First measurement of $F_+^{4\pi}$ in $D \rightarrow 4\pi$ decays
&
A new method for measuring CPV in charm decays

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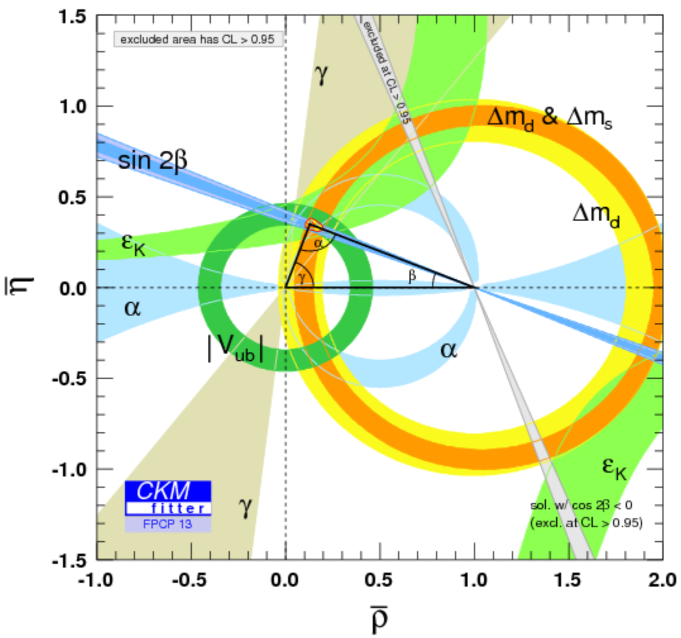
Outline



- Previous talk discussed how the knowledge of F_+ allowed use of $\pi\pi\pi^0$ and $KK\pi^0$ as quasi-GLW states for determining CKM angle γ
- Describe the measurement of F_+ for the decay D→ 4π, further increasing channels that can be sensitive to γ in this way
- Describe how these measurements are useful for CPV in charm decays

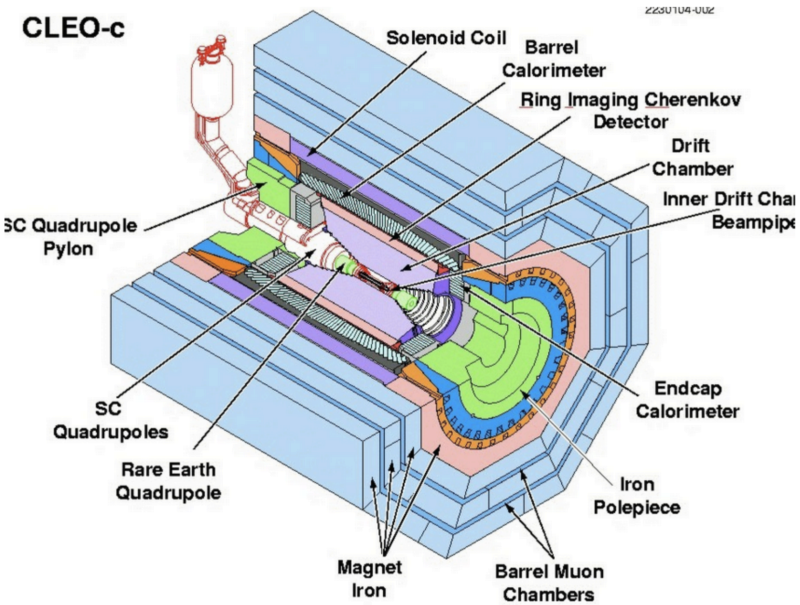
- Work based on
  - S. Malde et al arXiv:1504.05878 [hep-ex]
  - S. Malde, C. Thomas & G. Wilkinson arXiv: 1502.04560

$D \rightarrow 4\pi$

- Previous talk discussed the result for $D \rightarrow \pi\pi\pi^0$, $KK\pi^0$
- Another candidate is $D \rightarrow 4\pi$
- Self conjugate decay mode, relatively high branching fraction ~0.7 %
- Fully pionic final state – higher selection efficiency than other decay modes

CLEO-c and quantum coherence

- Hermitic detector based at CESR e^+e^- collider
- Operated at threshold energy
- Study $\psi(3770) \rightarrow D^0\overline{D^0}$ decays
- Key: C= -1 for $\psi(3770)$ at threshold
- Strong decay, C is conserved
- Hence the decays of D^0 and $\overline{D^0}$ are quantum correlated

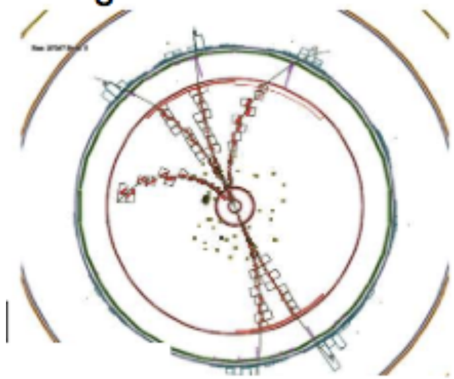


i.e If one D meson decay is in a CP eigenstate the other D meson decays has opposite CP

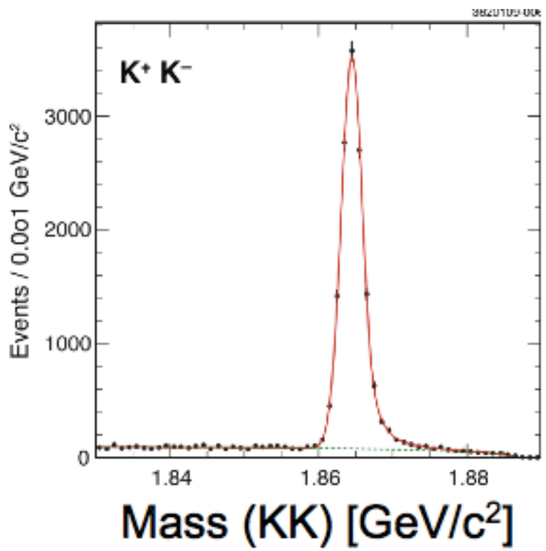
Strengths of the CLEO-c detector

- Very clean events
- S/B ~ 10- 100

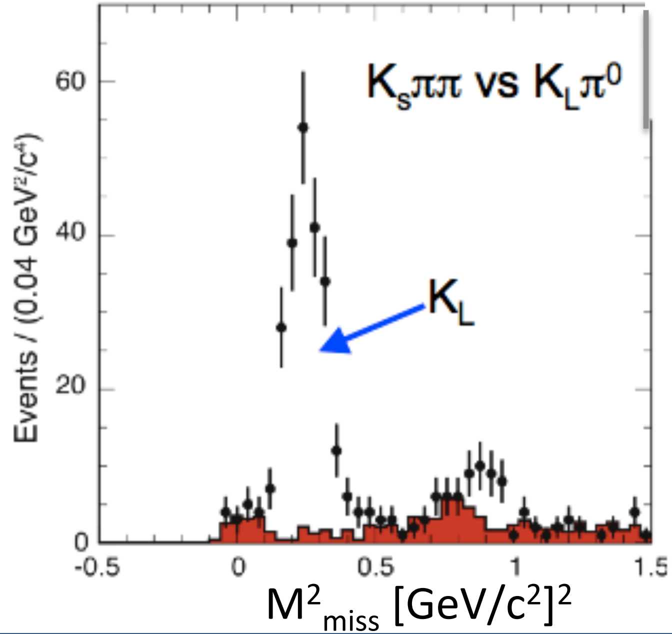
$K_s\pi\pi$ vs $K\pi$



- Excellent E-M and hadron calorimetry and PID

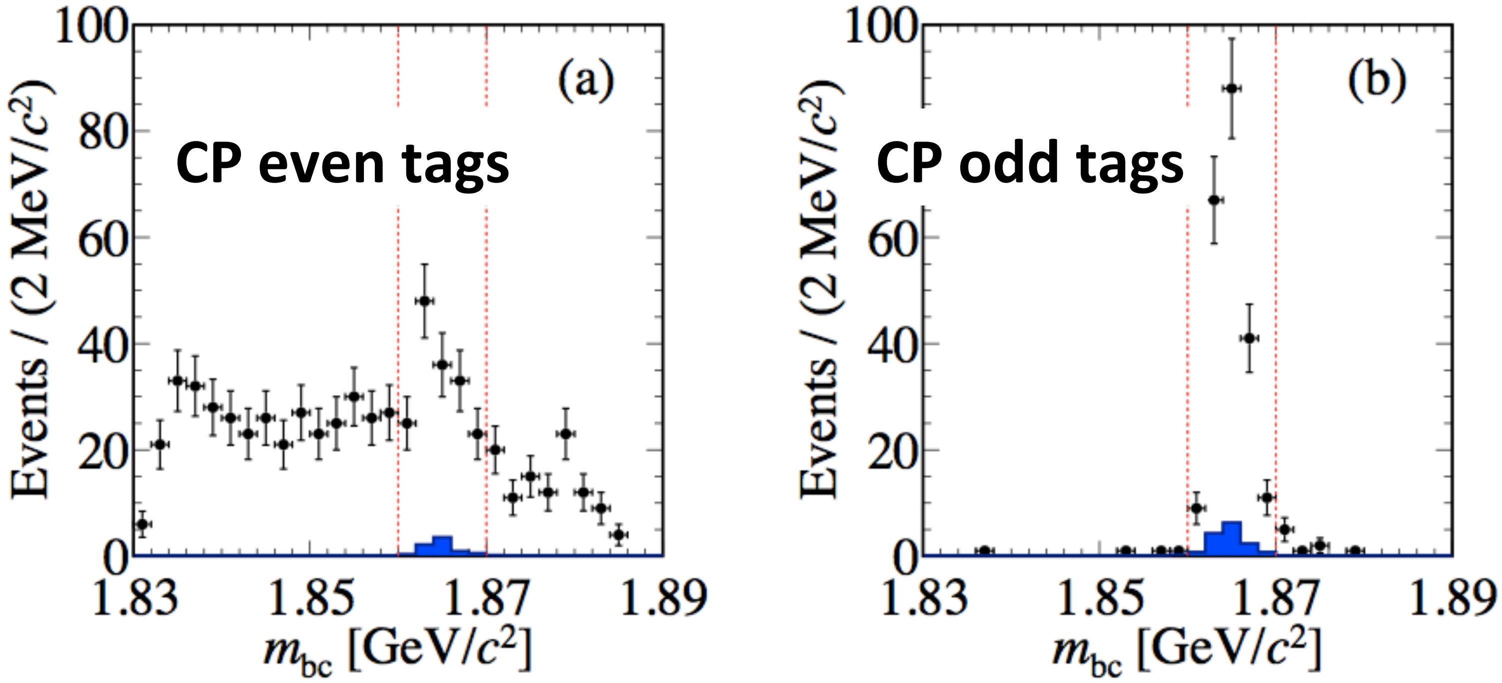


- K_L reconstruction possible through missing mass technique
- CP eigenstates with K_L and $K_L\pi\pi$ tags are possible



Using CLEO-c data to measure F+

- Idea : Determine double tag yields where one D meson decays to 4π and the other to a CP eigenstate : **$M(4\pi|CP_X)$**



Fully reconstructed double tags only shown

Using CLEO-c data to measure F+

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- For normalisation require knowledge of the single tag yield – number of D→CP eigenstate decays in the dataset : **$S(CP_X)$**

$$\frac{M(4\pi|CP_X)}{S(CP_X)} = \frac{2N_{D\bar{D}}\boldsymbol{B}(4\pi)\boldsymbol{B}(CP_X)\varepsilon(4\pi|CP_X)[1-\eta_X(2F_+^{4\pi}-1)]}{2N_{D\bar{D}}\boldsymbol{B}(CP_X)\varepsilon(CP_X)} = N^{-\eta_X}$$

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- Ratio removes dependence on overall normalisation, and the CP tag branching fraction and efficiency (assume the efficiency factorises)

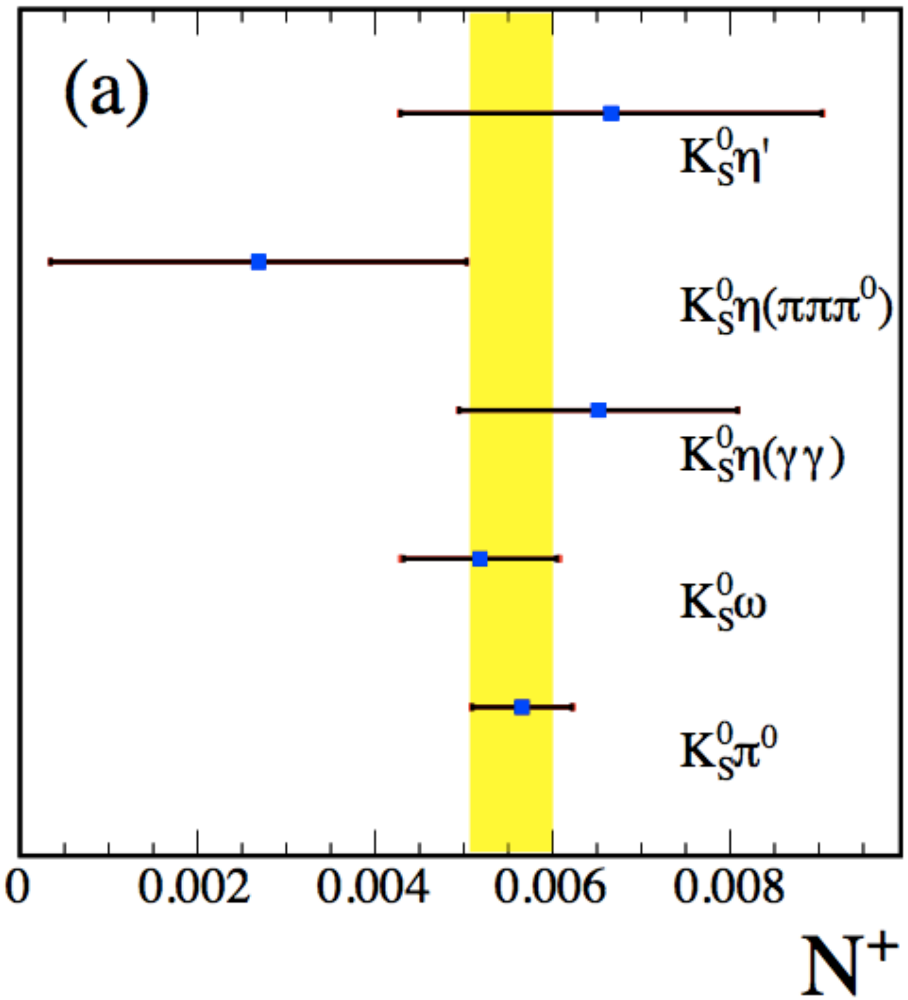
Relation to $F_+^{4\pi}$

$$\frac{N^+}{N^+ + N^-} = \frac{\boldsymbol{B}(4\pi)\varepsilon(4\pi)[1-(2F_+^{4\pi}-1)]}{\boldsymbol{B}(4\pi)\varepsilon(4\pi)[1-(2F_+^{4\pi}-1)+1+(2F_+^{4\pi}-1)]}$$

$$\frac{N^+}{N^+ + N^-} = F_+^{4\pi}$$

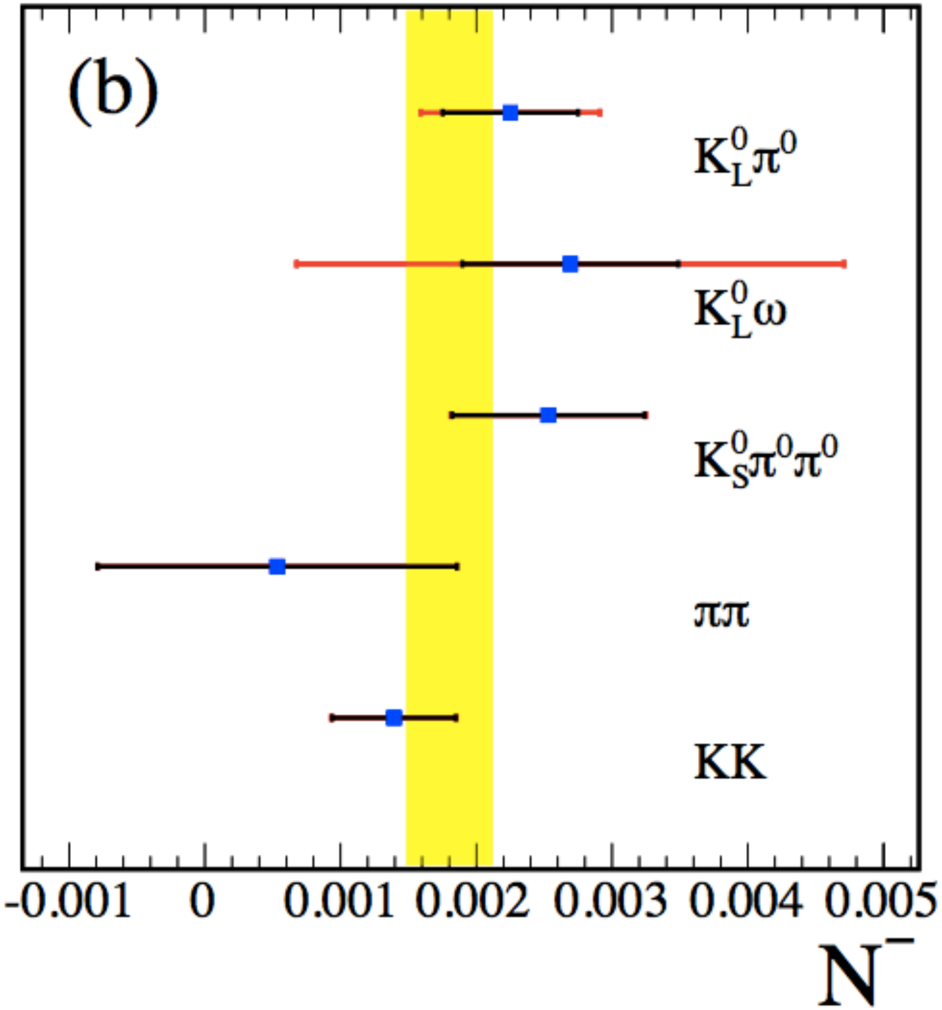
- Double ratio removes dependence on branching fraction and efficiency of the 4π decay
- Clean measurement – few external constraints, minimises systematic uncertainties

Results of 4π vs CP odd tags



- Good consistency between tags
- Systematic uncertainties arise from single tag estimates, corrections for D mixing
- Sufficiently small to not be visible by eye

Results of 4π vs CP even tags



- Good consistency between tags
- Not possible to determine single tag yield for K_L tags
- Effective single tag yield is estimated from BF, and N_{DD} and efficiencies.
- Large uncertainties on the BF and the efficiencies
- Impact of $K_L\omega$ tag minimal
- Similar uncertainties not present for $\pi\pi\pi^0$ $KK\pi^0$ since the yields were ~0

- **$F_+^{4\pi} = 0.754 \pm 0.031 \pm 0.021$**

Using other tags where the CP fraction is known

- Can extend the method to use other tags e.g $\pi\pi\pi^0$
- Require knowledge of the $\pi\pi\pi^0$ CP fraction

$$\frac{N^{\pi\pi\pi^0}}{N^+} = \frac{\left[1-\left(2F_+^{4\pi}-1\right)\left(2F_+^{\pi\pi\pi^0}-1\right)\right]}{2F_+^{4\pi}}$$

$$F_+^{4\pi} = \frac{N^+F_+^{\pi\pi\pi^0}}{N^{\pi\pi\pi^0}-N^+ + 2N^+F_+^{\pi\pi\pi^0}}$$

- Double tag yield 75.5±15.7

- **$F_+^{4\pi} = 0.695 \pm 0.050 \pm 0.021$**

Utilising $K^0\pi\pi$ tags

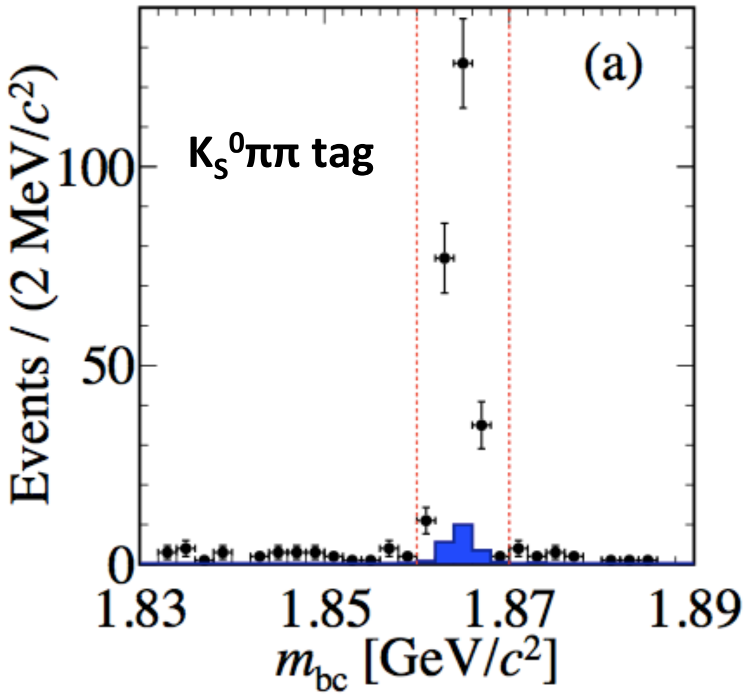
- Further sensitivity can be gained by tagging 4π decays by particular regions of the $K^0\pi\pi$ Dalitz plot. For $K_S{}^0\pi\pi$:

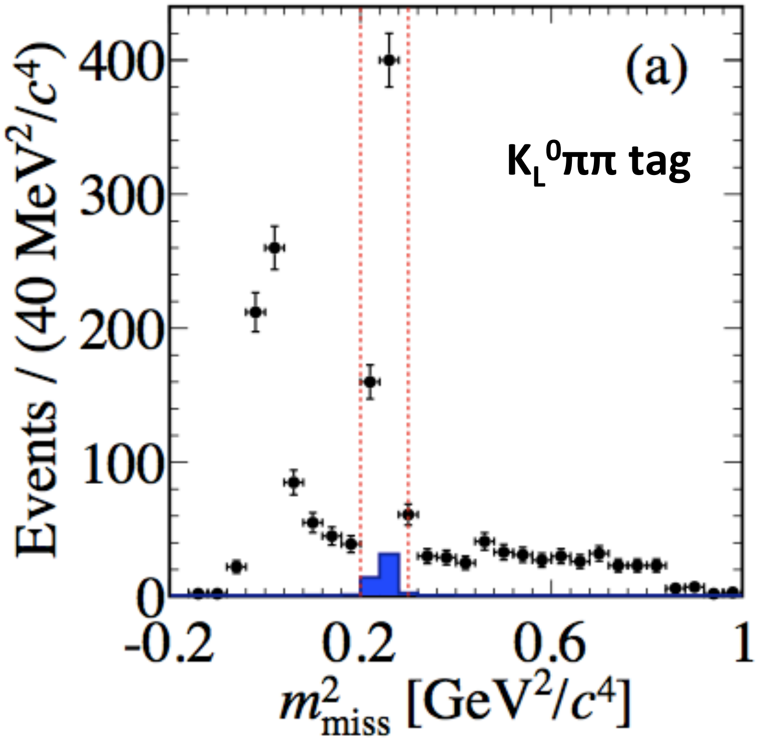
$$M_{|i|} = h\left[K_i + K_{-i} - \left(2F_+ - 1\right)2c_i\sqrt{K_iK_{-i}}\right]$$

  - Similar expression for $K_L{}^0\pi\pi$
  - $|i|$ is some region on the $K^0\pi\pi$ Dalitz plot
  - K_i is the fraction of the flavour tagged yield of the D^0 meson that falls into bin *i*
    - determined from BaBar model for $K_S\pi\pi$ and from CLEO data for $K_L\pi\pi$
  - c_i is the average strong-phase difference over the region *i*
    - Measured at CLEO-c PRD 82 112006

Utilising $K^0\pi\pi$ tags

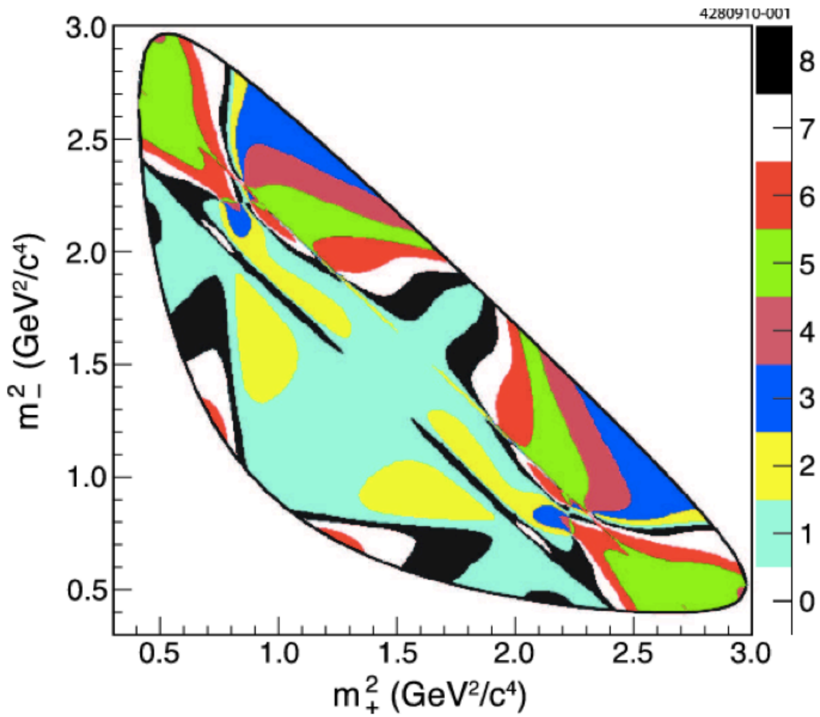
- Integrated Data over the $K^0\pi\pi$ Dalitz plots



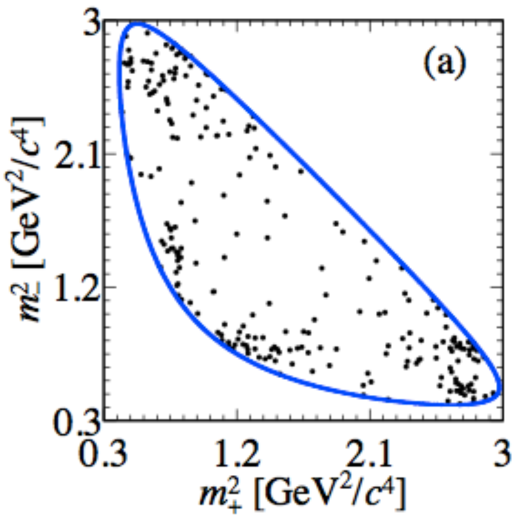


- Peaking bkg mainly $K_S^0\pi\pi$ mis-identified as 4π on the signal side
- Peaking bkg mainly $K_S^0\pi\pi$ mis-identified as $K_L^0\pi\pi$ on the tag side

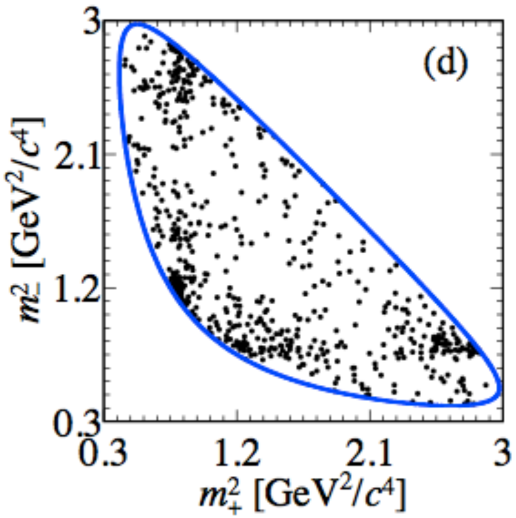
Utilising $K^0\pi\pi$ tags



Binning in which the K_i and c_i numbers are known.

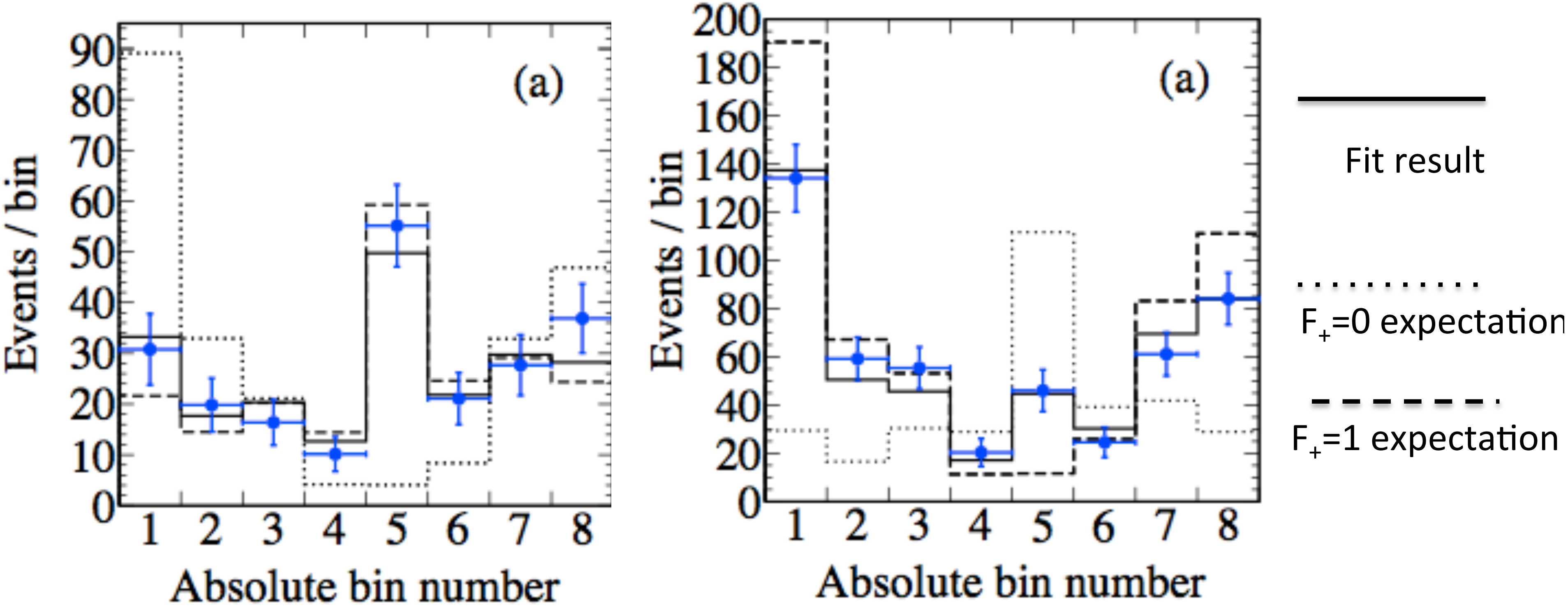


$K_S^0\pi\pi$ tag



$K_L^0\pi\pi$ tag

Some plots



- Yields are corrected for background and varying efficiency
- Fit performed to the binned yields to determine F_+
- **$F_+^{4\pi}$ = 0.737 ± 0.049 ± 0.024**

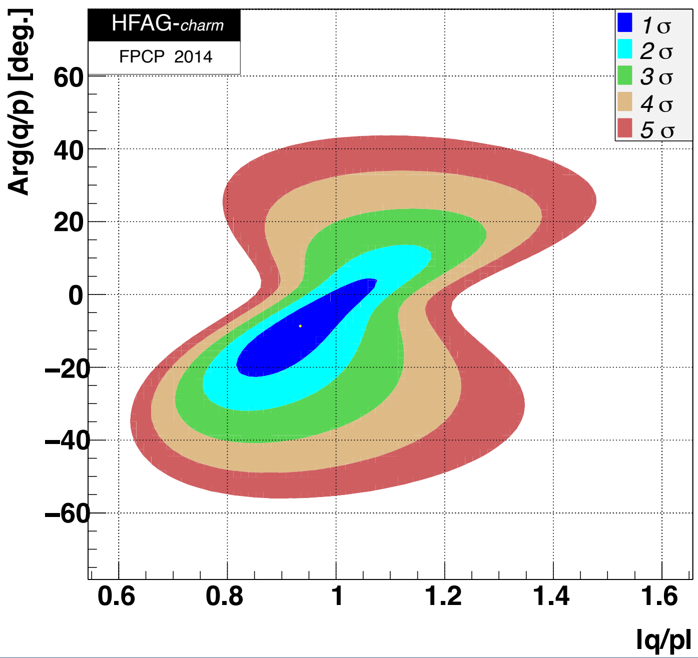
Combination

Tag	$F_{+}^{4\pi}$
CP eigenstates	$0.754 \pm 0.031 \pm 0.021$
$K^0_{\mathrm{S,L}}\pi^+\pi^-$	$0.737 \pm 0.049 \pm 0.024$
$\pi^+\pi^-\pi^0$	$0.695 \pm 0.050 \pm 0.021$
Combined	0.737 ± 0.028

- Value is quite high
- Good decay to add to the quasi-GLW measurements to add to the CKM angle γ measurements
- However there is another use too

The power of D decays

- In the Standard model indirect CP violation in charm decays is expected to be well below current level of precision than we can achieve
- Many models of New Physics predict enhancements
- Perfect place to search for New Physics effects.



- Current measurement consistent with no CPV
- Expanding the repertoire of measurements we can make is crucial to exploit all available data

A_Γ and y_{CP}

- A_Γ is one of the leading CP violating observables
- Measured from a difference in lifetimes of the decays of D^0 and $\bar{D}^0$ to a CP eigenstate, e.g KK

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to KK) - \hat{\Gamma}(\bar{D}^0 \to KK)}{\hat{\Gamma}(D^0 \to KK) + \hat{\Gamma}(\bar{D}^0 \to KK)}$$

$$y_{CP} = \frac{\hat{\Gamma}(D^0 \to KK) + \hat{\Gamma}(\bar{D}^0 \to KK)}{2\Gamma} - 1$$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$|p|^2 + |q^2| = 1, r_{CP} \equiv \frac{q}{p} e^{i\phi_{CP}}$$

$$\begin{aligned} A_\Gamma &\approx \frac{1}{2} y \cos\phi_{CP} \left(r_{CP} - \frac{1}{r_{CP}} \right) - \\ &\quad \frac{1}{2} x \sin\phi_{CP} \left(\frac{1}{r_{CP}} + r_{CP} \right), \\ y_{CP} &\approx \frac{1}{2} y \cos\phi_{CP} \left(\frac{1}{r_{CP}} + r_{CP} \right) - \\ &\quad \frac{1}{2} x \sin\phi_{CP} \left(r_{CP} - \frac{1}{r_{CP}} \right). \end{aligned}$$

Indirect CPV when $r_{CP} \neq 1$ and/or $\phi_{CP} \neq 0$
x, y are the mixing parameters

Limiting factor

- Measurements rely on CP eigenstates
  -To date these have involved the following modes:
  KK, ππ, CP odd component of KsKK
- Other CP eigenstates include K_L or other particles with low reconstruction efficiencies
- BF of currently used modes are less 0.5%
- What if useful information can be gained from CP conjugate states rather than requiring a CP eigenstate?

Consider multibody decays

Following the derivation in arXiv : 1502.04560

$$\begin{aligned} A_{\Gamma}^{\rm eff} &\approx \frac{1}{2}(2F_{+}-1)y\cos\phi_{CP}\left(r_{CP}-\frac{1}{r_{CP}}\right)- \\ &\quad \frac{1}{2}(2F_{+}-1)x\sin\phi_{CP}\left(r_{CP}+\frac{1}{r_{CP}}\right), \\ y_{CP}^{\rm eff} &\approx \frac{1}{2}(2F_{+}-1)y\cos\phi_{CP}\left(r_{CP}+\frac{1}{r_{CP}}\right)- \\ &\quad \frac{1}{2}(2F_{+}-1)x\sin\phi_{CP}\left(r_{CP}-\frac{1}{r_{CP}}\right). \end{aligned}$$

- $A_{\Gamma}^{eff} = A_{\Gamma}/(2F_{+} -1)$
- If F_{+} = 0 or 1 then the expressions reduce to A_{Γ} and y_{CP}
- If F_{+} = 0.5, then there is no sensitivity to the parameters of interest
- Extensions including direct CPV can also be taken into account : see arXiv:1502.04560

Prospects

- Derive relative sensitivity to KK mode for indirect CPV in D decays
- Use relative BF, and F_+ values
- Assume the selection efficiency is equal in all cases

	K^+K^-	$\pi^+\pi^-$	$\pi^+\pi^-\pi^0$	$\pi^+\pi^-\pi^+\pi^-$
BF [$\times 10^{-2}$]	0.396	0.1402	1.43	0.742
F_+	1	1	0.973	0.737
Uncertainty	1	1.68	0.56	1.54

- $\pi\pi\pi^0$ is very powerful due to high F_+ and high BF
  -- Reconstruction efficiency should be high at BELLE-II
- 4π will provide valuable additional sensitivity, high reconstruction efficiency at LHCb

Summary and Conclusion

- High $F_+^{4\pi}$ value in D→4π
- Another mode to add to quasi-GLW for CKM angle γ measurements like $\pi\pi\pi^0$ and $KK\pi^0$
- All these D decay modes can also be used to improve D mixing and indirect CPV parameters by measuring A_Γ^{eff} and $y_{CP}^{eff.}$
- Interpretation of the potential measurements in terms of direct and indirect CPV also possible

- Look forward to the use of these modes to constrain r_{CP} and ϕ_{CP}