W Mass Direct Measurement at CEPC

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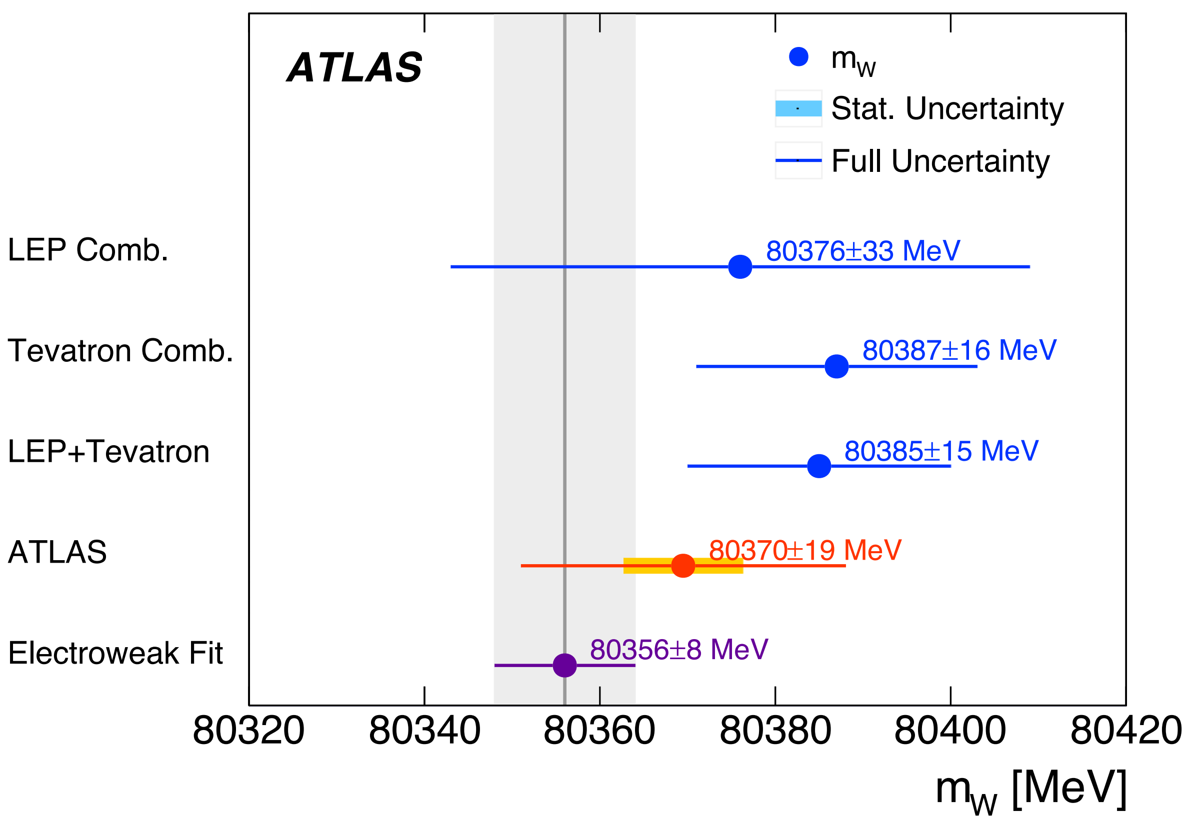
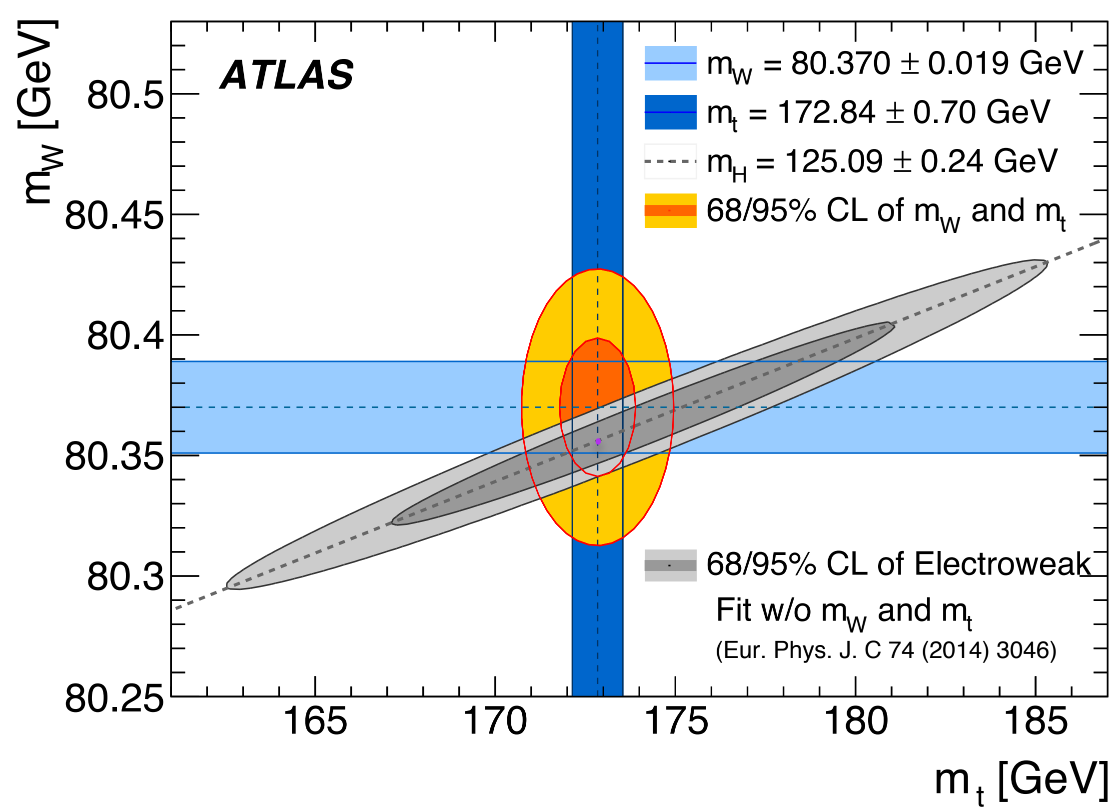
Outline

- Motive of W mass direct measurements and currently results
- Benefit of direct measurement
- The jet energy resolution and jet energy scale at CEPC
  - Leading and sub-leading jet performances
  - Compare the results with CMS and ALEPH
  - Boson mass resolution in dijet final state
- Event selections
- Results
- Conclusion and future

Motive of W Mass Measurement

- **More precise measurement of W mass could lead to more precise weak mixing angle. Weak mixing angle describes the rotation of the original W^0 and B^0 vector states into the observed γ and Z bosons as the results of spontaneous symmetry breaking. (test Higgs mechanism)**
- **Very sensitive to electroweak radiative corrections. (test electroweak theory)**
- **Very sensitive to new physics. Z-Z' mixing would cause the deviate with SM prediction.**
- **Current results** $\sin^2\theta_W = 0.23153 \pm 0.00016$





$$\frac{m_W}{m_Z} = \cos\theta_W$$

Ref. [6]

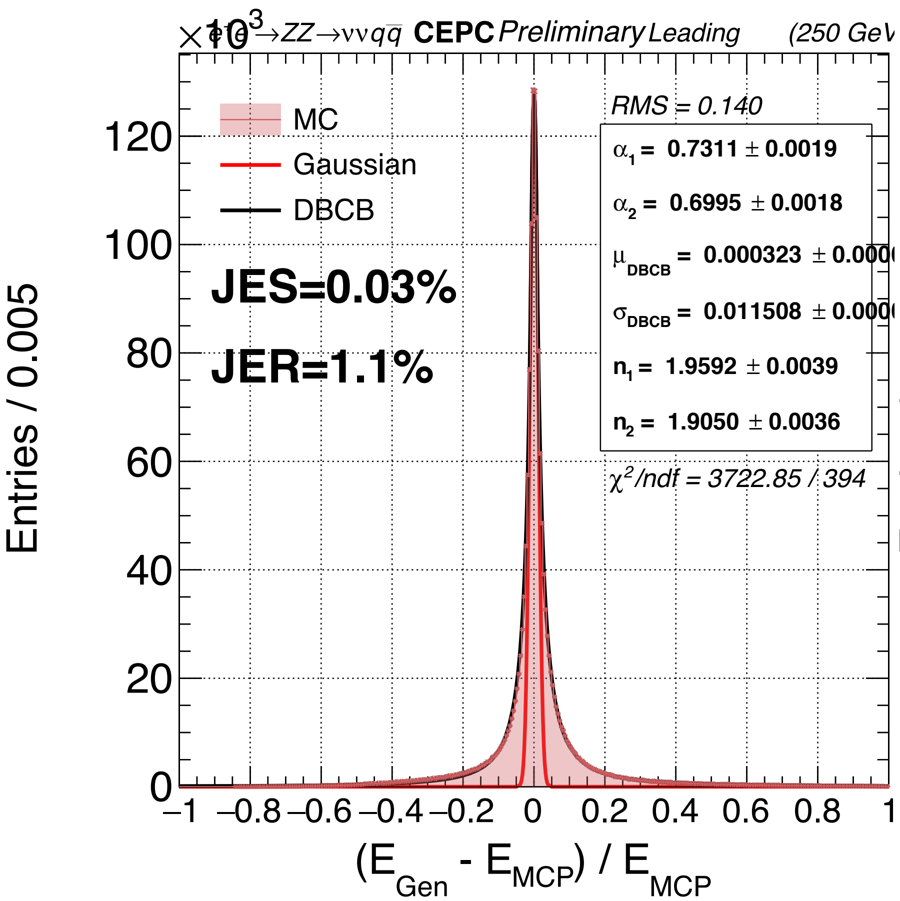
Benefit of direct measurement

- **Use the LO WW→$\mu\nu$qq MC sample to directly measure the W boson mass. The effective luminosity is 10 ab^{-1}.**

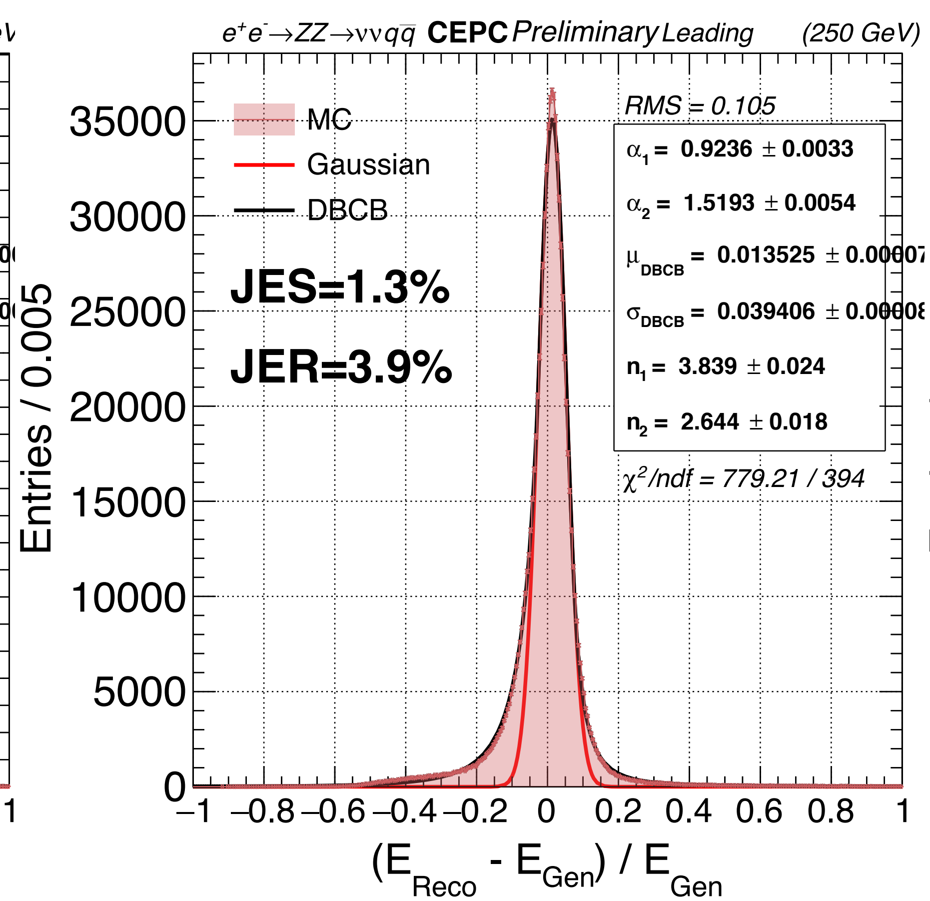
1. **No dedicated run is needed: all the measurements can be done in ZH runs with $\sqrt{s}$ = 240 GeV. This thing also represents that this method has a lower requirement for accelerator performance.**
2. **Have more statistic than lepton channel.**
3. **Provide a better measurement than threshold scans at LEP.**
4. **Main challenge is to handle the uncertainty due to QED radiation. It can be reduced to the 1 MeV level using 1000 fb^{-1}.**
5. **From the Pre-CDR the total uncertainty of direct W mass measurement is expected to be 3 MeV at CEPC.**

Leading JER & JES

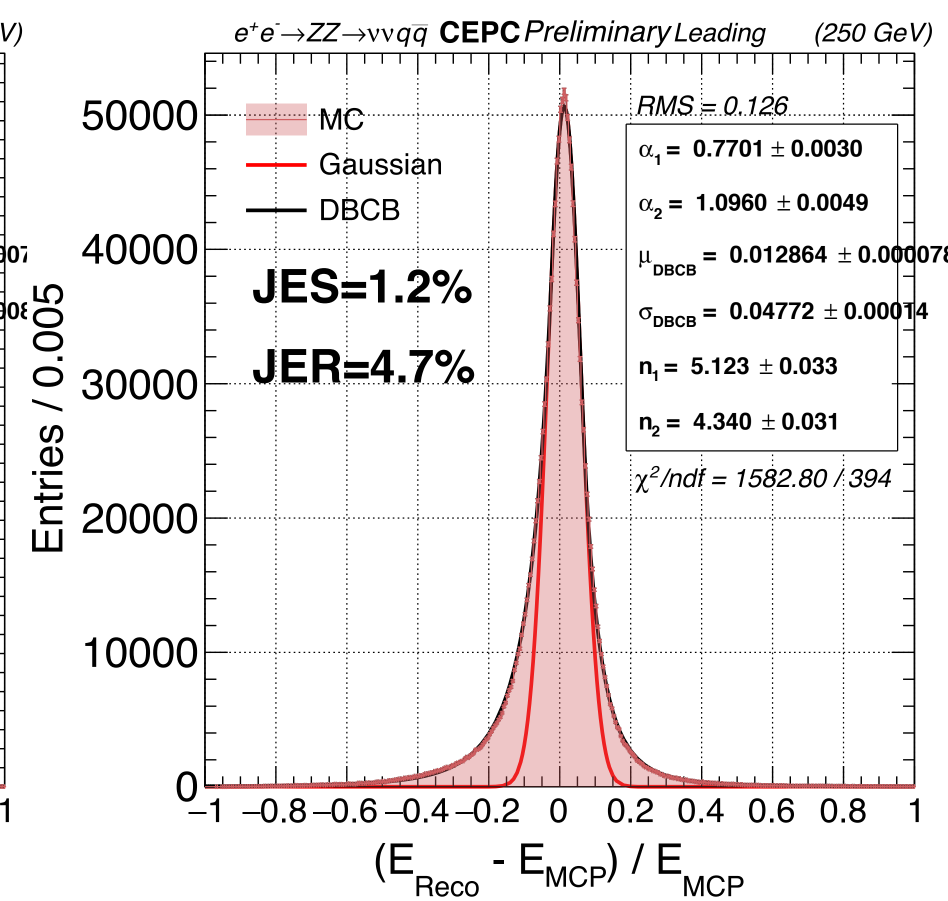
Gen-MCP



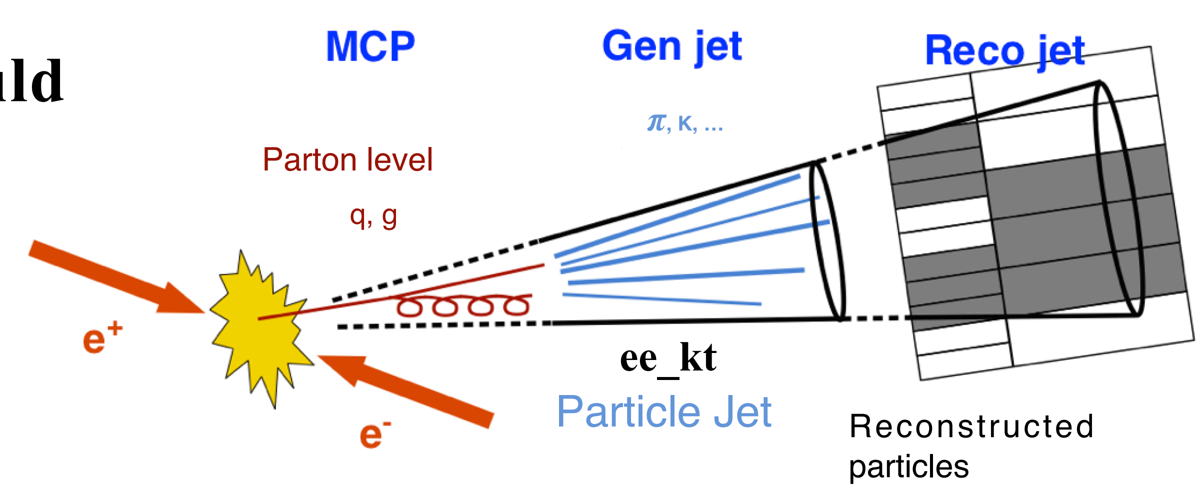
Reco-Gen



Reco-MCP

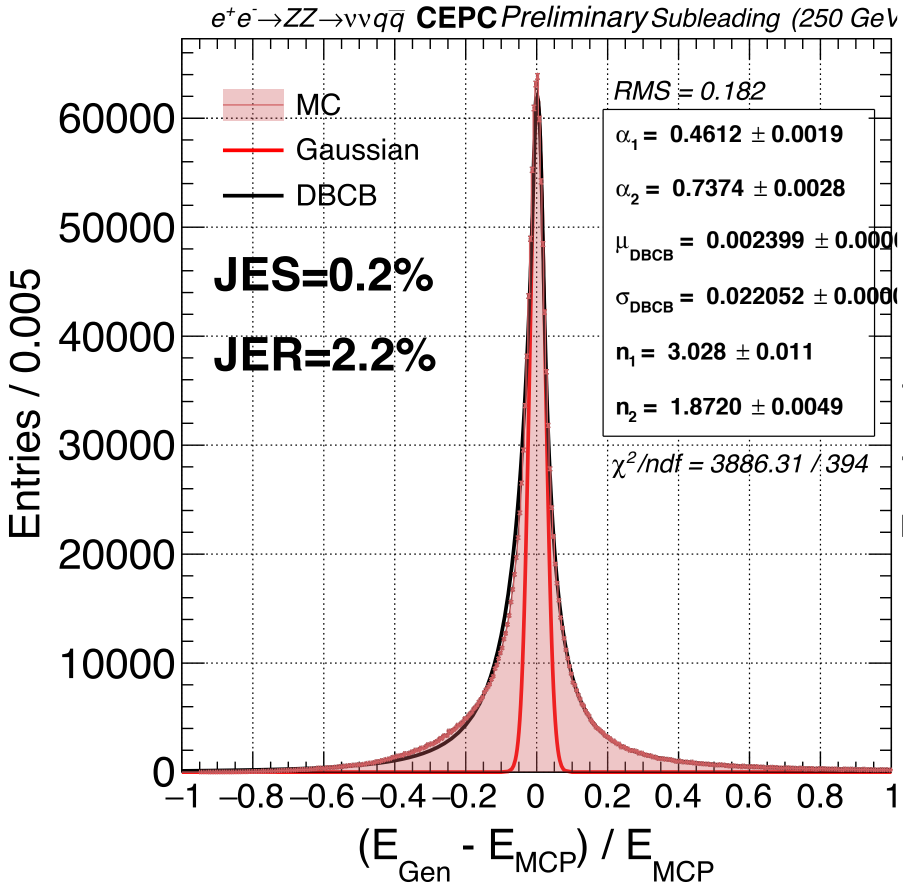


- **JER/JES between reco jet and MCP would combine the effects of two previous stages.**

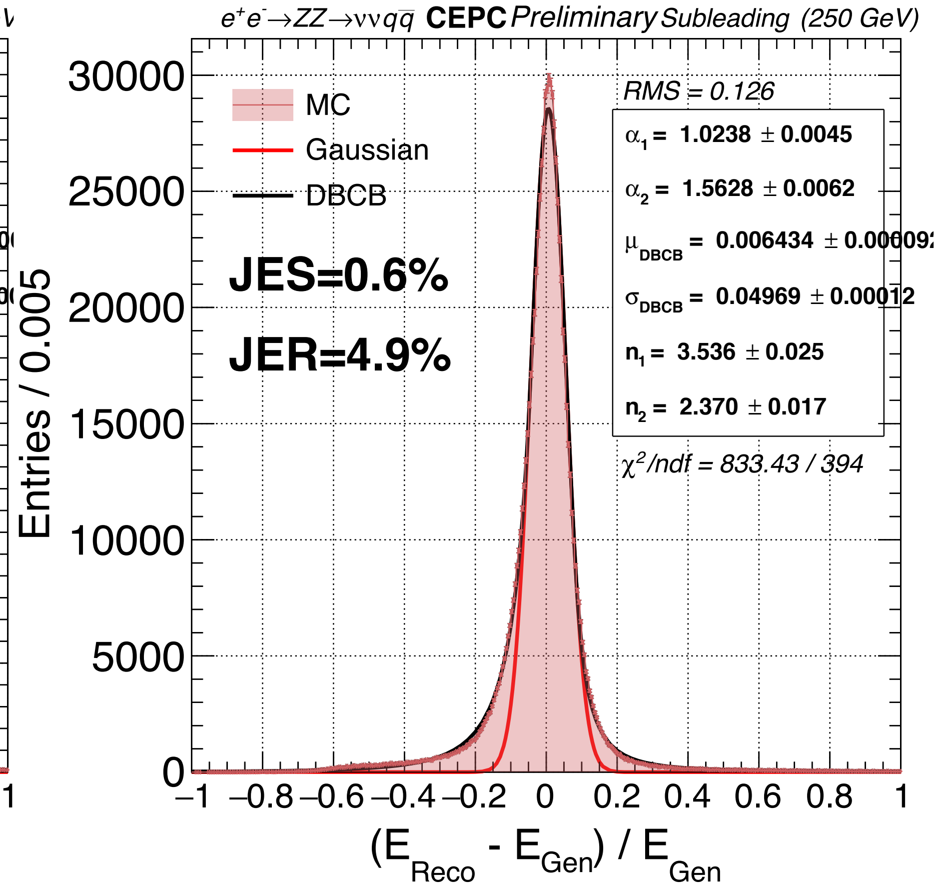


Sub-leading JER & JES

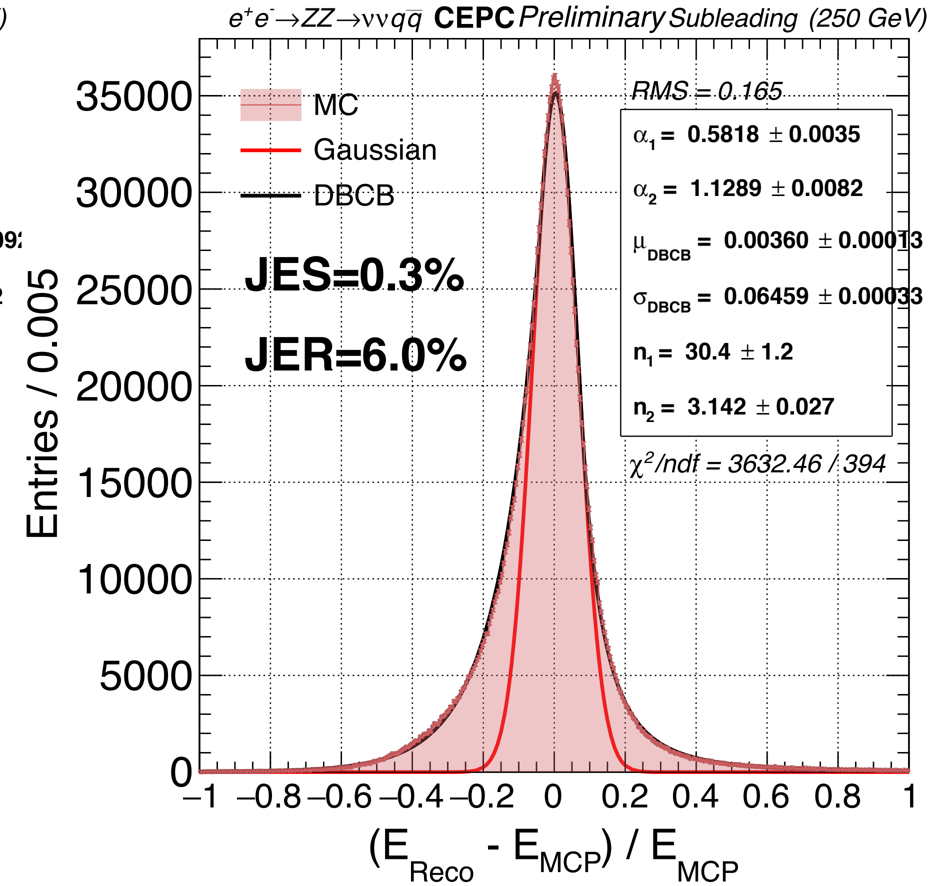
Gen-MCP



Reco-Gen



Reco-MCP



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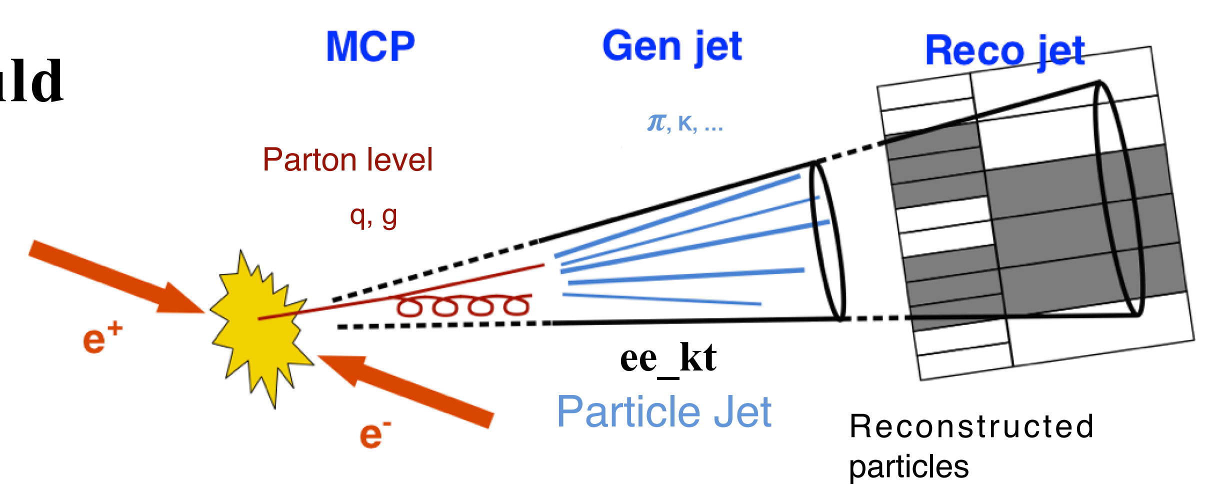
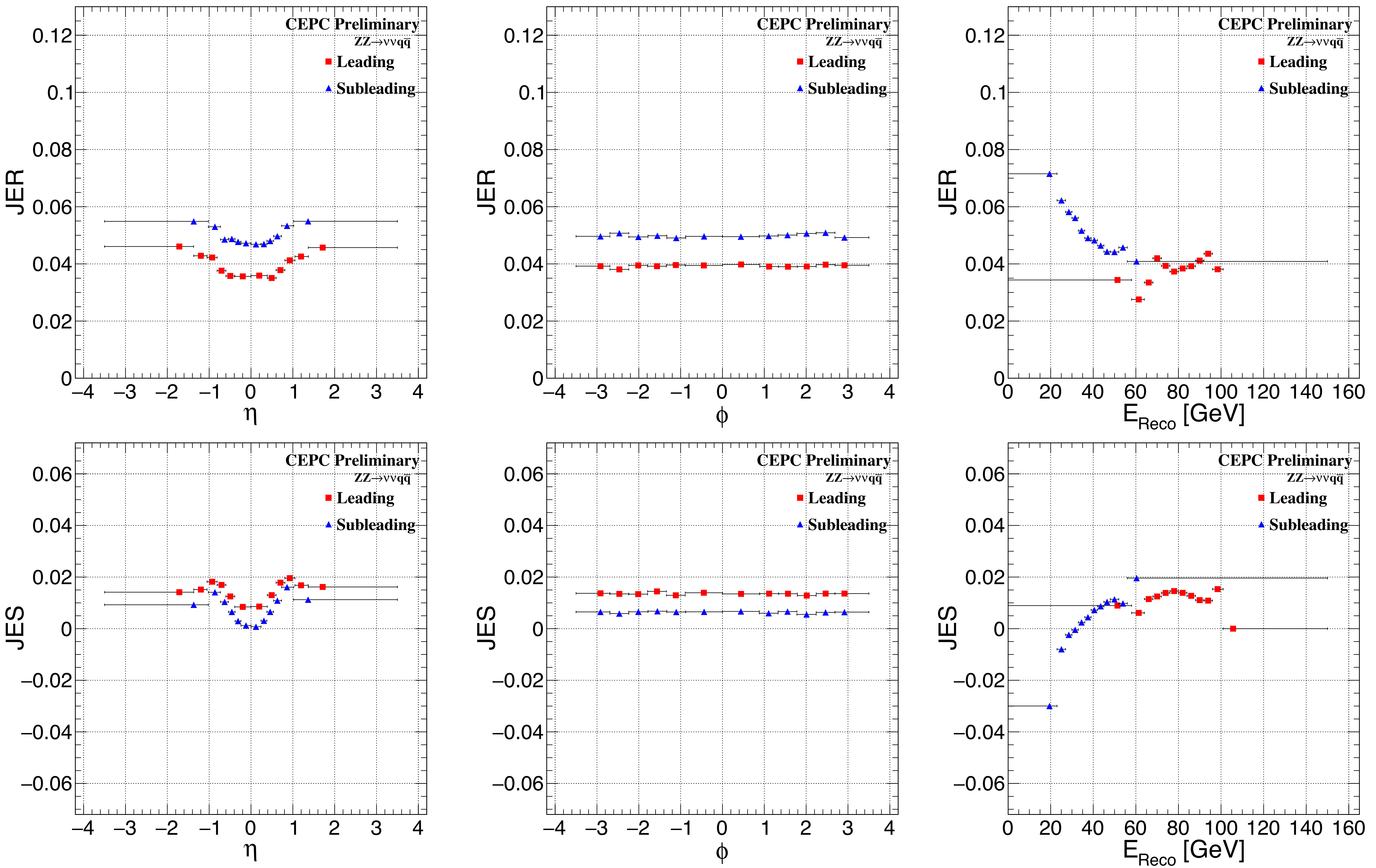


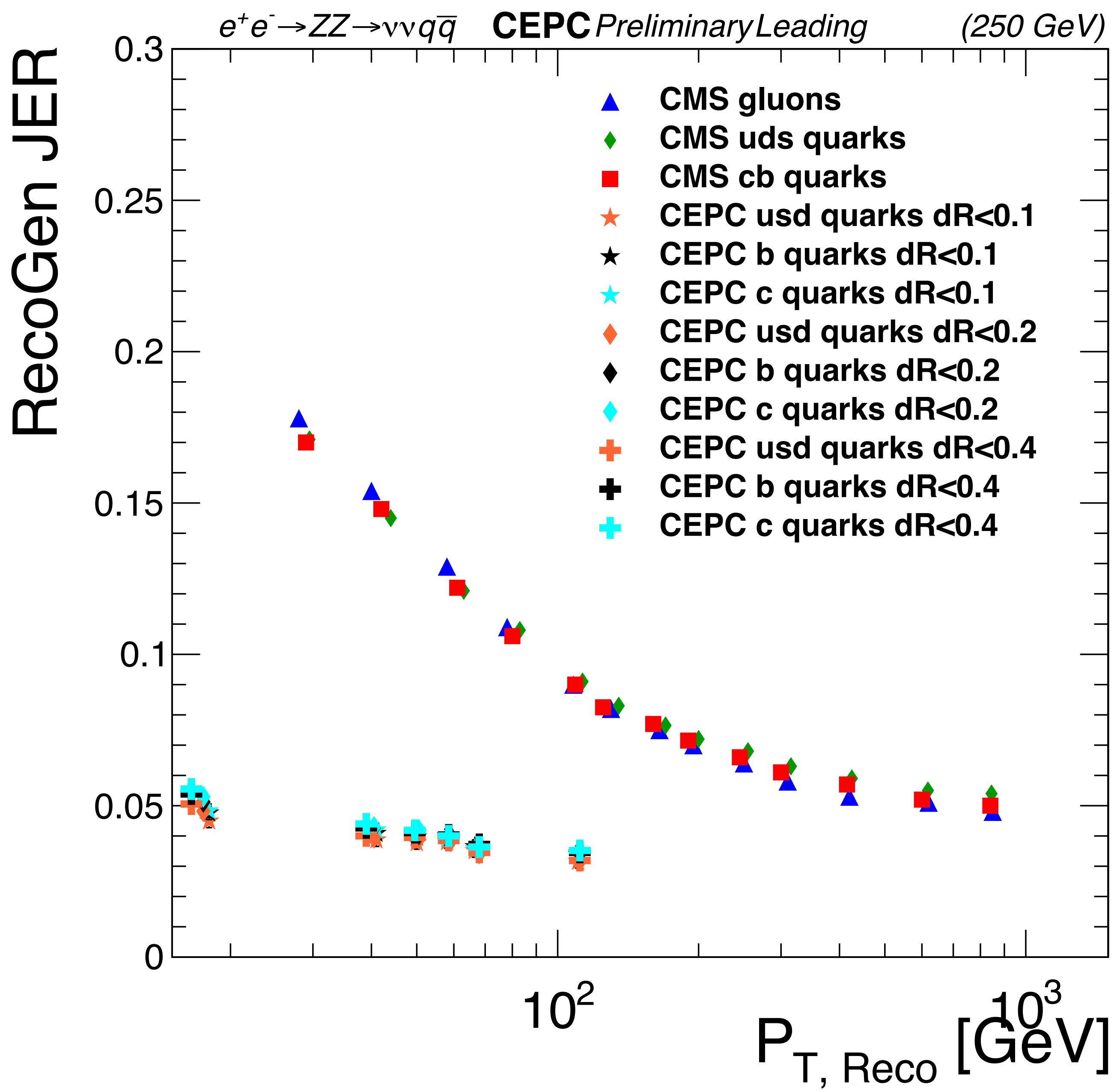
JER & JES(Reco-Gen)



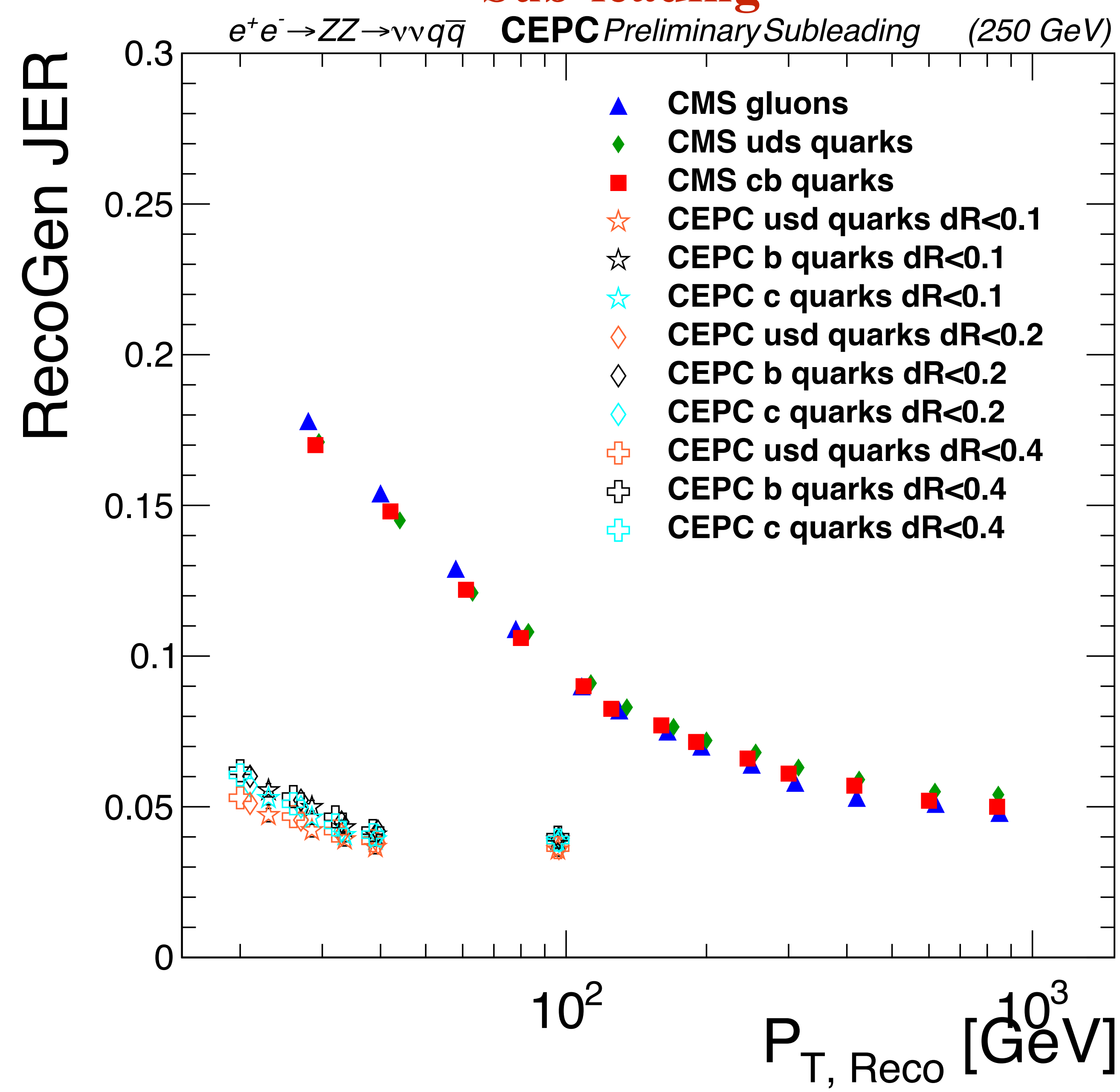
Both JER/JES are slightly dependent of Eta.

Comparison with CMS at LHC

Leading



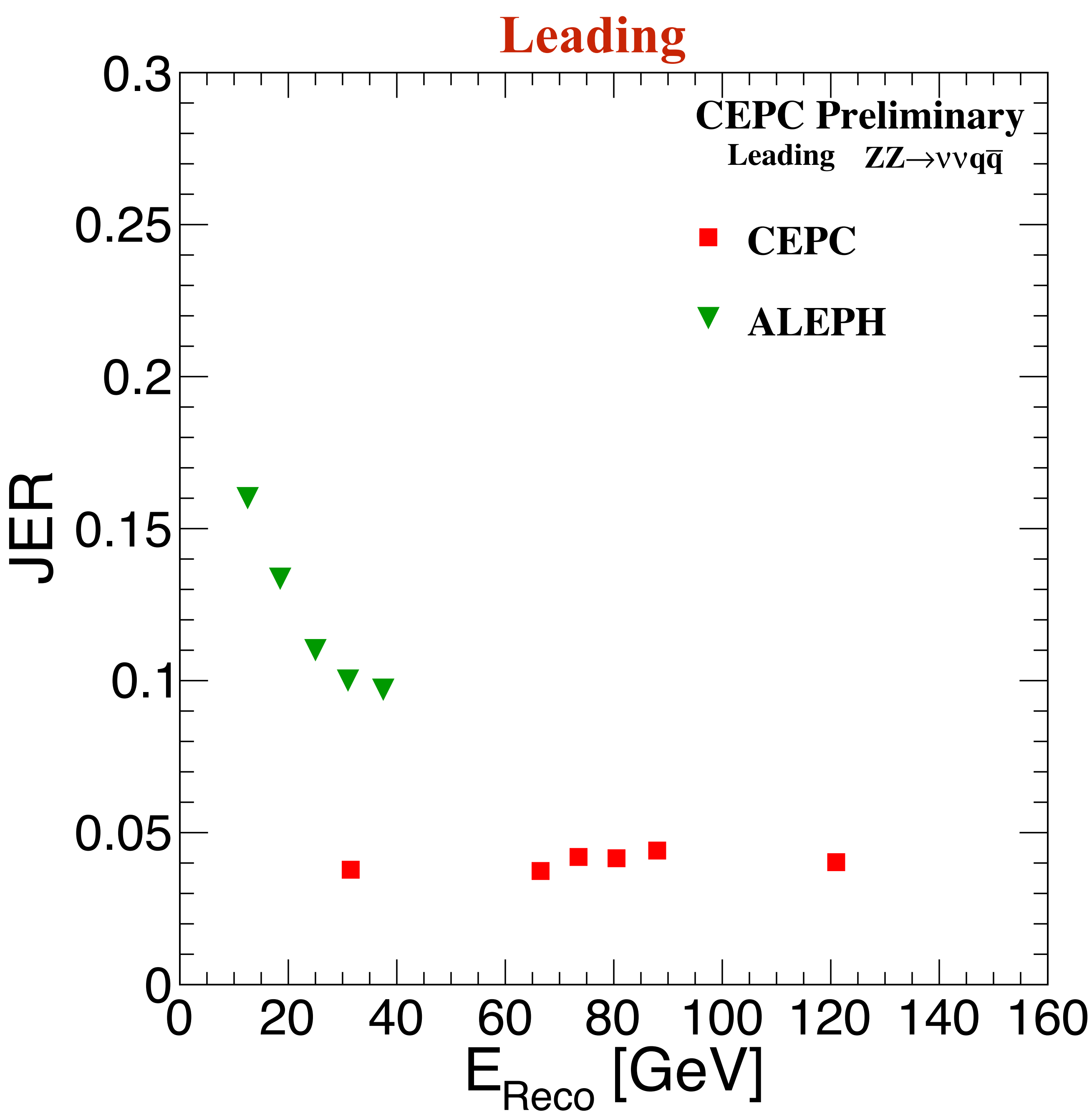
Sub-leading

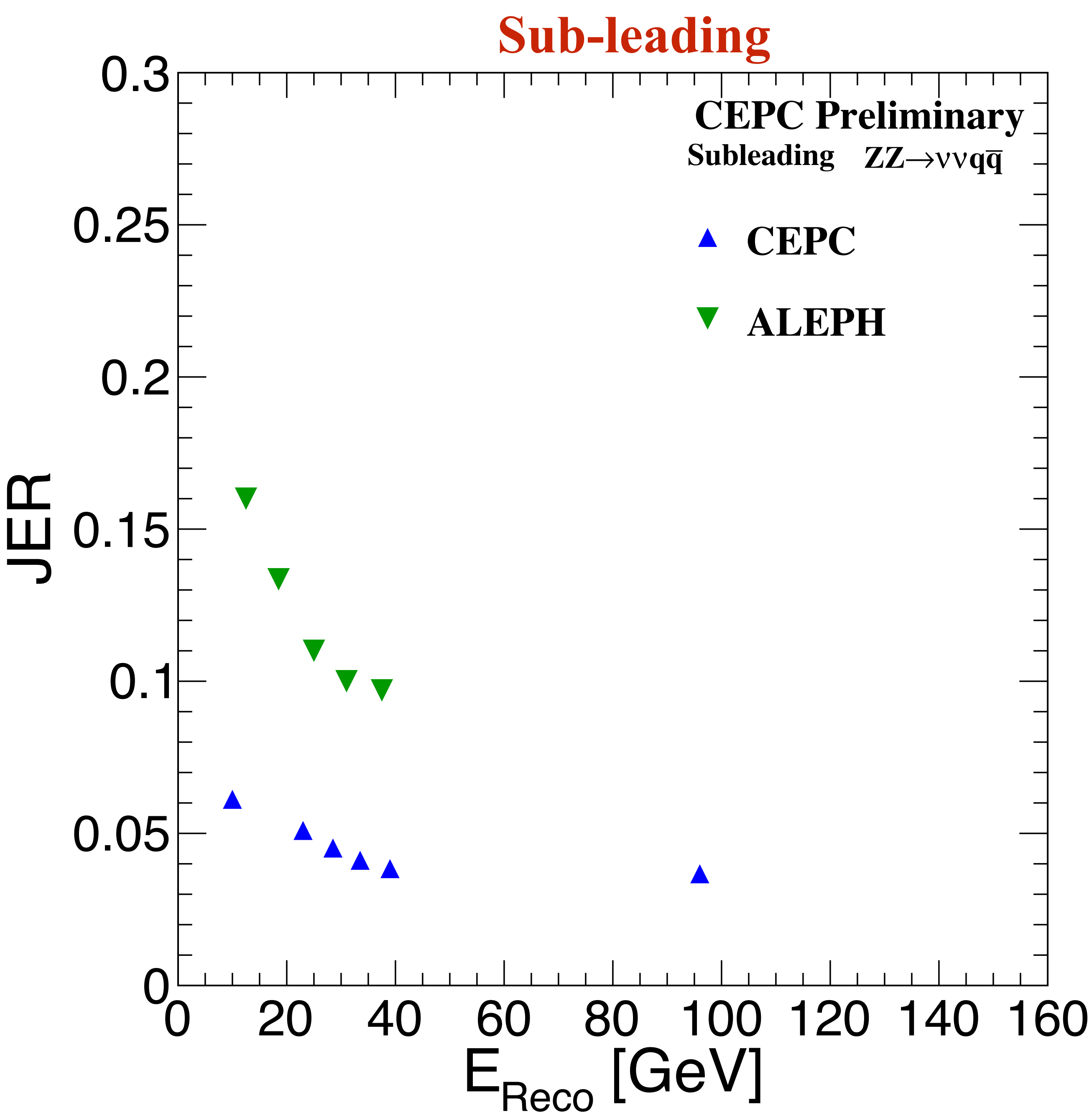


- **Our JER is better than CMS as what it should be.**
- **Heavy flavors have a little worse JER.**
- **Different matching criteria only improve JER a little bit.**

Ref. [3]

Comparison with ALEPH at LEP

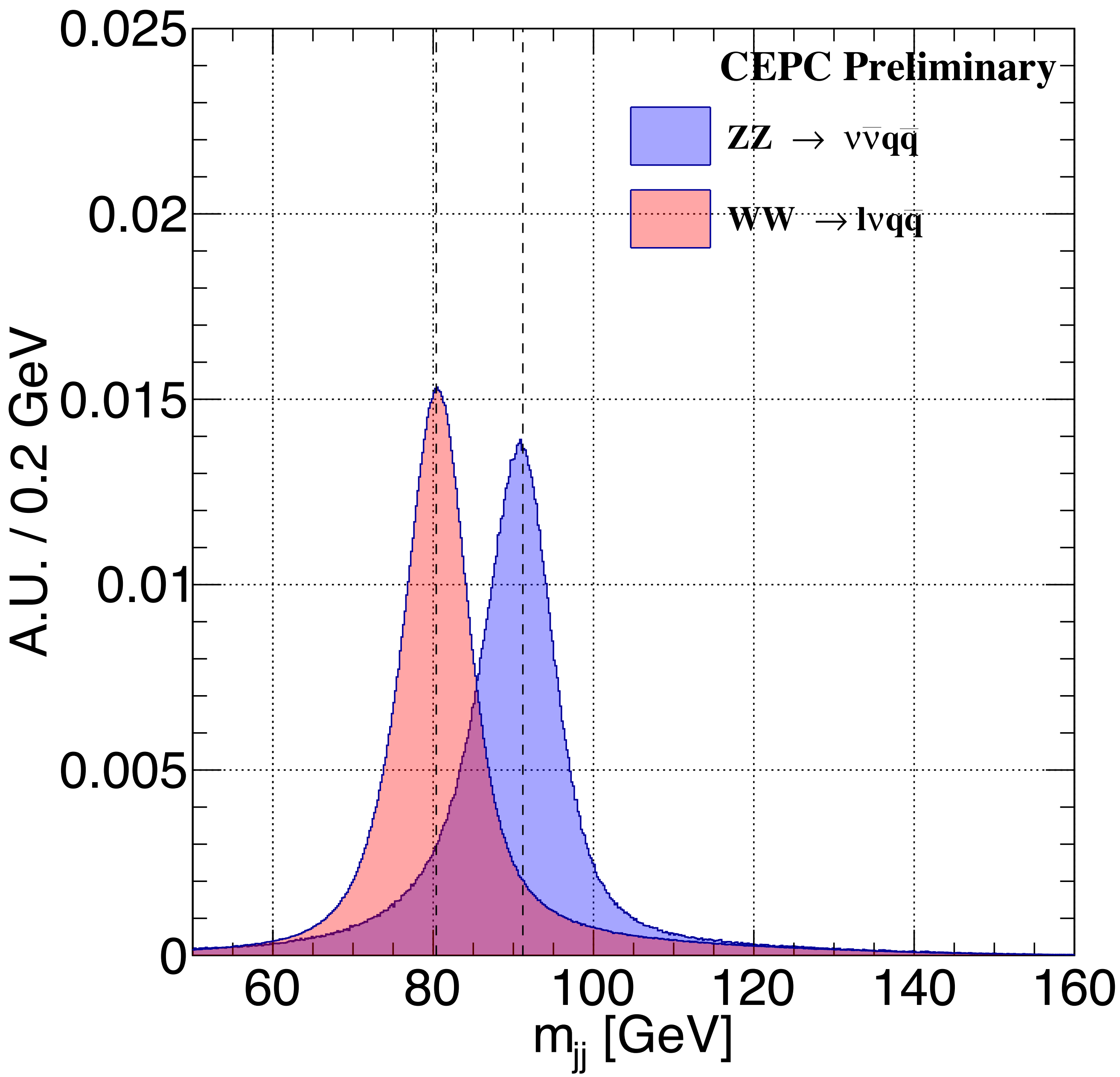


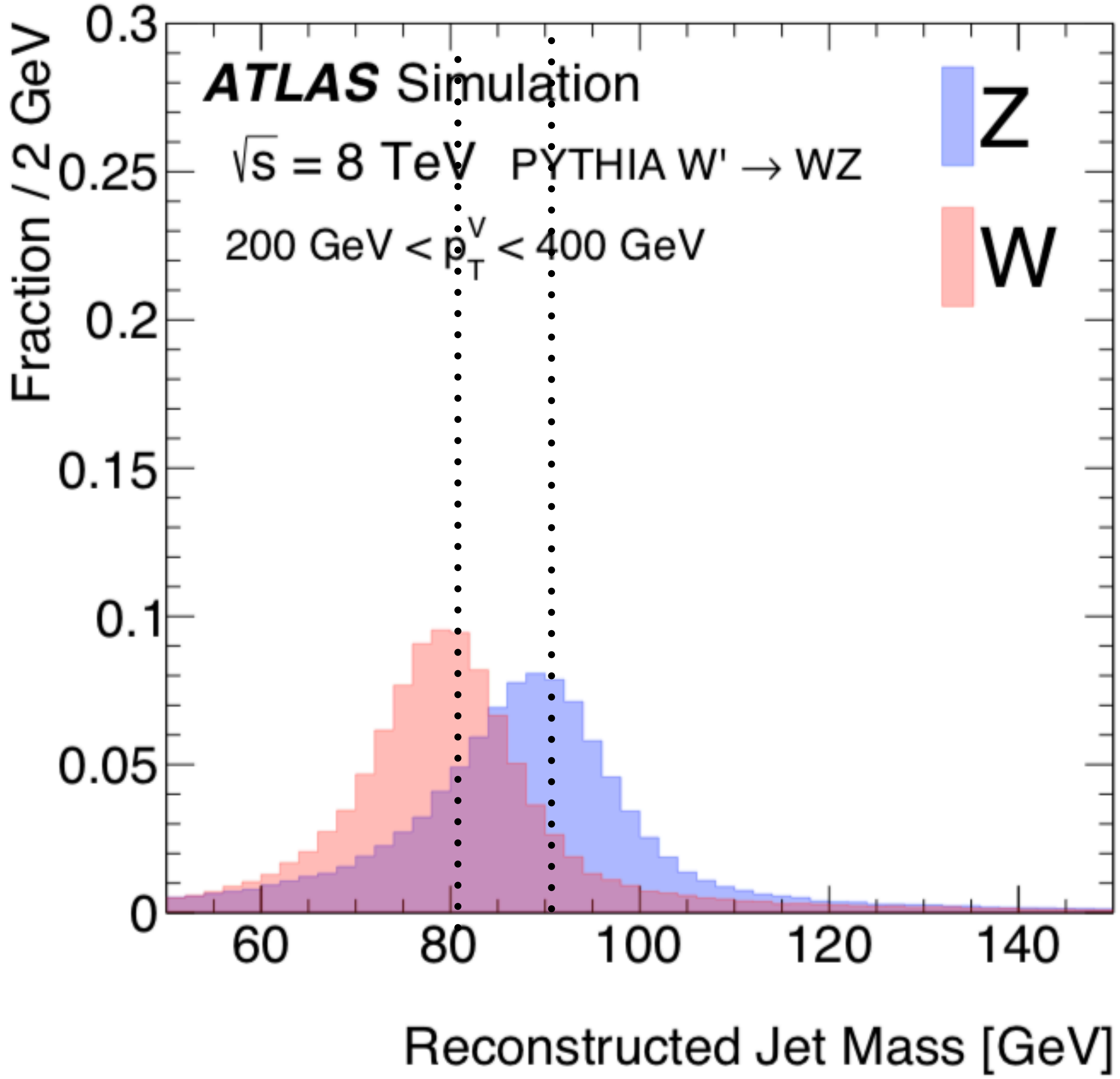


- **Our JER is better than ALEPH.**

Ref. [4]

Boson Mass Resolution

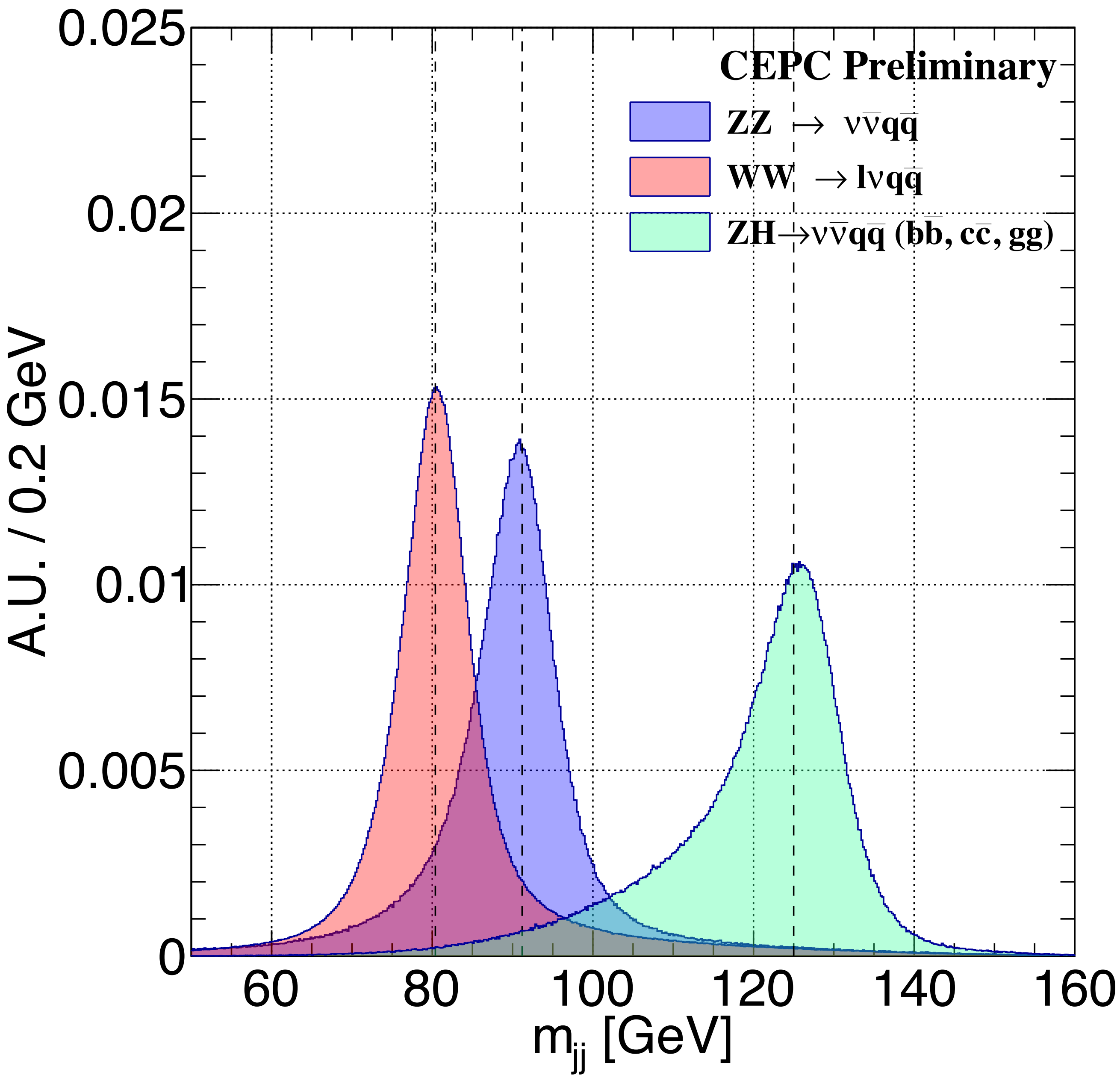


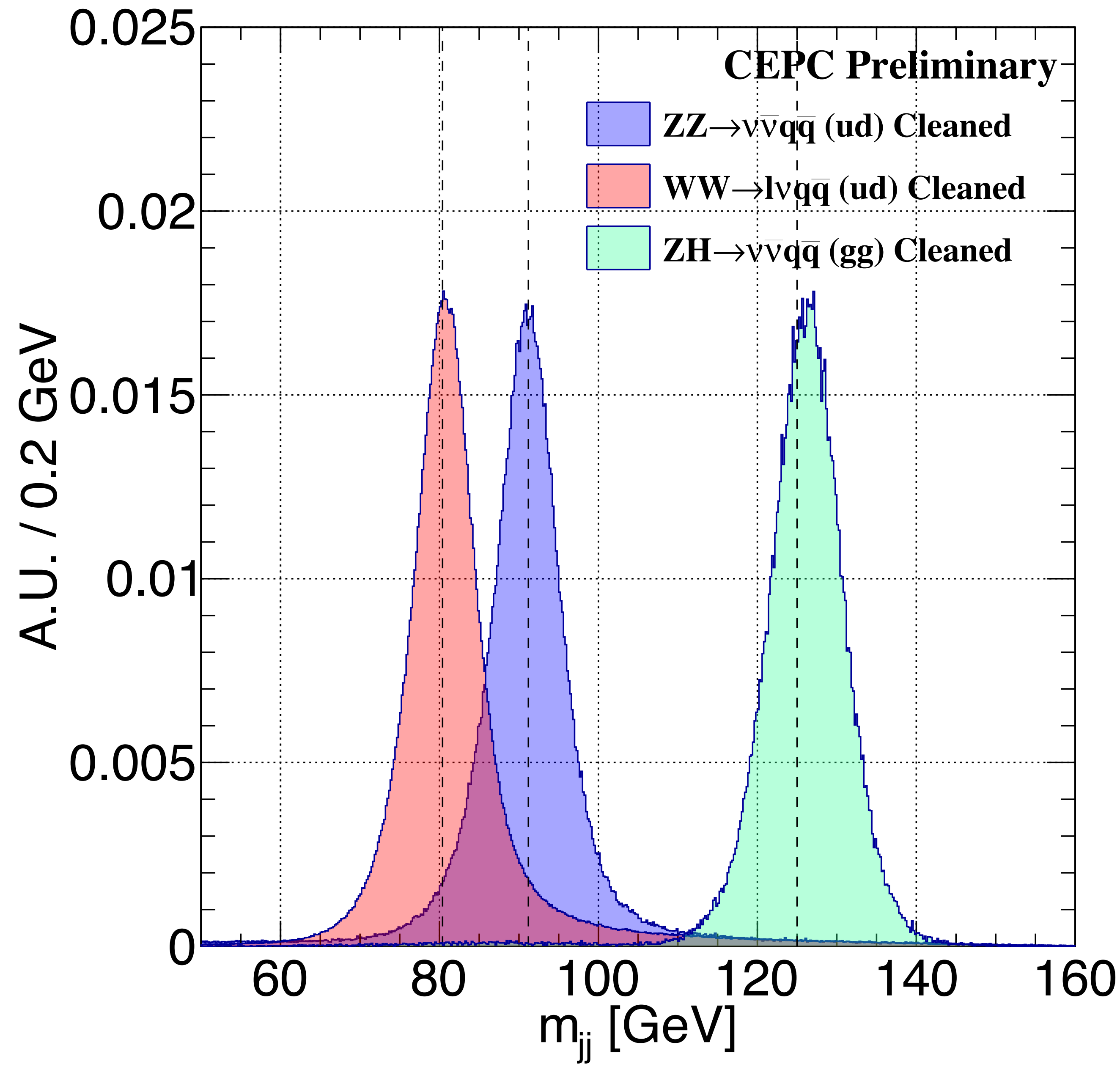


- **The separation of Z and W at CEPC is much better than ATLAS, because we have better jet energy resolution**

Ref. [5]

Massive Boson Separation

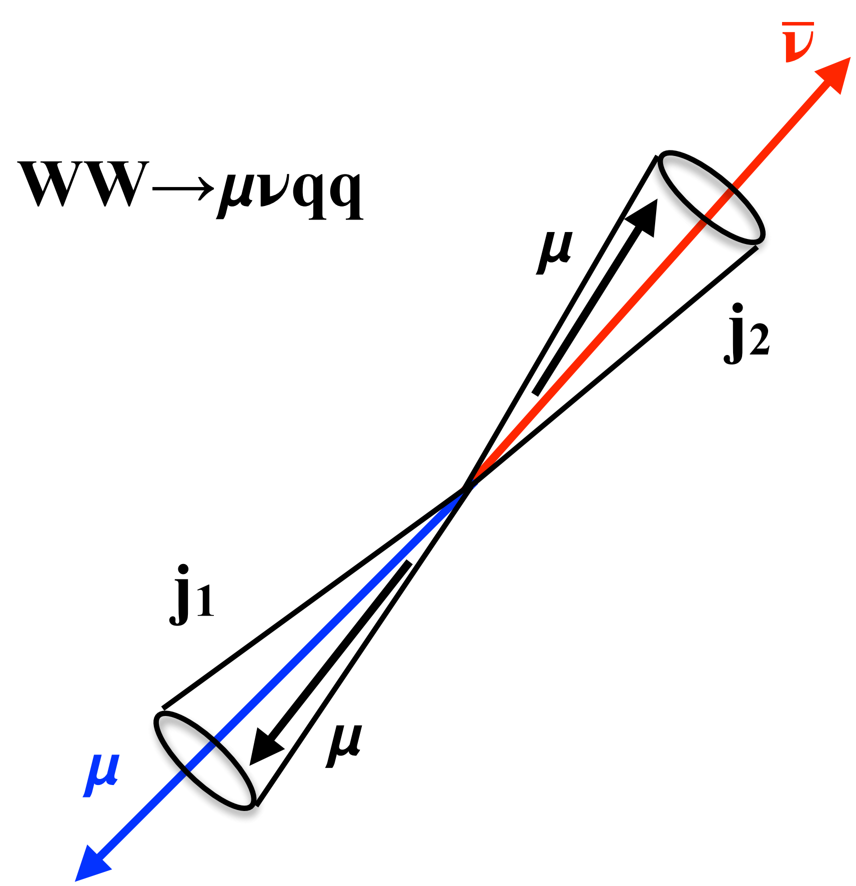




The Z, W, and Higgs bosons can be well separated in CEPC.

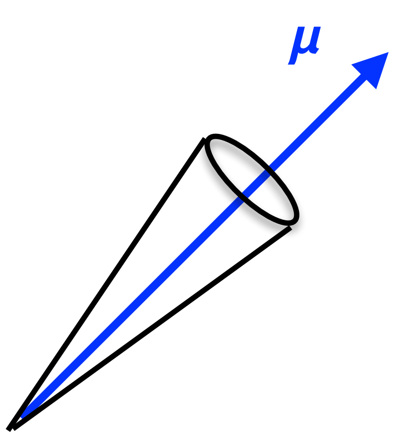
Direct W Mass Measurement

- However, we need to deal with the prompt muon problem. Prompt muon could go into the jet and lead to the wrong W boson mass measurement.
- In principle, ee_kt jet clustering algorithm would cluster the number of jets we want by all of the particles we put in. Therefore, the probability of the prompt muon inside the jet is 100% if we do nothing.
- We need to identify the prompt muon first!



Prompt μ Veto Criteria

- In order to veto the prompt muon in WW to $\mu\nu q\bar{q}$, there is a code called "ISOlatedLeptonFinderProcessor" before putting PFOs into the jet clustering algorithm.
- The veto criteria are as following(should satisfy all of them at the same time)
  - Pass μ ID (from Arbor)
  - R0 < 0.01 mm
  - Track energy > 30 GeV
  - Apply ISOlatedPolynomial decision

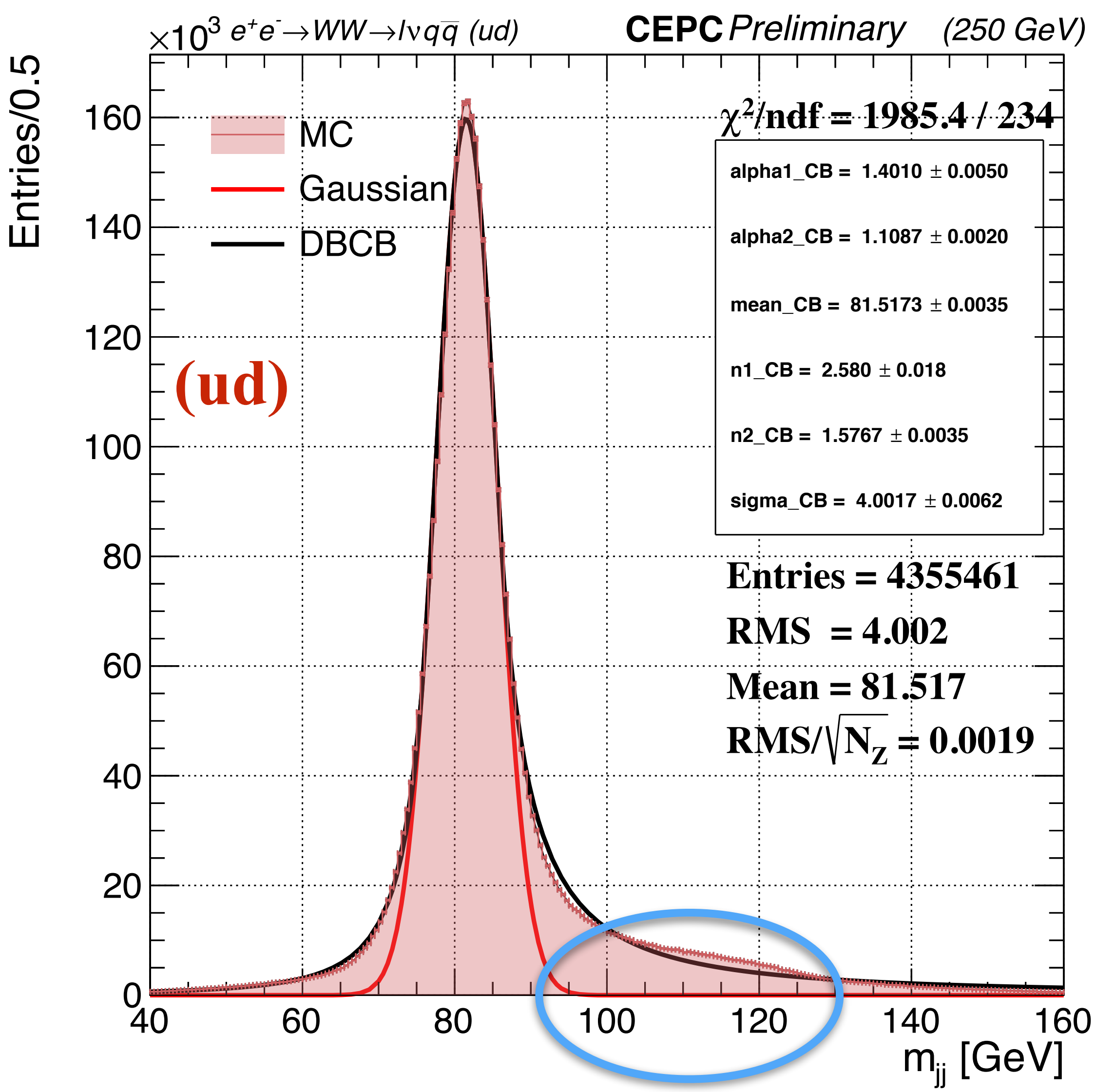


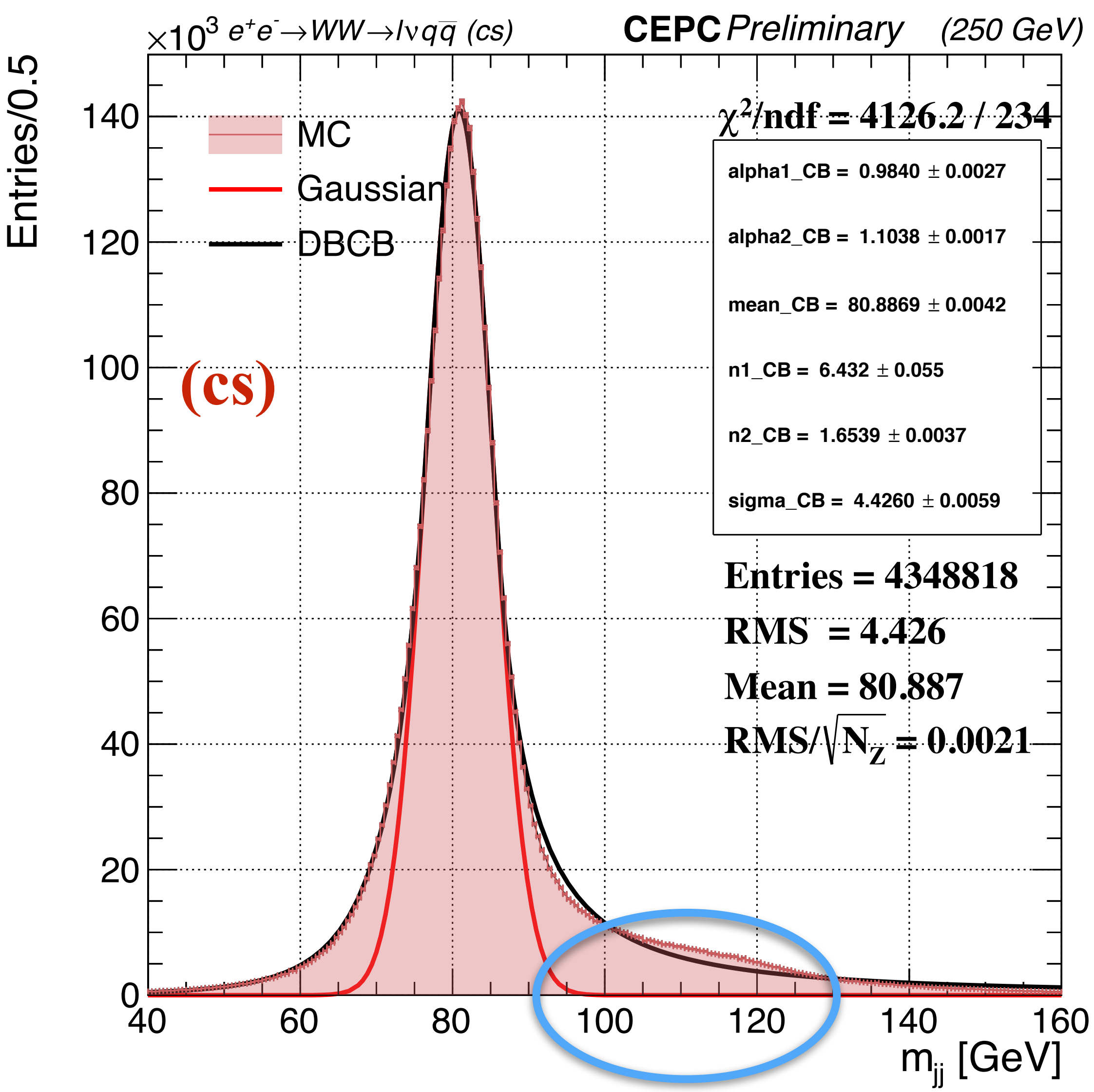
$$\cos\Delta\theta_{cone} = 0.98$$

coneE = Energy in the Cone(excepts the muon) / Energy of muon

ISOlatedPolynomial: $(coneE)^2 <= 20E_{\mu} - 300$

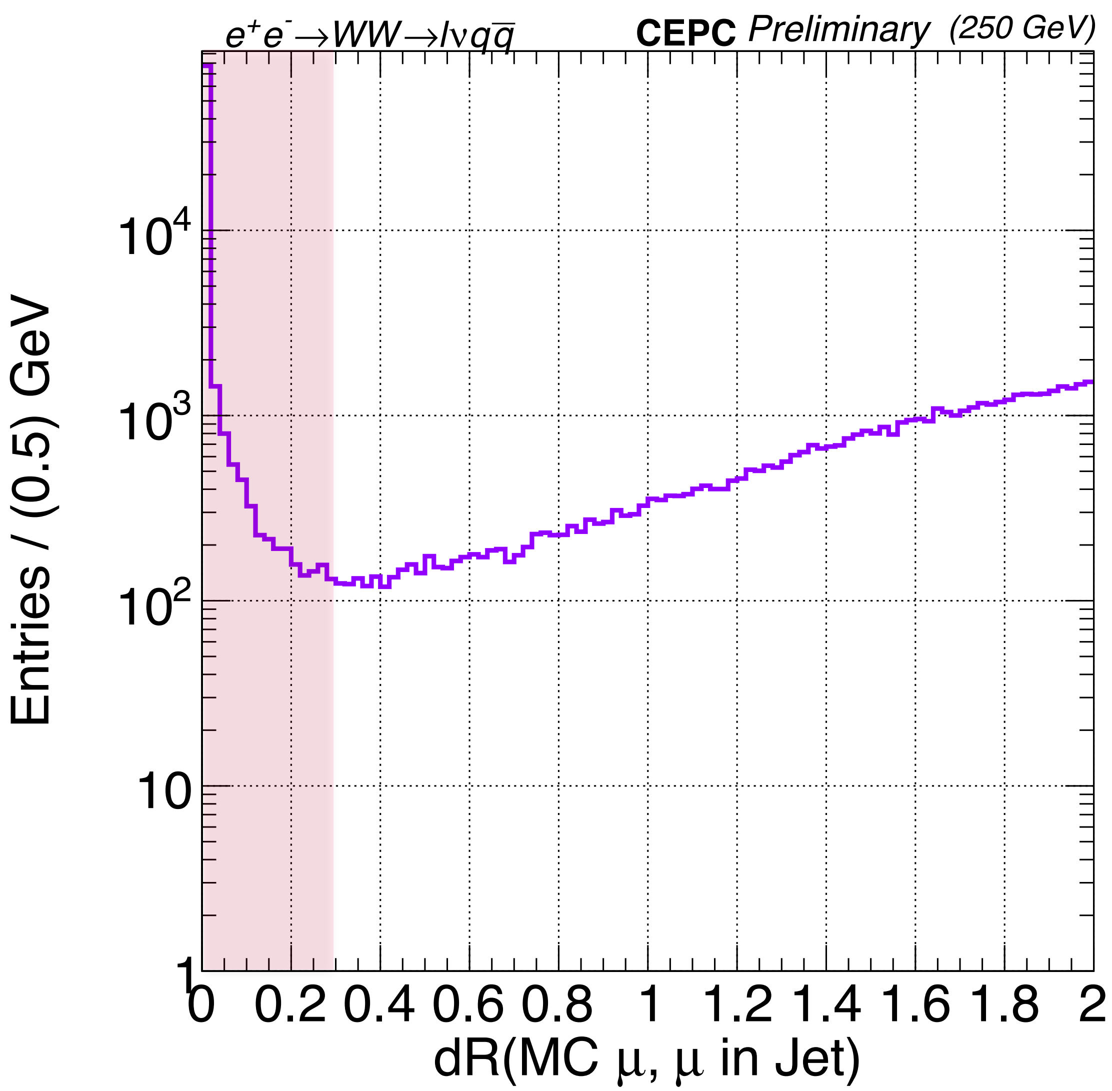
W->(ud, cs) (40<m_W<160)

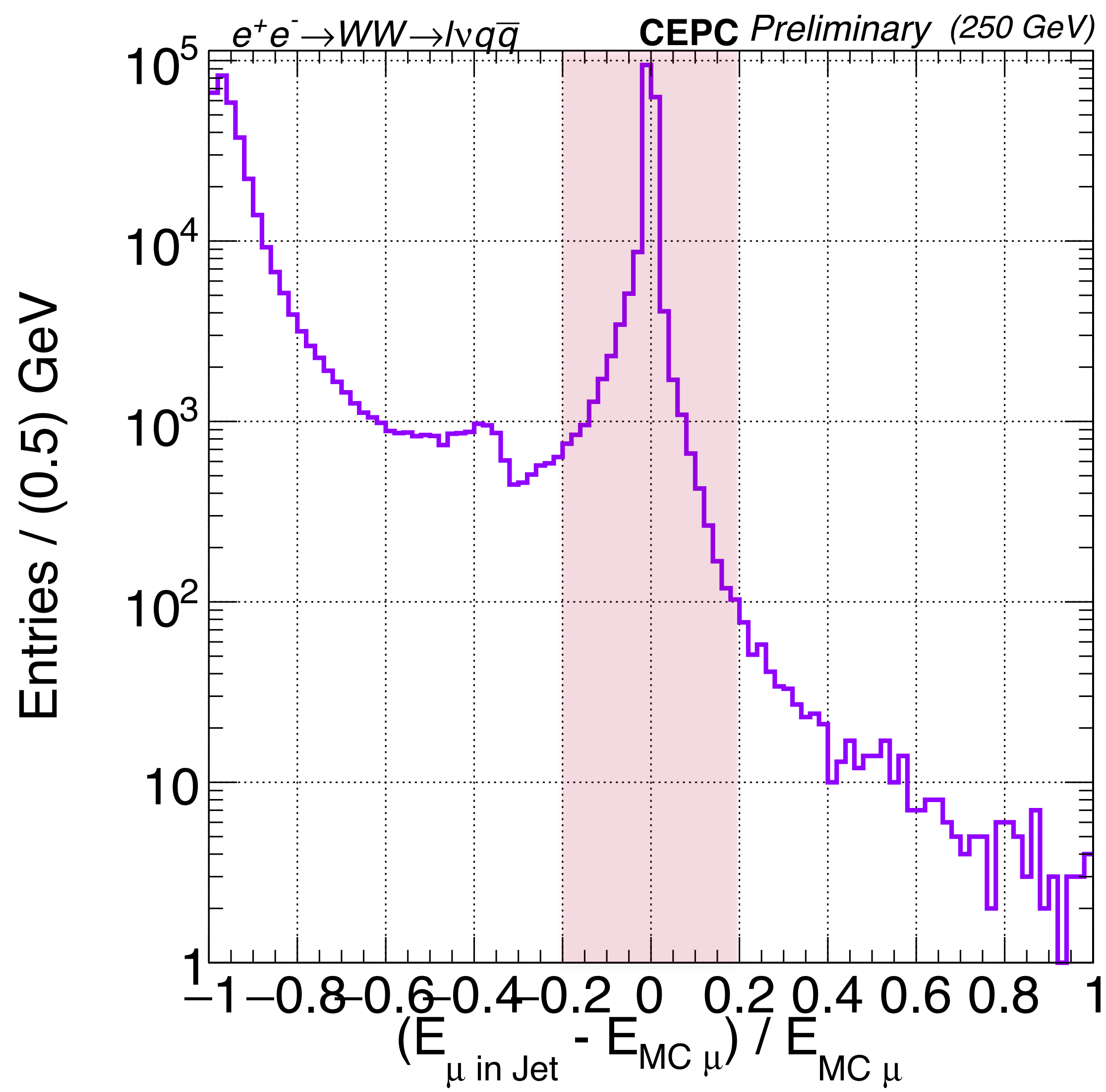




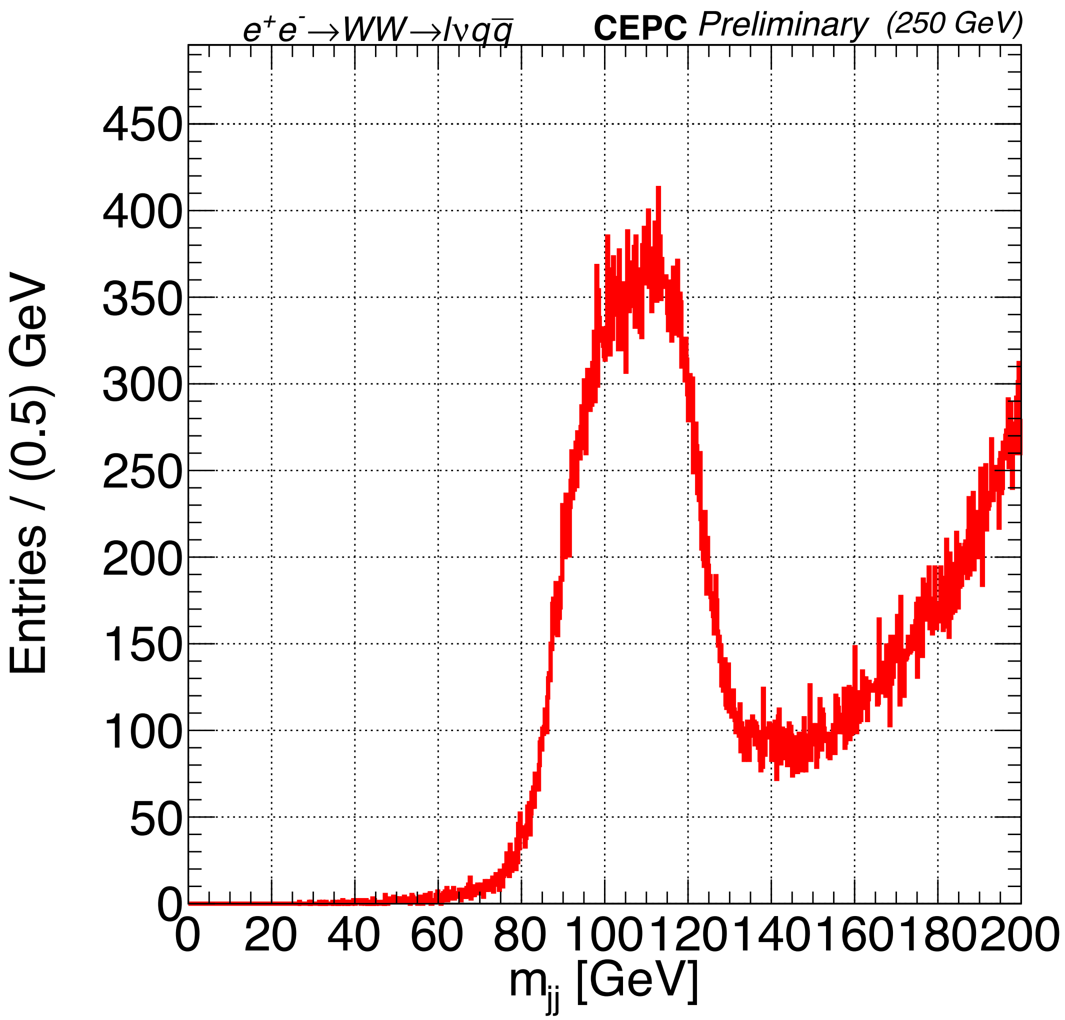
- **After using prompt muon veto criteria, some events still remain a prompt muon inside the jet. It causes a shoulder on the high mass region.**
- **We need additional veto using generator level information for the time being.**
- **A more sophisticated method will be developed in the future.**

MC Matching(Prompt μ, μ in jet)

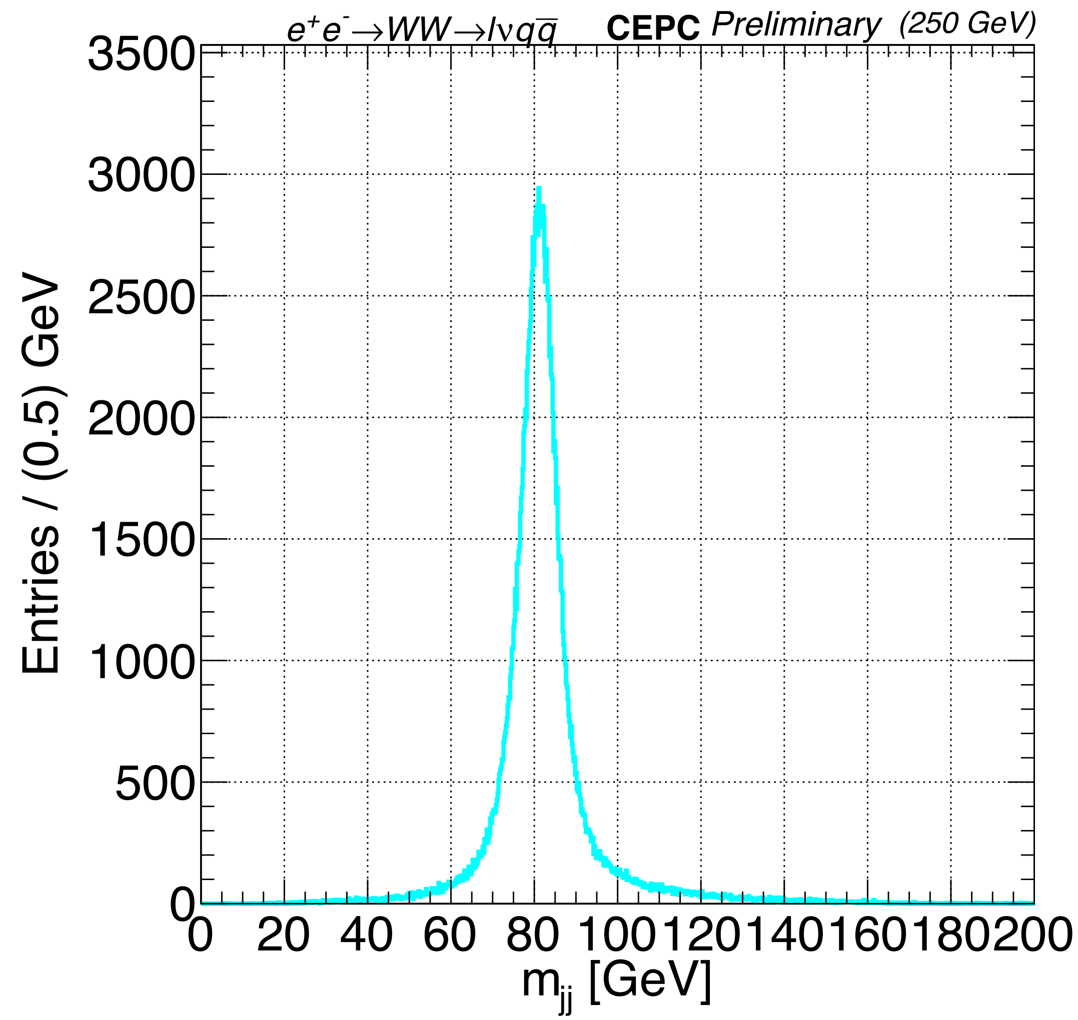




- Use the MC true information to veto the prompt muon cleaner.
- dR between "muon in the jet" and MC prompt muon less than 0.3 and |dE/E| less than 0.2 is identified as the prompt muon.
- If there are more than one muon pass through the criteria, the lowest |dE/E| is chosen as the prompt muon.



Same events →

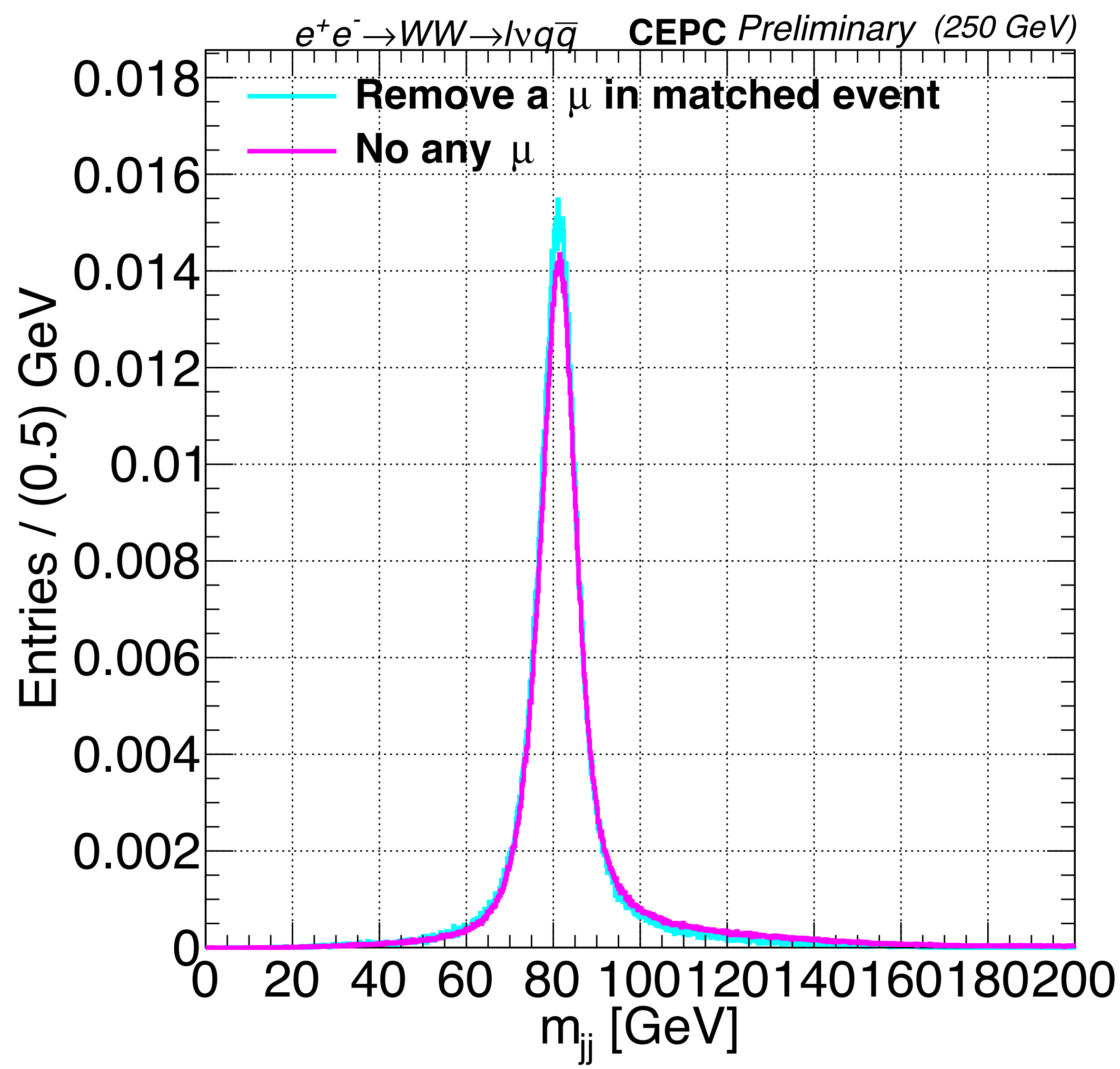


The event has a matched muon. This muon must come from another W.

The event has a matched muon. After I kicked off this match muon.(by subtracting its four-vector)

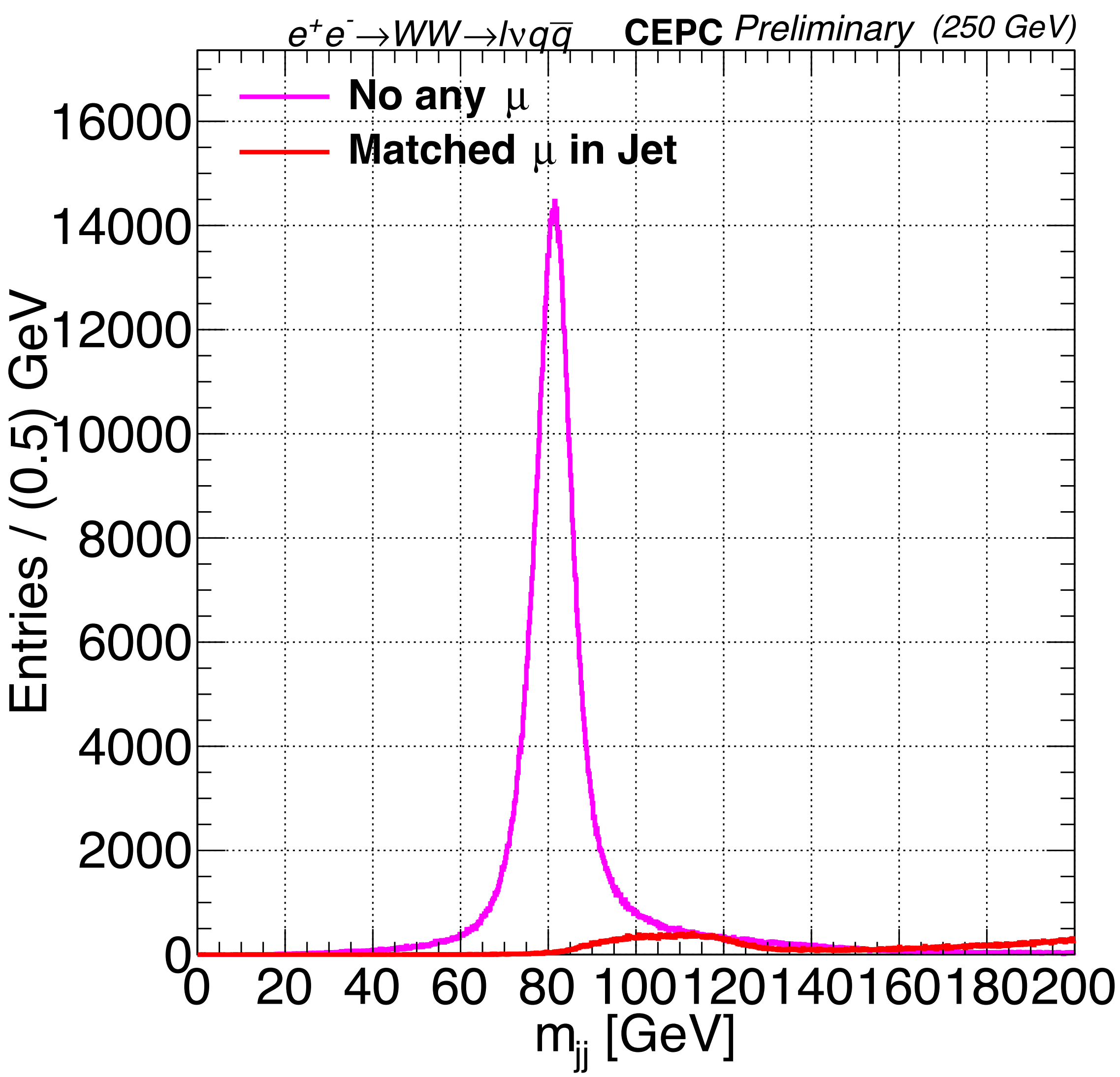
- **After vetoing a muon in the polluted event, dijet invariant mass can be recovered.**

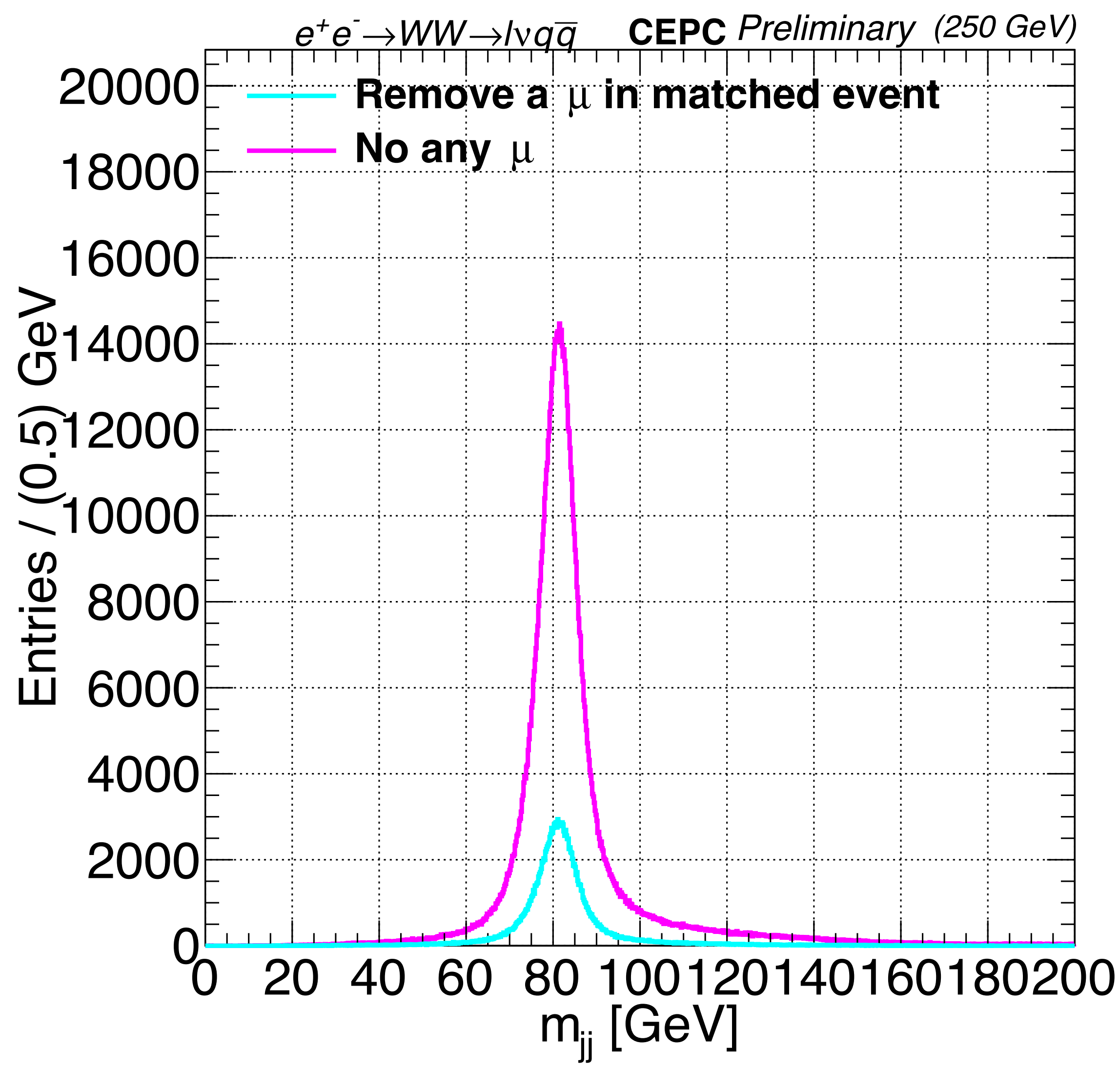
After Finding the Prompt μ



- "No any μ" means two jets don't contain any muon in these events.
- "Remove a μ in matched event" means the blue plot in S16.
- After vetoing a muon in the polluted event, dijet invariant mass can be recovered.

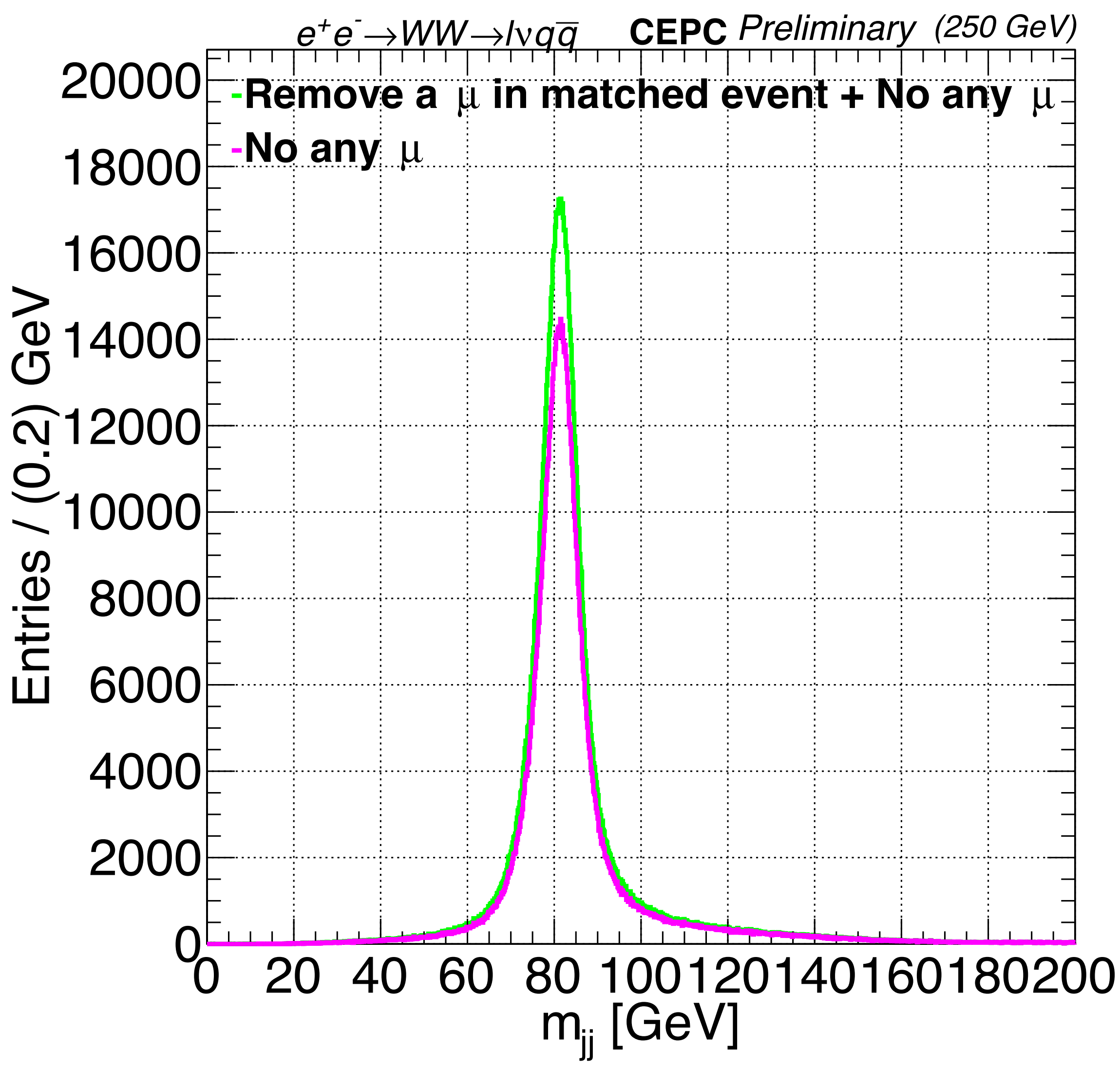
After Finding the Prompt μ

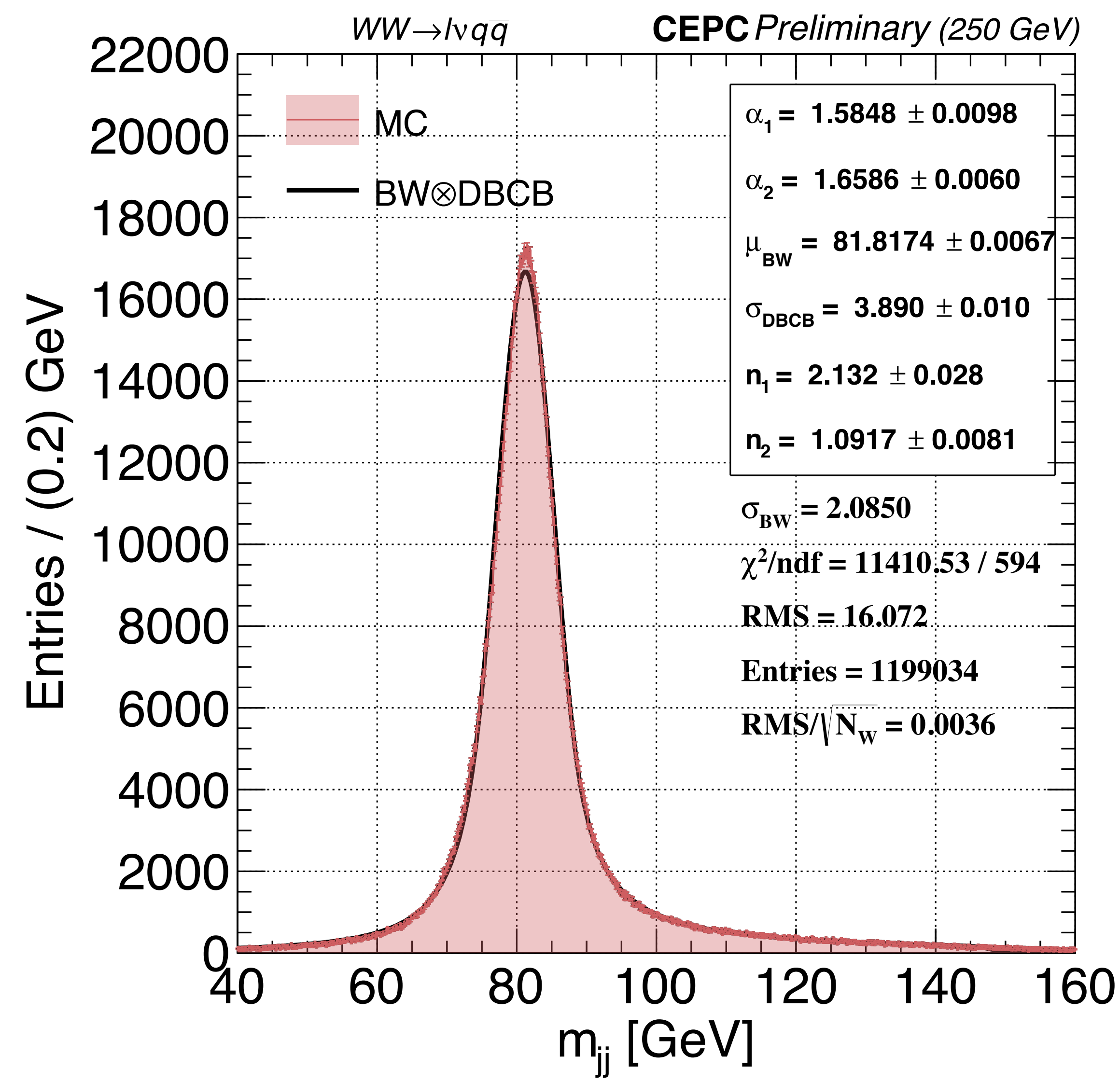




- **We knew the polluted event only occupy ~2% in the total event, but it can cause the shoulder in the dijet mass distribution.**

Final Plot



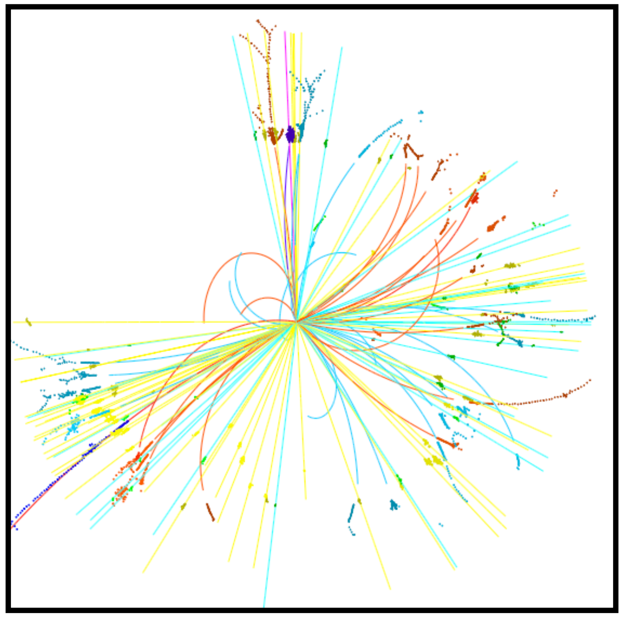


- **After cleaning the polluted event, it could improve the mass resolution and remove the shoulder**
- **The preliminary result of W boson mass direct measurement is 81817.4 ± 6.7 MeV.**

Conclusion and Future

- **The preliminary result for W mass direct measurement is 81817.4 ± 6.7 MeV. The uncertainty can achieve less than current electroweak fit (8 MeV).**
- **Optimize the W boson measurement by kinematic fitting.**
- **The optimization of event selections is progressing. The prompt muon veto and sensitivity will be taken into account.**
- **Study the performance of different jet clustering algorithms and try to find out the best one for CEPC.**
- **Apply the best one to multi-jet processes (ee->ZH->4b) to promote precision.**

ee->ZH->4b



Thank for your attention

Reference

[1] CMS-Physics-Technical-Design-Report-2006-001

[2] http://cms.web.cern.ch/tags/particle-jet

[3] CMS-JME-13-004, CERN-PH-EP "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV"

[4] https://goo.gl/ZvTvoy // ALEPH

[5] CERN-PH-2015-194

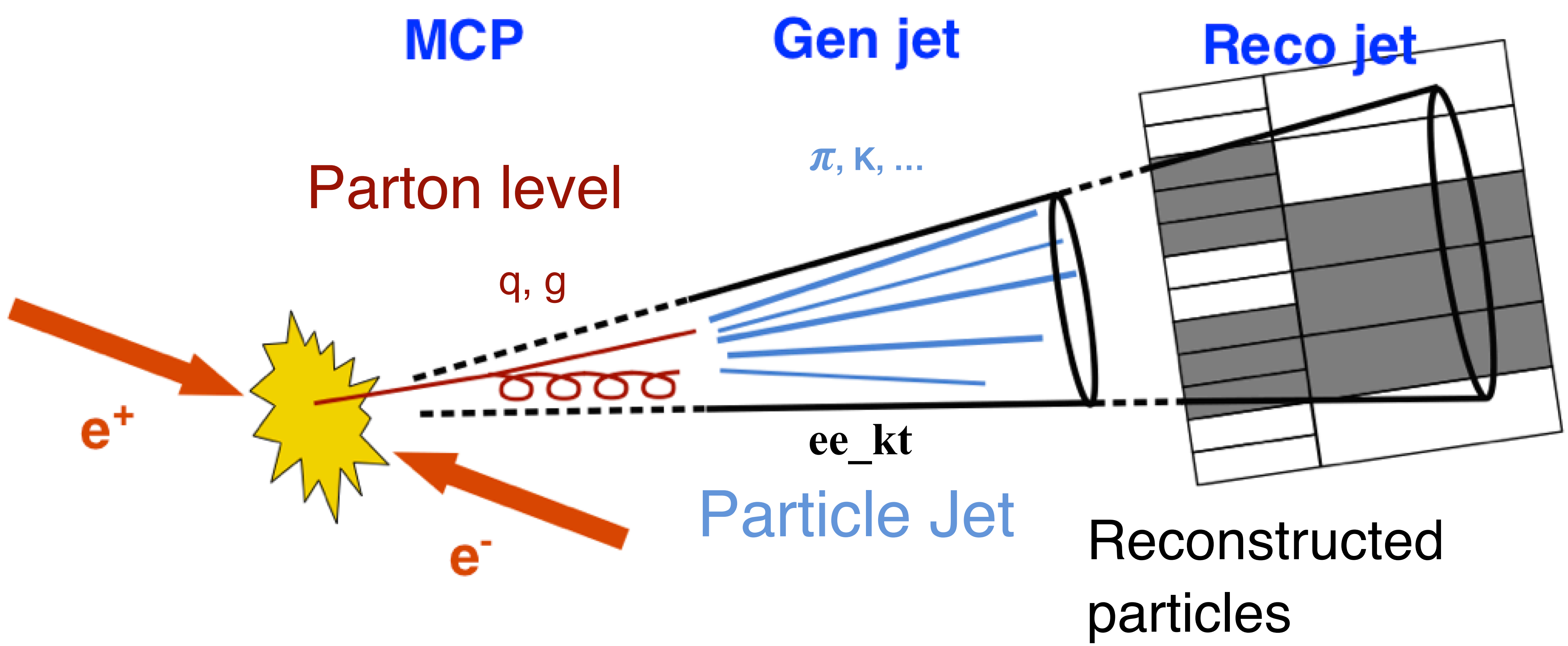
[6] arXiv:1701.07240 [hep-ex]

Back up

Benefit of direct measurement

ΔM_W(MeV)	LEP	CEPC
$\sqrt{s}$(GeV)	161	250
∫ L(fb-1)	3	1000
Channel	lvqq, qqqq	lvqq
Beam energy	9	1.0
Hadronization	13	1.5
Radiative corrections	8	1.0
Lepton and missing energy scale	10	1.5
Bias in mass reconstruction	3	0.5
Statistics	30	1.0
Overal systematics	21	2.5
Total	36	3.0

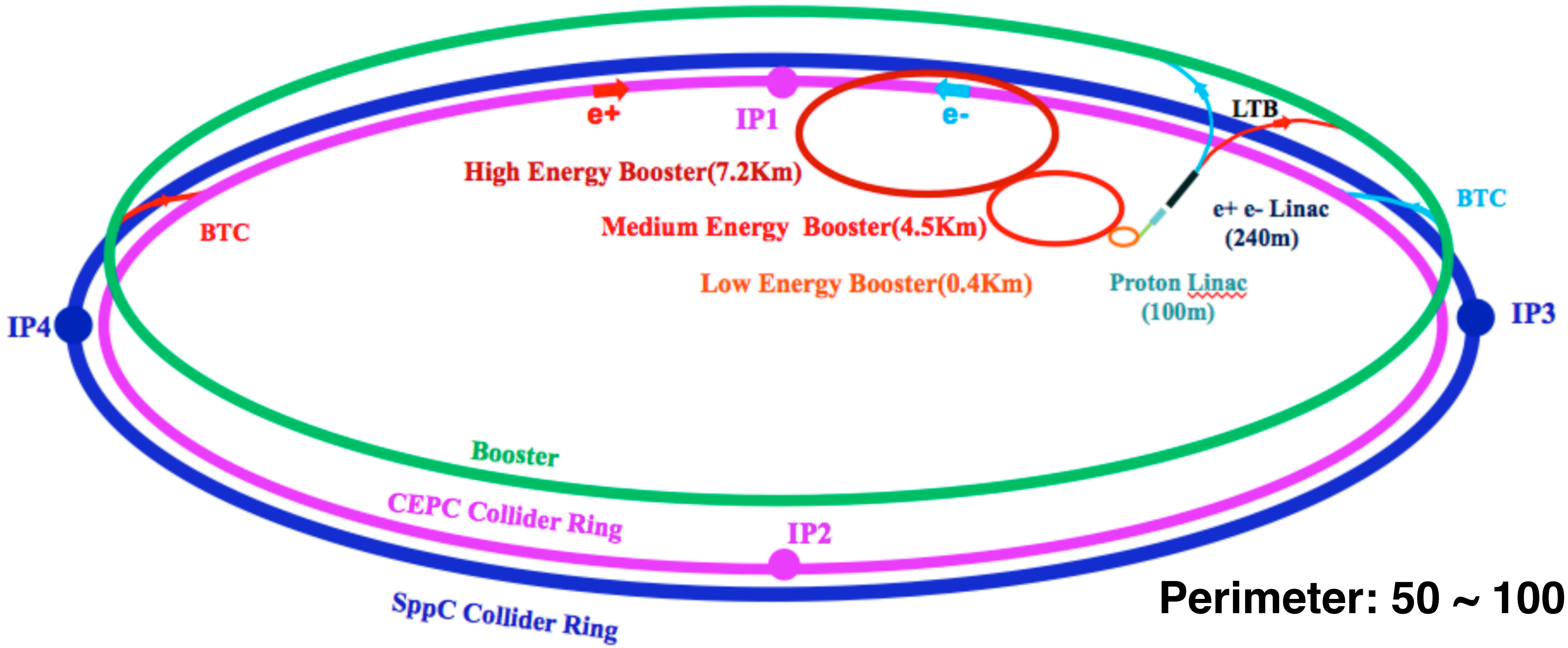
■ **Jet reconstruction plays an important role in particle physics. To study the performance of the jet reconstruction in CEPC, we look at the simulation which contains MC particle(MCP), Gen jet, Reco jet.**



Ref. [2]

- Higgs mass ~ 125 GeV, it is possible to build a Circular e+e- Higgs factory(CEPC), followed by a proton collider (SPPC) in the same tunnel
- Looking for Hints (from Higgs) at CEPC → direct search at SPPC

Circular **E**lectron-**P**ositron **C**ollider**(CEPC)**, **√s = 90 ~250 GeV**
Super **P**roton-**P**roton **C**ollider**(SPPC)**, **√s = 70 ~140 TeV**

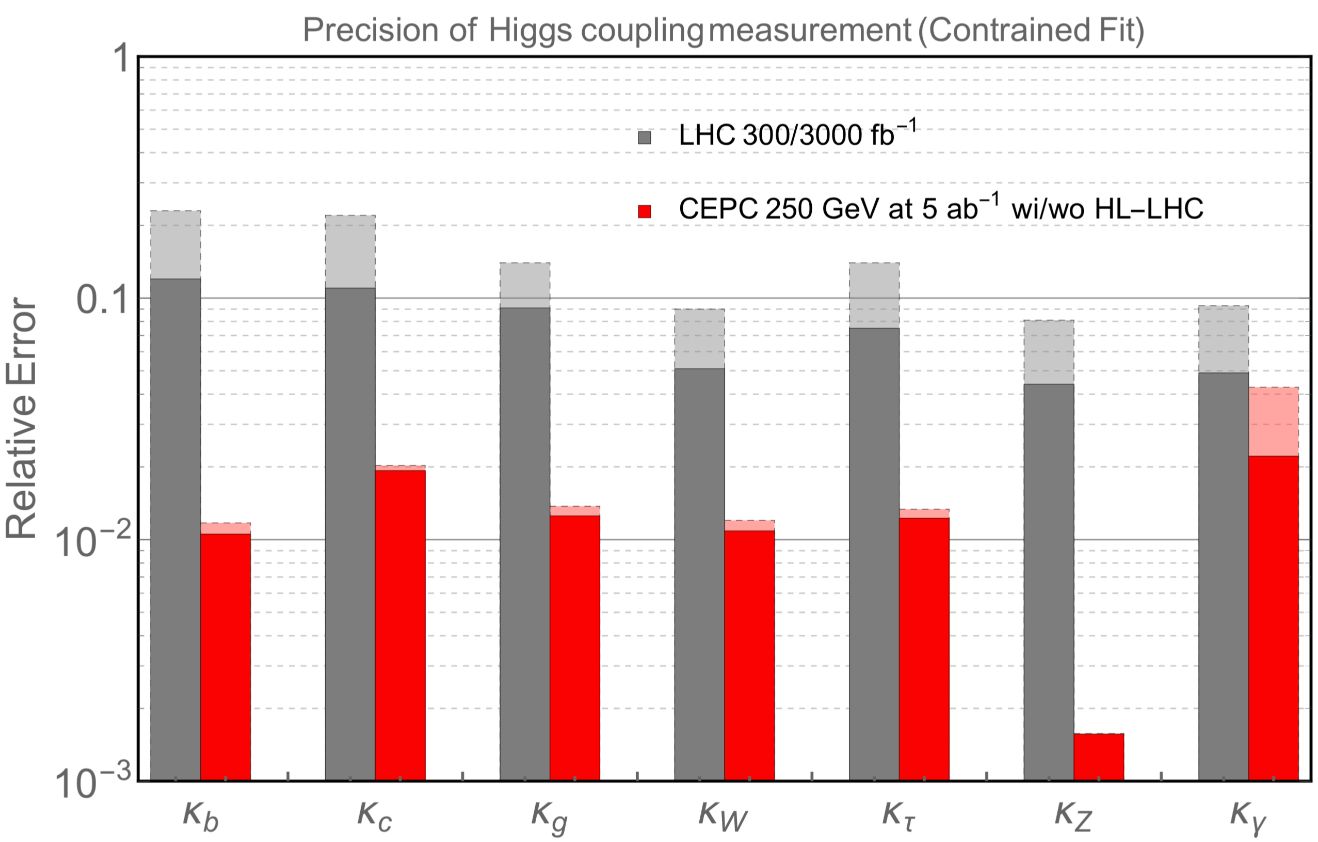


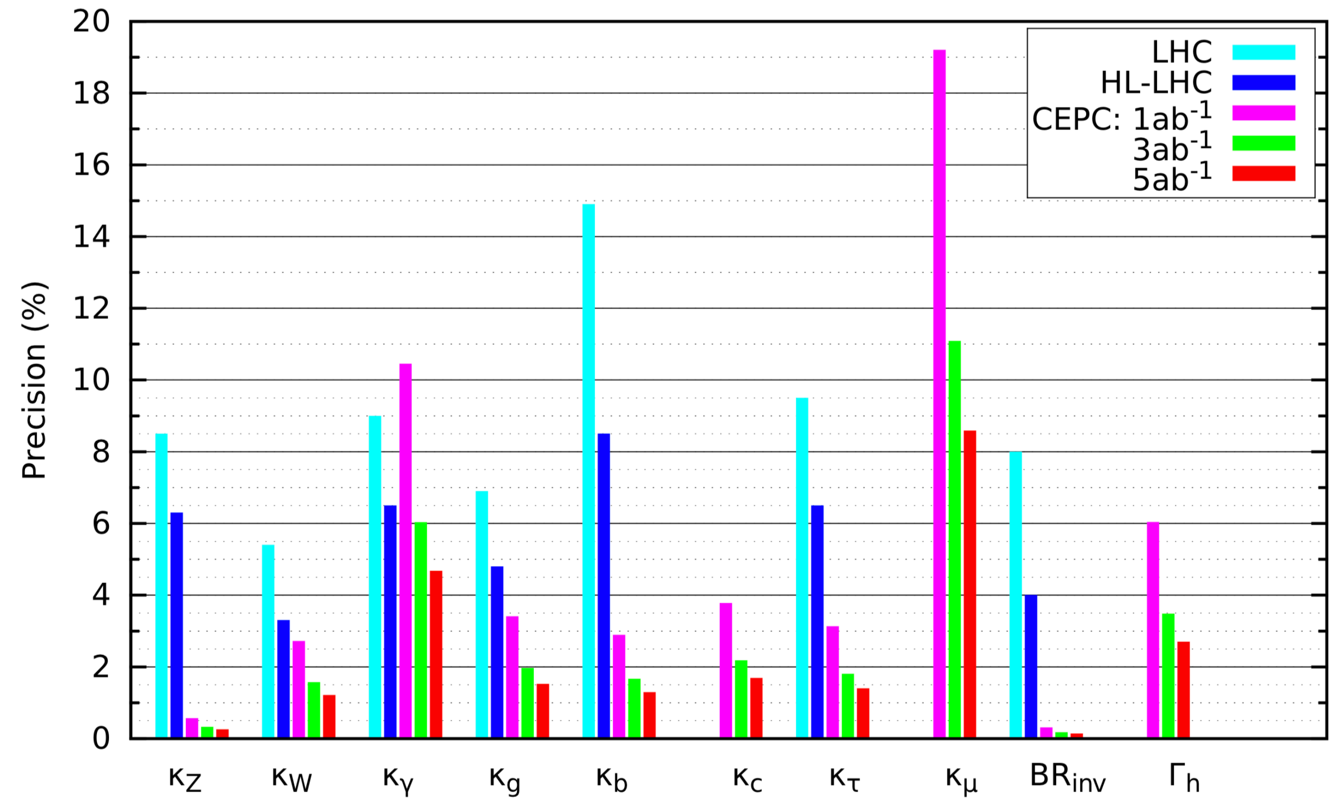
Perimeter: 50 ~ 100km

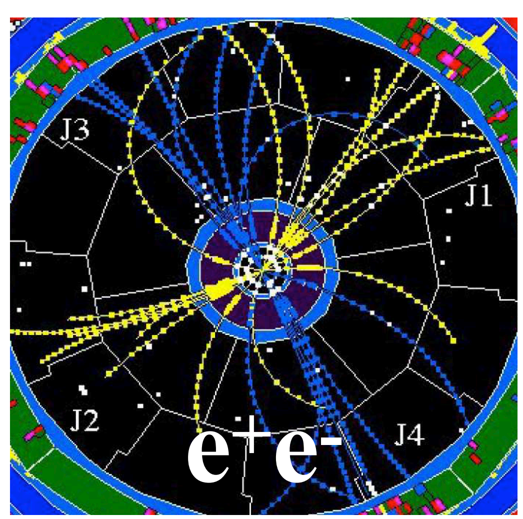
Ref. [1]

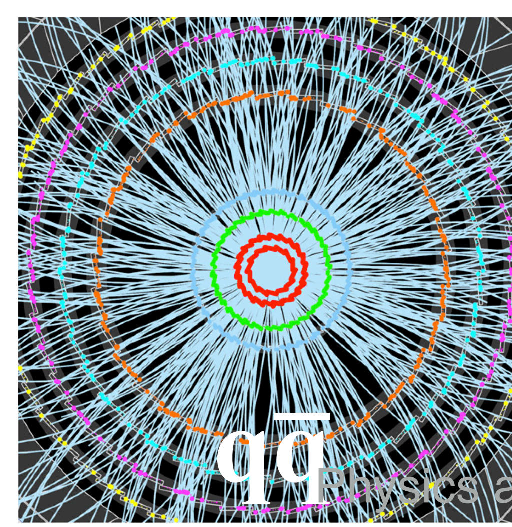
Introduction

- **Higgs factory: 1M Higgs boson**
  - **Absolute measurements of Higgs boson width and couplings**
  - **Searching for exotic Higgs decay modes (New Physics)**
- **Flavor factory: b, c, τ, and QCD studies (Highly correlate with jet)**







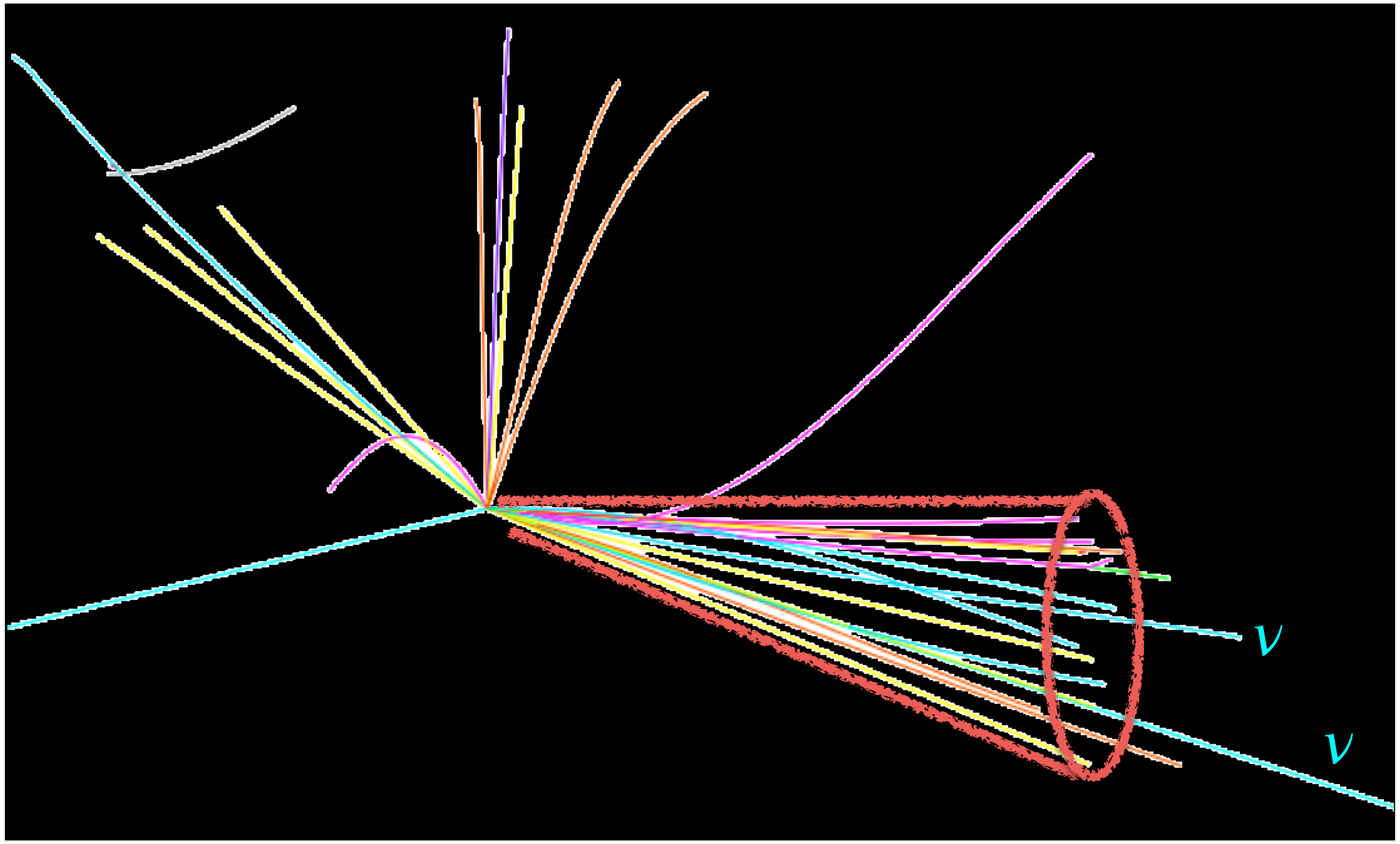


Ref. [1-3]

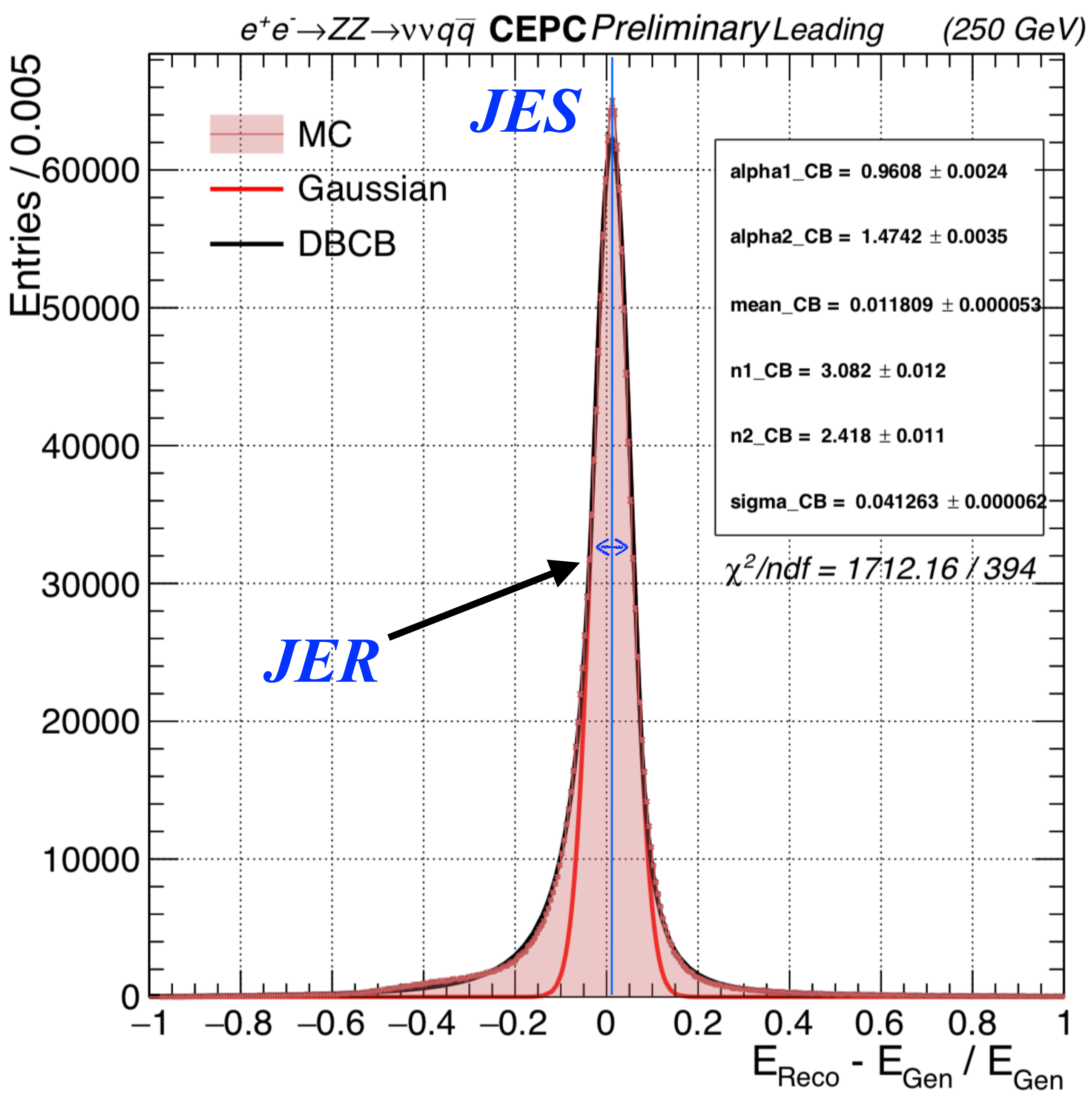
Difficulties in jet reconstruction

- **Poor clustering**
- **Neutrinos cannot be detected**
- **The detector responses(i.e. energy threshold)**

Wrong measurement leads to wrong physical results!



- Double-sided crystal ball(DBCB) function are used to extract energy resolution.
- The bin size of histogram is 0.5%.

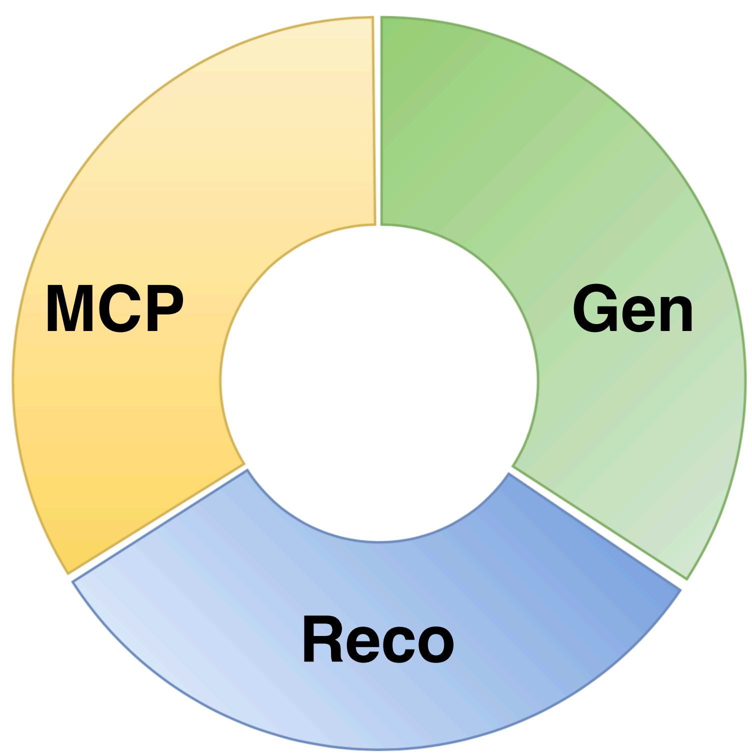


Relativity difference

$$\frac{E_{Reco} - E_{Gen}}{E_{Gen}}$$

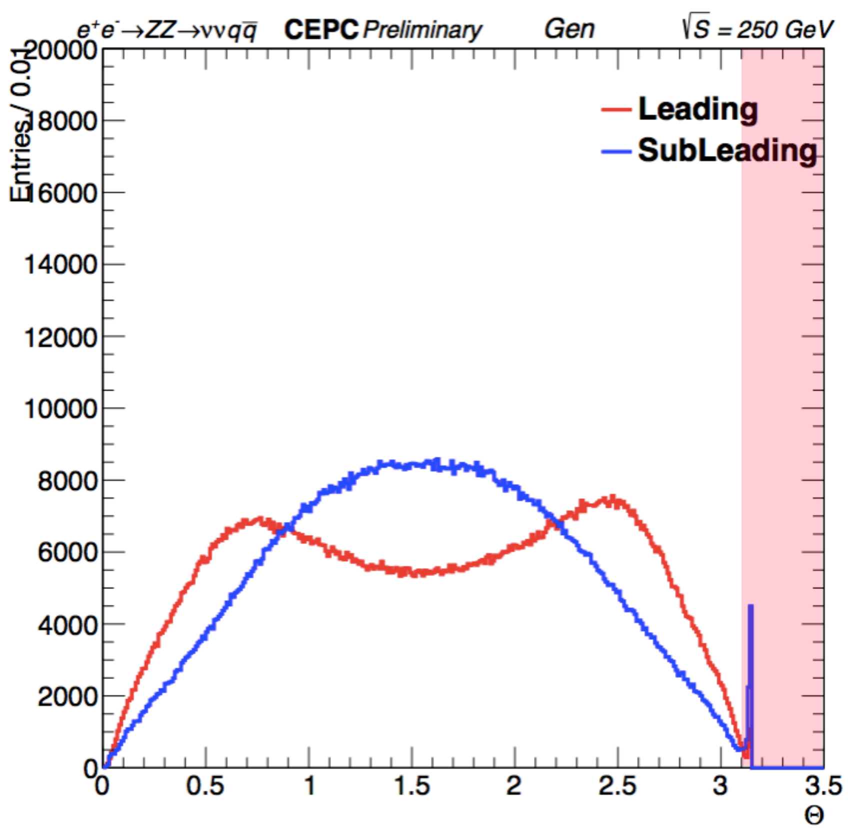
Strategy

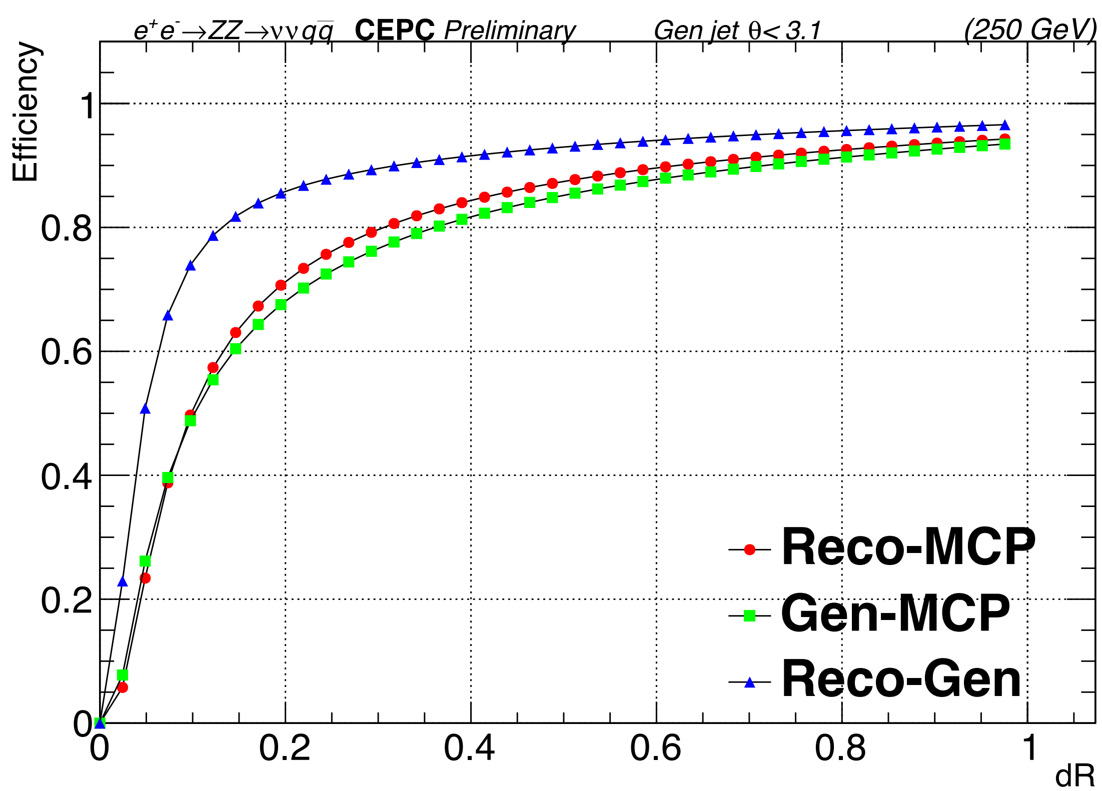
- **The jet energy resolution and scale(JER/JES) in ee->ZZ->vvq$\bar{q}$ process have been studied.**
- **The JER/JES relation between each simulation stage(Reco-Gen, Gen-MCP, Reco-MCP).**
- **Angular and energy dependence of JER/JES.**
- **To exclude the influence of jet clustering algorithm, matching reco jet and MC particle by $\Delta R < 0.1$.**



Event Selection

Items	JER/JES(Reco-Gen)	JER/JES(Gen-MCP)
Gen jet theta < 3.1	✓	✓
ΔR(Reco-MCP) < 0.1	✓	✗



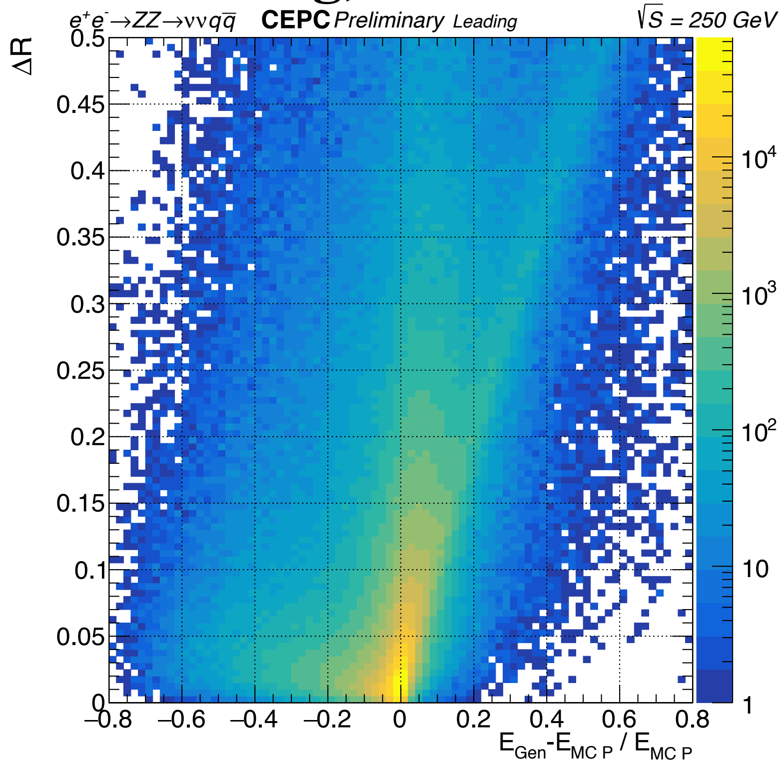


$$\text{Efficiency} = \frac{\text{\# of leftover event}}{\text{\# of total event}}$$

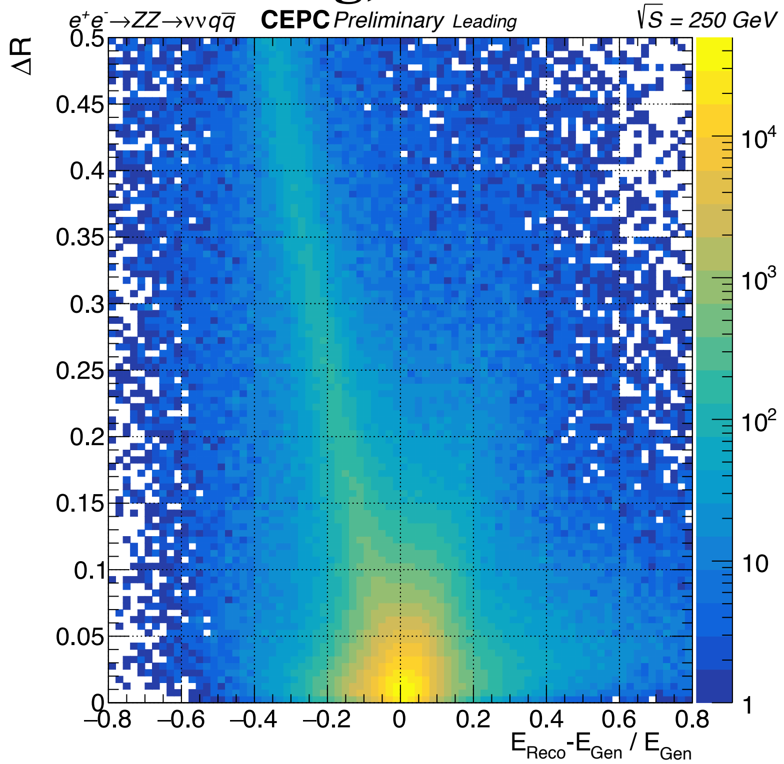
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

The Reason for ΔR Cut

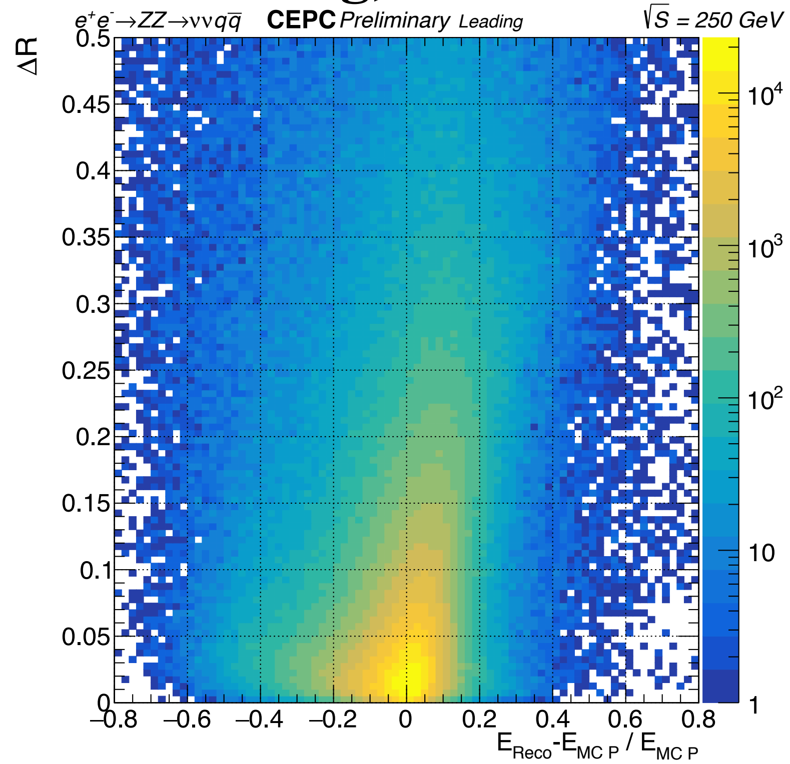
Leading, Gen-MCP



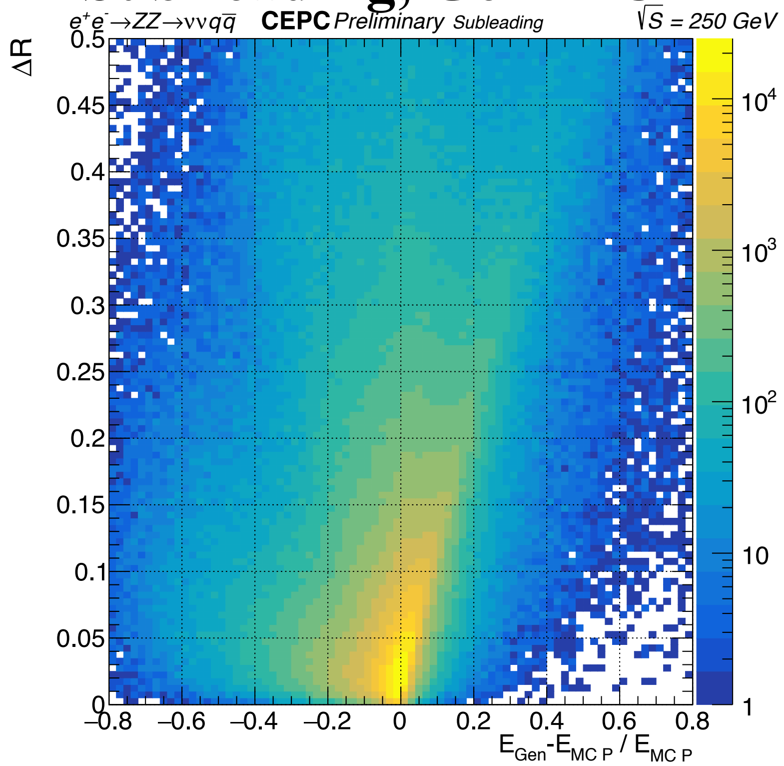
Leading, Reco-Gen



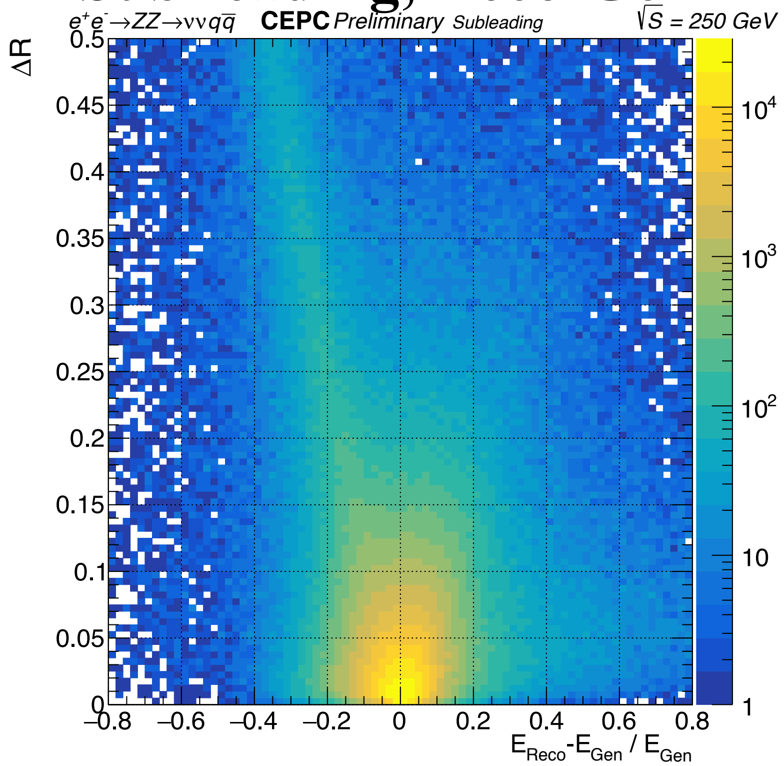
Leading, Reco-MCP



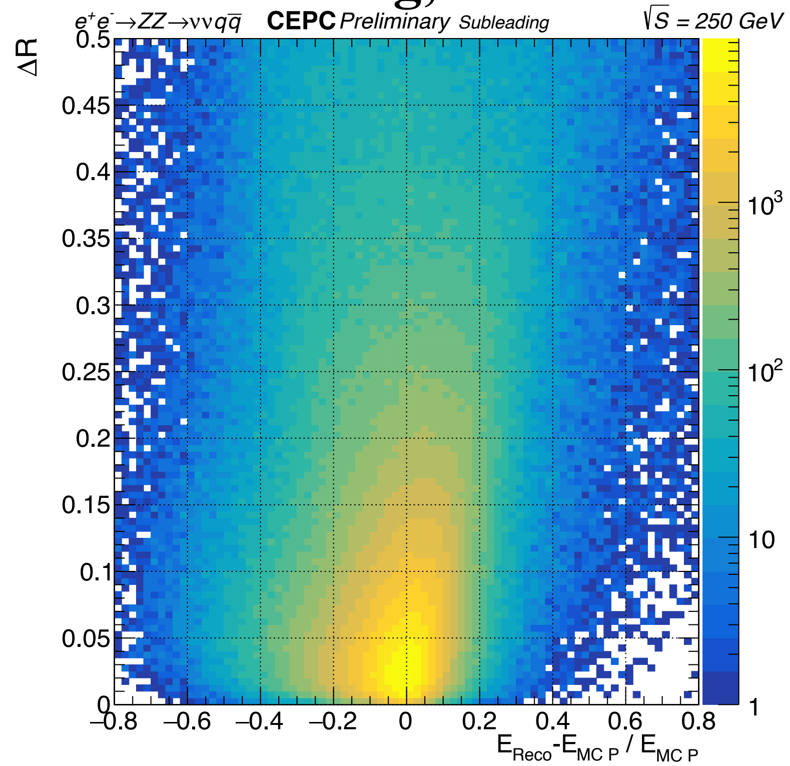
Sub-leading, Gen-MCP



Sub-leading, Reco-Gen

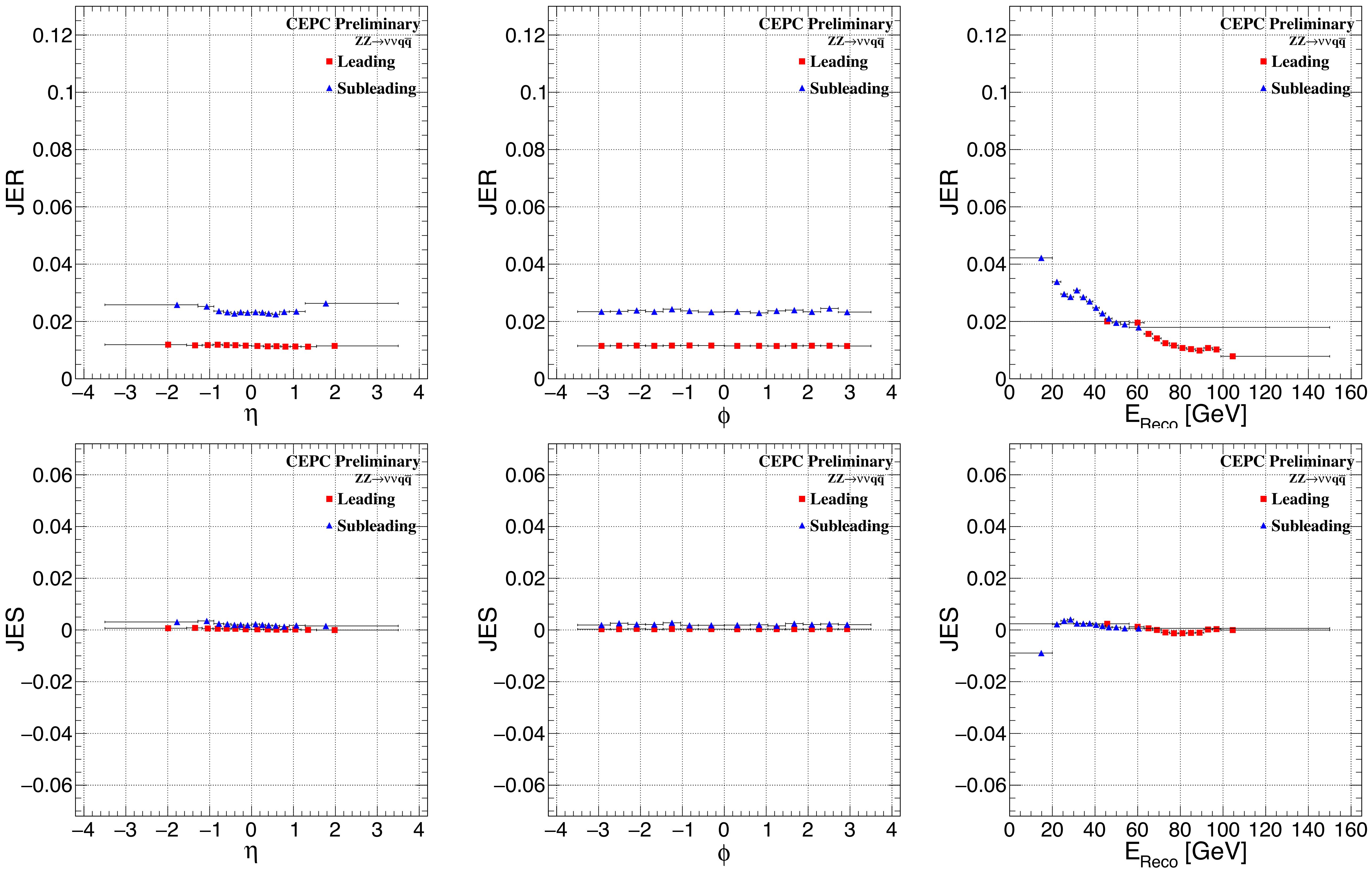


Sub-leading, Reco-MCP



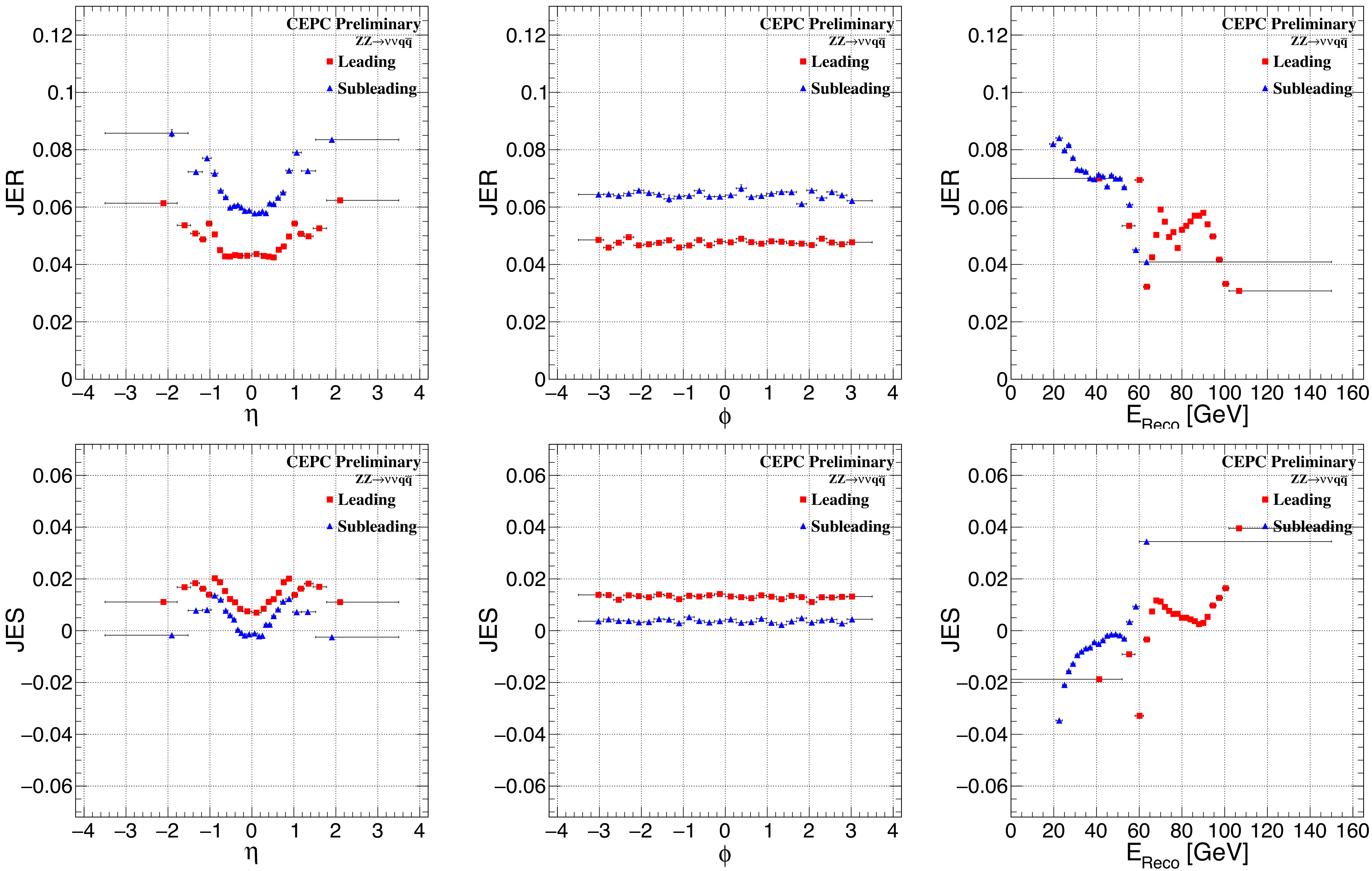
The jet clustering brings in a significant uncertainty.

JER & JES(Gen-MCP)



The jet clustering is independent of direction.

JER & JES(Reco-MCP)

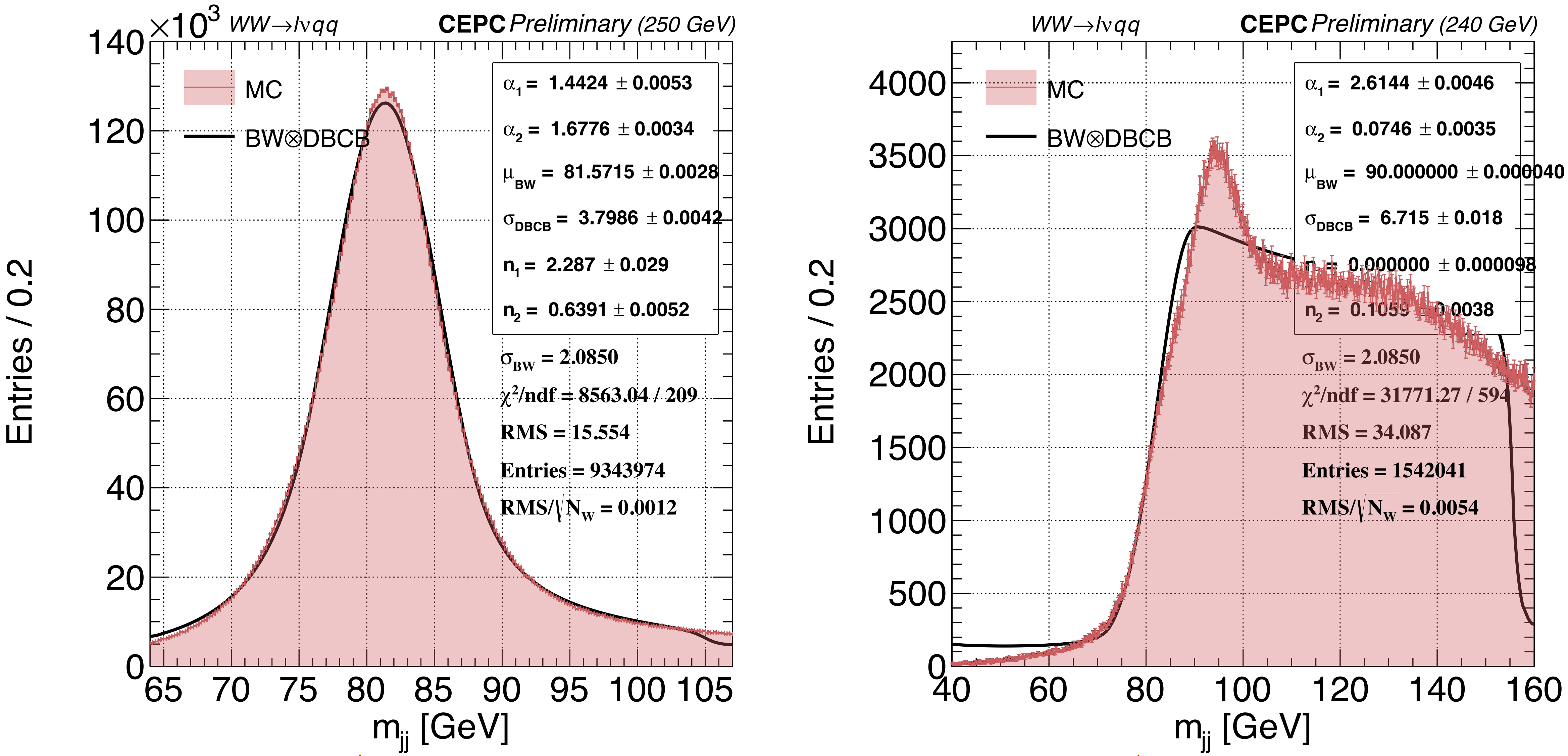


Both JER/JES depend on Eta within 2%.

Switch to New Detector Design(V4)

- **To compare with ILC(International Linear Collider) we produced the sample with the centre of mass energy 250 GeV. Our original design is 240 GeV.**
- **Make the detector design more efficient in terms of the cost and performance.**
- **On the cost side, the new detector is smaller than V1. The new detector is less expensive.**
- **Optimize the sub-detector. e.g. reduce the radius of TPC to 1.8m, cell size and the number of layer of ECAL and HCAL.**

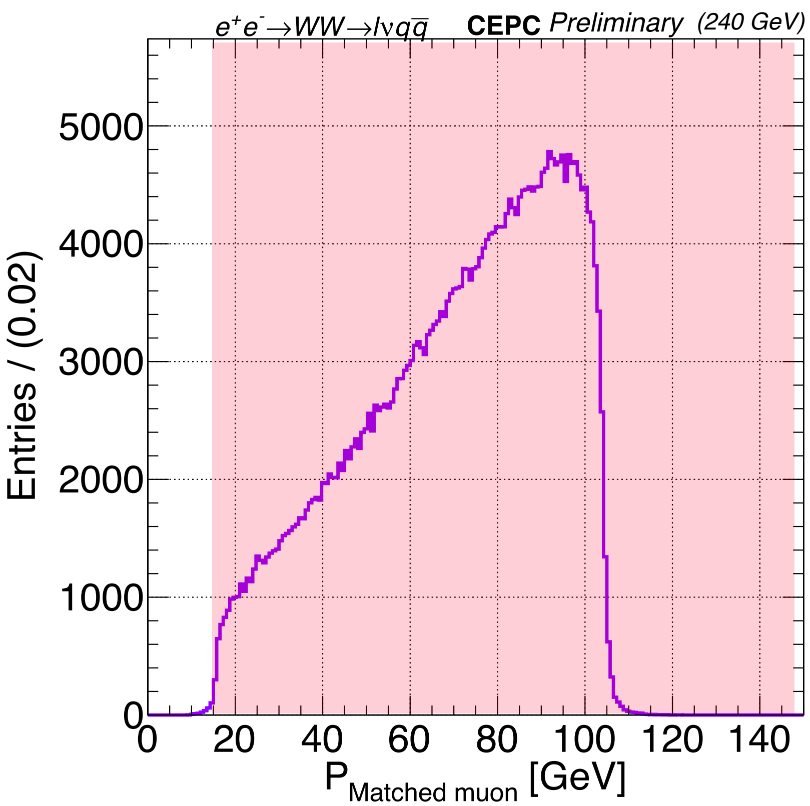
V1($\sqrt{s}$=250GeV) vs. V4($\sqrt{s}$=240GeV)

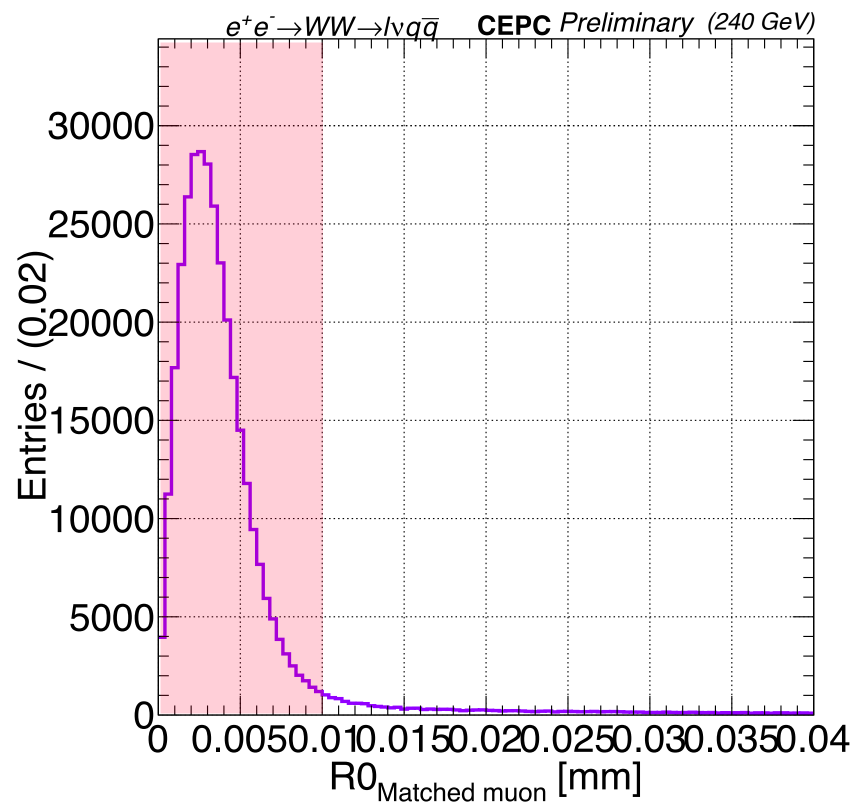


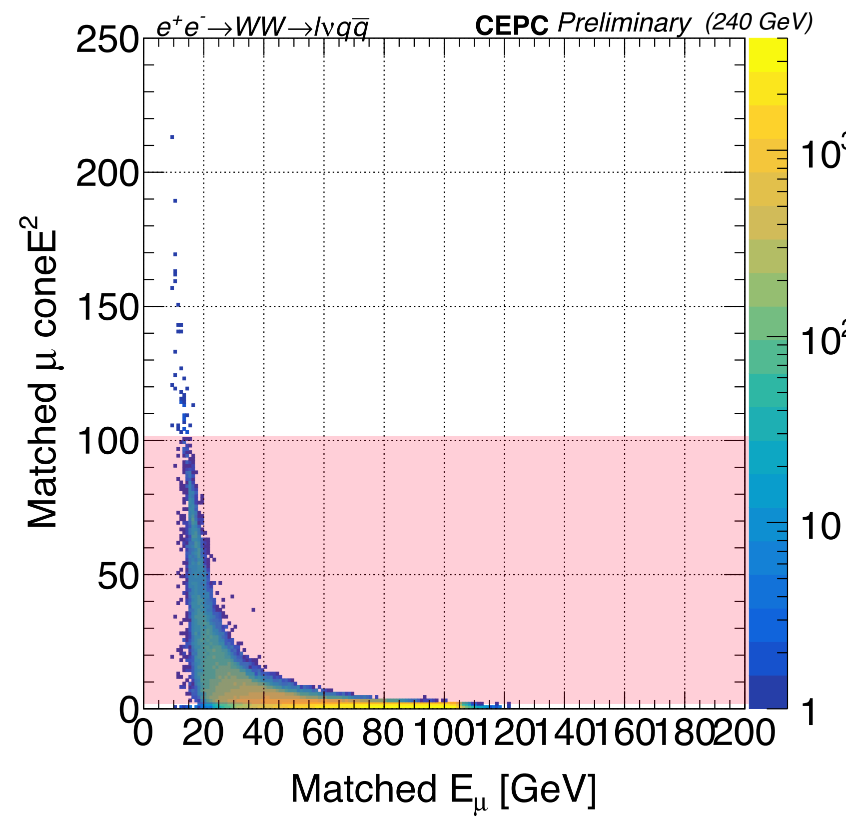
$\sqrt{s}$ = 250 GeV　　　　$\sqrt{s}$ = 240 GeV

- **After using the same approach to cluster jet in V4, I found some problems in reco jet. (Shoulder and peak position)**

Optimize Prompt μ Veto Criteria in V4







- These plots are done by the matched muon(prompt) muon.
- After studying these veto criteria, I made some changes(in red).
  - Pass μ ID (from Arbor)
  - R0 < 0.01 mm
  - Track energy > 15 GeV
  - Apply ISOlatedPolynomial decision
- If there are more than two muons pass through these selections, I will pick up the most energetic muon.
- I will do more detail study for the event selections.

ISOlatedPolynomial: $(coneE)^2 <= 100$

Select the Final State($\mu\nu q\bar{q}$) in V4

V4	# of event	Efficiency
Tot # of event	135506	—
> 7 Tracks	134898	99%
E_{Miss} & P_{Miss} > 35 GeV	89284	65%
Select a μ	72712	54%
Detector acceptance $\lvert\cos(\theta_\mu)\rvert < 0.995$	72712	54%

- I followed the ALEPH paper to do these selections(track, missing energy and momentum).
- "Select a μ" is used the selections in S33.
- These results are very preliminary. I will study the event selection more carefully.

Summary

- The jet clustering brings a significant or even leading uncertainty.
- After comparison, the CEPC detector has excellent jet energy resolution.
- Z, W, Higgs boson mass can be well separated in CEPC.
- These results have been accepted for publication by EPJC.(https://doi.org/10.1140/epjc/s10052-018-5876-z)

Gen-MCP

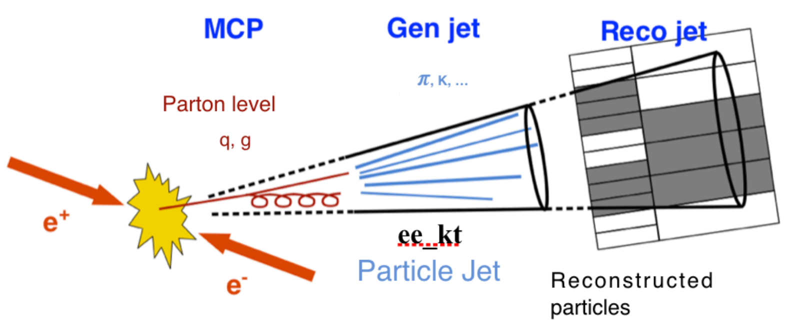
	JER		JES	
Type	Lead	Sub-Lead	Lead	Sub-Lead
Barrel	1%	2%	0	0
Endcaps	1%	2%	0	0
En > 60 GeV	1%	2%	0	0

Reco-Gen

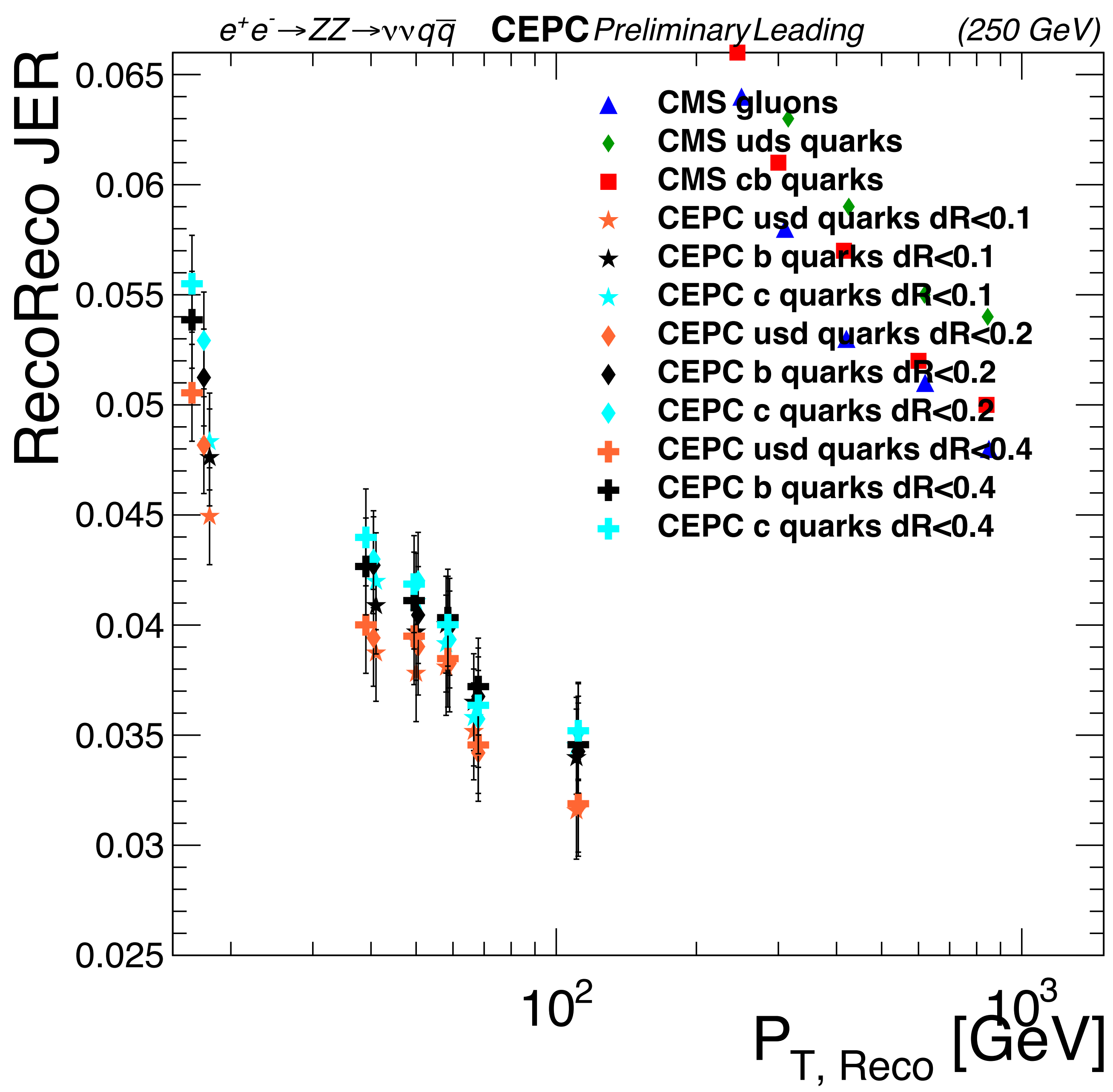
	JER		JES	
Type	Lead	Sub-Lead	Lead	Sub-Lead
Barrel	3.5%	4.5%	1%	0
Endcaps	4%	5%	1.5%	0.5%
En > 60 GeV	4%	4.5%	1%	1.5%

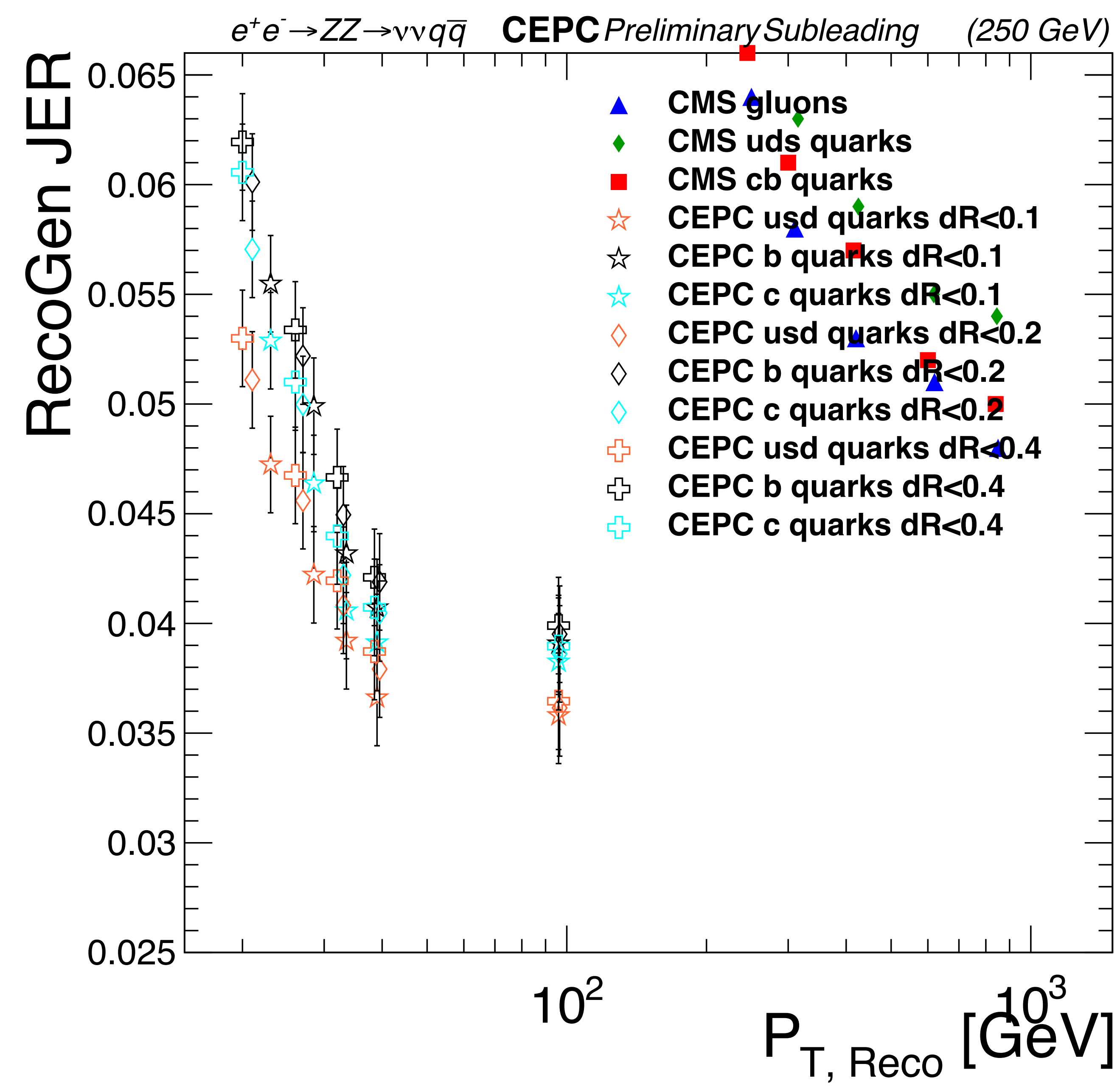
Reco-MCP

	JER		JES	
Type	Lead	Sub-Lead	Lead	Sub-Lead
Barrel	4.5%	6%	1%	0
Endcaps	5%	6.5%	1.5%	0.5%
En > 60 GeV	5%	6%	0.5%	1.5%



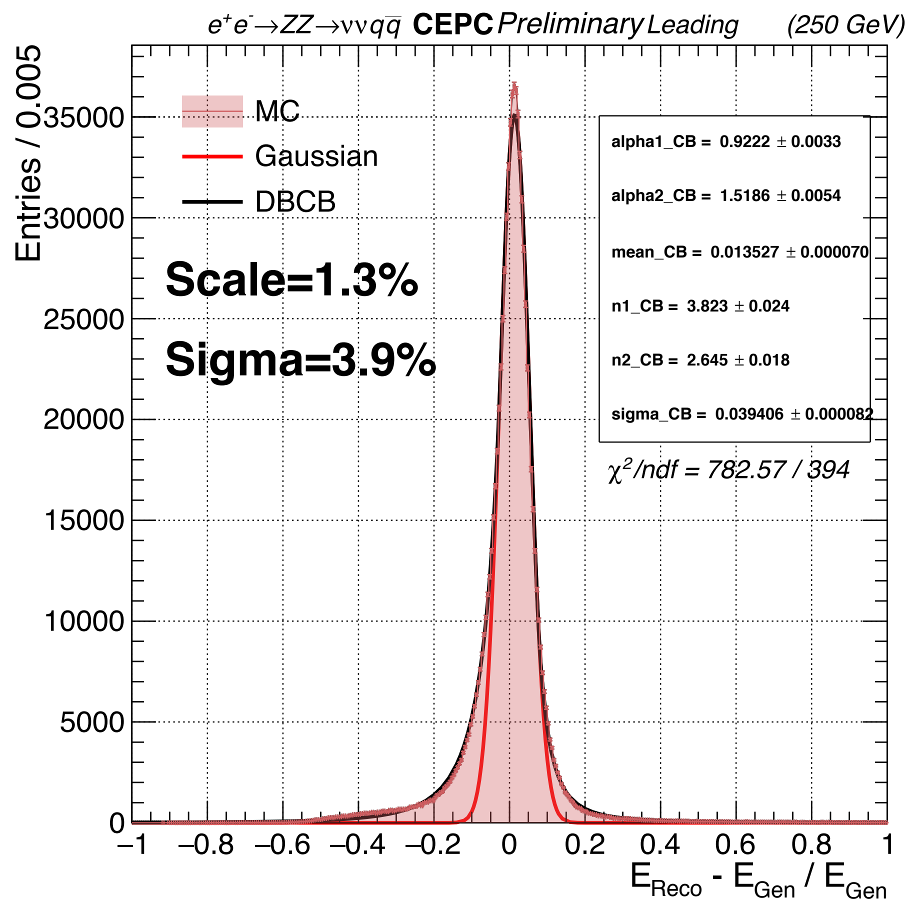
JER with Different dR

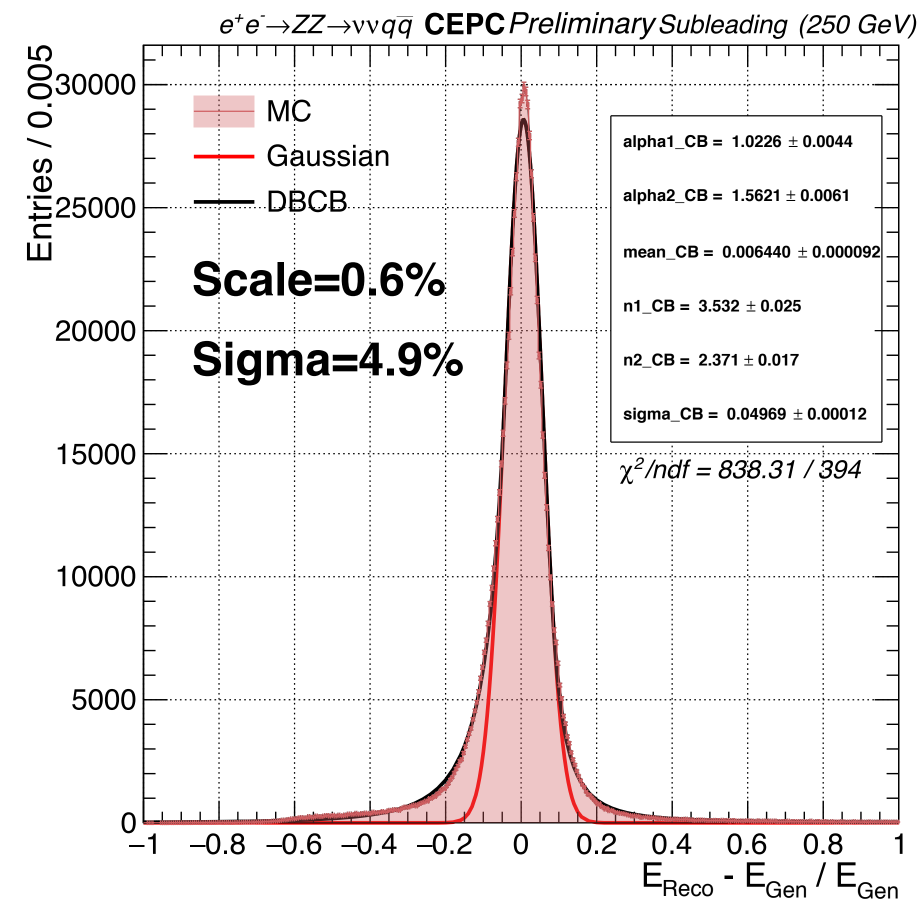


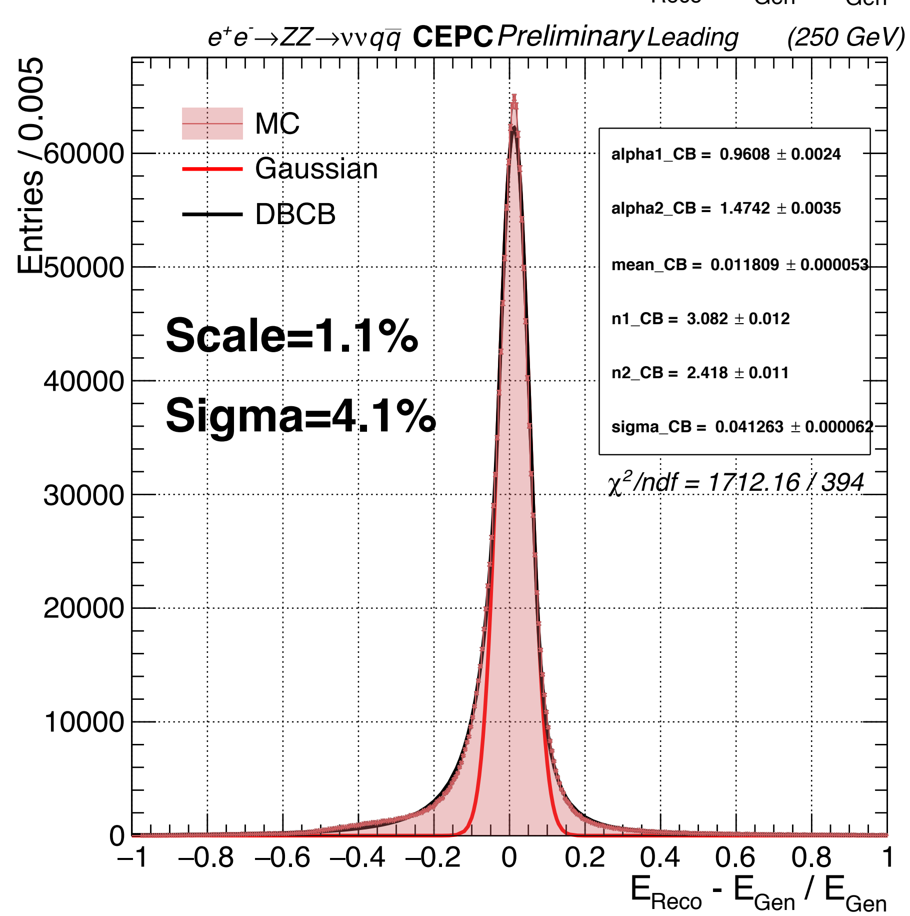


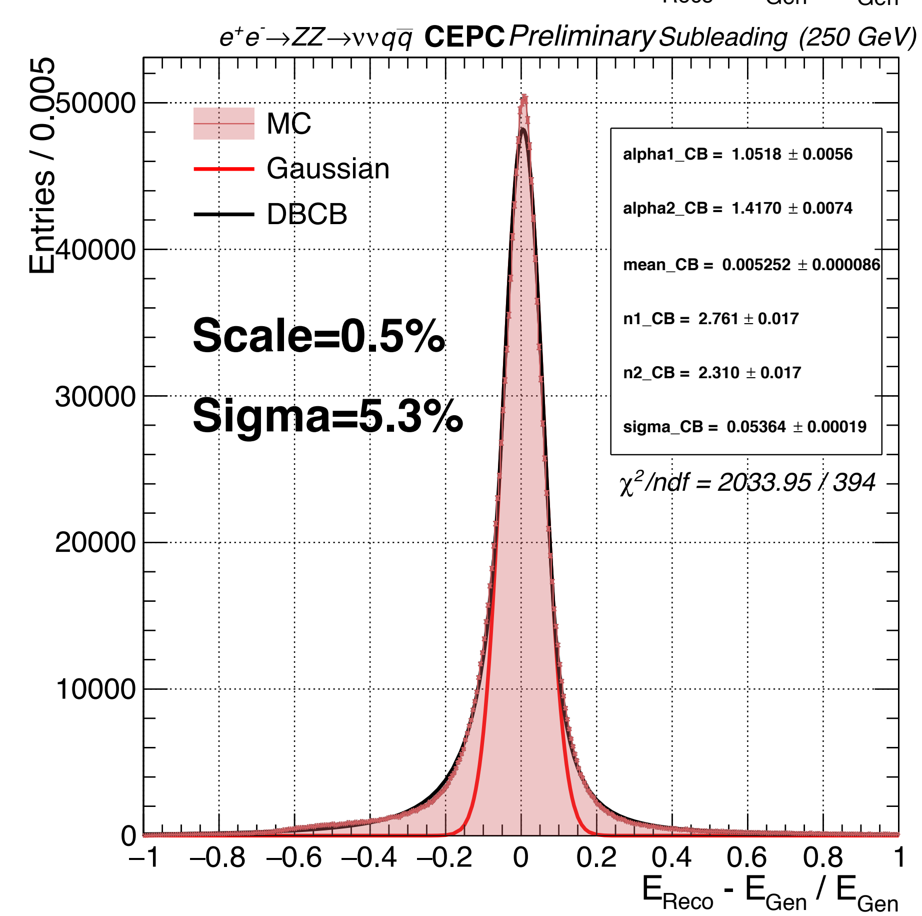
Compare the Results Whether with dR Cut (Reco-Gen)

dR < 0.1



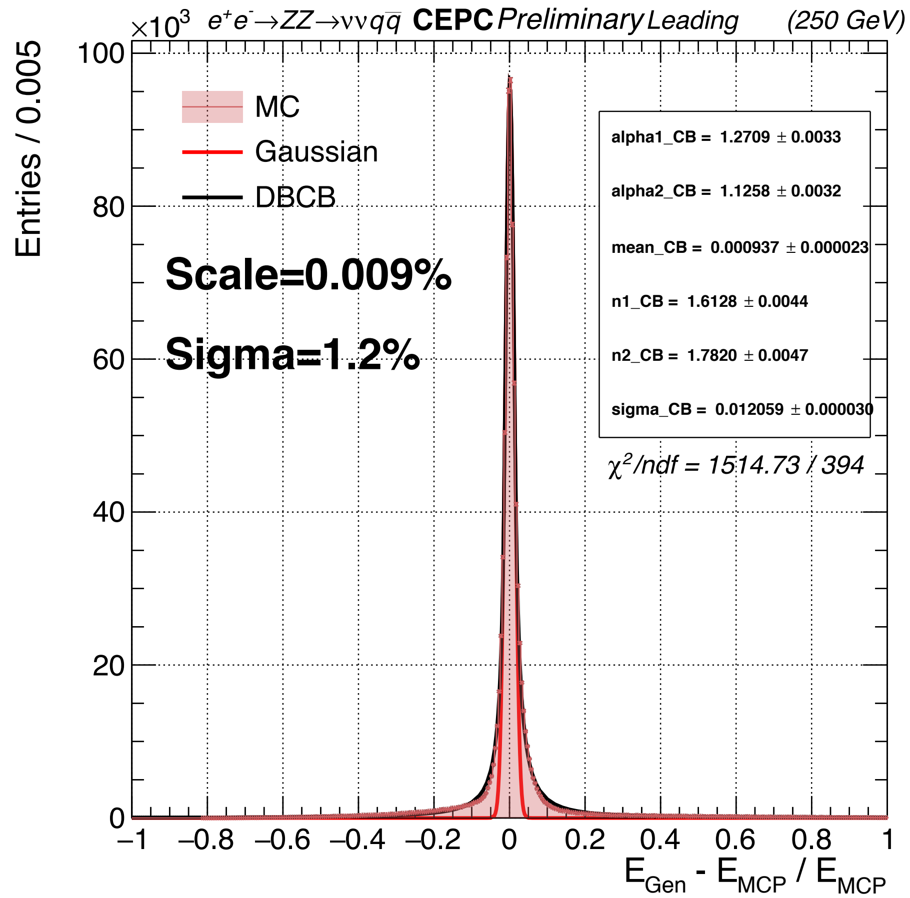


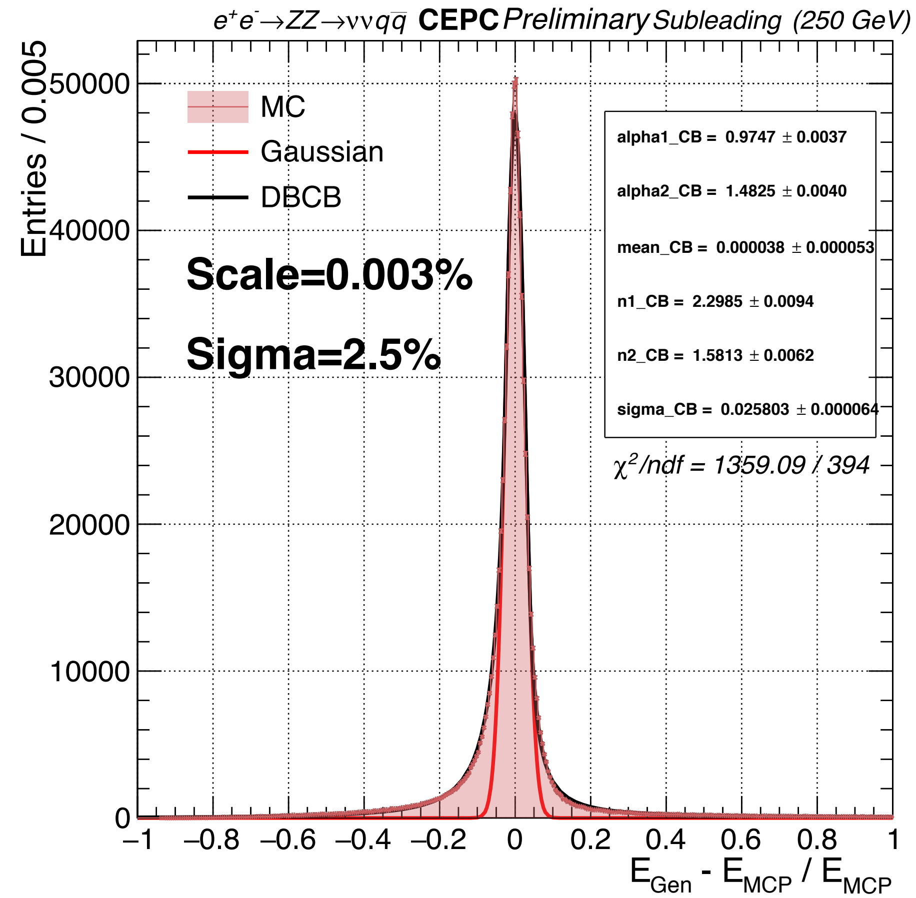


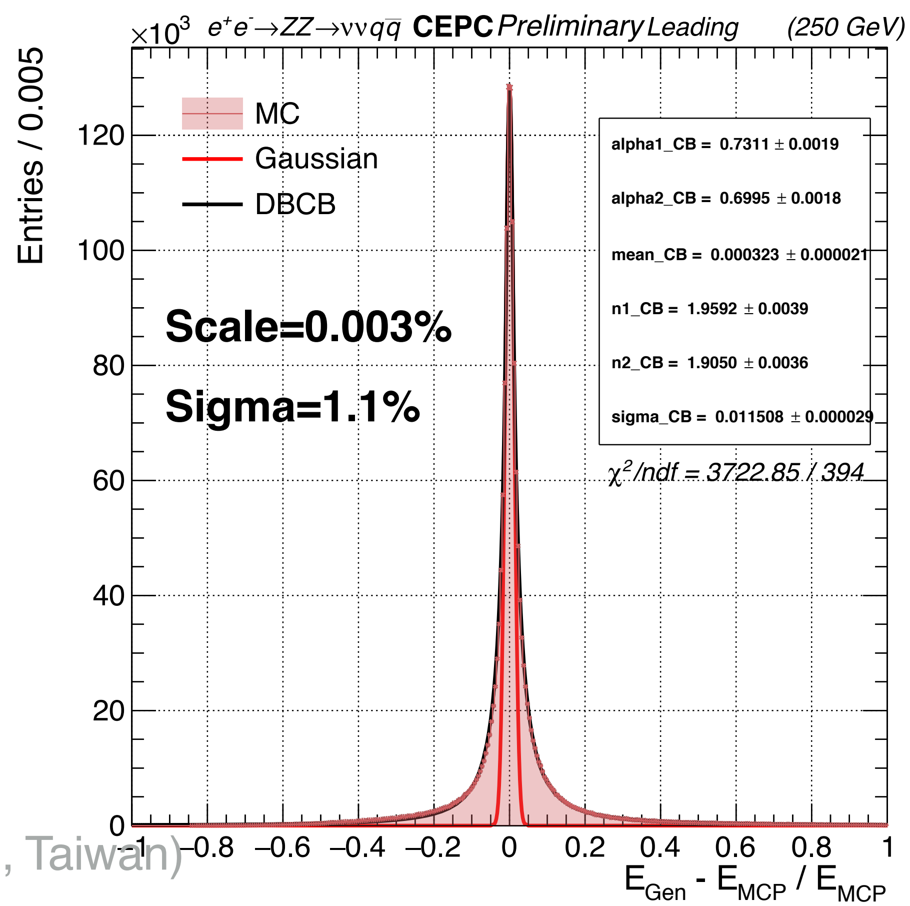


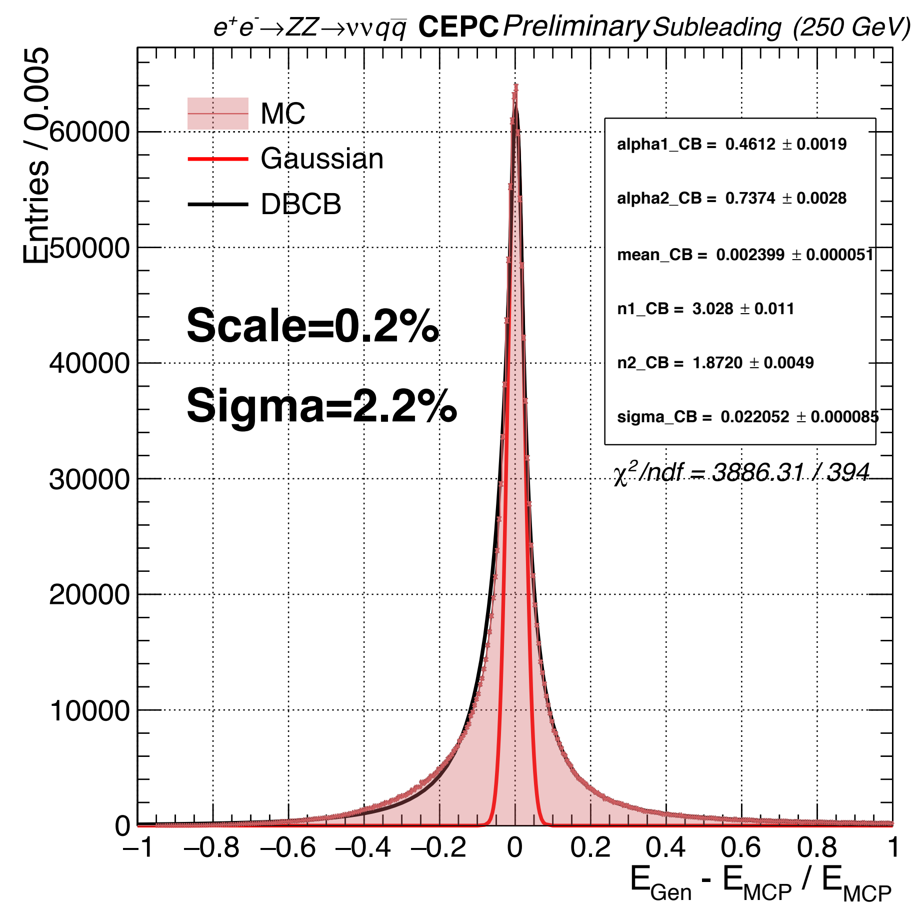
Compare the Results Whether with dR Cut (Gen-MCP)

dR < 0.1



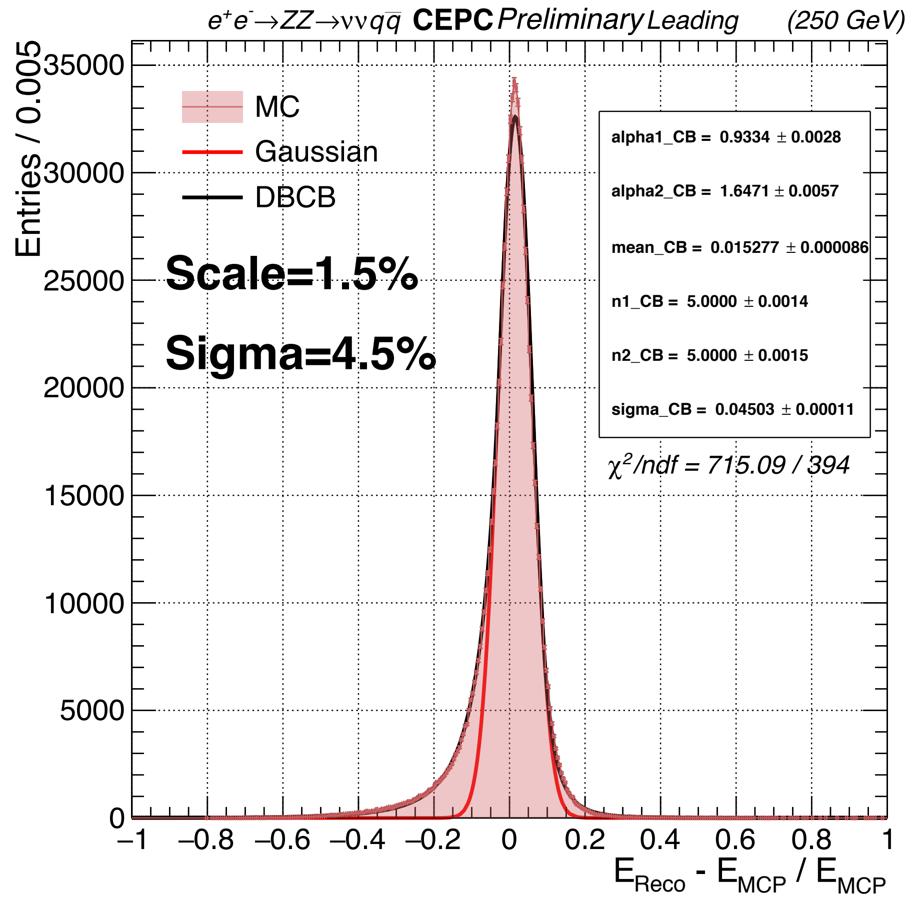


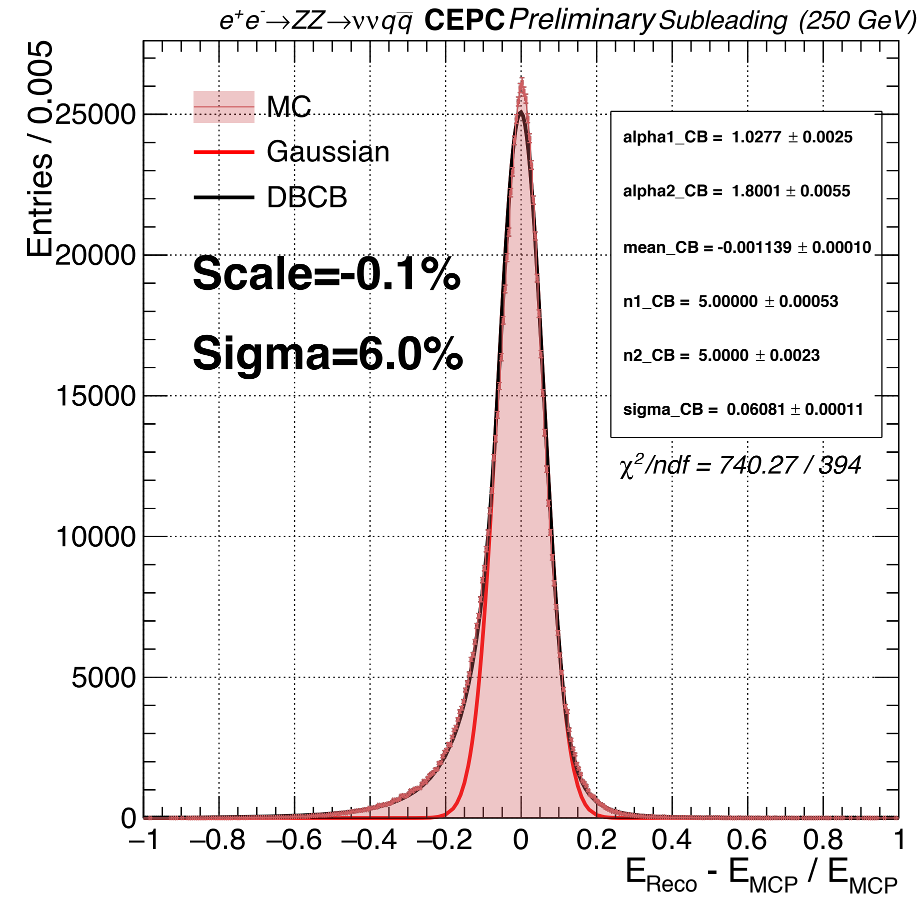


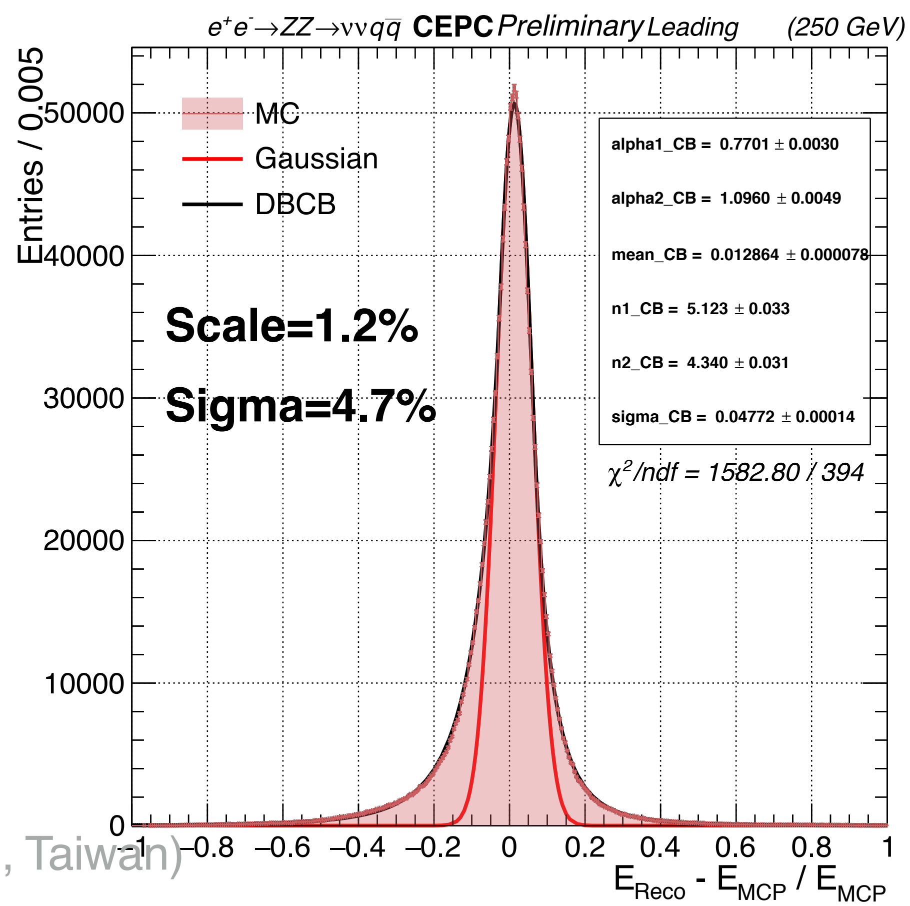


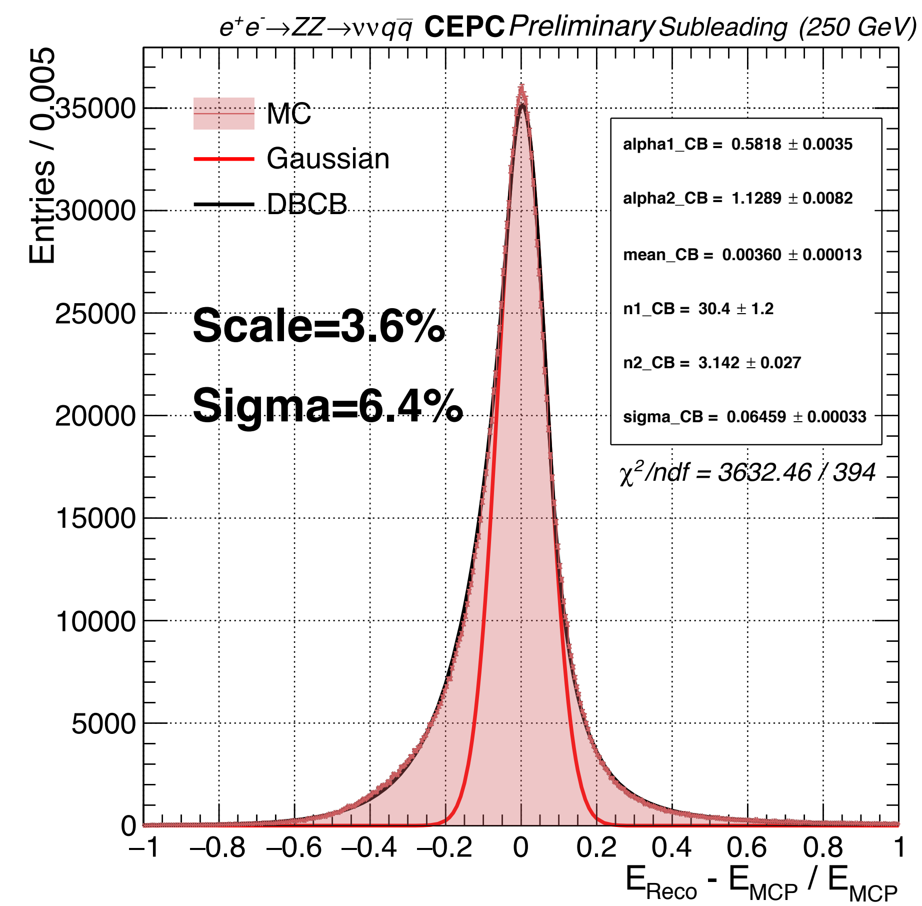
Compare the Results Whether with dR Cut (Reco-MCP)

dR < 0.1

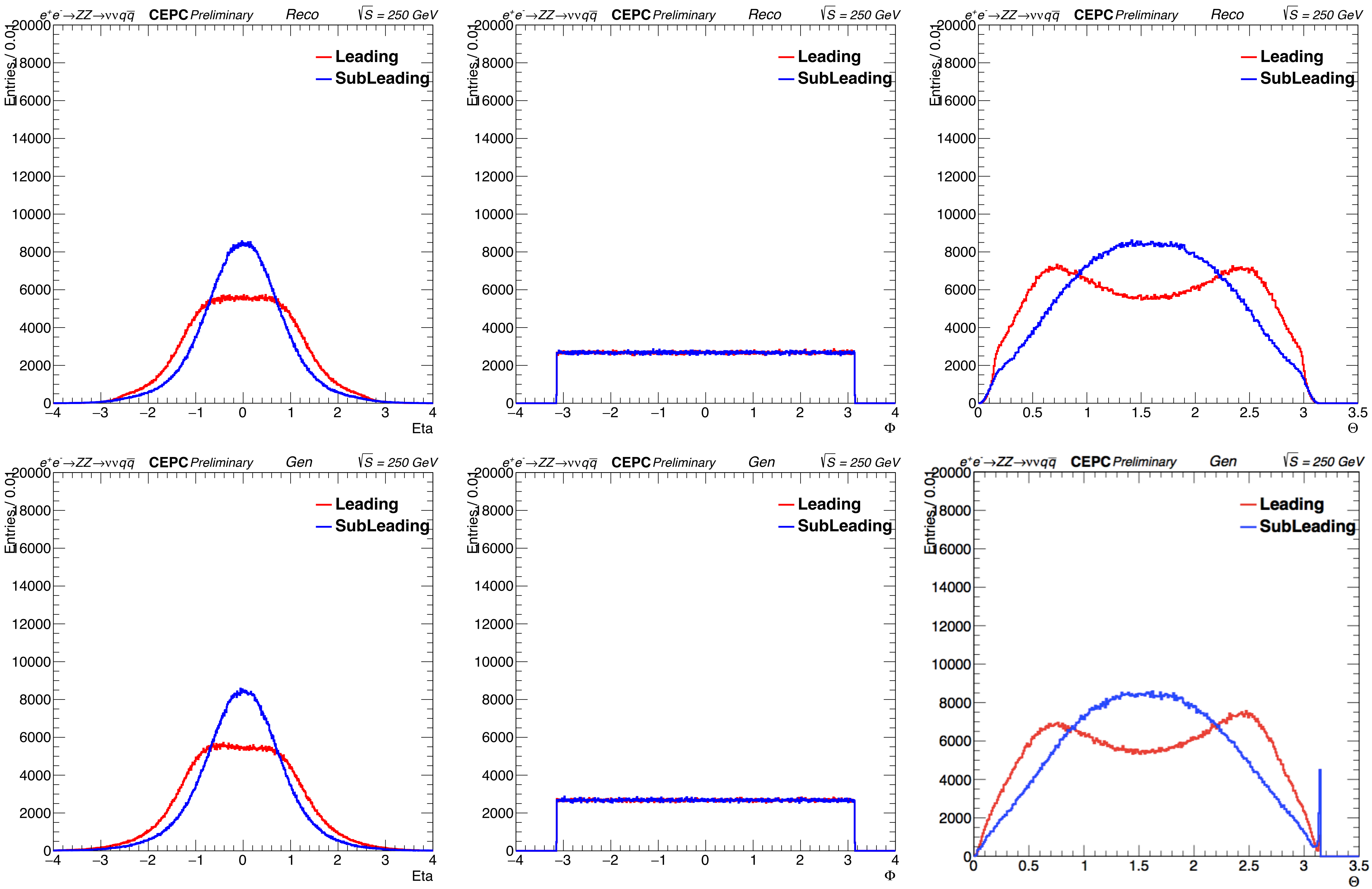




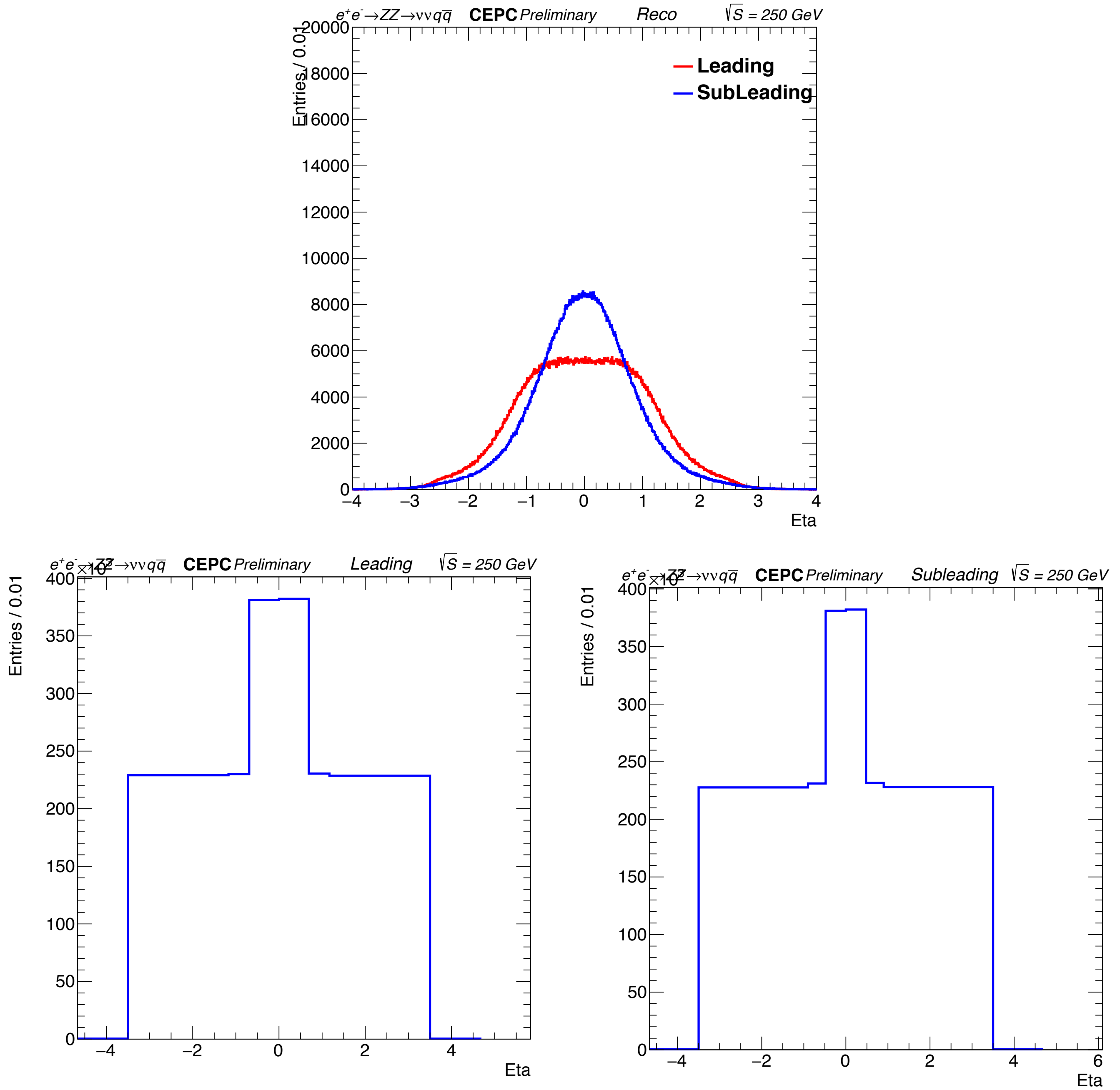




Angular Distribution of Gen and Reco

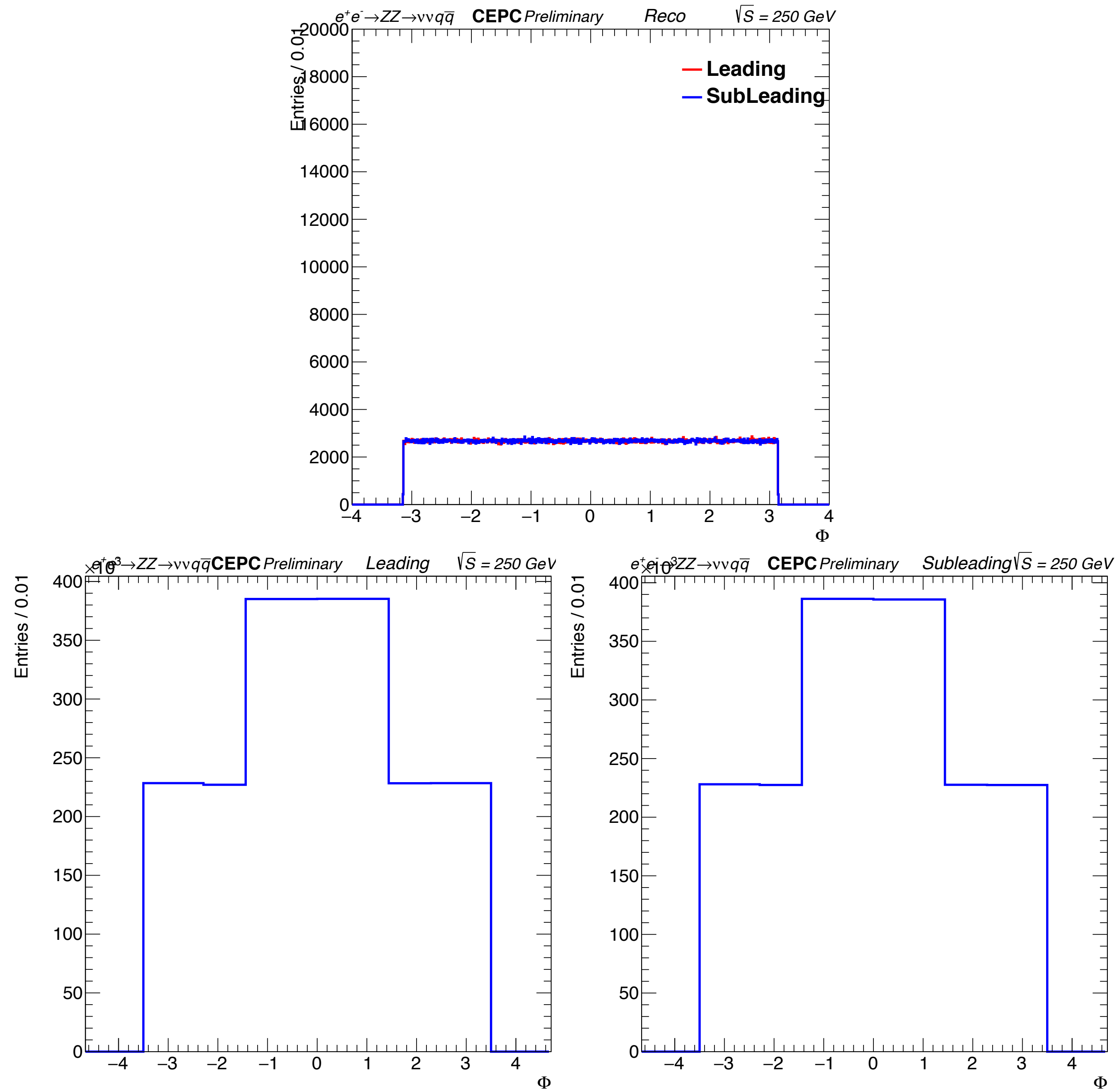


The Distribution of Unequal Eta Bin



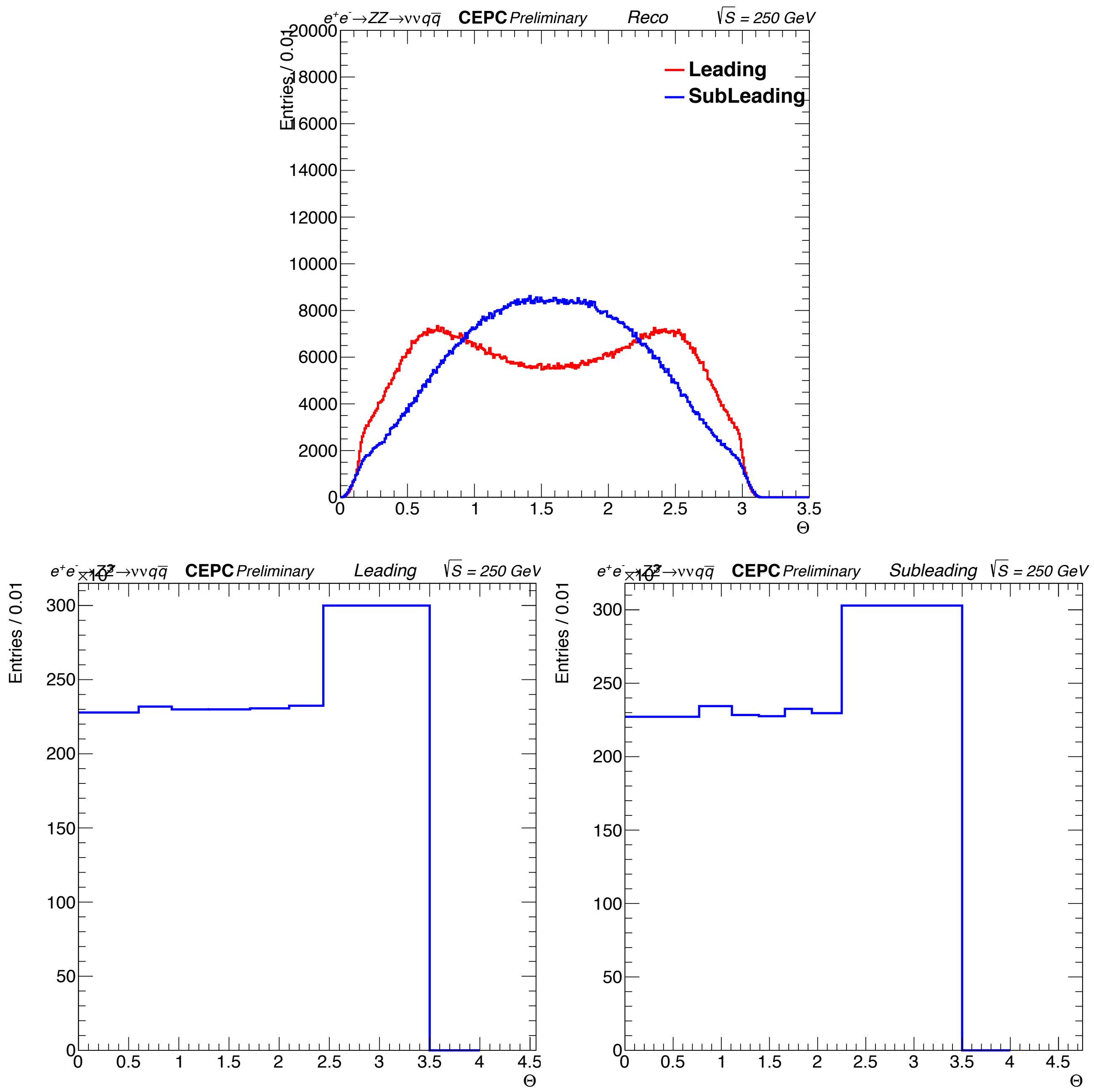
- **When divided the angular bin, I have required the statistical uncertainty should less than 0.21% for each angular bin I also sorted the jet by energy. I want the unequal angular symmetry on zero. Therefore, the bin around zero with more the number of events.**

The Distribution of Unequal Phi Bin

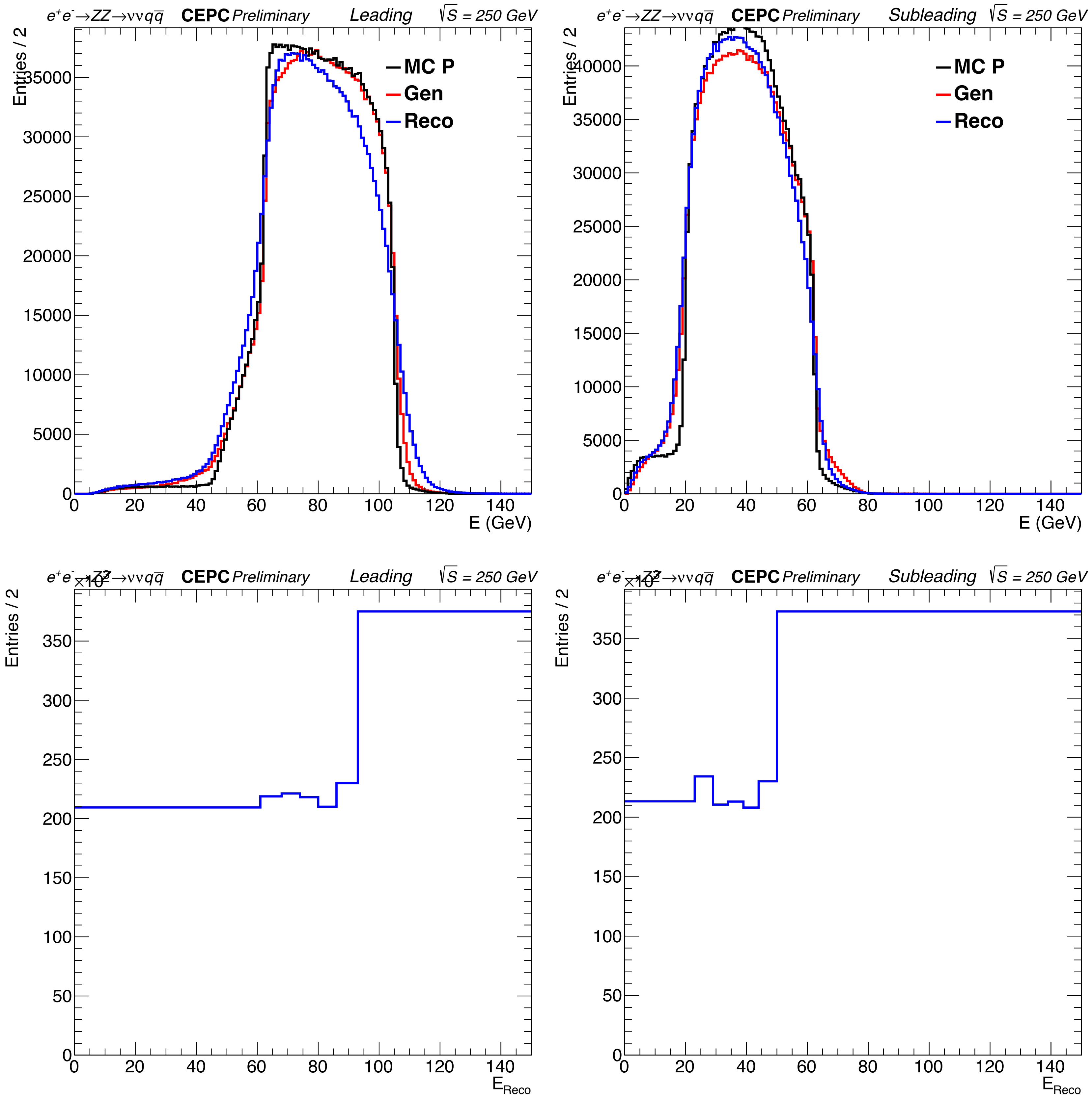


- **When divided the angular bin, I have required the statistical uncertainty should less than 0.21% for each angular bin I also sorted the jet by energy. I want the unequal angular symmetry on zero. Therefore, the bin around zero with more the number of events.**

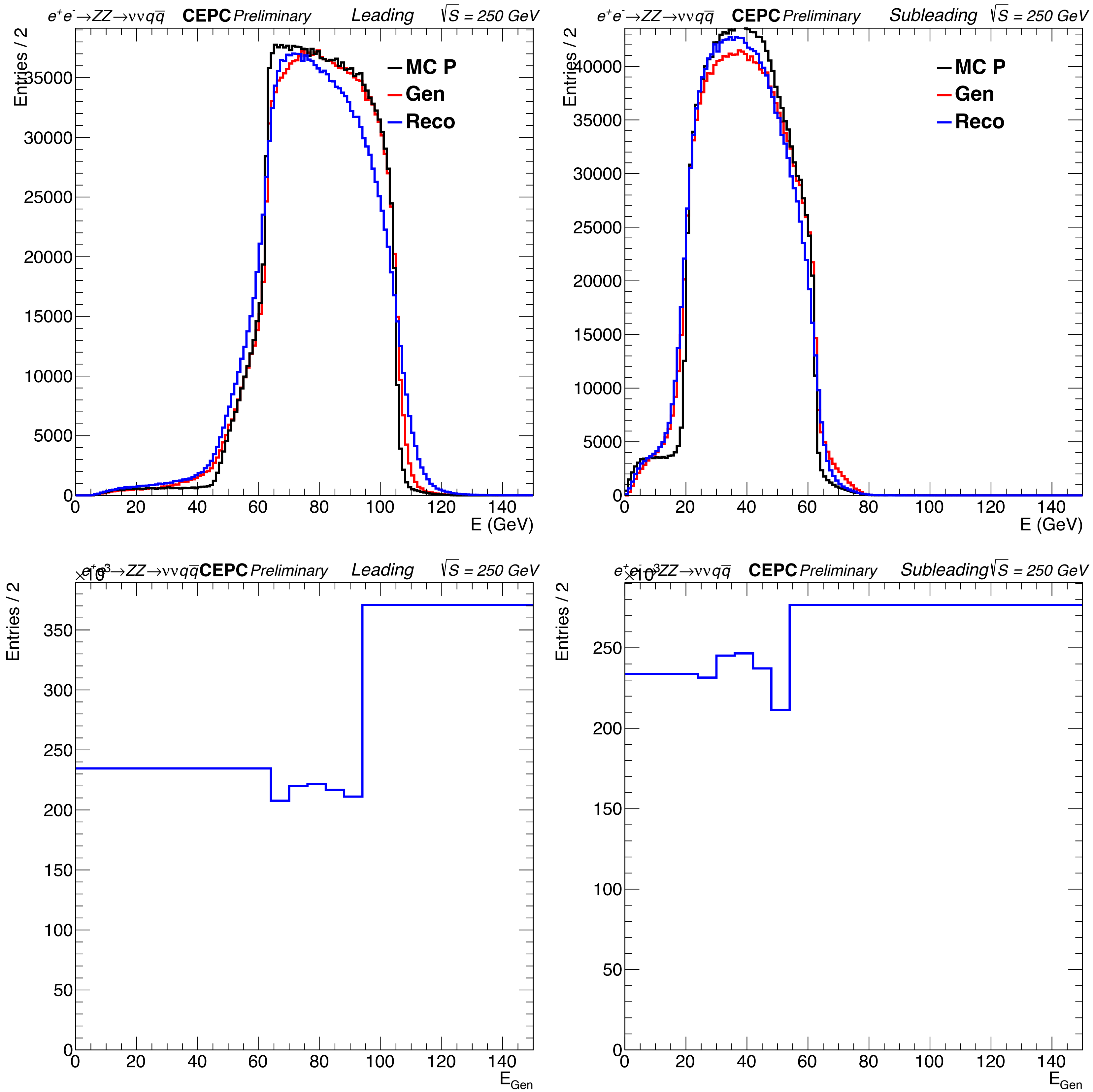
The Distribution of Unequal Theta Bin



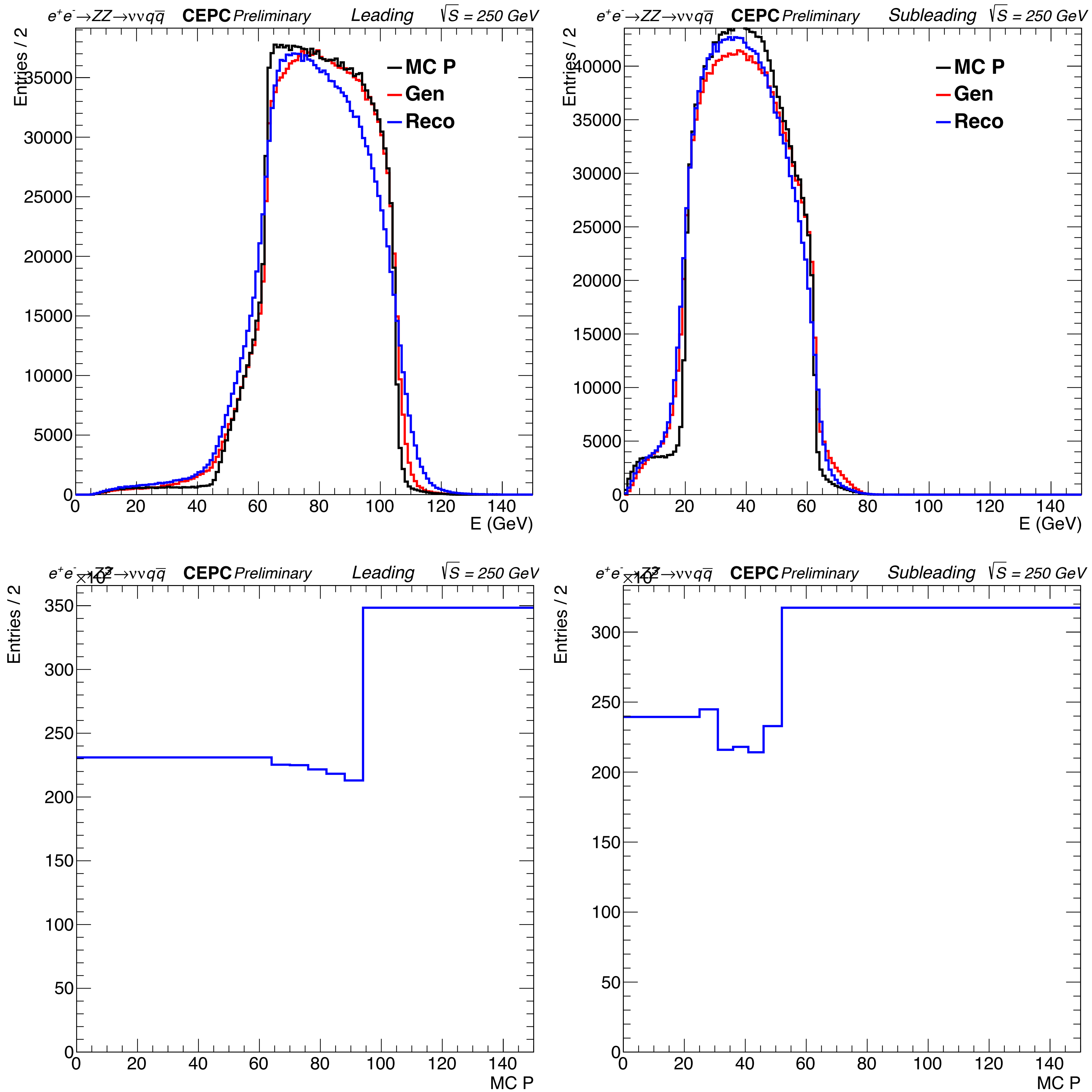
The Distribution of Unequal Reco Energy Bin



The Distribution of Unequal Gen Energy Bin



The Distribution of Unequal MCP Energy Bin



Summary

Gen-MCP

	JER		JES	
Type	Lead	Sub-Lead	Lead	Sub-Lead
Eta	1% Stable	2% Stable	0 Stable	0 Stable
Phi	1% Stable	2% Stable	0 Stable	0 Stable
Theta	1% Stable	2% Stable	0 Stable	0 Stable
Reco	1.5-0.5% ↘	4.5-2% ↘	0 Stable	0 Stable
Gen	2-1% ↘	5-2.5% ↘	0 Stable	0 Stable
MCP	1.5-1% ↘	4-2% ↘	0 Stable	0 Stable

Reco-Gen

	JER		JES	
Type	Lead	Sub-Lead	Lead	Sub-Lead
Eta	4.5-3.5-4.5	5.5-4.5-5.5	1.5-1-1.5	1-0-1
Phi	4% Stable	5% Stable	1.5 Stable	0.5 Stable
Theta	4.5-3.5-4.5	5.5-4.5-5.5	1.5-1-1.5	1.5-1-1.5
Reco	4-4.5%	6.5-4.5% ↘	0.5-2% ↗	-1.5-1.5% ↗
Gen	4-3.5%	6.5-4% ↘	1.5% Stable	0-0.5% ↗
MCP	4-4.3%	6.5-4.5% ↘	1.5% Stable	0-0.5% ↗

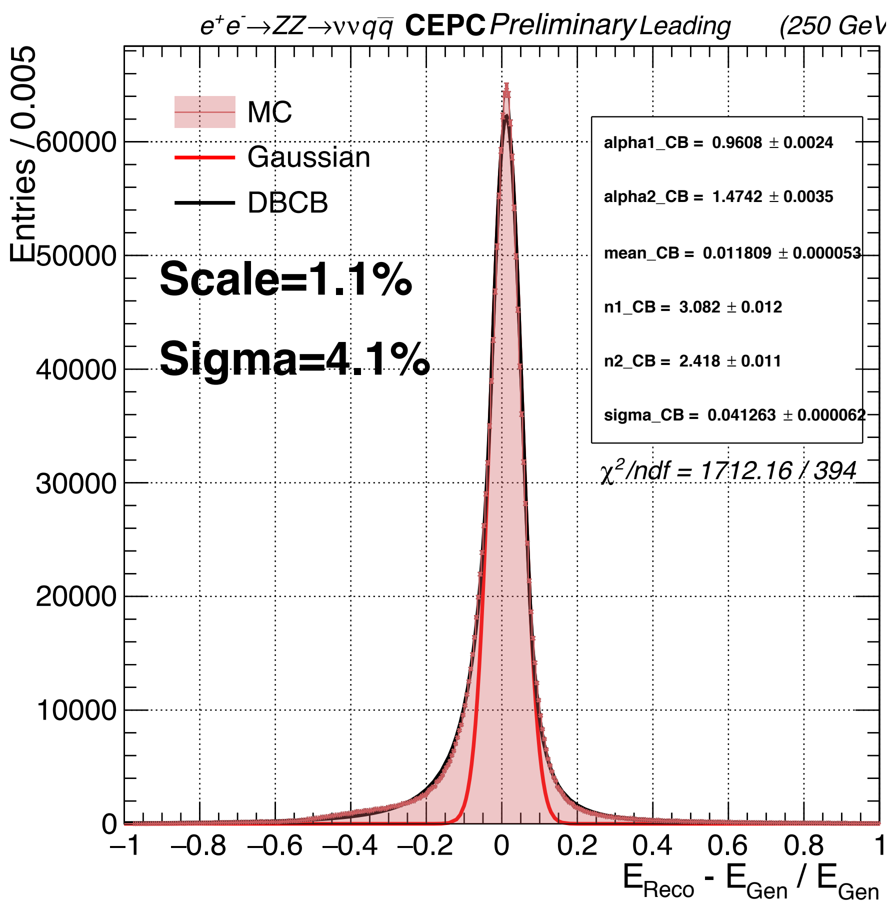
Reco-MCP

	JER		JES	
Type	Lead	Sub-Lead	Lead	Sub-Lead
Eta	5.5-4.5-5.5	7.5-6-7.5	1.5-1-1.5	0.5-0-0.5
Phi	5% Stable	6.5% Stable	1.5 Stable	0.5 Stable
Theta	5.5-4.5-5.5	7.5-6-7.5	1.5-1-1.5	0.5-0-0.5
Reco	6-5% ↘	10-6% ↘	-1.5-2.5% ↗	-7-1.5% ↗
Gen	6-5%	13-6.5% ↘	1.5% Stable	-6.5-0.5% ↗
MCP	5-5.3%	10-6% ↘	1.5% Stable	-1.5-0.5% ↗

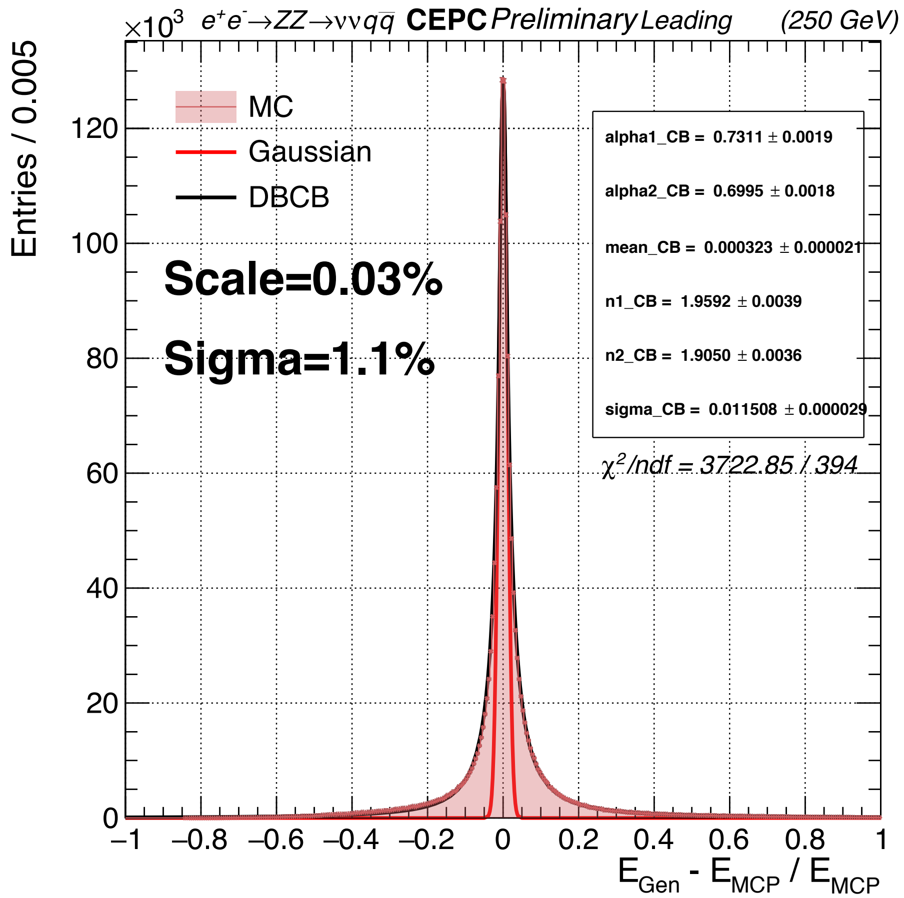
Summary

- **Gen-MCP**
  - **JES is about "Zero" and stable in both angular and energy bin.**
  - **JER is stable as the function of the angular. Leading is 1% and Sub-leading is 2%.**
  - **For leading JER is 1.5-0.5% as the function of the energy of reco jet and for sub-leading JER is 4.5-2%.**
- **Reco-Gen**
  - **Both JER/JES are independent of the Phi.**
  - **In the barrel region, leading JER is 3.5% and sub-leading JER is 4.5%. Leading JES is about 1%. Sub-leading JES is about zero.**
  - **In the 60-100 GeV region, leading and sub-leading JER is 4%, JES is 1.5%.**
- **Reco-MCP**
  - **Both JER/JES are stable as the function of the Phi.**
  - **In the barrel region, leading JER is 4.5%, JES is 1%; sub-leading JER is 6%, JES is zero.**
  - **In the 60-100 GeV region, leading and sub-leading JER is 5%, JES is 1%.**

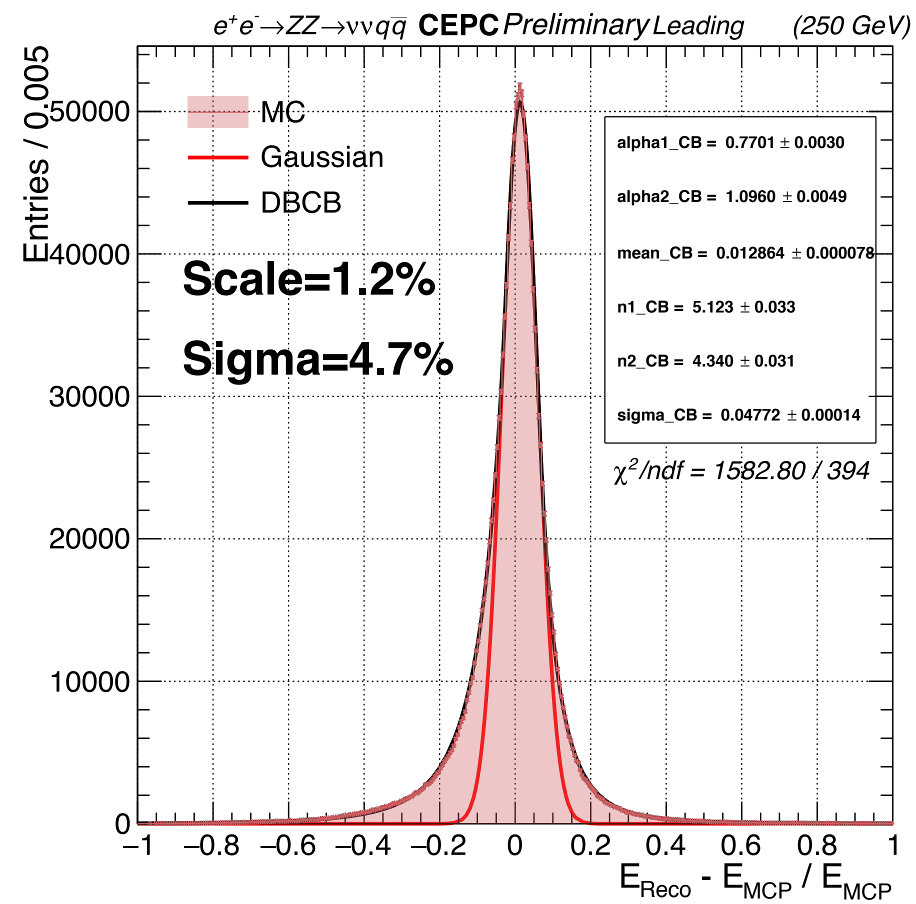
JER & JES



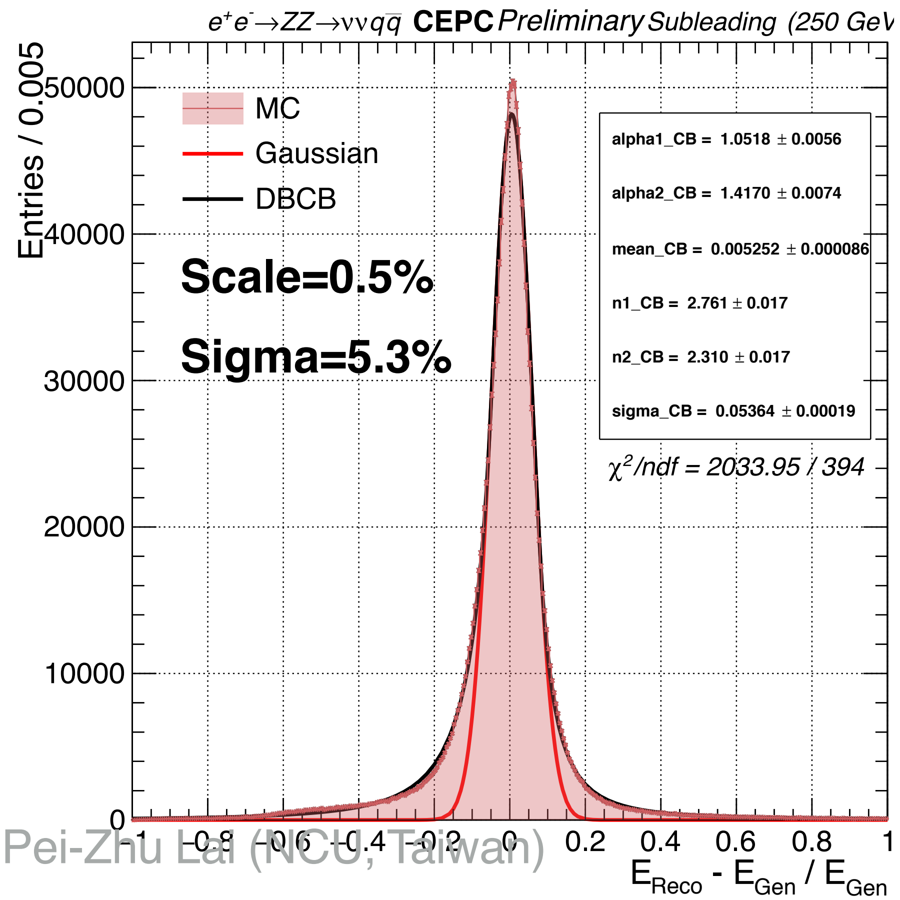
e+e-→ZZ→ννqq̄ CEPC Preliminary Leading (250 GeV
Entries / 0.005
MC
Gaussian
DBCB
Scale=1.1%
Sigma=4.1%
alpha1_CB = 0.9608 ± 0.0024
alpha2_CB = 1.4742 ± 0.0035
mean_CB = 0.011809 ± 0.000053
n1_CB = 3.082 ± 0.012
n2_CB = 2.418 ± 0.011
sigma_CB = 0.041263 ± 0.000062
χ2/ndf = 1712.16 / 394
E_Reco - E_Gen / E_Gen



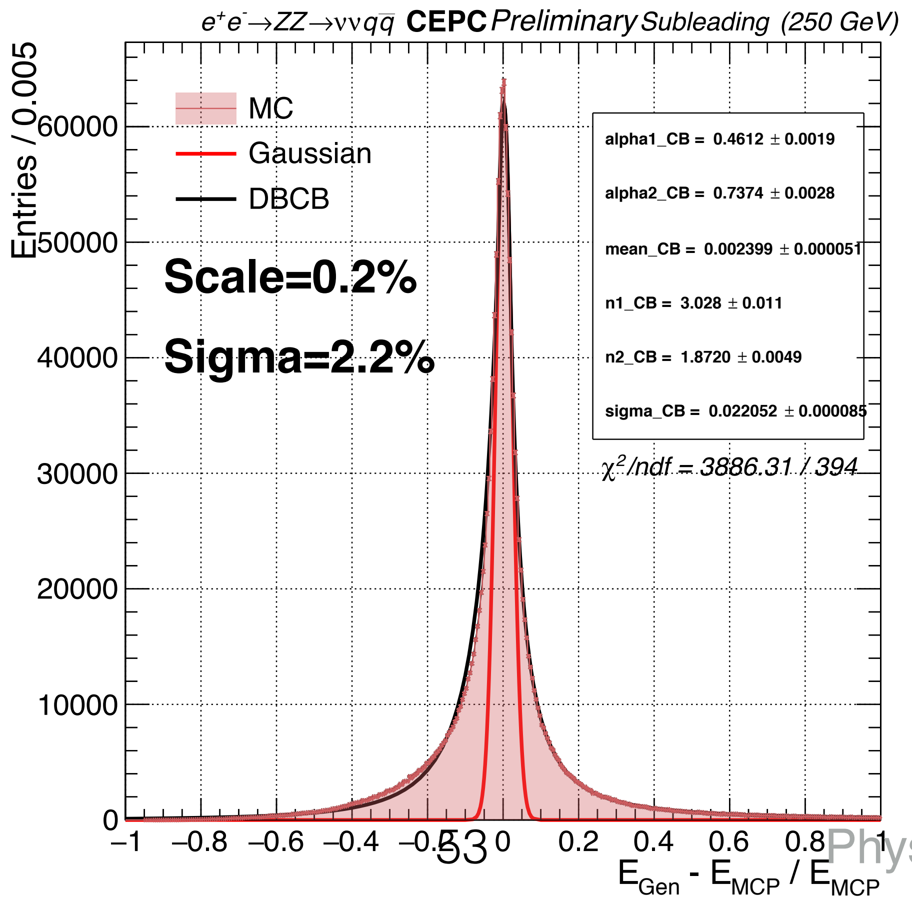
×10^3 e+e-→ZZ→ννqq̄ CEPC Preliminary Leading (250 GeV)
Entries / 0.005
MC
Gaussian
DBCB
Scale=0.03%
Sigma=1.1%
alpha1_CB = 0.7311 ± 0.0019
alpha2_CB = 0.6995 ± 0.0018
mean_CB = 0.000323 ± 0.000021
n1_CB = 1.9592 ± 0.0039
n2_CB = 1.9050 ± 0.0036
sigma_CB = 0.011508 ± 0.000029
χ2/ndf = 3722.85 / 394
E_Gen - E_MCP / E_MCP



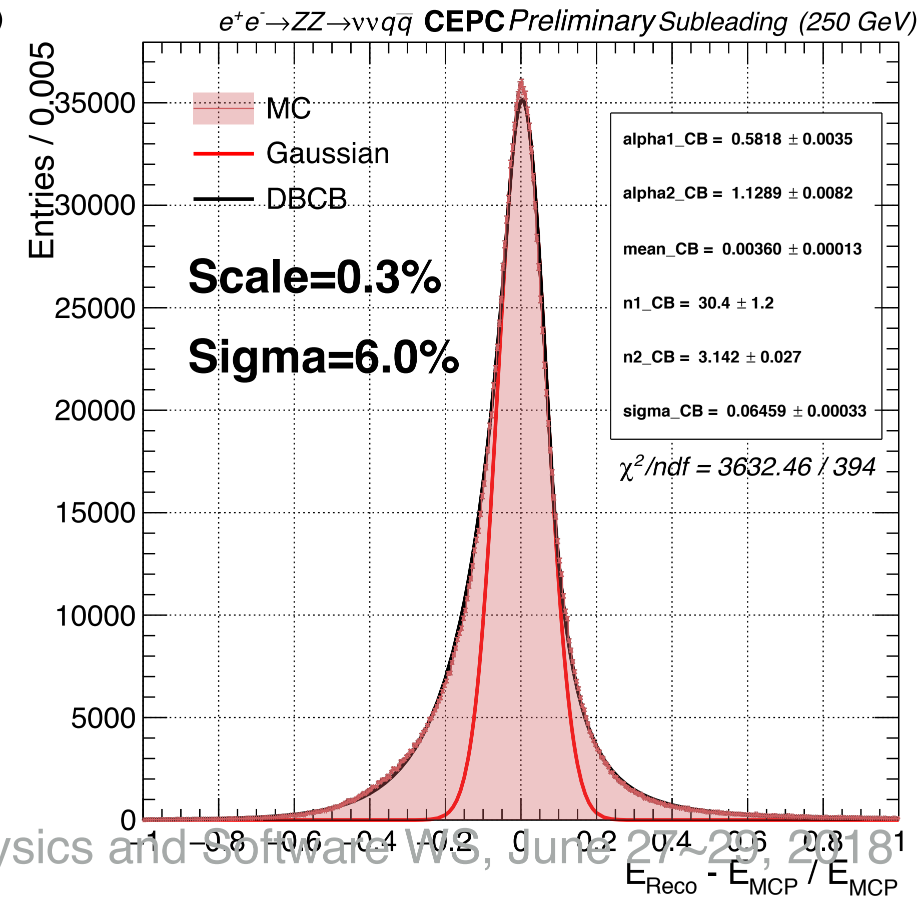
e+e-→ZZ→ννqq̄ CEPC Preliminary Leading (250 GeV)
Entries / 0.005
MC
Gaussian
DBCB
Scale=1.2%
Sigma=4.7%
alpha1_CB = 0.7701 ± 0.0030
alpha2_CB = 1.0960 ± 0.0049
mean_CB = 0.012864 ± 0.000078
n1_CB = 5.123 ± 0.033
n2_CB = 4.340 ± 0.031
sigma_CB = 0.04772 ± 0.00014
χ2/ndf = 1582.80 / 394
E_Reco - E_MCP / E_MCP



e+e-→ZZ→ννqq̄ CEPC Preliminary Subleading (250 GeV
Entries / 0.005
MC
Gaussian
DBCB
Scale=0.5%
Sigma=5.3%
alpha1_CB = 1.0518 ± 0.0056
alpha2_CB = 1.4170 ± 0.0074
mean_CB = 0.005252 ± 0.000086
n1_CB = 2.761 ± 0.017
n2_CB = 2.310 ± 0.017
sigma_CB = 0.05364 ± 0.00019
χ2/ndf = 2033.95 / 394
E_Reco - E_Gen / E_Gen

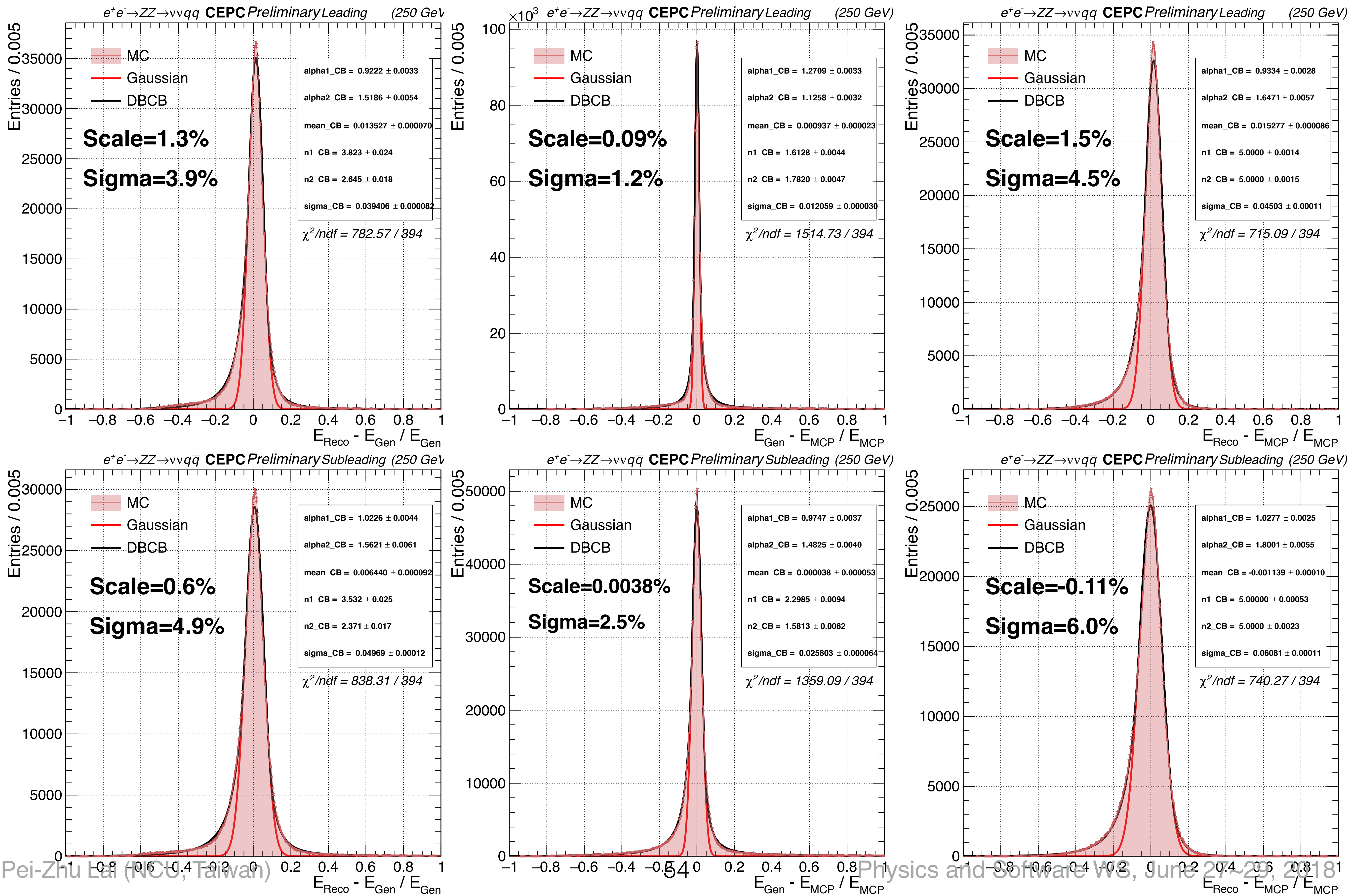


e+e-→ZZ→ννqq̄ CEPC Preliminary Subleading (250 GeV)
Entries / 0.005
MC
Gaussian
DBCB
Scale=0.2%
Sigma=2.2%
alpha1_CB = 0.4612 ± 0.0019
alpha2_CB = 0.7374 ± 0.0028
mean_CB = 0.002399 ± 0.000051
n1_CB = 3.028 ± 0.011
n2_CB = 1.8720 ± 0.0049
sigma_CB = 0.022052 ± 0.000085
χ2/ndf = 3886.31 / 394
E_Gen - E_MCP / E_MCP



e+e-→ZZ→ννqq̄ CEPC Preliminary Subleading (250 GeV)
Entries / 0.005
MC
Gaussian
DBCB
Scale=0.3%
Sigma=6.0%
alpha1_CB = 0.5818 ± 0.0035
alpha2_CB = 1.1289 ± 0.0082
mean_CB = 0.00360 ± 0.00013
n1_CB = 30.4 ± 1.2
n2_CB = 3.142 ± 0.027
sigma_CB = 0.06459 ± 0.00033
χ2/ndf = 3632.46 / 394
E_Reco - E_MCP / E_MCP

JER & JES($\Delta R<0.1$)



Motivation