$B^0 \to \eta'(\to \eta\pi^+\pi^-)K^0_S$ Time Dependent $\not{CP}$ sensitivity study for BelleII

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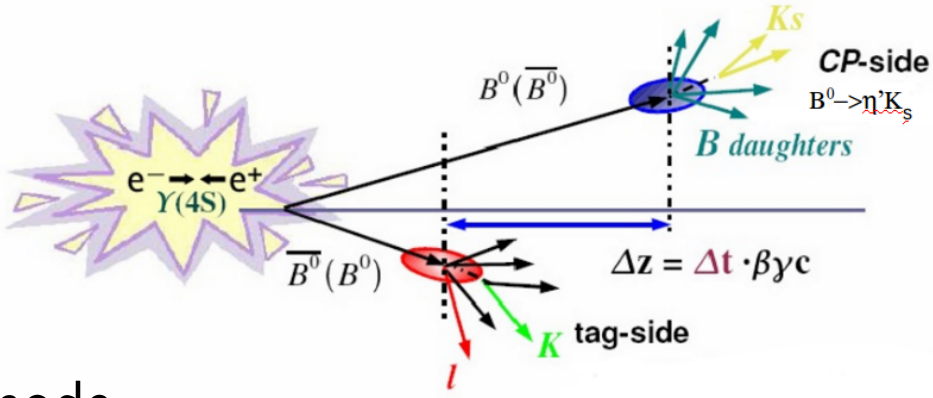
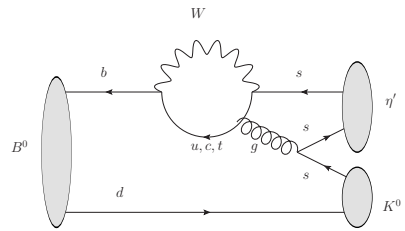
Introduction and motivations

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

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

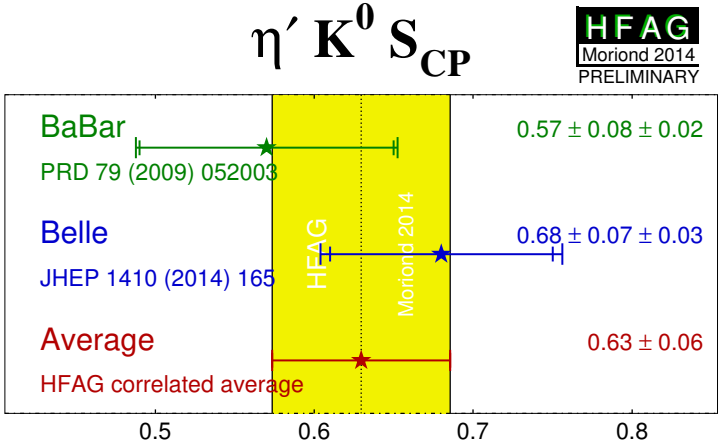


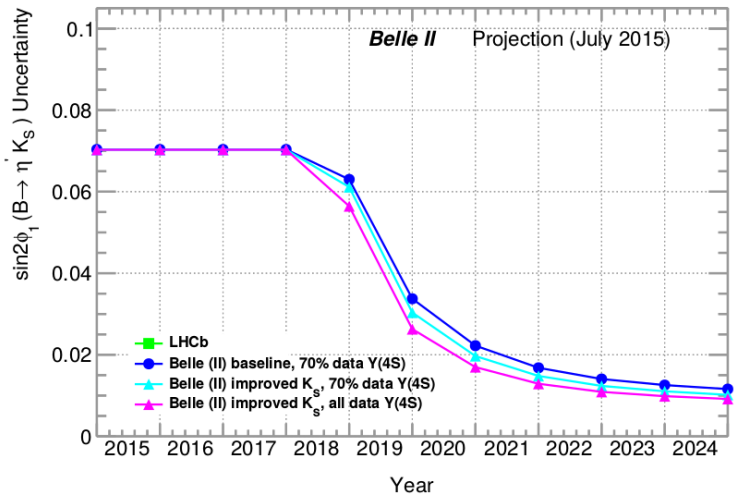
- $B^0 \to \eta' K^0$ is a penguin dominated mode
- Precision not competitive with that from golden channel $B^0 \to J/\psi\phi$
- $S_{\eta' K^0} = \sin 2\phi_1^{eff}$ tightly related to $\sin 2\phi_1$ measured in $b \to cs\bar{s}$ decay
- identical if only penguin diagram were present: not so;
  - QCD 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 ($\sim$ 3500 events for all final states);
  - syst: ± 0.025 from Δt resolution, ± 0.014 from vertexing, ± 0.013 from $\eta' K^0_S$ fraction;





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

Decay channels

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

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

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

Selection

candidate selection: main cuts

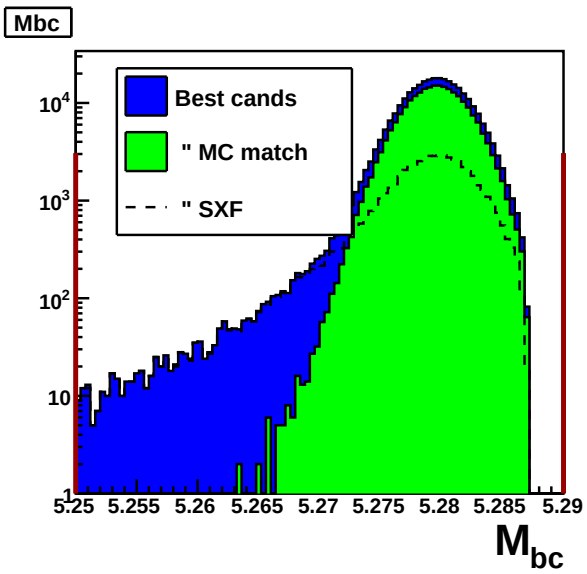
- Reconstruct decay chain with mass constrains for π^0, η, η', K^0_S,
  - vertex only (w/o mass) for B^0 (more later)

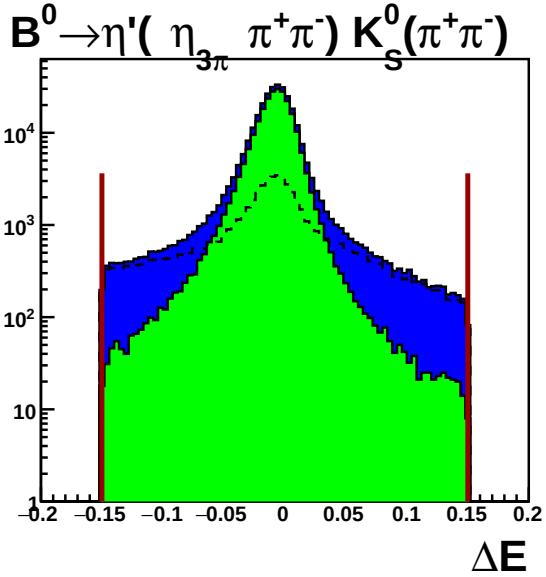
- π^0, $\eta_{\gamma\gamma}$:
  - $0.06 < E_\gamma < 6\,\text{GeV}$, $E_9/E_{25} > 0.75$
  - $M(\pi^0) \in [100, 150]\,\text{MeV}$
  - $M(\eta_{\gamma\gamma}) \in [0.52, 0.57]\,\text{GeV}$;
- $\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-$:
  - $d_0(\pi^\pm) < 0.08\text{mm}$; $z_0(\pi^\pm) < 0.1\text{mm}$;
  - N hits$_{PXD}(\pi^\pm) > 1$, PID
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
- $\eta' \to \eta_{3\pi}\pi^+\pi^-$:
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
- $K^0 \to \pi^+\pi^-$:
  - $M(K^0_S \to \pi^+\pi^-) \in [0.48, 0.52]\,\text{GeV}$;
- $B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\,\pi^-)K^{0+-}_S$
  - $M_{bc} > 5.25\,\text{GeV}$;
  - $|\Delta E| < 0.1\,\text{GeV}$;
- $B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K^{0+-}_S$
  - $|\Delta E| < 0.15\,\text{GeV}$;

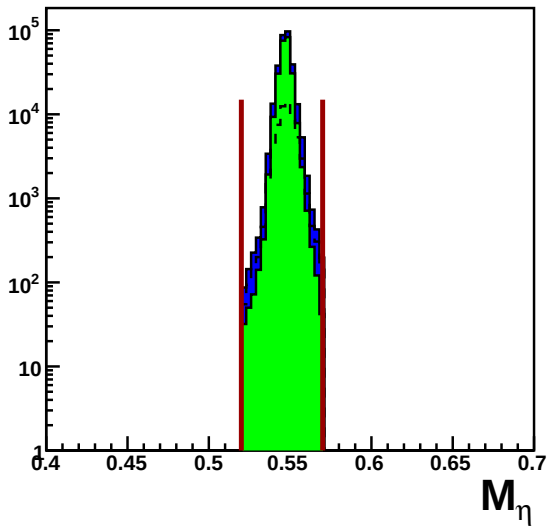
if $N_{cands} > 1$, select that with best reduced χ^2 for η, η', K^0_S inv. masses

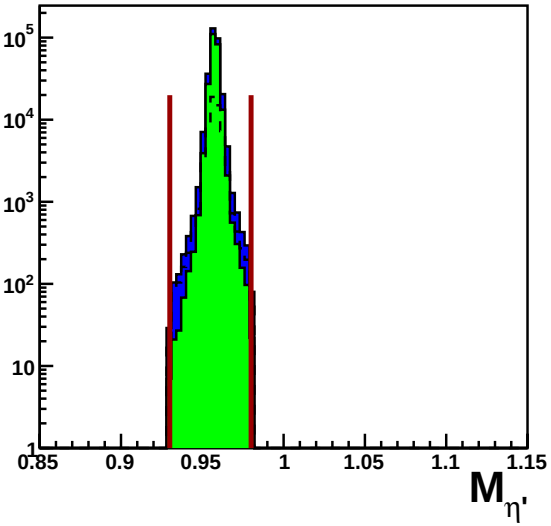
Signal distribution $B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_S^{0+-}$

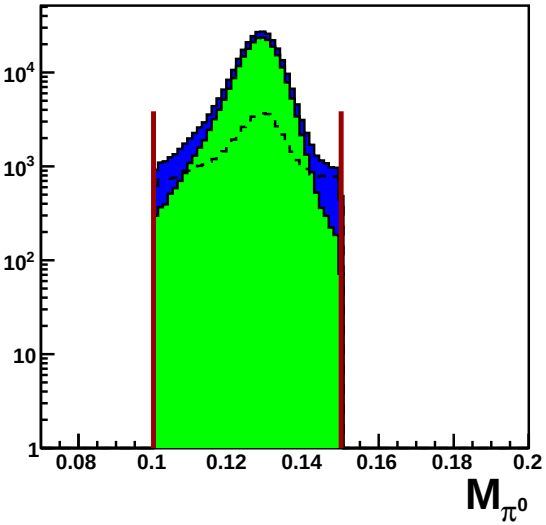
Best candidates, after selections

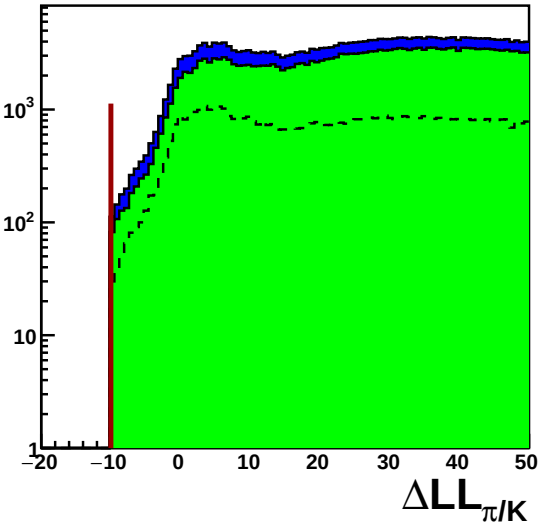












Efficiency and combinatorics

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

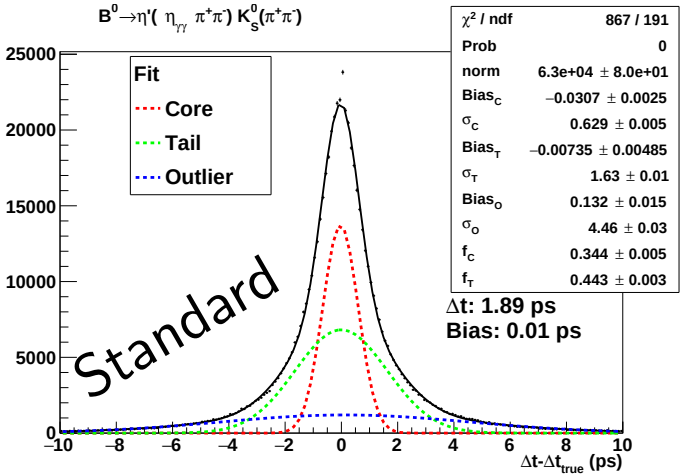
- Efficiency drop due to π^0 reco, likely to improve;
- presence of π^0 increase also combinatorics and signal cross feed

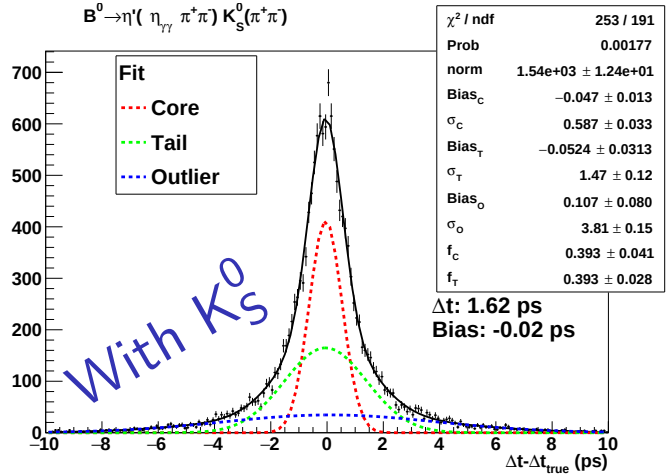
SxF : signal event but with wrong particle association;

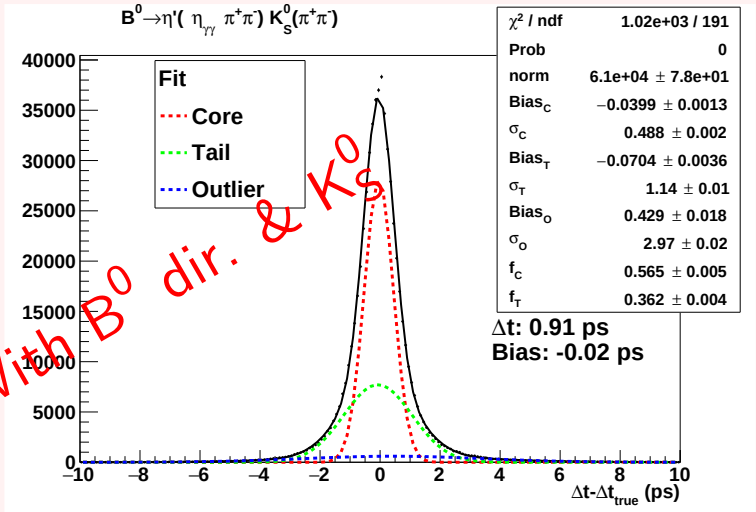
- $B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K^0_S(\to \pi^0\pi^0)$ not used in Belle and BaBar analysis.

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

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







With beamspot (x, y) & K^0_S:

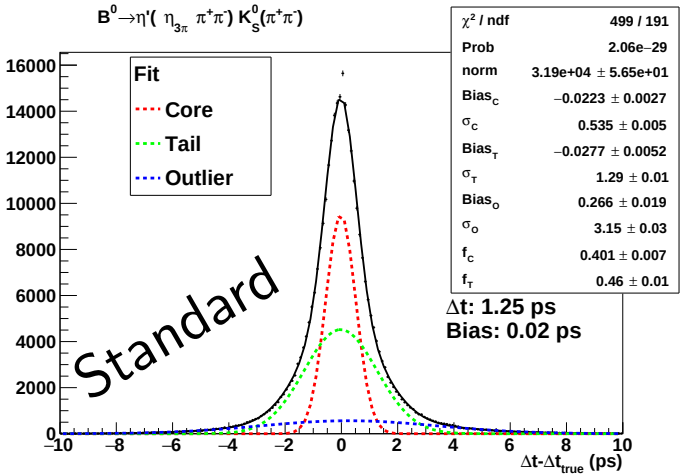
No efficiency loss

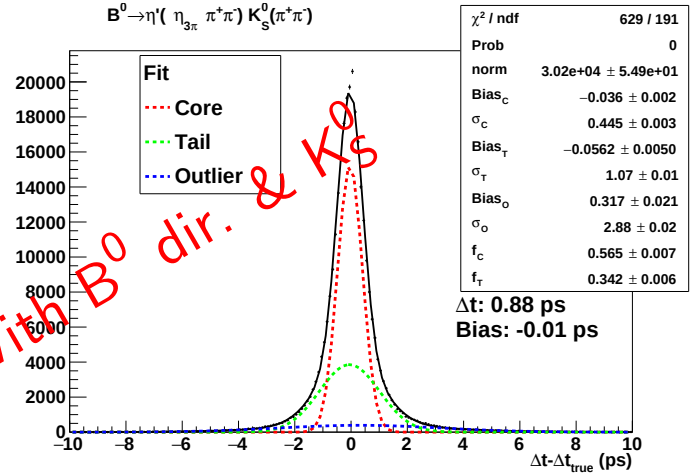
important improvement in Δt resolution

$1.89 \to 1.62 \to 0.91$ *ps*

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

Standard reconstruction uses four charged tracks:
$\pi^\pm$ from $\eta' \to \eta\pi^\pm$ and $\eta \to \pi^\pm\pi^0$





With B^0 dir. & K_S^0:

No efficiency loss

$1.25 \to 0.88$ *ps*

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

Backgrounds

- **Combinatorial**: from continuum background $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$
  - 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)
    - ★ past issues w/ variables "fixed"
- **Peaking**: any other B decays possibly with real η' and/or K^0_S
  - evaluated from MC of generic $B^0\overline{B}^0$, B^+B^-
    - ★ actual $B^0 \to \eta' K^0$ removed.
- Current results based on BGx0 production, namely w/o machine background
  - impact of machine background under study
  - signal w/ machine background already produced
- Next table numbers before Continuum Suppression cut

Background reduction (before CS cut)

Sample	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	contiuum	$B^0\overline{B}^0$	B^+B^-
Input ev (M)	1284	321	306	1063	2974	2160	2070
$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_S^{0+-}$							
ϵ_{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	13	6
$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_S^{0+-}$							
ϵ_{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 $\eta_{\gamma\gamma}$

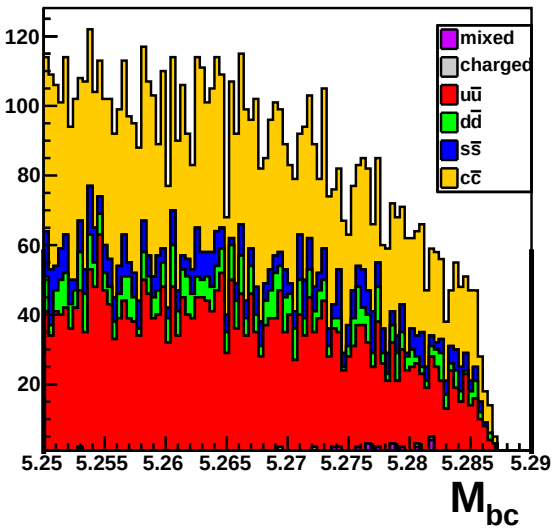
$\eta_{\gamma\gamma}$ mostly $u\bar{u}$ and $c\bar{c}$

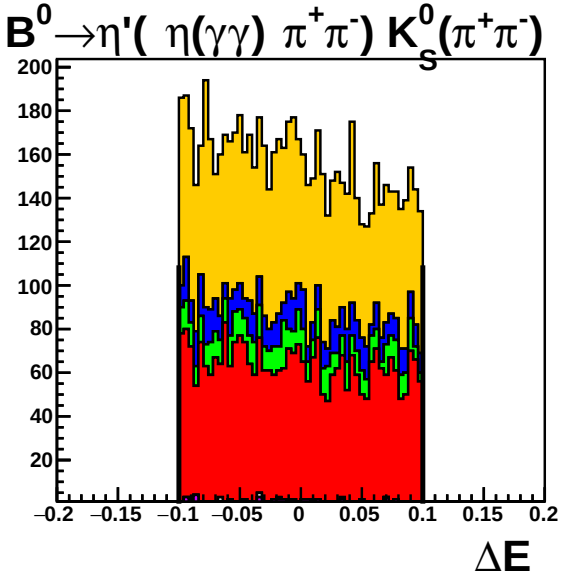
$\eta_{3\pi}$ mostly $c\bar{c}$

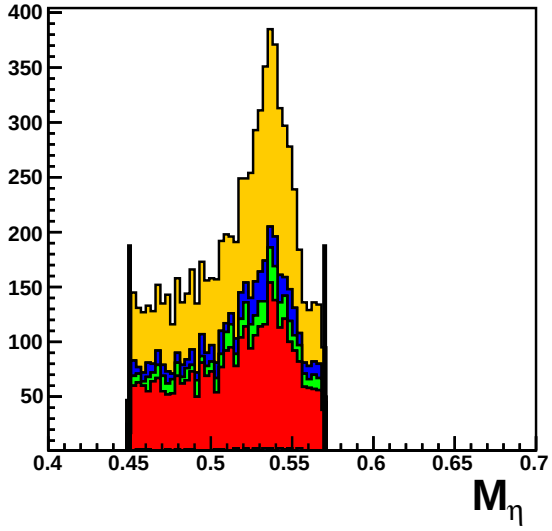
- peaking background is small
  - analyzed whole 5 ab^{-1} dataset from MC5
- preliminary study on w/ machine background shows similar rates

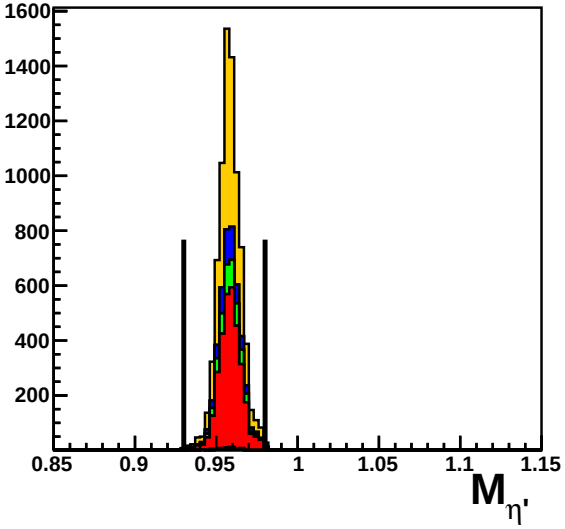
Background distributions

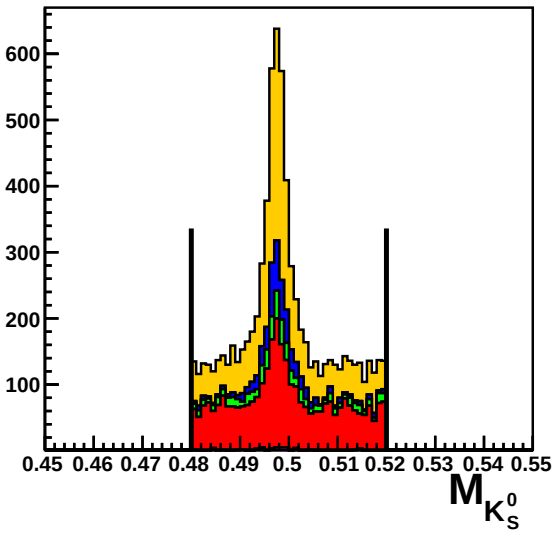
Best candidates, after selections

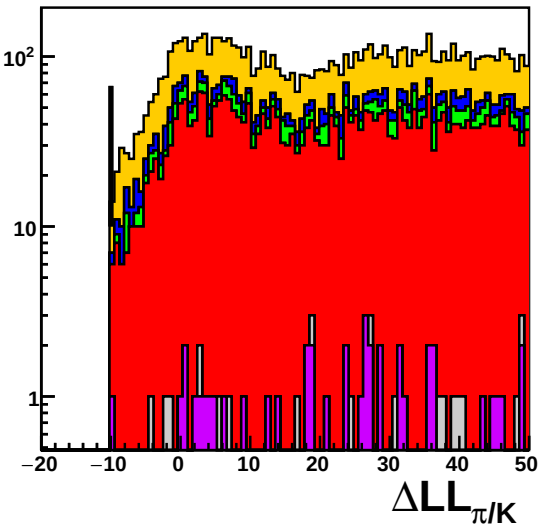




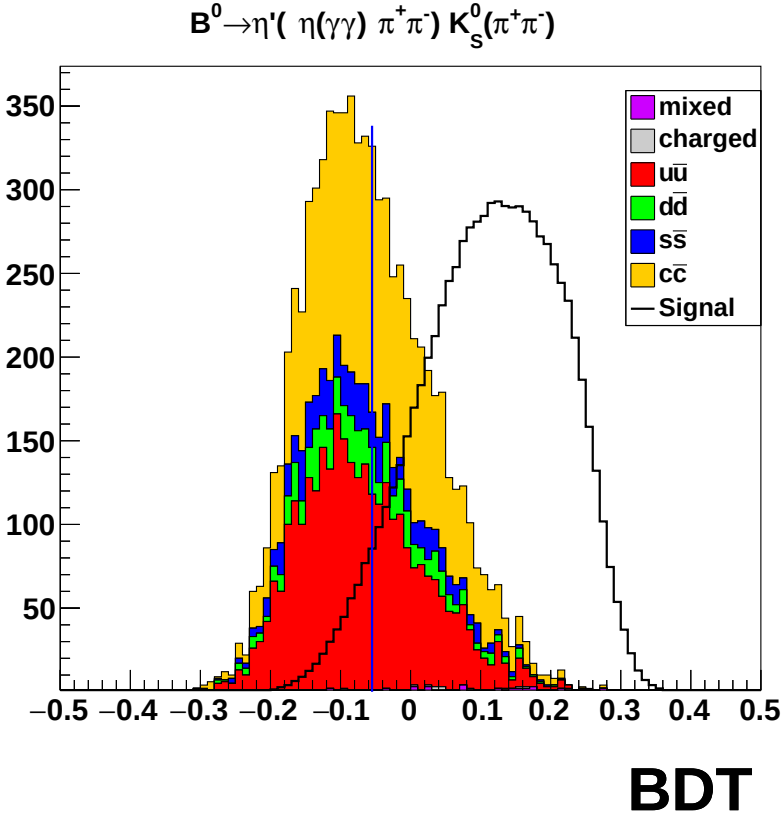


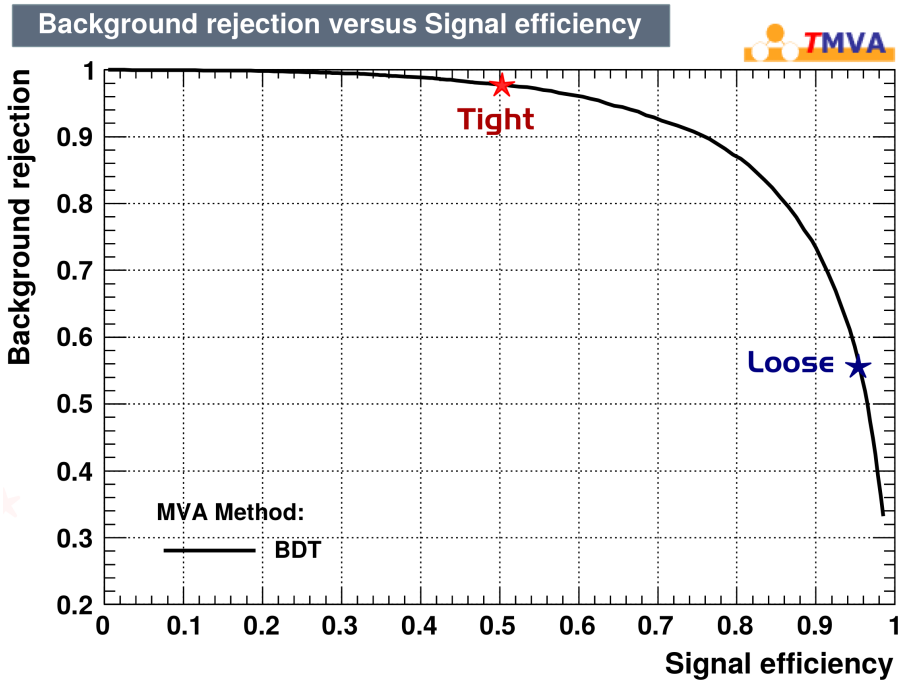






Continuum suppression





Working point

- **Tight**: $BDT > 0.124$, $\epsilon_{signal} = 50\%$, $(1 - \epsilon_{background}) = 97.5\%$,
- **Loose**: $BDT > -0.055$, $\epsilon_{signal} = 95\%$, $(1 - \epsilon_{background}) = 58\%$,
- **no cut**: include the BDT in the likelihood

Likelihood fit

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):

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

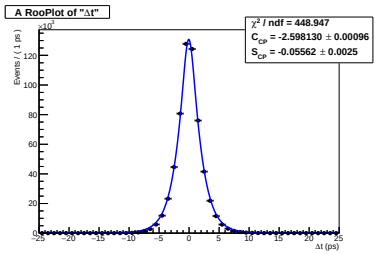
variables (x_k) used, in addition to Δt

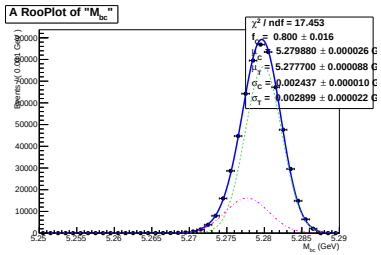
- M_{bc}
- ΔE
- Cont. Suppr.

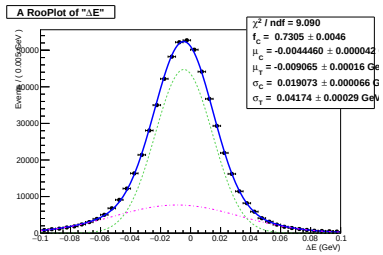
Parameters:

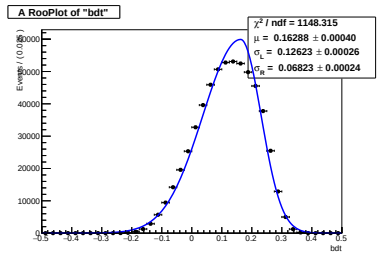
- effective tagging efficiency: $Q = \epsilon(1-2w)^2 = 0.33$
  - $w = 0.21$, $\Delta w = 0.02$
- Δt resolution as shown previously (convoluted)
- τ, Δm from PDG

PDF fit results examples

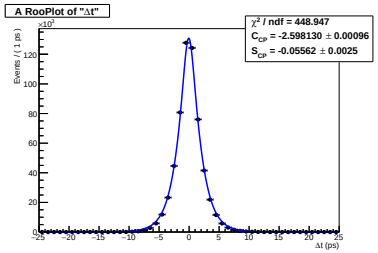


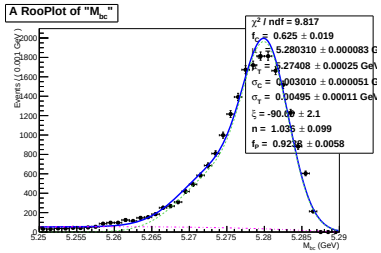


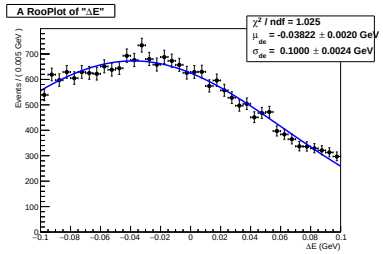


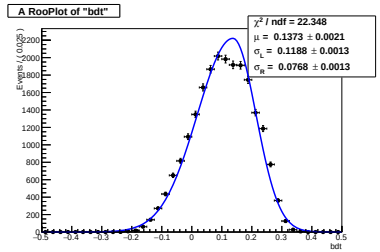


Signal

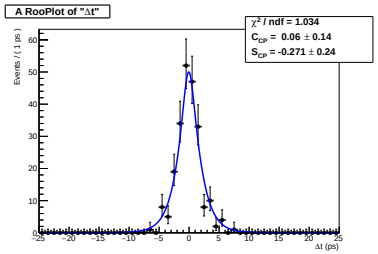


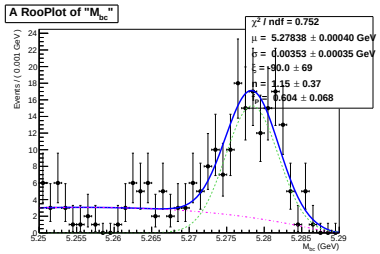


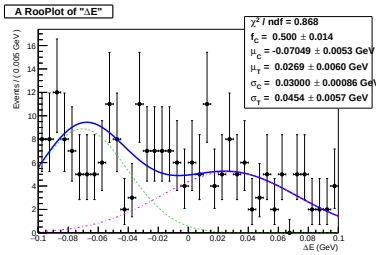


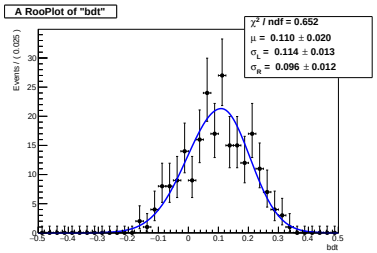


SxF

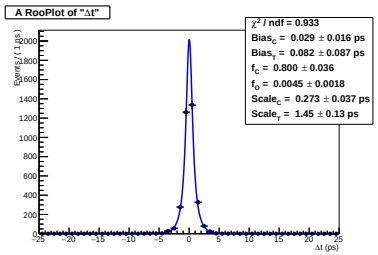


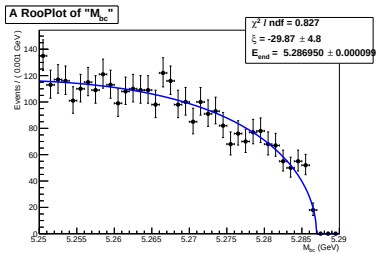


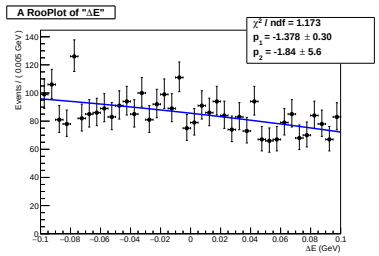


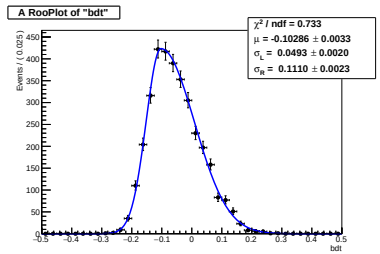


Peaking bkgnd









Continuum

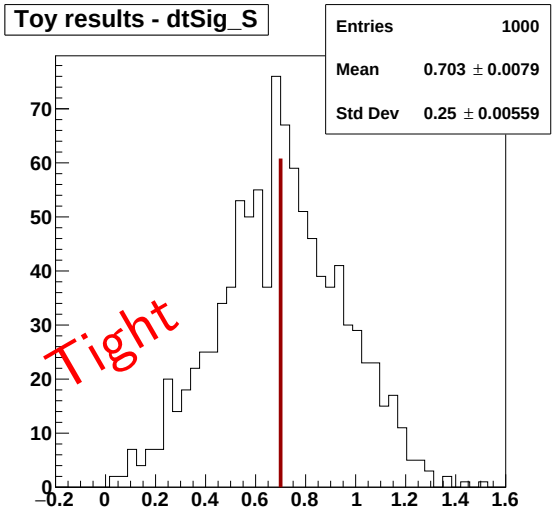
ΔT M_{bc} ΔE CS variable

Toy MC

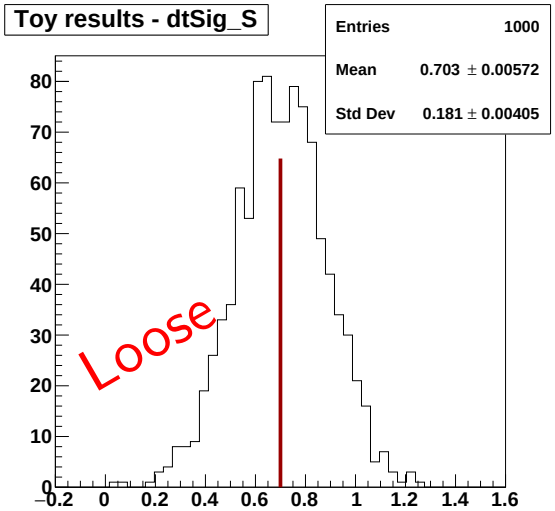
- Testing fit machinery with Toy MC;
- Yield estimated for $L = 300\ \text{fb}^{-1}$: $N(\text{B}\overline{\text{B}}) \sim 330 \cdot 10^6$
  - width of distribution related to the expected statistical uncertainty;
  - check also for bias;
  - input CP asymmetry parameter: S=0.7 C=0.0
  - testing two different CS scenarios:
    - ★ Tight
    - ★ Loose
    - ★ No cut
  - Partially embedded toys
    - ★ Signal and SXF from MC;
    - ★ Continuum and Peaking background from pdf;

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

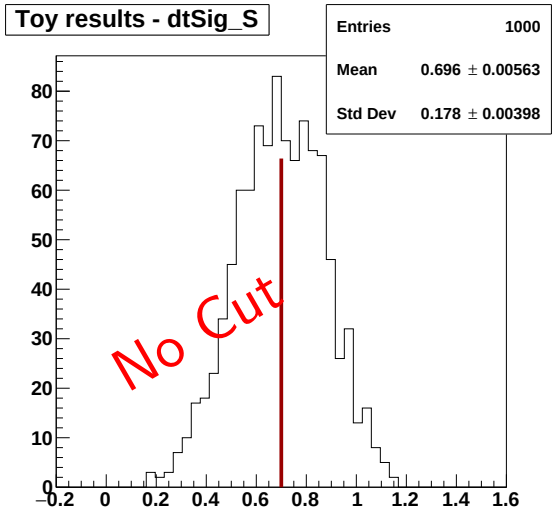
$L = 300\,\text{fb}^{-1}$: $N_{sig} = 390$, $N_{sxf} = 15$, $N_{cont} = 3300$, $N_{peak} = 30$



$\sigma_S = 0.26$



$= 0.181$



$= 0.178$

Preliminary results

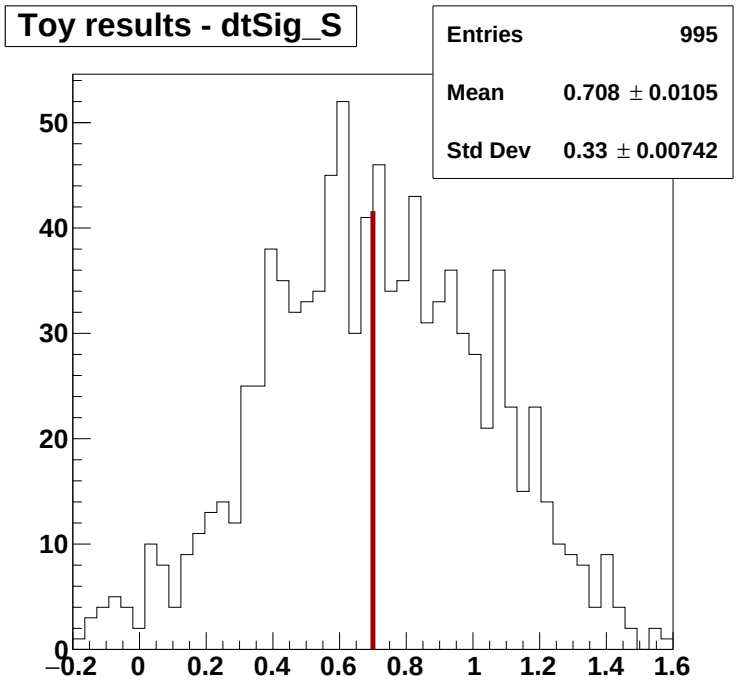
Par	Bias	RMS
S (0.7)	0.696 ± 0.005	0.178
C (0.0)	0.005 ± 0.004	0.13
nSig	390.7 ± 0.8	24.7

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

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

Toy results $B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_S^{0+-}$ Loose

$L = 300\,\text{fb}^{-1}$: $N_{sig} = 106$, $N_{sxf} = 25$, $N_{cont} = 360$, $N_{peak} = 27$



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

Less events due to lower BR and reduced efficiency

Belle[1] ($772 \cdot 10^6$ $B\overline{B}$): $N_{sig} = 104$, $\sigma_S = 0.21$, $\sigma_C = 0.18$

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

[1] including also $\eta' \to \rho^0\gamma$

Summary

- Almost a complete analysis chain for sensitivity study for ~~CP~~ in $B^0 \to \eta' K^0_S$ channel;
- Presente at last B2TIP workshop;
- preliminary results are encouraging;
  - comparison with Belle and BaBar results looks fine;
- many thing to do:
  - include machine background (in progress)
  - complete $K^0_S \to \pi^+\pi^-$ channels;
  - study $K^0_S \to \pi^0\pi^0$ final states;
  - add $\eta' \to \rho^0\gamma K^{0\,+-}_S / K^{0\,00}_S$ channel;
  - systematics uncertainties evaluation;
  - documentation
  - ...
- manpower: a new postDoc student from Padova, **Alessandro Mordà**, is joining me for this work at $\sim 50\%$

Additional stuff

Additional or backup slides

Selection

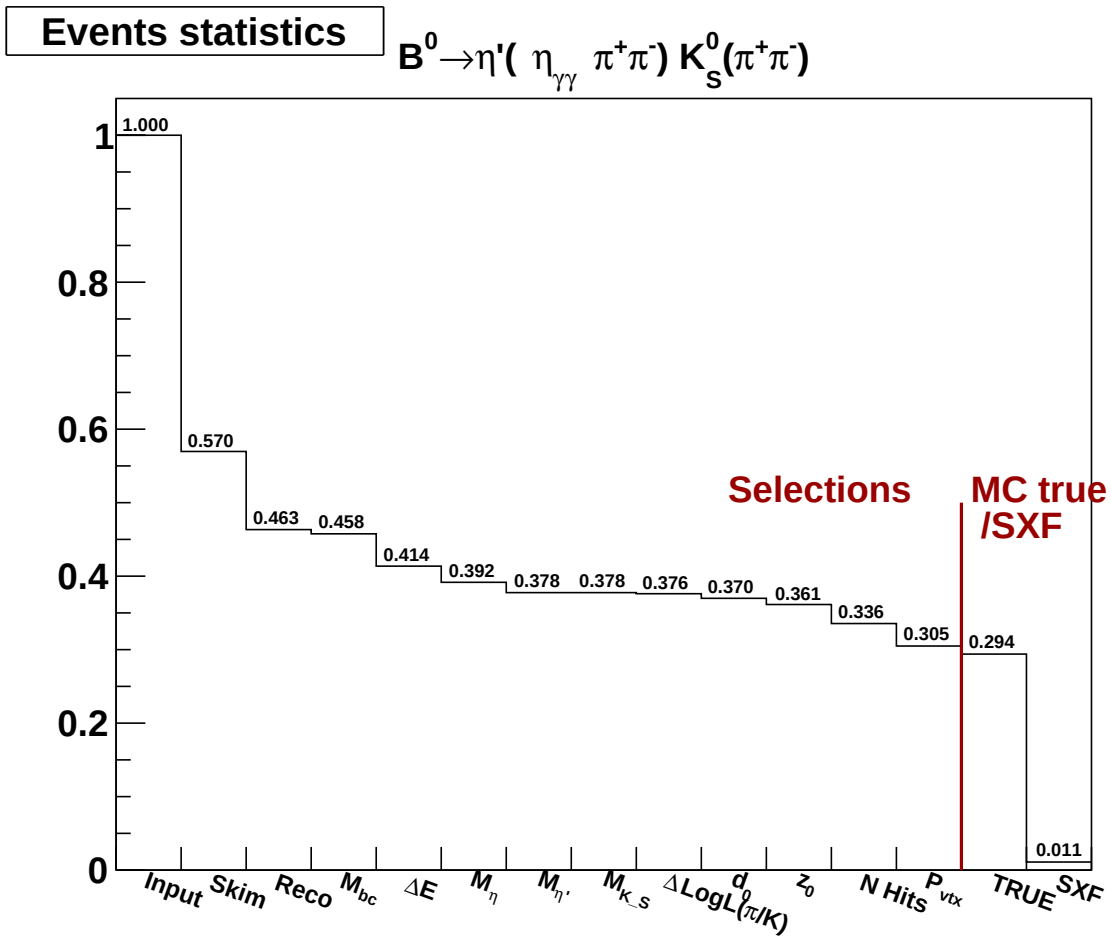
good candidate selection $B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\,\pi^-)K_S^{0+-}$:

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

- $\eta \to \gamma\gamma$:
  - `gamma:all`: $0.06 < E_\gamma < 6\,\text{GeV}$, $-150 < clus_{time} < 0$, $E_9/E_{25} > 0.75$
  - $M(\eta_{\gamma\gamma}) \in [0.52, 0.57]\,\text{GeV}$;
- $\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-$:
  - `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 hits$_{PXD}(\pi^\pm) > 1$
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
- $K^0 \to \pi^+\pi^-$:
  - `K_S0:mdst`
  - $M(K_S^0 \to \pi^+\pi^-) \in [0.48, 0.52]\,\text{GeV}$;
- $B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\,\pi^-)K_S^{0+-}$
  - $M_{bc} > 5.25\,\text{GeV}$;
  - $|\Delta E| < 0.1\,\text{GeV}$;
  - P-value$_{vtx}(B_0, \eta', K_S^0) > 1 \cdot 10^{-5}$

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

Selection breakdonw



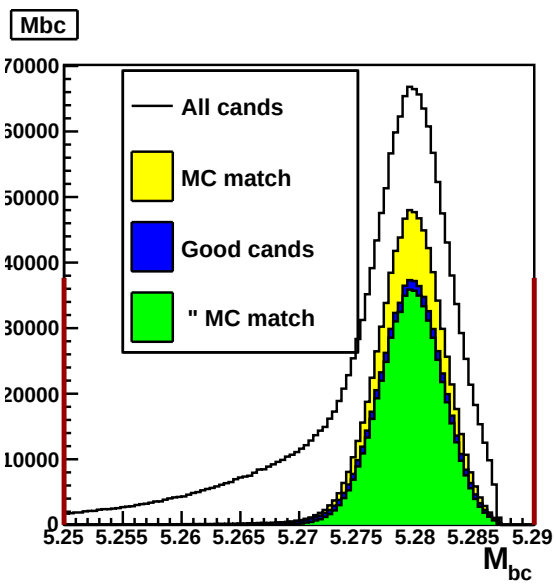
Combinatorics

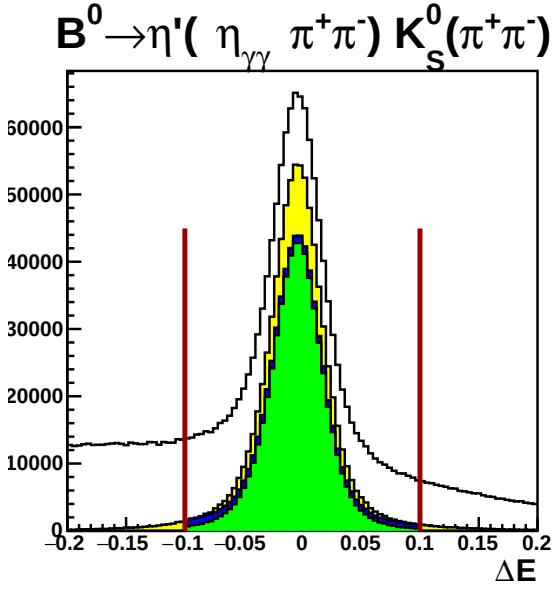
Cands mult.: 1.88

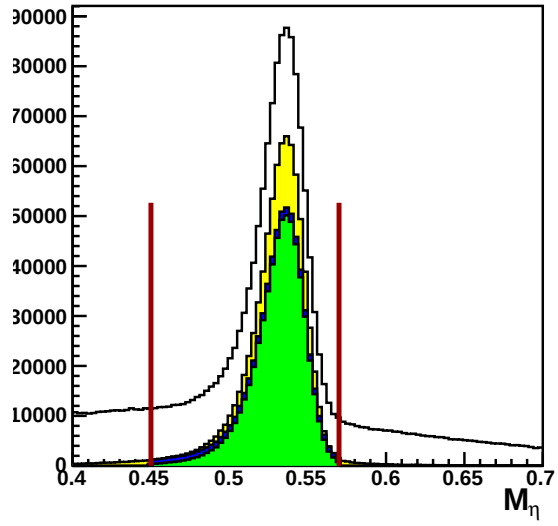
Good cands mult.: 1.06

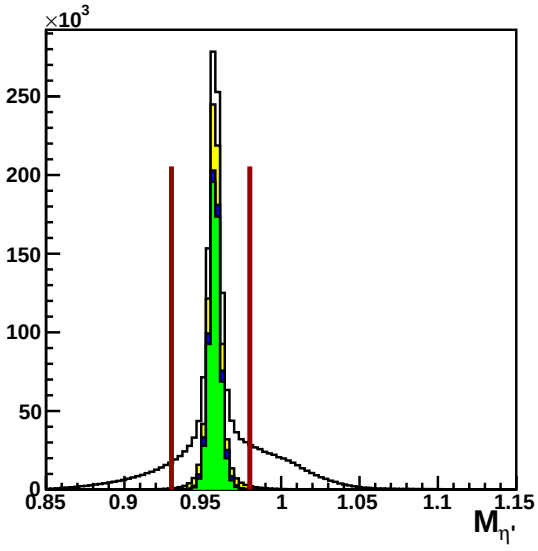
Efficiency %	
skim	57.0
preselection	46.1
good cands	30.5
MC true	29.4
SXF	1.1

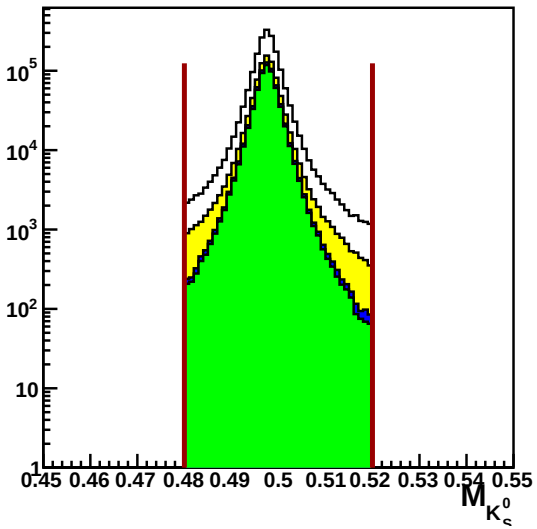
Signal distribution $B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_S^{0+-}$

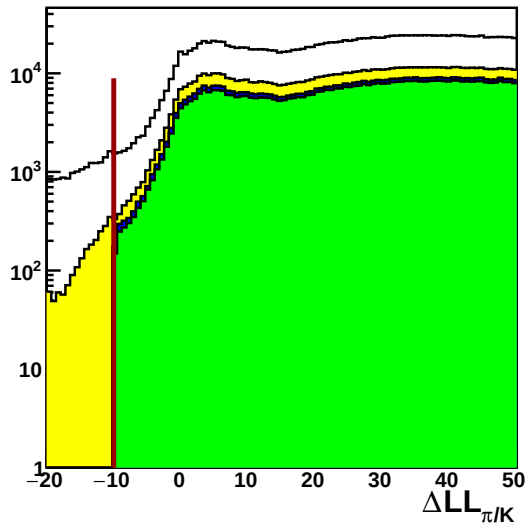






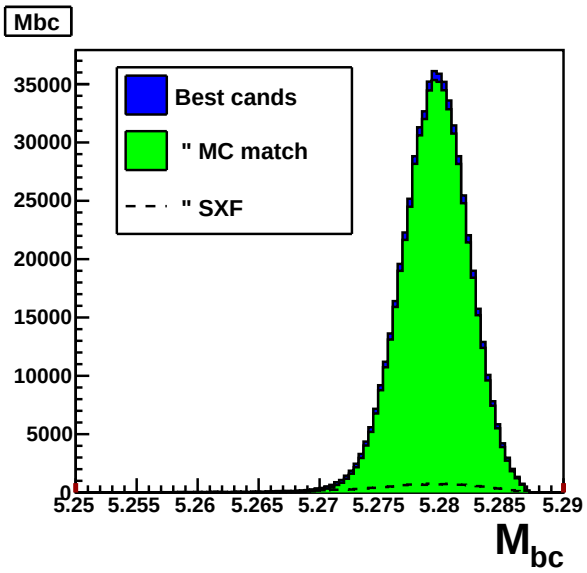


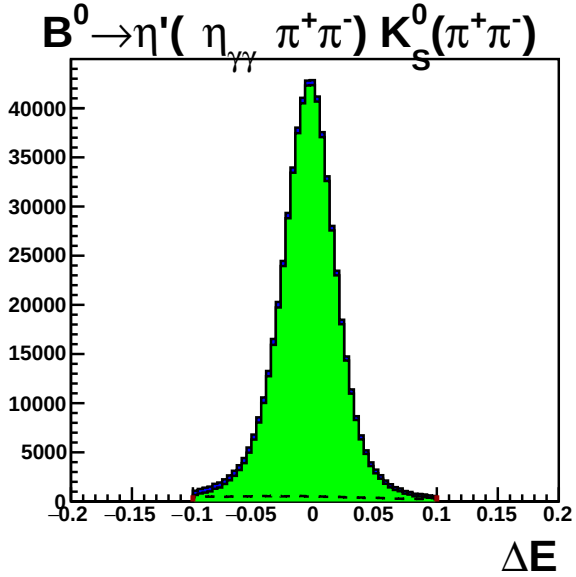


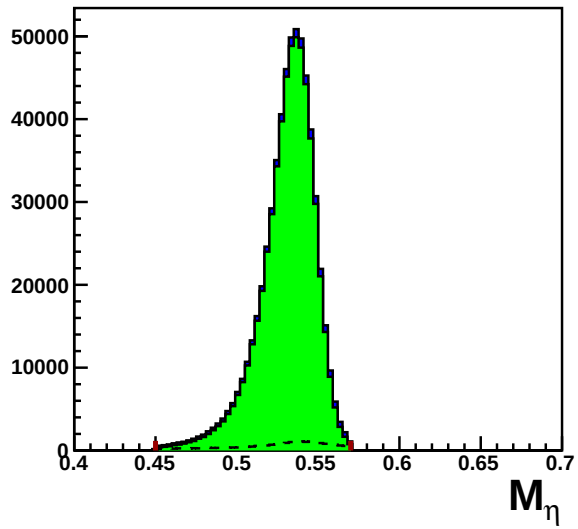


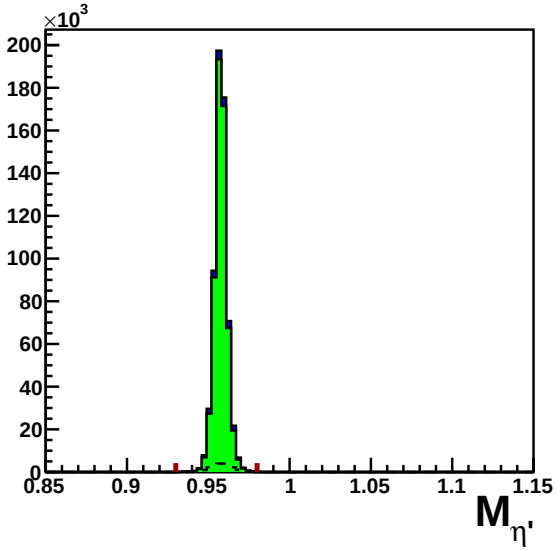
Signal distribution $B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_S^{0+-}$

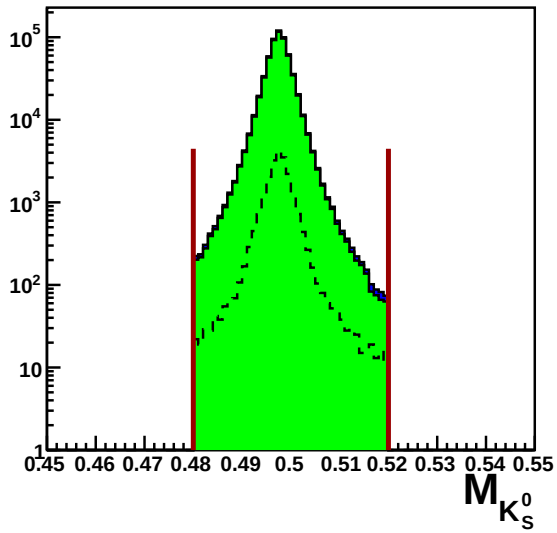
Best candidates, after selections

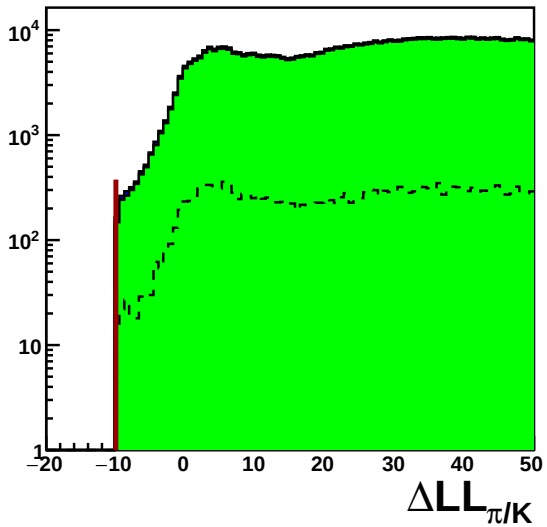












Selection

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

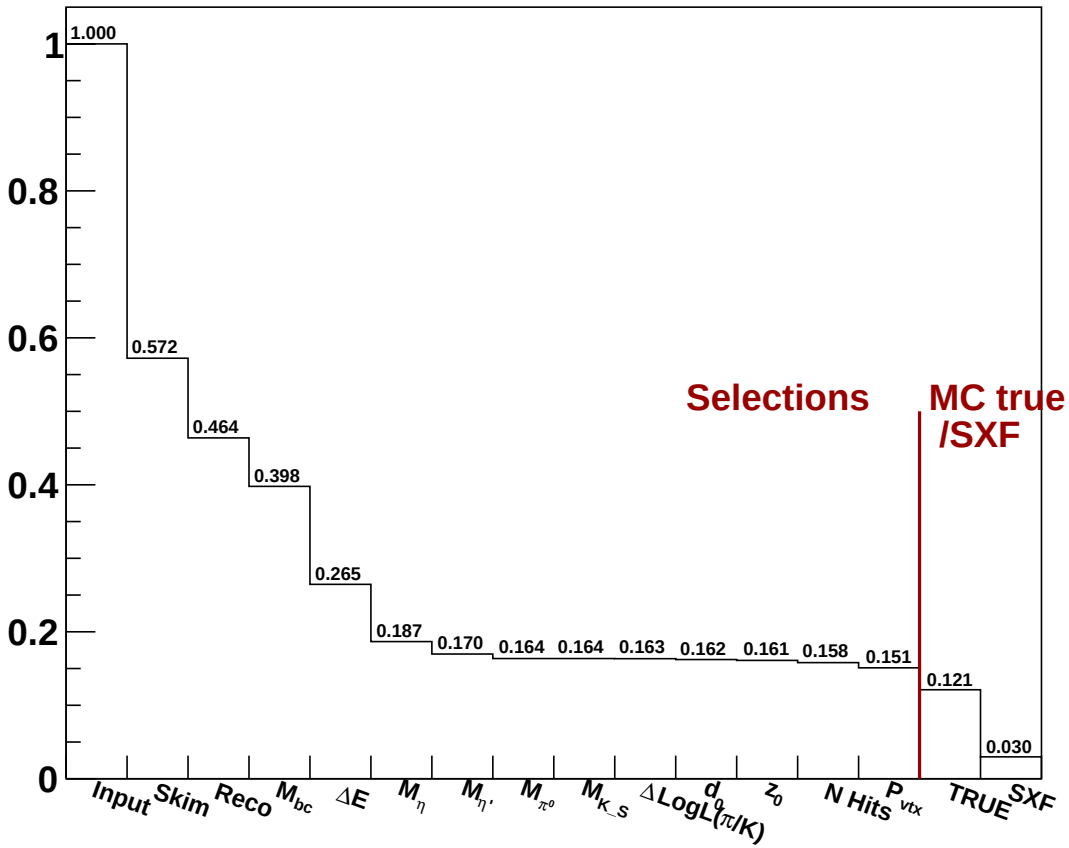
- Reconstruct decay chain with mass constrains for η, η', K_S^0,
  - vertex only (w/o mass) for B^0

- π^0:
  - `gamma:all`: $0.06 < E_\gamma < 6\,\text{GeV}$, $-150 < clus_{time} < 0$, $E_9/E_{25} > 0.75$
  - $M(\pi^0) \in [100, 150]\,\text{MeV}$
- $\eta \to \pi^+\pi^-\pi^0$:
  - `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$_{PXD}(\pi^\pm) > 1$
- $\eta' \to \eta_{3\pi}\pi^+\pi^-$:
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
- $K^0 \to \pi^+\pi^-$:
  - `K_S0:mdst`
  - $M(K_S^0 \to \pi^+\pi^-) \in [0.48, 0.52]\,\text{GeV}$;
- $B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_S^{0+-}$
  - $M_{bc} > 5.25\,\text{GeV}$;
  - $|\Delta E| < 0.15\,\text{GeV}$;
  - P-value$_{vtx}(B_0, \eta', K_S^0) > 1 \cdot 10^{-5}$

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

Selection breakdonw

Events statistics $B^0 \to \eta'(\eta_{3\pi}\ \pi^+\pi^-)\ K^0_S(\pi^+\pi^-)$



Combinatorics

Cands mult.: 21.5

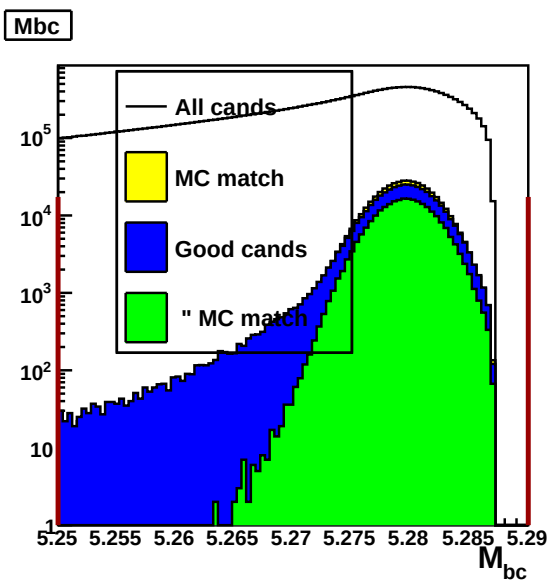
Good cands mult.: 1.45

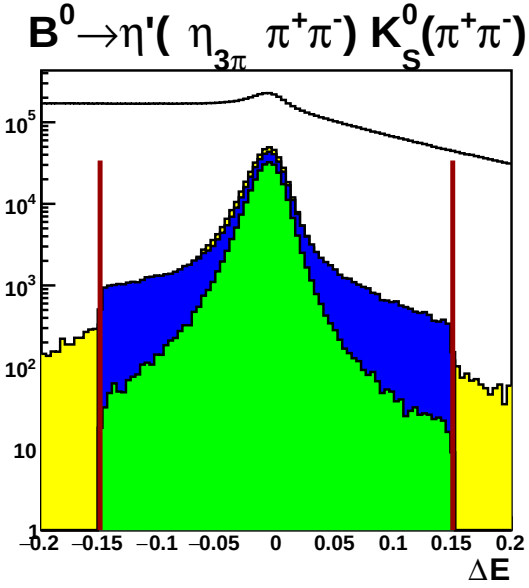
Efficiency %	
skim	57.2
preselection	46.2
good cands	**15.1**
MC true	12.1
SXF	3.0

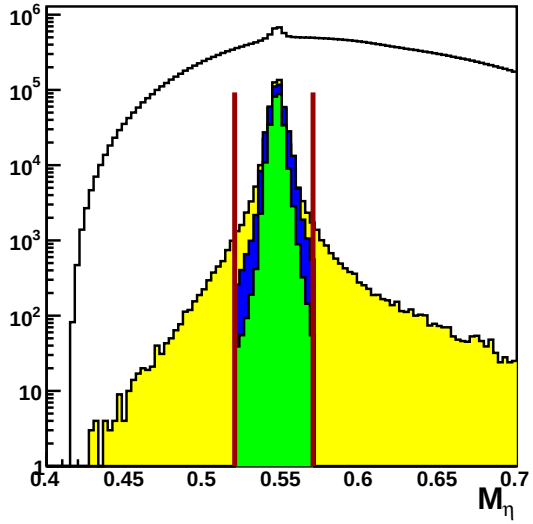
Reco eff is as good as $\eta_{\gamma\gamma}$ channel.

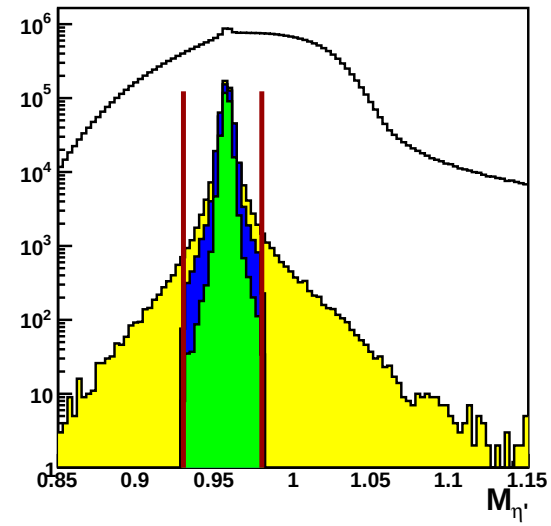
50% eff drop due to poor resolution on M_{bc}, ΔE, M_η all coming from π^0 reconstruction in $\eta \to \pi^+\pi^-\pi^0$ decay

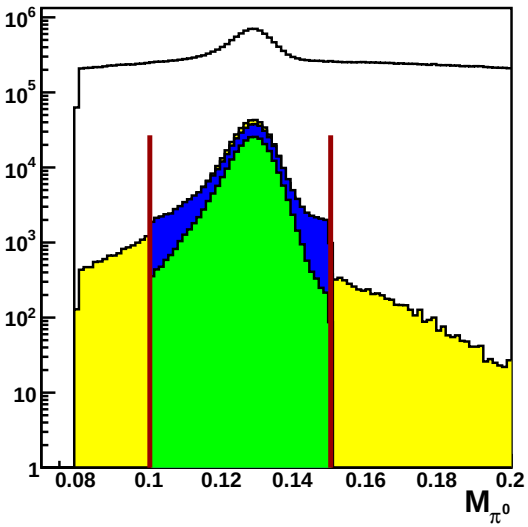
Signal distribution $B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_S^{0\,+-}$

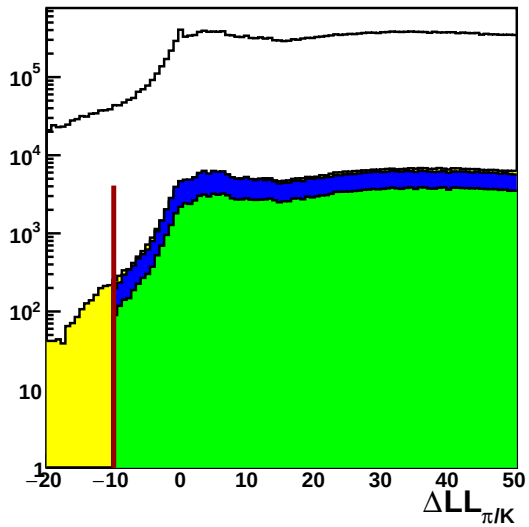






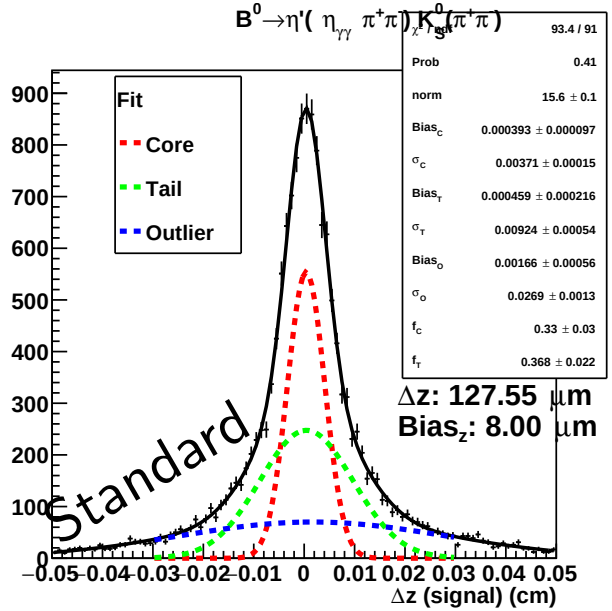


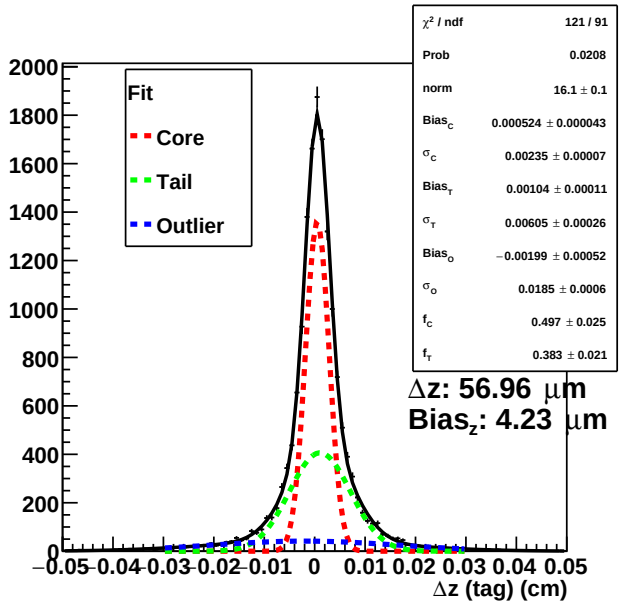


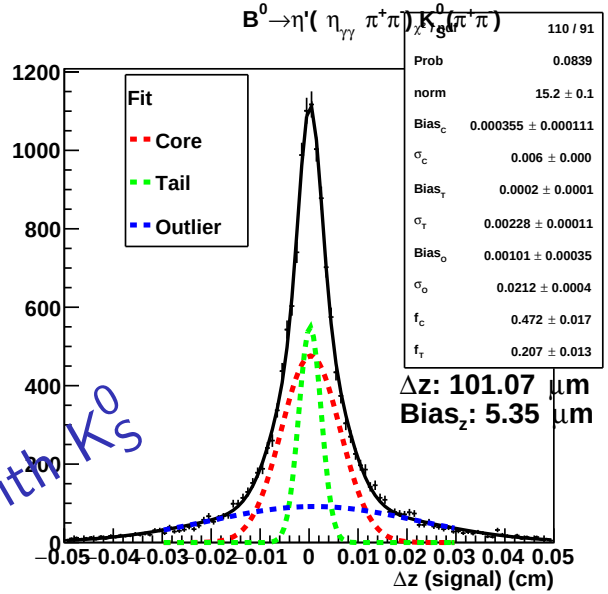


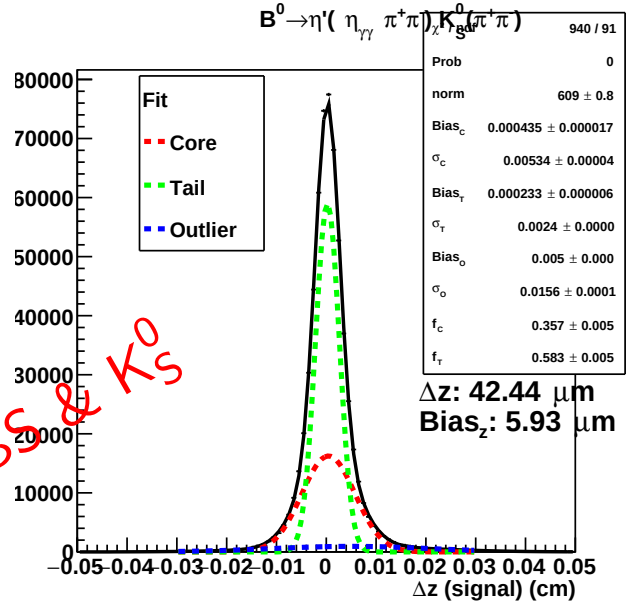
Vtx reco: signal and tag side

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





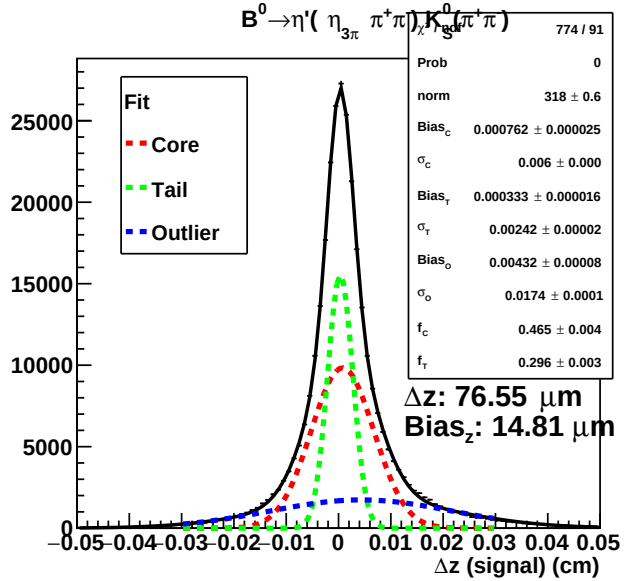


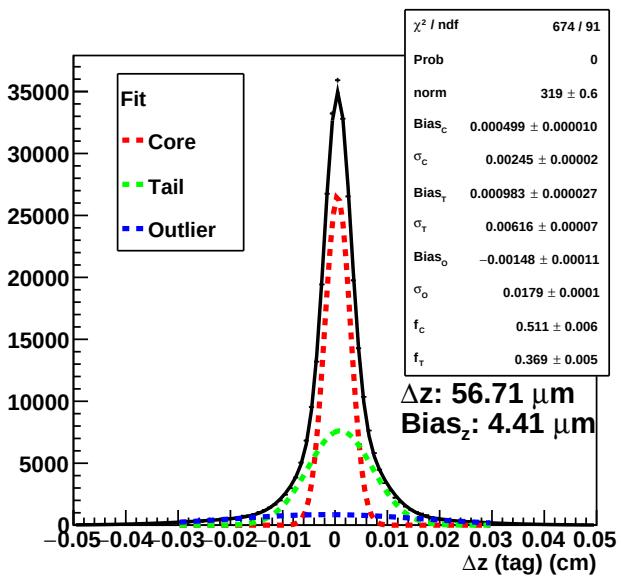


Vtx reco: signal and tag side

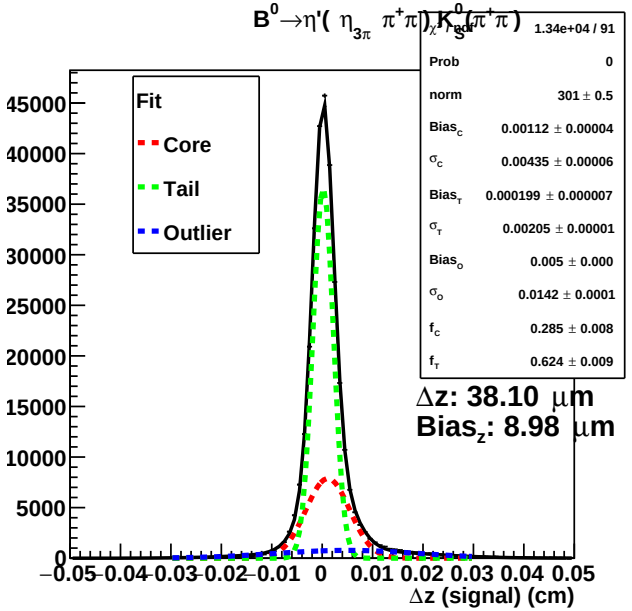
$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)K_S^{0+-}$

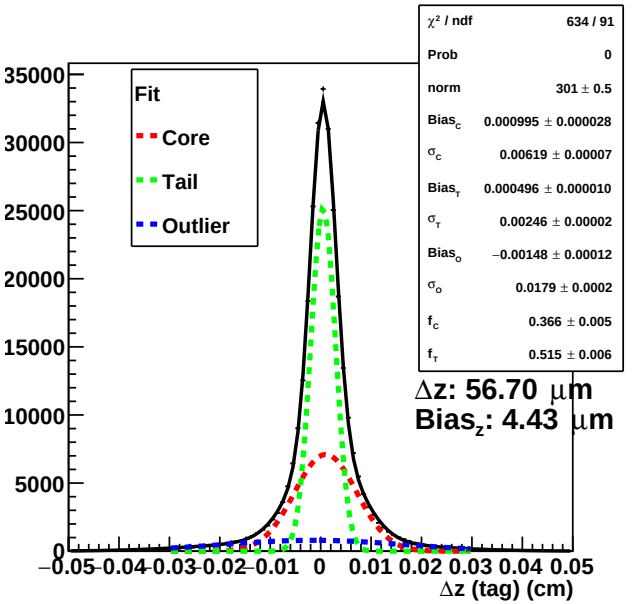
Standard





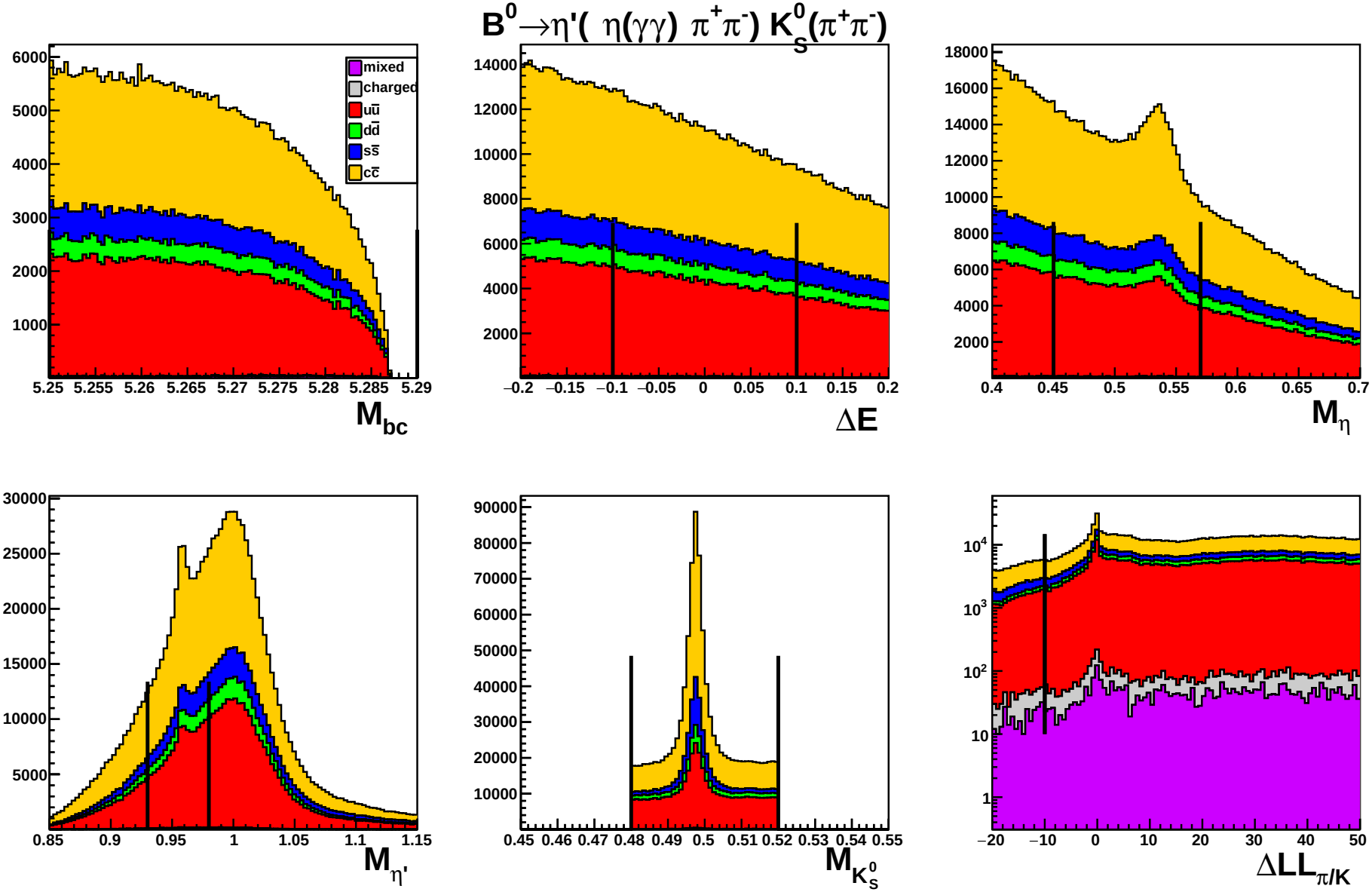
With BS & K_S^0





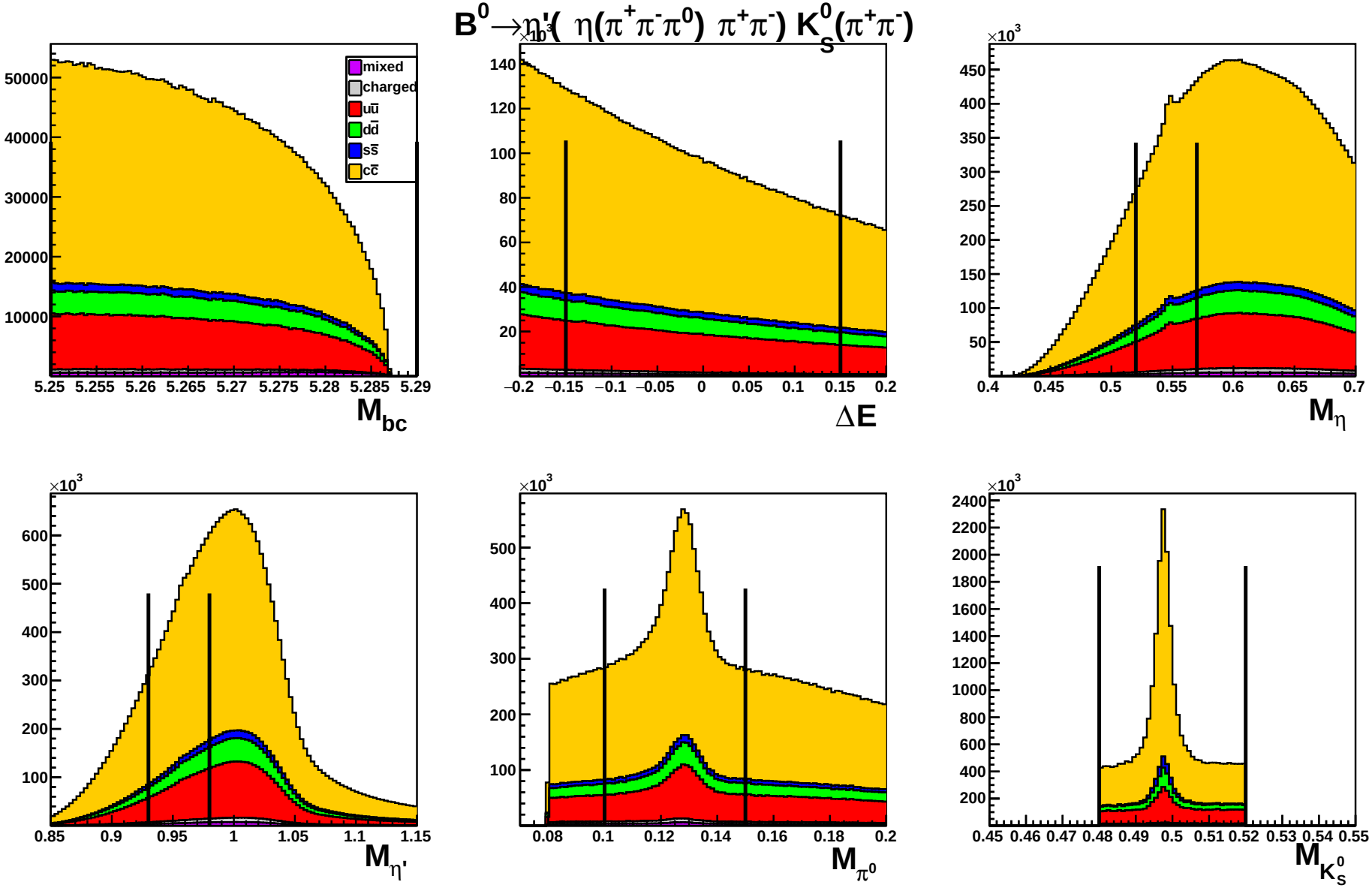
Background distribution

All candidates



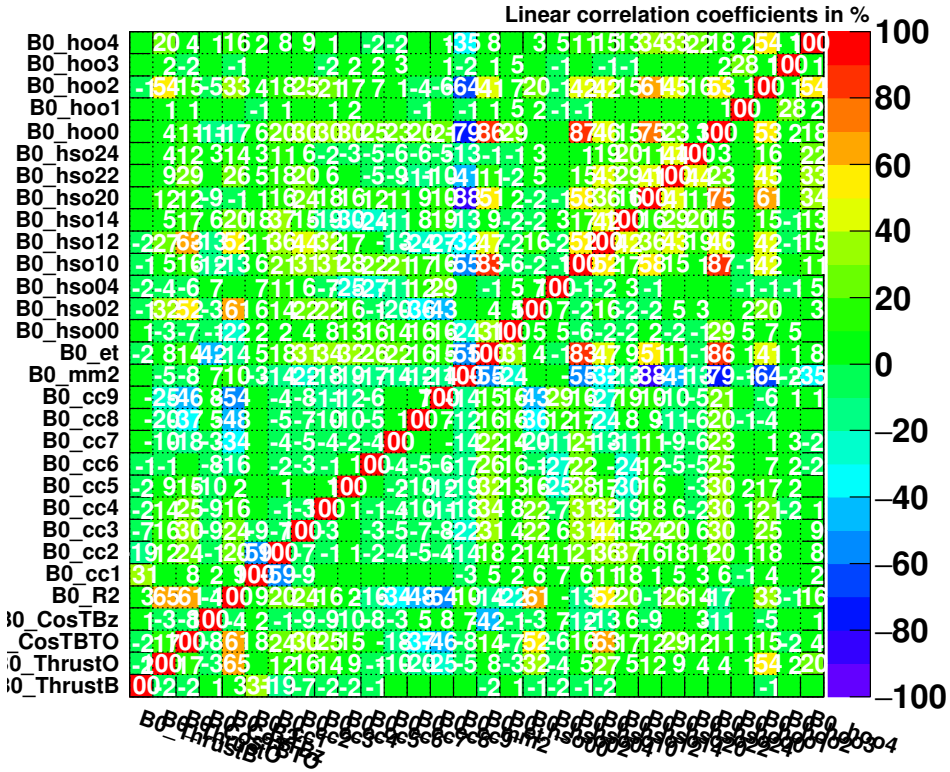
Background distribution

All candidates

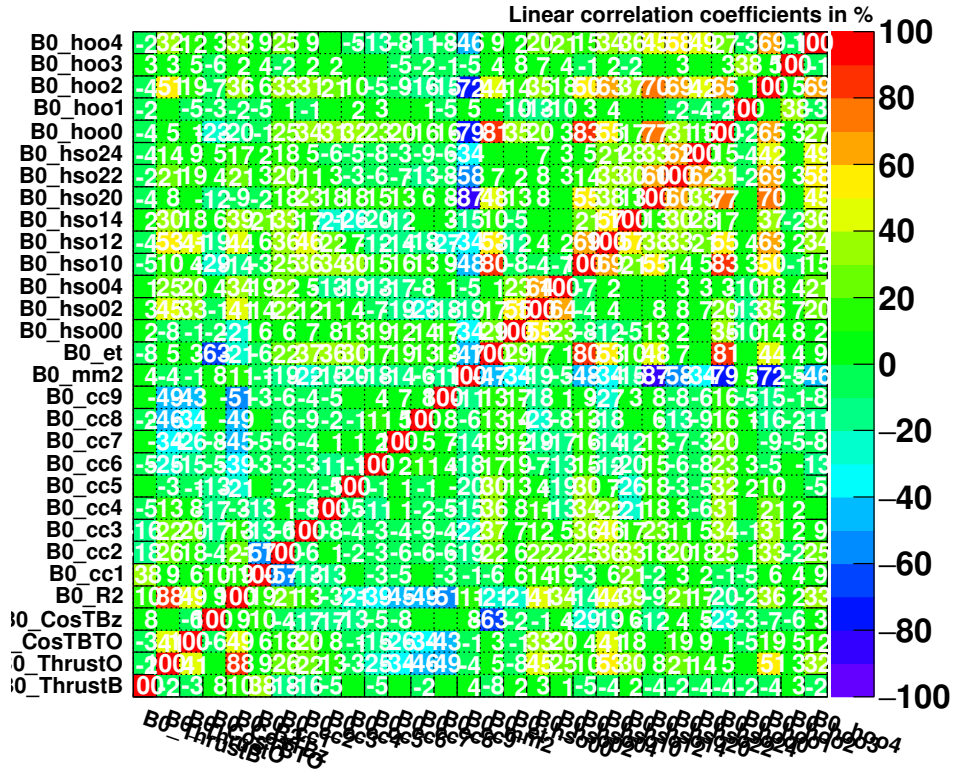


Continuum Suppression correlation matrix

Correlation Matrix (signal)



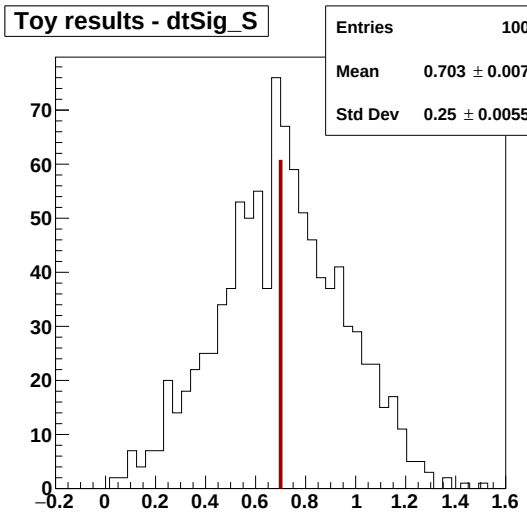
Correlation Matrix (background)

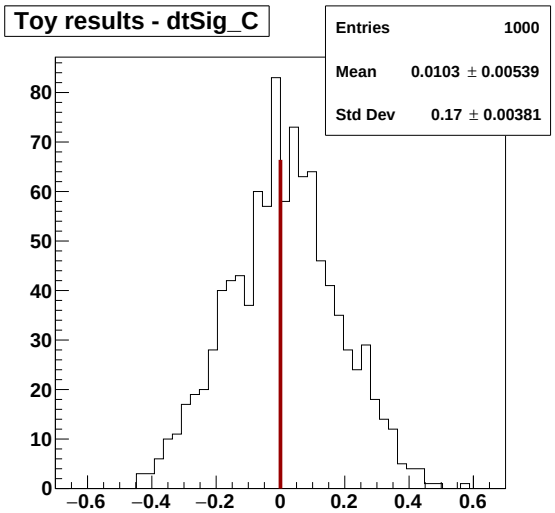


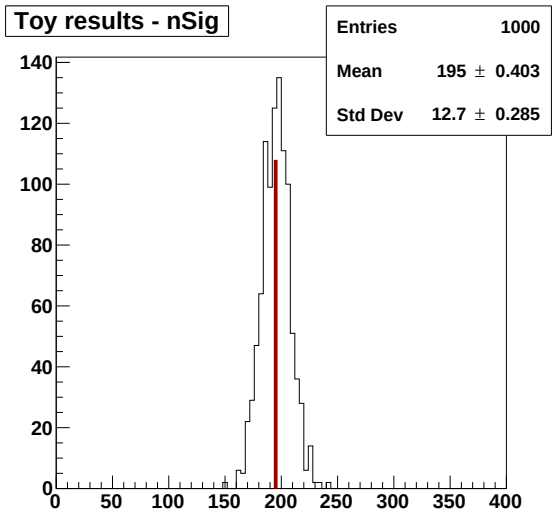
Toy results $B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_S^{0+-}$ Tight CS

Tight: $\epsilon_{sig,sxf,peaking} = 50\%$, $\epsilon_{continuum} = 2.5\%$

$N_{sig} = 195$, $N_{sxf} = 8$, $N_{cont} = 83$, $N_{peak} = 15$





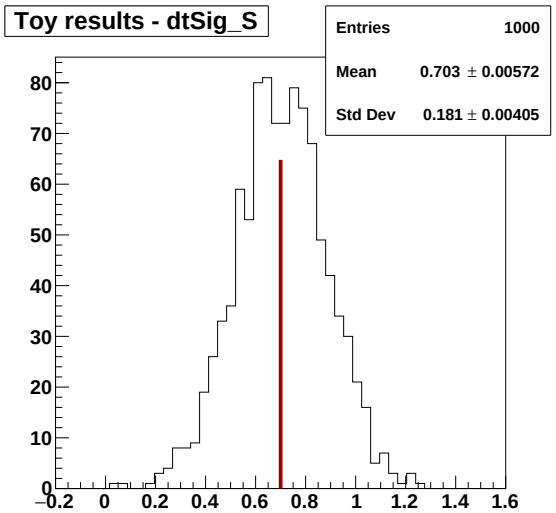


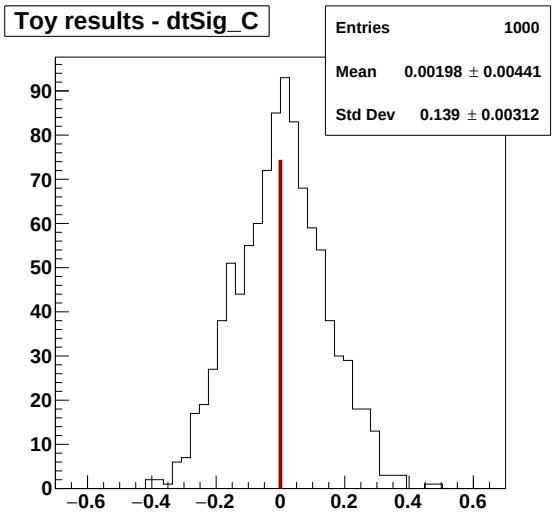
Par	Bias	RMS
S (0.7)	0.703 ± 0.008	0.25
C (0.0)	0.010 ± 0.005	0.17
nSig	195.4 ± 0.4	12.7

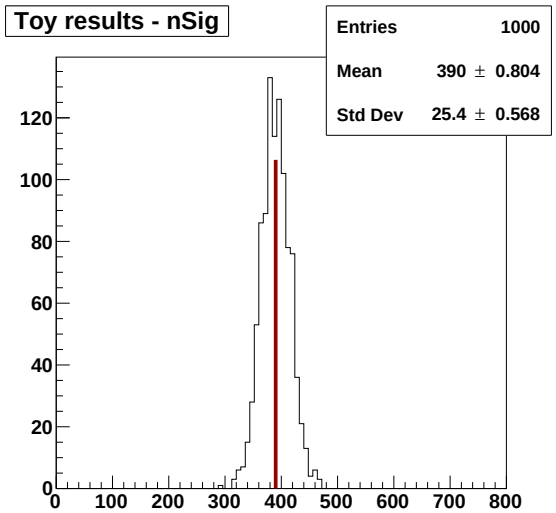
Toy results $B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K_S^{0+-}$ Loose CS

Loose: $\epsilon_{sig,sxf,peaking} = 95\%$, $\epsilon_{continuum} = 42\%$

$N_{sig} = 390$, $N_{sxf} = 14$, $N_{cont} = 1400$, $N_{peak} = 28$







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

Comparison with Belle/BaBar

	This analysis*			Belle[Belle(2014)]			BaBar[BABAR(2009)]		
mode	(340 M B $\overline{\text{B}}$)			(772 M B $\overline{\text{B}}$)			(467 M B $\overline{\text{B}}$)		
$\eta' \to \pi^{\pm}\eta$	N_{sig}	σ_S	σ_C	N_{sig}	σ_S	σ_C	N_{sig}	σ_C	σ_S
$\eta_{\gamma\gamma}\text{K}_S^{0\,+-}$	390	0.19	0.11	648	0.15	0.098	472	0.17	0.11
$\eta_{\gamma\gamma}\text{K}_S^{0\,00}$	Just started			104	$0.21^{\dagger}$	$0.18^{\dagger}$	105	0.34	0.30
$\eta_{3\pi}\text{K}_S^{0\,+-}$	106	0.33	0.25	174	0.26	0.18	171	0.26	0.20
$\eta_{3\pi}\text{K}_S^{0\,00}$	Will try			Not used					
$\eta' \to \rho^0\gamma\text{K}_S^{0\,+-}$	Not yet			1411	0.098	0.069	1005	0.12	0.09
$\eta' \to \rho^0\gamma\text{K}_S^{0\,00}$	Not yet			162	$0.21^{\dagger}$	$0.18^{\dagger}$	206	0.33	0.26

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

Warning: no machine background yet

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

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