

$B^0 \rightarrow \eta'(\rightarrow \eta\pi^+\pi^-)K_S^0$ Time Dependent $\mathcal{CP}$ sensitivity study for BelleII

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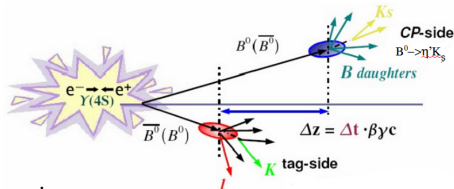
INFN Padova

B2TIP workshop,
Pittsburgh, 23 May 2016

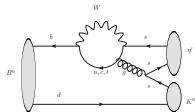
Introduction and motivations

A sensitivity study for Time-Dependent CP violation analysis in the $B^0 \rightarrow \eta' K^0$ channel, a charmless $b \rightarrow sq\bar{q}$ decay

CP asymmetry from time-dependent decay rate into CP eigenstates;

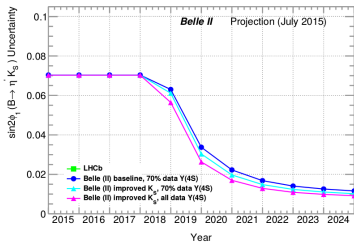
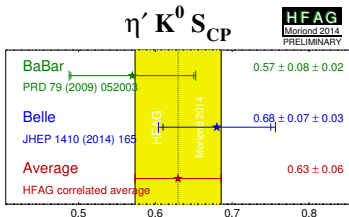


- $B^0 \rightarrow \eta' K^0$ is a penguin dominated mode
- Precision not competitive with that from golden channel $B^0 \rightarrow J/\psi \phi$
- $S_{\eta' K^0} = \sin 2\phi_1^{eff}$ tightly related to $\sin 2\phi_1$ measured in $b \rightarrow cs\bar{s}$ decay
- identical if only penguin diagram were present: not so;
 - ▶ QCD factorization: $\Delta S_{\eta' K^0} \in [-0.03, 0.03]$ [Williamson and Zupan(2006)]
 - ▶ $SU(3)_F$ approach: $\Delta S_{\eta' K^0} \in [-0.05, 0.09]$ [Gronau et al.(2006)]
 - ▶ new physics can enter in the loop, shifting $\Delta S_{\eta' K^0}$ more than SM expectation



Current results

- Channel have been analyzed in B-factory ^[BABAR(2009), Belle(2007), Belle(2014)];
- analysis based on quasi-two body approach;
- $\sin 2\phi_1^{eff} = +0.68 \pm 0.07 \pm 0.03$ ^[Belle(2014)] $= +0.57 \pm 0.08 \pm 0.02$ ^[BABAR(2009)]
- uncertainties are mostly statistical (~ 3500 events for all final states);
 - syst: ± 0.025 from Δt resolution, ± 0.014 from vertexing, ± 0.013 from $\eta' K_S^0$ fraction;



- projected for 50 ab^{-1} $\sigma_{stat} = 0.008, \sigma_{syst} = 0.008$ ^[Urquijo(2015)]
- no competition from LHCb

many decay channels available $B^0 \rightarrow \eta' K^0$

decay channel		
$\eta' \rightarrow \rho^0 (\rightarrow \pi^+ \pi^-) \gamma$	BR=29%	not yet
$\eta' \rightarrow \eta \pi^+ \pi^-$	43%	today
$\searrow \eta \rightarrow \gamma \gamma$	40%	$\eta_{\gamma\gamma}$
$\searrow \eta \rightarrow \pi^+ \pi^- \pi^0$	23%	$\eta_{3\pi}$
$K_S^0 \rightarrow \pi^+ \pi^-$	69%	today
$K_S^0 \rightarrow \pi^0 \pi^0$	31%	just started
K_L^0		not yet
$B_0 \rightarrow \eta' (\rightarrow \eta_{\gamma\gamma} / \eta_{3\pi} \pi^+ \pi^-) K_S^0 (\rightarrow \pi^+ \pi^-)$	BR=19%	

- Complex final state, neutrals, large combinatorics;
- final states considered so far in red
- more to be studied ($\rho^0, K_S^0 \rightarrow \pi^0 \pi^0, K_L^0$)

candidate selection: main cuts

- Reconstruct decay chain with mass constrains for π^0 , η , η' , K_S^0 ,
 - vertex only (w/o mass) for B^0 (more later)

■ $\pi^0, \eta_{\gamma\gamma}$:

- $0.06 < E_\gamma < 6 \text{ GeV}, E_9/E_{25} > 0.75$
- $M(\pi^0) \in [100, 150] \text{ MeV}$
- $M(\eta_{\gamma\gamma}) \in [0.52, 0.57] \text{ GeV};$

■ $\eta' \rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-$:

- $d_0(\pi^\pm) < 0.08 \text{ mm};$
 $z_0(\pi^\pm) < 0.1 \text{ mm};$
- $N \text{ hits}_{PXD}(\pi^\pm) > 1, \text{ PID}$
- $M(\eta') \in [0.93, 0.98] \text{ GeV};$

■ $\eta' \rightarrow \eta_{3\pi} \pi^+ \pi^-$:

- $M(\eta') \in [0.93, 0.98] \text{ GeV};$

■ $K^0 \rightarrow \pi^+ \pi^-$:

- $M(K_S^0 \rightarrow \pi^+ \pi^-) \in [0.48, 0.52] \text{ GeV};$

■ $B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^{0+-}$

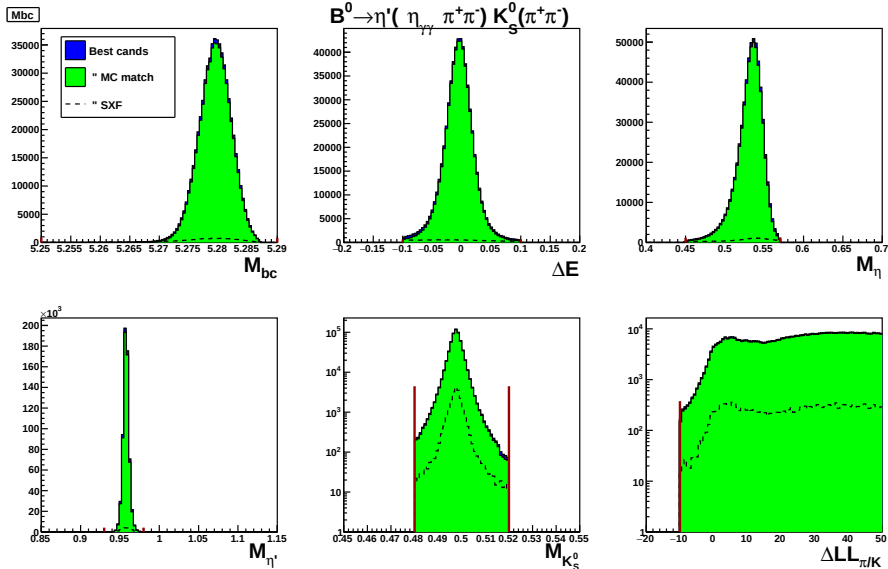
- $M_{bc} > 5.25 \text{ GeV};$

- $|\Delta E| < 0.1 \text{ GeV};$

■ $B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^{0+-}$

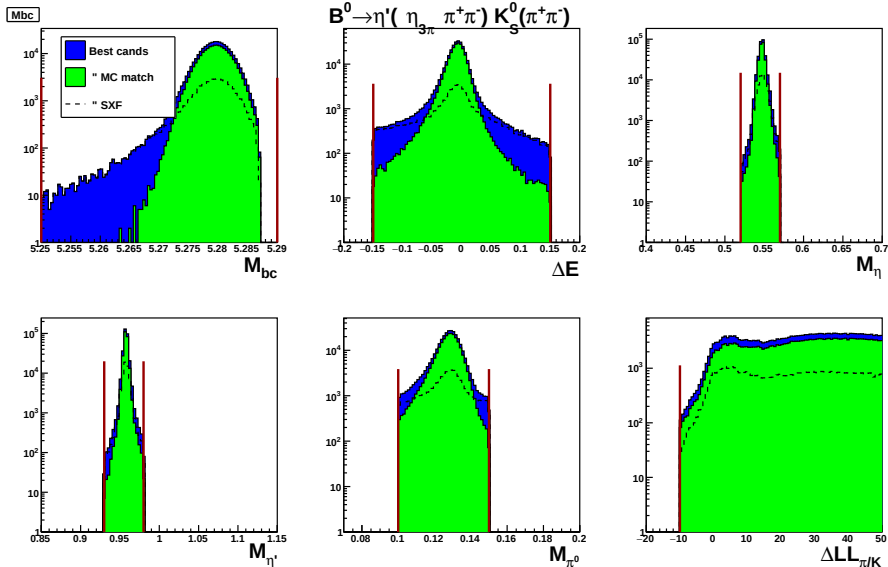
- $|\Delta E| < 0.15 \text{ GeV};$

if $N_{cands} > 1$, select that with best reduced χ^2 for η, η', K_S^0 inv. masses



Signal distribution $B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^{0+-}$

Best candidates, after selections

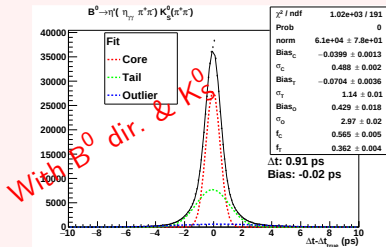
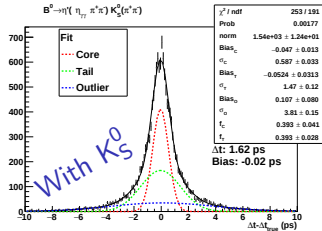
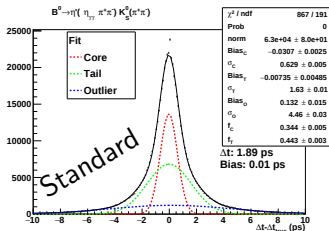


channel	ϵ %	SxF %	cands/ev
$B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^0(\rightarrow \pi^+ \pi^-)$	29.4	1.1	1.06
$B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^0(\rightarrow \pi^+ \pi^-)$	12.1	3.1	1.45
$B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^0(\rightarrow \pi^0 \pi^0)$	13.5	2.2	~ 5
$B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^0(\rightarrow \pi^0 \pi^0)$	6.0	3.8	~ 30

- Efficiency drop due to π^0 reco, likely to improve;
- presence of π^0 increase also combinatorics and signal cross feed
SxF : signal event but with wrong particle association;
- $B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^0(\rightarrow \pi^0 \pi^0)$ not used in Belle and BaBar analysis.

Vtx reco and Δt resolution: $\eta_{\gamma\gamma}$ channel

- 1 Fit the B_0 vertex from charged tracks; ($\pi^\pm$ from $\eta' \rightarrow \eta \pi^\pm$)
- 2 add also constraint from reconstructed K_S^0 direction; ($K_S^0 \rightarrow \pi^+ \pi^-$)
- 3 add also constraint from B^0 boost direction, transverse plane only.



With beamspot (x, y) & K_S^0 :

No efficiency loss

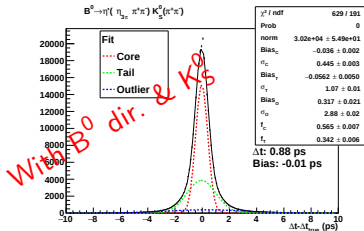
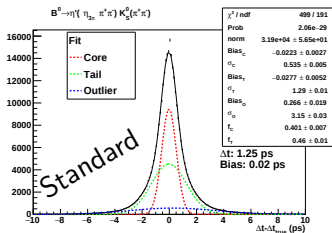
important improvement in Δt resolution

$1.89 \rightarrow 1.62 \rightarrow 0.91 \text{ ps}$

Vtx reconstruction for $B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^0 \pi^+ \pi^-$

Standard reconstruction uses four charged tracks:

$\pi^\pm$ from $\eta' \rightarrow \eta \pi^\pm$ and $\eta \rightarrow \pi^\pm \pi^0$



With B^0 dir. & K_S^0 :

No efficiency loss

1.25 $\rightarrow$ 0.88 ps

In both cases, Δt resolution better than in Belle, in spite of lower boost

- **Combinatorial:** from continuum background $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$
 - ▶ evaluated from M_{bc} side bands on real data
 - ▶ now from MC production: **NB: still w/o machine background!**
 - ▶ use **Continuum Suppression variable**
 - ★ multivariate variables sensitive to event topology
 - ★ central (signal) vs jet-like (continuum)
- **Peaking:** any other B decays possibly with real η' and/or K_S^0
 - ▶ evaluated from MC of generic $B^0\bar{B}^0, B^+B^-$
 - ★ actual $B^0 \rightarrow \eta'K^0$ removed.
- Current results based on BGx0 production, namely w/o machine background
 - ▶ impact of machine background under study
- Next table numbers before Continuum Suppression cut

Background reduction (before CS cut)

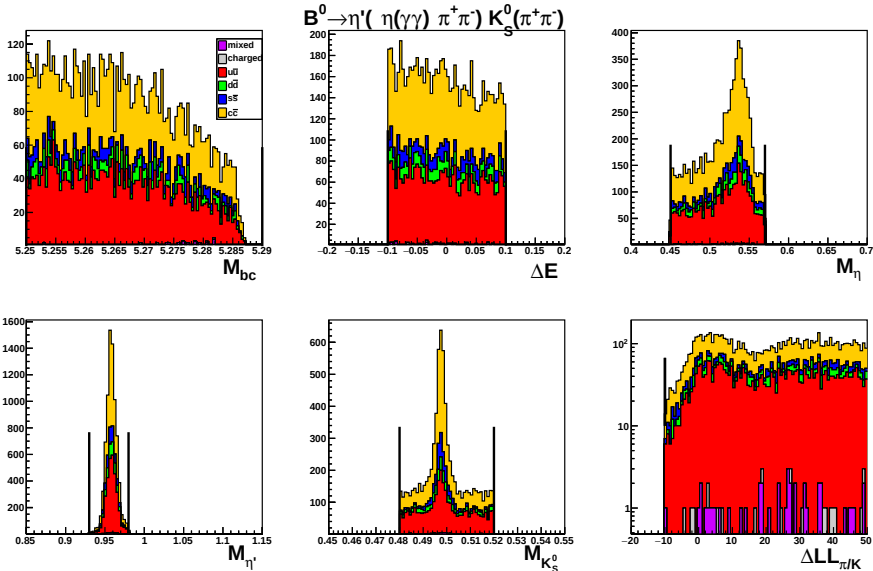
Sample	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	continuum	$B^0\bar{B}^0$	B^+B^-
Input ev (M)	1284	321	306	1063	2974	429	420
$B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^{0+-}$							
$\epsilon_{sel} (\cdot 10^{-6})$	2.69	3.06	2.40	3.62	3.0	0.11	0.038
ev for 300 fb^{-1}	1247	369	275	1445	3335	18	6
$B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^{0+-}$							
$\epsilon_{sel} (\cdot 10^{-6})$	0.34	0.54	0.17	1.50	0.76	0.14	0.02
ev for 300 fb^{-1}	166	65	20	597	847	24	3

- Background reduction better for $\eta_{3\pi}$ than for $\eta_{\gamma\gamma}$

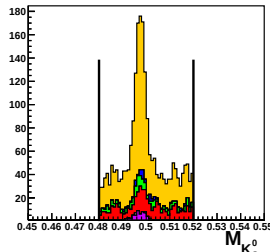
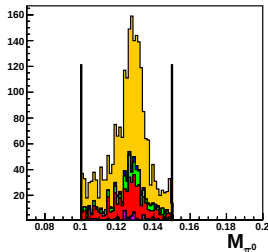
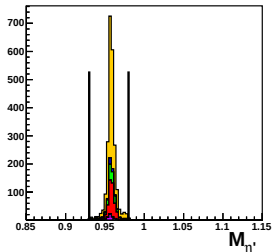
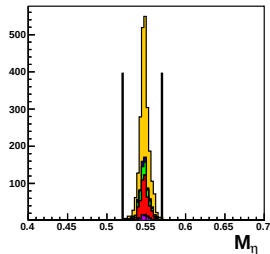
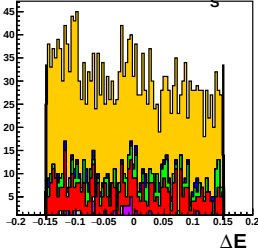
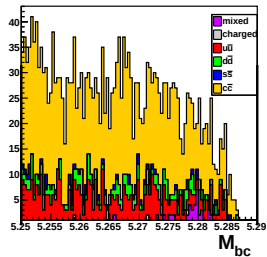
$\eta_{\gamma\gamma}$ mostly $u\bar{u}$ and $c\bar{c}$

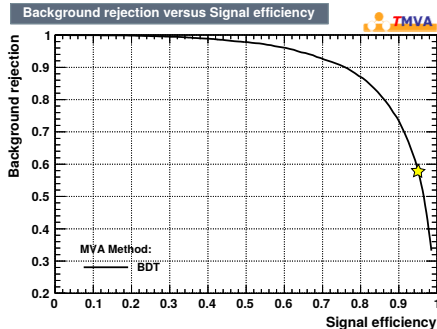
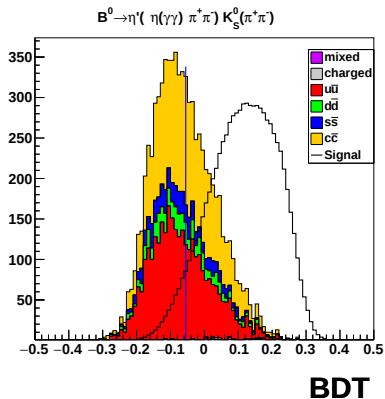
$\eta_{3\pi}$ mostly $c\bar{c}$

- peaking background is small
- preliminary study on w/ machine background shows similar rates



$$B^0 \rightarrow \eta'(\eta(\pi^+\pi^-\pi^0) \pi^+\pi^-) K_S^0(\pi^+\pi^-)$$





Working point

- $BDT > -0.055$, $\epsilon_{signal} = 95\%$, $(1 - \epsilon_{background}) = 58\%$,
- **todo:** no cut, but include the BDT in the likelihood not yet

Multi dim. extended maximum likelihood fit to extract **S** and **C**.

Pdf is of the form:

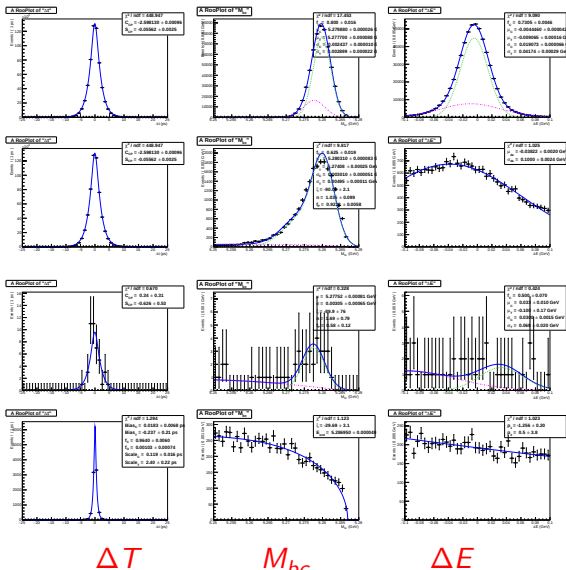
$$\mathcal{P}_j^i = \underbrace{\mathcal{T}_j \left(\Delta t^i, \sigma_{\Delta t}^i, \eta_{CP}^i \right)}_{\text{time-dep part}} \prod_k \underbrace{\mathcal{Q}_{k,j}(x_k^i)}_{\text{time integrated}}$$

time-dependent part, taking into account mistag rate ($\eta_f = \pm 1$ is CP state):

$$f(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left\{ 1 \mp \Delta w \pm (1 - 2w) \right. \\ \left. \times \left[-\eta_f S_f \sin(\Delta m \Delta t) - C_f \cos(\Delta m \Delta t) \right] \right\}$$

Parameters:

- variables (x_k) used, in addition to Δt
- M_{bc}
 - ΔE
 - Cont. Suppr. not yet
 - effective tagging efficiency:
 $Q = \epsilon(1 - 2w)^2 = 0.33$
 $\triangleright w = 0.21, \Delta w = 0.02$
 - Δt resolution as shown previously (convoluted)
 - $\tau, \Delta m$ from PDG



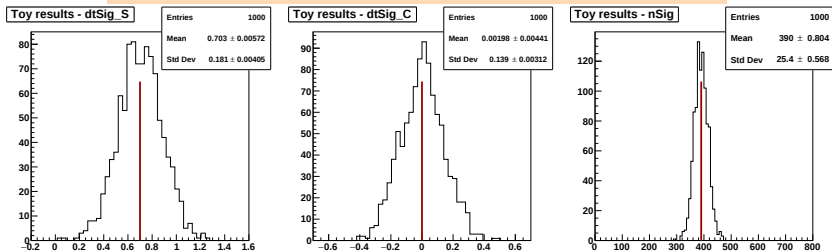
Still problem to fit the continuum suppression variable: very spiky

- Testing fit machinery with Toy MC;
- Yield estimated for $L = 300 \text{ fb}^{-1}$
- $N(B\bar{B}) \sim 330 \cdot 10^6$
- width of distribution related to the expected statistical uncertainty;
- check also for bias;
- input CP asymmetry parameter: $S=0.7 \quad C=0.0$
- Partially embedded toys
 - ▶ Signal and SXF from MC;
 - ▶ Continuum and Peaking background from pdf;

Toy results $B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^{0+-}$

$L = 300 \text{ fb}^{-1}$, $N(B\bar{B}) \sim 330 \cdot 10^6$:

$N_{sig} = 390$, $N_{sxf} = 14$, $N_{cont} = 1400$, $N_{peak} = 23$



Preliminary results

Par	Bias	RMS
S (0.7)	0.703 ± 0.005	0.18
C (0.0)	0.002 ± 0.004	0.14
nSig	389.8 ± 0.8	25.4

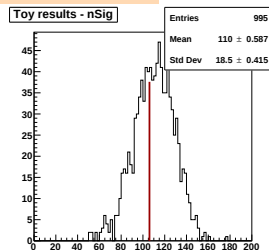
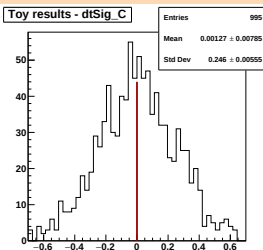
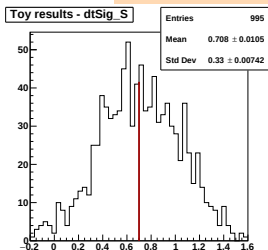
Belle ($772 \cdot 10^6 B\bar{B}$): $N_{sig} = 648$, $\sigma_S = 0.15$, $\sigma_C = 0.10$

BaBar ($467 \cdot 10^6 B\bar{B}$): $N_{sig} = 472$, $\sigma_S = 0.17$, $\sigma_C = 0.11$

Toy results $B^0 \rightarrow \eta'(\rightarrow \eta_3\pi^+\pi^-)K_S^{0+-}$ Loose CS

$L = 300 \text{ fb}^{-1}$, $N(B\bar{B}) \sim 330 \cdot 10^6$:

$N_{sig} = 106$, $N_{sxf} = 25$, $N_{cont} = 360$, $N_{peak} = 27$



Preliminary results

Par	Bias	RMS
S (0.7)	0.708 ± 0.010	0.330
C (0.0)	-0.013 ± 0.008	0.246
nSig	110.2 ± 0.6	18.5

Belle¹ ($772 \cdot 10^6 B\bar{B}$): $N_{sig} = 104$, $\sigma_S = 0.21$, $\sigma_C = 0.18$

BaBar ($467 \cdot 10^6 B\bar{B}$): $N_{sig} = 105$, $\sigma_S = 0.26$, $\sigma_C = 0.20$

¹including also $\eta' \rightarrow \rho^0\gamma$

- First presentation on sensitivity study for $\mathcal{CP}$ in $B^0 \rightarrow \eta' K_S^0$ channel;
- not complete, yet, but preliminary results are encouraging;
 - ▶ comparison with Belle and BaBar results looks fine;
- many thing to do:
 - ▶ include machine background
 - ▶ complete $K_S^0 \rightarrow \pi^+ \pi^-$ channels;
 - ▶ study $K_S^0 \rightarrow \pi^0 \pi^0$ final states;
 - ▶ add $\eta' \rightarrow \rho^0 \gamma K_S^{0+-} / K_S^{000}$ channel;
 - ▶ systematics uncertainties evaluation;
 - ▶ documentation
 - ▶ ...

More results (and work) for next B2TIP workshop.

Additional or backup slides

good candidate selection $B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^{0+-}$:

- Reconstruct decay chain with mass constrains for η , η' , K_S^0 ,
 - vertex only (w/o mass) for B^0

■ $\eta \rightarrow \gamma\gamma$:

- gamma:all: $0.06 < E_\gamma < 6 \text{ GeV}$,
 $-150 < \text{clus}_{\text{time}} < 0$, $E_9/E_{25} > 0.75$

- $M(\eta_{\gamma\gamma}) \in [0.52, 0.57] \text{ GeV}$;

■ $\eta' \rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-$:

- pi:all

- $\Delta \log \mathcal{L}(\pi, K) > -10$; new

- $d_0(\pi^\pm) < 0.08 \text{ mm}$;

- $z_0(\pi^\pm) < 0.1 \text{ mm}$;

- $N \text{ hits}_{\text{PXD}}(\pi^\pm) > 1$

- $M(\eta') \in [0.93, 0.98] \text{ GeV}$;

■ $K^0 \rightarrow \pi^+ \pi^-$:

- K_S0:mdst

- $M(K_S^0 \rightarrow \pi^+ \pi^-) \in [0.48, 0.52] \text{ GeV}$;

■ $B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^{0+-}$

- $M_{bc} > 5.25 \text{ GeV}$;

- $|\Delta E| < 0.1 \text{ GeV}$;

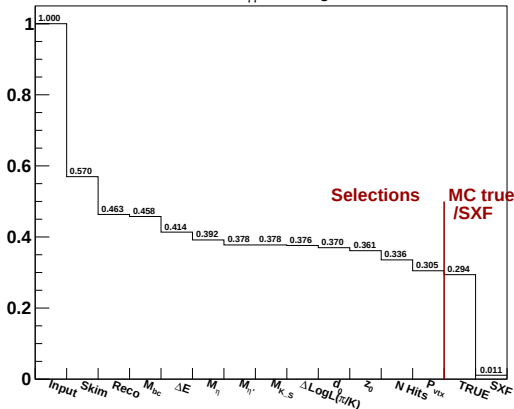
- $\text{P-value}_{\text{vtx}}(B_0, \eta', K_S^0) > 1 \cdot 10^{-5}$

if $N_{\text{cands}} > 1$, select candidate with highest $\text{P-value}_{\text{vtx}}(B_0, \eta', \eta, K_S^0)$

Selection breakdown

Events statistics

$$B^0 \rightarrow \eta'(\eta_{\gamma\gamma} \pi^+ \pi^-) K_S^0(\pi^+ \pi^-)$$



Combinatorics

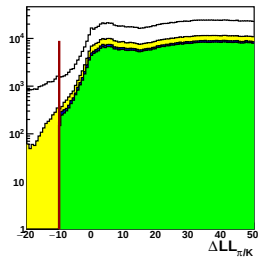
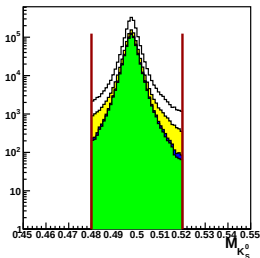
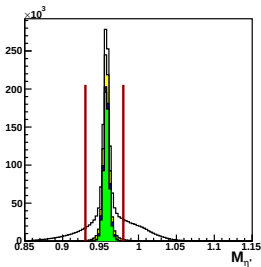
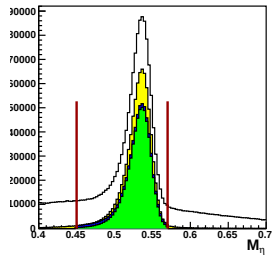
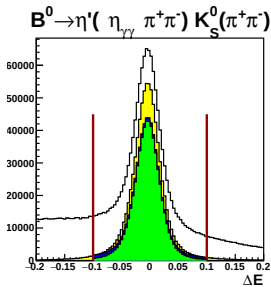
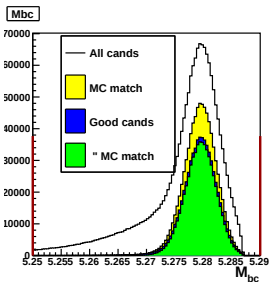
Cands mult.: 1.88

Good cands mult.: 1.06

Efficiency %

skim	57.0
preselection	46.1
good cands	30.5
MC true	29.4
SXF	1.1

Signal distribution $B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^{0+-}$



good candidate selection $B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^{0+-}$:

- Reconstruct decay chain with mass constrains for η , η' , K_S^0 ,

- vertex only (w/o mass) for B^0

■ π^0 :

- gamma:all: $0.06 < E_\gamma < 6 \text{ GeV}$,
 $-150 < \text{clus}_{time} < 0$, $E_9/E_{25} > 0.75$

- $M(\pi^0) \in [100, 150] \text{ MeV}$

■ $\eta \rightarrow \pi^+ \pi^- \pi^0$:

- pi:all
 - $\Delta \log \mathcal{L}(\pi, K) > -10$; new
 - $M(\eta_{3\pi}) \in [0.52, 0.57] \text{ GeV}$;
 - $d_0(\pi^\pm) < 0.08 \text{ mm}$;
 - $z_0(\pi^\pm) < 0.1 \text{ mm}$;
 - N hits_{PXD}($\pi^\pm$) > 1

■ $\eta' \rightarrow \eta_{3\pi} \pi^+ \pi^-$:

- $M(\eta') \in [0.93, 0.98] \text{ GeV}$;

■ $K^0 \rightarrow \pi^+ \pi^-$:

- K_S0:mdst
 - $M(K_S^0 \rightarrow \pi^+ \pi^-) \in [0.48, 0.52] \text{ GeV}$;

■ $B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^{0+-}$

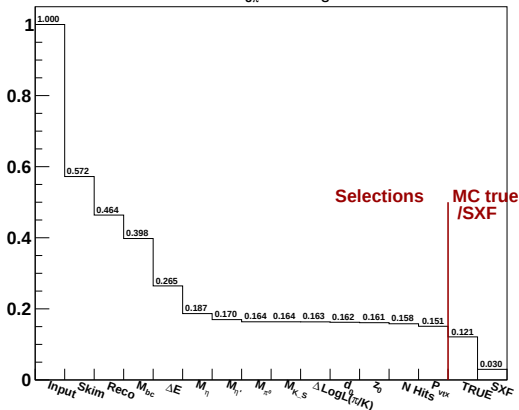
- $M_{bc} > 5.25 \text{ GeV}$;
 - $|\Delta E| < 0.15 \text{ GeV}$;
 - P-value_{vtx}(B_0, η', K_S^0) > $1 \cdot 10^{-5}$

if $N_{cands} > 1$, select candidate with highest P-value_{vtx}(B_0, η', η, K_S^0)

Selection breakdown

Events statistics

$$B^0 \rightarrow \eta'(\eta_{3\pi} \pi^+ \pi^-) K_S^0(\pi^+ \pi^-)$$



Combinatorics

Cands mult.: 21.5

Good cands mult.: 1.45

Efficiency %

skim 57.2

preselection 46.2

good cands **15.1**

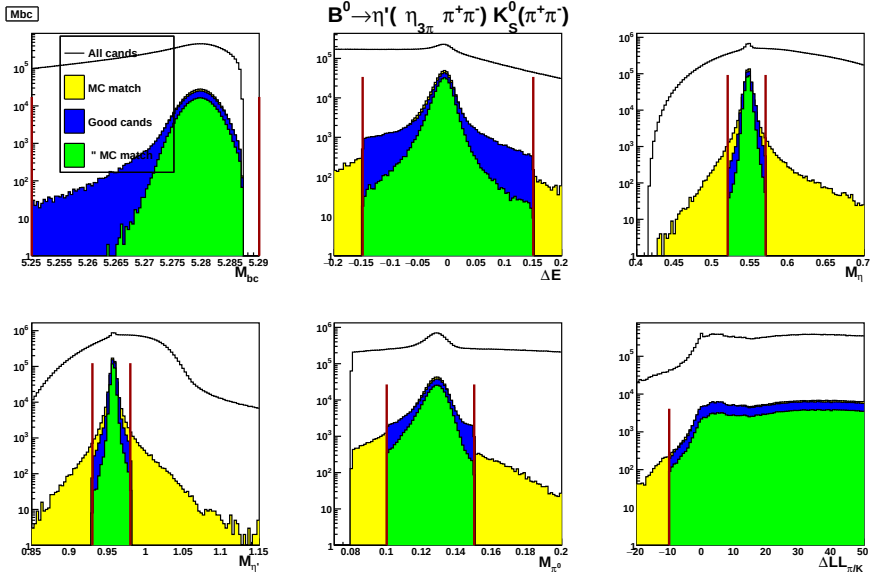
MC true 12.1

SXF 3.0

Reco eff is as good as $\eta_{\gamma\gamma}$ channel.

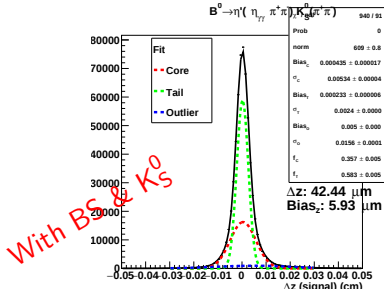
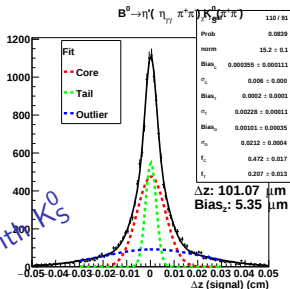
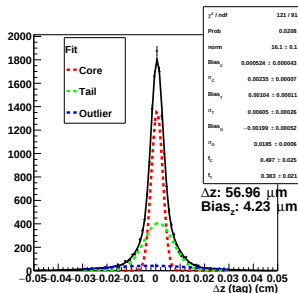
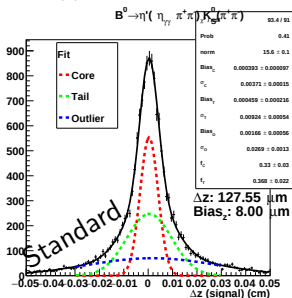
50% eff drop due to poor resolution on M_{bc} , ΔE , M_η all coming from π^0 reconstruction in $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay

Signal distribution $B^0 \rightarrow \eta'(\rightarrow \eta_{3\pi} \pi^+ \pi^-) K_S^{0+-}$



Vtx reco: signal and tag side

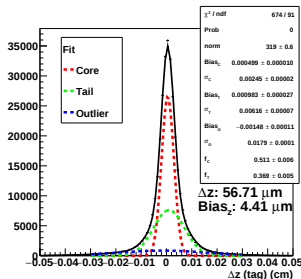
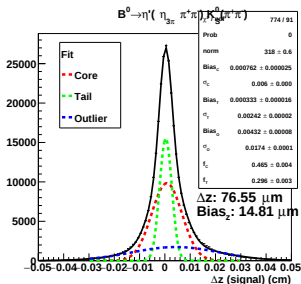
$$B^0 \rightarrow \eta'(\rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-) K_S^{0+-}$$



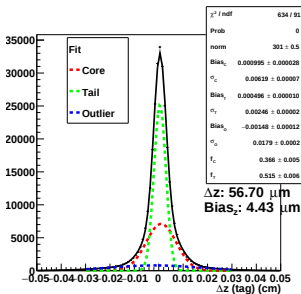
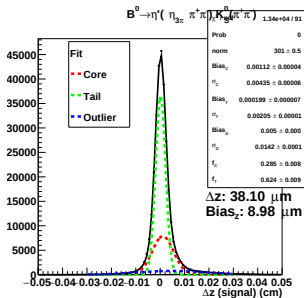
Vtx reco: signal and tag side

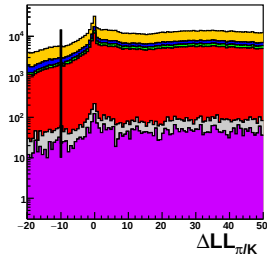
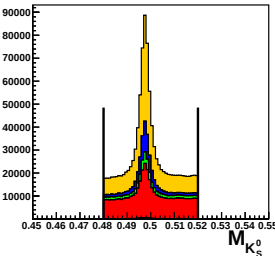
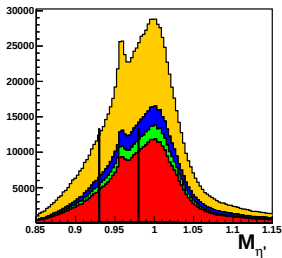
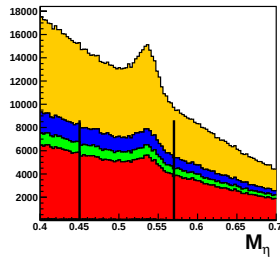
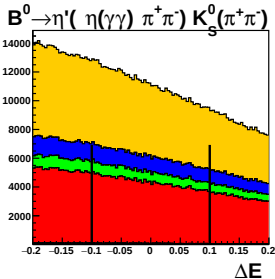
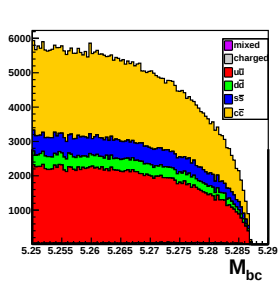
$$B^0 \rightarrow \eta'(\rightarrow \eta_3 \pi^+ \pi^-) K_S^{0+-}$$

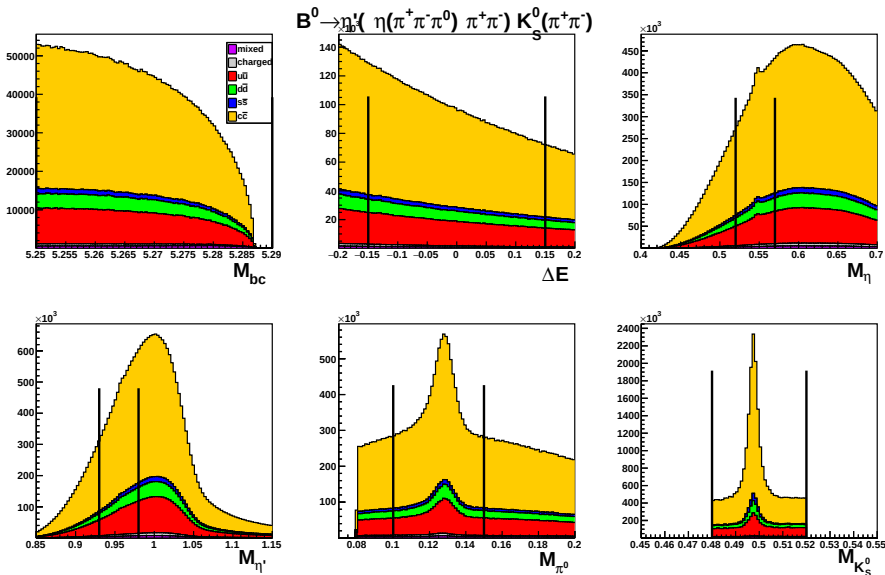
Standard



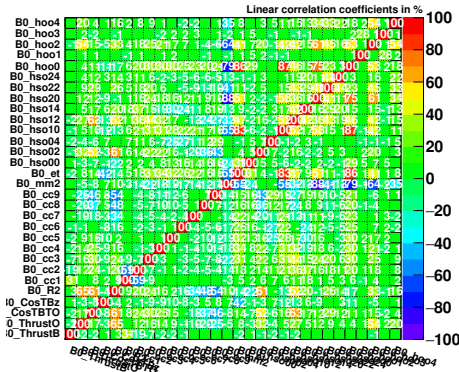
With BS & K_S⁰



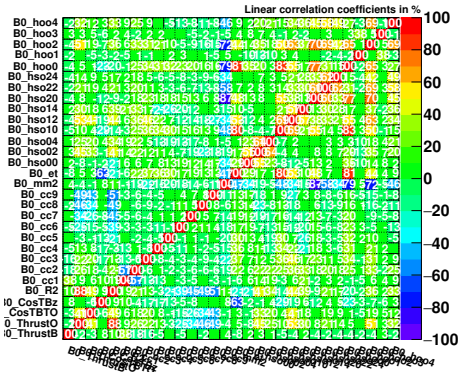




Correlation Matrix (signal)



Correlation Matrix (background)



	This analysis*			Belle ^[Belle(2014)]			BaBar ^[BABAR(2009)]		
mode	(340 M B $\bar{B}$)			(772 M B $\bar{B}$)			(467 M B $\bar{B}$)		
$\eta' \rightarrow \pi^\pm \eta$	N_{sig}	σ_S	σ_C	N_{sig}	σ_S	σ_C	N_{sig}	σ_C	σ_S
$\eta_{\gamma\gamma} K_S^{0+-}$	390	0.19	0.11	648	0.15	0.098	472	0.17	0.11
$\eta_{\gamma\gamma} K_S^{000}$	Just started			104	0.21 [†]	0.18 [†]	105	0.34	0.30
$\eta_{3\pi} K_S^{0+-}$	106	0.33	0.25	174	0.26	0.18	171	0.26	0.20
$\eta_{3\pi} K_S^{000}$	Will try			Not used					
$\eta' \rightarrow \rho^0 \gamma K_S^{0+-}$	Not yet			1411	0.098	0.069	1005	0.12	0.09
$\eta' \rightarrow \rho^0 \gamma K_S^{000}$	Not yet			162	0.21 [†]	0.18 [†]	206	0.33	0.26

*Very preliminary estimate based on toy MC, $L = 300 \text{ fb}^{-1}$

Warning: no machine background yet

[†]Results combining $\eta' \rightarrow \pi^\pm \eta_{\gamma\gamma}$ and $\eta' \rightarrow \rho^0 \gamma$

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- [CLEO(1998)] CLEO. Observation of high momentum η' production in B decays. *PRL*, 81:1786, 1998. doi: 10.1103/PhysRevLett.81.1786. URL <http://link.aps.org/doi/10.1103/PhysRevLett.81.1786>.
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- [Belle(2007)] Belle. Observation of time-dependent cp violation in $B^0 \rightarrow \eta' K^0$ decays and improved measurements of cp asymmetries in $B^0 \rightarrow \varphi K^0$, $K_S^0 K_S^0 K_S^0$ and $B^0 \rightarrow j/\psi K^0$ decays. *PRL*, 98:031802, 2007. doi: 10.1103/PhysRevLett.98.031802. URL <http://link.aps.org/doi/10.1103/PhysRevLett.98.031802>.