

# **Belle**

**(recent and coming results)**

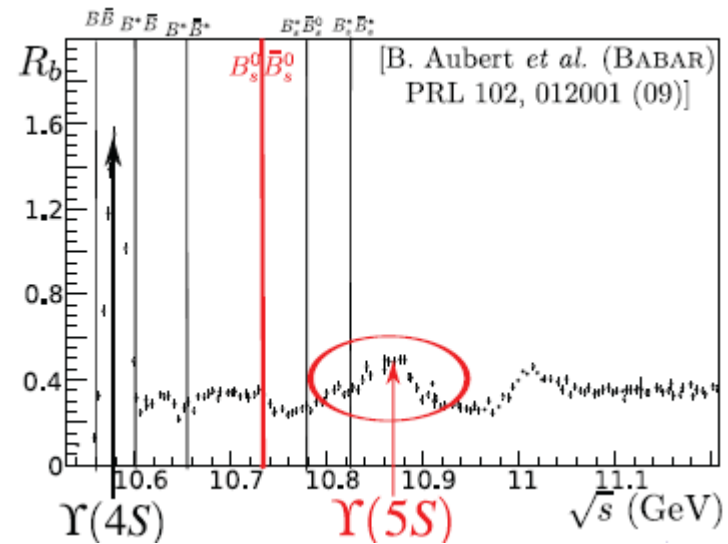
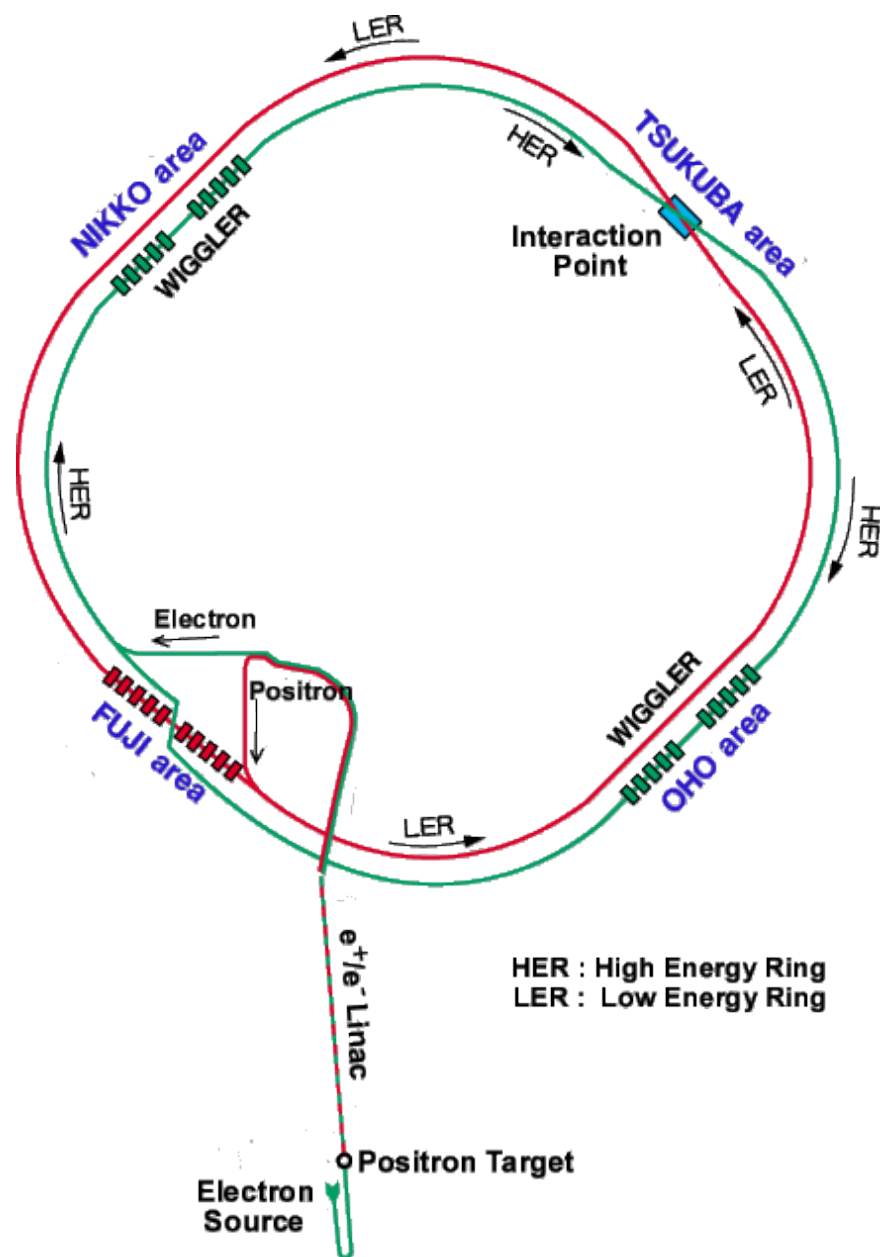
**Karim Trabelsi**  
for the Belle collaboration

karim.trabelsi@kek.jp

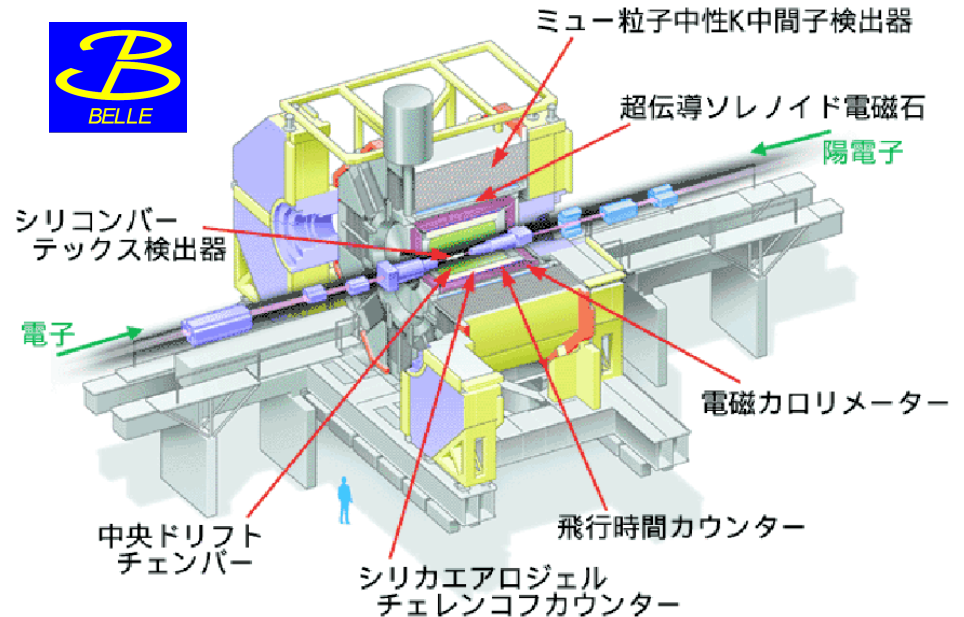


**LAL, Orsay**  
**Oct 14, 2011**

# KEKB collider and Belle in a nutshell



Belle is an international collaboration  
15 countries, 64 institutes  
365 members



# Belle shutdown last June (2010)

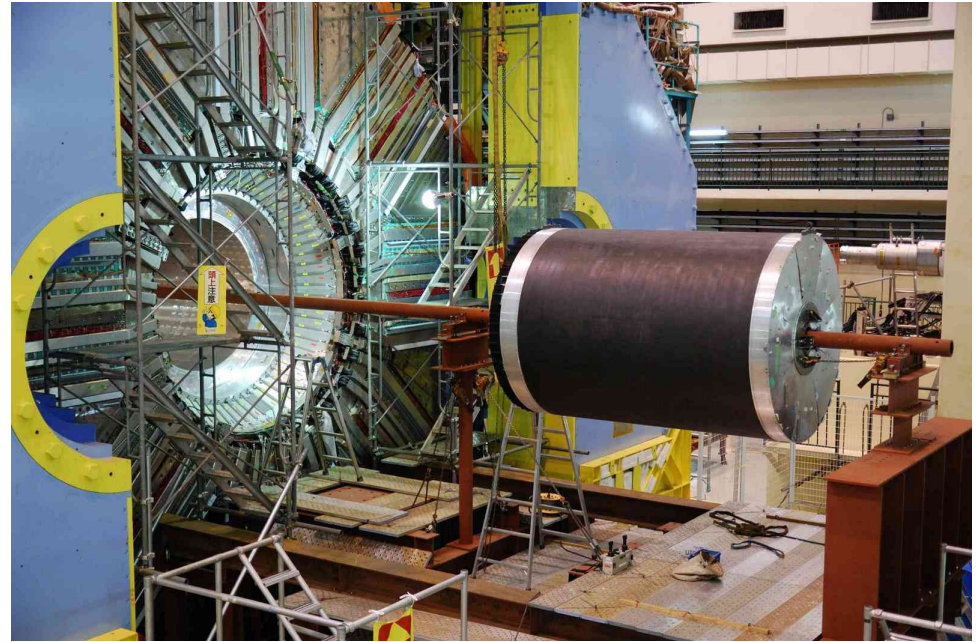


Belle these days...

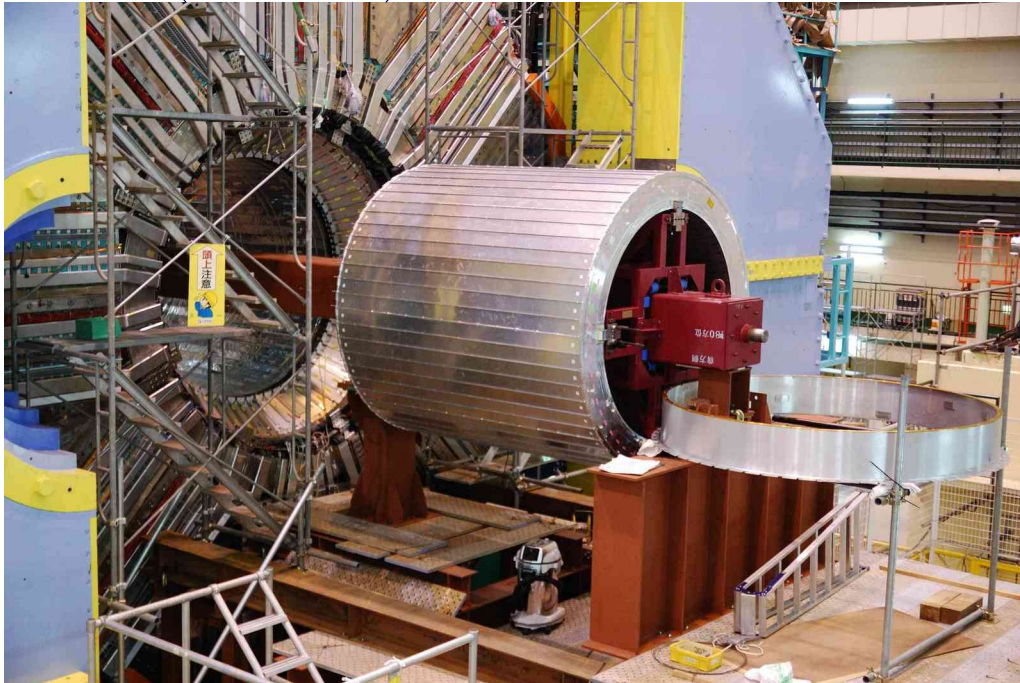
ECL (backward endcap)



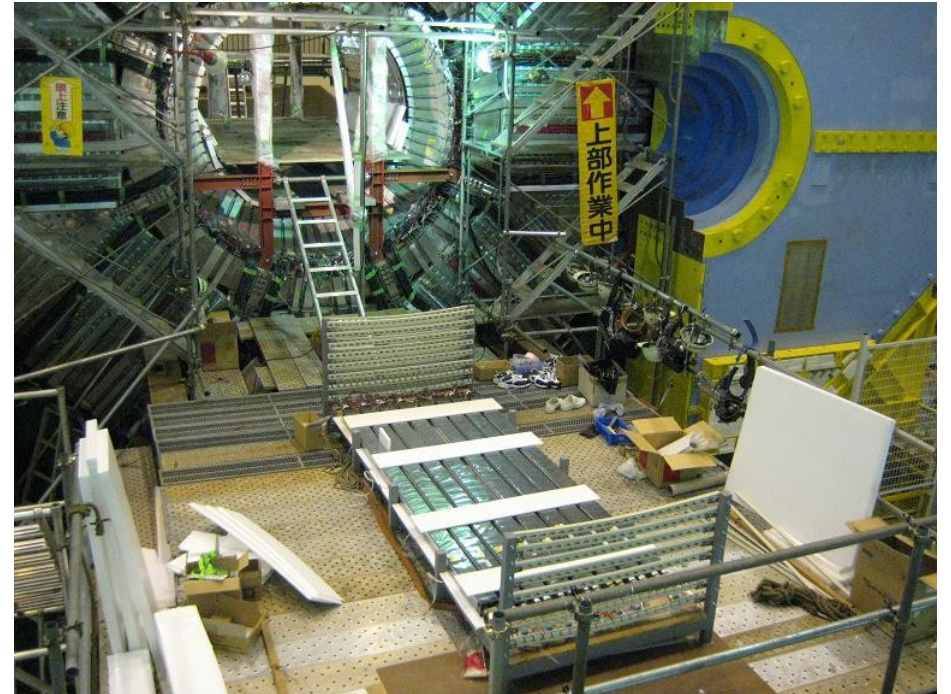
CDC



ACC (barrel)

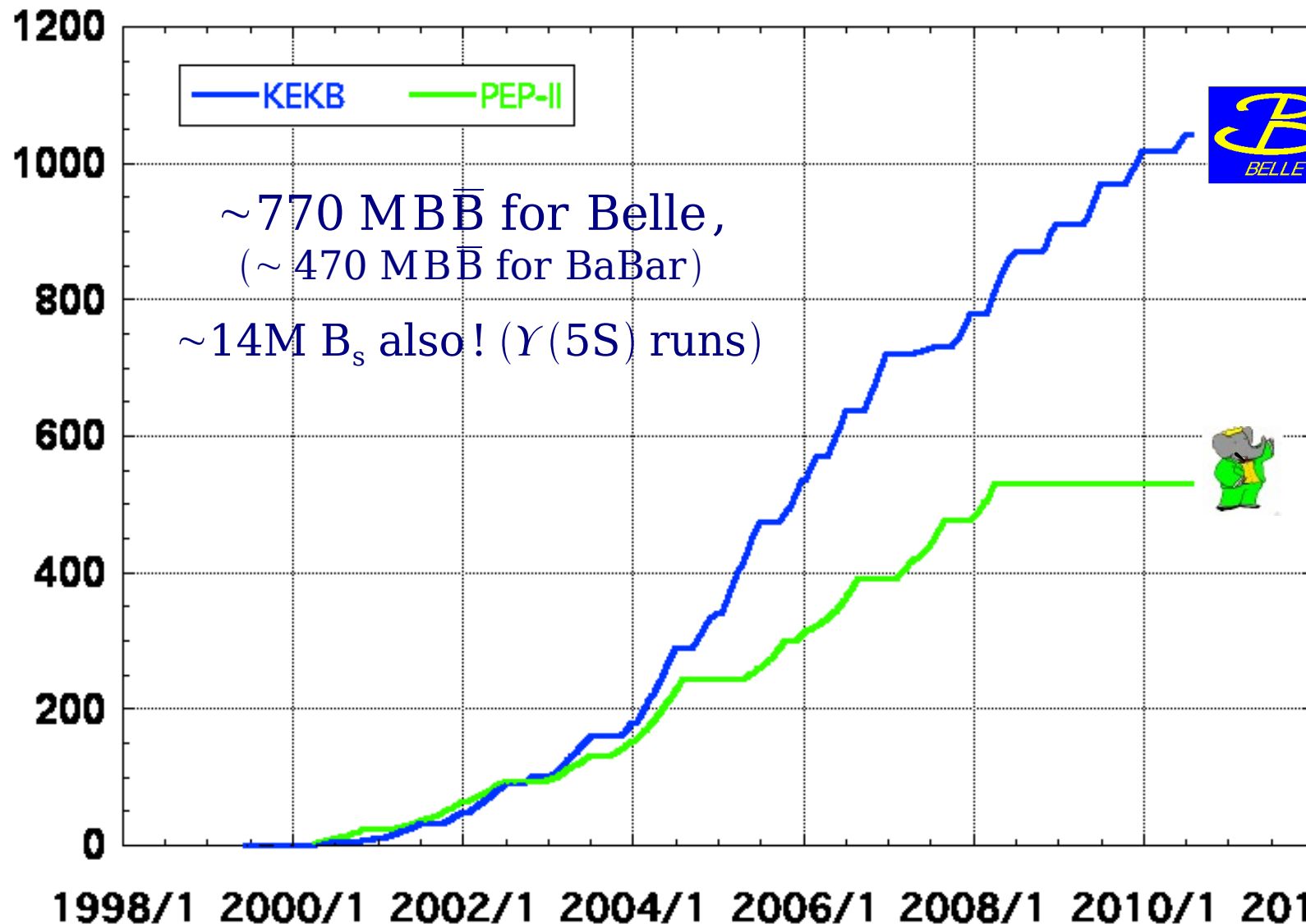


TOF



# Luminosity at B factories

(fb<sup>-1</sup>)



> 1 ab<sup>-1</sup>

**On resonance:**

$\Upsilon(5S)$ : 121 fb<sup>-1</sup>

**$\Upsilon(4S)$ : 711 fb<sup>-1</sup>**

$\Upsilon(3S)$ : 3 fb<sup>-1</sup>

$\Upsilon(2S)$ : 24 fb<sup>-1</sup>

$\Upsilon(1S)$ : 6 fb<sup>-1</sup>

**Off reson./scan:**

~ 100 fb<sup>-1</sup>

~ 550 fb<sup>-1</sup>

**On resonance:**

$\Upsilon(4S)$ : 433 fb<sup>-1</sup>

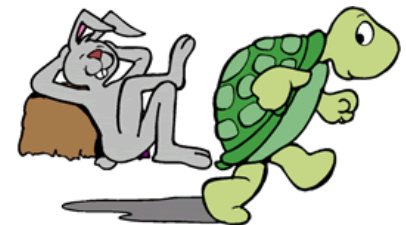
$\Upsilon(3S)$ : 30 fb<sup>-1</sup>

$\Upsilon(2S)$ : 14 fb<sup>-1</sup>

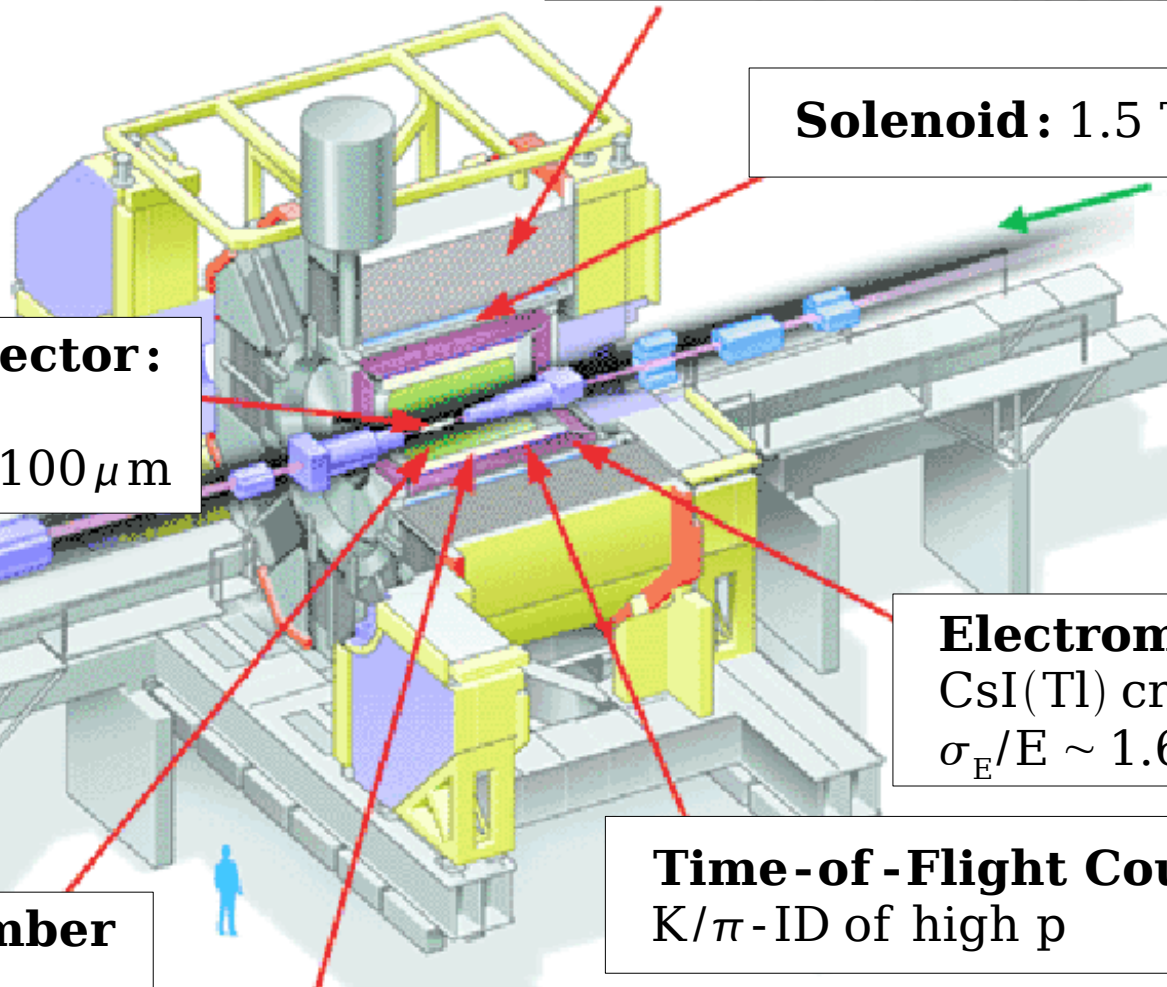
**Off resonance:**

~ 54 fb<sup>-1</sup>

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  $\sim 100\mu\text{m}$

**8.0 GeV  $e^-$**

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

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

**Time-of-Flight Counter:**  
 $K/\pi$ -ID of high  $p$

**Aerogel Cerenkov Counter:**  
Refractive index  $n=1.01-1.03$   
 $K/\pi$  of middle  $p$

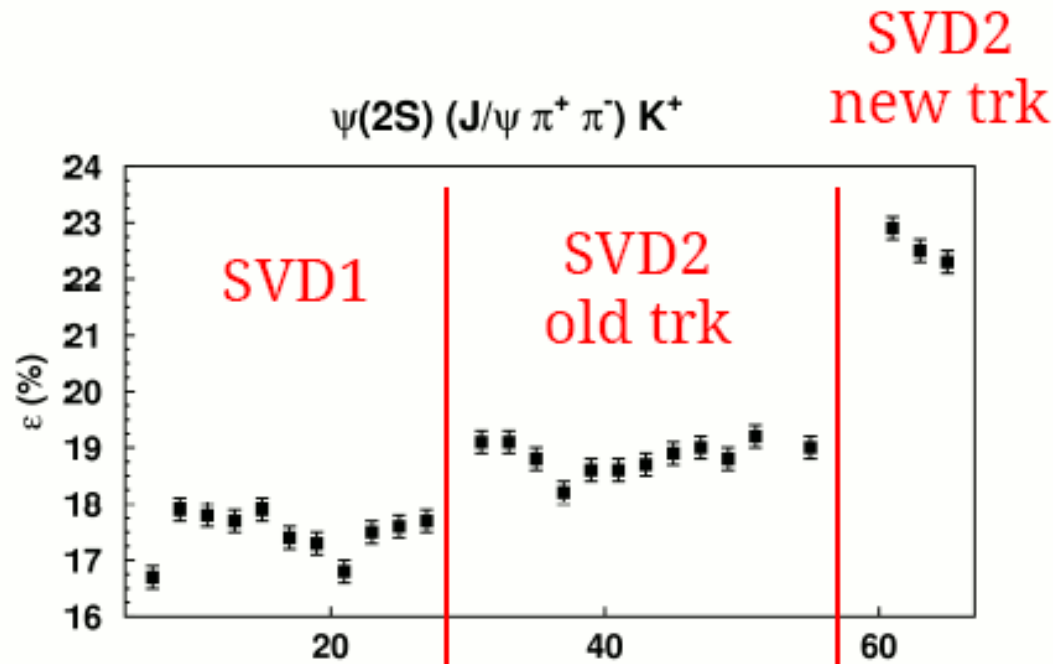
very stable detector, good particle identification, (kaon, pion, electron, muon),

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

# Toward the final Belle results...

- include the last part of the data ( $> 100 \text{ fb}^{-1}$ , often much more...)
- reprocessed data ( $\sim 2/3$  of the data, tracking efficiency increase  $> 20\%$ )

## Efficiency for $B^+ \rightarrow \psi(2S) (J/\psi \pi^+ \pi^-) K^+$



reconstruction systematics improved:  
tracking efficiency systematics at high  $P_t$   
 $1.2\% \rightarrow 0.35\%$  (update)

$K_S : 4.5\% \rightarrow 2\%$

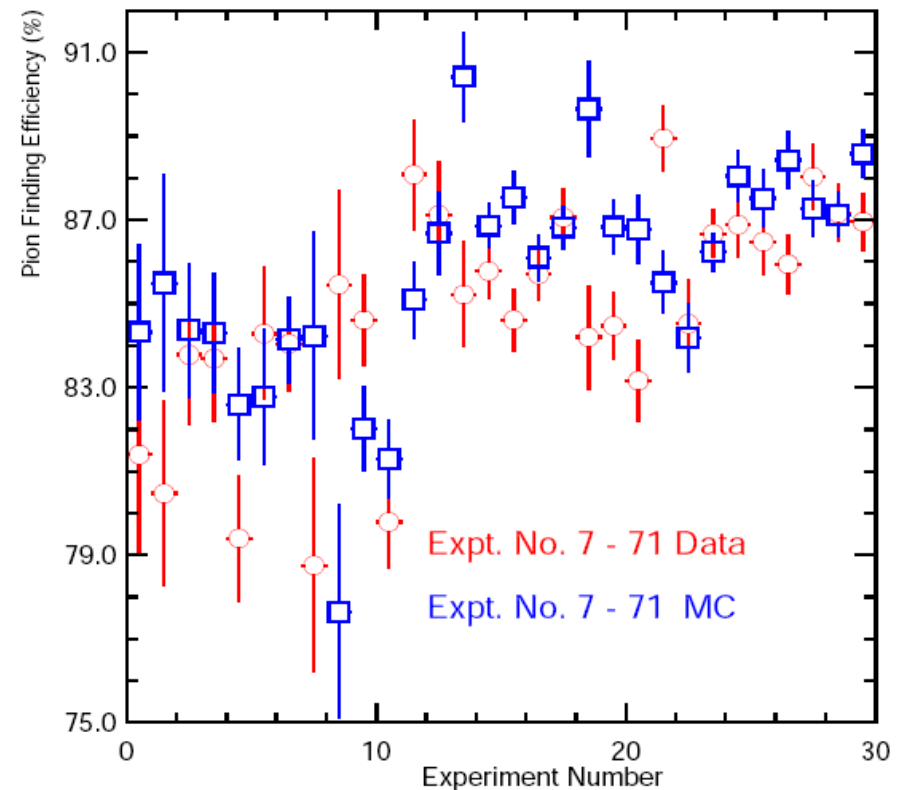
$\pi^0 : 4\% \rightarrow ??$

## Example of $D \rightarrow K_S \pi \pi$

0.5M signal candidates in  $540 \text{ fb}^{-1}$   
**PRL 99, 131803 (2007)**

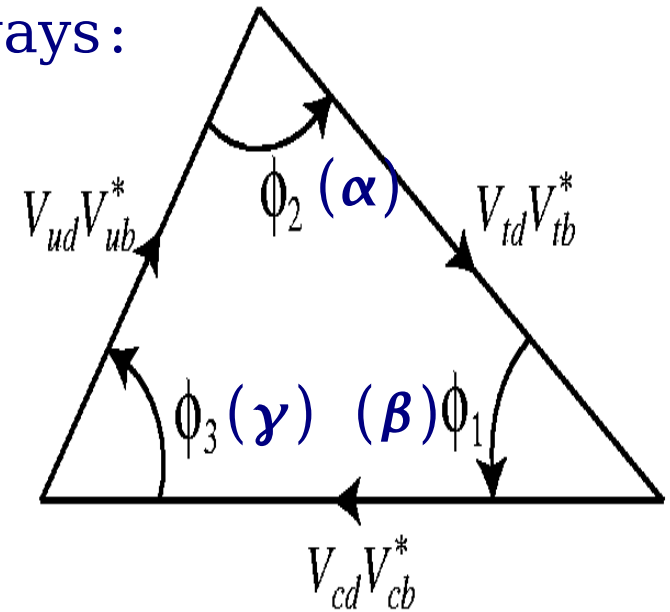
status of the update:

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

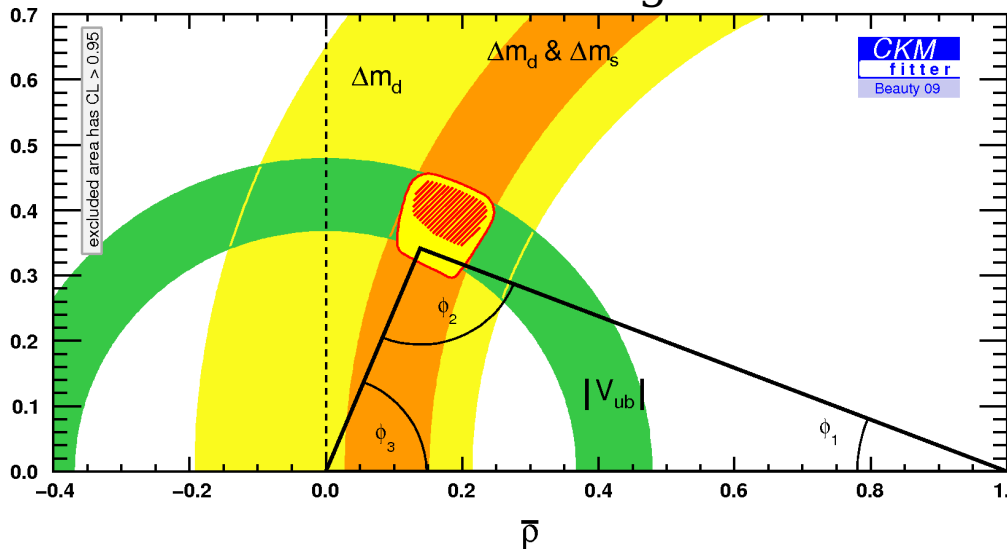


# Main motivation of Belle

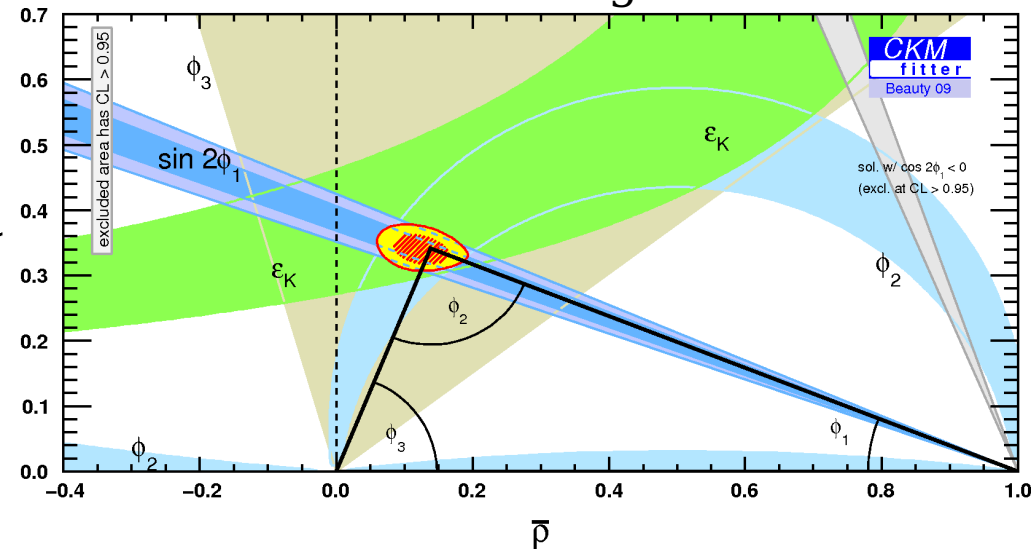
- Overconstrain the CKM matrix: measure fundamental parameters, constrain new physics effects
- Measure the 4 free parameters in various ways:
  - CP conserving  $\{|V_{us}|, |V_{cb}|, |V_{td}|, |V_{ub}|\}$
  - CP violating  $\{\epsilon_K, \phi_s, \phi_1, \phi_3\}$
  - Tree level  $\{\dots, \dots, |V_{ub}|, \phi_3\}$
  - Loop level  $\{\dots, \dots, |V_{td}|, \phi_1\}$
  - ...



CP conserving

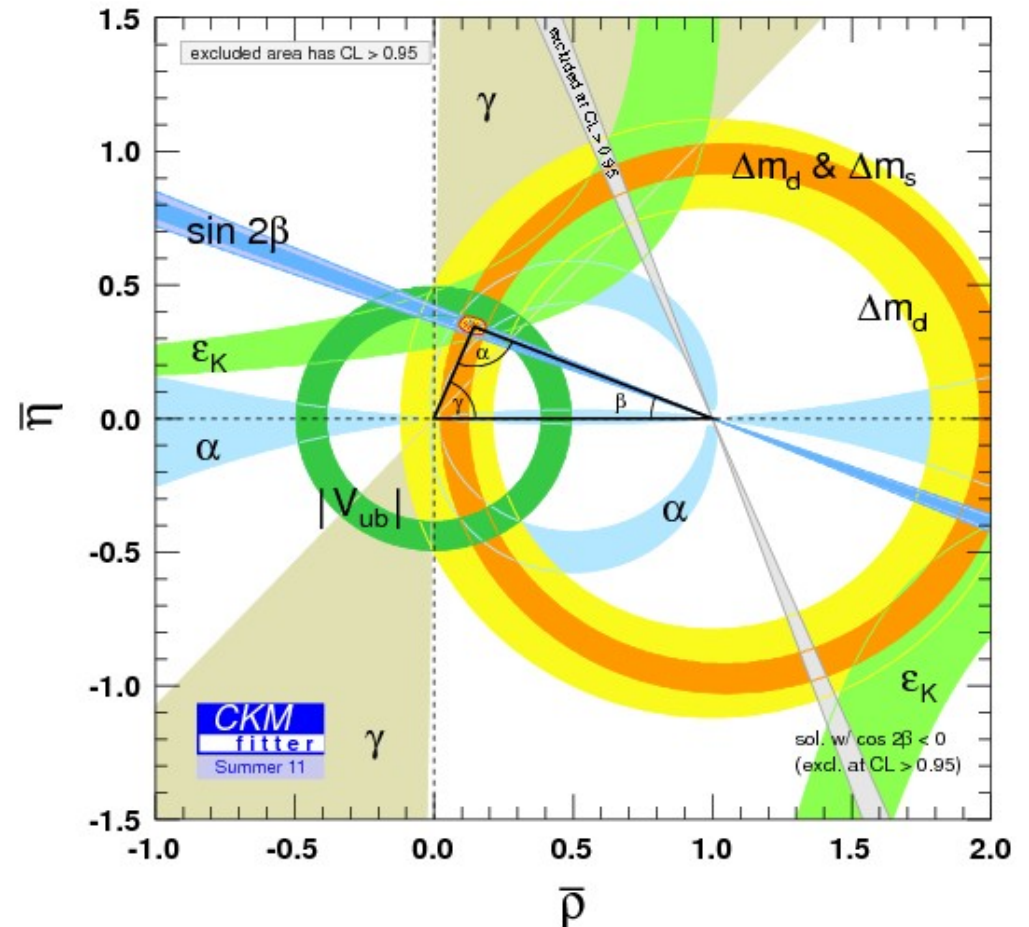
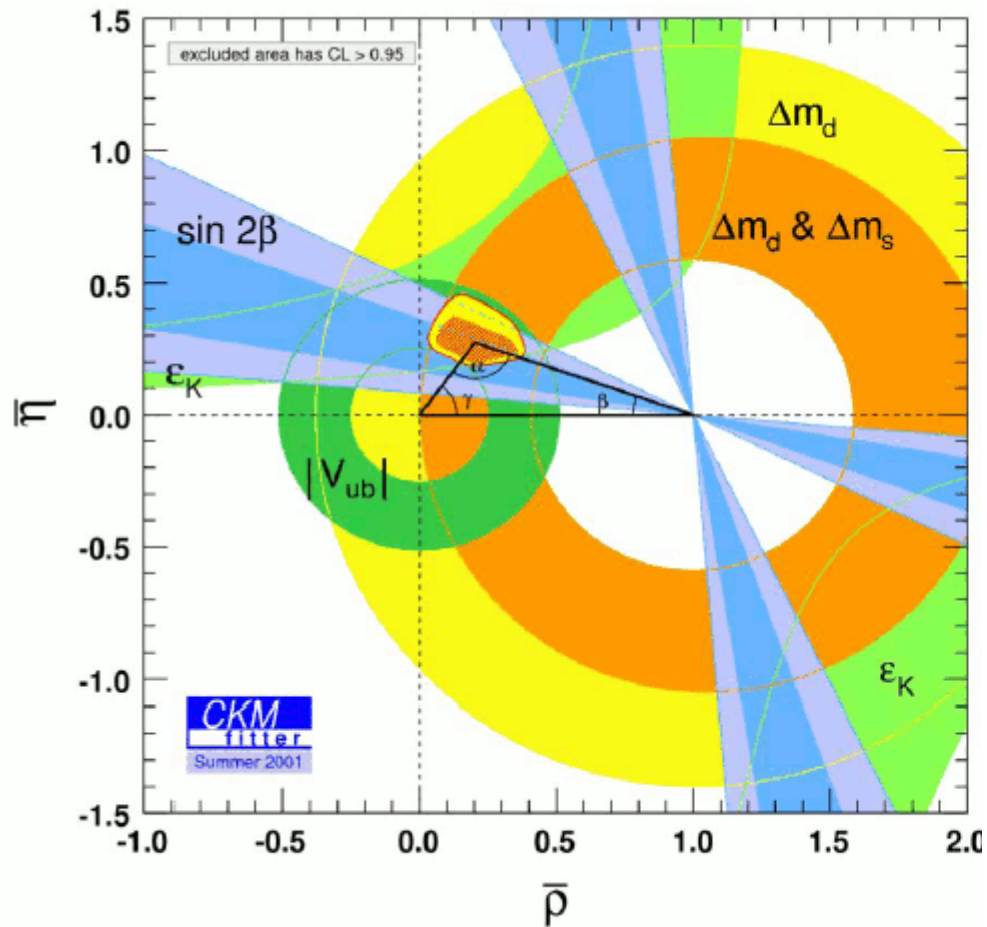


CP violating



from EPS 2001...

...to LP 2011



**$\Rightarrow$  clear impact on B-factories (angles and sides) !**

# Outline

## Recent updates for UT:

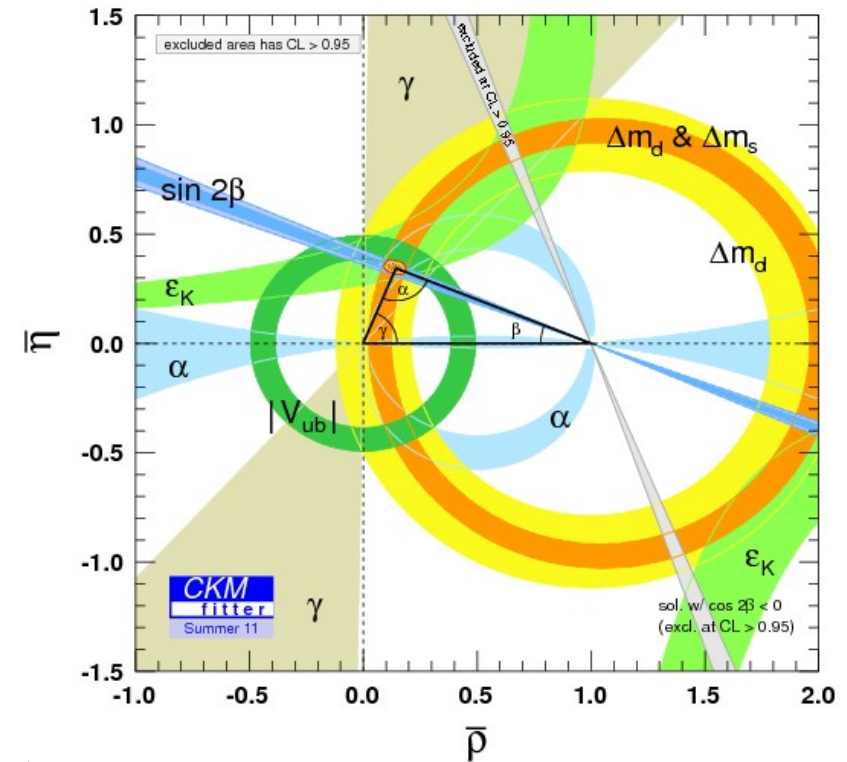
$$\phi_1/\beta: b \rightarrow c\bar{c}s, b \rightarrow c\bar{c}d$$

$$\phi_3/\gamma: B^+ \rightarrow DK^+$$

$$B \rightarrow \tau \nu$$

(and modes with missing energy)

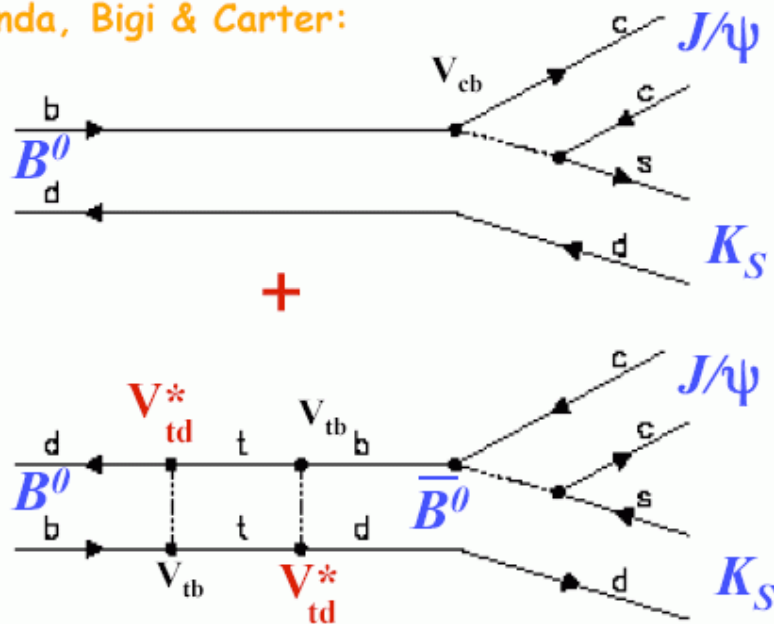
## Physics at $\Upsilon(5S)$ : $B_s$ and bottomonium



# Time-dependent CP asymmetries in decays to CP eigenstates

$\sin 2\phi_1$  from  $B \rightarrow f_{CP} + B \leftrightarrow \bar{B} \rightarrow f_{CP}$  interf.

Sanda, Bigi & Carter:



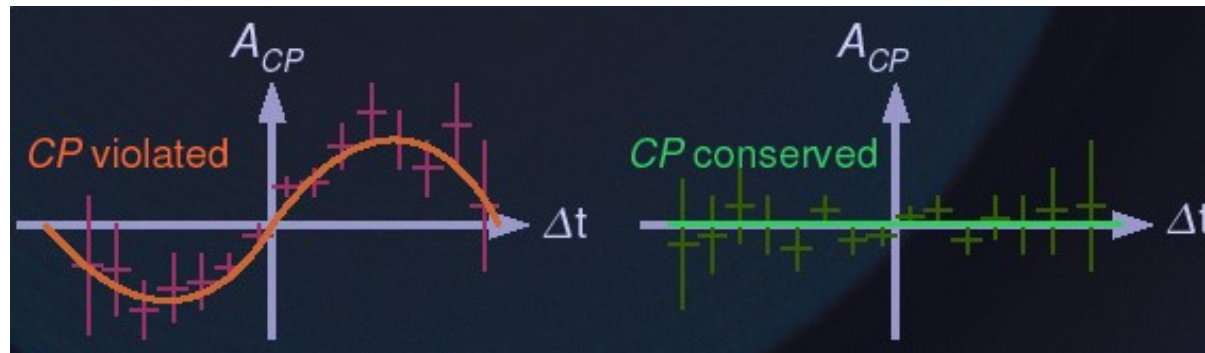
$$A_{CP}(f; t) = \frac{N(\bar{B}^0(t) \rightarrow f) - N(B^0(t) \rightarrow f)}{N(\bar{B}^0(t) \rightarrow f) + N(B^0(t) \rightarrow f)}$$

$$= \mathbf{S} \sin \Delta m_d t + \mathbf{A} \cos \Delta m_d t$$

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

$$\lambda = \frac{q}{p} \frac{A(\bar{B}^0 \rightarrow f)}{A(B^0 \rightarrow f)} = e^{-i2\phi_1} \frac{\bar{A}_f}{A_f}$$

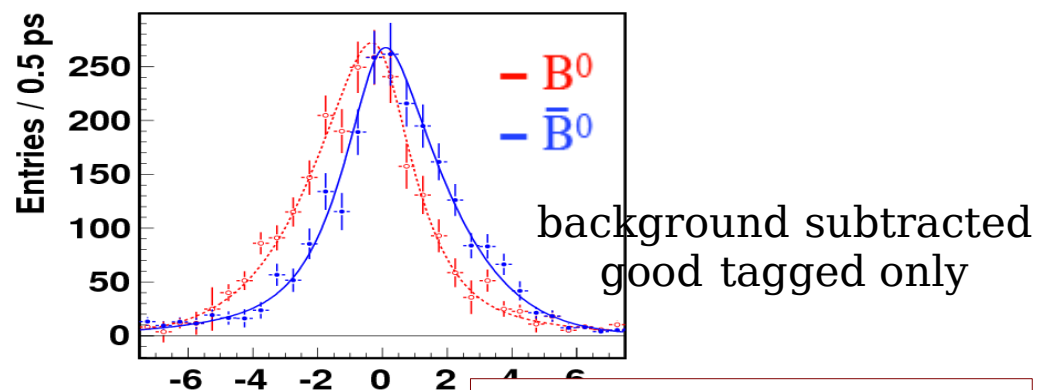
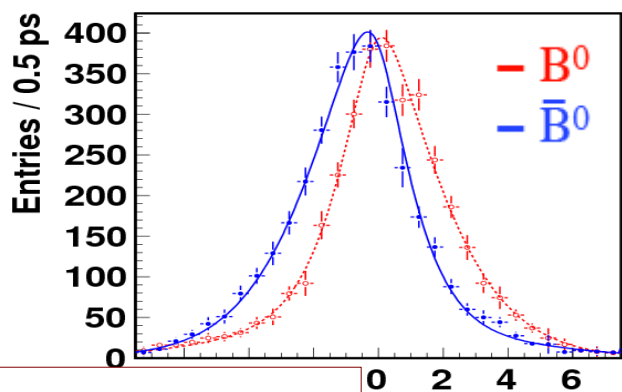
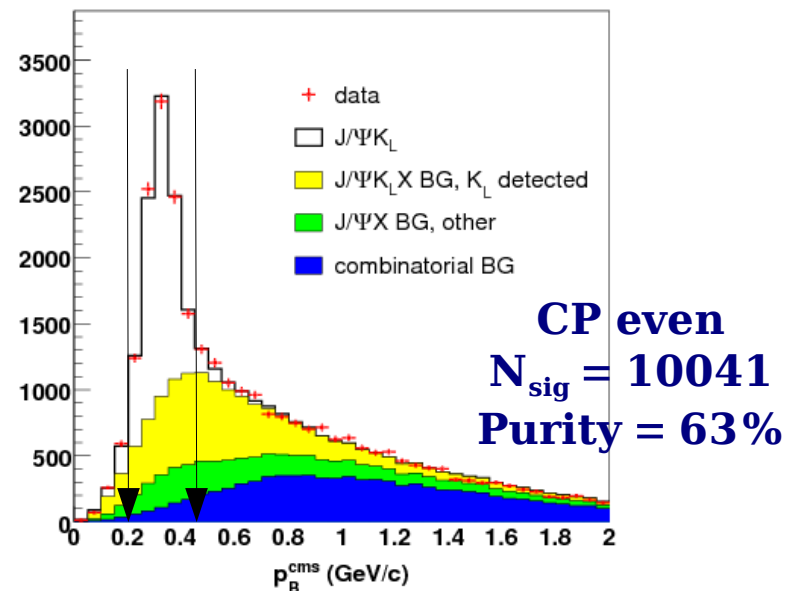
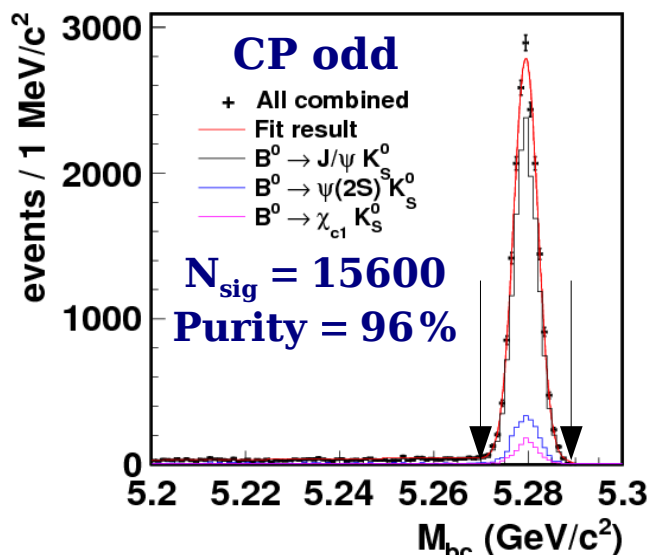
- $\mathbf{A} = 0$  and  $\mathbf{S} = -\xi_f \sin 2\beta$  for  $(c\bar{c})K_{S/L}$  ( $\xi_f = \mp 1$ )
- $\mathbf{A} = 0$  and  $\mathbf{S} = \sin 2\alpha$  for  $\pi^+ \pi^-$  (if tree only)



$$\mathbf{C} = -\mathbf{A}$$

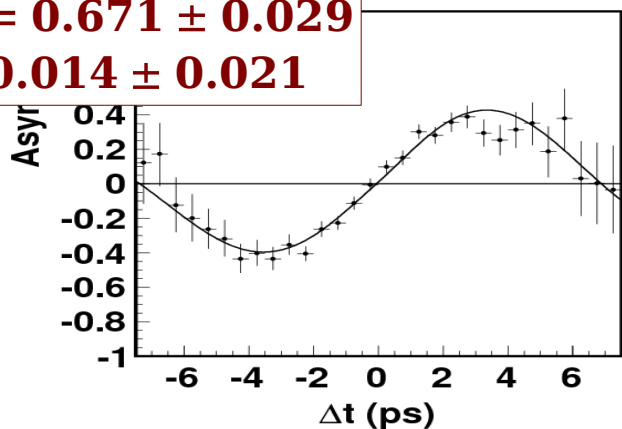
# $c\bar{c} K_S$ and $J/\psi K_L$

$772 \times 10^6 B\bar{B}$  pairs



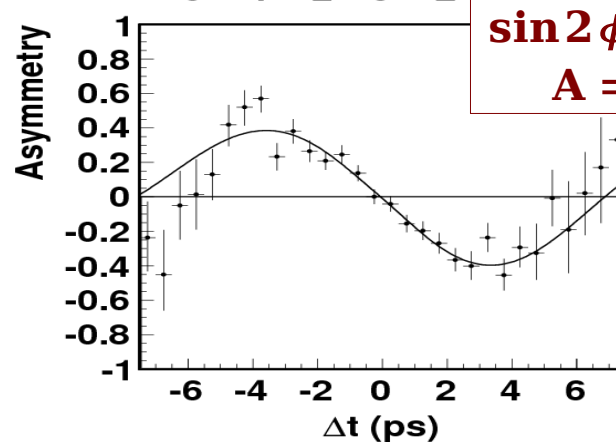
$$\sin 2\phi_1 = 0.671 \pm 0.029$$

$$A = -0.014 \pm 0.021$$

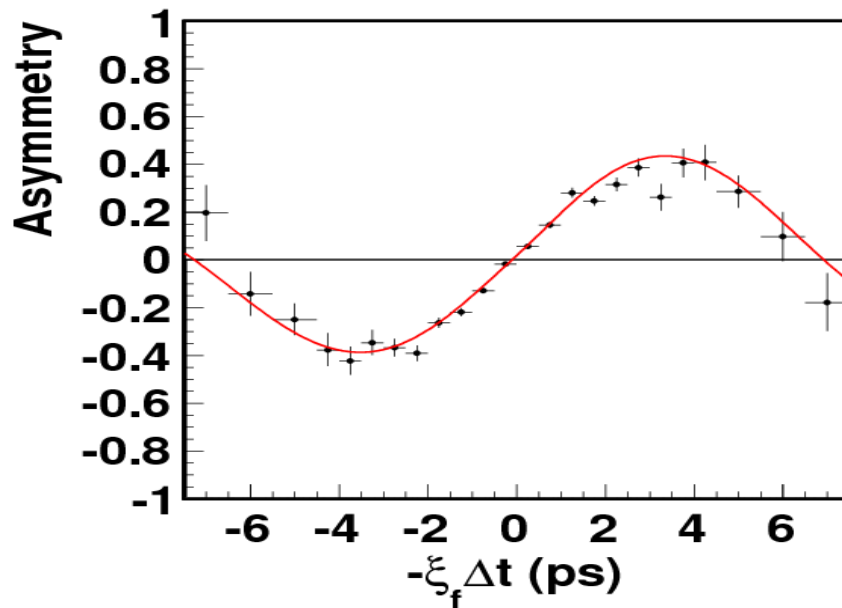
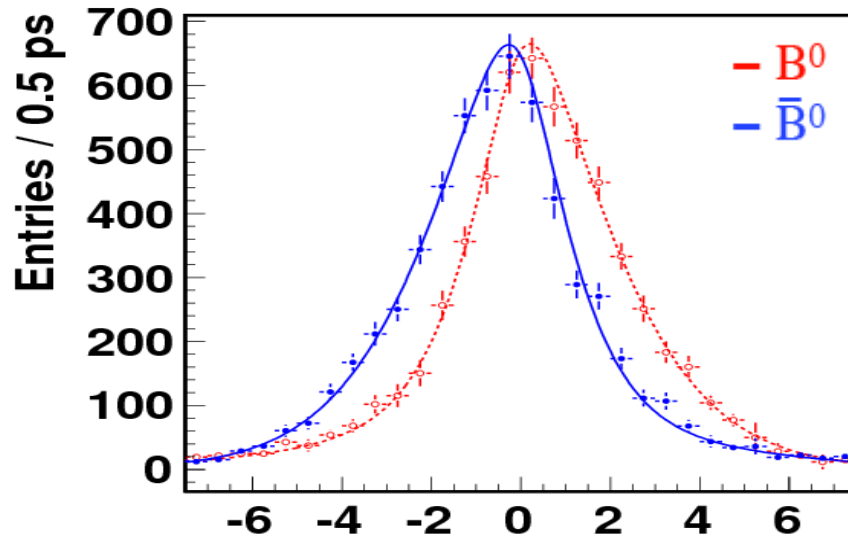


$$\sin 2\phi_1 = 0.641 \pm 0.047$$

$$A = 0.019 \pm 0.026$$



$\sin 2\phi_1$  in  $(c\bar{c})K^0 \dots 772 \times 10^6 B\bar{B}$  pairs

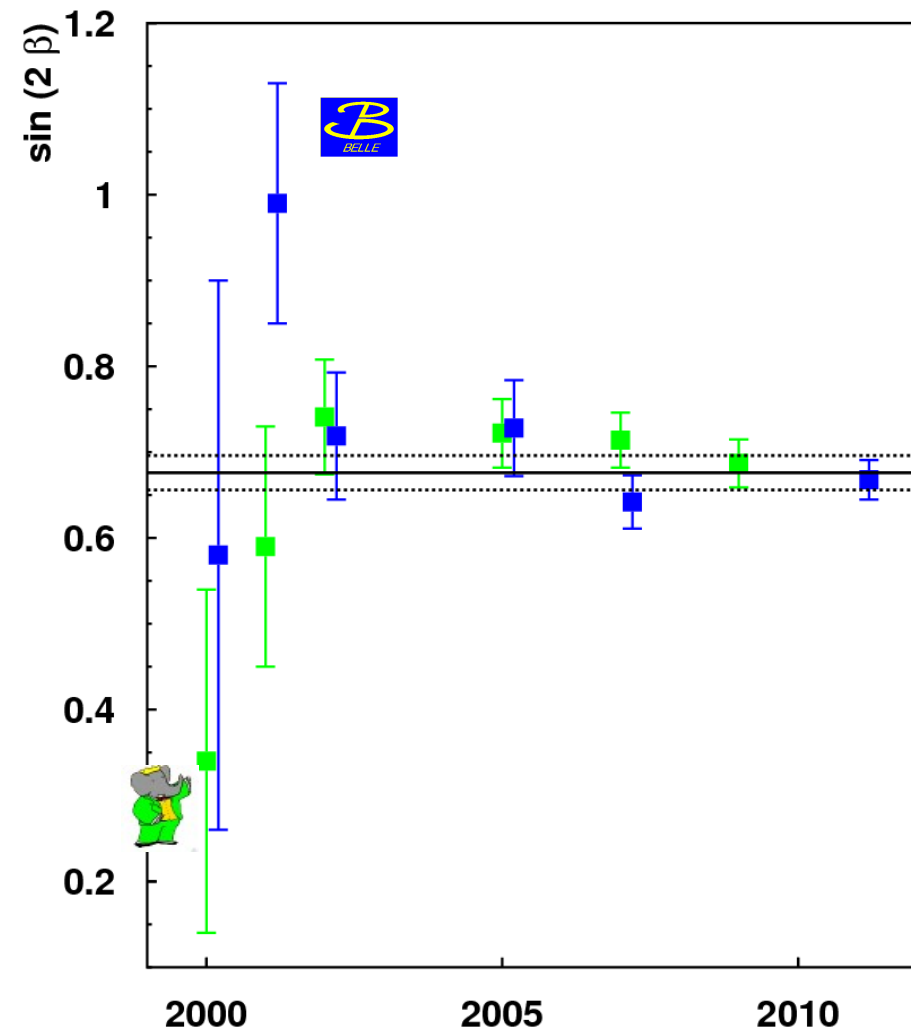


$$\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$$

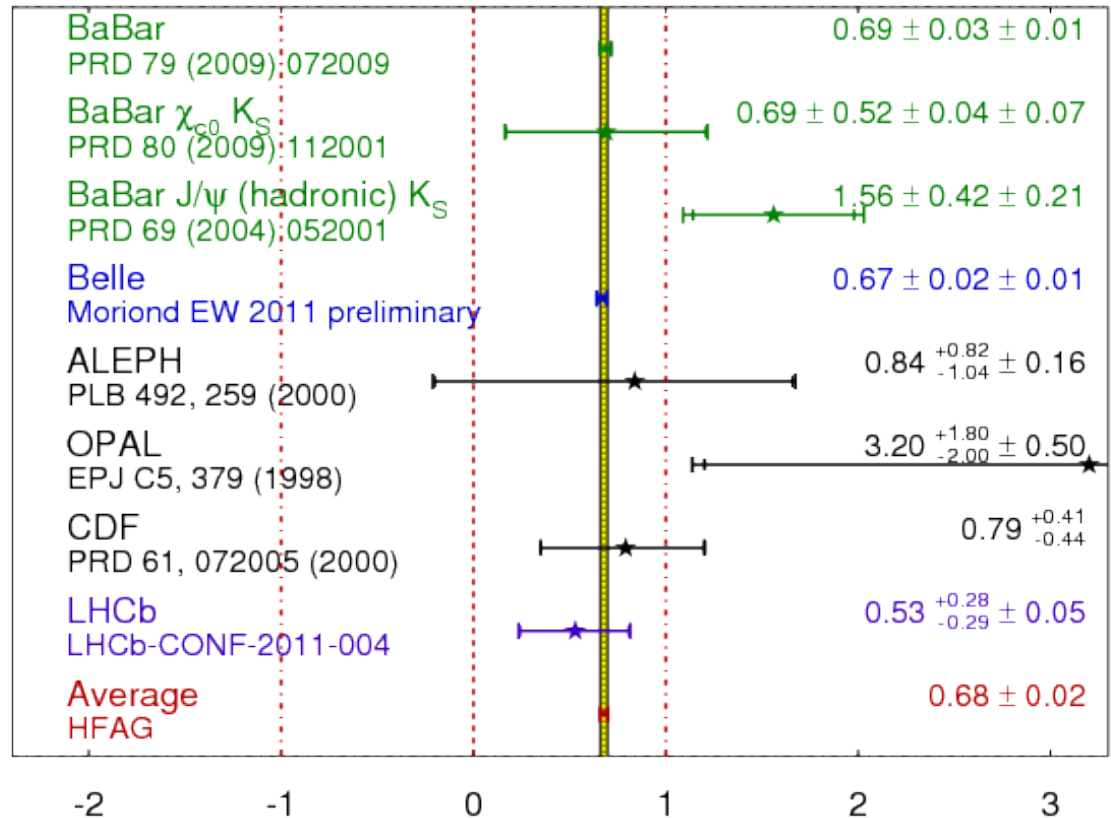
$$A = 0.007 \pm 0.016 \pm 0.013$$

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

# La raison d'être of the B factories



$\sin(2\beta) \equiv \sin(2\phi_1)$  **HFAG**  
Beauty 2011  
PRELIMINARY



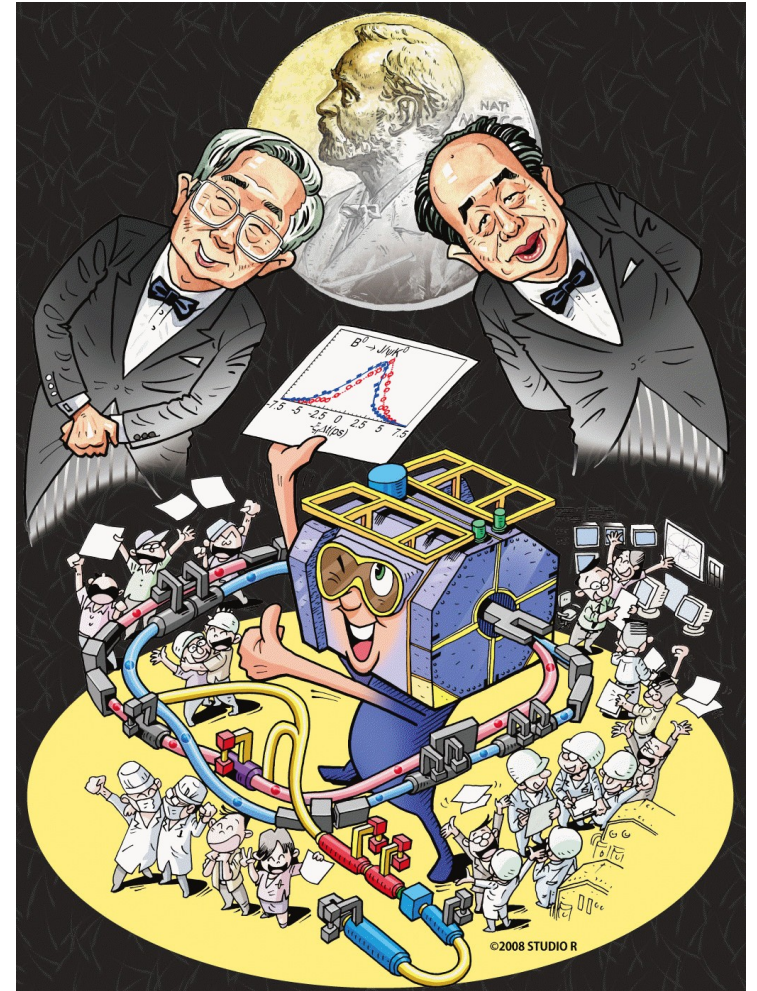
$$\beta = (21.4 \pm 0.8)^\circ$$

What is the source of CP violation ?

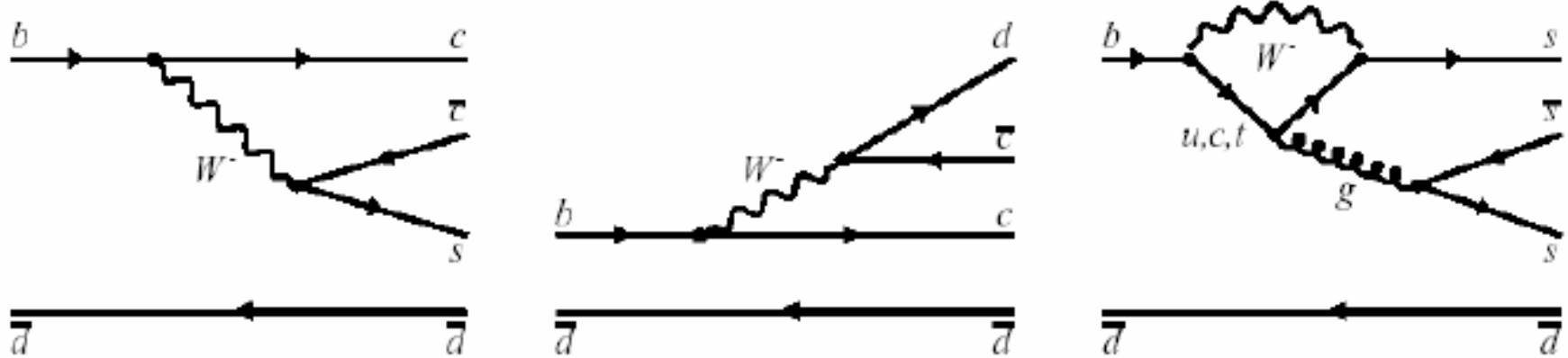
The Kobayashi-Maskawa phase is the source

Critical role of the B factories in  
the verification of the KM hypothesis

**A single irreducible phase in the  
weak interaction matrix accounts  
for most of the CPV observed  
in kaons and B's**



# $\beta$ in other modes



$J/\psi K_S^0, \psi(2S) K_S^0, \chi_{c1} K_S^0,$   
 $\eta_c K_S^0, J/\psi K_L^0,$   
 $J/\psi K^{*0} (K^{*0} \rightarrow K_S^0 \pi^0)$

$D^{*+} D^-, D^+ D^-$   
 $J/\psi \pi^0, D^{*+} D^{*-}$

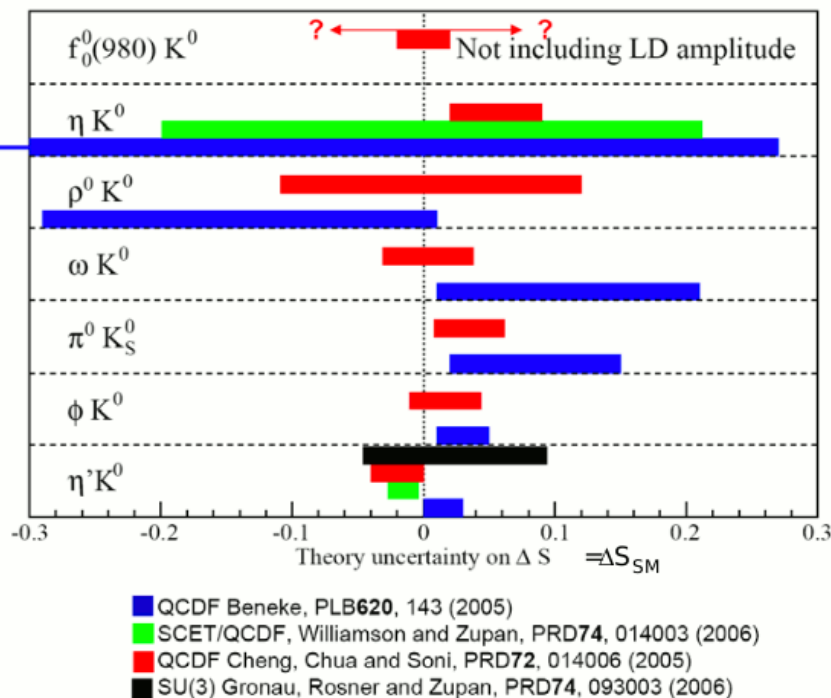
$\phi K^0, K^+ K^- K_S^0,$   
 $K_S^0 K_S^0 K_S^0, \eta' K^0, K_S^0 \pi^0,$   
 $\omega K_S^0, f_0(980) K_S^0$

← increasing tree diagram amplitude

← increasing sensitivity to new physics →

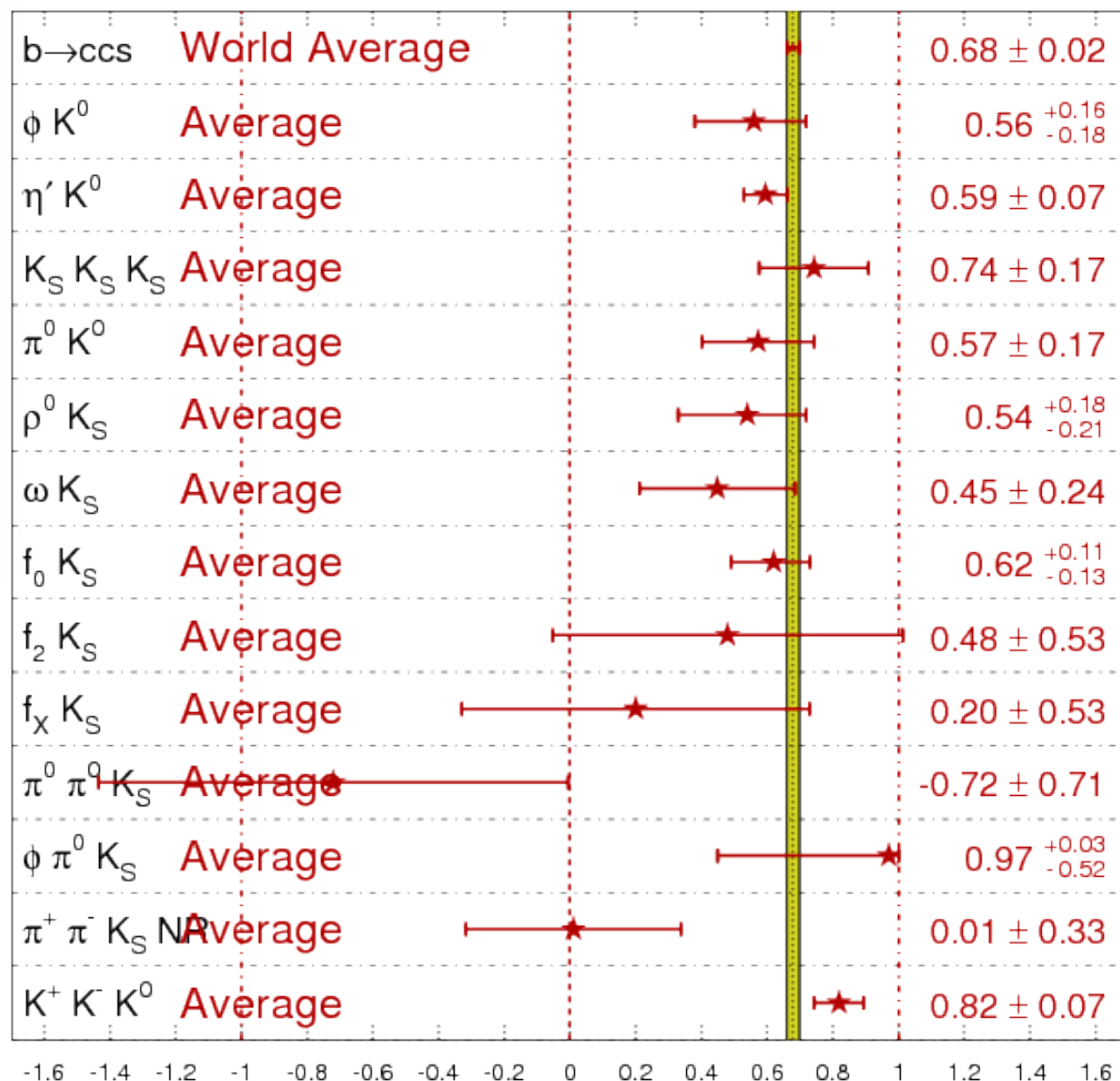
possible new sources of CPV ?

# $\beta$ with $b \rightarrow s$ penguins



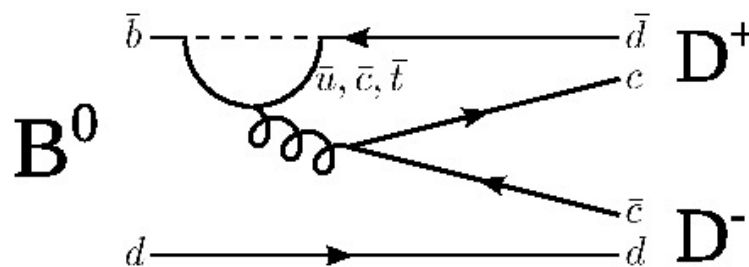
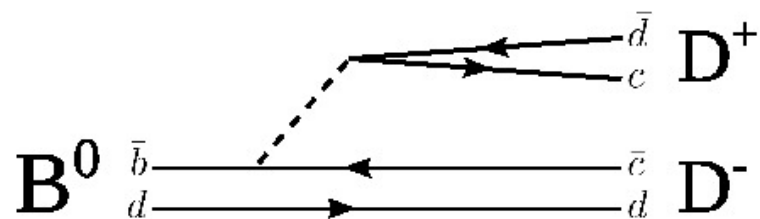
$$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$$

**HFAG**  
Beauty 2011  
PRELIMINARY



More statistics crucial  
for mode-by-mode studies

# Recent update of $B^0 \rightarrow D^+ D^-$ mode



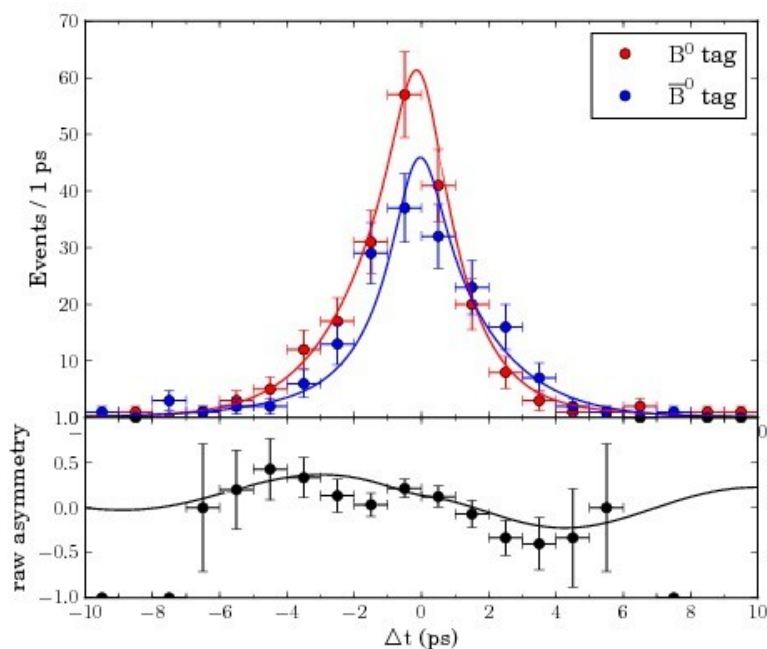
$772 \times 10^6$   $B\bar{B}$  pairs  
preliminary  
shown at EPS11

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

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

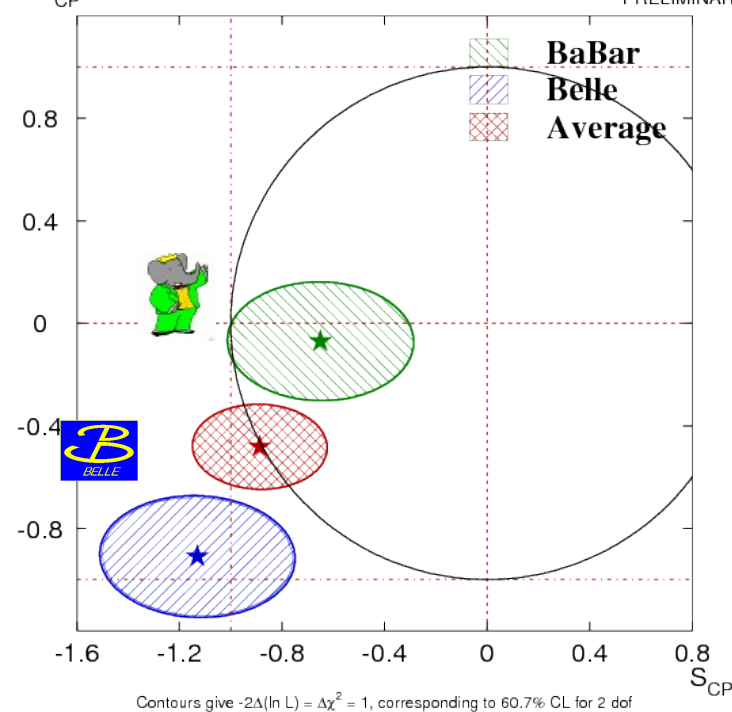
$$\rightarrow (K^- \pi^+ \pi^+)(K_S^0 \pi^-)$$

[ $> \times 2$  signal yield compared to previous analysis (535 MBB)]

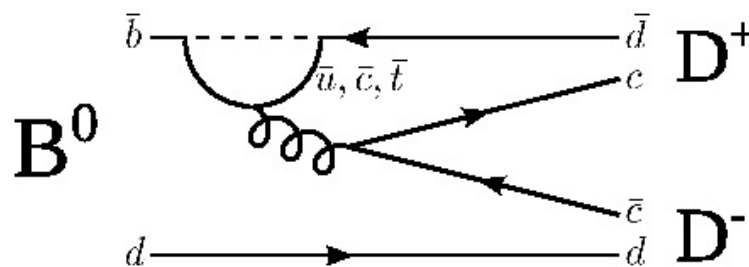
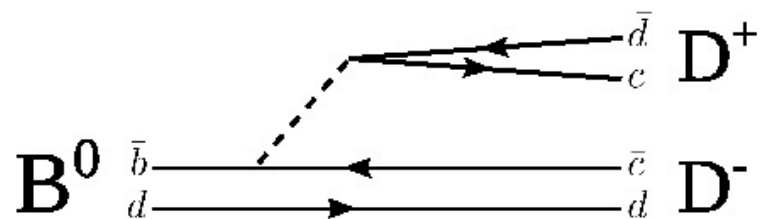


$D^+ D^- S_{CP}$  vs  $C_{CP}$

HFAG  
Winter 2009  
PRELIMINARY



# Recent update of $B^0 \rightarrow D^+ D^-$ mode



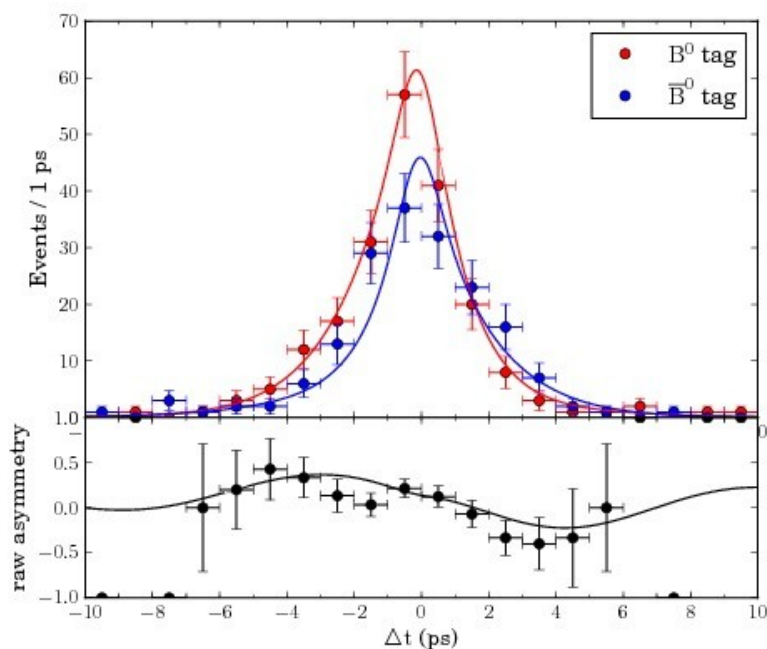
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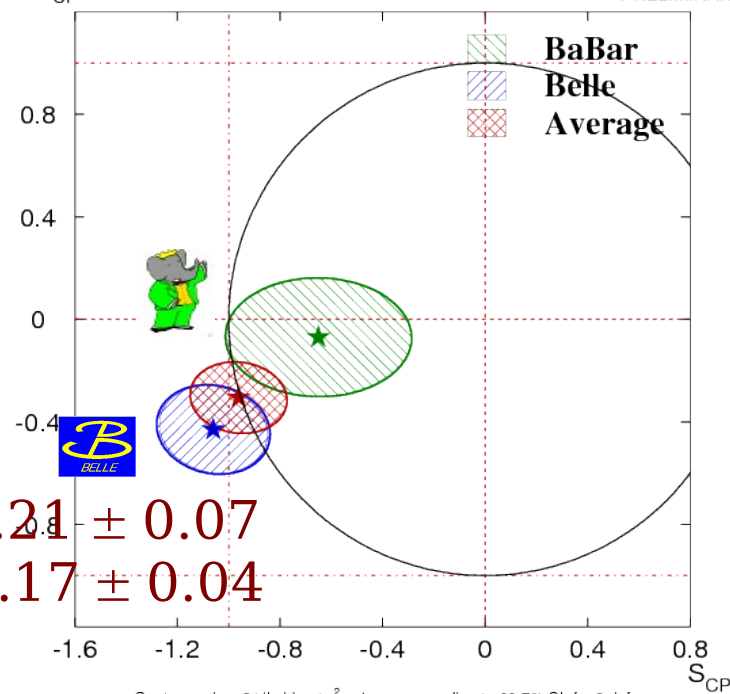
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$D^+ D^- S_{CP}$  vs  $C_{CP}$

HFAG  
EPS 2011  
PRELIMINARY

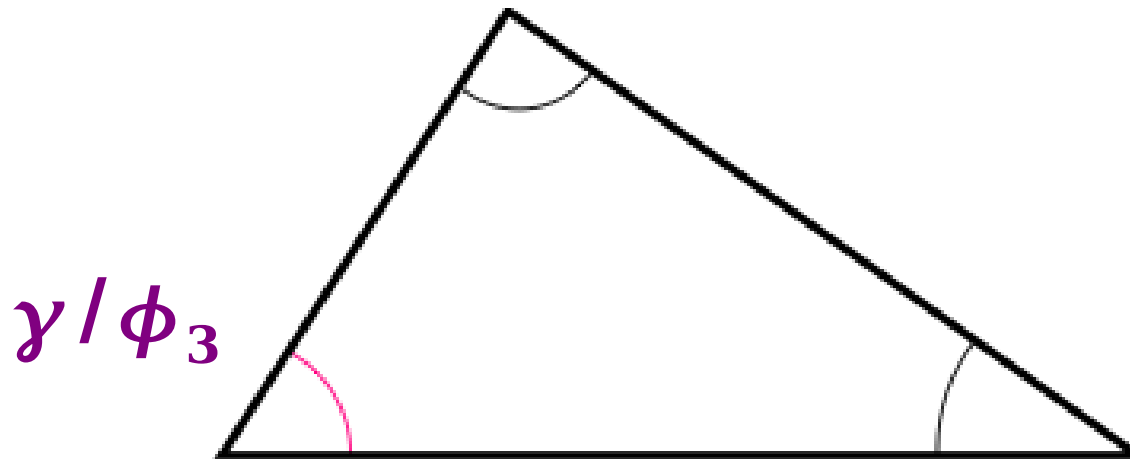


$$S = -1.06 \pm 0.21 \pm 0.07$$

$$A = +0.43 \pm 0.17 \pm 0.04$$

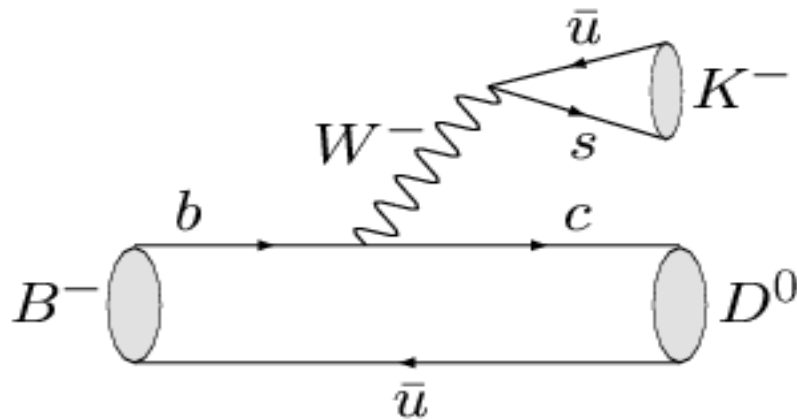
Contours give  $-2\Delta(\ln L) = \Delta\chi^2 = 1$ , corresponding to 60.7% CL for 2 dof

# Measurement(s) of the CKM angle $\gamma/\phi_3$ at Belle

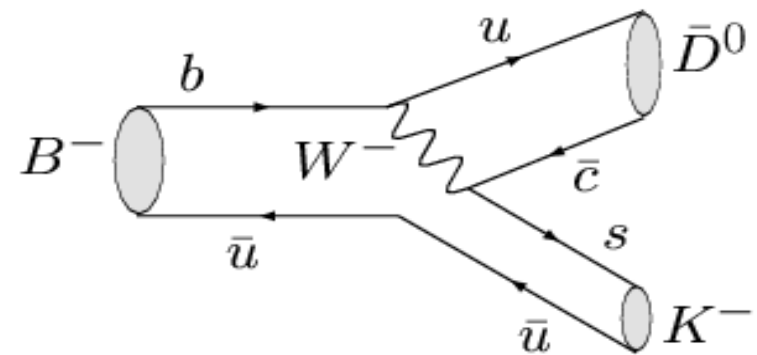


# $\gamma$ measurements from $B^\pm \rightarrow DK^\pm$

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



color allowed  
 $B^- \rightarrow D^0 K^- \sim V_{cb} V_{us}^*$   
 $\sim A\lambda^3$



color suppressed  
 $B^- \rightarrow \bar{D}^0 K^- \sim V_{ub} V_{cs}^*$   
 $\sim A\lambda^3(\rho - i\eta)$

relative magnitude of suppressed amplitude is  $r_B$

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

relative weak phase is  $\gamma$ , relative strong phase is  $\delta_B$

# $\gamma$ measurements from $B^\pm \rightarrow DK^\pm$

- Reconstruct D in final states accessible to both  $D^0$  and  $\bar{D}^0$ 
  - $D = D_{\text{CP}}$ , CP eigenstates as  $K^+ K^-$ ,  $\pi^+ \pi^-$ ,  $K_S \pi^0$   
**GLW method (Gronau-London-Wyler)**
  - $D = D_{\text{sup}}$ , Doubly-Cabbibo suppressed decays as  $K \pi$   
**ADS method (Atwood-Dunietz-Soni)**
  - Three-body decays as  $D \rightarrow K_S \pi^+ \pi^-$ ,  $K_S K^+ K^-$   
**GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)**
- Largest effects due to
  - charm mixing
  - charm CP violation

} negligible  
Y.Grossman, A.Soffer, J.Zupan  
[PRD 72, 031501 (2005)]
- Different B decays ( $DK$ ,  $D^* K$ ,  $DK^*$ )
  - different hadronic factors ( $r_B$ ,  $\delta_B$ ) for each

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

Reconstruction of three-body final states  $D^0, \bar{D}^0 \rightarrow K_S \pi^+ \pi^-$

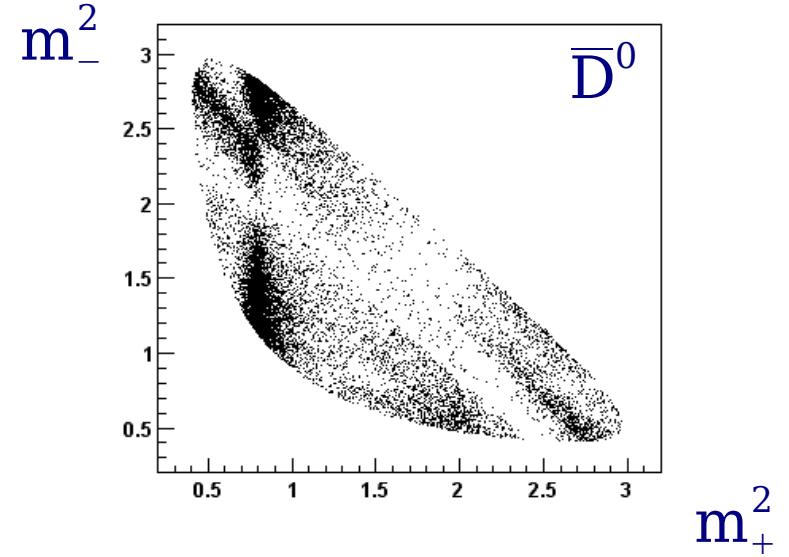
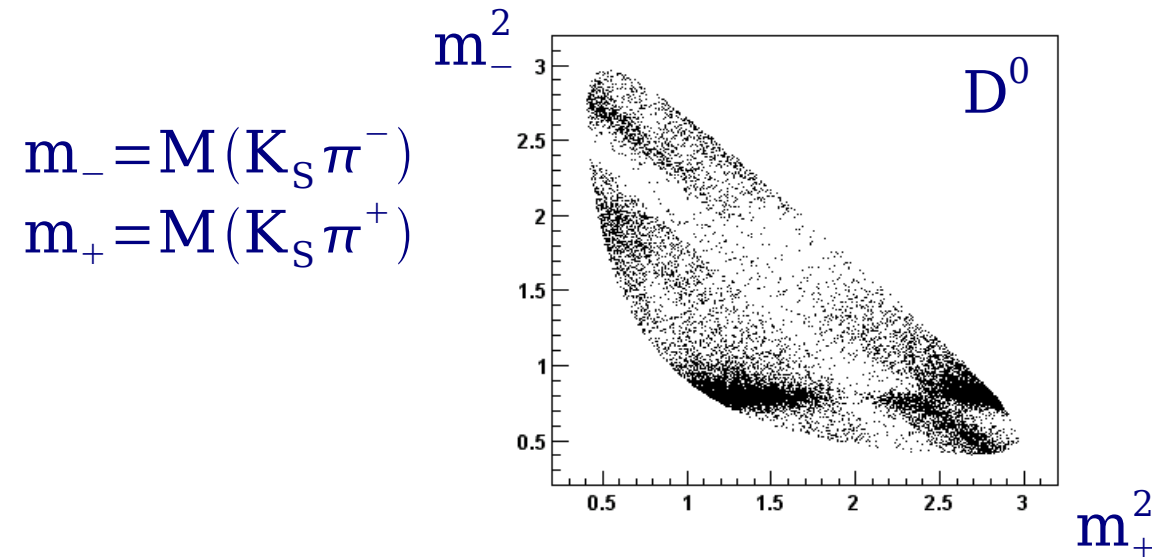
Amplitude for each Dalitz point is described as:

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

$$D^0 \rightarrow K_S \pi^+ \pi^- \sim f(m_-^2, m_+^2)$$

model the amplitudes  
(using tagged D sample)

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



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

Simultaneous fit of  $B^+$  and  $B^-$  to extract parameters  $r_B$ ,  $\gamma$  and  $\delta_B$

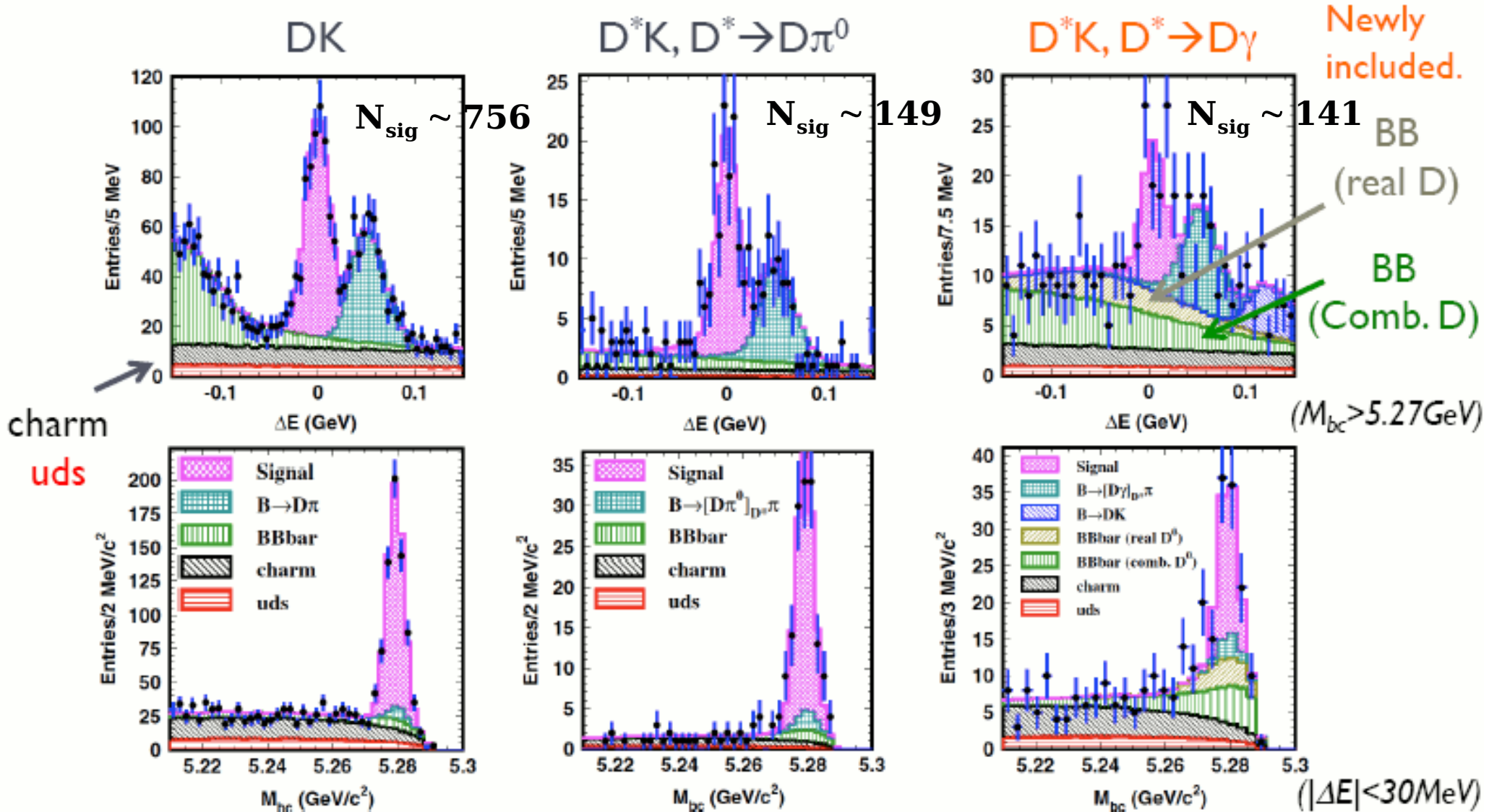
Note: 2 fold ambiguity on  $\gamma$ :  $(\gamma, \delta_B) \rightarrow (\gamma + \pi, \delta_B + \pi)$

# $B^- \rightarrow D^{(*)}(K_S \pi \pi) K^-$ Dalitz, $\Delta E$ and $M_{bc}$ projections

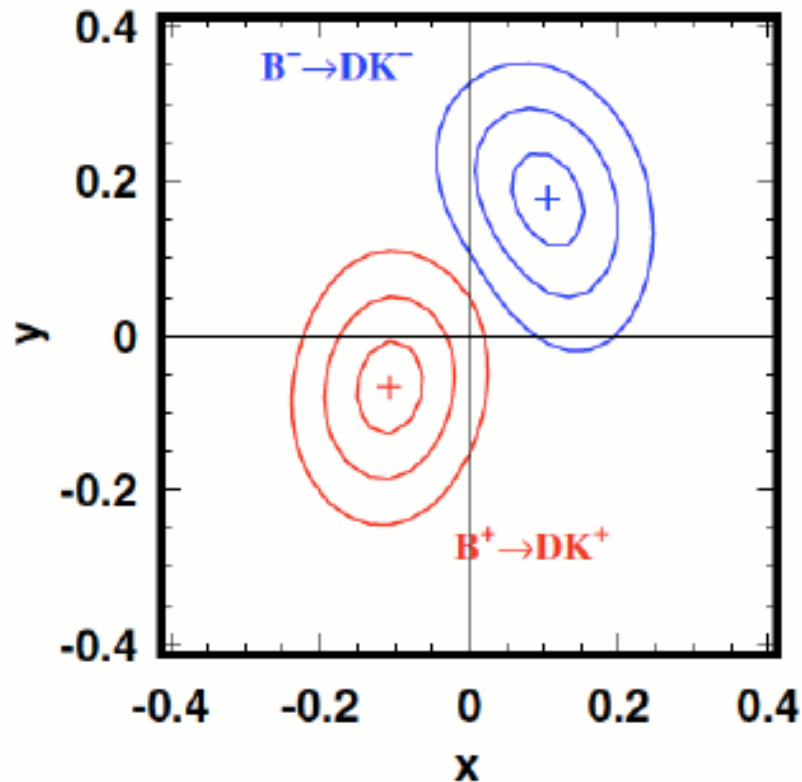
$|\cos \theta_{thr}| < 0.8$  and  $F > -0.7$

PRD 81, 112002 (2010)

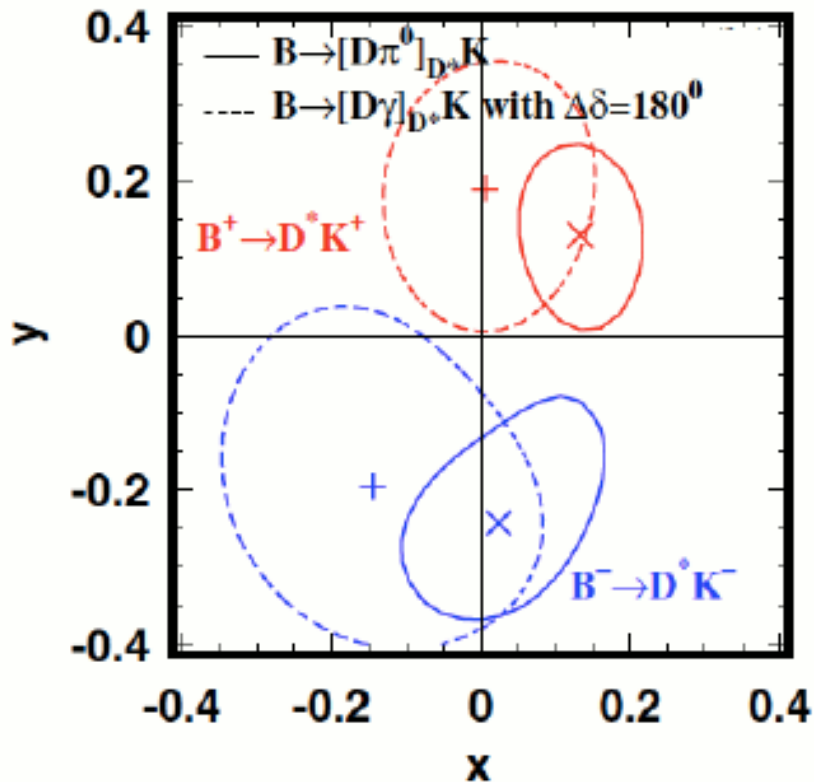
$657 \times 10^6 B\bar{B}$  pairs



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



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



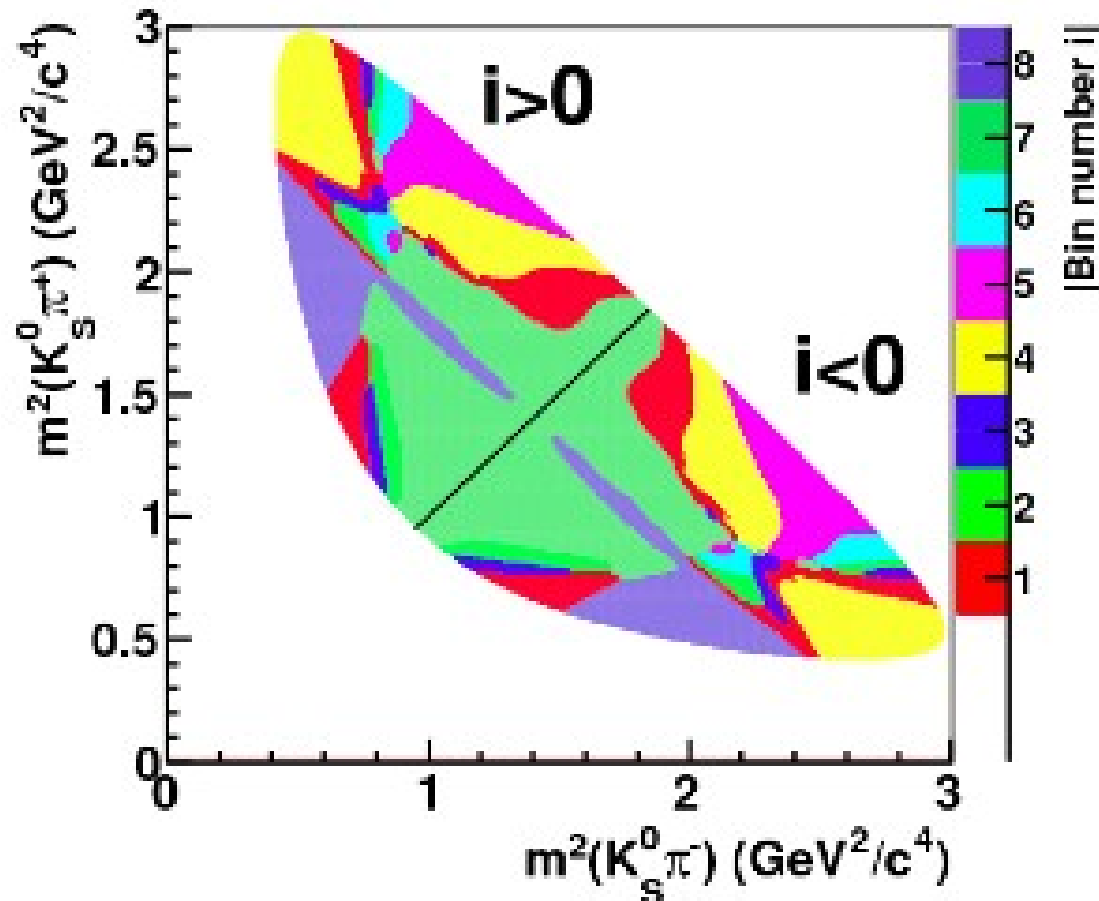
$$\begin{aligned} \gamma &= (73.9^{+18.9}_{-20.2} \pm 4.2 \pm 8.9)^\circ \\ r_B &= 0.196^{+0.073}_{-0.072} \pm 0.013^{+0.062}_{-0.012} \\ \delta_B &= (341.7^{+18.6}_{-20.9} \pm 3.2 \pm 22.9)^\circ \end{aligned}$$

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

**CPV significance is 3.5 standard deviations**

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

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



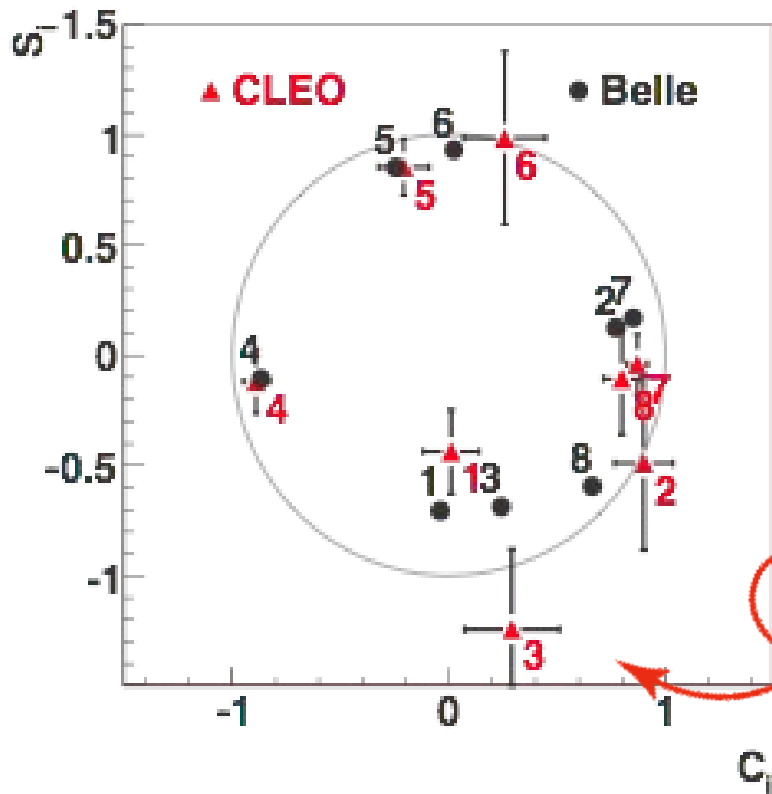
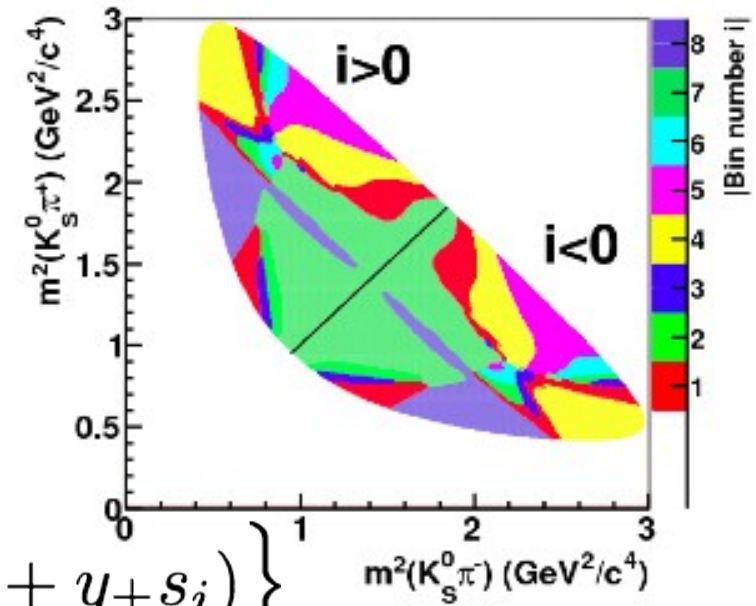
Bondar and  
Poluektov  
EPJ C55, 51 (2008)

choice of bins guided by model, but extracted  $\gamma$  is  
not biased by this choice

Binned Dalitz method: minimize  $\chi^2$   
in fit to all bins for each mode

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

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



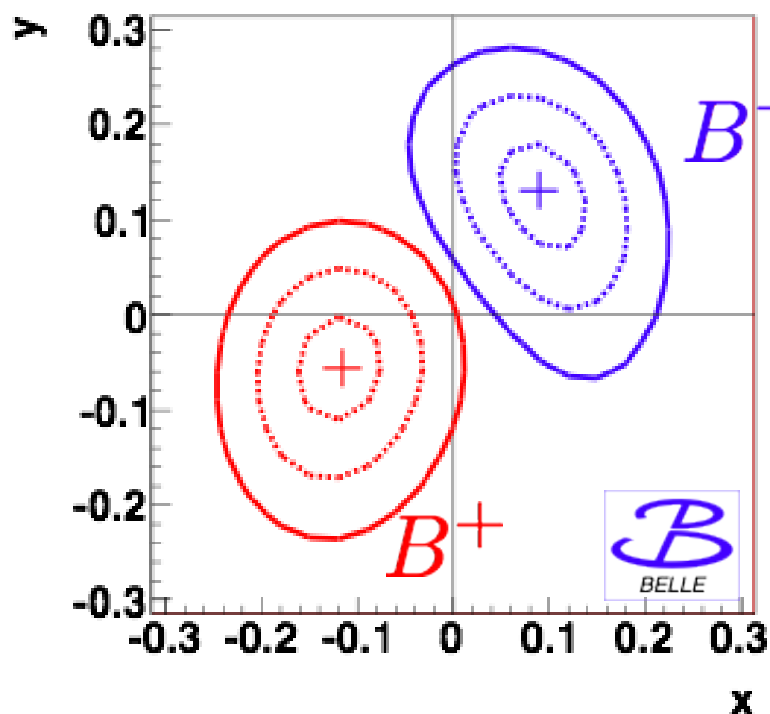
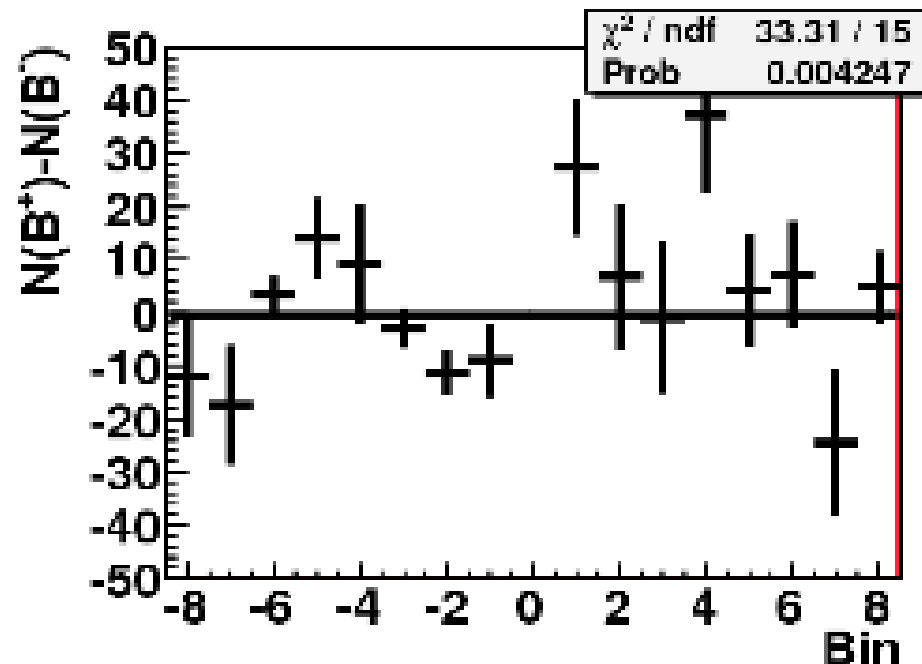
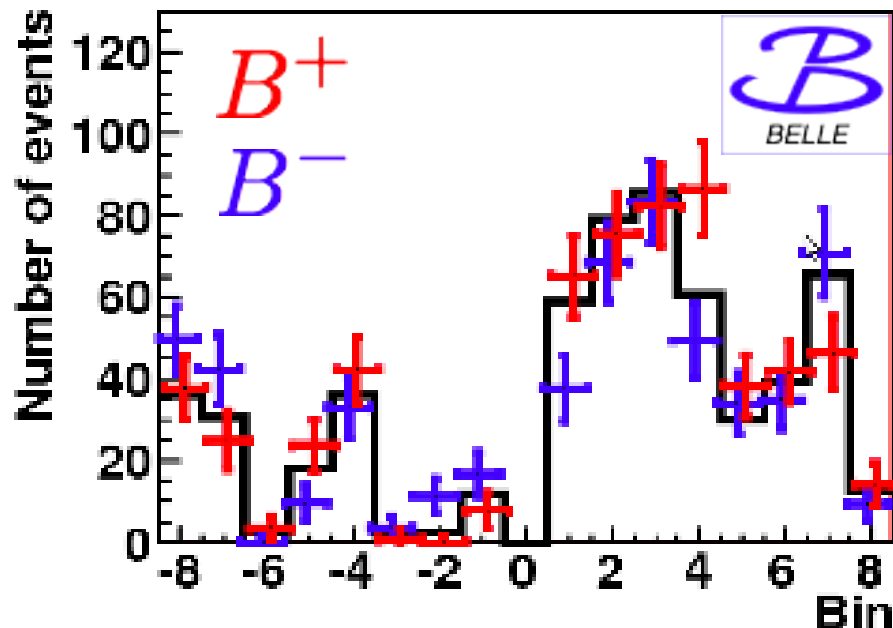
$K_i$  is the # of events in bin  $i$  from a  
flavour-tagged sample ( $D^{*\pm} \rightarrow D\pi^\pm$ )

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

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

# Binned Dalitz method result in $B \rightarrow DK$ from 772 million events

arXiv:1106.4046



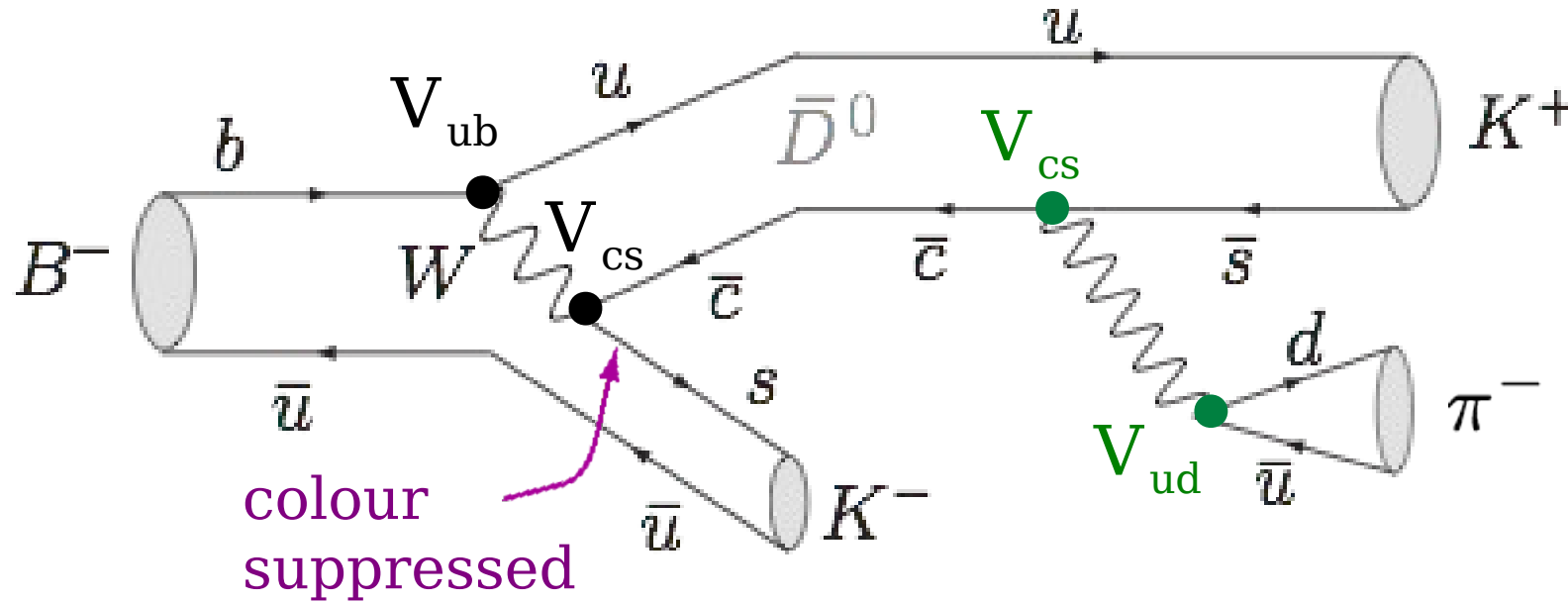
$$\gamma = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ$$

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

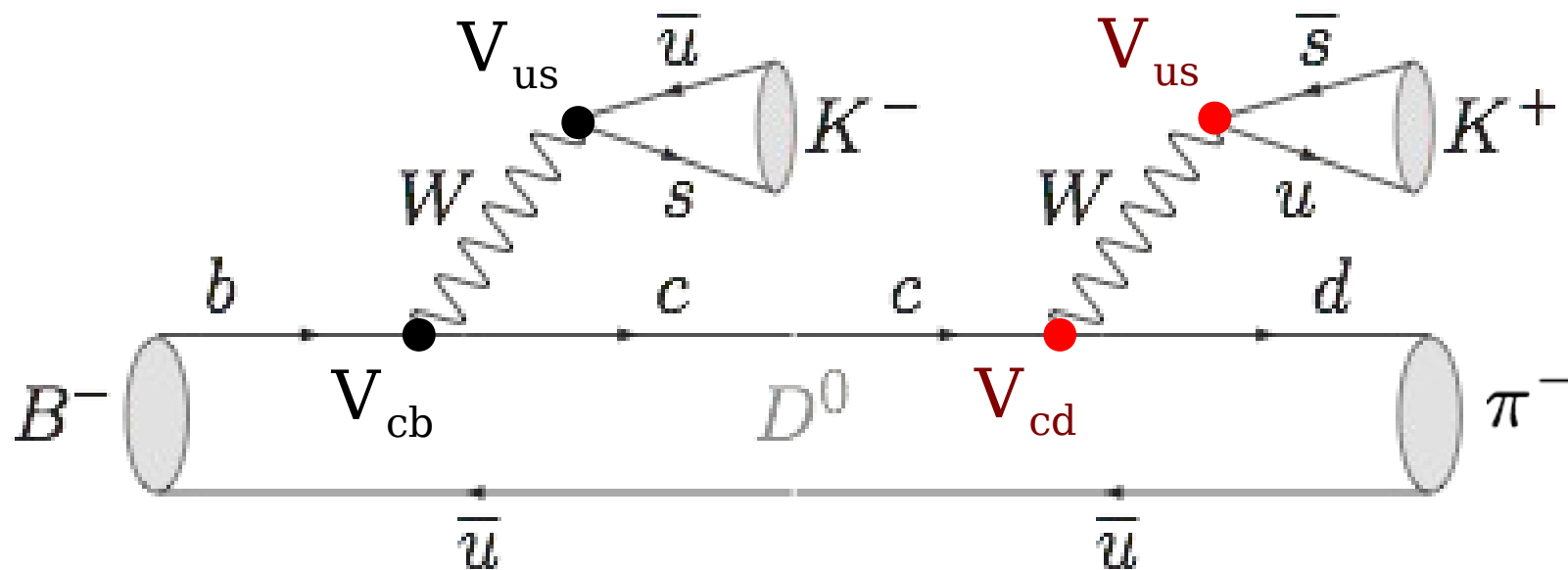
$$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ$$

uncertainty in  $c_i, s_i$   
from CLEO data  
(can reduce using  
future BES-III data)

**ADS method** measures  $\phi_3$  via the interference in rare  $B^- \rightarrow [K^+ \pi^-]_D K^-$  decays



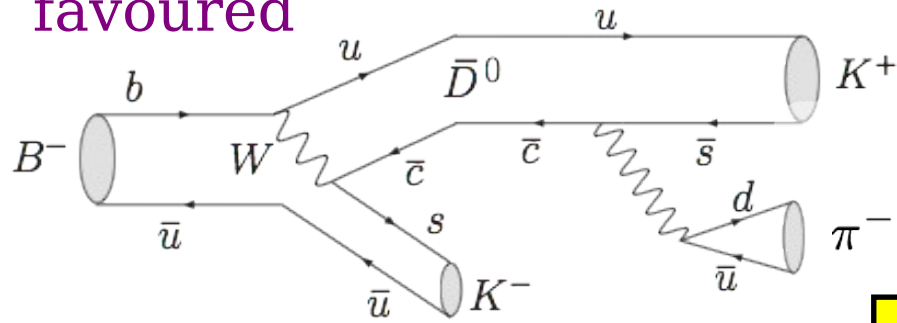
Cabibbo  
favoured  
D decay



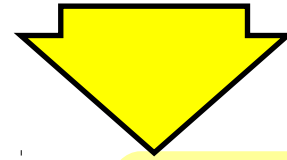
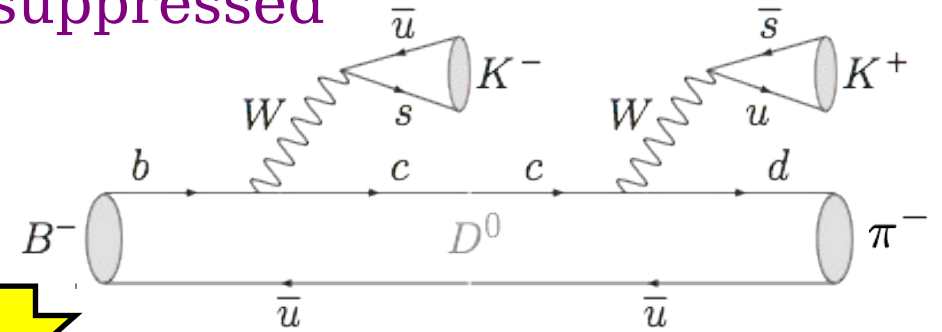
doubly  
Cabibbo  
suppressed  
D decay

# ADS rate and asymmetry (relative to the common decay):

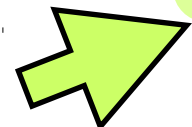
favoured



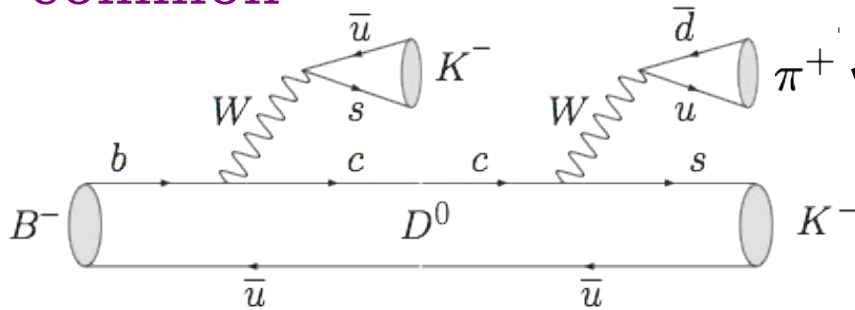
suppressed



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



common



$$= r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \phi_3$$

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

$$= 2r_B r_D \sin(\delta_B + \delta_D) \sin \phi_3 / \mathcal{R}_{DK}$$

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

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

Main background is  $e^+ e^- \rightarrow q \bar{q}$  ( $q=u, d, s, c$ ) continuum  
combine 10 variables with neural network:

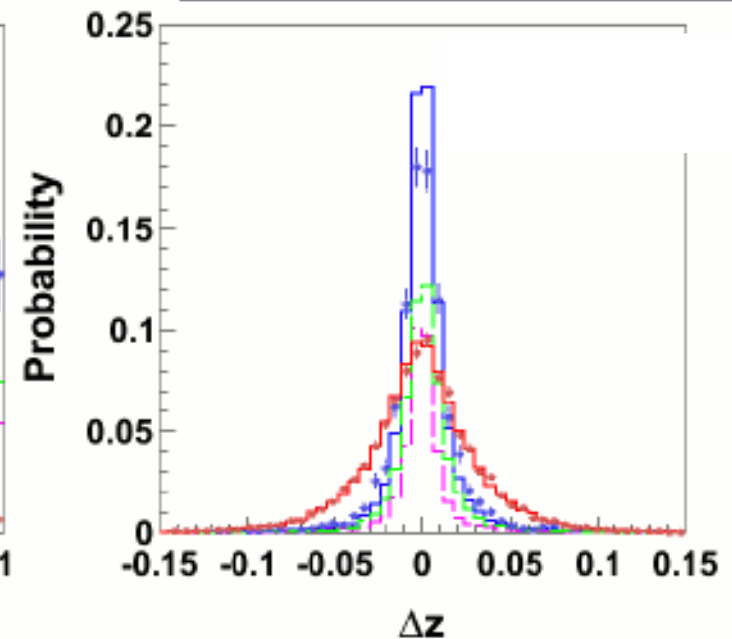
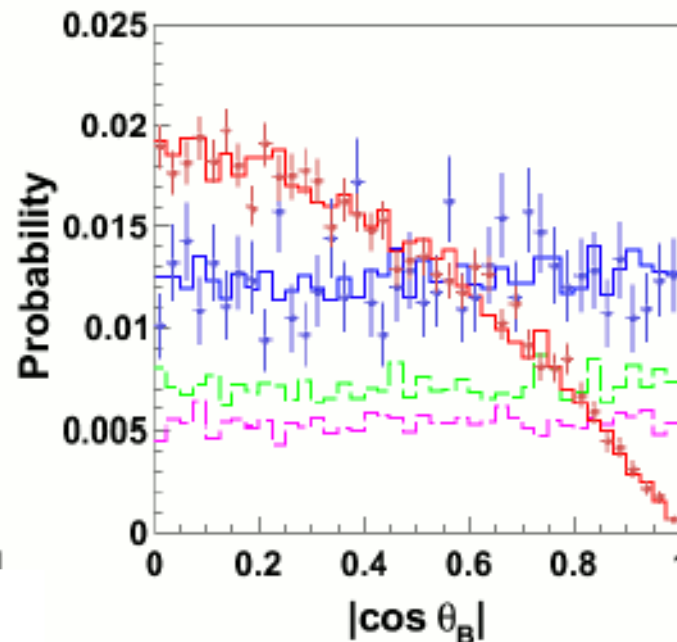
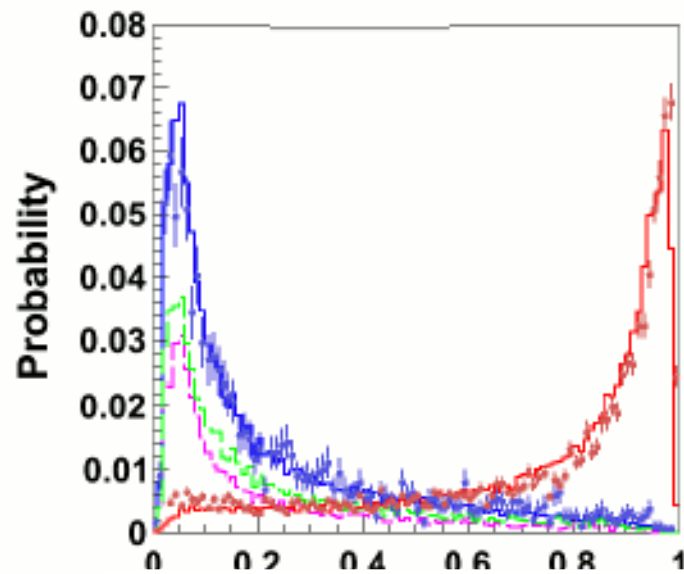
- Variables which have different distributions for signal and  $q\bar{q}$  background are used.

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

histogram: MC, dots: data

signal

$qq = \text{charm} + \text{uds}$



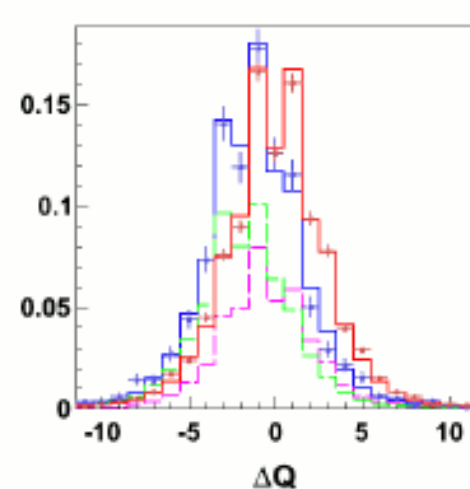
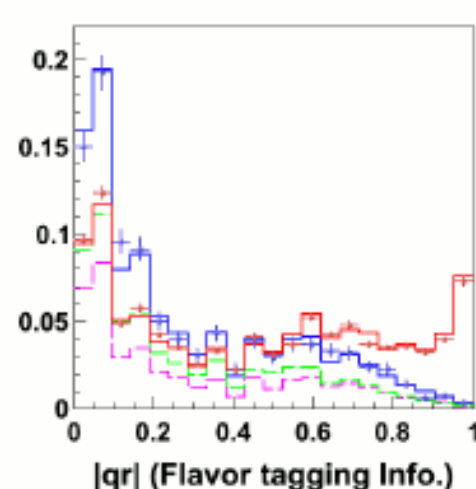
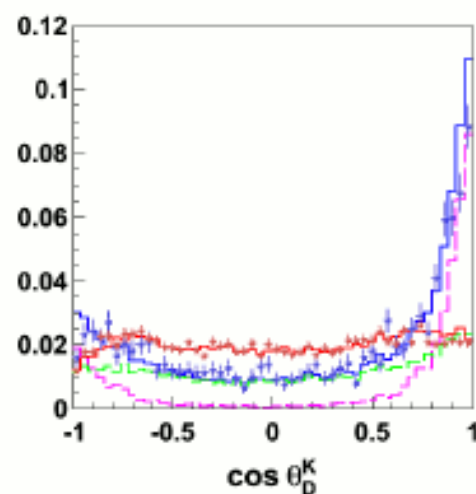
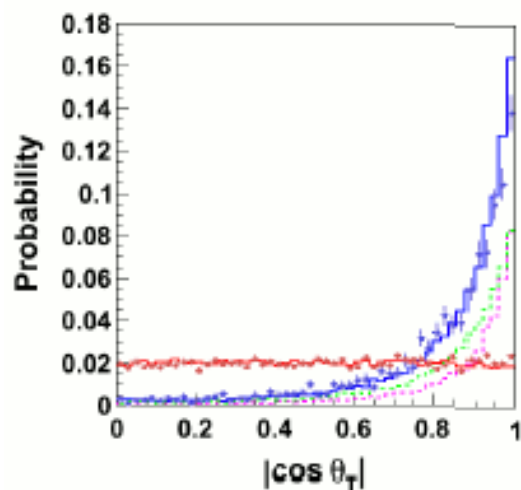
(Here, we use "old" package.)  
(RooKSF is also possible.)

Most powerful.

$\theta_B$  is angle between  $B$ -flight direction and beam axis.



If tag is not possible,  $\Delta z = -999$ .  
NB deals with as a  $\delta$ -function.

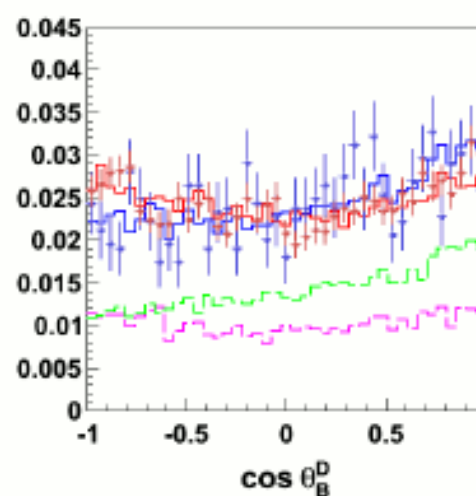
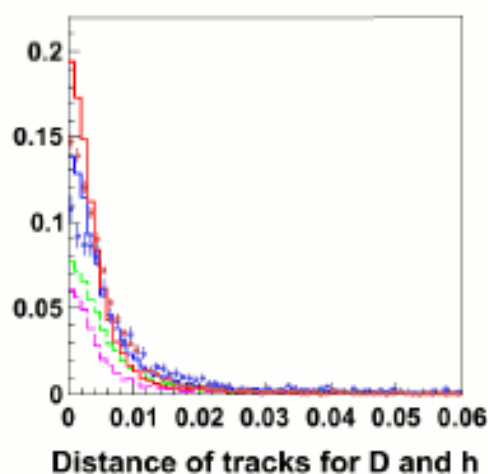
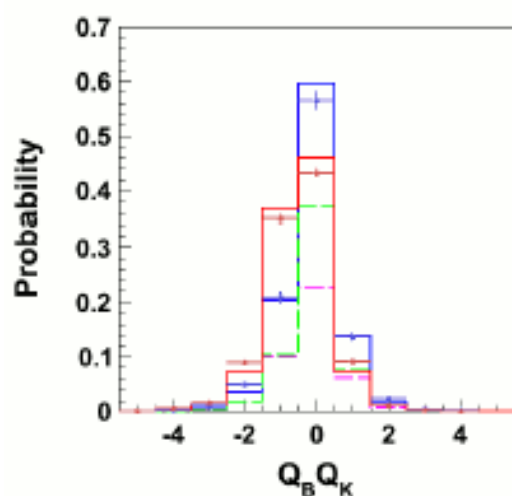


Angle between thrust axes  
of B decay and remainder.  
*No full correlation to LR(KSFW).*

*Decay angle* of  $D \rightarrow K\pi$ .

*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  $B \rightarrow DK$ .

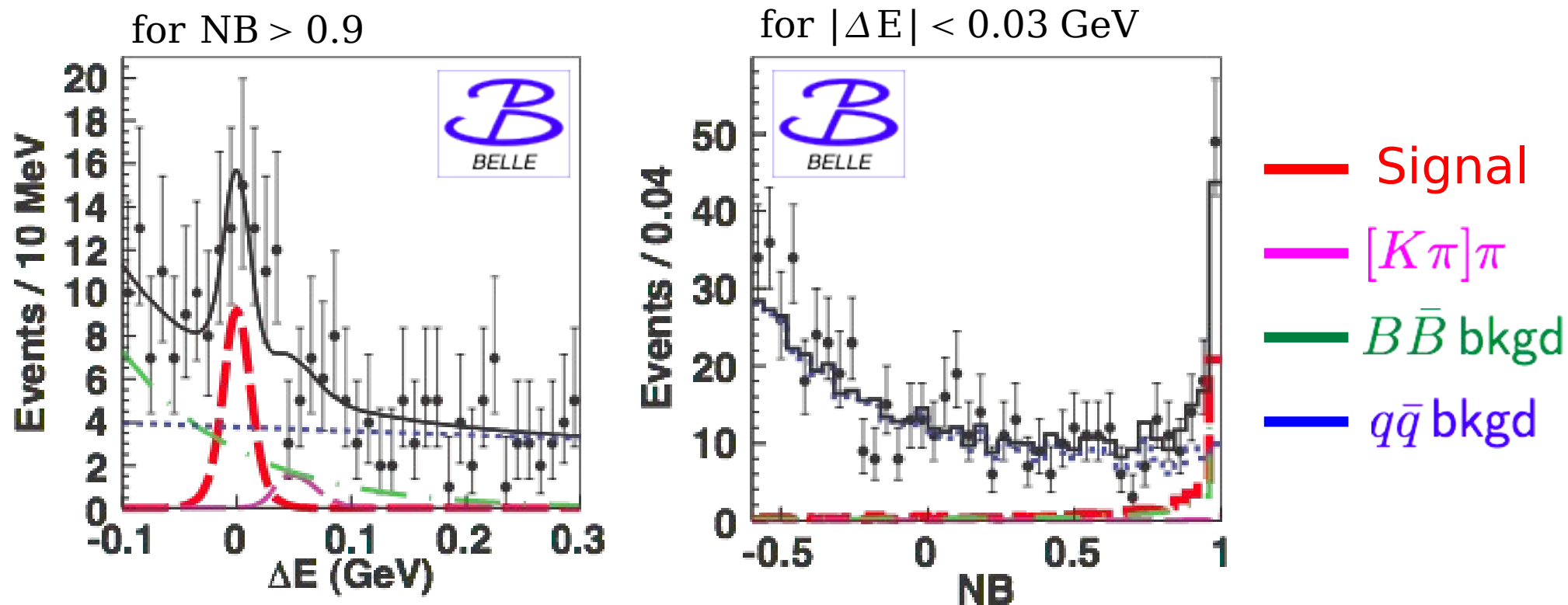
10 variables combined  
to obtain a single  
NN output (NB)

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

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

PRL 106, 231803 (2011)

Fit  $\Delta E$  and NB distributions together to extract signal



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

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

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

**First evidence obtained  
with a significance of  $3.8\sigma$   
(including syst.)**

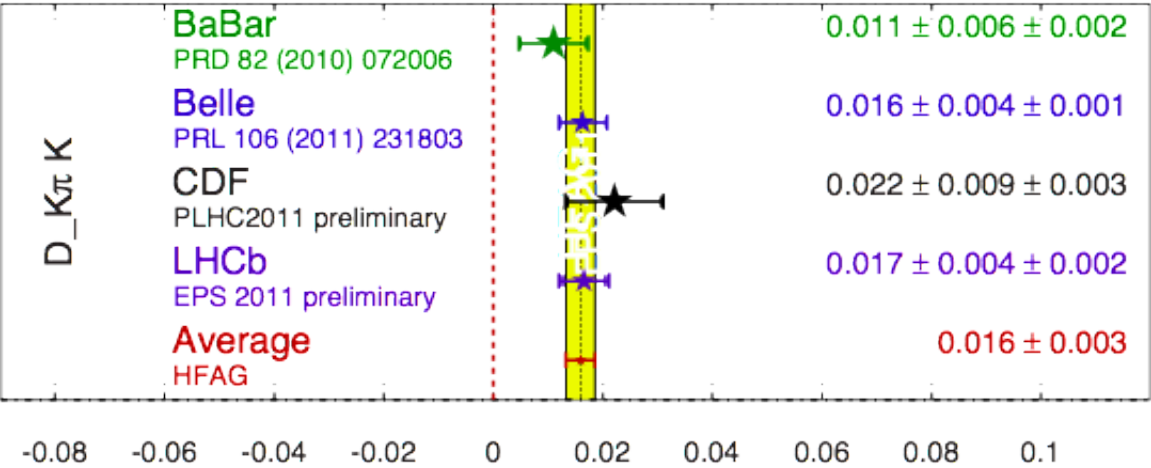
# Results for the ADS mode $B^- \rightarrow [K^+ \pi^-]_D K^-$ from 772 million $B\bar{B}$ events

PRL 106, 231803 (2011)

## $R_{ADS}$ Averages



EPS 2011  
 PRELIMINARY





$$(1.63^{+0.44+0.07}_{-0.41-0.13}) \times 10^{-2}$$

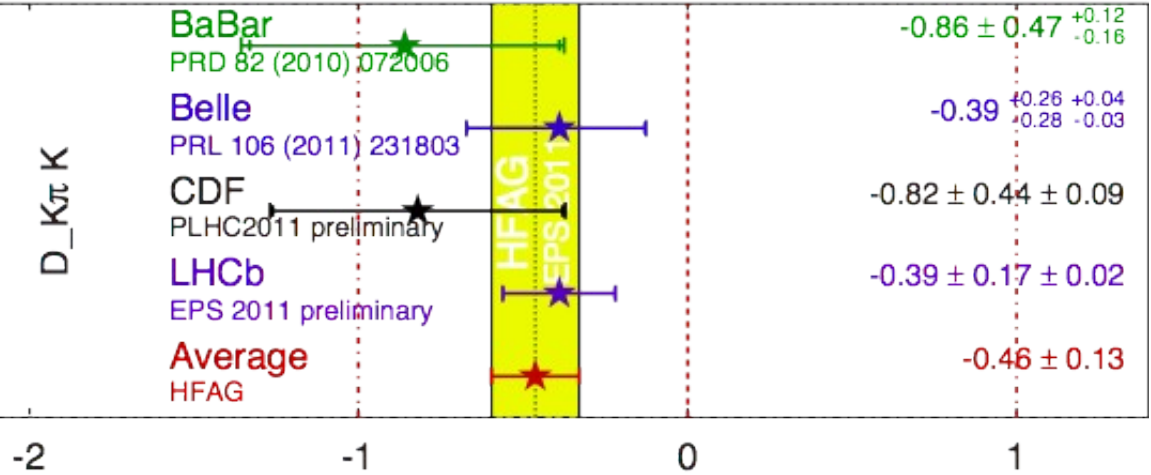


$$\Rightarrow r_B \neq 0$$

## $A_{ADS}$ Averages



EPS 2011  
 PRELIMINARY





$$-0.39^{+0.26+0.04}_{-0.28-0.03}$$



# First evidence for the ADS mode $B^- \rightarrow [K^+ \pi^-]_{D^*} K^-$ from Belle 772 million $B\bar{B}$ events

**Preliminary  
LP 2011**

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

**Signal seen  
with a significance of  $3.5\sigma$   
for  $D^* \rightarrow D\gamma$  mode**

**Ratio to favored mode:**

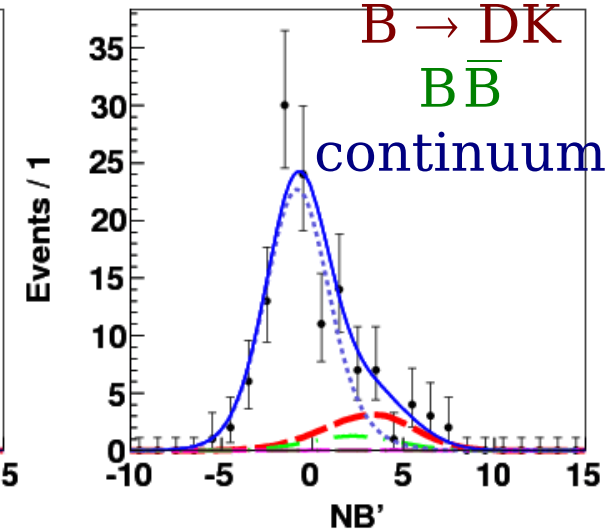
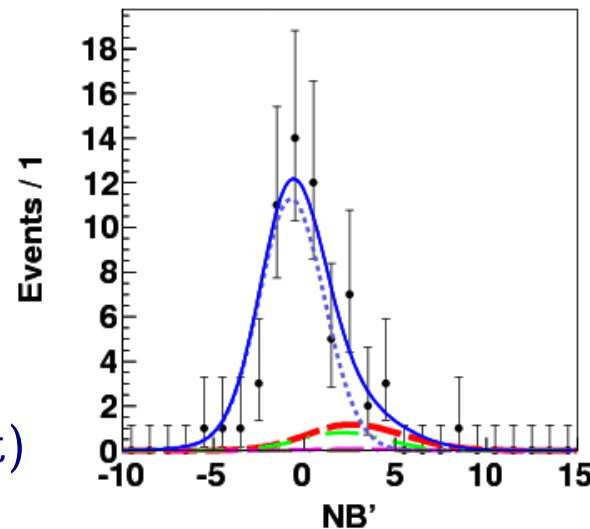
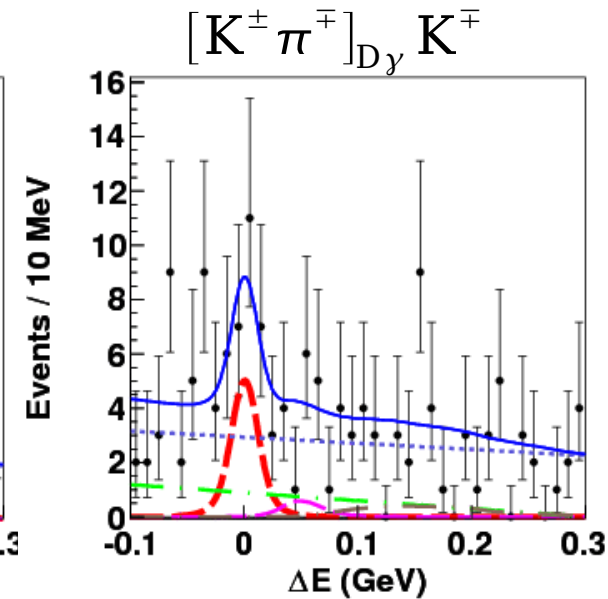
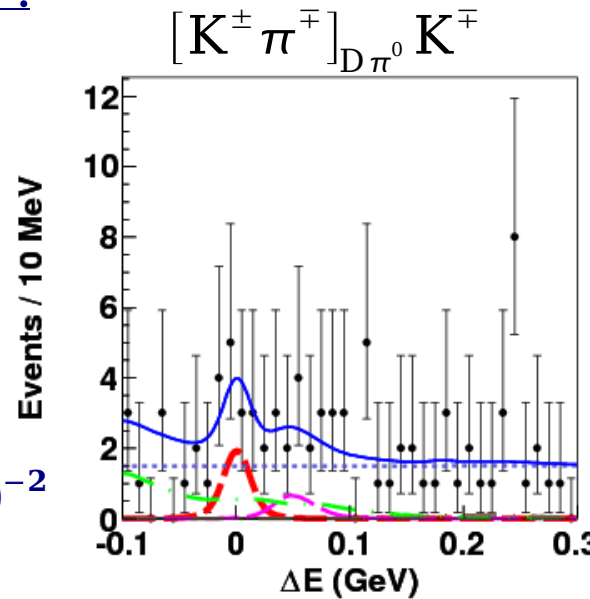
$$R_{D\pi^0} = (1.0^{+0.8}_{-0.7}(\text{stat})^{+0.1}_{-0.2}(\text{syst})) \times 10^{-2}$$

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

**asymmetry:**

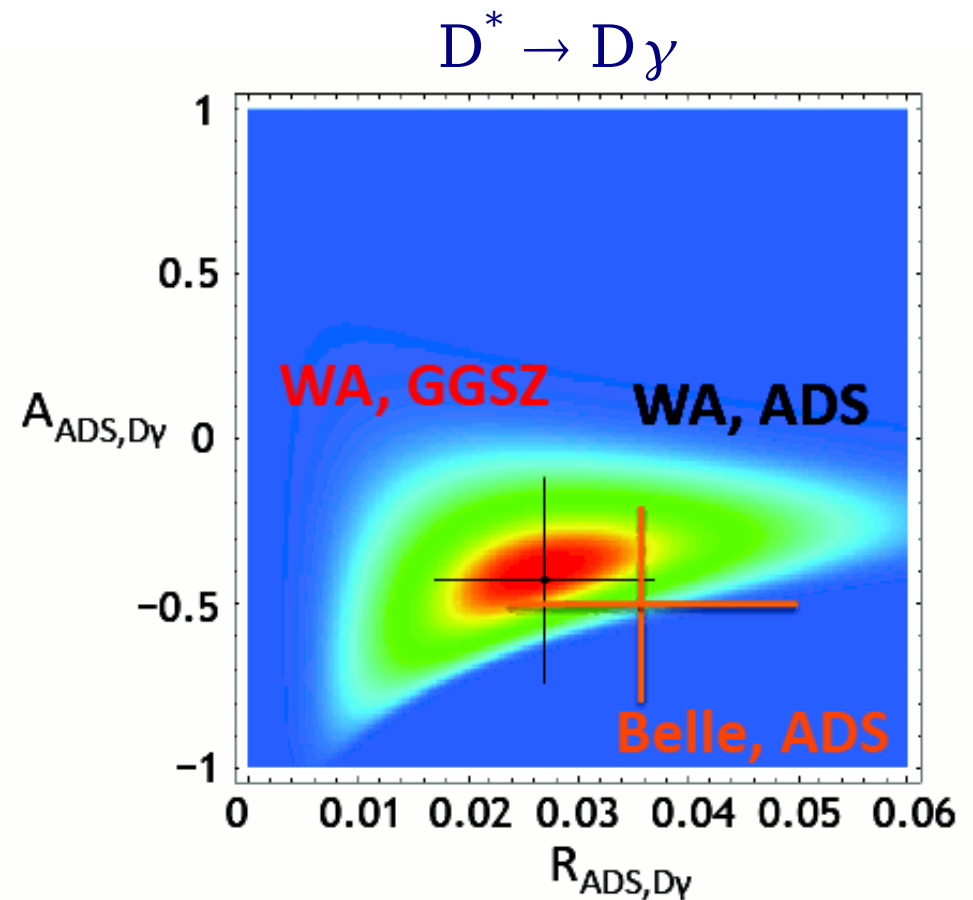
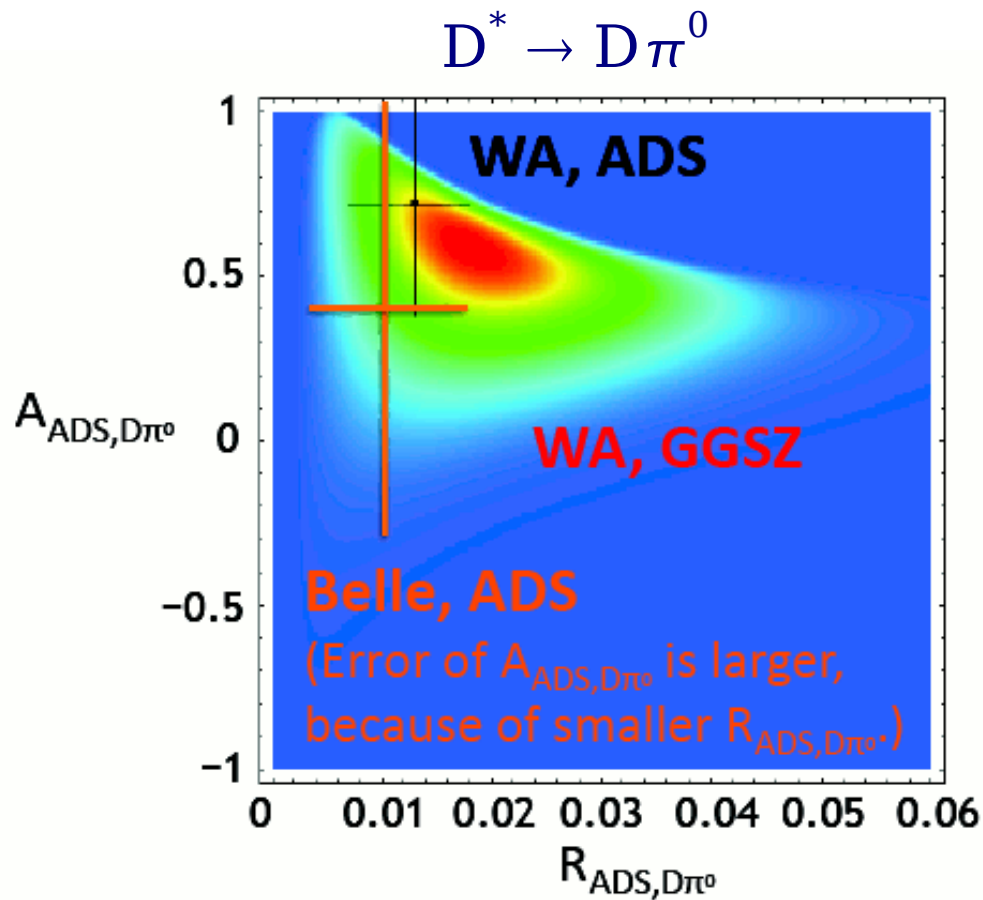
$$A_{D\pi^0} = 0.4^{+1.1}_{-0.7}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$$

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



# Comparison of the results obtained for $D^* K$ with expectations

(where "expectations" are derived from the GGSZ observables)



*WA taken from HFAG 2011 summer.*

# GLW with $D_{CP}K$

D decays to CP eigenstates

Relation between  $(A_{CP+}, A_{CP-}, R_{CP+}, R_{CP-})$  and  $(\gamma, r_B, \delta_B)$

$$R_{CP\pm} \simeq \frac{R_{D_{CP\pm}}}{R_{D_{fav}}}$$

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

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

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

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

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

# $B \rightarrow Dh, D \rightarrow K\pi \rightarrow R_{D_{\text{fav}}}$ data (772 MB $\bar{B}$ )

$B \rightarrow D\pi$

$B \rightarrow DK$

$B\bar{B}$

continuum

h is a pion candidate ( $KID < 0.6$ )

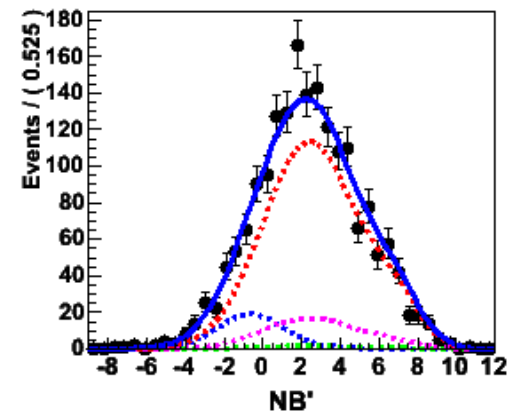
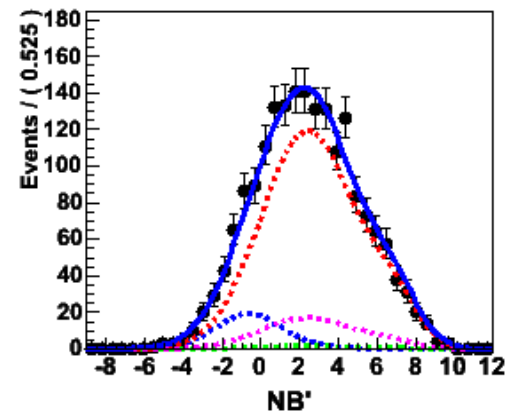
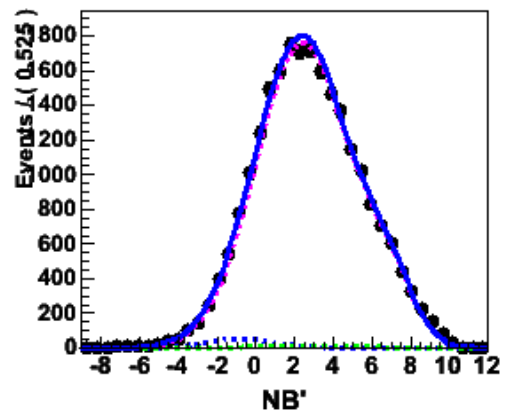
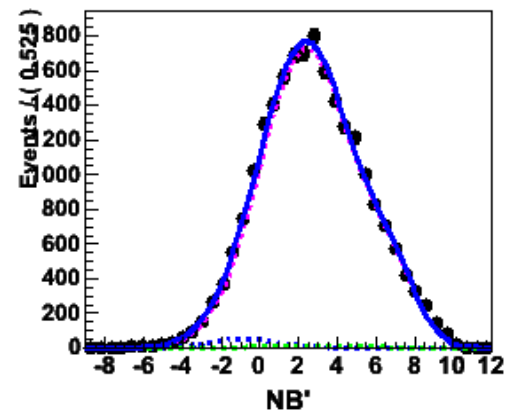
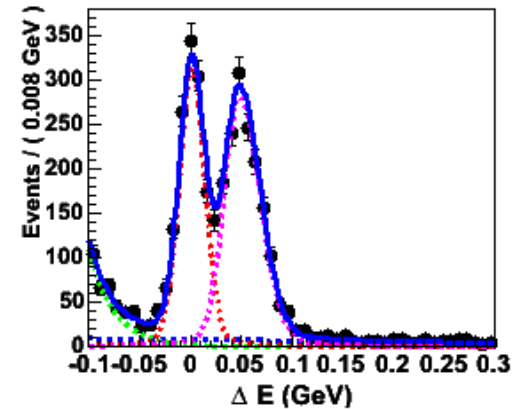
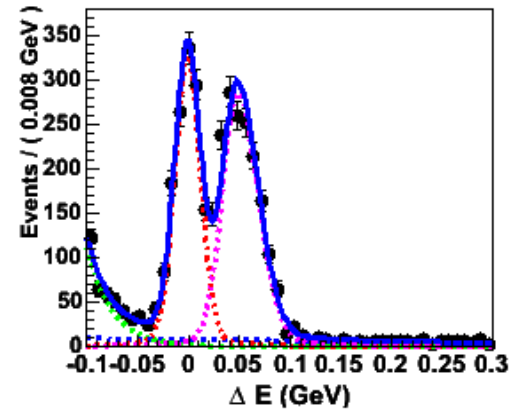
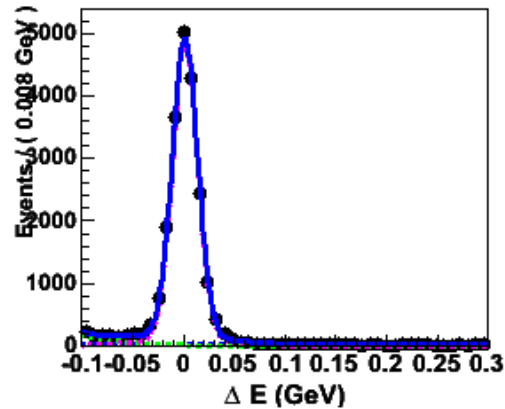
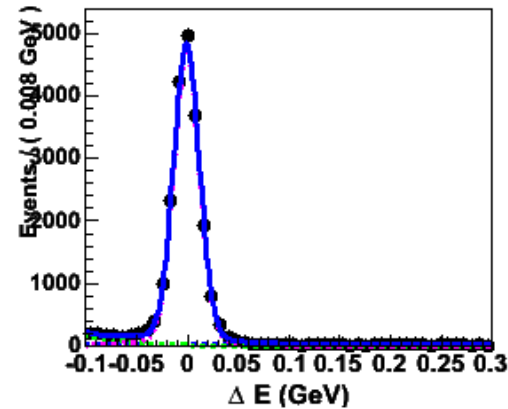
$B^- \rightarrow Dh^-$

$B^+ \rightarrow Dh^+$

h is a kaon candidate ( $KID > 0.6$ )

$B^- \rightarrow Dh^-$

$B^+ \rightarrow Dh^+$



$$\Rightarrow R_{D_{\text{fav}}} = (7.32 \pm 0.16)\%, \quad A(DK) = (1.4 \pm 2.0)\%$$

# $B \rightarrow Dh, D \rightarrow K\pi \rightarrow R_+$

data (772 MB  $\bar{B}$ )

$D \rightarrow K^+ K^-, \pi^+ \pi^-$

Preliminary  
LP 2011

$B \rightarrow D\pi$

$B \rightarrow DK$

$B\bar{B}$

continuum

h is a pion candidate (KID < 0.6)

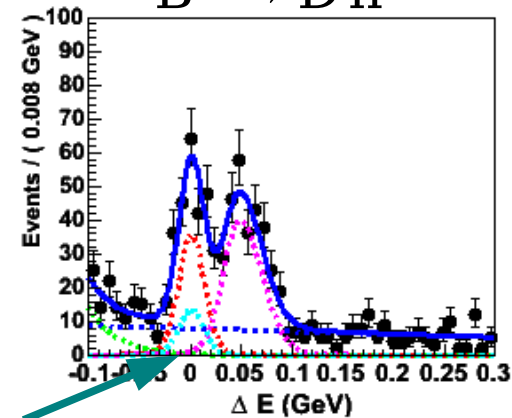
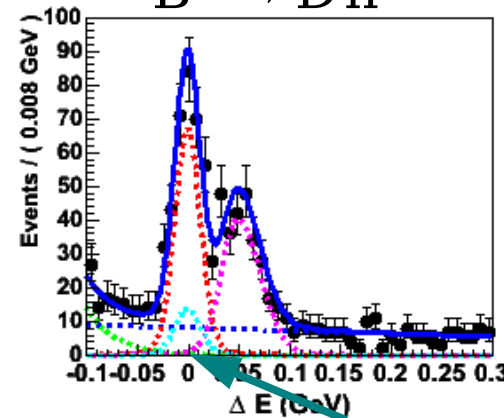
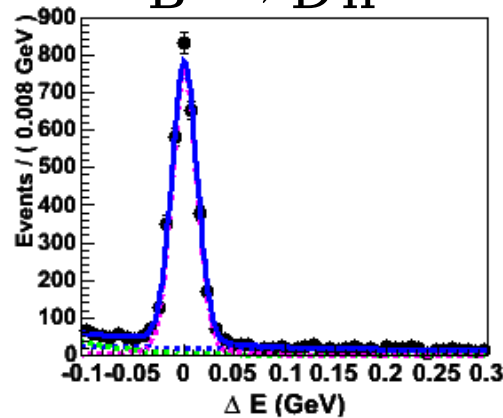
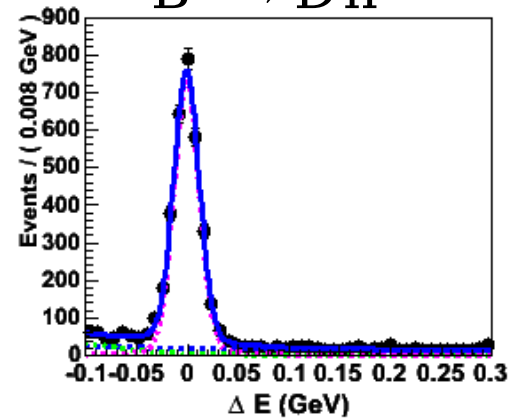
h is a kaon candidate (KID > 0.6)

$B^- \rightarrow Dh^-$

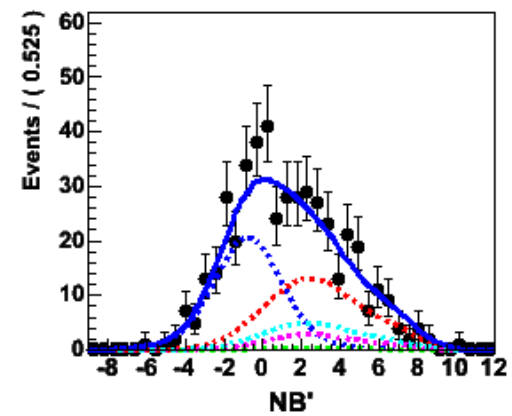
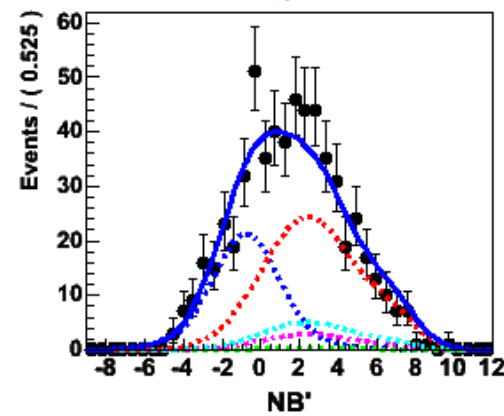
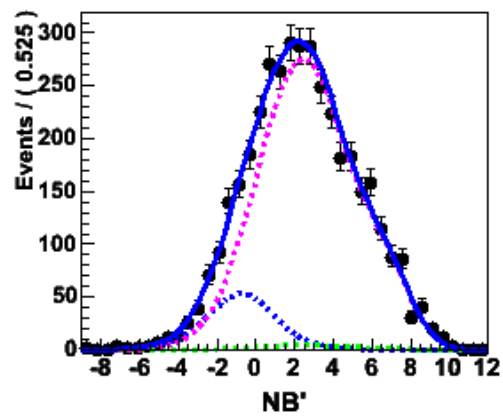
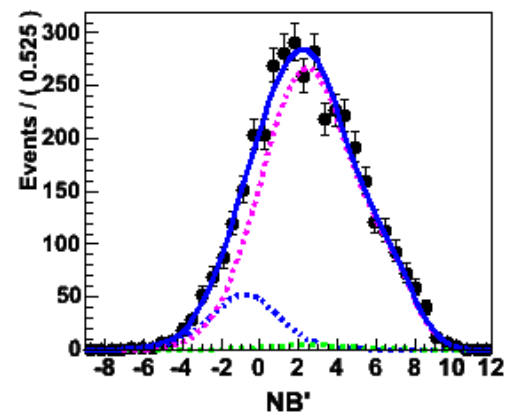
$B^+ \rightarrow Dh^+$

$B^- \rightarrow Dh^-$

$B^+ \rightarrow Dh^+$



large KKK contribution !!



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

large asymmetry !!

# $B \rightarrow Dh, D \rightarrow K\pi \rightarrow R_-$

data (772 MB  $\bar{B}$ )

$D \rightarrow K_S \pi^0, K_S \eta (\gamma\gamma)$

Preliminary  
LP 2011

$B \rightarrow D\pi$

$B \rightarrow DK$

$B\bar{B}$

continuum

h is a pion candidate (KID < 0.6)

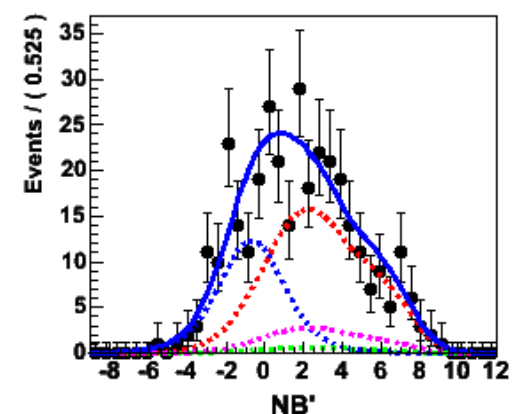
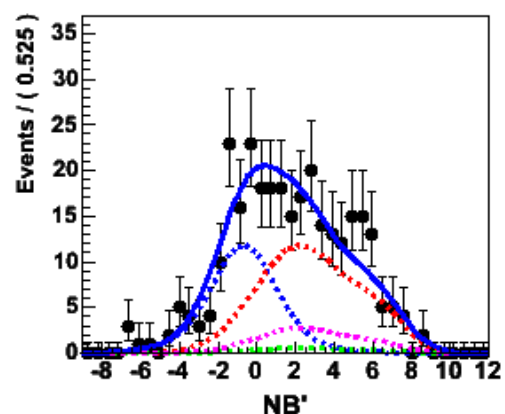
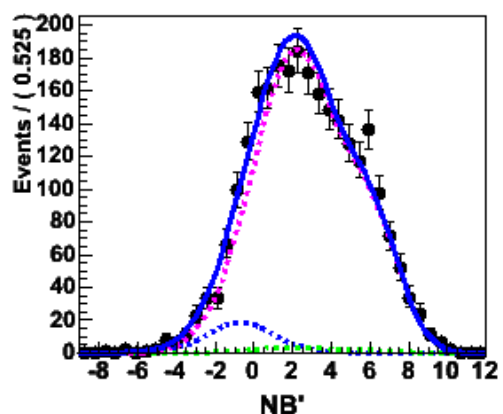
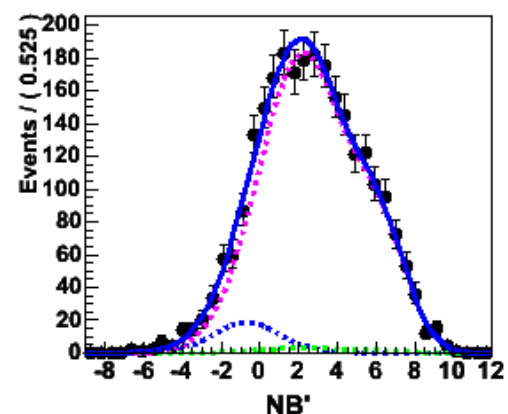
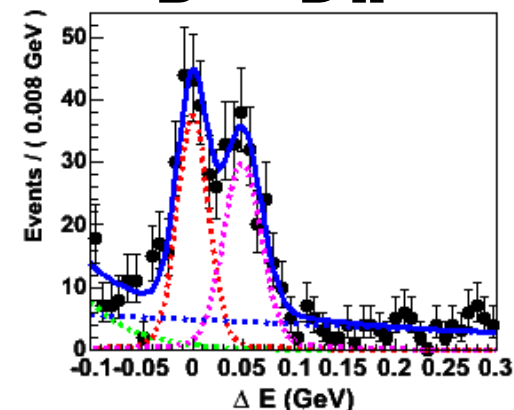
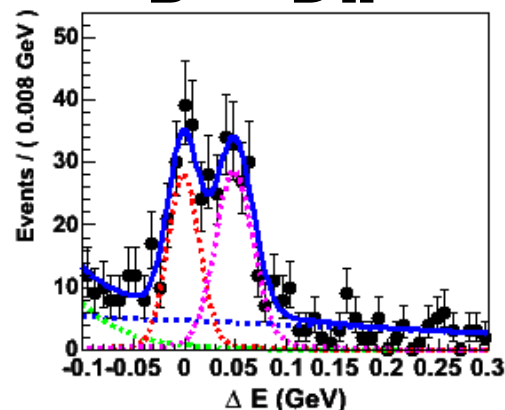
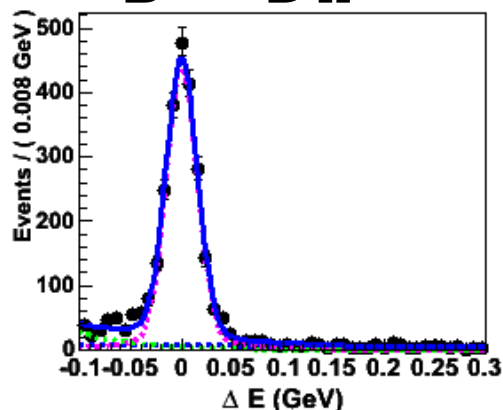
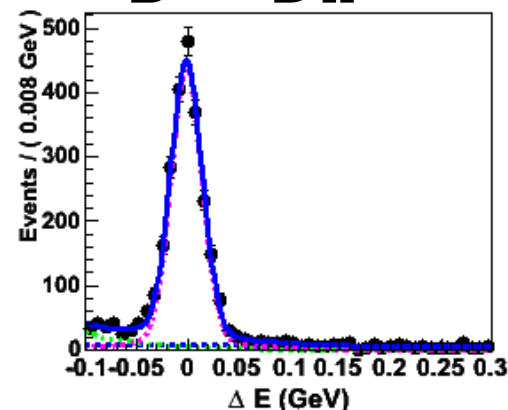
h is a kaon candidate (KID > 0.6)

$B^- \rightarrow Dh^-$

$B^+ \rightarrow Dh^+$

$B^- \rightarrow Dh^-$

$B^+ \rightarrow Dh^+$



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

opposite asymmetry !!

# GLW Results

Preliminary  
LP 2011

| Yields                                       | $\mathbf{B \rightarrow D \pi}$ | $\mathbf{B \rightarrow DK}$ |
|----------------------------------------------|--------------------------------|-----------------------------|
| $\mathbf{D \rightarrow K \pi}$               | $50432 \pm 243$                | $3692 \pm 83$               |
| $\mathbf{D \rightarrow KK, \pi \pi}$         | $7696 \pm 106$                 | $582 \pm 40$                |
| $\mathbf{D \rightarrow K_S \pi^0, K_S \eta}$ | $5745 \pm 91$                  | $476 \pm 37$                |

$$\mathbf{R_{CP+} = 1.03 \pm 0.07 \pm 0.03}$$

$$\mathbf{R_{CP-} = 1.13 \pm 0.09 \pm 0.05}$$

$$\mathbf{A_{CP+} = +0.29 \pm 0.06 \pm 0.02}$$

$$\mathbf{A_{CP-} = -0.12 \pm 0.06 \pm 0.01}$$

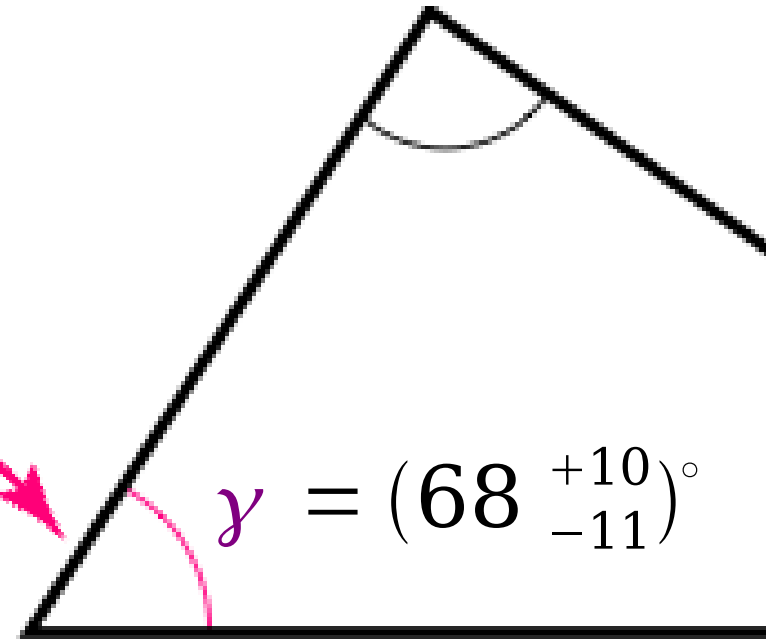
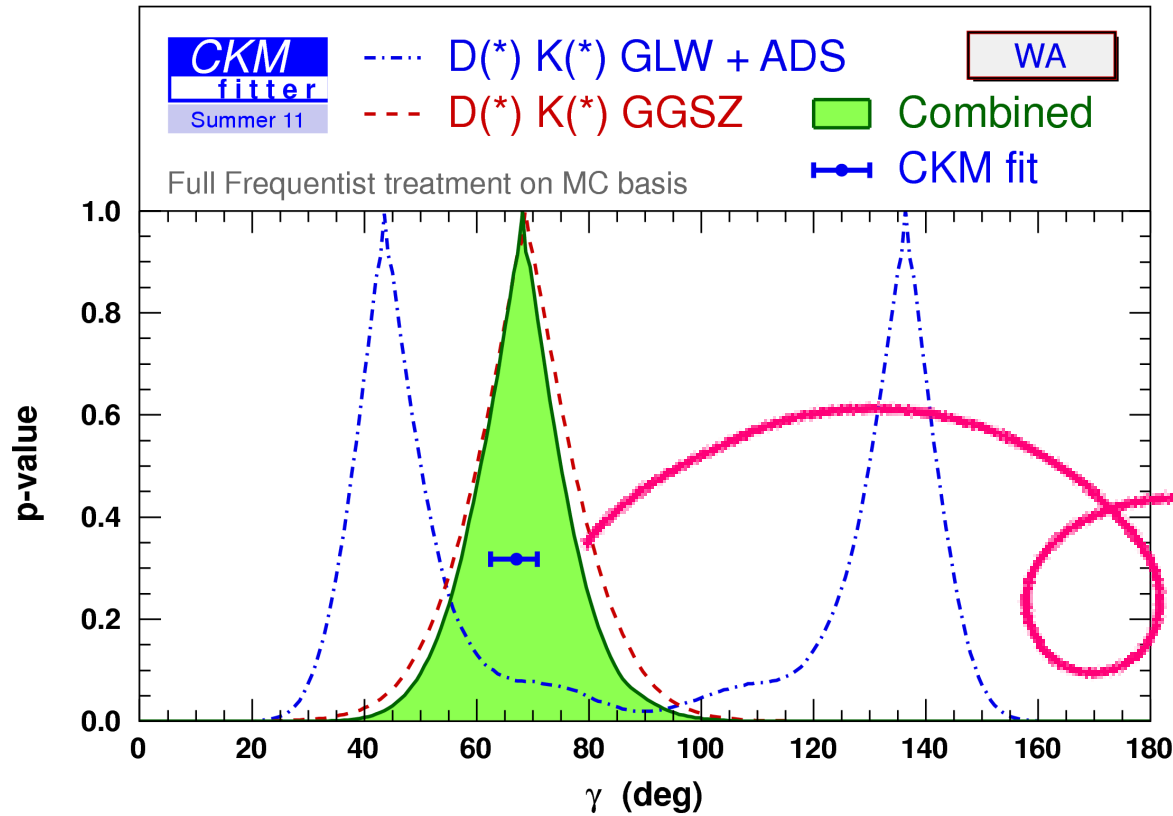
systematics dominated by peaking background,  
double ratio approximation

coming improvement: adding  $K_S \omega, K_S \eta'$  for CP-odd modes

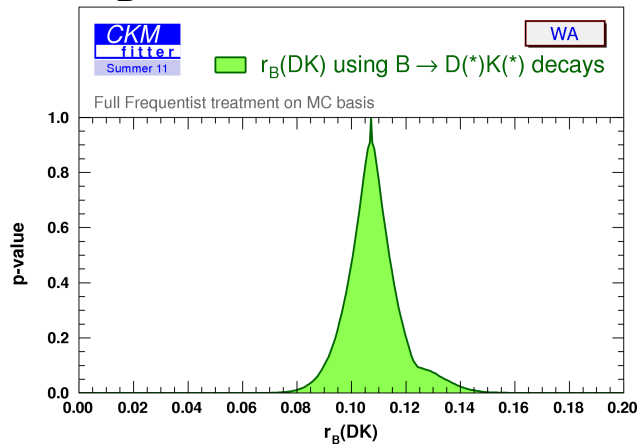
coming update:  $D^* K$  modes

# Combined measurements for $\gamma$ from all methods

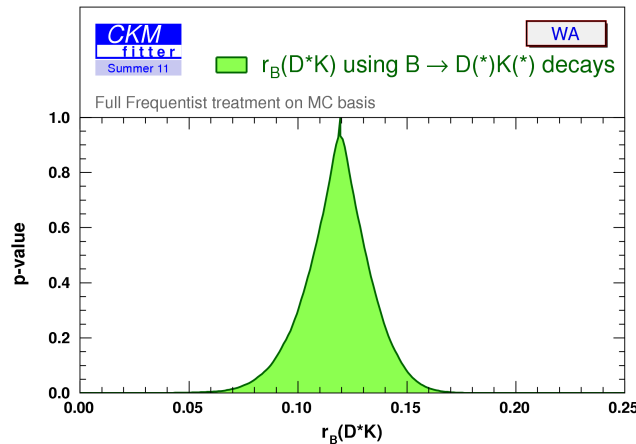
<http://ckmfitter.in2p3.fr/>



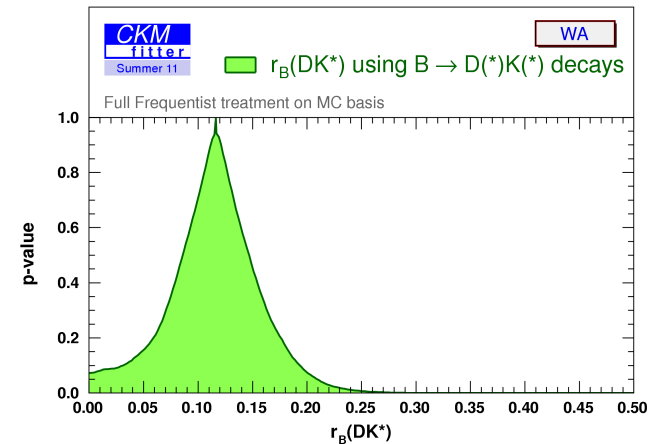
$$r_B(DK) = 0.107 \pm 0.010$$

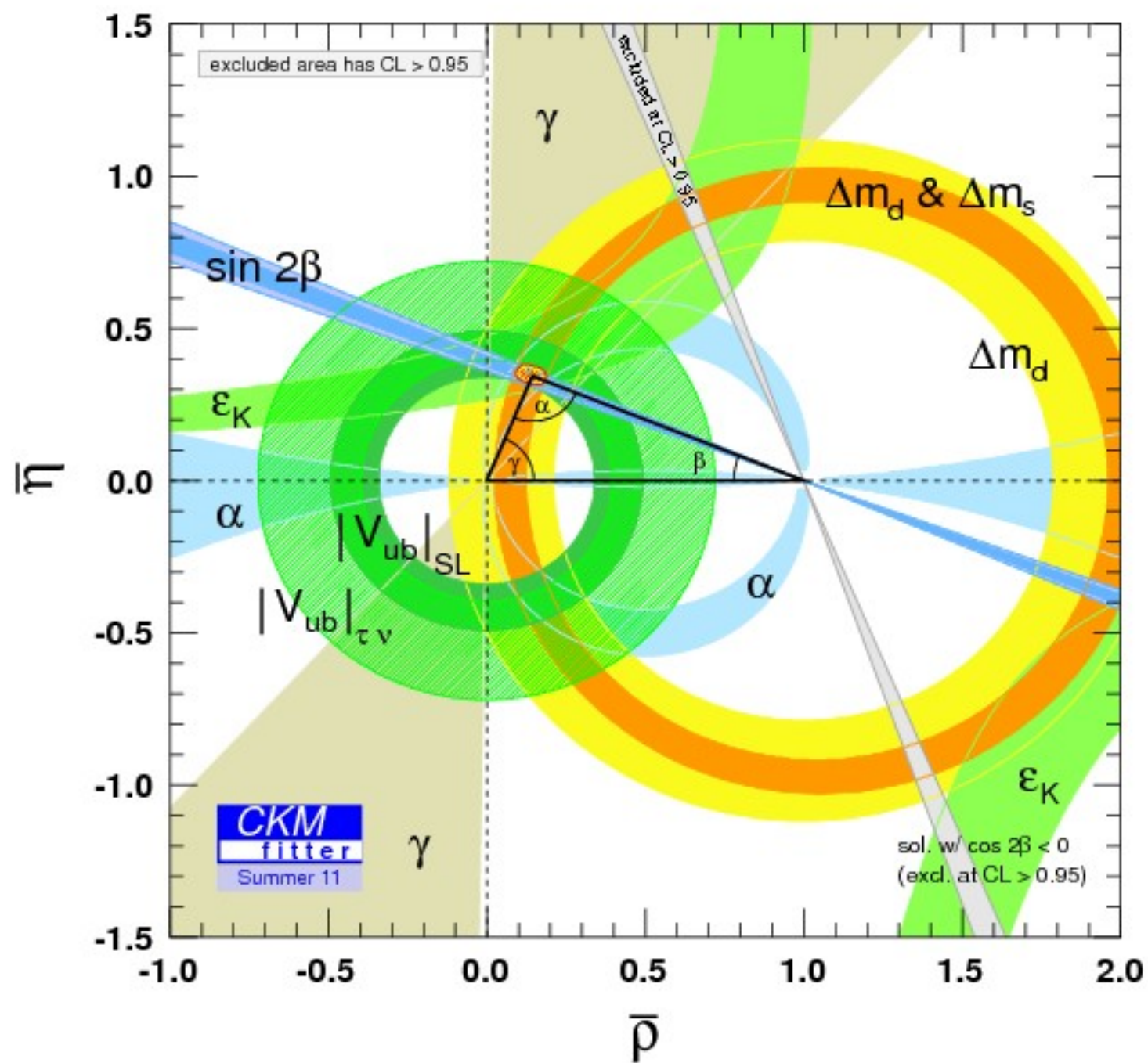


$$r_B(D^*K) = 0.119^{+0.018}_{-0.019}$$

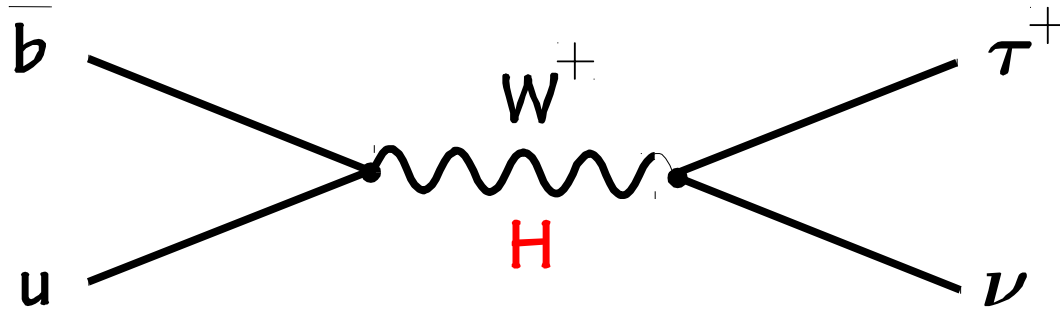


$$r_B(D^*K) = 0.116^{+0.045}_{-0.044}$$





# Tauonic B decays



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

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

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

# Event reconstruction in $B \rightarrow \tau \nu$

$$\underline{B_{\text{sig}} \rightarrow \tau \nu}$$

(70 % of all  $\tau$  decays)

$$\tau \rightarrow e \nu \nu, \mu \nu \nu,$$

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

$e, \mu$

$B_{\text{sig}}$

$B^+$

$\tau^+$

$\Upsilon(4S)$

$B^-$

$B_{\text{tag}}$

$\underline{B_{\text{tag}}}$

hadronic tag

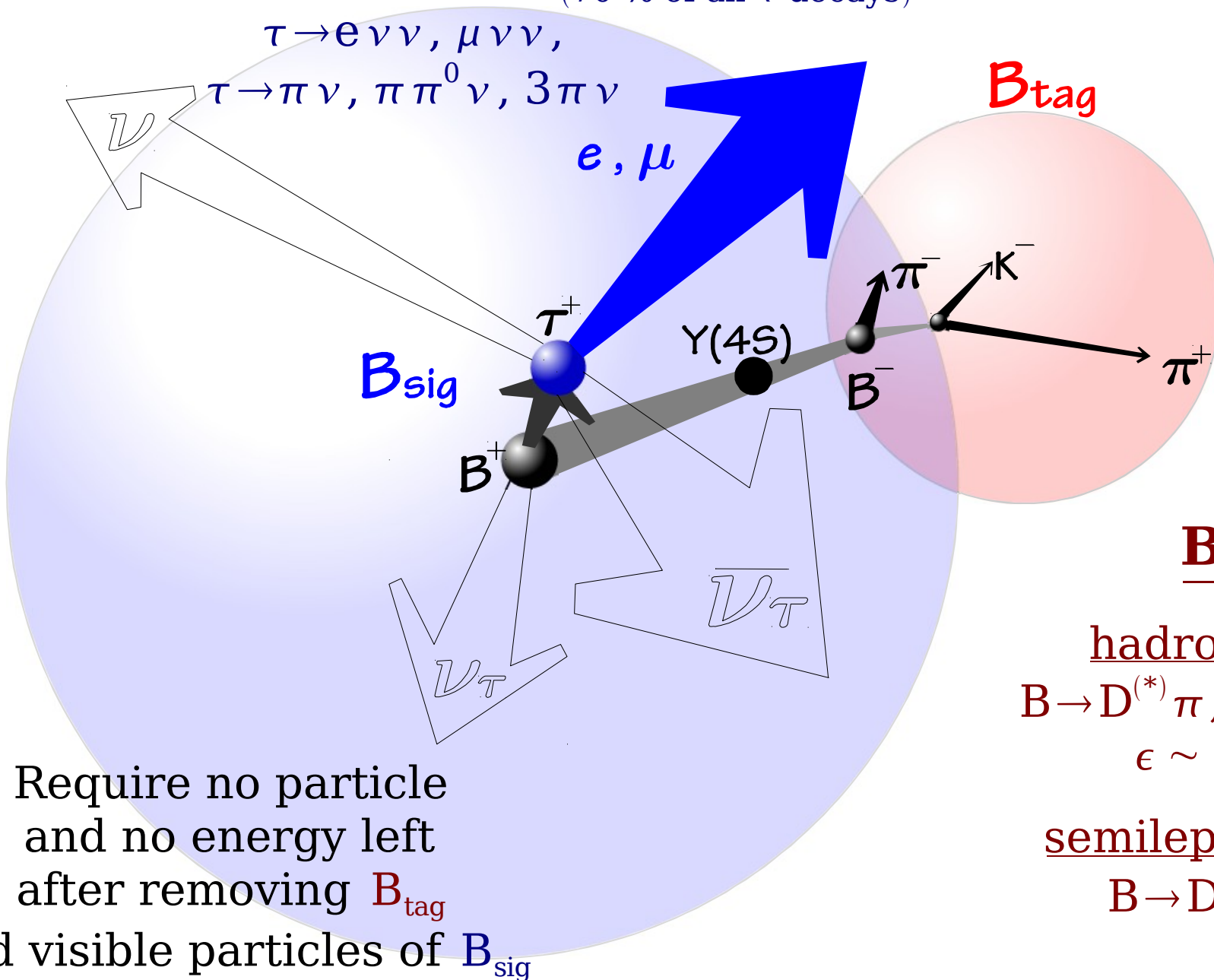
$$B \rightarrow D^{(*)} \pi, D^{(*)} \rho \dots$$

$$\epsilon \sim 0.2\%$$

semileptonic tag

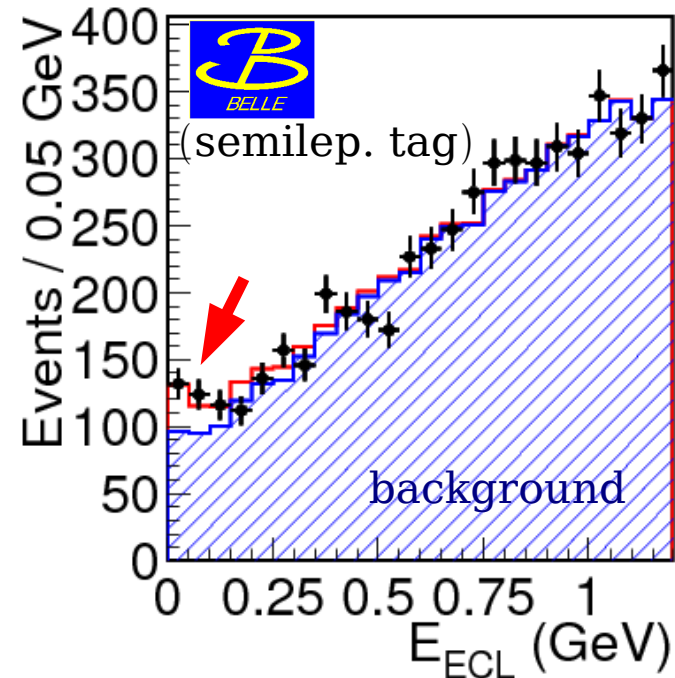
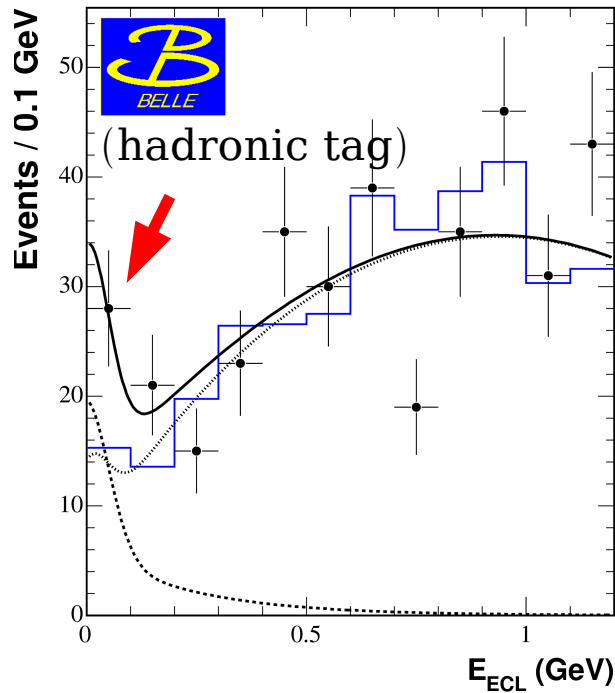
$$B \rightarrow D^{(*)} l \nu X$$

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



# $B^+ \rightarrow \tau^+ \nu$ results

Extra calorimeter energy:  $E_{\text{ECL/extra}}$  (GeV)



| Belle        | $N_{B\bar{B}}$ | $B$ ( $10^{-4}$ )                  | $\Sigma(\sigma)$ |                      |
|--------------|----------------|------------------------------------|------------------|----------------------|
| Hadronic tag | (449 M)        | $(1.79^{+0.56+0.46}_{-0.49-0.51})$ | 3.5              | PRL97, 251802 (2006) |
| Semilep. tag | (657 M)        | $(1.54^{+0.38+0.29}_{-0.37-0.31})$ | 3.6              | PRD82, 071101(R)2010 |
| BaBar        |                |                                    |                  |                      |
| Hadronic tag | (468 M)        | $(1.80^{+0.57}_{-0.54} \pm 0.26)$  | 3.6              | arXiv:1008.0104      |
| Semilep. tag | (459 M)        | $(1.7 \pm 0.8 \pm 0.2)$            | 2.3              | PRD81, 051101 (2010) |

# $B^+ \rightarrow \tau^+ \nu$ results

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

2HDM (type II):

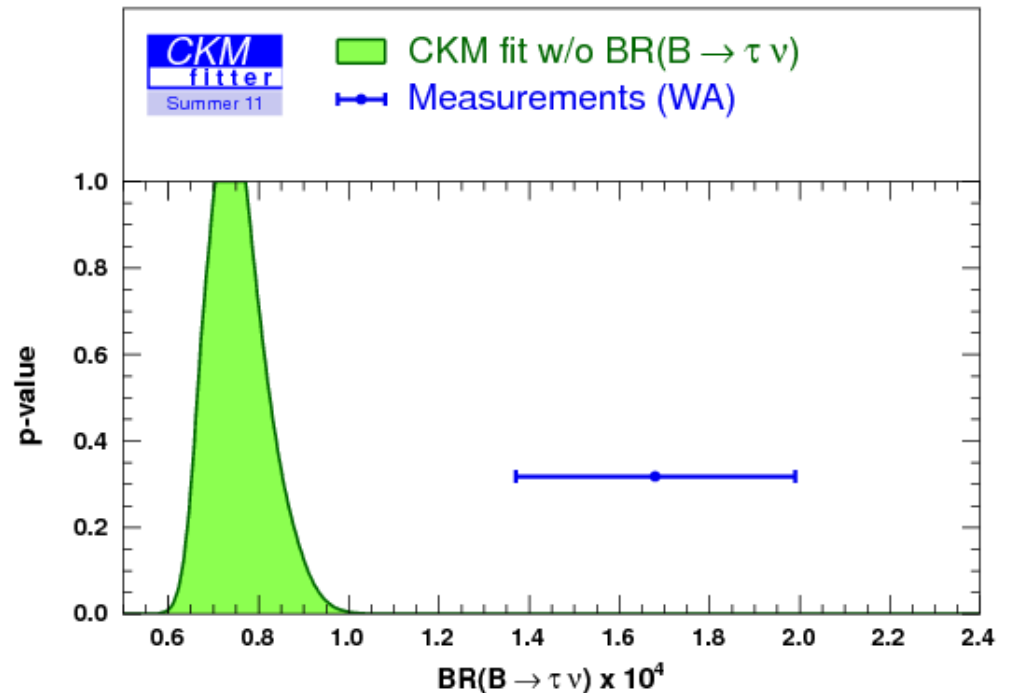
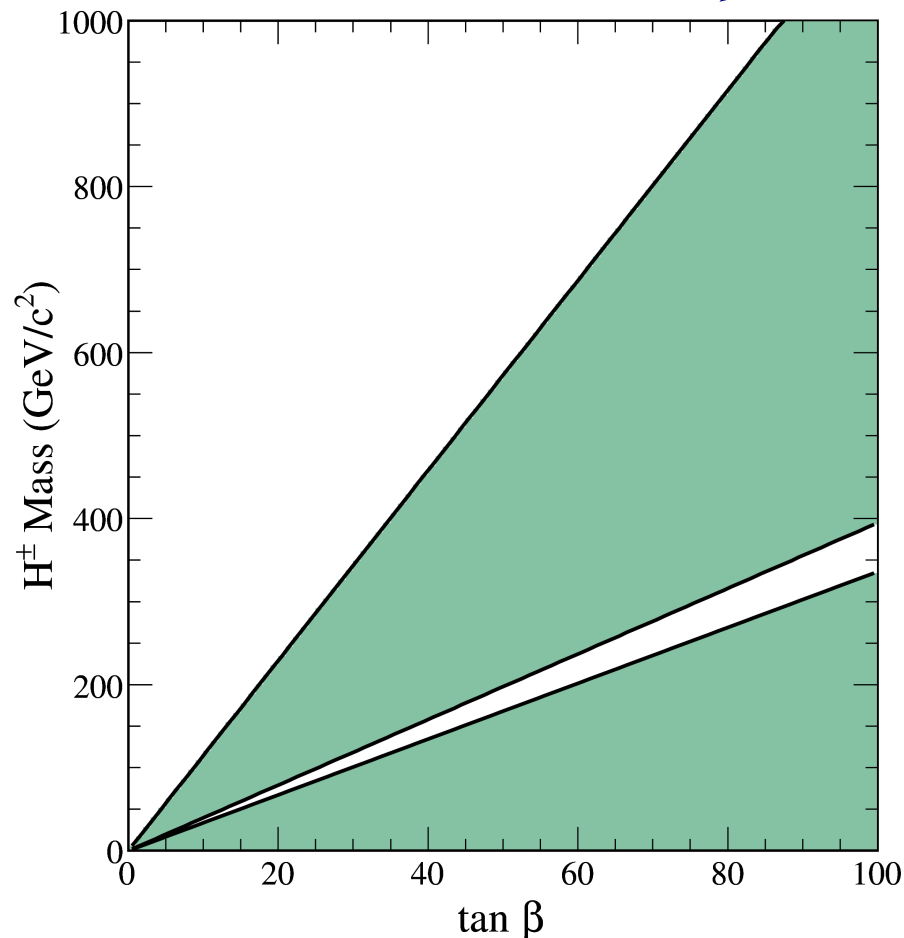
$$B(B^+ \rightarrow \tau^+ \nu) = B_{\text{SM}} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right)^2$$

$$B_{\text{SM}}(B^+ \rightarrow \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4}$$

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

$$\text{CKMfitter: } B_{\text{SM}}(B^+ \rightarrow \tau^+ \nu) = (0.763^{+0.114}_{-0.061}) \times 10^{-4}$$

**$2.8\sigma$  difference**



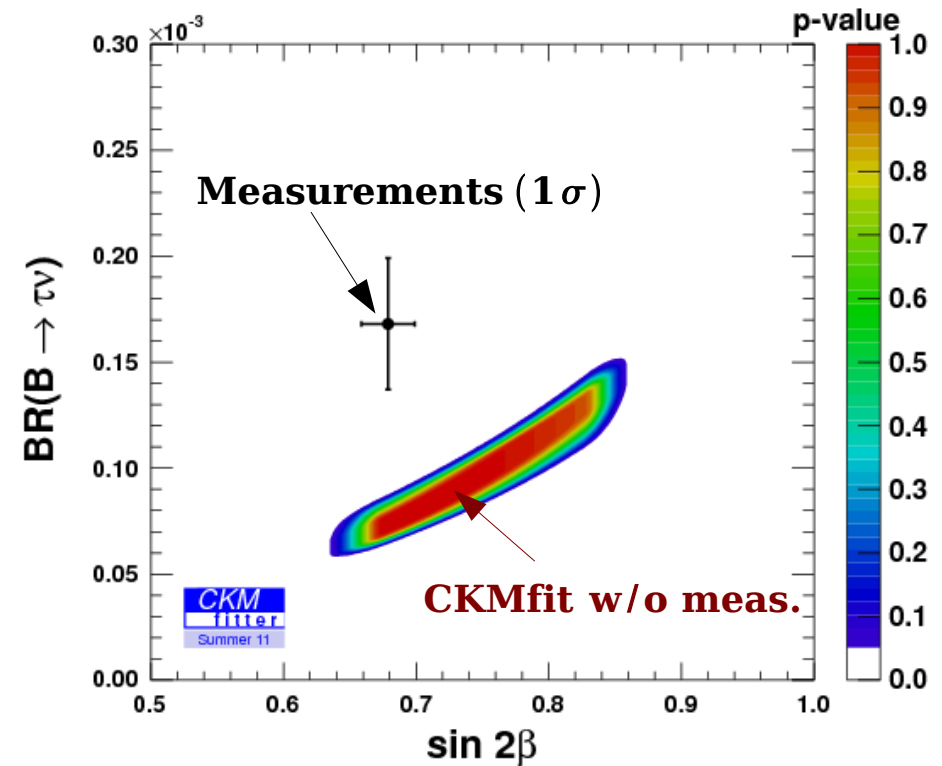
→ **update this year, especially with hadronic tag**

→ **also  $B^+ \rightarrow \mu^+ \nu$  !!!  $B^{\text{exp}} \sim 6 \times 10^{-7}$ , best U.L. (BaBar)  $< 10^{-6}$  @ 90% C.L.**

# $B^+ \rightarrow \tau^+ \nu$ versus...

...  $\sin 2\beta_{cc}$

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



...  $|V_{ub}|$  [A.Khodjamirian et al, arXiv:1103.2655]

$$R_{s/l}(q_1^2, q_2^2) \equiv \frac{\Delta B_{B \rightarrow \pi l \nu}(q_1^2, q_2^2)}{B(B \rightarrow \tau \nu_\tau)} \left( \frac{\tau_{B^-}}{\tau_{B^0}} \right)$$

high  $q^2$ : comparison with lattice QCD results:

$$R_{s/l} = 0.20_{-0.05}^{+0.08} \text{ (BaBar)}, 0.28_{-0.07}^{+0.13} \text{ (Belle)}$$

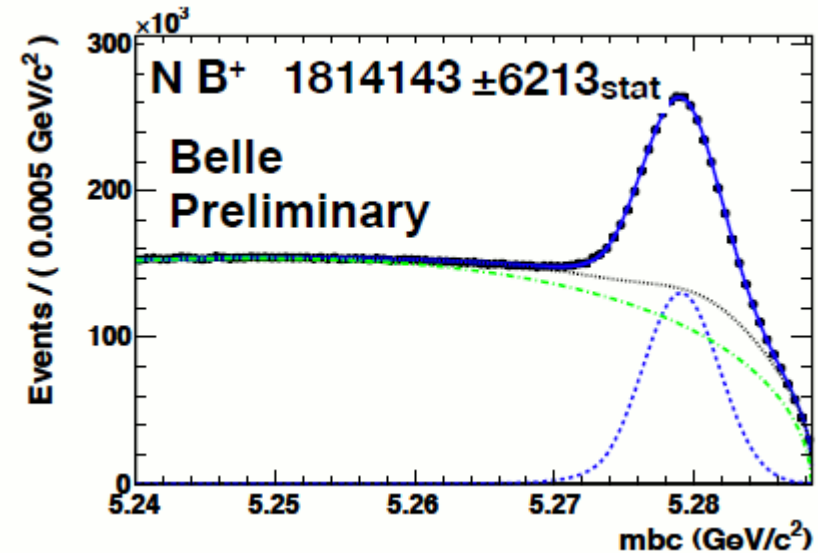
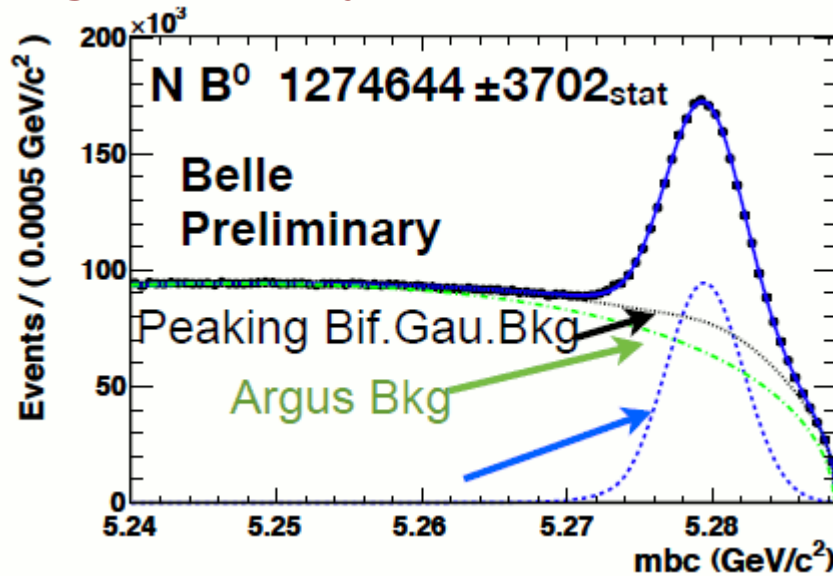
$$= 0.52 \pm 0.16 \text{ (HPQCD)}, 0.46 \pm 0.10 \text{ (FNAL/MILC)}$$

low  $q^2$ : similar discrepancy btw data QCD sum rule

$\Rightarrow$  **important to update  $B(B \rightarrow \tau \nu)$**

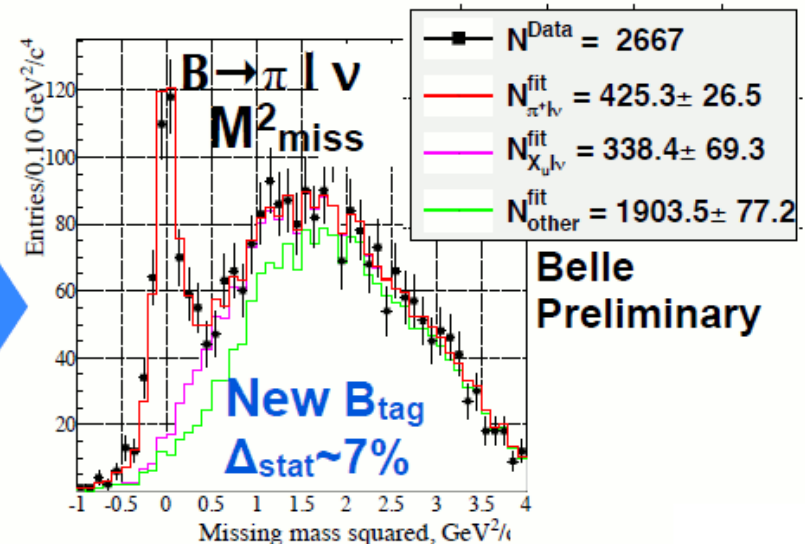
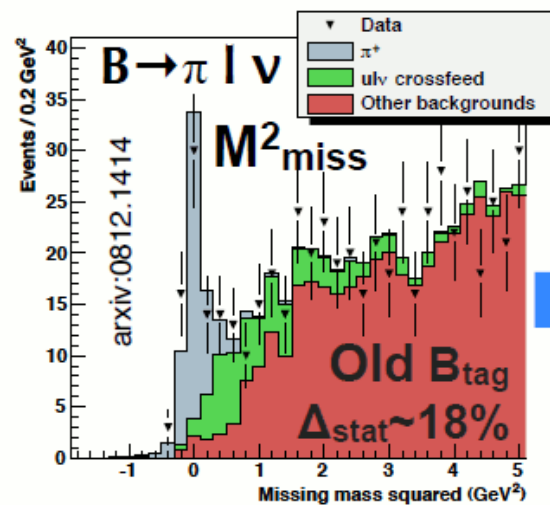
# New full reconstruction

- reprocessed data sample with improved tracking efficiency
- none of the results shown for rare B decays use full data sample yet
- **had tag efficiency improved: effective luminosity increased by factor  $> \times 2$**



**All hadron tag B analyses (leptonic and semileptonic decays) are being reviewed**

**e.g.  $B \rightarrow \pi l \nu$**   
(teaser !)



**Belle Preliminary**

**⇒ new results coming soon !**

**$B \rightarrow \tau \nu, \mu \nu, K^{(*)} \nu \bar{\nu}$ , exclusive  $b \rightarrow u l \nu, D^{(*)} \tau \nu \dots$**

# Luminosity at B factories

$> 1 \text{ ab}^{-1}$

On resonance:

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

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

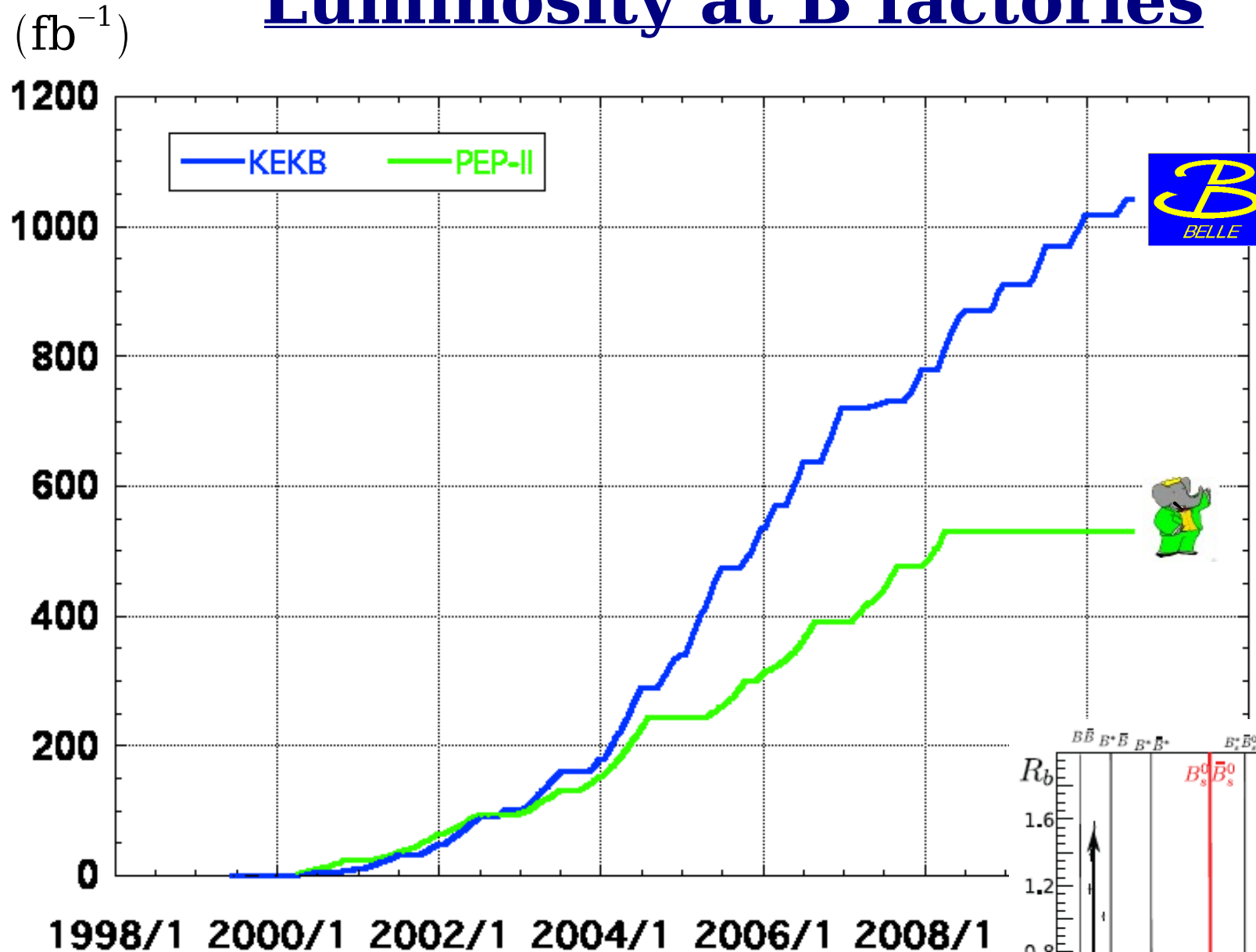
$\Upsilon(3S): 3 \text{ fb}^{-1}$

$\Upsilon(2S): 24 \text{ fb}^{-1}$

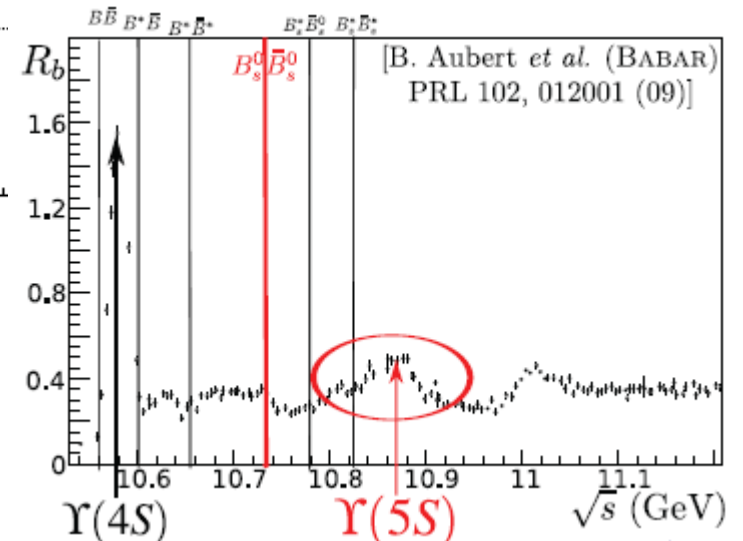
$\Upsilon(1S): 6 \text{ fb}^{-1}$

Off reson./scan:

$\sim 100 \text{ fb}^{-1}$



Data taken at  $\Upsilon(5S)$  ( $\sqrt{s} = 10867 \pm 1 \text{ MeV}$ )



# $B_s$ production at $\Upsilon(5S)$

Hadronic  $\Upsilon(5S)$  events

udsc continuum

$b\bar{b}$  events

$$\sigma(b\bar{b}) = (302 \pm 14) \text{ pb}$$

Cleo (PRD 75, 012002)  
Belle (PRL 98, 052001)

$b\bar{b}$  cross section : subtraction of taken below open-beauty threshold

$$\sigma(b\bar{b}) = \frac{N_{5S}^{b\bar{b}}}{L_{5S}}$$

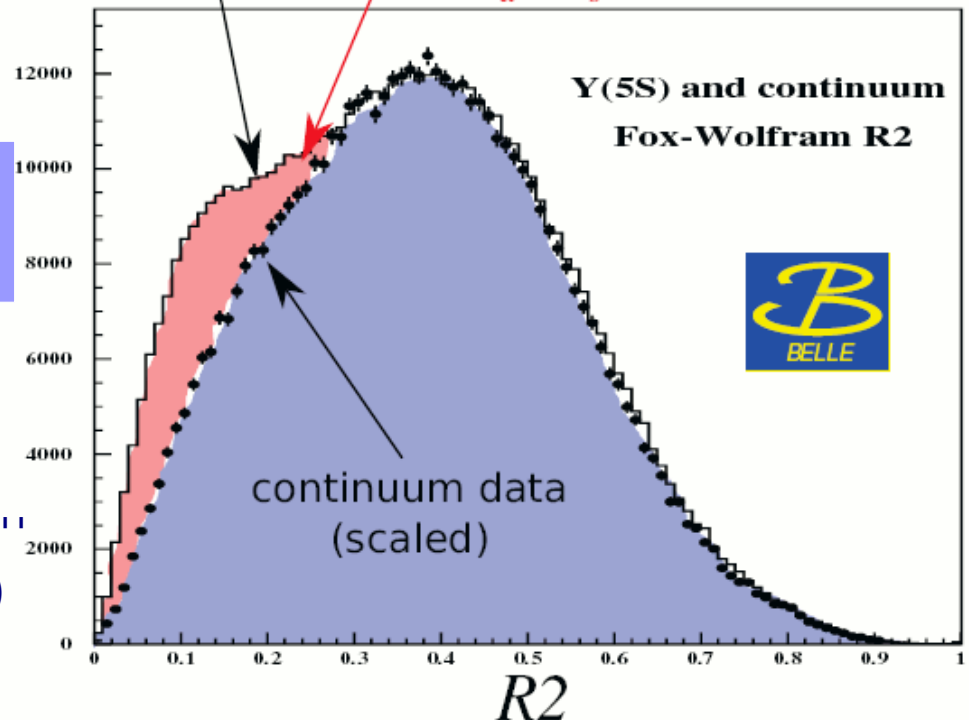
$$= \frac{1}{L_{5S}} \frac{1}{\epsilon_{5S}^{b\bar{b}}} (N_{5S}^{\text{had}} - \underbrace{N_{\text{cont}}^{\text{had}} \frac{L_{5S}}{L_{\text{cont}}} \frac{E_{\text{cont}}^2}{E_{5S}^2} \frac{\epsilon_{5S}^{\text{rec}}}{\epsilon_{\text{cont}}^{\text{rec}}}}_{\text{scaling factor}})$$

Continuum data below open-beauty threshold

On resonance data

resonance data  
(1.86 /fb)

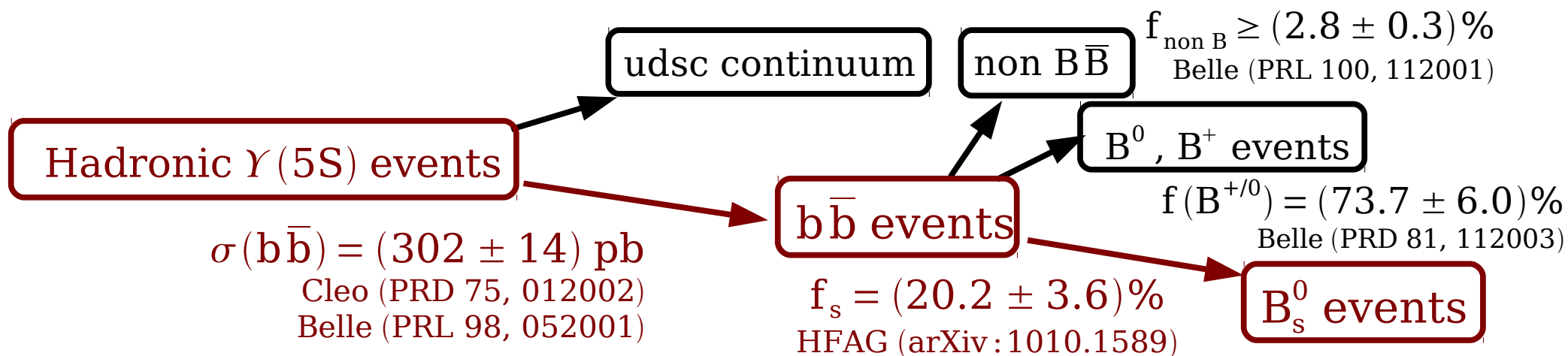
$B^+, B_d, B_s$



$R_2$ : 2nd Fox-Wolfram moment  $\sim$  event "jettiness"  
 $\rightarrow$  smaller values for  $B\bar{B}$  events (more spherical)

(measurement done with  $1.86 \text{ fb}^{-1}$ )

# $B_s$ production at $\Upsilon(5S)$



$f_s$  = fraction of  $B_s$ . Inclusive measurements:

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

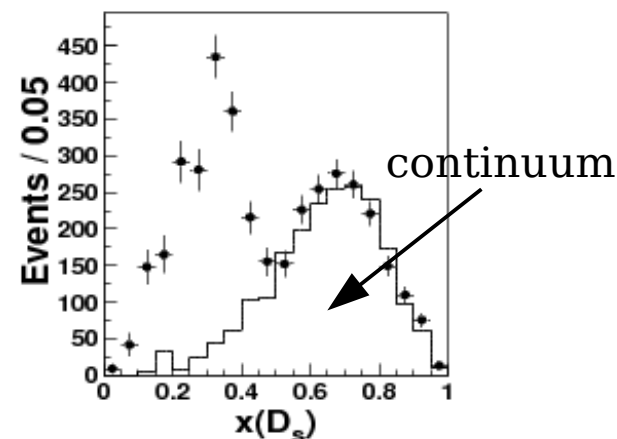
**15% uncertainty**, mainly due to model-dependent estimate

**$\Rightarrow$  dominant systematics for our branching fractions**

In  $121 \text{ fb}^{-1}$ :

$$N_{B_s^0} = 2 L_{\text{int}} \cdot \sigma(b\bar{b}) \cdot f_s \approx 14 \times 10^6$$

measurement with  $1.86 \text{ fb}^{-1}$



# $B_s$ production at $\Upsilon(5S)$

3 productions modes:

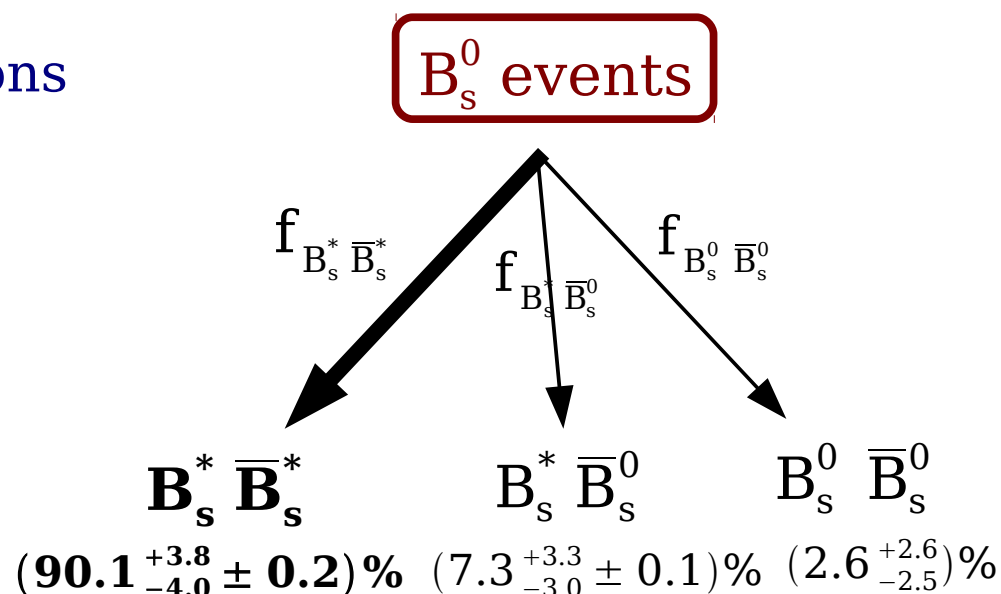
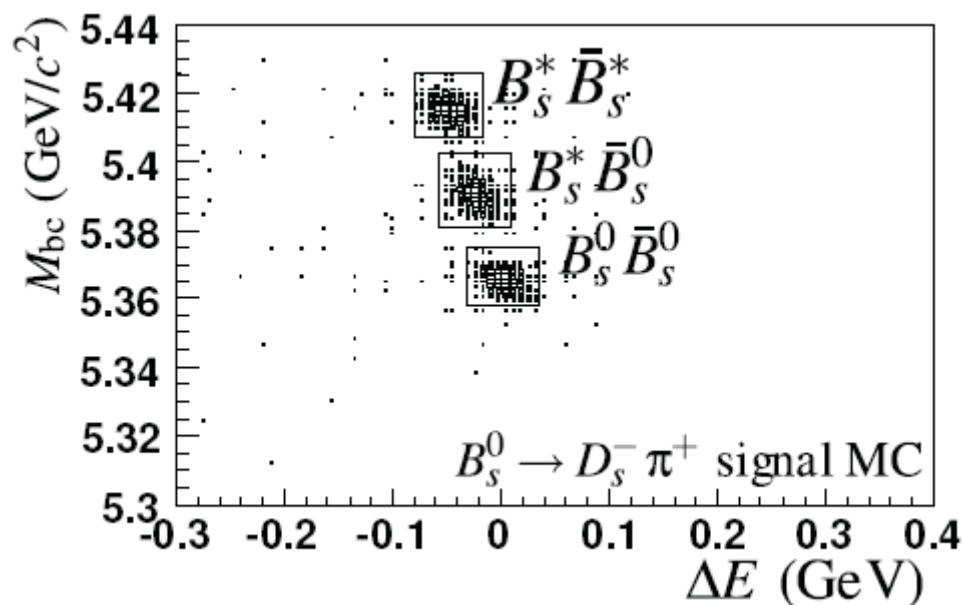
$$\Upsilon(5S) \rightarrow B_s^* \bar{B}_s^*, \quad \Upsilon(5S) \rightarrow B_s^* \bar{B}_s^0, \quad \Upsilon(5S) \rightarrow B_s^0 \bar{B}_s^0$$

$B_s^* \rightarrow B_s^0 \gamma$  is not reconstructed ( $\gamma$  too soft)

Full reconstruction of the  $B_s^0$  with observables: ( $E_b^* = \sqrt{s}/2$ )

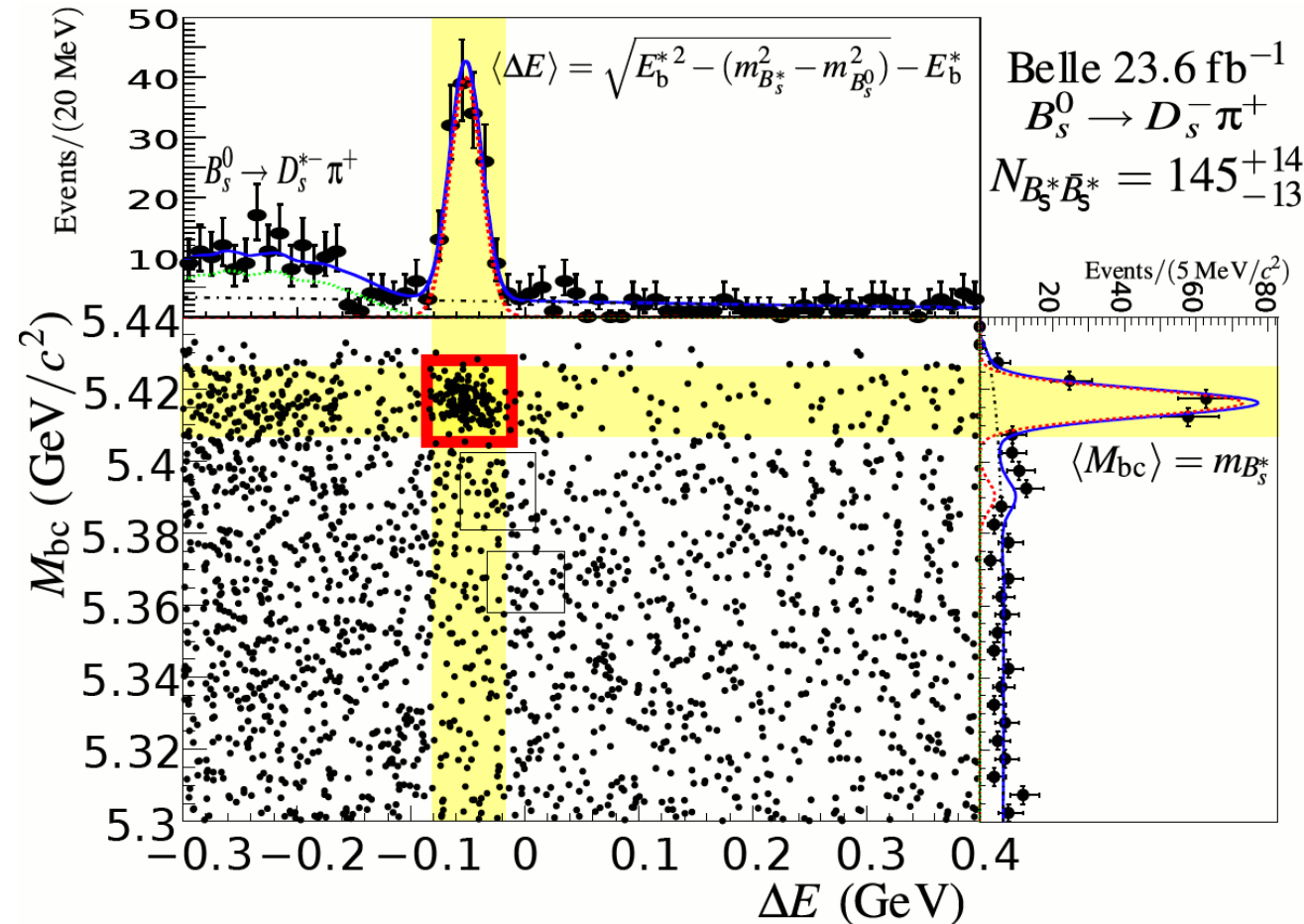
- **Beam-constrained mass:**  $M_{bc} = \sqrt{E_b^{*2} - \mathbf{p}_{B_s^0}^{*2}}$
- **Energy difference:**  $\Delta E = E_{B_s^0}^* - E_b$

$\Rightarrow B_s^0$  candidates are in 3 signal regions



# Study of $B_s^0 \rightarrow D_s^- \pi^+$

Phys. Rev. Lett. **102**, 021801 (2009)



$$f_{B_s^* \bar{B}_s^*} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$$

$$m_{B_s^*} = (5416.4 \pm 0.4 \pm 0.5) \text{ MeV}/c^2$$

$$m_{B_s^0} = (5364.4 \pm 1.3 \pm 0.7) \text{ MeV}/c^2$$

$$B(B_s^0 \rightarrow D_s^- \pi^+) = (3.67^{+0.35}_{-0.33} {}^{+0.43}_{-0.42} \pm 0.49 (f_s)) \times 10^{-3}$$

- 20% uncertainties,  $f_s$  is a crucial source of systematics
- large  $f_{B_s^* \bar{B}_s^*}$  confirmed (1st Belle value:  $(93^{+7}_{-9} \pm 1)\%$  [PRD 76, 012002 (07)])
- $m_{B_s^*}$  is  $2.6\sigma$  larger than CLEO [PRL 96, 152001 (06)]
- $m_{B_s^*}$  ( $m_{B_s}$ ) is the 1st (2nd) most precise measurement so far

# $B_s \rightarrow$ CP eigenstates decays and more...

- CP eigenstates:

- $B_s \rightarrow KK$
- $B_s \rightarrow J/\psi \phi$  (especially BR)
- $B_s \rightarrow J/\psi f_0(980)$  (silver mode at LHCb to measure  $\beta_s$ )
- $B_s \rightarrow J/\psi \eta, J/\psi \eta', J/\psi K_S^0 \dots$

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

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

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

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

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

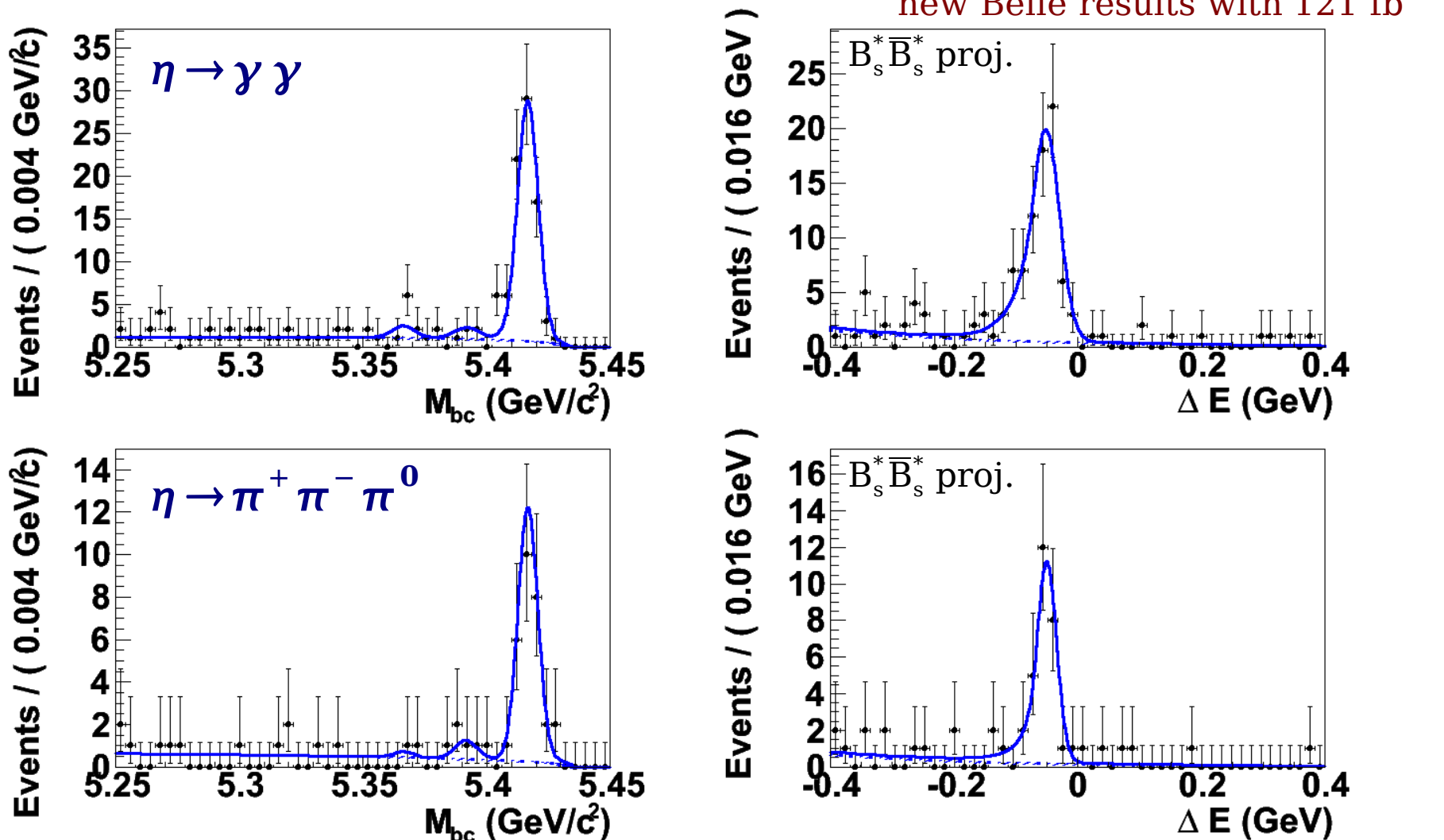
- Dominates  $\Delta \Gamma$  (this relation has few % theoretical uncertainty)

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

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

# $B_s^0 \rightarrow \text{CP-eigenstate Decay Modes}$

- Large data sample recorded at  $\Upsilon(5S)$  ( $121 \text{ fb}^{-1}$ )
- Precise measurements of exclusive modes, including CP modes  
for example, "Observation of  $B_s^0 \rightarrow J/\psi f_0(980)\dots$ ", PRL 106, 121802 (2011)
- $B_s \rightarrow J/\psi \eta$  in  $\eta \rightarrow \gamma\gamma, \eta \rightarrow \pi^+\pi^-\pi^0$  channels**



$$\text{Br}(B_s \rightarrow J/\psi \eta) = (5.11 \pm 0.50 \text{ (stat)} \pm 0.35 \text{ (syst)} \pm 0.68 \text{ (f}_s\text{)}) \times 10^{-4}$$

# $\mathbf{B}_s^0 \rightarrow \mathbf{D}_s^{(*)+} \mathbf{D}_s^{(*)-}$ Analysis

Preliminary, summer 2011

- CP-even final states
  - $\mathbf{D}_s^+ \mathbf{D}_s^-$  pure CP-even
  - $\mathbf{D}_s^{*+} \mathbf{D}_s^{*-}$  predominantly CP-even
- In the heavy-quark limit, while  $(m_b - 2m_c) \rightarrow 0$  and  $N_c \rightarrow \infty$ 
  - $b \rightarrow c \bar{c} s$  processes contribute constructively to  $\Delta \Gamma_s$
  - $\Gamma[\mathbf{B}_s^0 (\text{CP}+) \rightarrow \mathbf{D}_s \mathbf{D}_s]$  saturates  $\Delta \Gamma_s^{\text{CP}}$
  - assuming negligible CP violation, we can estimate  $\Delta \Gamma_s / \Gamma_s$

$$\frac{\Delta \Gamma_s}{\Gamma_s} = \frac{2 \times \mathbf{B}(\mathbf{B}_s^0 \rightarrow \mathbf{D}_s^{(*)+} \mathbf{D}_s^{(*)-})}{1 - \mathbf{B}(\mathbf{B}_s^0 \rightarrow \mathbf{D}_s^{(*)+} \mathbf{D}_s^{(*)-})}$$

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

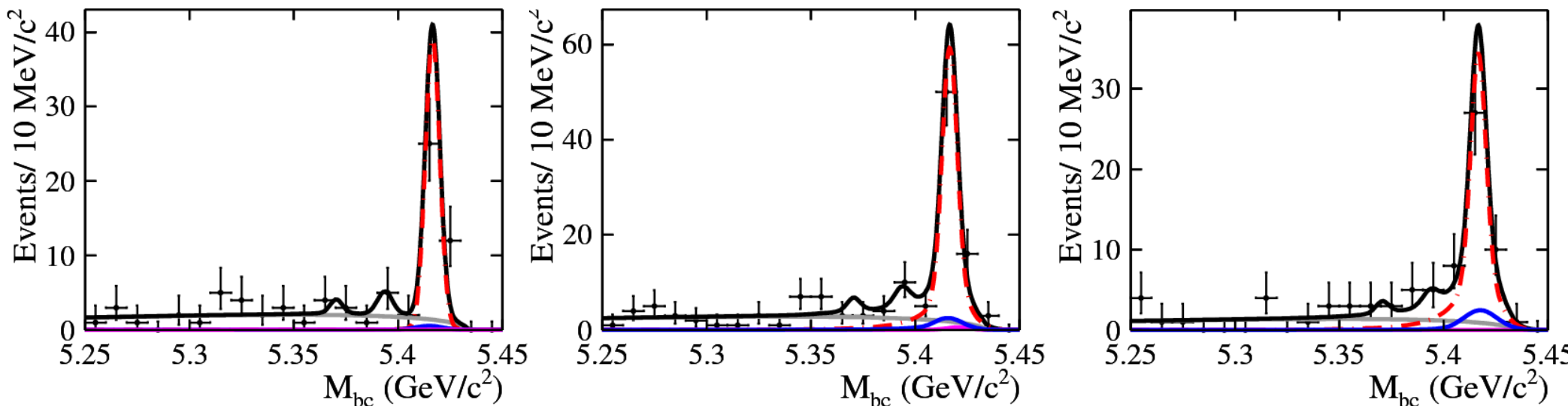
- Full reconstruction of  $\mathbf{B}_s^0 \rightarrow \mathbf{D}_s^{(*)+} \mathbf{D}_s^{(*)-}$ : large B.R. ( $\sim 10^{-2}$ ) but low efficiency ( $\sim 10^{-4}$ )
- $\mathbf{D}_s^+$  reconstructed in 6 final states:  $\phi \pi^+$ ,  $\mathbf{K}_S^0 \mathbf{K}^+$ ,  $\bar{\mathbf{K}}^{*0} \mathbf{K}^+$ ,  $\phi \rho^+$ ,  $\mathbf{K}_S^0 \mathbf{K}^{*+}$  and  $\bar{\mathbf{K}}^{*0} \mathbf{K}^{*+}$
- $\mathbf{D}_s^{*+} \rightarrow \mathbf{D}_s^+ \gamma$ : photon energy is low ( $E_\gamma < 150 \text{ MeV}$ ) !
- Contamination between the 3 modes (cross feed) when a photon is missing or added by error

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

Preliminary  
summer 2011

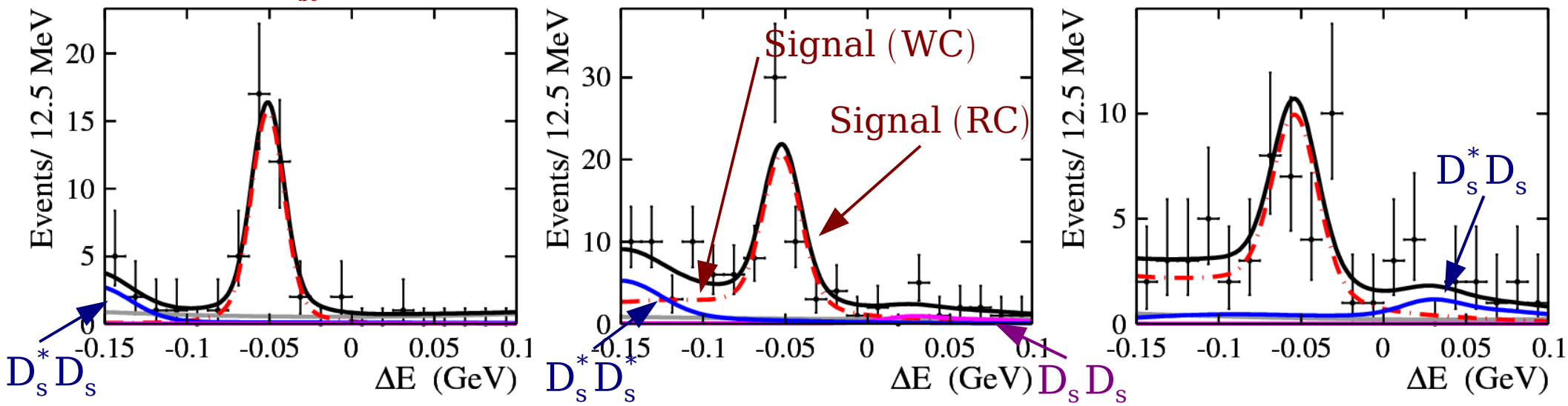
- Simultaneous fit of the 3 modes. For each mode, cross feed from the 2 others is included
- Signal has 2 components: right and wrong combinations

select events in  $\Delta E \in [-0.1, 0.0]$



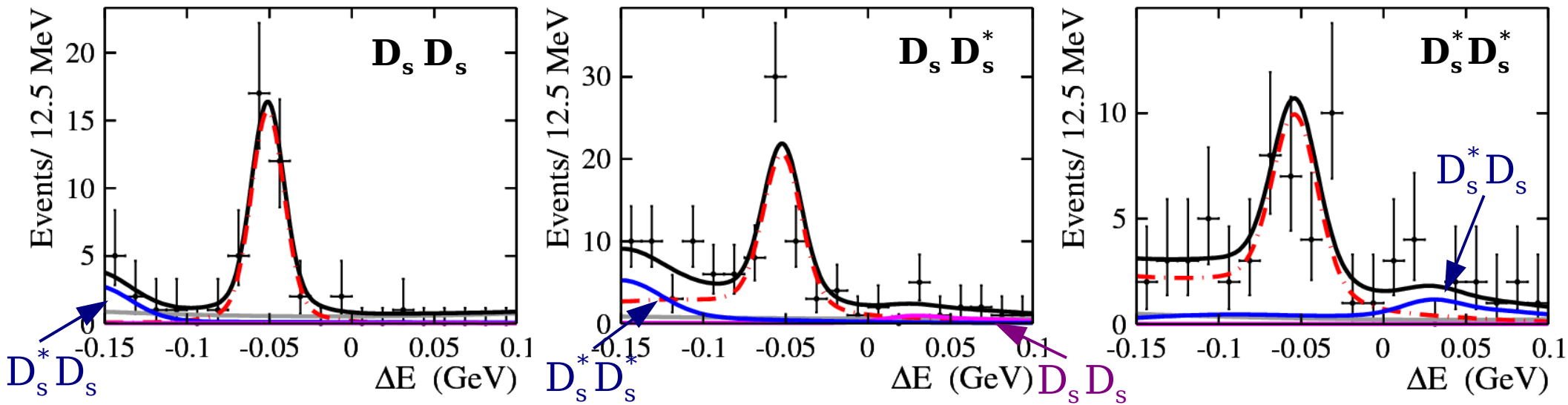
$$N_S(D_s^\pm D_s^\mp) = 33.1^{+6.0}_{-5.4} (11.6\sigma) \quad N_S(D_s^{*\pm} D_s^\mp) = 44.5^{+5.8}_{-5.5} (13.3\sigma) \quad N_S(D_s^{*\pm} D_s^{*\mp}) = 24.4^{+4.1}_{-3.6} (8.6\sigma)$$

select events in  $M_{bc} \in [5.4, 5.43]$



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

Preliminary, summer 2011



$\Rightarrow$  3 modes are seen separately (102 signal events)

$$B(B_s^0 \rightarrow D_s^+ D_s^-) = (0.58^{+0.11}_{-0.09} \pm 0.13)\%$$

consistent with CDF [PRL 100, 021803]

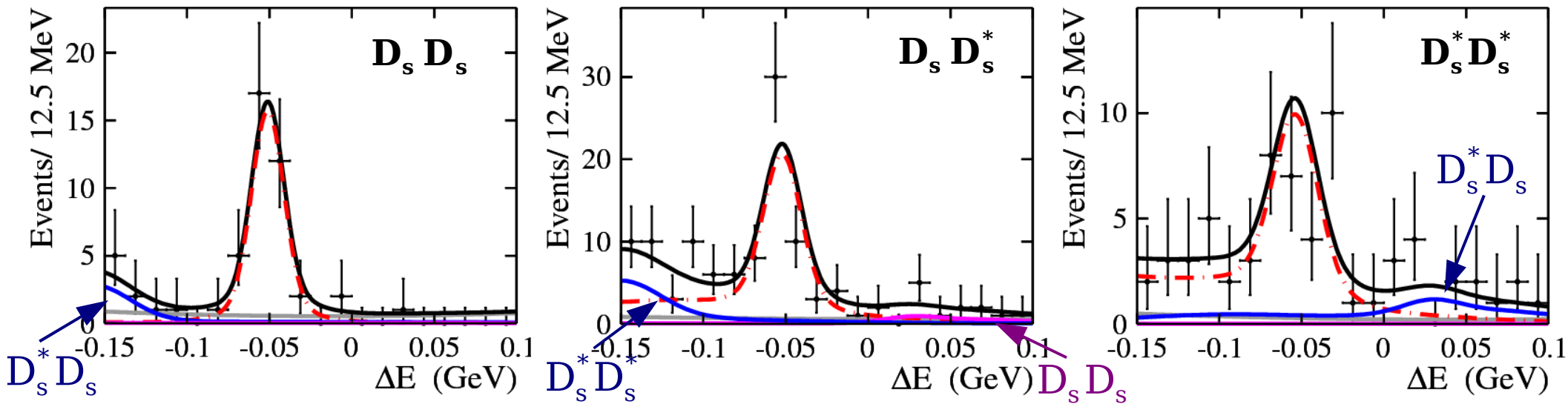
$$B(B_s^0 \rightarrow D_s^{*\pm} D_s^\mp) = (1.8 \pm 0.2 \pm 0.4)\% \Rightarrow B(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%$$

$$B(B_s^0 \rightarrow D_s^{*+} D_s^{*-}) = (2.0 \pm 0.3 \pm 0.5)\%$$

first observation

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

Preliminary, summer 2011



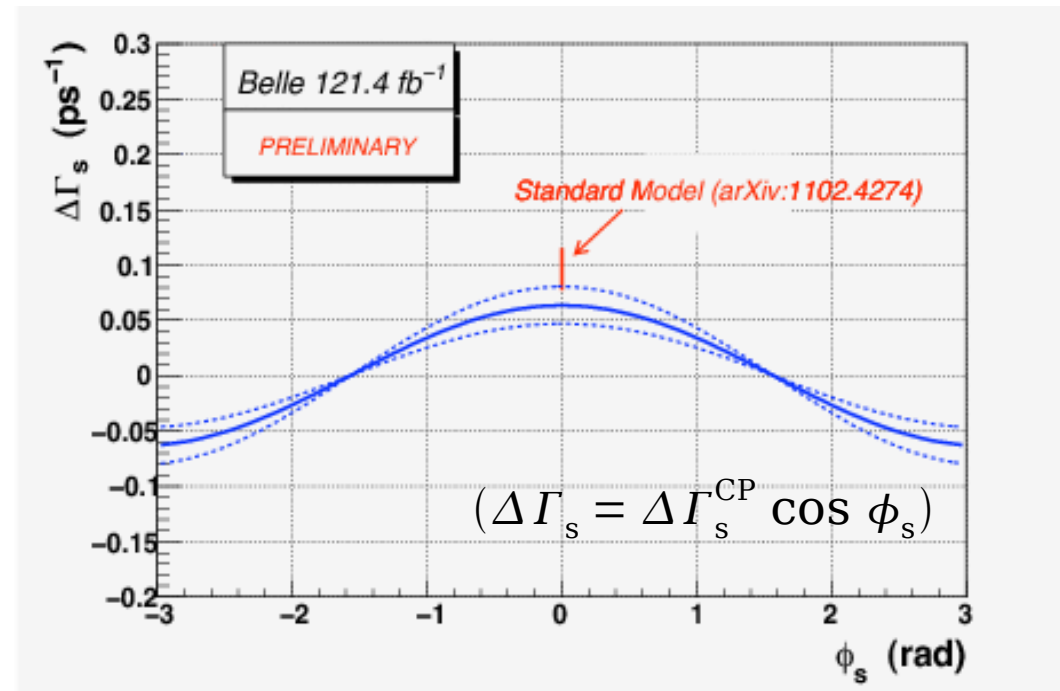
$$B(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%$$

$$\Delta\Gamma_s / \Gamma_s = 2B / (1 - B)$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = (9.0 \pm 0.9 \pm 2.2)\%$$

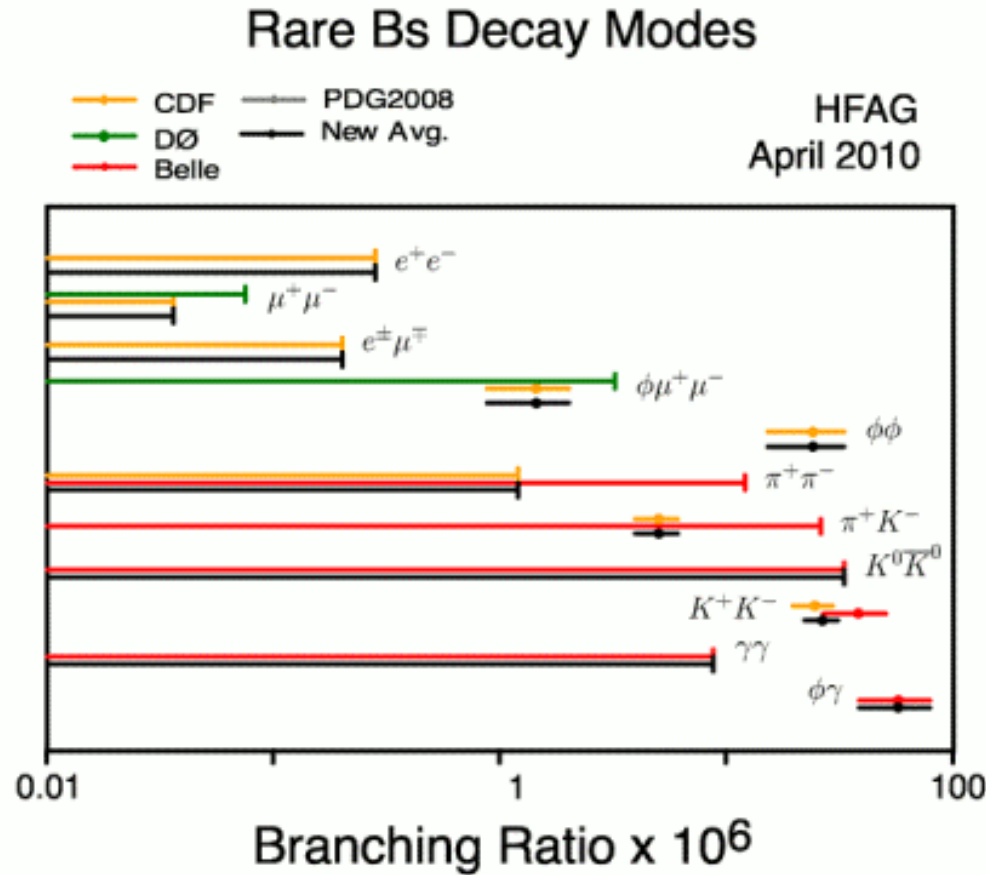
CDF:  $(12 \pm 10)\%$  [PRL 100, 121803]

D0:  $(7.2 \pm 3.0)\%$  [PRL 102, 091801]



# Rare $B_s$ decays

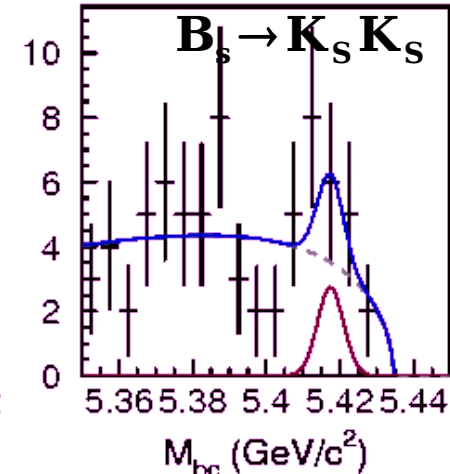
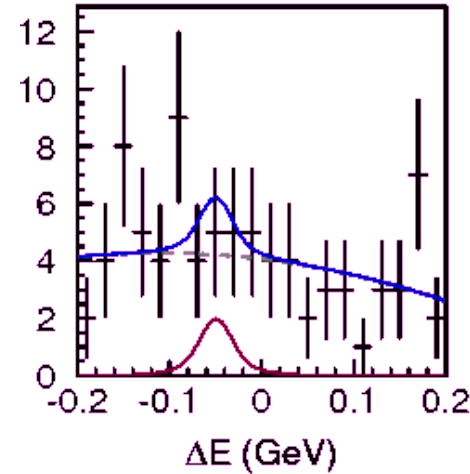
(still using 1/5 of the  $\Upsilon(5S)$  data sample available)



⇒ complementarity between B-factories and LHCb

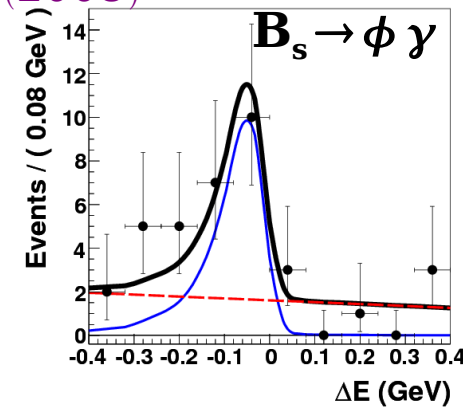
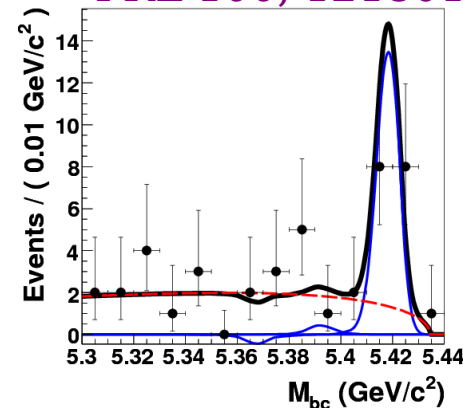
Belle can do neutrals, cleaner, but have less statistics...

arXiv:1006.5115

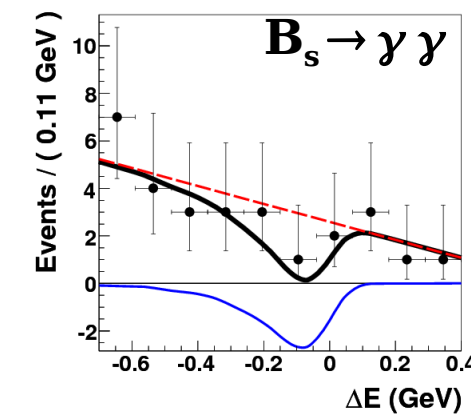
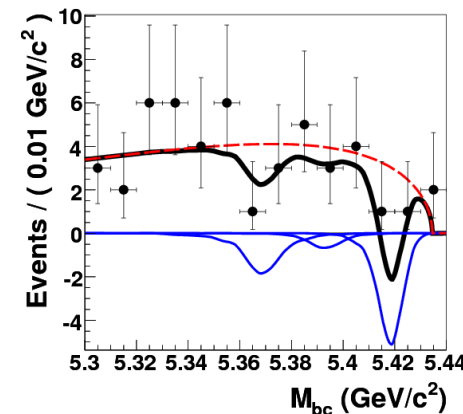


$$B(B_s \rightarrow K^0 \bar{K}^0) < 6.6 \times 10^{-5} \text{ @ 90\% C.L.}$$

PRL 100, 121801 (2008)



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



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

# Nature of $\Upsilon(5S)$

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

PRL 100, 112001 (2008)  $\Gamma$  (MeV)

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

$\times 10^2$

1. Rescattering  $\Upsilon(5S) \rightarrow BB\pi\pi \rightarrow \Upsilon(nS)\pi\pi$  ?

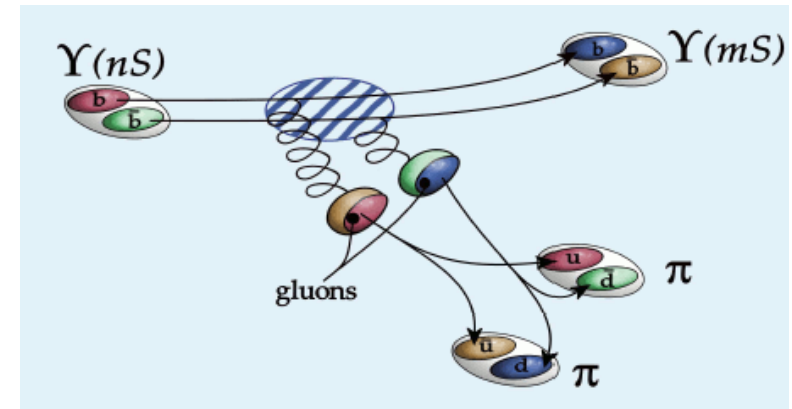
Simonov, JETP Lett 87, 147 (2008)

2. Similar effect as in charmonium ?

$\Rightarrow$  assume a  $Y_b$  exists close to  $\Upsilon(5S)$

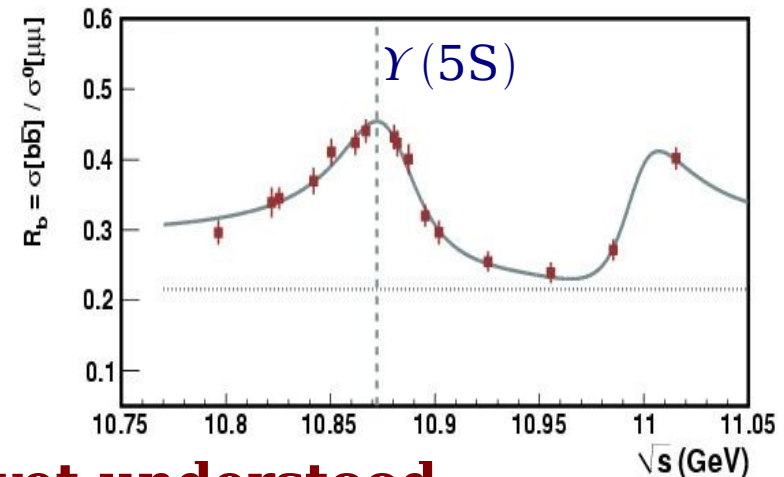
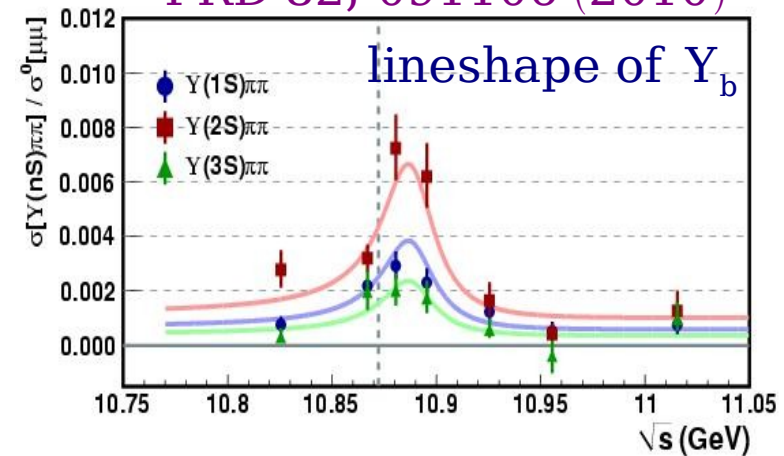
to distinguish them: energy scan  $\rightarrow$

$\Rightarrow$  shapes of  $R_b$  and  $\sigma(Y\pi\pi)$  different (only  $2\sigma$ )



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

PRD 82, 091106 (2010)



**Nature of  $\Upsilon(5S)$  is puzzling and not yet understood**

# Looking for $h_b(nP)$

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

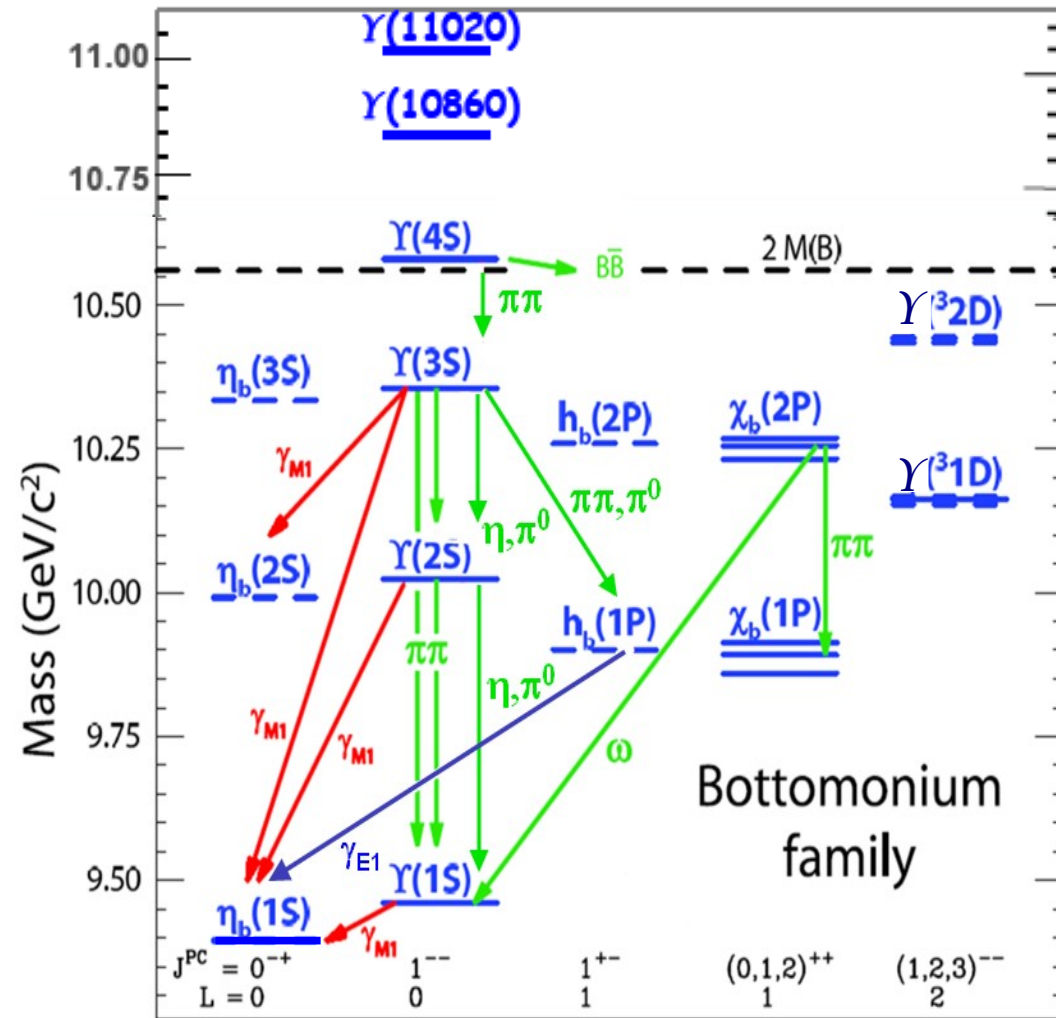
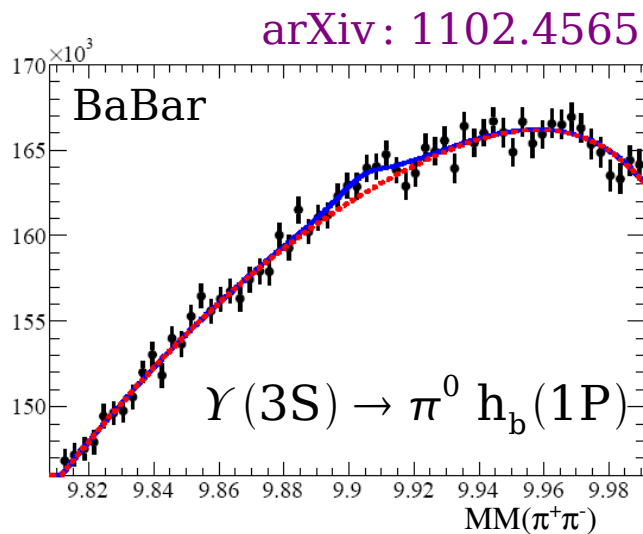
$(b\bar{b})$ :  $S=0, L=1, J^{PC}=1^{+-}$

Expected mass

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

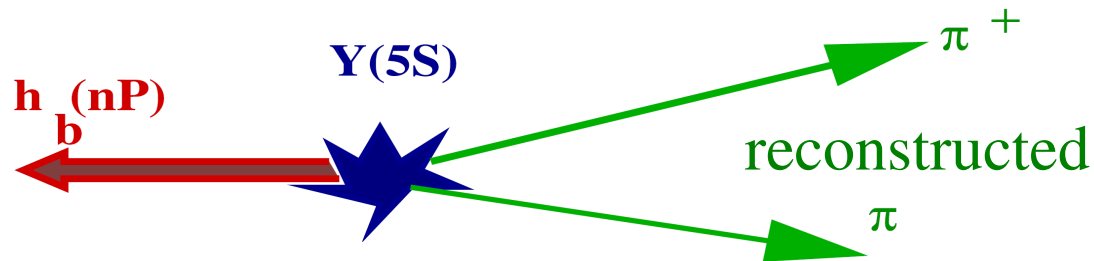
$\Delta M_{\text{HF}} \Rightarrow$  test of hyperfine interaction

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



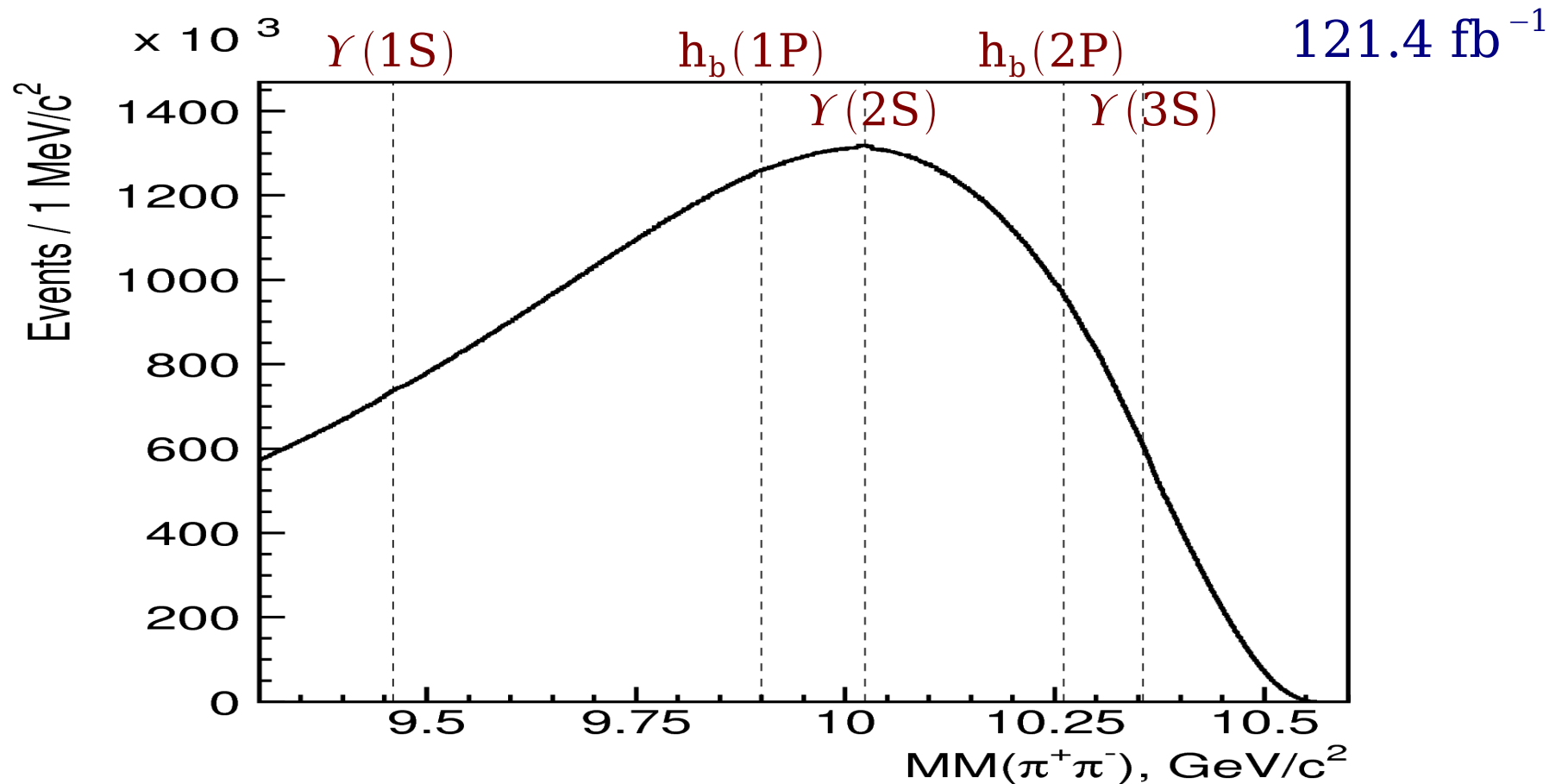
# $\Upsilon(5S) \rightarrow h_b \pi^+ \pi^-$ reconstruction

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



"Missing mass"

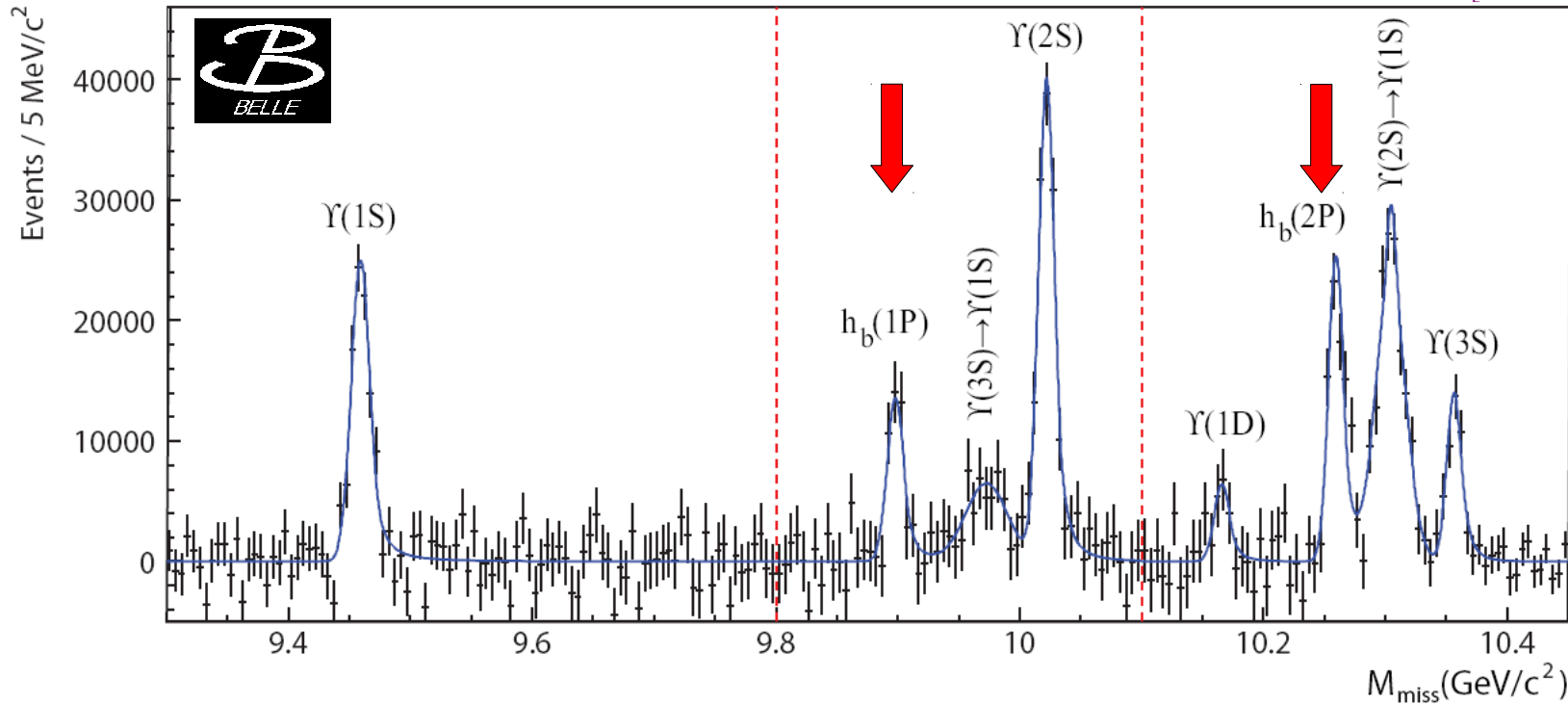
$$M(h_b) = \sqrt{(E_{\text{CM}} - E_{\pi^+ \pi^-}^*)^2 - \mathbf{p}_{\pi^+ \pi^-}^{*2}} \equiv M_{\text{miss}}(\pi^+ \pi^-)$$



# Results

121.4 fb<sup>-1</sup>

[arXiv:1103.3419]



|                           | Yield, 10 <sup>3</sup>                      | Mass, MeV/c <sup>2</sup>                      | Significance |
|---------------------------|---------------------------------------------|-----------------------------------------------|--------------|
| Υ(1S)                     | 105.2 ± 5.8 ± 3.0                           | 9459.4 ± 0.5 ± 1.0                            | 18.2 σ       |
| <i>h<sub>b</sub></i> (1P) | 50.4 ± 7.8 <sup>+4.5</sup> <sub>-9.1</sub>  | 9898.3 ± 1.1 <sup>+1.0</sup> <sub>-1.1</sub>  | 6.2 σ        |
| 3S → 1S                   | 56 ± 19                                     | 9973.01                                       | 2.9 σ        |
| Υ(2S)                     | 143.5 ± 8.7 ± 6.8                           | 10022.3 ± 0.4 ± 1.0                           | 16.6 σ       |
| Υ(1D)                     | 22.0 ± 7.8                                  | 10166.2 ± 2.6                                 | 2.4 σ        |
| <i>h<sub>b</sub></i> (2P) | 84.4 ± 6.8 <sup>+23.</sup> <sub>-10.</sub>  | 10259.8 ± 0.6 <sup>+1.4</sup> <sub>-1.0</sub> | 12.4 σ       |
| 2S → 1S                   | 151.7 ± 9.7 <sup>+9.0</sup> <sub>-20.</sub> | 10304.6 ± 0.6 ± 1.0                           | 15.7 σ       |
| Υ(3S)                     | 45.6 ± 5.2 ± 5.1                            | 10356.7 ± 0.9 ± 1.1                           | 8.5 σ        |

Significance  
w/ systematics

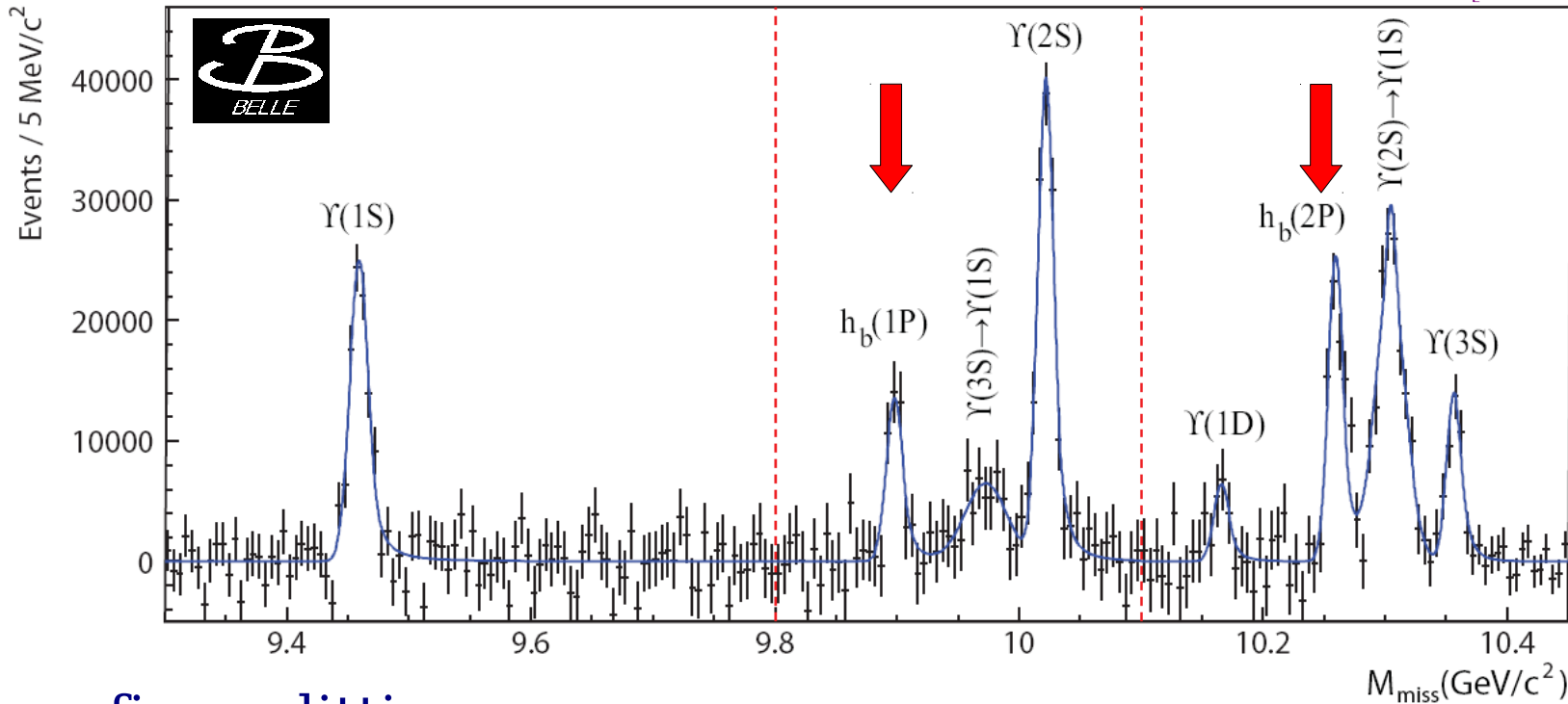
*h<sub>b</sub>*(1P) 5.5 σ

*h<sub>b</sub>*(2P) 11.2 σ

# Results

121.4 fb<sup>-1</sup>

[arXiv:1103.3419]



## Hyperfine splitting

deviations from CoG of  $\chi_{bj}$  masses  
consistent with zero, as expected

$(1.6 \pm 1.5) \text{ MeV}/c^2$  for  $h_b(1P)$

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

## Ratio of production rates

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

splin- flip 
  
no splin- flip 

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

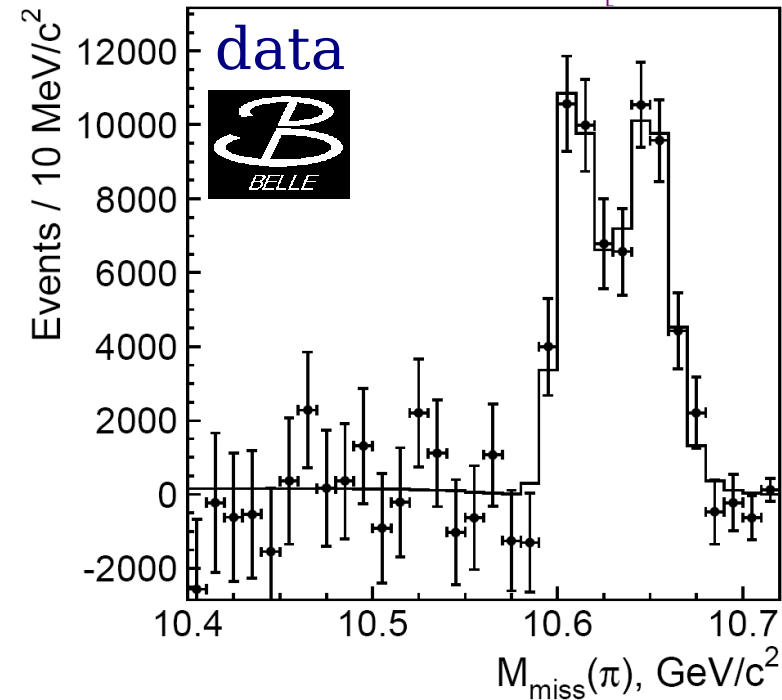
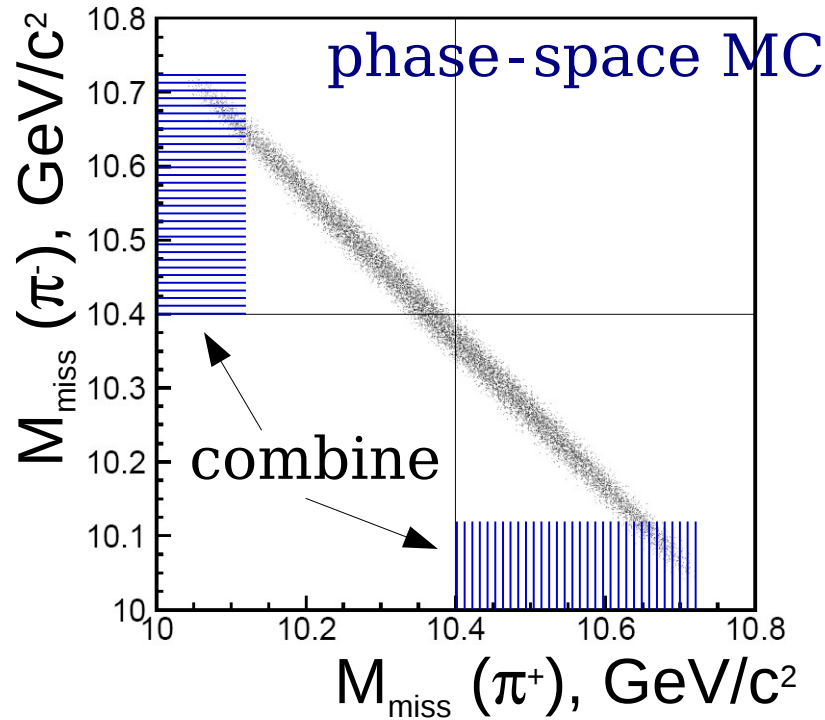
**Mechanism of  $\Upsilon(5S) \rightarrow h_b(nP) \pi^+ \pi^-$  decay seems exotic !** [arXiv:1108.2197]

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

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

121.4 fb<sup>-1</sup>

[arXiv:1110.2251]



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

Results

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

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

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

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

Significances

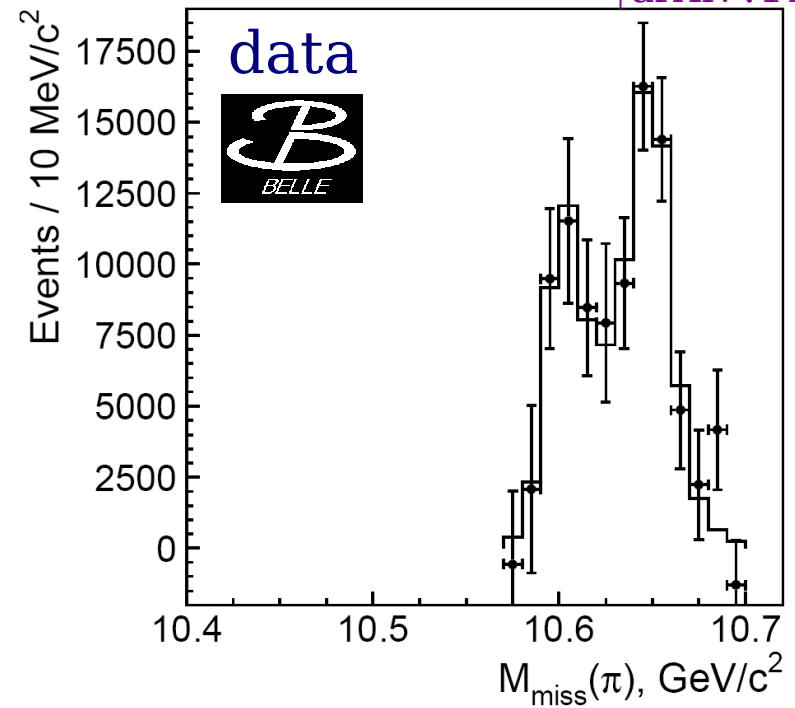
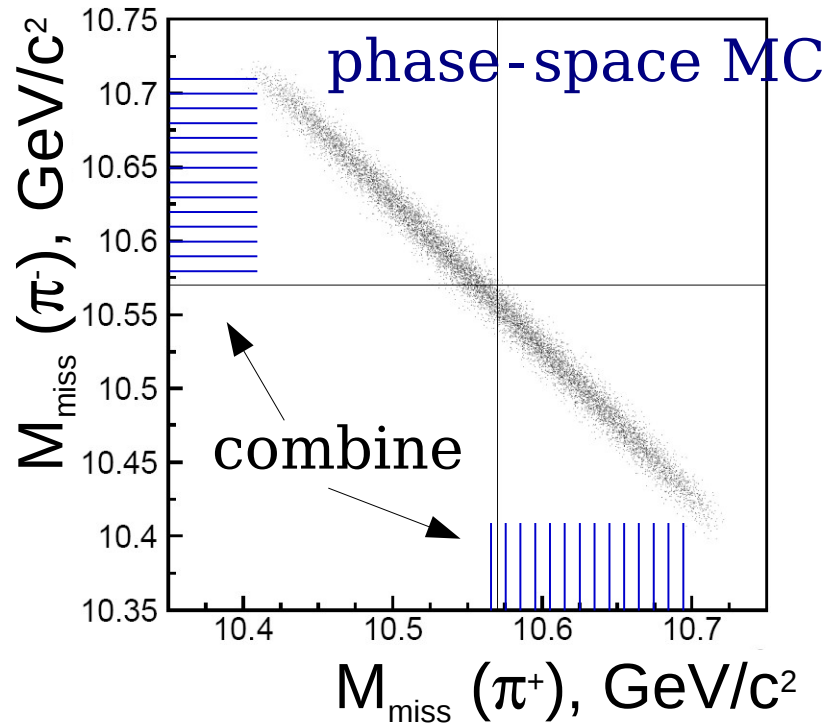
18 $\sigma$  (16 $\sigma$  w/syst)

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

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

121.4 fb<sup>-1</sup>

[arXiv:1110.2251]



**$h_b(1P) \pi^+ \pi^-$**

$$M_1 = 10605 \pm 2^{+3}_{-1} \text{ MeV}/c^2$$

$$\Gamma_1 = 11.4^{+4.5}_{-3.9} {}^{+2.1}_{-1.2} \text{ MeV}$$

$$M_2 = 10654 \pm 3^{+1}_{-2} \text{ MeV}/c^2$$

$$\Gamma_2 = 20.9^{+5.4}_{-4.7} {}^{+2.1}_{-5.7} \text{ MeV}$$

$$a = 1.39 \pm 0.37^{+0.05}_{-0.15}$$

$$\phi = (187^{+44}_{-57} {}^{+3}_{-12})^\circ$$

**$h_b(2P) \pi^+ \pi^-$  (consistent)**

$$10599^{+6}_{-3} {}^{+5}_{-4} \text{ MeV}/c^2$$

$$13^{+10}_{-8} {}^{+9}_{-7} \text{ MeV}$$

$$10651^{+2}_{-3} {}^{+3}_{-2} \text{ MeV}/c^2$$

$$19 \pm 7^{+11}_{-7} \text{ MeV}$$

$$1.6^{+0.6}_{-0.4} {}^{+0.4}_{-0.6}$$

$$(181^{+65}_{-105} {}^{+74}_{-109})^\circ$$

Significances

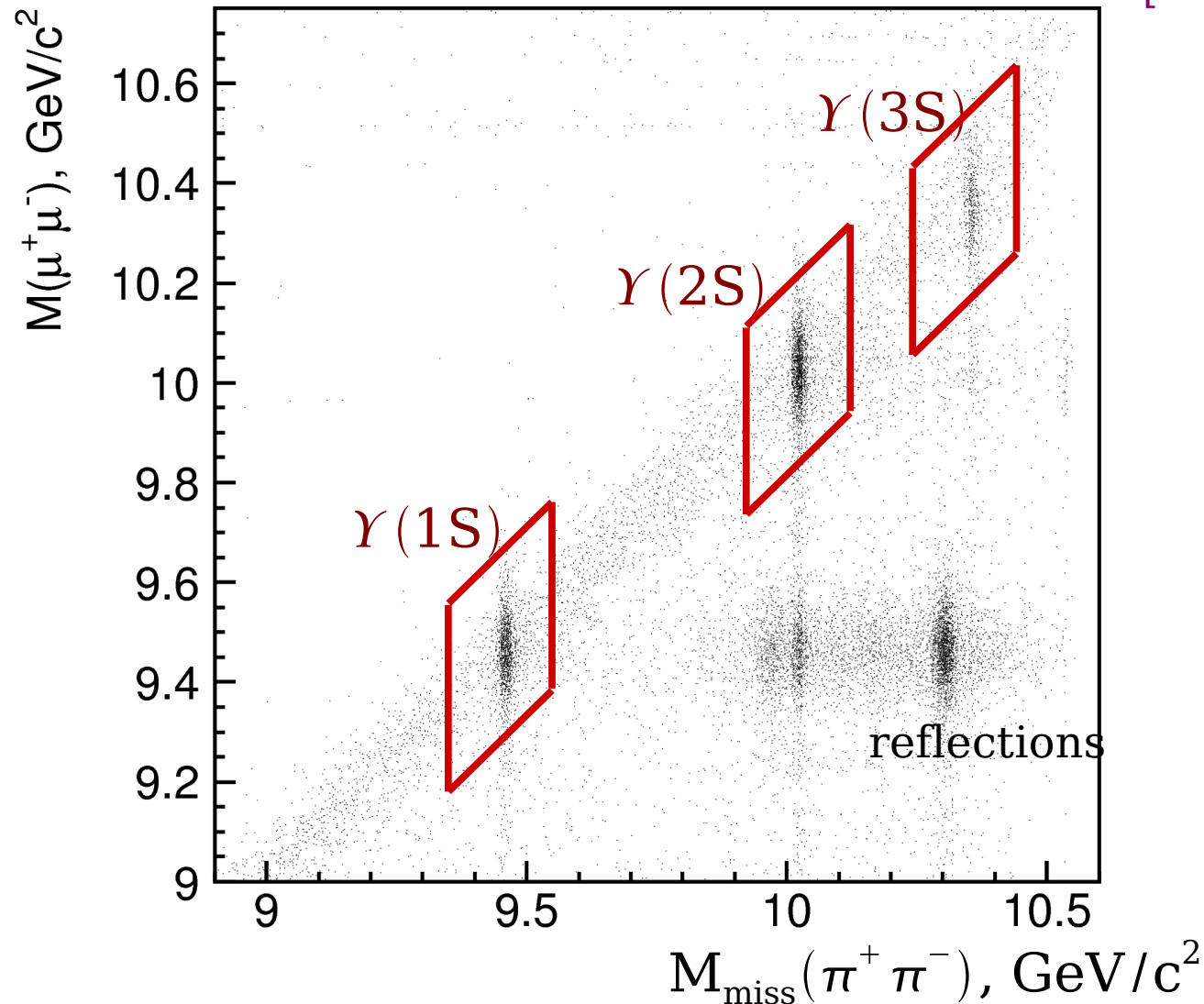
6.7 $\sigma$  (5.6 $\sigma$  w/syst)

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

( $n = 1, 2, 3$ )

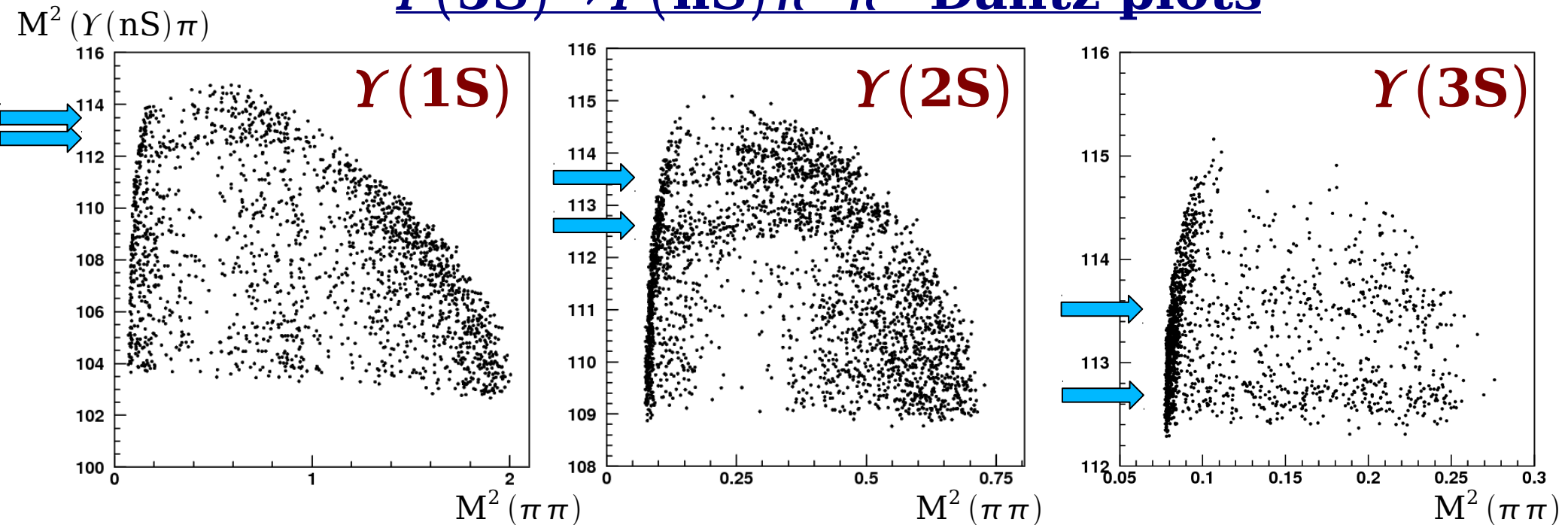
$121.4 \text{ fb}^{-1}$

[arXiv:1110.2251]



Note:  $\Upsilon(nS) \rightarrow \mu^+ \mu^-$

# $\Upsilon(5S) \rightarrow \Upsilon(nS) \pi^+ \pi^-$ Dalitz plots



⇒ **two resonances**

⇒ **clear signs of interference ⇒ amplitude analysis is required**

Signal amplitude parameterization:

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

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

Flatte

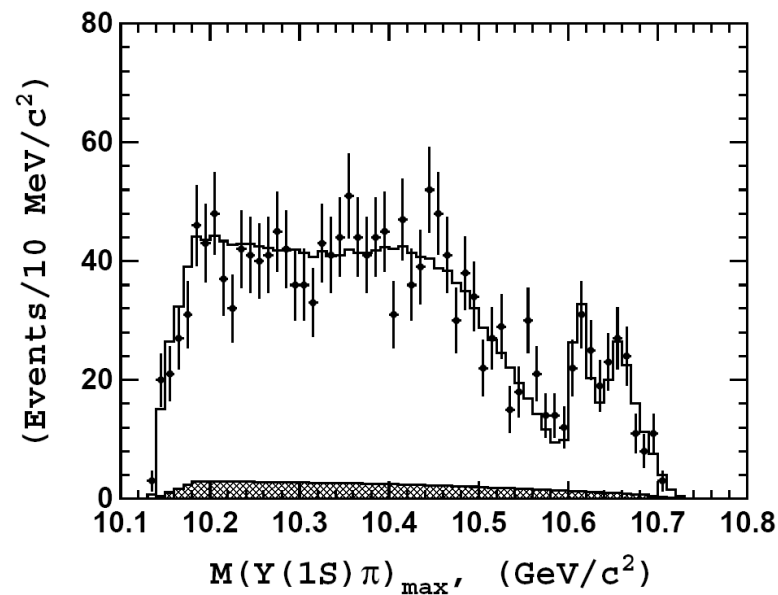
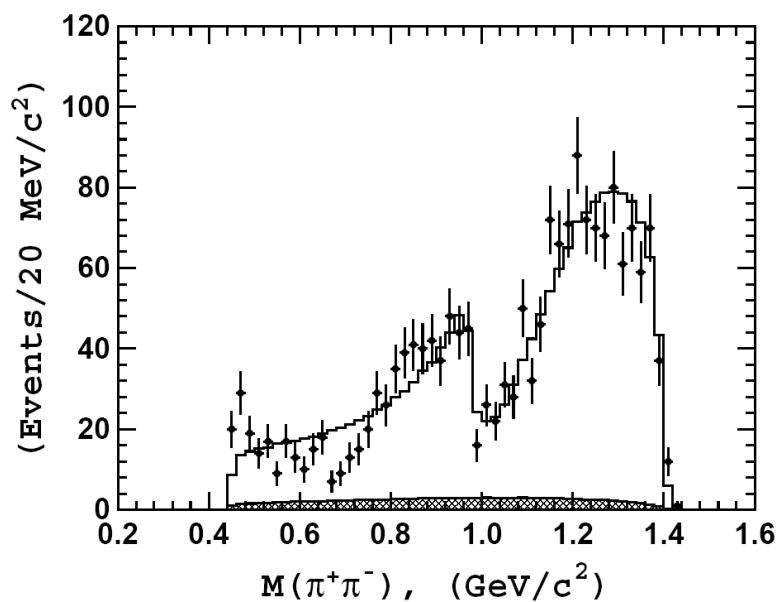
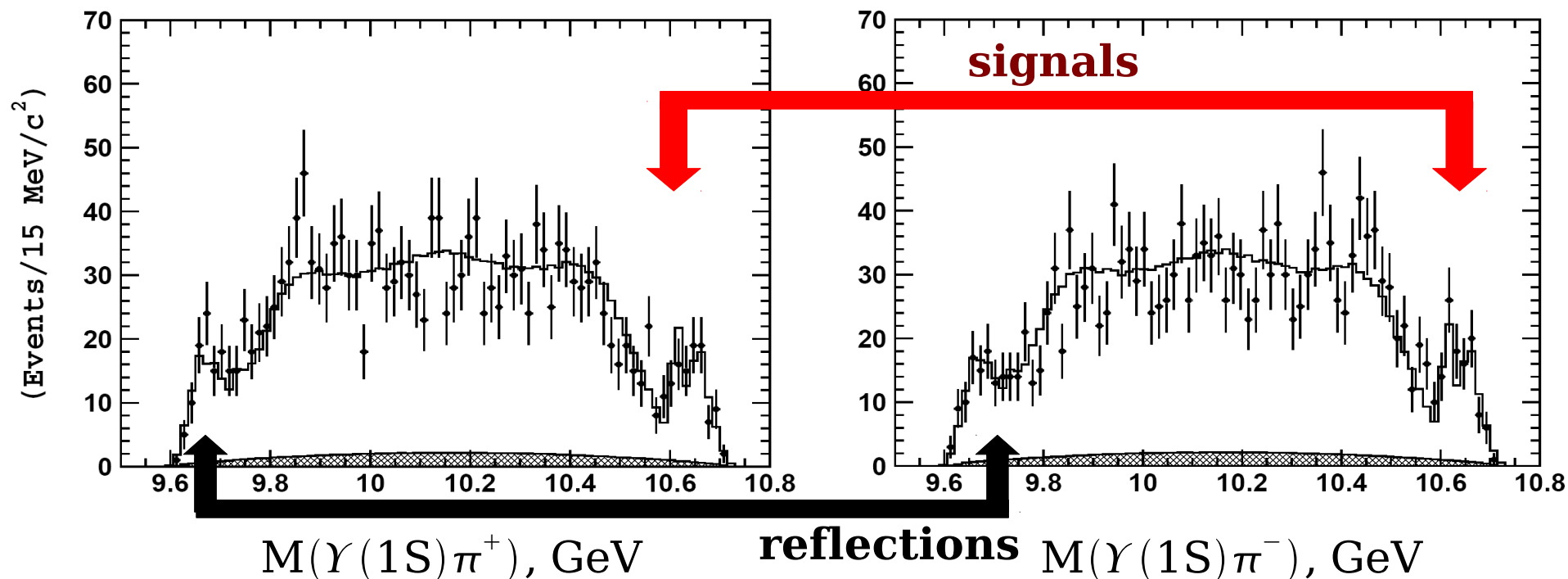
Breit-Wigner

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

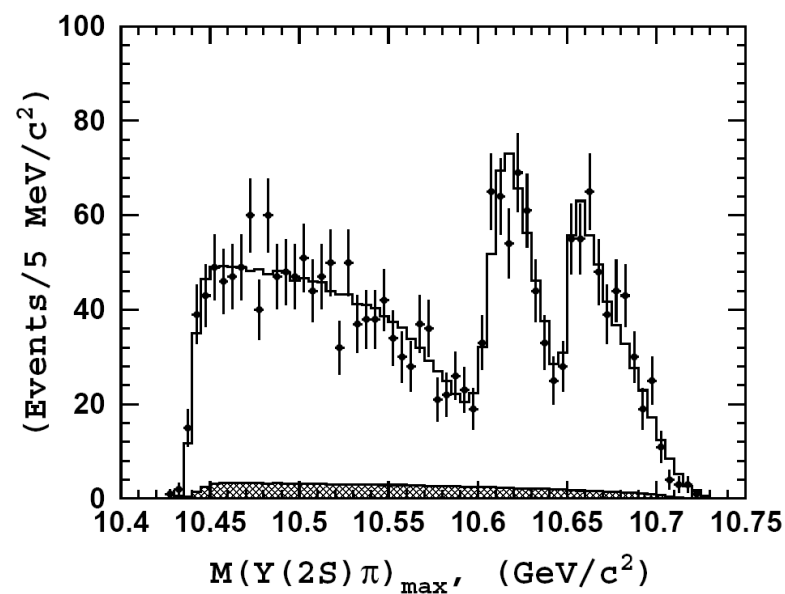
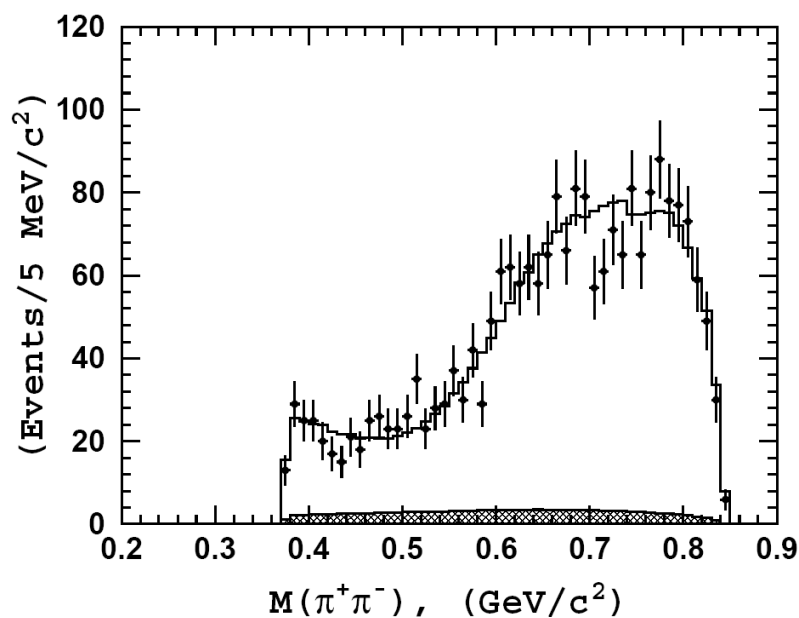
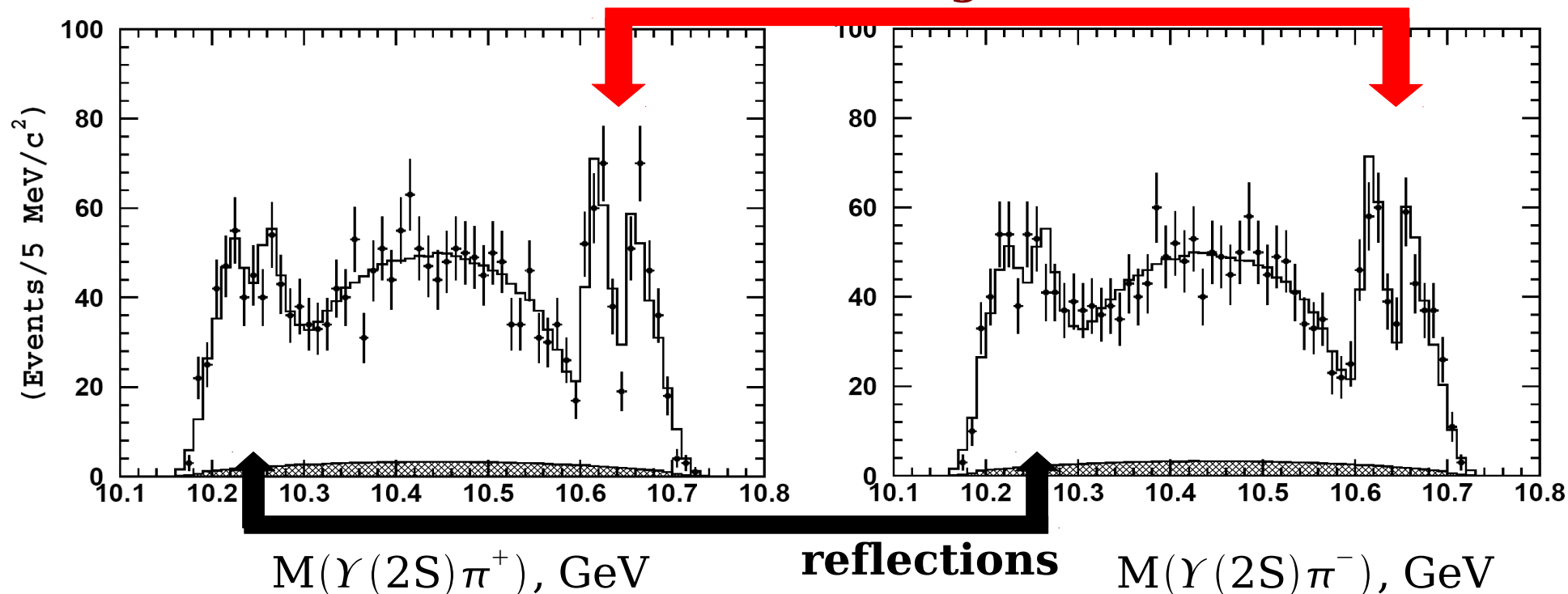
# Results: $\Upsilon(1S)\pi^+\pi^-$



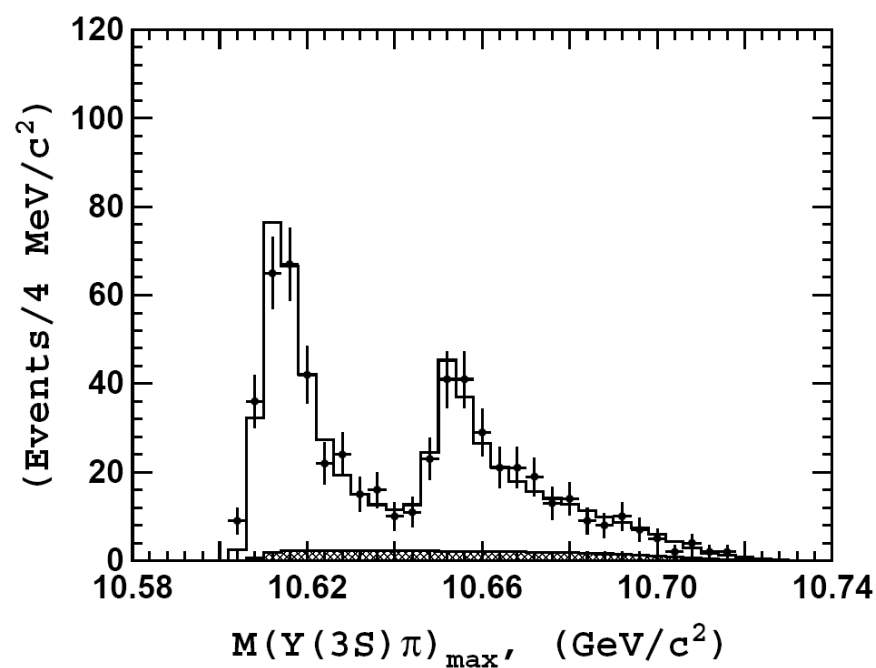
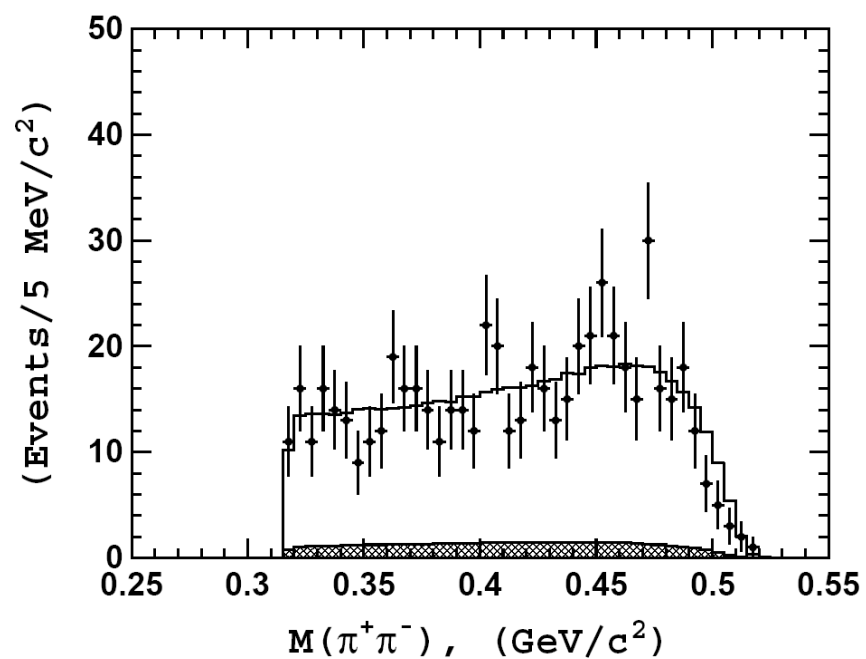
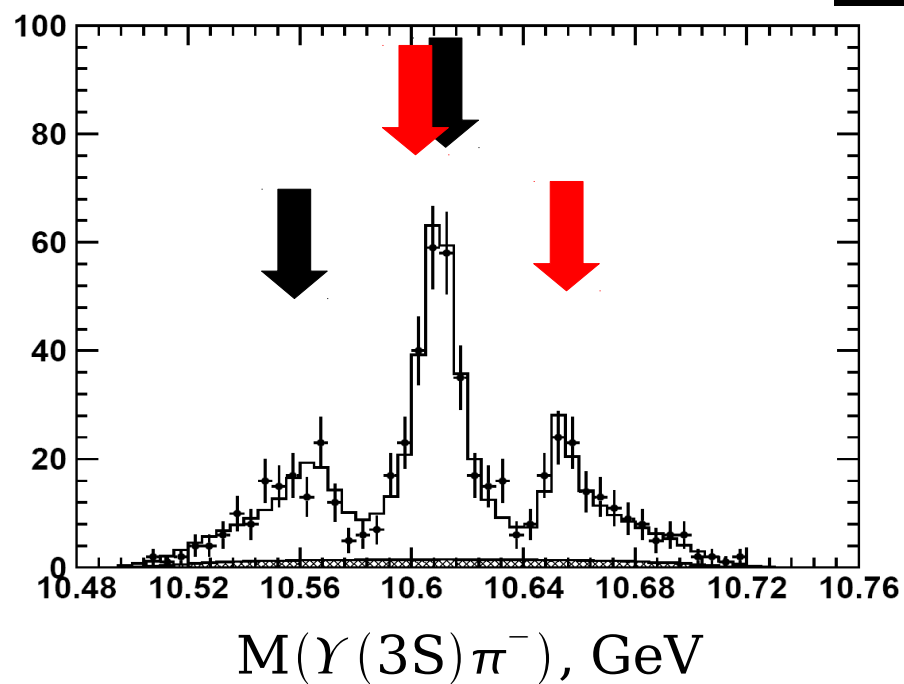
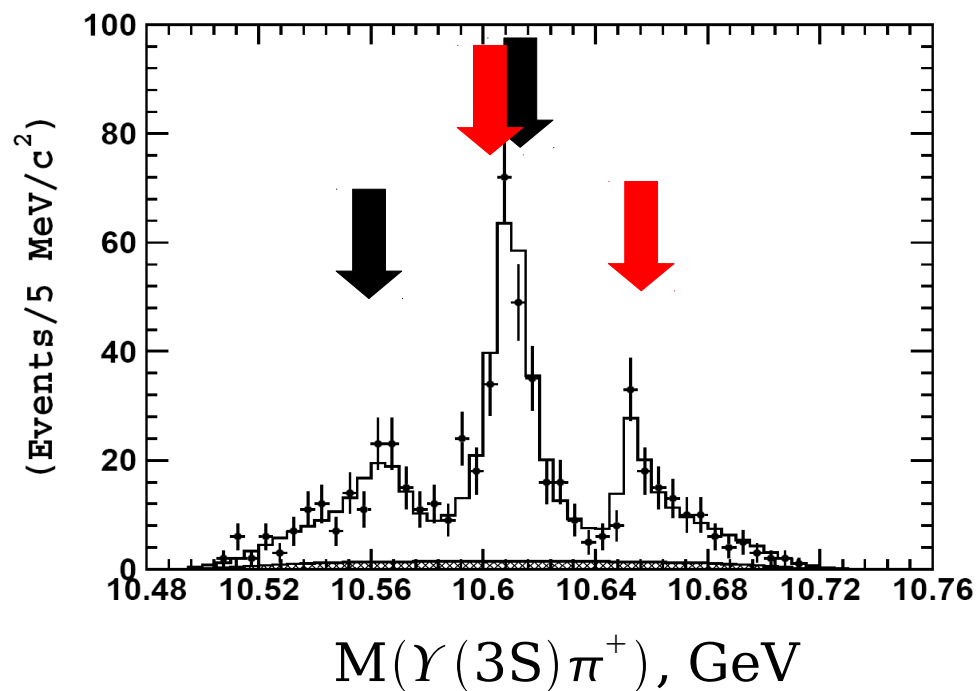
# Results: $\Upsilon(2S)\pi^+\pi^-$



signals

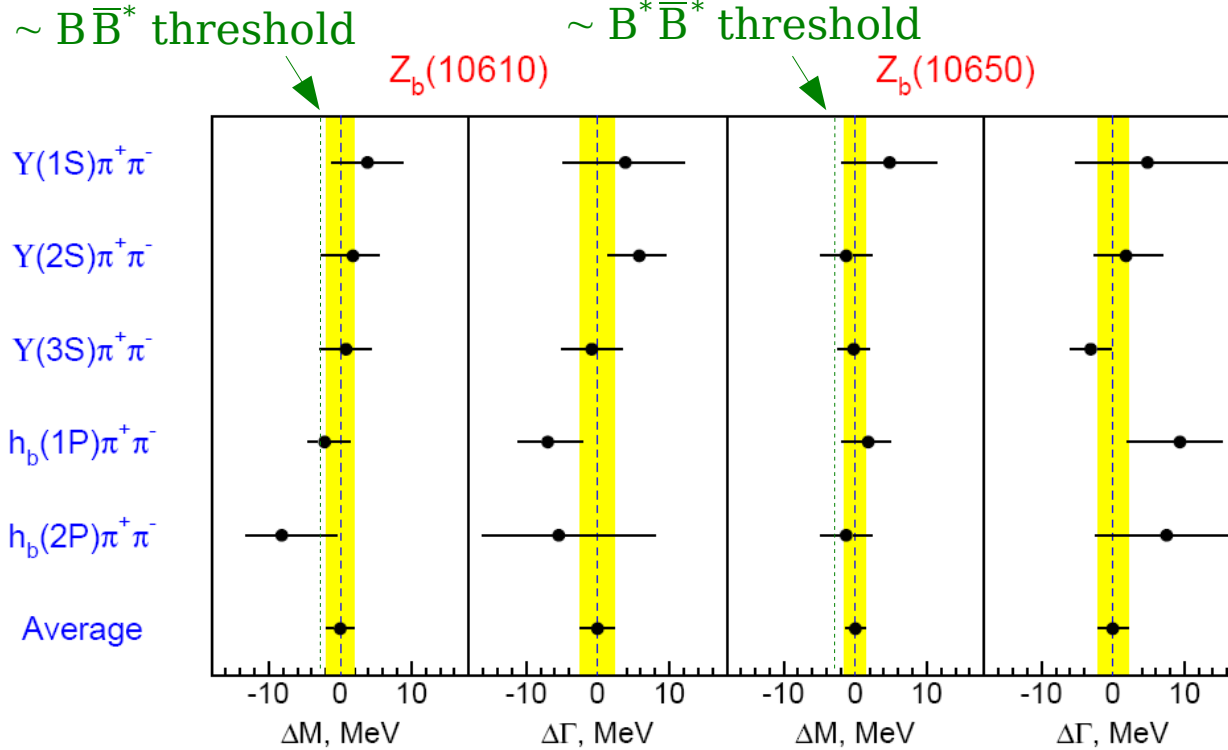


# Results: $\Upsilon(3S)\pi^+\pi^-$



# Summary of parameters of charged $Z_b$ states

[arXiv:1110.2251]



**$Z_b(10610)$**

$M = 10607.2 \pm 2.0 \text{ MeV}$

$\Gamma = 18.4 \pm 2.4 \text{ MeV}$

**$Z_b(10650)$**

$M = 10652.2 \pm 1.5 \text{ MeV}$

$\Gamma = 11.5 \pm 2.2 \text{ MeV}$

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

- Masses and width are consistent
- Relative yield of  $Z_b(10610)$  and  $Z_b(10650) \sim 1$
- Relative phases are swapped for  $\Upsilon$  and  $h_b$  final states

## and more...

### Expected decays of $h_b$

[Godfrey & Rosner, PRD 66, 014012 (2002)]

$h_b(1P) \rightarrow ggg$  (57%),  $\eta_b(1S)\gamma$  (41%),  $\gamma g g$  (2%)

$h_b(2P) \rightarrow ggg$  (63%),  $\eta_b(1S)\gamma$  (13%),  $\eta_b(2S)\gamma$  (19%),  $\gamma g g$  (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 $\eta_b$

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

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

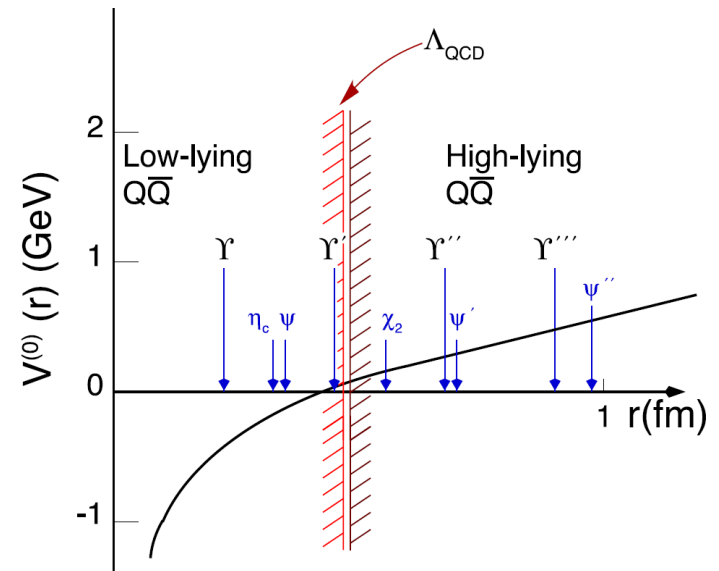
pNRQCD:  $41 \pm 14 \text{ MeV}$

[Kniehl et al., PRL 92, 242001 (2004)]

Lattice:  $60 \pm 8 \text{ MeV}$

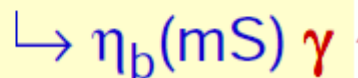
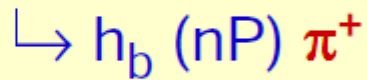
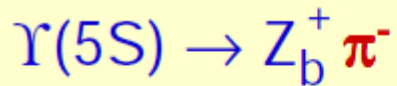
[Meinel, PRD 82, 114502 (2010)]

$\eta_b$  – small radius system,  
precise calculation of mass



## Method

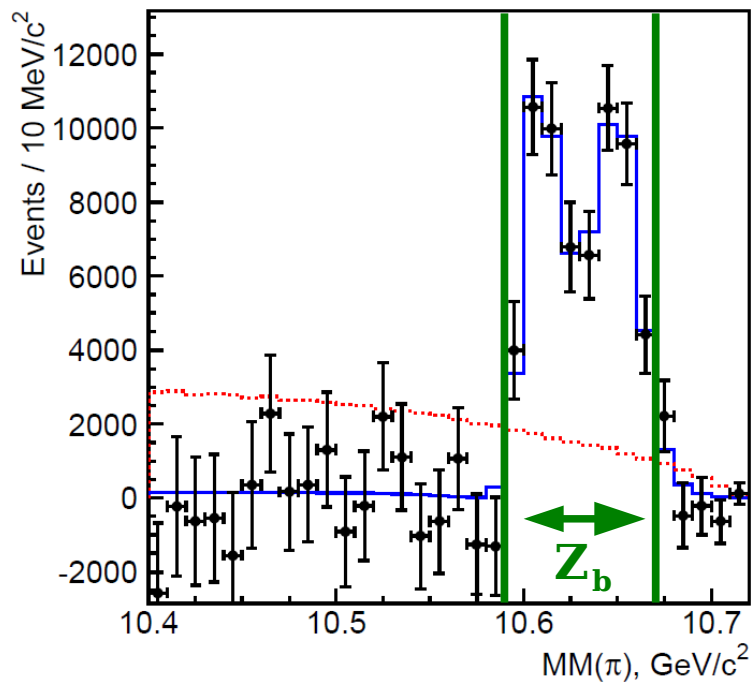
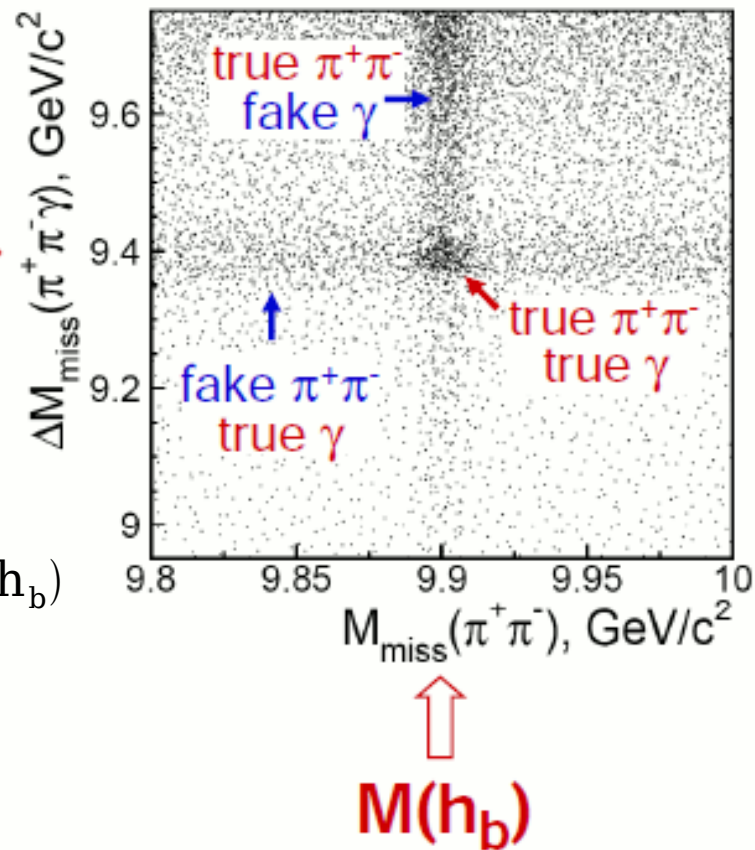
## Decay chain:



$$\Delta \mathbf{M}_{\text{miss}}(\pi^+ \pi^- \gamma) \equiv \mathbf{M}_{\text{miss}}(\pi^+ \pi^- \gamma) - \mathbf{M}_{\text{miss}}(\pi^+ \pi^-) + \mathbf{M}(\mathbf{h}_b)$$

$$M(\eta_b) \Rightarrow$$

## MC simulation



Require intermediate  $Z_b$ :

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

bg. suppression  $\times 5.2$

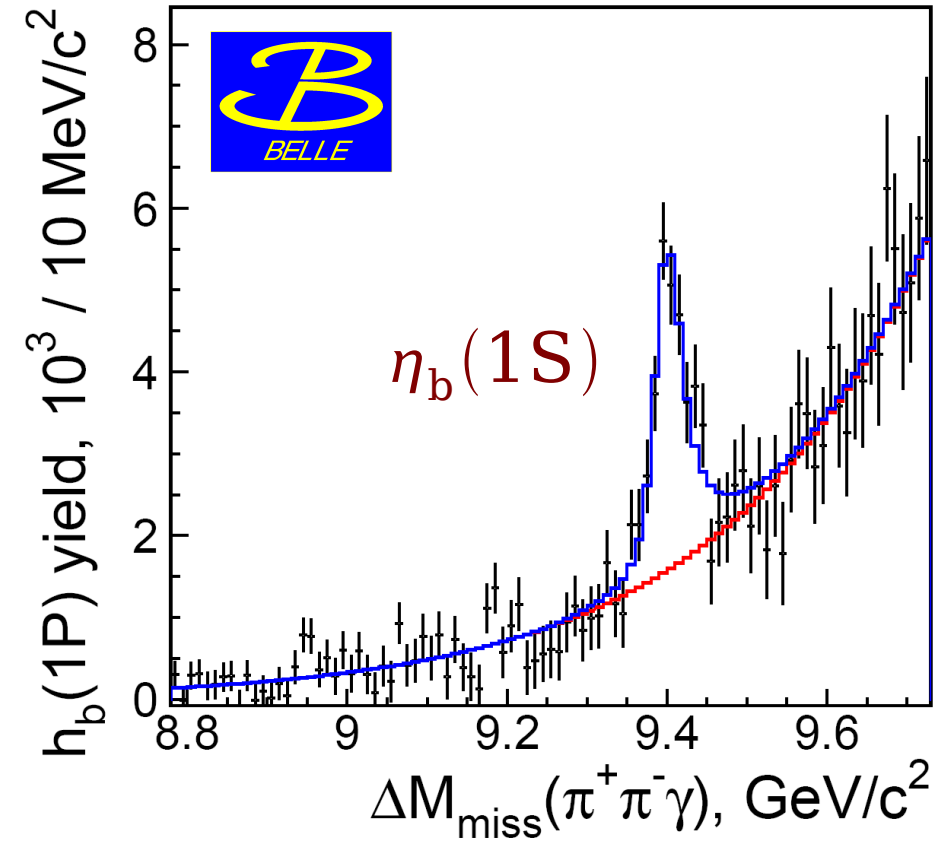
approach:

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

# Results

preliminary, shown at QWG

non-relativistic BW  $\otimes$  resolution + exponential func.



Hyperfine splitting

$$\Delta M_{\text{HF}}[\eta_b(1S)] = 59.3 \pm 1.9^{+2.4}_{-1.4} \text{ MeV}/c^2$$

single most precise  
measurement of  $\eta_b(1S)$  mass

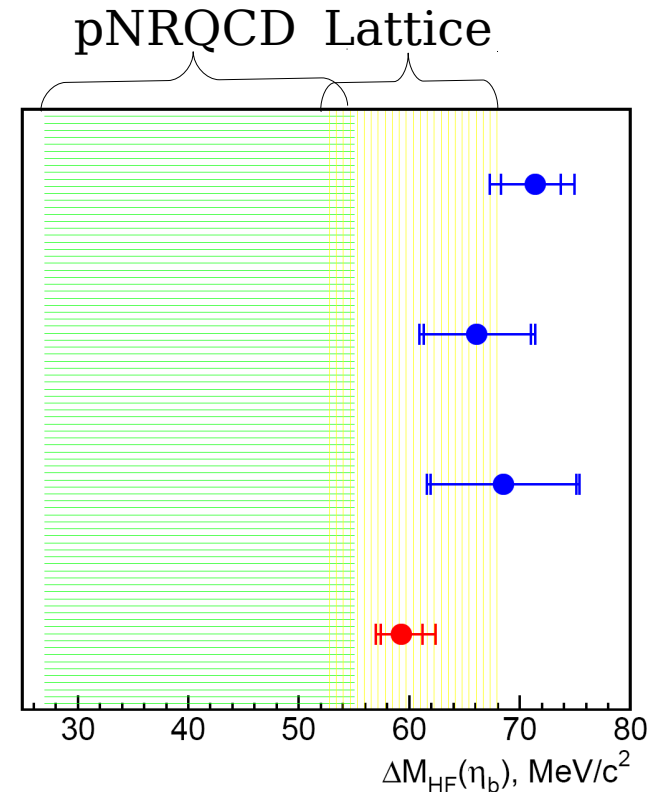
$\Rightarrow$  radiative decays of  $h_b(2P)$ , search for  $\eta_b(2S)$  coming...

$$N[\eta_b(1S)] = (21.9 \pm 2.0^{+5.6}_{-1.7}) \times 10^3$$

$$M[\eta_b(1S)] = (9401.0 \pm 1.9^{+1.4}_{-2.4}) \text{ MeV}/c^2$$

$$\Gamma[\eta_b(1S)] = (12.4^{+5.5}_{-4.6} {}^{+11.5}_{-3.4}) \text{ MeV}$$

$$B[h_b(1P) \rightarrow \eta_b(1S)\gamma] = (49.8 \pm 6.8^{+10.9}_{-5.2}) \%$$



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

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

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

Belle  
preliminary

# Summary

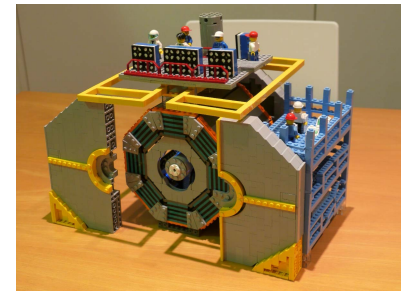
Exciting new results in 2011 :

- ⇒ new (updated) measurements for the UT angles  $\beta, \gamma$
- ⇒ new results with full  $\Upsilon(5S)$  data sample  
( $B_s$  decays but also bottomonium studies)

**Final Belle data sample is yet to be fully analyzed !**

- **more on  $\alpha$  ( $\pi^0 \pi^0, \rho^+ \rho^0$ ),  $\gamma$  ...**
- **Rare B decays:  $K^{(*)} \nu \bar{\nu}, \tau \nu, \mu \nu, \gamma \gamma, \dots$**
- **Results on  $B_s$  decays with  $5 \times$  more stat**
- **$\tau$  physics (lifetime, LVF decays), charm (mixing  $K \pi, K K, K_S \pi \pi$ ),  
new particles (X, Y, Z), bottomonium...**

**Even more interesting results at Super B factories  
with two orders of magnitude larger data samples !**





# Search for $B_s^0 \rightarrow J/\psi f_0(980)$

Contribution to FPCP 2010 (arXiv:1009.2605)

- Silver mode at LHCb to measure  $\beta_s$  (CP-violating phase in the  $B_s$  mixing)
- BR is smaller than  $B_s \rightarrow J/\psi \phi$  but  $B_s \rightarrow J/\psi f_0(980)$  is a pure CP-eigenstate
  - no angular analysis is required as in  $B_s \rightarrow J/\psi \phi$
- CP-eigenstate (odd) mode with a final state with only 4 charged particles
- Expectations:

$$- \frac{B(B_s^0 \rightarrow J/\psi f_0) B(f_0 \rightarrow \pi^+ \pi^-)}{B(B_s^0 \rightarrow J/\psi \phi) B(\phi \rightarrow K^+ K^-)} \approx 0.2 \quad (\text{Stone + Zhang [PRD 79, 074024]})$$

$$- \frac{B(B_s^0 \rightarrow J/\psi f_0) B(f_0 \rightarrow \pi^+ \pi^-)}{B(B_s^0 \rightarrow J/\psi \phi) B(\phi \rightarrow K^+ K^-)} = 0.42 \pm 0.11 \quad (\text{CLEO } (D_s \rightarrow f_0 e^+ \nu_e) [\text{PRD 80, 052009}])$$

$$\rightarrow \mathbf{B(B_s^0 \rightarrow J/\psi f_0) B(f_0 \rightarrow \pi^+ \pi^-) \approx (1.3 - 2.7) \times 10^{-4}}$$

$$- B(B_s^0 \rightarrow J/\psi f_0) = (3.1 \pm 2.4) \times 10^{-4} \quad \text{QCD (LO) [PRD 81, 074001]}$$

with  $B(f_0 \rightarrow \pi^+ \pi^-) = (50_{-9}^{+7})\%$  BES data [CLEO, PRD 80, 052009]

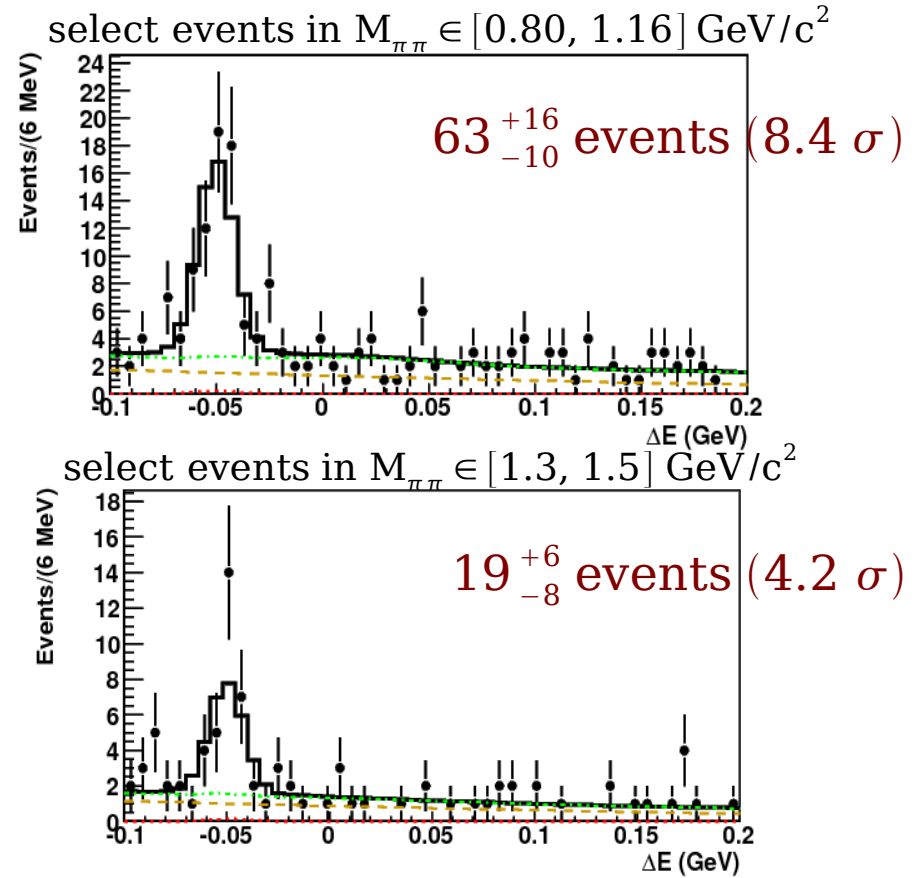
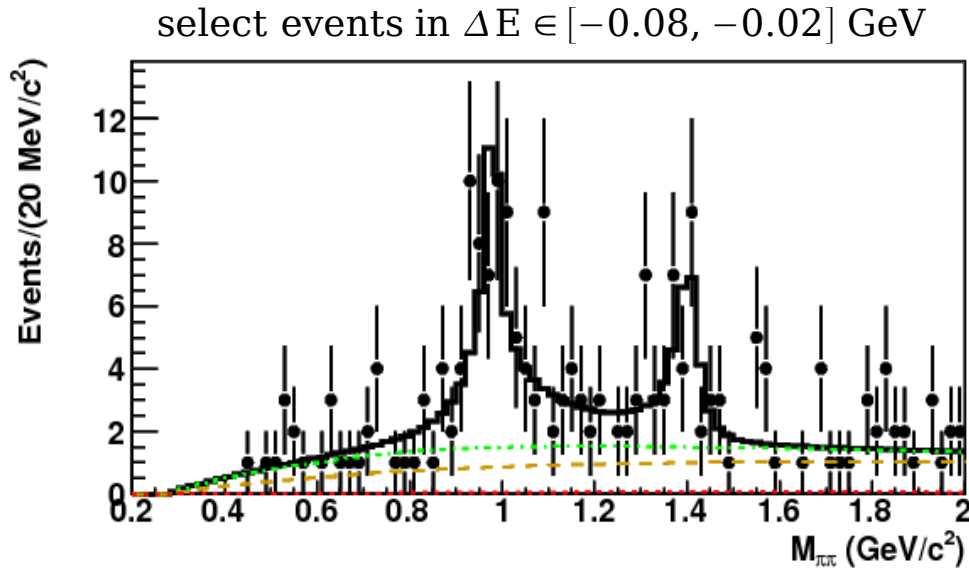
$$\rightarrow \mathbf{B(B_s^0 \rightarrow J/\psi f_0) B(f_0 \rightarrow \pi^+ \pi^-) \approx (1.6 \pm 1.3) \times 10^{-4}}$$

# Search for $B_s^0 \rightarrow J/\psi f_0(980)$

Belle ( $121 \text{ fb}^{-1}$ )

PRL 106, 121802 (2011)

- $J/\psi \rightarrow e^+ e^-$  or  $\mu^+ \mu^-$ ,  $f_0 \rightarrow \pi^+ \pi^-$
- $(\Delta E, M_{\pi^+ \pi^-})$  2D fit in  $-0.1 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$  and  $M_{\pi^+ \pi^-} < 2.0 \text{ GeV}/c^2$
- includes backgrounds from  $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$  (peaks in  $\Delta E$ ) and other  $J/\psi$  modes



$$B(B_s^0 \rightarrow J/\psi f_0) \times B(f_0 \rightarrow \pi^+ \pi^-) = (1.16^{+0.31}_{-0.19}(\text{stat})^{+0.15}_{-0.17}(\text{syst})^{+0.26}_{-0.18}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4} \text{ (at 90\% C.L.)}$$

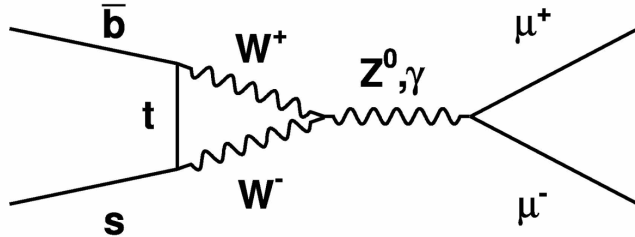
# Motivation for BR measurements

- $B_s \rightarrow \mu^+ \mu^-$ :

sensitive probe to New Physics, very suppressed in SM:

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (3.35 \pm 0.32) \times 10^{-9}$$

[M.Blanke et al, hep-ph/0604057]



- NP can lead to enhancement of the BR up to an order of magnitude (for example, constrained versions of the MSSM  $\sim 20 \times 10^{-9}$ )

**$\Rightarrow$  BUT could be ''only'' a factor 2 above SM value !!**

- Need normalization with BR of  $B_{(s)}$  decays
  - for example, Tevatron experiments use  $B^+ \rightarrow J/\psi K^+$
  - $\sigma_{\text{syst}} \sim 13\%$ : dominant error from  $\frac{f(B_s)}{f(B)}$

**$\Rightarrow$  not sufficient if  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 10^{-8}$**

- Need normalization mode meas with higher accuracy, preferably  $B_s$  mode

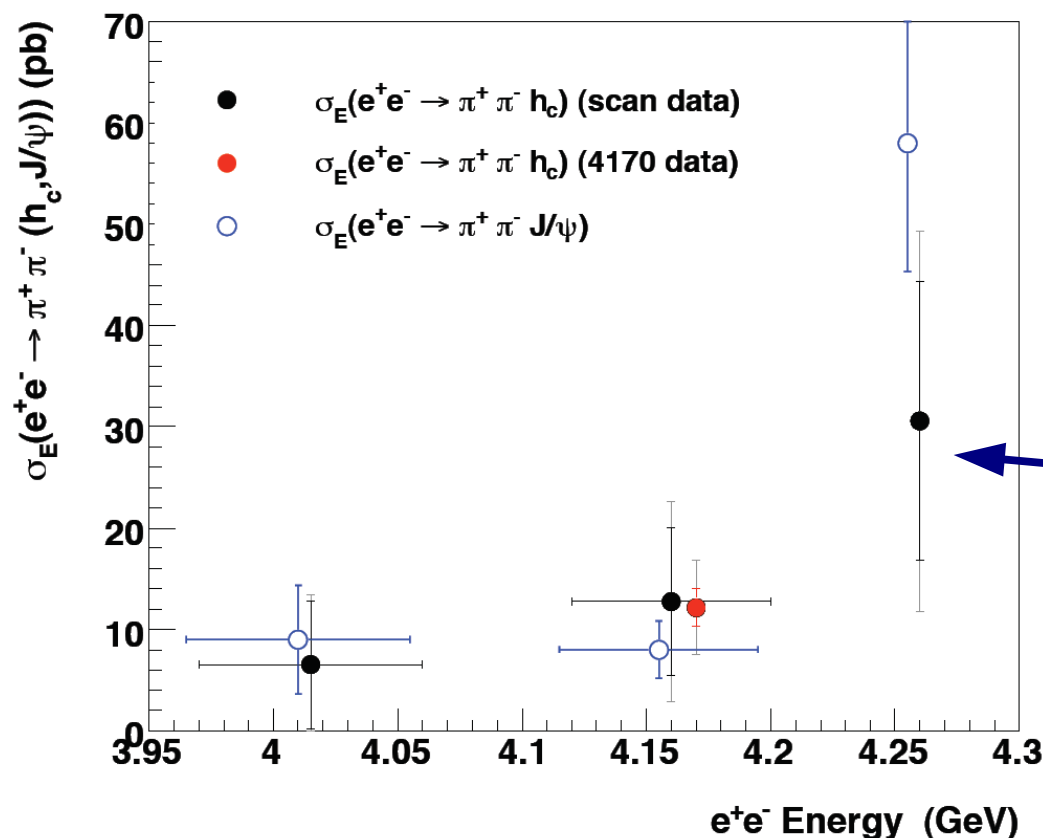
**$\Rightarrow$  measure  $B_s$  branching fraction in  $\Upsilon(5S)$  decays !**  
(for example  $B_s \rightarrow J/\psi \phi$ ) so need to improve  $f_s$

# Trigger

Observation of  $e^+e^- \rightarrow \pi^+\pi^- h_c$  above  $D\bar{D}$  threshold by CLEO

Energy dependence of the cross-section

(R.Mitchell @ CHARM2010)



**Production of  $h_c$   
is unsuppressed  
relative to  $J/\psi$**

Enhancement at  $Y(4260)$  ?

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

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  $\eta_b$  by BABAR in radiative Y(3S) and Y(2S) decays, followed by CLEO.

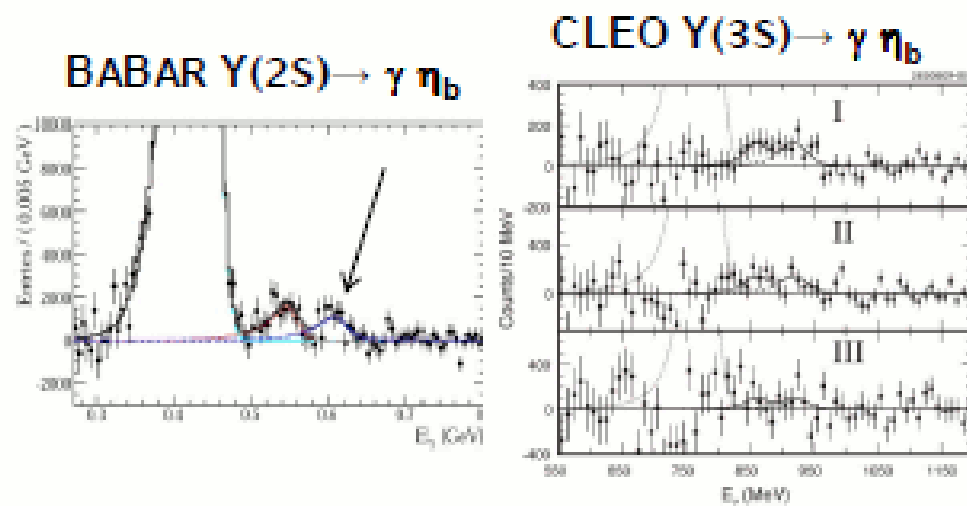
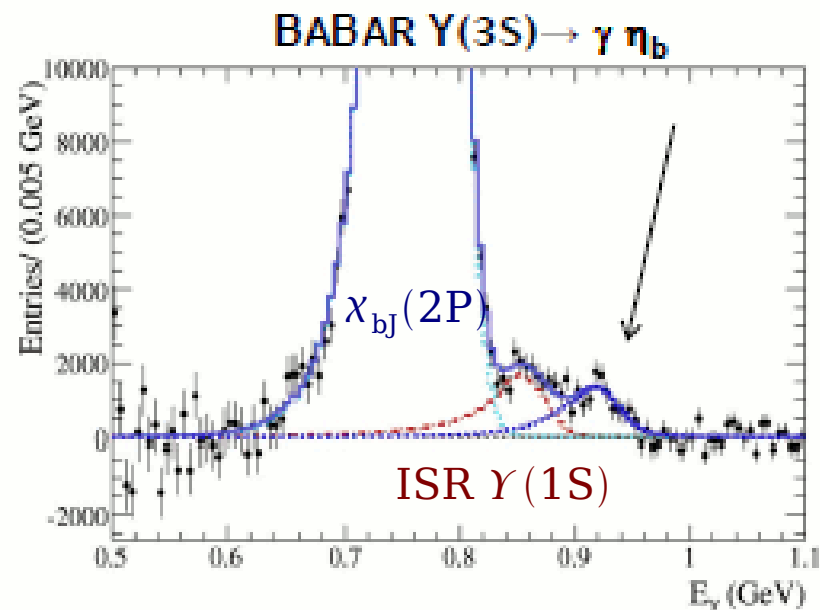
## Measured parameters

|                                                         |                               |
|---------------------------------------------------------|-------------------------------|
| BF (Y(3,2S) $\rightarrow \gamma \eta_b$ ) ( $10^{-4}$ ) | $5.1 \pm 0.7$ / $3.9 \pm 1.5$ |
| Y(1S) - $\eta_b$ (1S) mass splitting:                   | $69.3 \pm 2.8$ MeV            |

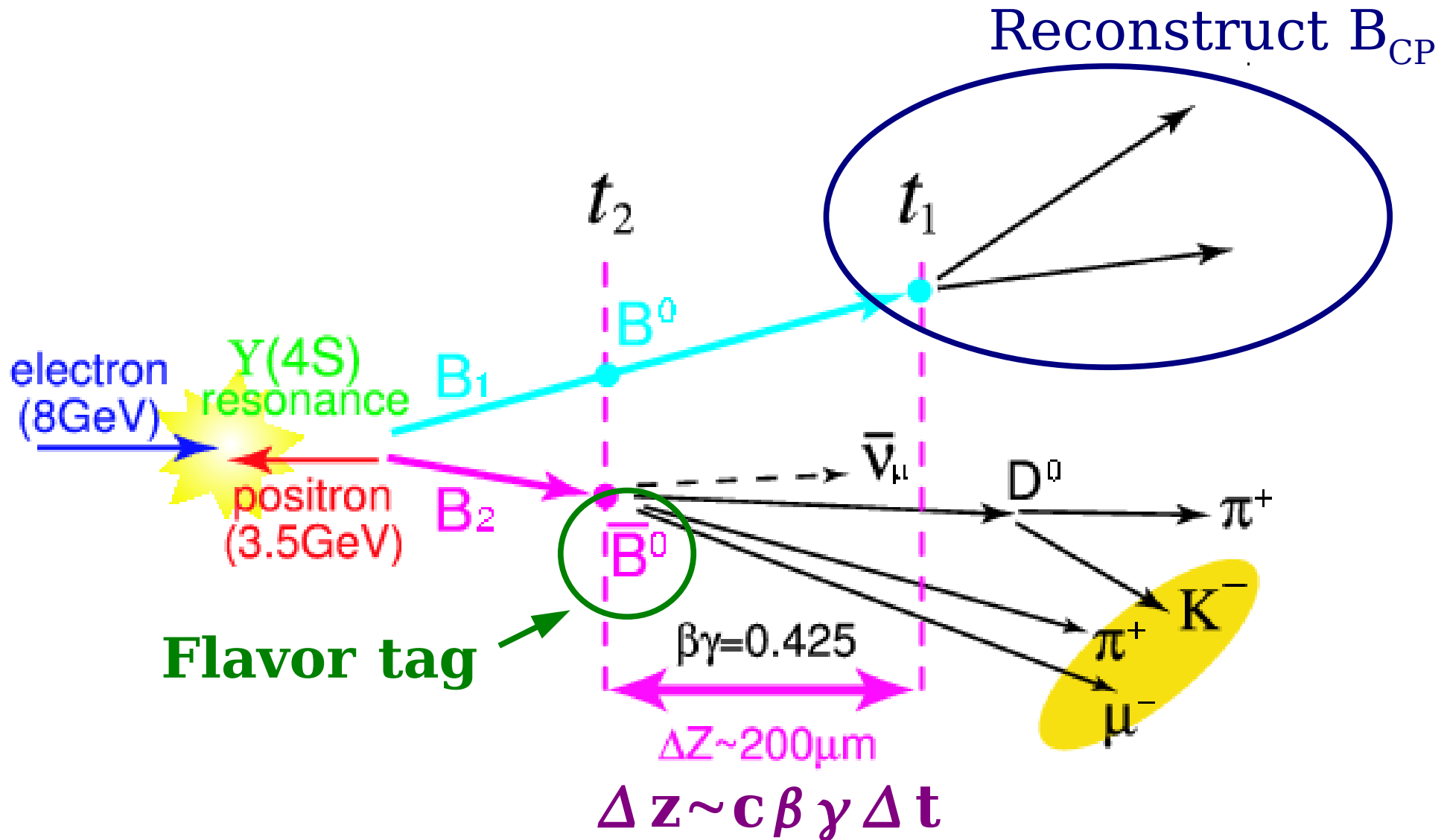
## Hyperfine mass splitting predictions (MeV):

|                   |                                |
|-------------------|--------------------------------|
| Potential models: | 36-100 (36-87 recent models)   |
| pNRQCD:           | $60.3 \pm 5.5 \pm 3.8 \pm 2.1$ |
| Lattice QCD:      | 40-71                          |

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



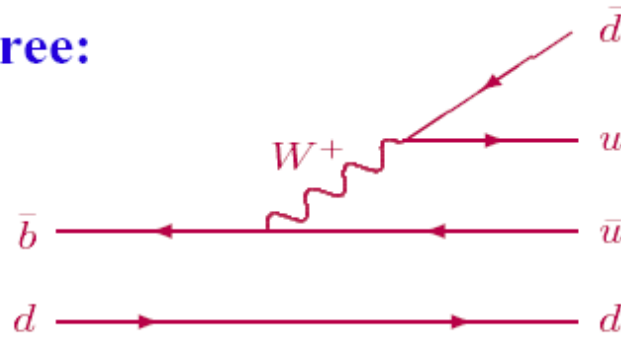
# Measuring the CP parameters **S** and **A**



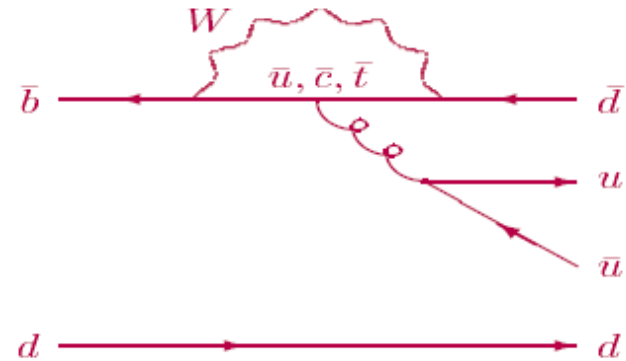
$$\frac{dP_{\text{sig}}}{dt}(\Delta \mathbf{t}, \mathbf{q}) = \frac{e^{-|\Delta \mathbf{t}|/\tau_B}}{4\tau_B} (1 + \mathbf{q}(\mathbf{S} \sin(\Delta m_d \Delta \mathbf{t}) - \mathbf{C} \cos(\Delta m_d \Delta \mathbf{t})))$$

# $\phi_2$ determination

**Tree:**



**Penguin:**



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

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

**from time dependent CP, we can measure  $\phi_2^{\text{eff}}$ , but we want  $\phi_2$  !**

$$S_{\pi^+ \pi^-} = \sin 2\phi_2 + 2r \cos \delta \sin(\phi_1 + \phi_2) \cos 2\phi_2 + O(r^2)$$

$$r = |P|/|T|$$

# $\phi_2$ determination with isospin analysis

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

$$A_{+-} = A(B^0 \rightarrow \pi^+ \pi^-) = e^{-i\phi_2} T^{+-} + P$$

$$\sqrt{2} A_{00} = \sqrt{2} A(B^0 \rightarrow \pi^0 \pi^0) = e^{-i\phi_2} T^{00} + P$$

$$\sqrt{2} A_{+0} = \sqrt{2} A(B^+ \rightarrow \pi^+ \pi^0) = e^{-i\phi_2} (T^{00} + T^{+-})$$

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

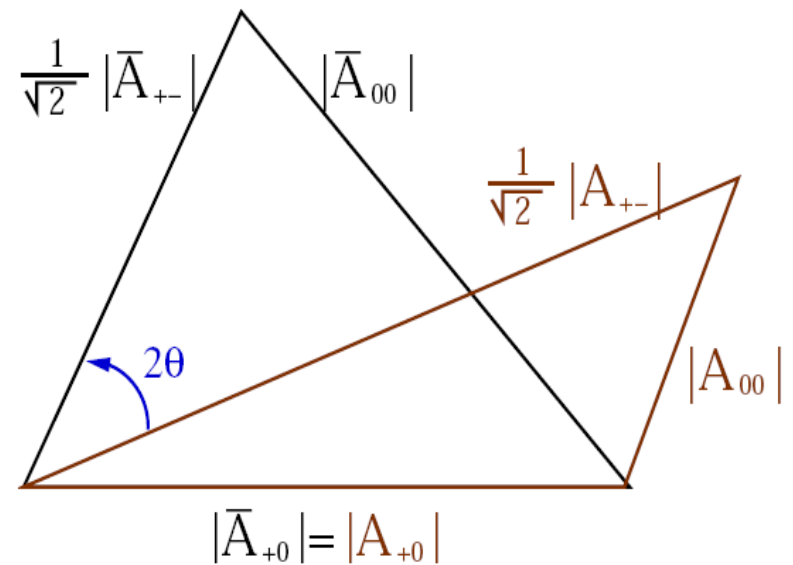
$$\bar{A}_{+-} + \sqrt{2} \bar{A}_{00} = \sqrt{2} \bar{A}_{+0}$$

- neglecting EWP  $\Rightarrow A_{+0}$  pure tree

$$|A_{+0}| = |\bar{A}_{+0}|$$

- Isospin breaking (d and u charges different,  $m_u \neq m_d$ )
- $\pi - \eta - \eta'$  and  $\rho - \omega$  mixing

[J.Zupan, hep-ph/0701004]



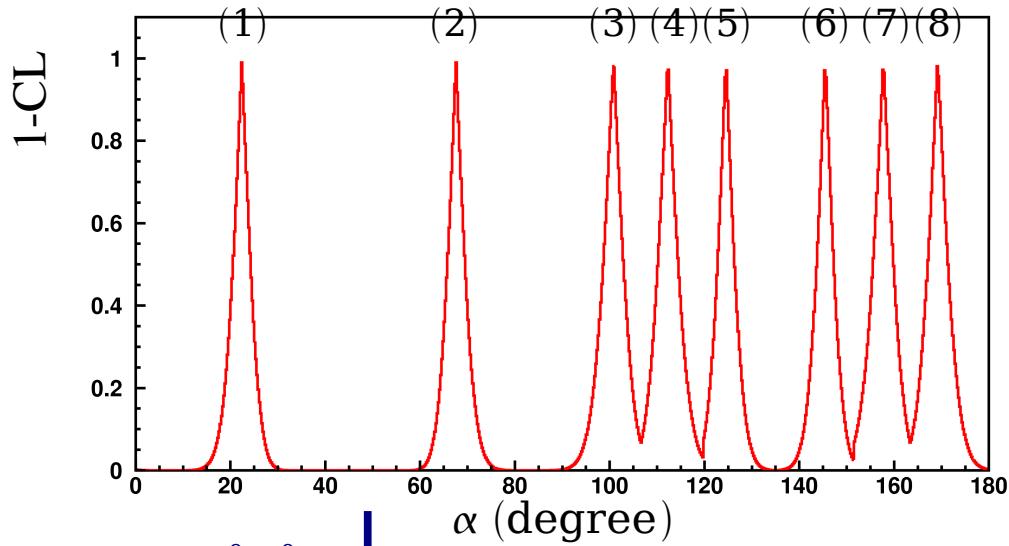
**$\phi_2$  can be resolved up to an 8-fold ambiguity ( $\phi_2 \in [0, \pi]$ )**

# Some examples to illustrate $\phi_2$ extraction

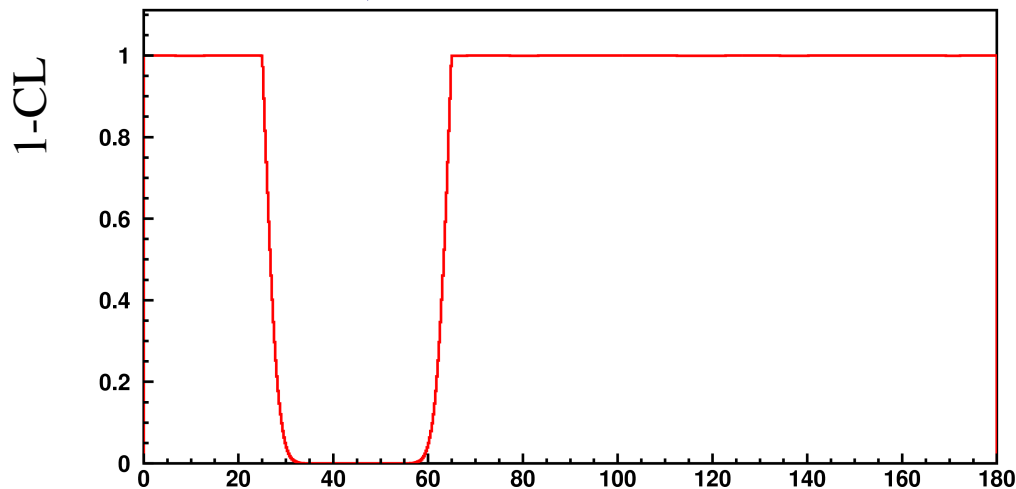
$$\begin{aligned}\text{Br}(\pi^+ \pi^-) &= (5.0 \pm 0.2) \times 10^{-6} \\ \text{Br}(\pi^0 \pi^0) &= (1.5 \pm 0.1) \times 10^{-6} \\ \text{Br}(\pi^+ \pi^0) &= (3.5 \pm 0.2) \times 10^{-6} \\ C(\pi^+ \pi^-) &= -0.40 \pm 0.03 \\ S(\pi^+ \pi^-) &= -0.50 \pm 0.04 \\ C(\pi^0 \pi^0) &= -0.30 \pm 0.10\end{aligned}$$



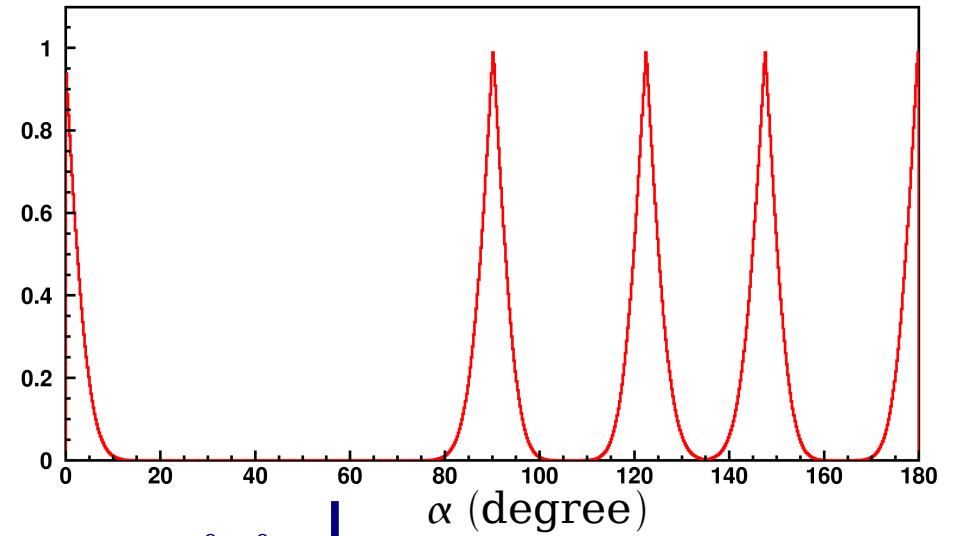
$$\begin{aligned}\text{Br}(\pi^+ \pi^-) &= (2.0 \pm 0.2) \times 10^{-6} \\ \text{Br}(\pi^0 \pi^0) &= (0.5 \pm 0.1) \times 10^{-6} \\ \text{Br}(\pi^+ \pi^0) &= (3.5 \pm 0.2) \times 10^{-6} \\ C(\pi^+ \pi^-) &= -0.40 \pm 0.03 \\ S(\pi^+ \pi^-) &= -0.50 \pm 0.04 \\ C(\pi^0 \pi^0) &= -0.30 \pm 0.10\end{aligned}$$



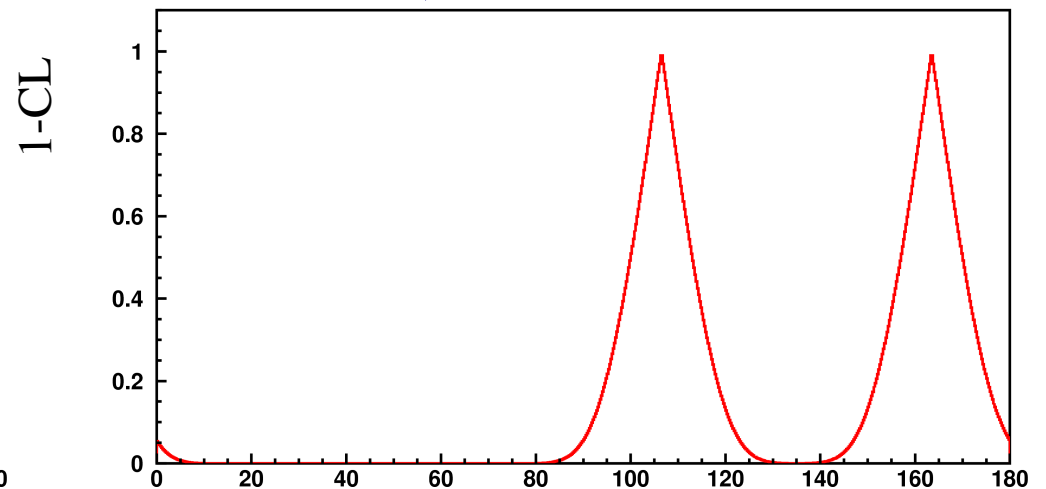
no  $C(\pi^0 \pi^0)$



1-CL



no  $C(\pi^0 \pi^0)$



1-CL

# $\phi_2: \pi\pi$ system

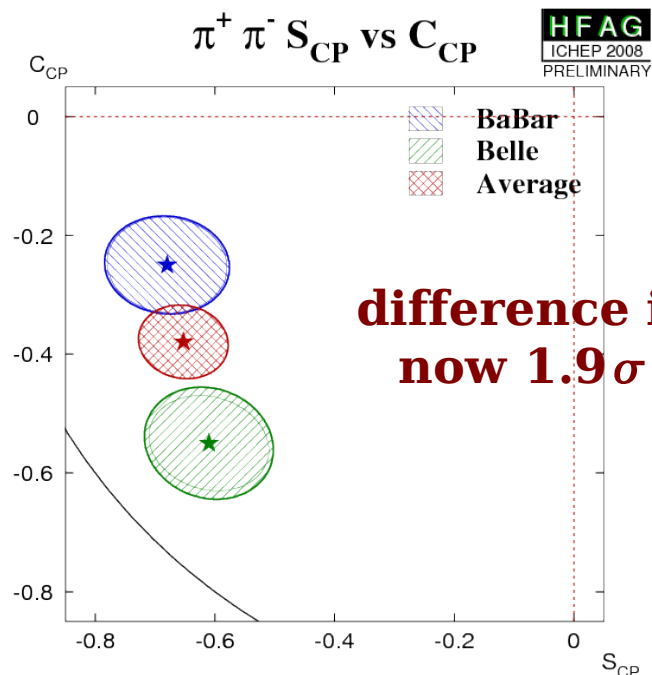


$535 \times 10^6 B\bar{B}$  pairs  
PRL 98, 221801(2007)

$$C = -0.55 \pm 0.08 \pm 0.05$$

$$S = -0.61 \pm 0.10 \pm 0.04$$

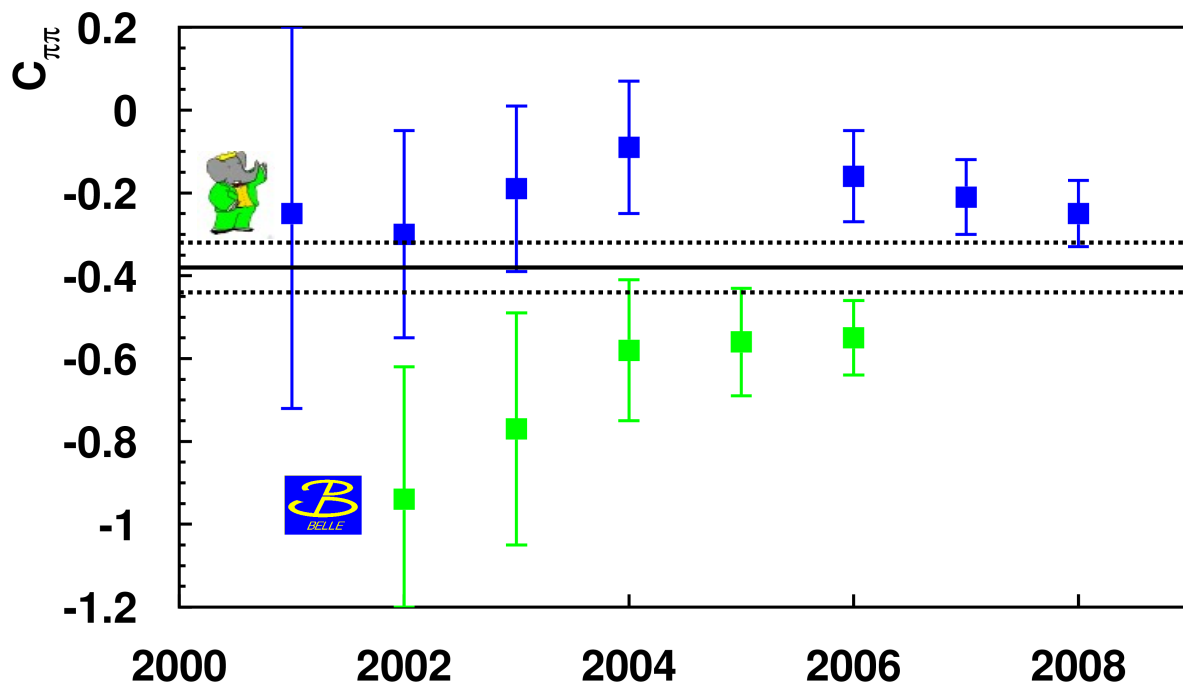
direct CPV @  $5.5\sigma$



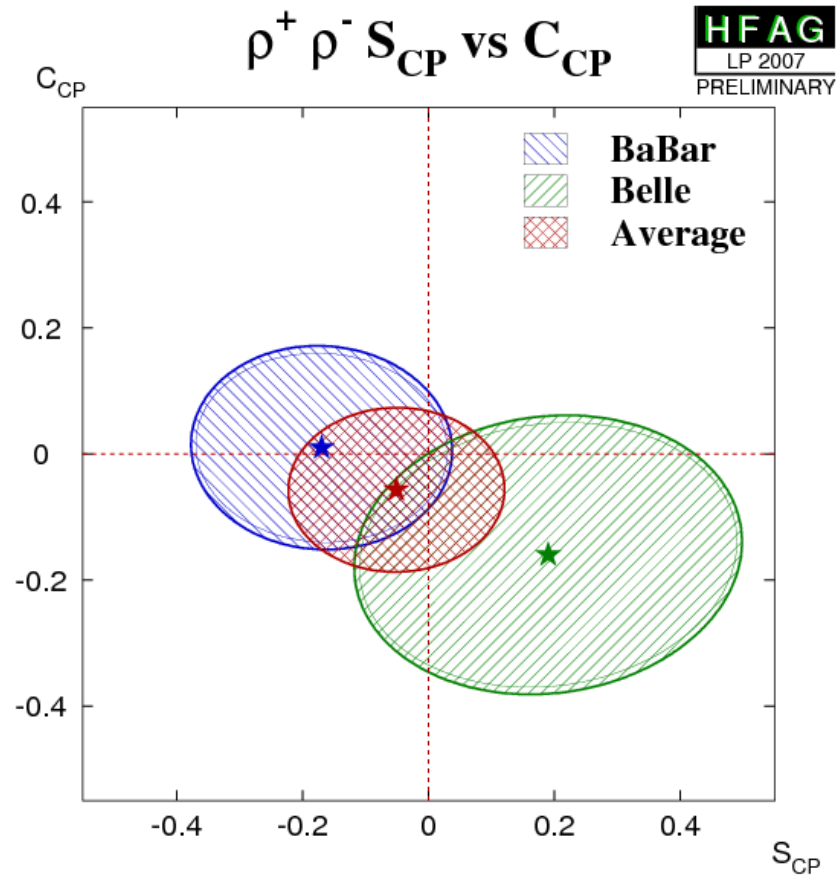
$467 \times 10^6 B\bar{B}$  pairs  
ArXiv:0807.4226

$$C = -0.25 \pm 0.08 \pm 0.02$$

$$S = -0.68 \pm 0.10 \pm 0.03$$



$\rho\rho$  system (5 observables for 6 parameters)  
 $(\text{Br}(B \rightarrow \rho^+ \rho^-), S_{\rho^+ \rho^-}, C_{\rho^+ \rho^-}, \text{Br}(B \rightarrow \rho^+ \rho^0), \text{Br}(B \rightarrow \rho^0 \rho^0)) + f_L$



**$535 \times 10^6 B\bar{B}$  pairs**  
**PRD76, 011104(R)(2007)**

$$C = -0.16 \pm 0.21 \pm 0.07$$

$$S = +0.19 \pm 0.30 \pm 0.07$$

**$387 \times 10^6 B\bar{B}$  pairs**  
**PRD76, 052007(R)(2007)**

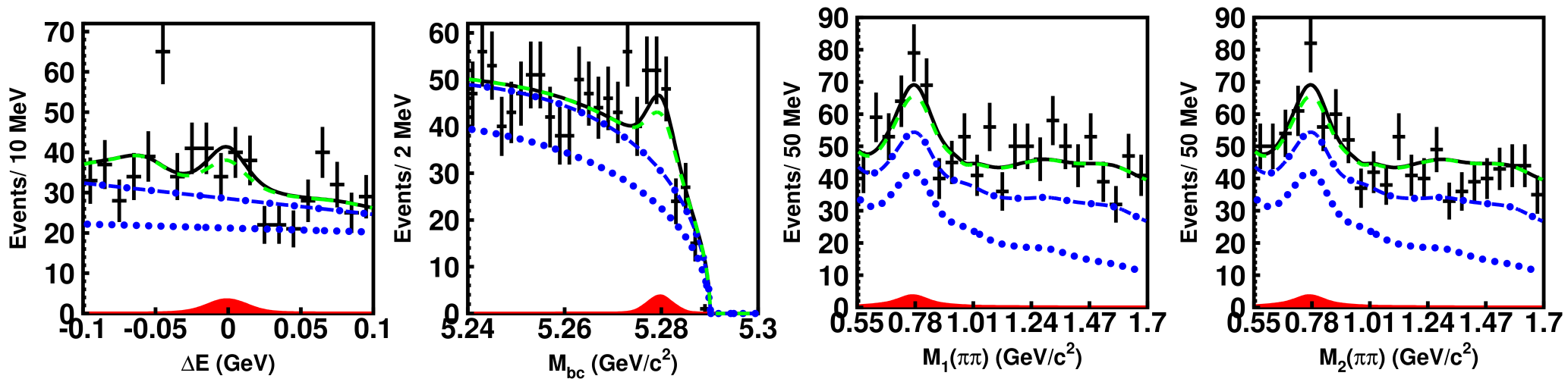
$$C = +0.01 \pm 0.15 \pm 0.06$$

$$S = -0.17 \pm 0.20^{+0.05}_{-0.06}$$

# $\rho^0 \rho^0$ mode



$657 \times 10^6$   $B\bar{B}$  pairs  
PRD78, 111102(R)(2008)



$$\text{Br}(B^0 \rightarrow \rho^0 \rho^0) < 1.0 \times 10^{-6} \text{ @ 90\% C.L.}$$

$$= (0.4 \pm 0.4^{+0.2}_{-0.3}) \times 10^{-6}$$

$$N_S(\rho^0 \pi^+ \pi^-) = 113^{+67}_{-66} \pm 52 \quad (\Sigma = 1.3 \sigma)$$

$$\text{Br}(B^0 \rightarrow \rho^0 \pi^+ \pi^-) < 12.0 \times 10^{-6} \text{ @ 90\% C.L.}$$

$$= (5.9^{+3.5}_{-3.4} \pm 2.7) \times 10^{-6}$$

$$N_S(4\pi^\pm) = 161^{+61+28}_{-59-25} \quad (\Sigma = 2.5 \sigma)$$

$$\text{Br}(B^0 \rightarrow 4\pi^\pm) < 19.3 \times 10^{-6} \text{ @ 90\% C.L.}$$

$$= (12.4^{+4.7+2.1}_{-4.6-1.9}) \times 10^{-6}$$

**$\text{Br}(\rho^0 \rho^0)$  is small !  $\text{SU}(2)$  triangle even more squashed...**

# $\rho^0 \rho^0$ mode

$465 \times 10^6$   $B\bar{B}$  pairs  
[PRD78, 071104(R)]



10-dim fit to extract yields,  $f_L$ ,  $C_L^{00}$ ,  $S_L^{00}$ :

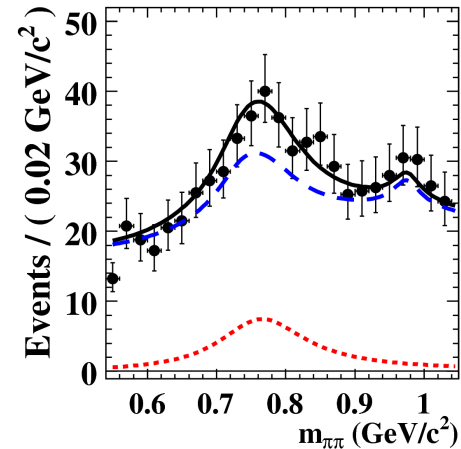
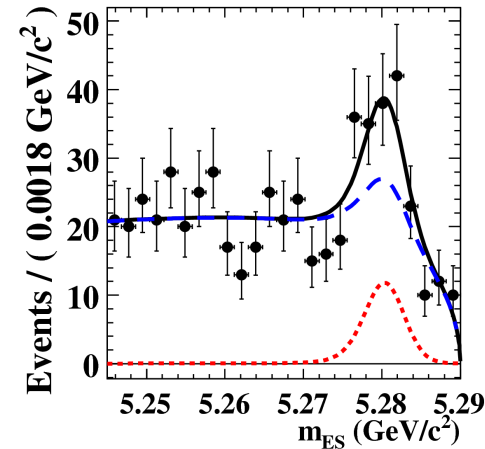
$$N_S(\rho^0 \rho^0) = 99^{+35}_{-34} \pm 15 \quad (\Sigma = 3.1 \sigma)$$

$$N_S(\rho^0 \pi^+ \pi^-) = -12^{+39}_{-35} \pm 52$$

$$\text{Br}(B^0 \rightarrow \rho^0 \pi^+ \pi^-) < 8.7 \times 10^{-6} \text{ @ 90 \% C.L.}$$

$$N_S(4\pi^\pm) = 8^{+30}_{-25} \pm 6$$

$$\text{Br}(B^0 \rightarrow 4\pi^\pm) < 21.1 \times 10^{-6} \text{ @ 90 \% C.L.}$$

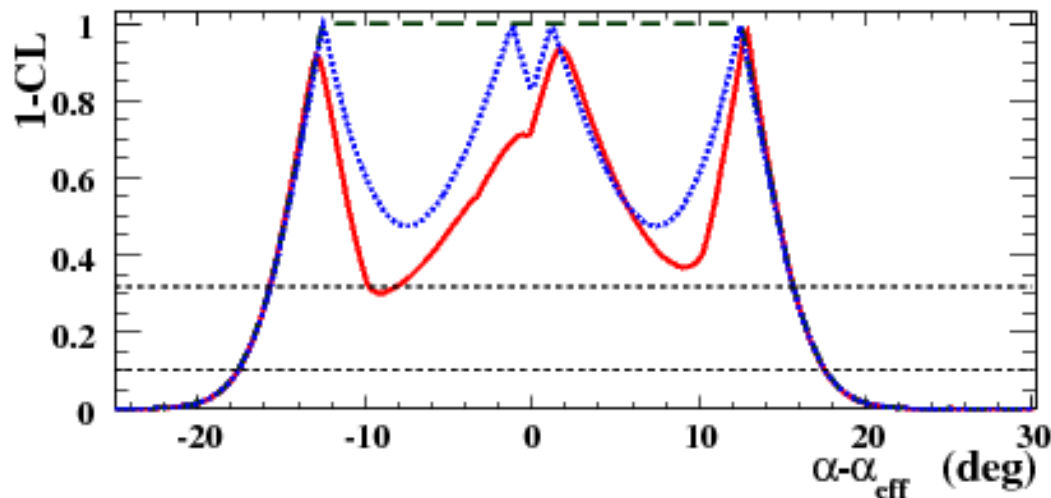


$$\text{Br}(B^0 \rightarrow \rho^0 \rho^0) = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$$

$$f_L = 0.75^{+0.11}_{-0.14} \pm 0.04$$

$$S_L^{00} = 0.3 \pm 0.7 \pm 0.2$$

$$C_L^{00} = 0.2 \pm 0.8 \pm 0.3$$

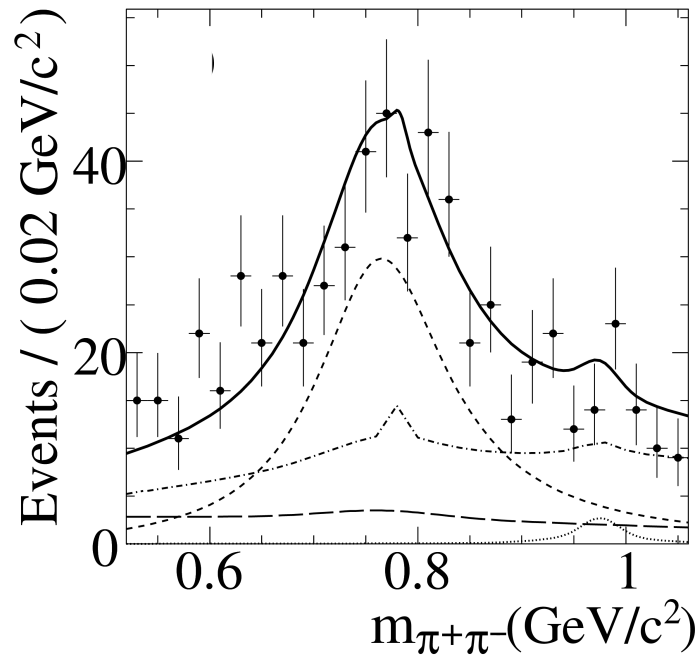
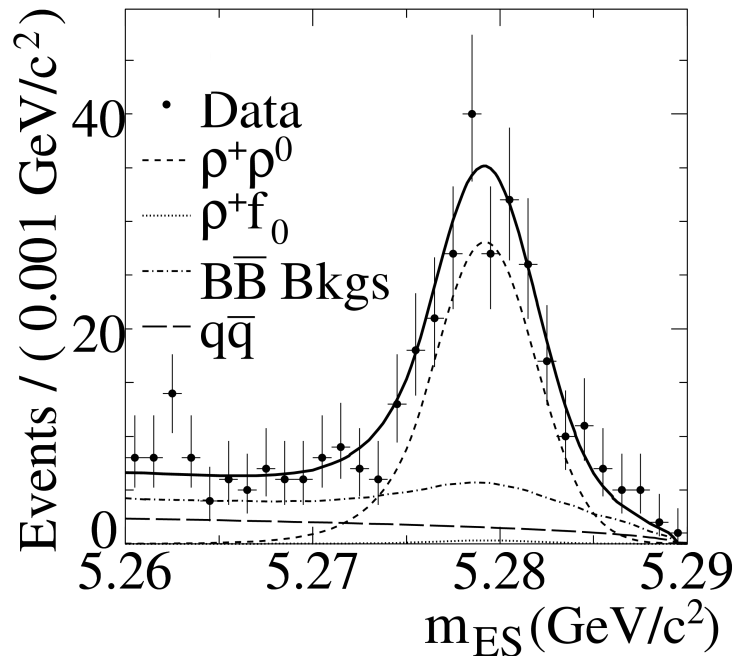


...  $C^{00}$

...  $C^{00}$  &  $S^{00}$

# $\rho^+ \rho^0$ mode

$465 \times 10^6 B\bar{B}$  pairs  
[ArXiv:0901.3522]



$$N_S(\rho^+ \rho^0) = 1122 \pm 63(\text{stat})$$

$$\text{Br}(B^+ \rightarrow \rho^+ \rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$$

$$f_L = 0.950 \pm 0.015 \pm 0.006$$

Previous results:

$232 \times 10^6 B\bar{B}$  pairs [PRL97, 261801 (2006)]

$$\text{Br}(B^+ \rightarrow \rho^+ \rho^0) = (16.8 \pm 2.2 \pm 2.3) \times 10^{-6}$$

$$f_L = 0.905 \pm 0.042^{+0.023}_{-0.027}$$

$85 \times 10^6 B\bar{B}$  pairs [PRL91, 221801 (2003)]

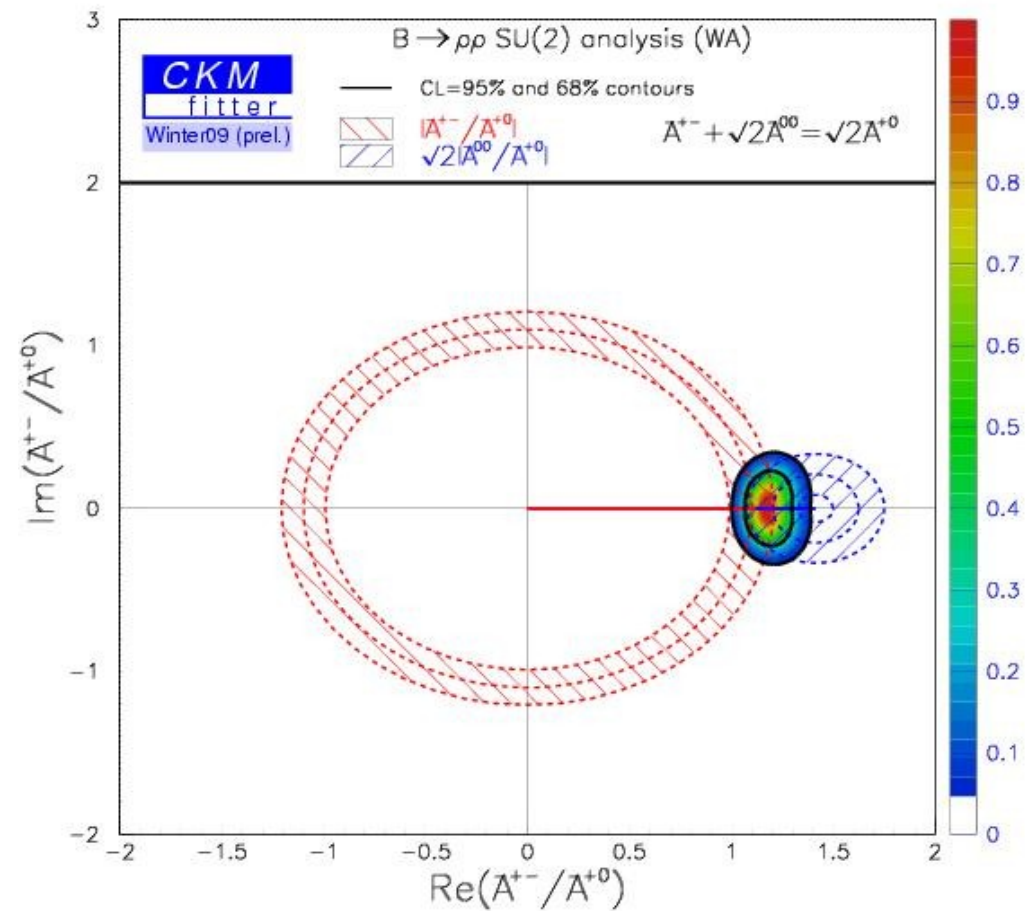
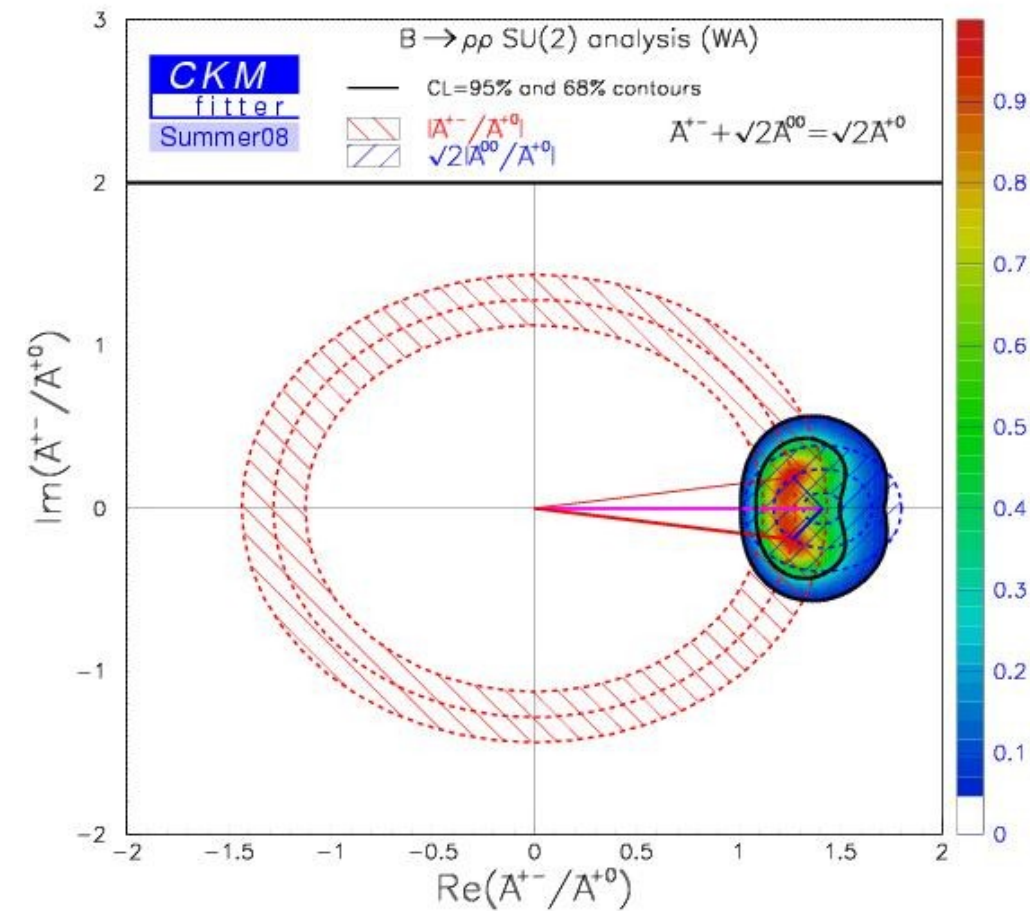
$$\text{Br}(B^+ \rightarrow \rho^+ \rho^0) = (31.7 \pm 7.1^{+3.8}_{-6.7}) \times 10^{-6}$$

$$f_L = 0.948 \pm 0.106 \pm 0.021$$

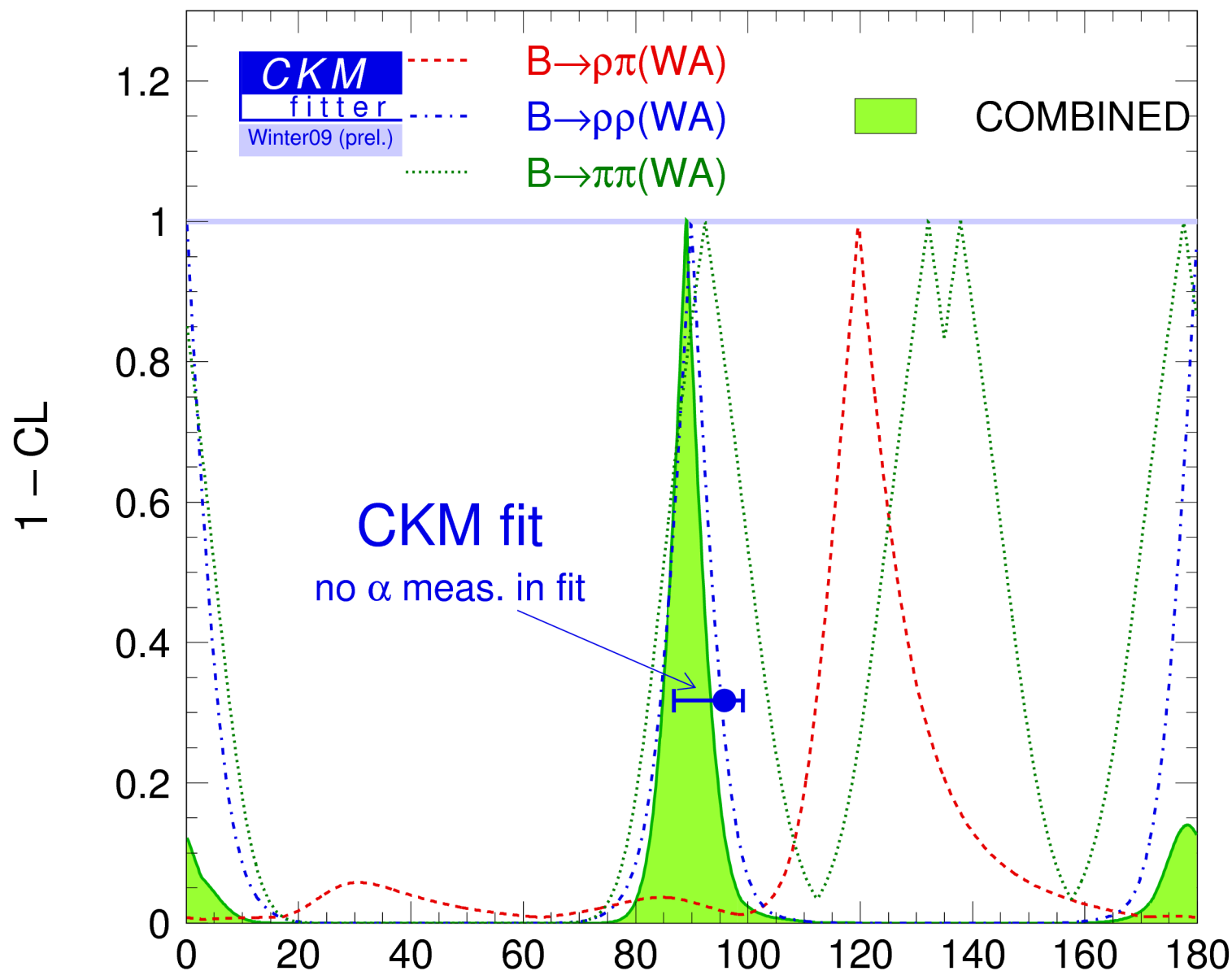


# Isospin triangles (Summer 08 to Winter 09)

$B \rightarrow \rho\rho$  case



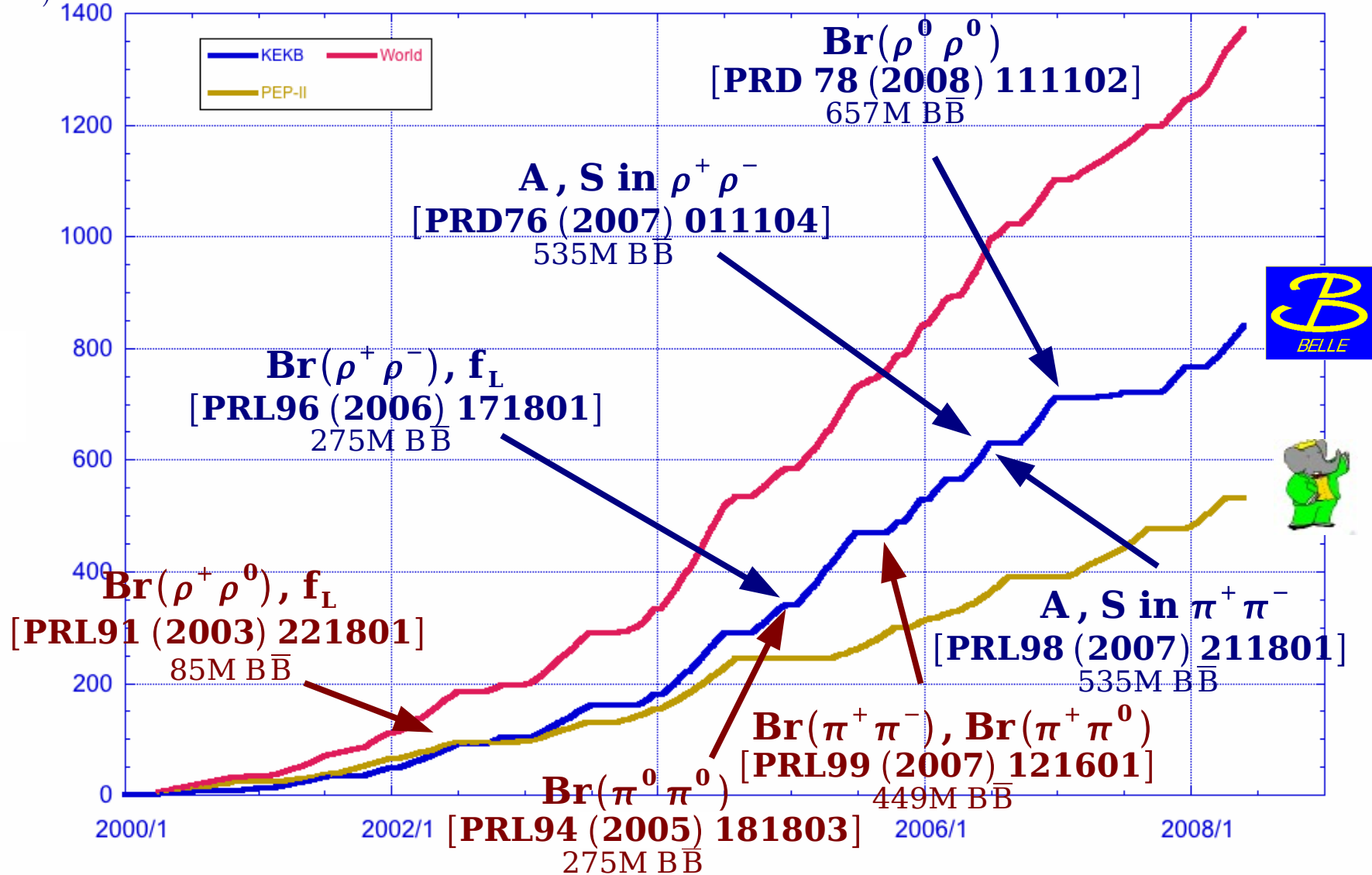
# $\phi_2$ determination



**68% C.L. interval:  $\alpha = (89.0^{+4.4}_{-4.2})^\circ$**

# measurements related to $\phi_2$

Lum( $\text{fb}^{-1}$ )



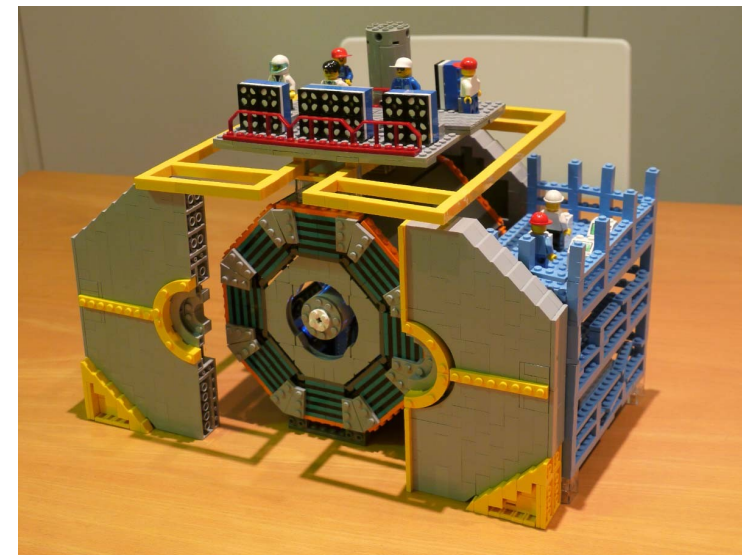
- $\rho^0 \rho^0$  and  $\rho^+ \rho^0$  : isospin triangles closing properly ?
- final Belle  $A(\pi^+ \pi^-), \text{Br}(\pi^0 \pi^0)$  (full advantage of reprocessing)
- first Belle measurement in  $a_1^\pm \pi^\mp$  mode

# and then...

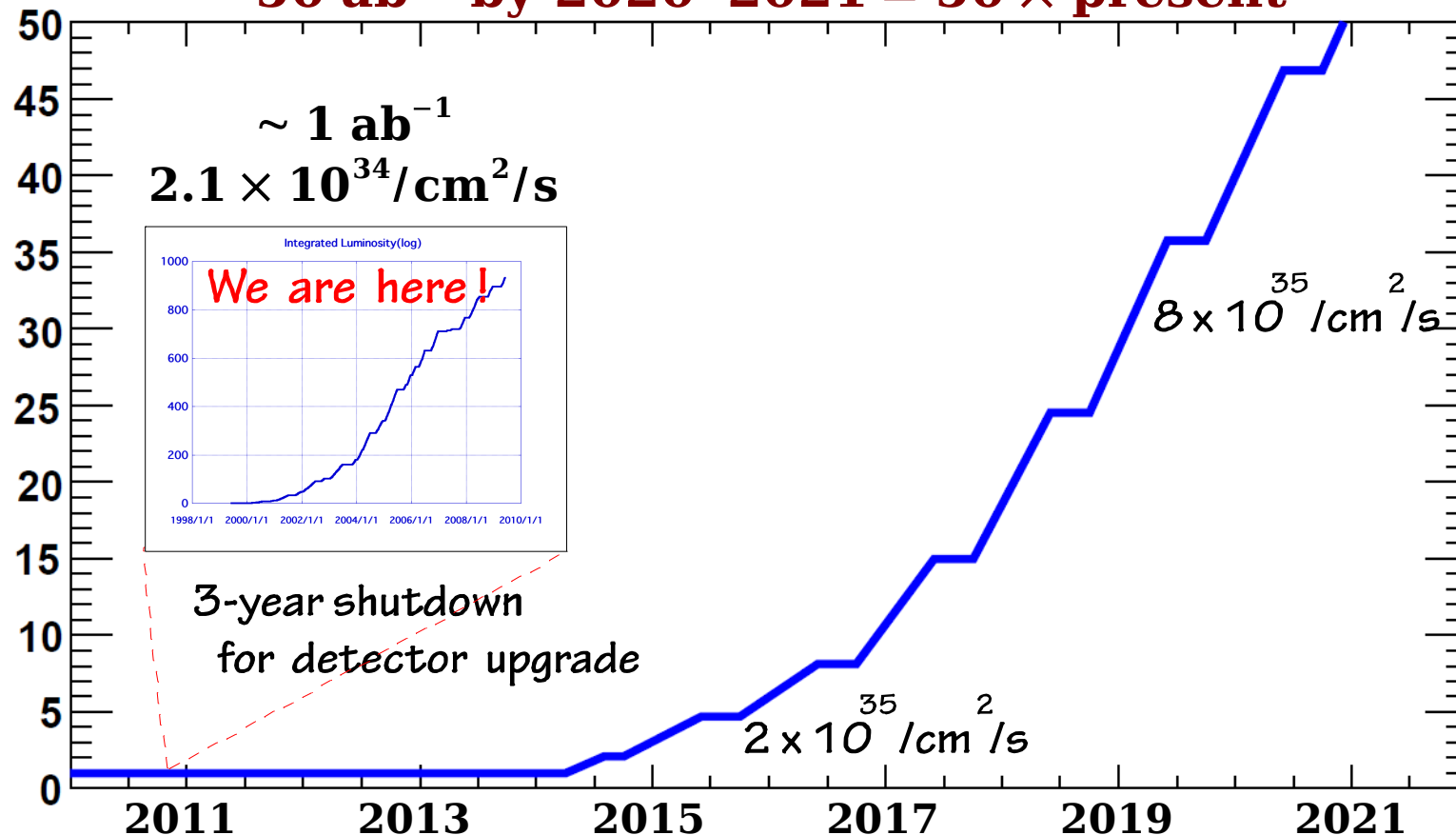
⇒ physics with  $O(10^{10})$  B,  $\tau$ , D....

SuperKEKB/Belle II (in Japan)

⇒ KEKB upgrade has been approved  
100 oku yen<sup>(\*)</sup> for machine (FY 2010-2012)



**$50 \text{ ab}^{-1}$  by 2020-2021 =  $50 \times$  present**

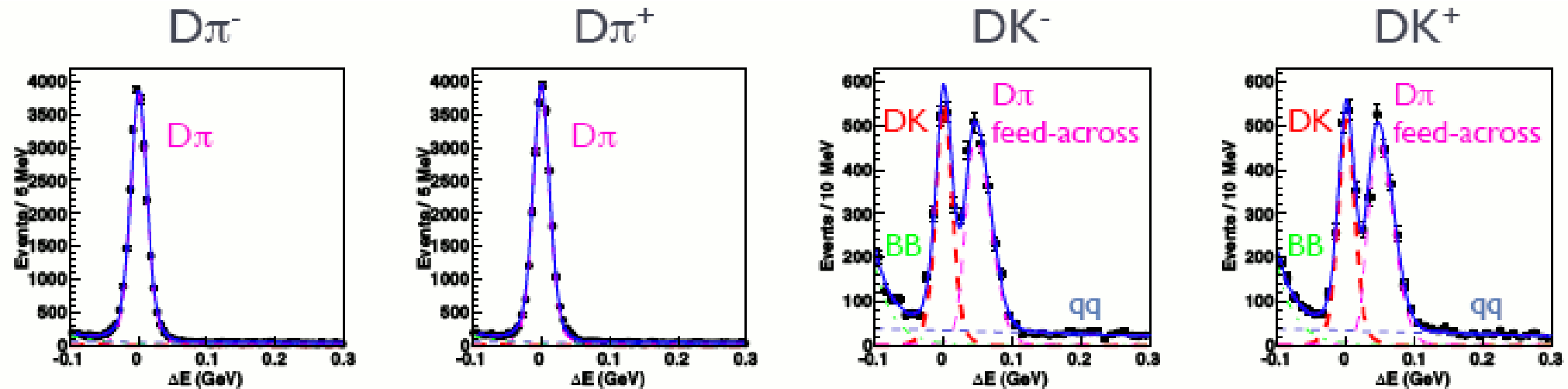


(\*) 100 oku yen  $\sim$  88.6M euros (Jul 26, 2010)

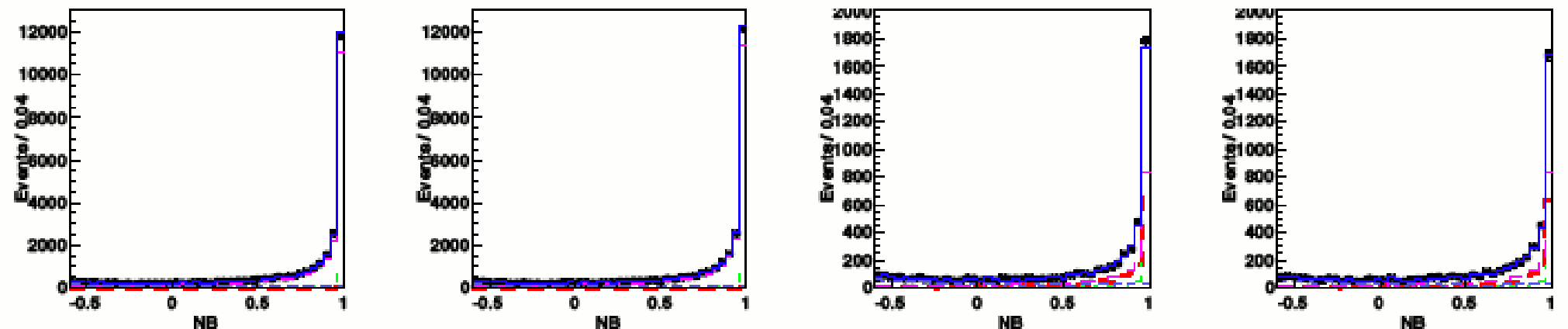
# Simultaneous fit for $B^- \rightarrow [K^- \pi^+]_D h^-$ (calibration modes)

PRL 106, 231803 (2011)

2D fit with  $\Delta E$  and NB for  $D\pi$  and  $DK$



(Projections for all fitted regions are shown.)



$\Delta E$ :  $Dh$ : 2 Gaussians (the same free shape for  $\pi/K$ ).  
 $D\pi$  feed-across: 2 Asym. Gaussians ( $\mu$ ,  $\sigma_{l, \text{right}}$  free).  
 $BB$ : free exponential.  $qq$ : free linear.

NB:  $Dh$ : Hist. from  $|\Delta E| < 10$  MeV.  $\leftrightarrow$  Subtract  $qq$ .  
 $D\pi$  feed-across: Hist. from  $|\Delta E - 50 \text{ MeV}| < 10$  MeV.  
 $BB$ : Hist. from MC.  $qq$ : Hist. from  $M_{\text{rec}}$  sideband.

$$\underline{\mathbf{B} \rightarrow \mathbf{D}h, \mathbf{D} \rightarrow \mathbf{K} \pi \rightarrow \mathbf{R}_{\mathbf{D}_{\text{fav}}}}$$

MC (case B)

$$\mathbf{B} \rightarrow \mathbf{D} \pi$$

$$\mathbf{B} \rightarrow \mathbf{DK}$$

$$\mathbf{B} \bar{\mathbf{B}}$$

continuum

$$\begin{aligned} N_{\eta, KID > 0.6}^{DK} &= \frac{1}{2} (1 - \eta A^{DK}) N_{tot}^{D\pi} R_{K/\pi} \epsilon \\ N_{\eta, KID < 0.6}^{DK} &= \frac{1}{2} (1 - \eta A^{DK}) N_{tot}^{D\pi} R_{K/\pi} (1 - \epsilon) \\ N_{\eta, KID > 0.6}^{D\pi} &= \frac{1}{2} (1 - \eta A^{D\pi}) N_{tot}^{D\pi} \kappa \\ N_{\eta, KID < 0.6}^{D\pi} &= \frac{1}{2} (1 - \eta A^{D\pi}) N_{tot}^{D\pi} (1 - \kappa) \end{aligned}$$

|      | kaon fake<br>(1- $\epsilon$ ) | kaon eff<br>$\epsilon$ | pion eff<br>(1- $\kappa$ ) | pion fake<br>$\kappa$ |   |
|------|-------------------------------|------------------------|----------------------------|-----------------------|---|
| MC   | $14.70 \pm 0.06$              | $85.41 \pm 0.06$       | $95.42 \pm 0.03$           | $4.47 \pm 0.03$       | ← |
| data | $15.86 \pm 0.40$              | $84.32 \pm 0.39$       | $92.13 \pm 0.46$           | $7.94 \pm 0.31$       |   |

Table 5: Efficiency and fake rate (in %) for kaon and pion, for data and MC.  $\epsilon$  will be fixed in the fit but  $\kappa$  will be floated (see text for further explanations). These numbers are obtained after properly weighting the values provided by PID group for SVD1 and SVD2.

$$\Rightarrow \kappa = (4.58 \pm 0.10)\% \text{ in the MC fit}$$

# $B \rightarrow Dh, D \rightarrow K\pi \rightarrow R_D$

MC

$B \rightarrow D\pi$

$B \rightarrow DK$

$B\bar{B}$

continuum

$$\begin{aligned}
 N_{\eta, KID>0.6}^{DK} &= \frac{1}{2} (1 - \eta A^{DK}) N_{tot}^{D\pi} R_{K/\pi} \epsilon \\
 N_{\eta, KID<0.6}^{DK} &= \frac{1}{2} (1 - \eta A^{DK}) N_{tot}^{D\pi} R_{K/\pi} (1 - \epsilon) \\
 N_{\eta, KID>0.6}^{D\pi} &= \frac{1}{2} (1 - \eta A^{D\pi}) N_{tot}^{D\pi} \kappa \\
 N_{\eta, KID<0.6}^{D\pi} &= \frac{1}{2} (1 - \eta A^{D\pi}) N_{tot}^{D\pi} (1 - \kappa)
 \end{aligned}$$

KID < 0.6

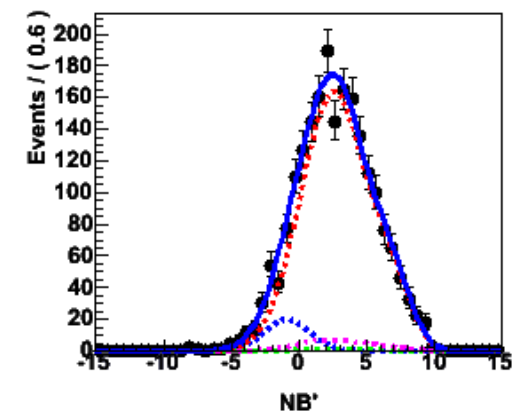
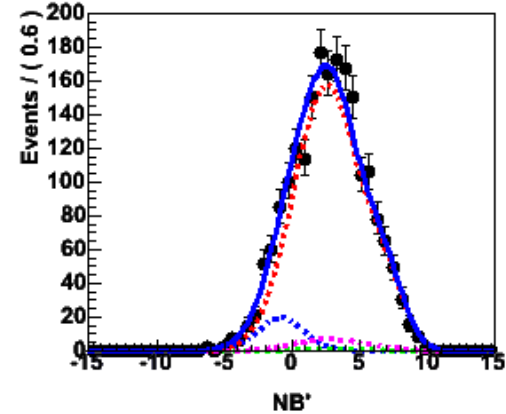
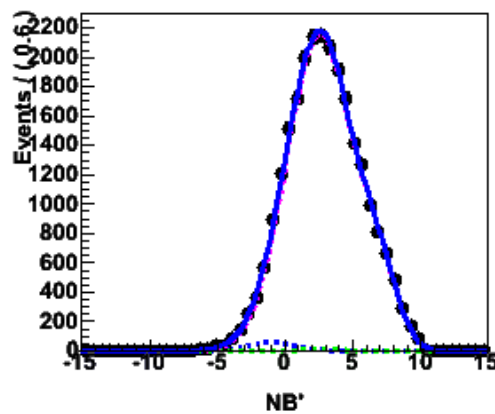
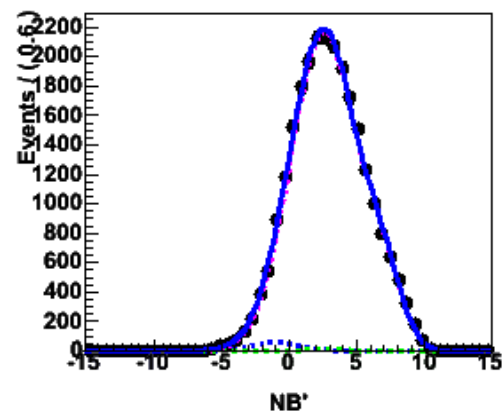
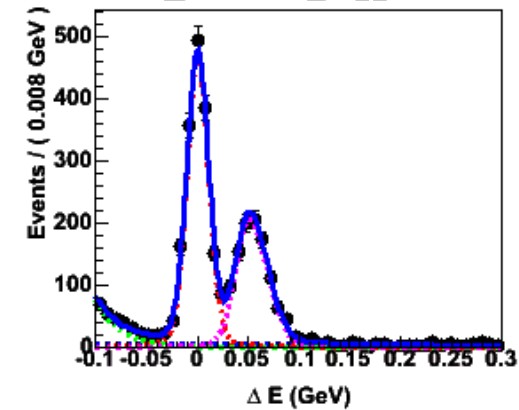
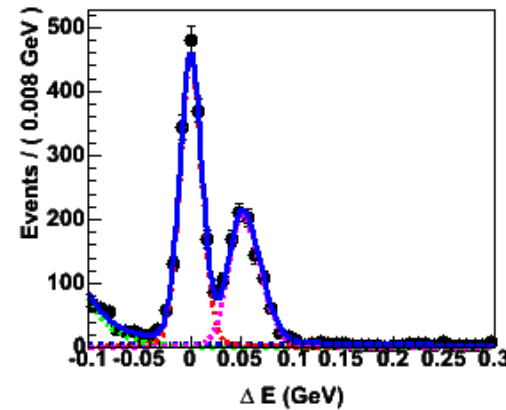
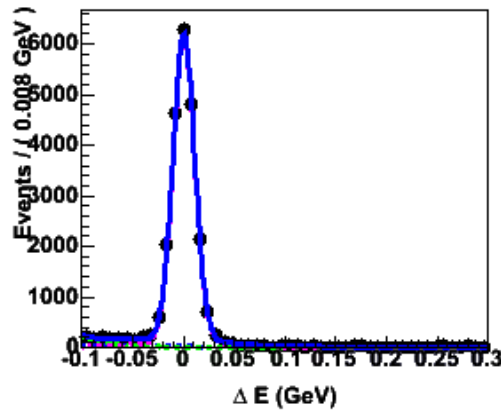
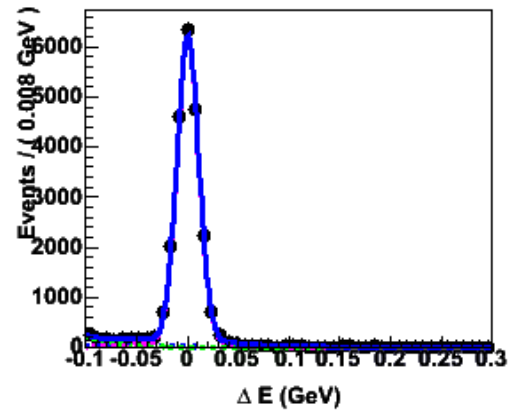
KID > 0.6

$B^+ \rightarrow Dh^+$

$B^- \rightarrow Dh^-$

$B^+ \rightarrow Dh^+$

$B^- \rightarrow Dh^-$



Viola Sordini, CKM2008:

$$\gamma = (78 \pm 12)^\circ \quad \begin{array}{l} \text{Updated for CKM 2008} \\ \text{(since ichep'08 new BaBar GLW } DK^*) \end{array}$$

$$r_B(DK) = 0.102 \pm 0.017$$

$$r_B(D^* K) = 0.089 \pm 0.034$$

$$r_S(DK^*) = 0.103^{+0.068}_{-0.064}$$

Marcella Bona, EPS2011:

$$\gamma = (76 \pm 11)^\circ$$