Constraining CKM γ angle at LHCb

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on behalf of the **LHCb collaboration**

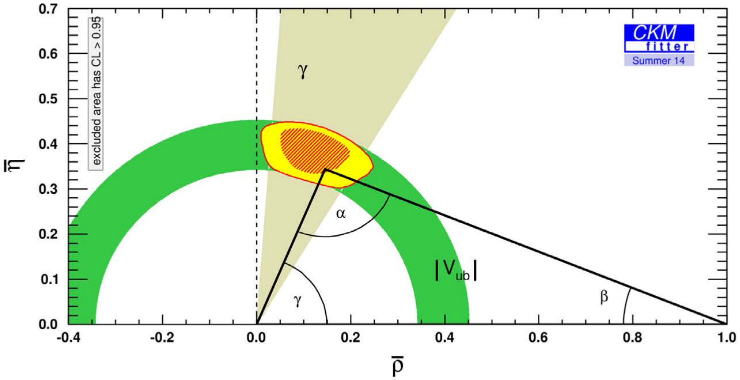
rencontres de Moriond 50th since 1966
2015 Conferences
March 14th - 28th
La Thuile, Aosta Valley - Italy

γ a standard candle to probe new physics

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

- The only angle measurable from **tree only processes**.
- **Theoretically clean** : $\delta\gamma/\gamma \lesssim \mathcal{O}(10^{-7})$
  [JHEP 1401(2014)051]
- γ is the **least known CKM angle.**
- **Direct measurements:**
  - BaBar: $(69^{+17}_{-16})^\circ$ [PRD 87(2013)052015]
  - Belle: $(68^{+15}_{-14})^\circ$ [arXiv:1301.2033]
  - LHCb: $(73^{+9}_{-10})^\circ$ [LHCb-CONF-2014-004]

With only "Tree" quantities



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- **Indirect measurements** (dominated by loops):
  - CKMFitter: $(66.9^{+1.0}_{-3.7})^\circ$ (global fit w/o γ meas.)

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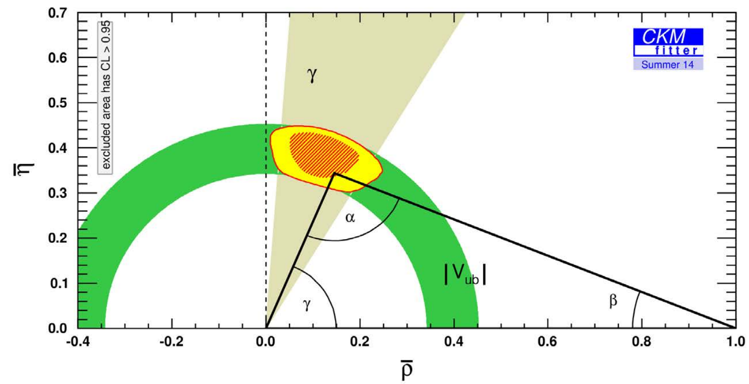
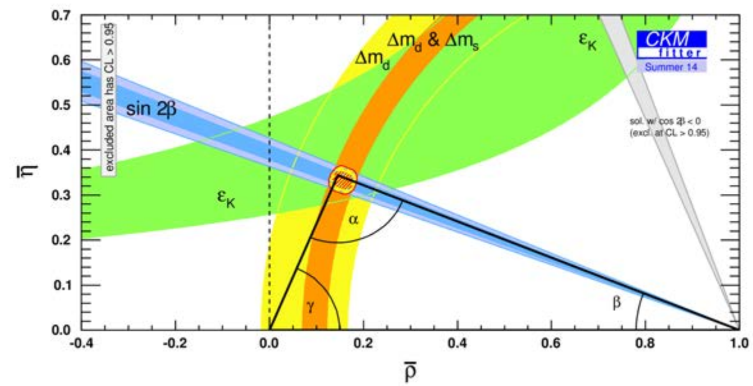


With only “Loop” quantities



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Goal: highlight or **discard** tension between direct and indirect measurements.

Need better precision from direct measurements.

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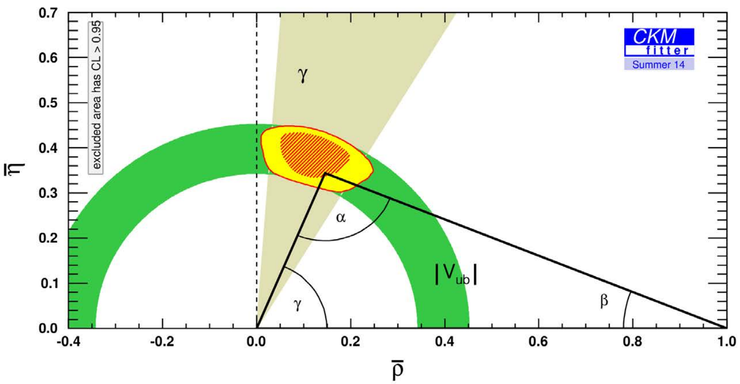
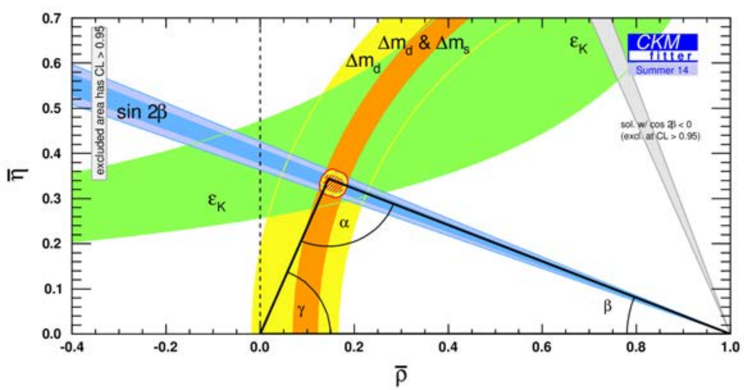
With only “Tree” quantities

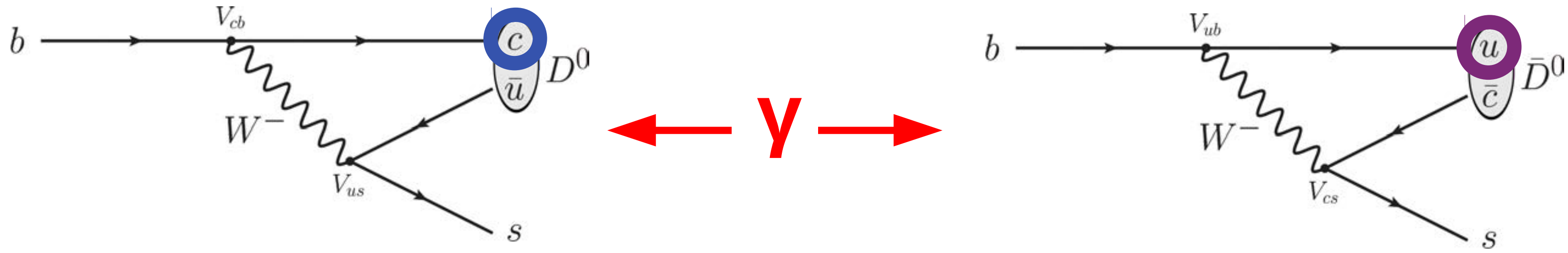


With only “Loop” quantities



γ from time independent measurement

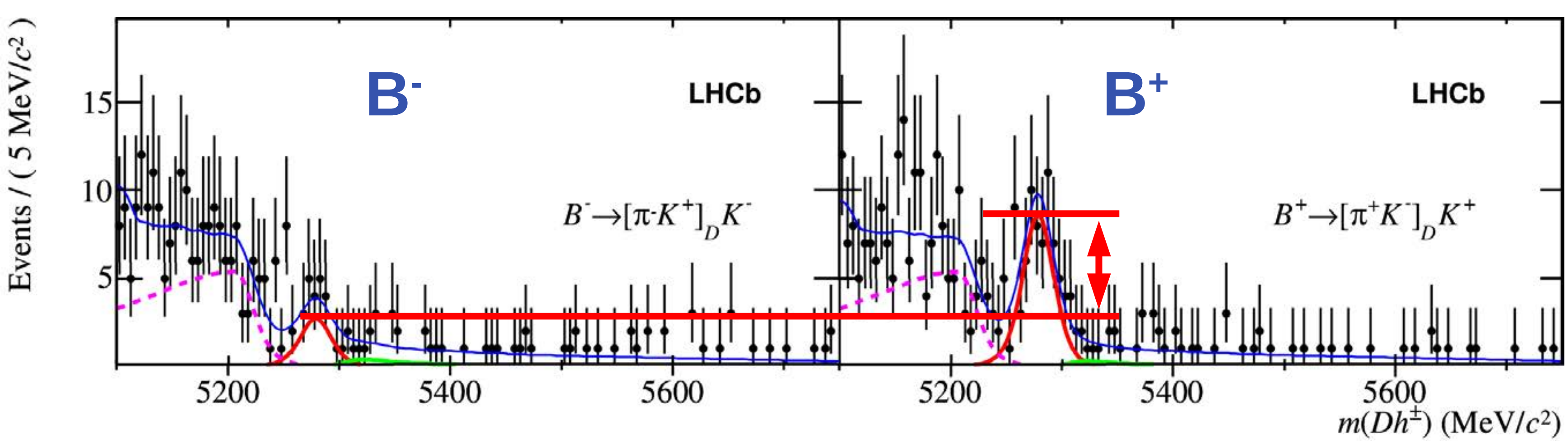
- Interference between **b→c$\bar{u}$s** and **b→u$\bar{c}$s**: sensitive to weak phase **γ**.



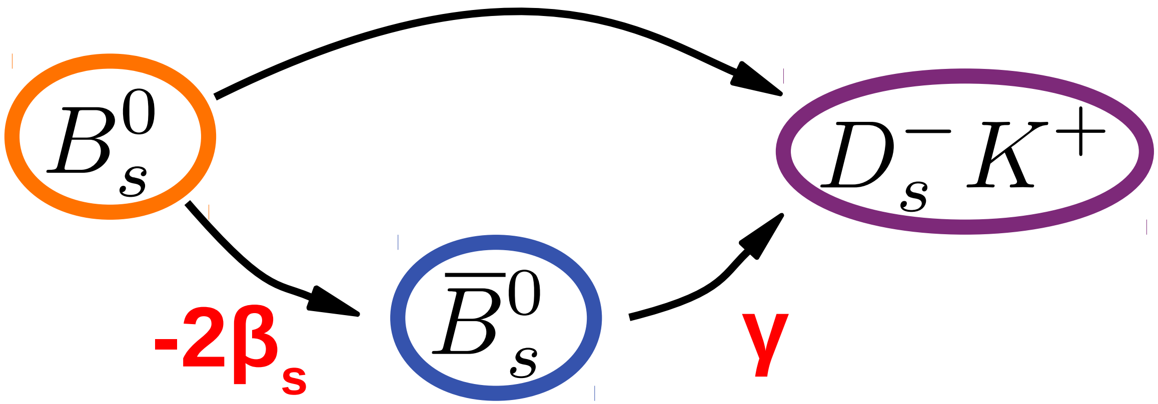
- Several D decays are used:
  - Counting analysis:
    - **GLW:** CP eigenstates (e.g. D→KK) [1,2]
    - **ADS:** flavoured states (e.g. D→Kπ) [3-5]
    - **GLS:** singly Cabbibo suppressed (e.g. D→K^0_SKπ) [6]
  - Amplitude analysis:
    - **GGSZ:** 3-body CP conjugate states (e.g. D→K^0_Sππ) [7,8]

} Decay width **asymmetries** and **ratios**

} **Dalitz plot** distributions



Time dependent measurement with $B^0_s \to D_s K^\pm$



- CP violation in the **mixing and decay**.
- Same tree level process as presented previously.
- **Time dependent** measurement.
- **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).

Inputs for LHCb γ combination

- Two combinations:
  - **Robust:** $B \to DK$-like and **Full:** $B \to DK$-like and $B \to D\pi$ [LHCb-CONF-2014-004]
- Measurements included in the combination:
  - $B^+ \to Dh^+$, $D \to hh$, GLW/ADS ,$1\,\text{fb}^{-1}$ [Phys. Lett. B712 (2012) 203]
  - $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS, $1\,\text{fb}^{-1}$ [Phys. Lett. B723 (2013) 44]
  - $B^+ \to DK^+$, $D \to K^0_S hh$, model independent GGSZ, $3\,\text{fb}^{-1}$ [JHEP 10 (2014) 097]
  - $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS, $3\,\text{fb}^{-1}$ [Phys. Lett. B733 (2014) 36]
  - $B^0 \to DK^{*0}$, $D \to hh$, GLW/ADS, $3\,\text{fb}^{-1}$ [Phys. Rev. D90 (2014) 112002]
  - $B^0_s \to D^{\mp}_s K^{\pm}$, time-dependent, $1\,\text{fb}^{-1}$ [JHEP 11 (2014) 060]
- All these modes have a **limited statistics**:
  - **Branching ratio ~ 10^{-7}**, some final states with K^0_S (hard to reconstruct)

➡ **The γ measurement power comes from the combination**

Inputs for LHCb γ combination

- Two combinations:
  - **Robust:** B→DK-like and **Full:** B→DK-like and B→Dπ [LHCb-CONF-2014-004]
- Measurements included in the combination:
  - $B^+ \to Dh^+$, $D \to hh$, GLW/ADS ,1 fb^{-1}
  - $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS, 1 fb^{-1}
  - $B^+ \to DK^+$, $D \to K^0_\mathrm{S} hh$, model independent GGSZ, 3 fb^{-1}
  - $B^+ \to DK^+$, $D \to K^0_\mathrm{S} K\pi$, GLS, 3 fb^{-1}
  - $B^0 \to DK^{*0}$, $D \to hh$, GLW/ADS, 3 fb^{-1}
  - $B^0_s \to D_s^\mp K^\pm$, time-dependent, 1 fb^{-1}

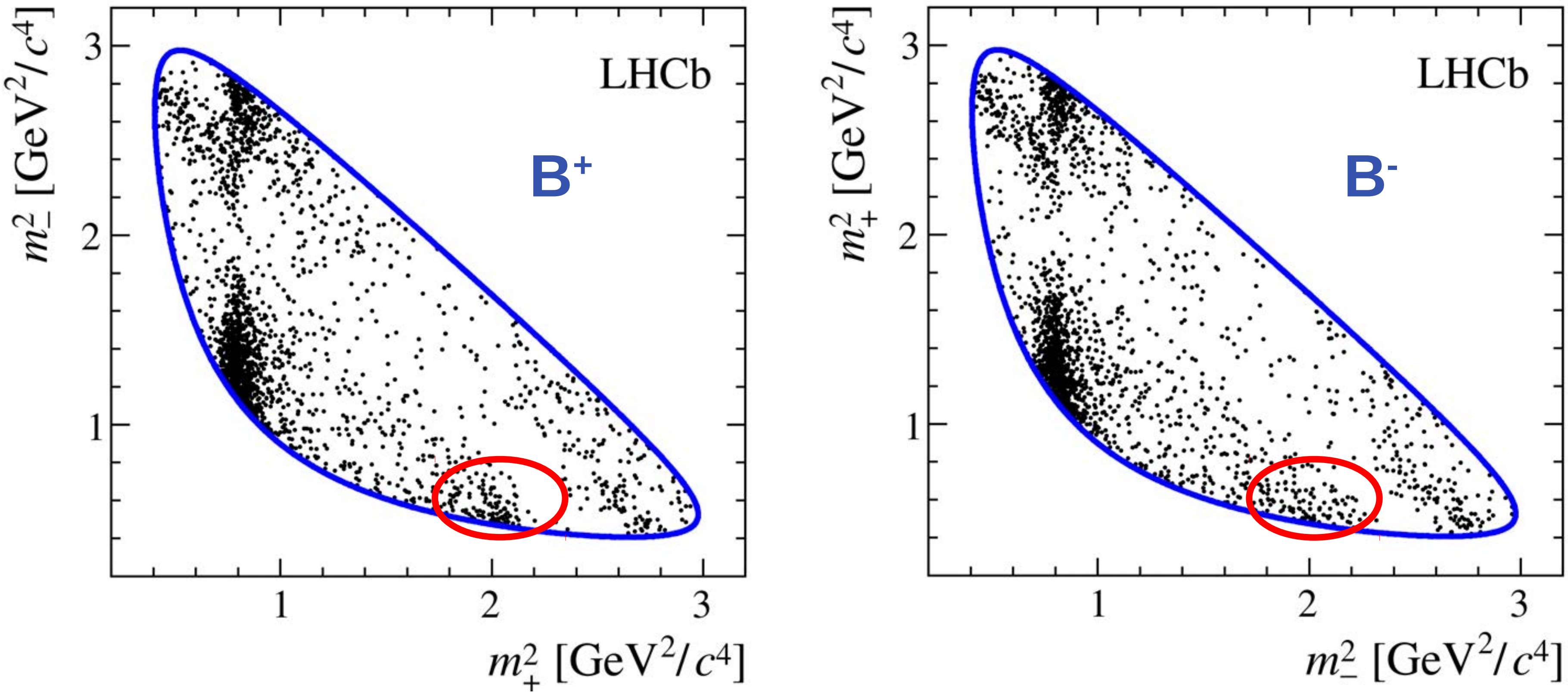
Briefly present these two measurements

- All these modes have a limited statistics:
  - Branching ratio ~ 10^{-7}, some final states with $K^0{}_S$ (hard to reconstruct)

➡ **The γ measurement power comes from the combination**

$B^{\pm} \rightarrow DK^{\pm}$ GGSZ

[JHEP 10 (2014) 097]



- Use B→DK with: $D \rightarrow K_S^0 \pi^+ \pi^-$ and $D \rightarrow K_S^0 K^+ K^-$
- Dalitz plot made with: $m_\pm^2 \equiv m^2(K_S^0 h^\pm)$
- **World most precise single γ measurement:** $\gamma = \left(62^{+15}_{-14}\right)^\circ$

γ with $B^0_s \to D_s K^\pm$

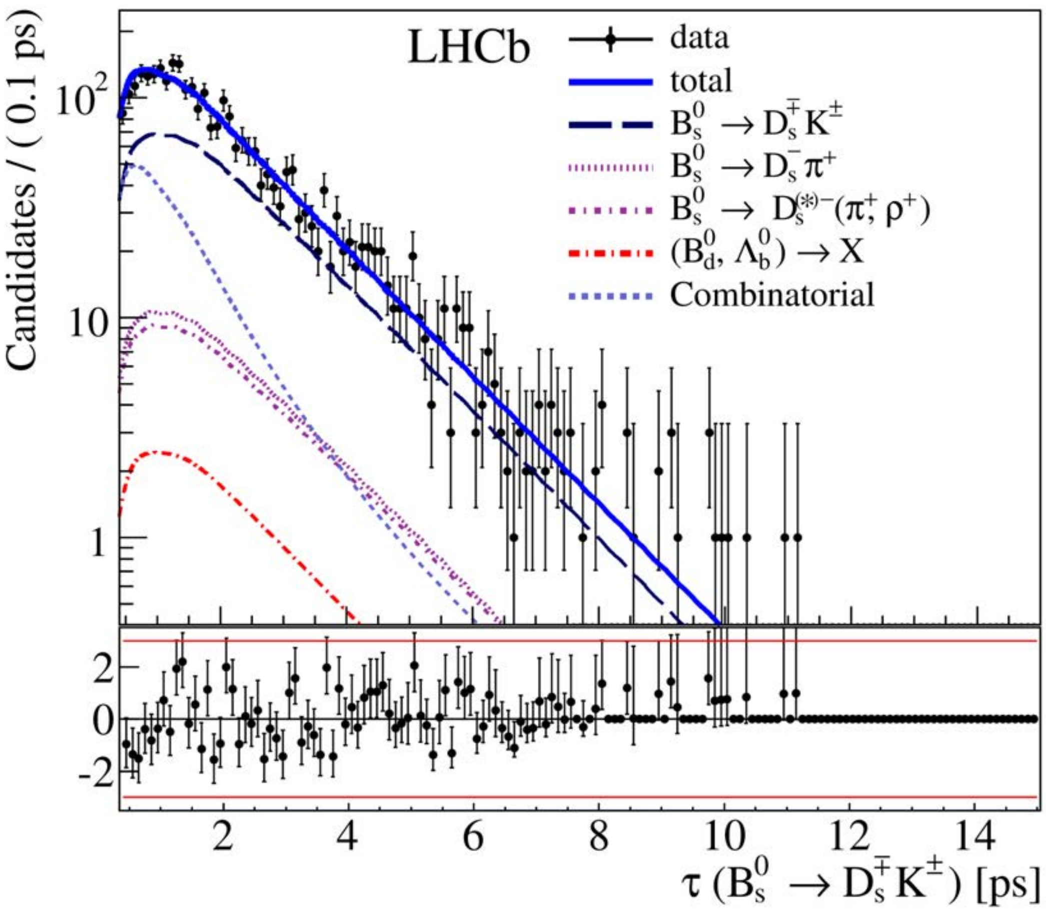
[JHEP 11 (2014) 060]

Time dependent tagged decay rate:

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

$$D_f \propto \cos(\delta - (\gamma - 2\beta_s))$$

$$S_f \propto \sin(\delta - (\gamma - 2\beta_s))$$



- Assumes $-2\beta_s \approx \phi_s$
- Take LHCb Φ_s meas. ($1fb^{-1}$)
  [Phys. Rev. D87 (2013) 112010]
- World first measurement with this technique!

$$\gamma = (115^{+28}_{-43})^\circ$$

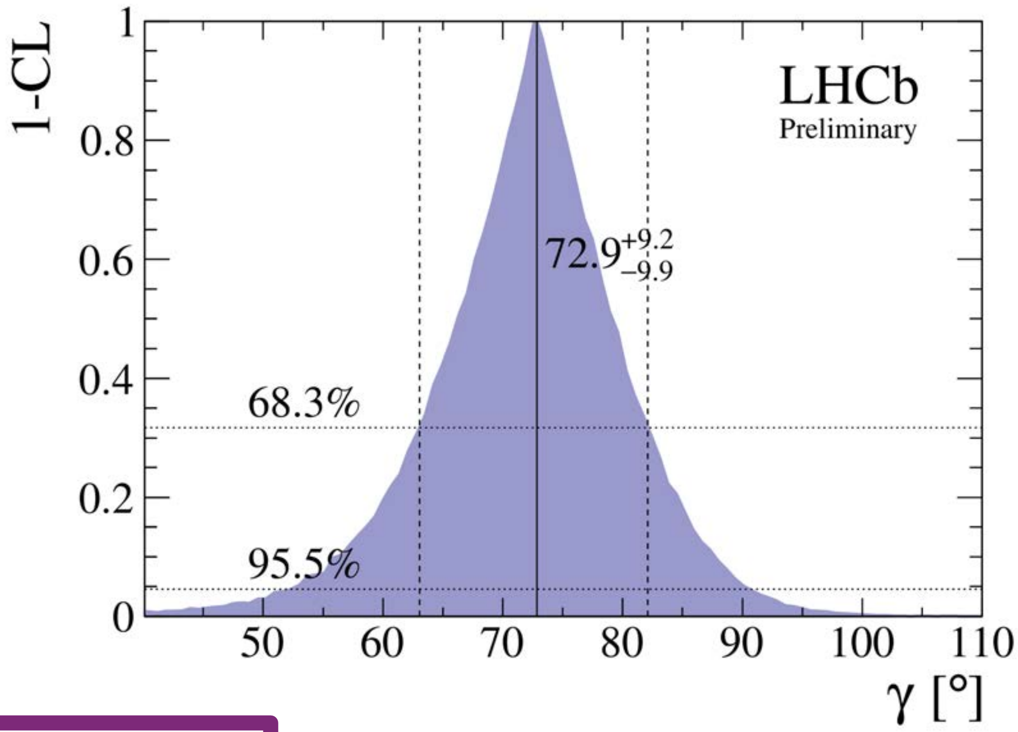
- To be updated with full Run 1 dataset (add 2012 data).

Result of LHCb γ combination

[LHCb-CONF-2014-004]

- Frequentist combination.
- Takes into account D mixing.
- Auxiliary inputs for some hadronic parameters (HFAG, CLEO).
- Bayesian cross-check in good agreement.
- Reaching the 10° precision:

Robust: only B→DK like

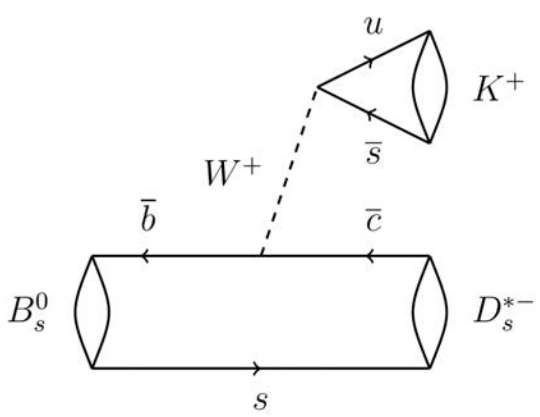


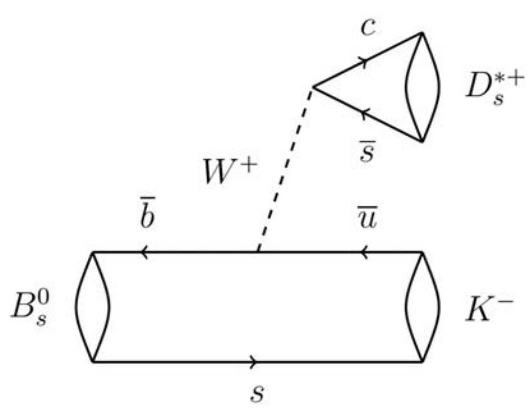
$$\gamma = (73^{+9}_{-10})^\circ$$

First observation of $B^0_s \to D_s^* K^\pm$

[LHCb-PAPER-2015-008, to be submitted]

NEW





Channel **sensitive to angle γ** like $B^0_s \to D_s K$

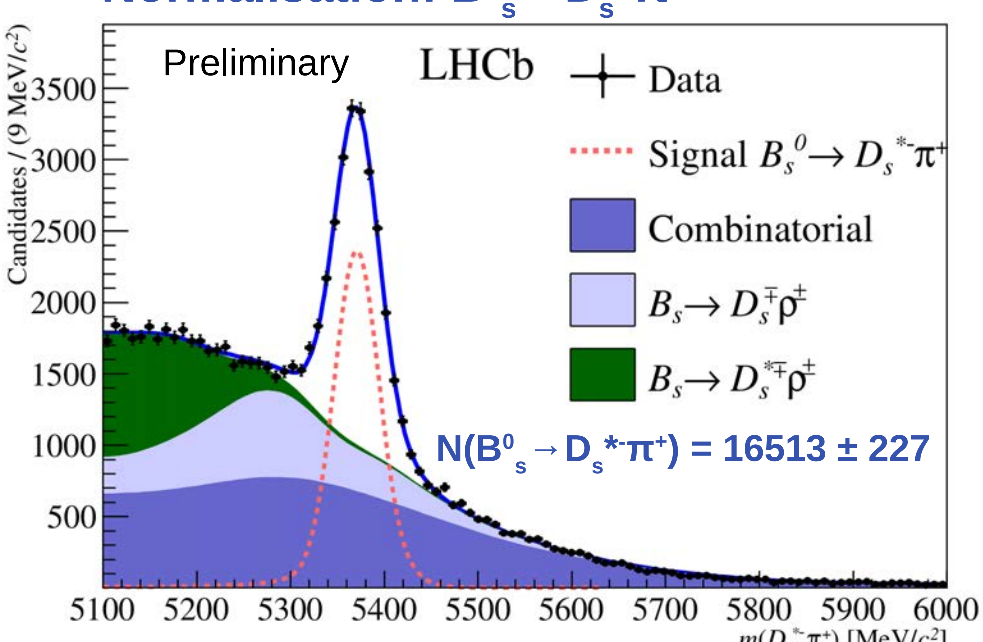
- Has **never been observed** before.
- D^*_s reconstructed with $D^*_s \to D_s(KK\pi)\ \gamma$
  - **Soft photon** → challenge with LHCb!
- **Branching ratio** as a first step (full Run1 data set) :

$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B^0_s \to D_s^{*\mp} K^\pm)}{\mathcal{B}(B^0_s \to D_s^{*-}\pi^+)} = \frac{N_{K^\pm}}{N_{\pi^+}} \frac{\varepsilon_{\pi^+}}{\varepsilon_{K^\pm}}$$

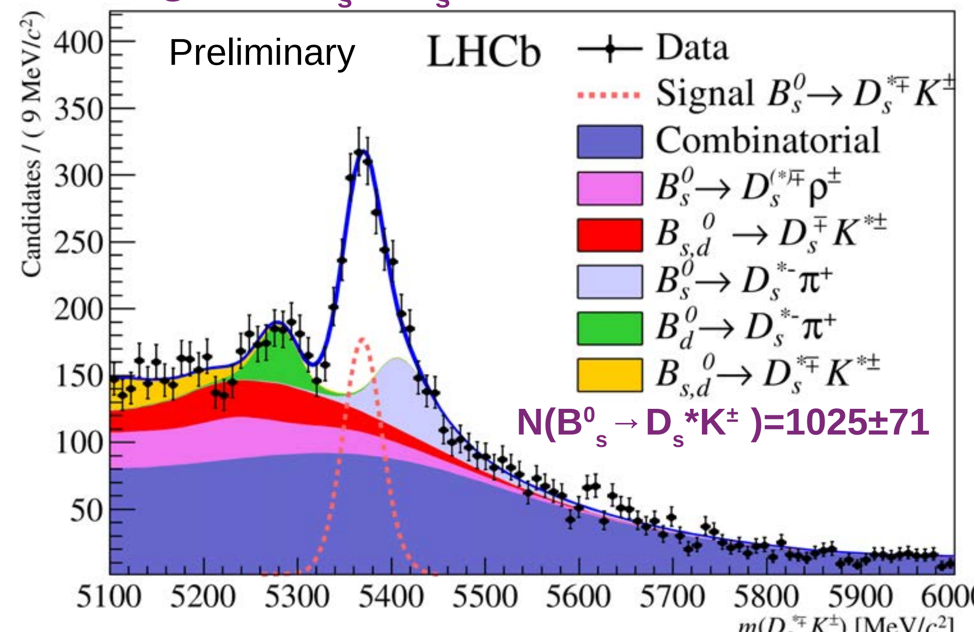
First observation of $B^0_s \to D_s^* K^\pm$

[LHCb-PAPER-2015-008]

Normalisation: $B^0_s \to D_s^* \pi$



Signal: $B^0_s \to D_s^* K$



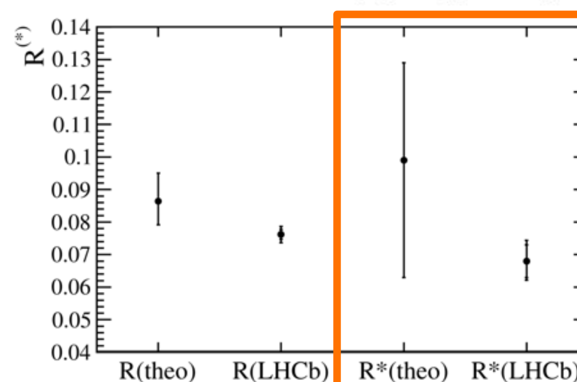
On the same dataset: **$N(B^0_s \to D_s K^\pm) = 5101 \pm 100$** [arXiv:1412.7653]

- Branching fraction ratio:

$$\mathcal{R}^* = 0.068 \pm 0.005\,(\text{stat.})\ ^{+0.004}_{-0.003}\,(\text{sys.})$$

Preliminary

mainly combi. Background uncert.



- With $\mathcal{B}(B^0_s \to D_s^{*-}\pi^+)$ from Belle:

$$\mathcal{B}\,(B_s^0 \to D_s^{*\mp} K^{\pm}) = 16.3 \pm 1.2\,(\text{stat.})\ ^{+1.0}_{-0.7}\,(\text{sys.}) \pm 4.8\,(\text{bf}) \times 10^{-5}$$

Preliminary

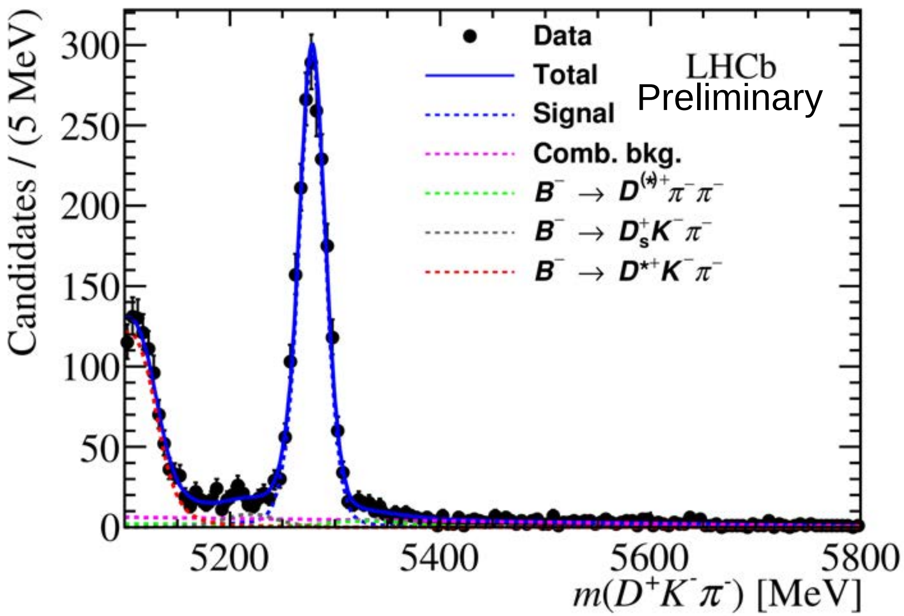
First observation of $B^- \to D^+ K^- \pi^-$

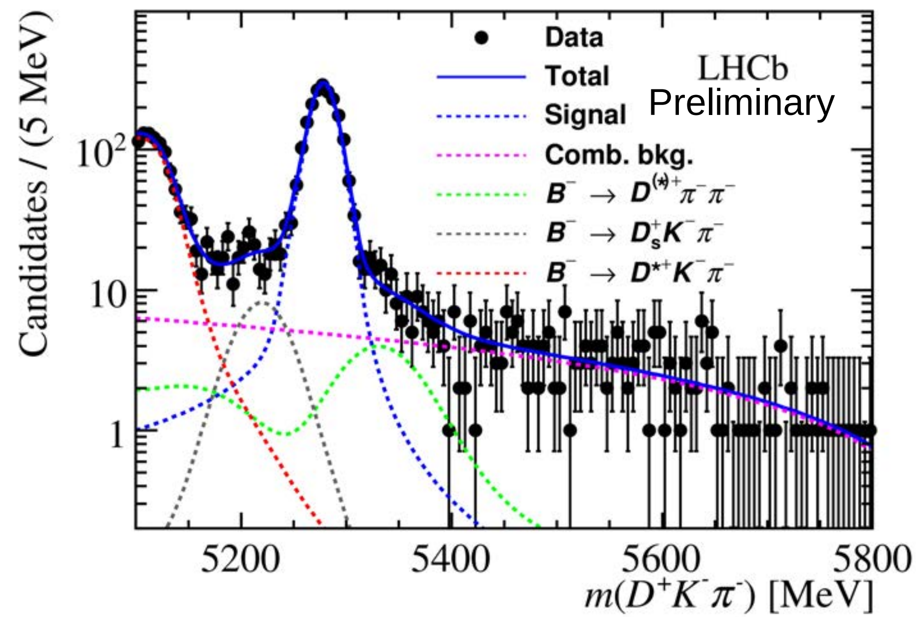
[LHCb-PAPER-2015-007, arXiv:1503.02995, submitted to PRD]

Subm. Last week

- $B^- \to D^+ K^- \pi^-$ interesting for:
  - **Properties of neutral D**** states measurement (spin-parity).
  - Determine **potential for γ** measurement with $B^- \to D^{**} K^-$ (measure interf. magnitude r_B).

- **First observation of the decay**: ~2000 signal candidates (60σ)





- Normalised to $B^- \to D^+ \pi^- \pi^-$ (PDG value) :

$$\mathcal{B}(B^- \to D^+ K^- \pi^-) = (7.92 \pm 0.23 \pm 0.24 \pm 0.42) \times 10^{-5}$$

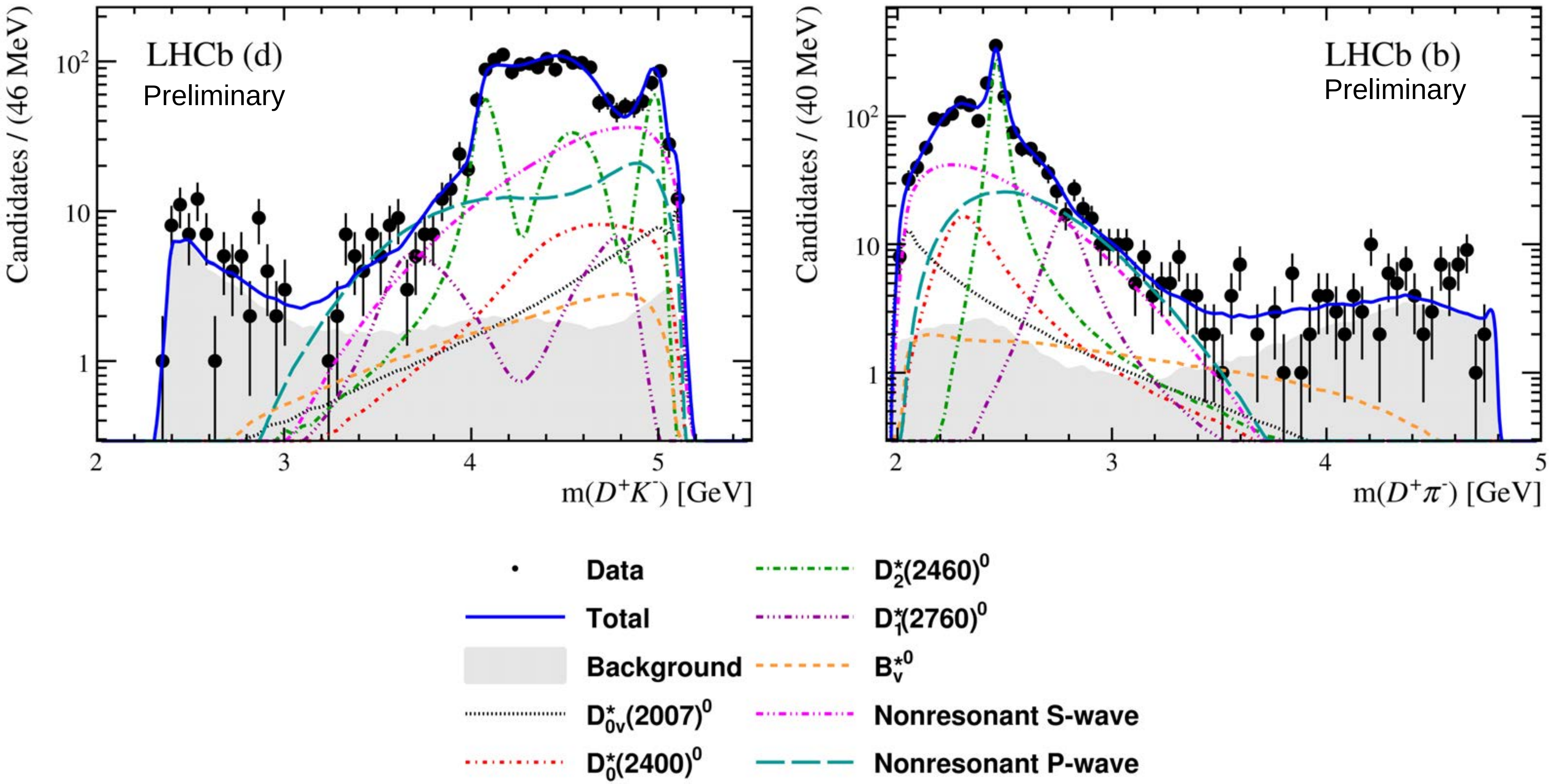
Preliminary

stat. syst. normalisation

Dalitz Plot of $B^- \to D^+ K^- \pi^-$

[LHCb-PAPER-2015-007, arXiv:1503.02995]

- A Dalitz plot model is determined with an isobar approach (coherent sum of resonant an non-resonant amplitudes)



Results of $B^- \to D^+ K^- \pi^-$ Amplitude Analysis

[LHCb-PAPER-2015-007, arXiv:1503.02995]

- $D_J^*(2760)^0$ determined to have **spin 1**: $D_1^*(2760)^0$
- Masses and widths of $D_2^*(2460)^0$ and $D_1^*(2760)^0$ reported:

$$
\begin{aligned}
m(D_2^*(2460)^0) &= (2464.0 \pm 1.4 \pm 0.5 \pm 0.2)\,\text{MeV} \\
\Gamma(D_2^*(2460)^0) &= (43.8 \pm 2.9 \pm 1.7 \pm 0.6)\,\text{MeV} \\
m(D_1^*(2760)^0) &= (2781 \pm 18 \pm 11 \pm 6)\,\text{MeV} \\
\Gamma(D_1^*(2760)^0) &= (177 \pm 32 \pm 20 \pm 7)\,\text{MeV}
\end{aligned}
$$

Preliminary — stat. syst. Dalitz model

- $D_2^*(2460)^0$ mass and width: Good agreement with PDG
- $D_1^*(2760)^0$ mass: Good agreement with prev. meas.*
- $D_1^*(2760)^0$ width: Larger than prev. meas.* by ~3σ

- **Can be used in the future for γ measurement.**
- **Improved knowledge of D** states useful for other Dalitz analyses.**
  - For instance $B^0 \to D^0 K^+ \pi^-$ is promising for a γ measurement.

[PRD 80 (2009) 092002, arXiv:0909.1495]

** BaBar PRD 82 (2010) 111101 and LHCb JHEP 09 (2013) 145.*

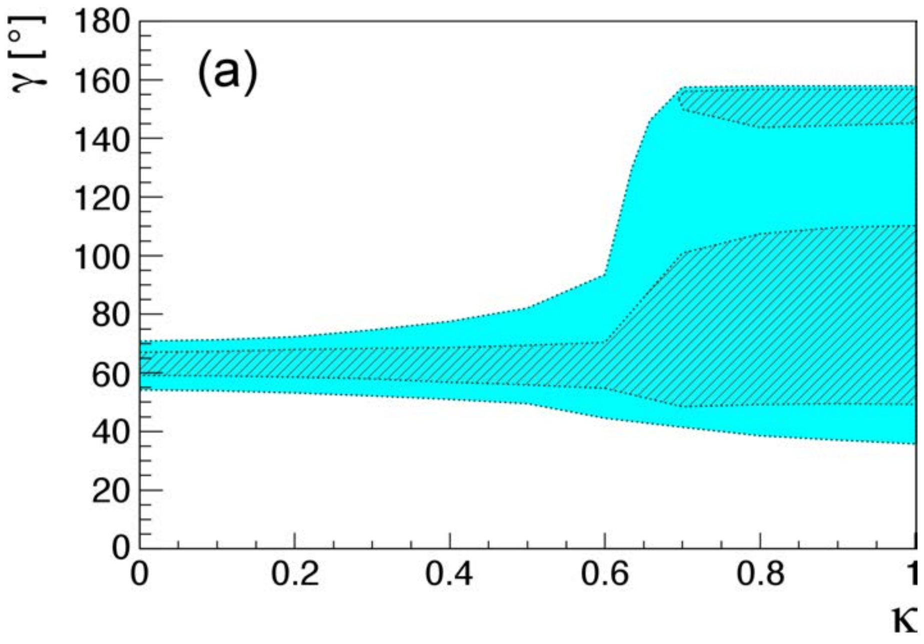
γ from charmless B decays

[Phys. Lett. B 741 (2015) 1-11]

- Combine CP violation time dependent measurements of :

$B^0 \to \pi^+\pi^-$, **$B^0_s \to K^+K^-$**, **$B^0 \to \pi^0\pi^0$** and **$B^+ \to \pi^+\pi^0$**. Suggested by [9-13]

- Sensitive to penguin diagrams contributions.
- Exploits isospin and U-spin ($d \leftrightarrow s$) symmetries.
- Bayesian analysis with floating maximal magnitude of U-spin breaking (κ).



- Assuming up to 50% of U-spin symmetry breaking:

$$\gamma = (63.5^{+7.2}_{-6.7})^{\circ}$$

- Measurement **compatible** and **competitive** with the one obtained from **tree decays**.
- **However need better theoretical understanding of U-spin breaking**.

Conclusion and Outlook

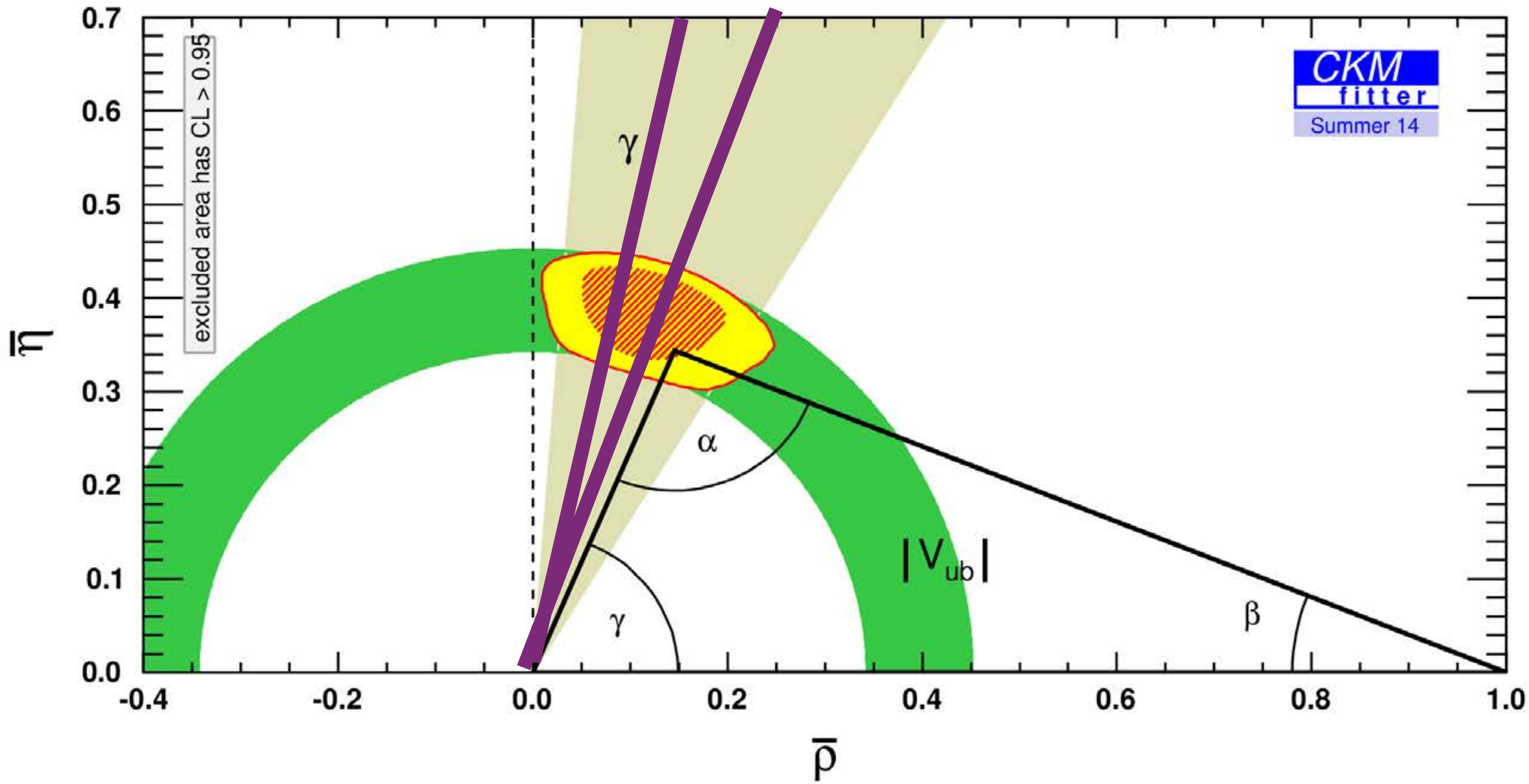
- The LHCb experiment has reached the **10° precision** on the CKM angle γ:

$$\gamma = \left(73^{+9}_{-10}\right)^{\circ}$$

[LHCb-CONF-2014-004]

- **Large room for improvement:**
  - The current combination still includes some measurement with only 2011 Data.
  - We will add extra decay channels (with B^0, new Dalitz analyses, and photon and π^0 in final states).
- **On the track to reach the 4° precision by 2018!**

Conclusion and Outlook



- **On the track to reach the 4° precision by 2018!**

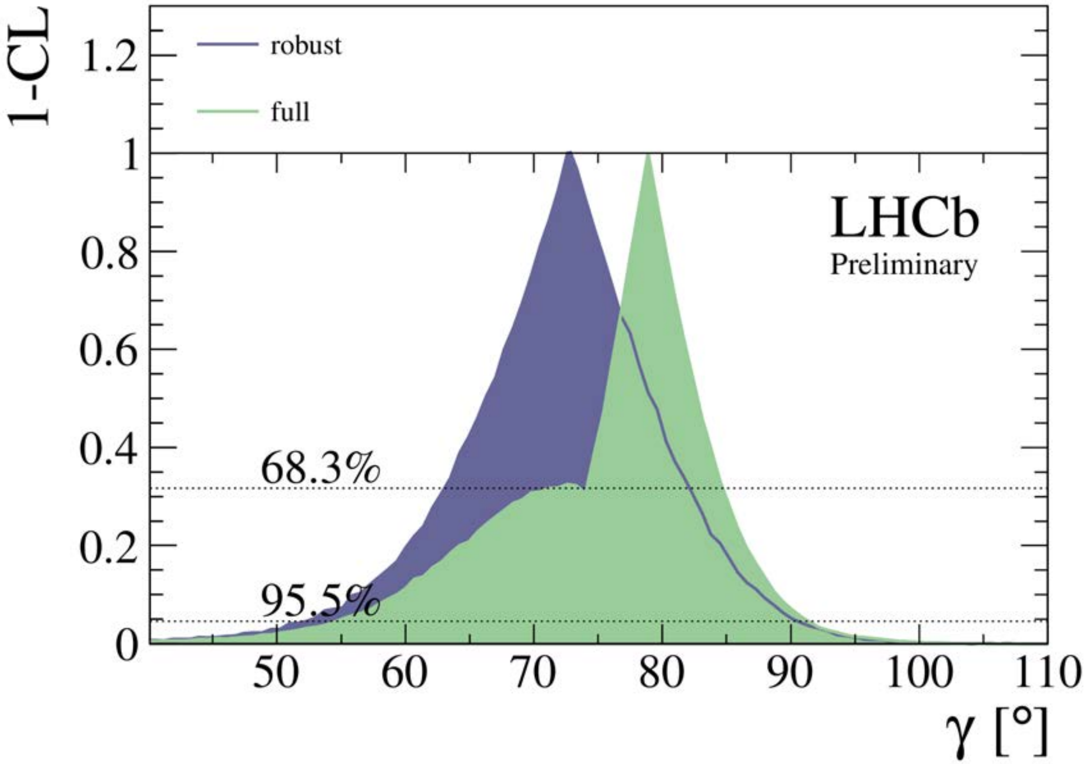
BACKUP

LHCb γ combination – Adding B→Dπ

- **B → Dπ less sensitive to γ.**
  - Interference much smaller.
  - $r_B^{D\pi} \sim r_B^{DK}/15$.
- **B → Dπ data sample 10x larger.**
- Full combination:
  - Sharp max at $\gamma = 78.9^\circ$
  - Secondary max ~ Robust max
  - Unexpected large value of $r_B^{D\pi}$ (0.027 instead of ~0.006)
- 95% Confidence level intervals agree between both combination:

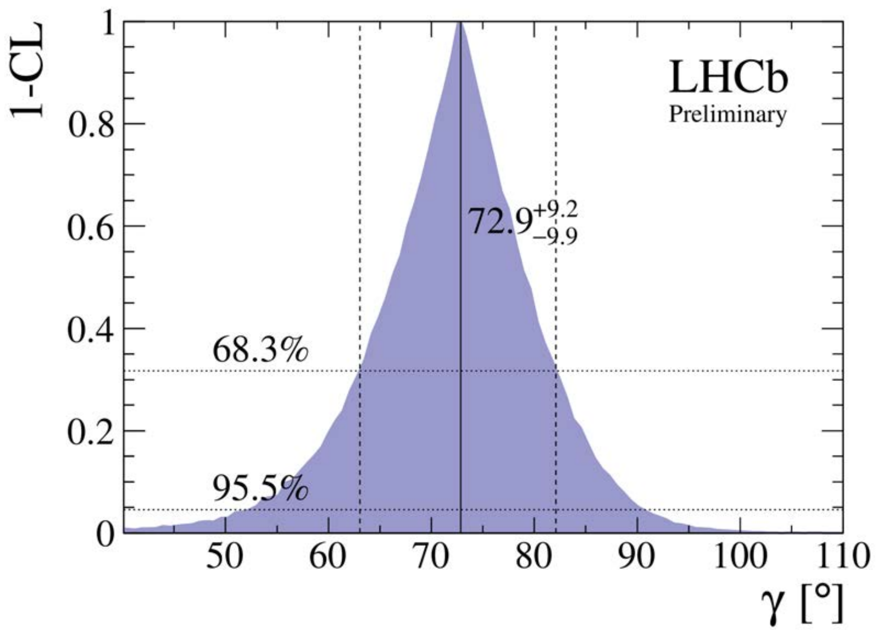
robust	$\gamma \in [52.0,\ 90.5](^\circ)$
full	$\gamma \in [54.6,\ 91.4](^\circ)$

Robust: only B→DK like
Full: add B→Dπ

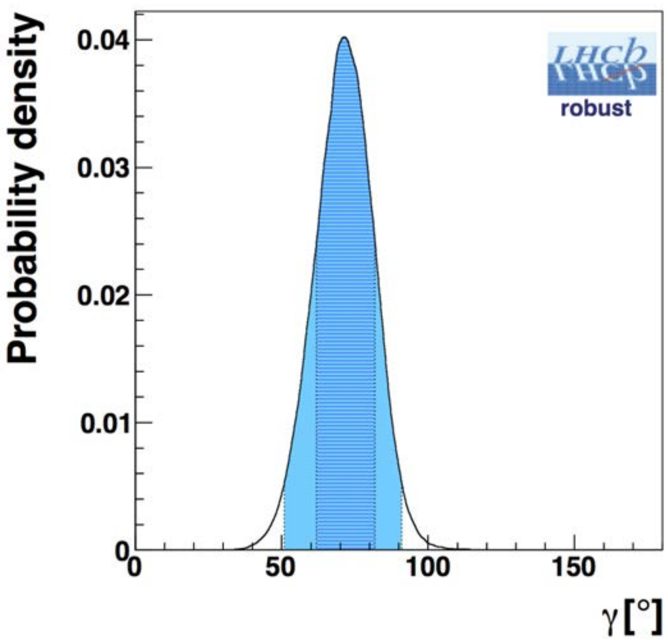


LHCb γ combination – Bayesian interpretation

Frequentist combination



Bayesian combination



	Central value	68% Interval
Frequentist γ combination (°)	72.9	[63.0, 82.1]
Bayesian γ combination (°)	71.9	[61.9, 81.8]

γ from time independent measurement- References

[1] M. Gronau and D. London, PLB 253 (1991) 483

[2] M. Gronau and D. Wyler PLB 265 (1991) 172

[3] D. Atwood and I. Dunietz and A. Soni, PRL 78 (1997) 3257

[4] D. Atwood, I. Dunietz and A. Soni, PRD 63 (2001) 036005

[5] D. Atwood and A. Soni, PRD 68 (2003) 033003

[6] Y. Grossman, Z. Ligeti and A. Soffer, PRD 67 (2003) 071301

[7] A. Giri, Y. Grossman, A. Soffer and J. Zupan, PRD 68 (2003) 054018

[8] A. Bondar, Proceedings of BINP special analysis meeting on Dalitz analysis, 2002, unpublished

γ from charmless B decays - Parametrisation

- Express CP asymmetries and BR as a function of weak and hadronic param. :

$$O = f\left(\beta, \gamma, \underbrace{|D|, d, \vartheta, q, \vartheta_q}_{\substack{B^0\to\pi^+\pi^- \\ B^0\to\pi^0\pi^0 \\ B^+\to\pi^+\pi^0}}, \underbrace{|D'|, d', \vartheta'}_{B_s^0\to K^+K^-}\right)$$

<u>Observable</u>:
Asymmetry
Branching Ratio

$\sin(2\beta) = 0.682 \pm 0.019$ (HFAG)

- Take into account non factorizable U-spin breaking correction:

$$|D'| = \underbrace{\left|\frac{D'}{D}\right|_{\rm fact}}_{1.41^{+0.20}_{-0.11}} |D||1 + r_D e^{i\vartheta_{r_D}}|$$

$1.41^{+0.20}_{-0.11}$ (QCD sum rules*)

$$d' e^{i\vartheta'} = d e^{i\vartheta} \frac{1 + r_G e^{i\vartheta_{r_G}}}{1 + r_D e^{i\vartheta_{r_D}}}$$

- Use flat priors:

Quantity	Prior range
d	$[0, 20]$
ϑ	$[-180°, 180°]$
q	$[0, 20]$
ϑ_q	$[-180°, 180°]$
r_D	$[0, \kappa]$
ϑ_{r_D}	$[-180°, 180°]$
r_G	$[0, \kappa]$
ϑ_{r_G}	$[-180°, 180°]$
γ (analysis C only)	$[-180°, 180°]$

* [PRD78 (2008) 054015]

γ from charmless B decays - References

[9] R. Fleischer, Phys. Lett. B 459 (1999) 306, arXiv:hep-ph/9903456

[10] R. Fleischer, Eur. Phys. J. C 52 (2007) 267, arXiv:0705.1121

[11] R. Fleischer, R. Knegjens, Eur. Phys. J. C 71 (2011) 1532, arXiv:1011.1096

[12] M. Ciuchini, E. Franco, S. Mishima, L. Silvestrini, JHEP 1210 (2012) 029, arXiv:1205.4948

[13] M. Gronau, D. London, Phys. Rev. Lett. 65 (19990) 3381