Measurements of the CPV γ angle

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on behalf of the **LHCb Collaboration**

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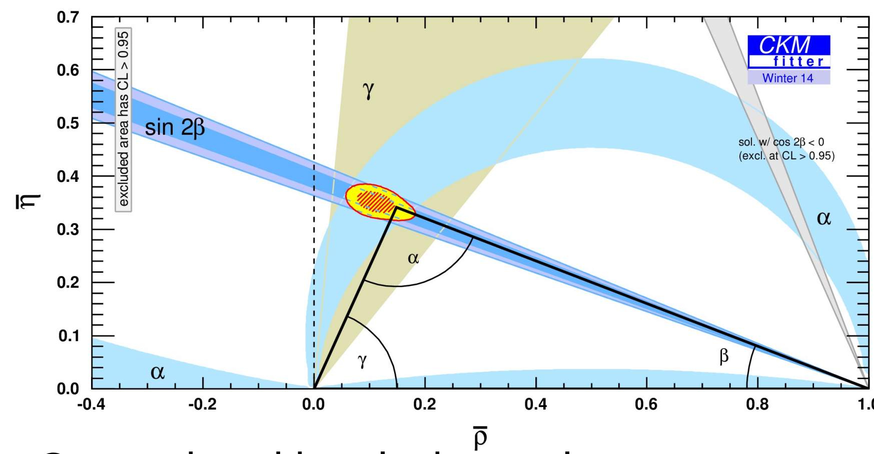
γ a standard candle to probe new physics

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \approx \arg\left(-V_{ub}^*\right)$$

- γ is the least known CKM parameter:
  - BaBar: $(69^{+17}_{-16})°$ [PRD 87(2013)052015]
  - Belle: $(68^{+15}_{-14})°$ [arXiv:1301.2033]
  - LHCb: (67±12)° [LHCb-CONF-2013-006]
  - CKM Fitter: $(66.5^{+1.3}_{-2.5})°$ (global fit)



Constraint with only the angle measurements

- The only angle measurable from **tree processes** (loops negligible).
- **Theoretically clean** : $\delta\gamma/\gamma \lesssim \mathcal{O}(10^{-7})$ [JHEP 1401(2014)051].

➡ Excellent **Standard Model reference** to probe New Physics.

Need a better precision from direct measurement.

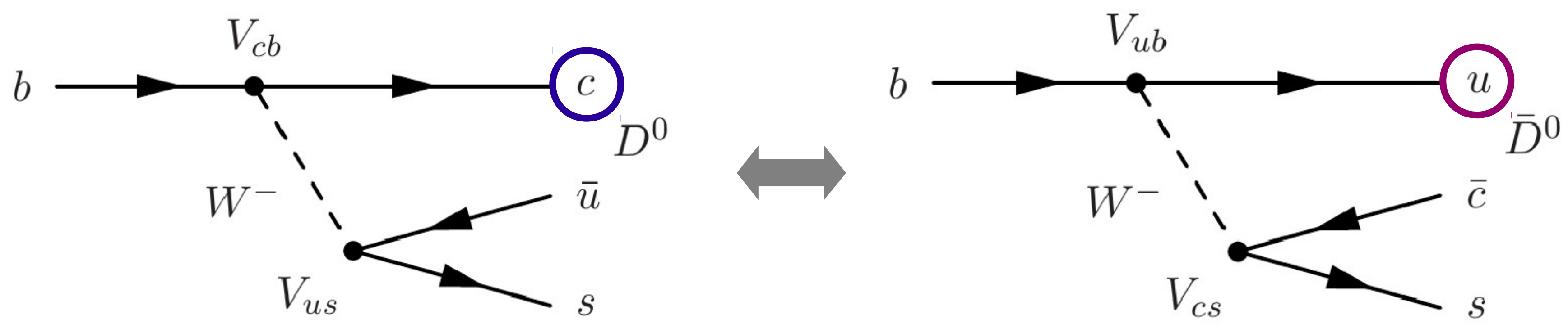
Today's menu

Four recent LHCb results (to be submitted to journals soon):

- **$B^{\pm} \to D(K^0_S \pi^+ \pi^-) K^{\pm}$**, Amplitude analysis, Model-dependent (1 fb^{-1}).
  [LHCb-PAPER-2014-017]
- **$B^{\pm} \to D(K^0_S h^+ h^-) K^{\pm}$**, Amplitude analysis, Model-independent (3 fb^{-1}).
  [LHCb-PAPER-2014-041]
- **$B^0 \to DK^{*0}$**, Counting analysis (3 fb^{-1}).
  [LHCb-PAPER-2014-028]
- **$B^0_s \to D_s K^{\pm}$**, Time dependent analysis (1 fb^{-1}).
  [LHCb-PAPER-2014-038]

Time integrated measurements

- Interference between **b→c$\bar{u}$s** and **b→u$\bar{c}$s**.



- D^0 and $\overline{D}^0$ must decay to the same final state:
  - Counting Analysis : ADS (D→Kπ), GLW (D→hh) [PLB253(1991)483, PLB265(1991)172] [PRL78(1997)3257, PRD63(2001)036005]

$$A_{B^\pm} = A_D + e^{i(\delta_B \pm \gamma)} A_{\bar{D}}$$

  - Dalitz plot analysis: GGSZ [PRL78(1997)3257; PRD68(2003)054018; A. Bondar, Proceedings of BINP special analysis meeting on Dalitz analysis, 2002, unpublished]

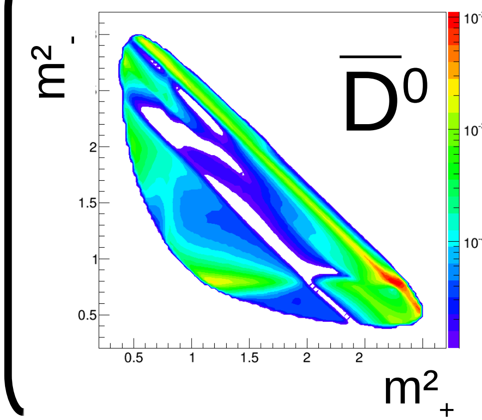
$$A_{B^\pm}(\mathcal{D}) = A_D(\mathcal{D}) + e^{i(\delta_B \pm \gamma)} A_{\bar{D}}(\mathcal{D})$$

D meson phase space

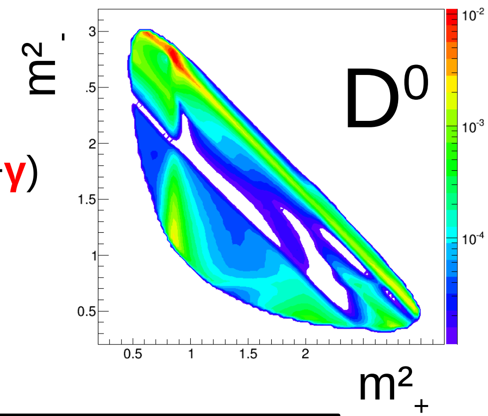
Dalitz analysis of $B^{\pm} \to D(K^0_s h^+ h^-)K^{\pm}$

- Large asymmetry in some regions of the Dalitz plot.
- To infer something on the weak phase γ, **strong phase variation** over the Dalitz plot must be known:
  - **Model Dependent** approach: use BaBar's model. [PRL 105, 081803 (2010)]
  - **Model Independent** approach: use CLEO-c measurements as inputs. [PRD 82(2010)112006]

$A(B^+) = |A(B^+ \to \overline{D}^0 K^+)|$ x (



$+ \; r_B e^{i(\delta+\gamma)}$



)

Interference amplitude

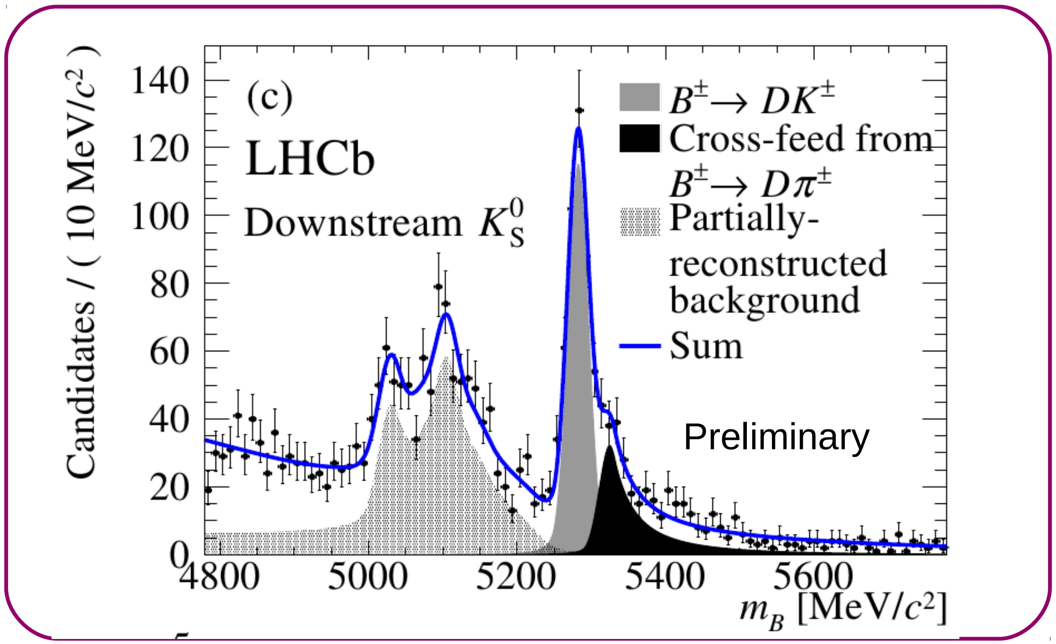
$m^2_{\pm} = m^2(K^0_s \pi^{\pm})$

$B^{\pm} \rightarrow D(K^0_S h^+ h^-)K^{\pm}$ Model Dependent - Method

B → DK

K_S decay inside Vertex Detector: 217

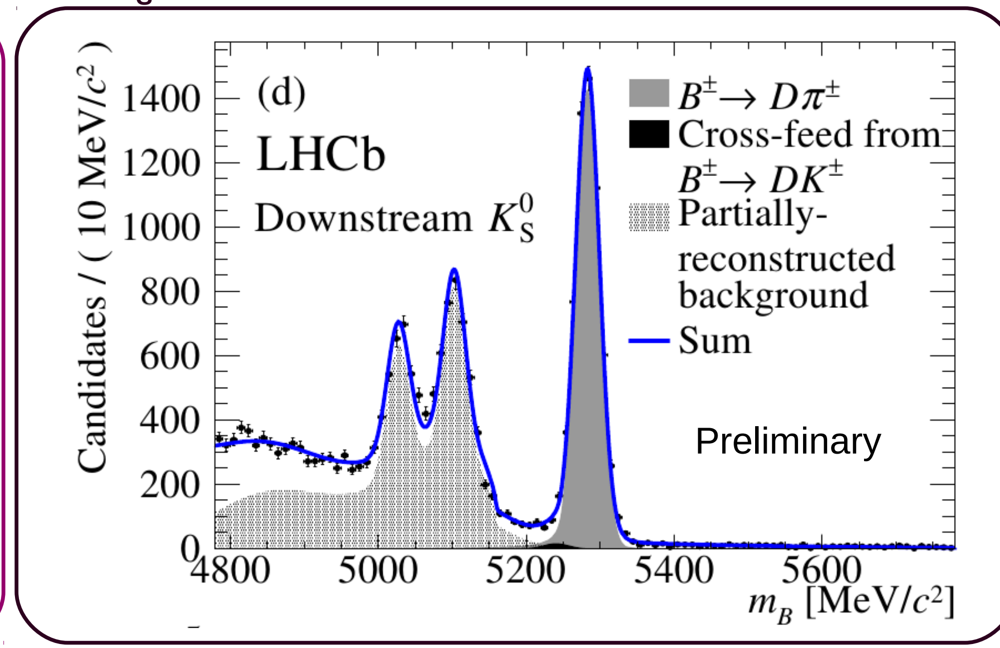
K_S decay outside Vertex Detector: 420



B → Dπ

K_S decay inside Vertex Detector: 2906

K_S decay outside Vertex Detector: 5960



[LHCb-PAPER-2014-017]

- Fit simultaneously B→DK & B→Dπ

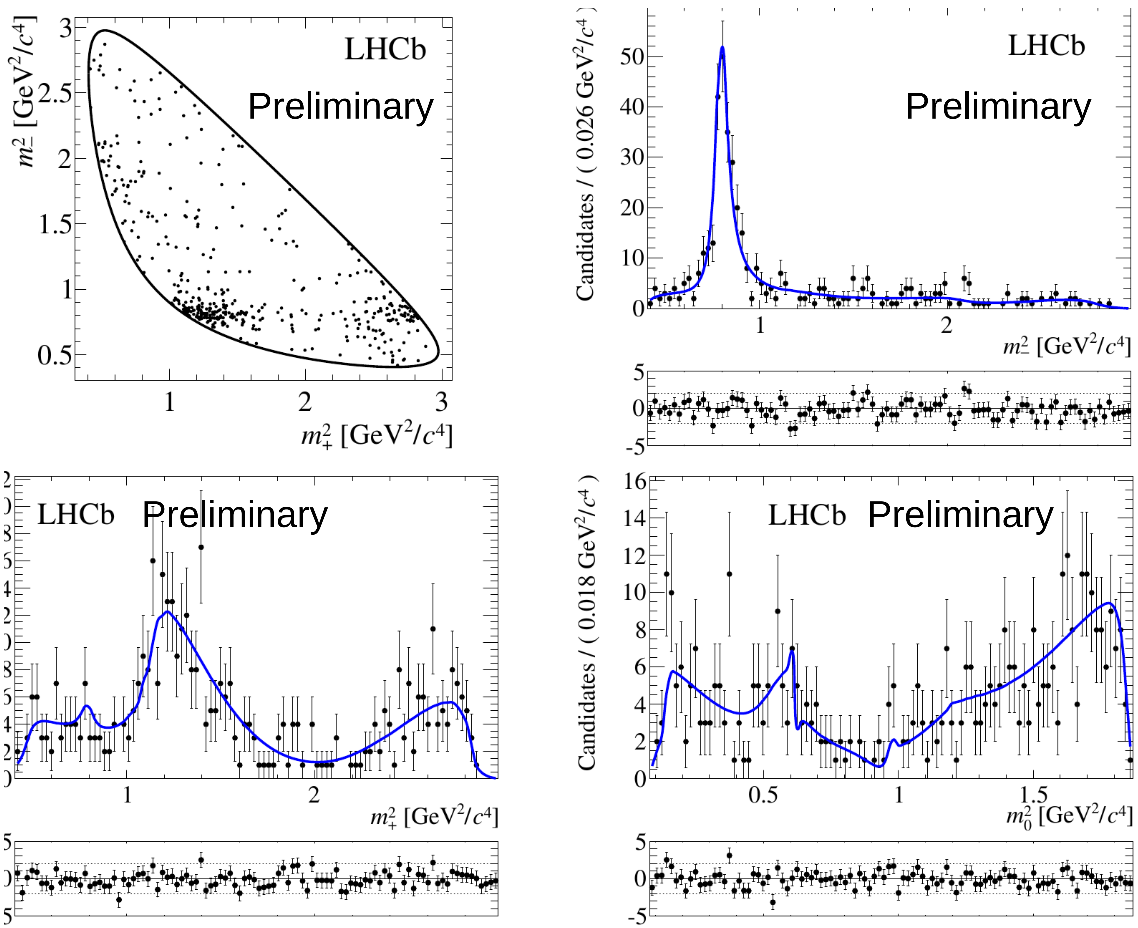
  1) Mass fit (phase-space integrated): fix signal and background yields.

  2) Dalitz fit: extract r_B, γ and δ_B from cartesian coordinates.

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

$B^{\pm} \to D(K^0_S h^+ h^-) K^{\pm}$ MD – Dalitz fit

- D strong phase variation evaluated with an **amplitude model** (BaBar latest).
- **B → Dπ** determine the **efficiency on the Dalitz plot** (assuming no CPV).
- Use only $D \to K^0_S \pi\pi$ (1 fb^{-1}).



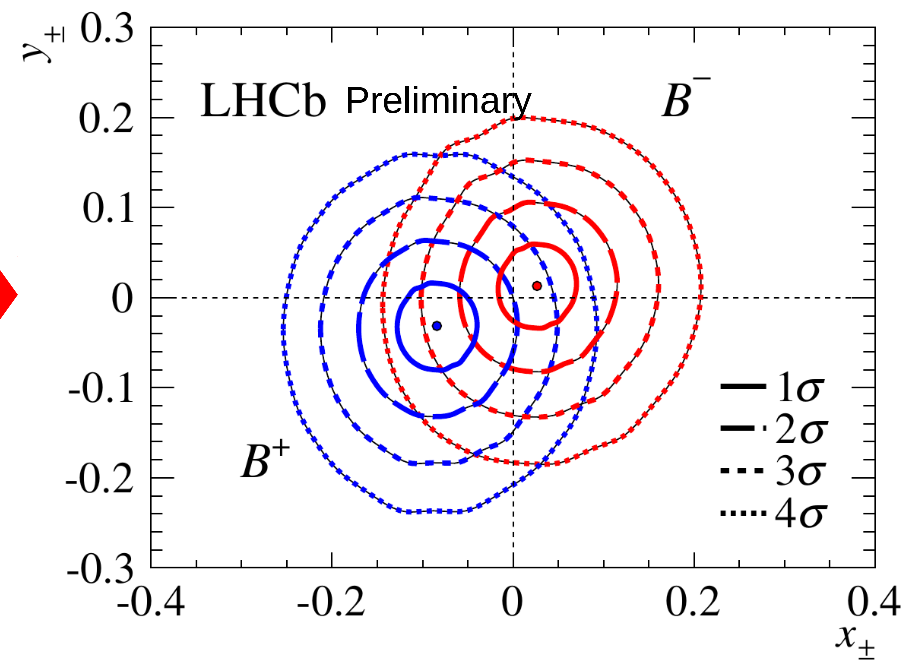
$B^{\pm} \to D(K^0_S h^+ h^-)K^{\pm}$ MD - Results

syst. Dalitz model

syst. exp.

stat.

$$
\begin{aligned}
x_- &= +0.027 \pm 0.044 \,^{+0.010}_{-0.008} \pm 0.001, \\
y_- &= +0.013 \pm 0.048 \,^{+0.009}_{-0.007} \pm 0.003, \\
x_+ &= -0.084 \pm 0.045 \pm 0.009 \pm 0.005, \\
y_+ &= -0.032 \pm 0.048 \,^{+0.010}_{-0.009} \pm 0.008,
\end{aligned}
$$



- Model systematics:
  - test several alternative models.
- Leading experimental systematics:
  - Efficiency.
  - Background descriptions uncertainties.
- Results consistent with the $1 fb^{-1}$ model independent analysis.
- To be improved with $3 fb^{-1}$.

$$\gamma = (84^{+49}_{-42})^{\circ}$$

Preliminary

$B^{\pm} \to D(K^0_S h^+ h^-)K^{\pm}$ model independent - Method-

- D strong phase variation measured by CLEO-c in a particular binning scheme.
- Analysis = **counting experiment in each bins of the Dalitz plot**.

$$N^{+}_{\pm i} = h_{B^+}\left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} \mp y_+ s_{\pm i})\right]$$

D from B+ events falling in bin ±i

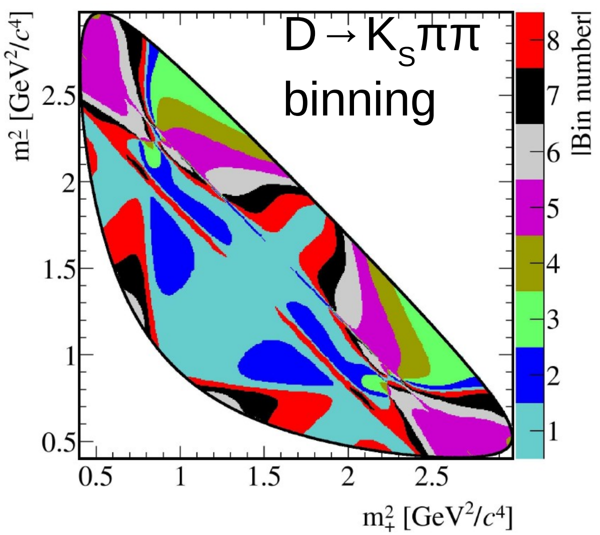
Fraction of pure D^0 events in a given bin, taking into account the signal efficiency profile

CLEO-c inputs

c_i and s_i are the averaged cosine and sine of the strong phase difference in bin i.

F_i are determine with $B^0 \to D^*(D^0\pi^+)\mu^-\nu$ LHCb data. (efficiency correction from MC)

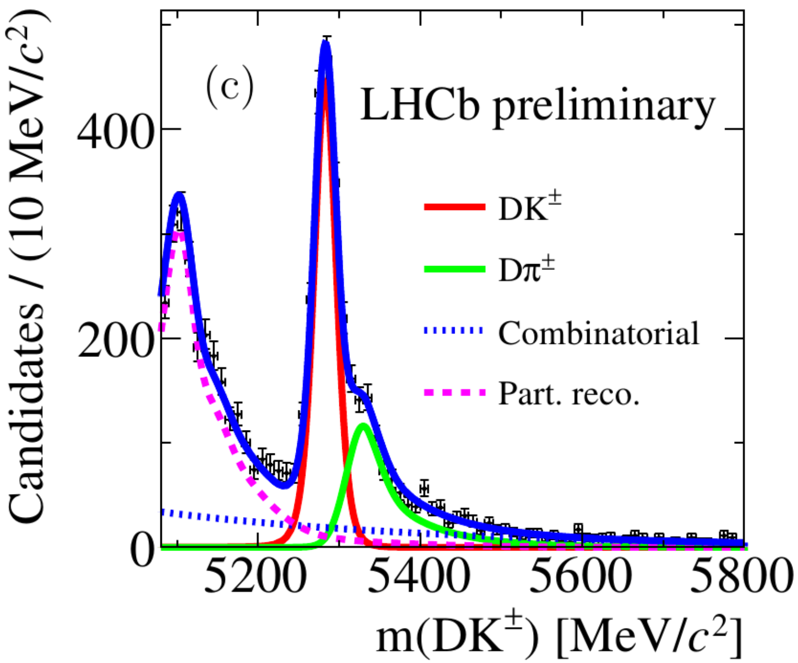
Simultaneous mass fit in every bins to extract $x_\pm$ and $y_\pm$.



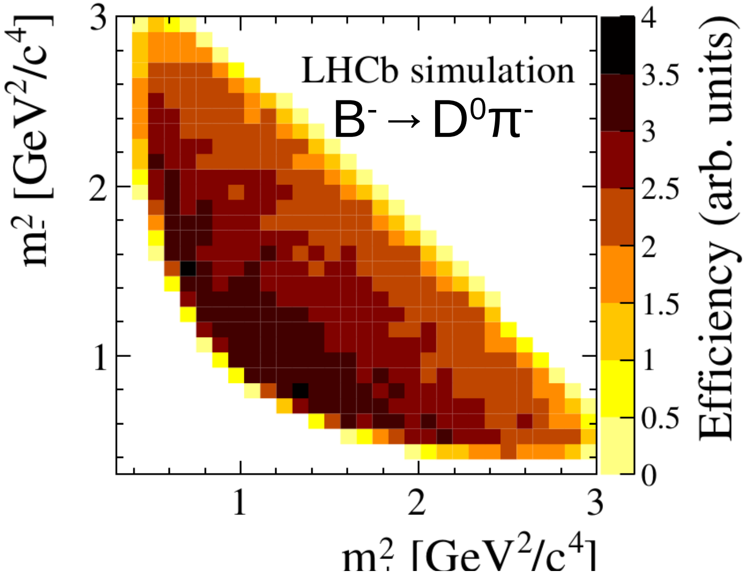
[LHCb-PAPER-2014-041]

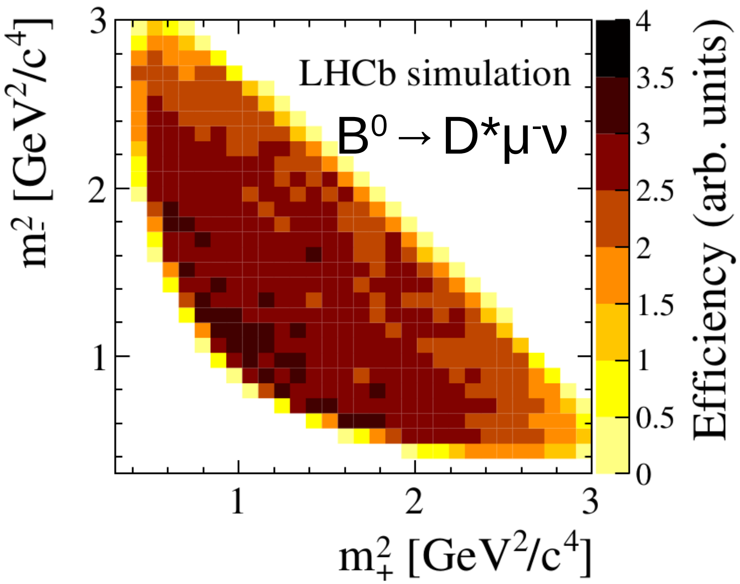
Mass fit

- First, mass fit over the full phase space:
  - Total DK candidates ~ 2600
  - Split data into $K_S\pi\pi$ and K_SKK, and K_S position decay.
  - Purity ~75% in signal region.
- Fix all mass model PDF for the second fit in each Dalitz bin which determines $x_\pm$ and $y_\pm$.



$B^0 \to D^*(D^0\pi^+)\mu^-\nu$ efficiency discrepancy





- $B^0 \to D^*\mu^-\nu$ excellent proxy to determine the F_i :
  - High purity and statistics.
  - D^0 is tagged from the D* slow pion.

- Small efficiency discrepancy observed between $B^\pm \to Dh^\pm$ and $B^0 \to D^*\mu^-\nu$, in the MC.

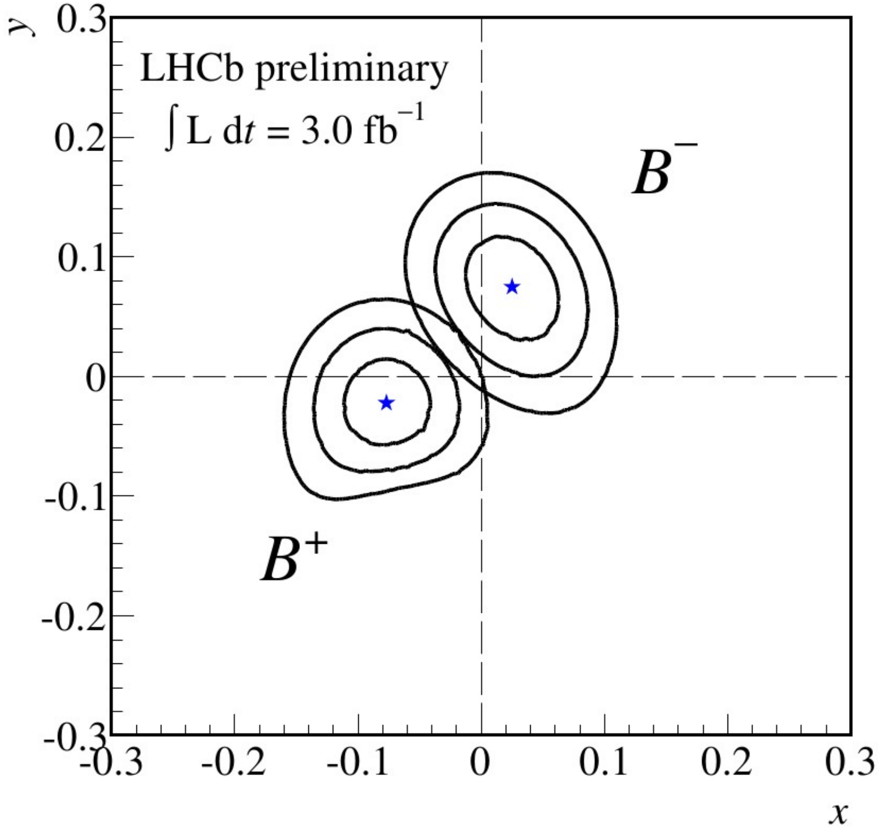
- **F_i determination:**
  - Fit $B^0 \to D^*\mu^-\nu$ data $\to$ yields in dalitz bins.
  - Correct these yields with the MC.

Model independent results (3 fb^{-1})

Most precise measurement of x and y to date:

$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2}$$
$$x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2}$$
$$y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2}$$
$$y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2}$$

stat. | Exp. Syst. | Cleo input Syst.



Compare to 1fb^{-1} measurement:

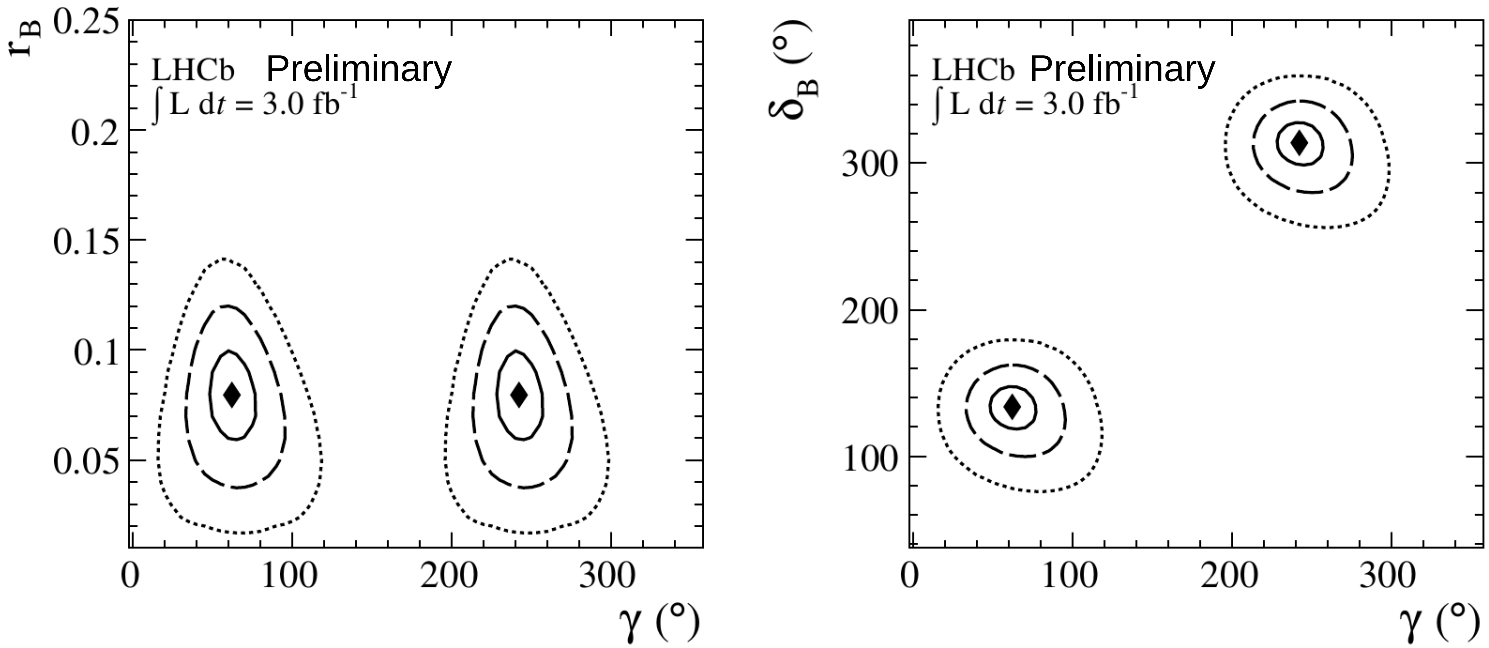
- Higher statistics = smaller statistical error.
- Experimental systematic error reduced with the new $B^0 \to D^* \mu^- \nu$ control mode (prev. it was $B^\pm \to D\pi^\pm$, assuming no CPV).
- Smaller D strong phase systematic thanks to increased sample size.

Results on polar coordinates

- Confidence intervals with stat+syst uncertainty on x and y.
- 1 fb^{-1} result : $(44^{+43}_{-38})°$
- **Precision reach the B factories separate γ combination result.**

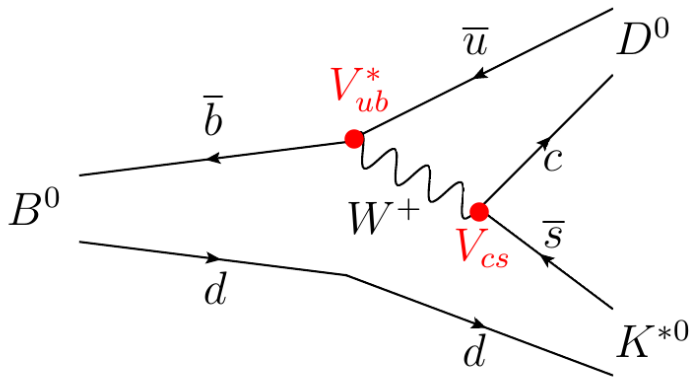
$$r_B = 0.080^{+0.019}_{-0.021}$$
$$\gamma = (62^{+15}_{-14})^\circ$$
$$\delta_B = (134^{+14}_{-15})^\circ$$

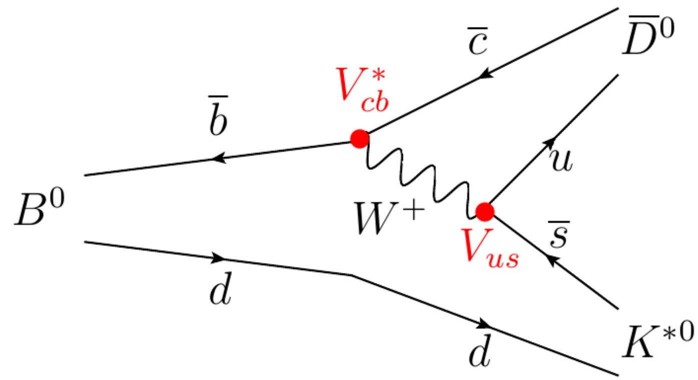
Preliminary



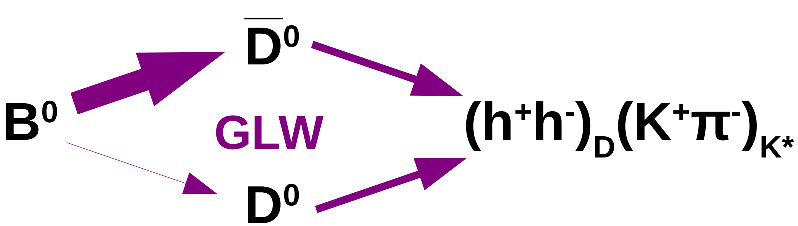
2D projections of confidence regions (all uncertainties included)

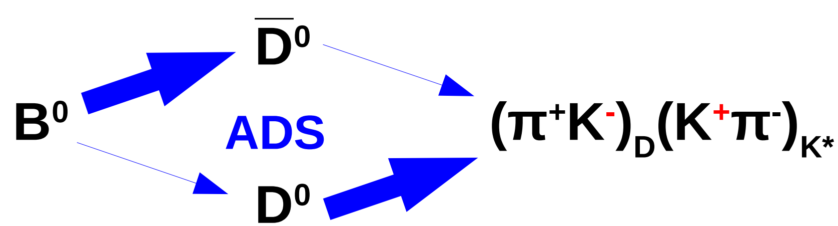
$B^0 \to DK^{*0}$





- Both diagrams colour suppressed: **larger r_B than in $B \to DK$**.
  - Expect better sensitivity to gamma.
  - Experimentally more challenging.
- **Self-tagged decay** thanks to $K^{*0} \to K^+\pi^-$.
- So far only the 2-body modes available ($3\ fb^{-1}$).





CPV observables

Several observables sensitive to γ can be built, for instance:

- Asymmetries in D → CP eigenstates (KK or ππ):

$$\mathcal{A}_d^{hh} \equiv \frac{\Gamma(\overline{B}^0 \to D(h^+h^-)\overline{K}^{*0}) - \Gamma(B^0 \to D(h^+h^-)K^{*0})}{\Gamma(\overline{B}^0 \to D(h^+h^-)\overline{K}^{*0}) + \Gamma(B^0 \to D(h^+h^-)K^{*0})} = \frac{2r_B\kappa \sin\delta_B \sin\gamma}{1 + r_B^2 + 2r_B\kappa\cos\delta_B\cos\gamma}$$

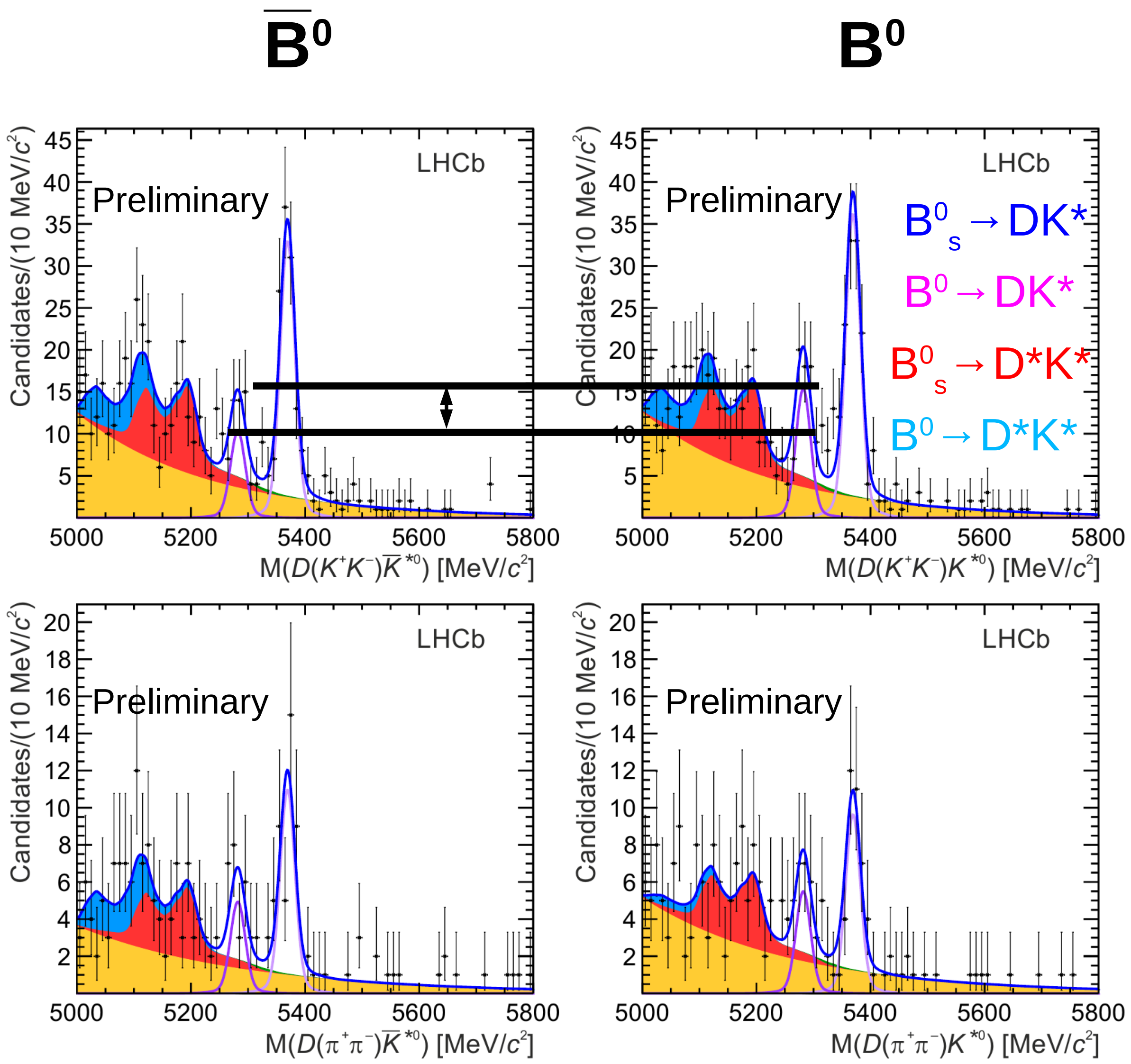
- Ratio with the DCS decay $D^0 \to K^+\pi^-$ and CF $D^0 \to K^-\pi^+$:

$$\mathcal{R}_d^+ \equiv \frac{\Gamma(B^0 \to D(\pi^+K^-)K^{*0})}{\Gamma(B^0 \to D(K^+\pi^-)K^{*0})} = \frac{r_B^2 + r_D^2 + 2r_Br_D\kappa\cos(\delta_B + \delta_D + \gamma)}{1 + r_B^2r_D^2 + 2r_Br_D\kappa\cos(\delta_B - \delta_D + \gamma)}$$

$$\mathcal{R}_d^- \equiv \frac{\Gamma(\overline{B}^0 \to D(\pi^-K^+)\overline{K}^{*0})}{\Gamma(\overline{B}^0 \to D(K^-\pi^+)\overline{K}^{*0})} = \frac{r_B^2 + r_D^2 + 2r_Br_D\kappa\cos(\delta_B + \delta_D - \gamma)}{1 + r_B^2r_D^2 + 2r_Br_D\kappa\cos(\delta_B - \delta_D - \gamma)}$$

κ is the coherence factor taking into account the effect of the $B^0 \to DK^+\pi^-$ non resonant contribution in the K^{*0} signal region.

$B^0 \to D(hh)K^{*0}$



- Signal significance:
  - KK : 8.6σ
  - ππ : 5.8σ
- Production and efficiency asymmetries are taken into account

$$\mathcal{A}_d^{KK} = -0.20 \pm 0.15 \pm 0.02$$
$$\mathcal{A}_d^{\pi\pi} = -0.09 \pm 0.22 \pm 0.02$$

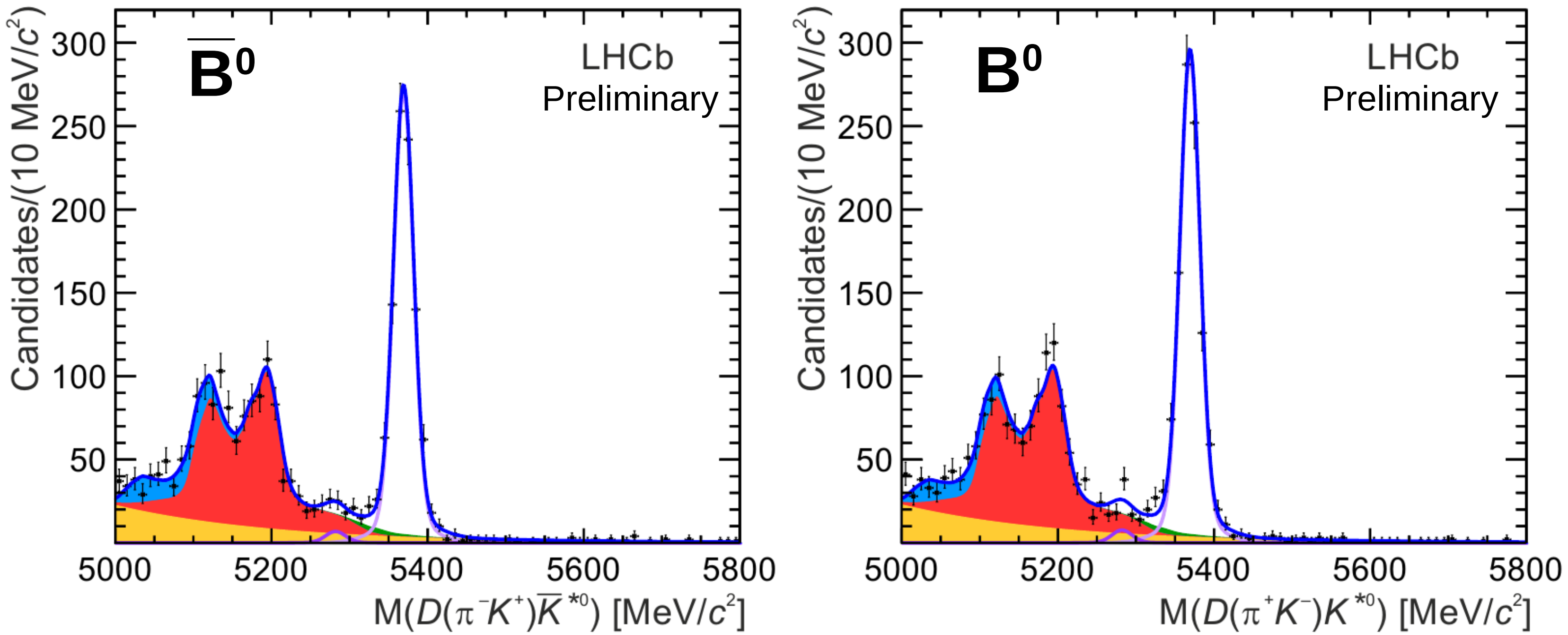
Preliminary

$B^0 \to D(\pi K)K^{*0}$

- Combined signal significance: 2.9σ

$$\mathcal{R}_d^+ = 0.06 \pm 0.03 \pm 0.01$$
$$\mathcal{R}_d^- = 0.06 \pm 0.03 \pm 0.01$$

Preliminary



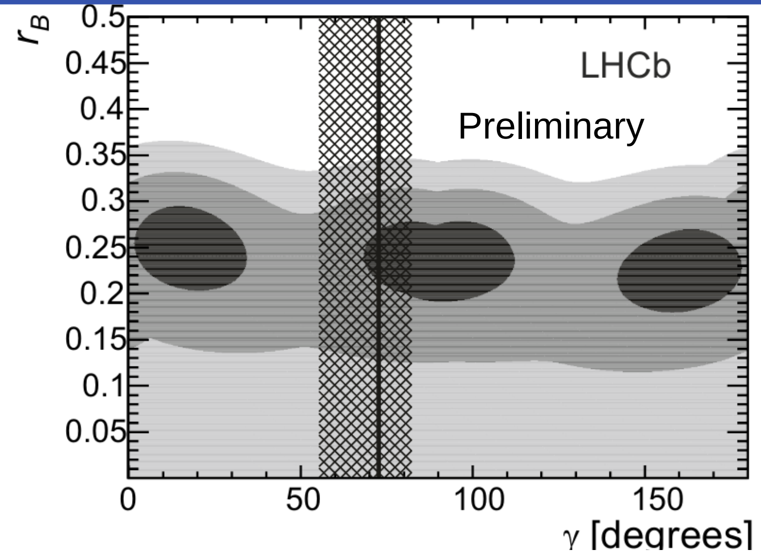
Implication on the value of r_B

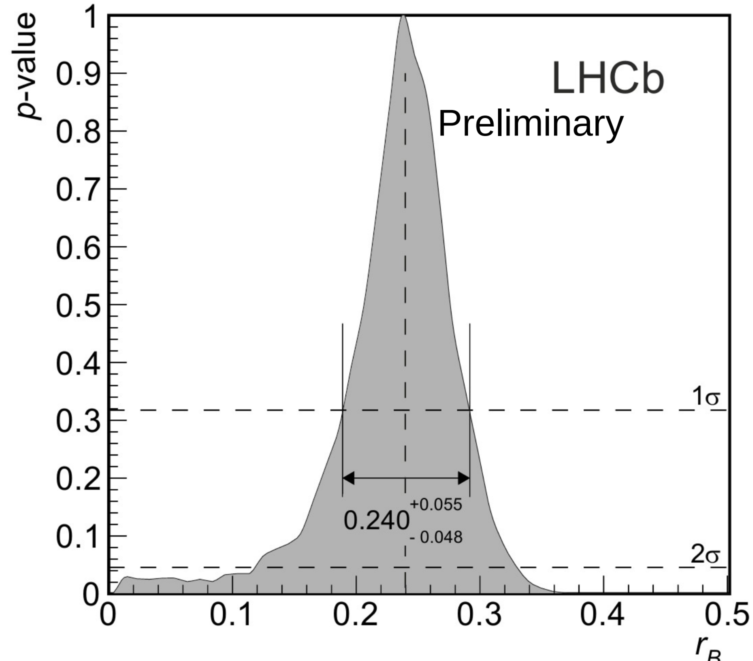
- Frequentist scan of (r_B,γ,δ_B).
- **κ = 0.95±0.03** from a simulation study with a realistic model of $B^0 \to DK\pi$.
- r_B estimation at a 68.3% CL:

$$r_B = 0.240\,^{+0.055}_{-0.048}$$

Preliminary

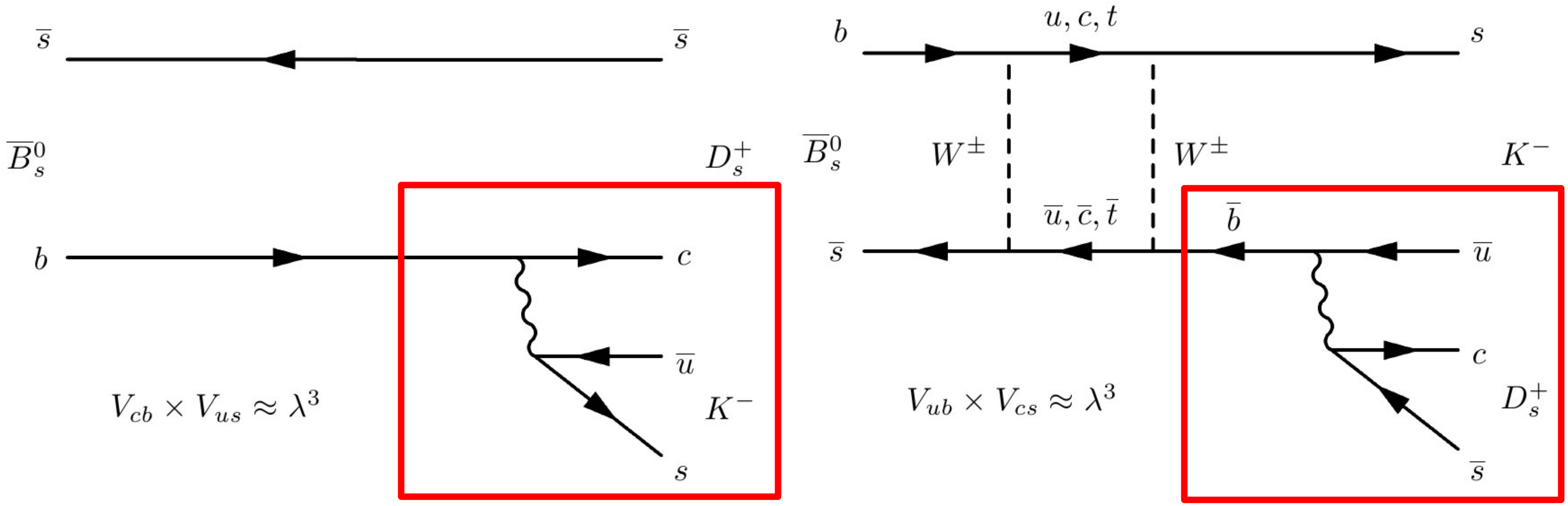
- **Most precise measurement to date.**
- High r_B value : encouraging for a better γ measurement.





[LHCb-PAPER-2014-028]

$B^0_s \to D_s K^{\pm}$



- CP violation in the **mixing and decay**.
- Same tree level process as presented previously.
- **Time dependent** measurement (more complex).
- **Measure (γ-2β_s)**
- Assume Φ_s=-2β_s and use as external input the Φ_s measurement from $B^0_s \to J/\psi\Phi$ (much better precision).

CP violation observables

- A_f = decay amplitude of B^0_s to final state f
- $\lambda_f = (q/p)(\bar{A}_f/A_f)$

Time dependent decay rate:

$$\frac{\mathrm{d}\Gamma_{B^0_s\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right]$$

$$\frac{\mathrm{d}\Gamma_{\bar{B}^0_s\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right]$$

CP observables:

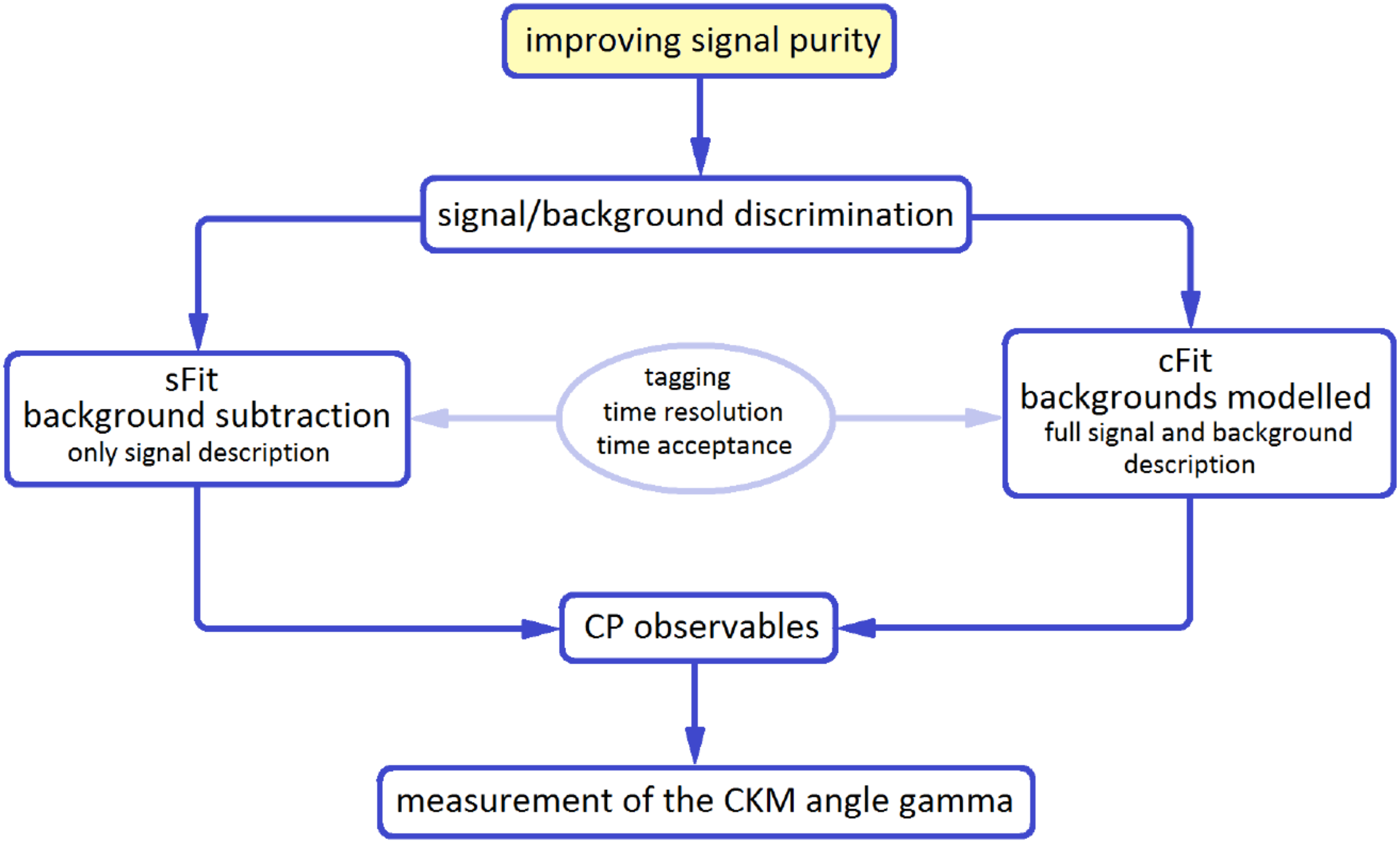
$$C_f = \frac{1-r^2_{D_sK}}{1+r^2_{D_sK}},$$

$$A_f^{\Delta\Gamma} = \frac{2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r^2_{D_sK}}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r^2_{D_sK}},$$

$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r^2_{D_sK}}, \quad S_{\bar{f}} = \frac{2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r^2_{D_sK}}.$$

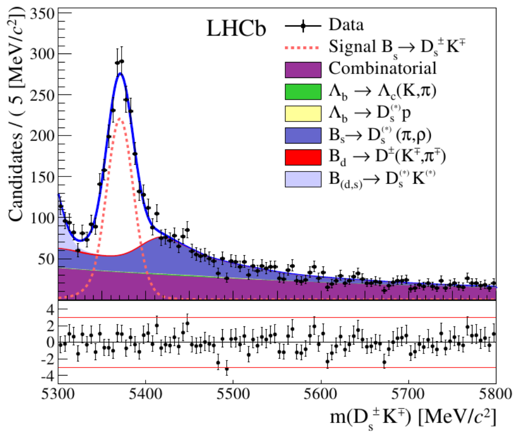
 [LHCb-PAPER-2014-038]

Strategy

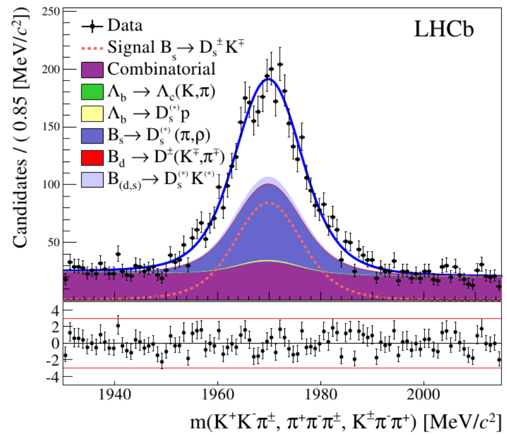

improving signal purity
signal/background discrimination
sFit
background subtraction
only signal description
tagging
time resolution
time acceptance
cFit
backgrounds modelled
full signal and background
description
CP observables
measurement of the CKM angle gamma

Signal/Background discrimination

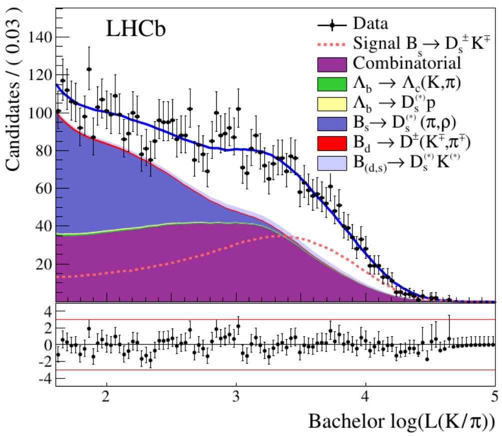
$D_s K$ mass



$KK\pi$, $K\pi\pi$, $\pi\pi\pi$ mass



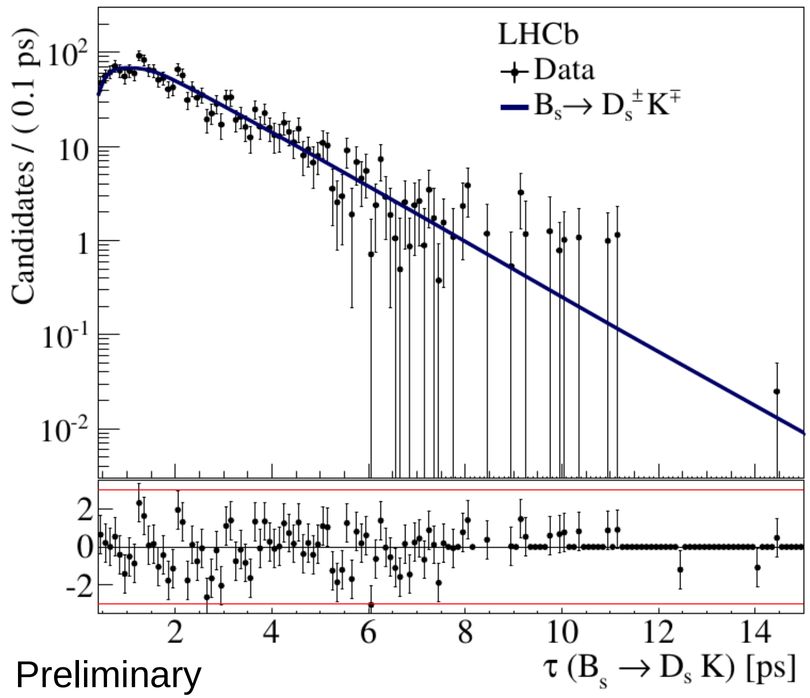
K bachelor ID

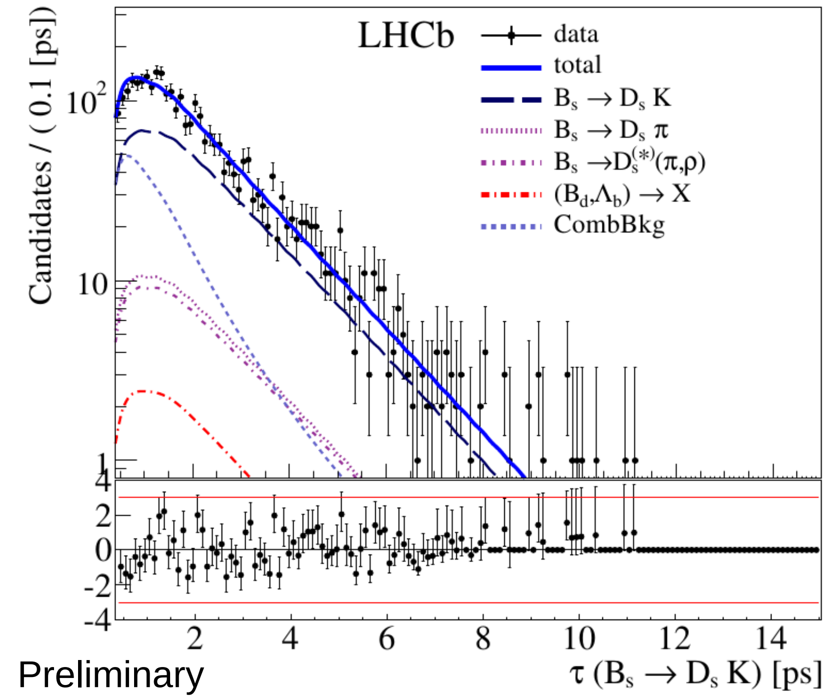


All preliminary

- Consider 3 D_s decays: $KK\pi$, $K\pi\pi$, $\pi\pi\pi$.
- Simultaneous 3D fit of $B^0_s \to D_s K^{\pm}$ and $B^0_s \to D_s \pi^{\pm}$.
  - **$m(B_s)$**, **$m(D_s)$** and **PID variable** on the **K/π** from the B (bachelor).
- Discrimination of signal and background.
- Signal weights determination.

Decay Time fit result





Parameter	*sFit* fitted value	*cFit* fitted value
C_f	$0.52 \pm 0.25 \pm 0.04$	$0.53 \pm 0.25 \pm 0.04$
$A_f^{\Delta\Gamma}$	$0.29 \pm 0.42 \pm 0.17$	$0.37 \pm 0.42 \pm 0.20$
$A_{\overline{f}}^{\Delta\Gamma}$	$0.14 \pm 0.41 \pm 0.18$	$0.20 \pm 0.41 \pm 0.20$
S_f	$-0.90 \pm 0.31 \pm 0.06$	$-1.09 \pm 0.33 \pm 0.08$
$S_{\overline{f}}$	$-0.36 \pm 0.34 \pm 0.06$	$-0.36 \pm 0.34 \pm 0.08$

- Leading syst.: acceptance, Γ_s,$\Delta\Gamma_s$.
- **Excellent agreement.**

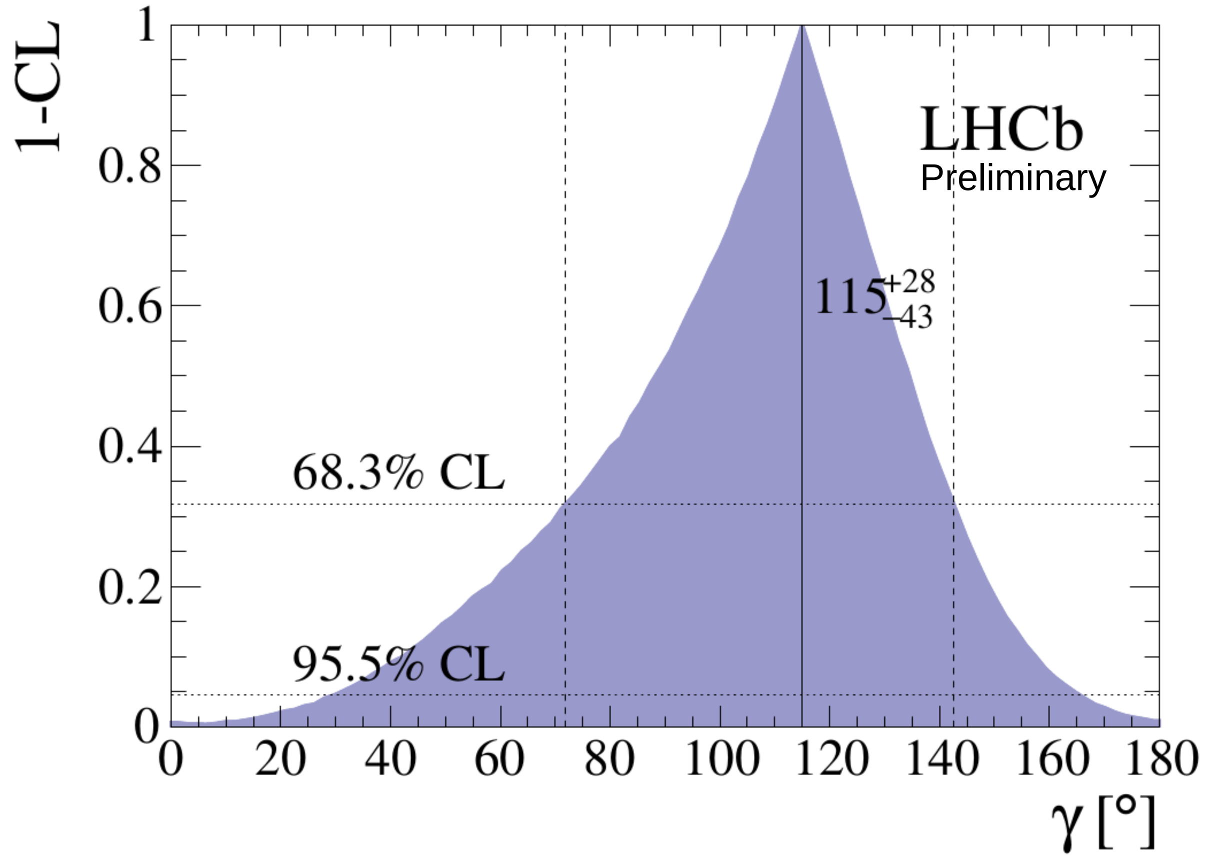
Interpretation on γ angle

- Take cfit results to make 68% CL.
- Statistical+Systematics (and Correlation) taken into account.
- Use only 1 fb^{-1}.

$$\gamma = (115^{+28}_{-43})^\circ\,,$$
$$\delta = (3^{+19}_{-20})^\circ\,,$$
$$r_{D_sK} = 0.53^{+0.17}_{-0.16}\,,$$

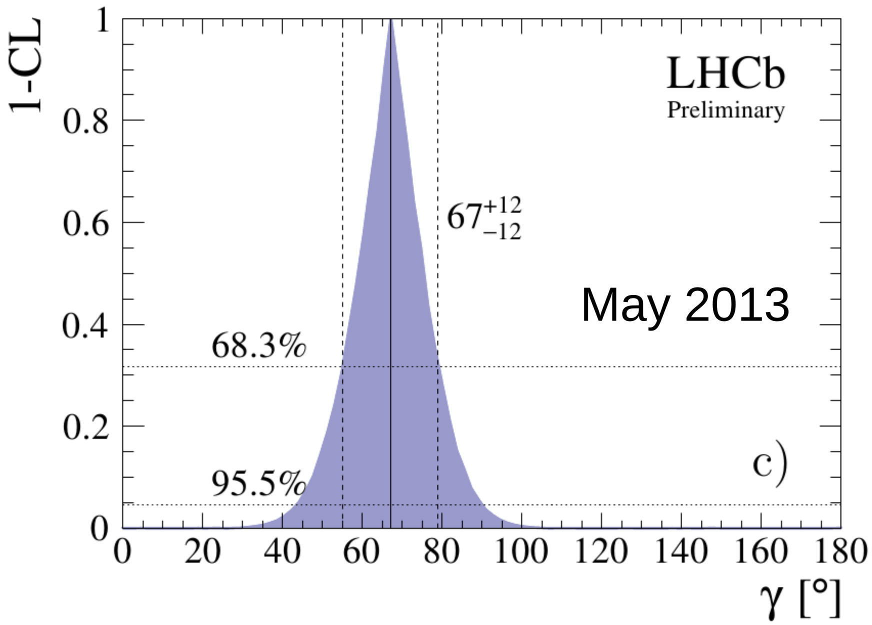
Preliminary

World first measurement of γ from $B^0_s \to D_s K^\pm$!



Perspectives

- The updated GGSZ 3fb^{-1} improved significantly from the previous (2+1 fb^{-1}).
- $B^0 \rightarrow DK^{*0}$ and $B_s \rightarrow D_s K$ will contribute to reduce the uncertainty.
- Other $B \rightarrow DK$, $B \rightarrow DX$ analysis carried on:
  - updating from 1fb^{-1} to 3 fb^{-1}.
  - New D decays.
- γ from loop measurement coming soon.



Stay tune for the next LHCb γ combination!

BACKUP

$B^0_s \to D_s K^\pm$ time fit inputs

- **Tagging:**
  - Combination of OS and SS tagging.
  - Efficiency for tagging an event : 67.53%
  - Effective tagging power: 5.07%
- **Time acceptance:**
  - Taken from $B^0_s \to D_s\pi^\pm$ (with simulation correction).
- **Time resolution:**
  - Use per event error, with average resolution of 47 fs.
- **External inputs:**
  - Γ_s, $\Delta\Gamma_s$, Γ_d, $\Gamma_{\Lambda b}$ and Δm_s fixed from other measurements