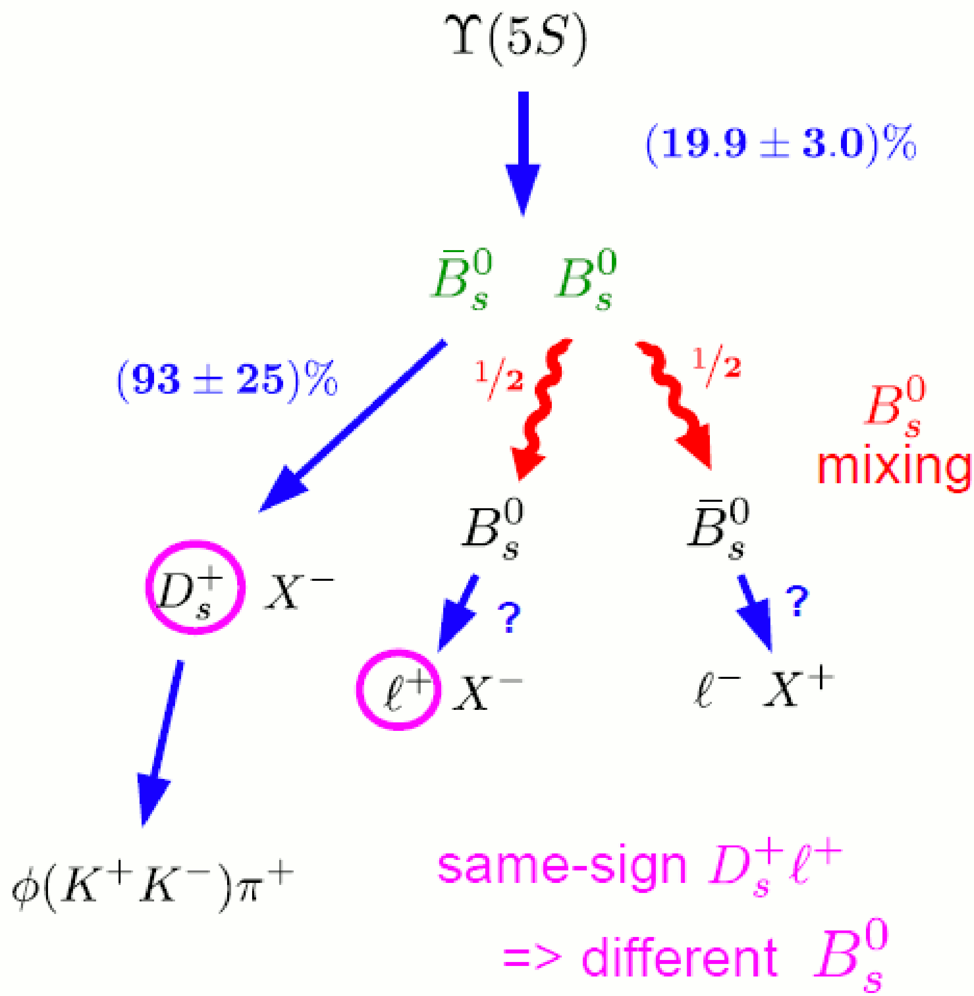


Important parameter for determination of B_s^0 production at LHC and B factories

Theory: ***SU(3) – Flavour Symmetry***:

$$\frac{\Gamma(B_s^0 \to X\ell\nu)}{\Gamma(B^0 \to X\ell\nu)} \approx 0.99 \qquad \ell = e, \mu$$

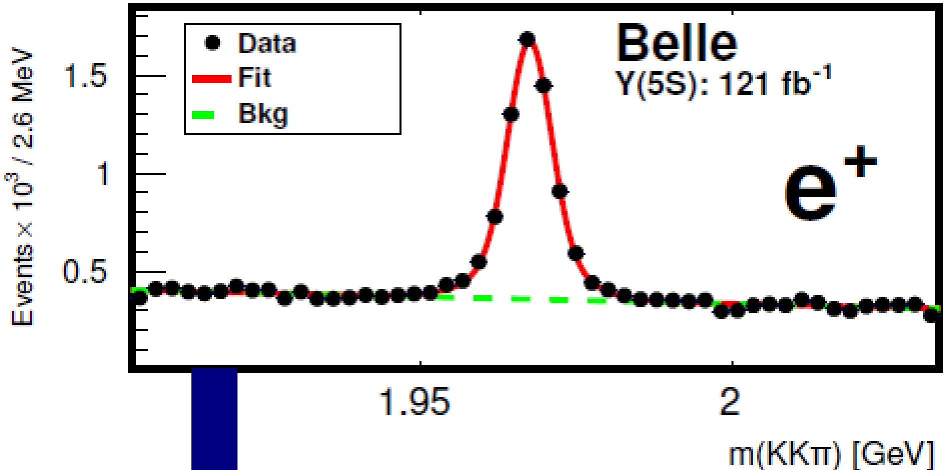
[JHEP1109,012(2011)]



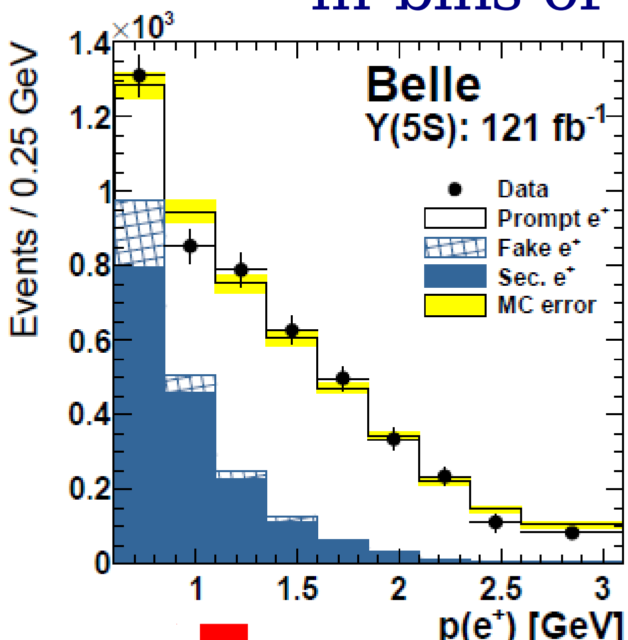
$$\mathcal{R} = \frac{\mathcal{N}(D_s^+\ell^+)}{\mathcal{N}(D_s^+)} \propto \frac{\mathcal{N}(B_s^0 \to \ell)}{\mathcal{N}(B_s^0)} = \mathcal{B}(B_s^0 \to X\ell\nu) \qquad \frac{\mathcal{N}_s(D_s^+\ell^+) + \mathcal{N}_{u,d}(D_s^+\ell^+)}{\mathcal{N}_s(D_s^+) + \mathcal{N}_{u,d}(D_s^+)}$$

$B_s \to X l \nu$: Results

[arXiv:1212.6400]
to appear in PRD



Fits to $M(D_s^+)$
in bins of $p(l^+)$

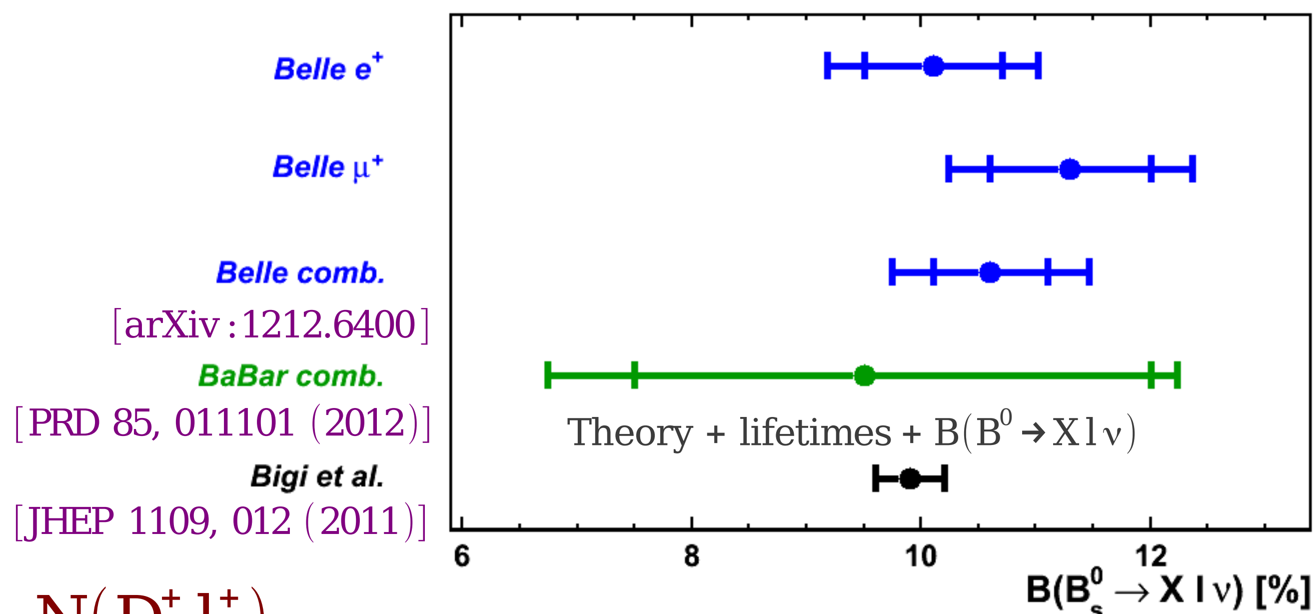


Fit to $p(l^+) \Rightarrow N(D_s^+ l^+)$

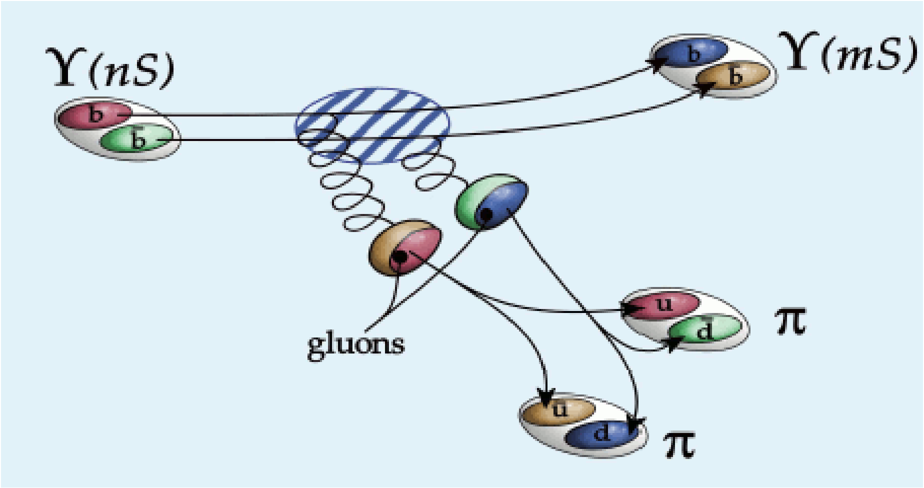
Most precise measurement:

$$B(B_s^0 \to X l \nu) = [10.6 \pm 0.5(stat) \pm 0.7(syst)]\%$$

dominant uncertainty:
B_s^0 production at $\Upsilon(5S)$



Nature of Υ(5S)



Zweig-suppressed diagram for the transition Υ(nS) → Υ(mS)$\pi^+\pi^-$

Anomalous production of Υ(nS)$\pi^+\pi^-$

PRL 100, 112001 (2008)

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

$\times 10^2$

Nature of Υ(5S) is puzzling and not yet understood

Looking for $h_b(nP)$

(triggered by the observation of $e^+e^- \to \pi^+\pi^- h_c$ above $D\bar{D}$ threshold by CLEO)

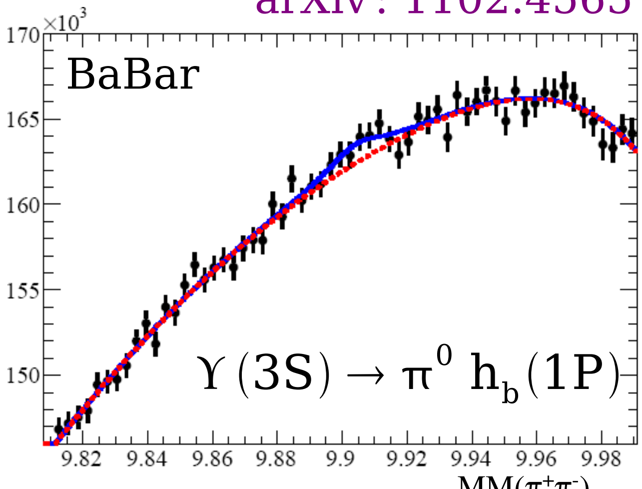
$(b\bar{b})$: $S=0$, $L=1$, $J^{PC}=1^{+-}$

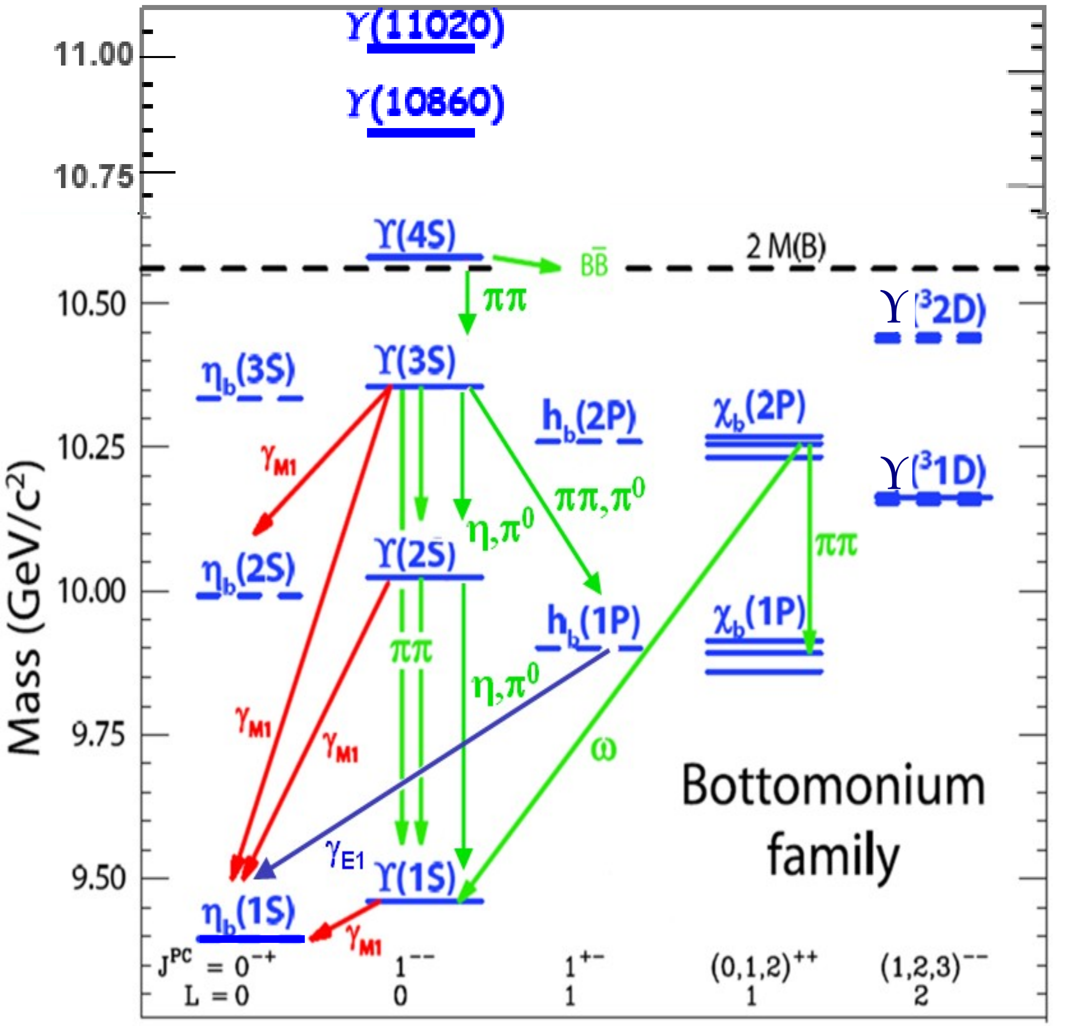
Expected mass
$\approx (M(\chi_{b0}) + 3\,M(\chi_{b1}) + 5\,M(\chi_{b2}))/9$

$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

for h_c: $\Delta M_{HF} = -0.12 \pm 0.30$ MeV,
expect smaller deviation for $h_b(nP)$

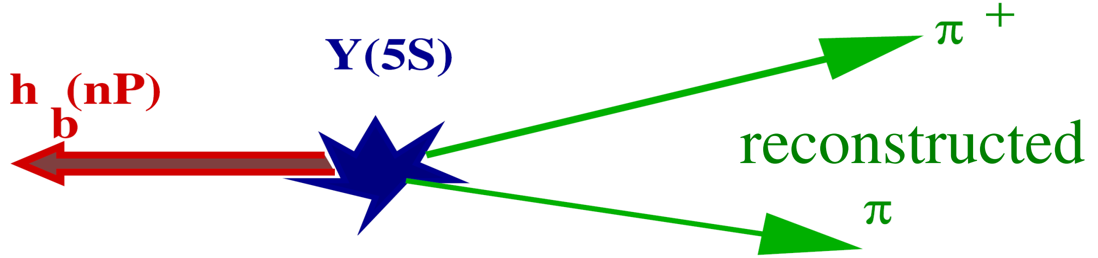
arXiv: 1102.4565



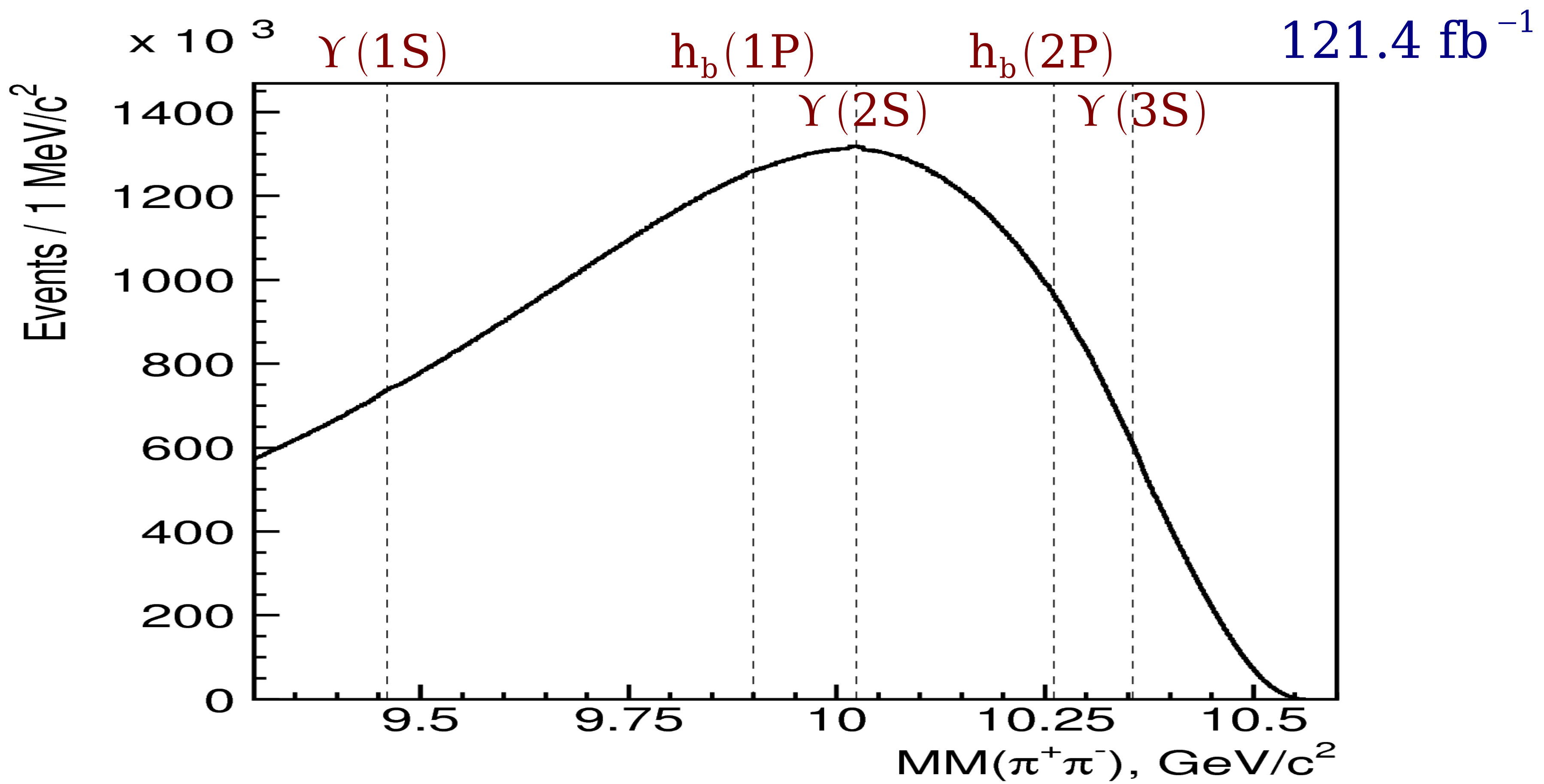


$\Upsilon(5S) \to h_b\pi^+\pi^-$ reconstruction

$h_b \to ggg\,,\ \eta_b\,\gamma\ \Rightarrow$ no good exclusive final states



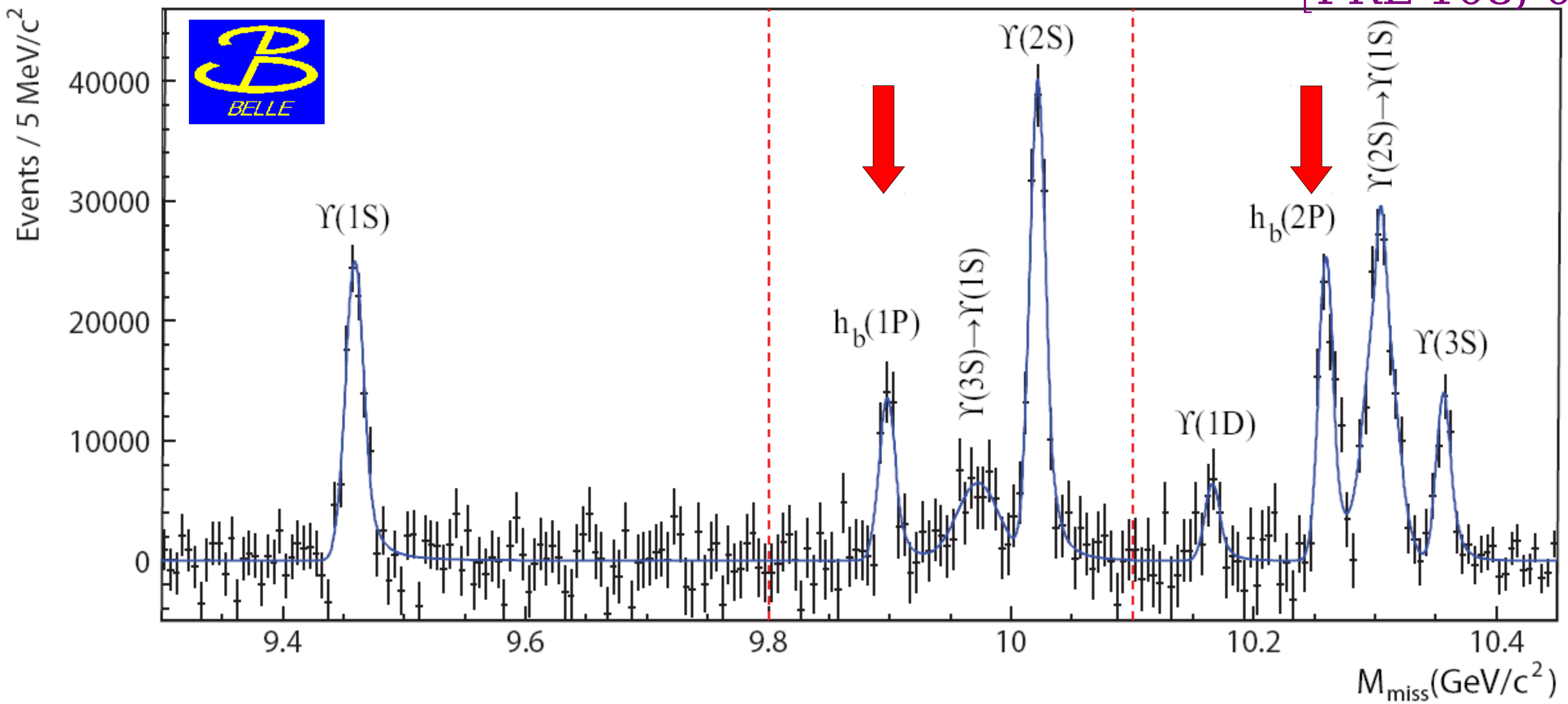
"Missing mass" $M(h_b) = \sqrt{(E_{CM} - E^*_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}} \equiv M_{miss}(\pi^+\pi^-)$



Results

121.4 fb^{-1}

[PRL 108, 032001 (2012)]



	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$105.0 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.1\,\sigma$
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	$6.1\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.8 \pm 8.7 \pm 6.8$	$10022.2 \pm 0.4 \pm 1.0$	$17.1\,\sigma$
$\Upsilon(1D)$	22.4 ± 7.8	10166.1 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.0 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.3\,\sigma$
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

Significance w/ systematics

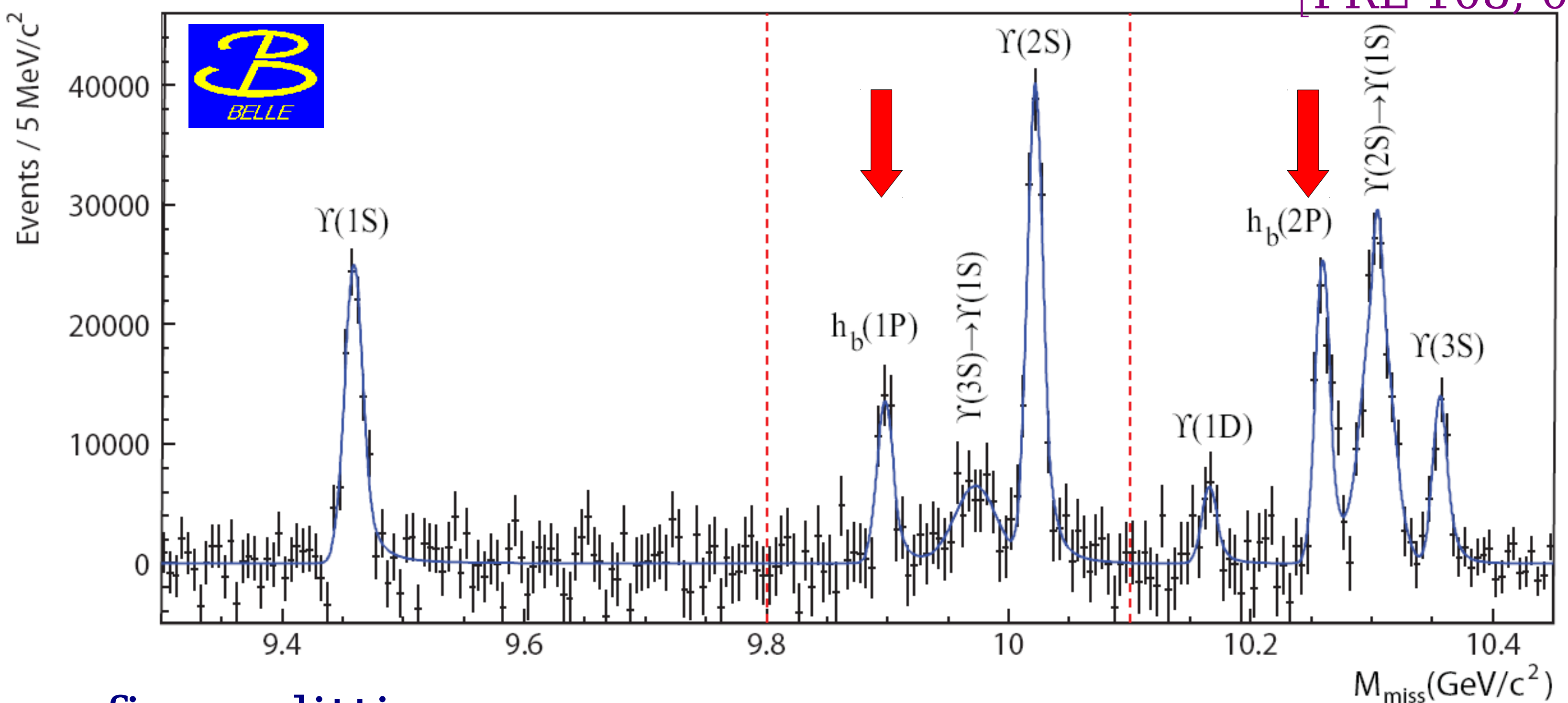
$h_b(1P)$ 5.5 σ

$h_b(2P)$ 11.2 σ

Results

$121.4\ \mathrm{fb}^{-1}$

[PRL 108, 032001 (2012)]



Hyperfine splitting

deviations from CoG of χ_{bJ} masses consistent with zero, as expected

$(1.7 \pm 1.5)\ \mathrm{MeV}/c^2$ for $h_b(1P)$

$(0.5\ ^{+1.6}_{-1.2})\ \mathrm{MeV}/c^2$ for $h_b(2P)$

Ratio of production rates

splin-flip $b\bar{b}$

$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.45 \pm 0.08\ ^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08\ ^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no splin-flip $b\bar{b}$

supposed to be suppressed by $1/m_b$ in the amplitude

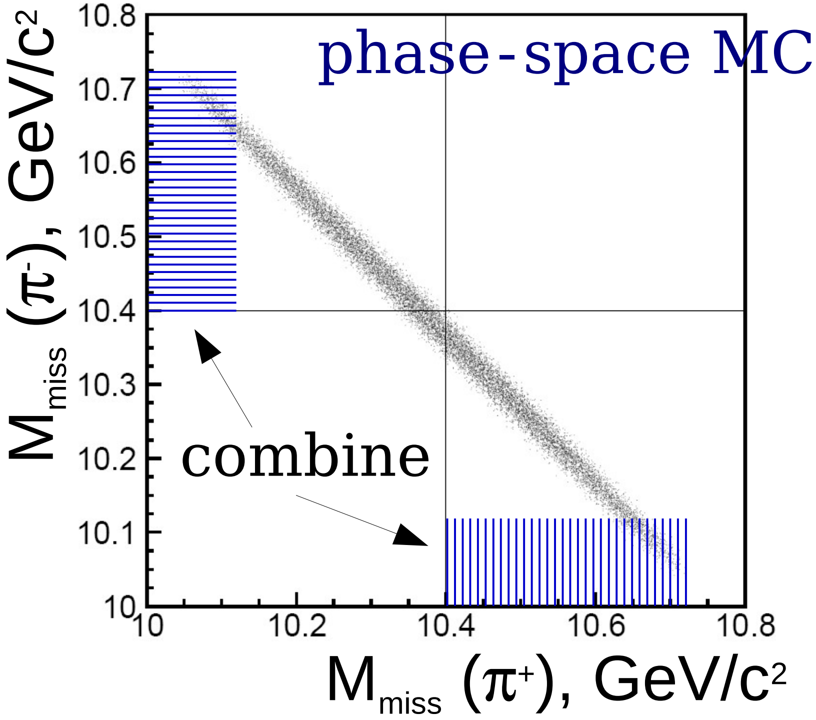
Mechanism of $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ decay seems exotic ! [arXiv:1108.2197]

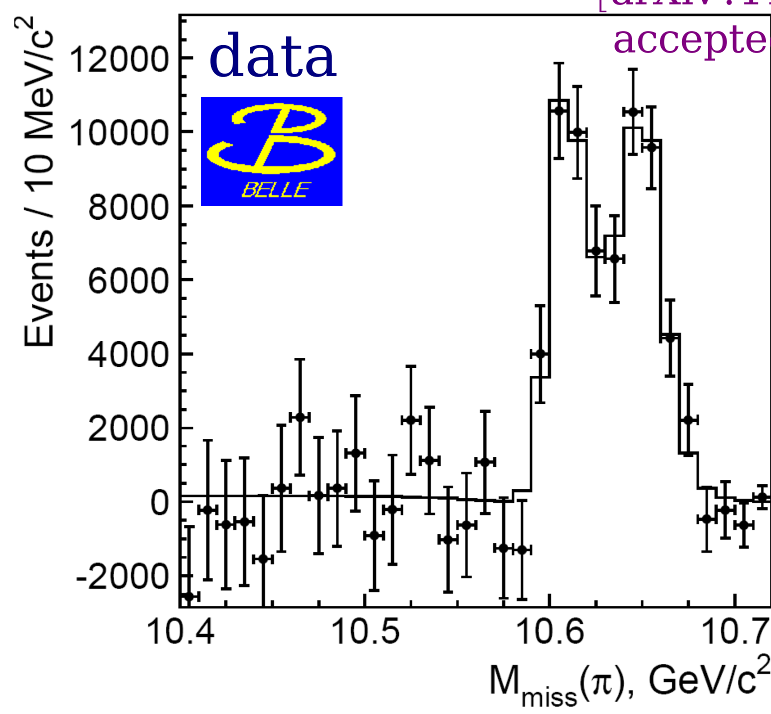
Resonant structure of $\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$

$M(h_b\pi^+) \equiv M_{miss}(\pi^-)$

121.4 fb^{-1}

[arXiv:1110.2251]
accepted by PRL





Fit function $\quad |BW(s, M_1, \Gamma_1) + a e^{i\phi} BW(s, M_2, \Gamma_2) + b e^{i\psi}|^2 \frac{qp}{\sqrt{s}}$

Results

$M_1 = 10605 \pm 2\ ^{+3}_{-1}$ MeV/c² $\quad \sim B\bar{B}^*$ threshold

$\Gamma_1 = 11.4\ ^{+4.5}_{-3.9}\ ^{+2.1}_{-1.2}$ MeV $\quad a = 1.39 \pm 0.37\ ^{+0.05}_{-0.15}$

$M_2 = 10654 \pm 3\ ^{+1}_{-2}$ MeV/c² $\quad \sim B^*\bar{B}^*$ threshold

$\Gamma_2 = 20.9\ ^{+5.4}_{-4.7}\ ^{+2.1}_{-5.7}$ MeV $\quad \phi = (187\ ^{+44}_{-57}\ ^{+3}_{-12})^\circ$

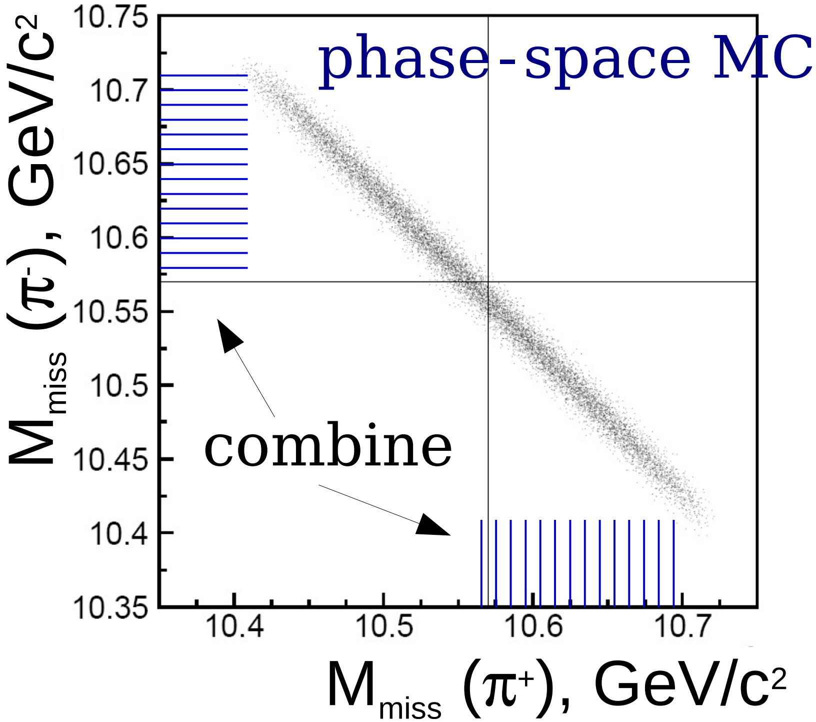
Significances
18σ (16σ w/syst)

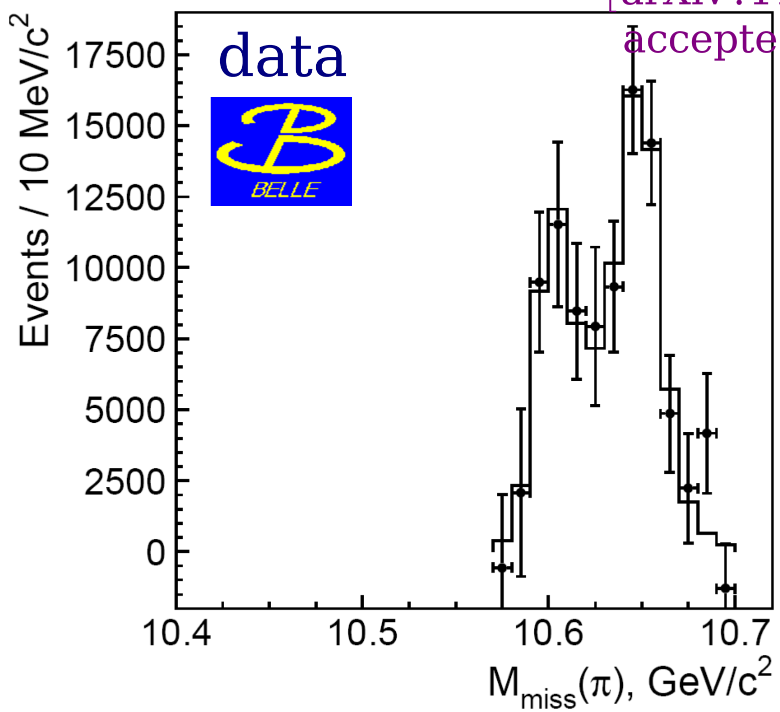
Resonant structure of $\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$

$M(h_b\pi^+) \equiv M_{miss}(\pi^-)$

121.4 fb^{-1}

[arXiv:1110.2251]
accepted by PRL





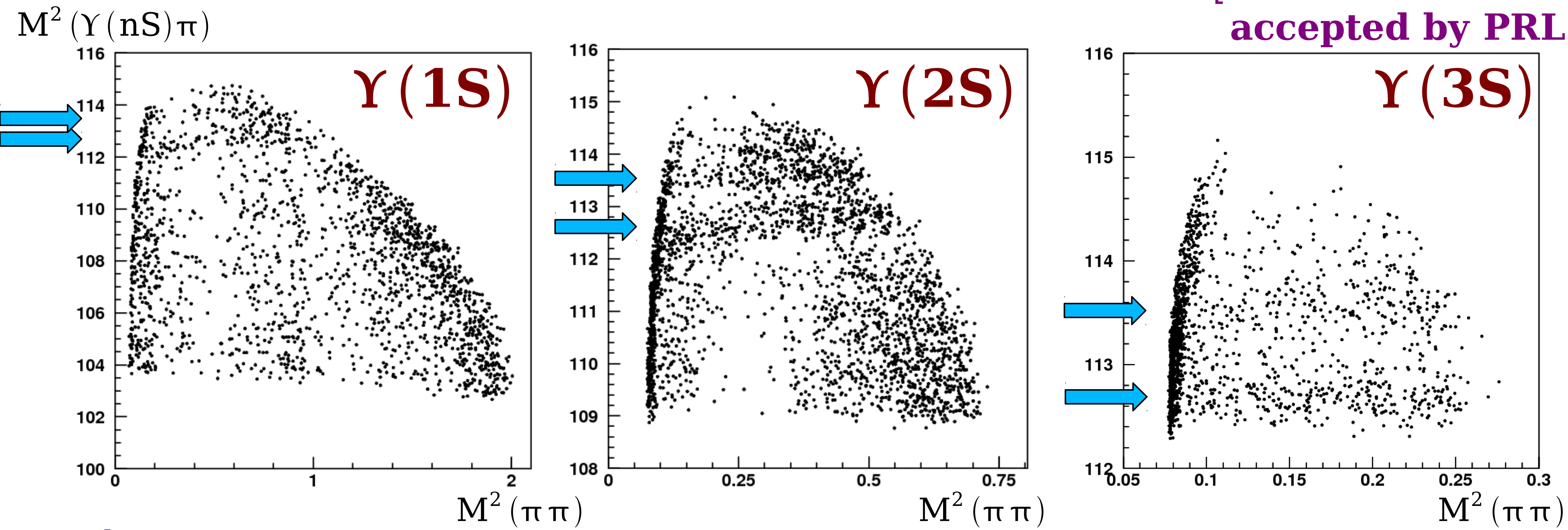
$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$ (consistent)
$M_1 = 10605 \pm 2\ ^{+3}_{-1}$ MeV/c^2	$10599\ ^{+6}_{-3}\ ^{+5}_{-4}$ MeV/c^2
$\Gamma_1 = 11.4\ ^{+4.5}_{-3.9}\ ^{+2.1}_{-1.2}$ MeV	$13\ ^{+10}_{-8}\ ^{+9}_{-7}$ MeV
$M_2 = 10654 \pm 3\ ^{+1}_{-2}$ MeV/c^2	$10651\ ^{+2}_{-3}\ ^{+3}_{-2}$ MeV/c^2
$\Gamma_2 = 20.9\ ^{+5.4}_{-4.7}\ ^{+2.1}_{-5.7}$ MeV	$19 \pm 7\ ^{+11}_{-7}$ MeV
$a = 1.39 \pm 0.37\ ^{+0.05}_{-0.15}$	$1.6\ ^{+0.6}_{-0.4}\ ^{+0.4}_{-0.6}$
$\phi = (187\ ^{+44}_{-57}\ ^{+3}_{-12})^\circ$	$(181\ ^{+65}_{-105}\ ^{+74}_{-109})^\circ$

Significances
6.7σ (5.6σ w/syst)

…and what about $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ final state ?

(n = 1, 2, 3)

[arXiv:1110.2251]
accepted by PRL



- ⇒ **two resonances**
- ⇒ **clear signs of interference ⇒ amplitude analysis is required**

Signal amplitude parameterization:

Flatte

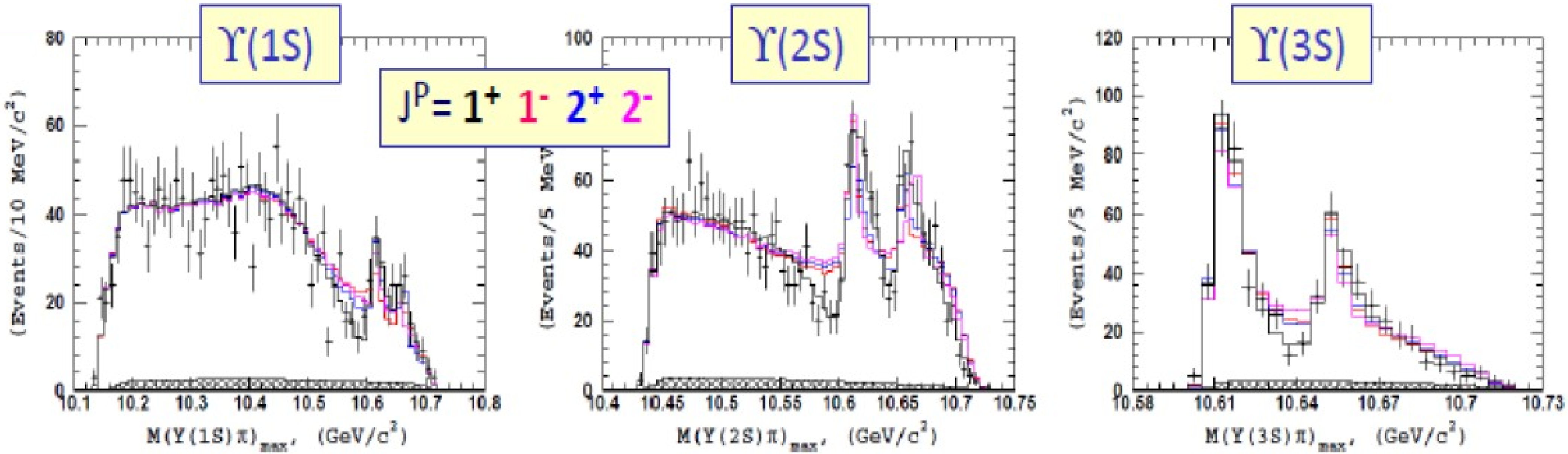
$$S(s_1, s_2) = A(Z_{b1}) + A(Z_{b2}) + A(f_0(980)) + A(f_2(1275)) + A_{NR}$$

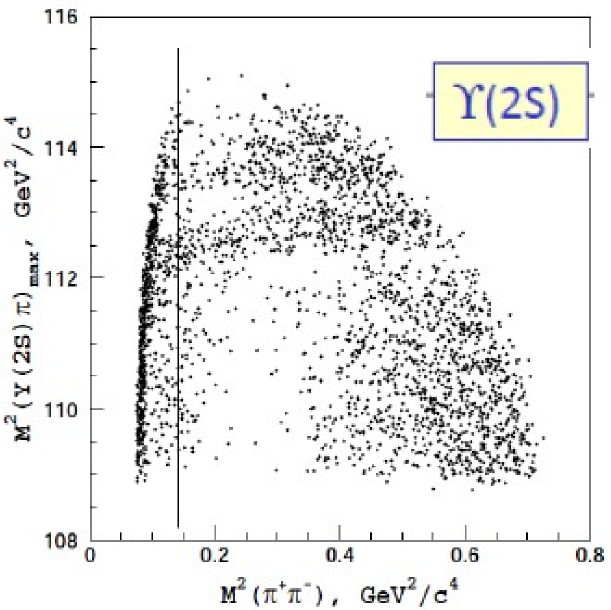
Breit-Wigner

$$A_{NR} = C_1 + C_2 \,.\, m^2(\pi\pi)$$

Parameterization of the non-resonant amplitude as discussed in:

[1] M.B.Voloshin, Prog. Part. Nucl. Phys. 61:455, 2008
[2] M.B.Voloshin, Phys. Rev. D74:054022, 2006





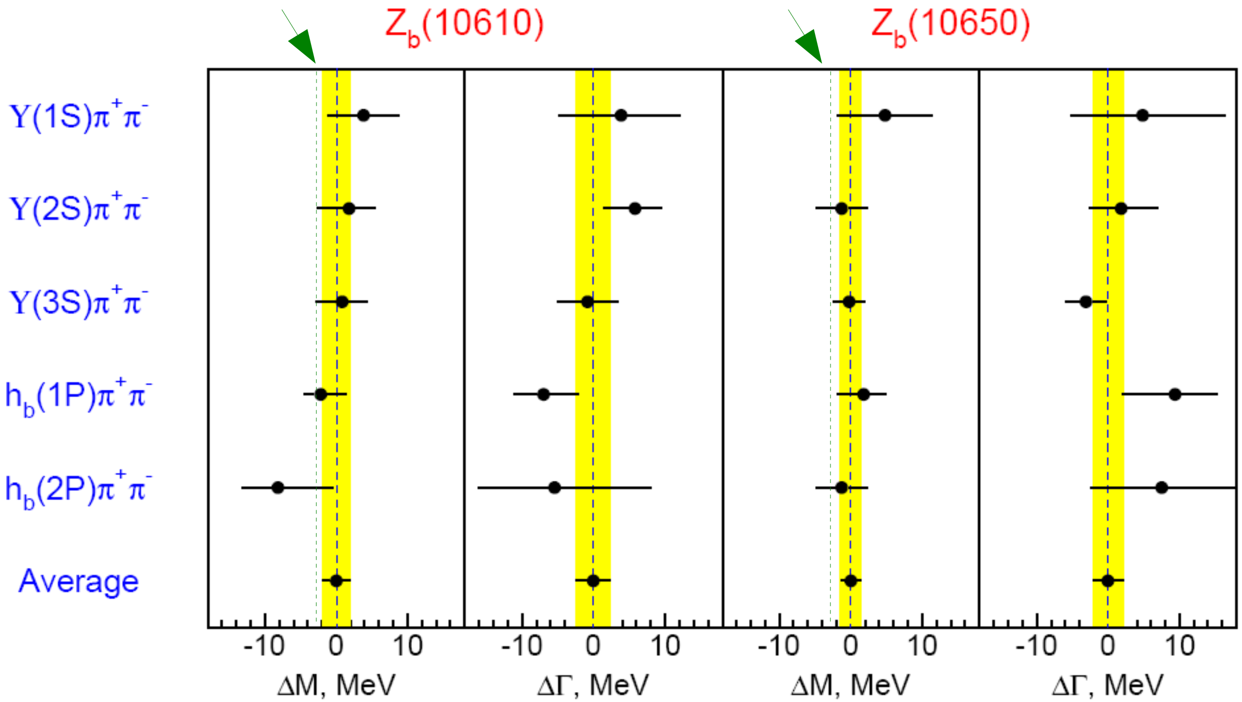
J^P \ Mode	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	
1^+	0	0	0	
1^-	64	264	73	20σ
2^+	41	207	87	18σ
2^-	59	304	125	22σ

Spin parity of Zb(10610) and Zb(10650) is 1^+.

All other $J^P<3$ are excluded.

Summary of parameters of charged Z_b states

$\sim B\bar{B}^*$ threshold $\sim B^*\bar{B}^*$ threshold



[arXiv:1110.2251]

$Z_b(10610)$

$M = 10607.2 \pm 2.0$ MeV

$\Gamma = 18.4 \pm 2.4$ MeV

$Z_b(10650)$

$M = 10652.2 \pm 1.5$ MeV

$\Gamma = 11.5 \pm 2.2$ MeV

- Masses and width are consistent
- Relative yield of $Z_b(10610)$ and $Z_b(10650) \sim 1$
- Relative phases are swapped for Υ and h_b final states
  (phase between Z_b and Z_b' is $\sim 0^\circ$ for $\Upsilon(nS)\pi\pi$ and $\sim 180^\circ$ for $h_b(mP)\pi\pi$)
- **Proximity to thresholds $\Rightarrow B^*B^{(*)}$ molecules ?**
  - $B^{(*)}B^*$ channels dominate Z_b decays ! [arXiv:1209.6450]
  - $\Upsilon(nS)\pi^0\pi^0$ consistent with Z_b^0 partner [arXiv:1308.2646]

and more...

Expected decays of h_b [Godfrey & Rosner, PRD 66, 014012 (2002)]

$$h_b(1P) \to ggg\ (57\%),\ \eta_b(1S)\gamma\ (41\%),\ \gamma gg\ (2\%)$$
$$h_b(2P) \to ggg\ (63\%),\ \eta_b(1S)\gamma\ (13\%),\ \eta_b(2S)\gamma\ (19\%),\ \gamma gg\ (2\%)$$

and Belle recently observed large yields of $h_b(1P)$ and $h_b(2P)$!

opportunity to study $\eta_b(nS)$ states...

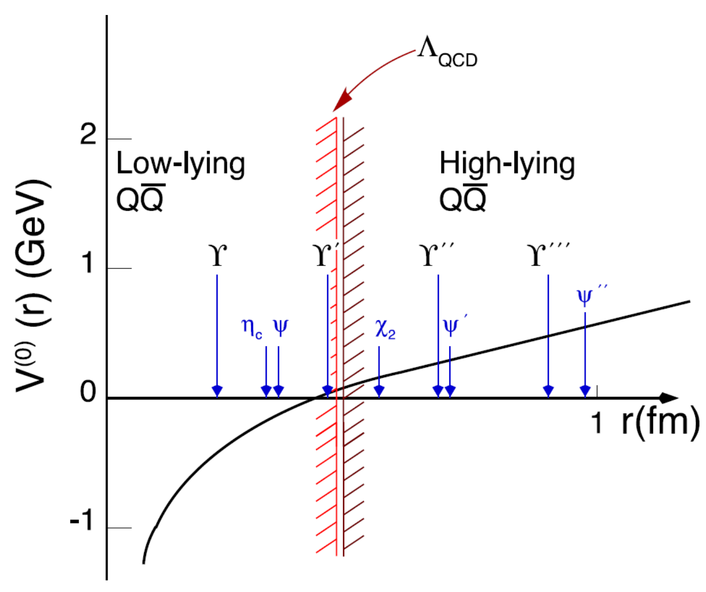
Experimental status of η_b

$$M[\eta_b(1S)] = 9390.9 \pm 2.8 \text{ MeV (BaBar + CLEO)}$$
$$M[\Upsilon(1S)] - M[\eta_b(1S)] = 69.3 \pm 2.8 \text{ MeV}$$

pNRQCD: 41 ± 14 MeV
[Kniehl et al., PRL 92, 242001 (2004)]

Lattice: 60 ± 8 MeV
[Meinel, PRD 82, 114502 (2010)]

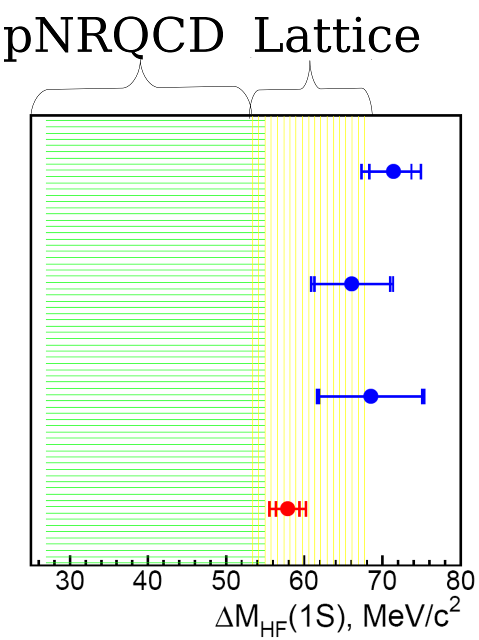
η_b – small radius system, precise calculation of mass



Observation of $h_b(1P, 2P) \to \eta_b(1S)\gamma$

$\Upsilon(5S) \to Z_b^+ \pi^-$
$\hookrightarrow h_b(nP)\,\pi^+$
$\hookrightarrow \eta_b(mS)\,\gamma$

Hyperfine splitting: $\Delta M_{HF}[\eta_b(1S)] = 57.9 \pm 2.3$ MeV/c^2

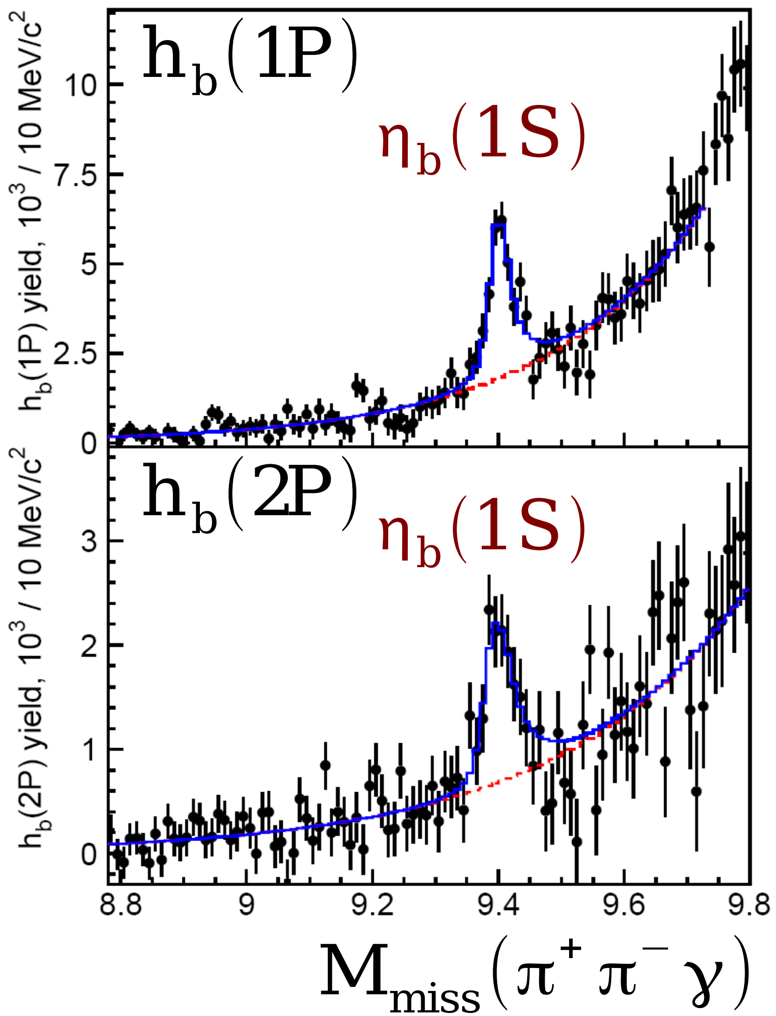


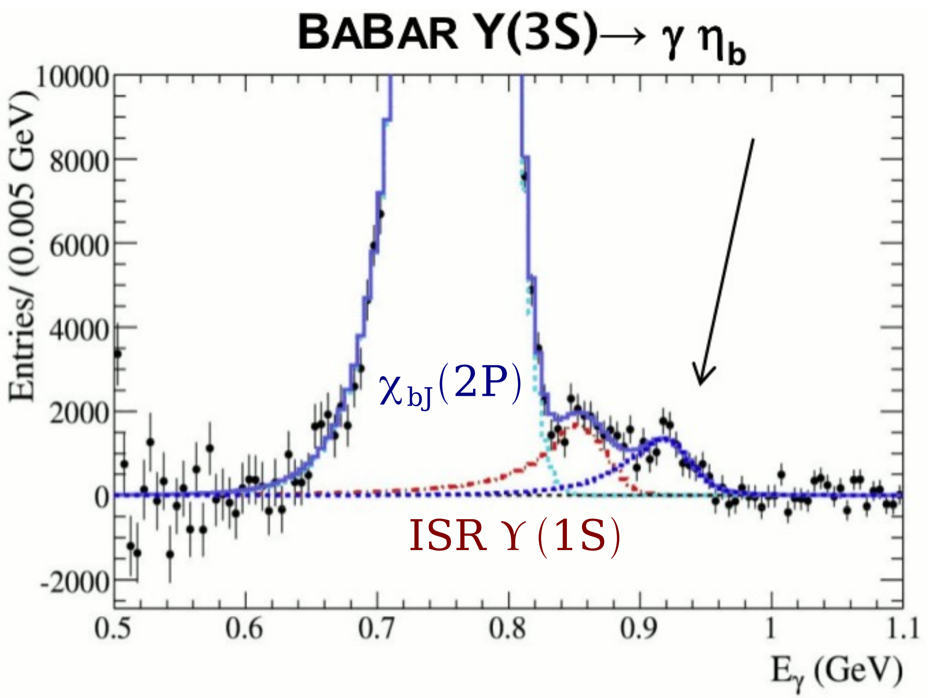
BaBar $\Upsilon(3S) \to \eta_b(1S)\gamma$

BaBar $\Upsilon(2S) \to \eta_b(1S)\gamma$

CLEO $\Upsilon(3S) \to \eta_b(1S)\gamma$

Belle [PRL 109, 232002 (2012)]





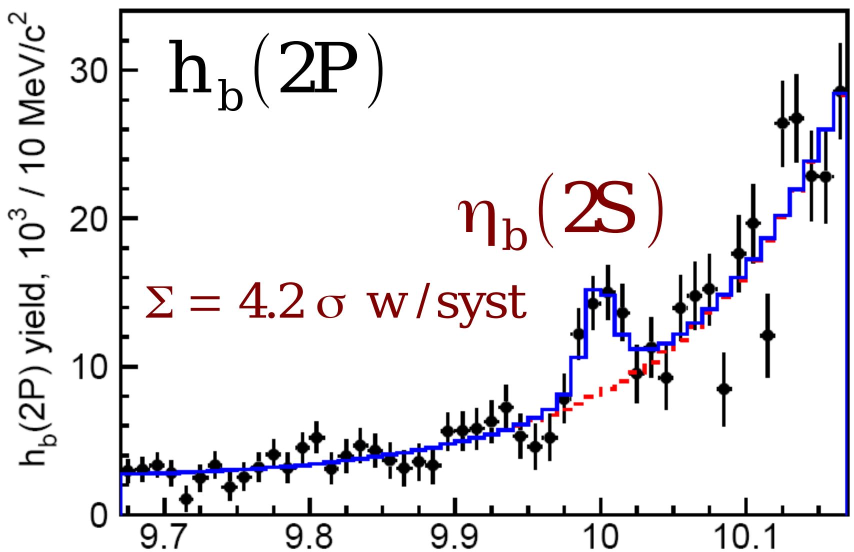
First evidence for $\eta_b(2S)$

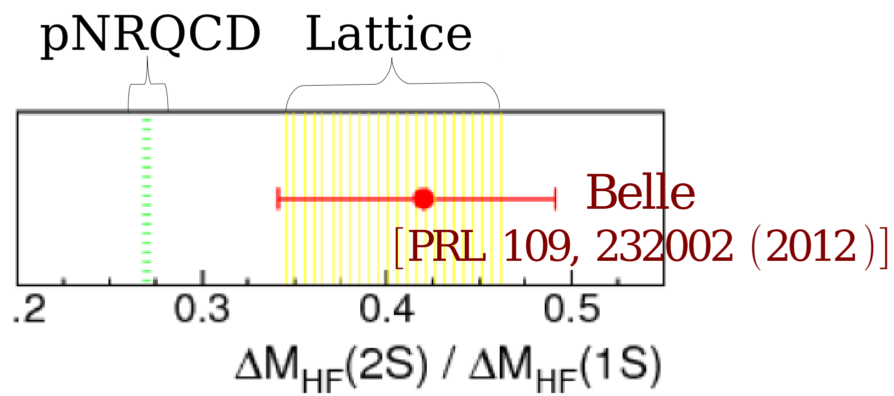
$\Upsilon(5S) \to Z_b^+ \pi^-$
$\hookrightarrow h_b(nP)\, \pi^+$
$\hookrightarrow \eta_b(mS)\, \gamma$

Hyperfine splitting:

$\Delta M_{HF}[\eta_b(2S)] = 24.3\,^{+4.0}_{-4.5}$ MeV/c^2

in agreement with theory





Branching fractions

Expectations

Godfrey, Rosner, PRD66, 014012 (2002)

$BF[h_b(1P) \to \eta_b(1S)\gamma] = (49.2 \pm 5.7 \pm 5.6)\%$	41 %
$BF[h_b(2P) \to \eta_b(1S)\gamma] = (22.3 \pm 3.8 \pm 3.1)\%$	13 %
$BF[h_b(2P) \to \eta_b(2S)\gamma] = (47.5 \pm 10.5 \pm 6.8)\%$	19 %

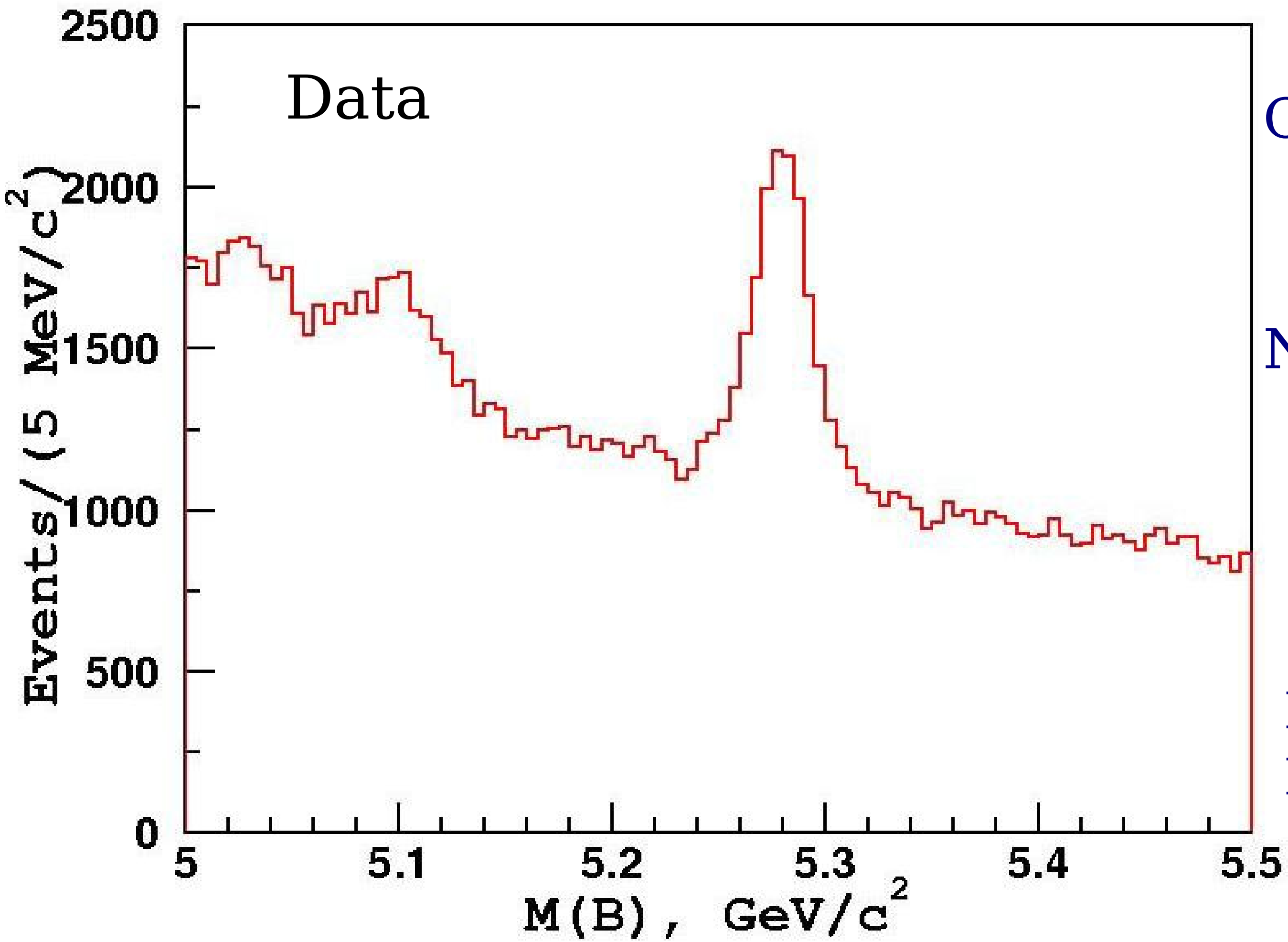
Conclusion

- Belle was designed to observe CPV and verify the CKM scheme of the weak interaction
- Lot of exciting results: CPV, rare B, charm, τ LFV, charmonium(-like) spectroscopy... (more to come)
- Unique Υ(5S) data sample allowed to obtain relevant B_s results and few unexpected discoveries (Z_b's)
- Next step → Belle II, start taking data from end of 2016 aiming for 50 ab^{-1} by 2023

$\Upsilon(5S) \to Z_b(10610)\pi^+ \to B B^* \pi^+$ [arXiv:1209.6450]

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

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



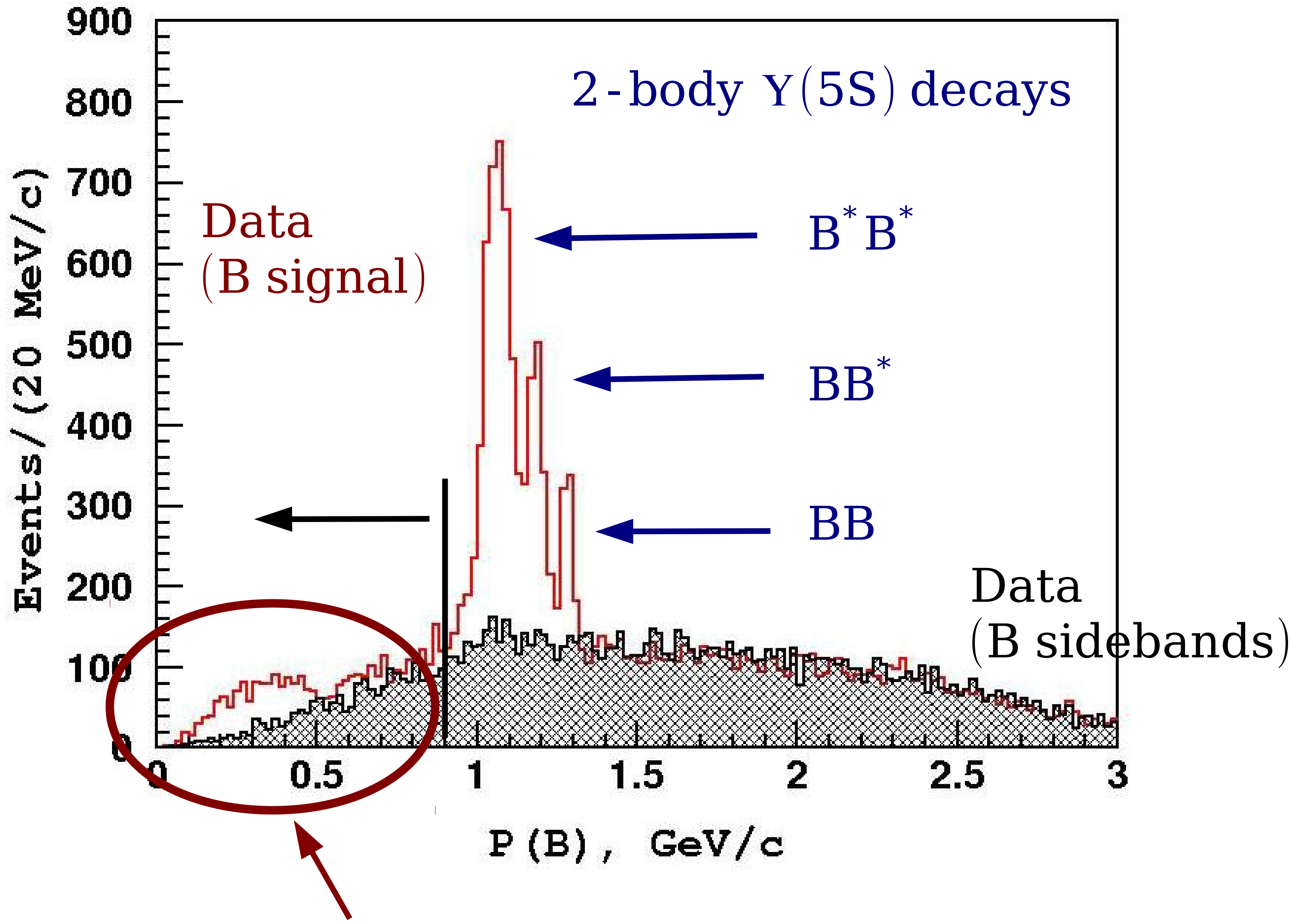
Charged B:
- $D^0[K\pi, K\pi\pi\pi]\pi^-$
- $J/\psi[\mu\mu]K^-$

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

Effective B fraction:
$Br[B \to f] = (143 \pm 15) \times 10^{-5}$

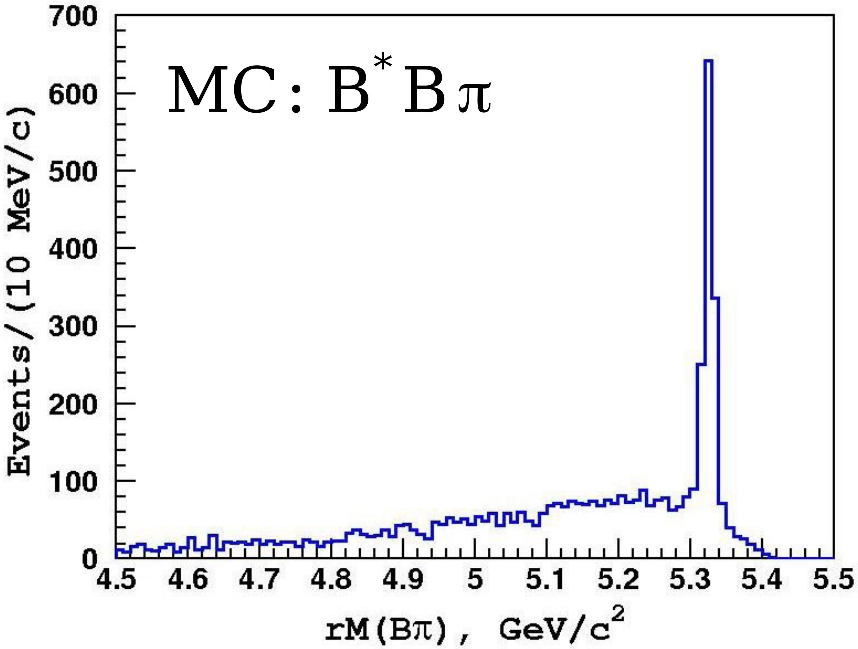
B candidate invariant mass distribution. All modes combined. Select B signal within 30-40 MeV (depending on B decay mode) around B nominal mass.

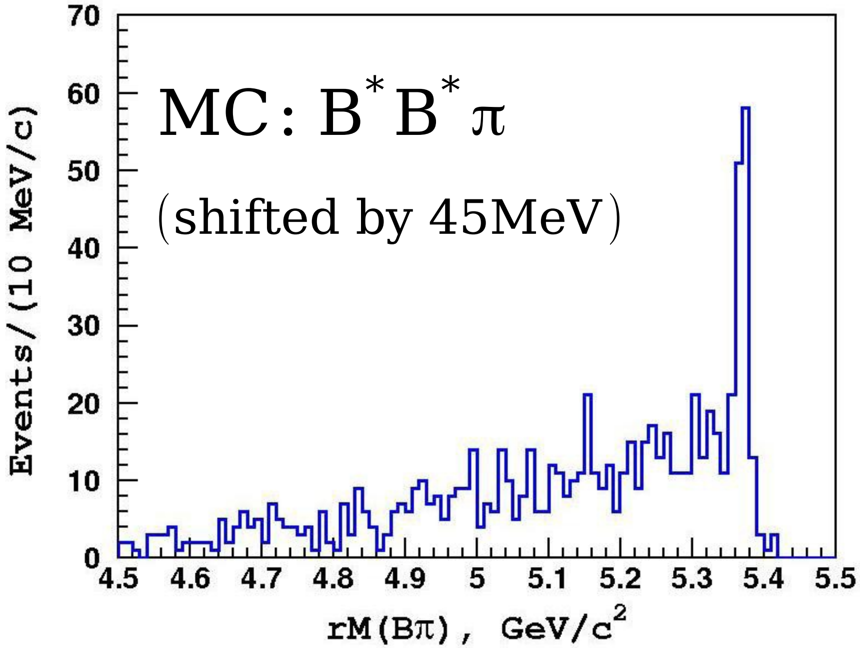
$\Upsilon(5S) \to B^* B^{(*)} \pi^+$: B selection

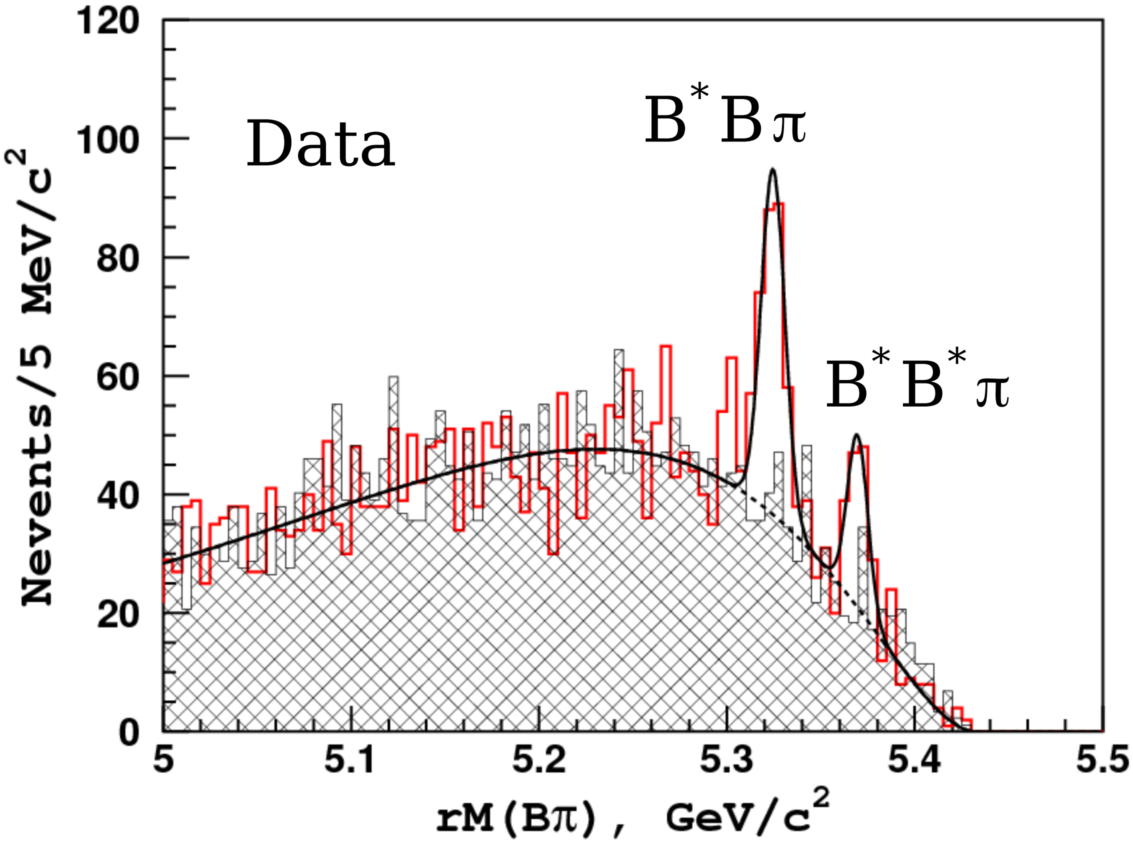


3-body $\Upsilon(5S) \to B^{(*)} B^{(*)} \pi$ decays & rad. return to $\Upsilon(4S)$: $P(B) < 0.9$ GeV/c

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







Red histogram – right sign $B\pi$ combinations

Hatched histogram – wrong sign $B\pi$ combinations

Solid line – fit to right sign data.

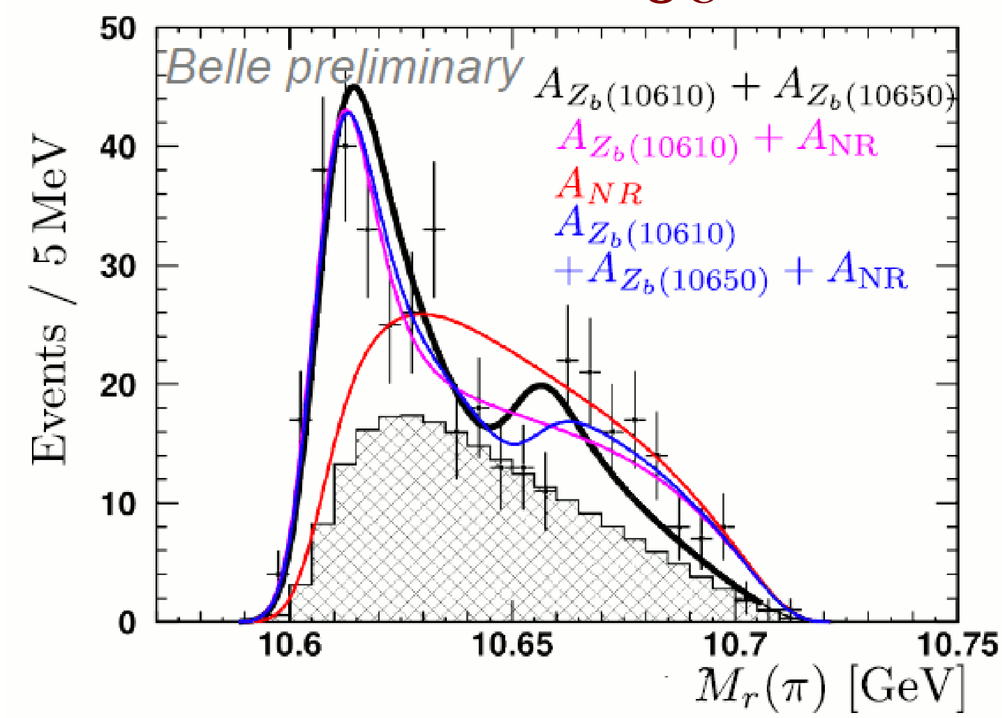
Fit yields: $N(BB\pi) = (0.3 \pm 14)$

$N(BB^{*}\pi) = (184 \pm 19)\ (9.3\ \sigma)$

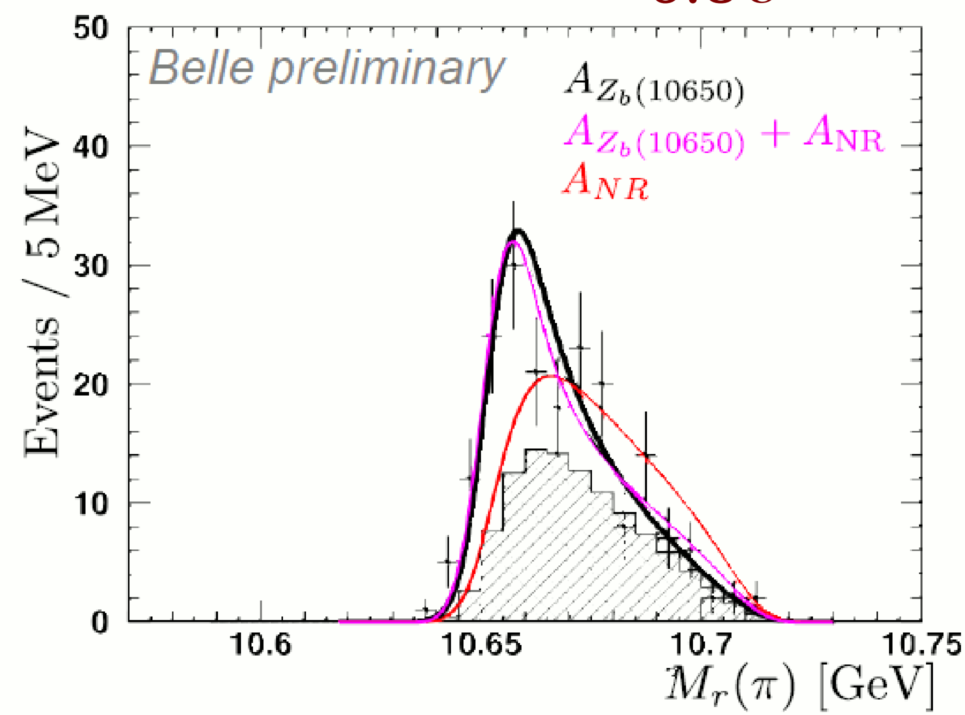
$N(B^{*}B^{*}\pi) = (82 \pm 11)\ (5.7\ \sigma)$

$\Upsilon(5S) \to B^*B^{(*)}\pi^+$: signal data

$BB^*\pi^+$ $Z_b(10610)$ 8σ



$B^*B^*\pi^+$ $Z_b(10650)$ 6.8σ



points – right sign $B\pi$ combinations (data)
lines – fit to data with various models (times PHSP, convolved with resolution function = Gaussian with σ=6MeV).
hatched histogram – background component

$B^*B^*\pi$ signal is well fit to just $Z_b(10650)$ signal alone

$B^*B^*\pi$ data fits (almost) equally well to a sum of $Z_b(10610)$ and $Z_b(10650)$ or to a sum of $Z_b(10610)$ and non-resonant.

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

Branching fractions of $\Upsilon(10680)$ decays (including neutral modes):

$BB\pi < 0.60\%$ (@ 90% C.L.)
$BB^*\pi = 4.25 \pm 0.44 \pm 0.69$ %
$B^*B^*\pi = 2.12 \pm 0.29 \pm 0.36$ %

To be compared with PRD 81 (2010)
$f(BB^*\pi) = (7.3 \pm 2.2 \pm 0.8)\%$
$f(B^*B^*\pi) = (1.0 \pm 1.4 \pm 0.4)\%$

Assuming Z_b decays are saturated by the already observed $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ channels, one can calculate complete table of relative branching fractions:

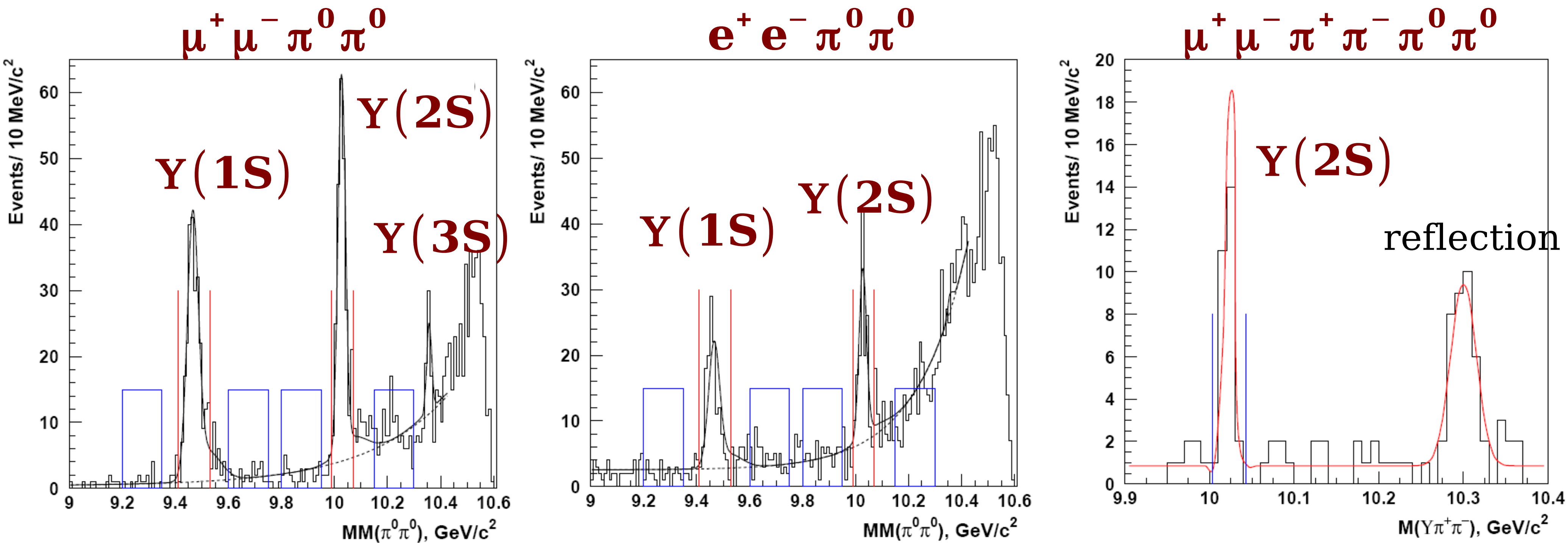
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ±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

$B^{(*)}B^*$ channels dominate Z_b decays !

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

[arXiv:1308.2646] to appear in PRD

Signal of $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$: $\Upsilon(1, 2, 3S) \to \mu^+\mu^-, e^+e^-, \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$



$$\sigma(e^+e^- \to \Upsilon(5S) \to \Upsilon(1S)\pi^0\pi^0) = (1.16 \pm 0.06 \pm 0.10)\ \text{pb}$$

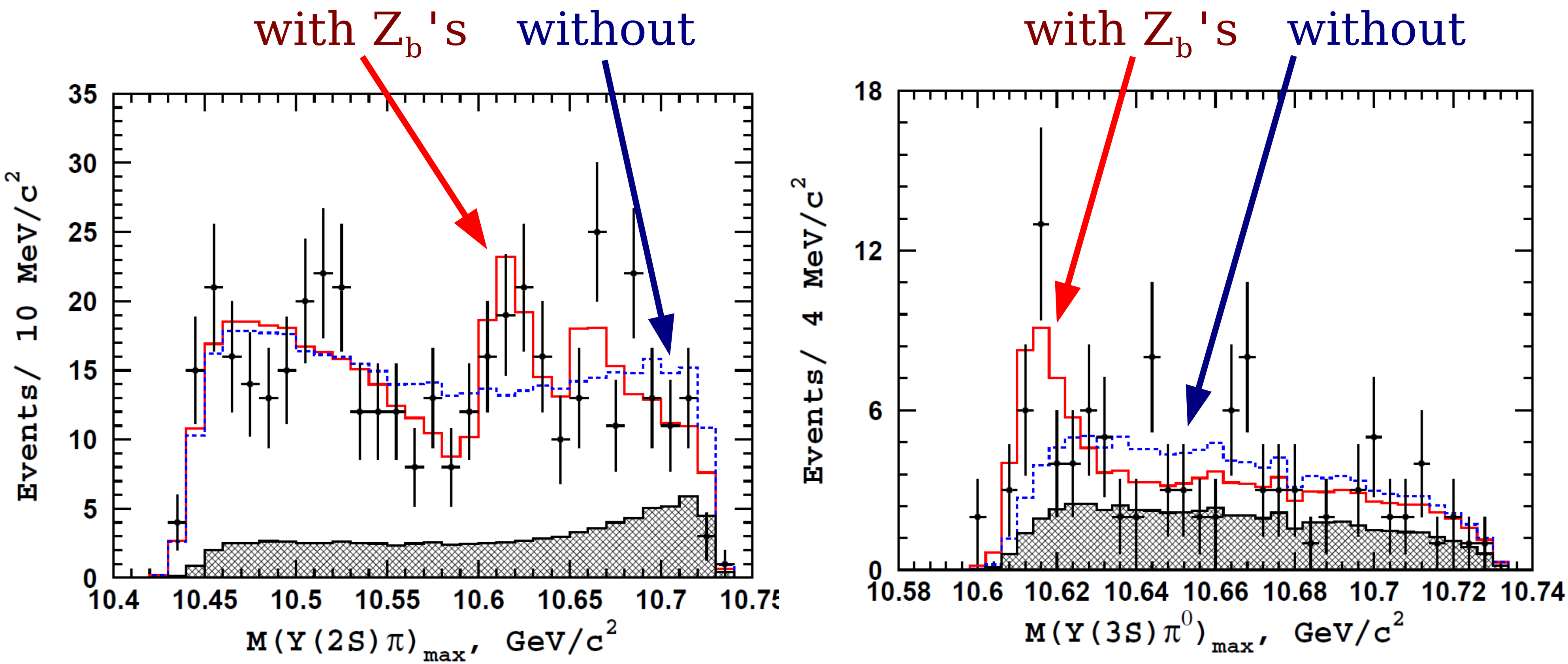
$$\sigma(e^+e^- \to \Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0) = (1.87 \pm 0.11 \pm 0.23)\ \text{pb}$$

$$\sigma(e^+e^- \to \Upsilon(5S) \to \Upsilon(3S)\pi^0\pi^0) = (0.98 \pm 0.24 \pm 0.19)\ \text{pb}$$

~ 1/2 of corresponding values of $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$
in agreement with isospin relations

Resonant structure of $\Upsilon(2,3S)\pi^0\pi^0$

Dalitz plot analysis: $M(s_1, s_2) = A_{Z_1} + A_{Z_2} + A_{f_0} + A_{f_2} + A_{NR}$



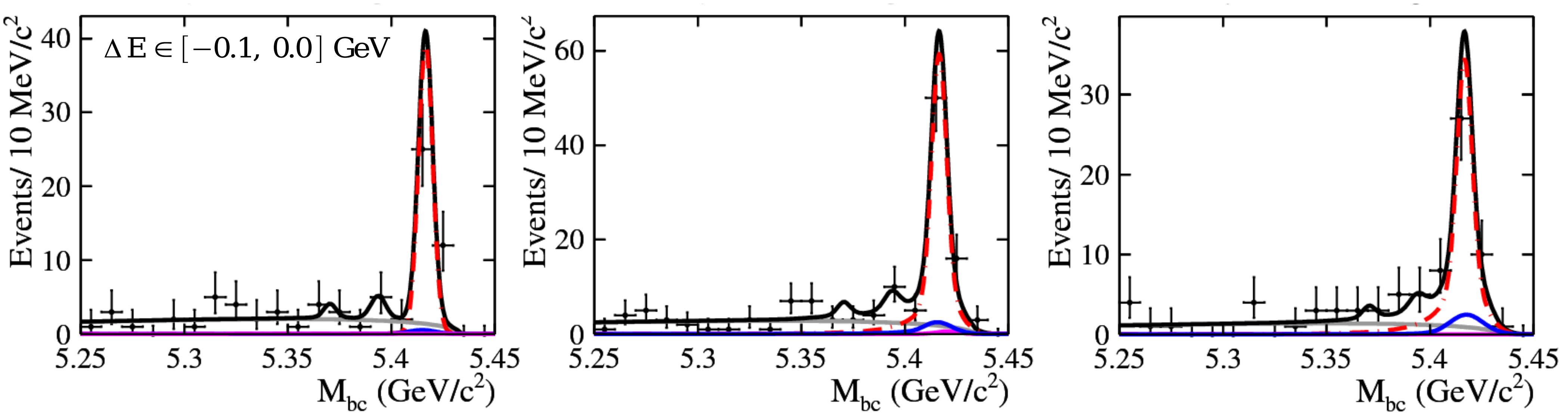
- Clear Z_b^0's signals are seen in $\Upsilon(2S)\pi^0\pi^0$ and $\Upsilon(3S)\pi^0\pi^0$
- Significance of $Z_b^0(10610)$ is 6.5σ with systematics
- $Z_b^0(10650)$ is less significant $(\sim 2\sigma)$
- Fit to the $Z_b^0(10610)$ mass gives $M = (10609 \pm 4 \pm 4)$ MeV

  $(M(Z_b^+) = 10607.2 \pm 2.0$ MeV$)$

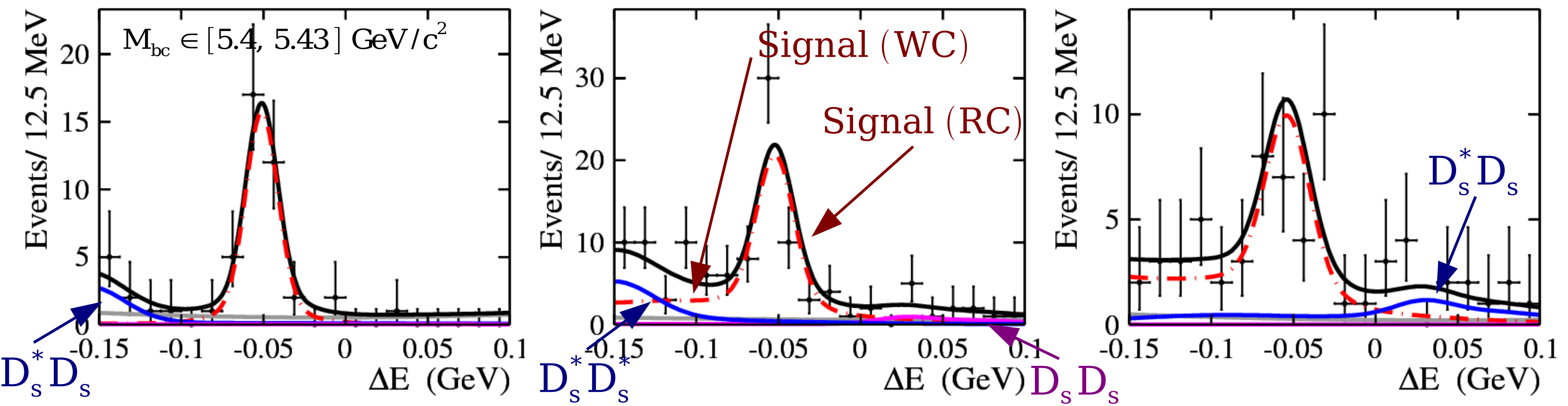
Observation of $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$

[PRD 87, 031101 (R)(2013)]

- Simultaneous fit of the 3 modes. For each mode, cross feed from the 2 others is included
- Signal has 2 components: right and wrong combinations

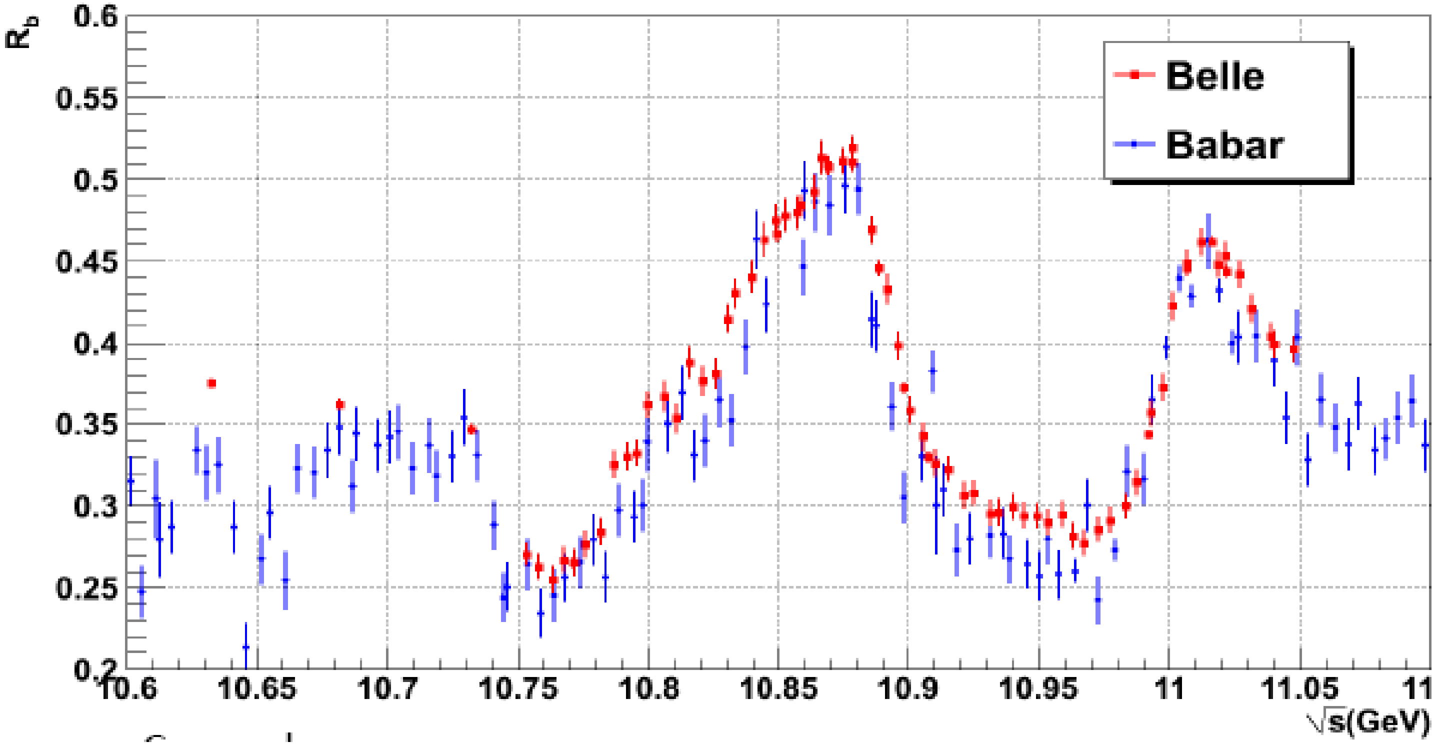


$N_S(D_s^{\pm} D_s^{\mp}) = 33.1^{+6.0}_{-5.4}\ (11.5\,\sigma)$ $N_S(D_s^{*\pm} D_s^{\mp}) = 44.5^{+5.8}_{-5.5}\ (10.1\,\sigma)$ $N_S(D_s^{*\pm} D_s^{*\mp}) = 24.4^{+4.1}_{-3.6}\ (7.8\,\sigma)$



$\Rightarrow\ \mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%$ $\quad (\Delta\Gamma_s / \Gamma_s = 2\mathcal{B}/(1-\mathcal{B}))$

R_b measurements



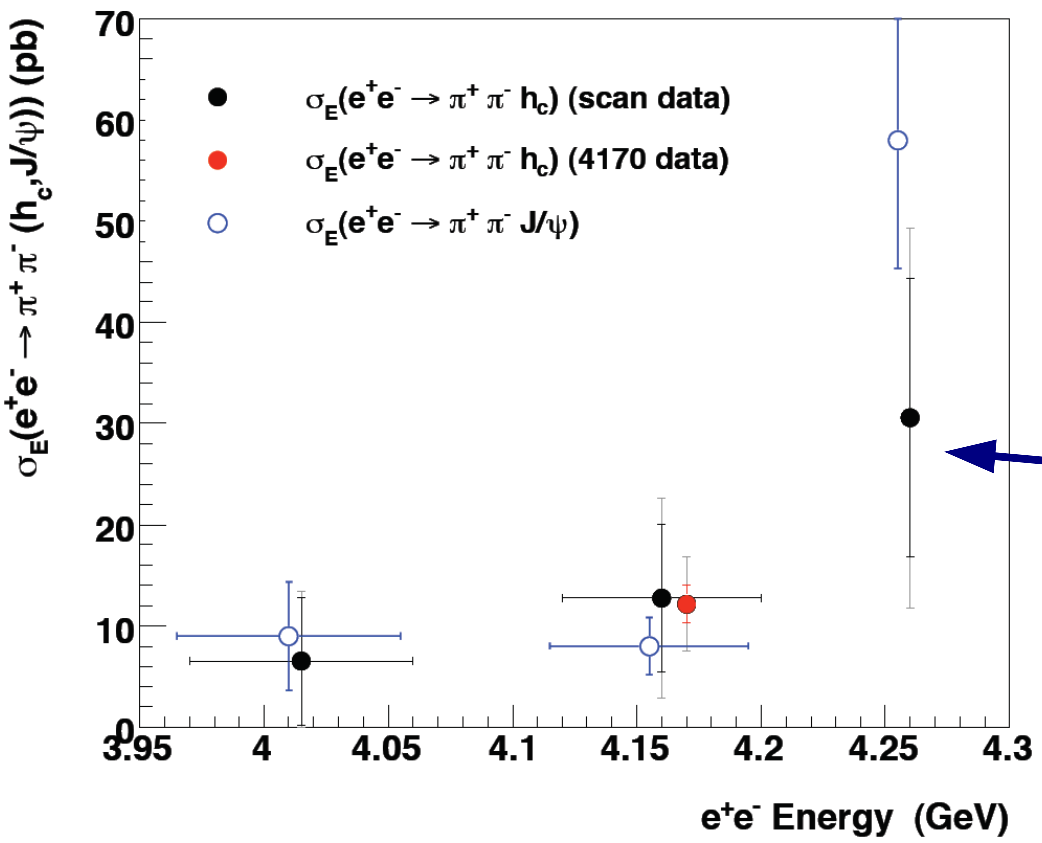
- Better statistic errors, but covers a smaller energy range compared to Babar
- R_b is slightly higher by 0.0185
- No Ali's $Y_B(10900)$ (Phys. Lett. B 684, 28 (2010)), $\Gamma_{ee} < 36$ eV

Trigger

Observation of $e^+e^- \to \pi^+\pi^- h_c$ above $D\,\overline{D}$ threshold by CLEO

Energy dependence of the cross-section

(R.Mitchell @ CHARM2010)

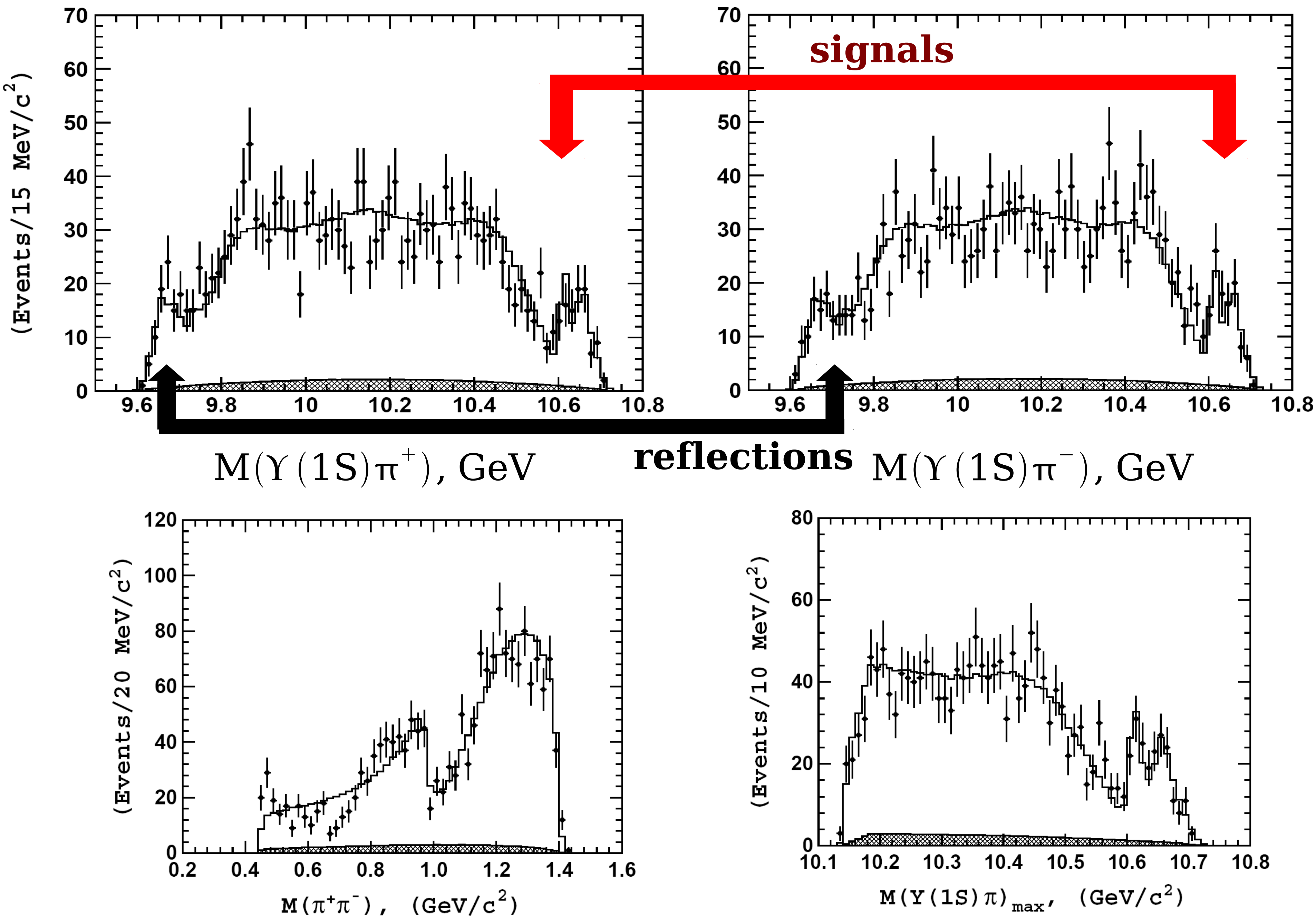


Production of h_c is unsuppressed relative to J/ψ

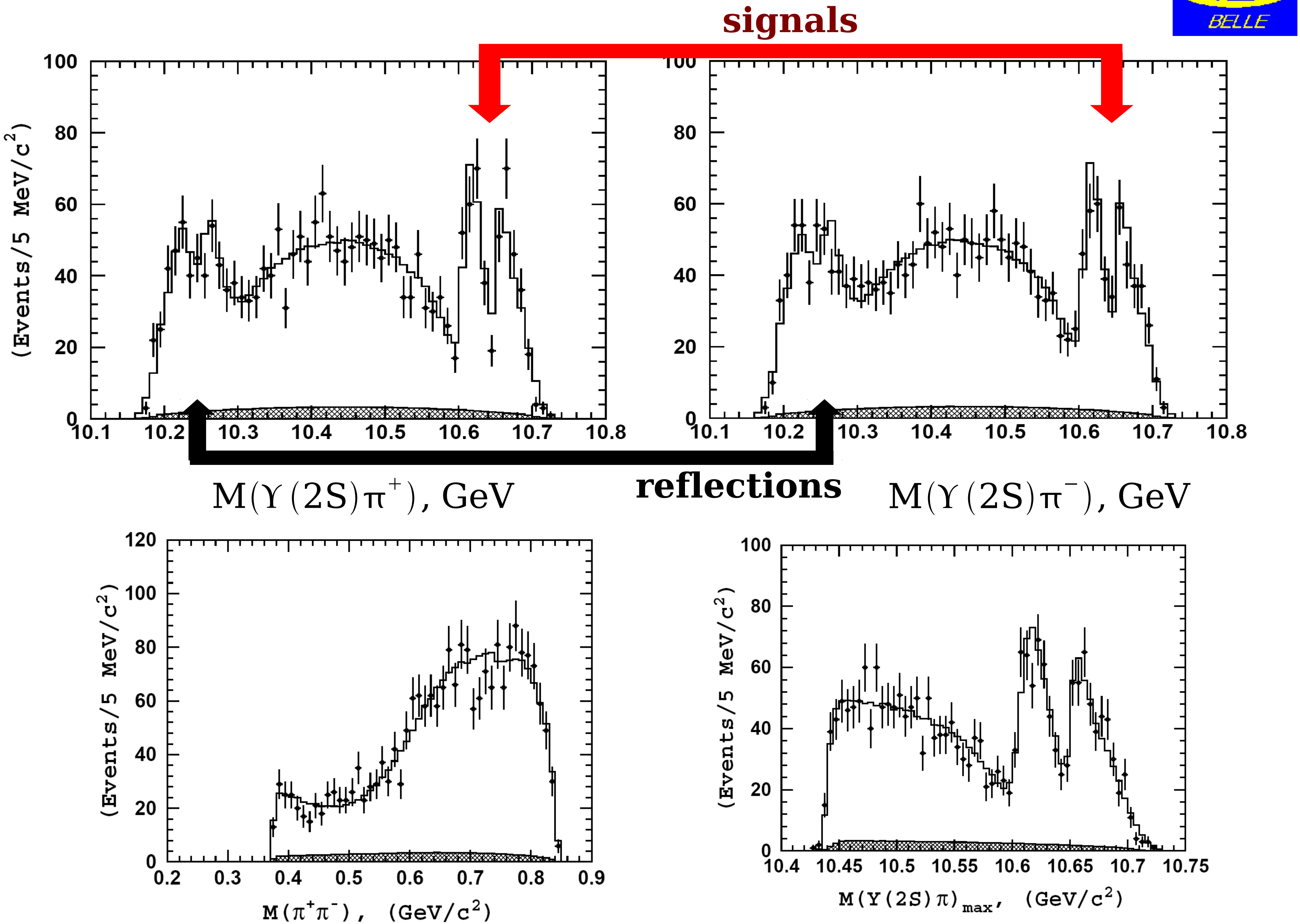
Enhancement at $\Upsilon(4260)$?

Belle sees $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$,
so should search for $\Upsilon(5S) \to h_b\pi^+\pi^-$!

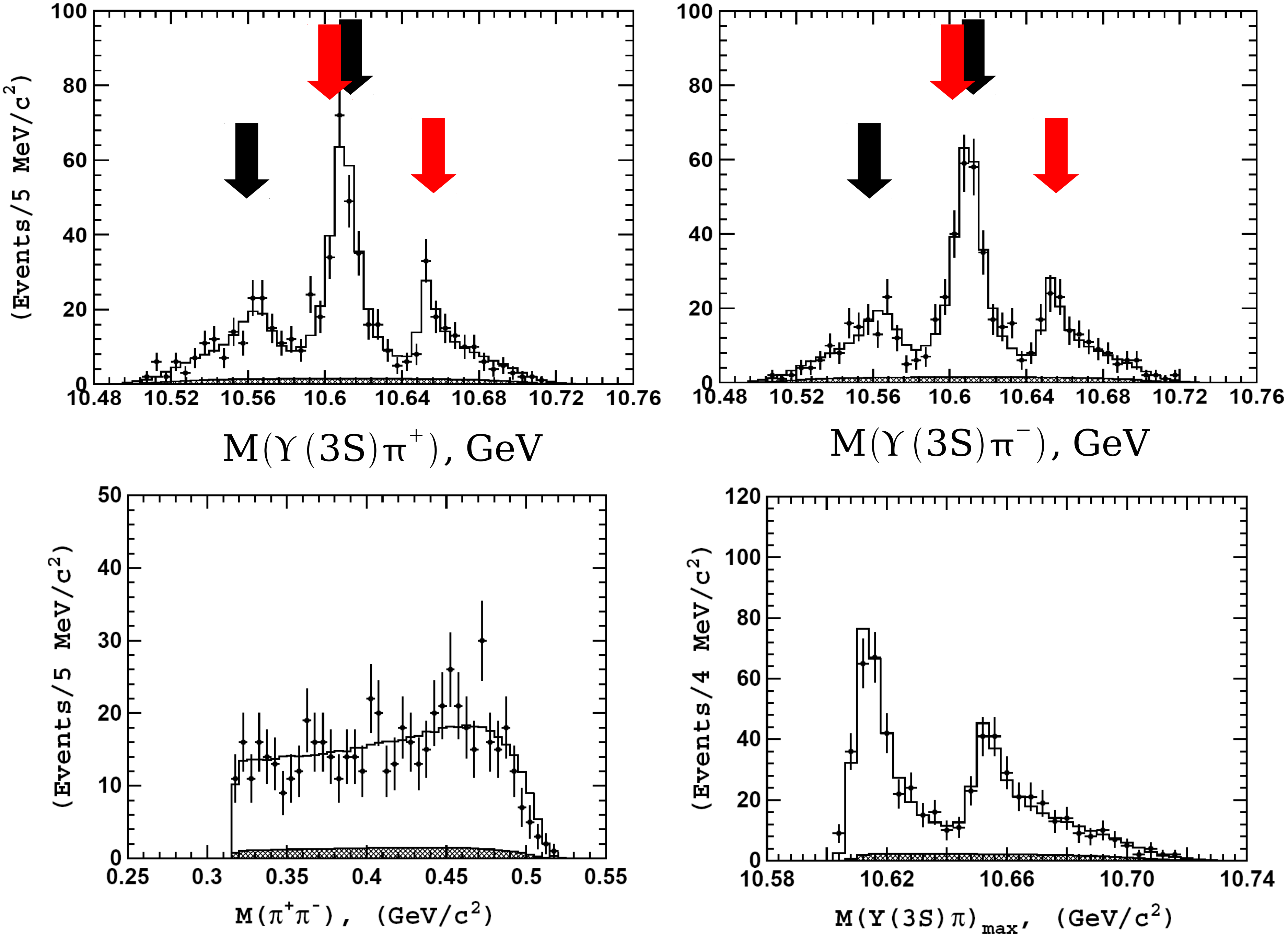
Results: $\Upsilon(1S)\pi^+\pi^-$



Results: $\Upsilon(2S)\pi^+\pi^-$



Results: $\Upsilon(3S)\pi^+\pi^-$

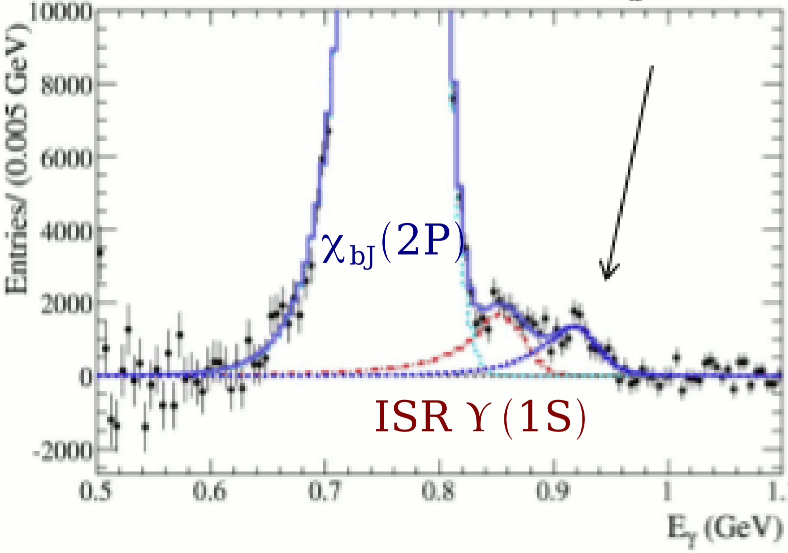


Bottomonium ground state η_b

Non-observation of the bottomonium ground state was an annoying thorn in the side of quarkonium spectroscopy. Finally, after 30 years of work

First measurement of η_b by BABAR in radiative Y(3S) and Y(2S) decays, followed by CLEO.

BABAR Y(3S)→ γ η_b



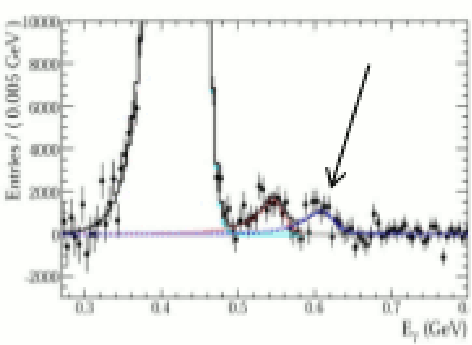
Measured parameters

BF (Y(3,2S)→γ η_b) (10^{-4})	5.1 ± 0.7 / 3.9 ± 1.5
Y(1S) – η_b(1S) mass splitting:	69.3 ± 2.8 MeV

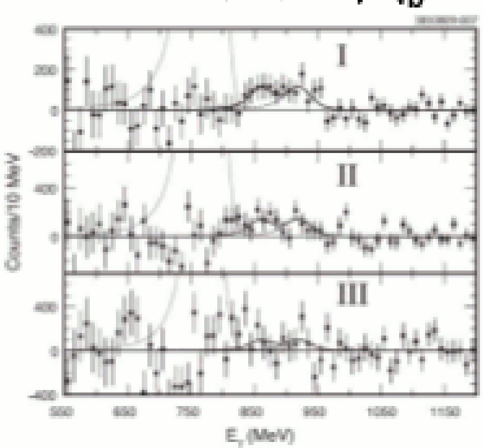
Hyperfine mass splitting predictions (MeV):

Potential models:	36-100 (36-87 recent models)
pNRQCD:	60.3 ± 5.5 ± 3.8 ± 2.1
Lattice QCD:	40-71

BABAR Y(2S)→ γ η_b



CLEO Y(3S)→ γ η_b



Confirmation from independent experiment or other decay channel desirable, as well as observation of η_b(2S)

Method

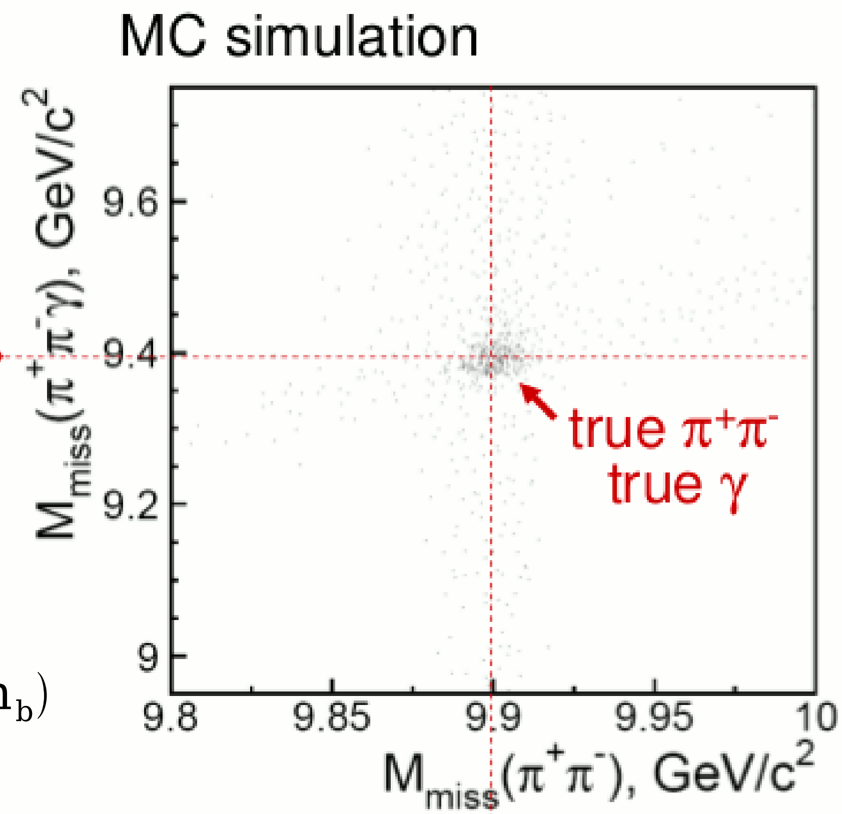
Decay chain:

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

$\hookrightarrow h_b(nP)\, \pi^+$

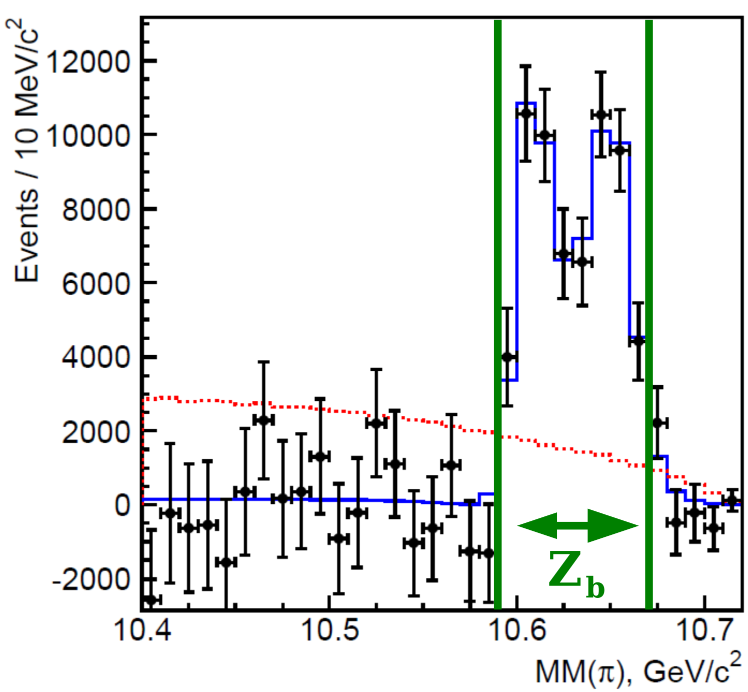
$\hookrightarrow \eta_b(mS)\, \gamma$

$M(\eta_b)$ ⇨



$$\Delta M_{miss}(\pi^+\pi^-\gamma) \equiv M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + M(h_b)$$

⇧ $M(h_b)$



Require intermediate Z_b:

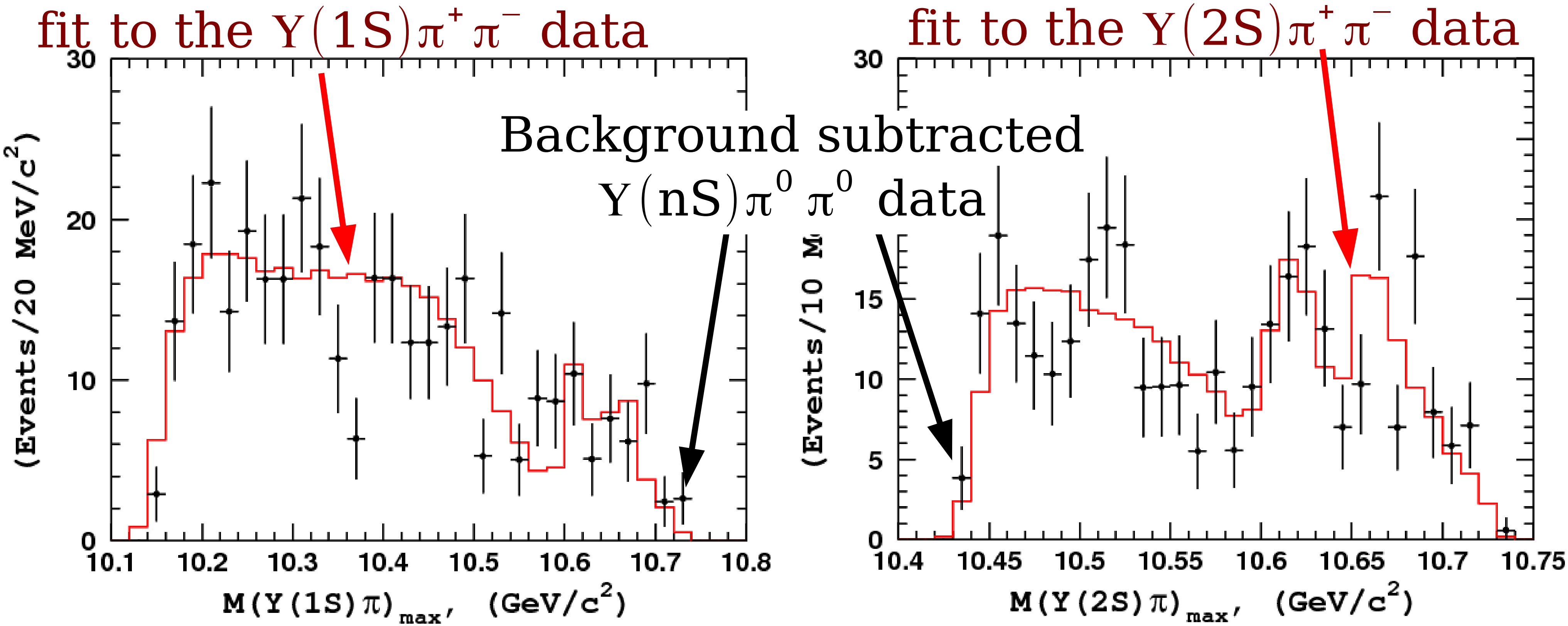
$$10.59 < MM(\pi) < 10.67 \text{ GeV}$$

bg. suppression $\times$ 5.2

approach:

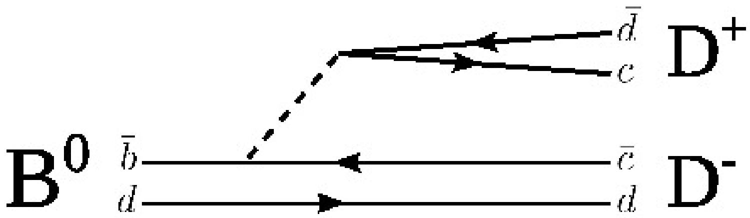
fit $M_{miss}(\pi^+\pi^-)$ spectra in $\Delta M_{miss}(\pi^+\pi^-\gamma)$ bins

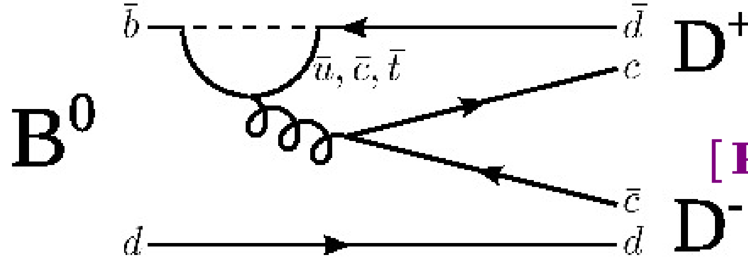
Comparison with $\Upsilon(nS)\pi^+\pi^-$



→ mass spectrum consistent with what happens for Z_b^+

Update of $B^0 \to D^+ D^-$ mode





772×10^6 $B\bar{B}$ pairs
[PRD 85, 091106 (2012)]
[arXiv:1203.6647]

SM prediction: $S = -\sin 2\beta$ and $A \approx 0$ [Z.Z Xing, PRD61, 014010 (1999)]

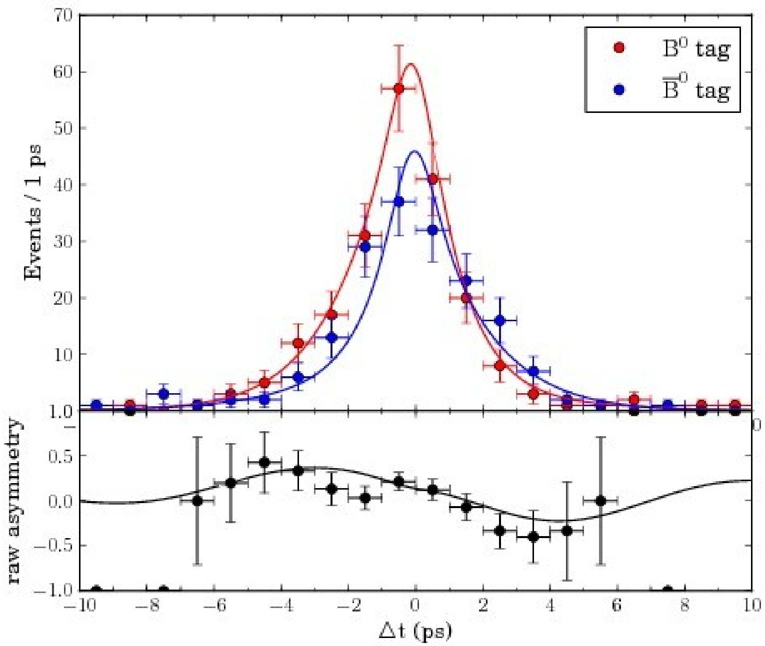
$B^0 \to D^+ D^- \to (K^- \pi^+ \pi^+)(K^+ \pi^- \pi^-)$
$\to (K^- \pi^+ \pi^+)(K_S^0 \pi^-)$

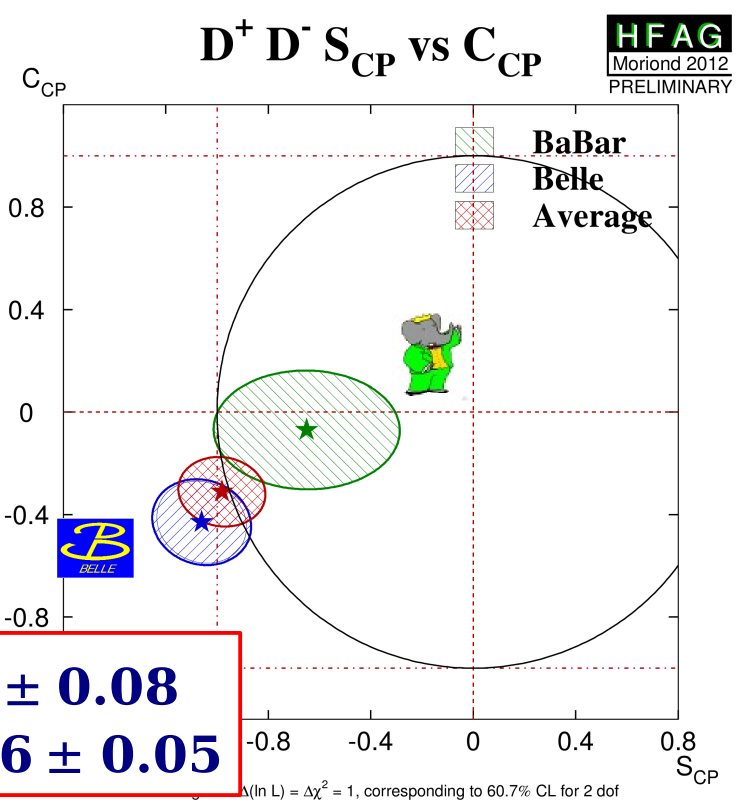
[> × 2 signal yield compared to previous analysis (535 MBB)]

Signal events = 269 ± 21

$Br(B^0 \to D^+ D^-) = (2.12 \pm 0.16 \pm 0.18) \times 10^{-4}$

[PDG: $(2.11 \pm 0.31) \times 10^{-4}$]





$S = -1.06\ ^{+0.21}_{-0.14} \pm 0.08$

$A = +0.43 \pm 0.16 \pm 0.05$

Update of $B^0 \to D^{*+} D^{*-}$ mode

Final state is a mixture of CP eigenstates

772×10^6 $B\bar{B}$ pairs
[PRD 86, 071103 (2012)]
[arXiv:1207.5611]

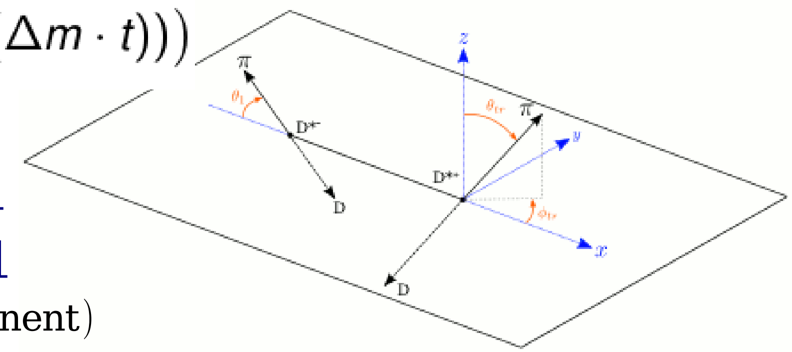
Signal = 1225 ± 59

$Br(B^0 \to D^{*+} D^{*-}) = (7.82 \pm 0.38 \pm 0.60) \times 10^{-4}$ [PDG: $(8.2 \pm 0.9) \times 10^{-4}$]

[take full advantage of the reprocessing of Belle data]

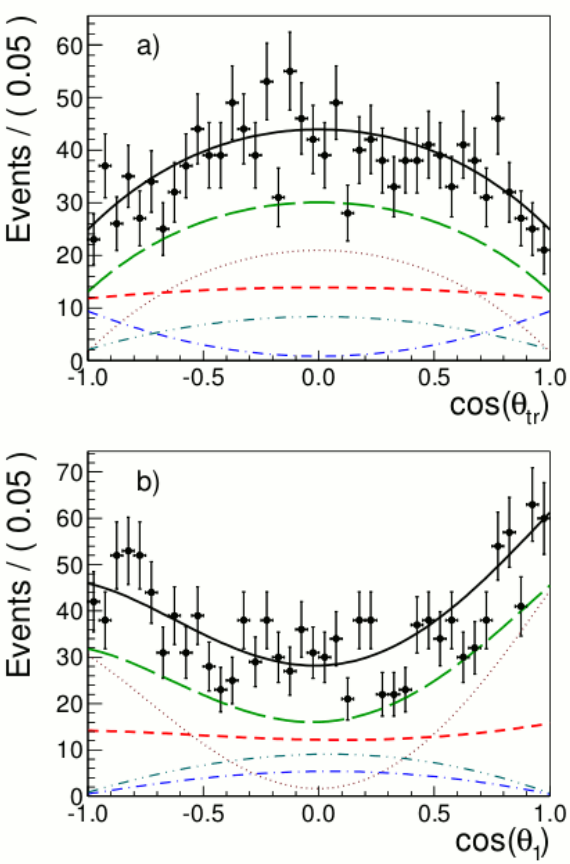
$$\mathcal{P}(t) = \frac{1}{4\tau_{B^0}} e^{-|t|/\tau_{B^0}} \left(1 + q\left((1 - 2P_{\text{odd}}) S \sin(\Delta m \cdot t) + A \cos(\Delta m \cdot t)\right)\right)$$

Transversity base



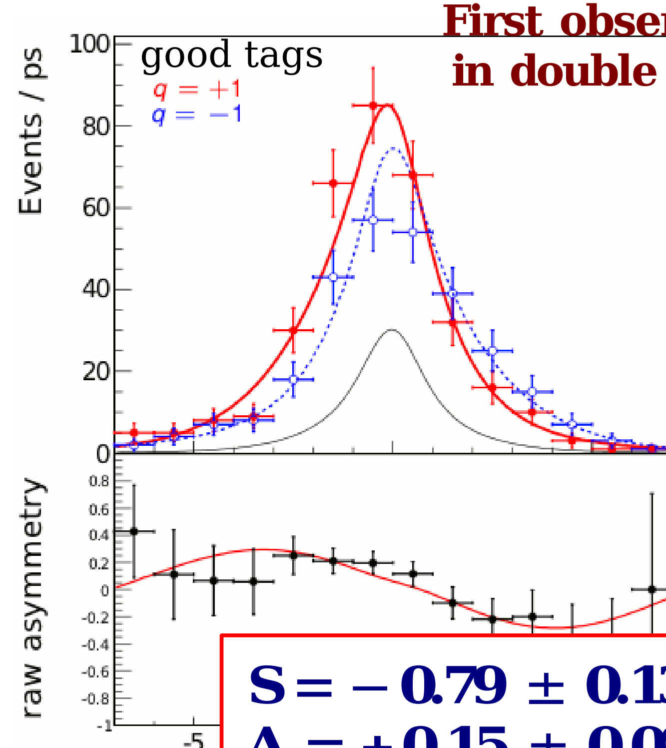
angular analysis to decompose CP-even and odd:

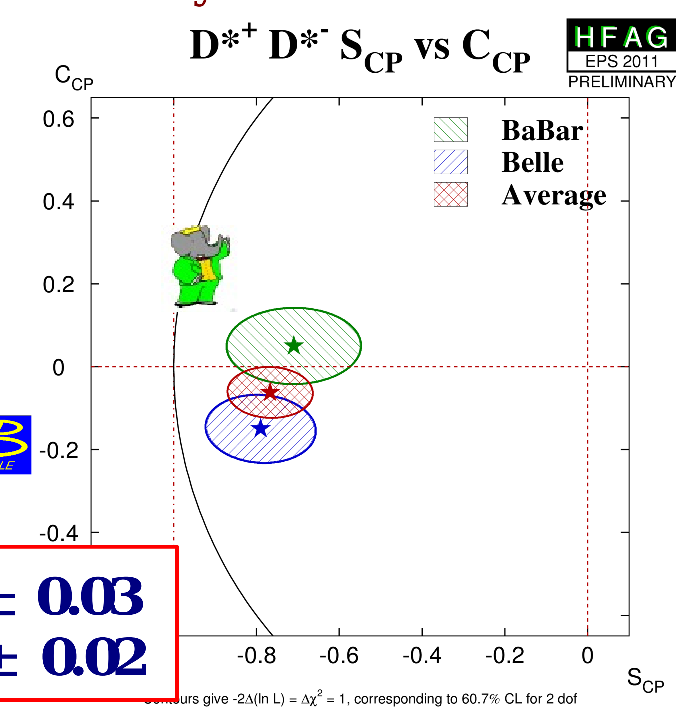
green: signal (CP-even + CP-odd)
red: background
blue: CP-odd



$R_0 = 0.62 \pm 0.03 \pm 0.01$
$R_\perp = 0.14 \pm 0.02 \pm 0.01$
($R_\perp$ corresponds to CP-odd component)

First observation of CPV in double charm decays

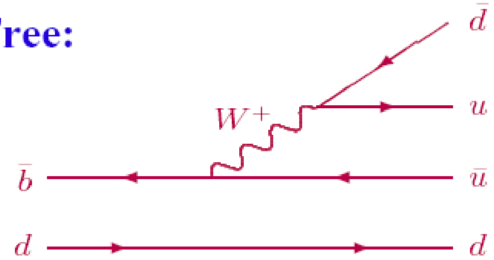


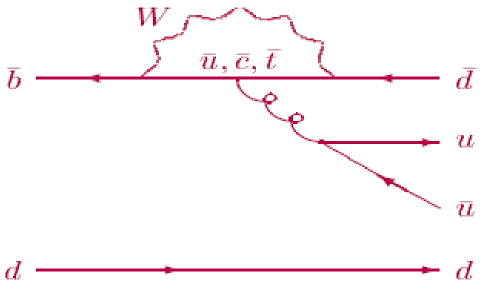


$S = -0.79 \pm 0.13 \pm 0.03$
$A = +0.15 \pm 0.08 \pm 0.02$

α determination...

$$A(B^0 \to \pi^+\pi^-) = T^{+-} e^{i\gamma} + P$$

Tree: 

Penguin: 

$$\begin{aligned} A(t) &= S_{\pi^+\pi^-} \sin(\Delta m t) + A_{\pi^+\pi^-} \cos(\Delta m t) \\ &= \sqrt{1 - A^2_{\pi^+\pi^-}} \sin 2\alpha_{eff} \sin(\Delta m t) + A_{\pi^+\pi^-} \cos(\Delta m t) \end{aligned}$$

from time dependent CP, we can measure α^{eff}, but we want α !

$$\mathbf{S_{\pi^+\pi^-}} = \mathbf{\sin 2\alpha} + 2r \cos\delta \sin(\beta + \alpha) \cos 2\alpha + O(r^2) \qquad r = |P|/|T|$$

→ additional inputs required to determine the penguin pollution

... with isospin analysis

[Gronau-London, PRL65, 3381 (1990)]

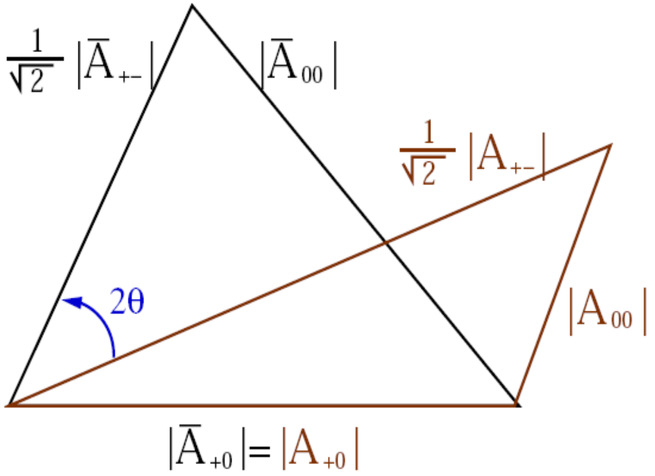
$$A_{+-} = A(B^0 \to \pi^+\pi^-) = e^{-i\alpha} T^{+-} + P$$

$$\sqrt{2} A_{00} = \sqrt{2} A(B^0 \to \pi^0\pi^0) = e^{-i\alpha} T^{00} + P$$

$$\sqrt{2} A_{+0} = \sqrt{2} A(B^+ \to \pi^+\pi^0) = e^{-i\alpha} (T^{00} + T^{+-})$$

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

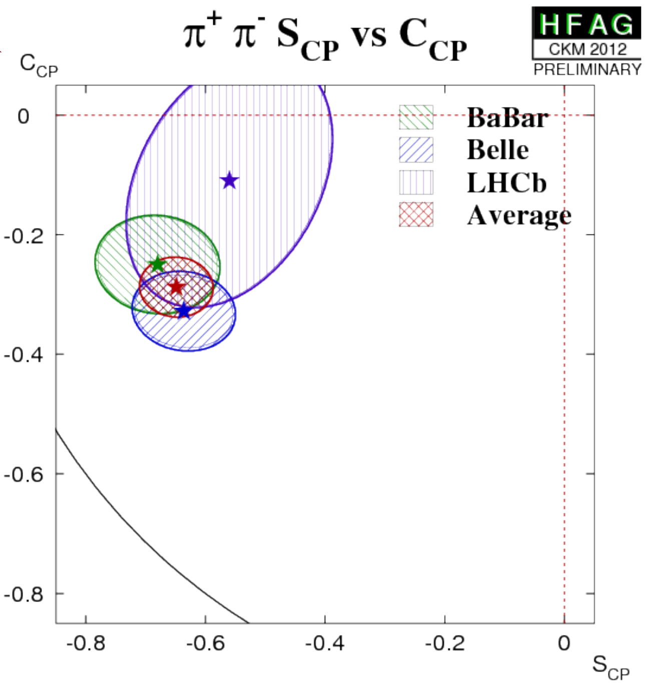
$$\bar{A}_{+-} + \sqrt{2} \bar{A}_{00} = \sqrt{2} \bar{A}_{+0}$$



α can be resolved up to an 8-fold ambiguity ($\alpha \in [0, \pi]$)

$\alpha: \pi\pi$ system

difference was more than 2σ



772×10^6 $B\overline{B}$ pairs
CKM2012 preliminary

$$C = -0.33 \pm 0.06 \pm 0.03$$
$$S = -0.64 \pm 0.08 \pm 0.03$$

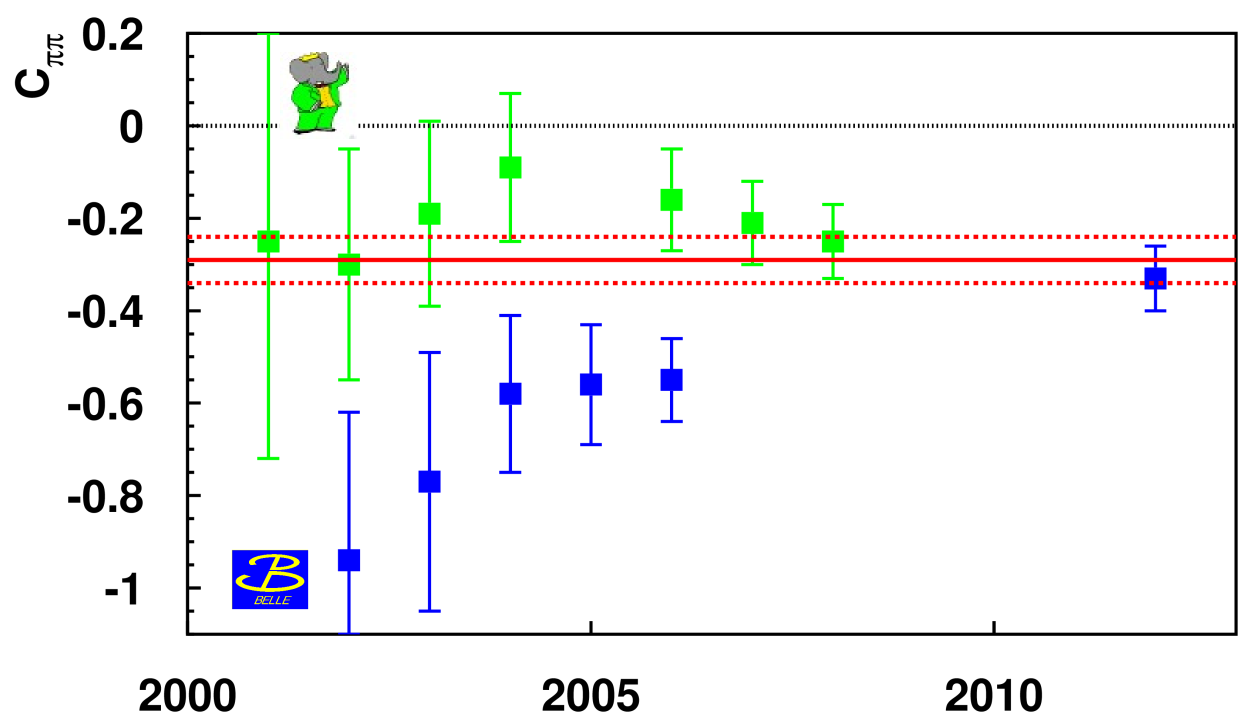
direct CPV @ 5σ

467×10^6 $B\overline{B}$ pairs
arXiv:1206.3525

$$C = -0.25 \pm 0.08 \pm 0.02$$
$$S = -0.68 \pm 0.10 \pm 0.03$$

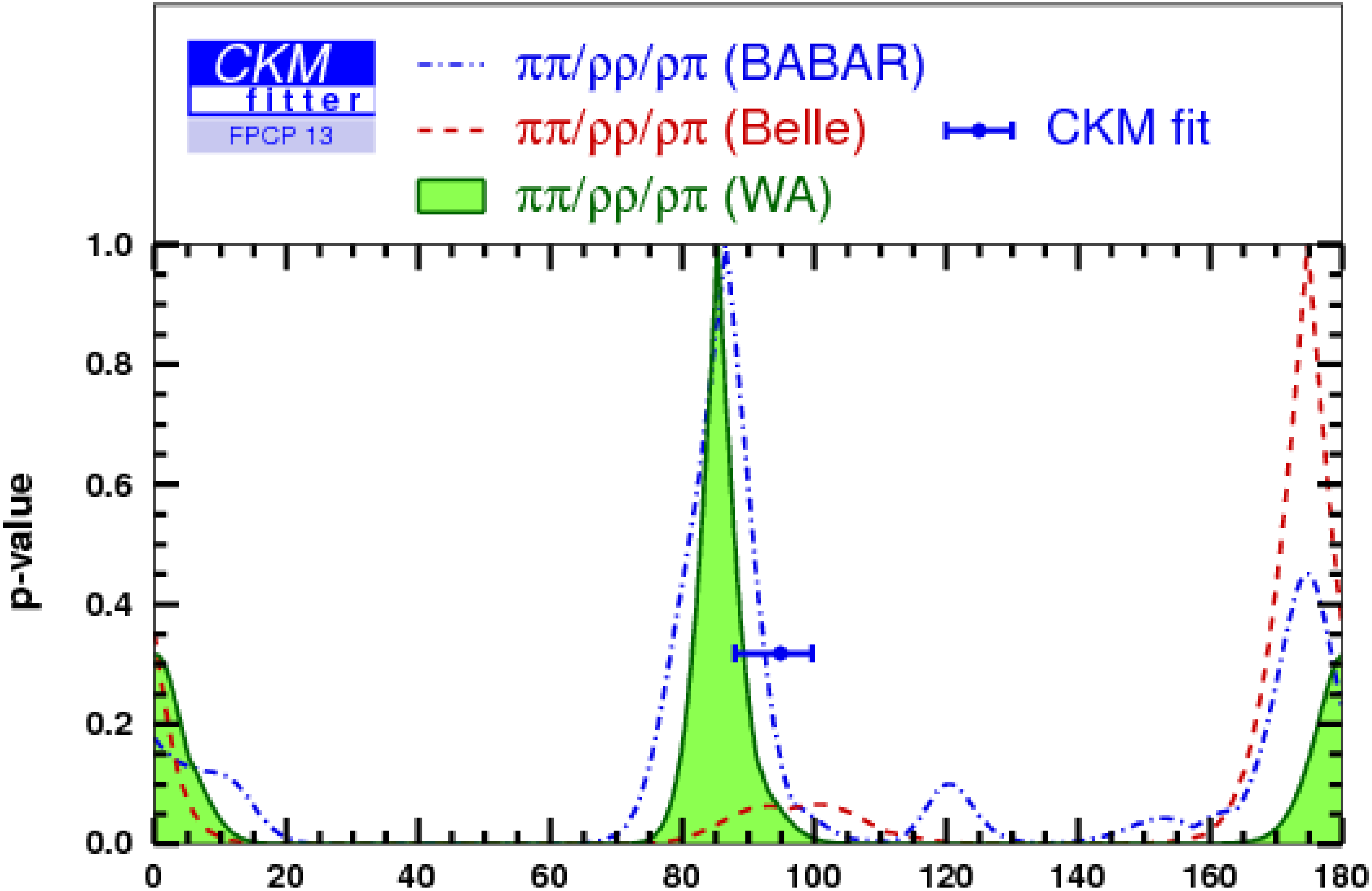
LHCb: $C = -0.11 \pm 0.21 \pm 0.03$
$S = -0.56 \pm 0.17 \pm 0.03$

PUBLISHED



Combined ($\pi\pi$, $\rho\pi$, $\rho\rho$) measurements for α determination

dominated by the $B \to \rho\rho$ measurements (though flat isospin triangles)



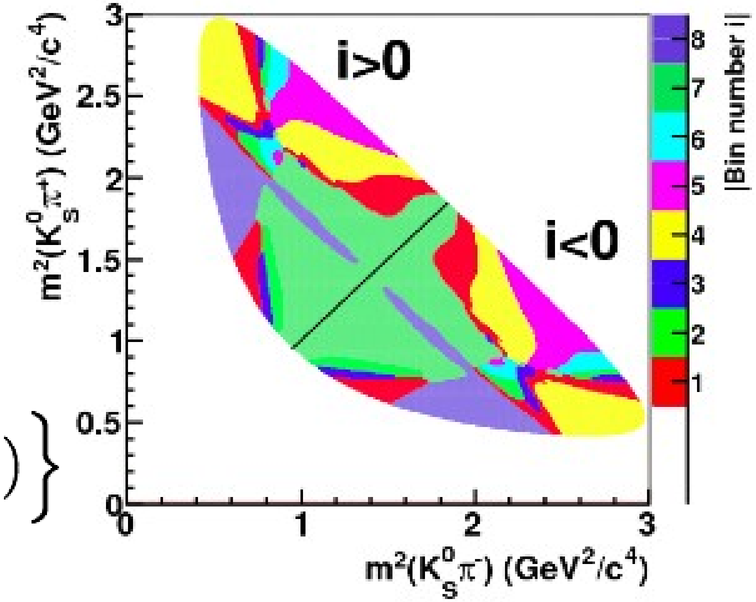
$$\alpha = \left(85.4\,^{+4.0}_{-3.8}\right)^\circ$$

Binned Dalitz method: avoid the modeling error by "optimal" binning of the Dalitz plot

Bondar and Poluektov
EPJ C55, 51 (2008)

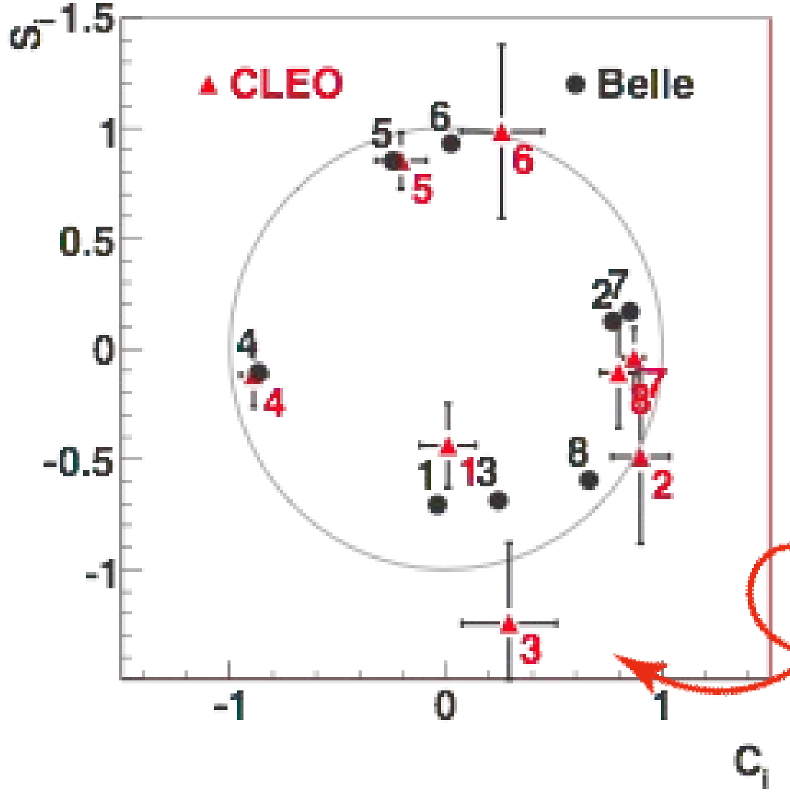
[choice of bins guided by model, but extraction of γ is not biased by this choice]

minimize χ^2 in fit to all bins for each mode



Expected number of $B^\pm \to DK^\pm$ events in bin i is:

$$N_i^\pm = h\left\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i + y_\pm s_i)\right\}$$



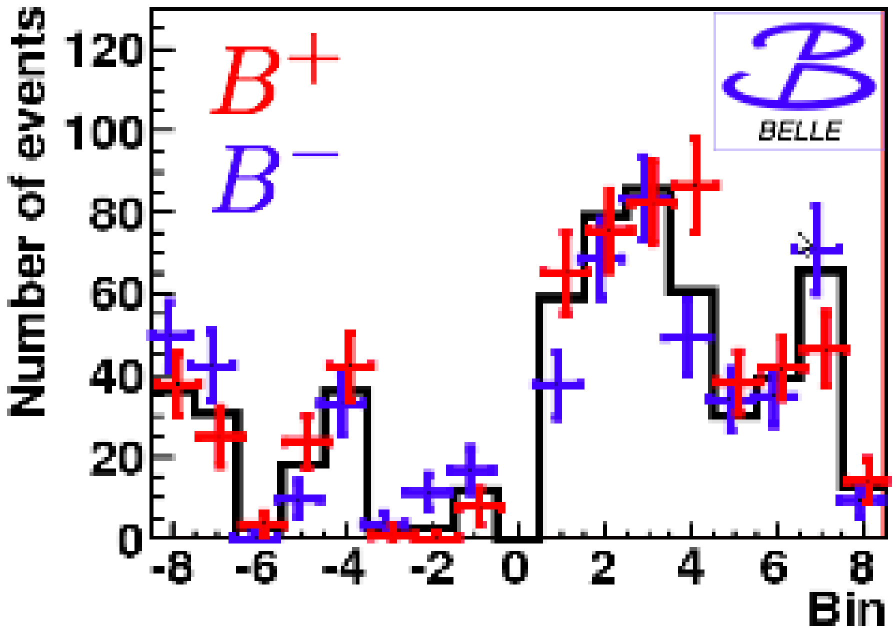
K_i is the # of events in bin i from a flavour-tagged sample ($D^{*\pm} \to D\pi^\pm$)

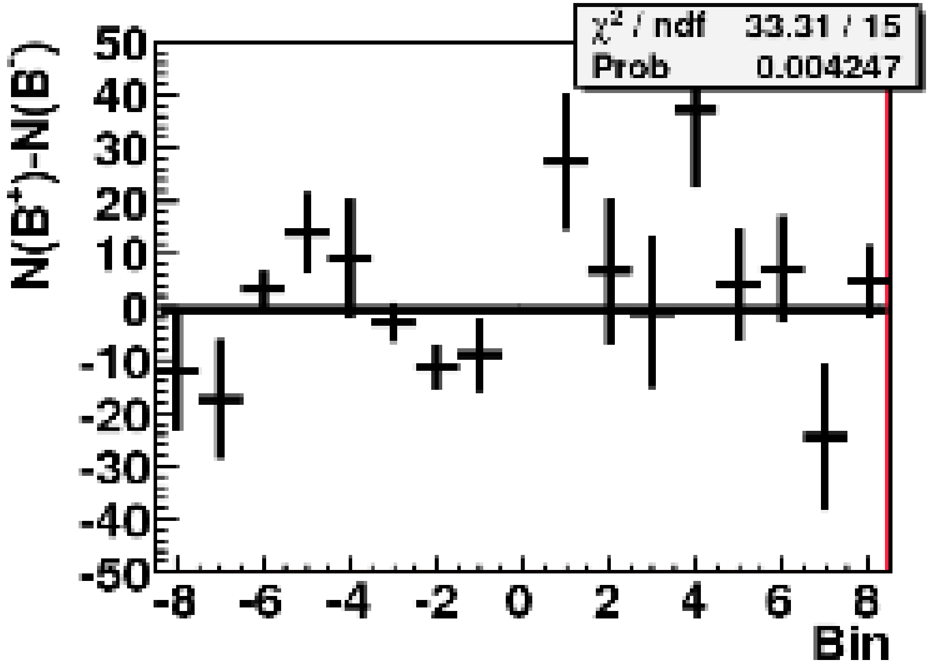
c_i and s_i contain information about the strong-phase difference in bin i

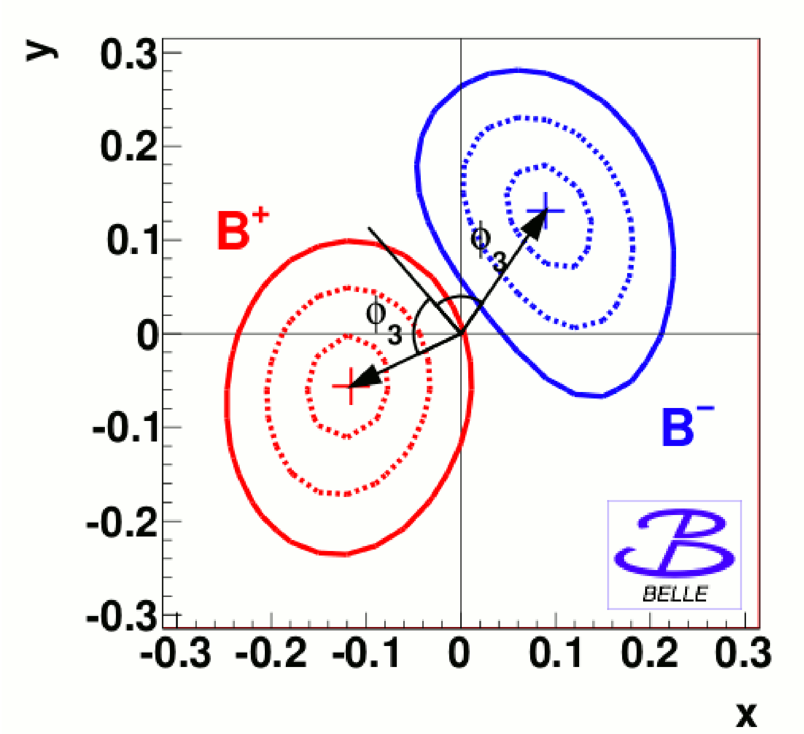
(use CLEO data for $\psi(3770) \to D^0 \overline{D}^0$ here; can be measured by BES-III too)

Binned Dalitz method result in B → DK

772M $B\bar{B}$
PRD 85, 112014 (2012)
[arXiv:1204.6561]







$$\gamma = (77.3\,^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$

$$r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011$$

$$\delta_B = (129.9 \pm 15.0 \pm 3.8 \pm 4.7)^\circ$$

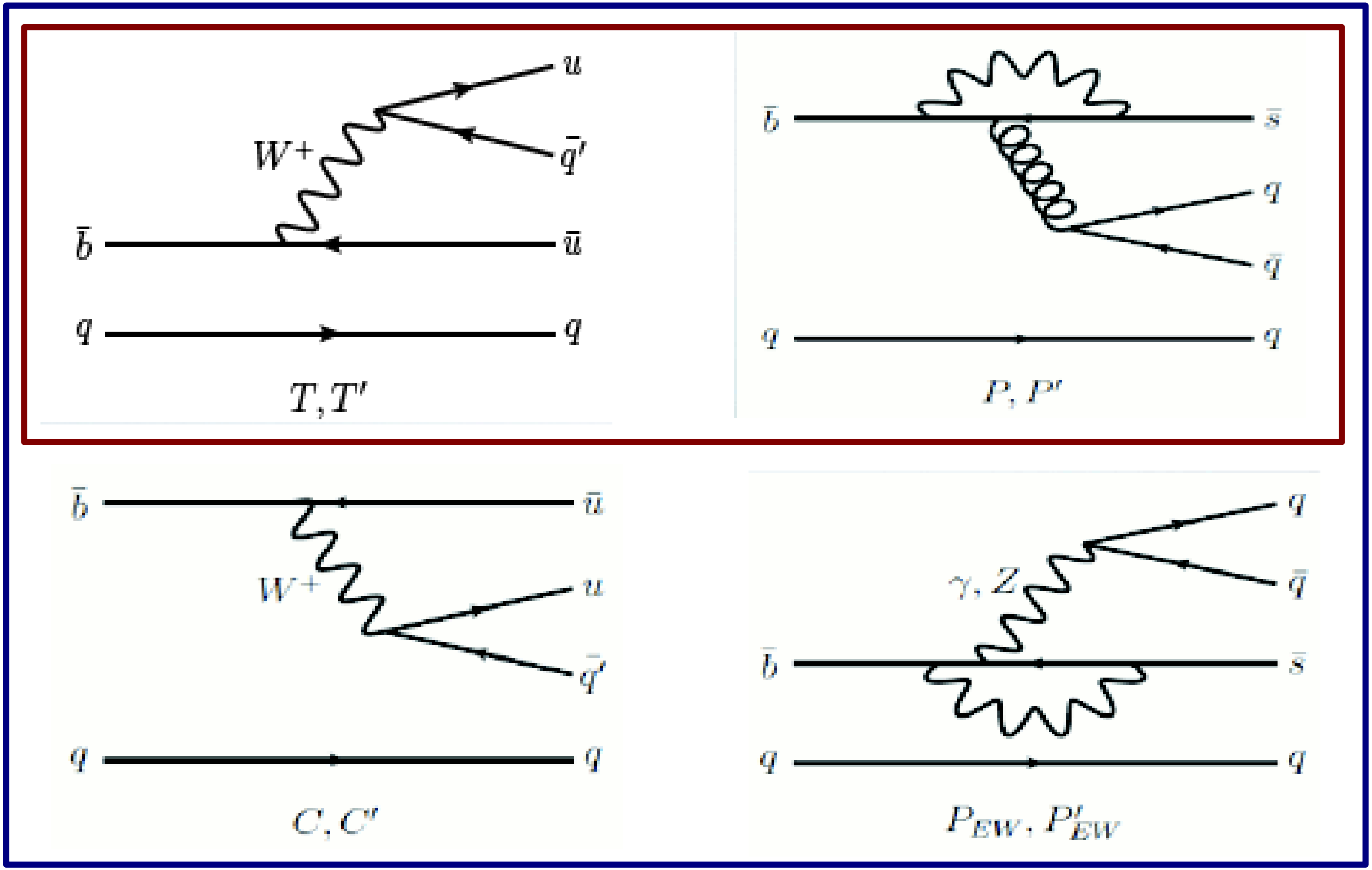
uncertainty in c_i, s_i
from CLEO data size
(can be reduced using
future BES-III data)

Measuring direct CPV with $B \to K\pi$

$$A_{CP} \equiv \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)} \propto \sin\Delta\varphi \ \sin\Delta\delta$$

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

$B^+ \to K^+ \pi^0$

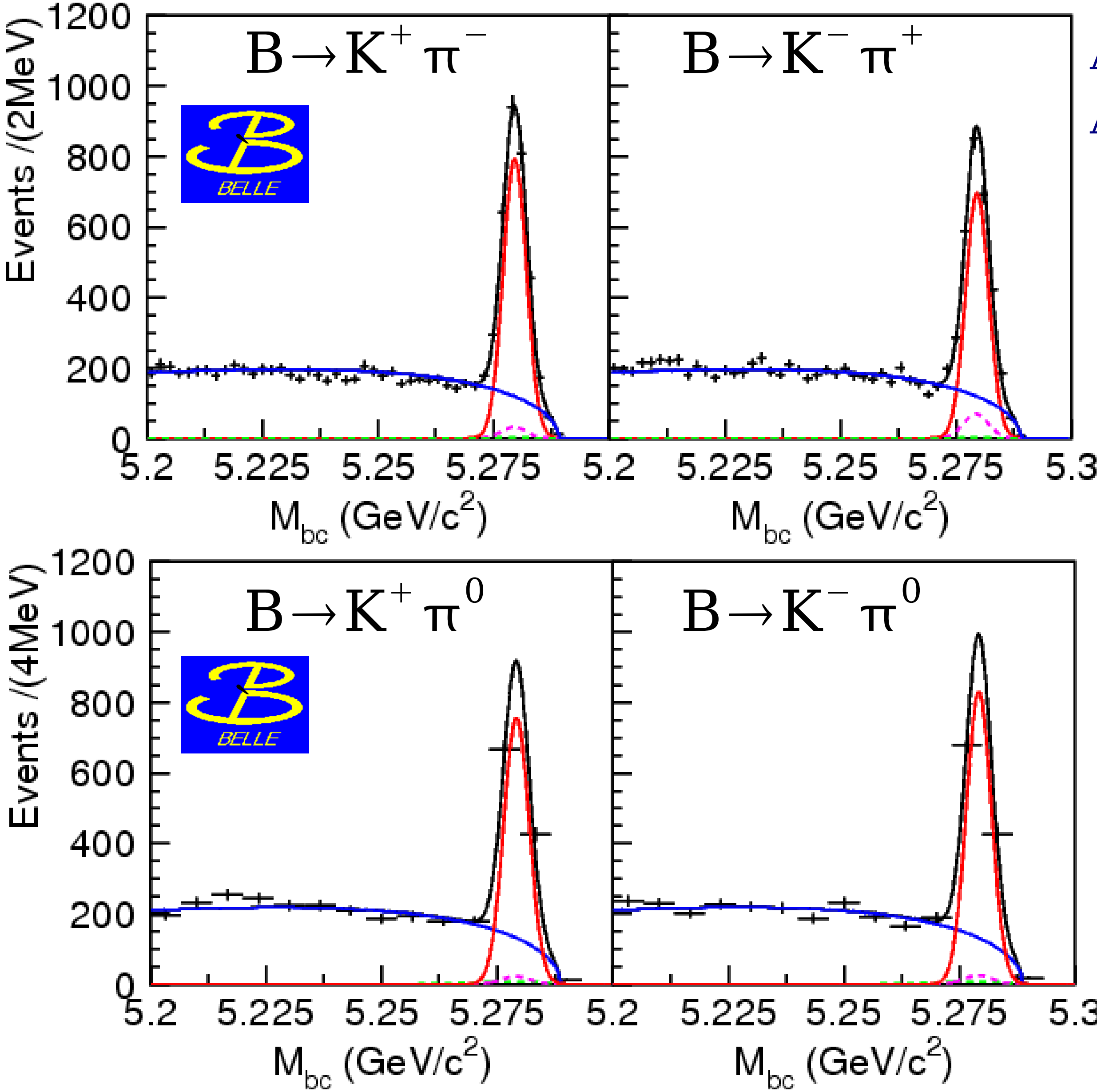


Diagrams identical except for spectator quark ?

$\Rightarrow$ strong and weak phases are the same, A_{CP} should be the same ?

B→Kπ measurements at B-factories...

Kπ puzzle: $\Delta A_{K\pi} = A_{CP}(K\pi^0) - A_{CP}(K\pi)$

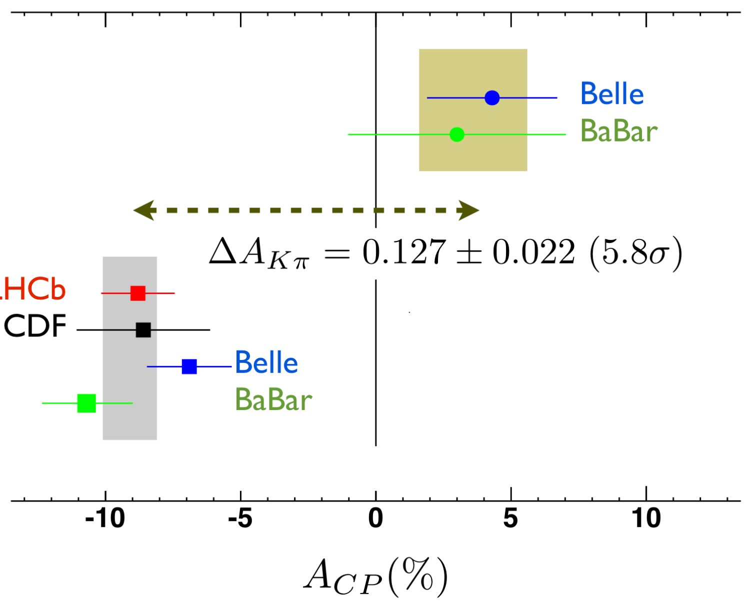


$A_{CP}(K^{\pm}\pi^0) = +0.043 \pm 0.024 \pm 0.002$

$A_{CP}(K^{\pm}\pi^{\mp}) = -0.069 \pm 0.014 \pm 0.007$

Belle preliminary:

$\Delta A_{K\pi} = +0.112 \pm 0.028$ @4.0σ



$\Delta A_{K\pi} = +0.121 \pm 0.022$ @5.5σ

⇒ NEW PHYSICS !!?

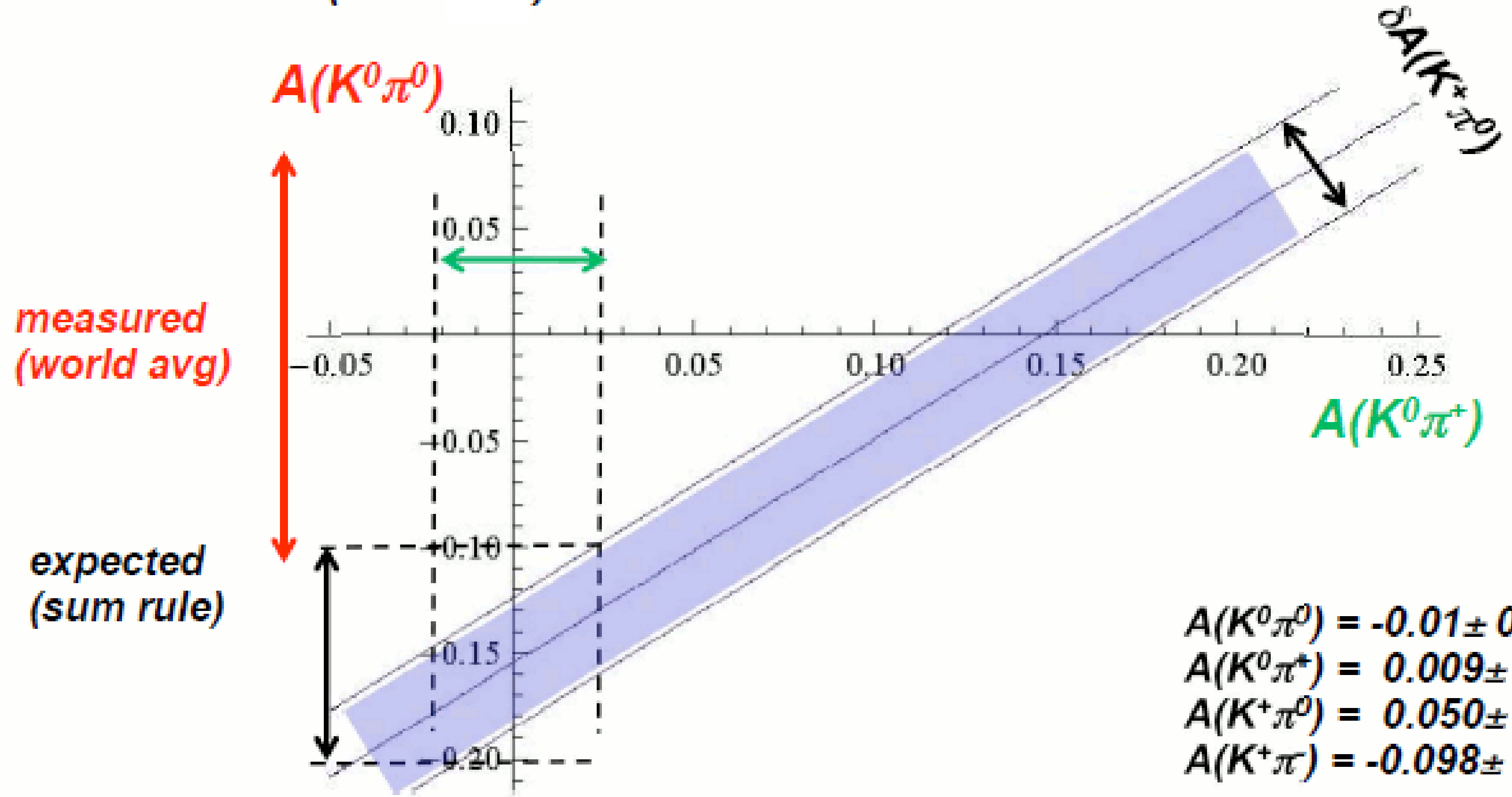
Measuring direct CPV

''Model independent'' sum rule for all four modes:

[Gronau, PLB 627, 82 (2005), Atwood & Soni, PRD 58, 036005 (1998)]

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{Br(K^0\pi^+)}{Br(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\,Br(K^+\pi^0)}{Br(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\,Br(K^0\pi^0)}{Br(K^+\pi^-)}$$

B factories now (~1.4 ab^{-1}):



$A(K^0\pi^0)$ = -0.01± 0.10

$A(K^0\pi^+)$ = 0.009± 0.025

$A(K^+\pi^0)$ = 0.050± 0.025

$A(K^+\pi^-)$ = -0.098± 0.012

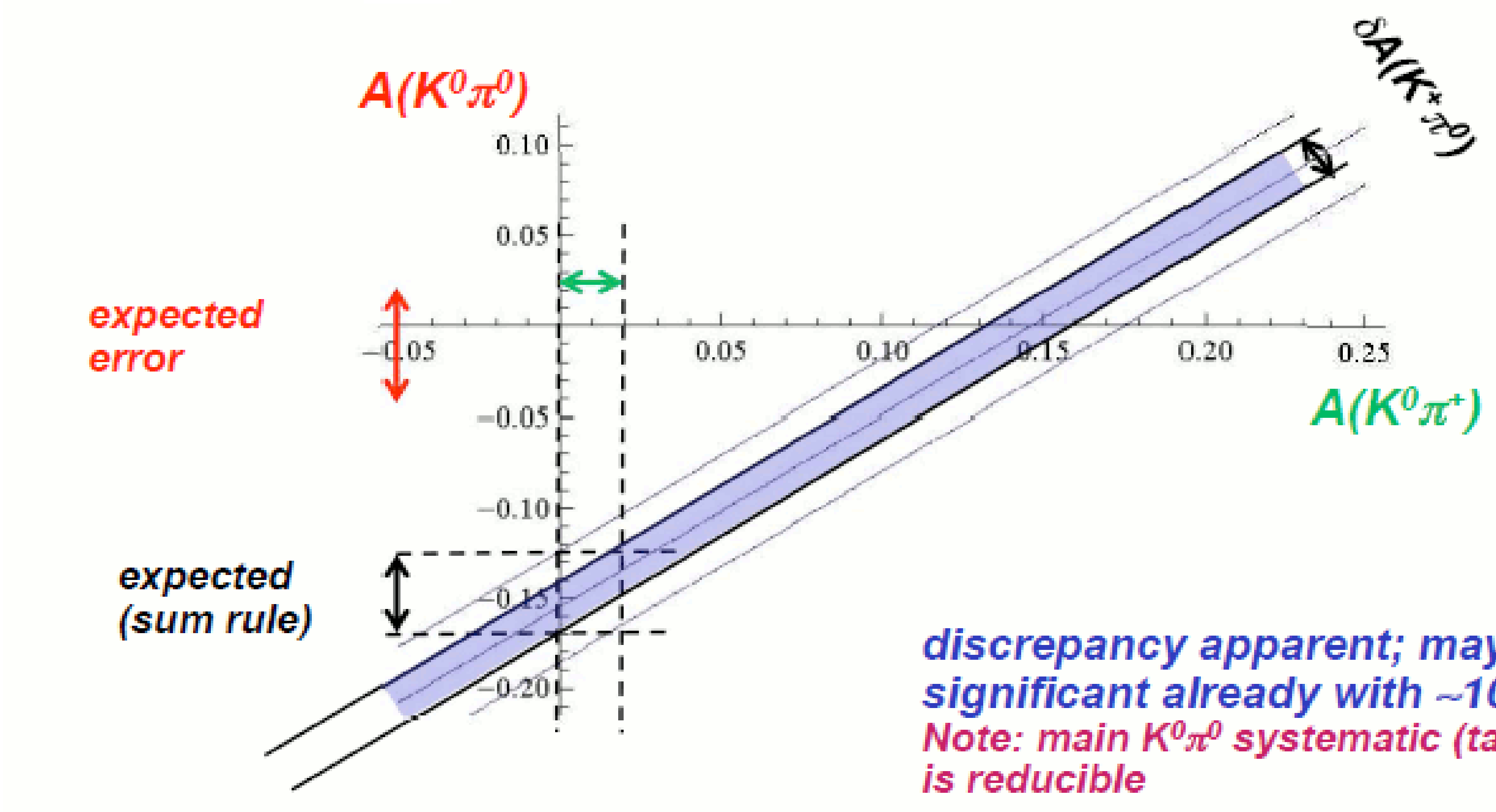
Measuring direct CPV

"Model independent" sum rule for all four modes:

[Gronau, PLB 627, 82 (2005), Atwood & Soni, PRD 58, 036005 (1998)]

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{Br(K^0\pi^+)}{Br(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\,Br(K^+\pi^0)}{Br(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\,Br(K^0\pi^0)}{Br(K^+\pi^-)}$$

B factory at 50 ab^{-1}, with today's central values:



discrepancy apparent; may be significant already with ~10 ab^{-1}

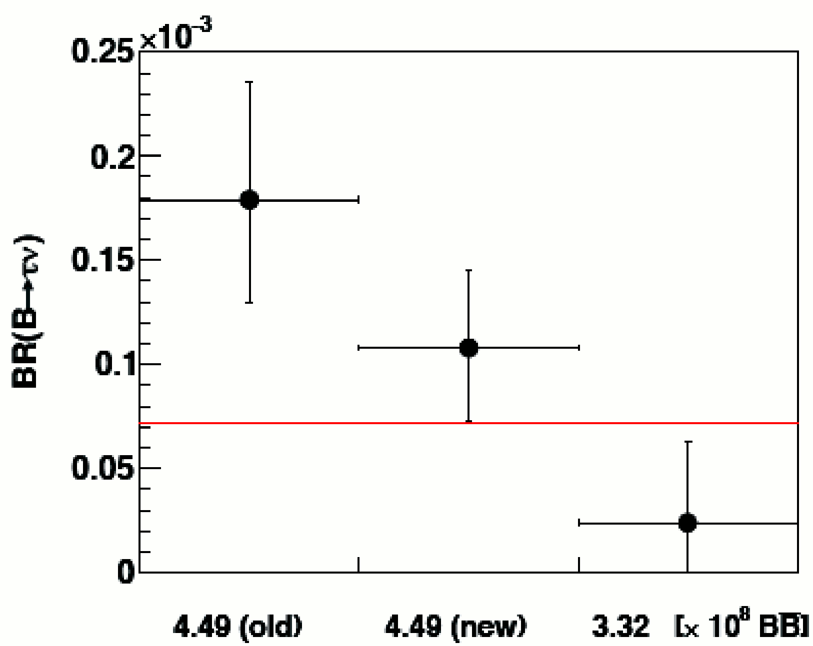
Note: main $K^0\pi^0$ systematic (tag-side interference) is reducible

$\Rightarrow$ **ideal for a super B-factory...**

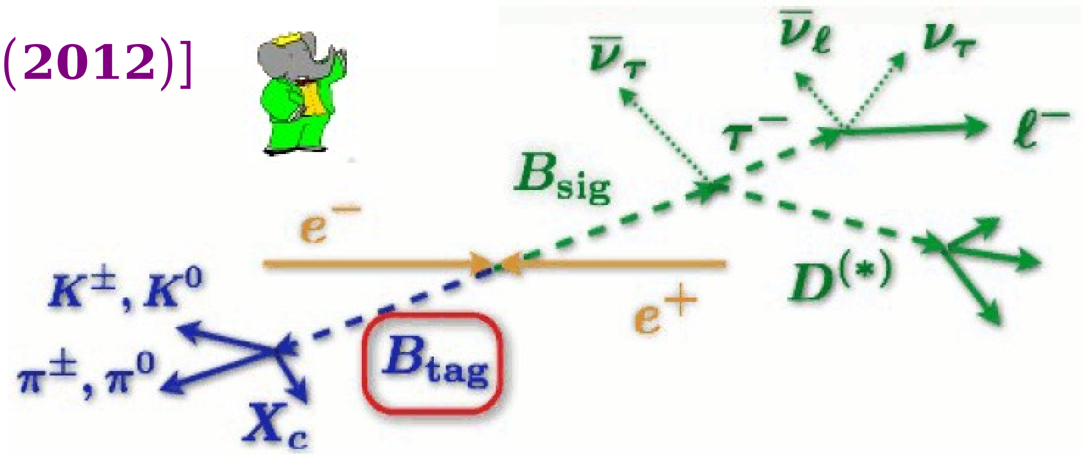
Comparison for B→τν Using Hadronic Tag at Belle

	PRL 97 (2006)	This analysis	
Tag	Hadronic tag	Hadronic tag (new)	
Number of $B\overline{B}$ events ($\times 10^8$)	4.49	4.49	3.22
Efficiency ($\times 10^{-4}$)	3.0	11.2	11.2
Signal yield	$24.1^{+7.6}_{-6.6}$	$54.1^{+18.8}_{-17.4}$	$8.6^{+14.0}_{-12.4}$
$\mathcal{B}(B^- \to \tau^- \overline{\nu}_\tau)$ ($\times 10^{-4}$)	$1.79^{+0.56}_{-0.49}$	$1.08^{+0.37}_{-0.35}$	$0.24^{+0.39}_{-0.34}$

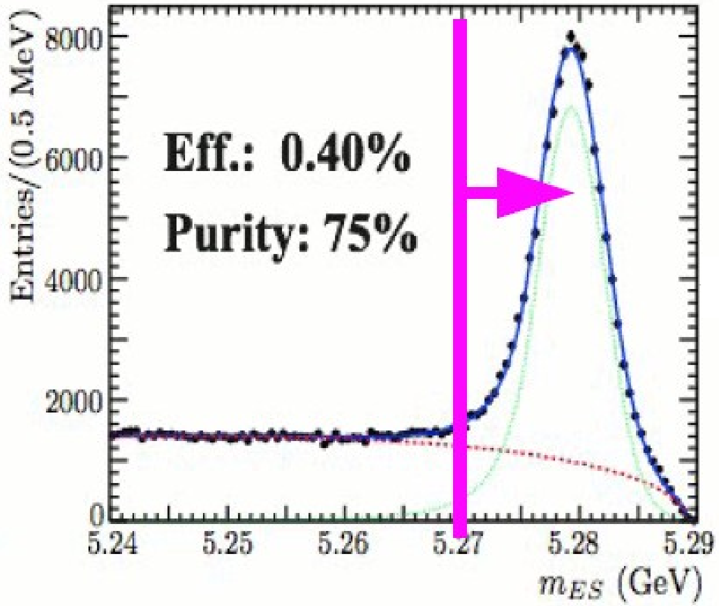
- New analysis is based on improved tag, loose event selection, and reprocessed data.
- Most of the data after the selection are independent from old analysis.
- Assuming that all events in old analysis are included in new analysis, the remaining data sample in $N_{BB} = 4.49 \times 10^8$ provides BR ~ $(0.6 \pm 0.4) \times 10^{-4}$ (1.9σ from old result).



$B \to D^{(*)} \tau \nu$ [PRL 109, 101802 (2012)]

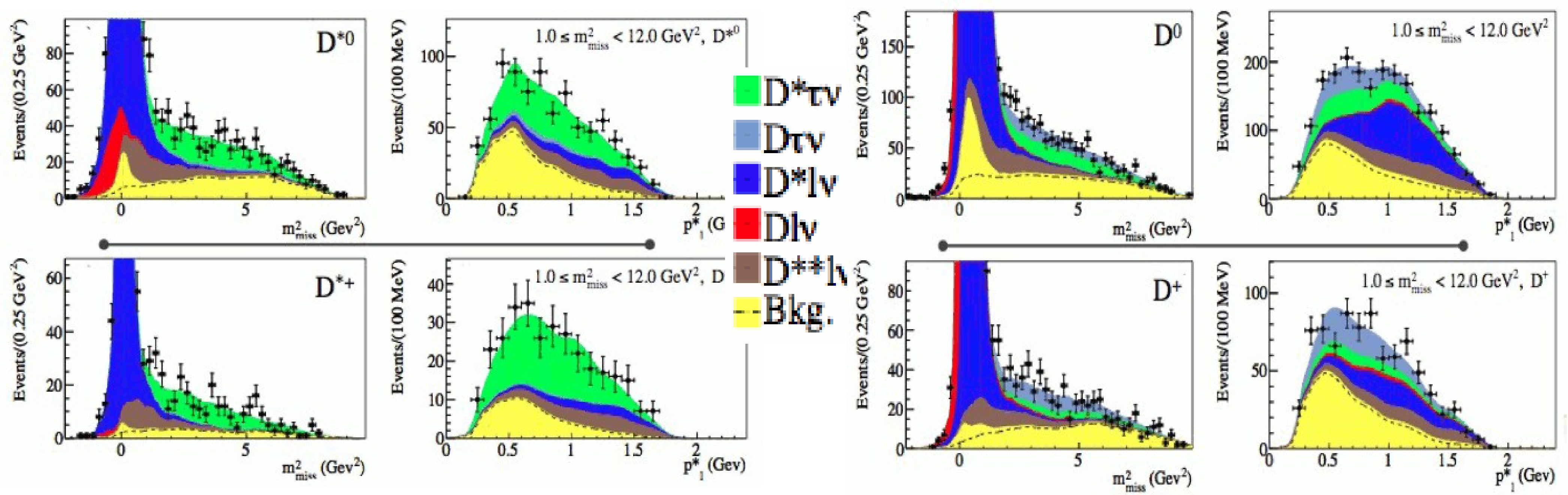


1,768 decay chains

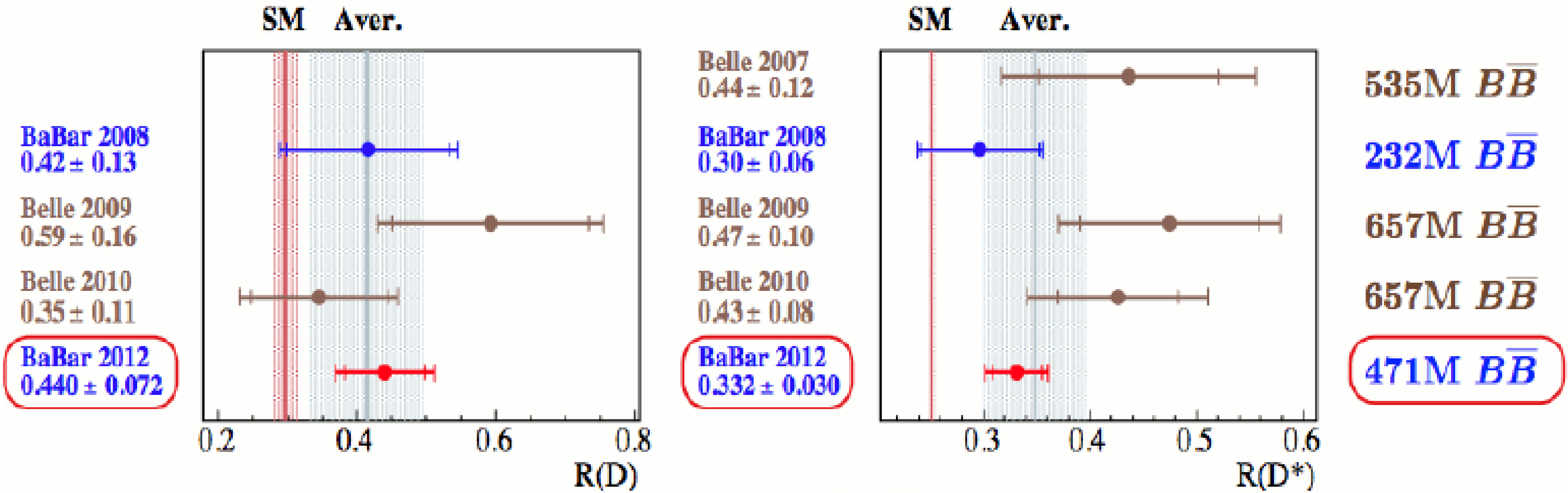


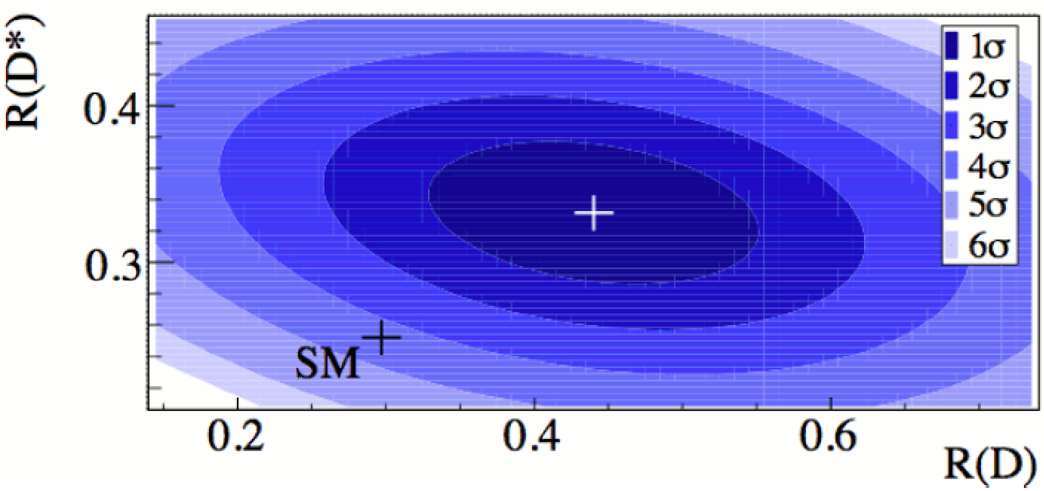
- 2D unbinned fit to m^2_{miss} and p^*_l
- fitted samples
  - 4 $D^{(*)}l$ samples ($D^0 l$, $D^{*0} l$, $D^+ l$ and $D^{*+} l$)
  - 4 $D^{(*)}\pi^0 l$ control samples ($D^{**}(l/\tau)\nu$)

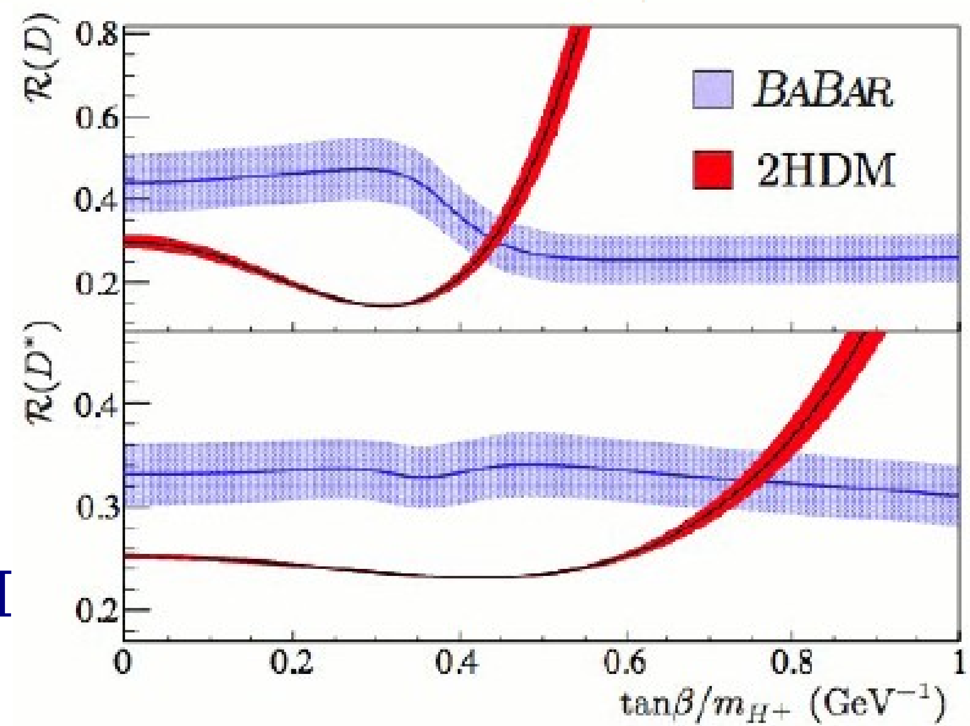
⇒ $D\tau\nu$ and $D^*\tau\nu$ clearly observed



$B \to D^{(*)} \tau \nu$

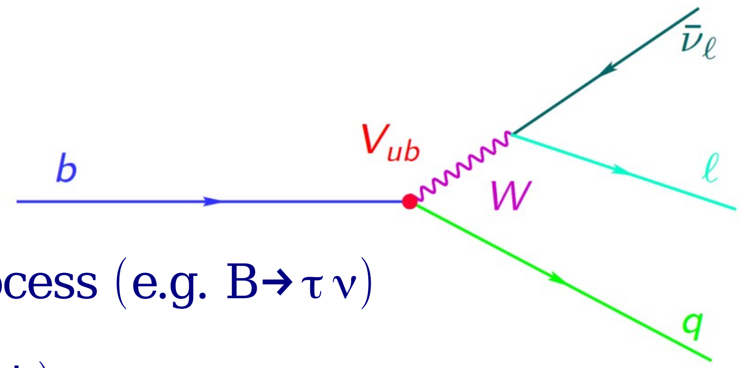






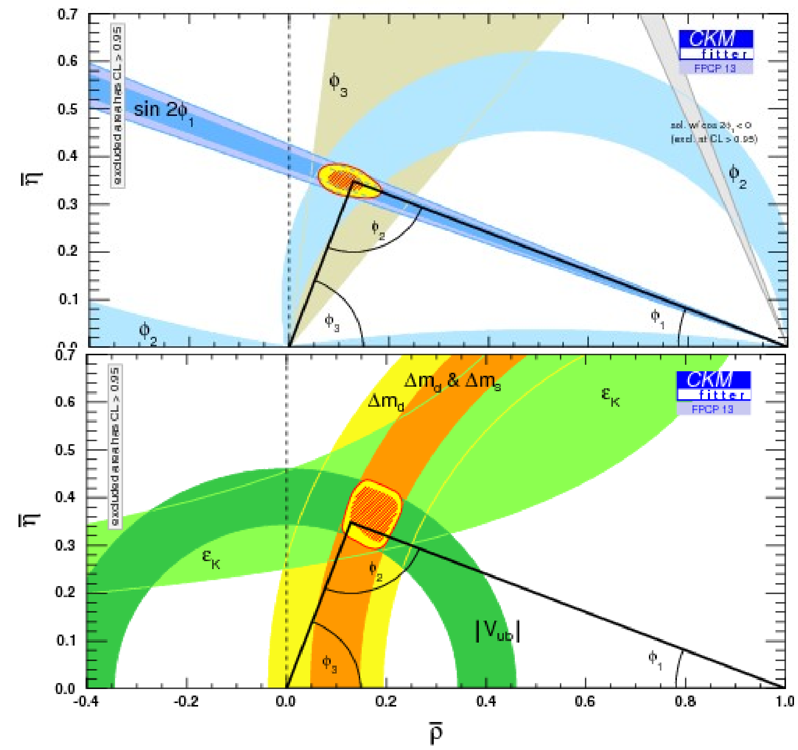
- combined 3.4σ away from SM
- doesn't fit 2HDM Type II
- Belle will show its new result soon

Exclusive Semileptonic Decays



- $|V_{ub}|$ is a valuable input for predictions of other process (e.g. $B \rightarrow \tau \nu$)
- Precision on $|V_{ub}|$ is poor (relative to $\sin 2\beta$ and $|V_{cb}|$)
- Some tension exists in inclusive vs exclusive determinations of $|V_{ub}|$
  - Important to clarify for further consistency checks
- Matrix element of $B \rightarrow X_u l \nu$:

$$\mathcal{M}(B \rightarrow X_u \ell \bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} V_{ub} L^\mu H_\mu, \quad L^\mu = \bar{u}_\ell \gamma^\mu (1 - \gamma^5) v_\nu$$

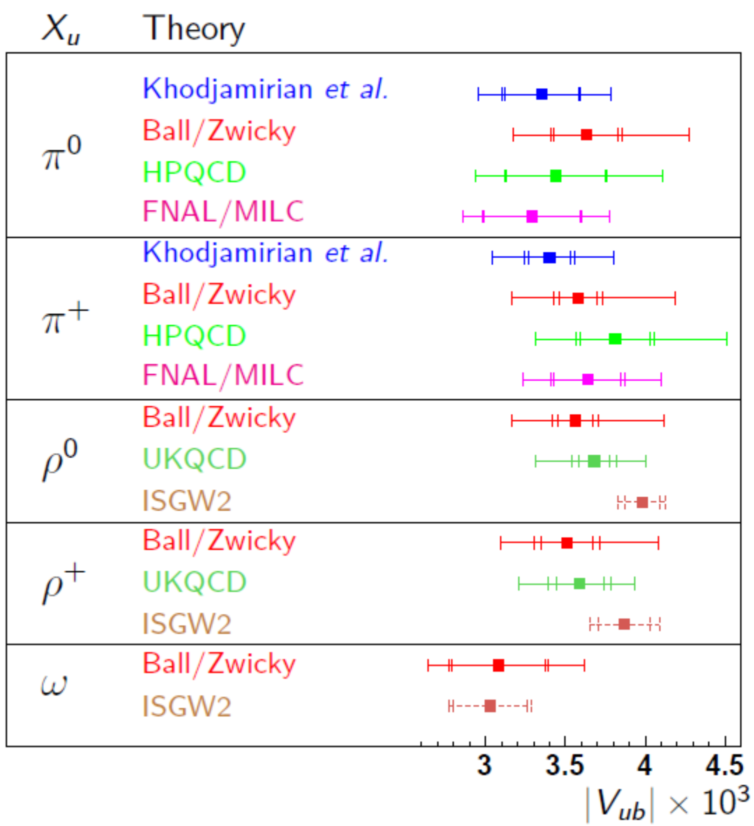


- For example, decay rate for π mode has form:

$$\frac{d\Gamma(B \rightarrow \pi \ell \bar{\nu}_\ell)}{dq^2} = \frac{G_F^2 p_\pi^3}{24\pi^3} |V_{ub}|^2 |f_+(q^2)|^2$$

- Measurements allow clean extraction of $|V_{ub}|$:
  - For π mode, Bourrely et al (BCL) parameterization can be used to determine $f_+(q^2)$ in a model-independent way [PRD 79, 013008 (2009)]

Impacts on $|V_{ub}|$



Khodjamirian *et al.*
PRD **83**, 094031 (2011)

Ball/Zwicky
PRD **71**, 014015 (2005)
PRD **71**, 014029 (2005)

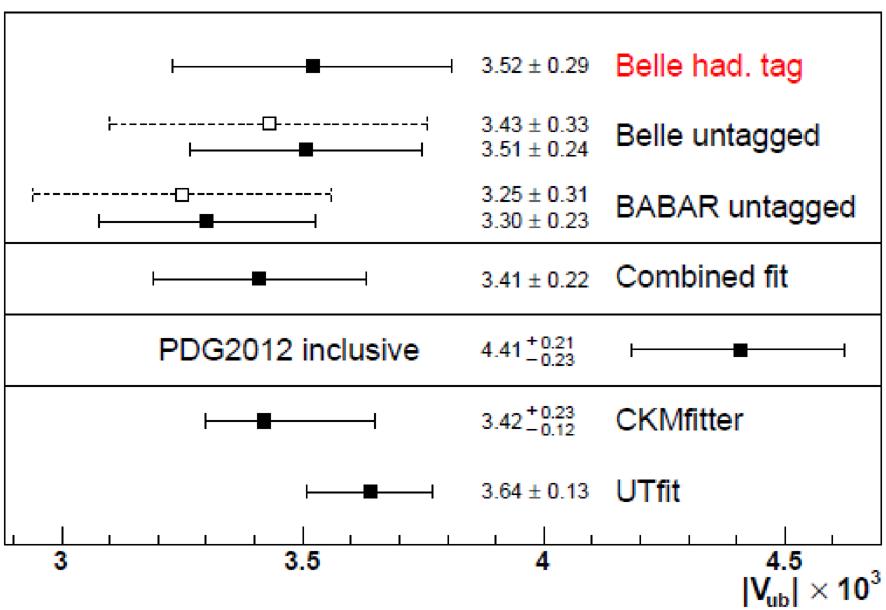
HPQCD
PRD **73**, 074502 (2006)

FNAL/MILC
PRD **79**, 054507 (2009)

UKQCD
PLB **416**, 392 (1998)

ISGW2
PRD **52**, 2783 (1995)
Theory error is not available.

- These results can be used to estimate $|V_{ub}|$ based on various theoretical predictions of form factor
- Experimental uncertainty typically ~2 times less than theoretical uncertainty



- $|V_{ub}|$ can be studied in a model-independent way using $B \to \pi l \nu$ decays and BCL form factor parameterization
  - Simultaneous fit to available $B \to \pi l \nu$ data and LCSR/LQCD form factor prediction

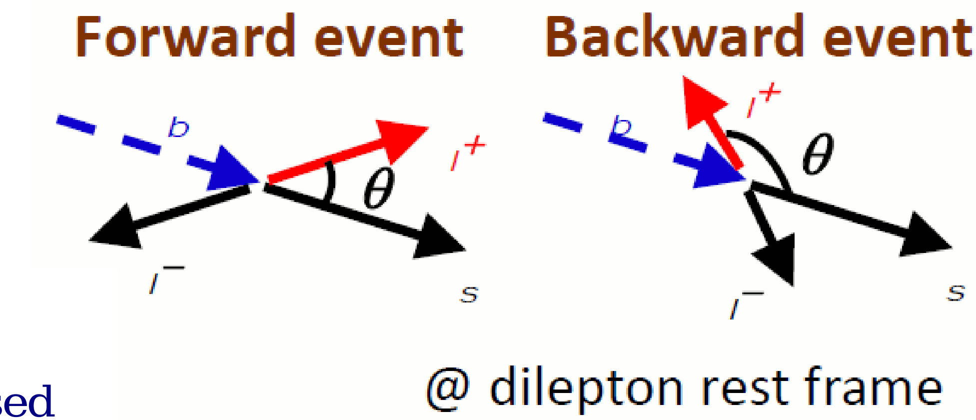
LCSR	JHEP **1205**, 092 (2012) [arXiv:1203.1359]
LQCD	PRD **79**, 054507 (2009) [arXiv:0811.3640]
Belle had. tag	PRD 88, 032005 (2013) [arXiv:1306.2781]
Belle	PRD **83**, 071101(R) (2011) [arXiv:1012.0090]
BABAR	PRD **86**, 092004 (2012) [arXiv:1208.1253]

Forward–backward asymmetry in inclusive $B \to X_s l^+ l^-$

Semi-inclusive reconstruction (sum of exclusive) method:

$X_s = K^{\pm}/K_S +$ up to four π (at most one π^0)

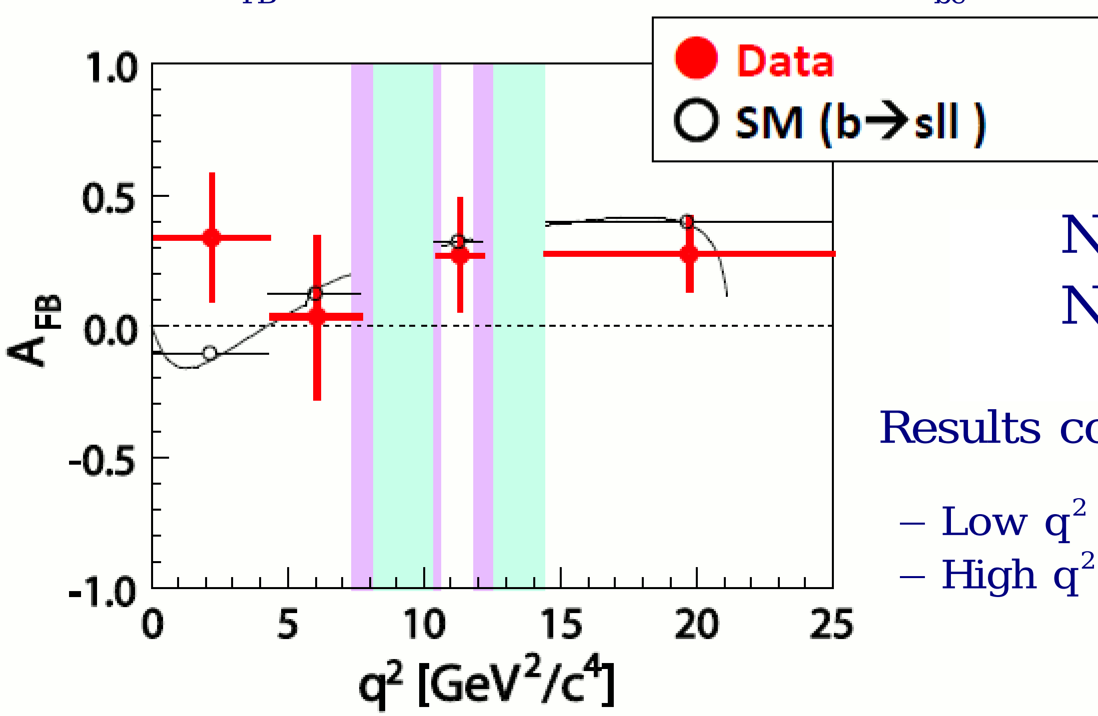
[K] : K, K_S
[$K\pi$] : $K\pi$, $K_S\pi$, $K\pi^0$, $K_S\pi^0$
[$K2\pi$] : $K2\pi$, $K_S 2\pi$, $K\pi\pi^0$, $K_S\pi\pi^0$
[$K3\pi$] : $K3\pi$, $K_S 3\pi$, $K2\pi\pi^0$, $K_S 2\pi\pi^0$
[$K4\pi$] : $K4\pi$, $K_S 4\pi$, $K3\pi\pi^0$, $K_S 3\pi\pi^0$



- For B^0, only self-tagging modes with $K^{\pm}$ used
- $K4\pi$ states not used due to low expected signal

fraction of all X_s decays covered by those 10 final states ~ 50%

Extract A_{FB} from simultaneous fit of M_{bc} of forward/backward evts in e/μ channels



$N_{sig}^{ee} = 139.9 \pm 18.6$ evts
$N_{sig}^{\mu\mu} = 160.8 \pm 20.0$ evts

Results consistent with SM

- Low q^2 (1st bin): consistent with the SM within 1.8σ
- High q^2 (3rd and 4th bin): exclude $C_{10} \times C_9 > 0$ with 2.3σ