中国科学院高能物理研究所
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CEPC

Measurement of $B^0/B_s \to \pi^0\pi^0$ at CEPC

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Outline

- **Introduction of B^0 & Bs → $\pi^o\pi^o$**
- **Reconstruction of π^o**
- **Separation of B^0 and Bs**
- **Preliminary study on Bs → $\pi^o\pi^o$**
- **Summary**

Introduction of $B^0 \to \pi^0\pi^0$

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ **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	$e^+e^- \to \Upsilon(4S)$

PHYSICAL REVIEW D **96**, 032007 (2017)

Measurement of the branching fraction and *CP* asymmetry in $B^0 \to \pi^0\pi^0$ decays, and an improved constraint on ϕ_2

T. Julius,[43] M. E. Sevior,[43] G. B. Mohanty,[66] I. Adachi,[14,11] H. Aihara,[70] S. Al Said,[65,32] D. M. Asner,[58] V. Aulchenko,[3,56] T. Aushev,[46] R. Ayad,[65] V. Babu,[66] I. Badhrees,[65,31] A. M. Bakich,[64] V. Bansal,[58] E. Barberio,[43] M. Barrett,[13] M. Berger,[62] V. Bhardwaj,[16] B. Bhuyan,[18] J. Biswal,[27] T. Bloomfield,[43] A. Bobrov,[3,56] A. Bondar,[3,56] G. Bonvicini,[75] A. Bozek,[53] M. Bračko,[41,27] T. E. Browder,[13] D. Červenkov,[4] M.-C. Chang,[9] Y. Chao,[52] V. Chekelian,[42] A. Chen,[50] B. G. Cheon,[12] K. Chilikin,[37,45] K. Cho,[33] Y. Choi,[63] D. Cinabro,[75] N. Dash,[17] S. Di Carlo,[75] Z. Doležal,[4] D. Dossett,[43] Z. Drásal,[4] D. Dutta,[66] S. Eidelman,[3,56] H. Farhat,[75] J. E. Fast,[58] T. Ferber,[7] B. G. Fulsom,[58] V. Gaur,[74] N. Gabyshev,[3,56] A. Garmash,[3,56] R. Gillard,[75] P. Goldenzweig,[29] J. Haba,[14,11] T. Hara,[14,11] K. Hayasaka,[55] H. Hayashii,[49] W.-S. Hou,[52] C.-L. Hsu,[43] T. Iijima,[48,47] K. Inami,[47] A. Ishikawa,[68] R. Itoh,[14,11] Y. Iwasaki,[14] W. W. Jacobs,[20] I. Jaegle,[8] Y. Jin,[70] D. Joffe,[30] K. K. Joo,[5] J. Kahn,[39] G. Karyan,[7] P. Katrenko,[46,37] T. Kawasaki,[55] C. Kiesling,[42] D. Y. Kim,[61] H. J. Kim,[35] J. B. Kim,[34] K. T. Kim,[34]

We measure the branching fraction and *CP* violation asymmetry in the decay $B^0 \to \pi^0\pi^0$, using a data sample of 752×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- collider. The obtained branching fraction and direct *CP* asymmetry are $\mathcal{B}(B \to \pi^0\pi^0) = [1.31 \pm 0.19(\text{stat}) \pm 0.19(\text{syst})] \times 10^{-6}$ and $A_{CP} = +0.14 \pm 0.36(\text{stat}) \pm 0.10(\text{syst})$, respectively. The signal significance, including the systematic uncertainty, is 6.4 standard deviations. We combine these results with Belle's earlier measurements of $B^0 \to \pi^+\pi^-$ and $B^\pm \to \pi^\pm\pi^0$ to exclude the *CP*-violating parameter ϕ_2 from the range $15.5° < \phi_2 < 75.0°$ at 95% confidence level.

(Belle Collaboration)

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

Introduction of Bs → π°π°

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 $f_{B_s} = 12.0 \pm 3.0\%$.

ELSEVIER

16 November 1995

PHYSICS LETTERS B

Physics Letters B 363 (1995) 127–136

Search for neutral charmless B decays at LEP

L3 Collaboration

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

Table 2

Resolutions (σ of a Gaussian fit to the signal Monte Carlo invariant mass distribution), efficiencies and experimental limits for B_d^0 and B_s^0 branching ratios. The (I) and (II) modes refer respectively to the search for a four photon final state or one with a photon pair for one η and a single cluster for the other one. The first error on the efficiencies is statistical, the second systematic.

Process	Resolution (MeV)	Efficiency (%)	Upper limit 90% C.L.
$B_d^0 \to \eta\eta$ (I)	107 ± 10	$2.5 \pm 0.2^{+0.2}_{-0.2}$	
$B_d^0 \to \eta\eta$ (II)	146 ± 11	$4.6 \pm 0.3^{+0.02}_{-0.2}$	
$B_d^0 \to \eta\eta$			$< 4.1 \times 10^{-4}$
$B_d^0 \to \eta\pi^0$	79 ± 5	$4.5 \pm 0.3^{+0.05}_{-0.03}$	$< 2.5 \times 10^{-4}$
$B_d^0 \to \pi^0\pi^0$	97 ± 4	$7.6 \pm 0.4^{+0.2}_{-0.5}$	$< 6.0 \times 10^{-5}$
$B_s^0 \to \eta\eta$ (I)	101 ± 10	$2.4 \pm 0.2^{+0.2}_{-0.2}$	
$B_s^0 \to \eta\eta$ (II)	129 ± 8	$4.8 \pm 0.3^{+0.2}_{-0.3}$	
$B_s^0 \to \eta\eta$			$< 1.5 \times 10^{-3}$
$B_s^0 \to \eta\pi^0$	81 ± 1	$4.3 \pm 0.3^{+0.02}_{-0.1}$	$< 1.0 \times 10^{-3}$
$B_s^0 \to \pi^0\pi^0$	99 ± 4	$8.3 \pm 0.4^{+0.4}_{-0.7}$	$< 2.1 \times 10^{-4}$

Introduction of Bs → $\pi^o\pi^o$

Theoretical estimation

ALI, KRAMER, LI, LÜ, SHEN, WANG, AND WANG PHYSICAL REVIEW D **76,** 074018 (2007)

TABLE III. The *CP*-averaged branching ratios ($\times 10^{-6}$) of $B_s \to PP$ decays obtained in the pQCD approach (This work); the errors for these entries correspond to the uncertainties in the input hadronic quantities, from the scale dependence, and the CKM matrix elements, respectively. We have also listed the current experimental measurements and upper limits (90% C.L.) wherever available [13]. For comparison, we also cite the theoretical estimates of the branching ratios in the QCD factorization framework [16] and in SCET [20], quoting two estimates in the latter case for some decays.

Modes	Class	QCDF	SCET	This work	Experiment
$\bar{B}_s^0 \to K^+\pi^-$	T	$10.2^{+4.5+3.8+0.7+0.8}_{-3.9-3.2-1.2-0.7}$	$4.9 \pm 1.2 \pm 1.3 \pm 0.3$	$7.6^{+3.2+0.7+0.5}_{-2.3-0.7-0.5}$	$5.0 \pm 0.75 \pm 1.0$
$\bar{B}_s^0 \to K^0\pi^0$	C	$0.49^{+0.28+0.22+0.40+0.33}_{-0.24-0.14-0.14-0.17}$	$0.76 \pm 0.26 \pm 0.27 \pm 0.17$	$0.16^{+0.05+0.10+0.02}_{-0.04-0.05-0.01}$	
$\bar{B}_s^0 \to K^+K^-$	P	$22.7^{+3.5+12.7+2.0+24.1}_{-3.2-8.4-2.0-9.1}$	$18.2 \pm 6.7 \pm 1.1 \pm 0.5$	$13.6^{+4.2+7.5+0.7}_{-3.2-4.1-0.2}$	$24.4 \pm 1.4 \pm 4.6$
$\bar{B}_s^0 \to K^0\bar{K}^0$	P	$24.7^{+2.5+13.7+2.6+25.6}_{-2.4-9.2-2.9-9.8}$	$17.7 \pm 6.6 \pm 0.5 \pm 0.6$	$15.6^{+5.0+8.3+0.0}_{-3.8-4.7-0.0}$	
$\bar{B}_s^0 \to \pi^0\eta$	$P_{\rm EW}$	$0.075^{+0.013+0.030+0.008+0.010}_{-0.012-0.025-0.010-0.007}$	$0.014 \pm 0.004 \pm 0.005 \pm 0.004$ $0.016 \pm 0.0007 \pm 0.005 \pm 0.006$	$0.05^{+0.02+0.01+0.00}_{-0.02-0.01-0.00}$	<1000
$\bar{B}_s^0 \to \pi^0\eta'$	$P_{\rm EW}$	$0.11^{+0.02+0.04+0.01+0.01}_{-0.02-0.04-0.01-0.01}$	$0.006 \pm 0.003 \pm 0.002^{+0.064}_{-0.006}$ $0.038 \pm 0.013 \pm 0.016^{+0.260}_{-0.036}$	$0.11^{+0.05+0.02+0.00}_{-0.03-0.01-0.00}$	
$\bar{B}_s^0 \to K^0\eta$	C	$0.34^{+0.19+0.64+0.21+0.16}_{-0.16-0.27-0.07-0.08}$	$0.80 \pm 0.48 \pm 0.29 \pm 0.18$ $0.59 \pm 0.34 \pm 0.24 \pm 0.15$	$0.11^{+0.05+0.06+0.01}_{-0.03-0.03-0.01}$	
$\bar{B}_s^0 \to K^0\eta'$	C	$2.0^{+0.3+1.5+0.6+1.5}_{-0.3-1.1-0.3-0.6}$	$4.5 \pm 1.5 \pm 0.4 \pm 0.5$ $3.9 \pm 1.3 \pm 0.5 \pm 0.4$	$0.72^{+0.20+0.28+0.11}_{-0.16-0.17-0.05}$	
$\bar{B}_s^0 \to \eta\eta$	P	$15.6^{+1.6+9.9+2.2+13.5}_{-1.5-6.8-2.5-5.5}$	$7.1 \pm 6.4 \pm 0.2 \pm 0.8$ $6.4 \pm 6.3 \pm 0.1 \pm 0.7$	$8.0^{+2.6+4.7+0.0}_{-1.9-2.5-0.0}$	<1500
$\bar{B}_s^0 \to \eta\eta'$	P	$54.0^{+5.5+32.4+8.3+40.5}_{-5.2-22.4-6.4-16.7}$	$24.0 \pm 13.6 \pm 1.4 \pm 2.7$ $23.8 \pm 13.2 \pm 1.6 \pm 2.9$	$21.0^{+6.0+10.0+0.0}_{-4.6-5.6-0.0}$	
$\bar{B}_s^0 \to \eta'\eta'$	P	$41.7^{+4.2+26.3+15.2+36.6}_{-4.0-17.2-8.5-15.4}$	$44.3 \pm 19.7 \pm 2.3 \pm 17.1$ $49.4 \pm 20.6 \pm 8.4 \pm 16.2$	$14.0^{+3.2+6.2+0.0}_{-2.7-3.9-0.0}$	
$\bar{B}_s^0 \to \pi^+\pi^-$	ann	$0.024^{+0.003+0.025+0.000+0.163}_{-0.003-0.012-0.000-0.021}$	...	$0.57^{+0.16+0.09+0.01}_{-0.13-0.10-0.00}$	<1.36
$\bar{B}_s^0 \to \pi^0\pi^0$	ann	$0.012^{+0.001+0.013+0.000+0.082}_{-0.001-0.006-0.000-0.011}$	...	$0.28^{+0.08+0.04+0.01}_{-0.07-0.05-0.00}$	<210

~ 3×10^{-7}

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

Why choose $B^0/B_s \to \pi^o\pi^o$?

- Clear dependence on detector and reconstruction performance
  - $\pi^o \to \gamma\gamma$, EM object, ECAL performance
  - Bs, b-tagging, background rejection

- CEPC can achieve Tera-Z (~10^{10} Bs) >> LEP
  - promising to observe this rare decay

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16 November 1995

PHYSICS LETTERS B

Physics Letters B 363 (1995) 127–136

Search for neutral charmless B decays at LEP

L3 Collaboration

Since no candidate event has been found in data for any of the eight final configurations, upper limits at 90% confidence level have been set using the following numerical values: $N_{had} = 3\,088\,053$ as the number of Z bosons decaying to hadrons, $\Gamma_{\bar{b}}/\Gamma_{had} = 0.222 \pm 0.003(\text{stat.}) \pm 0.007(\text{syst.})$ as the partial width of Z decays into b quark with respect to the hadronic decays [20], $f(b \to B^0_d) = 39.5 \pm 4.0\%$ and $f(b \to B^0_s) = 12.0 \pm 3.0\%$ as the fractions of $B^0_{d(s)}$ produced in the fragmentation of b quarks at LEP, in agreement with the available measurements [21], $Br(\eta \to \gamma\gamma) = 38.8\%$ and $Br(\pi^0 \to \gamma\gamma) = 98.8\%$ [22]. The errors on

The following results are all from fast simulation…

Reconstruction of π°

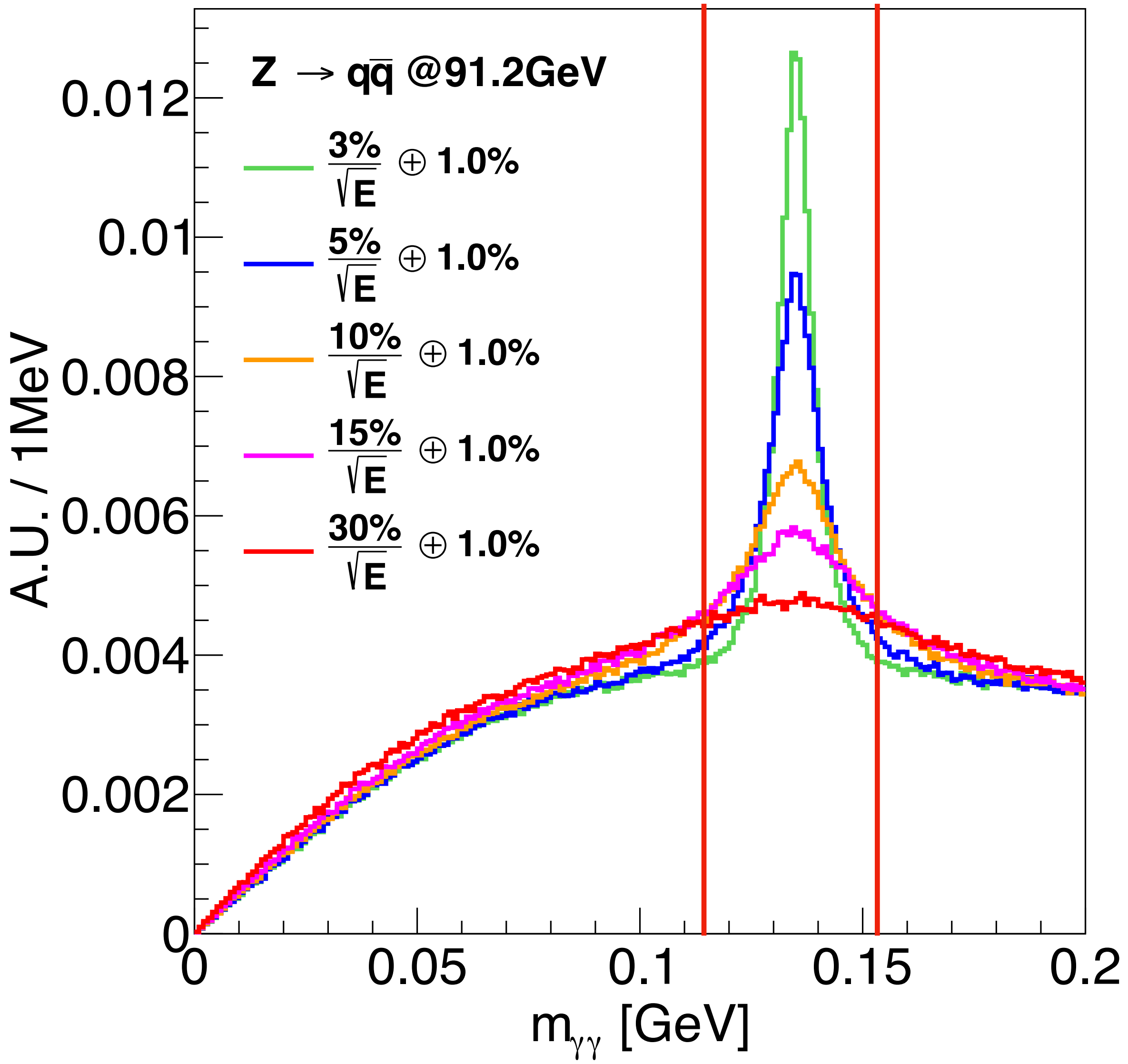
Decay channel: π° → γγ

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

Optimize the mass window to get maximal efficiency × purity

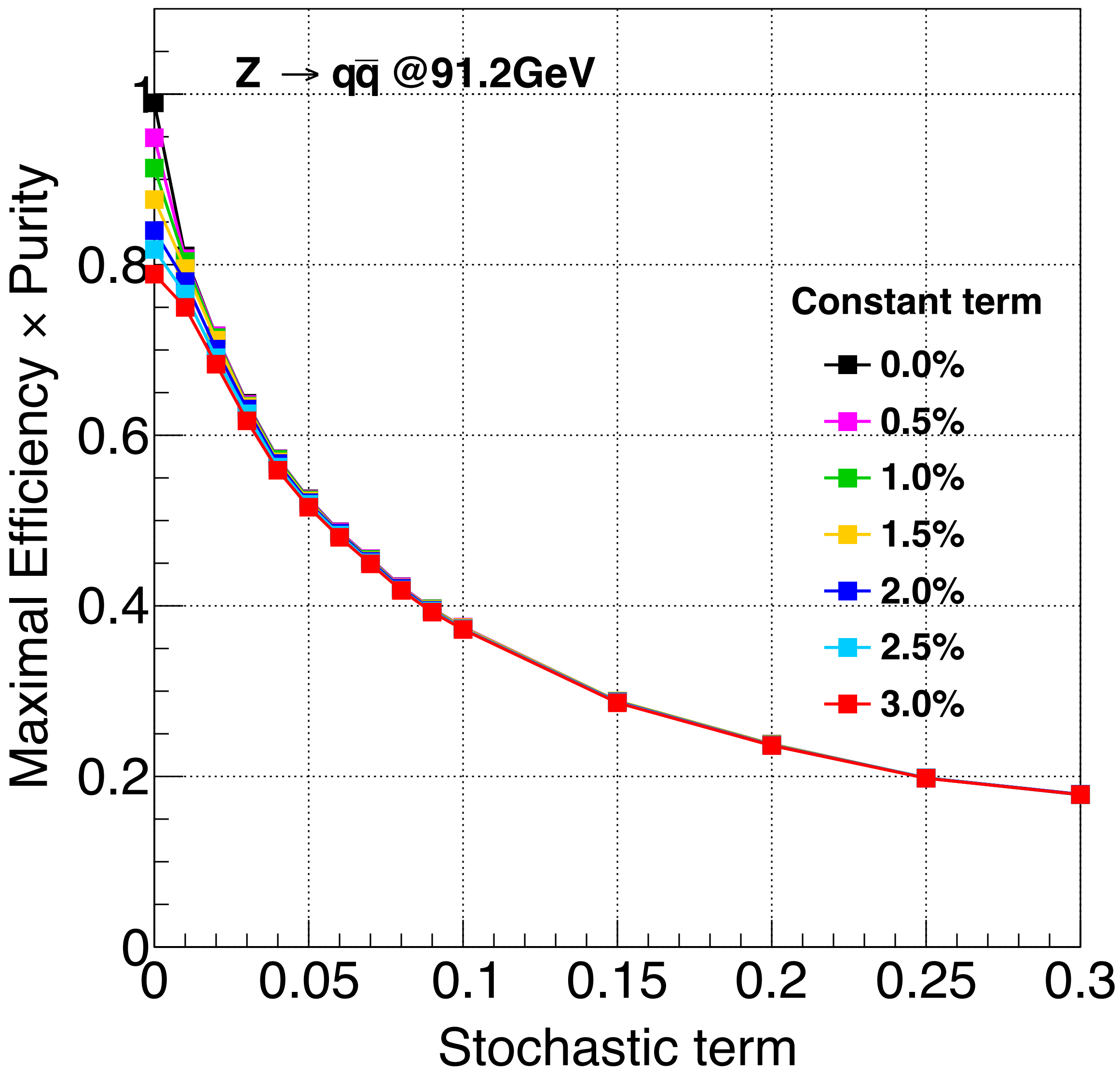
$$\epsilon = \frac{Number\ of\ selected\ \pi^0 s\ that\ are\ true\ \pi^0 s\ in\ Monte\ Carlo}{Number\ of\ all\ generated\ \pi^0 s}$$

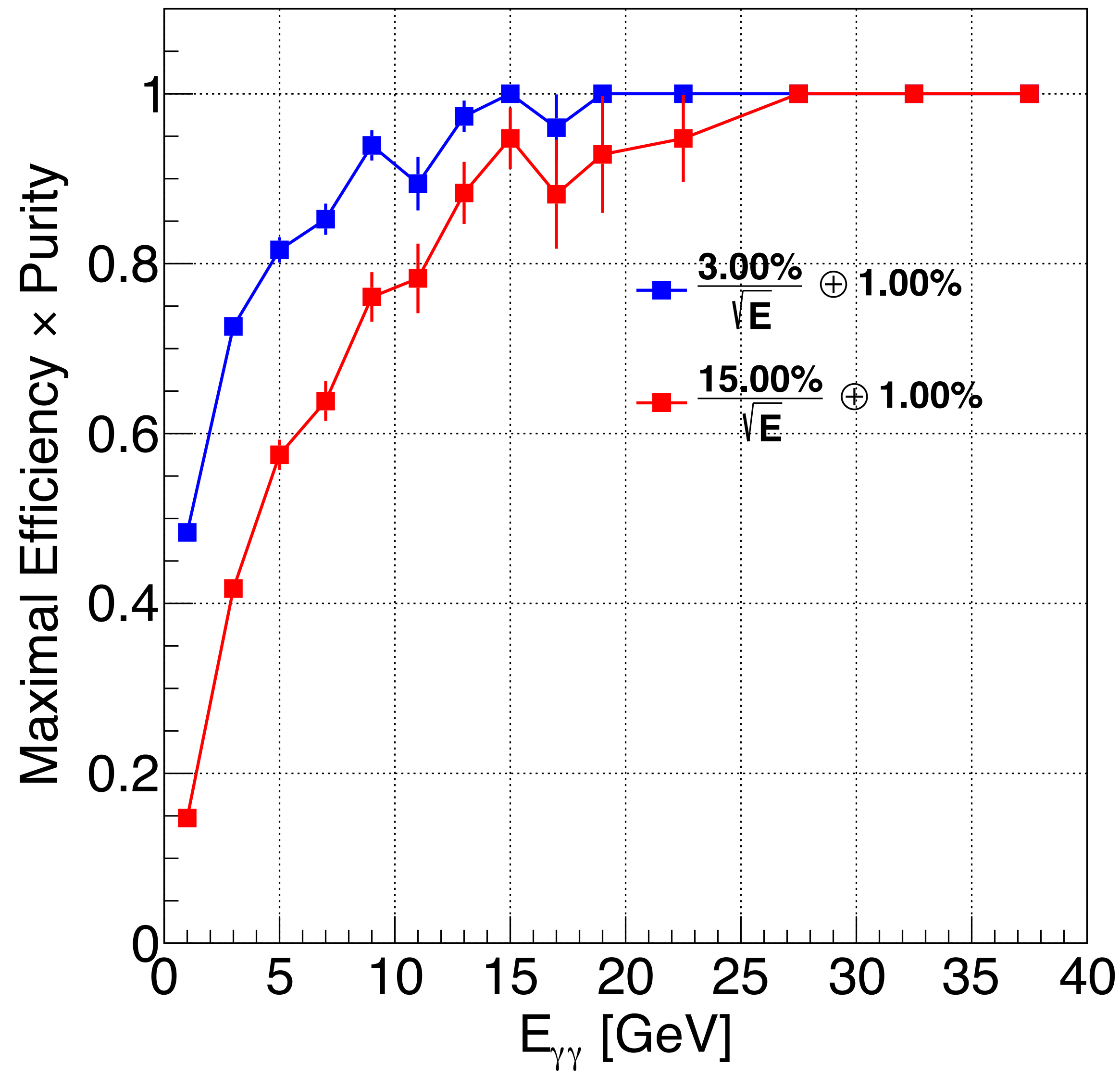
$$p = \frac{Number\ of\ selected\ \pi^0 s\ that\ are\ true\ \pi^0 s\ in\ Monte\ Carlo}{Number\ of\ all\ selected\ \pi^0 s}$$



Reconstruction of π⁰

maximal efficiency × purity

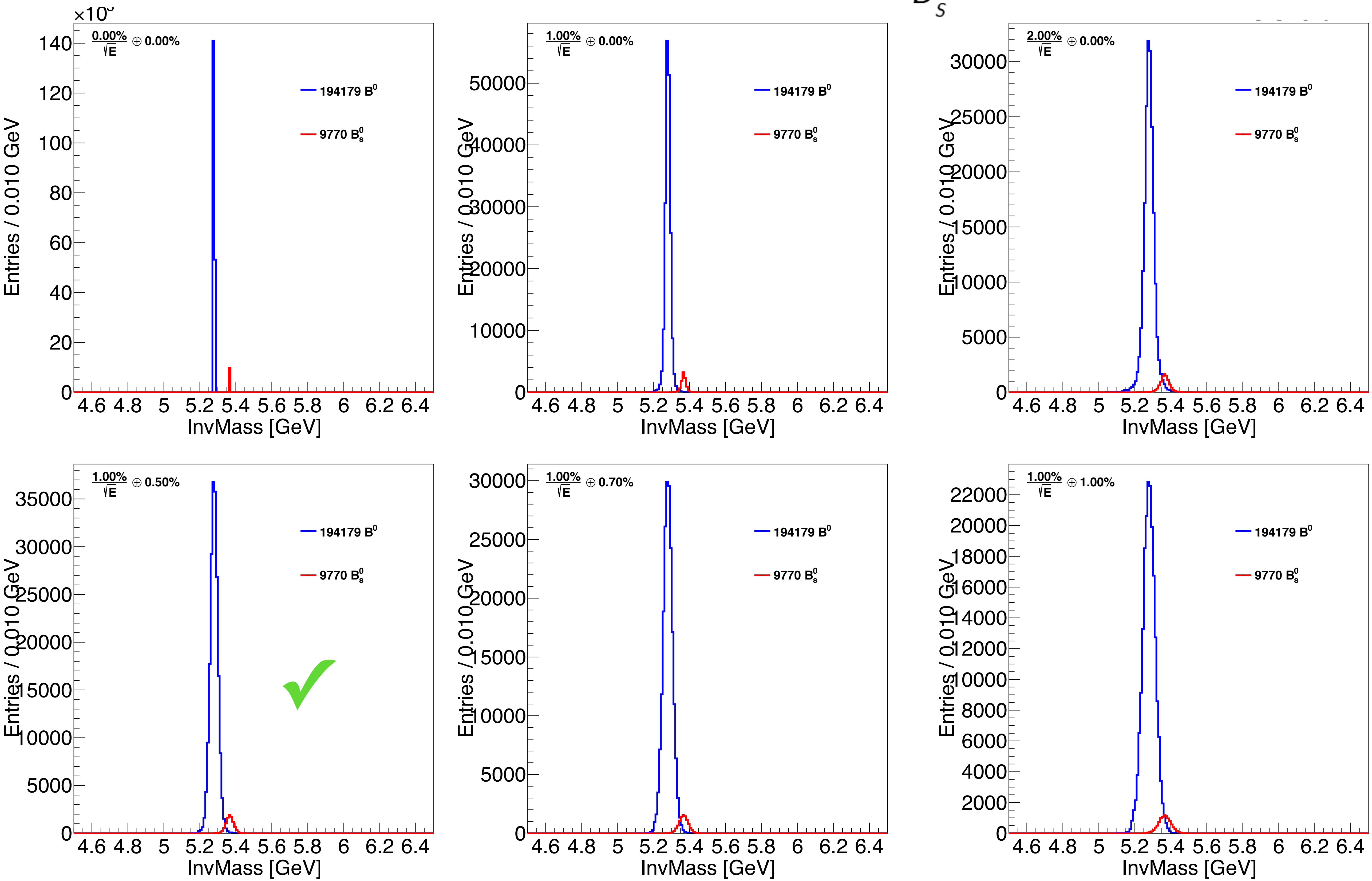




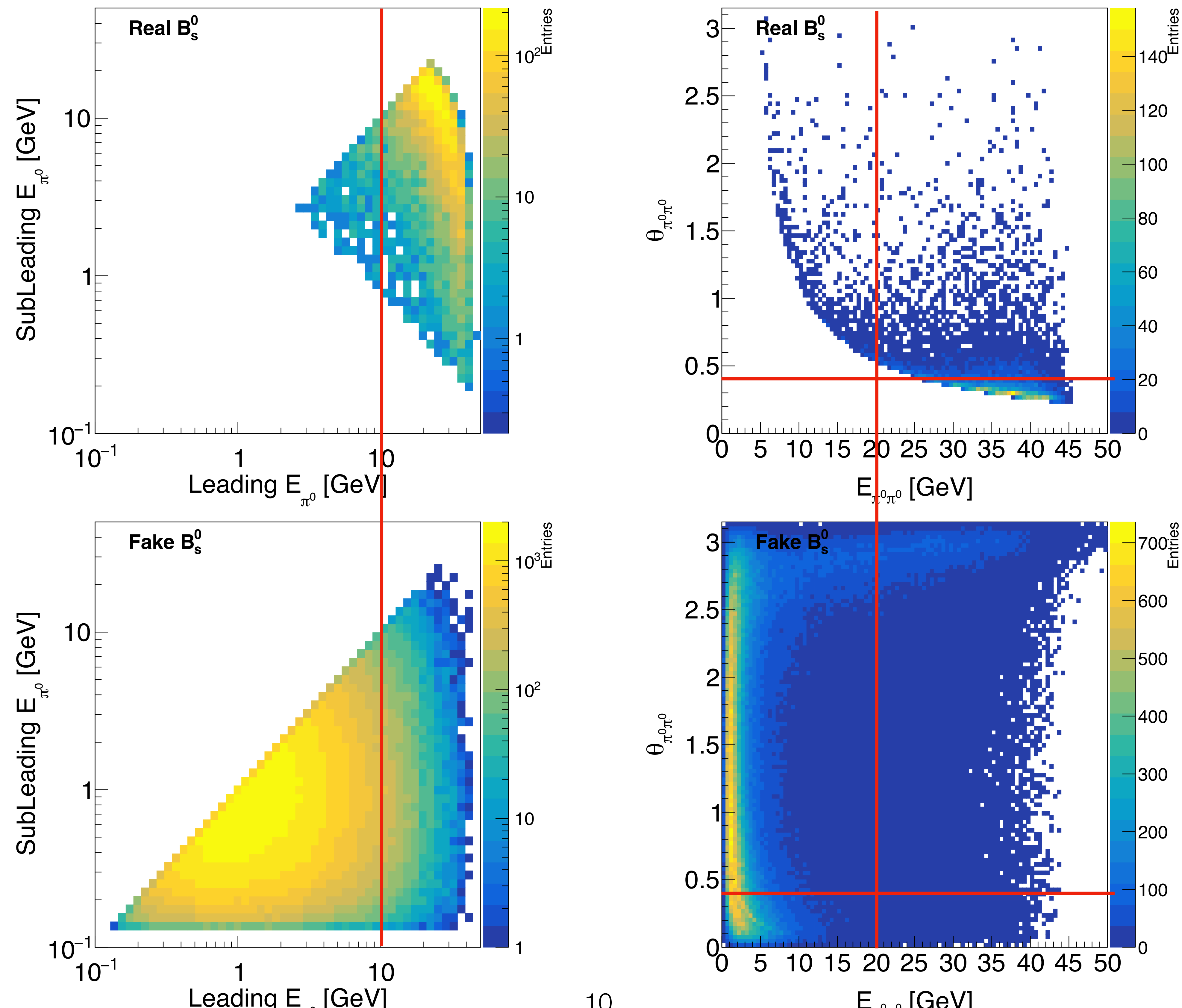
Separation of B^0 and Bs

Mass $m_{B^0} = 5279.63 \pm 0.15$ MeV

Mass $m_{B_s^0} = 5366.89 \pm 0.19$ MeV



MCTruth Distribution of Bs → $\pi^o\pi^o$



Bs → π°π°

Cut chain

Table 1
Final cuts for all the B_d^0 and B_s^0 decay modes. The (I) and (II) modes refer to the search for a four photon final state, or one with a photon pair for one η and a single cluster for the other one, respectively. "Kinematics" refers to global kinematic variables of the $B^0_{d(s)}$ candidate, "Photons", "Cluster" and "2nd cluster" to the cuts on purity of photons, single cluster or most energetic π^0 single cluster, if any.

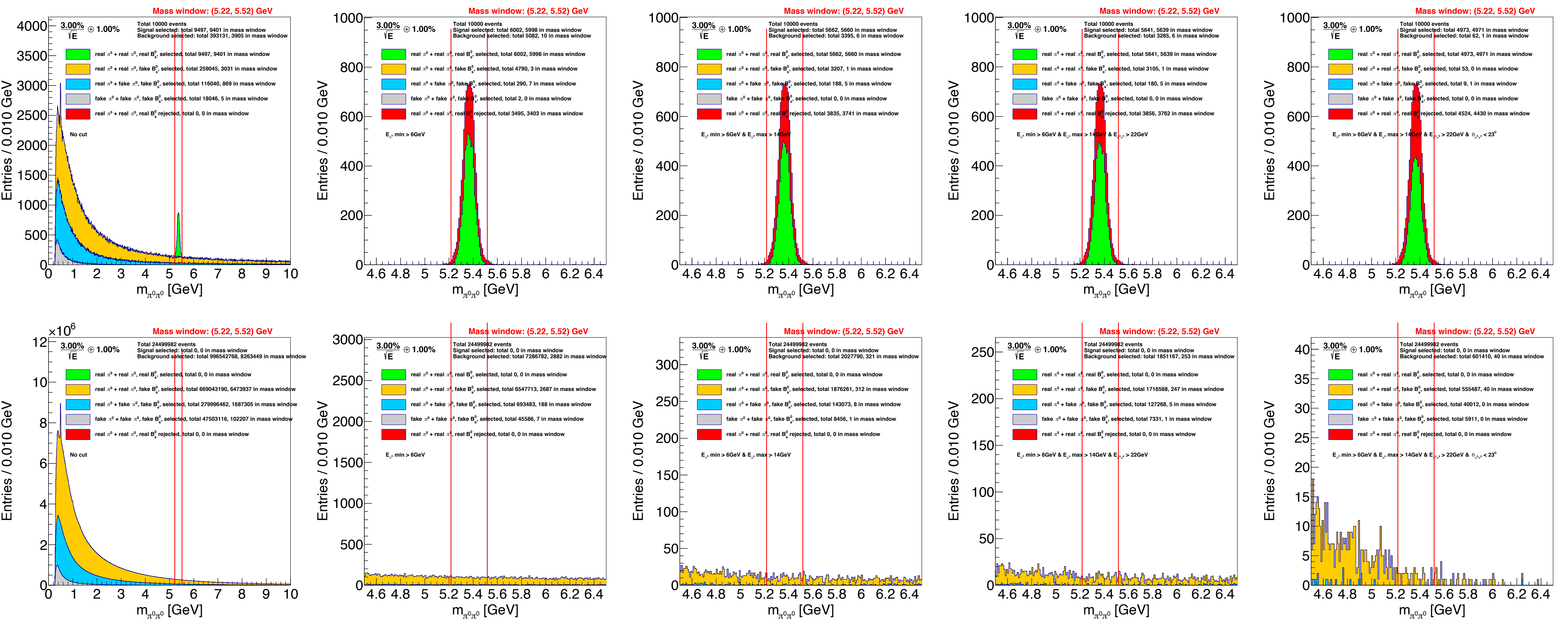
	Cut	$B^0_{d(s)} \to \eta\eta$ (I)	$B^0_{d(s)} \to \eta\eta$ (II)	$B^0_{d(s)} \to \eta\pi^0$	$B^0_{d(s)} \to \pi^0\pi^0$
Kinematics	$M_{\gamma\gamma}$ (GeV)	0.51–0.58	0.530–0.564	0.530–0.564	–
	$\cos\theta^*$	0.7	0.775	0.75	0.6
	θ_{mesons}	28°	25°	26°	23°
	Total energy	17.0	27.5	25.0	22.0
Photons	Energy (GeV)	0.3	0.5	1.0	–
	χ^2_{em}	10.0	8.0	8.0	–
	θ_{3D} (mrad)	30.0	50.0	50.0	–
Cluster	Energy (GeV)	–	10.0	13.0	6.0
	χ^2_{em}	–	–	8.0	30.0
	θ_{3D} (mrad)	–	50.0	50.0	40.0
2nd cluster	Energy (GeV)	–	–	–	14.0
	χ^2_{em}	–	–	–	5.0
	θ_{3D} (mrad)	–	–	–	40.0

As a starting point, just use the values in L3 paper:

Pi0 Emin > 6GeV & Emax > 14GeV & Total E > 22GeV & angle < 23°

Bs → π⁰π⁰

Cut chain



An artificial sample contains 1e4 Bs → π⁰π⁰ signal and 2.5e7 Z → qq bkg

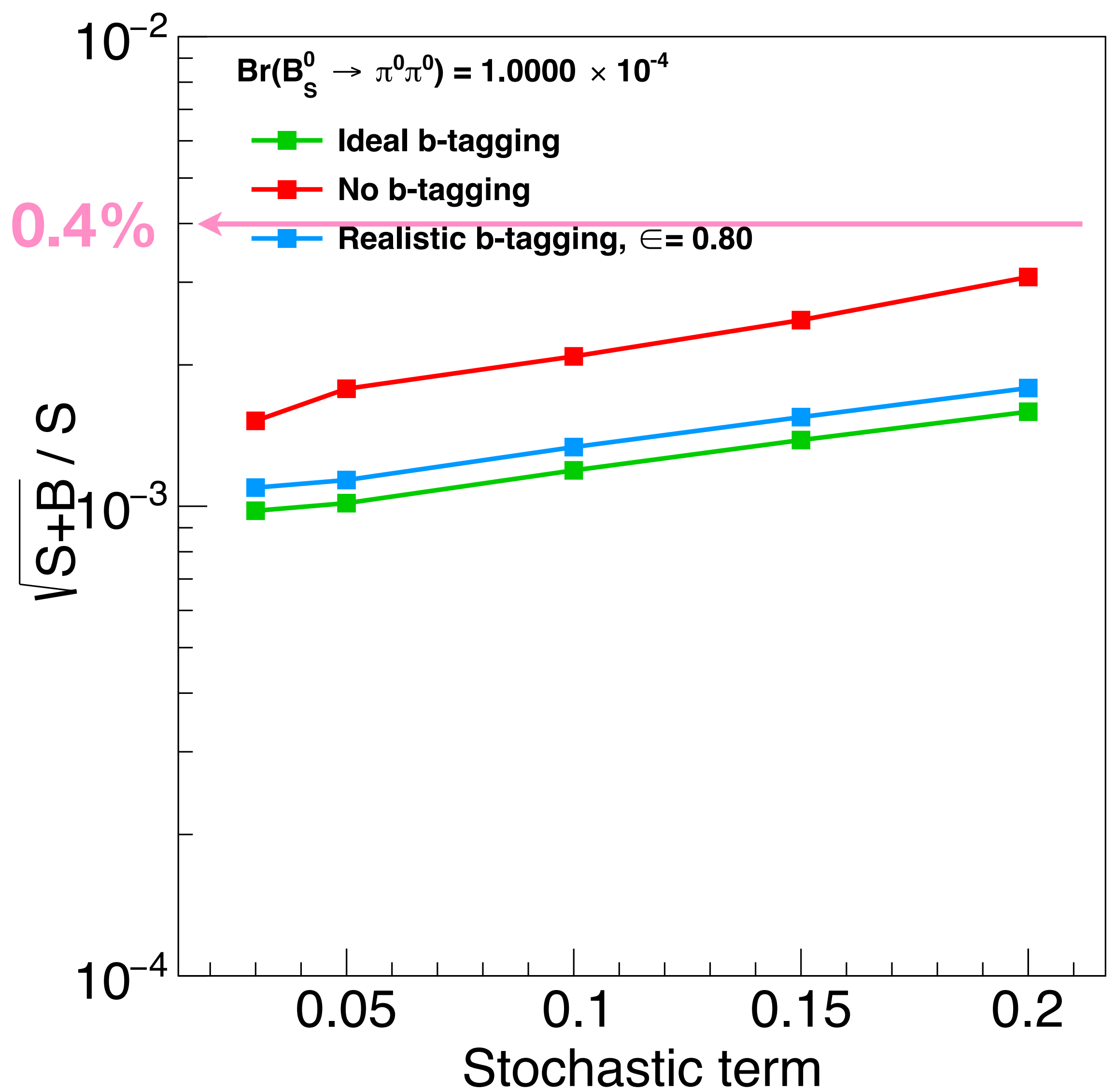
Cut chain	10000 Bs_2Pi0				Bkg Z_qq	
	3%+1%, Mass window: (5.22, 5.52) GeV					
	Signal		Bkg		Bkg	
	Total	In mass window	Total	In mass window	Total	In mass window
No cut	9497	9401	393131	3905	996542768	8263449
Emin > 6GeV	6002	5998	5082	10	7286782	2882
Emax > 14GeV	5662	5660	3395	6	2027790	321
ESum > 22GeV	5641	5639	3285	6	1851167	253
Angle < 23º	4973	4971	62	1	601410	40

Just raw data, need to be scaled to Tera-Z

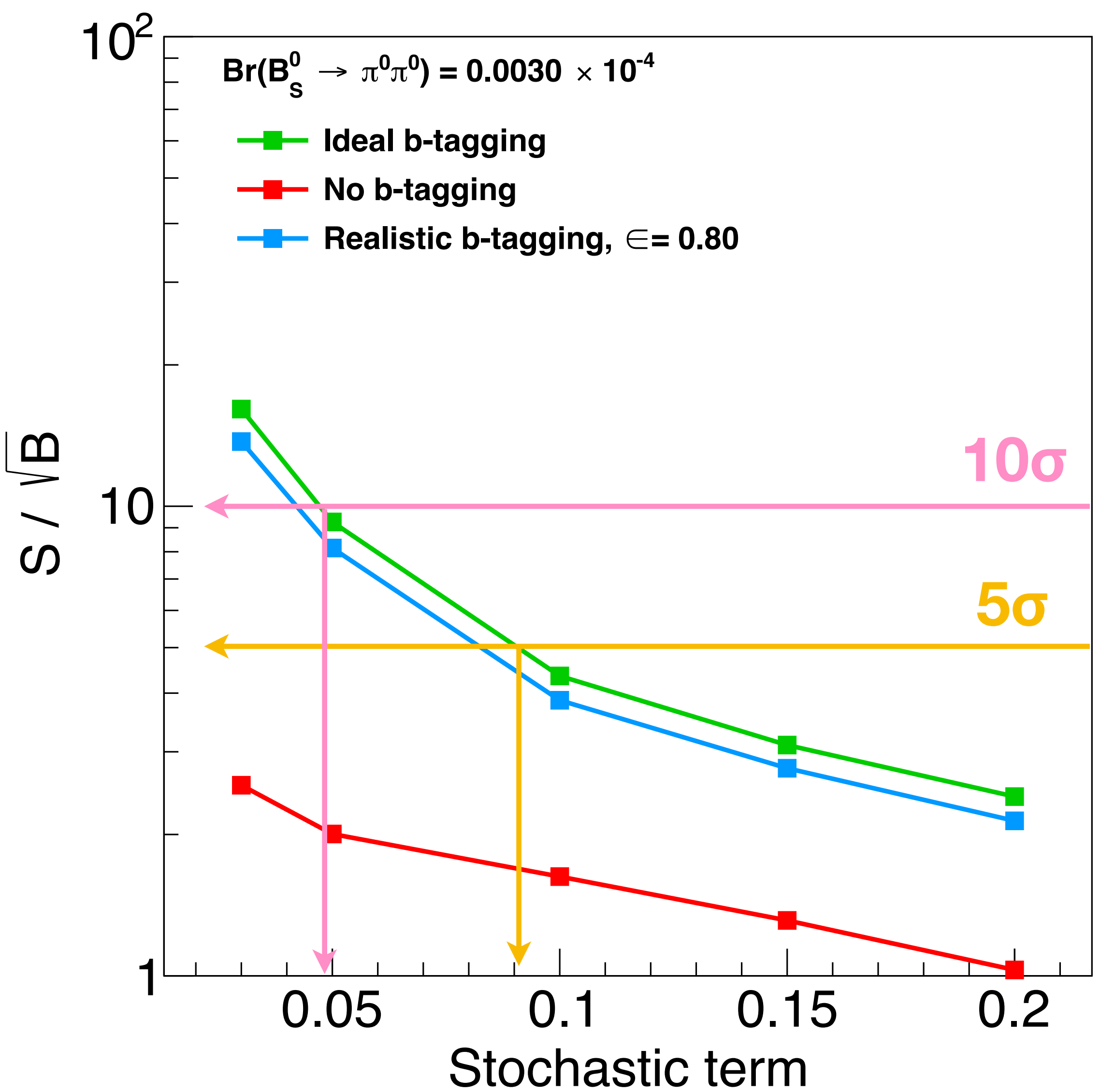
Bs → $\pi^0\pi^0$

Signal accuracy and significance

Accuracy



Significance



Summary

Fast simulation study

- Reconstruction of π^o
  - relies on ECAL resolution and π^o energy (sample dependent)
- Separation of B^0 & Bs
  - strong limitation on ECAL resolution
  - stochastic term better than 1%
  - constant term better than 0.5%
- Preliminary exercise on Bs $\rightarrow \pi^o\pi^o$
  - develop the reconstruction and analysis flow
- Mixed measurement of B^0 & Bs $\rightarrow \pi^o\pi^o$
  - need to be updated later…

Thanks!

Backup

Unique Opportunities at Z pole

Giga-Z, Tera-Z and 10×Tera-Z: a phase of future linear/circular lepton colliders. [Fujii et al.(2019), Dong et al.(2018), Abada et al.(2019)]

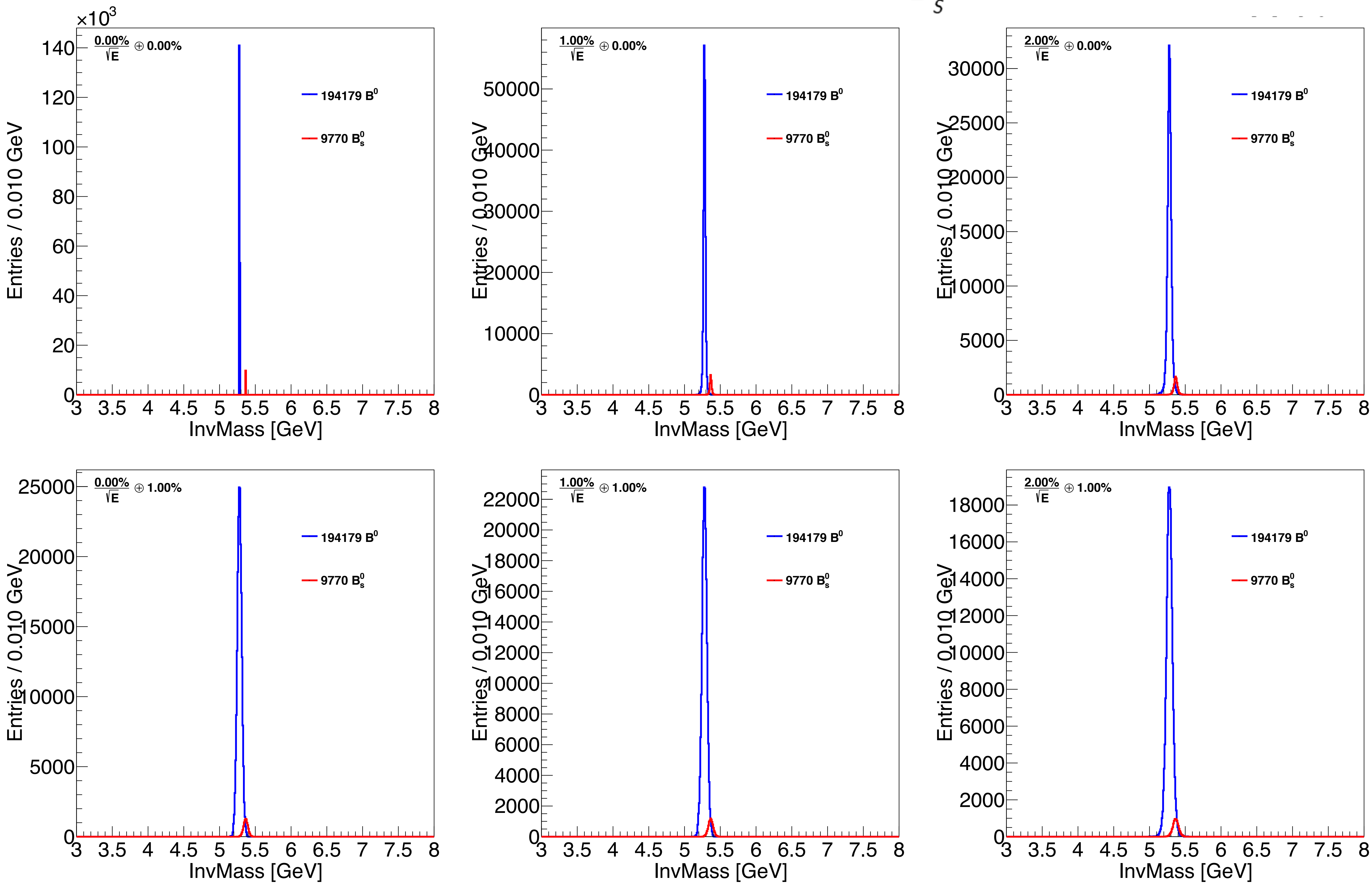
Z factories are also $b(c/\tau)$ factories:

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10×Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}	1.2×10^{12}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^8	$\sim 2 \times 10^{13}$	3.2×10^7	3.2×10^{10}	3.2×10^{11}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^5	2.2×10^8	2.2×10^9
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^7	1.0×10^{10}	1.0×10^{11}

Separation of B0 and Bs

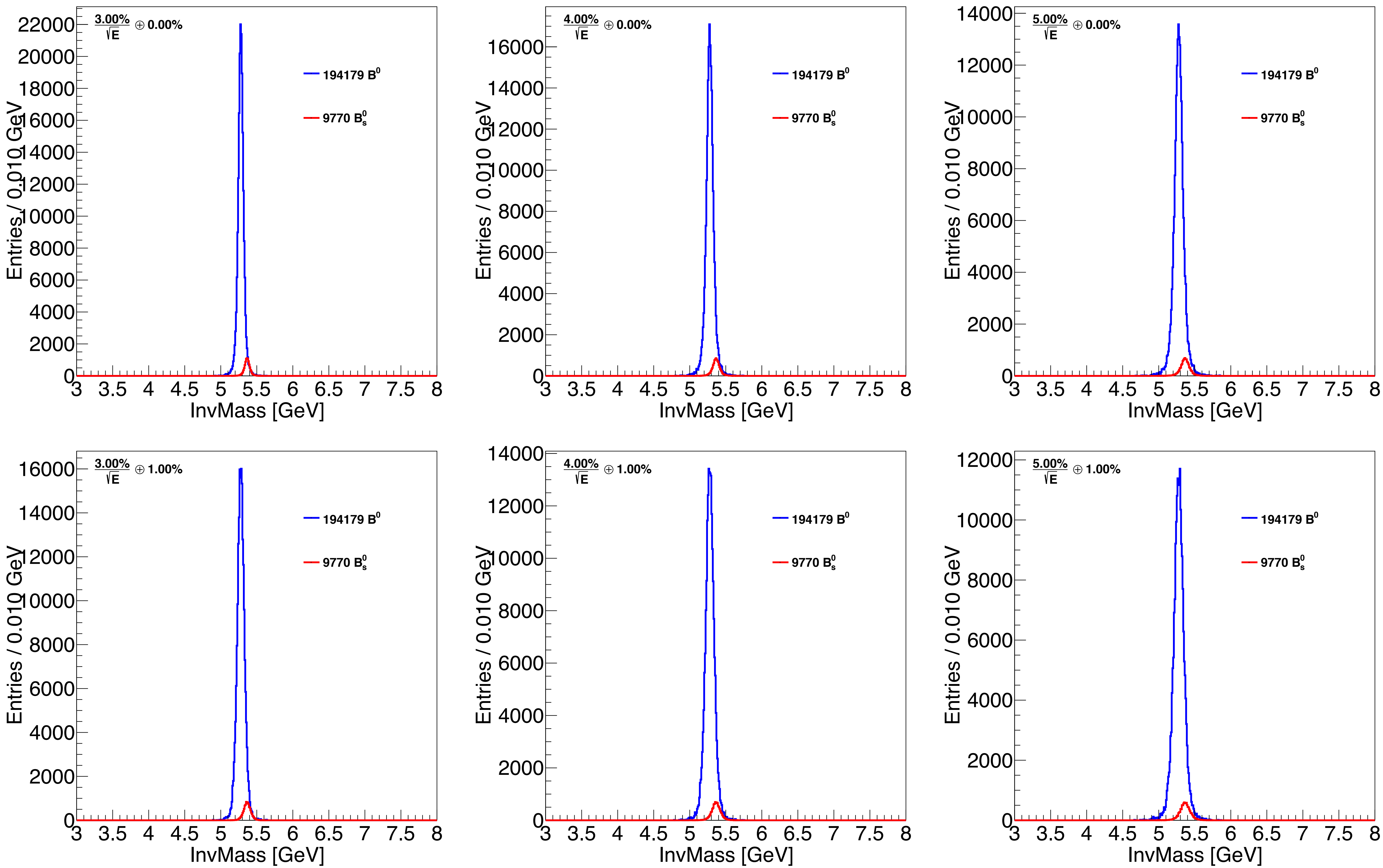
Mass $m_{B^0} = 5279.63 \pm 0.15$ MeV

Mass $m_{B_s^0} = 5366.89 \pm 0.19$ MeV



Separation of B0 and Bs

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



Separation of B0 and Bs

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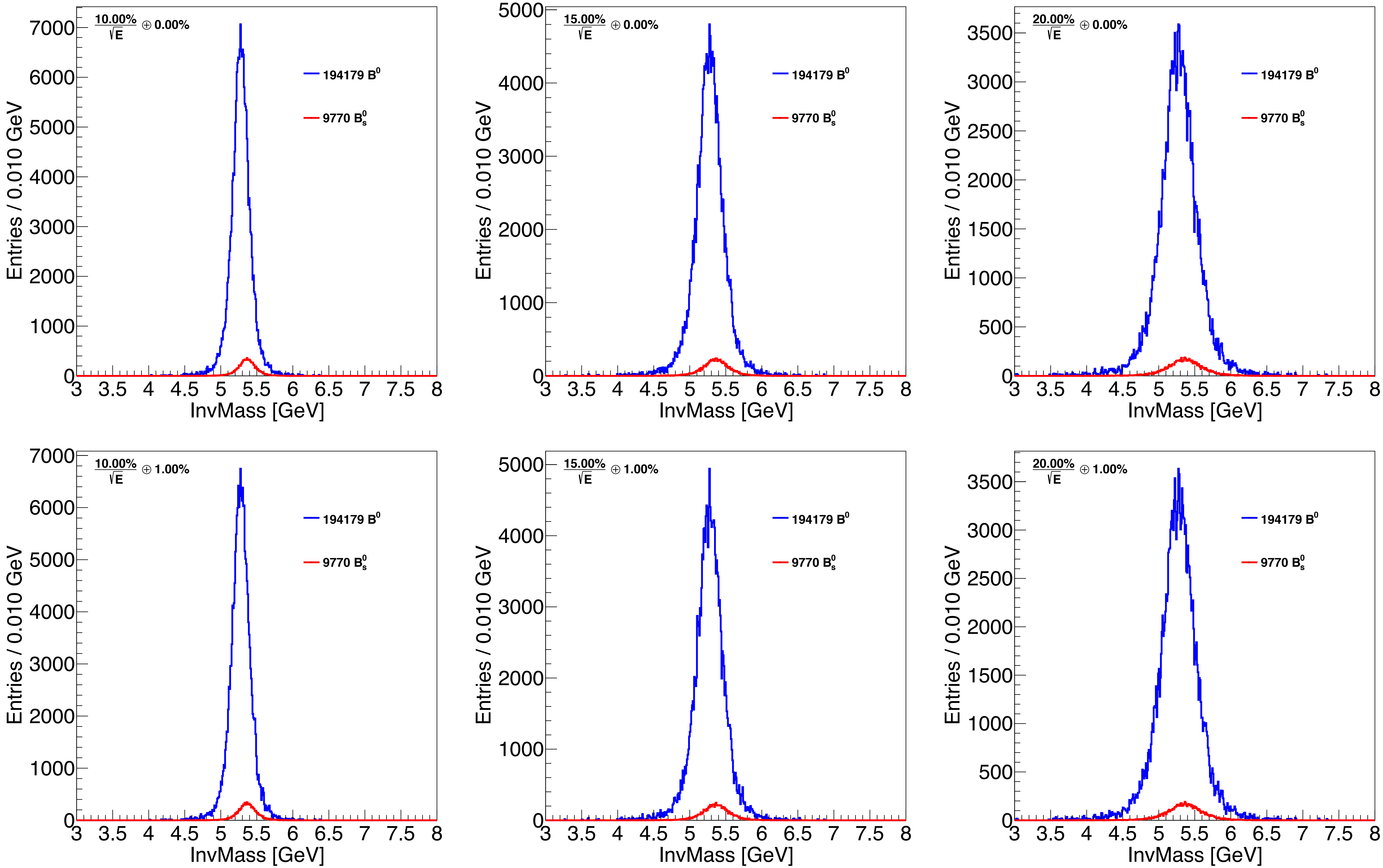
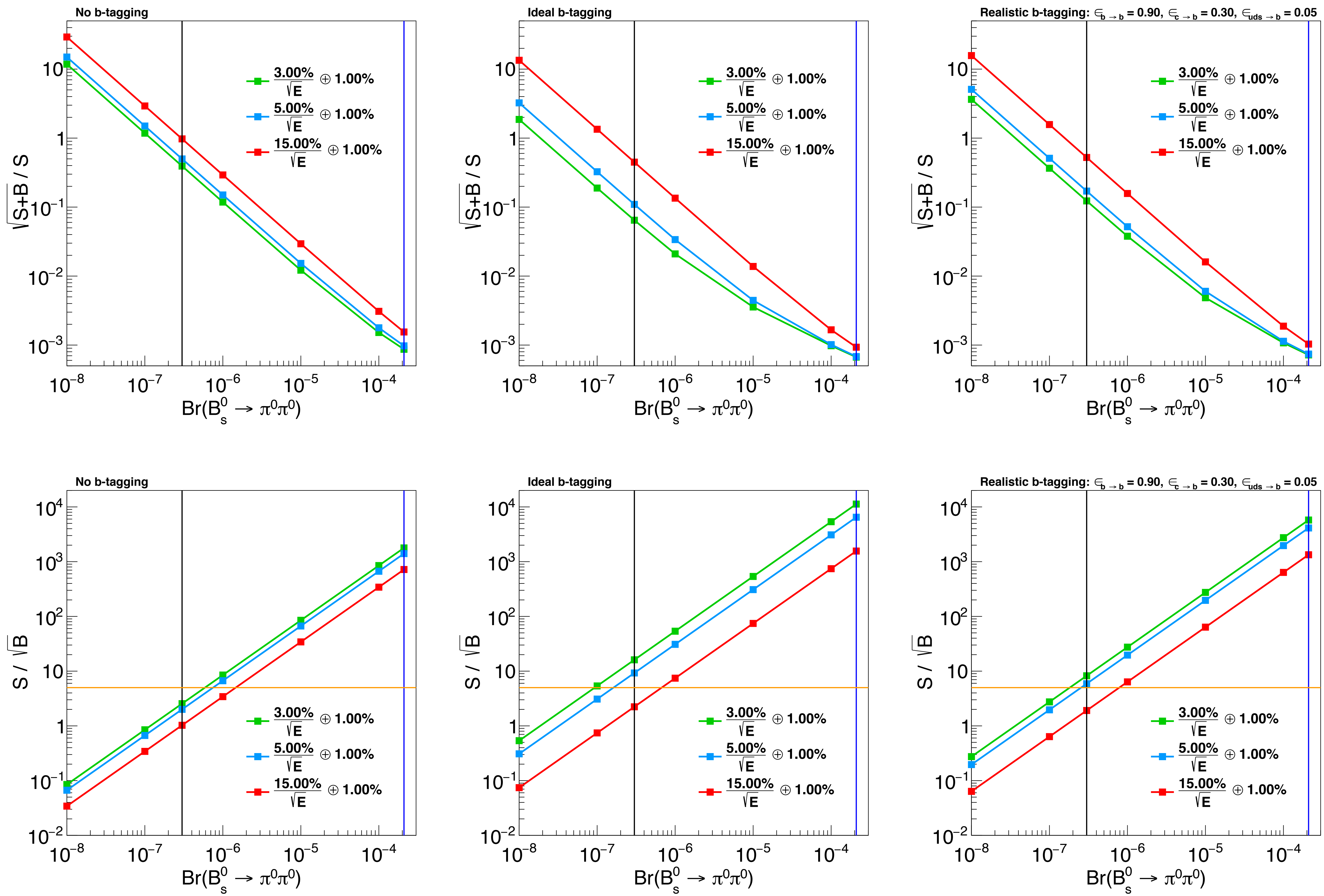
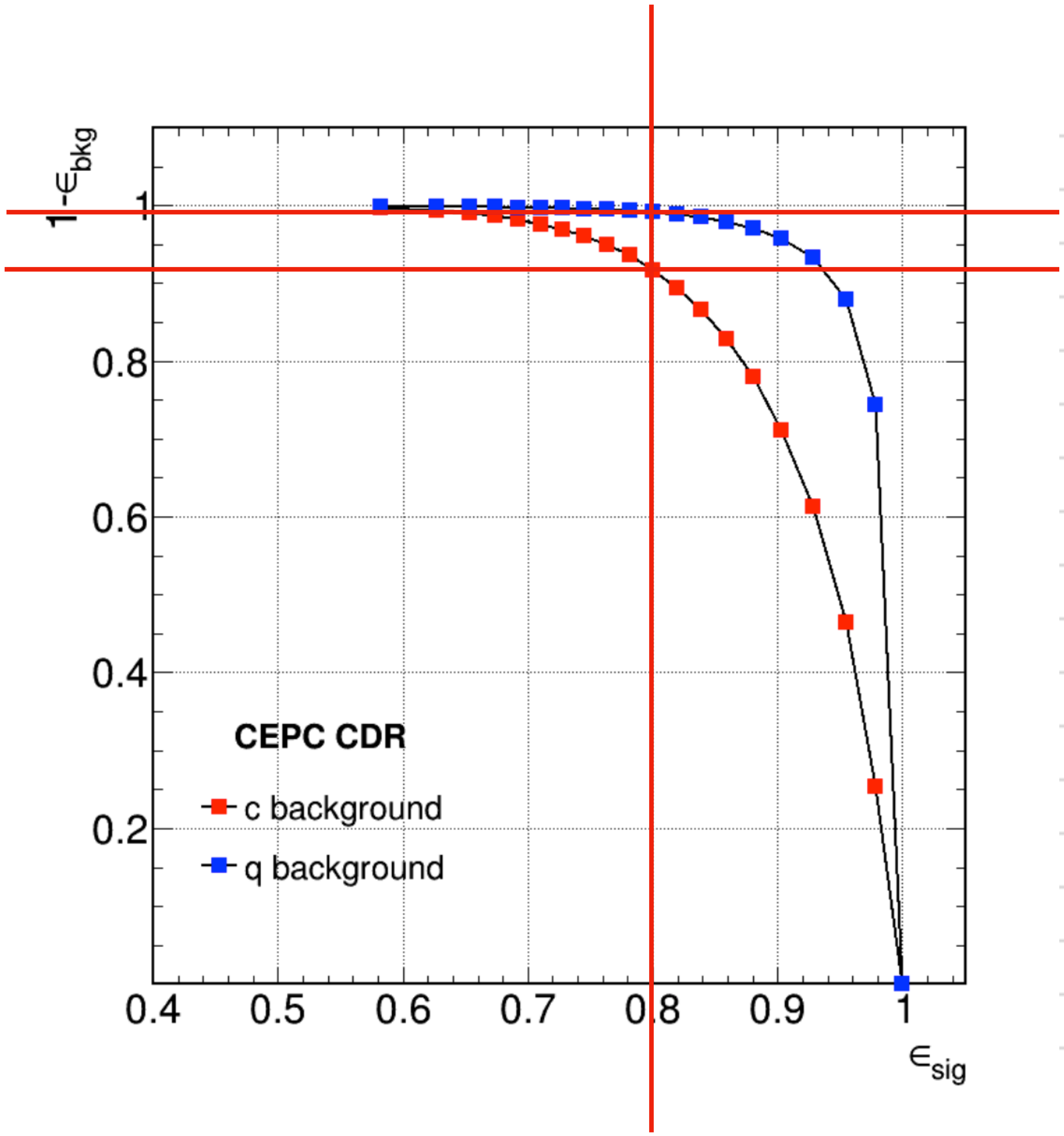


Signal accuracy and significance



b-tagging efficiency



eff_bb	eff_cb	eff_qb	Purity	eff*pur
1	1	1	0.216	0.216
0.98	0.75	0.25	0.4287798	0.4202042
0.96	0.54	0.13	0.5459716	0.5241327
0.93	0.39	0.06	0.6593147	0.6131627
0.9	0.3	0.05	0.70282	0.632538
0.88	0.22	0.03	0.7718045	0.6791879
0.86	0.17	0.02	0.8174617	0.7030171
0.84	0.14	0.01	0.8573049	0.7201361
0.82	0.1	0.005	0.8973554	0.7358314
0.8	0.08	0	0.9262436	0.7409949
0.78	0.06	0	0.9422819	0.7349799
0.76	0.05	0	0.95022	0.7221672
0.74	0.04	0	0.9587332	0.7094626
0.72	0.03	0	0.9678865	0.6968783
0.69	0.01	0	0.9885911	0.6821279
0.58	0	0	1	0.58

Cut chain

fraction	0.216	0.101	2.10E-04	
Z_qq	Z_bb	b_Bs	Bs_2Pi0	
1.00E+12	2.16E+11	2.18E+10	4581360	← 按比例估算的样本数
20000000	4.32E+06	4.36E+05	91.6272	
24499982	5.29E+06	5.34E+05	112.2432375	
Signal Z_bb_Bs_2Pi0	10000			
Bkg Z_qq	24499982	4.08E+04		← 实际用的样本数

Scale 到 10^{12} Z_qq

Accuracy

Cut chain	10000 Bs_2Pi0				Bkg Z_qq		Scale 到 10^{12} Z_qq				Accuracy	
	3%+1%, Mass window: (5.22, 5.52) GeV											
	Signal		Bkg		Bkg		Bkg		Signal		sqrt(S+B)/S	
	Total	In mass window	Total	In mass window	Total	In mass window	Total	In mass window	efficiency	statistic		
No cut	9497	9401	393131	3905	996542768	8263449	4.07E+13	3.37E+11	0.9497	4350917.592	0.133481	13.348%
Emin > 6GeV	6002	5998	5082	10	7286782	2882	2.97E+11	1.18E+08	0.6002	2749732.272	0.003990	0.399%
Emax > 14GeV	5662	5660	3395	6	2027790	321	8.28E+10	1.31E+07	0.5662	2593966.032	0.001527	0.153%
ESum > 22GeV	5641	5639	3285	6	1851167	253	7.56E+10	1.03E+07	0.5641	2584345.176	0.001390	0.139%
Angle < 23º	4973	4971	62	1	601410	40	2.45E+10	1.63E+06	0.4973	2278310.328	0.000868	0.087%
	5%+1%, Mass window: (5.17, 5.57) GeV											
	Signal		Bkg		Bkg							
	Total	In mass window	Total	In mass window	Total	In mass window						
No cut	9373	9221	391802	5132	977467312	10865031	3.99E+13	4.43E+11	0.9373	4294108.728	0.155082	15.508%
Emin > 6GeV	5979	5975	5116	15	7314274	3894	2.99E+11	1.59E+08	0.5979	2739195.144	0.004642	0.464%
Emax > 14GeV	5638	5636	3420	9	2039971	431	8.33E+10	1.76E+07	0.5638	2582970.768	0.001739	0.174%
ESum > 22GeV	5616	5614	3301	9	1862127	342	7.60E+10	1.40E+07	0.5616	2572891.776	0.001580	0.158%
Angle < 23º	4953	4951	64	3	604305	64	2.47E+10	2.61E+06	0.4953	2269147.608	0.000974	0.097%
	15%+1%, Mass window: (4.87, 5.87) GeV											
	Signal		Bkg		Bkg							
	Total	In mass window	Total	In mass window	Total	In mass window						
No cut	8703	8582	375216	12078	914833745	25133276	3.73E+13	1.03E+12	0.8703	3987157.608	0.254027	25.403%
Emin > 6GeV	5766	5755	5113	38	7261955	10001	2.96E+11	4.08E+08	0.5766	2641612.176	0.007673	0.767%
Emax > 14GeV	5448	5441	3409	29	2048452	1133	8.36E+10	4.62E+07	0.5448	2495924.928	0.002797	0.280%
ESum > 22GeV	5420	5413	3292	27	1870910	937	7.64E+10	3.82E+07	0.542	2483097.12	0.002570	0.257%
Angle < 23º	4778	4774	79	16	607747	227	2.48E+10	9.27E+06	0.4778	2188973.808	0.001546	0.155%