CP Violation in B Decays and Search for New Physics

Leo Piilonen, Virginia Tech
on behalf of the Belle Collaboration

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Kay Kinoshita, Hiroshi Nakano, Martin Ritter, Veronika Chobanova, Luis Pesántez, Gagan Mohanty, Zbynek Drásal, Minakshi Nayak, Simone Donati, Rose Koopman, Tadeusz Lesiak, Dan Johnson, Antonio Romero Vidal, Anton Poluektov, D. Vieira, Marta Calvi, Angelo Di Canto, Laurence Carson, Francesca Dordei, Julian Wishahi, Adam Davis, Mirco Dorigo … *and probably many others*

See parallel-session talks (LHCb):

- Matthew Reid: time-dependent ~~CP~~ in $B \to J/\psi\, h\, h$
- Jeremy Dalseno: direct ~~CP~~ in $B \to D\, K$
- Elvina Gersabeck: ~~CP~~ in D decays

CP symmetry is broken in the Standard Model.

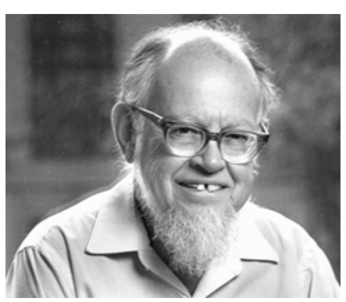
3x3 quark-mixing matrix has one CP-violating phase.

Prog. Theo. Phys. 49, 2 (1973)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Kobayashi

Maskawa



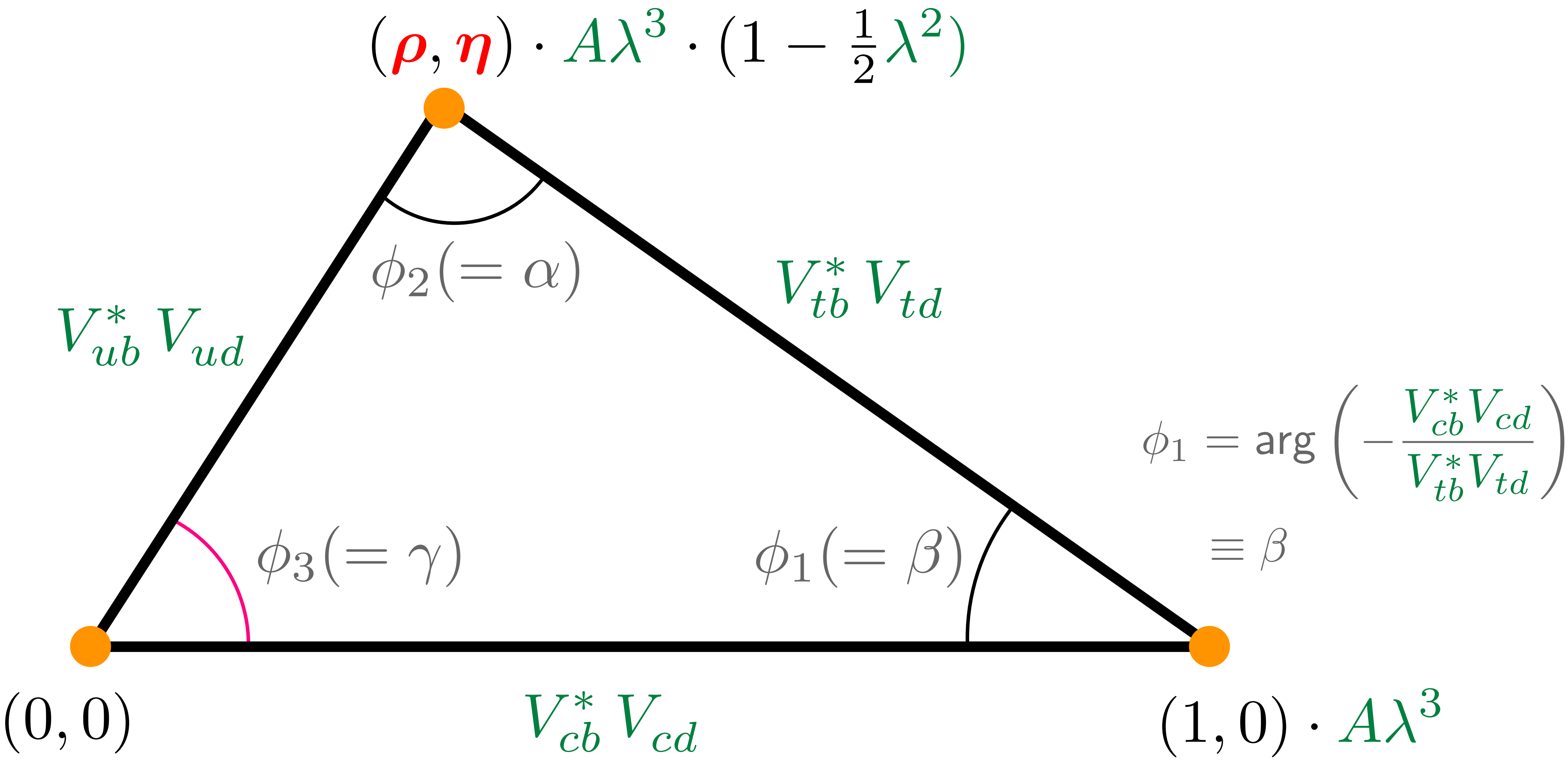
Wolfenstein

Cabibbo

$$\sin\theta_C$$

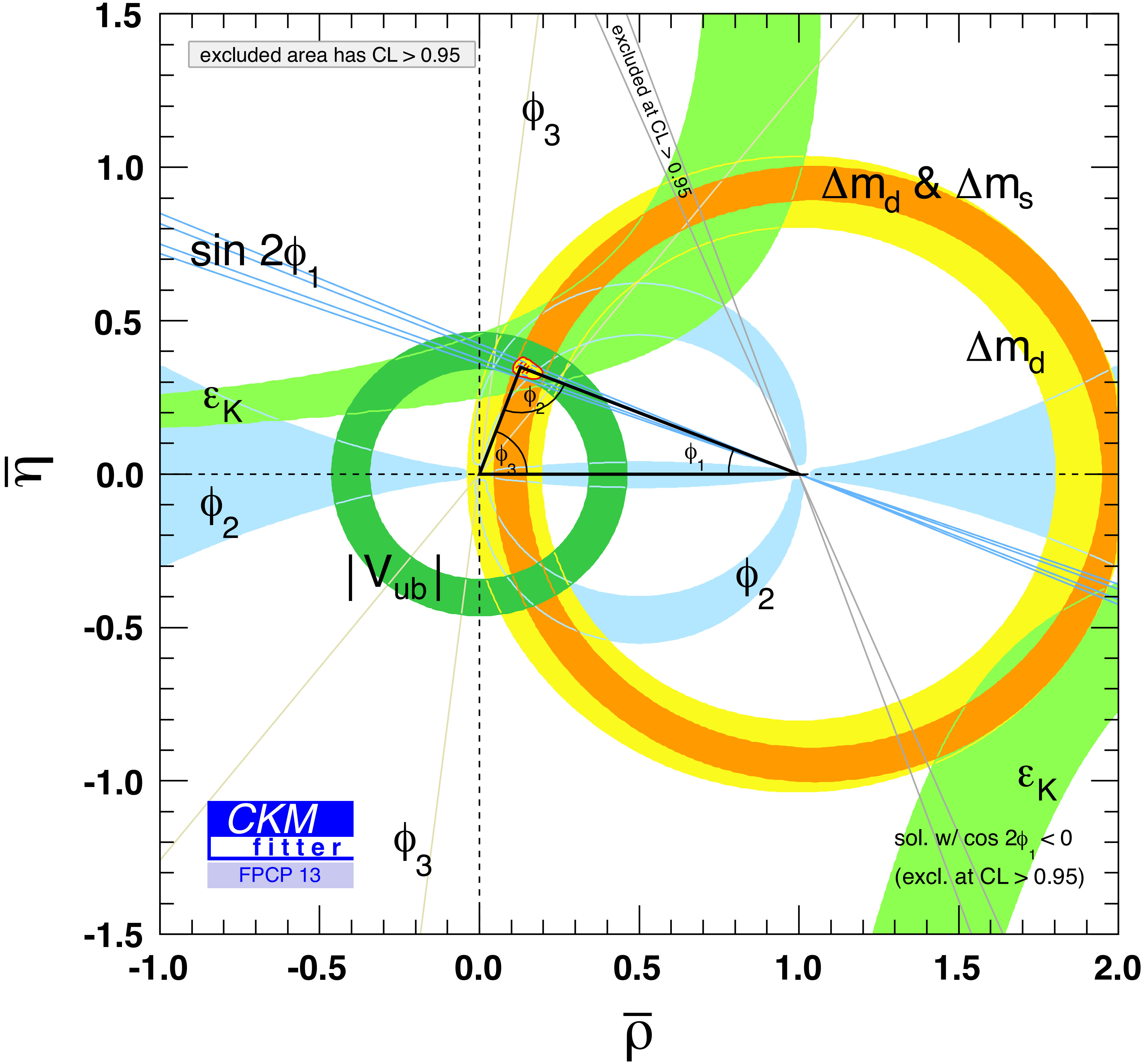
$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Unitarity $\Rightarrow$ 6 triangle relations in the complex plane,
e.g., $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$



¶ Overconstrain by measuring angles and sides.

All measurements agree with the CKM mechanism.

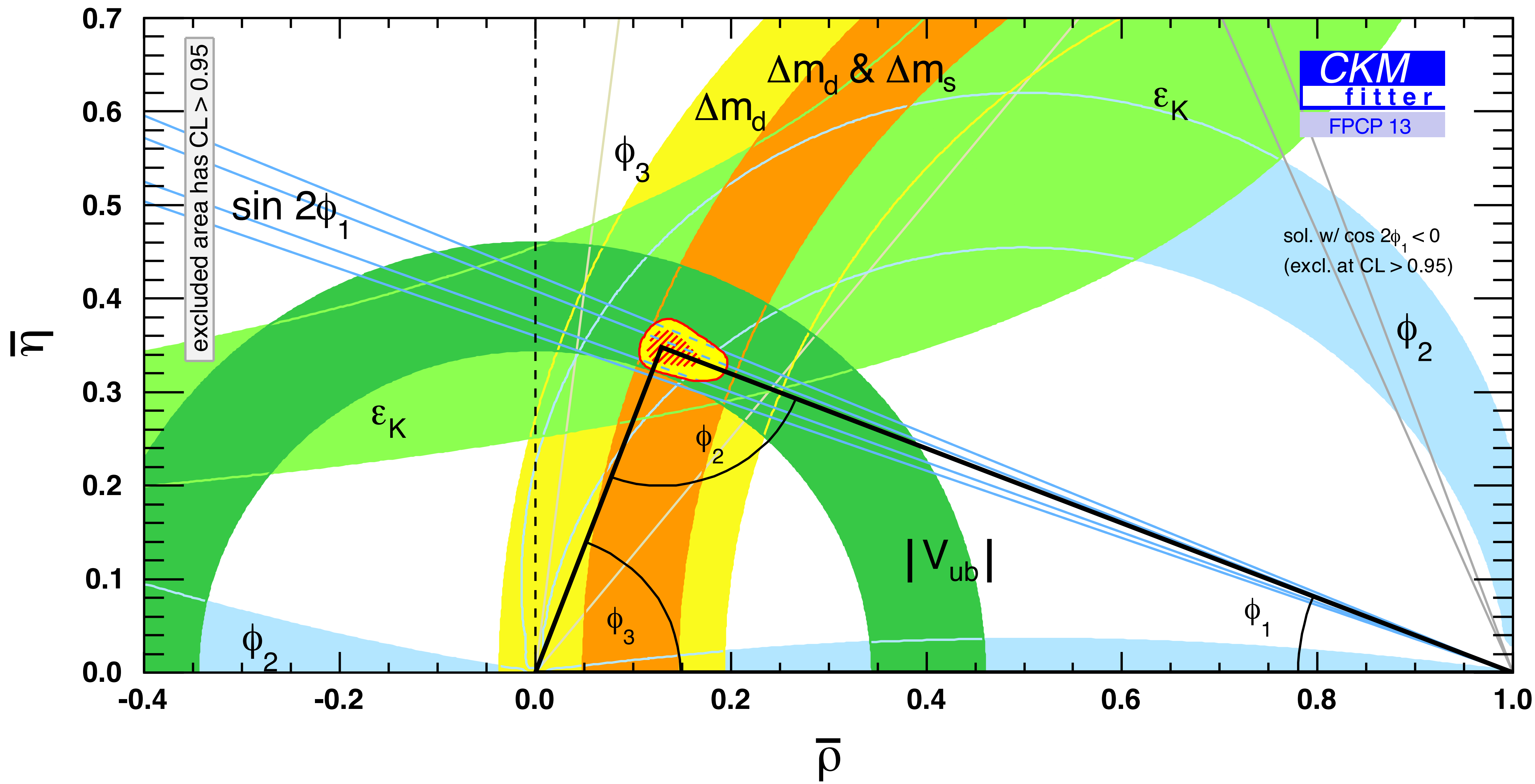


$$\phi_1 \leftrightarrow \beta$$

$$\phi_2 \leftrightarrow \alpha$$

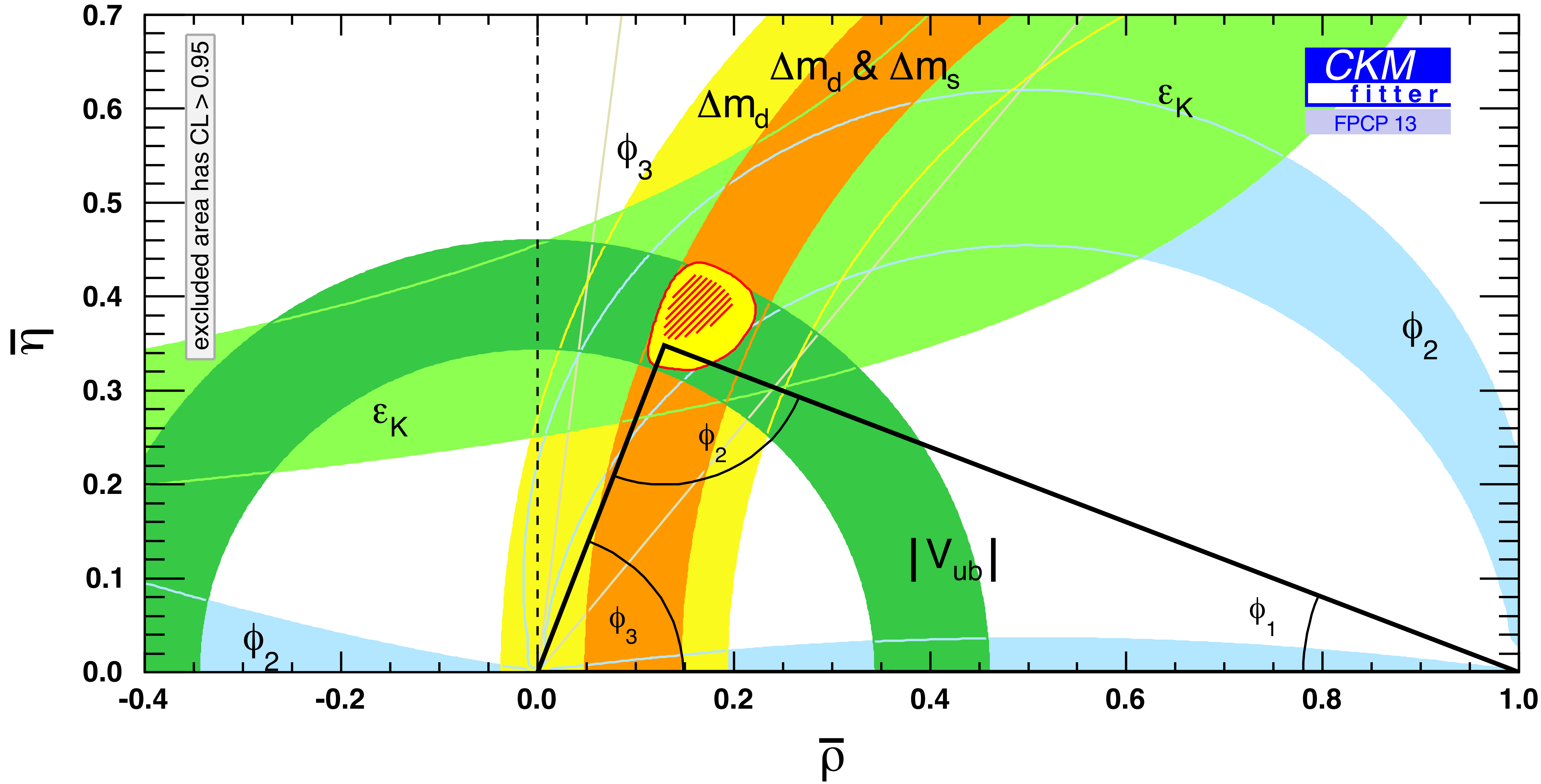
$$\phi_3 \leftrightarrow \gamma$$

Is there some room for New Physics here?



including $\sin 2\phi_1$ in the fit

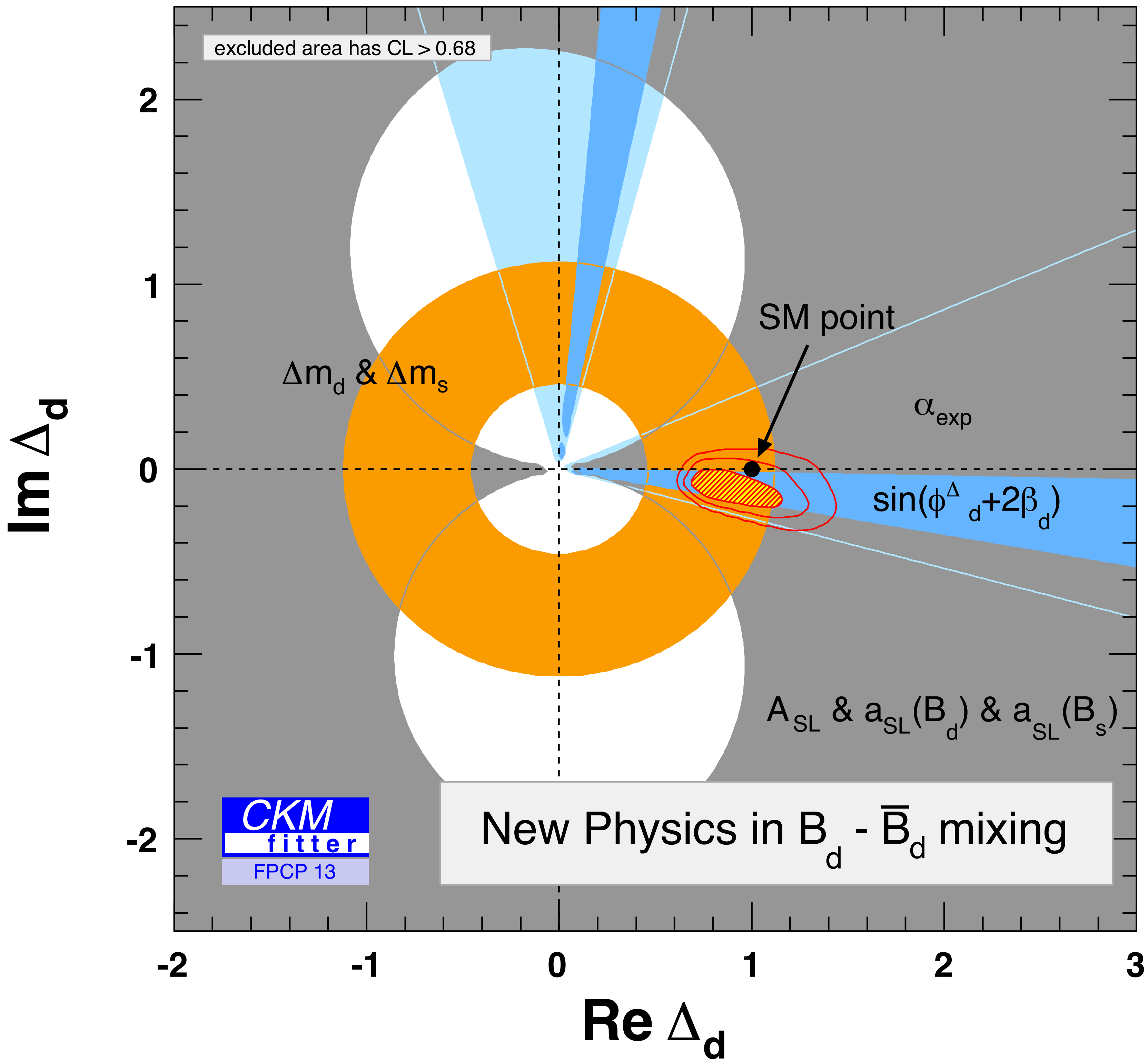
Is there some room for New Physics here?



excluding $\sin 2\phi_1$ from the fit

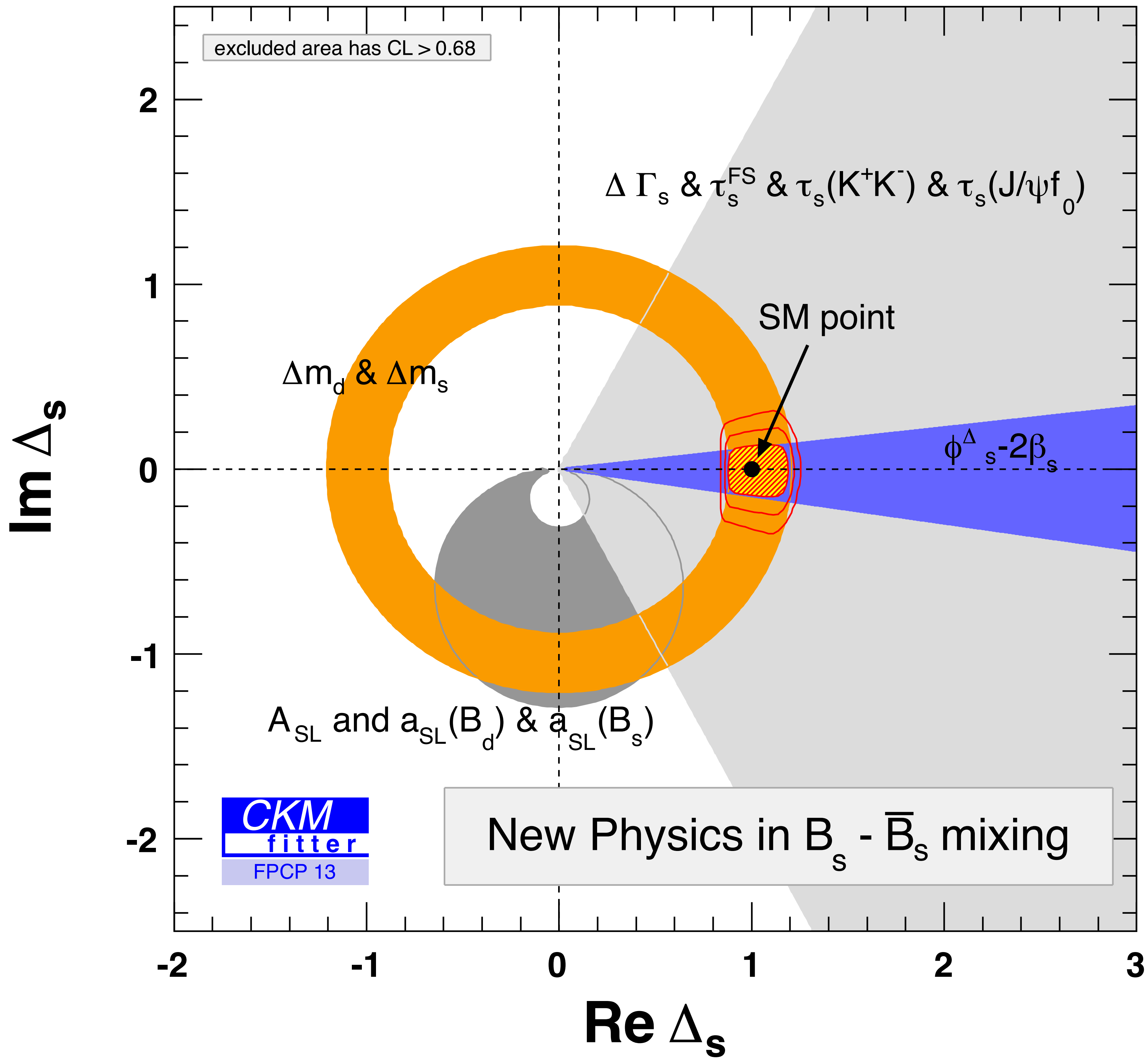
Is there some room for New Physics here?

¶ Scale M_{12}^d by complex factor Δ_d in $B_d^0 - \bar{B}_d^0$ mixing:



Is there some room for New Physics here?

¶ Scale M_{12}^s by complex factor Δ_s in $B_s^0 - \bar{B}_s^0$ mixing:



There are three distinct ways to measure $\cancel{CP}$:

- direct $\cancel{CP}$ in decay (charged & neutral)

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f}) \qquad |\bar{\mathcal{A}}_{\bar{f}}/\mathcal{A}_f| \neq 1$$

- $\cancel{CP}$ in mixing (neutral)

$$\Gamma(B \to \bar{B}) \neq \Gamma(\bar{B} \to B) \qquad |B_{H,L}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$$

$$|q/p| \neq 1$$

- $\cancel{CP}$ in interference between mixing & decay (neutral)

$$\Gamma(B \to f_{\mathsf{CP}}) \neq \Gamma(\bar{B} \to f_{\mathsf{CP}}) \qquad \arg\left|\frac{q}{p}\frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right| \neq 0$$

Notes: B could be replaced by D.
f_{CP} is a CP eigenstate.

Direct CP Violation

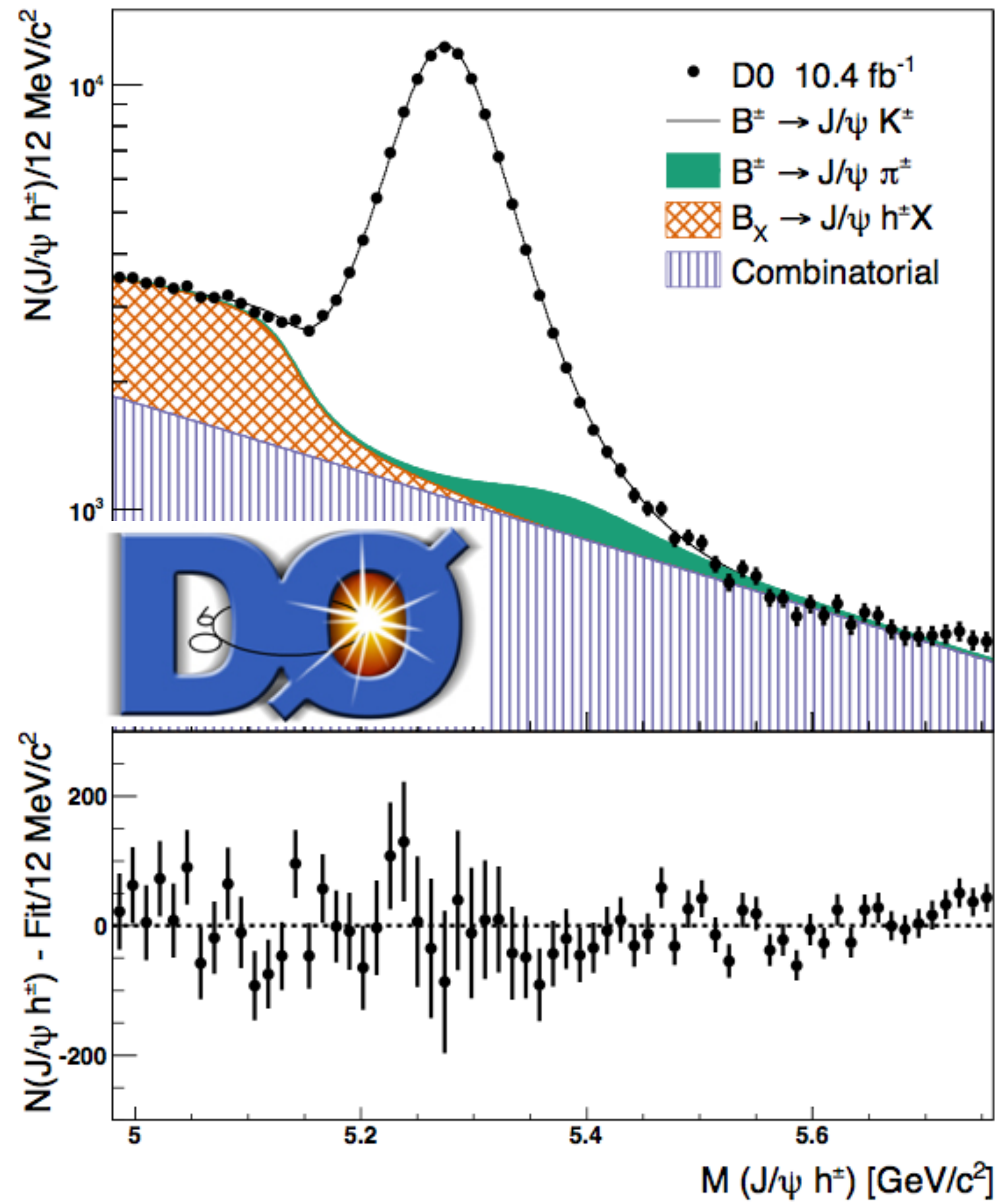
Direct CPV in $B^+ \to J/\psi K^+$, $B^+ \to J/\psi \pi^+$

No effect expected in $b \to scc$ ($J/\psi K$), possible in $b \to dcc$ ($J/\psi\pi$)

$A(J/\psi X) = A(J/\psi X)_{RAW} + A(X)$

Correction in rec. asym. between X^+ and X^-

Raw asym. between rec. B^+ and B^-



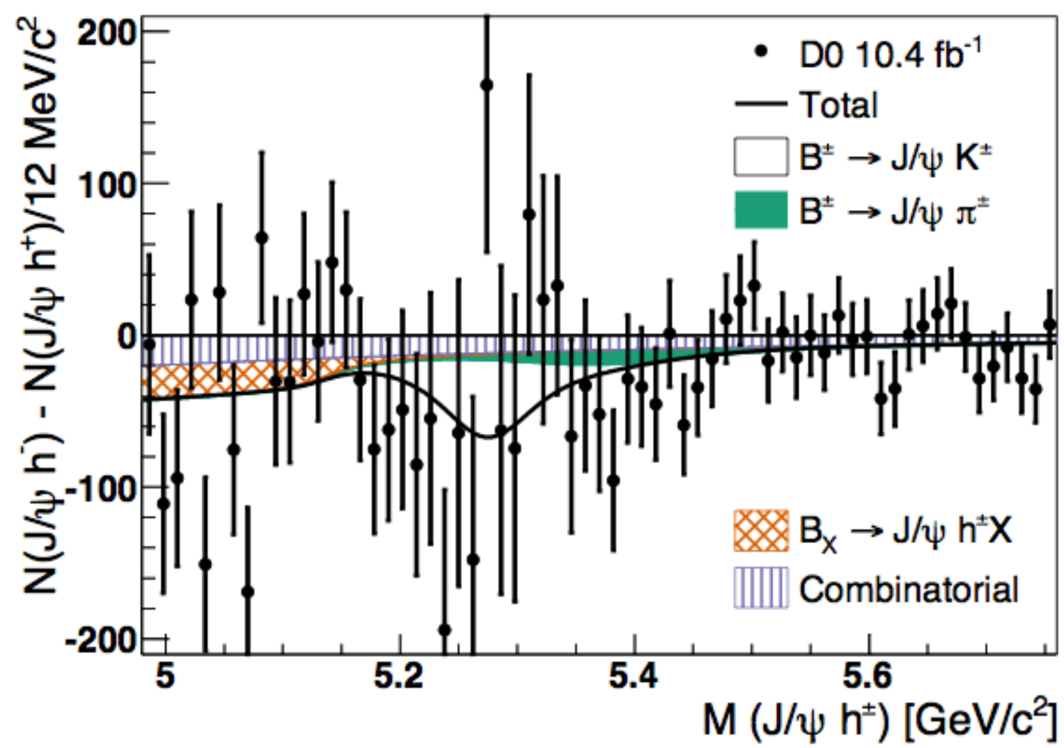
- Regular reversal of magnetic field minimizes $A(\pi)$
- $A(K)$ measured in $K^{*0} \to K^+\pi^-$

Event selection chosen to minimize statistical uncertainty on $A(J/\psi K)_{RAW}$

PRL **110, 241801** (2013)

Direct CPV in $B^+ \to J/\psi K^+$, $B^+ \to J/\psi \pi^+$

Type of uncertainty	$A^{J/\psi K}$ (%)	$A^{J/\psi \pi}$ (%)
Statistical	0.36	4.4
Mass range	0.022	0.55
Fit function	0.011	0.69
$\Delta A_{\text{tracking}}$	0.05	0.05
ΔA_K	0.043	n/a
Total systematic uncertainty	0.07	0.9
Total uncertainty	0.37	4.5



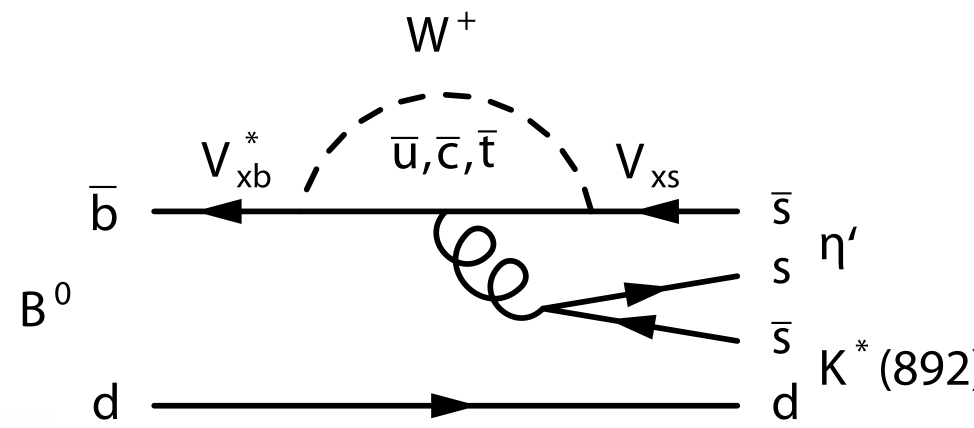
$A(J/\psi K)$ = [0.59 ±0.36(stat) ±0.07(syst)] %
with a 1 % correction due to K^+/K^- asymmetry

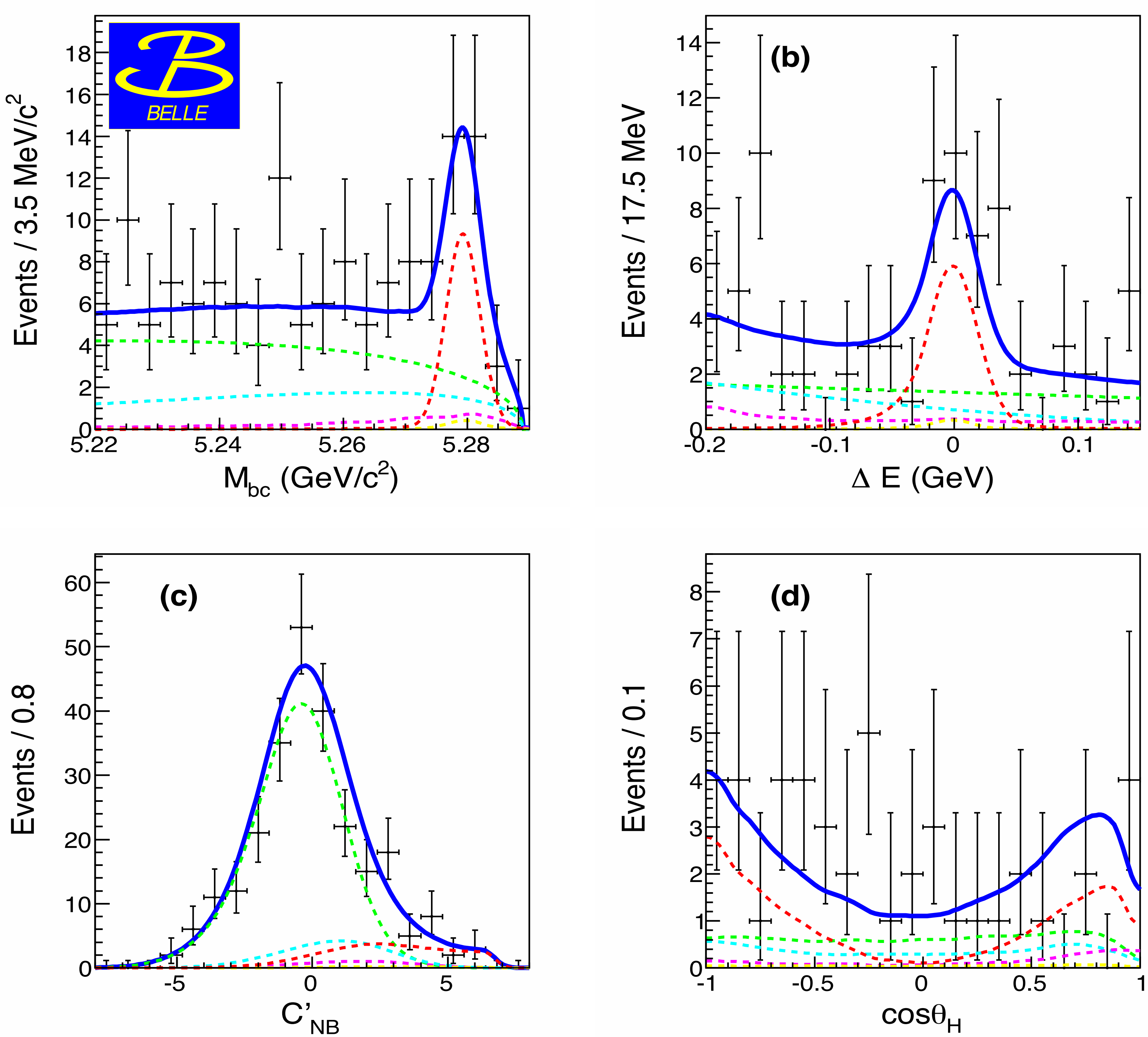
$A(J/\psi \pi)$ = [-4.2 ±4.4(stat) ±0.9(syst)] %

PRL **110, 241801** (2013)

$B_d^0 \to \eta' K^*(892)$

preliminary





penguin-dominated mode

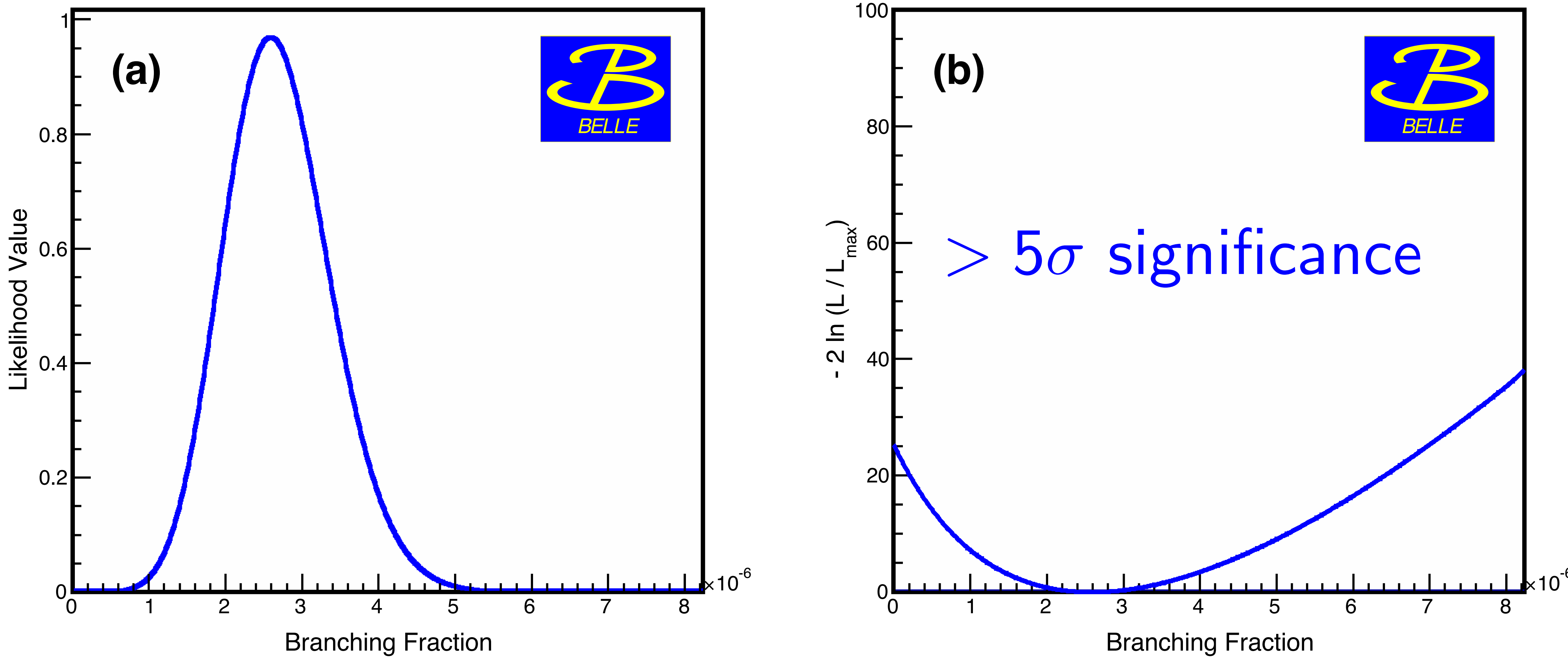
4-dimensional unbinned extended maximum-likelihood fit

projections shown here

$B_d^0 \to \eta' \, K^*(892)$

preliminary

$$\mathcal{B}\left(B^0 \to \eta' K^*(892)\right) = \left(2.6 \pm {}^{0.7}_{0.6} \pm 0.2\right) \times 10^{-6}$$



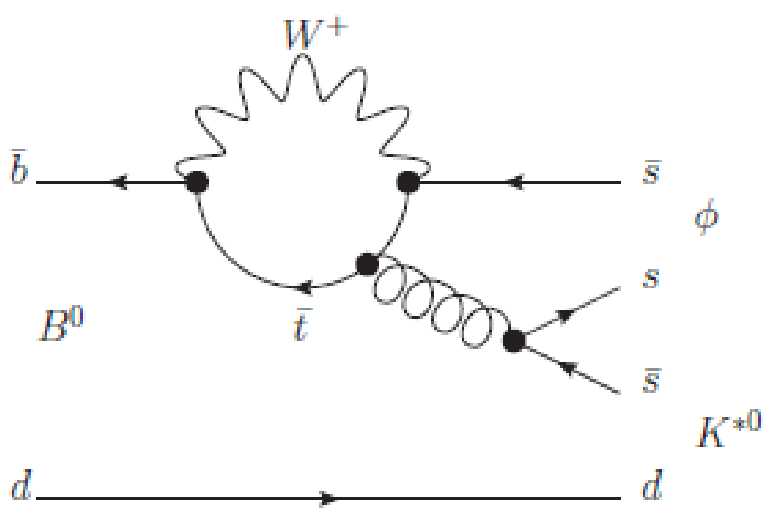
$$\mathcal{A}_{\mathrm{CP}} = -0.22 \pm {}^{0.18}_{0.17} \pm {}^{0.02}_{0.03}$$

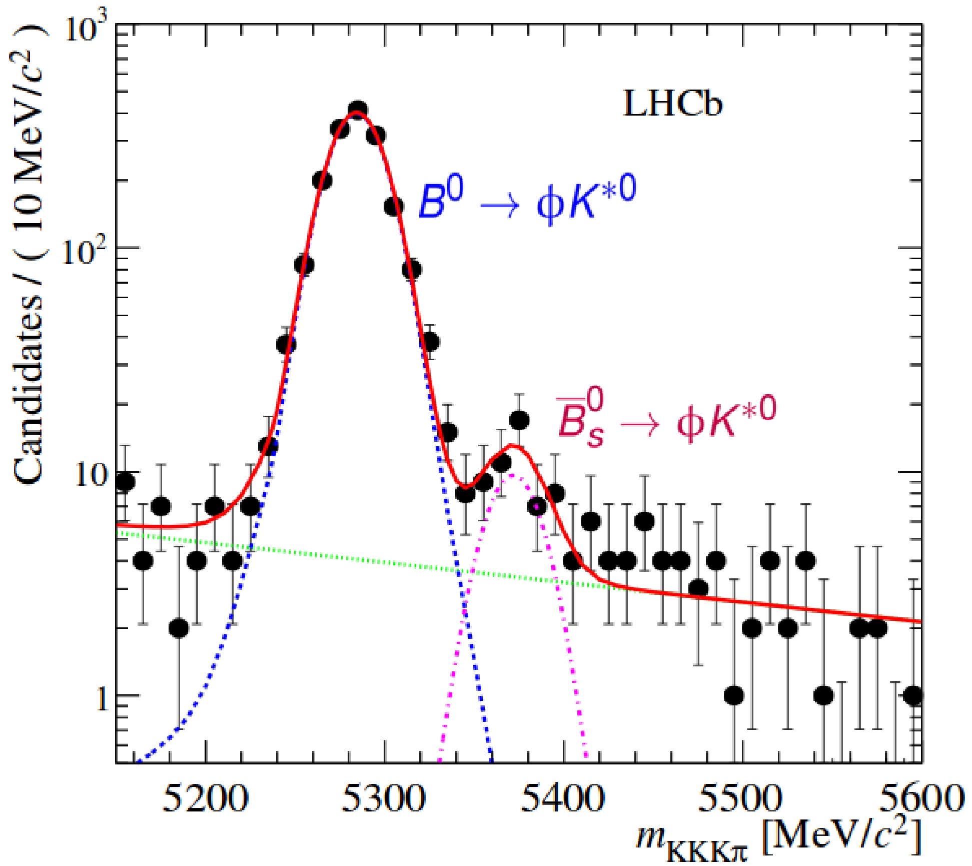
Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

[arXiv:1403.2888]

$B^0 \to \phi K^*(892)^0$

- $b \to s s\bar{s}$ FCNC decay, penguin in SM $\Longrightarrow$ sensitive to NP contributions in the loop.
- $B^0 \to K^+ K^- K^+ \pi^-$ final state studied.
- $\boxed{N_{\rm sig} = 1655 \pm 42}$

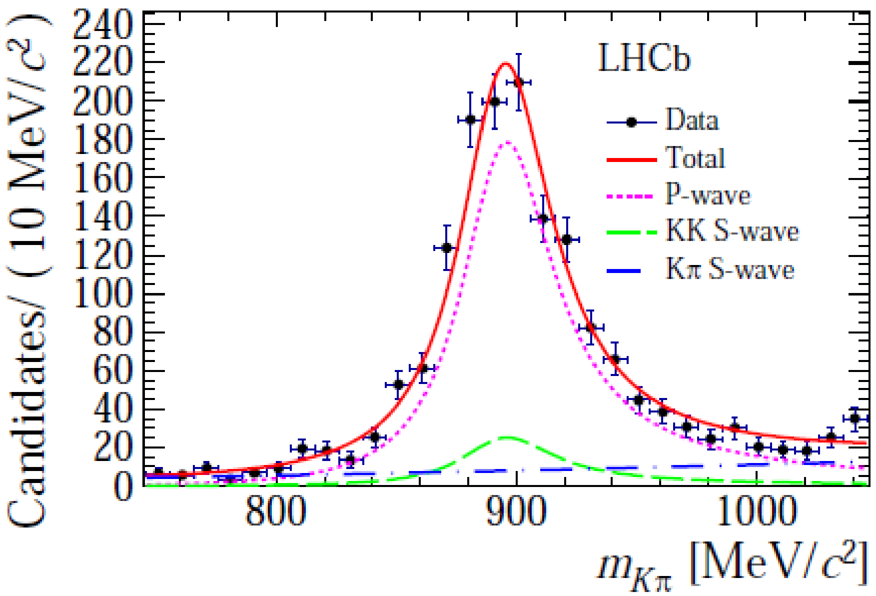


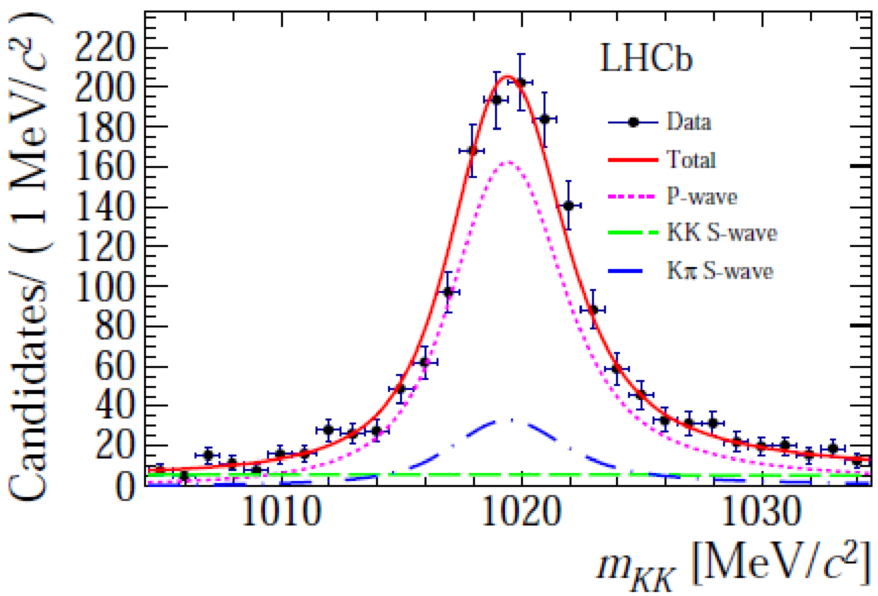


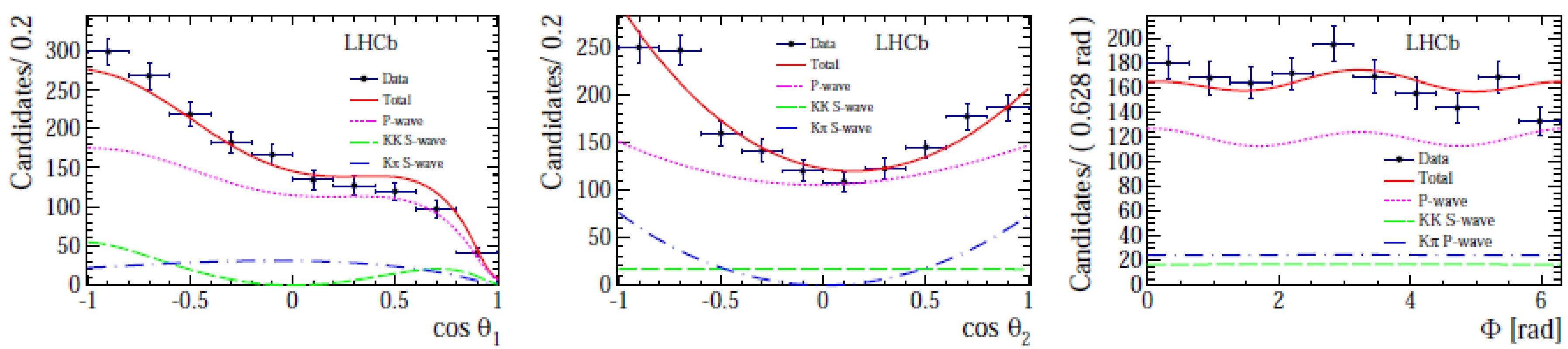
- **Angular analysis** of time-integrated decay rates to disentangle helicity structure of the $P \to VV$ decay (L= 0, 1, 2):
  - **P-wave**: longitudinal $\mathcal{A}_0$ and transverse, parallel $\mathcal{A}_\parallel$ and perpendicular $\mathcal{A}_\perp$;
  - **S-wave**: $\mathcal{A}_S(K\pi)$ ($B^0 \to \phi K^+\pi^-$) and $\mathcal{A}_S(KK)$ ($B^0 \to K^*(892)^0 K^- K^+$).

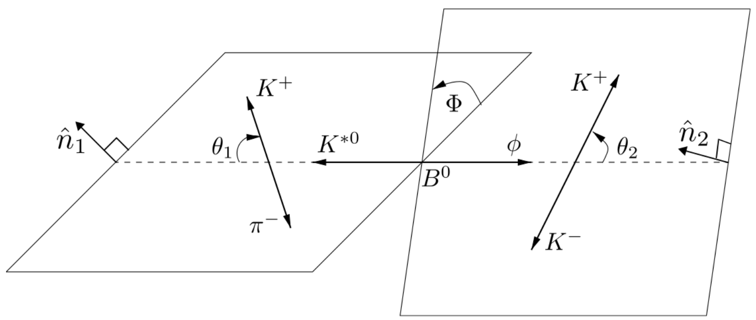
Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\text{fb}^{-1}$

[arXiv:1403.2888]









A_0^{CP}	= -0.003 $\pm$ 0.038 (stat) $\pm$ 0.005 (syst)
$A_\perp^{CP}$	= +0.047 $\pm$ 0.072 (stat) $\pm$ 0.009 (syst)
$A_{S(K\pi)}^{CP}$	= +0.073 $\pm$ 0.091 (stat) $\pm$ 0.035 (syst)
$A_{S(KK)}^{CP}$	= -0.209 $\pm$ 0.105 (stat) $\pm$ 0.012 (syst)

- B^0 and $\overline{B}^0$ decays are separated according to the charge of the kaon from the K^{*0}.
- CP-asymmetries consistent with zero.

Direct $\not{CP}$ in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

[arXiv:1403.2888]

- Final state tagged by $K^{*0} \to K^+\pi^-$ decay.
- Raw asymmetry measured from integrated rates:

$$A = \frac{N(\overline{B}^0 \to \phi \overline{K}^*(892)^0) - N(B^0 \to \phi K^*(892)^0)}{N(\overline{B}^0 \to \phi \overline{K}^*(892)^0) + N(B^0 \to \phi K^*(892)^0)}$$

- Correcting for production and detection asymmetries (determined using the control channel $B^0 \to J/\psi K^*(892)^0$):

$$\boxed{A^{CP}(\phi K^{*0}) = (+1.5 \pm 3.2\,(\mathrm{stat}) \pm 0.5\,(\mathrm{syst}))\%}$$

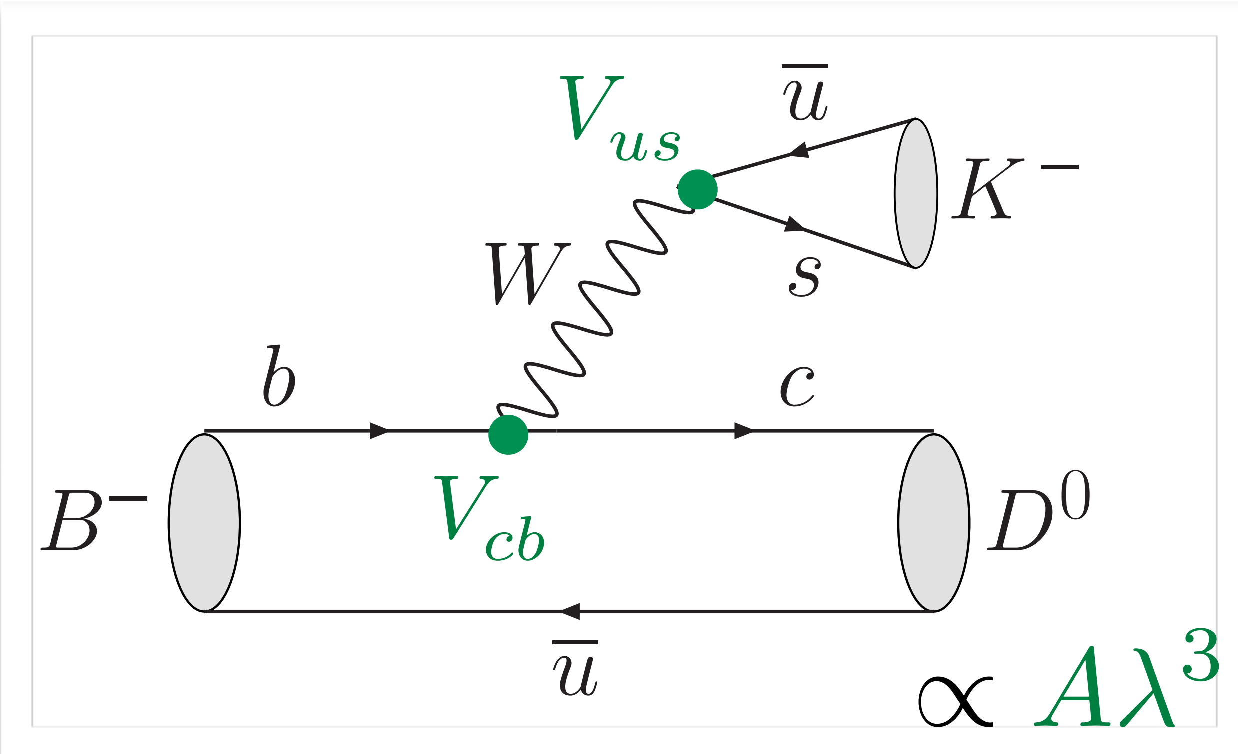
  - Systematic uncertainty from the difference in kinematic and trigger used to select $B^0 \to J/\psi K^*(892)^0$ events.

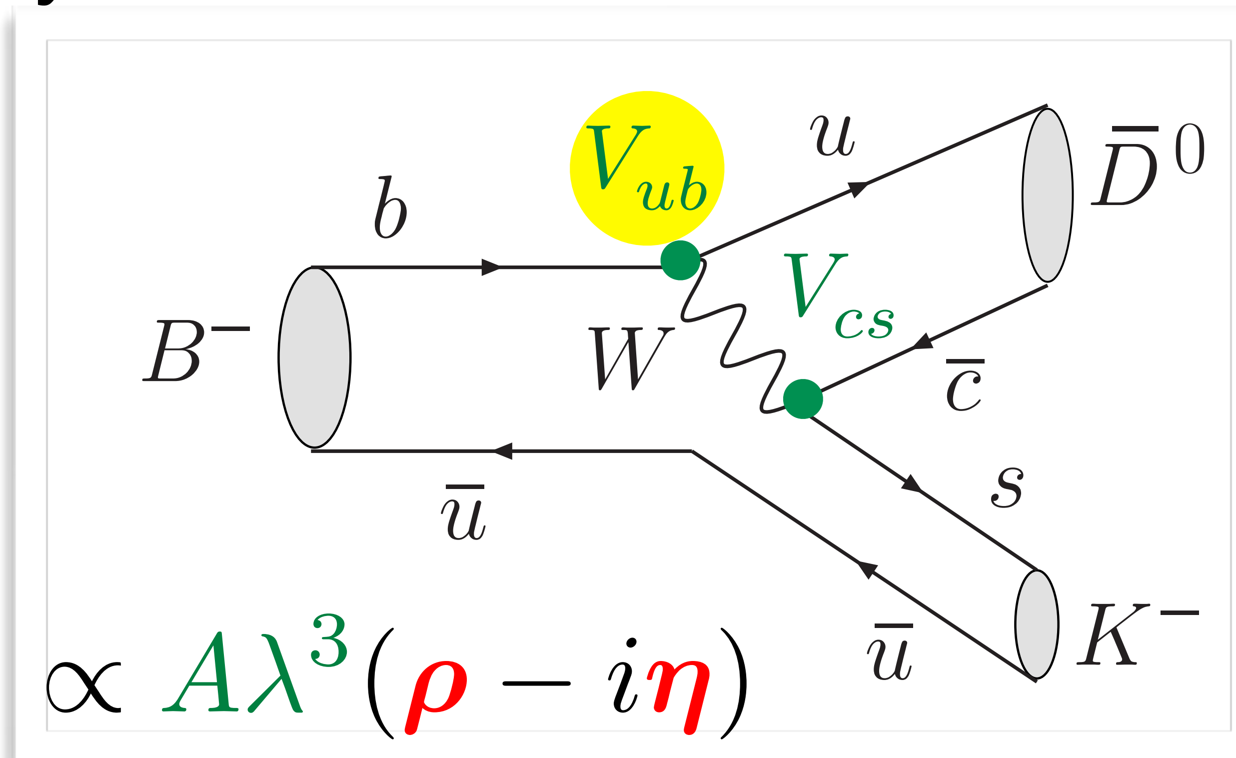
- No direct $\not{CP}$ in agreement with (and a factor of 2 more precise than):

$$A^{CP}(\phi K^{*0}) = (+1 \pm 6\,(\mathrm{stat}) \pm 3\,(\mathrm{syst}))\%$$ Babar [Phys.Rev.D 78, 092008(2008)]

$$A^{CP}(\phi K^{*0}) = (-0.7 \pm 4.8\,(\mathrm{stat}) \pm 2.1\,(\mathrm{syst}))\%$$ Belle [Phys.Rev.D 88, 072004(2013)]

The weak phase ϕ_3 is measured in $B^- \to D^{(*)}K^{(*)-}$ decays by the interference between two amplitudes if both $D^{(*)0}$ and $\bar{D}^{(*)0}$ decay to a common final state





Then $B^- \to \bar{\tilde{D}}K^-$ ***with*** $|\bar{\tilde{D}}\rangle \propto |D^0\rangle + r_B e^{i(\delta_B - \phi_3)}|\bar{D}^0\rangle$

and $B^+ \to \tilde{D}K^+$ ***with*** $|\tilde{D}\rangle \propto |D^0\rangle + r_B e^{i(\delta_B + \phi_3)}|\bar{D}^0\rangle$

where $r_B = \left|\dfrac{\mathcal{A}(B^- \to \bar{D}^0 K^-)}{\mathcal{A}(B^- \to D^0 K^-)}\right| \approx \mathcal{O}(0.1)$ **including colour suppression**

Three techniques to measure ϕ_3 use rare decays of the form $B^- \to \overset{(-)}{D}{}^0 K^-$

- ✓ GLW: use CP eigenstates $|D\rangle_{1,2} \propto |D^0\rangle \pm \overline{D}^0\rangle$
  Gronau and London, PLB 253, 483 (1991)
  Gronau and Wyler, PLB 265, 172 (1991)
  Gronau, PRD 58, 037301 (1998)
  Gronau, PLB 557, 198 (2003)

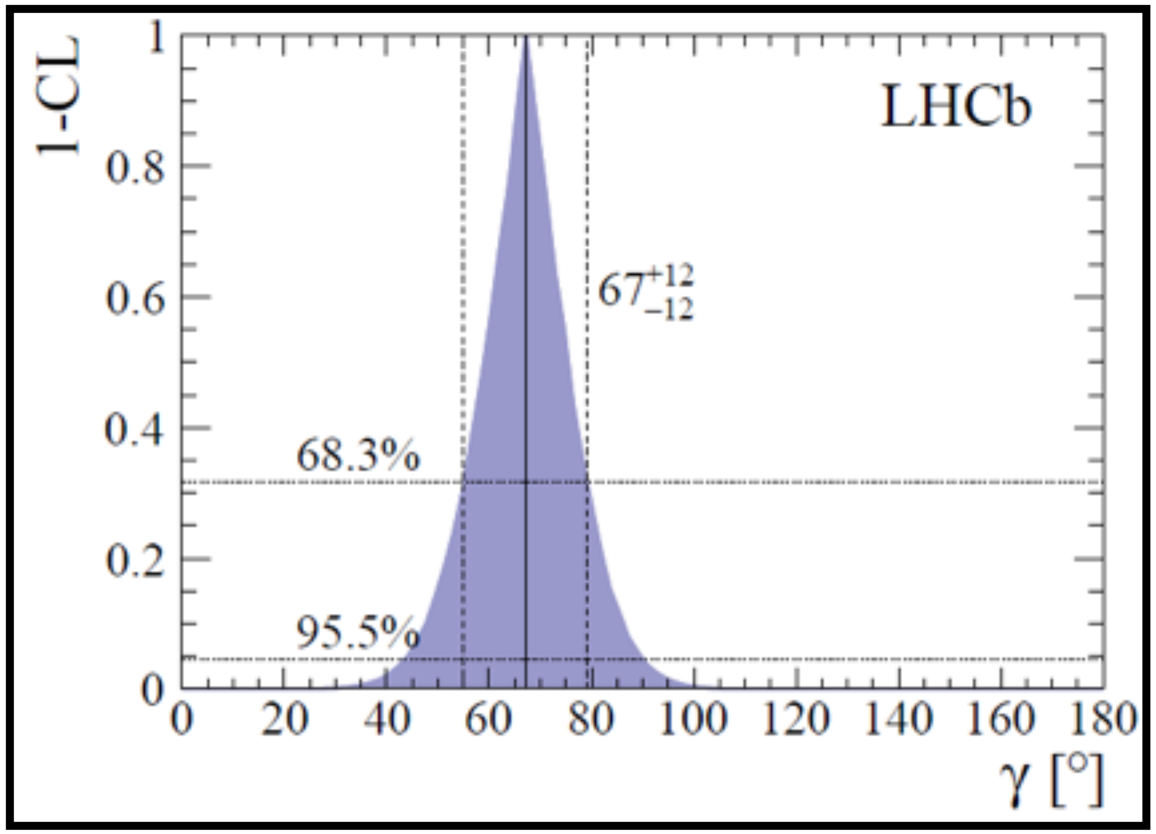
- ✓ ADS: use $|K^+\pi^-\rangle$ state (CF for $\overline{D}^0$; DCS for D^0)
  Atwood, Dunietz and Soni, PRL 78, 3257 (1997)

- ✓ GGSZ: use Dalitz analysis of $|K_S\pi^+\pi^-\rangle$ state
  Giri, Grossman, Soffer and Zupan, PRD 68, 054018 (2003)
  Bondar, Proc BINP Dalitz Analysis Meeting (2002) (unpublished)

$B^- \to \overset{(-)}{D}{}^0 K^-$ to measure ϕ_3 ($=\gamma$): all 3 methods

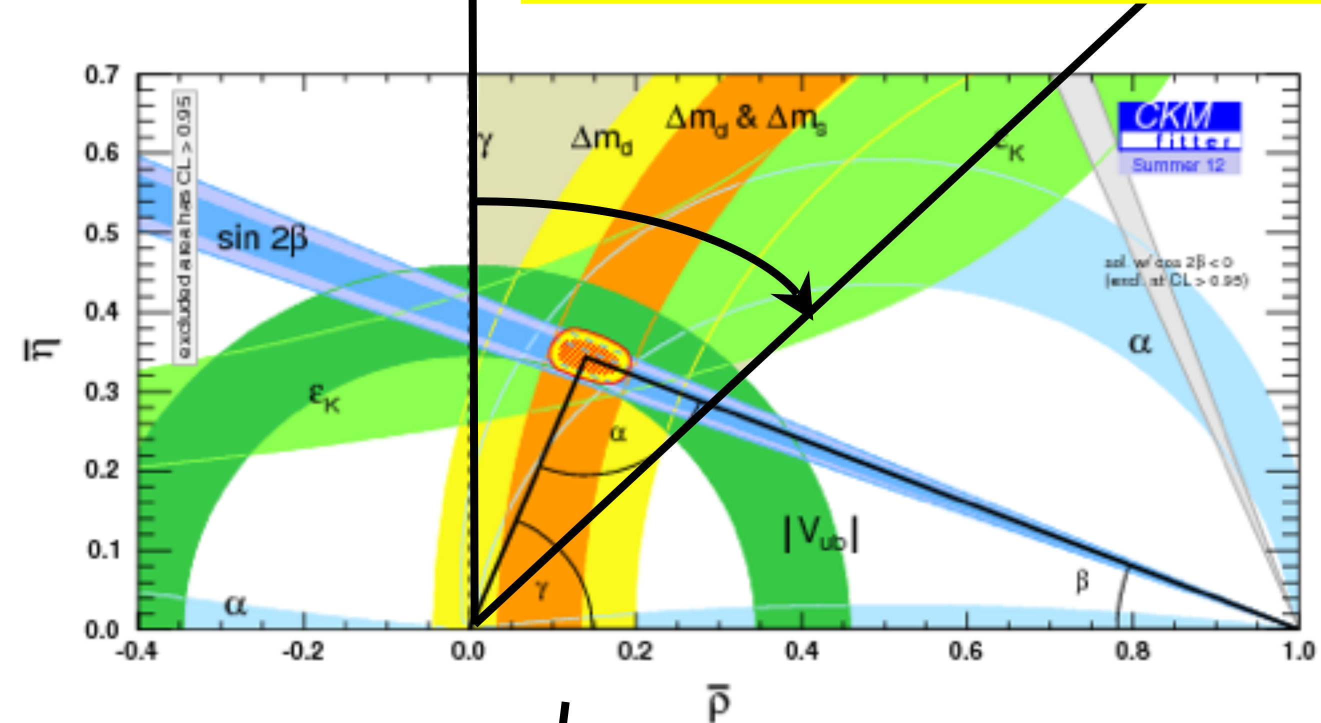
Combined ADS, GLW (1 fb^{-1}) and GGSZ (3 fb^{-1})

PLB **726**, 151 (2013)

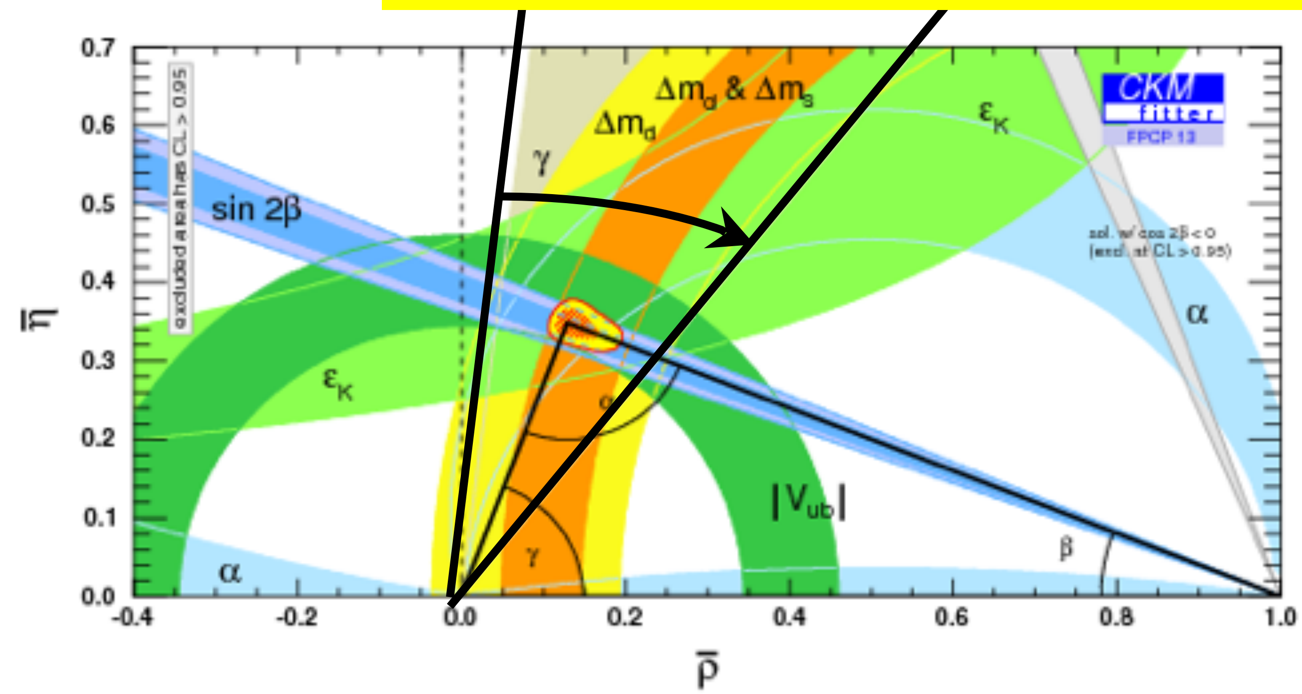


$\gamma = (67 \pm 12)^\circ$

2012: Before 1st LHCb results



2013: After including LHCb results



By 2018, expect $\sigma_\gamma \sim 4^\circ$

$B \to X_{s+d}\,\gamma$

Expectations:

Channel	A_{CP} (SM)
B$\to X_s\gamma$	[-0.6% , +2.8%]
B$\to X_d\gamma$	[-62% ,+14%]
B$\to X_{s+d}\gamma$	0

PRL 106, 141801 (2011)

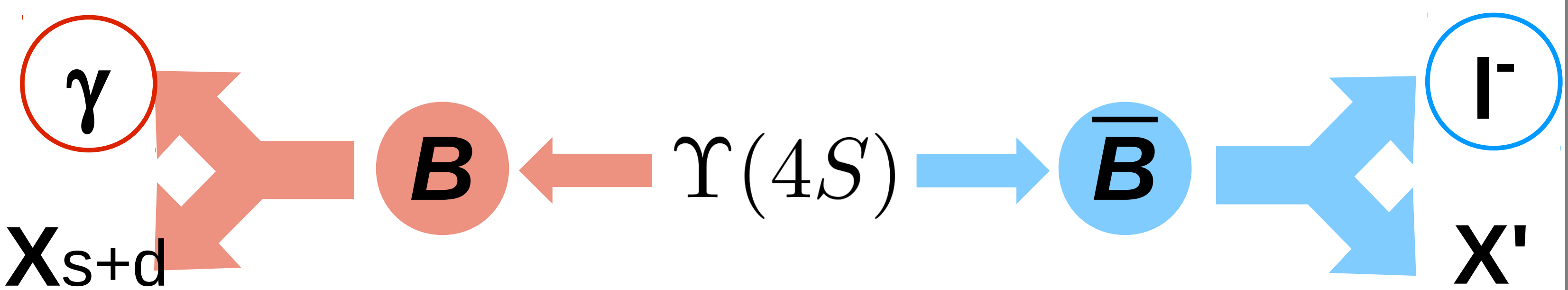
Cancellation due to unitarity, negligible theory error!

$f = X_{s+d}\gamma$

$$A_{CP} = \frac{\Gamma(\bar{B}\to\bar{f}) - \Gamma(B\to f)}{\Gamma(\bar{B}\to\bar{f}) + \Gamma(B\to f)}$$

Using tag-lepton charge

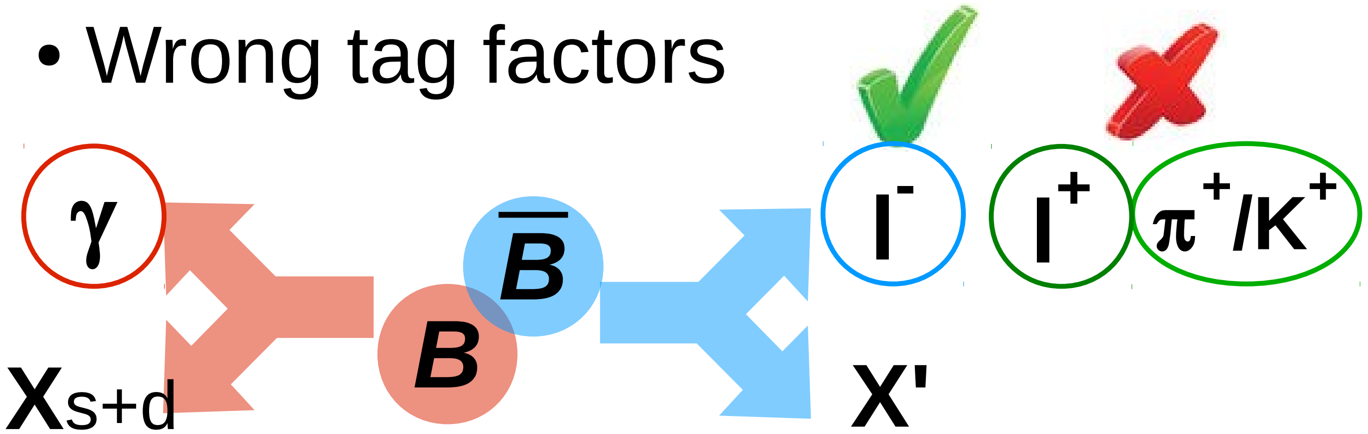
$$A_{CP} = \frac{N^+ - N^-}{N^+ + N^-}$$



- Inclusive method: reduce model uncertainty but has high background.
- High energy photon (1.7 – 2.8 GeV) and lepton (e, μ) for tagging
- Mass veto for $\pi^0(\eta) \to \gamma\gamma$

$$B \to X_{s+d}\,\gamma$$

- Wrong tag factors



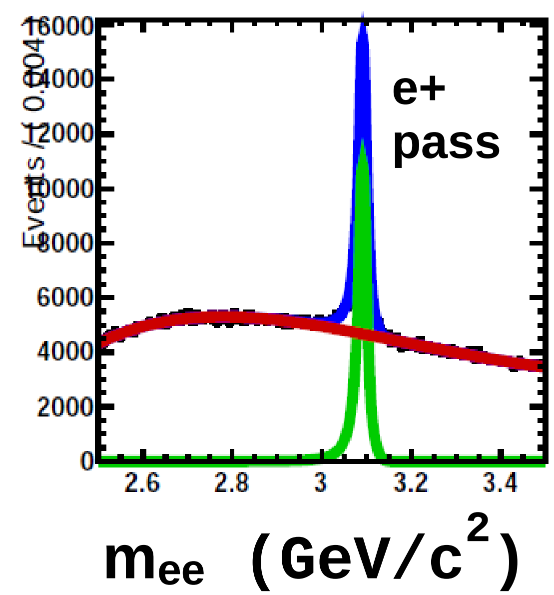
$$\omega = \omega_{\rm osc} + \omega_{2nd} + \omega_{\rm misID} = 0.1413 \pm 0.0052$$

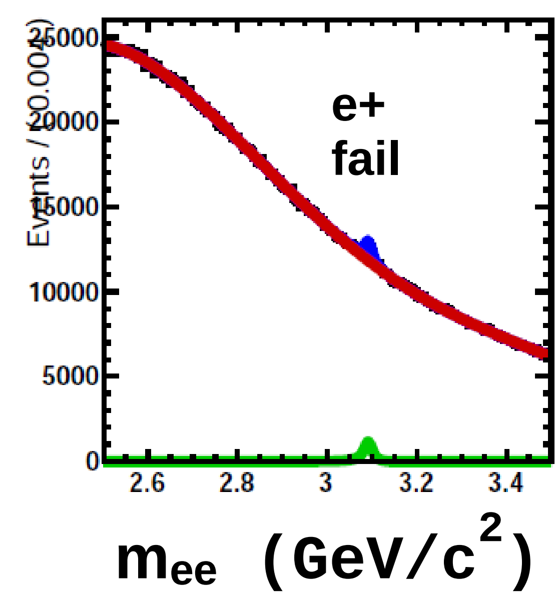
$$A_{\rm CP} = \frac{1}{1-2\omega} A_{\rm CP}^{\rm meas}$$

- Asymmetry in lepton ID, study in $B \to X\, J/\Psi\,(l^+l^-)$, tag-and-probe

$$\varepsilon^{\pm} = \frac{N_{\rm pass}}{N_{\rm pass} + N_{\rm fail}}$$

$$\mathrm{A_{det}} = \frac{\varepsilon^+ - \varepsilon^-}{\varepsilon^+ + \varepsilon^-} \qquad \boxed{\mathrm{A_{det}} = (0.10 \pm 0.22)\%}$$

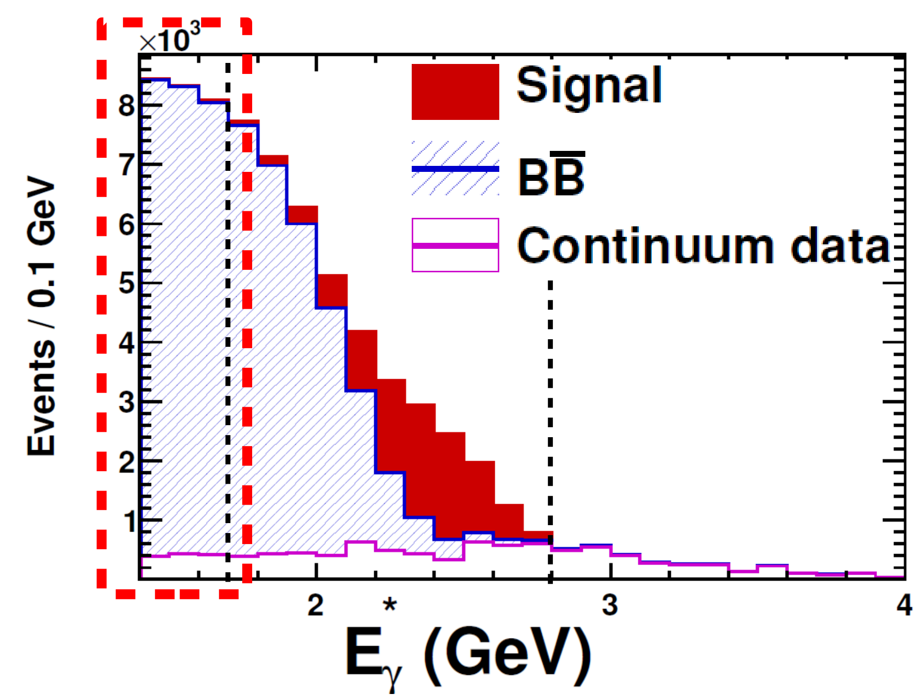




- Asymmetry in BB bkg: measured in data ($E_\gamma^* < 1.7$ GeV)

$$\mathrm{A_{bkg}} = \frac{N^+ - N^-}{N^+ + N^-} \qquad \boxed{\mathrm{A_{bkg}} = (-0.14 \pm 0.78)\%}$$

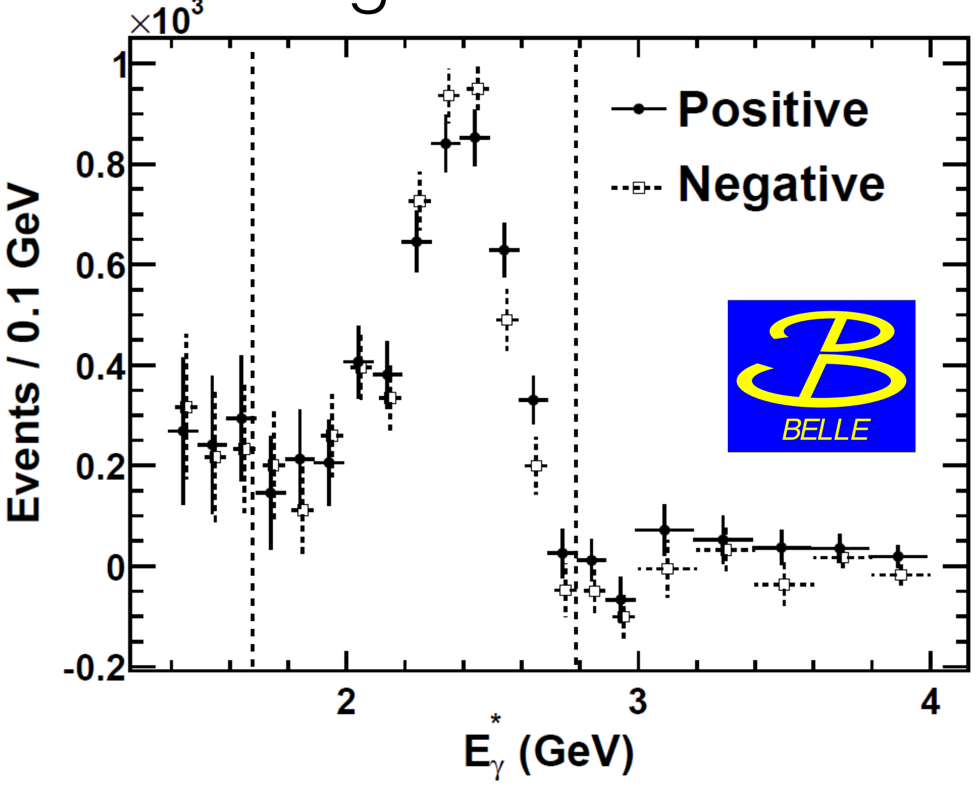
- These asymmetries are bias!, must correct them



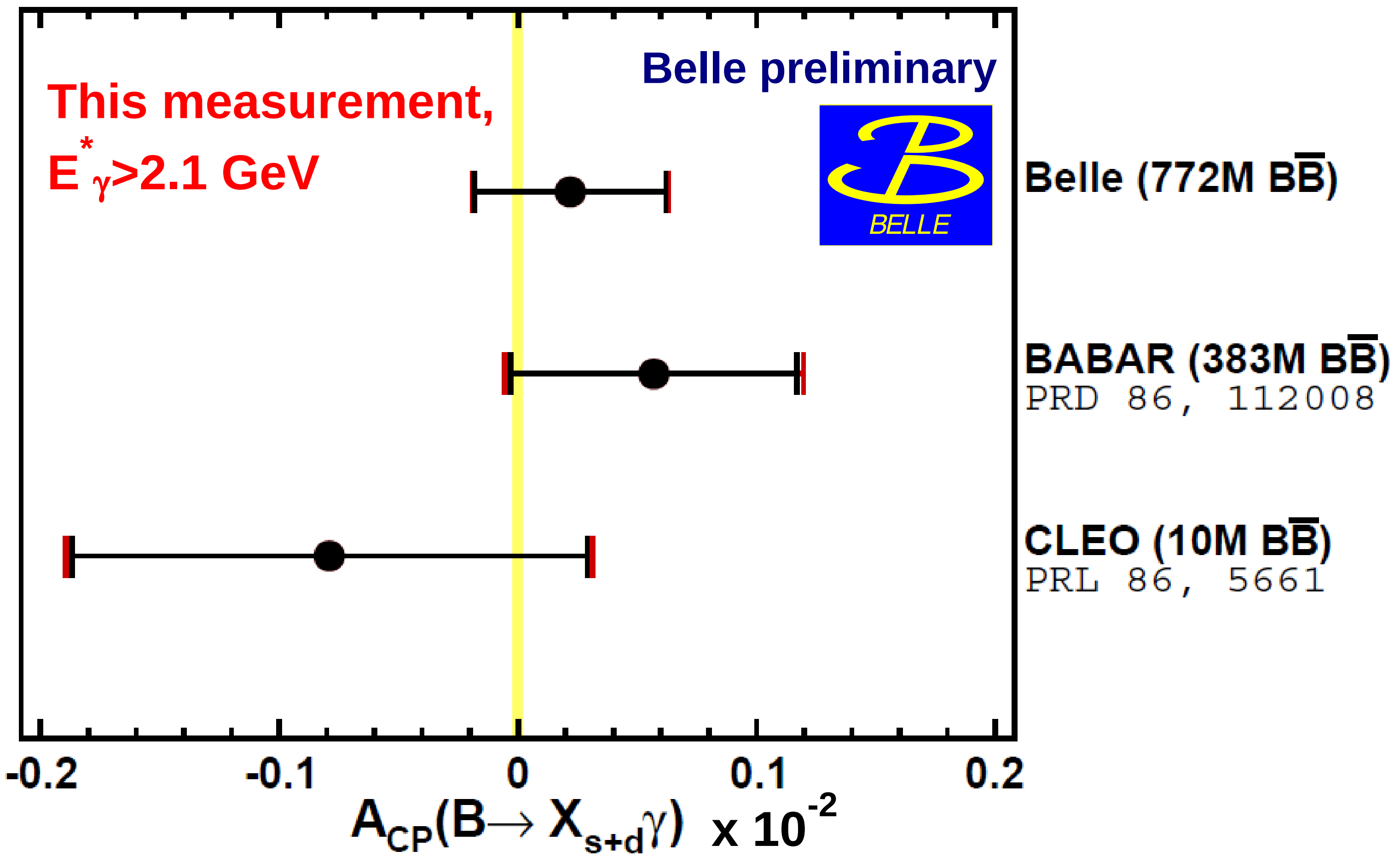
$B \to X_{s+d}\,\gamma$

preliminary

After background subtraction



Raw asymmetry is corrected for mis-tagging and asymmetry bias (see previous page)



CP Violation in $B^0\bar{B}^0$ Mixing

$\cancel{CP}$ in mixing, time-integrated: a^s_{sl} PLB **728**, 607 (2014)

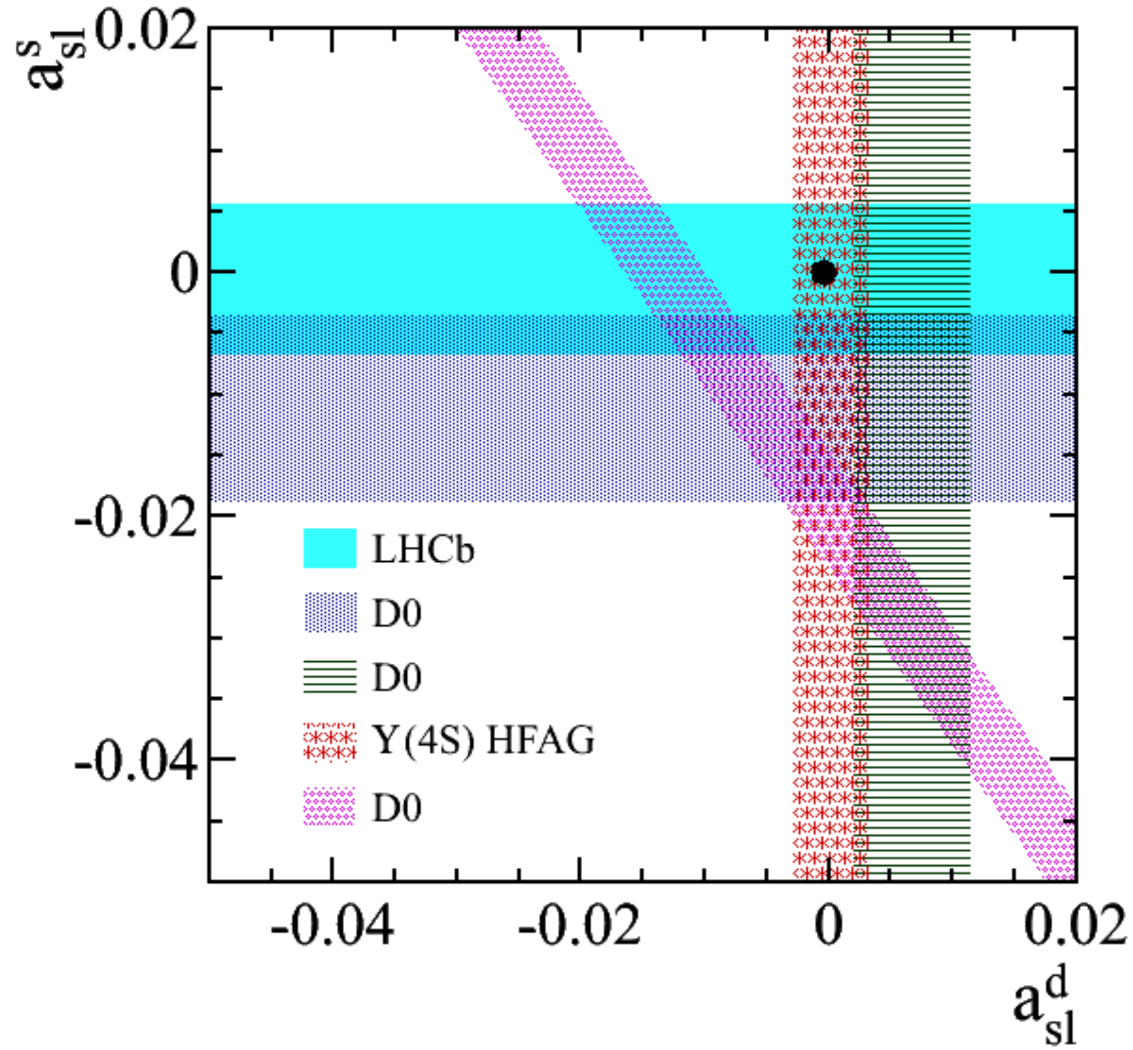
Analyse $B_s^0 \rightarrow D_s X \mu\nu$ decays (2011 data).

$$A_{\mathrm{meas}} \equiv \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]}$$
$$= \frac{a^s_{\mathrm{sl}}}{2} + \left[a_{\mathrm{P}} - \frac{a^s_{\mathrm{sl}}}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)\,dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)\,dt}$$

B_s^0 production asymmetry negligible: highly suppressed (10^{-4}) due to fast oscillations.

Opposite magnet polarities: cancel most of detection asymmetries of charged particles.

Using large control samples: correct for tracking (0.13%) and background asymmetries (0.05%); account for difference in trigger and PID efficiencies for μ^+ and μ^-.

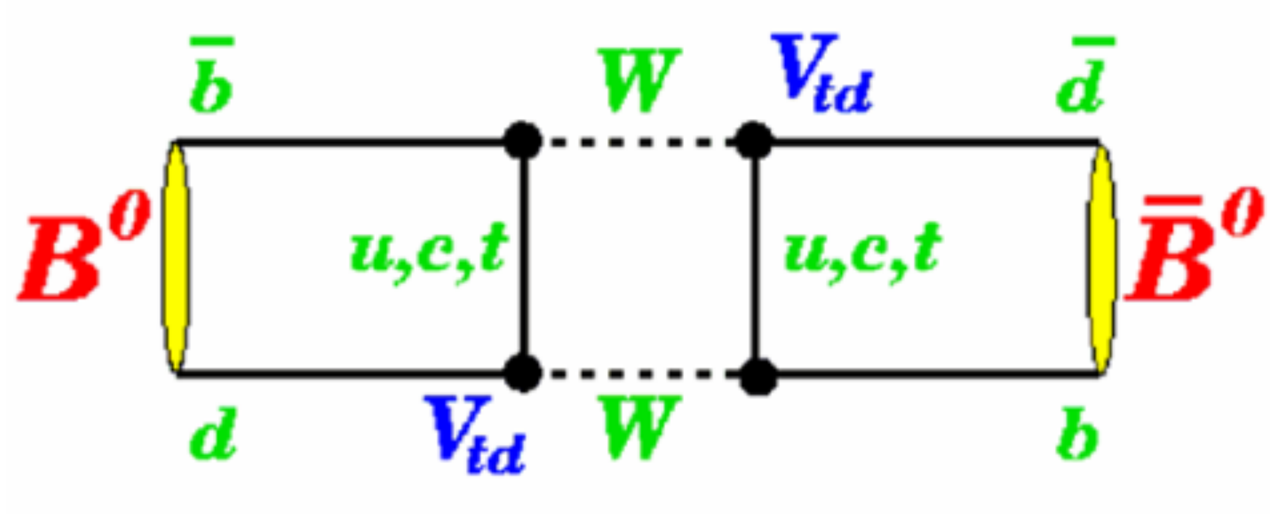


a^s_{sl}=(-0.06 ± 0.50 ± 0.36)%

World's best measurement, consistent with SM expectation

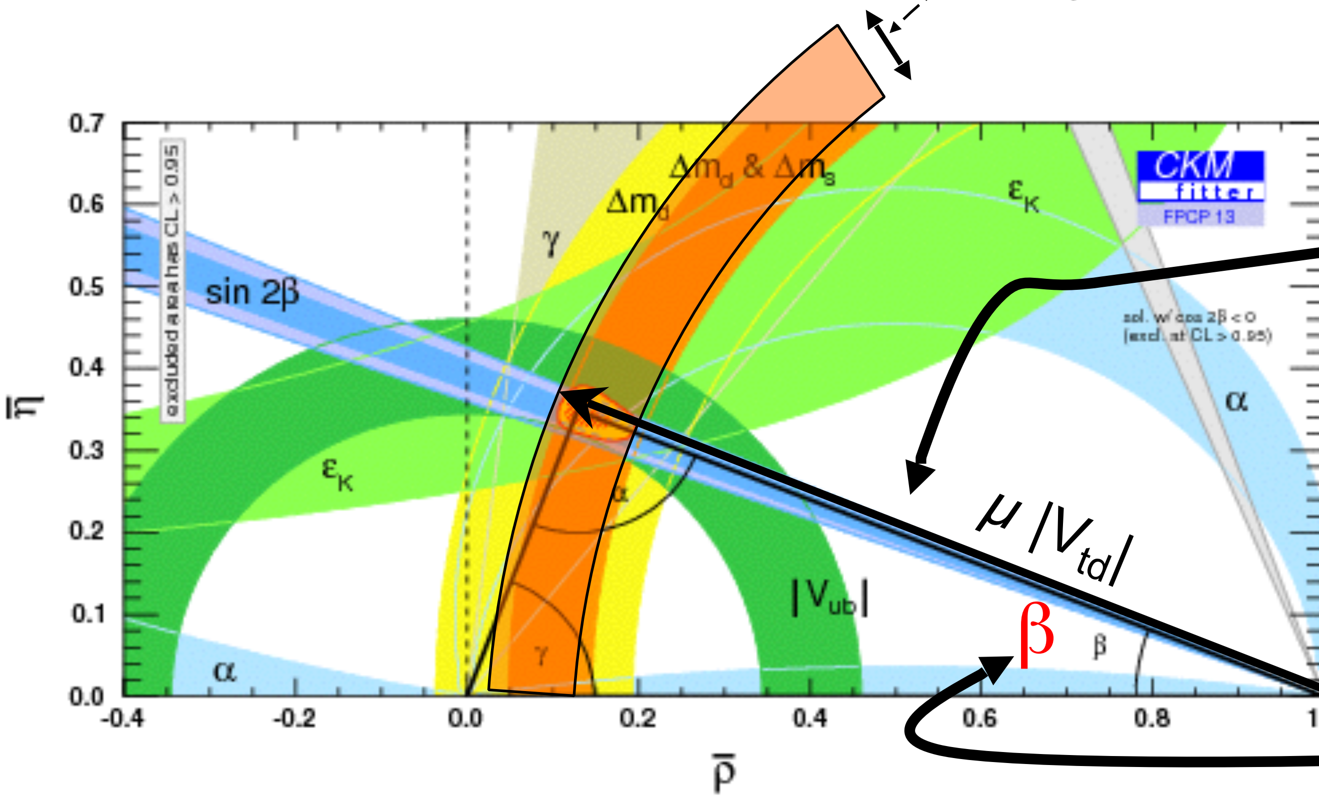
D0 3σ deviation from SM neither ruled out nor confirmed

~~CP~~ in mixing with time-dependence:



$$H = \begin{pmatrix} m_0 & M_{12} \\ M_{12}^* & m_0 \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

- Mixing due to 2nd order weak transition, M_{12}, $\Gamma_{12} \neq 0$
- NP could contribute to M_{12} ($m >> m_B$)
- Imperative to measure amplitude and phase of M_{12} precisely!
  - Theoretical input (lattice) CRUCIAL here to shrink this band

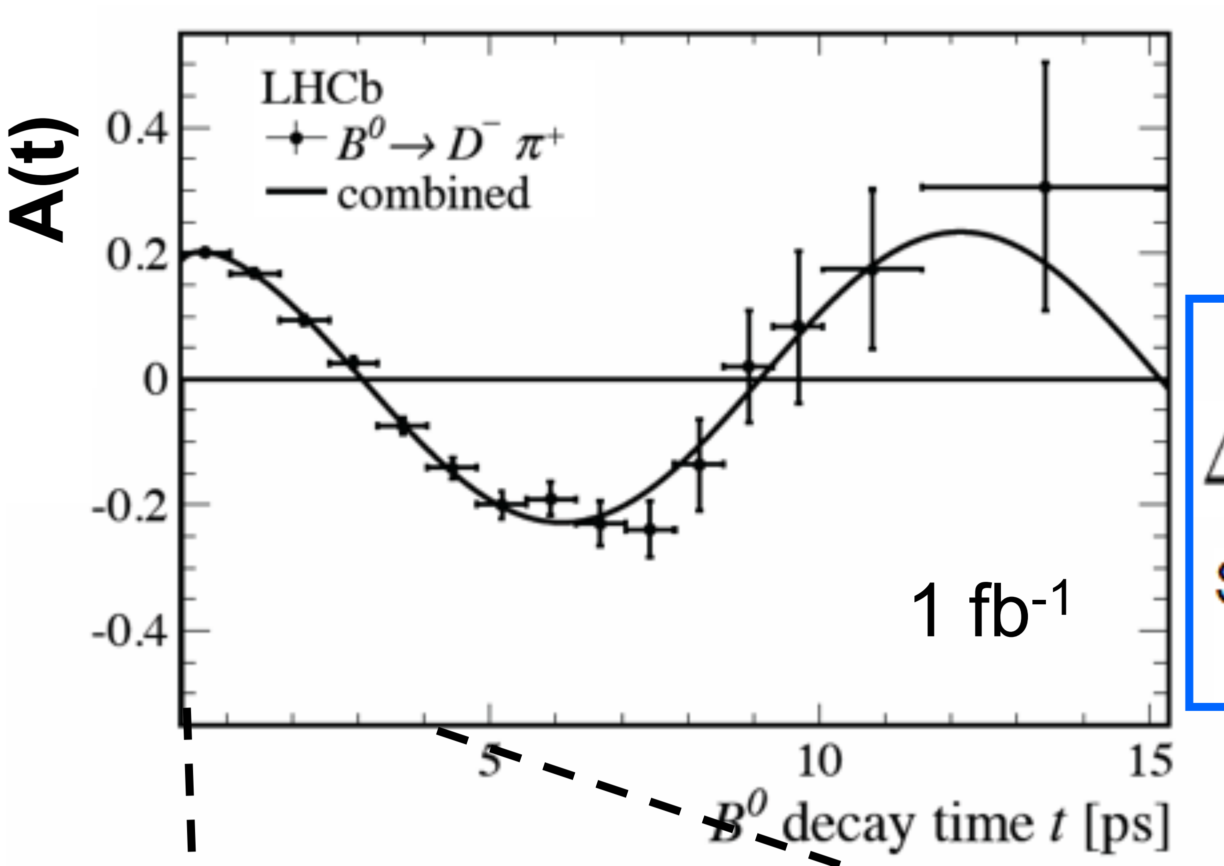


- Measure oscillation frequency
  $\Delta m \sim 2|M_{12}|$ μ $|V_{td}|$
- Phase of M_{12} (or V_{td}) obtained via TD CPV.

$$A(t) = \frac{\Gamma(f_{CP}) - \bar{\Gamma}(f_{CP})}{\Gamma(f_{CP}) + \bar{\Gamma}(f_{CP})} \propto \sin(2\beta)\sin(\Delta m t)$$

- V_{td} and sin(2β) also measure apex using NP-sensitive processes!

Amplitude of $B^0_{(s)}\bar{B}^0_{(s)}$ time-dependent mixing

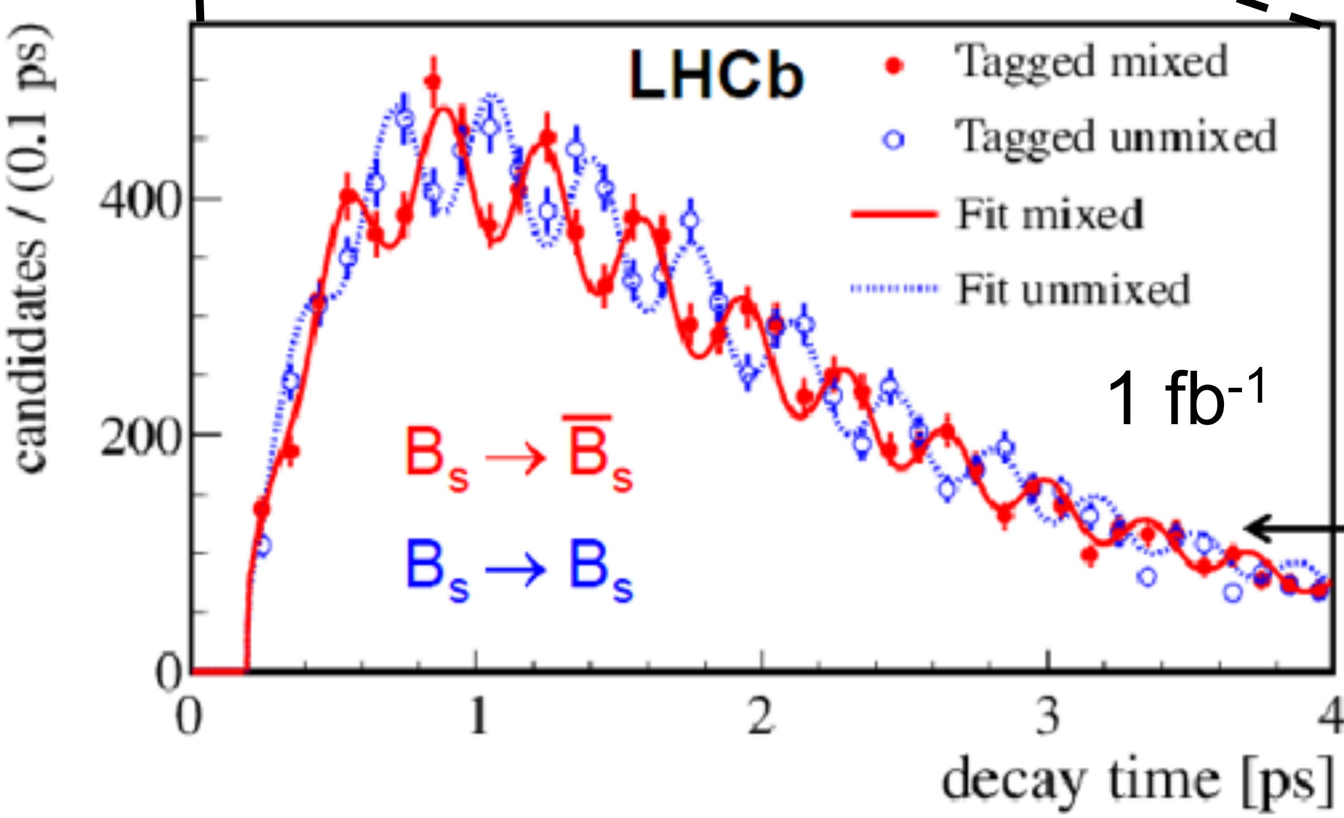


LHCb Phys.Lett. B719, 318 (2013)

Δm_d = 0.5156 ± 0.0051 (stat) ± 0.0033 (syst) ps^{-1}

Single best measurement by BELLE

$\Delta m_d = 0.511 \pm 0.005 \pm 0.006\,\mathrm{ps}^{-1}$



New J. Phys. 15 (2013) 053021

Δm_s = 17.768 ± 0.023 ± 0.006 ps^{-1}

(B_s oscillates ~35X faster than B^0!)

CDF, PRL 97, 242003 (2006)

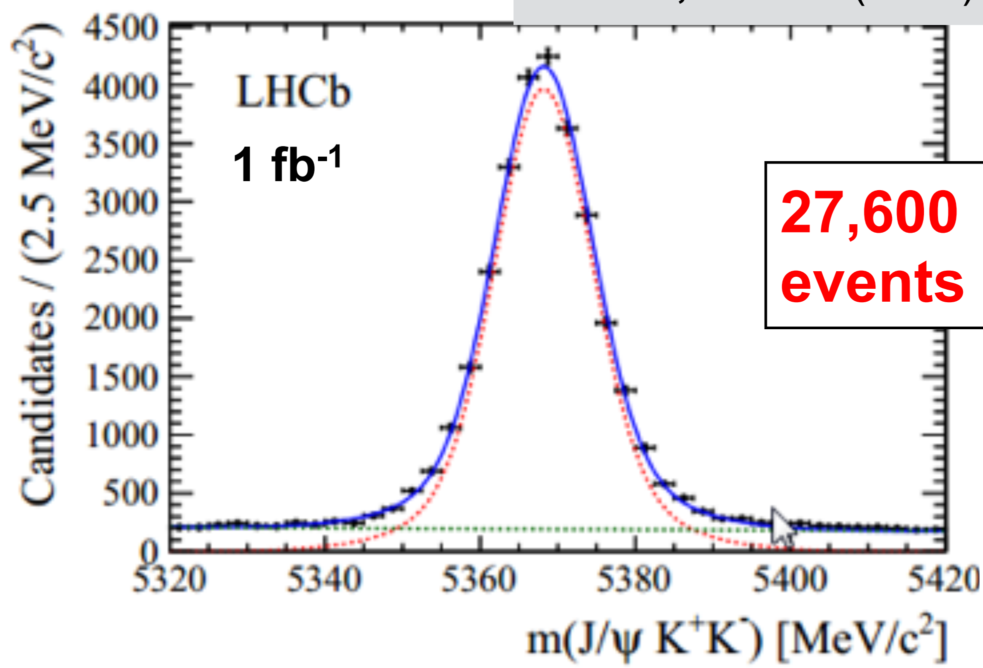
$$\Delta m_s = 17.77 \pm 0.10 \pm 0.07\ ps^{-1}$$

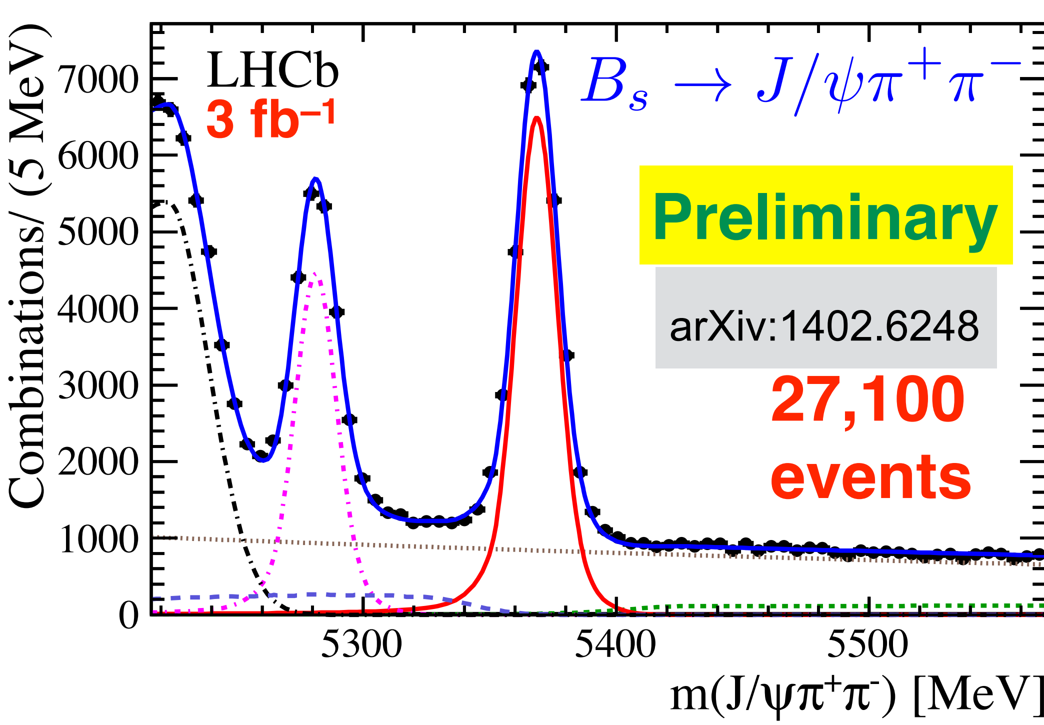
Phase of $B_s^0\bar{B}_s^0$ mixing ϕ_s

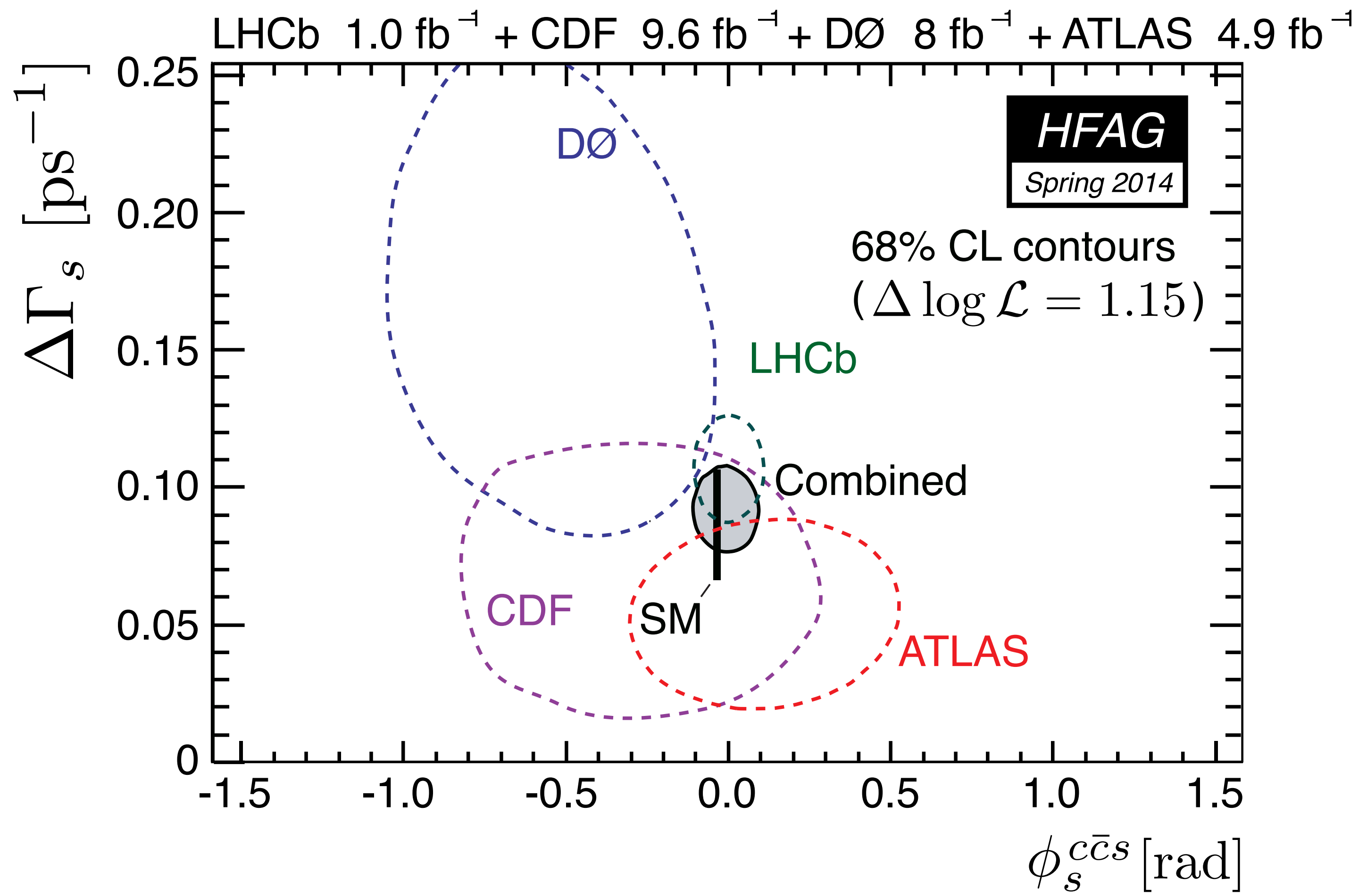
$$A(t)=\frac{\Gamma(f_{CP})-\bar{\Gamma}(f_{CP})}{\Gamma(f_{CP})+\bar{\Gamma}(f_{CP})}\propto \sin\phi_s \sin(\Delta m_s t)$$

$B_s \to J/\psi\,\phi$ ($\phi \to K^+K^-$)

PRD **87, 112010** (2013)







$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad},\\
\Gamma_s &= 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1},\\
\Delta\Gamma_s &= 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}.
\end{aligned}$$

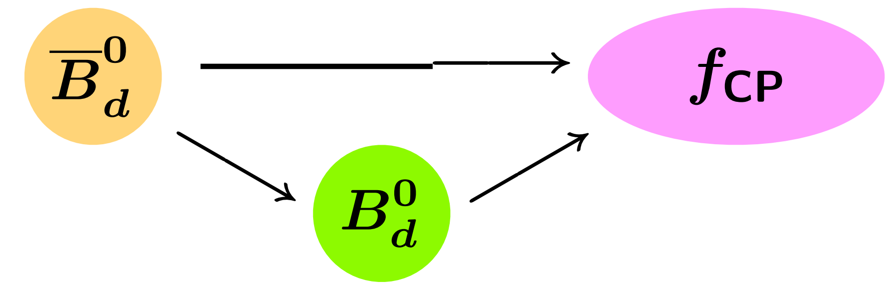
- Large improvement in precision on ϕ_s

  →Tight constraints on NP, but O(20%) NP contributions not ruled out.

$$\phi_s = 0.075 \pm 0.067 \pm 0.008$$

CP Violation
in Mixing & Decay
Interference

Time-dependent CP asymmetry in mixing & decay interference:



$$\text{Asymmetry}(\Delta t) = \frac{\Gamma(\bar{B} \to f_{\rm CP}) - \Gamma(B \to f_{\rm CP})}{\Gamma(\bar{B} \to f_{\rm CP}) + \Gamma(B \to f_{\rm CP})}$$

$$= \mathcal{A}_{\rm CP} \cos(\Delta m\, \Delta t) + \mathcal{S}_{\rm CP} \sin(\Delta m\, \Delta t)$$

also denoted $-\mathcal{C}_{\rm CP}$

Mixing & decay interference: $\mathcal{S}_{\rm CP} = +\dfrac{2{\rm Im}\lambda_{\rm CP}}{1+|\lambda_{\rm CP}|^2} \quad = -\xi_{f_{\rm CP}} \sin(2\phi_1)$

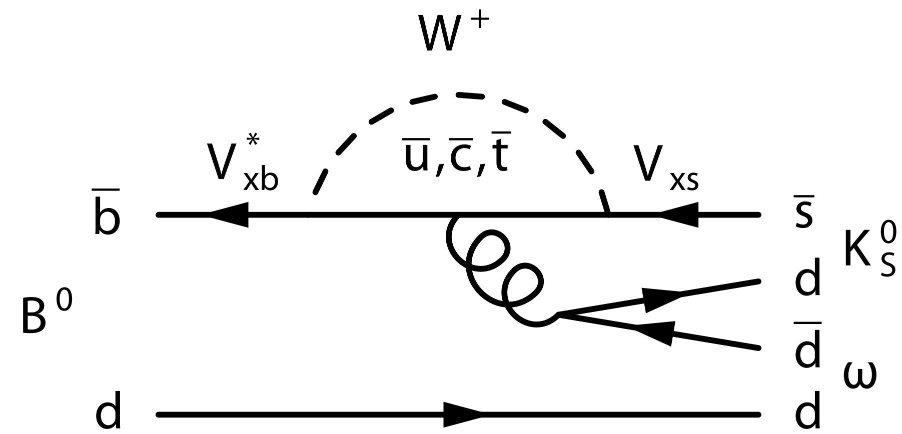
Decay via multiple paths: $\mathcal{A}_{\rm CP} = -\dfrac{1-|\lambda_{\rm CP}|^2}{1+|\lambda_{\rm CP}|^2} \quad = 0$

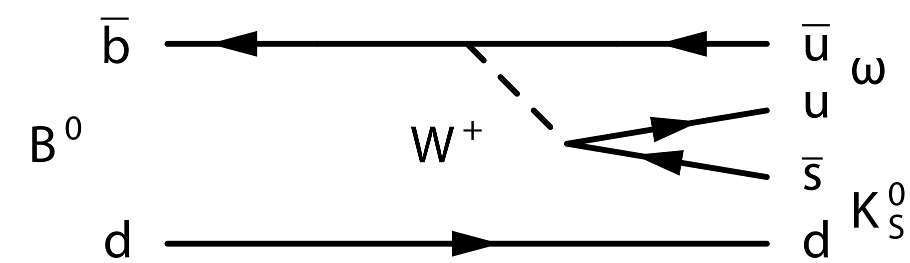
for single Feynman diagram to $f_{\rm CP}$

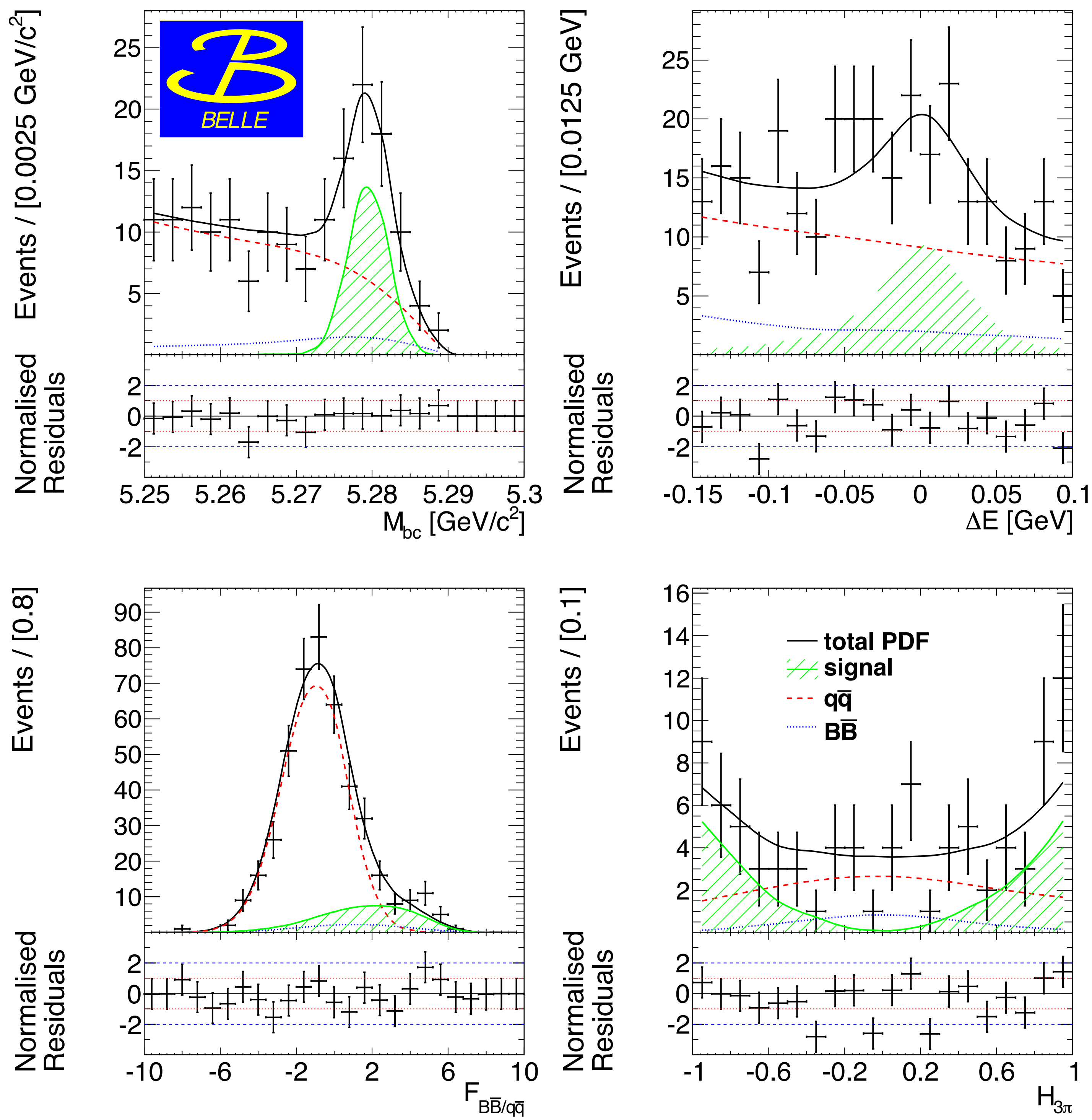
where $\lambda_{\rm CP} = \xi_{f_{\rm CP}} \dfrac{q}{p} \dfrac{\bar{A}_{f_{\rm CP}}}{A_{f_{\rm CP}}}$

$B_d^0 \to \omega K_S^0$

preliminary







penguin-dominated (tree is color- and Cabibbo-suppressed)

7-dimensional unbinned extended maximum-likelihood fit

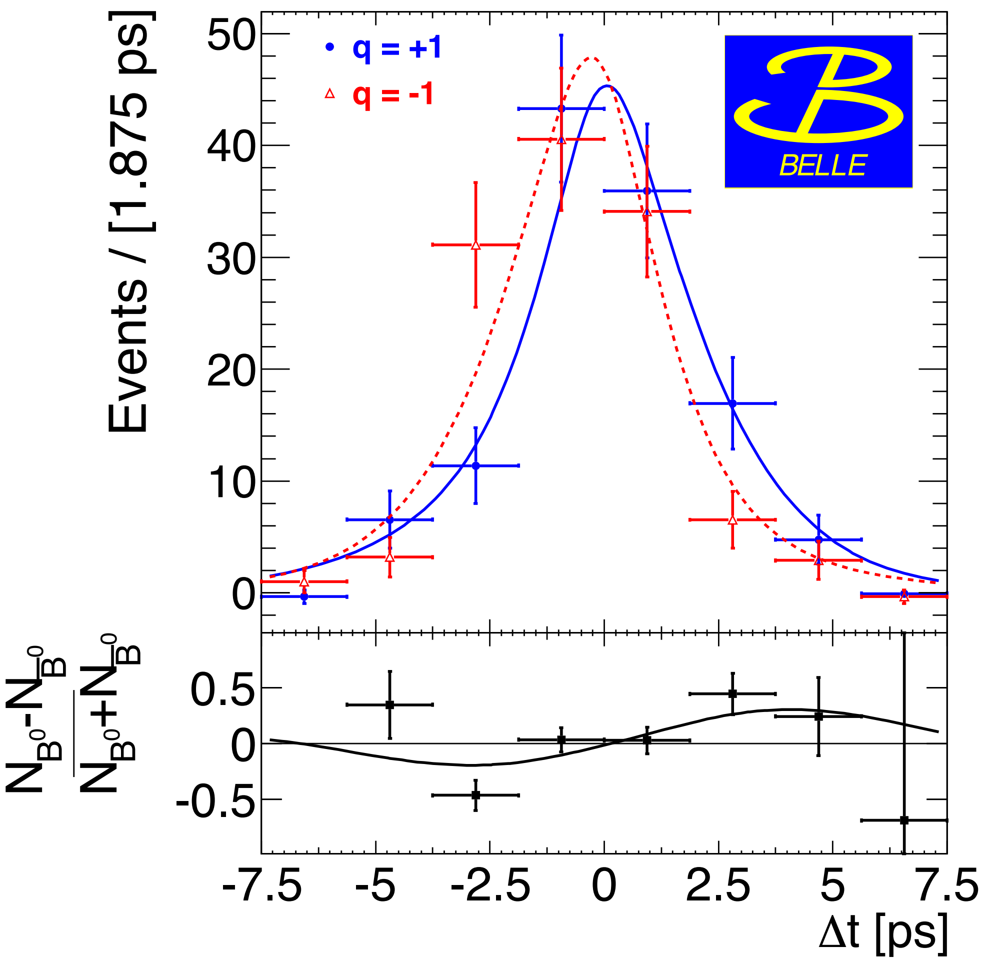
4 projections shown here

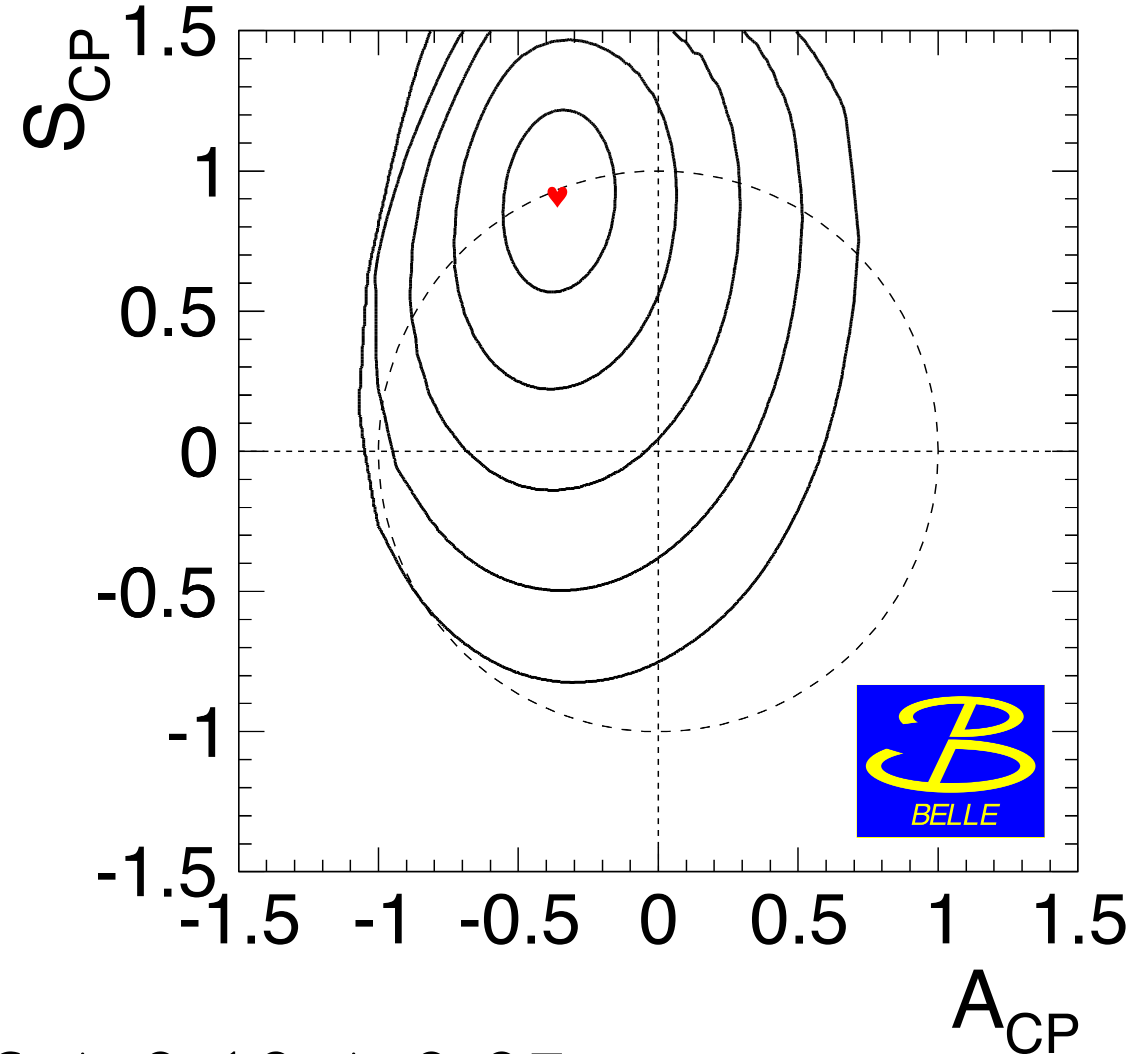
arXiv: 1311.6666
submitted to PRD

$B_d^0 \to \omega K_S^0$

preliminary

arXiv: 1311.6666
submitted to PRD



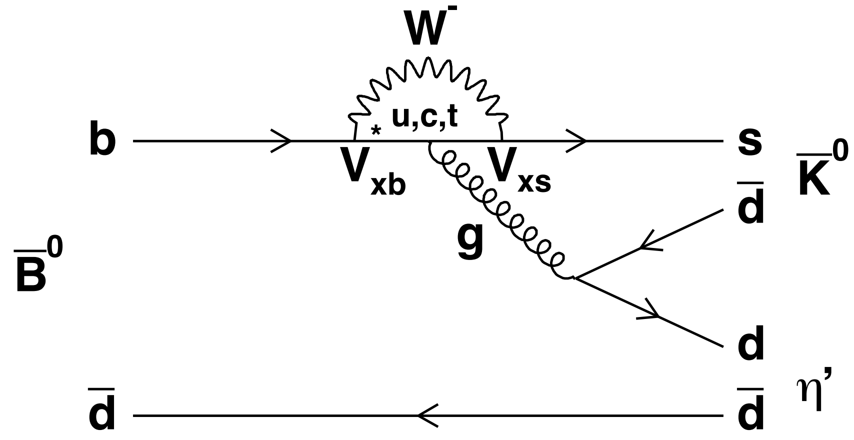


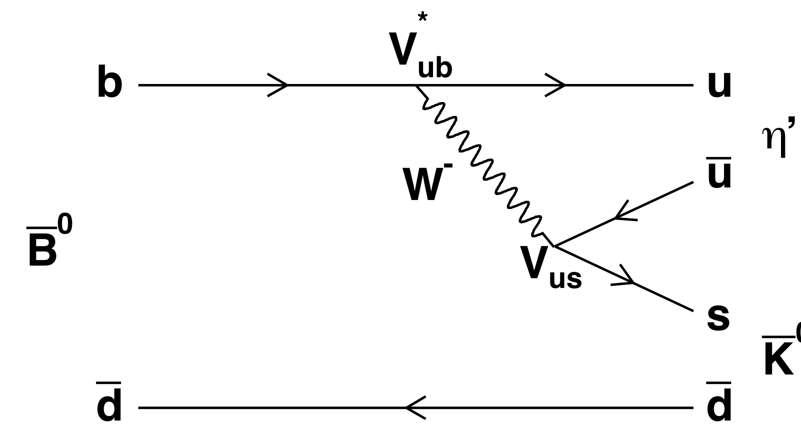
$$\mathcal{A}_{\mathrm{CP}} = -0.36 \pm 0.19 \pm 0.05$$
$$\mathcal{S}_{\mathrm{CP}} = +0.91 \pm 0.32 \pm 0.05$$

First evidence (3.1σ) for $\not{C}\not{P}$ in this mode.
No sign of New Physics.

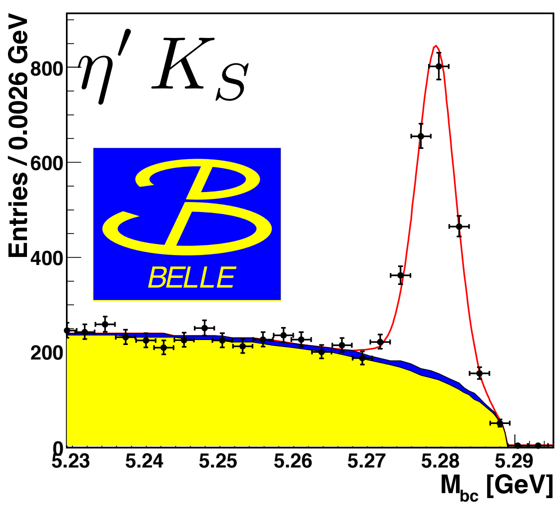
$B_d^0 \to \eta' K^0$

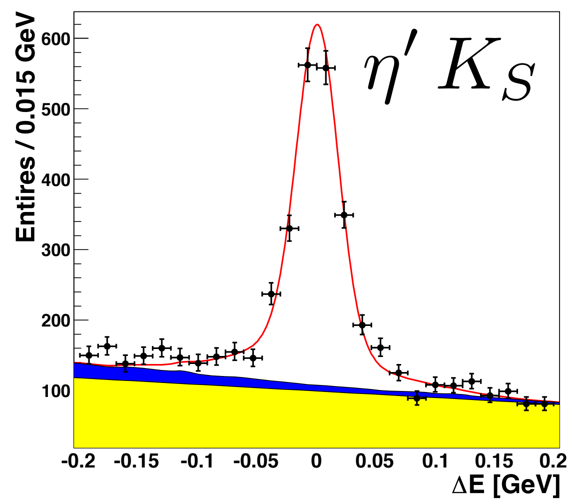
preliminary

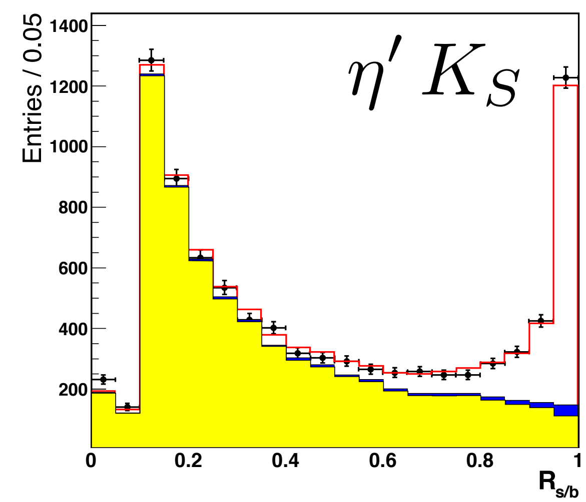




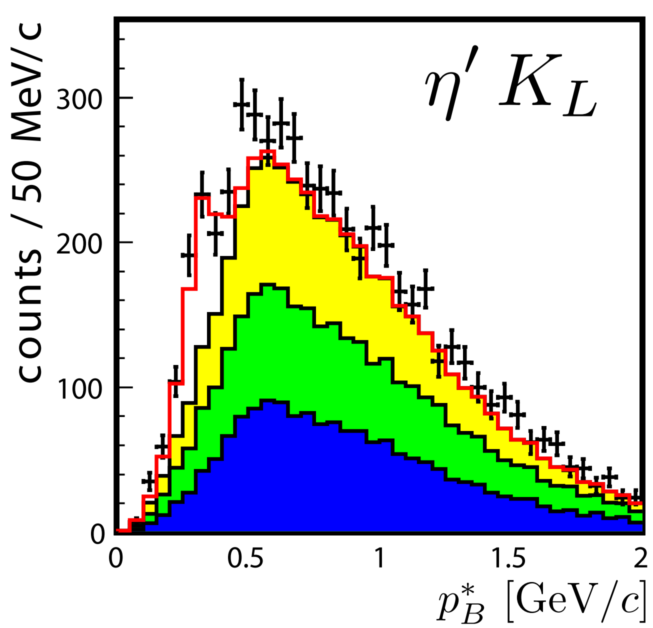
penguin-dominated (tree is color- and Cabibbo-suppressed)

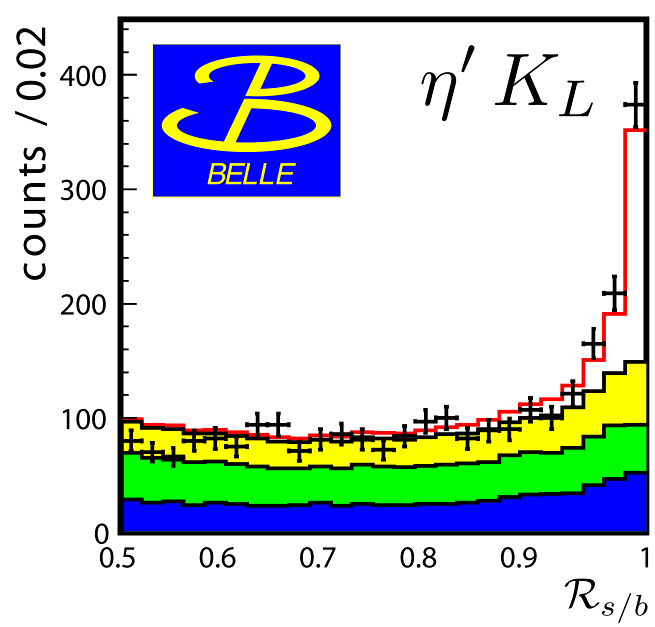






— total
b → u, d, s, c BG
$q\bar{q}$ BG



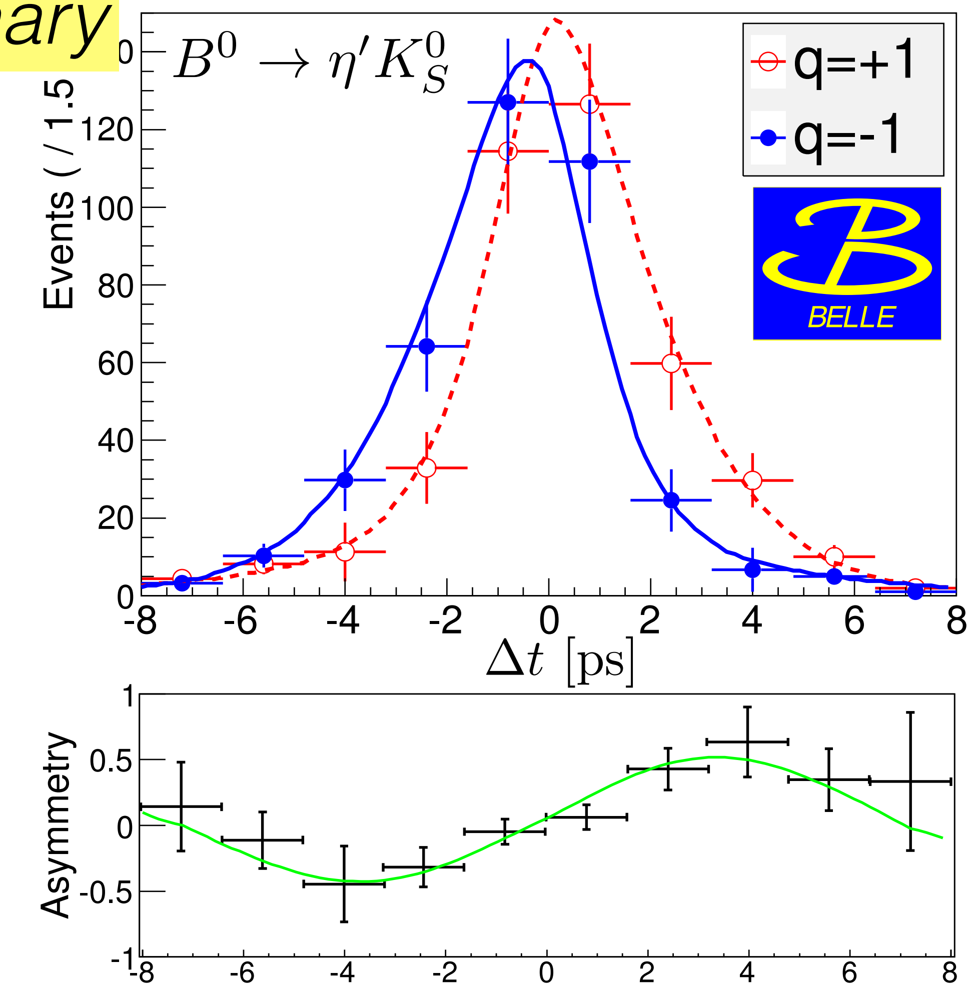


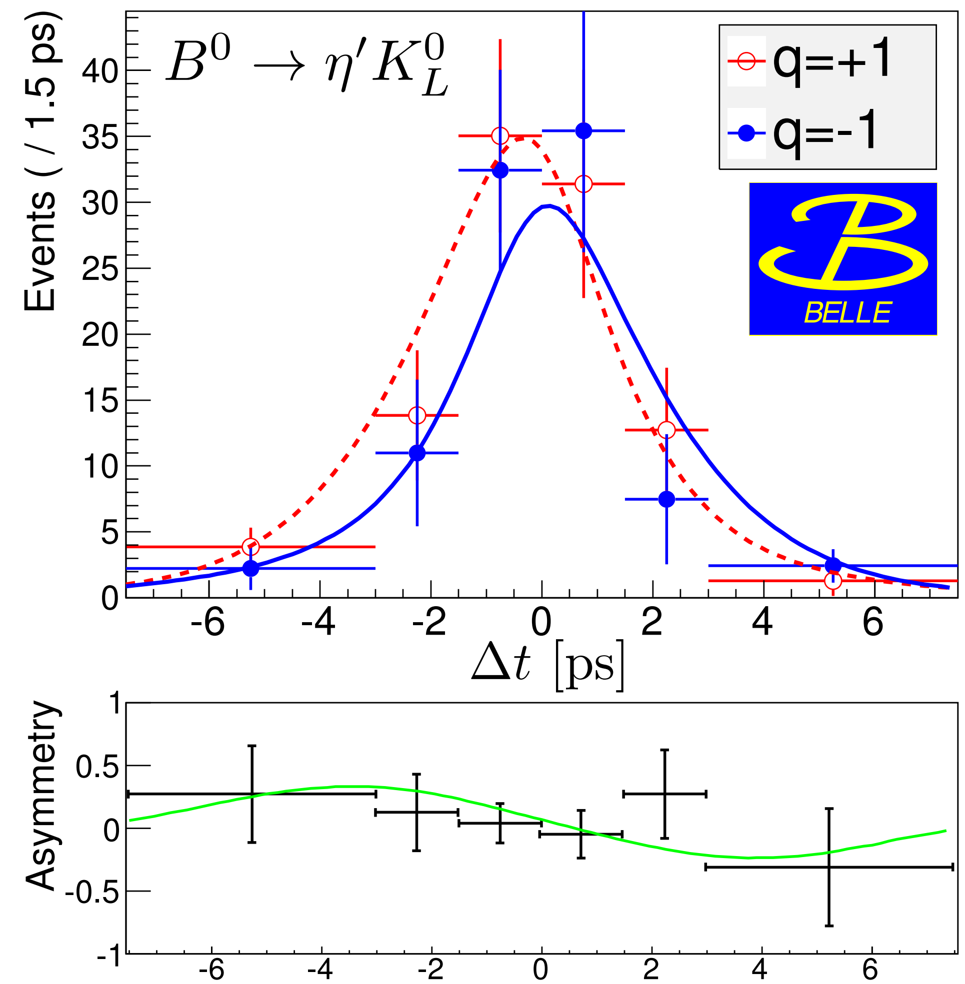
— total
comb. BG with fake η′
comb. BG with fake K_L^0
comb. BG with real η′ and K_L^0

$B_d^0 \to \eta' K^0$

preliminary

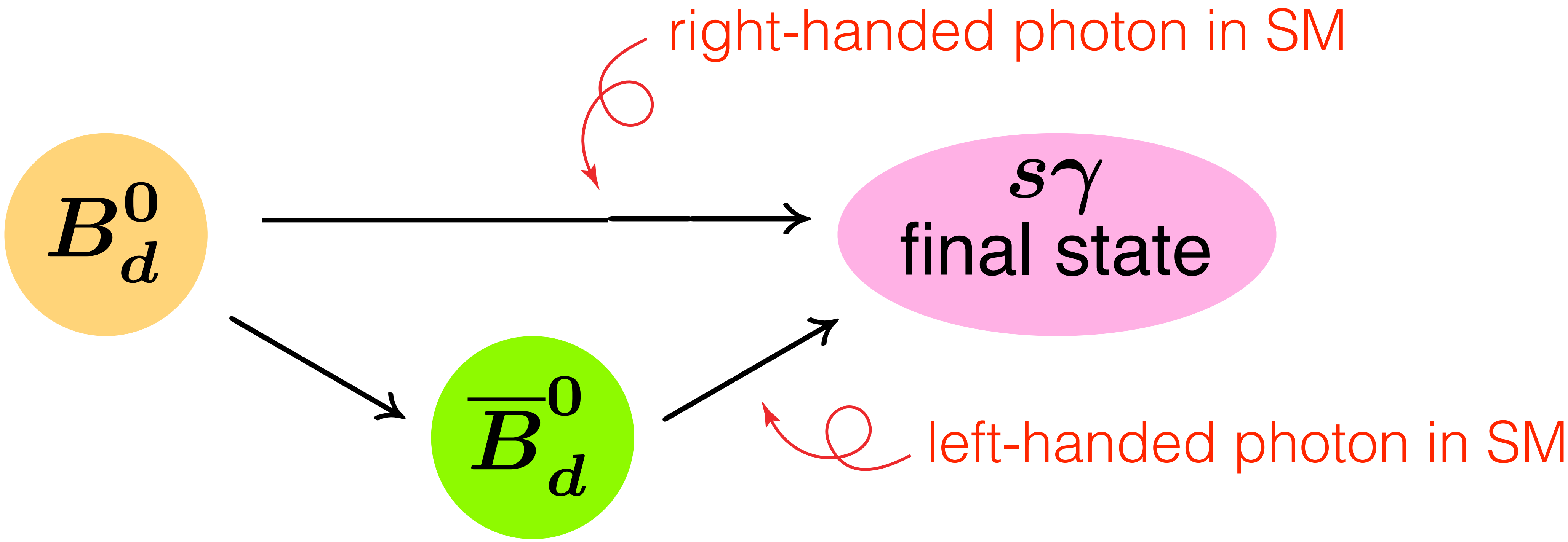
No sign of New Physics





Decay mode	$-\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$\eta' K_S^0$	$+0.71 \pm 0.07$	$+0.02 \pm 0.05$
$\eta' K_L^0$	$+0.46 \pm 0.21$	$+0.09 \pm 0.14$
$\eta' K^0$	$+0.68 \pm 0.07 \pm 0.03$	$+0.03 \pm 0.05 \pm 0.04$

$B_d^0 \to K_S\,\eta\,\gamma$



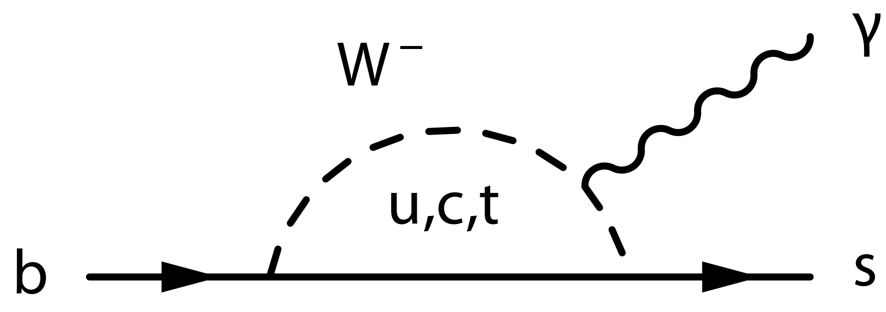
For 100% photon polarization, there is no common $s\vec{\gamma}$ final state $\Rightarrow$ no time-dependent $\not{C}\!\not{P}$. In reality, for $B^0 \to K_S\,\eta\,\gamma$, SM expectation is $\mathcal{S}_{\text{CP}} \approx 2(m_s/m_b)\sin(2\phi_1)$.

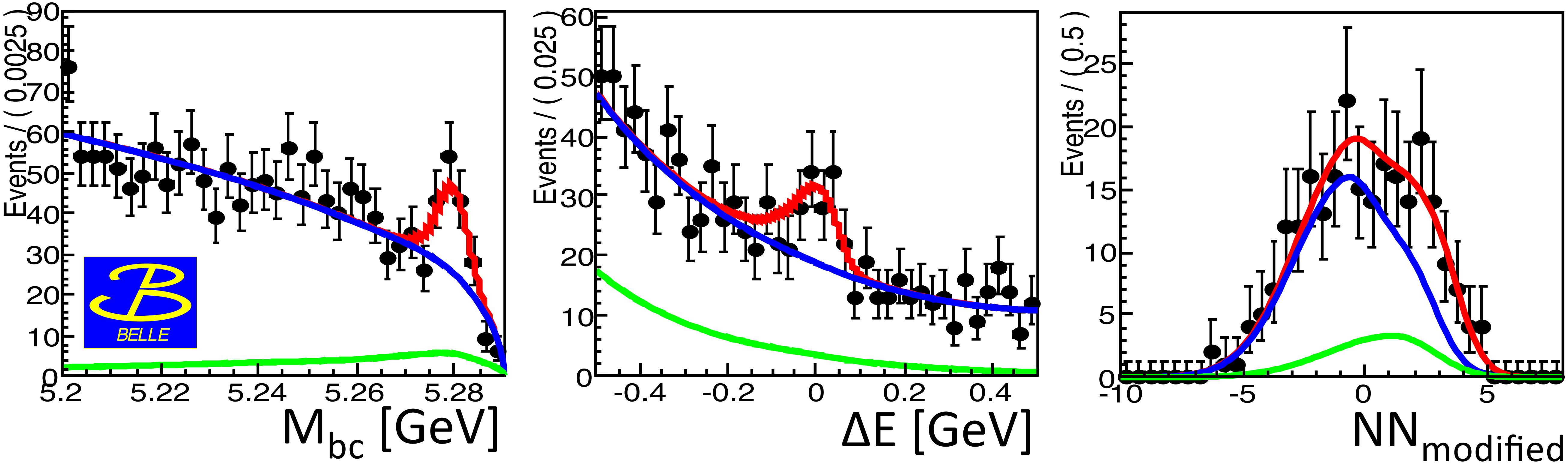
New Physics with alternate helicity structure can give time-dependent $\not{C}\!\not{P}$ without affecting $\Gamma(b \to s\gamma)$.

Atwood, Soni, Gronau: PRL 79, 185 (1997)
Atwood, Gershon, Hazumi, Soni: PRD 71, 076003 (2005)

$$B_d^0 \to K_S\,\eta\,\gamma$$

preliminary



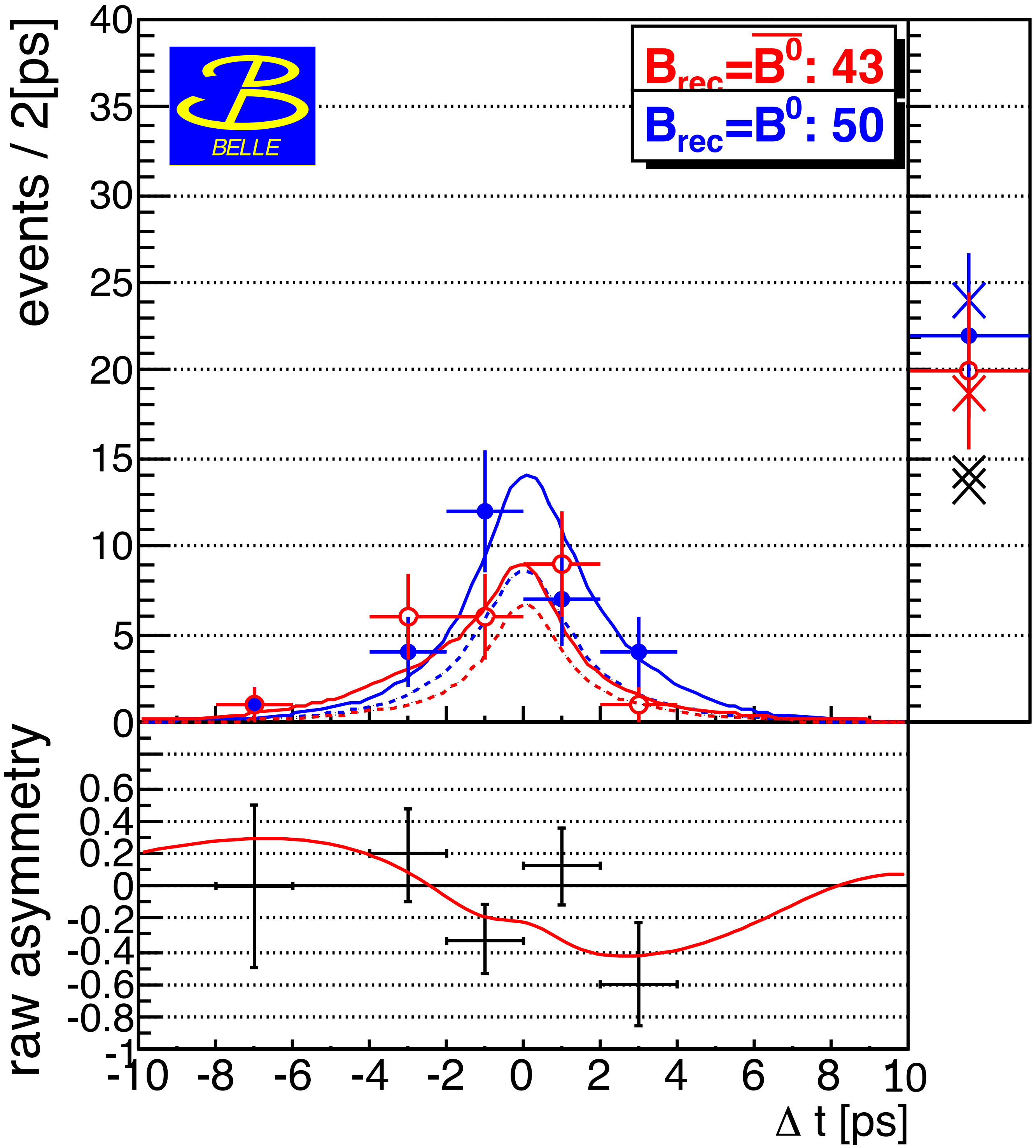


penguin mode

3-dimensional extended maximum-likelihood fit

$B_d^0 \to K_S\,\eta\,\gamma$

preliminary



$$\mathcal{A}_{\mathrm{CP}} = -0.48 \pm 0.41 \pm 0.07$$

$$\mathcal{S}_{\mathrm{CP}} = -1.32 \pm 0.77 \pm 0.36$$

… both consistent with 0

Time dependent $\cancel{CP}$ in $B_s^0 \to K^+K^-$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

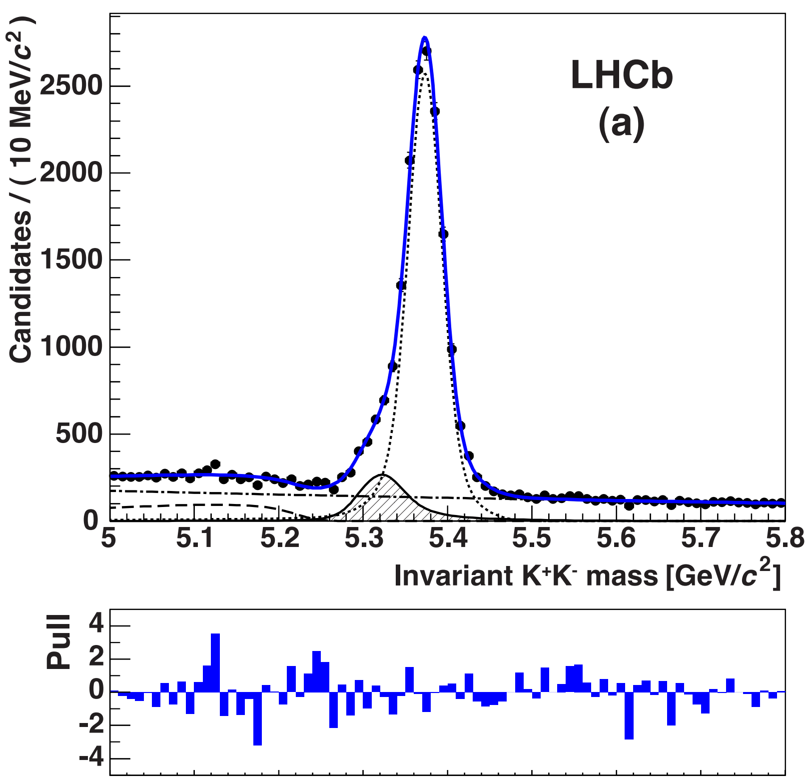
[J. High Energy Phys. 10 (2013) 183]

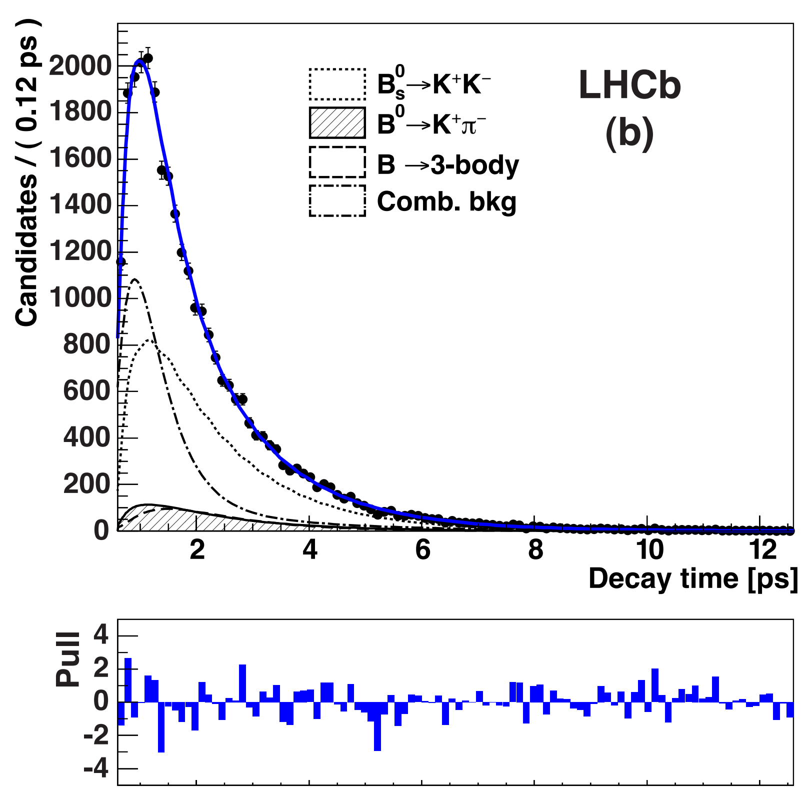
Time-dependent CP asymmetry:

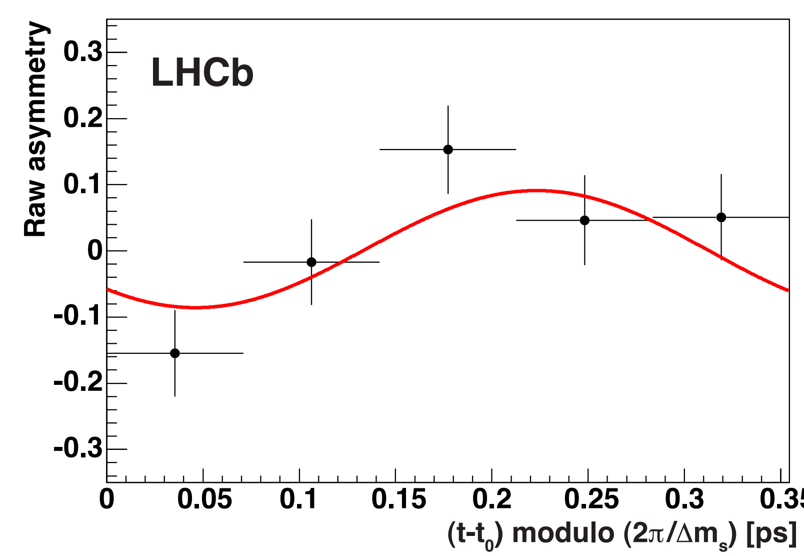
$$A^{CP}(t) = \frac{\Gamma_{\overline{B}_s^0 \to KK}(t) - \Gamma_{B_s^0 \to KK}(t)}{\Gamma_{\overline{B}_s^0 \to KK}(t) + \Gamma_{B_s^0 \to KK}(t)} = \frac{-C_{KK}\cos(\Delta m_s t) + S_{KK}\sin(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \mathcal{A}_{KK}^{\Delta\Gamma_s}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right)}$$

where C_{KK} = direct $\cancel{CP}$, S_{KK} = mixing-induced $\cancel{CP}$ and $\mathcal{A}_{KK}^{\Delta\Gamma_s}$ = $\cancel{CP}$ in interference.

Time-dependent analysis, flavour-tagging to identify initial B_s^0 flavour: calibrated using flavour-specific $B^0 \to K^+\pi^-$ events.







C_{KK}	$= 0.14 \pm 0.11 \pm 0.03$
S_{KK}	$= 0.30 \pm 0.12 \pm 0.04$

Time dependent $\cancel{CP}$ in $B^0 \to \pi^+\pi^-$ - $\mathcal{L} = 1\ \mathrm{fb}^{-1}$

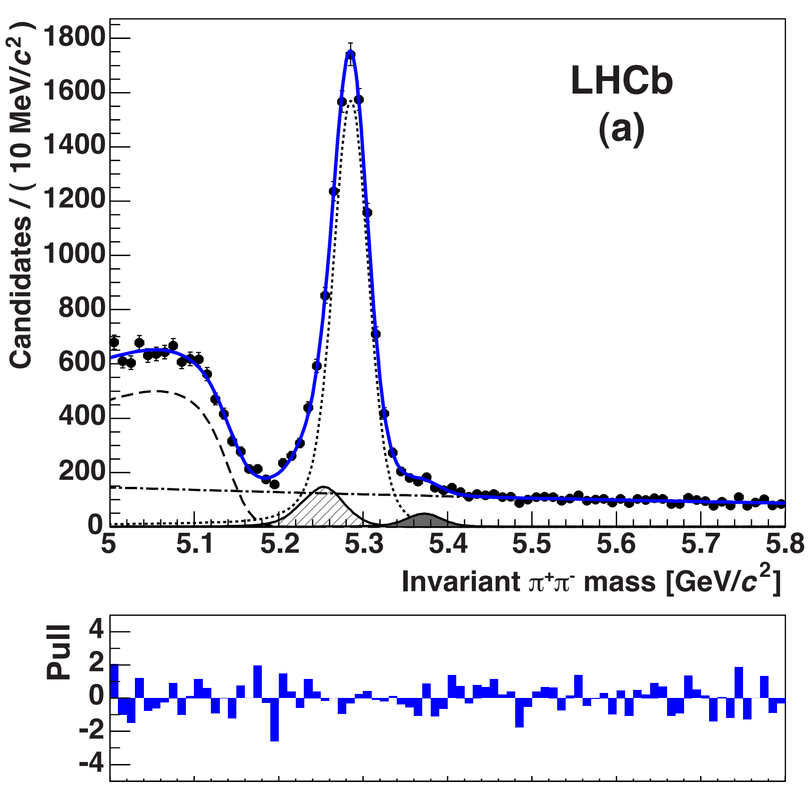
[J. High Energy Phys. 10 (2013) 183]

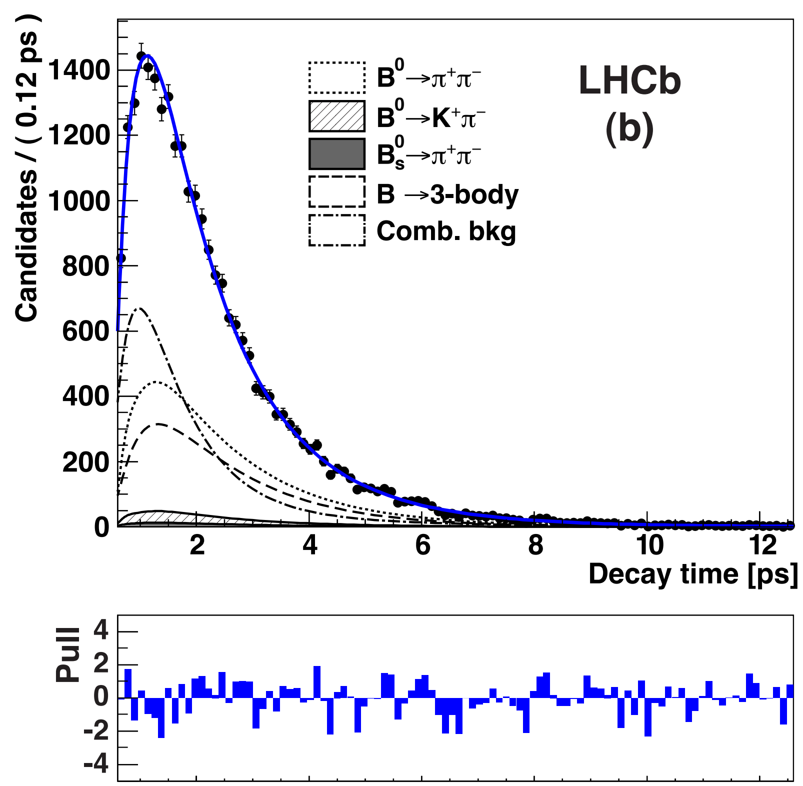
Time-dependent CP asymmetry:

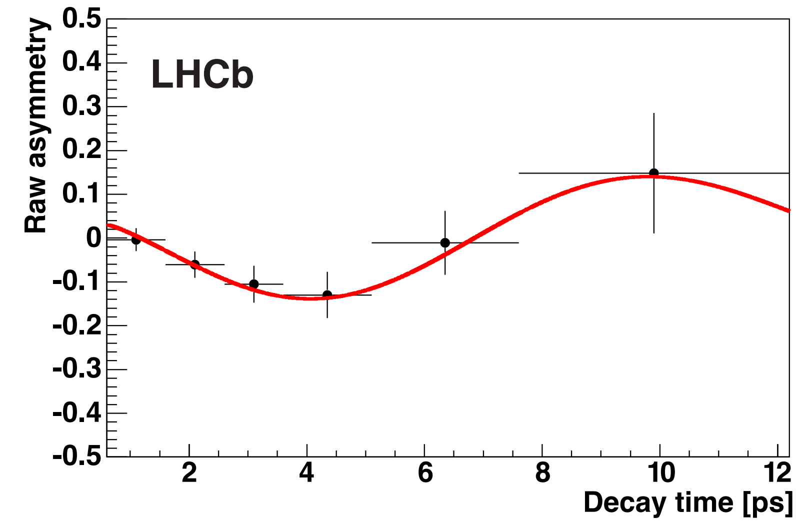
$$A^{CP}(t) = \frac{\Gamma_{\overline{B}^0\to\pi\pi}(t) - \Gamma_{B^0\to\pi\pi}(t)}{\Gamma_{\overline{B}^0\to\pi\pi}(t) + \Gamma_{B^0\to\pi\pi}(t)} = \frac{-C_{\pi\pi}\cos(\Delta m_d t) + S_{\pi\pi}\sin(\Delta m_d t)}{\cosh\left(\frac{\Delta\Gamma_d}{2}t\right) - \mathcal{A}^{\Delta\Gamma_d}_{\pi\pi}\sinh\left(\frac{\Delta\Gamma_d}{2}t\right)}$$

where $C_{\pi\pi}$ = direct $\cancel{CP}$, $S_{\pi\pi}$ = mixing-induced $\cancel{CP}$ and $\mathcal{A}^{\Delta\Gamma_s}_{KK}$ = $\cancel{CP}$ in interference.

Time-dependent analysis, flavour-tagging to identify initial B^0 flavour: calibrated using flavour-specific $B^0 \to K^+\pi^-$ events.





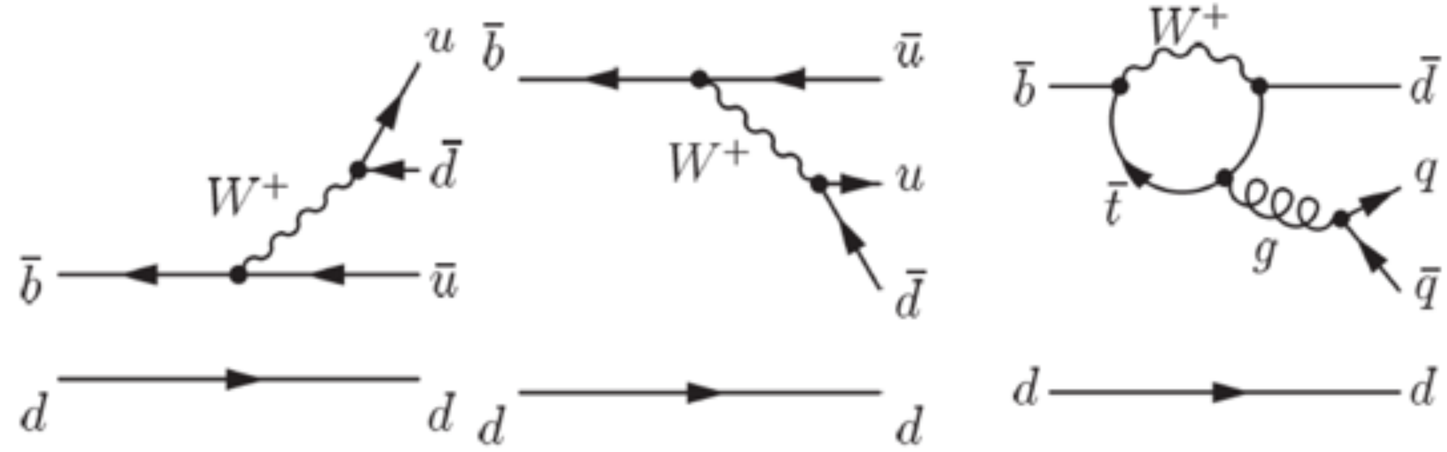


$C_{\pi\pi}$	= -0.38 $\pm$ 0.15 $\pm$ 0.02
$S_{\pi\pi}$	= -0.71 $\pm$ 0.13 $\pm$ 0.02

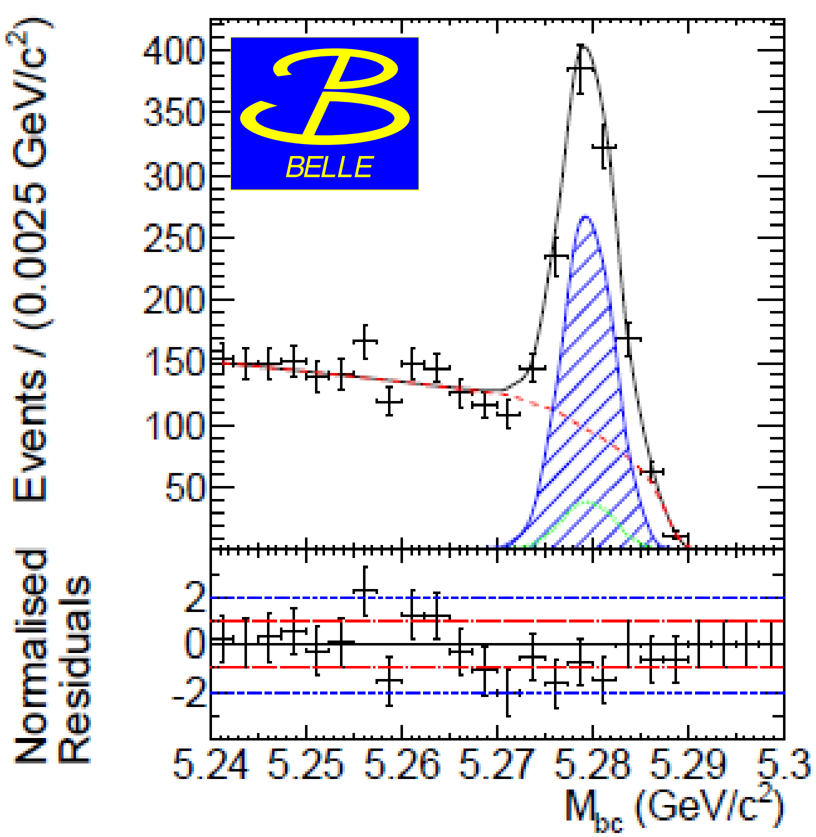
5.6 σ from (0, 0)

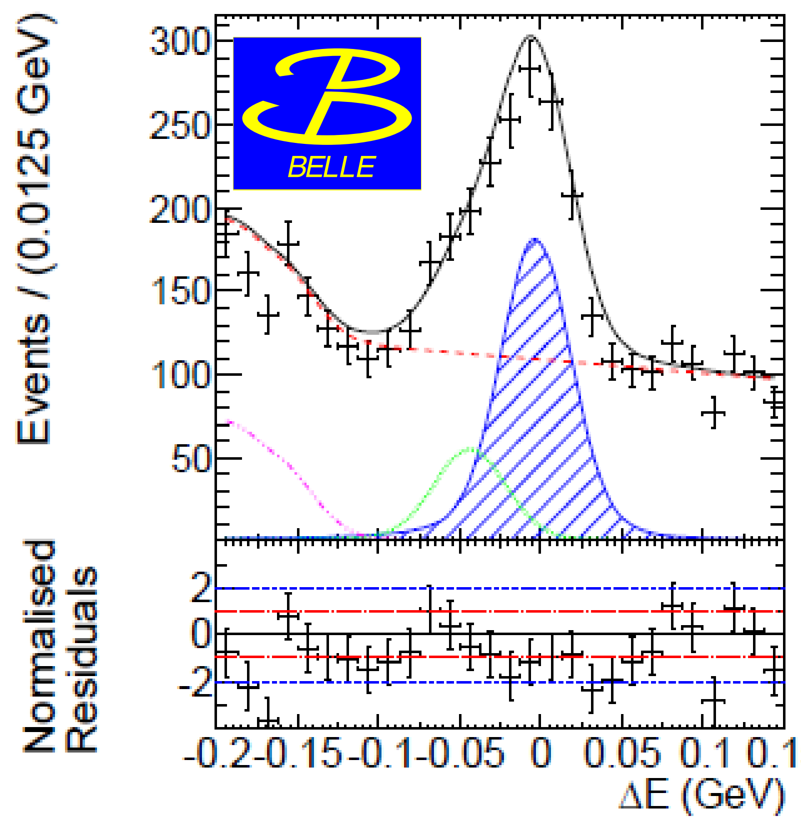
$B_d^0 \to \pi^+\pi^-$

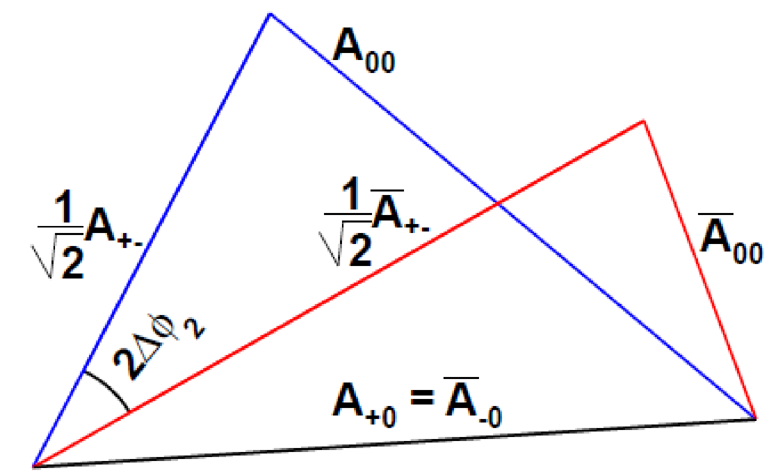
tree-dominated mode
with penguin pollution



7-dimensional unbinned extended maximum- likelihood fit







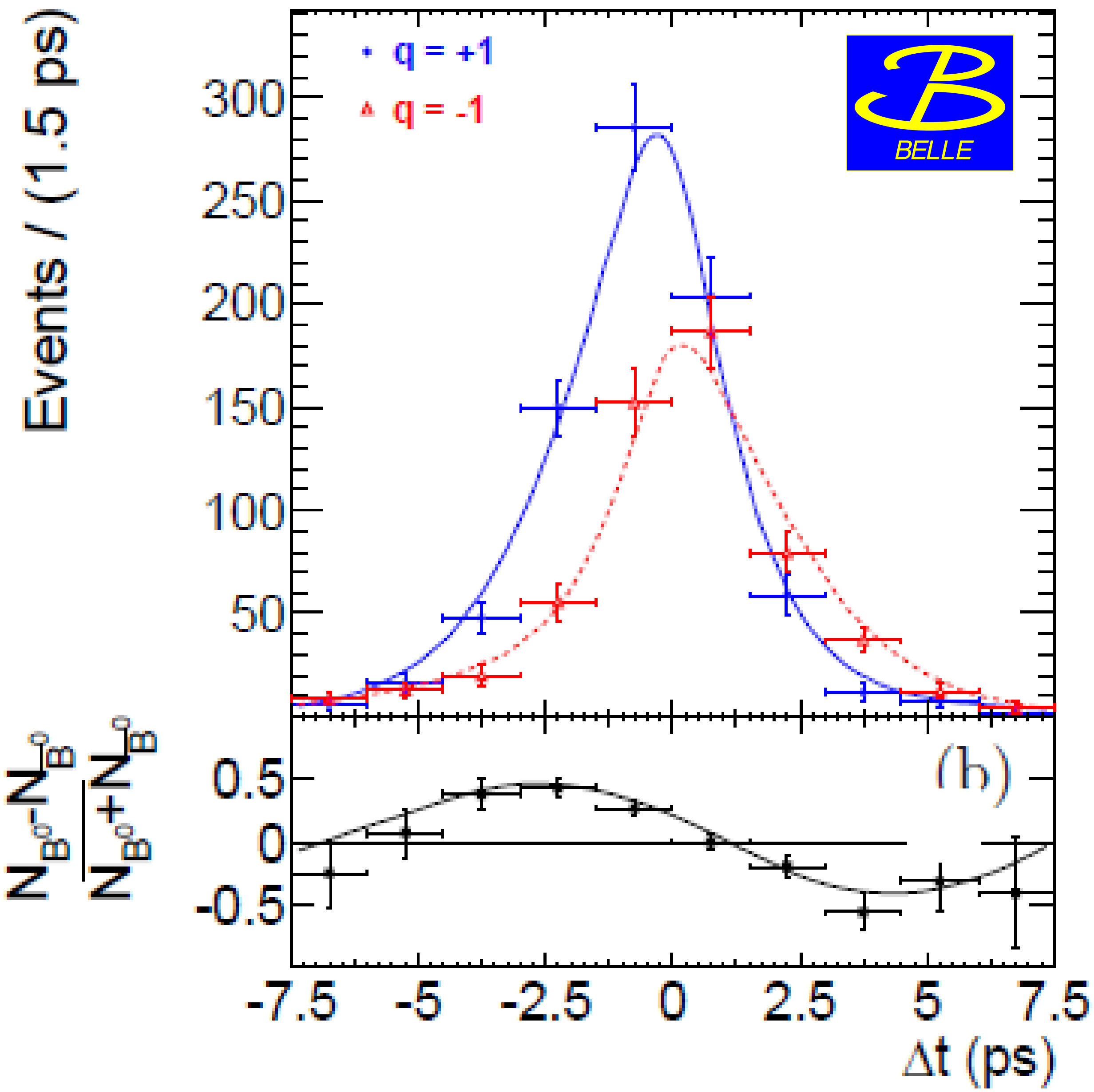
$$A_{+0} = \frac{1}{\sqrt{2}} A_{+-} + A_{00}, \quad \bar{A}_{-0} = \frac{1}{\sqrt{2}} \bar{A}_{+-} + \bar{A}_{00}$$

$$\left.\begin{array}{l} \mathcal{B}(B^0 \to \pi^+\pi^-) \\ \mathcal{B}(B^0 \to \pi^0\pi^0) \\ \mathcal{B}(B^+ \to \pi^+\pi^0) \\ \mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) \\ \mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) \\ \mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) \end{array}\right\}$$

8-fold ambiguity

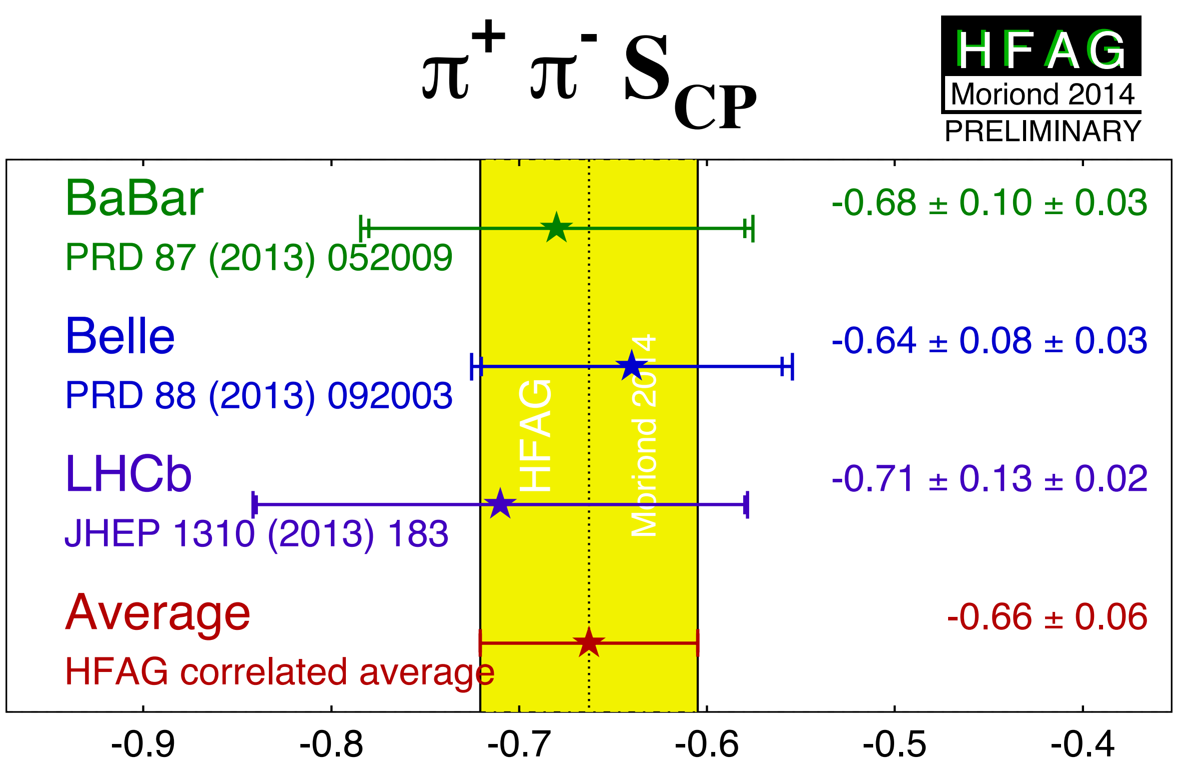
$$B_d^0 \to \pi^+\pi^-$$

PRD **88, 092003** (2013)

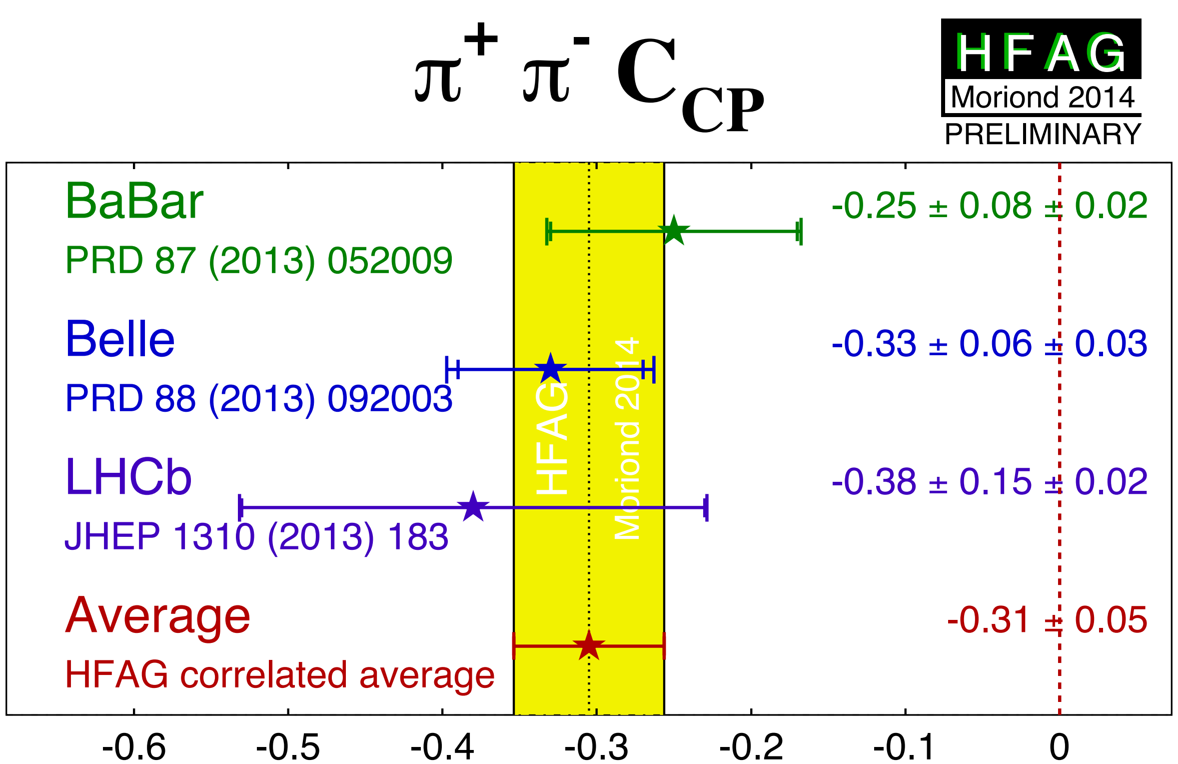


$$\mathcal{S}_{\mathrm{CP}} = -0.64 \pm 0.08 \pm 0.03$$

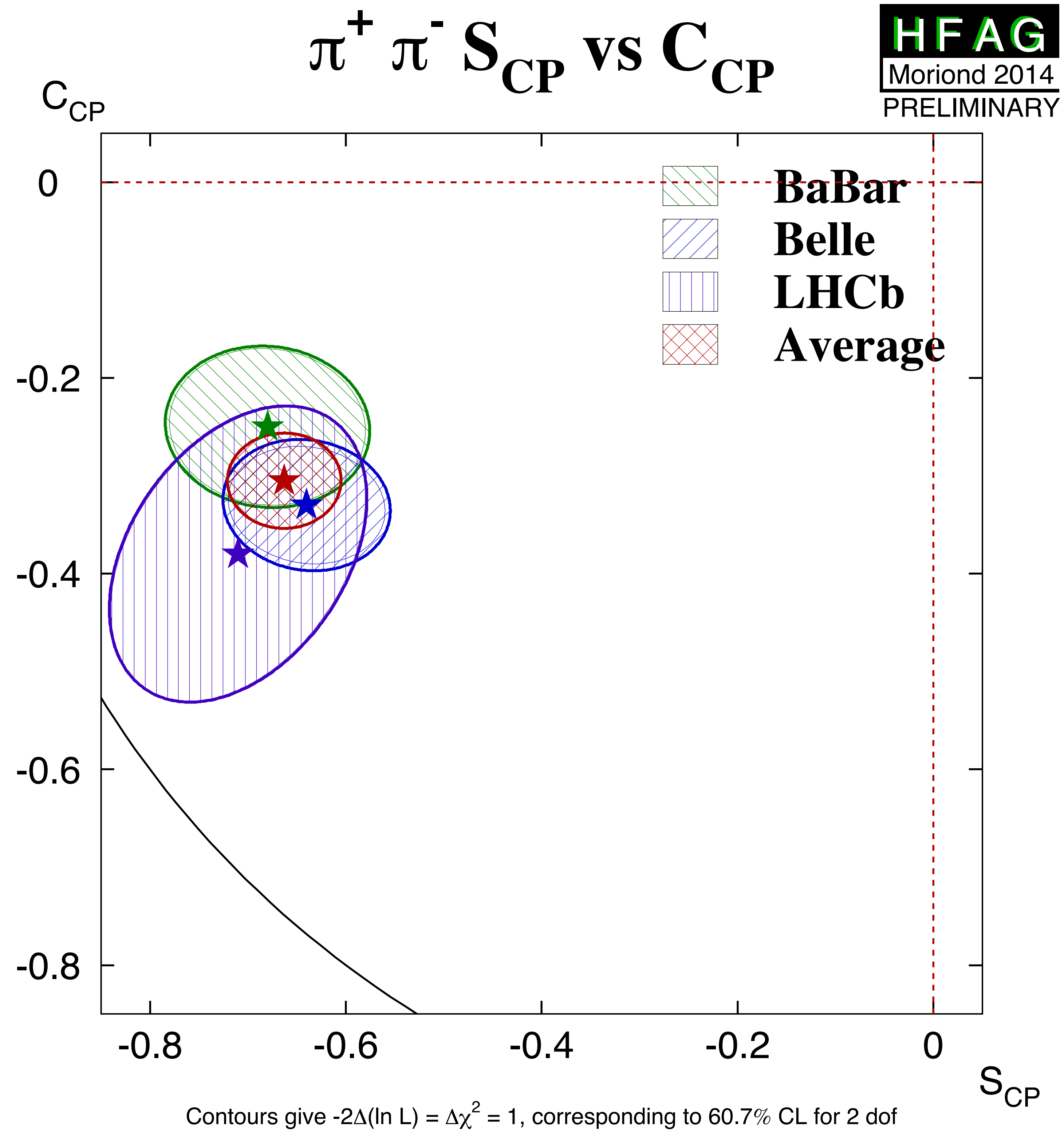
$$\mathcal{A}_{\mathrm{CP}} = +0.33 \pm 0.06 \pm 0.03$$



$\pi^+ \pi^- S_{CP}$
HFAG
Moriond 2014
PRELIMINARY
BaBar
PRD 87 (2013) 052009
-0.68 ± 0.10 ± 0.03
Belle
PRD 88 (2013) 092003
-0.64 ± 0.08 ± 0.03
LHCb
JHEP 1310 (2013) 183
-0.71 ± 0.13 ± 0.02
Average
HFAG correlated average
-0.66 ± 0.06
HFAG
Moriond 2014
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4

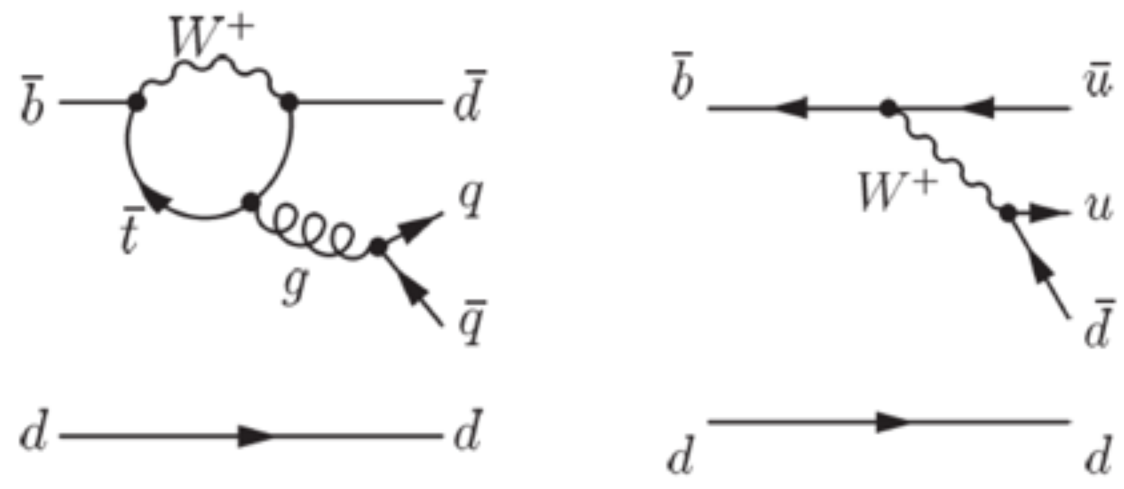


$\pi^+ \pi^- C_{CP}$
HFAG
Moriond 2014
PRELIMINARY
BaBar
PRD 87 (2013) 052009
-0.25 ± 0.08 ± 0.02
Belle
PRD 88 (2013) 092003
-0.33 ± 0.06 ± 0.03
LHCb
JHEP 1310 (2013) 183
-0.38 ± 0.15 ± 0.02
Average
HFAG correlated average
-0.31 ± 0.05
HFAG
Moriond 2014
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0



$\pi^+ \pi^- S_{CP}$ vs C_{CP}
HFAG
Moriond 2014
PRELIMINARY
C_{CP}
0
-0.2
-0.4
-0.6
-0.8
BaBar
Belle
LHCb
Average
-0.8
-0.6
-0.4
-0.2
0
S_{CP}
Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

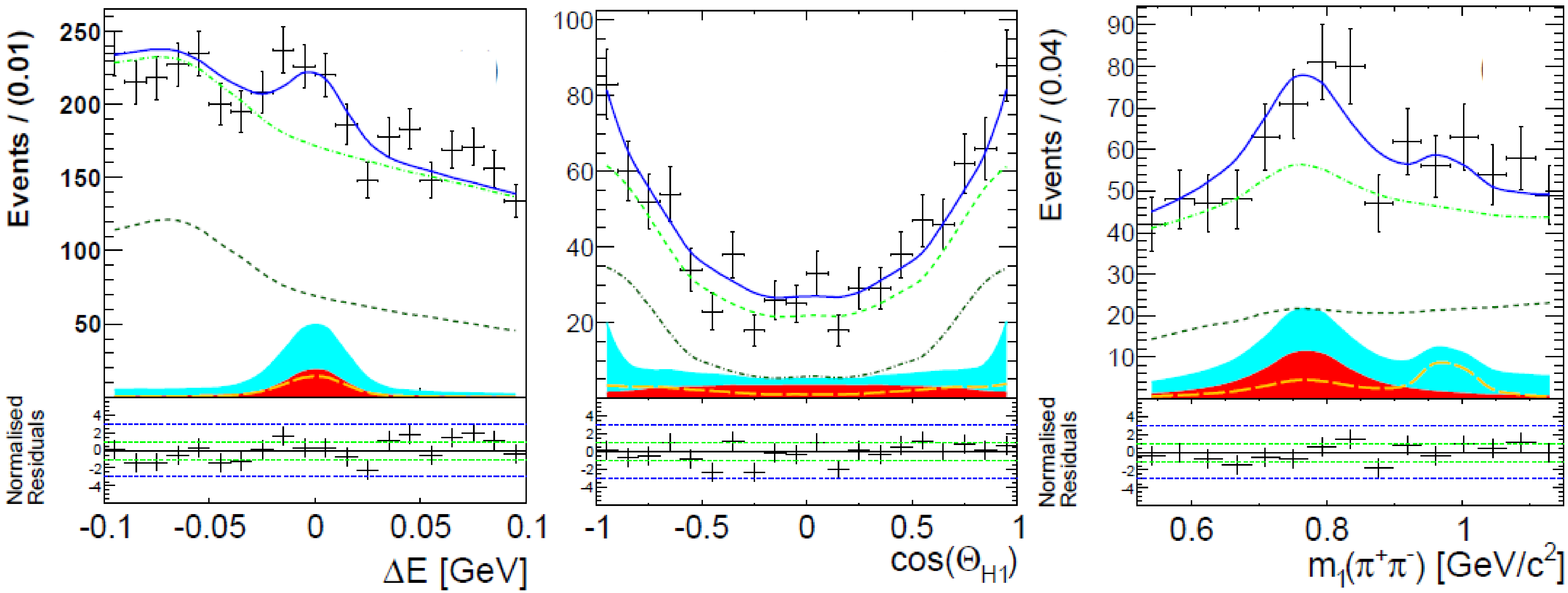
$B_d^0 \to \rho^0 \rho^0$



penguin-dominated mode with color-suppressed tree

not a pure CP eigenstate; needs angular analysis to extract the longitudinal component and isospin analysis to extract ϕ_2

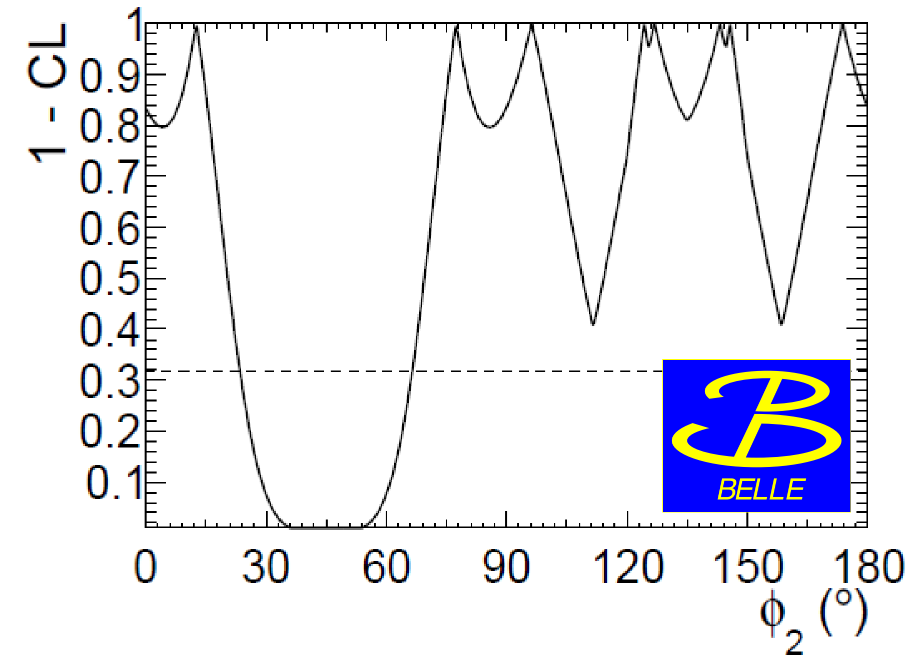
6-dimensional unbinned extended maximum- likelihood fit



$B_d^0 \to \rho^0\rho^0$ and $B_d^0 \to \pi^+\pi^-$: extract ϕ_2

$\boxed{B \to \pi\pi}$

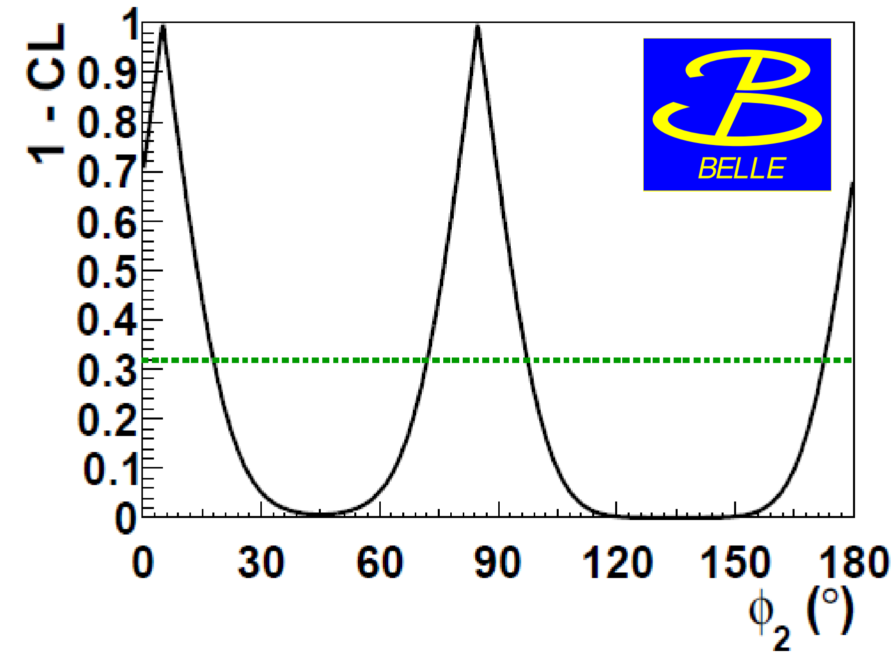
$23.8^\circ < \phi_2 < 66.8^\circ$
is excluded @ 1σ C.L.



$B^0 \to \pi^+\pi^-$ 772M $B\bar{B}$ pairs used
$B^+ \to \pi^+\pi^0$ 772M $B\bar{B}$
$B^0 \to \pi^0\pi^0$ 275M $B\bar{B}$

$\boxed{B \to \rho\rho}$

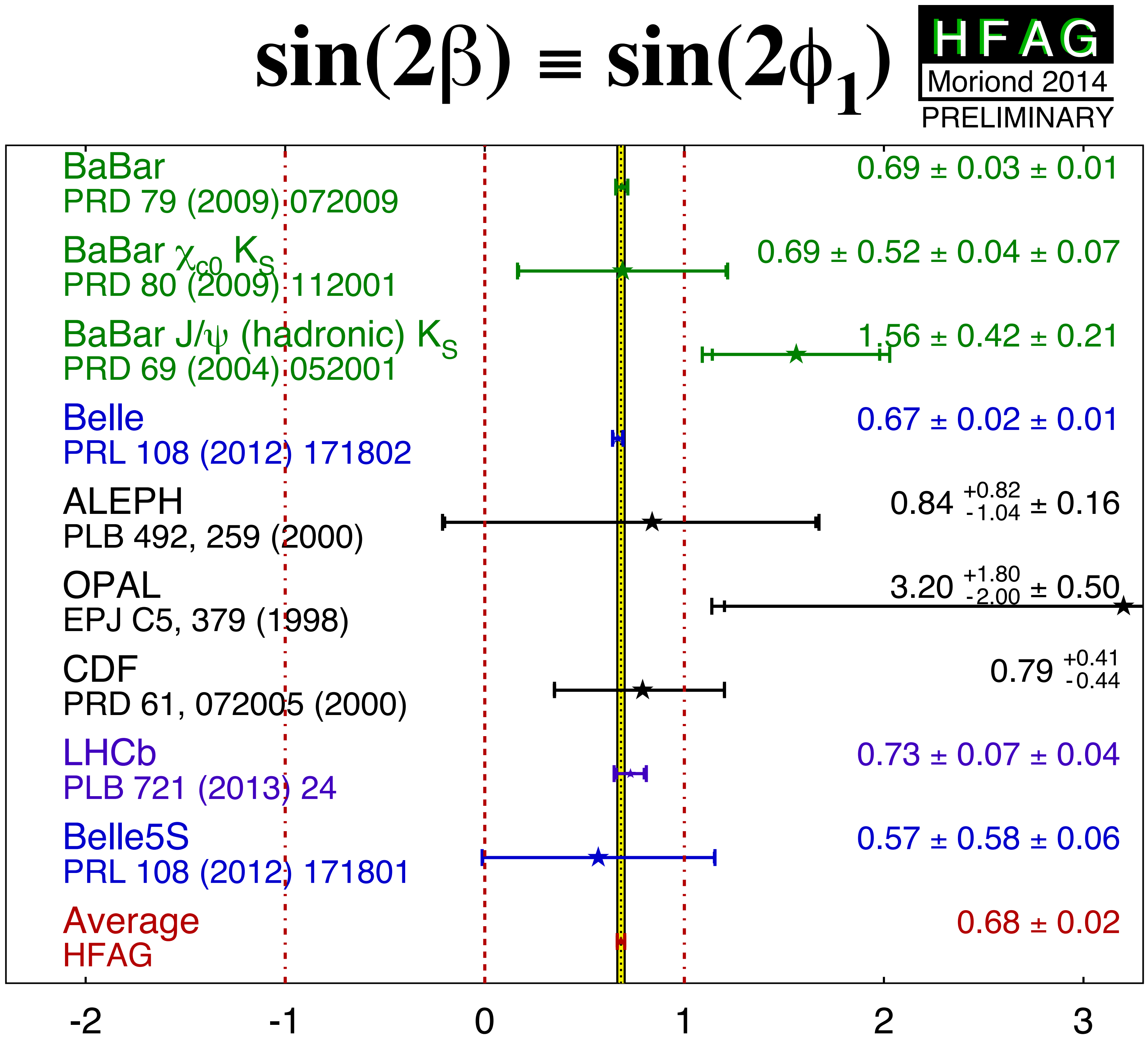
$\phi_2 = (84.9 \pm 12.9)^\circ \quad \Delta\phi_2 = (0.0 \pm 9.6)^\circ$



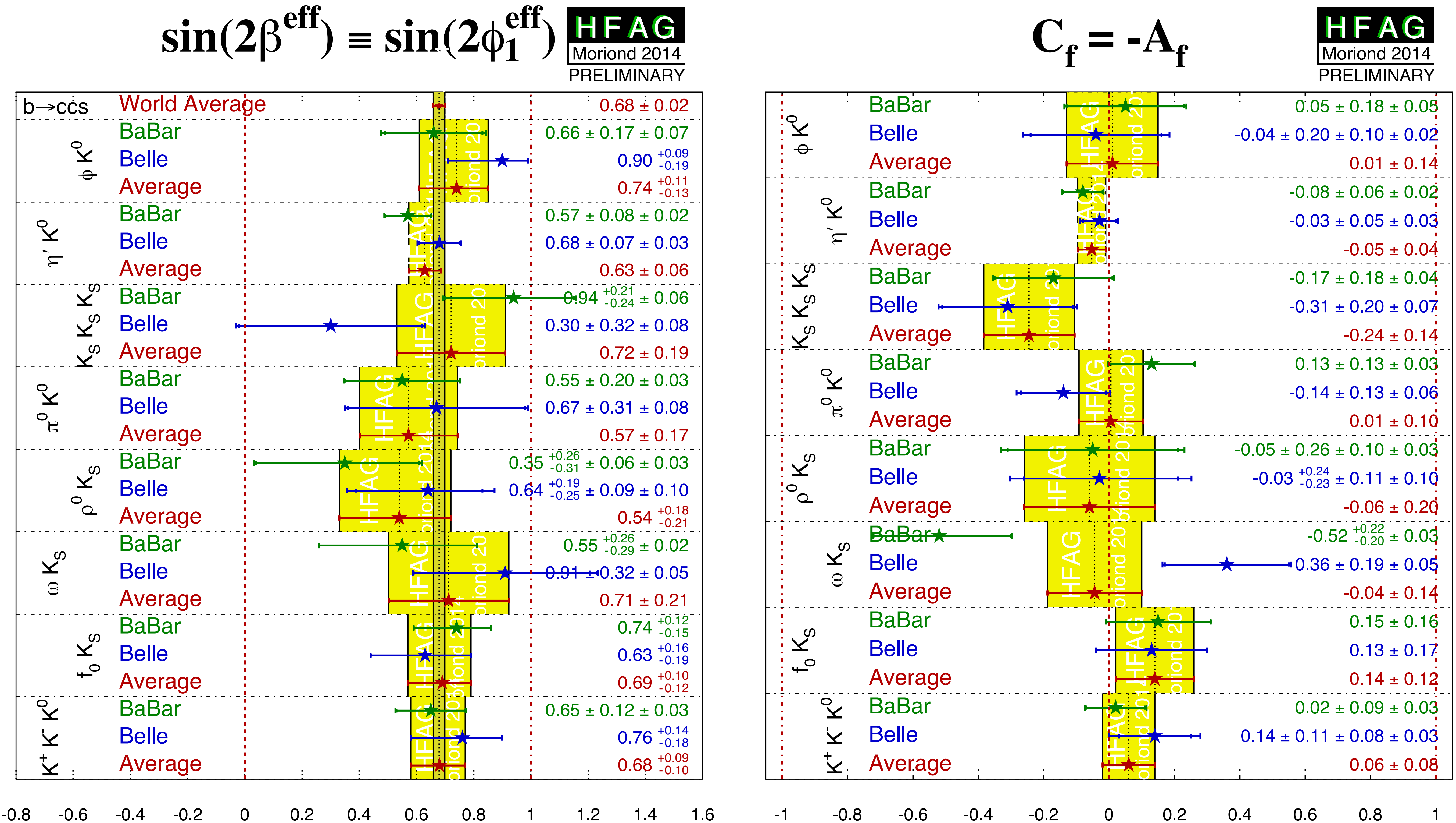
$B^0 \to \rho^0\rho^0$ 772M $B\bar{B}$ pairs used
$B^\pm \to \rho^\pm\rho^0$ 85M $B\bar{B}$
$B^0 \to \rho^+\rho^-$ 535M $B\bar{B}$

PRD **88, 092003** (2013)

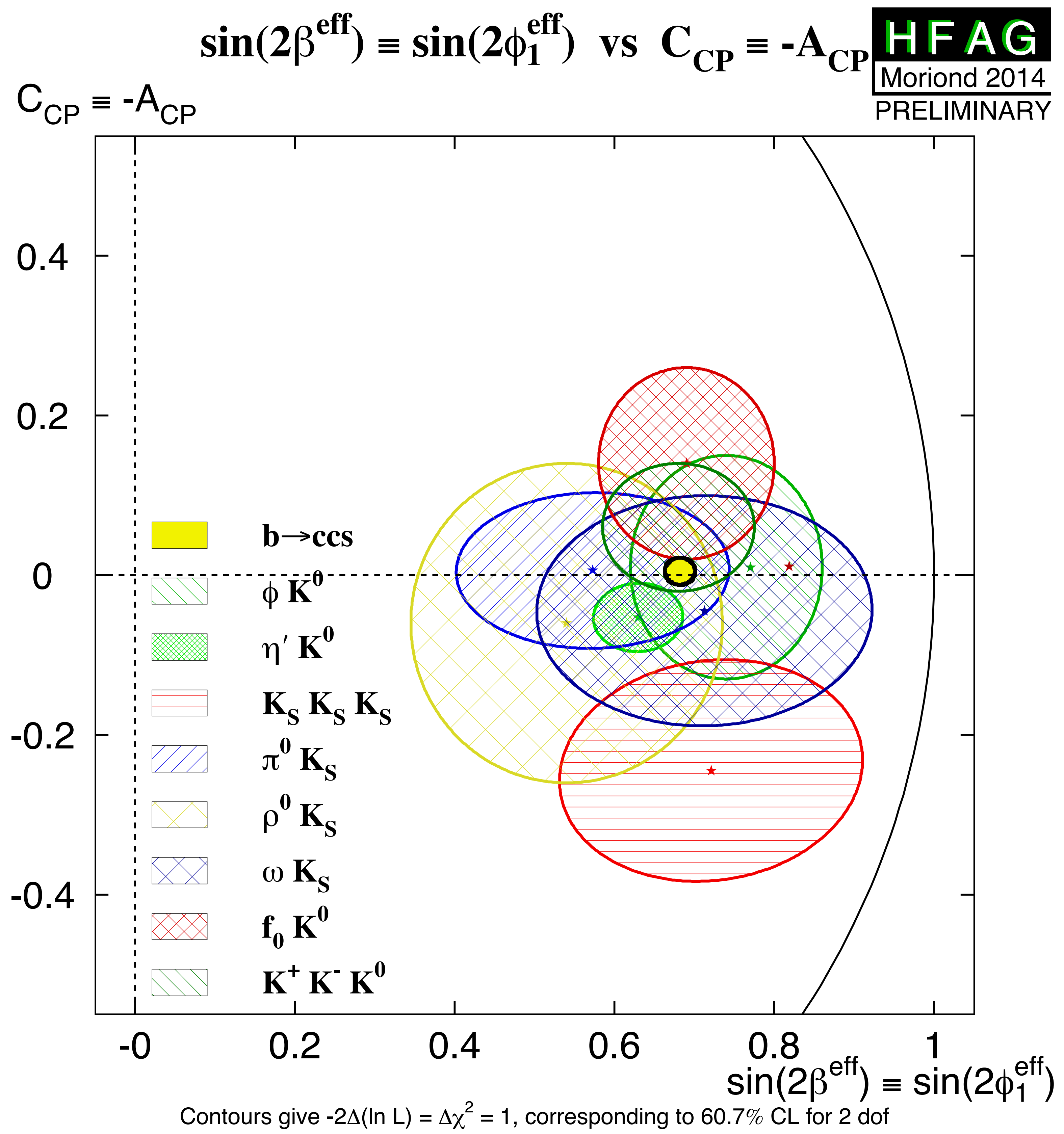
TCPV summary for $b \to c\bar{c}s$



TCPV summary for $b \to sq\bar{q}$ penguins



TCPV summary for $b \to sq\bar{q}$ penguins

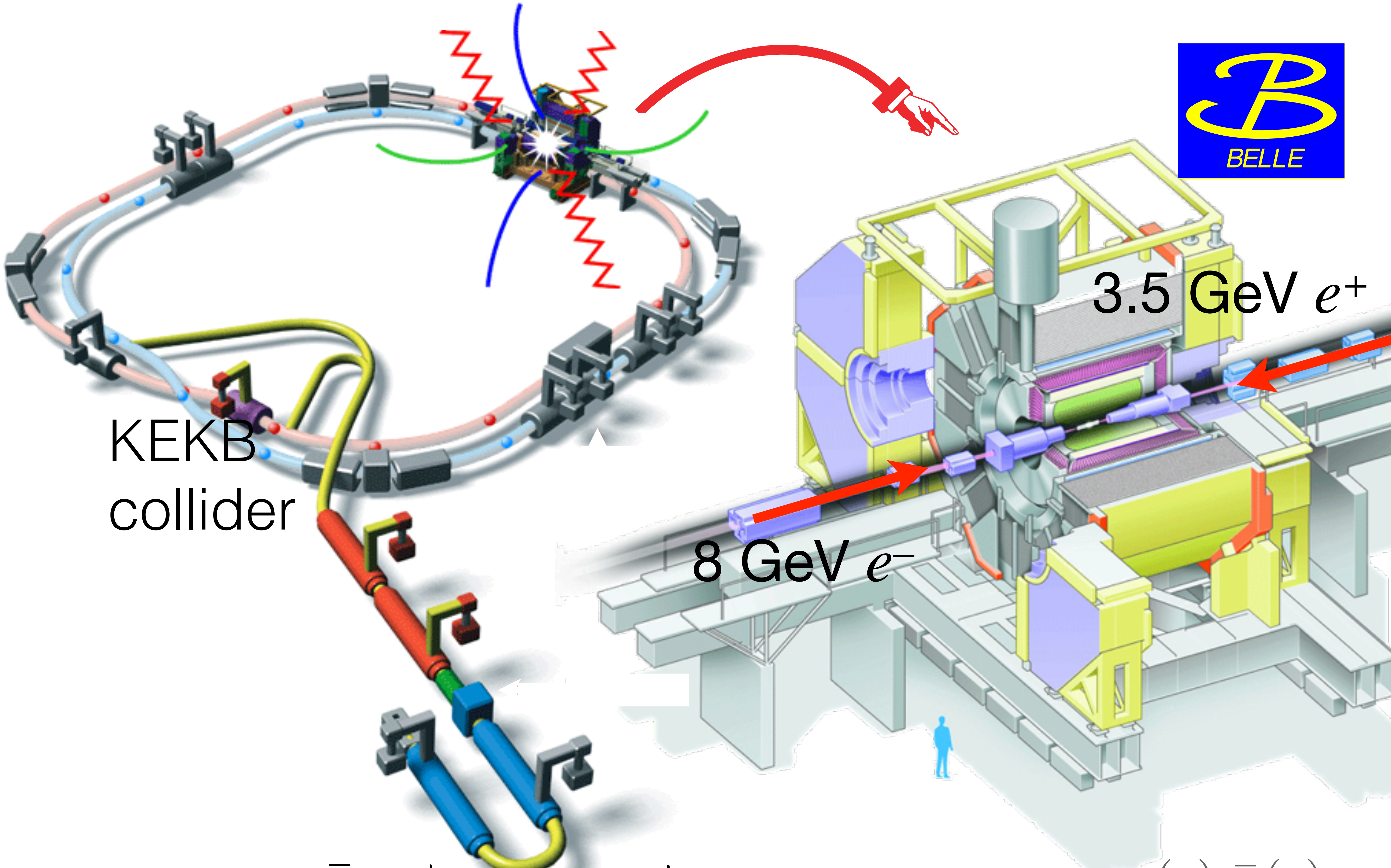


Summary

- Many new CP-asymmetry results emerging from Belle, LHCb, …
- I did not have time to talk about D decays here
- No significant deviations from Standard Model expectations – no New Physics yet
- Many results are still statistics-limited
- Many LHCb analyses have used only 1/3 of existing data set; more data will arrive in 2015
- Belle II will take up where Belle left off – physics running starts in 2016

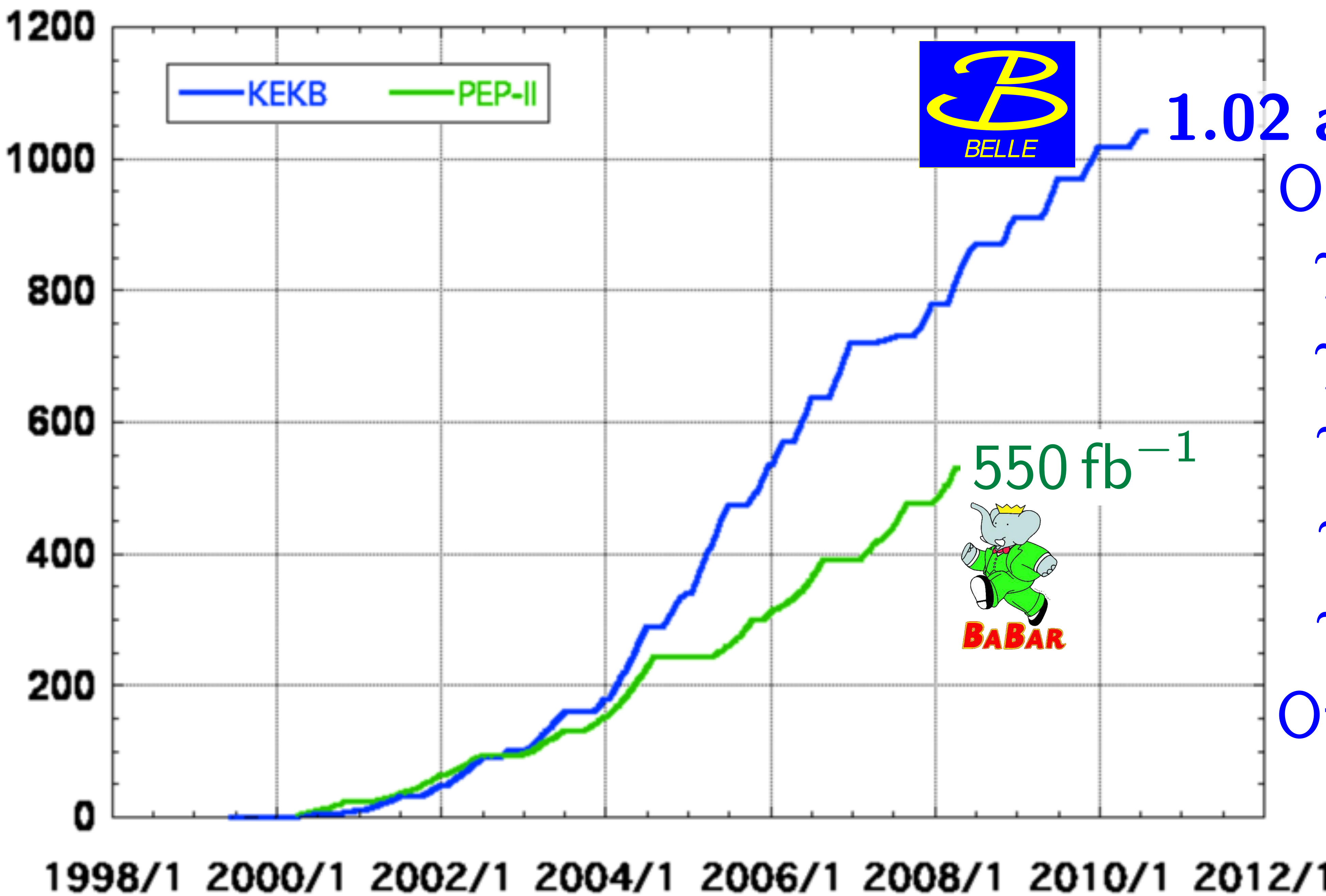
Backup

KEK B Factory and Belle: 1999–2010



$$c\bar{c},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow \boldsymbol{e^+e^-} \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Integrated luminosity at the B factories



1.02 ab^{-1}

On resonance:

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

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

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

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

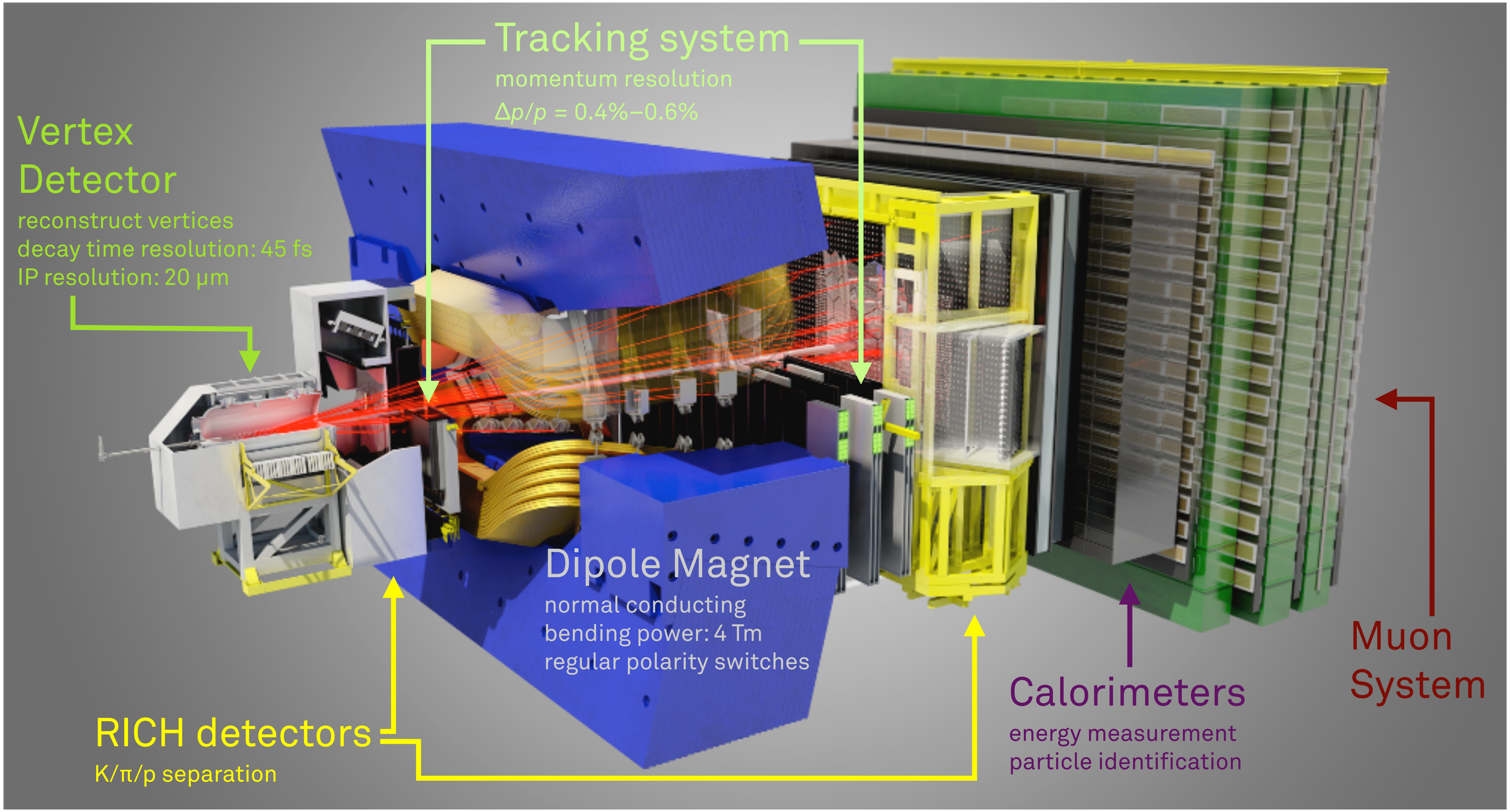
$\Upsilon(1S)$: 6 fb^{-1}

Off resonance/scan:

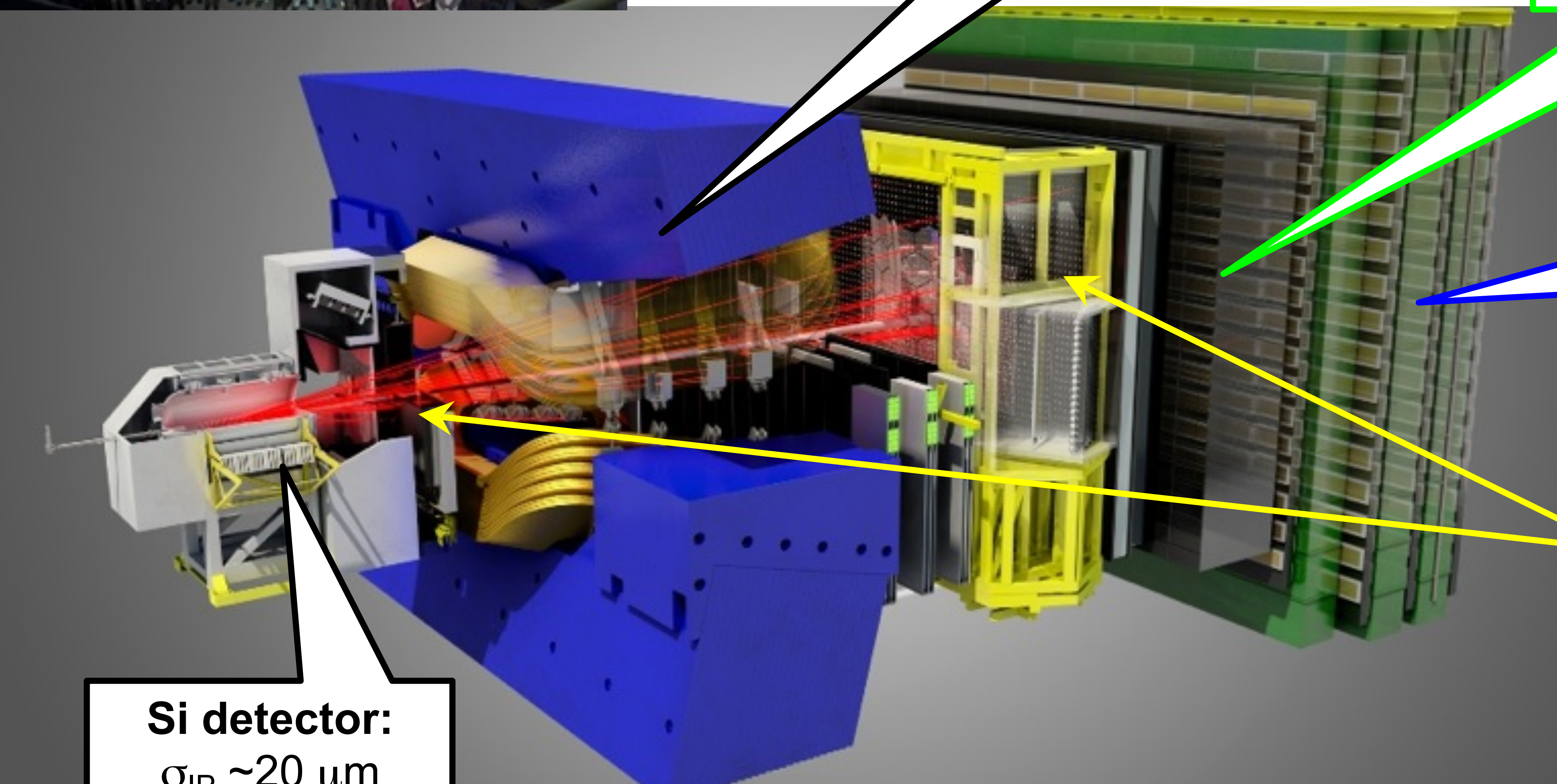
155 fb^{-1}

of $B\bar{B}$ @ $\Upsilon(4S)$: 772M (Belle) and 475M (BaBar)

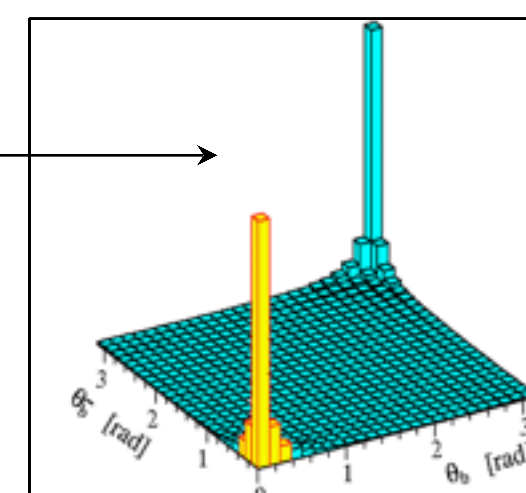
LHCb Detector



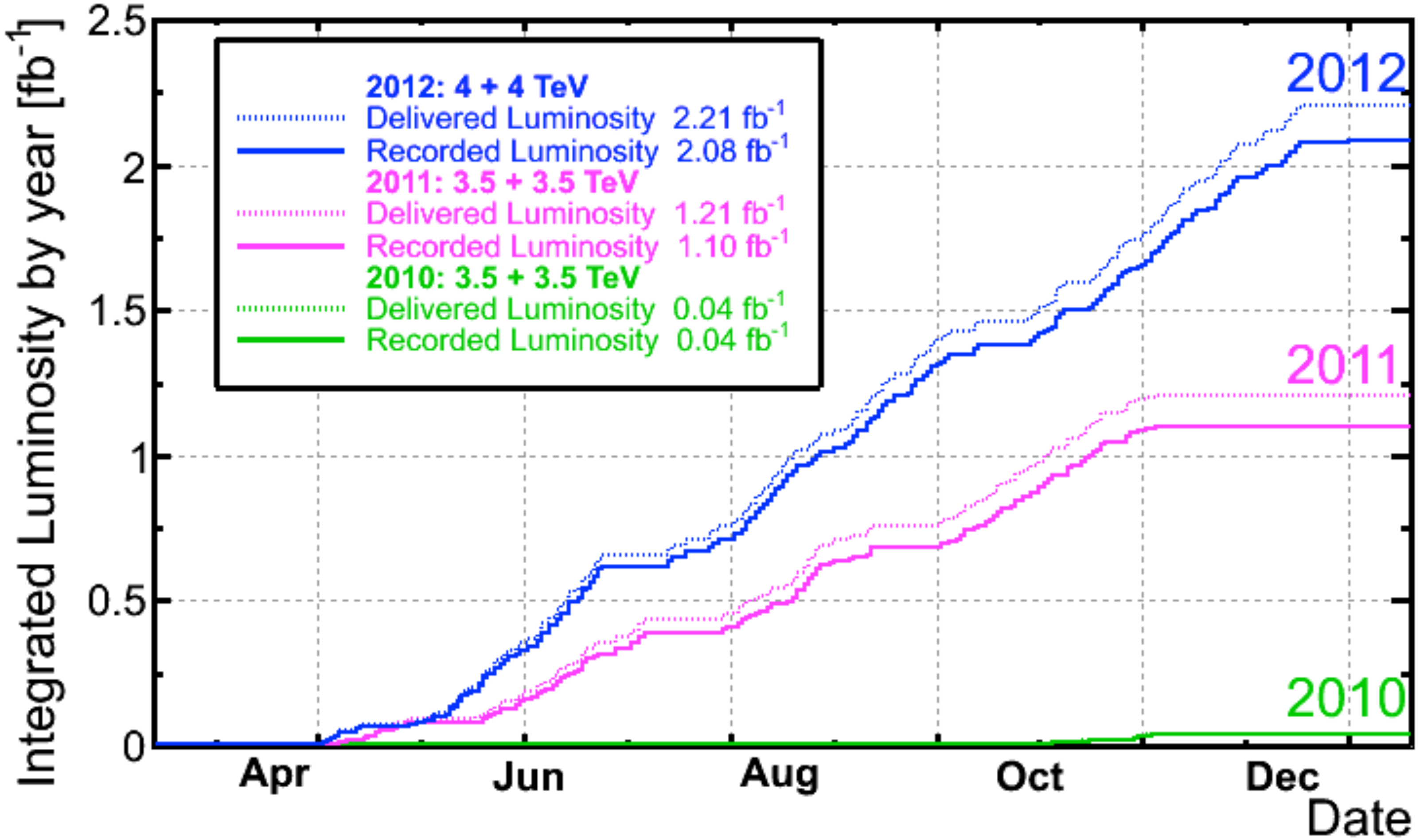
LHCb detector: Key aspects



- ❑ Large $b\bar{b}$ xs in forward region (~50,000 b / sec into LHCb).
- ❑ Precision vertexing, excellent PID – crucial for b,c physics
- ❑ High BW trigger (~4kHz to tape ~ 10X CMS, ATLAS)
- ❑ Fully hadronic b triggers (in addition to μ, $\mu\mu$, etc)
- ❑ **LHCb is a GPD: If it's in our acceptance, we can trigger on it!**

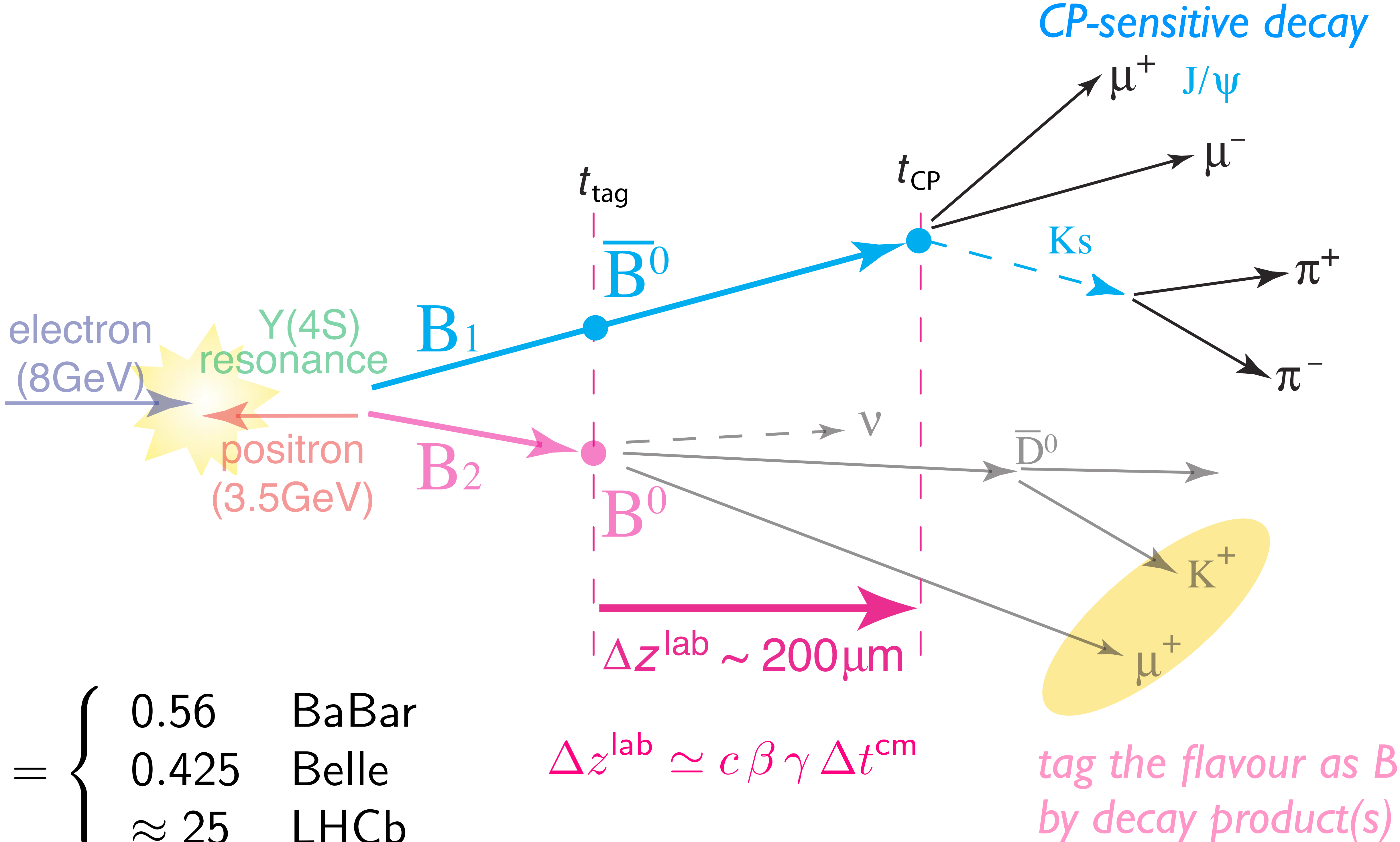


LHCb Data Taking 2011 & 2012



- integrated luminosity
  - 1 fb^{-1} @ 7 TeV (2011)
  - 2 fb^{-1} @ 8 TeV (2012)
- data taking efficiency >93%
  - >99% of detector channels working
  - >99% of collected data good for analysis

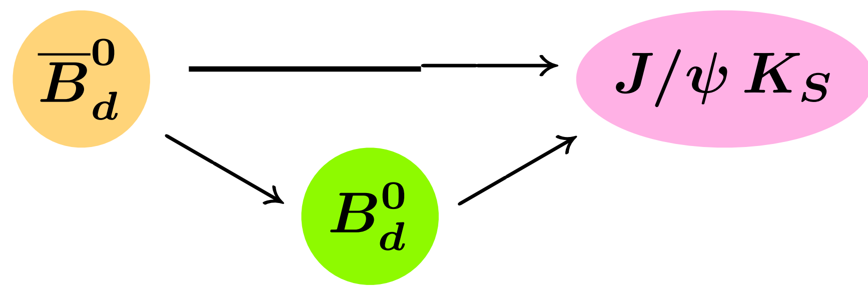
A moving centre of mass is required to measure the time-dependent $\not{C}\not{P}$ in $B^0 \to J/\psi\ K^0$ etc

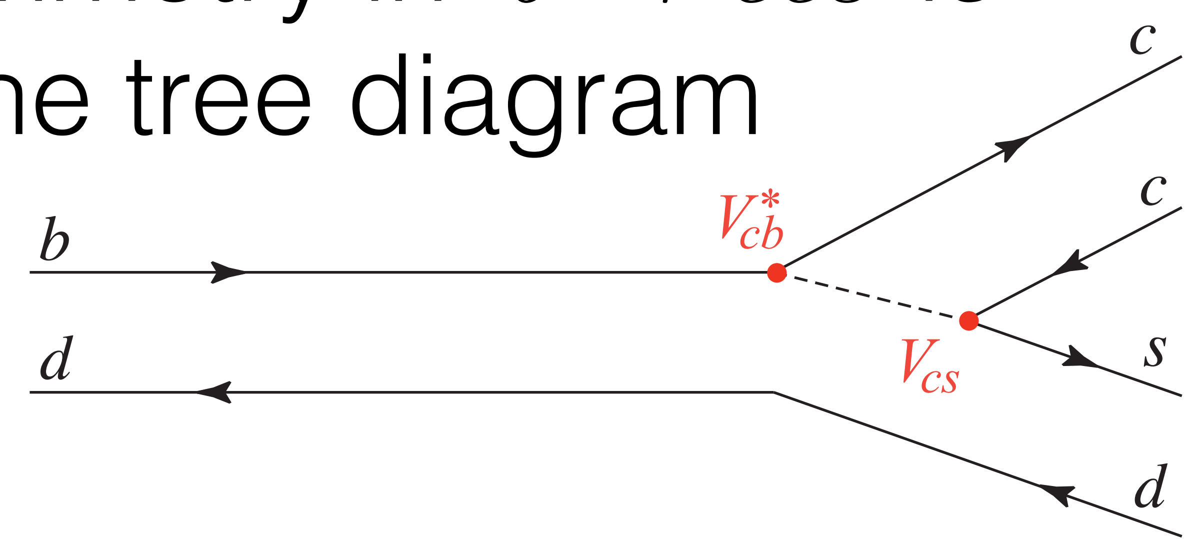


$$\beta\gamma = \begin{cases} 0.56 & \text{BaBar} \\ 0.425 & \text{Belle} \\ \approx 25 & \text{LHCb} \end{cases}$$

$$\Delta z^{\text{lab}} \simeq c\,\beta\,\gamma\,\Delta t^{\text{cm}}$$

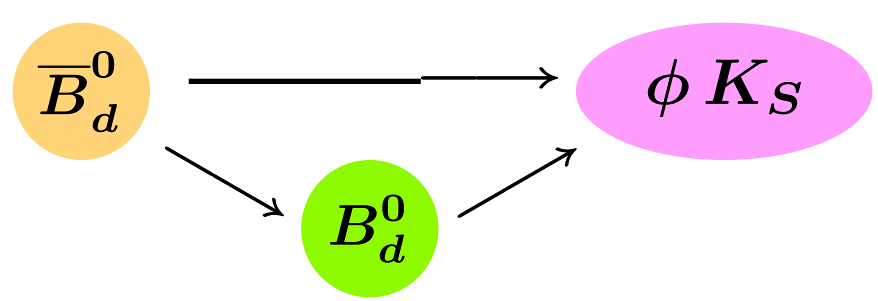
Time-dependent CP asymmetry in $b \to c\bar{c}s$ is typically dominated by one tree diagram

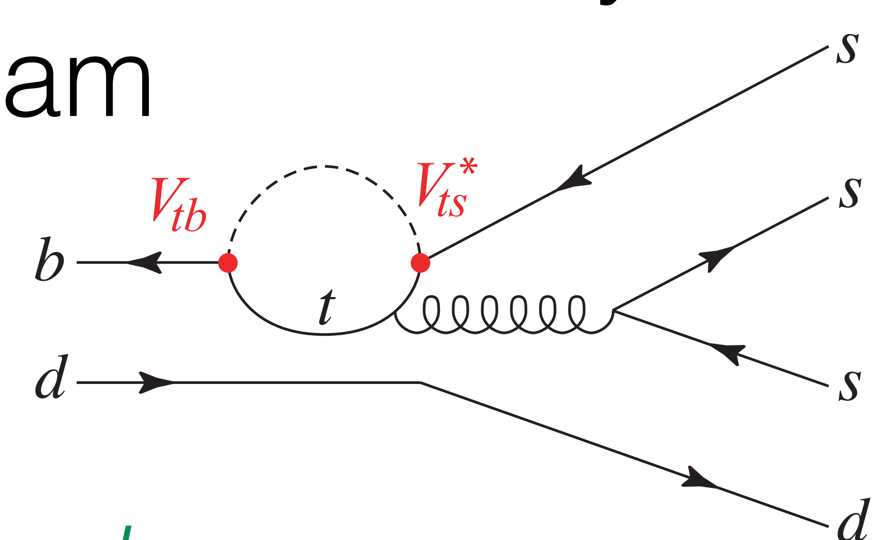




- limited opportunity for New Physics in tree; more likely (?) to appear in $B\,\bar{B}$ mixing

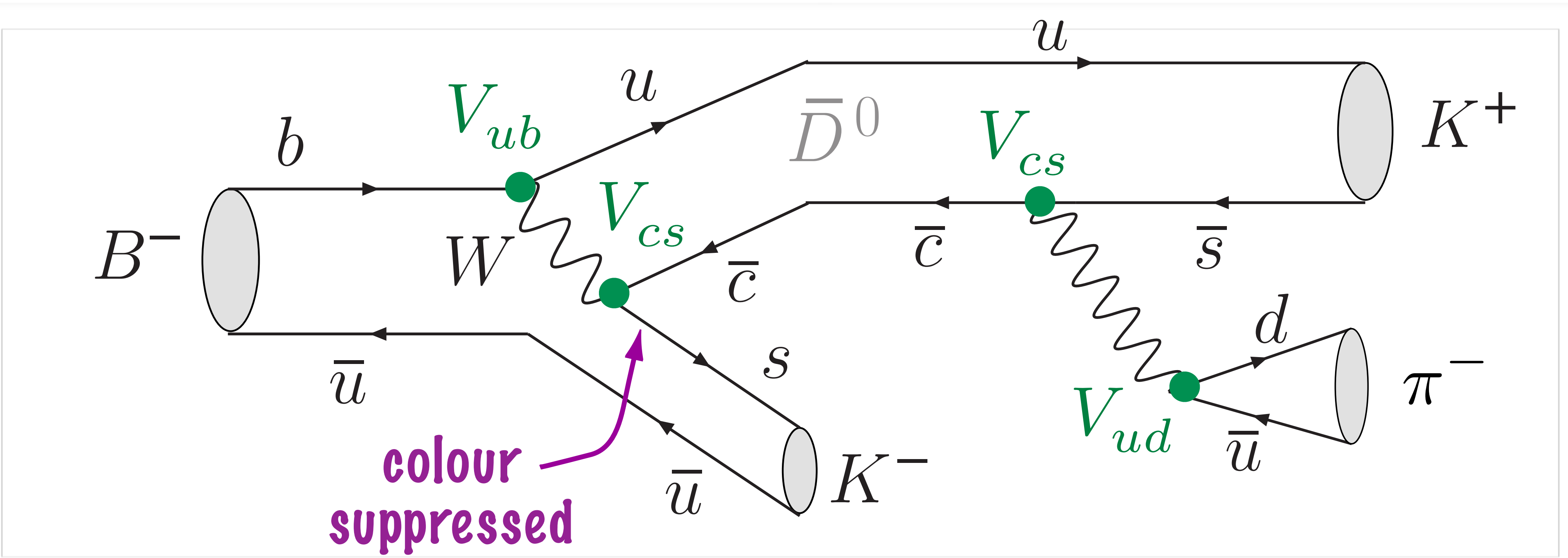
… but in $b \to s\bar{u}u,\ s\bar{d}d,\ s\bar{s}s$ is dominated by (or has only one) penguin diagram



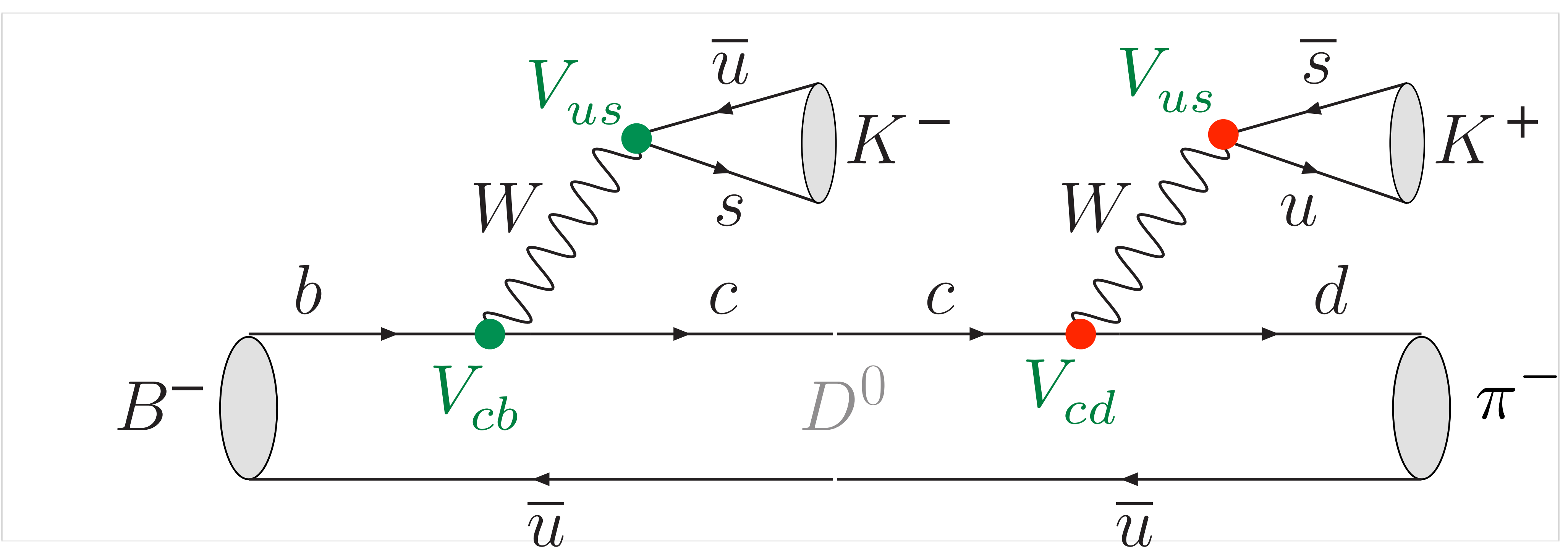


- *New Physics may appear in the loop*

ADS method measures ϕ_3 via the interference in rare $B^- \to [K^+\pi^-]_D K^-$ decays

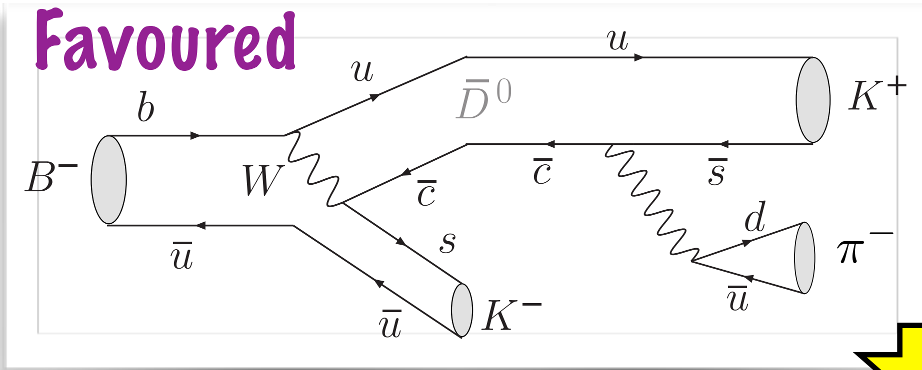


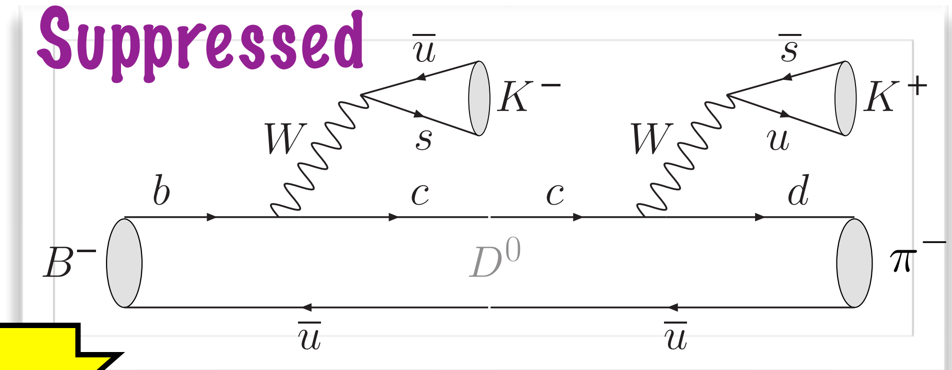
Cabibbo favoured D decay

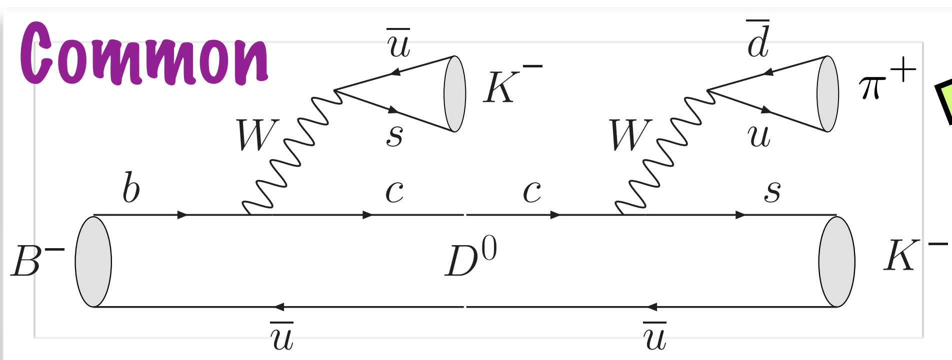


doubly Cabibbo suppressed D decay

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







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

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

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

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

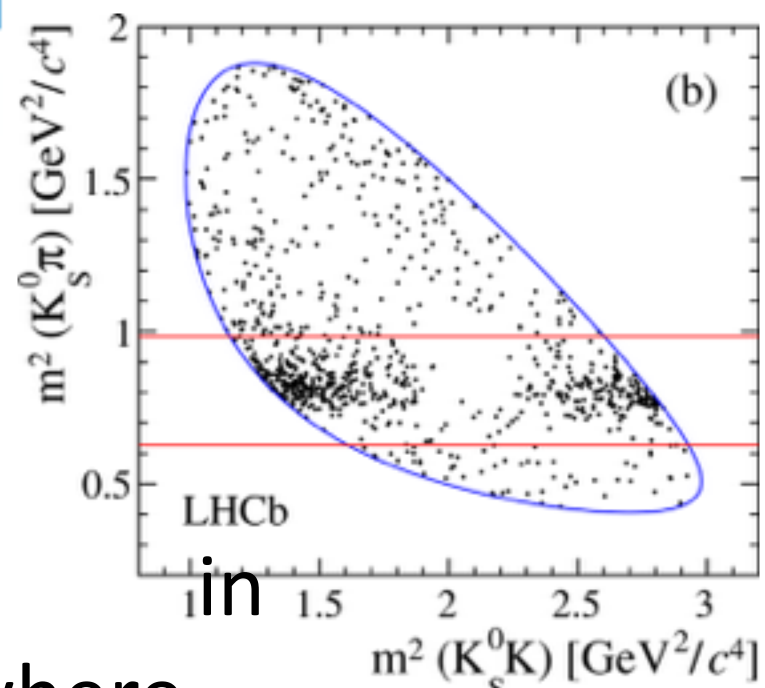
where $r_D = \left| \frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(\bar{D}^0 \to K^+\pi^-)} \right| = 0.0613 \pm 0.0010$

and r_B *was defined earlier*

Observables for $B^+ \to D^0(\to K_S K\pi)h^+$ NEW!

- This is the first ADS-like analysis to use Singly-Cabibbo-Suppressed (SCS) modes. Label final states as OS or SS comparing $K^\pm$ with $B^\pm$
- Analysing three-body *D* final state requires knowledge of how the average interference amplitude ($\kappa_{K_S K\pi}$) and strong phase difference ($\delta_{K_S K\pi}$) vary across the *D* Dalitz plot
  - This is taken from a CLEO-c measurement, Phys. Rev. **D 85** (2012) 092016
- Decay rates for $B^+ \to D^0 K^+$ are:

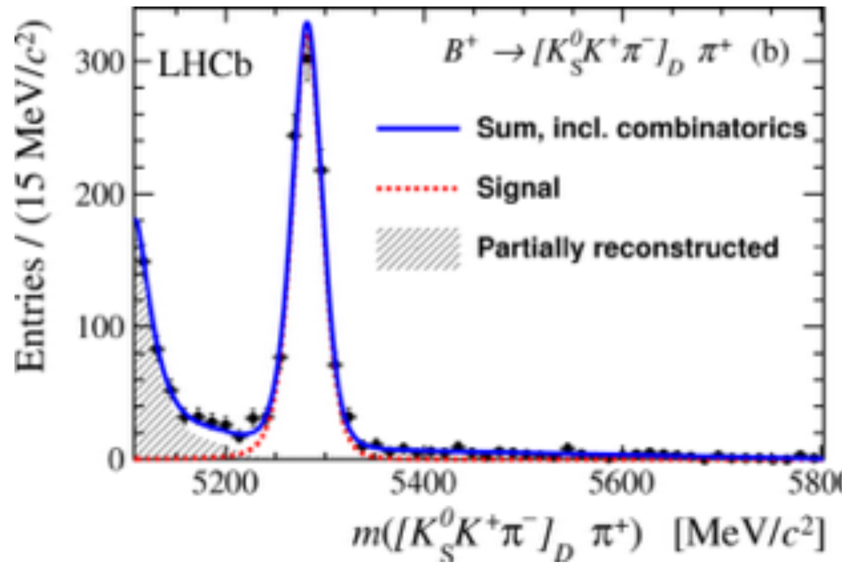
$$\Gamma^{\pm}_{\mathrm{SS},\,DK} = z[\ 1 + r_B^2 r_D^2 + 2 r_B r_D \kappa_{K_S^0 K\pi} \cos(\delta_B \pm \gamma - \delta_{K_S^0 K\pi})\ ]$$
$$\Gamma^{\pm}_{\mathrm{OS},\,DK} = z[\ r_B^2 + r_D^2 + 2 r_B r_D \kappa_{K_S^0 K\pi} \cos(\delta_B \pm \gamma + \delta_{K_S^0 K\pi})\ ]$$

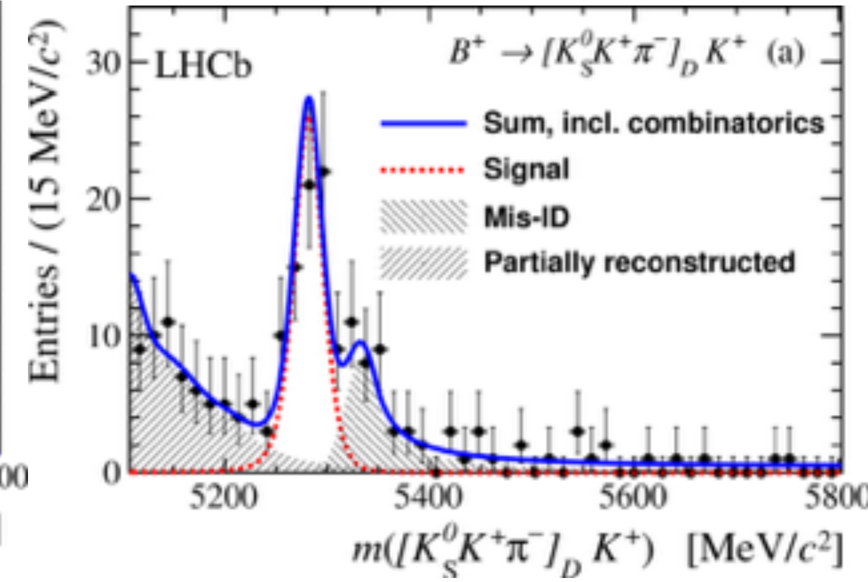


- Measure yield ratios (e.g. $\mathcal{R}_{DK/D\pi,\,SS}$) and charge asymmetries (e.g. $\mathcal{A}_{SS,DK}$) between the OS and SS samples, and between *DK* and *Dπ* final states.
- Analysis is done across whole Dalitz plane, and in a restricted region around the $K^{*\pm}$ resonance, where the coherence factor $\kappa_{K_S K\pi}$ is higher (≈1.0 vs ≈0.7).

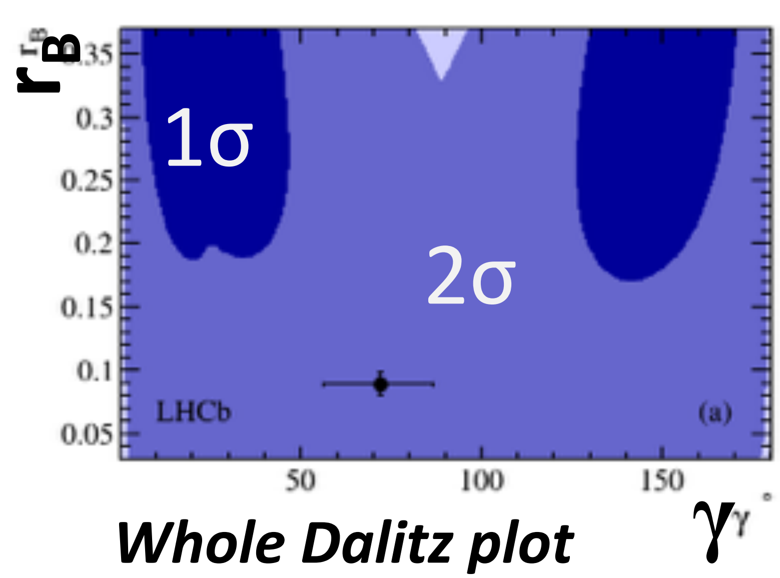
Results for $B^+ \to D^0(\to K_S K \pi) h^+$ NEW!

- Measure 8 yields, with $B^+ \to D^0 K^+$ and $B^+ \to D^0 \pi^+$ separated by OS/SS and charge of $B^\pm$
- Charge-summed yields for OS and SS $D^0 K^+$ are 71 and 145 respectively.
- Sensitivity to γ appears to be improved by taking $K^{*\pm}$ region, due to higher coherence factor.
- Good prospects for future analysis of $K^{*\pm}$ region with more statistics.

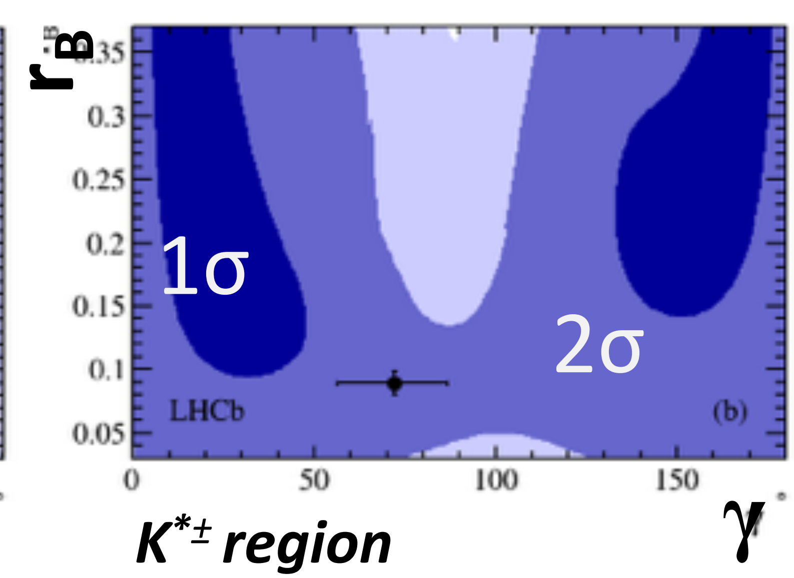




Observable	Whole Dalitz plot	$K^*(892)^\pm$ region
$\mathcal{R}_{SS/OS}$	$1.528 \pm 0.058 \pm 0.025$	$2.57 \pm 0.13 \pm 0.06$
$\mathcal{R}_{DK/D\pi,\,SS}$	$0.092 \pm 0.009 \pm 0.004$	$0.084 \pm 0.011 \pm 0.003$
$\mathcal{R}_{DK/D\pi,\,OS}$	$0.066 \pm 0.009 \pm 0.002$	$0.056 \pm 0.013 \pm 0.002$
$\mathcal{A}_{SS,\,DK}$	$0.040 \pm 0.091 \pm 0.018$	$0.026 \pm 0.109 \pm 0.029$
$\mathcal{A}_{OS,\,DK}$	$0.233 \pm 0.129 \pm 0.024$	$0.336 \pm 0.208 \pm 0.026$
$\mathcal{A}_{SS,\,D\pi}$	$-0.025 \pm 0.024 \pm 0.010$	$-0.012 \pm 0.028 \pm 0.010$
$\mathcal{A}_{OS,\,D\pi}$	$-0.052 \pm 0.029 \pm 0.017$	$-0.054 \pm 0.043 \pm 0.017$



Whole Dalitz plot



$K^{*\pm}$ region