First glance at $B^0 \to \eta' K^0$ time-dependent CP analysis

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Outline

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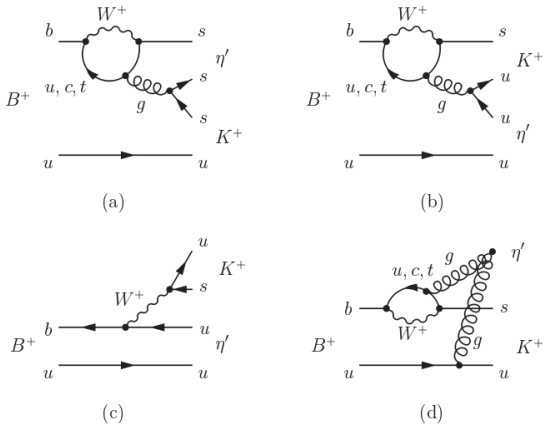
Introduction and motivations

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;
- $S_{\eta' K^0} = \sin 2\phi_1^{eff}$ tightly related to $\sin 2\phi_1$
  - identical if only penguin diagram were present;
  - QCD factorization $\Delta S_{\eta' K^0} \in [-0.03, 0.03]$
  - new physics can enter in the loop, shifting $\Delta S_{\eta' K^0}$ more than SM expectation



- Similar to $B^0 \to \phi K^0$, see work by Alessandro Gaz
  - more complex final state;
  - η' is a scalar (ϕ a vector);
  - large BR: $\sim 6.6 \cdot 10^{-5}$ ($\sim 10x\text{BR}(B^0 \to \phi K^0)$)[CLEO(1998)]
    - ★ constructive interference between penguin diagrams
  - actual uncertainties $\sigma_{stat} = 0.07, \sigma_{syst} = 0.03$[Belle(2014)]
  - projected for 50 ab^{-1} $\sigma_{stat} = 0.008, \sigma_{syst} = 0.008$[Urquijo(2015)]
  - no competition from LHCb;

Status

- Channel have been analyzed in B-factory [BABAR(2009), Belle(2007), Belle(2014)];
- uncertainties are mostly statistical ($\sim$ 3500 events for all final states);
- quasi-two body approach;
- many decay channels available $B^0 \to \eta' K^0_S$
  - $\eta' \to \rho\gamma$; BR:29% not yet
  - $\eta' \to \eta\pi^+\pi^-$; BR:43%

  $\eta_{\gamma\gamma}$: $\eta \to \gamma\gamma$; BR:40%

  $\eta_{3\pi}$: $\eta \to \pi^+\pi^-\pi^0$; BR:23%
  - $K^0_S \to \pi^+\pi^-$, $K^0_S \to \pi^0\pi^0$,
  - Total BR($B_0 \to \eta'(\to \eta_{\gamma\gamma}/\eta_{3\pi}\pi^+\pi^-)K^0_S$) = 27% today
- $B^0 \to \eta' K^0_L$ not yet studied
- Complex final state, neutrals, large combinatorics;

Technicalities

- Release used `rel-00-05-03`
- code in GIT https://github.com/lacaprara/b2pd_analysis
- data used:
  - Privately produced signal;
  - MC5 for signal (BGx0) (still partially);
  - MC5 BGx1 sample for continuum background;
    - Still only a fraction of produced dataset;
    - Skim (with loose selection) on large dataset;
    - Full selection on skimmed events;
    - trying to produce a single skim for all channels, not finalized yet
    - got problem (memory and crash in mixed and charged, respectively): to be investigated;

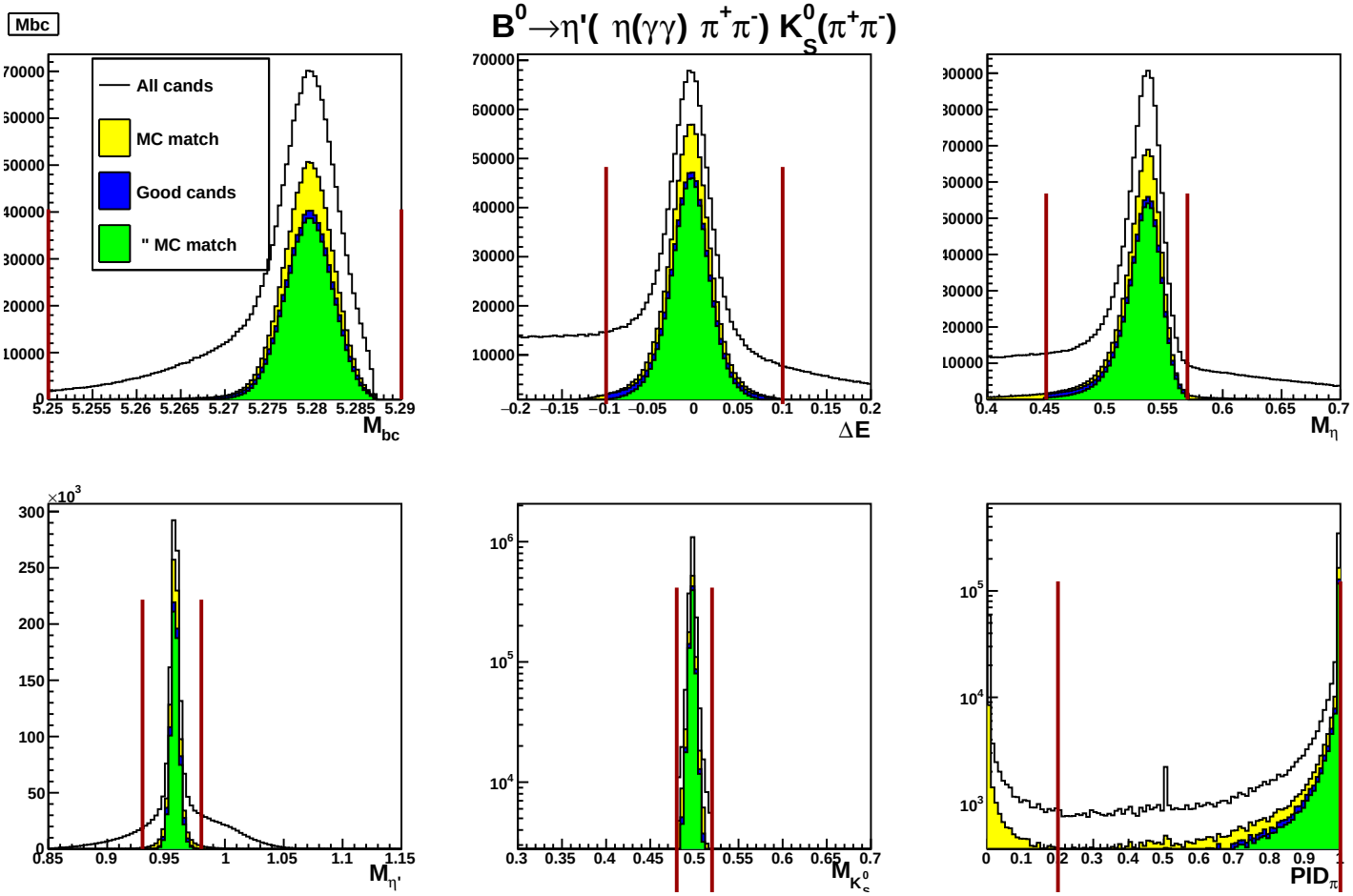
Outline

Selections

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

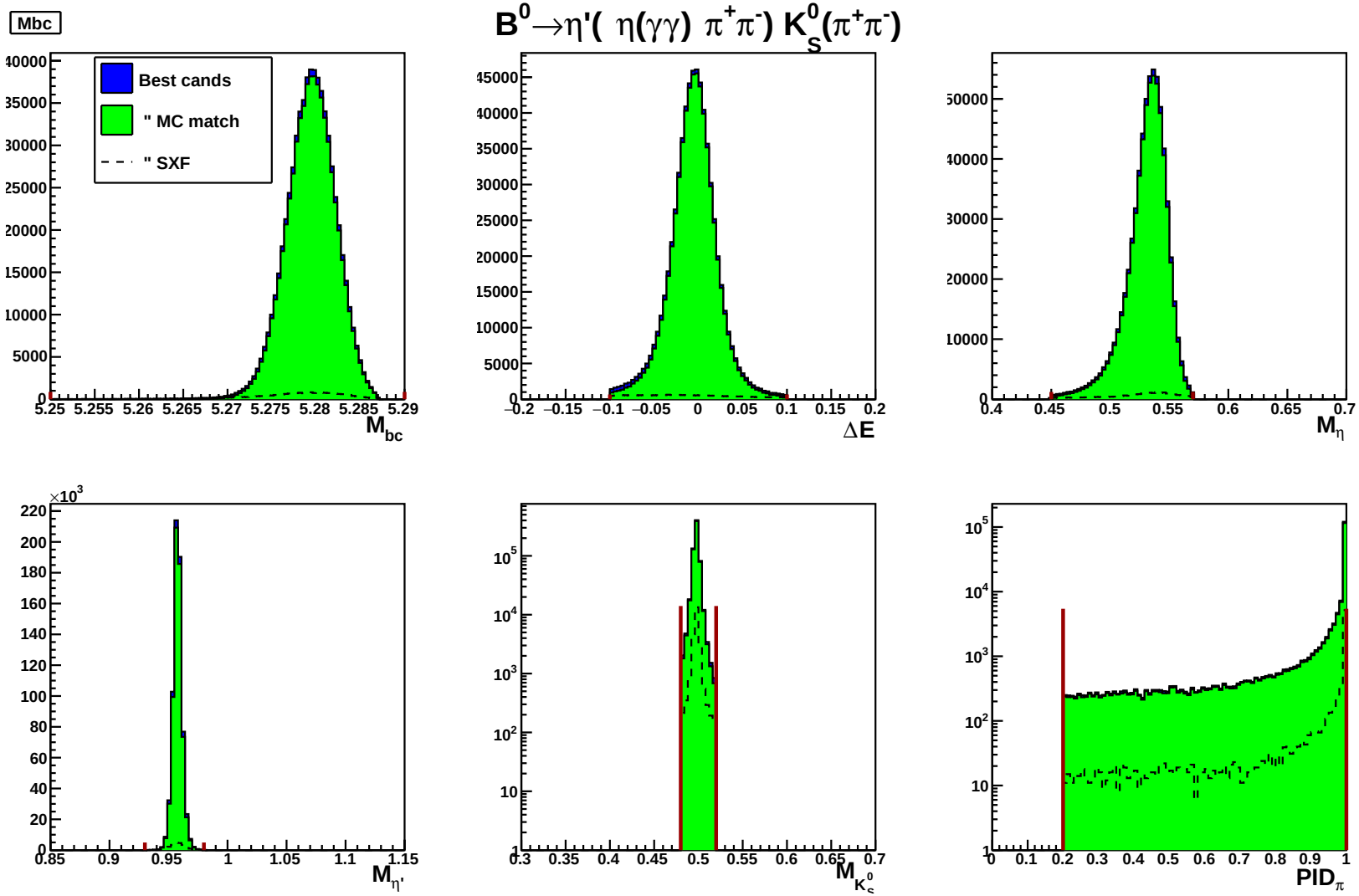
- **pre-selection** at least one decay chain have been reconstructed
- **good candidate selection**:
  - $M_{bc} > 5.25\,\text{GeV}$;
  - $|\Delta E| < 0.1\,\text{GeV}$;
  - $M(\eta_{\gamma\gamma}) \in [0.45, 0.57]\,\text{GeV}$;
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
  - $M(K^0_S \to \pi^+\pi^-) \in [0.48, 0.52]\,\text{GeV}$;
  - $\text{PID}_\pi(\pi^\pm) > 0.2$;
  - $d_0(\pi^\pm) < 0.08\text{mm}$;
  - $z_0(\pi^\pm) < 0.1\text{mm}$;
  - $\text{N hits}_{PXD}(\pi^\pm) > 1$
  - $\text{P-value}_{vtx}(B_0, \eta', K^0_S) > 1 \cdot 10^{-5}$
- if $N_{cands} > 1$, select candidate with highest $\text{P-value}_{vtx}(B_0, \eta', \eta, K^0_S)$

Distributions: all/good candidates



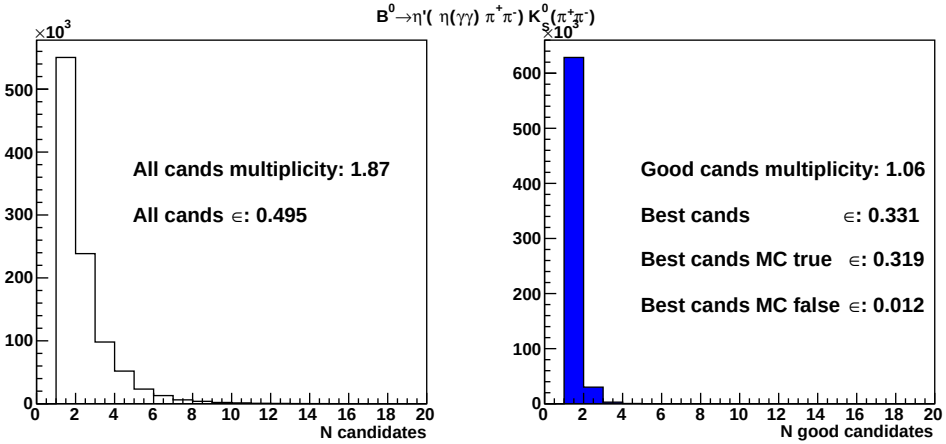
- combinatorics small
- some true cand lost (mostly due to PID(π) and N hits$_{PXD}(\pi^{\pm}) > 1$);
- almost all good candidate(s) are true;
- M_η has a lower tail;

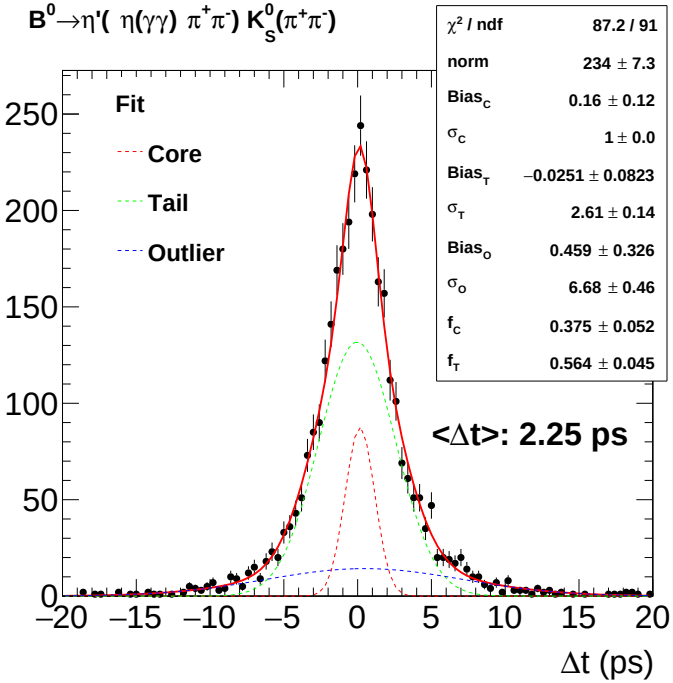
Distributions: best candidate



All best candidates are true: SXF is negligible

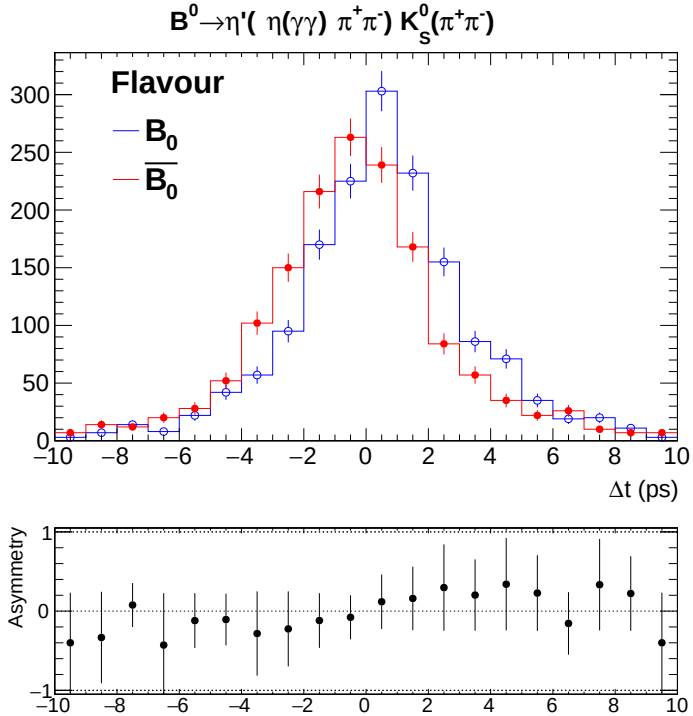
Efficiency and Δt resolution





from private production (10k ev) for tech reason

Efficiency %	
preselection	49.5
good cands	33.1
best cand	31.9
SXF	1.2



Flavour tagging is random, with $\epsilon(1-2w)^2 = 32\%$ dilution

Background

Background selection done in two steps:

1. **Skim:** require a reconstructed decay chain, in any of the four channels, w/ loose selection and w/o vertex fit and constraint (for speed);
   - Trying to run skim on continuum background once for all channels;
2. **Selection:** apply all selection cuts
   - 2.1 **Pre-selection:** re-reconstruct the proper decay chain (exclusive) w/ vertex and mass constraint
   - 2.2 **Final:** apply all selection cuts

- NB No cut (yet) on continuum discriminating variable
- still learning how to use it
- Alessandro showed some issue in $B^0 \to \phi K^0$presentation on 2015/12/11

Background reduction

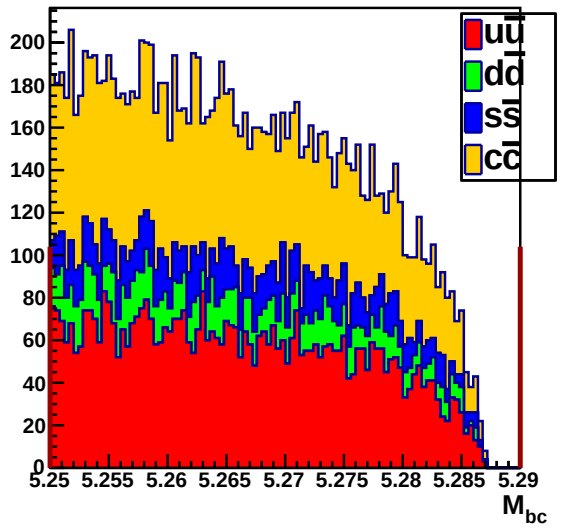
$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)(K^0_S \to \pi^+\pi^-)$

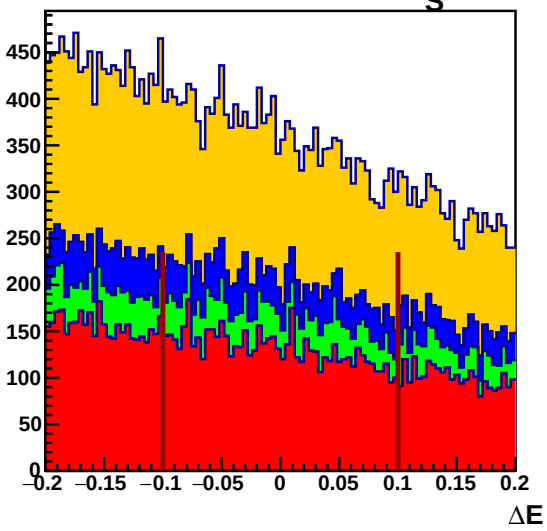
- Background MC sample **BGx1**;
- L=30 fb^{-1};
- need to process the full MC5 dataset to increment statistics of selected events;
  - NB No cut (yet) on continuum discriminating variable

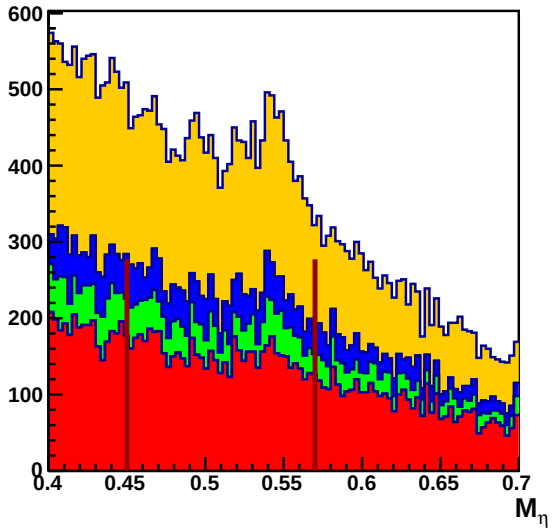
Sample	# Ev (M)	Skim (M)	ϵ_{skim}	pre-sel	sel	ϵ_{sel}
$u\bar{u}$	48.15	1.023	$2.13 \cdot 10^{-2}$	8196	93	$1.96 \cdot 10^{-6}$
$d\bar{d}$	13.03	0.274	$2.27 \cdot 10^{-2}$	2333	37	$2.84 \cdot 10^{-6}$
$s\bar{s}$	11.49	0.238	$2.07 \cdot 10^{-2}$	2334	18	$1.57 \cdot 10^{-6}$
$c\bar{c}$	38.87	1.127	$2.90 \cdot 10^{-2}$	9911	123	$1.09 \cdot 10^{-6}$
total	111.54	2.662	$2.39 \cdot 10^{-2}$	22774	271	$2.43 \cdot 10^{-6}$

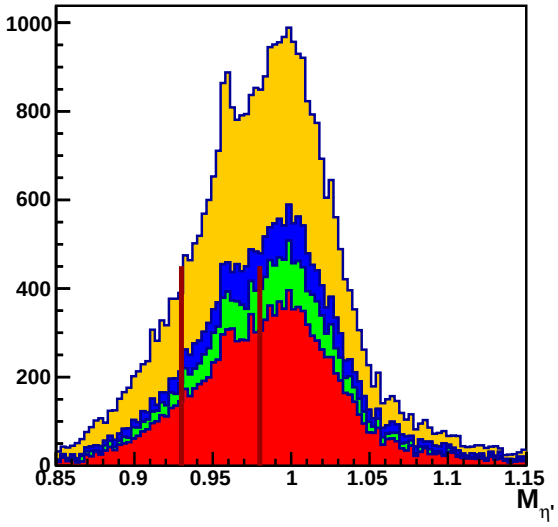
Background distribution at preselection level

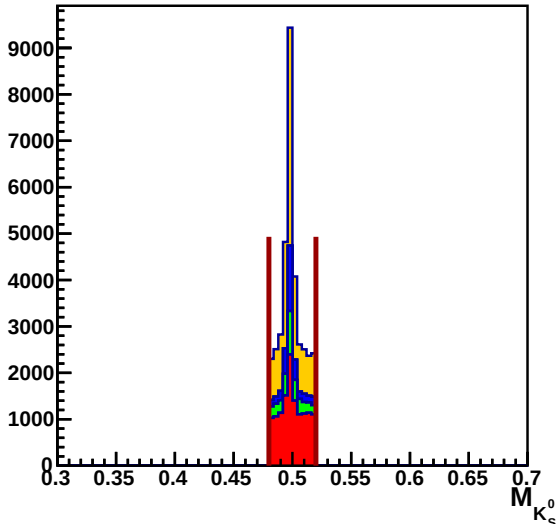
$B^0 \to \eta'(\ \eta(\gamma\gamma)\ \pi^+\pi^-)\ K^0_S(\pi^+\pi^-)$

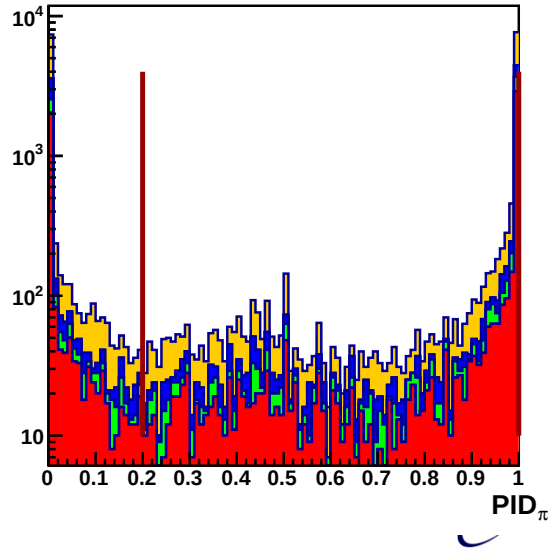






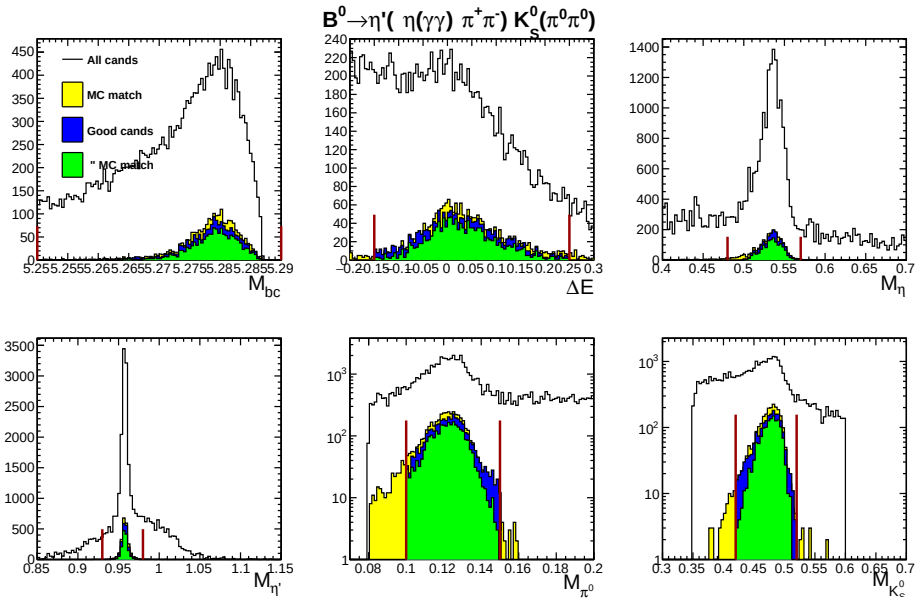






$B^0 \to \eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)(K^0_S \to \pi^0\pi^0)$

- Similar selection as in $K^0_S \to \pi^+\pi^-$ case, taking into account the more difficult π^0 reconstruction
  - $\Delta E \in [-0.15, 0.25]$ GeV; (< 0.1 for $K^0_S \to \pi^+\pi^-$)
  - $M(\pi^0) \in [0.1, 0.15]$ GeV;
  - $M(K^0_S \to \pi^0\pi^0) \in [0.42, 0.52]$ GeV;A
  - (full list in backup)



- combinatorics larger but still manageable
- lower tails for $M_{\pi^0, K^0_S, \eta}$;
- SXF still small

Efficiency %	
preselection	38.2
good cands	15.3
best cand	13.1
SXF	2.1

$\epsilon(K^0_S \to \pi^0\pi^0) \sim 0.5\ \epsilon(K^0_S \to \pi^+\pi^-)$

Outline

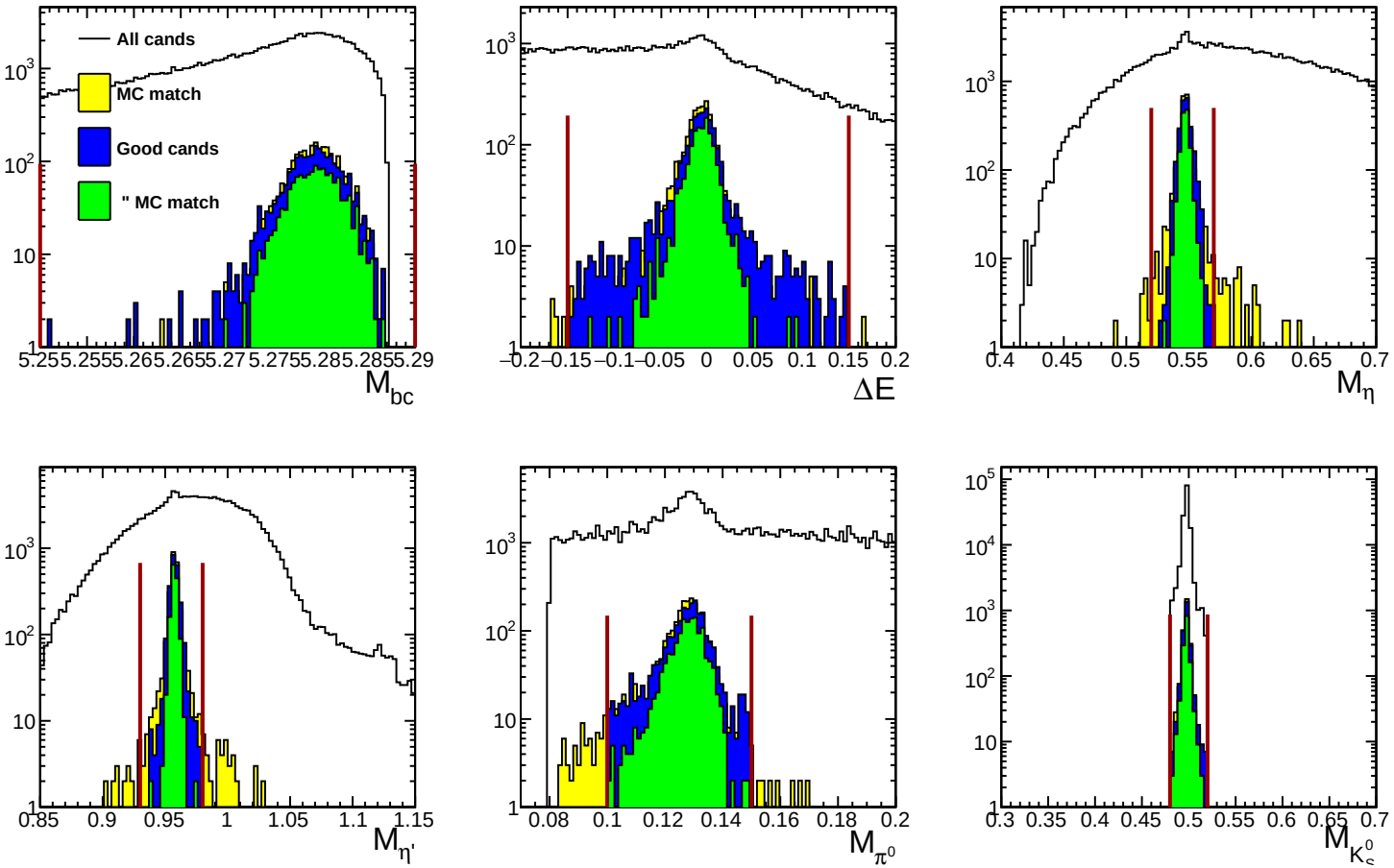
Selections $\eta_{3\pi}$

- **preselection** at least one decay chain have been reconstructed
- **good candidate selection**:
  - $M_{bc} > 5.25\,\text{GeV}$;
  - $\Delta E \in [-0.15, 0.15]\,\text{GeV}$;
  - $M(\eta_{3\pi}) \in [0.52, 0.57]\,\text{GeV}$;
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
  - $M(\pi^0) \in [0.1, 0.15]\,\text{GeV}$;
  - $M(K^0_S \to \pi^+\pi^-) \in [0.48, 0.52]\,\text{GeV}$;
  - $\text{PID}_\pi(\pi^\pm) > 0.2$;
  - $d_0(\pi^\pm) < 0.08\text{mm}$;
  - $z_0(\pi^\pm) < 0.15\text{mm}$;
  - $\text{N hits}_{PXD}(\pi^\pm) > 1$
  - $\text{P-value}_{vtx}(B_0, \eta', \eta, K^0_S) > 1 \cdot 10^{-5}$
- if $N_{cands} > 1$, select candidate with highest $\text{P-value}_{vtx}(B_0, \eta', \eta, K^0_S)$

Distributions: all/good candidates

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

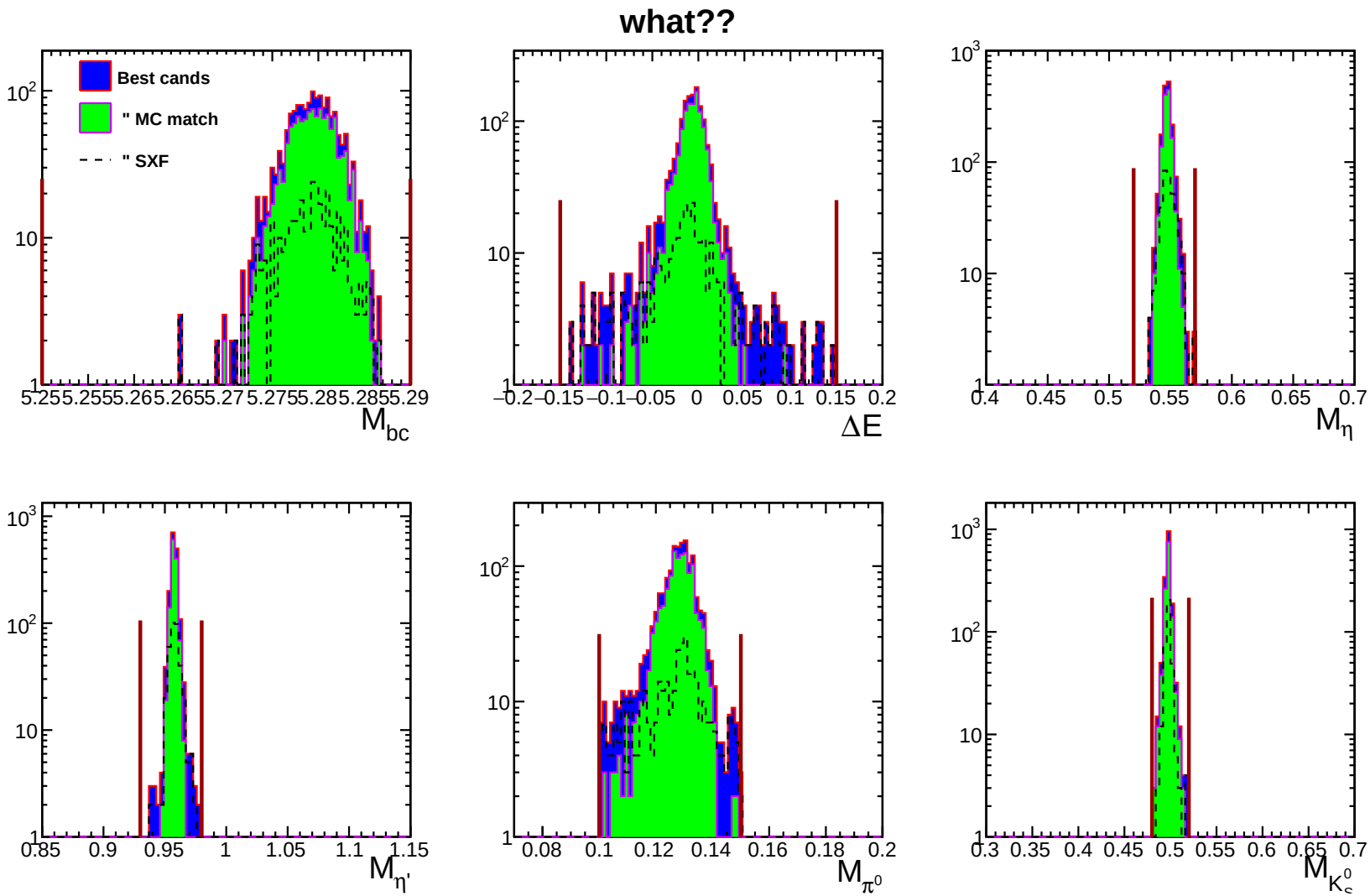
what??



- Combinatorics is huge ($6\pi^{\pm}$);
- same problem with π^0;
- η' and $\eta_{3\pi}$ well reconstructed
- some 20% of good candidates are false
- can have a tighter cut on ΔE

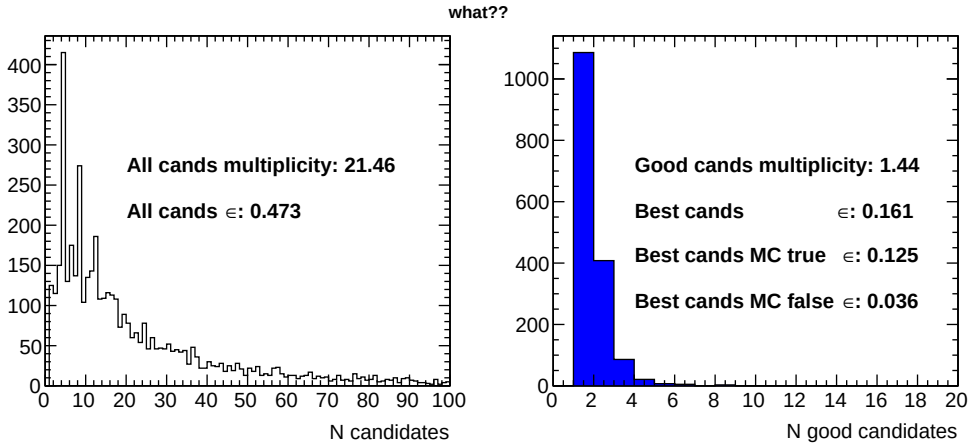
private production (10k ev)

Distributions: best candidate



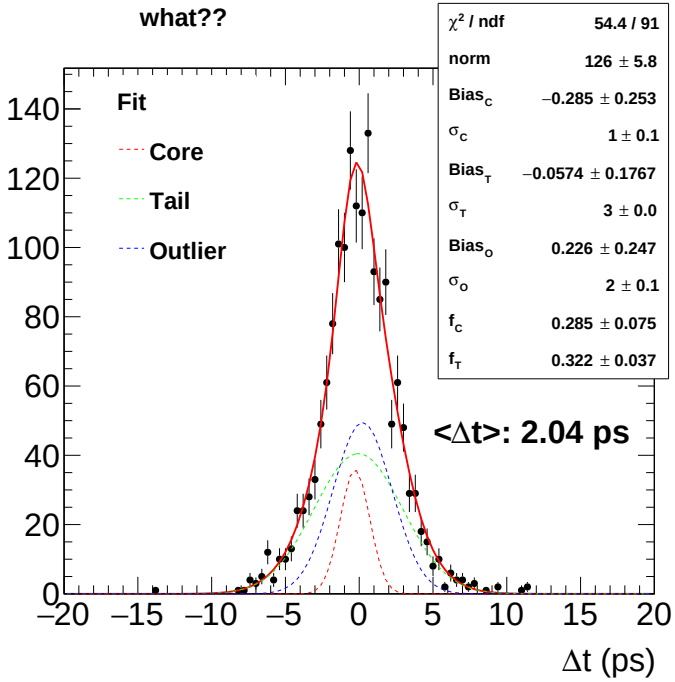
Sizeable SXF $\sim$ 20%, smarter best cand selection is possible

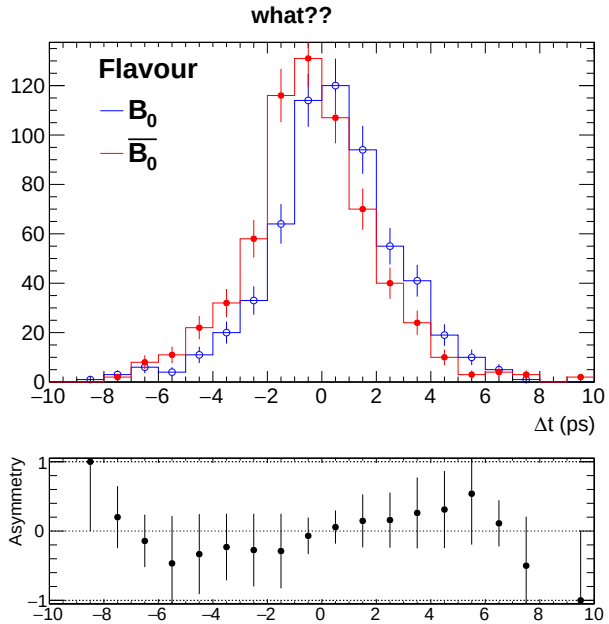
Efficiency and Δt resolution



Efficiency %	
preselection	47.3
good cands	16.1
best cand	12.5
SXF	3.6

Lower efficiency: only π^0?





Better resolution ($4\pi^{\pm}$)

Flavour tagging is random, with $\epsilon(1-2w)^2 = 32\%$ dilution

Background reduction

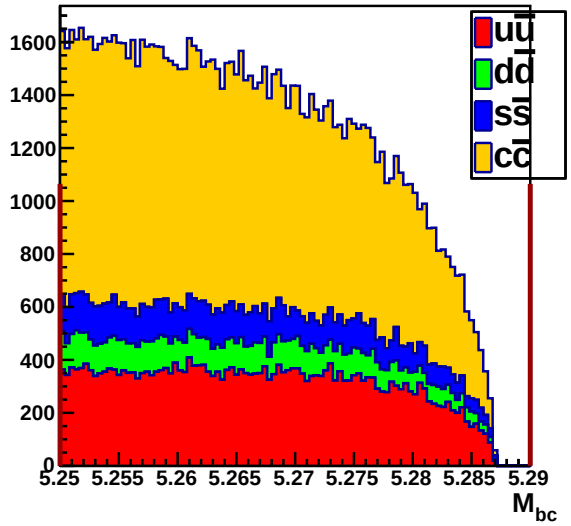
$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)(K^0_S \to \pi^+\pi^-)$

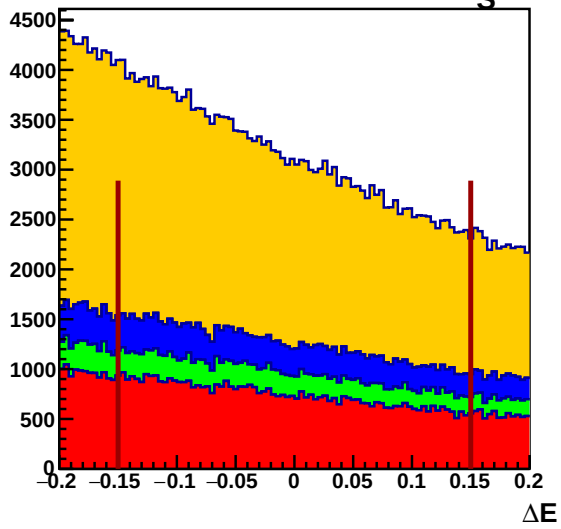
- Background MC sample **BGx1**;
- L=30 fb^{-1};
- really need to process the full MC5 dataset to increment statistics of selected events;
  - NB No cut (yet) on continuum discriminating variable
- larger contribute from $c\bar{c}$
- reduction is larger ($\sim 10x$) than for $\eta_{\gamma\gamma}$channel (but ϵ as well)

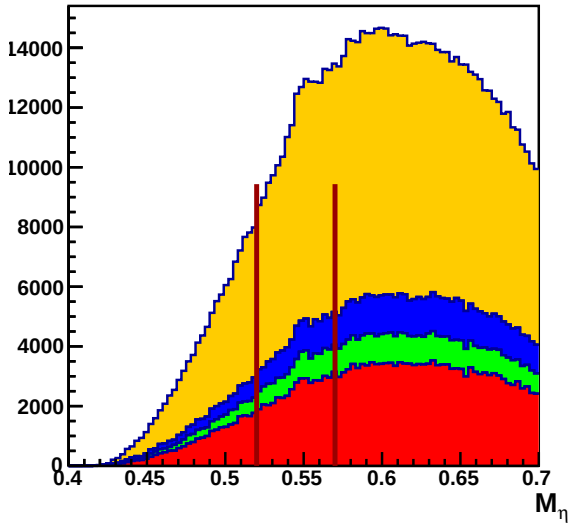
Sample	# Ev (M)	Skim (M)	ϵ_{skim}	pre-sel	sel	ϵ_{sel}
$u\bar{u}$	48.15	1.023	$2.13 \cdot 10^{-2}$	24037	14	$2.91 \cdot 10^{-7}$
$d\bar{d}$	13.03	0.274	$2.27 \cdot 10^{-2}$	6552	6	$1.25 \cdot 10^{-7}$
$s\bar{s}$	11.49	0.238	$2.07 \cdot 10^{-2}$	9686	5	$1.04 \cdot 10^{-7}$
$c\bar{c}$	38.87	1.127	$2.90 \cdot 10^{-2}$	56653	40	$8.31 \cdot 10^{-7}$
total	111.54	2.662	$2.39 \cdot 10^{-2}$	96928	271	$1.35 \cdot 10^{-7}$

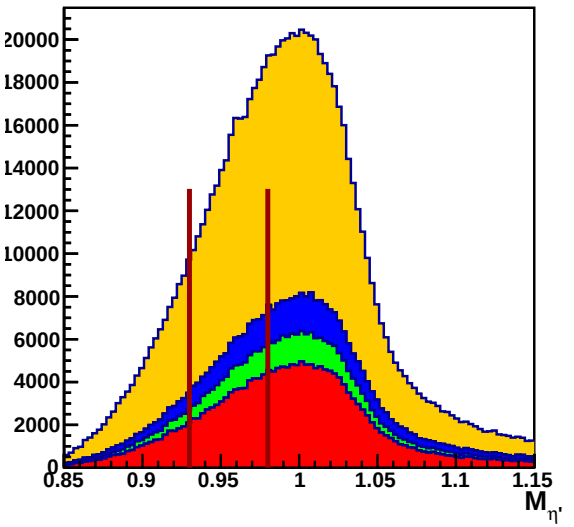
Background distribution at preselection level

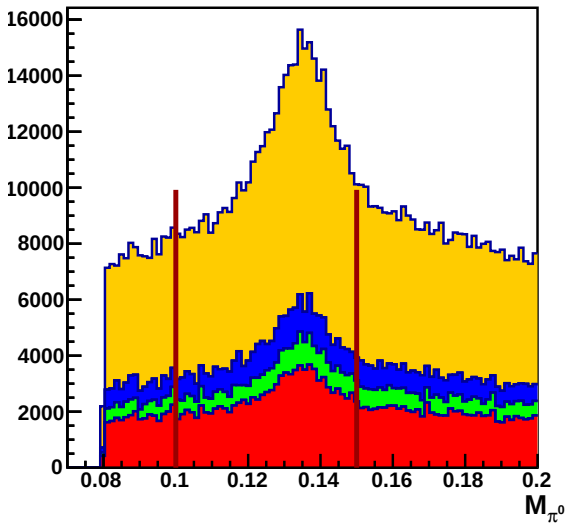
$B^0 \to \eta'(\ \eta(\pi^+\pi^-\pi^0)\ \pi^+\pi^-)\ K^0_S(\pi^+\pi^-)$

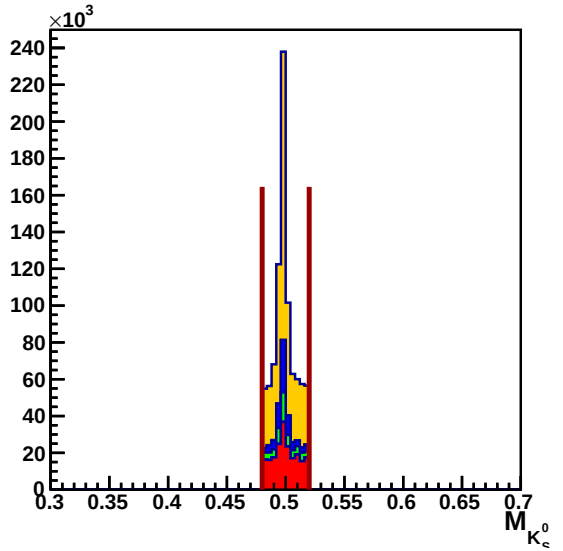






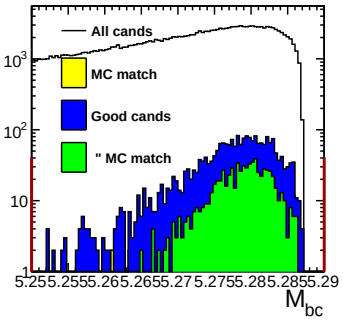




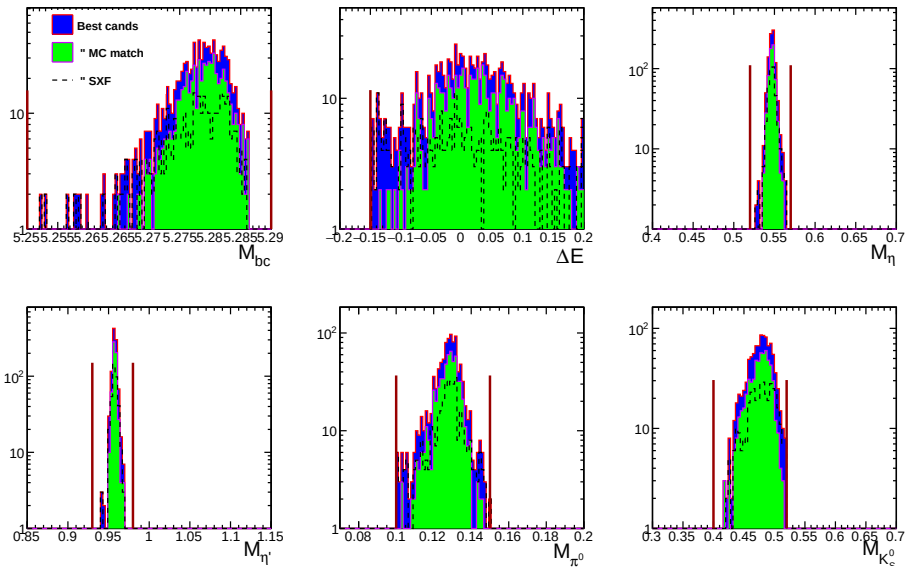


$B^0 \to \eta'(\to \eta_{3\pi}\pi^+\pi^-)(K^0_S \to \pi^0\pi^0)$

- Channel not used in Belle
- Selection $\sim$ as before
  - $\Delta E \in [-0.15, 0.25]$ GeV; (< 0.15 for $K^0_S \to \pi^+\pi^-$)
  - (full list in backup)



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



- combinatorics is even larger (~ 25 candidates per event)
- Sizeable SXF $\sim 30\%$, smarter best cand selection is possible
- $\epsilon(K^0_S \to \pi^0\pi^0) \sim 0.5\ \epsilon(K^0_S \to \pi^+\pi^-)$

Efficiency %	
preselection	35.5
good cands	10.1
best cand	5.96
SXF	3.8

Outline

Channels summary

With some comparison to $B^0 \to \phi K^0$and $J/\psi(\to 2\mu)K^0_S$ channels

$B^0 \to$	BR 10^{-5}	Eff. sel. %	SXF %	Bgnd.* $\cdot 10^{-6}$	Δt reso
$\eta'(\to \eta_{\gamma\gamma}\pi^+\pi^-)K^0_S$	1.1	31.9 $\pi^+\pi^-$ 13.1 $\pi^0\pi^0$	1.2 2.1	2.43 1.25	2.25 ps
$\eta'(\to \eta_{3\pi}\pi^+\pi^-)K^0_S$	0.6	12.5 $\pi^+\pi^-$ 6.0 $\pi^0\pi^0$	3.5 3.8	0.58 0.38	2.04 ps 1.84 ps†
$\phi(\to K^+K^-)K^0_S$	0.6	35.2 $\pi^+\pi^-$ 13.7 $\pi^0\pi^0$		~ 20 ~ 4	2.11 ps
$\phi(\to 2\pi)K^0_S$	0.07	28.3 $\pi^+\pi^-$		~ 700	1.42 ps
$J/\psi(\to 2\mu)K^0_S$	52	-	-	-	0.92 ps

* NB. w/o continuum suppression cut! †: to be investigated

Outlook

- Study is still very preliminary
- So far only looked at signal $\eta' \to \eta\pi^+\pi^-$, with $\eta_{\gamma\gamma}$ and $\eta_{3\pi}$;
  - look also at $\rho\gamma$ channel;
  - will analyze official MC5 production for signal (done only partially so far);
  - selection still to be optimized, but first attempt is good enough to start with;
- first look at continuum background (from MC5 campaign);
  - No continuum suppression yet
- need to look at peaking background;
- signal extraction and fit to be implement
  - synergies with $B^0 \to \phi K^0$analysis;
- Still long road toward a full scale sensitivity exercise, but at least started

Additional stuff

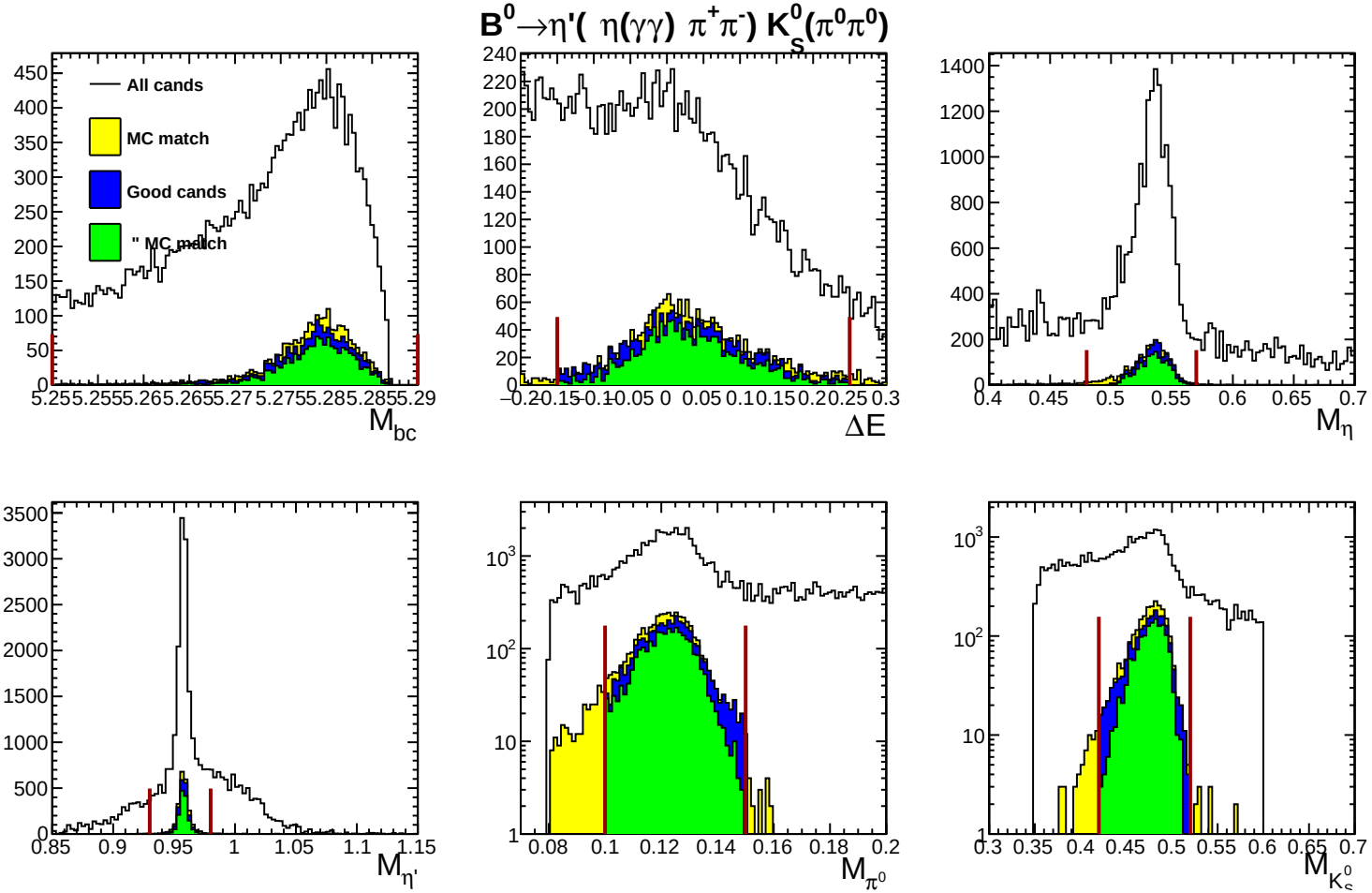
Additional or backup slides

Selections

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

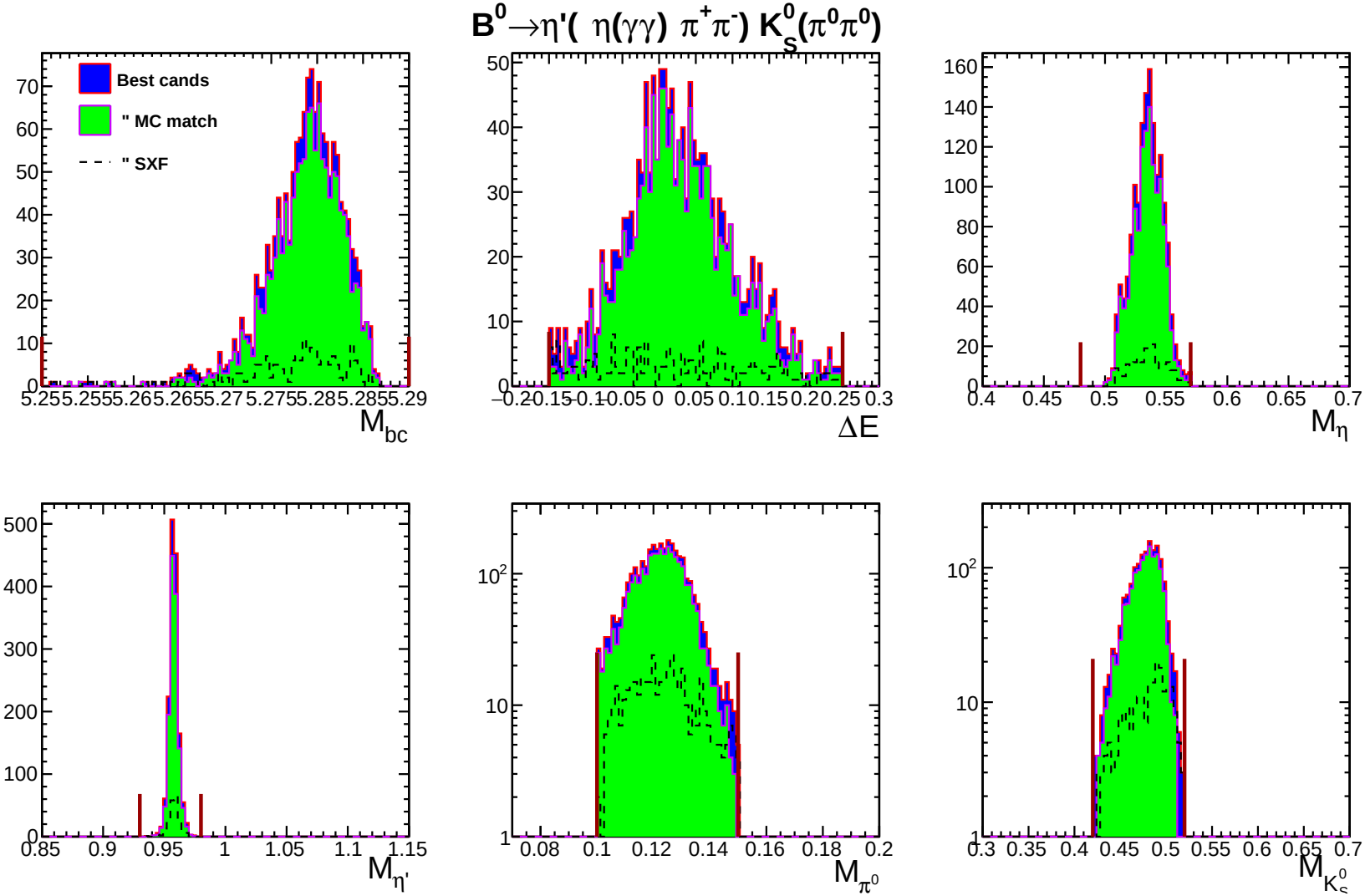
- **preselection** at least one decay chain have been reconstructed
- **good candidate selection**:
  - $M_{bc} > 5.25\,\text{GeV}$;
  - $\Delta E \in [-0.15, 0.25]\,\text{GeV}$; ($< 0.1$ for $K^0_S \to \pi^+\pi^-$)
  - $M(\eta_{\gamma\gamma}) \in [0.45, 0.57]\,\text{GeV}$;
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
  - $M(\pi^0) \in [0.1, 0.15]\,\text{GeV}$;
  - $M(K^0_S \to \pi^0\pi^0) \in [0.42, 0.52]\,\text{GeV}$;
  - $\text{PID}_\pi(\pi^\pm) > 0.2$;
  - $d_0(\pi^\pm) < 0.08\text{mm}$;
  - $z_0(\pi^\pm) < 0.15\text{mm}$;
  - $\text{N hits}_{PXD}(\pi^\pm) > 1$
  - $\text{P-value}_{vtx}(B_0, \eta', \eta, K^0_S) > 1 \cdot 10^{-5}$
- if $N_{cands} > 1$, select candidate with highest $\text{P-value}_{vtx}(B_0, \eta', \eta, K^0_S)$

Distributions: all/good candidates



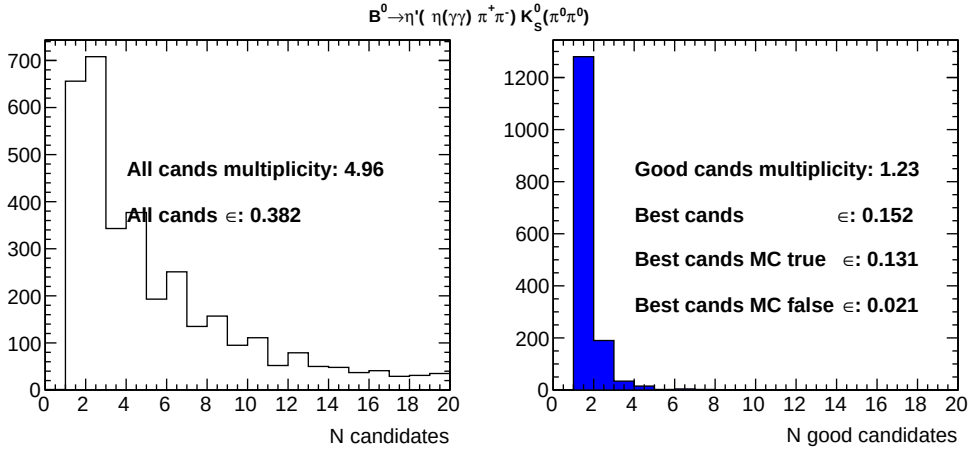
- combinatorics larger but still manageable
- lower tails for $M_{\pi^0, K^0_S, \eta}$;
- still most of all good candidate(s) are true;

Distributions: best candidate



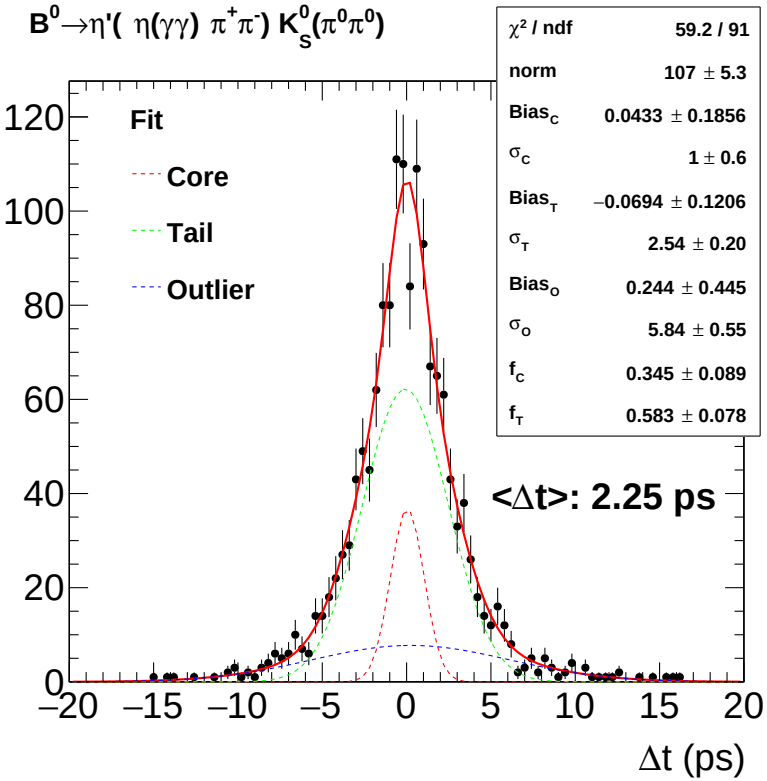
Most best candidates are true: SXF is small $\sim 2\%$

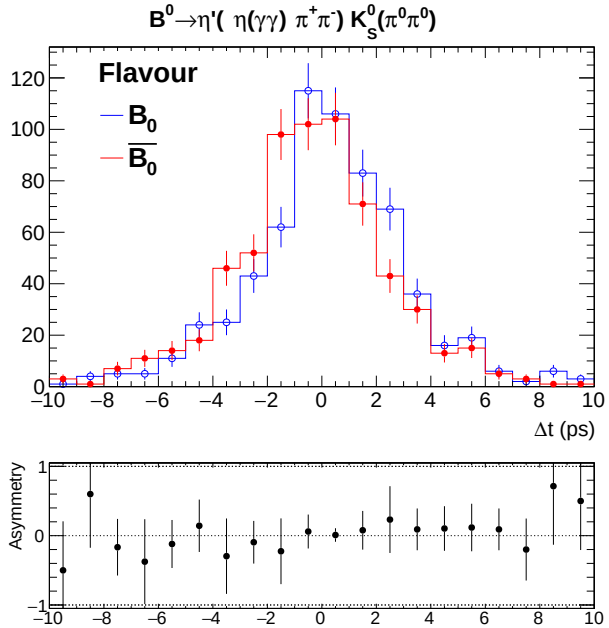
Efficiency and Δt resolution



Efficiency %	
preselection	38.2
good cands	15.3
best cand	13.1

$\epsilon(K^0_S \to \pi^0\pi^0) \sim 0.5\ \epsilon(K^0_S \to \pi^+\pi^-)$

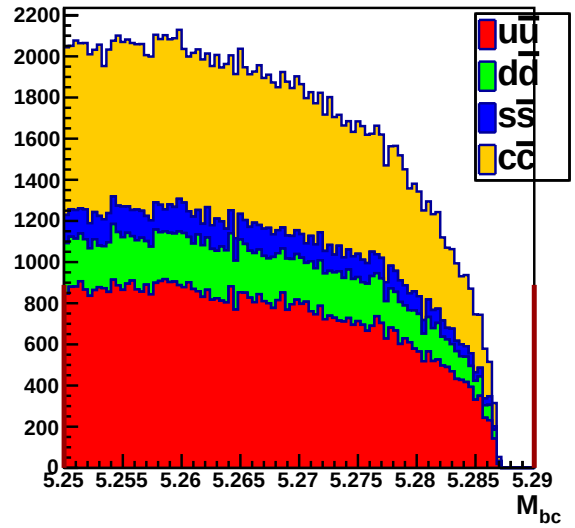


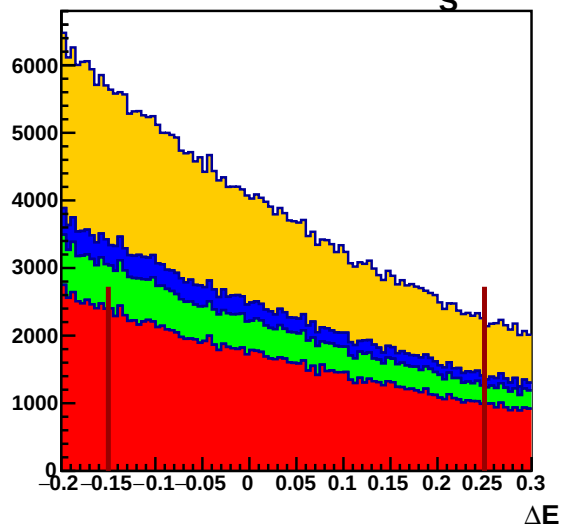


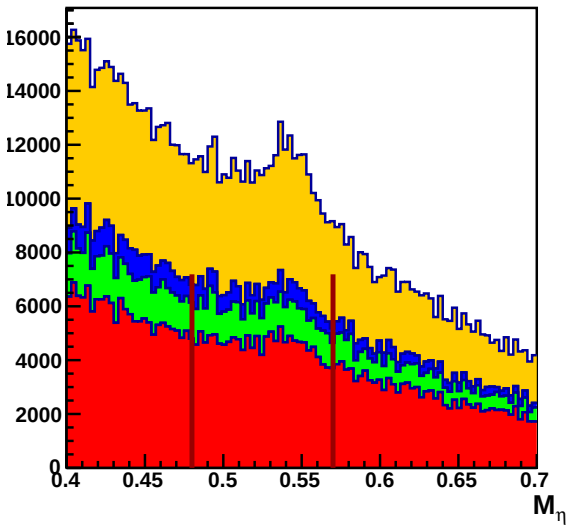
Flavour tagging is random,
with $\epsilon(1-2w)^2) = 32\%$ diluition

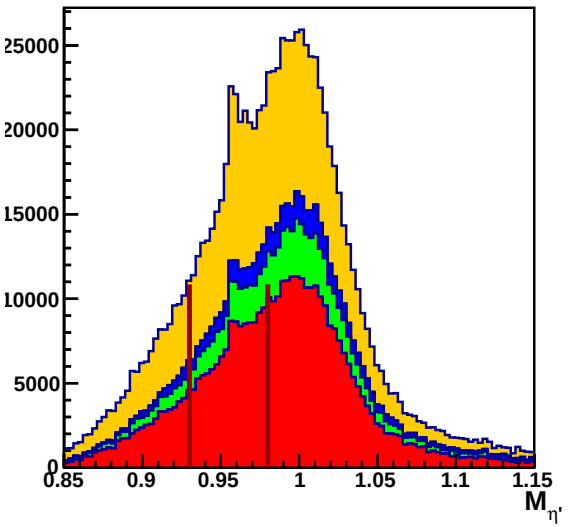
Background distribution at preselection level

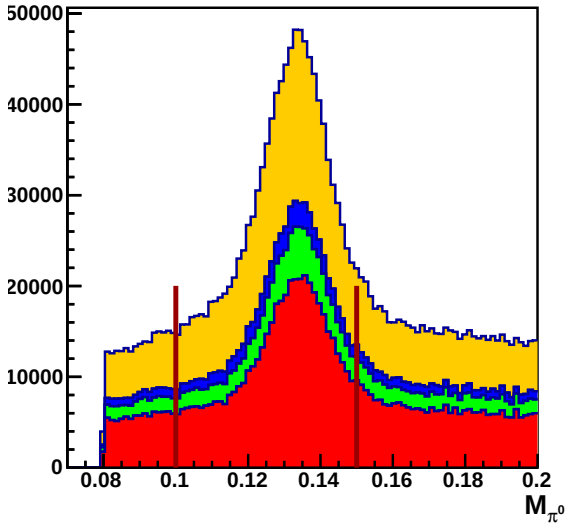
$B^0 \to \eta'(\eta(\gamma\gamma)\,\pi^+\pi^-)\,K^0_S(\pi^0\pi^0)$

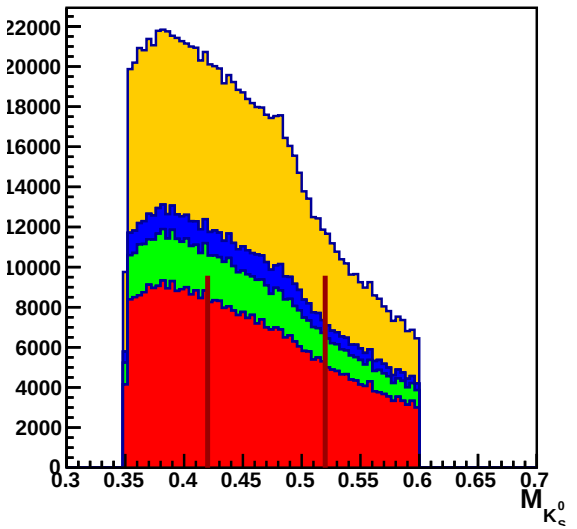










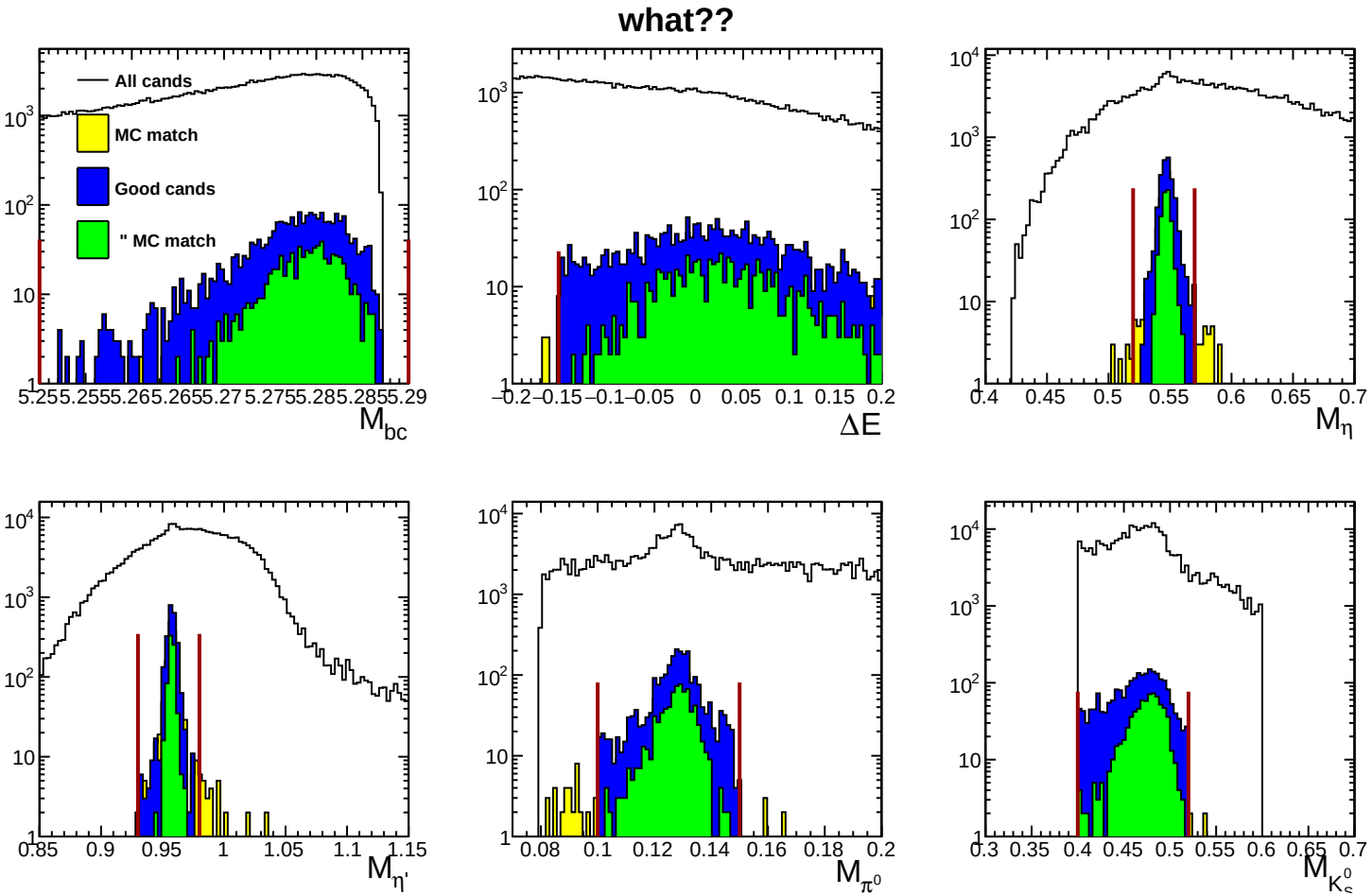


Selections

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

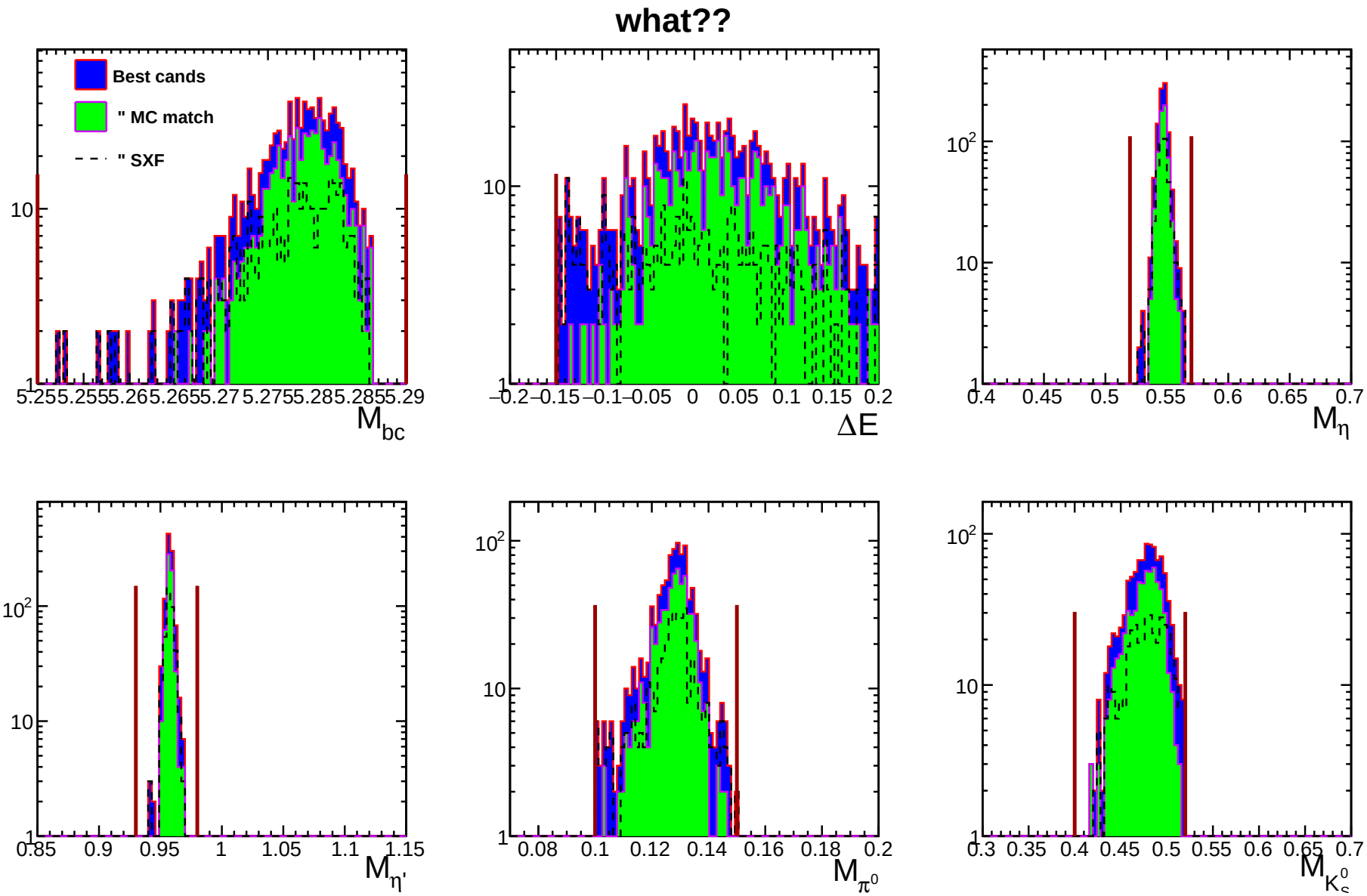
- **preselection** at least one decay chain have been reconstructed
- **good candidate selection**:
  - $M_{bc} > 5.25\,\text{GeV}$;
  - $\Delta E \in [-0.15, 0.25]\,\text{GeV}$;
  - $M(\eta_{3\pi}) \in [0.52, 0.57]\,\text{GeV}$;
  - $M(\eta') \in [0.93, 0.98]\,\text{GeV}$;
  - $M(\pi^0) \in [0.1, 0.15]\,\text{GeV}$;
  - $M(K^0_S \to \pi^0\pi^0) \in [0.4, 0.52]\,\text{GeV}$;
  - $\text{PID}_\pi(\pi^\pm) > 0.2$;
  - $d_0(\pi^\pm) < 0.08\text{mm}$;
  - $z_0(\pi^\pm) < 0.15\text{mm}$;
  - $\text{N hits}_{PXD}(\pi^\pm) > 1$
  - $\text{P-value}_{vtx}(B_0, \eta', \eta) > 1 \cdot 10^{-5}$
- if $N_{cands} > 1$, select candidate with highest $\text{P-value}_{vtx}(B_0, \eta', \eta, K^0_S)$

Distributions: all/good candidates



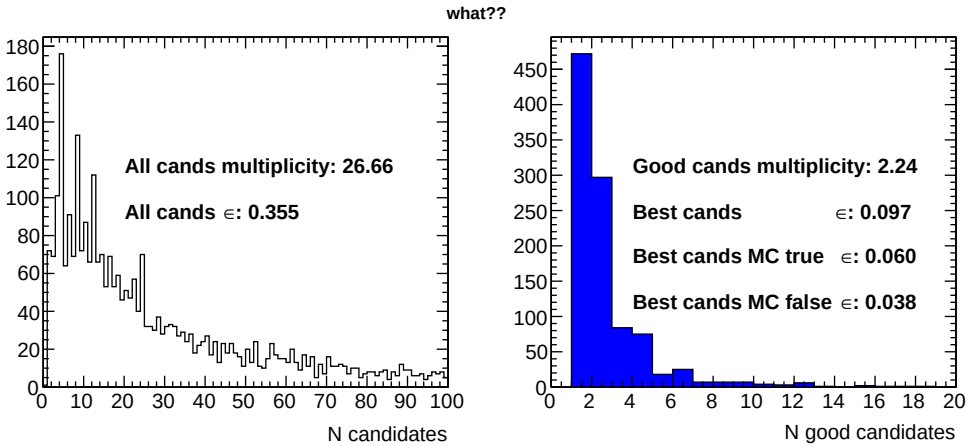
- NB: channel not used in Belle
- combinatorics is huge
- η and η' reconstruction is good

Distributions: best candidate



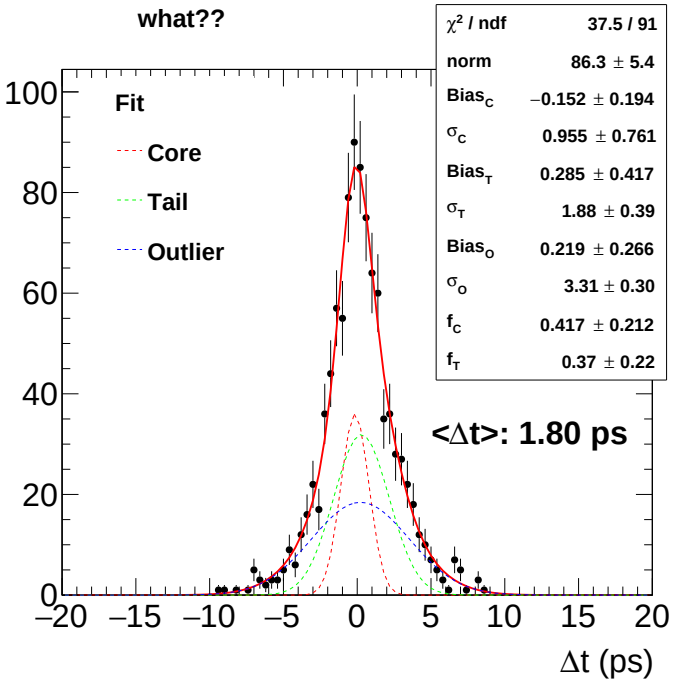
Sizeable SXF $\sim$ 30%, smarter best cand selection is possible

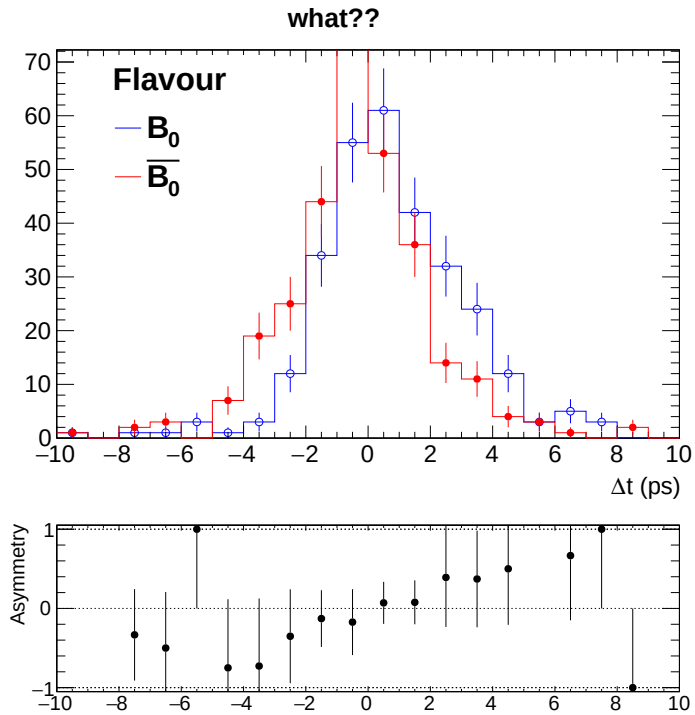
Efficiency and Δt resolution



Efficiency %	
preselection	35.5
good cands	10.1
best cand	5.96
SXF	3.8

$\epsilon(K_S^0 \to \pi^0\pi^0) \sim 0.5\ \epsilon(K_S^0 \to \pi^+\pi^-)$

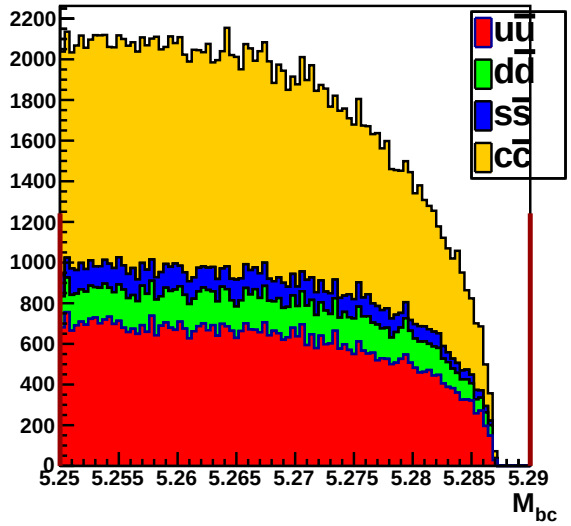


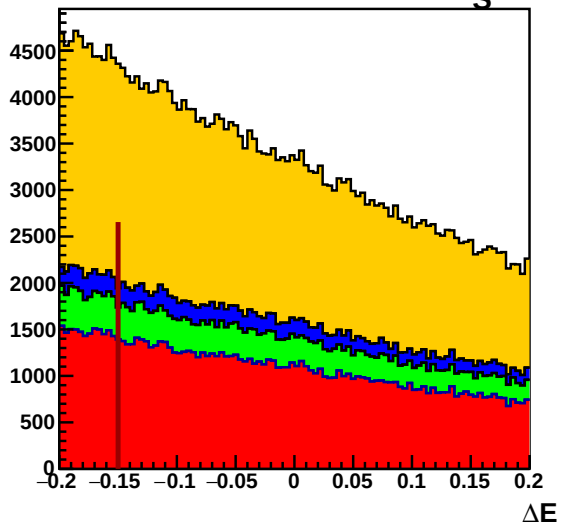


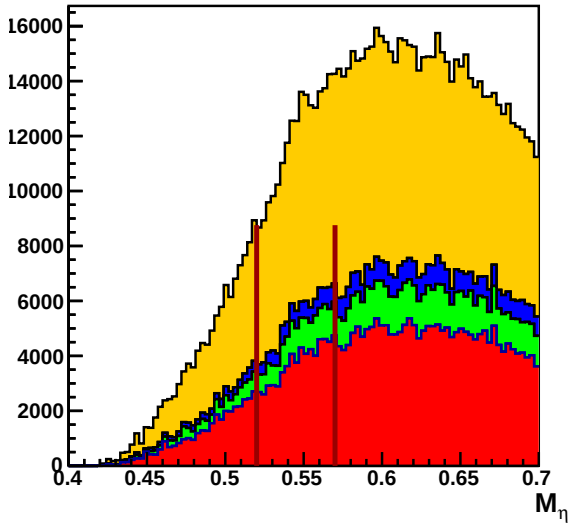
Even better resolution why?

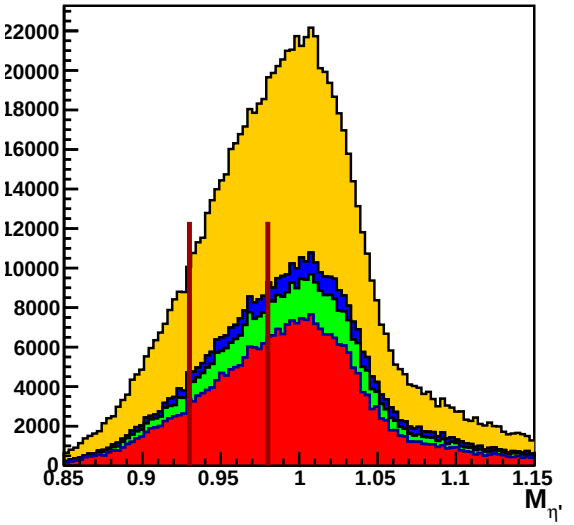
Background distribution at preselection level

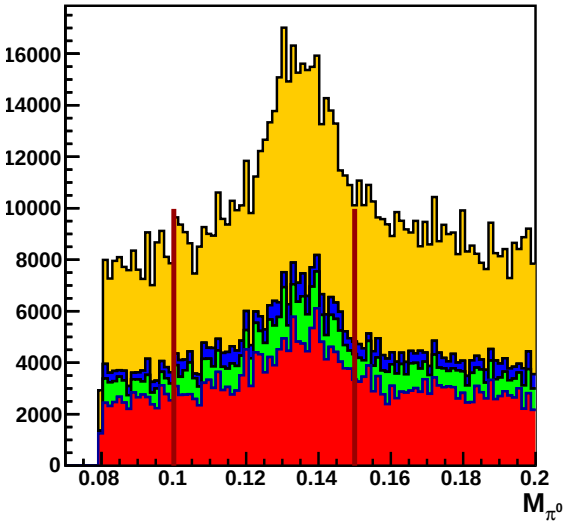
$B^0 \to \eta'(\ \eta(\pi^+\pi^-\pi^0)\ \pi^+\pi^-)\ K^0_S(\pi^0\pi^0)$

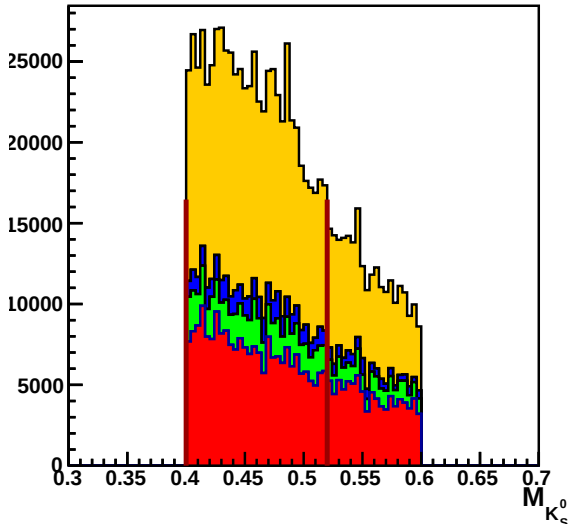












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