Quantum Correlations in $D^0\bar{D}^0$ Decays at CLEO-c

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LLWI 2008
Feb. 20

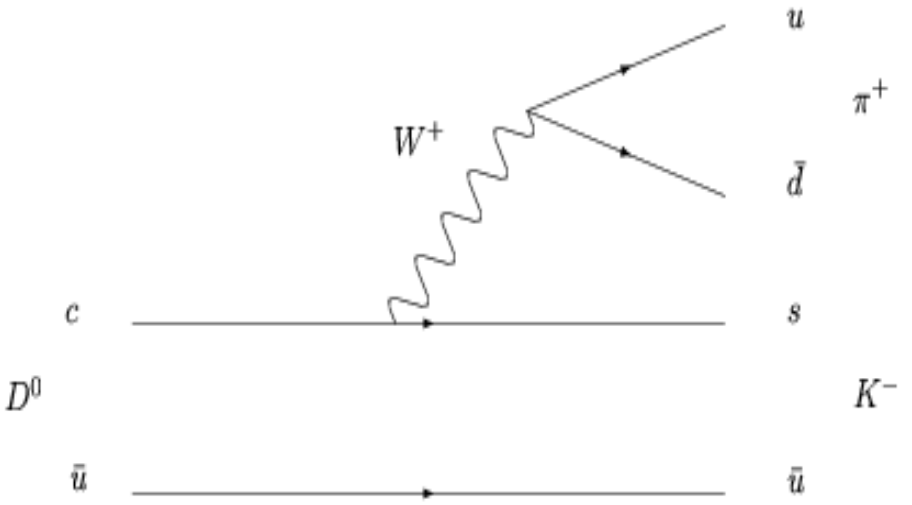
Motivation

- $D^0\bar{D}^0$ mixing is described by two small parameters:
  - $x = 2(M_2 - M_1)/(\Gamma_2+\Gamma_1)$
  - $y = (\Gamma_2-\Gamma_1)/(\Gamma_2+\Gamma_1)$

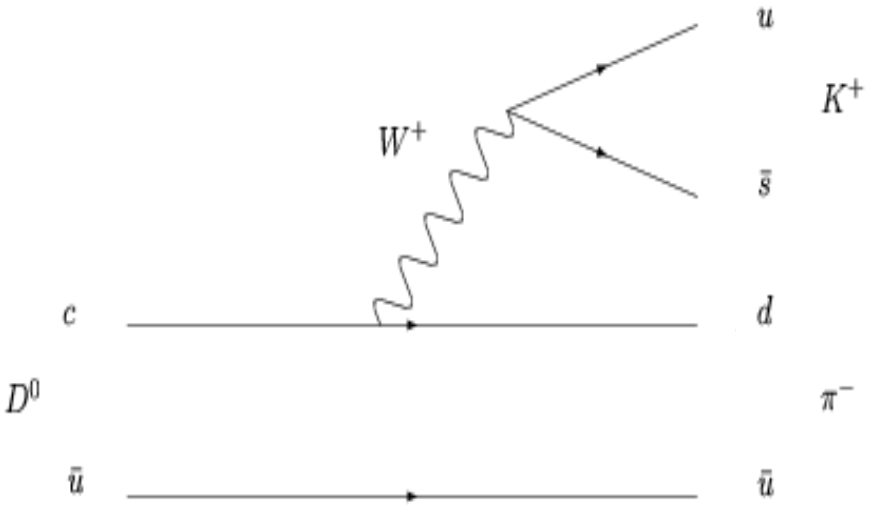
  where $M_{2,1}$ and $\Gamma_{2,1}$ are the masses and widths of neutral D CP eigenstates.
- y can be measured by comparing $D^0 \to K^+K^-/\pi^+\pi^-$ lifetimes to that in $D^0 \to K^-\pi^+$
- $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ can be measured through D^0 lifetime in "wrong-sign" $D^0 \to K^+\pi^-$ decays
- Measurements of y and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ are not directly comparable because has $\delta_{K\pi}$ not been previously measured.

Motivation

- Strong phase $\delta_{K\pi}$: phase of $K\pi$ DCS to CF amplitude ratio
- r: magnitude of $K\pi$ DCS to CF amplitude ratio



Cabibbo Favored (CF)



Doubly Cabibbo Suppressed (DCS)

- CLEO-c is uniquely sensitive to this strong phase because of the production of quantum correlated $D\bar{D}$ pairs

The method

$$ee \rightarrow \gamma^* \rightarrow D^0\bar{D}^0 \text{ is C = -1}$$

- In $\psi(3770) \rightarrow D^0\bar{D}^0$, decay rates are more sensitive to mixing parameters and $\delta_{K\pi}$ than rates from uncorrelated D^0 decay. These quantum correlated pairs allow for a simultaneous fit to yields to determine x^2, y, r^2, and cos $\delta_{K\pi}$.

- We use:
  - Flavor tags: hadronic decay to non-CP eigenstate. CF or DCS are possible. We use $D^0 \rightarrow K^-\pi^+$ (f) and $\bar{D}^0 \rightarrow K^+\pi^-$ ($\bar{f}$).
  - CP tags: hadronic decay to state of definite CP. We use

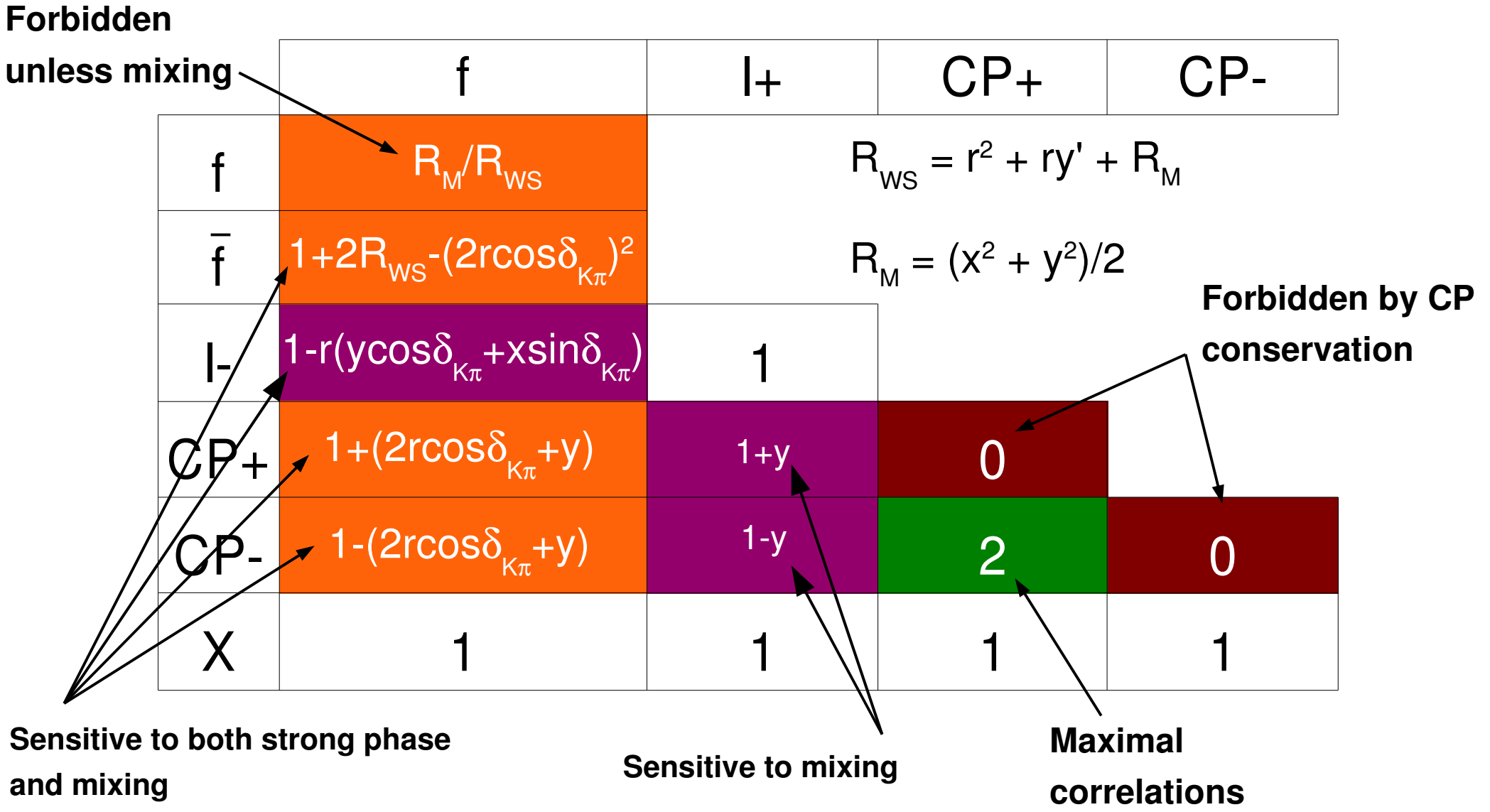
    $D^0/\bar{D}^0 \rightarrow K_s\pi^0$ $D^0/\bar{D}^0 \rightarrow K_s\eta$ $D^0/\bar{D}^0 \rightarrow K_s\omega$ (CP-)

    $D^0/\bar{D}^0 \rightarrow K^+K^-$ $D^0/\bar{D}^0 \rightarrow \pi^+\pi^-$ $D^0/\bar{D}^0 \rightarrow K_s\pi^0\pi^0$ $D^0/\bar{D}^0 \rightarrow K_L\pi^0$ (CP+)
  - Semileptonics: inclusive, decay of form $D^0 \rightarrow X\, e^+\nu$ (l+). Charge of lepton always tells us charm/anti-charm of parent D.

The method

- We measure yields for:
  - $f/\bar{f}$ opposite anything, CP+/- opposite anything. These are single tags (ST).
  - All combinations of $f/\bar{f}$ opposite CP+/-, $f/\bar{f}$ opposite $f/\bar{f}$, and CP+/- opposite CP+/-. These are hadronic double tags (DT).
  - Semileptonic opposite $f/\bar{f}$ and semileptonic opposite CP+/-. These are semileptonic double tags.
- **Fit inputs**: 8 hadronic single tag yields, 29 hadronic double tag yields, 14 semileptonic double tag yields, efficiencies, crossfeeds, background branching fractions and efficiencies.
- Measurements of branching fractions and mixing parameters from other CLEO-c and external analyses are also included for optimal precision $\delta_{K\pi}$.
- **Fit outputs**: y, x^2, $\cos\delta_{K\pi}$, r^2, and branching fractions for f, each CP mode, X e^+ ν, and number of $D^0\bar{D}^0$ pairs produced.
- Precision on mixing parameters limited by number of CP tags

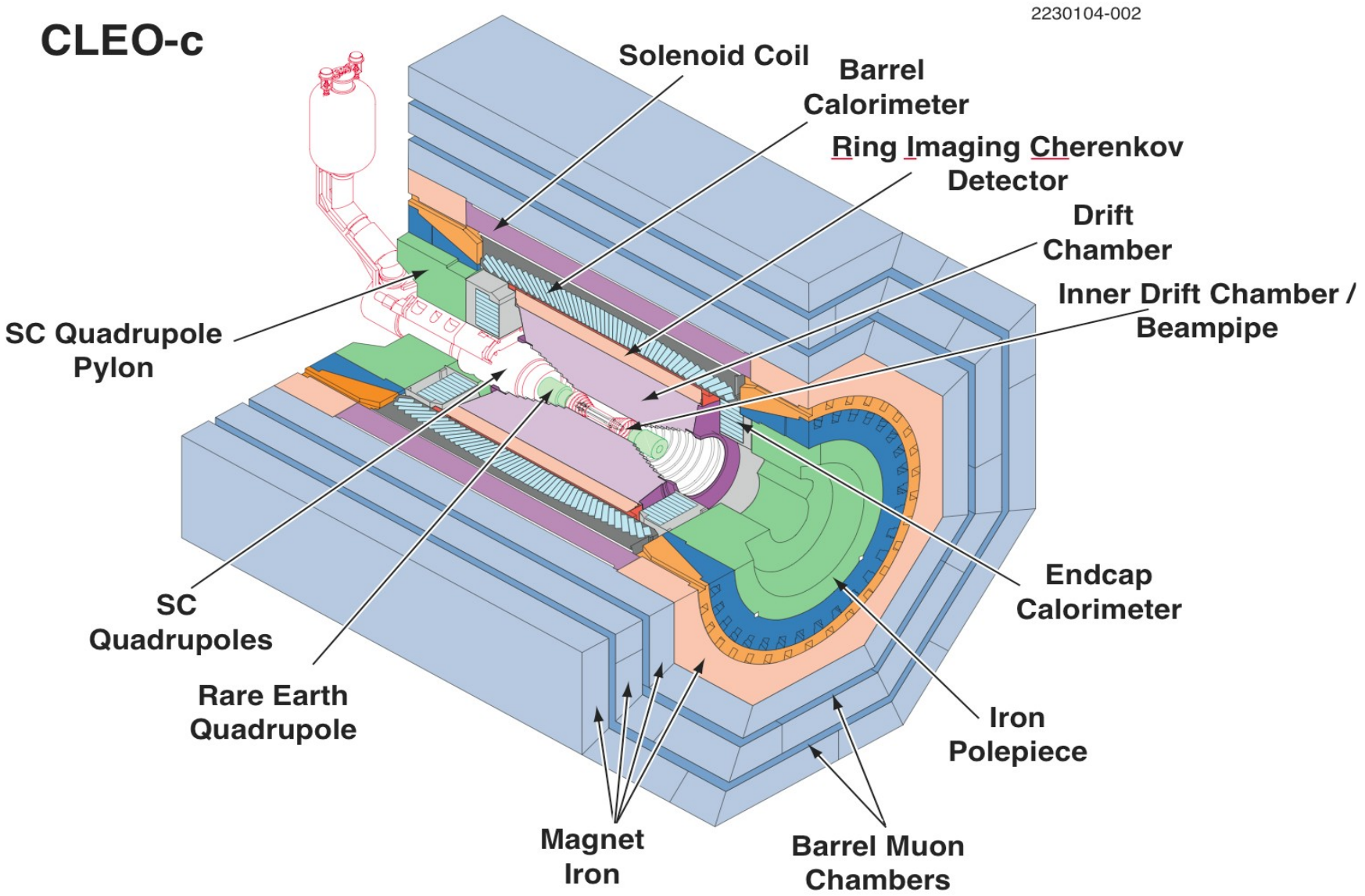
Rate enhancement factors



To 1st order. If no quantum correlation, all entries would be 1.

See PRD 73 034024 (2006) [hep-ph/0507238] by Asner and Sun

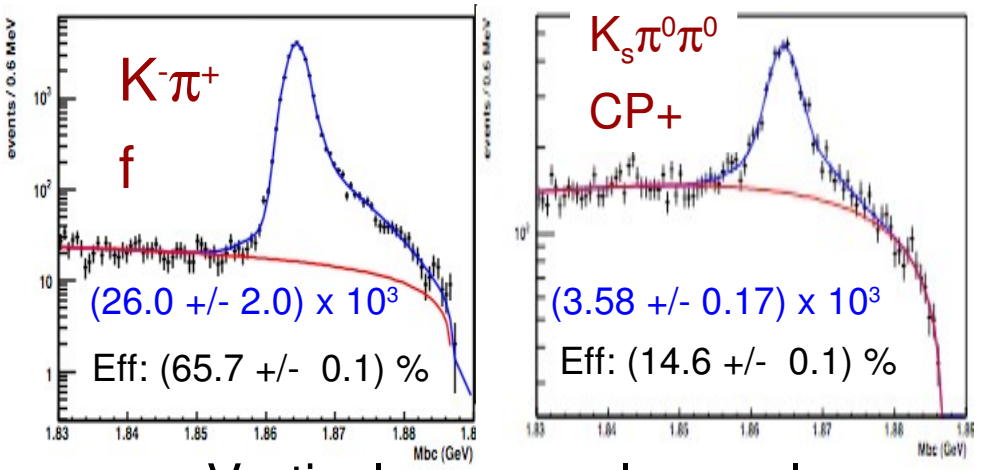
CLEO-c Detector



- These results use CLEO-c data on the ψ'', 281 pb^{-1}, which corresponds to 1 million $D^0\bar{D}^0$ pairs.

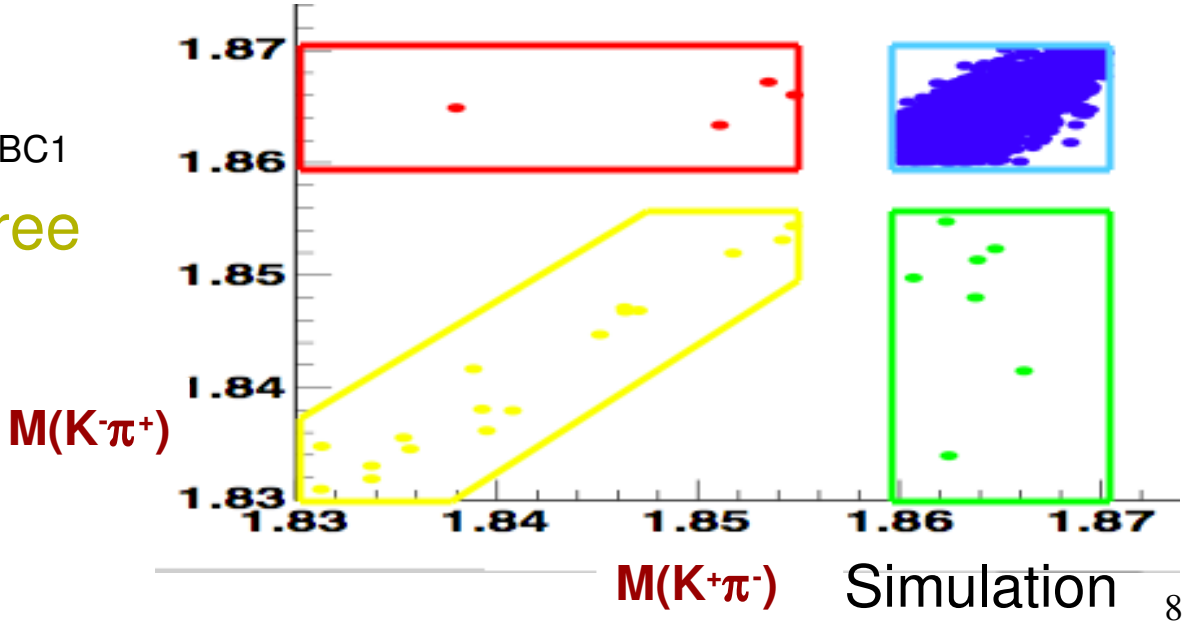
Hadronic Single and Double Tags

- STs: Cut on ΔE, fit M_{BC} distribution to signal and background shapes.
  $M_{BC} = \mathrm{sqrt}(E^2_{beam} - p^2_D)$

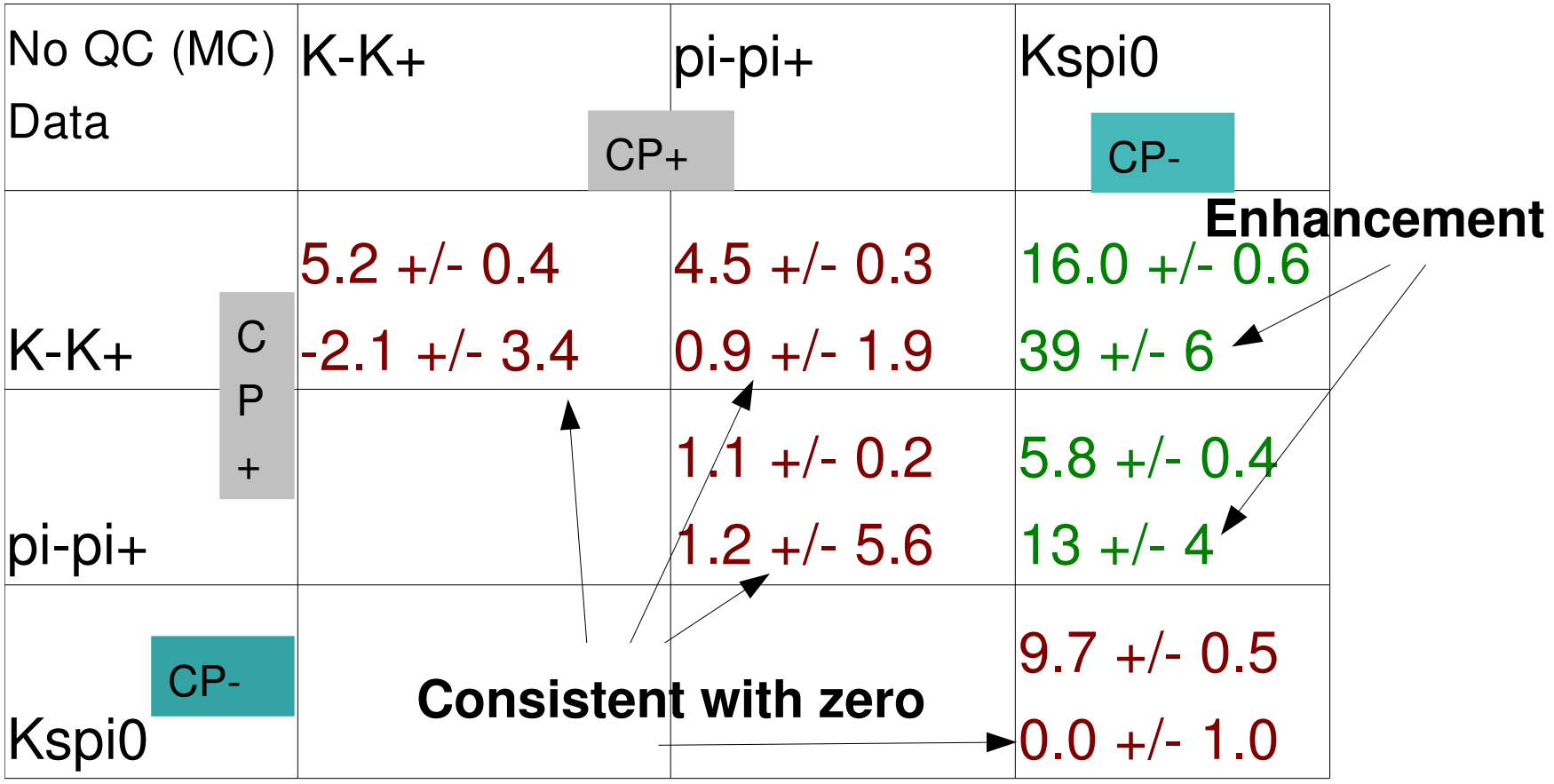


Vertical axes are log scale

- DTs: Cut and count in M_{BC1} vs. M_{BC2} plane, define three sidebands.



Double Tags in Data

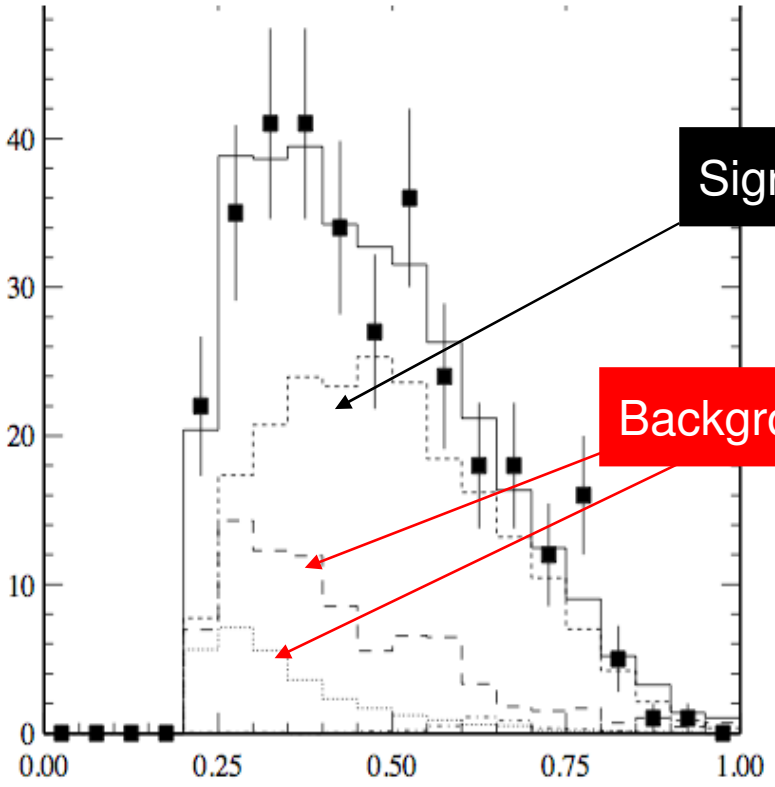


CP tags vs CP tags clearly shows Quantum Correlation

Semileptonics

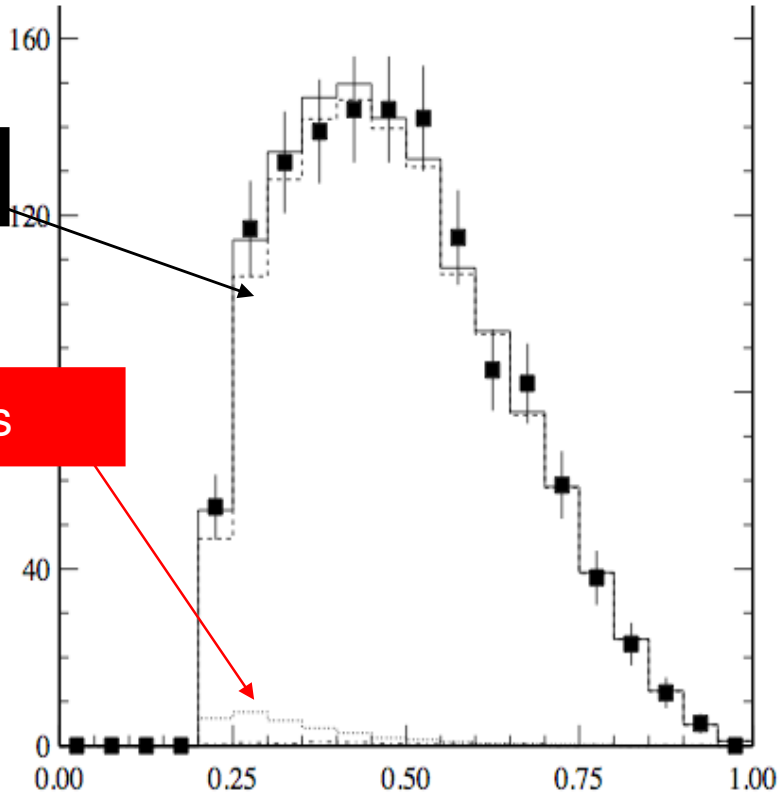
Tag one side with Kπ or CP+/- (excluding $K_L\pi^0$), search for electron in remainder of event. Fit electron momentum spectrum to signal and three background shapes from MC.

Opposite CP+ Tag



Electron Momentum (GeV)

Opposite Kπ Flavor Tag



Electron Momentum (GeV)

Systematic Uncertainties

- Systematics on fit inputs are included in covariance matrix given to fitter
  - E.g., tracking efficiency, semileptonic fit variations, ST signal lineshape
- Systematics due to inclusion of external measurements and constraints on $x\sin\delta_{K\pi}$
  - Standard fit assumes $x\sin\delta_{K\pi} = 0$ and includes external inputs for branching fractions, R_M, and R_{WS}
  - Including external inputs for y and y' allows us to get a meaningful measurement of $x\sin\delta_{K\pi}$, so extended fit with these inputs allow $x\sin\delta_{K\pi}$ to float
  - See hep-ex/0802.2264 (sub. to PRL), hep-ex/0802.2268 (sub. to PRD) for details

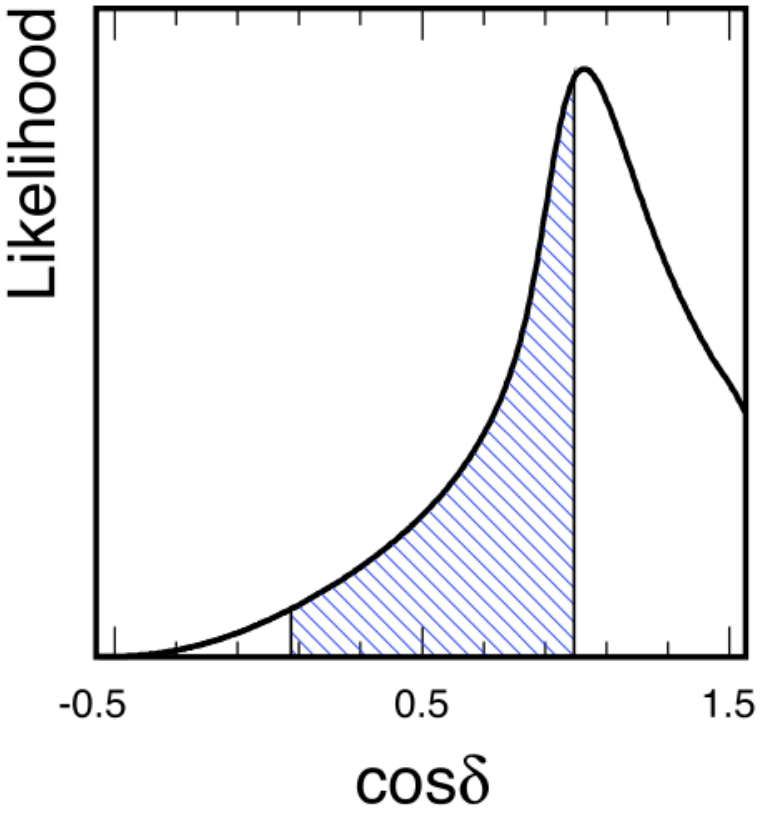
Not well determined with no ext. inputs on y and y'

First determination

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

Additional Uncertainties on $\cos\delta_{K\pi}$

- Repeating standard fit at fixed $\cos\delta_{K\pi}$, recording change in χ^2, and computing likelihood gives non-Gaussian shape
- Additional asymmetric uncertainties are assigned to fit result for $\cos\delta_{K\pi}$



Summary and Future Plans

- CLEO-c production of $D\bar{D}$ pairs gives unique sensitivity to $\cos\delta_{K\pi}$
- A simultaneous fit to hadronic ST, DT, and semileptonic DT yields can determine x^2, y, r^2, and $\cos\delta_{K\pi}$

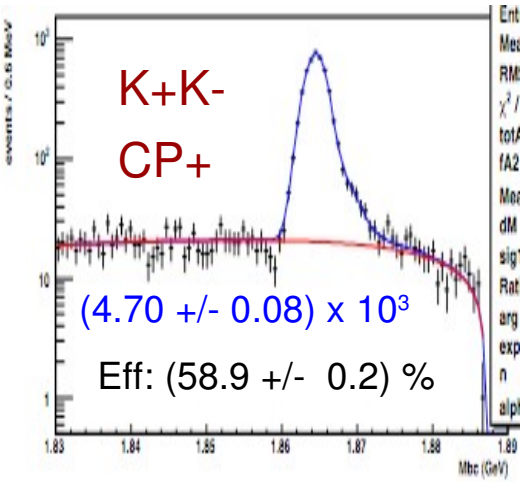
- First determination of strong phase $\delta_{K\pi}$:
  - $\cos\delta_{K\pi} = 1.03^{+0.31}_{-0.17} +/- 0.06$

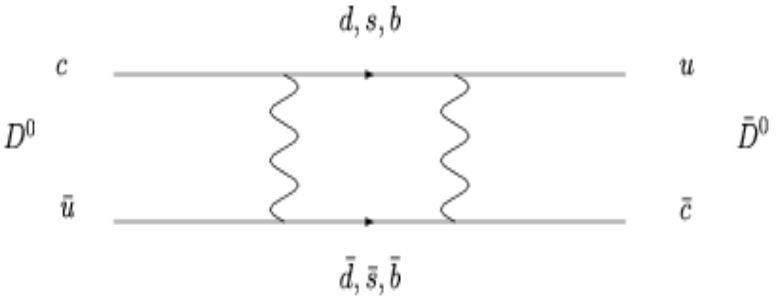
- Future plans:
  - Include entire CLEO-c ψ'' dataset
  - Wrong sign Kπ vs. semileptonics
  - More K_L modes ($K_L\pi^0\pi^0$, $K_L\eta$, $K_L\omega$)
  - C-even information from 4170 MeV data

- Determination including external mixing measurements:
  - $\cos\delta_{K\pi} = 1.10 +/- 0.35 +/- 0.07$
  - $x\sin\delta_{K\pi} = (4.4^{+2.7}_{-1.8} +/- 2.9) \times 10^{-3}$
  - $y = (6.5 +/- 0.2 +/- 2.1) \times 10^{-3}$
  - $\delta_{K\pi} = (22^{+11}_{-12}{}^{+9}_{-11})^o$, determined by fixing $\cos\delta_{K\pi}$ and $\sin\delta_{K\pi}$ and repeating fit

Extra Slides

- References:
  - Goldhaber, Rosner: **PRD 15, 1254 (1977).**
  - Xing: **PRD 55, 196 (1997).**
  - Gronau, Grossman, Rosner: **hep-ph/0103110**.
  - Atwood, Petrov: **PRD 71, 054032 (2005)**.
  - Asner, Sun: **hep-ph/0507238.**





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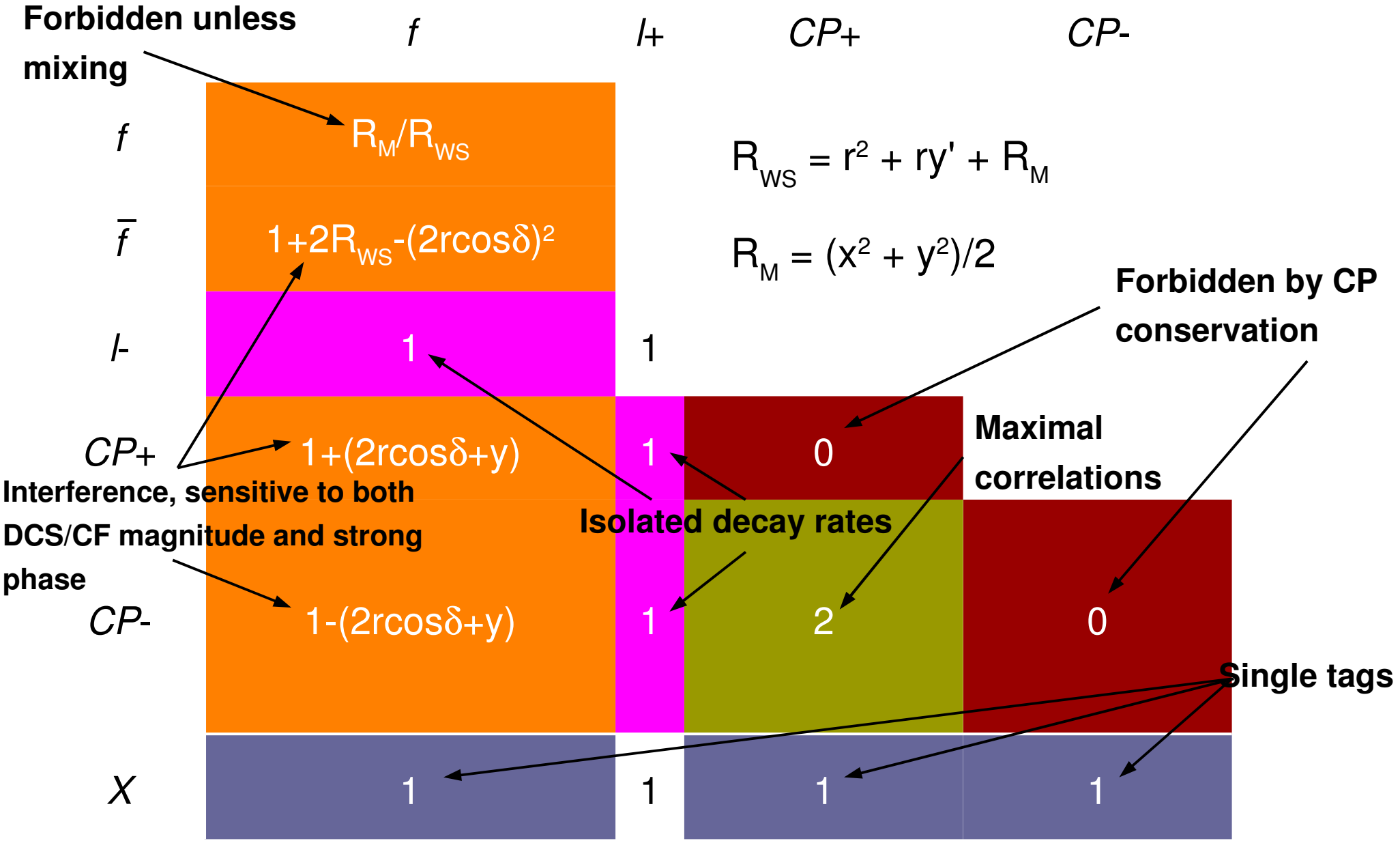

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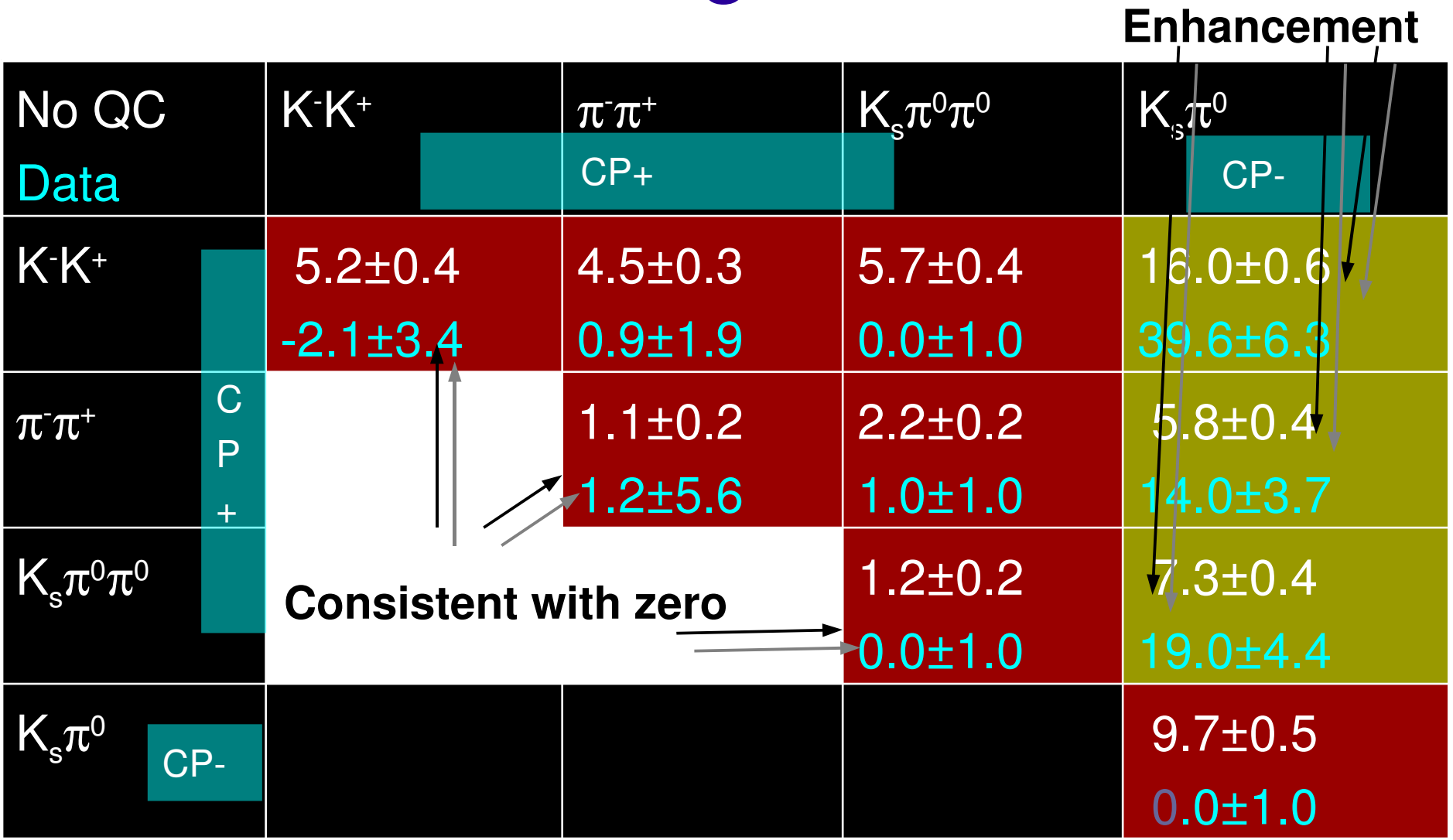

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