Jet Reconstruction Performance & Distinguish between Multi-jet Events

Pei-Zhu Lai

NCU (Taiwan)
On the behalf of the CEPC Collaboration
(pei-zhu.lai@cern.ch)

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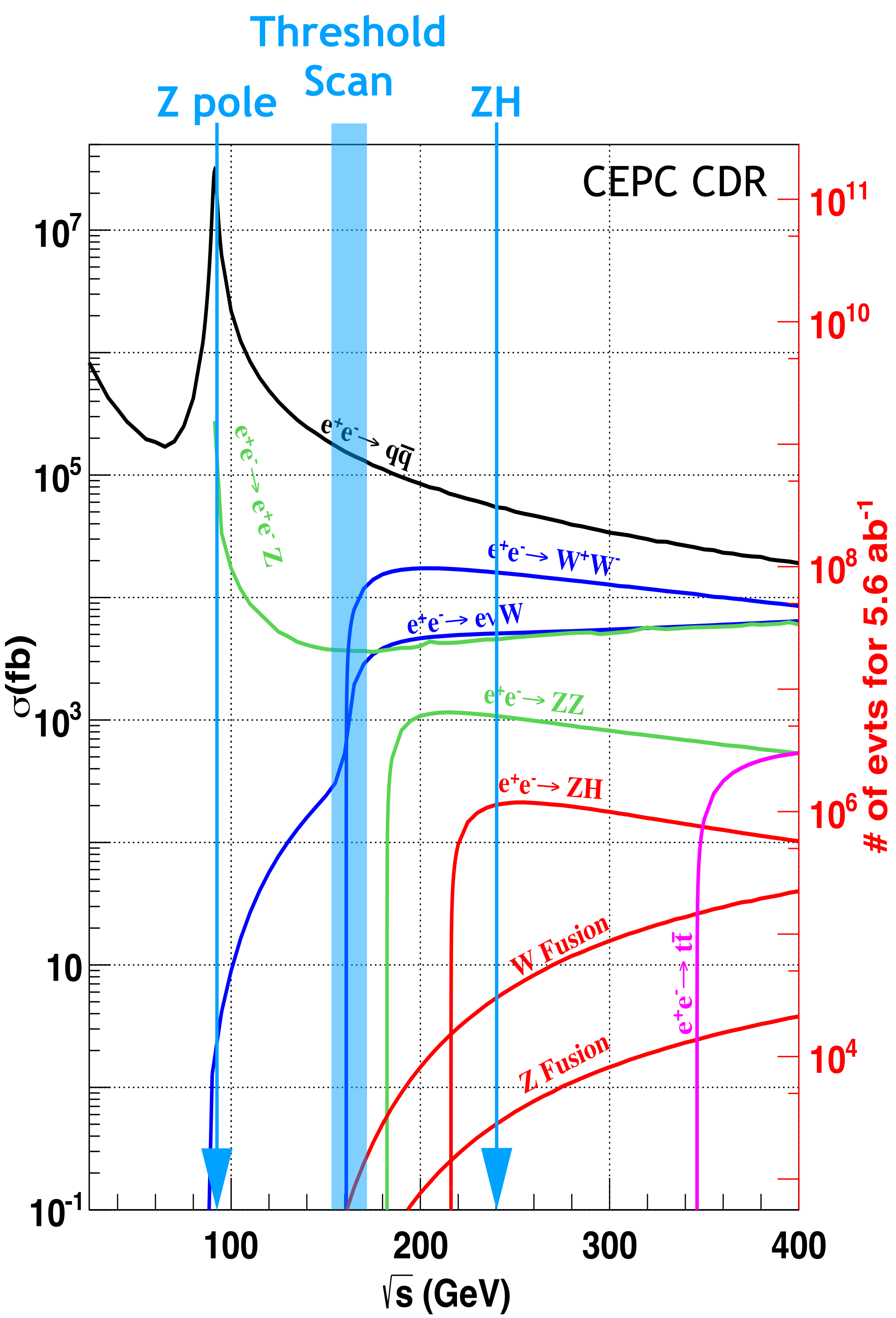
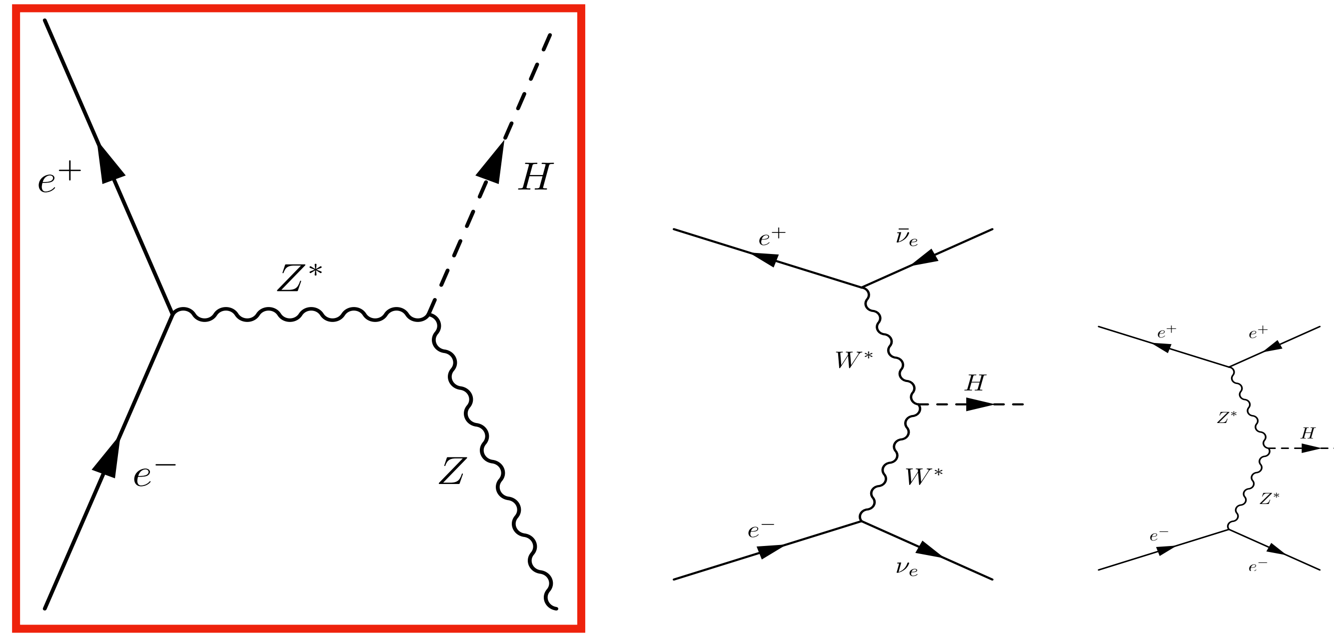
Outline

- Higgs production at CEPC
- ZH decay mode
- Jets at the Higgs Signal
- Jet performance in different physic benchmark
- Summary

Higgs Production at CEPC



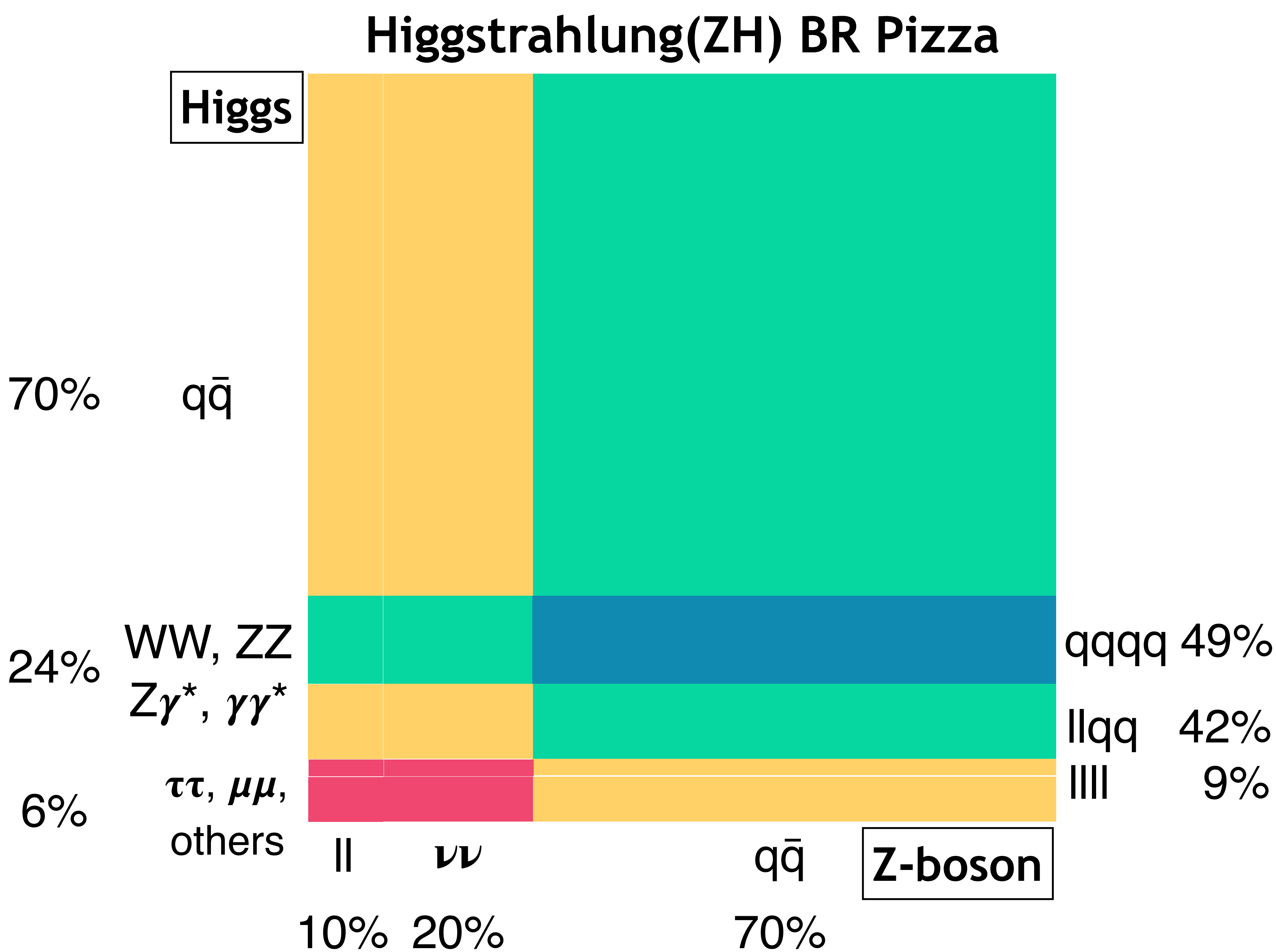


Process	Cross section(fb)	Events in 5.6 ab^{-1}
$e^+e^- \to ZH$	196.2	1.10×10^{6}
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^{4}
$e^+e^- \to e^+e^- H$	0.28	1.57×10^{3}
Total	203.7	1.14×10^{6}

S : B = 1 : (100 ~ 1000)

- **Observables: Higgs mass, CP, σ(ZH), event rate (σ(ZH, vvH)*Br(H→X)), Diff. distributions**
  → Absolute Higgs width, branching ratio, couplings

Jets at the Higgs Signal

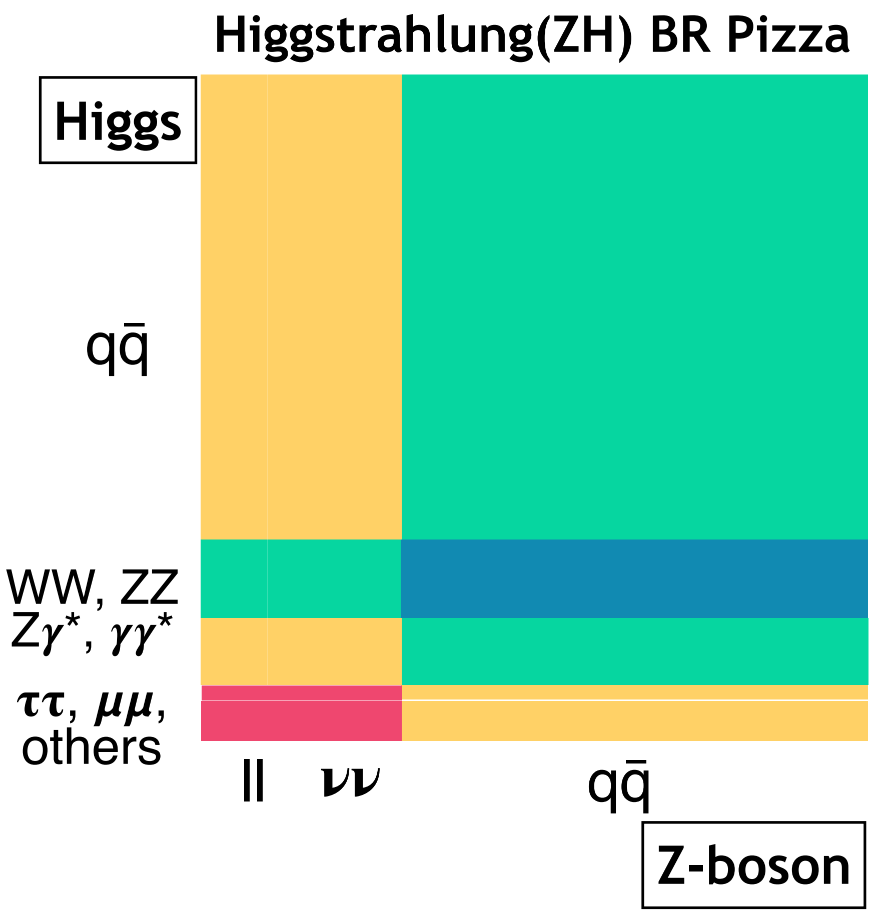


# of jets	Probability
0	2.44%
2	29.73%
4	59.58%
6	8.23%

~ 97% with Jets

- Up to 97% of Higgstrahlung(ZH) final-states associates to jets.
- Jets are also critical for many EW precision measurements.

Jets at the Higgs Signal



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2/3 of ZH events
- Dominance statistic is $ZH \to q\bar{q}q\bar{q}$.
- Major uncertainty is on wrong jet pairing. (Potential huge impact)

- **67% (4 + 6 jets) needs dedicated color-singlet identification: grouping the hadronic final-state particles into color-singlets (Z, W, H, γ^*). Can be done via jet clustering and pairing.**
- **Jet clustering is also essential for differential & EW precision measurements (e.g. TGCs).**

Physics Benchmarks

BMI: Massive bosons invariant mass resolutions

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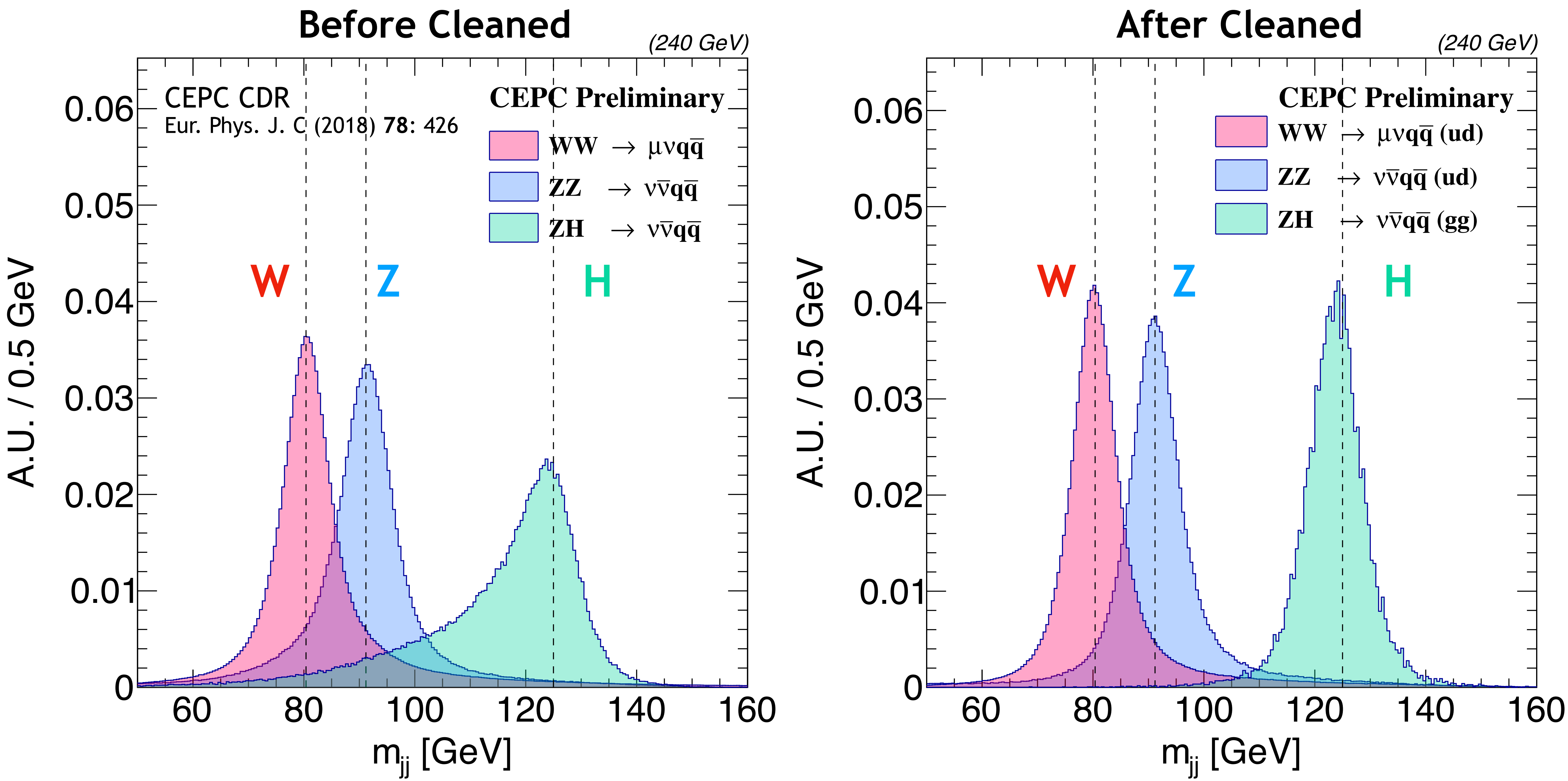
BM1: Massive Boson Mass Resolution



- W-, Z-, and Higgs-boson masses in dijet final state can be well separated at CEPC.
- After cleaned, Z- and W-boson could be separated ≈ 2σ, and the Higgs Boson Mass Resolution = 3.8% achieving the CEPC baseline.

Cleaned: Select the light flavor jet event with low energy ISR, low energy neutrino inside jet, and within |cosθ| < 0.85.

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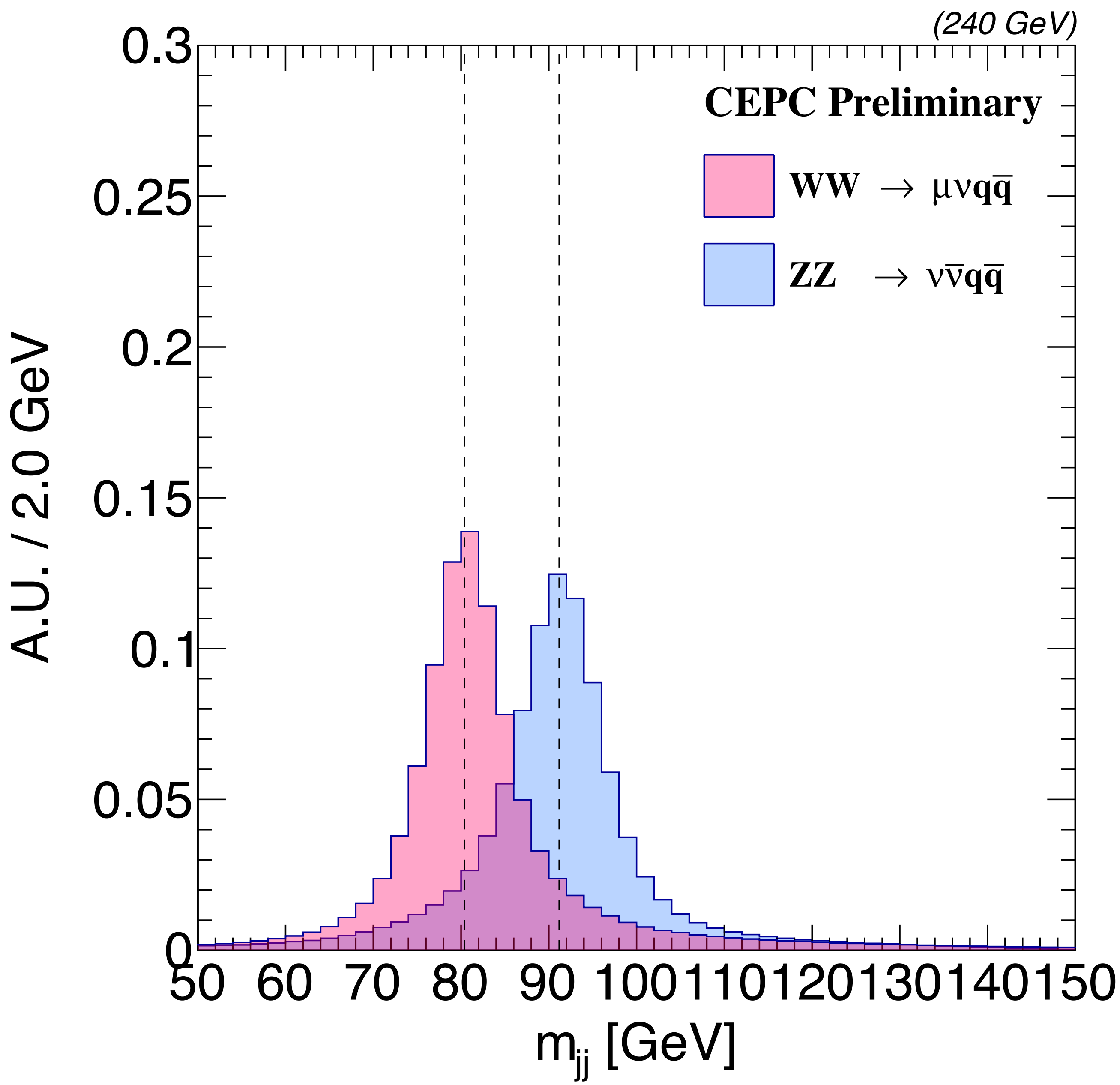

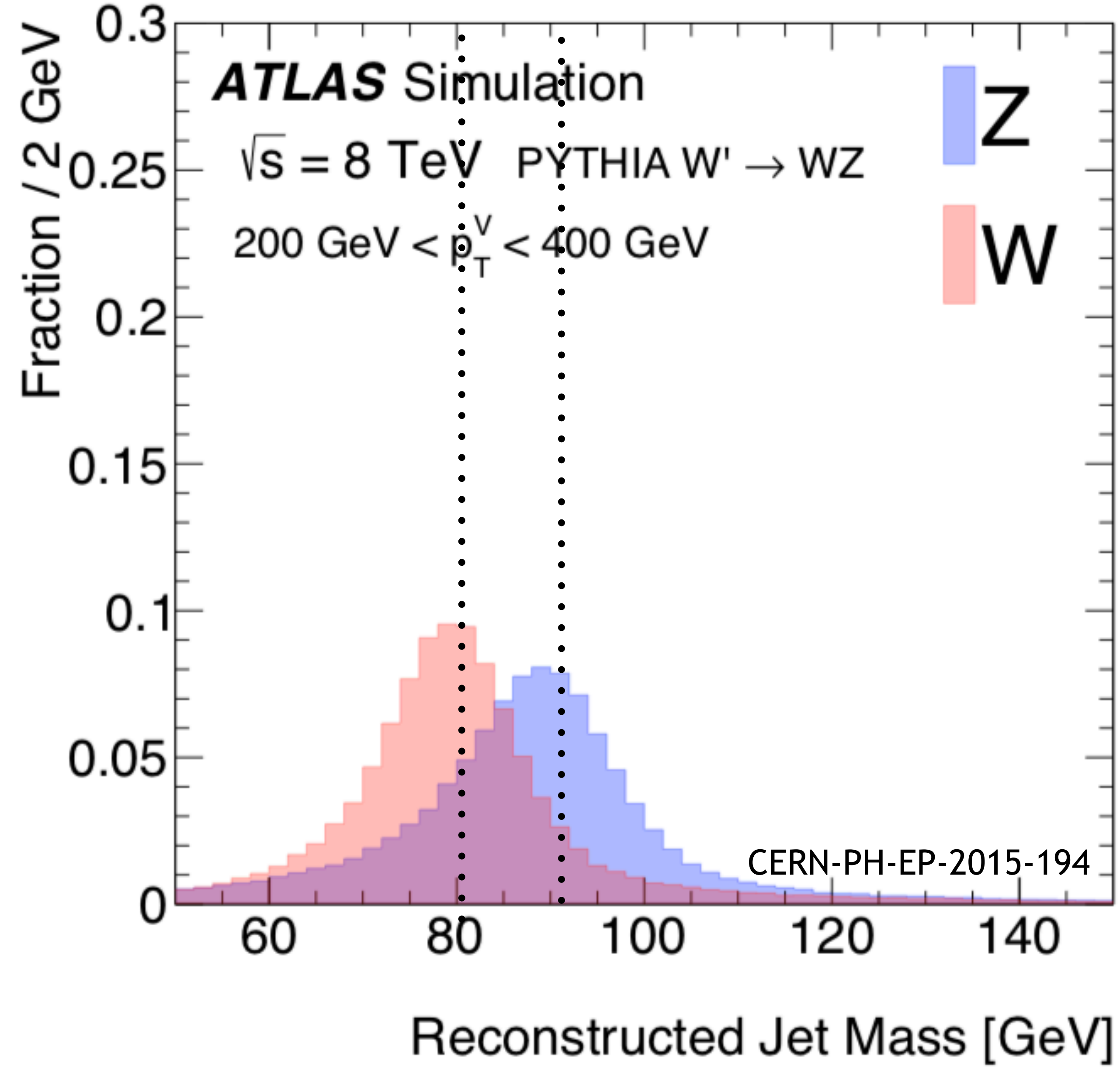

- **The separation of Z- and W-boson at CEPC is much better than ATLAS as it should be, because of the better collision environment and detector response.**

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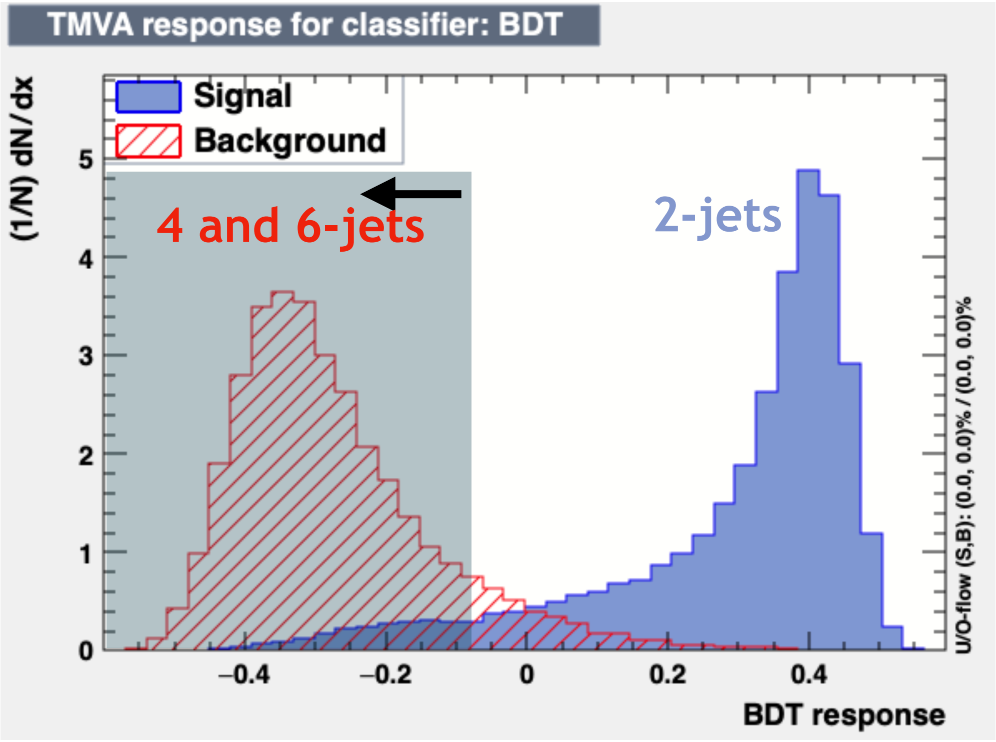
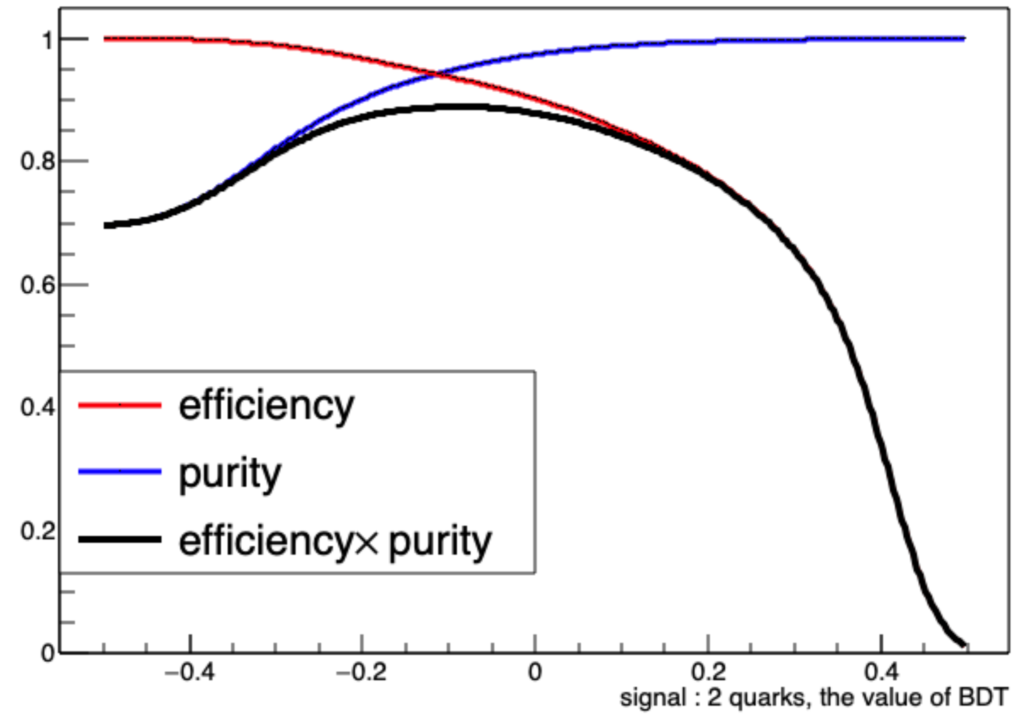




Samples:

$e^+e^- \to q\bar{q}$ (2 jets)

$ZZ \to q\bar{q}q\bar{q}$ (4 jets)

$W^+W^- \to q\bar{q}q\bar{q}$ (4 jets)

$ZH \to q\bar{q}q\bar{q}$ (4 jets)

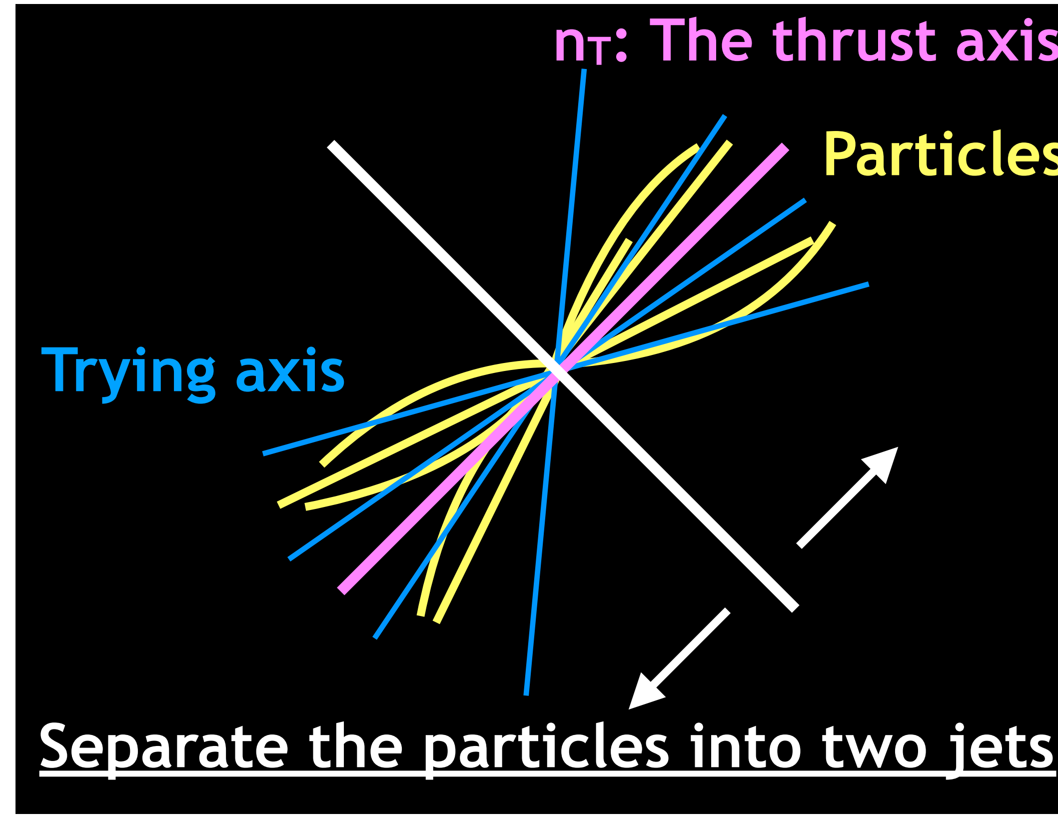
$ZH \to q\bar{q}H \to qqqqqq$ (6 jets)

Signal	*Efficiency × purity*
2 jets	88.4%
6 jets	1.8%

20 event-shape variables are combined with the multi-variate analysis to separate 2, 4, and 6 jets final-states.

BM2: Thrust Jet Clustering Method

$$T \equiv max \frac{\sum_j^N |P_j \cdot n_T|}{\sum_i^N |P_i|}$$



P_i or P_j: Momentum of each particle

n_T: A unit vector ($\sin\theta\times\cos\phi$, $\sin\theta\times\sin\phi$, $\cos\theta$)

- "Thrust" is one kind of event-shape variables.
- The nature clustering idea for the single boson decays to di-jet events, thrust.
  1. First, boost the system back to the rest frame.
  2. Find out a vector in the θ and ϕ phase space which has highest momentum flux.
  3. System is divided into 2 hemispheres with the thrust axis, and each identified as a jets. (Only applicable to 2 jets final-state)

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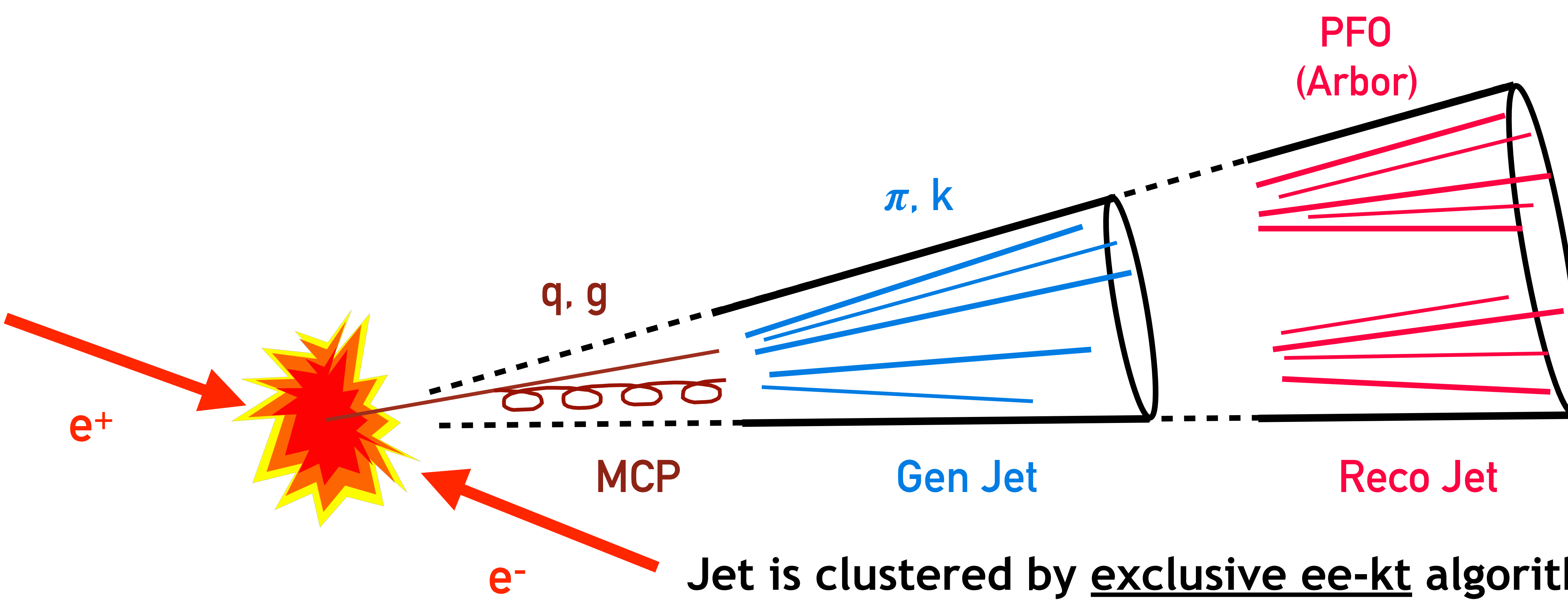
BM3: Jet energy and angular differential response

Objects Definition

- MCP represents initial parton of MC quark. The original state of quark.
- GenJets are grouped all MC particles except neutrinos with $c\tau$ > 1 cm through exclusive ee-kt jet clustering algorithm.
- RecoJets are grouped with the particle flow objects by exclusive ee-kt jet clustering algorithm.



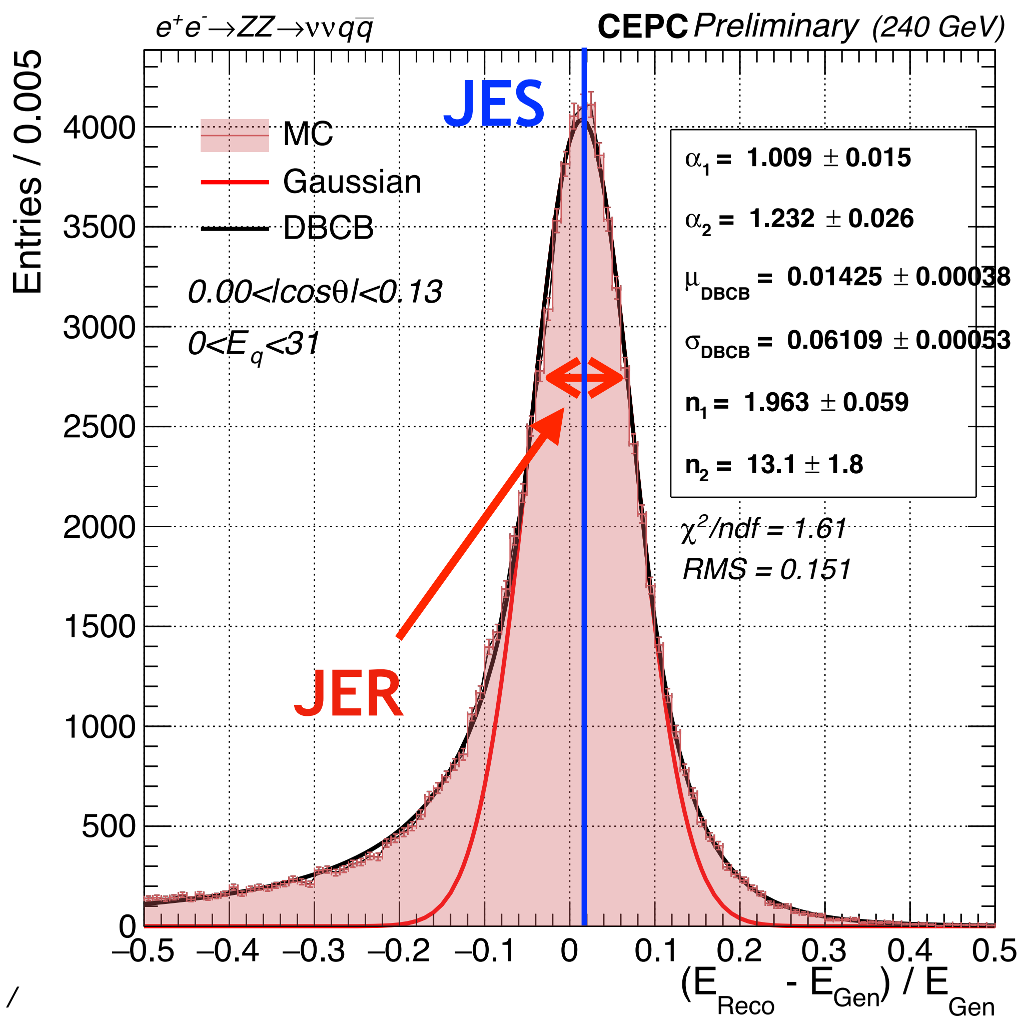
Jet is clustered by exclusive ee-kt algorithm.

Quantify the Performance

- Double-sided crystal ball(DBCB) function is used to extract energy and angular resolution and scale.

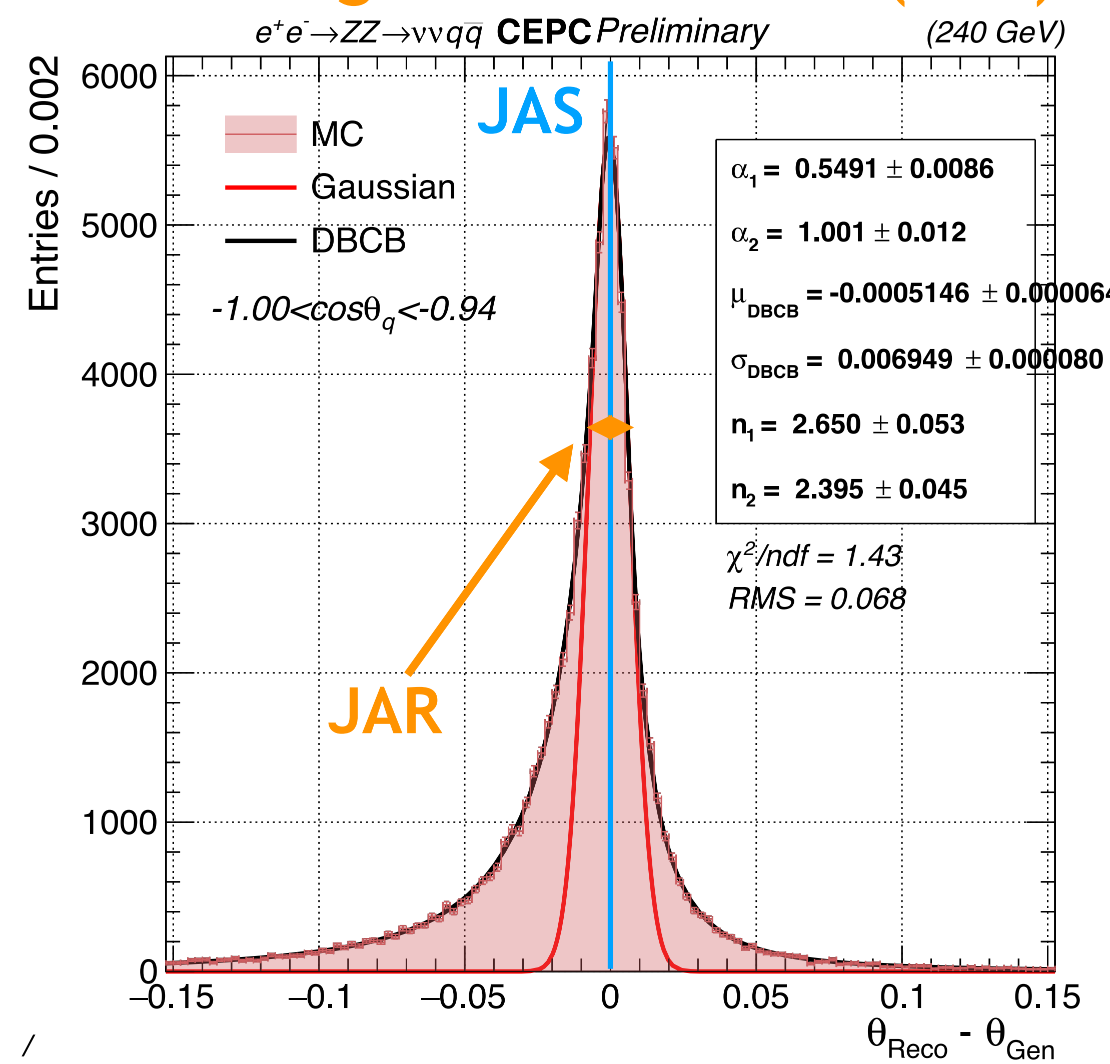
Jet Energy Scale (JES)

Jet Energy Resolution (JER)



Jet Angular Scale (JAS)

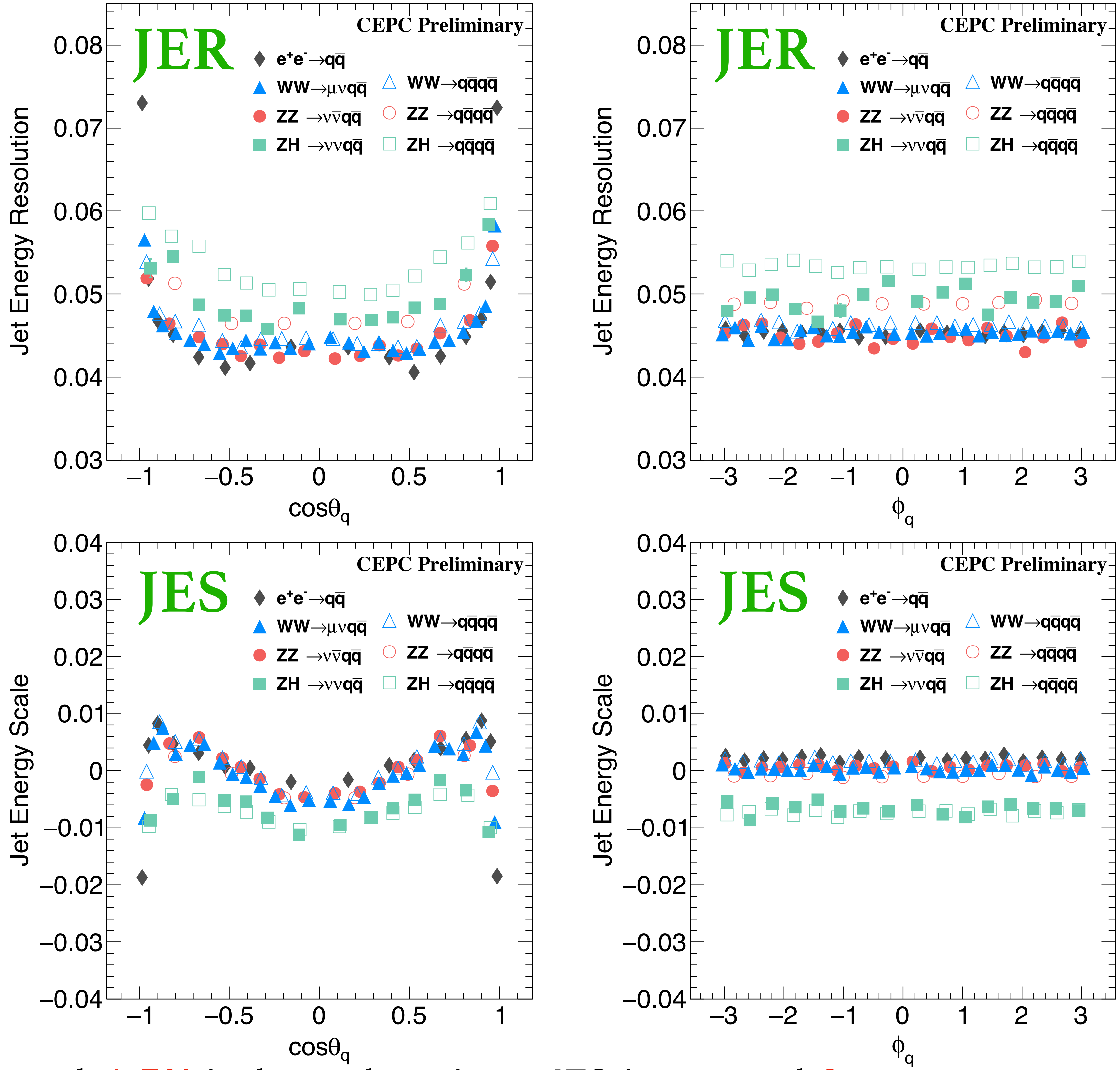
Jet Angular Resolution (JAR)



Relative difference : $\dfrac{E_{Reco} - E_{Gen}}{E_{Gen}}$

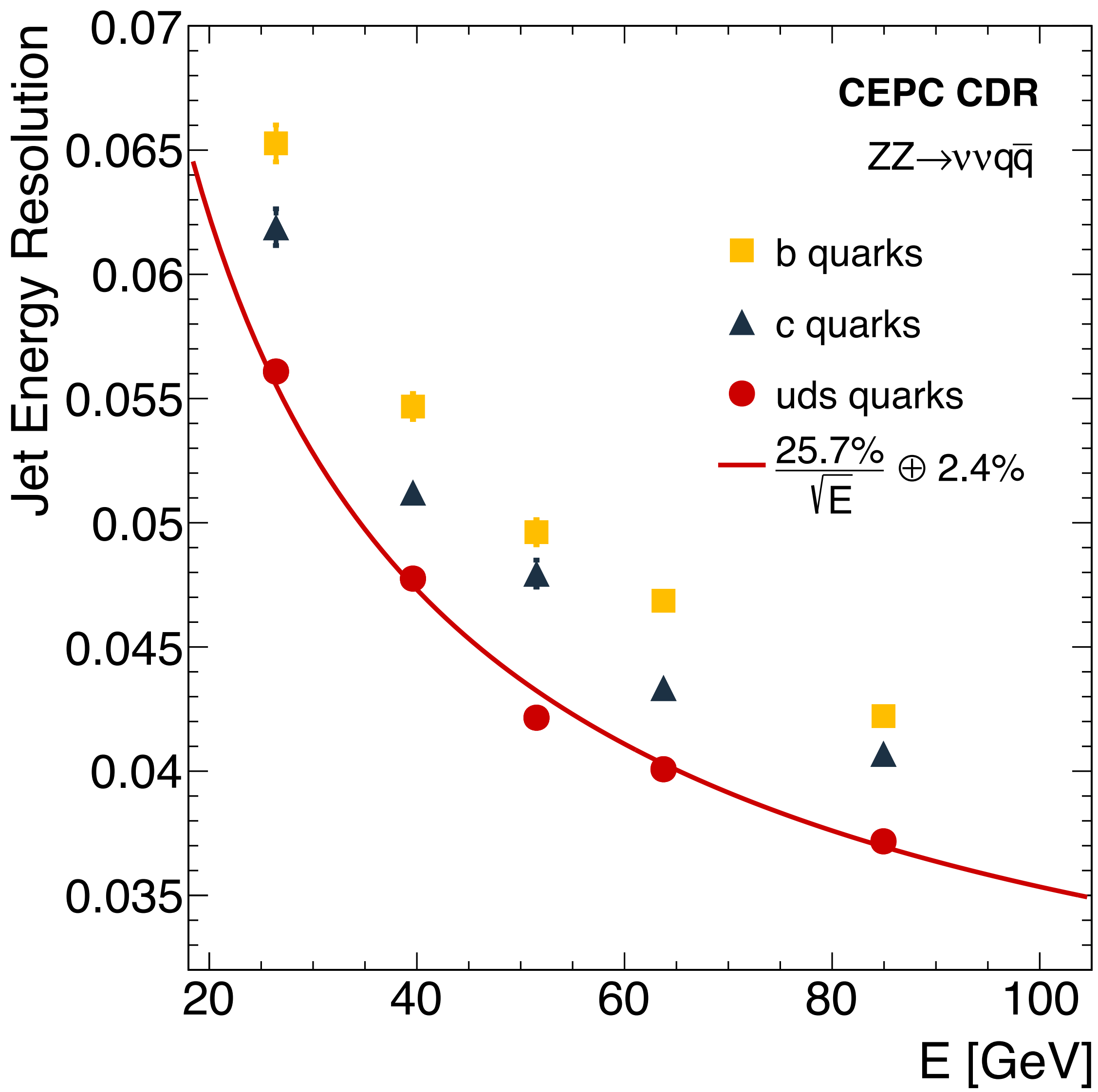
Difference : $\theta_{Reco} - \theta_{Gen}$

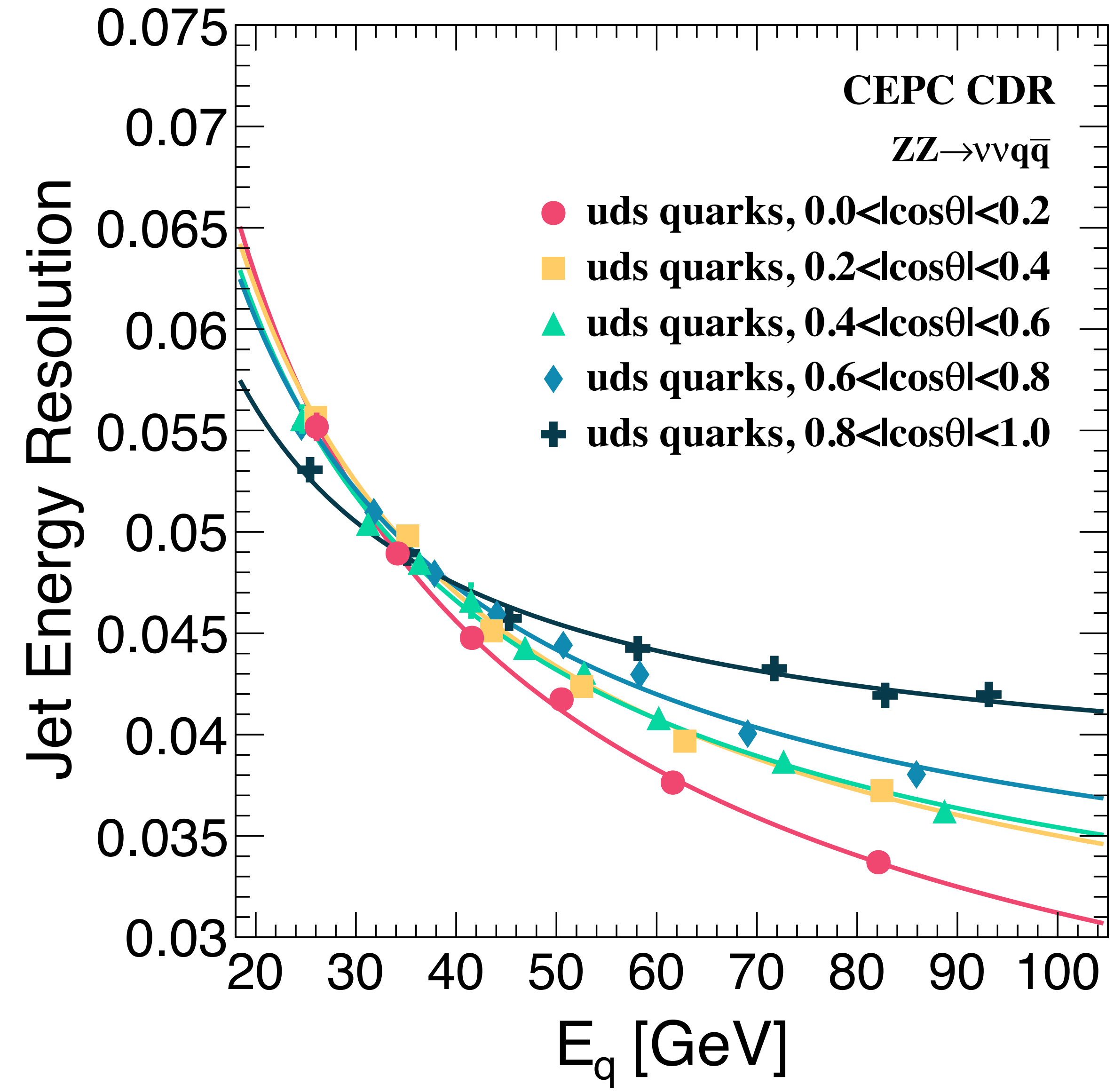
BM3: JER & JES (Reco-Gen)



- JER is around 4.5% in barrel region; JES is around 0.
- The difference between 2 and 4 jets final-state is controlled within 1% level.

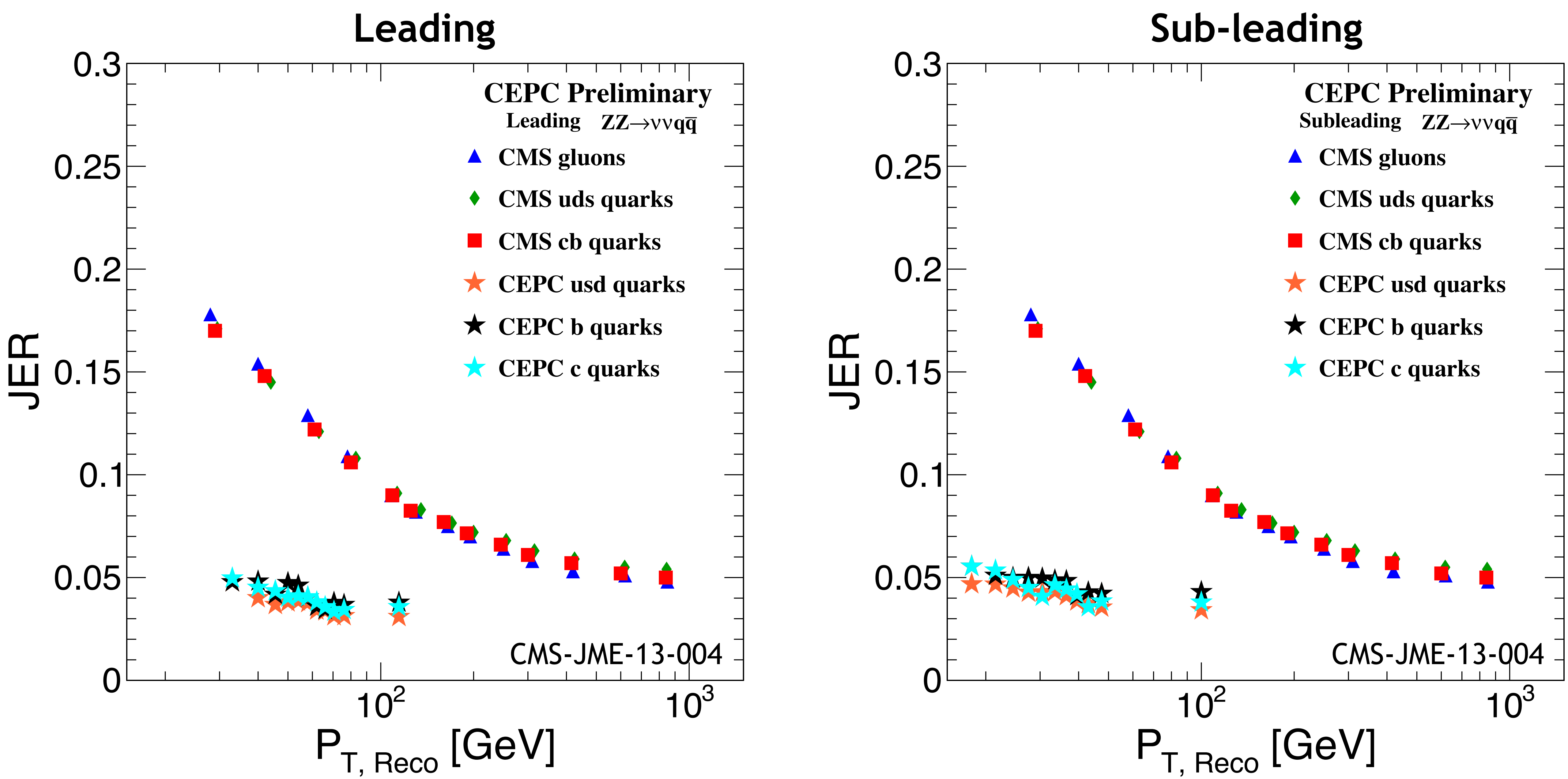
BM3: JER (Reco-Gen)





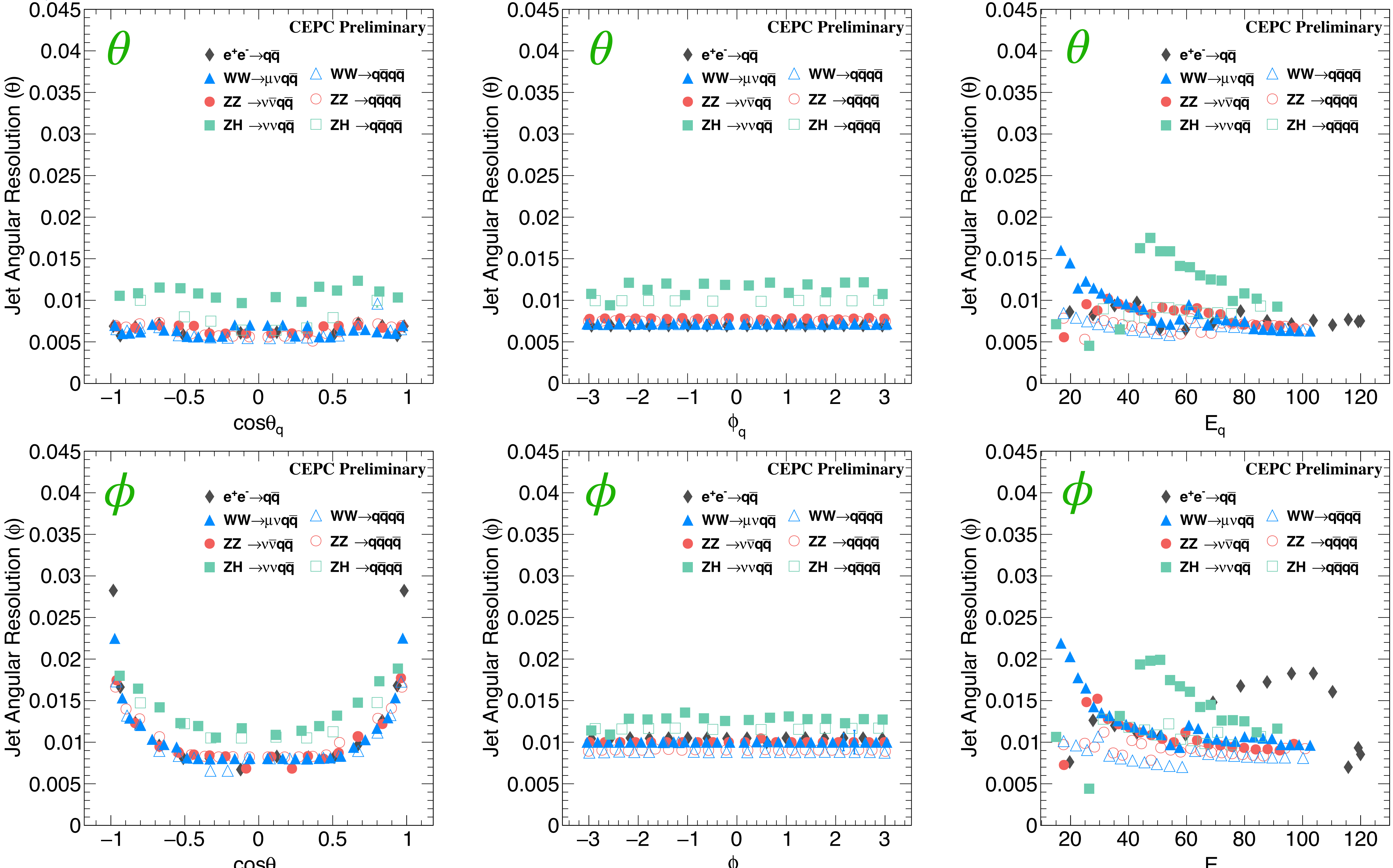
- **JER also depends on jet flavors.**
- **For light-flavor jets with high energy and within central region of barrel, JER could reach 3%.**

Compare to CMS at LHC



- JER at CEPC is better than CMS as it should be; 2-4 times better in the same energy region.

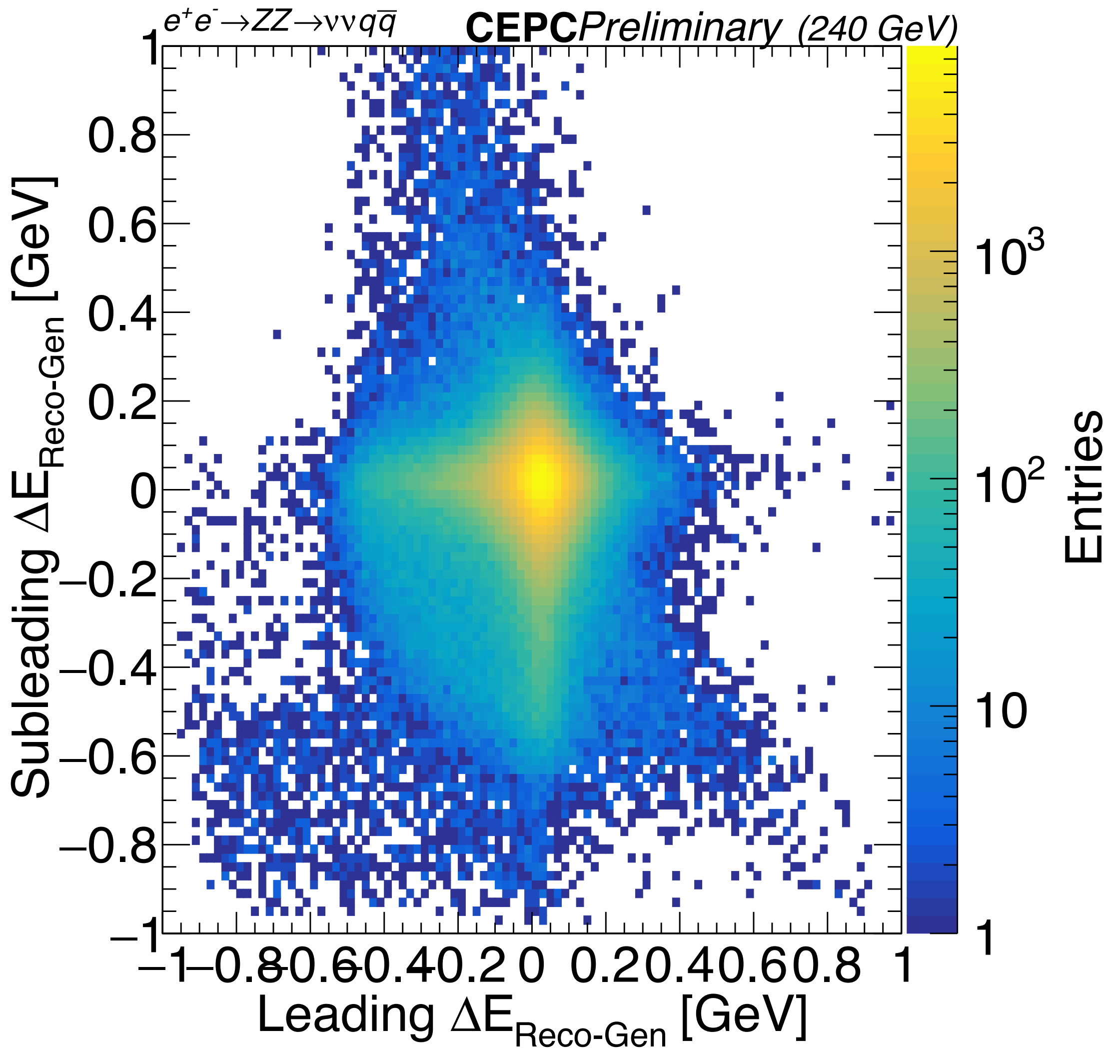
BM3: JAR (Reco-Gen)



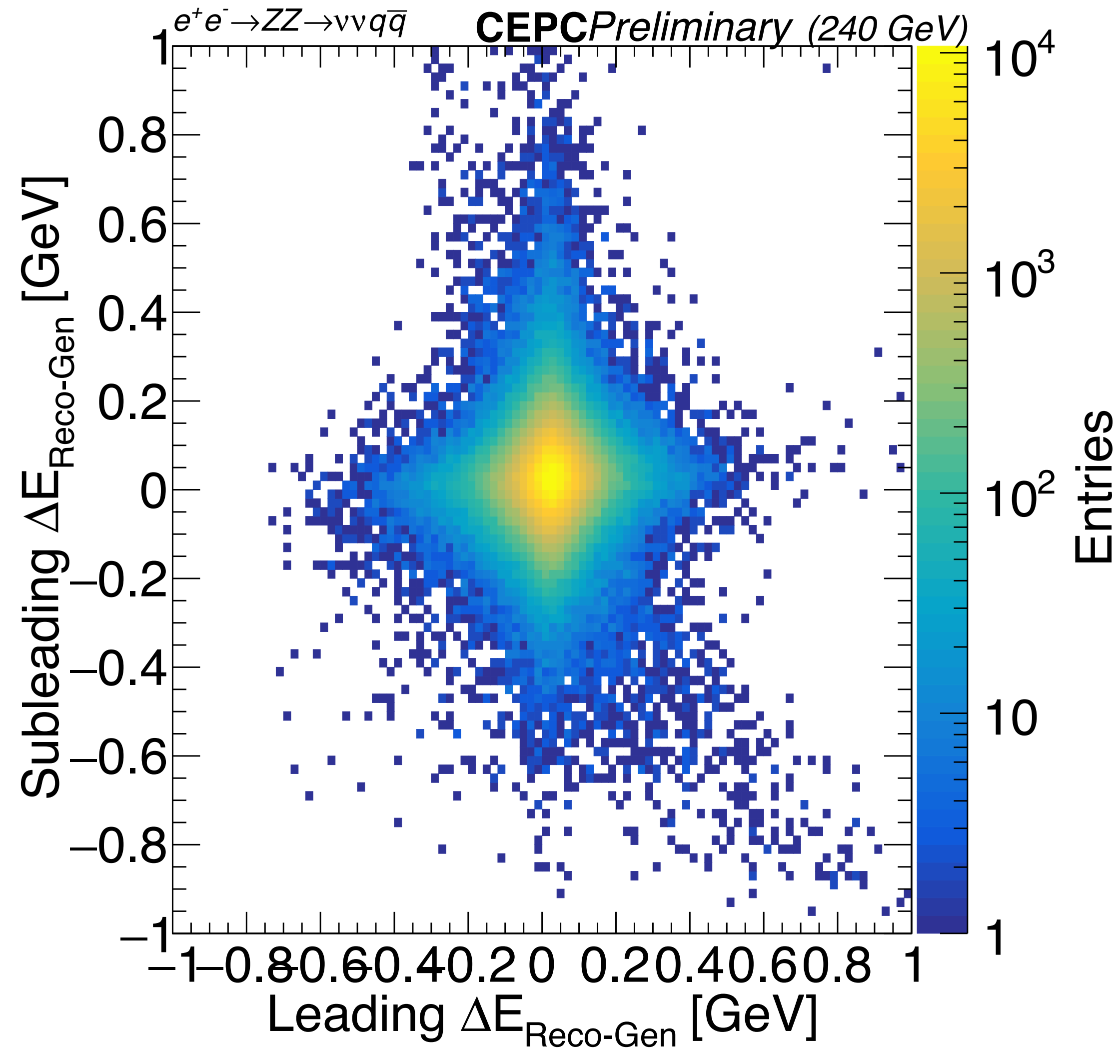
- JAR is around 1% in barrel region; JAS is independent of ϕ and energy.
- The difference between 2 and 4 jets final-state is controlled within 1% level.

BM3: Thrust Jet Clustering Method

ee-kt



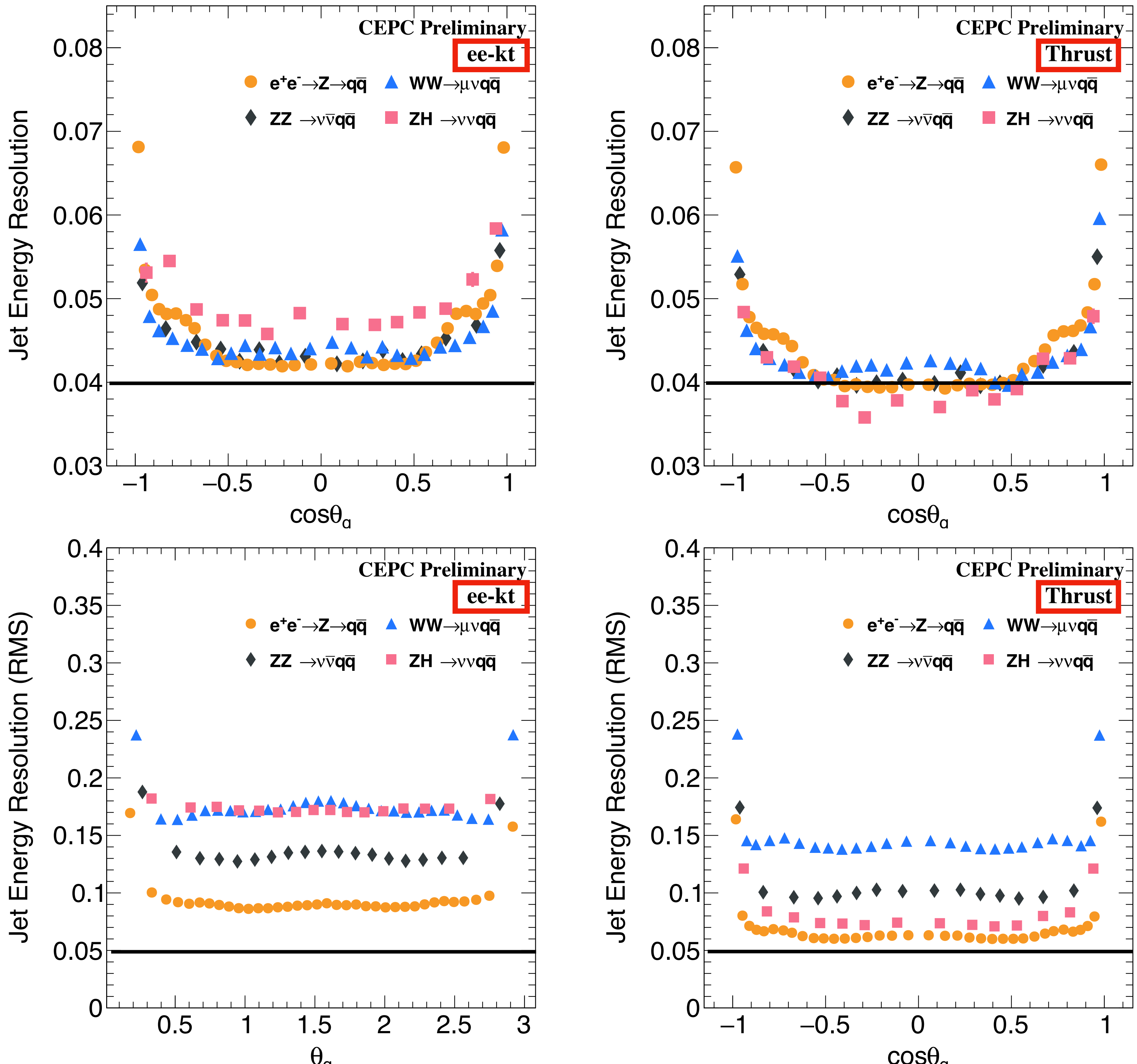
Thrust



- Identify the 2 jets final-state event with (efficiency x purity) = 88.4%, the thrust jet clustering method could be employed.
- After "cleaned" selection, the thrust method has significant tail suppressed → expected to have improvement on jet energy and angular response.

Cleaned: Select the light flavor jet event with low energy ISR, low energy neutrino inside jet, and within $|\cos\theta| < 0.85$.

BM3: JER (ee-kt—Thrust)

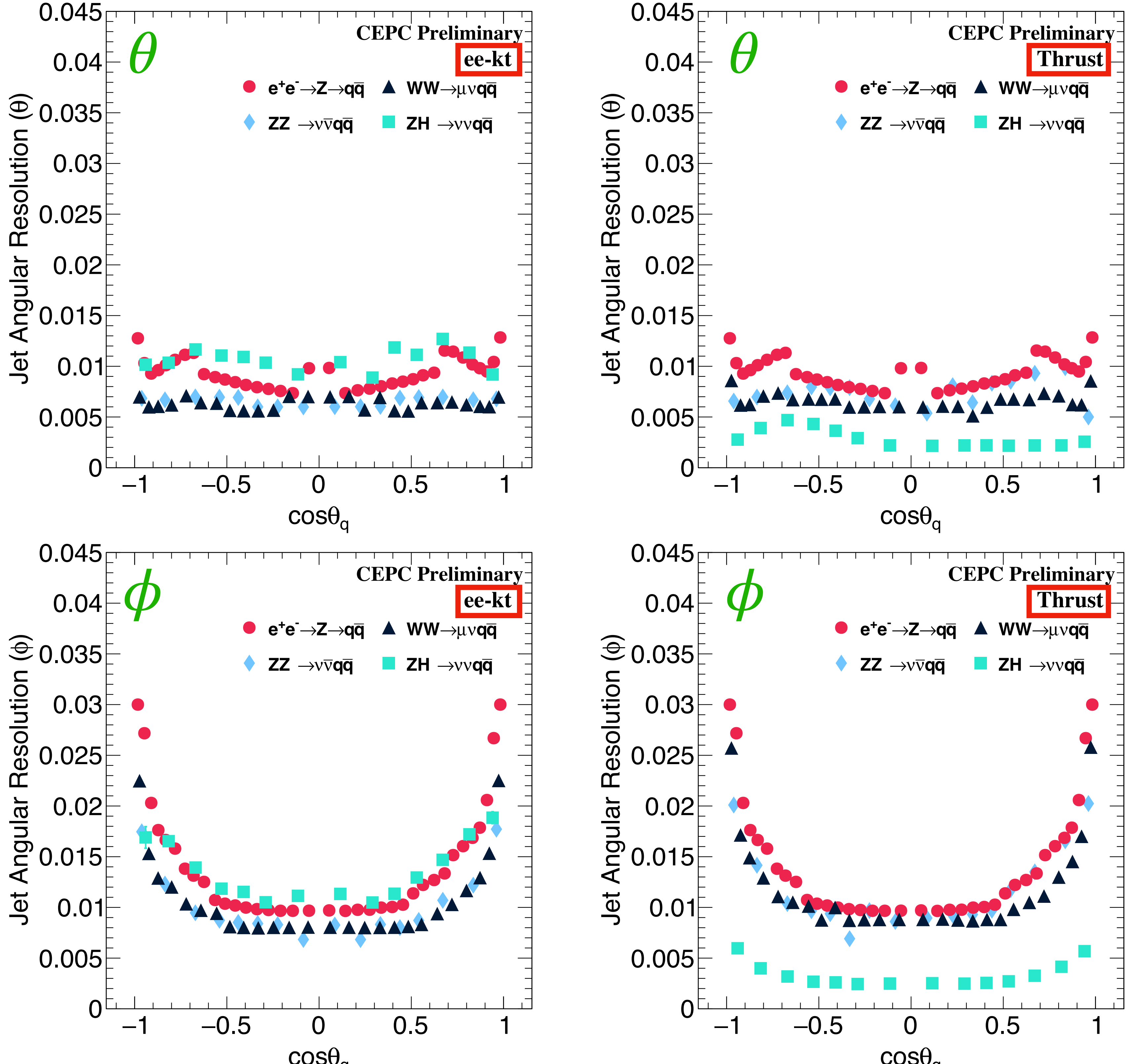


Improved 20% w.r.t ee-kt

Improved 40% w.r.t ee-kt

- Improvement maybe came from <u>boosting the system back to the rest frame with the neutrons' information</u>.

BM3: JAR (ee-kt—Thrust)



- **Both of jet θ and ϕ angular resolution are also improved by thrust method, 20%.**

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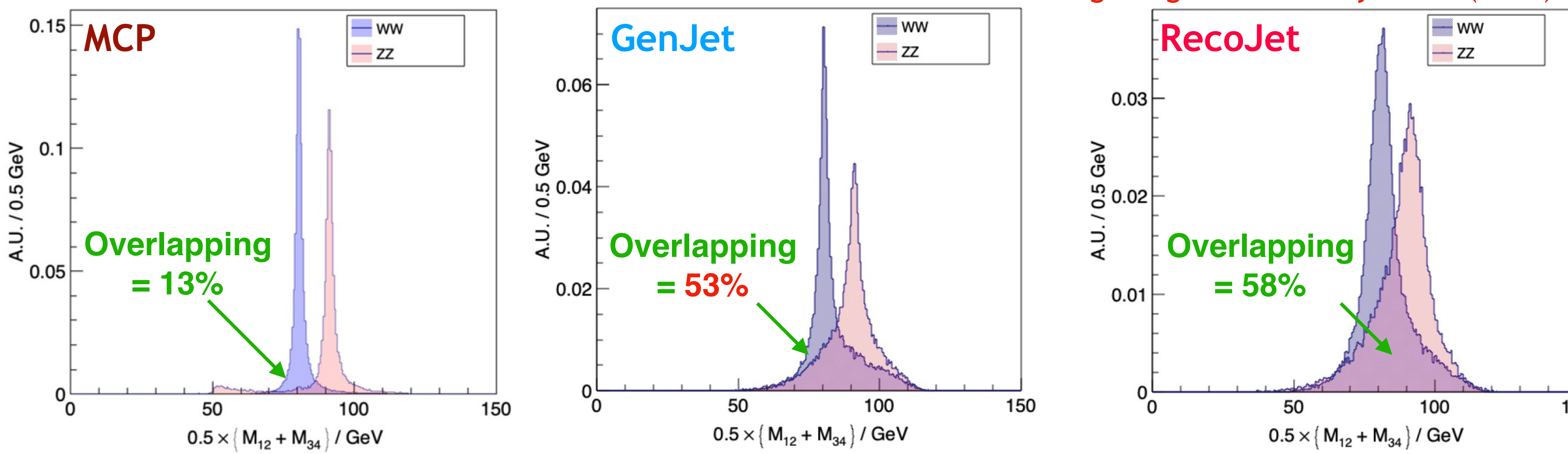
BM4: WW & ZZ to 4 Jets Separation

Yong-Feng Zhu—Eur. Phys. J. C (2019) 79:274



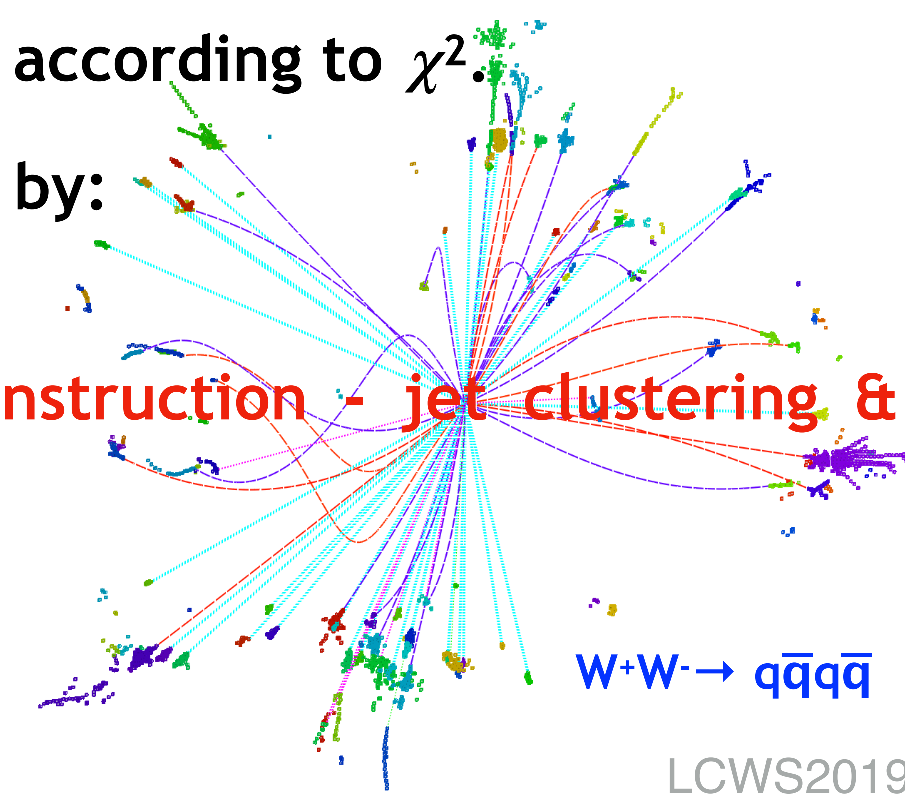
- Low energy jet (20-120 GeV)
- Typical multiplicity could be 10^2.

$$\chi^2 = \frac{(M_{12}-M_B)^2+(M_{34}-M_B)^2}{\sigma_B^2}$$

- GenJet and RecoJet are clustered by ee-kt and paired according to χ^2.
- WW & ZZ to 4 jets final-state separation is determined by:
  1. (13%) Intrinsic boson mass/width (10 GeV)
  2. (53%) Wrong jet pairing for color singlet reconstruction - jet clustering & pairing.
  3. (58%) Detector response

40%

5%



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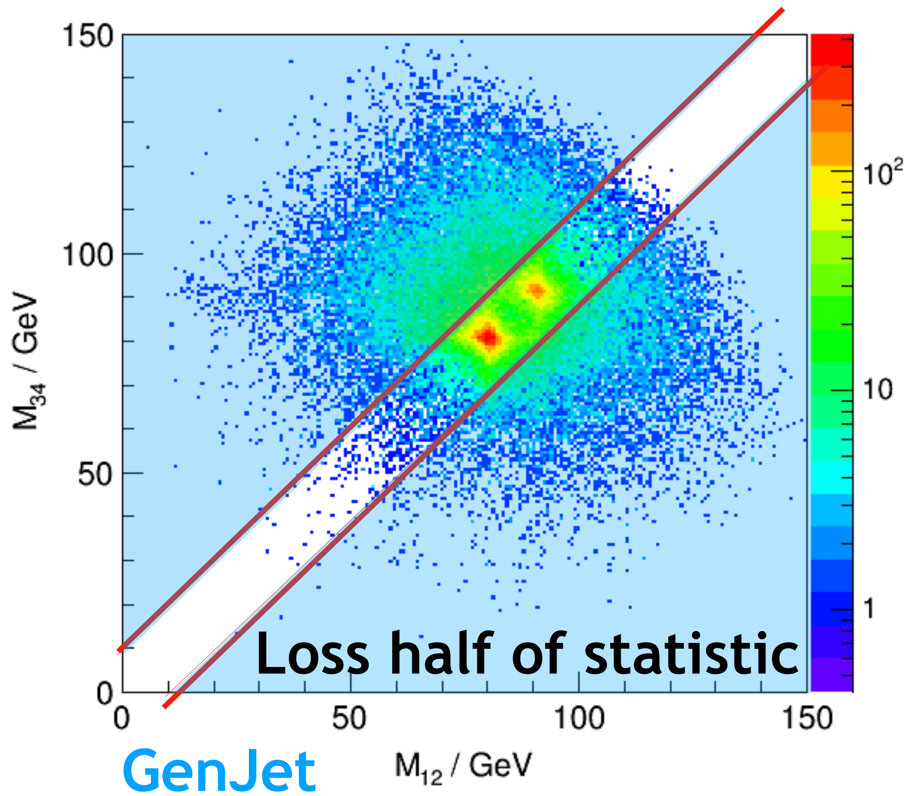
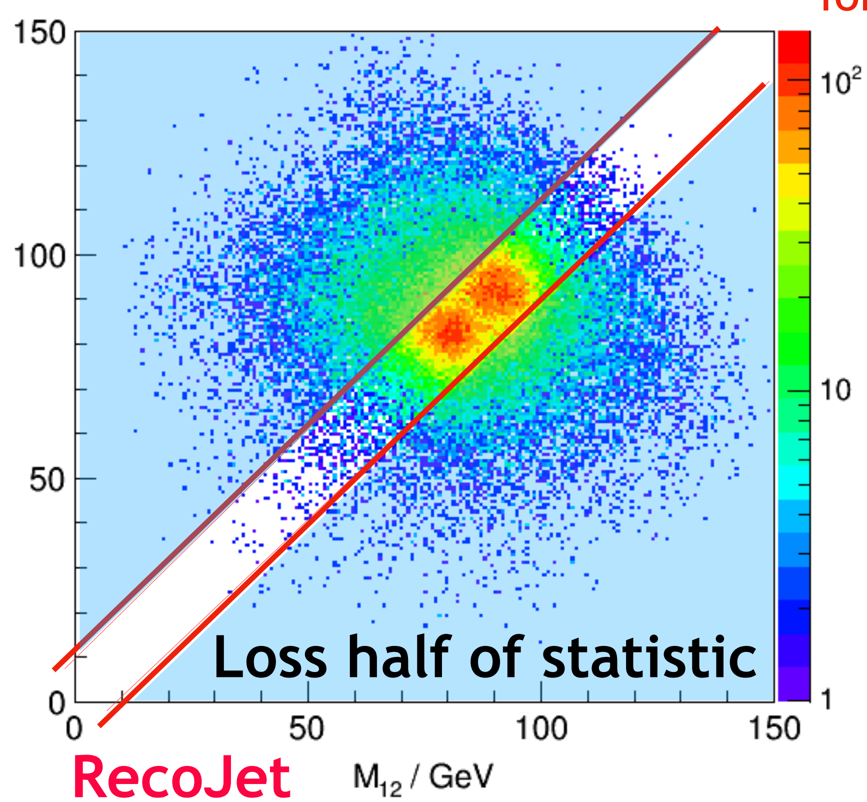
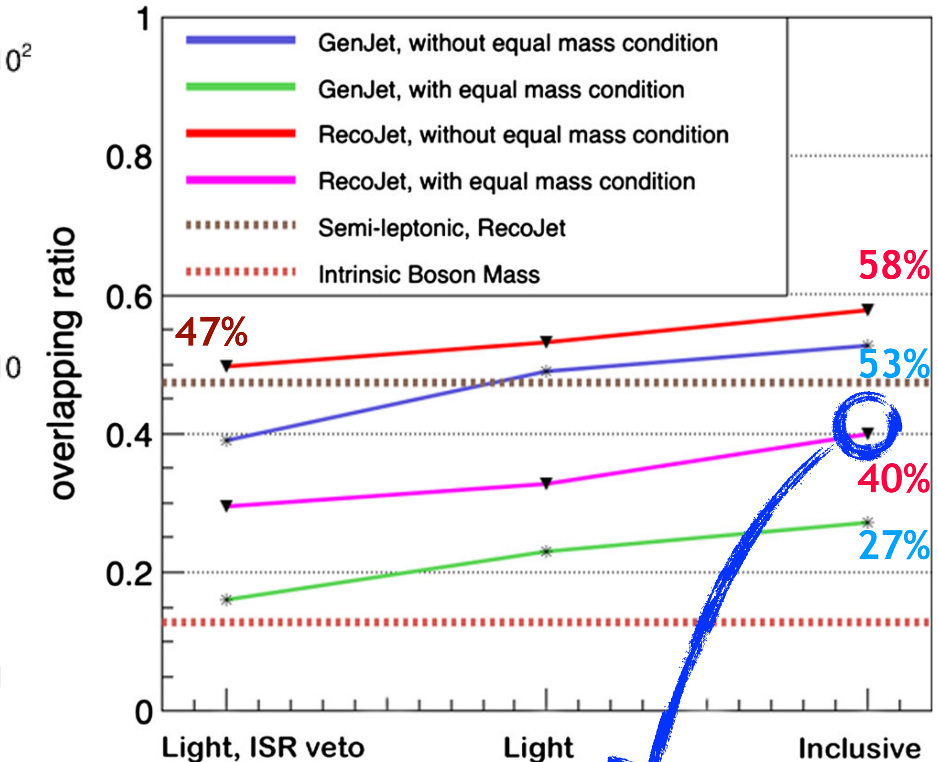
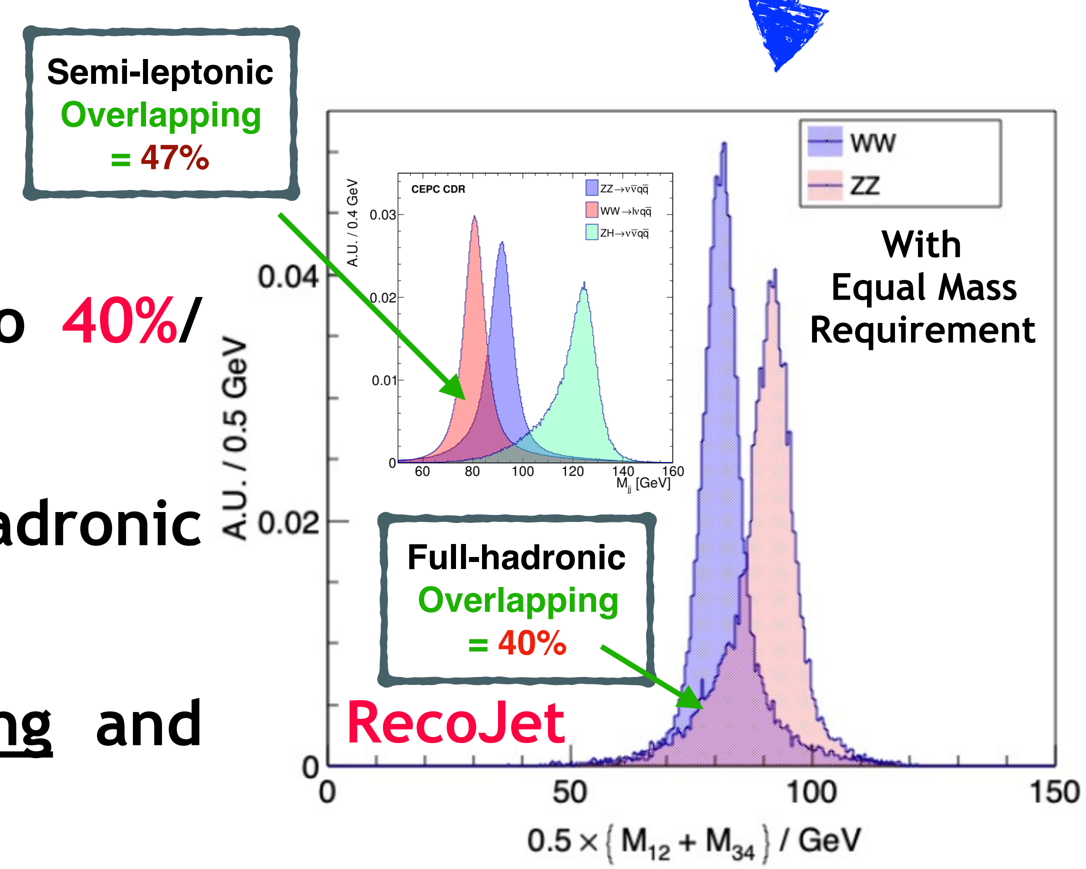








- Equal mass requirement: $|M_{12} - M_{34}| < 10$ GeV
  - Cost half of the statistic.
  - Overlapping can be reduced from 58%/53% to 40%/27% for the RecoJet/GenJet.
- CEPC baseline could separate WW & ZZ with full hadronic final-state.
- Improve from the naive jet clustering & pairing and control the ISR photon in the event.
- ZH full hadronic final-state analysis is on the way.

Summary

- **Jets are crucial for the CEPC Higgs physics**
  - 97% of ZH events evolve jets
  - 1/3 only come from single Z or Higgs boson.
  - 2/3 has more than one boson (e.g. ZH→$q\bar{q}q\bar{q}$) - need color singlet identification algorithm.

I. **BMR < 4% is critical. Achieved at the CEPC baseline (3.8%)**

- ✱ W, Z, Higgs boson can be efficiently separated at both semi-leptonic & full hadronic.
- ✱ By Z-boson di-jet recoil mass to distinguish the ZH from ZZ process.

II. **2 jets final-state could be identified with *efficiency×purity* = 88.4%.**

- ✱ Could be clustered by dedicated jet clustering algorithm, thrust.

III. **Single Jet — JER ~ 3-5% & JAR ~ 1%.**

- ✱ Thrust clustering method is recommended for two jets final-state. It could improve the JER 20%, 40% on tail (RMS), and JAR 20%.

IV. **Need a better color singlet identification algorithm.**

- ✱ Wrong jet pairing is the dominant effect to induce overlapping in full hadronic WW-ZZ separation.
- ✱ Equal mass requirements: Reduce the overlapping to be better than semi-leptonic, but very costly.
- ✱ Other physical impact is significant: ISR photon etc.

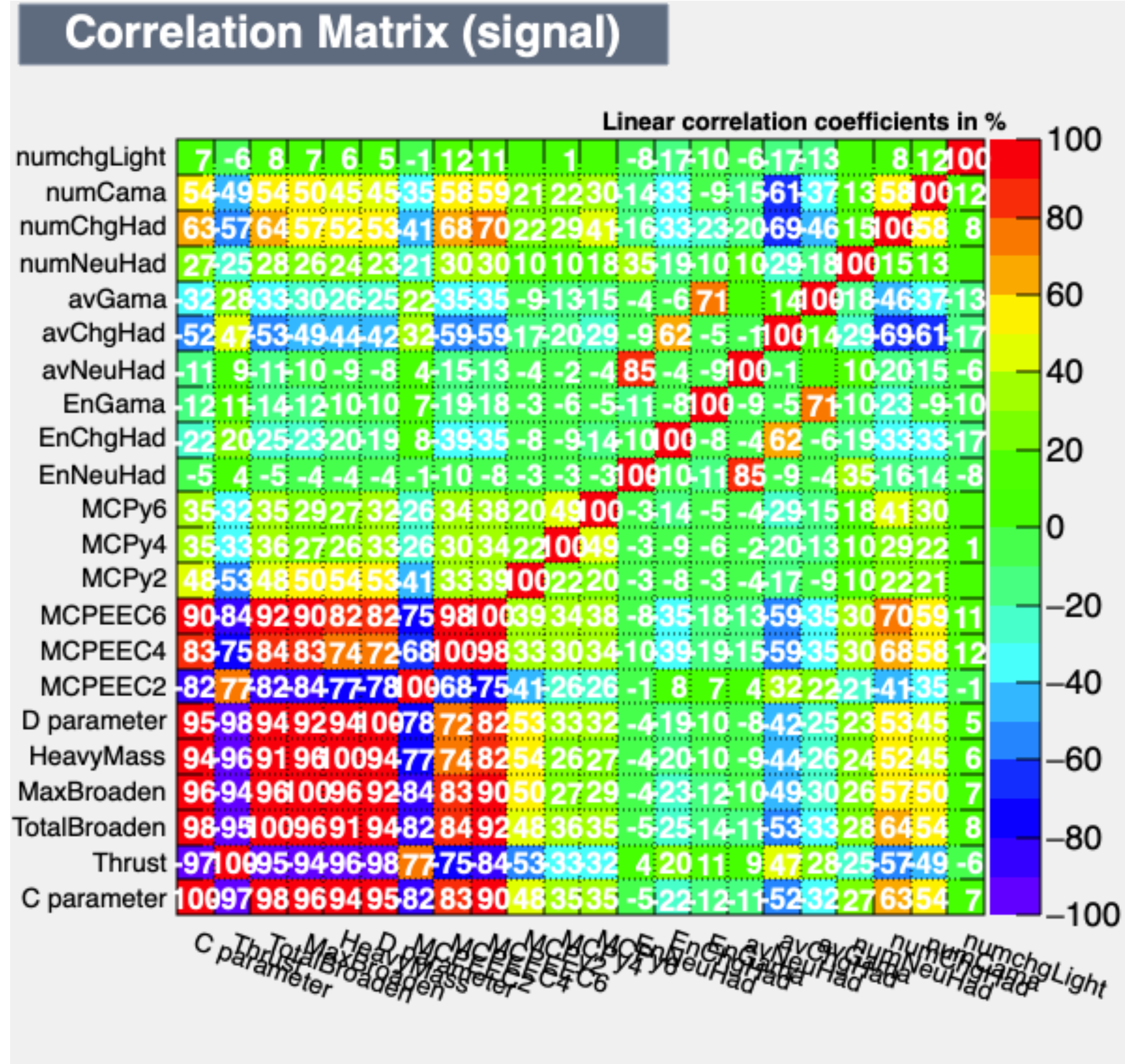
Thank for your attention

Back up

BM2: Number of Jet Identification

20 Variables

# of charge lepton	EEC 6
# of γ	EEC 4
# of charge hadron	EEC 2
# of neutro hadron	C parameter
$\bar{E}_{\gamma}$	D parameter
$\bar{E}_{\text{Charge hadron}}$	Heavy Mass
$\bar{E}_{\text{Neutro hadron}}$	Max Broaden
E_{γ}	Total Broaden
$E_{\text{Charge hadron}}$	Thrust
$E_{\text{Neutro hadron}}$	y_{23}, y_{45}, y_{67}



- **Event-shape variables basic multi-variable analysis to separate 2, 4, and 6 jets final-state.**

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Event-shape Variables

Heavy Jet Mass

$$M_1^2 = \frac{1}{(\sqrt{s})^2}(\sum_i^N P_i)^2$$

$$M_2^2 = \frac{1}{(\sqrt{s})^2}(\sum_i^N P_i)^2$$

C and D Parameter

$$L^{ab} = \frac{1}{\sum_{j=1}^N |P_j|} \sum_{i=1}^N \frac{P_i^a P_i^b}{|P_i|}$$

$$C = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$$

$$D = 27\lambda_1\lambda_2\lambda_3$$

Jet Broadening

$$B_1 = \frac{1}{2\sum_{j=1}^N |P_j|} \sum_{i=1}^N |P_i \times n_T|, (P_i \times n_T) > 0$$

$$B_2 = \frac{1}{2\sum_{j=1}^N |P_j|} \sum_{i=1}^N |P_i \times n_T|, (P_i \times n_T) < 0$$

Energy-Energy Correlation

$$EEC = \frac{1}{\sigma_{tot}} \sum_{ij} \int d\sigma \frac{E_i E_j}{Q^2} \delta(cos\chi - cos\theta_{ij})$$

$$likelihood = \frac{\sum (P1_i) \times P2_i}{\sqrt{\sum (P1_i \times P2_i) \times \sum (P2_i \times P2_i)}}$$

Jet Transition variable, y_{23}, y_{45}, y_{67}

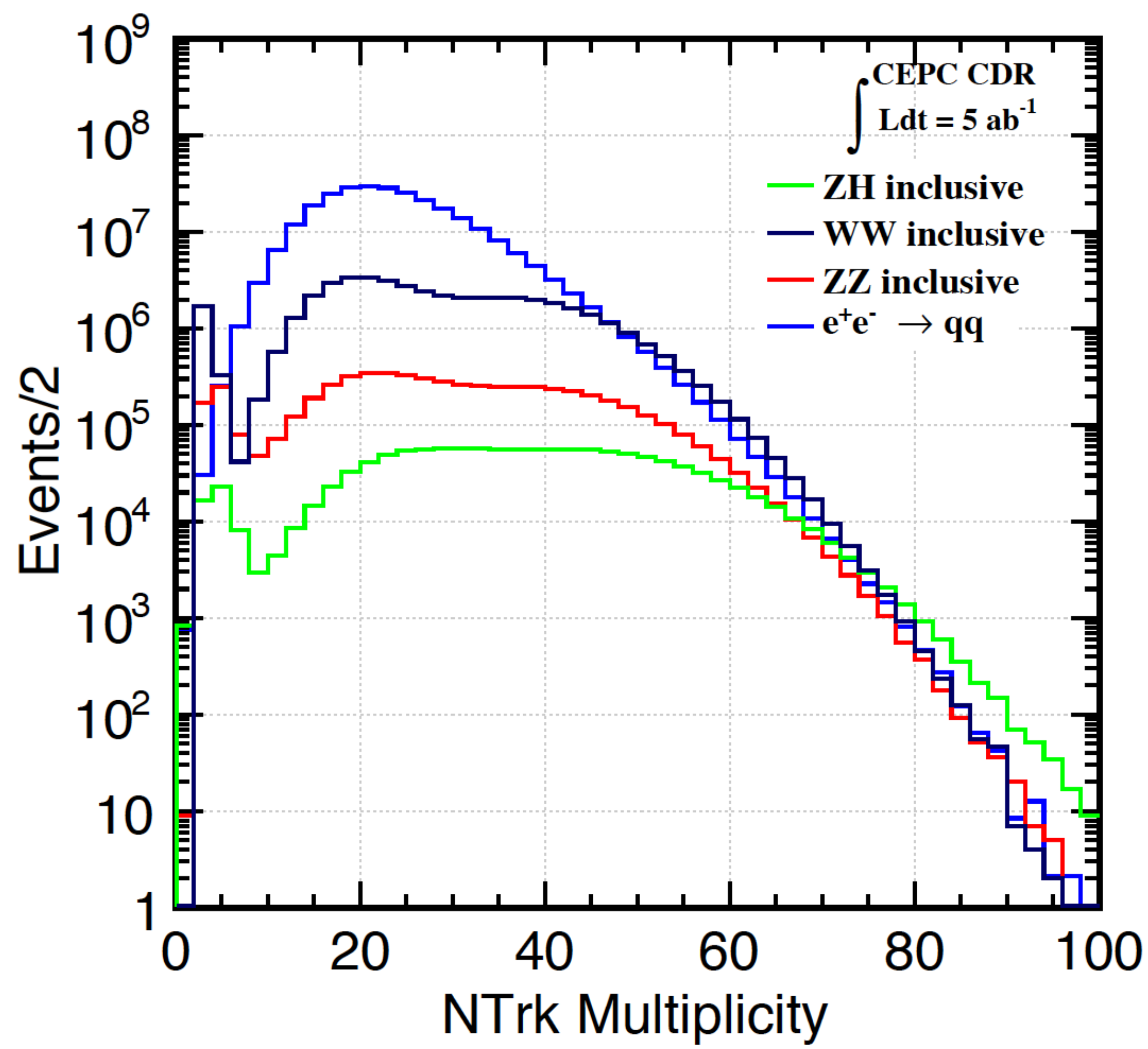
ee-kt jet clustering algorithm

$$d_{ij} = 2min(E_i^2, E_j^2)(1 - cos\theta_{ij})$$

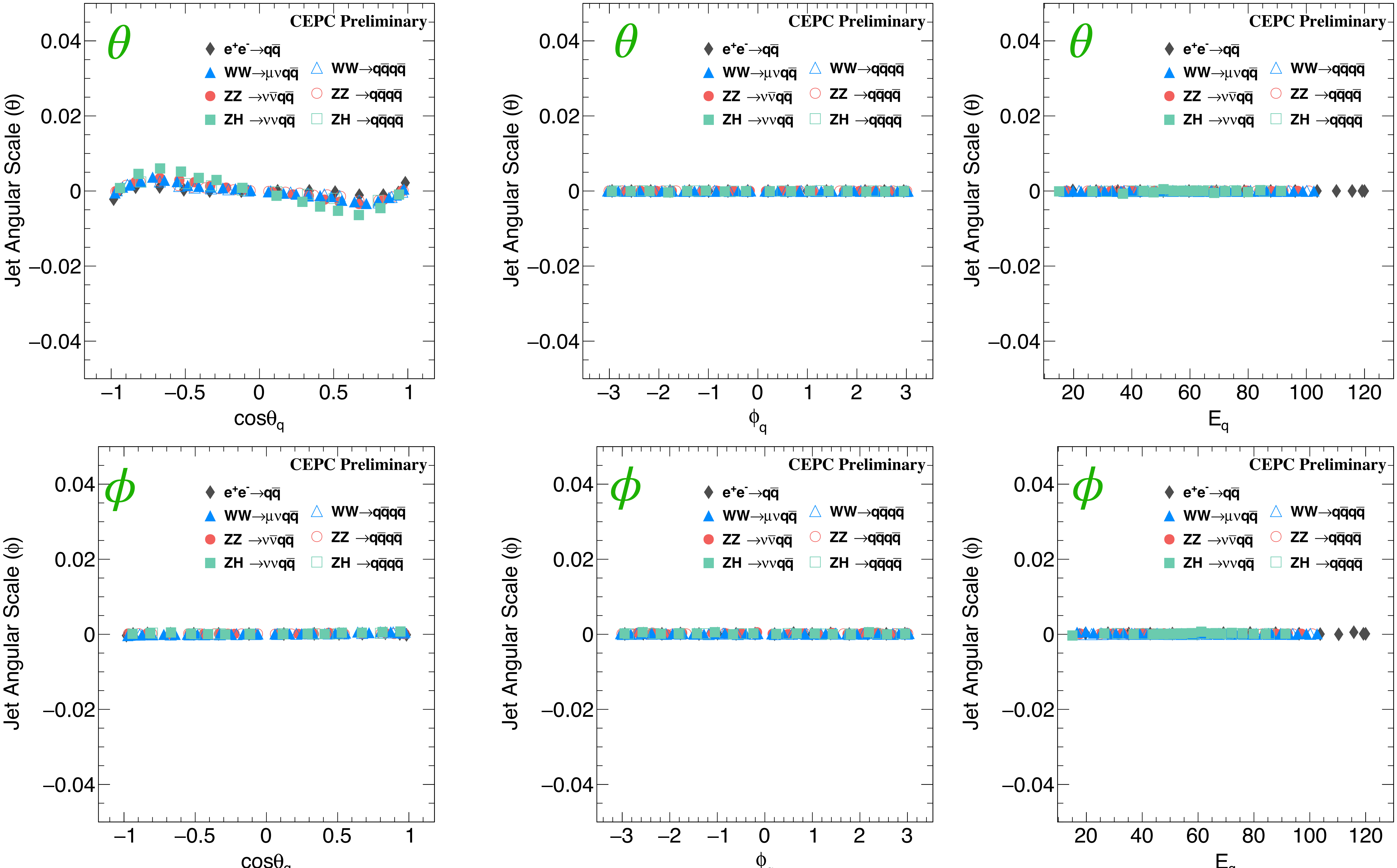
Double-sided Crystal Ball

$$f(x|\alpha_1, \alpha_2, n_1, n_2, \bar{x}, \sigma) = \begin{cases} \left(\frac{n_1}{|\alpha_1|}\right)^{n_1} e^{-\frac{|\alpha_1|^2}{2}} \left(\frac{n_1}{|\alpha_1|} - |\alpha_1| - \frac{x - \bar{x}}{\sigma}\right)^{-n_1} & \frac{x - \bar{x}}{\sigma} < -\alpha_1 \\ e^{-\frac{1}{2}\left(\frac{x - \bar{x}}{\sigma}\right)^2} & -\alpha_1 < \frac{x - \bar{x}}{\sigma} < \alpha_2 \\ \left(\frac{n_2}{|\alpha_2|}\right)^{n_2} e^{-\frac{|\alpha_2|^2}{2}} \left(\frac{n_2}{|\alpha_2|} - |\alpha_2| - \frac{x + \bar{x}}{\sigma}\right)^{-n_2} & \alpha_2 < \frac{x - \bar{x}}{\sigma} \end{cases}$$

Jet Multiplicity

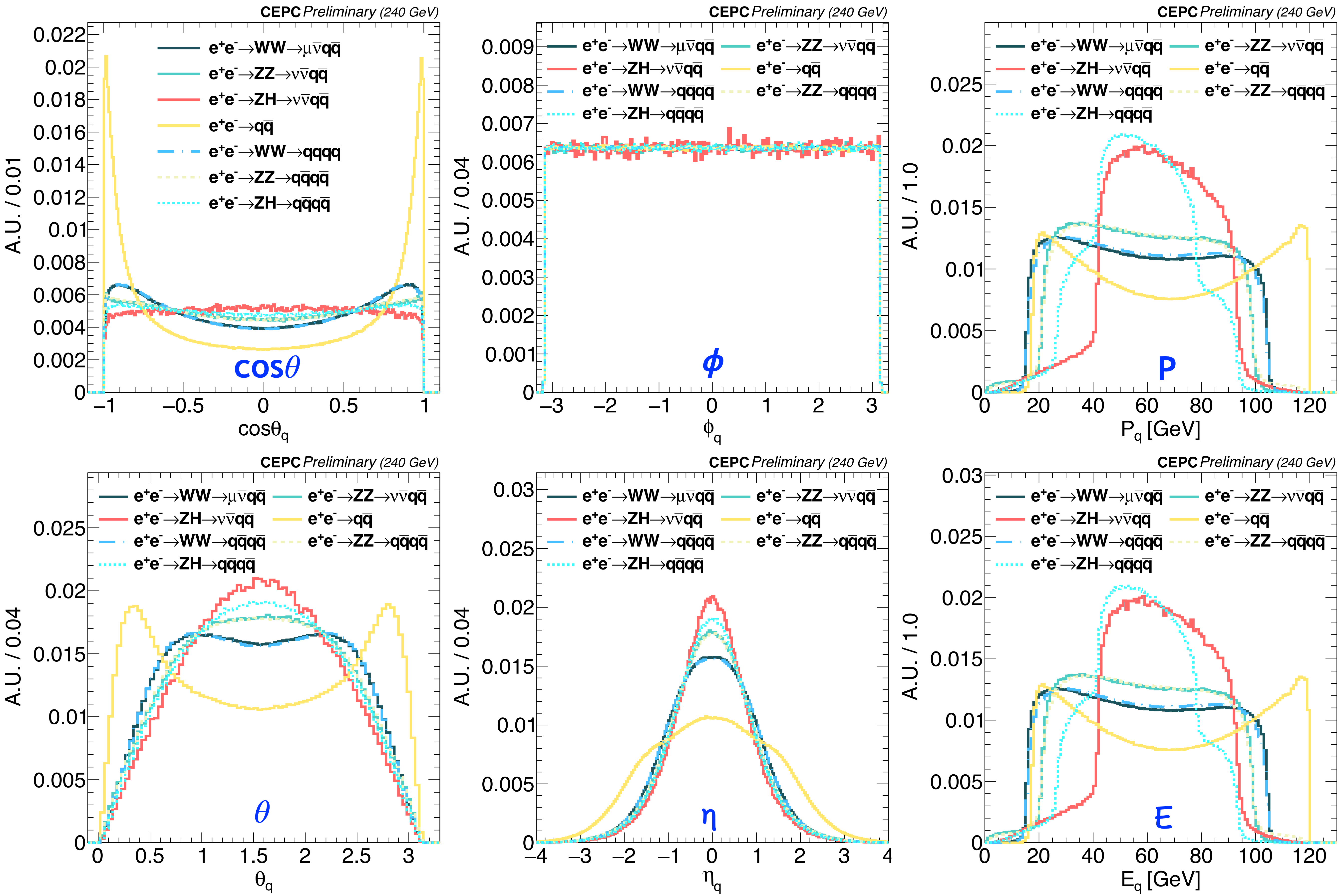


BM3: JAS (Reco-Gen)

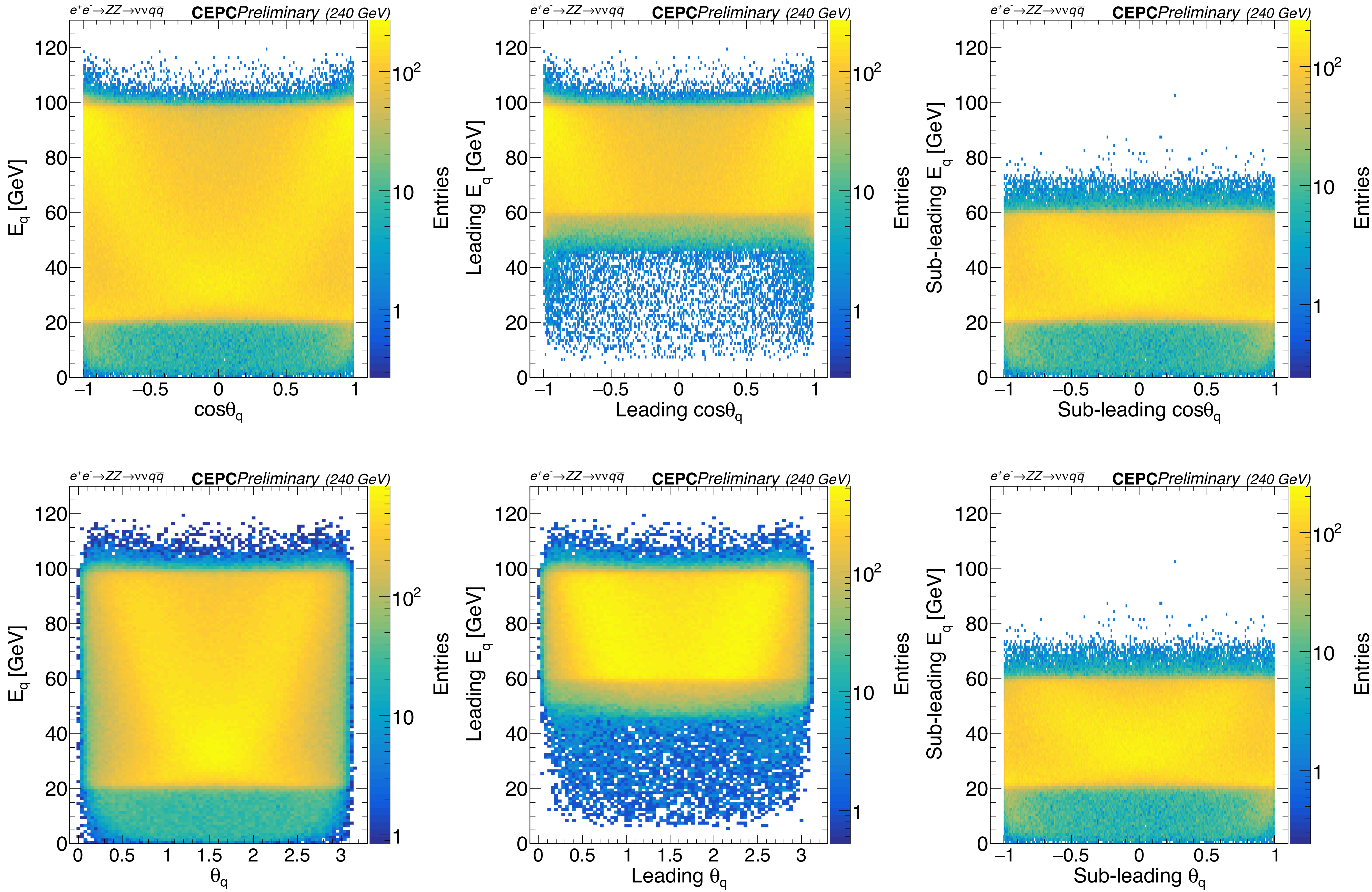


- JAR is around 1% in barrel region; JAS is independent of ϕ and energy.
- The difference between 2 and 4 jets final-state is controlled within 1% level.

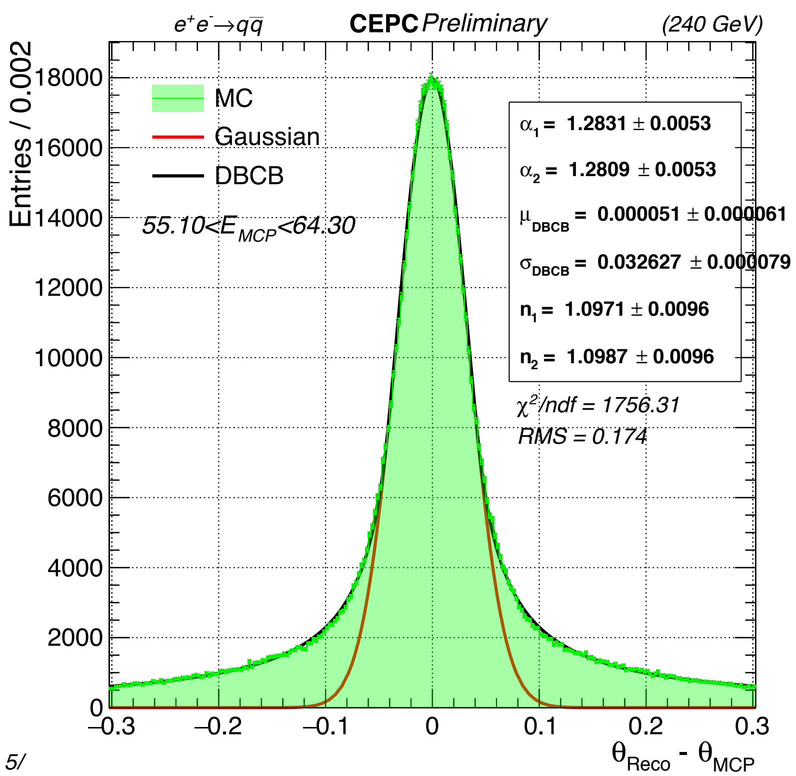
Kinematic Summary Plots(Parton level)



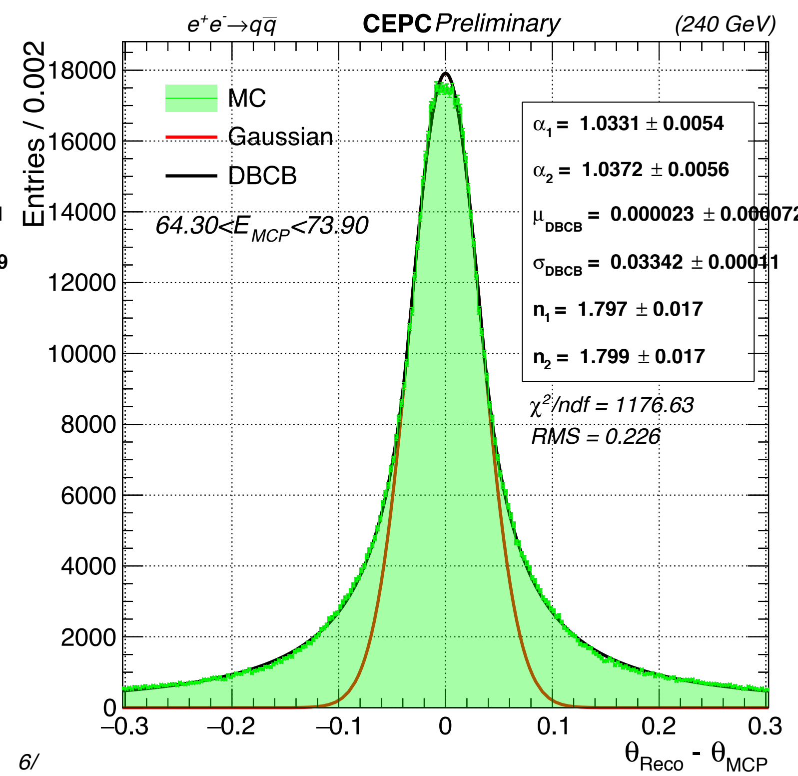
E as the function of the polar angle



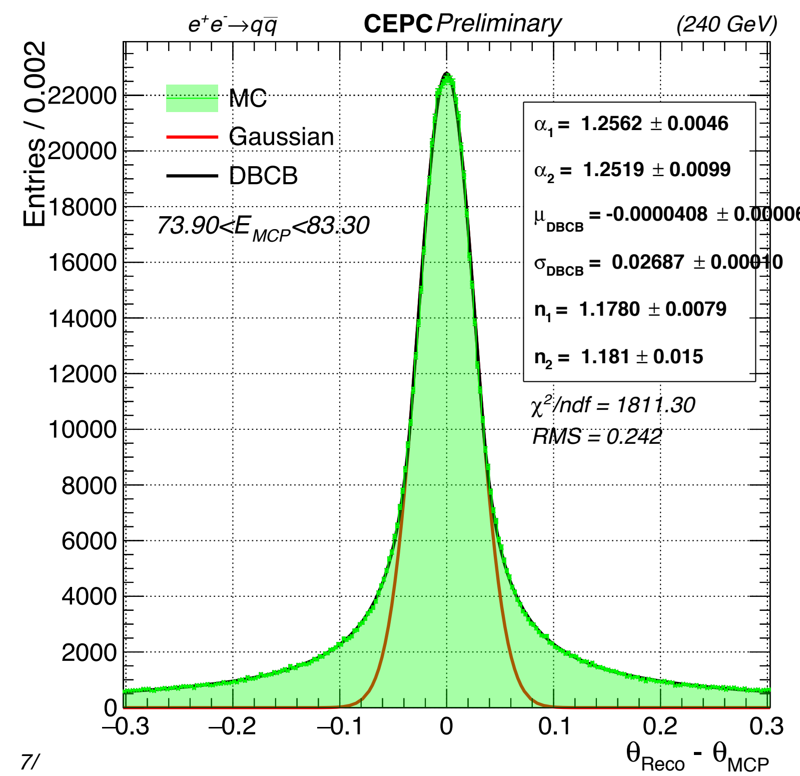
JAR(Reco-MCP)



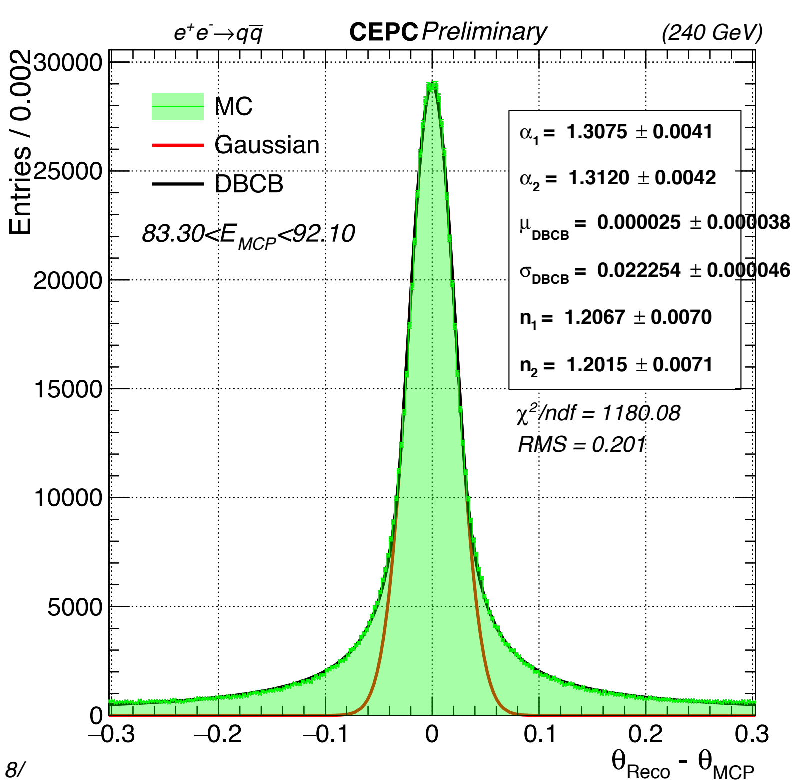
$e^+e^- \to q\bar{q}$
CEPC *Preliminary*
(240 GeV)
MC
Gaussian
DBCB
$55.10<E_{MCP}<64.30$
α_1 = 1.2831 ± 0.0053
α_2 = 1.2809 ± 0.0053
μ_{DBCB} = 0.000051 ± 0.000061
σ_{DBCB} = 0.032627 ± 0.000079
n_1 = 1.0971 ± 0.0096
n_2 = 1.0987 ± 0.0096
χ^2/ndf = 1756.31
RMS = 0.174
Entries / 0.002
$\theta_{Reco} - \theta_{MCP}$
5/



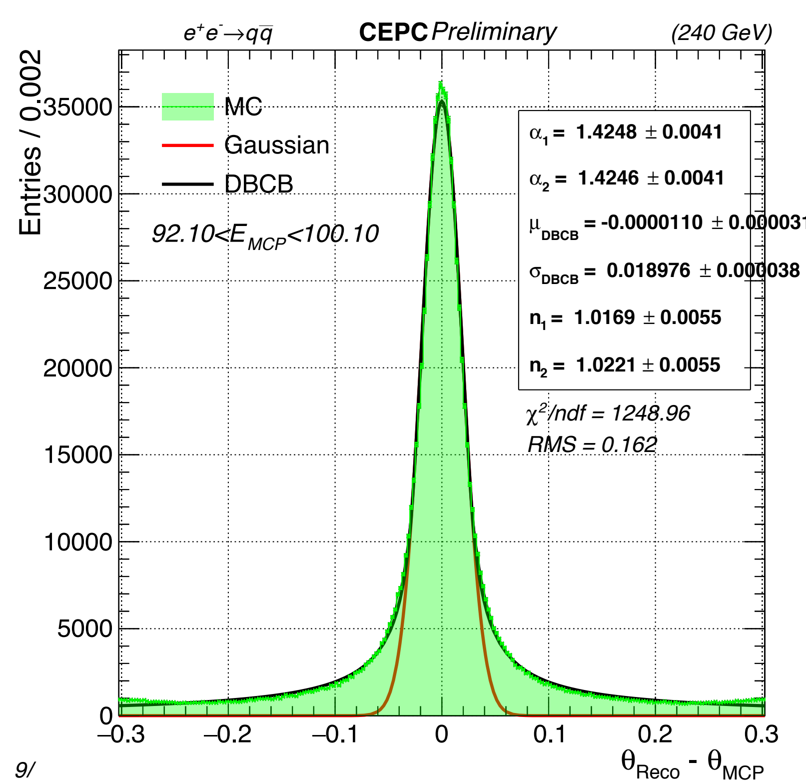
$e^+e^- \to q\bar{q}$
CEPC *Preliminary*
(240 GeV)
MC
Gaussian
DBCB
$64.30<E_{MCP}<73.90$
α_1 = 1.0331 ± 0.0054
α_2 = 1.0372 ± 0.0056
μ_{DBCB} = 0.000023 ± 0.000072
σ_{DBCB} = 0.03342 ± 0.00011
n_1 = 1.797 ± 0.017
n_2 = 1.799 ± 0.017
χ^2/ndf = 1176.63
RMS = 0.226
Entries / 0.002
$\theta_{Reco} - \theta_{MCP}$
6/



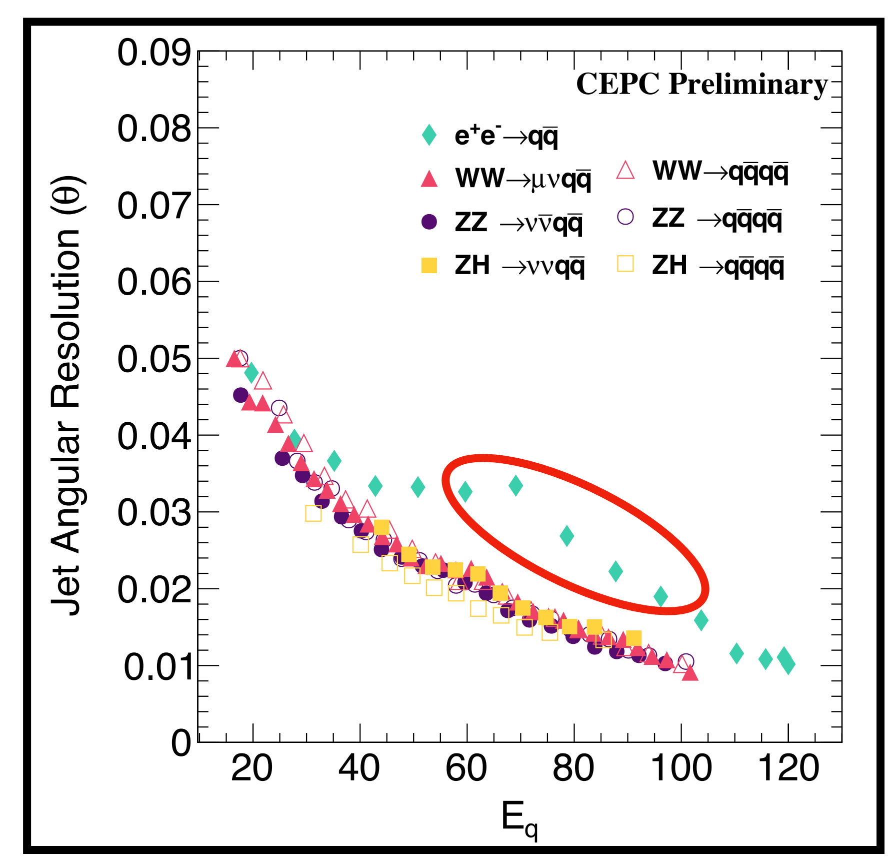
$e^+e^- \to q\bar{q}$
CEPC *Preliminary*
(240 GeV)
MC
Gaussian
DBCB
$73.90<E_{MCP}<83.30$
α_1 = 1.2562 ± 0.0046
α_2 = 1.2519 ± 0.0099
μ_{DBCB} = -0.0000408 ± 0.000006
σ_{DBCB} = 0.02687 ± 0.00010
n_1 = 1.1780 ± 0.0079
n_2 = 1.181 ± 0.015
χ^2/ndf = 1811.30
RMS = 0.242
Entries / 0.002
$\theta_{Reco} - \theta_{MCP}$
7/



$e^+e^- \to q\bar{q}$
CEPC *Preliminary*
(240 GeV)
MC
Gaussian
DBCB
$83.30<E_{MCP}<92.10$
α_1 = 1.3075 ± 0.0041
α_2 = 1.3120 ± 0.0042
μ_{DBCB} = 0.000025 ± 0.000038
σ_{DBCB} = 0.022254 ± 0.000046
n_1 = 1.2067 ± 0.0070
n_2 = 1.2015 ± 0.0071
χ^2/ndf = 1180.08
RMS = 0.201
Entries / 0.002
$\theta_{Reco} - \theta_{MCP}$
8/



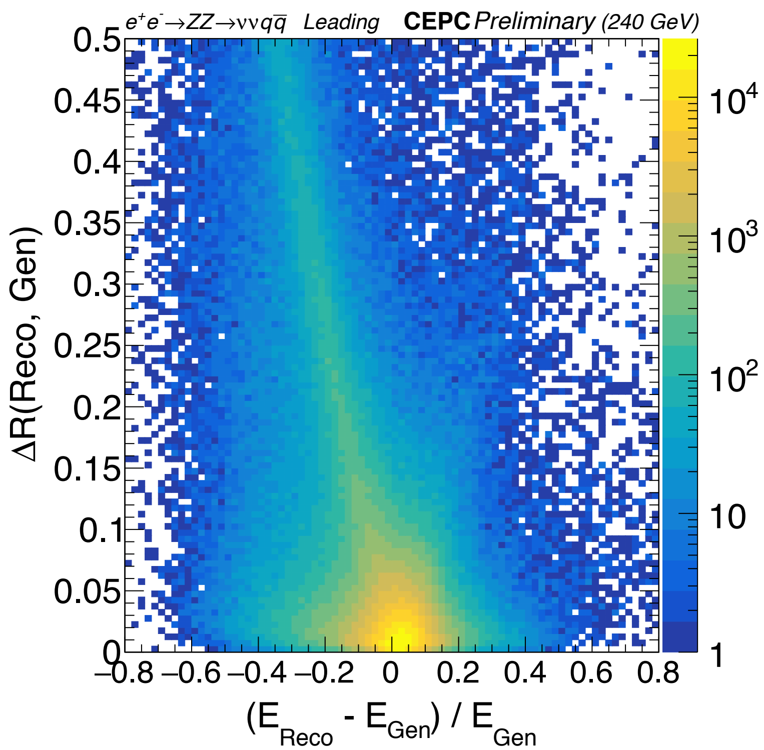
$e^+e^- \to q\bar{q}$
CEPC *Preliminary*
(240 GeV)
MC
Gaussian
DBCB
$92.10<E_{MCP}<100.10$
α_1 = 1.4248 ± 0.0041
α_2 = 1.4246 ± 0.0041
μ_{DBCB} = -0.0000110 ± 0.000031
σ_{DBCB} = 0.018976 ± 0.000038
n_1 = 1.0169 ± 0.0055
n_2 = 1.0221 ± 0.0055
χ^2/ndf = 1248.96
RMS = 0.162
Entries / 0.002
$\theta_{Reco} - \theta_{MCP}$
9/



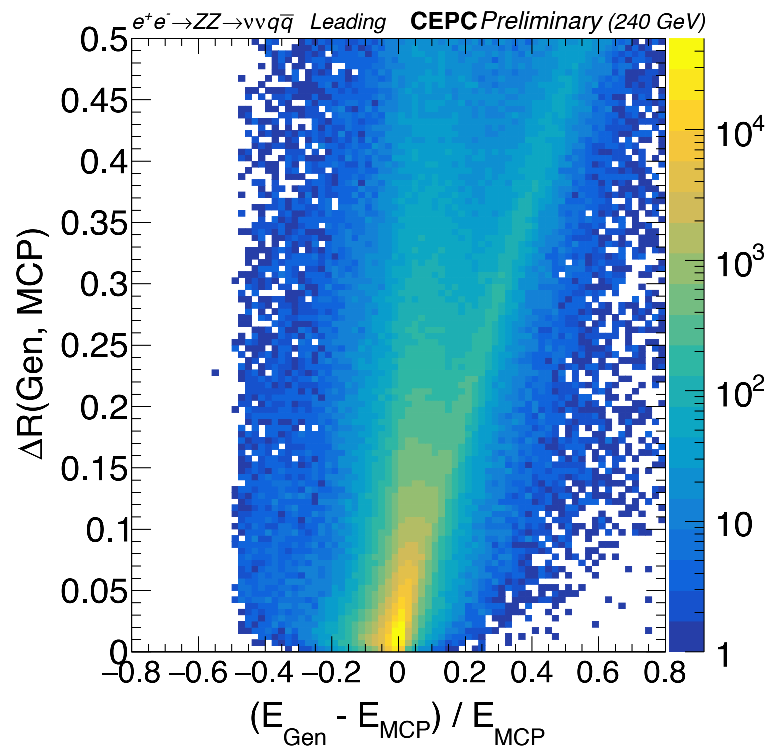
CEPC Preliminary
$e^+e^- \to q\bar{q}$
$WW \to \mu\nu q\bar{q}$
$WW \to q\bar{q}q\bar{q}$
$ZZ \to \nu\bar{\nu}q\bar{q}$
$ZZ \to q\bar{q}q\bar{q}$
$ZH \to \nu\nu q\bar{q}$
$ZH \to q\bar{q}q\bar{q}$
Jet Angular Resolution (θ)
E_q

ΔR as the function of ΔE

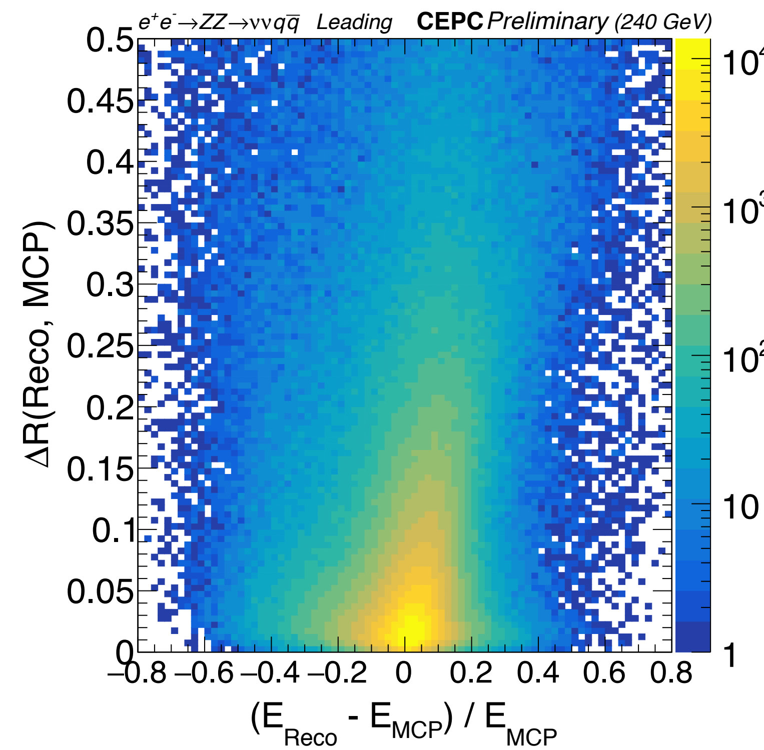
Leading, Gen-MCP



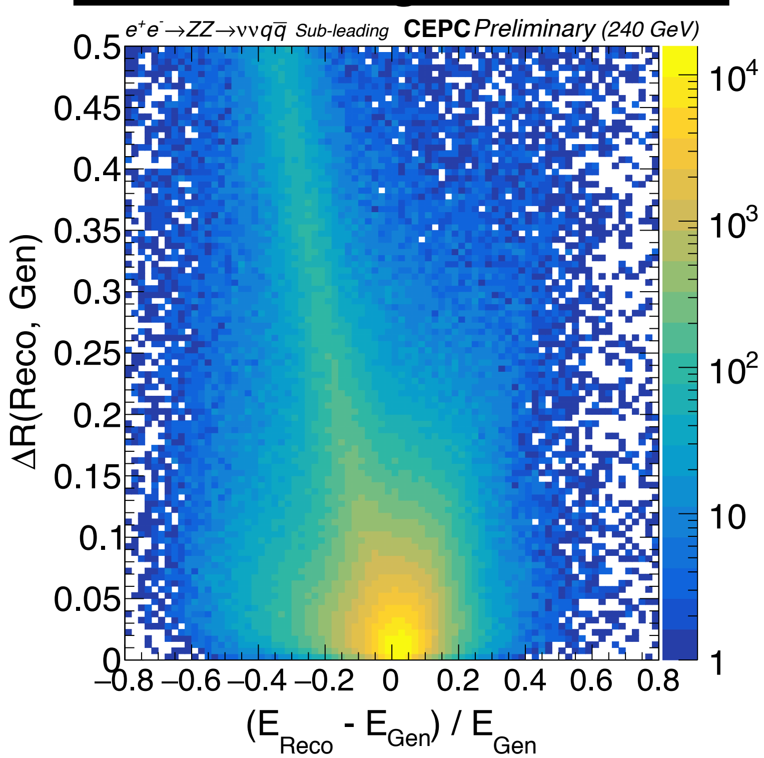
Leading, Reco-Gen



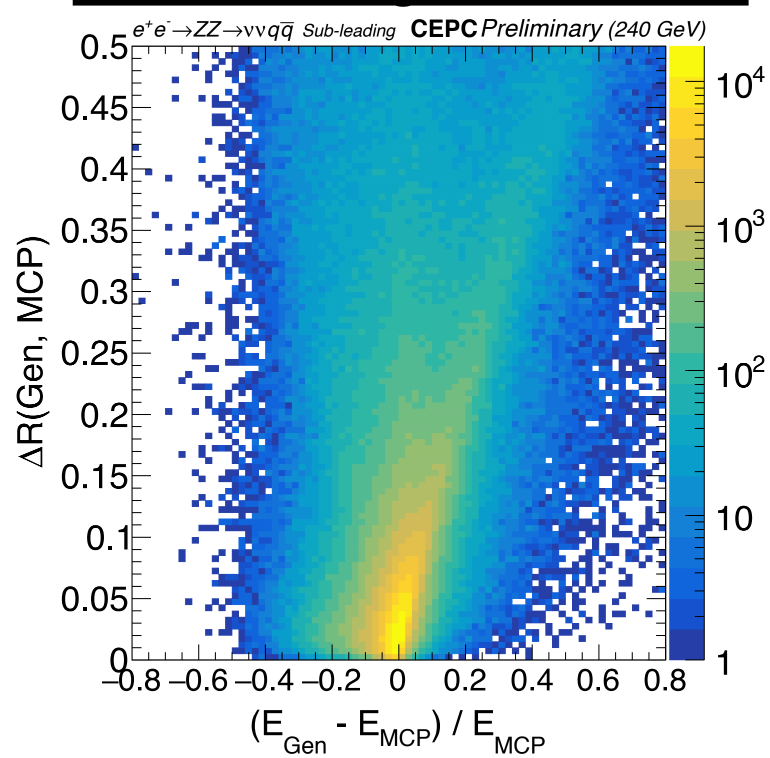
Leading, Reco-MCP



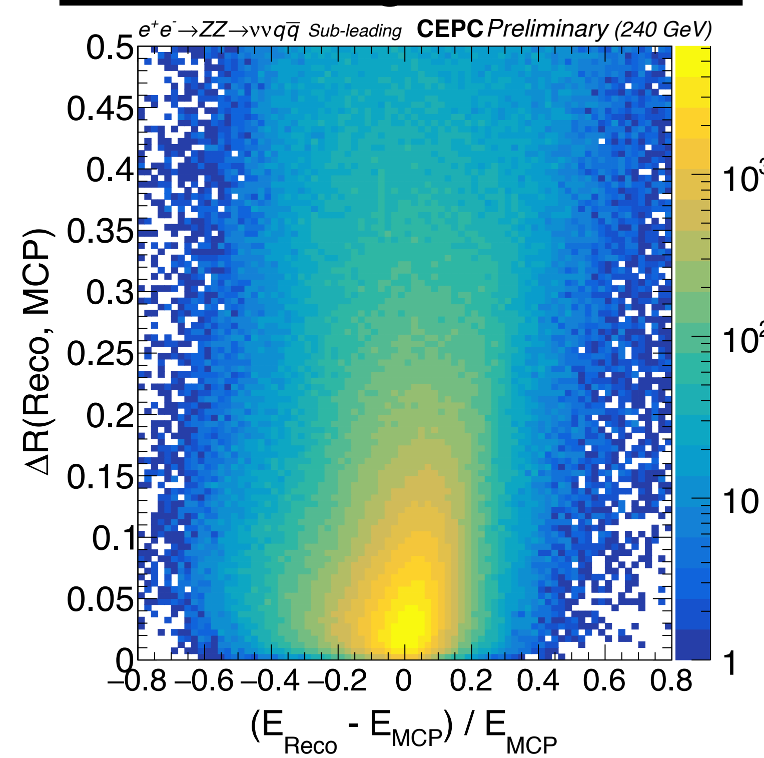
Sub-leading, Gen-MCP



Sub-leading, Reco-Gen



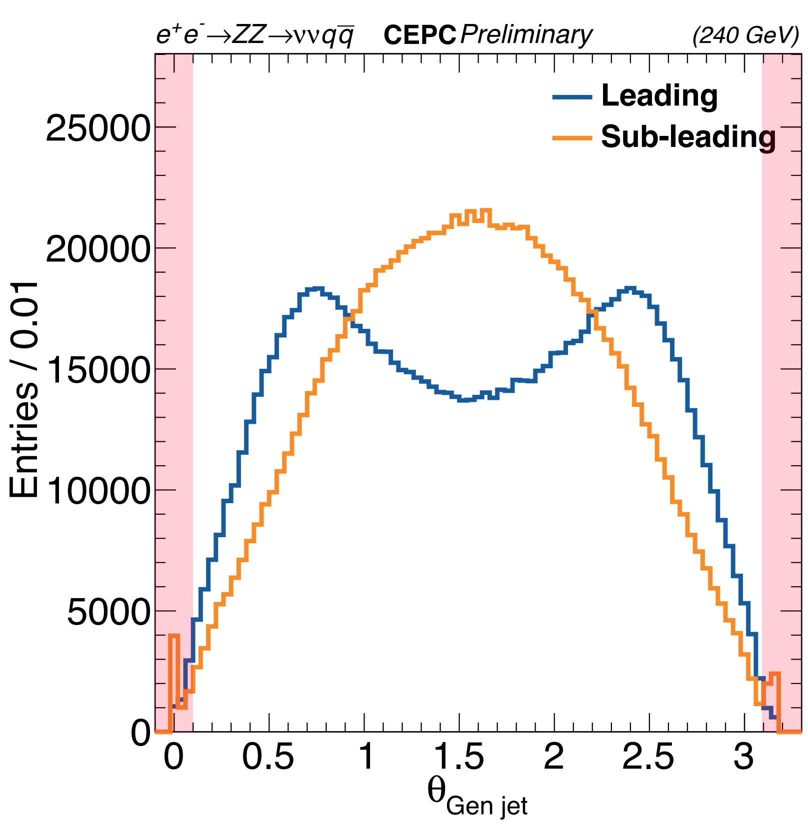
Sub-leading, Reco-MCP

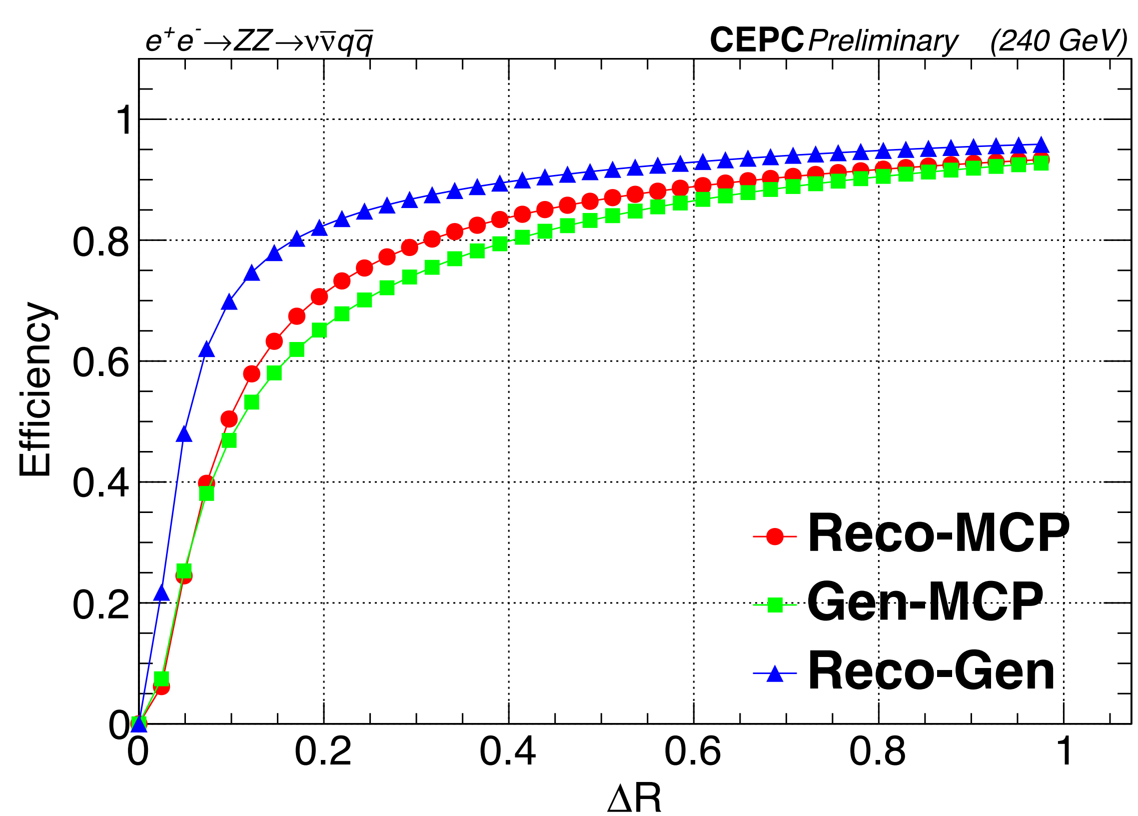


The jet clustering brings a significant uncertainty.

Event Selection

Items	(Reco-Gen)	(Gen-MCP)
$\theta_{\text{Gen jet}} > 0.1$ & $\theta_{\text{Gen jet}} < 3.1$	✓	✓
ΔR(Reco-MCP) < 0.1	✓	✗





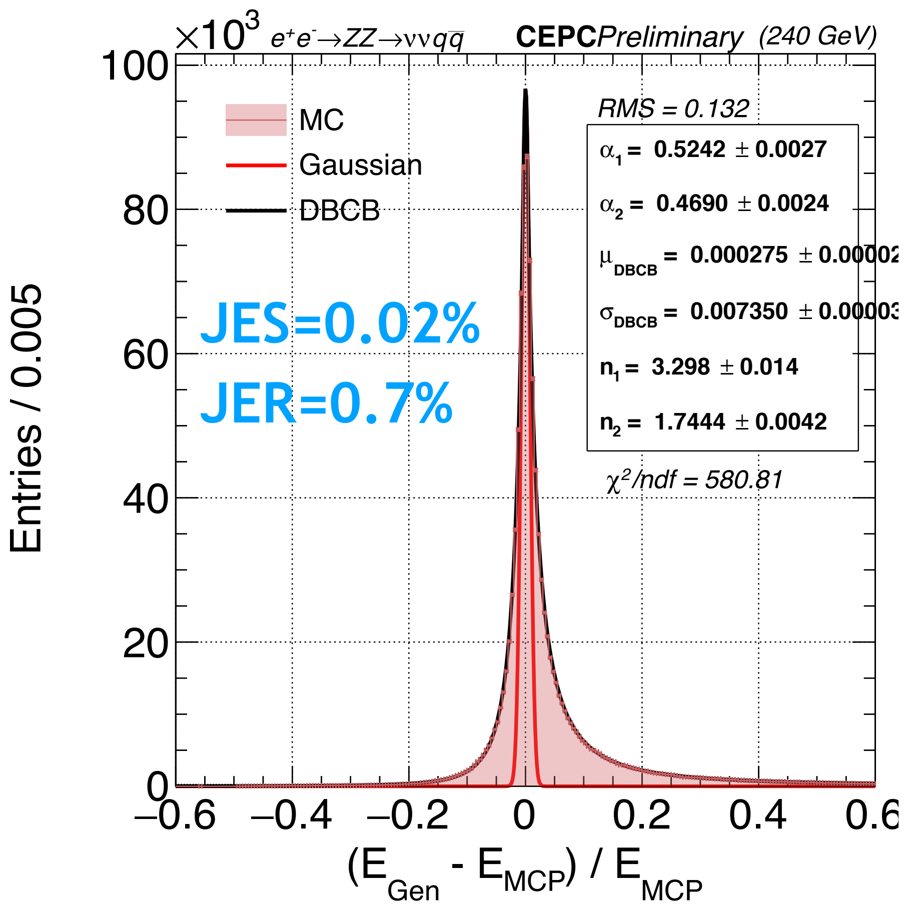
Efficiency=

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

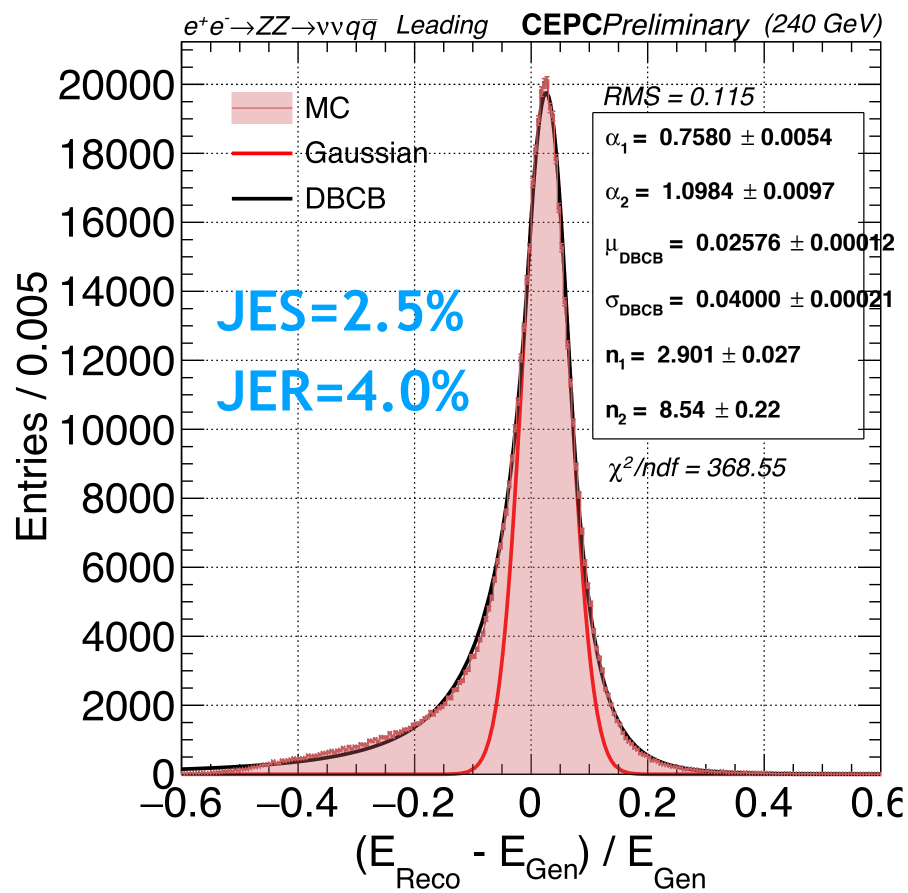
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

Leading JER & JES

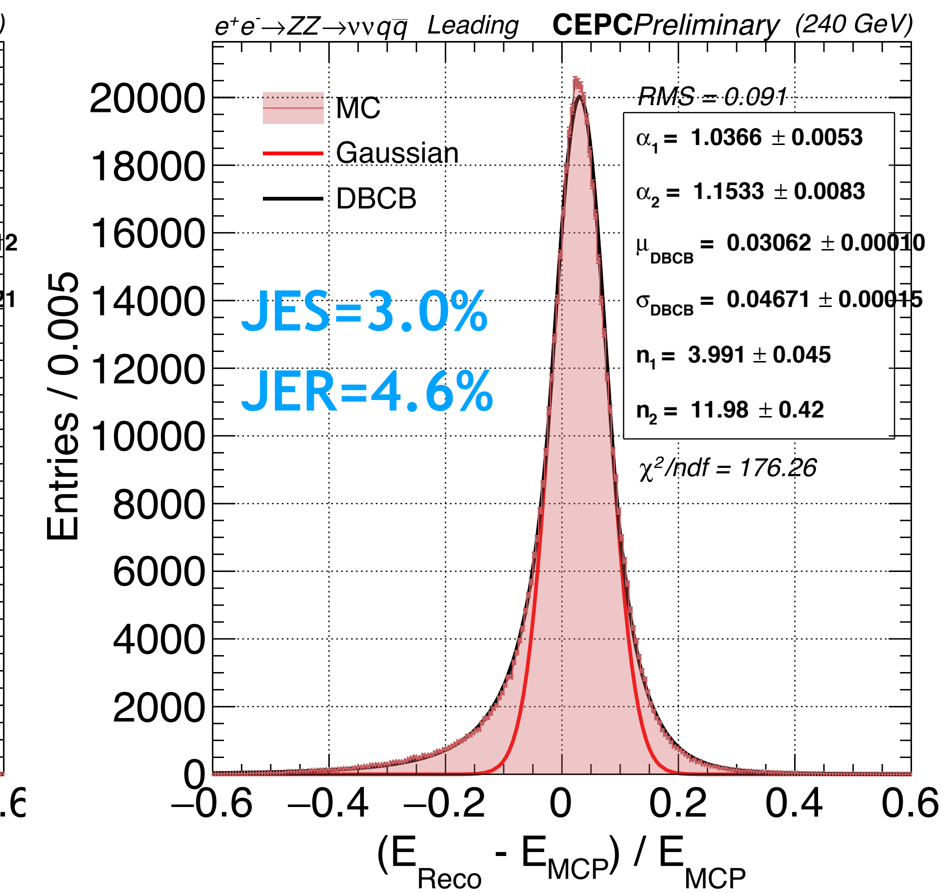
Gen-MCP



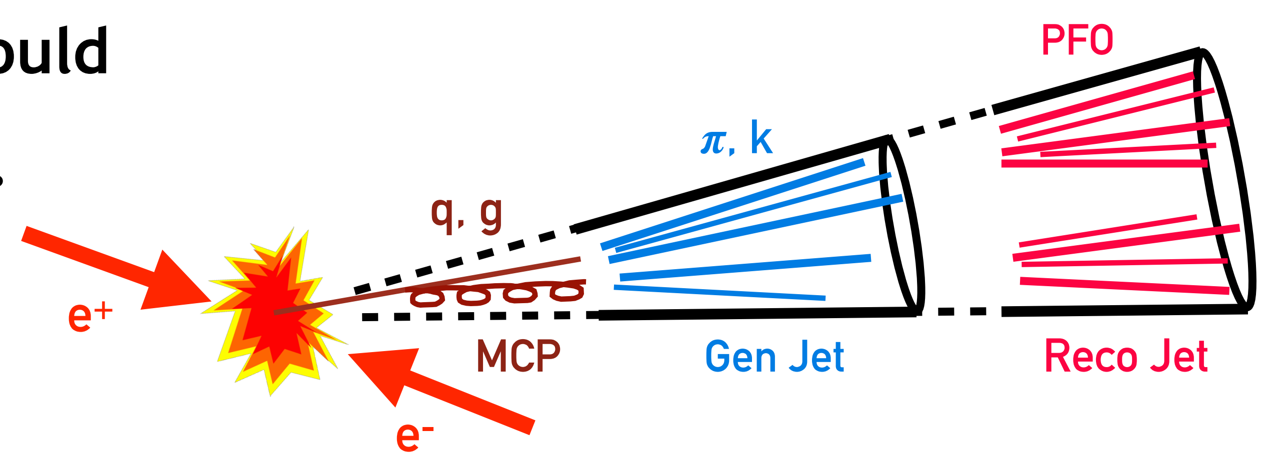
Reco-Gen



Reco-MCP

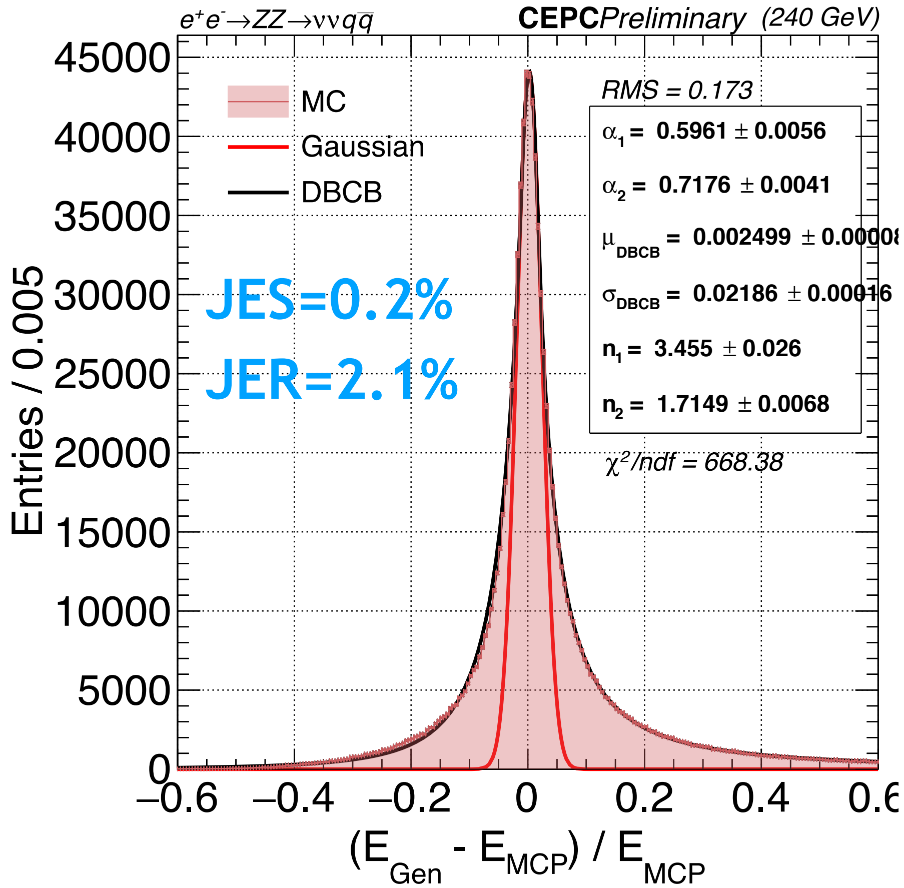


- JER/JES between Reco jet and MCP would combine the effects of two previous stages.

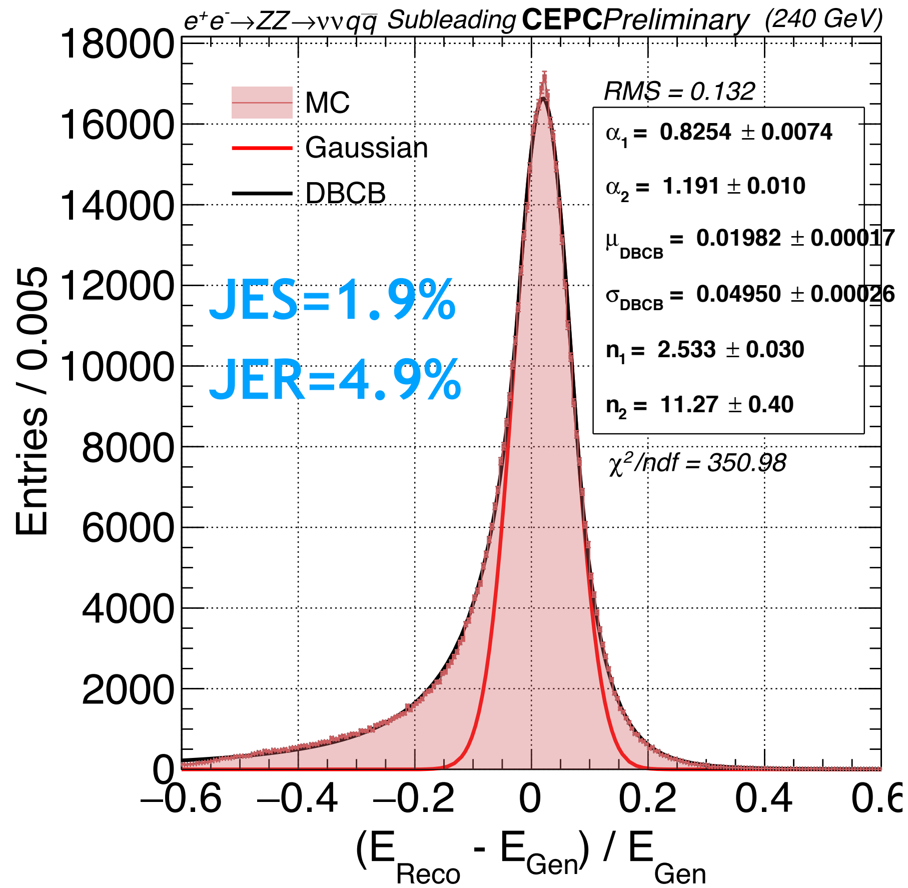


Sub-leading JER & JES

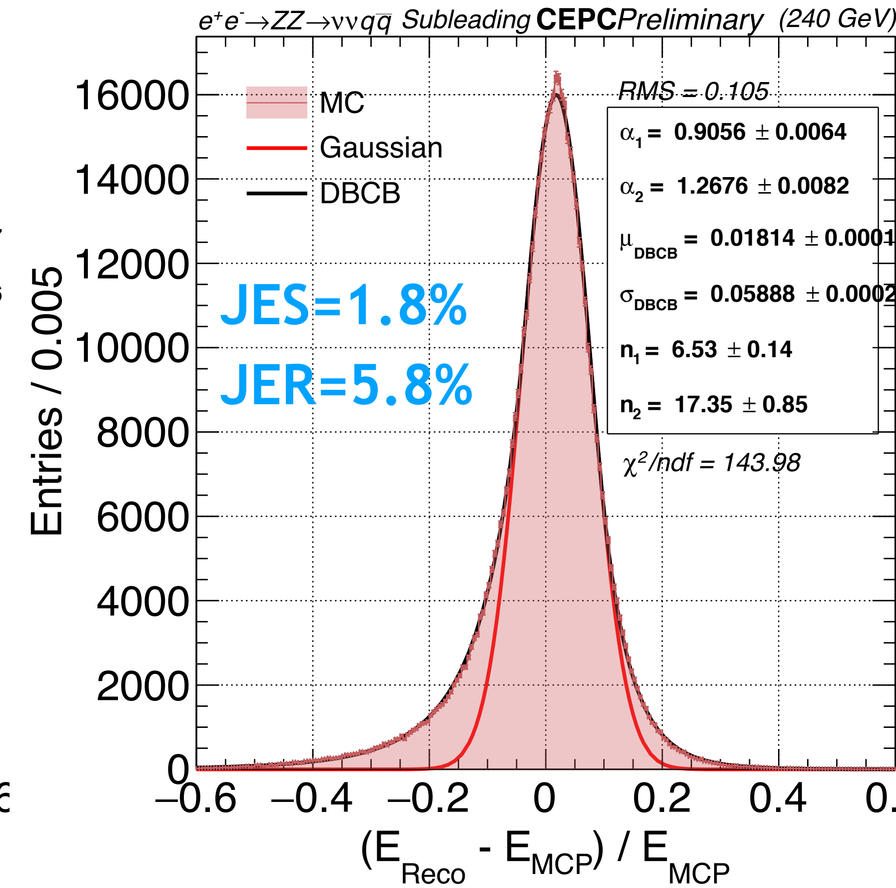
Gen-MCP

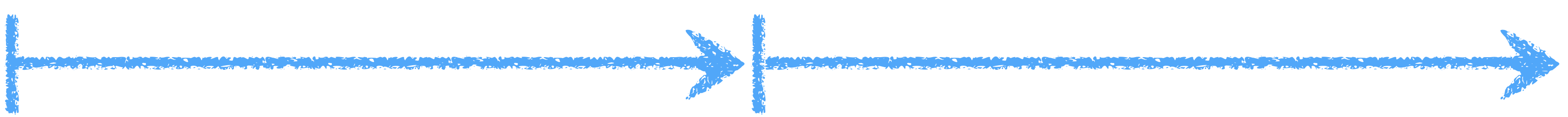


Reco-Gen



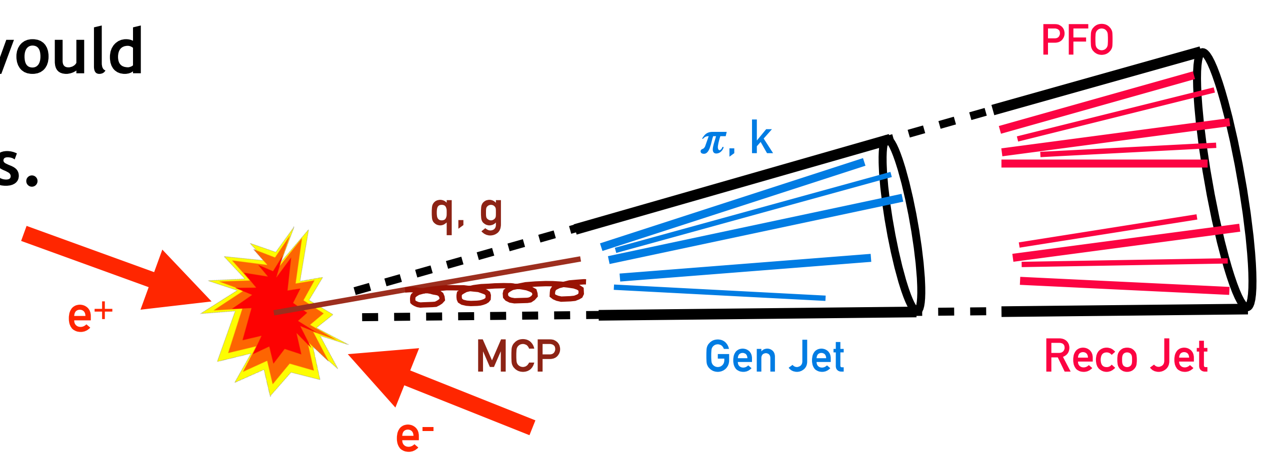
Reco-MCP





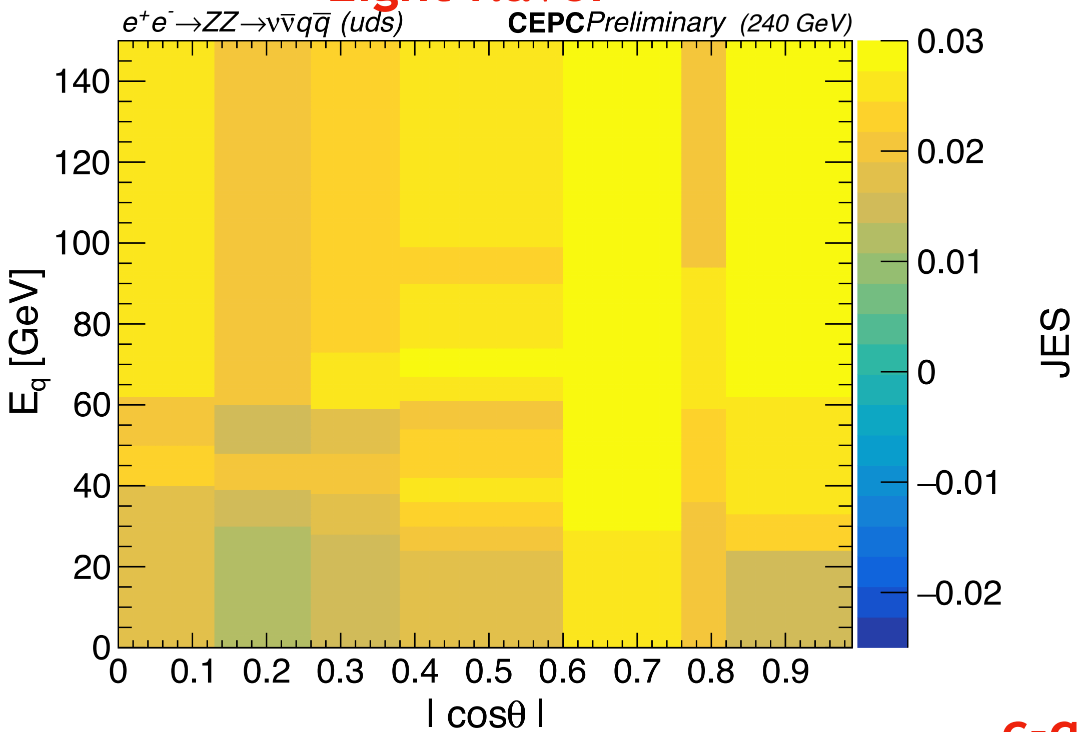
MCP **Gen jet** **Reco jet**

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

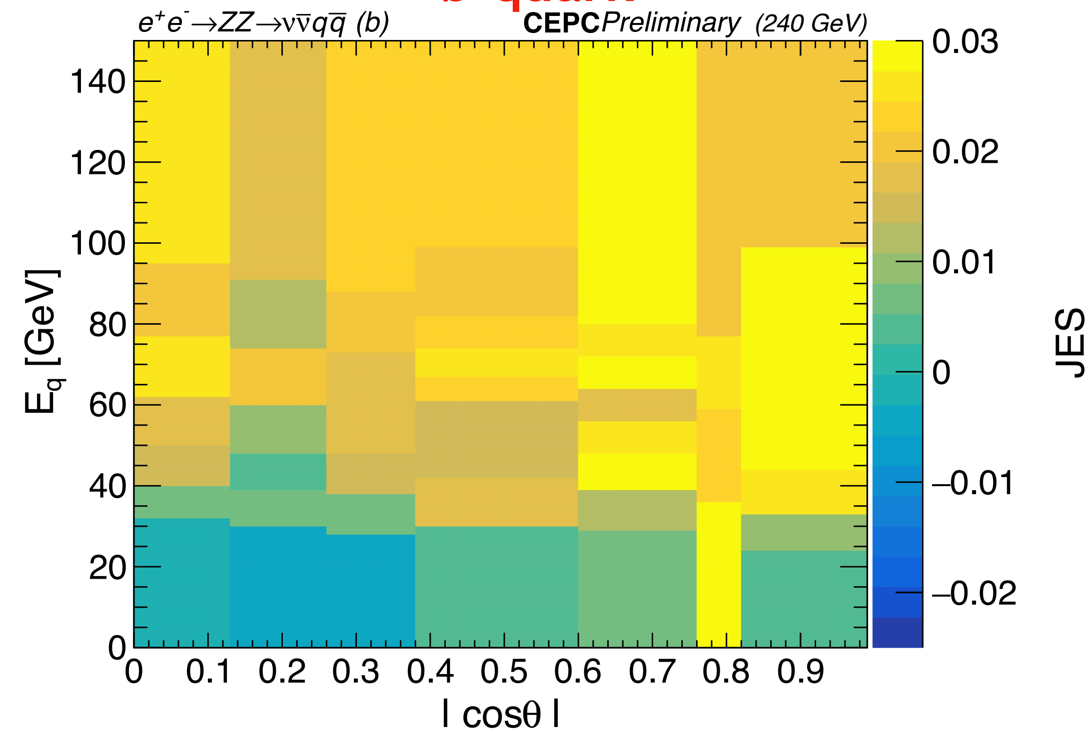


JES in Phase Space

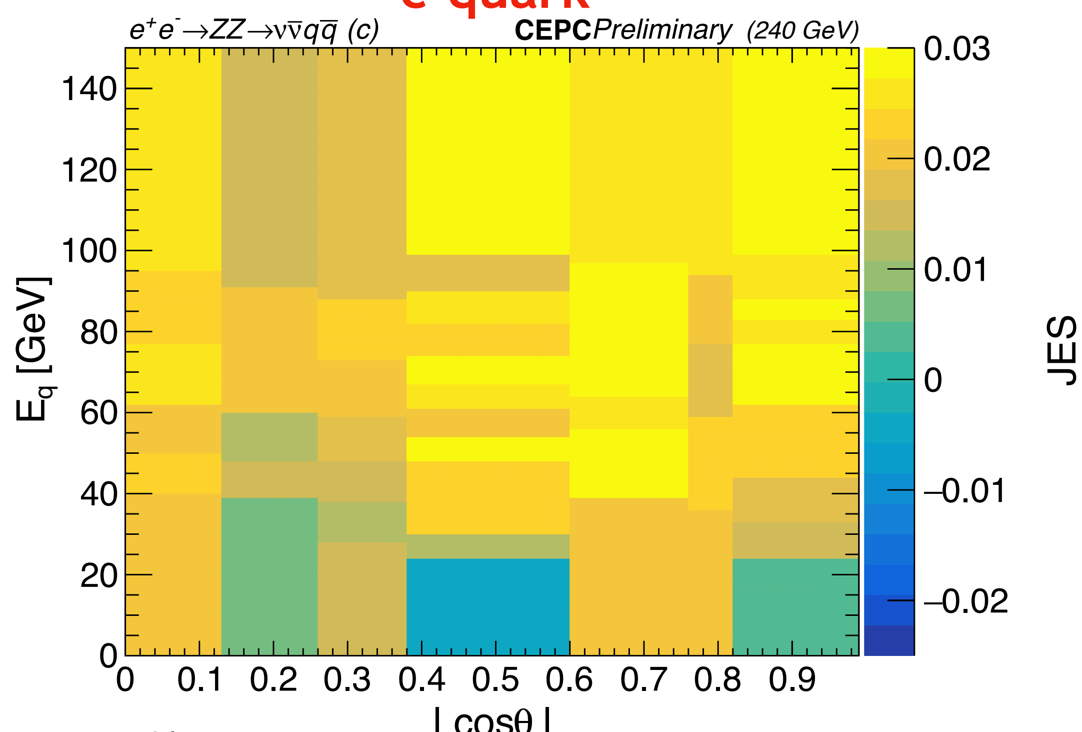
Light flavor



b-quark



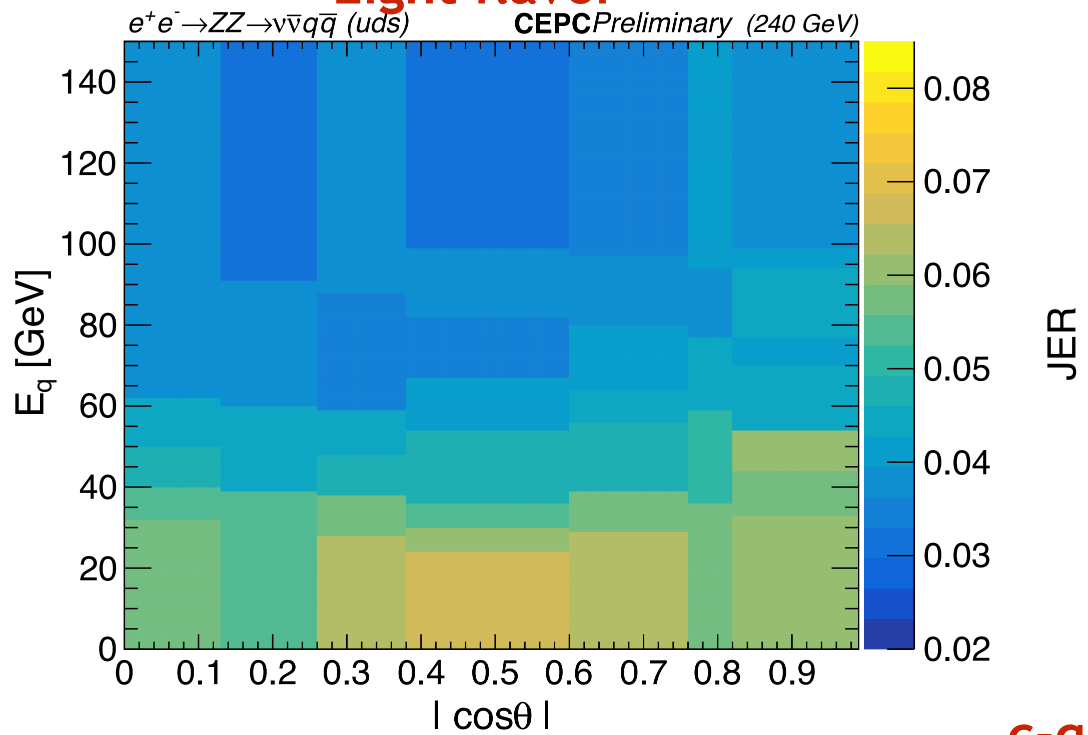
c-quark



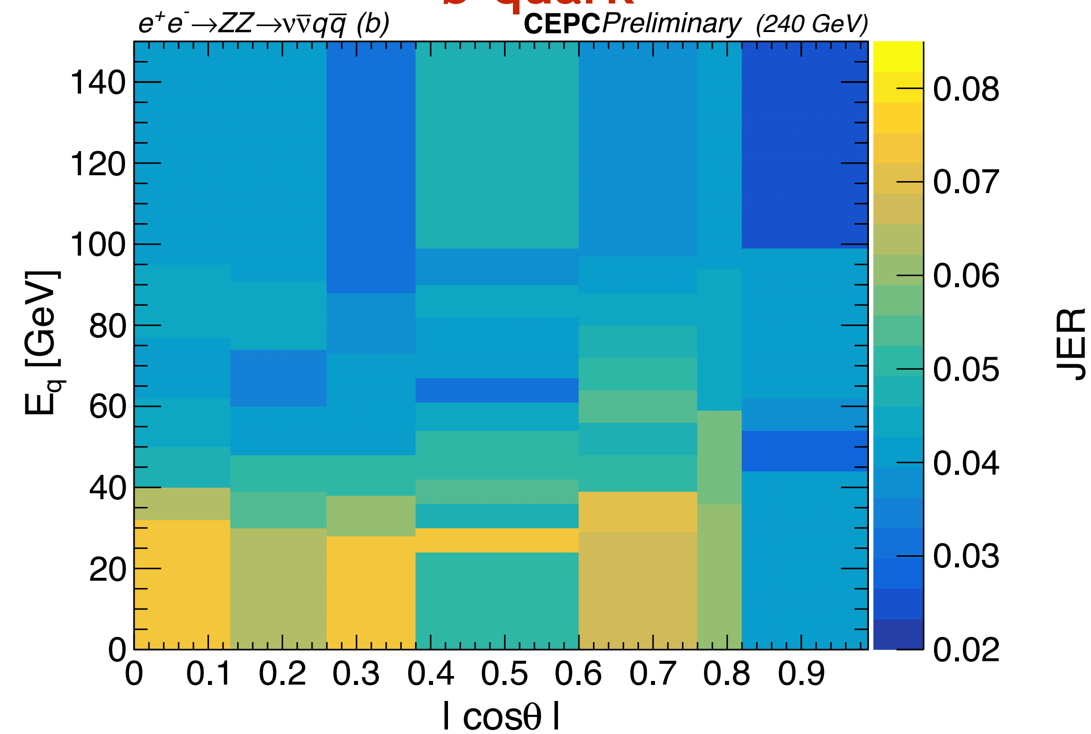
- **JES also depends on the jet flavor.**
- **Light flavor jet has higher energy deviation.**

JER in Phase Space

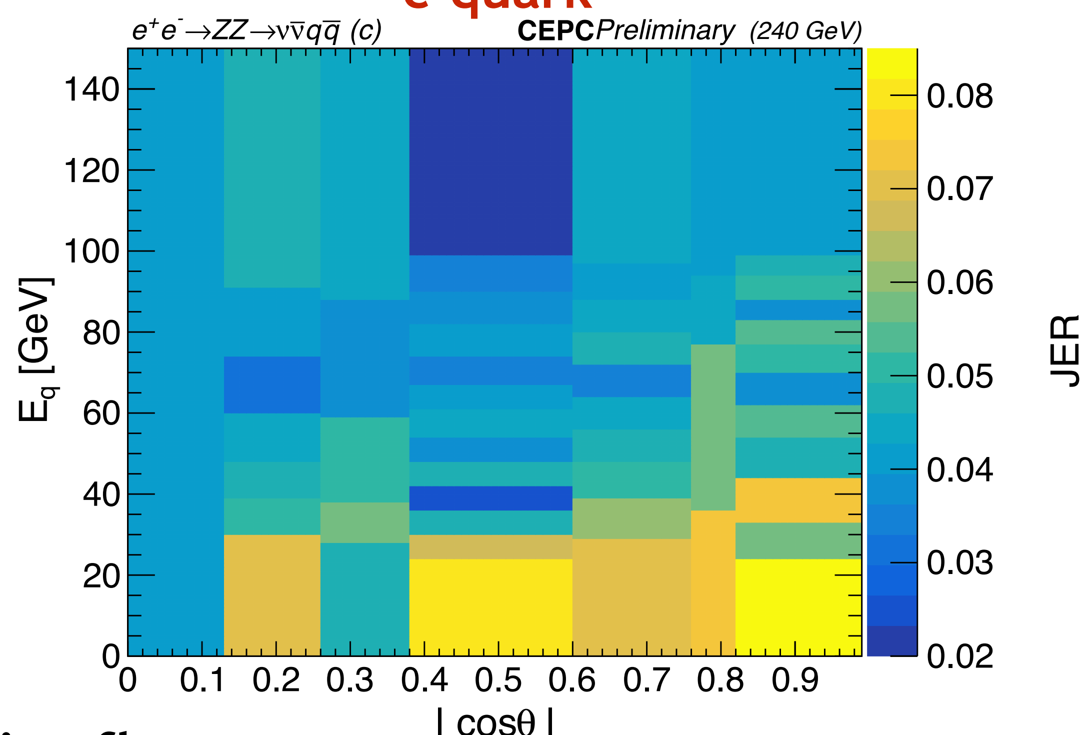
Light flavor



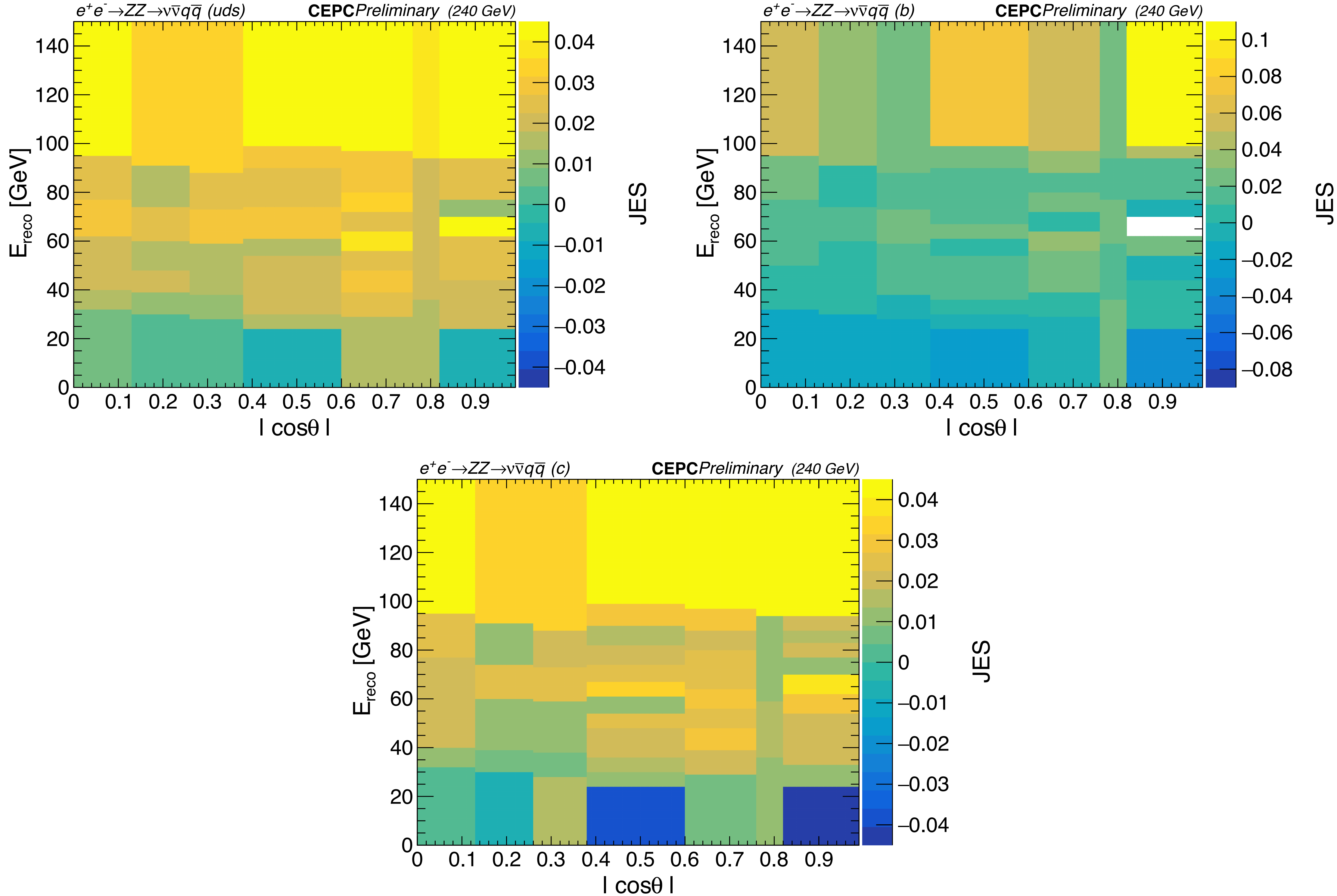
b-quark



c-quark

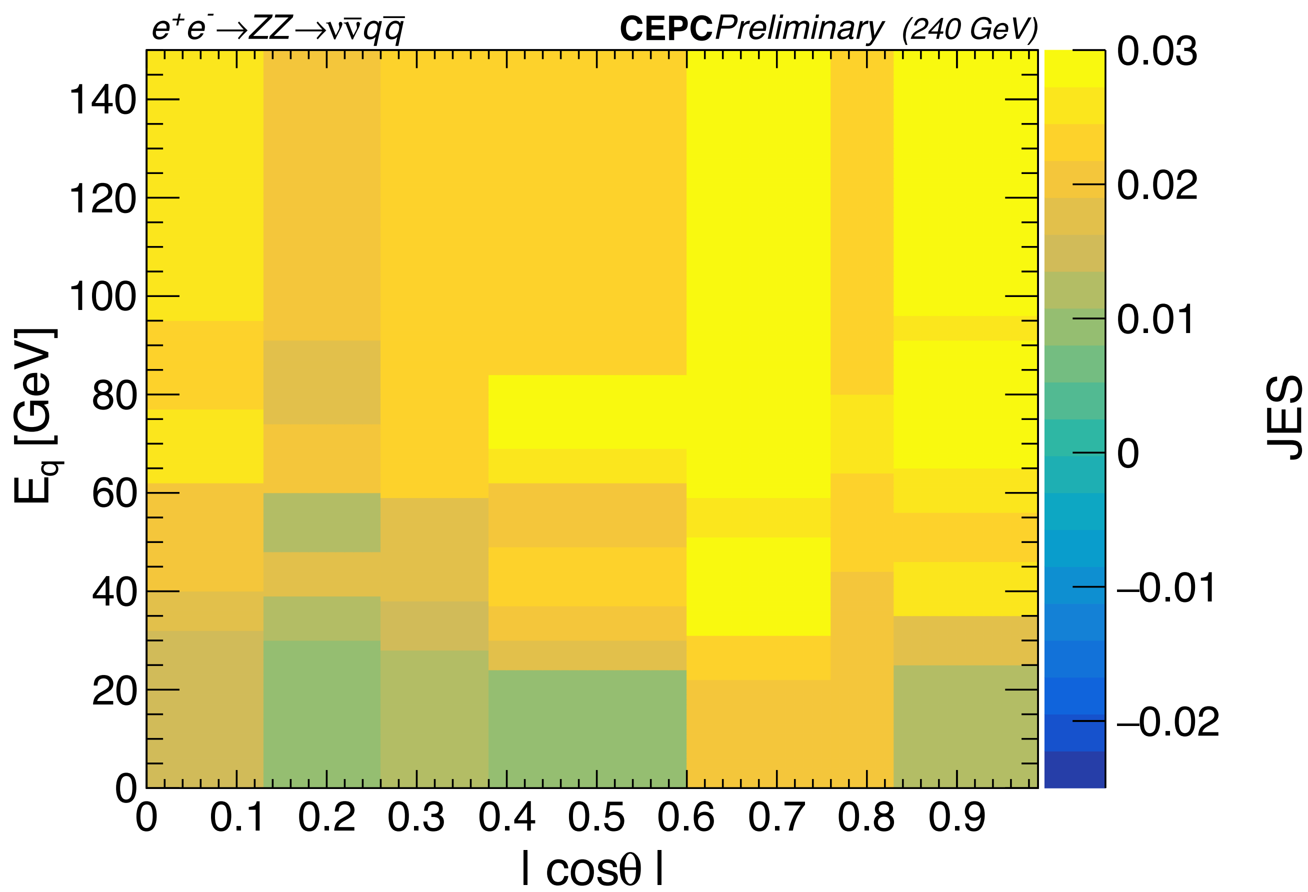


- **JER also depends on the jet flavor.**
- **Higher jet energy and within central region of barrel, JER has impressive performance.**

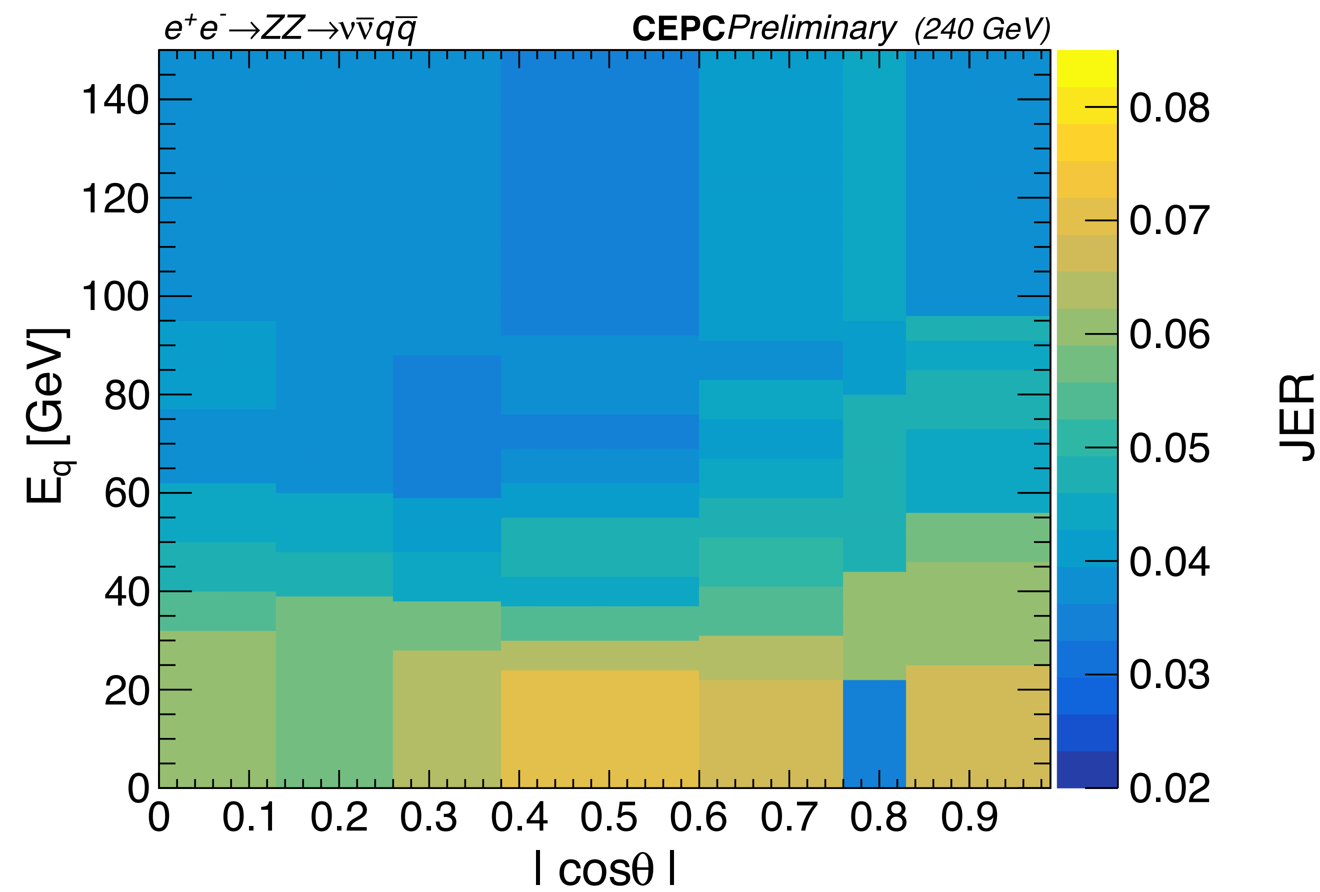


$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$ (uds)
CEPC Preliminary (240 GeV)
E_{reco} [GeV]
| cosθ |
JES
$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$ (b)
CEPC Preliminary (240 GeV)
E_{reco} [GeV]
| cosθ |
JES
$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$ (c)
CEPC Preliminary (240 GeV)
E_{reco} [GeV]
| cosθ |
JES

JER & JES

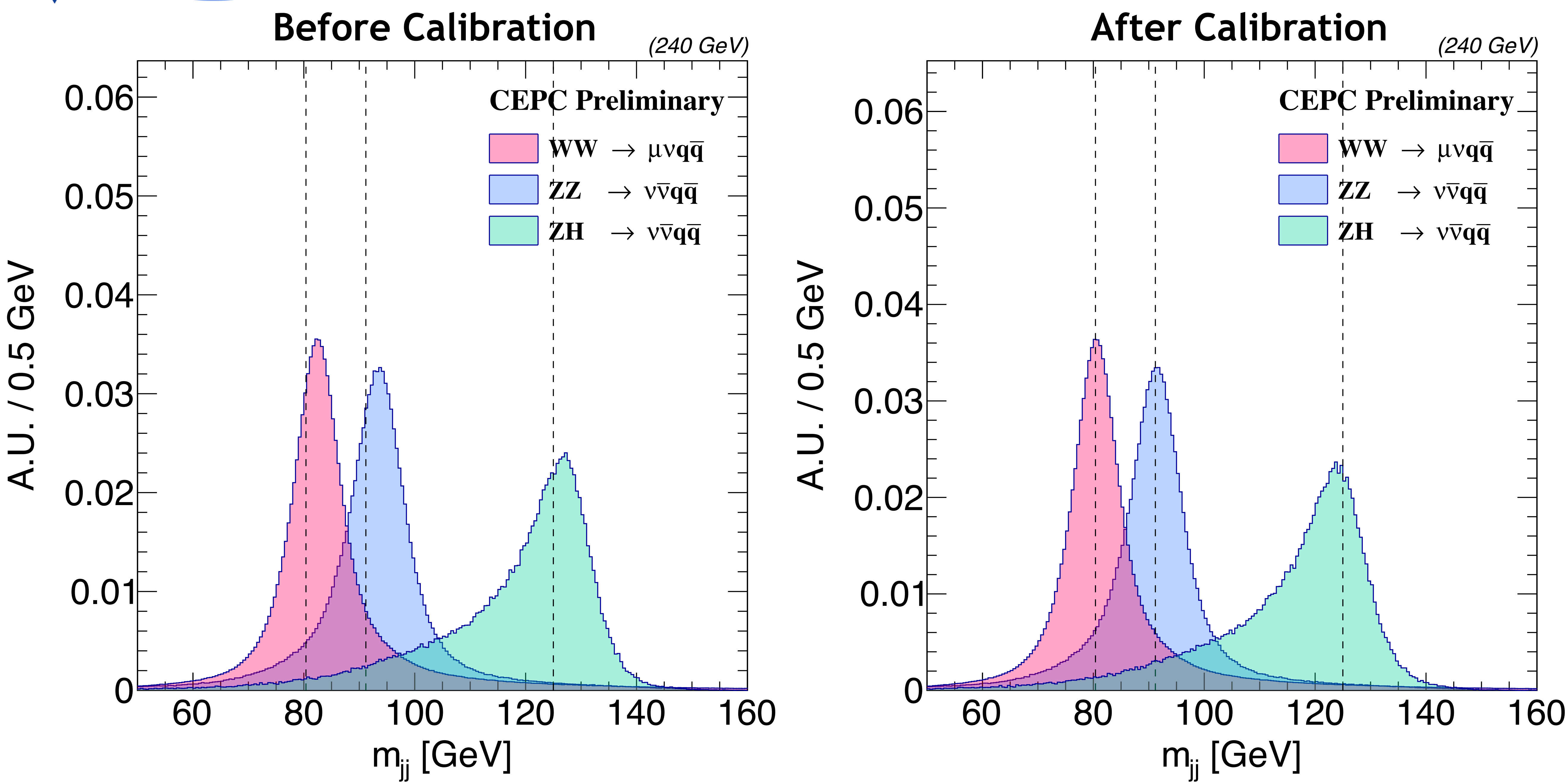


$e^+e^- \rightarrow ZZ \rightarrow \nu\bar{\nu}q\bar{q}$
CEPC *Preliminary* (240 GeV)
E_q [GeV]
| cosθ |
JES
0.03
0.02
0.01
0
−0.01
−0.02



$e^+e^- \rightarrow ZZ \rightarrow \nu\bar{\nu}q\bar{q}$
CEPC *Preliminary* (240 GeV)
E_q [GeV]
| cosθ |
JER
0.08
0.07
0.06
0.05
0.04
0.03
0.02

Jet Energy Calibration

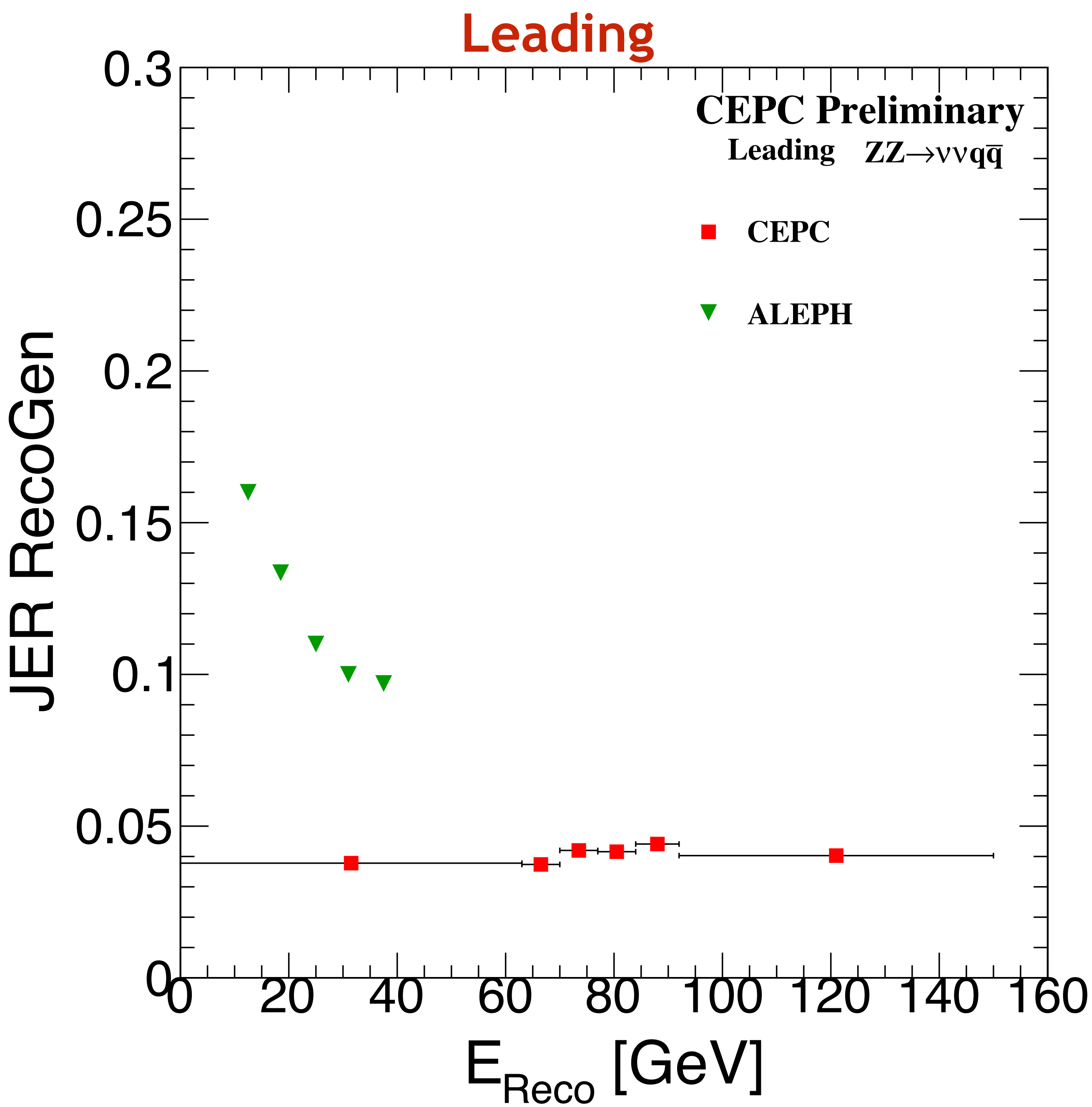


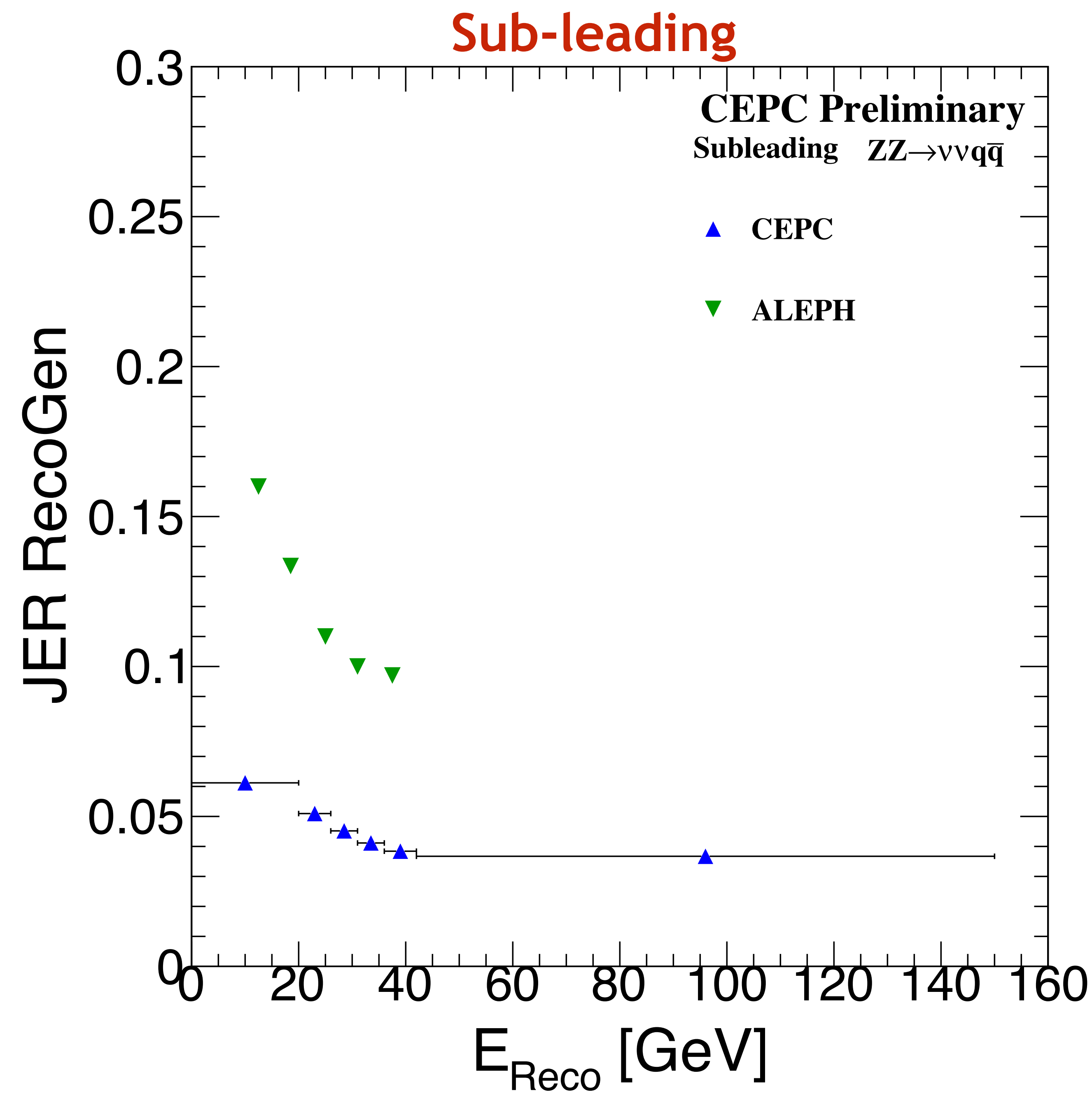
- Since the double-counting effect, jet energy would be overestimated.
- According to MC true energy and cosθ distribution, JES can be used to calibrate the dijet invariant mass back to the value we put into simulation.
- After calibration, boson mass resolution is improved about 1%.

Summary

m_W (GeV)	m_Z (GeV)	m_H (GeV)	Jets / PFOs	wi/wo Clean	wi/wo Cali
82.66 ± 3.54	93.69 ± 3.89	127.48 ± 4.93	Jets	0	0
82.79 ± 3.34	93.95 ± 3.48	127.31 ± 4.54	Jets	1	0
80.72 ± 3.46	91.67 ± 3.77	125.02 ± 5.11	Jets	0	1
80.82 ± 3.23	91.76 ± 3.39	124.39 ± 4.39	Jets	1	1
82.63 ± 3.53	93.69 ± 3.89	127.57 ± 4.80	PFOs	0	0
82.77 ± 3.32	93.90 ± 3.54	127.83 ± 4.50	PFOs	1	0

Compare with ALEPH at LEP





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