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The CKM unitarity triangle angle γ at LHCb (Experiment)

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on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects

CERN, 15th October 2013

Outline

As the angle γ is the least experimentally constrained parameter of the UT
The precision measurement of γ is one of the main goals of the LHCb experiment

- **γ with trees**
  - Introduction
  - Combination formalism
  - Updated Results
- **γ with loops**
  - Introduction
  - Preliminary results

will not cover three-body charmless decays

$B \to DK$ & $B \to D\pi$
Including D mixing
GGSZ with 3fb-1

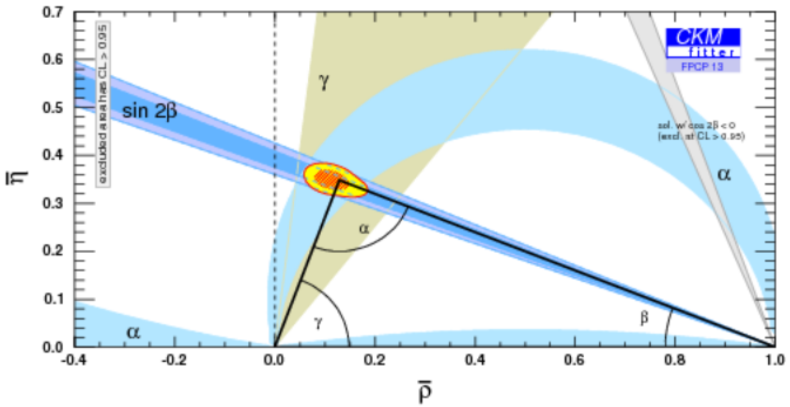
Bayesian approach
Updated with latest
$B \to hh$ LHCb results

Most results are preliminary

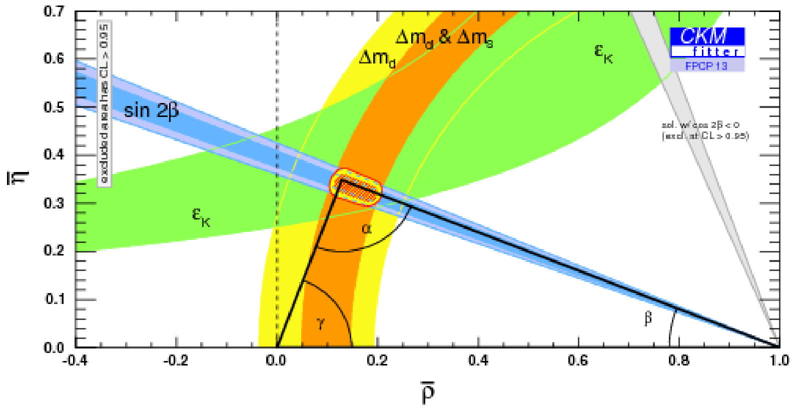
Global Combinations

Courtesy of CKMfitter
(updated August 6, 2013, FPCP)

"Tree" quantities



"Loop" quantities



We present here efforts to extract γ in different ways/many approach
Aim is to generate some discussion
I will not go into many details of the individual analysis

γ from trees

$B \to DK$ & $B \to D\pi$

LHCb has published a combination with a frequentist approach

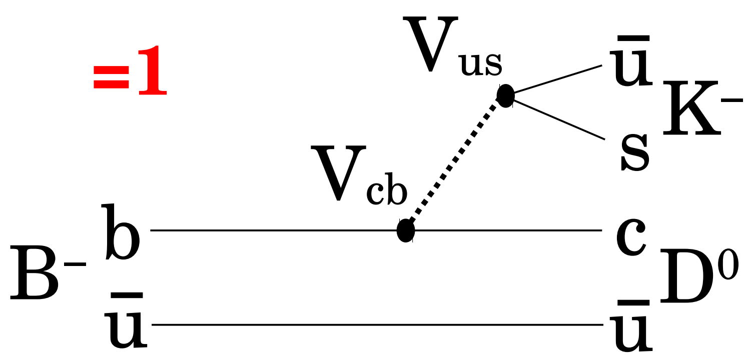
Work ongoing with a Bayesian approach

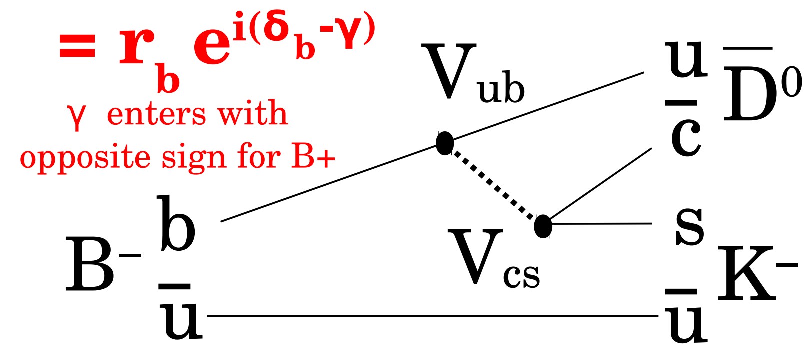
Introduction

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

From the first and third column of CKM

Idea: tree level determination of γ using $B^{\pm} \to DK^{\pm}$ decays
No contribution from penguins → Theoretically clean
Negligible theoretical uncertainty $\delta\gamma/\gamma \sim O(10^{-7})$





In principle one can use B → Dπ as well
Same formalism → add little sensitivity
Now we fully include B → Dπ in the combination

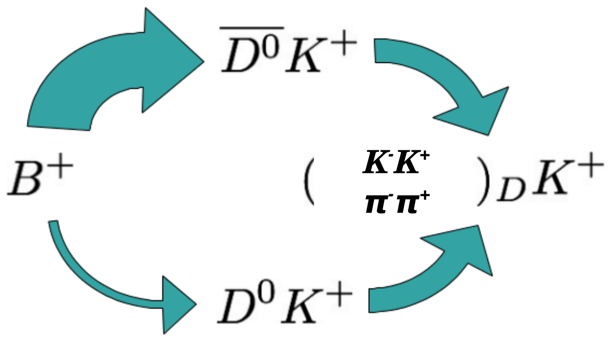
$B^{\pm} \to Dh^{\pm}$ formalism

Exploit interference: D^0 and $\overline{D}^0$ must decay to the same final state

GLW

D →KK
D → ππ

Gronau, London, Wyler
Phys. Lett. B 265 17 (1991)



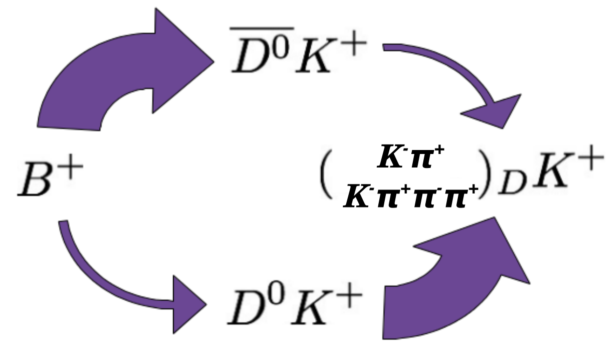
CP eigenstates like **K^+K^-** and **$\pi^+\pi^-$**

Colour FAVOURED
Colour SUPPRESSED
} *Interference O(10%)*

ADS

D →Kπ
D → Kπππ

Atwood, Dunietz, Soni
Phys.Rev.Lett. 78 (1997)



FAV followed by SUP

Reverse suppression leads to comparable amplitudes contributing to the decay } Large interference

GGSZ

Giri, Grossman, Soffer, Zupan
Phys. Rev. D68 (2003) 054018

- 3-body decays: **$D \to K_S\pi\pi, K_SKK$**
- Interference on the Dalitz plot exploited
- Strong phase δ_D varies on Dalitz space

Other modes can be considered as well, but not included yet in the combination

Strategy and Observables

- General Idea: measure as many γ-related quantities as possible
- Experimental observables are:
- **Charge asymmetries** and **yield ratios** (many systematics cancel)

DK/Dπ yield ratio

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to D[\to f]K^-) + \Gamma(B^+ \to D[\to f]K^+)}{\Gamma(B^- \to D[\to f]\pi^-) + \Gamma(B^+ \to D[\to f]\pi^+)}$$

Charge asymmetries

$$A^f_h = \frac{\Gamma(B^- \to D[\to f]h^-) - \Gamma(B^+ \to D[\to f]h^+)}{\Gamma(B^- \to D[\to f]h^-) + \Gamma(B^+ \to D[\to f]h^+)}$$

- Also one can define **Suppressed/Favoured decay ratio**

$$R^{\pm}_h = \frac{\Gamma(B^{\pm} \to D[\to f_{\rm sup}]h^{\pm})}{\Gamma(B^{\pm} \to D[\to f]h^{\pm})} = \frac{r_f^2 + (r_B^h)^2 + 2r_B^h r_f \kappa \cos(\delta_B^h + \delta_f \pm \gamma)}{1 + (r_B^h r_f)^2 + 2r_B^h r_f \kappa \cos(\delta_B^h - \delta_f \pm \gamma)}$$

r ,δ,κ

Extra hadronic parameters

depend on the B and D final state

Frequentist Combination

- Inputs combined to extract γ
- System of equations → **solvable if enough equations are considered**
- Measured quantities used in the combination:

B → Dh decays		
2body ADS/GLW:	**D → [Kπ,KK,ππ]**	2011 (1 fb^{-1})
4body ADS:	**D → [Kπππ]**	2011 (1 fb^{-1})
3body GGSZ:	**D → [K_sππ,K_sKK]**	2011 + 2012 (3 fb^{-1})

- Adopt a frequentist approach (Plugin)
- Assume almost Gaussian observables
- Gaussian systematic uncertainties
- Correct for undercoverage of the method

Update to the paper!

Phys Lett B 726 (2013) 1-3 151

Strategy

Combine all measurement in a likelihood

$$L(r_B^K, \delta_B^K, \gamma) = \exp\left(-\frac{1}{2}\left[\vec{\mathbf{x}}_{\rm meas} - \vec{\mathbf{x}}_{\rm true}\right]^T \mathbf{V}_{\rm TOT}^{-1}\left[\vec{\mathbf{x}}_{\rm meas} - \vec{\mathbf{x}}_{\rm true}\right]\right)$$

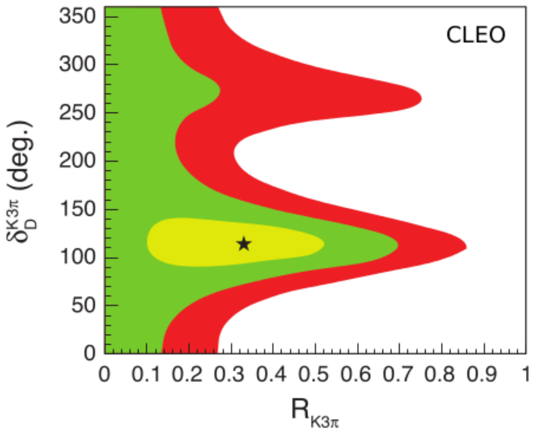
$$\mathbf{V}_{\rm TOT} = \mathbf{V}_{\rm stat} + \mathbf{V}_{\rm sys}$$

Constraints

- Include external constraints in the combination:

CLEO measurements of
D → hh, Kπππ systems

Phys. Rev. D80 (2009) 031105



- CP violation in the decays D → KK or D → ππ affects the GLW equations
- Modify the GLW asymmetries, leave the ratios unchanged

$$A_{CP}^{\text{dir}}(KK) = (-0.31 \pm 0.24) \times 10^{-2}$$

$$A_{CP}^{\text{dir}}(\pi\pi) = (+0.36 \pm 0.25) \times 10^{-2}$$

HFAG

$$A^{KK} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + (r_B)^2 + 2r_B \cos\delta_B \cos\gamma} + A_{CP}^{\text{dir}}(KK)$$

- **D^0 mixing is now fully considered in the B decay (and in the D params)**
- **Included in the published paper (all analyses with 1fb-1)**

Combination rerun with latest results available

Including D^0 mixing in the formalism

More details in
arXiv:1307.4384

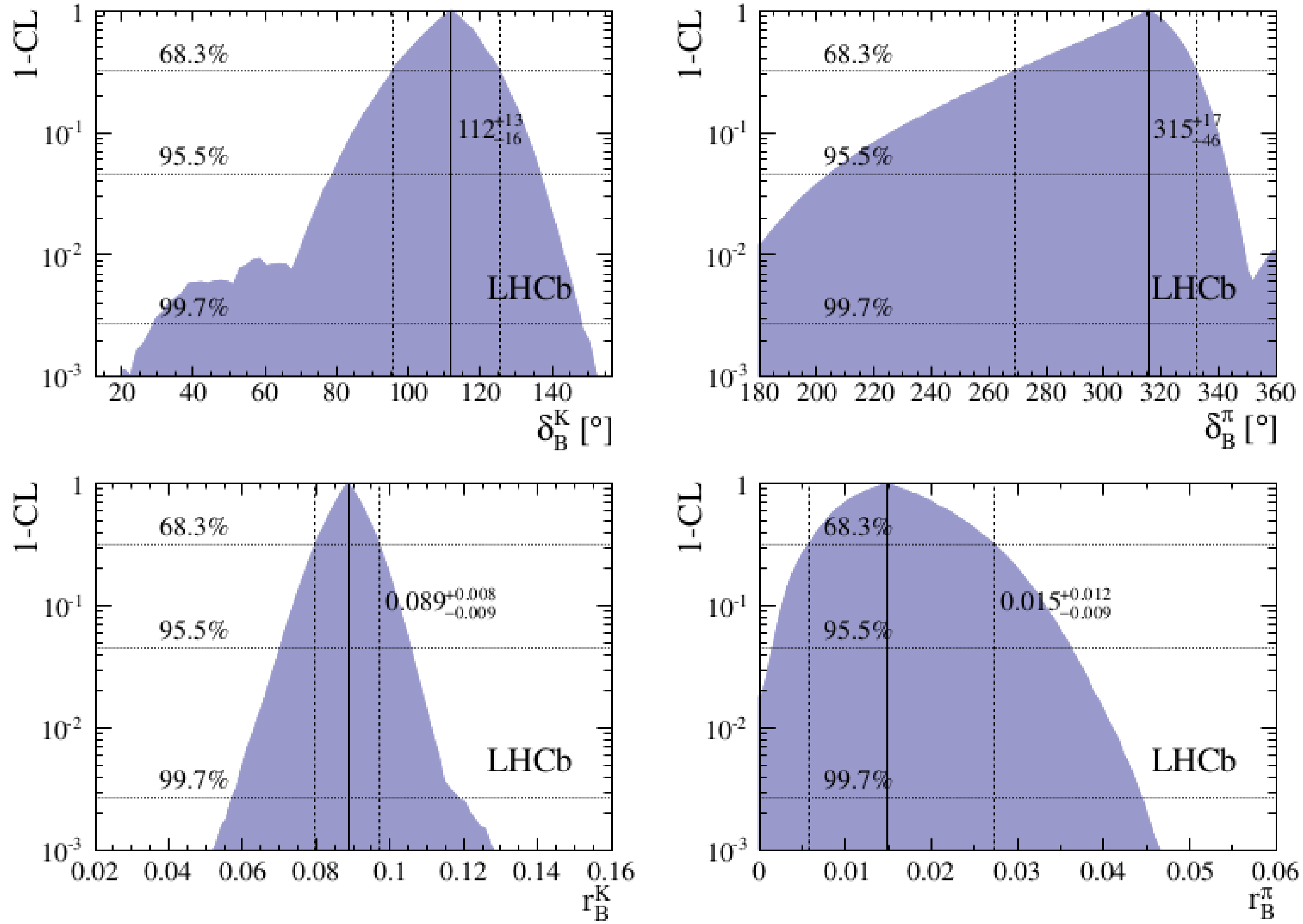
- Not going into the details of the calculations
- Same formalism → need to add corrections in the equations (extra terms)
- It can be shown that:
  - Effect is negligible for the model-independent GGSZ method
  - Effect is negligible for GLW method (corrections cancel in A_{CP} and are suppressed in double ratio)
  - **It affects the ADS method using B→DK at the 10% level**
  - **It affects the ADS method using B→Dπ at the 100% level**
- Combination is corrected:
  - Fully considering D mixing in B→DK and B→Dπ GLW/ADS
  - **Considering the D decay time resolution and acceptance in LHCb**
  - **Using LHCb results on D mixing [Phys. Rev. Lett. 110 (2012) 101802]**

$$R_h^{\pm} = \frac{\Gamma(B^{\pm} \to D[\to f_{\text{sup}}]h^{\pm})}{\Gamma(B^{\pm} \to D[\to f]h^{\pm})} = \frac{r_f^2 + (r_B^h)^2 + 2r_B^h r_f \kappa \cos(\delta_B^h + \delta_f \pm \gamma) - 2[M_{\pm}^h]_{\text{sup}}}{1 + (r_B^h r_f)^2 + 2r_B^h r_f \kappa \cos(\delta_B^h - \delta_f \pm \gamma) + 2M_{\pm}^h}$$

Same Formulas
get extra correction factors

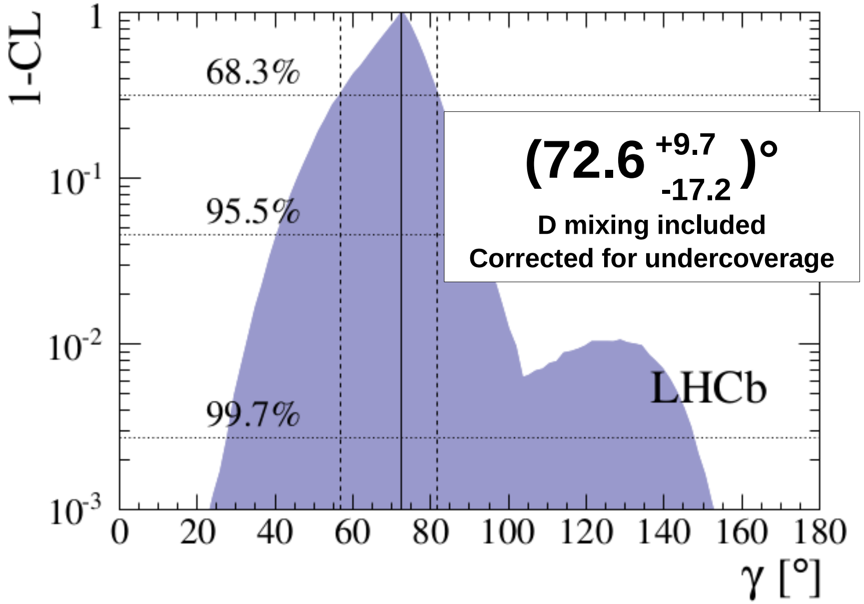
Results: B → DK & B → Dπ

- we include B → Dπ into a γ measurement
- First experimental γ combination that takes D mixing into account
- Published $1fb^{-1}$ result Phys Lett B 726 (2013) 151

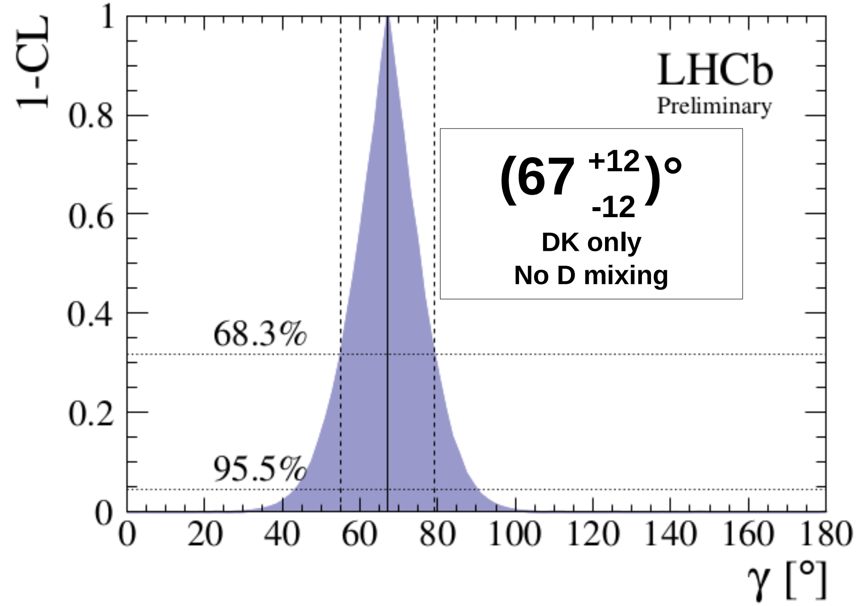


Results: B → DK & B → Dπ

Paper Phys Lett B 726 (2013) 151



LHCb-CONF-2013-006



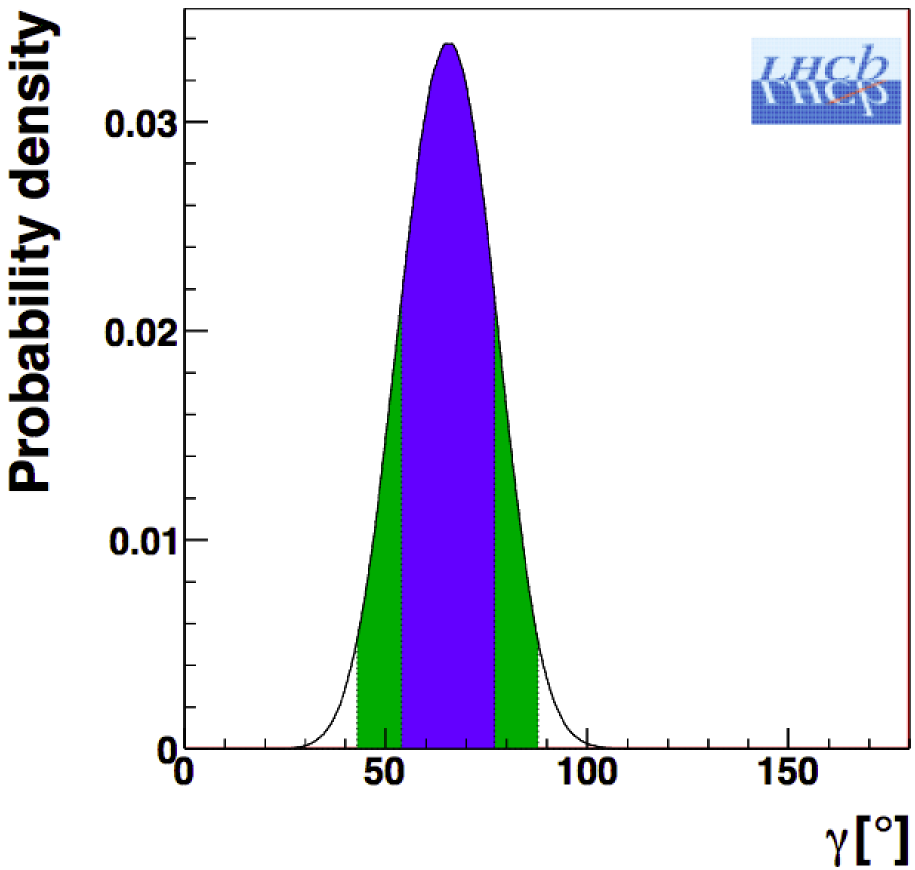
- LHCb has a complete set of $1fb^{-1}$ results: GLW, ADS, GGSZ
- GGSZ only is updated with $3fb^{-1}$ dataset (DK combo only)
- D^0 mixing is now included in the full formalism
- Impressive agreement with BaBar and Belle so far
- Expect updates of many analyses with full $3fb^{-1}$ dataset

BaBar γ = (69-16+17)°
Phys. Rev. D 87, 052015 (2013)

Belle **γ = (68-14+15)°**
arXiv:1301.2033

Bayesian Approach

- Work ongoing on a Bayesian combination for GWT
- To cross-check the combination…
- In general the agreement is encouraging, but some discrepancied must be understood
- In the DK system → very compatible results



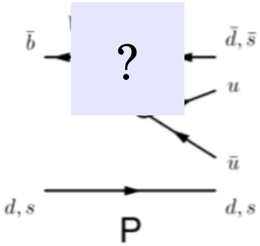
VERY PRELIMINARY

$(66^{+11}_{-12})°$
DK only
No D mixing

γ from loops

B → hh

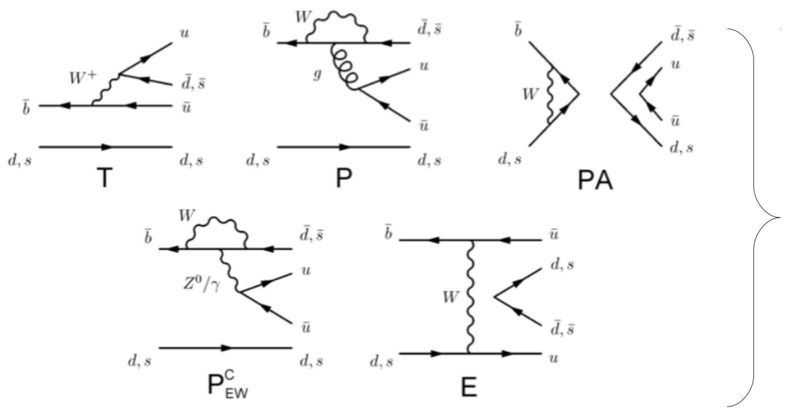
Work ongoing with a Bayesian approach
Comparison with GWT is important...



Bayesian Combination: B → hh

- Work ongoing for a Bayesian combination in LHCb
- Maily use charmless two body decays $B \to h^+h^-$
- γ can receive contributions from penguin diagrams
- Use U-spin symmetry to better constraint the system

- Several contributions: tree, strong/weak penguins, annihilation, exchange



Decay mode	Contributing diagrams
$B^0 \to \pi^+\pi^-$	$T,\ P,\ PA,\ P^C_{EW},\ E$
$B^0 \to K^+\pi^-$	$T,\ P,\ P^C_{EW}$
$B^0_s \to \pi^+K^-$	$T,\ P,\ P^C_{EW}$
$B^0_s \to K^+K^-$	$T,\ P,\ PA,\ P^C_{EW},\ E$
$B^0 \to K^+K^-$	$PA,\ E$
$B^0_s \to \pi^+\pi^-$	$PA,\ E$

This talk will not cover time dependent analysis → **see Denis' talk**
This talk will not cover three-body charmless decays → **see Irina's talk**

Methods (1)

- **Fleischer method**
  - Uses $B^0 \rightarrow \pi^+\pi^-$ and $Bs \rightarrow K^+K^-$ decays
  - BF and C,S (time dependent parameters)
  - 6 observables, 9 unknowns   D, D′, d, d′, θ, θ′, β, β_s, γ
  - U-spin → reduces number of unknown
  - Within factorization

Phys. Lett. B459, 306 (1999)
Eur. Phys. J. C52, 267 (2007)

d = d′, θ = θ′

D′/D = 1.46 ± 0.15

r_{fact}

Phys. Rev. D78 054015 (2008)

- **Gronau-London method**
  - Uses Bu,d → ππ (usual determination of γ = π-α-β)
  - BF and time dependent parameters
  - Amplitudes related with isospin
  - Can write system of equations as above, etc...

Phys. Rev. Lett. 65 (1990) 3381

Methods (2)

- Use approach proposed by Silvestrini et al.

JHEP 10 (2012) 29

- Combination of Gronau-London isospina analisis & Fleischer U-spin analysis
- Greatly improves sensitivity compared to GL alone

$$C_{\pi^+\pi^-} = -\frac{2d\sin(\vartheta)\sin(\gamma)}{1-2d\cos(\vartheta)\cos(\gamma)+d^2},$$

$$S_{\pi^+\pi^-} = -\frac{\sin(2\beta+2\gamma)+2d\cos(\vartheta)\sin(2\beta+\gamma)+d^2\sin(2\beta)}{1-2d\cos(\vartheta)\cos(\gamma)+d^2},$$

$$\mathcal{B}_{\pi^+\pi^-} = F(B^0)D^2(1-2d\cos(\vartheta)\cos(\gamma)+d^2),$$

$$C_{K^+K^-} = \frac{2\tilde{d}'\sin(\vartheta')\sin(\gamma)}{1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2},$$

$$S_{K^+K^-} = -\frac{\sin(-2\beta_s+2\gamma)+2\tilde{d}'\cos(\vartheta')\sin(-2\beta_s+\gamma)+\tilde{d}'^2\sin(-2\beta_s)}{1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2}$$

$$\mathcal{B}_{K^+K^-} = F(B_s^0)\frac{\lambda^2}{(1-\lambda^2/2)^2}D'^2(1+2\tilde{d}'\cos(\vartheta')\cos(\gamma)+\tilde{d}'^2),$$

$$C_{\pi^0\pi^0} = -\frac{2dT\sin(\vartheta_T-\vartheta)\sin(\gamma)}{T^2+2dT\cos(\vartheta_T-\vartheta)\cos(\gamma)+d^2},$$

$$\mathcal{B}_{\pi^0\pi^0} = F(B^0)\frac{D^2}{2}(T^2+2dT\cos(\vartheta_T-\vartheta)\cos(\gamma)+d^2),$$

$$\mathcal{B}_{\pi^+\pi^0} = F(B^+)\frac{D^2}{2}(1+T^2+2T\cos(\vartheta_T)),$$

- 9 observables
  - **$C_{\pi+\pi-}$, $S_{\pi+\pi-}$, $B_{\pi+\pi-}$, $C_{\pi0\pi0}$, $B_{\pi0\pi0}$, $B_{\pi+\pi0}$, C_{K+K-}, S_{K+K-}, B_{K+K-}**
- 11 unknowns (to be reduced using U-spin)
  - **D, D', d, d', T, θ, θ', θ_T, β, β_s, γ**

Combined Fleischer+GL analysis

Inputs

Channel	$\mathcal{B} \times 10^{-6}$	C_f	S_f	$\rho(C_f, S_f)$	Reference
$B^0 \to \pi^+\pi^-$	–	$-0.25 \pm 0.08 \pm 0.02$	$-0.68 \pm 0.10 \pm 0.03$	-0.06	BaBar
$B^0 \to \pi^+\pi^-$	–	$-0.33 \pm 0.06 \pm 0.03$	$-0.64 \pm 0.8 \pm 0.03$	-0.10	Belle
$B^0 \to \pi^+\pi^-$	–	$-0.38 \pm 0.15 \pm 0.02$	$-0.71 \pm 0.13 \pm 0.02$	0.38	LHCb
$B^0 \to \pi^+\pi^-$	5.10 ± 0.19	–	–	–	HFAG
$B_s^0 \to K^+K^-$	24.50 ± 1.80	–	–	–	HFAG
$B_s^0 \to K^+K^-$	–	$0.14 \pm 0.11 \pm 0.03$	$0.30 \pm 0.12 \pm 0.04$	0.02	LHCb

Parameter	Value	Reference
$\sin(2\beta)$	0.682 ± 0.019	HFAG
$2\beta_s$	$-0.01 \pm 0.07 \pm 0.01$	LHCb

Parameters

Parameter	Parameter's range
D	$[0, 10^{-3}]$
d	$[0, 2]$
θ	$[-\pi, \pi]$
T	$[0, 1.5]$
θ_T	$[-\pi, \pi]$
γ	$[-\pi, \pi]$

- Parameterise U-spin breaking
- Use flat priors
- Extra parameter κ

$$D' = D \cdot r_{fact} \cdot r_D$$

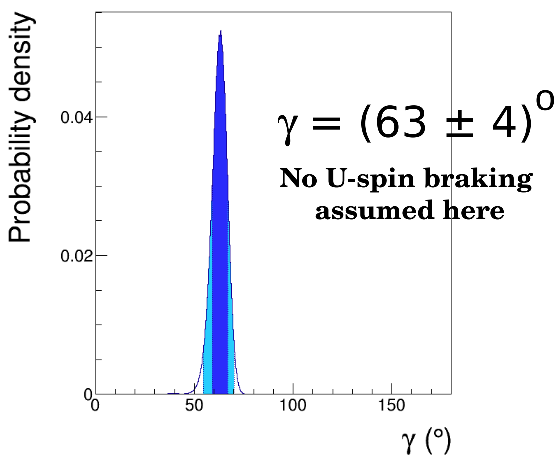
$$d' e^{i\theta'} = d e^{i\theta} \left(1 + r_d e^{i(r_\theta - \theta)}\right)$$

Flat priors

$$r_D \in [1-\kappa, 1+\kappa]$$

$$r_d \in [0, \kappa]$$

$$r_\theta \in [-\pi, \pi]$$

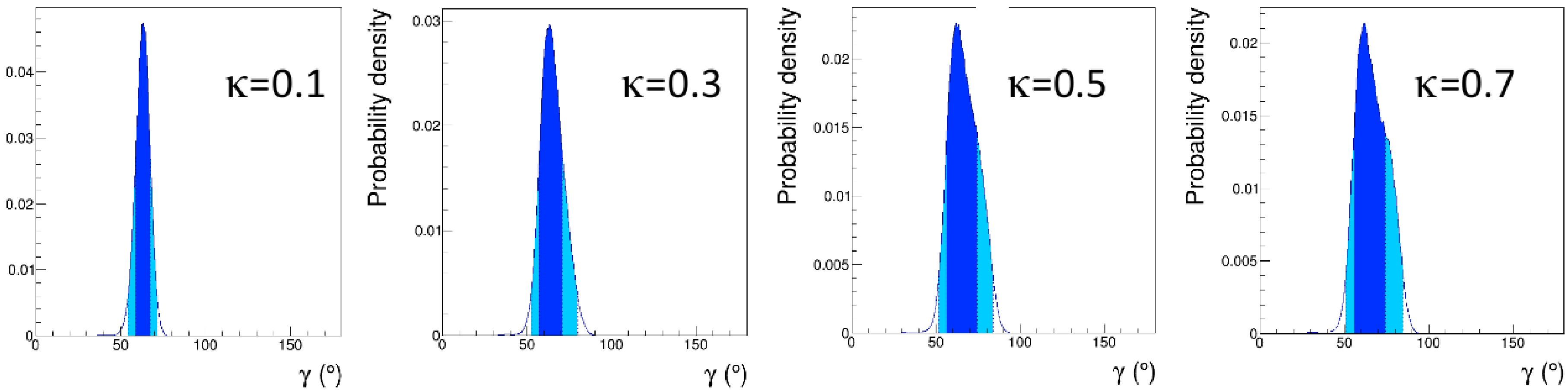


γ is determined with striking precision if no U-spin breaking is assumed

U-Spin Breaking

The parameter k governs the amount of non-factorizable U-spin breaking allowed

- k=0 means no U-spin breaking
- k=1 means up to 100% U-spin breaking



Interesting Questions

- What is a reasonable estimate of how much U-spin is broken in these decays?
- Is it possible to give any quantitative prediction?
- Can we expect progress from theory on U-spin breaking in the years to come?

Conclusions

γ from trees: $B \to Dh$

Frequestist paper published using LHCb only
CONF note updated using 3fb-1 GGSZ analysis

Paper	CONF
$(72.6^{+9.7}_{-17.2})°$ D mixing included Corrected for undercoverage	$(67^{+12}_{-12})°$ DK only No D mixing

Impressive agreement with BaBar and Belle
Work ongoing on Bayesian combination → comparison

γ from loops: $B \to hh$

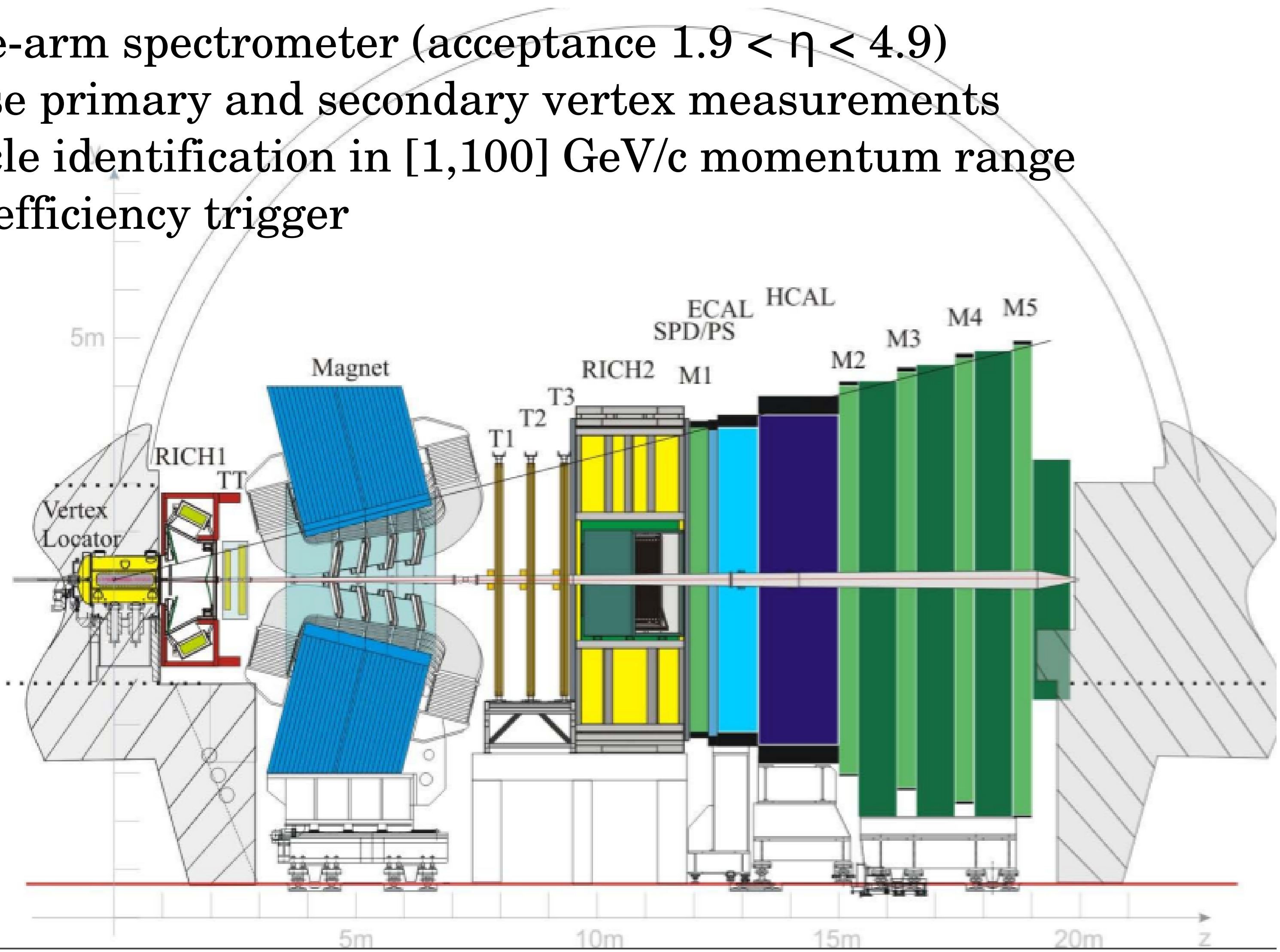
Using a combination of Gronau-London and Fleischer methods, γ can be determined from loop-mediated decays

- A sensitivity on γ of about ±10° is obtained accounting for large (up to 90%) non-factorizable U-spin breaking
- About ±4° in case of no breaking

Backup Slides

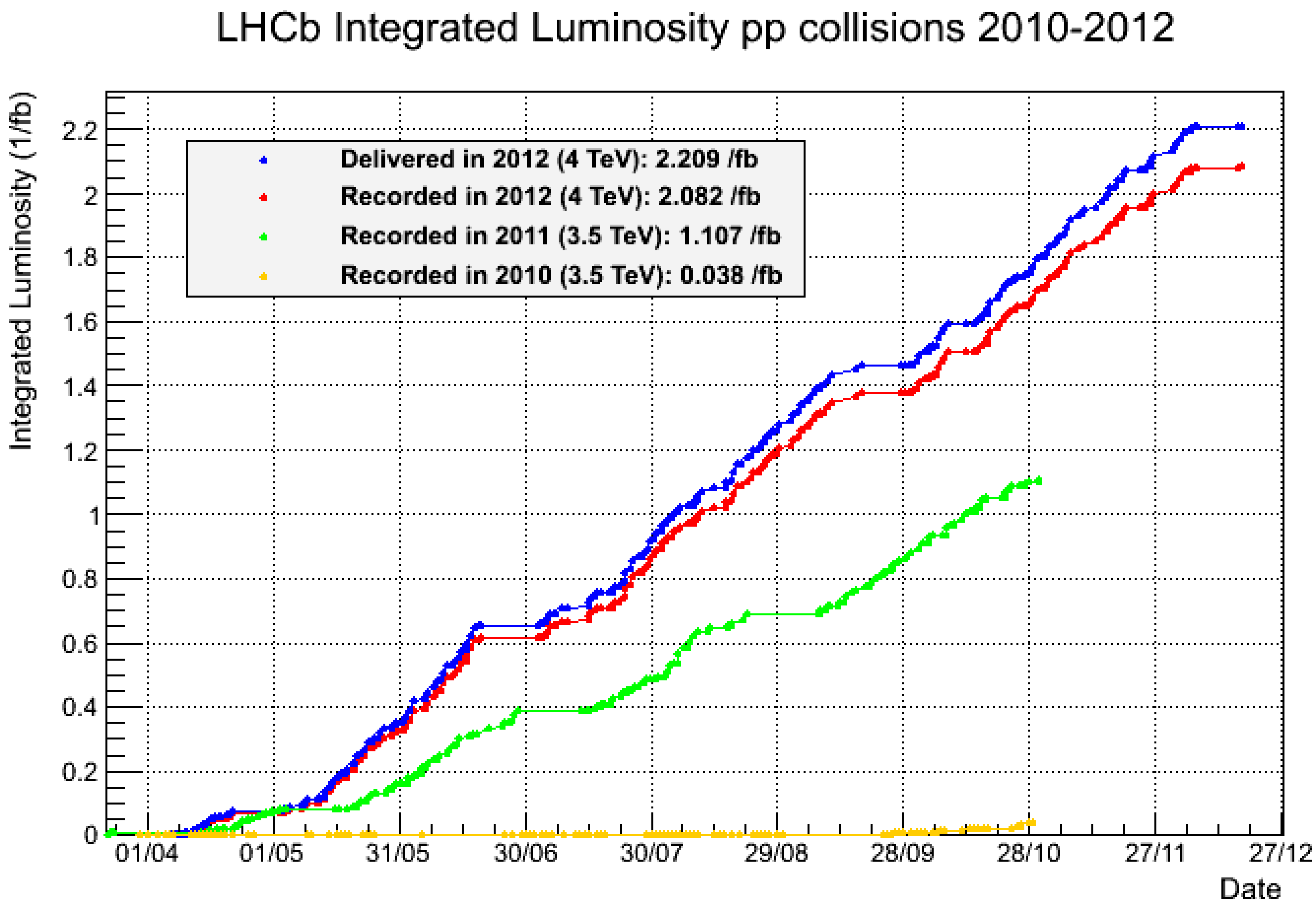
The LHCb experiment

- Single-arm spectrometer (acceptance $1.9 < \eta < 4.9$)
- Precise primary and secondary vertex measurements
- Particle identification in [1,100] GeV/c momentum range
- High efficiency trigger



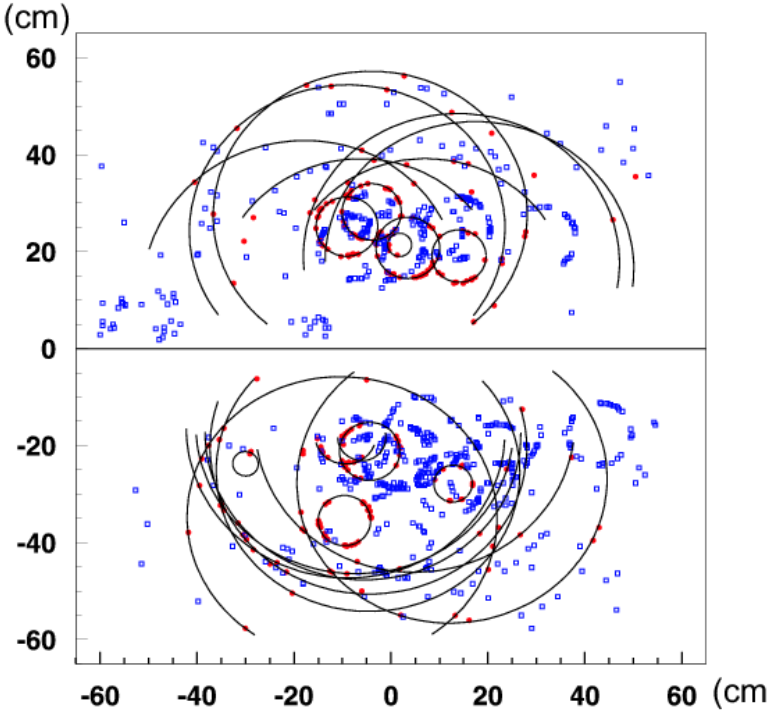
Luminosity

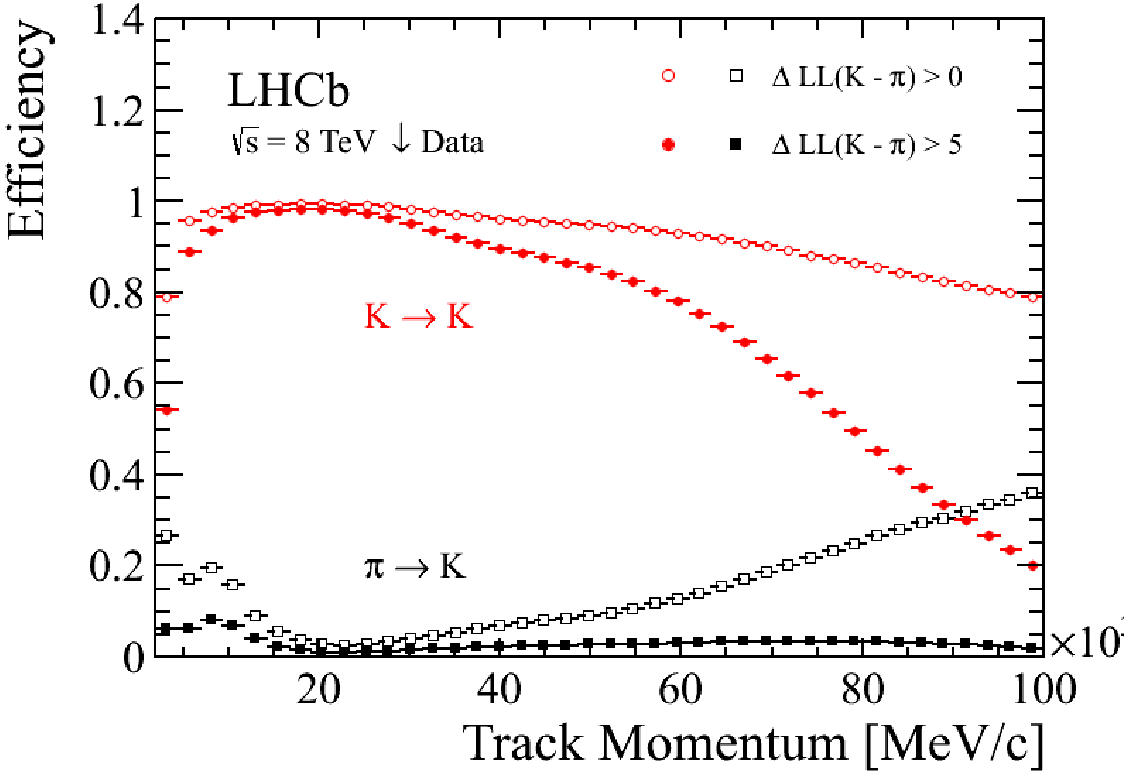
Collected (1.11 + 2.08) fb^{-1}



Particle Identification

- Fundamental to separate pions and kaons ($B \to DK$ vs $B \to D\pi$)
- RICH detectors with 3 separate radiators
- Particle identification up to p = 100GeV/c





Multibody modes: coherence factor

- Multibody modes have the same formalism and equations of 2body decays
- Equations get extra factors due to the integration on the Dalitz plot

- Interference can only occur at same points in phase space
- The hadronic parameters become **functions of the phase space**
- It is common to introduce **effective quantities averaged over phase space**

$$r^2_{K3\pi} = \frac{\int \bar{A}_D(\vec{m})^2 d\vec{m}}{\int A_D(\vec{m})^2 d\vec{m}}$$

$$\kappa_{K3\pi} e^{i\delta_{K3\pi}} = \frac{\int A_D(\vec{m}) \bar{A}_D(\vec{m}) e^{i\delta(\vec{m})} d\vec{m}}{\sqrt{\int \bar{A}_D(\vec{m})^2 d\vec{m} \times \int A_D(\vec{m})^2 d\vec{m}}}$$

$$R_\pm = (r_B^K)^2 + r^2_{K3\pi} + 2\kappa_{K3\pi} r_B^K r_{K3\pi} \cos(\pm\gamma + \delta_B^K + \delta_{K3\pi})$$

Coherence factor

Effective phase integrated on the phase space

Plugin Method

Scan for one specific physics parameter, x: For example γ

1. Find global minimum $\chi^2_{\rm min}$ and the most probable values for $\vec{x}$.
2. Fix x to x_0 and minimize with respect to the non-fixed parameters, i.e. obtain $\vec{x}'$, and $(\chi^2_{\rm min})'$. Calculate $\Delta\chi^2 = \chi^2_{\rm min} - (\chi^2_{\rm min})'$.
3. Generate a Toy MC result for $\vec{y}$, $\vec{y}_{\rm toy}$, by interpreting the likelihood as a PDF of $\vec{y}$.
4. Repeat the first two steps on the toy result, i.e. calculate $\Delta\chi^2_{\rm toy}$.
5. Calculate $(1 - {\rm CL})$ as the fraction

$$1 - {\rm CL} = \frac{N(\Delta\chi^2_{\rm toy} > \Delta\chi^2)}{N_{\rm toy}}. \quad (5)$$

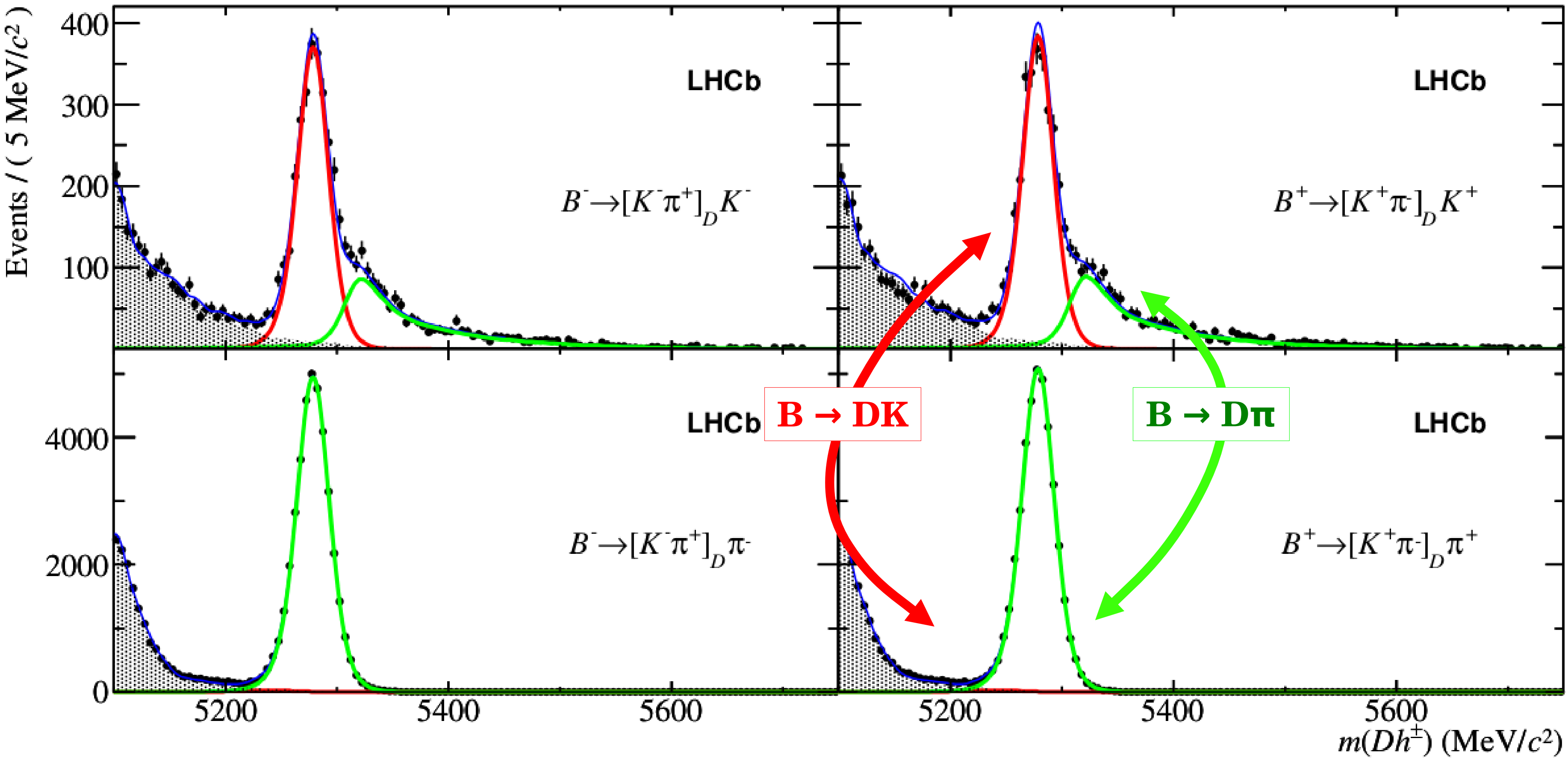
Use the best fit-values values for the parameters Can generate problem of undercoverage

Inputs: $B^{\pm} \rightarrow [K\pi]_D h^{\pm}$ Favoured

Simultaneous fit over all modes
Data divided in PASS & FAIL slices

Phys. Lett. B 712 (2012), pp. 203-212

2011 data set (1 fb^{-1})

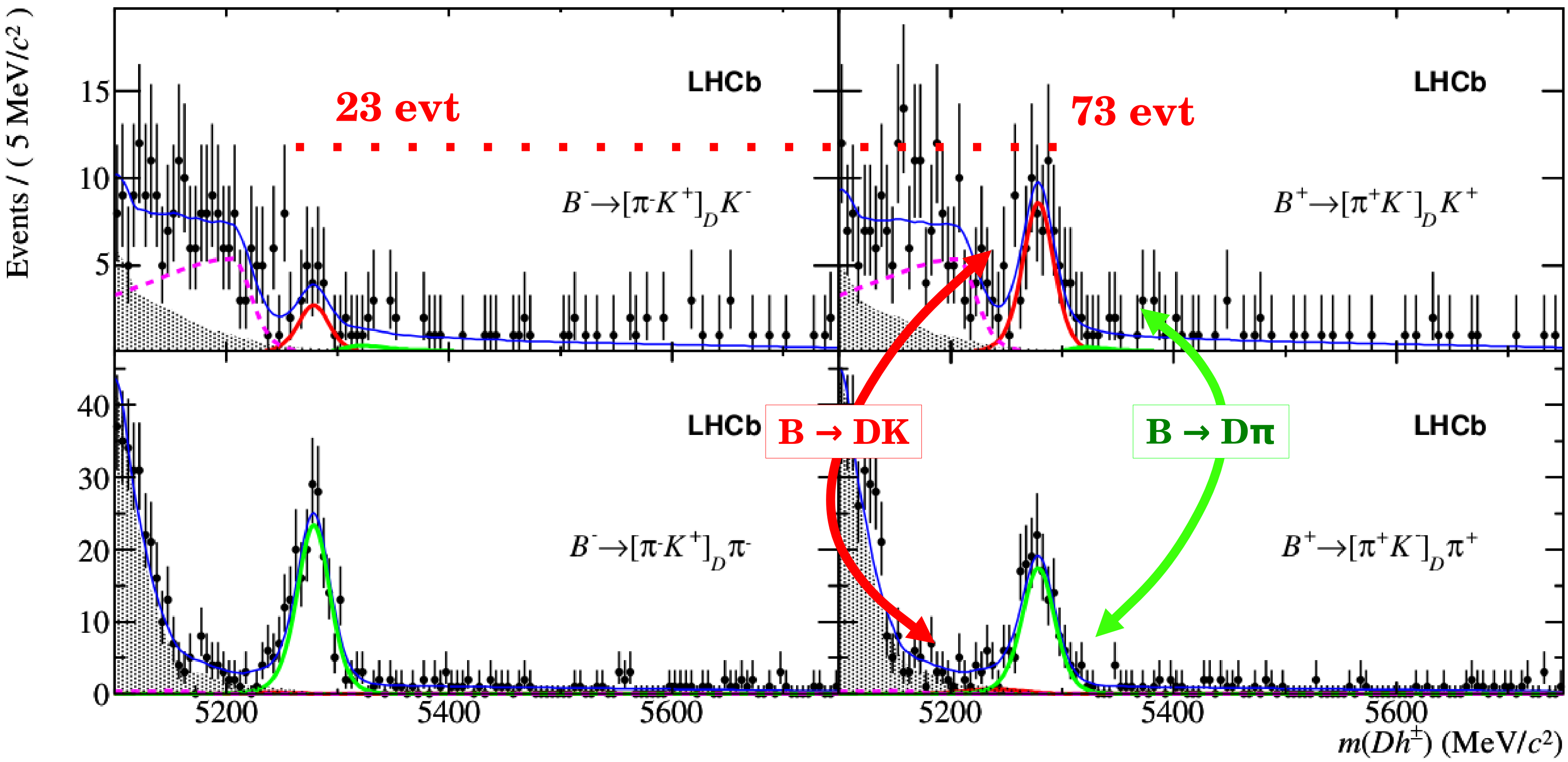


Inputs: $B^{\pm} \rightarrow [K\pi]_D h^{\pm}$ Suppressed

Simultaneous fit over all modes
Data divided in PASS & FAIL slices
Here only suppressed Kπ mode is shown
Benefit from the huge Cabibbo favoured mode

Phys. Lett. B 712 (2012), pp. 203-212

2011 data set (1 fb^{-1})

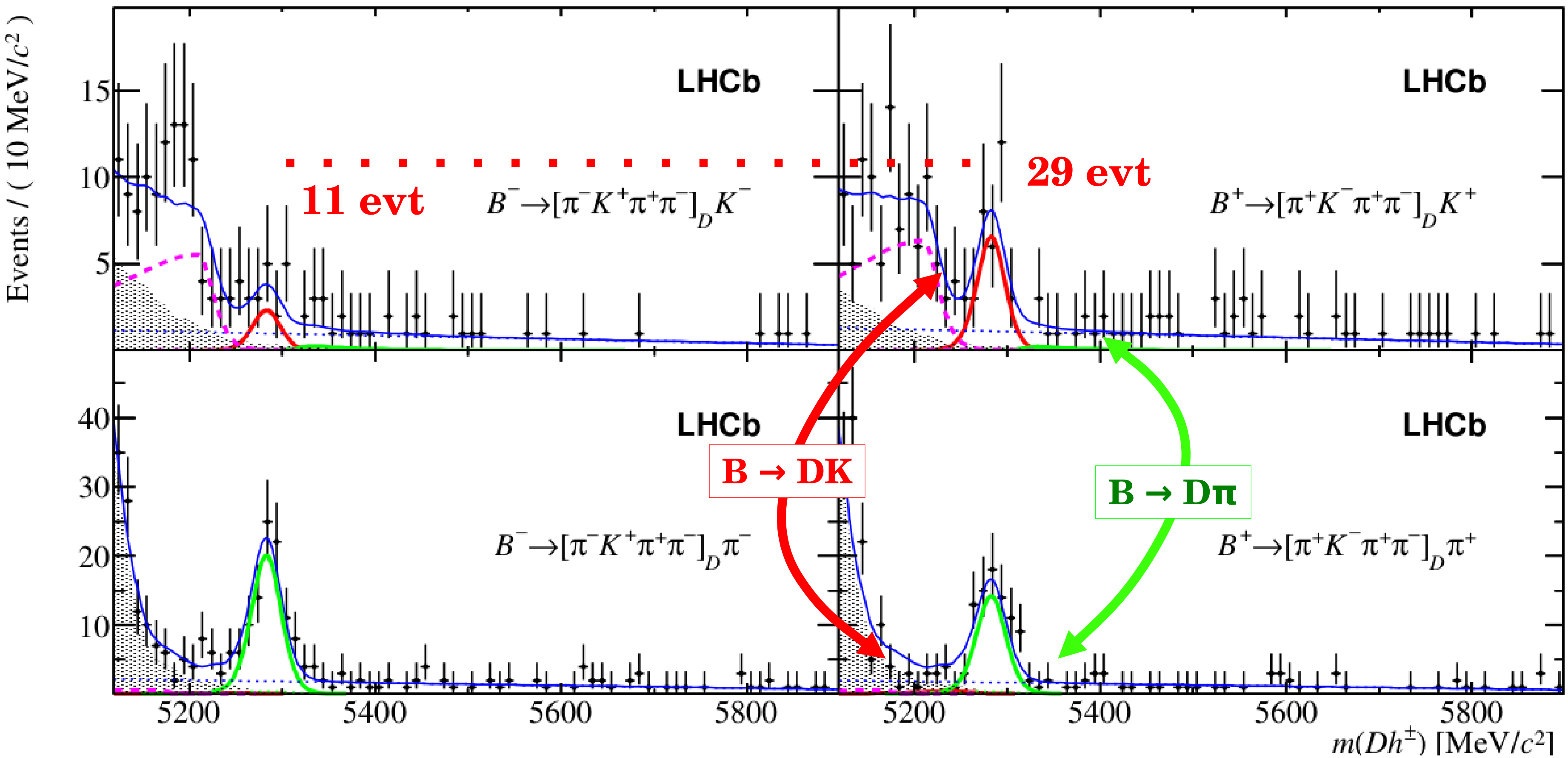


Inputs: $B^{\pm} \rightarrow [K\pi\pi\pi]_D h^{\pm}$

Simultaneous fit over all modes
Data divided in PASS & FAIL slices
First Observations

Phys Lett B 723 (2013) 44-53

2011 data set (1 fb^{-1})



Inputs: $B^{\pm} \to [K_s hh]_D K^{\pm}$

LHCb-CONF-2013-004

- Consider self-conjugate 3-body final states of the D
- Dependence of the strong phase on the Dalitz plot
- Phase variation measured by CLEO (used as input)

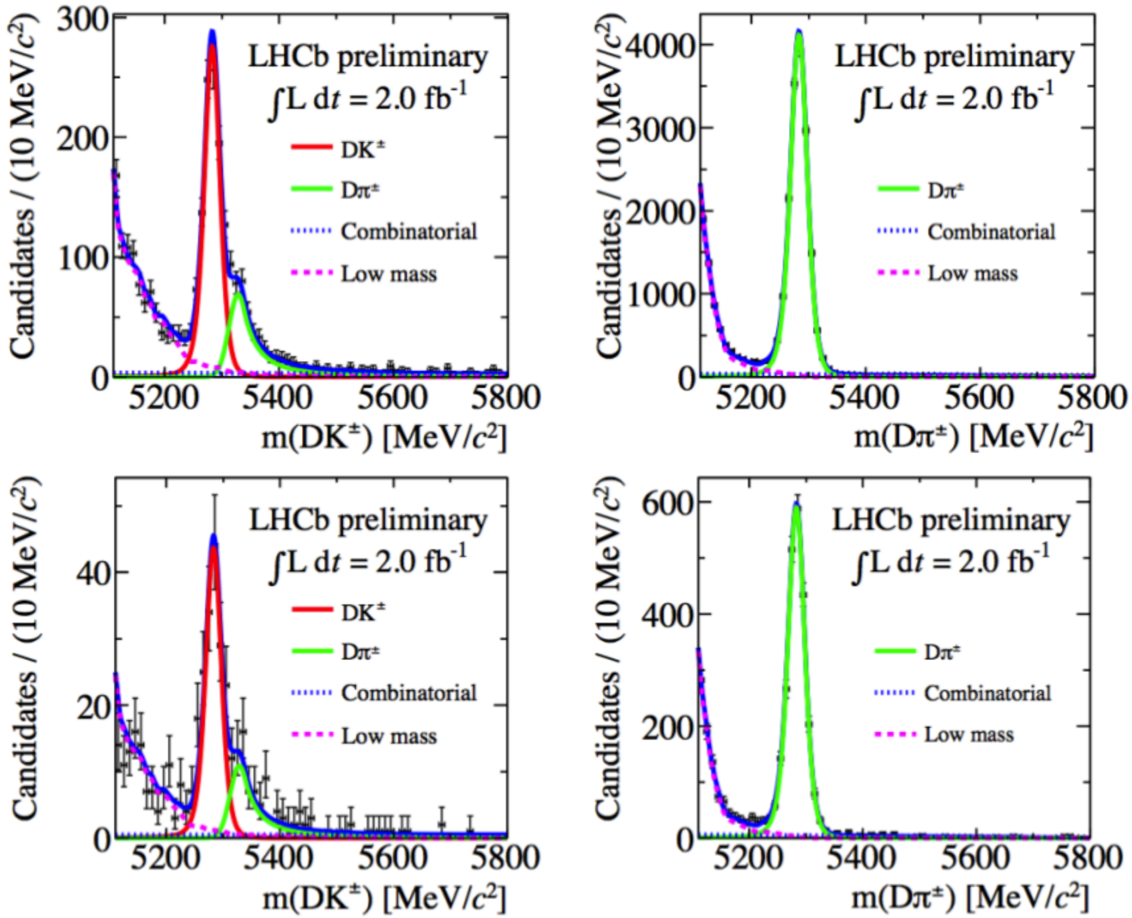
2011 +2012
data set (3 fb^{-1})

$B^{\pm} \to [K_s\pi\pi]_D h^{\pm}$

2012 only shown

$B^{\pm} \to [K_s KK]_D h^{\pm}$

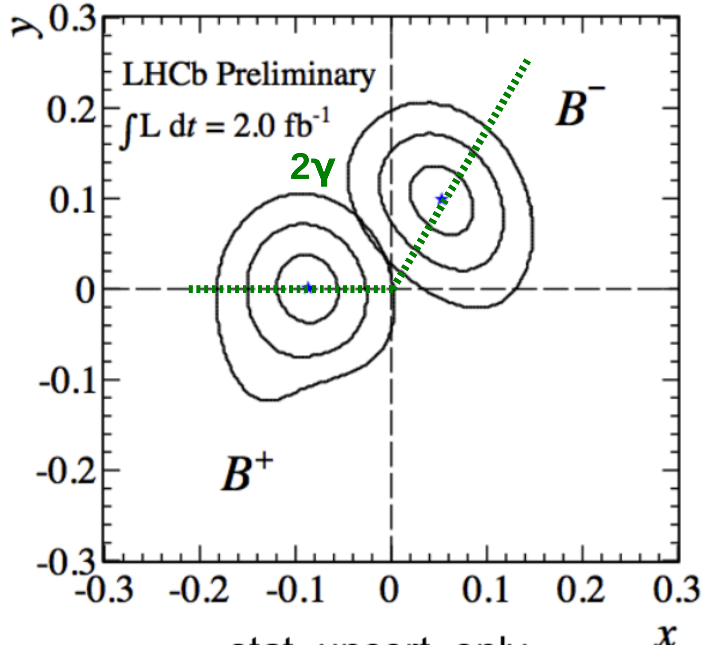
2012 only shown



Inputs: $B^\pm \to [K_s hh]_D K^\pm$

- **Efficiency on the Dalitz determined comp the D yield to the model prediction in B → Dπ**
- B → Dπ used as a control sample: assume no CPV (systematic assigned)
- Density information → used to estimate reco efficiency
- The efficiency is fed into the equations that determine CP quantities (part of the fit)

8 TeV 2012



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stat. uncert. only

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

independent measurement of γ = (57 ± 16)◦

Including D^0 mixing in the formalism

- Amplitudes now consider D mixing:

$$A(D^0(t) \to f) = g_+(t) A_f + q/p\, g_-(t) \overline{A}_f$$
$$A(\overline{D}^0(t) \to f) = g_+(t) \overline{A}_f + p/q\, g_-(t) \overline{A}_f$$
$$g_\pm = \frac{1}{2}\left(e^{-im_1 t - \frac{1}{2}\Gamma_1 t} \pm e^{-im_2 t - \frac{1}{2}\Gamma_2 t}\right)$$

- Neglecting terms of $O(x^2,y^2)$, assuming p/q = 1 and integrating for (t=0,∞), Amplitudes are:

$$\int_0^\infty |A(B^- \to D(\to f,t)h^-|^2 \mathrm{d}t = |A_D|^2 |\overline{A}_f|^2 \times \Big[$$
$$\left((r_B^h)^2 + r_f^2 + 2 r_B^h \kappa_f r_f \cos(\delta_B^h + \delta_f - \gamma)\right) I_+$$

zero at $O(x^2,y^2)$
$$+ \left(1 + (r_B^h)^2 r_f^2 + 2 r_B^h \kappa_f r_f \cos(\delta_B^h + \delta_f - \gamma)\right) I_-$$

Corrections O(x,y)
$$+2\left(\kappa_f r_f ((r_B^h)^2 + 1)\cos\delta_f + r_B^h (1 + r_f^2)\cos(\delta_B^h - \gamma)\right) I_y$$
$$-2\left(\kappa_f r_f ((r_B^h)^2 - 1)\sin\delta_f + r_B^h (1 - r_f^2)\sin(\delta_B^h - \gamma)\right) I_x \Big]$$

$$I_+ \equiv 1$$
$$I_y = -M_{xy} x_D / \Gamma$$
$$I_- = 0\,,$$
$$I_x = M_{xy} y_D / \Gamma$$

Gronau-London analysis

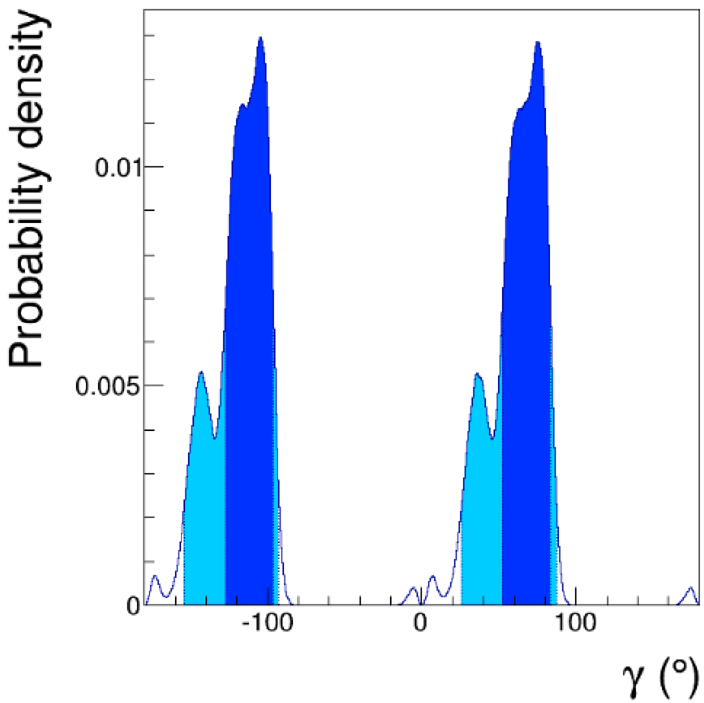
Inputs

Channel	$\mathcal{B}\times 10^{-6}$	C_f	S_f	$\rho(C_f, S_f)$	Reference
$B^0\to\pi^+\pi^-$	–	$-0.25\pm0.08\pm0.02$	$-0.68\pm0.10\pm0.03$	-0.06	BaBar
$B^0\to\pi^+\pi^-$	–	$-0.33\pm0.06\pm0.03$	$-0.64\pm0.8\pm0.03$	-0.10	Belle
$B^0\to\pi^+\pi^-$	–	$-0.38\pm0.15\pm0.02$	$-0.71\pm0.13\pm0.02$	0.38	LHCb
$B^0\to\pi^+\pi^-$	5.10 ± 0.19	–	–	–	HFAG
$B^0\to\pi^0\pi^0$	1.91 ± 0.23	-0.43 ± 0.24	–	–	HFAG
$B^+\to\pi^+\pi^0$	5.48 ± 0.35	–	–	–	HFAG

Parameter	Value	Reference
$\sin(2\beta)$	0.682 ± 0.019	HFAG

Parameters

Parameter	Parameter's range
D	$[0, 10^{-3}]$
d	$[0, 2]$
θ	$[-\pi, \pi]$
T	$[0, 1.5]$
θ_T	$[-\pi, \pi]$
γ	$[-\pi, \pi]$



γ = [52.5°, 83.6°] at 68% probability

γ = [25.9°, 87.6°] at 95% probability

VERY PRELIMINARY