中国科学院高能物理研究所
Institute of High Energy Physics
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Measurement of $B^0_{(s)} \to \pi^0\pi^0$ at CEPC

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Outline

1. Motivation
2. Separation of B^0 and B^0_s
3. Event selection
4. Dependence on b-tagging performance
5. Dependence on B mass resolution
6. Summary

Motivation

From physics aspect

- $B^0 \to \pi^0\pi^0$ combined with $B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$, golden channels to determine the CKM angle: α (Φ_2)
- "$B \to \pi\pi$ puzzle", the measured branching ratio of the $B^0 \to \pi^0\pi^0$ is significantly larger than the theoretical predictions.
- $B^0_s \to \pi^0\pi^0$, a pure annihilation process, BR ~10^{-7}, has not been observed.
- Tera-Z at CEPC with 10^{11} B^0 and 10^{10} B^0_s, 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

- b-tagging
- ECAL performance

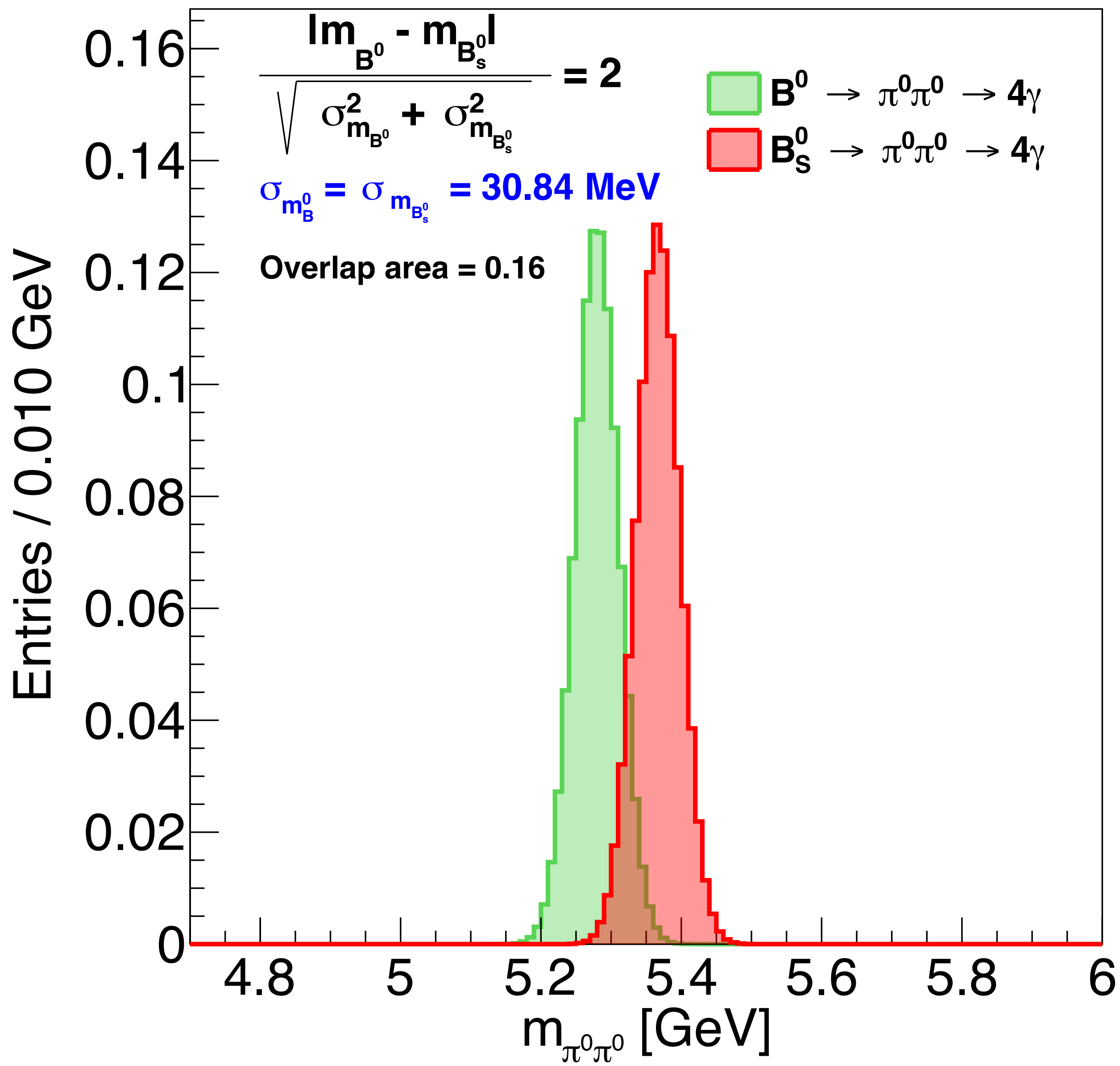
A Fast Simulation Analysis

Separation of B^0 and B^0_s

B meson mass

m_{B^0}	5279.65 ± 0.12 MeV
$m_{B^0_s}$	5366.88 ± 0.14 MeV
$m_{B^0_s} - m_{B^0}$	87.38 ± 0.16 MeV

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

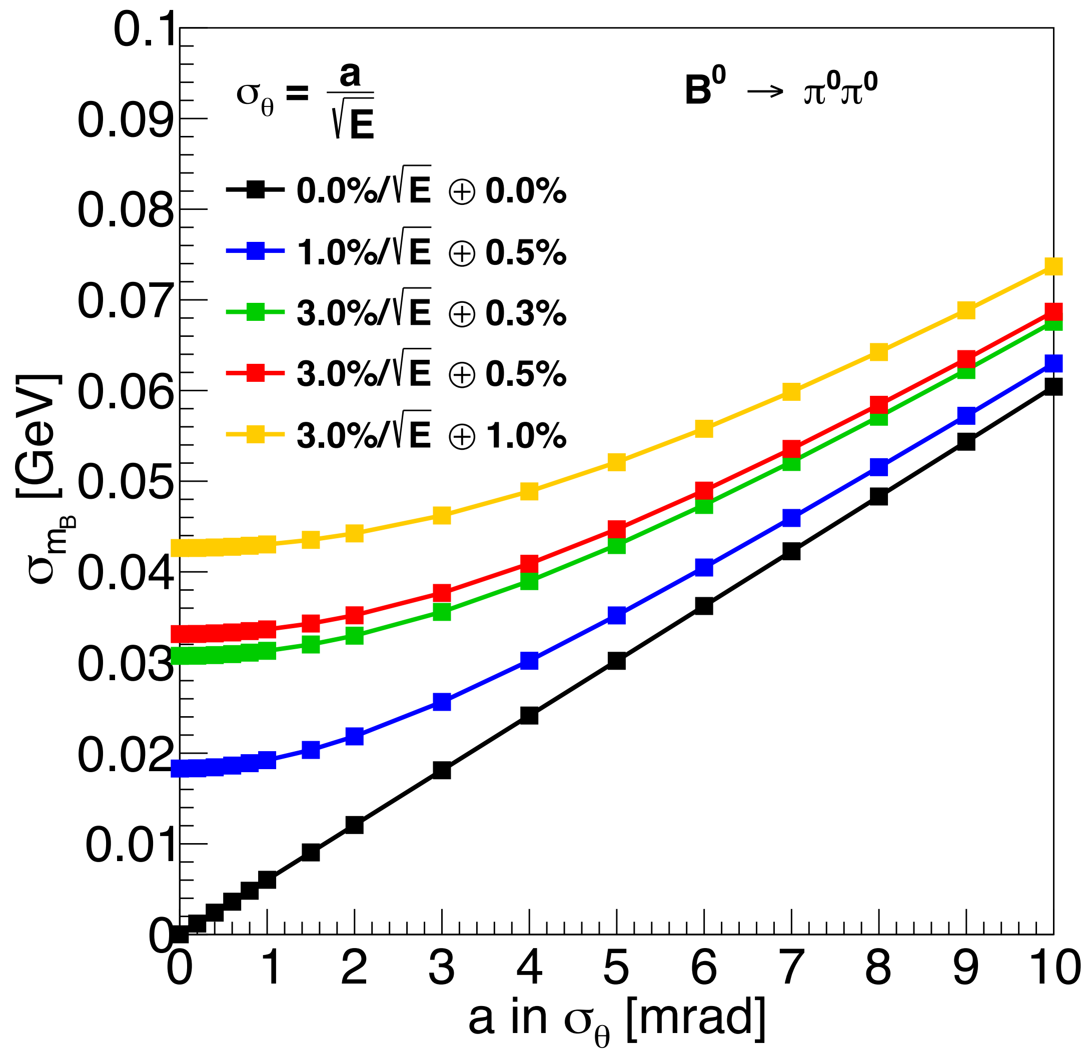


2σ separation requires B mass resolution σ_{mB} better than 30 MeV.

Dependence of B mass resolution on detector performance

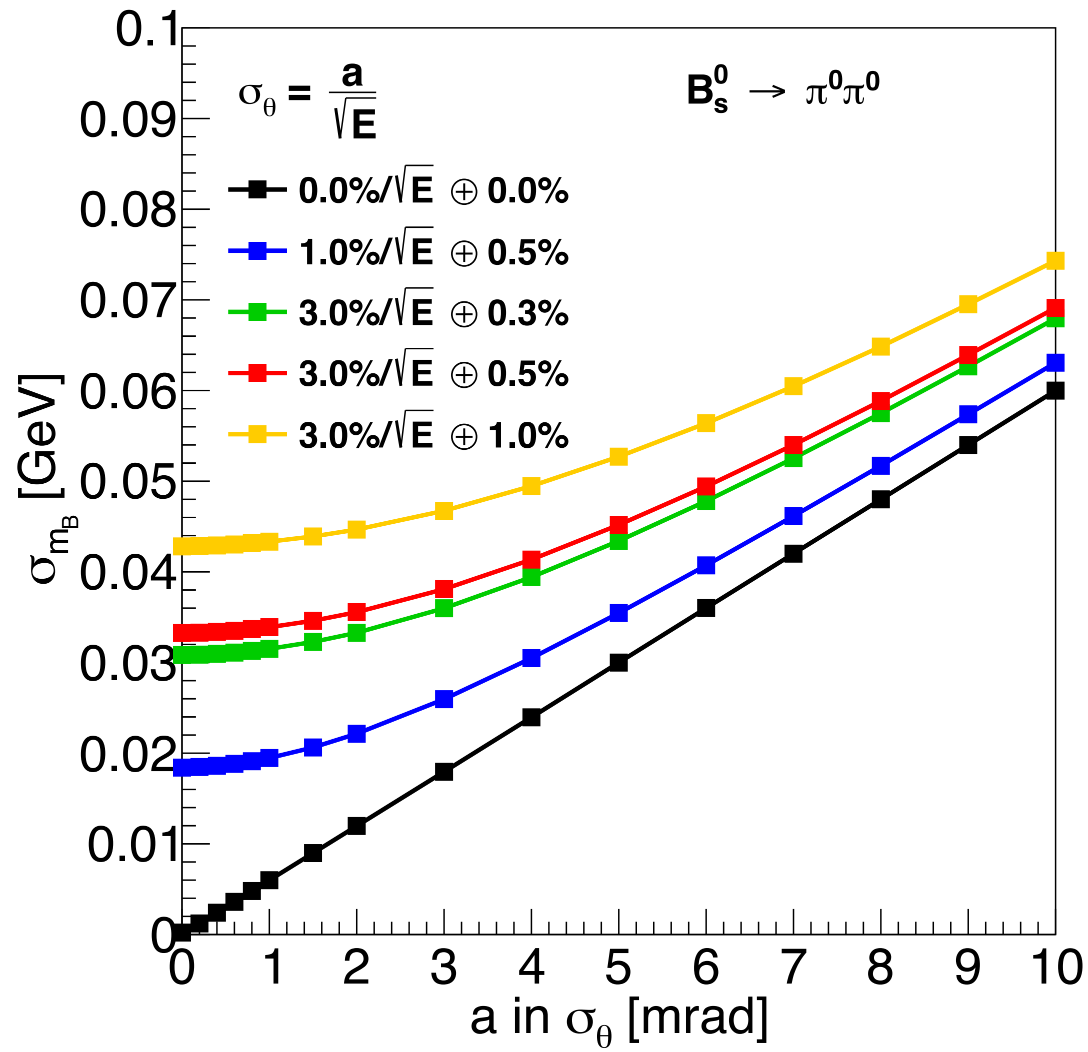
ECAL energy resolution

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus C$$



Photon angular resolution

$$\sigma_\theta = \frac{a}{\sqrt{E}}, \ \sigma_\phi = \frac{\sigma_\theta}{sin\theta}$$

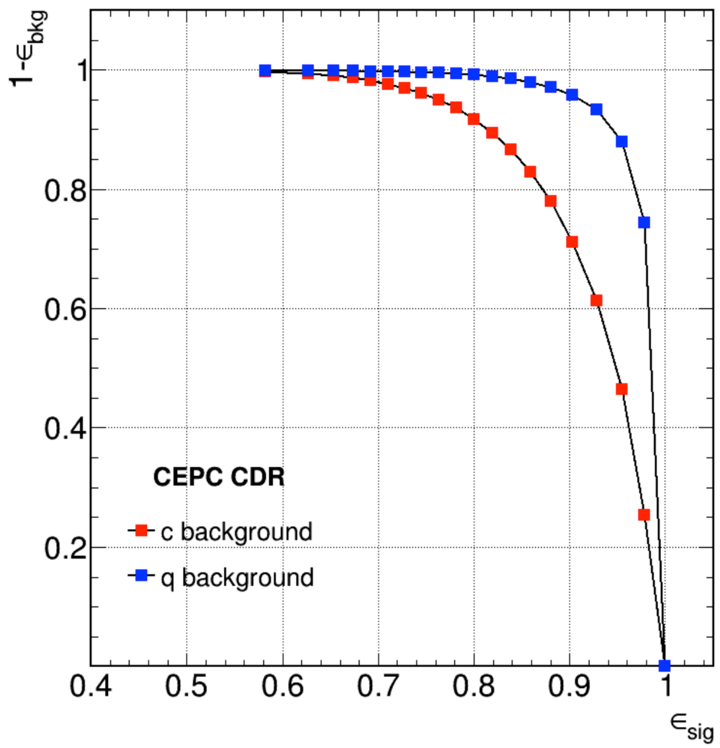


- **CEPC baseline single photon angular resolution ~1mrad/√E**
- **ECAL energy resolution dominates the contribution when σ_θ<1mrad/√E**
- **The following analysis only takes ECAL energy resolution into account**
- **σ_{mB} ~30 MeV requires ECAL energy resolution ~3%/√E⊕0.3%**

Event Selection

CEPC baseline b-tagging

80% efficiency and 90% purity



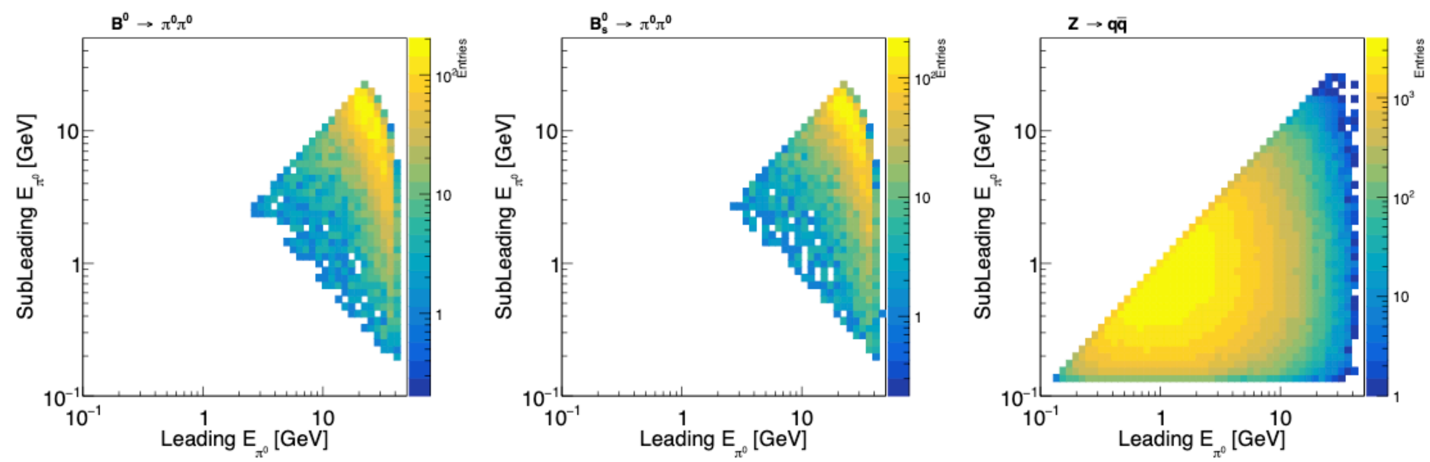
Numerical values used to estimate the signal statistics at Tera-Z.

$f(b \to B^0)$	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%	

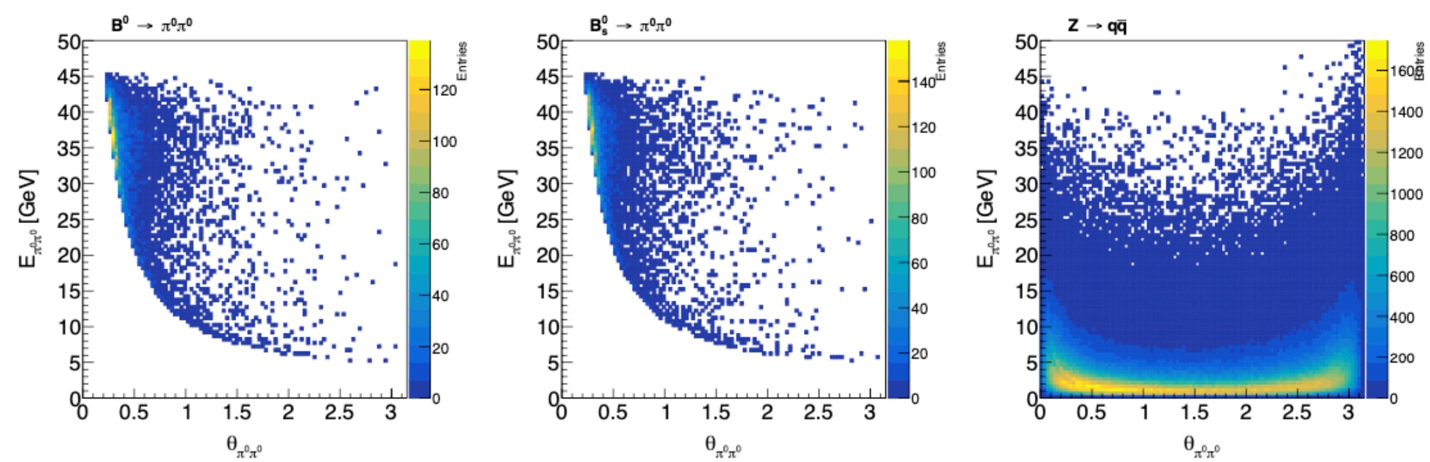
Cut chain table at 3%/√E⊕0.3% & CEPC baseline b-tagging

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%)	
$\pi^0 \to \gamma\gamma$	147932	6959	134272699126	3605151069	9908563142	120758984915	
Lower $E_{\pi^0} > 6$ GeV	92172	4396	15490570779	843830534	1598643569	13048096676	
Higher $E_{\pi^0} > 14$ GeV	87057	4148	2534286670	307734259	314762436	1911789975	
$E_{\pi^0\pi^0} > 22$ GeV	86807	4133	2233308564	289771547	281656846	1661880170	
$\theta_{\pi^0\pi^0} < 23^o$	77626	3644	825367542	119076559	102055313	604235671	
$m_{\pi^0\pi^0} \in (5.2188, 5.3405)$ GeV ($2.0\ \sigma_{m_{B^0}}$=2.0×0.0304GeV)	75374	717	17896	5640	1656	10600	0.4067% ± 0.0106%
$m_{\pi^0\pi^0} \in (5.3421, 5.3917)$ GeV ($0.8\ \sigma_{m_{B_s^0}}$=0.8×0.0310GeV)	3769	2394	5477	2400	507	2570	4.5070% ± 0.5563%

Event Selection



(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	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}$+$d\bar{d}$+$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
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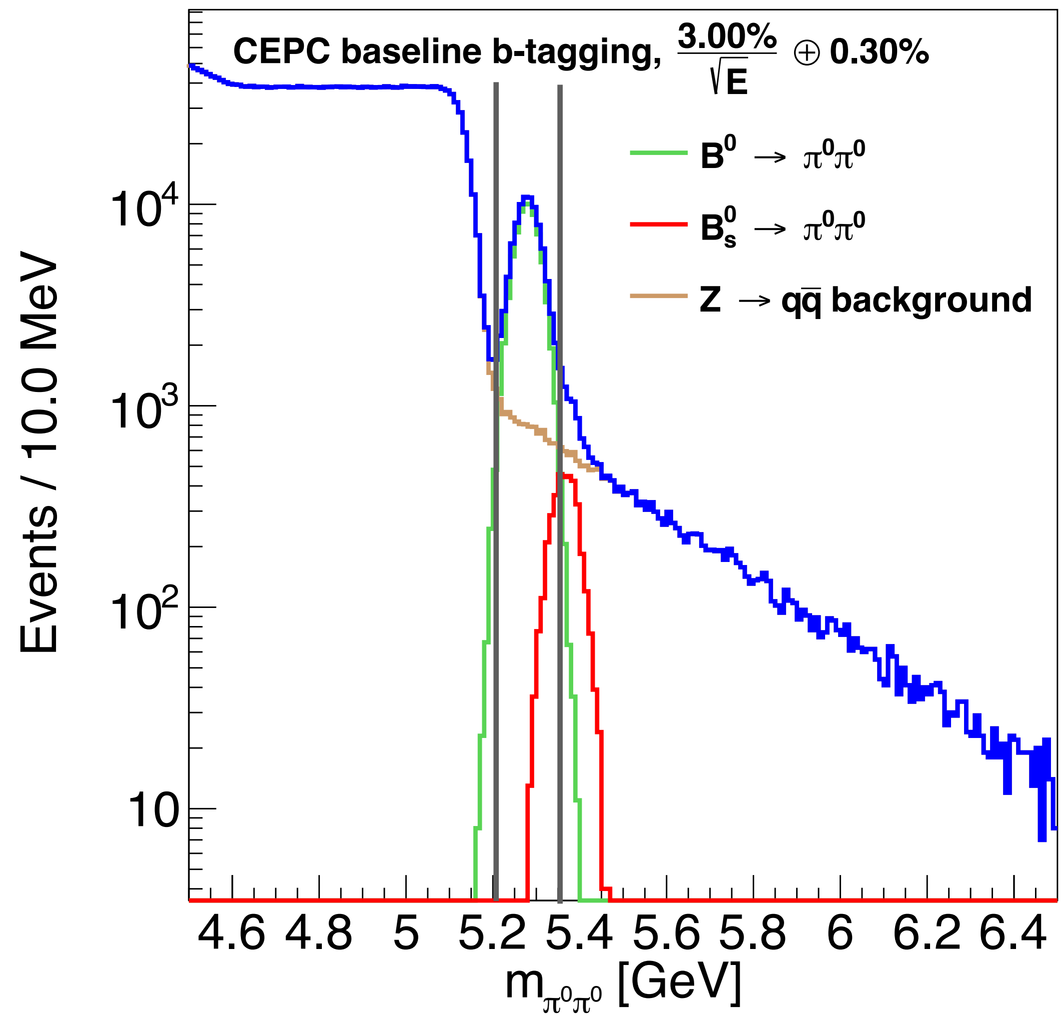
Event Selection



Cut chain	$B^0 \rightarrow \pi^0\pi^0$	$B_s^0 \rightarrow \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
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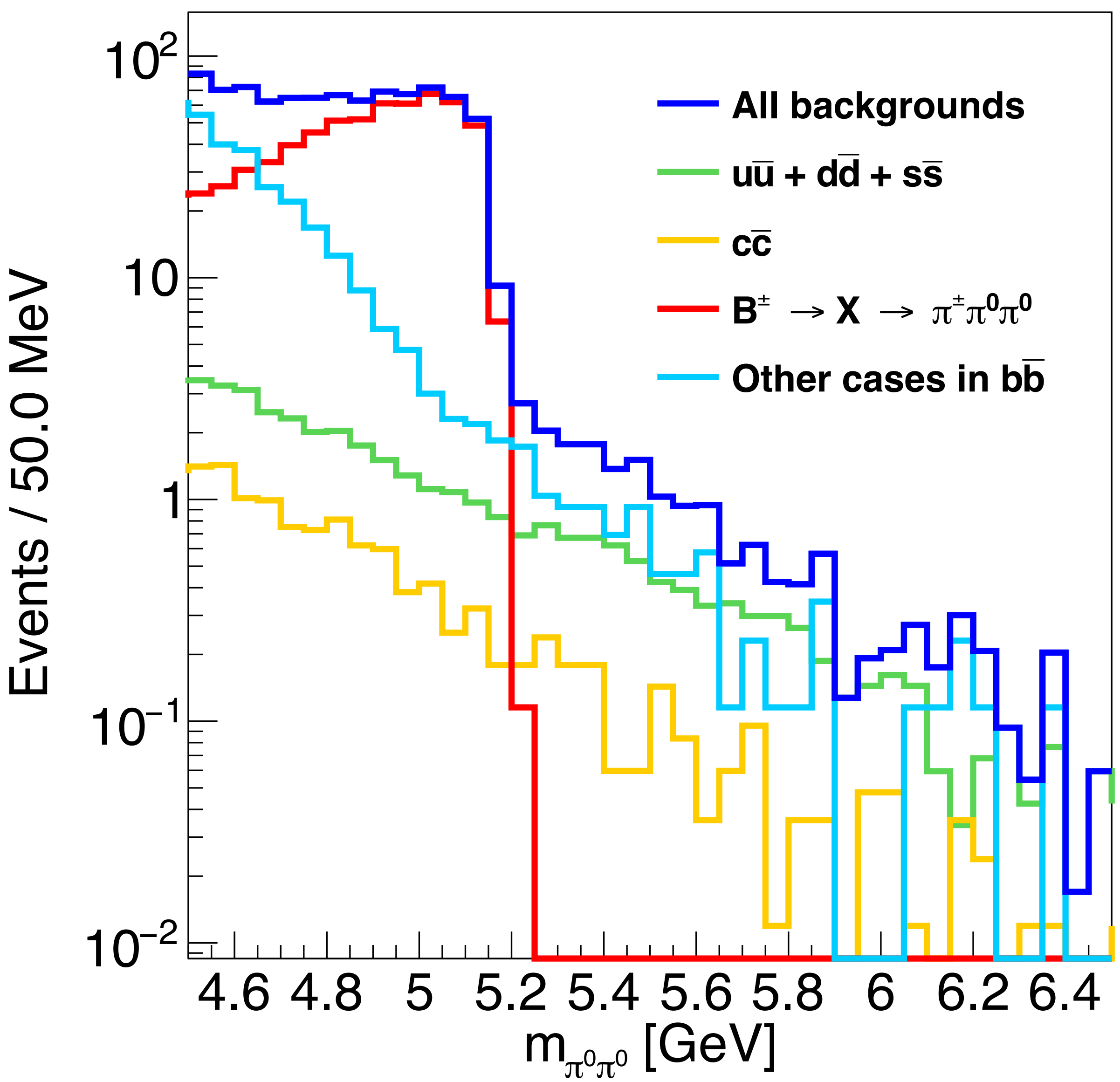
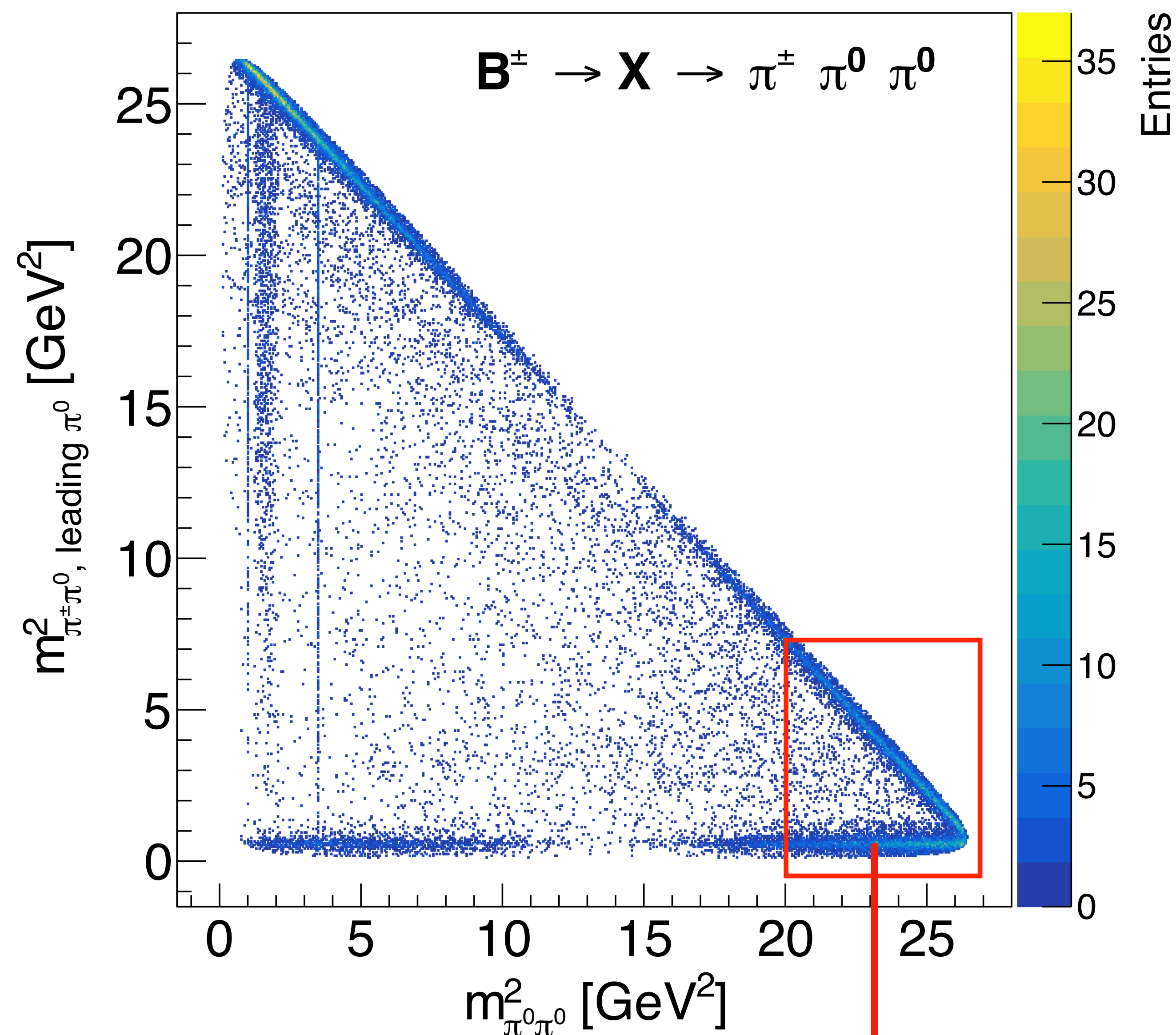
Optimized mass window

Background components





$\sim 93\ \%\ B^{\pm} \rightarrow \rho(770)^{\pm}\pi^{0},\ \rho(770)^{\pm} \rightarrow \pi^{\pm}\pi^{0}$

$\sim 7\ \%\ B^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

Dependence on b-tagging performance

Three b-tagging conditions, at 3%/√E⊕0.3%

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%)	(5.2370, 5.3222)	1.4	85986	311	517718	494139	15549	8030	0.9038% ± 0.0308%
CEPC baseline b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	(5.2188, 5.3405)	2.0	75374	717	17896	5640	1656	10600	0.4067% ± 0.0106%
Ideal b-tagging ($\epsilon_{b,c,uds\to b}$ = 100%, 0%, 0%)	(5.2188, 5.3405)	2.0	94217	896	13250	0	0	13250	0.3494% ± 0.0047%

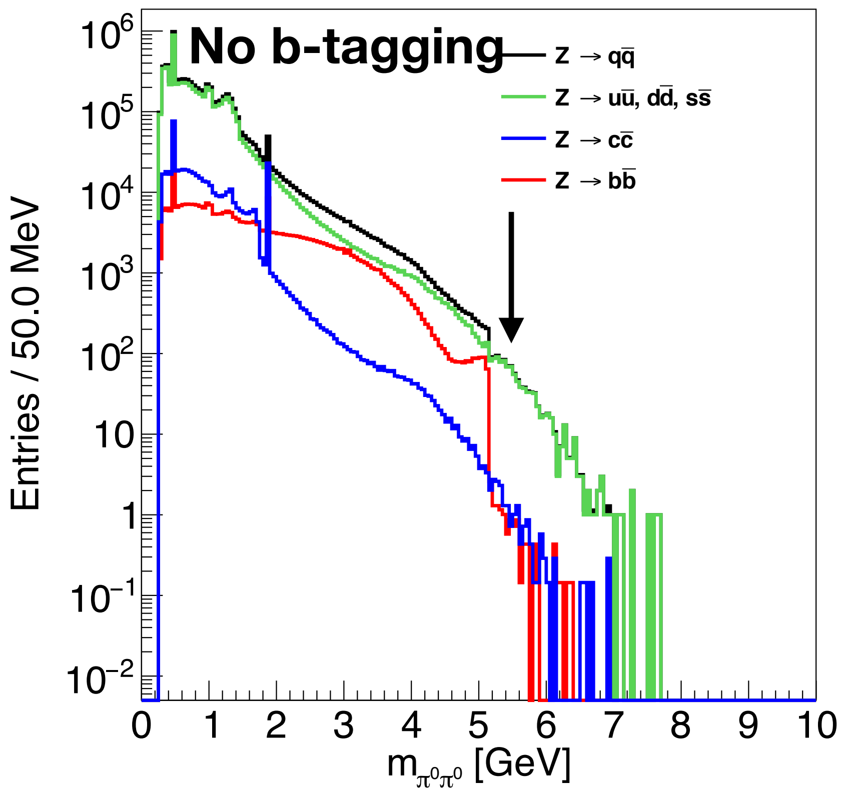
Bs → π°π°

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%)	(5.3328, 5.4010)	1.1	8563	3613	353469	338838	9411	5220	16.7354% ± 0.7580%
CEPC baseline b-tagging ($\epsilon_{b,c,uds\to b}$ = 80%, 8.26%, 0.85%)	(5.3421, 5.3917)	0.8	3769	2394	5477	2400	507	2570	4.5070% ± 0.5563%
Ideal b-tagging ($\epsilon_{b,c,uds\to b}$ = 100%, 0%, 0%)	(5.3421, 5.3917)	0.8	4712	2992	3212	0	0	3212	3.4917% ± 0.1953%

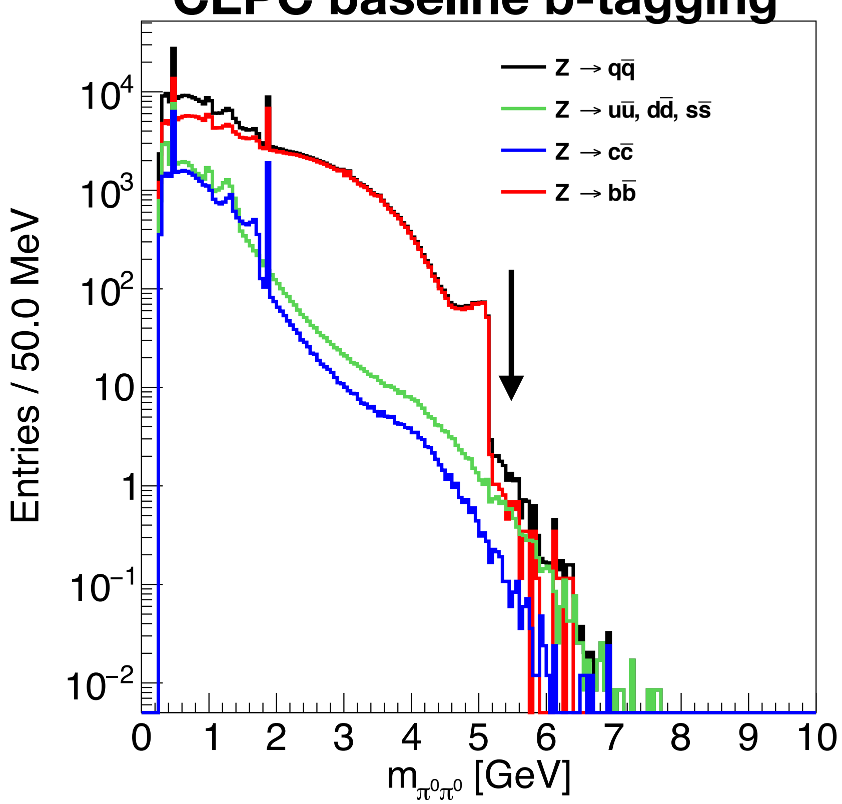
No b-tagging —(2~3 times)→ **CEPC baseline b-tagging** —(~1.2 times, comparable)→ **Ideal b-tagging**

Dependence on b-tagging performance

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



CEPC baseline b-tagging



π^0s in light-quark events (mainly from hadronization) are harder than those in cc and bb events (mainly from c and b hadrons)

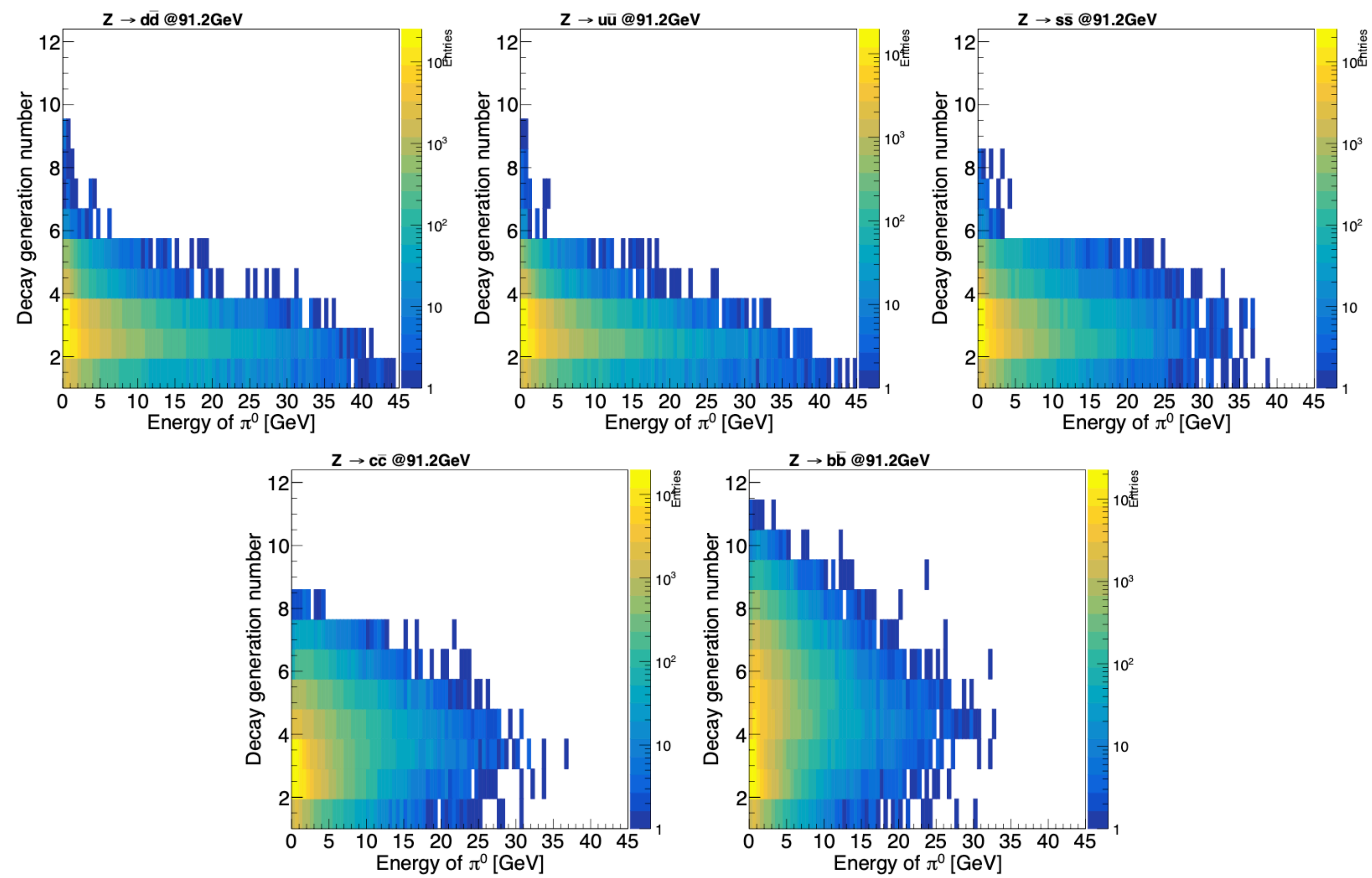
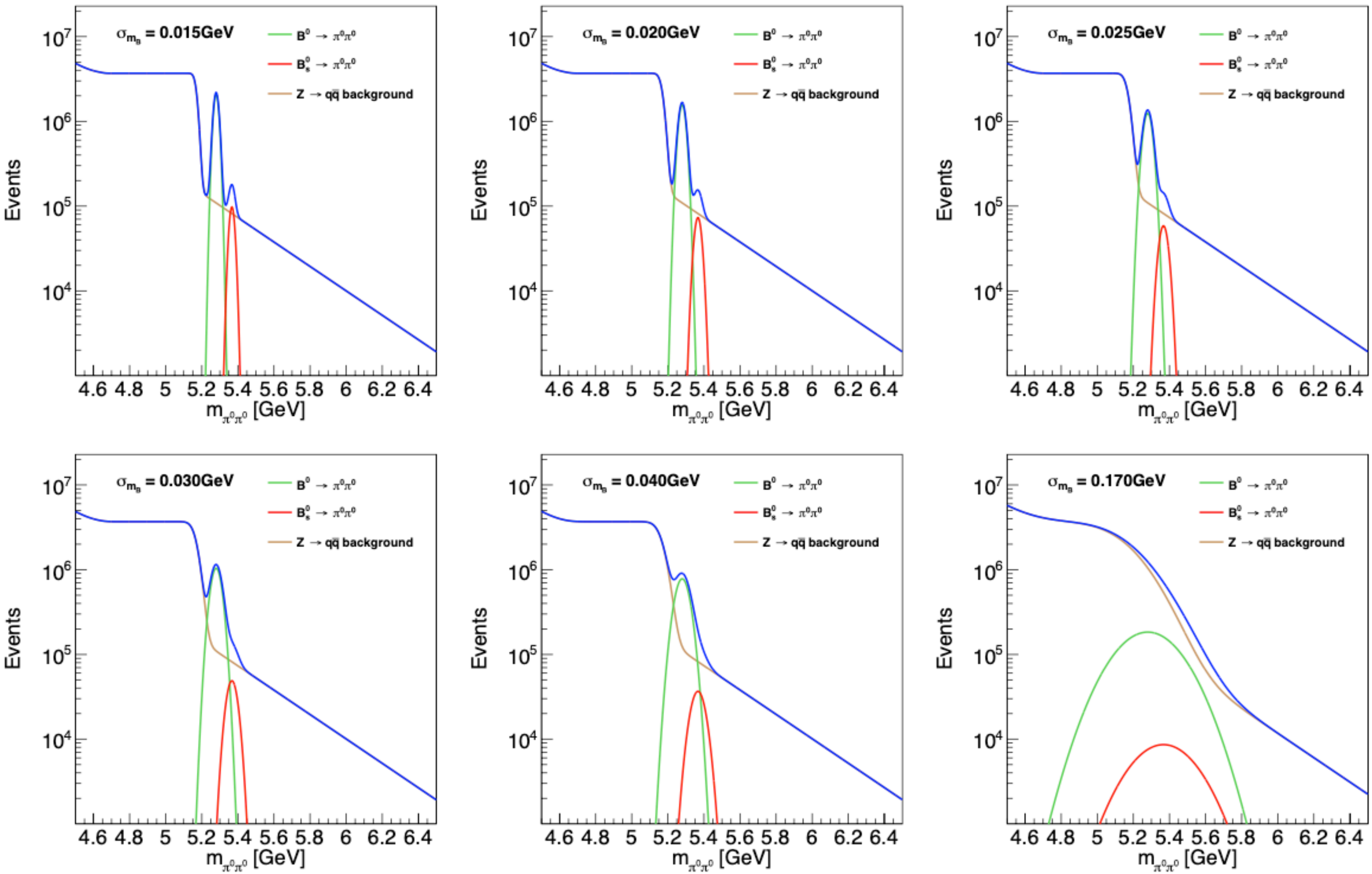


Figure 5: Decay generation number of π^0 vs E_{π^0} in $Z \to u\bar{u}$, $Z \to d\bar{d}$, $Z \to s\bar{s}$, $Z \to c\bar{c}$, $Z \to b\bar{b}$ events.

Dependence on B mass resolution

with CEPC baseline b-tagging



Dependence on B mass resolution

with CEPC baseline b-tagging

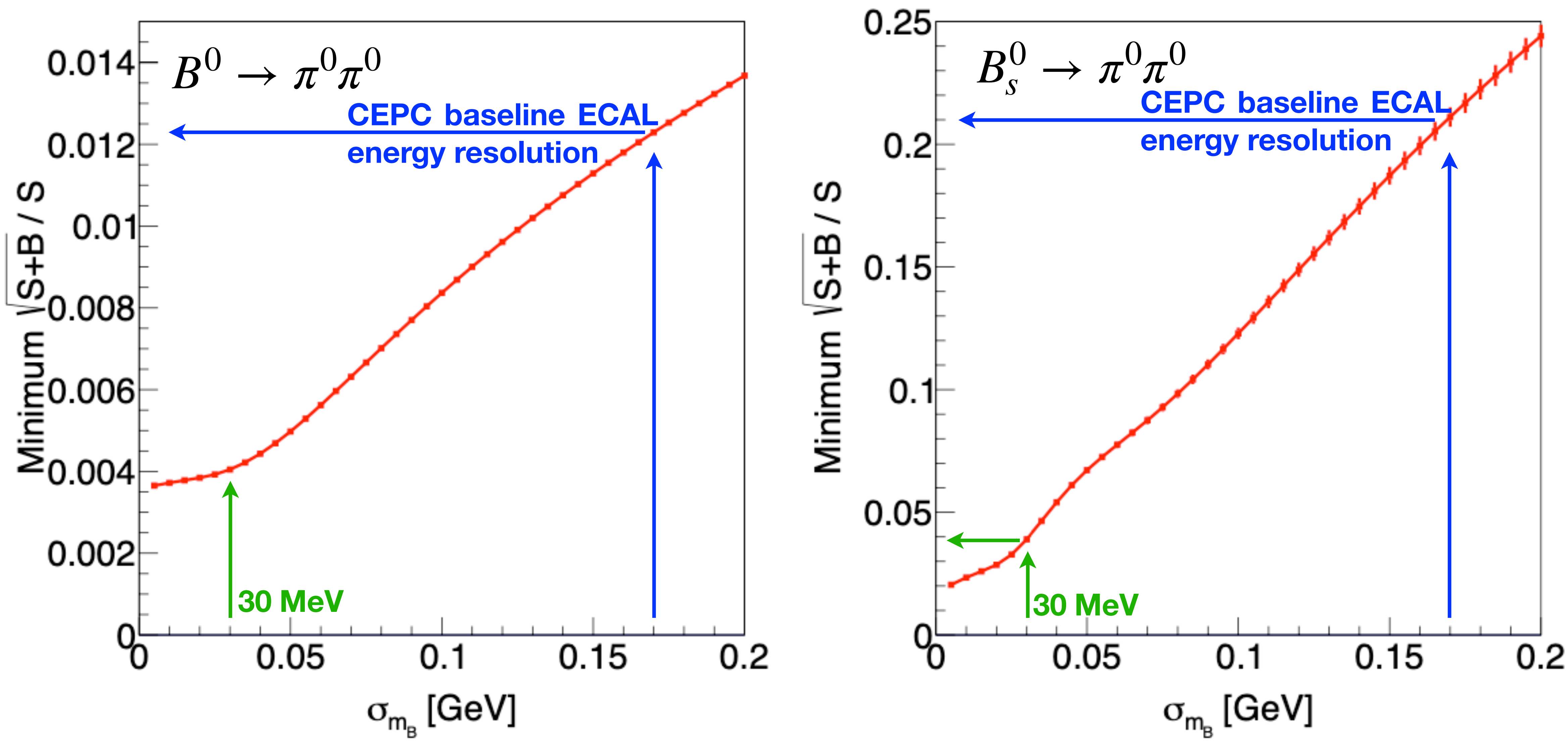


Figure 13: Accuracy of $B^0 \to \pi^0\pi^0$ (left) and $B_s^0 \to \pi^0\pi^0$ (right) vs σ_{m_B} (GeV).

- **CEPC baseline ECAL energy resolution ~17%/√E⊕1%**

Summary

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

- $B^0 \to \pi^0\pi^0$: CKM angle α and $B \to \pi\pi$ puzzle
- $B^0_s \to \pi^0\pi^0$: annihilation mechanism

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 combinatorial background in non-bb events

Accuracy at $3\%/\sqrt{E} \oplus 1\%$	$B^0 \to \pi^0\pi^0$	$B^0_s \to \pi^0\pi^0$
No b-tagging	0.9%	16.7%
CEPC baseline b-tagging	0.4%	4.5%

2~3 times improvement

❖ B mass resolution (σ_{mB}):

- 2σ separation of B0 and Bs requires σ_{mB} better than 30 MeV ($\sim 3\%/\sqrt{E} \oplus 0.3\%$).

Accuracy with CEPC baseline b-tagging	$B^0 \to \pi^0\pi^0$	$B^0_s \to \pi^0\pi^0$
$17\%/\sqrt{E} \oplus 1\%$ (CEPC baseline)	~1.2%	~21%
$3\%/\sqrt{E} \oplus 0.3\%$ (σ_{mB} ~30 MeV)	~0.4%	~4%

3~5 times improvement

☞ Need to further understand and estimate the corresponding improvement on the CKM-α measurement…

Thanks!

Backup

CKM Quark-Mixing Matrix

12.3 Phases of CKM elements

As can be seen from Fig. 12.1, the angles of the unitarity triangle are

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right),$$
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$
$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right). \quad (12.16)$$

Since CP violation involves phases of CKM elements, many measurements of CP-violating observables can be used to constrain these angles and the $\bar{\rho}, \bar{\eta}$ parameters.

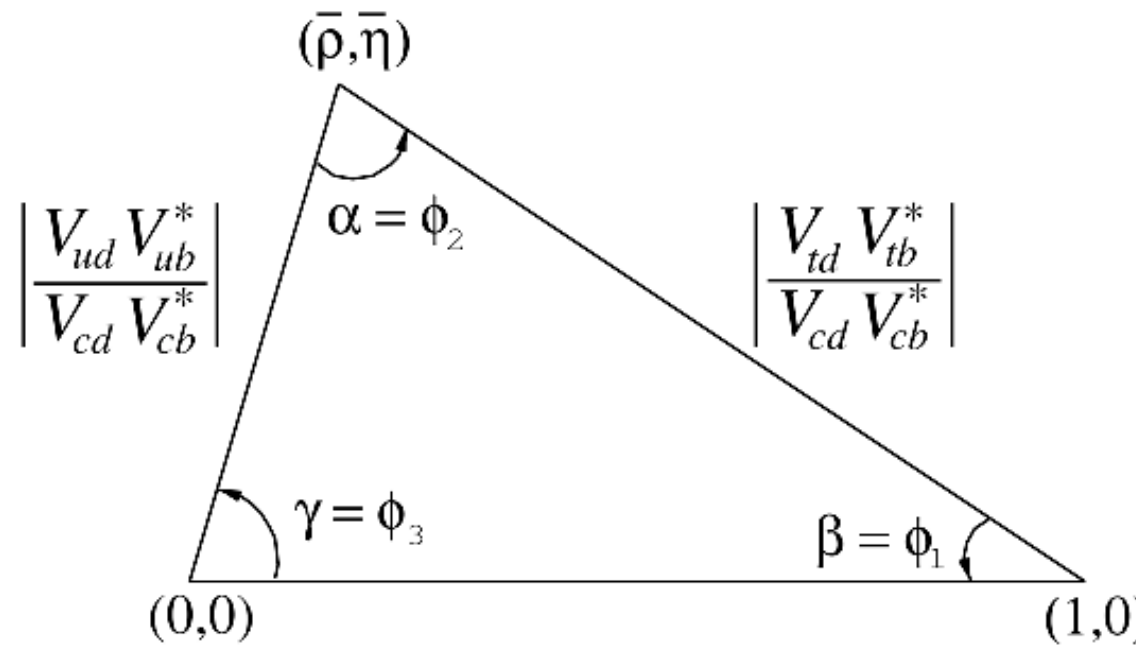
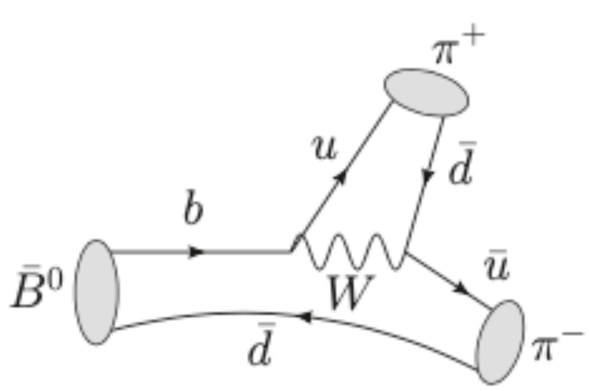
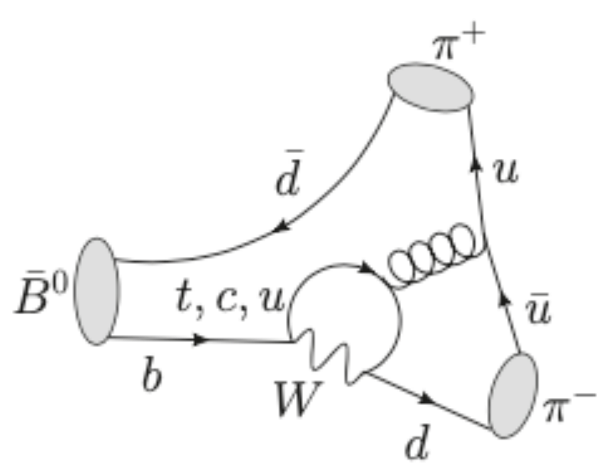


Figure 12.1: Sketch of the unitarity triangle.





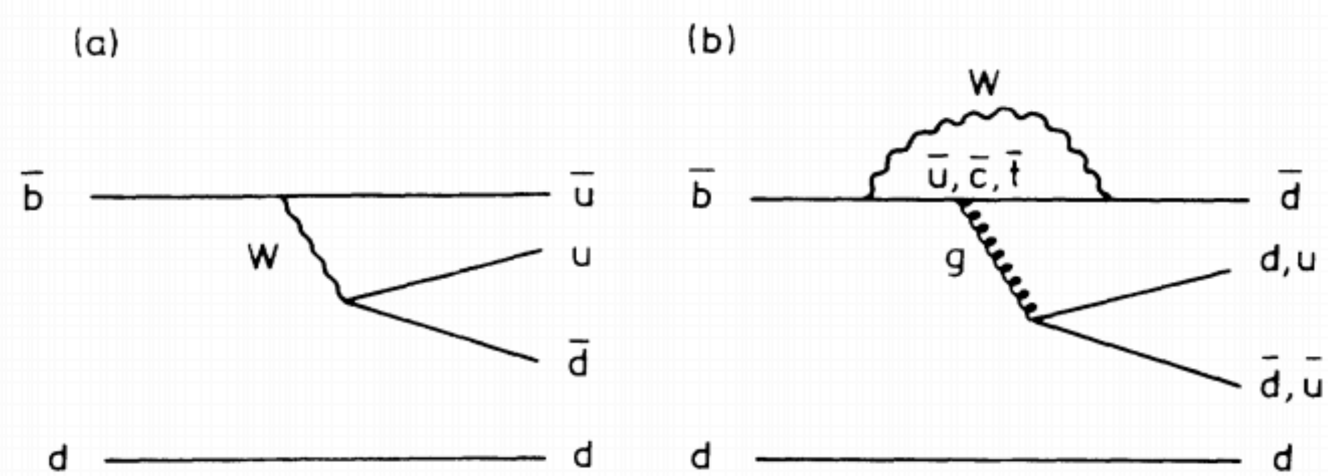
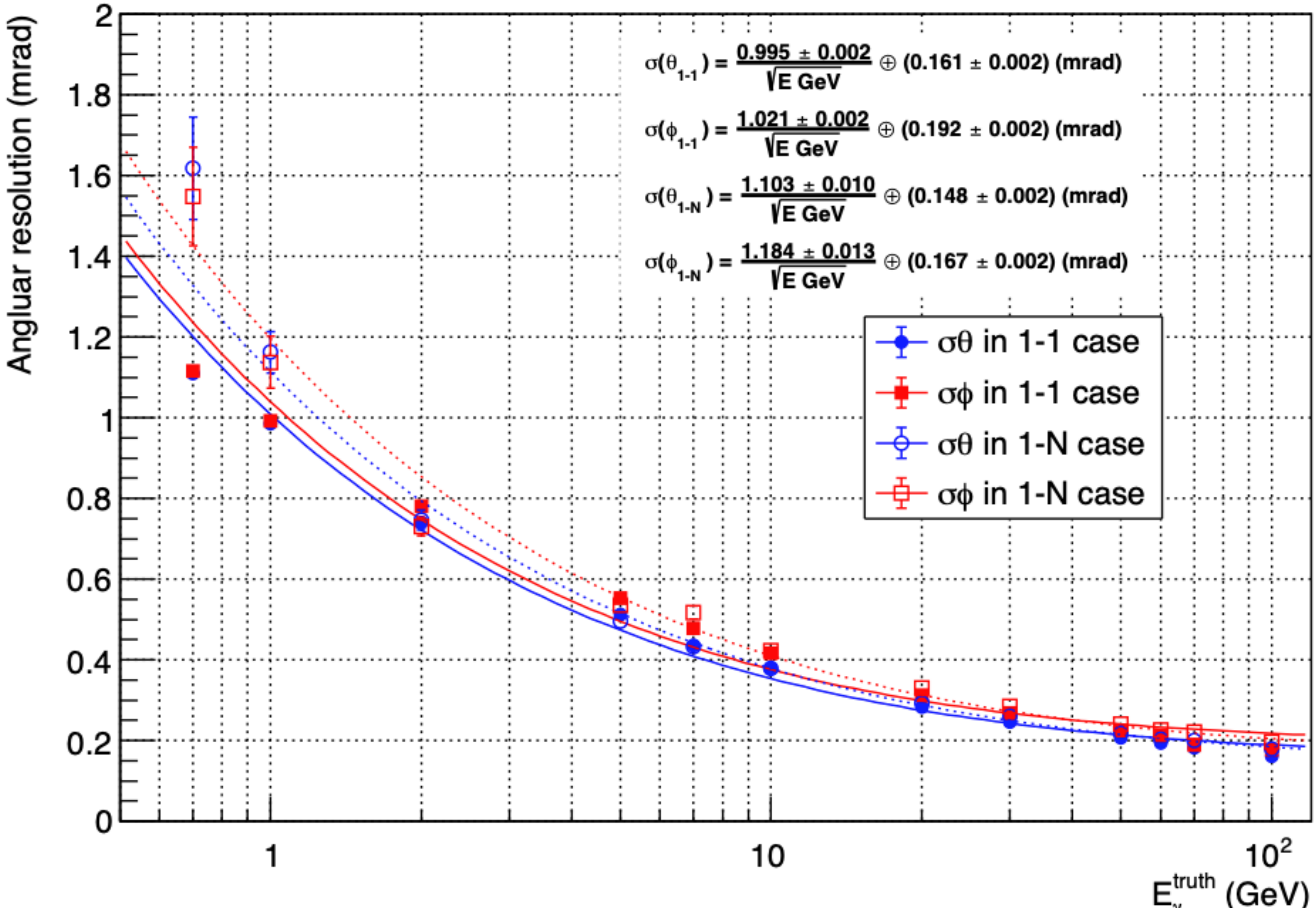


FIG. 1. (a) Tree-level and (b) penguin diagrams for the decay $B_d^0 \rightarrow \pi\pi$.

Single photon angular resolution

CEPC baseline full simulation results by Yuzhi



Efficiency induced by di-photon merging

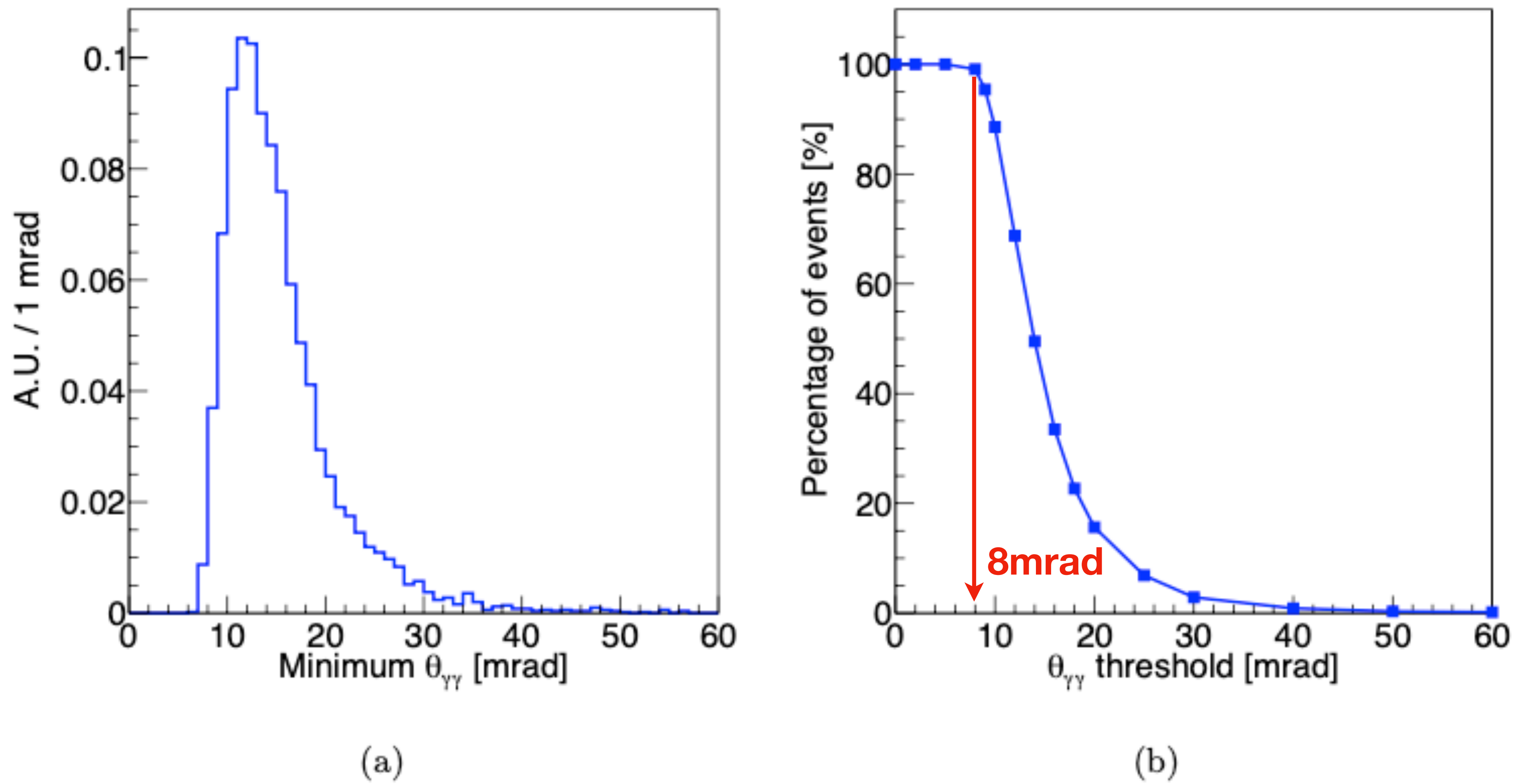


Figure 2: (a) Distribution of the minimum opening angle among 4 photons from $B^0_{(s)} \to \pi^0\pi^0$. (b) Percentage of $B^0_{(s)} \to \pi^0\pi^0$ signal events with minimum $\theta_{\gamma\gamma}$ over different $\theta_{\gamma\gamma}$ thresholds.

For radius = 1800 mm:

- **8 mrad ~ 14.4 mm separation distance, 100% efficiency.**
- **11 mrad ~ 20 mm, ~10% efficiency lost, accuracy is degraded by 10% at most.**

Event Selection

Cut chain	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
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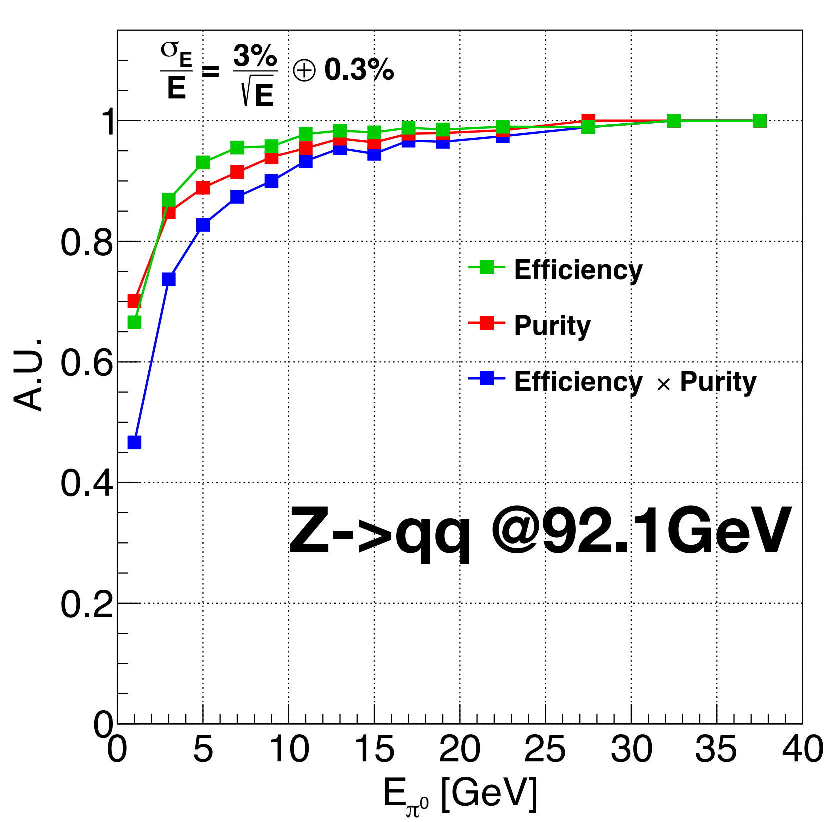
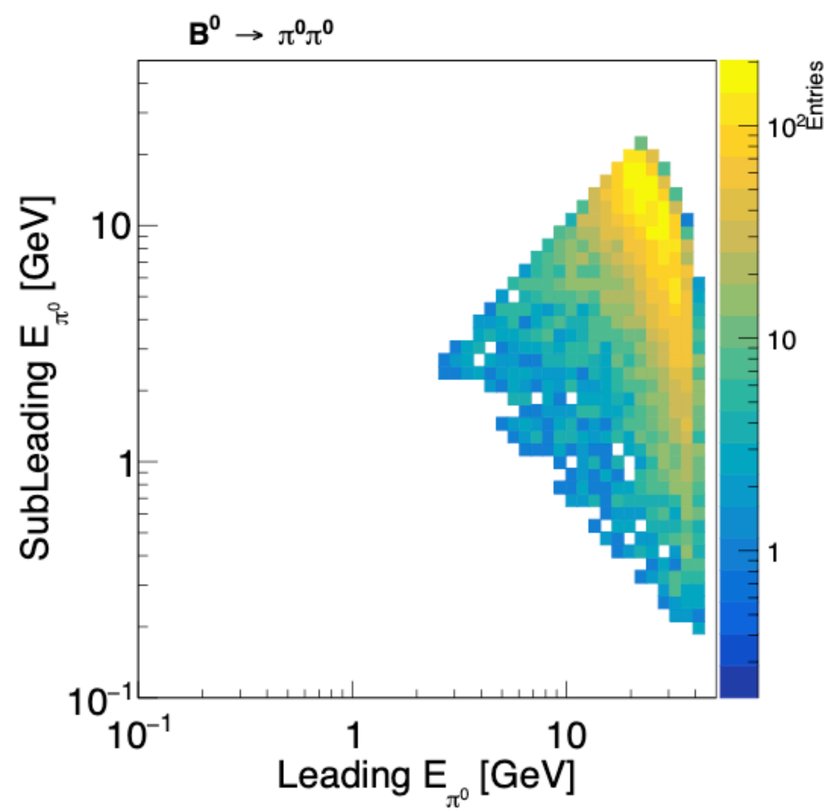
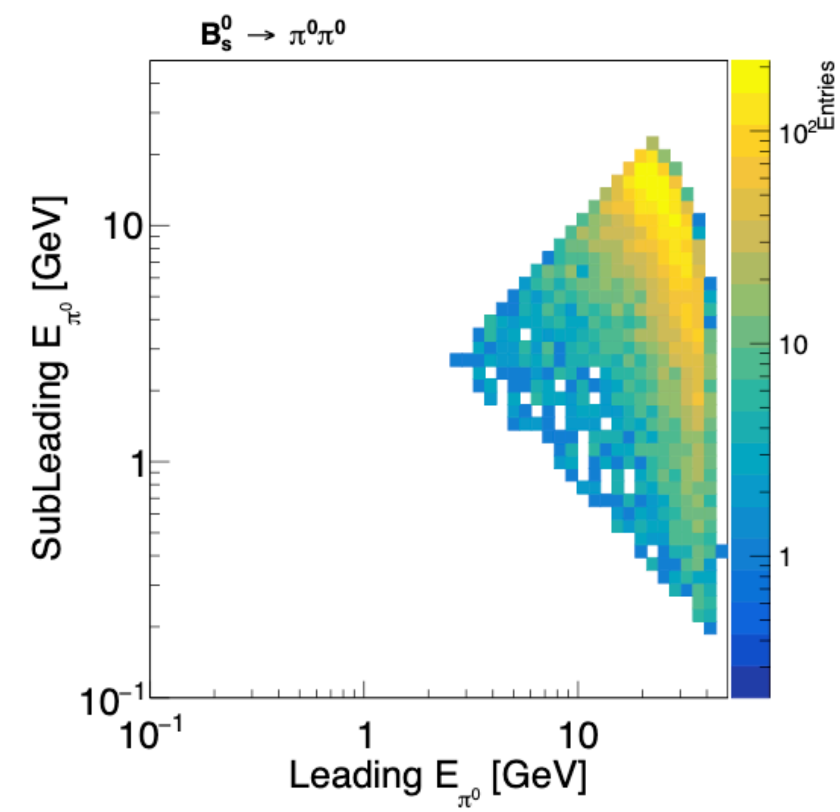
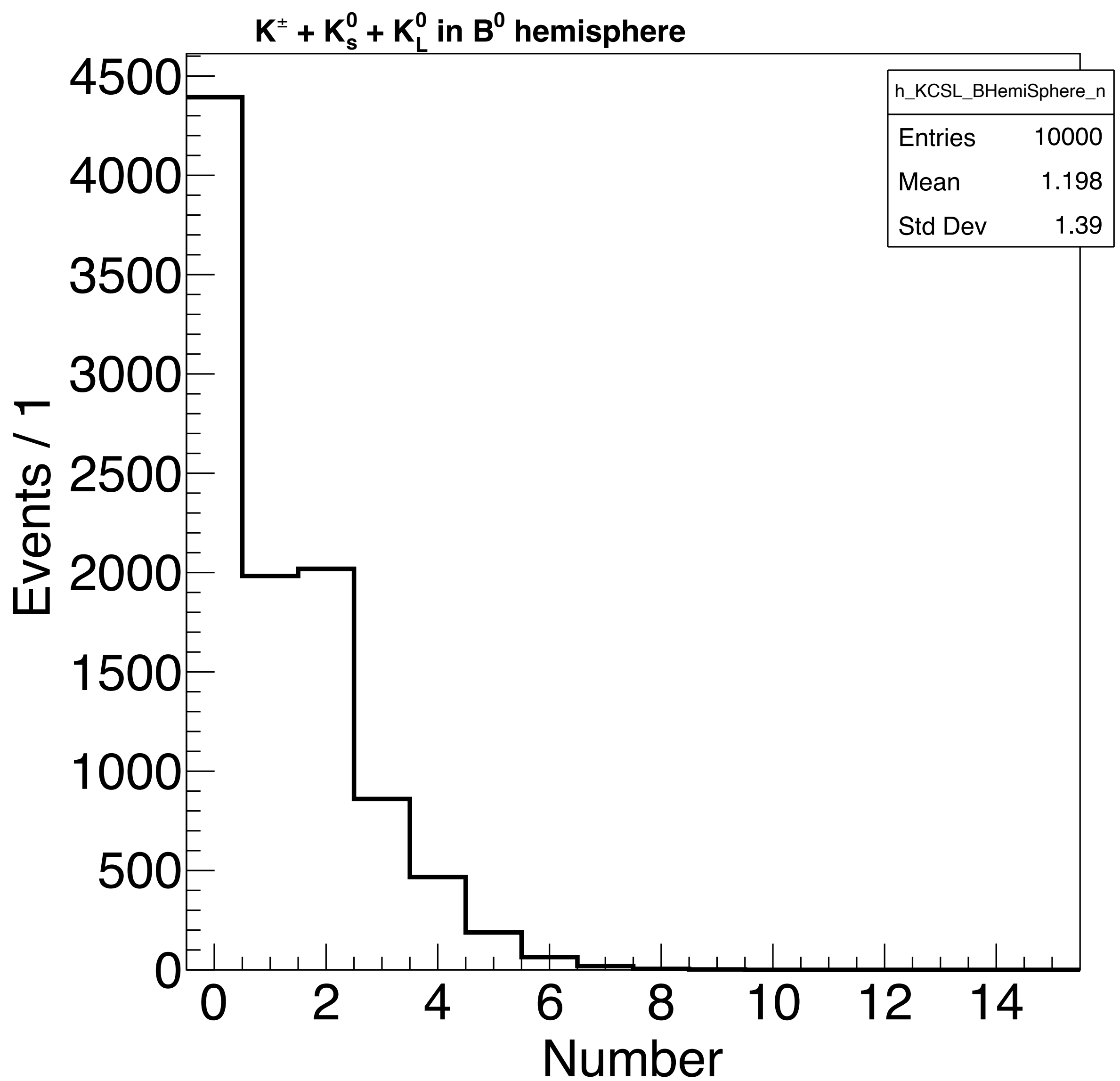
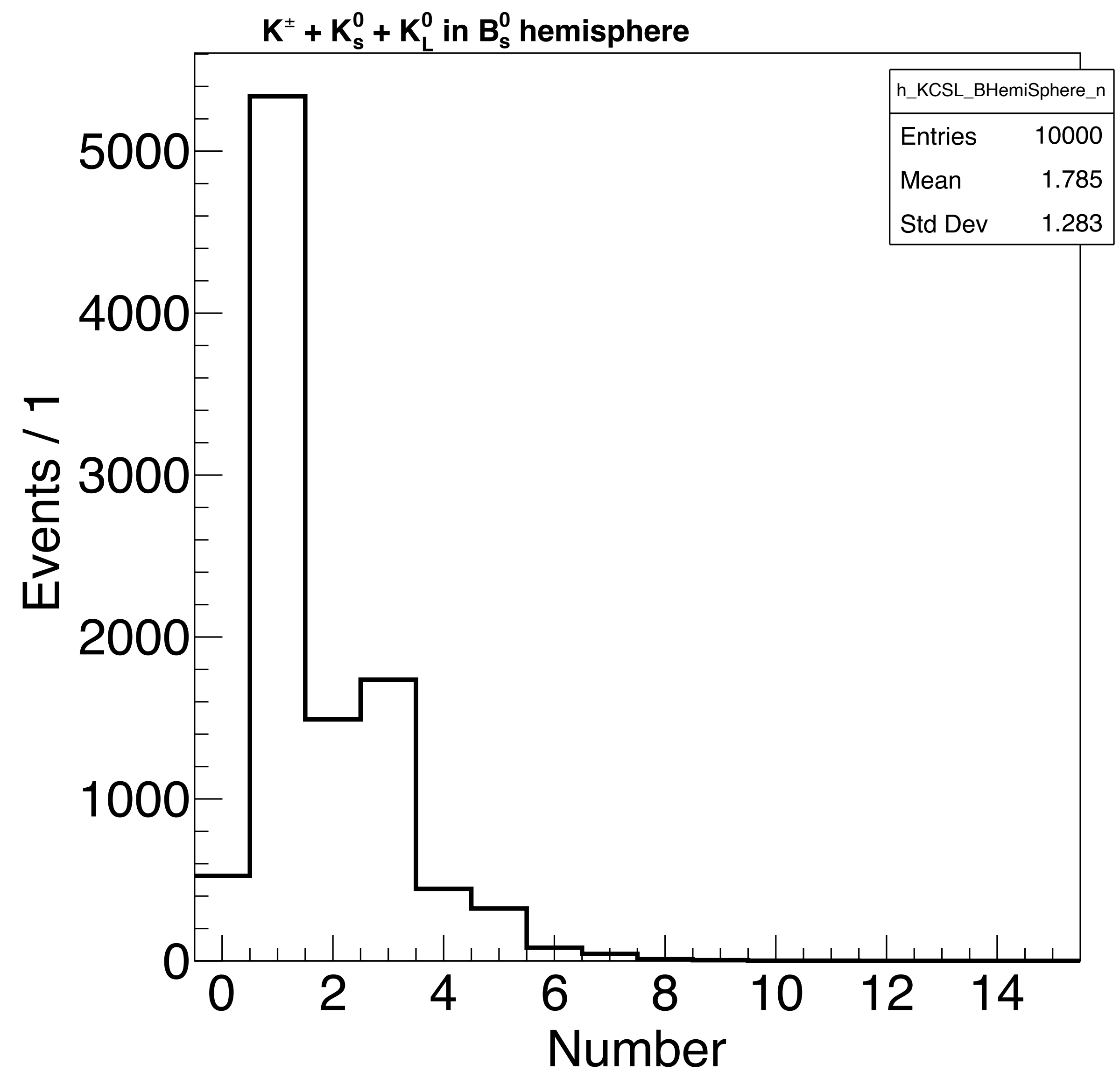






Leading kaon in B meson hemisphere





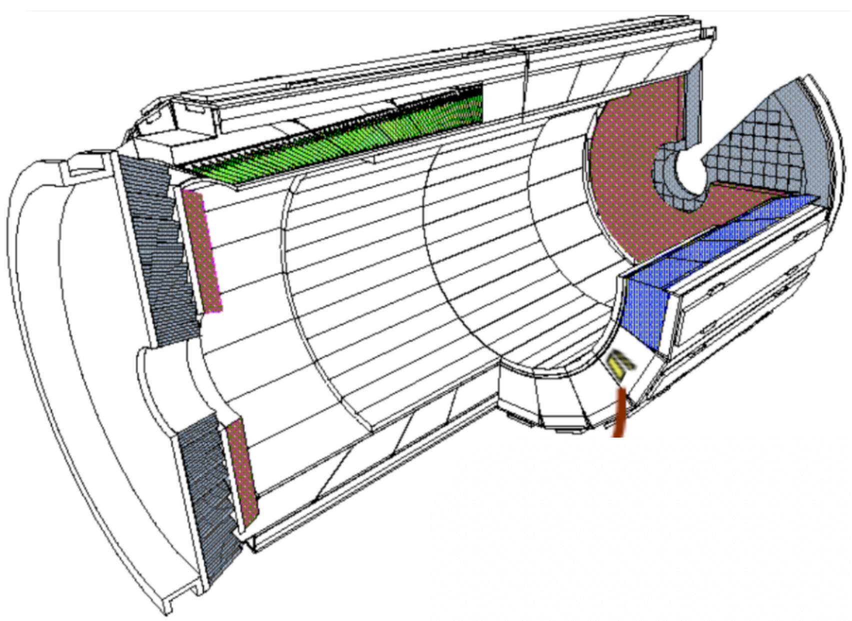
Results at a benchmark detector setup

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

ECAL energy resolution

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

LHC - CMS ($PbWO_4$)



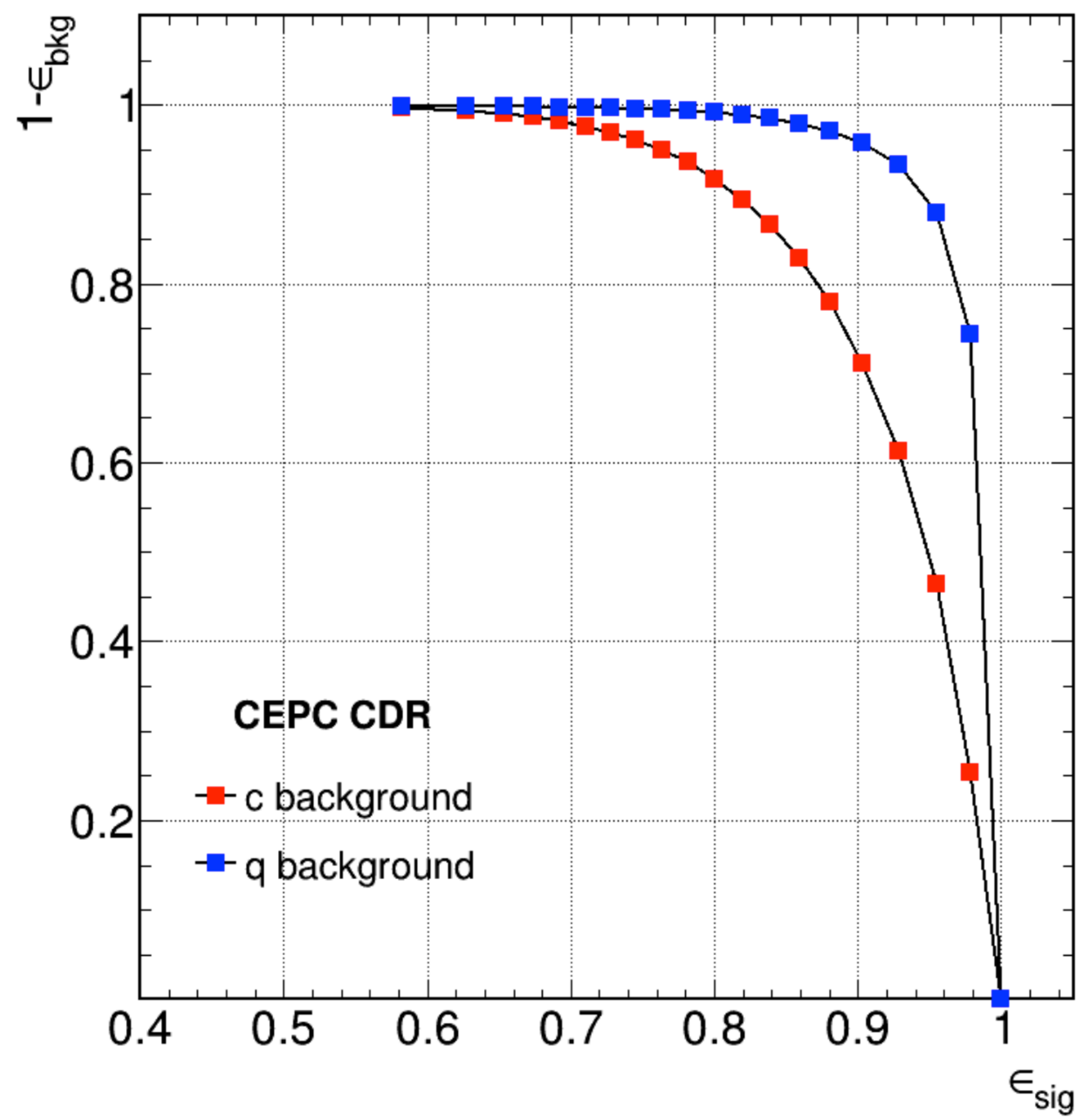
$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{12\%}{E(\mathrm{GeV})} \oplus 0.3\%.$$

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

b-tagging

CEPC baseline b-tagging

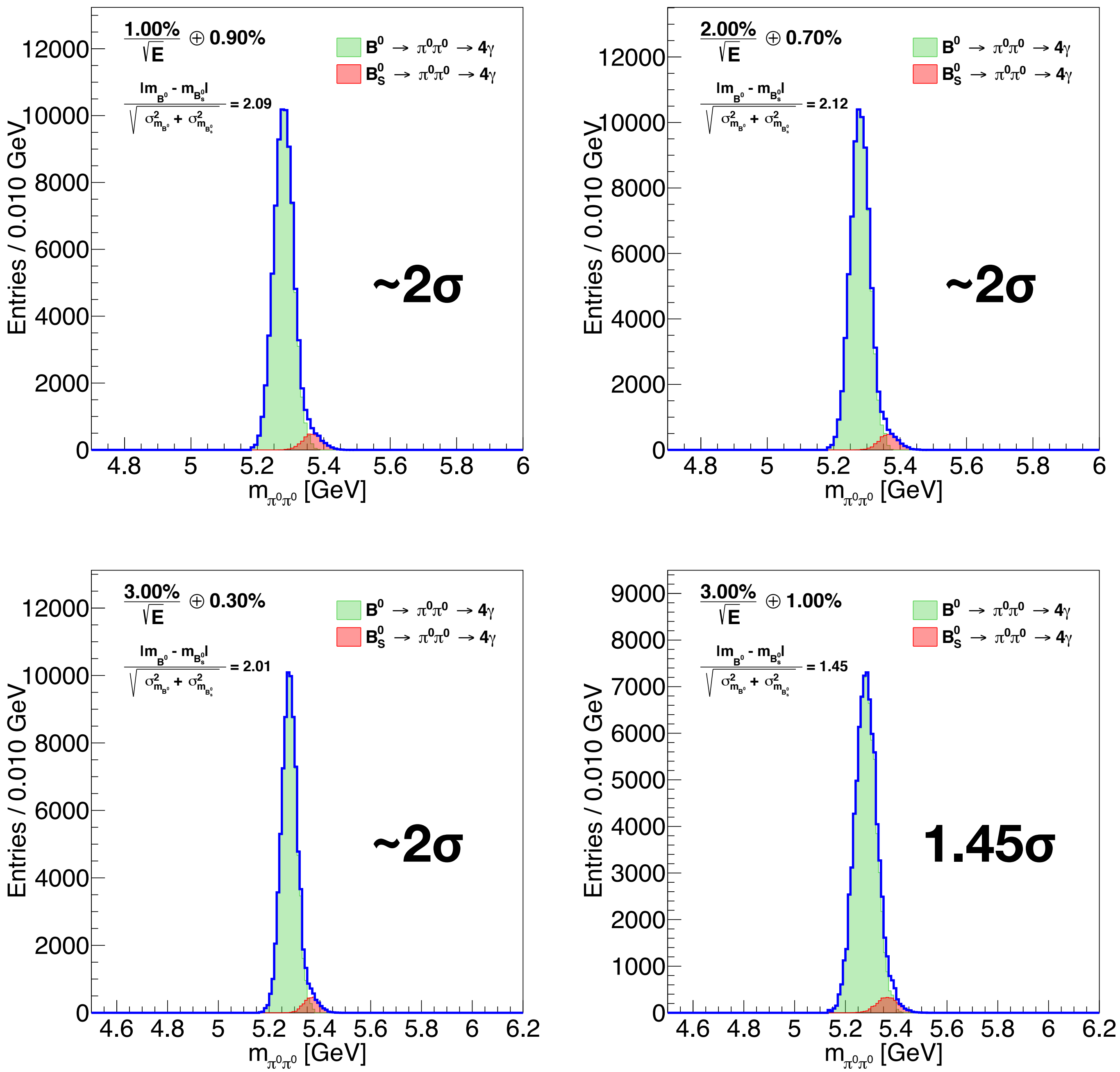
80% efficiency and 90% purity

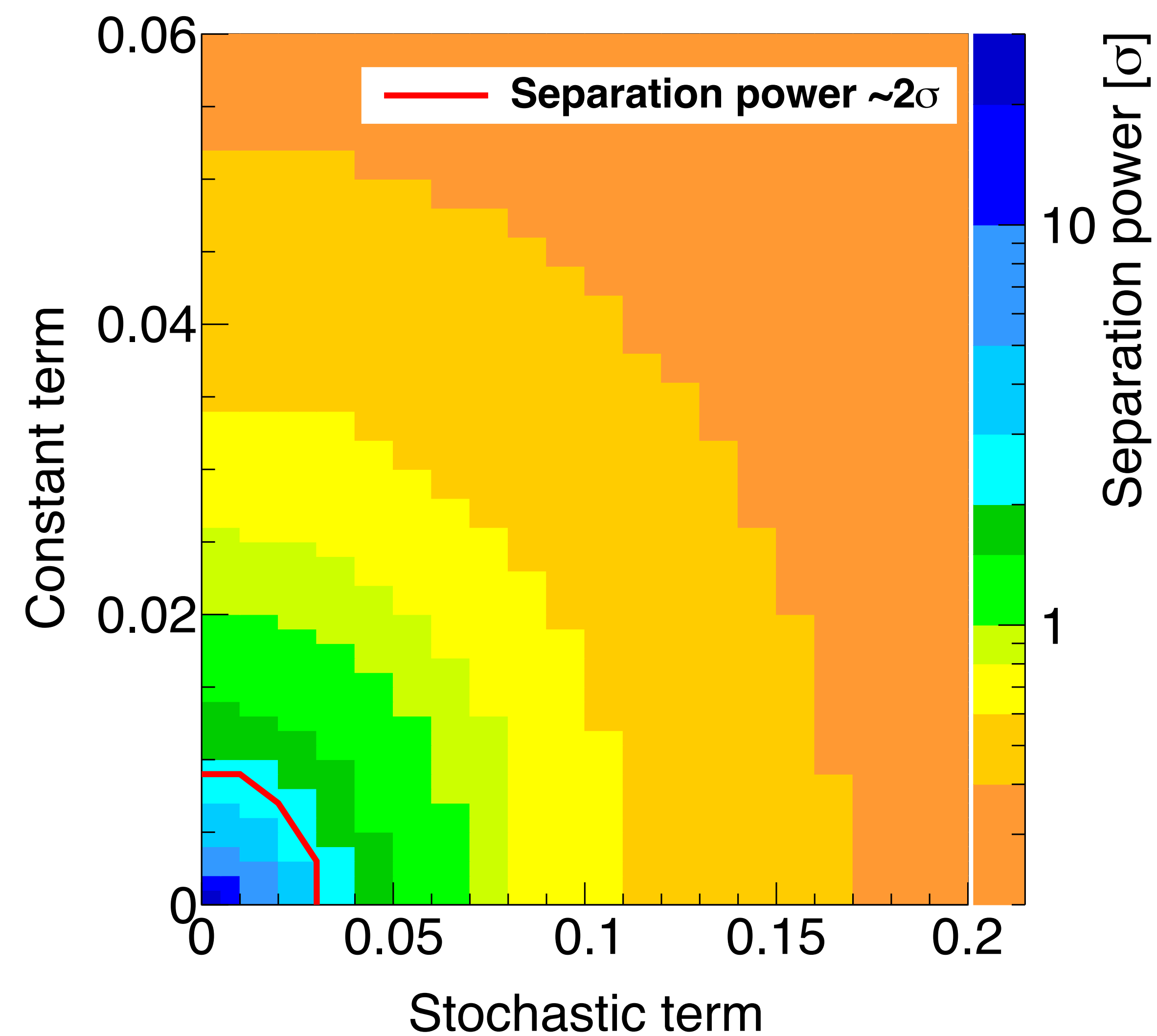


Separation of B⁰ and Bs

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

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

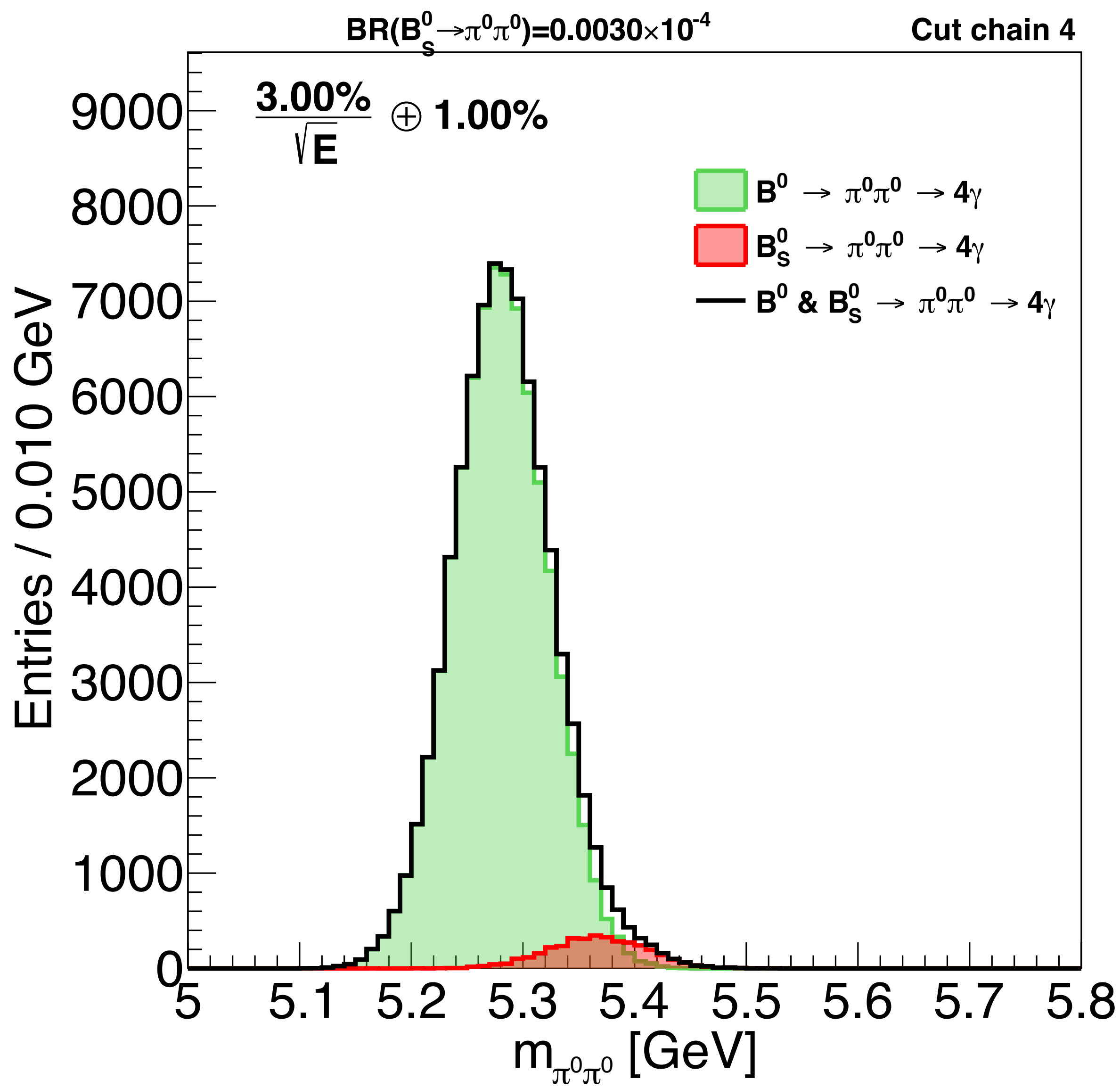


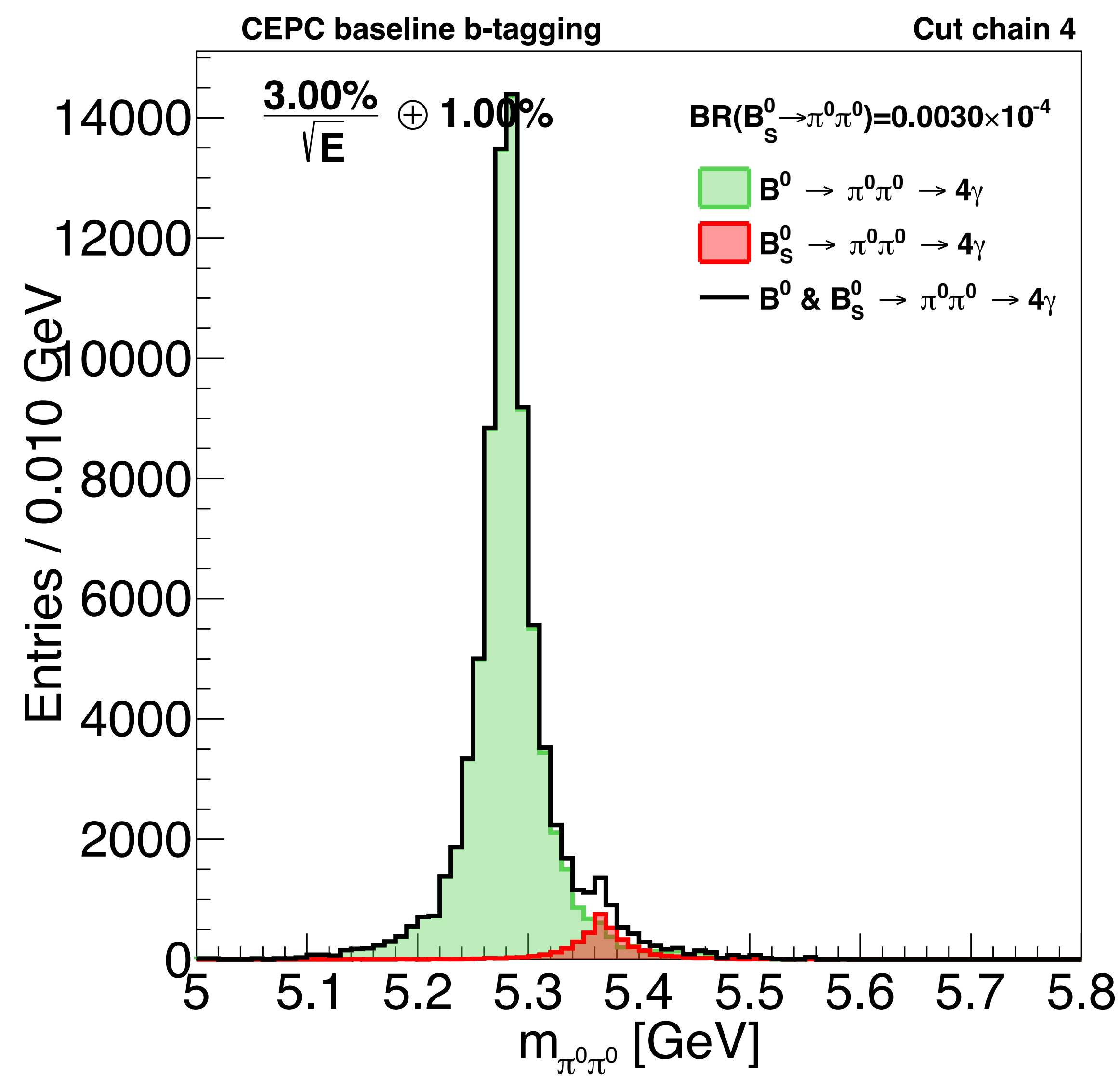


A 2σ separation requires ECAL energy resolution better than 3%/√E⊕0.3%

Kinematic Fit

at 3%/√E⊕1% ECAL resolution





Signal peak gets sharpened after Kinematic Fit

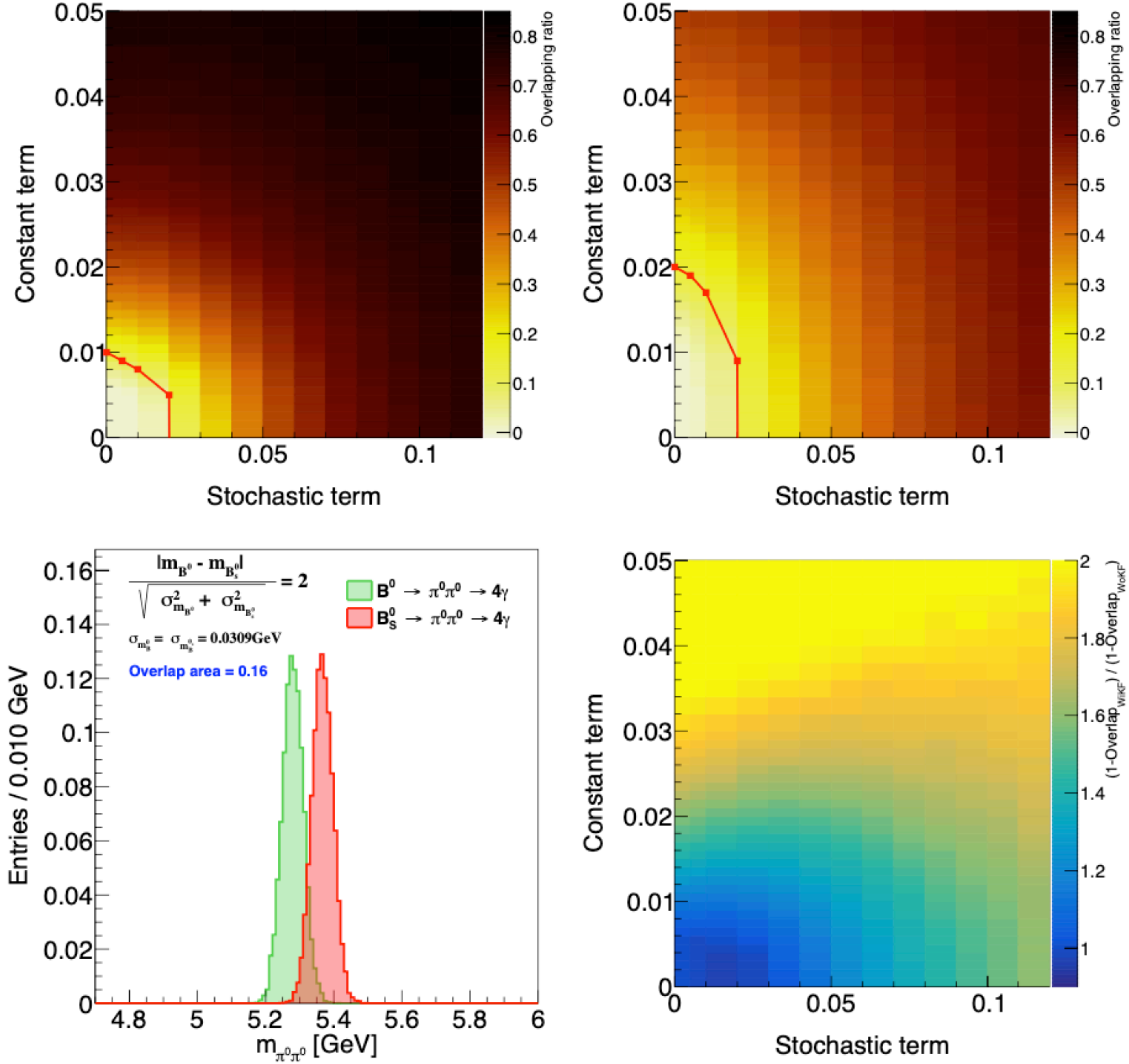


Figure 14: Separation power (overlapping area) at different ECAL resolutions wo/wi kinematic fit.