Constraining the CKM angle γ from Run 1 data at LHCb

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On behalf of the LHCb collaboration

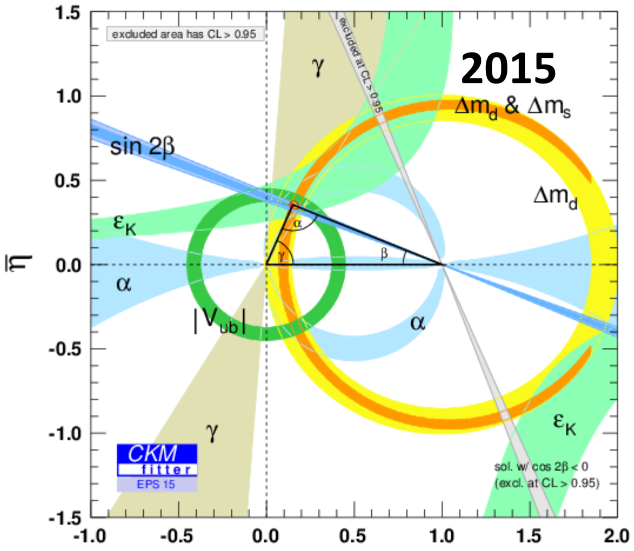
Why a precision measurement of γ is important

- Observables related to CPV can provide an insight to NP (there must be other sources of CPV beyond those predicted by the SM)

- Largest uncertainty is on γ, a process accessible at tree level - forms a SM benchmark*

- Theory uncertainty ~10^{-7} JHEP 01 (2014) 051

- Improvement in direct measurement precision required.



Global fit (including quantities from loop decays:

$$\gamma = (66.9^{+0.94}_{-3.44})^\circ$$

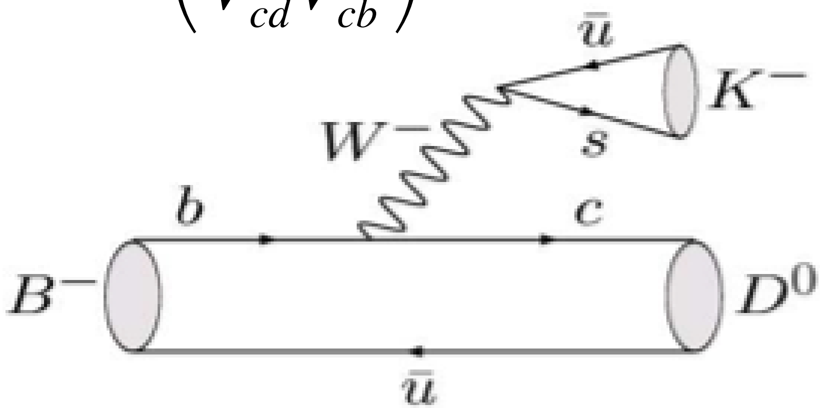
Direct (tree-level) measurements only:

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

*assuming no New Physics in tree decays PRD 92(3):033002 (2015)

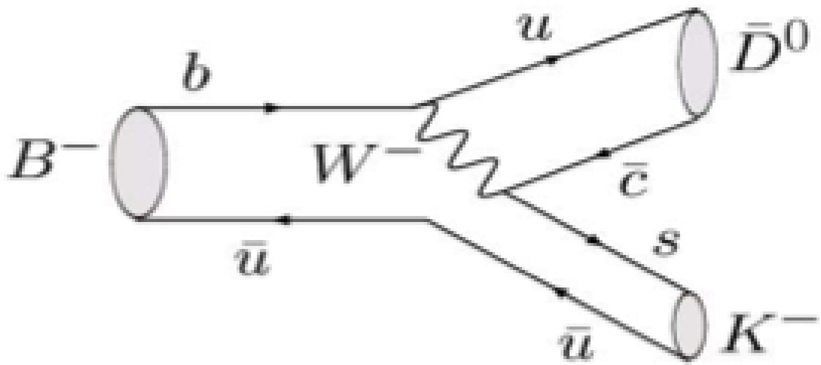
B→DK

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



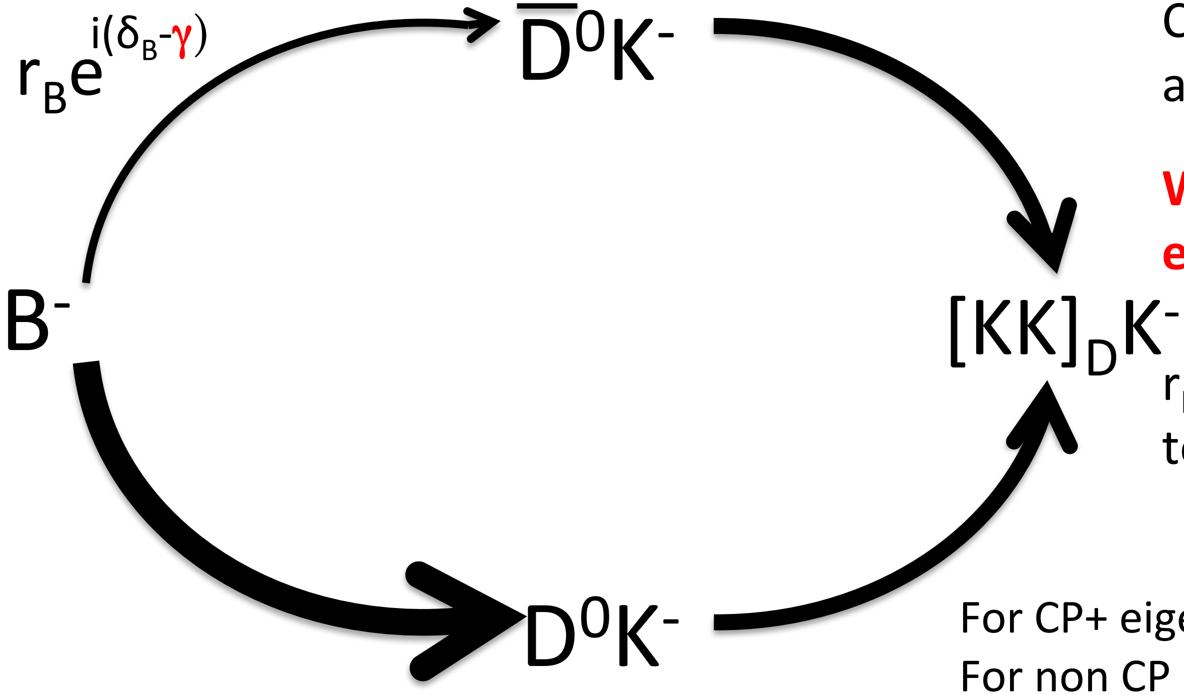
$b \to c$ (favoured)

$b \to u$ (suppressed)



- Interference possible if D^0 and $\overline{D^0}$ decay to same final state
  - Many choices of D final state
- Fully hadronic final state – well suited to LHCb
- Other B modes studied. Today some results from $B \to D\pi$ & $B^0 \to DK^*$

Interference with self conjugate states "(q)-GLW"



CP conjugate states equally accessible to D^0 and D^0

Weak phase changes sign for equivalent B^+ diagram

r_B (~0.1), δ_B hadronic parameters to be determined alongside γ.

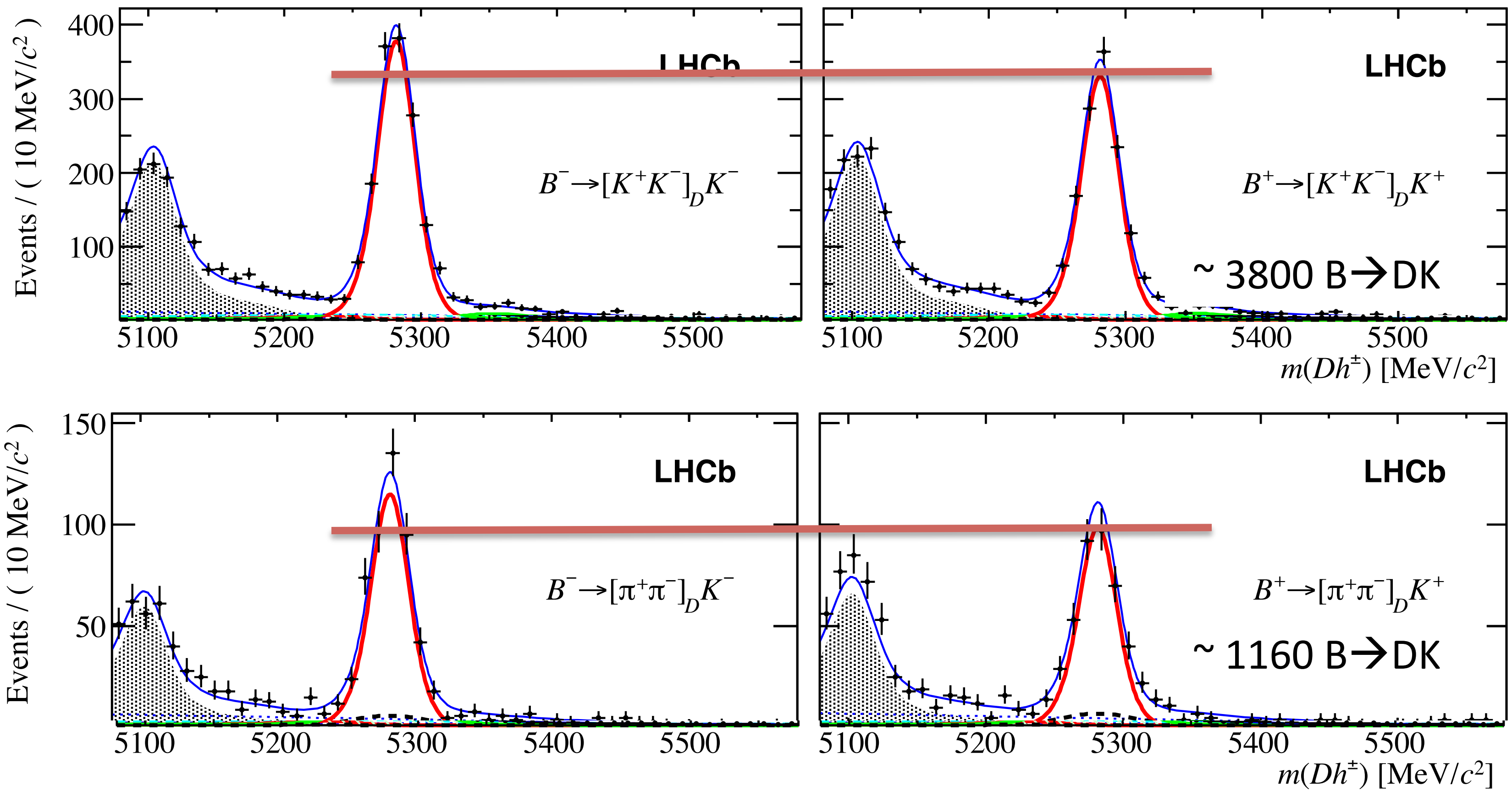
For CP+ eigenstates e.g KK, ππ $F_+ = 1$
For non CP eigenstates F_+ measured at CLEO

$$\frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+ - 1)\sin(\delta_B)\sin(\gamma)$$

$$\frac{N(B \to [KK]_D K) \times \Gamma(D \to K\pi)}{N(B \to [K\pi]_D K) \times \Gamma(D \to KK)} = R_{CP+} = 1 + r_B^2 + 2r_B(2F_+ - 1)\cos(\delta_B)\cos(\gamma)$$

 Gronau & London, PLB 253 (1991) 483, Gronau & Wyler PLB 265 (1991) 172 PLB 740 (2015) 1

B→D(hh)K



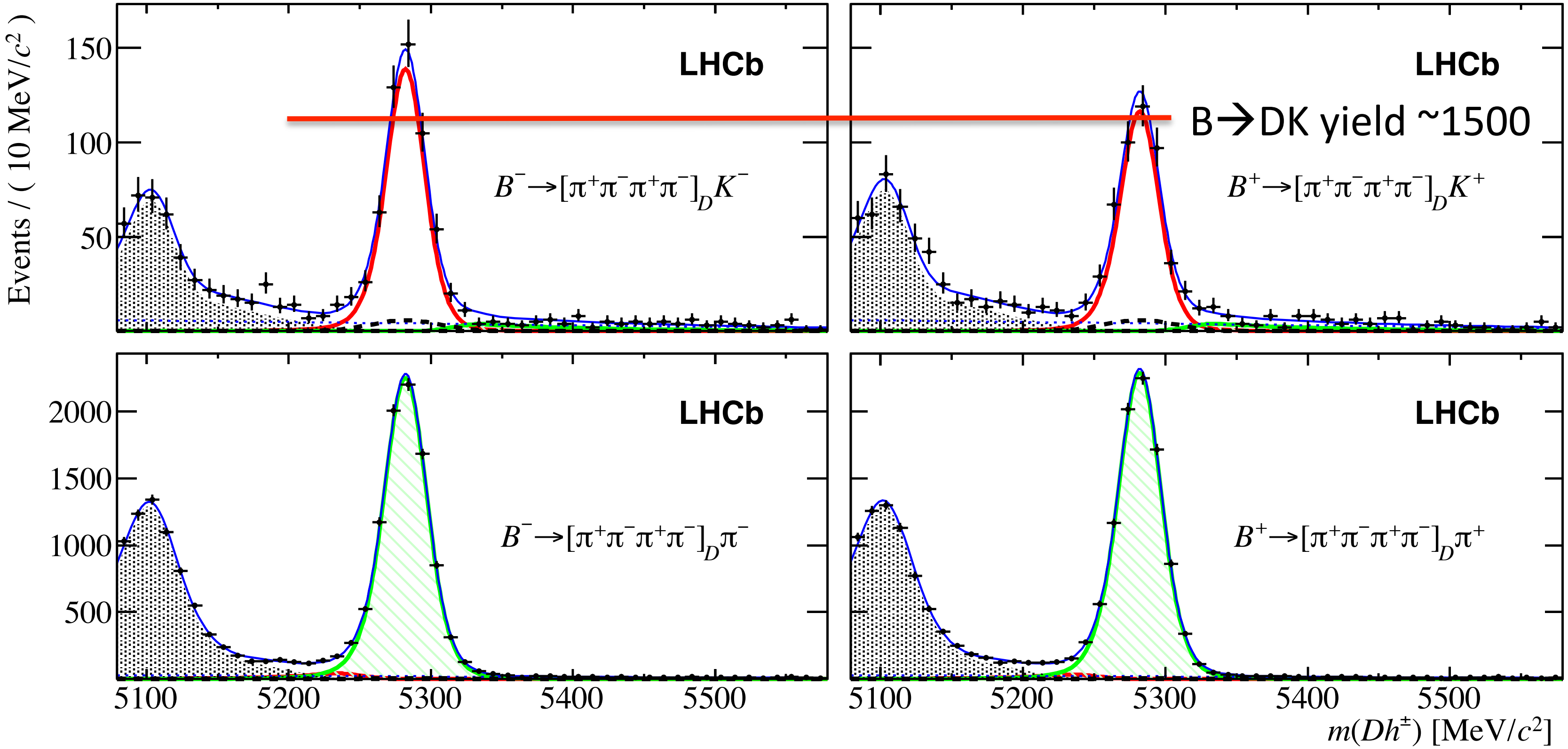
$$A_K^{KK} = 0.087 \pm 0.020 \pm 0.008$$

$$A_K^{\pi\pi} = 0.128 \pm 0.037 \pm 0.012$$

Combined → **5σ**

High purity, high yields.
Low crossfeed/other backgrounds
LHCb optimised for this type of physics

Results B→D(4π)h

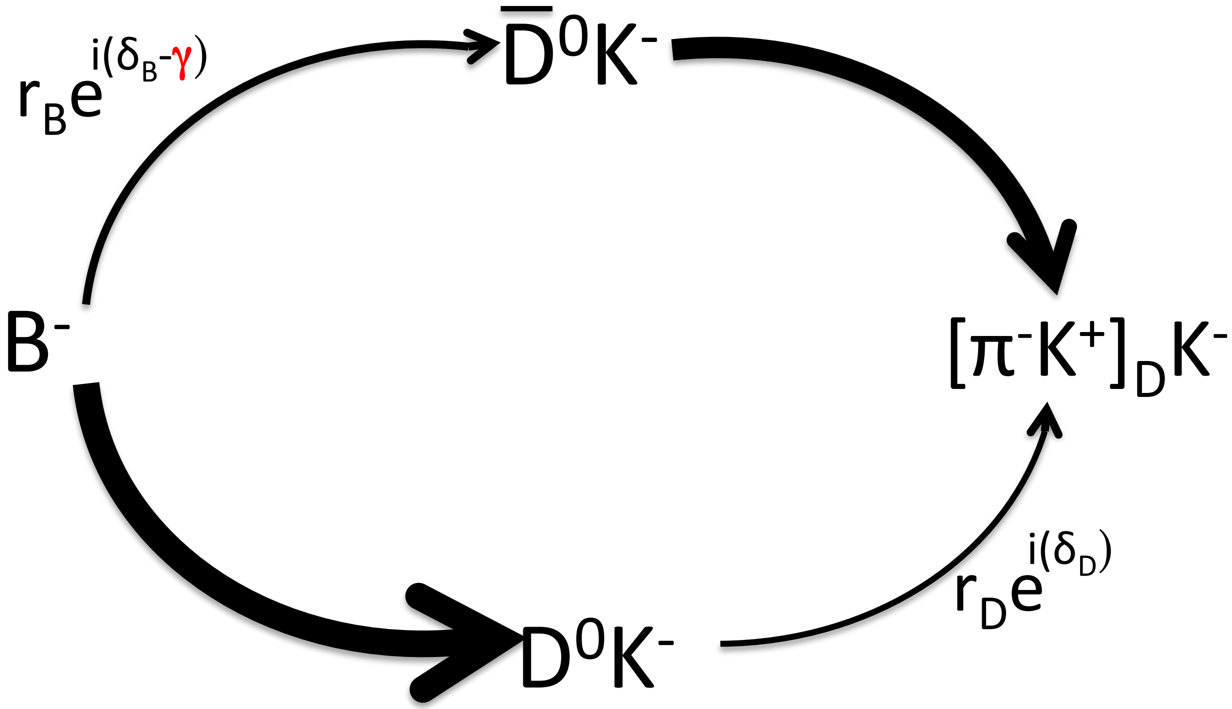


$$A_K^{\pi\pi\pi\pi} = 0.100 \pm 0.034 \pm 0.018$$

First use of this mode -possible due to measurements from CLEO

$F_+^{4\pi} = 0.737 \pm 0.028$ PLB 747 (2015) 9

Interference with flavour specific "ADS"



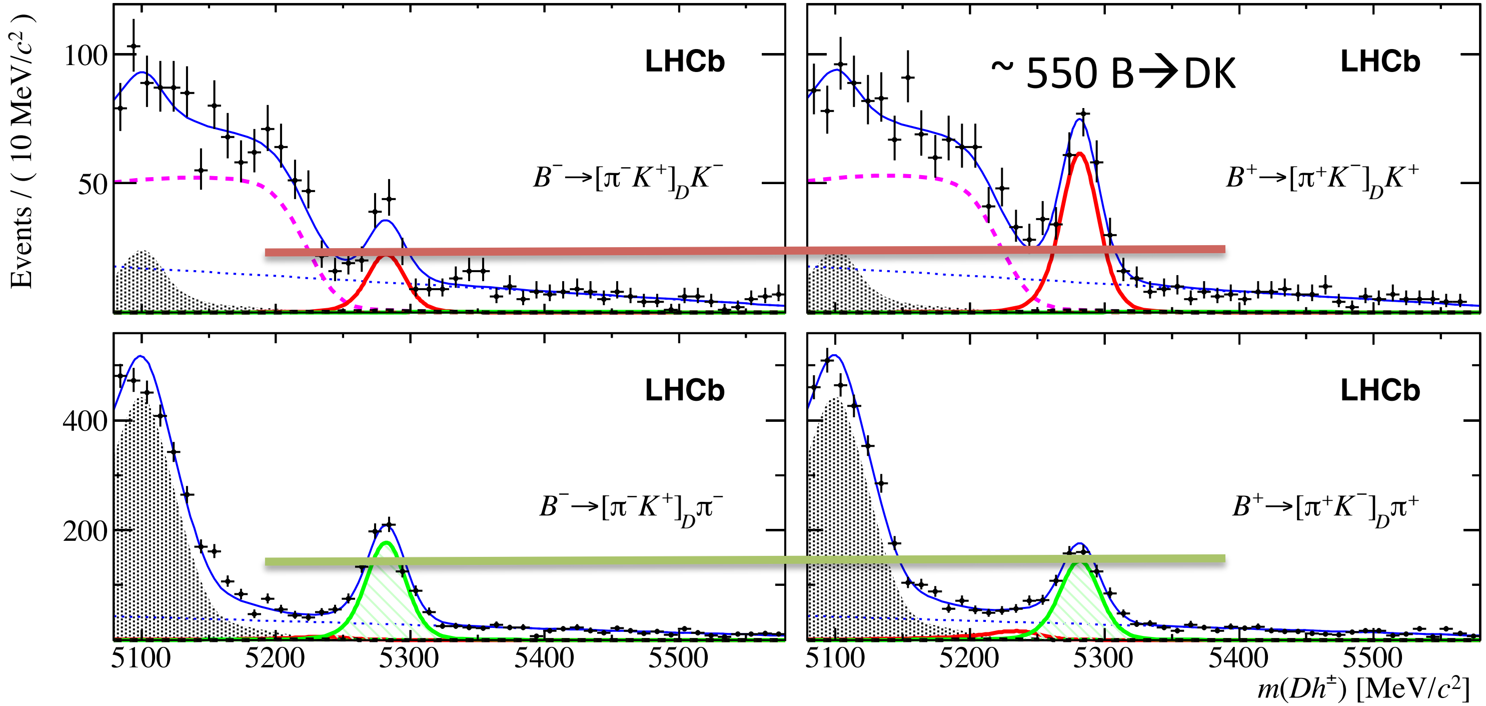
- Larger interference effects as both amplitudes of similar sizes.
- Additional parameters r_D, $\delta_{D,}$. External inputs from charm mixing
- Extensions to multibody decays possible

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{ADS} = \frac{1}{R_{ADS}} 2 r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)$$

$$\frac{N(B^\pm \to [\pi^\pm K^\mp]_D K^\pm)}{N(B^\pm \to [K^\pm \pi^\mp]_D K^\pm)} = R_{ADS} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)$$

Atwood, Dunietz & Soni PRL 78 (1997) 3257, PRD 63 (2001) 036005 (ADS)

B→D[πK]h



8σ

Only observed at LHCb, BF ~10^{-7} -- a rare decay

$$A_K^{\pi K} = -0.403 \pm 0.056 \pm 0.011$$

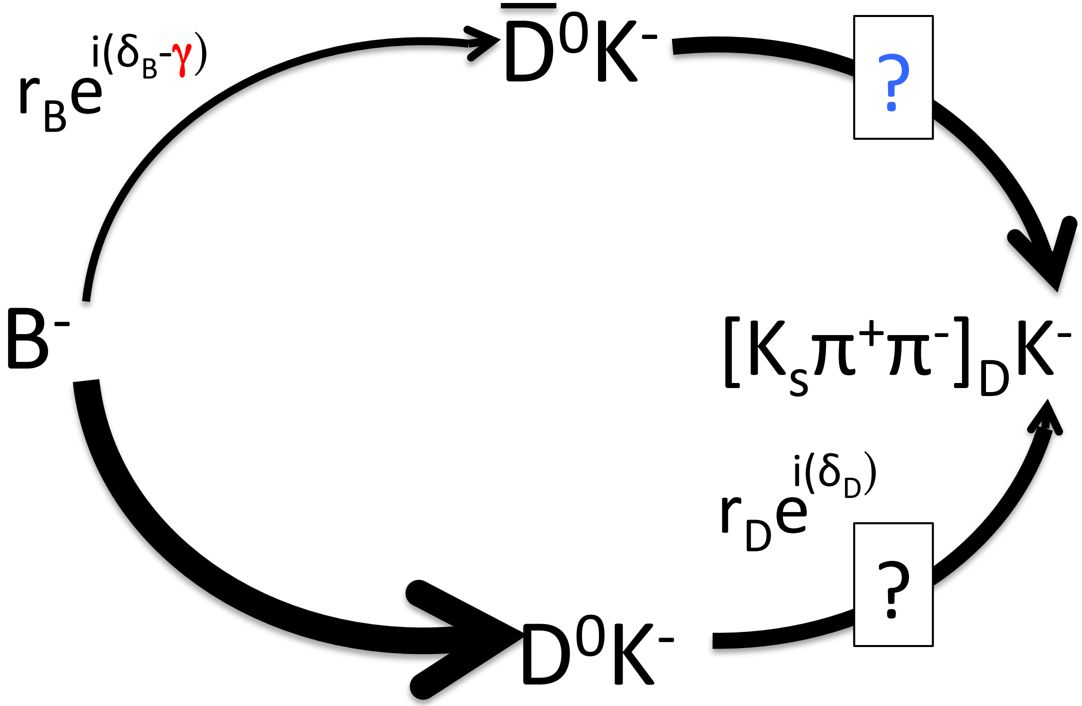
$$A_\pi^{\pi K} = 0.100 \pm 0.031 \pm 0.009$$

CPV starts to become visible in B→Dπ when combining all D→hh and D→4h modes.

3.9σ

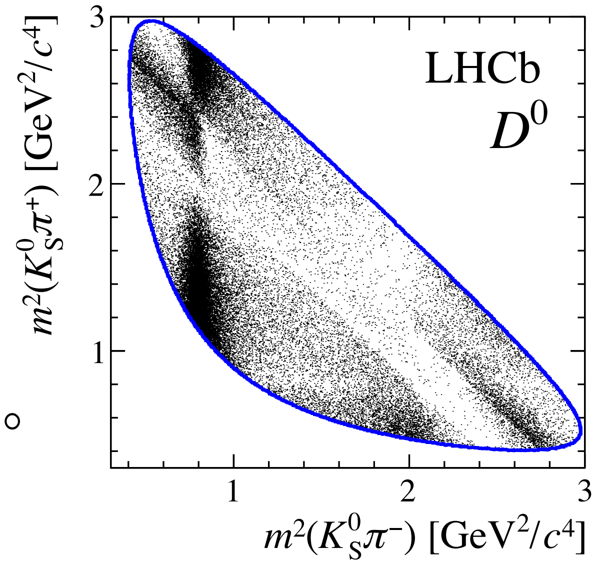
PLB 760 (2016) 117

Self-conjugate D decays using Dalitz plot "GGSZ"



Value of F_+ for certain self conjugate decays would be ~0.5

Hence inclusive treatment loses most of the sensitivity to γ → Analyse the Dalitz plot



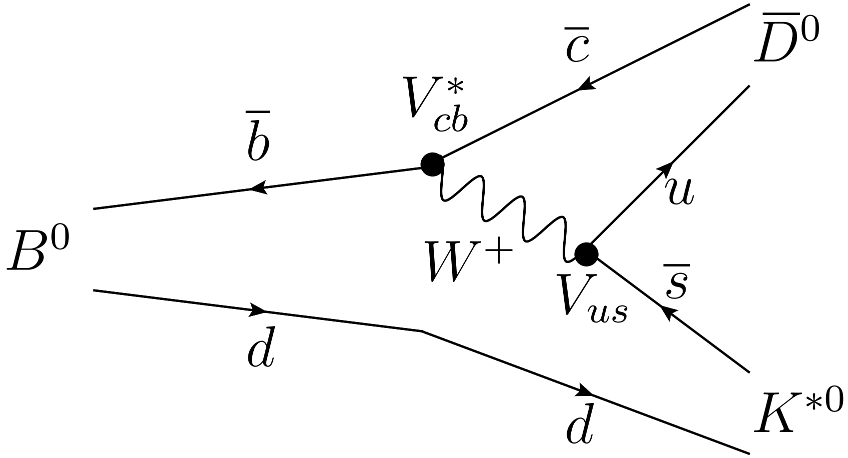
LHCb→DK analysis in this mode : JHEP 10 (2014) 097

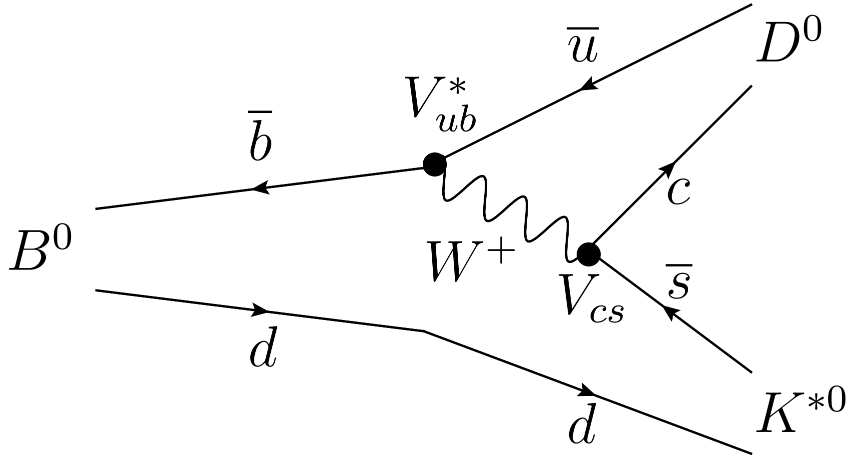
Best standalone measurement of $\gamma = (62^{+15}_{-14})^\circ$

Old result, today show this D decay using another B mode

Giri, Gronau, Soffer & Zupan, (GGSZ) PRD 68 (2003) 054018

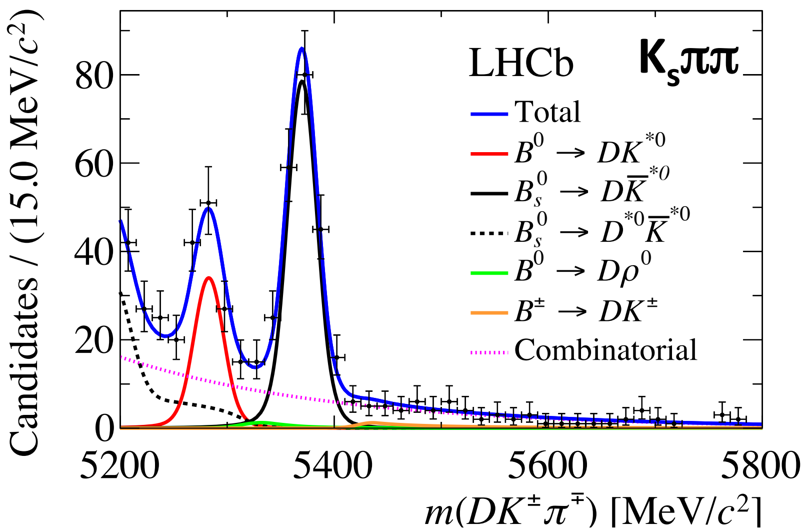
Other B modes

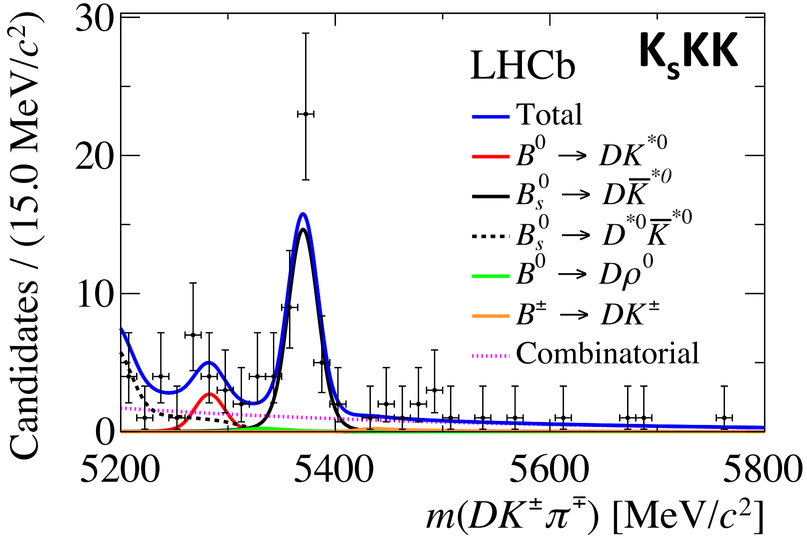




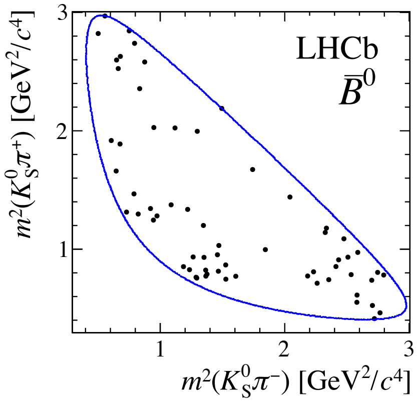
- Favoured and suppressed decay both colour suppressed
- Different r_B and δ_B: $r_B \sim 0.3 \rightarrow$ Larger interference
- Charge of kaon from K* tags tags flavour of B at decay – no need for time dependent analysis
- Yields at LHCb becoming viable for analysis

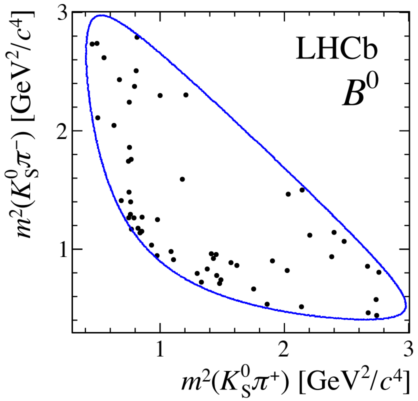
Selection of $B^0 \rightarrow DK^*$





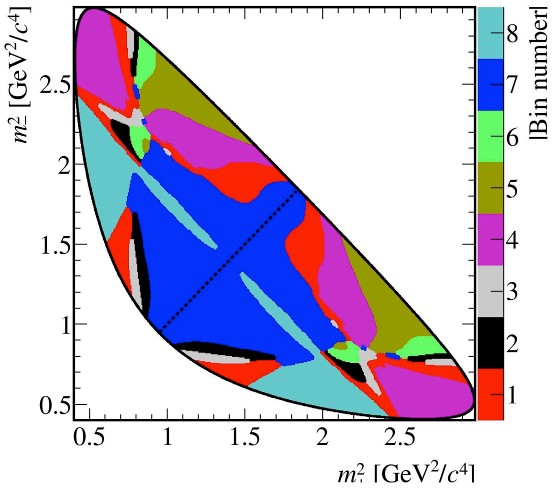
- Yields ~ 90 in $K_s\pi\pi$ and 10 in ~K_sKK
  - Twice yield of B factories
- Irreducible B_s backgrounds
- → Look for differences in the D Dalitz Plots distributions





JHEP 06 (2016) 131

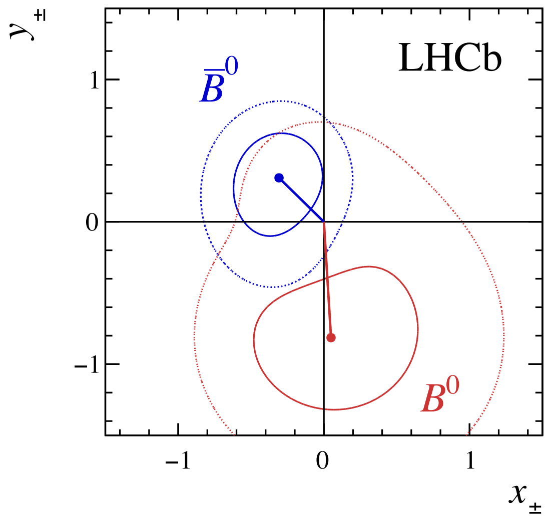
Model-independent GGSZ analysis

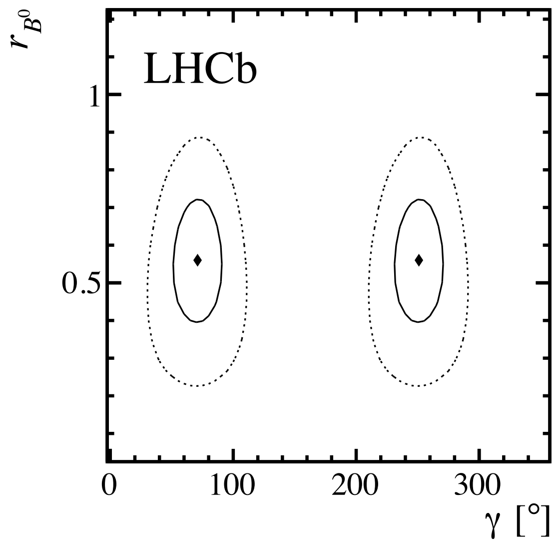


- Divide Dalitz plot into bins and look at asymmetries in yields
- Asymmetries related to γ if input on average strong phases from CLEO is used. PRD 82 (2010) 112006
- Measured parameters are x,y

$$x_{\pm} = r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$

$$y_{\pm} = r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$





- No observation of CPV.
- **γ = (71 ± 20)°**
- $\sigma(\gamma) \sim 1/r_{B0}$

Model-dependent analysis also performed, results compatible. arXiv:1605.01082

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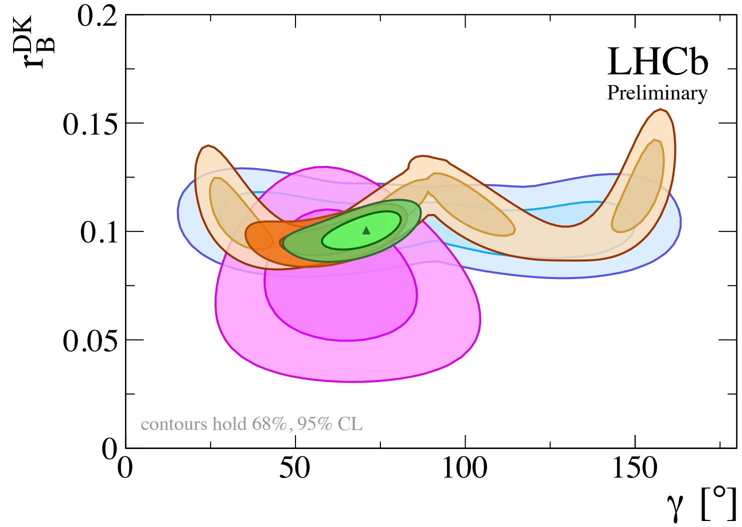
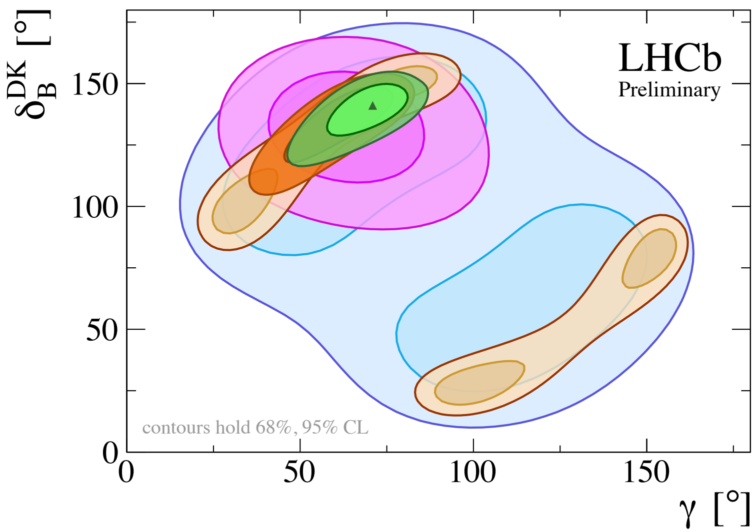
Interplay between different modes: $B^+ \rightarrow DK^+$

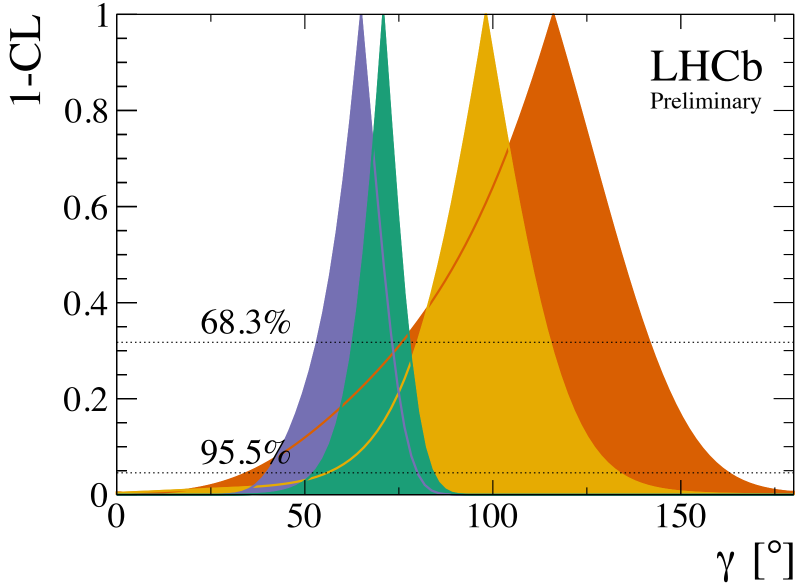




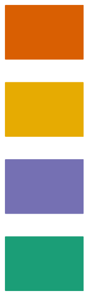
- ADS/GLW/q-GLW observables have non trivial trigonometric relations – leads to 4 solutions
- Single solution selected by GGSZ modes
- Combination can set strong constraints
- Other B modes improve that further
- No single mode dominates→ necessary to follow all paths

LHCb-PAPER-2016-032 supersedes LHCb-CONF-2016-001

Combination results



- Many more modes in total
- 71 observables and 32 parameters.
- Frequentist combination using 'plugin' method approximation.
- B→ Dπ(ππ) results excluded



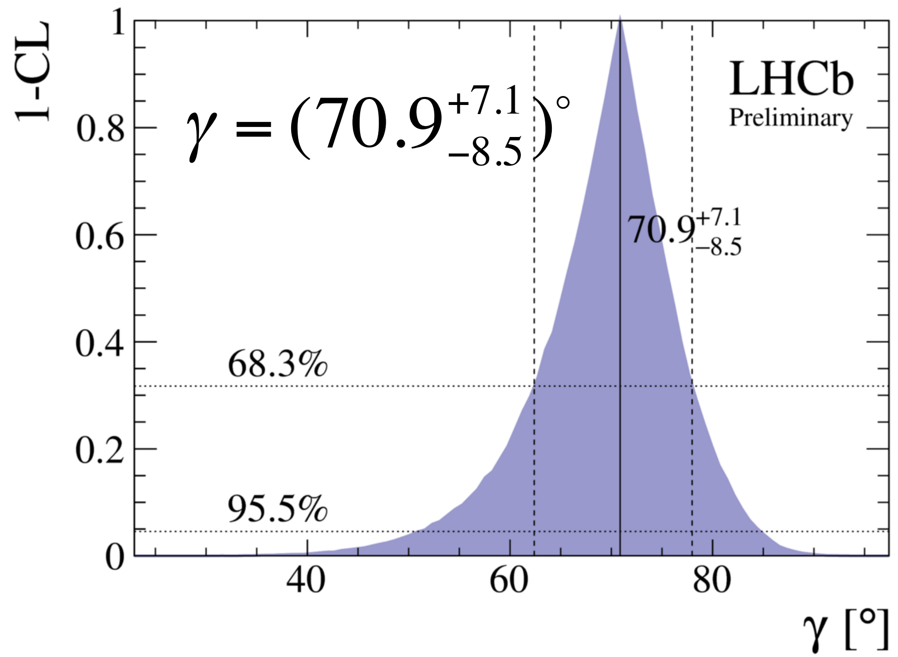
$$\gamma = (70.9^{+7.1}_{-8.5})^{\circ}$$

- 2^{nd} combination including B→Dπ, B→Dπππ performed.
- Very little real sensitivity in these modes
- Plugin approximation starts to breakdown– no 1D intervals shown.

- Improved precision compared to last combination by ~20%
- Good agreement with B factory results
- Bayesian interpretation is consistent

LHCb-PAPER-2016-032 supersedes LHCb-CONF-2016-001

Outlook



- Run 1 target of 8° attained
- Nearly all Run 1 analyses complete
- 2015 data + 2016 data being added
- New decay modes being added
- Run 2 target: 4°

- **LHCb upgrade projection (50 fb^{-1}) for γ is 0.9° (~15 yrs from now) -- no showstoppers forseen**

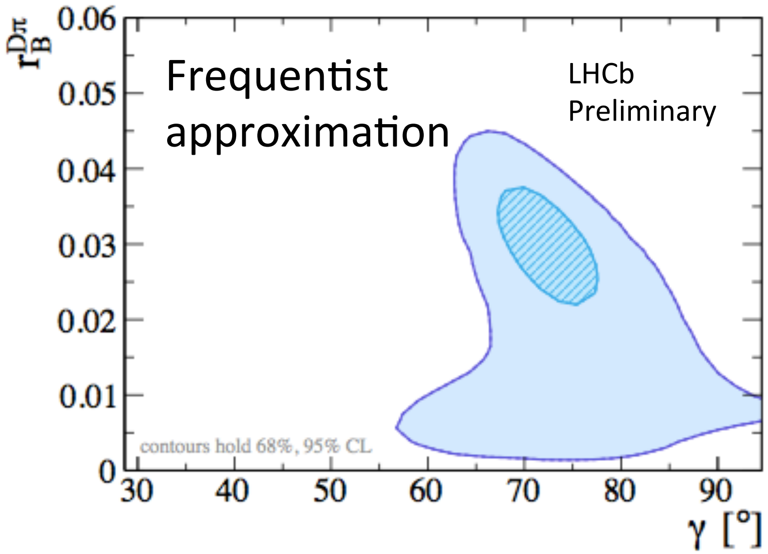
EPJC (2013) 73:2373

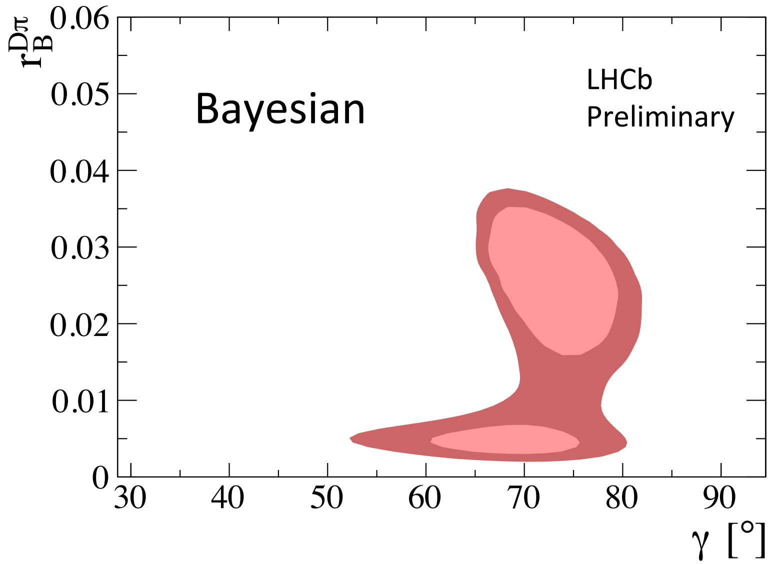
Degree level precision will be required to probe NP

LHCb demonstrates that it remains on target to do so.

End

Dh combination





- p-value from 2-D Plugin scan. 2σ contour wider for low (expected) values of $r_B^{D\pi}$.
- Behaviour not seen in 1-D Plugin scan – result of the approximation that all other nuisance parameters are fixed to best fit values.
- 1-D scan does not lead of accurate description of the Frequentist intervals, hence no result quoted.

Integrating the 2-D posterior PDF leads to non-Gaussian intervals.
Most probable value: 72.7°
Credibility intervals:
$\gamma \in [69.0°, 77.6°]$ @ 68.3%
$\gamma \in [57.0°, 83.1°]$ @ 95.5%
$\gamma \in [40.9°, 87.2°]$ @ 99.7%

LHCb-PAPER-2016-032 supersedes LHCb-CONF-2016-001

Combining results -LHCb inputs

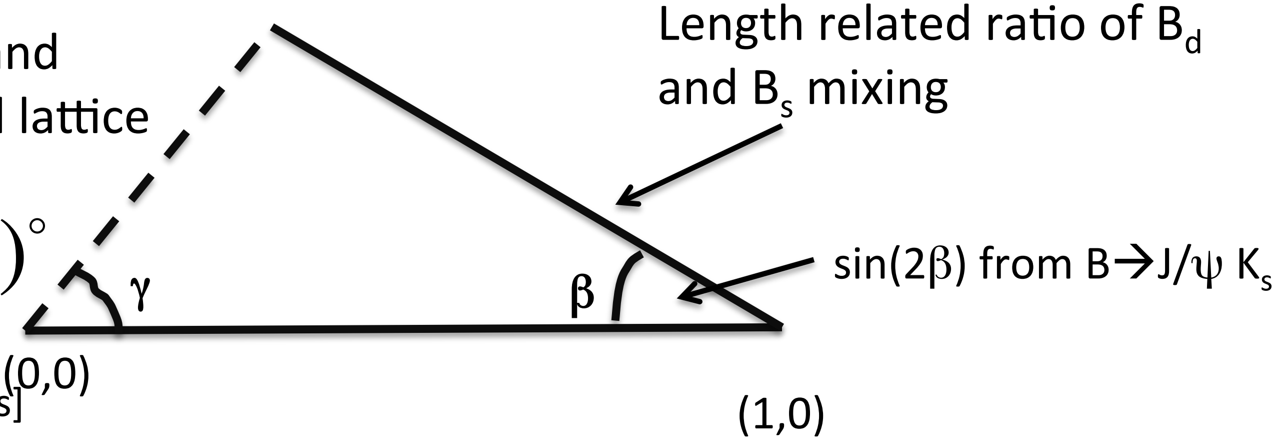
LHCb measurement	Type/ Dataset	Reference
$B^+ \rightarrow DK^+$ $D \rightarrow 2h,4h$	ADS/(q-)GLW ($3fb^{-1}$)	arXiv:1603.08993
$B^0 \rightarrow DK\pi$	Dalitz ($3fb^{-1}$)	arXiv: 1602.03455
$B^0 \rightarrow DK^*$ $D \rightarrow Ks\pi\pi$	GGSZ MD ($3fb^{-1}$)	arXiv: 1605.01082
$B^+ \rightarrow DK^+$ $D \rightarrow hh\pi^0$	ADS/q-GLW ($3fb^{-1}$)	PRD 91(2015) 112014
$B^+ \rightarrow DK\pi\pi$, $D \rightarrow 2h$	ADS/GLW ($3fb^{-1}$)	PRD 92 (2015) 112005
$B^0 \rightarrow DK^*$ $D \rightarrow 2h$	ADS ($3fb^{-1}$)	PRD 90 (2014) 112002
$B^+ \rightarrow DK$ $D \rightarrow K_shh$	GGSZ MI ($3fb^{-1}$)	JHEP 10 (2014) 097
$B^+ \rightarrow DK$, $D \rightarrow KsK\pi$	ADS ($3fb^{-1}$)	PLB 733 (2014) 36
$B_s \rightarrow D_sK$, $D_s \rightarrow hhh$	Time dep ($1fb^{-1}$)	JHEP 11 (2014) 060

γ from indirect determination

The unitarity triangle is constructed using mixing and sin(2β) measurements and lattice QCD

$$\gamma = (62.7 \pm 2.1)^\circ$$

EPJC (2016) 76 197 [Blanke, Buras]



Combination of all direct measurements (summer 2015)

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

Alternative approach from CKM fit excluding all direct measurements of γ

$$\gamma = (66.9^{+0.94}_{-3.44})^\circ$$

Uncertainties dominated by LQCD, expect to reduce over the next decade

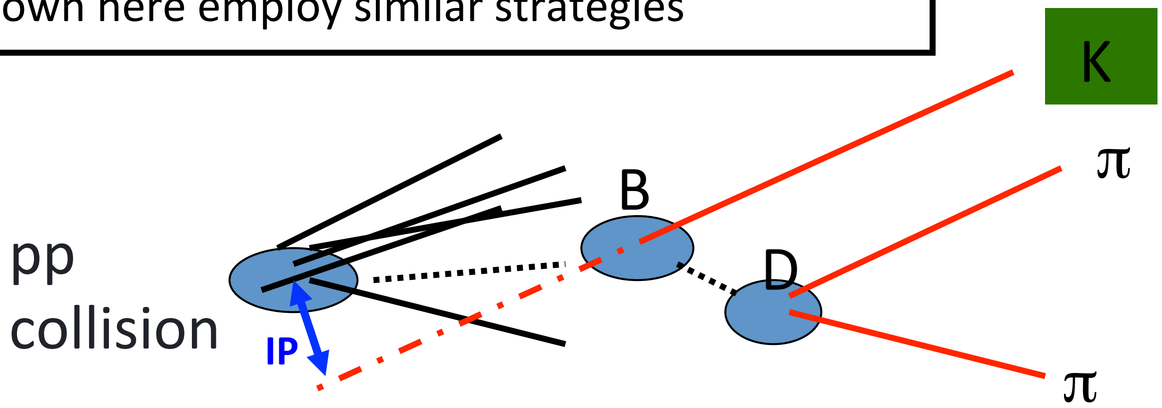
Reaching degree level precision from direct measurements is crucial

Combing results-other inputs

Parameters	Source	Reference
Charm mixing and CPV in $D \rightarrow hh$	HFAG	www.slac.stanford.edu/xorg/hfag/charm/index.html
κ, δ_D: $D \rightarrow K3\pi$, $D \rightarrow K\pi\pi^0$	LHCb & CLEO data	PLB 757 (2016) 520
κ, δ_D : $D \rightarrow K_s K\pi$	CLEO data	PRD 85 (2012) 092016
CP fraction $D \rightarrow 4\pi$, $D \rightarrow hh\pi^0$	CLEO data	PLB 747 (2015) 9
Strong phase information for $D \rightarrow K_s hh$	CLEO data	PRD 82 (2010) 112006
Constraint on ϕ_s	LHCb data	PRL 114 (2015) 041801

Selection

All analyses shown here employ similar strategies



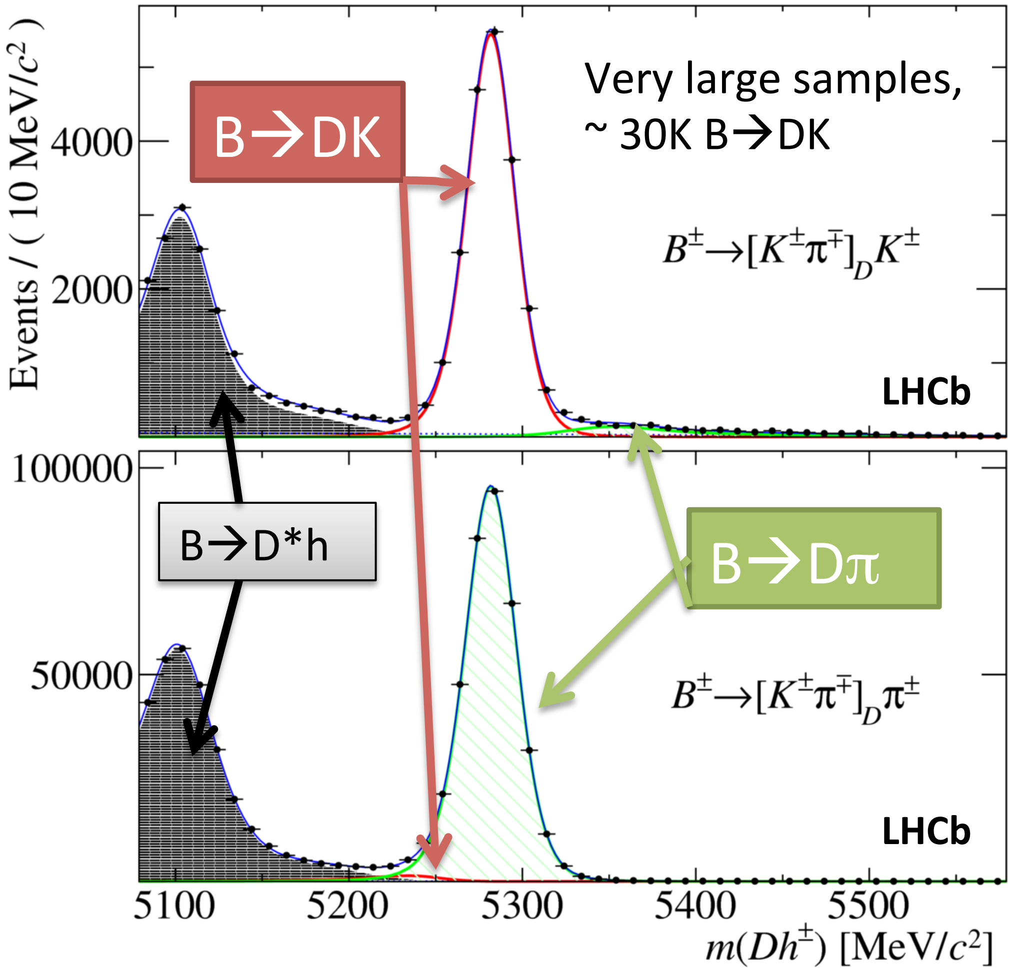
Separate the topology of interest from random combinations

Use of multi-variate analysis techniques. Useful variables include:

- Impact parameters
- Flight distances from primary. (B travels a ~cm)
- Flight distances from B – removes e.g B→Kππ backgrounds
- Vertex quality
- Particle ID

Specific vetos against particular backgrounds

B→D[Kπ]h – CF control mode



Difference between the two modes only the ID of the bachelor hadron

PID performance→ low crossfeed.

B->D*h where a π^0 or photon isn't reconstructed sits to the left

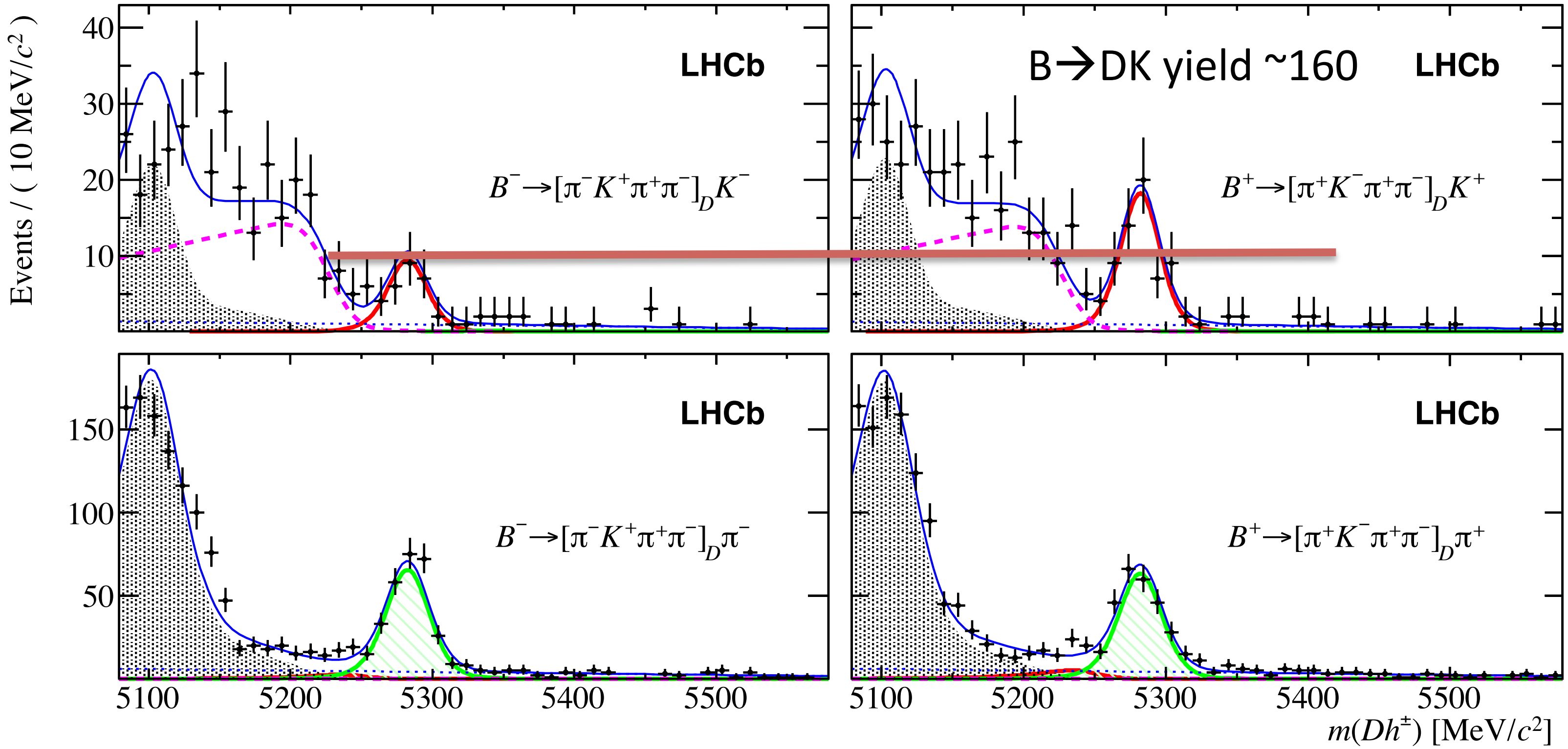
Extremely low level of combinatoric – clean environment

Control mode constrains the shapes of signal and backgrounds

Control mode also used to measure the $B^{\pm}$ production asymmetry. Detection asymmetries calibrated from other data.

Results also extracted for B→Dπ mode, interference level expected to be ~ magnitude smaller

Results D→K3π



$$A_K^{\pi K \pi\pi} = -0.313 \pm 0.102 \pm 0.038$$

Complementary information to two body modes.

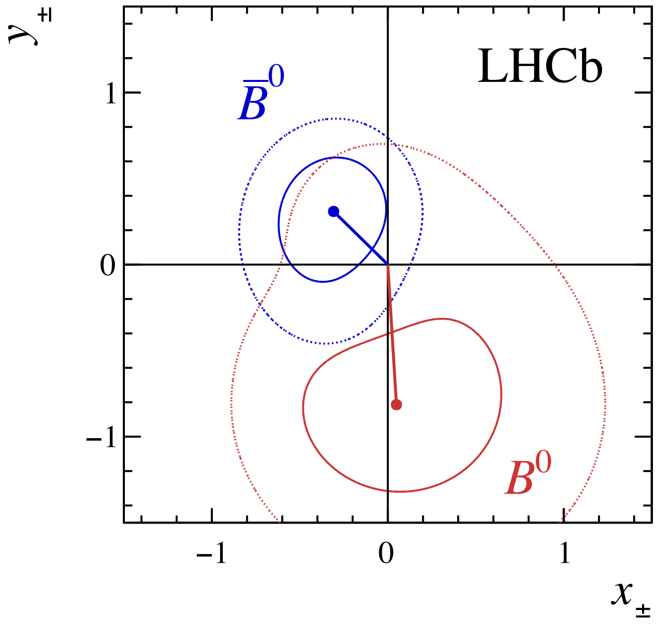
CPV starts to become visible in B→Dπ when combining all D→hh and D→4h modes.

3.9σ

PLB 760 (2016) 117

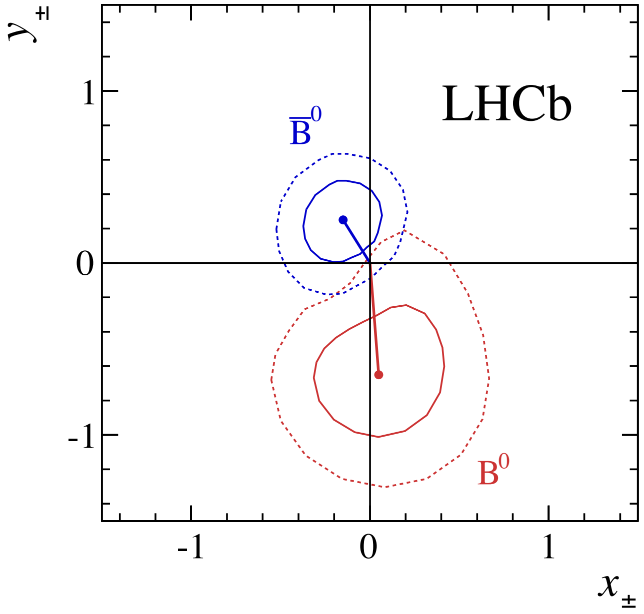
Results

Model - independent



$$x_+ = 0.05 \pm 0.35 \pm 0.02$$
$$y_+ = -0.81 \pm 0.28 \pm 0.06$$
$$x_- = -0.31 \pm 0.20 \pm 0.04$$
$$y_- = 0.31 \pm 0.21 \pm 0.05$$

Model - dependent



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

- Good agreement between methods
- Uncertainties from external strong phase information are ~0.02 for x and ~0.05 for y.
- Both methods give $\sigma(\gamma)$=20°

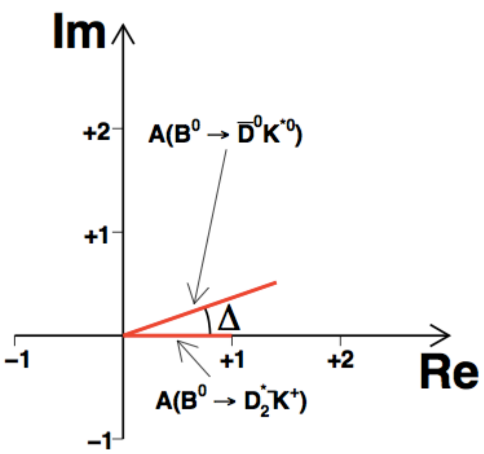
arXiv: 1604.01525

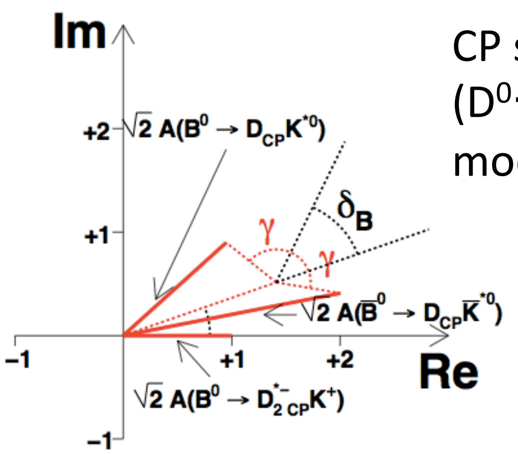
arXiv: 1605.01082

$B^0 \rightarrow DK\pi$ Dalitz plot analysis

- $B^0 \rightarrow DK^*$, $D \rightarrow CP+$, $K^* \rightarrow K\pi$ restricts the data to the K* resonance
- There is sensitivity to γ from the full $B^0 \rightarrow DK\pi$ decay in any $K\pi$ resonance
- Amplitude fit of $B^0 \rightarrow DK\pi$ decay exploits interference between different resonant contributions
- Complex amplitudes of the DK* determined relative to flavour-specific D_2^*K
- γ measured from amplitudes and not rates $\rightarrow$ more information than standard GLW analysis
- New method of measuring γ

Favoured ($D^0 \rightarrow K^+\pi^-$) mode:





CP sensitive ($D^0 \rightarrow KK, \pi\pi$) modes:

PRD 79 (2009) 051301

$B^0 \rightarrow DK\pi$ Dalitz plot analysis

Favoured ($D^0 \rightarrow K^+\pi^-$) mode:

$$A\left(m^2(D\pi), m^2(K\pi)\right) = \sum_{j=1}^{N} c_j F_j\left(m^2(D\pi), m^2(K\pi)\right)$$

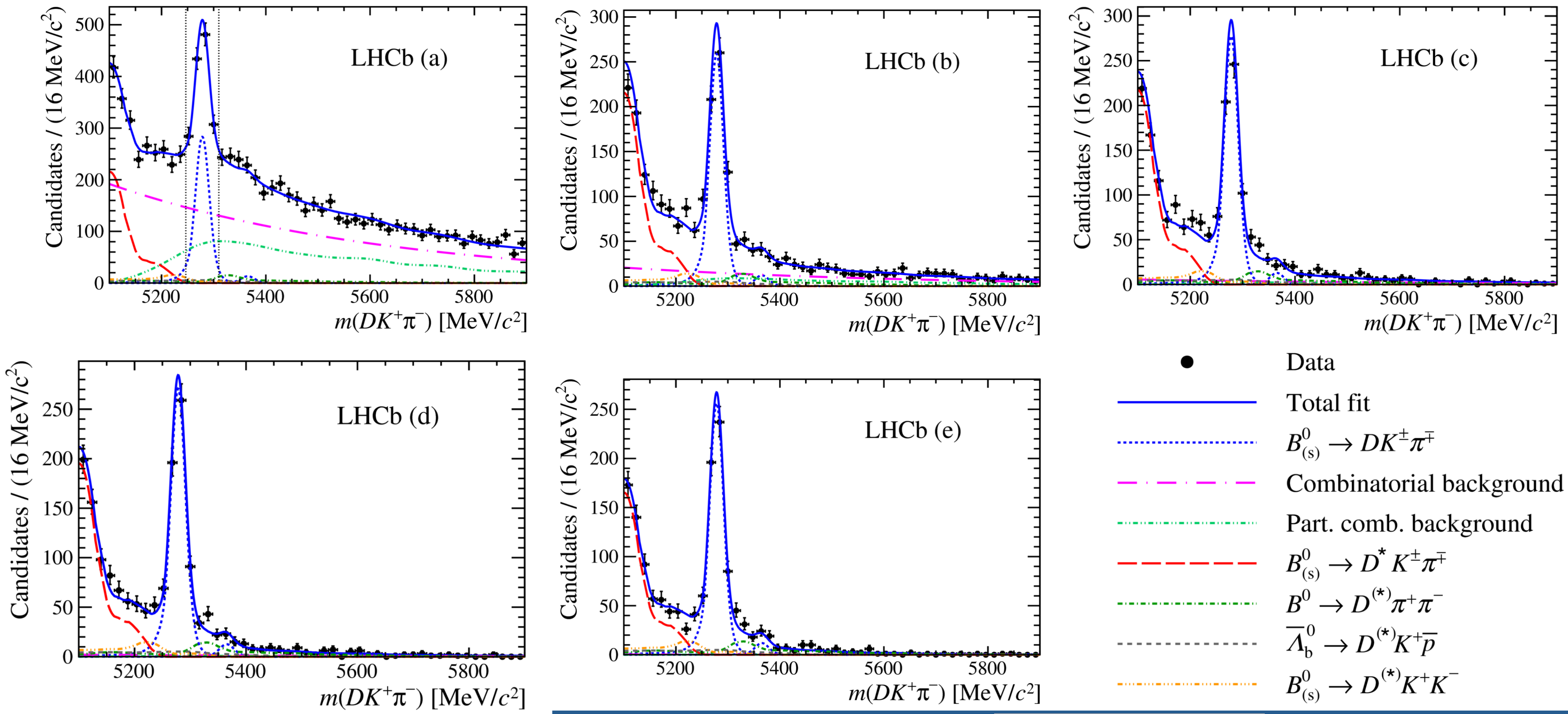
CP sensitive ($D^0 \rightarrow KK, \pi\pi$) modes:

$$c_j \longrightarrow \begin{cases} c_j & \text{for a } D\pi^- \text{ resonance}, \\ c_j\left[1 + x_{\pm,\,j} + iy_{\pm,\,j}\right] & \text{for a } K^+\pi^- \text{ resonance}, \end{cases}$$

arXiv: 1602.03455

Larger phasespace →higher combinatorics

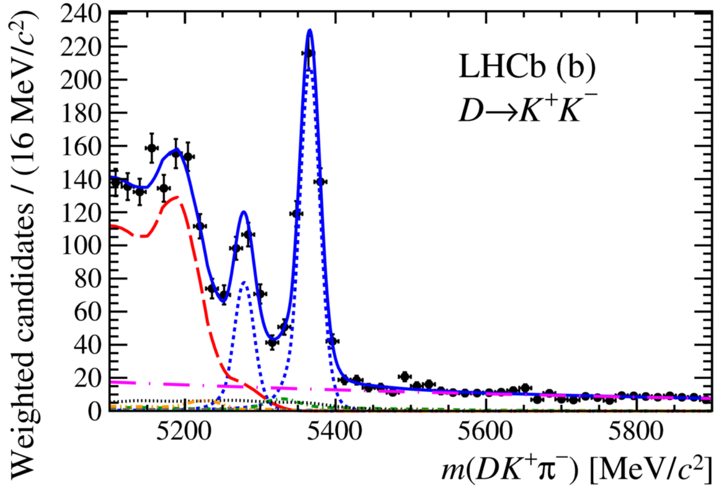
- Larger phasespace of the Kπ system leads to high combinatorics and larger amounts of physics bkgs.
- To avoid the need to cut hard data is divided into bin of NN output.
- Maximises the statistical sensitivity of the data

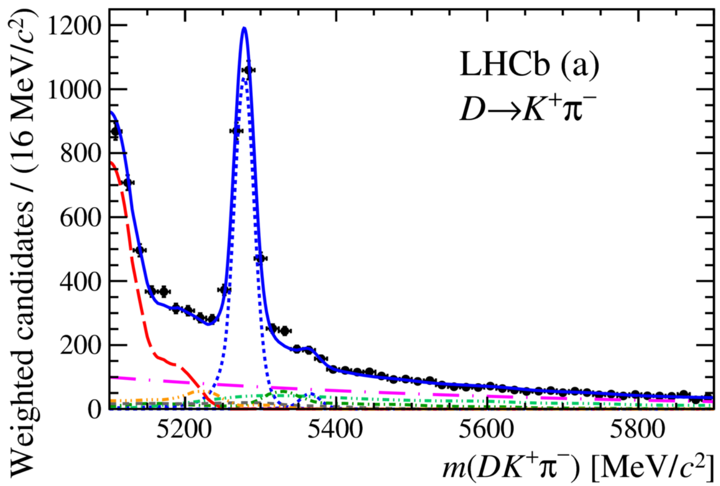


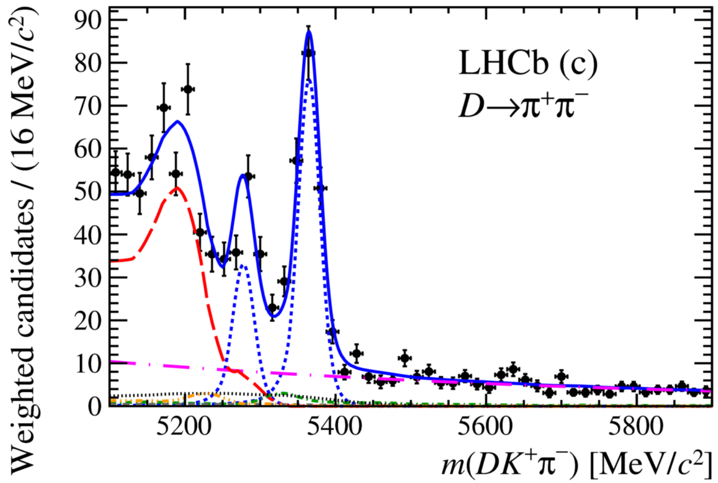
arXiv: 1602.03455

Signal yields

- To maximise statistical sensitivity data split in bins of MVA output
- Data shown with MVA bins combined weighted according to S/(S+B)
- 339+/-22 D→KK
- 168+/-19 D→ππ

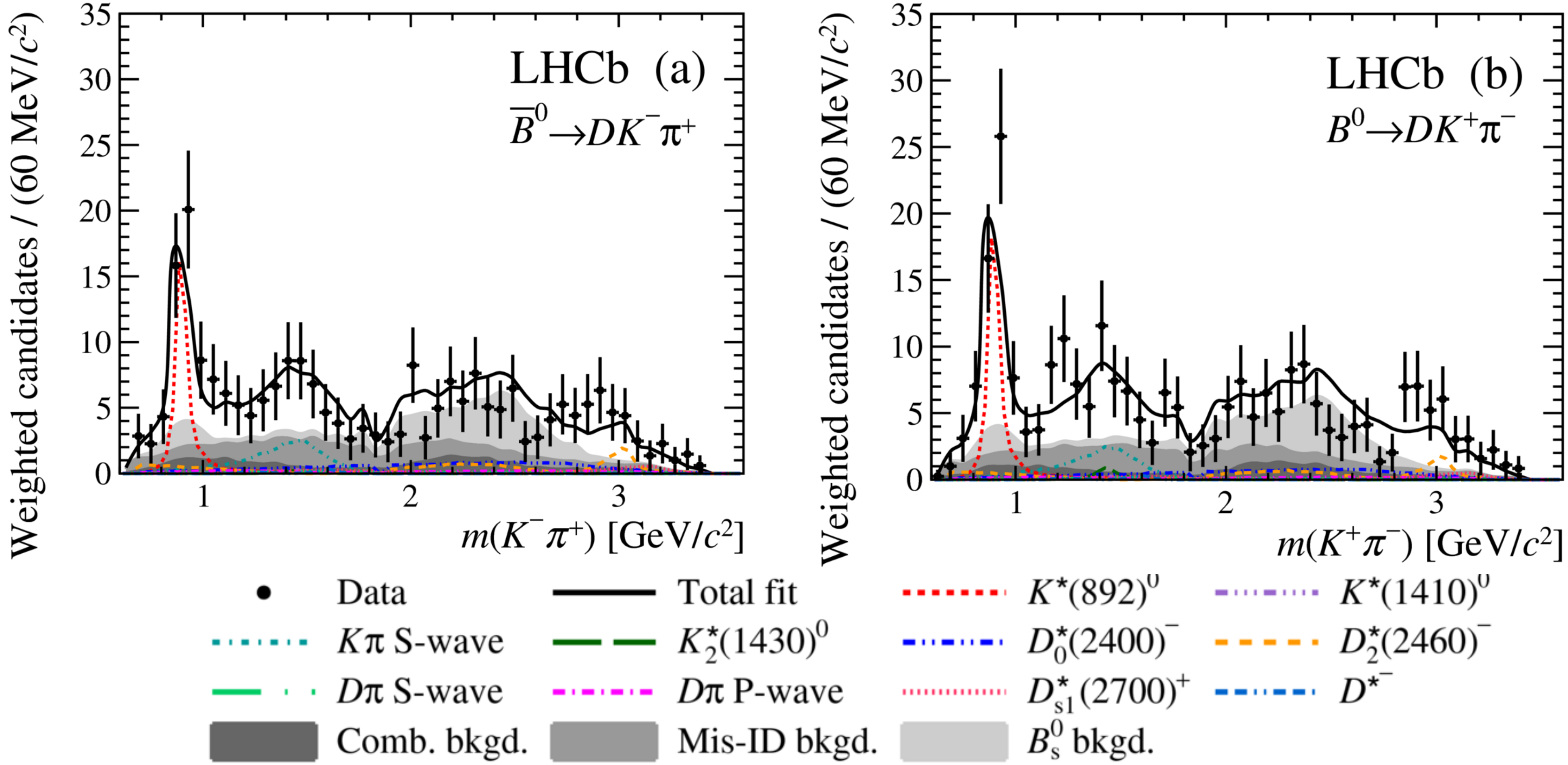






arXiv: 1602.03455

Dalitz Plot fit

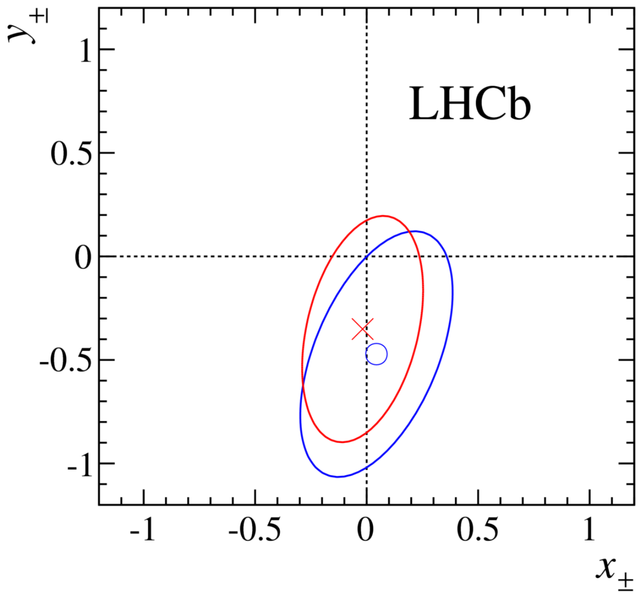


Fit projections of the D→KK and D→ππ samples combined

Only results from K*(892) used

Projections look very similar

Fit Results

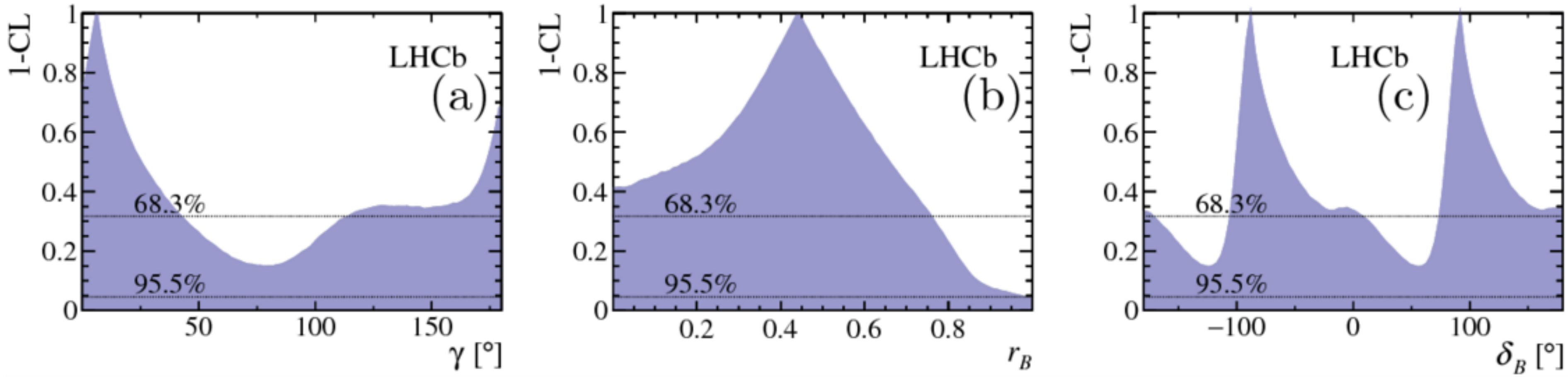


$$x_+ = 0.04 \pm 0.16 \pm 0.11$$
$$x_- = -0.02 \pm 0.13 \pm 0.14$$
$$y_+ = -0.47 \pm 0.28 \pm 0.22$$
$$y_- = -0.35 \pm 0.26 \pm 0.41$$

$$\kappa = 0.958^{+0.005+0.002}_{-0.010-0.045}$$

Results for pure K*

Also determine the coherence factor



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