Sensitivity studies on mixing and CP violation in charm at Ψ(3770) and Υ(4S) at SuperB

M. Giorgi[1], F. Martínez-Vidal[2], N. Neri[3], A. Oyanguren[2], M. Rama[4], P. Ruiz[2], P. Villanueva[2]

[1] Università and INFN Pisa, [2] IFIC Valencia, [3] INFN Milano, [4] INFN Laboratori Nazionali di Frascati

Workshop on Charm physics at threshold

21-23 October 2011, Bejing

Outline

- Goals and general considerations
- Monte Carlo studies
- Sensitivity studies and results
- Summary and next steps

Goal

- Estimate and compare the experimental sensitivity on charm mixing and CP violating parameters at SuperB:
  - Υ(4S)
  - Ψ(3770) as a function of CM boost and detector configuration
- First step: study the 2-body decays
  - preliminary results presented today
- Second step: include the 3-body decays

General considerations

- At ϒ(4S)
  - Flavor tagged D^0 through $D^{*+} \rightarrow D^0\pi^+$ decay. We denote the D* flavor tag with the label *l*X
  - D^0 can be reconstructed in flavor *l*X, CP, Kπ and multibody (e.g. Ksππ) final states. Relatively high purity due to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$
  - Flavor mistag ≈ 0.2%
  - Proper time resolution is about $\tau(D^0)/4 \approx 0.1$ ps
- At ψ(3770)
  - Coherent D^0D^0 production
  - Both D mesons can be reconstructed in *l*X, CP, Kπ and Ksππ final states, with very low background
  - Flavor mistag ≈ 0.2% with eX,
  - Time-dependent measurements require larger CM boost compared to the ϒ(4S) case to achieve similar time resolution, but reconstruction efficiency decreases with large CM boost. Need to determine the optimal boost range.

Double tags @ Ψ(3770)

Modes with D* tag @ ϒ(4S)

	CP–	Kπ	*l*X	Ksππ
CP+	X	X	XX	X
CP–		X	XX	X
Kπ		X	XX	X
*l*X			XX	XX
Ksππ				X

Time-dependent rates

- We have derived the time-dependent rates for several combinations of tags

	CP–	Kπ	*l*X	Ksππ
CP+	X	X	XX	X
CP–		X	XX	X
Kπ		X	XX	X
*l*X			XX	XX
Ksππ				X

  - Complete expressions
  - Simplified expressions with CPT invariance, CP conserved in decay, and second order in x, y

Example: flavor tag

At ψ(3770):

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

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

$$\left(|a_+|^2+|a_-|^2\right)\cosh(y\Gamma\Delta t)+\left(|a_+|^2-|a_-|^2\right)\cos(x\Gamma\Delta t)$$

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

$$a_+\equiv \bar{A}_{f_1}A_{f_2}-A_{f_1}\bar{A}_{f_2},$$

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

z = CPT violation parameter

q, p = indirect CP violation parameters

At ϒ(4S) using D^{*+} tagged events:

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

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

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

Example: Kπ vs CP tag

no direct CPV
assumed here

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

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

Example: double Kπ and lX tag

no direct CPV
assumed here

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

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

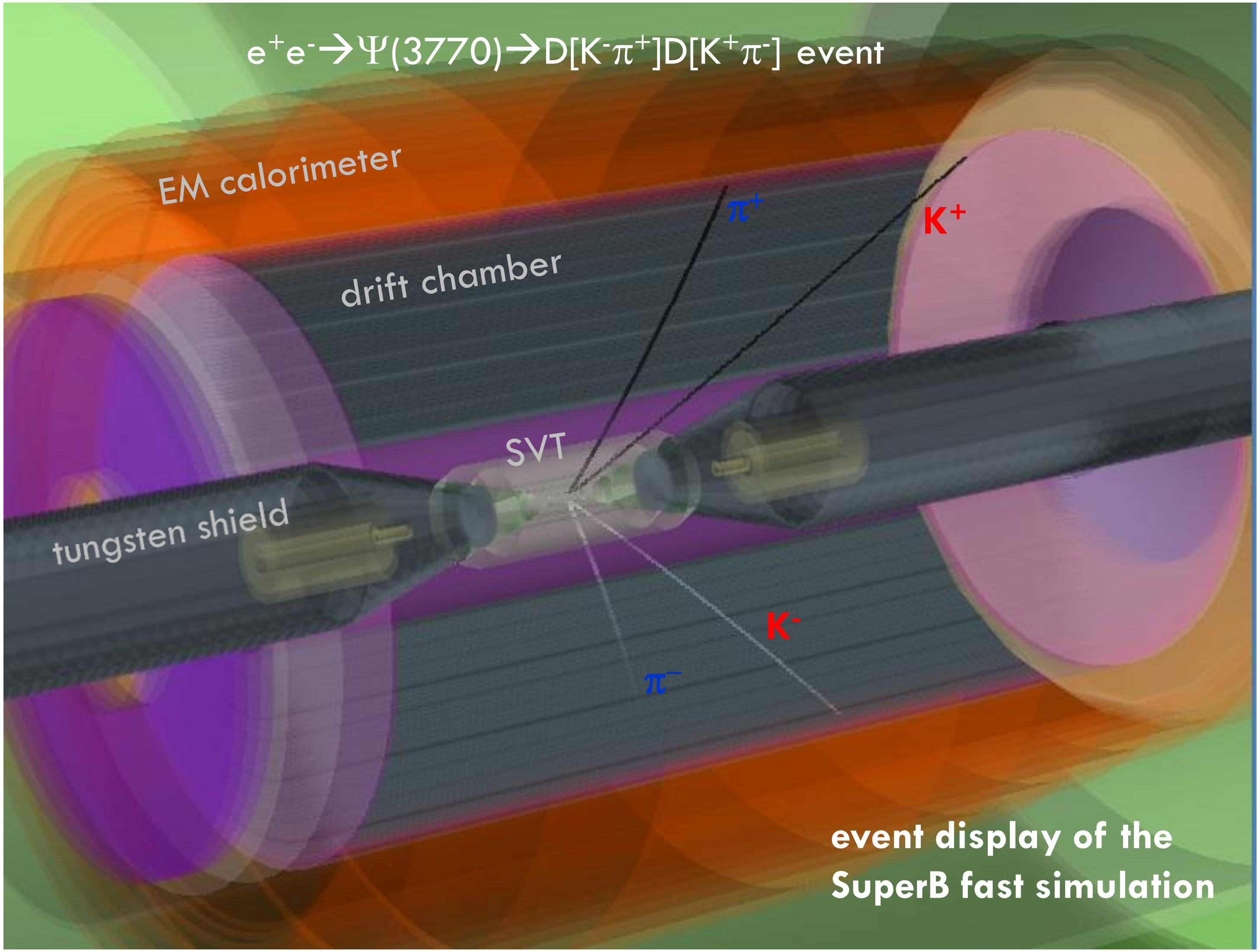
$$R_{odd}(K^+\pi^-, K^+\pi^-; \Delta t) = |A_{K^+\pi^-}|^4 \left|\frac{q}{p}\right|^2 \left[1 + \left|\frac{p}{q}\right|^4 R_D^2 - 2R_D \left|\frac{p}{q}\right|^2 \cos[2(\delta_{K\pi} + \phi)]\right] \frac{x^2+y^2}{2}(\Gamma\Delta t)^2$$

Double semileptonic decays

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

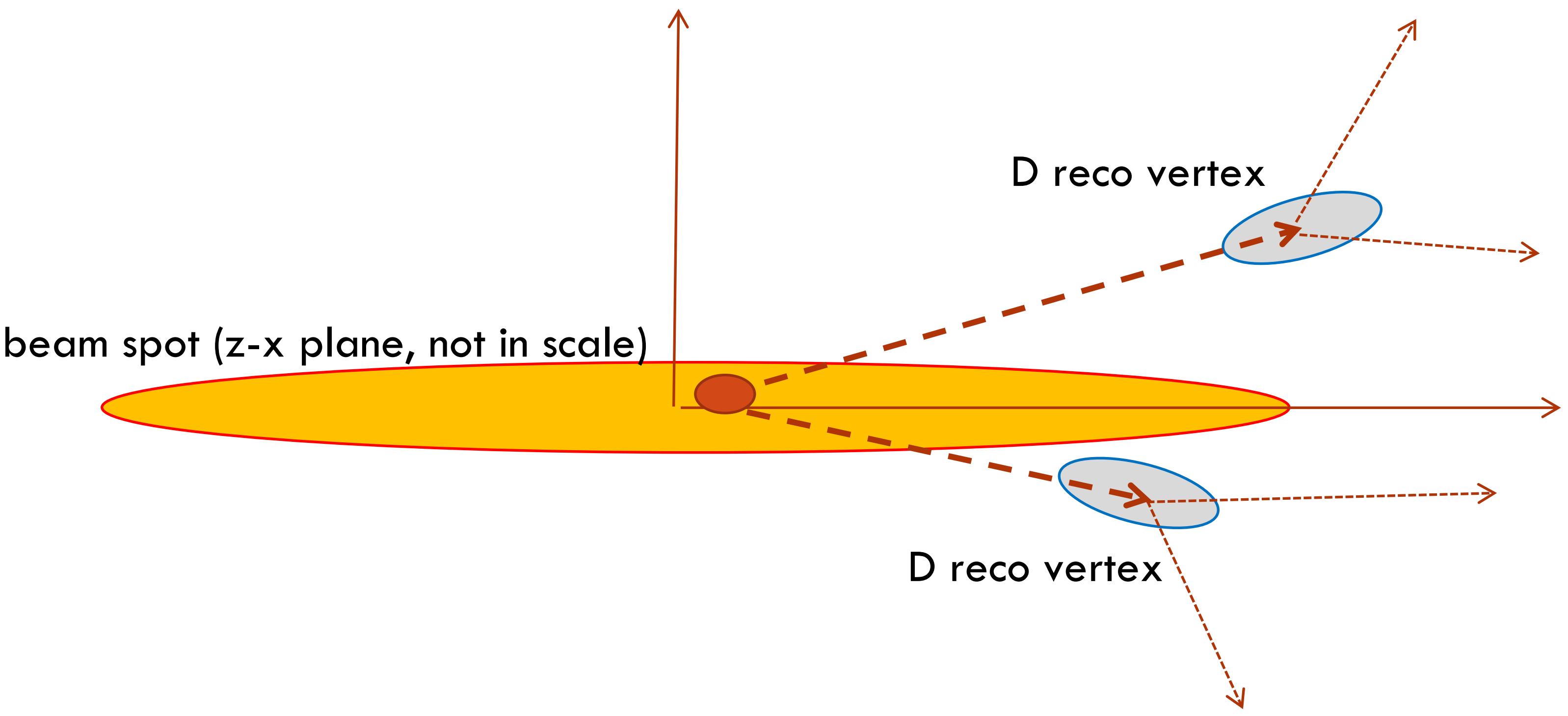
$$R_{odd}(l^-X^+, l^-X^+; \Delta t) = |A_{l^-X^+}|^4 \left|\frac{q}{p}\right|^2 \frac{x^2+y^2}{2}(\Gamma\Delta t)^2$$

SuperB fast simulation (FastSim)



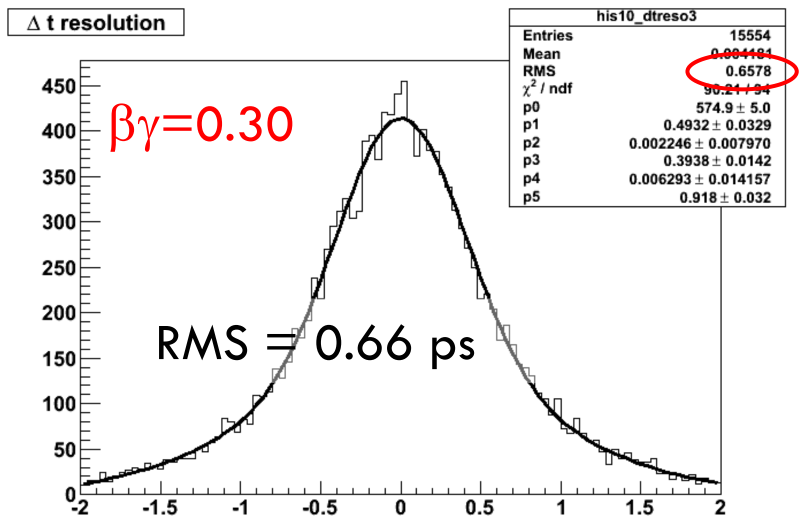
FastSim studies: Δt reconstruction

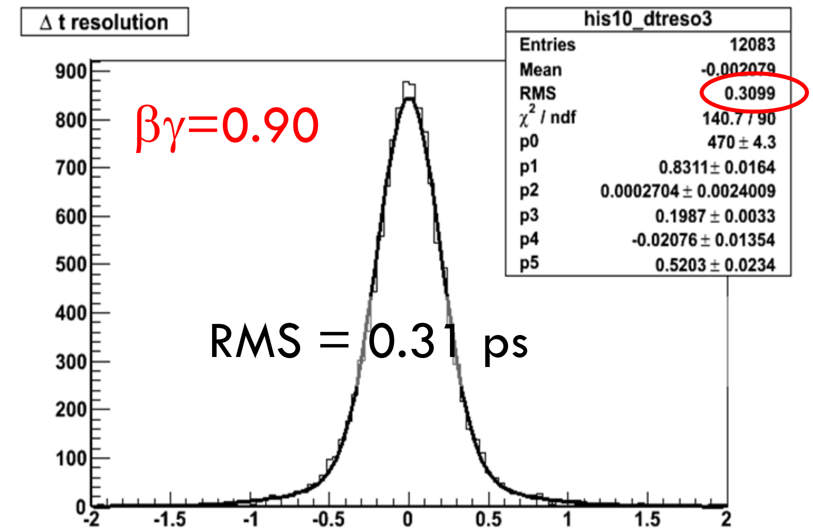
- The flight lengths of the two Ds are reconstructed through a combined beam spot constrained vertex fit
- Proper times are computed from the flight lengths and the D momenta

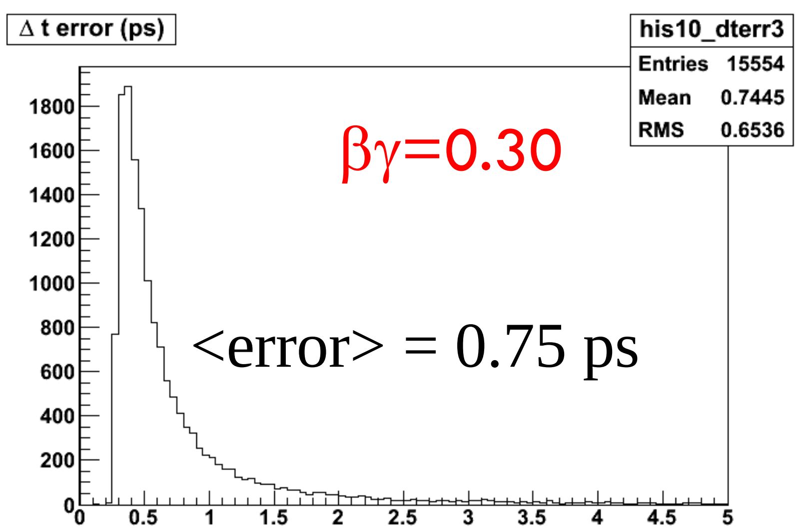


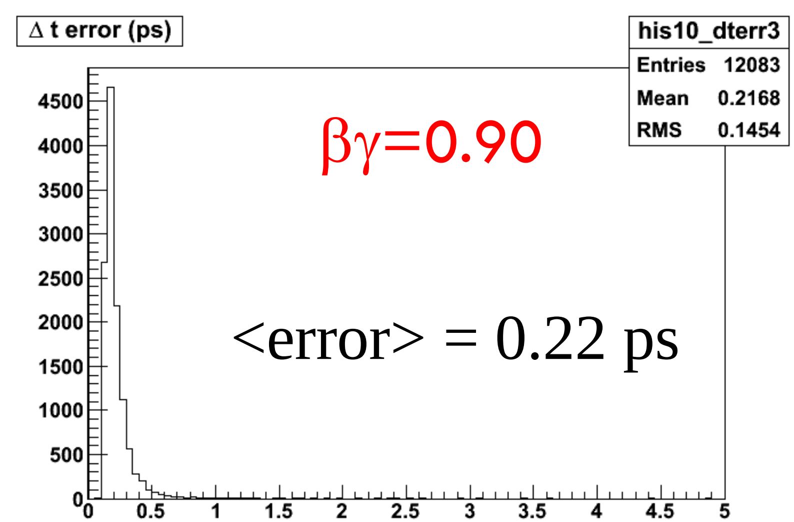
FastSim studies: Δt resolution

examples:

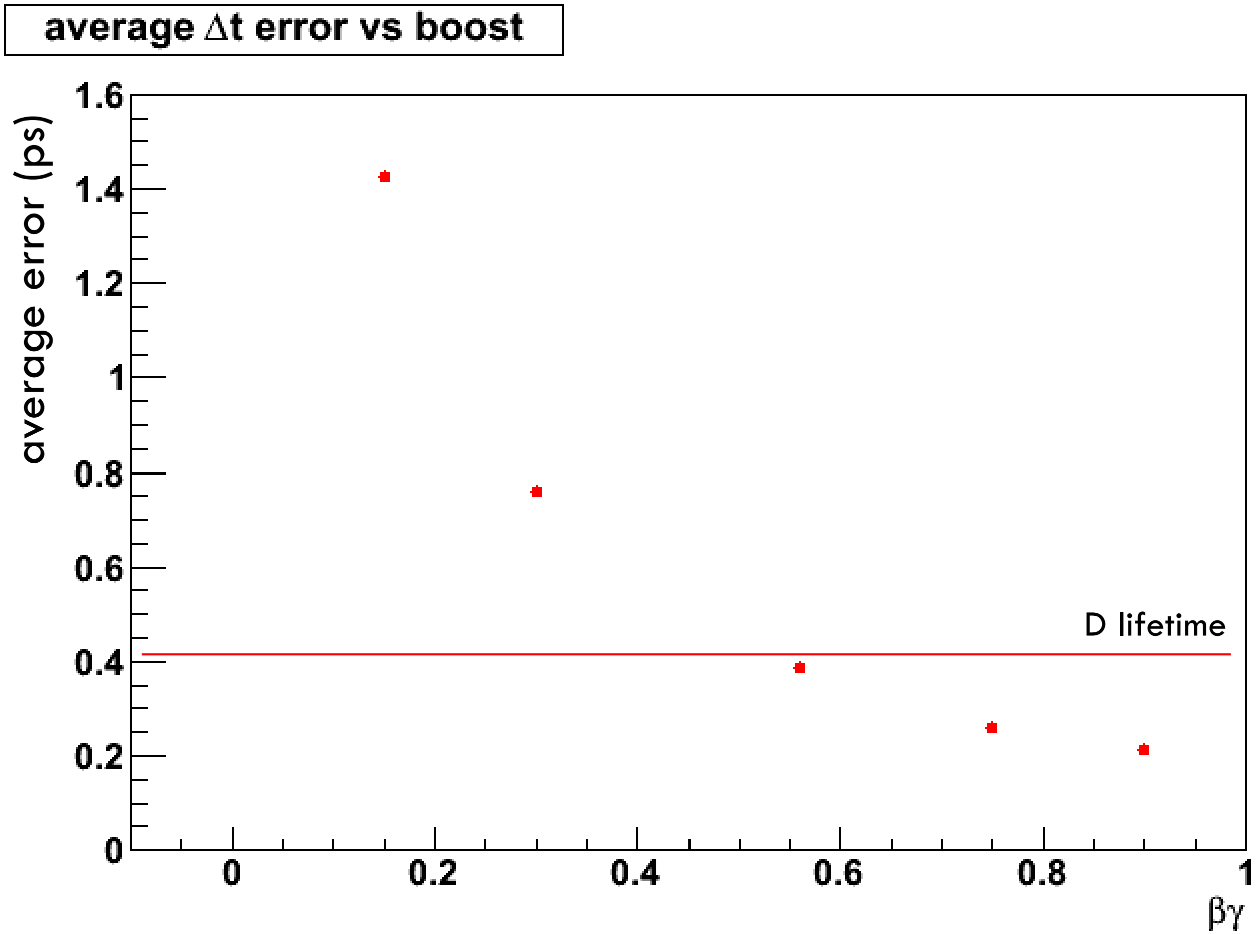




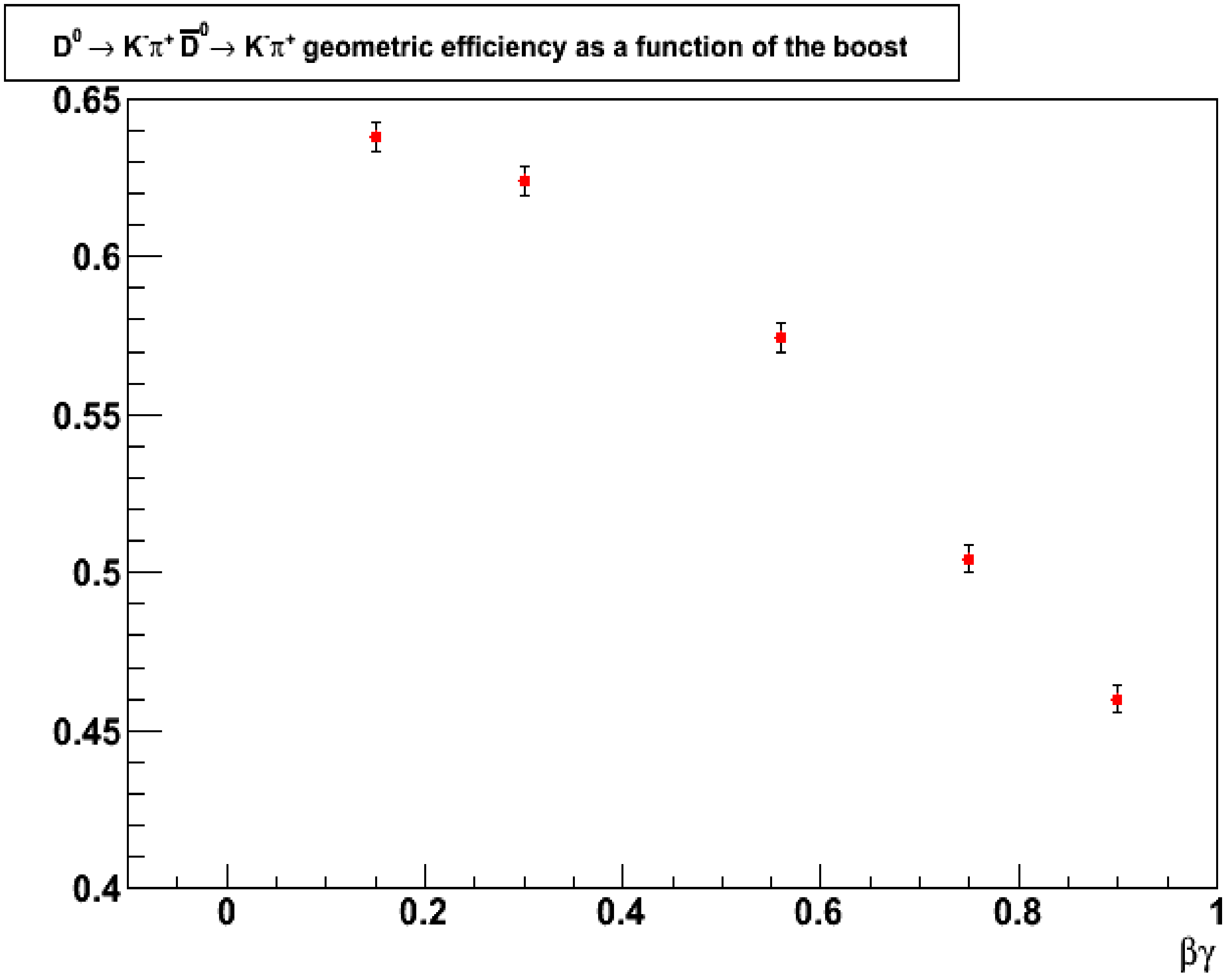




FastSim studies: Δt resolution vs CM boost



FastSim studies: ε_{geo} vs CM boost



Sensitivity studies: overview

- For $\psi(3770)$ modes
  - Extrapolate CLEOc yields (includes cross-sections and selection efficiencies)
  - Correct by SuperB geometrical efficiency vs CM boost
  - Evaluate triple Gaussian (TG) resolution function from FastSim vs CM boost
- For $\Upsilon(4S)$ modes, extrapolate BaBar yields
  - TG proper time resolution of ~0.15 ps (0.1 ps core)
- Toy MC generator and fitter developed
  - For now focus on 2-body decays
  - the next step will be 3-body decays

Double tags @ $\Psi(3770)$
Modes with D* tag @ $\Upsilon(4S)$
used in this study

	CP–	Kπ	*l*X
CP+	X	X	XX
CP–		X	XX
Kπ		X	XX
*l*X			XX

simulated datasets:
75 ab^{-1} at Y(4S)
0.5 ab^{-1} at $\Psi(3770)$

Sensitivity studies: overview

- Strategy:
  - Generate $O(100)$ experiments for each double tag
  - Perform combined UML fit of given ensemble of 2-body double tags, fitting simultaneously for the mixing and CPV parameters: x, y, arg(q/p), |q/p|
  - Assumed CP conservation in decay
  - $D \to K\pi$ strong phase kept fixed
  - Generated values are current HFAG averages

Double tags @ $\Psi(3770)$
Modes with D* tag @ $\Upsilon(4S)$
used in this study

	CP–	Kπ	*l*X
CP+	X	X	XX
CP–		X	XX
Kπ		X	XX
*l*X			XX

simulated datasets:
75 ab^{-1} at Y(4S)
0.5 ab^{-1} at $\Psi(3770)$

Sensitivity studies: expected num. of events

Selected decays	$\Upsilon(4S)$ $75\,\mathrm{ab}^{-1}$	LB ψ(3770): $\Psi(3770)$ $0.5\,\mathrm{ab}^{-1}$, $\beta\gamma = 0.238$	IB ψ(3770): $\Psi(3770)$ $0.5\,\mathrm{ab}^{-1}$, $\beta\gamma = 0.56$	HB ψ(3770): $\Psi(3770)$ $0.5\,\mathrm{ab}^{-1}$, $\beta\gamma = 0.91$
$l^{\pm}X^{\mp}$, $CP+$	19600000	569395	525890	418331
$l^{\pm}X^{\mp}$, $CP-$	30900000	685053	612430	491599
$l^{\pm}X^{\mp}$, $K^{\pm}\pi^{\mp}$	222900000	4181494	3862011	3072118
	(790000)	(13798)	(12744)	(10137)
$l^{\pm}X^{\mp}$, $K^0_S\pi^+\pi^-$	86600000	828850	689557	498370
$l^{\pm}X^{\mp}$, $l^{\mp}X^{\pm}$	85300000	1067615	986045	784370
	(50)	(51)	(47)	(38)
$K^{\mp}\pi^{\pm}$, $K^{\pm}\pi^{\mp}$	N/A	1067615	986045	784370
	(N/A)	(51)	(47)	(38)
$CP+$, $K^{\mp}\pi^{\pm}$	N/A	309608	285953	227467
$CP-$, $K^{\mp}\pi^{\pm}$	N/A	291814	260879	209408
$CP+$, $CP-$	N/A	92526	82717	66397
$CP+$, $K^0_S\pi^+\pi^-$	N/A	113691	91553	66770
$CP-$, $K^0_S\pi^+\pi^-$	N/A	115525	93030	67847
$K^0_S\pi^+\pi^-$, $K^0_S\pi^+\pi^-$	N/A	290342	217578	142875

Legend (color key: $\Upsilon(4S)$ column / ψ(3770) columns):

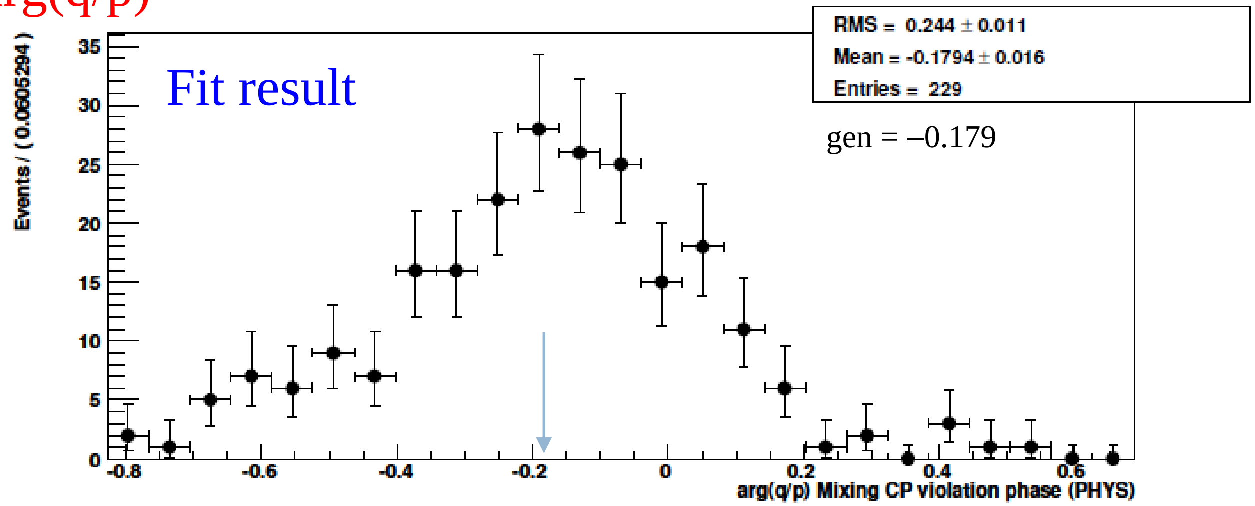
- Favored # of events
- Suppressed # of events

$\Upsilon(4S)$ ψ(3770)

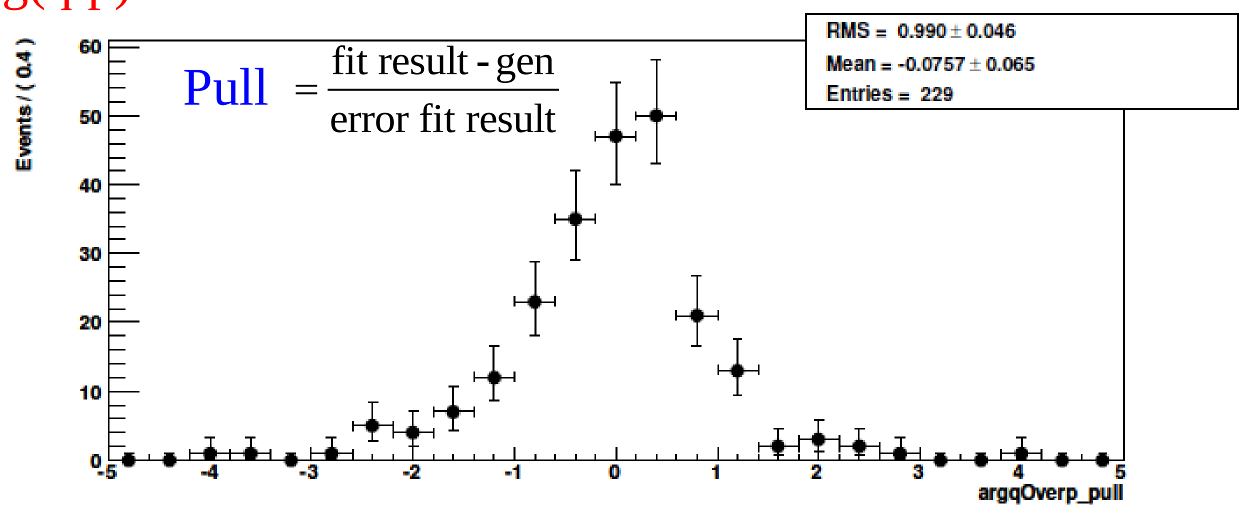
Sensitivity studies: toy MC at Ψ(3770)

example:

arg(q/p)



arg(q/p)

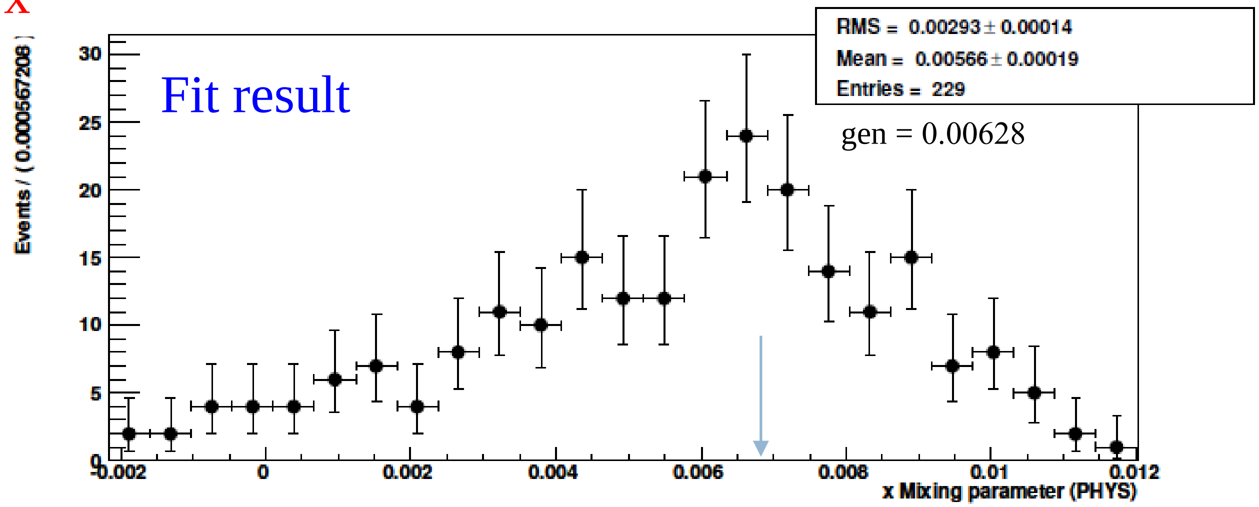


- Ψ(3770) , $\beta\gamma$=0.24, perfect resolution, no mistag
- ×10 less events (CPU memory limitation)

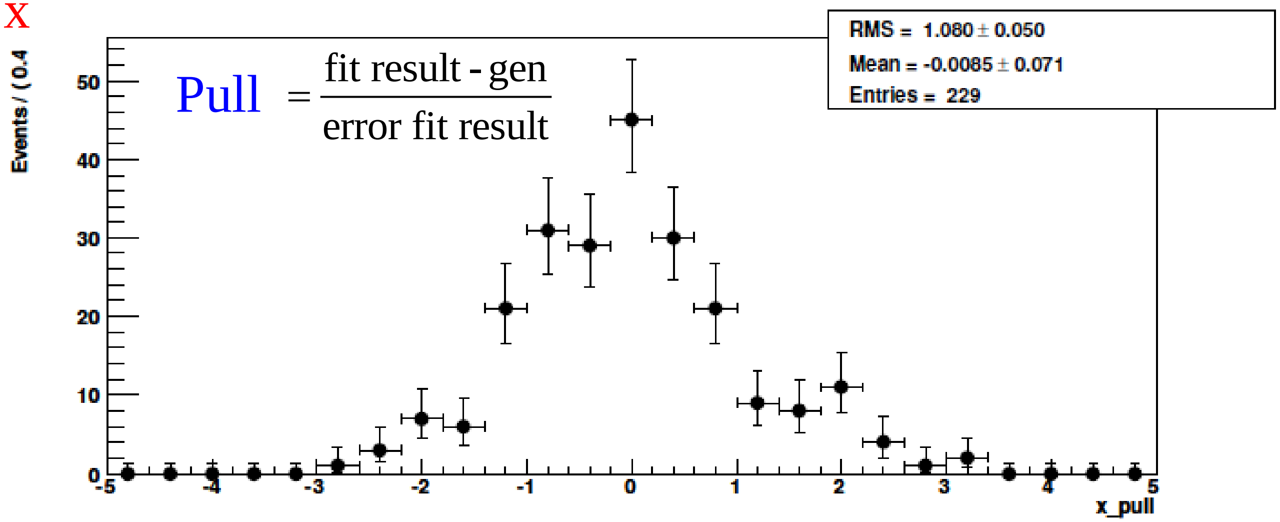
Sensitivity studies: toy MC at Ψ(3770)

example:

x



x

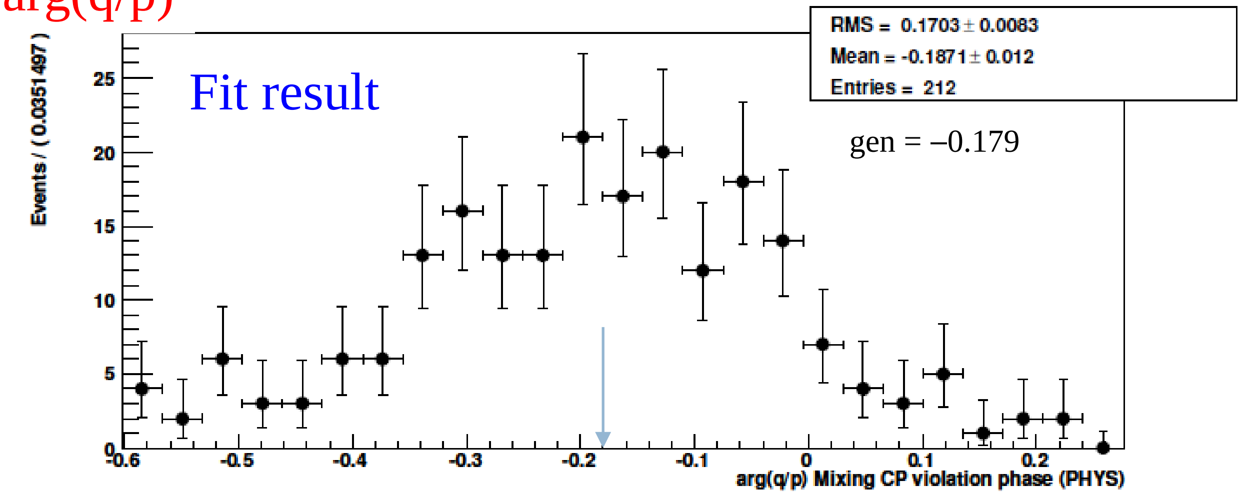


- Ψ(3770) , βγ=0.24, perfect resolution, no mistag
- ×10 less events (CPU memory limitation)

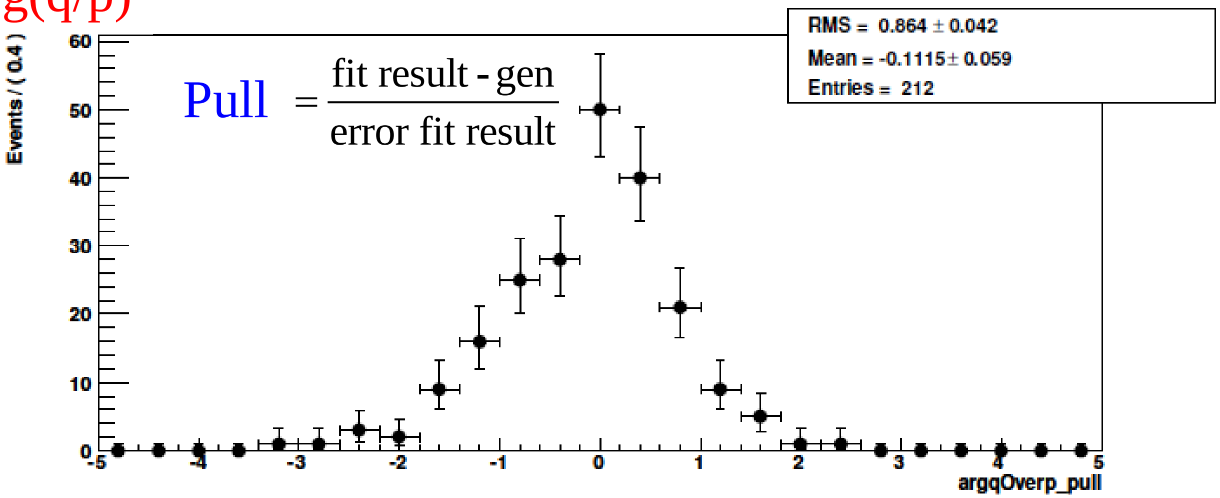
Sensitivity studies: toy MC at Υ(4S)

example:

arg(q/p)



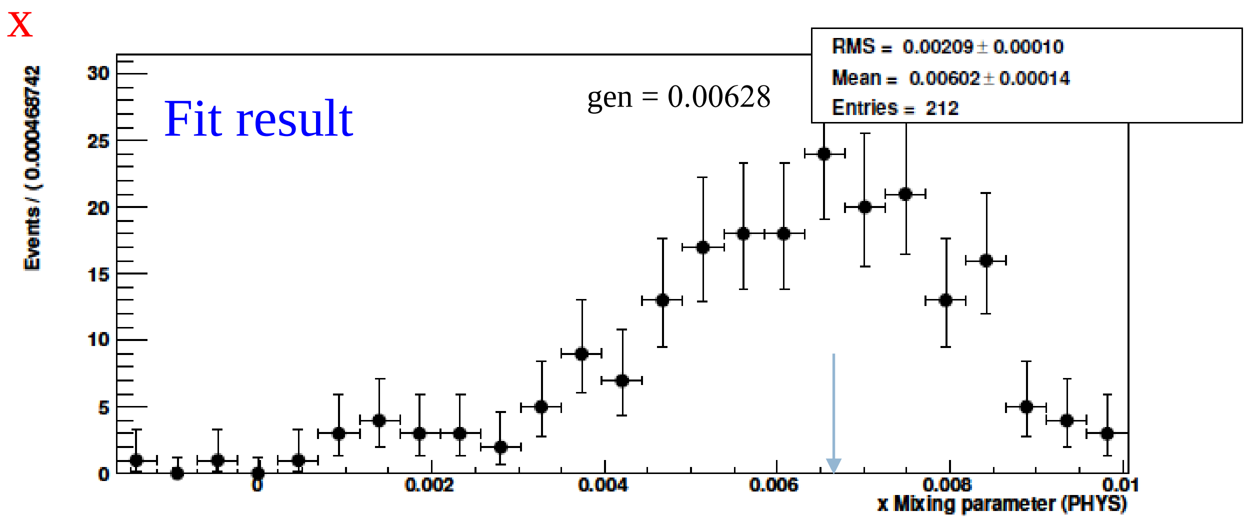
arg(q/p)

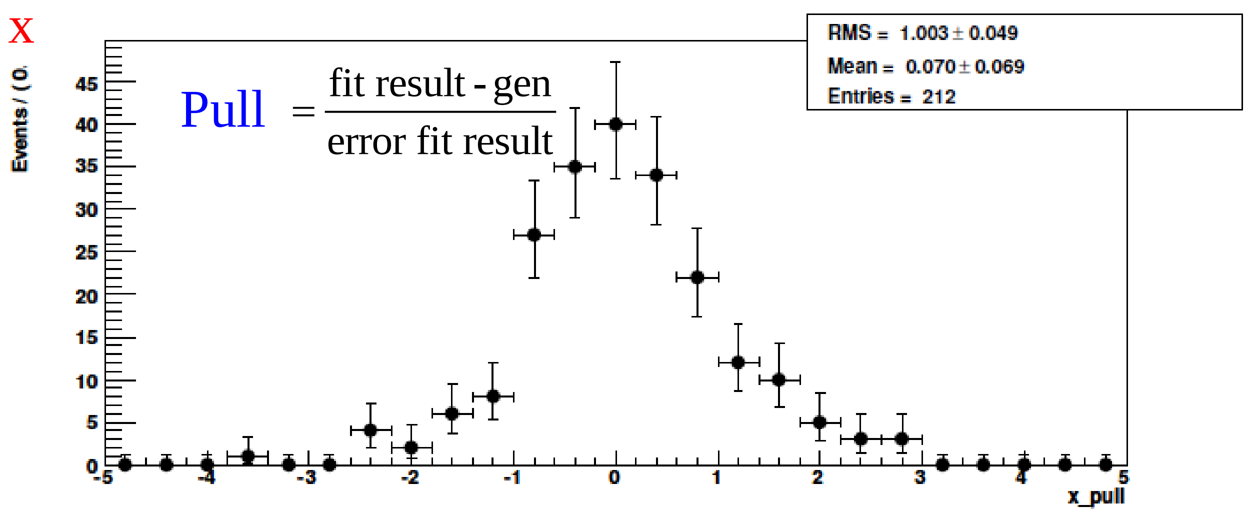


- Υ(4S) , perfect resolution, no mistag
- ×200 less events (CPU memory limitation)

Sensitivity studies: toy MC at Y(4S)

example:





- Y(4S) , perfect resolution, no mistag
- ×200 less events (CPU memory limitation)

Scenarios considered in our study

$\Psi(3770)$, 500 fb^{-1}

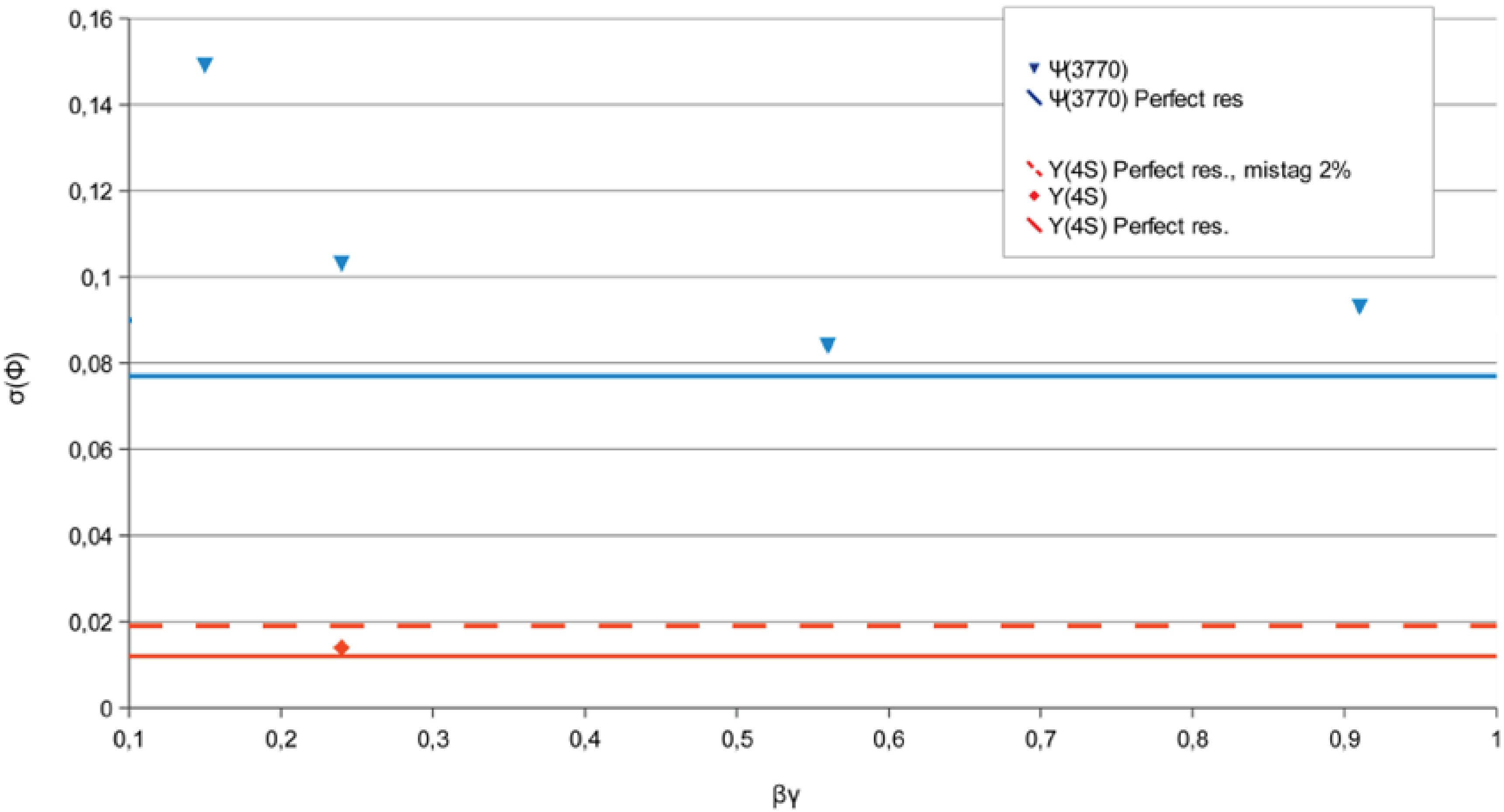
CM boost ($\beta\gamma$)	time resolution	mistag
0.24	realistic	0
0.56	realistic	0
0.90	realistic	0
0.24	perfect	0
0.24	the one at $\beta\gamma$=0.15	0
0.24	the one at $\beta\gamma$=0.56	0
0.24	the one at $\beta\gamma$=0.90	0
0.24 [large x,y]	perfect	0
0.24 [no CPV]	perfect	0

effect of ~0.2% mistag under evaluation

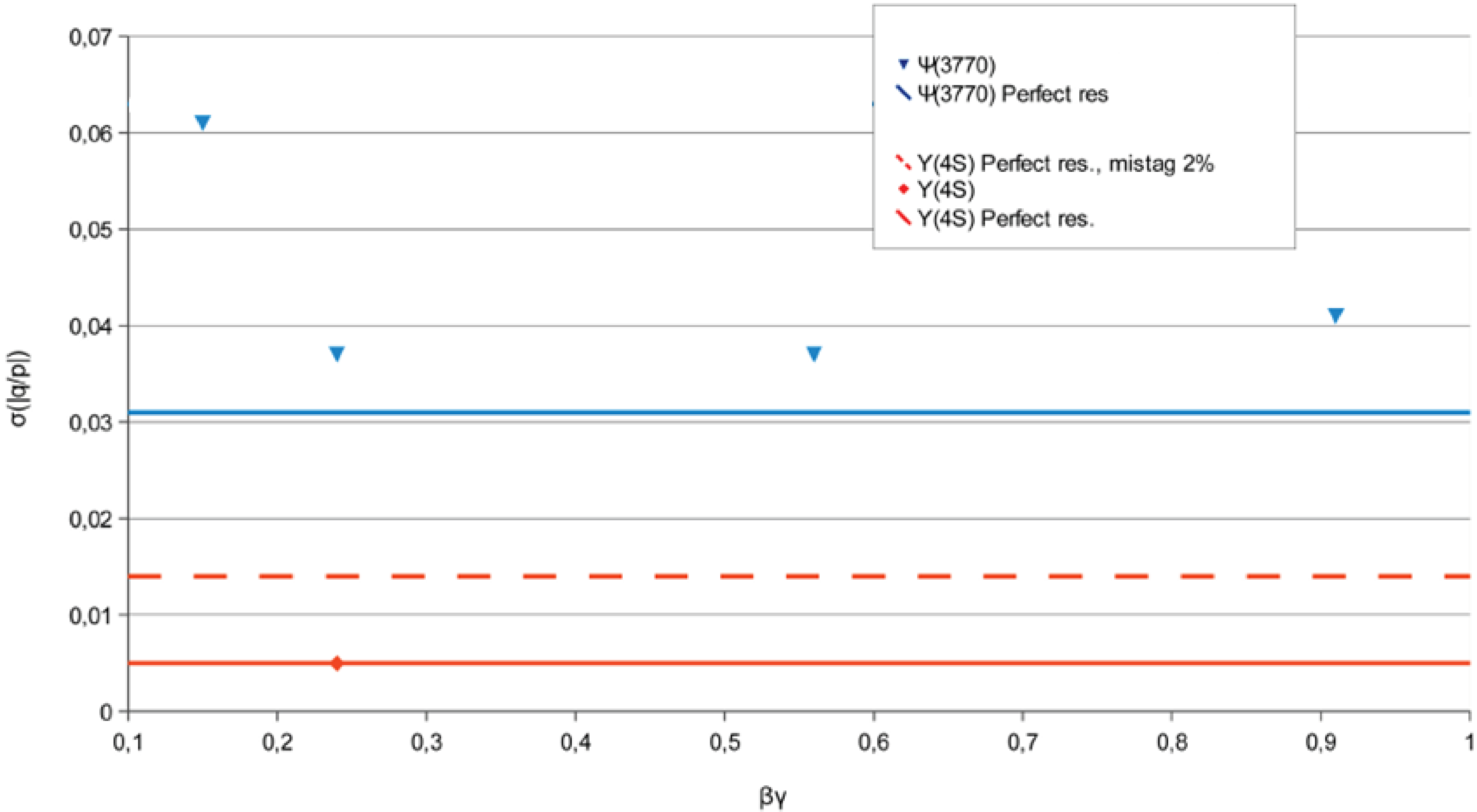
Y(4S), 75 ab^{-1}, $\beta\gamma$=0.24

time resolution	mistag	notes
realistic	0	
perfect	0	
perfect	2%	
perfect	0	large x,y
perfect	0	no CPV

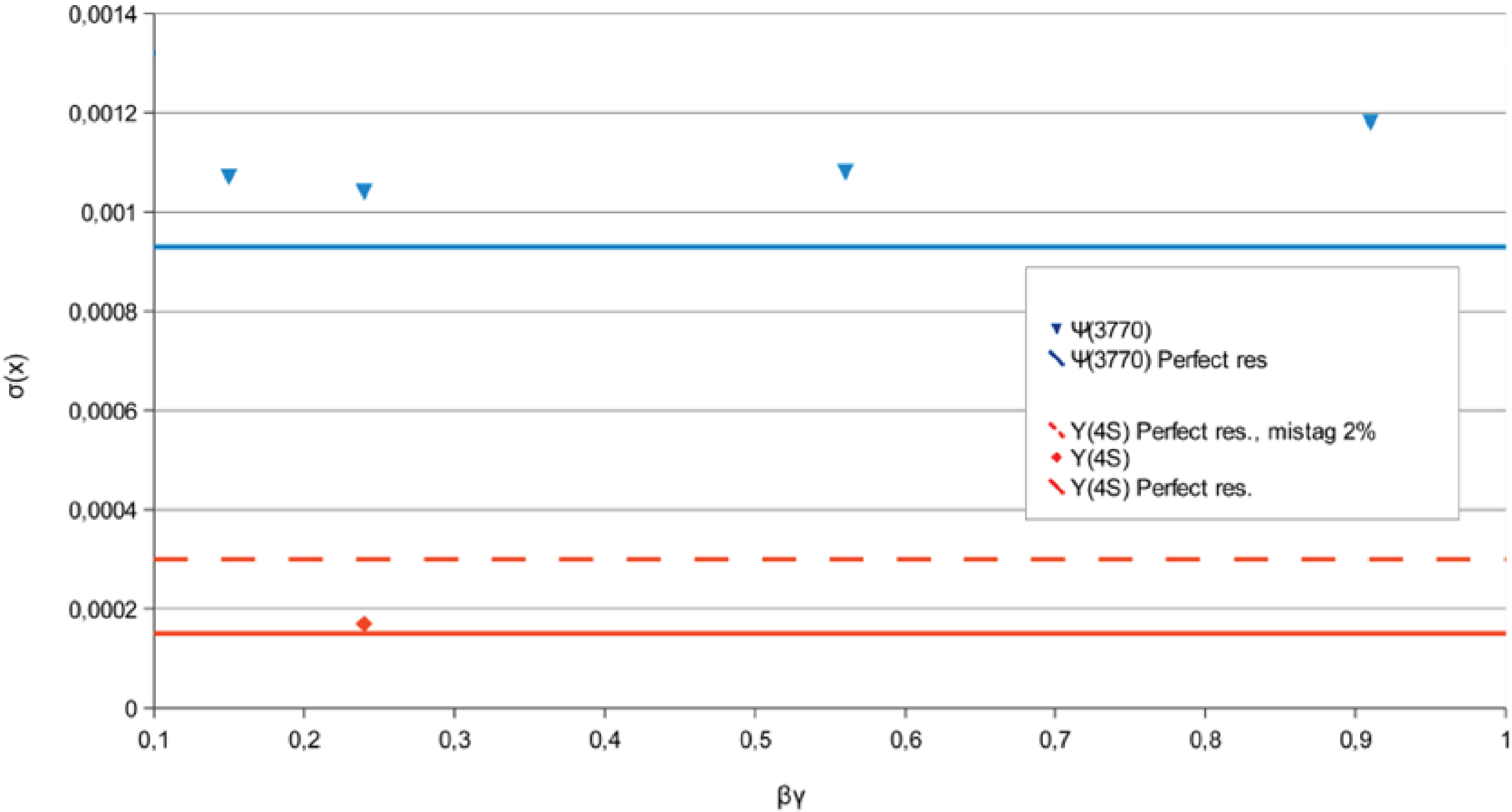
Sensitivity: ϕ=arg(q/p)



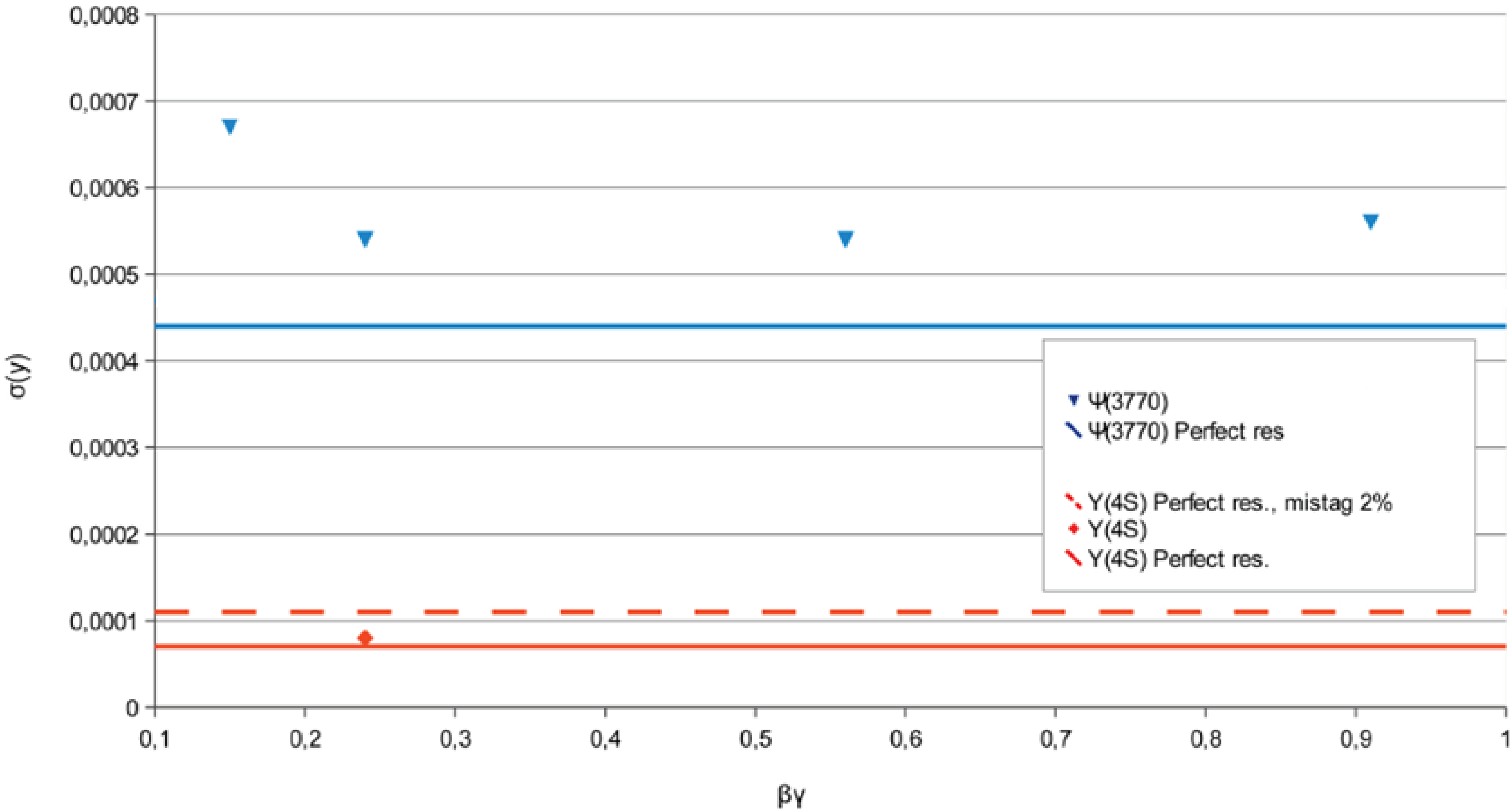
Sensitivity: |q/p|



Sensitivity: x



Sensitivity: y



Summary

- Flavor tag at $D\bar{D}$ threshold provides identical time-dependence than at $\Upsilon(4S)$ using D* tagging, and less events, although in a different environment
- $D\bar{D}$ threshold is unique to provide CP, $K\pi$ and $Ks\pi\pi$ tags
- Variation of Δt resolution and geometrical acceptance vs CM boost was evaluated
- Estimated the impact on physics with 2-body decays
  - Combined fit to all 2-body double-tags allows determination of x, y, arg(q/p), |q/p|
  - Best sensitivity at $\Psi(3770)$ for intermediate boost, $\beta\gamma \approx 0.3$-0.6

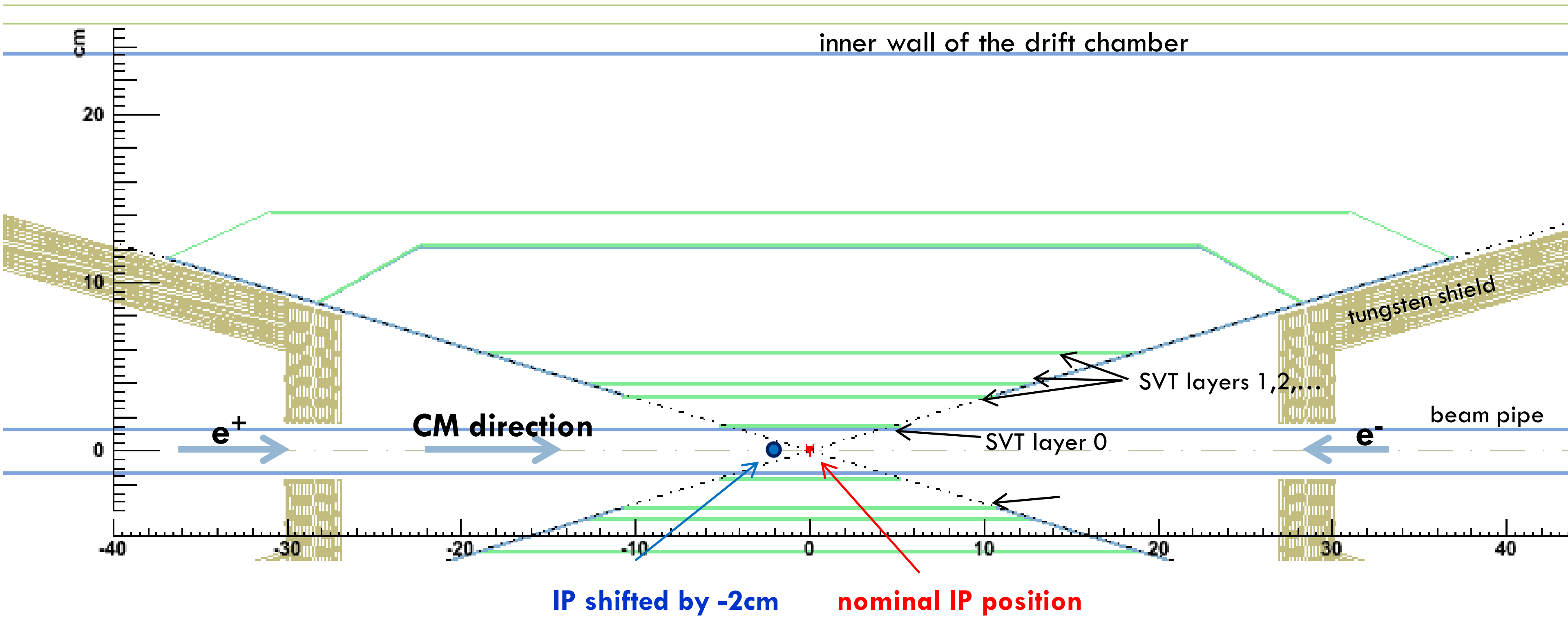
Parameter	Sensitivity @ $\Upsilon(4S)$ with time resolution, no mistag. 75 ab^{-1}	Best sensitivity @ $\psi(3770)$ with time resolution ($\beta\gamma$=0.56), no mistag. 0.5 ab^{-1}
x	0.017%	0.11%
y	0.008%	0.05%
Arg(q/p)	0.8 deg	4.8 deg
|q/p|	0.5%	3.7%

Relative effect of flavor mistag similar at $\Psi(3770)$ and $\Upsilon(4S)$

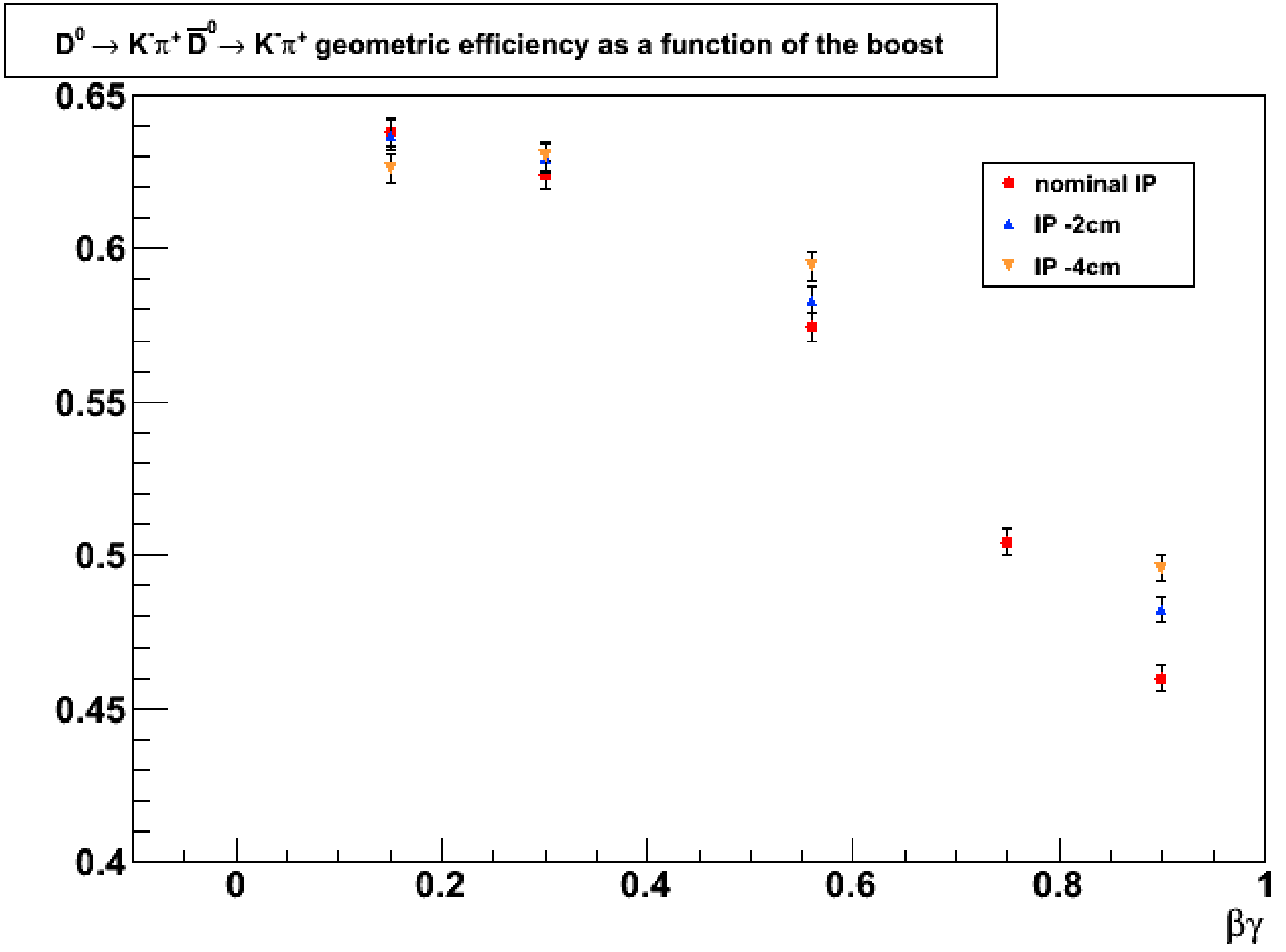
  - error per ab^{-1} at Y(3770) ~ ½ error per ab^{-1} at Y(4S) (2-body only, no mistag)
  - error at $\Psi(3770)$ [0.5ab^{-1}] ~ 6x error at $\Upsilon(4S)$ [75ab^{-1}] (2-body only, no mistag)

Ongoing study: performance vs IP position

Effect of a possible shift of the IP from the nominal position



ε_{geo} vs CM boost as a function of the IP position



Next steps

- Finalize 2-body sensitivity studies
- Sensitivity studies on mixing and CPV parameters for 3-body decays with a time-dependent Dalitz plot analysis:
  - Dalitz plot model independent approach is to be pursued at SuperB. For this, it is crucial to have access to $\Psi(3770)$ data
- Consider two different scenarios:
  - Time-dependent measurements at $\Upsilon(4S)$ with model independent coefficients (c_i, s_i) obtained with time-integrated Psi(3770) data
  - Time-dependent measurements at $\Psi(3770)$
- Set up simulation technology for 3-body Toy MC studies.

backup

FastSim design overview

- Simplified detector element description
  - cylinders, rings, cones, …
- Particle passage through detector fully modeled
  - ionization energy loss, multiple scattering, bremsstrahlung, photon conversion, EM/hadronic showering, …
- Parameterized detector response
  - track hit resolution, Cherenkov ring resolution, shower shape,…
- Reconstruction of tracks, clusters, Cherenkov rings, …
- Output compatible with BaBar analysis tools
  - vertexing, B-flavor tagging, particle Id selectors, …

HFAG averages

HFAG 2011

Parameter	No CPV	No direct CPV	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.65^{+0.18}_{-0.19}$	0.63 ± 0.19	$0.63^{+0.19}_{-0.20}$	[0.24, 0.99]
y (%)	0.74 ± 0.12	0.75 ± 0.12	0.75 ± 0.12	[0.52, 0.99]
δ (°)	$21.3^{+9.8}_{-11.1}$	$22.5^{+9.9}_{-11.2}$	$22.4^{+9.7}_{-11.0}$	[−2.2, 40.9]
R_D (%)	0.3308 ± 0.0080	0.3306 ± 0.0080	0.3311 ± 0.0081	[0.315, 0.347]
A_D (%)	–	–	-1.7 ± 2.3	[−6.3, 2.8]
$\lvert q/p \rvert$	–	1.02 ± 0.04	$0.89^{+0.17}_{-0.15}$	[0.61, 1.24]
ϕ (°)	–	$-1.05^{+1.89}_{-1.94}$	$-10.1^{+9.4}_{-8.8}$	[−27.2, 8.6]
$\delta_{K\pi\pi}$ (°)	$18.0^{+21.7}_{-22.8}$	$19.4^{+21.8}_{-22.9}$	$19.5^{+21.8}_{-22.9}$	[−26.1, 61.8]
A_π	–	–	0.22 ± 0.28	[−0.34, 0.76]
A_K	–	–	-0.20 ± 0.24	[−0.67, 0.27]
x_{12} (%)	–	0.63 ± 0.19	–	[0.25, 0.99]
y_{12} (%)	–	0.75 ± 0.12	–	[0.52, 0.99]
ϕ_{12}(°)	–	$2.5^{+5.2}_{-4.6}$	–	[−7.1, 15.8]

Sensitivity studies: summary of results

Data	Time resolution	Mistag	$\sigma(x)$	$\sigma(y)$	$\sigma(\phi)$	$\sigma(\lvert q/p \rvert)$
LB $\Psi(3770)$	Perfect	0	0.00076	0.00044	0.077	0.031
LB $\Psi(3770)$ large mixing	Perfect	0	0.00059	0.00043	0.007	0.003
LB $\Psi(3770)$ no CPV	Perfect	0	0.00081	0.00027	0	0
LB $\Psi(3770)$	HB TG (0.25/0.20 ps)	0	0.00098	0.00046	0.077	0.034
LB $\Psi(3770)$	IB TG (0.40/0.28 ps)	0	0.00100	0.00051	0.078	0.035
LB $\Psi(3770)$	LB TG (0.66/0.39 ps)	0	0.00104	0.00054	0.103	0.037
LB $\Psi(3770)$	VLB TG (1.27/0.76 ps)	0	0.00107	0.00067	0.149	0.061
HB $\Psi(3770)$	HB TG (0.25/0.20 ps)	0	0.00118	0.00056	0.093	0.041
IB $\Psi(3770)$	IB TG (0.40/0.28 ps)	0	0.00108	0.00054	0.084	0.037
LB $\Psi(3770)$	Perfect	2%	0.00210	0.00062	0.119	0.097
$\Upsilon(4S)$	Perfect	0	0.00021	0.00007	0.012	0.005
$\Upsilon(4S)$ large mixing	Perfect	0	0.00010	0.00008	0.001	0.001
$\Upsilon(4S)$ no CPV	Perfect	0	0.00012	0.00004	0	0
$\Upsilon(4S)$	TG (0.17/0.10 ps)	0	0.00017	0.00008	0.014	0.005
$\Upsilon(4S)$	Perfect	2%	0.00030	0.00011	0.019	0.014

Parameter	Sensitivity @ Υ(4S) with time resolution, no mistag. 75 ab^{-1}	Best sensitivity @ ψ(3770) with time resolution ($\beta\gamma$=0.56), no mistag. 0.5 ab^{-1}
x	0.017%	0.11%
y	0.008%	0.05%
Arg(q/p)	0.8 deg	4.8 deg
|q/p|	0.5%	3.7%

Relative effect of flavor mistag similar at Ψ(3770) and Υ(4S)