

W Mass Direct Measurement at CEPC

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4th CEPC Physics and Software Workshop, China

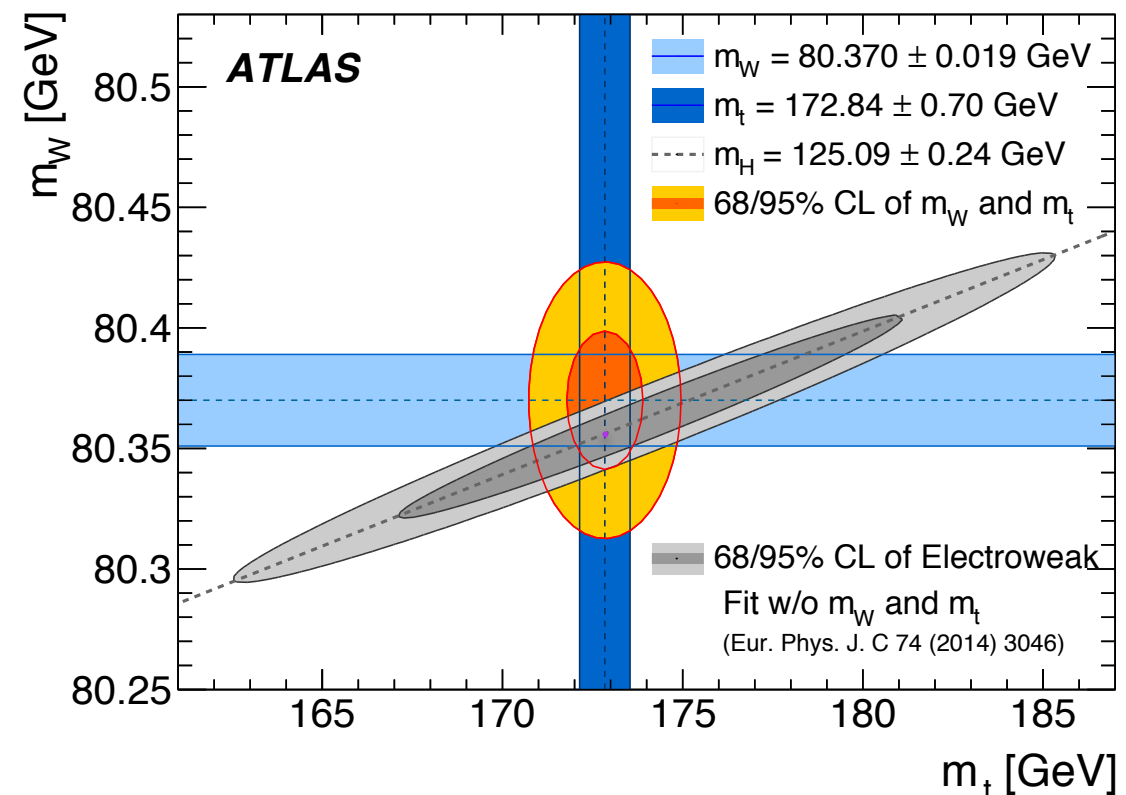
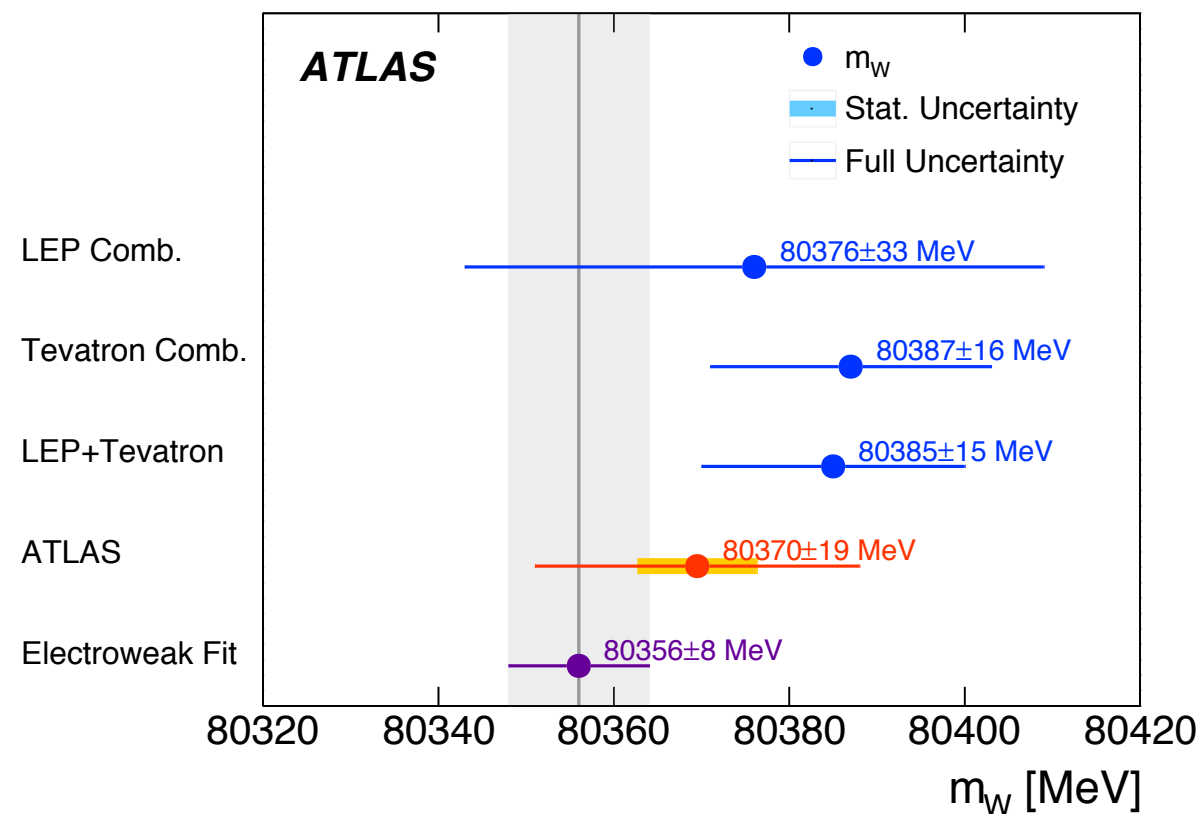
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- Motive of W mass direct measurements and current results
- Benefit of direct measurement
- The jet energy resolution and jet energy scale at CEPC
 - Leading and sub-leading jet performances
 - Compare the results with CMS and ALEPH
 - Boson mass 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]

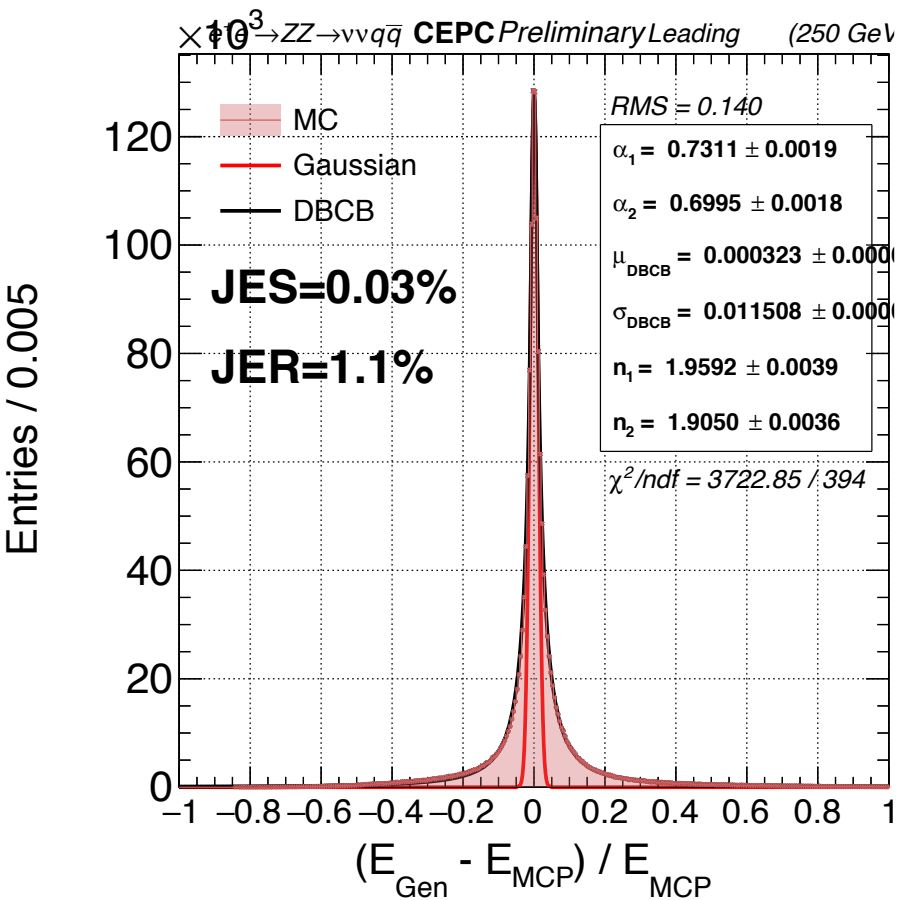
Benefit of direct measurement

- Use the LO $WW \rightarrow \mu\nu qq$ MC sample to directly measure the W boson mass.

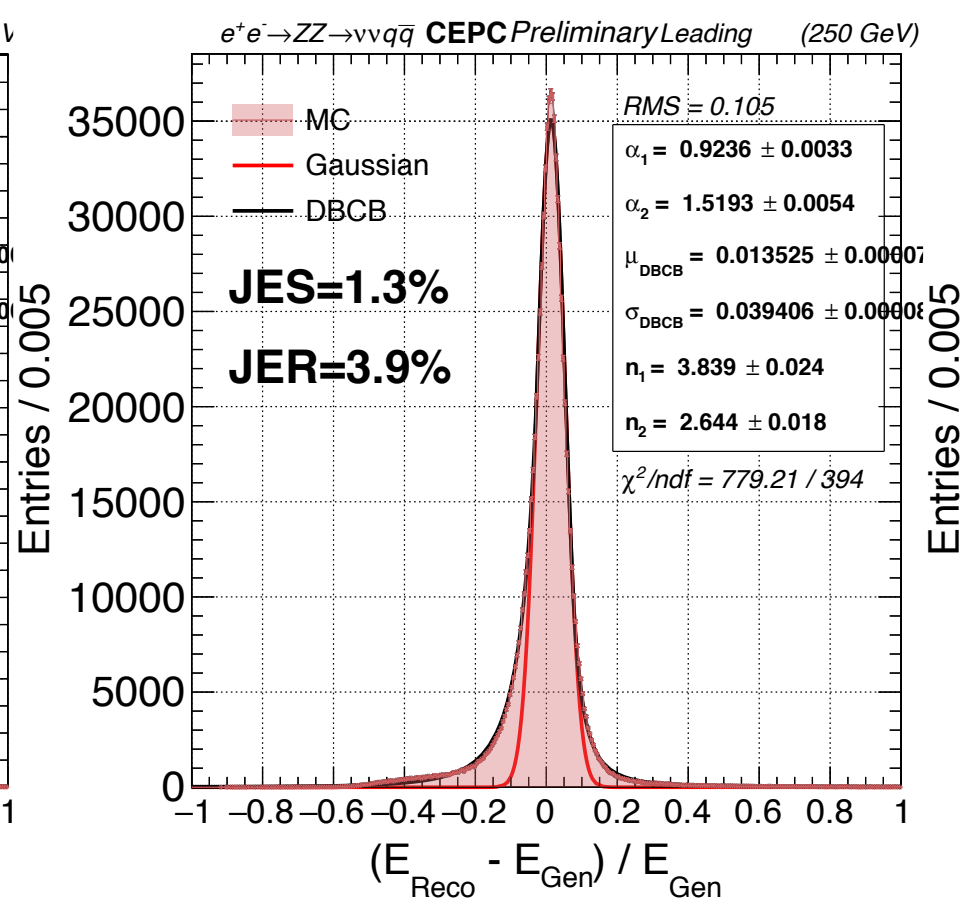
The effective luminosity is 10 ab^{-1} .

1. No dedicated run is needed: all the measurements can be done in ZH runs with $\sqrt{s} = 240 \text{ GeV}$. 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.

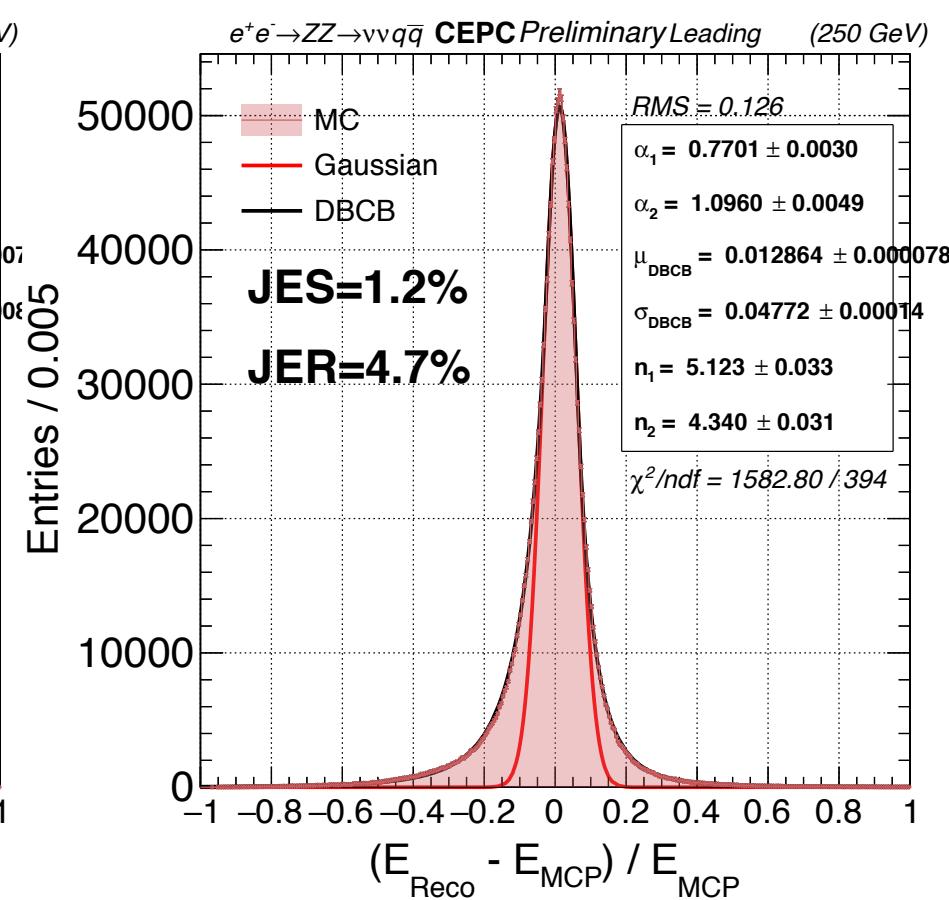
Gen-MCP



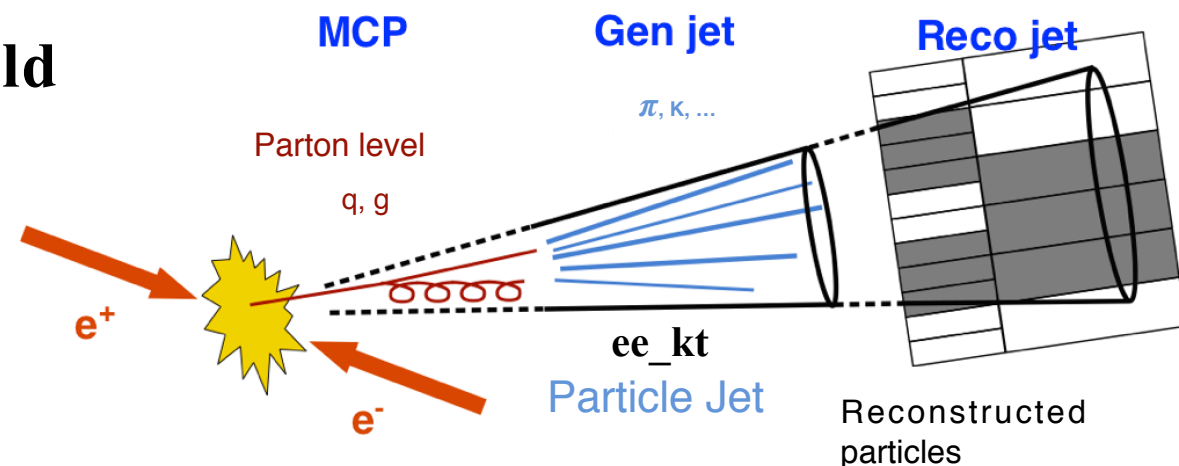
Reco-Gen



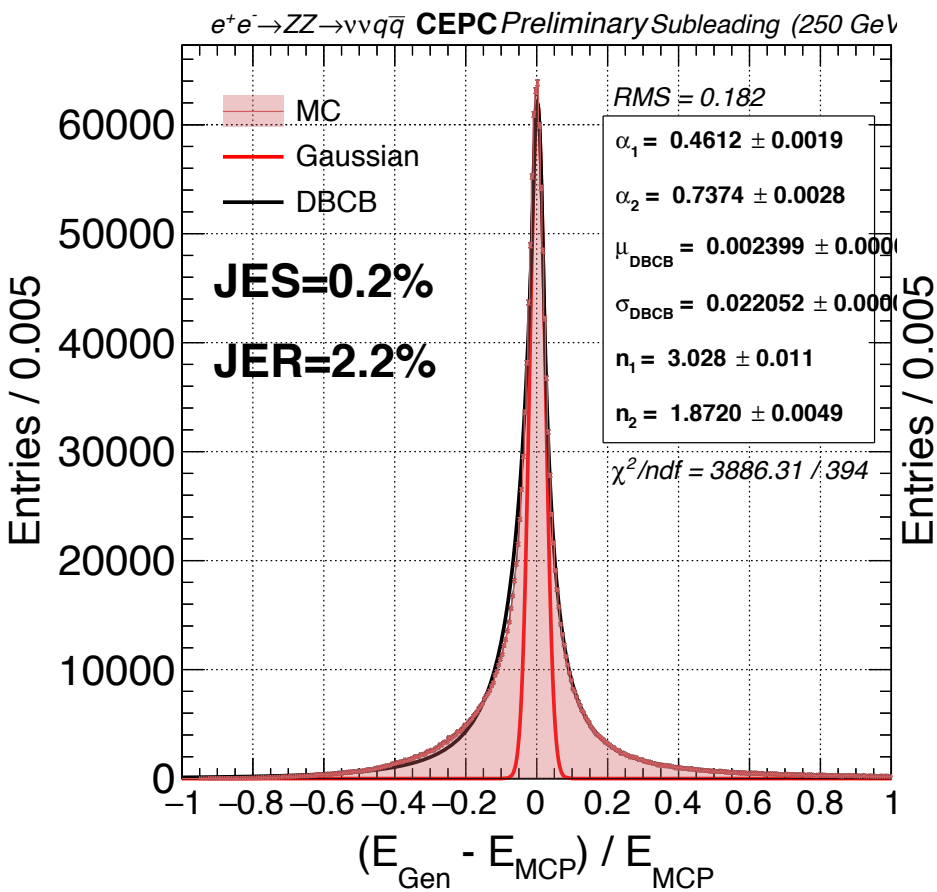
Reco-MCP



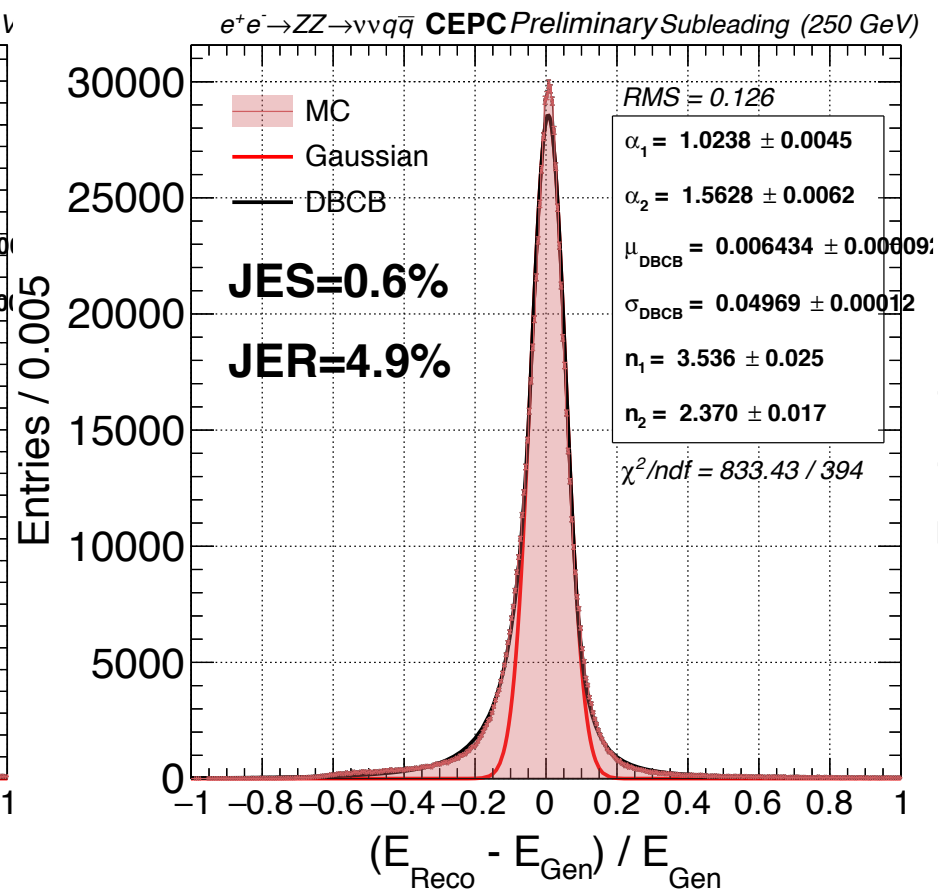
- JER/JES between reco jet and MCP would combine the effects of two previous stages.



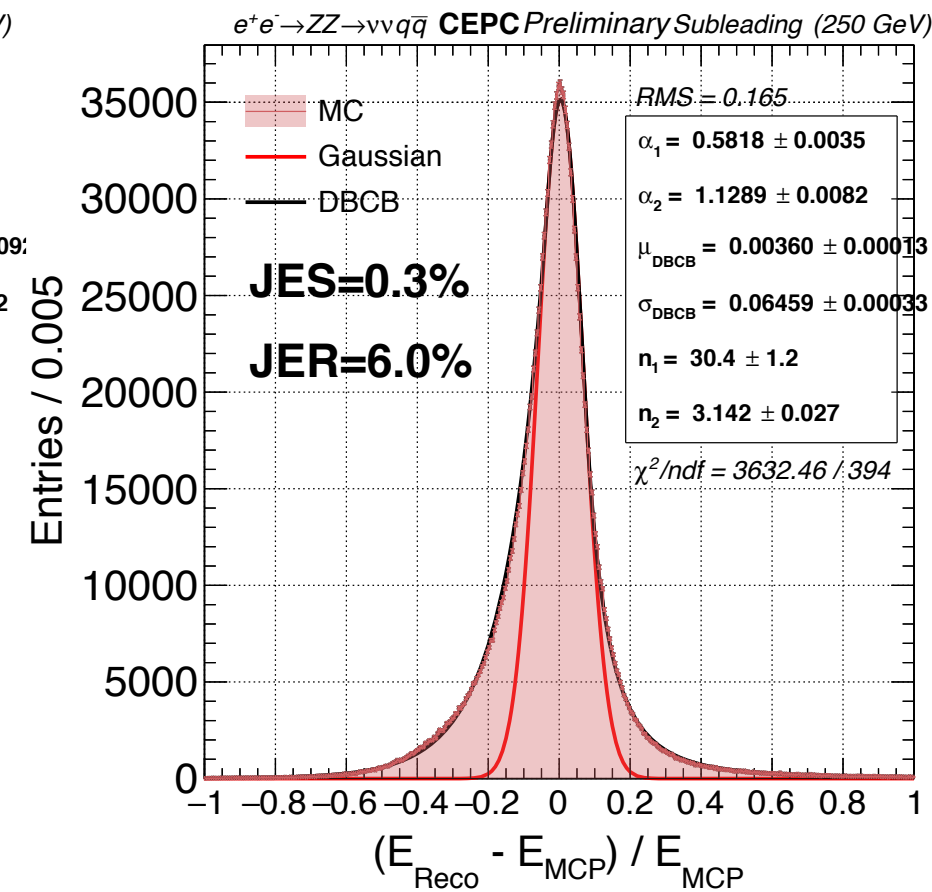
Gen-MCP



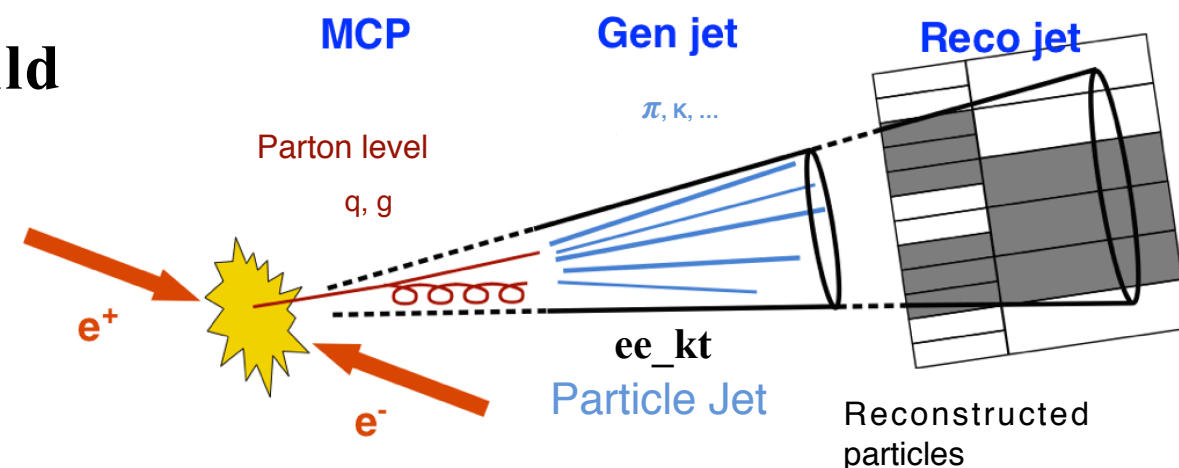
Reco-Gen

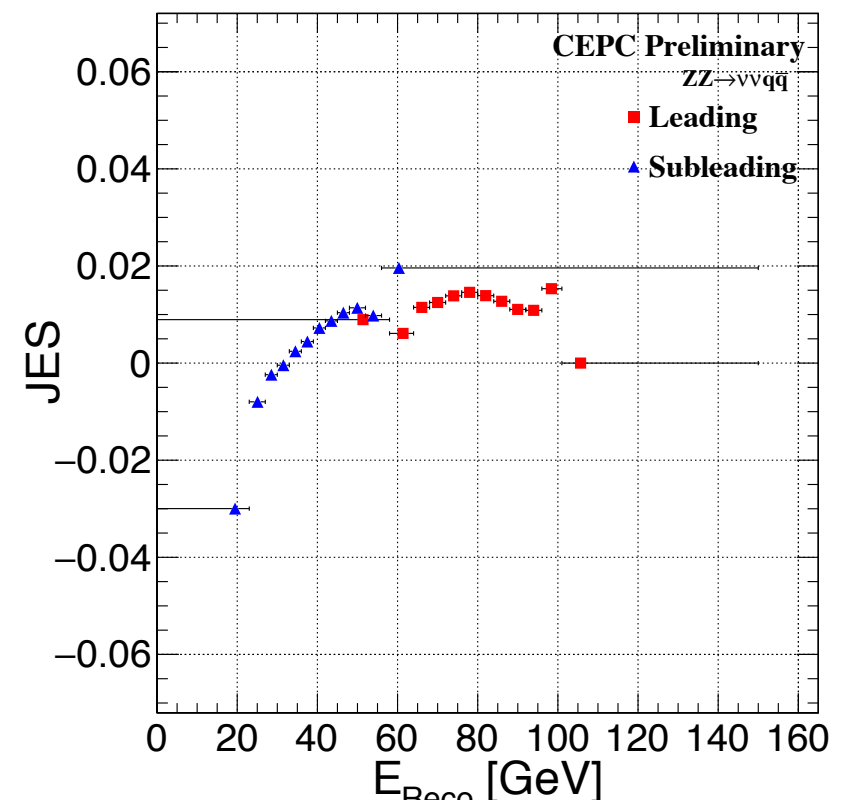
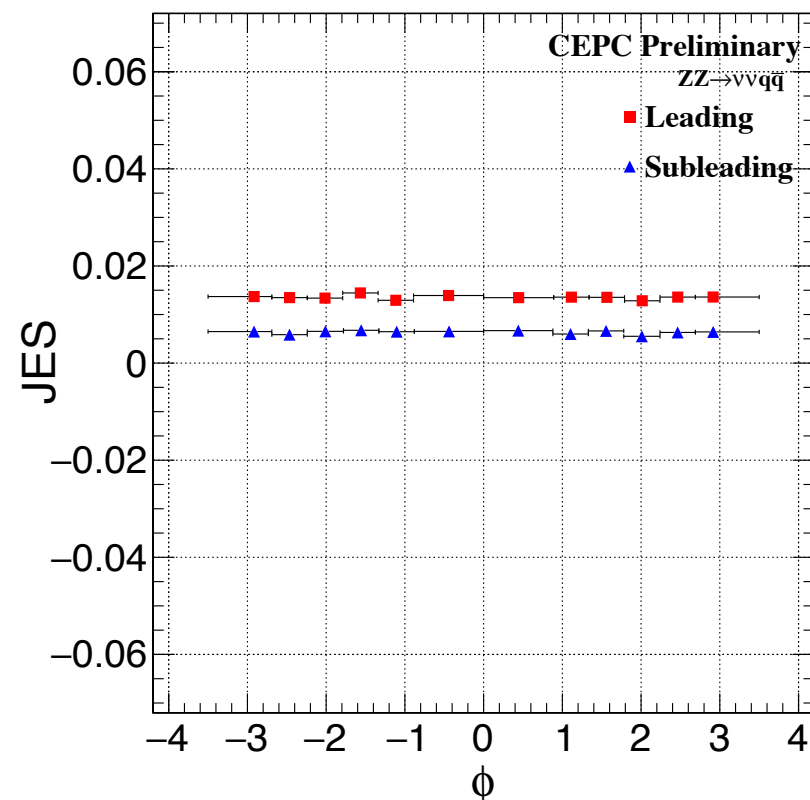
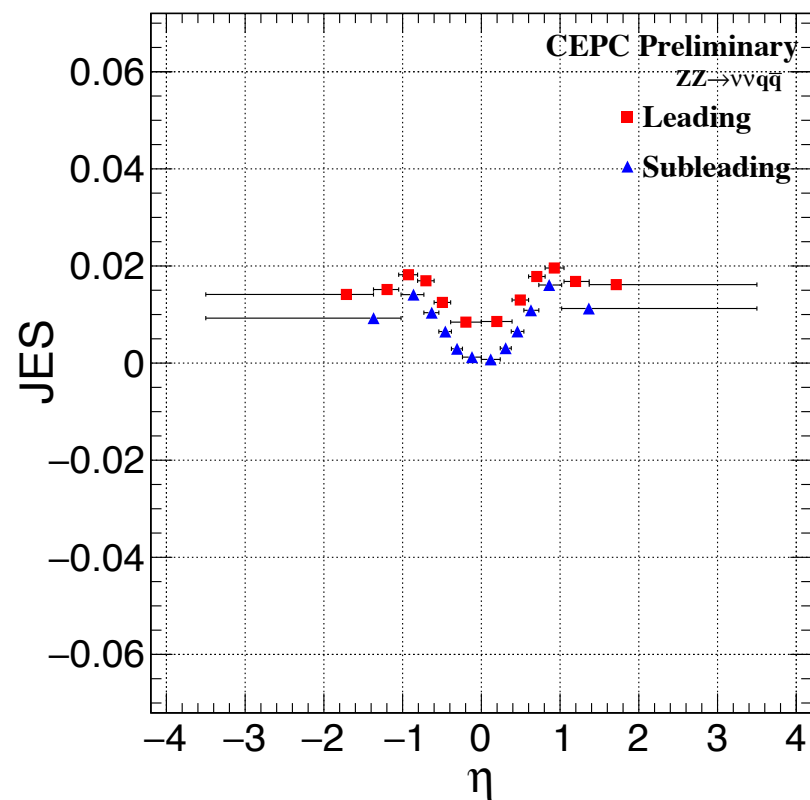
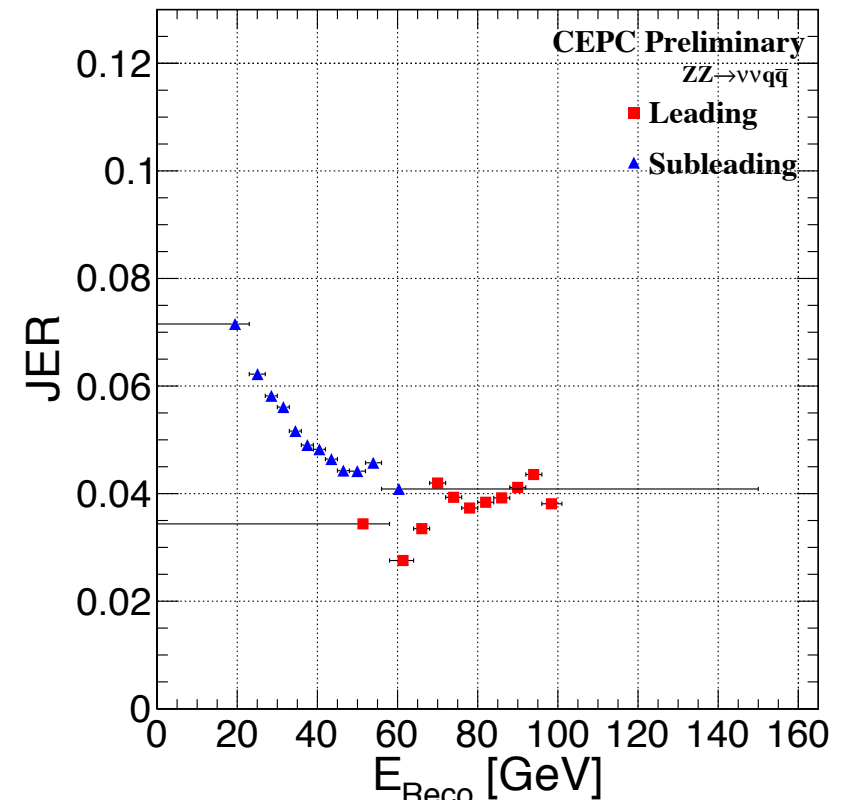
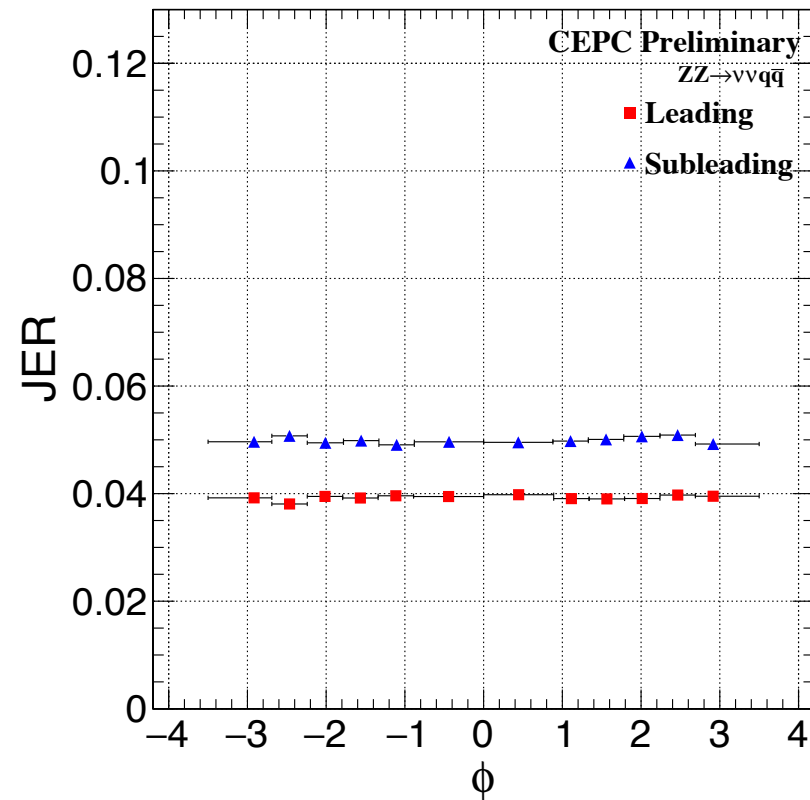
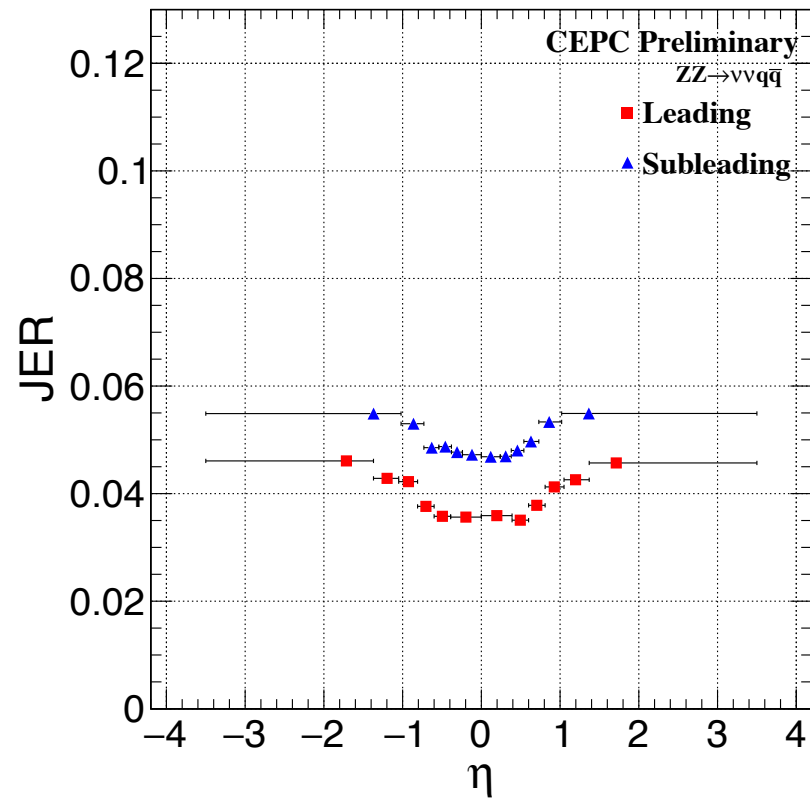


Reco-MCP

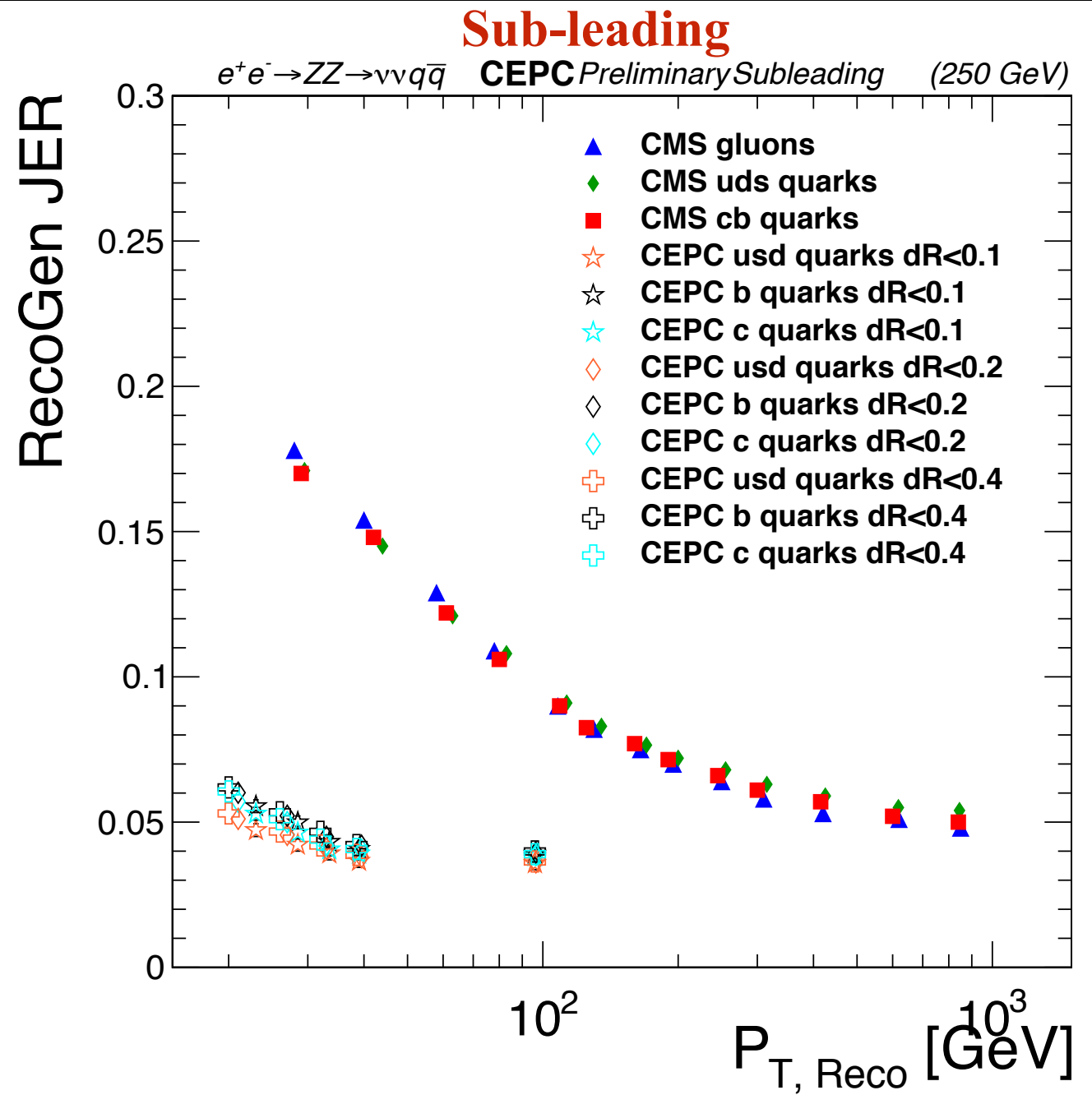
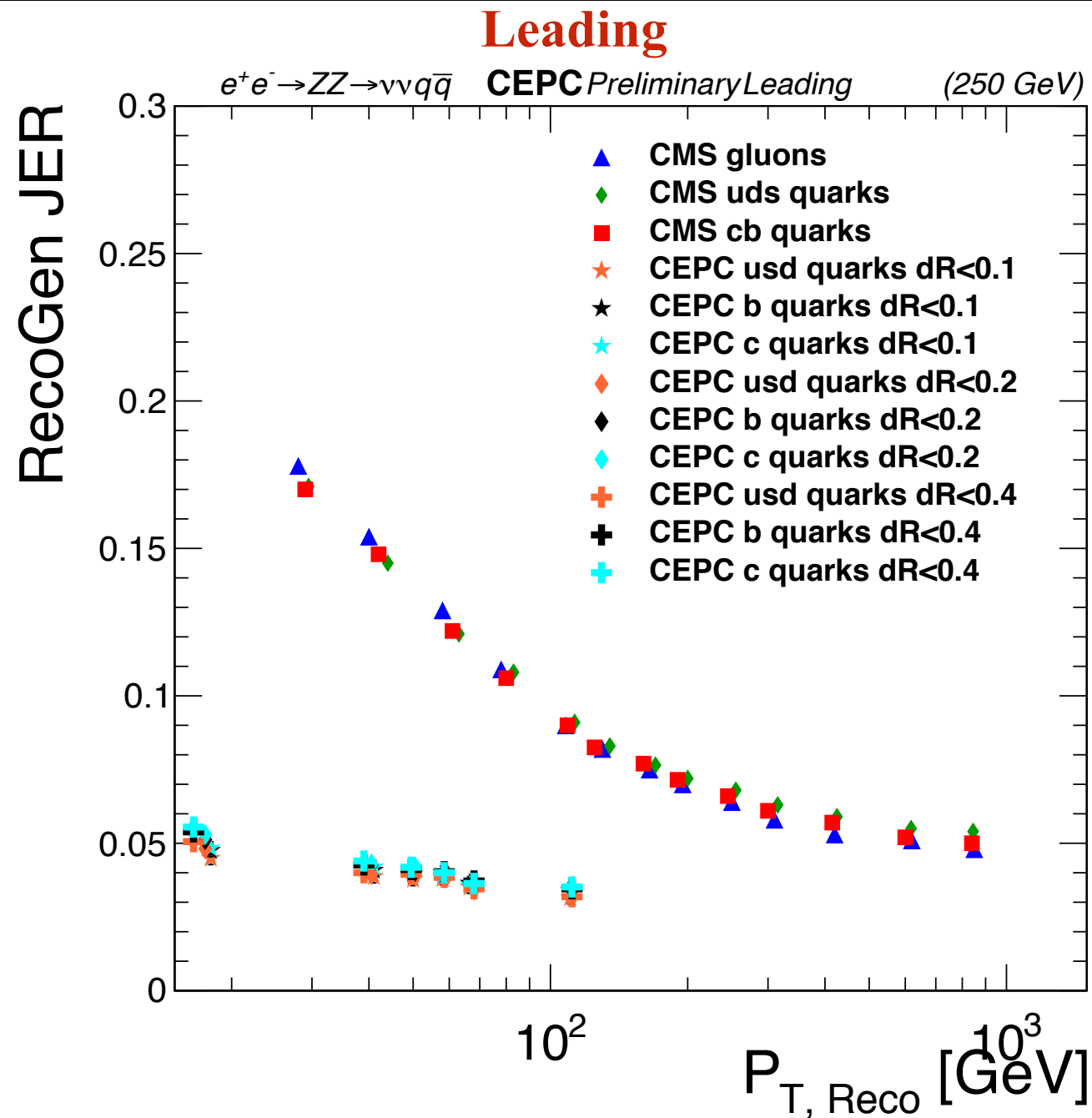


- JER/JES between reco jet and MCP would combine the effects of two previous stages.



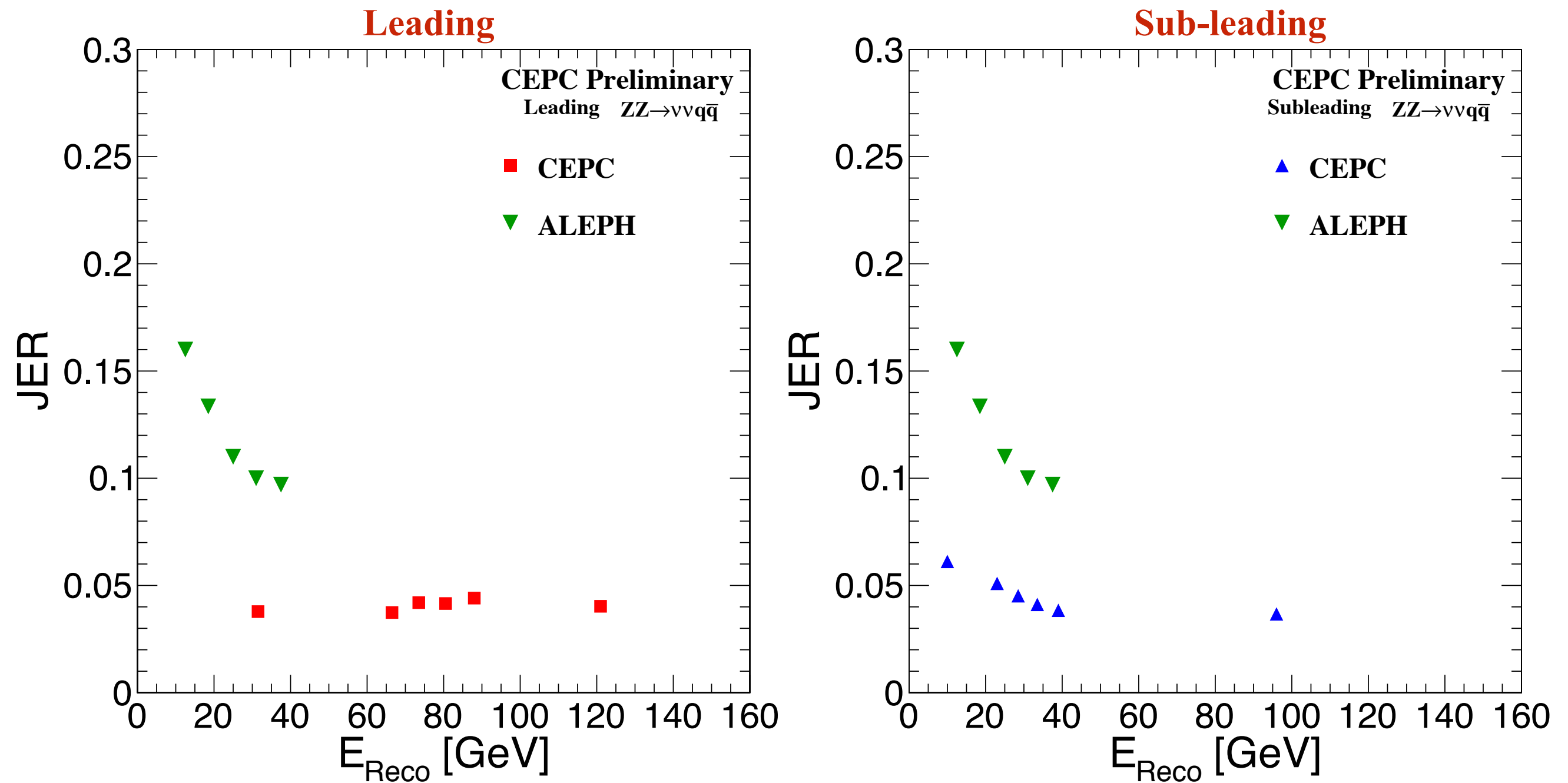


Both JER/JES are slightly dependent of Eta.



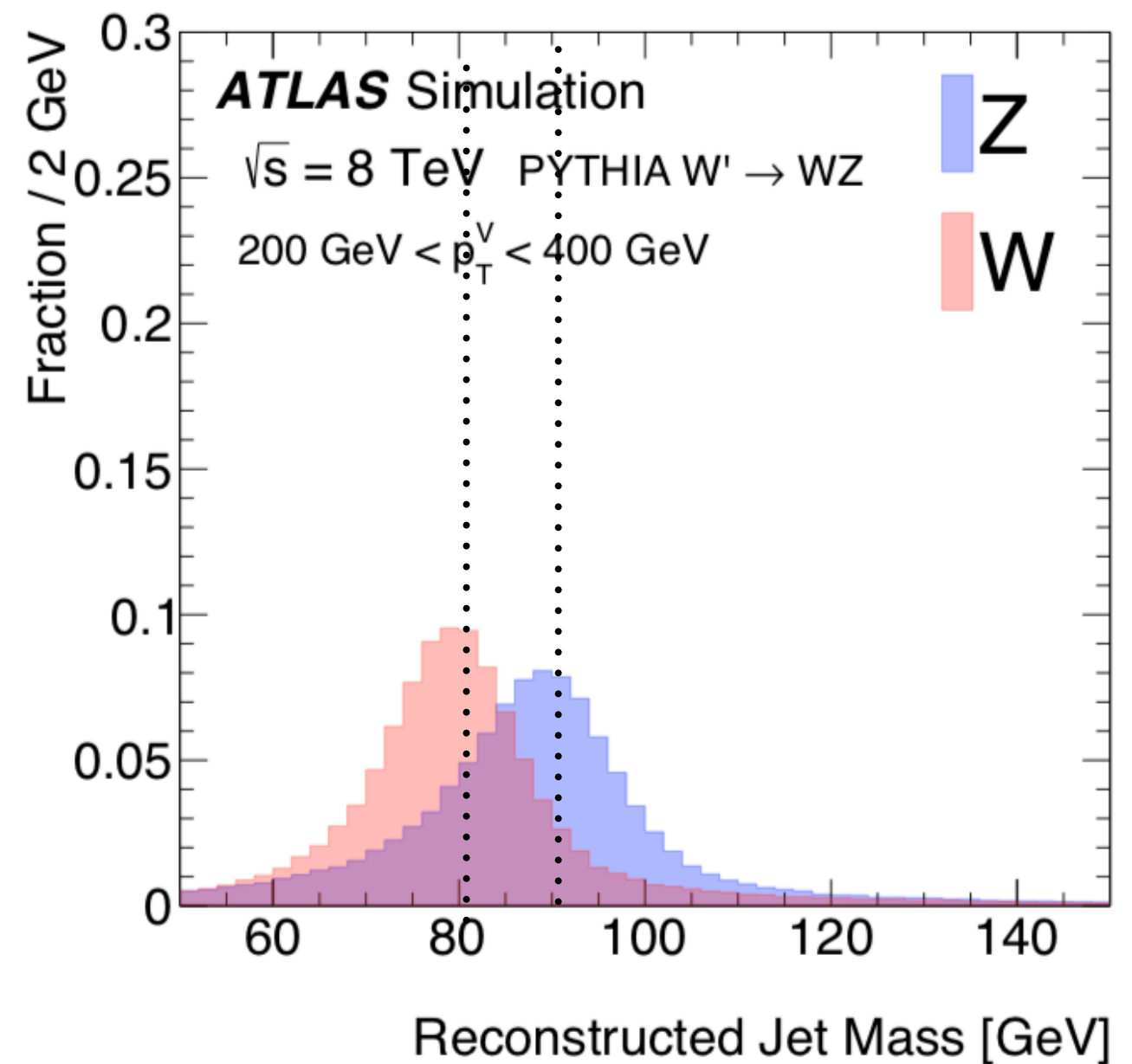
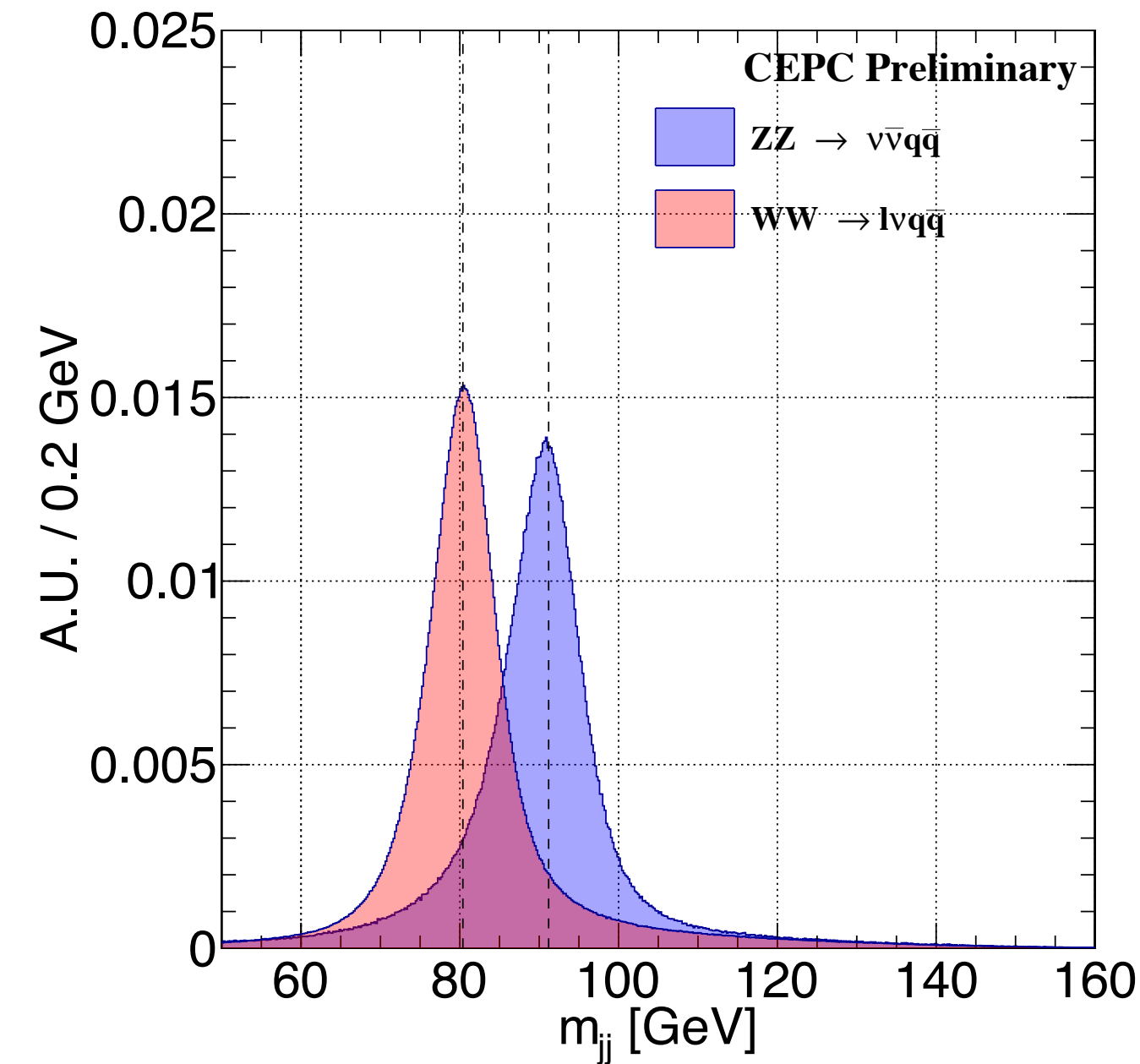
- Our JER is better than CMS as what it should be.
- Heavy flavors have a little worse JER.
- Different matching criteria only improve JER a little bit.

Ref. [3]



■ Our JER is better than ALEPH.

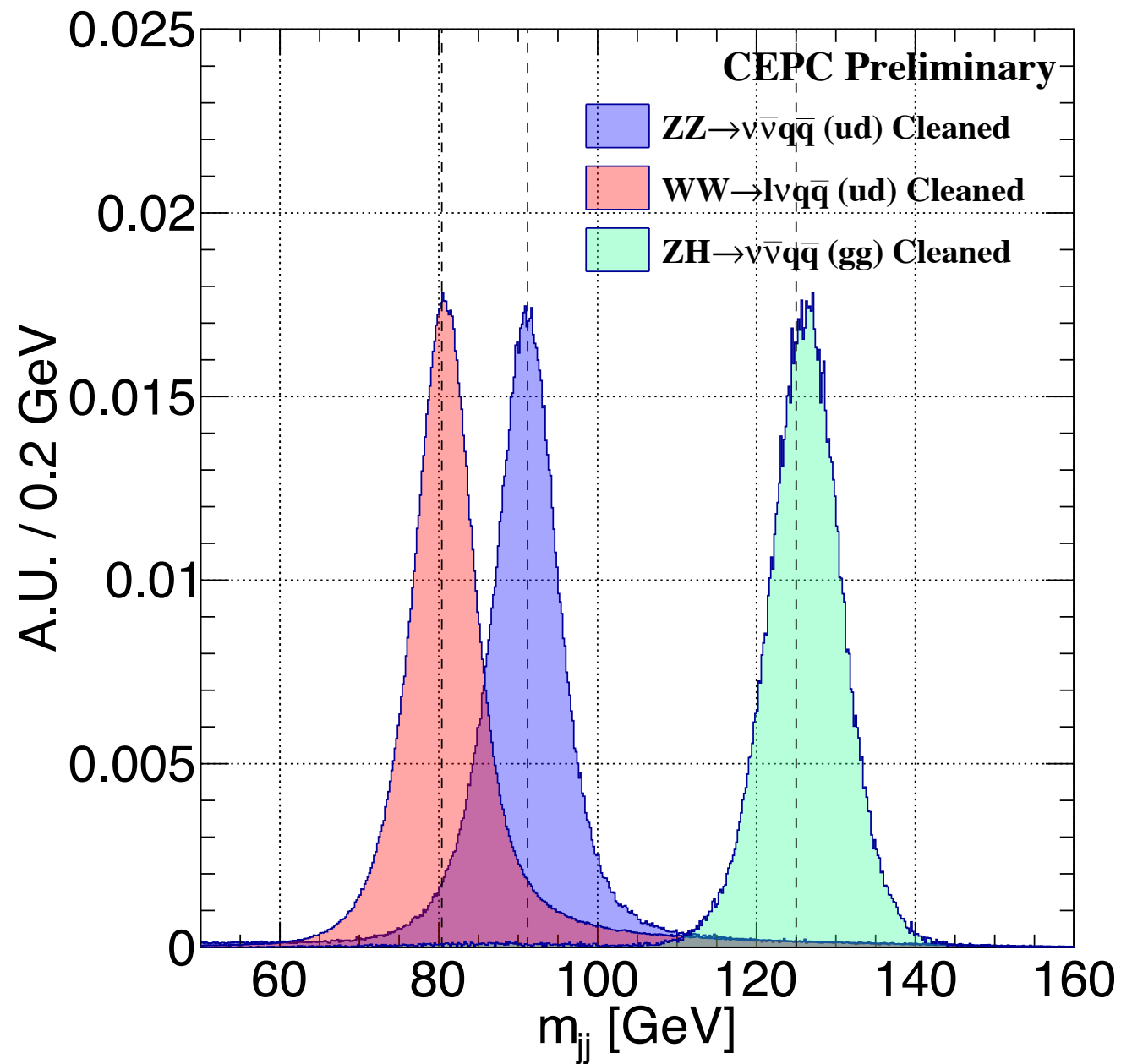
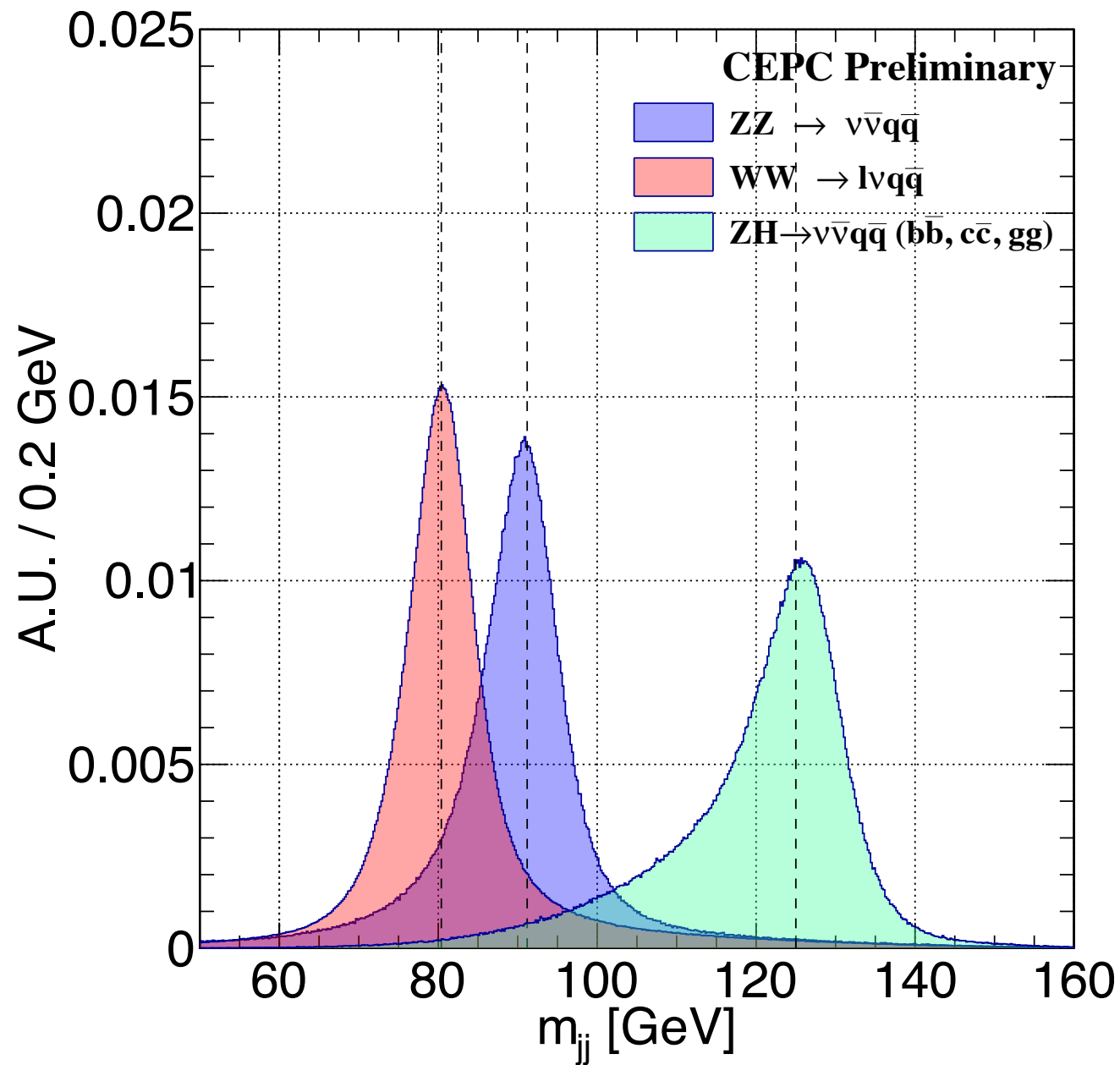
Ref. [4]



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

Ref. [5]

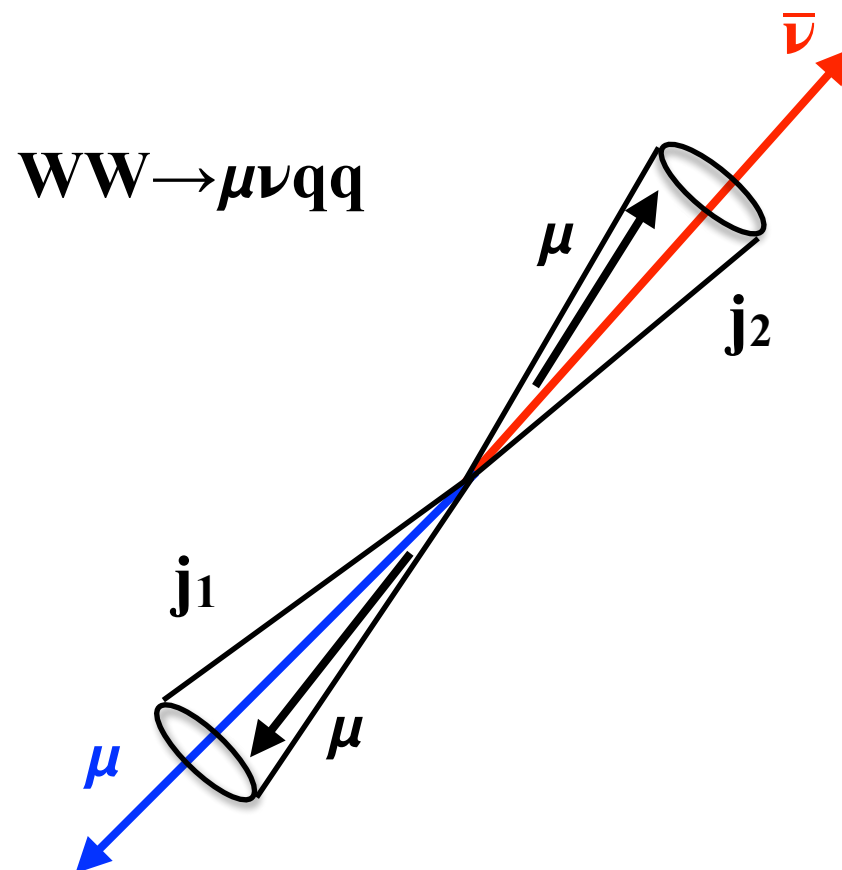
Massive Boson Separation



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

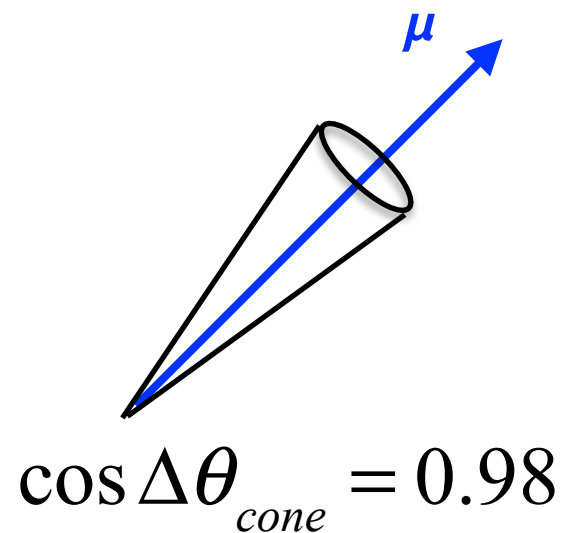
Direct W Mass Measurement

- 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!



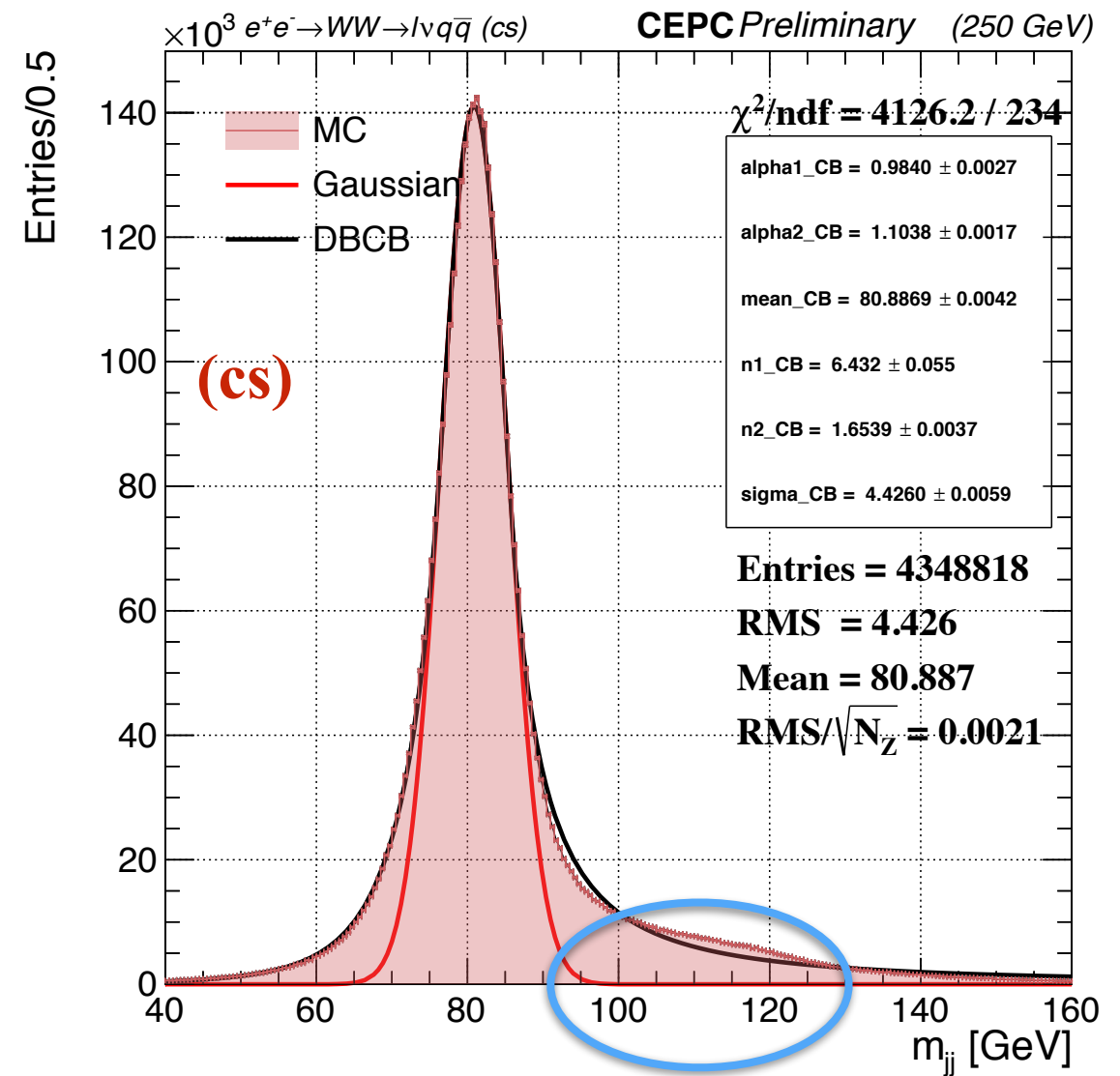
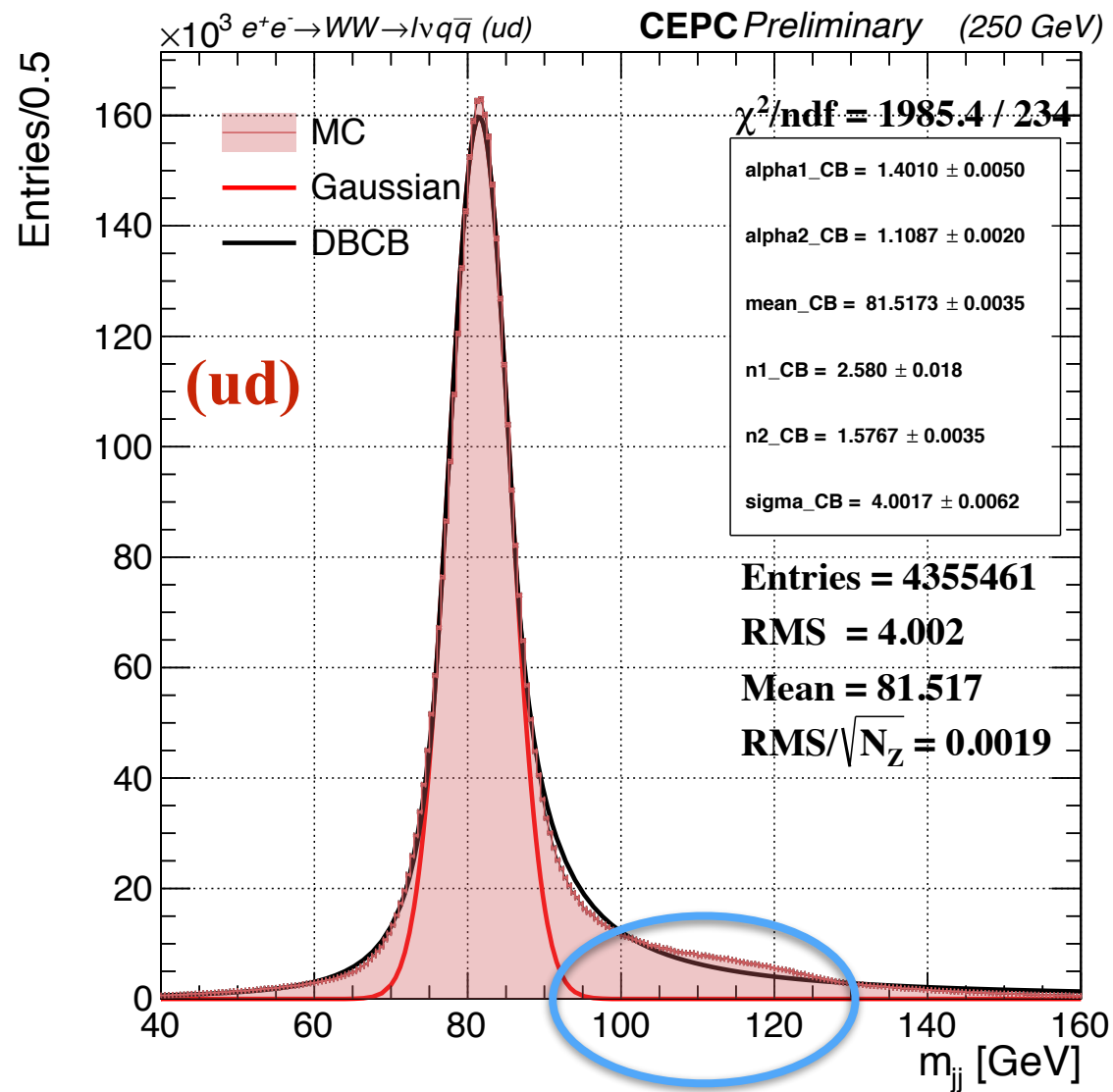
- In order to veto the prompt muon in WW to $\mu\nu q\bar{q}$, there is a code called “ISOLatedLeptonFinderProcessor” before putting PFOs into the jet clustering algorithm.
- The veto criteria are as following(should satisfy all of them at the same time)

- Pass μ ID (from Arbor)
- $R0 < 0.01$ mm
- Track energy > 30 GeV
- Apply ISOLatedPolynomial decision



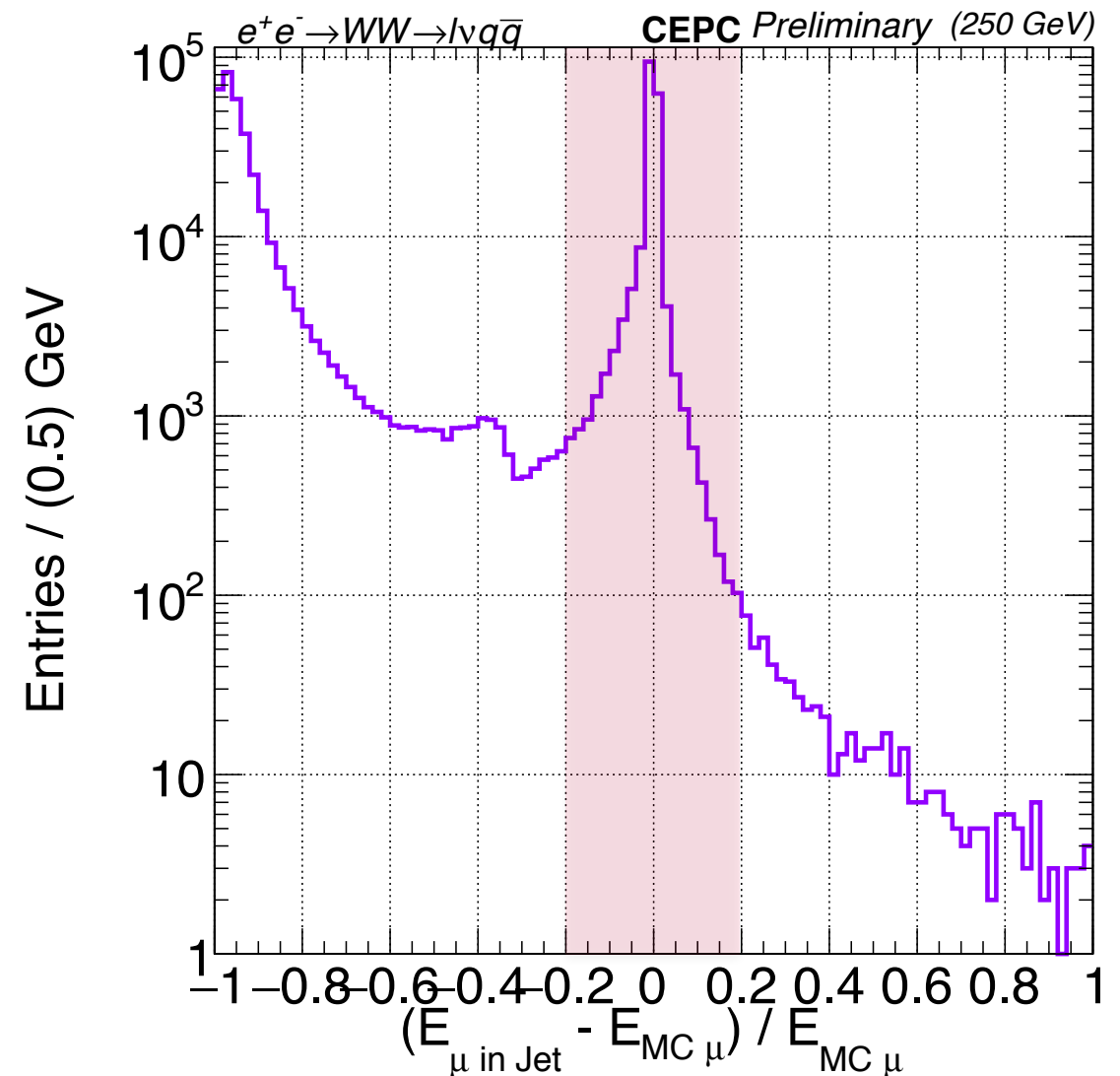
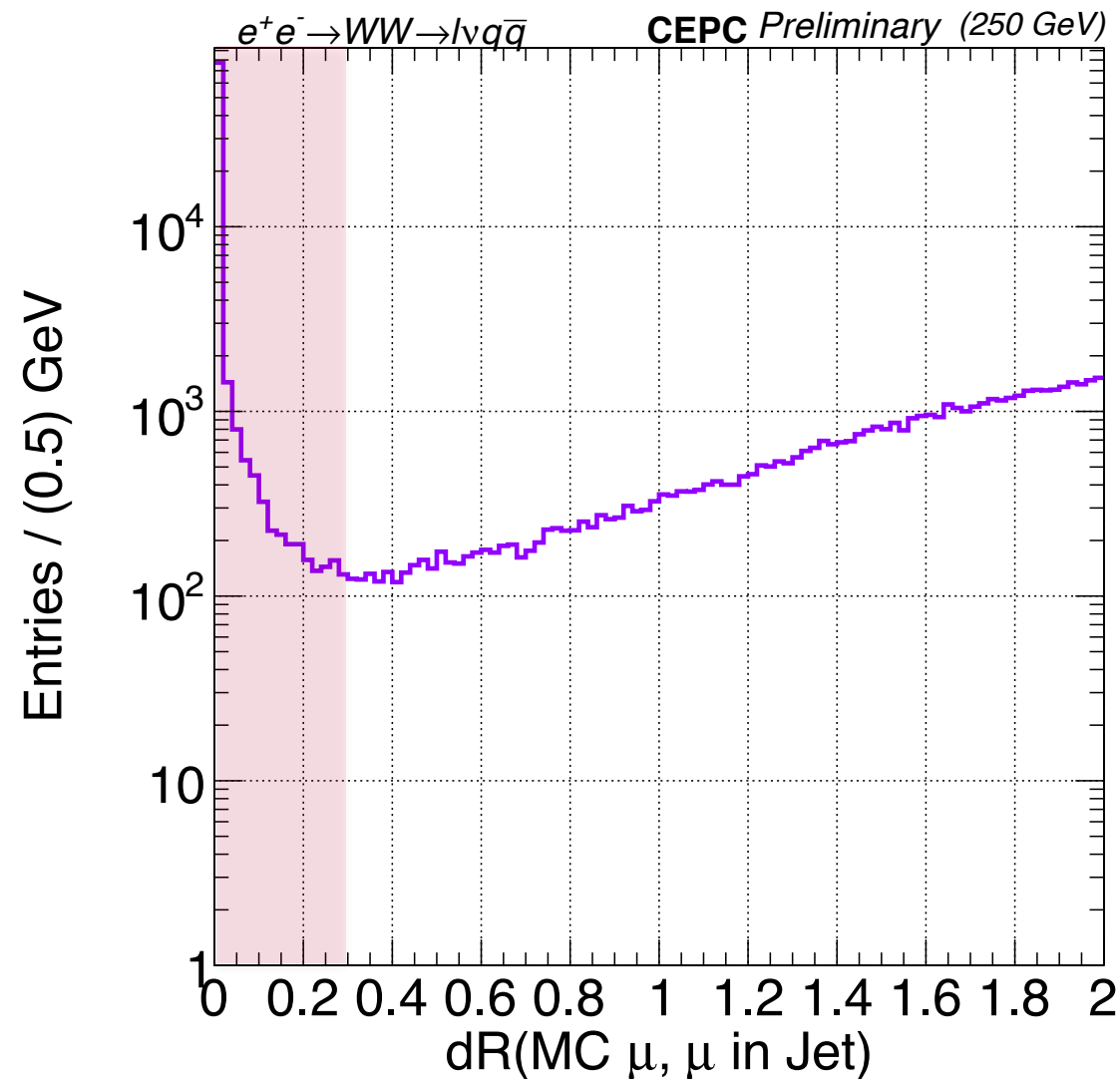
coneE = Energy in the Cone(excepts the muon) / Energy of muon

ISOLatedPolynomial: $(coneE)^2 \leq 20E_{\mu} - 300$



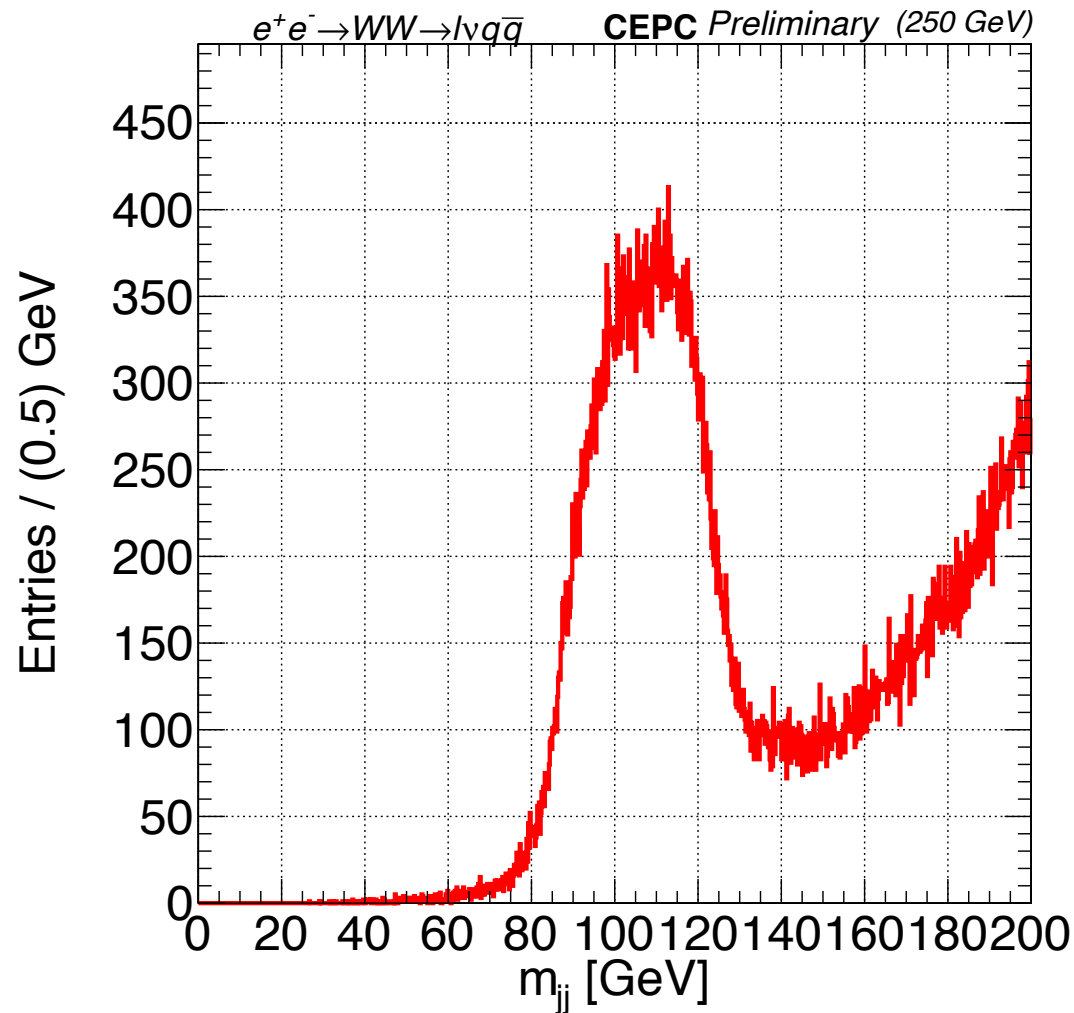
- After using prompt muon veto criteria, some events still remain a prompt muon inside the jet. It causes a shoulder on the high mass region.
- We need additional veto using generator level information for the time being.
- A more sophisticated method will be developed in the future.

MC Matching(Prompt μ , μ in jet)

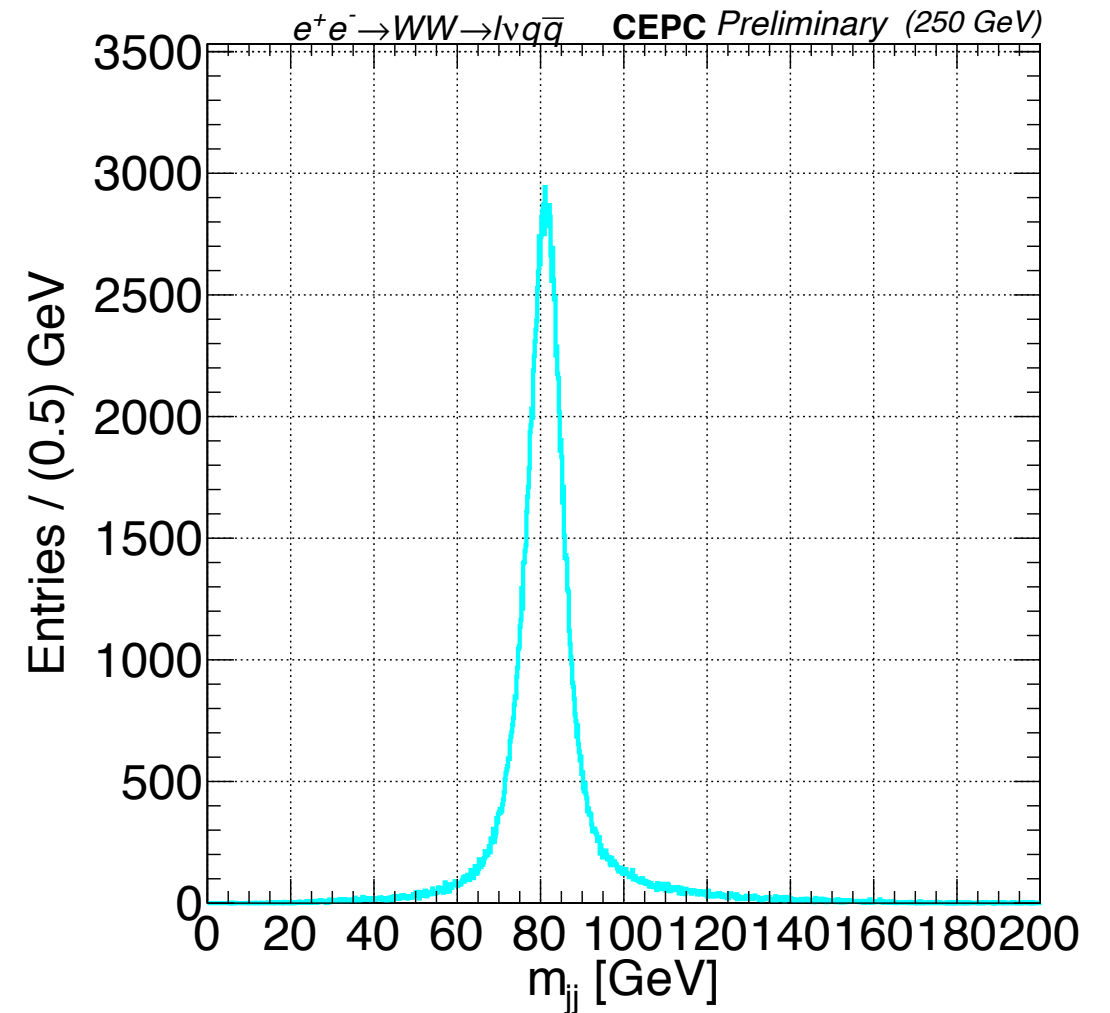


- **Use the MC truth to veto the prompt muon cleaner.**
- **dR between “muon in the jet” and MC prompt muon less than 0.3 and $|dE/E|$ less than 0.2 is identified as the prompt muon.**
- **If there are more than one muon passing the criteria, the lowest $|dE/E|$ is chosen as the prompt muon.**

After Finding the Prompt μ



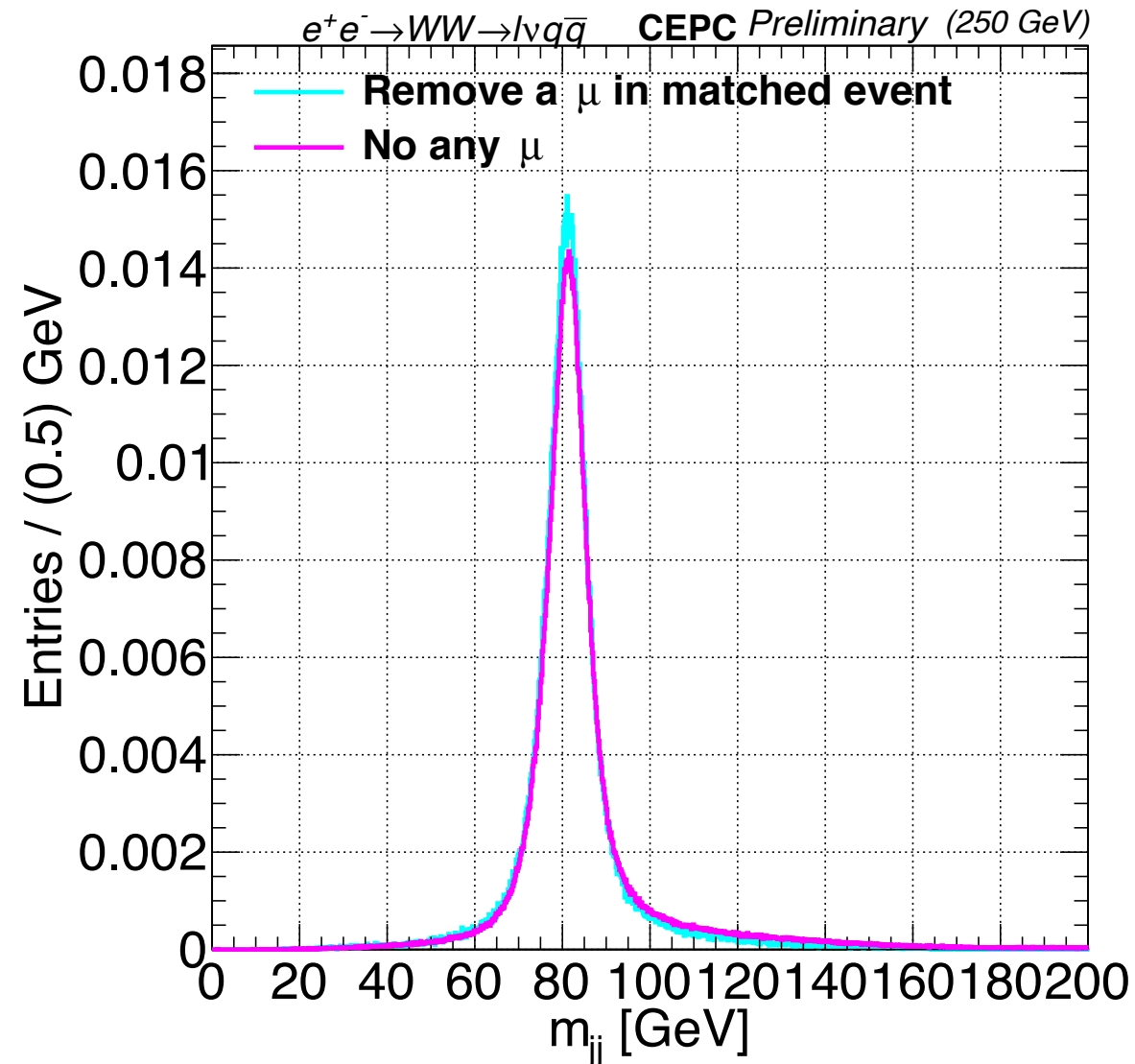
Same events



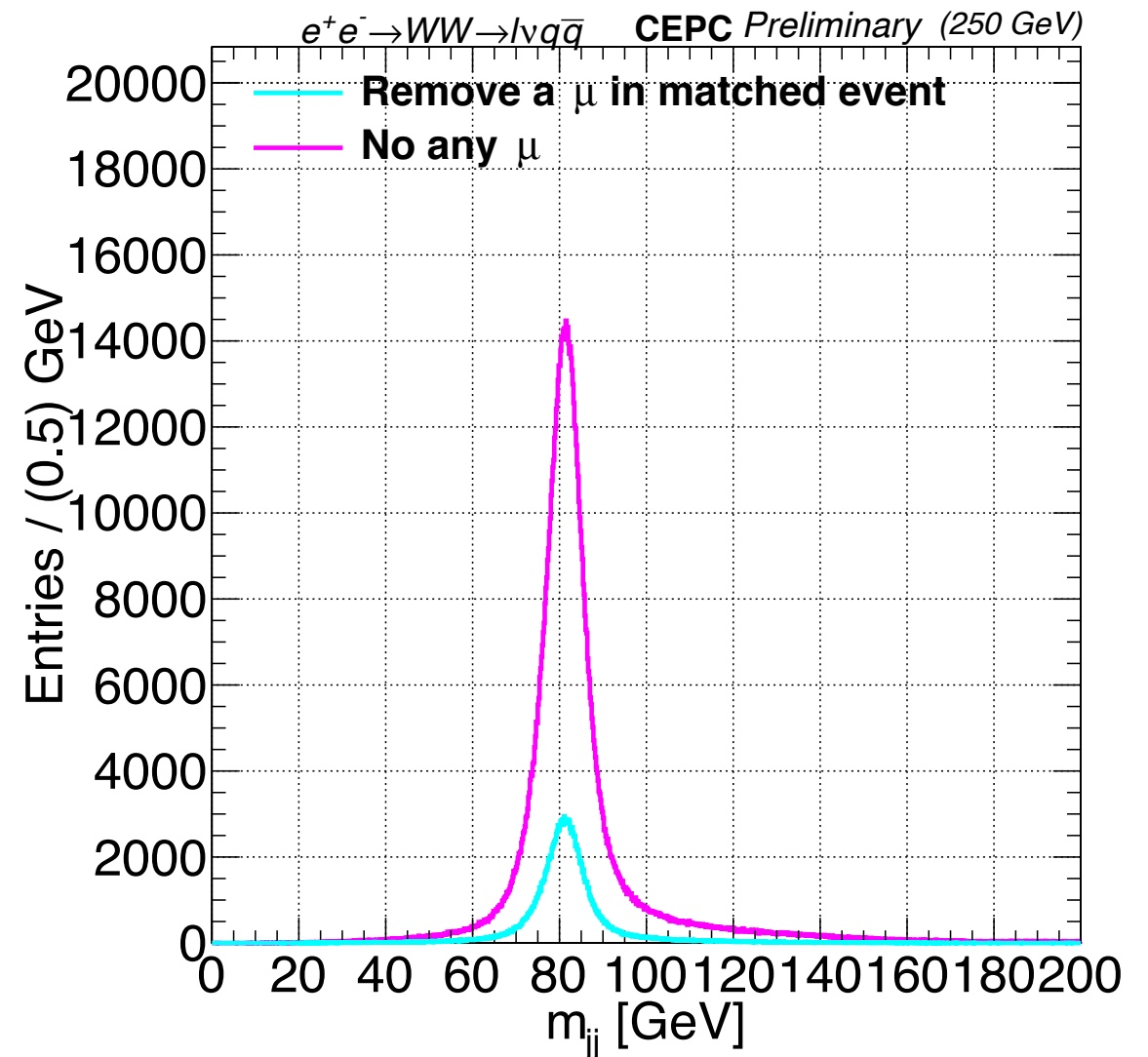
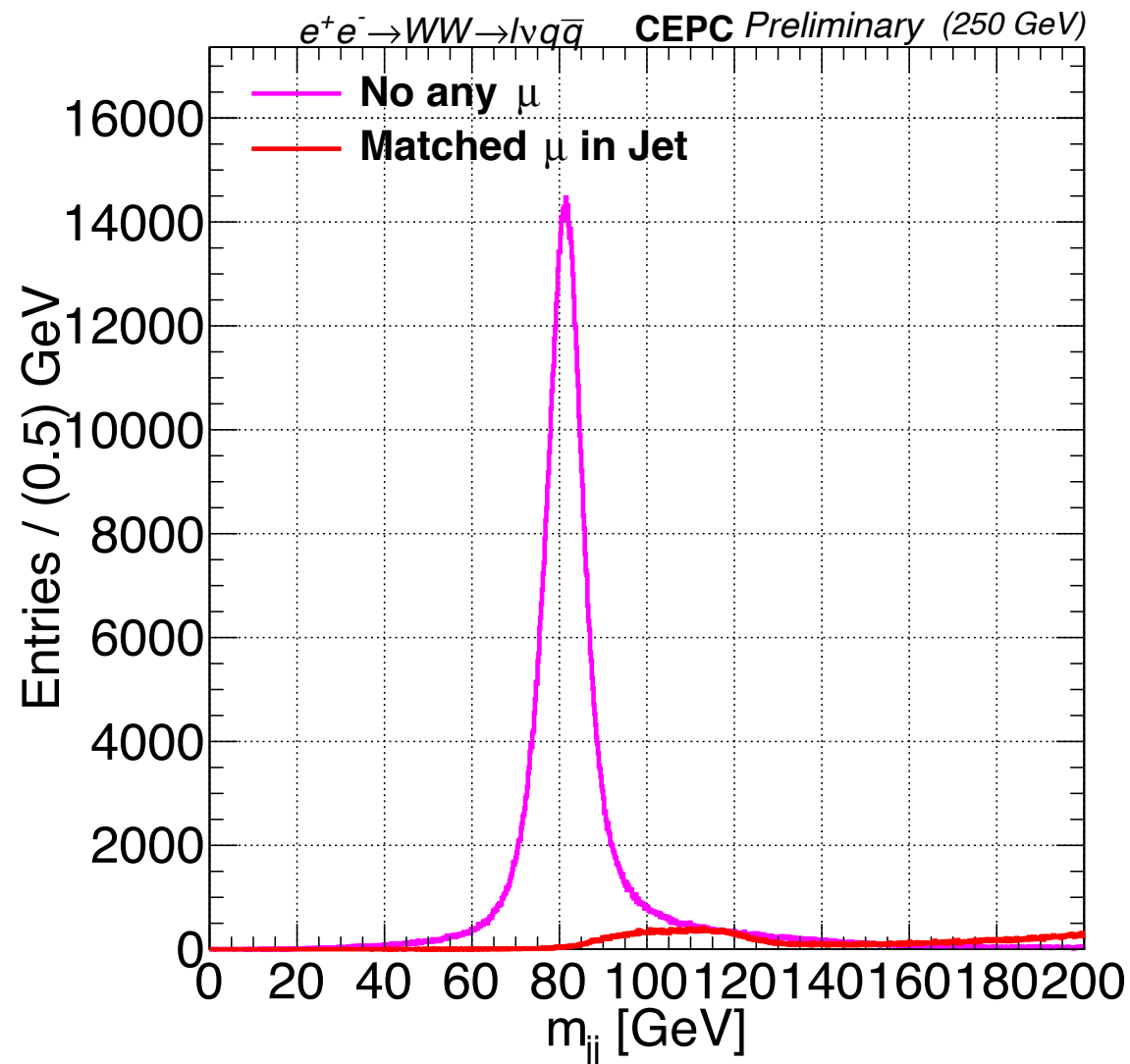
The event has a matched muon. This muon must come from another W.

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

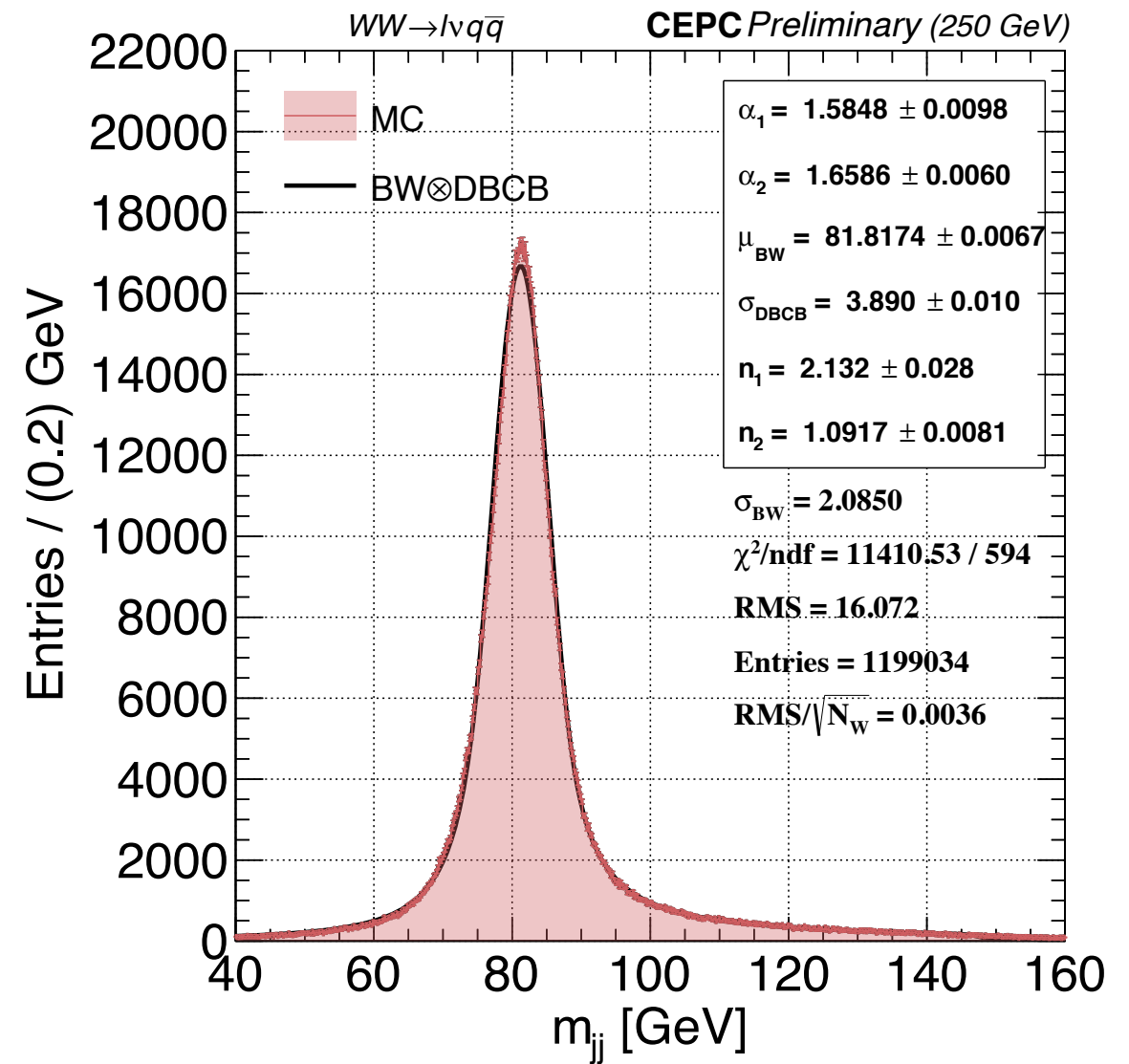
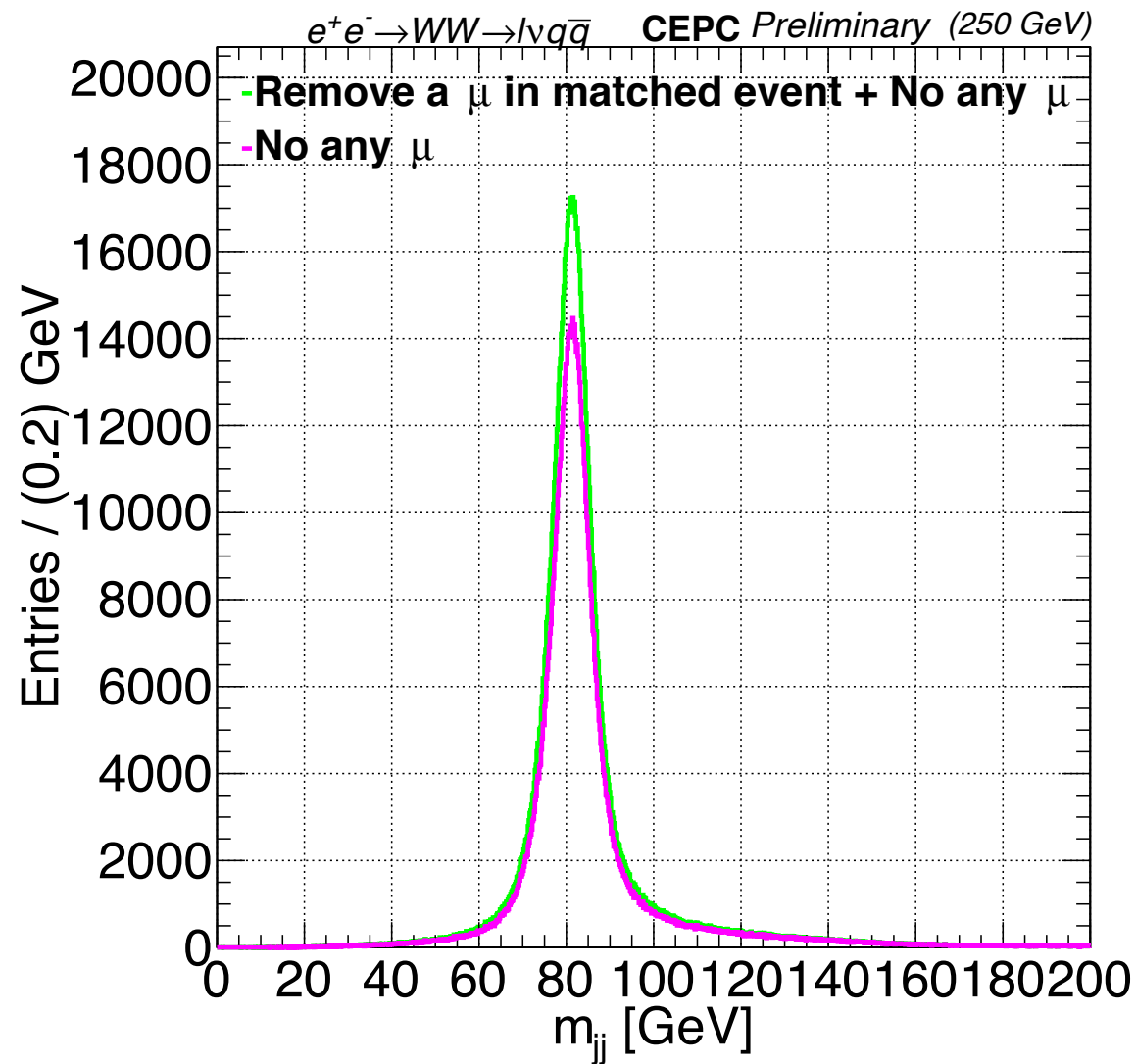
■ After vetoing a muon in the polluted event, dijet invariant mass can be recovered.



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



■ We knew the polluted event only occupy $\sim 2\%$ in the total event, but it can cause the shoulder in the dijet mass distribution.

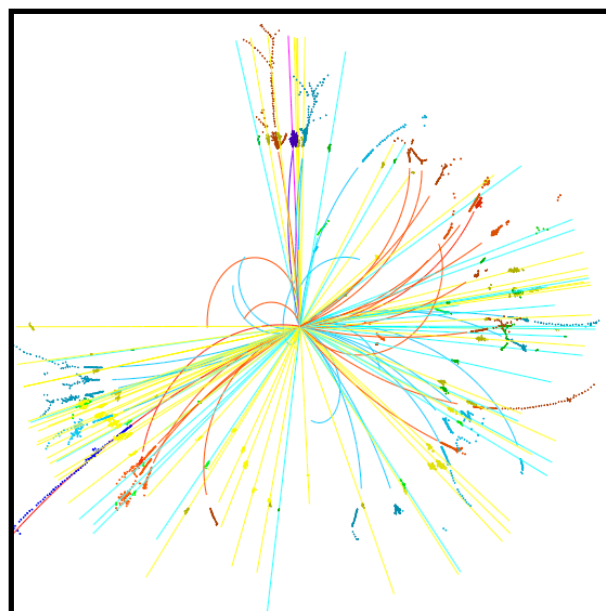


■ After cleaning the polluted event, it could improve the mass resolution and remove the shoulder

■ **The preliminary result of W boson mass direct measurement is 81817.4 ± 6.7 MeV.**

- The preliminary result for W mass direct measurement is $81817.4 \pm 6.7 \text{ MeV}$. The uncertainty can achieve less than current electroweak fit (8 MeV).
- Future
 - 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 ($ee \rightarrow ZH \rightarrow 4b$) to promote precision.

$ee \rightarrow ZH \rightarrow 4b$

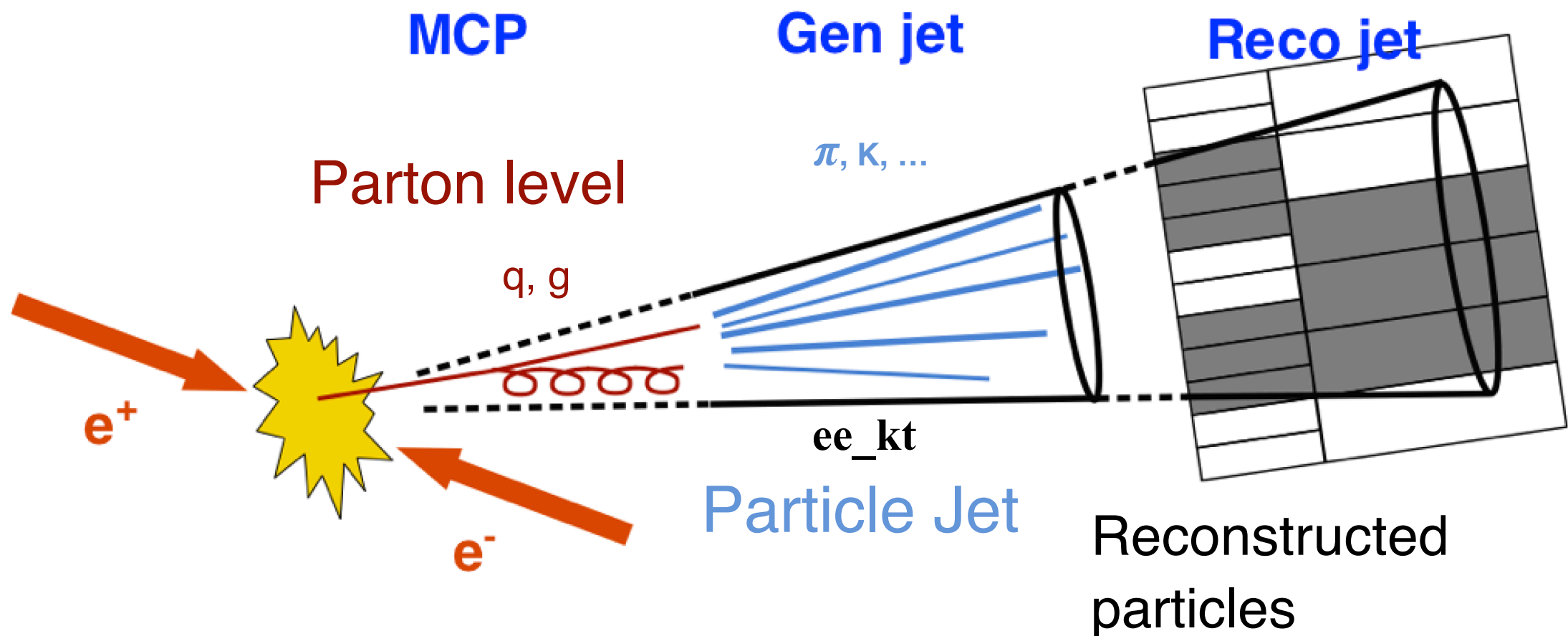


Thank for your attention

- [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]**

$\Delta M_W(\text{MeV})$	LEP	CEPC
$\sqrt{s}(\text{GeV})$	161	250
$\int L(\text{fb}^{-1})$	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
Overall systematics	21	2.5
Total	36	3.0

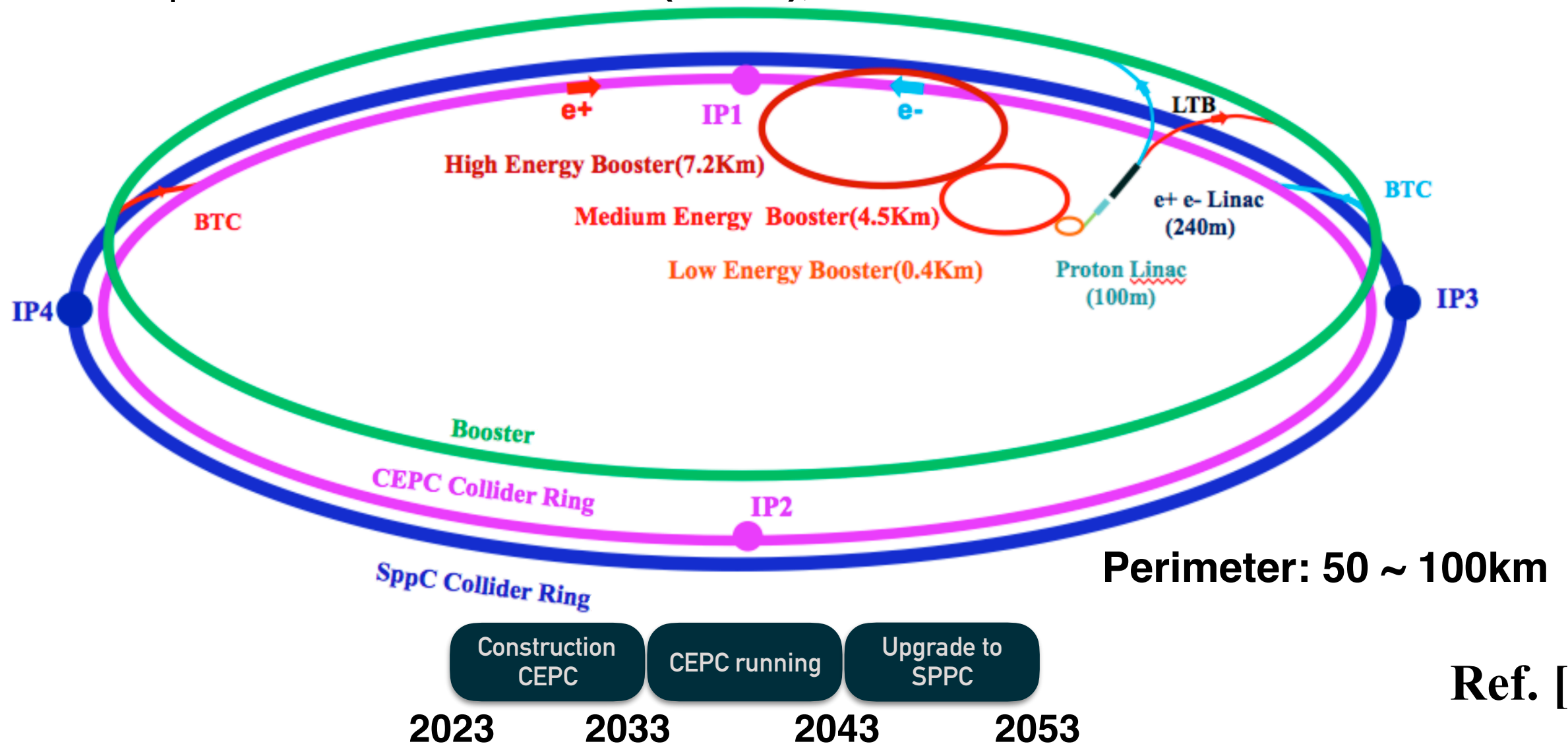
- Jet reconstruction plays an important role in particle physics. To study the performance of the jet reconstruction in CEPC, we look at the simulation which contains MC particle(MCP), Gen jet, Reco jet.



Ref. [2]

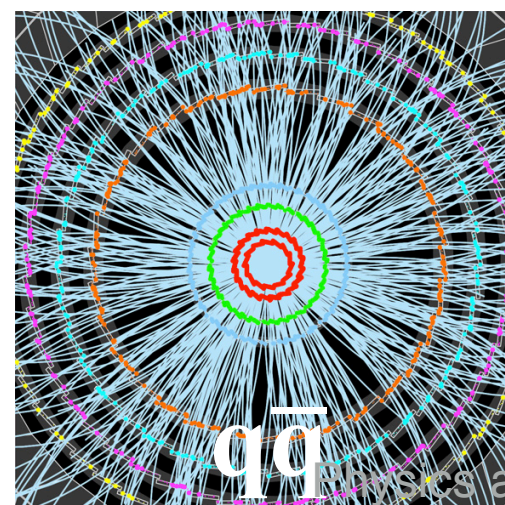
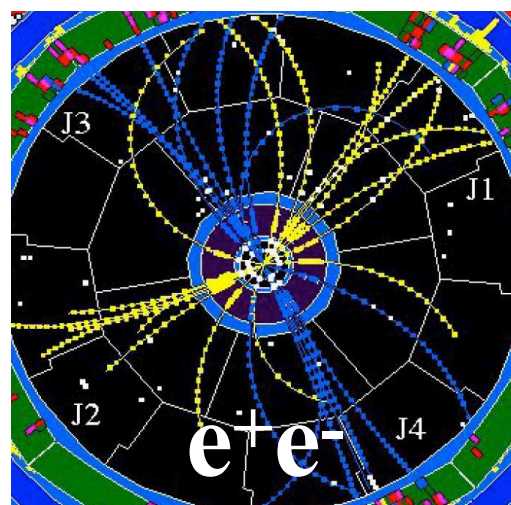
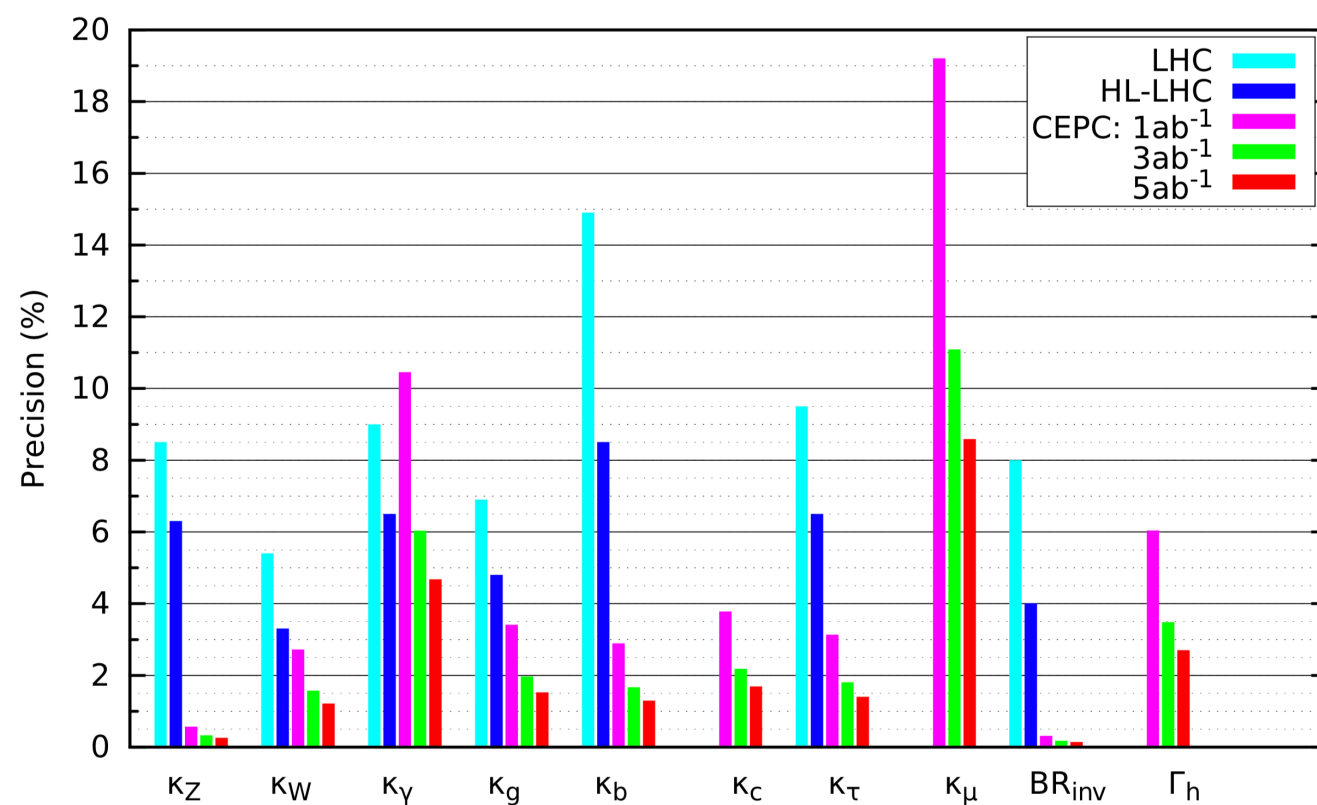
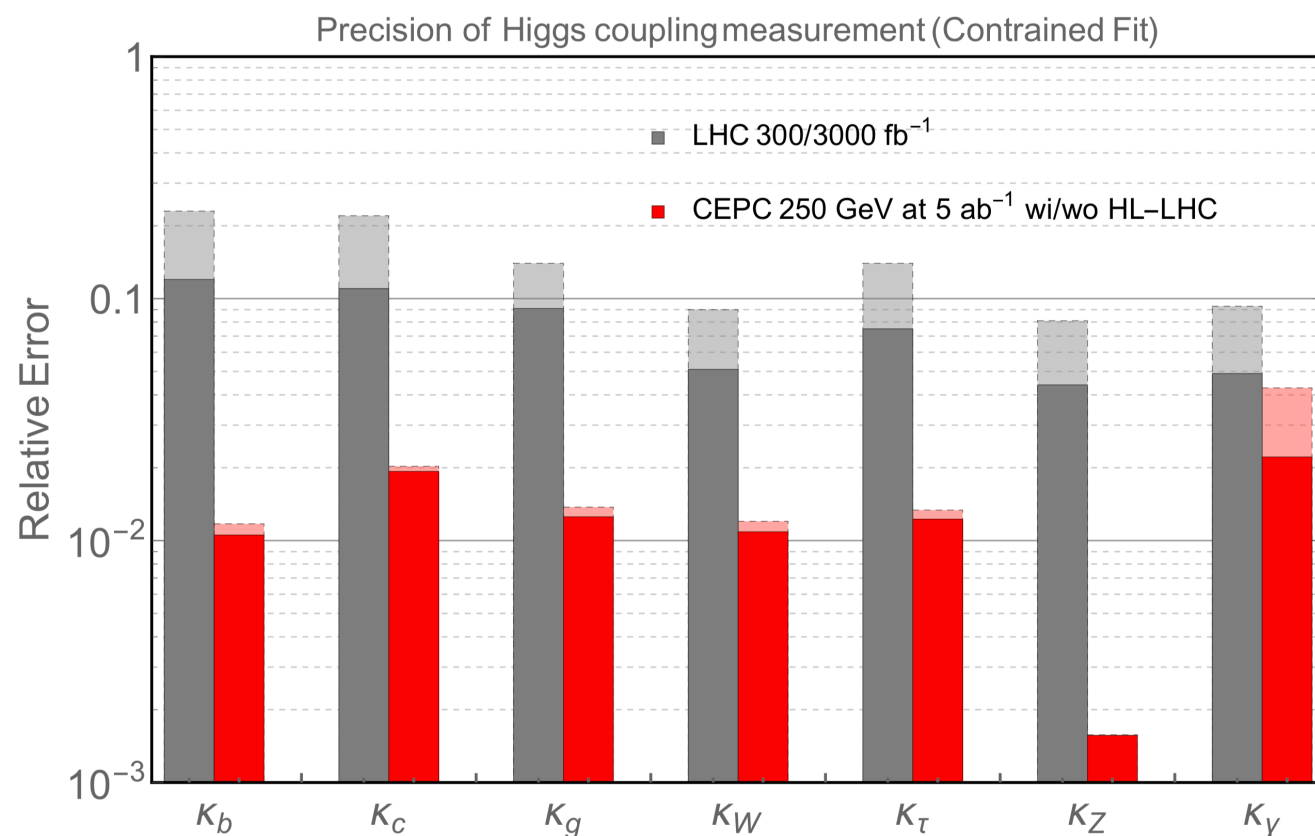
- Higgs mass ~ 125 GeV, it is possible to build a Circular e^+e^- Higgs factory(CEPC), followed by a proton collider (SPPC) in the same tunnel
- Looking for Hints (from Higgs) at CEPC $\rightarrow$ direct search at SPPC

Circular Electron-Positron Collider(CEPC), $\sqrt{s} = 90 \sim 250$ GeV
 Super Proton-Proton Collider(SPPC), $\sqrt{s} = 70 \sim 140$ TeV



Ref. [1]

- * 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)

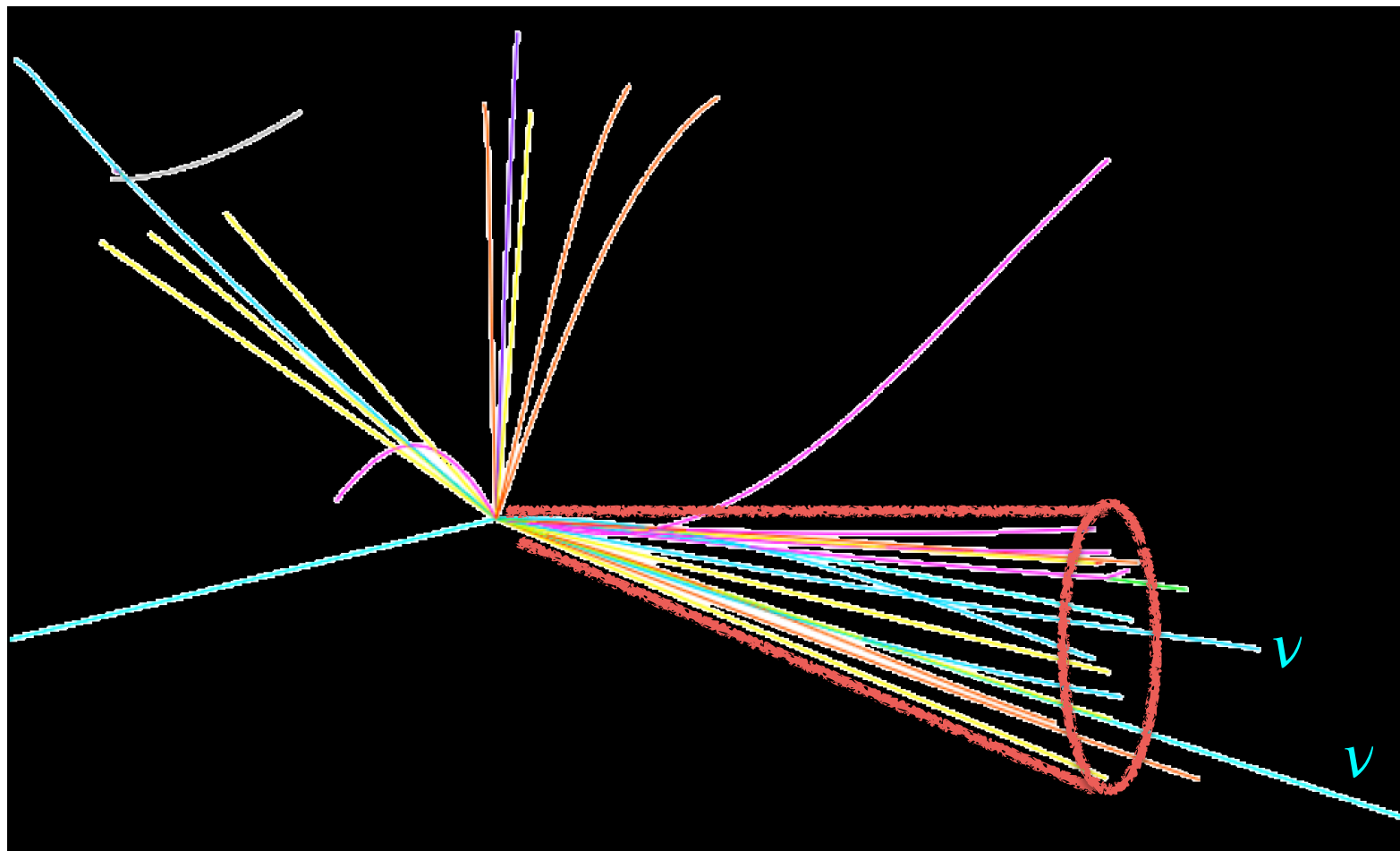


Ref. [1-3]

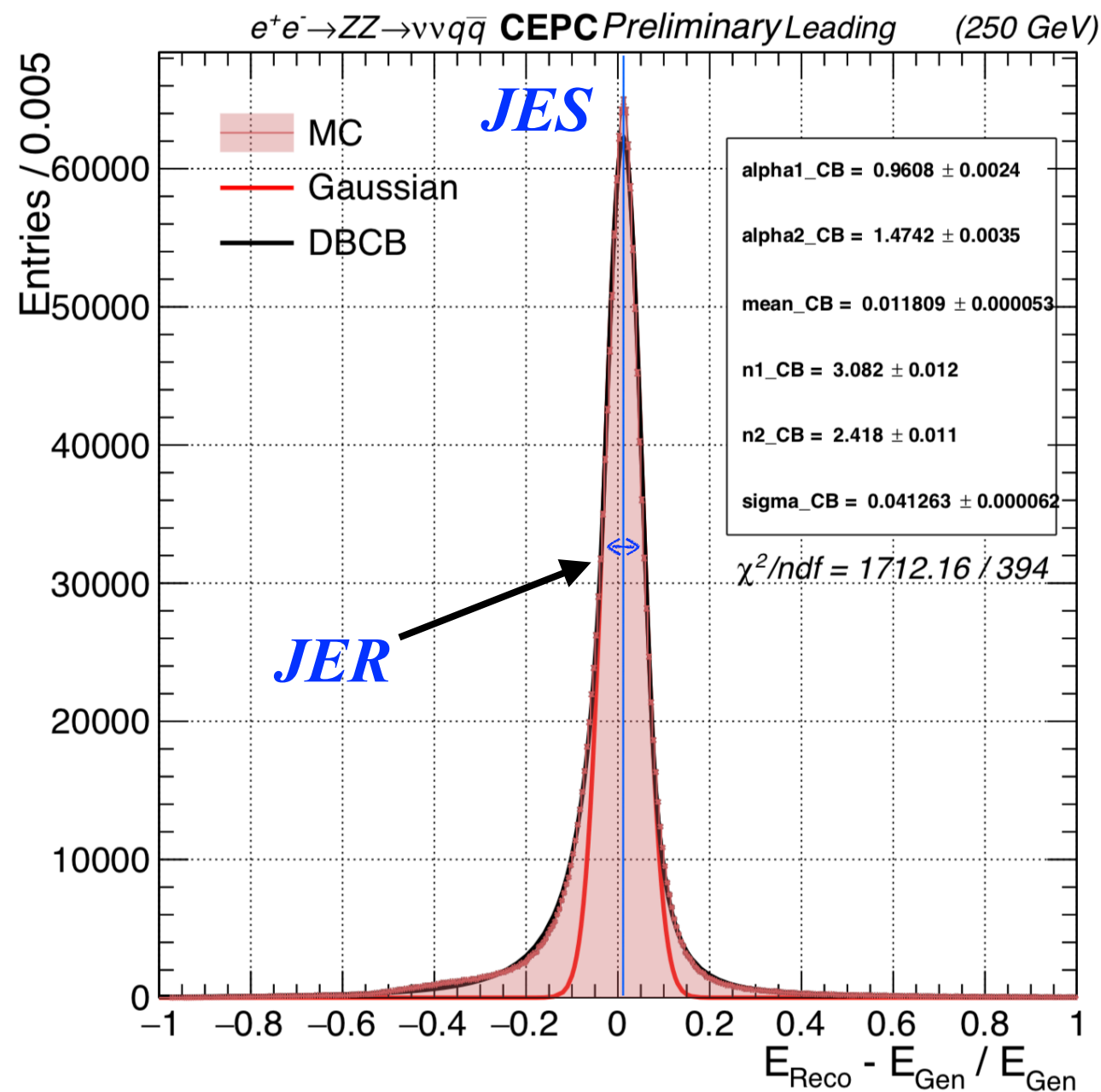
Difficulties in jet reconstruction

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

Wrong measurement leads to wrong physical results!



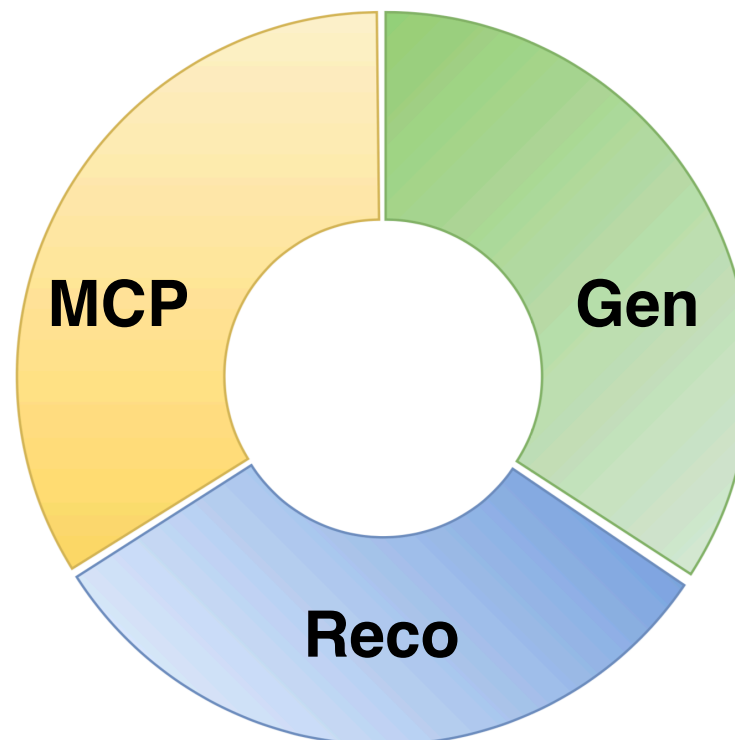
- Double-sided crystal ball(DBCB) function are used to extract energy resolution.
- The bin size of histogram is 0.5%.



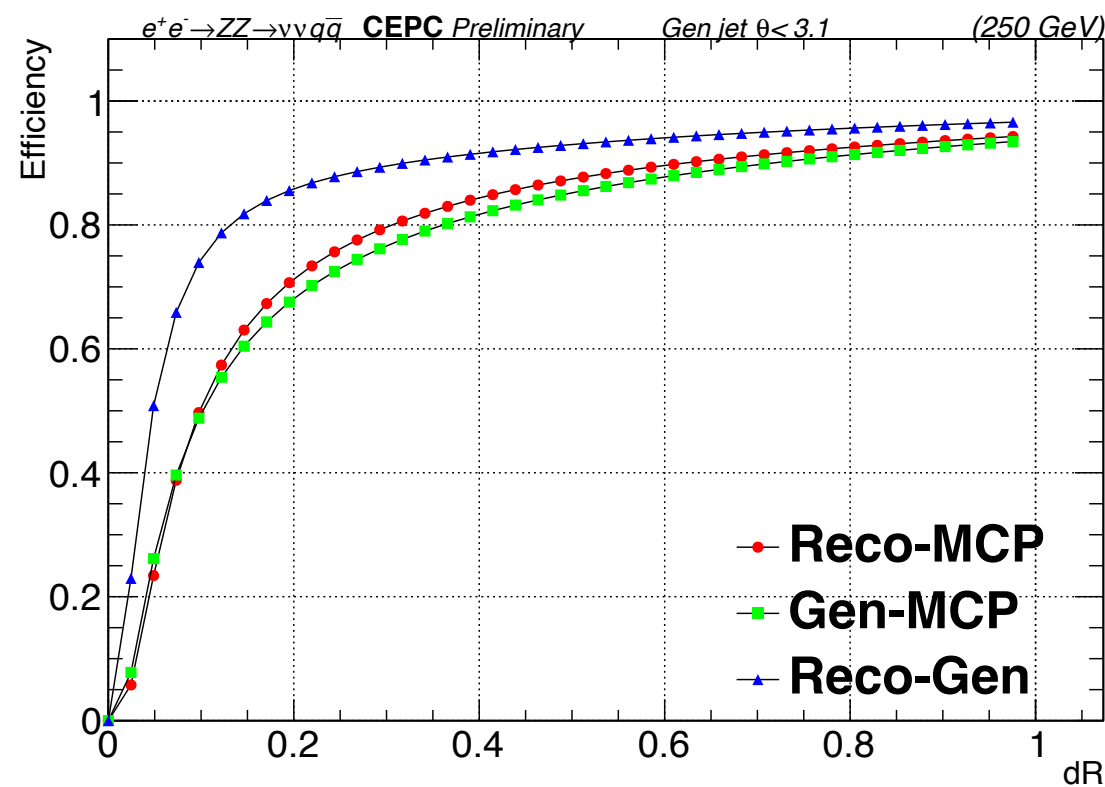
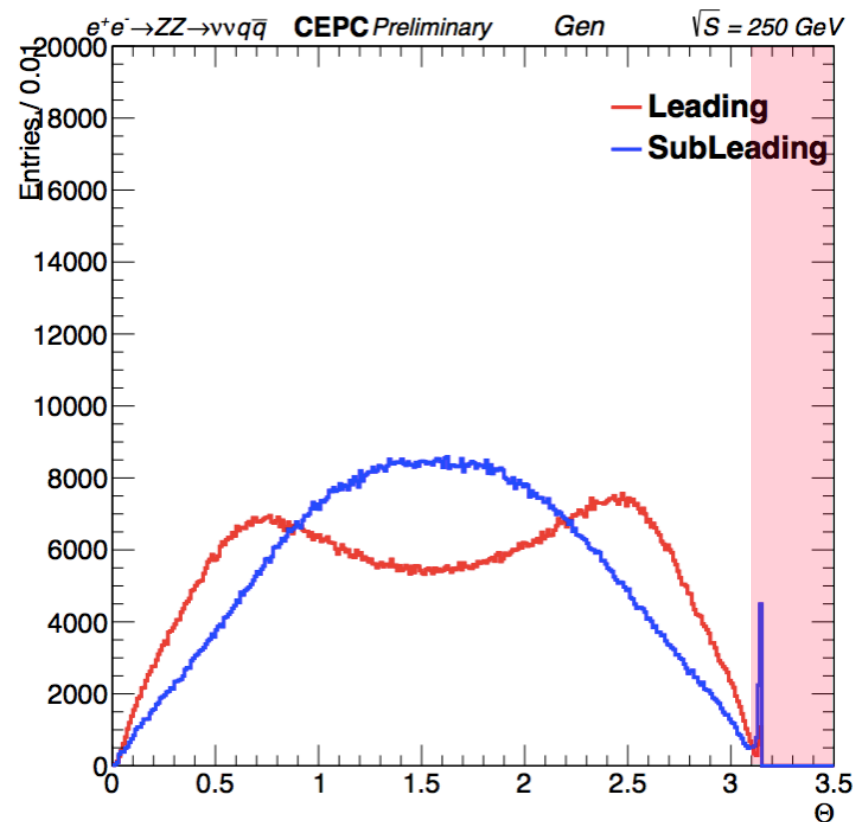
Relativity difference

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

- The jet energy resolution and scale(JER/JES) in $ee \rightarrow ZZ \rightarrow \nu\nu q\bar{q}$ 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 $\Delta R < 0.1$.



Items	JER/JES(Reco-Gen)	JER/JES(Gen-MCP)
Gen jet theta < 3.1	✓	✓
$\Delta R(\text{Reco-MCP}) < 0.1$	✓	✗

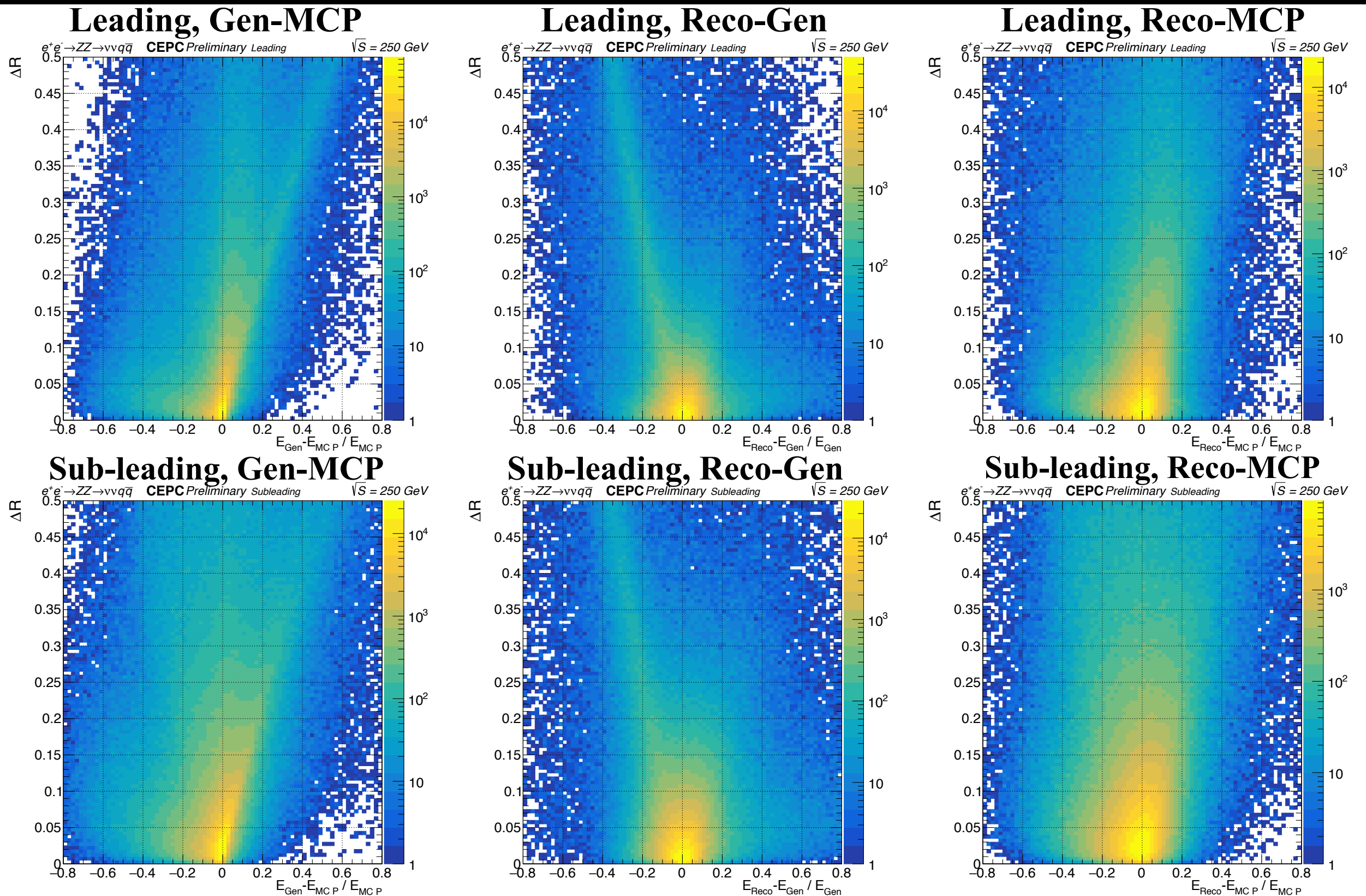


Efficiency =

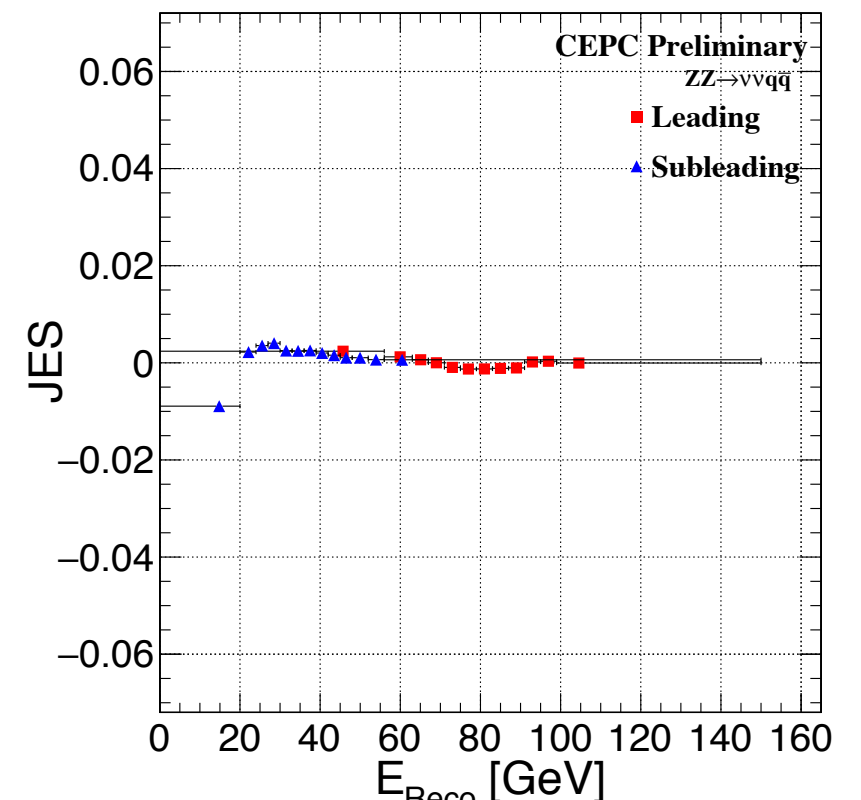
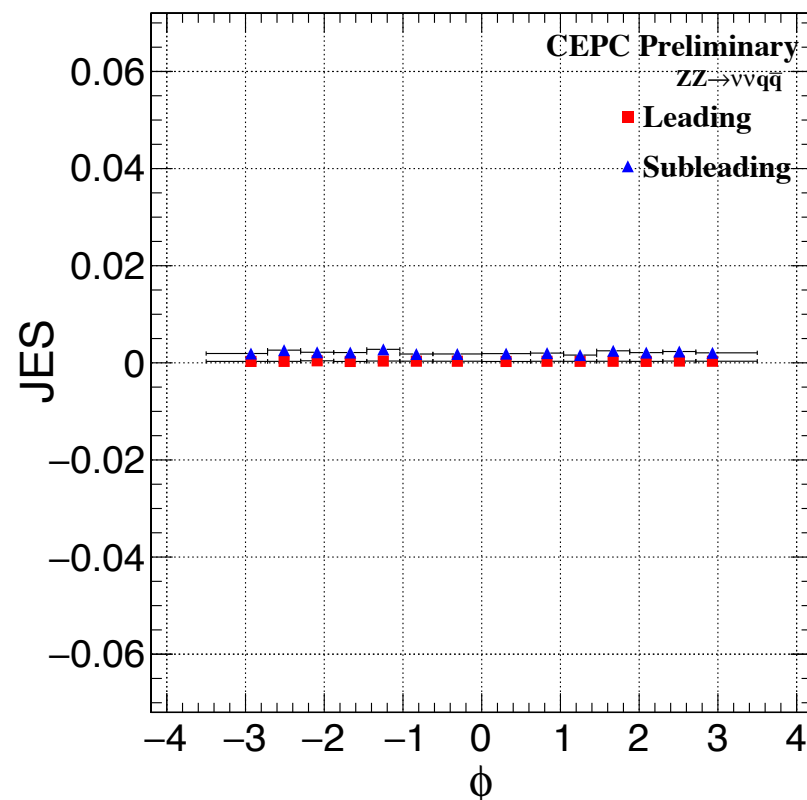
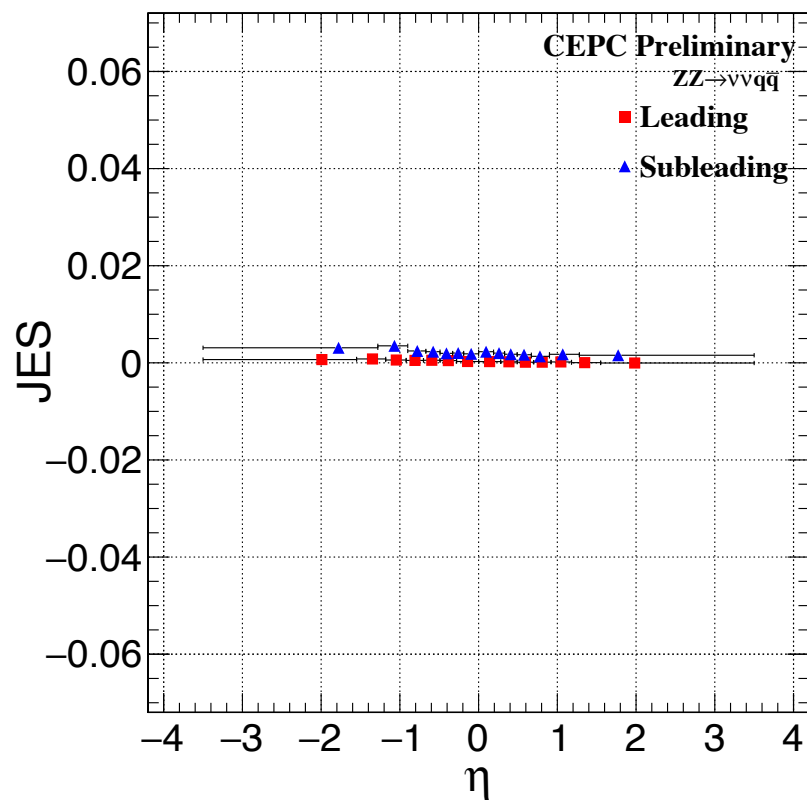
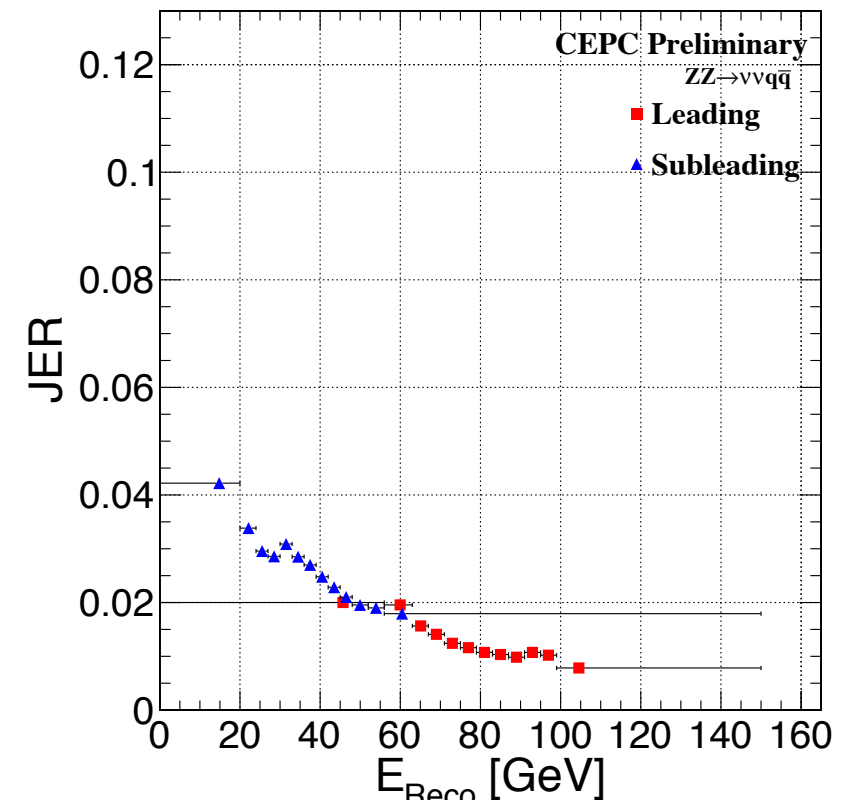
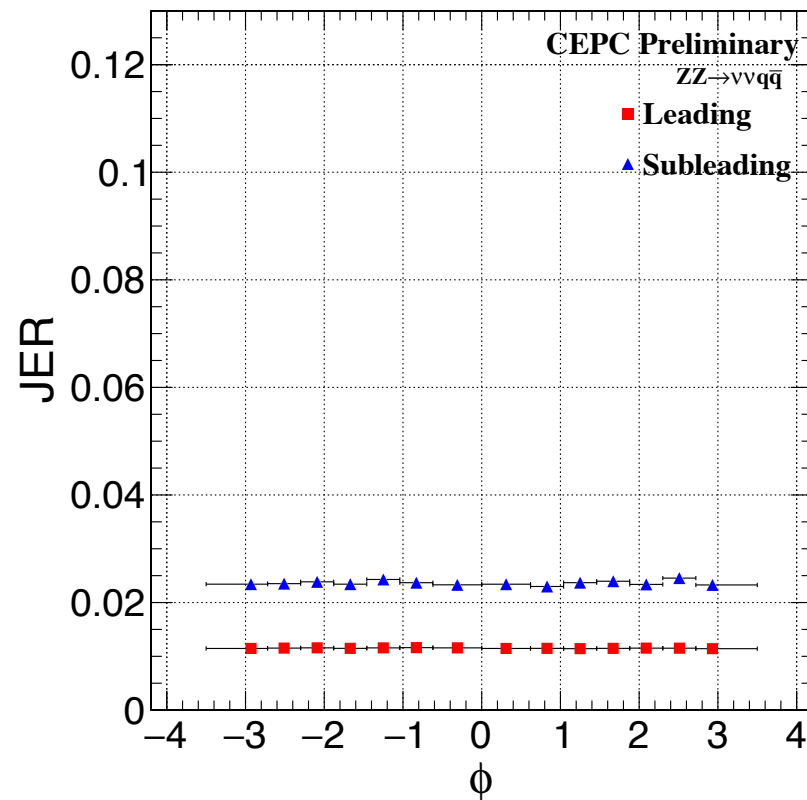
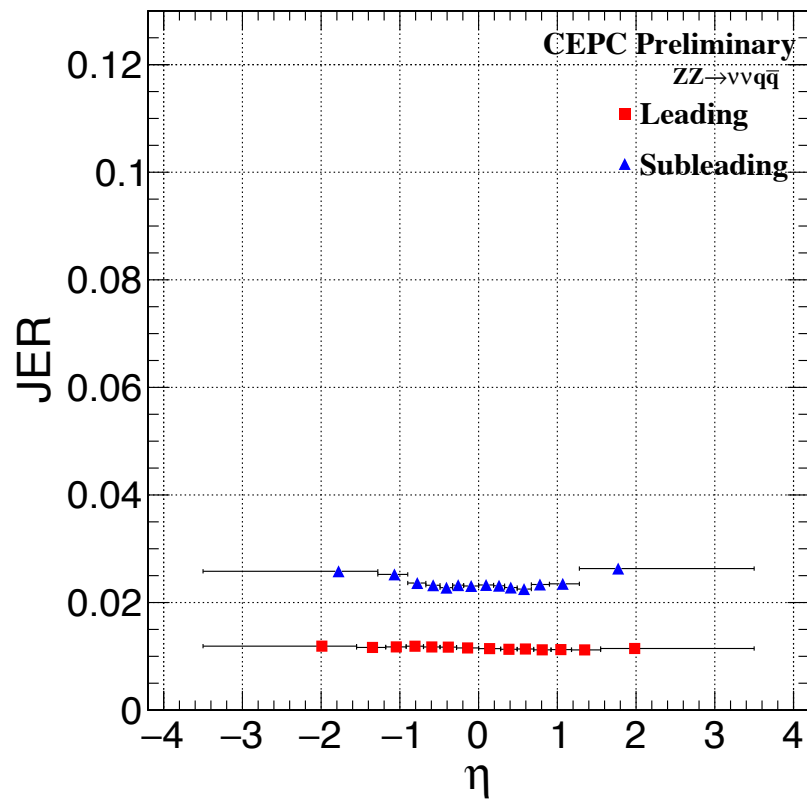
$$\frac{\text{\# of leftover event}}{\text{\# of total event}}$$

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

The Reason for ΔR Cut

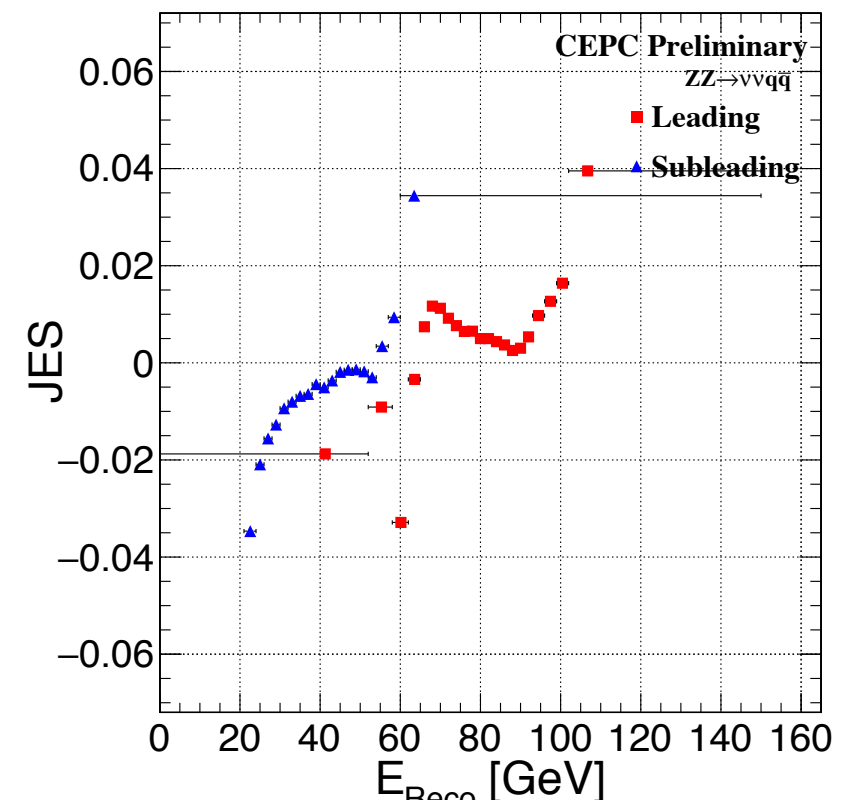
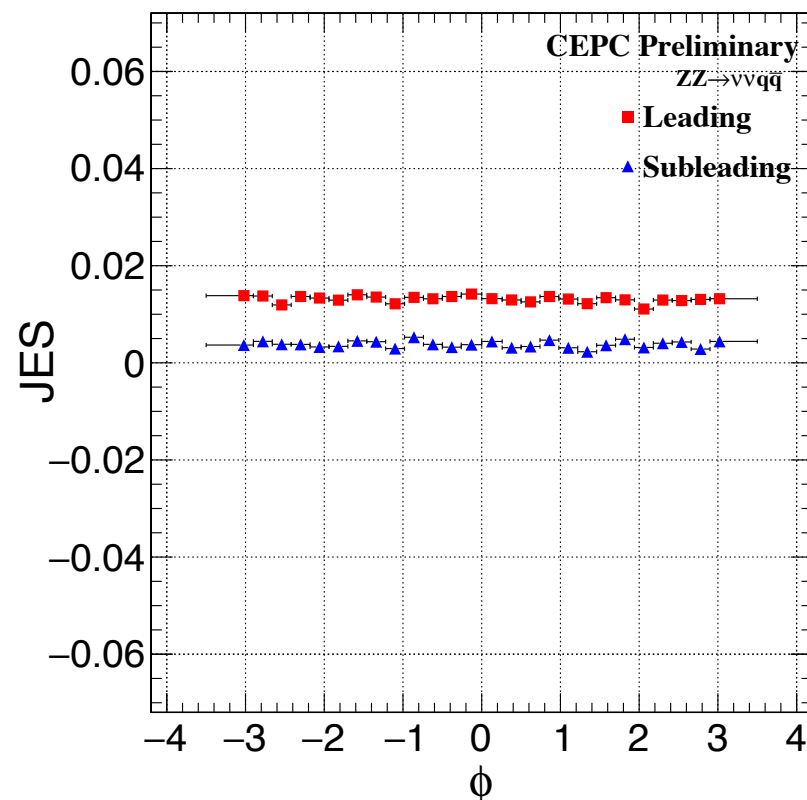
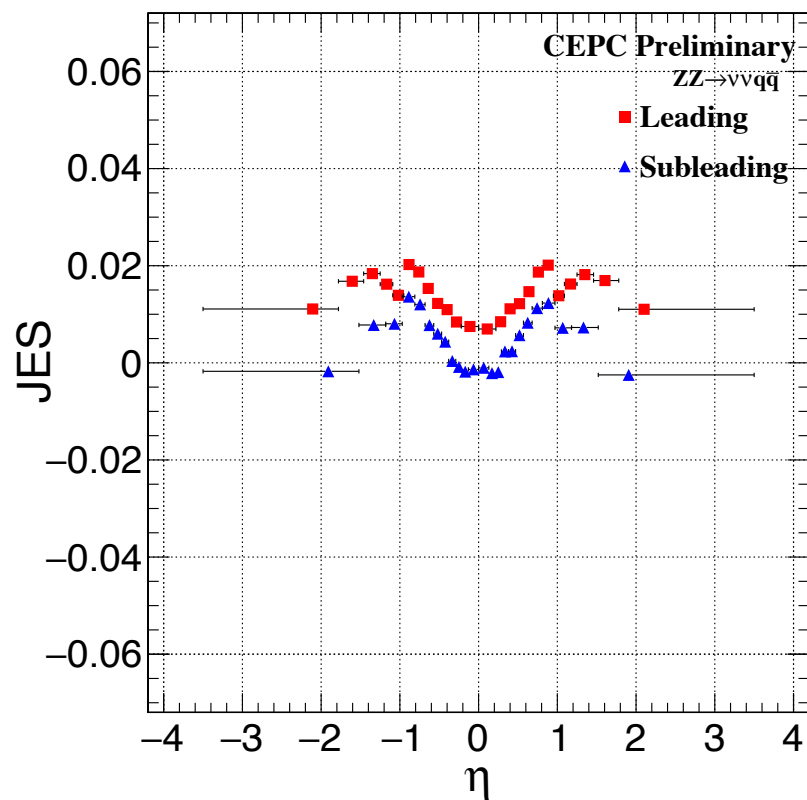
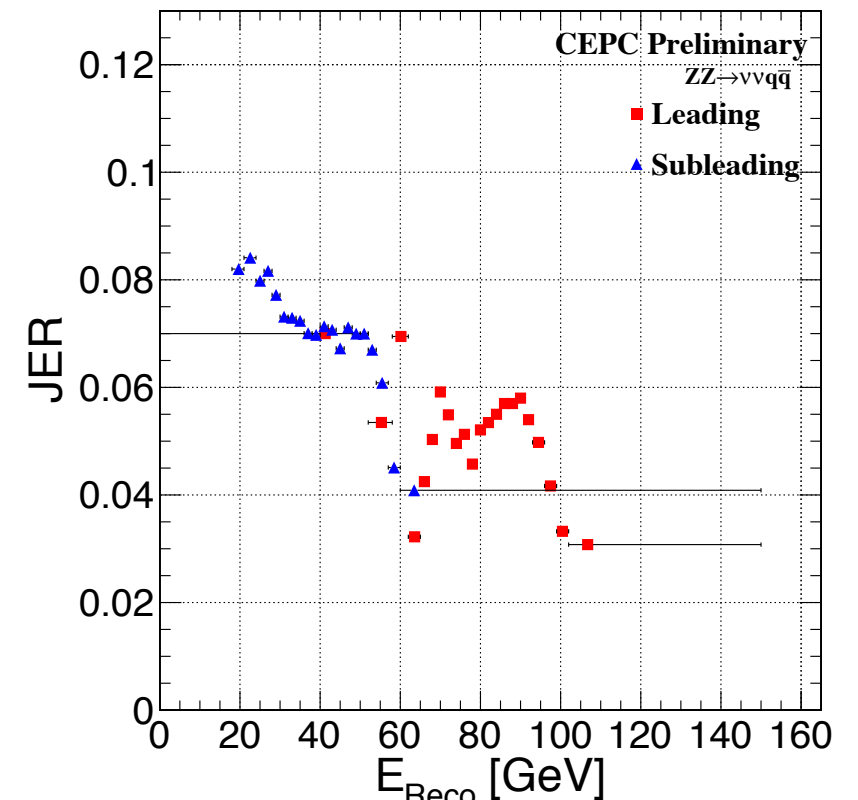
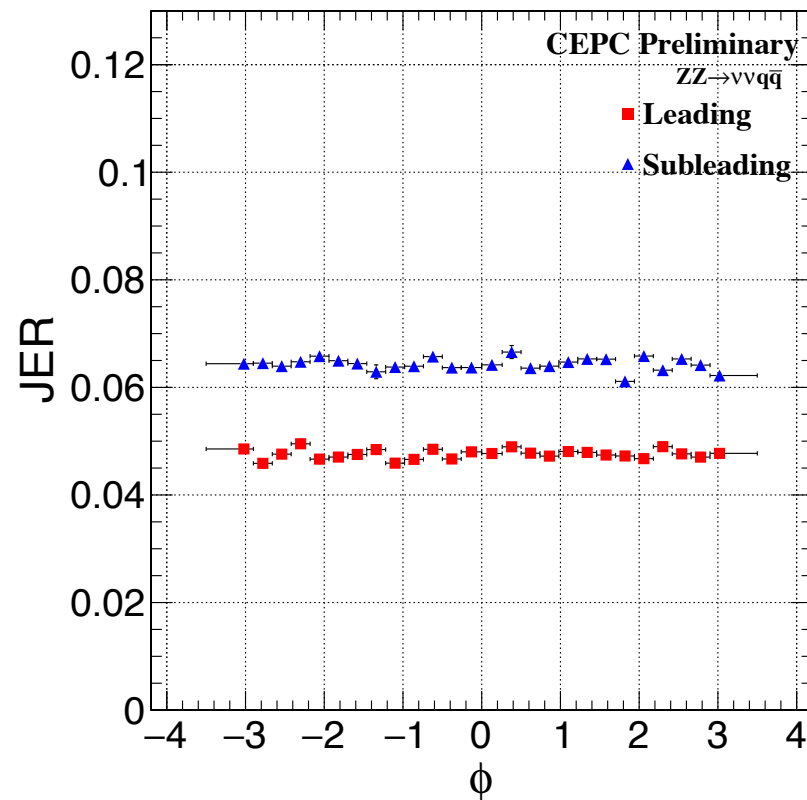
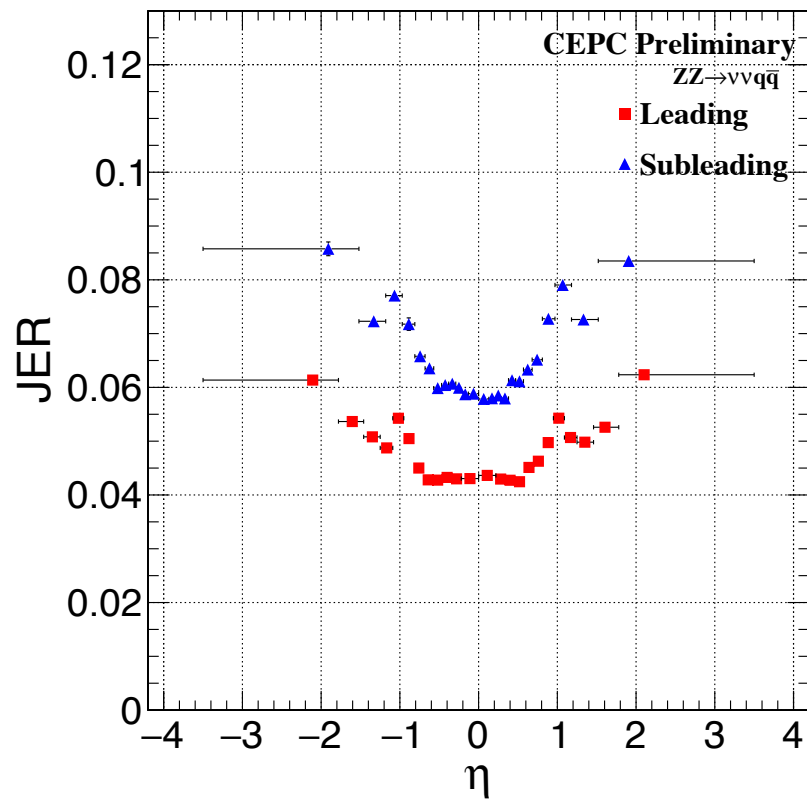


The jet clustering brings in a significant uncertainty.



The jet clustering is independent of direction.

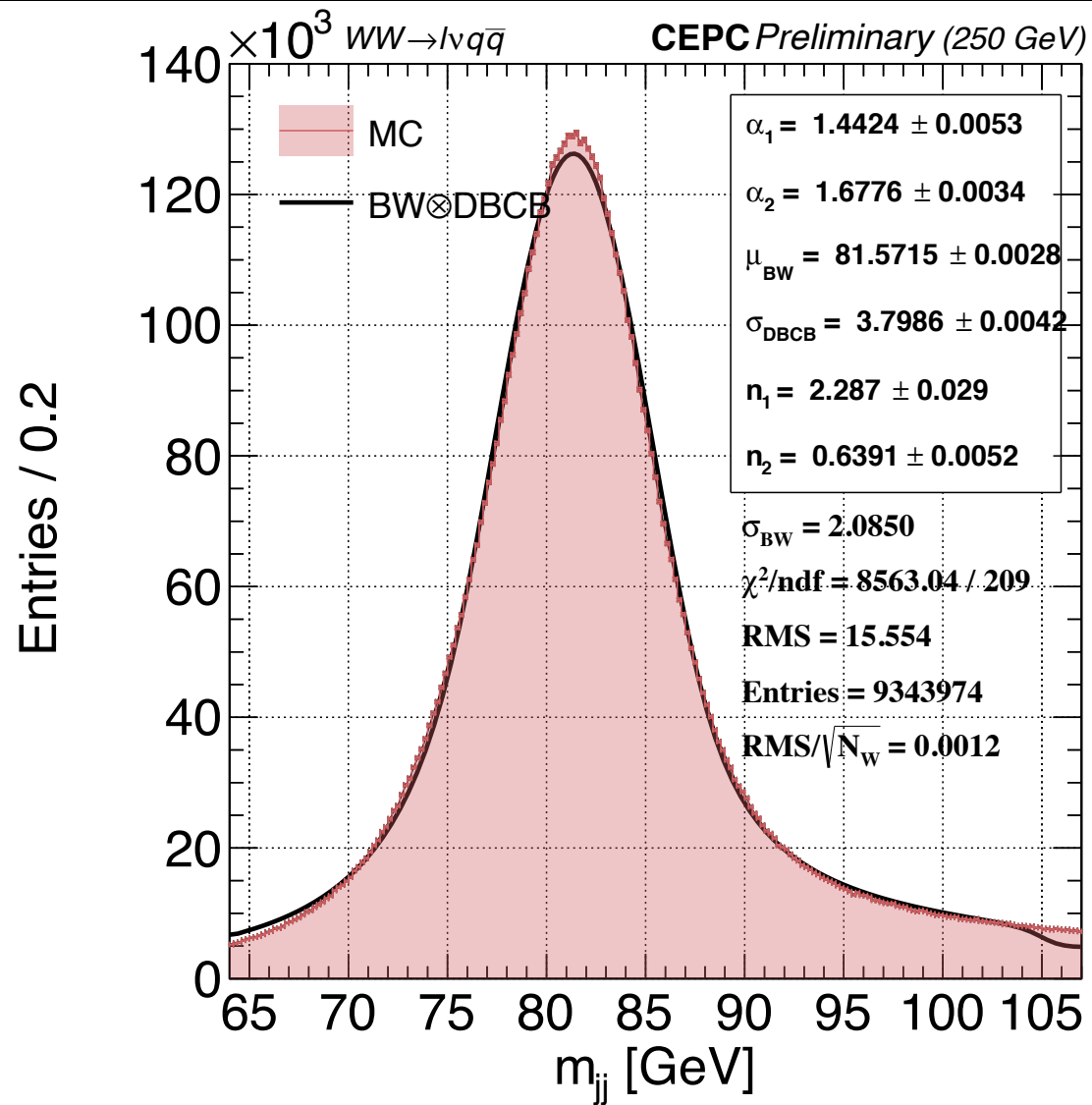
JER & JES(Reco-MCP)



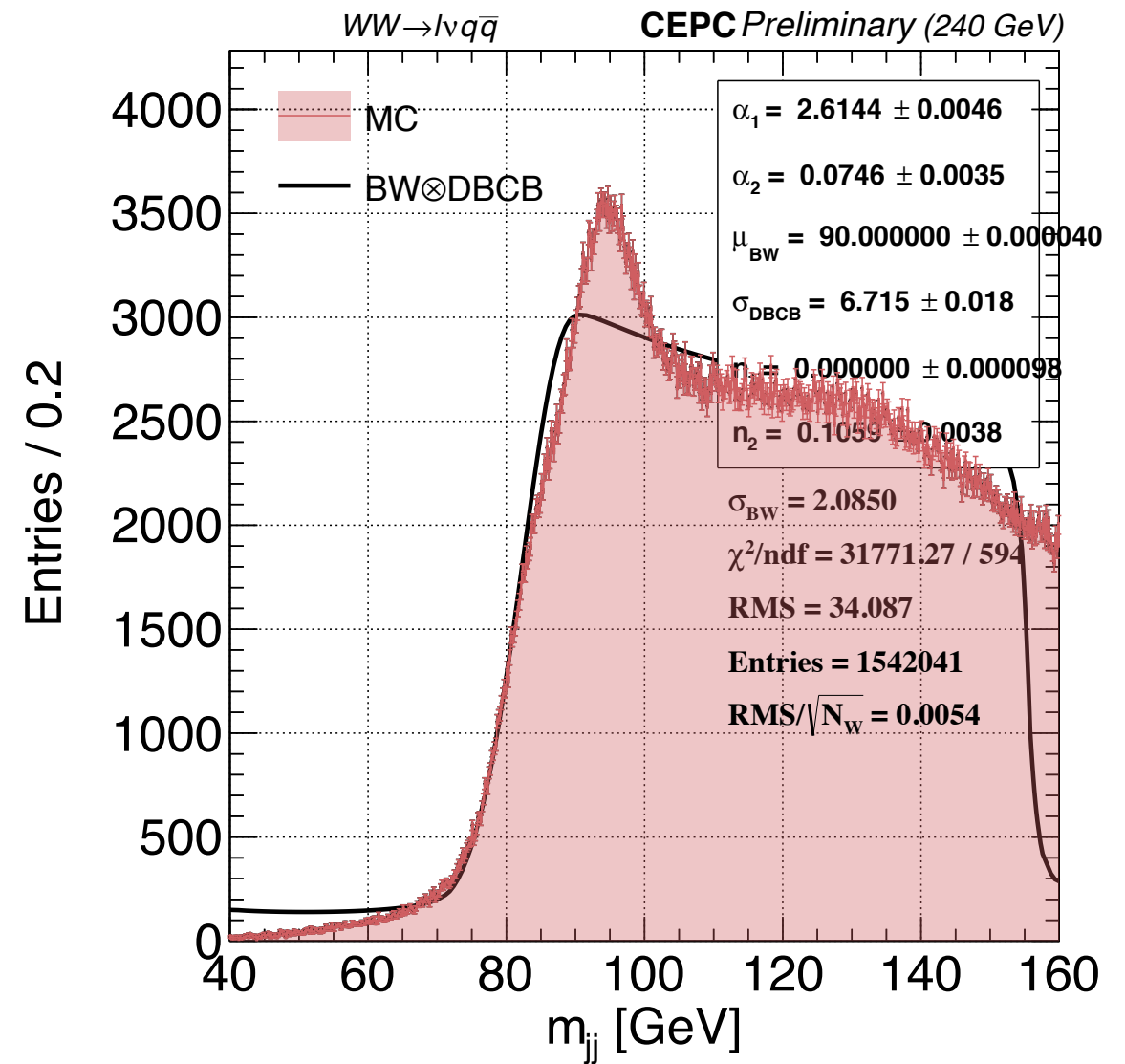
Both JER/JES depend on Eta within 2%.

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

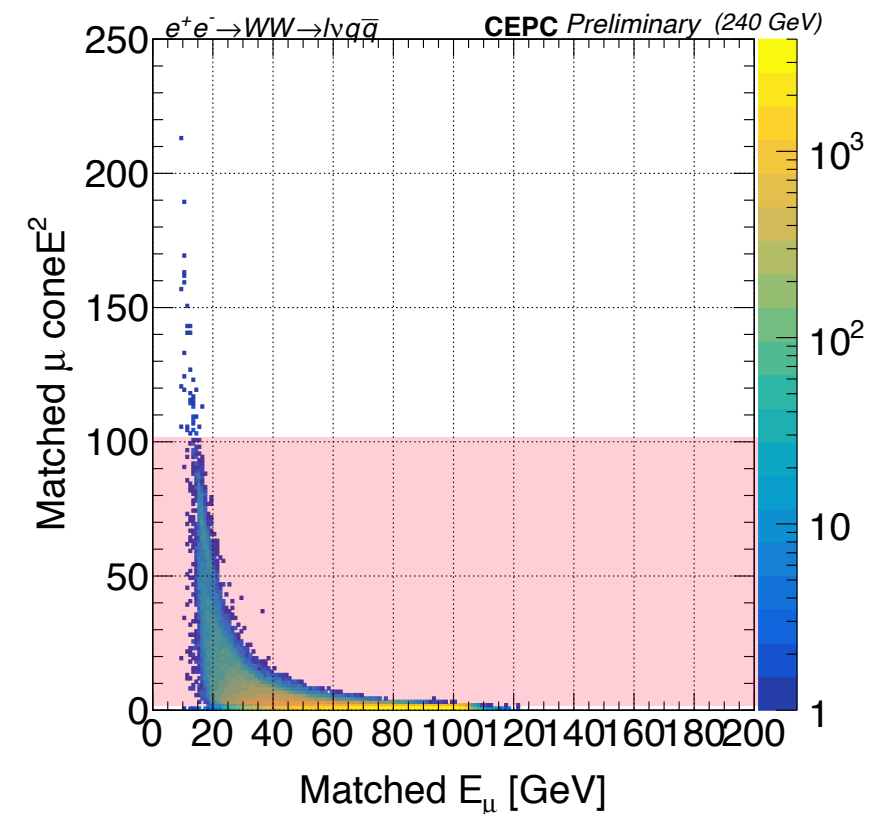
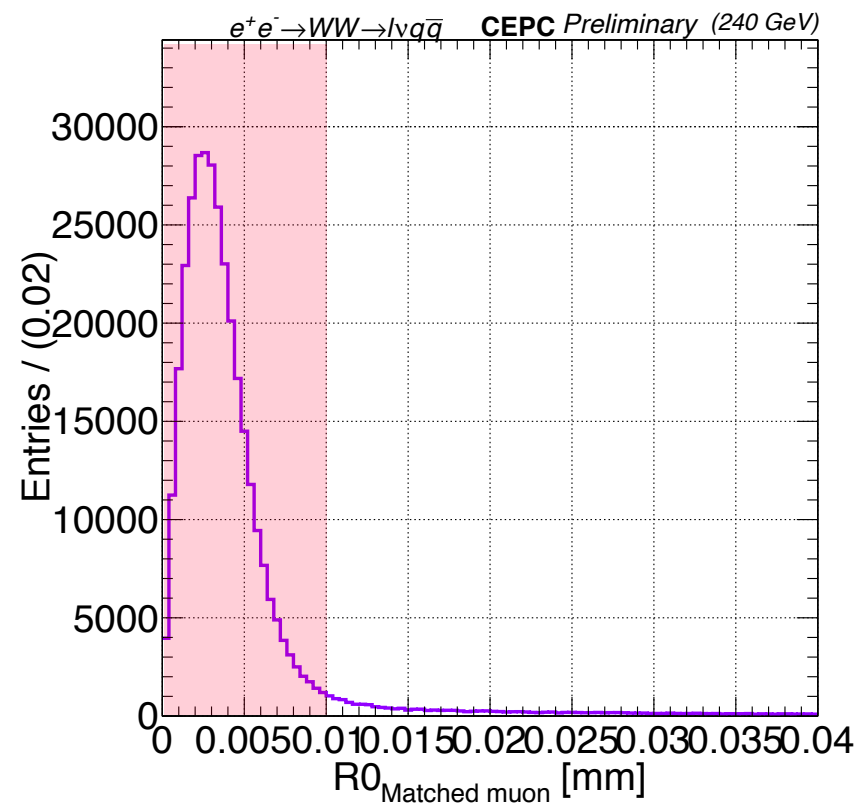
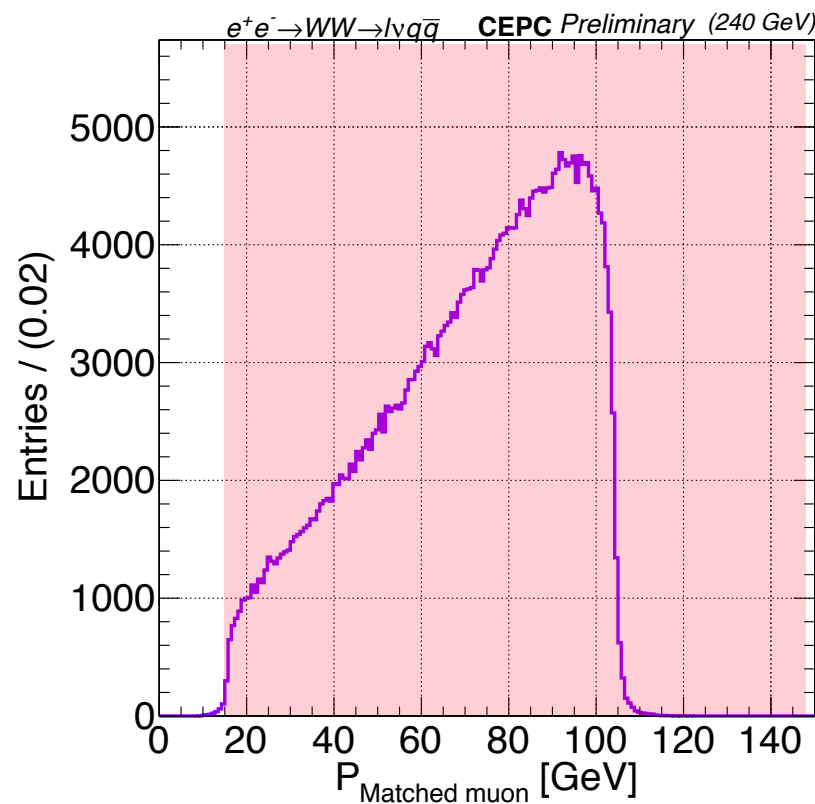


$\sqrt{s} = 250 \text{ GeV}$



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

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



■ 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: $(coneE)^2 \leq 100$

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

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

- 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

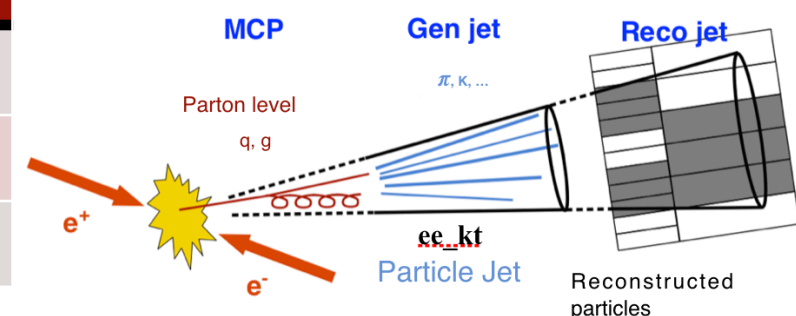
Type	JER		JES	
	Lead	Sub-Lead	Lead	Sub-Lead
Barrel	1%	2%	0	0
Endcaps	1%	2%	0	0
En > 60 GeV	1%	2%	0	0

Reco-Gen

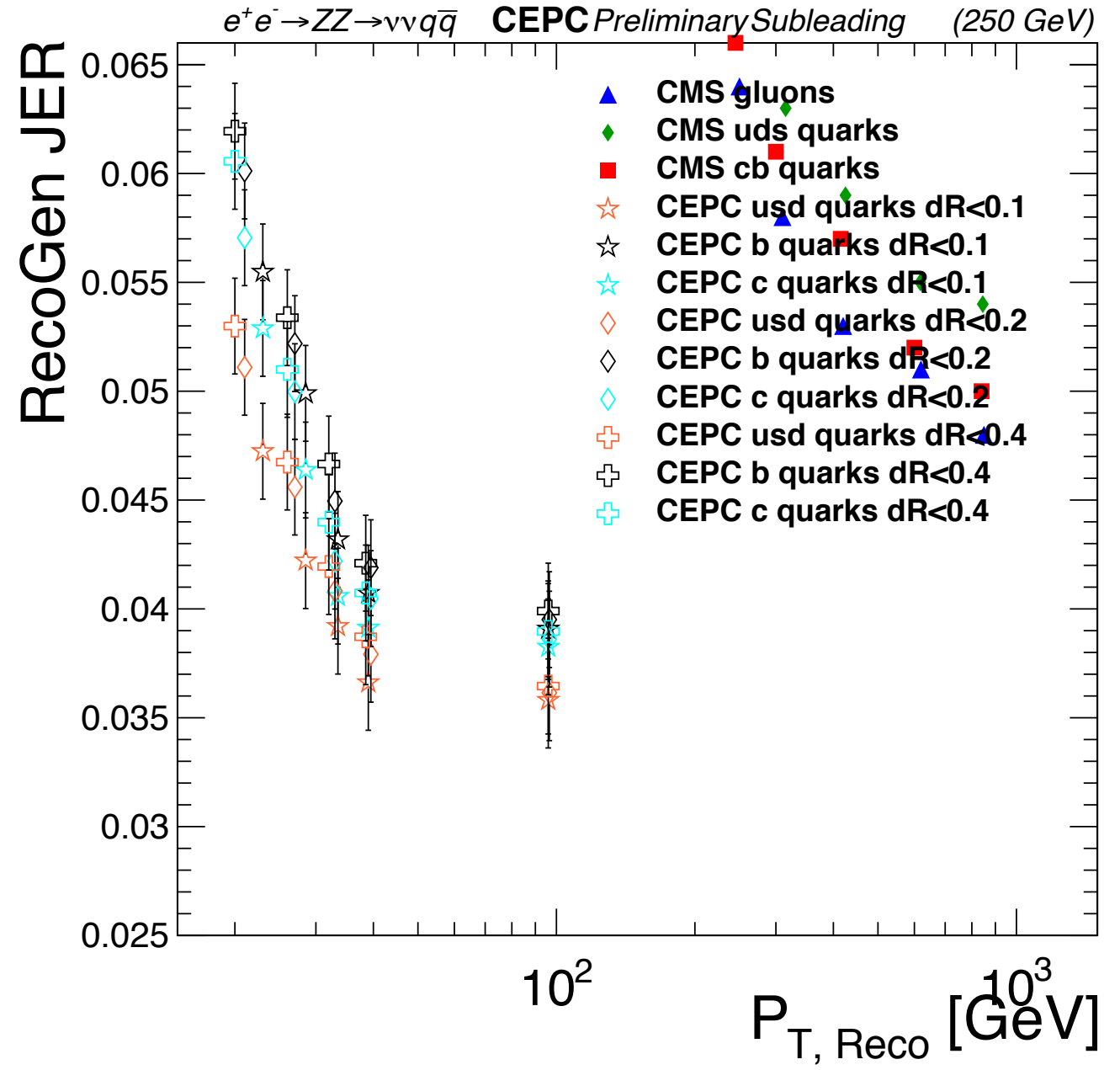
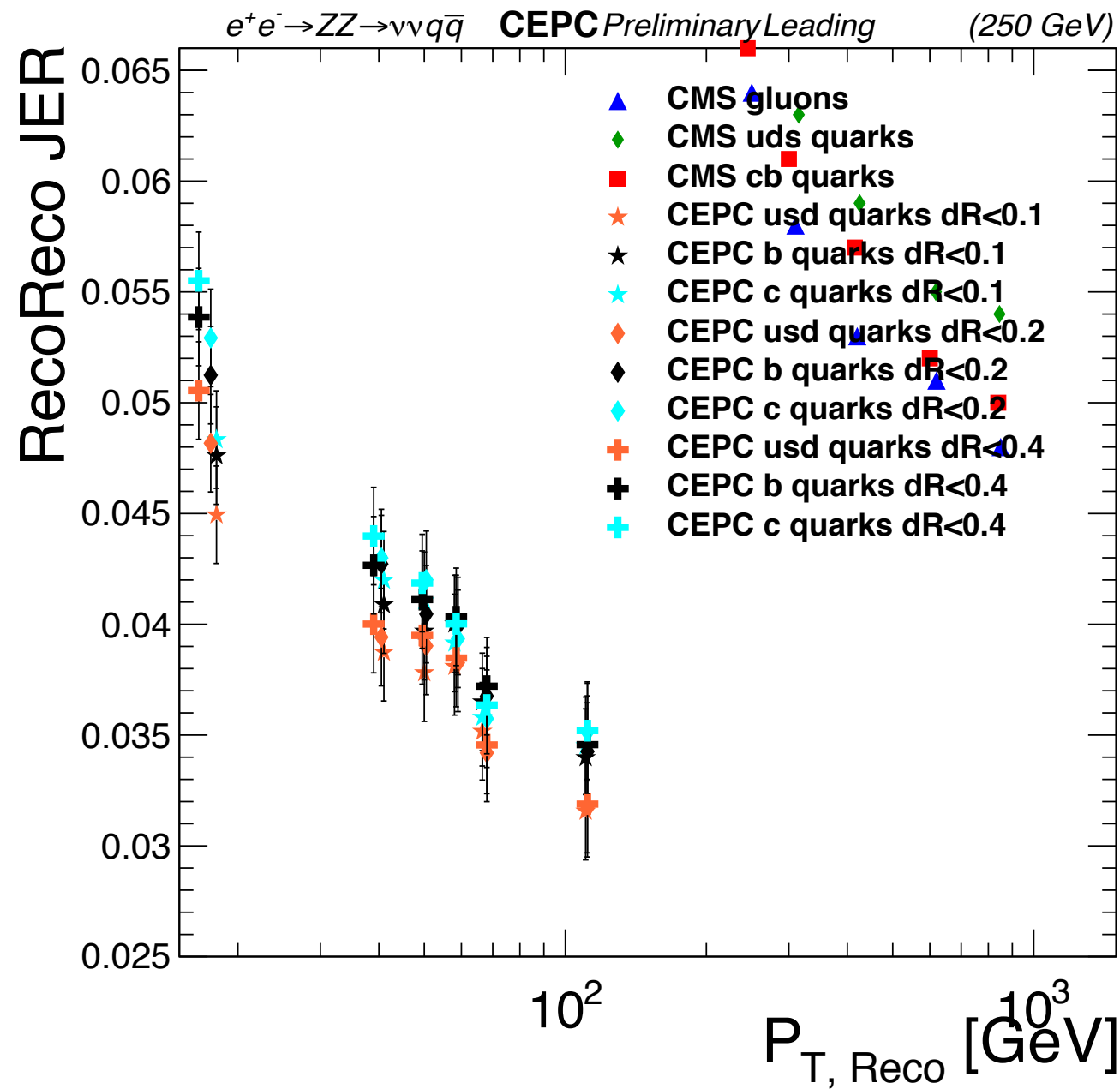
Type	JER		JES	
	Lead	Sub-Lead	Lead	Sub-Lead
Barrel	3.5%	4.5%	1%	0
Endcaps	4%	5%	1.5%	0.5%
En > 60 GeV	4%	4.5%	1%	1.5%

Reco-MCP

Type	JER		JES	
	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%

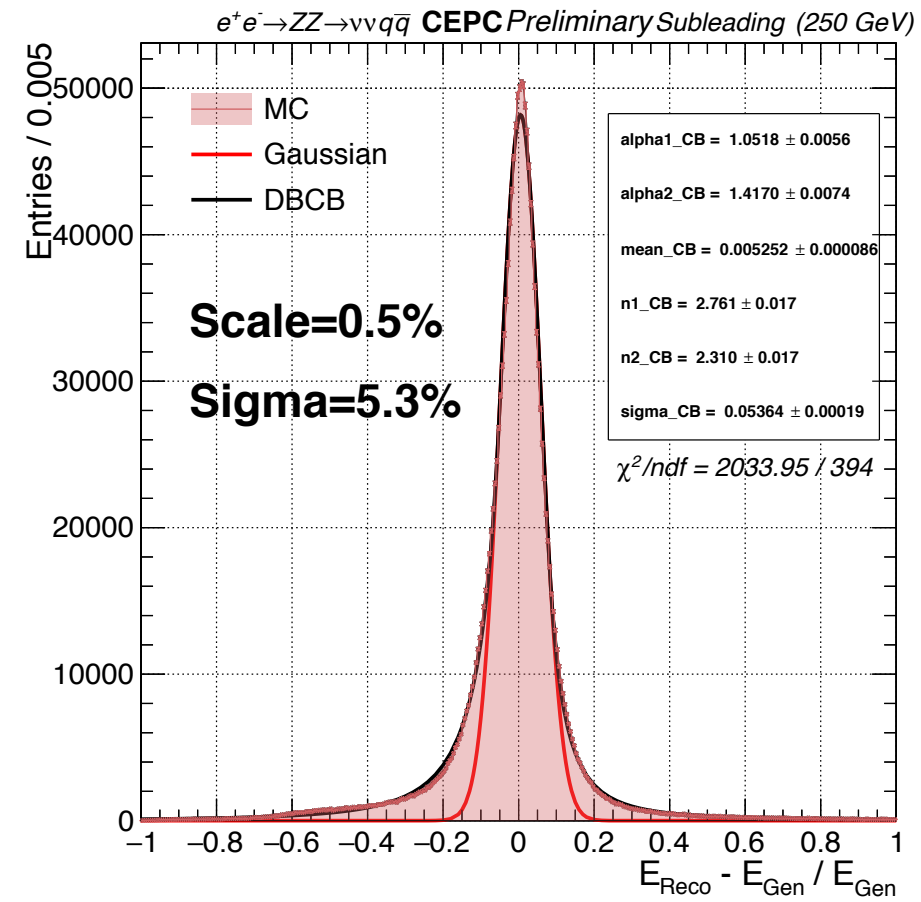
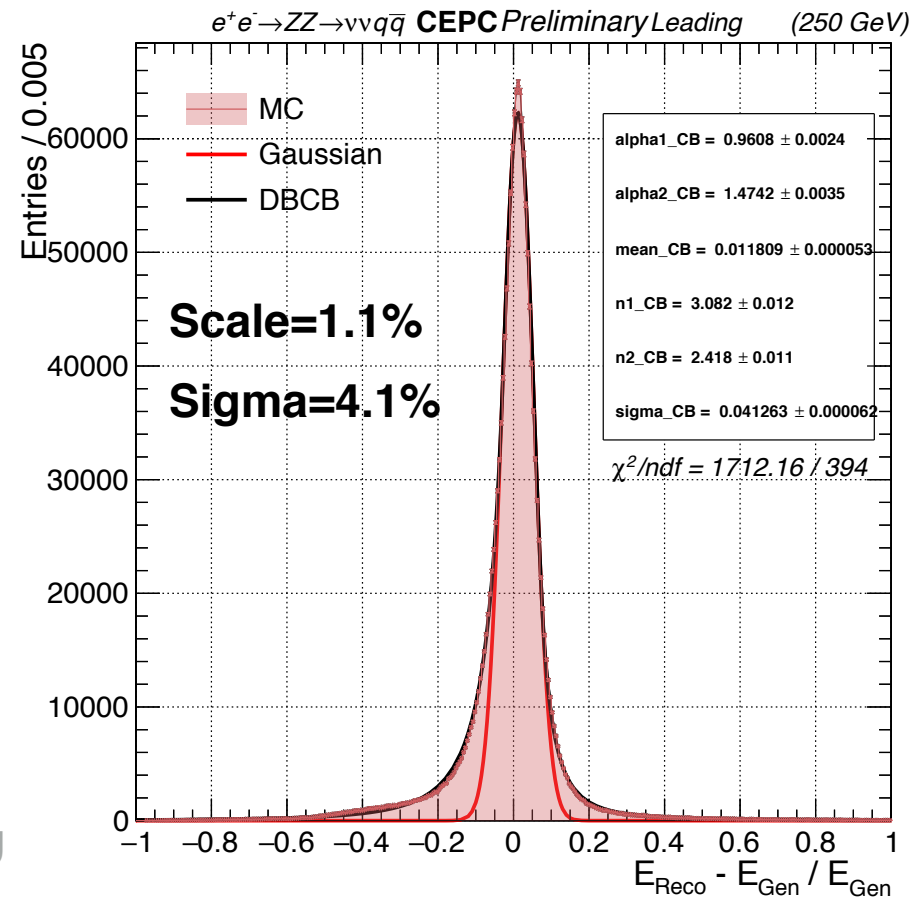
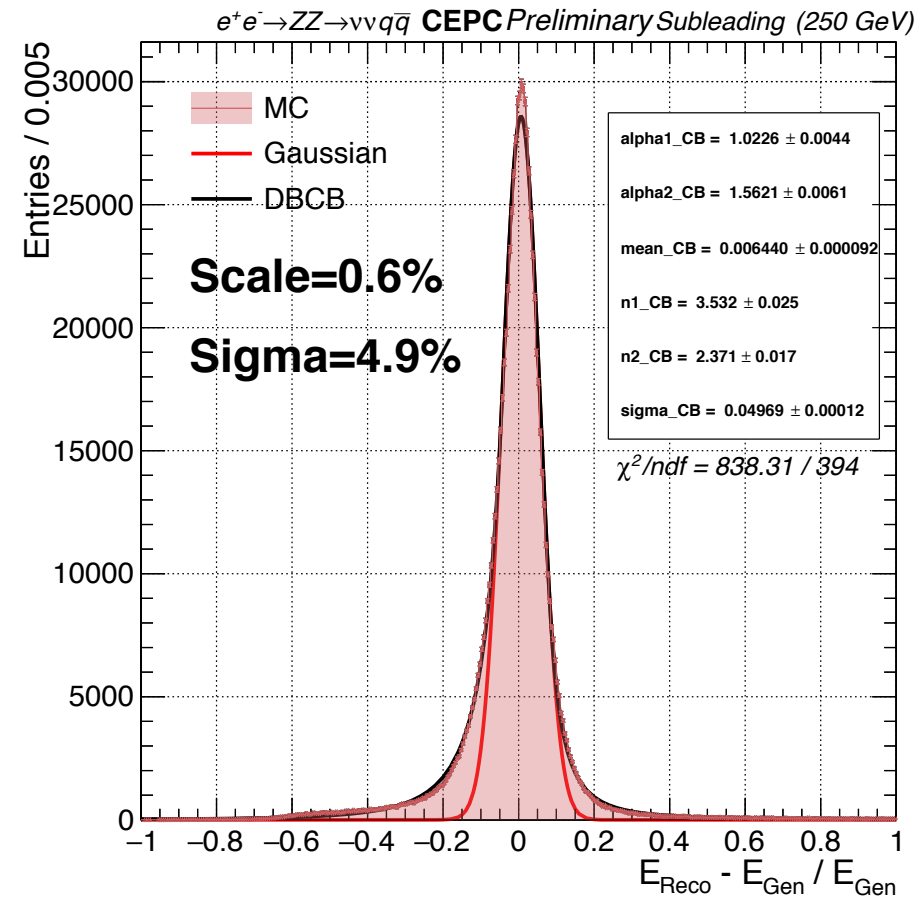
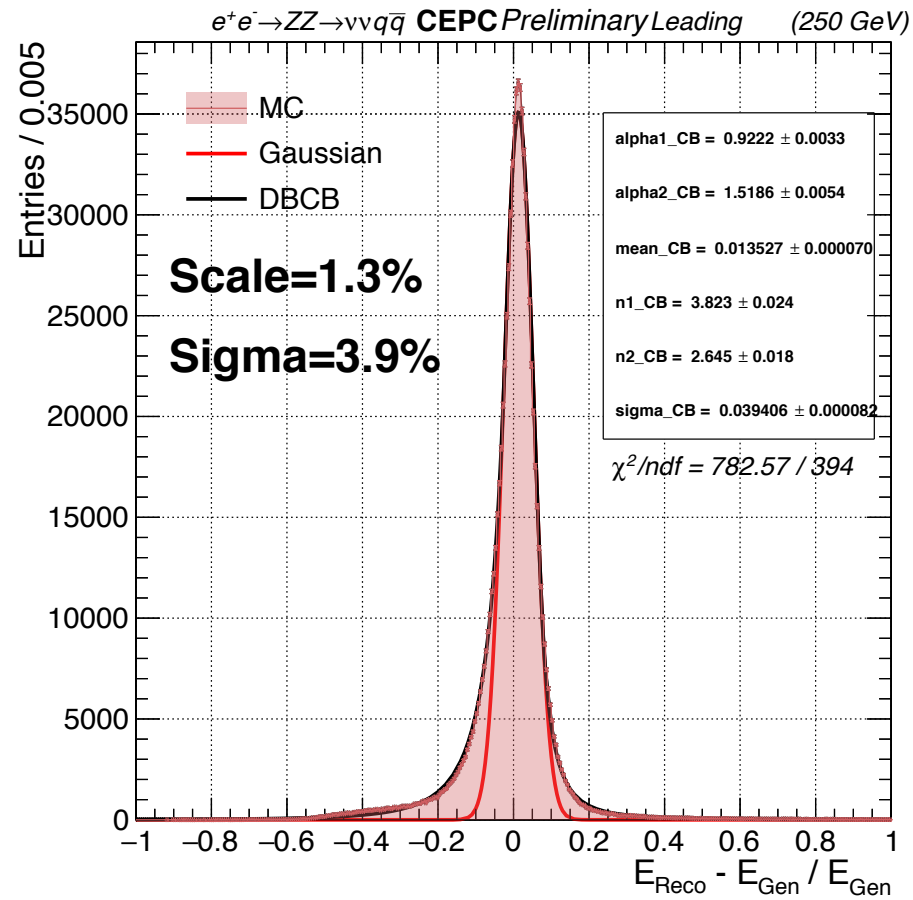


JER with Different dR



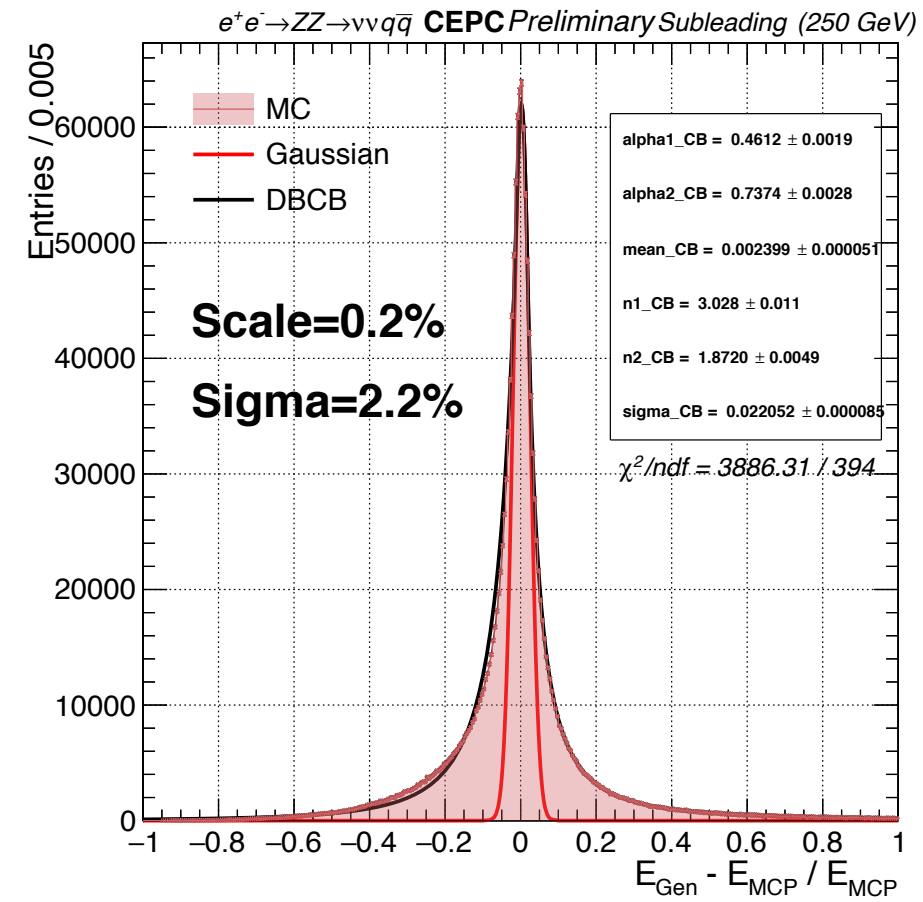
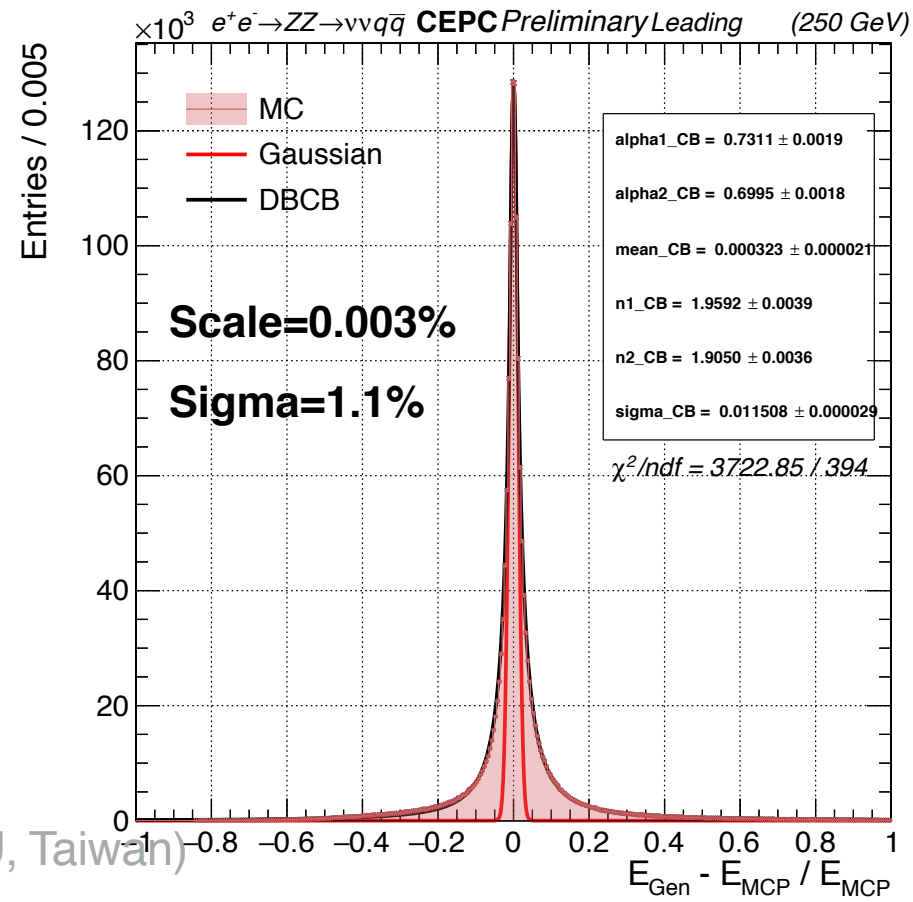
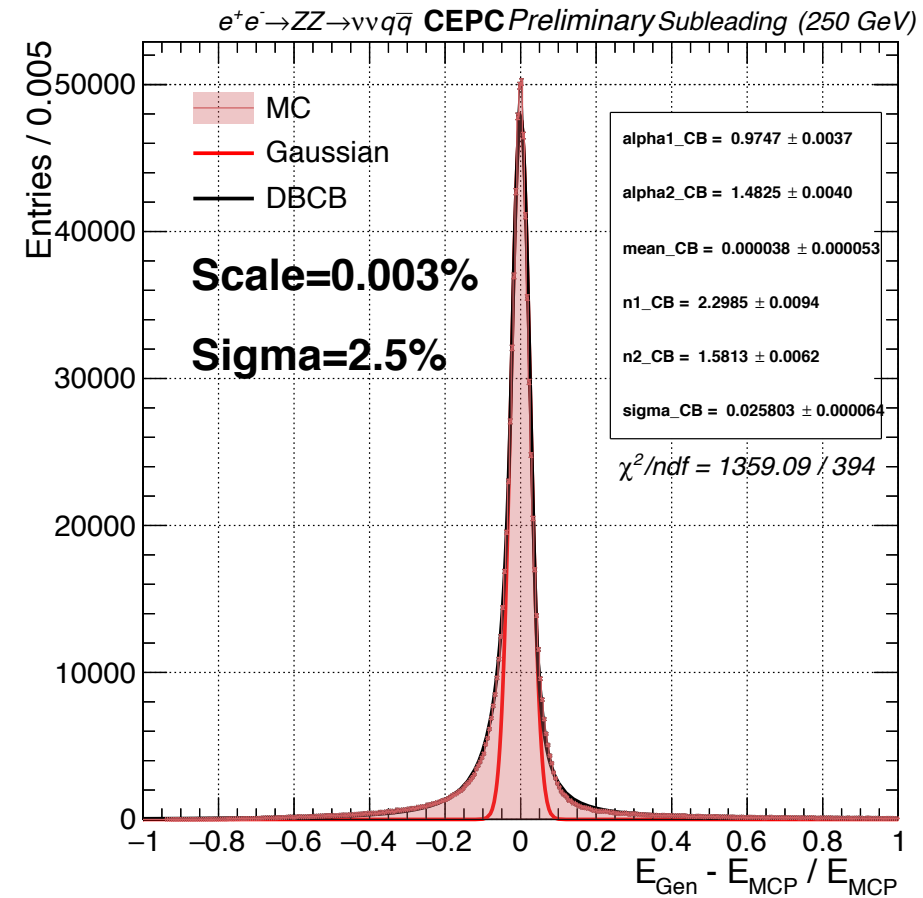
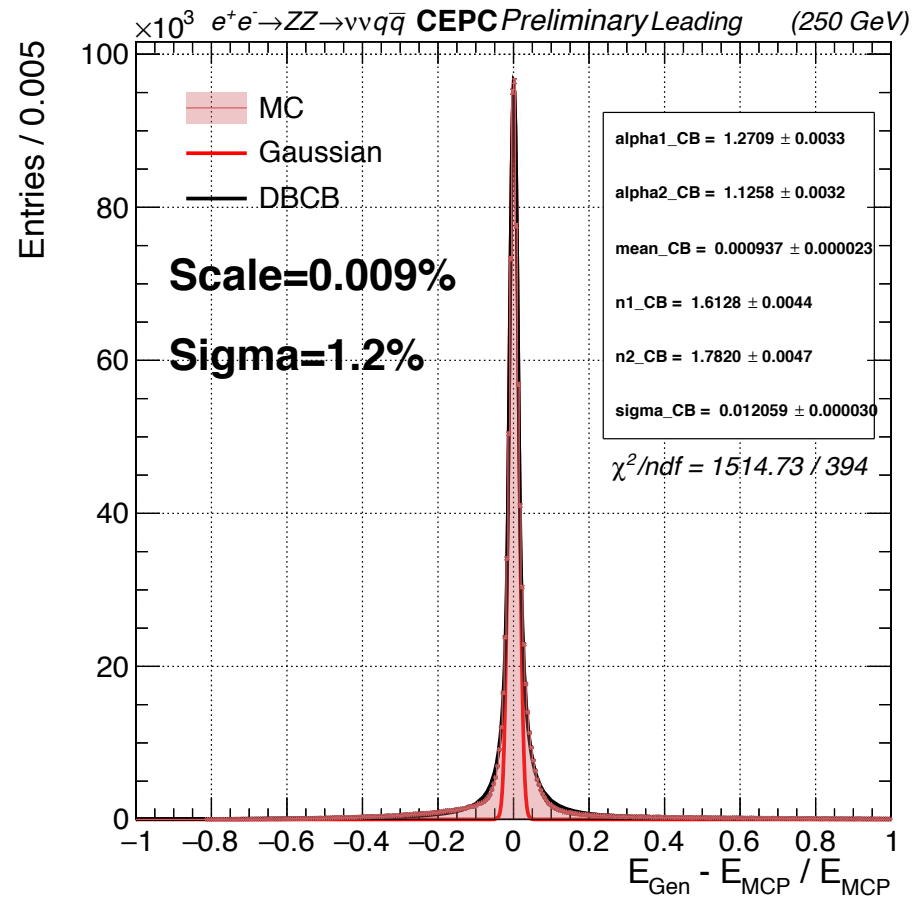
Compare the Results Whether with dR Cut (Reco-Gen)

dR < 0.1



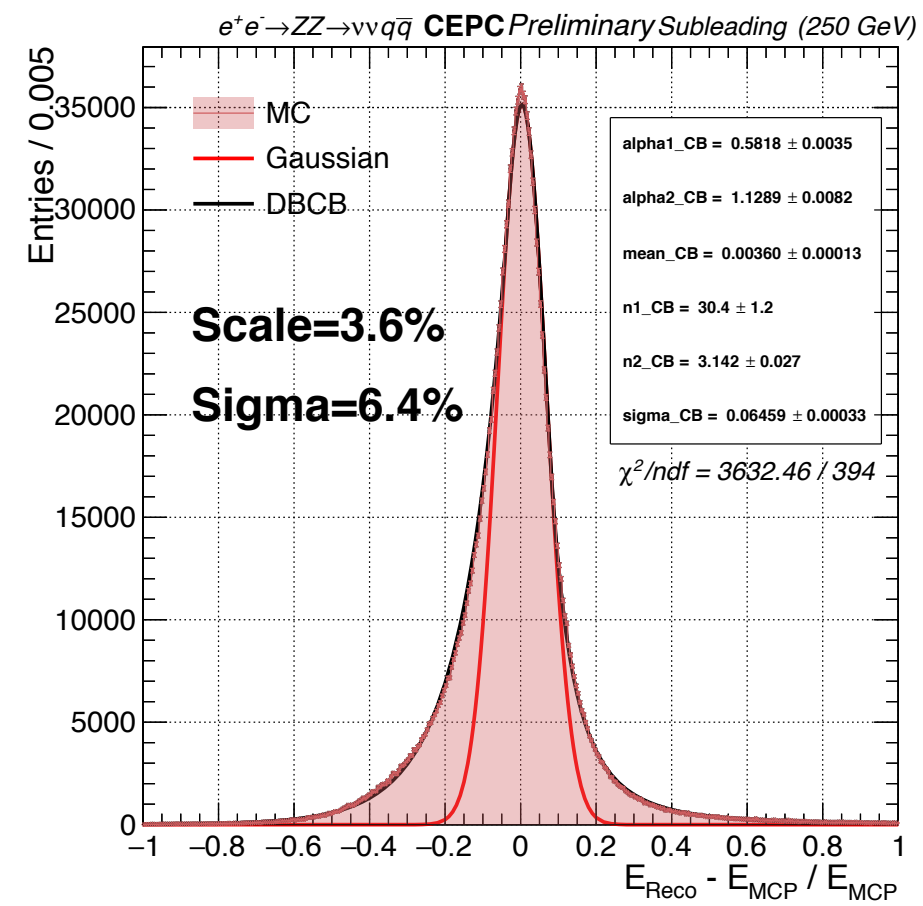
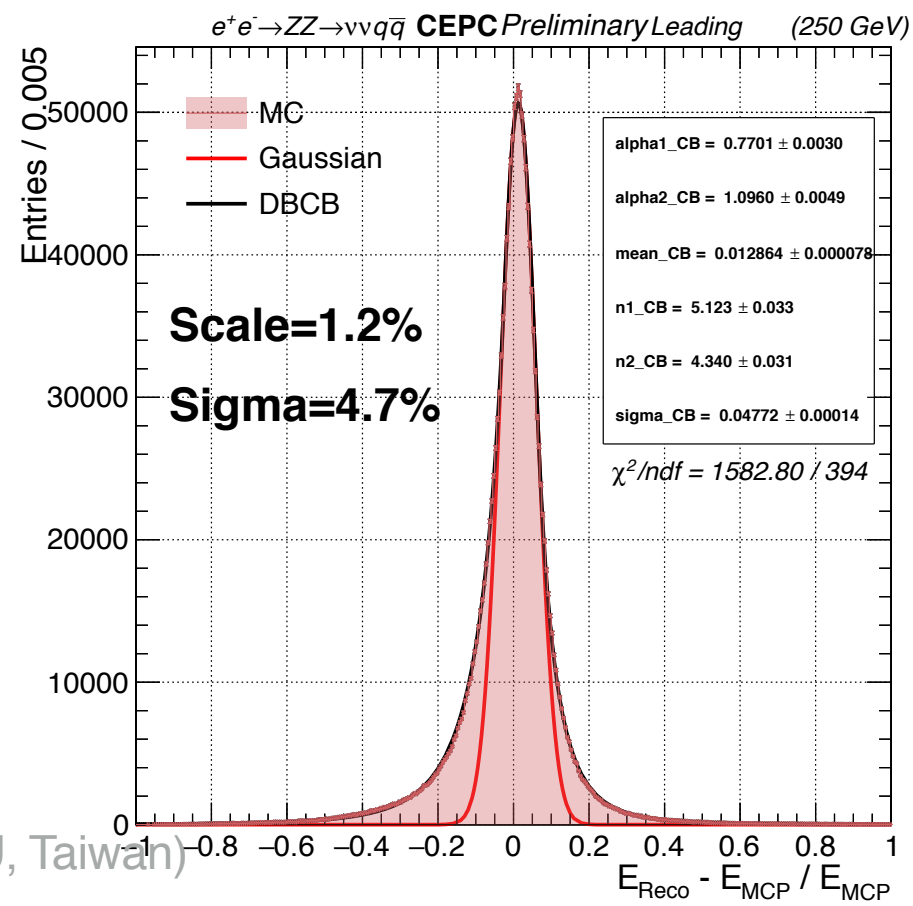
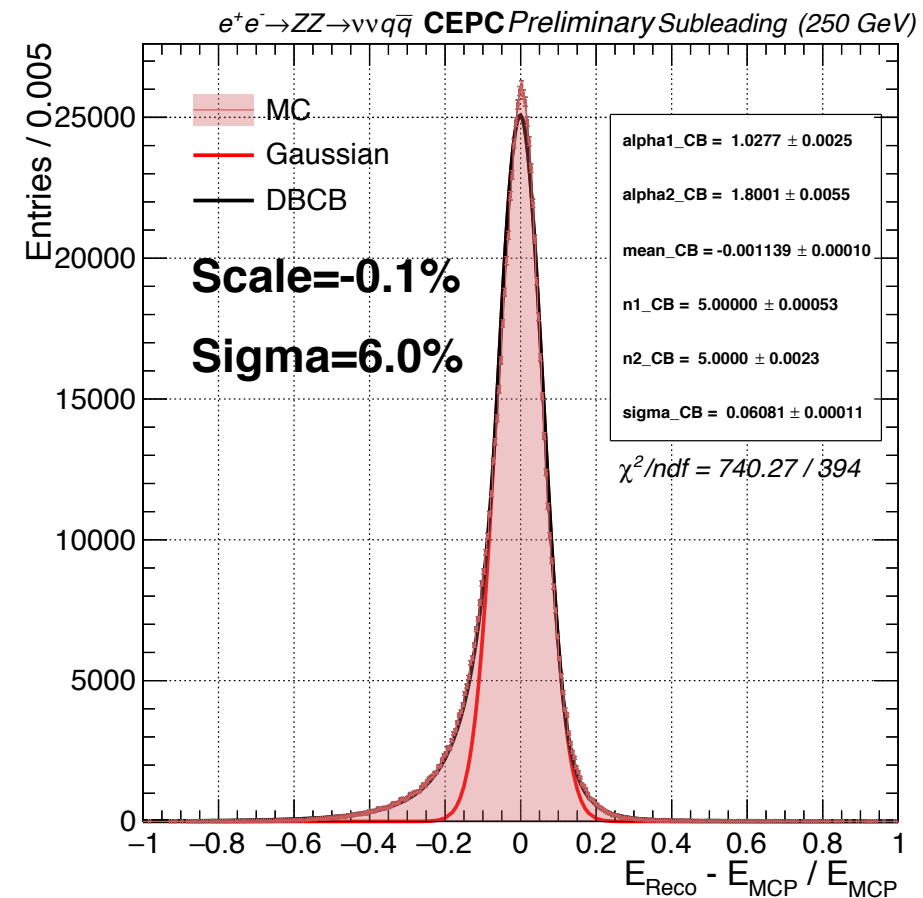
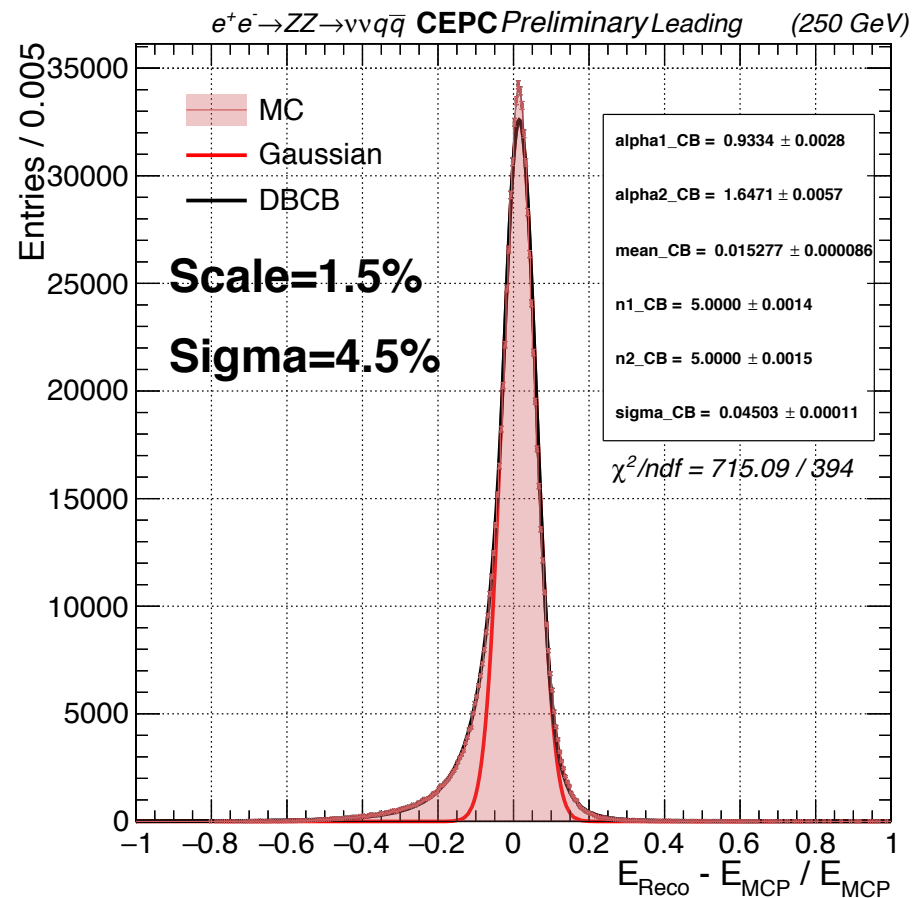
Compare the Results Whether with dR Cut (Gen-MCP)

dR < 0.1

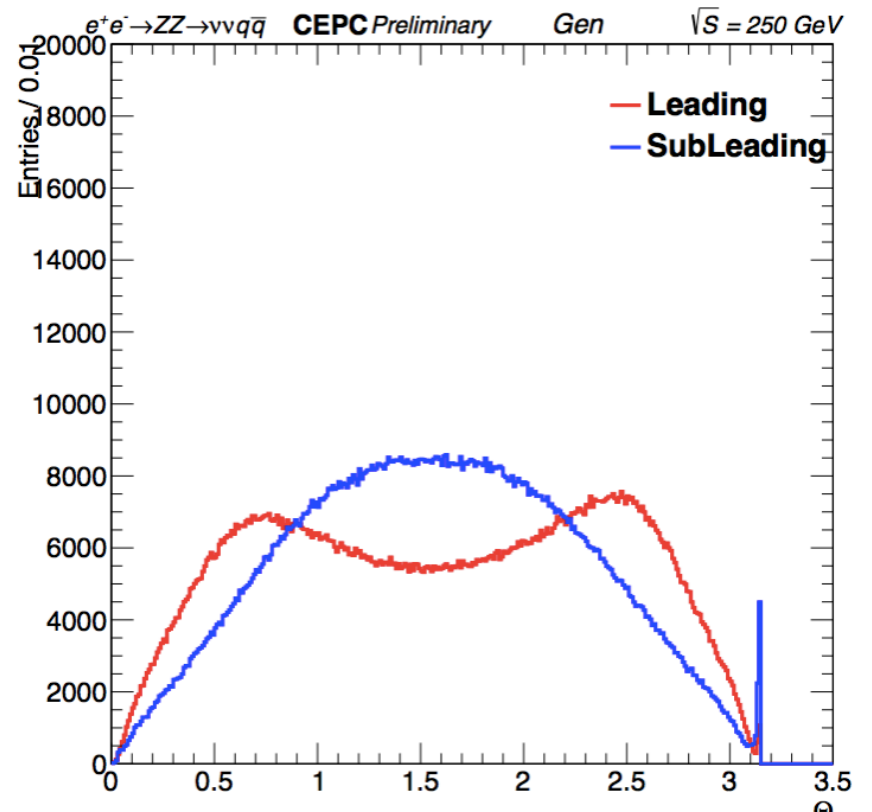
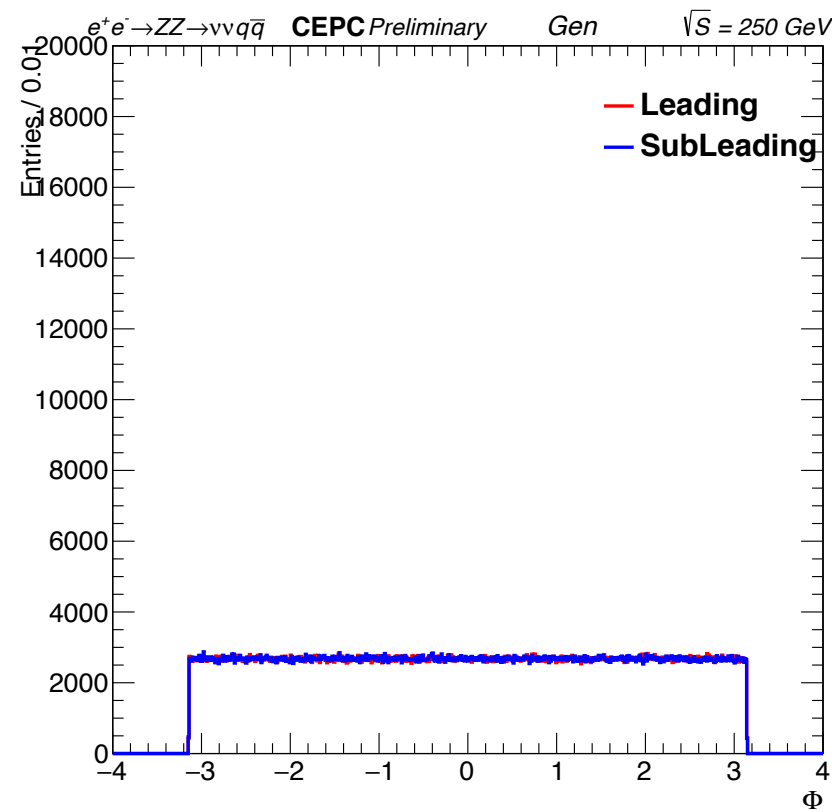
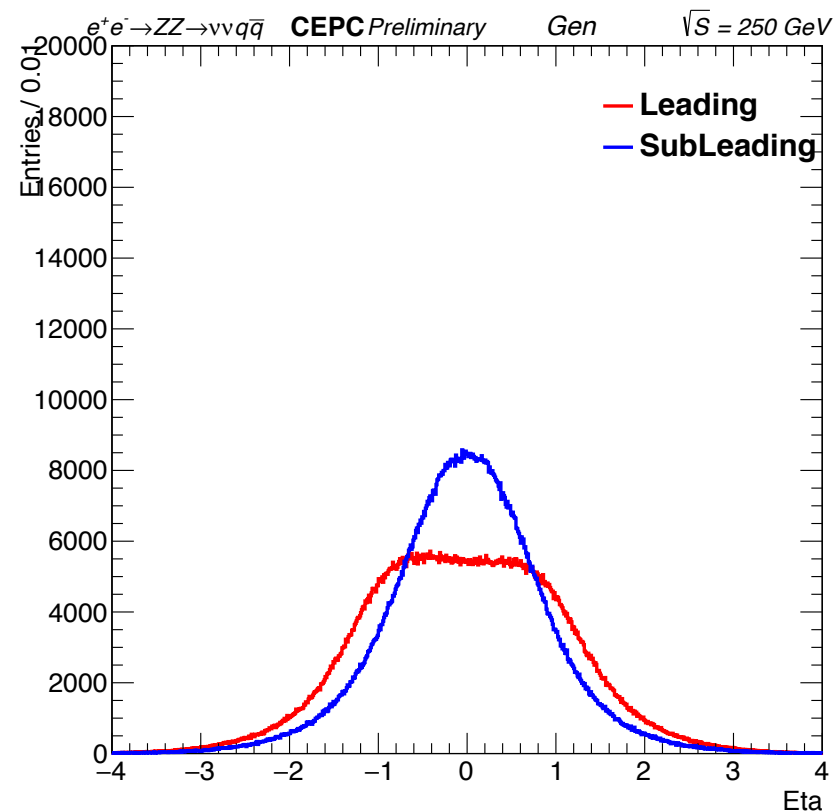
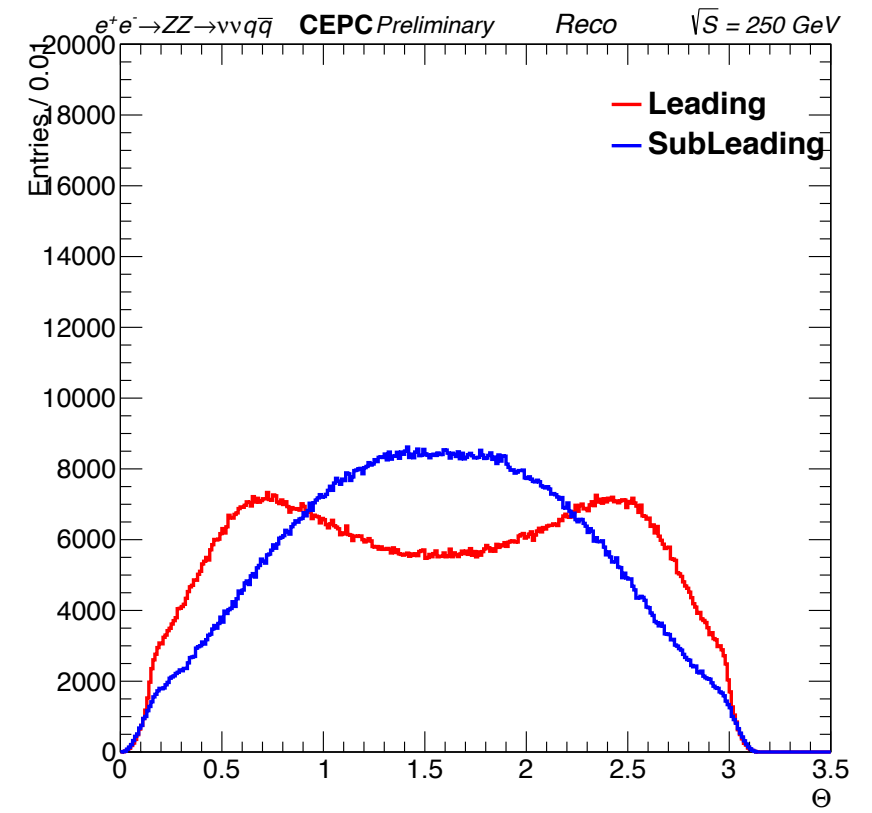
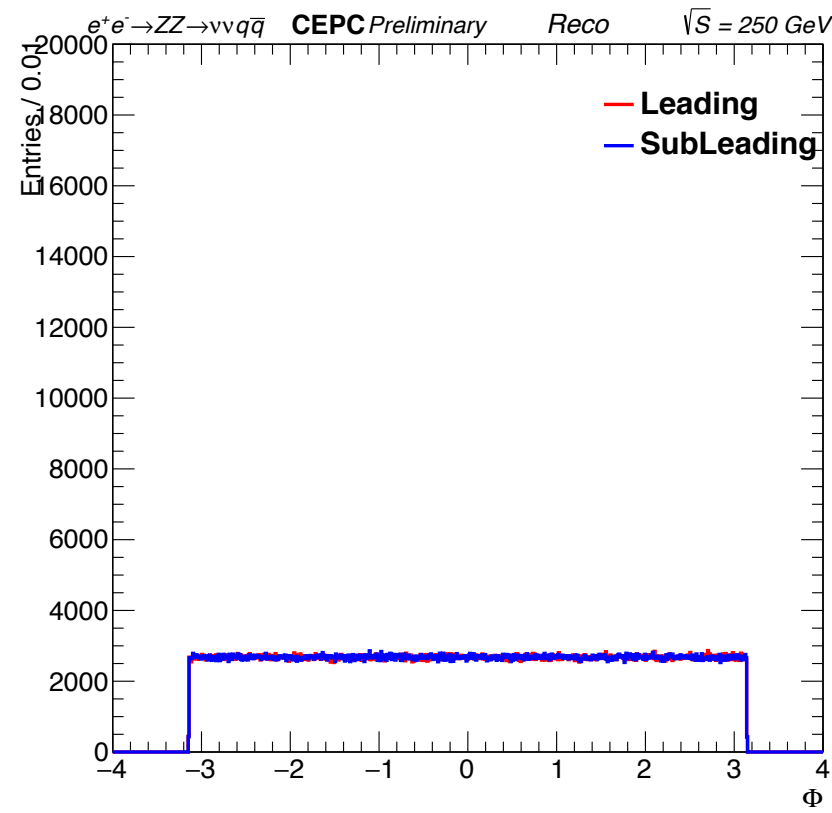
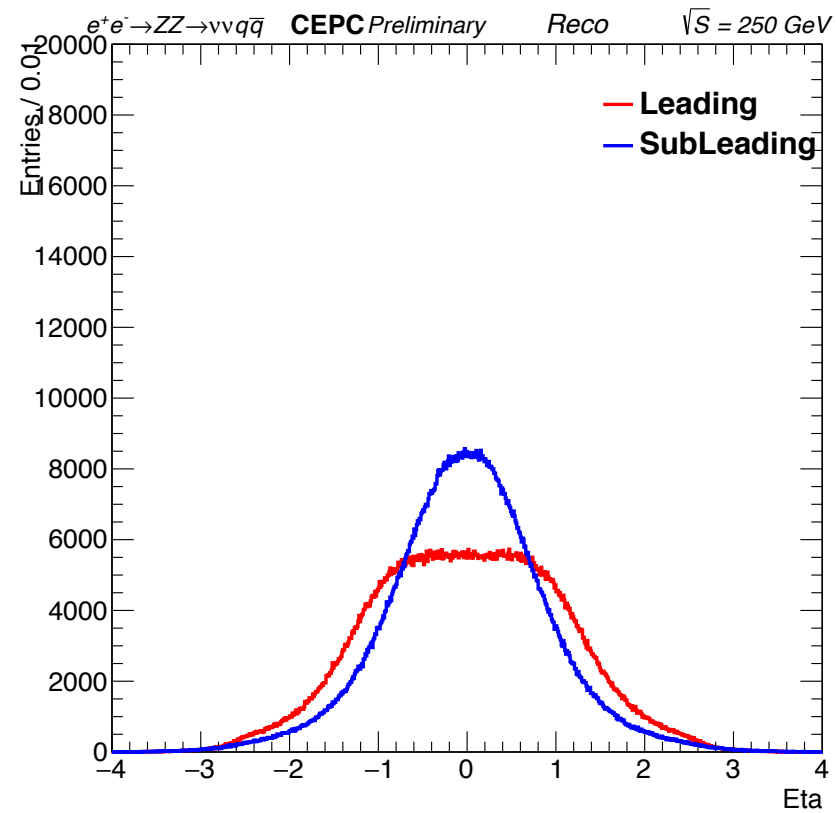


Compare the Results Whether with dR Cut (Reco-MCP)

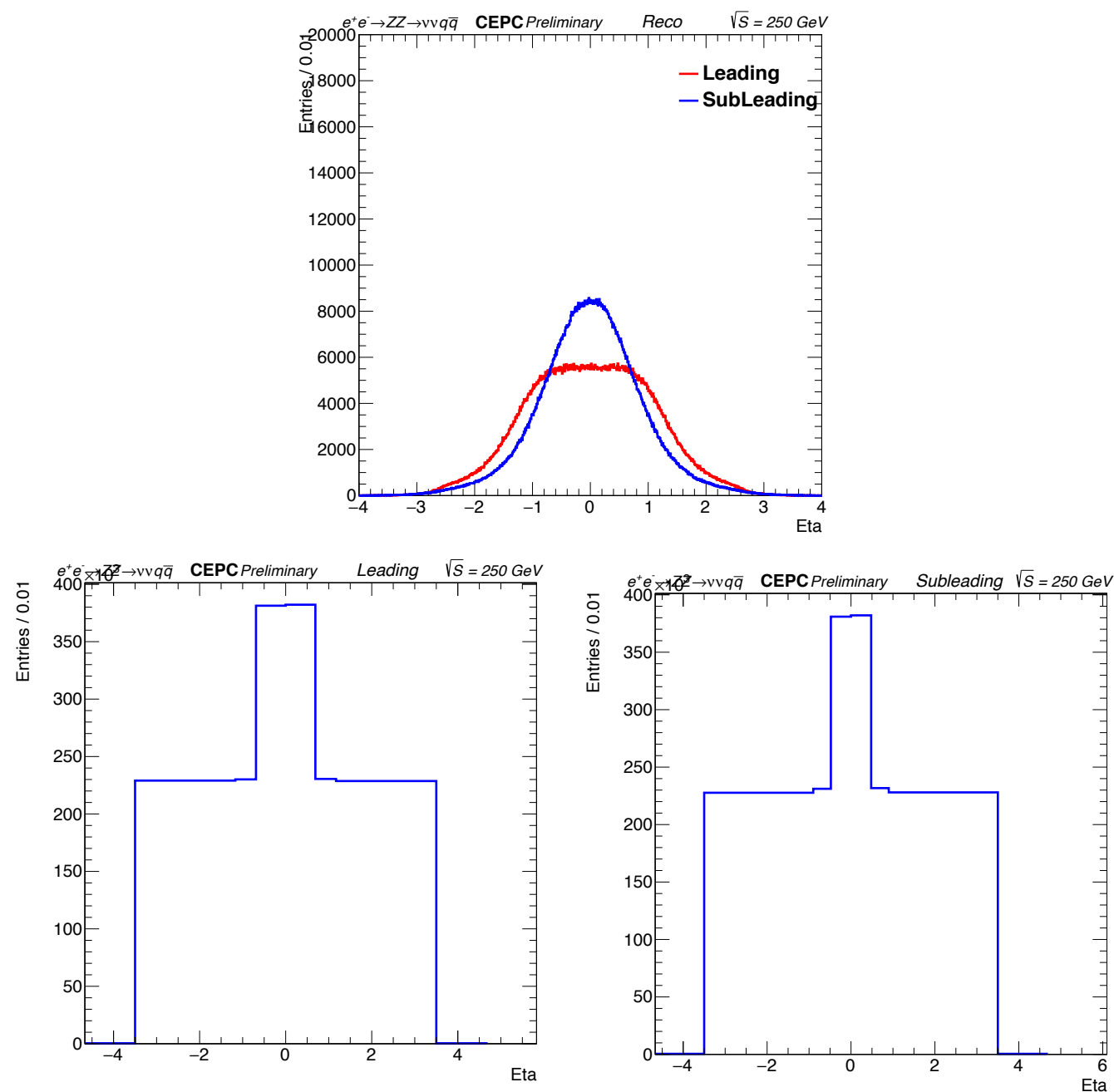
dR < 0.1



Angular Distribution of Gen and Reco

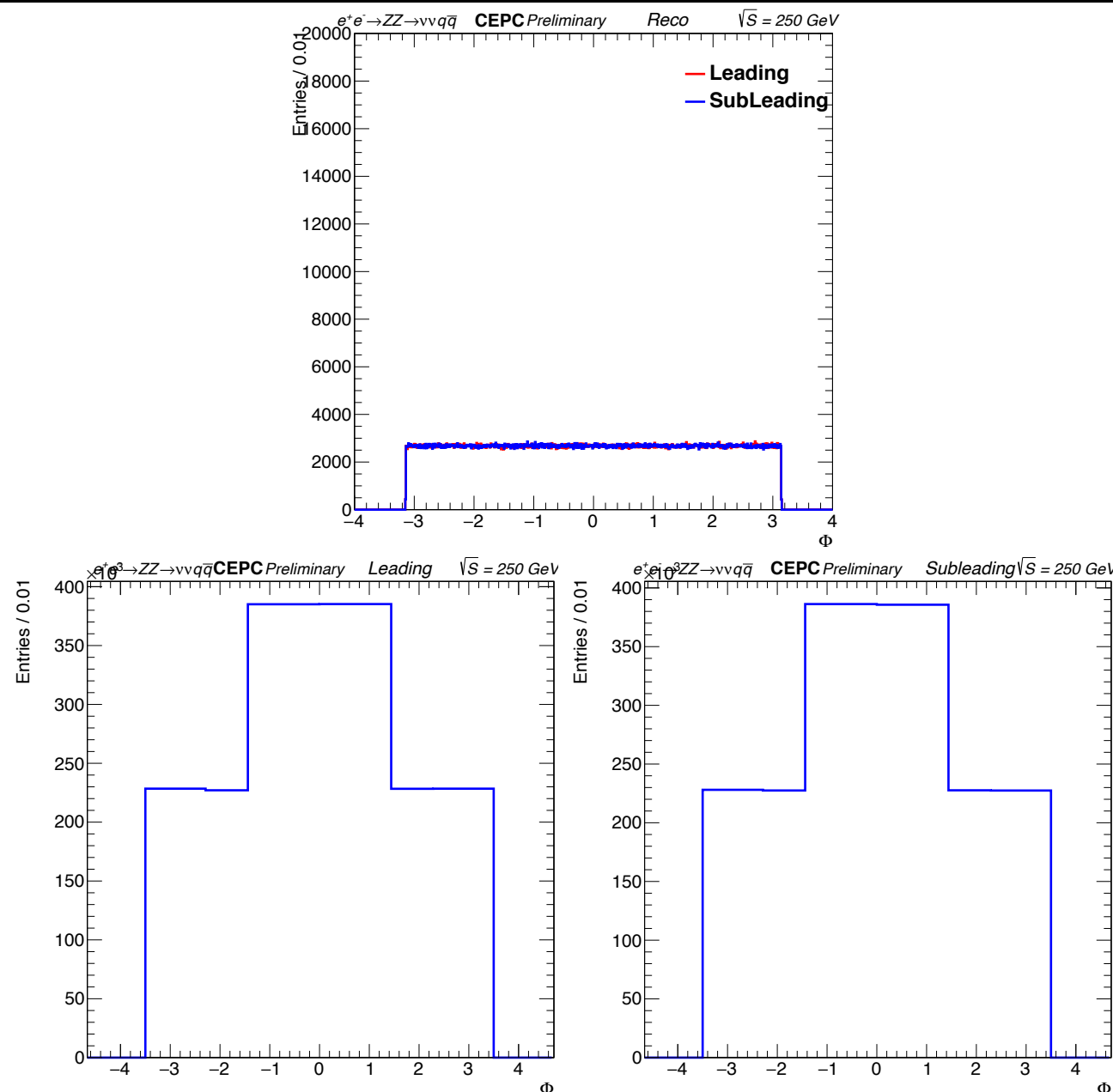


The Distribution of Unequal Eta Bin



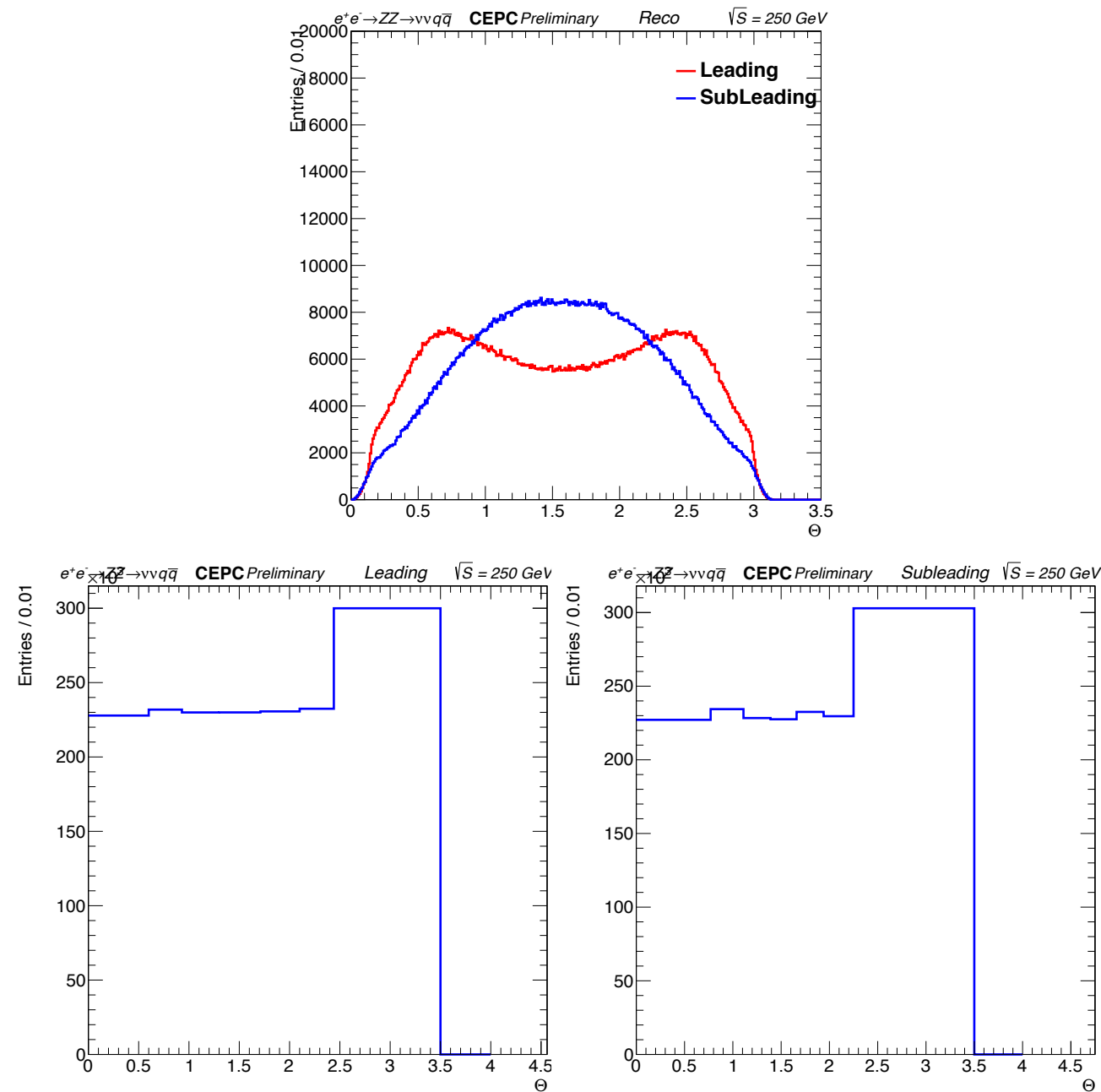
- When divided the angular bin, I have required the statistical uncertainty should less than 0.21% for each angular bin I also sorted the jet by energy. I want the unequal angular symmetry on zero. Therefore, the bin around zero with more the number of events.

The Distribution of Unequal Phi Bin

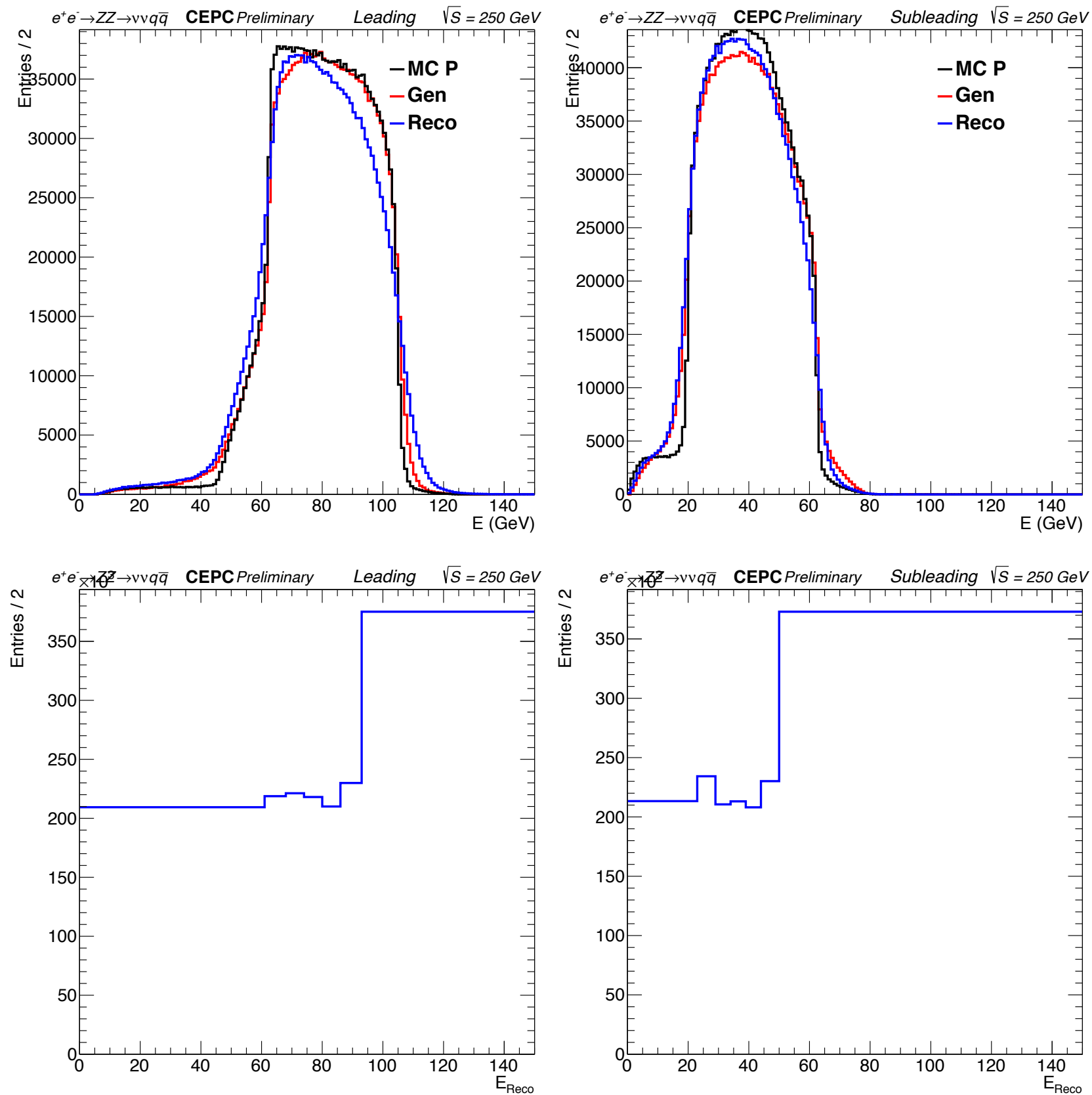


- When divided the angular bin, I have required the statistical uncertainty should less than 0.21% for each angular bin I also sorted the jet by energy. I want the unequal angular symmetry on zero. Therefore, the bin around zero with more the number of events.

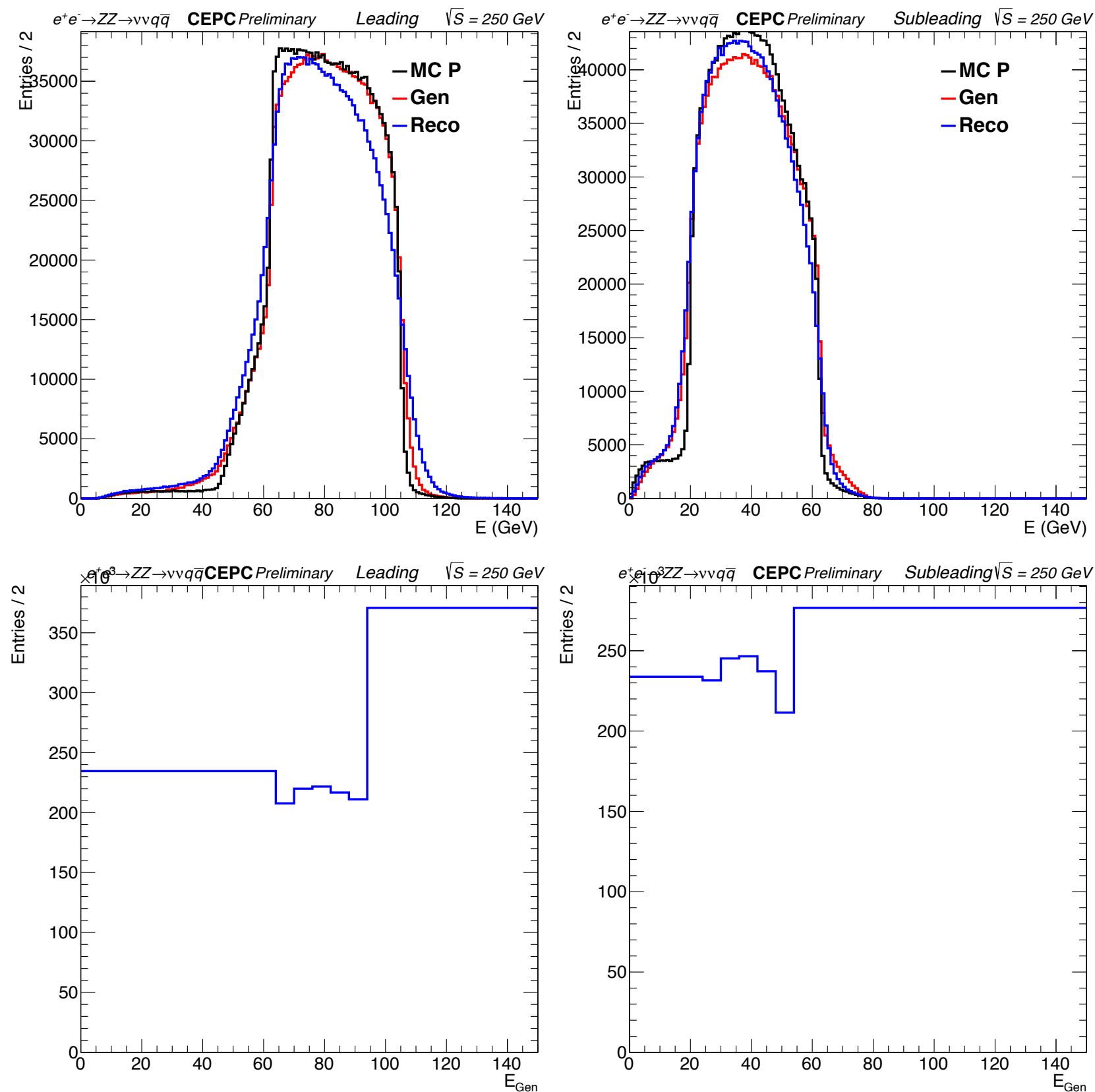
The Distribution of Unequal Theta Bin



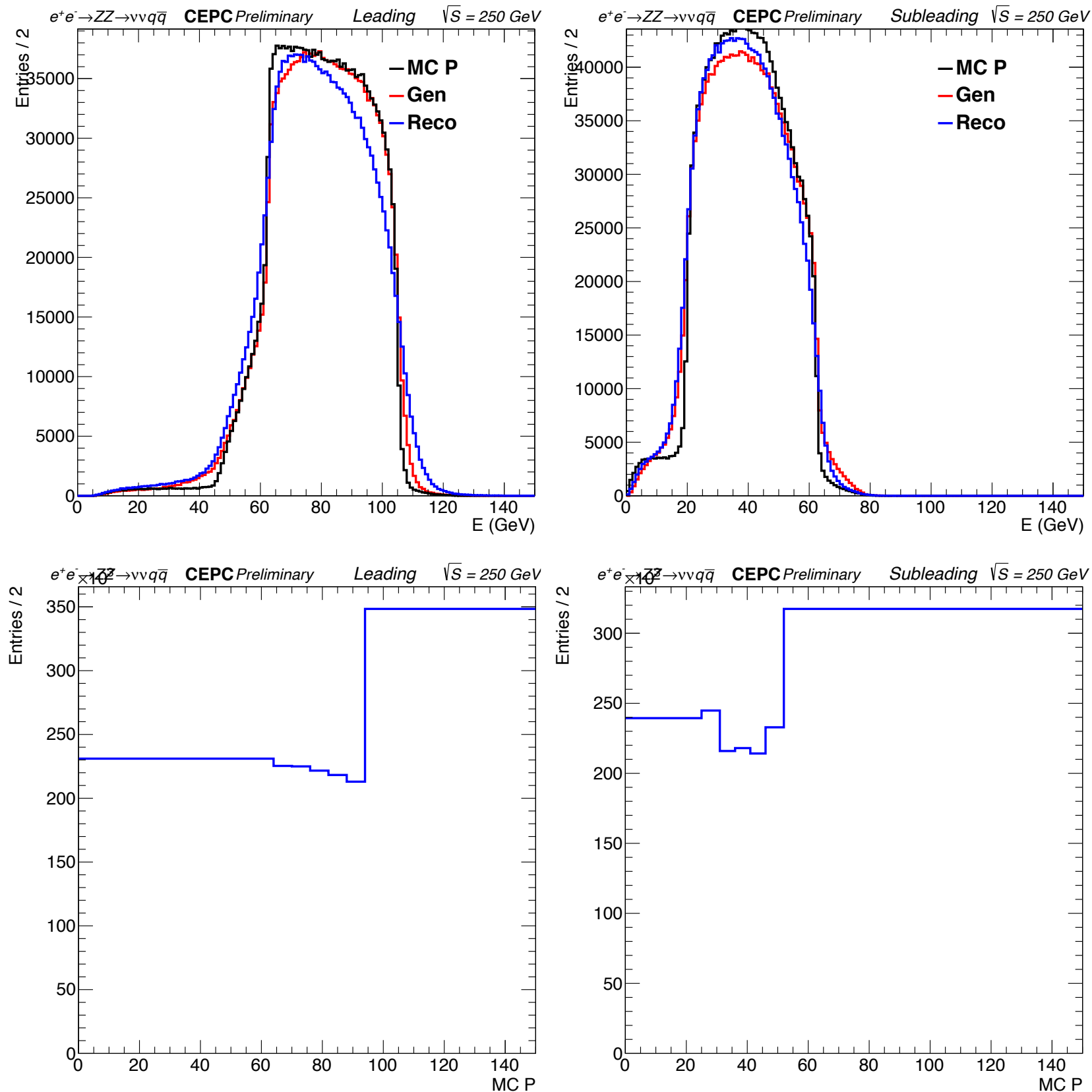
The Distribution of Unequal Reco Energy Bin



The Distribution of Unequal Gen Energy Bin



The Distribution of Unequal MCP Energy Bin



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% ↗

■ 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 Φ .
- 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 Φ .
- 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%.

