Constraining the CKM angle γ

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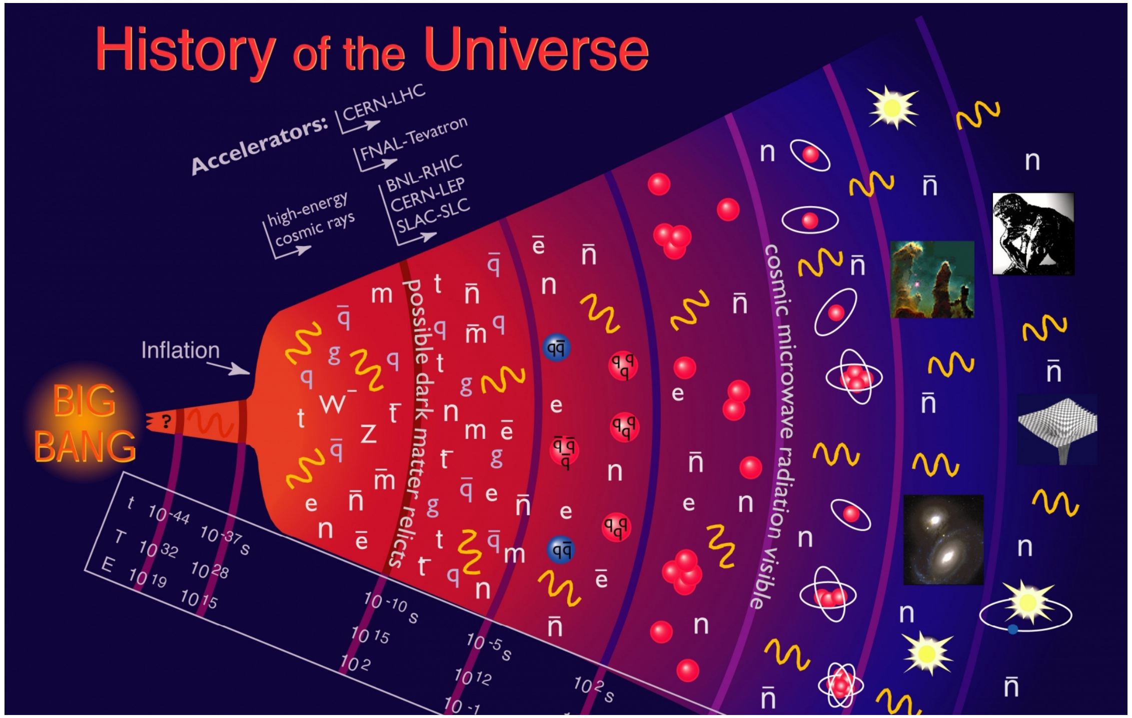
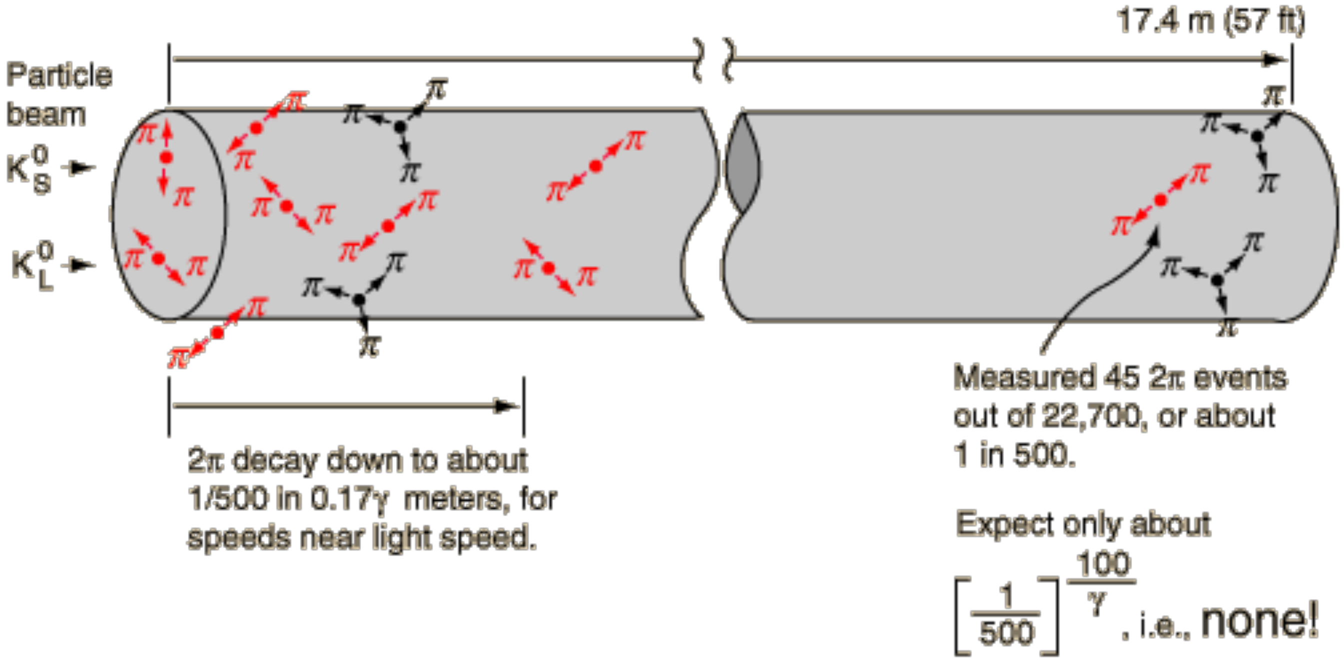
On behalf of the LHCb collaboration

Mystery



- The matter-anti asymmetry that is manifest in our universe is a mystery
- Requires a large source of CP violation

CP Violation and New Physics

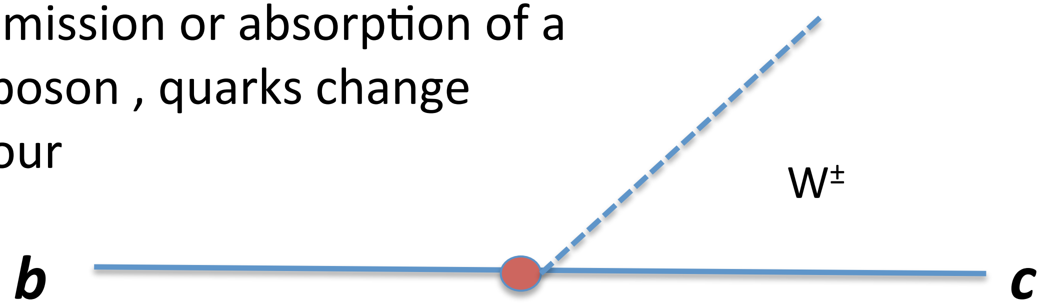


- First Observation of CPV in 1964 in the Kaon system
- Observed in B decays in 2001
- To date only observed in the quark sector, but at levels far below that required to explain the universe
- There must be additional sources of CPV in New Physics models

CKM Matrix

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \leftarrow W^{\pm} \rightarrow \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

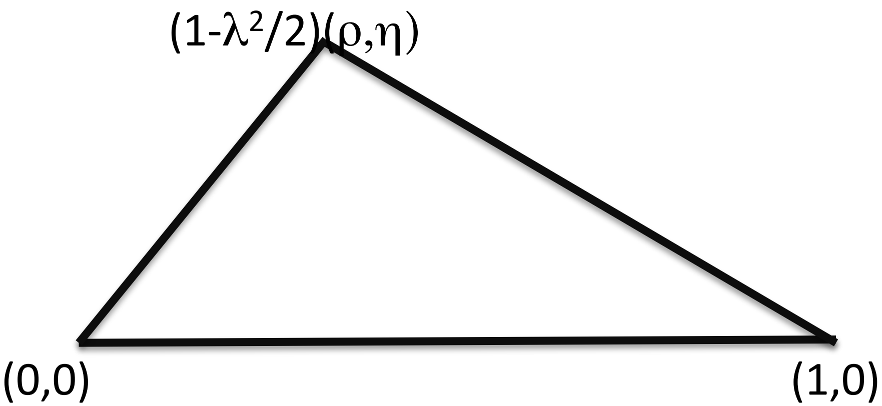
By emission or absorption of a $W^{\pm}$ boson , quarks change flavour



Unitarity triangle

- The CKM matrix is unitary, and reduces to three rotations and one phase.
- Wolfenstein parameterisation is commonly used where λ is the sine of the Cabibbo angle $\lambda \approx 0.22$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(1-\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & -A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

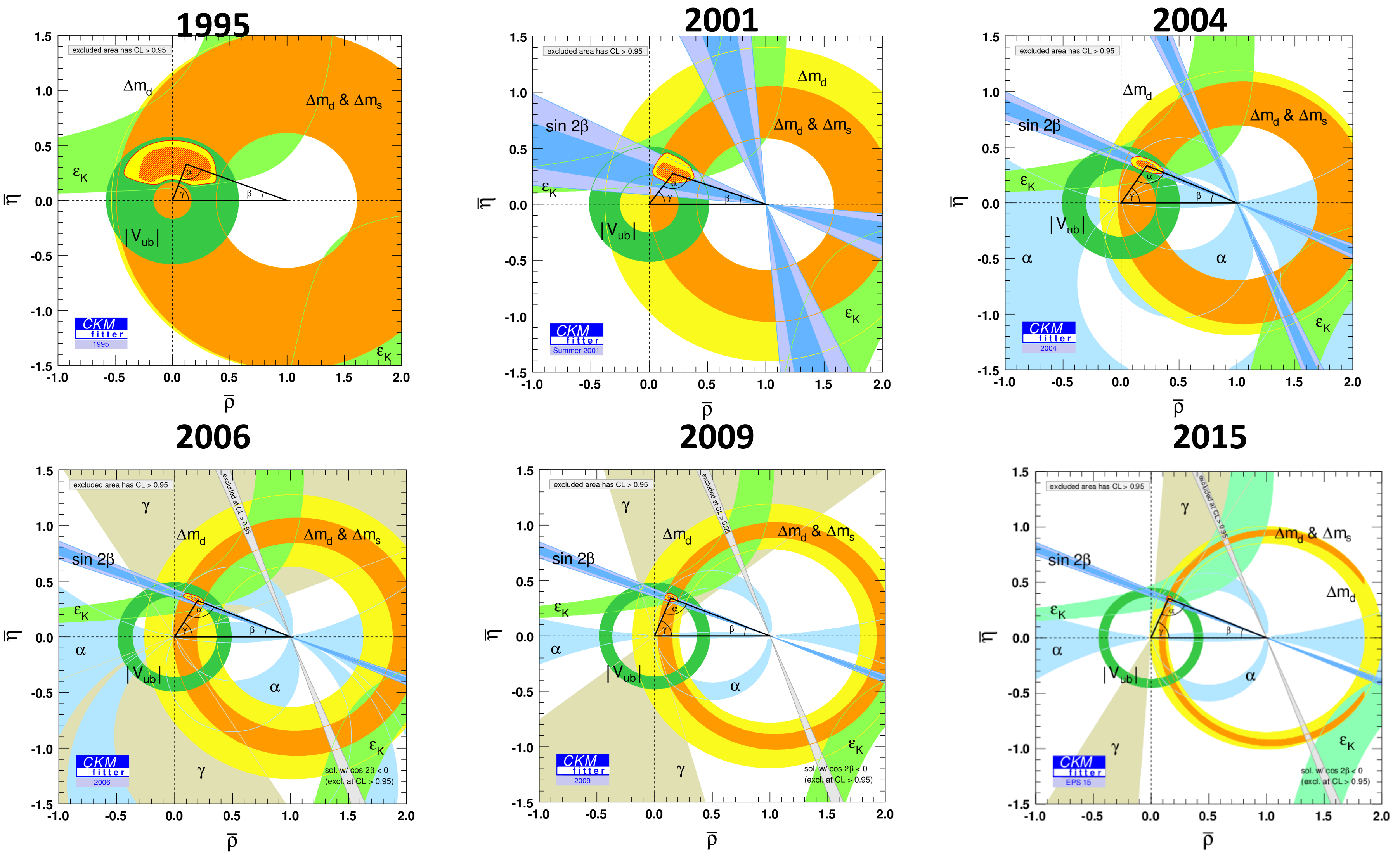


Using the properties of unitary matrices

$$0 = 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} + \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}$$

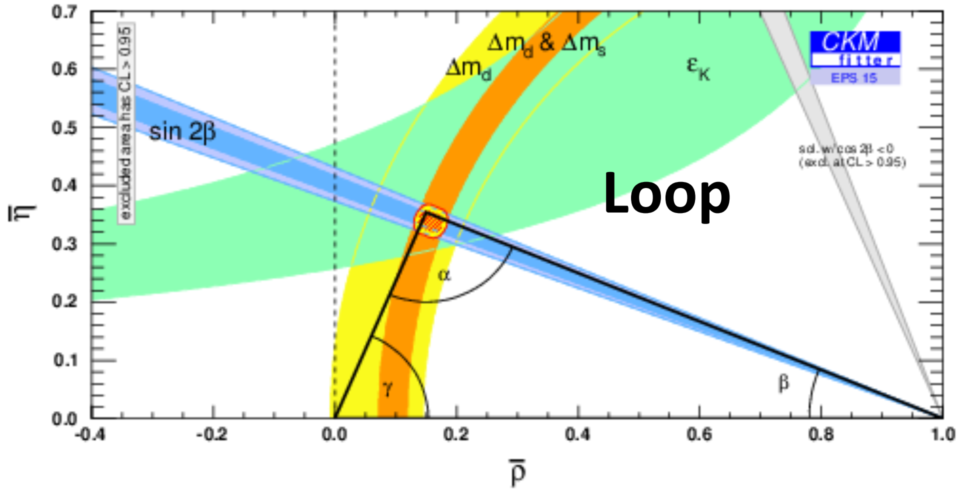
“Most open” triangle, others are possible

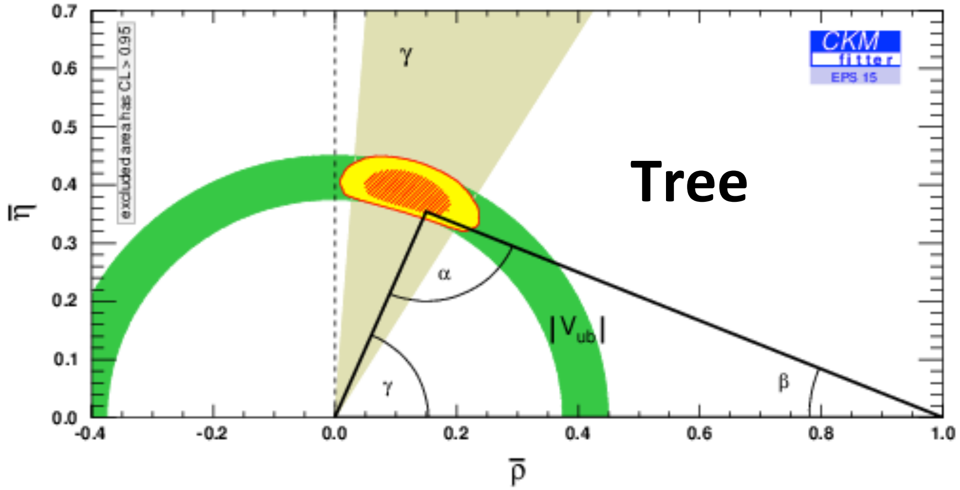
Is the triangle a triangle?



Loop/Tree

- Loop processes more easily altered by the presence of New Physics
- Constraints on the apex currently more stringent from loop decay measurements
- Largest uncertainty is on γ, a process accessible at tree level
- Forms a SM benchmark*
- Theoretically clean – uncertainty from observable to physics parameters ~10^{-7}

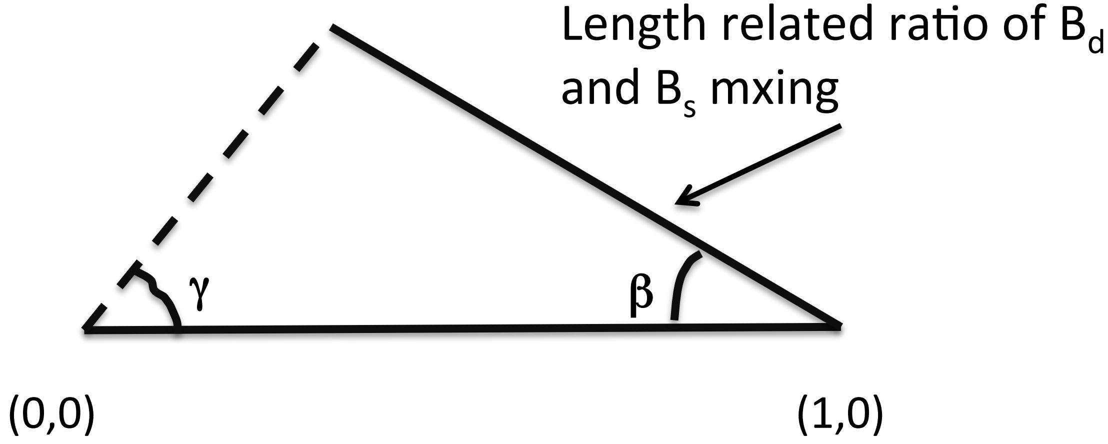




*assuming no New Physics in tree decays

Indirect predictions

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



arXiv:1602.04020 [Blanke, Buras]

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

Alternative approach from CKM fit excluding all direct measurements of γ

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

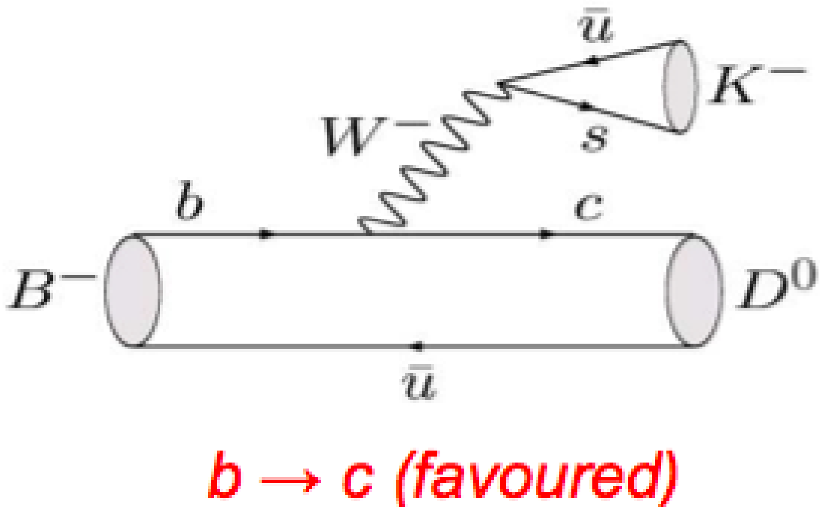
Combination of all direct measurements (summer 2015)

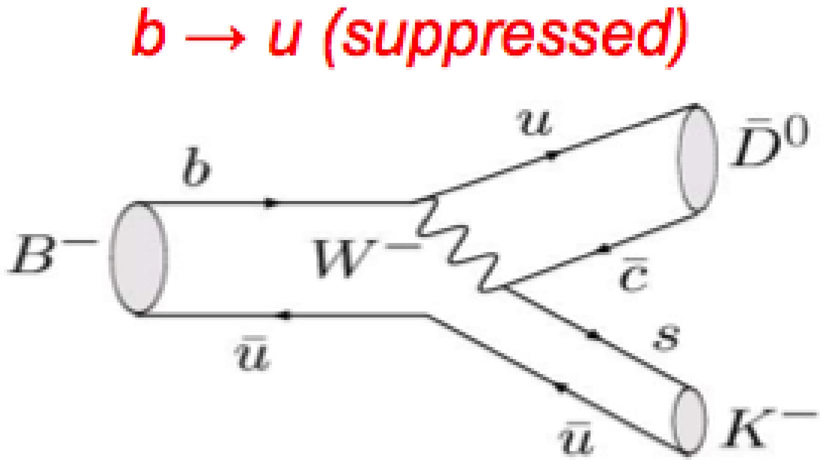
$$\gamma = (73.2^{+6.3}_{-7.0})^\circ$$

Why is γ a key goal

- New Physics must provide a new source of CPV
- γ is the least well measured parameter of the CKM triangle
- Only angle easily accessible at tree-level
- Theoretically pristine
- Provides a SM benchmark against which other measurements can be compared
- With the advent of LHCb the ideal of degree level precision starts to become reality

B→DK

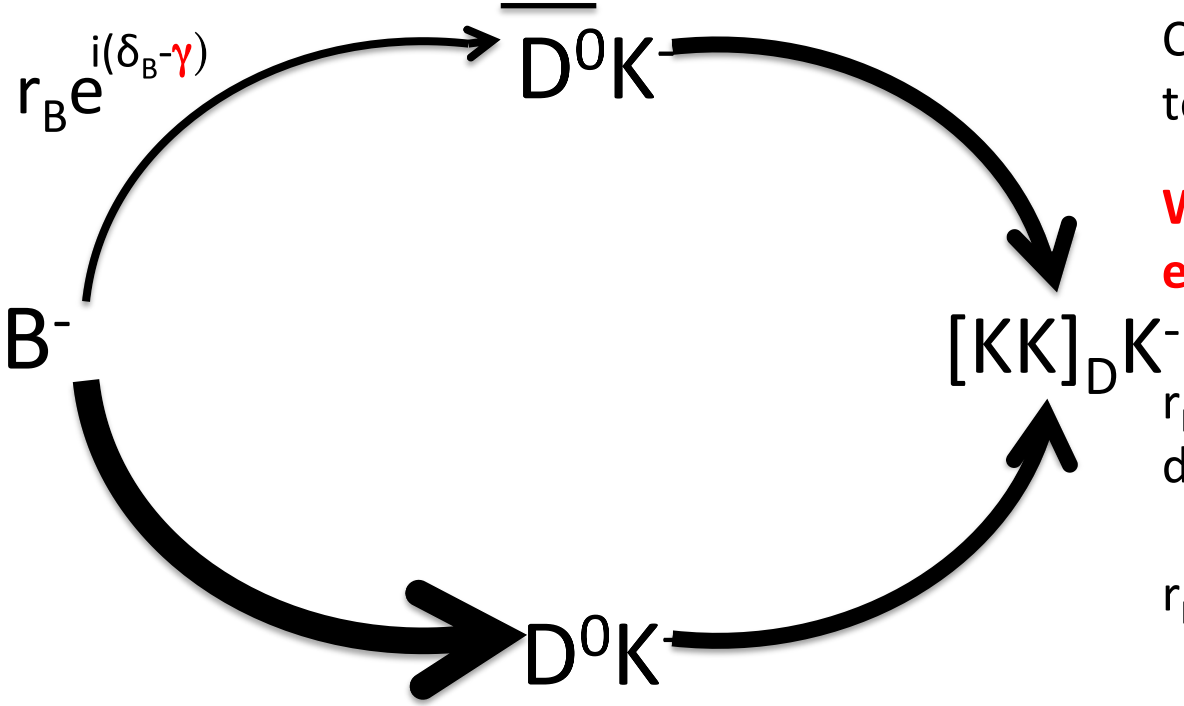




$$\gamma = -\arg\left(\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

Interference between these two decays possible if the D decay to a final state is accessible to both D flavours

Interference with CP eigenstates "GLW"



CP eigenstates equally accessible to D^0 and $\overline{D}^0$

Weak phase changes sign for equivalent B^+ diagram

r_B, δ_B hadronic parameters to be determined alongside γ

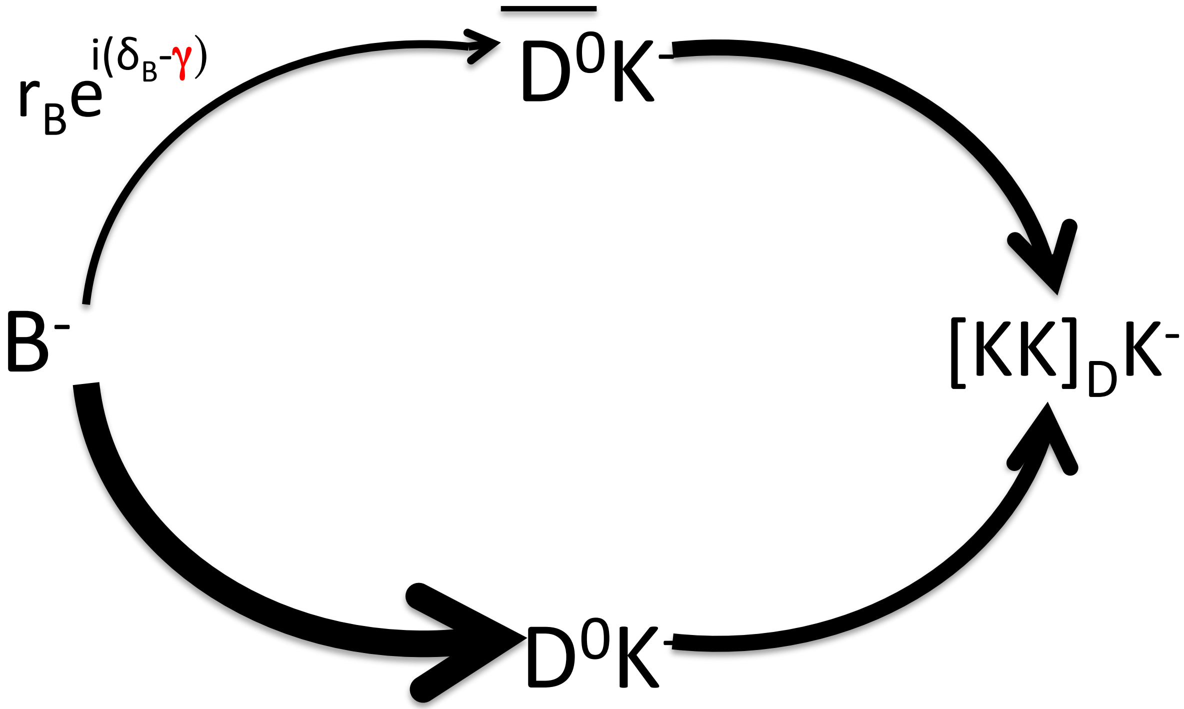
$r_B \sim 0.1$

Interested in the rate of observing this decay in B^- vs. B^+

Interested in the rate of observing this decay vs. one that is not affected by interference, e.g the Cabibbo favoured decay of the D^0

PLB 253 (1991) 483, PLB 265 (1991) 172

Interference with CP eigenstates “GLW”



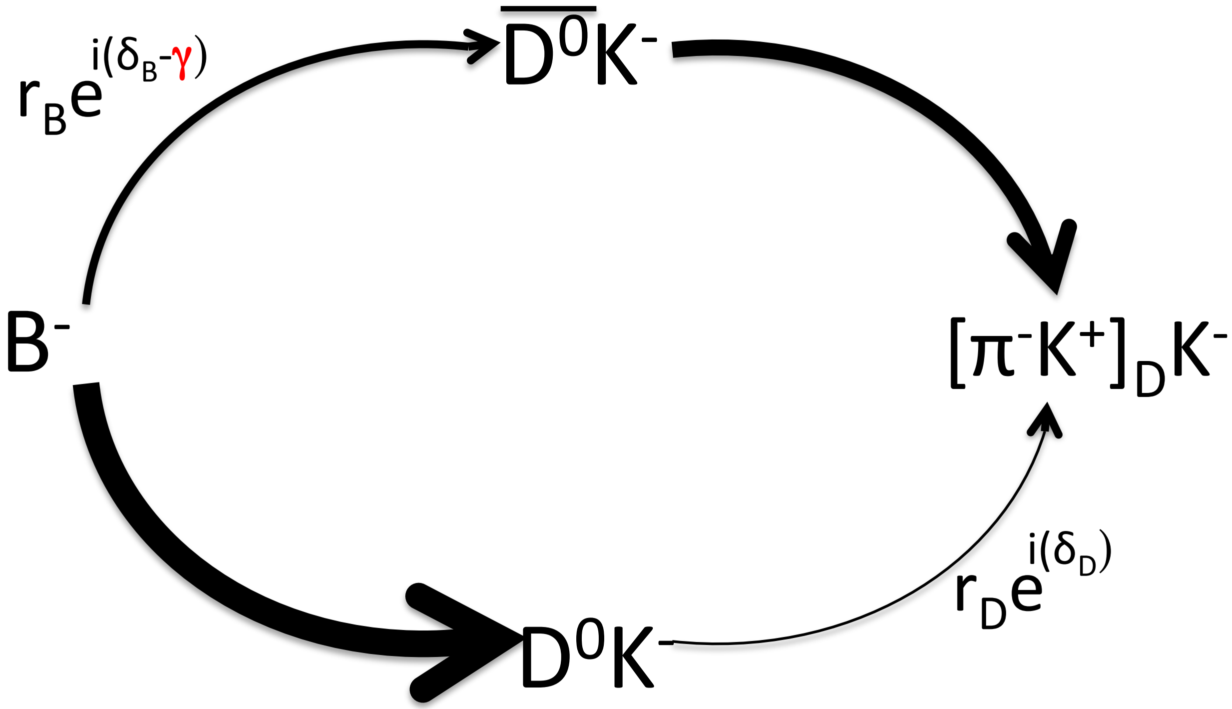
Equations simplified – assume no D mixing

For CP+ eigenstates e.g KK, ππ:

$$\frac{\Gamma(B^- \to [KK]_D K^-) - \Gamma(B^+ \to [KK]_D K^+)}{\Gamma(B^- \to [KK]_D K^-) + \Gamma(B^+ \to [KK]_D K^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B \sin(\delta_B)\sin(\gamma)$$

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

Interference with flavour specific "ADS"



Larger interference effects as both amplitudes of similar sizes.

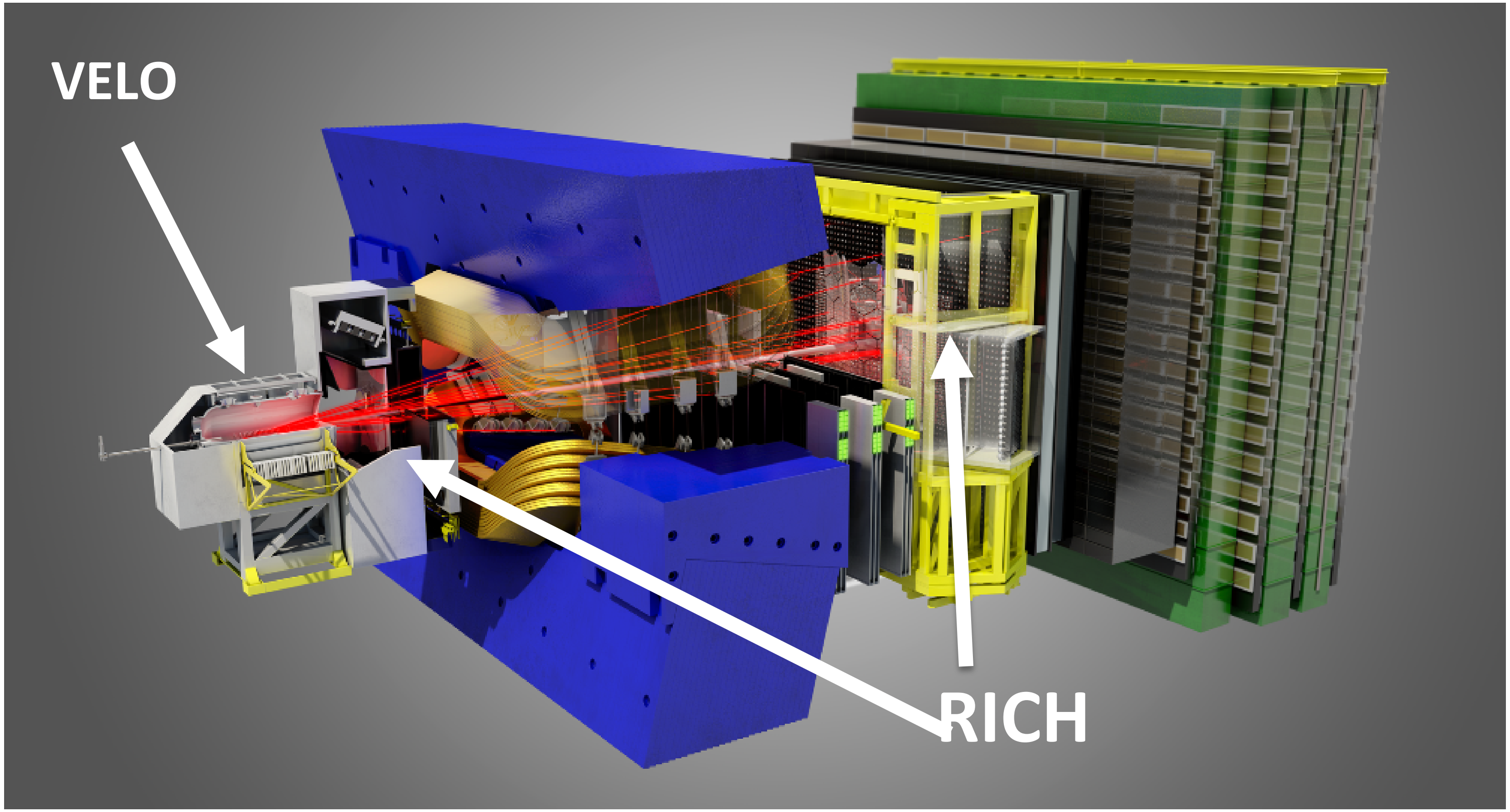
Additional two parameters r_D, δ_D . External inputs from charm mixing.

$$\frac{\Gamma(B^- \to [\pi^-K^+]_D K^-) - \Gamma(B^+ \to [\pi^+K^-]_D K^+)}{\Gamma(B^- \to [\pi^-K^+]_D K^-) + \Gamma(B^+ \to [\pi^+K^-]_D K^+)} = A_{ADS} = \frac{1}{R_{ADS}} 2 r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)$$

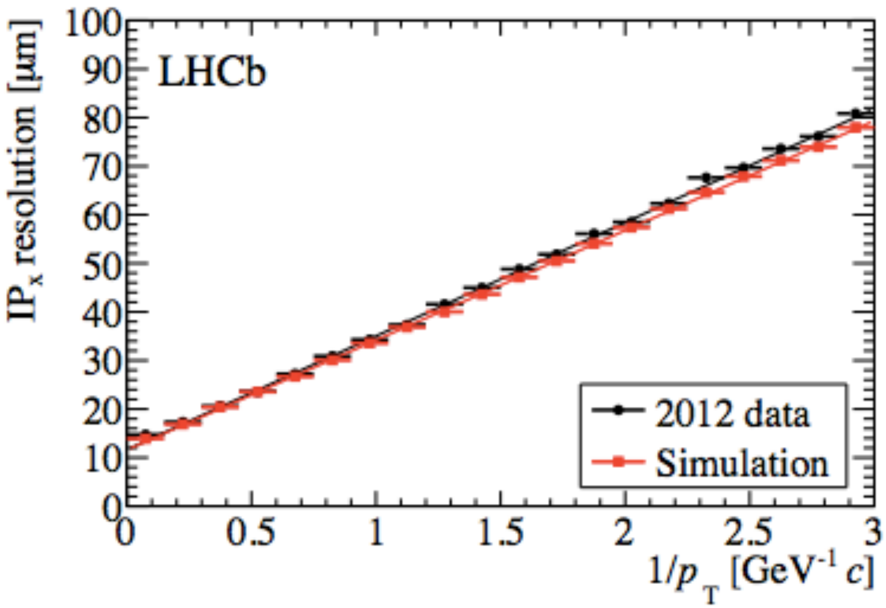
$$\frac{\Gamma(B^\pm \to [\pi^\pm K^\mp]_D K^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp]_D K^\pm)} = R_{ADS} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)$$

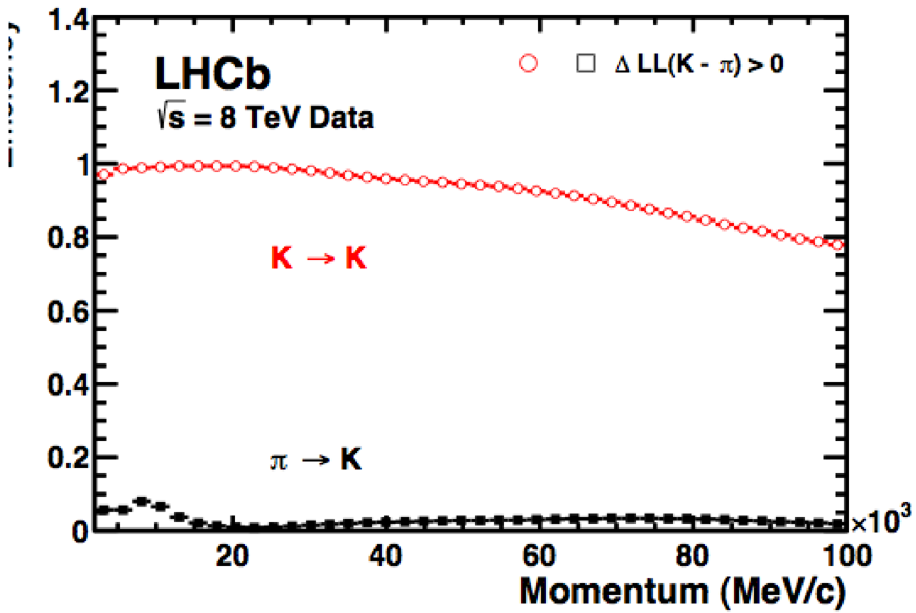
PRL 78 (1997) 3257, PRD 63 (2001) 036005

LHCb detector



Detector performance



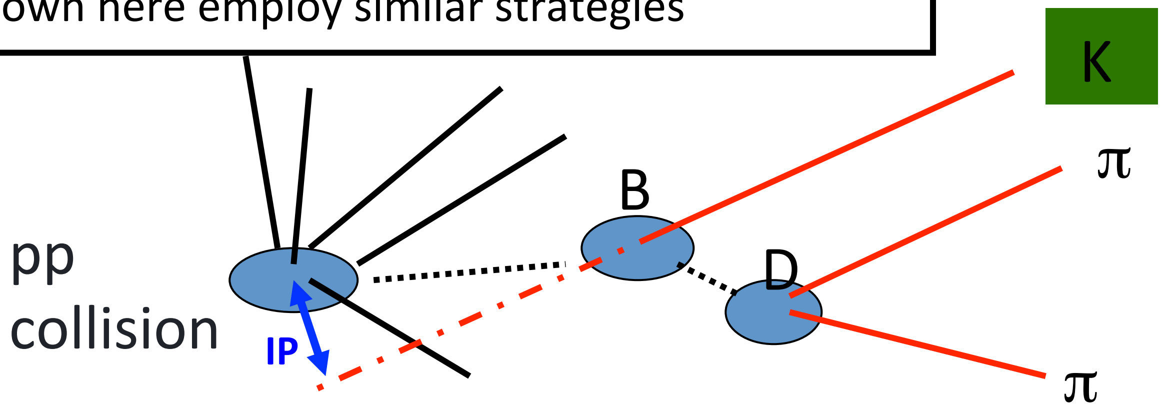


- Allows identification of displaced tracks
- Reconstruction of secondary vertices

- Separation between hadron species crucial

Selection

All analyses shown here employ similar strategies



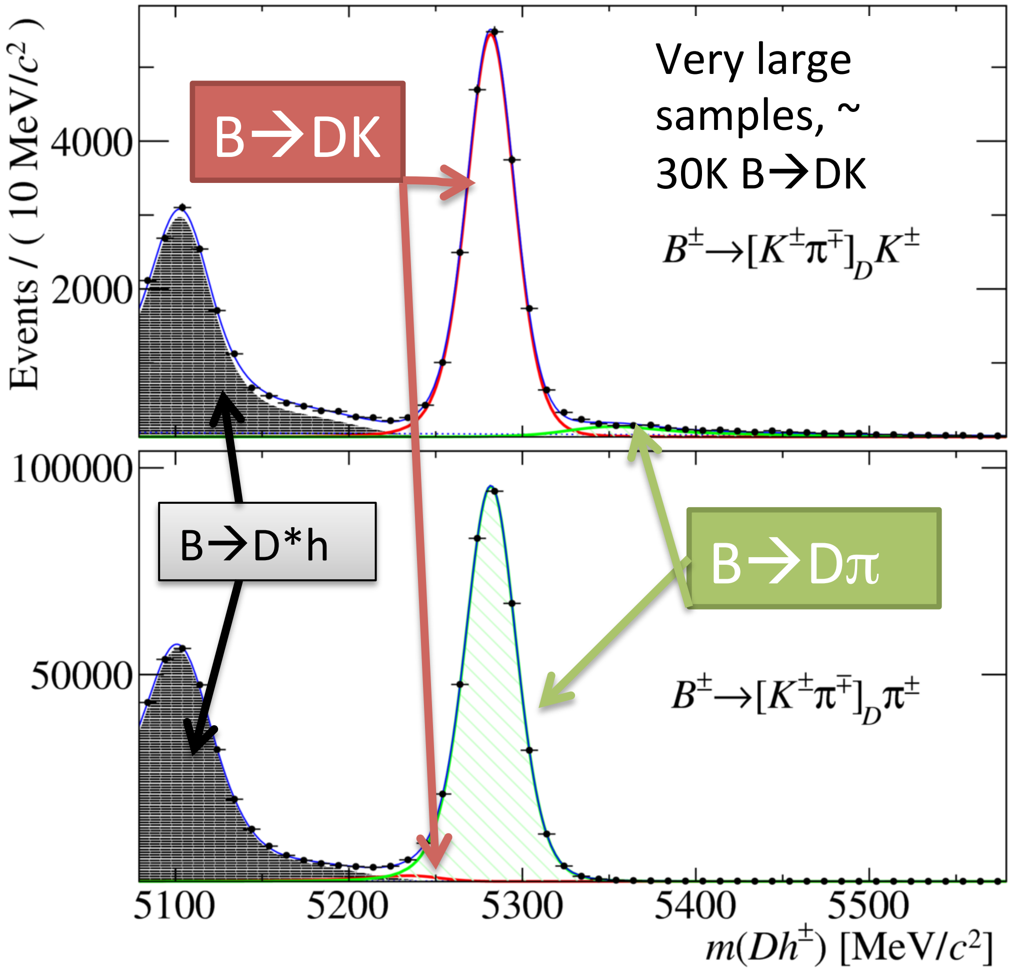
Separate the topology of interest from random combinations

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→Kpipi bkgs
- 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

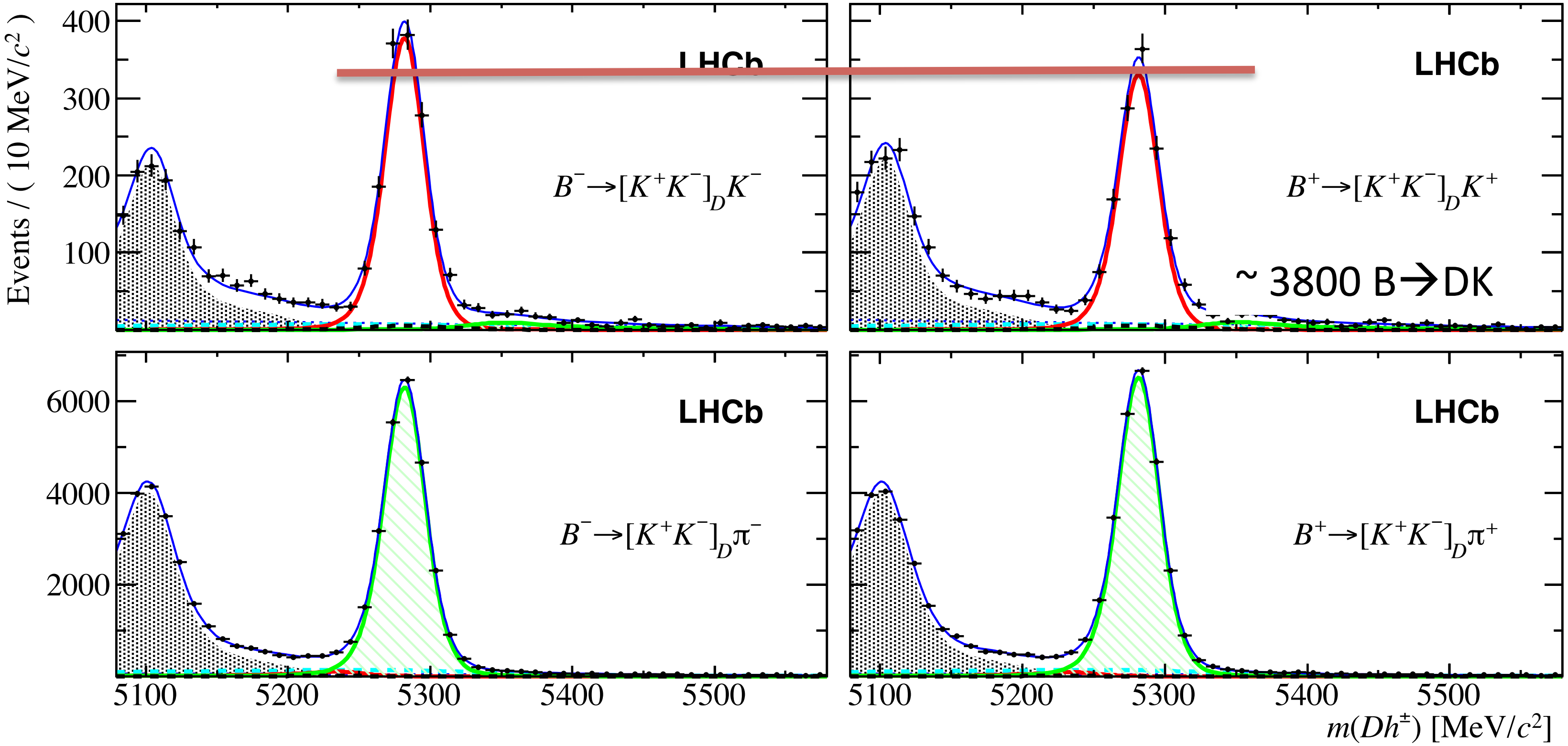
Control mode constrains the shapes of bkgs

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

arXiv:1603.08993

B→D(KK)h



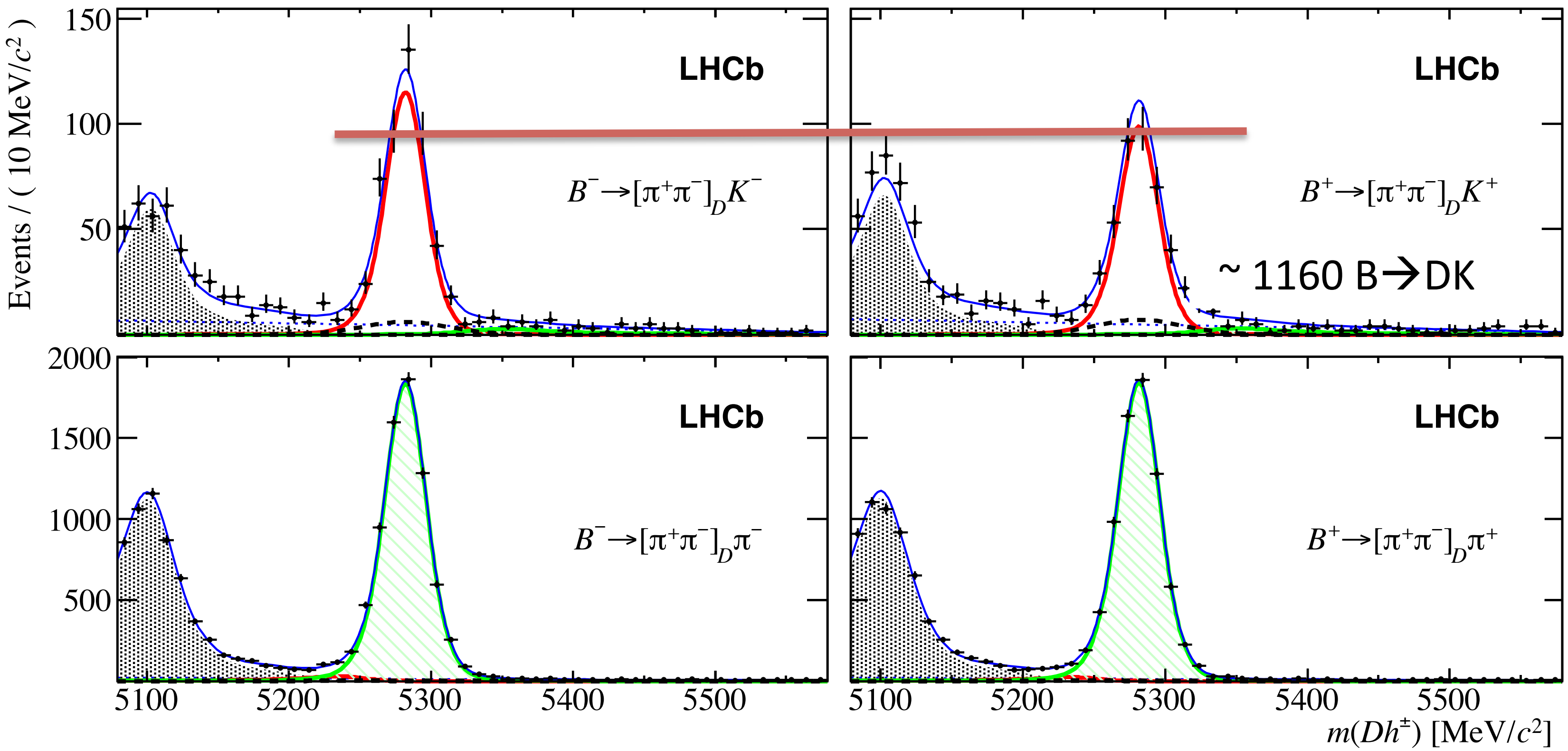
$$A_K^{KK} = 0.087 \pm 0.020 \pm 0.008$$

Statistical uncertainty dominant

Description of background is the leading systematic uncertainty

arXiv:1603.08993

B→D(ππ)h

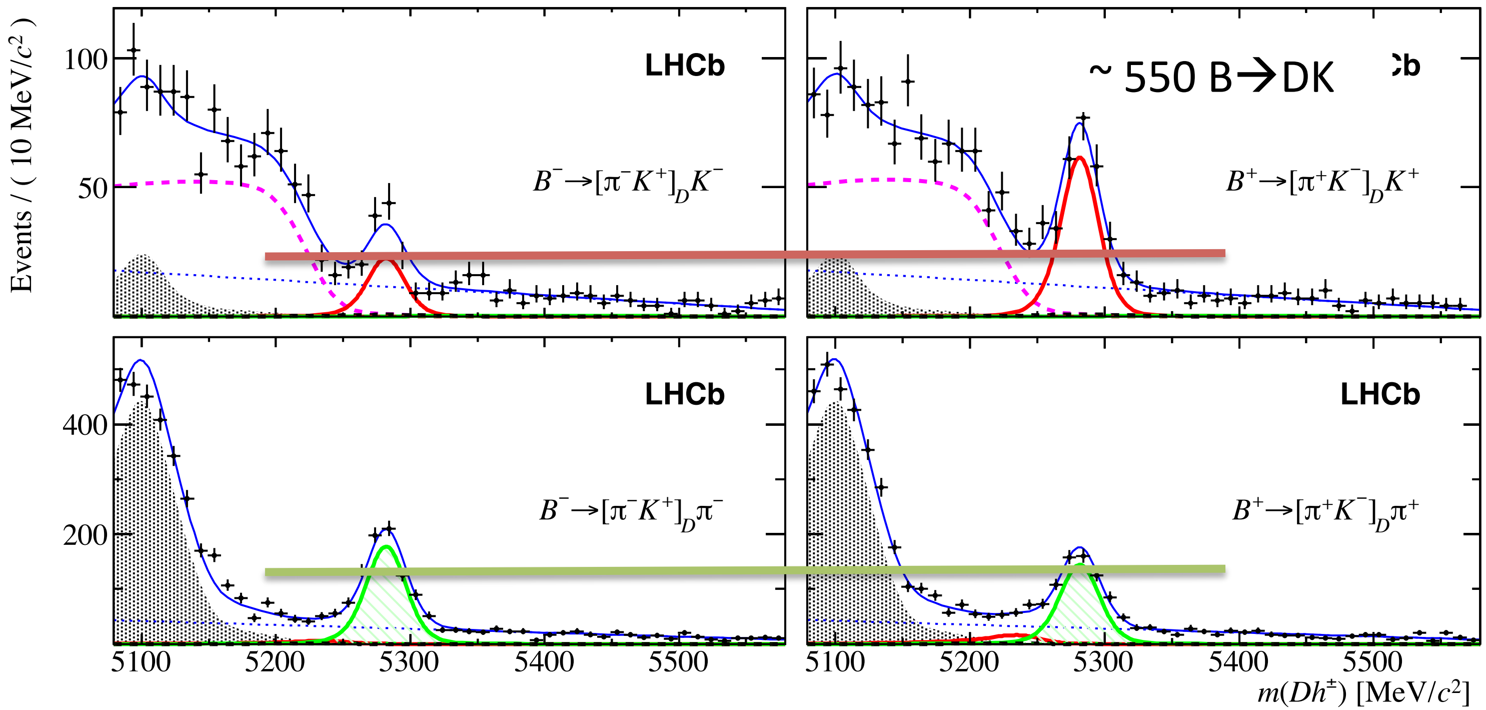


$$A_K^{\pi\pi} = 0.128 \pm 0.037 \pm 0.012$$

Asymmetry same direction as KK
Combined observation of CP violation

5σ

B→D[πK]h



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

Observation of CP violation in B→DK **8σ**

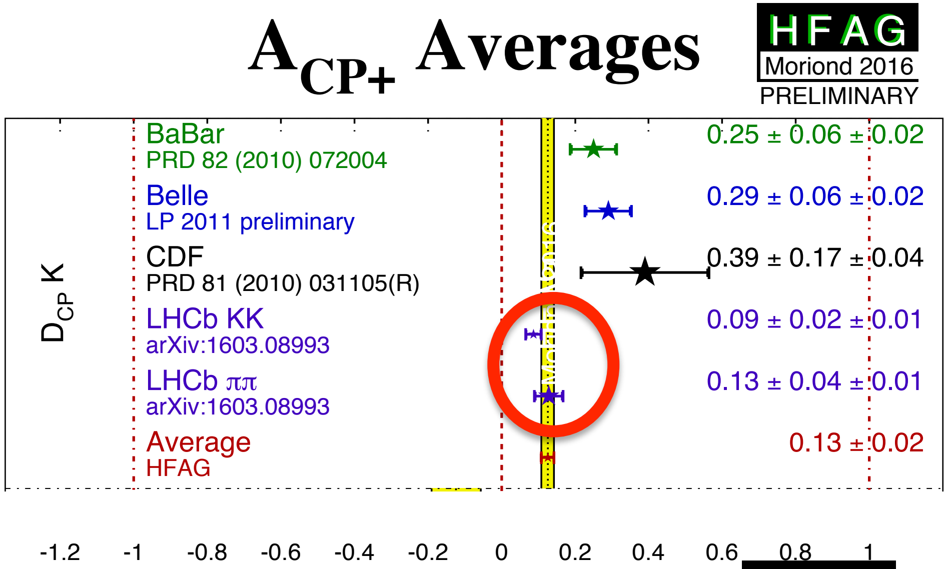
8σ

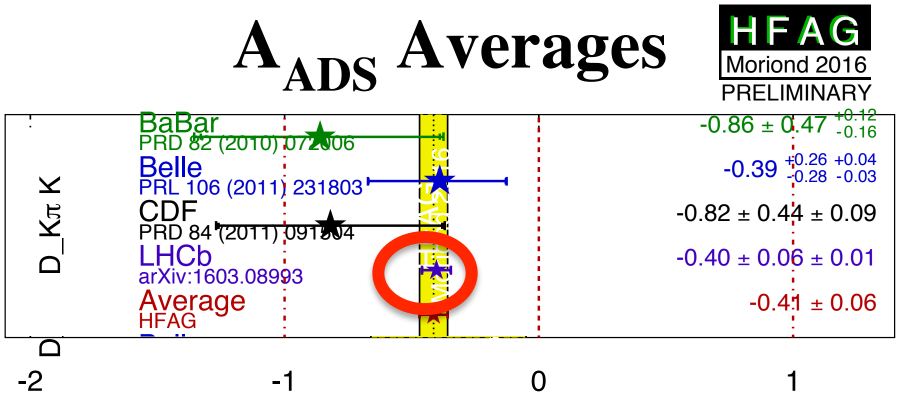
$$A_\pi^{\pi K} = 0.100 \pm 0.031 \pm 0.009$$

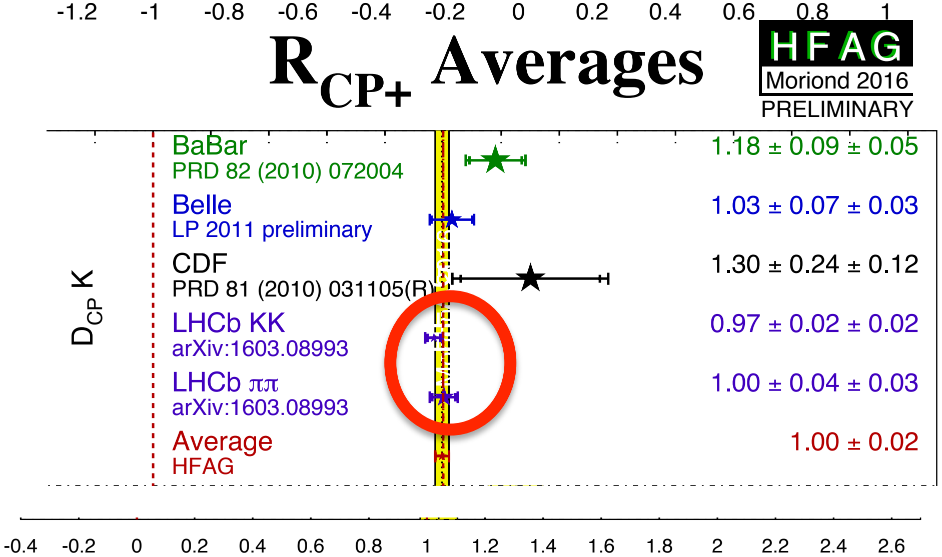
CPV starts to become visible in B→Dπ
Combined with D→KK D→ππ significance ~3.9σ

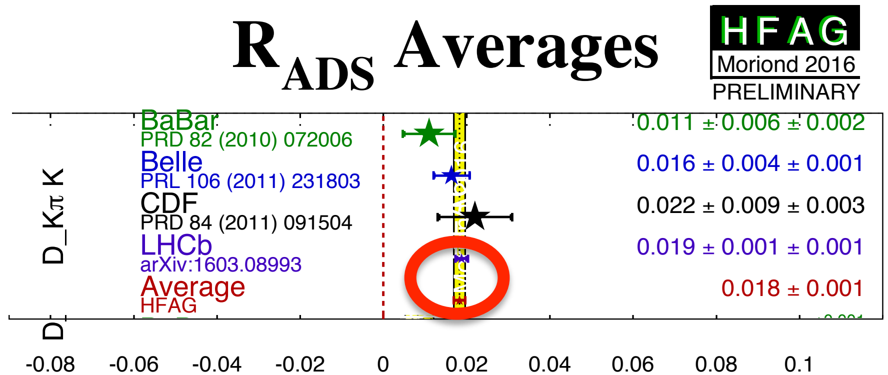
3.9σ

Comparison of results



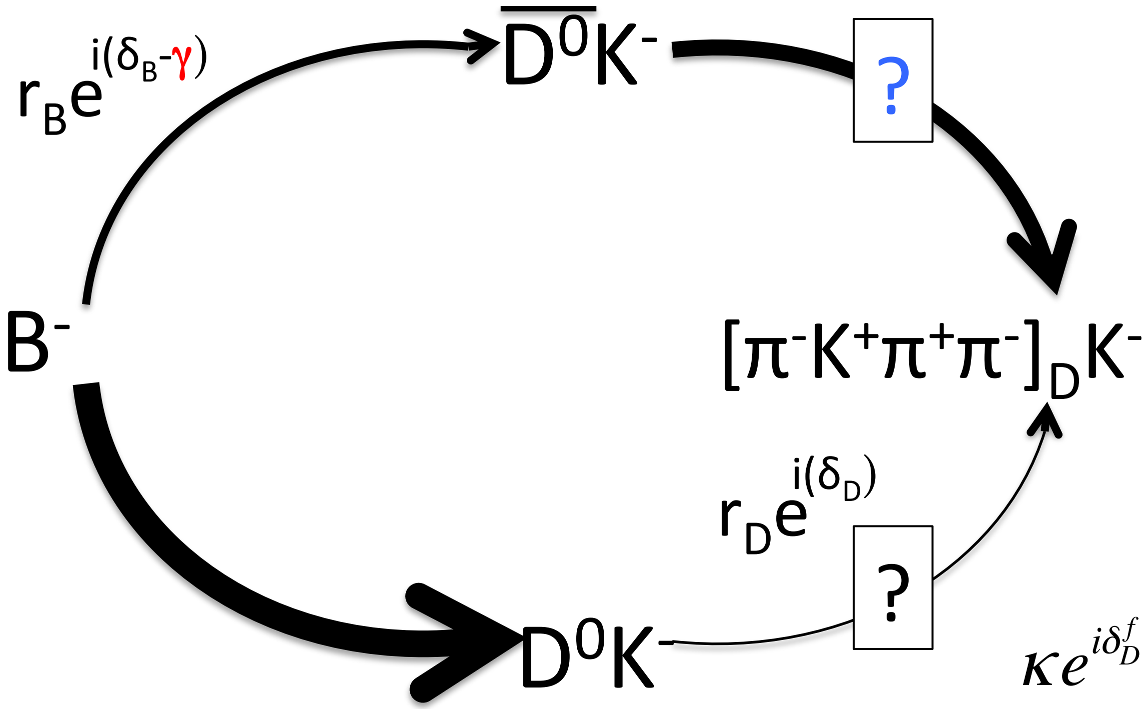






LHCb results dominate world averages

Multi-body flavour specific D decays



Plenty of multi-body D decays also accessible to both flavours

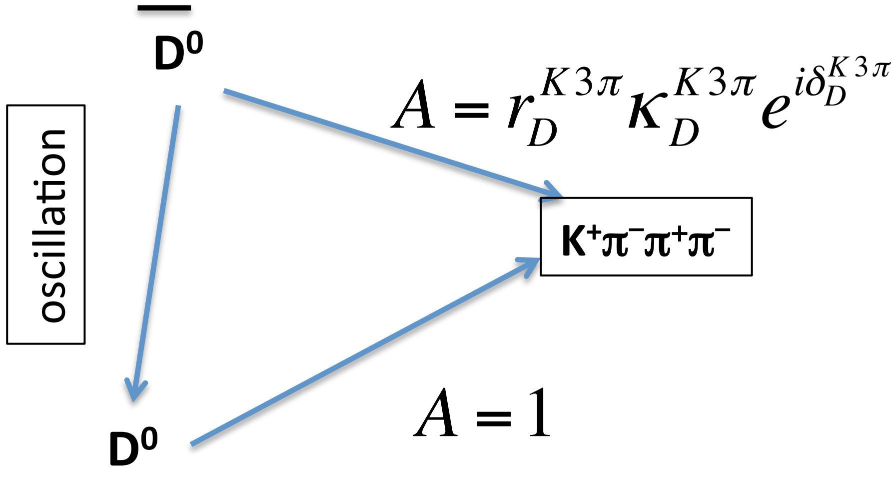
Treated inclusively to avoid consideration of intermediate states. Particularly useful for 4-body decay modes

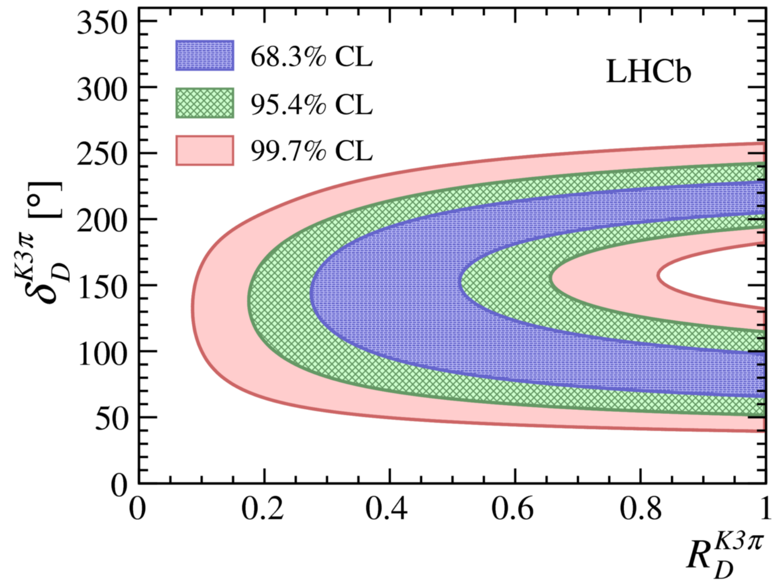
$$\kappa e^{i\delta_D^f} = \frac{\int A_f(x) A_{\bar{f}}(x)\,dx}{\sqrt{\int A_f^2(x)\,dx \int A_{\bar{f}}^2(x)\,dx}}$$

$$A_{ADS} = \frac{1}{R_{ADS}} 2 r_B r_D^{K3\pi} \kappa \sin(\delta_B + \delta_D^{K3\pi}) \sin(\gamma)$$

$$R_{ADS} = r_B^2 + r_D^2 + 2 r_B r_D^{K3\pi} \kappa \cos(\delta_B + \delta_D^{K3\pi}) \cos(\gamma)$$

Measurements of coherence factor





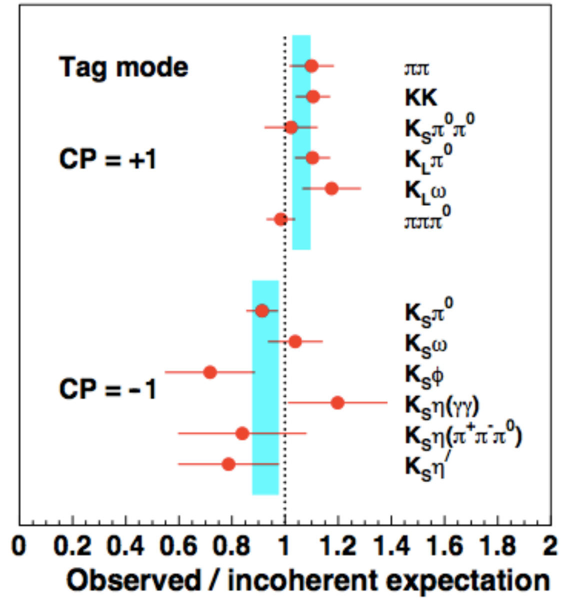
Interference between mixing and decay

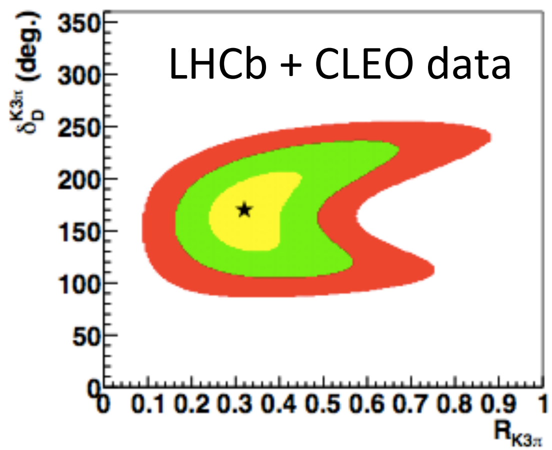
Strong phase and coherence factor determined from time-dependent decay rates.

$$R(t) \approx (r_D^{K3\pi})^2 - r_D^{K3\pi} \kappa_D^{K3\pi} \cdot (y \cos \delta_D^{K3\pi} - x \sin \delta_D^{K3\pi}) \frac{t}{\tau} + \frac{x^2 + y^2}{4} \left(\frac{t}{\tau} \right)$$

Measurements with CLEO data

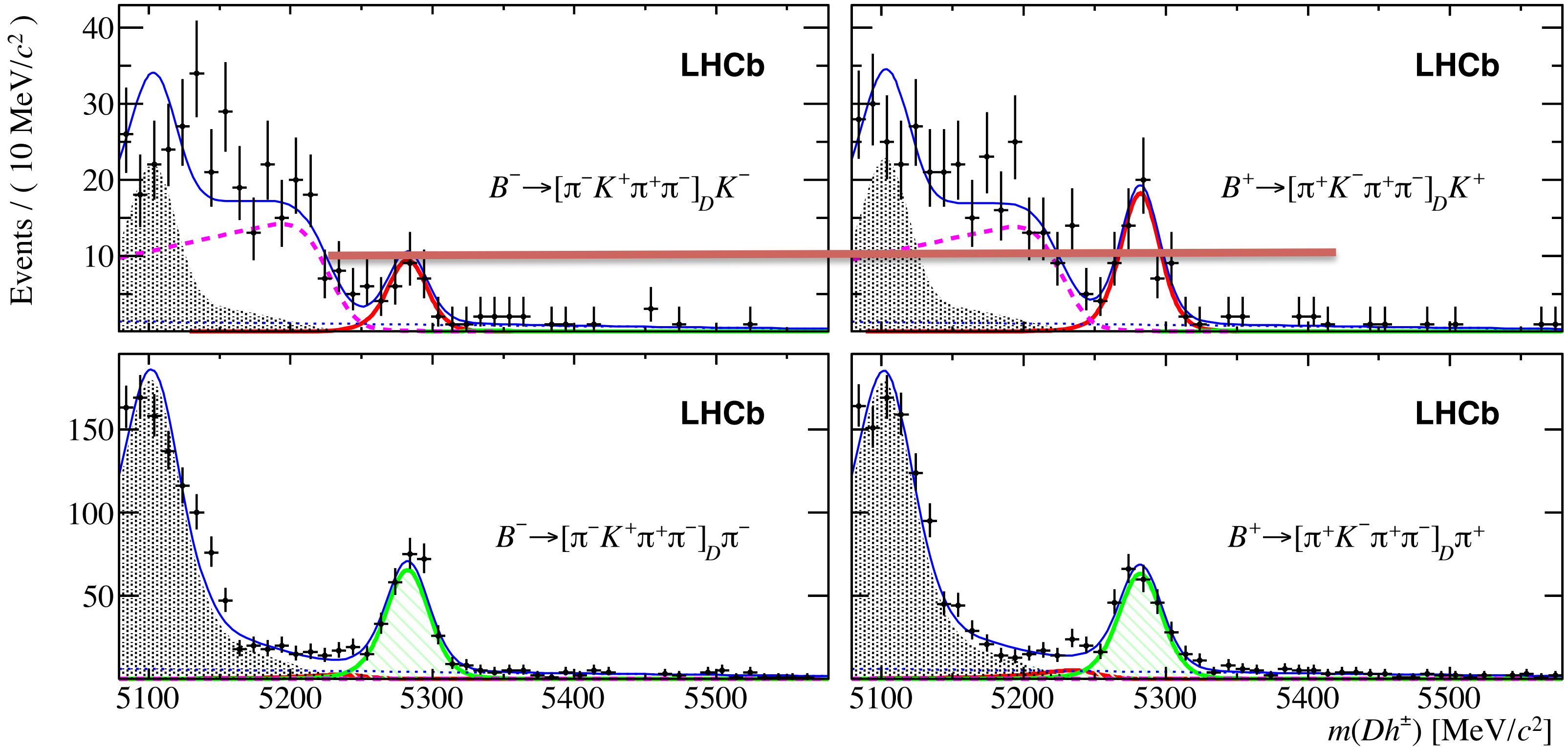
- Study ψ(3770) → $D^0\overline{D}^0$ decays
- Key: C= -1 for ψ(3770) at threshold
- Strong decay, C is conserved
- Hence the decays of D^0 and $\overline{D}^0$ are quantum correlated
- This provides the interference to access the phase information
- Study rates where one D meson decays to K3π and the other to either a flavour specific state or CP eigenstate.
- Rates are dependent on the kappa and strong phase
- Measurement at CLEO sensitive to different phase-space to LHCb mixing method
- Strong phase measurements in other decay modes follow same principles





PLB 757 (2016) 520

Results D→K3π

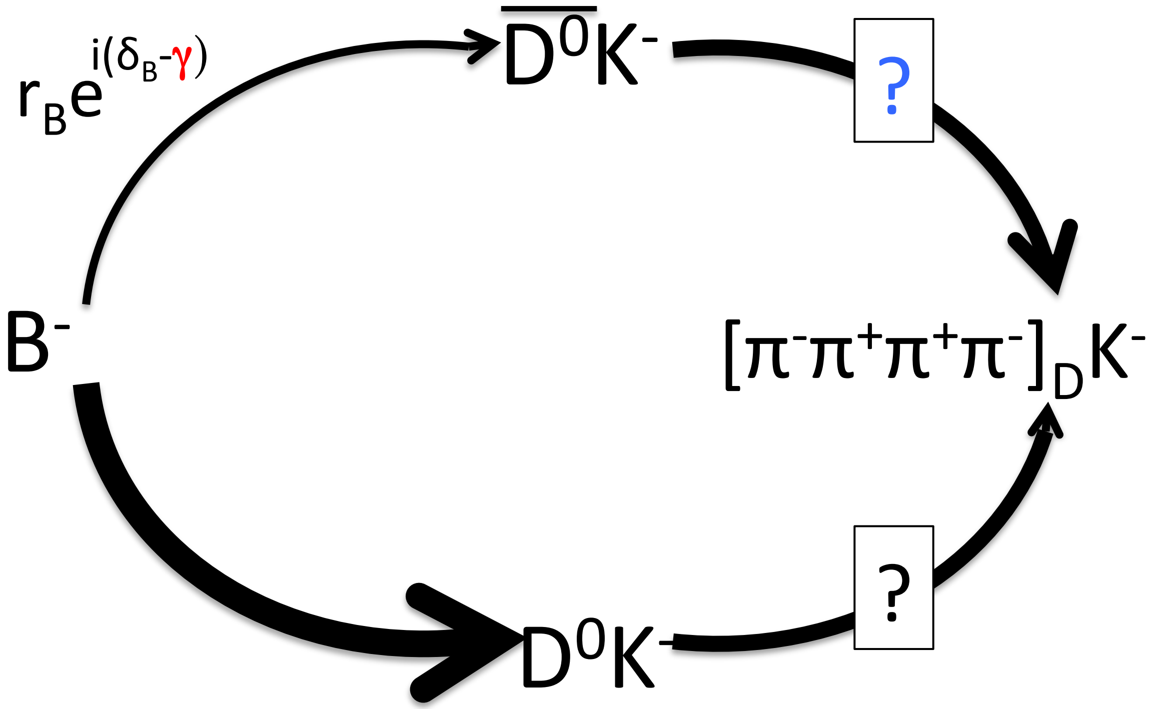


$$A_K^{\pi K \pi\pi} = -0.313 \pm 0.102 \pm 0.038$$

$\kappa = 0.32^{+0.12}_{-0.08}$

Sensitivity despite relatively low coherence

Multi-body self conjugate D decays "quasi-GLW"



If the CP even fraction is known then self-conjugate modes can also be used in a similar way to CP eigenstates.

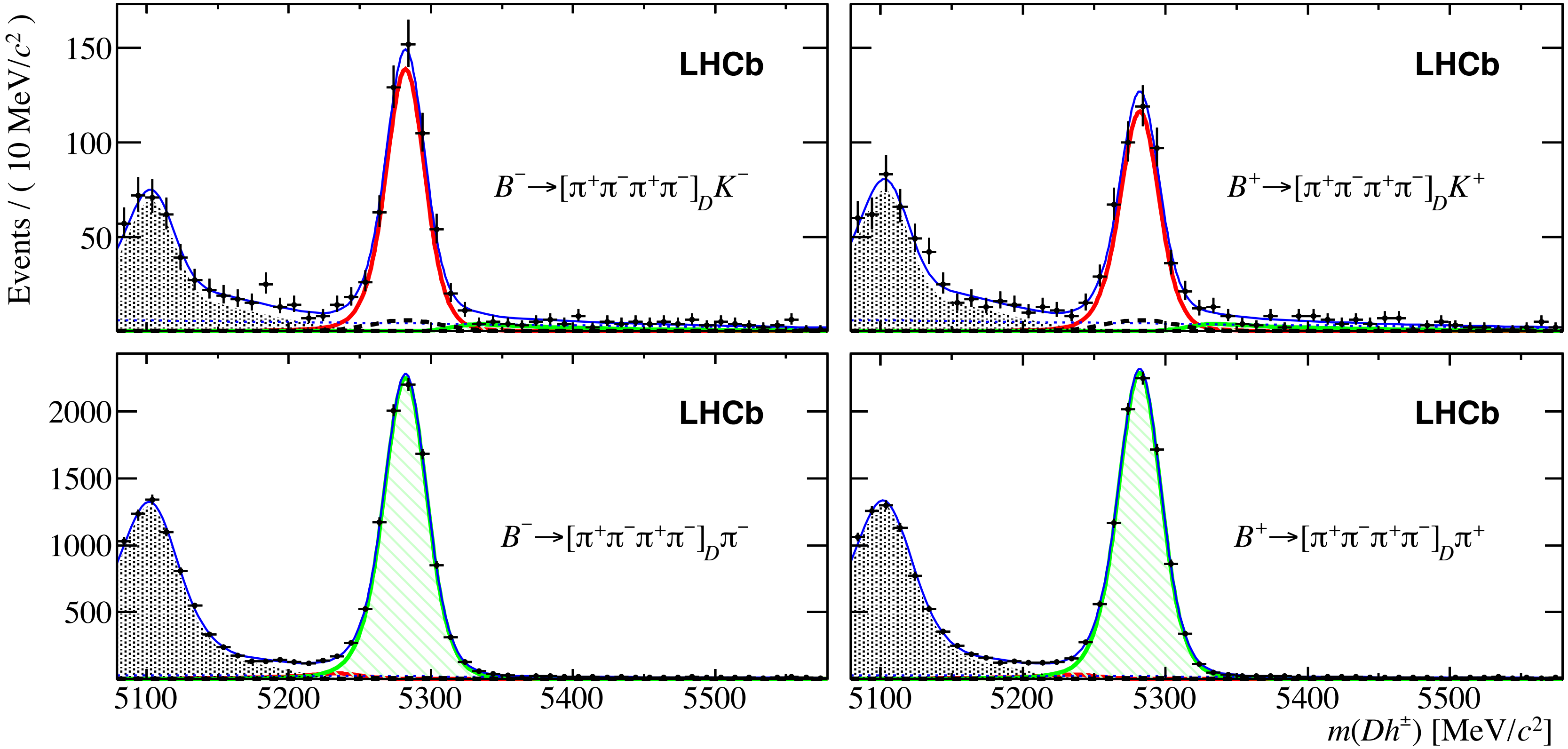
Measured at CLEO from quantum correlated data

$F_+^{4\pi} = 0.737 \pm 0.028$

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

$$R_{q-CP} = 1 + r_B^2 + 2r_B(2F_+ - 1)\cos(\delta_B)\cos(\gamma)$$

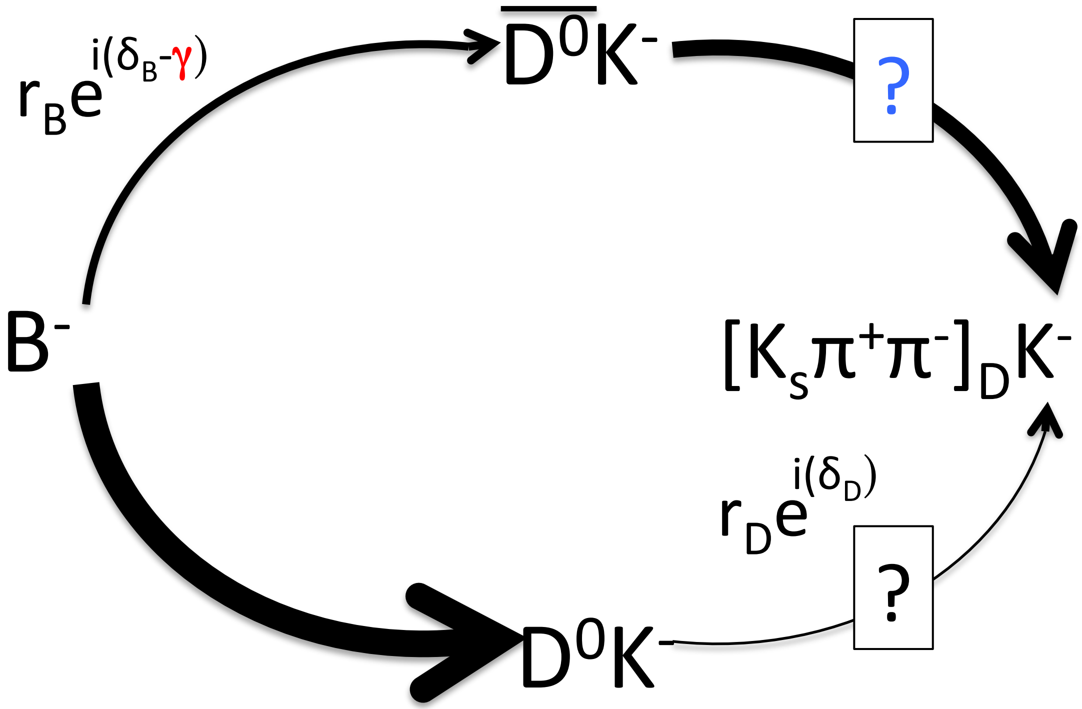
Results D→4π



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

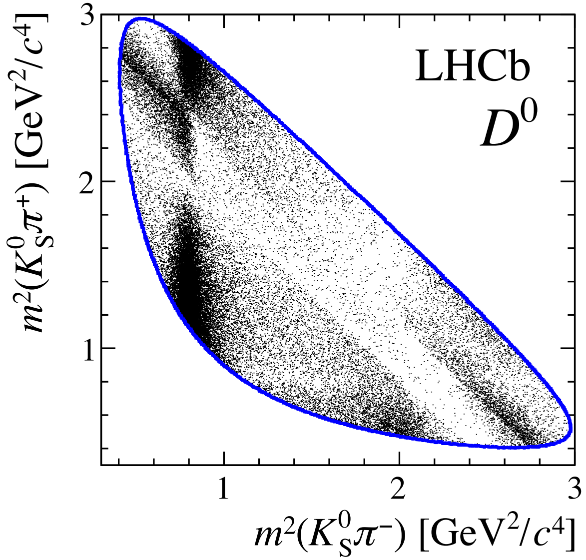
First use of this mode -possible due to measurements from CLEO

Self-conjugate D decays using Dalitz plot "GGSZ"



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

Hence inclusive treatment looses most of the sensitivity to γ



Dalitz Plot encodes all the kinematic information of the decay

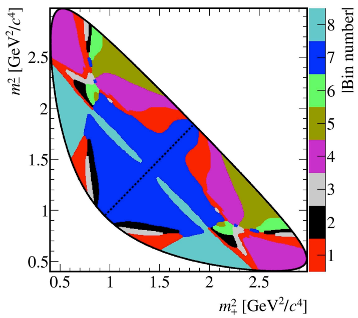
Each point on the Dalitz plot represents a different value of r_D and δ_D

PRD 68 (2003) 054018

Two methods for accessing the D decay information

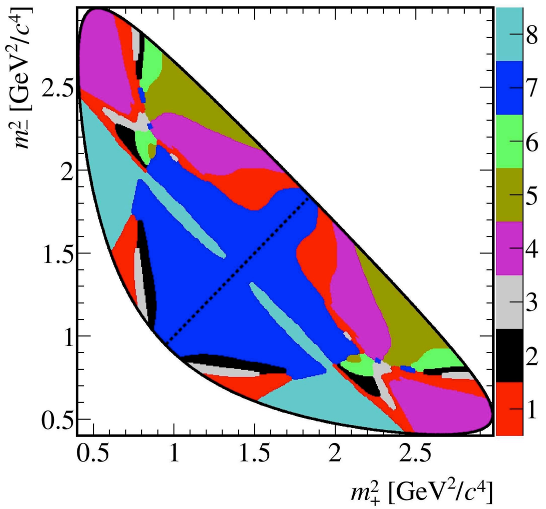
- D dalitz plot from B decay will be a superposition of D^0 and $\bar{D}^0$
- It will differ between B^+ and B^-
- Differences are related to r_B δ_B and γ

Two ways to deal with the varying r_D, δ_D

Model dependent	**Model independent**
r_D and δ_D determined from an amplitude model determined from flavour tagged decays	 Use CLEO data to measure average values of r_D and δ_D in bins
No interference, no direct access to phase information	Loss in statistical precision
Systematic uncertainties due to model hard to quantify	Direct phase information, uncertainties on which are easily propagated

PRD 82 (2010) 112006

Model-independent GGSZ analysis



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

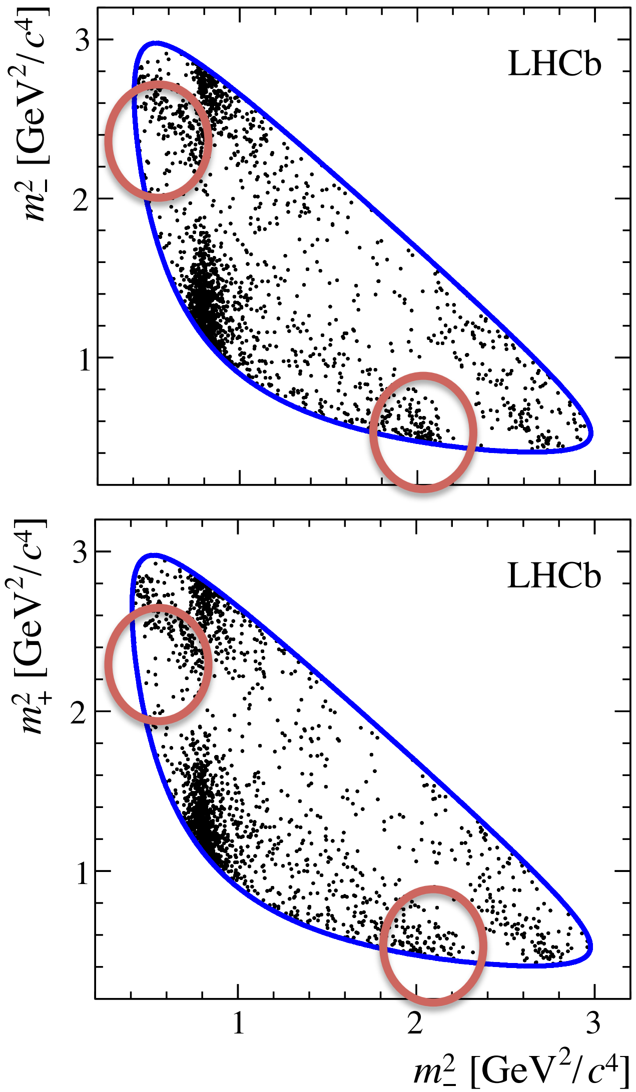
$$N_{\pm i}^{-} = h_{B^-}\left[F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$

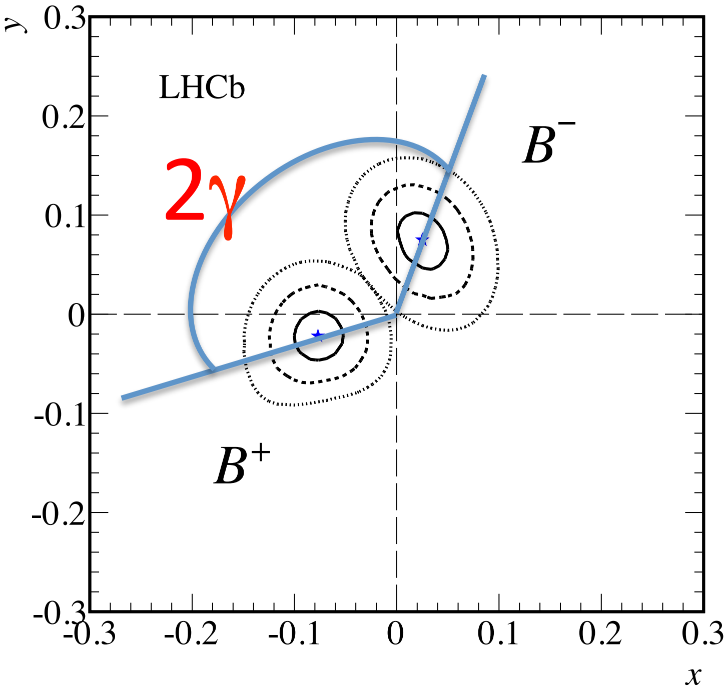
$$x_{\pm} \equiv r_B \cos(\delta_B \pm \gamma)$$

$$F_i = \frac{\int_{\mathcal{D}_i} |A|^2 \varepsilon \, d\mathcal{D}}{\sum_j \int_{\mathcal{D}_j} |A|^2 \varepsilon \, d\mathcal{D}} \qquad y_{\pm} \equiv r_B \sin(\delta_B \pm \gamma)$$

- Bin definition designed to minimise statistical loss ~ 90% of sensitivity remains
- Reduces to a counting experiment in bins of Dalitz Plot
- F_i determined from $B^0 \rightarrow D^* \mu\nu$ decays (flavour tagged)
- c_i and s_i external inputs from CLEO
- Arbitrary normalisation h_b means that insensitive to production asymmetries

B→D[Kshh]K (GGSZ)

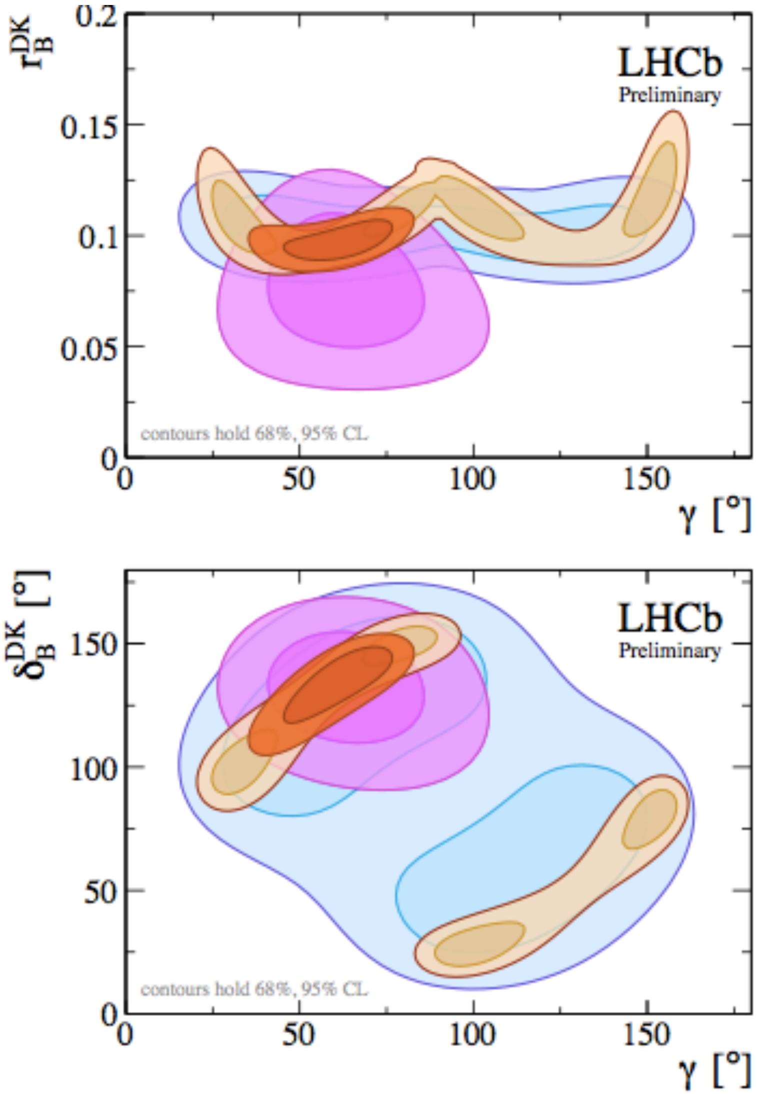


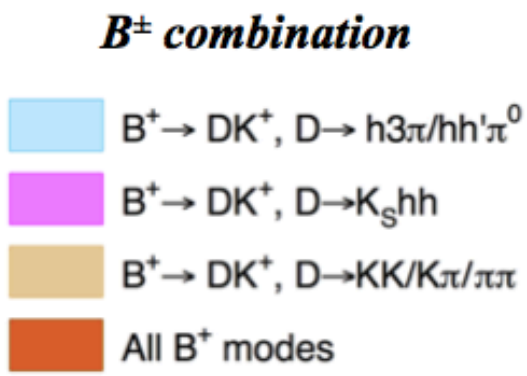


$K_s\pi\pi$ and K_sKK decay modes (not shown) used

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

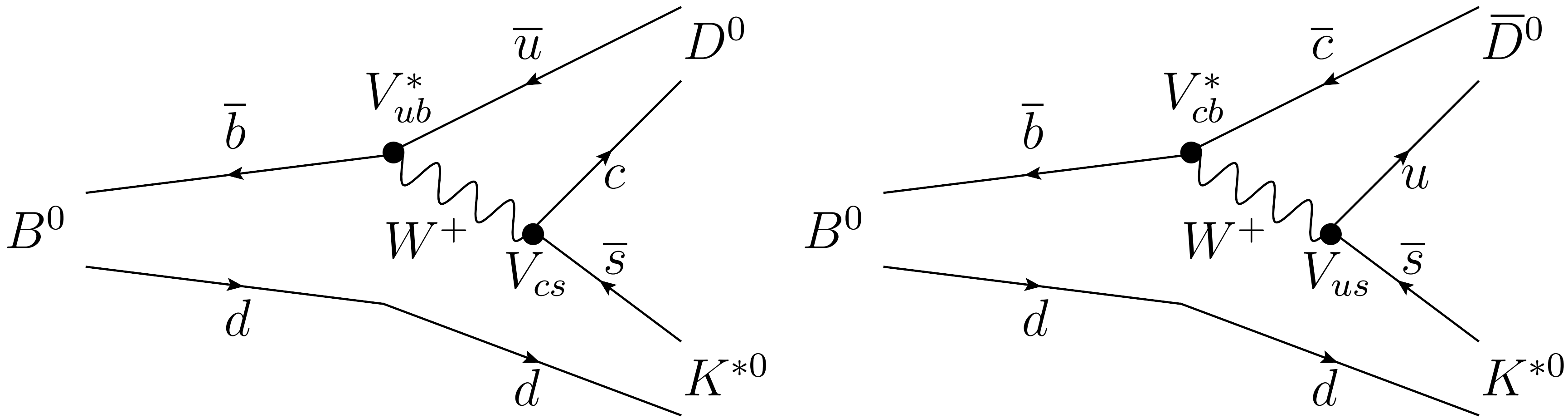
Interplay between different modes





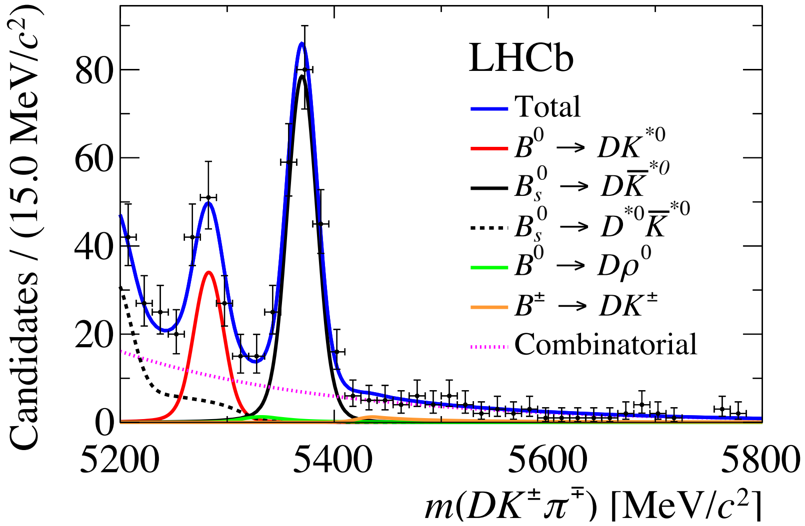
- ADS/GLW/q-GLW observables have non trivial trigonometic relations.
- Single solution selected by the GGSZ modes
- No single mode dominates→ necessary to follow all paths

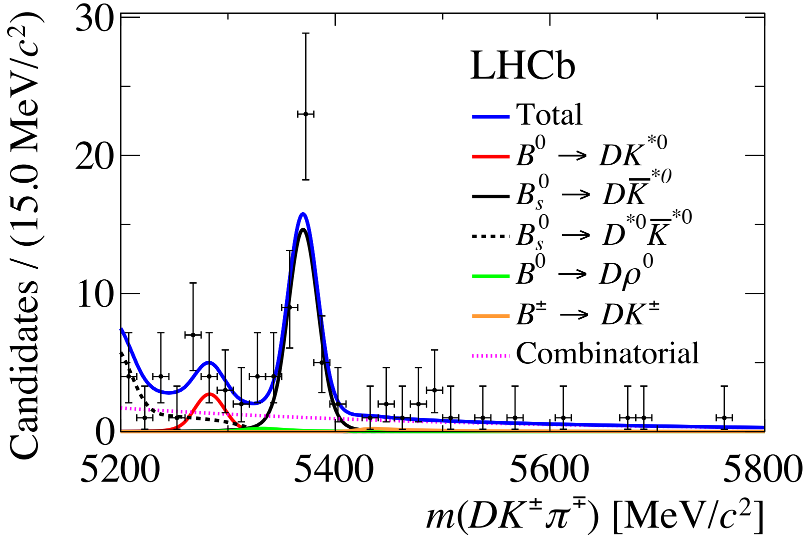
Other B modes



- Favoured and suppressed decay both color suppressed
- r_B ~ 0.3 → Larger interference
- $K^* \rightarrow K^+\pi^-$, charge of kaon tags flavour of B at decay – no need for time dependent analysis
- Yields at LHCb becoming viable for analysis
- ADS/GLW analysis already performed on full Run 1 dataset

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

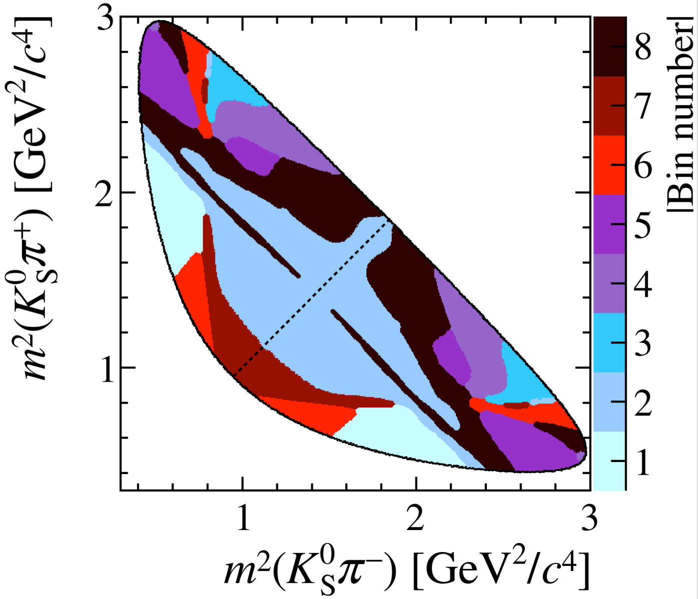


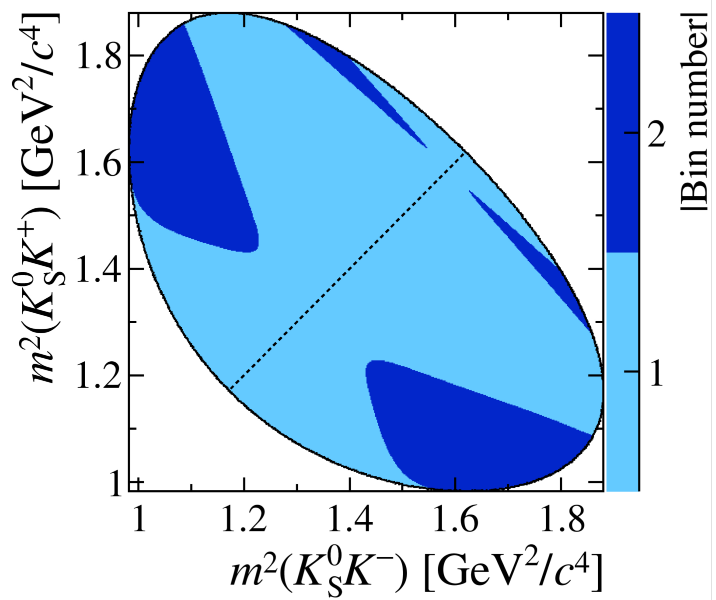


- Yields ~ 90 in $K_s\pi\pi$ and 10 in ~K_sKK
  - Twice yield of B factories
- Irreducible Bs backgrounds
- Width of K*(892) means non-resonant $K\pi$ decays can contribute to signal peak
- Coherence factor dependent on selection
- M(K*) <50 MeV/c^2;
- |cos(K helicity angle)|>0.4

arXiv: 1604.01525

GGSZ analysis

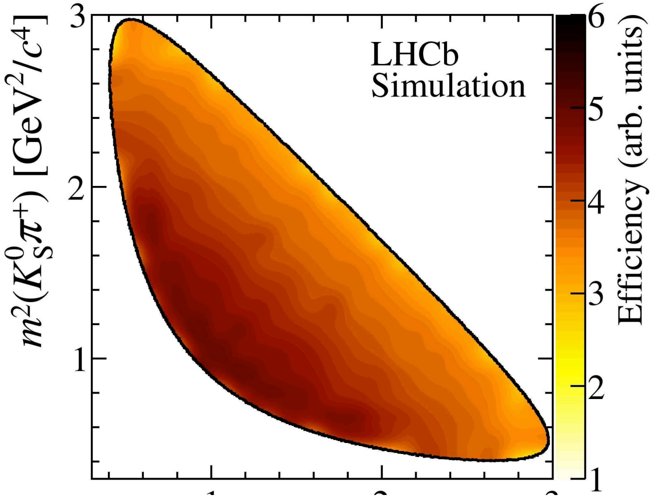




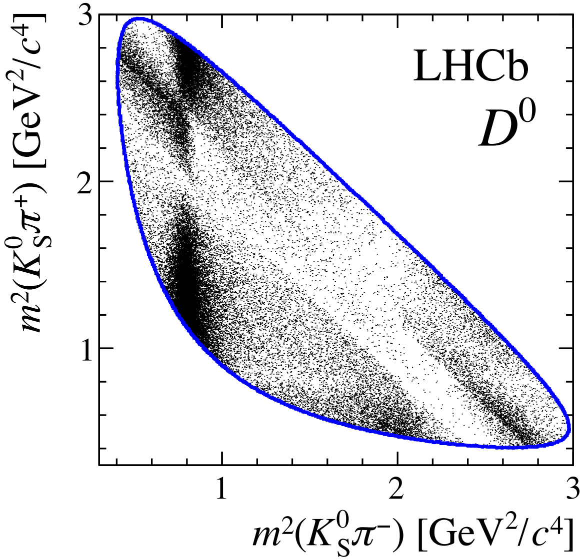
- Modified binning used for $K_s\pi\pi$ – better for low yield channels
- K_sKK split into 2 bins – low yields expected

arXiv: 1604.01525

Dalitz Plot efficiency



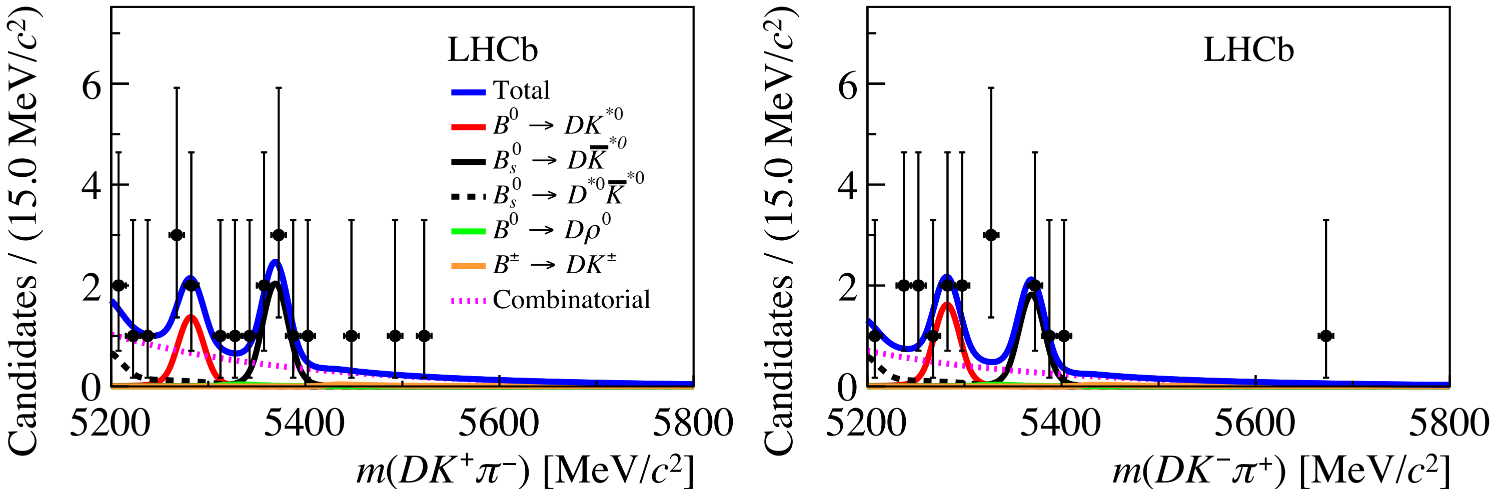
$$N^+_{\pm i} = n_+ \left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\kappa\sqrt{F_{+i}F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$
$$N^-_{\pm i} = n_- \left[F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\kappa\sqrt{F_{+i}F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})\right]$$



- Variation of efficiency on DP must be taken into account
- $B^0 \rightarrow D^*[D^0\pi]\,\mu\nu X$ used to determine Fi
- Small corrections required to take care of selection differences between control and signal decay
- Determined from simulation

arXiv: 1604.01525

Determining observables

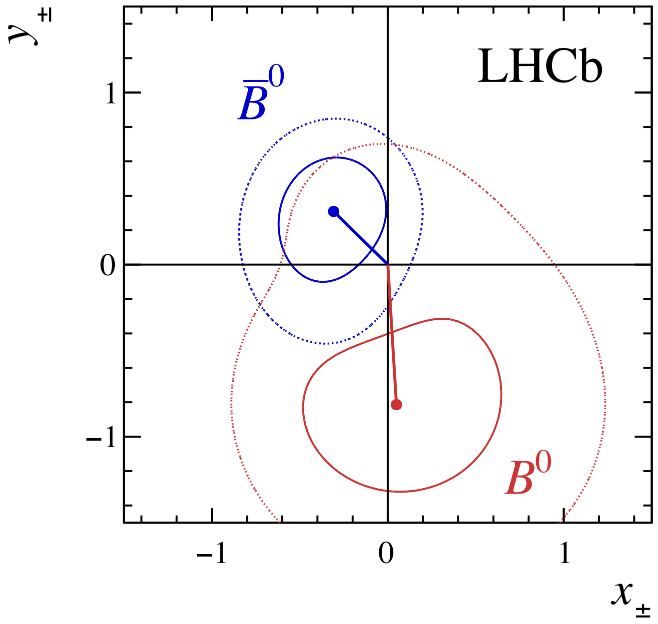


- Simultaneous fit to all bins to determine x, y
- Signal/background shapes fixed from first fit.
- Very few signal events per bin

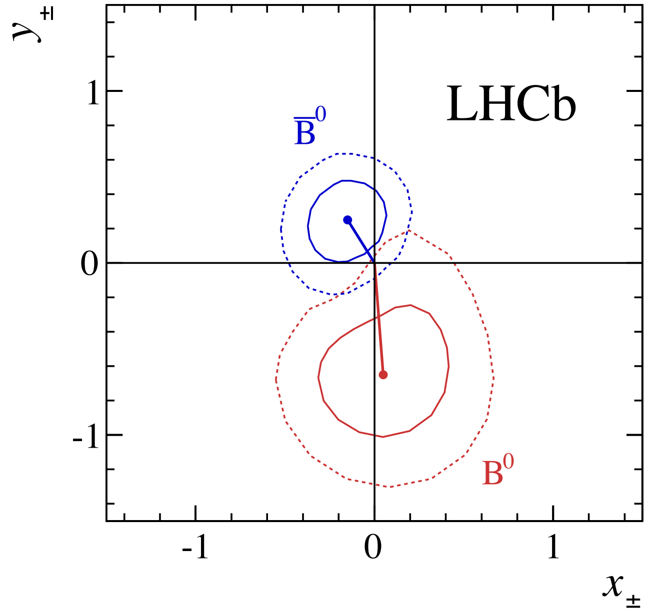
- Model dependent fit also perfomed
  - r_D and δ_D given by BaBar 2010 amplitude model

Results

Model - independent



Model - dependent



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

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

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

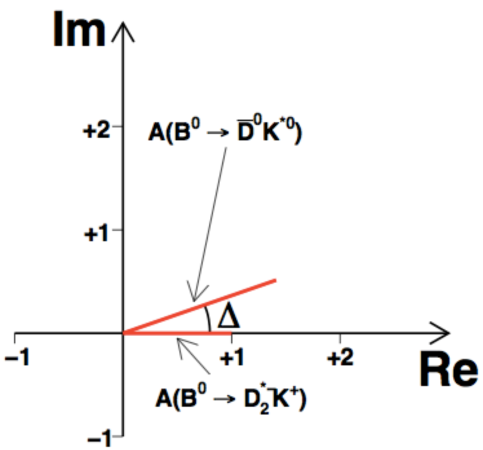
arXiv: 1604.01525

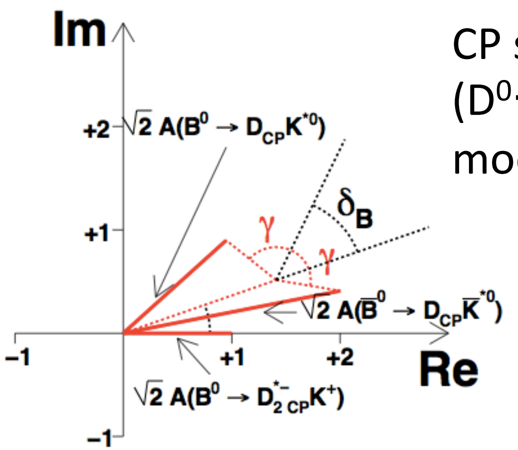
arXiv: 1605.01082

$B^0 \rightarrow DK\pi$ 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:

$B^0 \rightarrow DK\pi$ 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:

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

GLW:

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

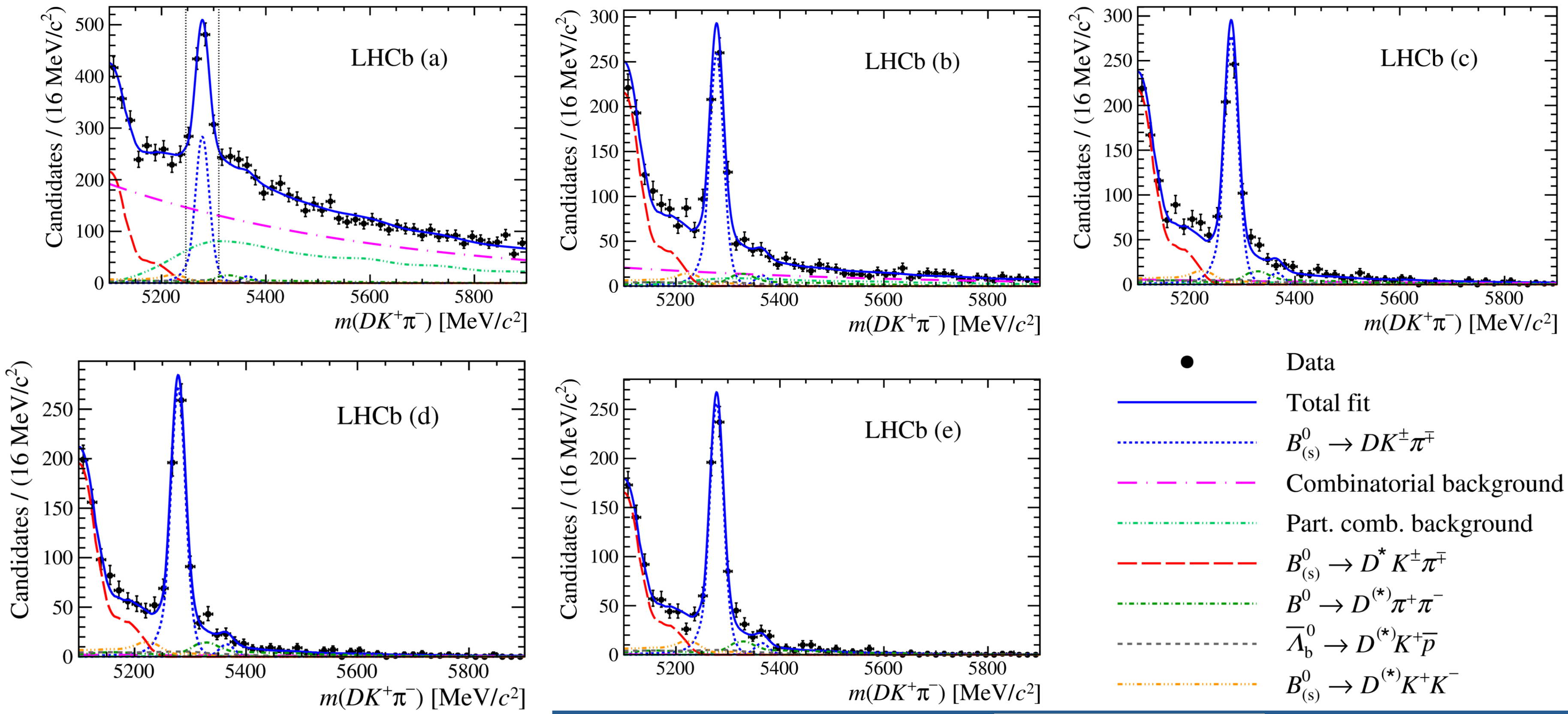
This analysis

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

arXiv: 1602.03455

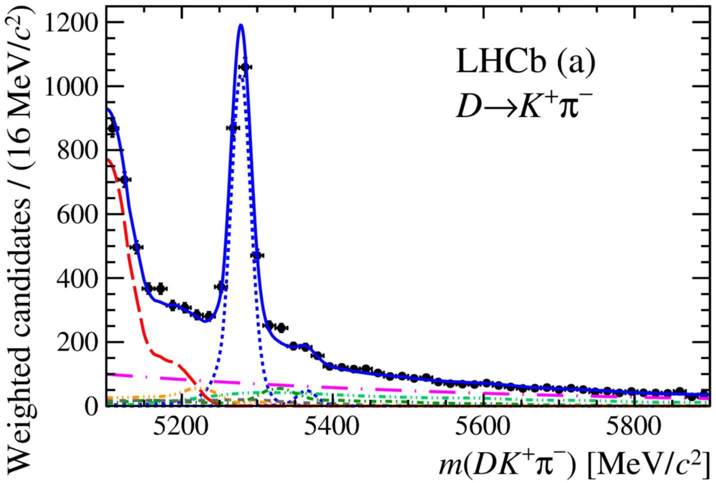
Larger phasespace →higher combinatorics

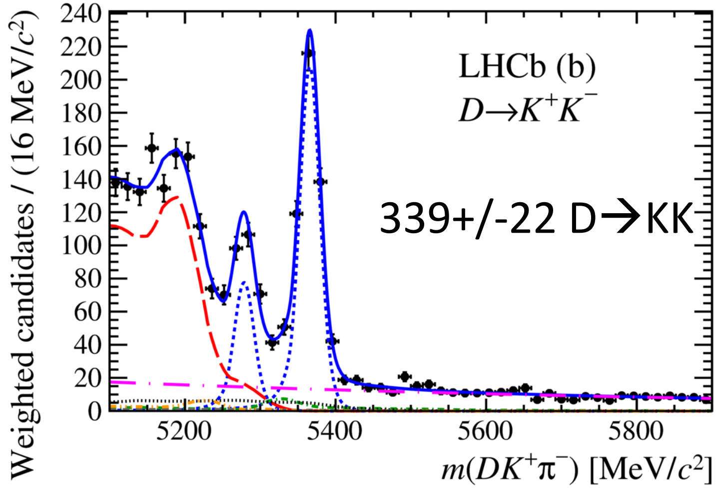
- Larger phasespace of the Kπ system leads to high combinatorics and larger amounts of physics bkgs.
- To avoid the need to cut hard data is divided into bin of NN output.
- Maximises the statistical sensitivity of the data



arXiv: 1602.03455

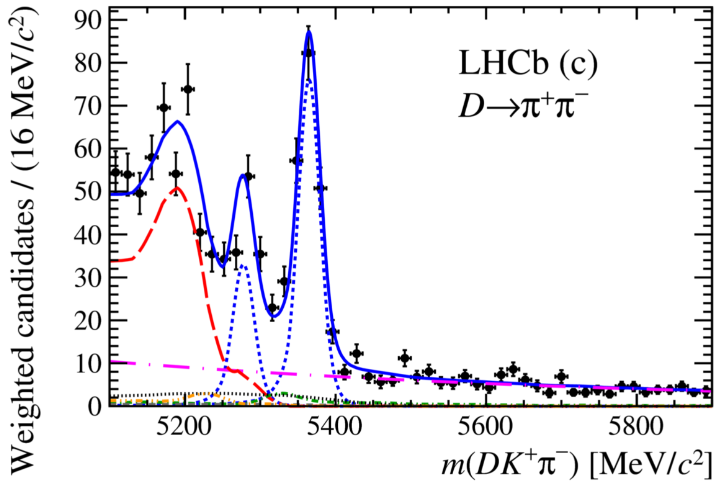
Signal yields



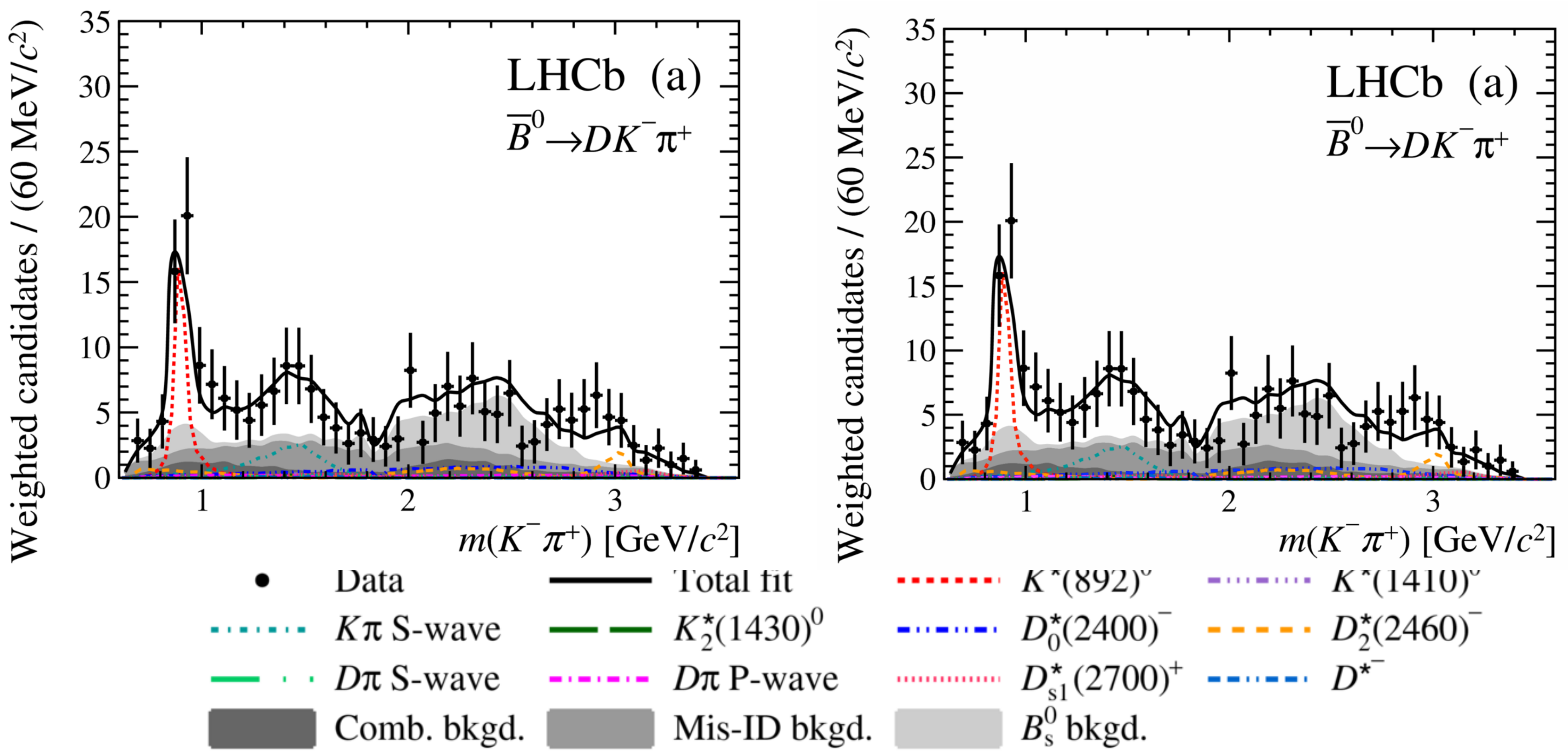


Data shown with NN bins combined weighted according to S/(S+B)

339+/-22 D→KK
168+/-19 D→ππ



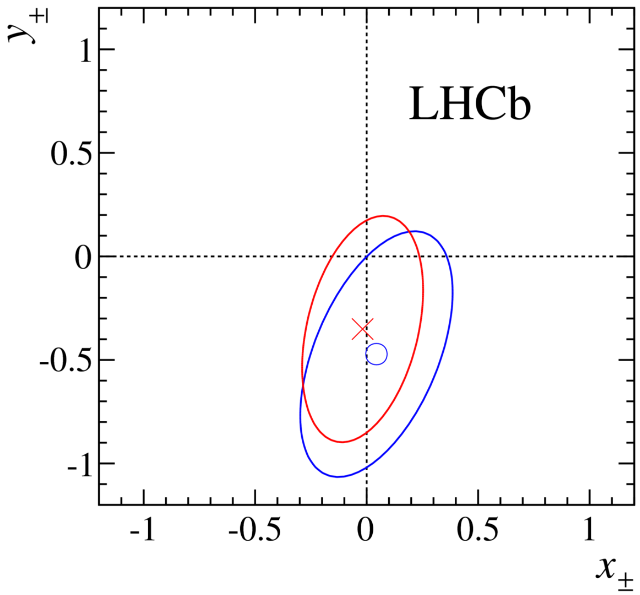
Dalitz Plot fit



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

Only results from K*(892) used

Fit Results



$$x_+ = 0.04 \pm 0.16 \pm 0.11$$

$$x_- = -0.02 \pm 0.13 \pm 0.14$$

$$y_+ = -0.47 \pm 0.28 \pm 0.22$$

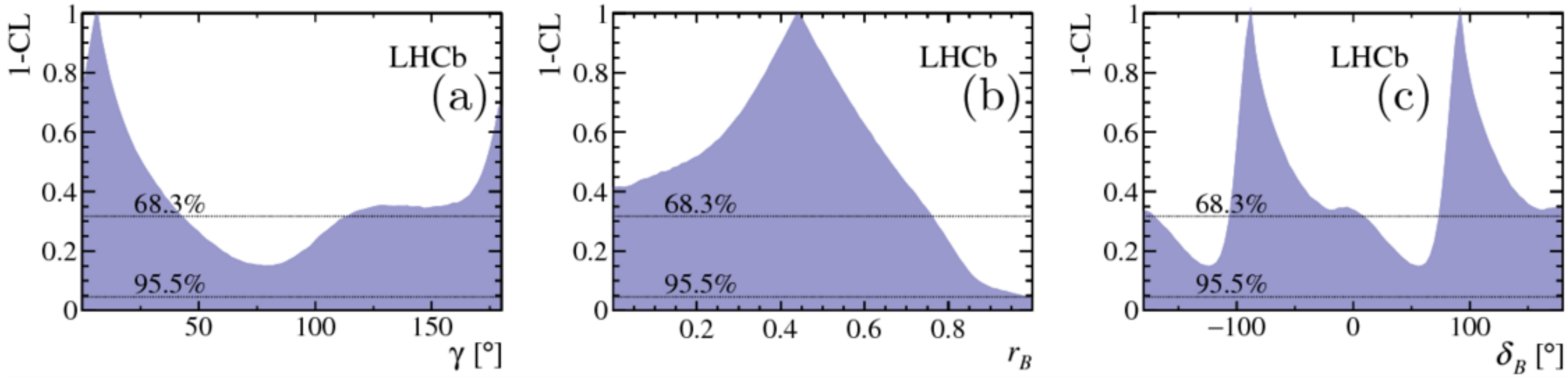
$$x_- = -0.35 \pm 0.26 \pm 0.41$$

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

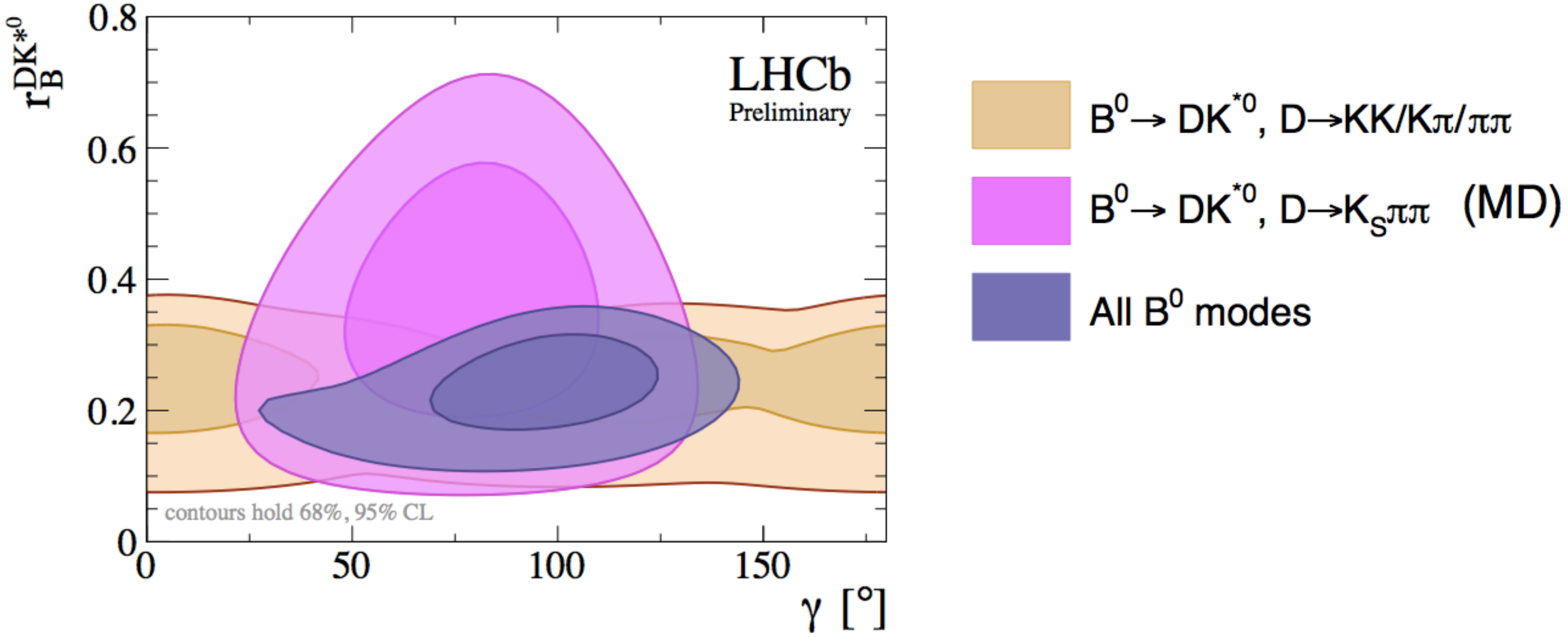
Results for pure K*

Determine factors to relate r_B and d_B from this analysis to those measured in $B^0 \rightarrow DK^*$

Also determine the coherence factor



B^0 combination



- Due to low statistics the $B^0 \to DK\pi$ unable to select a single solution
- In combination with the GGSZ and previous ADS analysis start to constrain the parameters of interest

Combining results -LHCb inputs

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

[Blue] Results discussed today, new or updated since last combination (2014)

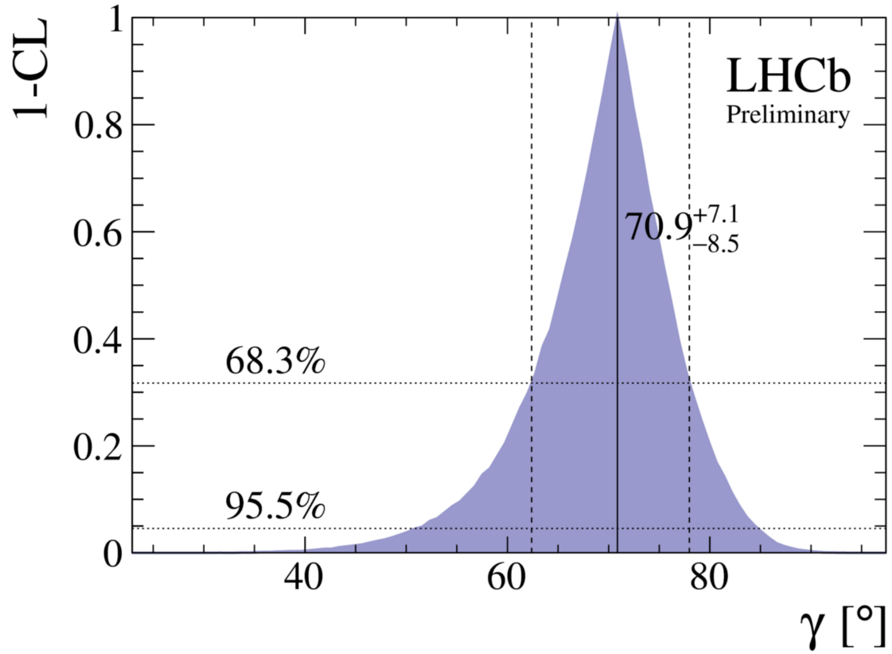
[Red] New results from 2015

[Yellow] Other $B \to DK$ 'like' results completed in 2014

Combing results-other inputs

Parameters	Source	Reference
Charm mixing and CPV in D→hh	HFAG	
κ, δ_D: D→K3π, D→K$\pi\pi^0$	LHCb & CLEO data	PLB 757 (2016) 520
κ, δ_D : D→K_sKπ	CLEO	PRD 85 (2012) 092016
CP fraction D→4π, D→hhπ^0	CLEO data	PLB 747 (2015) 9
c_i, s_i for D→$K_s$hh	CLEO	PRD 82 (2010) 112006
Constraint on ϕ_s	LHCb	PRL 114 (2015) 041801

Combination results



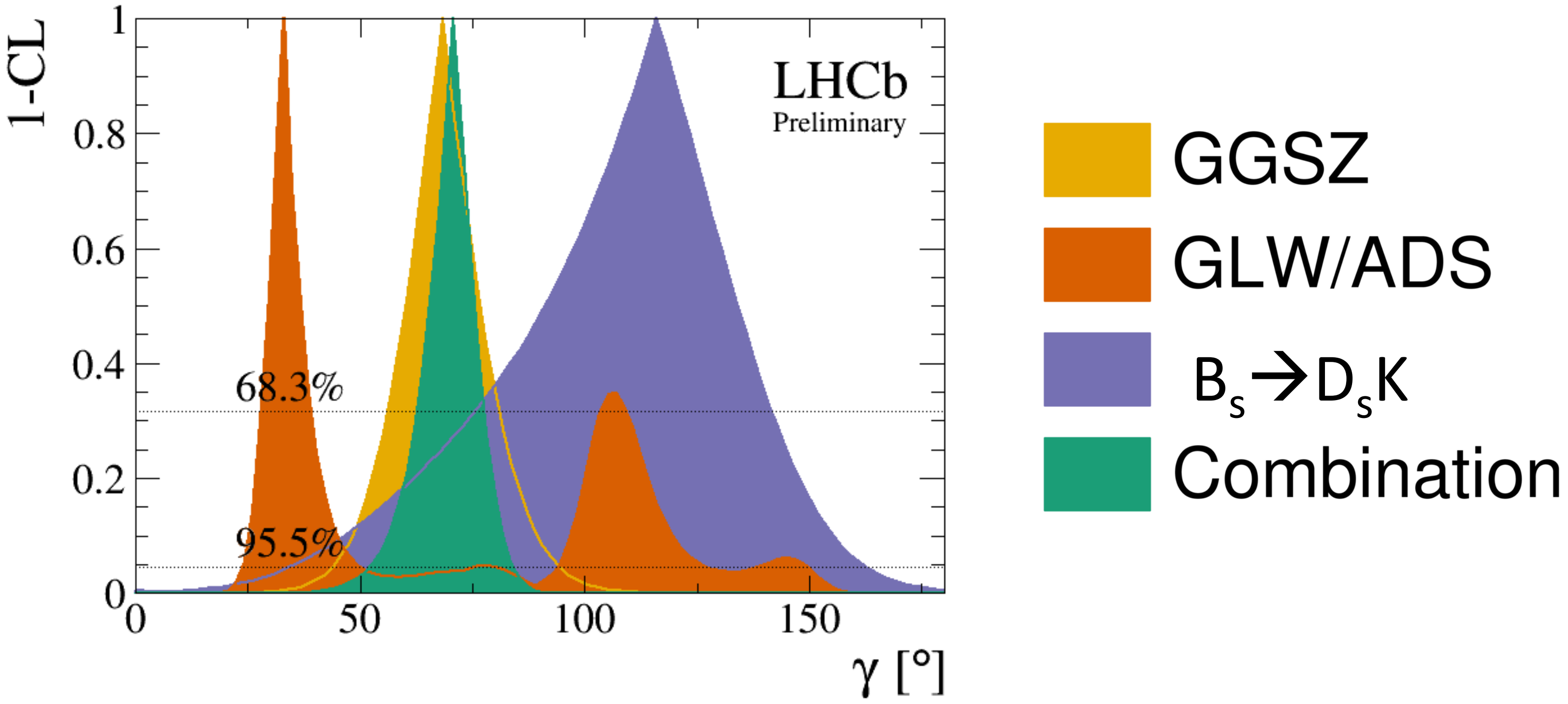
$$\gamma = (70.9^{+7.1}_{-8.5})^{\circ}$$

BaBar : $\gamma = (69^{+17}_{-16})^{\circ}$

Belle: $\gamma = (73^{+15}_{-14})^{\circ}$

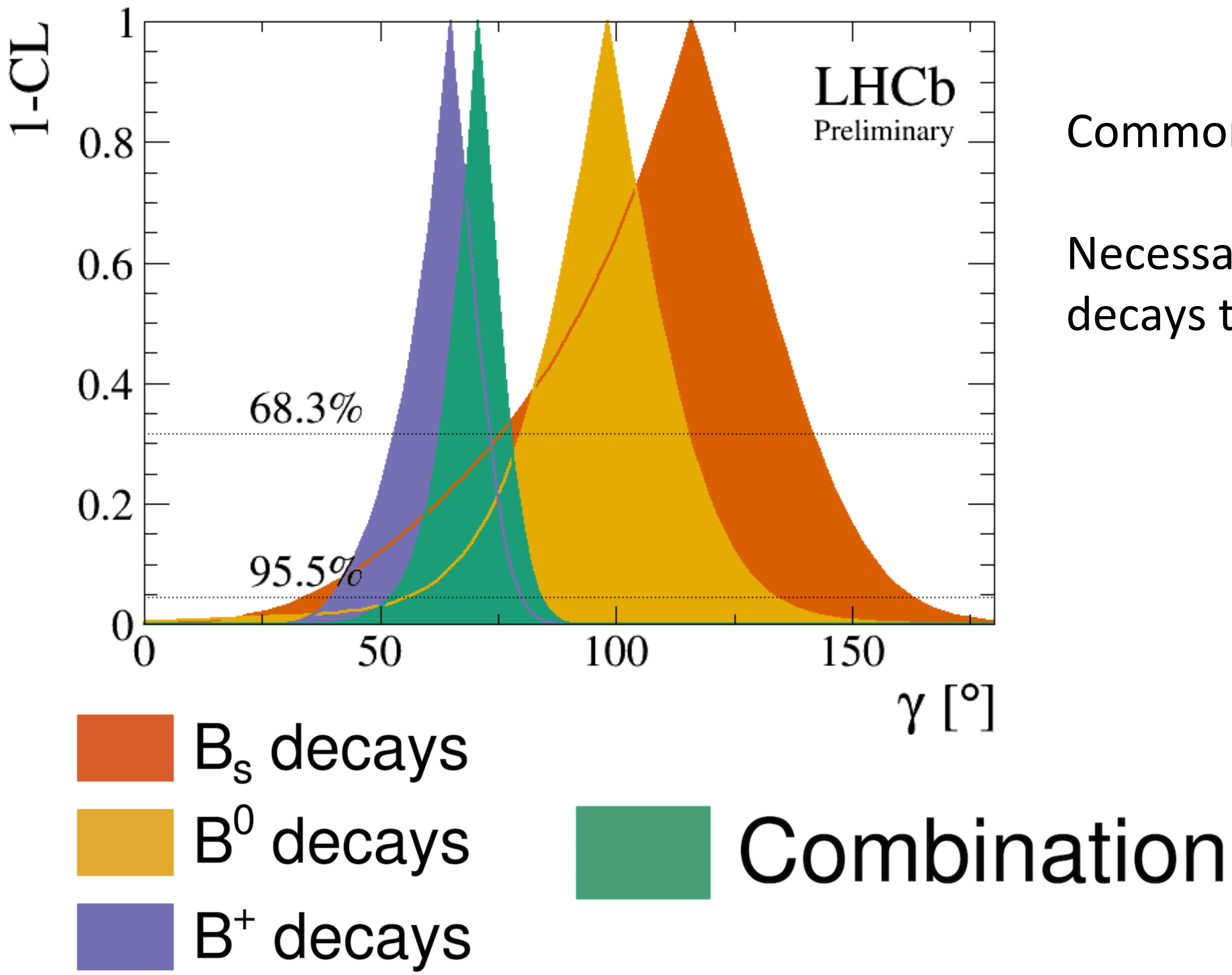
- Frequentist combination using ‘plugin’ method. 71 observables and 32 parameters.
- Only B→DK – like results included
- D-mixing taken into account
- Improved precision compared to last combination by ~20%
- Good agreement with B factory results
- Bayesian interpretation is consistent

Contribution from different methods



Demonstrates the need to pursue all methods

Contribution from different modes



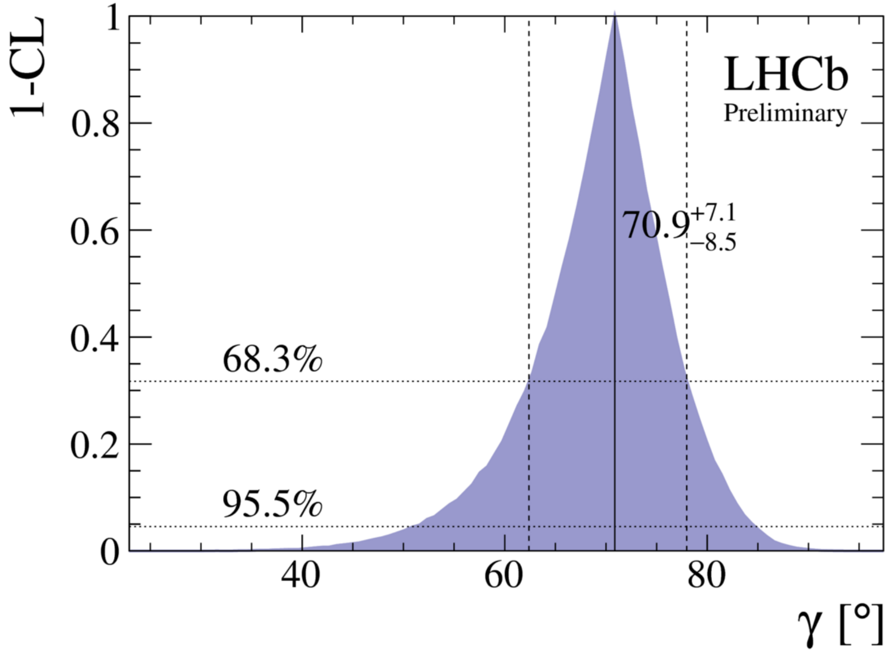
Common parameter is gamma

Necessary to pursue different B decays to provide crosschecks

Outlook and conclusion

- Run 1 target of 8 degree precision attained
- Wider variety of B and D modes now being pursued.
- 2015 data increased yields by ~ 20%
- 2016 data keenly looked forward too

- Current measurements all statistically dominated – no showstoppers forseen



On target to reach degree level precision

If nature is kind, this precision will allow for observation of New Physics