# Constraining the CKM angle $\gamma$

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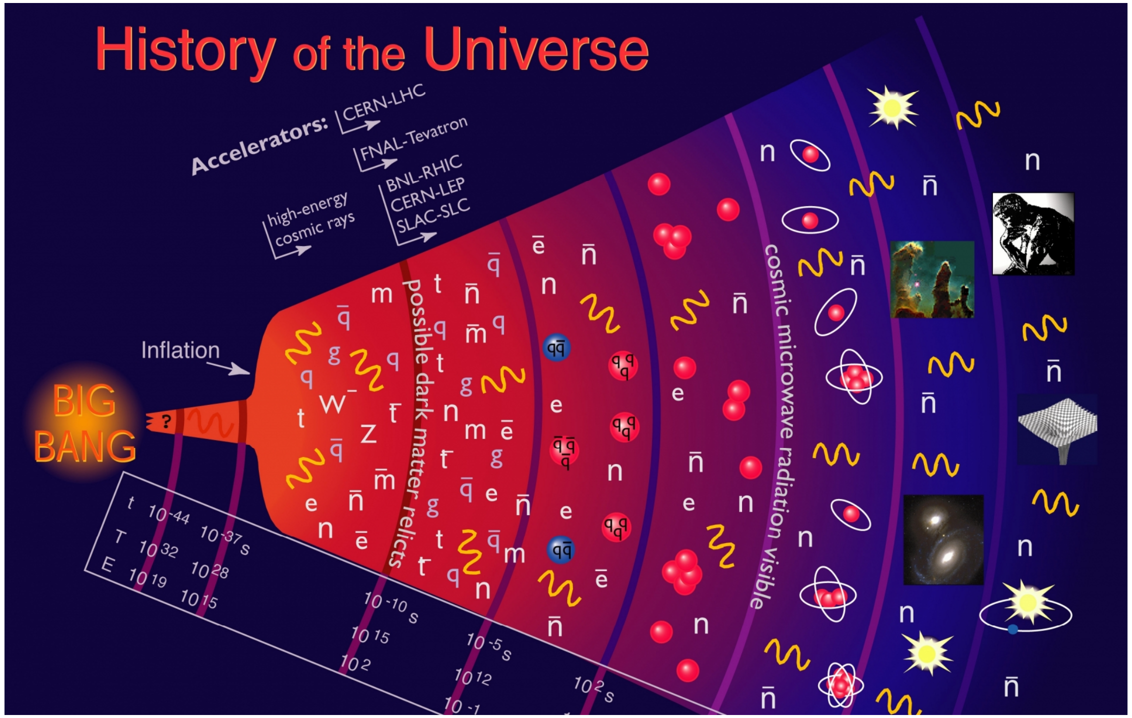
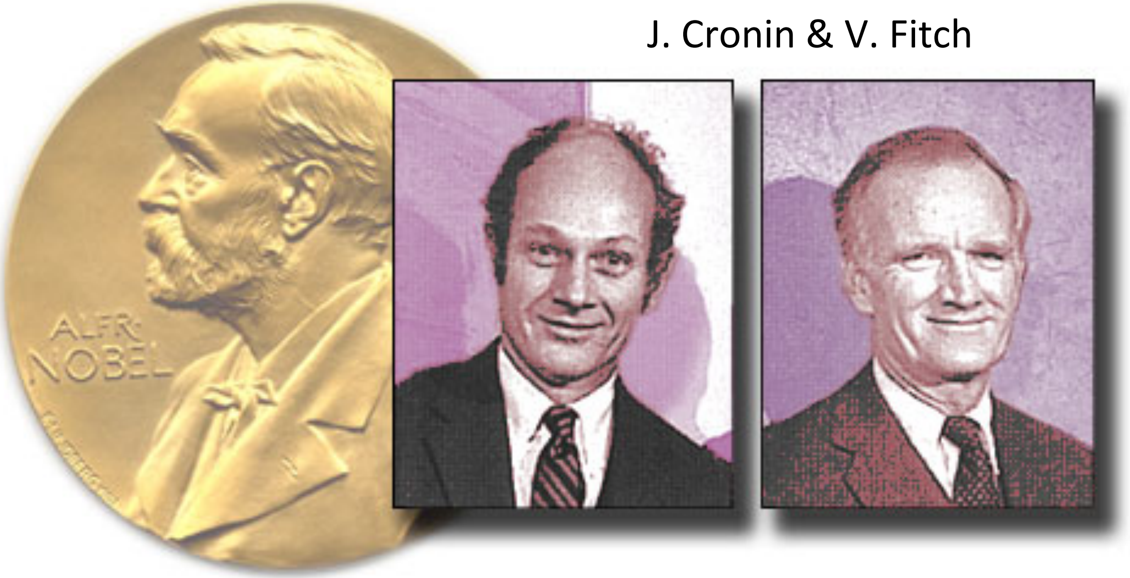
# Many reasons to believe New Physics exists



- The matter-anti asymmetry that is manifest in our universe is a mystery
- There must be a mechanism(s) by which differences between matter and anti-matter are generated.

# CP Violation and New Physics



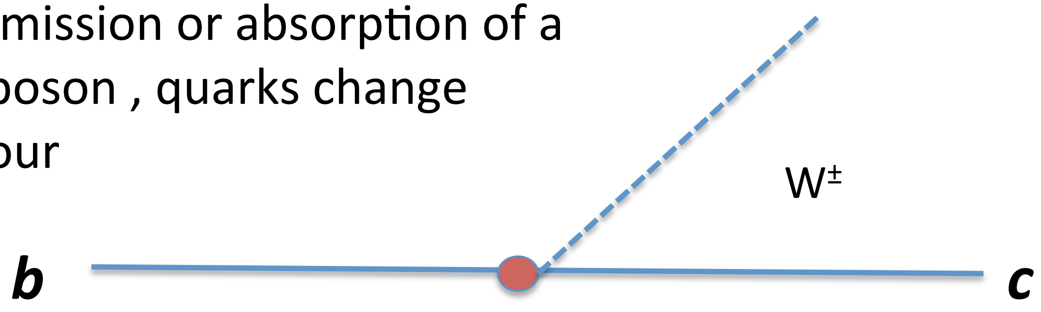
J. Cronin & V. Fitch

- First Observation of CPV in 1964 in the Kaon system
- Nobel prize awarded 1980
- Interest in CPV has continued to grow
- 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

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

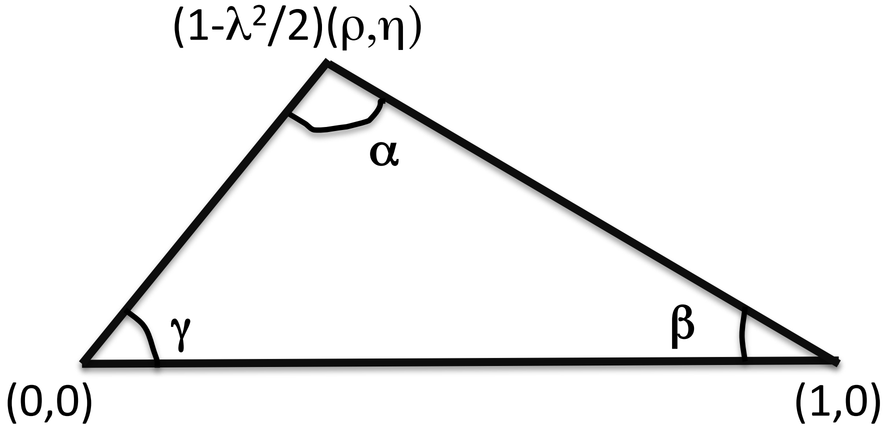
By emission or absorption of a W± boson , quarks change flavour



# Unitarity triangle

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

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

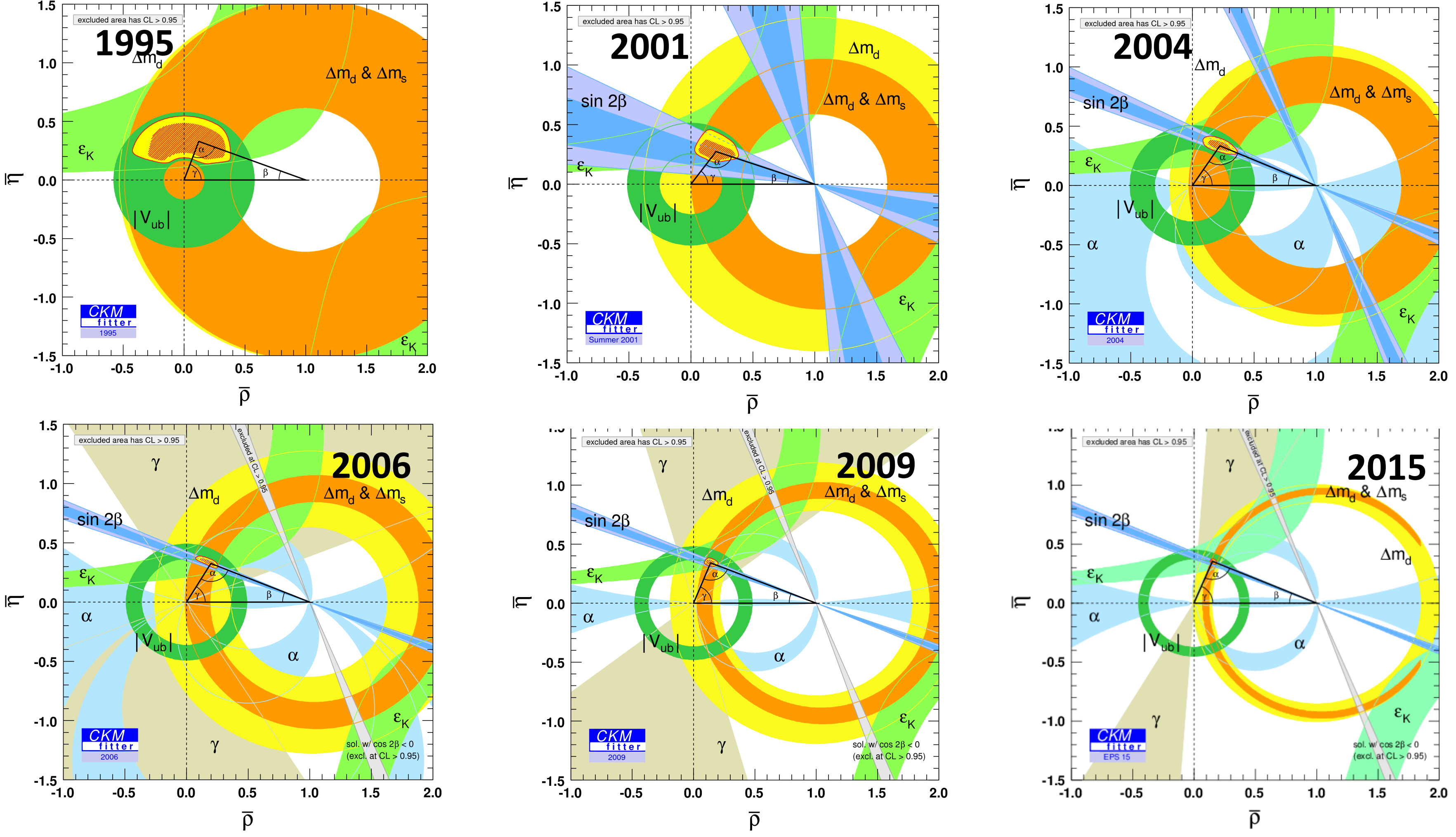


Using the properties of unitary matrices

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

“Most open” triangle, others are possible

# Is the triangle a triangle?



Improvements in constraints on triangle apex due to both experiment and theory advances

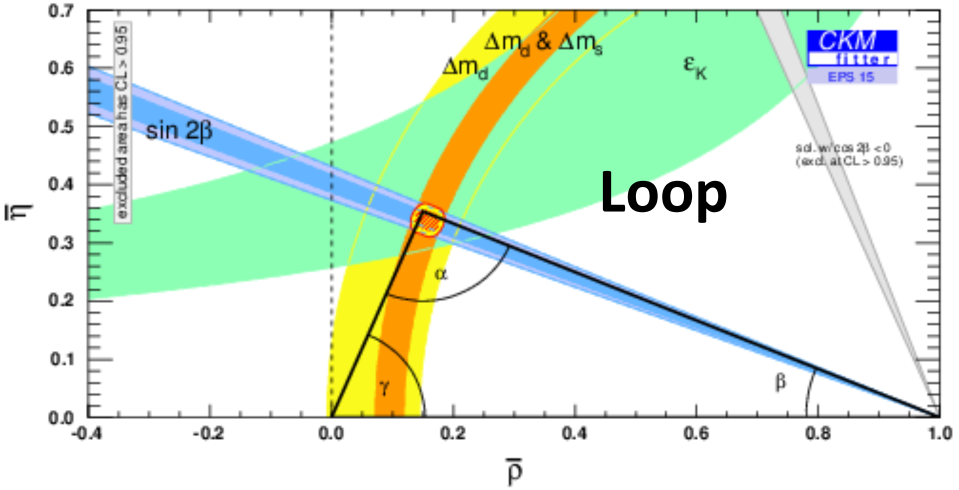
http://ckmfitter.in2p3.fr

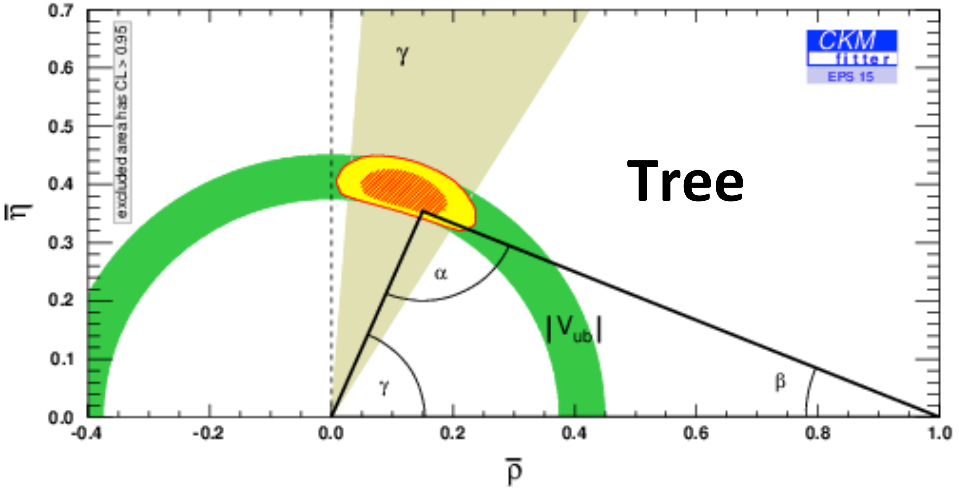
# Loop/Tree

- 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 $\gamma$, a process accessible at tree level
- Theoretically clean – uncertainty from observable to physics parameters ~$10^{-7}$
- Forms a SM benchmark*





*assuming no New Physics in tree decays

JHEP 01 (2014) 051

PRD 92(3):033002 (2015)

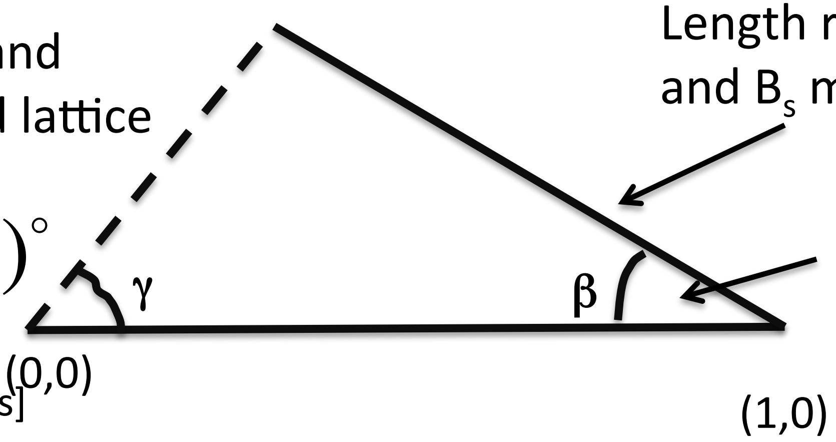
http://ckmfitter.in2p3.fr

# 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]



Length related ratio of $B_d$ and $B_s$ mixing

sin(2β) from B→J/ψ $K_s$

Combination of all direct measurements (summer 2016)

$$\gamma = (72.1^{+5.4}_{-5.8})^{\circ}$$

Alternative approach from CKM fit excluding all direct measurements of γ

$$\gamma = (65.33^{+0.96}_{-2.54})^{\circ}$$

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

**Reaching degree level precision from direct measurements is crucial**

EPJC (2016) 76 197

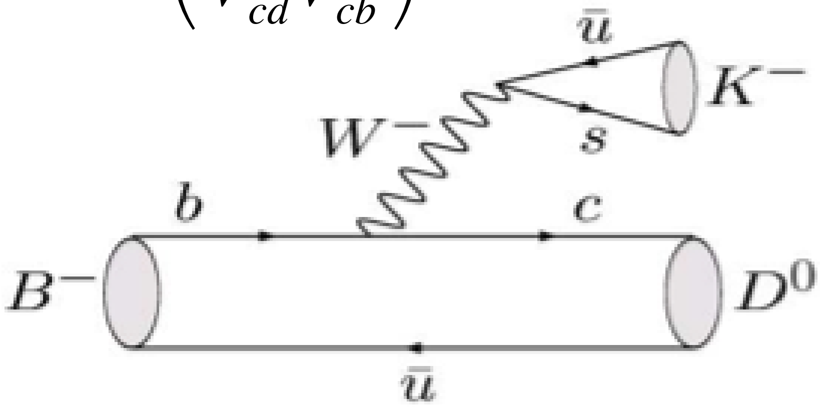
http://ckmfitter.in2p3.fr

# 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

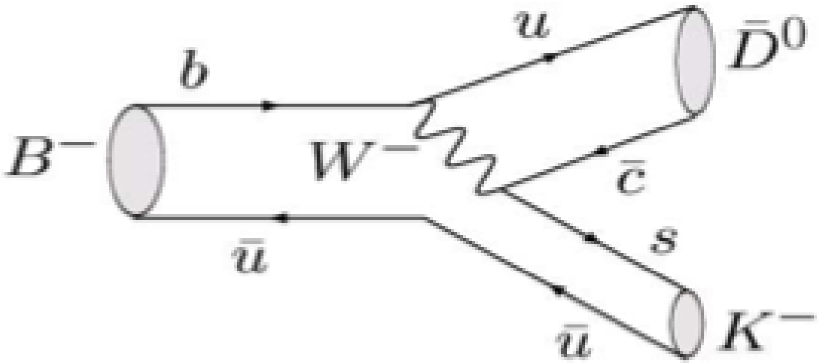
# B→DK

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



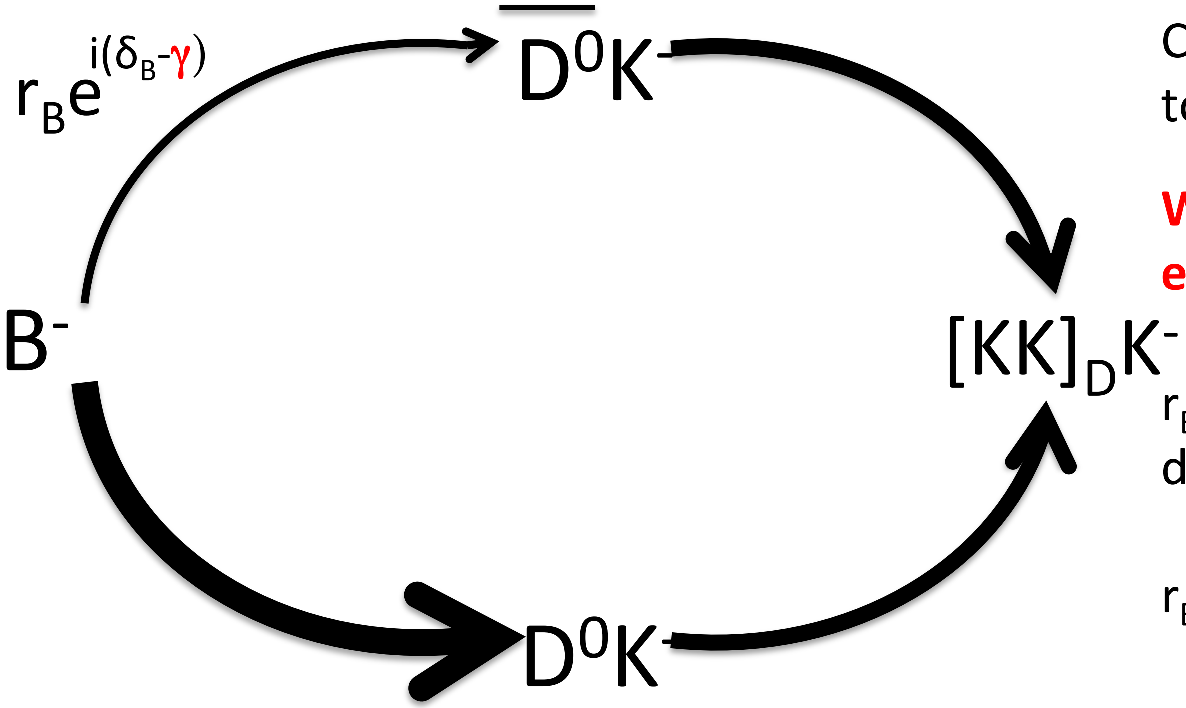
$b \rightarrow c$ (favoured)

$b \rightarrow u$ (suppressed)



- Interference possible if $D^0$ and $\bar{D}^0$ decay to same final state
- Branching fraction for favoured B decay ~$10^{-4}$
- Fully hadronic final state
- Measurements will require high statistics

# Interference with CP eigenstates “GLW”



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

**Weak phase changes sign for equivalent $B^+$ diagram**

$r_B$, $\delta_B$ hadronic parameters to be determined alongside $\gamma$

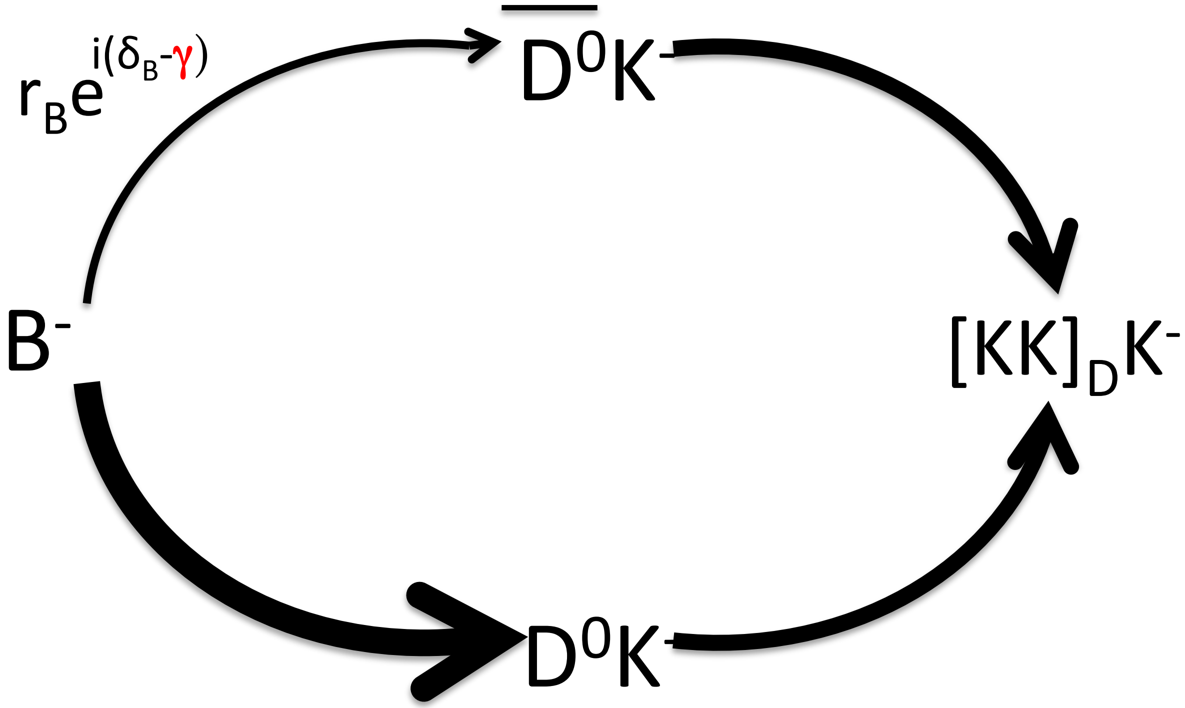
$r_B$ ~0.1

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 $D^0$

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

# Interference with CP eigenstates “GLW”



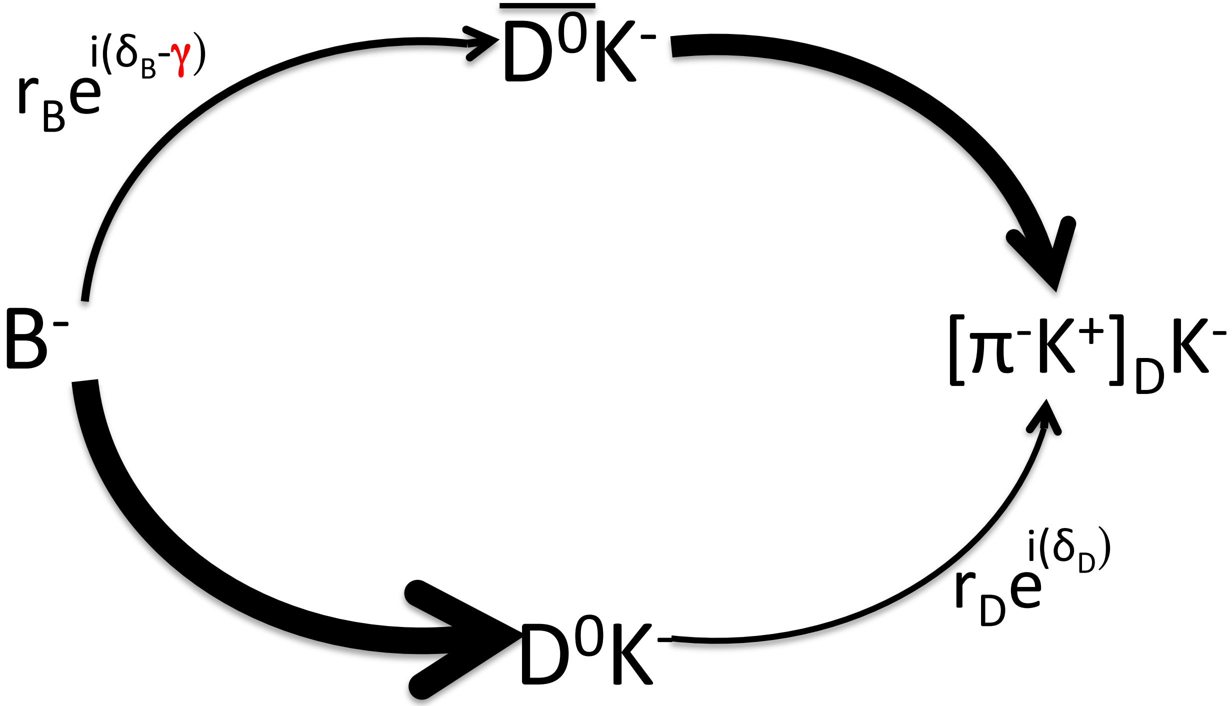
Equations simplified – assume no D mixing

For CP+ eigenstates e.g KK, ππ:

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

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

# Interference with flavour specific “ADS”



$\overline{D}^0 K^-$

$r_B e^{i(\delta_B - \gamma)}$

$B^-$

$[\pi^- K^+]_D K^-$

$r_D e^{i(\delta_D)}$

$D^0 K^-$

Larger interference effects as both amplitudes of similar sizes.

Additional two parameters $r_D$, $\delta_D$ . External inputs from charm mixing.

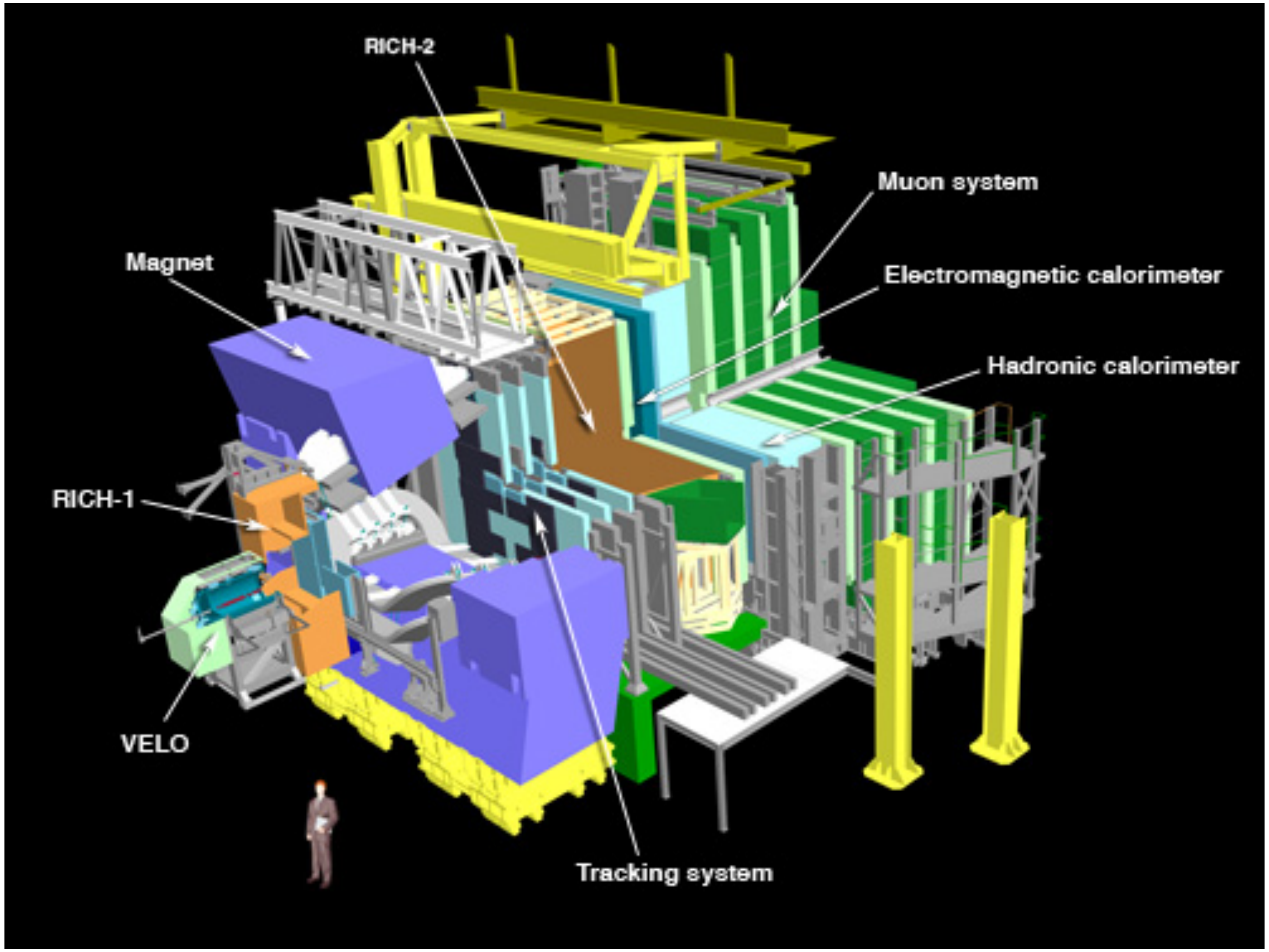
$r_D$ ~ 0.06

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

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

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

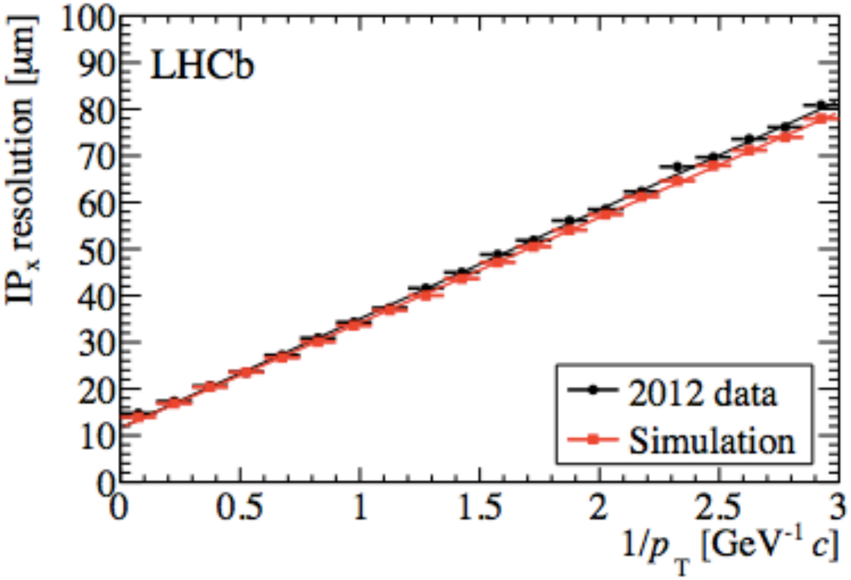
# LHCb detector



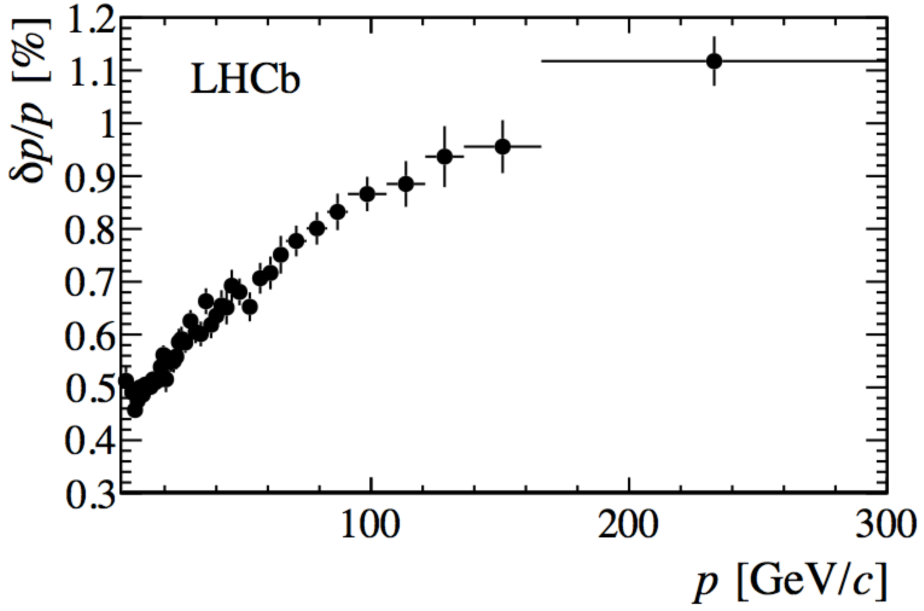
All except one analysis presented today come from full 2011 and 2012 datasets

# Detector performance (1)

VELO:
Impact parameter resolution

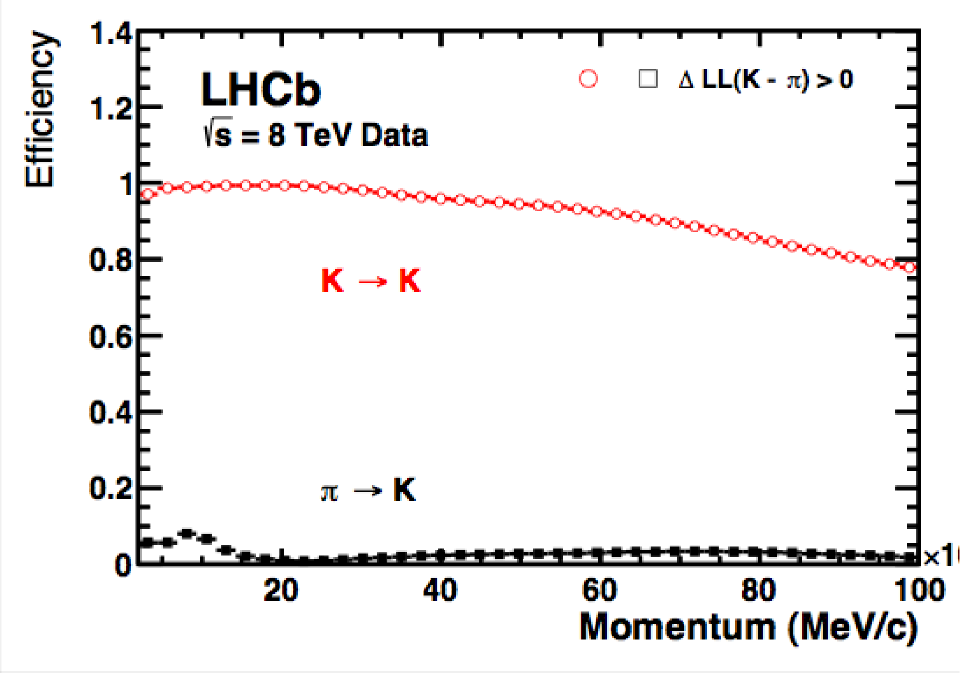


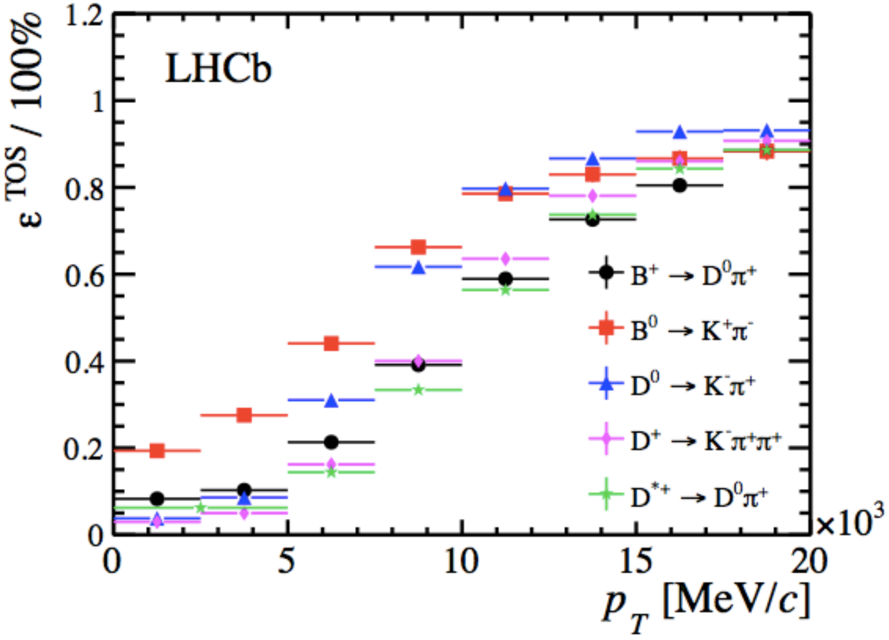
Tracking:
Momentum resolution



Int. J Mod. Phys A 30 (2015) 1530022

# Detector performance (2)





RICH detectors
Low π misidentification rate
High kaon identification

Hardware trigger
- hadronic trigger with high efficiency

Software trigger
- exploits decay topology

Int. J Mod. Phys A 30 (2015) 1530022

# Datasets

1 $\text{fb}^{-1}$ @ 7 TeV (2011)
2 $\text{fb}^{-1}$ @ 8 TeV (2012)

Pile up much lower than the GPDs ~ 2 collisions per bunch crossing

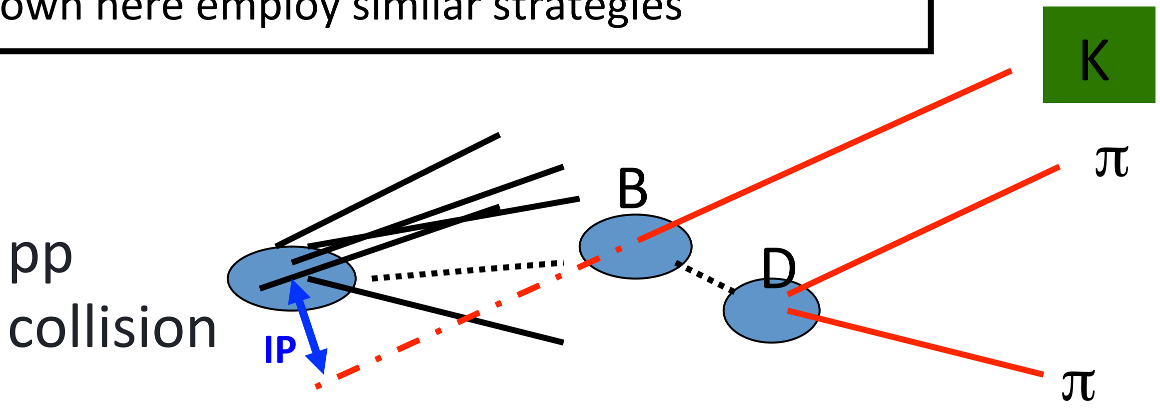
0.3 $\text{fb}^{-1}$ @ 13 TeV (2015)
1.7 $\text{fb}^{-1}$ @ 13 TeV (2016)

Pile up reduced to ~1 per bunch crossing
Increased cross section

Analyses today – all but one on Run 1 data
- Precision measurements take effort and time
- 2015 data only gives a modest increase.
- Most " Run 1" final results in this talk were produced in 2016

# Selection

All analyses shown here employ similar strategies



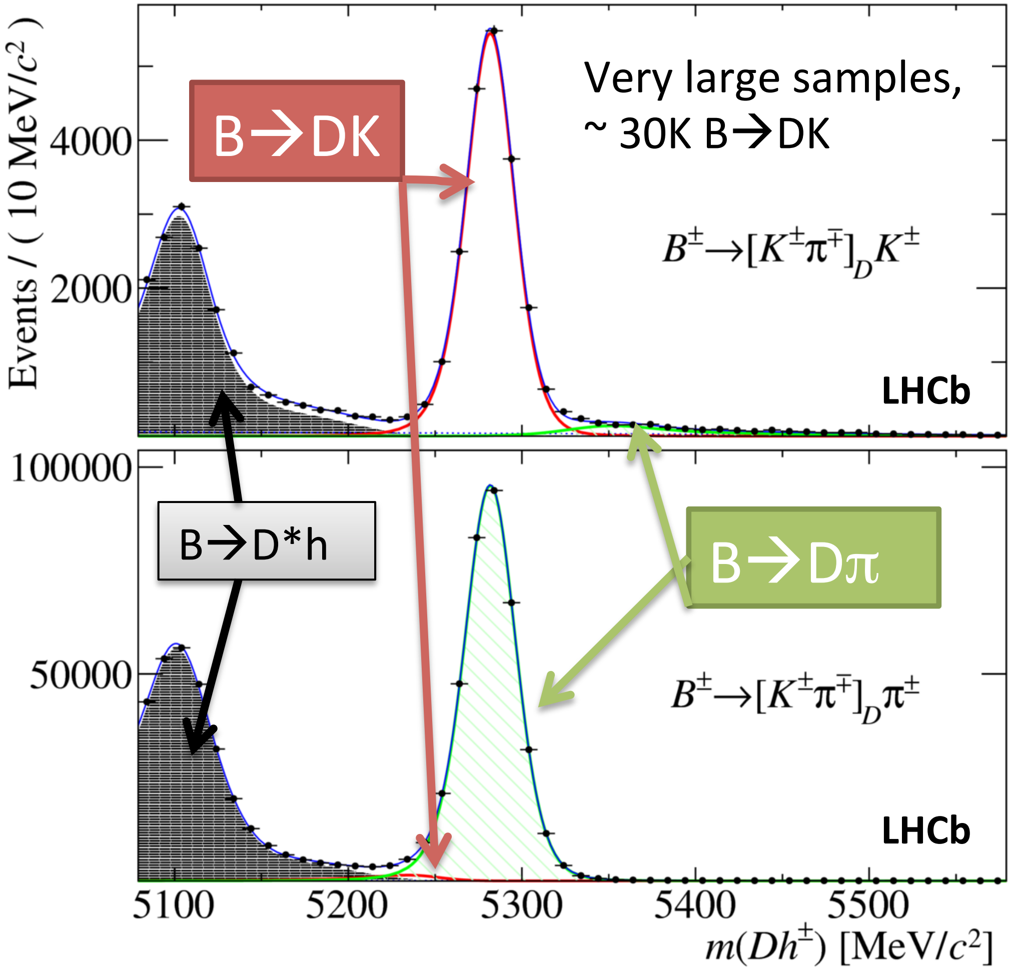
Separate the topology of interest from random combinations

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



Very large samples, ~ 30K B→DK

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

PID performance→ low crossfeed.

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

Extremely low level of combinatoric – clean environment

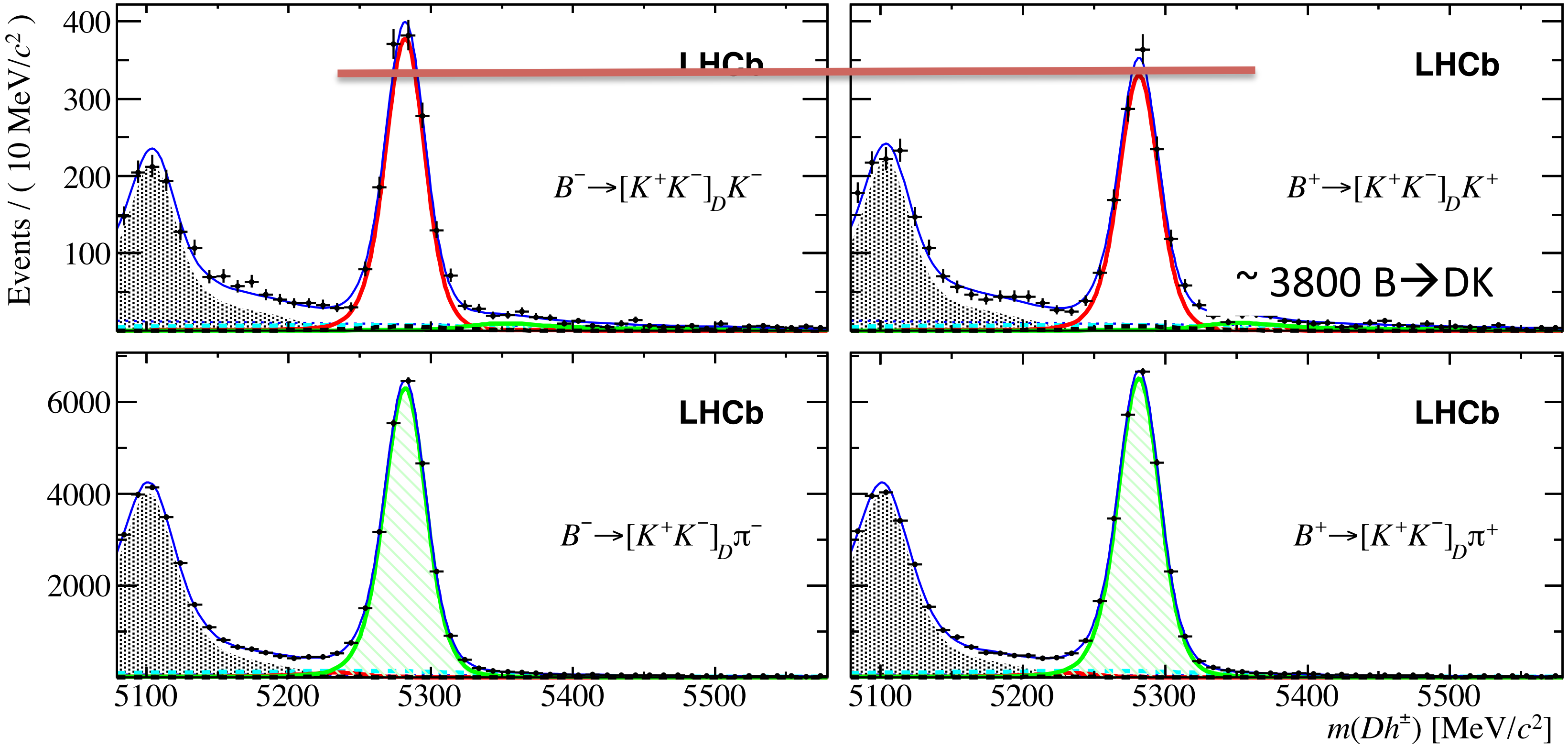
Control mode constrains the shapes of signal and backgrounds

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

arXiv:1603.08993

# B→D(KK)h



~ 3800 B→DK

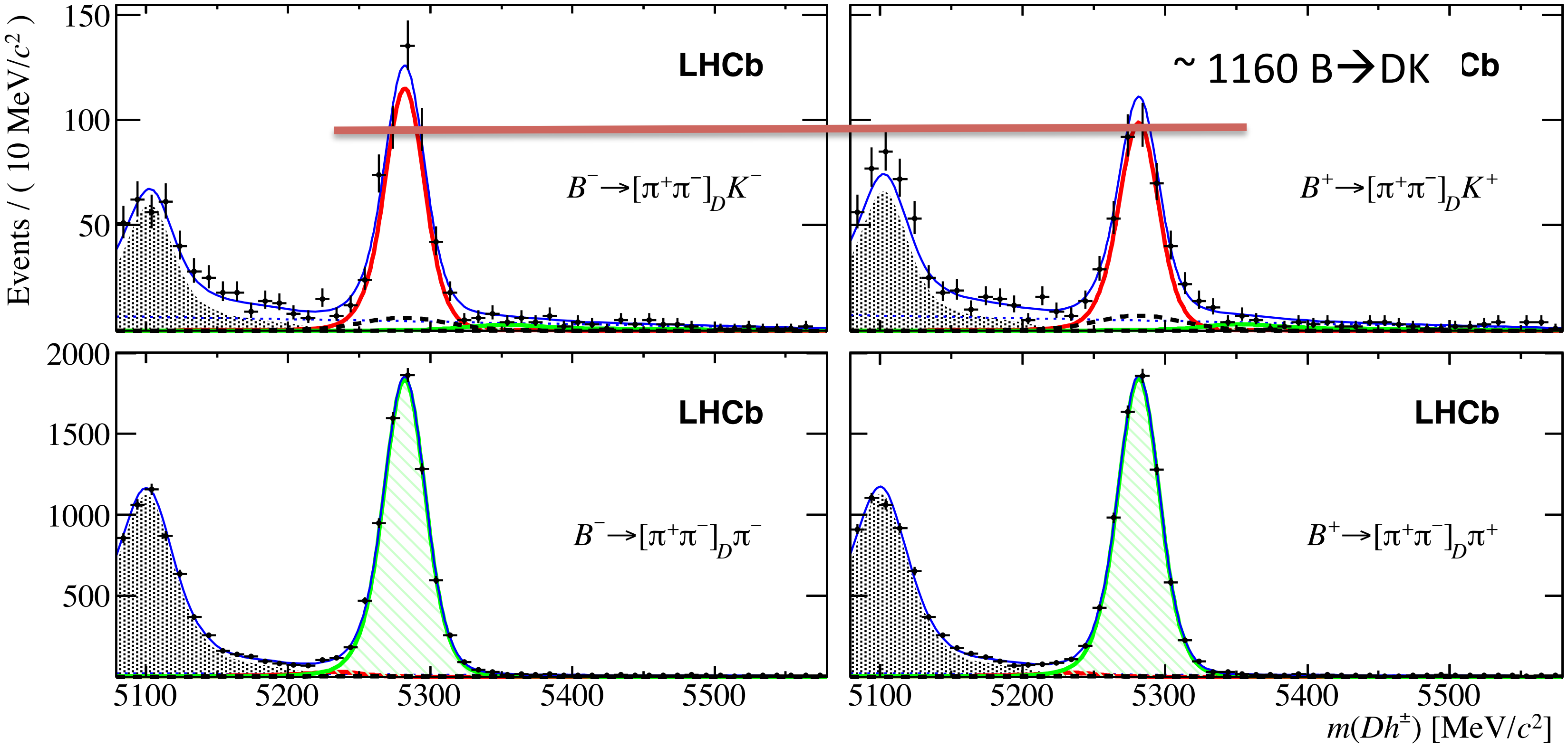
$$A_K^{KK} = 0.087 \pm 0.020 \pm 0.008$$

Statistical uncertainty dominant

Description of background is the leading systematic uncertainty

arXiv:1603.08993

# B→D(ππ)h



~ 1160 B→DK

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

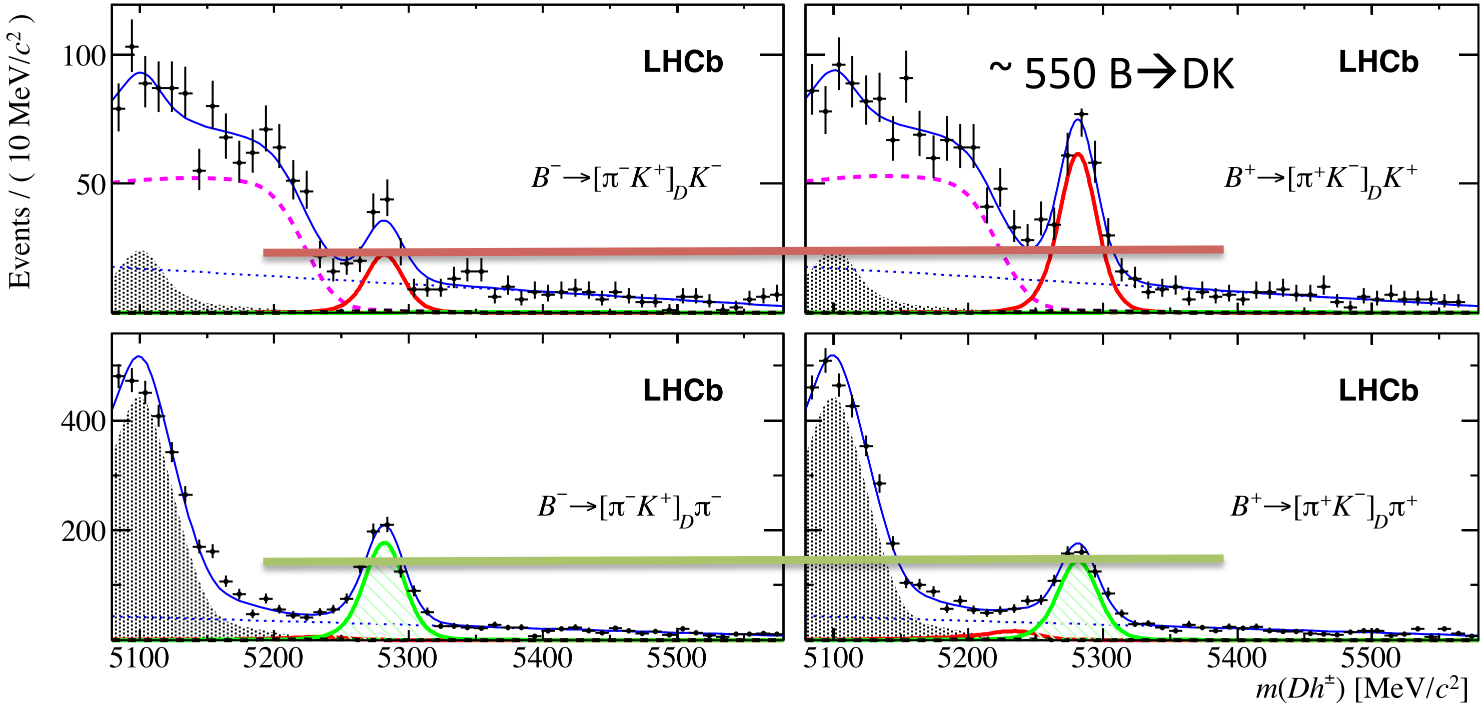
Asymmetry same direction as KK mode

Combined observation of CP violation

5σ

arXiv:1603.08993

# B→D[πK]h



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

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

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

Observation of CP violation in B→DK

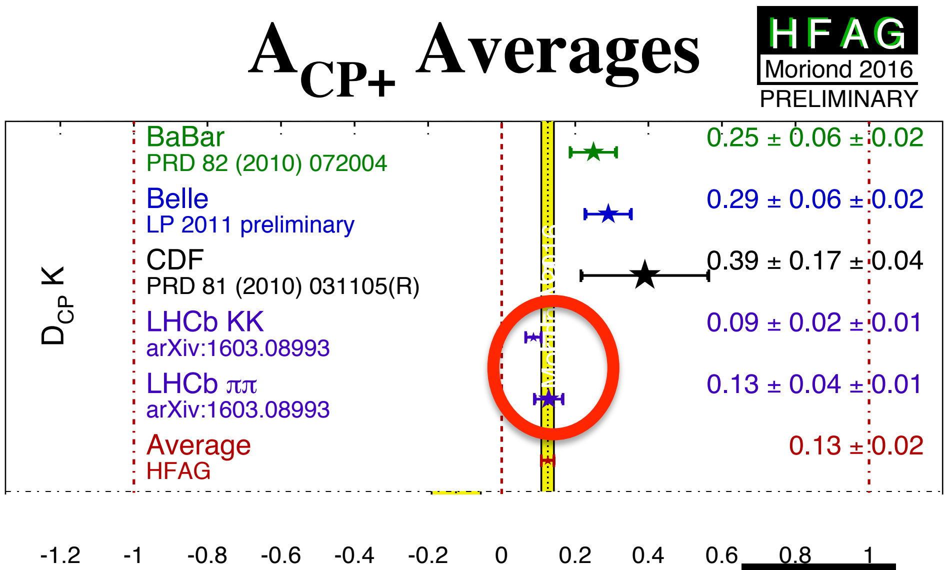
8σ

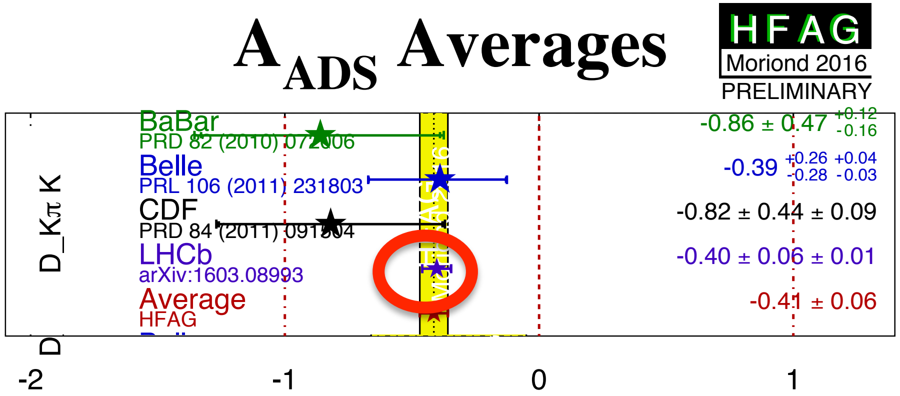
CPV starts to become visible in B→Dπ
Combined with D→KK D→ππ significance

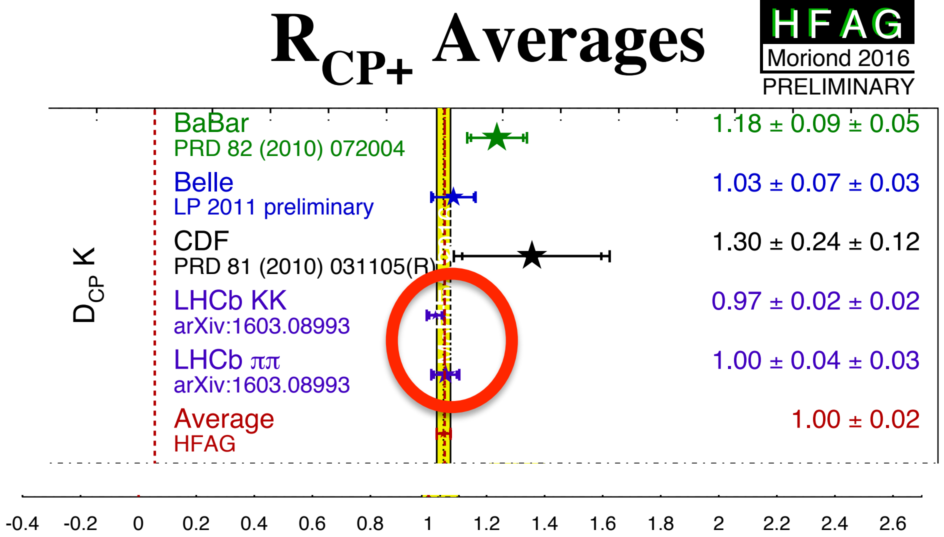
3.9σ

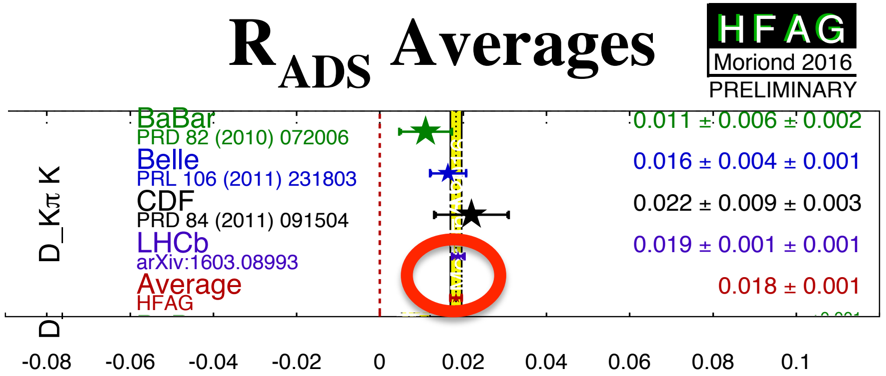
arXiv:1603.08993

# Comparison of results



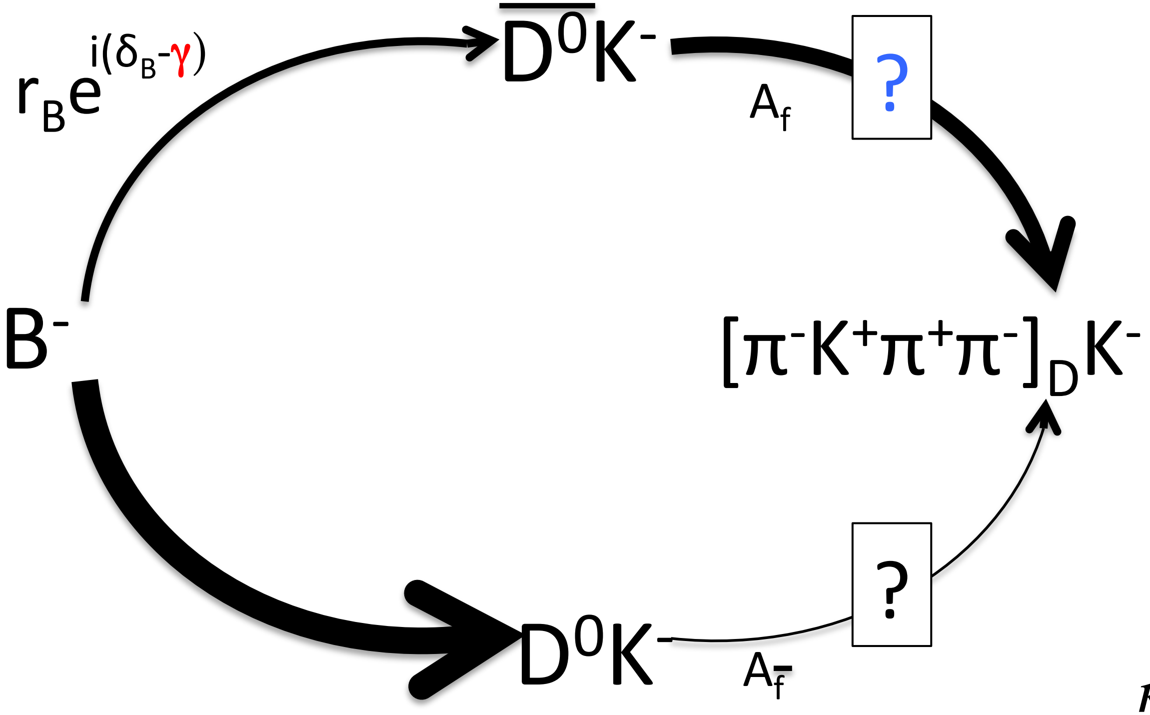






**LHCb results dominate world averages**

# Multi-body flavour specific D decays "ADS"



Treat multibody decays inclusively → avoids consideration of intermediate states. Particularly useful for 4-body decay modes

$$\frac{|A_f|}{|A_{\bar{f}}|} = r_D^{K3\pi} \sim 0.05$$

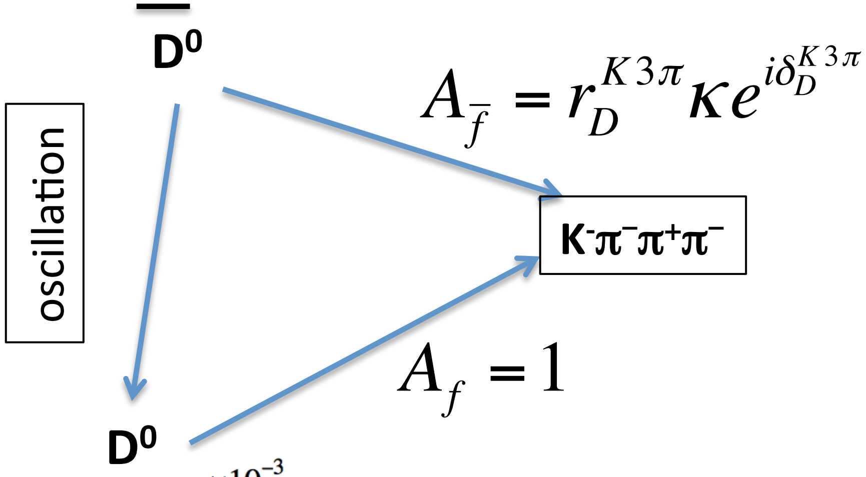
$$\kappa e^{i\delta_D^f} = \frac{\int A_f(x)A_{\bar{f}}(x)\,dx}{\sqrt{\int A_f^2(x)\,dx \int A_{\bar{f}}^2(x)\,dx}}$$

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

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

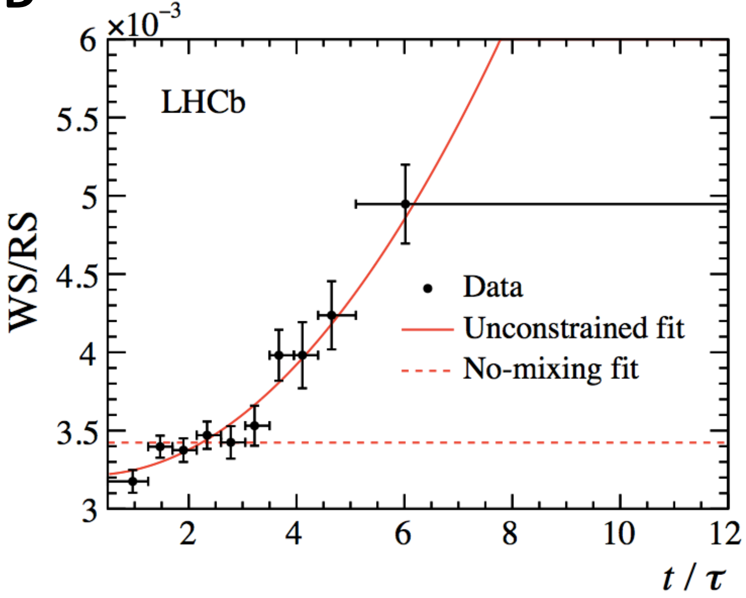
PRD 68 033003 (2003)

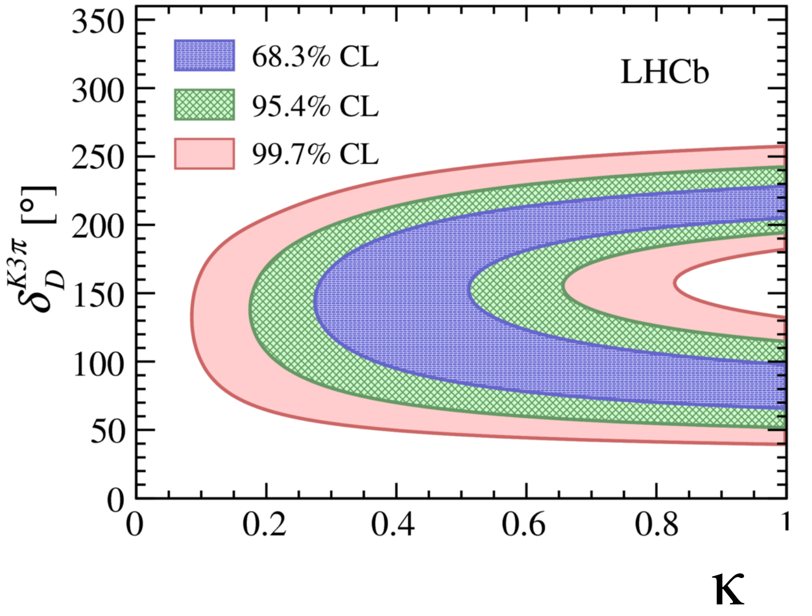
# Measurements of coherence factor



Interference between mixing and decay

$\kappa, \delta_D^{K3\pi}$ determined from time-dependent decay rates.

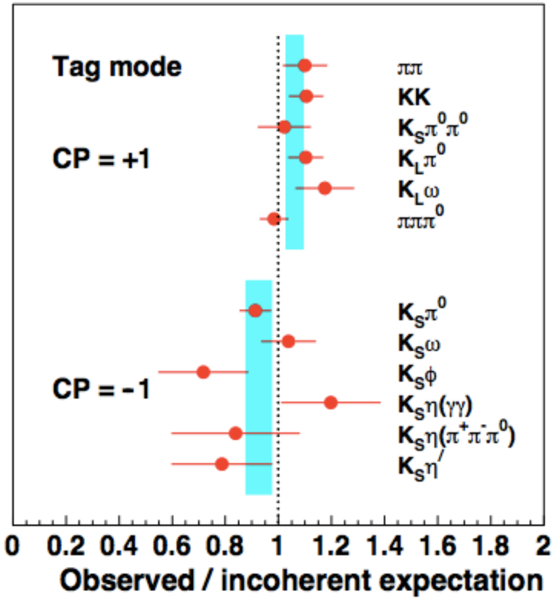


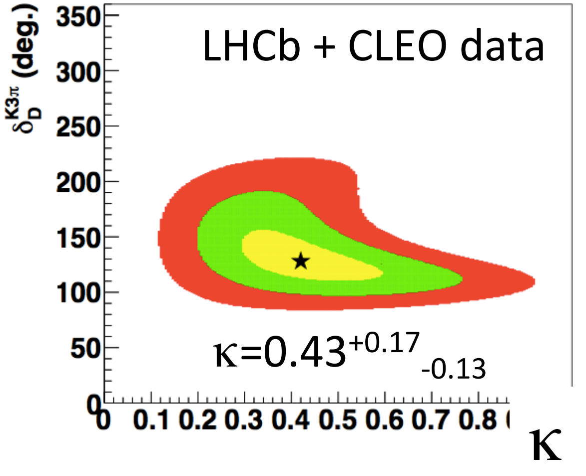


arXiv:1602.077224

# 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 CP eigenstate.
- Rates are dependent on the κ and $\delta^{K3\pi}$
- Synergy between two measurement – sensitive to different regions
- Strong phase measurements in other decay modes follow same principles

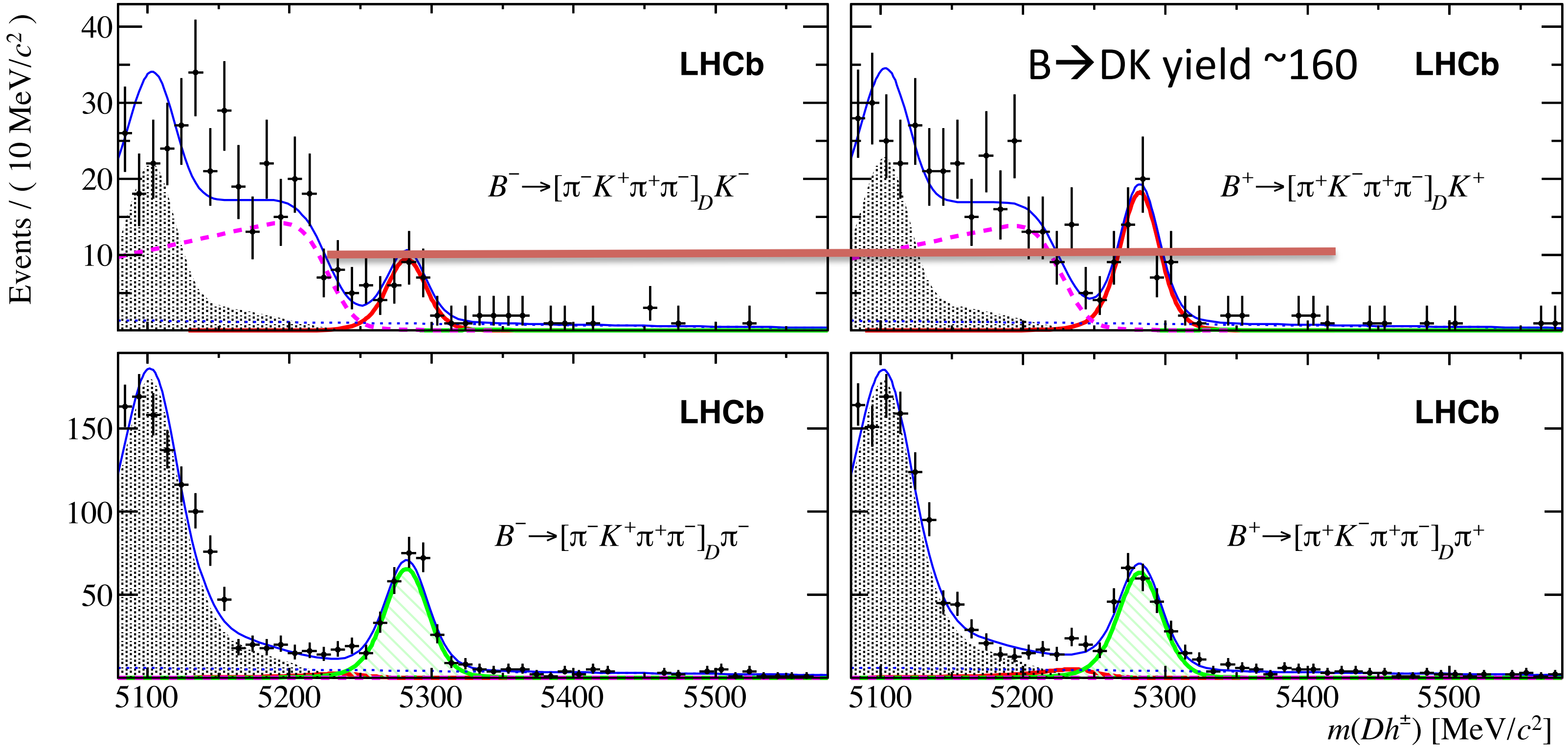




$\kappa = 0.43^{+0.17}_{-0.13}$

PLB 757 (2016) 520

# Results D→K3π



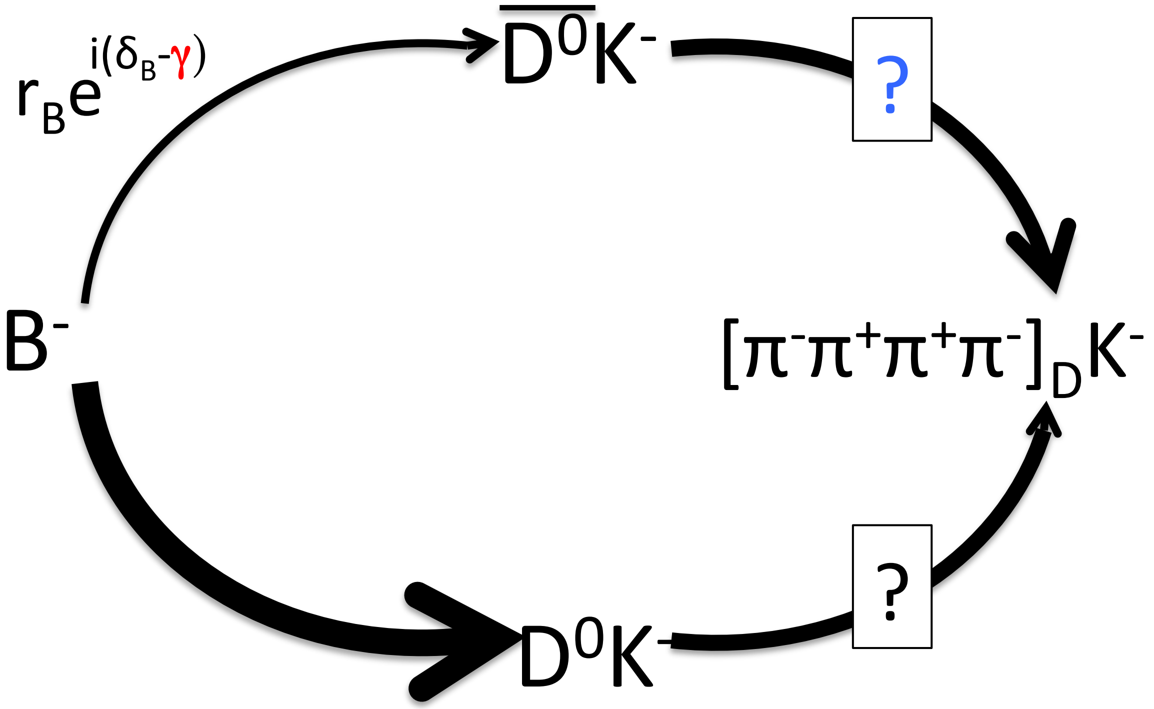
B→DK yield ~160

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

Complementary information to two body modes.

arXiv:1603.08993

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



$r_B e^{i(\delta_B - \gamma)}$

$\overline{D}^0 K^-$

?

$B^-$

$[\pi^-\pi^+\pi^+\pi^-]_D K^-$

?

$D^0 K^-$

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

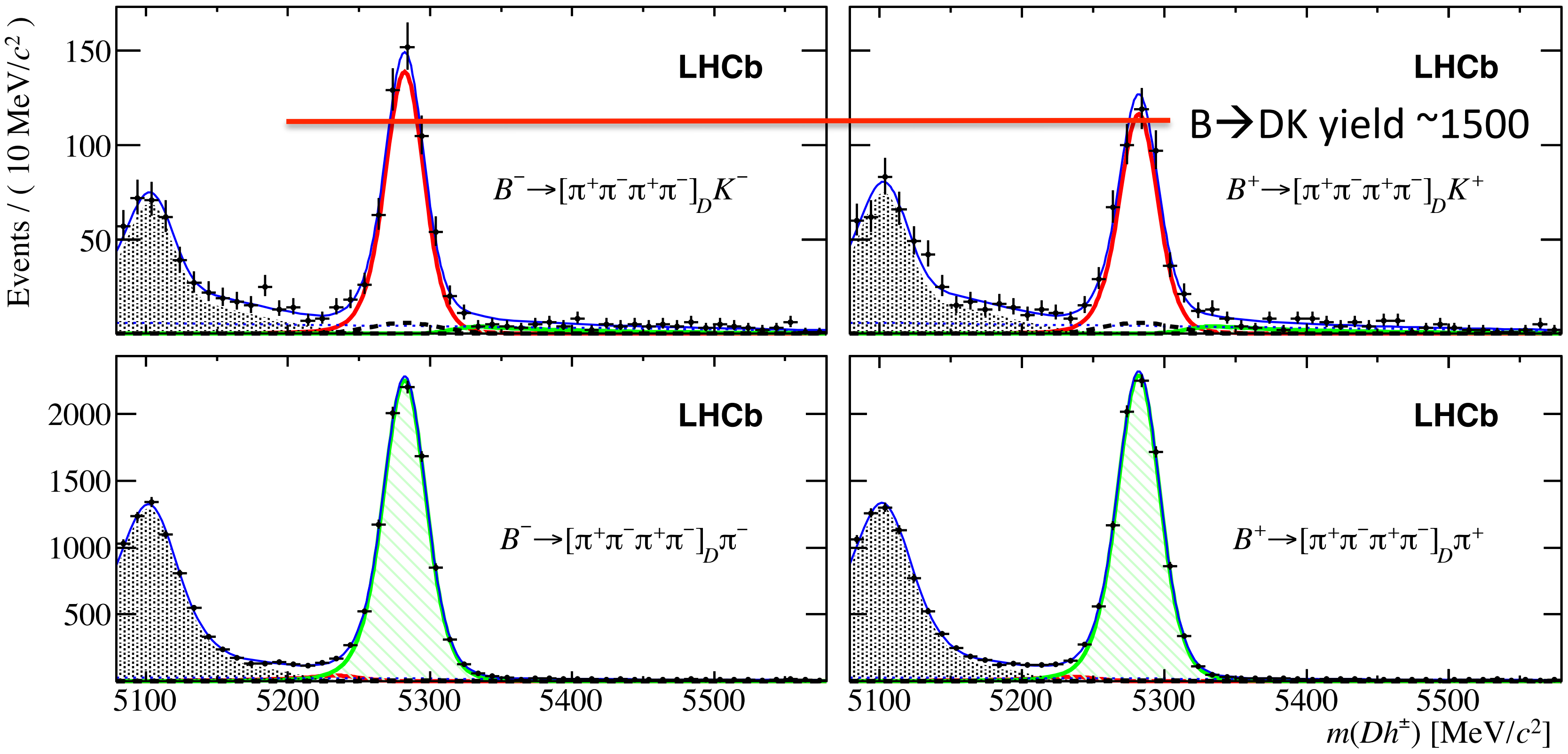
$F_+^{4\pi} = 0.737 \pm 0.028$

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

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

PLB 740 (2015) 1

# Results D→4π



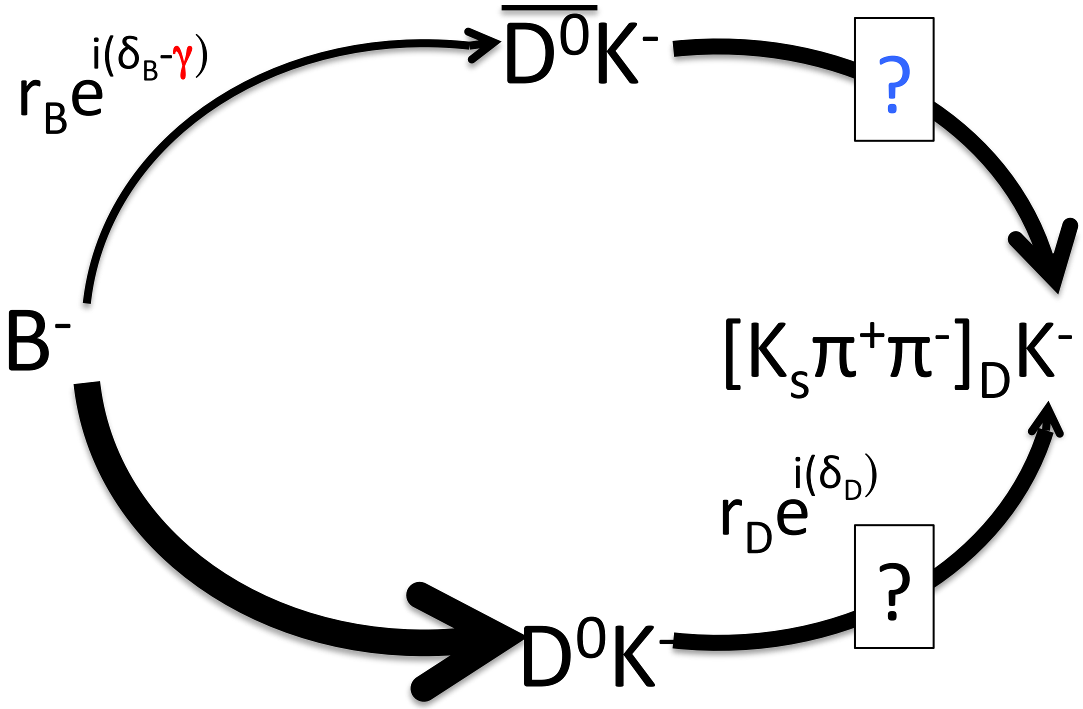
B→DK yield ~1500

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

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

arXiv:1603.08993

# Self-conjugate D decays using Dalitz plot “GGSZ”



$r_B e^{i(\delta_B-\gamma)}$

$\overline{D}^0K^-$

?

$B^-$

$[K_s\pi^+\pi^-]_D K^-$

$r_D e^{i(\delta_D)}$

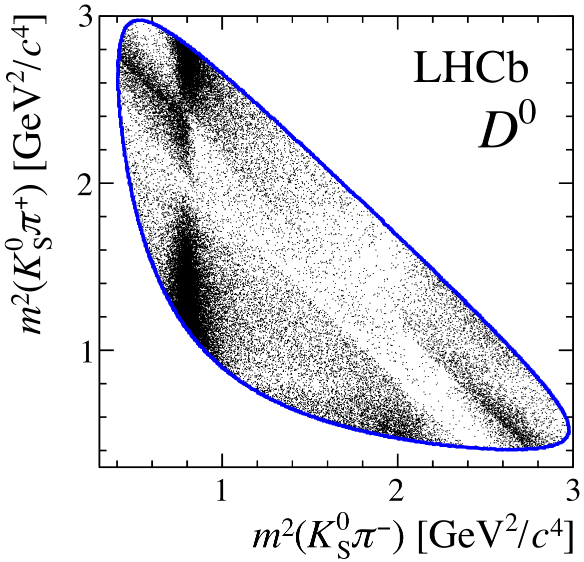
?

$D^0K^-$

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

Hence inclusive treatment loses most of the sensitivity to $\gamma$ → Analyse the Dalitz plot

Best standalone measurement of $\gamma$



Dalitz Plot encodes all the kinematic information of the decay

Each point on the Dalitz plot represents a different value of $r_D$ and $\delta_D$

Giri, Gronau, Soffer & Zupan, (GGSZ) 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 $\overline{D}^0$
- It will differ between $B^+$ and $B^-$
- Differences are related to $r_B$ $\delta_B$ and $\gamma$

Two ways to deal with the varying $r_D$, $\delta_D$

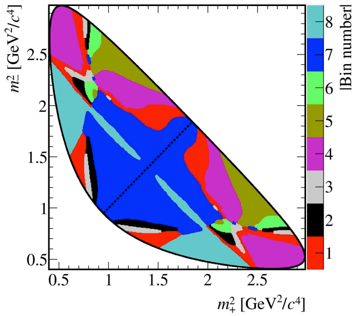
**Model dependent**

$r_D$ and $\delta_D$ determined from flavour tagged decays via amplitude model

No interference, no direct access to phase information

Systematic uncertainties due to model hard to quantify

**Model independent**



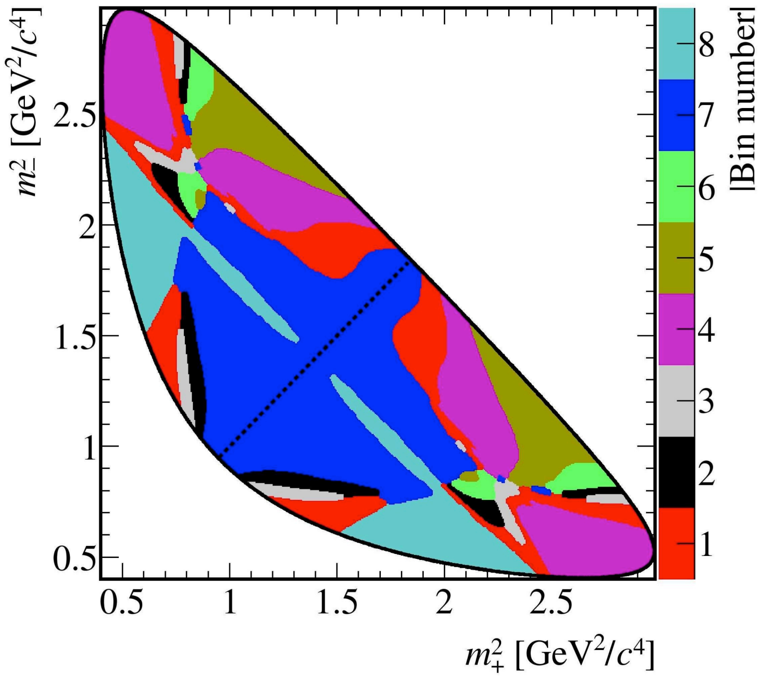
Use CLEO data to measure average values of $r_D$ and $\delta_D$ in bins

Small loss in statistical precision

Direct phase information, uncertainties on which are easily propagated

PRD 82 (2010) 112006

# Model-independent GGSZ analysis



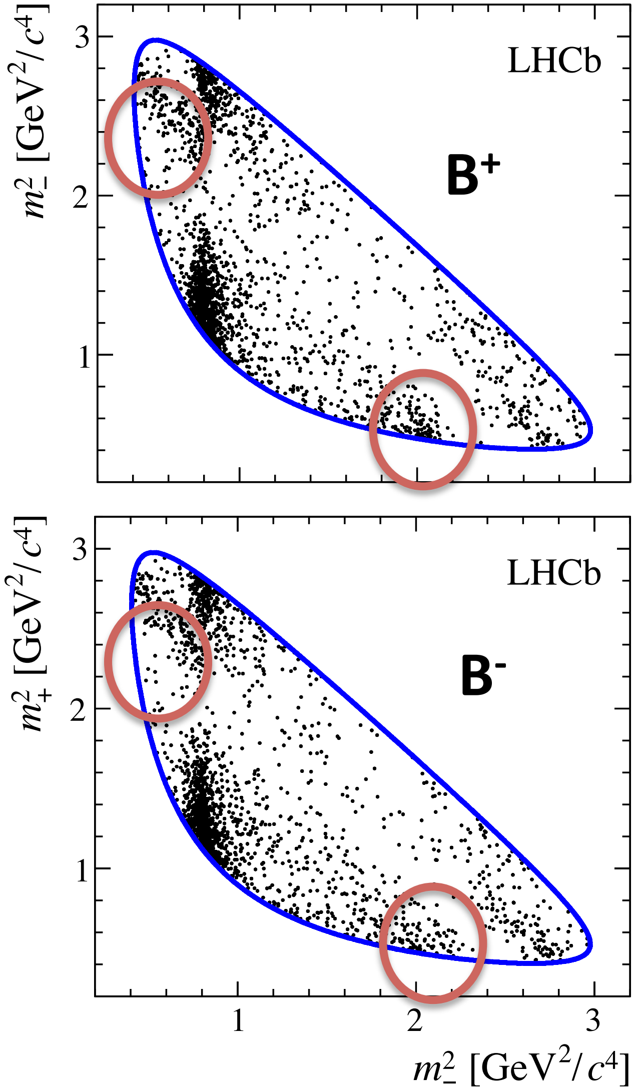
- Reduces to a counting experiment in bins of Dalitz Plot
- Bin definition designed to minimise statistical loss ~ 90% of sensitivity remains
- Bin yields + strong phase information → measurement of x and y

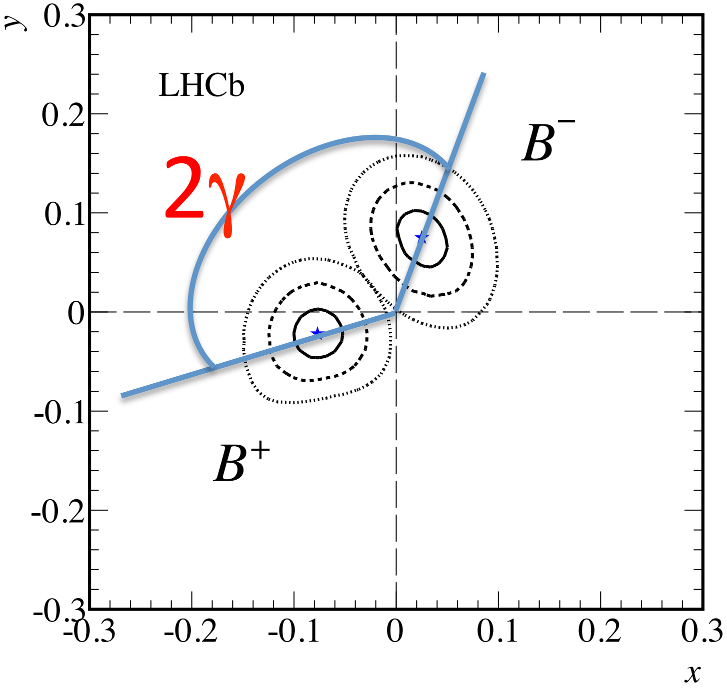
$$x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$$

$$y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$

PRD 82 (2010) 112006

# B→D[Kshh]K (GGSZ)





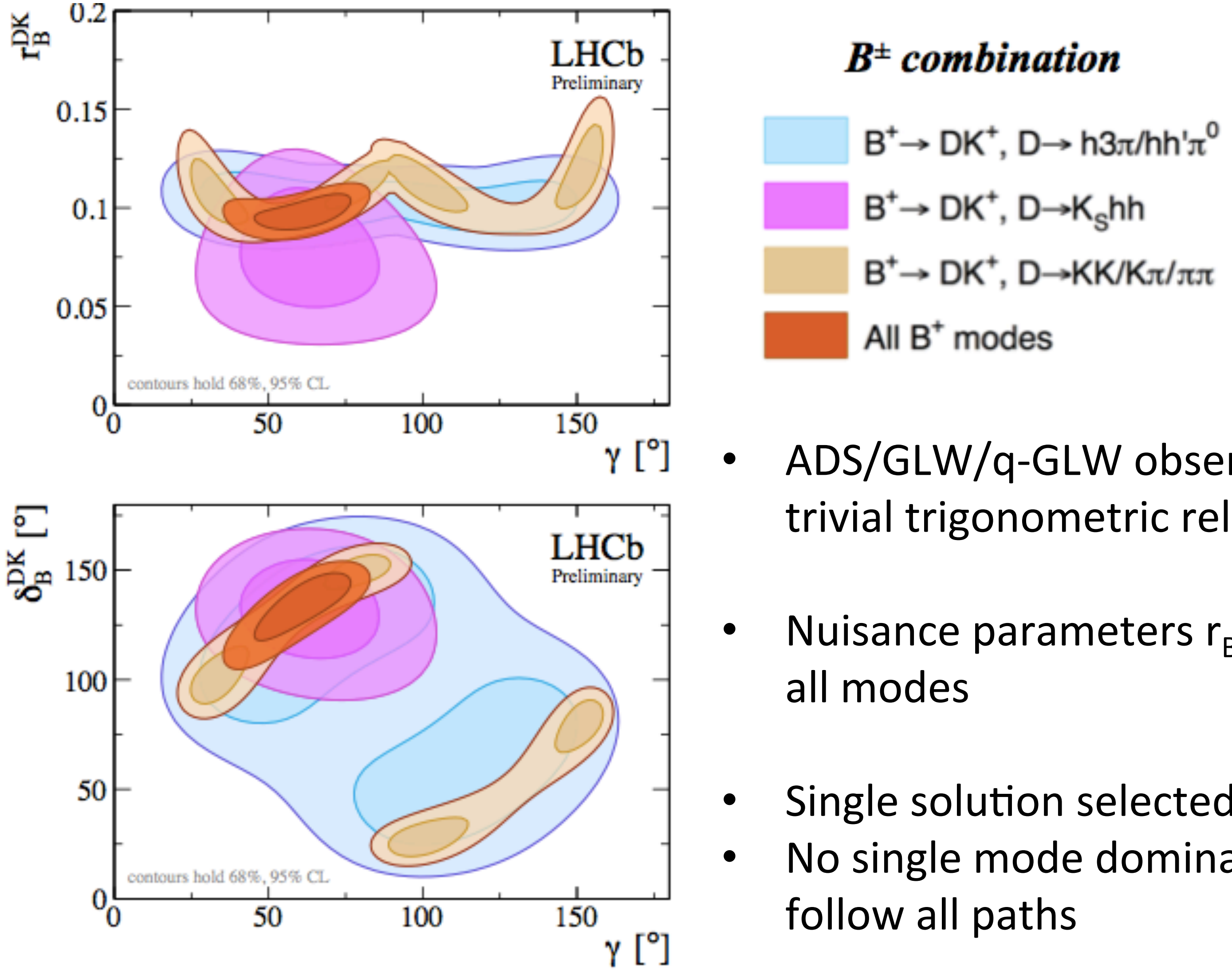
Separation $(x_+,y_+)$ , $(x_-,y_-)$ shows CPV

$K_s\pi\pi$ and $K_sKK$ decay modes (not shown) used. Signal yield ~2400

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

JHEP 10 (2014) 097

# Interplay between different modes



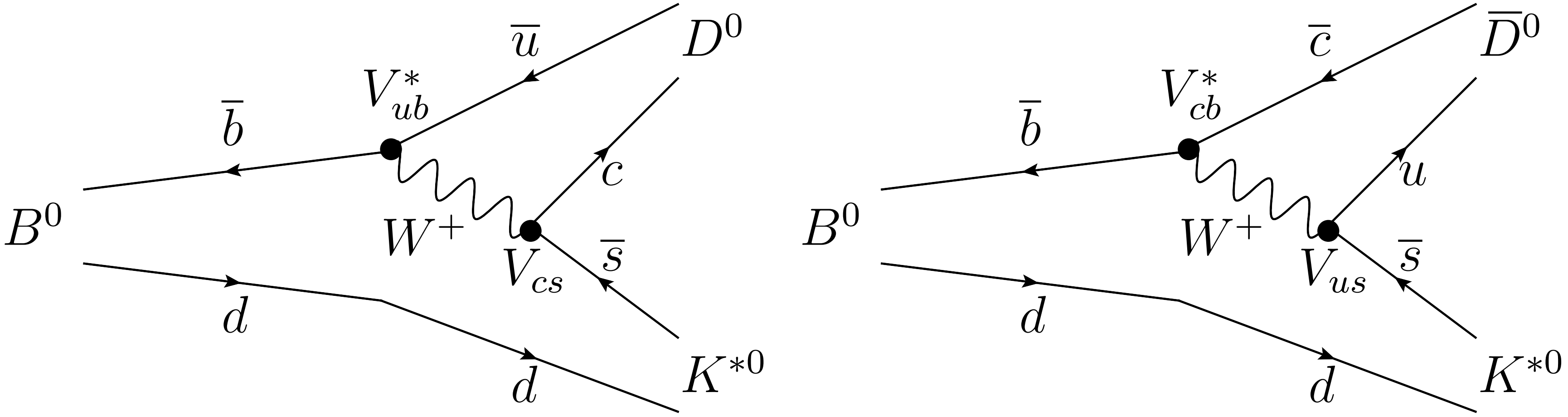
- ADS/GLW/q-GLW observables have non trivial trigonometric relations.

- Nuisance parameters $r_B$ and $\delta_B$ common to all modes

- Single solution selected by GGSZ modes
- No single mode dominates→ necessary to follow all paths

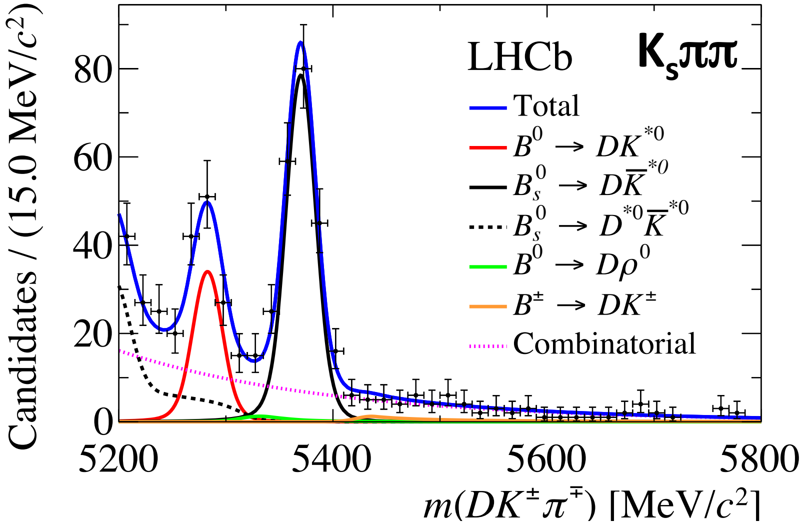
LHCb-CONF-2016-001

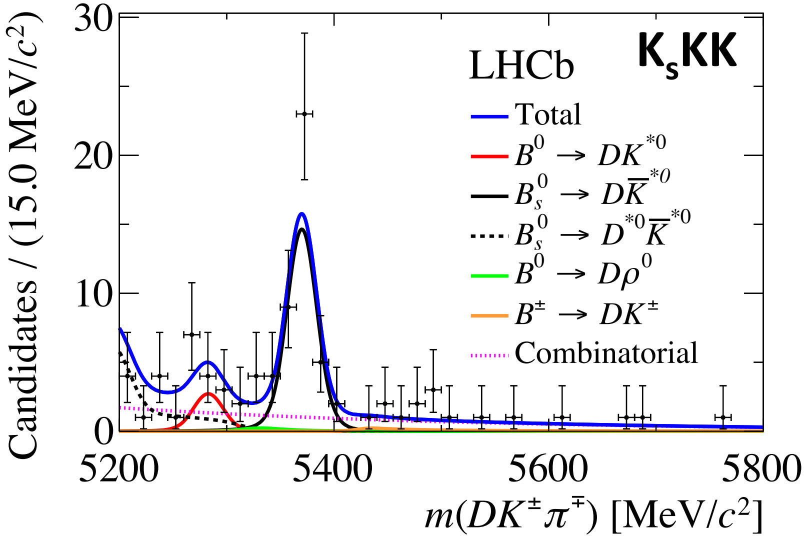
# Other B modes



- Favoured and suppressed decay both colour suppressed
- $r_B$ ~ 0.3 → Larger interference
- K* →$K^+\pi^-$, 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
- Different $r_B$ and $\delta_B$

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

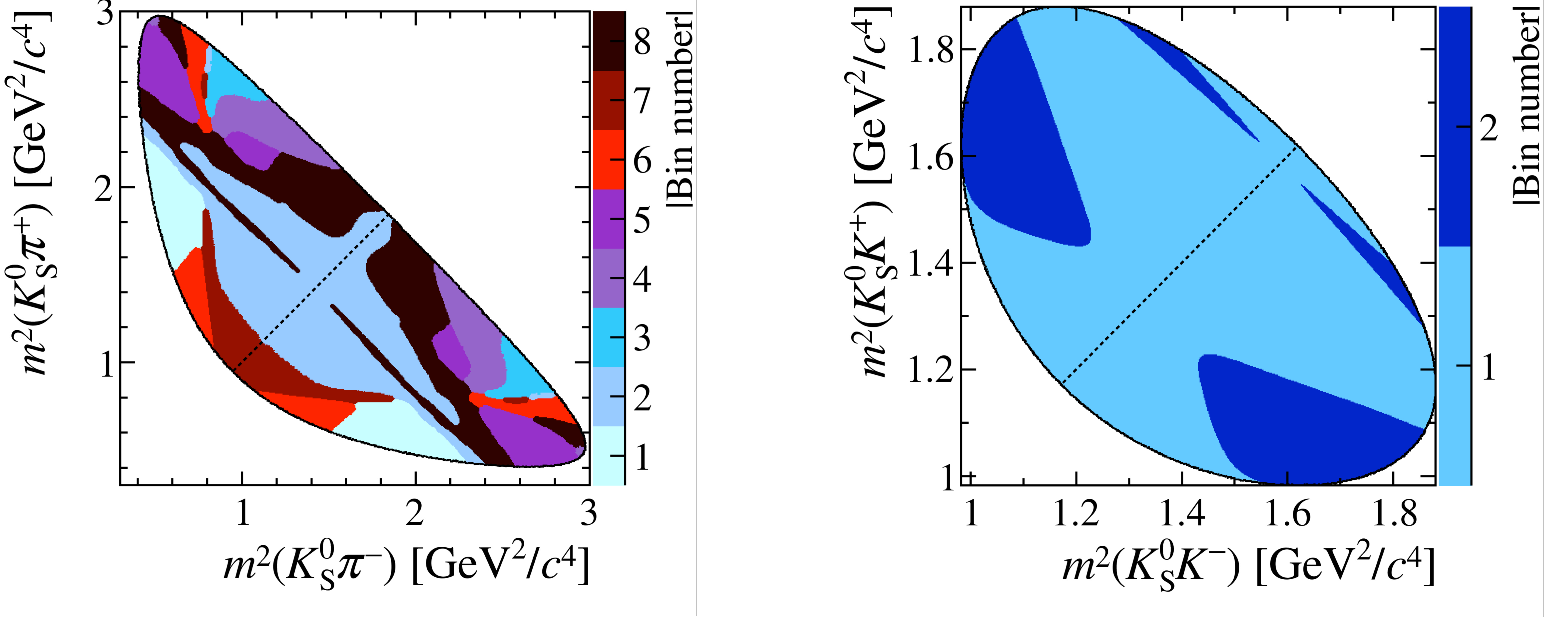




- Yields ~ 90 in $K_s\pi\pi$ and 10 in ~$K_sKK$
  - Twice yield of B factories
- Irreducible $B_s$ backgrounds
- Width of K*(892) means non-resonant $K\pi$ decays can contribute to signal peak
- Coherence factor dependent on selection
- $|M(K^*)-892| < 50$ MeV/$c^2$;
- |cos(K helicity angle)|>0.4

arXiv: 1604.01525

# GGSZ analysis

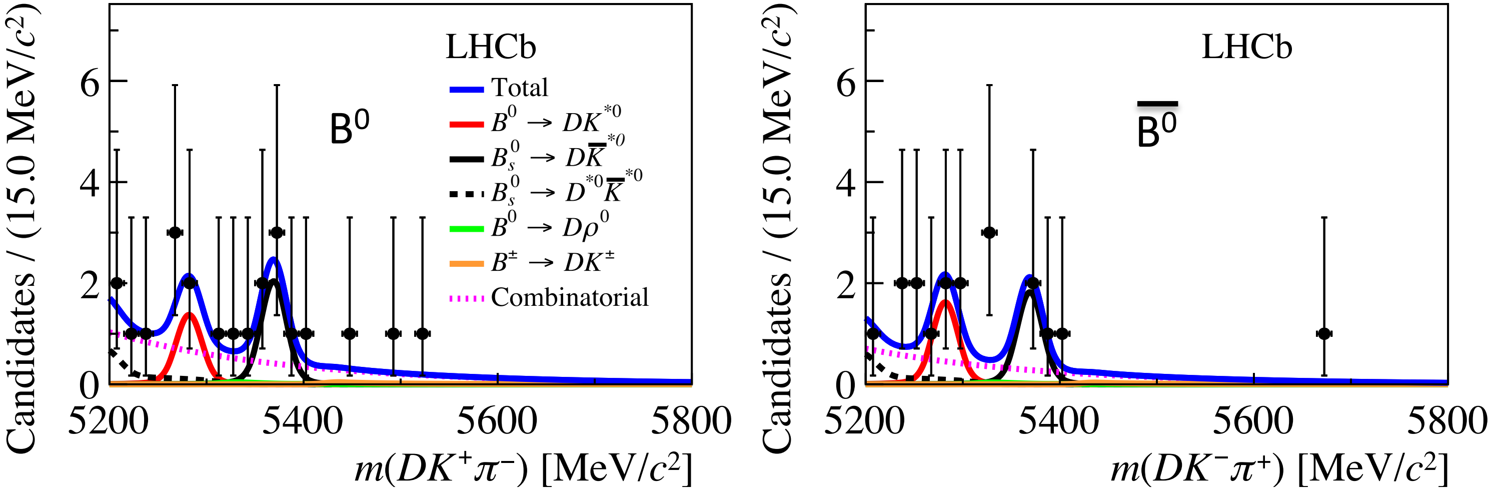


- Modified binning used for $K_s\pi\pi$ – better for low yield channels
- $K_s$KK split into 2 bins

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
- Example fit projection of one bin:



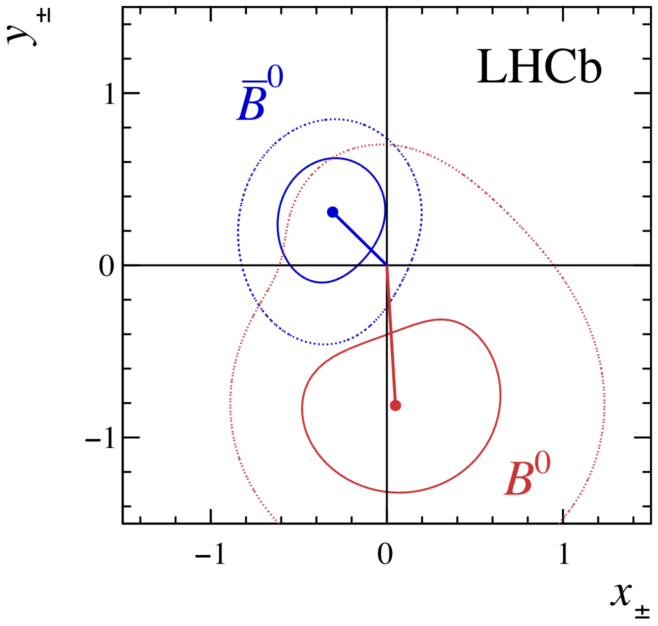
- Model dependent fit also performed
  - $r_D$ and $\delta_D$ given by BaBar 2010 amplitude model

arXiv: 1604.01525

arXiv: 1605.01082

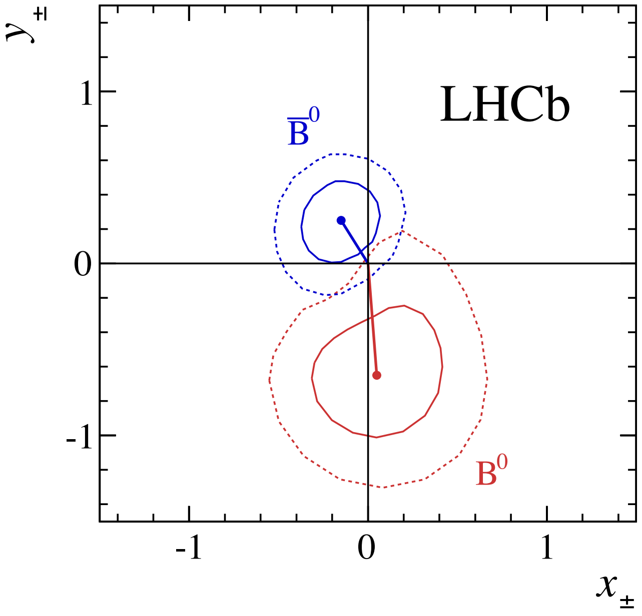
# Results

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



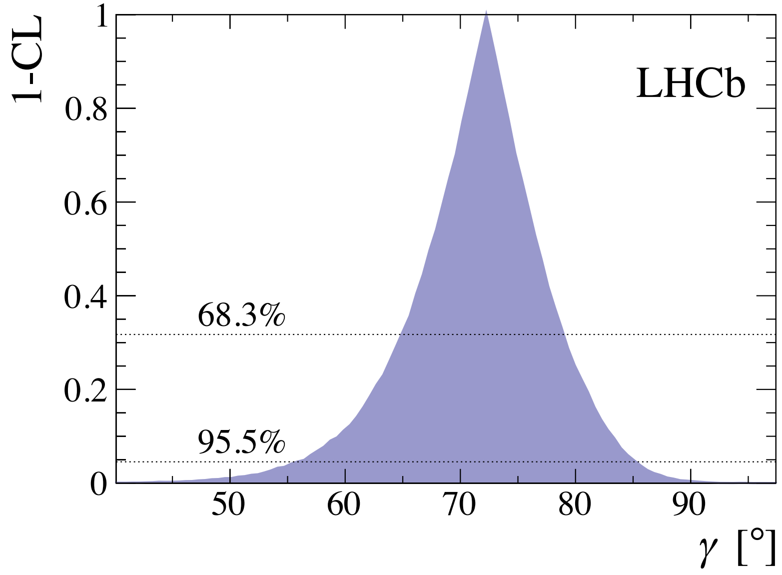
$$x_+ = 0.05 \pm 0.24 \pm 0.04 \pm 0.01$$
$$y_+ = -0.65^{+0.24}_{-0.23} \pm 0.08 \pm 0.01$$
$$x_- = -0.15 \pm 0.14 \pm 0.03 \pm 0.01$$
$$y_- = 0.25 \pm 0.15 \pm 0.06 \pm 0.01$$

- 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

# Combination results



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

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

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

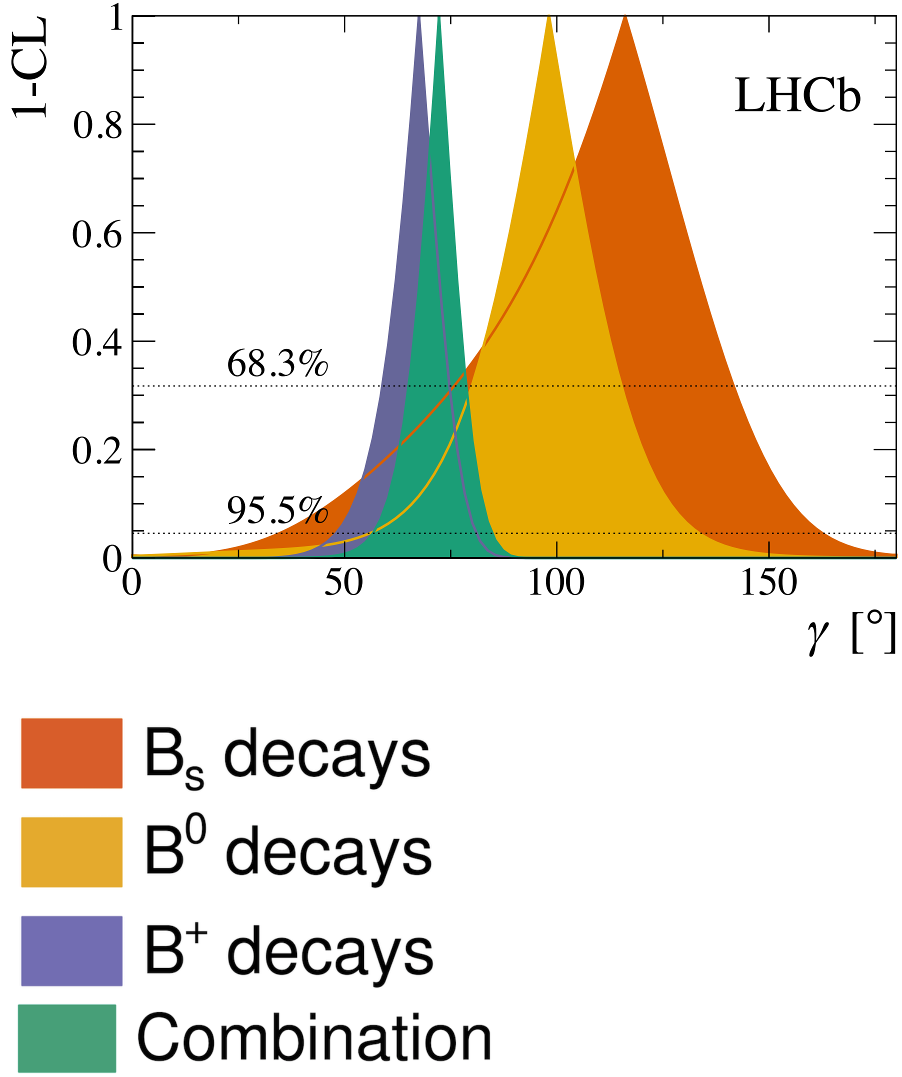
- Frequentist combination using 'plugin' method. 71 observables and 32 parameters.
- More analyses than shown today
- Only "B→DK – like" results included
- Only includes the 1fb$^{-1}$ $B_s$→$D_sK$ result
- Improved precision compared to last combination (2014) by ~20%
- Good agreement with B factory results
- Bayesian interpretation is consistent

PRD 87 (2013) 052015

arXiv:1301.2033

arXiv: 1611.03076

# Contribution from different modes



Common parameter is γ

Necessary to pursue different B decays to provide crosschecks

Current measurements are dominated by statistical uncertainties

arXiv: 1611.03076

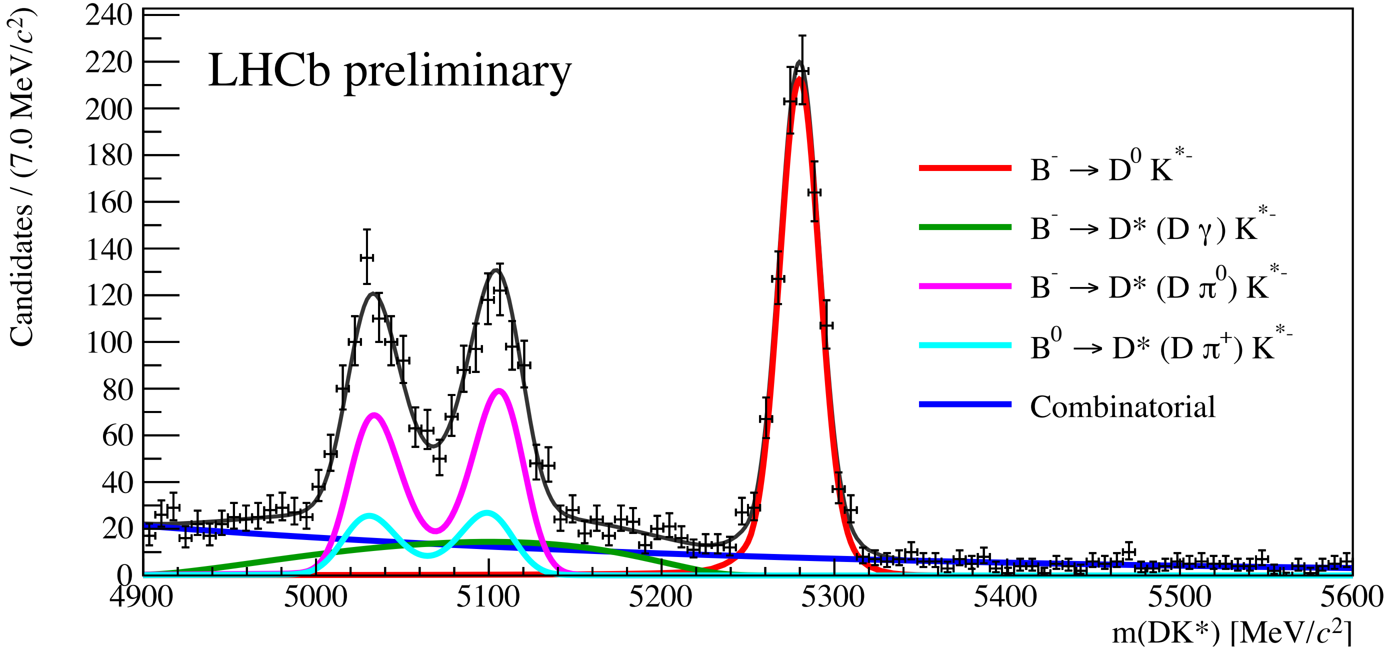
# Run 1 → Run 2

- 2015 – collected 300 $pb^{-1}$ @ 13 TeV
- 2016 – collected 1.7 $pb^{-1}$ @ 13 TeV
- Production cross section increases, improved particle identification, and slight improvements to trigger mean that yield per $pb^{-1}$ are 2-3 times larger in Run 2 (depending on decay mode)

- Starting to analyse new modes with Run 1 + Run 2 data – especially ones that weren't viable with Run 1 only.
- Run 2 target is officially 4°

- $B^+ \rightarrow DK^{*+}$, where $K^{*+} \rightarrow K_S\pi$
  - Should have similar $r_B$ to the usual $B^+ \rightarrow DK^+$ channel
  - However expect lower yields due to the $K_S$ reconstruction efficiency

# $B^+ \rightarrow DK^{*+}$



Signal well separated from any other physics background. High purity

Run 1 (3 $fb^{-1}$) + Run 2 (1 $fb^{-1}$). Yields in each data set are similar

Very exciting for the sensitivities we'd be able to achieve in other decay modes

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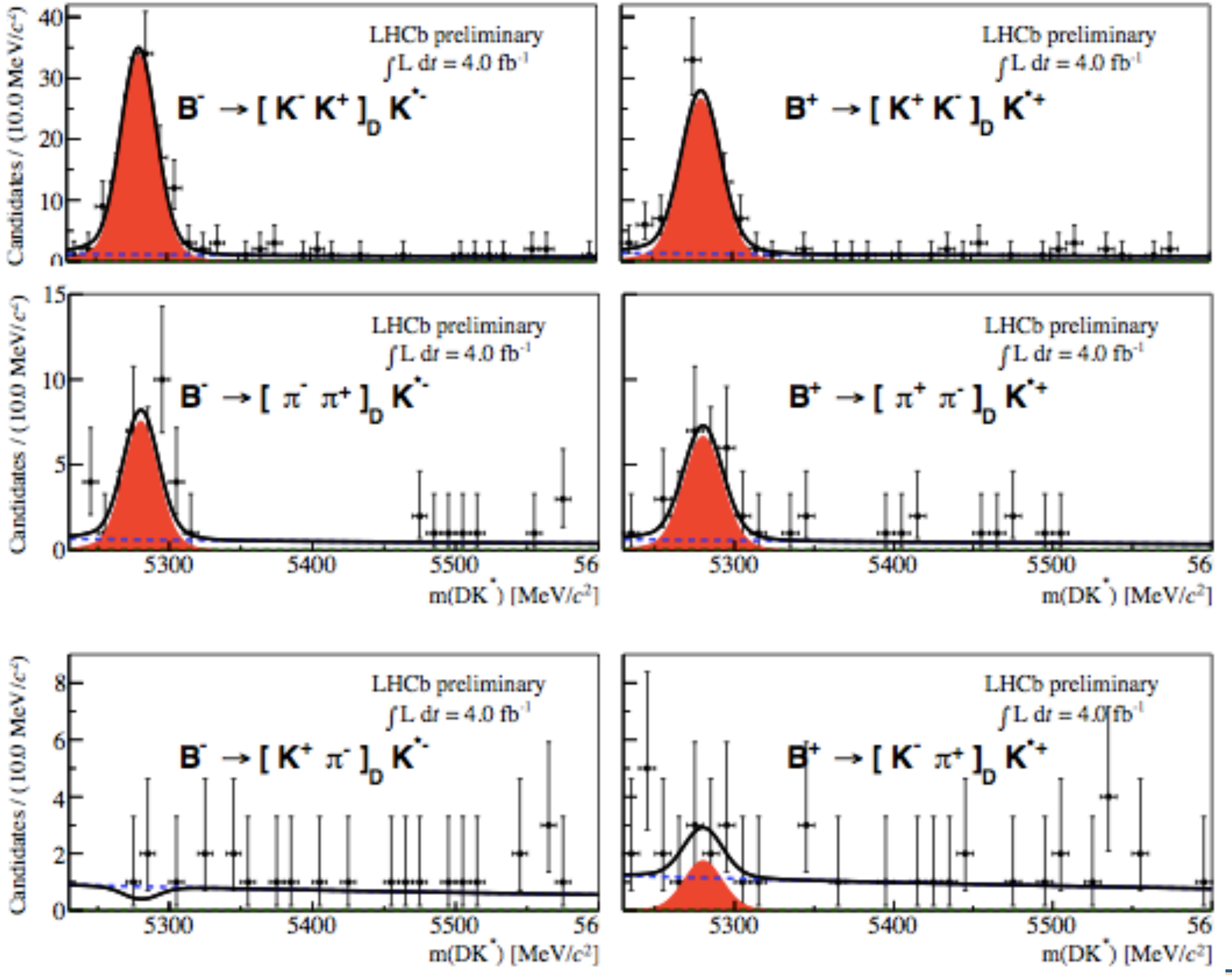
# ADS / GLW analysis



Not enough data to observe the supressed mode, or CPV.

Nonetheless remains promising for future due to high purity.

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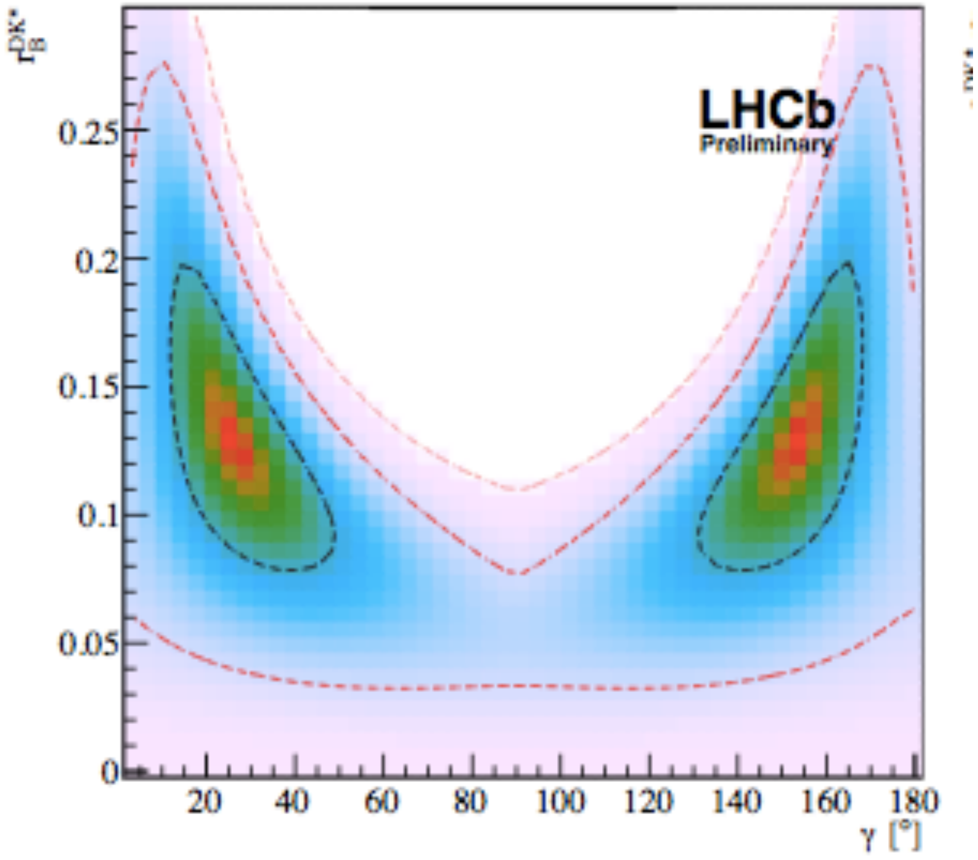
# Sensitivity to γ

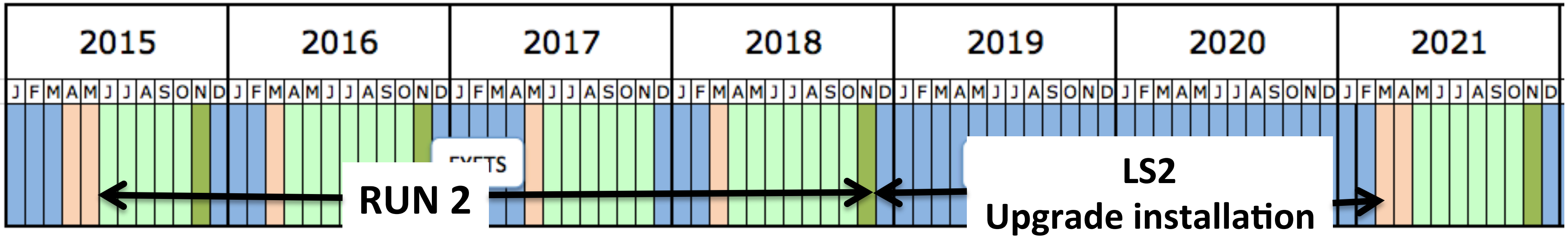


First CPV measurement to include Run 2 data

Add more D decays

In the future will provide a valuable cross check against other modes due to the lack of physics background.

# γ and LHCb upgrade



- Full upgrade in LS2
- Allows for running at higher luminosity in 2021 onwards
- L0 hardware trigger → software trigger
  - Increase trigger efficiency for hadronic modes

- Dominant experimental systematic uncertainties can be controlled
- External inputs will benefit from BES-III data

**LHCb upgrade projection (50 $\mathrm{fb}^{-1}$) for γ is 0.9° -- no showstoppers forseen**

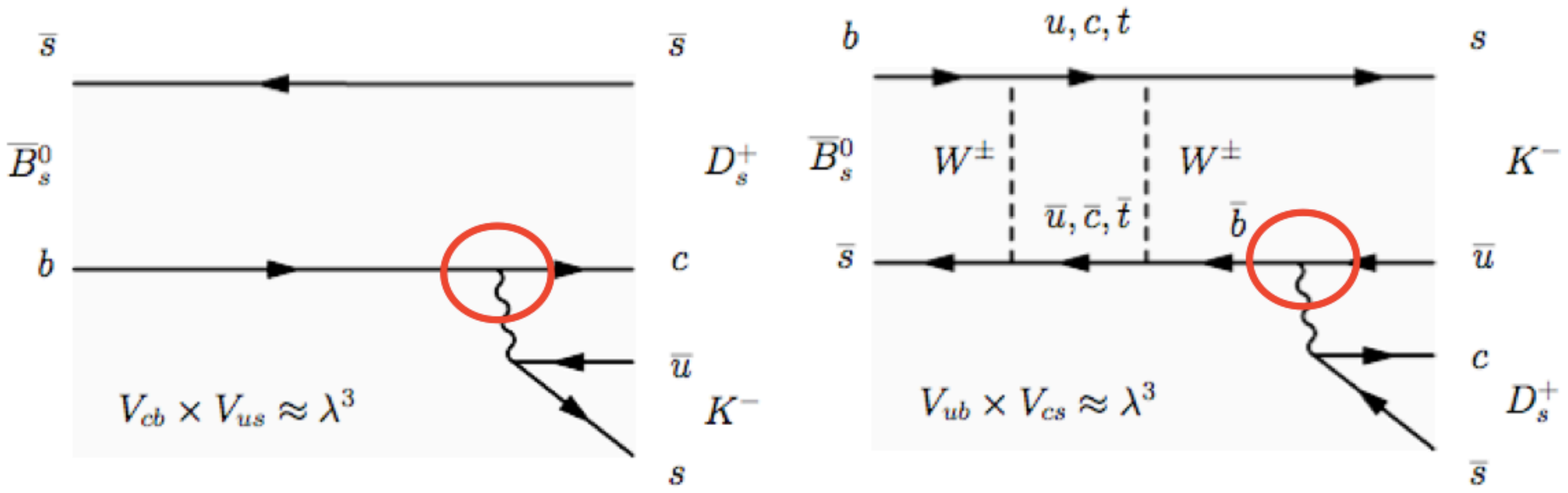
If nature is kind, this precision will allow for observation of New Physics

EPJC (2013) 73:2373

# End

# $B_s \rightarrow D_s K$

Measure CP violation in the interference of mixing and decay



Both decay amplitudes ~ $\lambda^3$ → Large interference

Tree level process like other analyses shown

Time-dependence increases the complexity of the analysis

Flavour-tagging also required to know the flavour of the initial $B_s$ state

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# CP observables

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

$$\lambda_f \equiv \frac{q}{p}\left(\frac{\bar{A}_f}{A_f}\right)$$

$A_f$ is the decay amplitude for $B_S$ to decay to final state f

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

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta - \boxed{(\gamma-2\beta_s))}}{1+r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta + \boxed{(\gamma-2\beta_s))}}{1+r_{D_sK}^2},$$
$$S_f = \frac{2r_{D_sK}\sin(\delta - \boxed{(\gamma-2\beta_s))}}{1+r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta + (\boxed{\gamma-2\beta_s))}}{1+r_{D_sK}^2}.$$

$\beta_s$ - mixing phase

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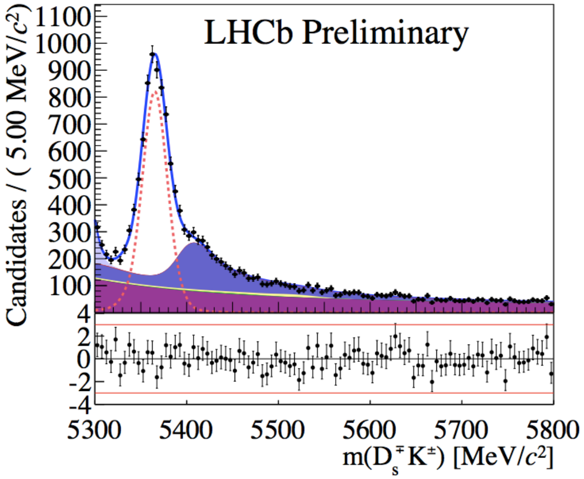
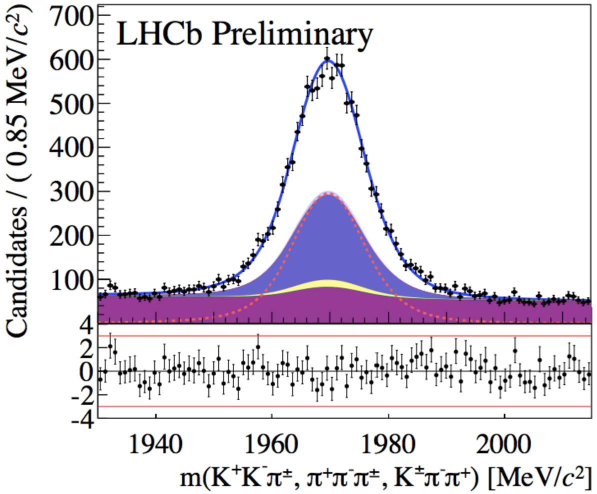
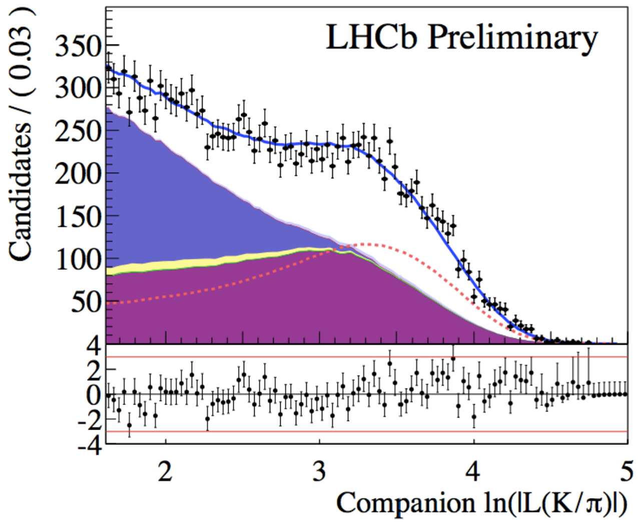
# Signal/background discrimination







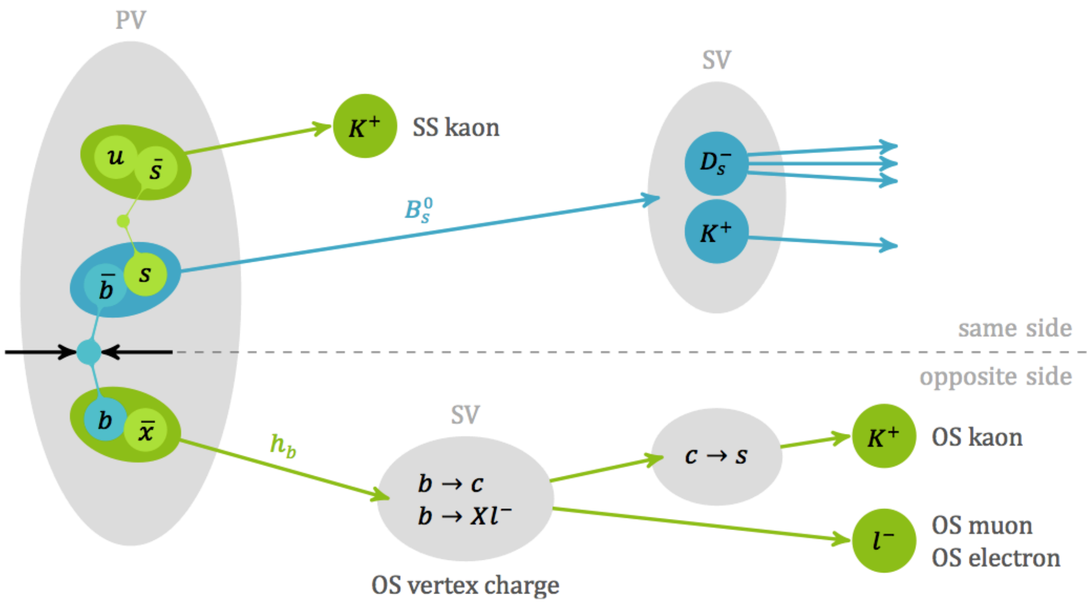
Three $D_s^-$ decays considered: $K^-K^+\pi^-$, $\pi^-\pi^+\pi^-$, $K^-\pi^+\pi^-$: Plots show all $D_s$ states combined

Simultaneous fit in 3 variables: M($B_s$), M($D_s$) and PID variable on the Kaon from the B

Allows for signal/background discrimination, and for determination of signal weights

Subsequent parts of the fit only parameterise the signal distributions with the use of the signal weights

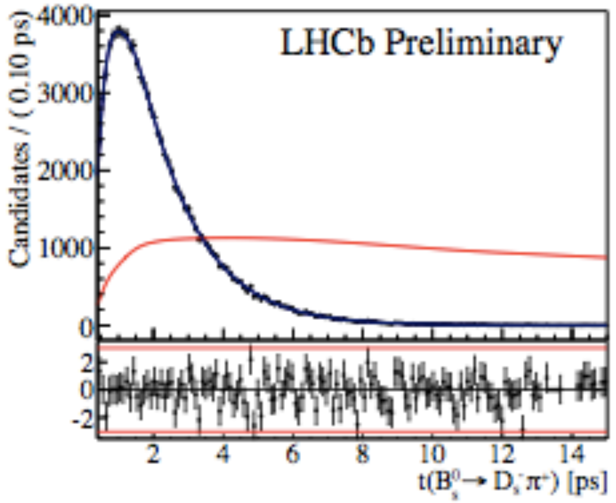
# Flavour tagging and time dependence



Efficiency of tagging an event ~ 65.7%

Effective tagging power ~ 5%

$B_s^0 \to D_s^- \pi^+$ decay-time



Time acceptance determined from $B_S \rightarrow D_s\pi$

Other physics inputs such as $B_S$ mixing and lifetime, and lifetime difference fixed from other measurements

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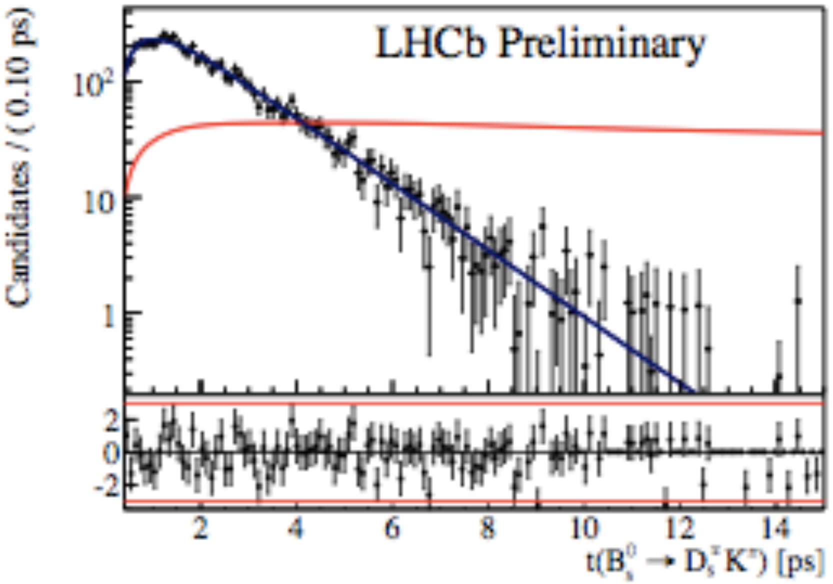
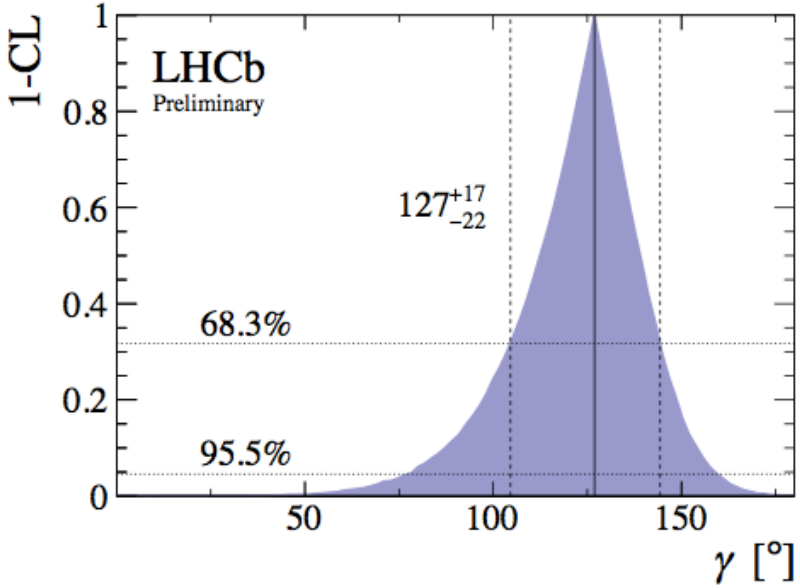
# Fit results and interpretation on γ





| CP parameter | Value |
|---|---|
| $C_f$ | $0.735 \pm 0.143 \pm 0.048$ |
| $A_f^{\Delta\Gamma}$ | $0.395 \pm 0.277 \pm 0.122$ |
| $A_{\bar{f}}^{\Delta\Gamma}$ | $0.314 \pm 0.274 \pm 0.107$ |
| $S_f$ | $-0.518 \pm 0.202 \pm 0.073$ |
| $S_{\bar{f}}$ | $-0.496 \pm 0.197 \pm 0.071$ |

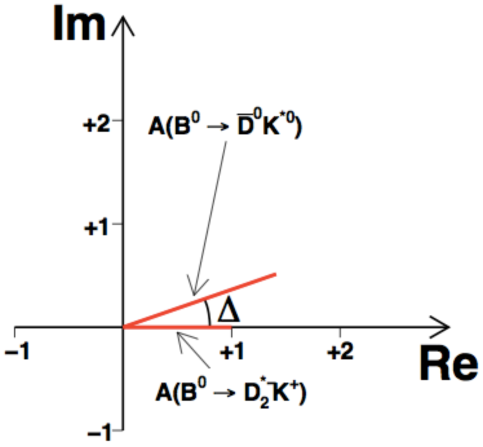
$$\gamma = (127^{+17}_{-22})^\circ$$
$$\delta_{D_sK} = (358^{+15}_{-16})^\circ$$
$$r_{D_sK} = 0.37^{+0.10}_{-0.09}$$

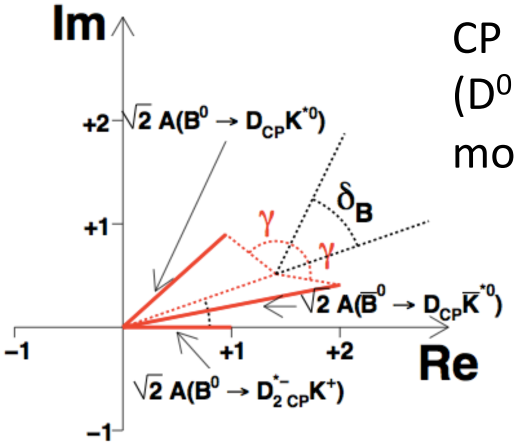
LHCb-CONF-2016-014

# $B^0 \rightarrow DK\pi$ 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 $\gamma$ 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 $D_2^{*}K$
- $\gamma$ measured from amplitudes and not rates → more information than standard GLW analysis
- New method of measuring $\gamma$

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

# 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

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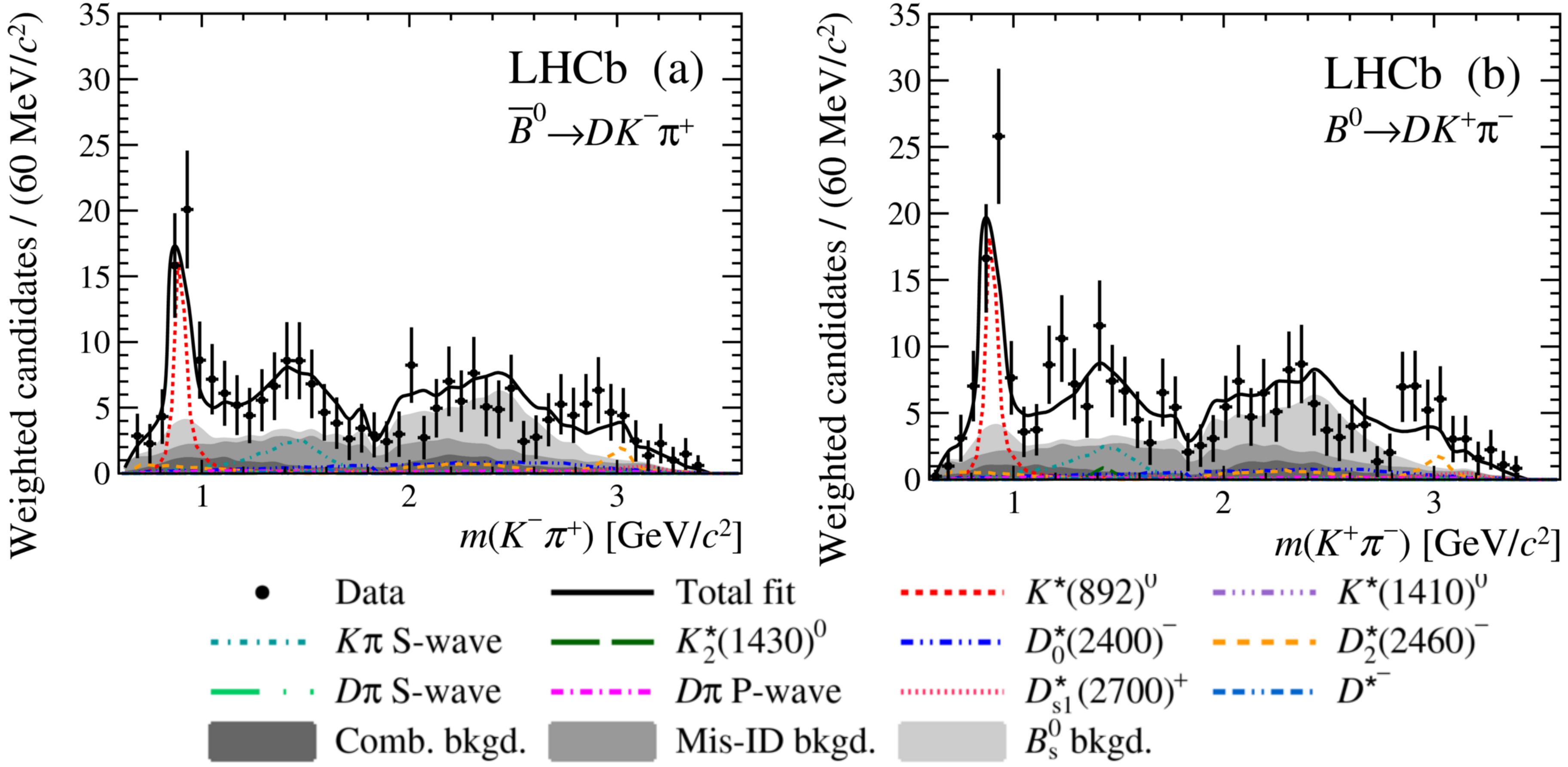
arXiv: 1602.03455

# Dalitz Plot fit



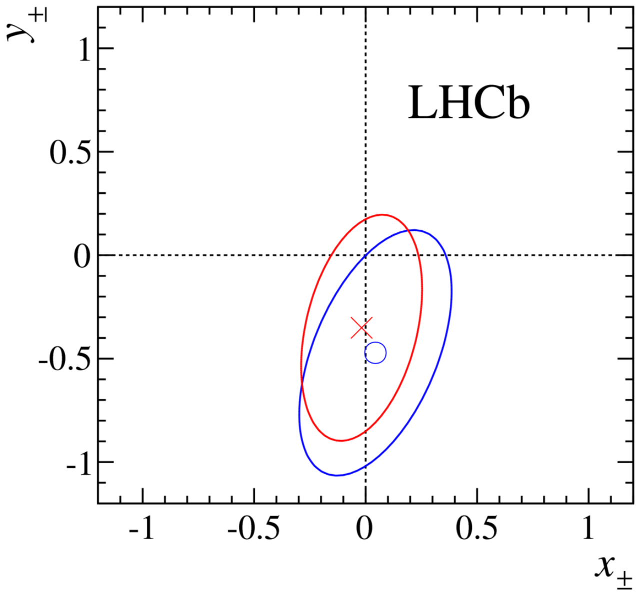
Fit projections of the D→KK and D→ππ samples combined

Only results from K*(892) used

Projections look very similar

arXiv: 1602.03455

# Fit Results



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

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

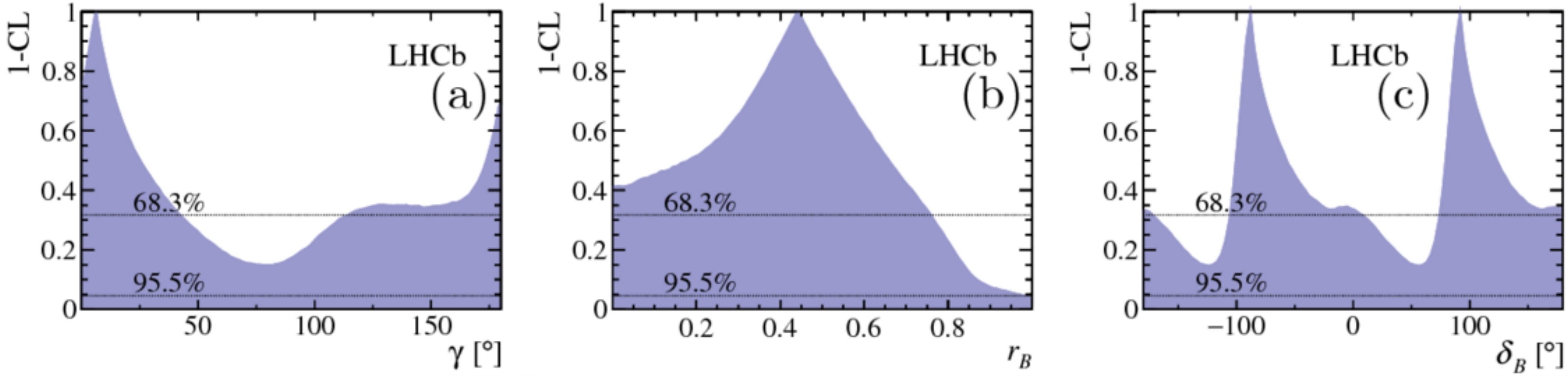
$$y_+ = -0.47 \pm 0.28 \pm 0.22$$

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

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

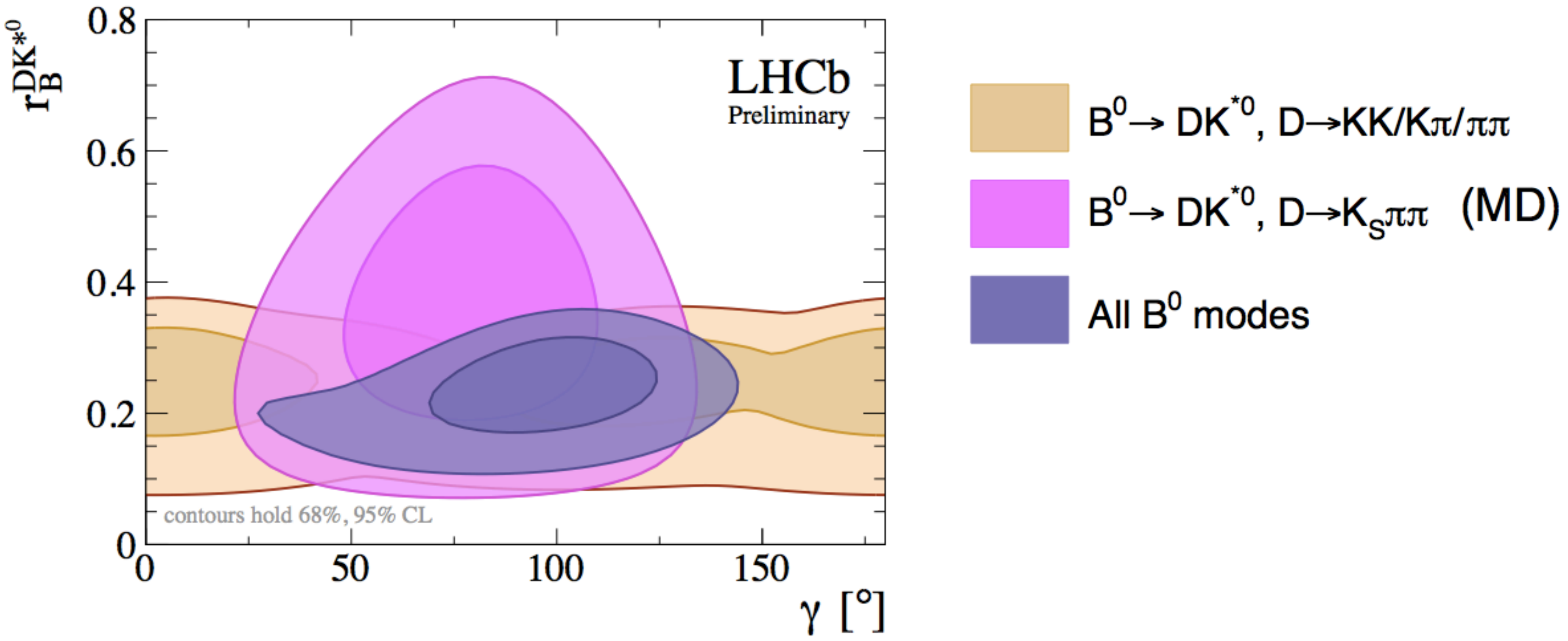
Results for pure K*

Also determine the coherence factor



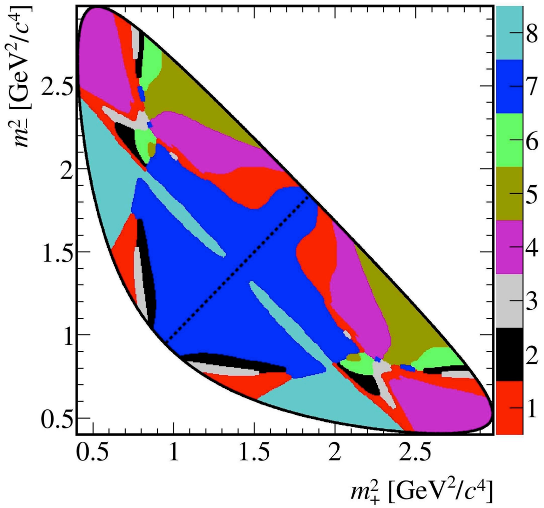
arXiv: 1602.03455

# $B^0$ combination



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

# Model-independent GGSZ analysis



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

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

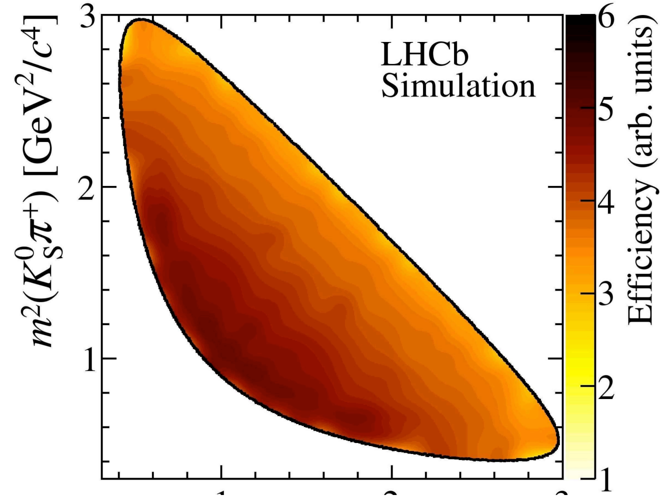
$$F_i = \frac{\int_{\mathcal{D}_i} |A|^2\, \varepsilon\, d\mathcal{D}}{\sum_j \int_{\mathcal{D}_j} |A|^2\, \varepsilon\, d\mathcal{D}}$$

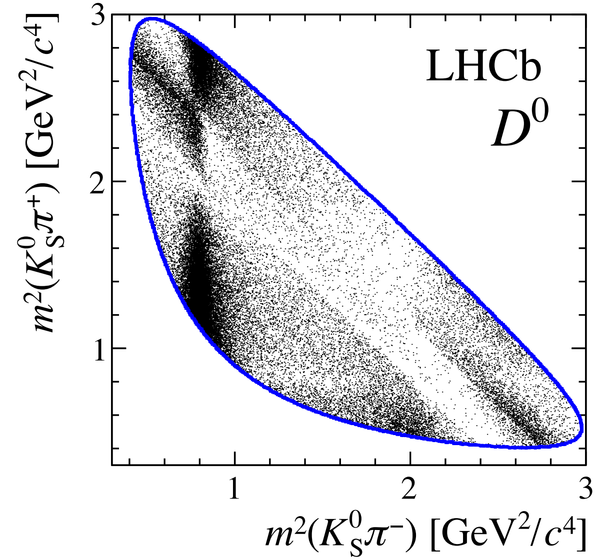
$$y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$

- Reduces to a counting experiment in bins of Dalitz Plot
- Bin definition designed to minimise statistical loss ~ 90% of sensitivity remains
- $F_i$ 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

PRD 82 (2010) 112006

# Dalitz Plot efficiency





- Variation of efficiency on DP must be taken into account

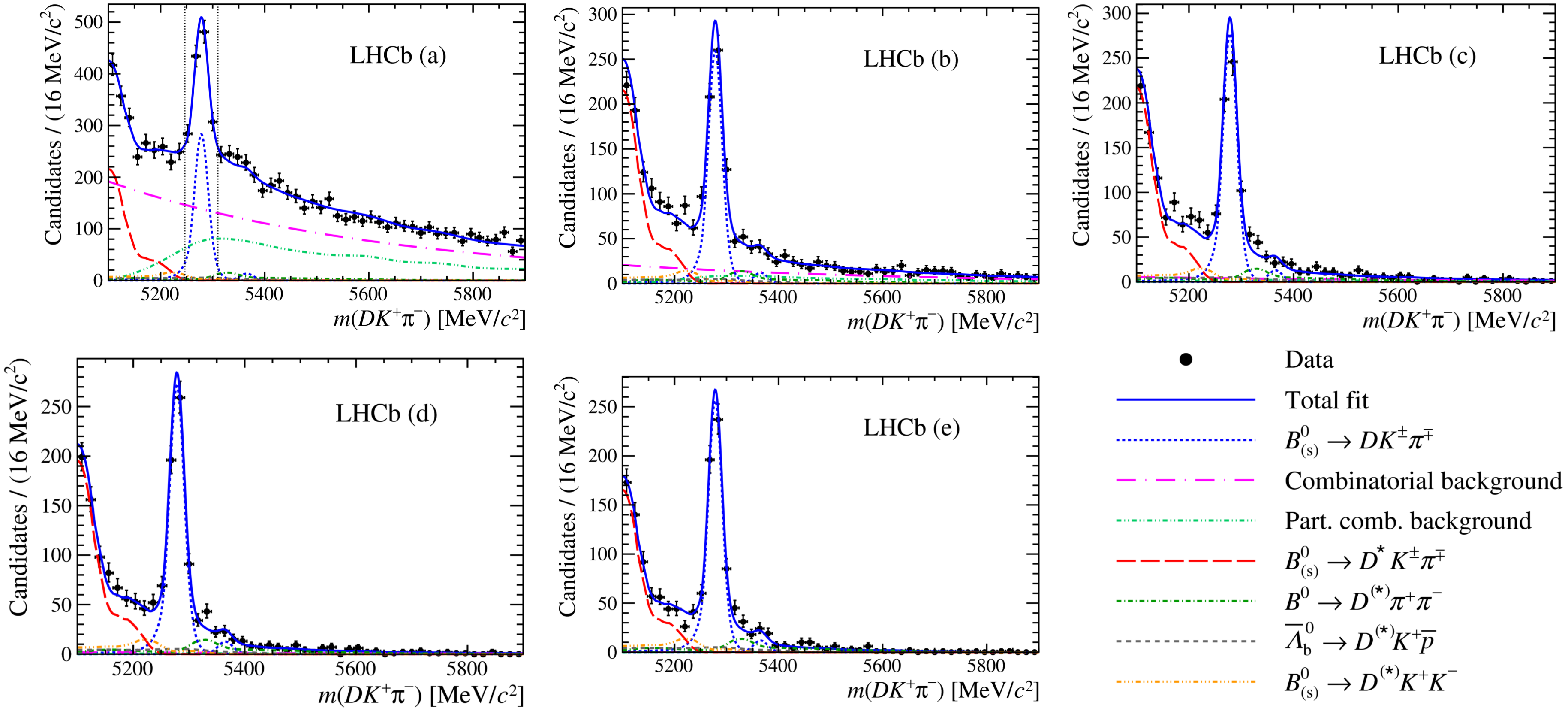
- $B^0 \rightarrow D^*[D^0\pi]\ \mu\nu X$ used to determine $F_i$

- Small corrections required to take care of selection differences between control and signal decay
- Determined from simulation

arXiv: 1604.01525

# 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

# 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 |

🟦 Results discussed today, new or updated since last combination (2014)

🟥 New results from 2015

🟨 Other B→DK 'like' results completed in 2014

# Combing results-other inputs

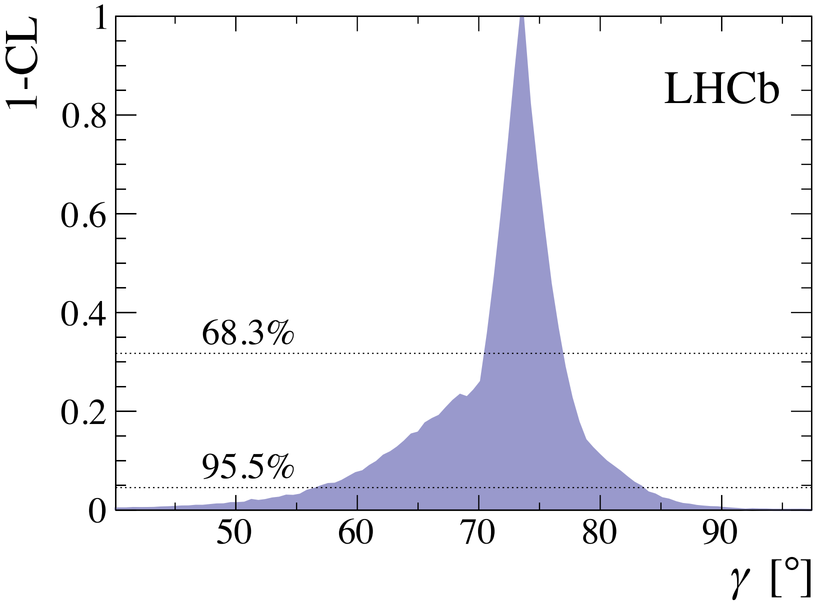
| Parameters | Source | Reference |
|---|---|---|
| Charm mixing and CPV in D→hh | HFAG | www.slac.stanford.edu/xorg/hfag/charm/index.html |
| $\kappa$, $\delta_D$: D→K3$\pi$, D→K$\pi\pi^0$ | LHCb & CLEO data | PLB 757 (2016) 520 |
| $\kappa$, $\delta_D$ : D→$K_s$K$\pi$ | CLEO data | PRD 85 (2012) 092016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

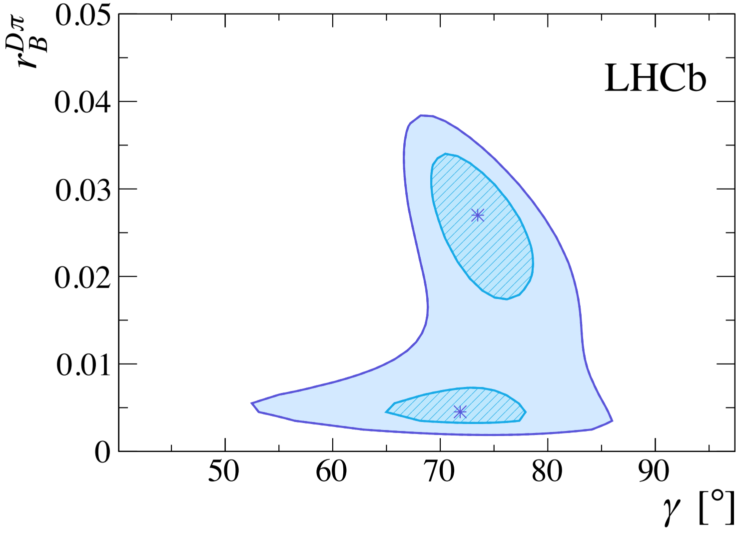
# Adding “B →Dπ” like

B → Dpi decays usually ignored as $r_{Dpi} << r_{DK}$

Don’t like waste!

From CKM elements expect $r_{Dpi}$ ~ 0.005



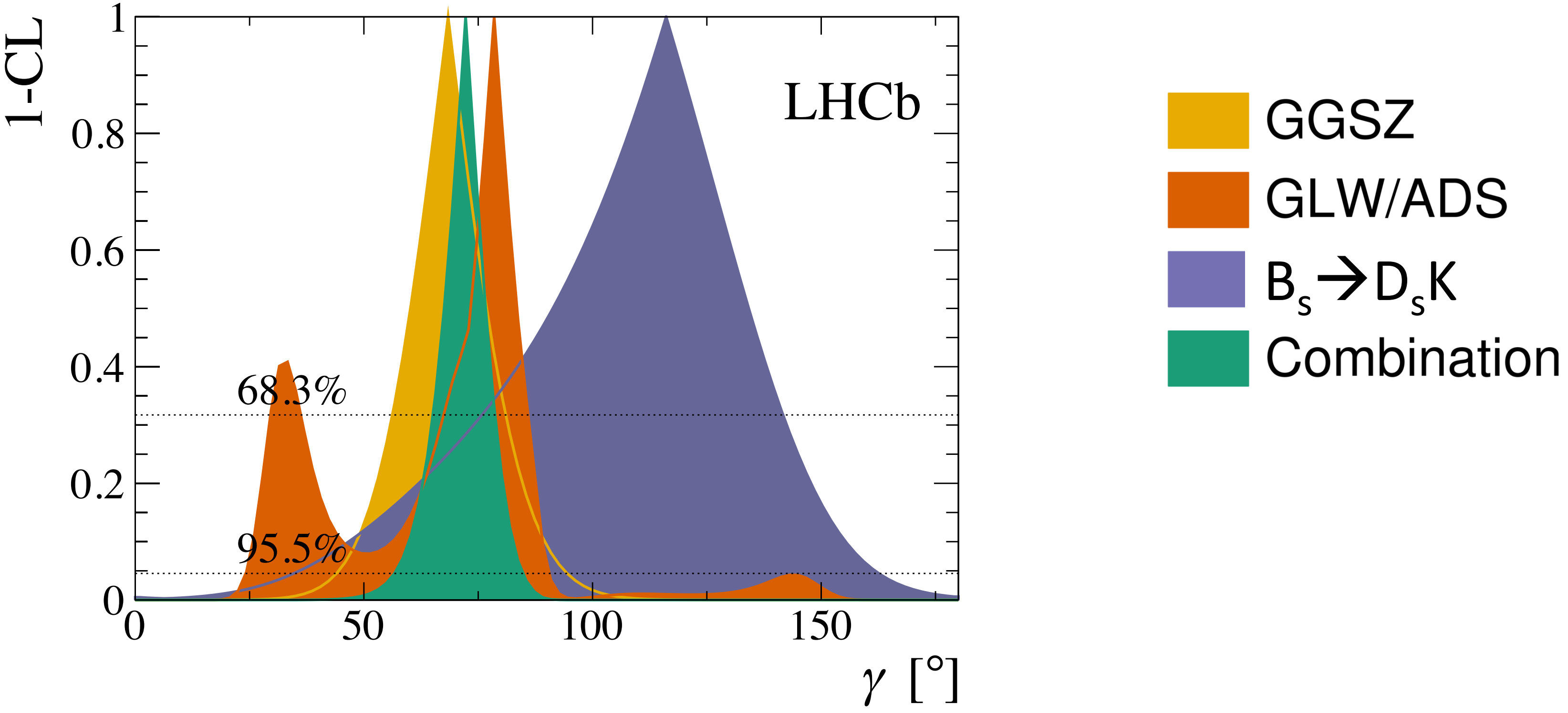


With the D modes analysed available the B→Dpi and B→Dpipipi doesn’t add much in sensitivity.

Aim to extend to other D modes to have a larger impact.

arXiv: 1611.03076

# Contribution from different methods



Demonstrates the need to pursue all methods

arXiv: 1611.03076