Searching for the Origin of CP violation in Cabibbo Suppressed D-meson Decays

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Outline

- What is the problem?

  ....Latest results

- Could CP violation in D decay be consistent with QCD?
- Additional measurements
- Six suggestions
- Conclusion

What is the problem? (before this morning)

- Measurements of CP violation in $D^0 \rightarrow P^+P^-$ show results apparently larger than expected:

$$A_{CP}(\pi^+\pi^-) = \begin{cases} +0.55 \pm 0.36 \pm 0.09\% \text{ (BELLE)} \\ +0.22 \pm 0.24 \pm 0.11 \text{ (CDF)} \end{cases}$$

$$A_{CP}(K^+K^-) = \begin{cases} -0.32 \pm 0.21 \pm 0.09\% \text{ (BELLE)} \\ -0.24 \pm 0.22 \pm 0.09\% \text{ (CDF)} \end{cases}$$

$$A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \begin{cases} -0.82 \pm 0.21 \pm 0.11\% \text{ (LHCb)} \\ -0.62 \pm 0.21 \pm 0.10\% \text{ (CDF)} \\ -0.87 \pm 0.42 \pm 0.06\% \text{ (BELLE)} \\ -0.68 \pm 0.15\% \text{ (HFAG combined)} \end{cases}$$

- Note in particular the >3-sigma signal in the combined result..

Could CP violation in D decay be consistent with SM and QCD?

- In particular, are such results too large to explain in the SM?
- First, consider what is happening on the quark level. In these final states we have interference between

$$c \to u\bar{d}d \qquad \text{vs} \qquad c \to u\bar{s}s$$

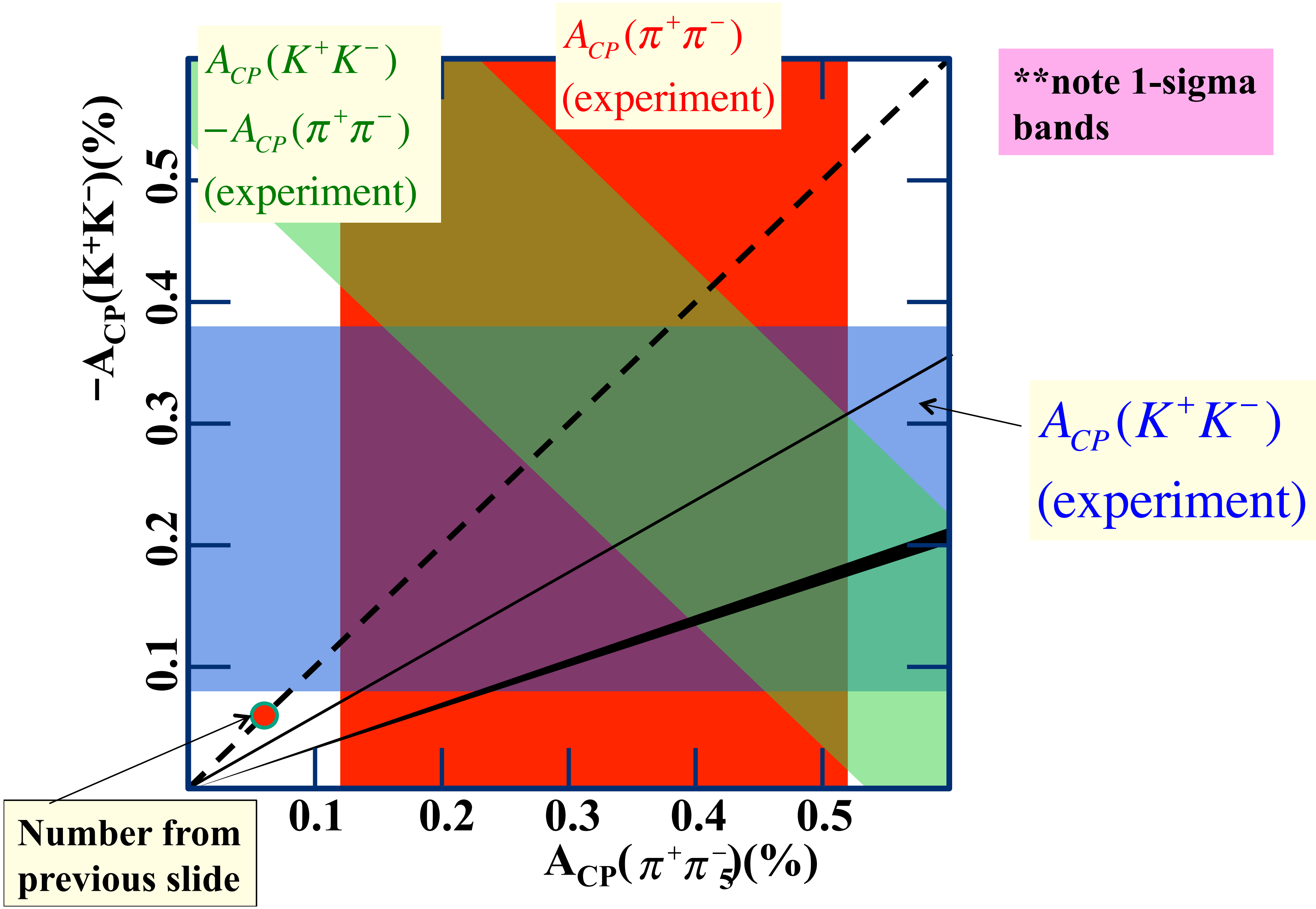
- Using evolution of effective operators, we can obtain an estimate of the asymmetry:

$$A_{CP}(c \to u\bar{d}d) = \mathrm{Im}\left[\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right] R \sin\Phi_{strong} \approx 6.4 \times 10^{-4} \sin\Phi_{strong}$$

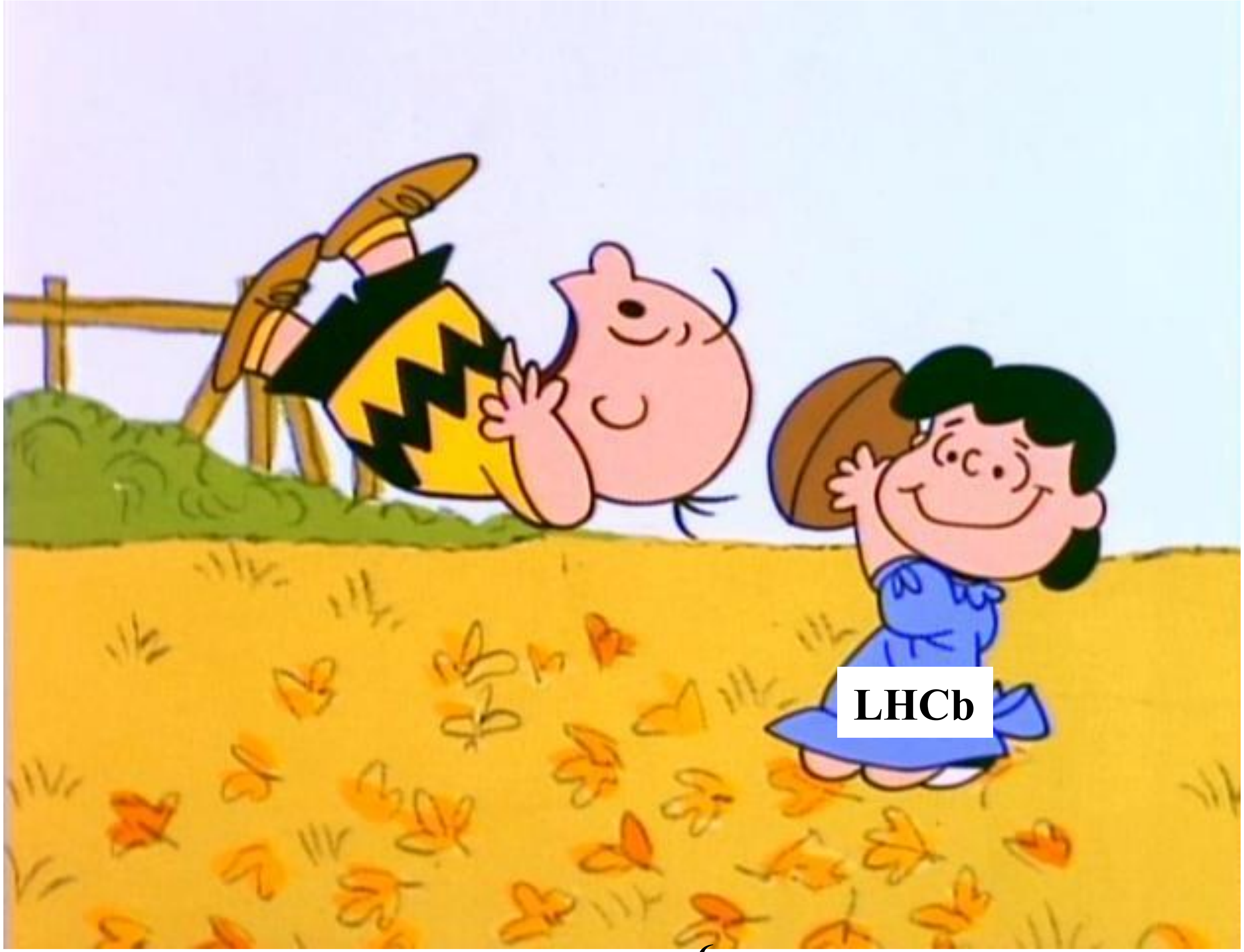
$$= -A_{CP}(c \to u\bar{s}s) \qquad \text{(by CPT)}$$

- Where R~1.2 is using 1 loop Willson coefs. and the strong phase arises form interactions in the final state.

The Quark Level Picture versus PP Results



New LHCb Results as of This Morning



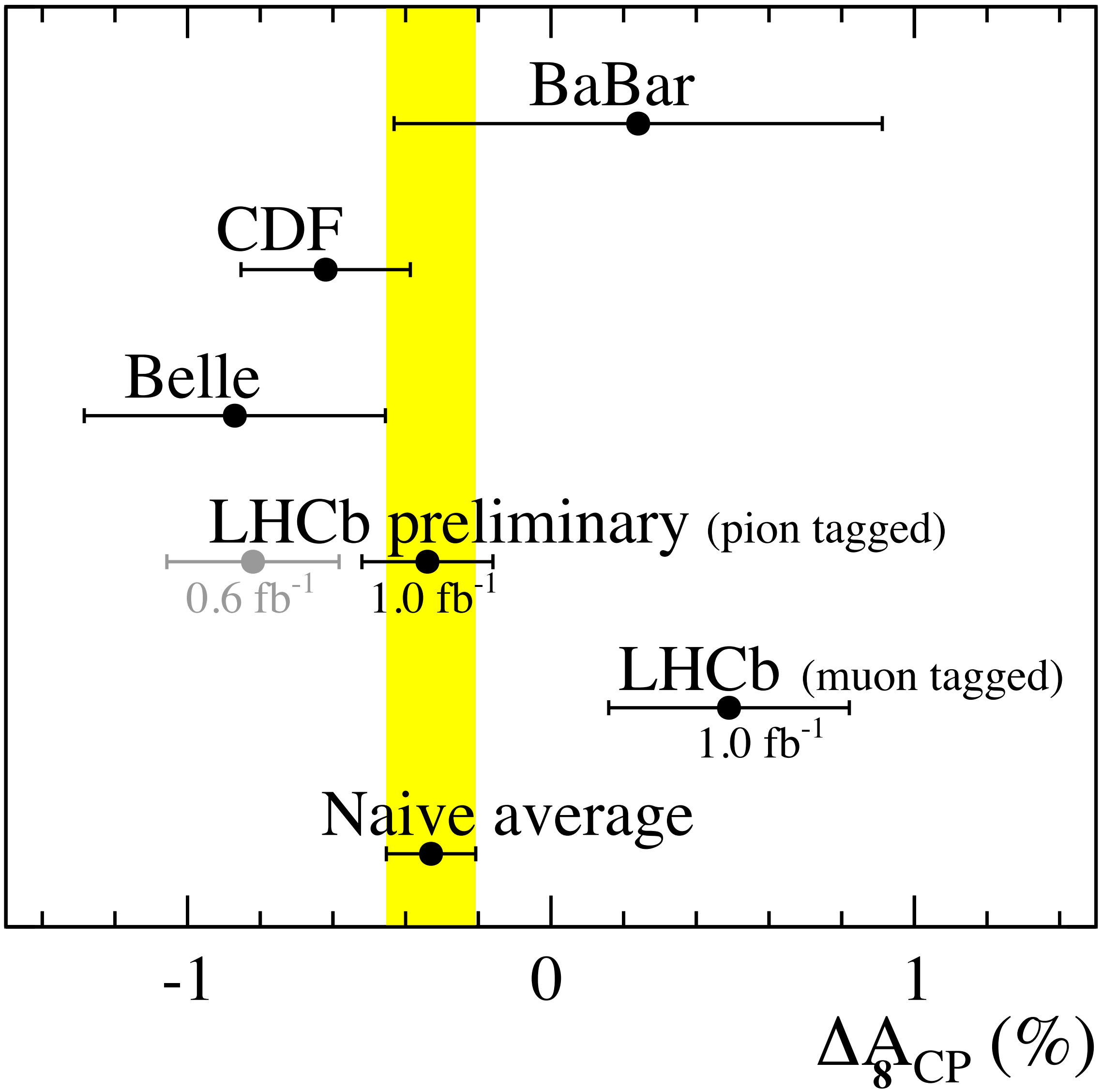
New LHCb Results as of This Morning

- Using soft pi D* tag: $\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$

- Using semileptonic tag for D's originating from B-hadron decay $\Delta A_{CP} = (+0.49 \pm 0.30 \pm 0.14)\%$ (note "wrong" sign)

- Naïve average of all results is $\Delta A_{CP} = (-0.33 \pm 0.12)\%$
  - An almost 3-sigma signal of CP violation
  - Not so far from the quark level estimate
  - Note that the wrong sign of muon-tagged result counter balances the larger CDF and Belle results so grand average is about the same as soft pi result (with slightly smaller error bar)

Overview plot of new LHCb Results



From morning talk by Sascha Stahl

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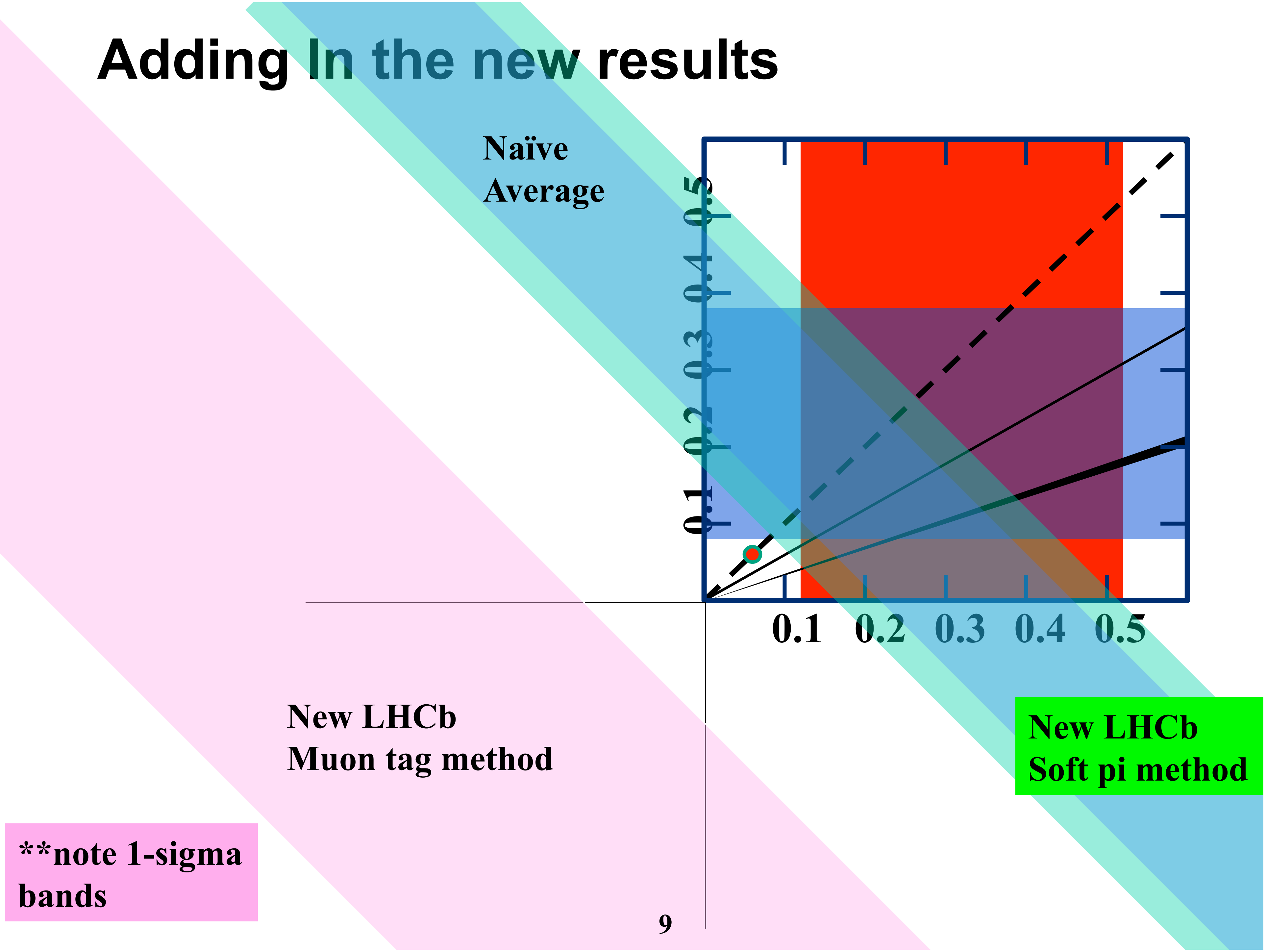
Adding In the new results



**note 1-sigma bands

What does this mean?

- The hadronization of quarks into the exclusive meson final state is not well understood
- One of the two must be true
  1. The CP violation is enhanced by QCD handronization effects in the 2bdy final state
  2. New physics is contributing to this process
  3. The result is spurious and will go away

My Preference

The way things are headed

- <u>Experiment</u>
  - Higher quality results in the future.
  - Future studies of other modes should be designed to distinguish between these.
- <u>Theory</u>
  - Better understanding of hadronization is also helpful
  - What additional data can distinguish SM and NP

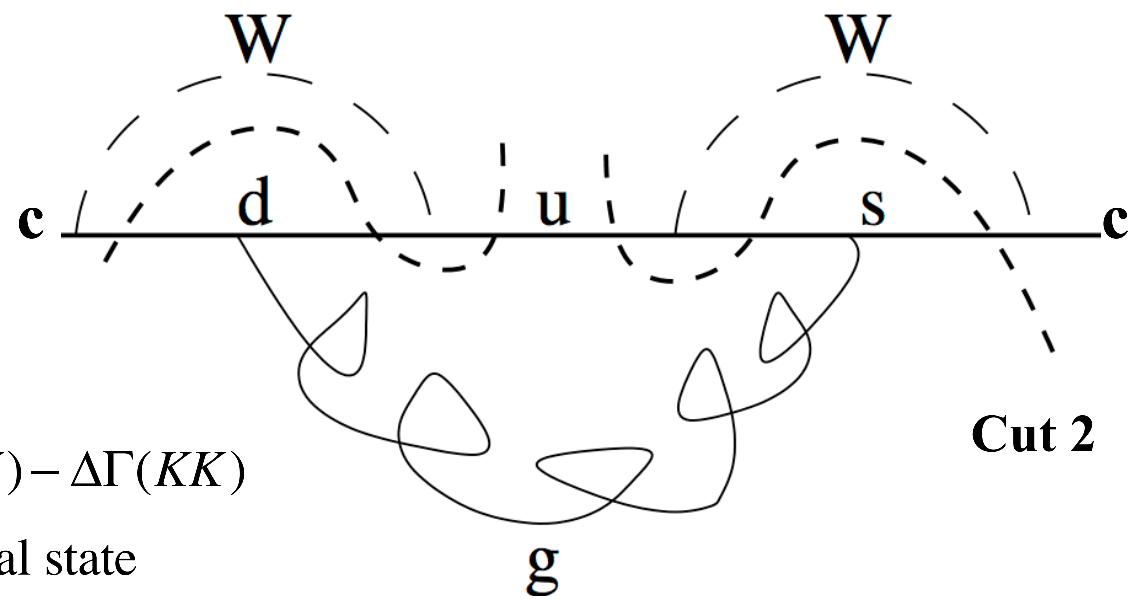
Additional Measurements

- Symmetries which are respected by QCD provide a way of sidestepping hadronization uncertainties.
- Some symmetries are:
  - CPT
  - Isospin
- Some other principles we can use are
  - Suppressed tree=larger asymmetry
  - Visible final states
  - Sensitivity to NP candidates

DA , Soni, 1211.1026

CPT Constraints

- CPT implies on the quark level $\Delta\Gamma(c \to u\bar{d}d) = -\Delta\Gamma(c \to u\bar{s}s)$
- This follows from the double penguin topology of the unitarity graph below
- On the hadron level we can think of this as exchange between 2K inclusive final states and 0K inclusive final states.



$$CPT \Rightarrow$$

$$\Delta\Gamma(0K+X) = -\Delta\Gamma(2K+X)$$

$$\Delta\hat{\Gamma}(0K+X) + \Delta\Gamma(\pi\pi) = -\Delta\hat{\Gamma}(2K+X) - \Delta\Gamma(KK)$$

$$\hat{\Gamma} = \text{inclusive with } \geq 3 \text{ particles in final state}$$

Suggestion 1: Inclusive CP

- Inclusive final states are more likely to agree with quark level calculations
- Thus we expect that $A_{CP}(2K+X)$ should be about the same as $A_{CP}(c \rightarrow u\bar{s}s)$.
  - If this quantity is $\leq 6.4\times 10^{-4}$ this would be consistent with the SM
  - If it is much large, that would be suggestive of NP.
- If SM is true it must be the case that there are enhancements in the KK final state so we might want to consider $\hat{A}_{CP}(2K+X)$ where we omit KK states form the sample➔ total kaon energy < m_D.

Isospin

- Isospin can provide separation between tree an penguin effects:
  - Tree graphs $\Delta I = \frac{1}{2}$ or $\Delta I = \frac{3}{2}$
  - Penguin graphs* $\Delta I = \frac{1}{2}$ only
- The SM implies that there is no CP violation in the $\Delta I = \frac{3}{2}$ channel.
- CP violation in a $\Delta I = \frac{3}{2}$ transition implies NP
- The simplest example of this is $D^+ \to \pi^+ \pi^0$
- More generally the three $D \to \pi\pi$ decays are derived from only two isospin amplitudes hence there is an isospin triangle relation.

***EW penguins negligible in this process**

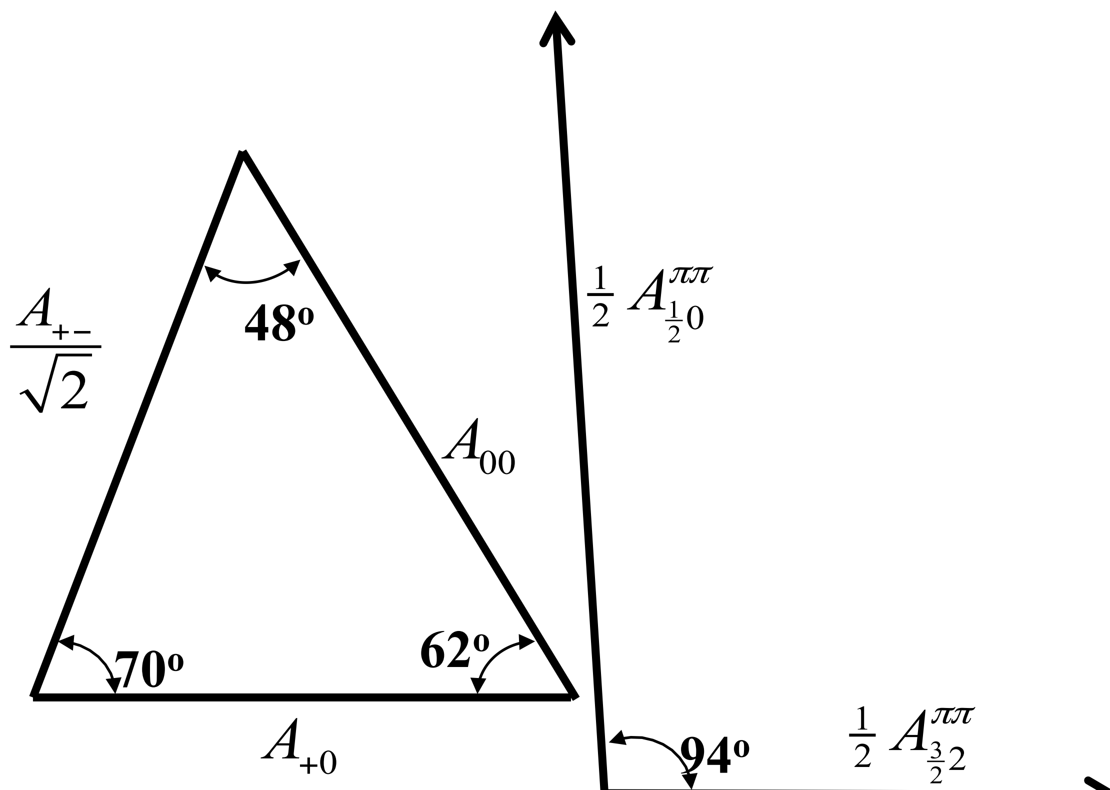
J. Brod et al. , JHEP 2012, 1203.6659

$$\frac{1}{\sqrt{2}}A^{\pi\pi}_{+-} + A^{\pi\pi}_{00} - A^{\pi\pi}_{+0} = 0 = \frac{1}{\sqrt{2}}\overline{A}^{\pi\pi}_{+-} + \overline{A}^{\pi\pi}_{00} - \overline{A}^{\pi\pi}_{-0}$$

$$A^{\pi\pi}_{+0} = \frac{\sqrt{3}}{2}A^{\pi\pi}_{\frac{3}{2},2}$$

$$A^{\pi\pi}_{+-} = \frac{1}{\sqrt{6}}A^{\pi\pi}_{\frac{3}{2},2} + \frac{1}{\sqrt{3}}A^{\pi\pi}_{\frac{1}{2},0}$$

$$A^{\pi\pi}_{00} = \frac{1}{\sqrt{3}}A^{\pi\pi}_{\frac{3}{2},2} - \frac{1}{\sqrt{6}}A^{\pi\pi}_{\frac{1}{2},0}$$



More Isospin Cases

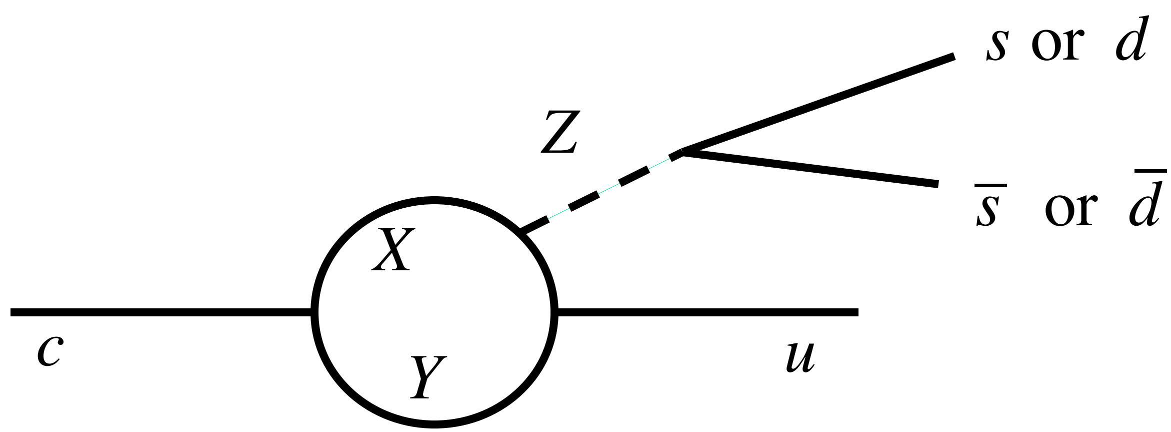
- Each polarization of the final state in $D \to \rho\rho$ is like $D \to \pi\pi$
- Thus CP violation in $D^+ \to \rho^+ \rho^0$ is a test of SM

Suggestion 2: Isospin 3/2 CP

- If CP violation is observed in $D^+ \to \pi^+\pi^0$ or $D^+ \to \rho^+\rho^0$ then NP is required.

c

- In particular the NP would have to contribute to the $\Delta I = \frac{3}{2}$ channel.
- For example Z-penguin topology



Isospin + Dalitz Plot

- Consider the overall decay $D^0 \to \pi^0\pi^+\pi^-$ it contains the following three pseudo-2 bdy decays:

$$D^0 \to \pi^0\rho^0; \quad \pi^+\rho^-; \quad \pi^-\rho^+$$

- From the Dalitz plot one can extract the magnitudes and relative phases of these channels
- Using isospin one can construct two combinations which are $\Delta I = \frac{3}{2}$

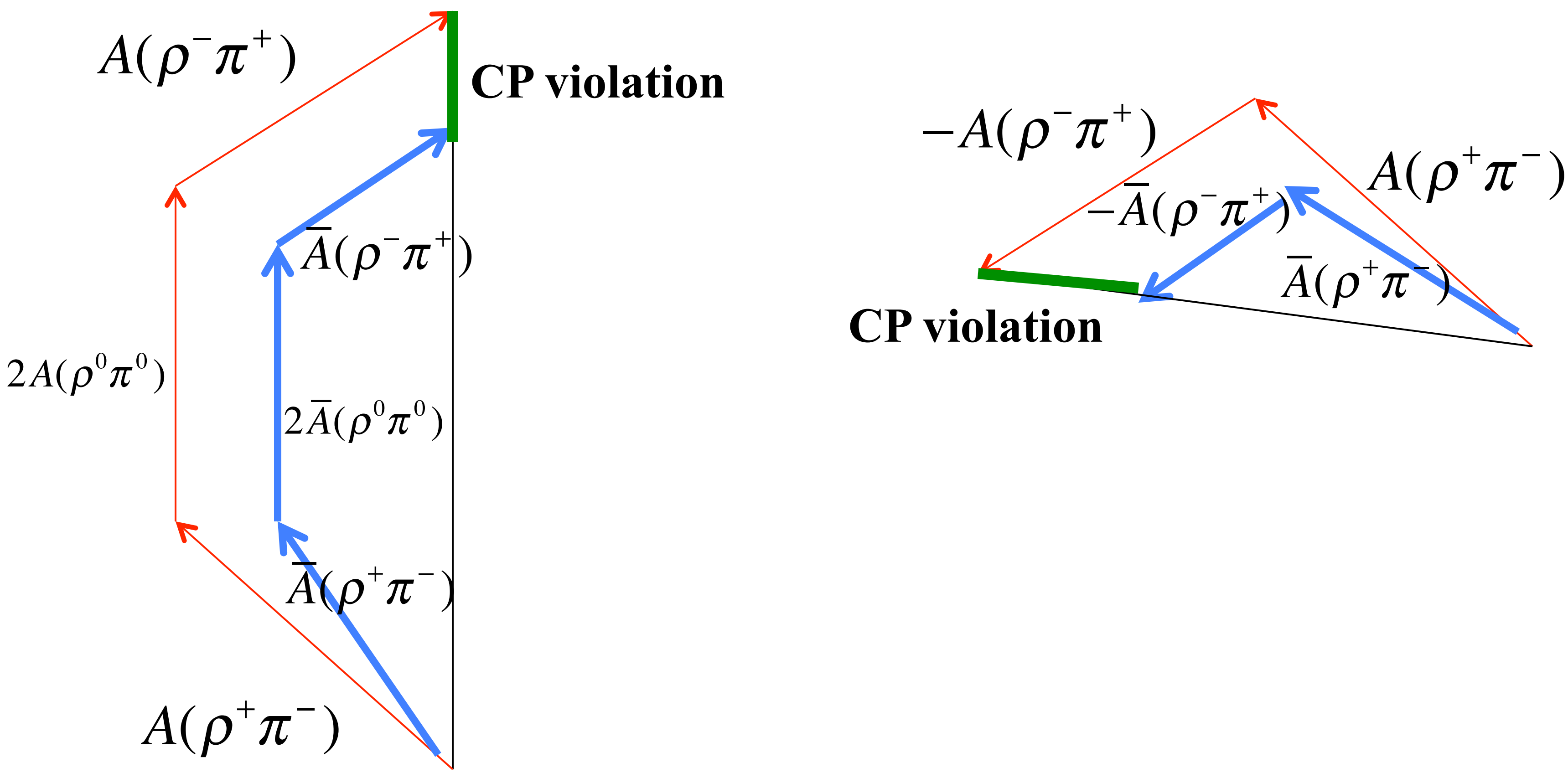
$$A_{\frac{3}{2},2} = A(\rho^+\pi^-) + A(\rho^-\pi^+) + 2A(\rho^0\pi^0)$$

$$A_{\frac{3}{2},1} = A(\rho^+\pi^-) - A(\rho^-\pi^+)$$

- Again CP violation in the $\Delta I = \frac{3}{2}$ channel implies NP.

J. Brod et al. , JHEP 2012, 1203.6659

Extracting $\Delta I = \frac{3}{2}$ From 3 pi Final States



Isospin + Dalitz in D_s decays

- We can use a similar strategy for

$$D_s \to \pi^+ K^{0*} \text{ or } \pi^0 K^{+*} \to \pi^+ \pi^0 K^0$$

- In this case the $\Delta I = \frac{3}{2}$ amplitude is given by

$$A_{\frac{3}{2}} = A(\pi^+ K^{*0}) + \sqrt{2}\, A(\pi^0 K^{*+})$$

Suggestion 3: Dalitz analysis to get CP in isospin 3/2 transitions

- Two CP violating quantities can be extracted from

$$D^0 \rightarrow \pi\rho \rightarrow \pi^+\pi^-\pi^0$$

- The same method can be used for a single CP violating parameter in

$$D_s^+ \rightarrow \pi K^* \rightarrow \pi^+\pi^0 K^0$$

Where else to look?

- The previous suggestions allow discrimination between SM and NP. There is also a hunger for CP violation in D decays so it is useful to think about the best places to look.
- Even if new (or, given latest LHCb results, first) CP violating signals don't point exactly at NP or SM, the more information the better in understanding what is happening.

Quasi-2 body modes

- A good place to look for CP violation should have the following desirable properties:
  - All charged final state (so experimentalists can see it)
  - The dominant tree is color suppressed (doesn't always work in D but)
- Running through all the possible 2bdy final states the following look promising

$$D_s^+ \to \rho^0 K^+$$

$$D^0 \to K^{(*)0} K^{(*)0} \longrightarrow$$ **Tree is suppressed**

$$D^0 \to \rho^0 \rho^0$$

$$D_s^+ \to \rho^0 K^{*+}$$

VV final states also have T-odd correlations.

Some Points

- Note that in T-odd correlations there is reduced need for D tagging (i.e. CP-odd=C-even X P-odd) (you need to ensure a $D\bar{D}$ balance)

- Of course $K^{0*}K^{0*}$ also has T-odd correlations

For additional T-odd cases see M. Gronau and J Rosner PRD (2011)

Suggestion 4: Quasi-2 bdy final states

- Quasi 2bdy final states provide a number of modes to be searched.
- The modes $D^0 \to \rho^0\rho^0; \quad D_s^+ \to \rho^0 K^+; \quad D_s^+ \to \rho^0 K^{*+}$ and $D^0 \to K^{(*)0}\overline{K}^{(*)0}$ are perhaps the most promising.
- VV final states allow T-odd correlations so CP violation may be observed with reduced sensitivity to flavor tagging (i.e. P-odd C-even)
- K^0K^0 final states have reduced tree therefore large Acp

Radiative Decays

- Many types of new physics give radiative decays on the quark level through penguin topologies: $c \longrightarrow u\gamma$
- Even if the NP only gives a gluonic penguin on the EW scale, it mixes into the photonic penguin when you run down to the charm scale.
- In any case if NP has a CP phase, CP violation could result
- This suggests the following candidates (br~10^{-5})

$$D^0 \to \rho^0\gamma; \quad D^0 \to \omega\gamma; \quad D^+ \to \rho^+\gamma$$

- In reasonable models A_{NP}/A_{SM}~10%
- However a strong phase is required but CPT argument suggest that this will be suppressed by α_s

G Isidori and J Kamenik PRL (2012)

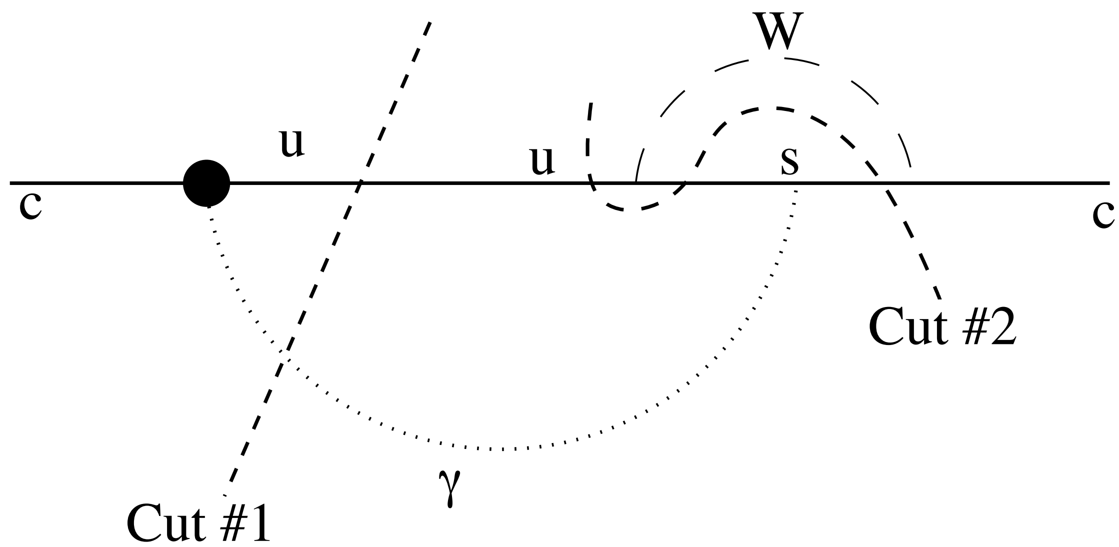


Diagram 1

Lowest order diagram
The strong phase cut #2 is not kinematically allowed.

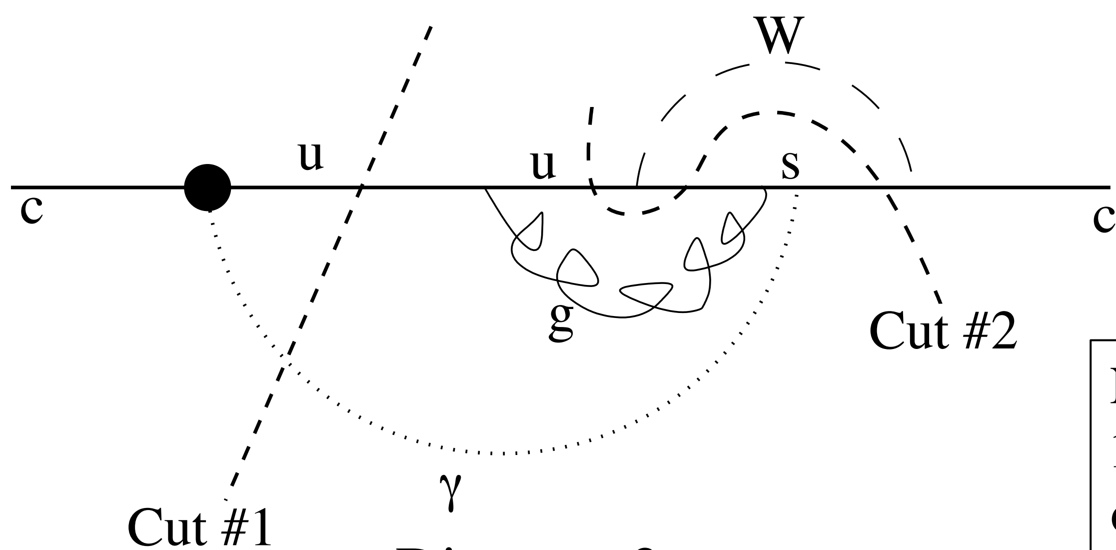


Diagram 2

QCD correction cut #2 is OK

Note: J Lyon and R Zwick 1210.6546 reach similar conclusions by different methods

Suggestion 5: Radiative decays

- Look for direct CP violation in radiative decays like
  $D^0 \rightarrow \rho^0 \gamma$
- In NP models O(1%) CP violation is plausible.

Phase information

- For a given self conjugate final state f the phase between $D^0 \to f$ and $\bar{D}^0 \to f$ is a CP violating quantity.
- This is complimentary to direct CP violation which is a difference in the magnitude of the amplitudes.
- To observe such a phase you need to prepare a mixed $D^0 / \bar{D}^0$ state and observe the quantum interference effects in its decay to f.

There are 4 ways I can think of to do this. All of them difficult to do in practice at the present levels of luminosity.

Preparation of mixed state

- $D^0 / \bar{D}^0$ oscillation. Just like with B mesons using the yet to be measured oscillation parameters.
  - It occurs naturally when you make a D meson
  - The disadvantage is you only get 1% mixing.

- Double oscillation: Consider a cascading B to D decay such as $B^0 \to \rho^0[\bar{D}^0 \to f]$
  - Most of the time dependent mixing is done by the B so you get high mixing rates
  - You are punished by the branching ratio for the parent decay: 10^{-3}-10^{-4} .
  - Perhaps time dependent B's with time integrated D's

Mixed states (continued)

- Charm factory: If $\psi(3770) \to D^0 \bar{D}^0$ and one of the D's decays hadronically, the other generally will be in a mixed state.
- Double charm B-decay: In a decay such as $B^+ \to D^0 \bar{D}^0 K^+$
  - If the phases in the Dalitz plot are understood then if one D decays to a hadronic final state the other will generally be in a mixed state.
- Crude estimate of the number of B's required:
  - Double charm and double oscillation methods need ~10^{11} B's
  - D oscillation needs ~10^{12} D's
  - Charm factory needs 10^9-10^{10} charm pairs.

Suggestion 6: CP violating phases

- Some time in the distant future measure the CP violating phase in various D^0 decays using one of the four methods suggested.

Conclusion

- Even with new results there is still almost a 3 sigma signal of CP violation in D^0 decays
- The following suggestions will help distinguish SM/NP:

1. Inclusive CP violation
2. CP violation in $\Delta I = \frac{3}{2}$ channels such as $D^+ \to \pi^0 \pi^+$
3. Further $\Delta I = \frac{3}{2}$ CP violation using Dalitz modes such as $D^0 \to \pi^0 \pi^+ \pi^-$
4. Modes with all charged final states such as $D^0 \to \rho^0 \rho^0$
   - Note: T-odd correlation
   - Also $K^0 K^0$ should have enhanced A_{CP}
5. CP violation in radiative decays such as $D^0 \to \rho^0 \gamma$
6. Determine the CP odd phase in D0 decays using quantum mixing (4 hard methods)