Time-dependent analyses at D^0-$\overline{D}^0$ threshold

M. Rama, N. Neri, M. Giorgi, F. Martínez-Vidal, A. Oyanguren

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Outline

- Introduction
- Time-dependence of correlated decays with CP violation
- Sensitivity studies: preliminary results
- Ideas for further studies

Some preliminary considerations

- Different situation from B^0-$\overline{B}^0$ system:
  - Flavor tagged D^0 through $D^{*+} \rightarrow D^0\pi^+$ decay allow time-dependent (TD) measurement at Y(4S) with a flavor mistag of about 0.1% and relatively high purity due to $\Delta m = m(D^{*+}) - m(D^0)$ cut.
  - Proper time resolution is about $\tau(D^0)/2 \approx 0.2$ ps at Y(4S) which is adequate for TD measurement.
- In principle TD measurement can be done at Y(4S) and it is not necessary to have coherent D^0-$\overline{D}^0$ production…

Pro and cons for running at charm threshold

- Pros:
  - Very clean environment, background extremely low;
  - Exploit quantum coherence: mixing, CPT, T, CPT analyses;
  - Produce CP-tagged events;
  - Access to D^0-$\overline{D}^0$ relative phases;
  - Systematic errors reduction -and different wrt ϒ(4S)- due to background and Dalitz model uncertainties.

- Cons:
  - Time-dependent measurements (might) require larger CM boost compared to the B^0-$\overline{B}^0$case to achieve adequate time resolution;
  - Reconstruction efficiency decreases with large CM boost. Need to determine the optimal boost value.

Time-dependence at D^0-$\bar{D}^0$ threshold and at Υ(4S)

At Psi(3770):

Identical time-dependence wrt Υ(4S) when using flavor tag!

$$\frac{d\Gamma[V_{\rm phys}(t_1,t_2)\to f_1 f_2]/dt}{e^{-\Gamma|\Delta t|}\mathcal{N}_{f_1 f_2}} =$$

$$(|a_+|^2+|a_-|^2)\cosh(y\Gamma\Delta t)+(|a_+|^2-|a_-|^2)\cos(x\Gamma\Delta t)$$
$$-2\mathcal{R}e((a_+^* a_-)\sinh(y\Gamma\Delta t)+2\mathcal{I}m(a_+^* a_-)\sin(x\Gamma\Delta t)$$

$$a_+ \equiv \bar{A}_{f_1}A_{f_2} - A_{f_1}\bar{A}_{f_2},$$
$$a_- \equiv -\sqrt{1-z^2}\left(\frac{q}{p}\bar{A}_{f_1}\bar{A}_{f_2} - \frac{p}{q}A_{f_1}A_{f_2}\right) + z\left(\bar{A}_{f_1}A_{f_2} + A_{f_1}\bar{A}_{f_2}\right)$$

z = CPT violation parameter
q, p = indirect CP violation parameters

At Υ(4S) using D^{*+} tagged events:

$$\frac{d\Gamma[M^0_{\rm phys}(t)\to f]/dt}{e^{-\Gamma t}\mathcal{N}_f} =$$

$$(|A_f|^2+|(q/p)\bar{A}_f|^2)\cosh(y\Gamma t)+(|A_f|^2-|(q/p)\bar{A}_f|^2)\cos(x\Gamma t)$$
$$+2\mathcal{R}e((q/p)A_f^*\bar{A}_f)\sinh(y\Gamma t)-2\mathcal{I}m((q/p)A_f^*\bar{A}_f)\sin(x\Gamma t)$$

Some numbers for comparison of D^0 flavor tagged modes

- $D^0 \to K^+\pi^-$ (WS) as an example:
  - Extrapolating from BaBar analysis (PRL 98, 211802, 2007) 4030 WS events (384 fb^{-1}) we expect 787K WS events at $\Upsilon(4S)$ with 75fb^{-1}. Purity is about 60% and mistag fraction is about 0.1%.
  - About 15K WS events (with semileptonic flavor tag) at $\Psi(3770)$ (500 fb^{-1}) with very high purity. Mistag level?

It looks like there is no advantage in running at Psi(3770) for reducing the statistical error for flavor tagged modes.

Decays considered for running at Psi(3770) - I

Double $K^{\mp}\pi^{\pm}$ decays

$$R_{odd}(K^-\pi^+, K^-\pi^+; \Delta t) = |A_{K^-\pi^+}|^4 \left|\frac{p}{q}\right|^2 \left[1 + \left|\frac{q}{p}\right|^4 R_D^2 - 2R_D \left|\frac{q}{p}\right|^2 \cos[2(\delta_{K\pi} - \phi)]\right] \frac{x^2+y^2}{2}(\Gamma\Delta t)^2$$

$$R_{odd}(K^+\pi^-, K^+\pi^-; \Delta t) = |A_{K^+\pi^-}|^4 \left|\frac{q}{p}\right|^2 \left[1 + \left|\frac{p}{q}\right|^4 R_D^2 - 2R_D \left|\frac{p}{q}\right|^2 \cos[2(\delta_{K\pi} + \phi)]\right] \frac{x^2+y^2}{2}(\Gamma\Delta t)^2$$

Double semileptonic decays

$$R_{odd}(l^+X^-, l^+X^-; \Delta t) = |A_{l^+X^-}|^4 \left|\frac{p}{q}\right|^2 \frac{x^2+y^2}{2}(\Gamma\Delta t)^2$$

$$R_{odd}(l^-X^+, l^-X^+; \Delta t) = |A_{l^-X^+}|^4 \left|\frac{q}{p}\right|^2 \frac{x^2+y^2}{2}(\Gamma\Delta t)^2$$

Expected about 50 events with 500 fb^{-1} of Psi(3770) data in both cases.

Time-integrated measurement is probably more appropriate.

Decays considered for running at Psi(3770) - II

$K^{\mp}\pi^{\pm}$ **decays with** CP **tag**

$$
\begin{aligned}
R_{odd}(S_\eta, K^-\pi^+;\Delta t) &= \left|A_{S_\eta}A_{K^-\pi^+}\right|^2 \Bigg\{ 2\left(1+2\eta\sqrt{R_D}\cos\delta_{K\pi}+R_D\right) \\
&+\Bigg[\left(\eta\left|\frac{p}{q}\right|\cos\phi+\sqrt{R_D}\cos(\delta_{K\pi}-\phi)\left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right)+R_D\left|\frac{q}{p}\right|\cos\phi\right)y \\
&+\left(-\eta\left|\frac{p}{q}\right|\sin\phi+\sqrt{R_D}\sin(\delta_{K\pi}-\phi)\left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right)+R_D\left|\frac{q}{p}\right|\sin\phi\right)x\Bigg](\Gamma\Delta t) \\
&+\frac{1}{2}\Bigg[\left(\left(1+\left|\frac{p}{q}\right|^2\right)+2\eta\sqrt{R_D}\left(\cos\delta_{K\pi}+\cos(\delta_{K\pi}-2\phi)\right)+R_D\left(1+\left|\frac{q}{p}\right|^2\right)\right)y^2 \\
&-\left(\left(1-\left|\frac{p}{q}\right|^2\right)+2\eta\sqrt{R_D}\left(\cos\delta_{K\pi}-\cos(\delta_{K\pi}-2\phi)\right)+R_D\left(1-\left|\frac{q}{p}\right|^2\right)\right)x^2\Bigg](\Gamma\Delta t)^2\Bigg\}
\end{aligned}
$$

Expected about 100K events with 500 fb^{-1} of Psi(3770) data.

Time-dependence exclusive at Psi(3770).

Ideas for further studies

- Time-dependent Dalitz plot analyses
- CPT/CP, CP/T studies
- Combined analysis of double-tags

Time-dependent Dalitz plot analyses

- Self-conjugate modes allow to extract mixing and CP violation parameters without D^0-$\overline{D}^0$ relative phase ambiguity when assuming CP is conserved in the decay.

$$A(D^0 \to K_S(p_1)\pi^-(p_2)\pi^+(p_3))$$
$$= A(\overline{D}^0 \to K_S(p_1)\pi^+(p_2)\pi^-(p_3))$$

  - In SM we expect CPV in the D^0 decay due to CPV in K_S mixing at the level of 3×10^{-3}.
    - Is the above assumption still valid for the precision that we aim at SuperB?

  - Dalitz model uncertainty can be reduced using Psi(3770) data. Is it possible to perform a TDDP analysis in a model independent way for extracting mixing and CPV parameters? Can we relax the assumption of CP conservation in decays?

Time-dependent Dalitz plot decay rates with CP tag

$$
\begin{aligned}
&R_{odd}(S_\eta, K^0_S h^+h^-;\Delta t) = \left|A_{S_\eta}\right|^2 \Big\{ 2\left(|A_f|^2 + |\bar{A}_f|^2 - 2\eta \mathcal{R}e(A^*_f\bar{A}_f)\right) \\
&+2\Bigg[\Bigg(\left|\frac{p}{q}\right|\left(\cos\phi\mathcal{R}e(A^*_f\bar{A}_f) - \sin\phi\mathcal{I}m(A^*_f\bar{A}_f) - \eta\cos\phi|A_f|^2)\right) + \\
&\qquad\qquad\qquad + \left|\frac{q}{p}\right|\left(\cos\phi\mathcal{R}e(A^*_f\bar{A}_f) - \sin\phi\mathcal{I}m(A^*_f\bar{A}_f) - \eta\cos\phi|\bar{A}_f|^2\right)\Bigg) y \\
&-\Bigg(\left|\frac{p}{q}\right|\left(-\cos\phi\mathcal{I}m(A^*_f\bar{A}_f) - \sin\phi\mathcal{R}e(A^*_f\bar{A}_f + \eta\sin\phi|A_f|^2)\right) + \\
&\qquad\qquad\qquad + \left|\frac{q}{p}\right|\left(\cos\phi\mathcal{I}m(A^*_f\bar{A}_f) + \sin\phi\mathcal{R}e(A^*_f\bar{A}_f) - \eta\sin\phi|\bar{A}_f|^2\right)\Bigg) x\Bigg] (\Gamma\Delta t) \\
&+\frac{1}{2}\Bigg[\left(|A_f|^2\left(1+\left|\frac{p}{q}\right|^2\right) + |\bar{A}_f|^2\left(1+\left|\frac{q}{p}\right|^2\right) - 4\eta\cos\phi\left(\cos\phi\mathcal{R}e(A^*_f\bar{A}_f) - \sin\phi\mathcal{I}m(A^*_f\bar{A}_f)\right)\right) y^2 \\
&-\left(|A_f|^2\left(1-\left|\frac{p}{q}\right|^2\right) + |\bar{A}_f|^2\left(1-\left|\frac{q}{p}\right|^2\right) - 4\eta\sin\phi\left(\sin\phi\mathcal{R}e(A^*_f\bar{A}_f) + \cos\phi\mathcal{I}m(A^*_f\bar{A}_f)\right)\right) x^2\Bigg] (\Gamma\Delta t)^2 \Big\}
\end{aligned}
$$

- We are currently trying to understand if there is the possibility to extract mixing and CPV observables in a model independent way and without assuming CP conservation in the decay.

Time-dependent Dalitz plot decay rates for double 3-body decays

$$
\begin{aligned}
&R_{odd}(K^0_S h^+ h^-, K^0_S h^+ h^-; \Delta t) = \\
&2\left[|\bar{A}_1 A_2|^2 + |A_1 \bar{A}_2|^2 - 2\mathcal{R}e(\bar{A}_1^* A_2^* A_1 \bar{A}_2)\right] \\
&-2\Bigg\{\Bigg[|A_2|^2\left(\left|\frac{p}{q}\right|(\cos\phi\mathcal{R}e(A_1\bar{A}_1^*) + \sin\phi\mathcal{I}m(A_1\bar{A}_1^*) - \mathcal{R}e(A_1\bar{A}_1^*))\right) \\
&\qquad -|A_1|^2\left(\left|\frac{p}{q}\right|(\cos\phi\mathcal{R}e(A_2\bar{A}_2^*) + \sin\phi\mathcal{I}m(A_2\bar{A}_2^*))\right) \\
&\qquad +|\bar{A}_2|^2\left(\left|\frac{q}{p}\right|(\cos\phi\mathcal{R}e(\bar{A}_1 A_1^*) - \sin\phi\mathcal{I}m(\bar{A}_1 A_1^*))\right)\Bigg] y \\
&\quad -\Bigg[|A_2|^2\left(\left|\frac{p}{q}\right|(\cos\phi\mathcal{I}m(A_1\bar{A}_1^*) - \sin\phi\mathcal{R}e(A_1\bar{A}_1^*) - \mathcal{I}m(A_1\bar{A}_1^*))\right) \\
&\qquad -|A_1|^2\left(\left|\frac{p}{q}\right|(\cos\phi\mathcal{I}m(A_2\bar{A}_2^*) - \sin\phi\mathcal{R}e(A_2\bar{A}_2^*))\right) \\
&\qquad +|\bar{A}_2|^2\left(\left|\frac{q}{p}\right|(\cos\phi\mathcal{I}m(\bar{A}_1 A_1^*) + \sin\phi\mathcal{R}e(\bar{A}_1 A_1^*))\right)\Bigg] x\Bigg\}(\Gamma\Delta t) \\
&+\frac{1}{2}\Bigg\{\left[|\bar{A}_1 A_2|^2 + |A_1\bar{A}_2|^2 - 2\mathcal{R}e(\bar{A}_1^* A_2^* A_1\bar{A}_2)\right](y^2 - x^2) \\
&\quad +\left[\left|\frac{p}{q}\right|^2 |A_1 A_2|^2 + \left|\frac{q}{p}\right|^2 |\bar{A}_1\bar{A}_2|^2 - 2\left(\cos(2\phi)\mathcal{R}e(A_1^* A_2^* \bar{A}_1\bar{A}_2) - \sin(2\phi)\mathcal{I}m(A_1^* A_2^* \bar{A}_1\bar{A}_2)\right)\right](x^2 + y^2) \\
&\qquad\qquad \Bigg\}(\Gamma\Delta t)^2
\end{aligned}
$$

- We are currently trying to understand if there is the possibility to extract mixing and CPV observables in a model independent way and without assuming CP conservation in the decay.

CPT/CP and CP/T studies

- Exploit quantum coherence as in B^0-B^0bar case where we use combination of B_{CP}, B_{FLAV} for B_{reco}, B_{TAG} modes.
- This approach might potentially be applied to D^0-D^0

B_{tag}	B_{rec}
B^0	B^0
B^0	$\overline{B}^0$
$\overline{B}^0$	B^0
$\overline{B}^0$	$\overline{B}^0$
B^0	B_{CP}
$\overline{B}^0$	B_{CP}

TABLE V: Dominant dependence of the time distributions on the physical parameters measured with fully reconstructed flavor and *CP* states. Sensitivity is specific to terms in the time dependence that are either *t*-even or *t*-odd. The flavor sample is much larger than the *CP* sample.

	B_{flav}		B_{CP}	
Parameter	*t*-even	*t*-odd	*t*-even	*t*-odd
$\lvert q/p \rvert$	×			
Δm	×			
Im z		×		
$(\mathrm{Re}\,\lambda_{CP}/\lvert\lambda_{CP}\rvert)\,\mathrm{Re}\,z$			×	
r_{CP}			×	
$\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})\Delta\Gamma/\Gamma$				×
$\mathrm{Im}\,\lambda_{CP}/\lvert\lambda_{CP}\rvert$				×

Important to have $\Delta t < 0$ and $\Delta t > 0$

Combining all doble tags

- Ultimately, exploit quantum coherence of the D^0-$\overline{D}^0$ system and different dependences for all possible combination of double-tags to extract mixing and CPV (in interference, mixing and decay), as well as CPTV

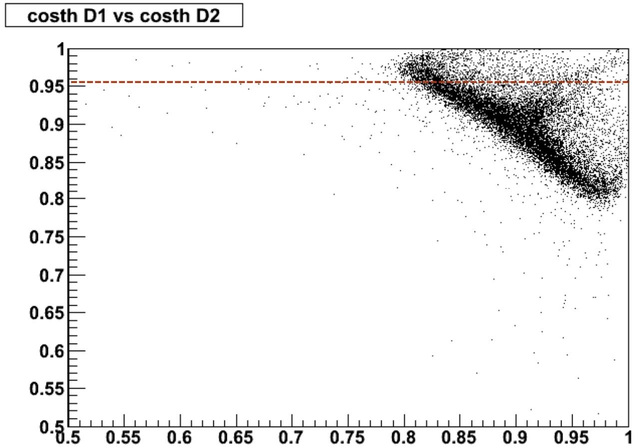
	CP	Kpi	Semilep	3-body
CP				
Kpi				
Semilep				
3-body				

Sensitivity studies: preliminary results

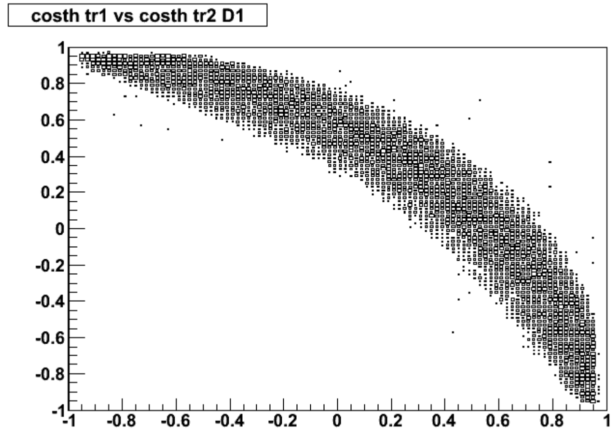
D kinematics: cosTheta distributions

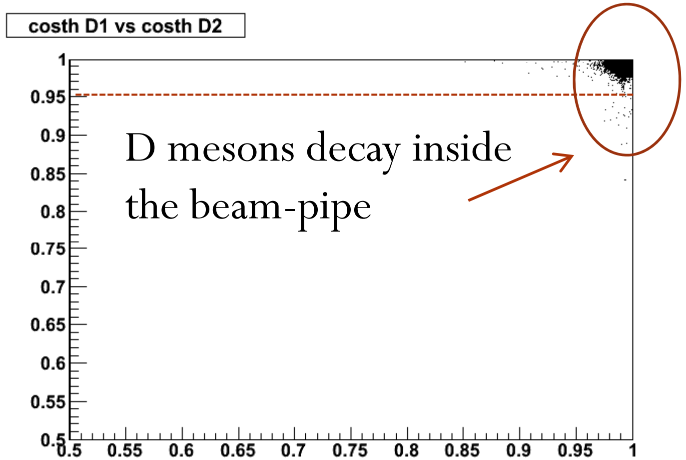
cosTheta D1 vs cosTheta D2

cosTheta K vs cosTheta π in D→Kπ

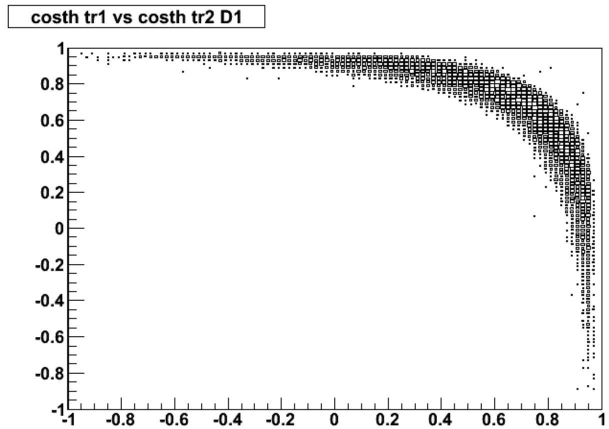


$\beta\gamma=0.30$

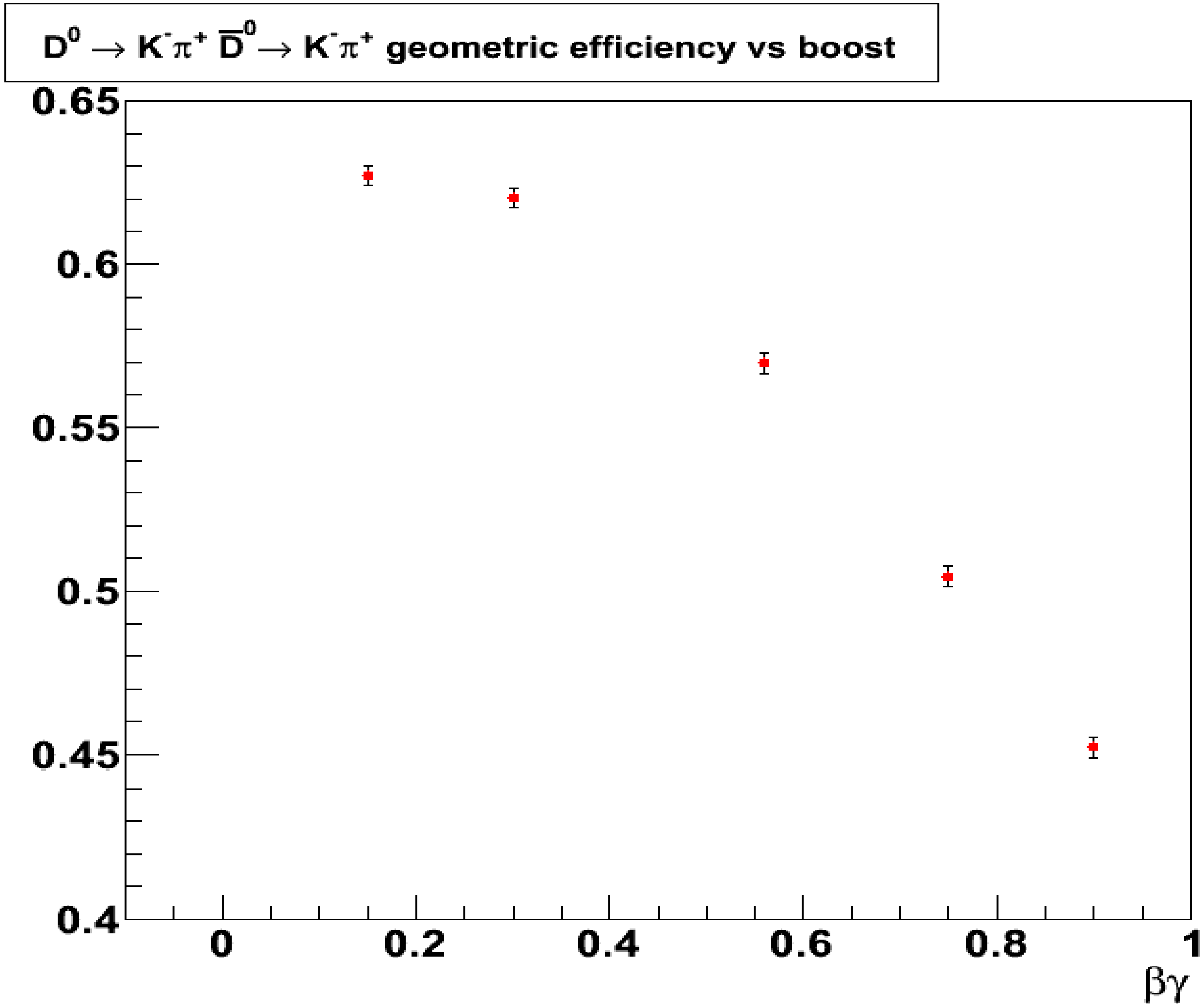




$\beta\gamma=0.90$

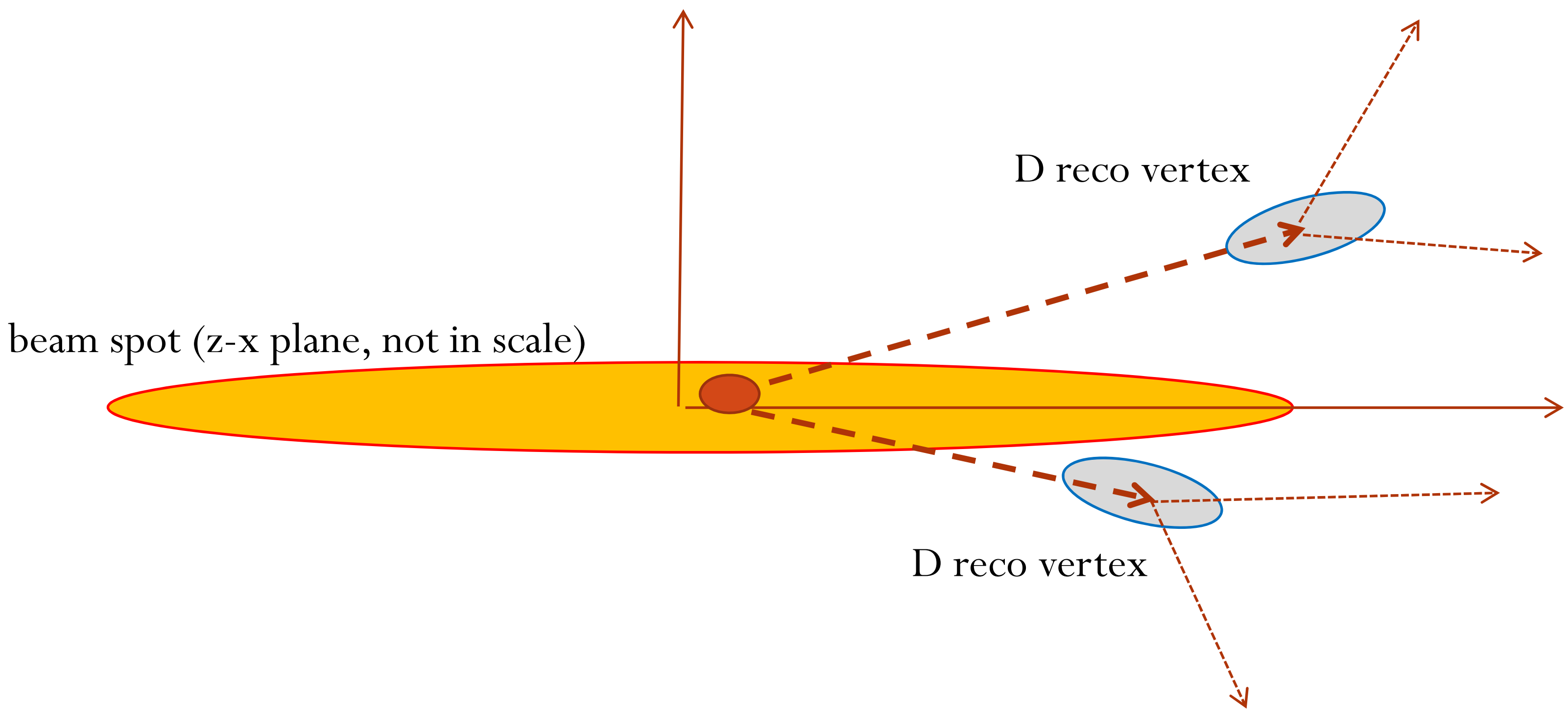


Geometric efficiency as a function of the CM boost

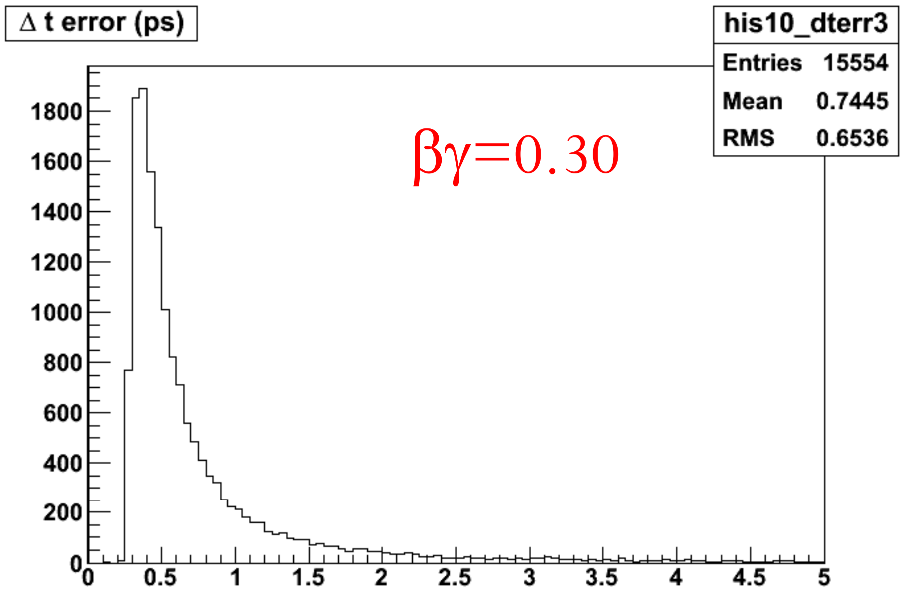


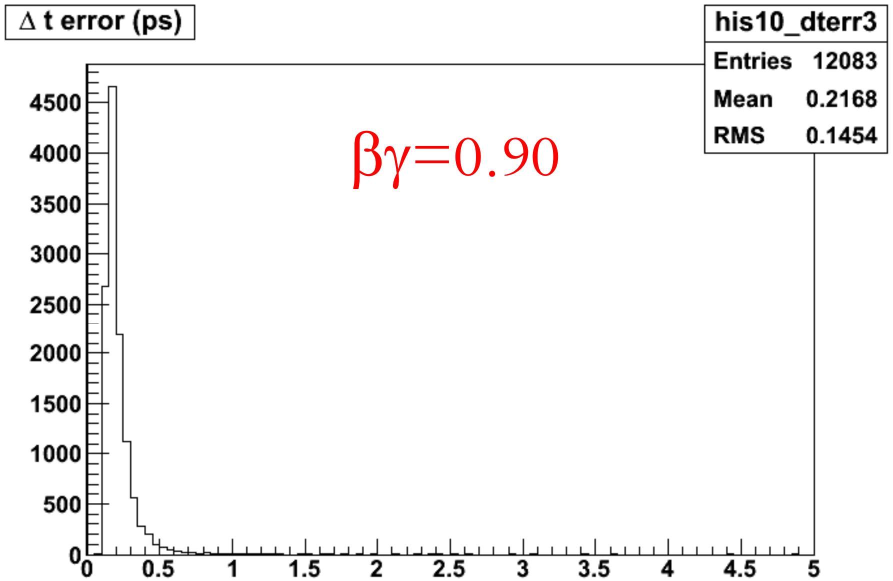
Δt reconstruction

- The flight lengths of the two Ds are reconstructed through a combined beam spot constrained vertex fit
- Proper times are computed from the flight lengths and the D momenta



Δt error distribution

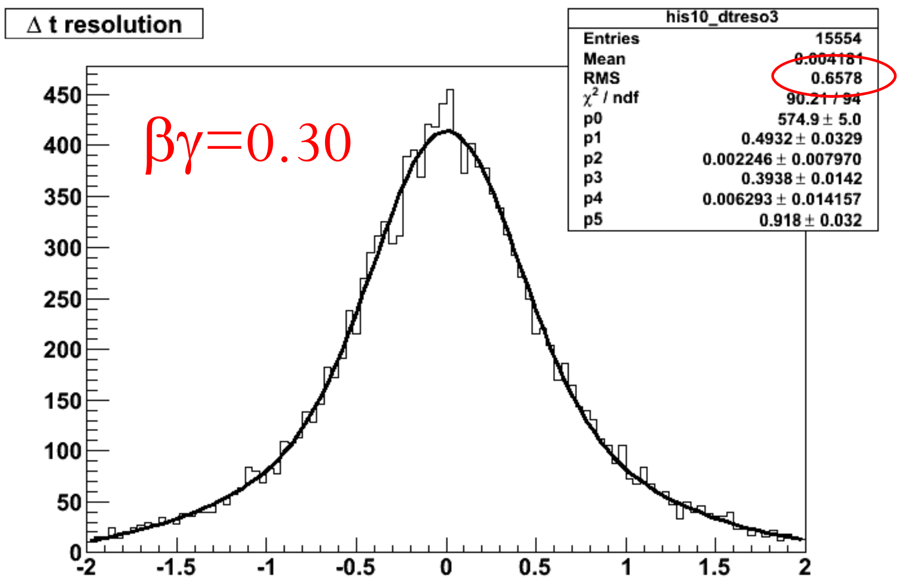


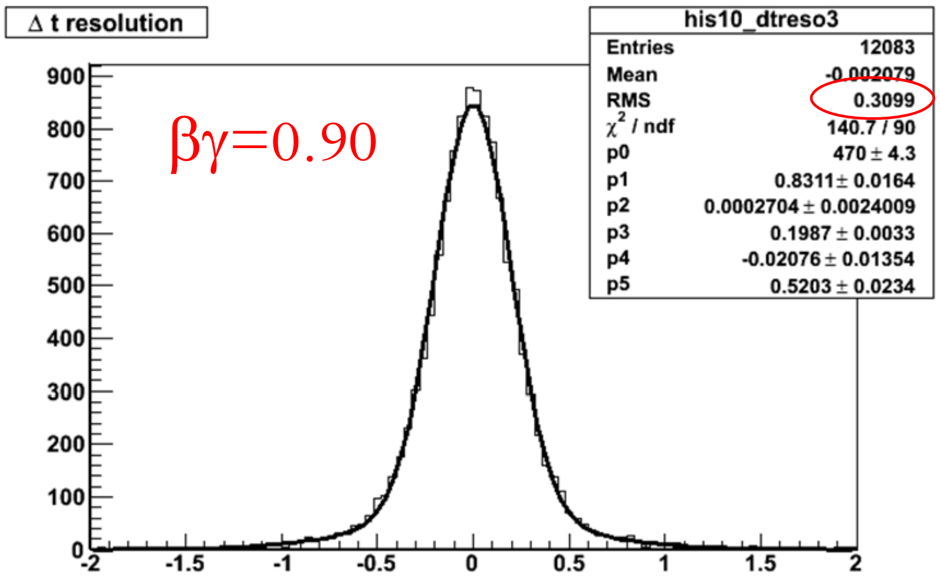


<error> = 0.745 ps

<error> = 0.217 ps

Δt resolutions

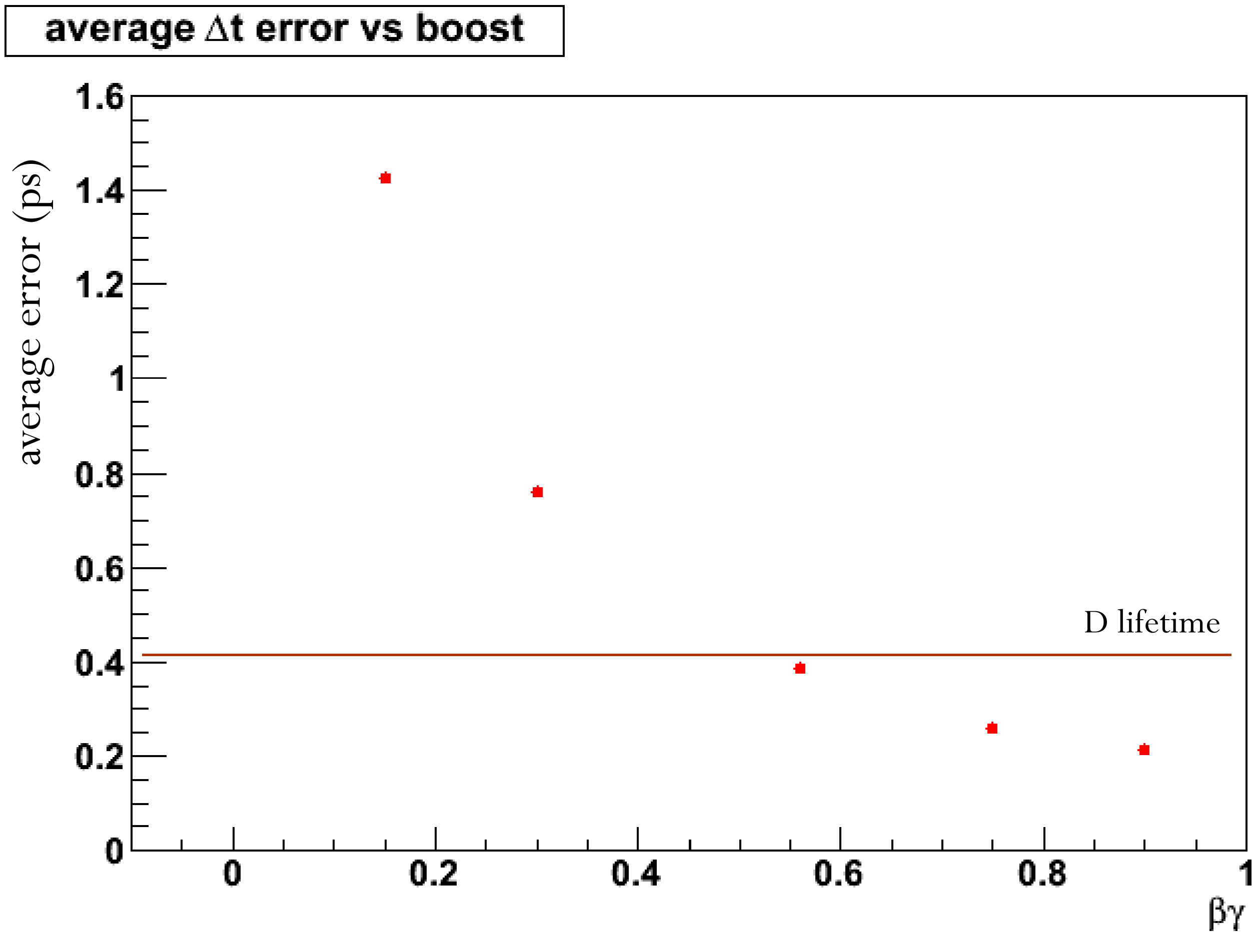




RMS = 0.658 ps
Res. fnc. is unbiased

RMS = 0.310 ps
Res. fnc. is unbiased

Δt average error as a function of the boost



Impact on physics

- Next step will be to use FastSim resolutions and geometrical efficiencies as a function of CM boost to evaluate effect on physics parameters
  - Use CLEOc reconstruction efficiencies corrected by geometrical acceptance
- Kernel of Toy MC generator and fitting code in place, starting to obtain first results for some combinations of double-tags (e.g. CP vs Kpi)
  - But results not in time for today…

Summary

- Flavor tag at D^0-$\overline{D}^0$ threshold provides identical time-dependence than at $\Upsilon(4S)$ using D* tagging, and less events, although in a different environment (different systematic uncertainties);
- D^0-$\overline{D}^0$ threshold is unique to provide CP tag, giving access to D^0-$\overline{D}^0$ relative phases;
- Ultimately, exploit quantum coherence with all possible combination of double-tags to extract mixing and CPV (in interference, mixing and decay), as well as CPTV
- Variation of Δt resolution and geometrical acceptance as a function of CM boost evaluated
- Now:
  - Assessing the impact on physics
  - Evaluating the possibility to extract mixing and CPV observables in a model independent way and without assuming CP conservation in the decay using 3-body decays (CP/flavor tags vs 3-body, double 3-body)
- Feed back from theorists very welcome !