Measurement of the CKM angle γ

Mark Whitehead on behalf of LHCb

Flavour Physics with High-Luminosity Experiments Workshop

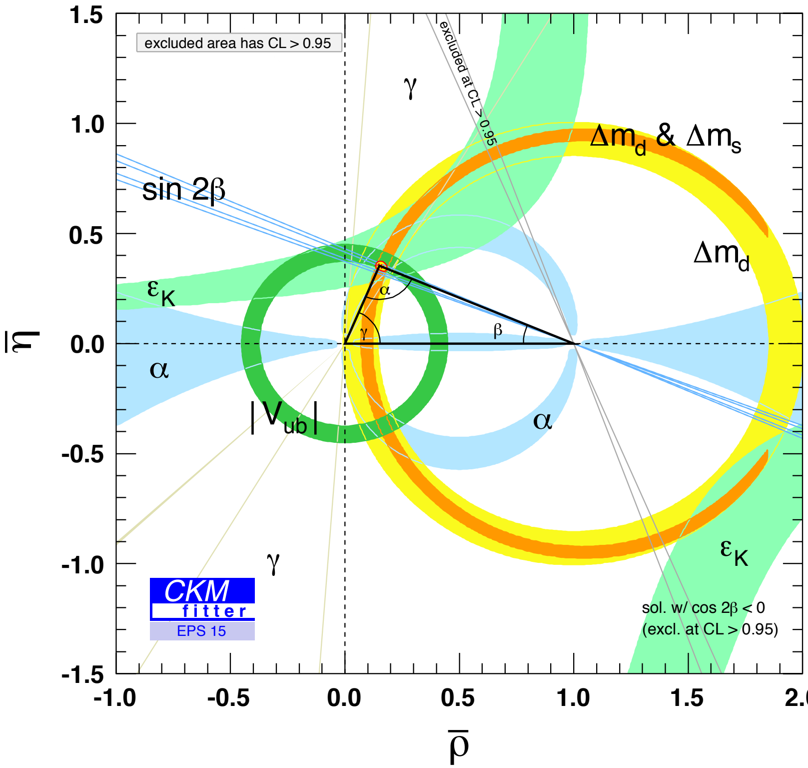
MIAPP, Germany

Introduction

- Why are we still measuring γ?
  - Least well known angle of the CKM unitarity triangle
  - Tree-level determination and extremely clean (theoretically)
  - Loop-level access to look for NP

$$\gamma = (73.2^{+6.3}_{-7.0})^{\circ}$$ [CKM fitter]

$$\gamma = (68.3 \pm 7.5)^{\circ}$$ [UT fit]



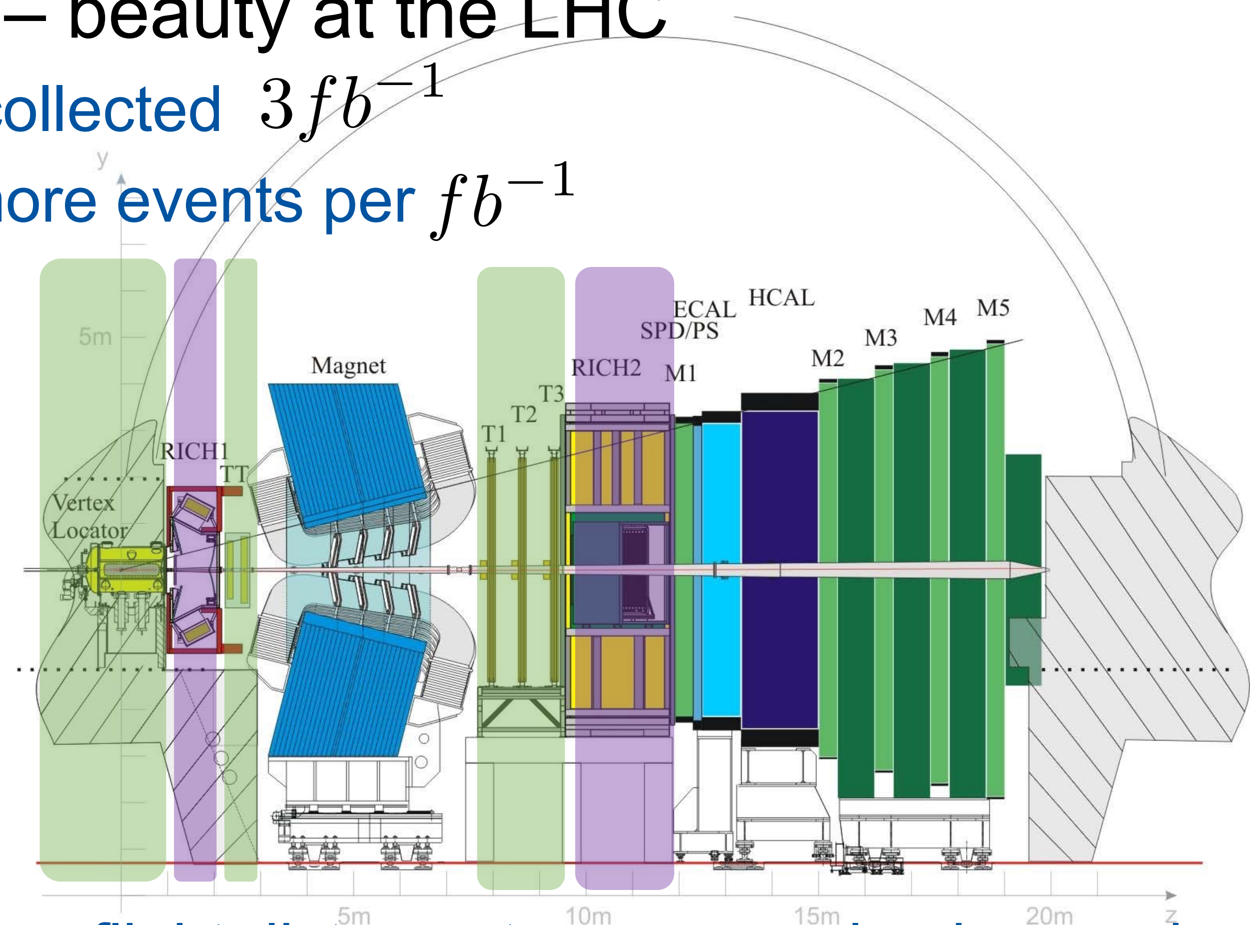
- Whats new from LHCb?
  - New decay modes
  - Updates to our full Run I sample
  - New combination

Detector

- Its all in the name – beauty at the LHC
  - During Run I we collected $3fb^{-1}$
  - Run II at 13TeV more events per fb^{-1}

Excellent tracking and vertex resolution

Particle ID for $K\pi$ separation



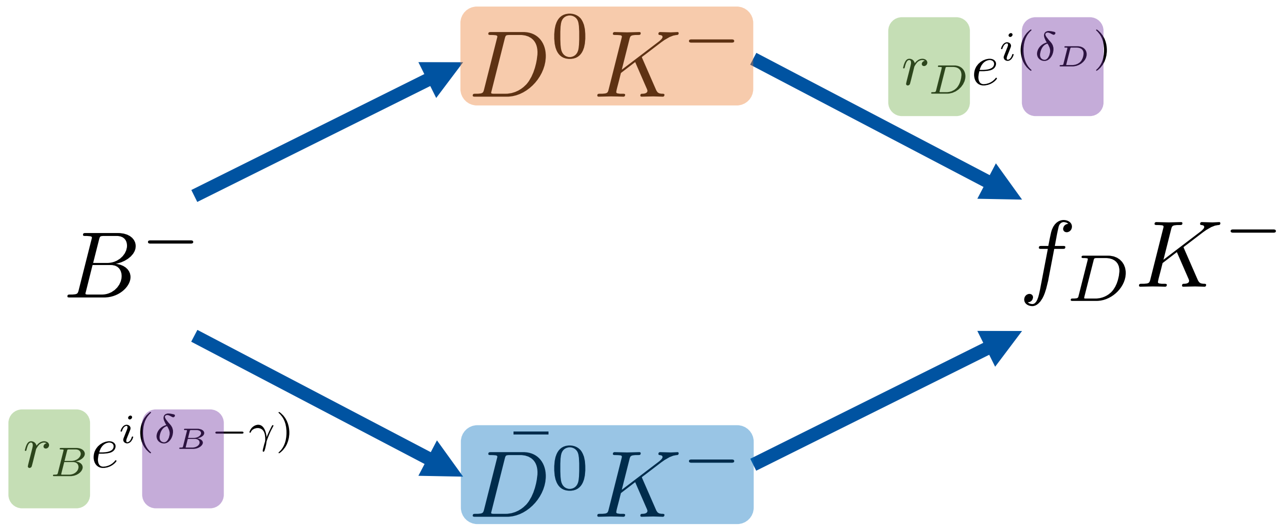
- Exploit B and D meson flight distance to suppress backgrounds

How to measure γ

- Interference
  - Two amplitudes giving the same final state
  - Golden example – $B^{\pm} \to DK^{\pm}$

$b \to cW \; (V_{cb})$

$b \to uW \; (V_{ub})$



- Amplitude ratios $r_B \, , r_D$
- Strong phase differences $\delta_B \, , \delta_D$

New results from LHCb

- Several new or updated inputs into the combination
  - Two body GLW/ADS [M. Gronau, D. Wyler, Phys. Lett. B265 (1991) 172] [M. Gronau, D. London, Phys. Lett. B253 (1991) 483]

$$B^{\pm} \to DK^{\pm}, D \to h^{+}h^{'-}$$

  - Four body GLW/ADS [D. Atwood, I. Dunietz, and A. Soni, Phys. Rev. Lett. 78 (1997) 3257, Phys. Rev. D63 (2001) 036005]

$$B^{\pm} \to DK^{\pm}, D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$$

  - GGSZ [A. Giri, Y. Grossman, A. Soffer, and J. Zupan, Phys. Rev. D68 (2003) 054018]

$$B^{0} \to DK^{*0}, D \to K^{0}_{S}\pi^{+}\pi^{-}$$

  - GLW-Dalitz [T. Gershon, Phys. Rev. D79 (2009) 051301] [T. Gershon, M. Williams, Phys. Rev. D80 (2009) 092002]

$$B^{0} \to DK^{+}\pi^{-}, D \to h^{+}h^{-}$$

New results from LHCb

- Several new or updated inputs into the combination
  - Two body GLW/ADS
    $B^{\pm} \to DK^{\pm}, D \to h^+h'^-$
  - Four body GLW/ADS
    $B^{\pm} \to DK^{\pm}, D \to h^+\pi^-\pi^+\pi^-$
  - GGSZ
    $B^0 \to DK^{*0}, D \to K^0_S\pi^+\pi^-$
  - GLW-Dalitz
    $B^0 \to DK^+\pi^-, D \to h^+h^-$

Update of LHCb γ combination

of $B \to DK$ like decays

and all $B \to Dh$ decays

- Several new or updated inputs into the combination
  - Two body GLW/ADS

    $$B^{\pm} \to DK^{\pm}\, , D \to h^{+}h^{'-}$$

  - Four body GLW/ADS

    $$B^{\pm} \to DK^{\pm}\, , D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$$

  - GGSZ

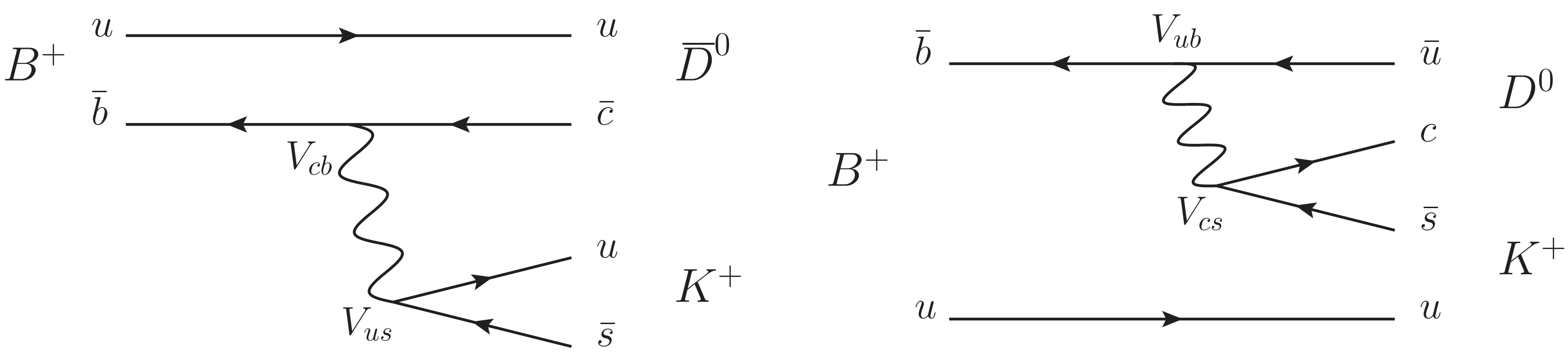
    $$B^{0} \to DK^{*0}\, , D \to K^{0}_{S}\pi^{+}\pi^{-}$$

  - GLW-Dalitz

    $$B^{0} \to DK^{+}\pi^{-}\, , D \to h^{+}h^{-}$$

Two and four body GLW/ADS

- Look at $B \to Dh$ decays
  - GLW: $D \to K^+K^-, \pi^+\pi^-, 2\pi^+2\pi^-$
  - ADS: $D \to K^+\pi^-, \pi^+K^-, K^+\pi^-\pi^+\pi^-, \pi^+K^-\pi^+\pi^-$

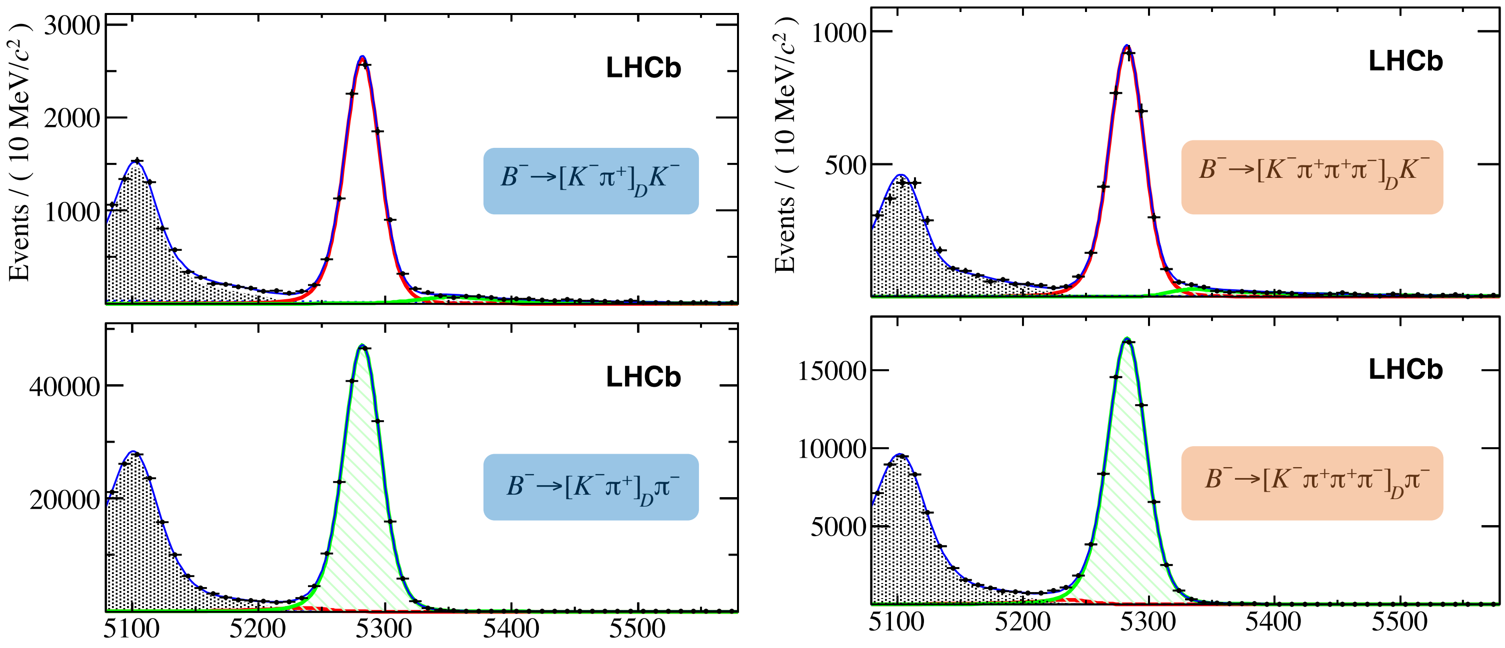


- Share signal shape parameters between 2(4) body modes
- Constrain crossfeed between DK and $D\pi$ modes (PID)
- Use $D\pi$ as a control mode; charmless background etc

ADS favoured signals

- Mass fits for the favoured modes

$B^{\pm} \to [K^{\pm}\pi^{\mp}]_D\,\pi^{\pm}$	378,050 ± 650
$B^{\pm} \to [K^{\pm}\pi^{\mp}]_D\,K^{\pm}$	29,470 ± 230
$B^{\pm} \to [K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}]_D\,\pi^{\pm}$	142,910 ± 390
$B^{\pm} \to [K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}]_D\,K^{\pm}$	11,330 ± 140

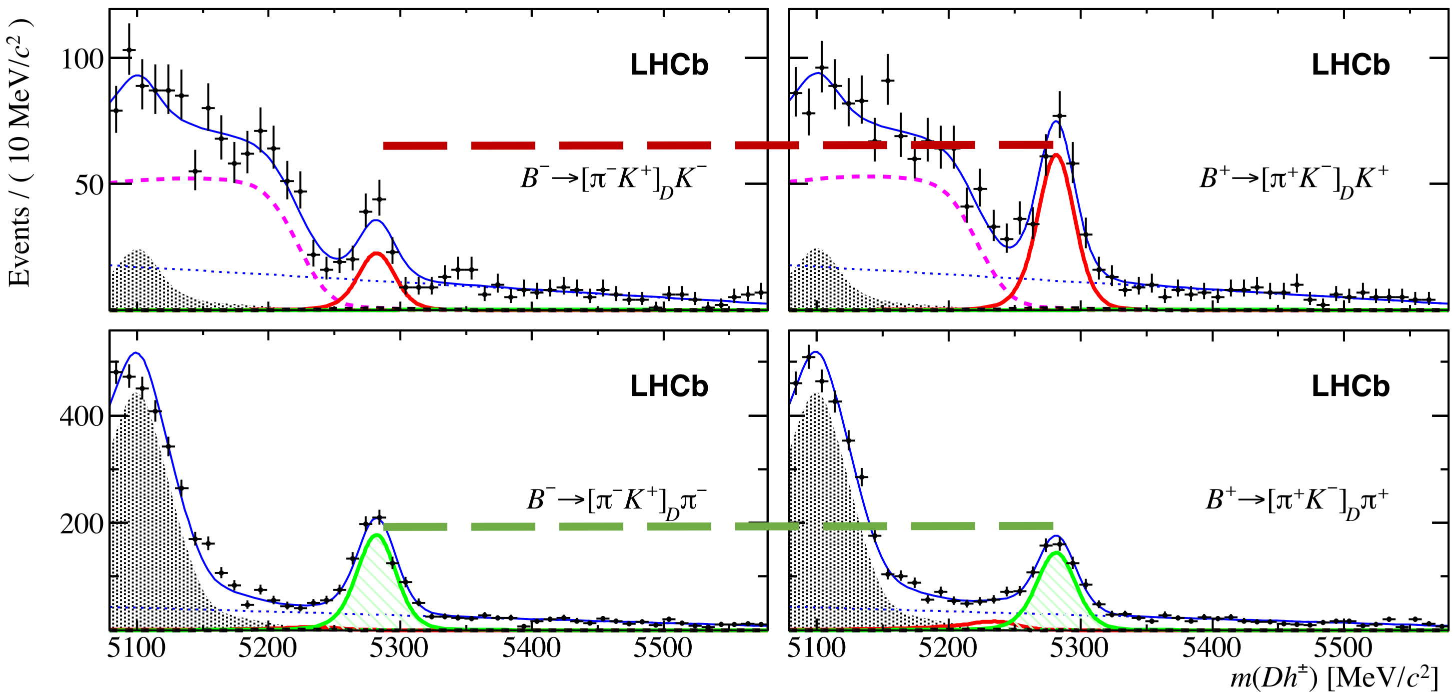


Low combinatorial background and tiny cross-feed contributions

2 body ADS suppressed signals

- Visible CP violation
  - Around 8 sigma!

$B^{\pm} \to [\pi^{\pm} K^{\mp}]_D K^{\pm}$	553 ± 34
$B^{\pm} \to [\pi^{\pm} K^{\mp}]_D \pi^{\pm}$	1360 ± 44

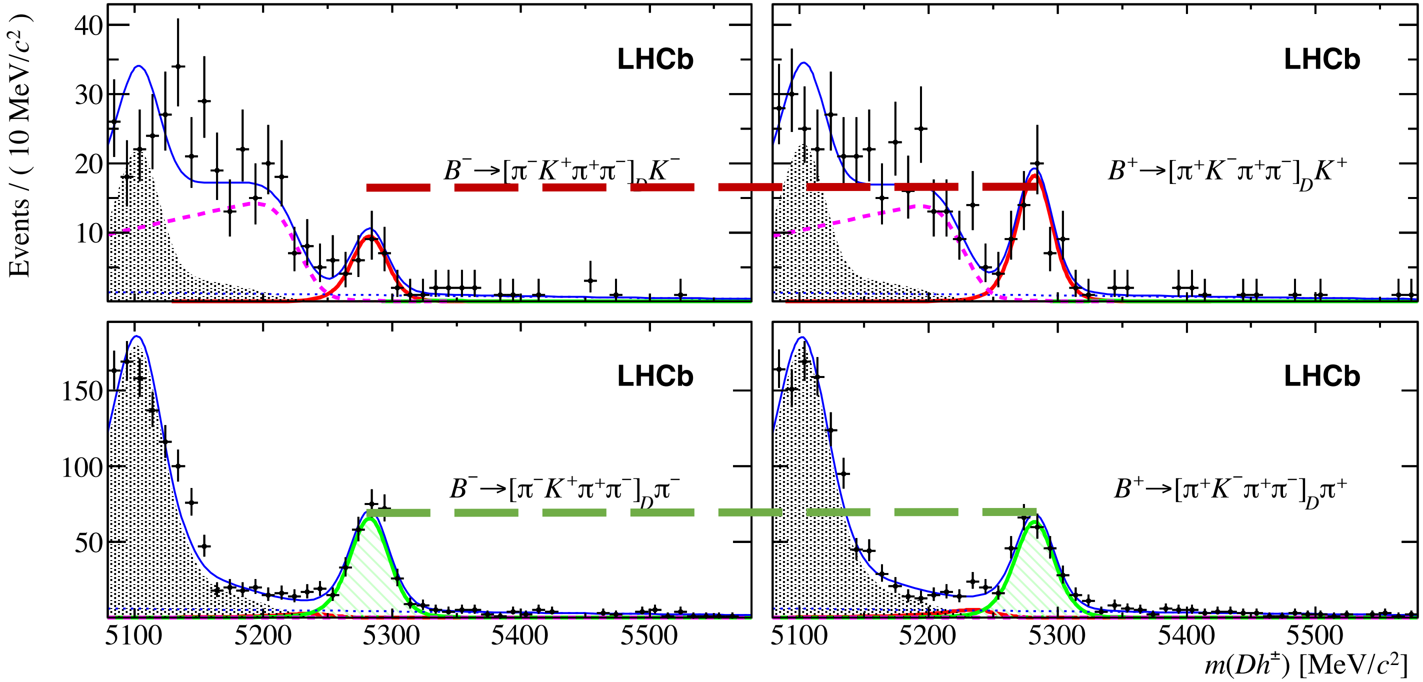


$$A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \pm 0.056 \pm 0.011 \qquad A^{\pi K}_{\mathrm{ADS}(\pi)} = 0.100 \pm 0.031 \pm 0.009$$

4 body ADS suppressed signals

- Visible CP asymmetry
  - Close to 3 sigma evidence

$B^{\pm} \rightarrow [\pi^{\pm} K^{\mp} \pi^{+} \pi^{-}]_D K^{\pm}$	159 ± 17
$B^{\pm} \rightarrow [\pi^{\pm} K^{\mp} \pi^{+} \pi^{-}]_D \pi^{\pm}$	539 ± 26

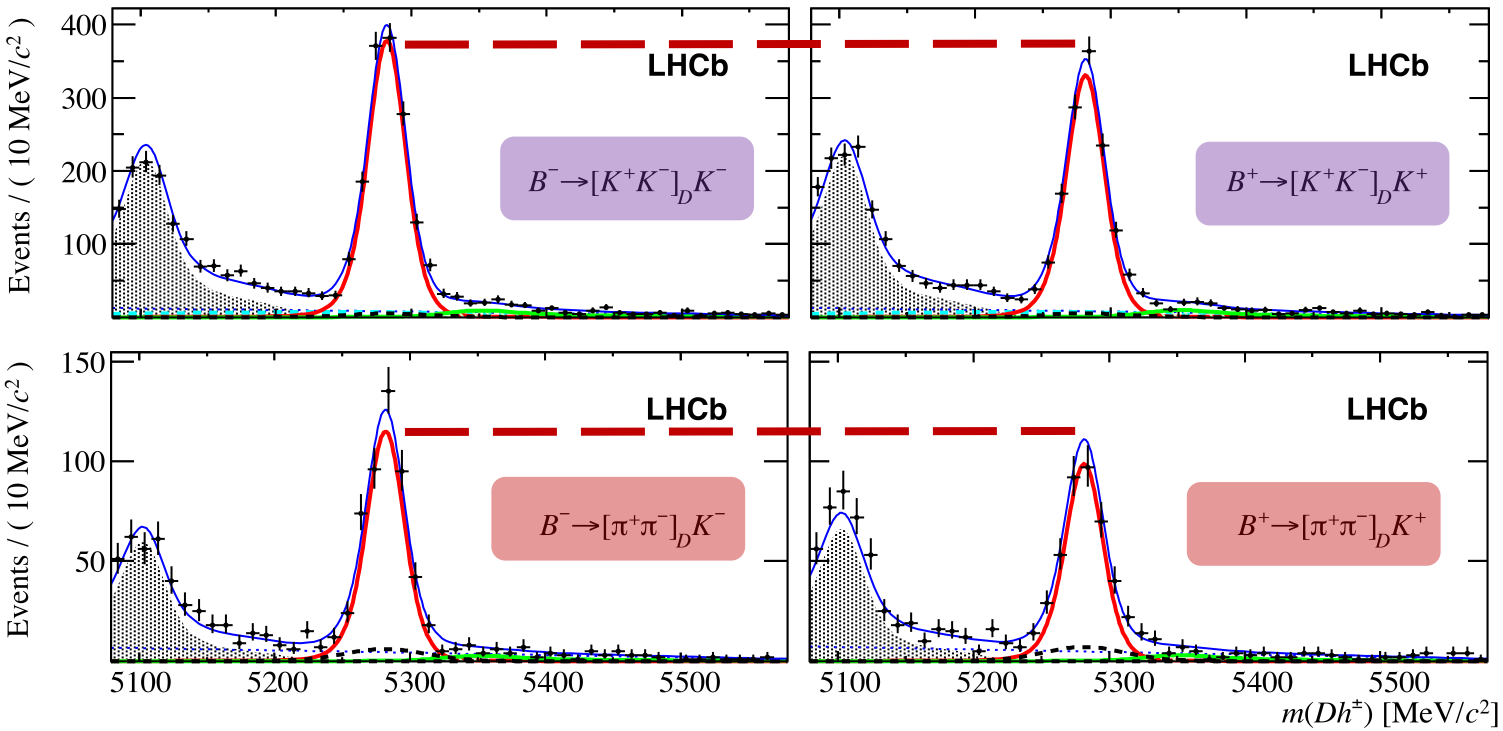


$$A^{\pi K \pi\pi}_{\mathrm{ADS}(K)} = -0.313 \pm 0.102 \pm 0.038 \quad A^{\pi K \pi\pi}_{\mathrm{ADS}(\pi)} = 0.023 \pm 0.048 \pm 0.005$$

2 body GLW modes

- Small asymmetries seen
  - About 5 sigma combined!

$B^{\pm} \to [K^{+}K^{-}]_D K^{\pm}$	3816 ± 92
$B^{\pm} \to [\pi^{+}\pi^{-}]_D K^{\pm}$	1162 ± 48

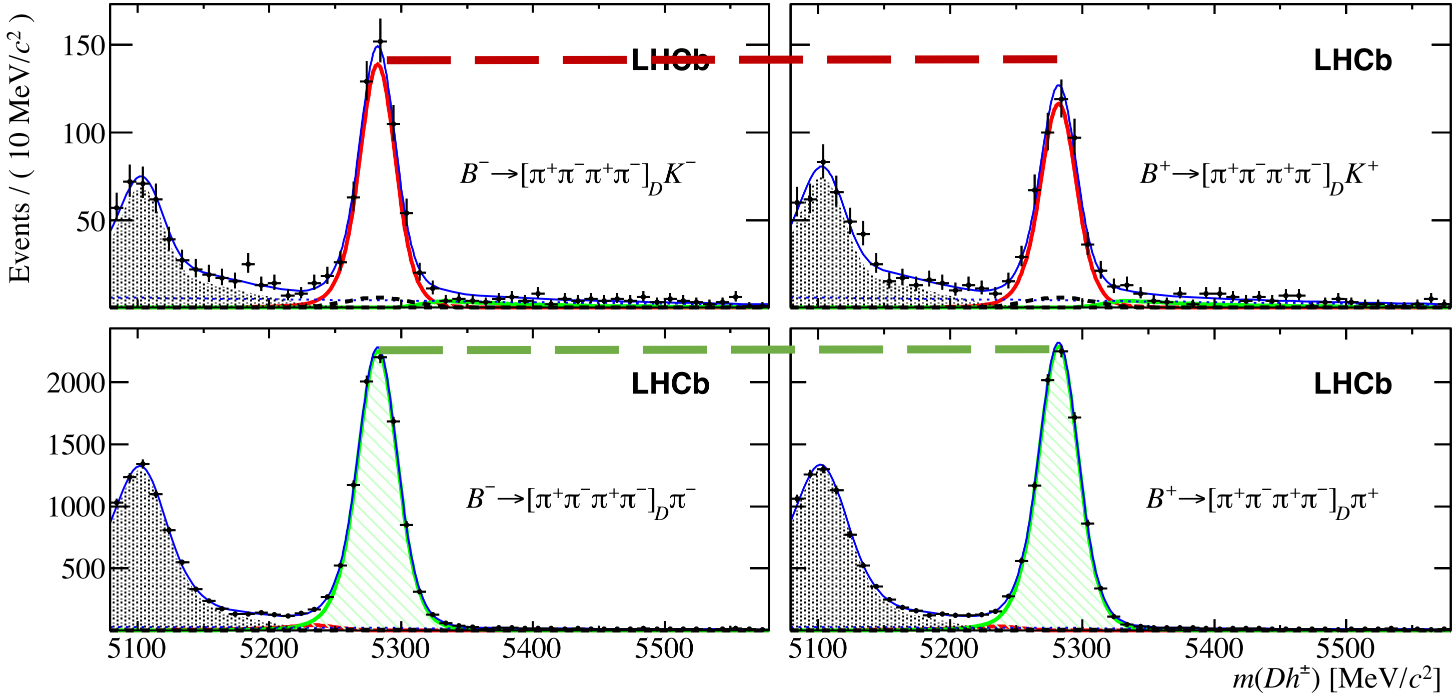


$$A_K^{KK} = 0.087 \pm 0.020 \pm 0.008 \qquad A_K^{\pi\pi} = 0.128 \pm 0.037 \pm 0.012$$

4 body GLW mode

- First use of this mode!
  - Decay ~75% CP even

$B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D K^{\pm}$	1497 ± 60
$B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D \pi^{\pm}$	$19{,}360 \pm 150$



$$A_K^{\pi\pi\pi\pi} = 0.100 \pm 0.034 \pm 0.018 \qquad A_\pi^{\pi\pi\pi\pi} = -0.0041 \pm 0.0079 \pm 0.0024$$

- Several new or updated inputs into the combination
  - Two body GLW/ADS

    $$B^{\pm} \to DK^{\pm}, D \to h^{+}h^{'-}$$

  - Four body GLW/ADS

    $$B^{\pm} \to DK^{\pm}, D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$$

  - GGSZ

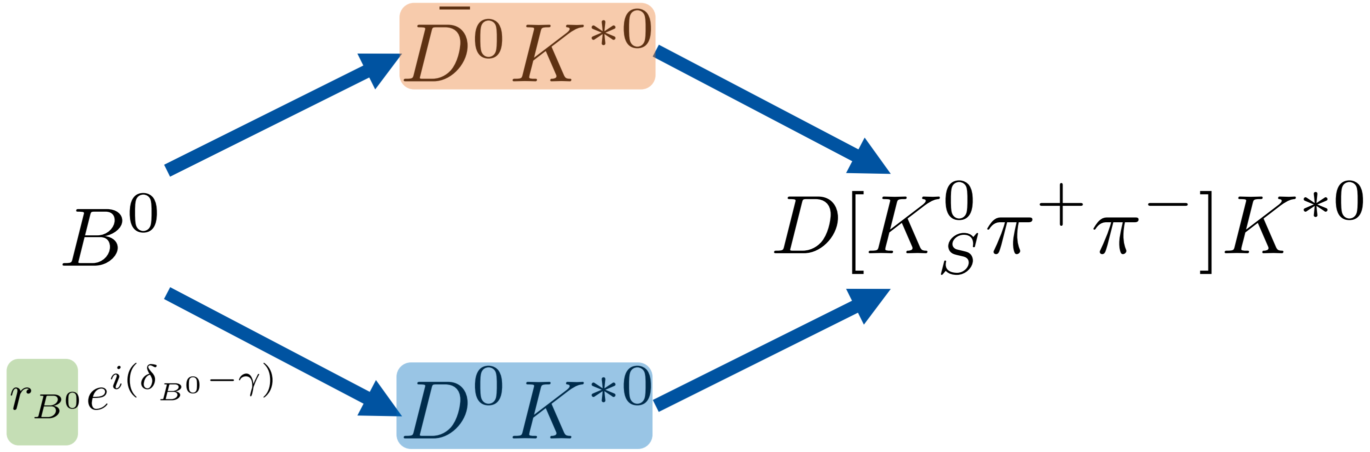
    $$B^{0} \to DK^{*0}, D \to K_{S}^{0}\pi^{+}\pi^{-}$$

  - GLW-Dalitz

    $$B^{0} \to DK^{+}\pi^{-}, D \to h^{+}h^{-}$$

GGSZ analysis

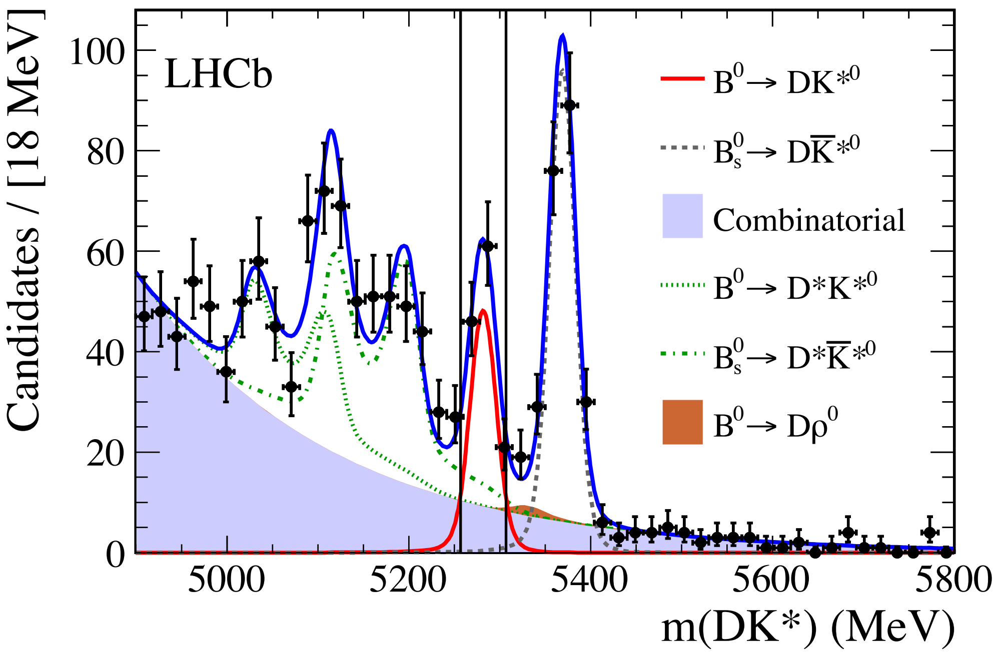
- Can also consider the neutral B channels
  - Decay chain $B^0 \to DK^{*0}, D \to K_S^0 \pi^+ \pi^-$
  - Yields lower than $B^\pm \to DK^\pm$ but $r_{B^0} \approx 3 r_B$
  - Model dependent uses model from BaBar (focus of this talk)
  - Model independent takes input from CLEO
    - Totally consistent results with comparable uncertainties



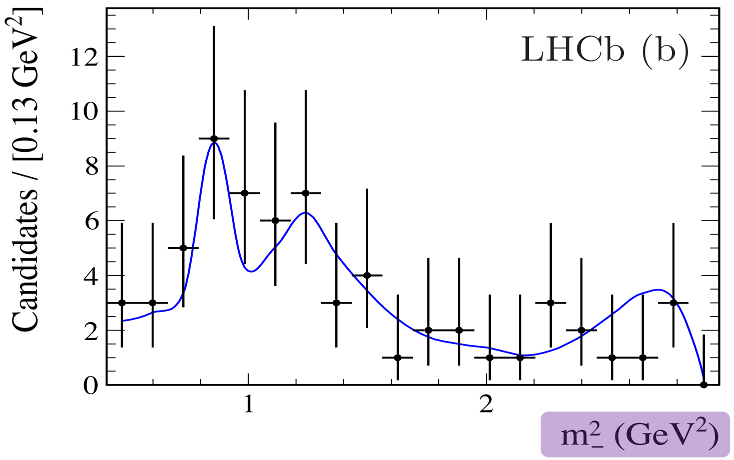
GGSZ analysis

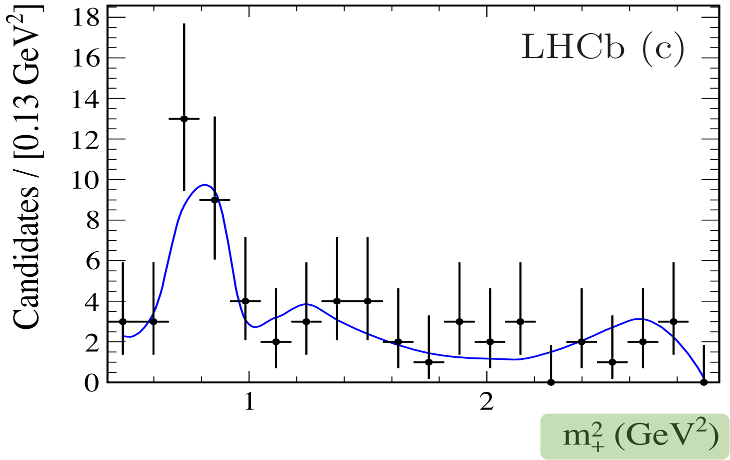
- Analysis strategy (model dependent)
  - First perform a fit to the B mass
  - Candidates within the black lines used in the CP fit
  - Fit the D Dalitz plot with the BaBar model
  - Note we couldn't use the Belle model

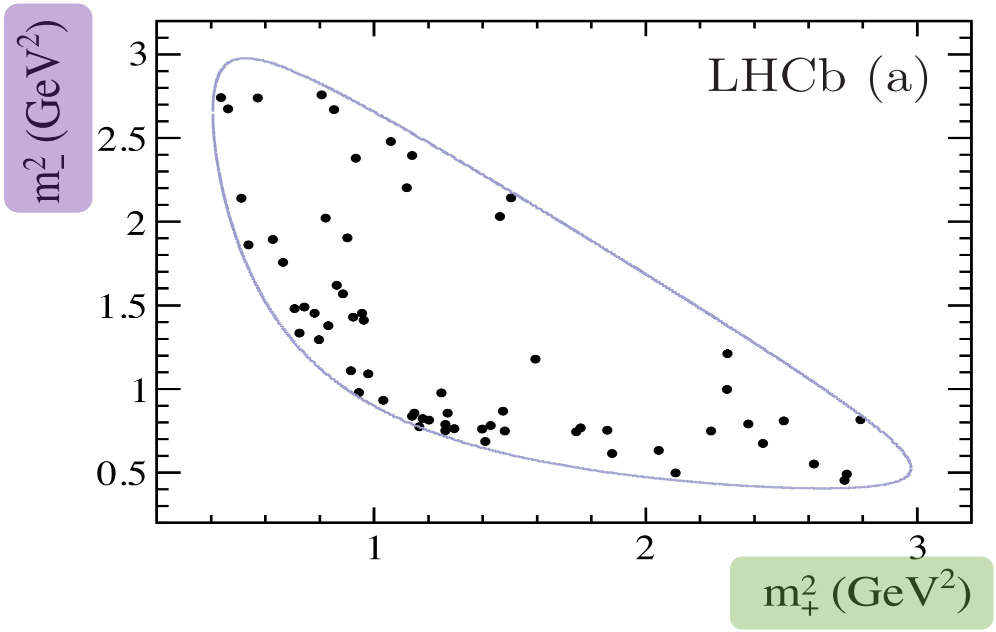
89 ± 11 events



GGSZ analysis







$$m^2_+ \equiv m^2(K^0_S\pi^+)$$

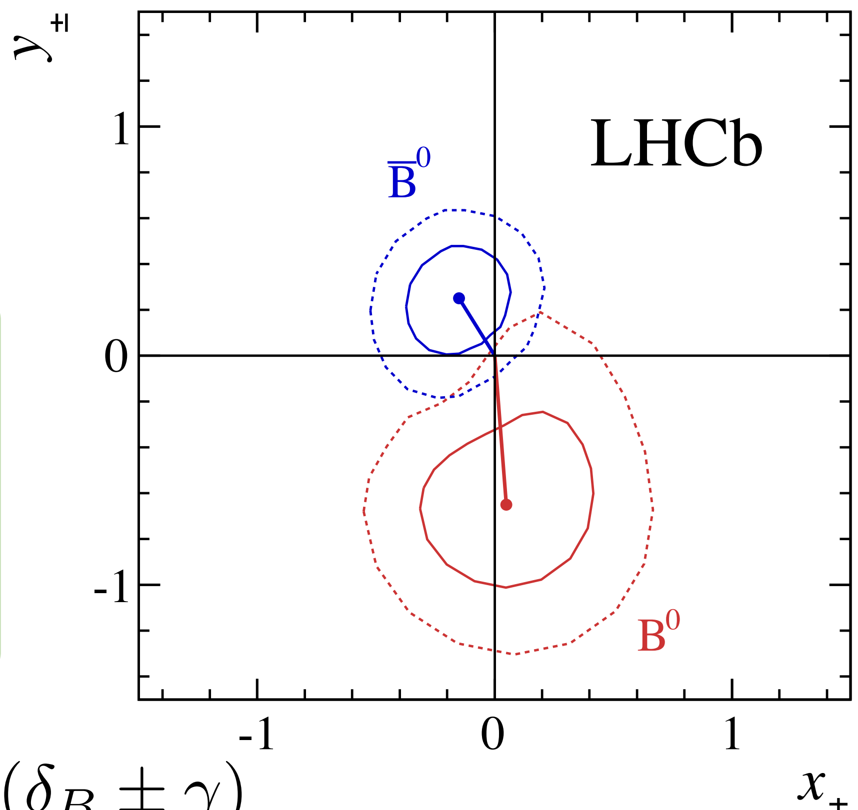
$$m^2_- \equiv m^2(K^0_S\pi^-)$$

B^0 plots

GGSZ analysis

- Model dependent results
  - Extract cartesian parameters from CP fit
  - No CPV at 2 sigma
  - 3rd uncertainty from DP model
  - Stat uncertainties dominate

$$x_- = -0.15 \pm 0.14 \pm 0.03 \pm 0.01,$$
$$y_- = 0.25 \pm 0.15 \pm 0.06 \pm 0.01,$$
$$x_+ = 0.05 \pm 0.24 \pm 0.04 \pm 0.01,$$
$$y_+ = -0.65 \,^{+0.24}_{-0.23} \pm 0.08 \pm 0.01,$$



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

- Several new or updated inputs into the combination
  - Two body GLW/ADS

$$B^{\pm} \to DK^{\pm}, D \to h^{+}h^{'-}$$

  - Four body GLW/ADS

$$B^{\pm} \to DK^{\pm}, D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$$

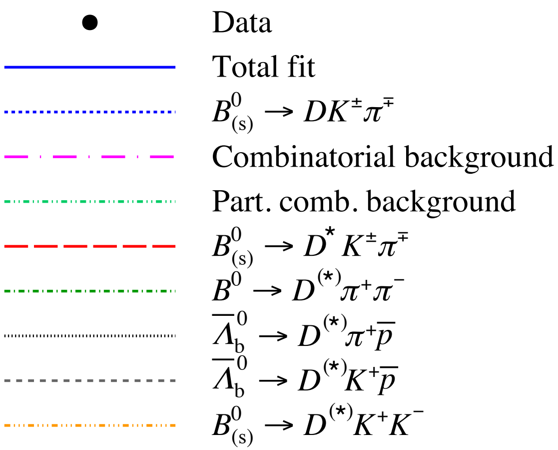
  - GGSZ

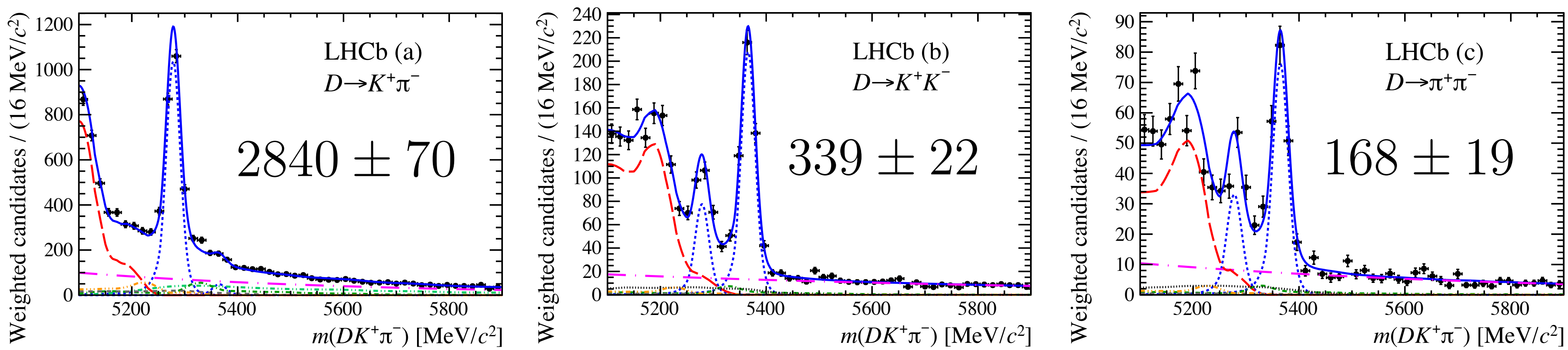
$$B^{0} \to DK^{*0}, D \to K_{S}^{0}\pi^{+}\pi^{-}$$

  - GLW-Dalitz

$$B^{0} \to DK^{+}\pi^{-}, D \to h^{+}h^{-}$$

- Measure γ using $B^0 \to DK^+\pi^-$ decays
  - Use CP even modes $D \to K^+K^-, \pi^+\pi^-$
  - Bin in output of the neural network
  - Simultaneous DP fit
  - Purity of the GLW modes hurt by $B_s^0 \to D^{(*)}K^-\pi^+$ contributions

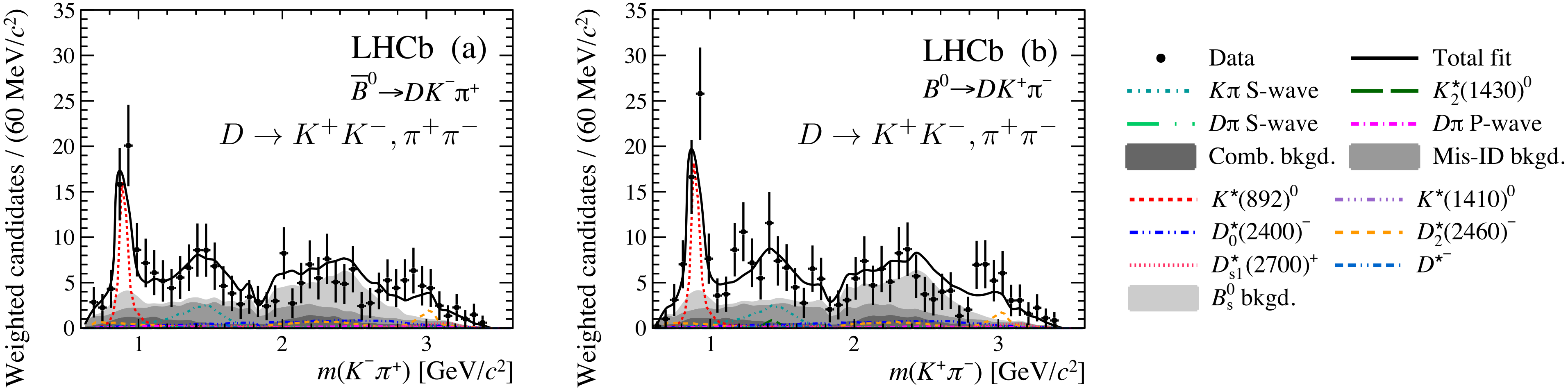




GLW-Dalitz analysis

- Amplitude fit based on previous results (see backups)
  - First time this method has been used
  - Use to $D \to K^+\pi^-$ help guide the fit – no CPV allowed
  - Include CPV for K*(892) amplitude

$$\mathcal{A}\left(m^2(D\pi^-), m^2(K^+\pi^-)\right) = \sum_{j=1}^{N} c_j F_j\left(m^2(D\pi^-), m^2(K^+\pi^-)\right) \qquad c_j \longrightarrow \begin{cases} c_j & \text{for a } D\pi^- \text{ resonance}, \\ c_j\left[1 + x_{\pm,j} + iy_{\pm,j}\right] & \text{for a } K^+\pi^- \text{ resonance} \end{cases}$$

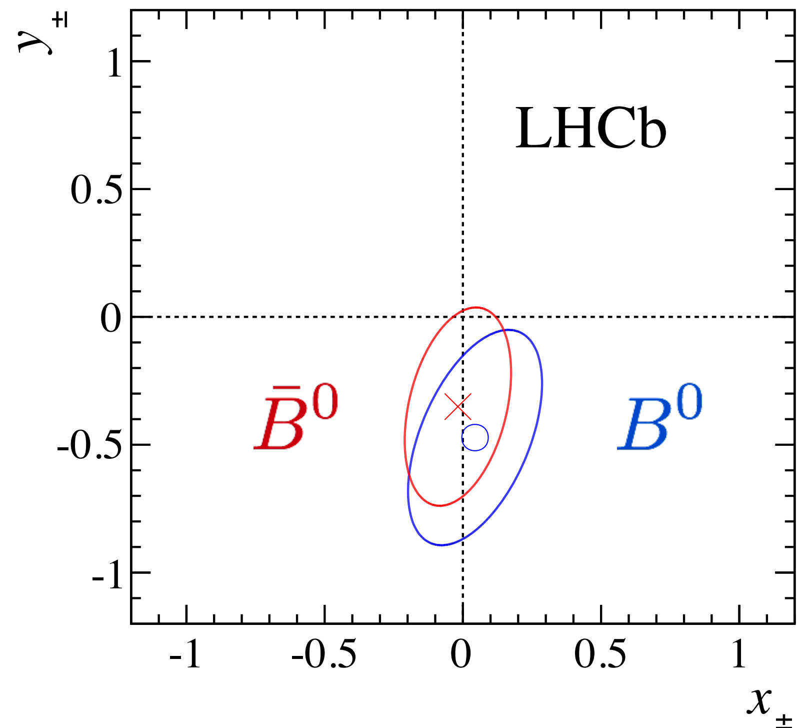


Phys. Rev. D93 (2016) 112018

GLW-Dalitz analysis

- Cartesian parameters reported
  - Consistent with no CPV
  - Statistics the biggest factor

$$x_+ = 0.04 \pm 0.16 \pm 0.11$$
$$x_- = -0.02 \pm 0.13 \pm 0.14$$
$$y_+ = -0.47 \pm 0.28 \pm 0.22$$
$$y_- = -0.35 \pm 0.26 \pm 0.41$$



- Report quasi-two-body values
  - Help combine with $B^0 \to DK^{*0}$ results
  - Coherence factor, relative magnitudes and strong phases

$\kappa = 0.958\,^{+0.005}_{-0.010}\,^{+0.002}_{-0.045}$, $\bar{R}_B = 1.02\,^{+0.03}_{-0.01} \pm 0.06$, $\Delta\bar{\delta}_B = 0.02\,^{+0.03}_{-0.02} \pm 0.11$

- Several new or updated inputs into the combination
  - Two body GLW/ADS

    $B^{\pm} \to DK^{\pm}, D \to h^{+}h^{'-}$

  - Four body GLW/ADS

    $B^{\pm} \to DK^{\pm}, D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$

  - GGSZ

    $B^{0} \to DK^{*0}, D \to K_{S}^{0}\pi^{+}\pi^{-}$

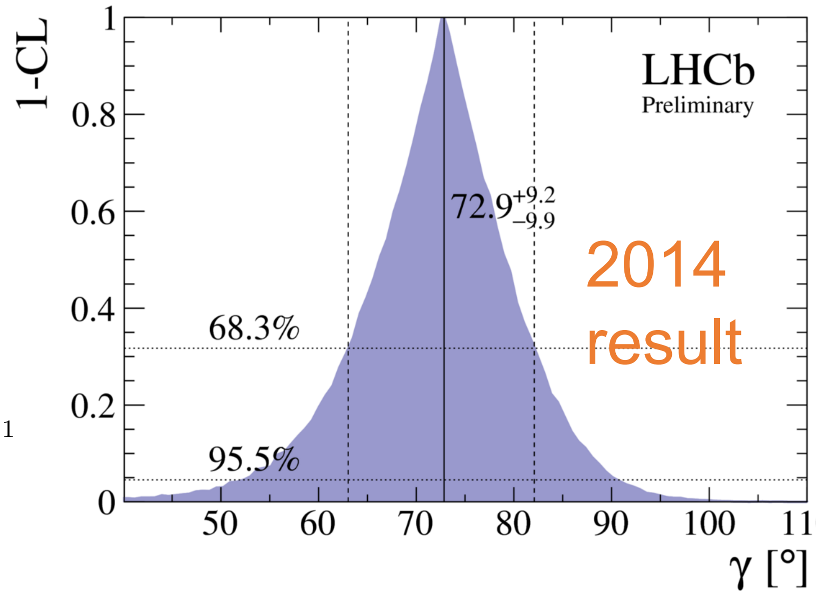
  - GLW-Dalitz

    $B^{0} \to DK^{+}\pi^{-}, D \to h^{+}h^{-}$

Update of LHCb γ combination of $B \to DK$ like decays

DK Combination

- Best knowledge from combining all LHCb analyses
  - Previous result from 2014
  - Only $B \to DK$ like decays



- $B^+ \to DK^+$, $D \to h^+h^-$, GLW/ADS, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to h^+\pi^-\pi^+\pi^-$, quasi-GLW/ADS, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to h^+h^-\pi^0$, quasi-GLW/ADS, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to K^0_S h^+h^-$, model-independent GGSZ, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+$, $D \to K^0_S K^+\pi^-$, GLS, $3\,\text{fb}^{-1}$
- $B^0 \to DK^+\pi^-$, $D \to h^+h^-$, GLW-Dalitz, $3\,\text{fb}^{-1}$
- $B^0 \to DK^{*0}$, $D \to K^+\pi^-$, ADS, $3\,\text{fb}^{-1}$
- $B^0 \to DK^{*0}$, $D \to K^0_S\pi^+\pi^-$, model-dependent GGSZ, $3\,\text{fb}^{-1}$
- $B^+ \to DK^+\pi^+\pi^-$, $D \to h^+h^-$, GLW/ADS, $3\,\text{fb}^{-1}$
- $B^0_s \to D_s^{\mp}K^{\pm}$, time-dependent, $1\,\text{fb}^{-1}$,

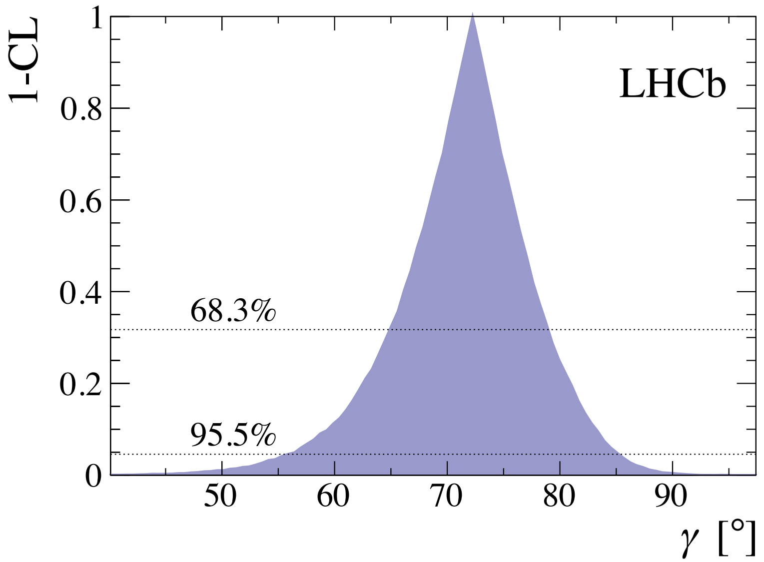
New or updated since the above result

Work in progress: $3\,fb^{-1}$

DK Combination

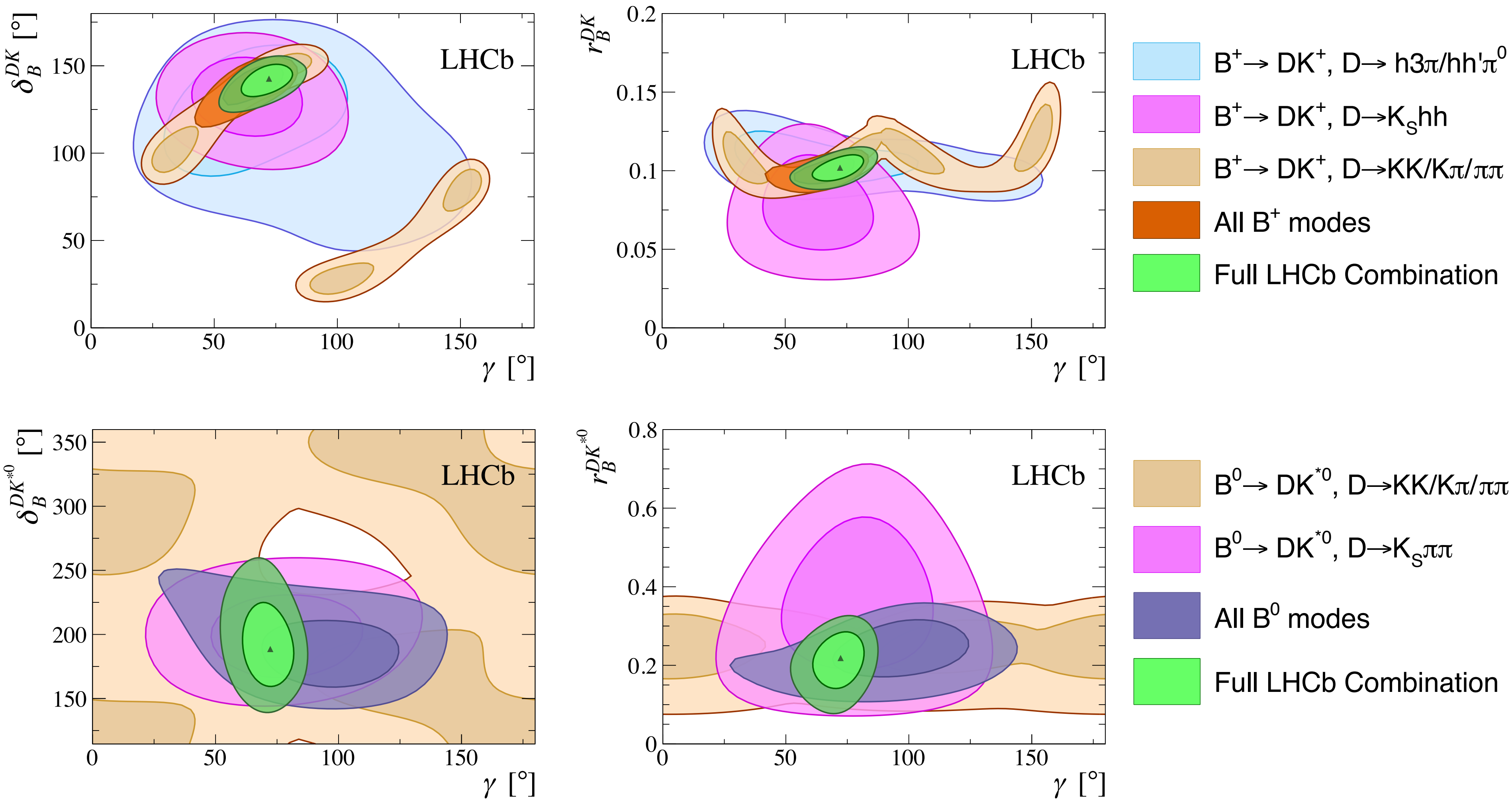
- New DK combination
  - Frequentist results here
  - Bayesian results agree well
  - Coverage is good

$$\gamma = (72.2\,^{+6.8}_{-7.3})^\circ$$



Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma\,(^\circ)$	72.2	[64.9, 79.0]	[55.9, 85.2]	[43.7, 90.9]
r_B^{DK}	0.1019	[0.0963, 0.1075]	[0.0907, 0.1128]	[0.0849, 0.1182]
$\delta_B^{DK}\,(^\circ)$	142.6	[136.0, 148.3]	[127.8, 153.6]	[116.2, 158.7]
$r_B^{DK^{*0}}$	0.218	[0.171, 0.263]	[0.118, 0.305]	[0.000, 0.348]
$\delta_B^{DK^{*0}}\,(^\circ)$	189	[169, 212]	[148, 241]	[123, 283]

DK Combination



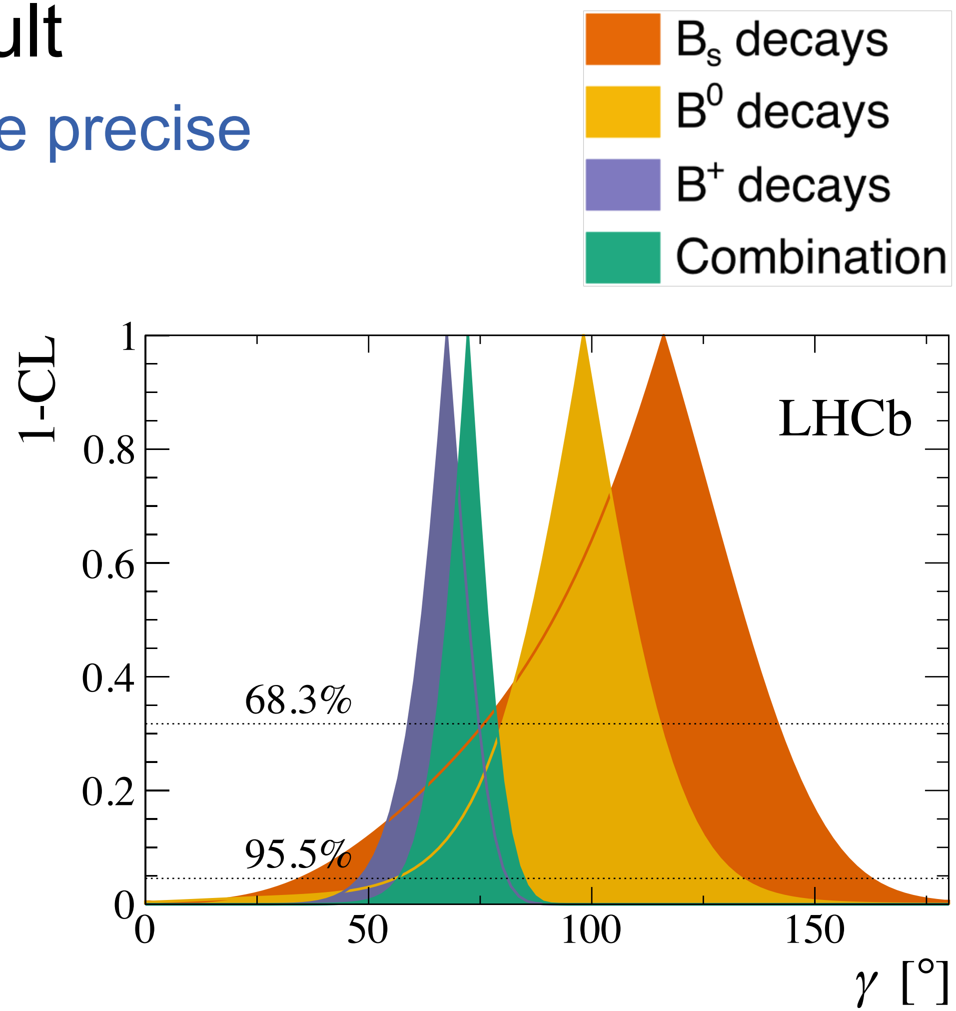
DK Combination

- Improvement on 2014 result
  - Around 2 or 3 degrees more precise

$$\gamma \in [64.9, 79.0]^\circ \text{ at } 68.3\% \text{ CL}$$

$$\gamma \in [55.9, 85.2]^\circ \text{ at } 95.5\% \text{ CL}$$

$$\gamma = (72.2\,^{+6.8}_{-7.3})^\circ$$



  - Still more from Run I?

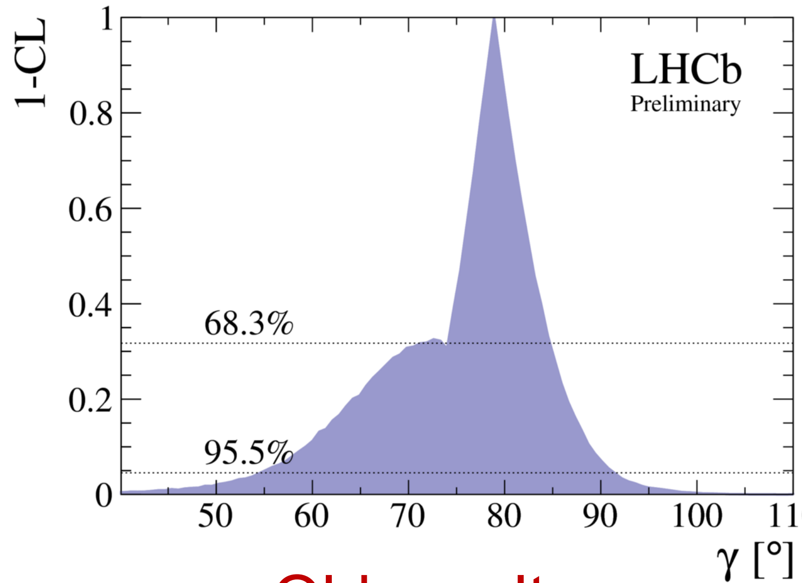
$$B_s^0 \rightarrow D_s^{\mp} K^{\pm}$$
$$B^{\pm} \rightarrow D^* K^{\pm}$$
$$B^{\pm} \rightarrow D K^{*\pm}$$

Update of LHCb γ combination of $B \to Dh$ like decays

- Several new or updated inputs into the combination
  - Two body GLW/ADS
    $$B^{\pm} \to DK^{\pm}, D \to h^{+}h^{'-}$$
  - Four body GLW/ADS
    $$B^{\pm} \to DK^{\pm}, D \to h^{+}\pi^{-}\pi^{+}\pi^{-}$$
  - GGSZ
    $$B^{0} \to DK^{*0}, D \to K_{S}^{0}\pi^{+}\pi^{-}$$
  - GLW-Dalitz
    $$B^{0} \to DK^{+}\pi^{-}, D \to h^{+}h^{-}$$

Dh Combination

- Try to squeeze sensitivity from $B \to D\pi$ like decays
  - Previous result from 2014
  - Several additional inputs w.r.t. the DK only combination



Old result

$$B^+ \to D\pi,\ D \to h^+h^-$$

$$B^+ \to D\pi,\ D \to h^+\pi^-\pi^+\pi^-$$

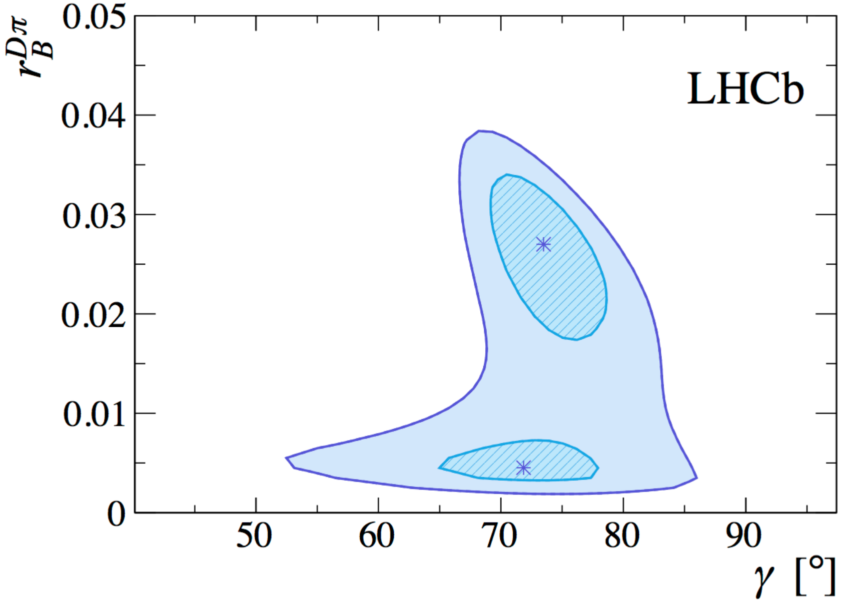
$$B^+ \to D\pi,\ D \to h^+h^-\pi^0$$

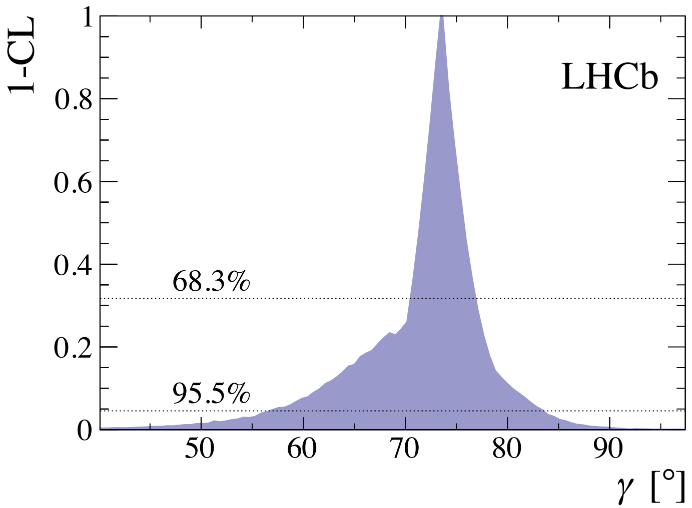
$$B^+ \to D\pi\pi\pi,\ D \to h^+h^-$$

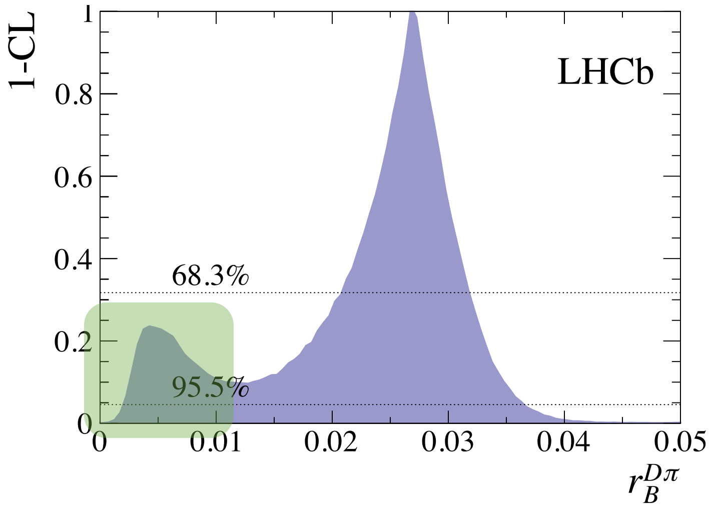
- Observables: 71 ⟶ 89 and parameters 32 ⟶ 38

Dh Combination

- New Dh combination
  - Frequentist results here
  - Two solutions observed in $r_B^{D\pi}$, low solution agrees with expectation suppressed by just over 1 sigma







Dh Combination

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma\,(^\circ)$	73.5	[70.5, 76.8]	[56.7, 83.4]	[40.1, 90.8]
r_B^{DK}	0.1017	[0.0970, 0.1064]	[0.0914, 0.1110]	[0.0844, 0.1163]
$\delta_B^{DK}\,(^\circ)$	141.6	[136.6, 146.3]	[127.2, 151.1]	[114.6, 155.7]
$r_B^{DK^{*0}}$	0.220	[0.173, 0.264]	[0.121, 0.307]	[0.000, 0.355]
$\delta_B^{DK^{*0}}\,(^\circ)$	188	[168, 211]	[148, 239]	[120, 280]
$r_B^{D\pi}$	0.027	[0.0207, 0.0318]	[0.0020, 0.0365]	[0.0008, 0.0425]
$\delta_B^{D\pi}\,(^\circ)$	348.3	[343.2, 352.9]	[220.5, 356.4]	[192.9, 359.8]

Bayesian combination favours low $r_B^{D\pi}$ solution instead, but everything is consistent at the 2 sigma level

arXiv 1611.03076

Dh Combination

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma\,(^\circ)$	73.5	[70.5, 76.8]	[56.7, 83.4]	[40.1, 90.8]
r_B^{DK}	0.1017	[0.0970, 0.1064]	[0.0914, 0.1110]	[0.0844, 0.1163]
$\delta_B^{DK}\,(^\circ)$	141.6	[136.6, 146.3]	[127.2, 151.1]	[114.6, 155.7]
$r_B^{DK^{*0}}$	0.220	[0.173, 0.264]	[0.121, 0.307]	[0.000, 0.355]
$\delta_B^{DK^{*0}}\,(^\circ)$	[illegible]	[illegible]	[illegible]	[illegible]

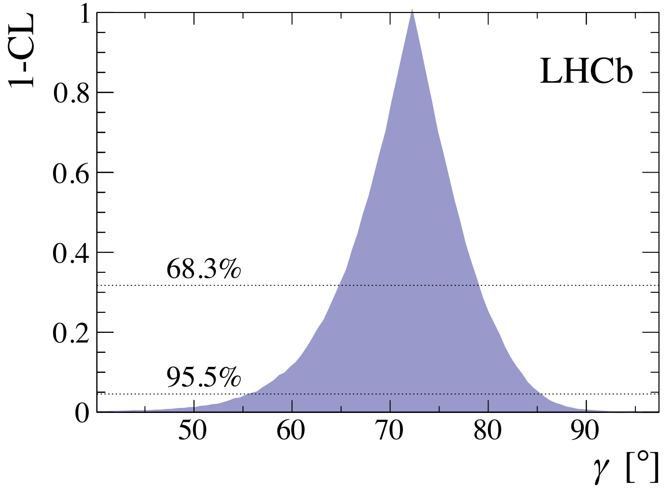
Such differences are not uncommon in the presence of a highly non-Gaussian likelihood function

Note that both frameworks find the same χ^2 minima

Summary

- New inputs to the combinations
  - New decay modes and methods used for the first time
  - Both DK only and Dh combinations performed
  - Reached the expected Run I sensitivity

$$\gamma = (72.2\,^{+6.8}_{-7.3})^{\circ}$$



- Time for a rest?
  - Plenty still to do!
  - New decay modes and updates from Run I
  - Should more than double the data sample with Run II

Outlook

- What comes next?
  - More channels for both B and D decays from Run I and II

$$B^+ \to D^{*0} K^+$$
$$B^+ \to D^0 K^{*+}$$
$$B^0 \to D^{\mp} \pi^{\pm}$$
$$B_s^0 \to D_s^{\mp} K^{\pm}$$
$$B_s^0 \to D_s^{*\mp} K^{\pm}$$

$$D \to KK\pi\pi$$
$$D \to K_S^0 \pi\pi\pi^0$$

All are being investigated, some in preparation for CKM 2016

Outlook

- Looking deeper into the crystal ball

Sample	$\mathcal{L}$ (fb $^{-1}$)	Units of Run I
Run I	3	1
Run II	5	3
Upgrade	≈ 50	≈ 60
Future upgrade	≈ 300	≈ 360

- Beauty cross section up by more than a factor 2 and small increases in trigger and selection efficiencies
- Hadronic trigger efficiency should roughly double

Outlook

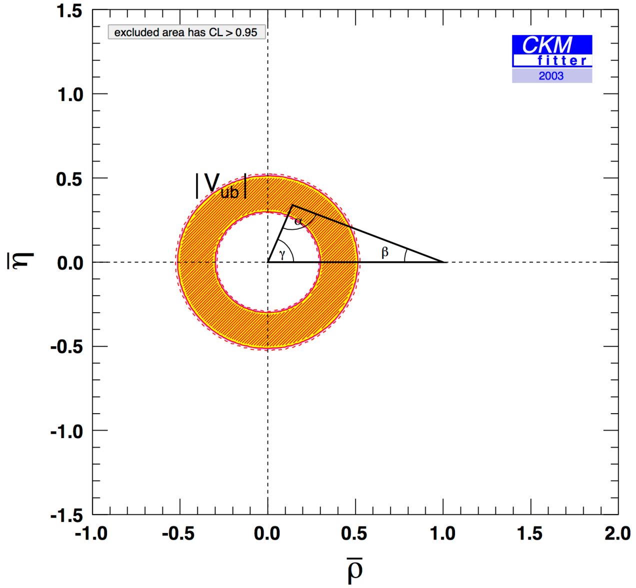
- Target sub-degree precision
  - Indirect measurements give γ to $(^{+1.0}_{-3.7})^\circ$
  - Lattice improvements will decrease the uncertainties
  - Expect statistical uncertainties to scale with data samples
  - Systematic uncertainties should also decrease

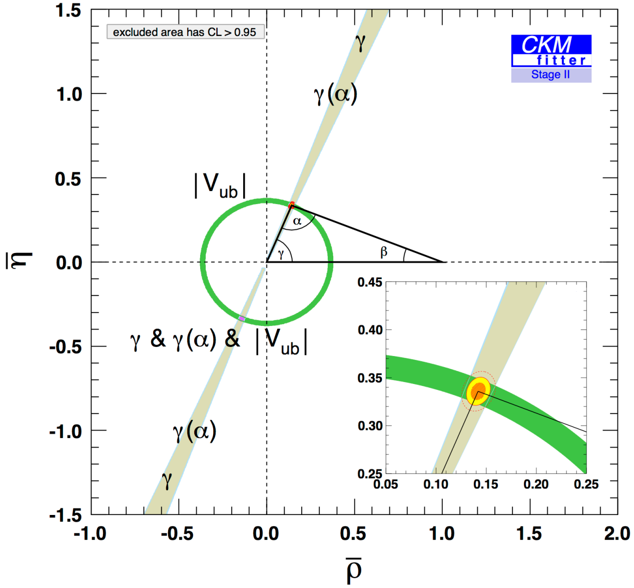
Sample	$\sigma_{\rm stat}\,(^\circ)$
Run I	8
Run II	4
Upgrade	≈ 1
Future upgrade	< 0.5

  - Anticipate similar precision to Belle II in upgrade era

Conclusion

- LHCb has made a big impact measuring γ
  - Hope to halve our uncertainties in Run II
  - Things should get exciting in the upgrade era (2021 ->)
  - We look forward to healthy competition with Belle II
  - Many areas where we can complement each other





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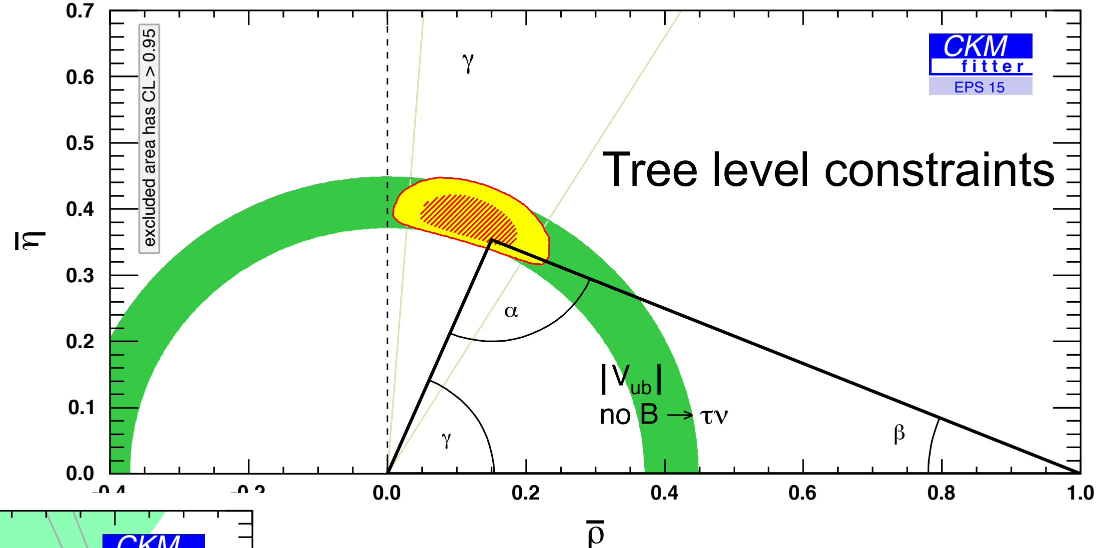
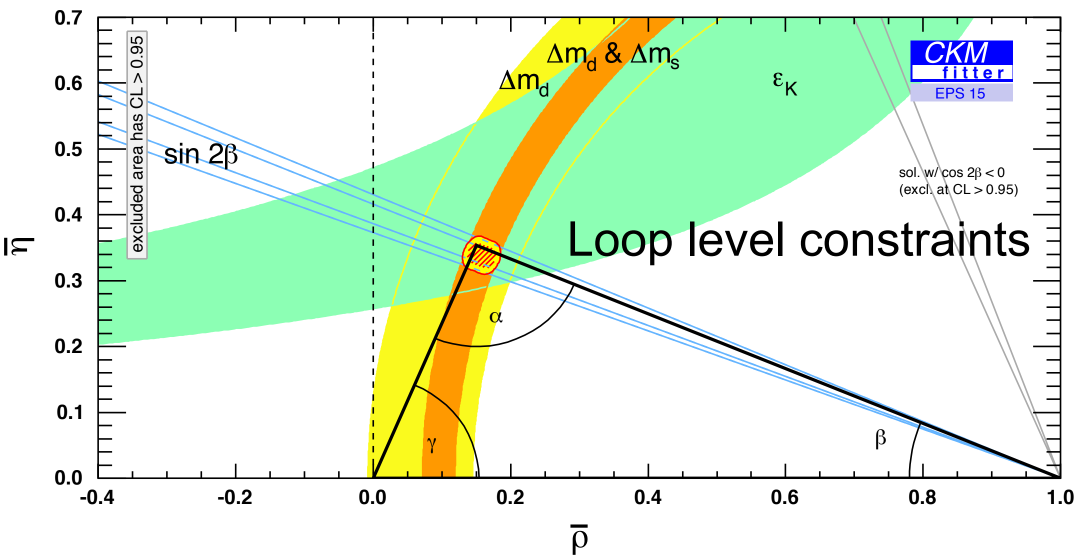
Backups

CKM picture

Room for improvement!



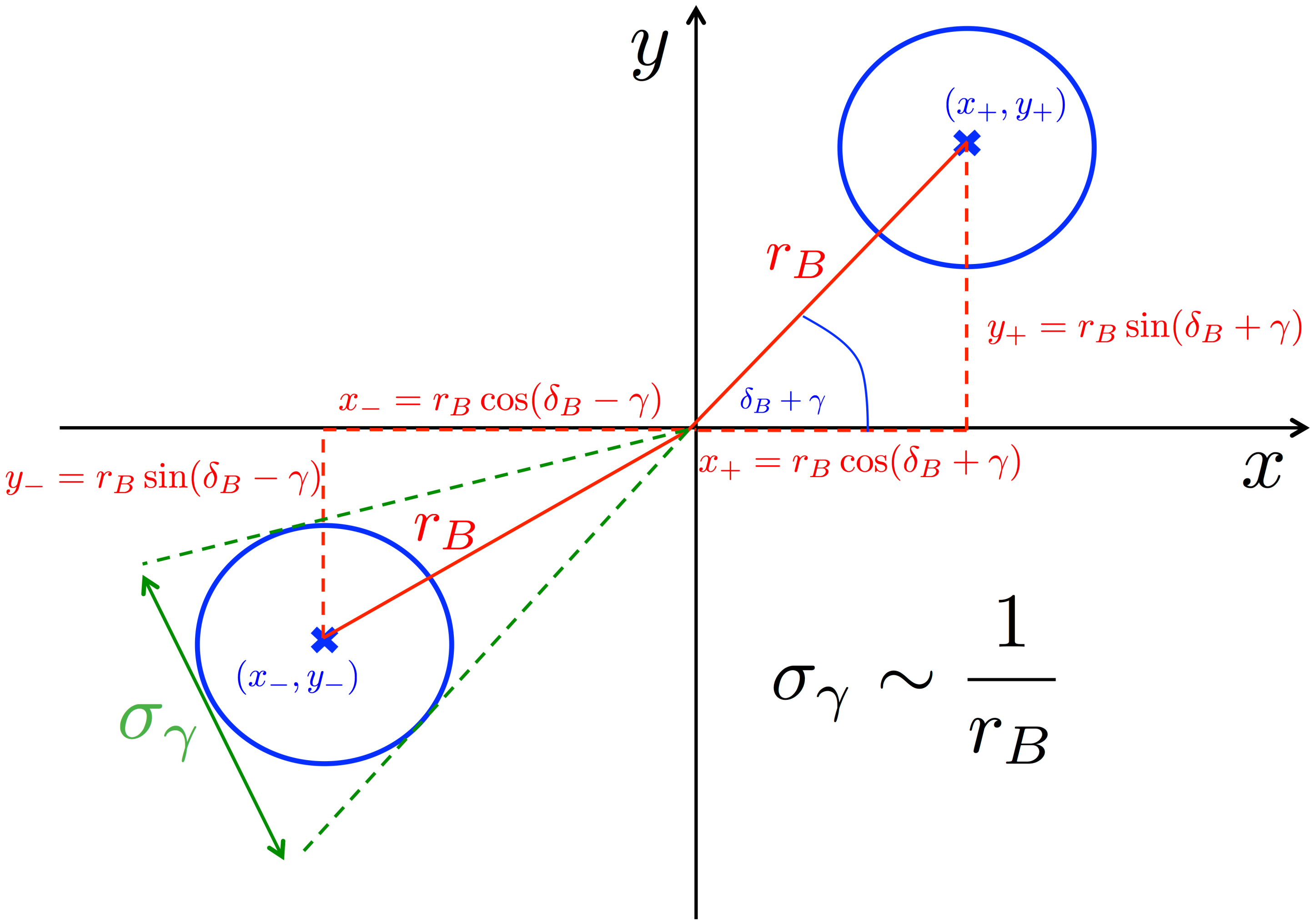


Gammacombo

- Framework available for anyone to use
  - See HEP Forge for more details
  - http://gammacombo.hepforge.org/web/HTML/index.html

- Used for the combinations in this talk
  - Frequentist treatment

Reading x and y

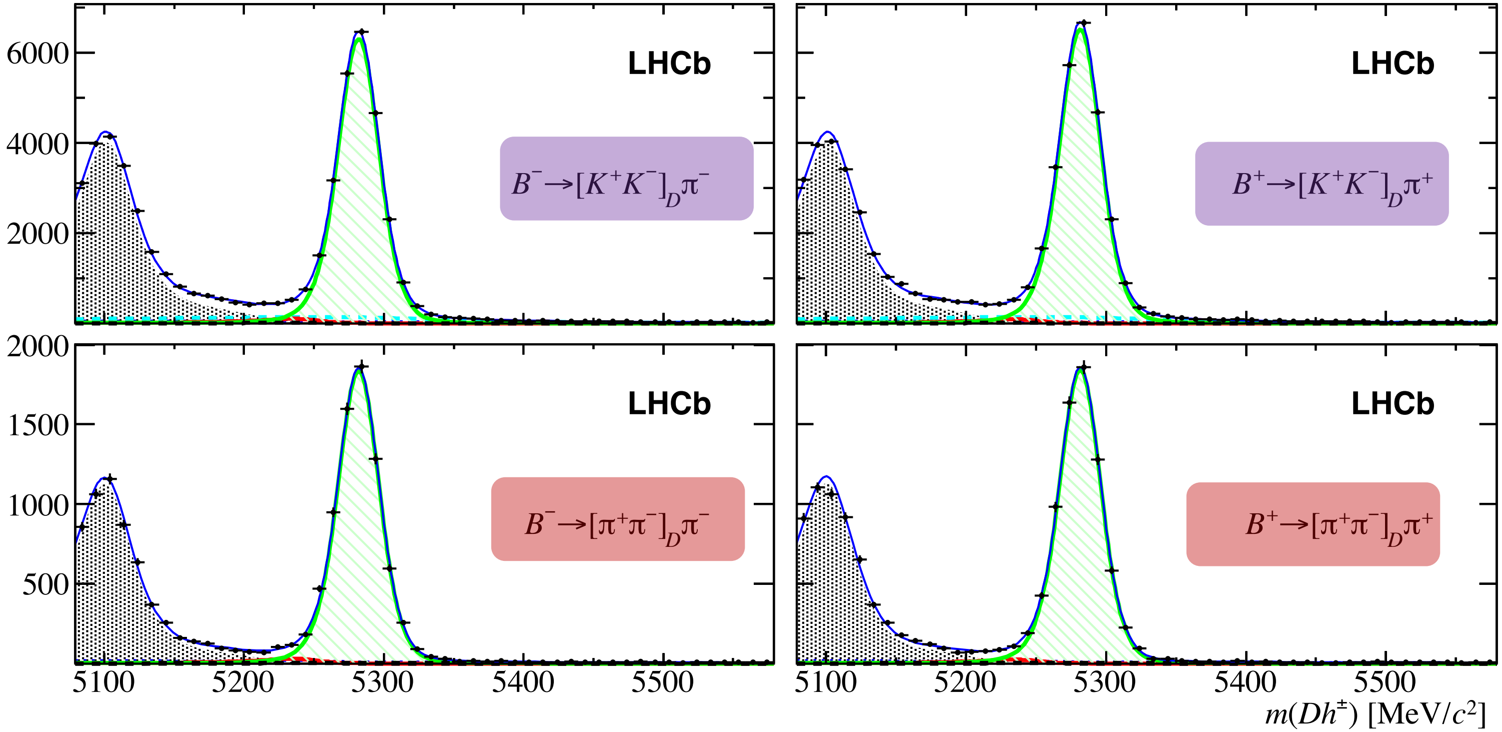


$$\sigma_\gamma \sim \frac{1}{r_B}$$

2 body GLW modes

- Not much to see…

$B^{\pm} \to [K^+K^-]_D \, \pi^{\pm}$	50,140 ± 270
$B^{\pm} \to [\pi^+\pi^-]_D \, \pi^{\pm}$	14,680 ± 130



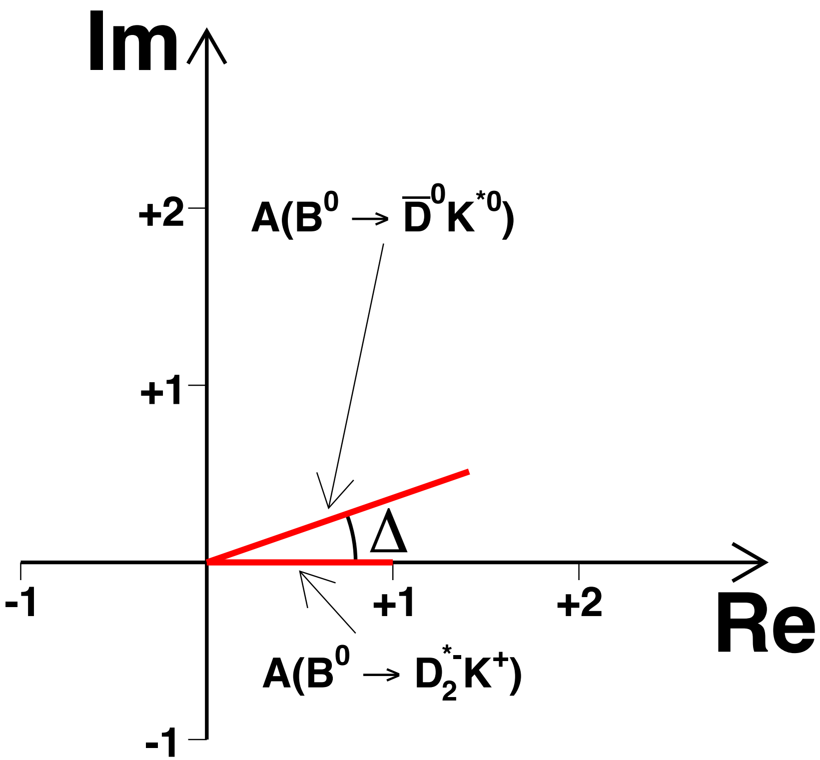
$A_{\pi}^{KK} = -0.0145 \pm 0.0050 \pm 0.0017$ $A_{\pi}^{\pi\pi} = 0.0043 \pm 0.0086 \pm 0.0031$

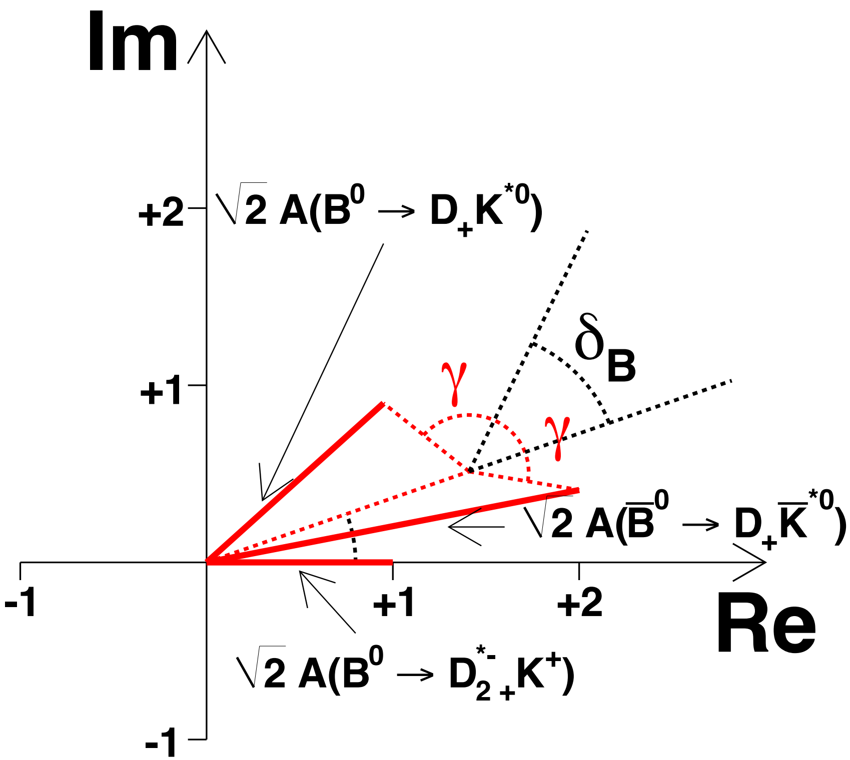
GLW-Dalitz

Table 8: Results for the complex coefficients c_j from the fit to data. Uncertainties are statistical only. All reported quantities are free to vary in the fit, except that the $D_2^*(2460)^-$ component is fixed as a reference amplitude, and the magnitude of the $D_{s1}^*(2700)^+$ component is constrained. The $K^+\pi^-$ S-wave is the coherent sum of the $K_0^*(1430)^0$ and the nonresonant $K\pi$ S-wave component [45].

Resonance	Real part	Imaginary part
$K^*(892)^0$	-0.07 ± 0.10	-1.19 ± 0.04
$K^*(1410)^0$	0.16 ± 0.04	0.21 ± 0.06
$K_0^*(1430)^0$	0.40 ± 0.08	0.67 ± 0.06
Nonresonant $K\pi$ S-wave	0.37 ± 0.07	0.69 ± 0.07
$K_2^*(1430)^0$	-0.01 ± 0.06	-0.48 ± 0.04
$D_0^*(2400)^-$	-1.10 ± 0.05	-0.18 ± 0.07
$D_2^*(2460)^-$	1.00	0.00
Nonresonant $D\pi$ S-wave	-0.44 ± 0.06	0.02 ± 0.07
Nonresonant $D\pi$ P-wave	-0.61 ± 0.05	-0.08 ± 0.06
$D_{s1}^*(2700)^+$	0.57 ± 0.05	-0.09 ± 0.19

GLW-Dalitz





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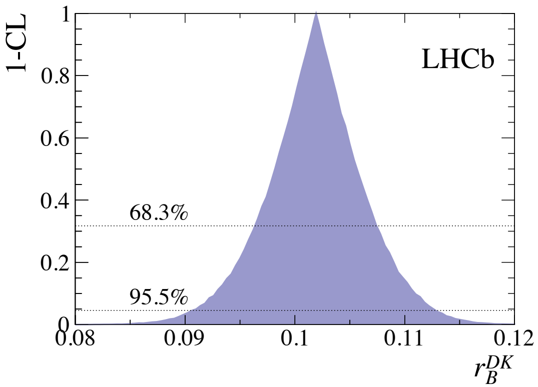
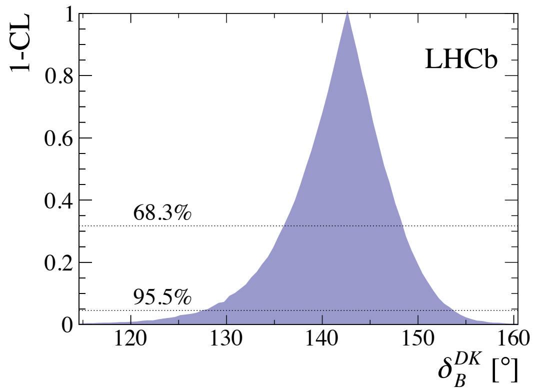
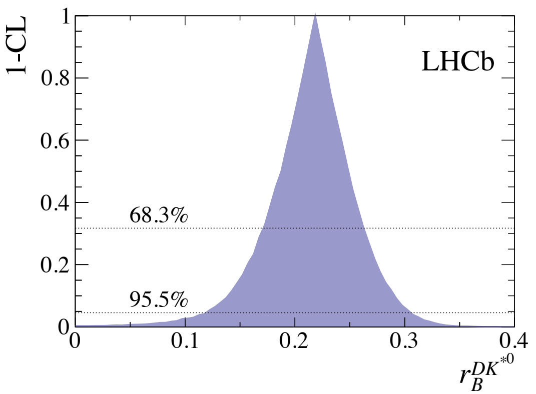
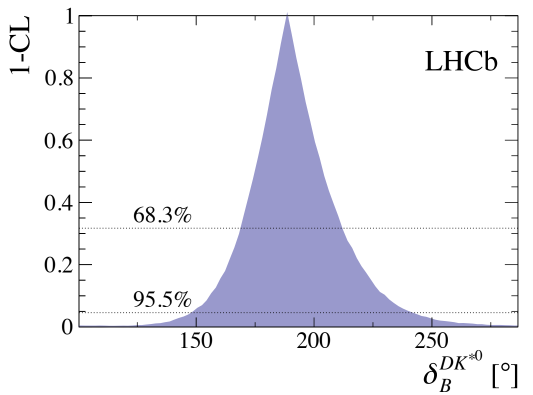
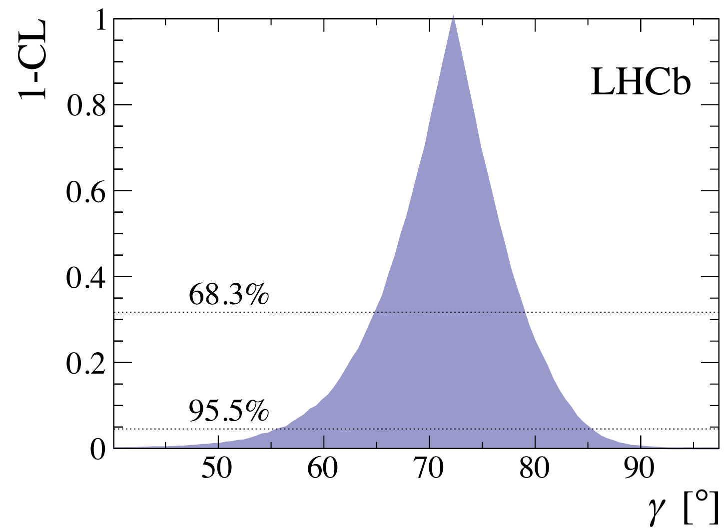
DK combination (frequentist)





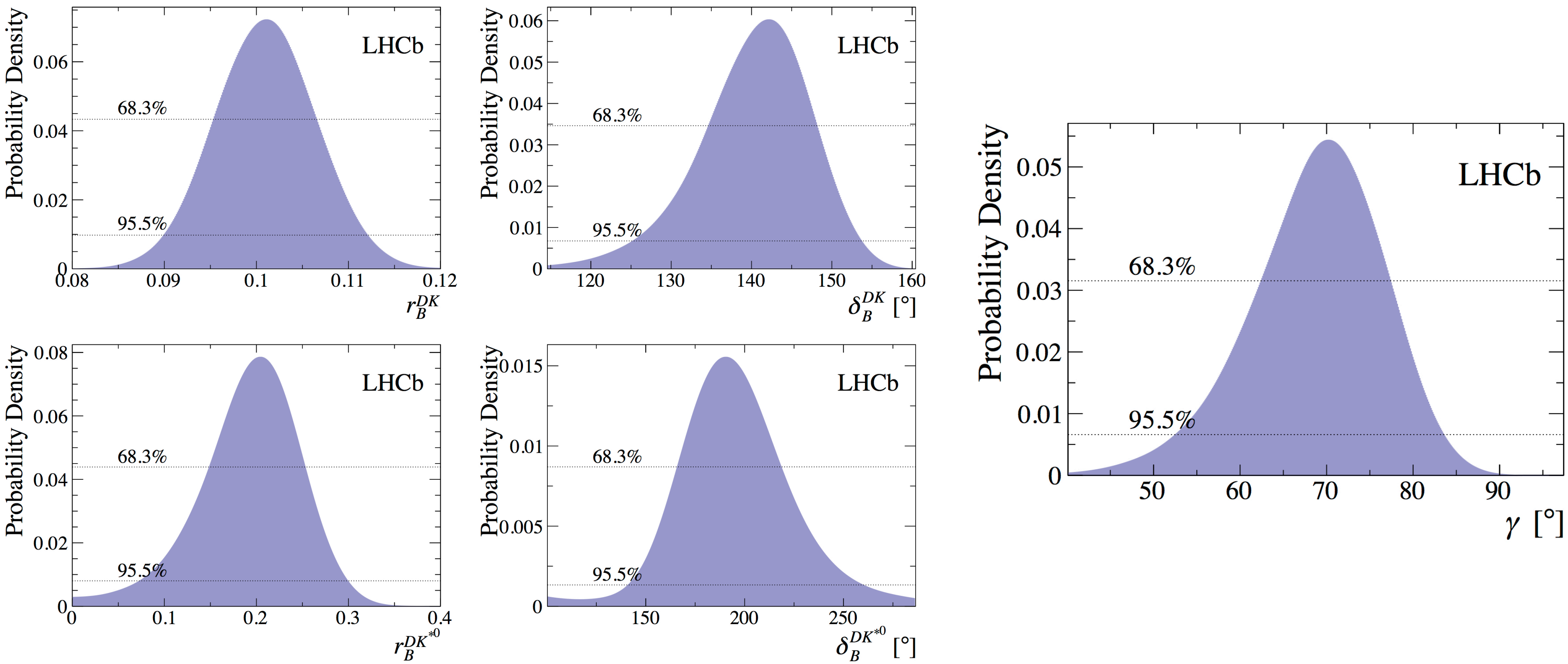




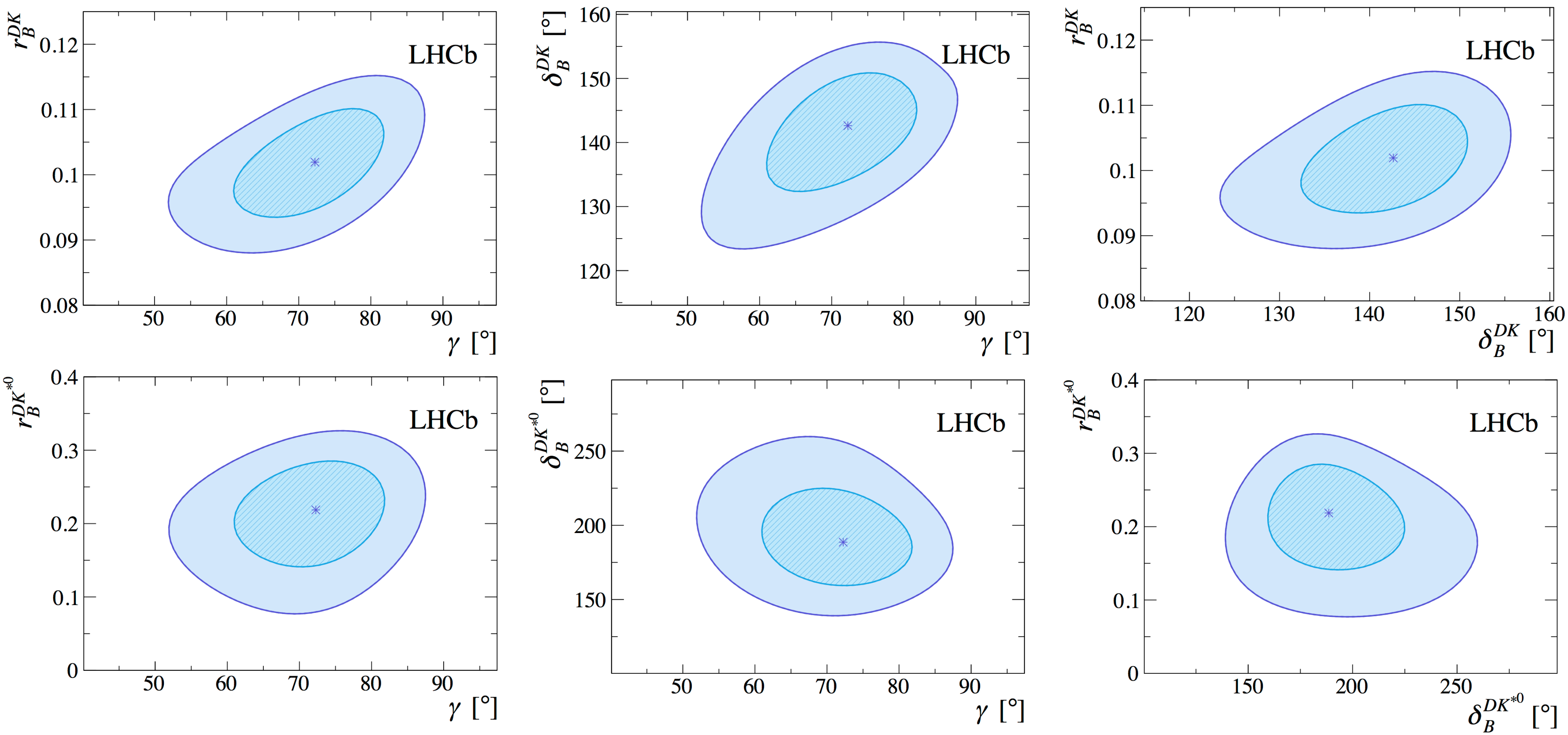


arXiv 1611.03076

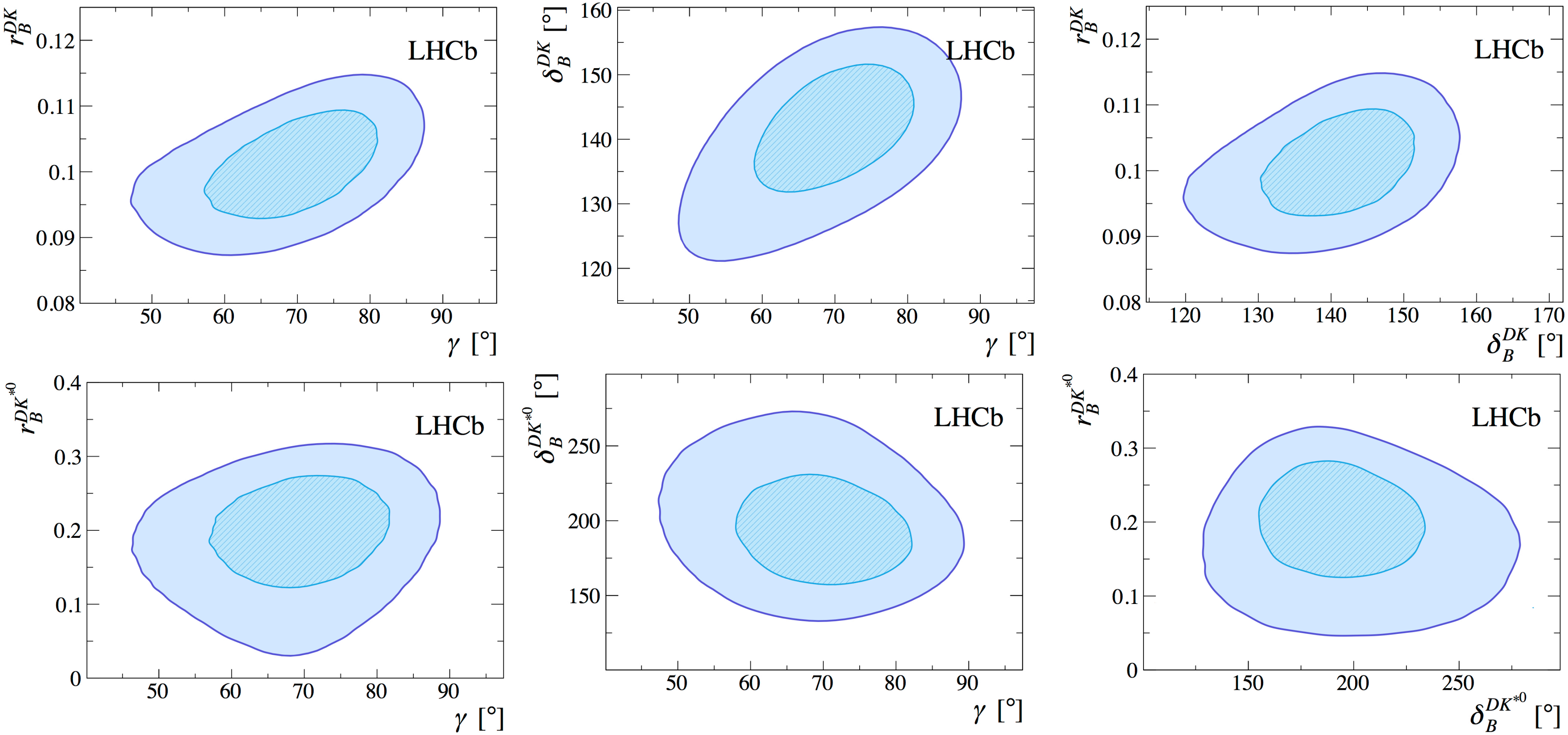
DK combination (Bayesian)



DK combination 2D (frequentist)



DK combination 2D (Bayesian)



arXiv 1611.03076

DK results summary

frequentist

Table 3: Confidence intervals and central values for the parameters of interest in the frequentist DK combination.

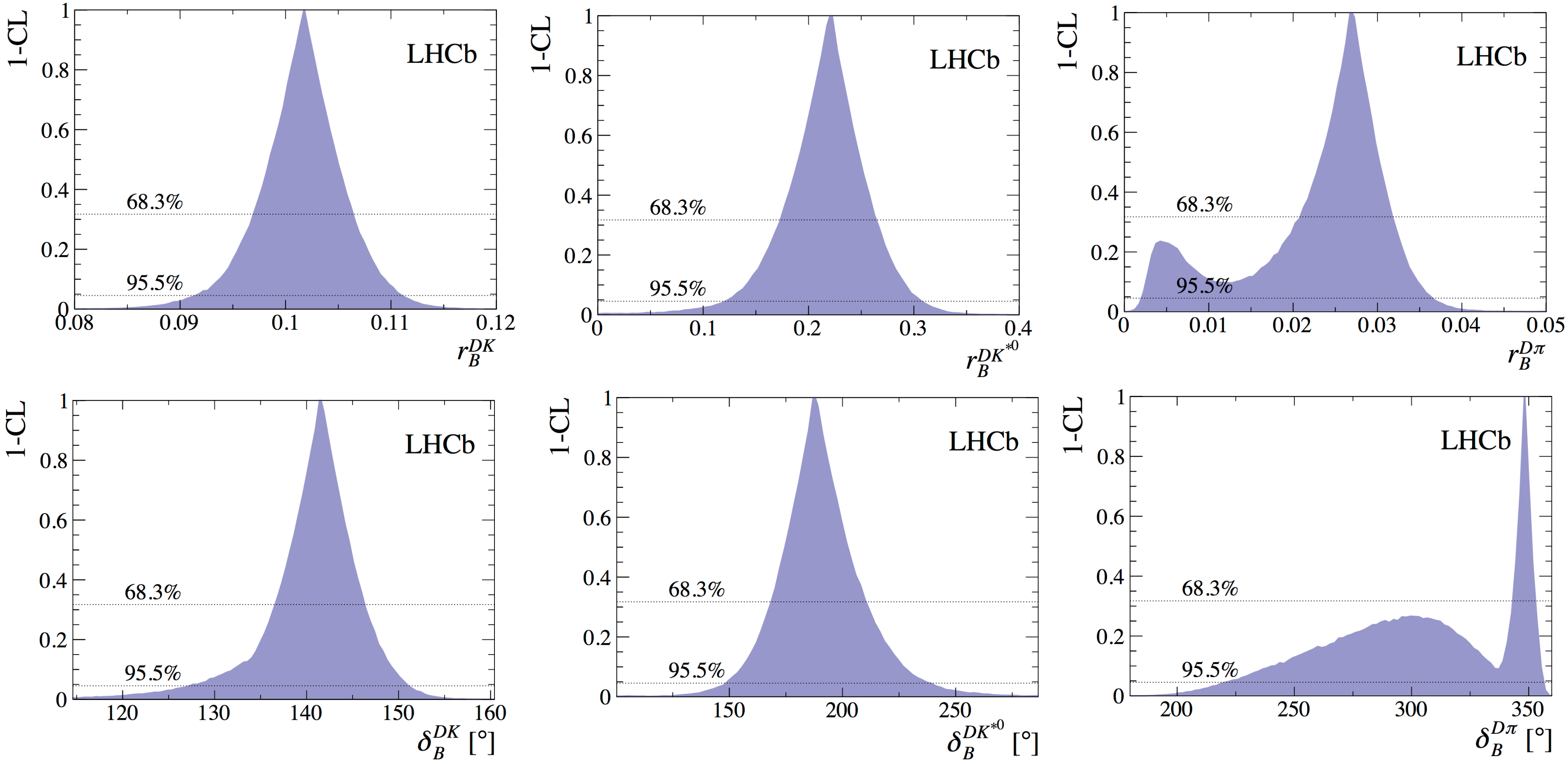
Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma(^\circ)$	72.2	$[64.9, 79.0]$	$[55.9, 85.2]$	$[43.7, 90.9]$
r_B^{DK}	0.1019	$[0.0963, 0.1075]$	$[0.0907, 0.1128]$	$[0.0849, 0.1182]$
$\delta_B^{DK}(^\circ)$	142.6	$[136.0, 148.3]$	$[127.8, 153.6]$	$[116.2, 158.7]$
$r_B^{DK^{*0}}$	0.218	$[0.171, 0.263]$	$[0.118, 0.305]$	$[0.000, 0.348]$
$\delta_B^{DK^{*0}}(^\circ)$	189	$[169, 212]$	$[148, 241]$	$[123, 283]$

Bayesian

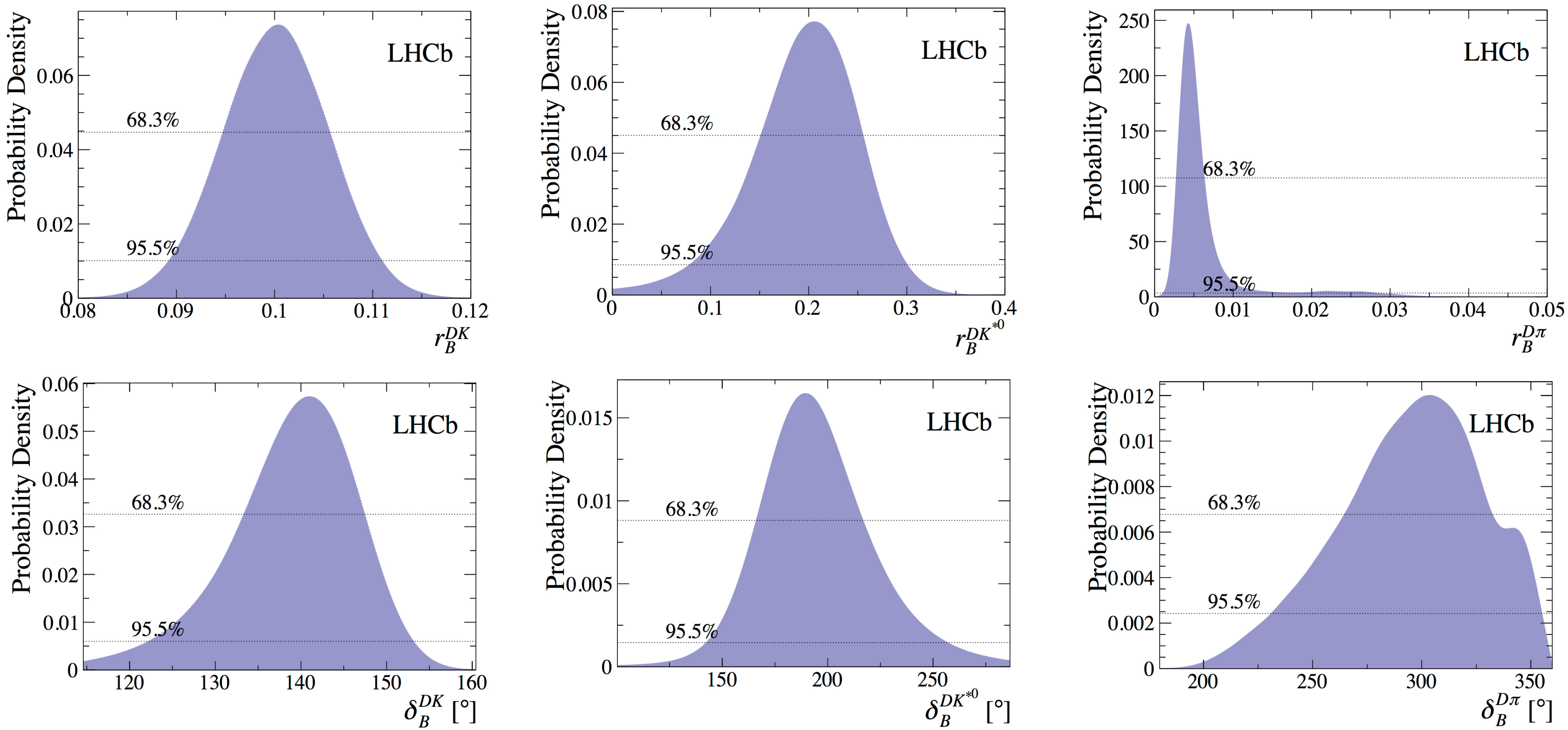
Table 6: Credibile intervals and most probable values for the hadronic parameters extracted from the DK Bayesian combination.

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma(^\circ)$	70.3	$[62.4, 77.4]$	$[52.6, 83.5]$	$[42.1, 88.4]$
r_B^{DK}	0.1012	$[0.0954, 0.1064]$	$[0.0900, 0.1120]$	$[0.0846, 0.1171]$
$\delta_B^{DK}(^\circ)$	142.2	$[134.7, 148.1]$	$[125.3, 153.7]$	$[113.2, 157.9]$
$r_B^{DK^{*0}}$	0.204	$[0.149, 0.253]$	$[0.073, 0.299]$	$[0.000, 0.322]$
$\delta_B^{DK^{*0}}(^\circ)$	190.3	$[165.8, 218.4]$	$[139.5, 263.4]$	$[117.8, 292.4]$

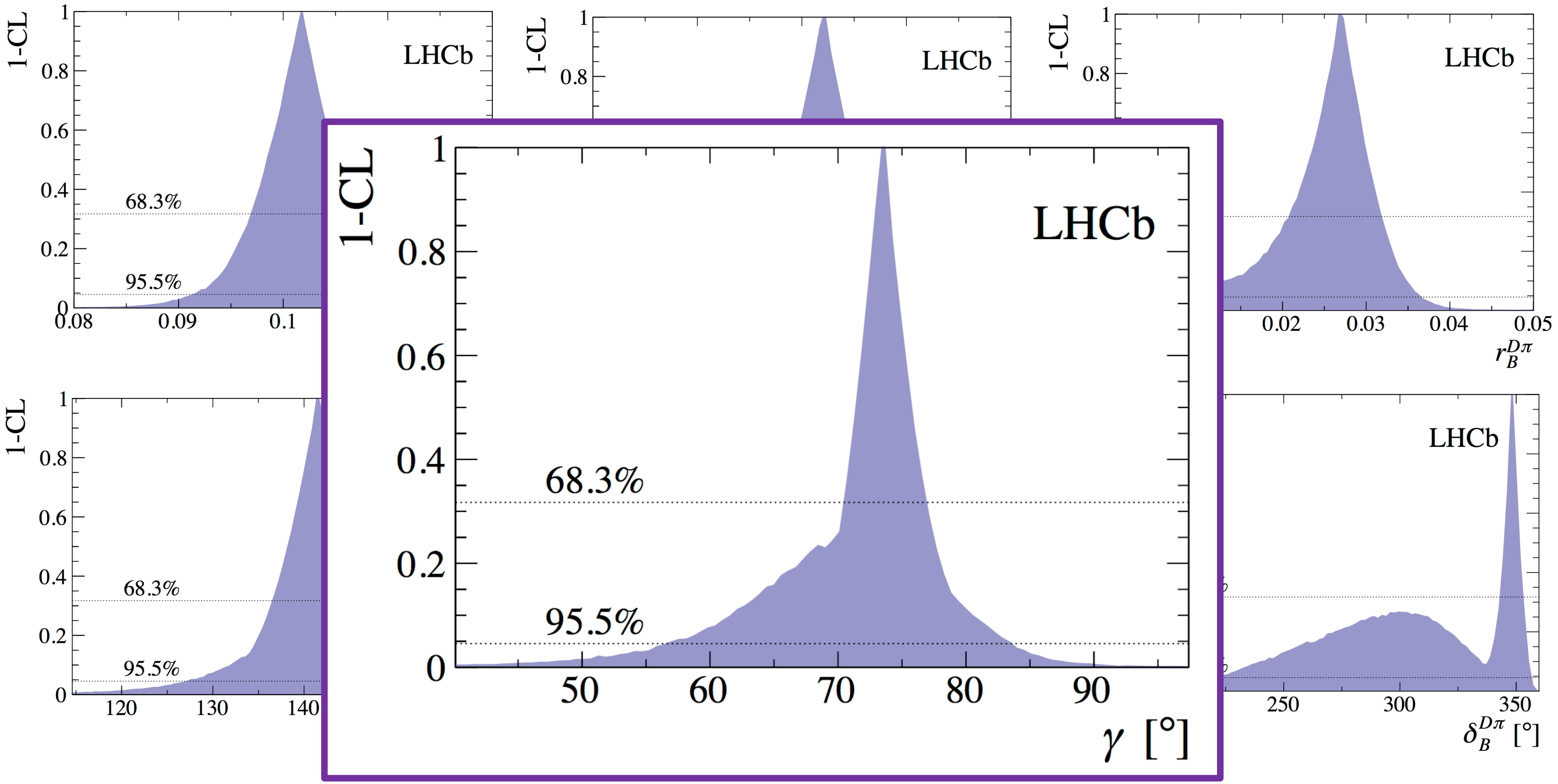
Dh combination (frequentist)



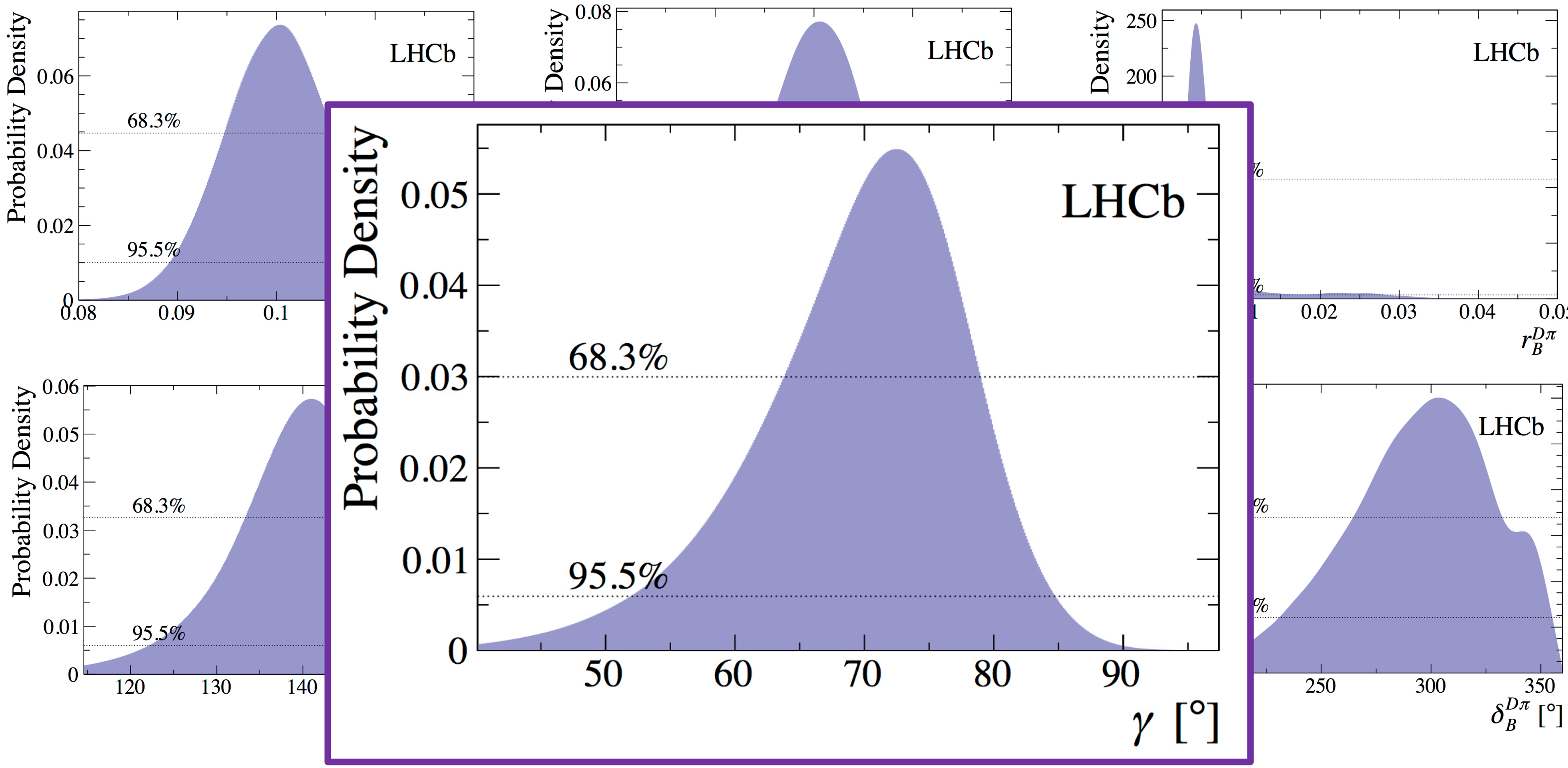
Dh combination (Bayesian)



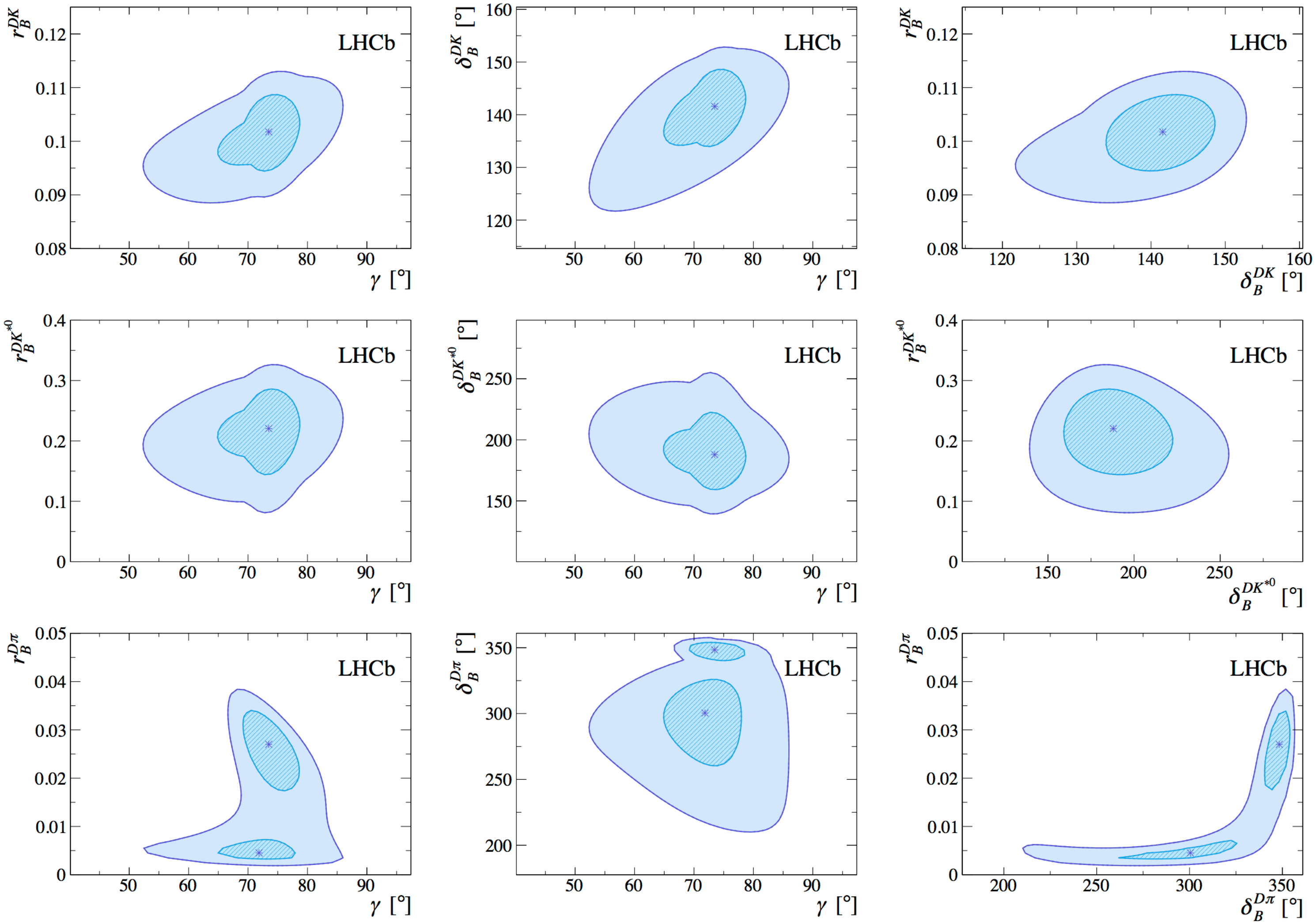
Dh combination (frequentist)



Dh combination (Bayesian)

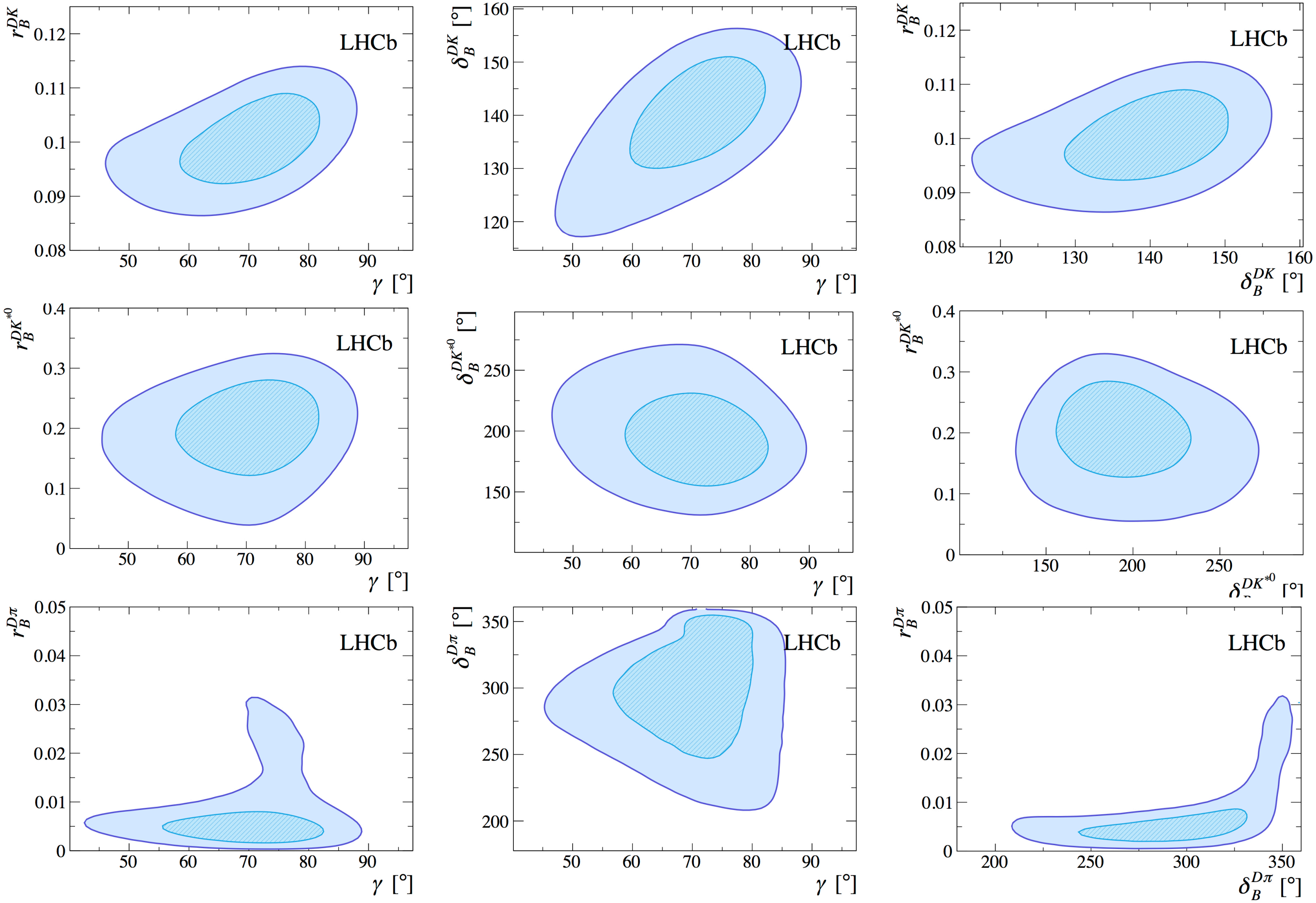


Dh combination 2D (frequentist)



arXiv 1611.03076

Dh combination 2D (Bayesian)



Dh results summary

frequentist

Table 4: Confidence intervals and central values for the parameters of interest in the frequentist *Dh* combination.

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma(^\circ)$	73.5	$[70.5, 76.8]$	$[56.7, 83.4]$	$[40.1, 90.8]$
r_B^{DK}	0.1017	$[0.0970, 0.1064]$	$[0.0914, 0.1110]$	$[0.0844, 0.1163]$
$\delta_B^{DK}(^\circ)$	141.6	$[136.6, 146.3]$	$[127.2, 151.1]$	$[114.6, 155.7]$
$r_B^{DK^{*0}}$	0.220	$[0.173, 0.264]$	$[0.121, 0.307]$	$[0.000, 0.355]$
$\delta_B^{DK^{*0}}(^\circ)$	188	$[168, 211]$	$[148, 239]$	$[120, 280]$
$r_B^{D\pi}$	0.027	$[0.0207, 0.0318]$	$[0.0020, 0.0365]$	$[0.0008, 0.0425]$
$\delta_B^{D\pi}(^\circ)$	348.3	$[343.2, 352.9]$	$[220.5, 356.4]$	$[192.9, 359.8]$

Bayesian

Table 7: Credibile intervals and most probable values for the hadronic parameters extracted from the *Dh* Bayesian combination.

Observable	Central value	68.3% Interval	95.5% Interval	99.7% Interval
$\gamma(^\circ)$	72.4	$[63.9, 79.0]$	$[52.1, 84.6]$	$[40.1, 89.5]$
r_B^{DK}	0.1003	$[0.0948, 0.1057]$	$[0.0893, 0.1109]$	$[0.0838, 0.1159]$
$\delta_B^{DK}(^\circ)$	141.0	$[133.3, 147.5]$	$[122.1, 153.1]$	$[108.6, 157.5]$
$r_B^{DK^{*0}}$	0.2072	$[0.1514, 0.2555]$	$[0.0788, 0.3007]$	$[0.0031, 0.3291]$
$\delta_B^{DK^{*0}}(^\circ)$	189.8	$[166.3, 216.5]$	$[143.9, 255.2]$	$[120.2, 286.0]$
$r_B^{D\pi}$	0.0043	$[0.0027, 0.0063]$	$[0.0011, 0.0281]$	$[0.0008, 0.0329]$
$\delta_B^{D\pi}(^\circ)$	303.7	$[264.7, 332.7]$	$[231.5, 355.2]$	$[202.7, 359.0]$

Systematic limitations

Limiting factors in the high-statistics era

Where will we become limited, as things stand:

- Most[1] $B \to DK$ modes rely on CLEO strong phase measurements at the $\psi(3770)$
- Allows for model independence; crucial in the high-statistics era
- Current systematic due to CLEO inputs $\sim 2^\circ$
- Some D modes not analysed by CLEO; some would benefit from D-phasespace-binned analysis

Available now:

- Quadruplication of the CLEO dataset at BES III ($\to$ systematic $\sim 1^\circ$)
  - Measurement in $D \to K\pi$ (Int.J.Mod.Phys.Conf.Ser. 31 1460305)
  - Preliminary results in $D \to K^0_S\pi\pi$
- Supplement (but not match) with strong phase measurements in charm mixing

To avoid systematic limitation in the upgrade era:

- Full spectrum of strong phase measurements with full 15-20 fb^{-1} at BES III

[1] not, e.g., $B^0_s \to D^+_s K$