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CP content of $D^0 \to h^+ h^- \pi^0$

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Based on

M. Nayak (now Wayne State) et al. Physics Letters **B740** (2015) 1

Partial update in S. Malde et al. arXiv:1504.05878 [hep-ex]

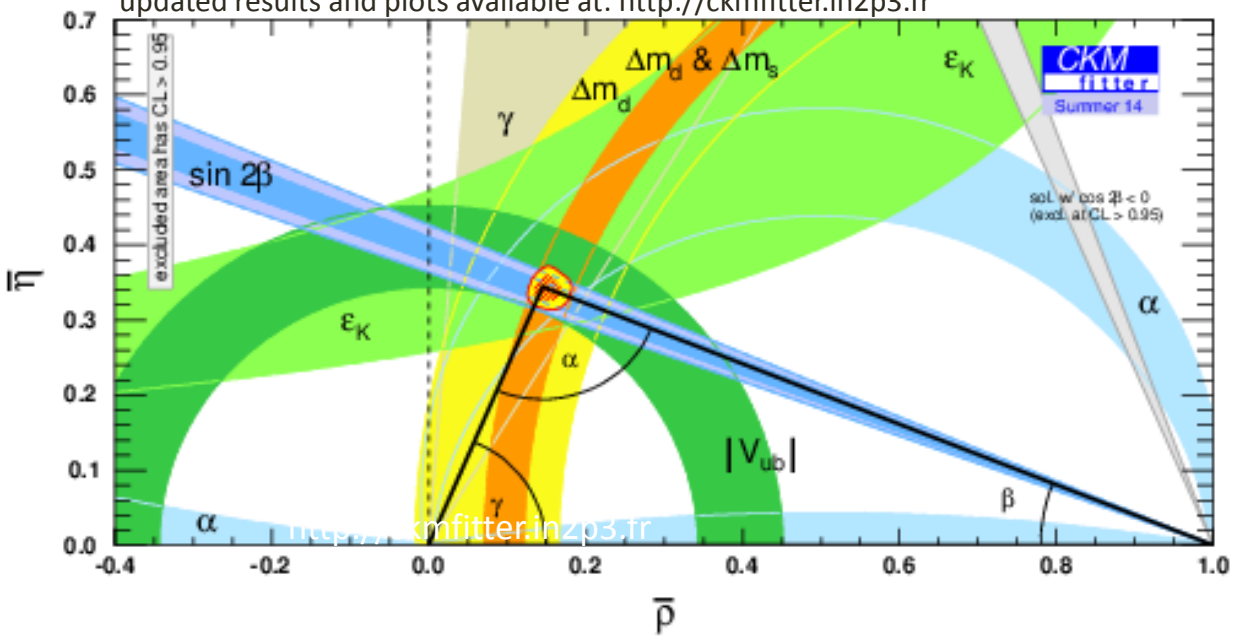
Outline

- Motivation
  - Measurement of γ
  - The role of CP eigenstates
- Quantum-correlated measurements and CLEO-c
- Measuring the CP content of $D^0 \to h^+ h^- \pi^0$
- Conclusion

Unitarity triangle

$$\mathbf{V}_{CKM}^{\dagger}\mathbf{V}_{CKM} = \mathbf{I} \Rightarrow V_{ud}V_{ub}^{*} + V_{td}V_{tb}^{*} + V_{cd}V_{cb}^{*} = 0$$

CKMfitter Group (J. Charles *et al.*), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr



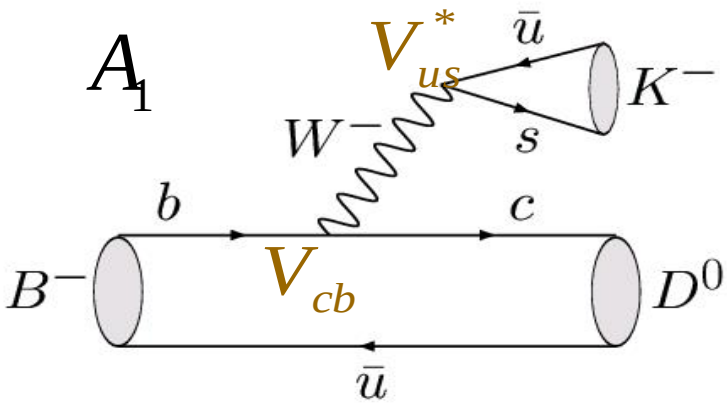
$$\gamma = \left(73.2^{+6.3}_{-7.0}\right)^{\circ}$$

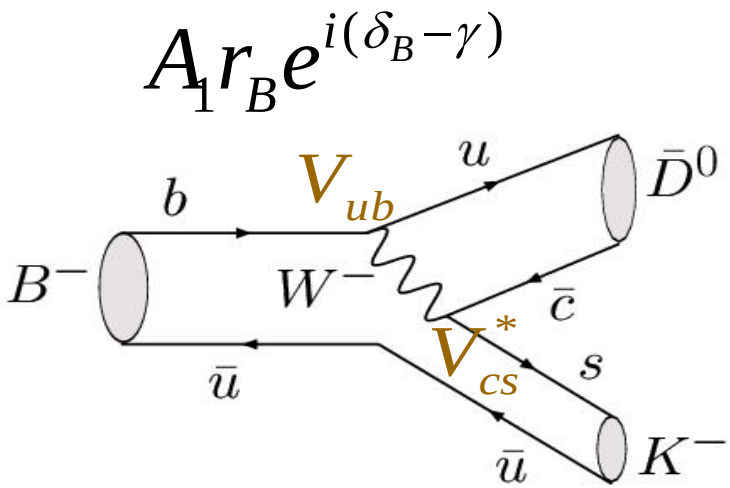
- Best experimental way to improve consistency checks of KM mechanism is to better determine γ
- New physics at the level of 4° possible
  - Brod, Lenz, Tetlalmatzi-Xolocotzi & Wiebusch arXiv:1412.1446

$B \to DK$

Also, an annihilation process, but depends on same CKM elements

- Tree-level determination γ



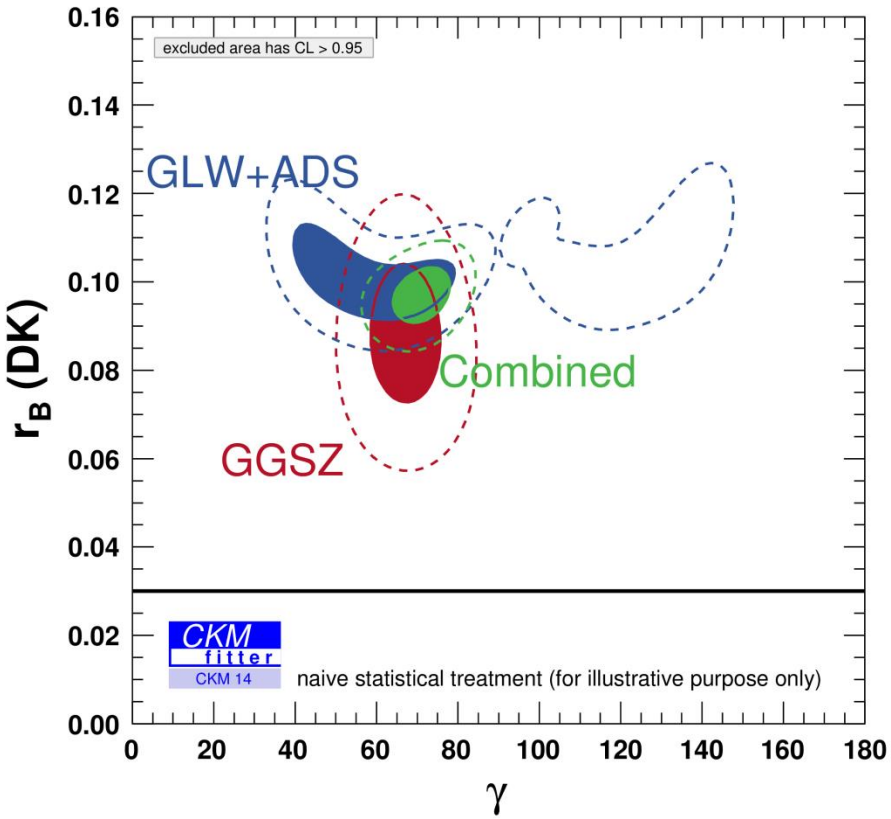


- Same final state for D and $\bar{D} \Rightarrow$ interference $\Rightarrow$ **the possibility of DCPV**
- Three types of D final states generally used
  - **CP-eigenstates [GLW]**
    - Gronau & London, PLB **253**, 483 (1991), Gronau, & Wyler, PLB **265**, 172 (1991)
  - **K^+X^- ($X^-=\pi^-$, $\pi^-\pi^0$, $\pi^-\pi^-\pi^+$) - CF and DCS [ADS]**
    - Atwood, Dunietz & Soni, PRD **63**, 036005 (2001)
  - **Self-conjugate multibody states: $K_S h^+ h^-$ [GGSZ and Dalitz]**
    - Giri, Grossman, Soffer and Zupan, PRD **68**, 054018 (2003); Bondar (unpublished)
  - **None of the above (SCS): $K_S K^+ \pi^-$ [GLS]**
    - Grossman, Ligeti and Soffer, Phys. Rev. D67 071301 (2003)

Another look at the world average

- Combination of the different techniques
  - **Statistically limited**

- ADS and GGSZ rely on inputs from charm
  - $\delta_{K\pi}$ from mixing
  - Coherence factors from threshold
  - c_i and s_i from threshold
  - See talk by BESIII (A. Onur) tomorrow



Questions:
Are there more D decays that can be used?
If so, what input from charm is needed?

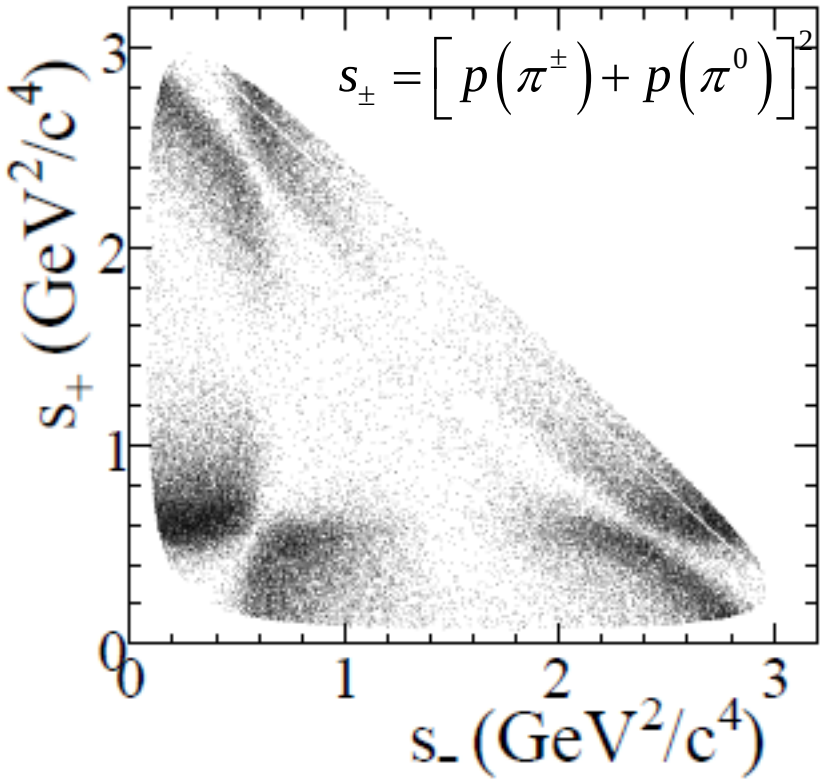
Additional CP eigenstates

- Several eigenstates have been studied in GLW measurements of B→DK decays

State	Eigenvalue	BR (%)
$D^0 \to \pi^+\pi^-$	+1	0.14
$D^0 \to K^+K^-$	+1	0.40
$D^0 \to K_S\pi^0$	−1	1.19
$D^0 \to K_S\eta$	−1	0.48

- Are there more states available?
- Not many easily reconstructible 2-body decays
  - What about 3-body?

$D^0 \to \pi^+ \pi^- \pi^0$: BR 1.43%



BABAR: PRL **99** (2007) 251801
Isospin analysis: Gaspero, Mishra, Meadows and Soffer
PRD **78** (2008) 014015

- Symmetry of the decay Dalitz plot indicates an isospin = 0 state of the three pions
- G-parity suggested that this should be an almost pure CP-even eigenstate
  - Suitable for GLW measurement
- How to check?

Quantum correlated measurements

At the ψ (3770) neutral *D* pairs produced in quantum entangled state:

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D^0\bar{D}^0 - \bar{D}^0 D^0\right]$$

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D_{CP-}D_{CP+} - D_{CP+}D_{CP-}\right]$$

$$\text{where } D_{CP\pm} = \tfrac{1}{\sqrt{2}}\left[D^0 \pm \bar{D}^0\right]$$

Reconstruct one D in decay of interest (eg. $\pi\pi\pi$), & other in CP eigenstate (eg. KK, $K_S\pi^0$ …) then CP of the other is fixed.

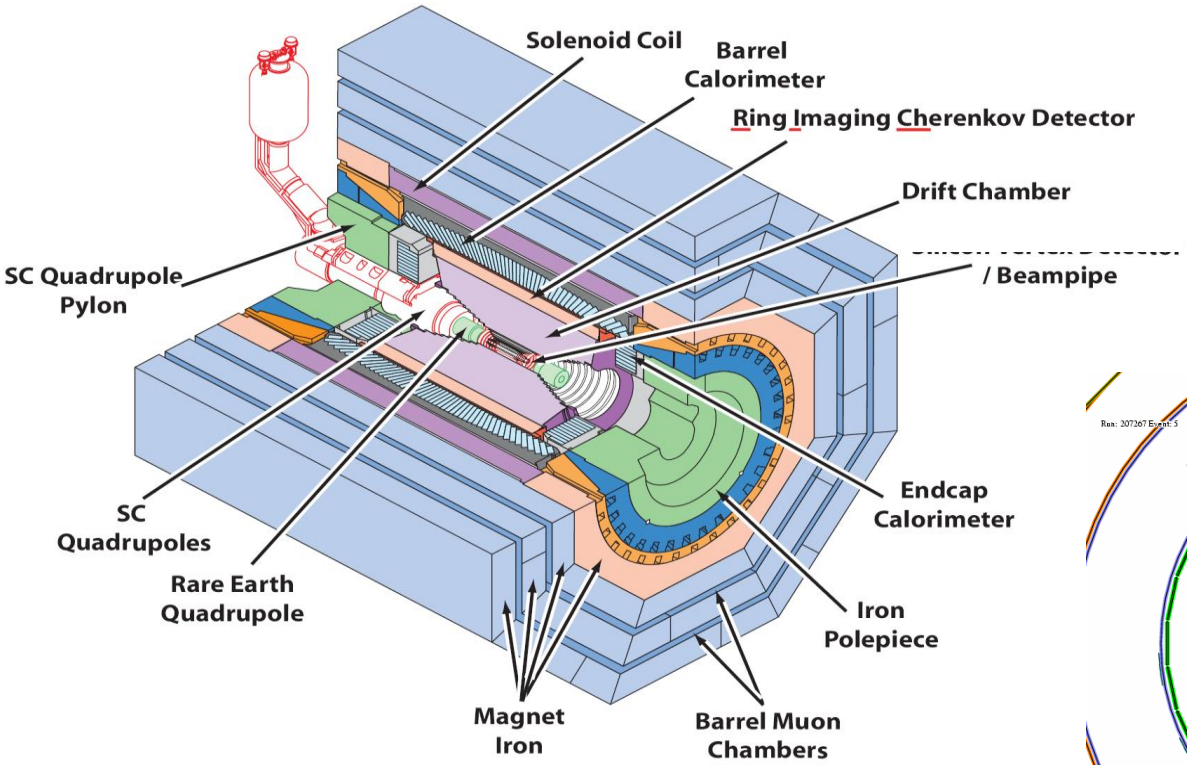
If the three pions in $\boldsymbol{D^0 \to \pi^+ \pi^- \pi^0}$ are in a CP-even eigenstate

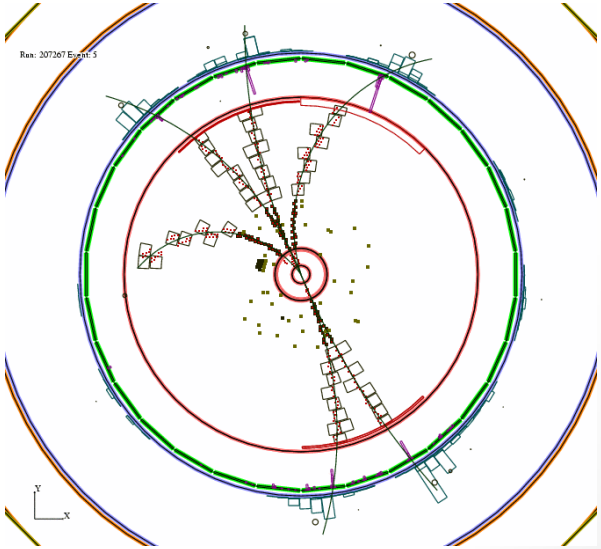
$\boldsymbol{D^0 \to \pi^+ \pi^- \pi^0}$ vs CP-even decay – no events

$\boldsymbol{D^0 \to \pi^+ \pi^- \pi^0}$ vs CP-odd decay – 2 x enhancement of events

CLEO-c

- CLEO-c collected 818 pb^{-1} at the $\psi(3770)$ – 3 million neutral D pairs

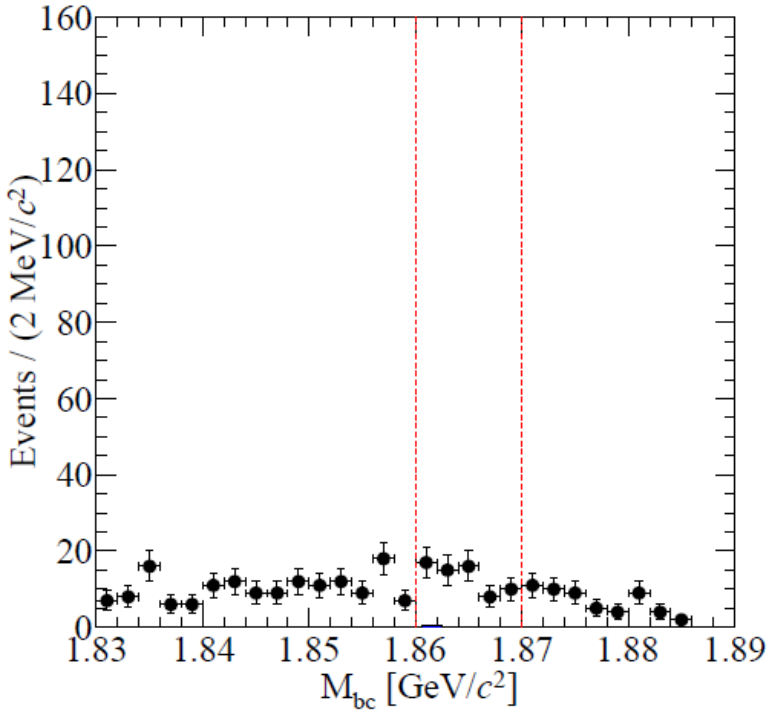




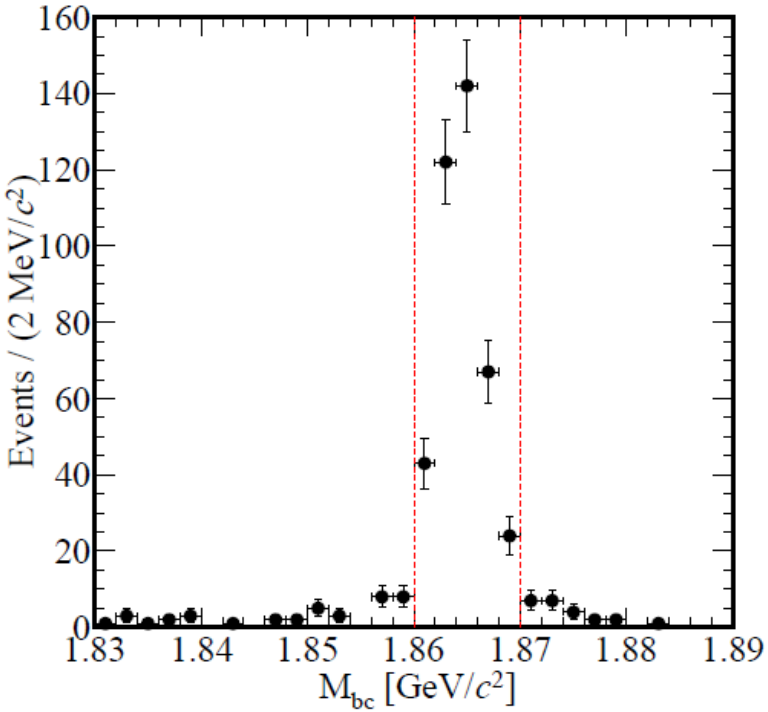
- Pristine environment
- Full reconstruction of both *D*s
- Including K_L using missing-mass

$\pi^+ \pi^- \pi^0$ invariant mass

Vs CP even

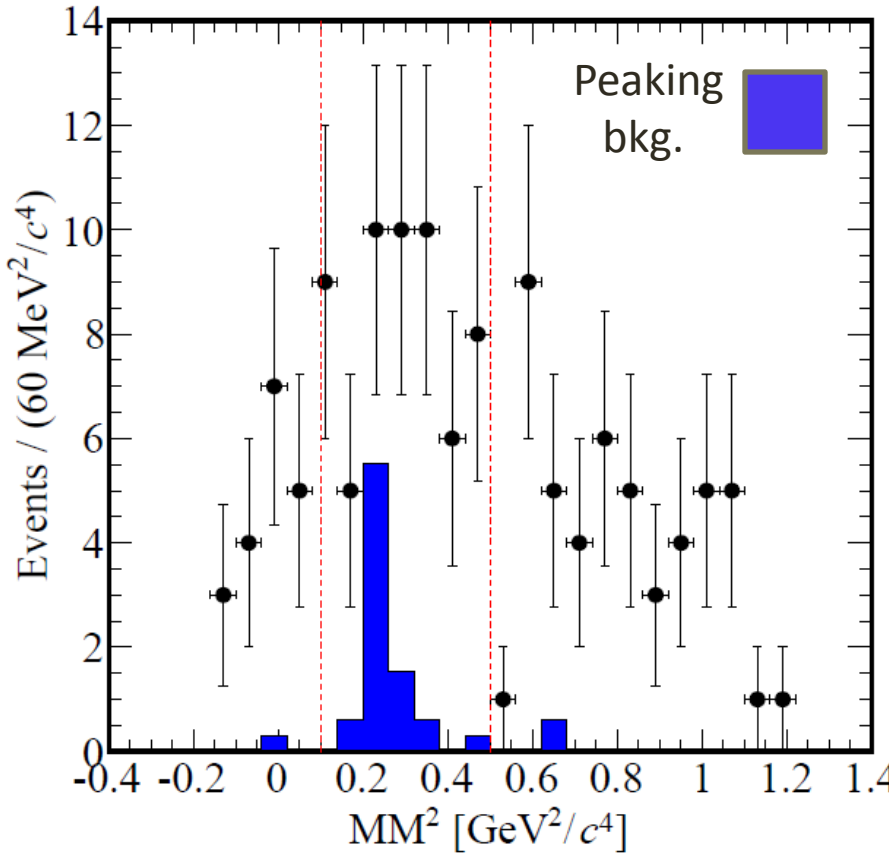


Vs CP odd



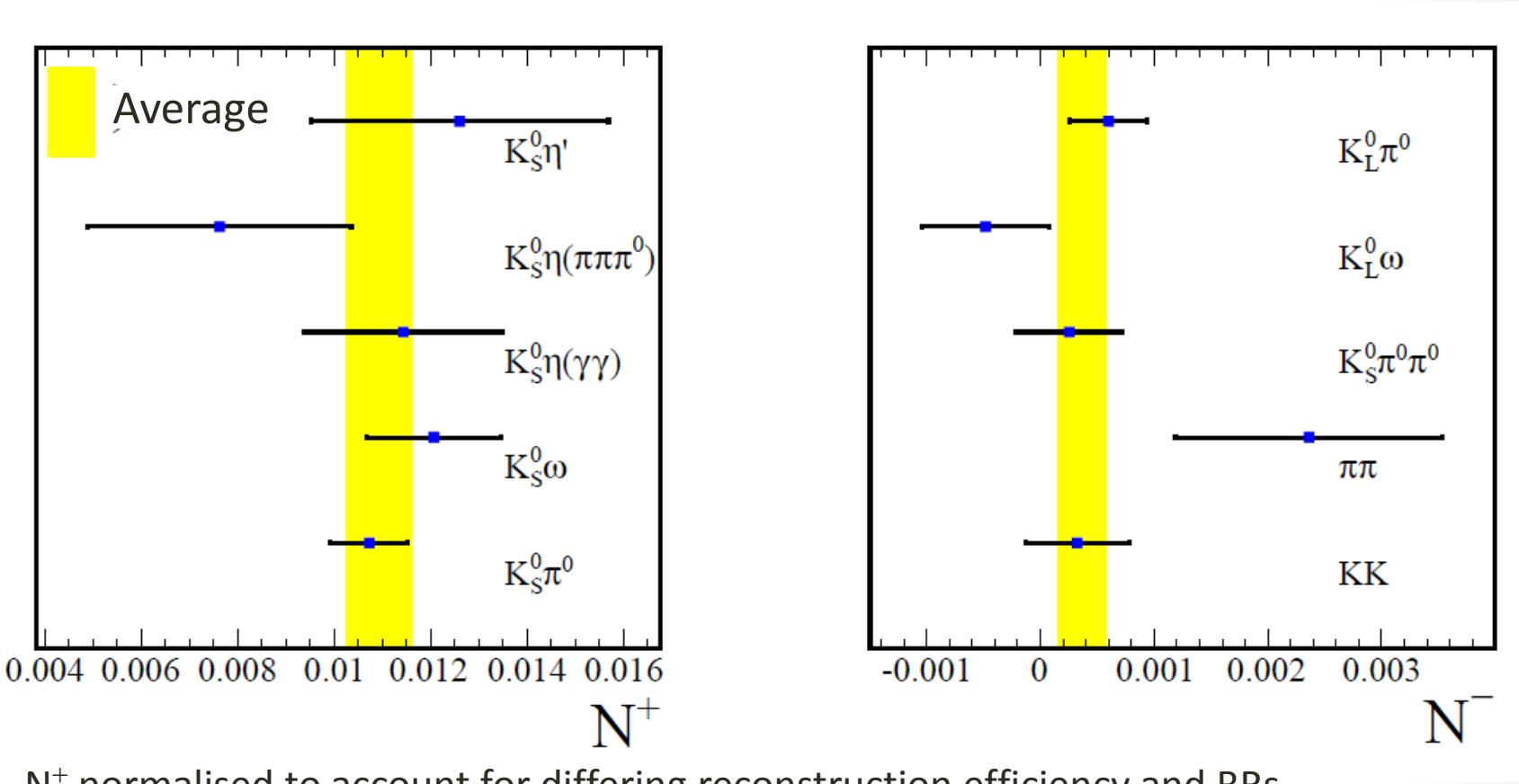
CP-even tags	CP-odd tags
KK, $\pi\pi$, $K_s\pi^0\pi^0$	$K_s\pi^0$, $K_s\,\omega$, $K_s\eta$, $K_s\eta'$

Add K_L tags: $K_L\pi^0$ and $K_L\omega$ (CP+)



Tag	$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0$	34.3 ± 20.0
K^+K^-	3.9 ± 5.5
$\pi^+\pi^-$	13.3 ± 6.6
$K^0_S\pi^0\pi^0$	1.9 ± 3.4
$K^0_L\pi^0$	14.6 ± 7.9
$K^0_L\omega$	-4.3 ± 4.0
$K^0_S\pi^0$	214.0 ± 15.0
$K^0_S\omega$	95.5 ± 9.9
$K^0_S\eta(\gamma\gamma)$	33.0 ± 5.8
$K^0_S\eta(\pi^+\pi^-\pi^0)$	8.8 ± 3.1
$K^0_S\eta'$	17.6 ± 4.2

Quantifying the result

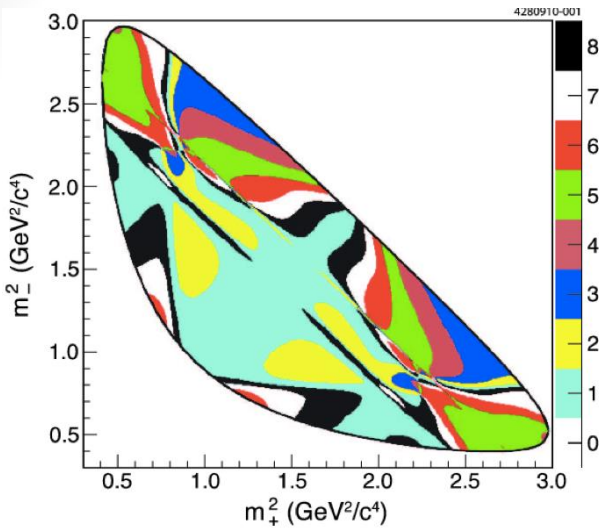


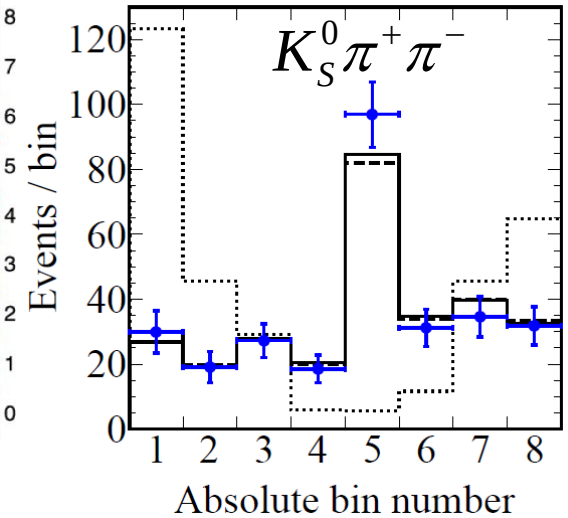
$N^{\pm}$ normalised to account for differing reconstruction efficiency and BRs -

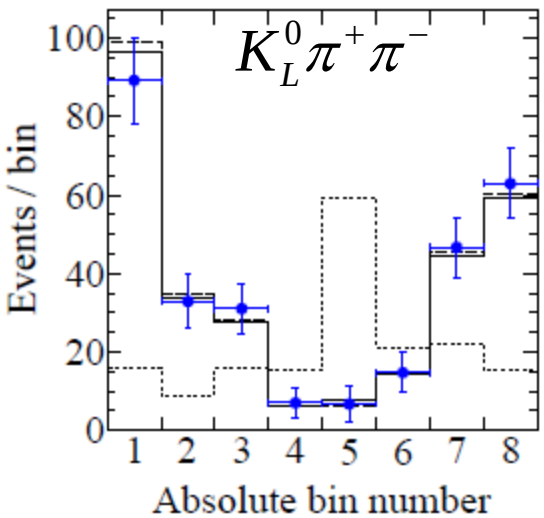
$$F_+ = \frac{N_+}{N_+ + N_-} = 0.968 \pm 0.017 \pm 0.006$$

arXiv:1504.05878 [hep-ex]

Update: $K^0\pi^+\pi^-$ tags







Tag	$F_+^{\pi\pi\pi^0}$
$K_S^0\pi^+\pi^-$	$1.034 \pm 0.054 \pm 0.023$
$K_L^0\pi^+\pi^-$	$0.971 \pm 0.075 \pm 0.033$
$K_{S,L}^0\pi^+\pi^-$	$1.014 \pm 0.045 \pm 0.022$

Solid – best fit

Dashed – $F_+ = 1$

Dotted – $F_+ = -1$

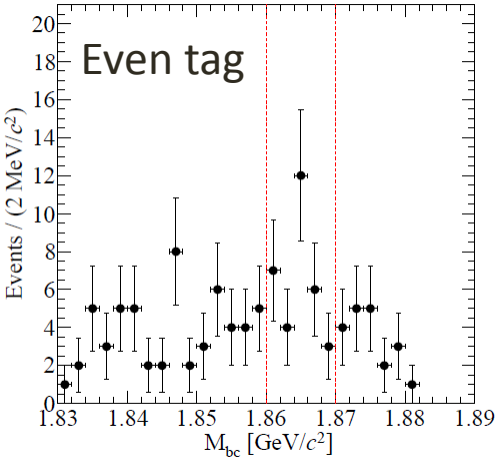
Consistent picture from all tags

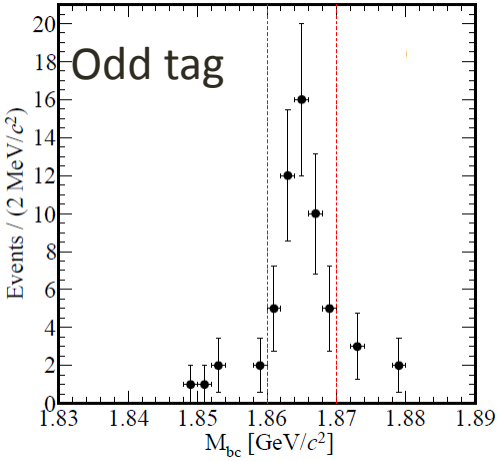
Almost a pure CP eigenstate

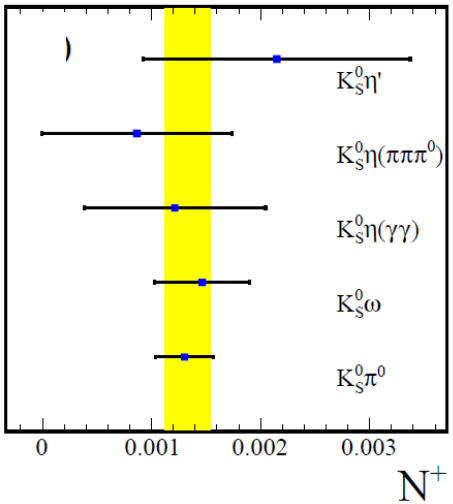
Tag	$F_+^{\pi\pi\pi^0}$
CP eigenstates	$0.968 \pm 0.017 \pm 0.006$
$K_{S,L}^0\pi^+\pi^-$	$1.014 \pm 0.045 \pm 0.022$
Combined	0.973 ± 0.017

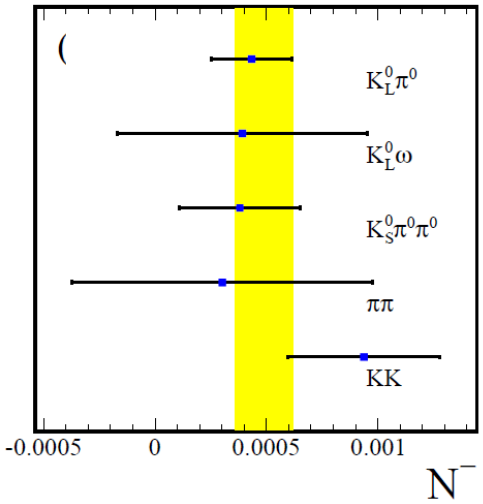
$D^0 \to K^+K^-\pi^0$

- Also measured but some disadvantages
- Not as symmetric a Dalitz plot
  PRD **76** (2007) 011102
- Smaller BF of 0.33%
- However, experimentally cleaner in $B \to DK$
- Consistent picture among all tags
- Predominantly CP-even









Tag	$F_+^{KK\pi^0}$
CP eigenstates	$0.731 \pm 0.058 \pm 0.021$
$K^0_{S,L}\pi^+\pi^-$	$0.734 \pm 0.106 \pm 0.054$
Combined	0.732 ± 0.055

Modified GLW formalism

- Can relate our measurement directly to a modified version of the observables in the GLW formalism of B→DK
  - Mixing can also be accounted for
- The usually reported ones are

$$R_{F_+} \equiv \frac{\Gamma(B^- \to D_{F_+} K^-) + \Gamma(B^+ \to D_{F_+} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \bar{D}^0 K^+)}$$

$$A_{F_+} \equiv \frac{\Gamma(B^- \to D_{F_+} K^-) - \Gamma(B^+ \to D_{F_+} K^+)}{\Gamma(B^- \to D_{F_+} K^-) + \Gamma(B^+ \to D_{F_+} K^+)}$$

- It can be shown that for a multibody D decay with a known F_+

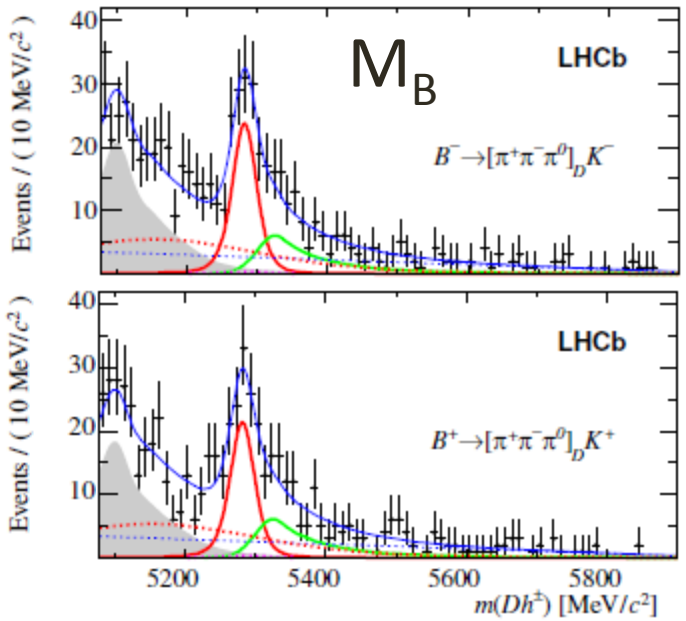
$$R_{F_+} = 1 + r_B^2 + (2F_+ - 1) \cdot 2r_B \cos\delta_B \cos\gamma,$$

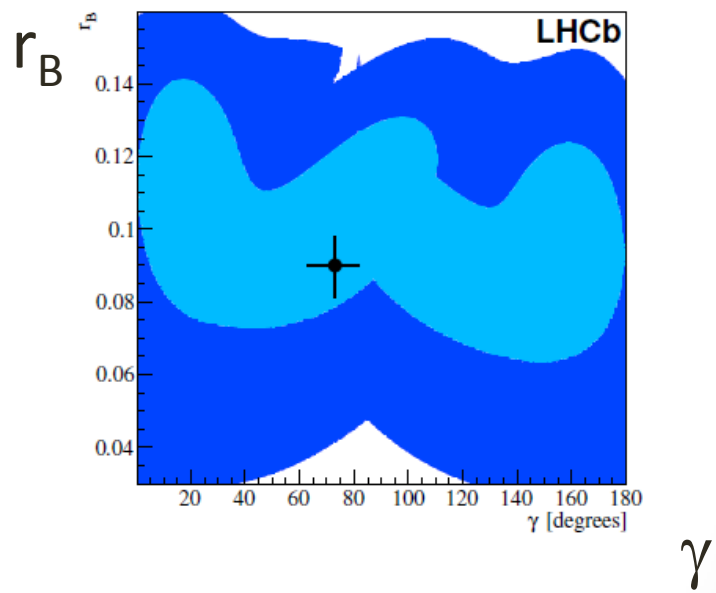
$$A_{F_+} = (2F_+ - 1) \cdot 2r_B \sin\delta_B \sin\gamma / R_{F_+},$$

- Introduces a dilution factor of 0.95 and 0.46 to the asymmetry in for $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$ respectively

Conclusion

- $D^0 \to \pi^+\pi^-\pi^0$ is an almost a pure CP even eigenstate
- $D^0 \to K^+K^-\pi^0$ is a predominantly CP even eigenstate
- Already measurements in B-decay - arXiv:1504.05442v1 [hep-ex]





- Promising for the future: Belle II and LHCb upgrade
- Also can be used to study possible non-Standard model CPV in charm decay: - S. Malde next talk