The Precise Measurement of the Angle γ

(Results and Prospects @ 2017 from LHCb)

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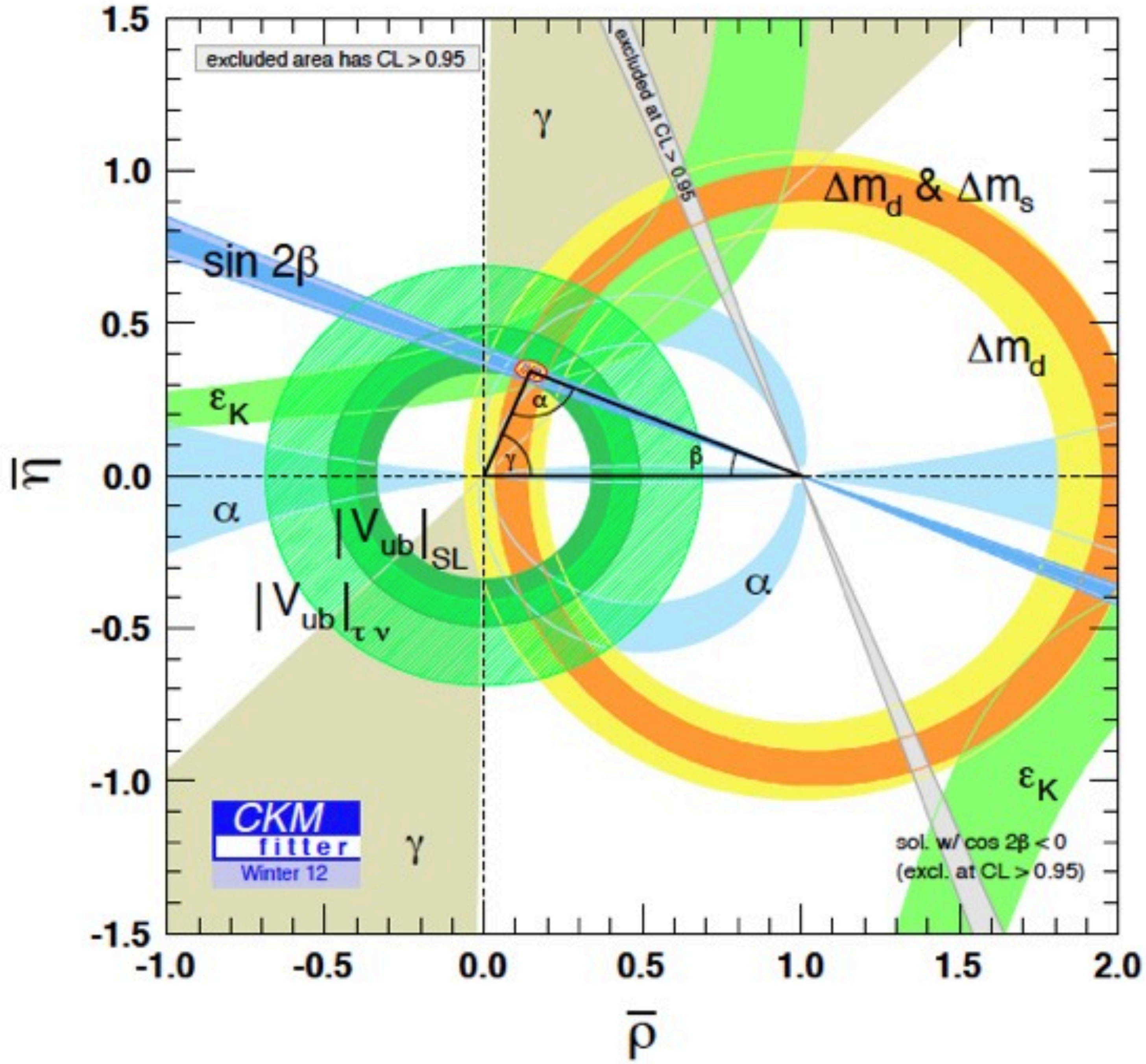
9th Franco-Italian meeting on B Physics
February,2013

CKM Angle γ

$$\gamma = \arg\left[-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)\right]$$



- **The least well known variable for unitarity constrain**

Babar: $\gamma = (69^{+17}_{-16})°$ **(arXiv:1301.1029)**

Belle: $\gamma = (68^{+15}_{-14})°$ **(CKM 2012)**

CKMFitter: $\gamma = (66\pm12)°$

UTFitter: $\gamma = (76\pm10)°$

γ from other constrains: ~ 4.3°

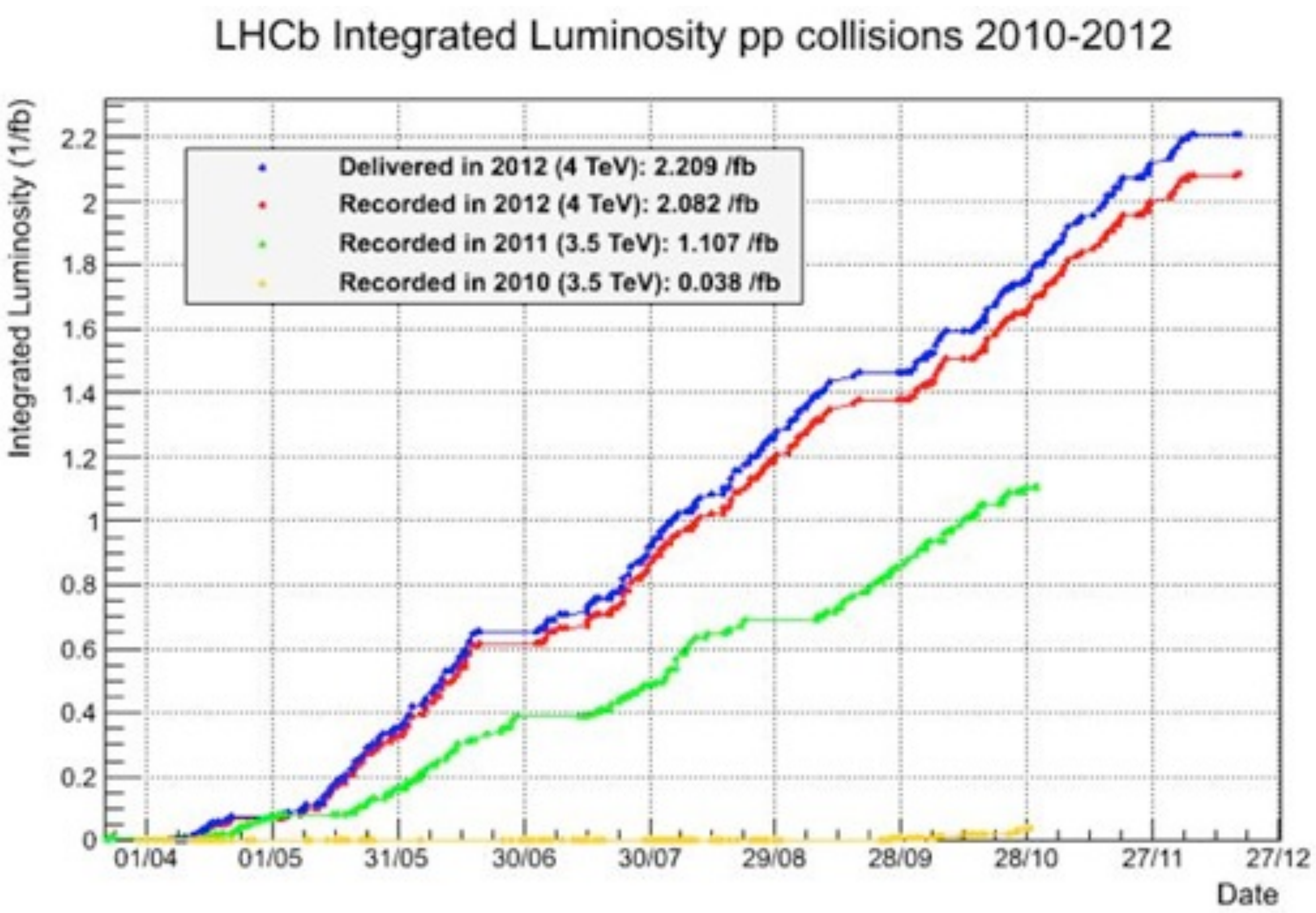
Theory: $\delta\gamma/\gamma \sim 0.0000001°$

- **Can be accessed through tree-level transitions (i.e. $B \rightarrow DK$) ➡ Test of standard model**

- **Can be accessed through loop-level transitions (i.e. $B_{(s)} \rightarrow \pi\pi(KK)$) ➡ Probe of new physics**

Effective Yields

- Integrated luminosity and Energy (proportion to b cross section)



- Designed: 2 fb^{-1} @ 14 TeV
- 2010: 0.04 fb^{-1} @ 7 TeV
- 2011: 1.0 fb^{-1} @ 7 TeV
- 2012: 2.0 fb^{-1} @ 8 TeV
- 2015-2017: 5-6 fb^{-1} @ 13 TeV

2017 Compared to current publications (mainly based on 2011 data):

A factor of 9 in integrated luminosity

A factor of 14 in production

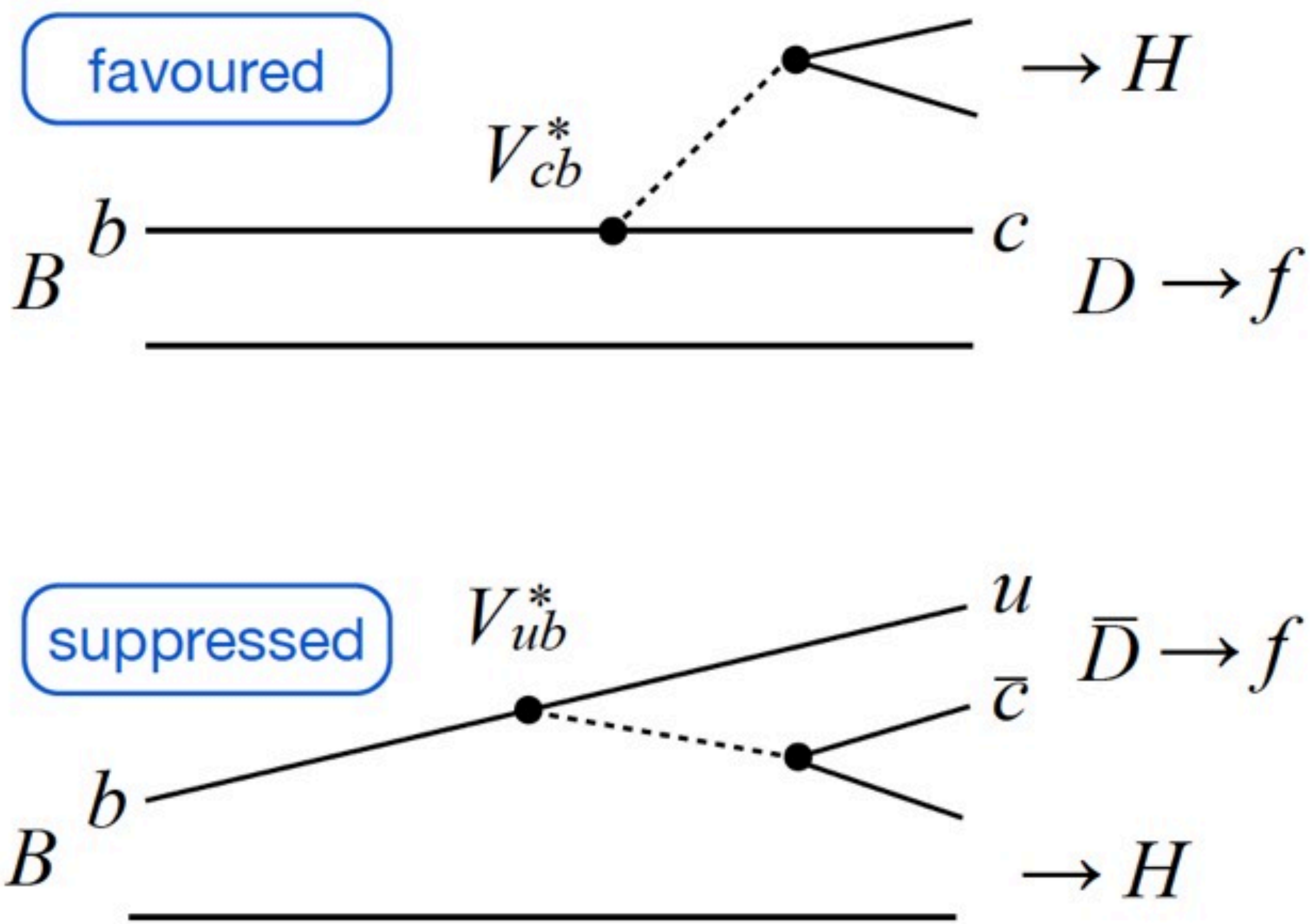
- Trigger, Selection etc.

  B decays with μμ
  ε (L0 x HLT) ~ 70-90 %
  B decays with hadrons
  ε (L0 x HLT) ~ 20-50 %

Improvement in 2012:
#CPU: +10%
Deferred trigger: +20%

Assuming a factor of 16 in effective yields

γ in Open Charm Decays



Combination of B mesons (hadrons), different H particles, different D decays offers dozens of channels to access γ in tree level

$$r_B = \frac{A_u}{A_c}$$

$$\Gamma(B \to D[\to f]H) = A_c^2(A_f^2 + r_B^2 A_{\bar{f}}^2 + 2r_B A_f A_{\bar{f}} Re(e^{i(\delta_B + \delta_D - \gamma)})$$

Neglecting CP and mixing in D

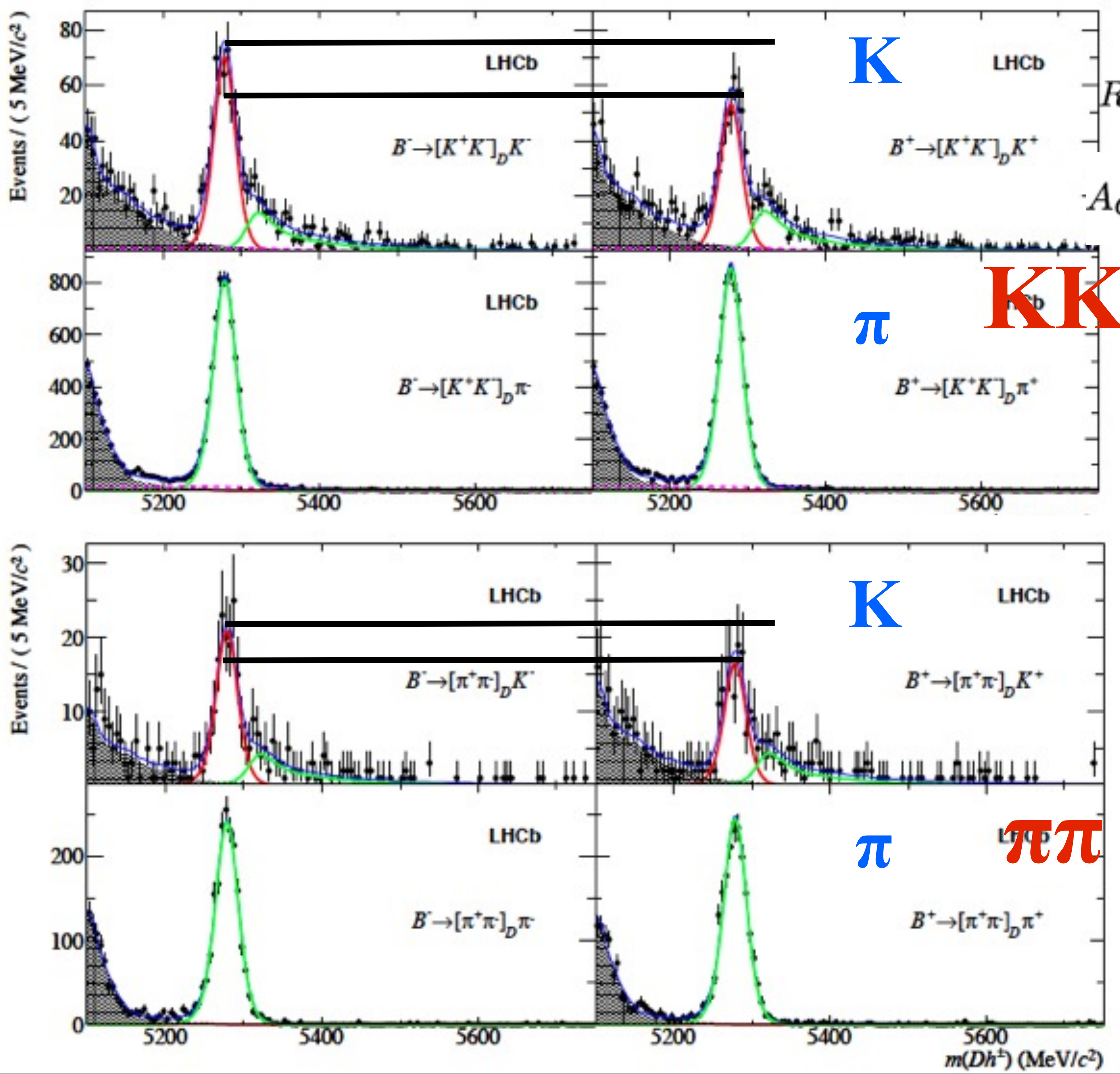
Sensitivity of γ depends largely on r_B (affected by color-suppressed factor, ratio of CKM elements etc.)

γ Studies with $B^+ \to D^0 h^+$ (1)

Phys. Lett. B 712 (2012) 203,
arXiv: 1203.3662

- ➢ h is π (r_B ~0.01) or K (r_B ~0.1); K channels thus offer better power on γ measurement

- ➢ D^0 can decay to KK, ππ (GLW modes)



$$R_{CP+} = \frac{2[\Gamma(B^- \to D_{CP+}h^-) + \Gamma(B^+ \to D_{CP+}h^+)]}{\Gamma(B^- \to D^0 h^-) + \Gamma(B^+ \to D^0 h^+)}$$

$$A_{CP+} = \frac{\Gamma(B^- \to D_{CP+}h^-) - \Gamma(B^+ \to D_{CP+}h^+)}{\Gamma(B^- \to D_{CP+}h^-) + \Gamma(B^+ \to D_{CP+}h^+)}$$

Averaging over KK and ππ channels and assuming no CP violation in h=π channels

$$R_{CP+} = 1.007 \pm 0.038 \pm 0.012\,,$$
$$A_{CP+} = 0.145 \pm 0.032 \pm 0.010\,,$$

4.5σ!!

Systematic ~ Statistic/4

γ Studies with $B^+ \to D^0 h^+$ (2)

Phys. Lett. B 712 (2012) 203, arXiv: 1203.3662

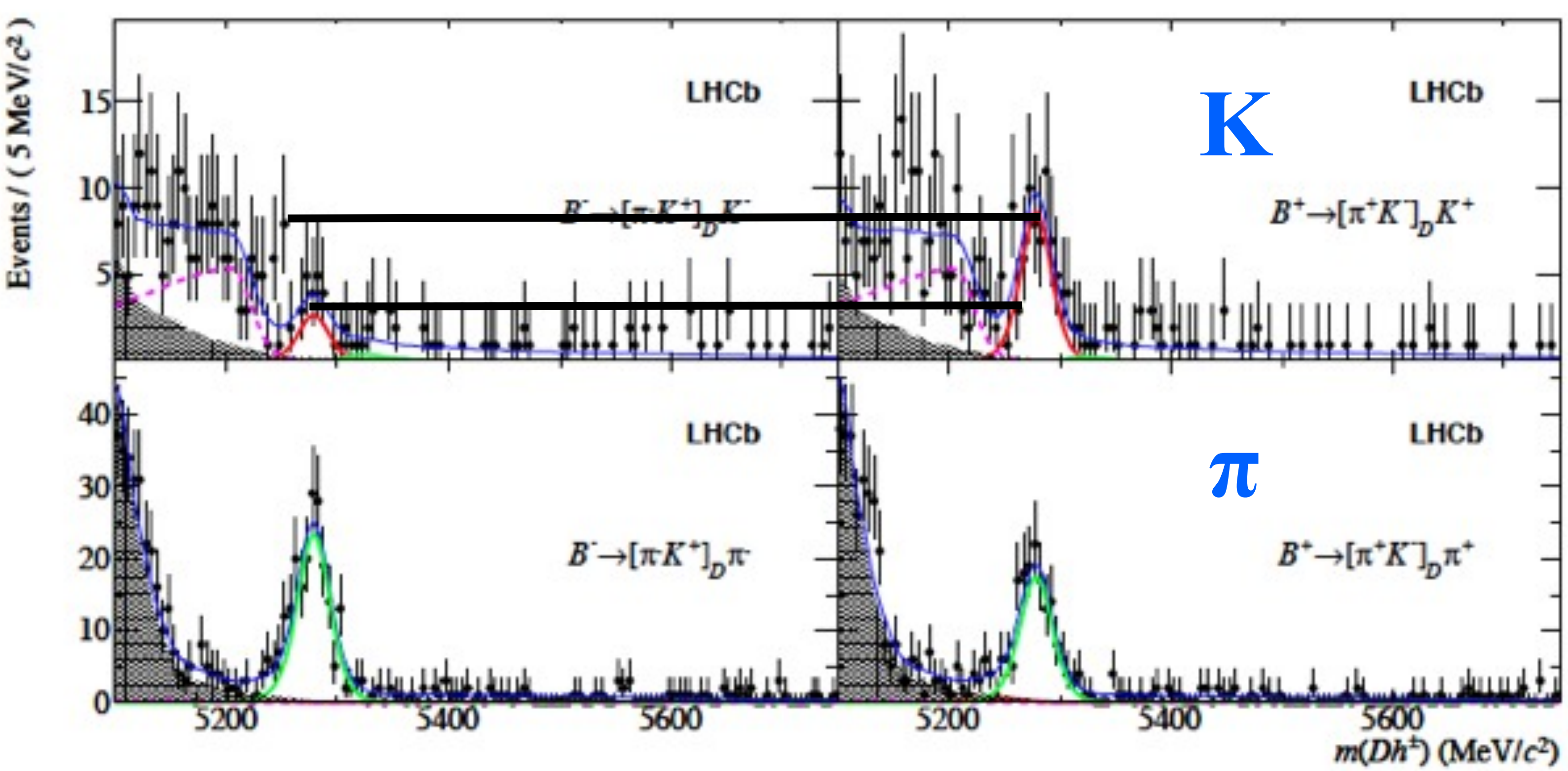
- h is π (r_B ~0.01) or K (r_B ~0.1); K channels thus offer better power on γ measurement

- D^0 can decay to $K^-\pi^+$ or $K^+\pi^-$ (ADS mode)

$$R_{\mathrm{ADS}} = \frac{\Gamma(B^- \to D[\to \pi^- K^+]h^-) + \Gamma(B^+ \to D[\to \pi^+ K^-]h^+)}{\Gamma(B^- \to D[\to K^- \pi^+]h^-) + \Gamma(B^+ \to D[\to K^+ \pi^-]h^+)}$$

$$A_{\mathrm{ADS}} = \frac{\Gamma(B^- \to D[\to \pi^- K^+]h^-) - \Gamma(B^+ \to D[\to \pi^+ K^-]h^+)}{\Gamma(B^- \to D[\to K^- \pi^+]h^-) + \Gamma(B^+ \to D[\to K^+ \pi^-]h^+)}$$

First observation of $B^+ \to D^0 K^+$ ADS mode: 5.1σ



$$R_{\mathrm{ADS}(K)} = 0.0152 \pm 0.0020 \pm 0.0004$$
$$A_{\mathrm{ADS}(K)} = -0.52 \pm 0.15 \pm 0.02$$

4.0σ!!

Systematic ~ Statistic/6

Combining GLW and ADS mode, we have 5.8σ! significance of direct CP violation

γ Studies with $B^+ \to D^0 h^+$ (3)

Phys. Lett. B 718 (2012) 43, arXiv: 1209.5869

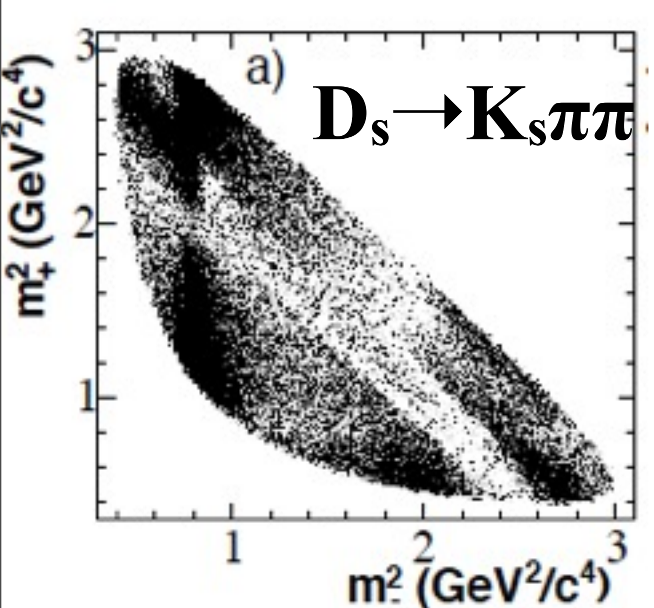
- h is π ($r_B \sim 0.01$) or K ($r_B \sim 0.1$); K channels thus offer better power on γ measurement
- D^0 can decay to $K_s\pi\pi$, K_sKK (GGSZ mode)
- Model dependent (amplitude analysis etc.) or model independent (using CLEO-c information)

$$x_\pm = \mathrm{Re}[r_B e^{i(\delta_B \pm \gamma)}] \qquad y_\pm = \mathrm{Im}[r_B e^{i(\delta_B \pm \gamma)}]$$

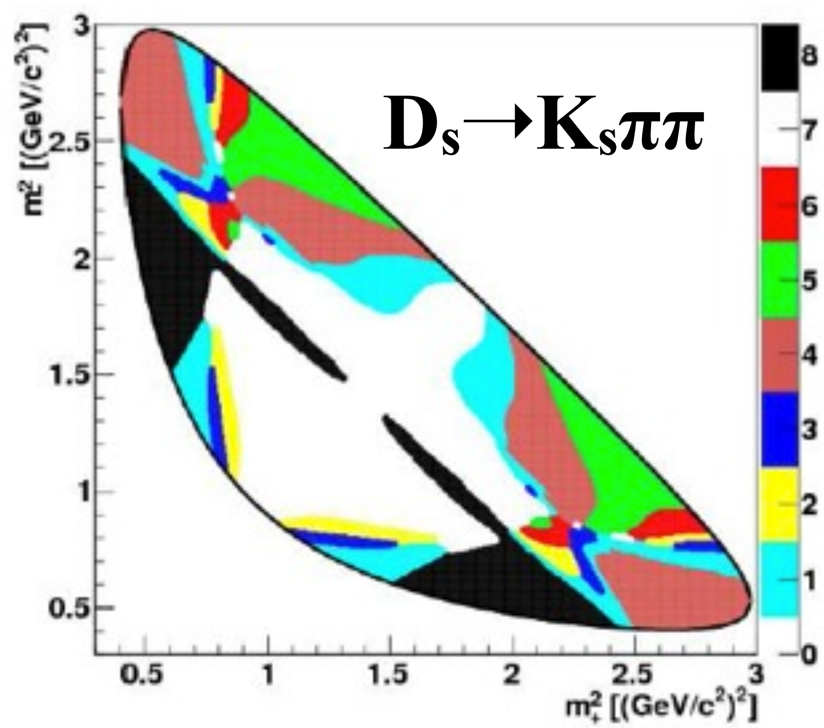
$$\Gamma(B^\mp \to D[\to K^0_S \pi^+\pi^-]K^\mp) \propto |f_\mp|^2 + r_B^2 |f_\pm|^2 + 2\left[x_\mp \mathrm{Re}[f_\mp f_\pm^*] + y_\mp \mathrm{Im}[f_\mp f_\pm^*]\right]$$

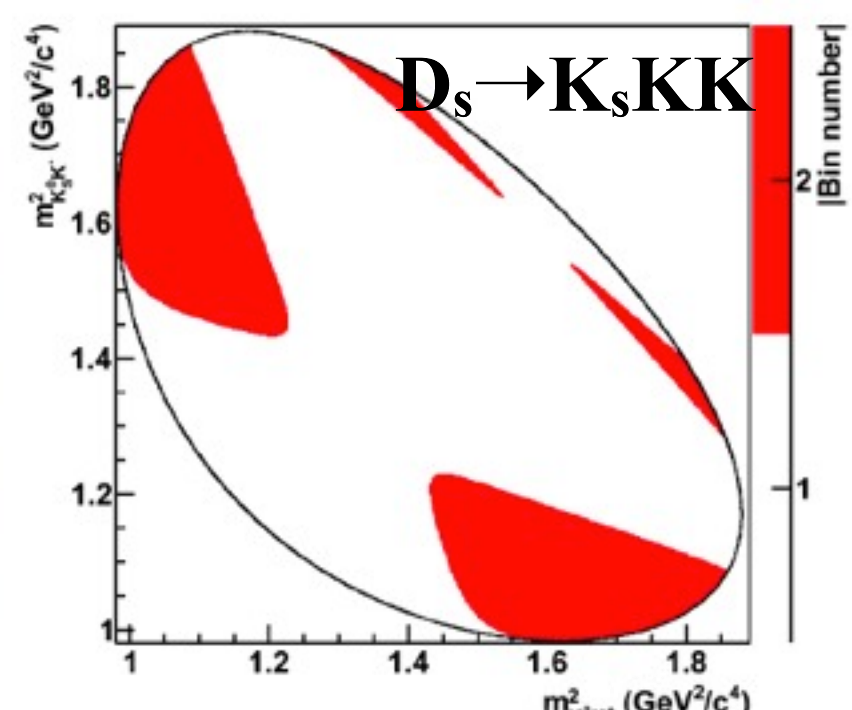
From Babar's flavor specified Dalitz analysis

CLEO-c information



Phys. Rev. Lett. 95(2005) 121802





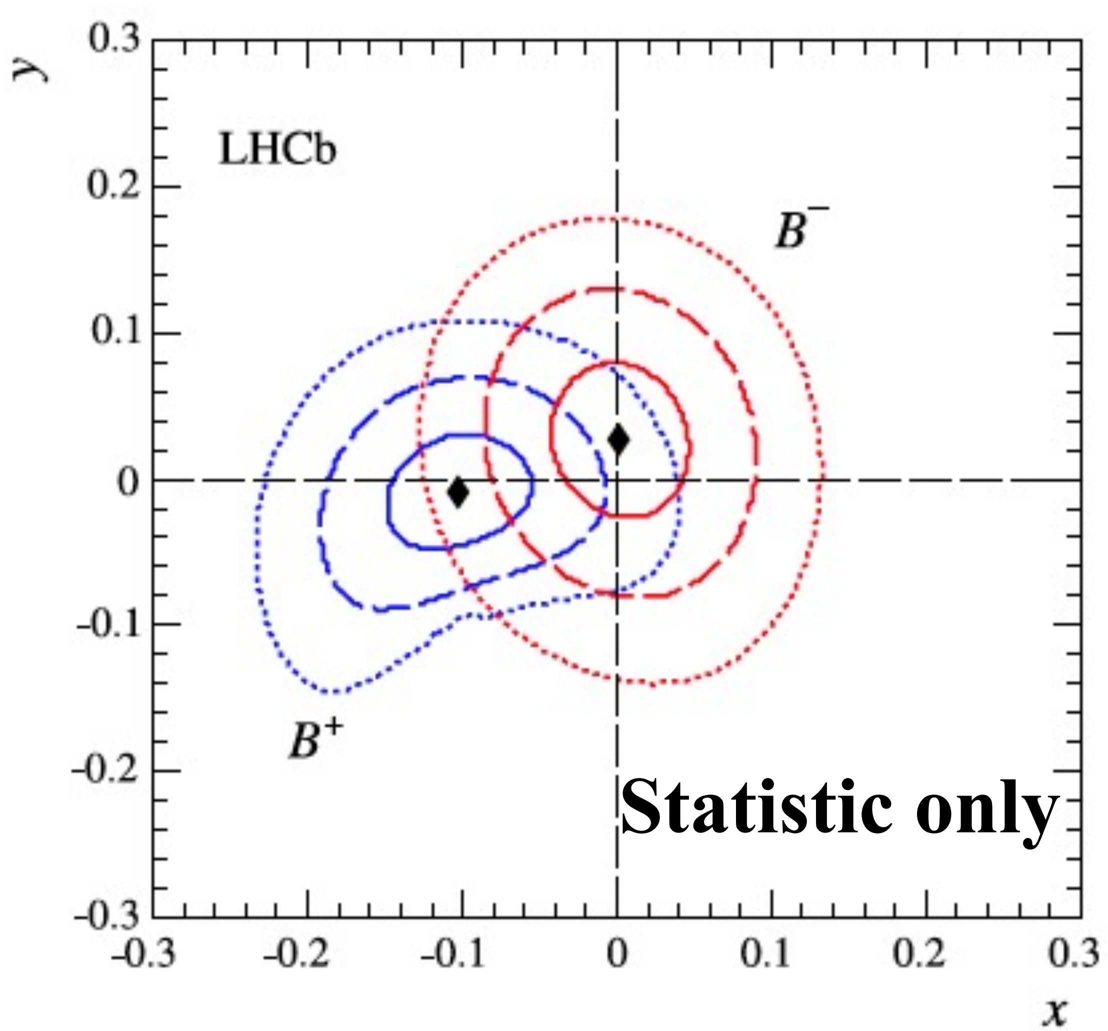
γ Studies with $B^+ \rightarrow D^0 h^+$ (3)

Phys. Lett. B 718 (2012) 43, arXiv: 1209.5869

- **h is π (r_B ~0.01) or K (r_B ~0.1); K channels thus offer better power on γ measurement**

- **D^0 can decay to $K_s\pi\pi$, K_sKK (GGSZ mode); Model independent**

Results with 690 signal in $K_s\pi\pi$ and 110 in K_sKK



$$x_- = (0.0 \pm 4.3 \pm 1.5 \pm 0.6) \times 10^{-2},$$

$$y_- = (2.7 \pm 5.2 \pm 0.8 \pm 2.3) \times 10^{-2},$$

$$x_+ = (-10.3 \pm 4.5 \pm 1.8 \pm 1.4) \times 10^{-2},$$

$$y_+ = (-0.9 \pm 3.7 \pm 0.8 \pm 3.0) \times 10^{-2},$$

Stat. Sys. CLEO-c input

Dominant sys. : no CP violation in $B \rightarrow D^0\pi$
Can be avoided with large dataset

Sys. due to CLEO input will reduce for large statistical analysis

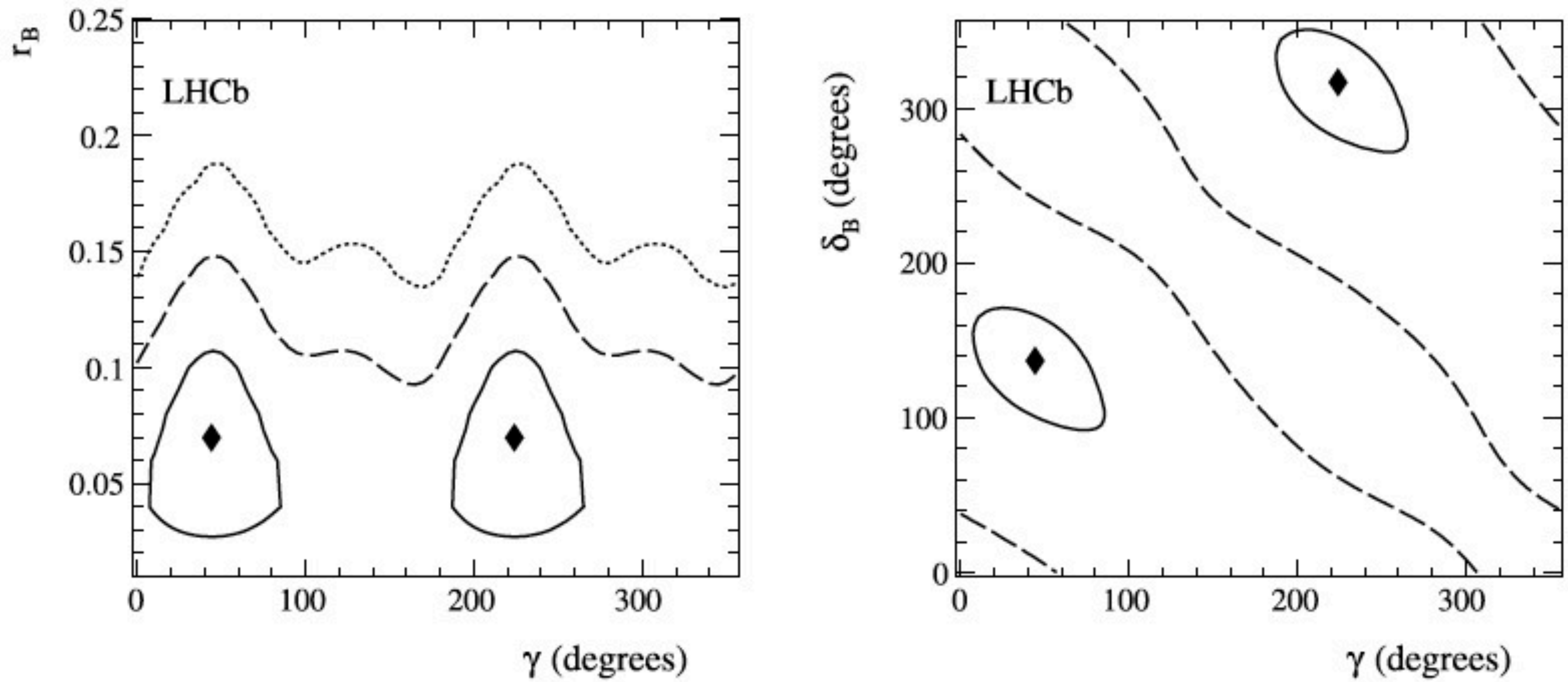
γ Studies with $B^+ \to D^0 h^+$ (4)

Phys. Lett. B 718 (2012) 43, arXiv: 1209.5869

➢ h is π ($r_B \sim 0.01$) or K ($r_B \sim 0.1$); K channels thus offer better power on γ measurement

➢ D^0 can decay to $K_s\pi\pi$, K_sKK (GGSZ mode); Model independent

$$r_B = 0.07 \pm 0.04 \qquad \gamma = (44^{+43}_{-38})^\circ \qquad \delta_B = (137^{+35}_{-46})^\circ$$



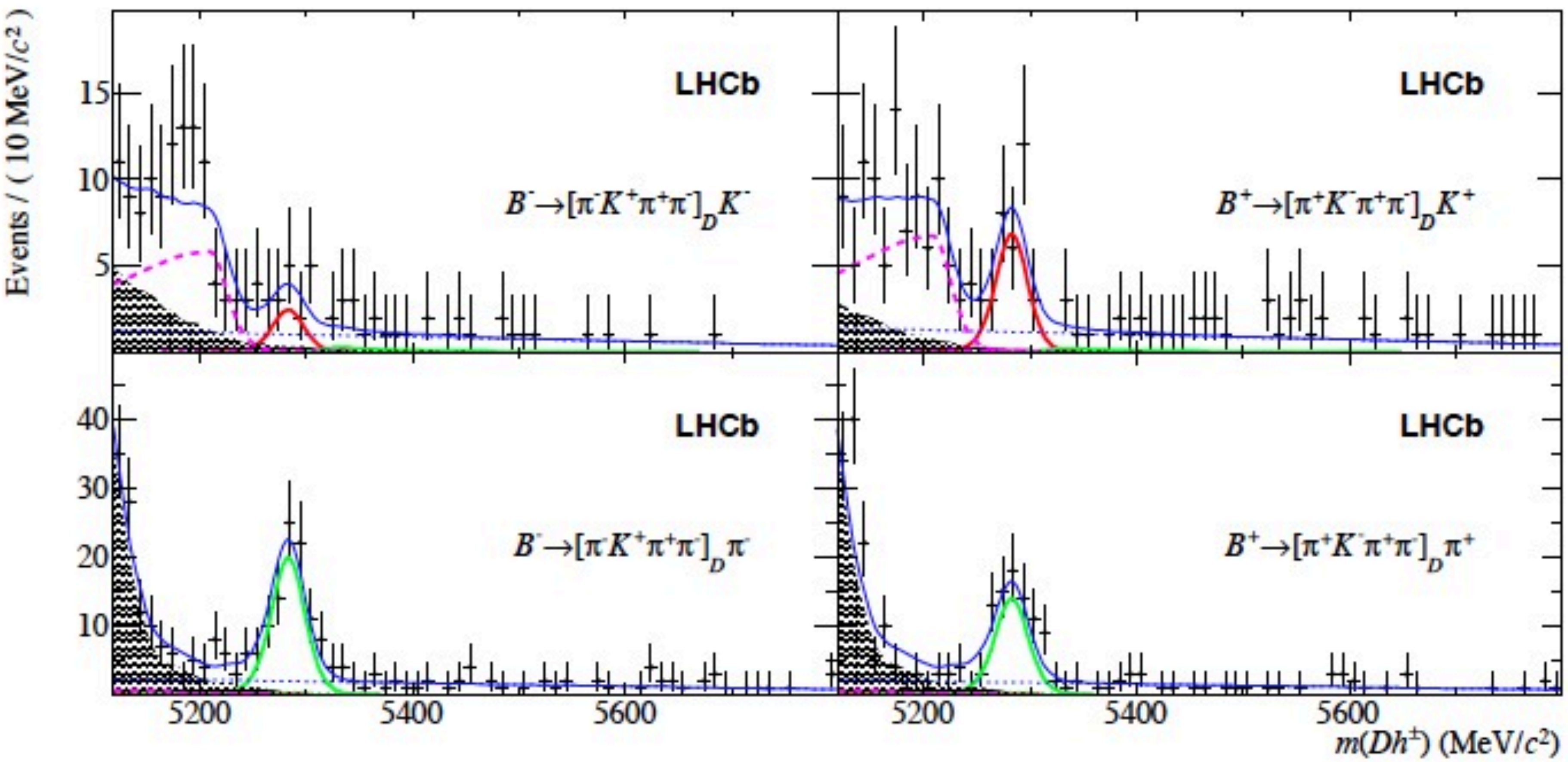
➢ r_B lower than world average (but consistent) → larger error on γ

➢ After 2018, GGSZ mode alone can reach a sensitivity of 9°

γ Studies with $B^+ \to D^0 h^+$ (4)

LHCb-CONF-2012-030

- **h is π ($r_B \sim 0.01$) or K ($r_B \sim 0.1$); K channels thus offer better power on γ measurement**
- **D^0 can decay to $K\pi\pi\pi$, $KK\pi\pi$, $\pi\pi\pi\pi$, $K_s\omega$, $K_sK\pi$ etc.**
- **Offer constrain to r_B:** $r_B^K = 0.097 \pm 0.011$



ADS mode

~ 40 B→DK

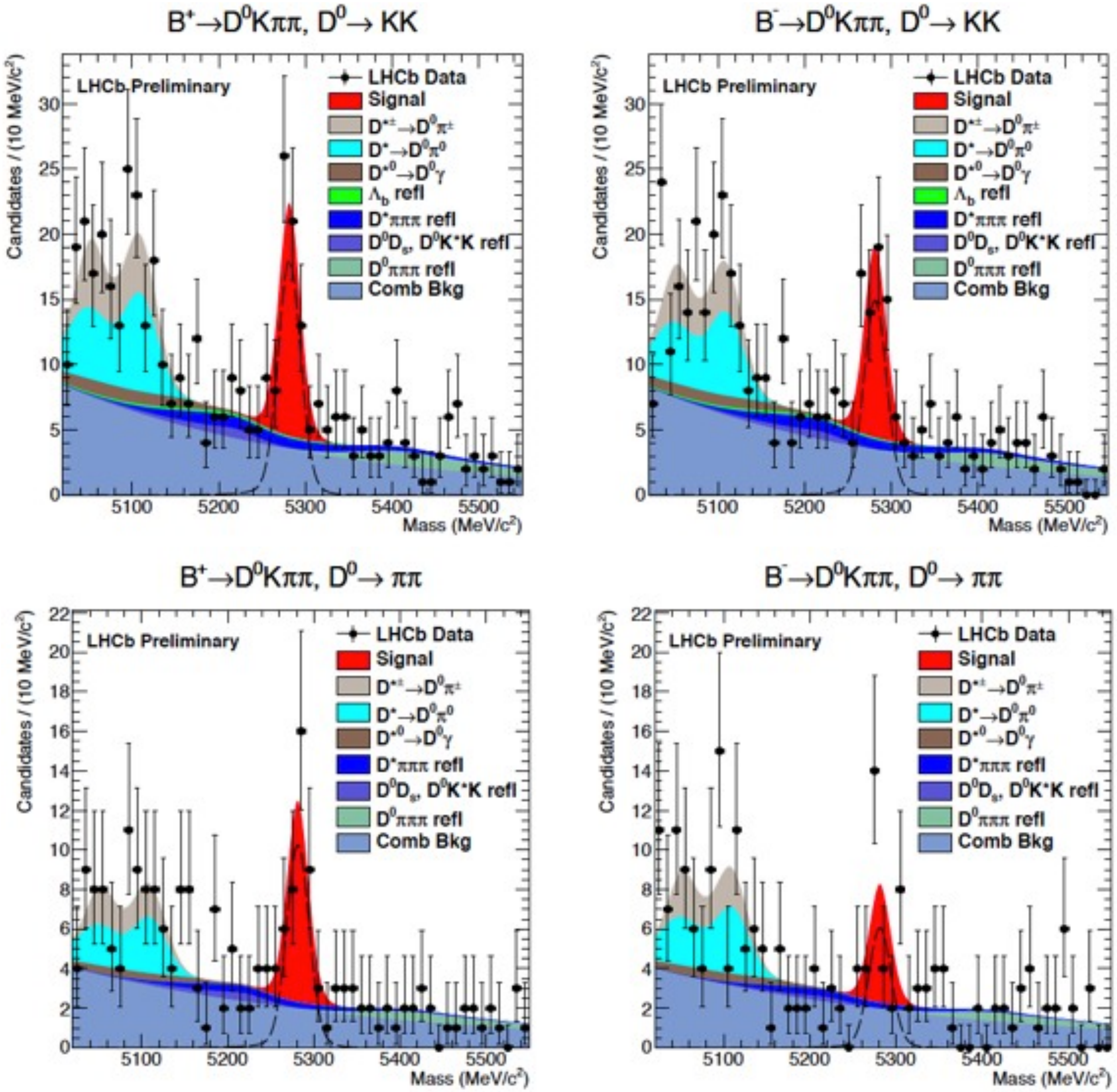
~ 160 B→Dπ

Statistic uncertainty limited, errors can be scaled with increased luminosity

γ Studies with $B^+ \to D^0 h^+ \pi\pi$

LHCb-CONF-2012-021

- **h is π or K; K channels offer better power on γ measurement**
- **D^0 can decay to KK, $\pi\pi$ (GLW modes), $K_s\pi\pi$, K_sKK (GGSZ mode)**



~120 signals for KK mode

~60 signals for $\pi\pi$ mode

$$A_s^{CP+} = -0.14 \ \pm 0.10 \ (\text{stat}) \pm 0.01 \ (\text{syst})$$

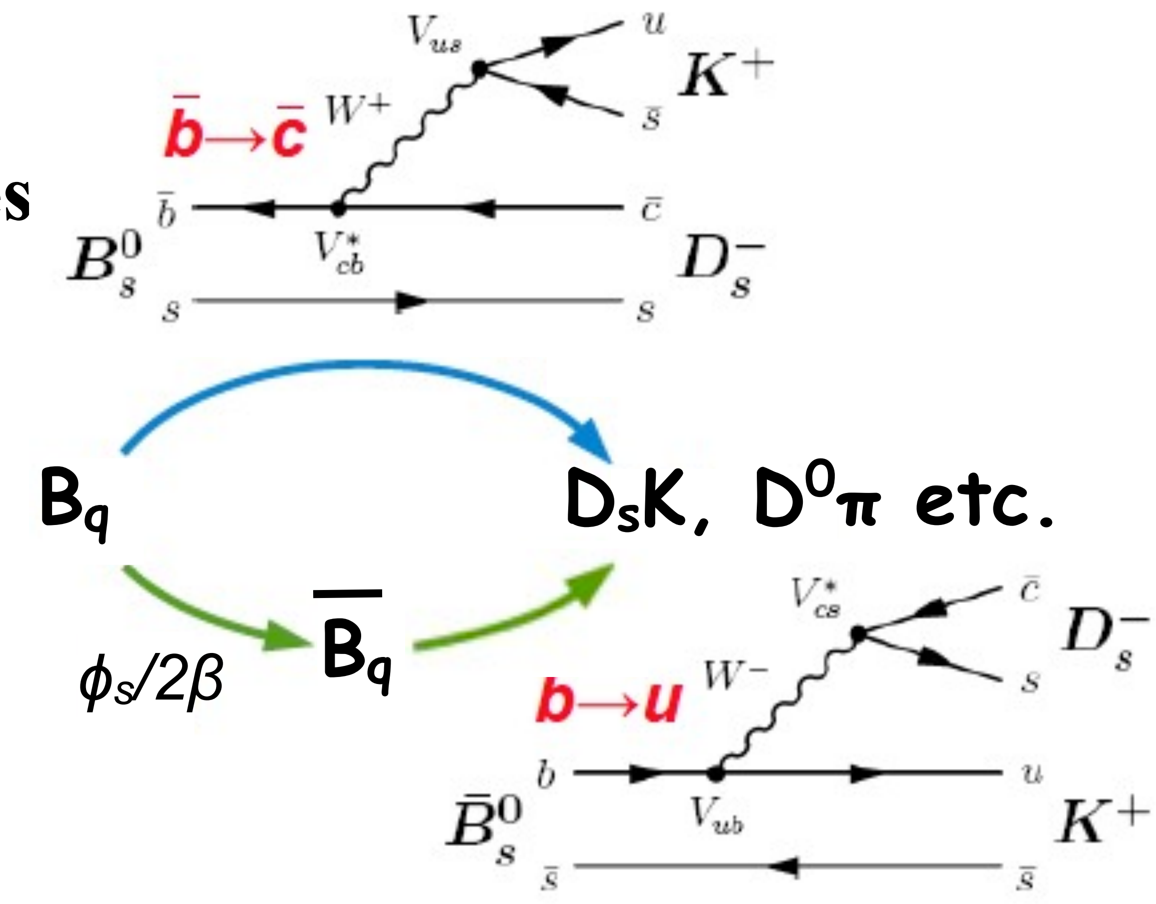
$K_s\pi\pi$, K_sKK modes: (Analysis ongoing)

~200/fb signals for two modes

Statistical uncertainty dominated, scaled with more statistics

γ Studies with other B mesons (1)

- **Two neutral B mesons: B^0, B_s; Flavor specified decay or decay to CP eigenstates**
- **Flavor specified decay: $B_s \rightarrow D_s K$ etc.**
- **$\gamma+\phi_s$ (2β) can be accessed through mixing of neutral B mesons, i.e. $B_s \rightarrow D_s K$ ($r_B \sim 0.3$), $B^0 \rightarrow D^0\pi$ ($r_B \sim 0.02$) etc.**



$$\frac{d\Gamma_{B_s\to f}(t)}{e^{-\Gamma_s t}} \propto [\cosh(\frac{\Delta\Gamma_s t}{2}) - D_f \sinh(\frac{\Delta\Gamma_s}{2}) \boxed{+} C\cos(\Delta m_s t) \boxed{-} S_f \sin(\Delta m_s t)]$$

$$\frac{d\Gamma_{\overline{B}_s\to f}(t)}{e^{-\Gamma_s t}} \propto [\cosh(\frac{\Delta\Gamma_s t}{2}) - D_f \sinh(\frac{\Delta\Gamma_s}{2}) \boxed{-} C\cos(\Delta m_s t) \boxed{+} S_f \sin(\Delta m_s t)]$$

Similar for $\overline{f}$

Change sign for $\overline{f}$

$$D_f = \frac{2r_{D_sK}\cos(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

$$C = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2}$$

$$S_f = \frac{2r_{D_sK}\sin(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

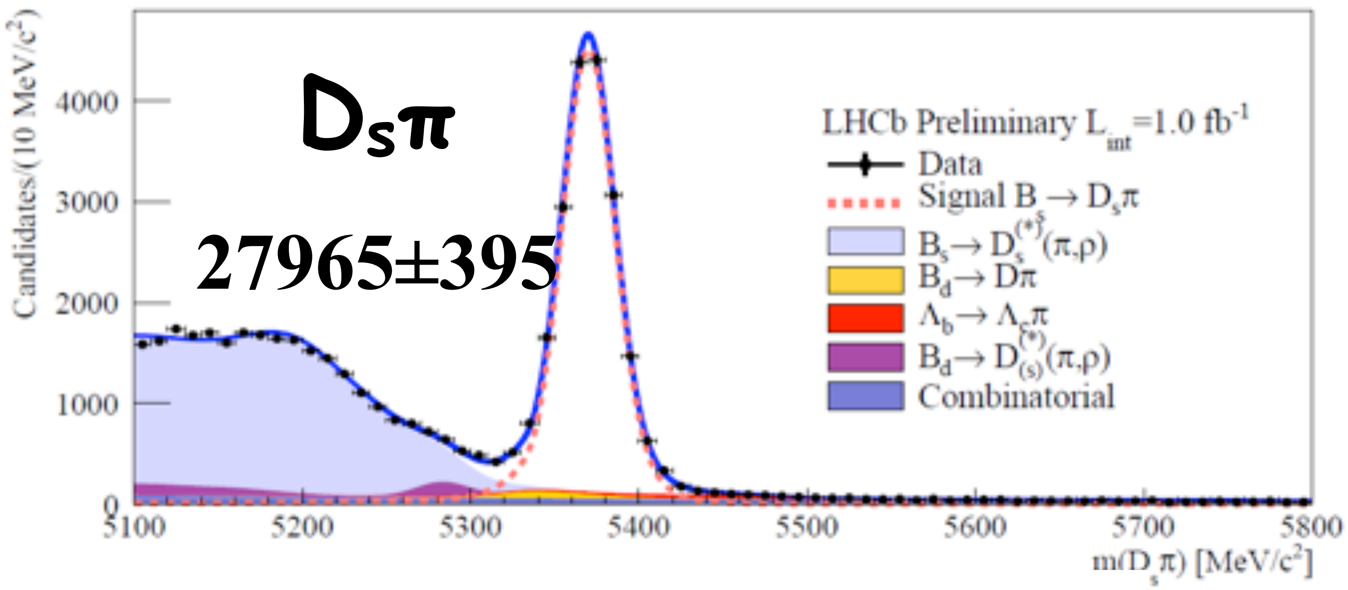
D_f can be measured due to non zero Γ_s
Independent of tagging

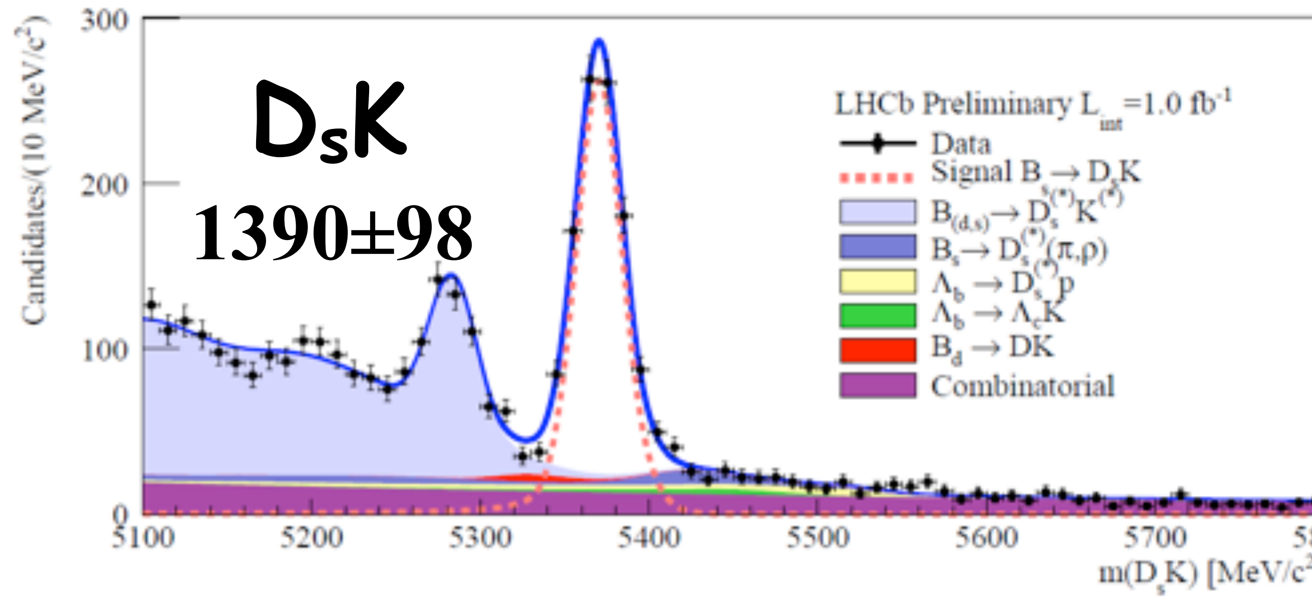
Tagging info. required

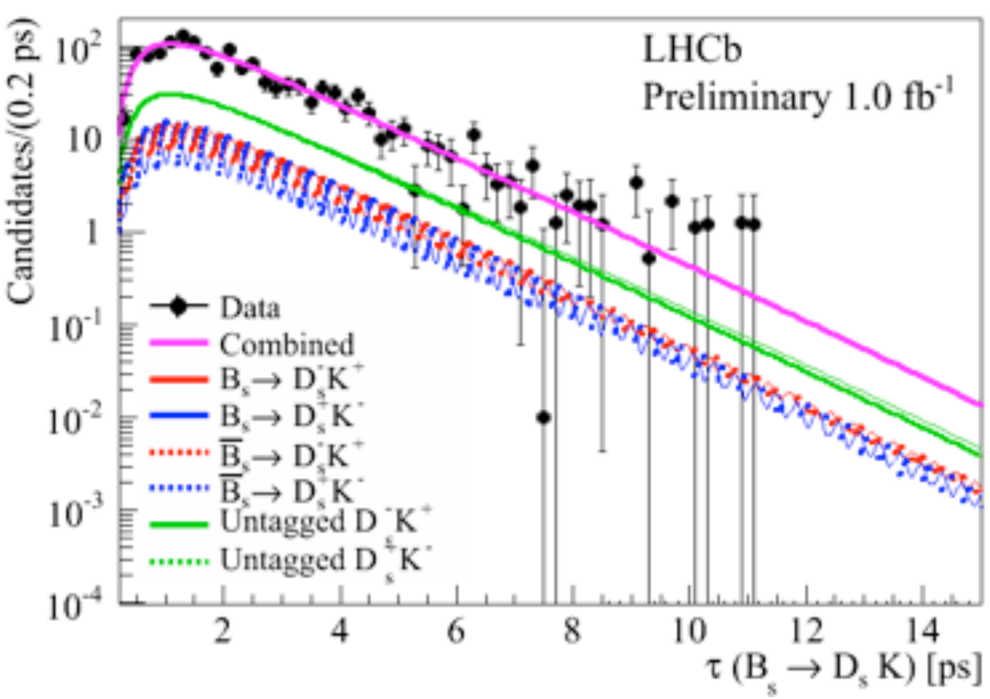
γ Studies with other B mesons (2)

LHCb-CONF-2012-029

➢ **Event Yields (with D_s decays to $KK\pi$, $K\pi\pi$ and $\pi\pi\pi$)**







Stat. Sys.

$$C = 1.01 \pm 0.50 \pm 0.23\,,$$
$$S_f = -1.25 \pm 0.56 \pm 0.24\,,$$
$$S_{\bar{f}} = 0.08 \pm 0.68 \pm 0.28\,,$$
$$D_f = -1.33 \pm 0.60 \pm 0.26\,,$$
$$D_{\bar{f}} = -0.81 \pm 0.56 \pm 0.26\,,$$

➢ **Systematic uncertainties dominated by fixed parameters (Δm_s, Γ_s, $\Delta\Gamma_s$), flavor tagging calibration, background description**

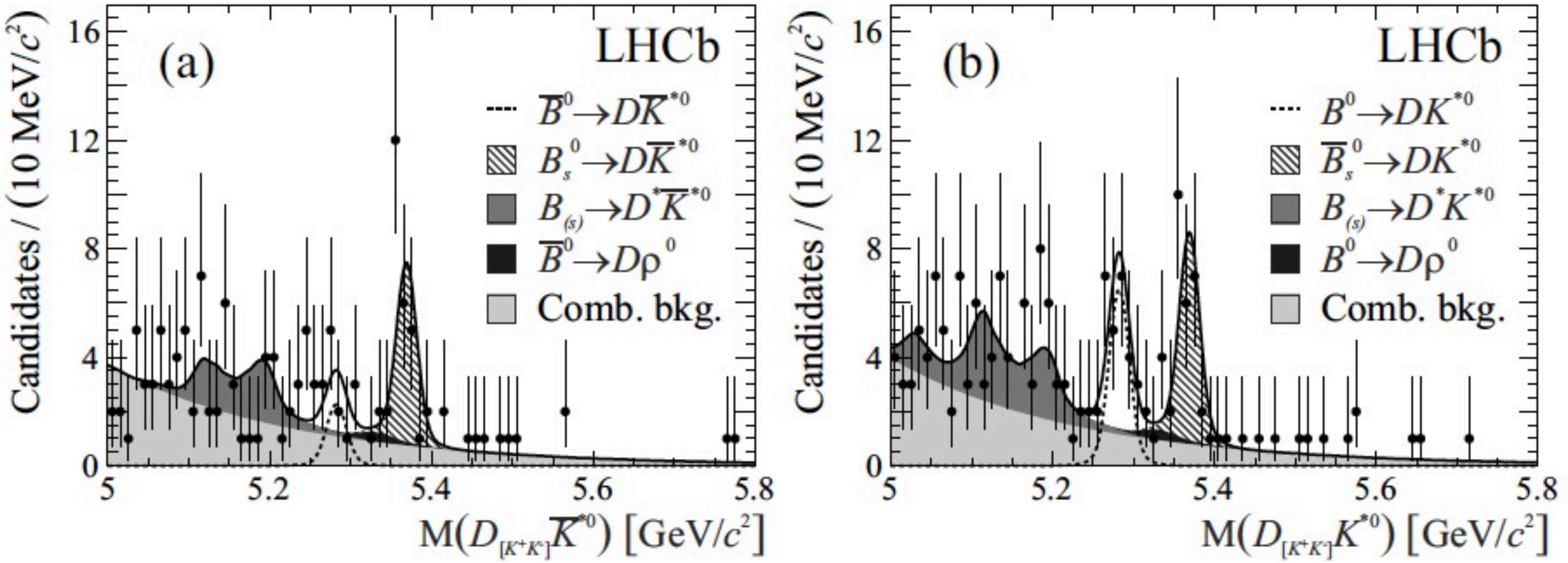
➢ **γ error expected to be ~9° at 2018; Similar analysis for $B_s \to D_s K\pi\pi$**

γ Studies with other B mesons (3)

LHCb-CONF-2012-024

➢ Flavor specified decay: $B^0 \to D^0 K\pi (K^*)$; Direct extension of $B \to D^0 K$; Dalitz analysis possible

~30 events



➢ Decay to CP eigenstates: $B^0 \to D^0(KK, \pi\pi)KK(\rho^0)$, ~900/fb signals; $B_s^0 \to D^0(KK, \pi\pi)KK(\phi)$ ~ 160/fb signals; Time dependent Dalitz analysis

➢ $B_c^+ \to D^+D^0$, $B_c^+ \to D_s^+D^0$: Observations with 2018 data

Large r_B

➢ Similar channels in b baryon, like $\Lambda_b \to D\Lambda$ etc.

γ Combination with LHCb data (1)

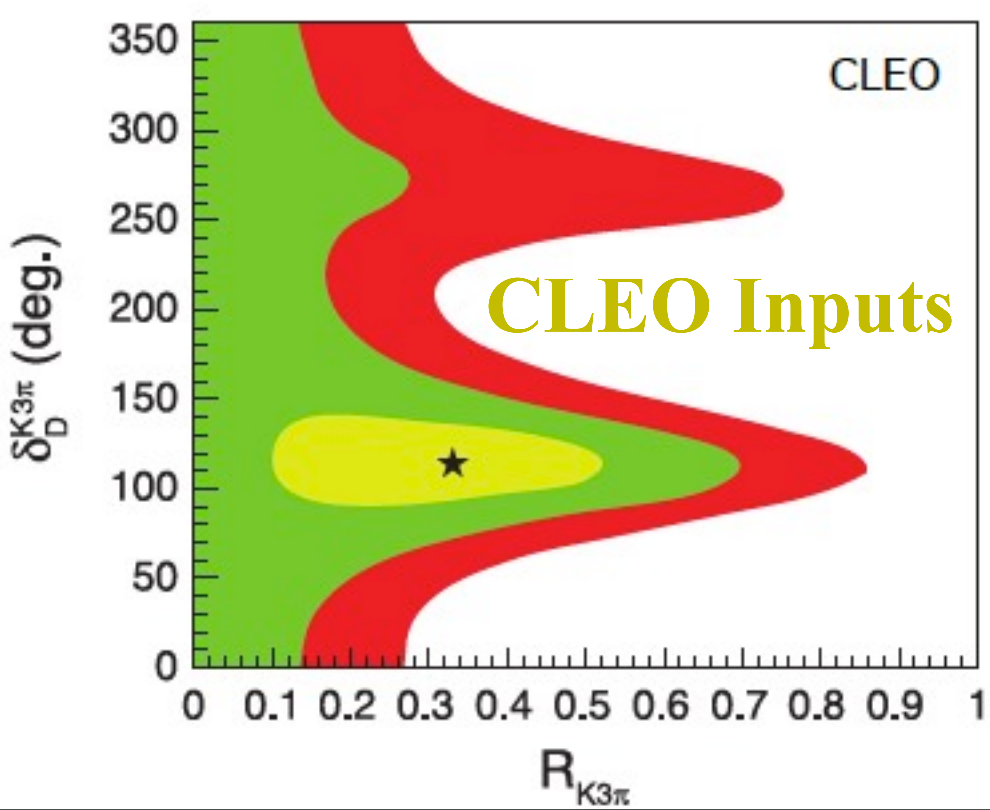
Analysis	N_{obs}	Parameters
$B^+ \to Dh^+$, $D \to hh$, GLW/ADS	14	γ, r_B, δ_B, r_B^π, δ_B^π, $R_{K/\pi}$, $r_{K\pi}$, $\delta_{K\pi}$, Δa_{CP}^{dir}
$B^+ \to DK^+$, $D \to K_s^0 h^+ h^-$, GGSZ	4	γ, r_B, δ_B
$B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS	7	γ, r_B, δ_B, r_B^π, δ_B^π, $R_{K/\pi}$, $r_{K3\pi}$, $\delta_{K3\pi}$, $\kappa_{K3\pi}$
Cleo $D^0 \to K\pi$, $D^0 \to K\pi\pi\pi$	9	x_D, y_D, $\delta_{K\pi}$, $\delta_{K3\pi}$, $\kappa_{K3\pi}$, $r_{K\pi}$, $r_{K3\pi}$, $\mathcal{B}(K\pi)$, $\mathcal{B}(K\pi\pi\pi)$
CP violation in the charm system	2	$A_{CP}^{D\to KK}$, $A_{CP}^{D\to\pi\pi}$
$B^0 \to DK^{0*}$, $D \to hh$, $K^* \to K\pi$, GLW	2	γ, $r_B^{K^{0*}}$, $\delta_B^{K^{0*}}$, $\kappa_B^{K^{0*}}$
$B^+ \to DK^+\pi^+\pi^-$, $D \to K\pi$, ADS	2	γ, $r_B^{DK\pi\pi}$, $\delta_B^{DK\pi\pi}$, $\kappa_B^{DK\pi\pi}$, $r_{K\pi}$, $\delta_{K\pi}$
$B^0 \to D^+\pi^-$ time dependent	5	γ, $\lambda_{D^+\pi^-}$, $\delta_{D^+\pi^-}$, Δm_d, $\sin 2\beta$
$B_s^0 \to D_s^+ K^-$ time dependent	5	γ, $\lambda_{D_s K}$, $\delta_{D_s K}$, Δm_s, Γ_s, $\Delta\Gamma_s$, ϕ_s

Included in Combination

Not Included in Combination

Observed variables

γ, r_B etc + nuisance parameters



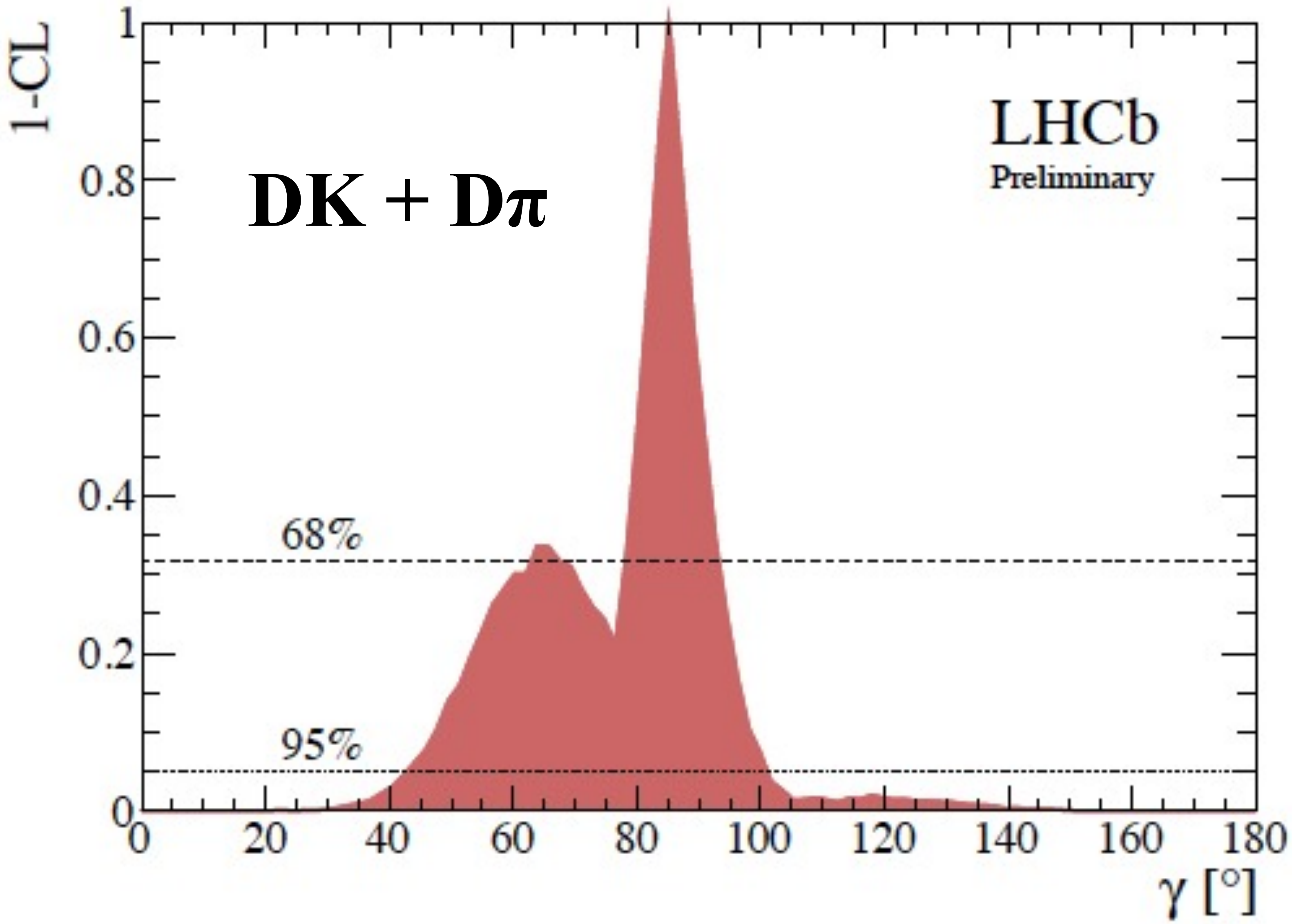
- ➢ D mixing ignored at this precision
- ➢ CP violation in charm system included

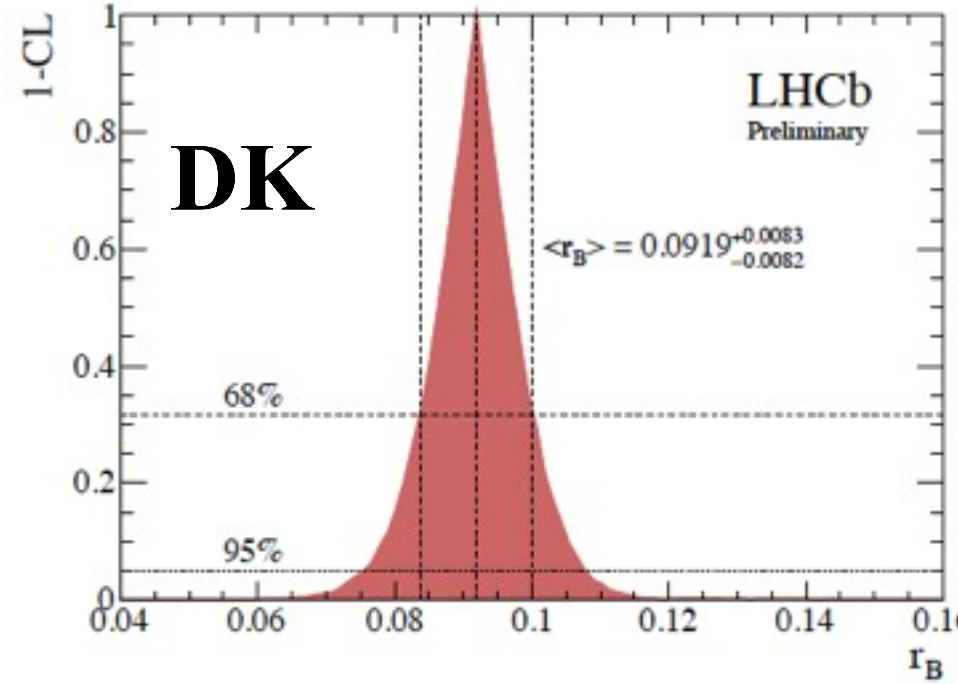
$$A_{CP,obs}^{D\to KK} = (-0.31 \pm 0.24) \times 10^{-2} ,$$
$$A_{CP,obs}^{D\to\pi\pi} = (0.36 \pm 0.25) \times 10^{-2} ,$$

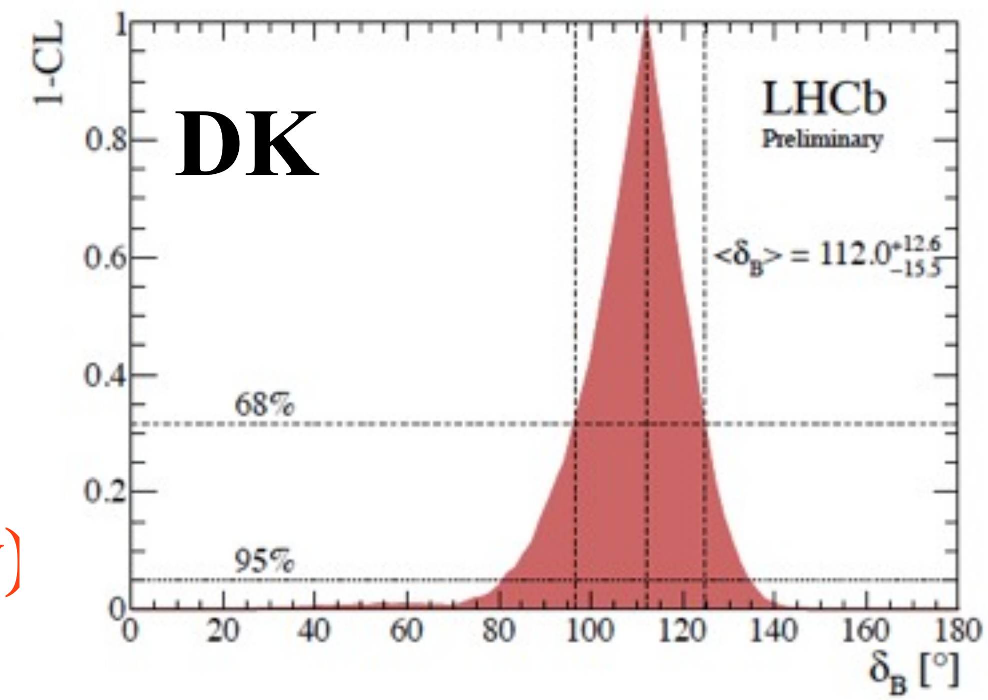
- ➢ Only combinations using frequentist approach is shown

γ Combination with LHCb data (2)

LHCb-CONF-2012-032







85.1° (71.1° if DK only)

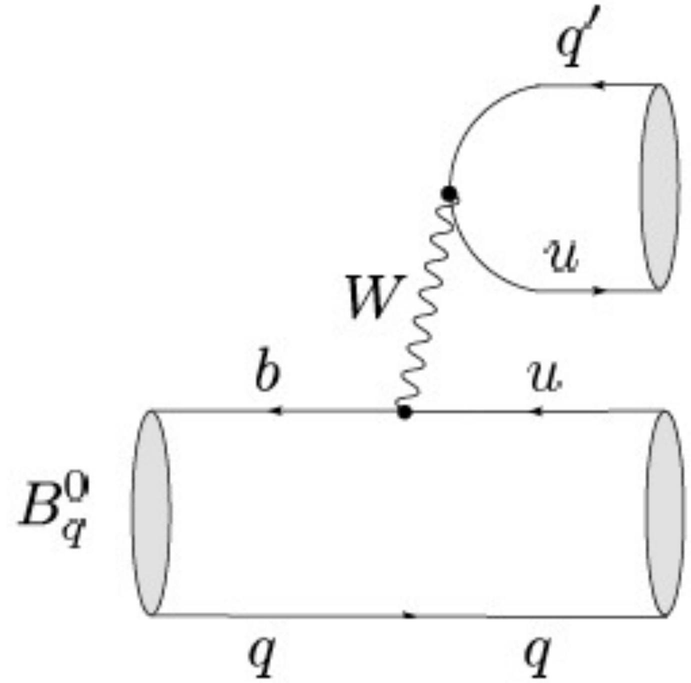
$$\gamma \in [61.8, 67.8]^\circ \quad \text{or} \quad [77.9, 92.4]^\circ \quad @\,68\%\ \text{CL}\ ,$$

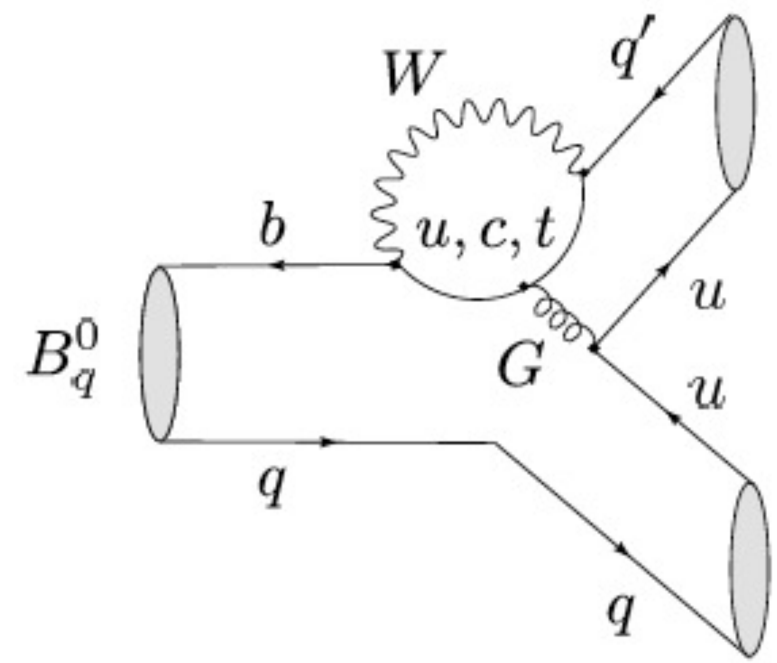
$$\gamma \in [43.8, 101.5]^\circ \quad @\,95\%\ \text{CL}\ ,$$

- **With 2018 dataset, γ error ~ 2° level (reduced by a factor of 4 + additional channels) as main systematic uncertainties is either not dominant or to be reduced by better treatment**

γ Using Loop-mediated Charmless B decays (1)

➢ **Instead of γ from interference between tree-level diagrams, γ could also be obtained from a tree-level b→u transition + loop level b→c transition**





2-Body

➢ **New physics can enter in penguin diagram; Comparing with γ from tree level only will indicate the contribution from new physics**

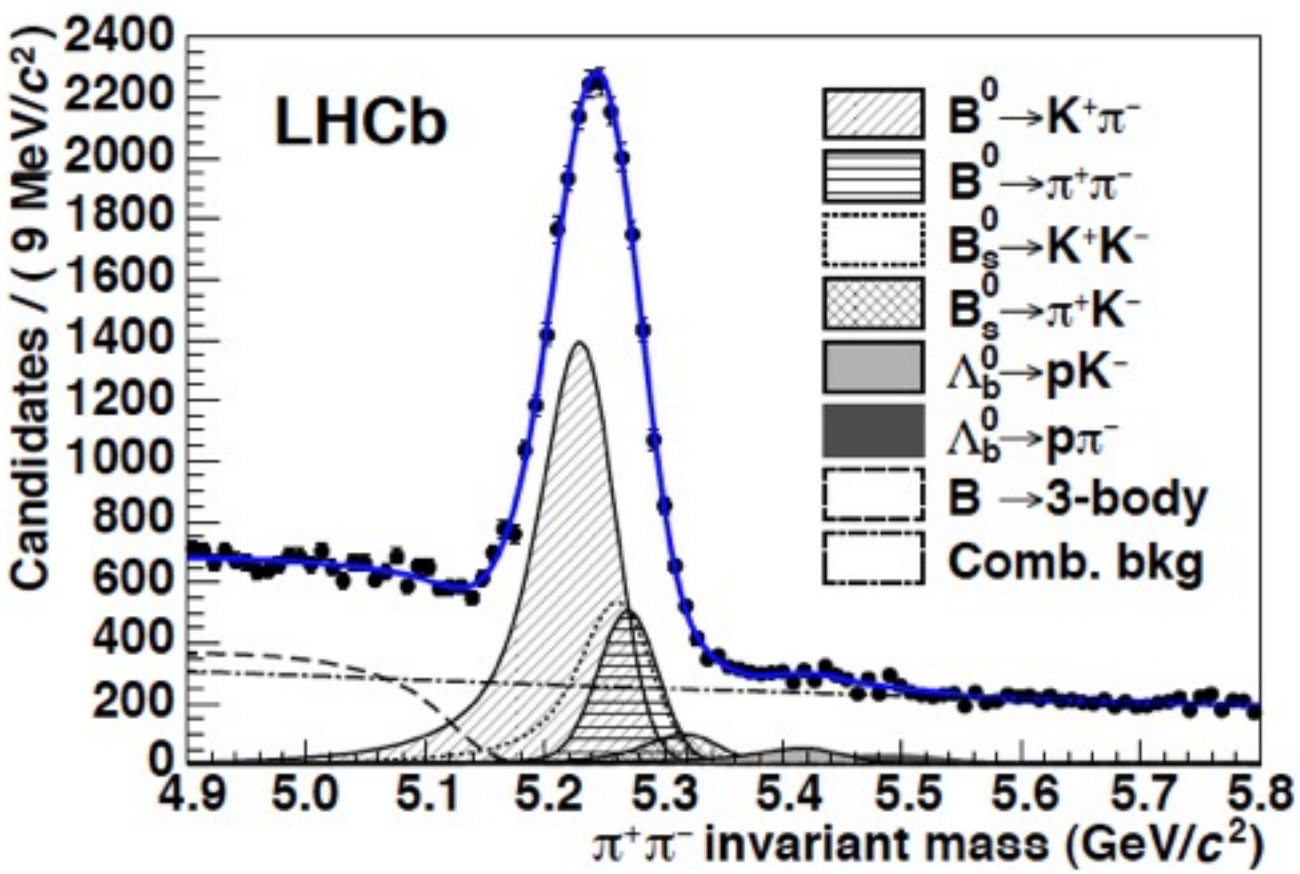
➢ **Benefit from combined Isospin analysis of $B^0 \to \pi^+\pi^-$, $\pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ and U-spin symmetry process $B_s \to KK$**

➢ **Inputs of combinations: branching fractions, direct and mixing-induced CP violation (time-dependent analysis needed)**

γ Using Loop-mediated Charmless B decays (2)

➢ **Branching fraction: 0.37 fb^{-1} data**

JHEP 10(2012) 037, arXiv:1202.2794



$$\mathcal{B}\left(B^0 \to \pi^+\pi^-\right) = (5.08 \pm 0.17 \pm 0.37) \times 10^{-6},$$
$$\mathcal{B}\left(B_s^0 \to K^+K^-\right) = (23.0 \pm 0.7 \pm 2.3) \times 10^{-6},$$
$$\mathcal{B}\left(B_s^0 \to \pi^+K^-\right) = (5.4 \pm 0.4 \pm 0.6) \times 10^{-6},$$
$$\mathcal{B}(B^0 \to K^+K^-) = (0.11\,^{+0.05}_{-0.04} \pm 0.06) \times 10^{-6},$$
$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (0.95\,^{+0.21}_{-0.17} \pm 0.13) \times 10^{-6}.$$

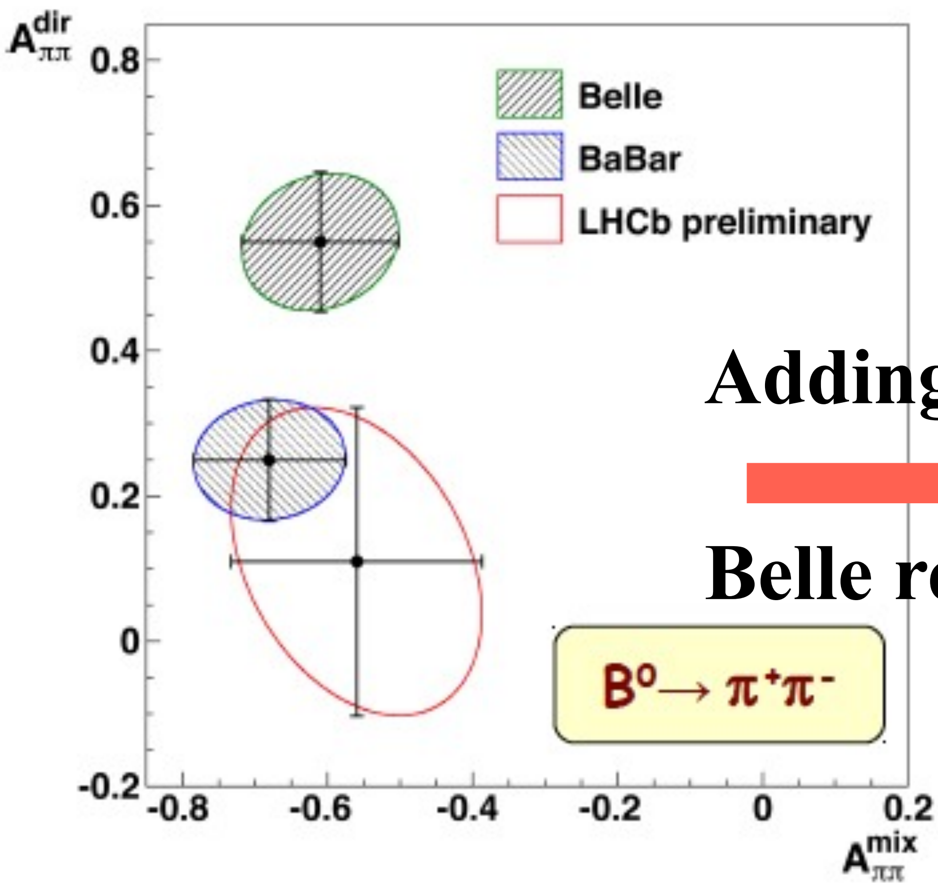
➢ **CPV measurements by time-dependent analysis with 0.69 fb^{-1} data with fixed values on Δm_d, Δm_s and sign of Γ_s (from LHCb)**

$$A_{CP}(t) = \frac{\Gamma(B^0_{(s)}(t=0) \to f) - \Gamma(\overline{B}^0_{(s)}(t=0) \to f)}{\Gamma(B^0_{(s)}(t=0) \to f) + \Gamma(\overline{B}^0_{(s)}(t=0) \to f)} = \frac{\boxed{A_f^{dir}} \cos(\boxed{\Delta m_{(s)}}\, t) + \boxed{A_f^{mix}} \cos(\boxed{\Delta m_{(s)}}\, t)}{\cosh(\frac{\boxed{\Delta\Gamma_{(s)}}}{2} t) - A_f^{\Delta\Gamma} \sinh(\frac{\boxed{\Delta\Gamma_{(s)}}}{2} t)}$$

γ Using Loop-mediated Charmless B decays (3)

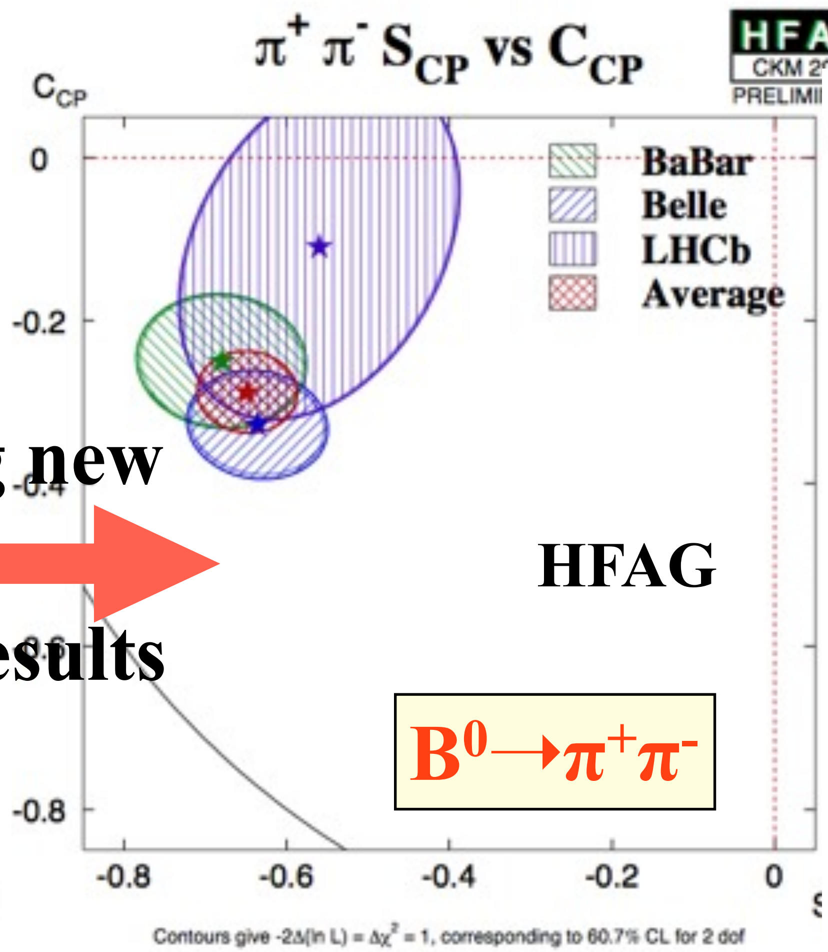
LHCb-CONF-2011-053

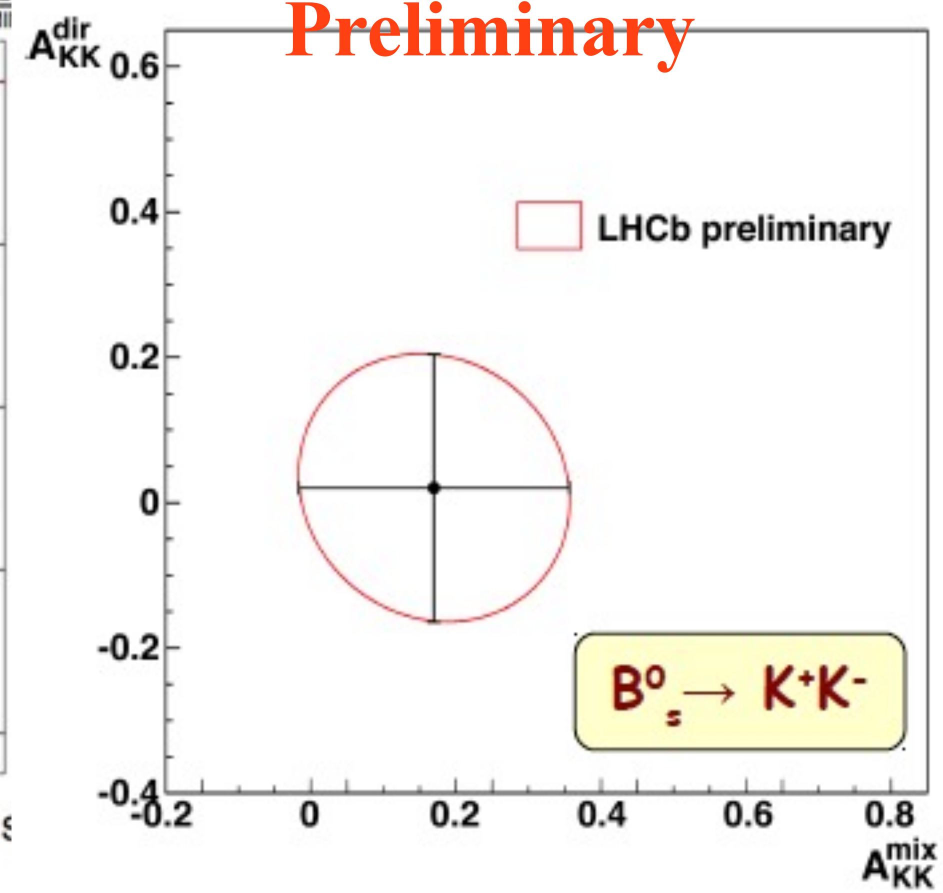
Preliminary



Adding new

Belle results





LHCb

$$A^{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$
$$A^{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$$

HFAG average:

$$A^{dir}_{\pi\pi} = 0.29 \pm 0.05$$
$$A^{mix}_{\pi\pi} = -0.65 \pm 0.06$$

LHCb

$$A^{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$$
$$A^{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$$

➢ **Combining current LHCb measurements + B factories (before middle 2012), a precision of ~10° on γ can be achieved**

γ Using Loop-mediated Charmless B decays (4)

- Analysis also performed with flavour-specific 2(3)-body final states

$$A_{CP} = \frac{\Gamma(B^0_{(s)} \to f) - \Gamma(\overline{B}^0_{(s)} \to \overline{f})}{\Gamma(B^0_{(s)} \to f) + \Gamma(\overline{B}^0_{(s)} \to \overline{f})}$$

- Using 0.35 fb^{-1} data:

Phys. Rev. Lett. 108 (2012), arXiv:1202.6251

$B^0 \to K^+\pi^-$ $\quad A_{CP} = (-0.088 \pm 0.011 \pm 0.008)$ $\quad > 6\sigma$

$B_s \to K^-\pi^+$ $\quad A_{CP} = (0.27 \pm 0.08 \pm 0.02)$ $\quad$ 3.2σ, first evidence

- Using 1 fb^{-1} data:

LHCb-CONF-2012-028, LHCb-CONF-2012-018

$B^+ \to K^+\pi^-\pi^+$ $\quad A_{CP}(K^\pm\pi^+\pi^-) = 0.034 \pm 0.009 \pm 0.004 \pm 0.007$

$B^+ \to K^+K^-K^+$ $\quad A_{CP}(K^\pm K^+ K^-) = -0.046 \pm 0.009 \pm 0.005 \pm 0.007$

$B^+ \to \pi^+\pi^-\pi^+$ $\quad A_{CP}(\pi^+\pi^-\pi^\pm) = 0.120 \pm 0.020 \pm 0.019 \pm 0.007$

$B^+ \to K^+K^-\pi^+$ $\quad A_{CP}(K^+K^-\pi^\pm) = -0.153 \pm 0.046 \pm 0.019 \pm 0.007$

Interesting CP structure over Dalitz plot

- SU(3) symmetry analysis can be performed to probe new physics underline

Conclusion: γ After 2018