Input from the charm threshold for the measurement of γ

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Outline

- Introduction
- CLEO-c and quantum correlation
- Charm threshold inputs
  - CP-content F_+
  - c_i and s_i
  - Coherence factor R
- Summary

CKM angles - current status

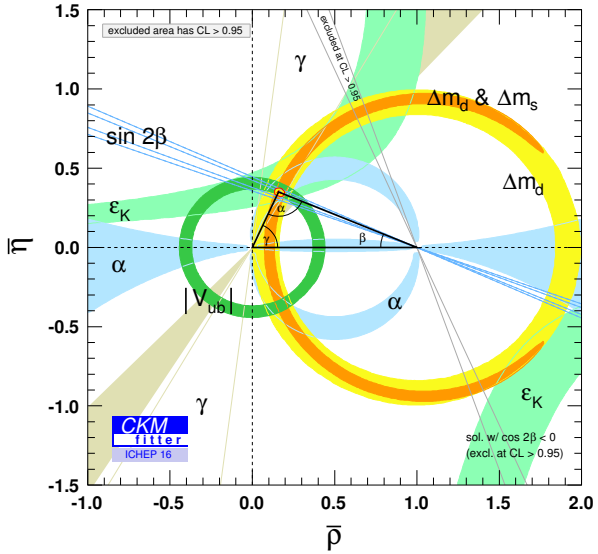


Figure : Constraints on CKM parameters [1].

Current best results for CKM angles [2]

- $\beta_{measured} = (21.9^{+0.7}_{-0.7})^{\circ}$
- $\gamma_{measured} = (73.5^{+4.2}_{-5.1})^{\circ}$
- $\gamma_{predicted} = (65.3^{+1.0}_{-2.5})^{\circ}$

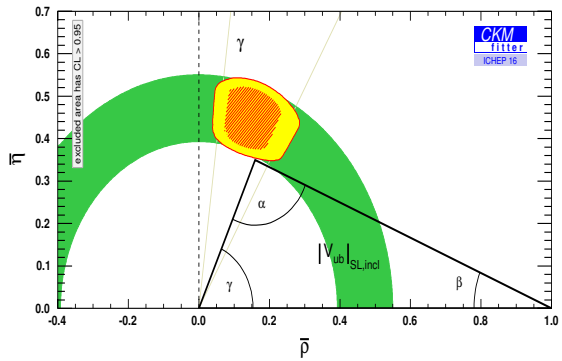


Figure : Constraints from tree quantities.

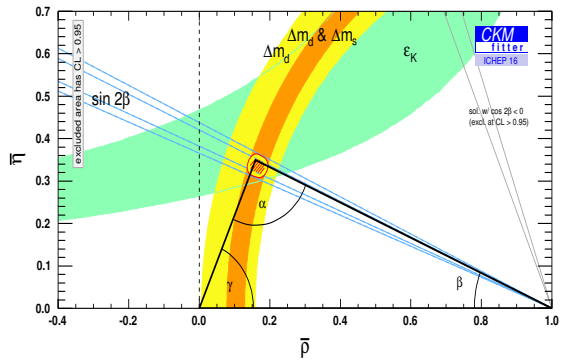


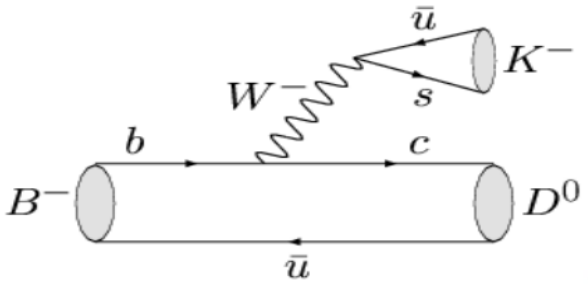
Figure : Constraints from loop quantities.

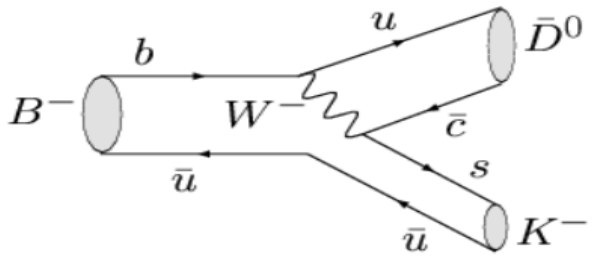
[1] http://ckmfitter.in2p3.fr

[2] http://www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml

γ measurements from $B \to DK$ decays

- Determine γ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$, tree-level diagrams $\Rightarrow 10^{-7}$ theoretical uncertainty [3].





colour allowed

$B^- \to D^0 K^- \approx V_{cb} V_{us}^*$

$\mathbf{A_1}$

colour suppressed

$B^- \to \bar{D}^0 K^- \approx V_{ub} V_{cs}^*$

$\mathbf{A_1 r_B e^{i(\delta_B - \gamma)}}$

- Three types of D final states generally used,
  - CP-eigenstates : **GLW method** [4].
  - $K^+X^-(X^- = \pi^-, \pi^-\pi^0, \pi^-\pi^+\pi^-)$, DCS modes : **ADS method** [5].
  - Multibody self-conjugate states : **GGSZ method** [6].

[3] J. Brod, J. Zupan, JHEP **01**, 051 (2014)

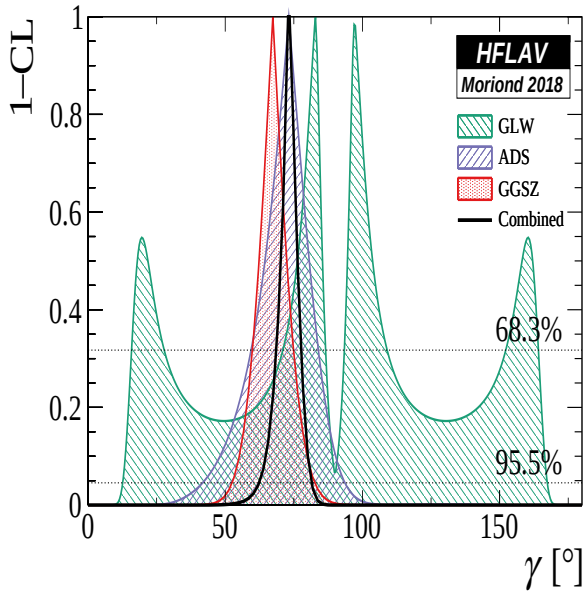
[4] M. Gronau and D. London, PLB **253**, 483 (1991); M. Gronau and D. Wyler, PLB **265**, 172 (1991)

[5] D. Atwood, I. Dunietz and A. Soni, PRL **78**, 3357 (1997)

[6] A. Giri, Yu. Grossman, A. Soffer and J. Zupan, PRD **68**, 054018 (2003)

γ measurements - charm inputs

- The results are statistically limited $\Rightarrow$ charm inputs measuring from B data leads to loss in precision.
- ADS and GGSZ methods need input from charm:
  - δ_D
  - coherence factor R
  - c_i, s_i
- New D modes can be added for GLW:
  - 3-body final states
  - CP-content F_+
- Inputs from charm threshold are crucial!
- The current CLEO-c inputs contribute 2° uncertainty to γ [7].



[2] http://www.slac.stanford.edu/xorg/hflav/triangle/moriond2018/index.shtml
[7] LHCb-PUB-2016-025

Quantum correlated D mesons at CLEO-c

- $\Psi \to D\bar{D}$ are produced coherently in the $C = -1$ state.

$$\frac{\left(|D\rangle\,|\bar{D}\rangle - |\bar{D}\rangle\,|D\rangle\right)}{\sqrt{2}}$$

- Good 4π solid angle coverage $\Rightarrow$ full reconstruction of $D\bar{D}$ event.
- High efficiency of track and photon reconstruction.
- If $\Psi(3770)$ decays into two states F and G, then decay rate (Γ) depends on their CP eigenvalue.

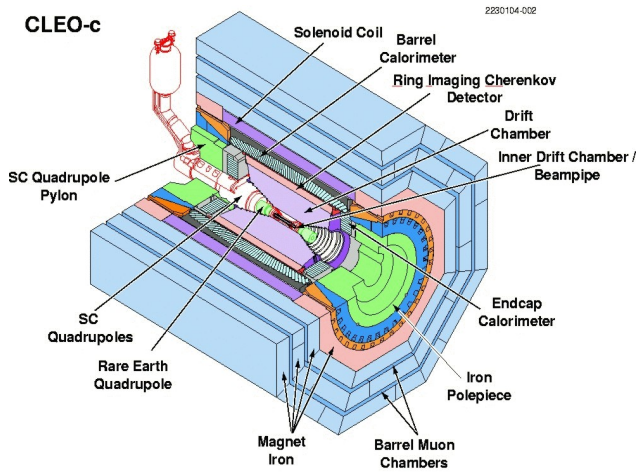
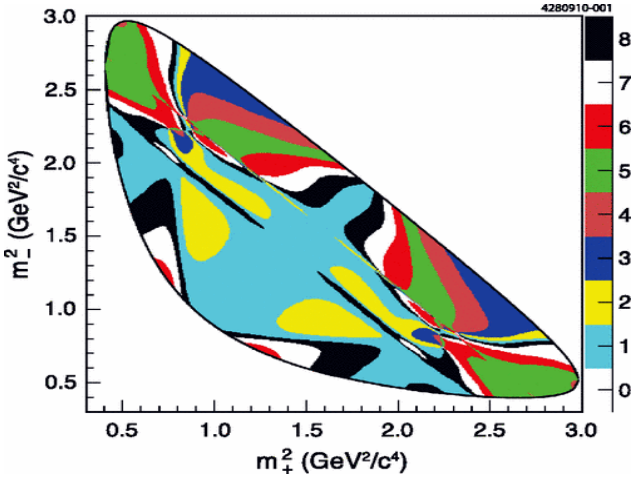


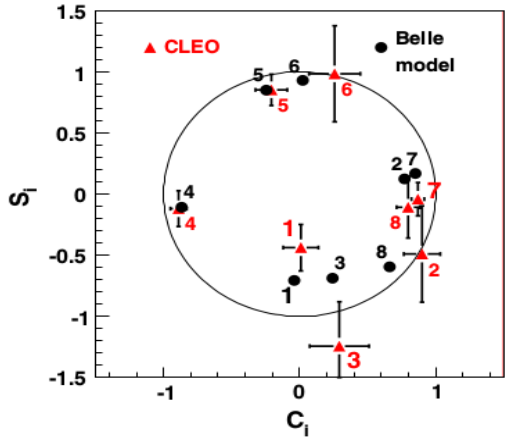
Figure : CLEO-c detector.

- $F = CP$ even (odd), $G = CP$ odd (even) $\Rightarrow$ two-fold enhancement.
- $F = CP$ even (odd), $G = CP$ even (odd) $\Rightarrow$ zero.
- Γ changes with F or G being quasi CP states ($\pi^+\pi^-\pi^0$) or self conjugate states ($K^0_S\pi^+\pi^-$).

$D \to K^0_S \pi^+ \pi^-$

- Golden mode to determine γ via GGSZ formalism.
- Optimal binning of Dalitz plot guided by amplitude model.
- c_i and s_i in each bin measured from quantum correlated D mesons at CLEO-c.





- Belle and LHCb ϕ_3/γ measurements with CLEO-c inputs :

$$\boxed{\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ}$$

(PRD **85**, 112014 (2012))

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

(JHEP **1410**, 097 (2014))

- Preliminary c_i, s_i results with BES III.

[8] PRD **82**, 112006 (2010)

$D \to K^0_S \pi^+ \pi^- \pi^0$

- Relatively large branching fraction of 5.2%.
- Analysed the mode against CP-eigenstates and $K^0_{S,L}\pi^+\pi^-$ as tags.

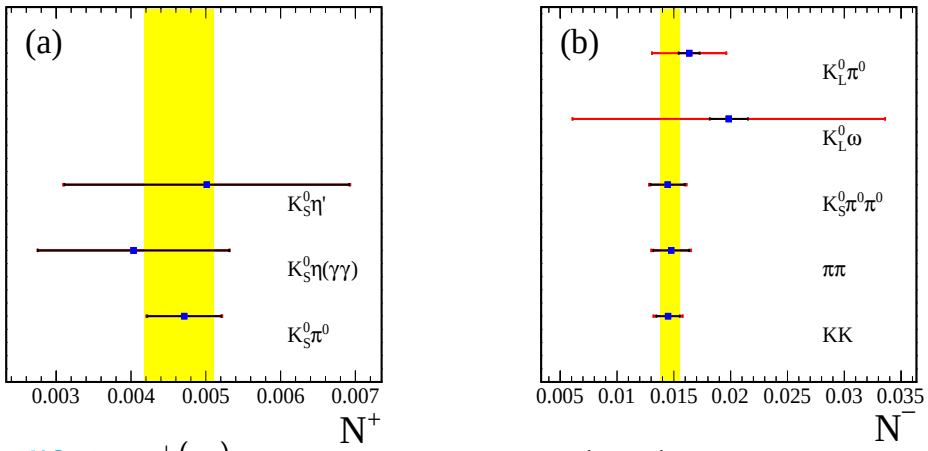


Figure : $N^{+(-)}$ values for the CP-odd (even) tags. The yellow region shows the average value.

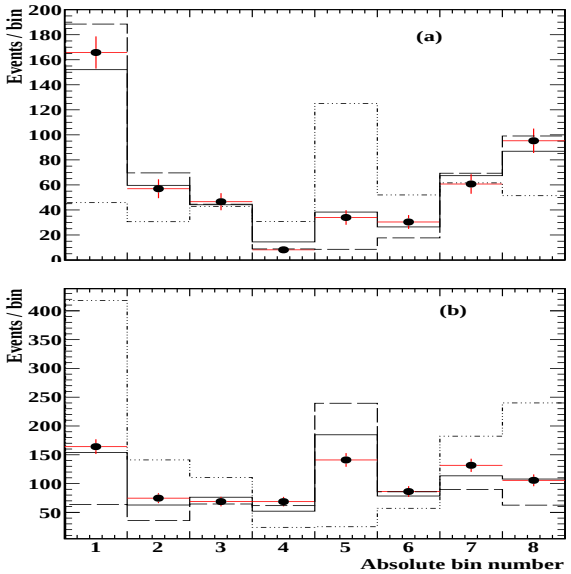


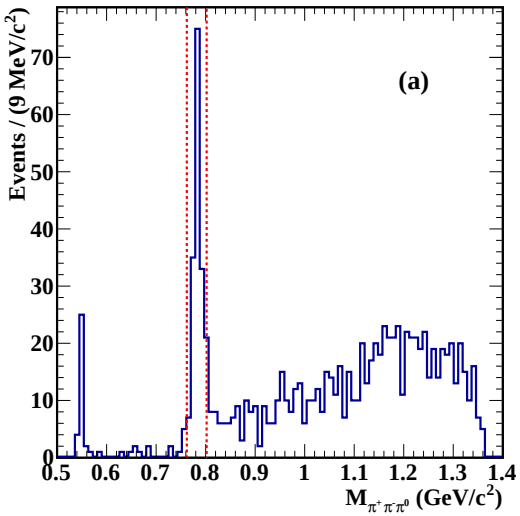
Figure : Expected and measured yields with $K^0_{S,L}\pi^+\pi^-$ tags.

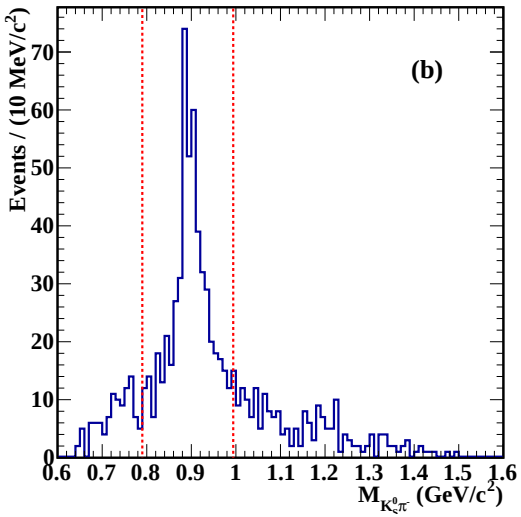
- $F_+ = \frac{N^+}{N^+ + N^-}$ for CP tags.
- Yield $\alpha\ 1 - (F_+^{\rm sig} - 1)(F_+^{\rm tag} - 1)$ for $K^0_{S,L}\pi^+\pi^-$ tags.
- $F_+ = \mathbf{0.238 \pm 0.018}$, almost a CP-odd state.

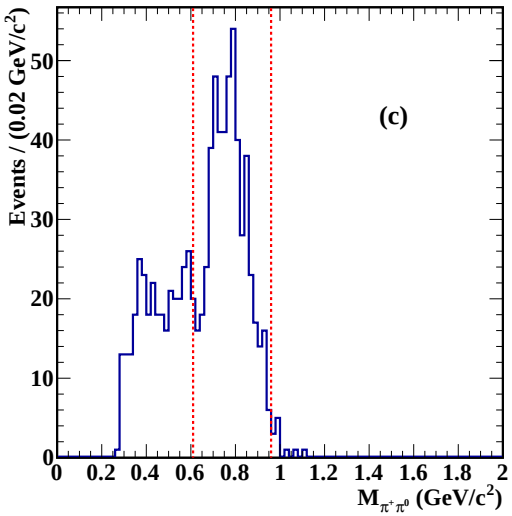
[9] JHEP **01**, 82 (2018)

$D \to K^0_S \pi^+ \pi^- \pi^0$

- Interesting resonance substructures.
  - $K^0_S \omega$ - *CP* eigenstate - GLW like.
  - $K^{*-} \pi^+ \pi^0$ - Cabibbo-favored state (CF) - ADS like.
- Binning the phase space around the resonances.







[9] JHEP **01**, 82 (2018)

$D \to K^0_S \pi^+ \pi^- \pi^0$

Bin	resonance	c_i	s_i
1	ω	$-1.11 \pm 0.09^{+0.02}_{-0.01}$	0.00
2	$K^{*-}\rho^+$	$-0.30 \pm 0.05 \pm 0.01$	$-0.03 \pm 0.09^{+0.01}_{-0.02}$
3	$K^{*+}\rho^-$	$-0.41 \pm 0.07^{+0.02}_{-0.01}$	$0.04 \pm 0.12^{+0.01}_{-0.02}$
4	K^{*-}	$-0.79 \pm 0.09 \pm 0.05$	$-0.44 \pm 0.18 \pm 0.06$
5	K^{*+}	$-0.62 \pm 0.12^{+0.03}_{-0.02}$	$0.42 \pm 0.20 \pm 0.06$
6	K^{*0}	$-0.19 \pm 0.11 \pm 0.02$	0.00
7	ρ^+	$-0.82 \pm 0.11 \pm 0.03$	$-0.11 \pm 0.19^{+0.04}_{-0.03}$
8	ρ^-	$-0.63 \pm 0.18 \pm 0.03$	$0.23 \pm 0.41^{+0.04}_{-0.03}$
9	remainder	$-0.69 \pm 0.15^{+0.15}_{-0.12}$	0.00

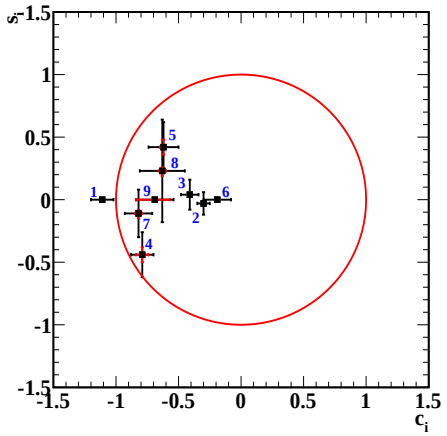
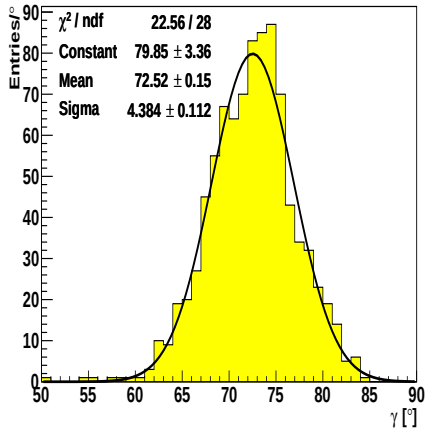


Figure : c_i and s_i results in various bins.

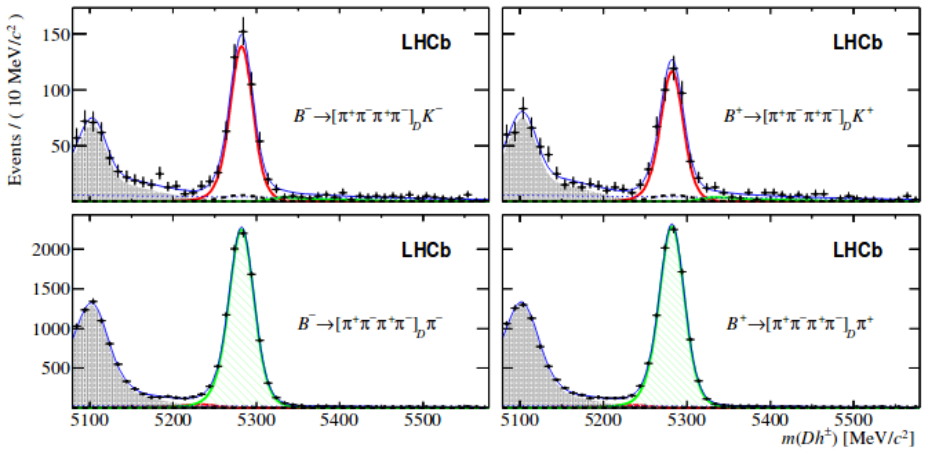
- Estimates of γ sensitivity with $B^\pm \to D(K^0_S \pi^+ \pi^- \pi^0) K^\pm$ give $\sigma_\gamma = \mathbf{4.4}^\circ$ with 50 ab^{-1} data from Belle II.
  - Assumed $\epsilon \times BF$ similar to $K^0_S \pi^+ \pi^-$.
- Improvements expected with
  - knowledge of an amplitude model,
  - finer binning from a larger statistics (BES III).

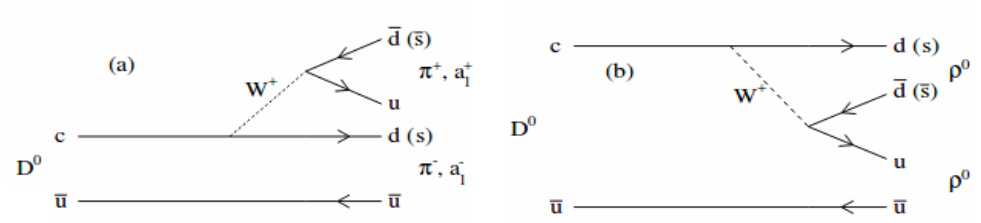


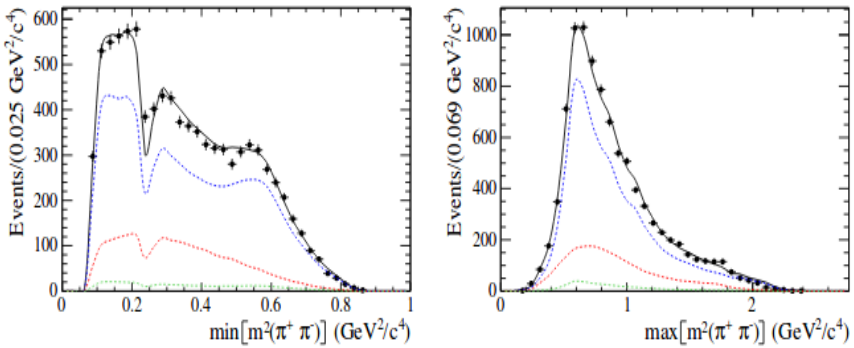
[9] JHEP **01**, 82 (2018)

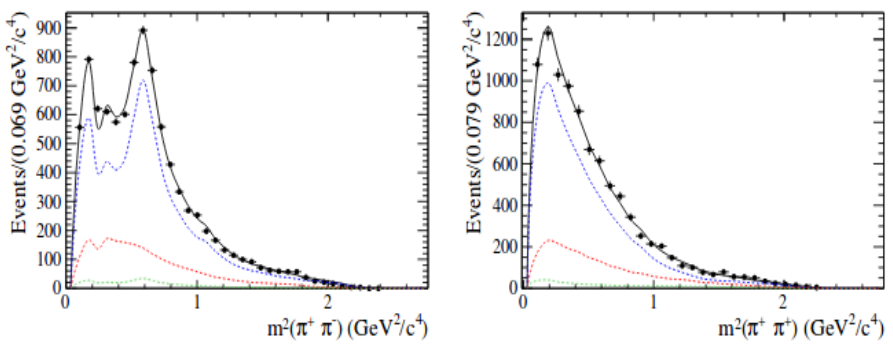
$D \to \pi^+\pi^-\pi^+\pi^-$

- All charged final state - clean detection - important for LHCb.
  (PLB **760** 117 (2016))
- Binning based on amplitude model.
- Prominent contributions $a_1(1260)^+$, $\rho(770)^0$.





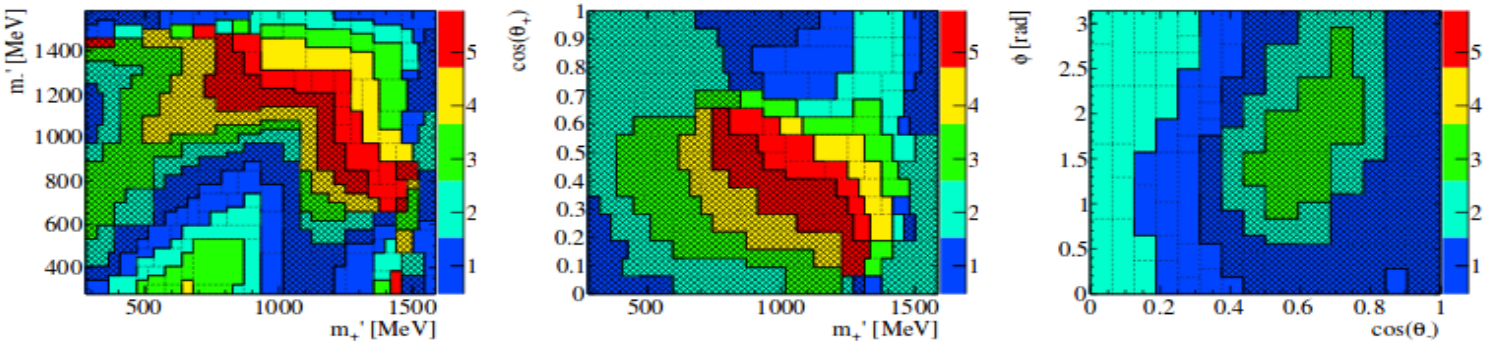




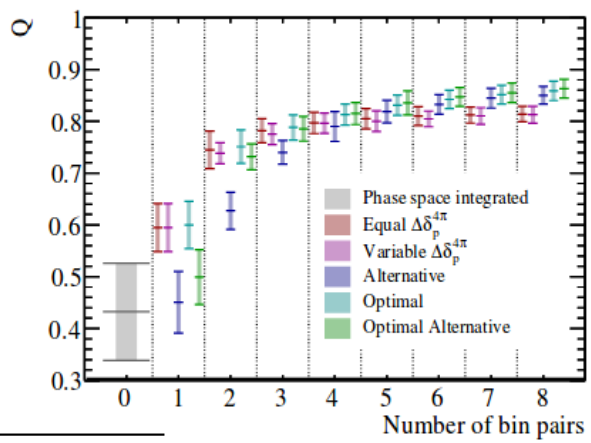
[10] JHEP **05**, 143 (2017)

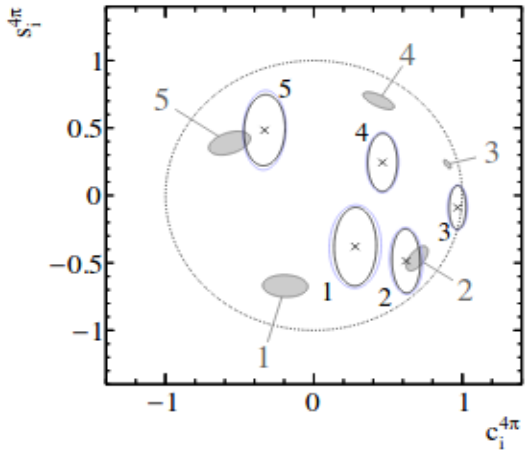
$D \to \pi^+\pi^-\pi^+\pi^-$

- Binning guided by the amplitude model, but the measurement of c_i and s_i is still model-independent.
- 5D binning based on $\{m_+, m_-, \cos\theta_+, \cos\theta_-, \phi\}$.



- Sensitivity to γ - in terms of Q value.

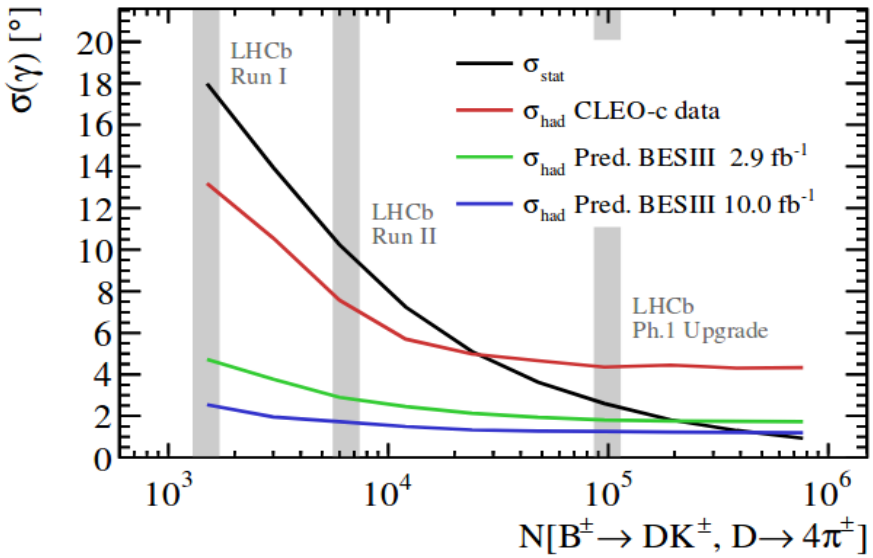




[11] JHEP **01**, 144 (2018)

- The sensitivity to γ with the obtained results:

Binning scheme	$\mathcal{N}$	$\sigma_{\rm stat}(\gamma) \oplus \sigma_{\rm had}(\gamma)$	
		LHCb Run II 8 fb^{-1}	LHCb Ph. 1 upgrade 50 fb^{-1}
Optimal	5	10.0⊕7.9	2.6⊕5.0
Optimal alternative	5	9.7⊕7.4	2.5⊕4.4



[11] JHEP **01**, 144 (2018)

$D \to \pi^+\pi^-\pi^+\pi^-$

- *CP*-content of $\pi^+\pi^-\pi^+\pi^-$ mode - from *CP* and $K^0_{S,L}\pi^+\pi^-$ tags.

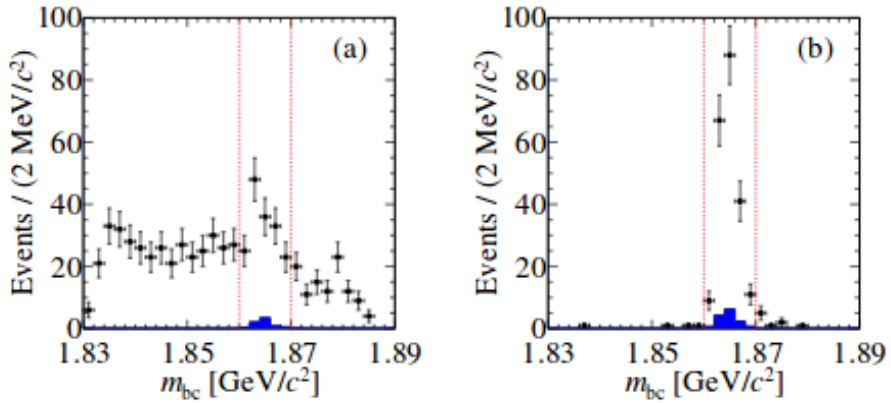
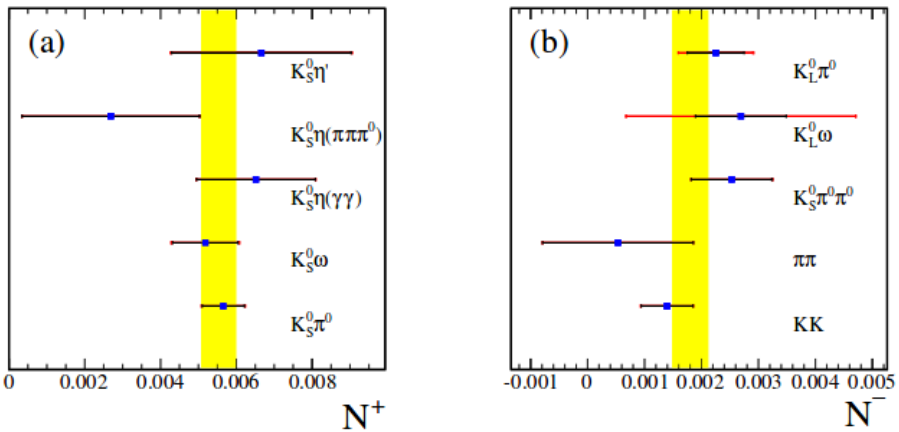


Figure : Average m_{bc} distributions for *CP*-even and *CP*-odd tags (non-K^0_L).



- $F_+^{4\pi} = \mathbf{0.737 \pm 0.028}$.
- Consistent results using amplitude model as well as c_i, s_i values.

[12] PLB **747**, 9 (2015)

$D \to K^-\pi^+\pi^+\pi^-$

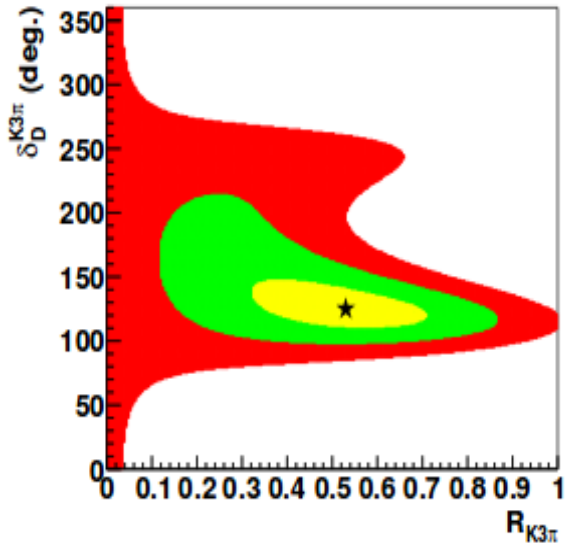
- Coherence factor $R_{K3\pi}$ to treat like two-body with single effective strong phase δ_D in ADS formalism.

$$R_{K3\pi} e^{-i\delta_D^{K3\pi}} = \frac{\int A^*_{K^-\pi^+\pi^+\pi^-}(x) A_{K^+\pi^-\pi^+\pi^-}(x) dx}{A_{K^-\pi^+\pi^+\pi^-} A_{K^+\pi^-\pi^+\pi^-}}$$

- Modulates the interference term of the ADS input parameters - charge averaged rate R_{ADS} and partial rate asymmetry A_{ADS}.

- With CLEO-c data

Parameter	Fitted values
$R_{K3\pi}$	$0.53^{+0.18}_{-0.21}$
$\delta_D^{K3\pi}$	$(125^{22}_{14})^\circ$



[13] PLB **757**, 520 (2016)

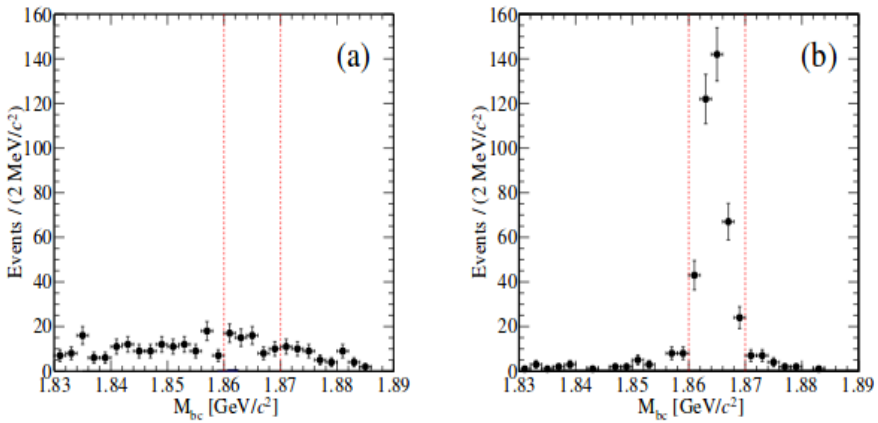
$D \to \pi^+\pi^-\pi^0$

- Symmetry of the $\pi^+\pi^-\pi^0$ Dalitz plot indicates an isospin $= 0$ state.

  (PRL **99** 251801 (2007))

- G-parity suggests an almost pure *CP*-even eigenstate.

  (PRD **78** 014015 (2008))



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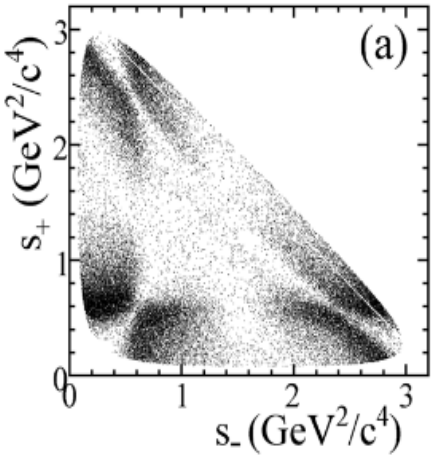


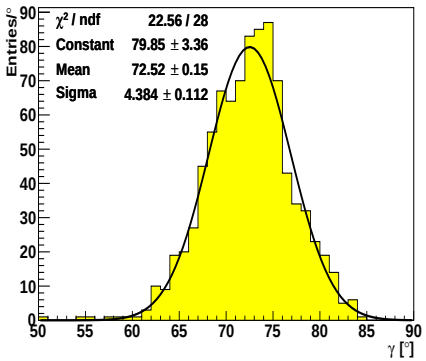
- With *CP*-eigenstates and $K^0_{S,L}\pi^+\pi^-$ as tags, $F_+ = \mathbf{0.973 \pm 0.017}$.
- Almost a pure *CP*-even state.
- Similar measurement for $D \to K^+K^-\pi^0$ yields $F_+ = \mathbf{0.732 \pm 0.055}$.

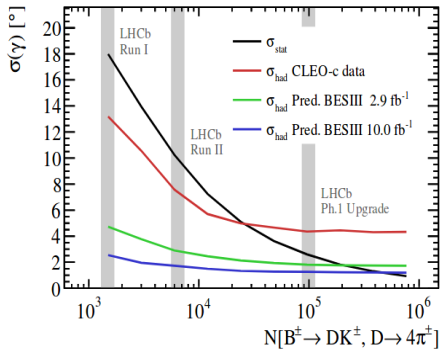
[12] PLB **747**, 9 (2015)
[14] PLB **740**, 1 (2015)

Summary

- Quantum correlated decays exploited to get charm inputs for γ measurements.
- c_i, s_i : input for GGSZ method.
  - Results for $K_S\pi^+\pi^-$, $K^0_S\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$.
- Coherence factor R : for multibody ADS analyses.
  - $K^-\pi^+\pi^+\pi^-$ mode, with also inputs from charm mixing.
- CP-content F_+ : allows additional 3-body D modes in GLW formalism.
  - Modes $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$ are good additions.

- Precision on γ reaching $\mathcal{O}(1^\circ)$.





- Inputs from BES III bring more improvements.

Back-up slides

$D \to K^-\pi^+\pi^+\pi^-$

- $D - \bar{D}$ mixing as input for γ measurements.
- Charm mixing results for $D \to K\pi\pi\pi$ from LHCb (PRL **116**, 24 (2016))

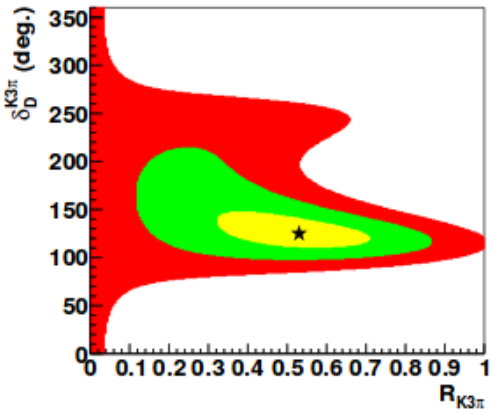


Figure : With CLEO-c

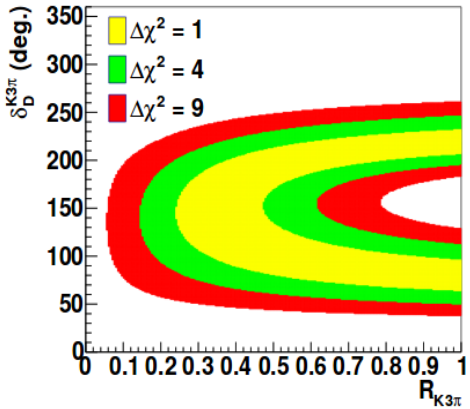


Figure : With charm mixing at LHCb

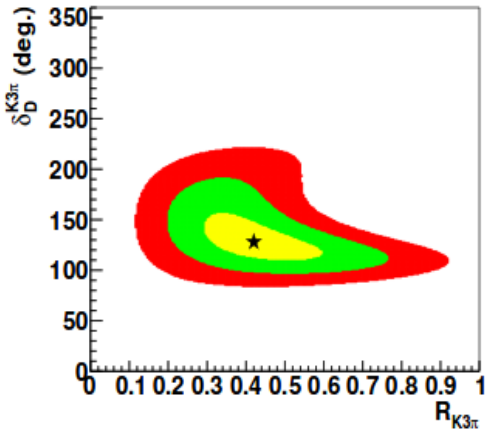
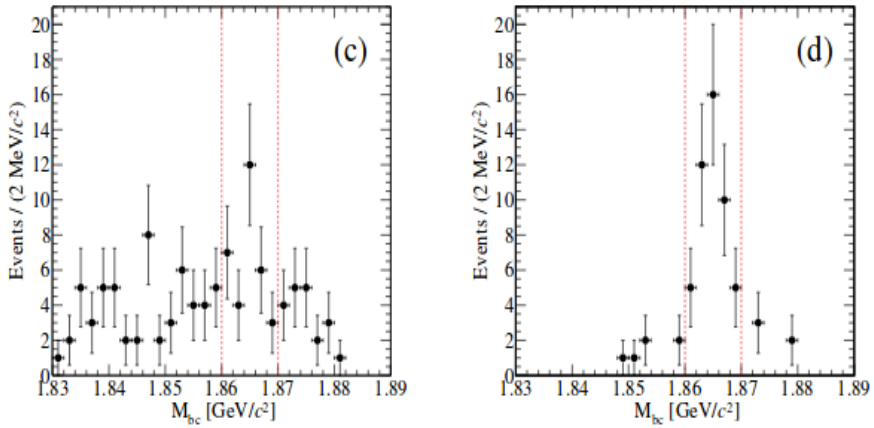


Figure : Combined result

[11] PLB **757**, 520 (2016).

$D \to K^+K^-\pi^0$

- Smaller branching fraction of 0.33%.
- But relatively cleaner to detect experimentally.



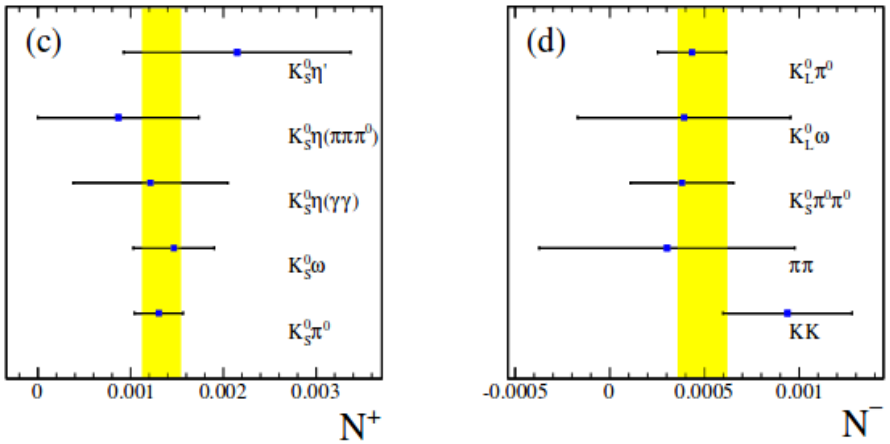


Figure : Average m_{bc} distributions for CP-even and CP-odd tags (non-K^0_L)

- $F_+ = \mathbf{0.732 \pm 0.055}$ with CP-eigenstates and $K^0_{S,L}\pi^+\pi^-$ as tags.
- Predominantly CP-even.

[10] PLB **747**, 9 (2015)
[12] PLB **740**, 1 (2015)