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π^0 reconstruction and physics measurement of $B^0/B_s \to \pi^0\pi^0$ at CEPC

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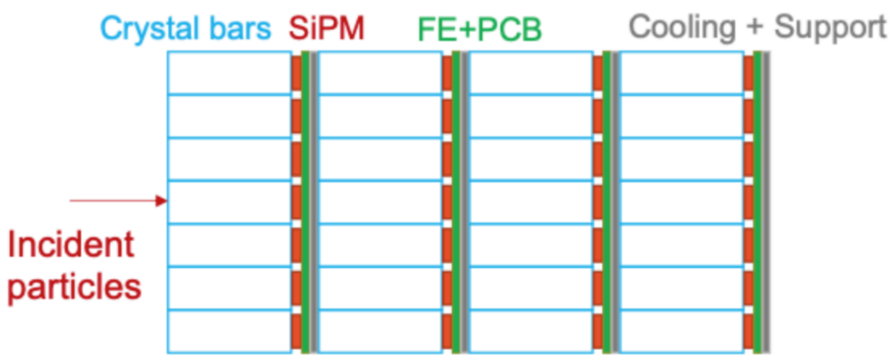
Outline

1. Motivation and introduction
2. Reconstruction of π^0
3. Separation of B^0 and Bs
4. Individual measurement of B^0/Bs → $\pi^0\pi^0$
5. Mixed measurement of B^0&Bs → $\pi^0\pi^0$
6. Summary

Motivation

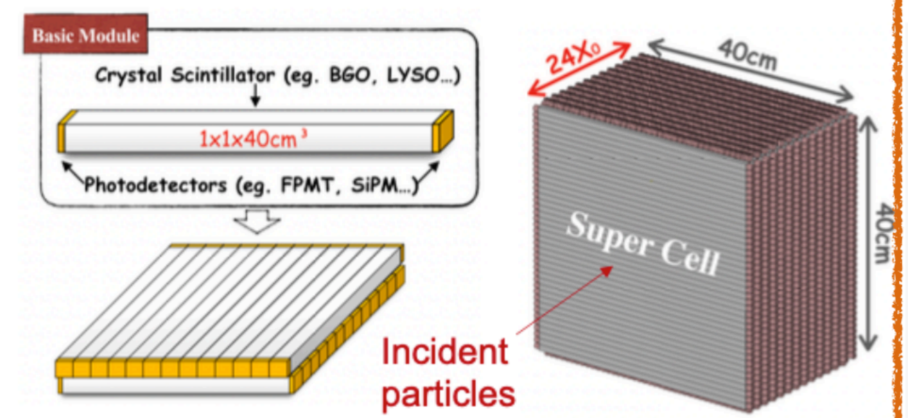
Physics requirements for the 4th Conceptual Detector with the Crystal ECAL Design

Design 1



- Longitudinal segmentation
- Fine transverse segmentation
  - 1×1cm or 2×2cm cells
- Single-ended readout with SiPM
- Potentials with PFA

Design 2



- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm cube
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar

	Homogeneous Crystal ECAL		Baseline sampling ECAL (in CEPC CDR)
EM resolution:	$3\,\%/\sqrt{E} \oplus 1\,\%$	**VS**	$17\,\%/\sqrt{E} \oplus 1\,\%$

- **π° → γγ, EM object, depends on ECAL performance**
- **How much can we benefit from this EM resolution improvement in physics measurement?**

Brief introduction of B^0 & Bs → $\pi^0\pi^0$

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

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ in PDG 2018 Γ_{388}/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	COMMENT
1.59±0.26 OUR AVERAGE		Error includes scale factor of 1.4.			
1.31±0.19±0.19		[1] JULIUS	17	BELL	$e^+e^- \to \Upsilon(4S)$
1.83±0.21±0.13		[1] LEES	13D	BABR	$e^+e^- \to \Upsilon(4S)$

(2017) https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.032007

Bs → $\pi^0\pi^0$

Experimental upper limit

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ in PDG 2018 Γ_{87}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.1 \times 10^{-4}$	90	[1] ACCIARRI	95H	L3	$e^+e^- \to Z$

[1] ACCIARRI 95H assumes $f_{B^0} = 39.5 \pm 4.0$ and $f_{B_s} = 12.0 \pm 3.0\%$.

(1995) https://www.sciencedirect.com/science/article/pii/037026939501042O

Theoretical estimation

$\bar{B}_s^0 \to \pi^+\pi^-$	ann	$0.024^{+0.003+0.025+0.000+0.163}_{-0.003-0.012-0.000-0.021}$	$\cdots$	$0.57^{+0.16+0.09+0.01}_{-0.13-0.10-0.00}$	<1.36
$\bar{B}_s^0 \to \pi^0\pi^0$	ann	$0.012^{+0.001+0.013+0.000+0.082}_{-0.001-0.006-0.000-0.011}$	$\cdots$	$0.28^{+0.08+0.04+0.01}_{-0.07-0.05-0.00}$	<210

(2007) https://journals.aps.org/prd/abstract/10.1103/PhysRevD.76.074018

~ 3×10^{-7}

Reconstruction of π^0

Decay channel: $\pi^0 \rightarrow \gamma\gamma$ (BR~98.8%)

Pair up photons and select π^0 candidates according to the invariant mass

Preliminary Fast Simulation modeling:

Currently focus on the energy response

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

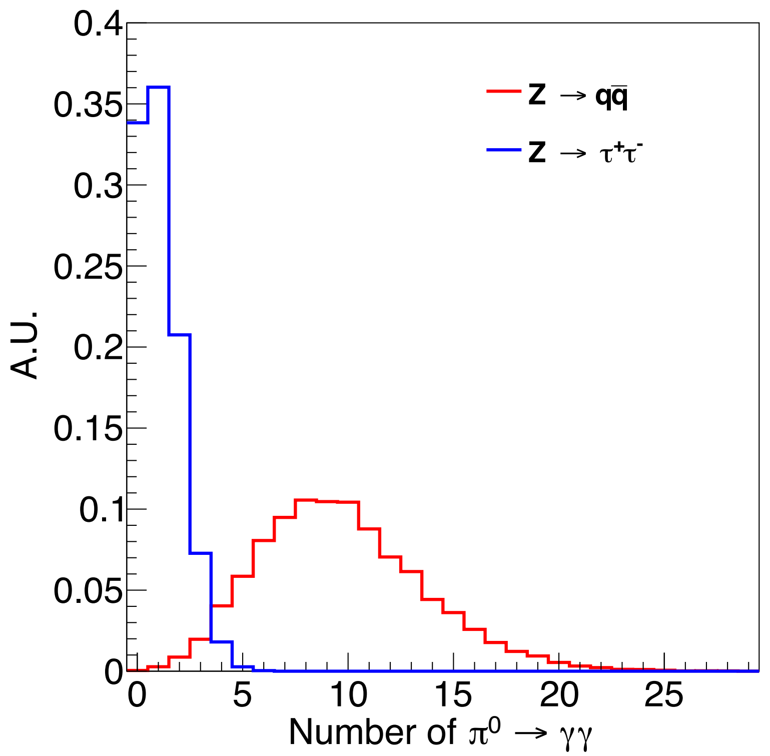
Some effects not included yet…

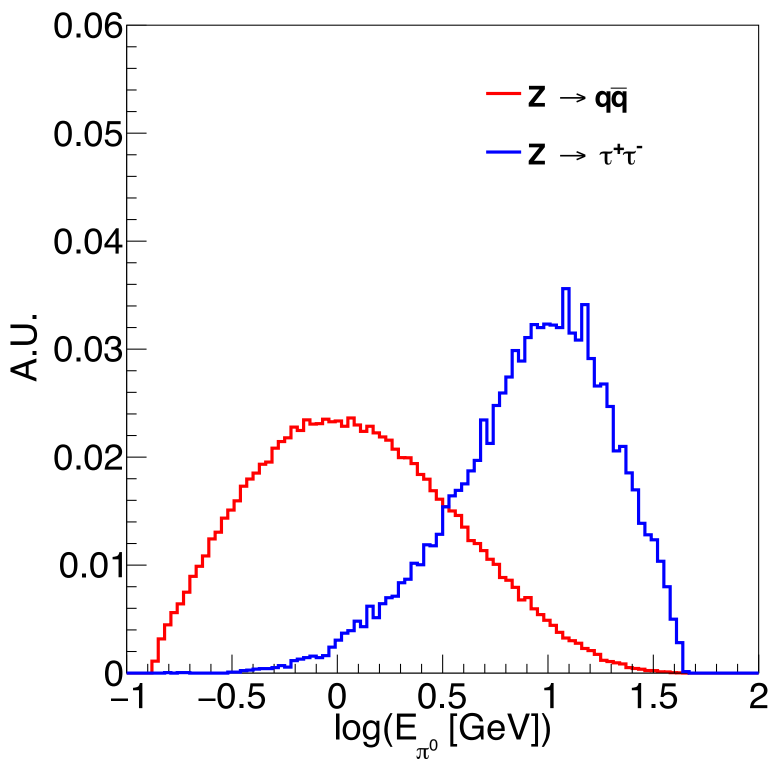
- *Photon angular resolution (~0.5 mrad, ~1cm)*
- *Di-photon separation (π^0<30GeV , >9 mrad, >1.6cm)*
- *Detector acceptance (|Cosθ|<0.99)*

Values in parentheses are results of baseline detector as a reference

Two samples at Z pole operation (91.2GeV):

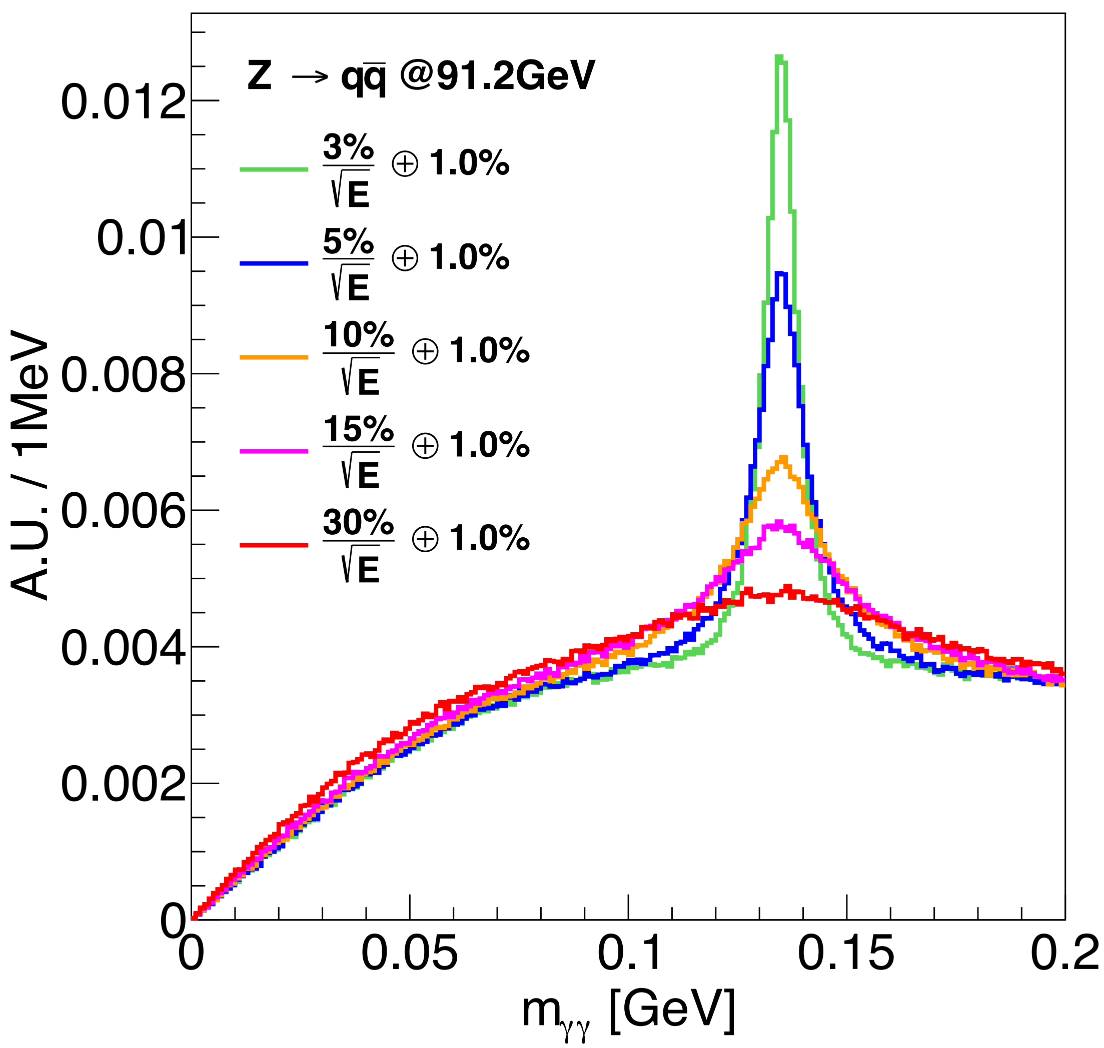
Z→qq & Z→ττ (with different topologies)

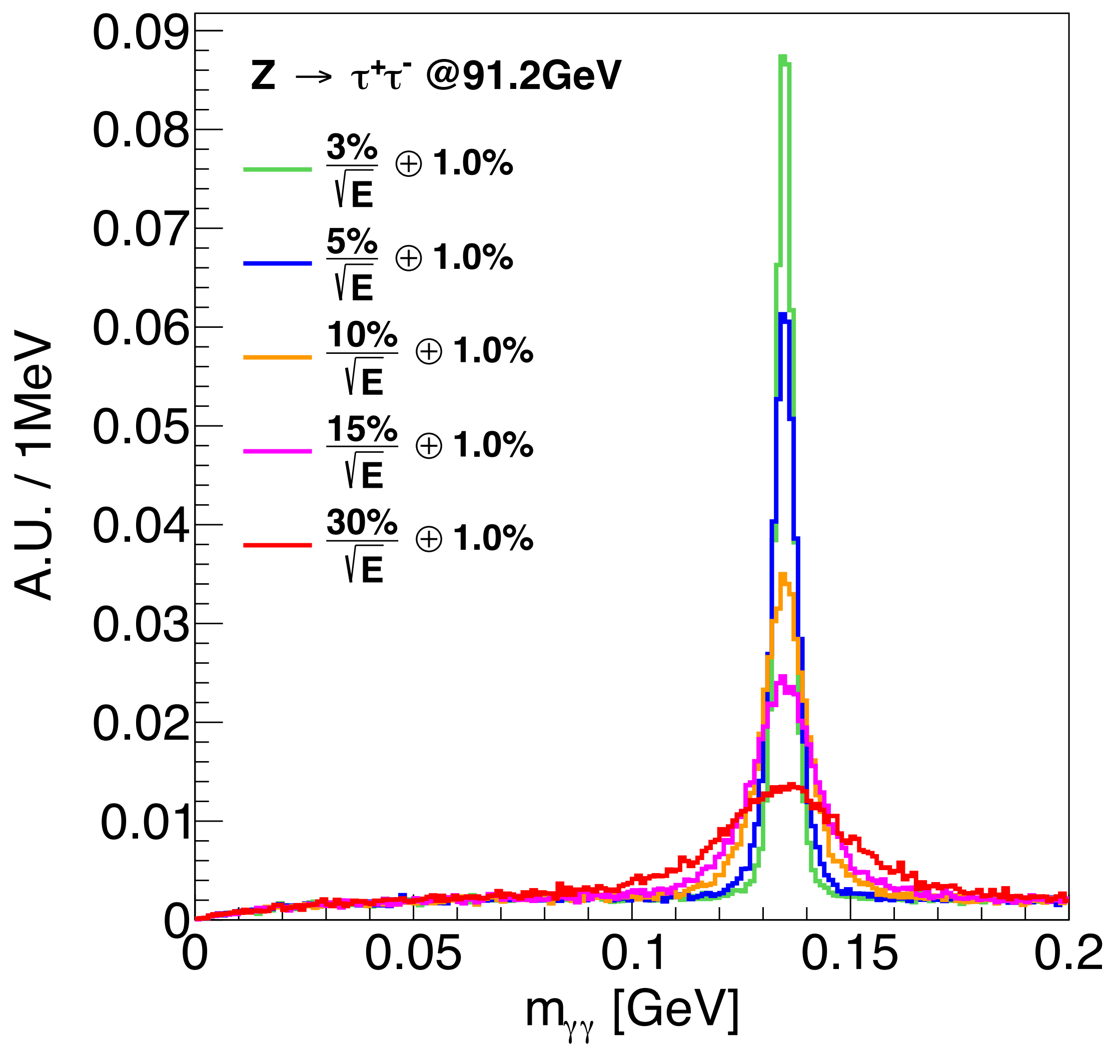




Reconstruction of π^0

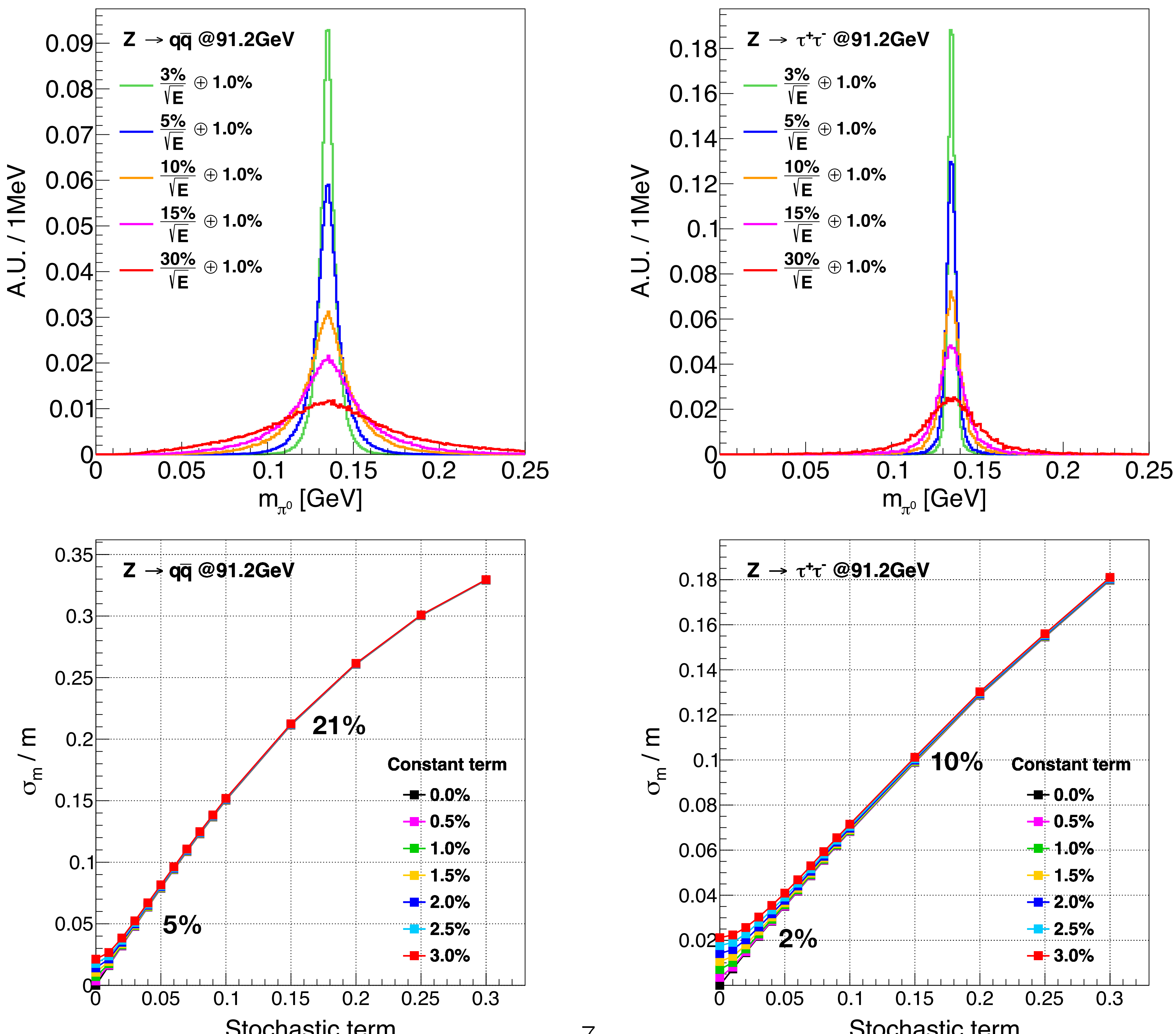
Distribution of $m_{\gamma\gamma}$





Reconstruction of π^0

π^0 mass resolution

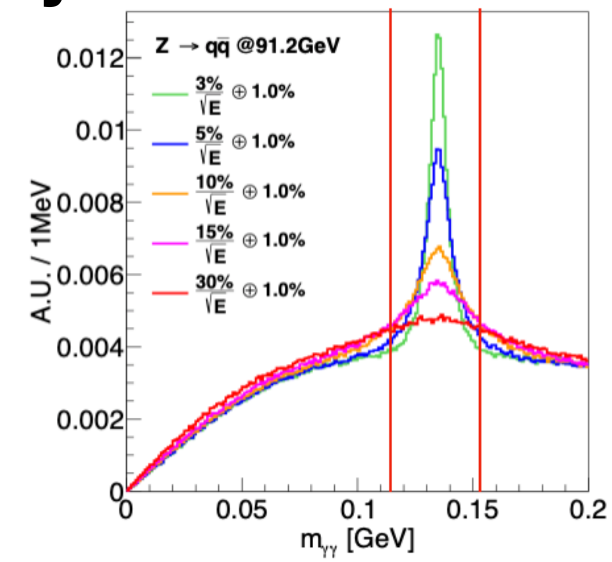


Reconstruction of π^0

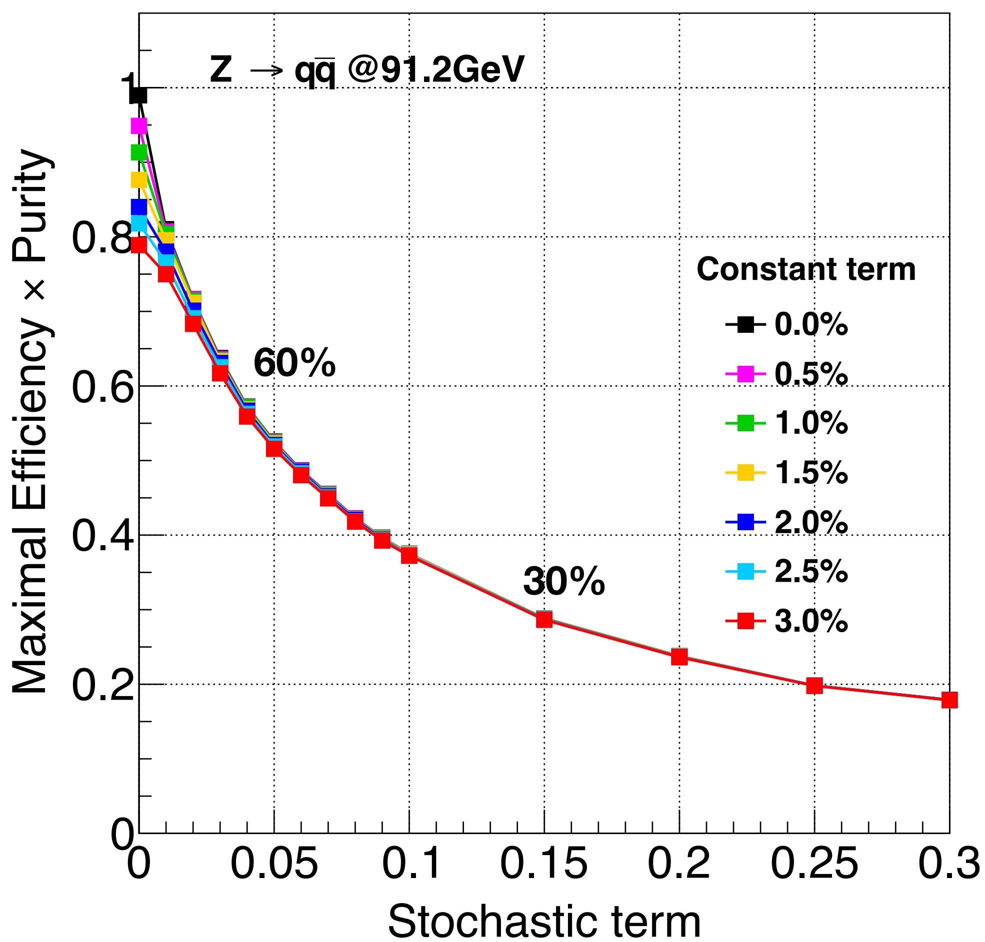
π^0 identification efficiency & purity

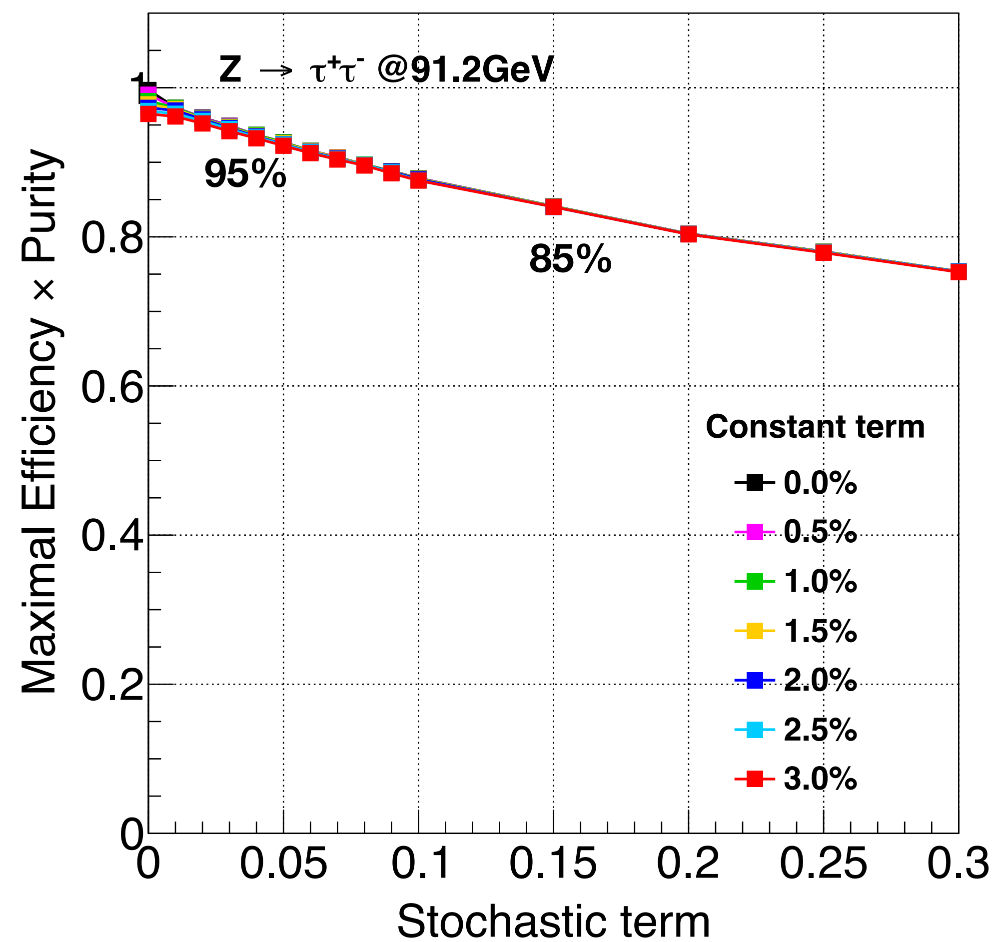
$$\epsilon = \frac{Number\ of\ selected\ \pi^0 s\ that\ are\ true\ \pi^0 s\ in\ Monte\ Carlo}{Number\ of\ all\ generated\ \pi^0 s}$$

$$p = \frac{Number\ of\ selected\ \pi^0 s\ that\ are\ true\ \pi^0 s\ in\ Monte\ Carlo}{Number\ of\ all\ selected\ \pi^0 s}$$



Simply energy sorted strategy to pair each photon at most once
Optimize the mass window to get maximal efficiency × purity

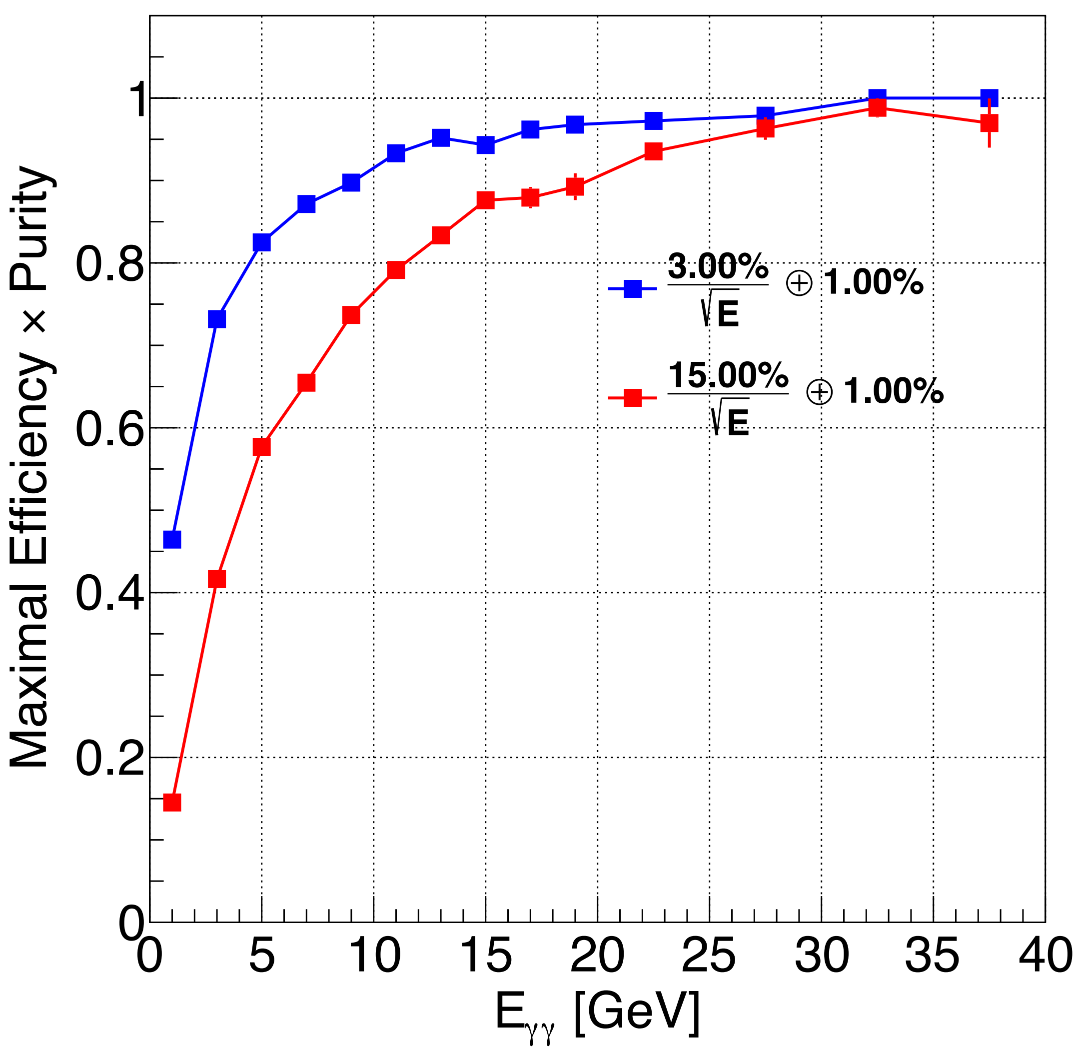




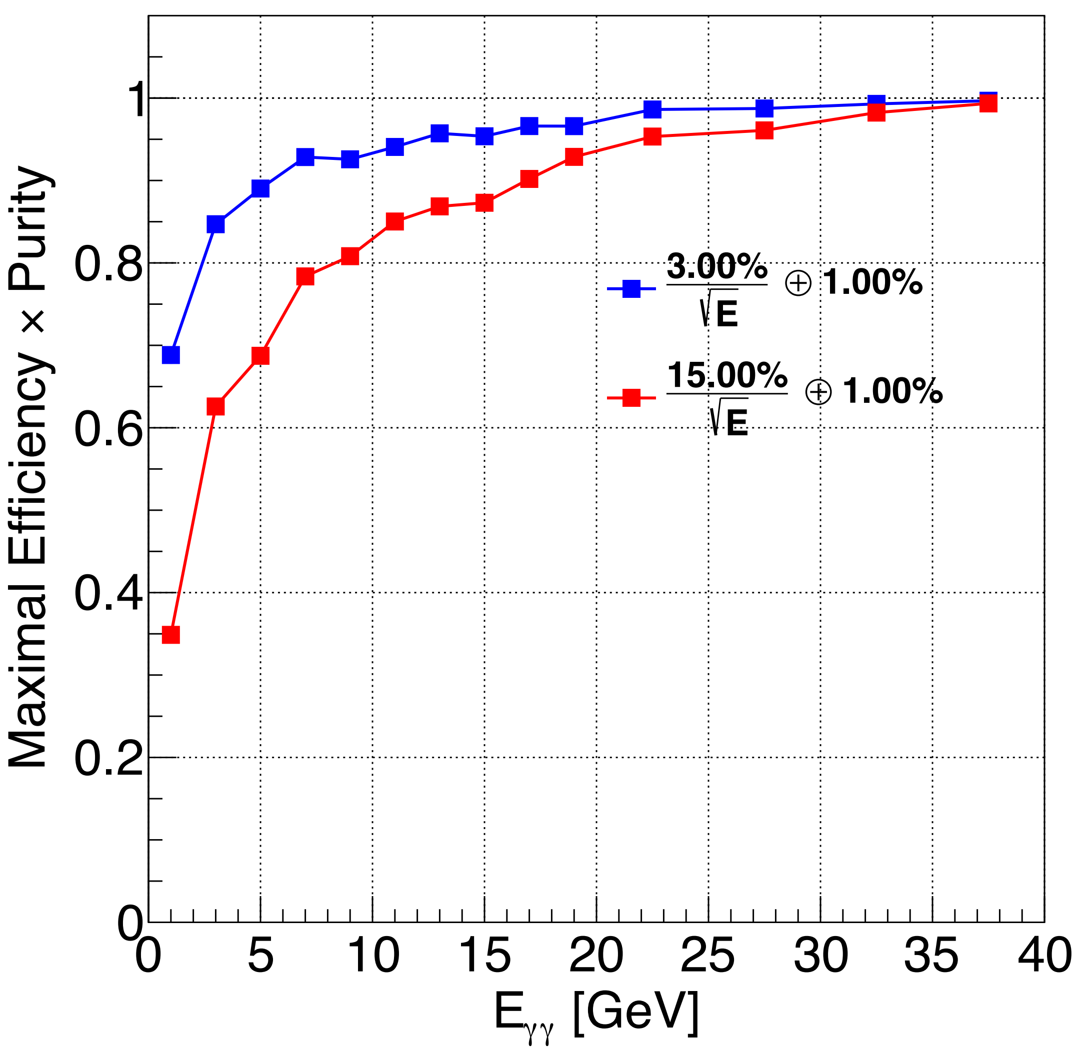
Reconstruction of π^0

Energy differential results

Z→qq



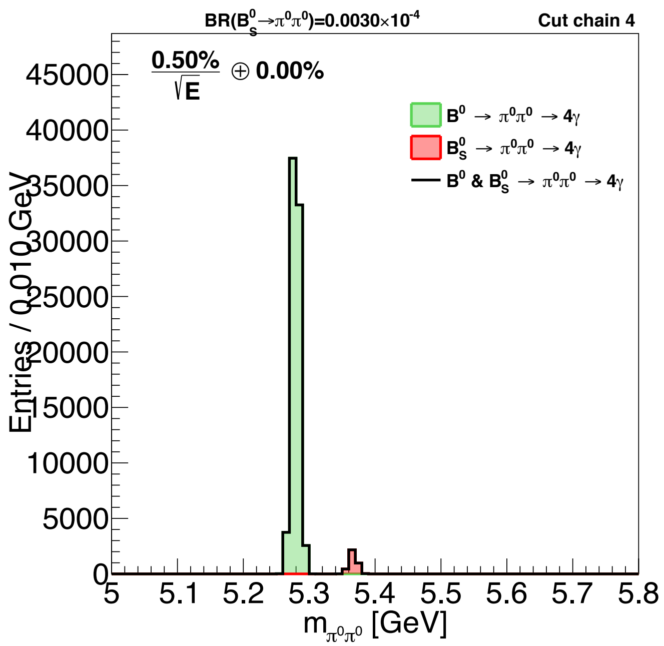
Z→ττ

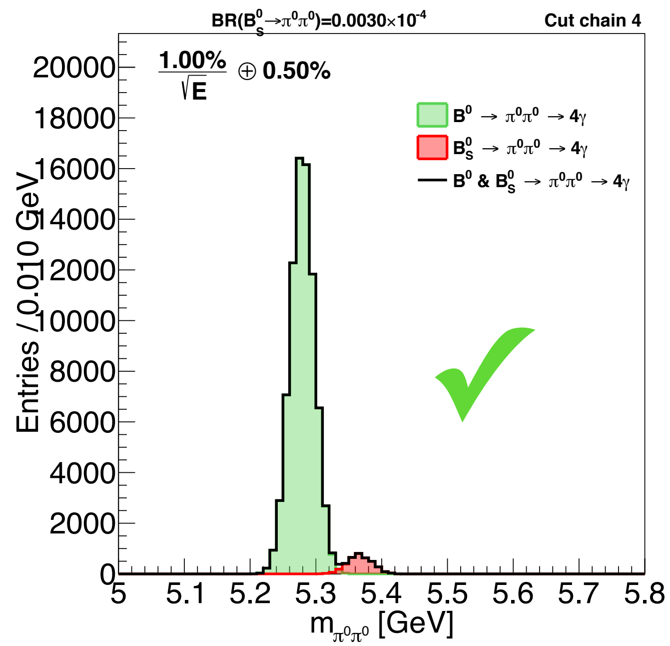


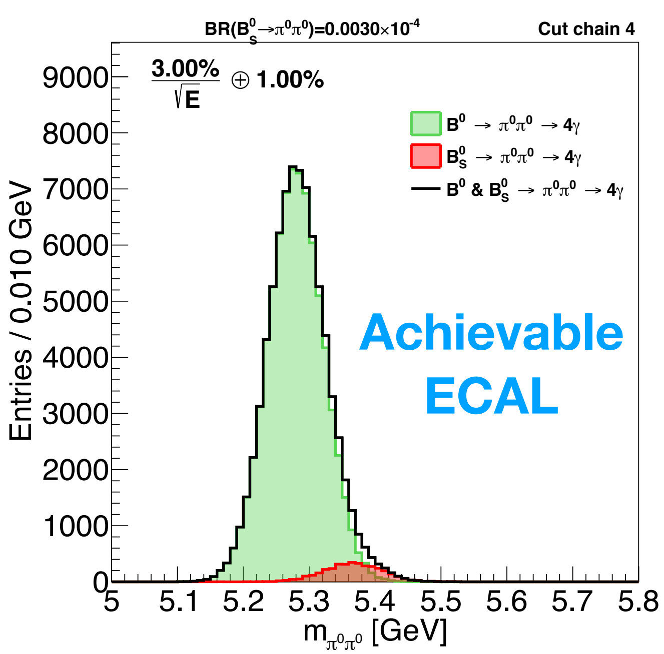
ε × p > 90% in energy range > 20GeV

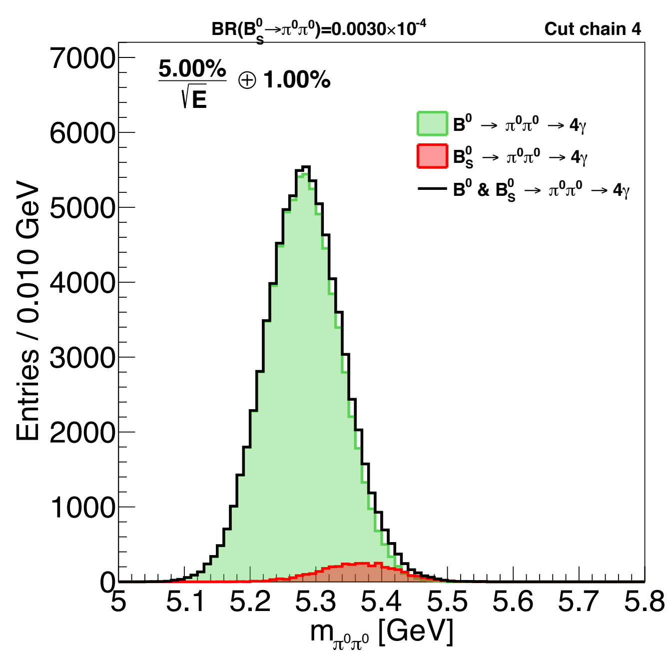
Separation of B⁰ and Bs

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

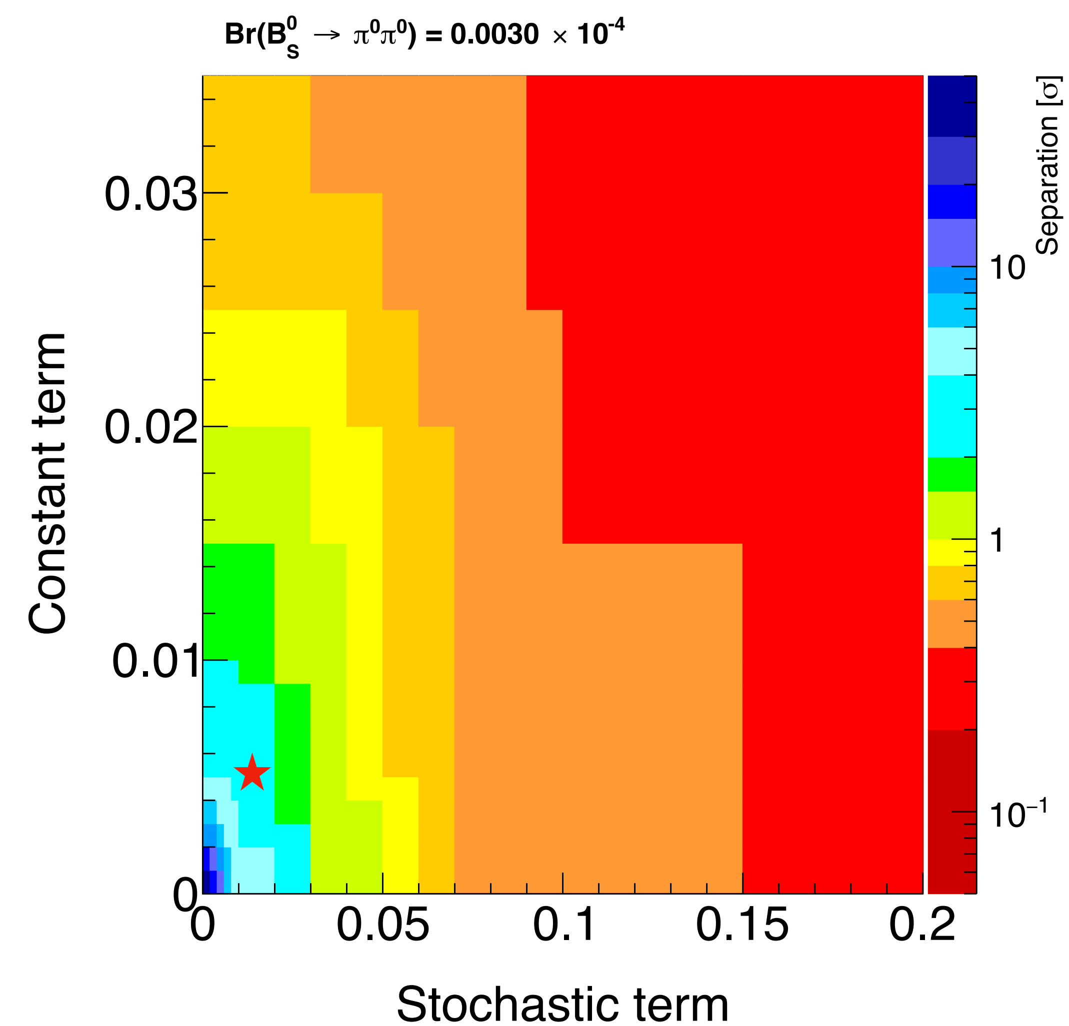






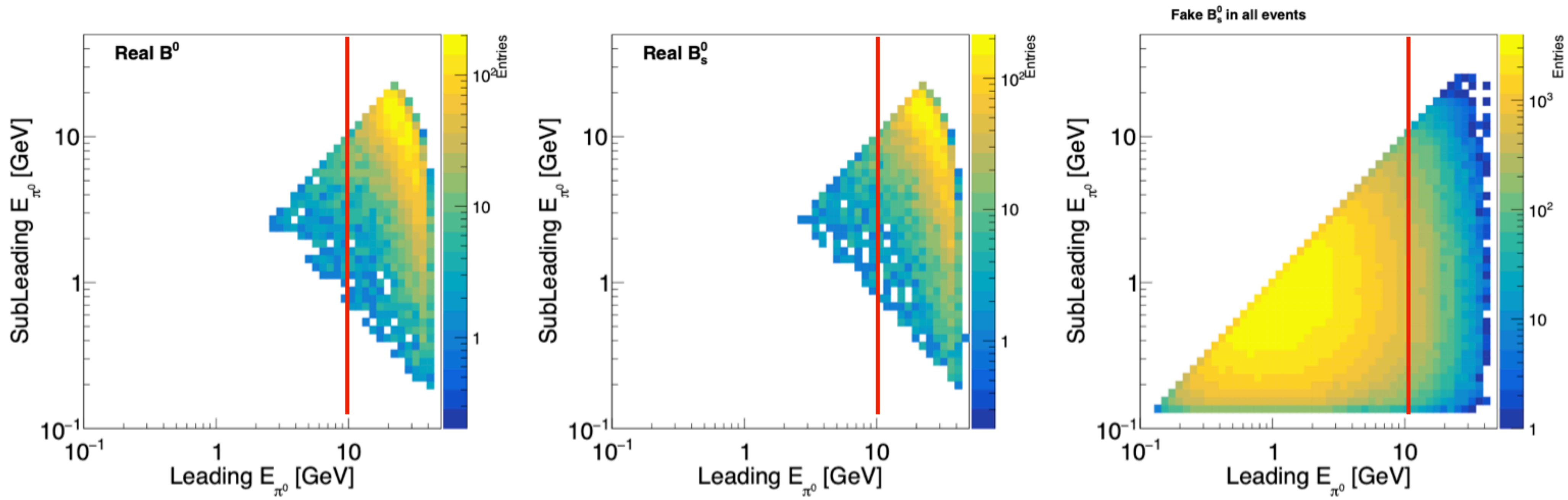


$$separation\ power = \frac{|\bar{m}_{B^0} - \bar{m}_{B_s^0}|}{\sqrt{\sigma^2_{m_{B^0}} + \sigma^2_{m_{B_s^0}}}}$$

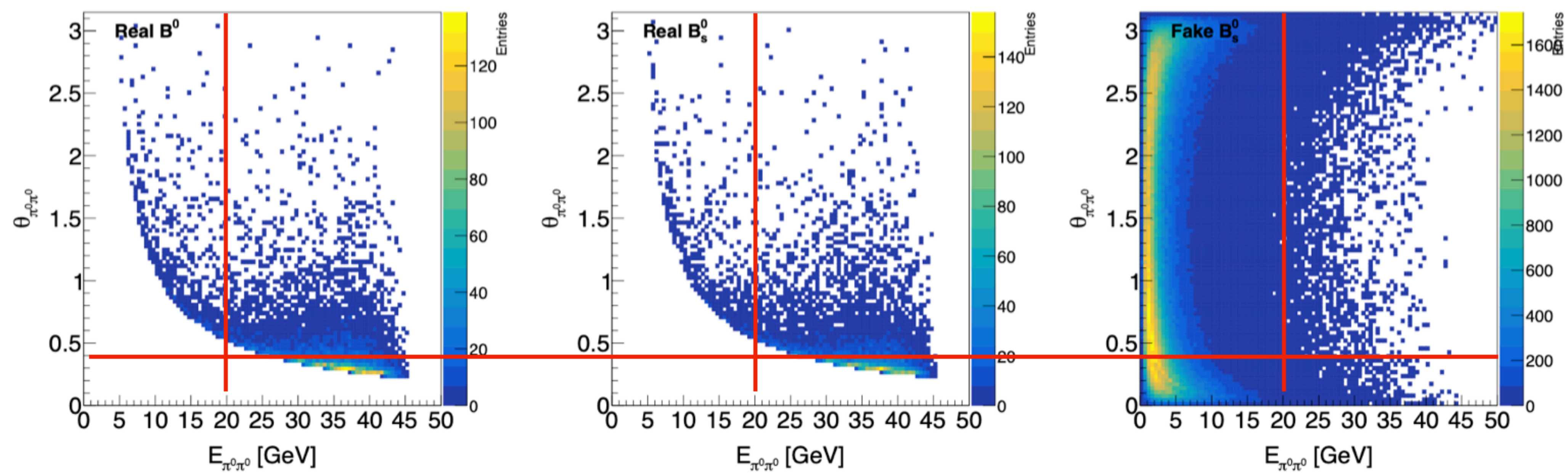


ECAL energy resolution better than 1%/√E⊕0.5% is required.

MCTruth Distribution of B⁰/Bs → π⁰π⁰



(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.



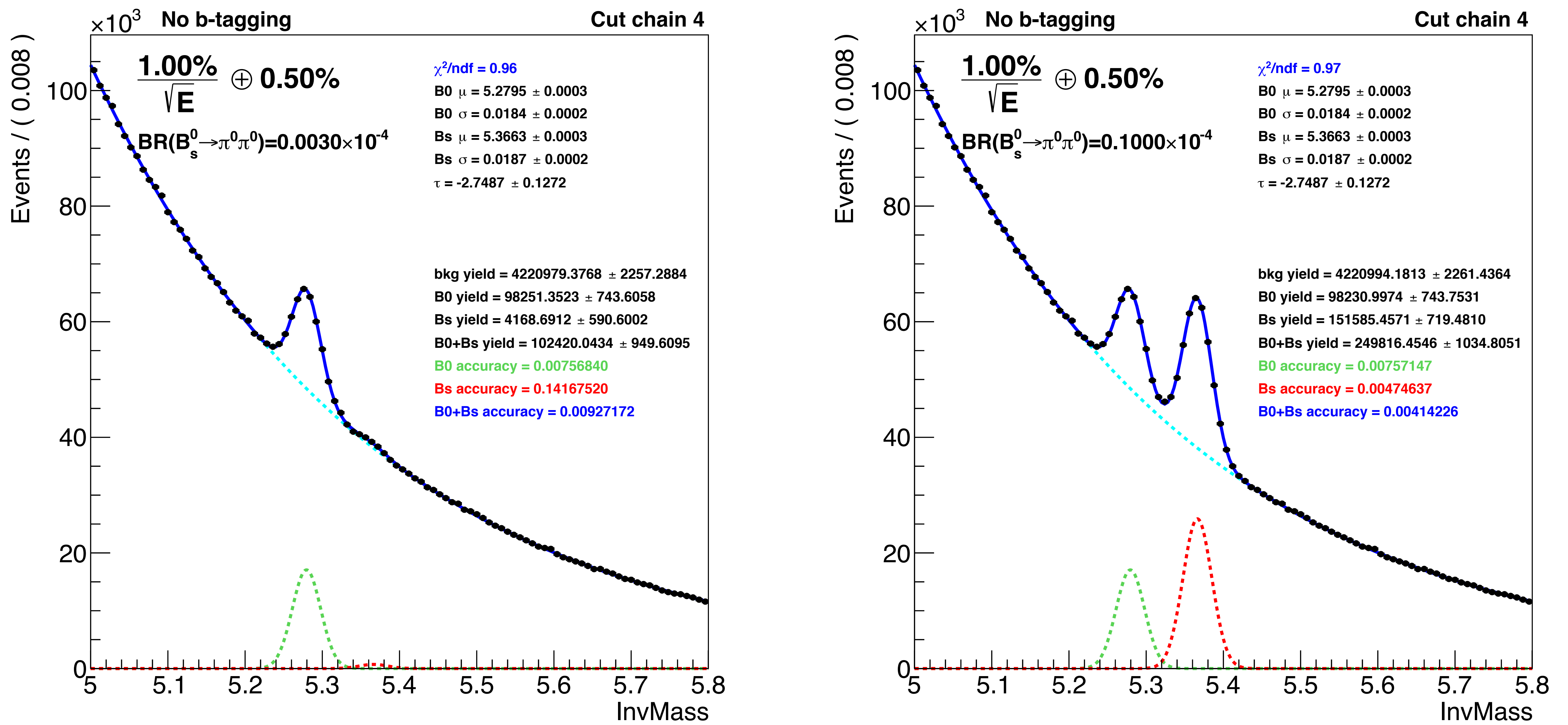
(b) $\theta_{\pi^0\pi^0}$ vs $E_{\pi^0\pi^0}$ in $B^0 \to \pi^0\pi^0$ (left), $B_s^0 \to \pi^0\pi^0$ (middle), and $Z \to q\bar{q}$ (right) events.

Energy and Angle cut on π^0

Emin > 6GeV & Emax > 14GeV & Total E > 22GeV & Angle < 23°

Individual measurement of $B^0/Bs \to \pi^0\pi^0$

at $1\%/\sqrt{E} \oplus 0.5\%$ ECAL resolution



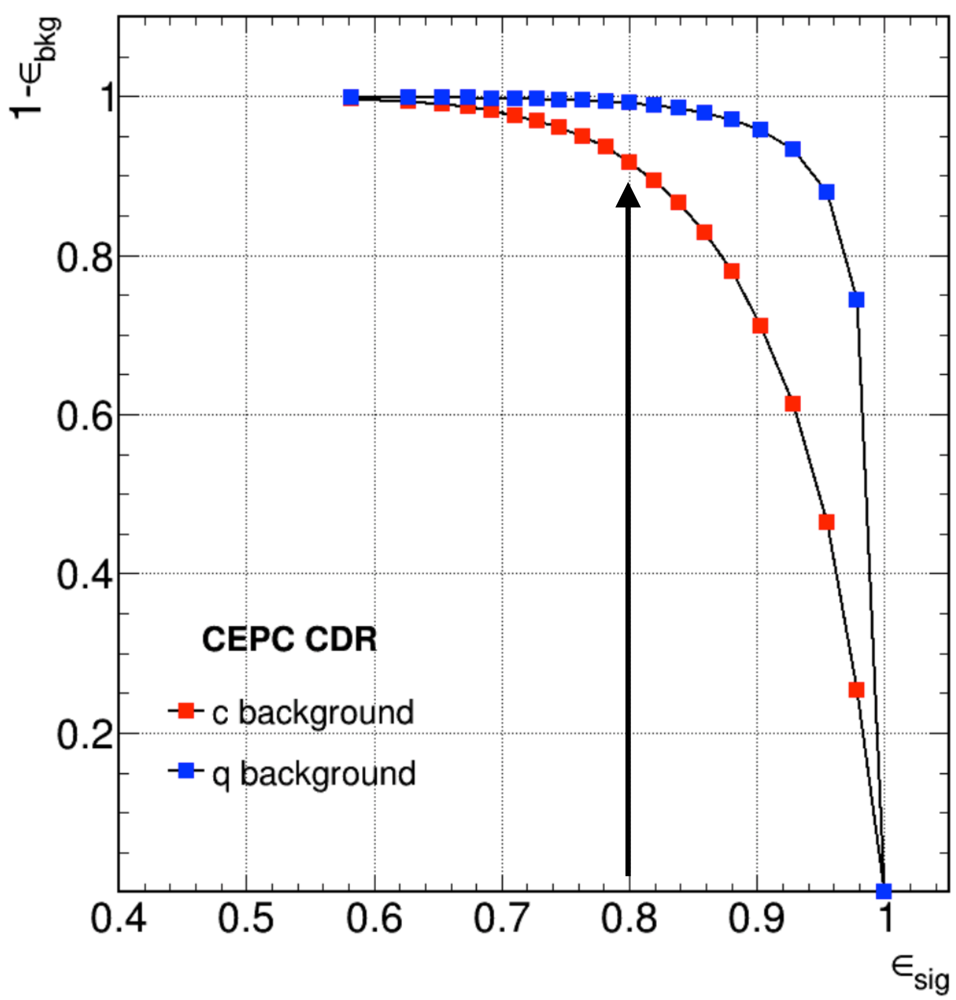
Gaussian signal + exponential background

Results without b-tagging

Individual measurement of $B^0/B_s \to \pi^0\pi^0$

Shape of background wo/wi b-tagging

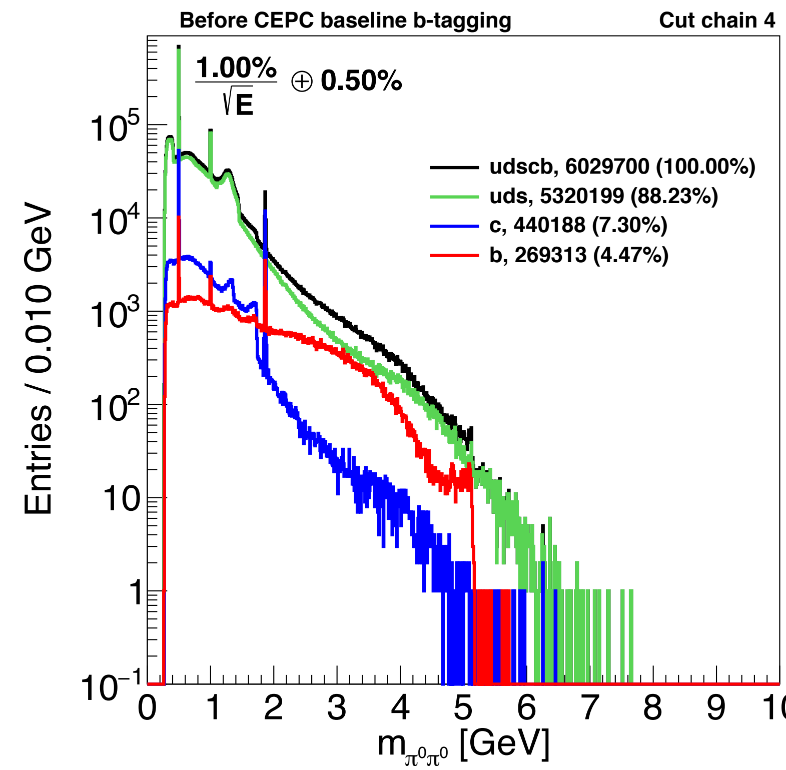
CEPC baseline b-tagging

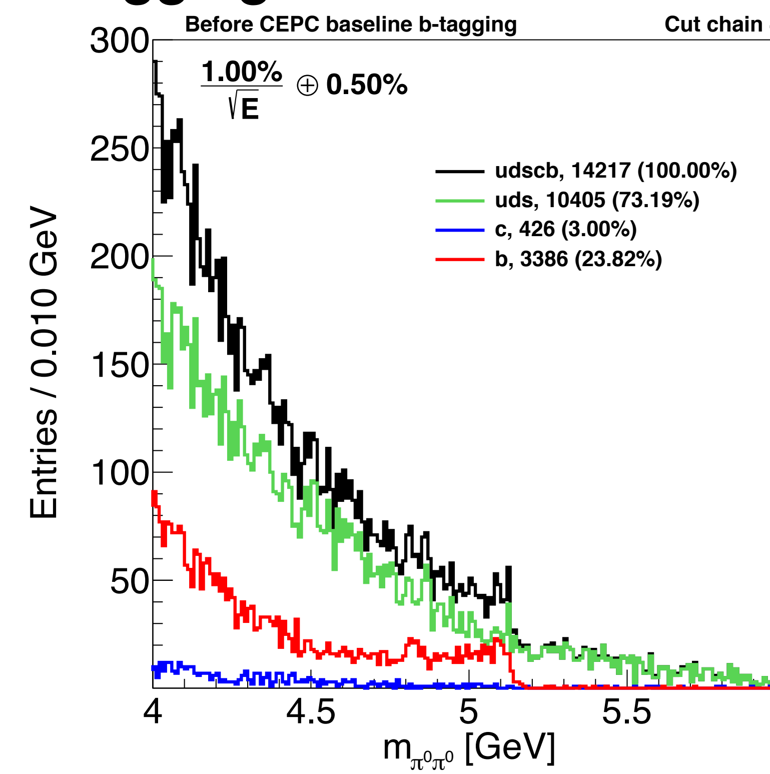


efficiency of 80%
purity of 90%

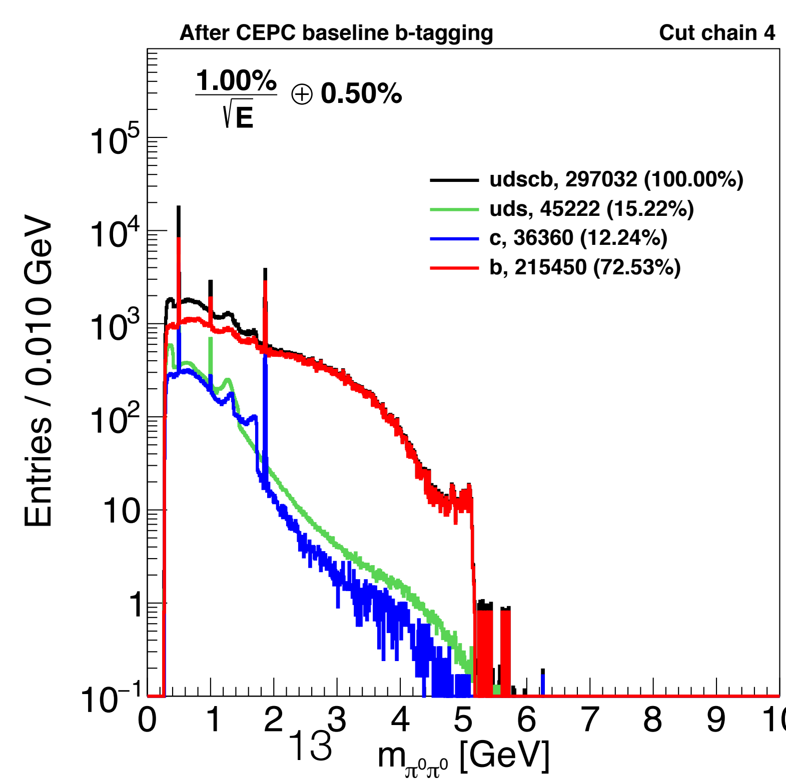
$$(\epsilon_{b\to b} = 80\%,\ \epsilon_{c\to b} = 8.26\%,\ \epsilon_{uds\to b} = 0.85\%)$$

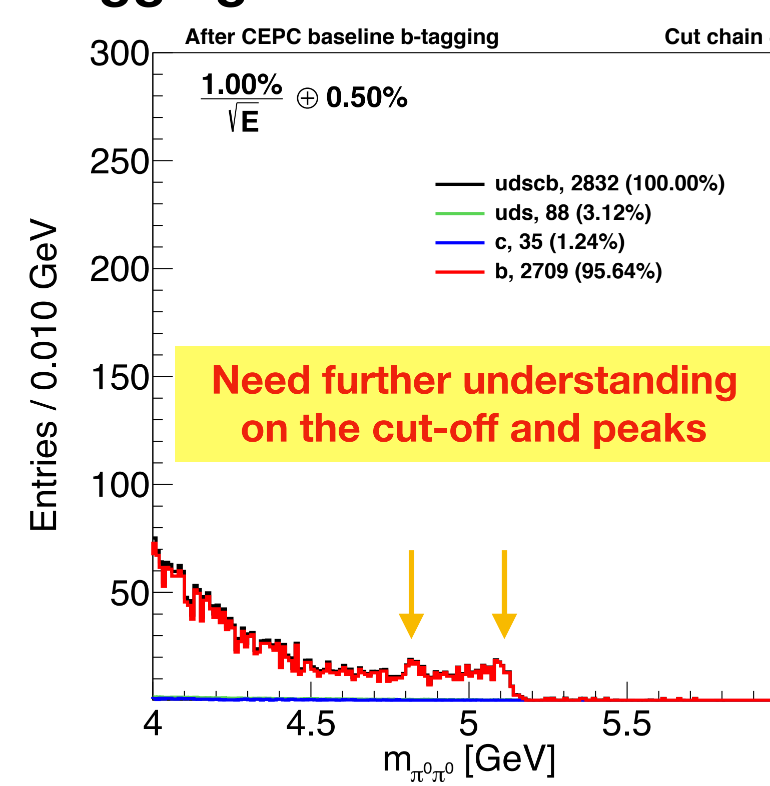
Before b-tagging





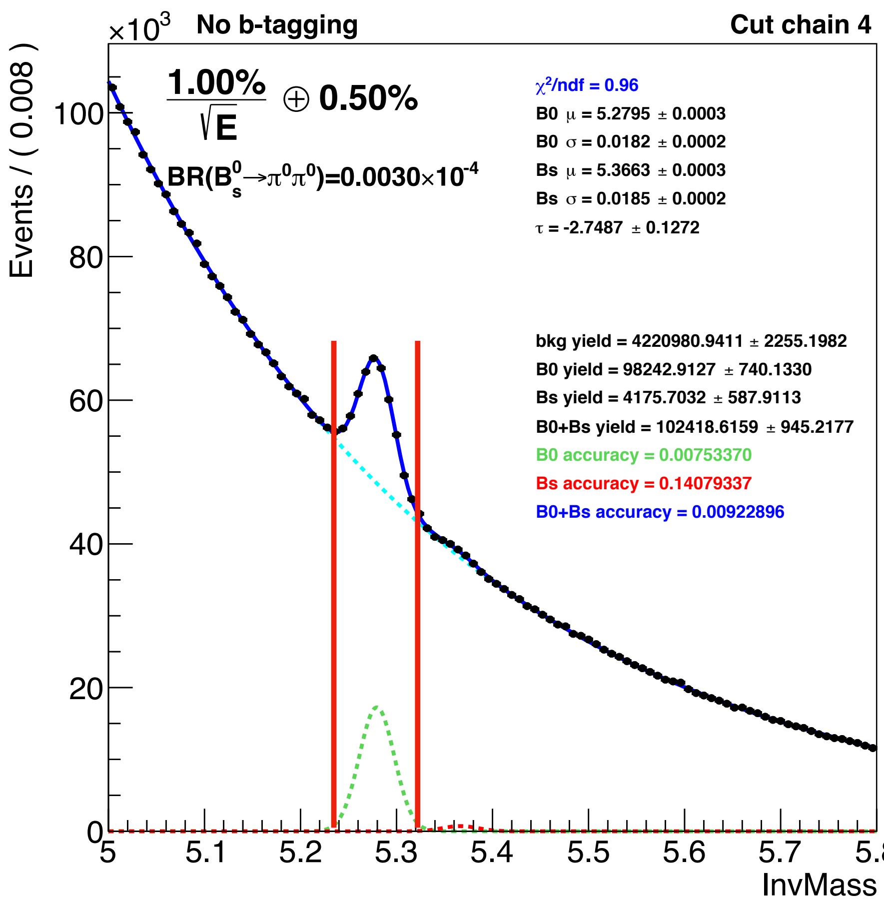
After b-tagging





Individual measurement of B⁰/Bs → $\pi^0\pi^0$

at 1%/√E⊕0.5% ECAL resolution



Mass window cut (counting) instead of **Fitting**

with results in the same order of magnitude

$$Accuracy = \sqrt{S+B}/S$$

	B^0	B_s^0
Fitting	0.75337%	14.079337%
Mass window cut	0.748274%	12.7002%

Cut chain	$B^0 \to \pi^0\pi^0 \to 4\gamma$	$B_s^0 \to \pi^0\pi^0 \to 4\gamma$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
Total generated	191113	8948	7e11 (100.00%)	4.285e11 (61.21%)	1.203e11 (17.19%)	1.512e11 (21.60%)	
$\gamma\gamma \to \pi^0$	187085	8760	28207036652152	15280186294352	5098265560853	7828584796947	
Lower $E_{\pi^0} > 6$ GeV	115684	5501	85022859011	64444435158	11390098533	9188325320	
Higher $E_{\pi^0} > 14$ GeV	109291	5190	19115874096	16695075894	1487448714	933349488	
$E_{\pi^0\pi^0} > 22$ GeV	108978	5171	17108689993	15097417243	1247342344	763930406	
$\theta_{\pi^0\pi^0} < 23^o$	97502	4557	17025770647	15022387179	1242937448	760446021	
$m_{\pi^0\pi^0} \in (5.2578, 5.3013)$ GeV (1.2 $\sigma_{m_{B^0}}$)	83268	1	304954	296483	2824	5647	0.748274%
$m_{\pi^0\pi^0} \in (5.3404, 5.3922)$ GeV (1.4 $\sigma_{m_{B^0_s}}$)	391	3981	251305	240010	5647	5647	12.700201%

Table 2: Scaled (to Tera-Z) statistics in wide range mass window (0,10) GeV, no b-tagging, at $\frac{1\%}{\sqrt{E}} \oplus 0.5\%$

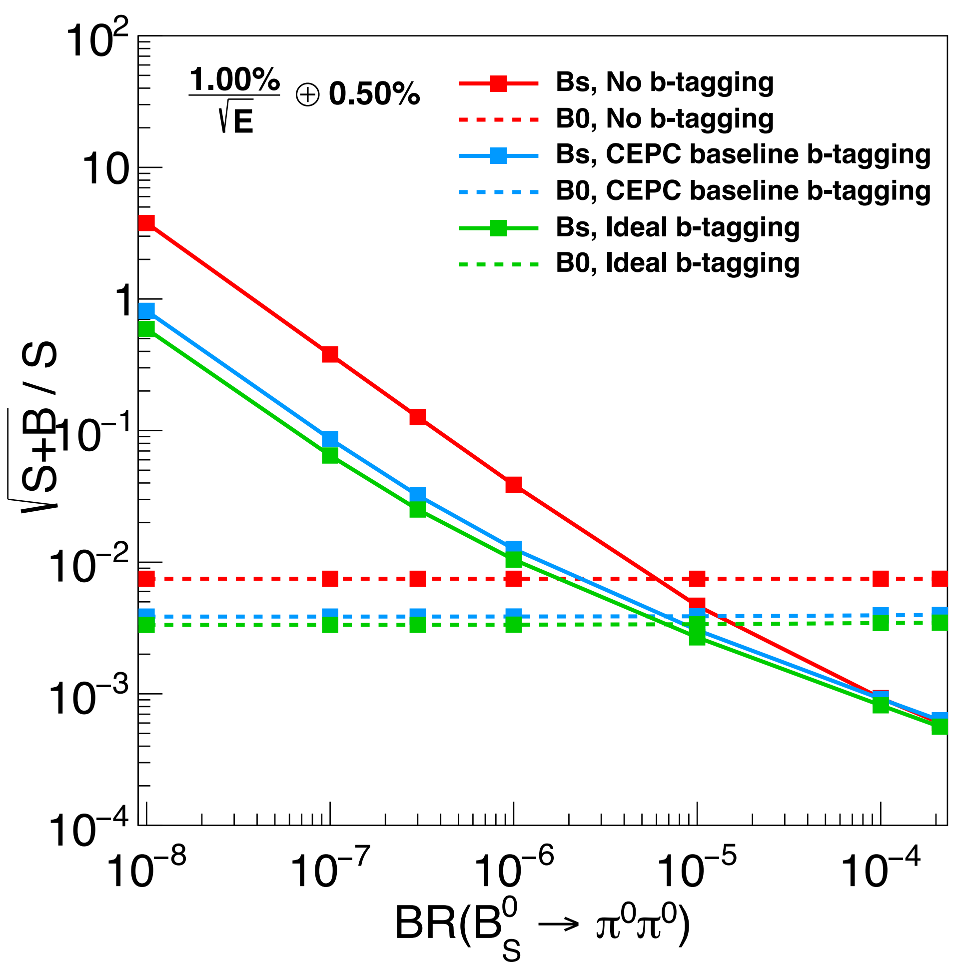
Individual measurement of $B^0/Bs \to \pi^0\pi^0$

at 1%/√E⊕0.5% ECAL resolution

Cut chain	$B^0 \to \pi^0\pi^0 \to 4\gamma$	$B_s^0 \to \pi^0\pi^0 \to 4\gamma$	$q\bar{q}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\sqrt{S+B}/S$
Total generated	191113	8948	7e11 (100.00%)	4.285e11 (61.21%)	1.203e11 (17.19%)	1.512e11 (21.60%)	
b-tagging ($\epsilon_{b\to b} = 80\%$, $\epsilon_{c\to b} = 8.26\%$, $\epsilon_{uds\to b} = 0.85\%$)	152890	7158	1.34539e11 (100.00%)	3.64225e9 (2.70%)	9.93678e9 (7.38%)	1.2096e11 (89.92%)	
$\gamma\gamma \to \pi^0$	149668	7008	6813866156386	129881583502	421116735326	7828584796947	
Lower $E_{\pi^0} > 6$ GeV	92547	4401	8839260094	547777699	940822139	7350660256	
Higher $E_{\pi^0} > 14$ GeV	87433	4152	1011451000	141908145	122863264	746679591	
$E_{\pi^0\pi^0} > 22$ GeV	87183	4137	842502849	128328047	103030478	611144325	
$\theta_{\pi^0\pi^0} < 23^o$	78001	3646	838713741	127690291	102666633	608356816	
$m_{\pi^0\pi^0} \in (5.2251, 5.3339)$ GeV ($3\ \sigma_{m_{B^0}}$)	77673	88	12307	5064	466	6777	0.386382%
$m_{\pi^0\pi^0} \in (5.3404, 5.3922)$ GeV ($1.4\ \sigma_{m_{B_s^0}}$)	313	3185	7024	2040	466	4518	3.220553%

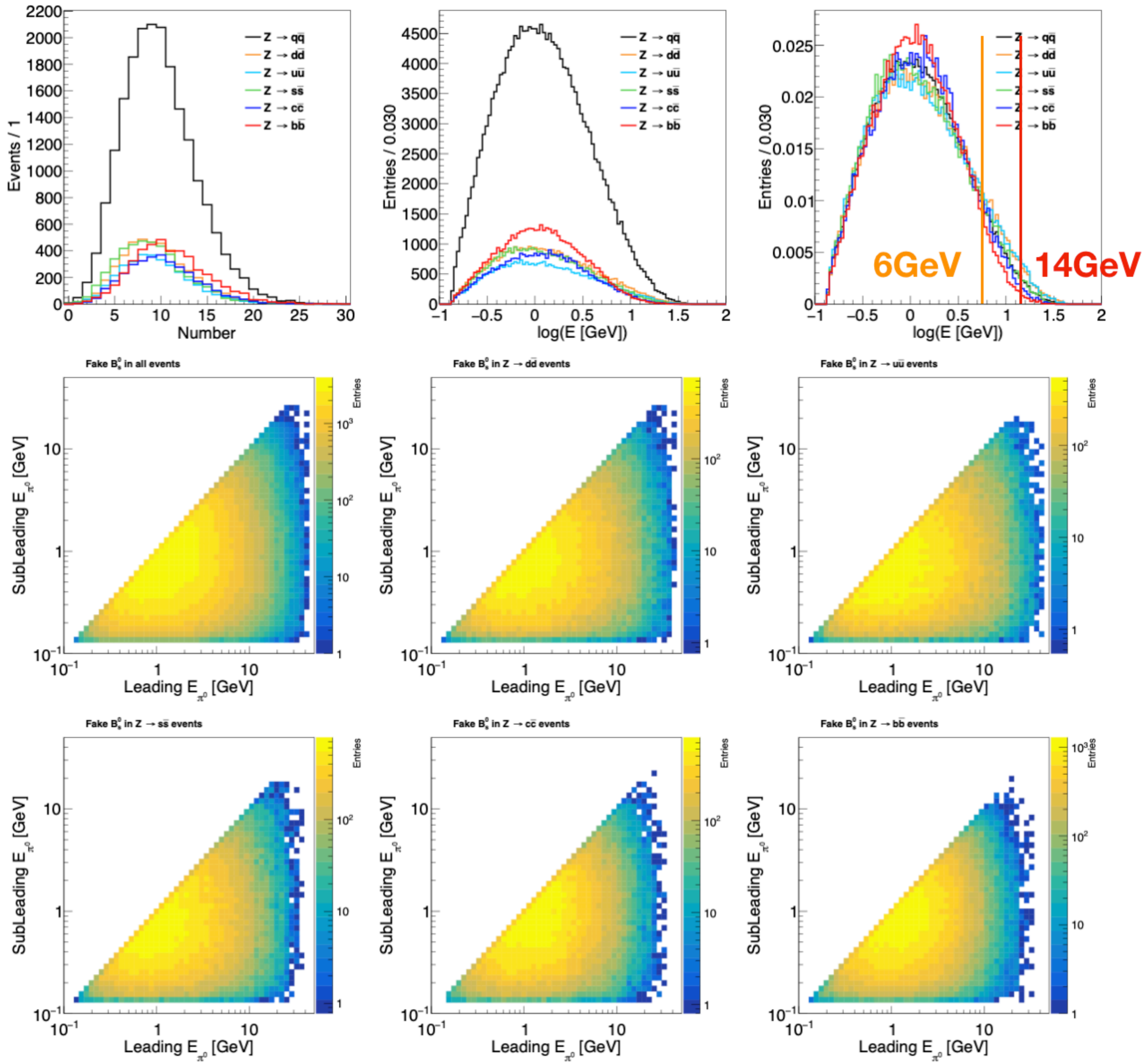
Table 4: Scaled (to Tera-Z) statistics in wide range mass window (0,10) GeV, CEPC baseline b-tagging, at $\frac{1\%}{\sqrt{E}} \oplus 0.5\%$

	B^0	B_s^0
No b-tagging	0.748274%	12.7002%
CEPC baseline b-tagging	0.386382%	3.220553%



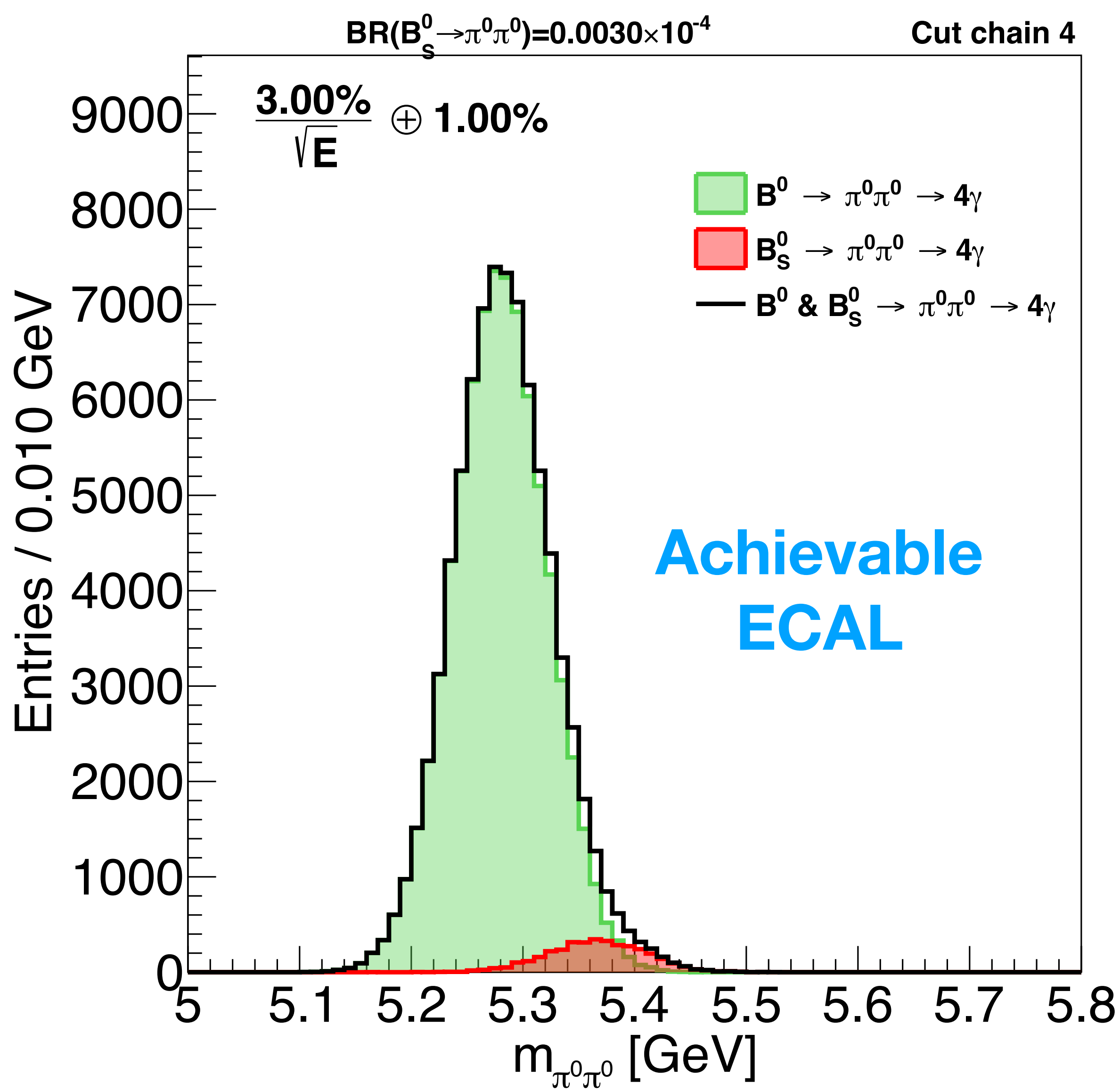
Further understanding on the effect of b-tagging

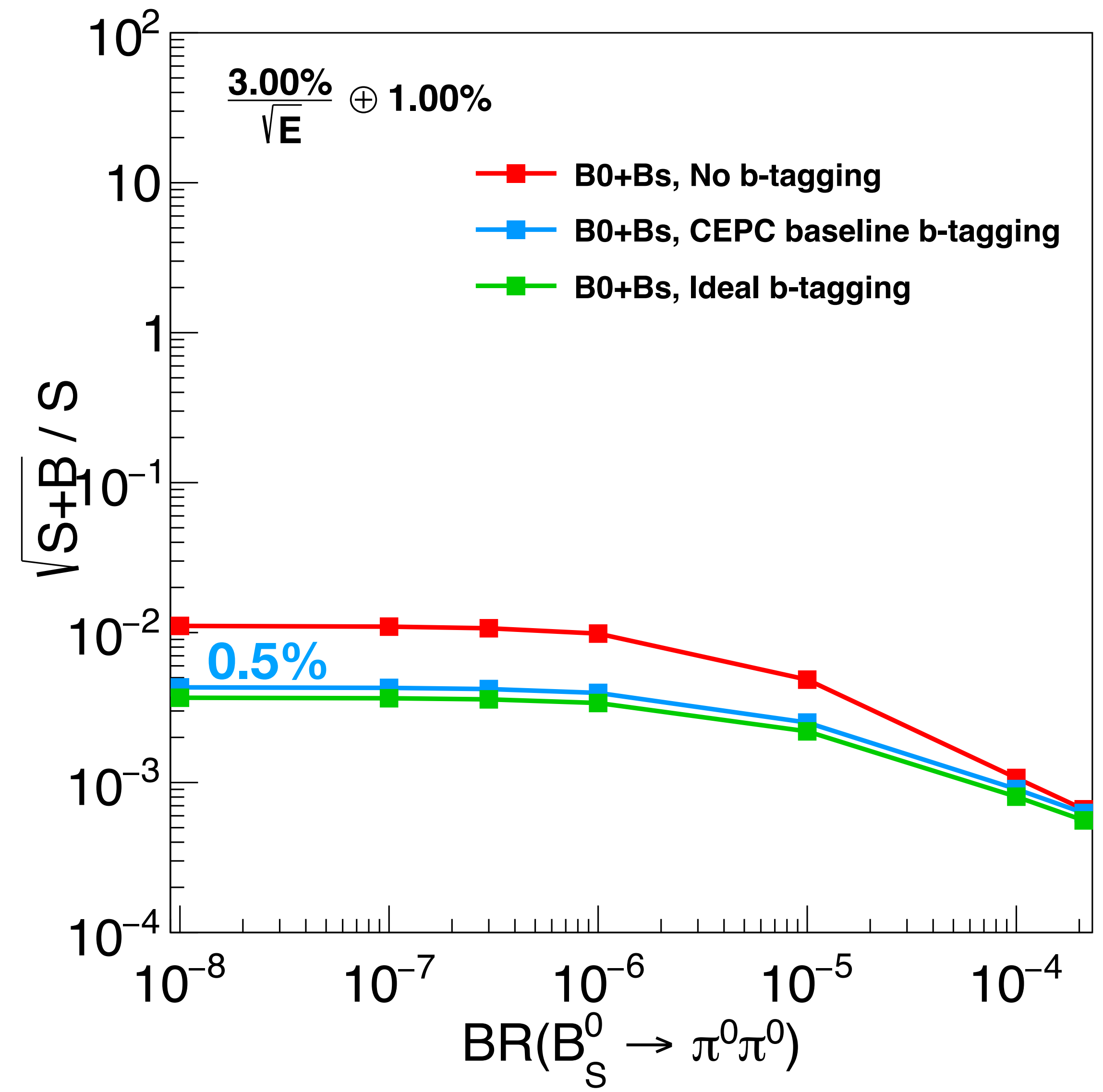
π° energy spectrum differs in different quark flavor events



Mixed measurement of $B^0/Bs \rightarrow \pi^0\pi^0$

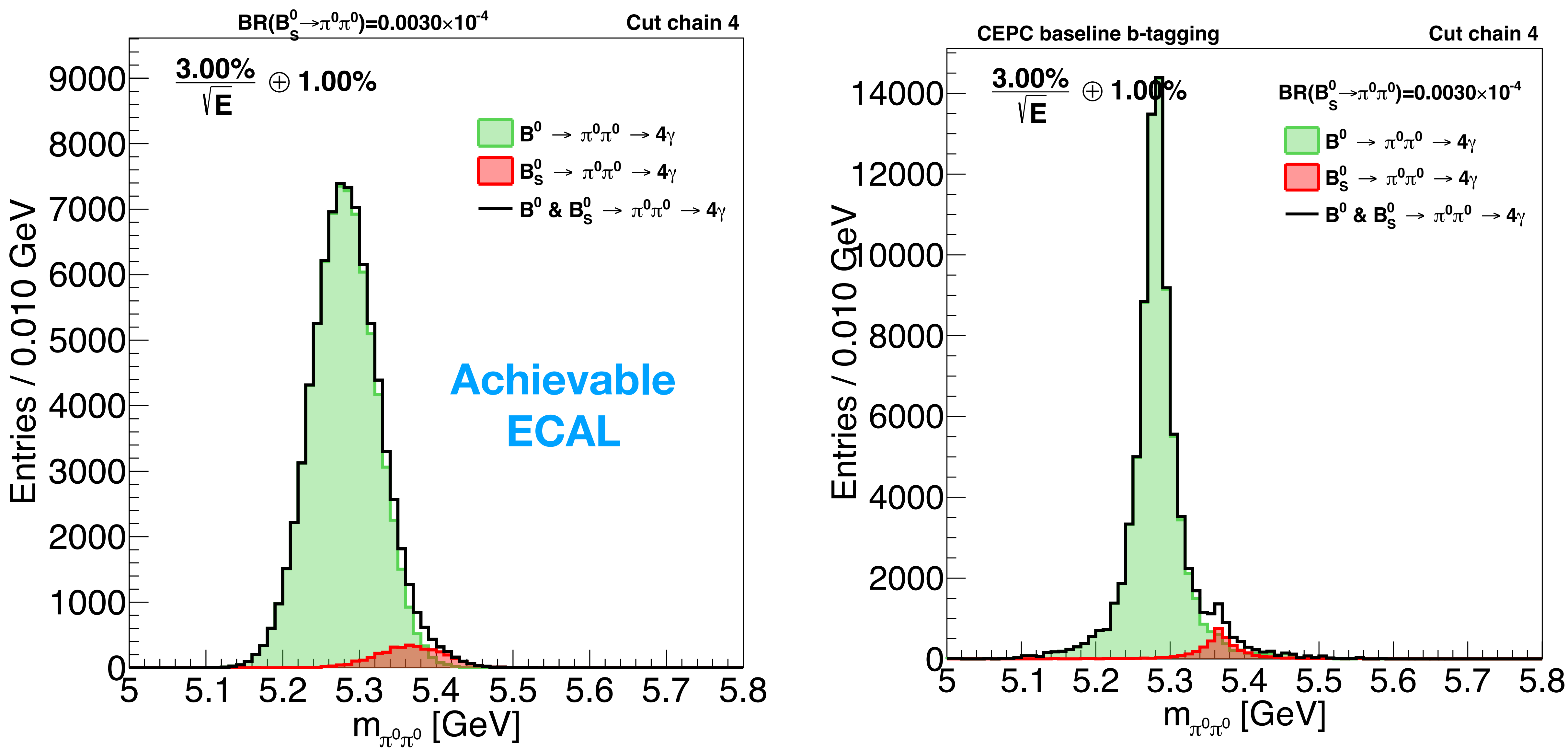
at 3%/√E⊕1% ECAL resolution





Kinematic Fit

at 3%/√E⊕1% ECAL resolution



Signal peak gets sharpened after Kinematic Fit
Still on-going work to model the signal and background

Summary

Fast simulation study

- **Reconstruction of π^0**
  - **EM resolution: $15\%/\sqrt{E} \oplus 1\% \rightarrow 3\%/\sqrt{E} \oplus 1\%$**
    - **π^0 mass resolution: 4-5 times improvement**
    - **$\varepsilon \times p > 60\%$ especially for high energy ones**
- **A neat separation of B^0 & Bs wo Kinematic fit requires ECAL resolution better than $1\%/\sqrt{E} \oplus 0.5\%$**
- **B-tagging is necessary: improve the accuracy by 2-4 times**

Future works

- **Further understanding on the shape of bb background**
- **Kinematic fit**

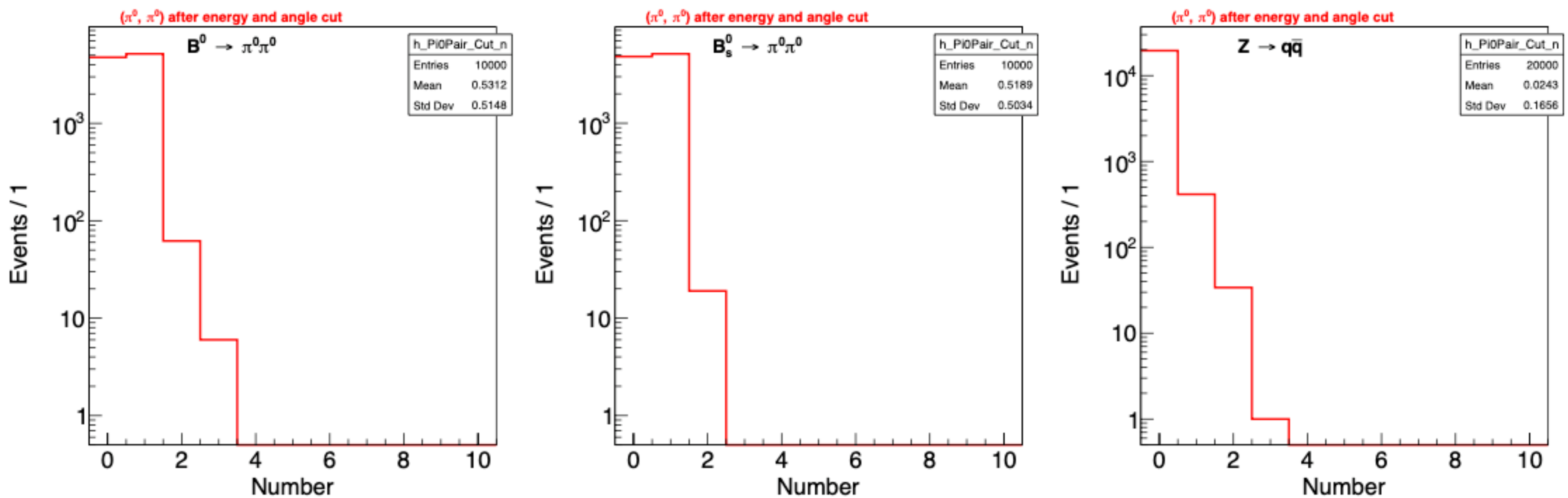
Thanks!

Backup

A Number of (π^0, π^0) after energy and angle cut

Information from MCTruth sample.

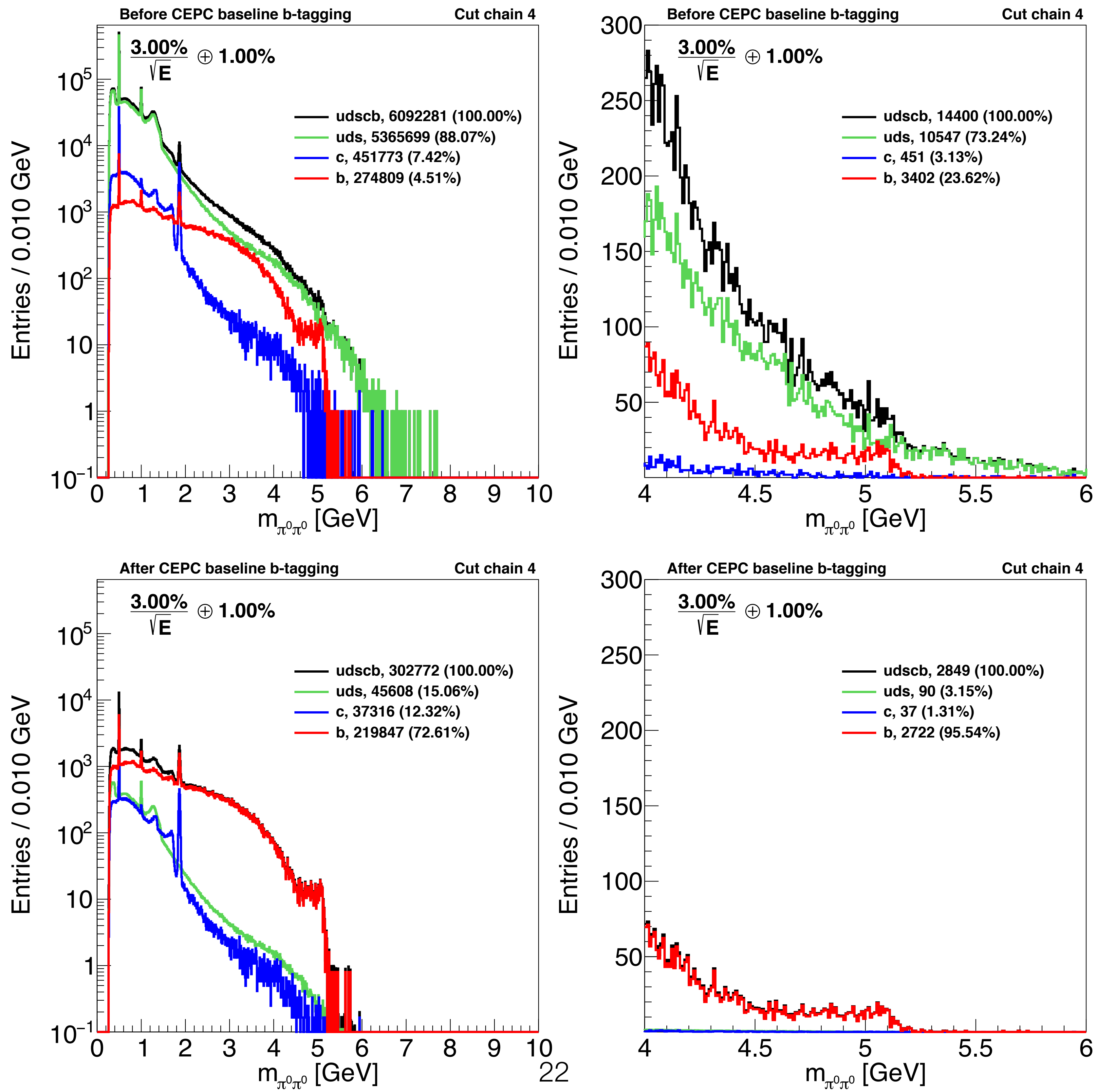
Cut: Lower E_{π^0} >6 GeV & Higher E_{π^0} >14 GeV & $E_{\pi^0\pi^0}$ >22 GeV & $\theta_{\pi^0\pi^0}$ <23°



Fraction of events remaining more than 1 π^0 pair after energy and angle cut is small.

Mixed measurement of B⁰/Bs → $\pi^0\pi^0$

at 3%/√E⊕1% ECAL resolution



Mixed measurement of $B^0/Bs \to \pi^0\pi^0$

at 3%/√E⊕1% ECAL resolution without b-tagging