Potential of $D \to K_s \pi \pi$ for mixing and CPV measurements at LHCb

Implications of LHCb measurements and future prospects
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On behalf of the LHCb collaboration

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Decay chain

$$D^{\star\pm} \rightarrow \tilde{D}^0 \pi_s^{\pm}$$

$$\tilde{D}^0 \rightarrow K_s \pi^+ \pi^-$$

1 2 3

$$K_s \rightarrow \pi^+ \pi^-$$

Formalism (mixing)

- Flavor eigenstates $|D^0\rangle \quad |\bar{D}^0\rangle$
- Hamiltonian eigenstates $|D_1\rangle \quad |D_2\rangle$

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

- Time evolution

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \qquad x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- Define

$$h_{1,2}(t) = e^{\mp(y+ix)\frac{\Gamma t}{2}} \qquad g_{\pm}(t) = e^{-\frac{\Gamma t}{2}} \frac{h_1(t) \pm h_2(t)}{2}$$

- Then

$$|D_{1,2}(t)\rangle = e^{-\frac{\Gamma t}{2}} h_{1,2}(t)\,|D_{1,2}\rangle$$

$$|D^0(t)\rangle = g_+(t)\,|D^0\rangle + \frac{q}{p} g_-(t)\,|\bar{D}^0\rangle$$

Formalism (CPV)

- Define $A_f = \langle f \left|\mathcal{H}\right| D^0 \rangle \qquad \bar{A}_f = \langle f \left|\mathcal{H}\right| \bar{D}^0 \rangle$
- Impose direct CP conservation $\left|\frac{\bar{A}_f(m^2_{13}, m^2_{12})}{A_f(m^2_{12}, m^2_{13})}\right| = 1$
- Fix the arbitrary global phase

$$\bar{A}_f(m^2_{13}, m^2_{12}) = A_f(m^2_{12}, m^2_{13})$$

- This implicitly fixes the arbitrary phase of q/p

$$\frac{q}{p} = r_{\mathrm{CP}} e^{i\boxed{\alpha_{\mathrm{CP}}}}$$

- CPV:
  - $r_{CP} \neq 1 \rightarrow$ CPV in the mixing
  - $\alpha_{CP} \neq 0, \pi \rightarrow$ CPV in the interference

Unbinned approach (MD)

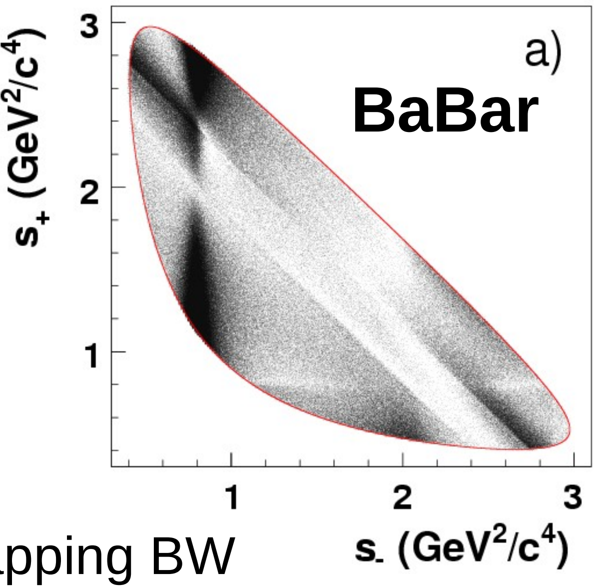
$$\left|\langle f|\mathcal{H}|D^0(t)\rangle\right|^2 = e^{-\Gamma t}\left|\frac{A_f + \frac{q}{p}\bar{A}_f}{2}h_1(t) + \frac{A_f - \frac{q}{p}\bar{A}_f}{2}h_2(t)\right|^2$$

- Model dependent (MD) approach is unbinned and requires a **model for A_f**. BaBar 2010 in our case, pretty old.
- Model independent (MI) approach is binned and gets **some** information about A_f from CLEO.

Decay model for the MD approach

$$\mathcal{A} = \sum_r a_r e^{i\phi_r} Z_\lambda(m^2_{ab}, m^2_{ac}, m^2_{bc}) B_{\lambda,r}(m^2_{ab}) \Delta_r(m^2_{ab})$$

- Begin with model taken from PRD 78, 034023 (2008) (BaBar).
  - Z_λ describe the angular distribution of the decay products.
  - $B_{\lambda,r}$ are the centrifugal barrier factors, usually parameterized using the Blatt-Weisskopf factors.
  - Δ_r is a propagator that describes the resonance.
    - Most of them are relativistic Breit-Wigner.
    - Gounaris-Sakurai for ρ^0.
    - K-matrix / LASS for a better description of overlapping BW resonances ($\pi\pi$ and $K\pi$ S waves).



- We need input from theorists for a model based on effective lagrangian densities.

Binned approach (MI)

$$\left|\langle f|\mathcal{H}|D^0(t)\rangle\right|^2 = e^{-\Gamma t}\left|\frac{A_f + \frac{q}{p}\bar{A}_f}{2}h_1(t) + \frac{A_f - \frac{q}{p}\bar{A}_f}{2}h_2(t)\right|^2$$

$$= e^{-\Gamma t}\left[\frac{\left|A_f\right|^2 + \left|\frac{q}{p}\right|^2\left|\bar{A}_f\right|^2}{2}\cosh(y\Gamma t) + \frac{\left|A_f\right|^2 - \left|\frac{q}{p}\right|^2\left|\bar{A}_f\right|^2}{2}\cos(x\Gamma t) - \right.$$

$$\left. - \mathrm{Re}\left(\frac{q}{p}A_f^\star\bar{A}_f\right)\sinh(y\Gamma t) + \mathrm{Im}\left(\frac{q}{p}A_f^\star\bar{A}_f\right)\sin(x\Gamma t)\right]$$

$$T_k = \int_k d\mathcal{P}\,\left|A_f\right|^2$$

$$T_{-k} = \int_k d\mathcal{P}\,\left|\bar{A}_f\right|^2$$

$$c_k + is_k = \frac{1}{\sqrt{T_k T_{-k}}}\int_k d\mathcal{P}\,\bar{A}_f^\star A_f$$

Given by CLEO

Parameter expression

$$c'_k + is'_k = \left(\frac{q}{p}\right)^\star (c_k + is_k)$$

Binned approach (MI)

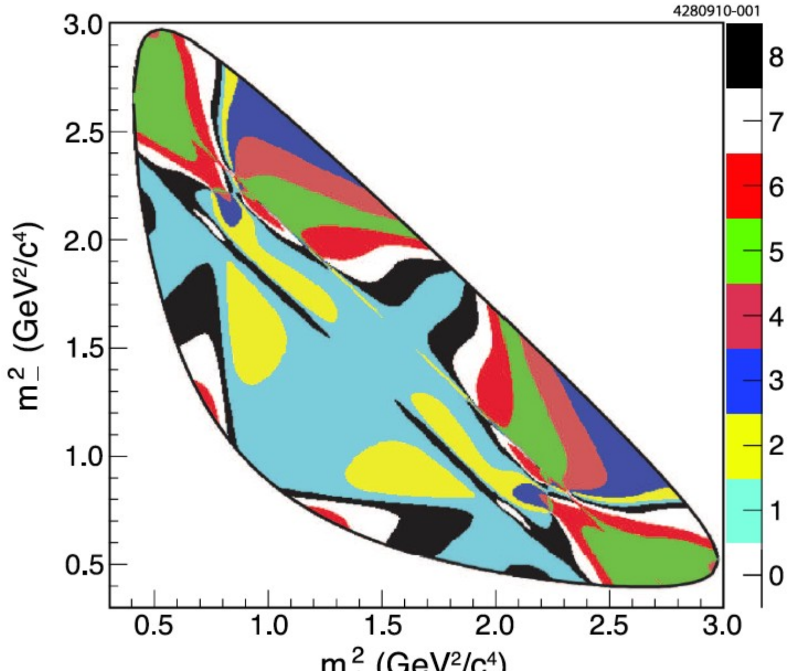
$$\int_k d\mathcal{P}\ \left|\langle f|\mathcal{H}|D^0(t)\rangle\right|_k^2 = e^{-\Gamma t}\left[\frac{T_k + \left|\frac{q}{p}\right|^2 T_{-k}}{2}\cosh(y\Gamma t) + \frac{T_k - \left|\frac{q}{p}\right|^2 T_{-k}}{2}\cos(x\Gamma t) - \right.$$

$$\left. - \sqrt{T_k T_{-k}}\left[c'_k \sinh(y\Gamma t) + s'_k \sin(x\Gamma t)\right]\right]$$

$$\approx e^{-\Gamma t}\left[T_k - \Gamma t\sqrt{T_k T_{-k}}(y c'_k + x s'_k)\right]$$

k-bin integrated amplitude

- CLEO published the values of $\{(T, c, s)_k\}$ for several bin collections.
- Using 8-binning such that strong phase diferences are minimized within a bin.



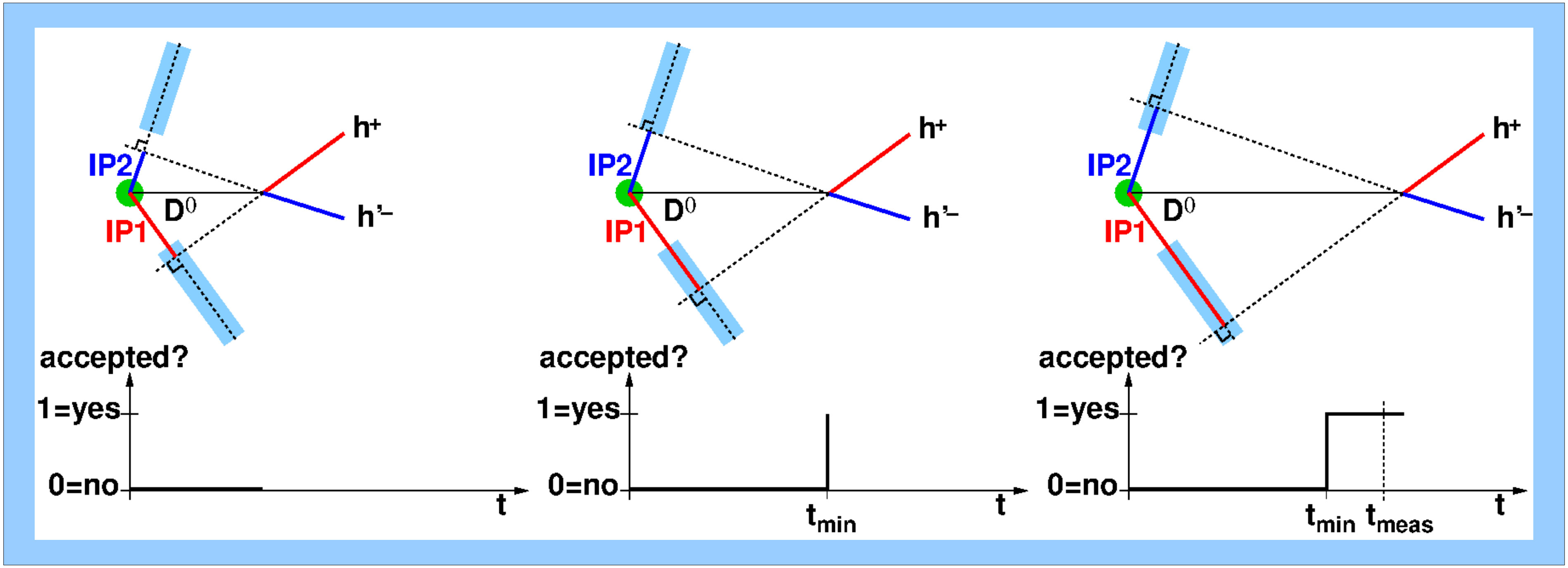
Selection

- Flavor tagging provided by $D^{*\pm} \rightarrow D^0 \pi_s^{\pm}$.
- Variables: m_D, Δm and $\log(\chi_{IP}^2)$
  - $\log(\chi_{IP}^2)$ excellent discriminator between primary and secondary charm production.
- Fit constraints:
  - Restrict π_s to be originated at the primary vertex.
  - m_D constraint to restrict phase space variables.
- 1 fb^{-1} ~ **200k** selected $D \rightarrow K_s \pi \pi$ events

Lifetime acceptance

Use ***swimming*** technique to obtain per-event D meson **decay time acceptance** from data.

R. Bailey et al, Z. Phys. C 28 (1985) 357
CERN-THESIS-2008-044
LHCB-PAPER-2011-032 (arXiv:1112.4698)



$$p(m_{12}^2, m_{13}^2, t) = \frac{1}{N}\left[\left|\langle f\,|\mathcal{H}|\,D^0(t)\rangle\right|^2 \otimes_t R(t)\right] \alpha(t)\,\varepsilon(m_{12}^2, m_{13}^2)$$

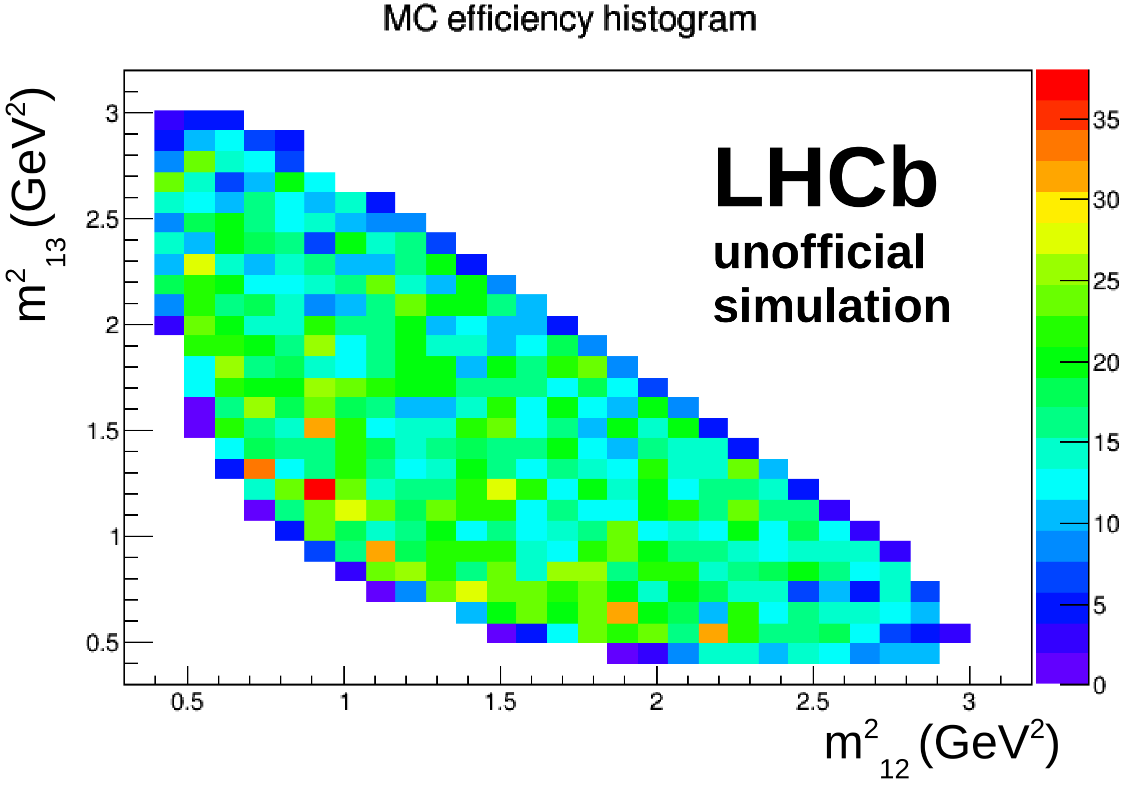
Efficiency over the phase space

$$\epsilon(m_{12}^2, m_{13}^2) = au^3 + bu^2 + cu^2v + du + euv + fv + gv^2 + hv^3$$

$$u = m_{12}^2 + m_{13}^2$$

$$v = |m_{12}^2 - m_{13}^2|$$

Obtained from a sample of nonresonant MC.



Sensitivity

arXiv:1209.0172v2, C. Thomas, G. Wilkinson

- Toy experiments of several sizes
  - In particular, 500 kevt, O(B-factories), with 8 bins

Parameter	Stat	Syst
$\sigma_x(\cdot 10^{-2})$	$0.251(3)$	$0.076(1)$
$\sigma_y(\cdot 10^{-2})$	$0.272(4)$	$0.087(1)$
$\sigma_{r_{\mathrm{CP}}}$	$0.175(2)$	$0.024(0)$
$\sigma_{\alpha_{\mathrm{CP}}}$	$12.46(16)^\circ$	$0.88(2)$

$(c,s)_k$ fixed, T_k floated

- MI statistical uncertainties 10-15% larger than MD's.
- ~10 Mevt needed in order to make the statistical uncertainty comparable to the systematic.

Conclusions

- $D \to K_s \pi \pi$ MD and MI analyses are in progress in LHCb
- Uncertainties are still comparable in size to the parameter values themselves with the 1 fb^{-1} dataset, dominated by the statistical uncertainty.
- Statistical uncertainty with 1 fb^{-1} of 2011 data is expected to be competitive with the results from B factories.

BACKUP

Unbinned approach (MD)

- Defining $$\chi = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$\left|\langle f|\mathcal{H}|D^0(t)\rangle\right|^2 = e^{-\Gamma t}\,|A_f|^2\left|\frac{1+\chi}{2}h_1(t) + \frac{1-\chi}{2}h_2(t)\right|^2$$

- Or by using the amplitudes

$$\left|\langle f|\mathcal{H}|D^0(t)\rangle\right|^2 = e^{-\Gamma t}\left|\frac{A_f + \frac{q}{p}\bar{A}_f}{2}h_1(t) + \frac{A_f - \frac{q}{p}\bar{A}_f}{2}h_2(t)\right|^2$$