Measurements related to the ADS determination of γ at CLEO-c

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On behalf of the CLEO-c collaboration

- Introduction to CLEO-c
- Measurements related to the determination of γ via $B^{\pm} \rightarrow DK^{\pm}$
  - $D \rightarrow K^{-}\pi^{+}$
  - $D \rightarrow K^{-}\pi^{+}\pi^{+}\pi^{-}$ and $D \rightarrow K^{-}\pi^{+}\pi^{0}$

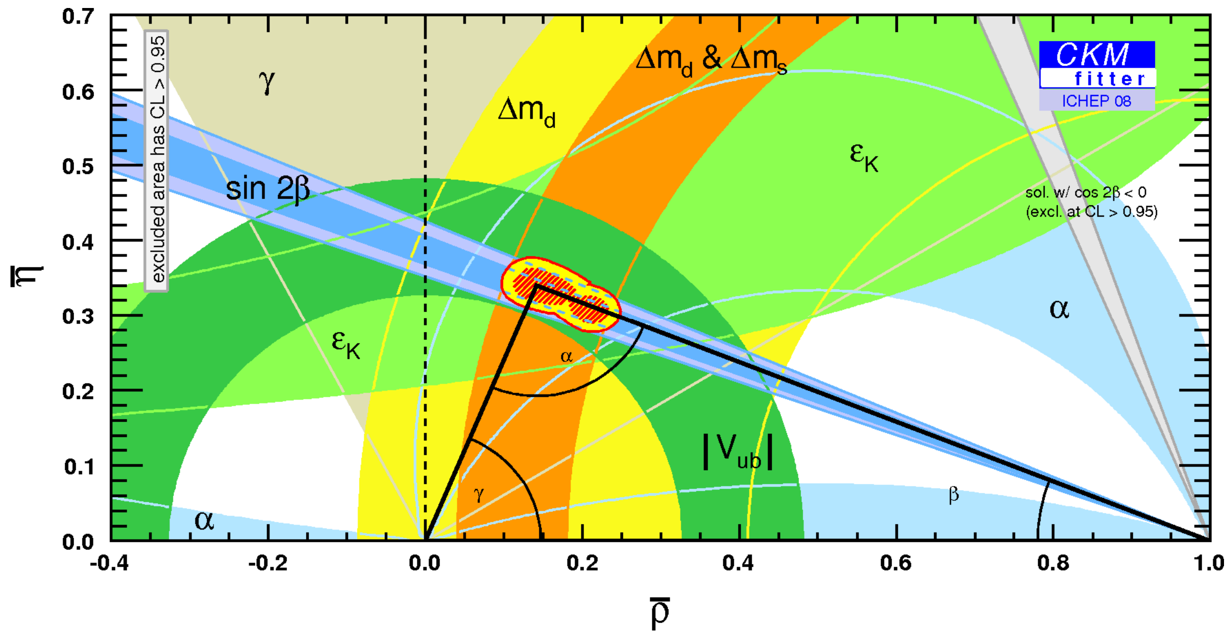
Introduction to CLEO-c

- Detector at the Cornell Electron Storage Ring (CESR)
- Operated at energies around $c\bar{c}$ threshold
- Data sets for flavour measurements:
  - E_{CM} = 4170 MeV $\mathscr{L}_{int}$ ~ 600 pb^{-1}
    Determination of decay constant f_{Ds} at CLEO-c is a critical test of lattice QCD and sensitive to new physics
  - ψ(3770) $\mathscr{L}_{int}$ = 818 pb^{-1} [This talk]

$$e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \qquad C = -1$$

- **Quantum correlated state:**
  For example, reconstruct one *D* decay to a *CP* eigenstate uniquely identifies the other *D* to be of opposite *CP*

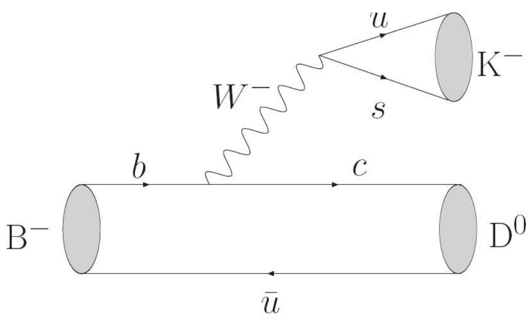
Status of direct determination of γ



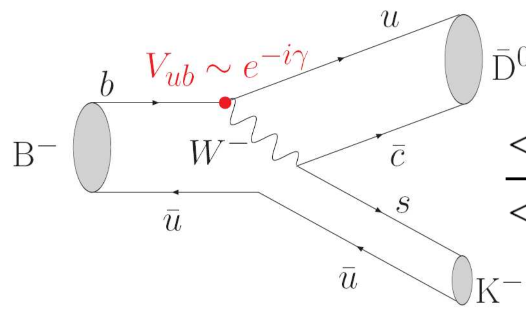
- γ is the least well determined angle of the unitarity triangle with an uncertainty of ~30° from direct measurements
  - $\sigma_{\beta} = 1°$
- Comparison of measurements of γ in tree and loop processes sensitive to new physics
  - **Side opposite - B-mixing measurements loop only**

γ from $B^{\pm} \to DK^{\pm}$

$B^- \longrightarrow D^0 K^-$



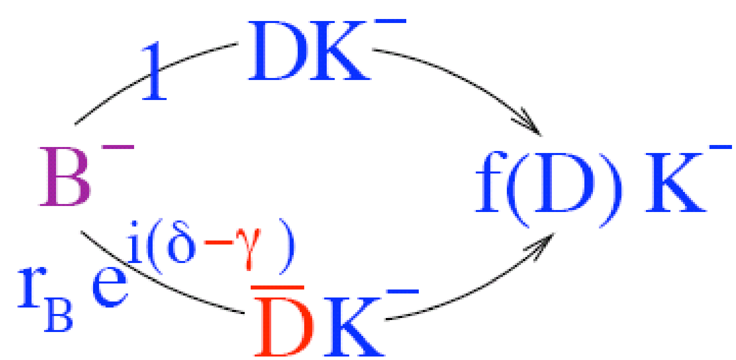
$B^- \longrightarrow \overline{D}^0 K^-$



Colour/CKM suppressed – r_B~0.1

$$\frac{\langle B^- \longrightarrow \overline{D}^0 K^- \rangle}{\langle B^- \longrightarrow D^0 K^- \rangle} = r_B e^{i(\delta_B - \gamma)}$$

- Extraction through interference between $b \to c$ and $b \to u$ transitions



- Require decay of D^0 and $\overline{D^0}$ to a common final state, f(D)
- A theoretically clean determination of γ
  - **SM 'standard candle'**

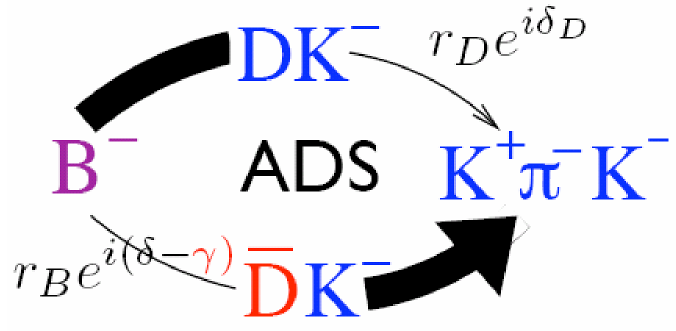
Atwood-Dunietz-Soni (ADS) Method

PRL 78, 3257 (1997)

f(D) = non-CP Eigenstate (e.g. $K^+\pi^-$)

$$\frac{< D^0 \longrightarrow K^+\pi^- >}{< \overline{D}^0 \longrightarrow K^+\pi^- >} = r_D e^{i\delta_D}$$

r_D ~0.06



$$\Gamma(B^- \to (K^-\pi^+)_D K^-) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B - \delta_D^{K\pi} - \gamma) \quad (1)$$

$$\Gamma(B^- \to (K^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} - \gamma) \quad (2)$$

$$\Gamma(B^+ \to (K^+\pi^-)_D K^+) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B - \delta_D^{K\pi} + \gamma) \quad (3)$$

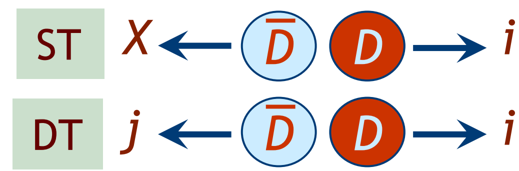
$$\Gamma(B^+ \to (K^-\pi^+)_D K^+) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cdot \cos(\delta_B + \delta_D^{K\pi} + \gamma) \quad (4)$$

- From counting these 4 rates, together with those from CP eigenstates (*KK*, *ππ*), a determination of γ can be made
- Can determine δ_D from rates but **external constraints extremely helpful**

Coherent vs. Incoherent Decay

D. Asner and W. Sun, Phys. Rev. D73, 034024 (2006)

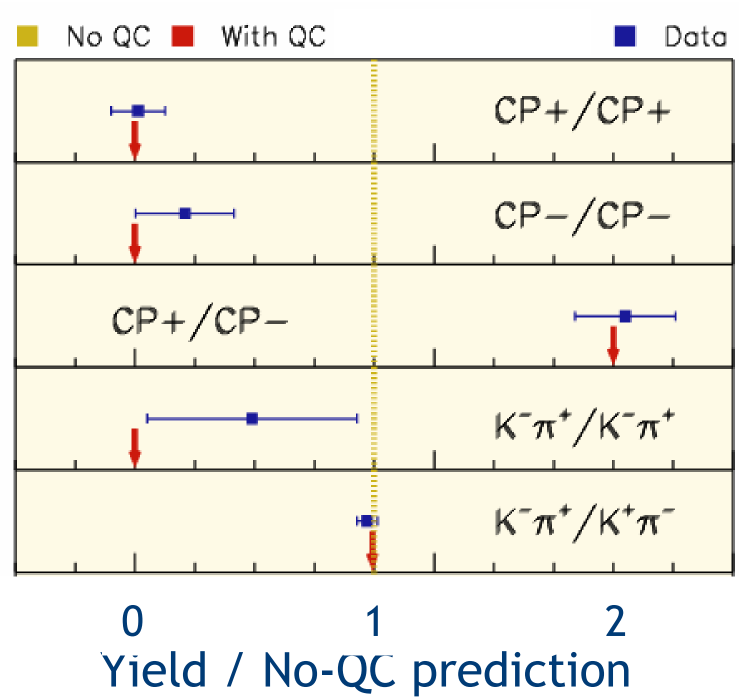
- Require yields for
  - single tags (one D reconstructed)
  - double tags (D and $\bar{D}$ reconstructed)



DT	$K^-\pi^+$	e^+	$CP+$	$CP-$
$K^-\pi^+$	R_M / R_{WS}			
$K^+\pi^-$	$1+2R_{WS}-4r\cos\delta\,(r\cos\delta+y)$			
e^-	$1-r\,(y\cos\delta+x\sin\delta)$	1		
$CP+$	$1+(2r\cos\delta+y)/(1+R_{WS})$	$1+y$	0	
$CP-$	$1-(2r\cos\delta+y)/(1+R_{WS})$	$1-y$	2	0
ST	1	1	1	1

$\dfrac{\text{QC rate}}{\text{incoherent rate}}$

$R_M = (x^2 + y^2)/2$ and $R_{WS} = r^2 + ry' + R_M$



Quantum correlations are seen

- Compare coherent/incoherent BFs
- Sources of incoherent BFs:
  - Externally measured BFs
  - Single tags at $\psi(3770)$

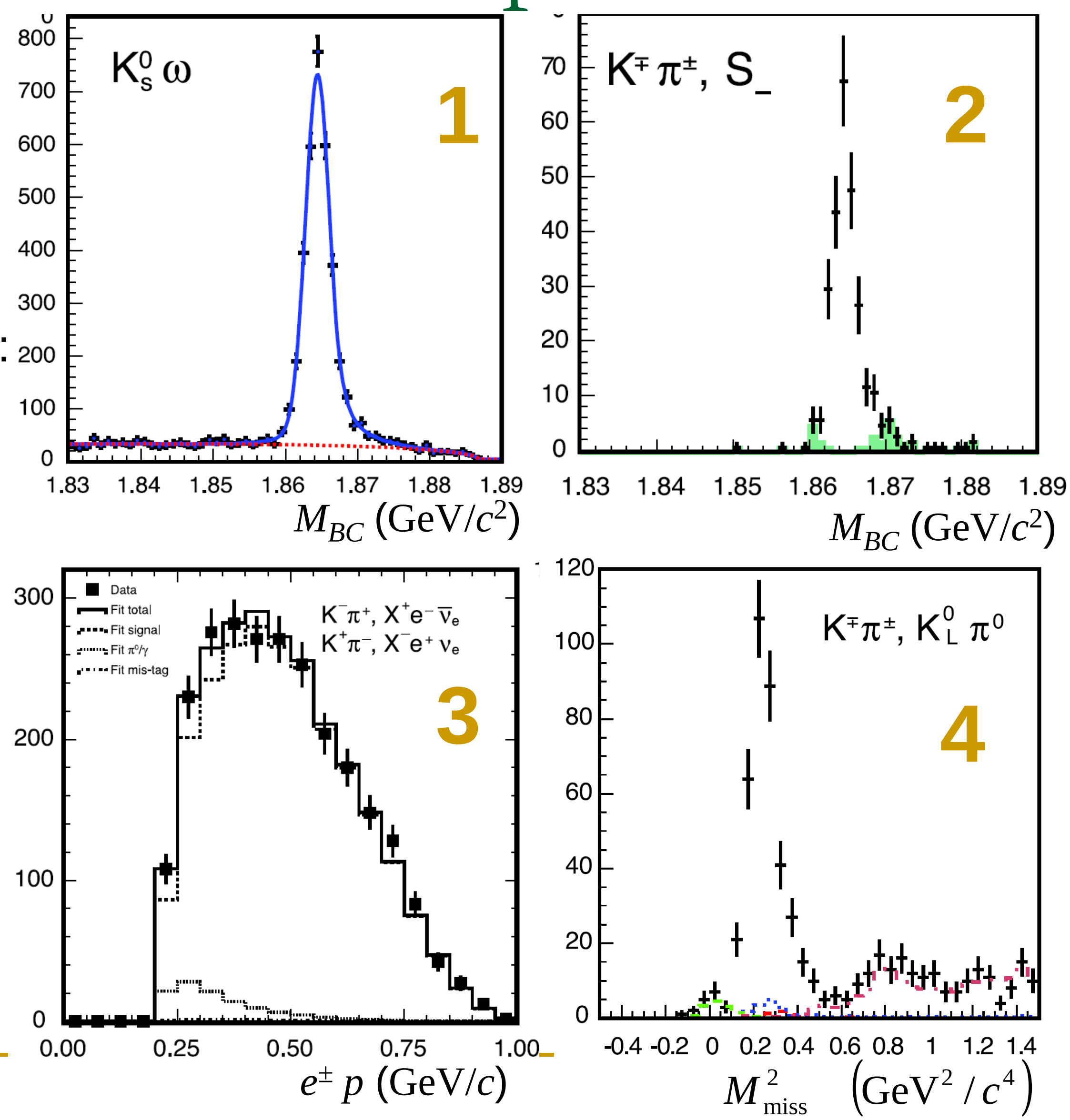
Yield measurements in 281 pb^{-1}

PRL 100, 221801 (2008)
PRD 78, 012001 (2008)

1. Fully-reconstructed single tags:
   - Fit beam-constrained mass distribution

$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$

2. Fully-reconstructed double tags:
   - Two fully-reconstructed STs
3. Inclusive semileptonic DTs:
   - One fully-reconstructed ST
   - Plus one electron candidate
   - Fit $e^{\pm}$ momentum spectrum
4. $K^0_L\pi^0$ double tags:
   - One fully-reconstructed ST
   - Plus one π^0 candidate
   - Compute missing mass^2
     - Signal peaks at $M^2(K^0)$.



External inputs

- External inputs improve y and $\cos\delta$ precision
- All correlations among measurements included in fit
- Standard fit includes:
  - Info on r needed to obtain $\cos\delta$:
    - $R_{WS} = r^2 + r\,y' + R_M$
    - $R_M = (x^2 + y^2)/2$
    - Assume $x\sin\delta = 0 \Rightarrow y' \approx y\cos\delta$
  - $K\pi$ and CP-eigenstate BFs
- Extended fit averages y and y':
  - CP+ lifetimes (y)
  - $K^0_S\pi^+\pi^-$ Dalitz analysis (x, y)
  - $K\pi$ CP-conserving fits (y', r^2, R_M)

Parameter	Average (%)
R_{WS}	0.409 ± 0.022
R_{M}	0.0173 ± 0.0387

Parameter	Value (%)
$\mathcal{B}(K^-\pi^+)$	3.81 ± 0.09
$\mathcal{B}(K^0_S\pi^0)$	1.15 ± 0.12
$\mathcal{B}(K^0_S\eta)$	0.380 ± 0.060
$\mathcal{B}(K^0_S\omega)$	1.30 ± 0.30
$\mathcal{B}(K^0_L\pi^0)$	1.003 ± 0.083
$\mathcal{B}(K^-K^+)/\mathcal{B}(K^-\pi^+)$	10.10 ± 0.16
$\mathcal{B}(\pi^-\pi^+)/\mathcal{B}(K^-\pi^+)$	3.588 ± 0.057

Parameter	Value (%)
y	0.662 ± 0.211
x	0.811 ± 0.334
r^2	0.339 ± 0.012
y'	0.34 ± 0.30
x'^2	0.006 ± 0.018

Results

First determination with 281 pb^{-1}

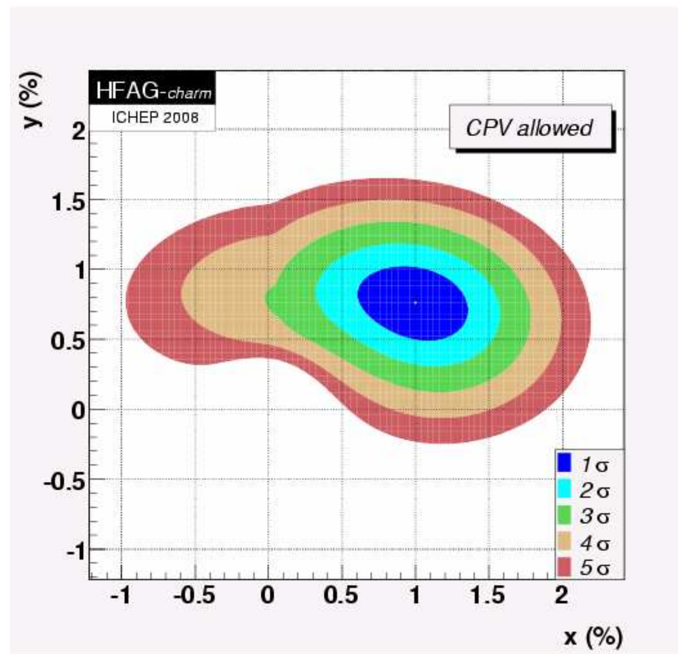
PRL 100, 221801 (2008)
PRD 78, 012001 (2008)

Parameter	Standard Fit	Extended Fit
y (10^{-3})	$-45 \pm 59 \pm 15$	$6.5 \pm 0.2 \pm 2.1$
r^2 (10^{-3})	$8.0 \pm 6.8 \pm 1.9$	$3.44 \pm 0.01 \pm 0.09$
$\cos\delta$	$1.03 \pm 0.19 \pm 0.06$	$1.10 \pm 0.35 \pm 0.07$
x^2 (10^{-3})	$-1.5 \pm 3.6 \pm 4.2$	$0.06 \pm 0.01 \pm 0.05$
$x\sin\delta$ (10^{-3})	0 (fixed)	$4.4 \pm 2.4 \pm 2.9$
$\chi^2_{\rm fit}/{\rm ndof}$	30.1/46	55.3/57

- Standard fit result important component in average of charm mixing
- Extended fit leads to measurement of:

$$\delta = \left(22^{+11+9}_{-12-11}\right)^\circ$$

From likelihood scan of physically allowed region



- Future improvements:
  - Full $\psi(3770)$ data set – 818 pb^{-1}
  - WS semileptonics vs. $K\pi$
  - Additional K^0_L modes
  - C-even information from 4170 MeV data

Multi-body ADS

Mode	Branching Ratio
$K\pi$	3.89%
$K\pi\pi^0$	13.9%
$K3\pi$	8.1%

- $B \to D(K\pi\pi\pi)K$ and $B \to D(K\pi\pi^0)K$ can also be used for ADS analyses
  - Significantly larger branching fractions than $B \to D(K\pi)K$
- However, need to account for the resonant substructure
  - In principle each point in the phase space has a different strong phase associated with it
- Atwood and Soni [PRD **68** 033003 (2003)] showed how to modify the usual ADS equations for this case
  - Introduce **coherence parameter $R_{K3\pi}$** which dilutes interference term sensitive to γ

$$\Gamma(B^- \to (K^+\pi^-\pi^-\pi^+)_D K^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} - \gamma)$$

- $R_{K3\pi}$ ranges from
  - 1=coherent (dominated by a single mode) to
  - 0=incoherent (several significant components)

Measuring R and δ at CLEO-c

- The coherent double-tagged rates give sensitivity to combinations of R and δ

Double Tag Rate	Sensitive To
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$	$(R_{K3\pi})^2$
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. CP	$R_{K3\pi}\cos(\delta^{K3\pi})$
$K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ vs. $K^{\pm}\pi^{\mp}$	$R_{K3\pi}\cos(\delta^{K\pi} - \delta^{K3\pi})$

- We perform selections of these double-tags
- In addition, it is also necessary to perform selections of the opposite sign $K^{\pm}$ modes to determine normalisation factors
- Also some CP tags are normalised to *Kπ vs* CP-tag to reduce dependence on poorly measured BFs

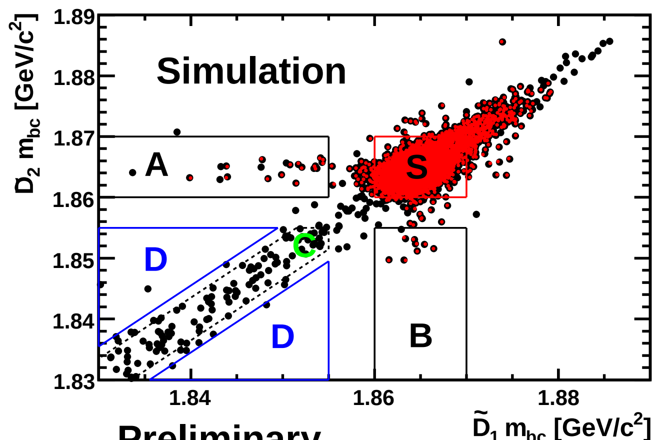
Event selection

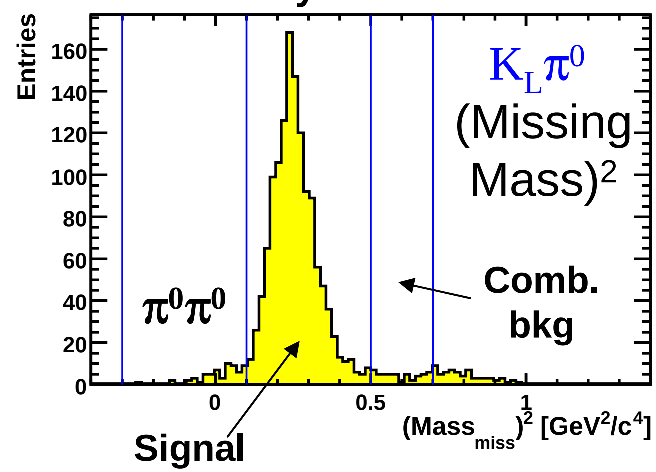
- Selections performed over all **ψ(3770)** data, corresponding to 818 pb^{-1}.
- Consider 10 different CP tags:

CP Tag	K3π yield	Kππ^0 yield
KK, ππ	782	1100
$K_S\pi^0$	705	891
$K_S\omega(\pi^+\pi^-\pi^0)$	319	389
$K_S\pi^0\pi^0$	283	406
$K_S\phi(K^+K^-)$	53	91
$K_S\eta(\{\gamma\gamma, \pi^+\pi^-\pi^0\})$	164	153
$K_S\eta'(\pi^+\pi^-\eta)$	36	61
$K_L\pi^0$	695	1234
$K_L\omega(\pi^+\pi^-\pi^0)$	296	449
Total	**3465**	**4774**

CP = 1, *CP* = -1

- Assess flat background from m_{bc} sidebands and peaking from MC:





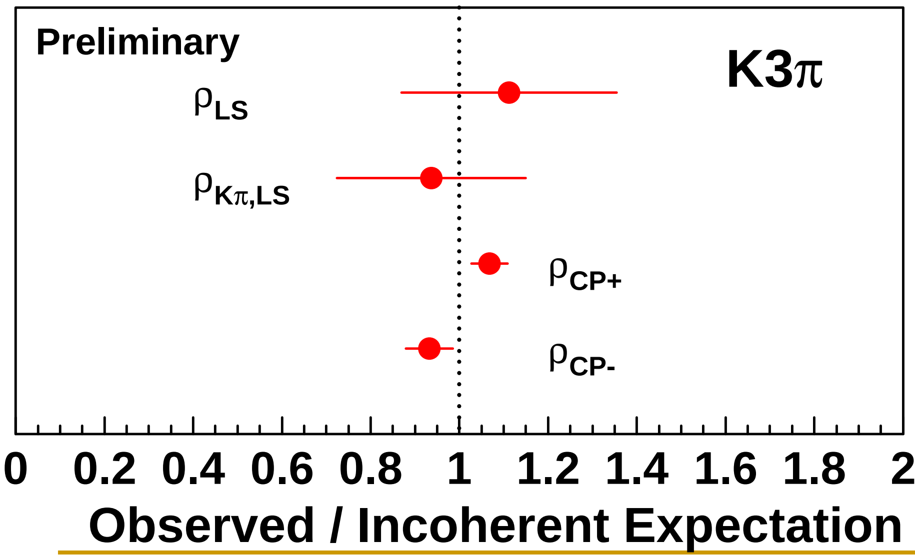
Observables

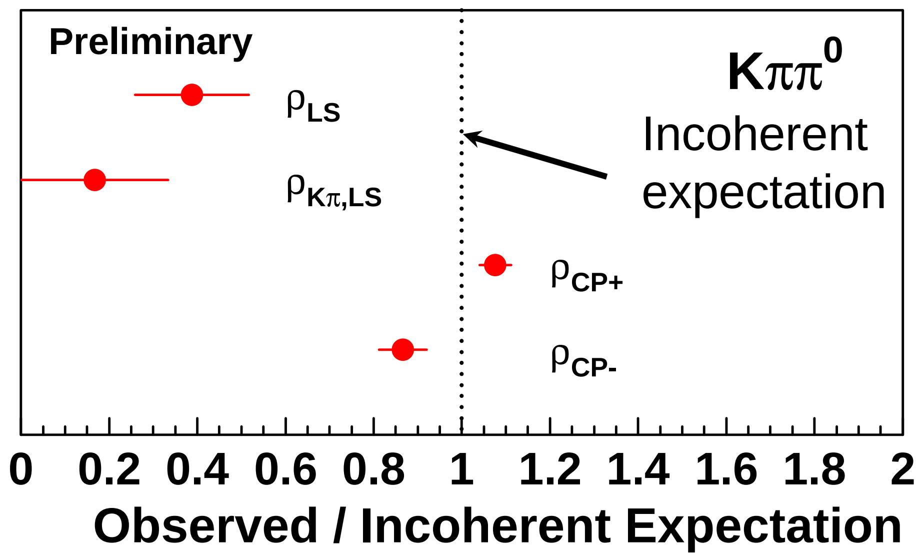
- Define observables which are the measured rates normalised to the incoherent expectation
  - Dependence on D mixing parameters and $\delta_D^{K\pi}$

$$\rho_{LS}^{K3\pi} \cong \frac{1-R_{K3\pi}^2}{1+\frac{x^2+y^2}{2\left(r_D^{K3\pi}\right)^2}-\frac{R_{K3\pi}}{r_D^{K3\pi}}\left(y\cos\delta_D^{K3\pi}-x\sin\delta_D^{K3\pi}\right)}$$

$$\rho_{K\pi,LS}^{K3\pi} \propto \frac{1+\left(\frac{r_D^{K3\pi}}{r_D^{K\pi}}\right)^2-2\frac{r_D^{K3\pi}}{r_D^{K\pi}}R_{K3\pi}\cos\delta_D^{K3\pi}}{1+\frac{x^2+y^2}{2\left(r_D^{K\pi}\right)^2}-\frac{1}{r_D^{K\pi}}\left(y\cos\delta_D^{K\pi}-x\sin\delta_D^{K\pi}\right)}$$

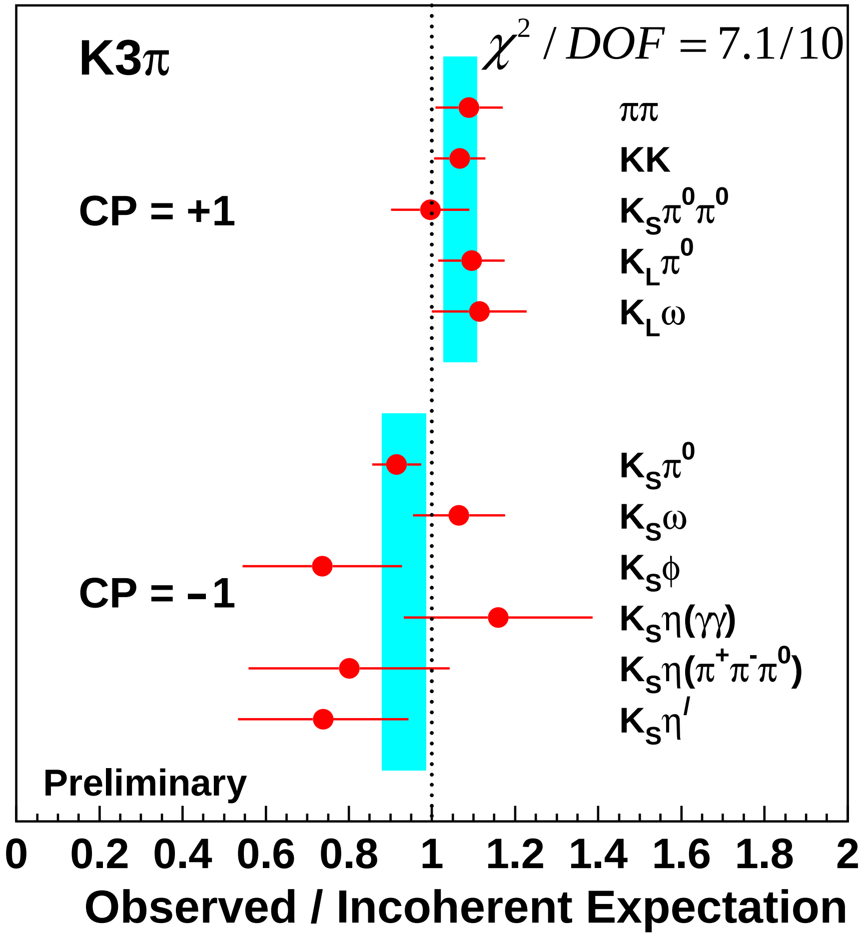
$$\rho_{CP\pm}^{K3\pi} \cong 1\pm\Delta_{CP}^{K3\pi} \text{ where } \Delta_{CP}^{K3\pi}=y-r_D^{K3\pi}R_{K3\pi}\cos\delta_D^{K3\pi}$$

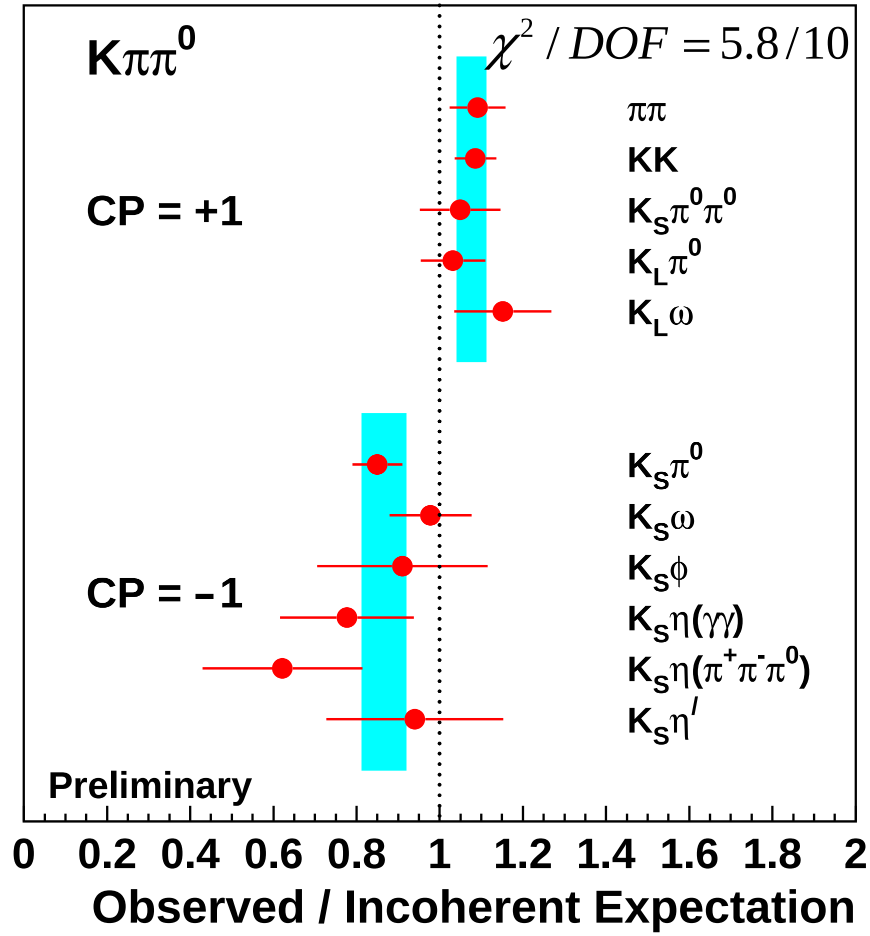




CP observables

Weighted averages





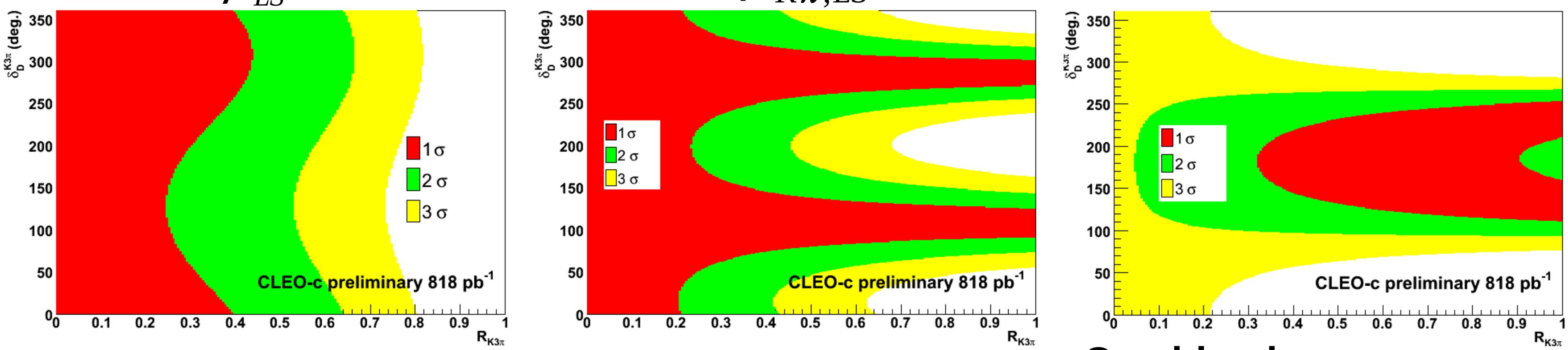
CLEO-c preliminary results

Observable	$K3\pi$	$K\pi\pi^0$
ρ_{LS}^{mode}	1.112±0.226±0.088	0.388±0.127±0.026
$\rho_{K\pi,LS}^{\text{mode}}$	0.937±0.176±0.120	0.167±0.099±0.134
Δ_{CP}	0.073±0.018±0.024	0.098±0.015±0.025

- Dominant systematic uncertainties:
  - ρ_{LS}: DCS branching fraction
  - $\rho_{K\pi,LS}$: $K^-\pi^+ \to K^+\pi^-$ mis-ID rate
  - Δ_{CP}: statistics of normalisation to $K\pi$ vs. *CP*-tag yields
    - Smaller uncertainty than using PDG branching fractions
    - Some reconstruction uncertainties cancel

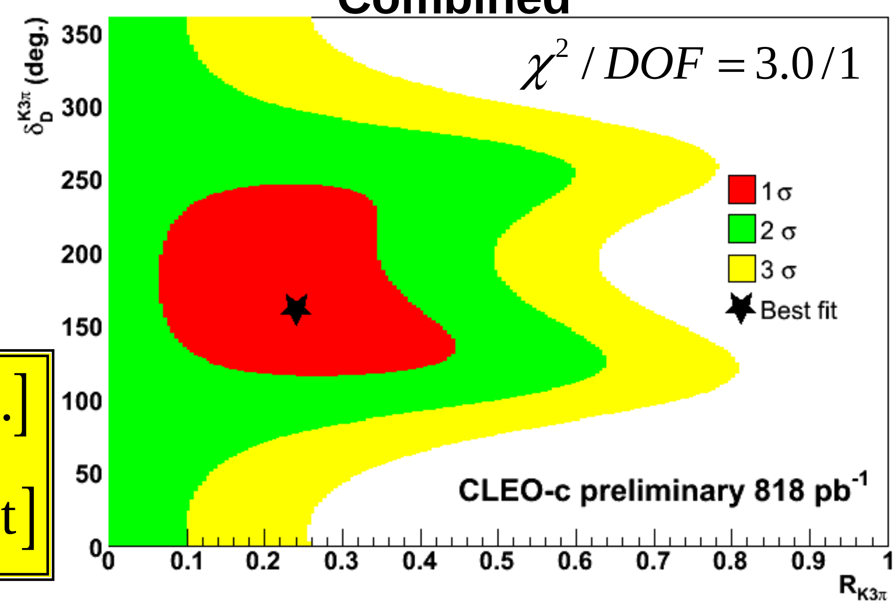
K3π likelihood scans

$\rho_{LS}^{K3\pi}$ $\rho_{K\pi,LS}^{K3\pi}$ Δ_{CP}



- Fit to observables and external constraints on D mixing parameters and branching fractions
  - Correlations included
- 2D likelihood shows regions R and δ space

Combined



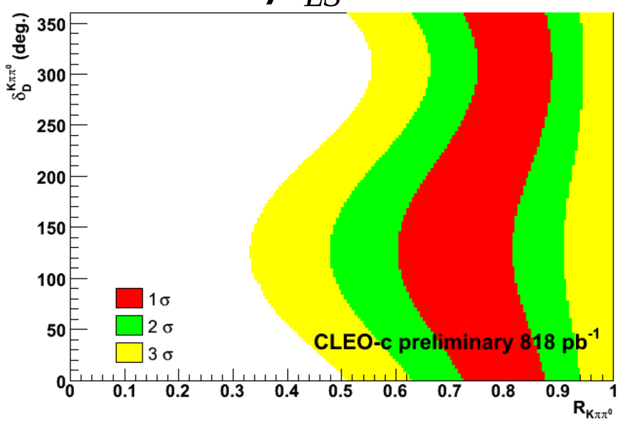
Preliminary

$$R_{K3\pi} = 0.24^{+0.21}_{-0.17} \quad [R_{K3\pi} < 0.57 \text{ at } 95\% \text{ c.l.}]$$

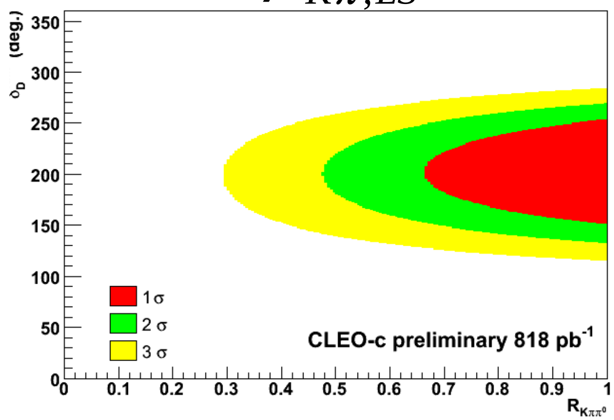
$$\delta_D^{K3\pi} = \left(161^{+85}_{+48}\right)^\circ \quad [\text{No } 95\% \text{ c.l. constraint}]$$

$K\pi\pi^0$ likelihood scans

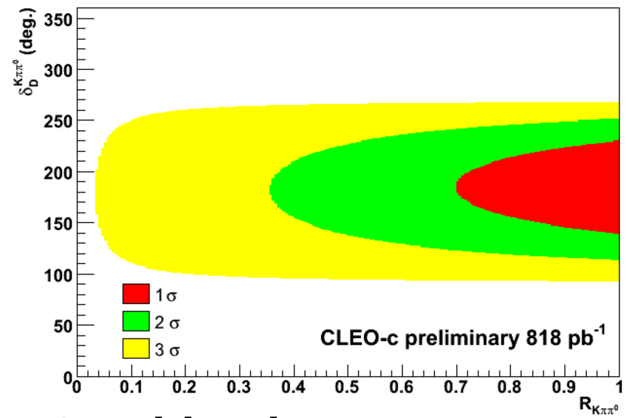
$\rho_{LS}^{K\pi\pi^0}$



$\rho_{K\pi,LS}^{K\pi\pi^0}$



Δ_{CP}

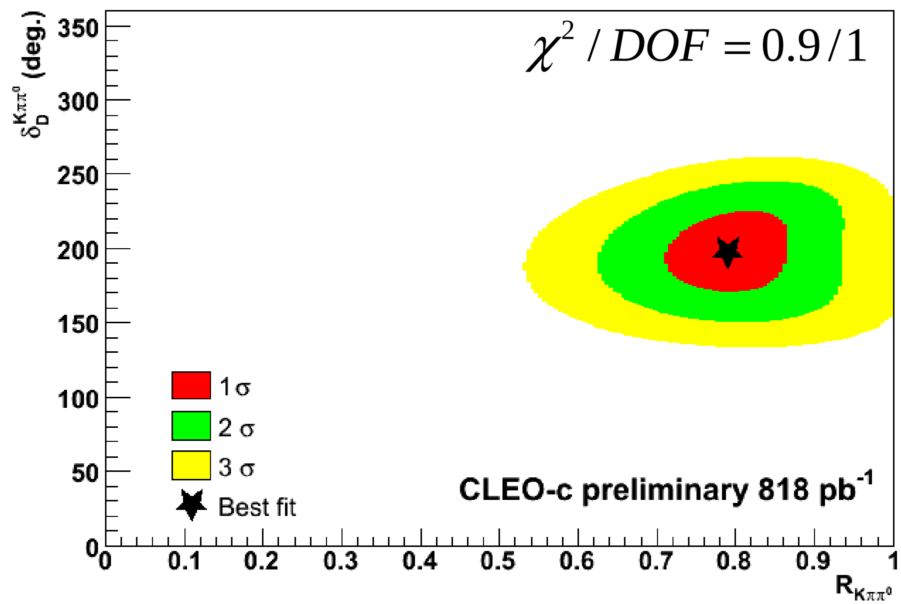


Preliminary

$$R_{K\pi\pi^0} = 0.79 \pm 0.08$$

$$\delta_D^{K\pi\pi^0} = \left(197_{-27}^{+28}\right)^\circ$$

Combined

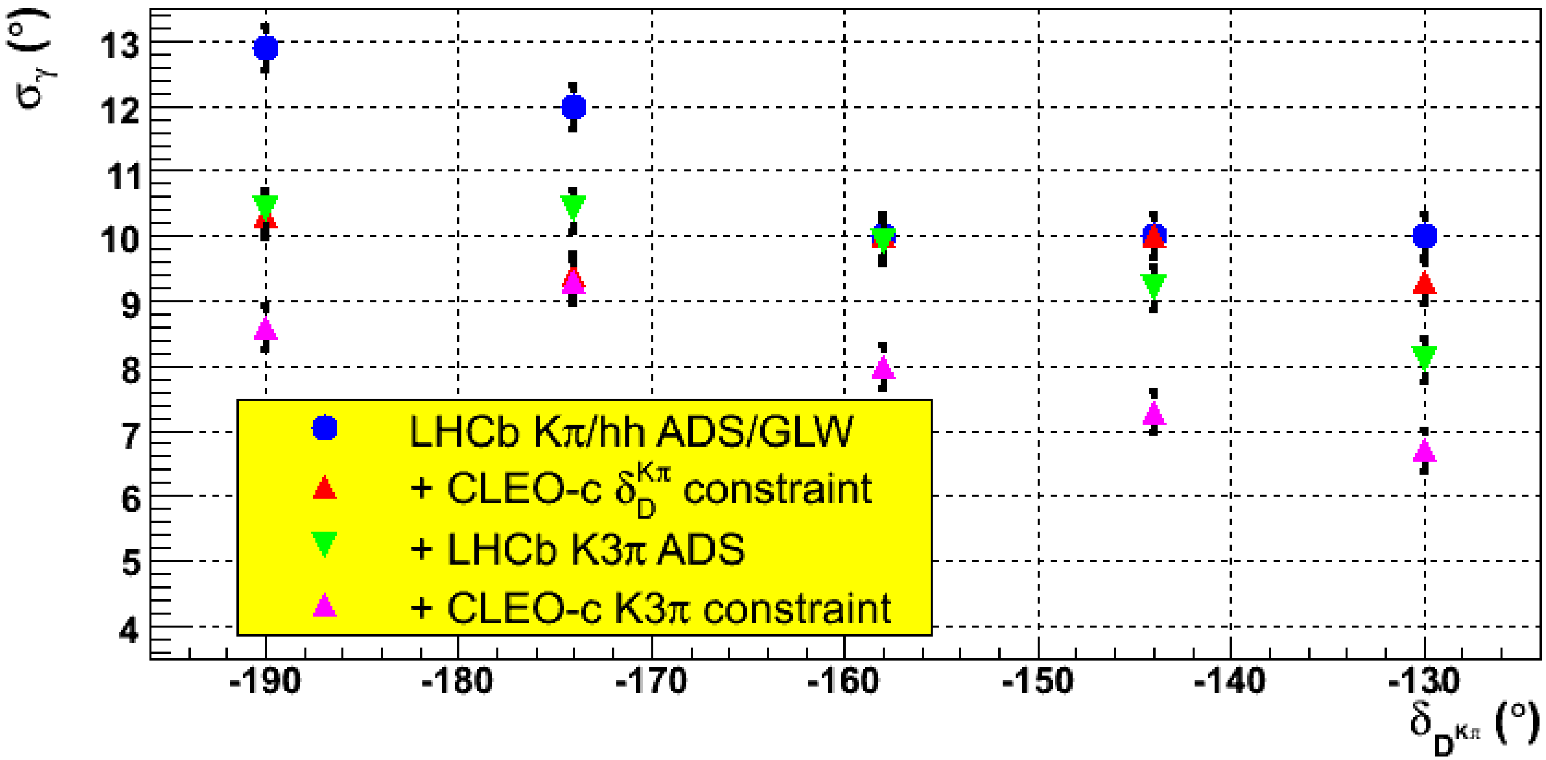


Coherence observed!

Impact of CLEO-c at LHCb

From prelim. result arXiv:0805.1722

- These D→K3π measurements have been input to ADS simulation studies by LHCb
  - Estimated yields documented in LHCb-2006-066 and LHCb-2007-004
- One nominal year of running results see significant improvement with the addition of *B→D(K3π)K* and the CLEO-c constraints

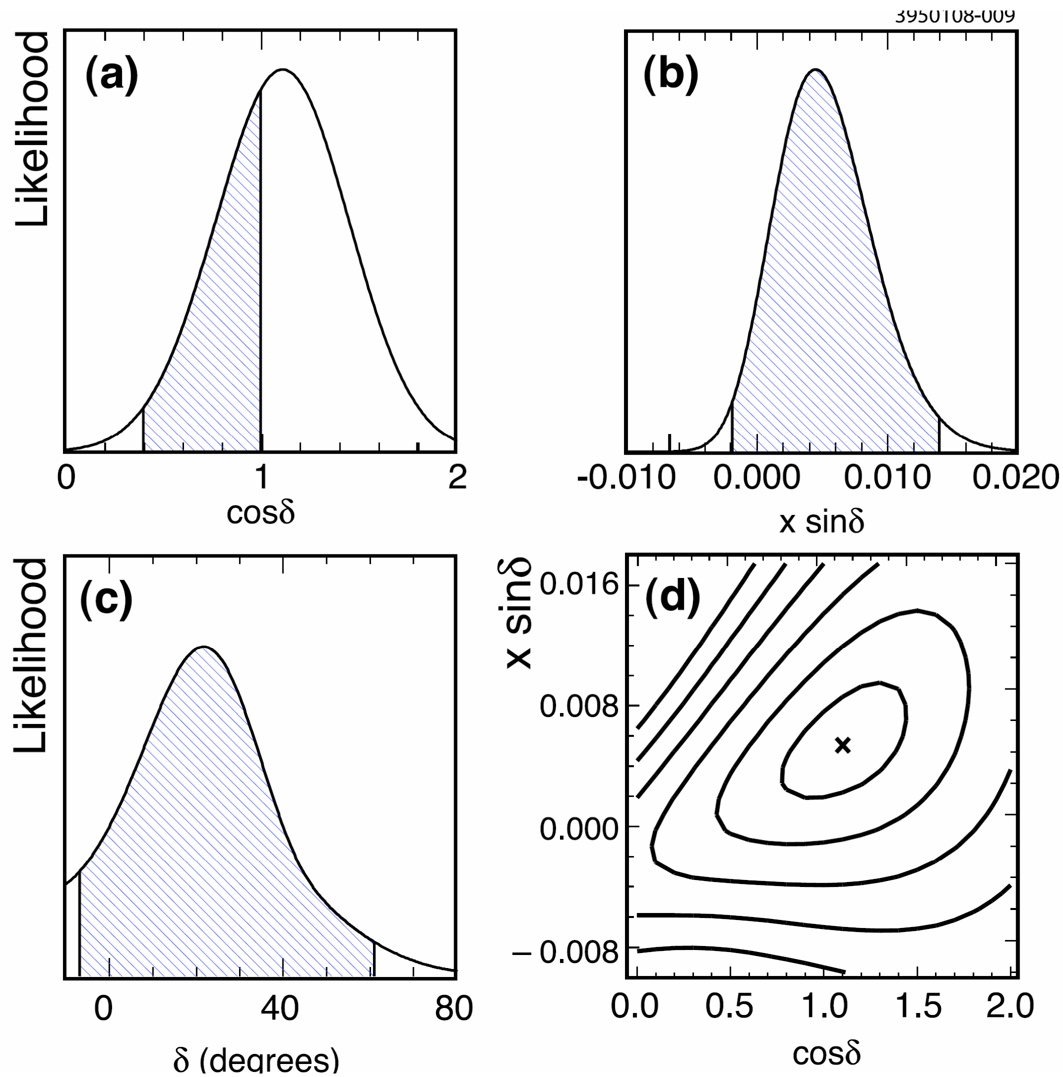


Conclusion

- CLEO-c data vital for γ extraction strategies with $B^{\pm} \to DK^{\pm}$
- First determination of strong phase difference for $D \to K\pi$
  - PRL 100, 221801 (2008) and PRD 78, 012001 (2008)
- Preliminary results for the $D \to K\pi\pi\pi$ and $D \to K\pi\pi^0$ coherence factor, R, and the average strong phase, δ_D
  - $D \to K\pi\pi^0$ very coherent acts almost like $D \to K\pi$
  - $D \to K3\pi$ not v. coherent but gives a powerful constraint on r_B

Backup

TQCA extended fit likelihoods



Systematics

	$\rho_{LS}^{K\pi\pi 0}$	$\rho_{K\pi,LS}^{K\pi\pi 0}$	$\Delta_{CP}^{K\pi\pi 0}$
Norm. Stats	0.005	0.005	0.003
$K\pi\pi^0$ BR CF	0.014	0.006	0.011
$K\pi\pi^0$ BR DCS	0.021	0.009	< 0.001
$K\pi$ BR CF	/	0.004	0.001
$K\pi$ BR DCS	/	0.013	0.002
CP BR	/	/	0.005
Rec/PID efficiencies	/	/	0.006
$K\pi$ vs CP stats	/	/	0.017
$K\pi$ norm. method	/	/	0.012
$\delta_{K\pi}$	/	/	0.006
Double misid	/	0.133	/
Total	0.026	0.134	0.026