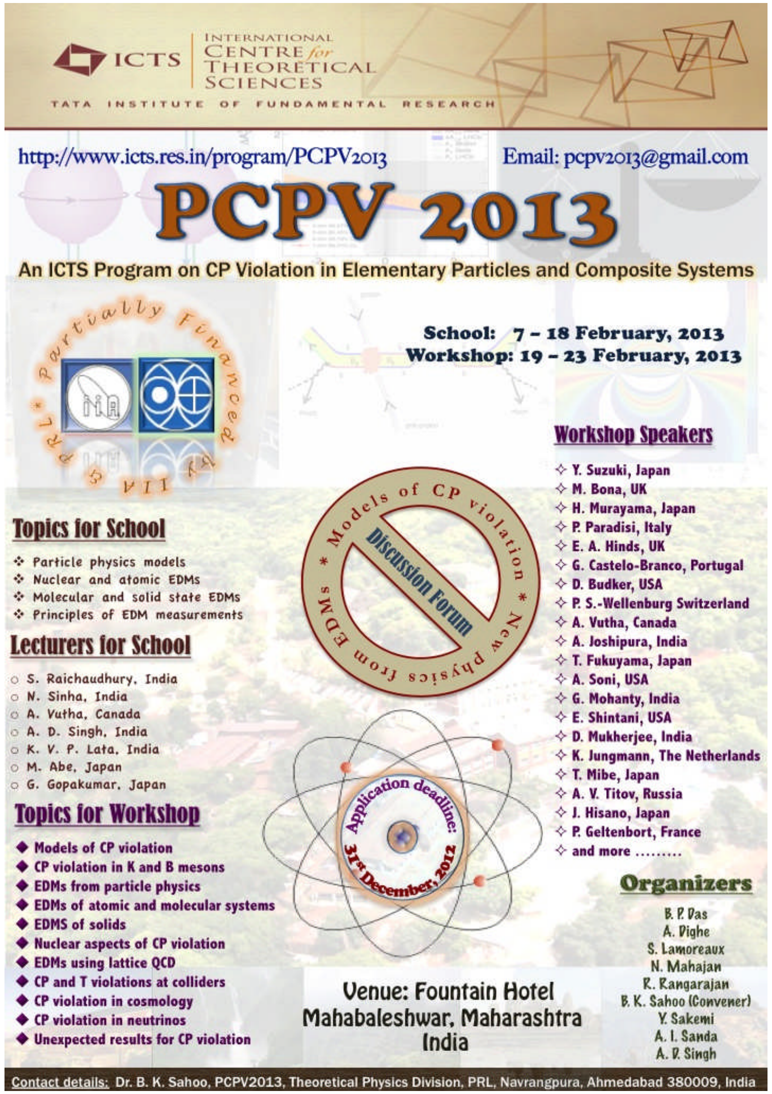
CP violation results from the quark sector



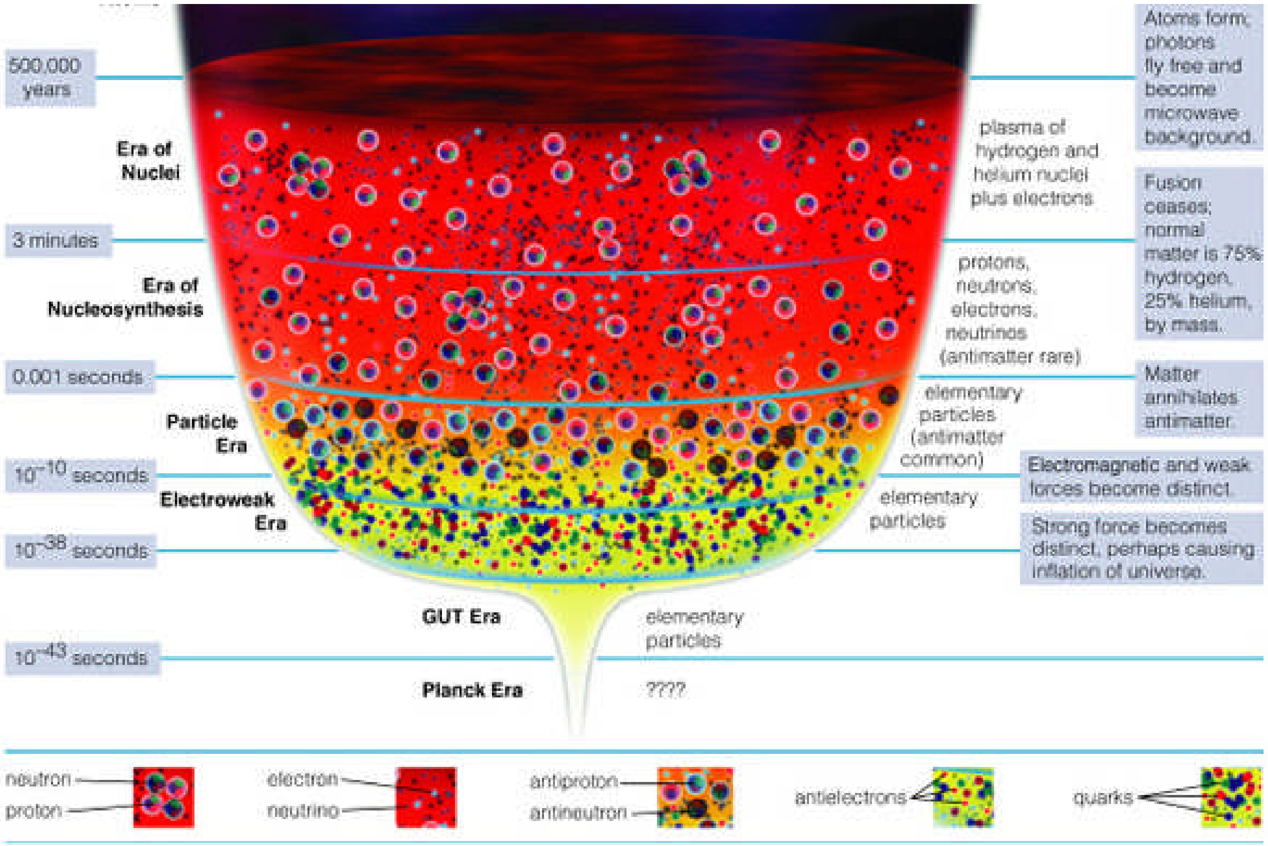
Gagan Mohanty
TIFR, Mumbai

BELLE

CDF

LHCb

~~CP~~ – A prelude

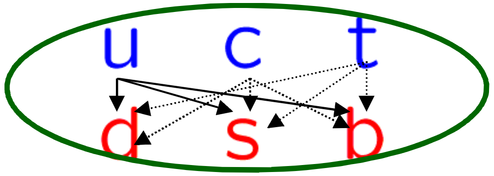


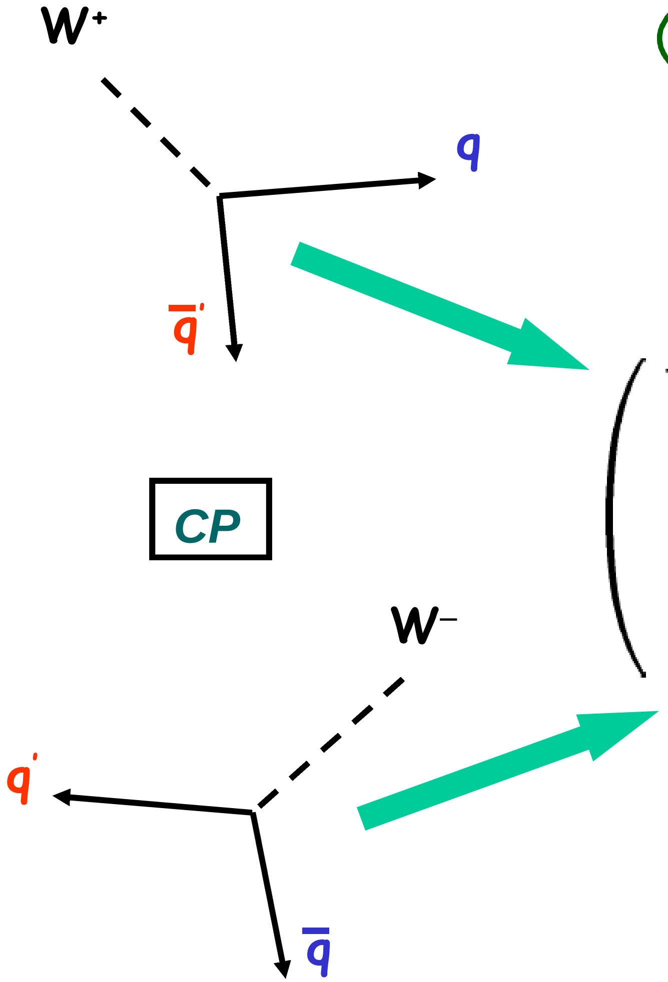
- Today's universe is matter dominated
- Where did all the antimatter go that were created in equal amounts at the beginning?
  - (antiproton/proton) ~10^{-4} in the cosmic ray
  - There is no evidence for annihilation photons with the baryon-to-photon ratio $\approx 6\times10^{-10}$ in intergalactic clouds

- Cosmological generation of asymmetry: Sakharov's three conditions (1967)
  - Baryon number violation, e.g., proton decay,
  - Thermal nonequilibrium, and
  - Violation of charge conjugation (C) and parity (P) symmetries

~~CP~~ in the Standard Model

- **The CKM paradigm in the charged vector-boson (W) decays provides the framework for CP violation in the quark sector of the SM**





$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V^{\dagger}V = 1 \Rightarrow$$

Key piece!!!

- One phase
- 3 real parameters

Hierarchical expansion of V_{CKM}

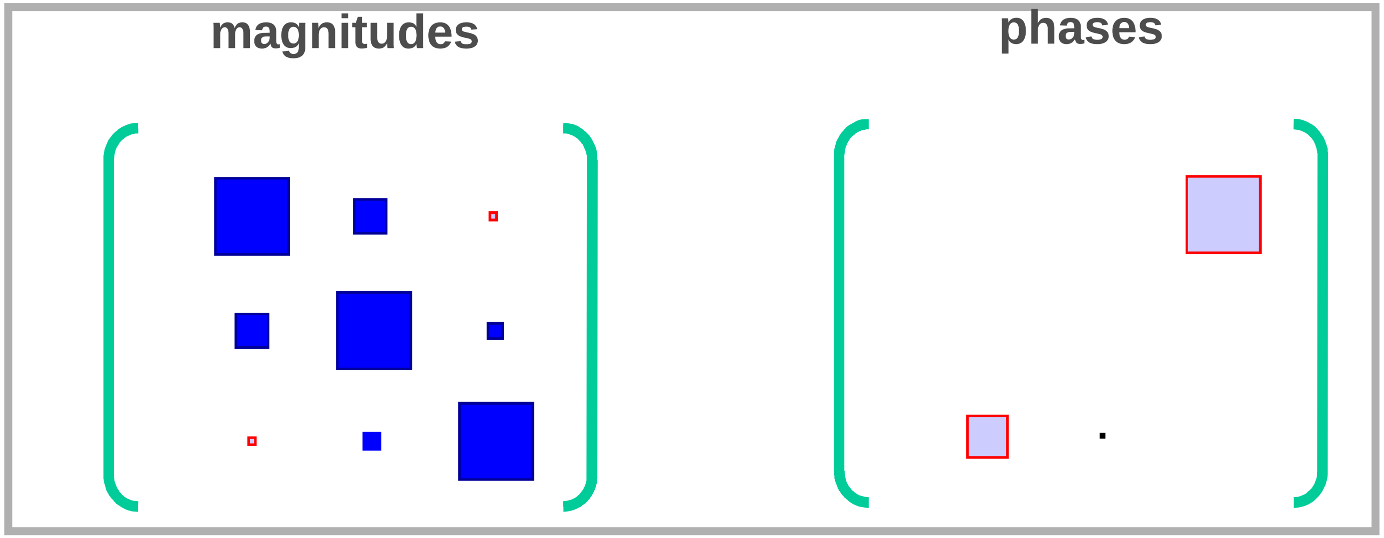
Wolfenstein parameterization of the CKM matrix V:

PRL 51 (1983) 1945

$$V = \begin{pmatrix} V_{ud} = 1 - \frac{1}{2}\lambda^2 & V_{us} = \lambda & V_{ub} = A\lambda^3(\rho - i\eta) \\ V_{cd} = -\lambda & V_{cs} = 1 - \frac{1}{2}\lambda^2 & V_{cb} = A\lambda^2 \\ V_{td} = A\lambda^3(1 - \rho - i\eta) & V_{ts} = -A\lambda^2 & V_{tb} = 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \quad \simeq \quad \sin\theta_c \simeq 0.22$$

λ~0.22	A~0.80
ρ~0.16	η~0.34



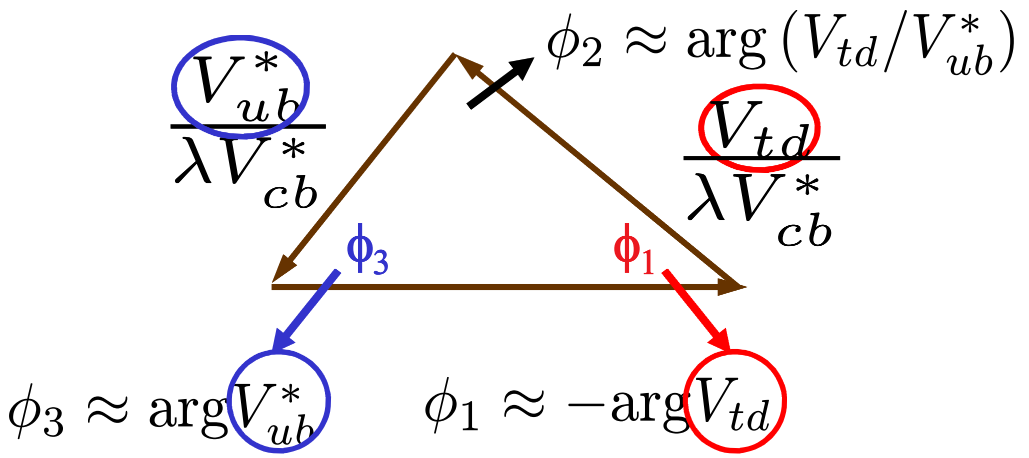
A triangle is at the heart

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

d·b* = 0 B Mesons

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Unitarity: 1st and 3rd columns



- Check consistency of the CKM framework by precisely measuring the sides and angles of the unitarity triangle
- Possible inconsistency between various measurements could be interpreted as potential new physics contribution

B meson: A threefold way

- CP violation in decay: **direct**

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

$$A_f = A(B \to f)$$
$$\bar{A}_{\bar{f}} = A(\bar{B} \to \bar{f})$$

$|\lambda| \neq 1$, where $\lambda = \left(\frac{q}{p}\right)\left(\frac{\bar{A}_{\bar{f}}}{A_f}\right)$

  - can occur in both neutral and charged B mesons
  - can have time-dependent and -independent manifestations
  - need two competing diagrams of different weak as well as strong phases

- CP violation in mixing: **indirect**

$$\left|\frac{q}{p}\right| \neq 1$$

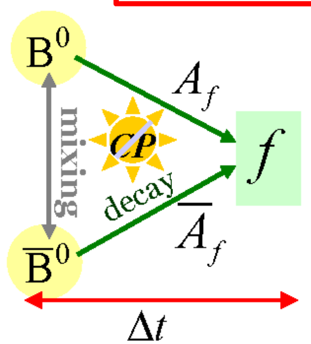
$$\left|B_{H,L}\right\rangle = p\left|B^0\right\rangle \pm q\left|\bar{B}^0\right\rangle$$

$$\left|\frac{q}{p}\right|_{SM} - 1 \simeq 4\pi \frac{m_b^2}{m_t^2} \sin\phi_1 \simeq 5 \times 10^{-4}$$

  - only neutral B mesons are possibly affected
  - SM predicts a very small effect

- CP violation from **mixing/decay interference**:

$$\text{Im}\,\lambda_{CP} \neq 0, \quad |\lambda_{CP}| = 1$$

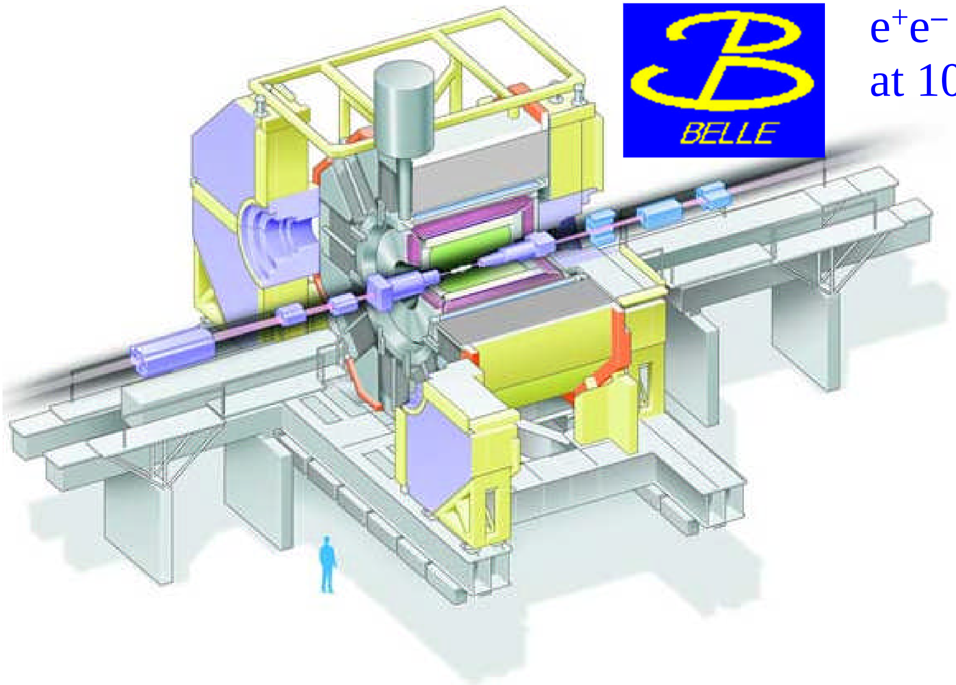


$$\lambda_{CP} = \eta_{CP} \frac{q}{p} \frac{\bar{A}_{\bar{f}}}{A_f}$$

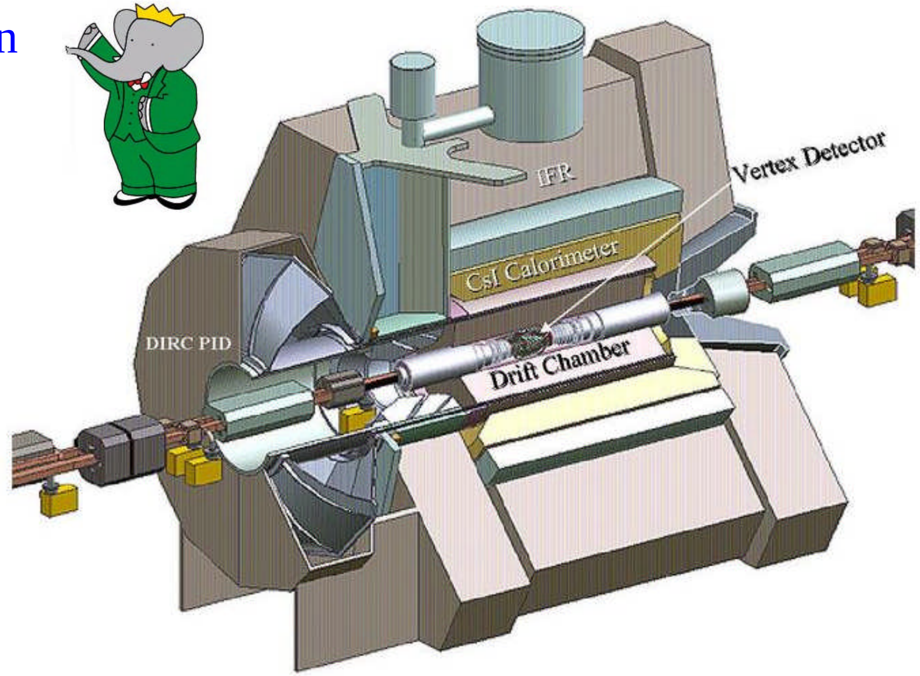
$f \equiv$ CP eigen-state

  - only neutral B mesons could be affected
  - purely a time-dependent effect
  - arises due to interference between decays with and without mixing

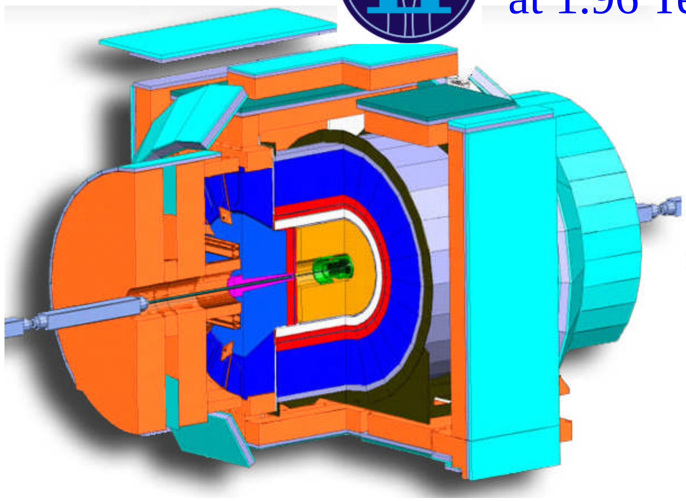
Major actors on our play

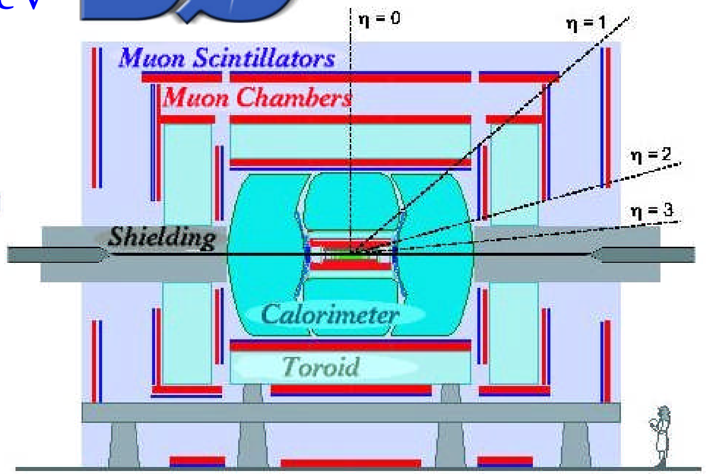


e^+e^- collision
at 10.6 GeV

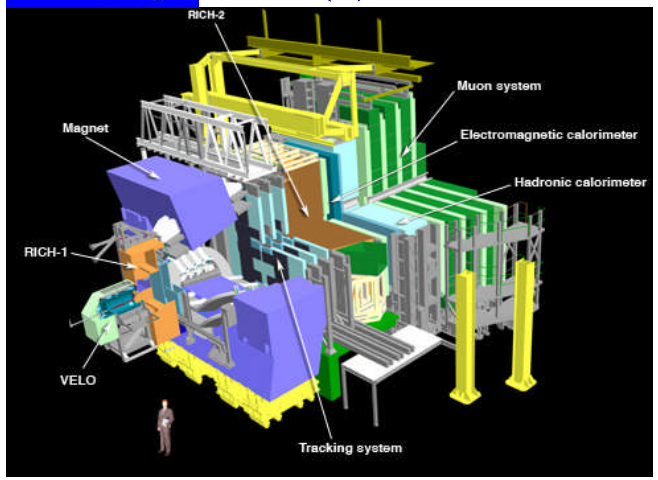


$p\bar{p}$ collision
at 1.96 TeV





pp collision
at 7 (8) TeV



Where do they stand now?

e^+e^- flavor factories

- BaBar stopped taking data since 2008; most of their results are finalized
- Belle is terminated w.e.f. June 2010; still finalizing some of their analyses
- Belle II experiment is on track to start taking data in the early 2016

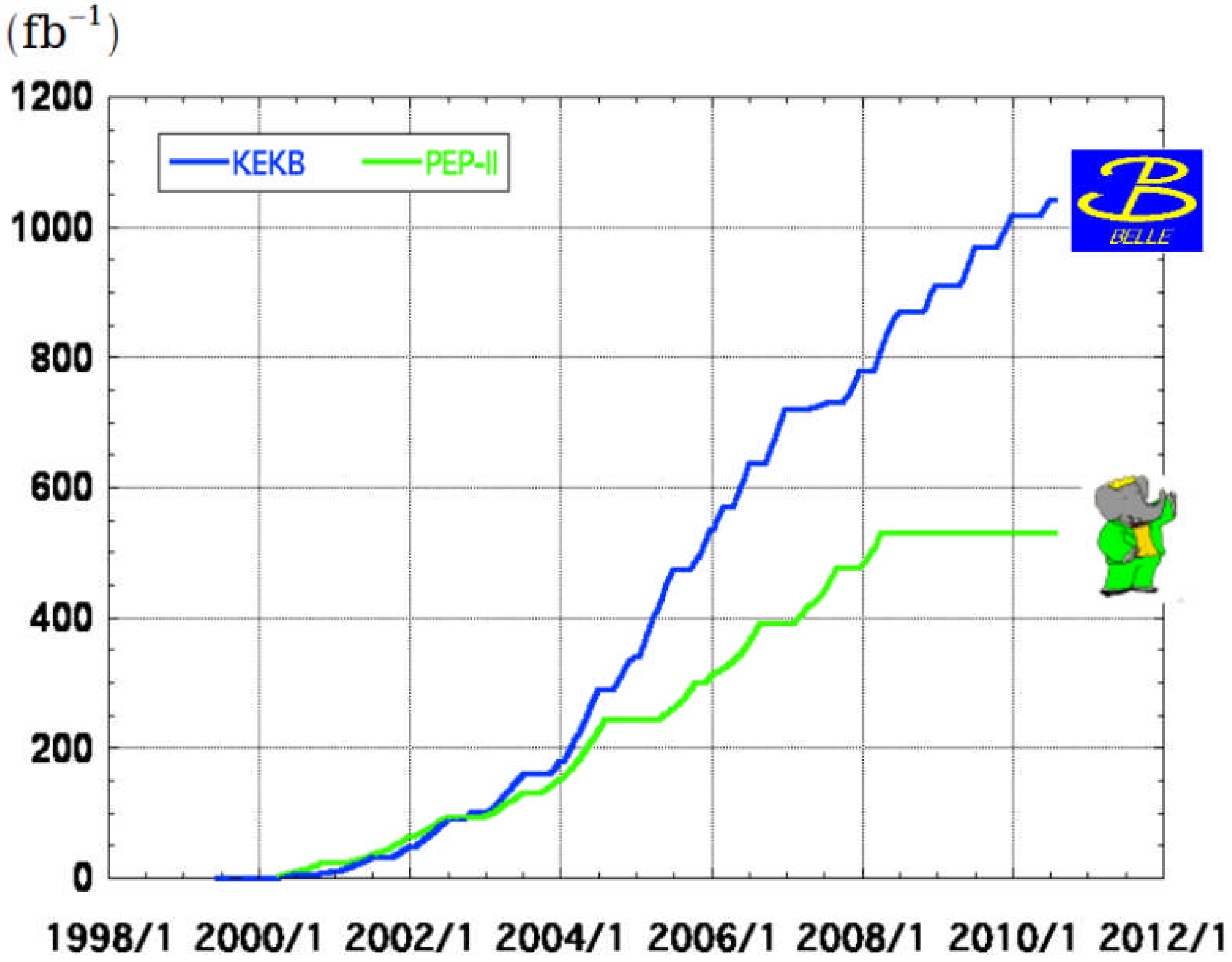
Hadron colliders

- CDF and D∅ have just stopped to take data
- ATLAS and CMS have an active B program but can't compete with…
- LHCb is the main player since 2010 and will continue to be so till 2016

Data recorded by LHCb

Year	Lum (fb^{-1})	$\sqrt{s}$ (TeV)
2010	0.04	7
2011	1.1	7
2012	2.2	8

B factories: performance to behold



> 1 ab^{-1}

On resonance:

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

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

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

$\Upsilon(2S)$: 25 fb^{-1}

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

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

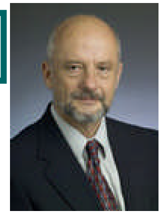
Off resonance:

~ 54 fb^{-1}

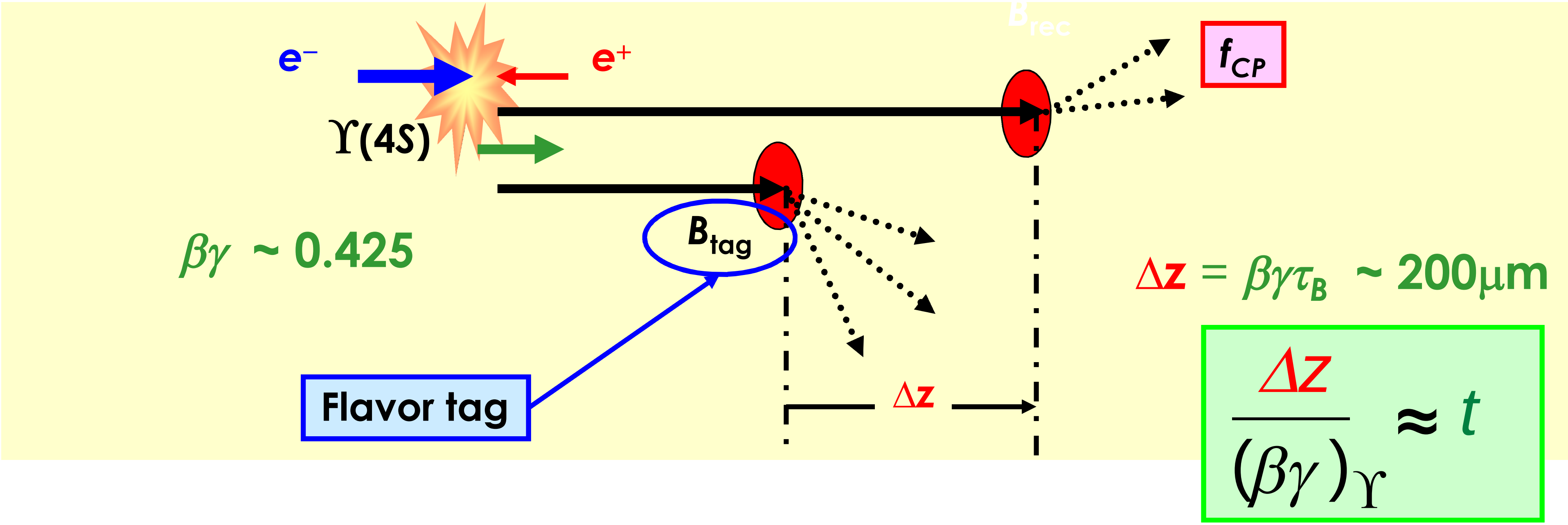
final samples { **BaBar: $467 \times 10^6 B\overline{B}$ pairs**
Belle: $772 \times 10^6 B\overline{B}$ pairs

How to measure mixing induced CP violation?

A brilliant idea from P. Oddone



- Reconstruct the B → f_{CP} decay
- Measure the proper time difference (t) between the two B mesons



$$\frac{\Delta z}{(\beta\gamma)_\Upsilon} \approx t$$

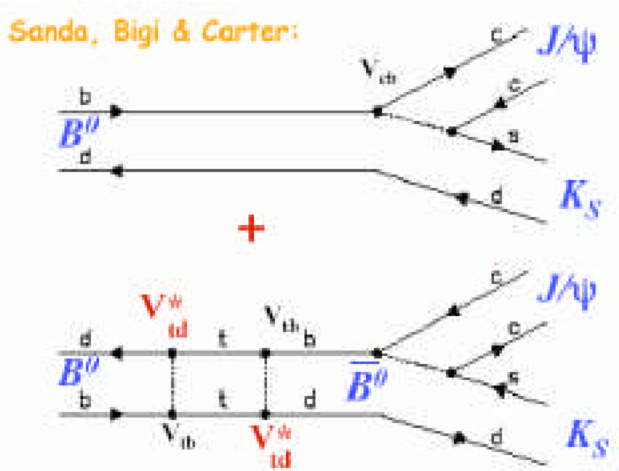
- Determine the flavor of B_{tag} (whether B^0 or $\overline{B}^0$) and then evaluate

$$A_{CP}(t) = \frac{N[\overline{B}^0(t) \to f_{CP}] - N[B^0(t) \to f_{CP}]}{N[\overline{B}^0(t) \to f_{CP}] + N[B^0(t) \to f_{CP}]} \qquad S_f \sin(\Delta m t) + A_f \cos(\Delta m t)$$

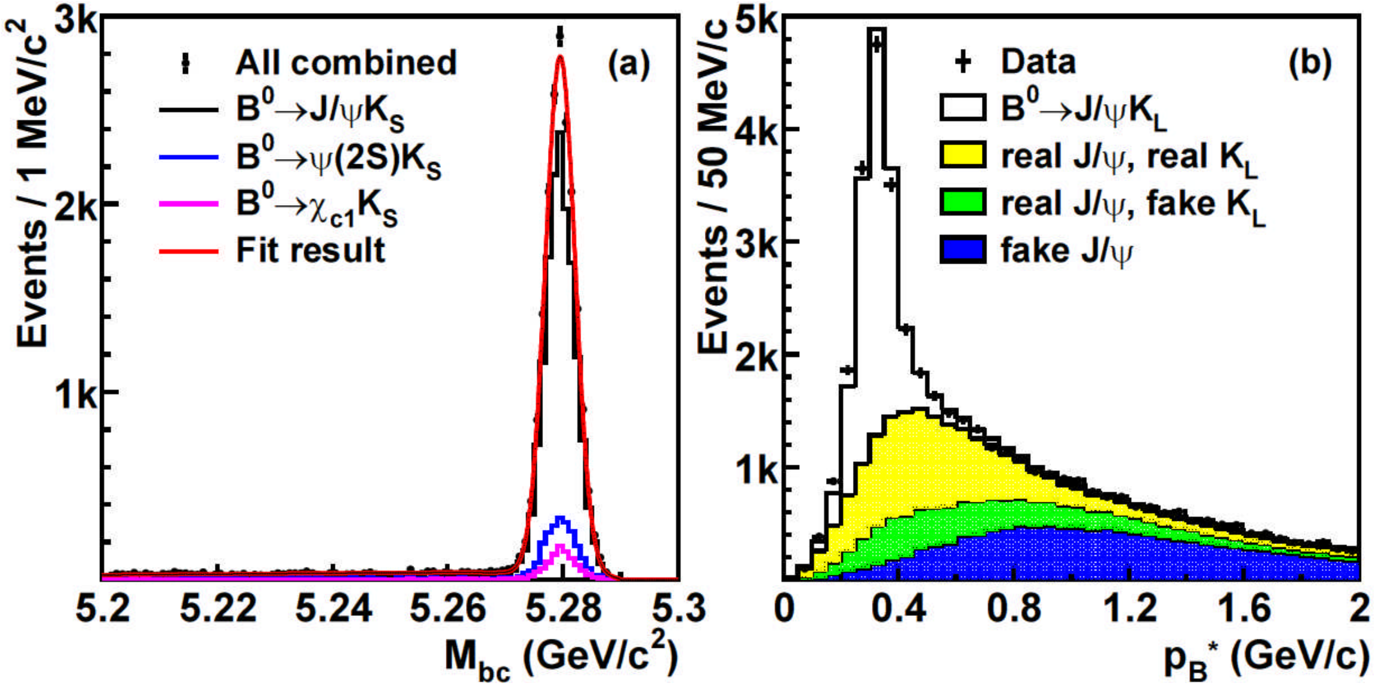
- S_f and A_f are measures of mixing-induced and direct CP violation, respectively

Measurement of $\sin(2\phi_1) \equiv \sin(2\beta)$ in $b \to c\bar{c}s$

- Golden mode for CP violation study with very small theoretical uncertainty



PRL 108 (2012) 171802



- Experimentally easy to identify

- CP-odd eigenstates $J/\psi K_S$, $\psi(2S)K_S$ and $\chi_{c1}K_S$, and CP-even eigenstate $J/\psi K_L$

Decay mode	ξ_f	$N_{\rm sig}$	Purity (%)
$J/\psi K_S^0$	-1	12649 ± 114	97
$\psi(2S)(\ell^+\ell^-)K_S^0$	-1	904 ± 31	92
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0$	-1	1067 ± 33	90
$\chi_{c1}K_S^0$	-1	940 ± 33	86
$J/\psi K_L^0$	$+1$	10040 ± 154	63

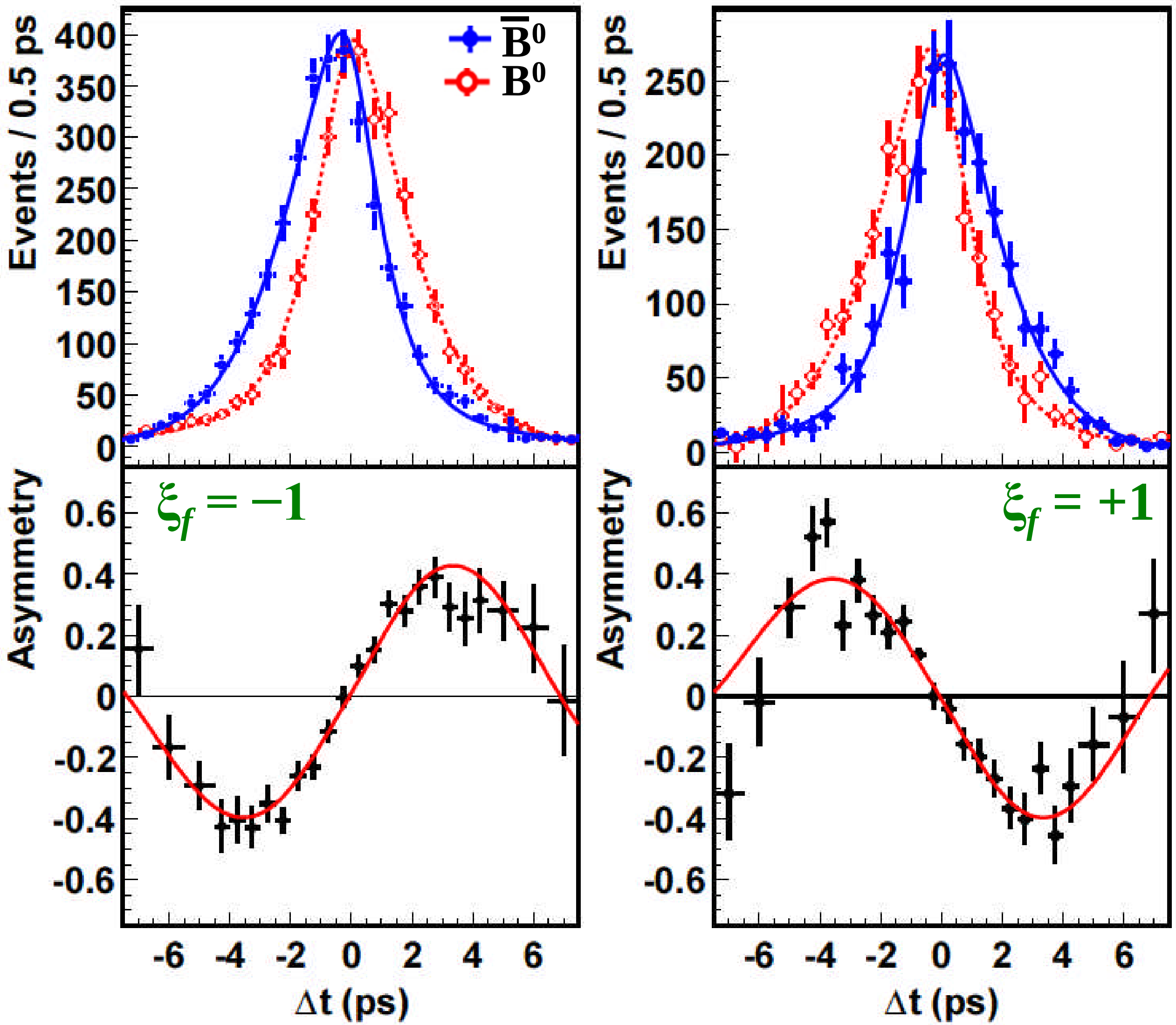
Results on $\sin(2\phi_1)\equiv\sin(2\beta)$ in $b \to c\bar{c}s$

PRL 108 (2012) 171802

- Most precise measurement of the mixing-induced CP violation in B-meson decay

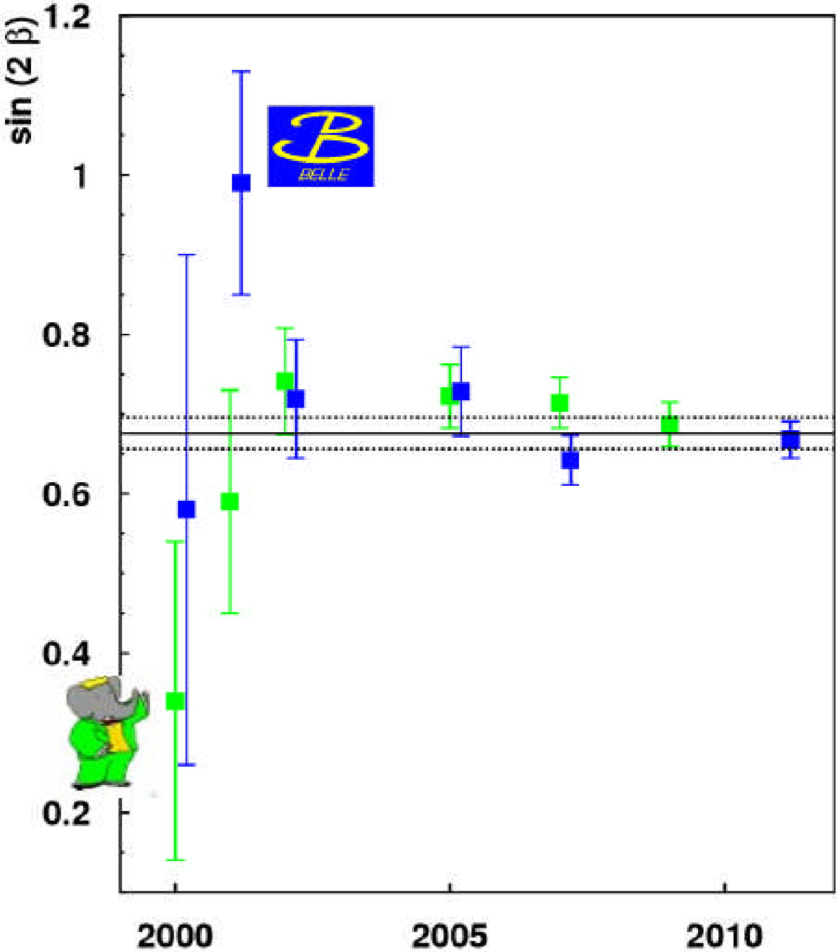
$$\sin 2\phi_1 = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst})$$
$$\mathcal{A}_f = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})$$

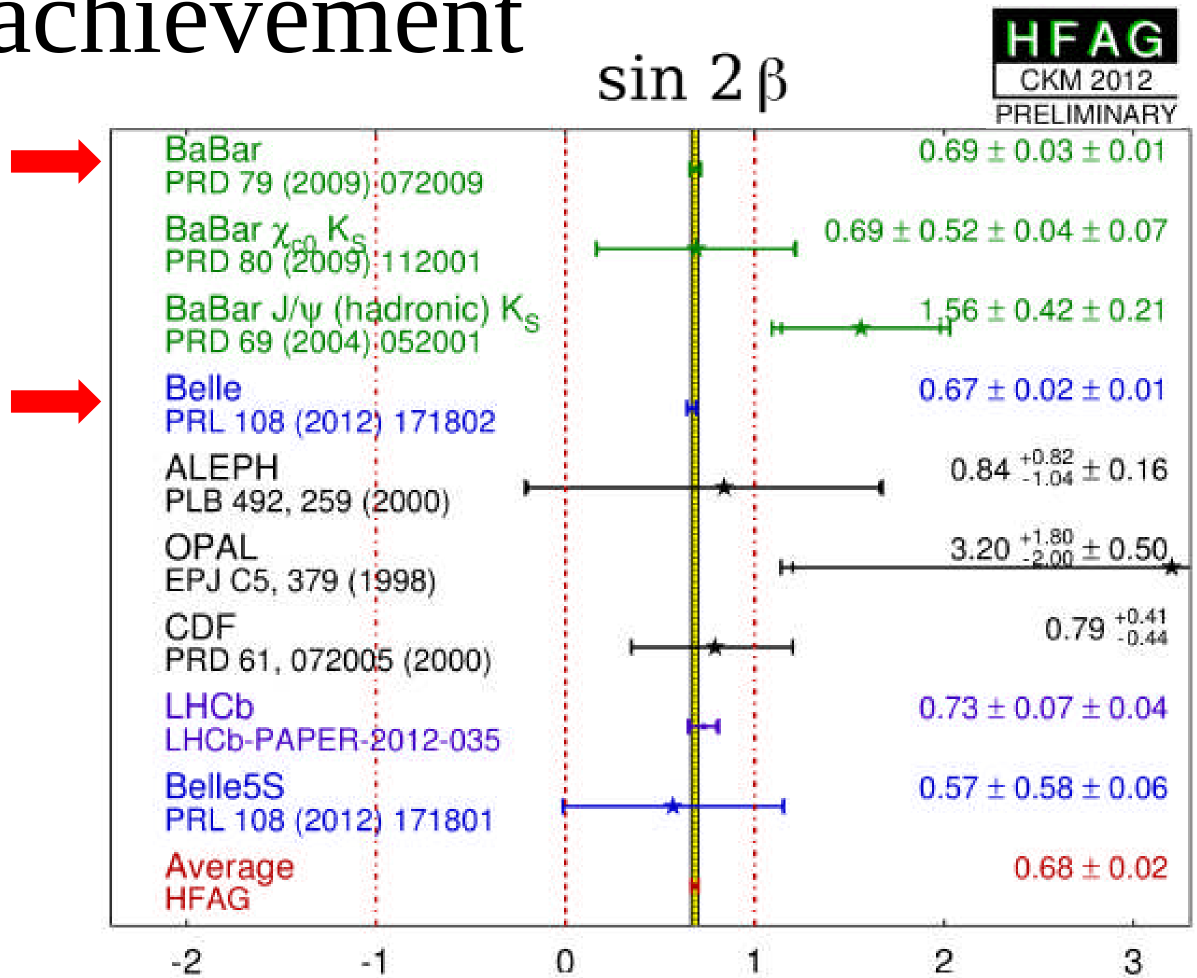
- Asymmetry pattern in line with the CP eigenvalue of the decay final states



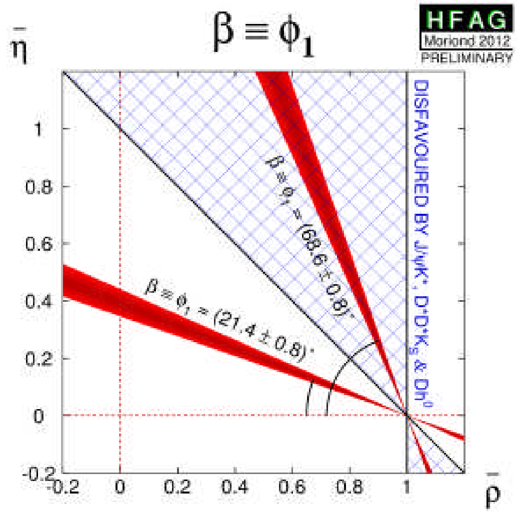
- Direct CP asymmetry is consistent with zero, as expected ➡ a negligible height difference between B^0 and $\overline{B}^0$ tagged decays

Indeed, a great achievement





$$\boxed{\phi_1 = (21.4 \pm 0.8)^\circ}$$

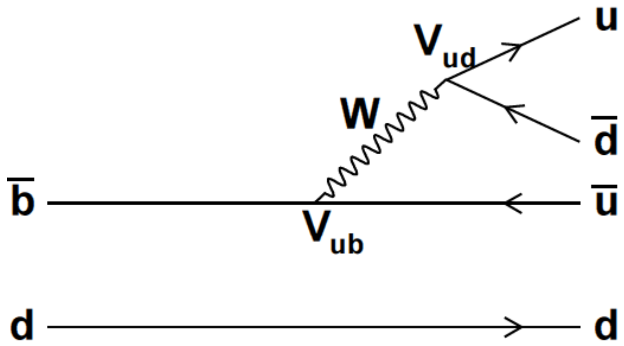


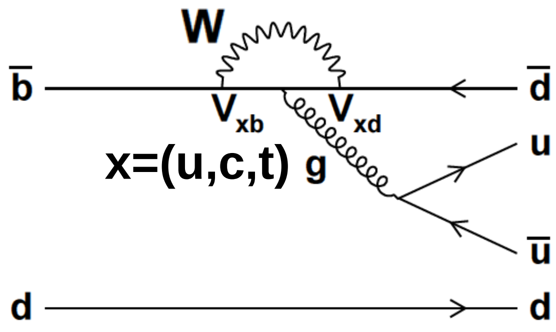
What is the source for CP violation in the SM?

the Kobayashi-Maskawa phase is the source

Determination of $\phi_2 \equiv \alpha$

- Measure time-dependent CP asymmetry in $b \rightarrow u$ tree dominated decays





- Additional complication arises due to possible $b \rightarrow d$ penguin contributions
- The sine coefficient (S_f) accessed in the time-dependent CP study here is not just $\sin(2\phi_2)$ rather $\sqrt{1-A_f^2}\,\sin(2\phi_2^{\rm eff})$

Considering relative penguin-to-tree contribution (r = |P|/|T|) and strong phase difference between the two diagrams (δ):

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

BaBar notation:

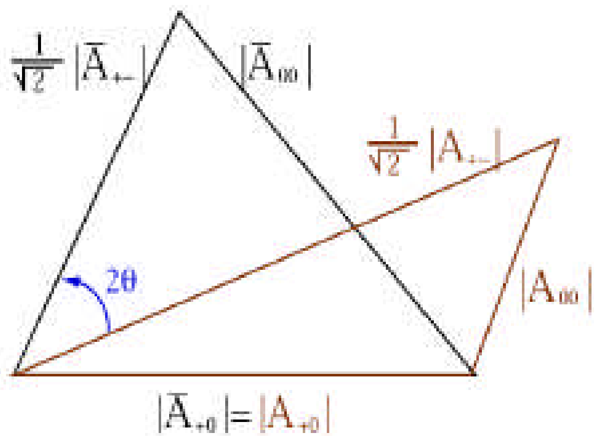
$C_f = -A_f$

➢ additional inputs required to determine the penguin pollution

- Employ an isospin analysis

Gronau and London PRL 65 (1990) 3381

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



ϕ_2 can be resolved up to an 8-fold ambiguity $\phi_2 \in [0,\pi]$

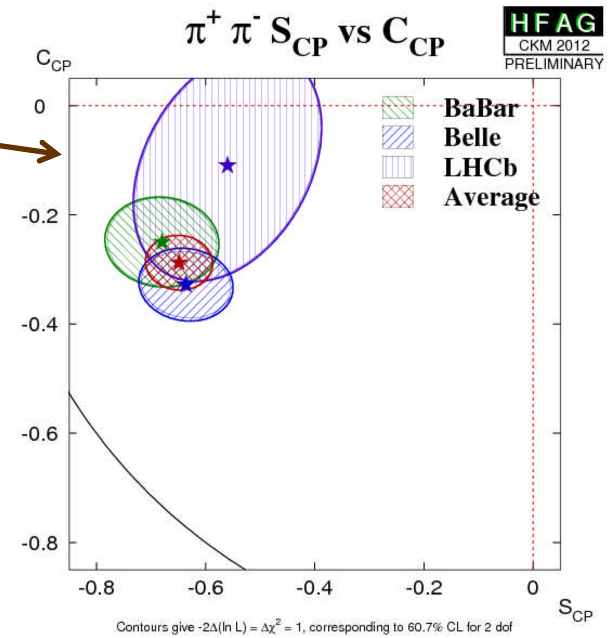
Results from the $\pi\pi$ system

difference used to be more than 2σ

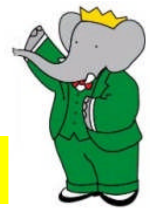
arXiv:1302.0551

C = –0.33 ± 0.06 ± 0.03
A = +0.64 ± 0.08 ± 0.03

direct CP violation @ 5σ



BaBar notation:
$C_f = -A_f$

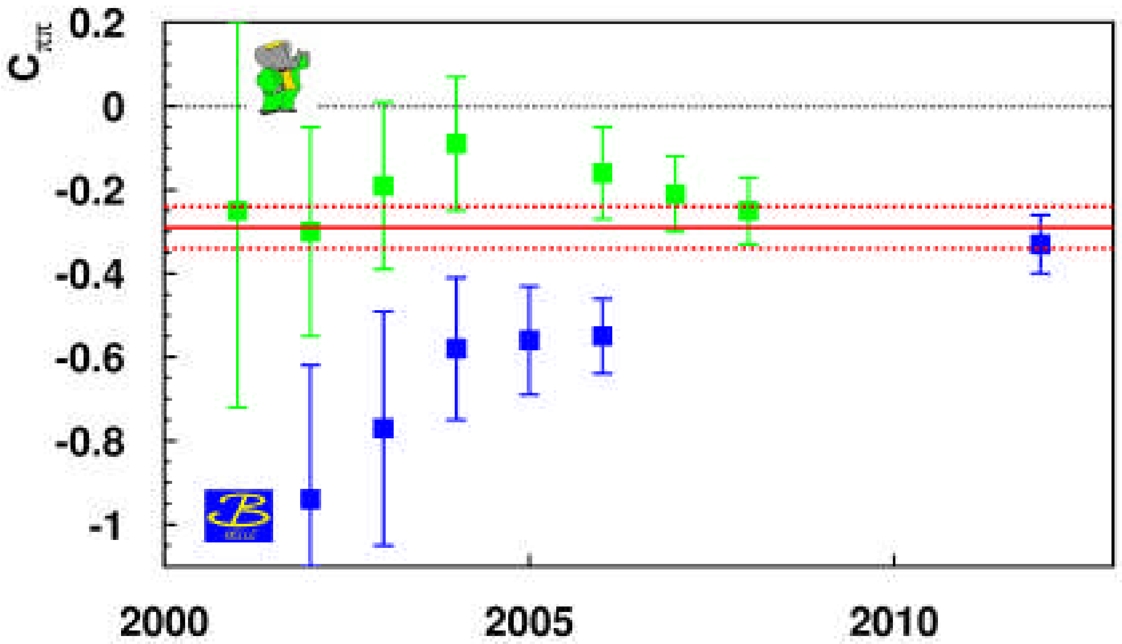


arXiv:1206.3525

C = –0.25 ± 0.08 ± 0.02
S = –0.68 ± 0.10 ± 0.03

LHCb-CONF-2012-007

C = –0.11 ± 0.21 ± 0.03
S = –0.56 ± 0.17 ± 0.03



➢ Both experiments are now in good agreement

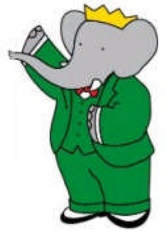
World average of $\phi_2 \equiv \alpha$

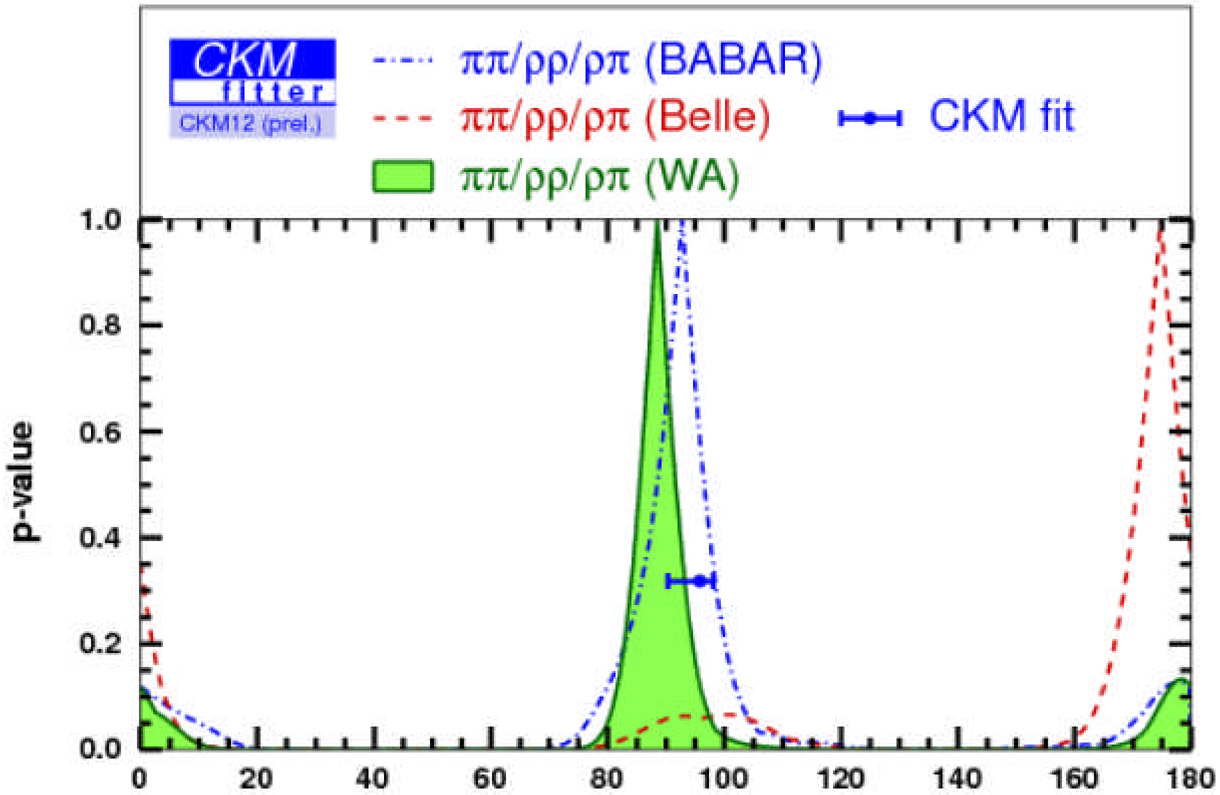
- Almost a precision measurement

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

- Dominated by BaBar's results on $B^+ \to \rho^+\rho^0$

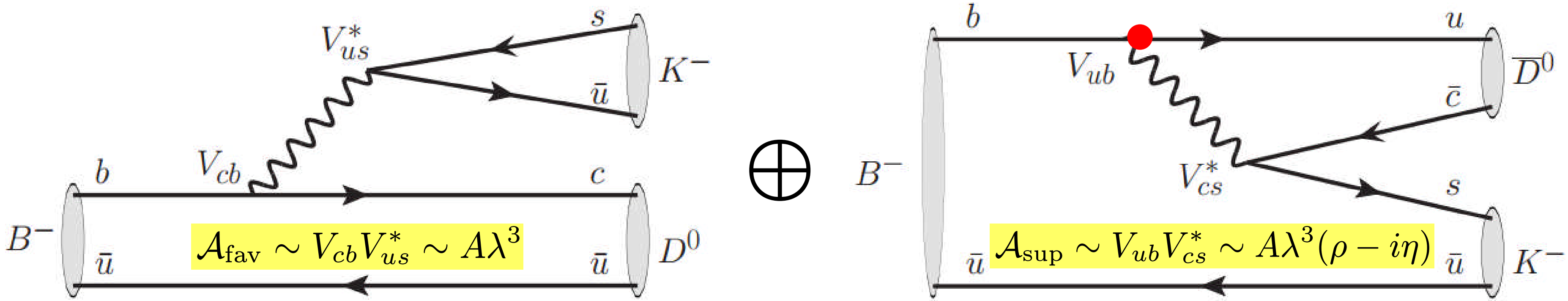
PRL 102 (2009) 141802





❖ BELLE final results on $B \to \rho\rho$, especially $B^+ \to \rho^+\rho^0$, are eagerly awaited for → nine times more data compared to its last result on $\rho^+\rho^0$

Measurement of the angle $\phi_3 \equiv \gamma$



- Interference between the two amplitudes where both D^0 and $\bar{D}^0$, coming from B^+ or B^-, decay to a common final state
- Relative magnitude of the suppressed amplitude

$$r_B = \frac{|\mathcal{A}_{\rm sup}|}{|\mathcal{A}_{\rm fav}|} \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times [\text{color supp}] = 0.1\text{-}0.2$$

- Relative weak phase is ϕ_3 and relative strong phase δ_B

Three proposals depending on the D final state

- ✓ $D \equiv D_{CP}$: CP eigenstates such as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$
  Gronau-London-Wyler (GLW) method
- ✓ $D \equiv D_{DCS}$: doubly Cabibbo suppressed decays such as $K\pi$
  Atwood-Dunietz-Soni (ADS) method
- ✓ $D \equiv D_{Dalitz}$: three-body decays such as $K_SK^+K^-$, $K_S\pi^+\pi^-$
  Giri-Grossman-Soffer-Zupan (GGSZ) method

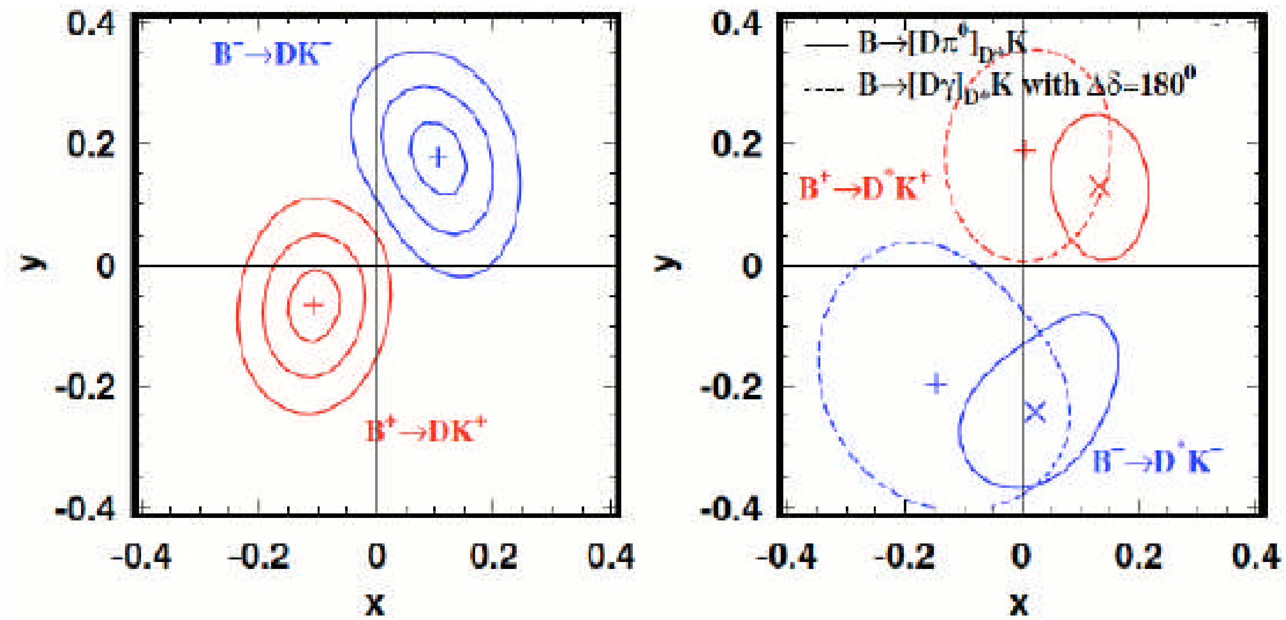
- Different B decays (DK, D^*K, DK^*) come with different (r_B, δ_B)

Going by the conventional method

- Sensitivity dominated by the measurements in D mesons decay to three-body final states (e.g., $K_S\pi^+\pi^-$) that exploit the difference between the B^+ and B^- decay Dalitz plots

Giri et al., PRD 68 (2003) 054018

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



PRD 81 (2010) 112002

$$\phi_3 = (80.8^{+13.1}_{-14.8} \pm 5.0 \pm 8.9)^\circ$$
$$r_B = (16.1^{+4.0}_{-3.8} \pm 1.1^{+5.0}_{-1.0})\%$$
$$\delta_B = (137.4^{+13.0}_{-15.7} \pm 4.0 \pm 22.9)^\circ$$

PRL 105 (2010) 121801 ⬅ Similar results from

$$\phi_3 = (73.9^{+18.9}_{-20.2} \pm 4.2 \pm 8.9)^\circ$$
$$r_B = (19.6^{+7.3}_{-7.2} \pm 1.3^{+6.2}_{-1.2})\%$$
$$\delta_B = (341.7^{+18.6}_{-20.9} \pm 3.2 \pm 22.9)^\circ$$

Combining both B modes, Belle obtains: $\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$

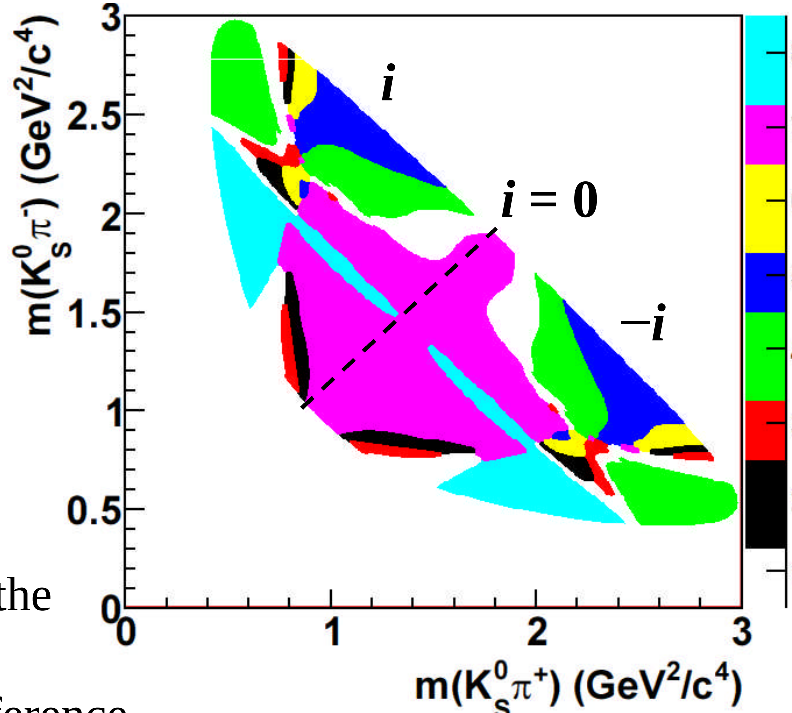
- Accuracy in the DP model description (last error in above results) is the second largest contributor to ϕ_3 after the statistical uncertainty
- It would *call the shot* in the precise determination of φ_3 at the next-generation flavor factory ➡ look for a suitable alternative

ϕ_3 from a model independent Dalitz-plot fit

- Avoid the model error by "optimal" binning of the Dalitz plot (choice of bins guided by model, but not the extraction of ϕ_3)

- Minimize χ^2 in fit to all bins for each mode

Bonder, Poluektov, EPJ C 55 (2008) 51



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

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

where $x_\pm = r_B\cos(\delta_B \pm \phi_3)$, $y_\pm = r_B\sin(\delta_B \pm \phi_3)$

K_i: # events in bin i from flavor-tagged $D \to K_S\pi^+\pi^-$ of the $D^* \to D\pi$ decay channel

c_i and s_i contain information about the strong-phase difference in bin i ➡ use the CLEO data for $\psi(3770) \to D^0\bar{D}^0$

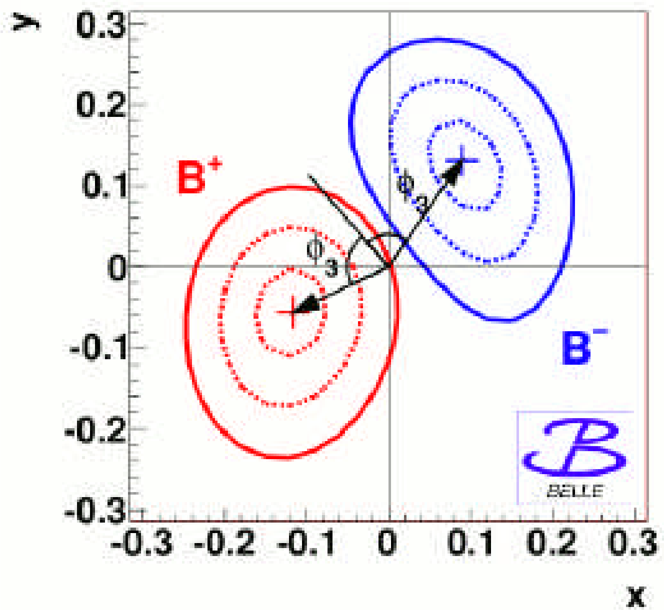
PRD 82 (2010) 112006

PRD 85 (2012) 112014

$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$

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

$$r_B = (14.5 \pm 3.0 \pm 1.0 \pm 1.1)\%$$

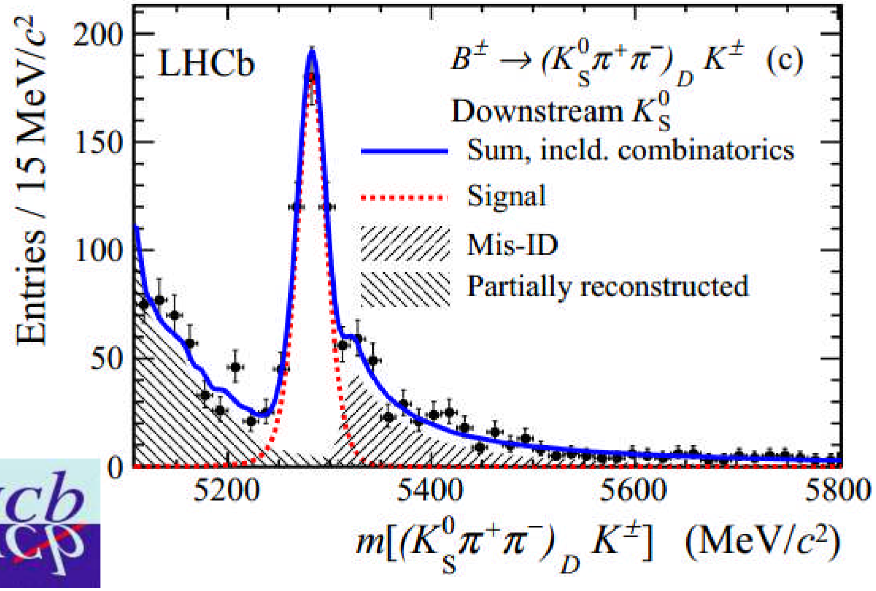


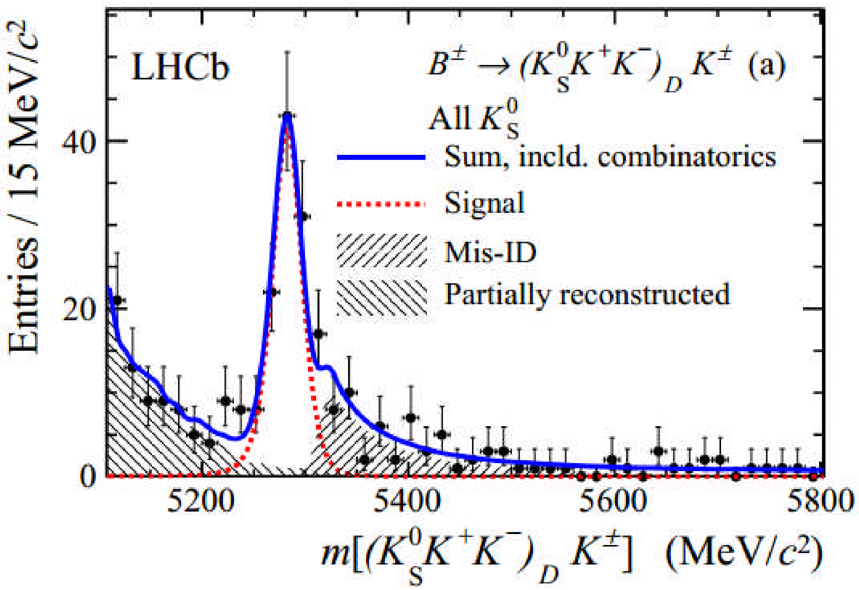
- 8.9° model error ➡ 4.3° ☺; stat error little worse due to (a) the method itself and (b) smaller r_B ➡ $\sigma \sim 1/r_B$

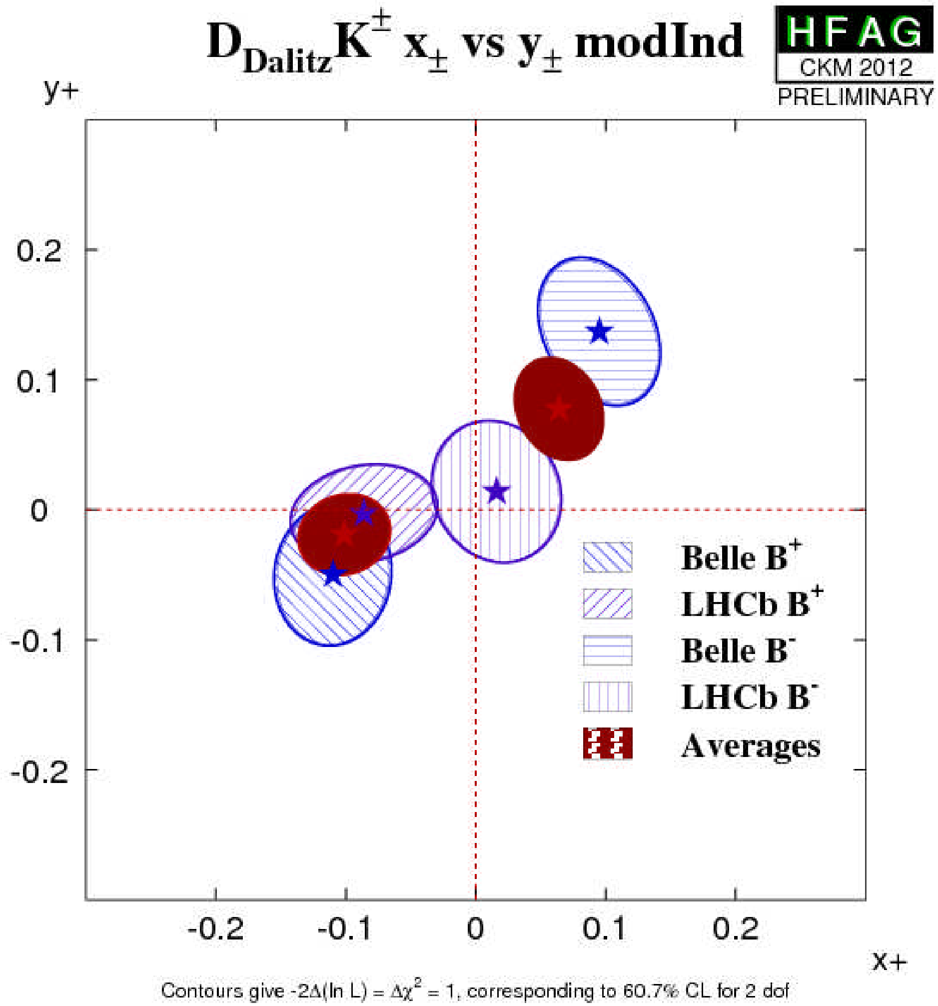
LHCb is rapidly catching up…

- First measurement of GGSZ (D → K_sKK, $K_s\pi\pi$ and model independent)

arXiv:1209.5869







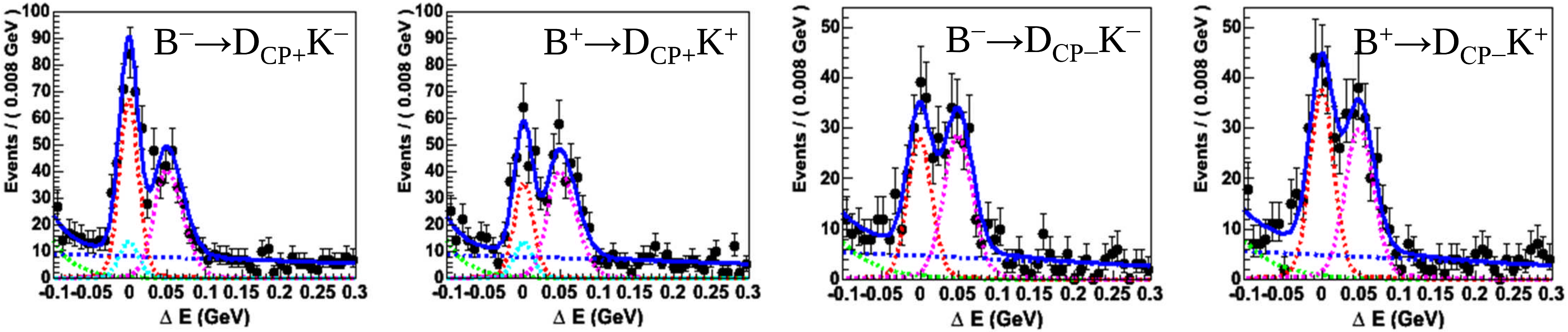
$$\phi_3 = (44^{+43}_{-38})^\circ,\ r_B = (7 \pm 4)\%,\ \delta_B = (137^{+35}_{-46})^\circ$$

φ_3 using GLW and ADS methods

- Two complementary approaches where D mesons decay to
  1) CP states, e.g., K^+K^-, $\pi^+\pi^-$ (CP+) & $K_S\pi^0$, $K_S\eta$ (CP−) GLW
  2) doubly CKM suppressed final state ADS

PLB 253, 483 (1991)
PLB 265, 172 (1991)

PRL 78, 3257 (1997) PRD 63, 036005 (1991)



Preliminary

- Observables sensitive to φ_3:

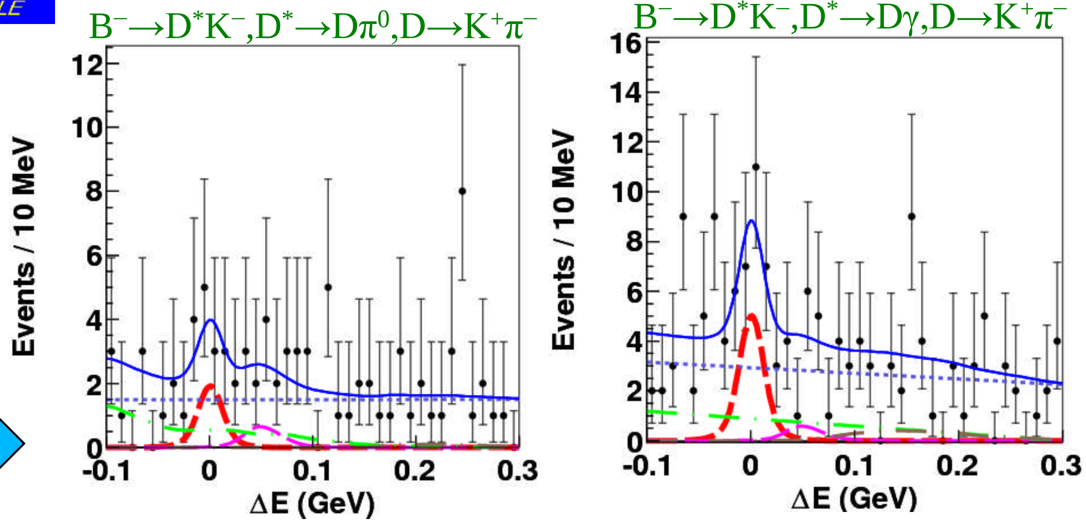
$$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$$

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

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

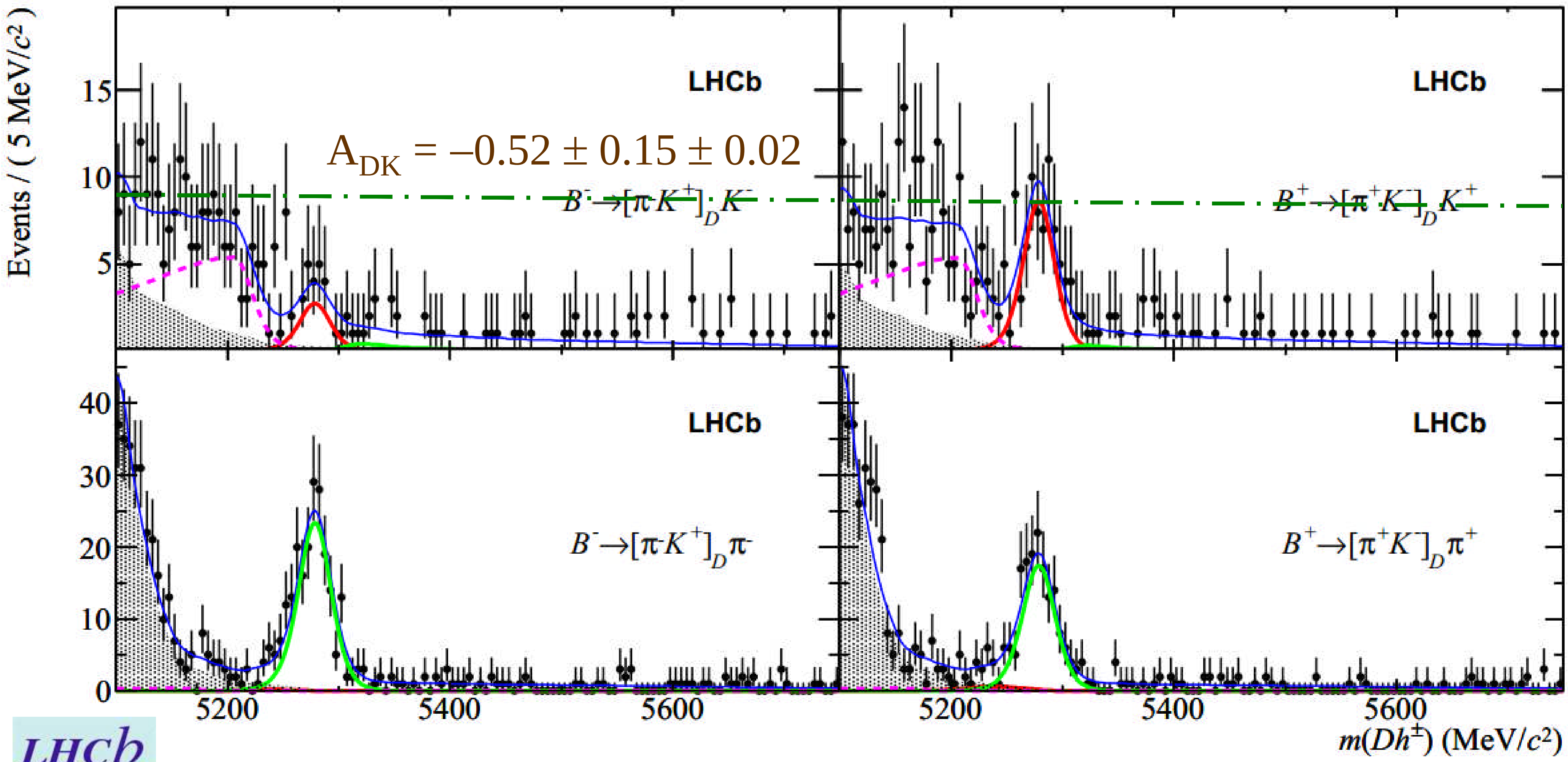
$$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$$

- 1st Evidence for ADS mode $B \to D^*K$ (3.5σ significance)



ADS results from LHCb

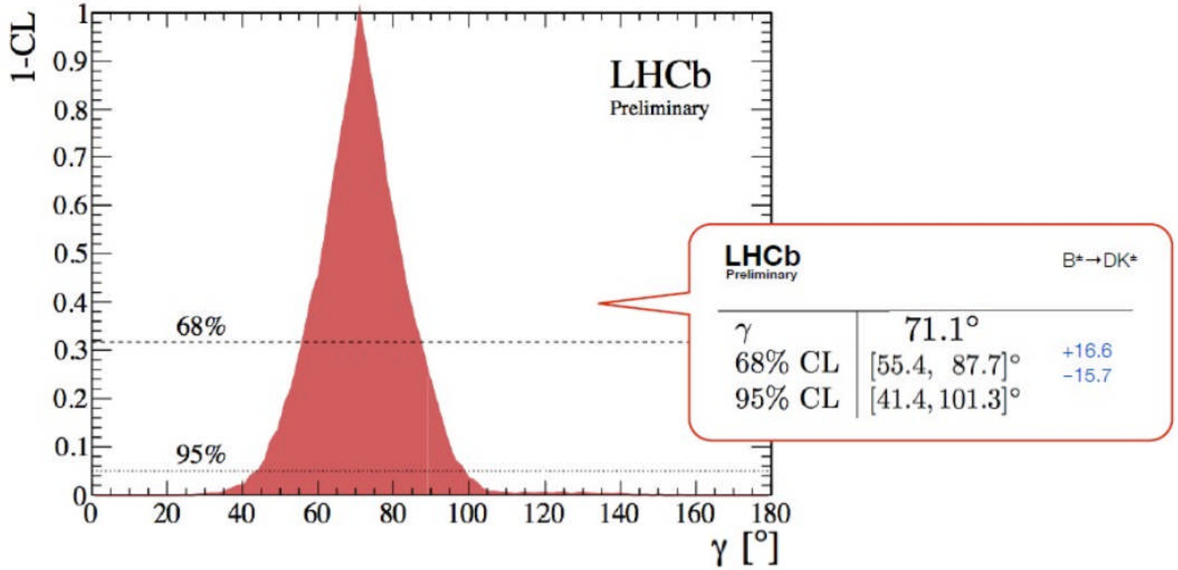
PLB 712 (2012) 203



➢ 1st observation (5.8σ significance) of the suppressed mode $B^{\pm} \to [\pi^{\pm} K^{\mp}]_D K^{\pm}$

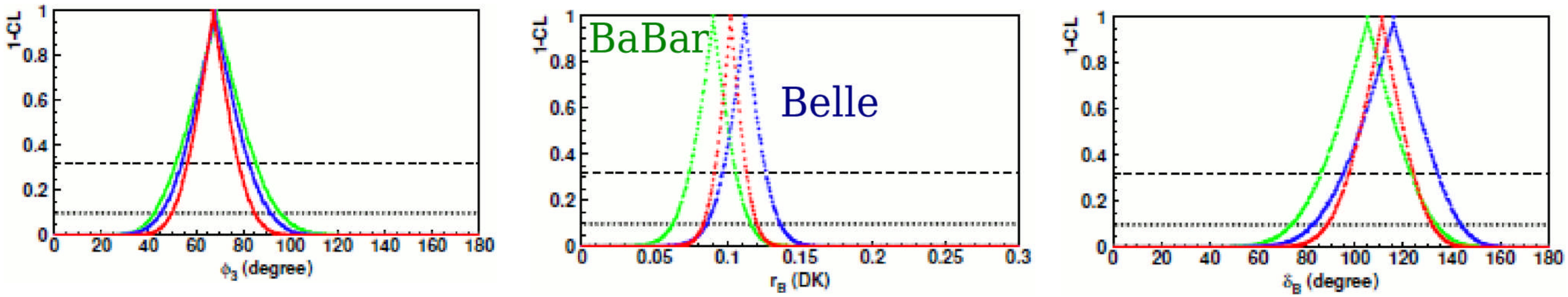
Combined measurement of $\phi_3 \equiv \gamma$

- From the new player (LHCb):



$$\phi_3 = (71^{+17}_{-16})^\circ$$
$$r_B = (9.5 \pm 0.9)\%$$
$$\delta_B = (119^{+10}_{-13})^\circ$$

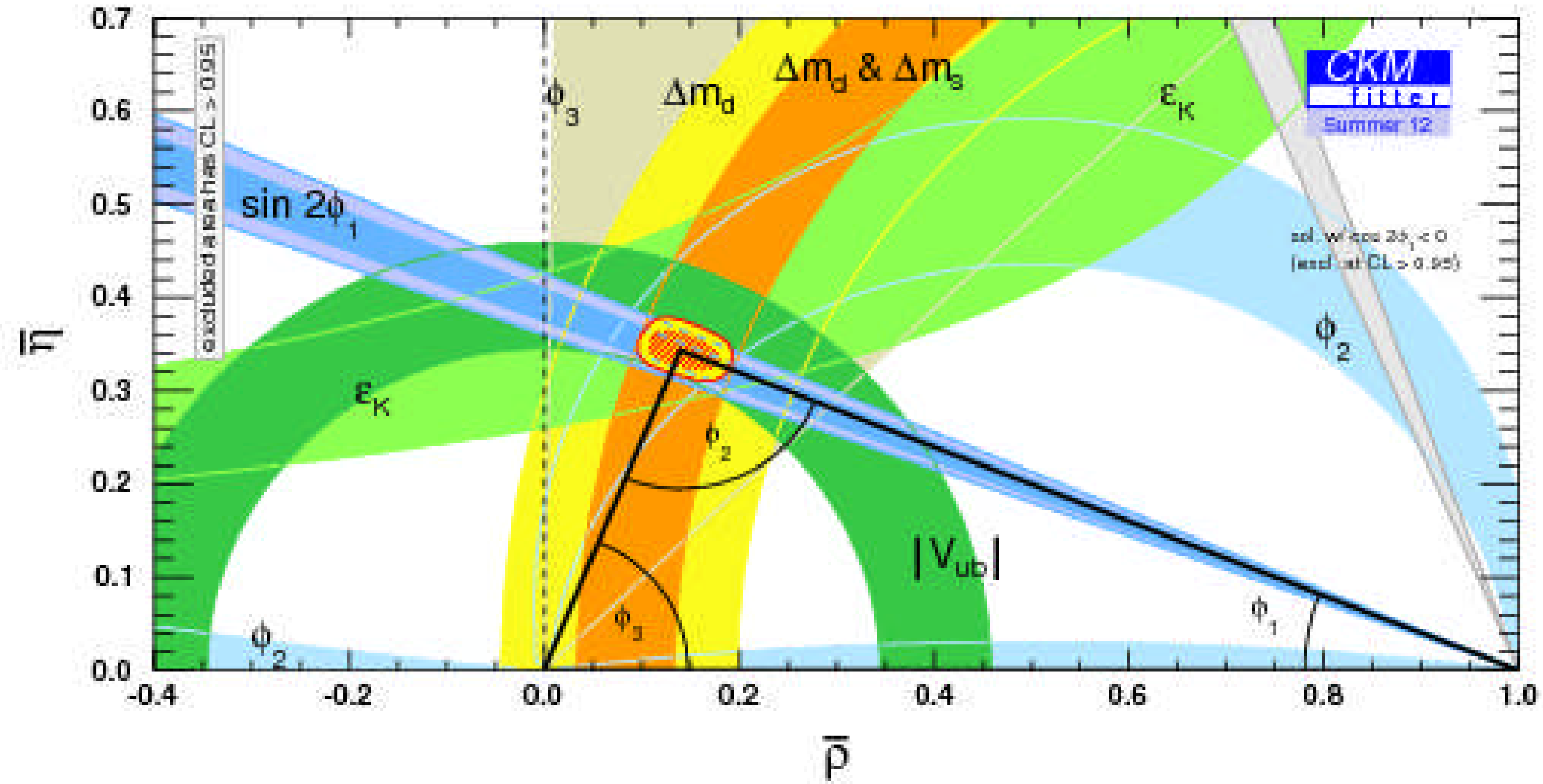
- From the old horses (Belle and BaBar):



	$\phi_3[^\circ]$	$r_B(DK)[\%]$	$\delta_B(DK)[^\circ]$
BaBar	69 ± 17	$9.0^{+1.6}_{-1.7}$	105 ± 19
Belle	68 ± 14	11.2 ± 1.5	116^{+19}_{-21}
B factories	67 ± 11	10.2 ± 1.1	111^{+13}_{-14}

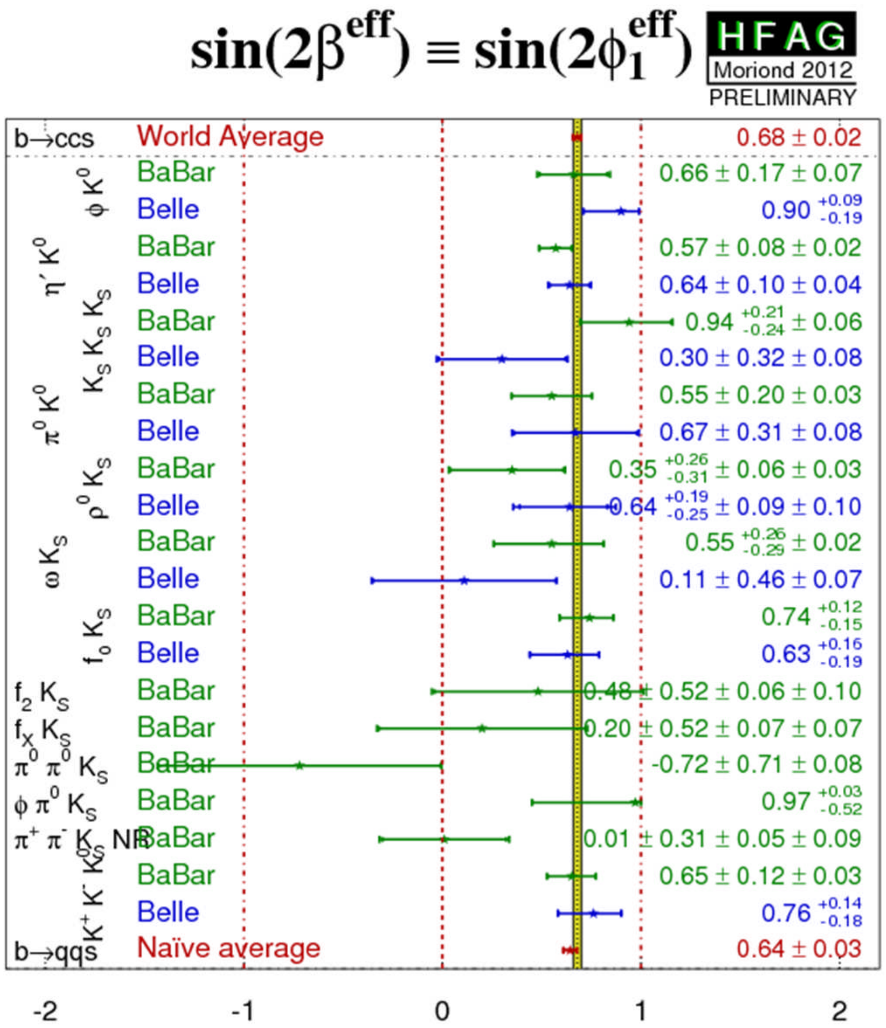
Overall picture

CKMfitter Group, J. Charles *et al*., EPJ C41 (2005) 1



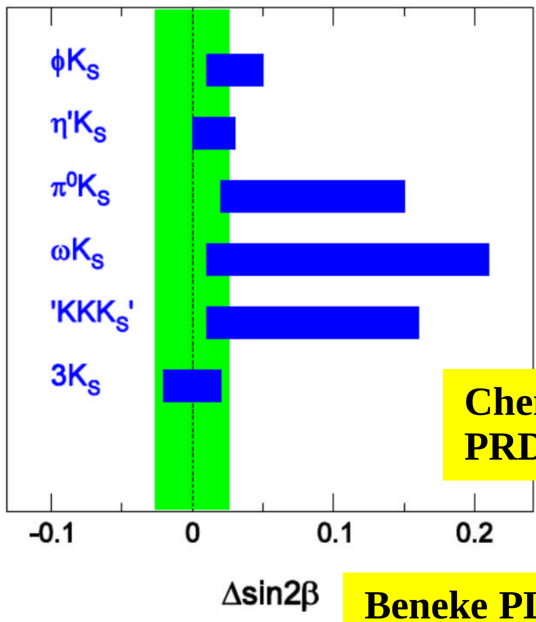
- Confirmation of the CKM paradigm as the lone source for CP violation in the SM ⇒ not sufficient enough to explain the matter-antimatter asymmetry observed in the universe
- Need additional source(s) beyond the realm of the SM

$\sin(2\phi_1)$ in $b \to q\bar{q}s$ transitions



- Naïve average of $\sin(2\phi_1^{eff})$ obtained in various $b \to q\bar{q}s$ processes is consistent with the value obtained in $b \to c\bar{c}s$
- However, we need to be very careful here because of

theory uncertainty



Cheng *et al.*, PRD72, 094003

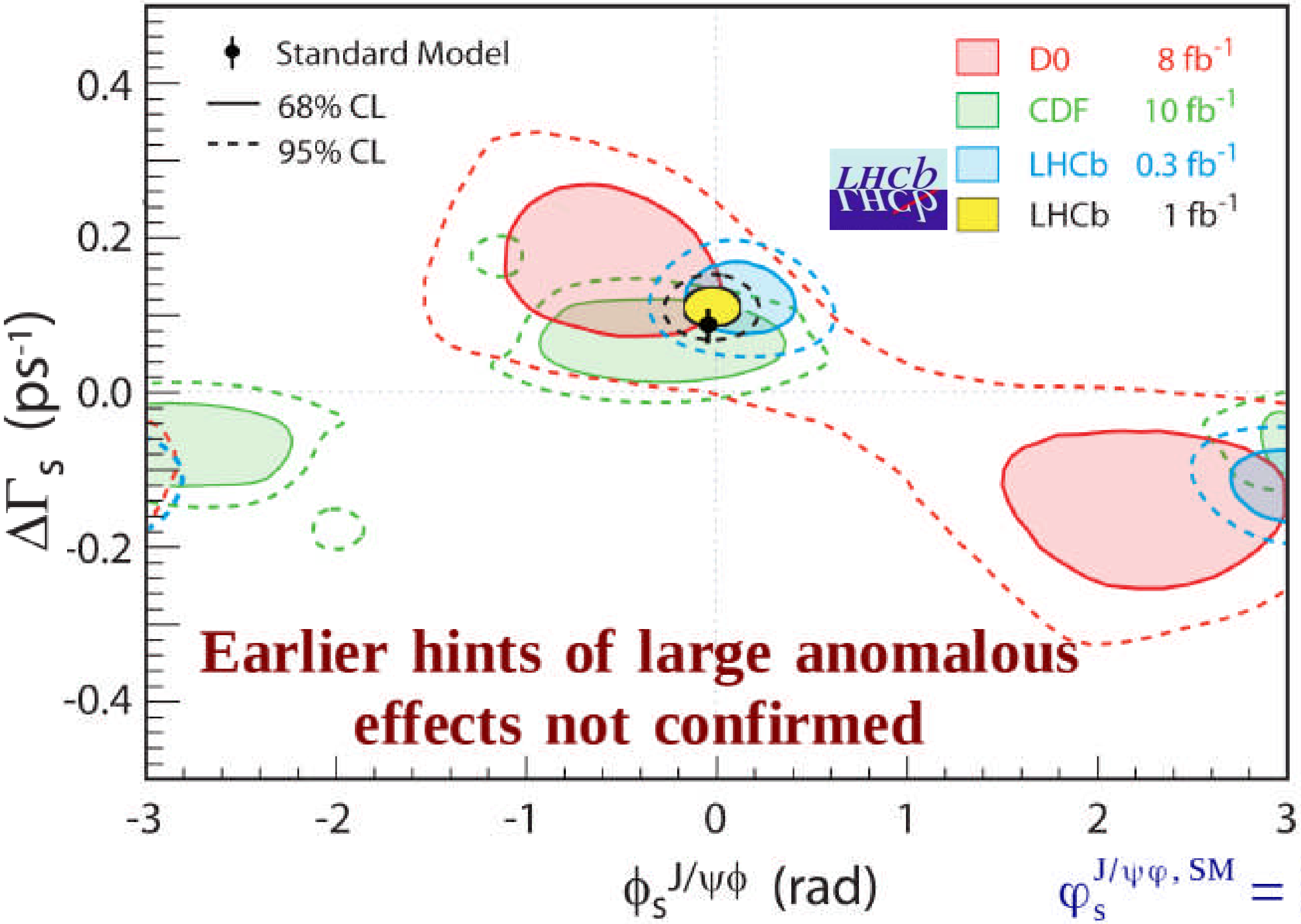
Beneke PLB 620, 143

Wiliamson and Zupan, PRD 74, 014003

- Need to pin down the experimental error on each of these measurements before we can draw any solid conclusion here (LHCb and Belle II would play a decisive role)

Gear change: β_s from $B_s \to J/\psi\phi$, $J/\psi\pi^+\pi^-$

Only measurable angle of the **s.b* = 0** triangle B_s meson



- Big improvement in precision ➡ LHCb is the key player
  LHCb-CONF-2012-002
- $\Delta\Gamma_s > 0$ is finally established
- Uncertainty on β_s almost four times that on $\beta \equiv \phi_1$
- Still long way to go before catching up with theory

$$\varphi_s^{J/\psi\varphi,\,SM} = (-0.036 \pm 0.002)\ \text{rad}$$

$\sigma_{\phi_s}^{stat}$	LHCb (1 fb^{-1})	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
$B_s^0 \to J/\psi\phi$	0.10	0.025	0.008	0.003
$B_s^0 \to J/\psi\pi\pi$	0.17	0.045	0.014	0.01

What about CP violation in B mixing?

- Semileptonic asymmetries in both B_d and B_s systems are expected to be small in the SM

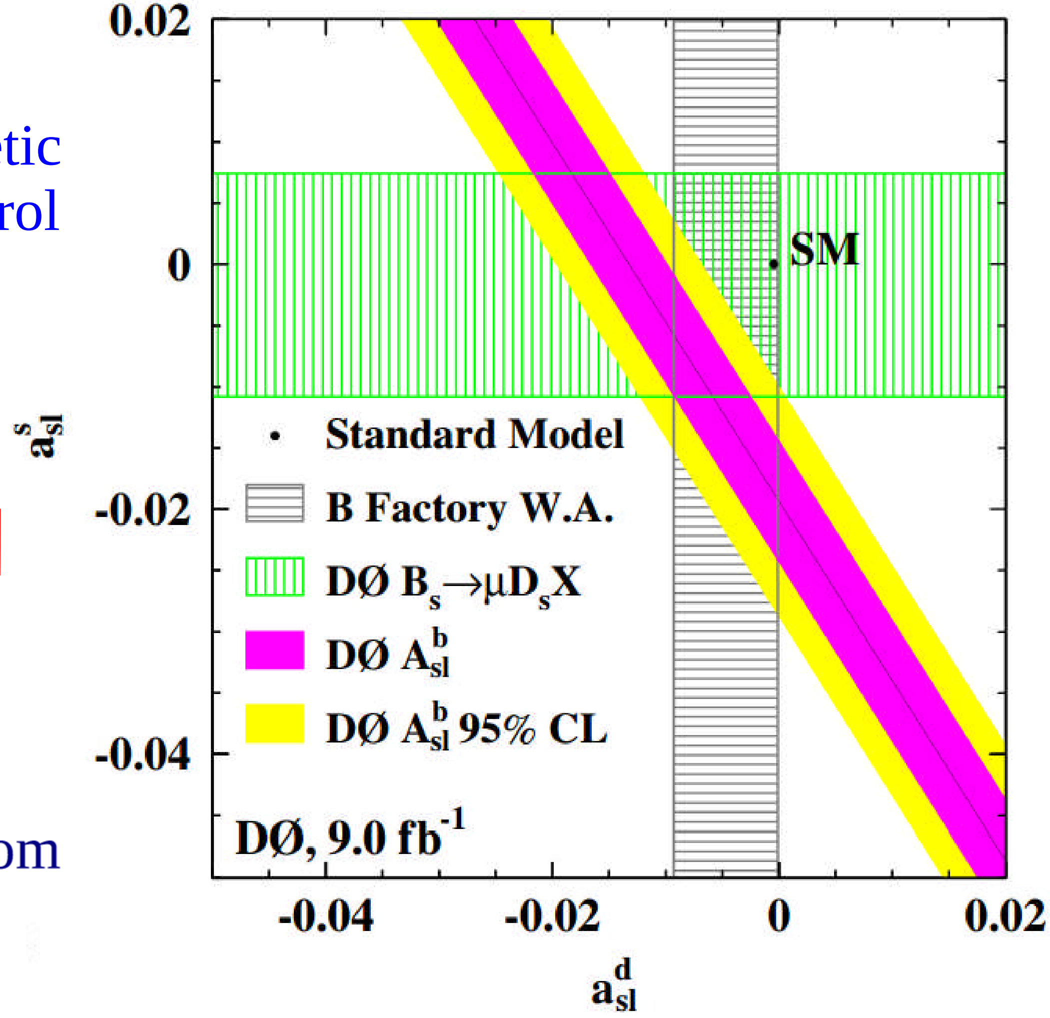
- DØ reported an inclusive dimuon asymmetry 3.9σ away from SM prediction

- Systematics suppressed by the magnetic polarity inversion and the use of control samples, such as single muon sample

$$A_{sl}^{b} = (0.594 \pm 0.022) a_{sl}^{d} + (0.406 \pm 0.022) a_{sl}^{s}$$

Constraint in $a_{sl}^{d} - a_{sl}^{s}$ plaine obtained from oscillated B_d or B_s enriched samples (cutting on impact parameter)

PRD 84 (2011) 052007



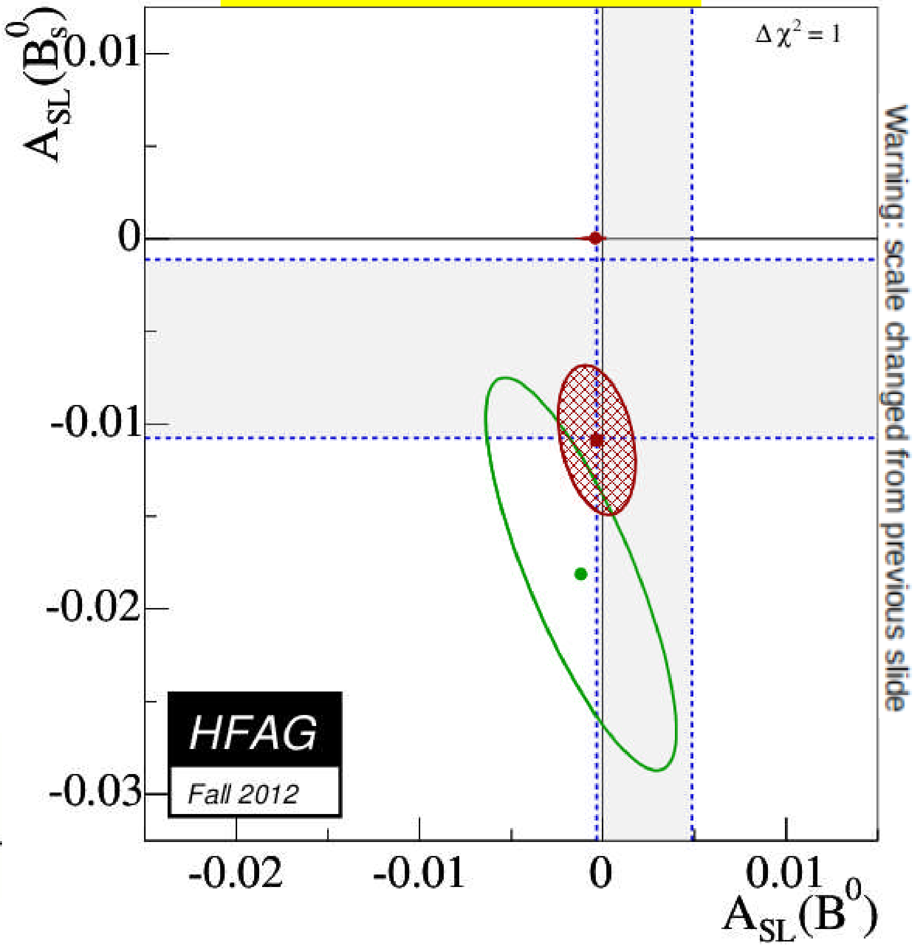
Different stories from LHCb and B factory

- Semileptonic asymmetries in both B_d and B_s systems are expected to be small in the SM
- DØ reported an inclusive dimuon asymmetry 3.9σ away from SM prediction
- Including results on a_{sl}^{d} and a_{sl}^{s} individually (from $D^{(*)+}\mu^{-}\nu X$ samples) puts combination at 2.9σ from the SM
- Further adding B-factory a_{sl}^{d} and LHCb a_{sl}^{s} results brings the average down to 2.4σ

PRD 84 (2011) 052007

arXiv:1207.1769 **arXiv:1208.5813**

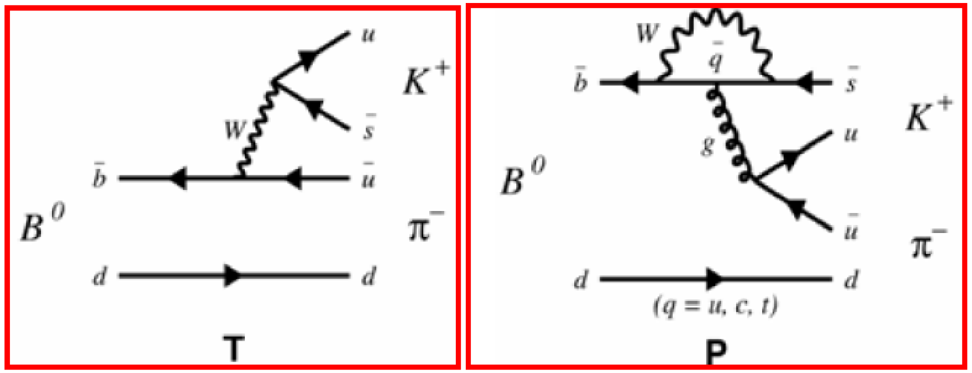
LHCb-CONF-2012-022



$$a_{sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%$$

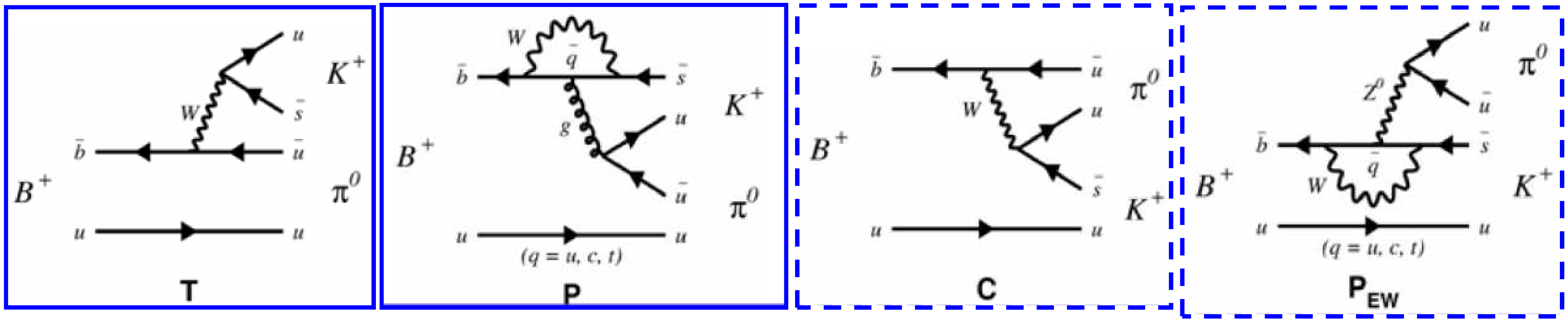
$\sigma^{stat}_{a^s_{sl}}$	LHCb (1 fb^{-1})	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
$B_s^0 \to D_s^{\pm}\mu^{\mp}X$	0.54%	0.06%	0.02%	0.003%

Direct CP violation from $B \to K\pi$



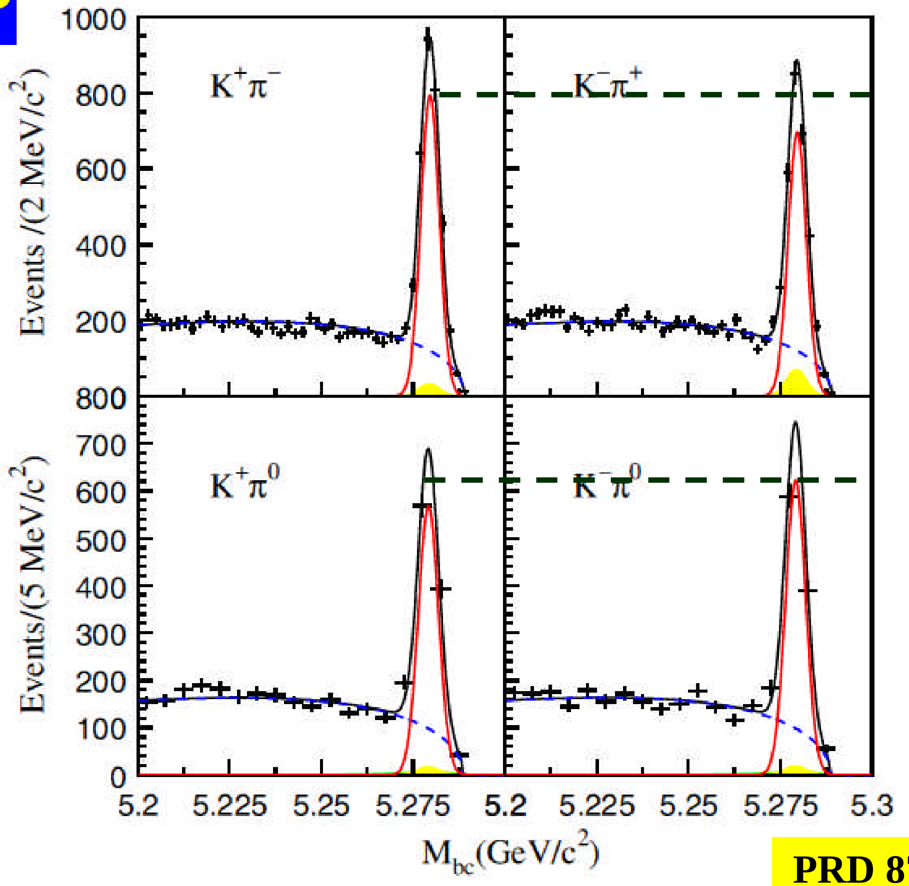
Mode	Diagrams
$B^0 \to K^+\pi^-$	**T** + **P**
$B^+ \to K^+\pi^0$	**T** + **P** + **C** + $\mathbf{P_{EW}}$

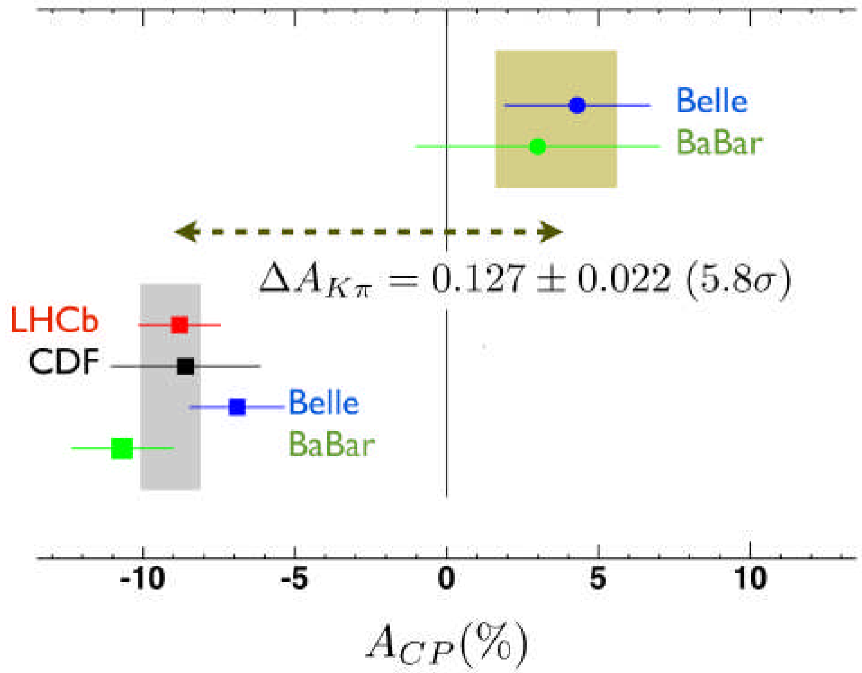
- Ignoring the suppressed C and P_{EW}, two modes have identical diagrams except for the spectator quark



- Direct CP asymmetry $A_{CP} \equiv \frac{\Gamma(\bar{B}\to\bar{f})-\Gamma(B\to f)}{\Gamma(\bar{B}\to\bar{f})+\Gamma(B\to f)} \propto \sin\Delta\phi \sin\Delta\delta$ where $\Delta\phi$ ($\Delta\delta$) is the weak (strong) phase difference between two diagrams that mostly contribute to $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$
- Now since strong and weak phases are same for these diagrams, we expect A_{CP} to be same ➡ ΔA_{CP} should be zero

But results are quite different!!!





PRD 87, 031103 (2013)

$$\Delta\mathcal{A}_{K\pi} \equiv \mathcal{A}_{CP}(K^+\pi^0) - \mathcal{A}_{CP}(K^+\pi^-) = +0.112 \pm 0.027 \pm 0.007$$

- ❑ LHCb is a new player in the field
- ❑ WA value $\Delta A_{K\pi}$ = 0.127±0.022 (5.5σ significance) ➡ New physics?

➢ We are one of the principal authors for this paper (accepted to PRD-RC)

Before concluding anything concrete…

- Model-independent sum rule proposed by Gronau, Atwood and Soni:

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathcal{A}_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

PLB 627 (2005) 82

PRD 58 (1998) 036005

- The neutral decay mode $B^0 \rightarrow K^0\pi^0$ holds the key here

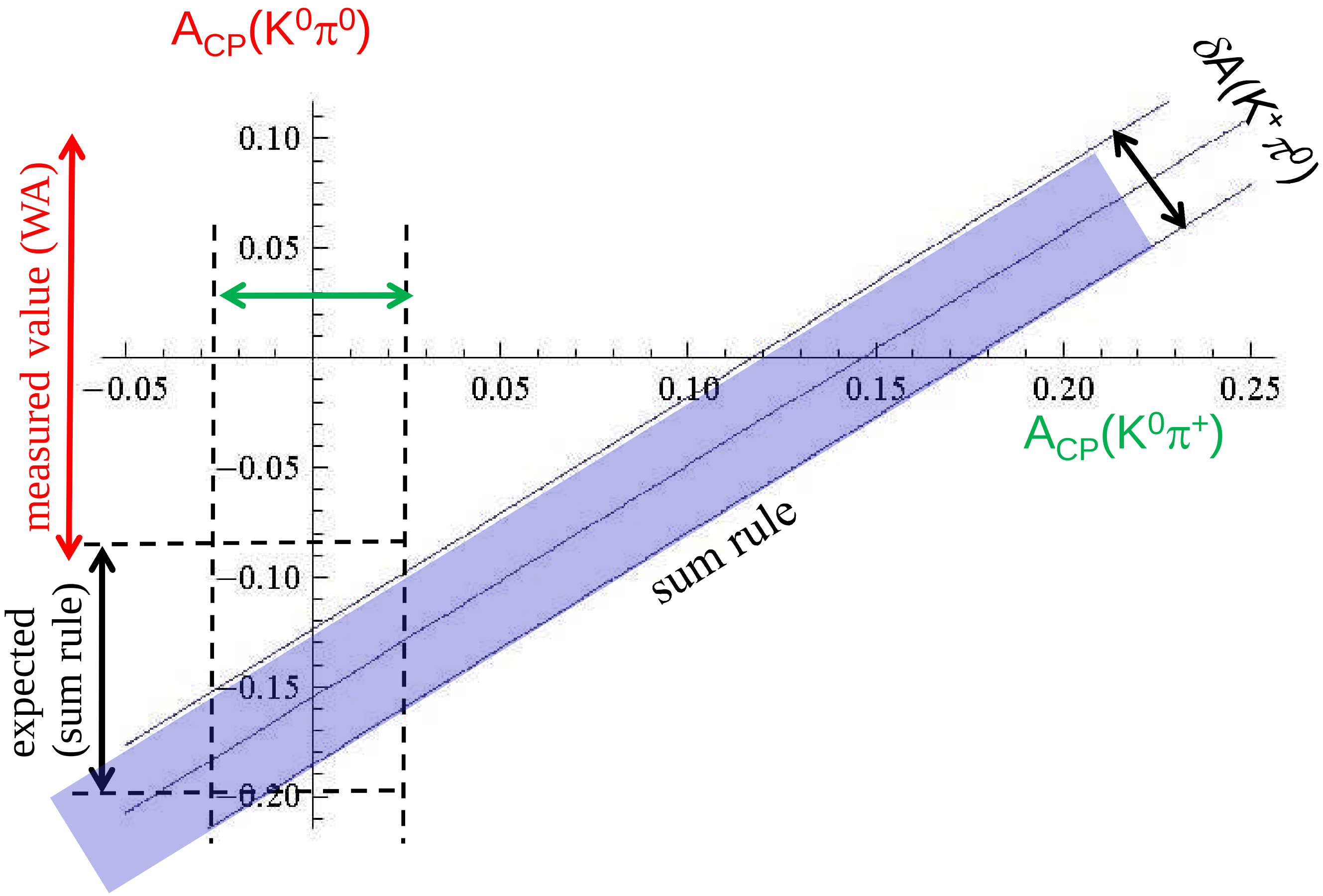
PRD 87 (2013) 031103

$$\mathcal{B} = (9.68 \pm 0.46 \pm 0.50) \times 10^{-6}$$

PRD 81 (2010) 011101

$$\mathcal{A}_{CP} = +0.14 \pm 0.13 \pm 0.06$$

- Improved precisions on both BF and A_{CP} are required



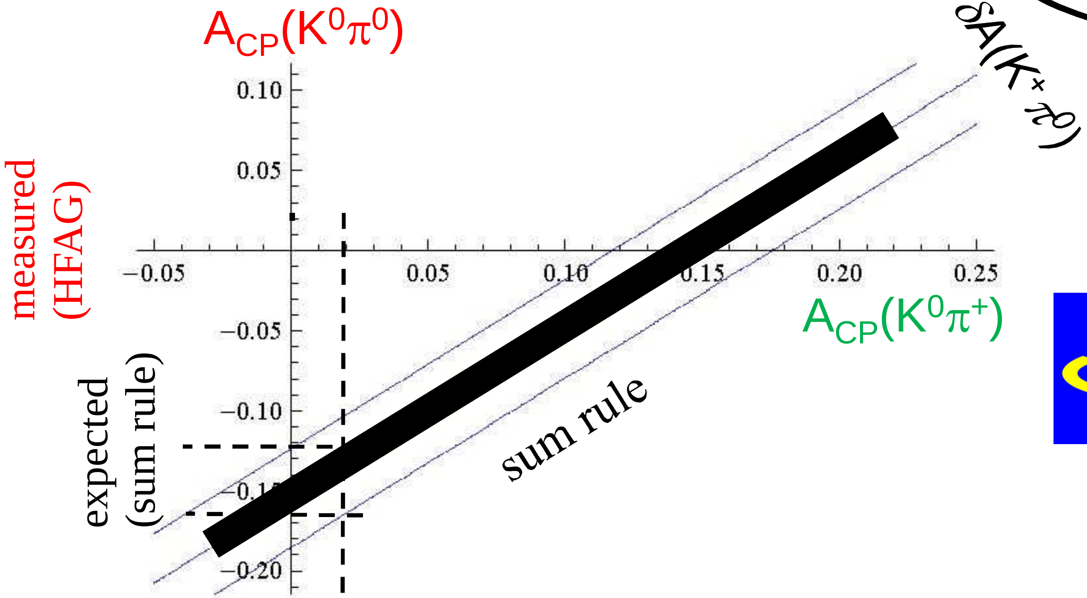
Test the same with much more data

- Model-independent sum rule proposed by Gronau, Atwood and Soni:

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathcal{A}_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

PLB 627 (2005) 82

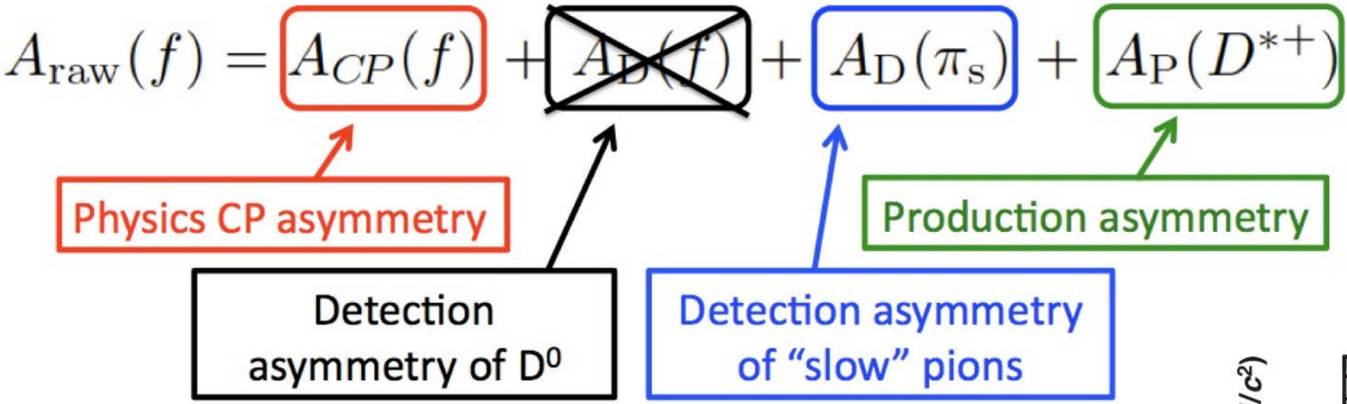
PRD 58 (1998) 036005



50 ab^{-1}

- In the above extrapolation, we have used current central values with the statistical uncertainties properly scaled up
- Although systematics are treated as non-scaling, the main $B^0 \rightarrow K^0\pi^0$ systematics (tag-side interference) can be reduced by measuring Δt in semileptonic B_{sig} decays

Hot off the press: CPV in charm decays



PRL 108 (2012) 111602

- No detection asymmetry for D^0 decays to self-conjugate modes such as K^+K^-, $\pi^+\pi^-$
- By taking the difference $A_{raw}(f) - A_{raw}(f')$, the production as well as pion detection asymmetries largely cancel out

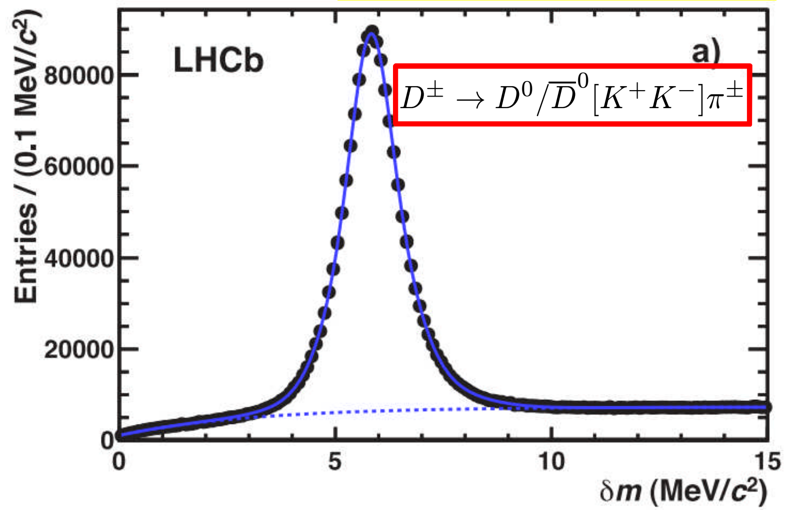
➢ Thus, LHCb measures the A_{CP} difference that is very robust against systematics

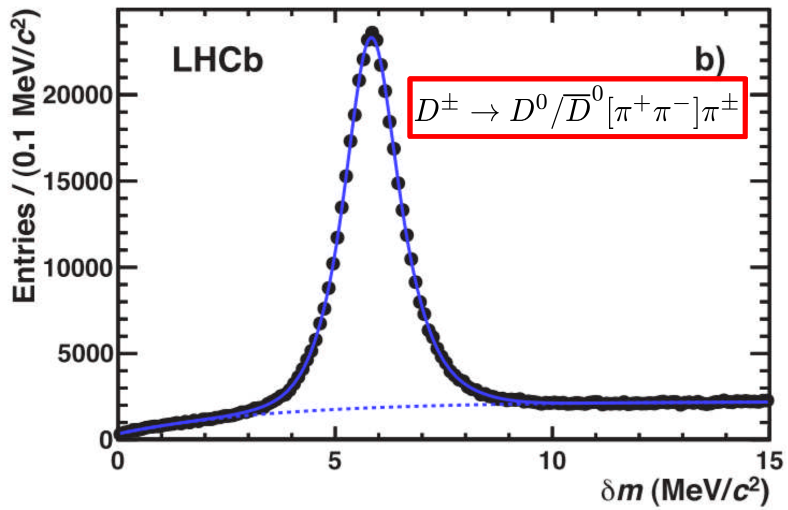
$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= [a_{CP}^{\rm dir}(K^+K^-) - a_{CP}^{\rm dir}(\pi^+\pi^-)] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\rm ind}$$

$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$

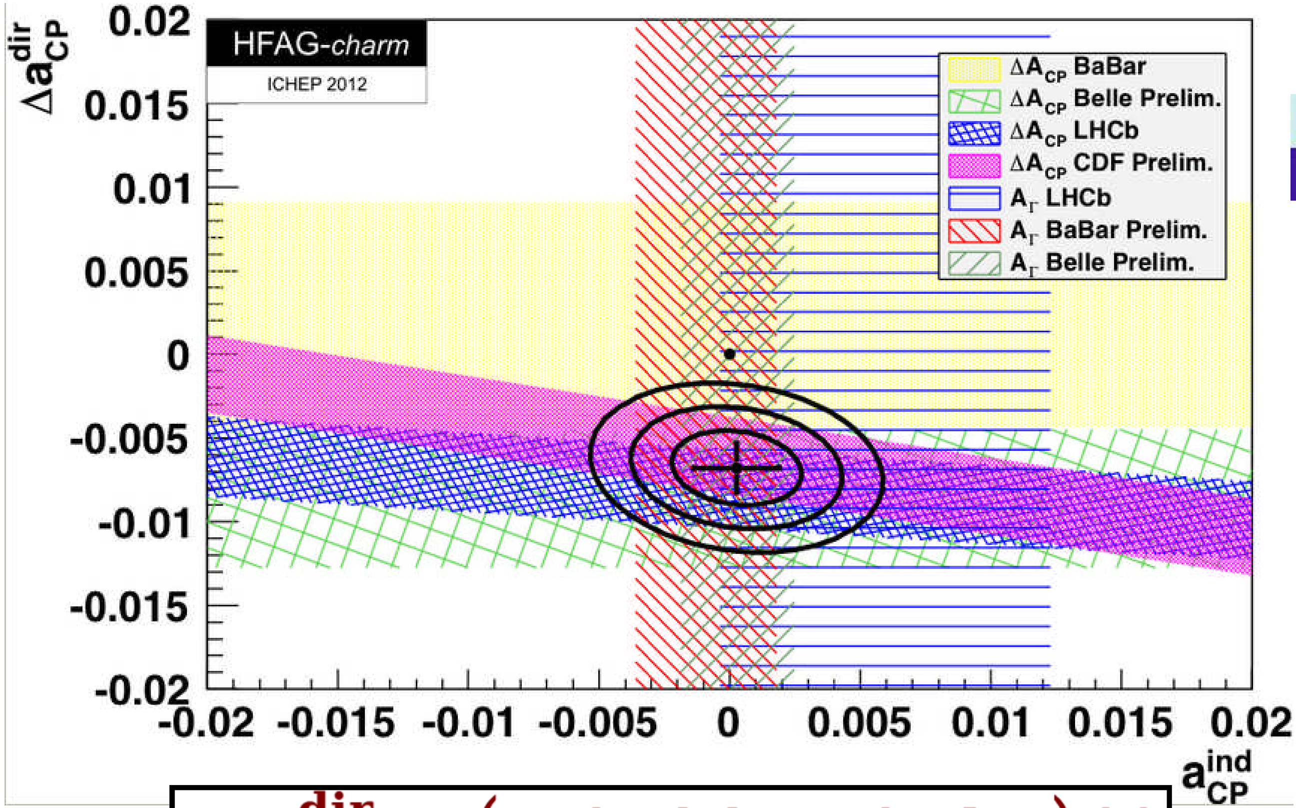
3.5σ away from zero

First evidence of CPV in the charm sector





LHCb leads the show…



PRL 108 (2012) 111602

PRL 109 (2012) 111801

ICHEP2012 preliminary

$$\Delta a_{CP}^{dir} = (-0.68 \pm 0.15)\%$$

- ΔA_{CP} related to mainly to direct CP violation as contributions from indirect CP is suppressed by the difference in mean decay time
- However, we need results from other related ππ and KK modes before interpreting the result as evidence for new physics or not

➢ We are involved with the search for CPV in the decay $D^0 \rightarrow \pi^0\pi^0$ at Belle

Conclusions and future prospect

- Results obtained on CP violation in the quark sector is consistent with the SM, except for
  1) Direct CP violation difference in $B \rightarrow K\pi$ decays
  2) Mixing-induced CP violation in $b \rightarrow q\bar{q}s$ transitions
  3) Very recently, CP violation in the charm sector
  4) and few more not described in this talk

- All these anomalies [especially 2)] beg for a more precise measurement

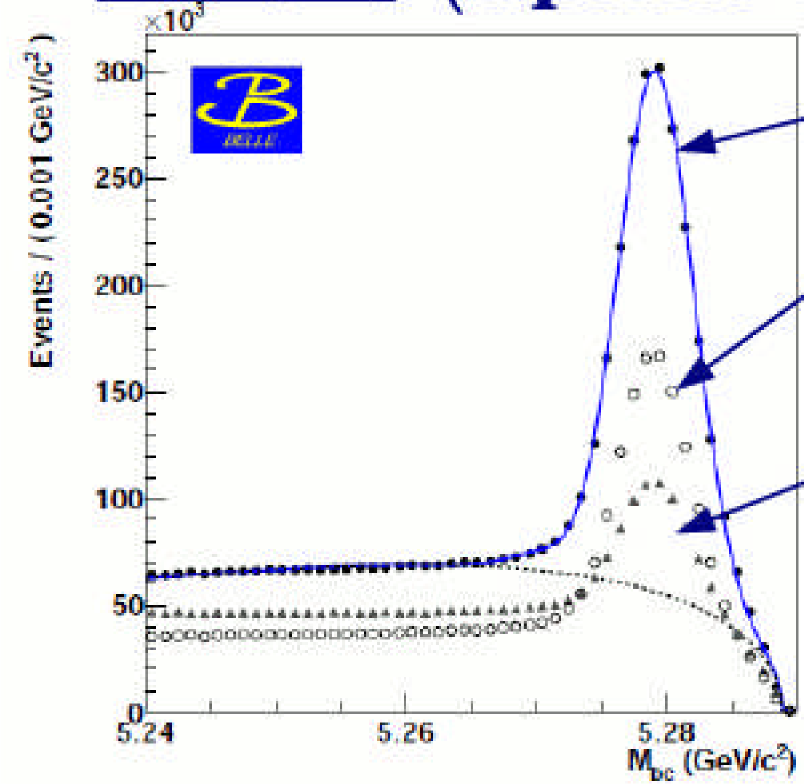
- Good motivation for Belle II as well as for the upgrade of LHCb

Thanks for your kind attention

Bonus slides

Some interesting non-CPV results (1)

$B^+ \to \tau^+ \nu$ (update hadronic tag) [arXiv:1208.4678]



new tag algorithm on full data (reprocessed)

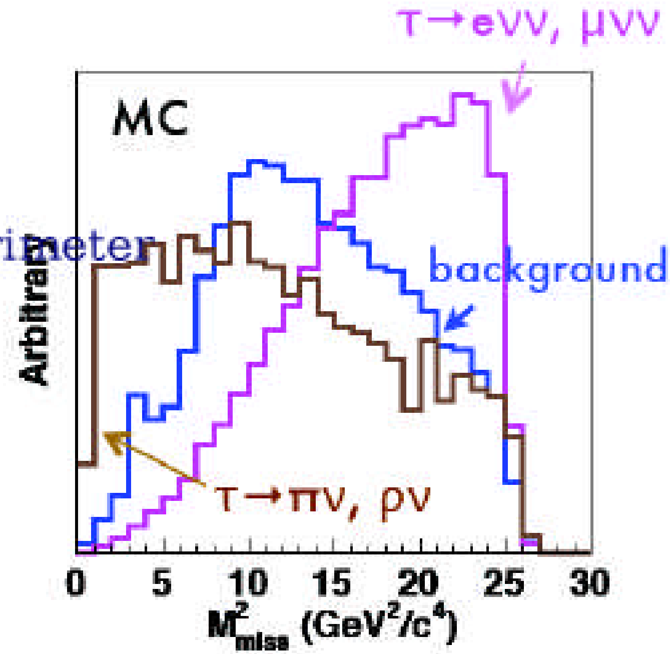
new tag algorithm on previous data
based on neural network & more B/D decays modes, NIM A654, 432 (2011)

previous tag algorithm on previous data

× 3 B_{tag} sample size
[purity also improved]

Signal extraction based on two variables:

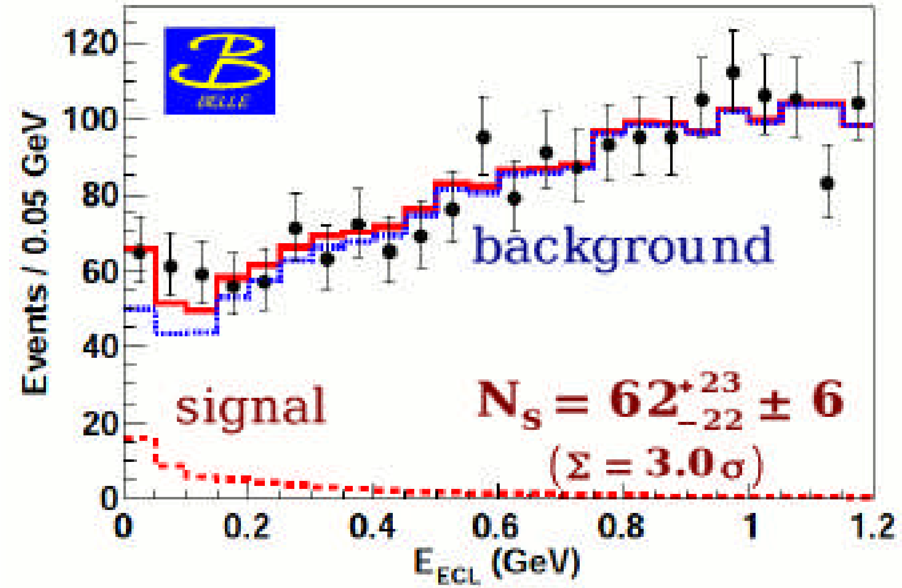
- E_{ECL}: remaining energy in electromagnetic calorimeter (peak at E_{ECL} = 0 GeV for signal)
- M^2_{miss}: missing mass squared (larger for $e\nu\nu/\mu\nu\nu$, smaller for $\pi\nu/\rho\nu$)

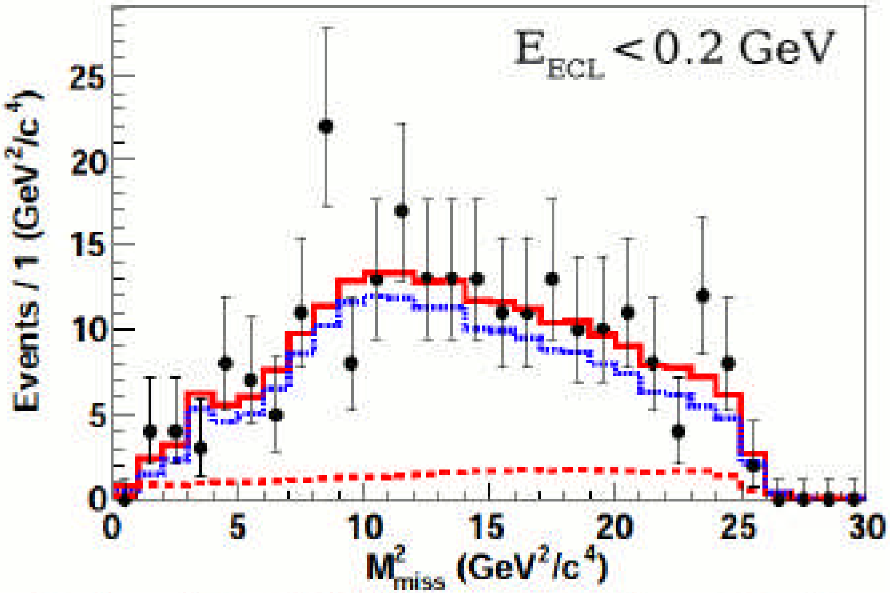


Some interesting non-CPV results (1)

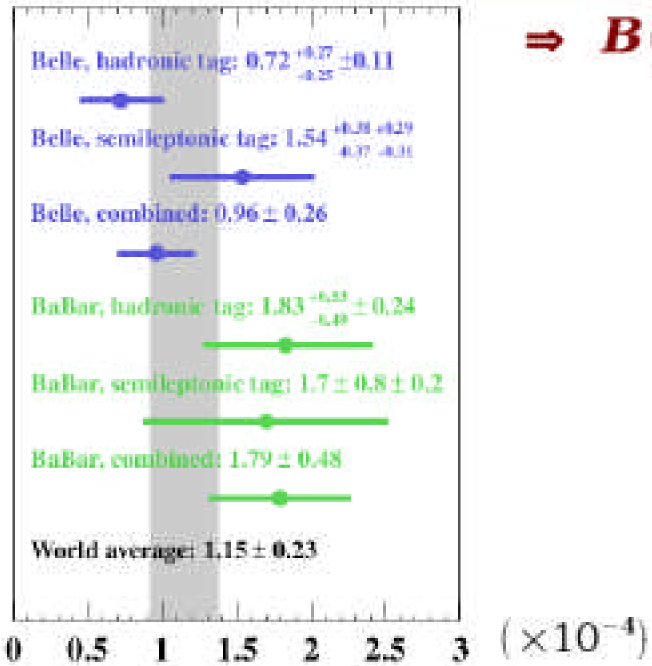
$B^+ \to \tau^+ \nu$ (update hadronic tag) [arXiv:1208.4678]

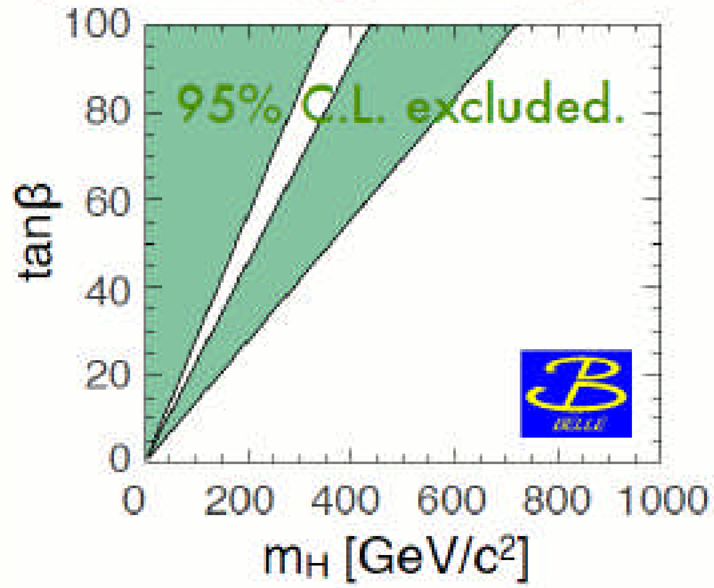
simultaneous fit to the different τ reconstruction modes ($\tau \to e\nu\nu, \mu\nu\nu, \pi\nu, \rho\nu$)





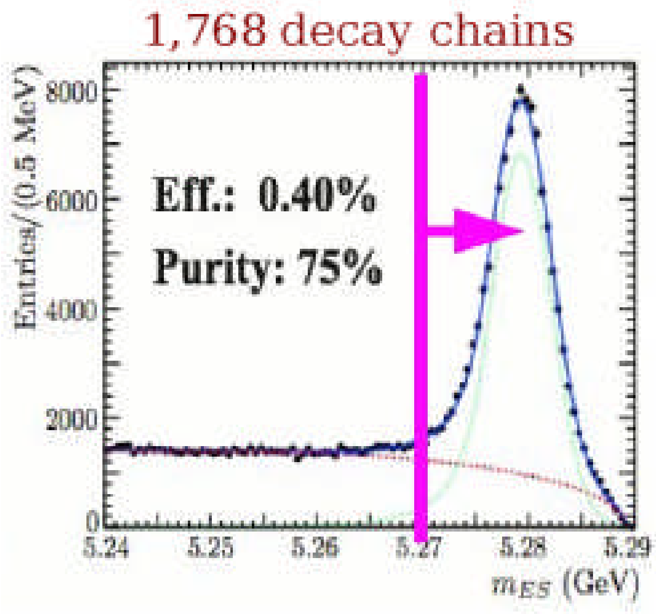
$\Rightarrow B(B^+ \to \tau^+ \nu) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$

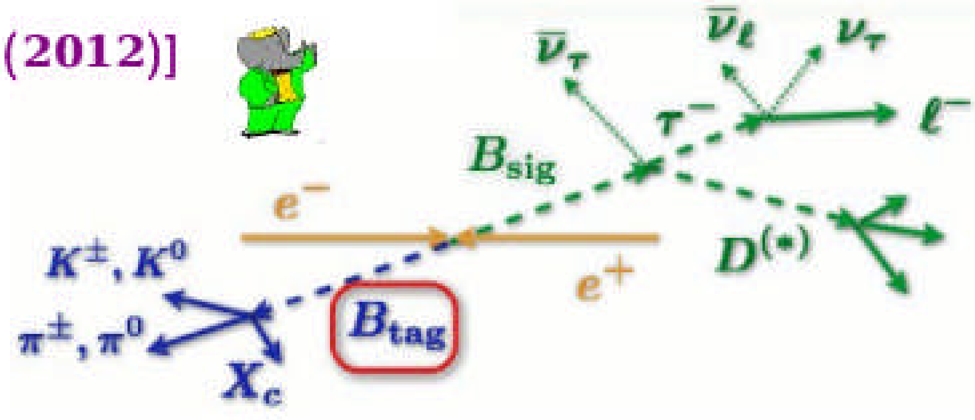




Some interesting non-CPV results (2)

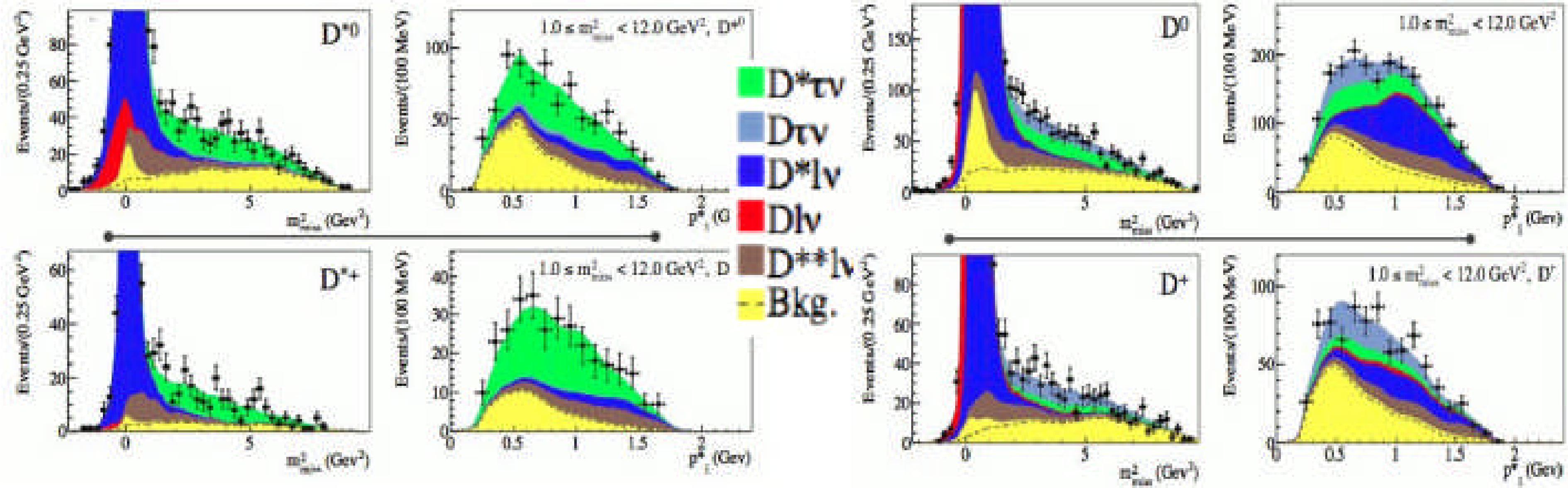
$B \to D^{(*)} \tau \nu$ [PRL 109, 101802 (2012)]





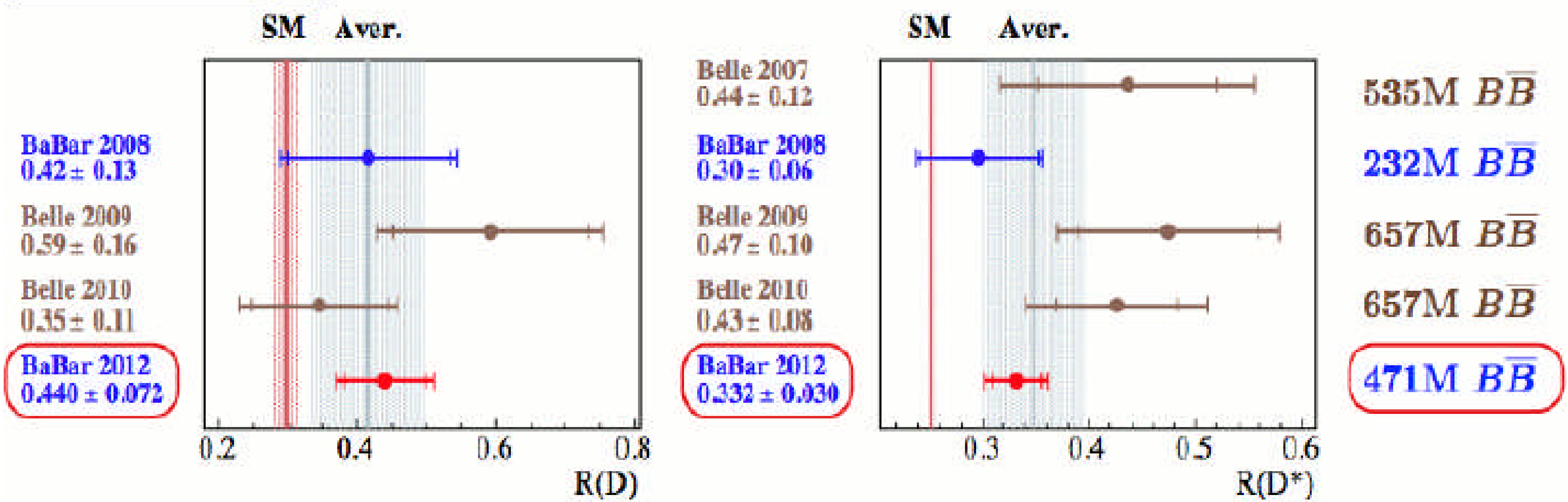
- 2D unbinned fit to m^2_{miss} and p^*_l
- fitted samples
  - 4 $D^{(*)}l$ samples ($D^0 l$, $D^{*0} l$, $D^+ l$ and $D^{*+} l$)
  - 4 $D^{(*)}\pi^0 l$ control samples ($D^{**}(l/\tau)\nu$)

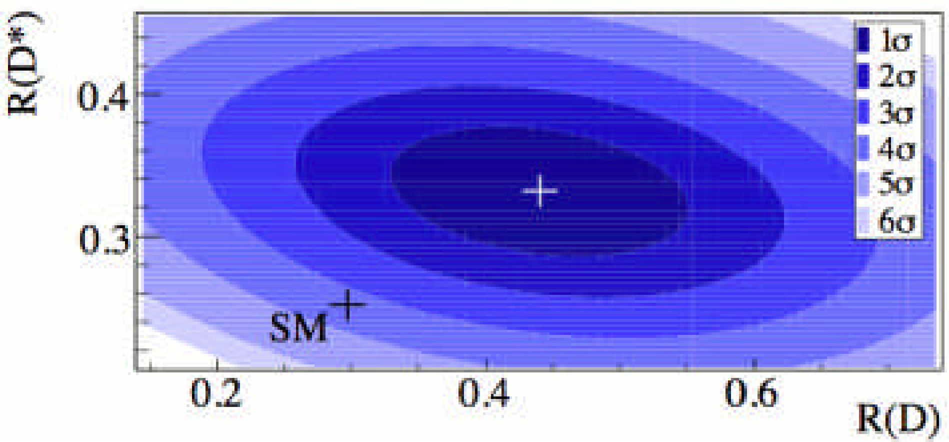
⇒ **$D\tau\nu$ and $D^*\tau\nu$ clearly observed**

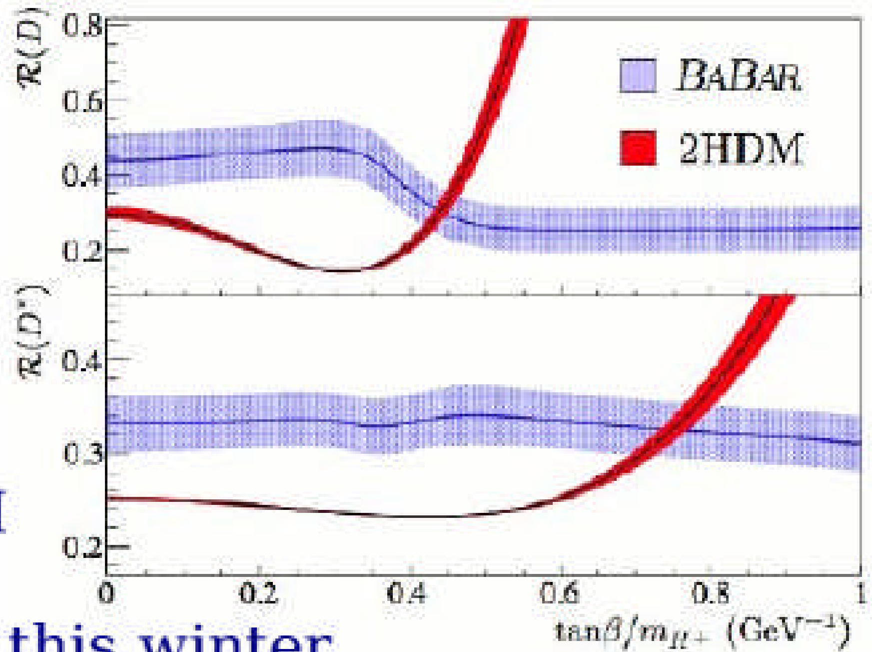


Some interesting non-CPV results (2)

B → D$^{(*)}$τν







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