中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

CEPC

Measurement of $B^0_{(s)} \to \pi^0\pi^0$ at CEPC

Yuexin Wang, Manqi Ruan

Outline

1. Motivation
2. Separation of B^0 and Bs
3. Results at a benchmark detector setup
4. Dependence on b-tagging performance
5. Dependence on ECAL energy resolution
6. Summary

Motivation

From physics aspect

- **"B→ππ puzzle", the measured branching ratio of the $B^0 \to \pi^0\pi^0$ is significantly larger than the theoretical predictions.**
- **$B_s \to \pi^0\pi^0$, a pure annihilation process, BR ~10^{-7}, has not been observed.**
- **Tera-Z at CEPC with 10^{11} B0 and 10^{10} Bs, at least 1-2 orders larger than Belle-II**

Modes	DATA [1]	SCET [2]	QCDF	pQCD
$B^+ \to \pi^+\pi^0$	5.5 ± 0.4	5.20 ± 2.71	$6.00^{+3.76}_{-3.07}$	$4.27^{+1.85}_{-1.47}$
$B^0 \to \pi^+\pi^-$	5.12 ± 0.19	5.40 ± 1.95	$8.90^{+5.55}_{-4.71}$	$7.67^{+3.27}_{-2.67}$
$B^0 \to \pi^0\pi^0$	1.59 ± 0.26	0.84 ± 0.46	$0.30^{+0.46}_{-0.26}$	$0.24^{+0.09}_{-0.07}$
$B^0_s \to \pi^+\pi^-$	0.7 ± 0.1	-	$0.26^{+0.10}_{-0.09}$	$0.52^{+0.21}_{-0.18}$
$B^0_s \to \pi^0\pi^0$	< 210	-	$0.13^{+0.05}_{-0.05}$	$0.21^{+0.10}_{-0.09}$

Table 1: Experimental mesaurements and theoretical predictions of the branching ratios (in unit of 10^{-6}) of $B \to \pi\pi$ system. The soft collinear effective theory (SCET), QCD factorization (QCDF), and perturbative QCD (pQCD) are three common theoretical techniques to deal with the hadronic B-meson decays.

From detector aspect

Clear dependence on the detector performance

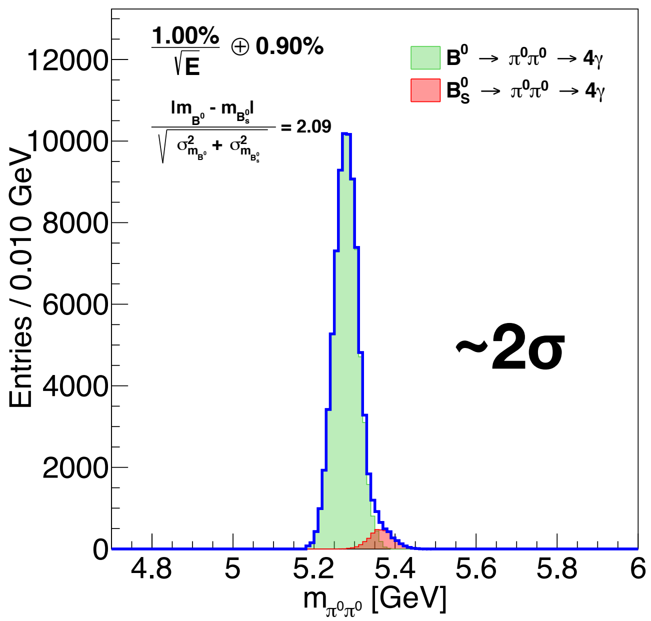
- **ECAL energy resolution**
- **b-tagging**

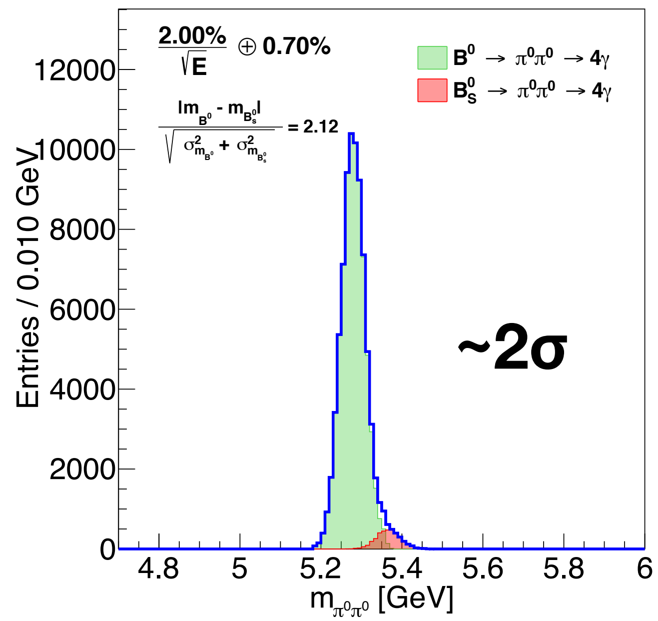
The Fast Simulation Analysis

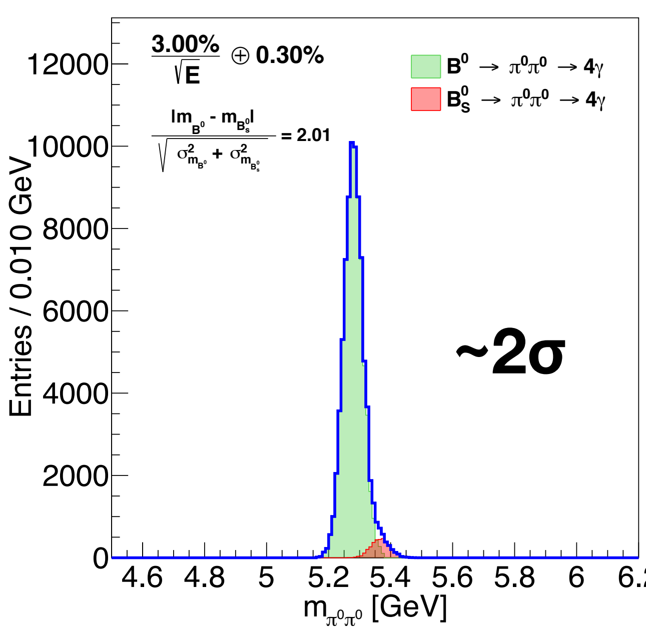
Separation of B⁰ and Bs

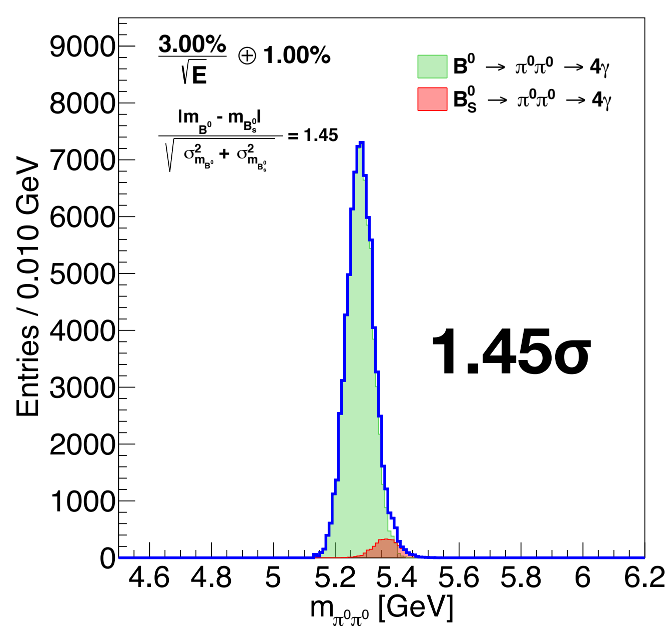
$m_{B^0} = 5279.63 \pm 0.15 MeV$ $m_{B_s^0} = 5366.89 \pm 0.19 MeV$

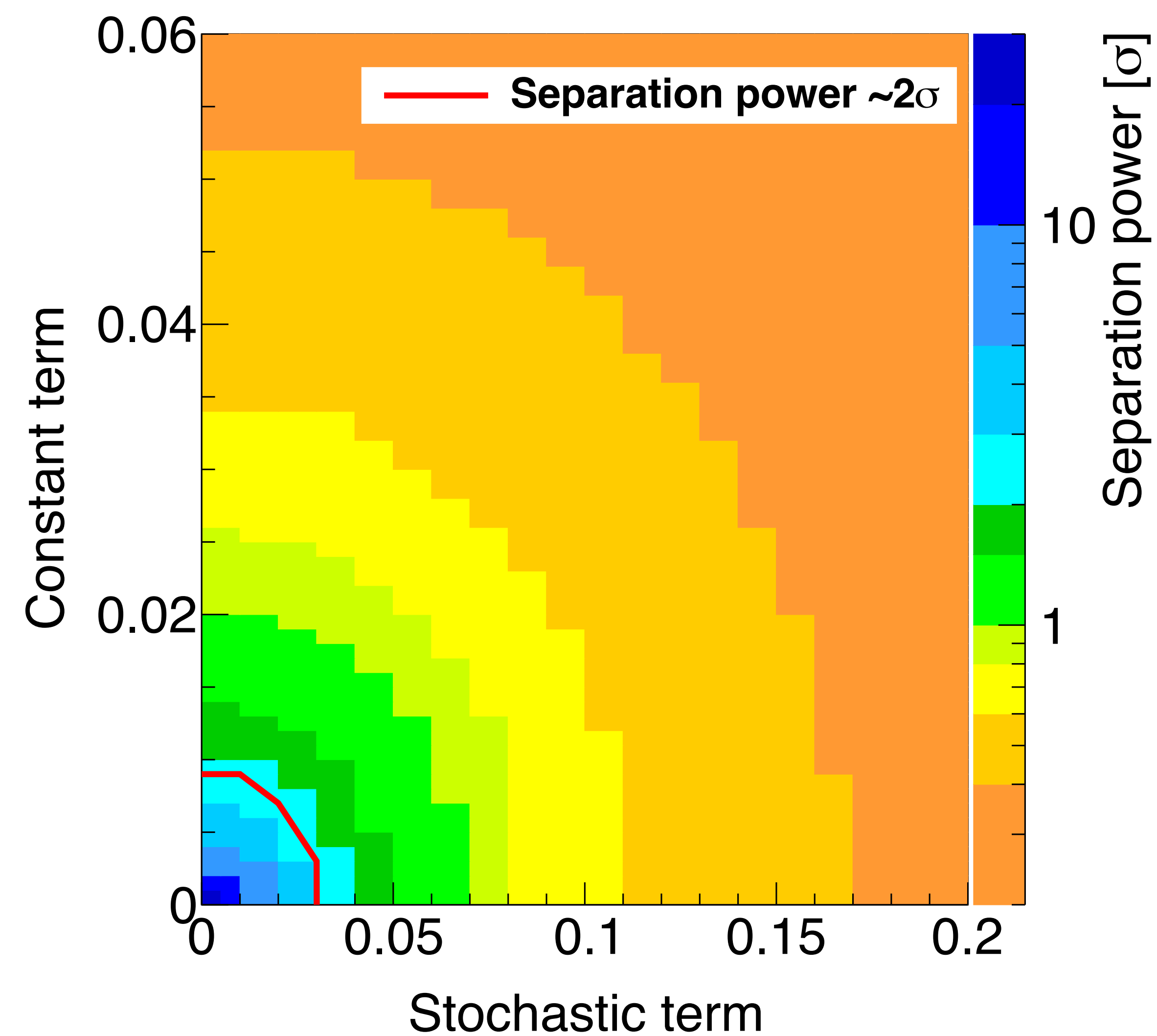
$$separation\ power = \frac{|\bar{m_{B^0}} - \bar{m_{B_s^0}}|}{\sqrt{\sigma^2_{m_{B^0}} + \sigma^2_{m_{B_s^0}}}}$$











A 2σ separation requires ECAL energy resolution better than 3%/√E⊕0.3%

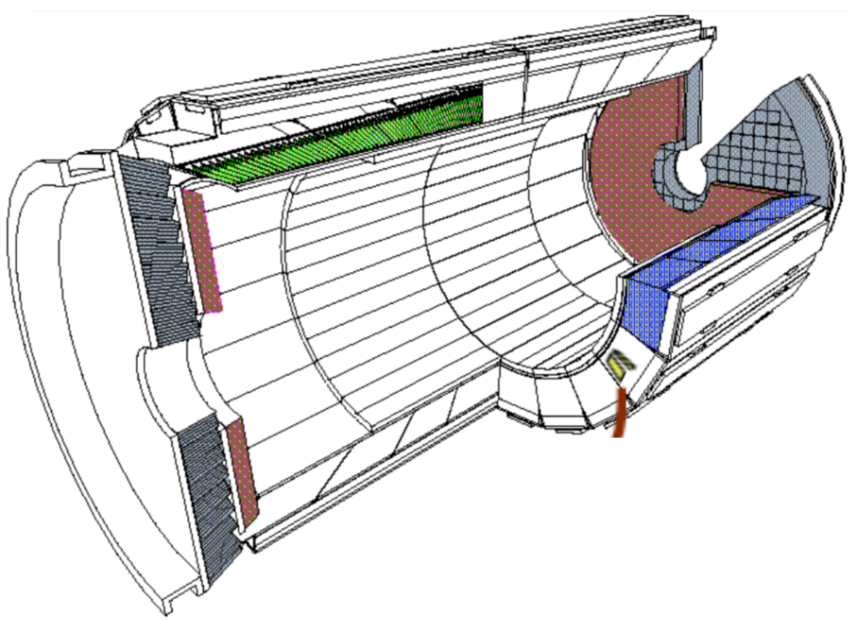
Results at a benchmark detector setup

A benchmark detector setup for $B^0_{(s)} \to \pi^0\pi^0$ measurement

ECAL energy resolution

$$3\,\%/\sqrt{E} \oplus 0.3\,\%$$

LHC - CMS ($PbWO_4$)



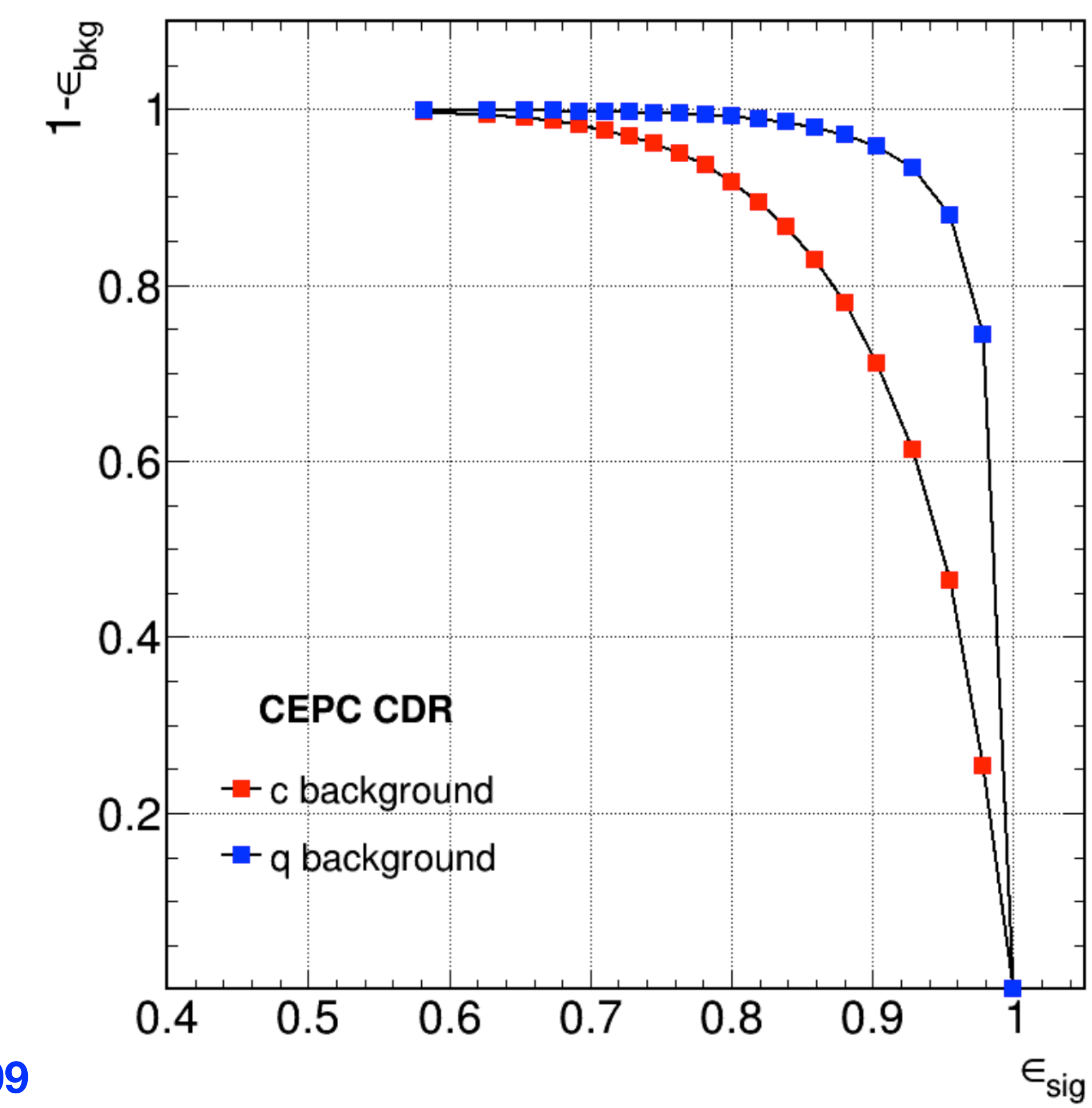
$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{12\%}{E(\mathrm{GeV})} \oplus 0.3\%$$

https://iopscience.iop.org/article/10.1088/1748-0221/8/09/P09009

b-tagging

CEPC baseline b-tagging

80% efficiency and 90% purity



Results at a benchmark detector setup

Cut chain table at 3%/√E⊕1%

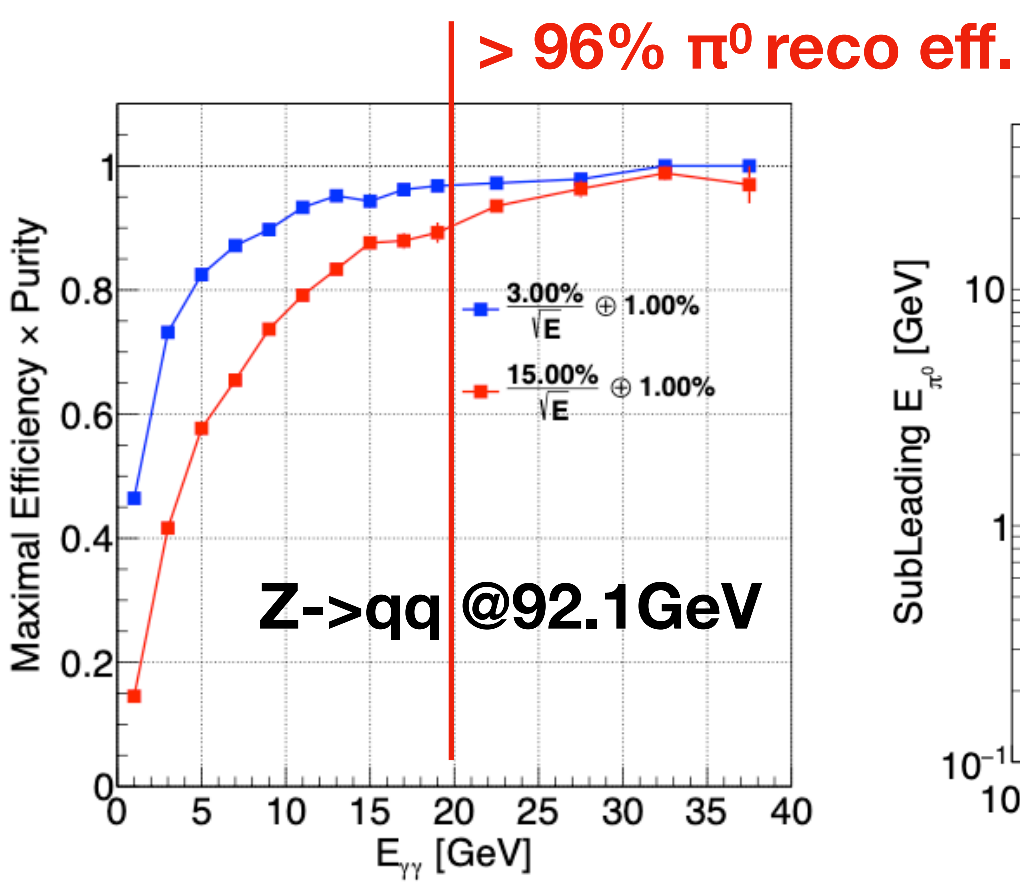
Cut chain	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
Total generated	191113	8948	7e11 (100.00%)	4.285e11 (61.21%)	1.203e11 (17.19%)	1.512e11 (21.60%)	
b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	152890	7158	1.34539e11 (100.00%)	3.64225e9 (2.70%)	9.93678e9 (7.38%)	1.2096e11 (89.92%)	
$\gamma\gamma \to \pi^0$	147885	6959	134270678121	3604997126	9908325272	120757355723	
Lower $E_{\pi^0} > 6$ GeV	92188	4398	15487349997	843612892	1598239684	13045497420	
Higher $E_{\pi^0} > 14$ GeV	87011	4149	2534464124	307686545	314766931	1912010648	
$E_{\pi^0\pi^0} > 22$ GeV	86745	4133	2233495276	289735018	281660057	1662100201	
$\theta_{\pi^0\pi^0} < 23^{o}$	77579	3644	825533789	119057502	102062343	604413944	
$m_{\pi^0\pi^0} \in (5.2163, 5.3429)$ GeV (1.5 $\sigma_{m_{B^0}}$=1.5×0.0422GeV)	69430	1015	20389	5664	1555	13170	0.4341% ± 0.0121%
$m_{\pi^0\pi^0} \in (5.3110, 5.4228)$ GeV (1.3 $\sigma_{m_{B_s^0}}$=1.3×0.0430GeV)	24197	3028	11174	4632	1082	5461	6.4708% ± 0.3558%

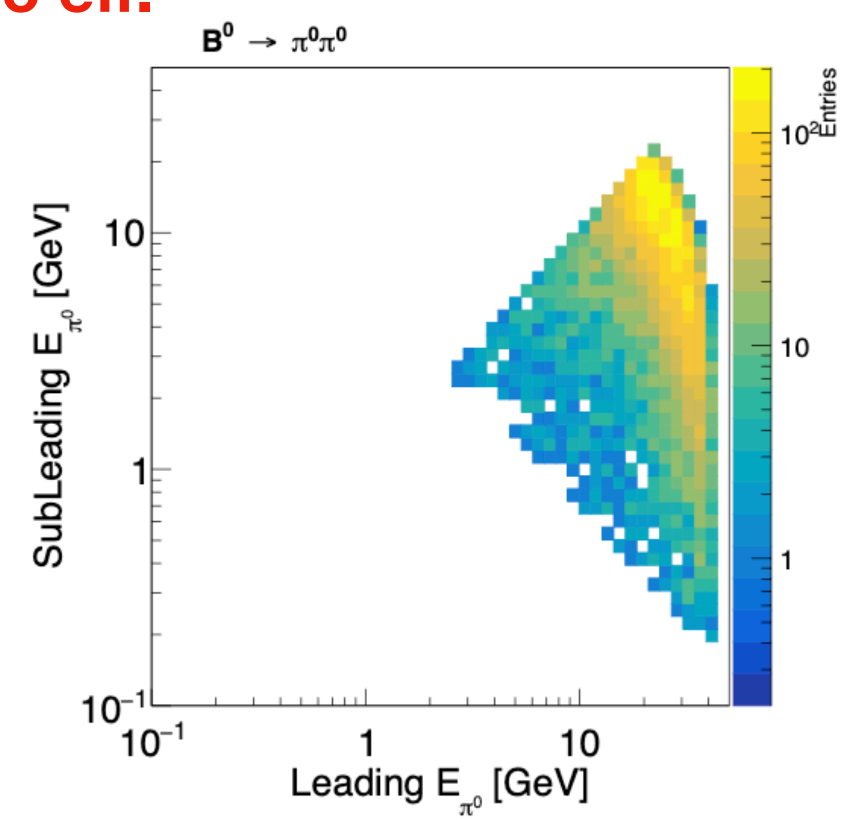
Numerical values used to estimate the signal statistics at Tera-Z.

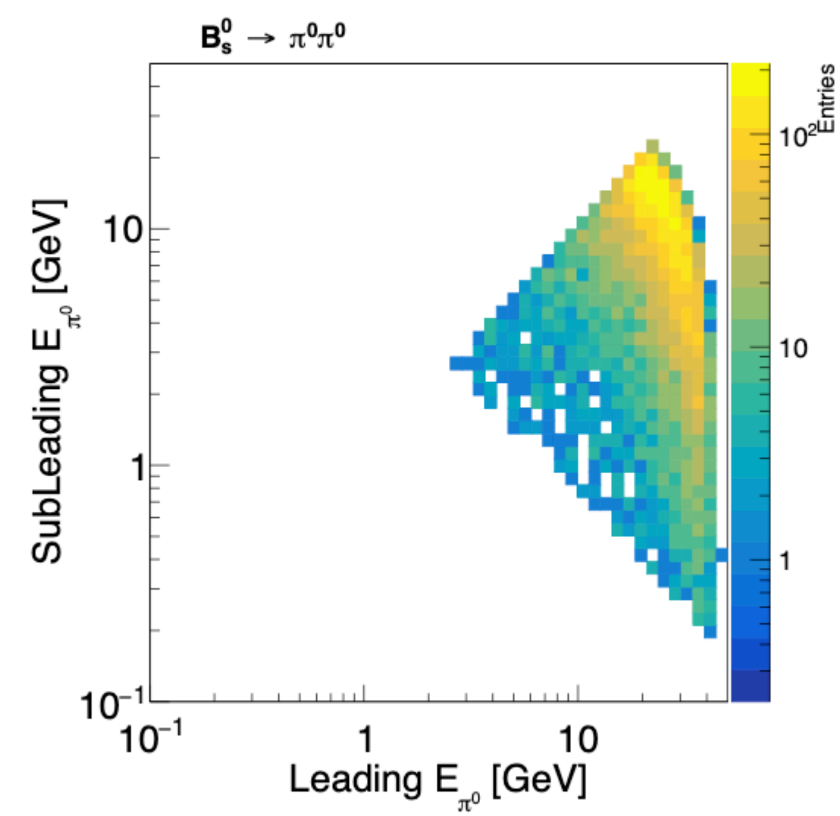
$f(b \to B^0)$	0.407 ± 0.007	
$f(b \to B_s^0)$	0.101 ± 0.008	
$Br(B^0 \to \pi^0\pi^0)$	1.59×10^{-6}	
$Br(B_s^0 \to \pi^0\pi^0)$	3×10^{-7}	SM prediction
$Br(\pi^0 \to \gamma\gamma)$	98.823%	

Results at a benchmark detector setup

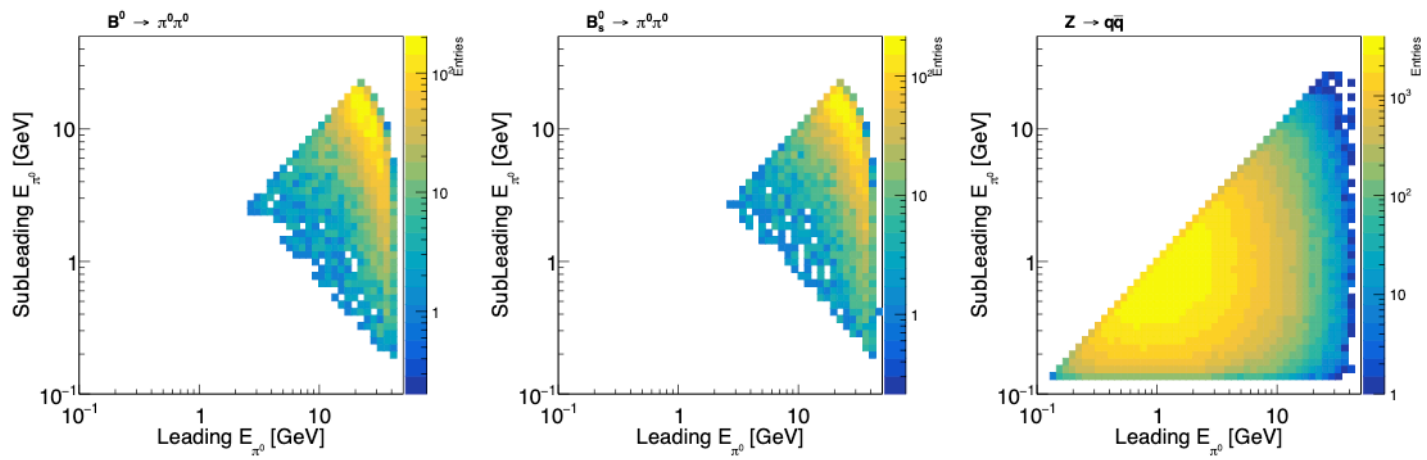
Cut chain	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
Total generated	191113	8948	7e11 (100.00%)	4.285e11 (61.21%)	1.203e11 (17.19%)	1.512e11 (21.60%)	
b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	152890	7158	1.34539e11 (100.00%)	3.64225e9 (2.70%)	9.93678e9 (7.38%)	1.2096e11 (89.92%)	
$\gamma\gamma \to \pi^0$	147885	6959	134270678121	3604997126	9908325272	120757355723	
Lower $E_{\pi^0} > 6$ GeV	92188	4398	15487349997	843612892	1598239684	13045497420	
Higher $E_{\pi^0} > 14$ GeV	87011	4149	2534464124	307686545	314766931	1912010648	
$E_{\pi^0\pi^0} > 22$ GeV	86745	4133	2233495276	289735018	281660057	1662100201	
$\theta_{\pi^0\pi^0} < 23^o$	77579	3644	825533789	119057502	102062343	604413944	
$m_{\pi^0\pi^0} \in (5.2163, 5.3429)$ GeV ($1.5\ \sigma_{m_{B^0}} = 1.5\times0.0422$GeV)	69430	1015	20389	5664	1555	13170	0.4341% ± 0.0121%
$m_{\pi^0\pi^0} \in (5.3110, 5.4228)$ GeV ($1.3\ \sigma_{m_{B_s^0}} = 1.3\times0.0430$GeV)	24197	3028	11174	4632	1082	5461	6.4708% ± 0.3558%



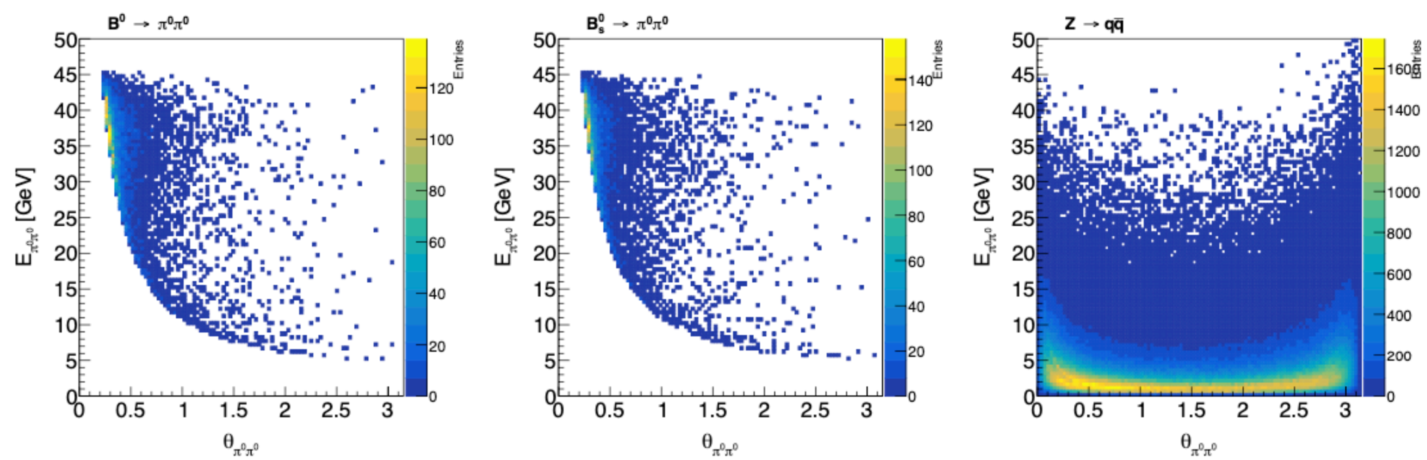




Results at a benchmark detector setup



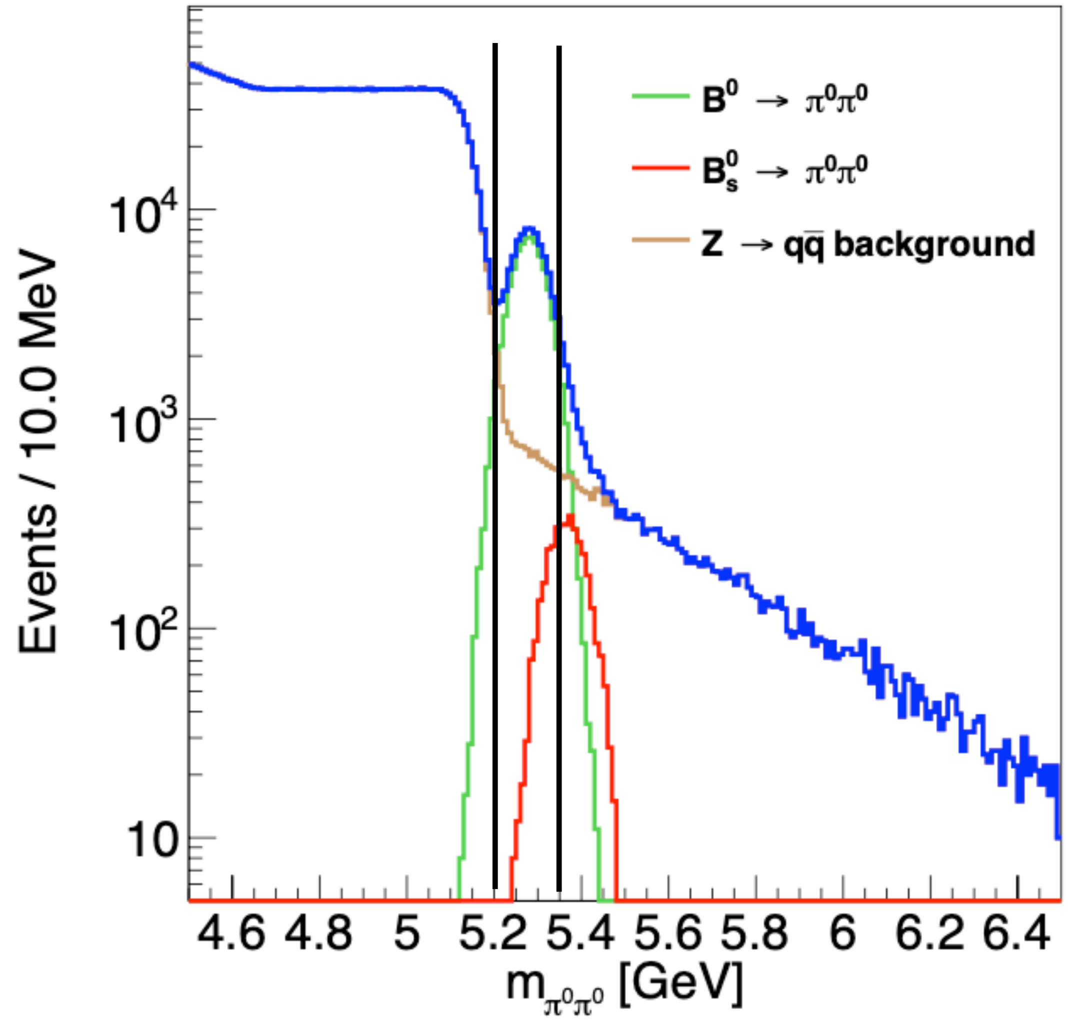
(a) Energy spectrum of π^0 pairs in $B^0 \to \pi^0\pi^0$ (left), $B_s^0 \to \pi^0\pi^0$ (middle), and $Z \to q\bar{q}$ (right) events.



(b) $\theta_{\pi^0\pi^0}$ vs $E_{\pi^0\pi^0}$ in $B^0 \to \pi^0\pi^0$ (left), $B_s^0 \to \pi^0\pi^0$ (middle), and $Z \to q\bar{q}$ (right) events.

Cut chain	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}$+$d\bar{d}$+$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
Total generated	191113	8948	7e11 (100.00%)	4.285e11 (61.21%)	1.203e11 (17.19%)	1.512e11 (21.60%)	
b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	152890	7158	1.34539e11 (100.00%)	3.64225e9 (2.70%)	9.93678e9 (7.38%)	1.2096e11 (89.92%)	
$\gamma\gamma \to \pi^0$	147885	6959	134270678121	3604997126	9908325272	120757355723	
Lower E_{π^0} > 6 GeV	92188	4398	15487349997	843612892	1598239684	13045497420	
Higher E_{π^0} > 14 GeV	87011	4149	2534464124	307686545	314766931	1912010648	
$E_{\pi^0\pi^0}$ > 22 GeV	86745	4133	2233495276	289735018	281660057	1662100201	
$\theta_{\pi^0\pi^0} < 23^o$	77579	3644	825533789	119057502	102062343	604413944	
$m_{\pi^0\pi^0} \in$ (5.2163, 5.3429) GeV ($1.5\ \sigma_{m_{B^0}}$=1.5×0.0422GeV)	69430	1015	20389	5664	1555	13170	0.4341% ± 0.0121%
$m_{\pi^0\pi^0} \in$ (5.3110, 5.4228) GeV ($1.3\ \sigma_{m_{B_s^0}}$=1.3×0.0430GeV)	24197	3028	11174	4632	1082	5461	6.4708% ± 0.3558%

Results at a benchmark detector setup



Cut chain	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}$+$d\bar{d}$+$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
Total generated	191113	8948	7e11 (100.00%)	4.285e11 (61.21%)	1.203e11 (17.19%)	1.512e11 (21.60%)	
b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	152890	7158	1.34539e11 (100.00%)	3.64225e9 (2.70%)	9.93678e9 (7.38%)	1.2096e11 (89.92%)	
$\gamma\gamma \to \pi^0$	147885	6959	134270678121	3604997126	9908325272	120757355723	
Lower E_{π^0} > 6 GeV	92188	4398	15487349997	843612892	1598239684	13045497420	
Higher E_{π^0} > 14 GeV	87011	4149	2534464124	307686545	314766931	1912010648	
$E_{\pi^0\pi^0}$ > 22 GeV	86745	4133	2233495276	289735018	281660057	1662100201	
$\theta_{\pi^0\pi^0}$ < 23°	77579	3644	825533789	119057502	102062343	604413944	
$m_{\pi^0\pi^0} \in$ (5.2163, 5.3429) GeV (1.5 $\sigma_{m_{B^0}}$=1.5×0.0422GeV)	69430	1015	20389	5664	1555	13170	0.4341% ± 0.0121%
$m_{\pi^0\pi^0} \in$ (5.3110, 5.4228) GeV (1.3 $\sigma_{m_{B_s^0}}$=1.3×0.0430GeV)	24197	3028	11174	4632	1082	5461	6.4708% ± 0.3558%

Optimized mass window

Dependence on b-tagging performance

3 b-tagging conditions, at 3%/√E⊕1%

Accuracy

$B^0 \to \pi^0\pi^0$

b-tagging	Mass window (GeV)	n σ_{m_B}	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
No b-tagging ($\epsilon_{b,c,uds\to b}$ = 100%, 100%, 100%)	(5.2290, 5.3303)	1.2	80570	922	595976	564730	17595	13652	1.0216% ± 0.0337%
CEPC baseline b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	(5.2163, 5.3429)	1.5	69430	1015	20389	5664	1555	13170	0.4341% ± 0.0121%
Ideal b-tagging ($\epsilon_{b,c,uds\to b}$ = 100%, 0%, 0%)	(5.2163, 5.3429)	1.5	86788	1269	16462	0	0	16462	0.3725% ± 0.0056%

Bs $\to \pi^0\pi^0$

b-tagging	Mass window (GeV)	n σ_{m_B}	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
No b-tagging ($\epsilon_{b,c,uds\to b}$ = 100%, 100%, 100%)	(5.3110, 5.4228)	1.3	30246	3785	564884	544965	13094	6826	20.4443% ± 0.7425%
CEPC baseline b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	(5.3110, 5.4228)	1.3	24197	3028	11174	4632	1082	5461	6.4708% ± 0.3558%
Ideal b-tagging ($\epsilon_{b,c,uds\to b}$ = 100%, 0%, 0%)	(5.3110, 5.4228)	1.3	30246	3785	6826	0	0	6826	5.3398% ± 0.1432%

No b-tagging —(2~3 times)→ **CEPC baseline b-tagging** —(~1.2 times, comparable)→ **Ideal b-tagging**

b-tagging is essential to reduce the hard combinatory background in non-b events

Dependence on b-tagging performance

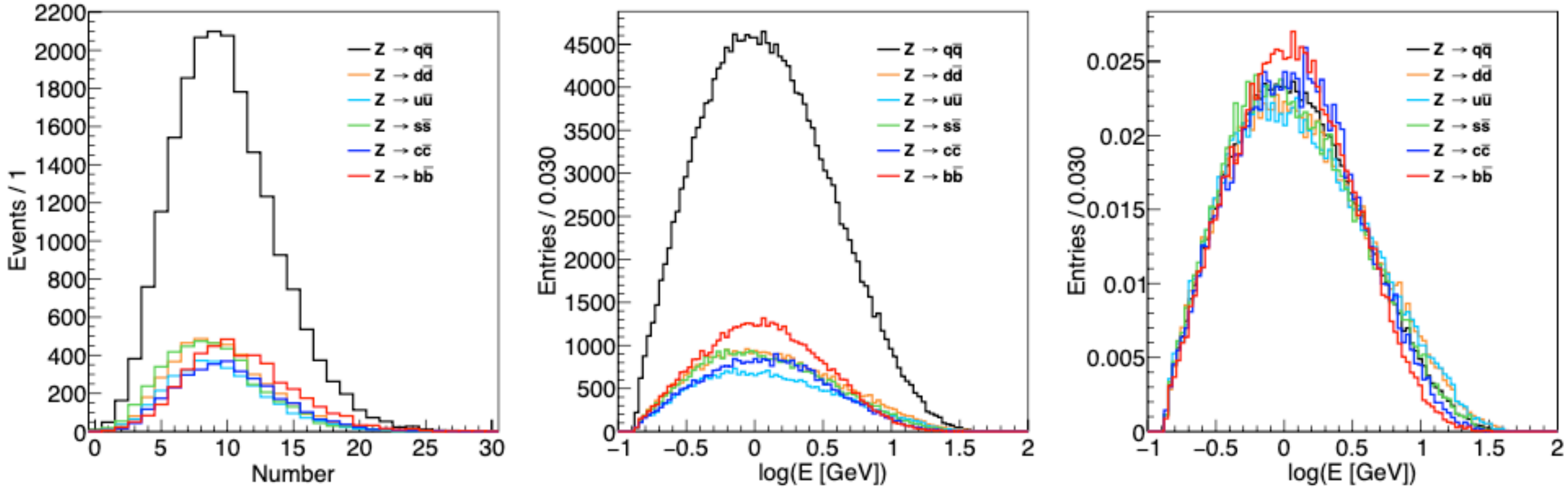
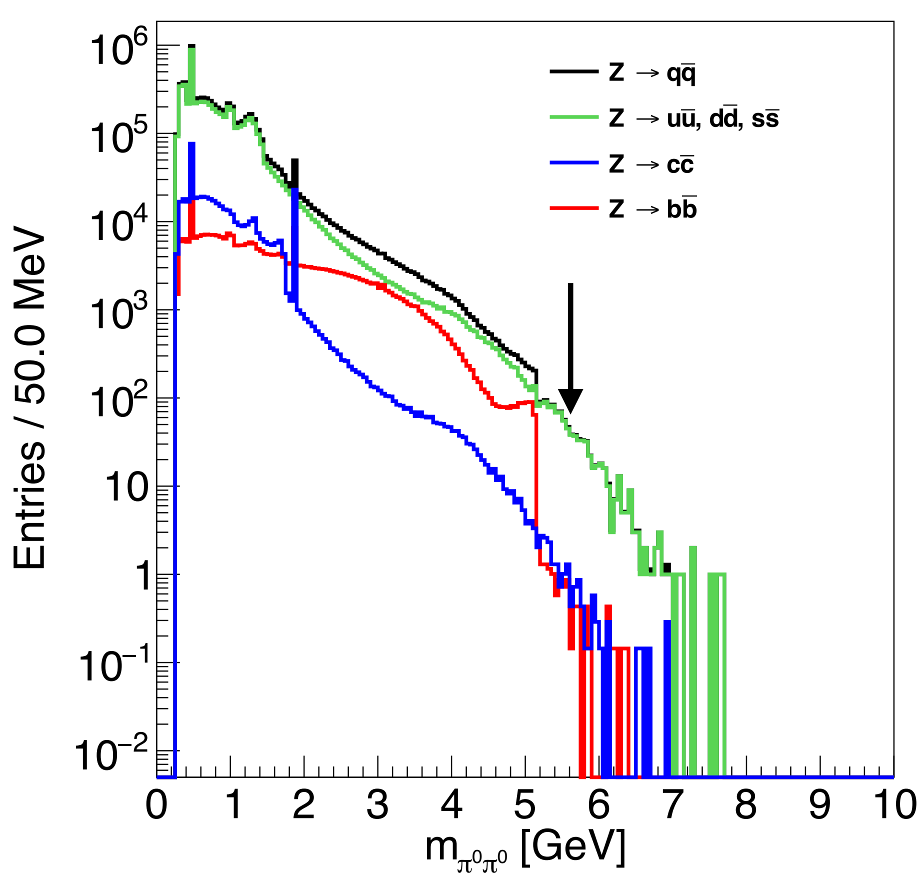
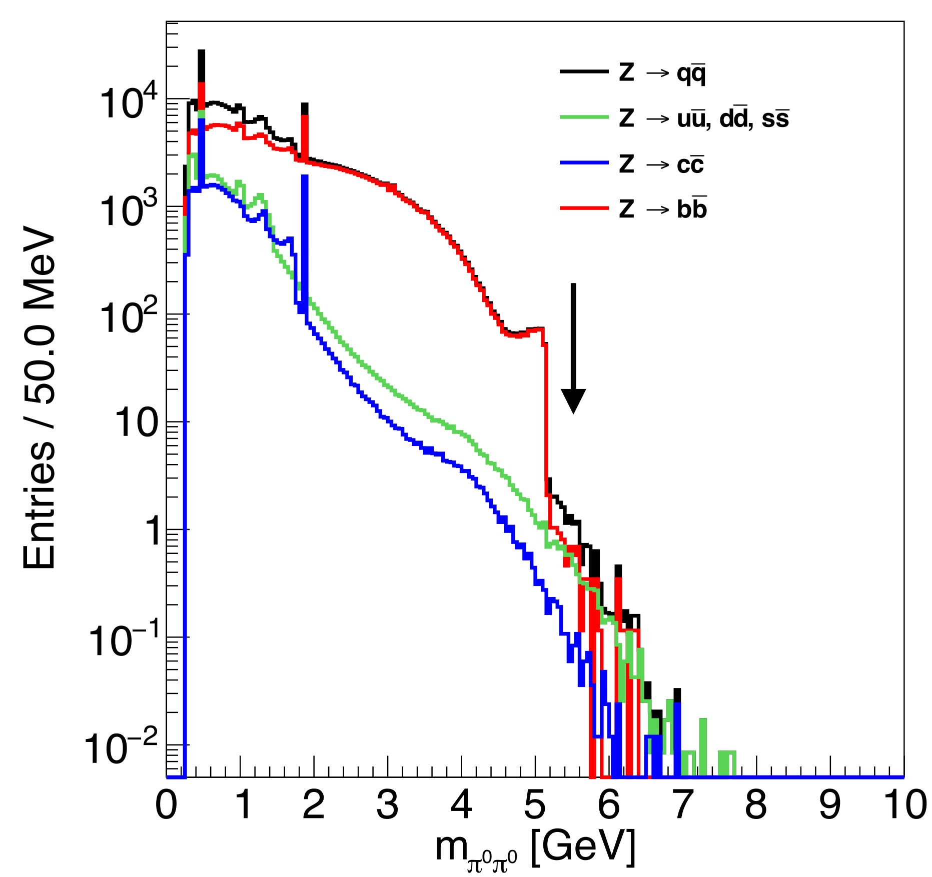


Figure 4: Number (left) and energy spectrum of π^0 in the form of log(E) in $Z \to q\bar{q}$ events with different quark flavors.

No b-tagging



CEPC baseline b-tagging



Dependence on ECAL energy resolution

with CEPC baseline b-tagging

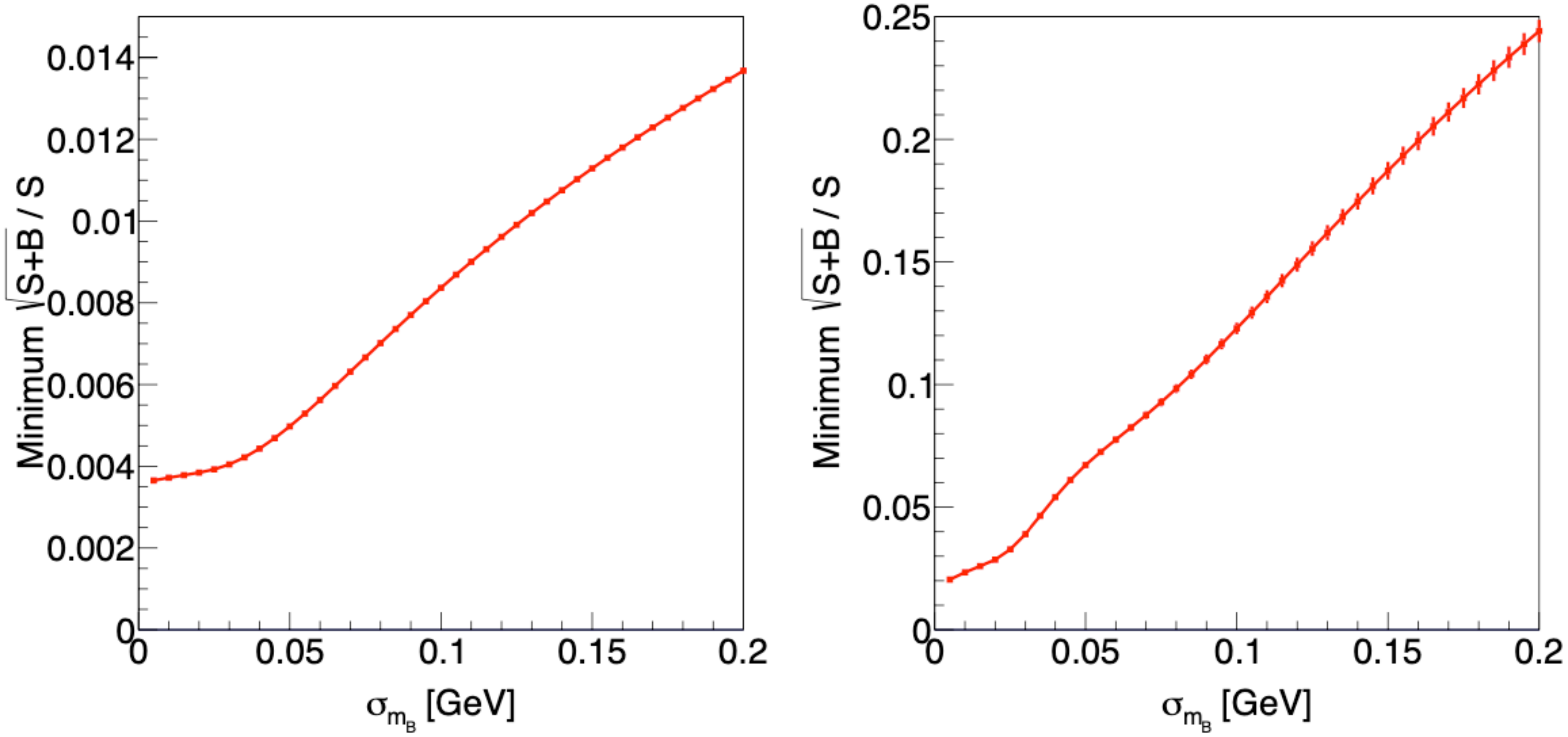
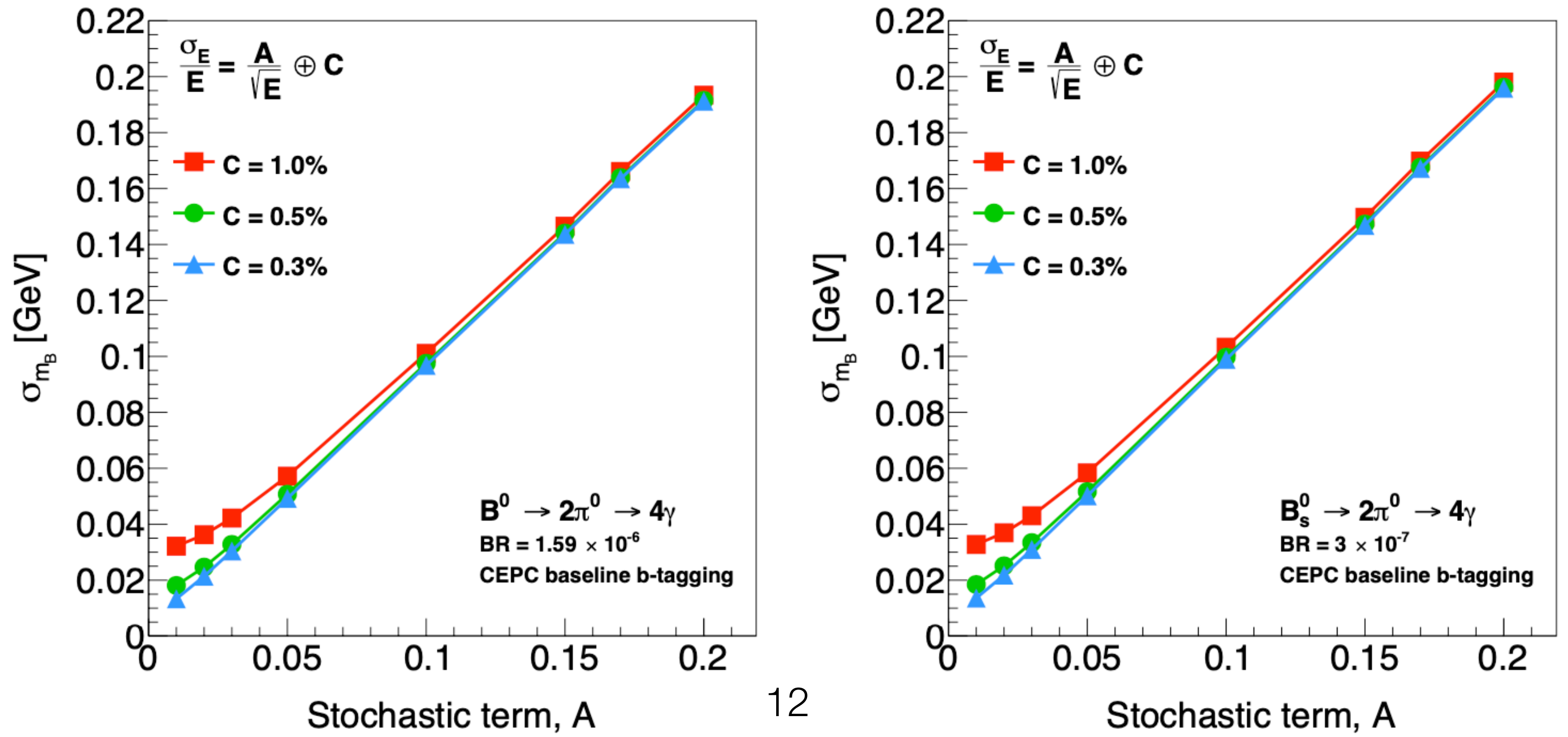


Figure 13: Accuracy of $B^0 \to \pi^0\pi^0$ (left) and $B_s^0 \to \pi^0\pi^0$ (right) vs σ_{m_B} (GeV).



Summary

$B^0_{(s)} \to \pi^0\pi^0$ are important to understand

- $B \to \pi\pi$ puzzle
- annihilation mechanism (in $B_s \to \pi^0\pi^0$)

Fast Simulation is used to study the dependence of $B^0_{(s)} \to \pi^0\pi^0$ accuracy on

b-tagging:

- essential to reduce the hard combinatory background in non-b events

Accuracy at $3\%/\sqrt{E} \oplus 1\%$	$B^0 \to \pi^0\pi^0$	$B_s \to \pi^0\pi^0$
No b-tagging	1.02%	20.44%
CEPC baseline b-tagging	0.43%	6.47%

2~3 times improvement

ECAL energy resolution:

- A 2σ separation of B0 and Bs requires ECAL energy resolution better than $3\%/\sqrt{E} \oplus 0.3\%$

Accuracy with CEPC baseline b-tagging	$B^0 \to \pi^0\pi^0$	$B_s \to \pi^0\pi^0$
$17\%/\sqrt{E} \oplus 1\%$	~1.20%	~20%
$3\%/\sqrt{E} \oplus 1\%$	0.43%	6.47%
$3\%/\sqrt{E} \oplus 0.3\%$	~0.40%	~4%

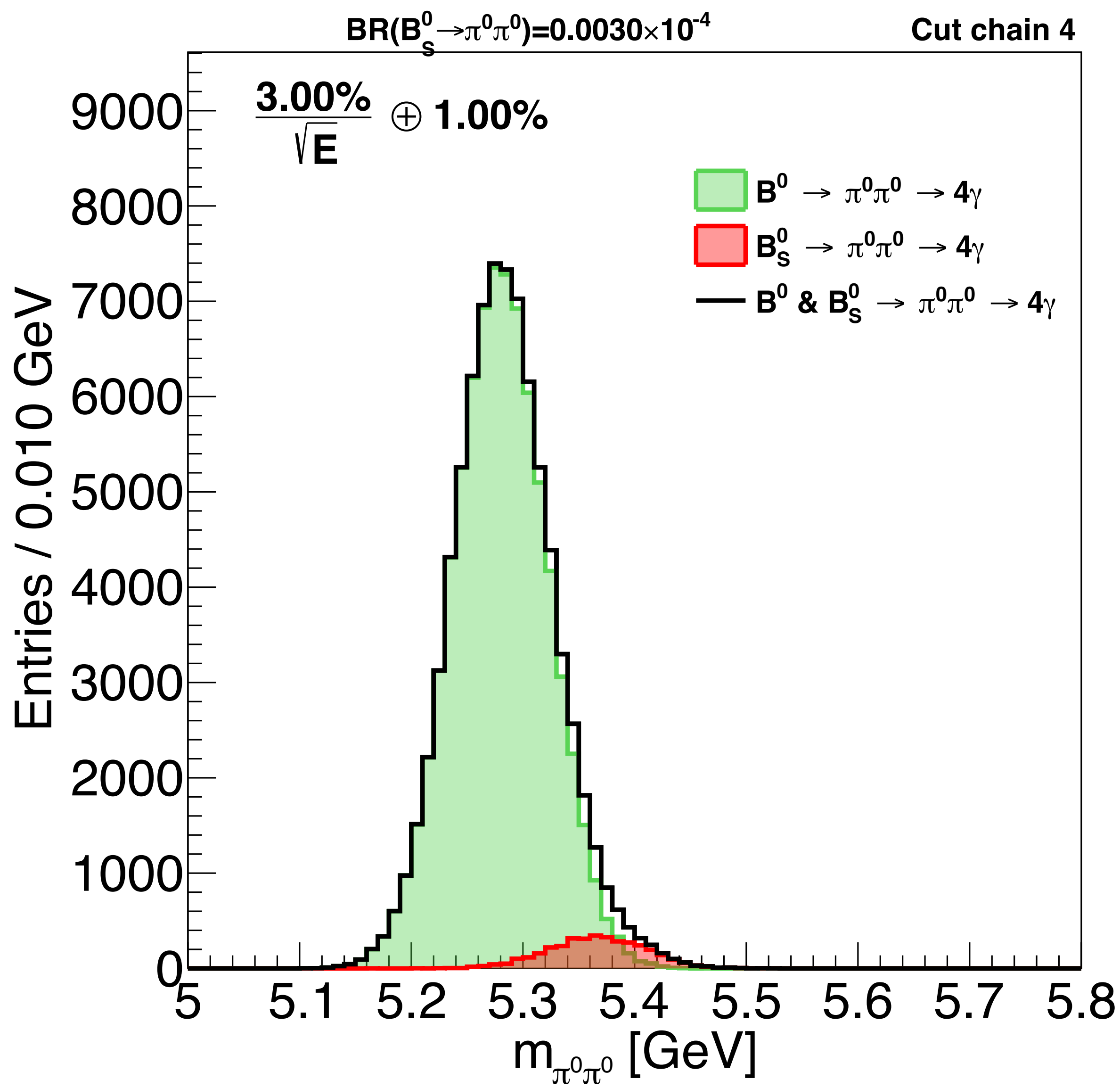
3 times improvement

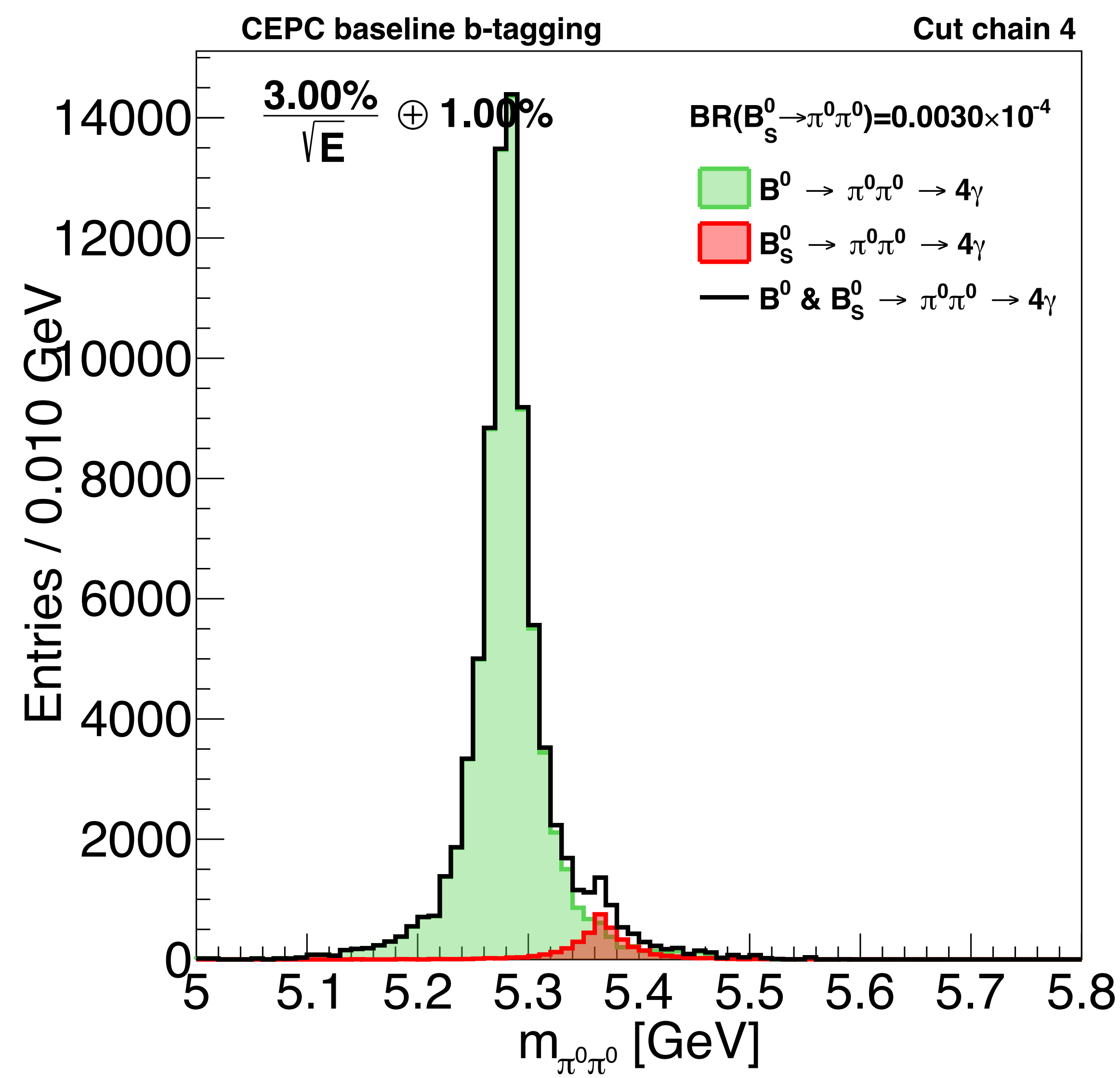
Thanks!

Backup

Kinematic Fit

at 3%/√E⊕1% ECAL resolution





Signal peak gets sharpened after Kinematic Fit

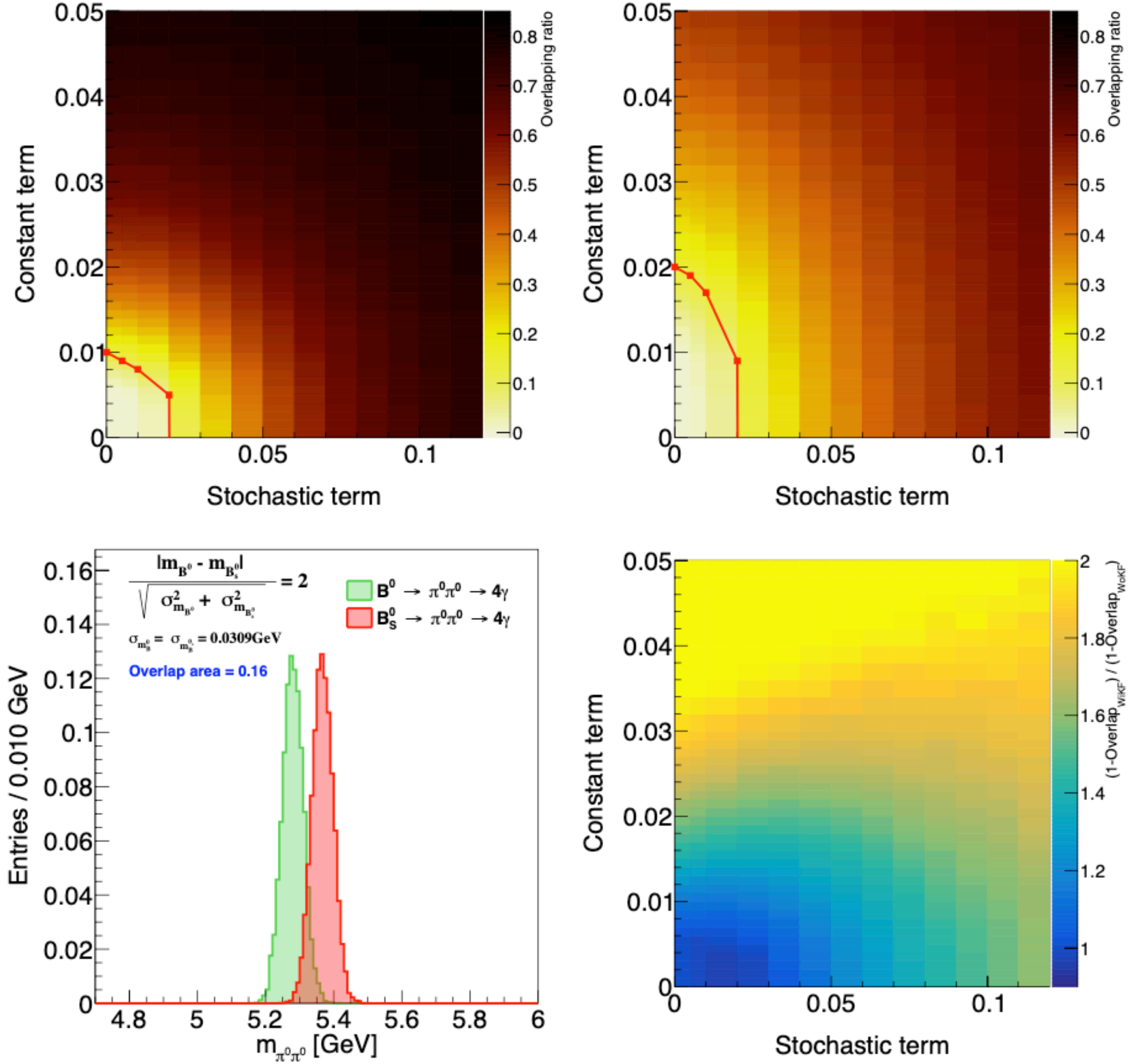
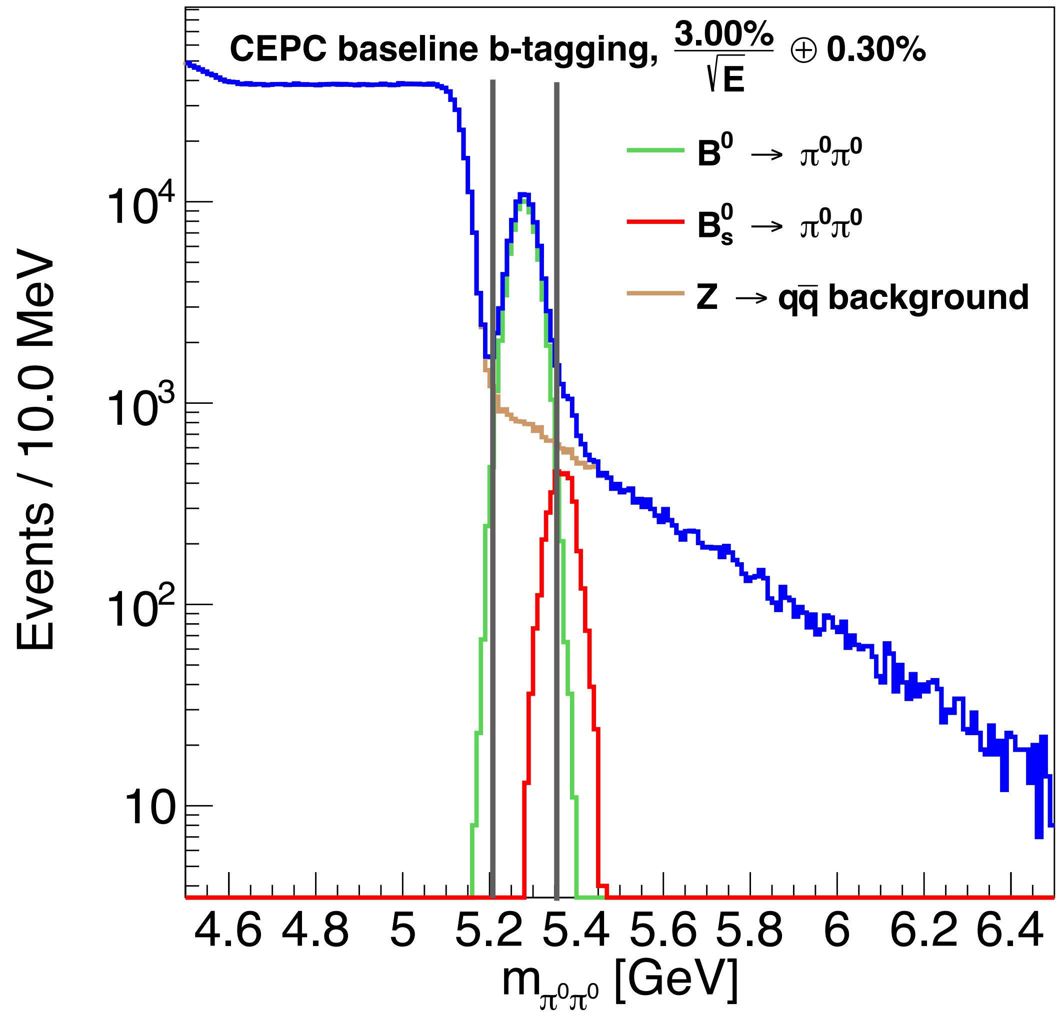


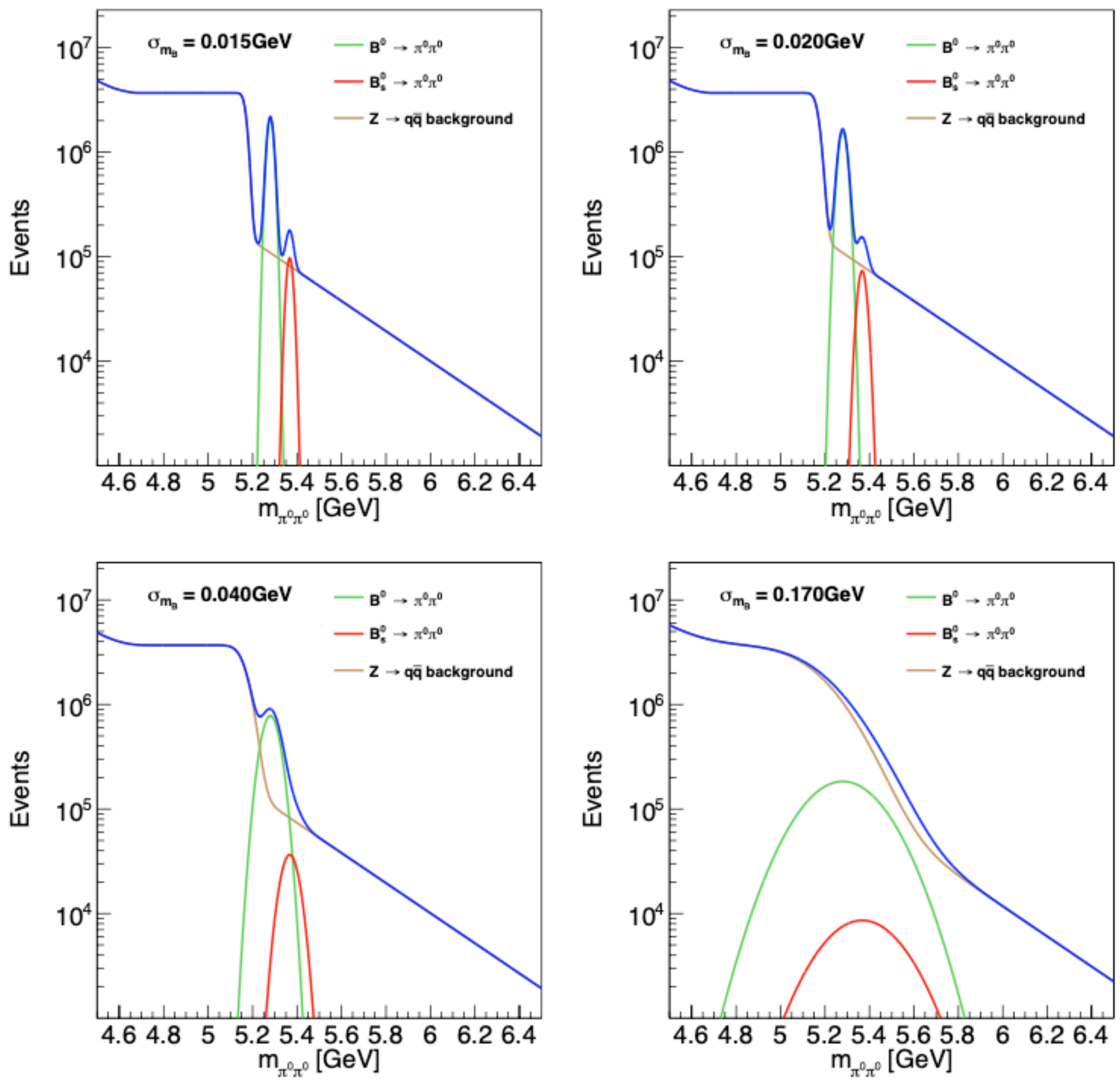
Figure 14: Separation power (overlapping area) at different ECAL resolutions wo/wi kinematic fit.

Results at a benchmark detector setup



Cut chain	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}$+$d\bar{d}$+$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
Total generated	191113	8948	7e11 (100.00%)	4.285e11 (61.21%)	1.203e11 (17.19%)	1.512e11 (21.60%)	
b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	152890	7158	1.34539e11 (100.00%)	3.64225e9 (2.70%)	9.93678e9 (7.38%)	1.2096e11 (89.92%)	
$\gamma\gamma \to \pi^0$	147885	6959	134270678121	3604997126	9908325272	120757355723	
Lower E_{π^0} > 6 GeV	92188	4398	15487349997	843612892	1598239684	13045497420	
Higher E_{π^0} > 14 GeV	87011	4149	2534464124	307686545	314766931	1912010648	
$E_{\pi^0\pi^0}$ > 22 GeV	86745	4133	2233495276	289735018	281660057	1662100201	
$\theta_{\pi^0\pi^0} < 23^o$	77579	3644	825533789	119057502	102062343	604413944	
$m_{\pi^0\pi^0} \in$ (5.2163, 5.3429) GeV (1.5 $\sigma_{m_{B^0}}$=1.5×0.0422GeV)	69430	1015	20389	5664	1555	13170	0.4341% ± 0.0121%
$m_{\pi^0\pi^0} \in$ (5.3110, 5.4228) GeV (1.3 $\sigma_{m_{B_s^0}}$=1.3×0.0430GeV)	24197	3028	11174	4632	1082	5461	6.4708% ± 0.3558%

Optimized mass window



σ_{m_B} = 0.015GeV
σ_{m_B} = 0.020GeV
σ_{m_B} = 0.040GeV
σ_{m_B} = 0.170GeV
$B^0 \rightarrow \pi^0\pi^0$
$B_s^0 \rightarrow \pi^0\pi^0$
$Z \rightarrow q\bar{q}$ background
Events
$m_{\pi^0\pi^0}$ [GeV]

Fast Simulation Strategy

Currently focus on the energy response

- *Smear E_γ with EM resolution*
- *Simply 10MeV E_γ threshold*

Some effects not included yet…

- *Photon angular resolution (~0.5 mrad, ~1cm)*
- *Di-photon separation (π^0<30GeV , >9 mrad, >1.6cm)*
- *Detector acceptance ($|Cos\theta|$<0.99)*

  Values in parentheses are results of baseline detector as a reference