The Performance of Jet Reconstruction and Distinguishment among Multi-jet Events at CEPC

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On the behalf of the CEPC Collaboration

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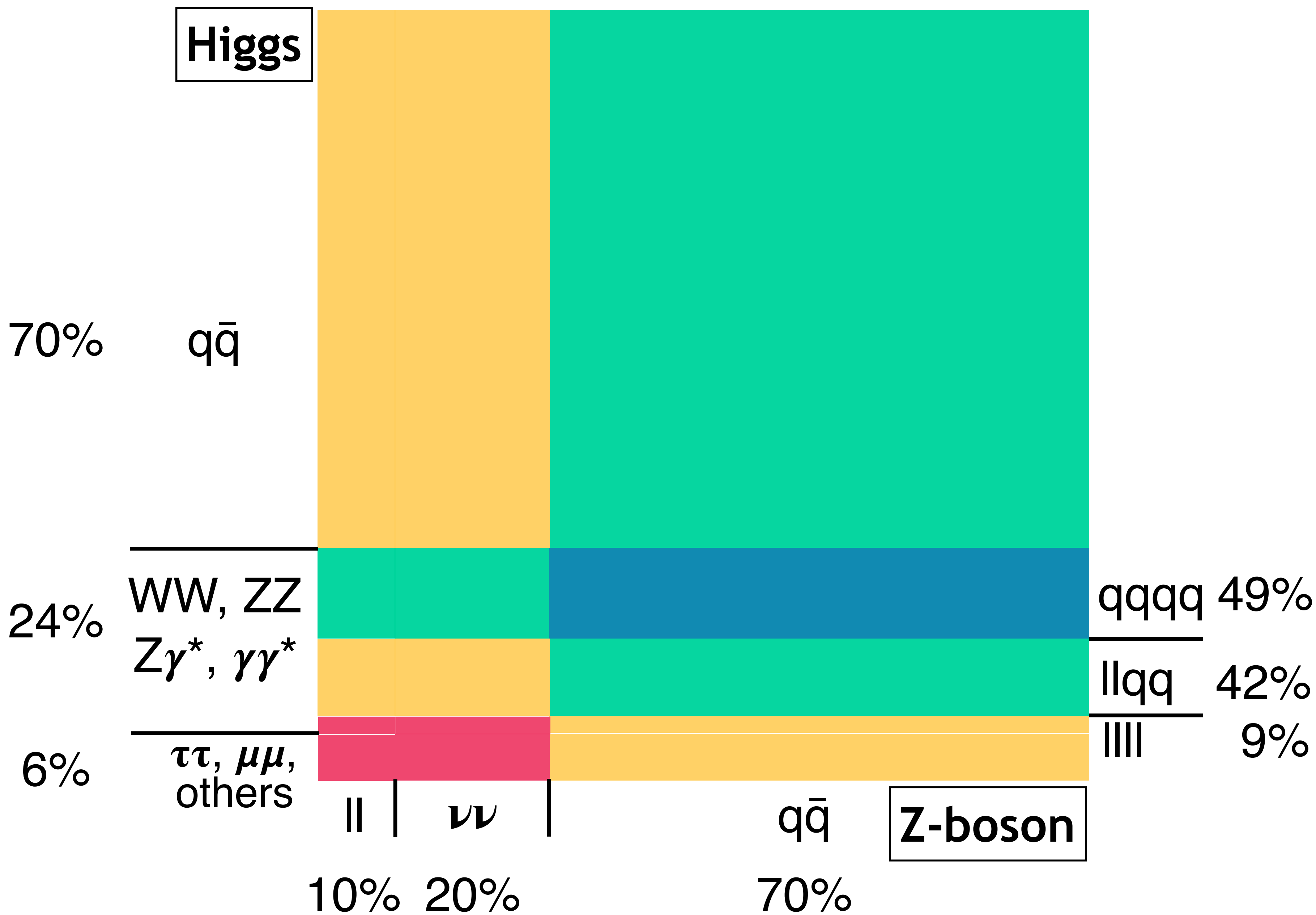
Annual Meeting of the Physical Society of Taiwan, NPTU, Pingtung Taiwan

Feb 05 - Feb 07, 2020

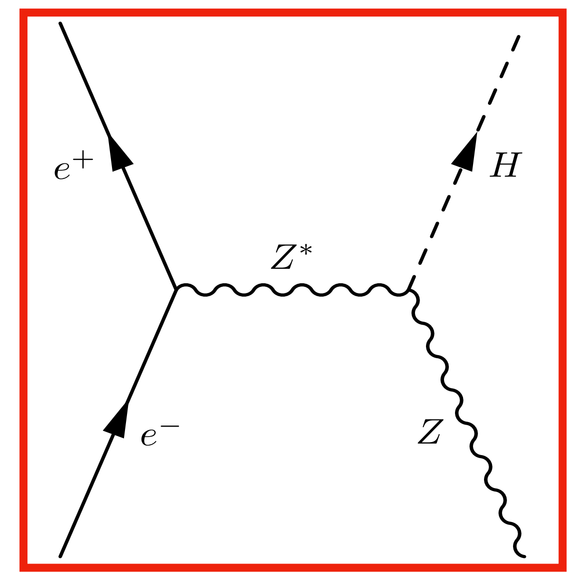
Jets at the Higgs Signal

Higgstrahlung(ZH) BR Pizza



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

~ 97% with Jets



- Circular Electron Positron Collider (CEPC) is a future collider aims to precisely measure the properties of the Higgs boson.
- Up to **97%** of Higgstrahlung(ZH) final-states associates to jets.
- Jets are also critical for many EW precision measurements.

Physics Benchmarks

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1/3 of ZH events
- Major SM Higgs decay modes.
- 1 color singlet could be identified. (Single Z or Higgs boson)

2/3 of ZH events
- Dominance statistic of $ZH \to q\bar{q}q\bar{q}$.
- 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, ee-k_t, is also essential for differential Higgs & EW precision measurements (e.g. TGCs).**

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BMI: Massive bosons invariant mass resolutions

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BM2: Jet energy and angular differential response

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BM3: # of jet identification & thrust based algorithm for 2-jet

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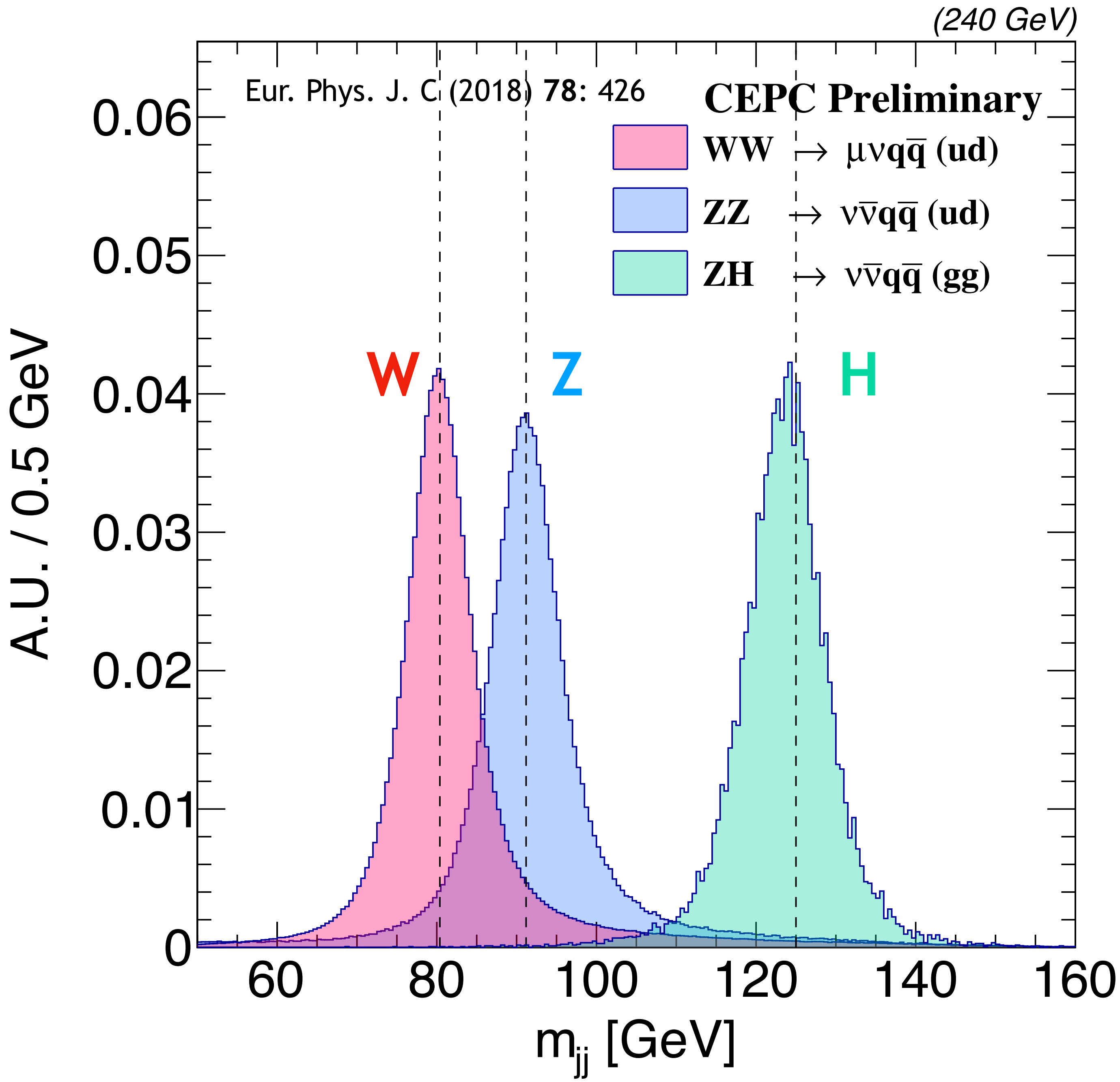
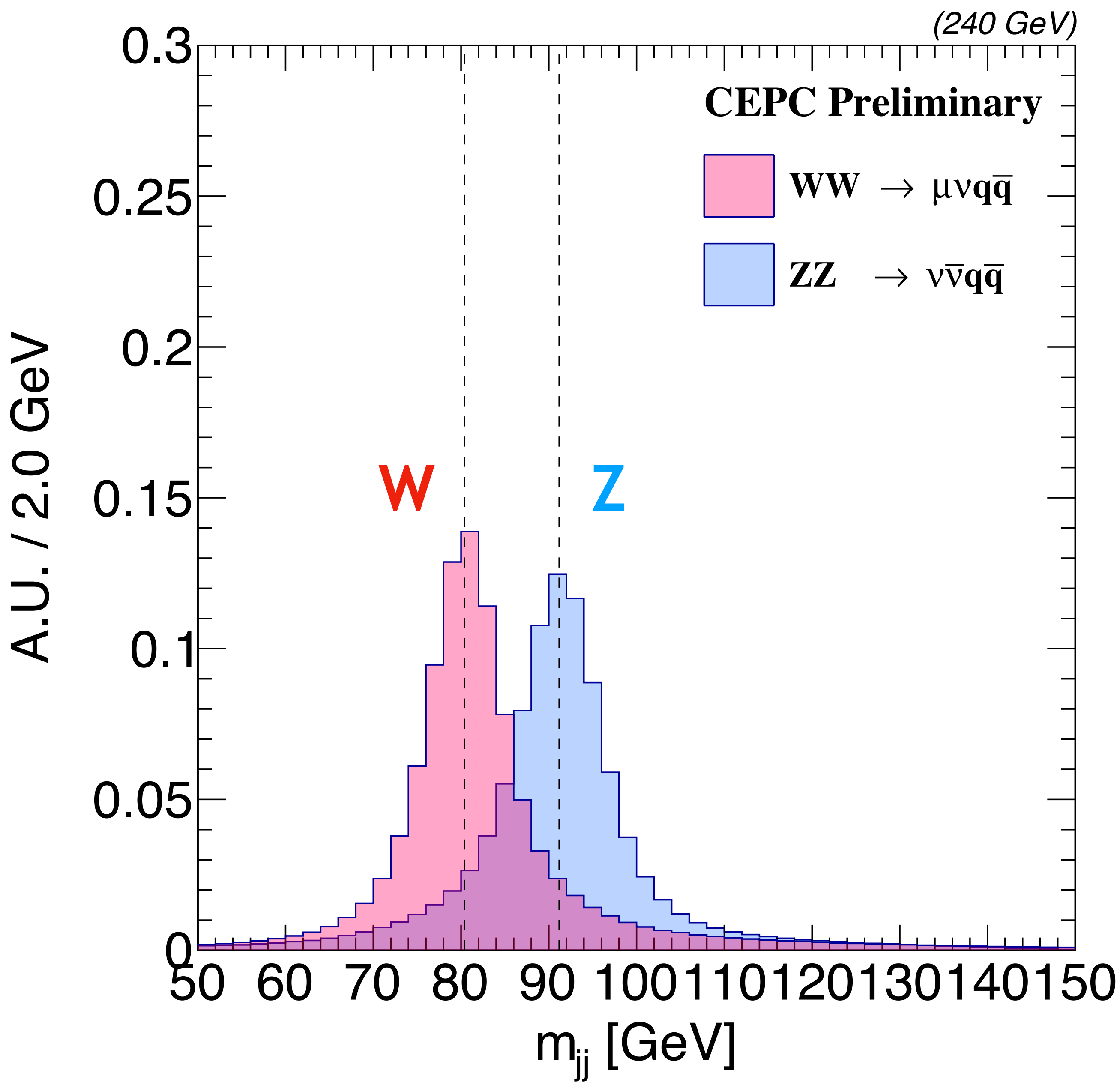
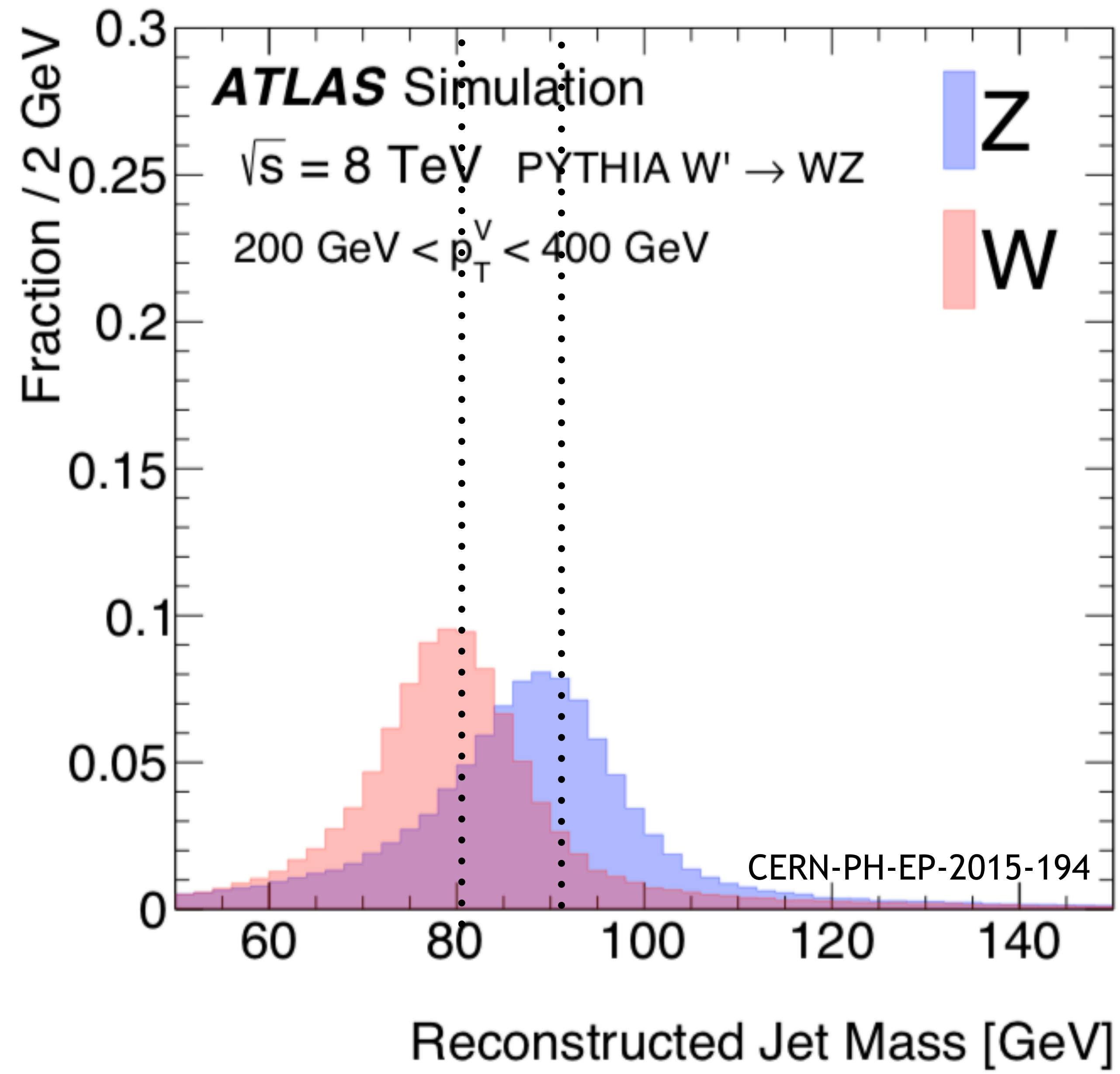
BM1: Massive Boson Mass Resolution



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

BM1: Massive Boson Mass Resolution





- **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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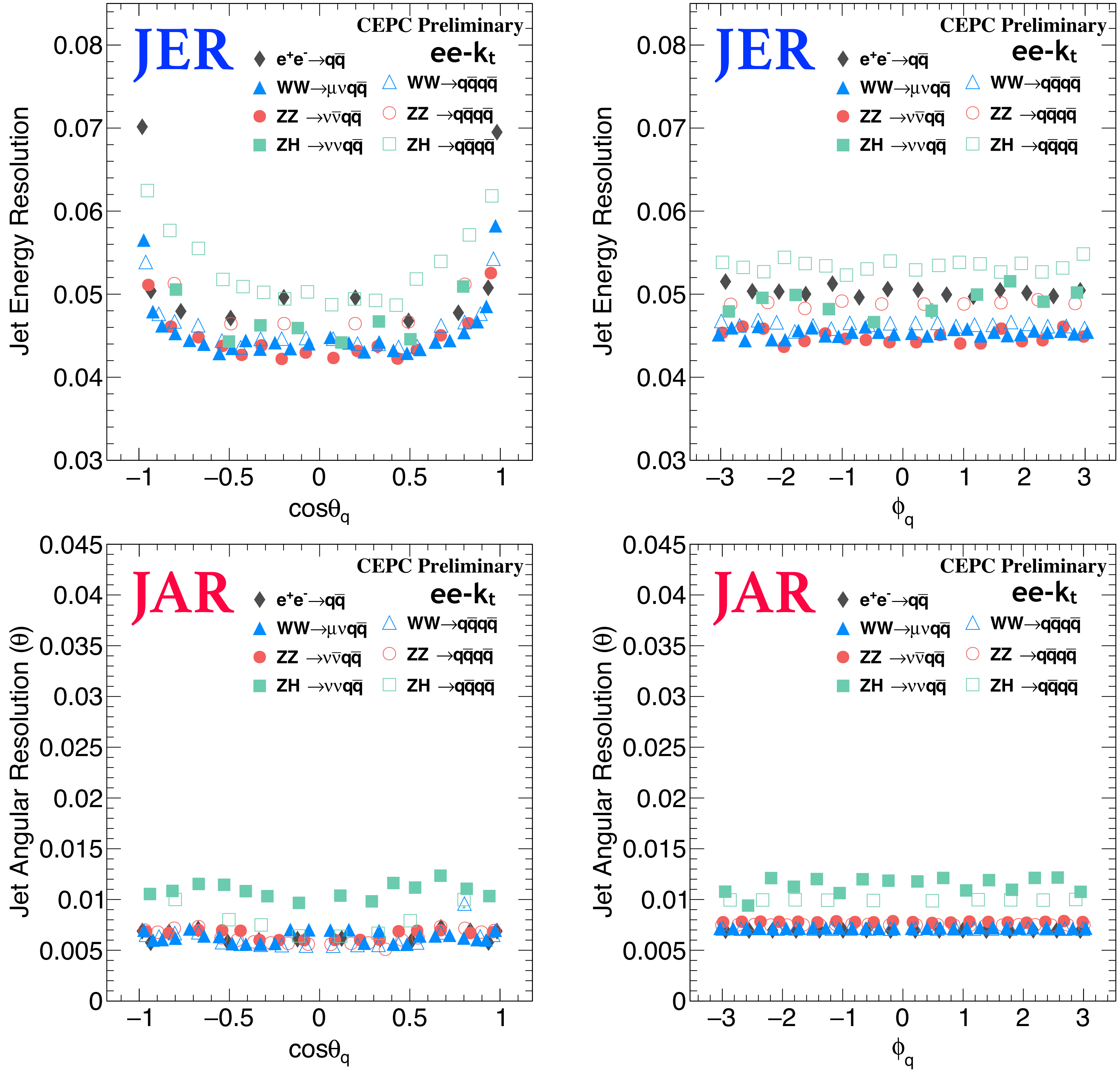
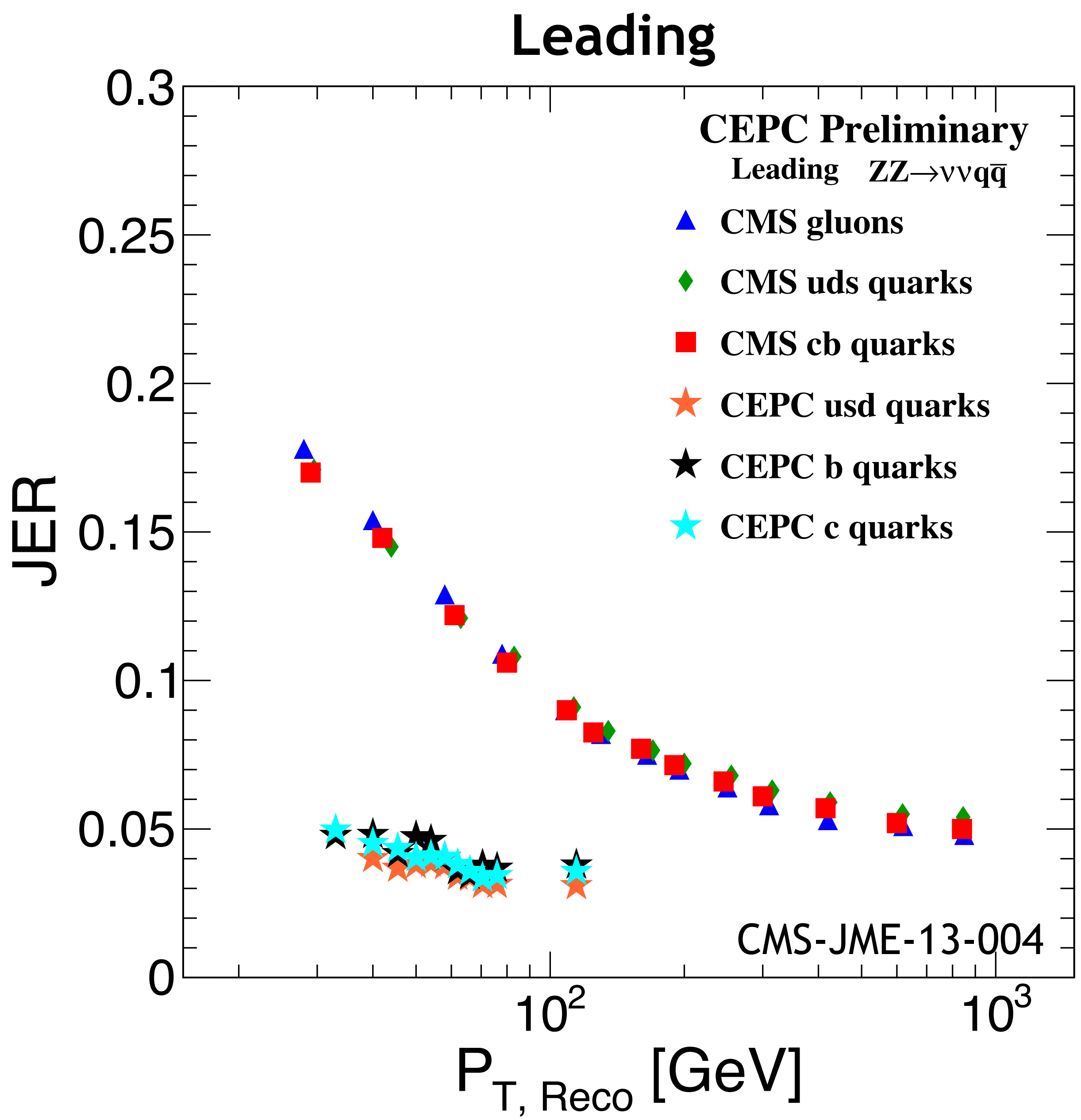
BM2: Jet energy and angular differential response

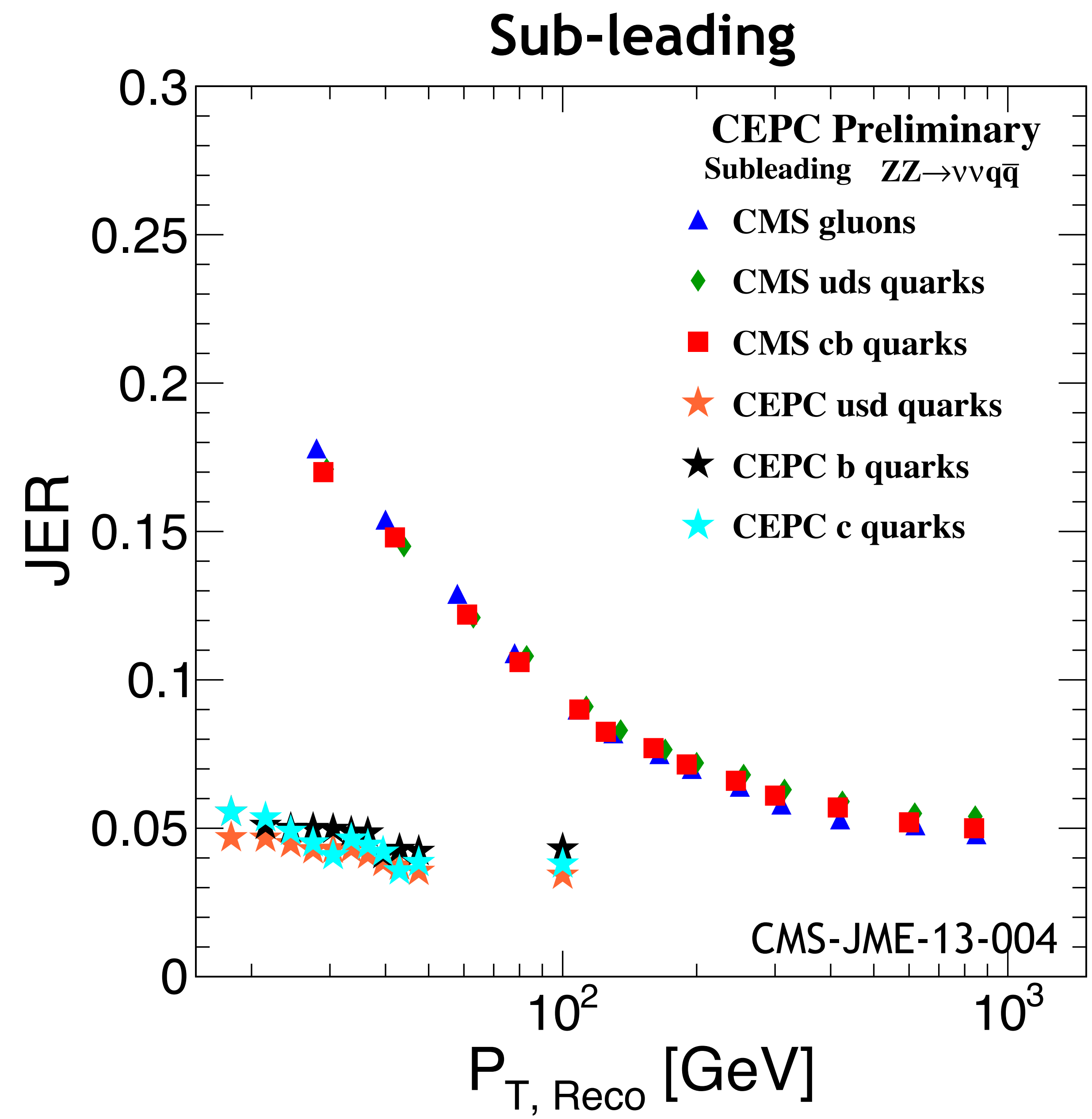
BM3: JER & JAR



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

Compare to CMS at LHC





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

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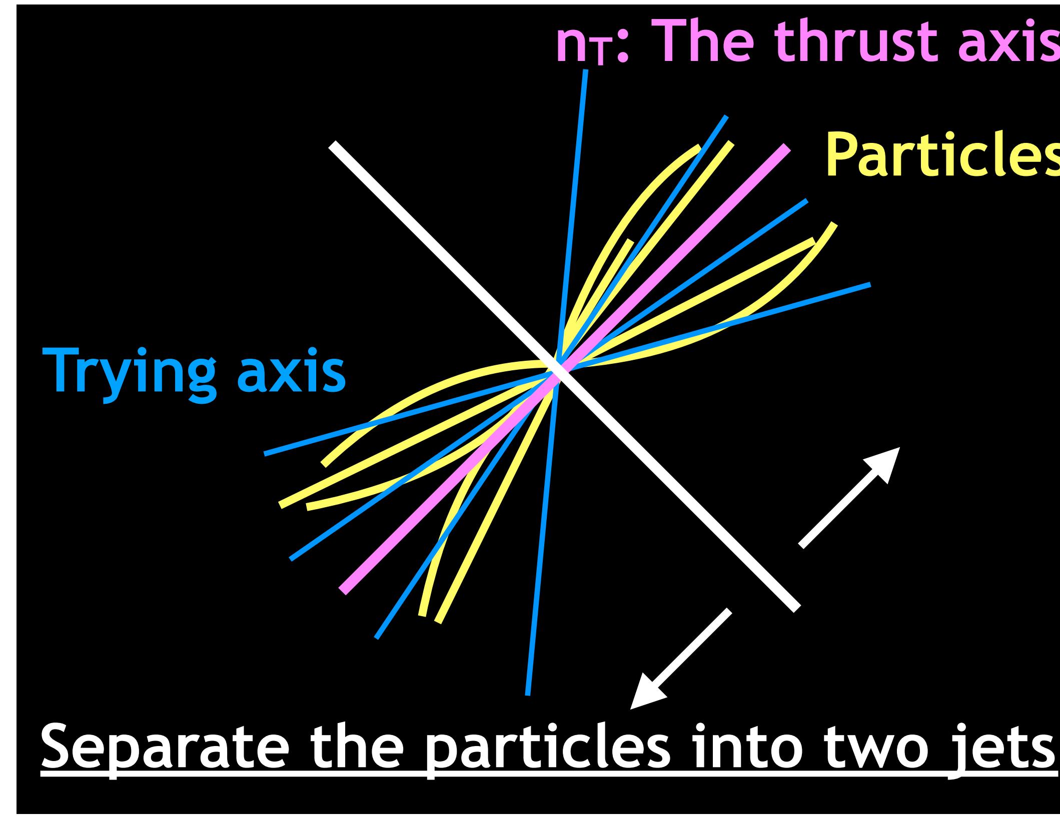
BM3: Thrust Based Algorithm

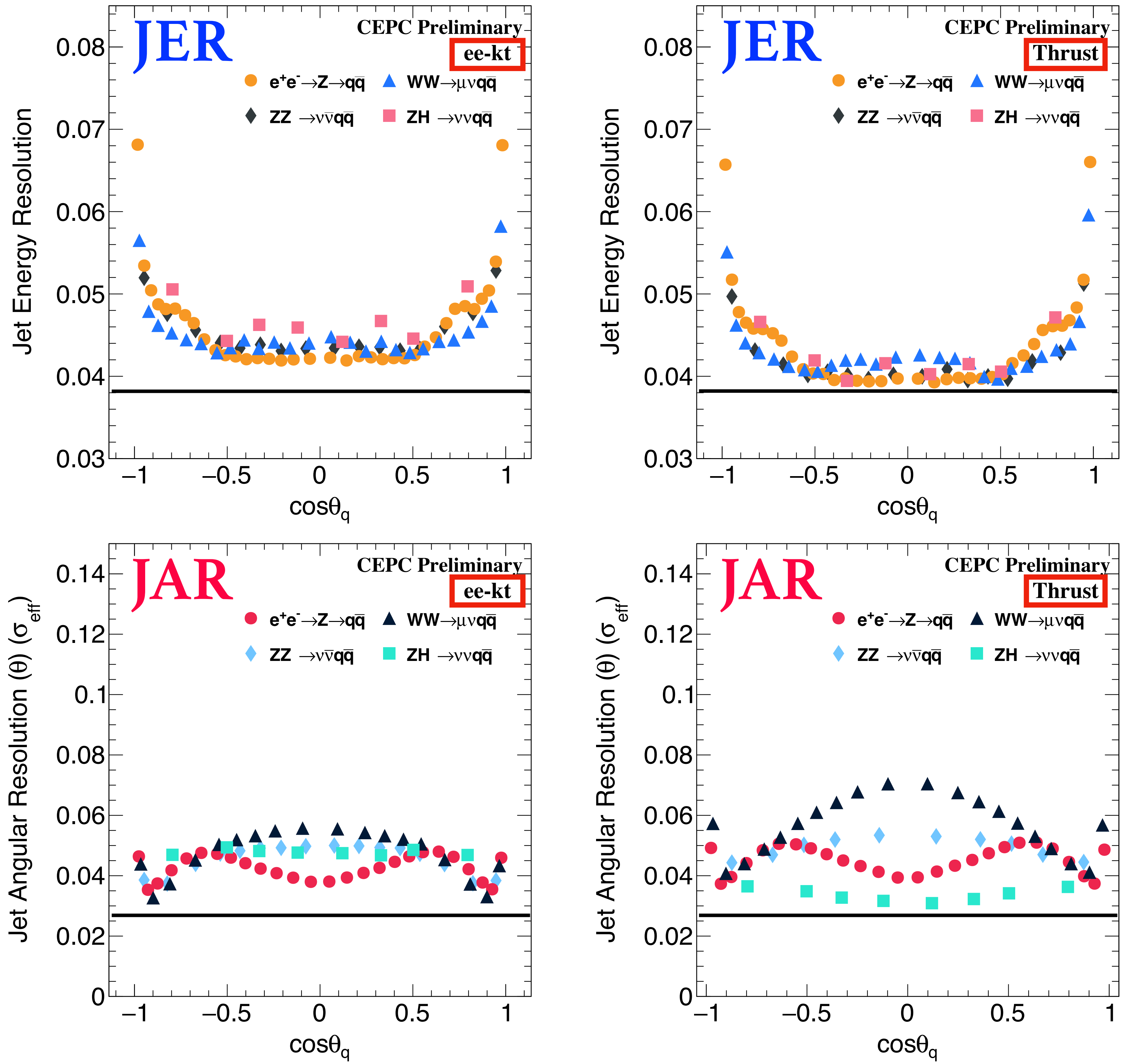
$$T \equiv max \frac{\sum_j^N |P_j \cdot n_T|}{\sum_i^N |P_i|}$$



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 back-to-back di-jet topology.
  1. Boost the system back to the rest frame.
  2. Find the thrust axis which has highest momentum efflux.
  3. Divide system into 2 hemispheres with the thrust axis, and each of them is identified as a jet.
- Applicable to all of 2-jet final-states at CEPC.
  (2-jet final-states could be identified with *efficiency*×*purity* = 88.4%.)

BM3: JER & JAR (ee-k_t — Thrust)



JERs are improved 20% w.r.t ee-kt

JARs are improved 20% w.r.t ee-kt

- Improvement may come from boosting the system back to the rest frame.

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BM4: Separation of WW, ZZ, and ZH decay to qqqq final state

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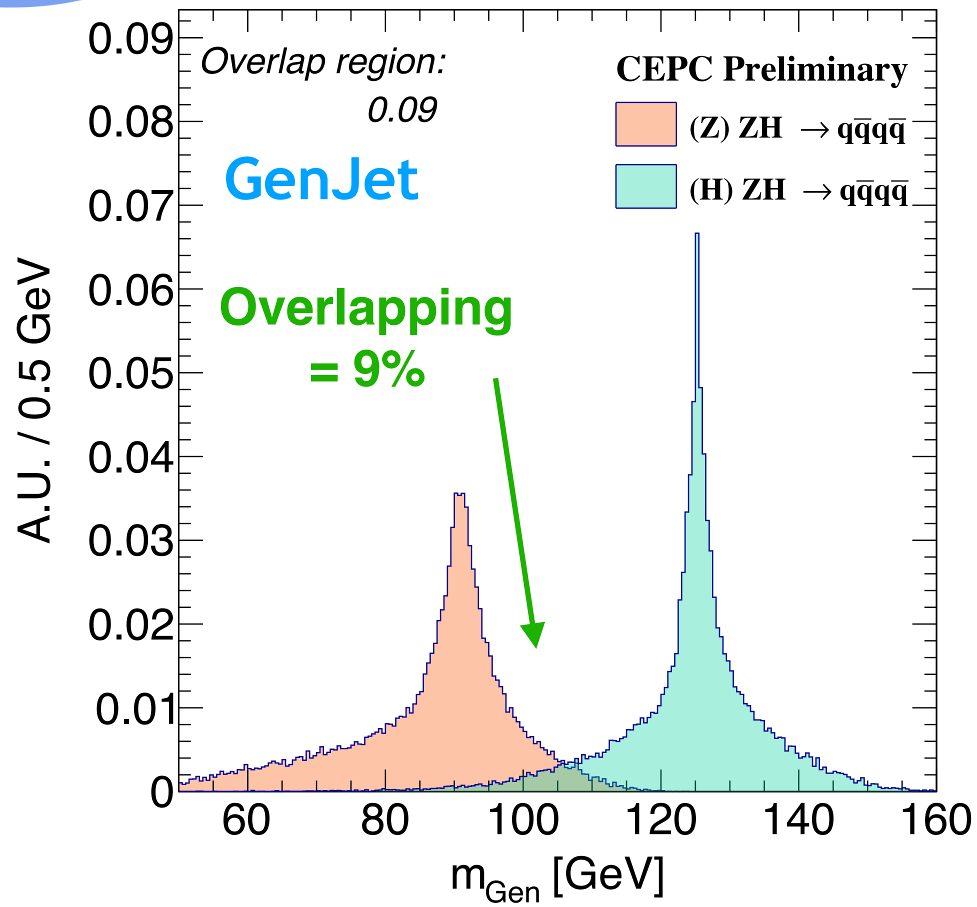
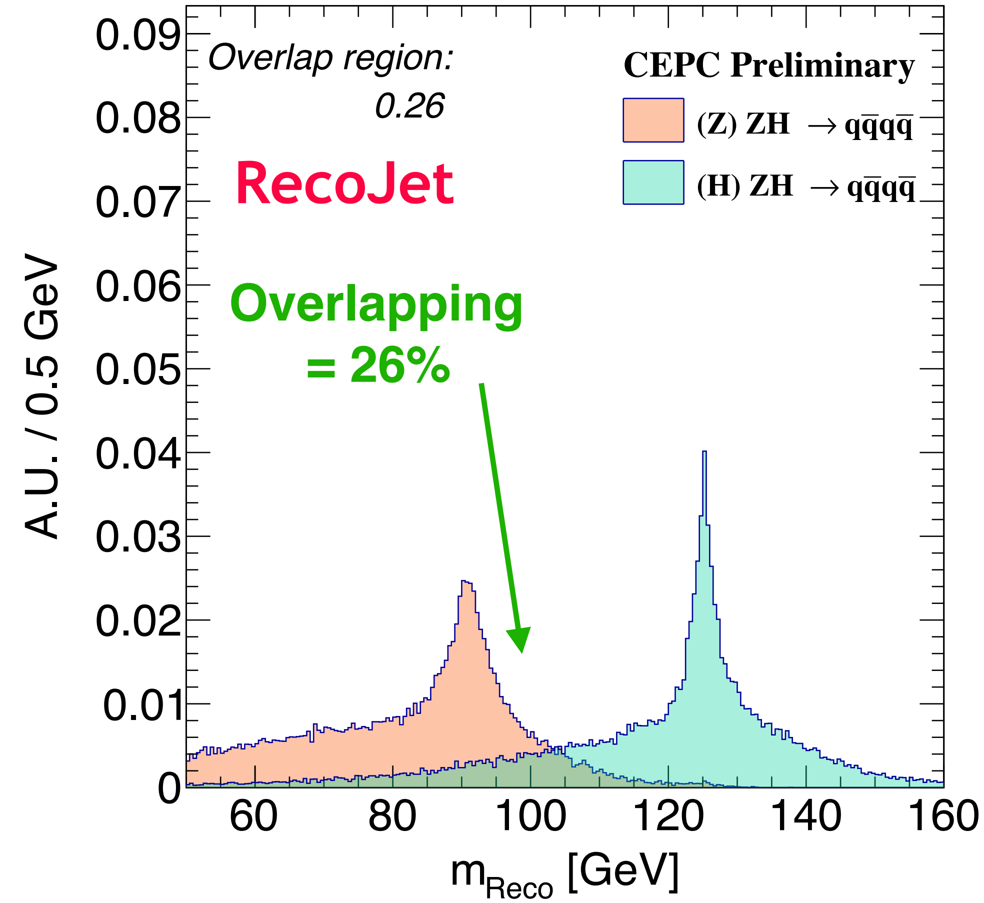
BM4: WW, ZZ, ZH to 4-jet Separation





GenJet

Sample \ Assignment(%)	WW	ZZ	ZH
WW	63.24	18.95	17.81
ZZ	16.09	57.89	26.02
ZH	9.99	13.84	76.17

RecoJet

Sample \ Assignment(%)	WW	ZZ	ZH
WW	64.98	19.07	15.94
ZZ	26.51	50.54	22.96
ZH	20.29	22.93	56.77

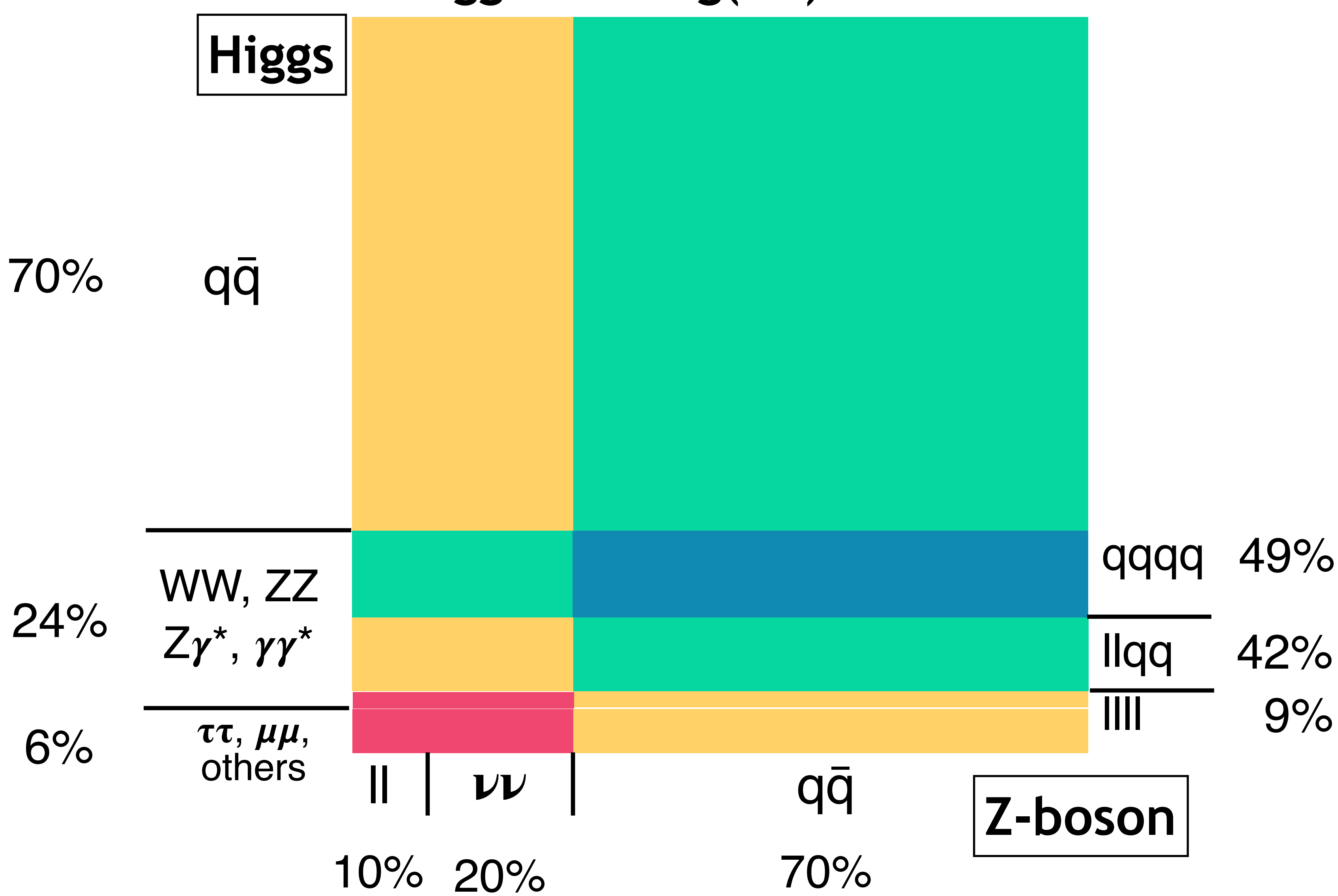
- χ^2 method is employed.

$$\chi^2 = \frac{|(m_{ij} - m_{boson})|^2 + |(m_{ij} - m_{boson})|^2}{\sigma^2}$$

- The *Efficiency x Purity* of ZH identification is expected 18% in the 5 ab^{-1} data.
- The statistical uncertainty of ZH to full hadronic final-state could achieve 0.25% after considering the WW and ZZ as bkg.

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

Higgstrahlung(ZH) BR Pizza



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1/3 (0 and 2 jets)

2/3 (4 and 6 jets)

~ 97% with Jets

Summary(2/2)

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 final-state.
   - Exploit Z-boson di-jet recoil mass to distinguish the ZH from ZZ process (main background).

II. **Jet energy resolution ~ 3-5% & Jet angular resolution ~ 1%.**

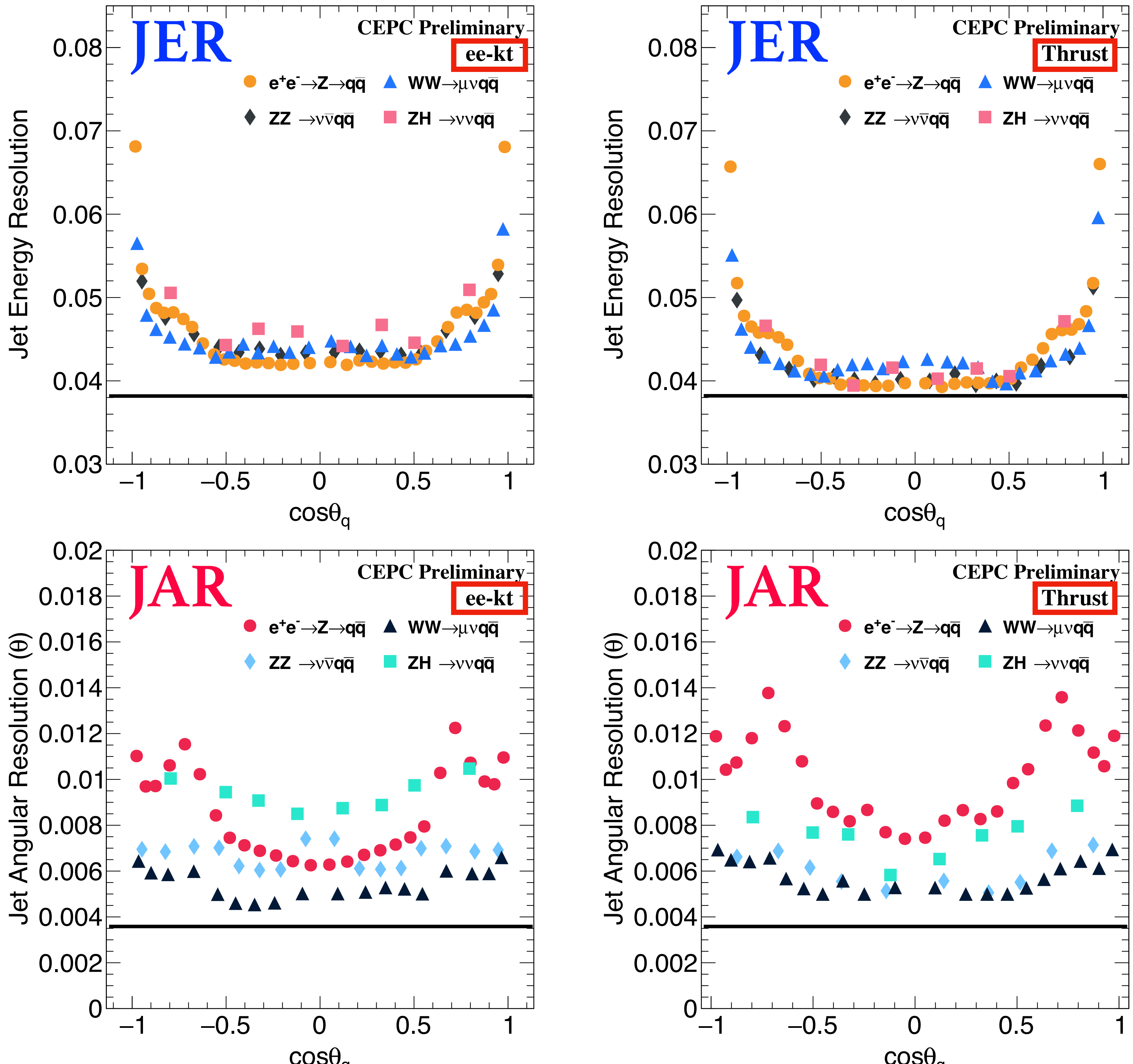
III. **2-jet final-states could be identified with *efficiency×purity* = 88.4%.**
   - Clustering by dedicated the jet clustering algorithm, thrust based algorithm.
   - Thrust based algorithm is recommended for 2-jet final-states because it brings the JER and JAR **20%** improvement.

IV. **Need a better color-singlet identification algorithm for full hadronic final-state.**
   - The statistical uncertainty of ZH to full hadronic final-state is expected to be **0.25%** currently when considering the WW and ZZ as background.

Thank for your attention

Back up

BM3: JER & JAR (ee-k_t — Thrust)

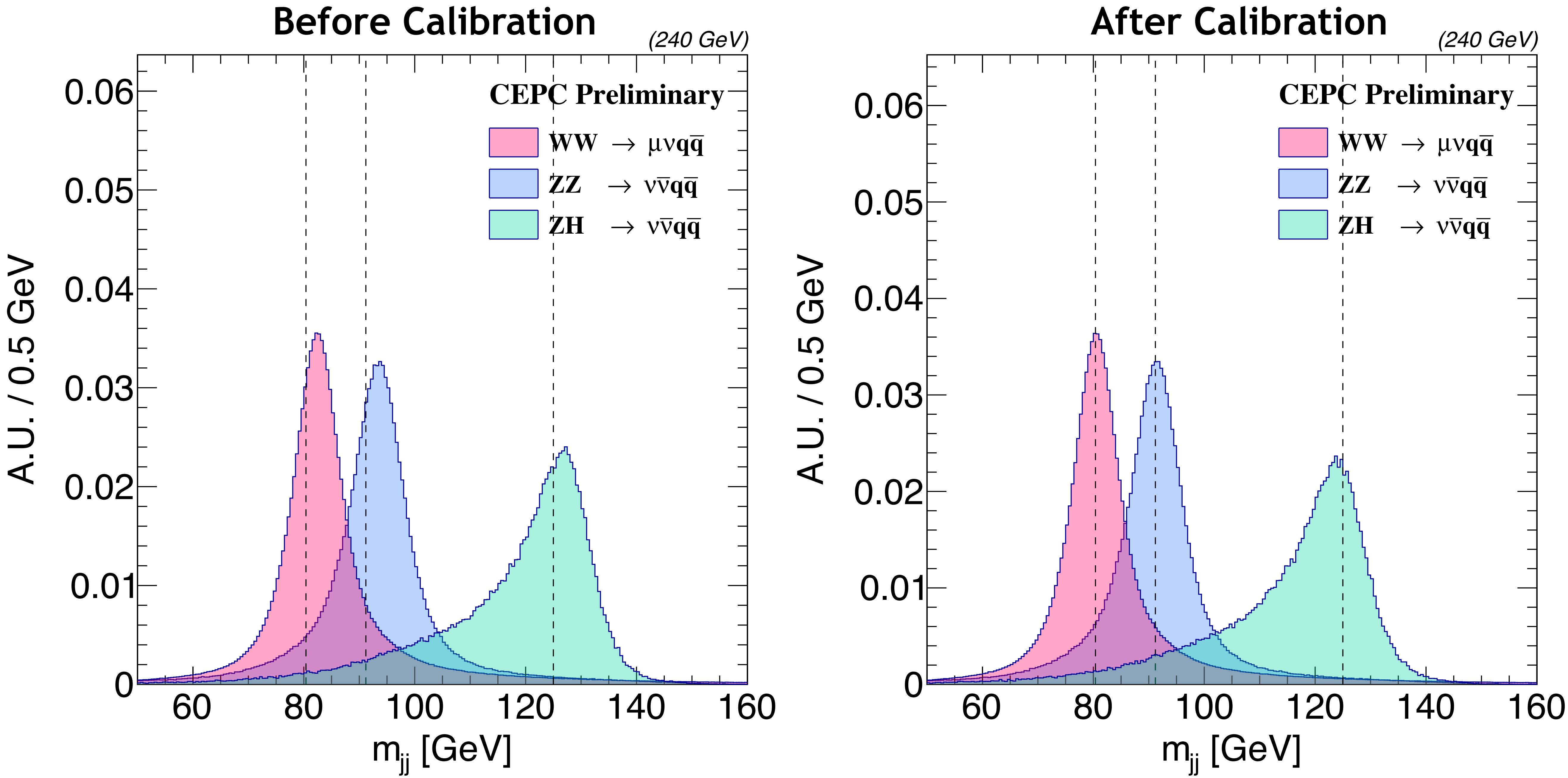


JERs are improved **20%** w.r.t ee-kt

JARs are improved **20%** w.r.t ee-kt

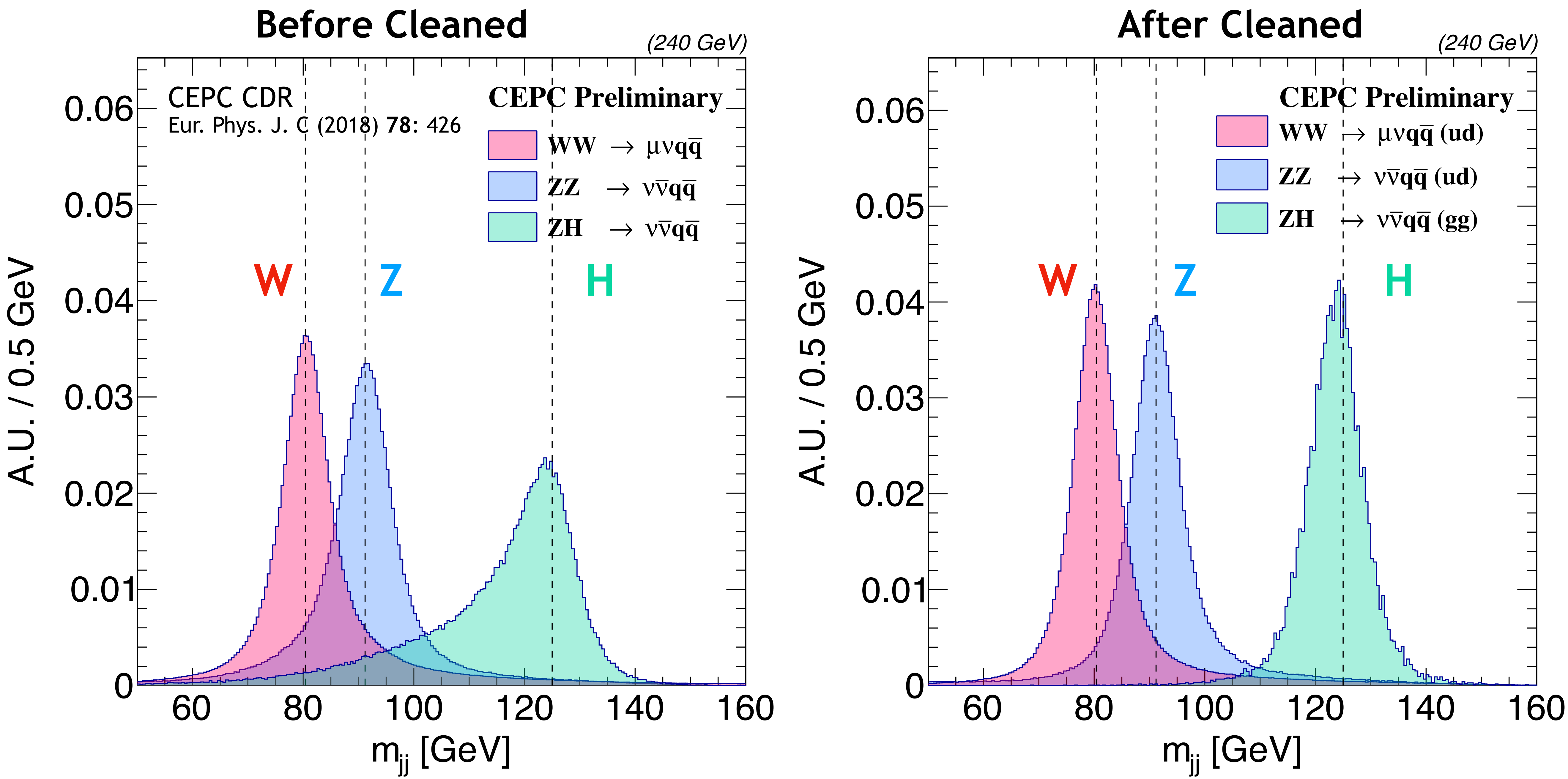
- Improvement maybe came from <u>boosting the system back to the rest frame with the neutrons' information</u>.

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%.**

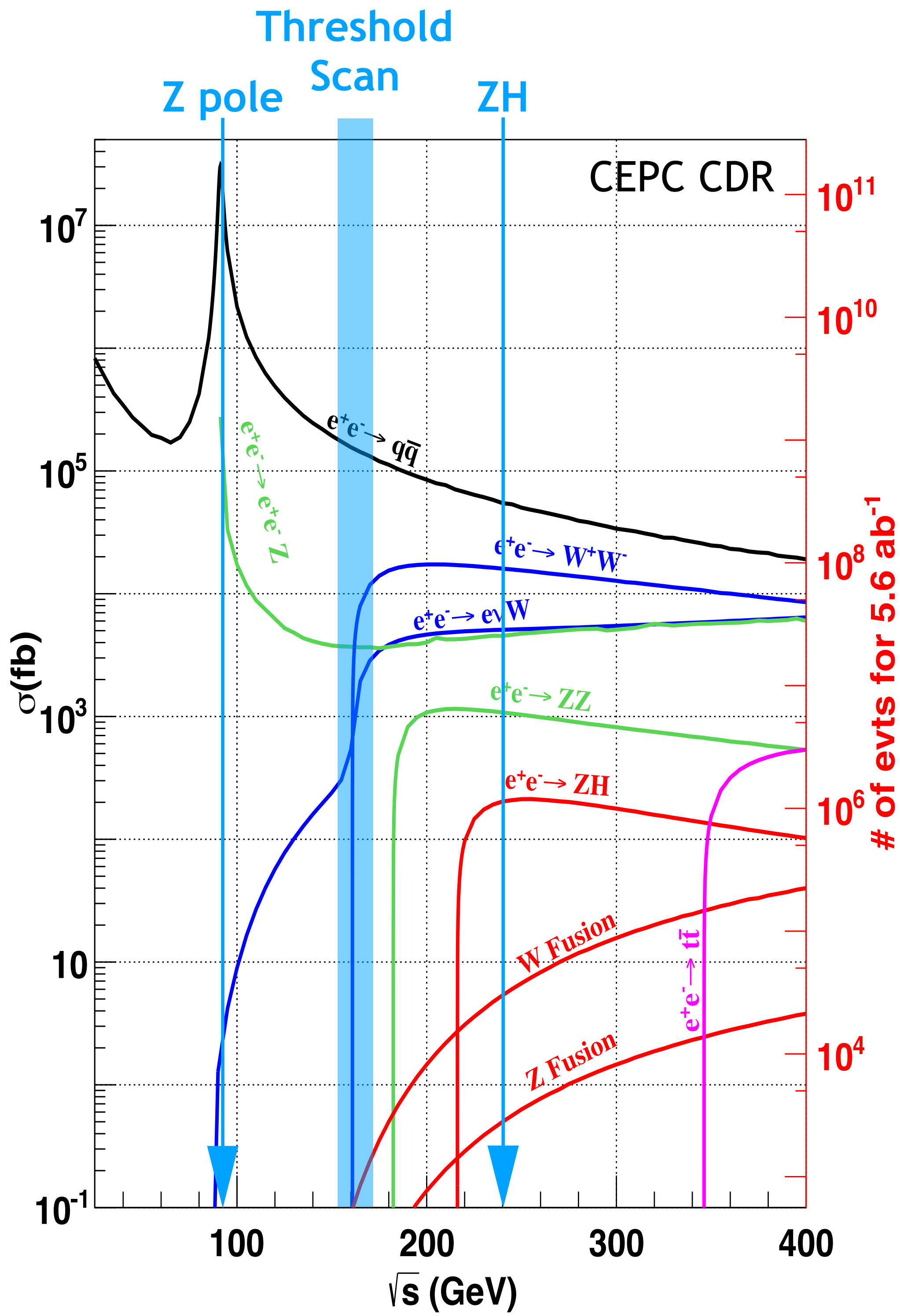
BM1: Massive Boson Mass Resolution

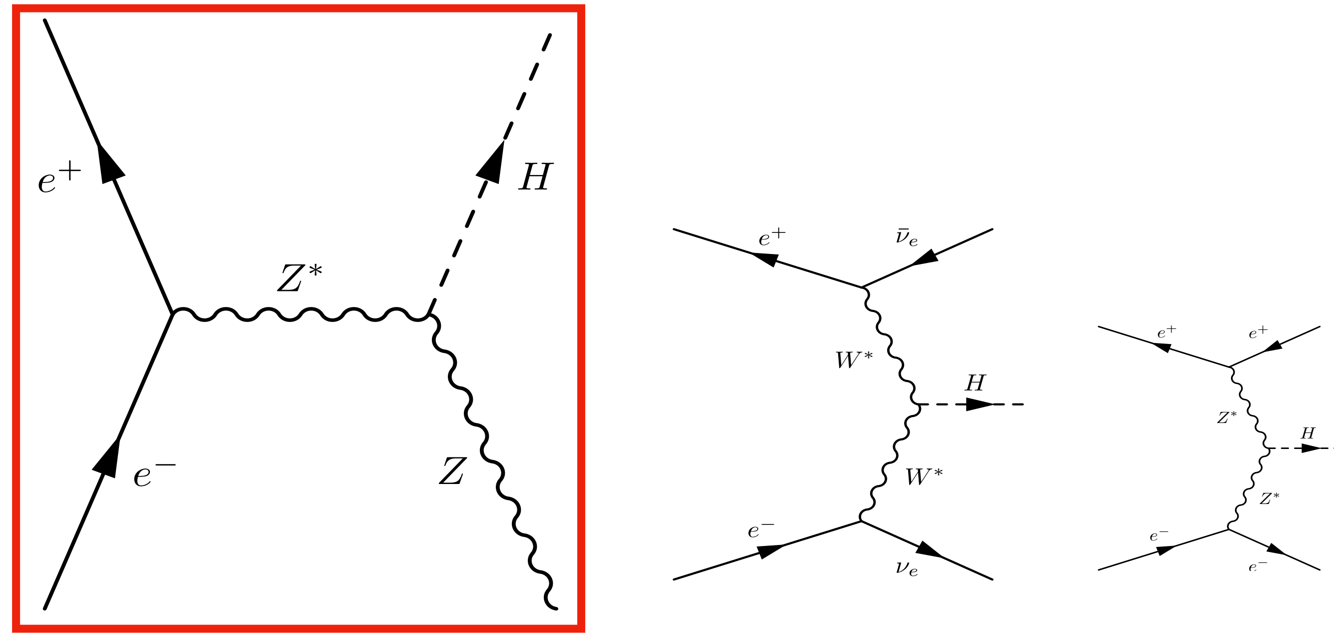


- W-, Z-, and Higgs-boson masses in dijet final state can be well separated at CEPC.
- After cleaned, Z- and W-boson could be separated ≈ 2σ, and the Higgs Boson Mass Resolution = 3.8% achieving the CEPC baseline.

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

Higgs Production at CEPC





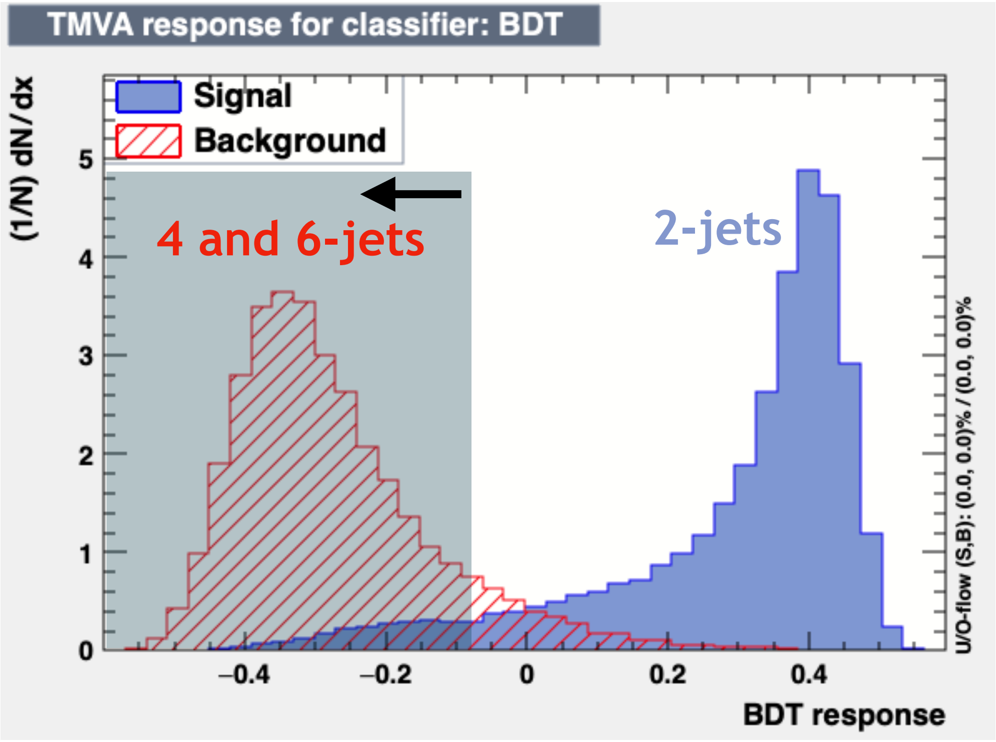
Process	Cross section(fb)	Events in 5.6 ab^{-1}
$e^+e^- \to ZH$	196.2	1.10×10^6
$e^+e^- \to \nu_e\bar{\nu}_eH$	6.19	3.47×10^4
$e^+e^- \to e^+e^-H$	0.28	1.57×10^3
Total	203.7	1.14×10^6

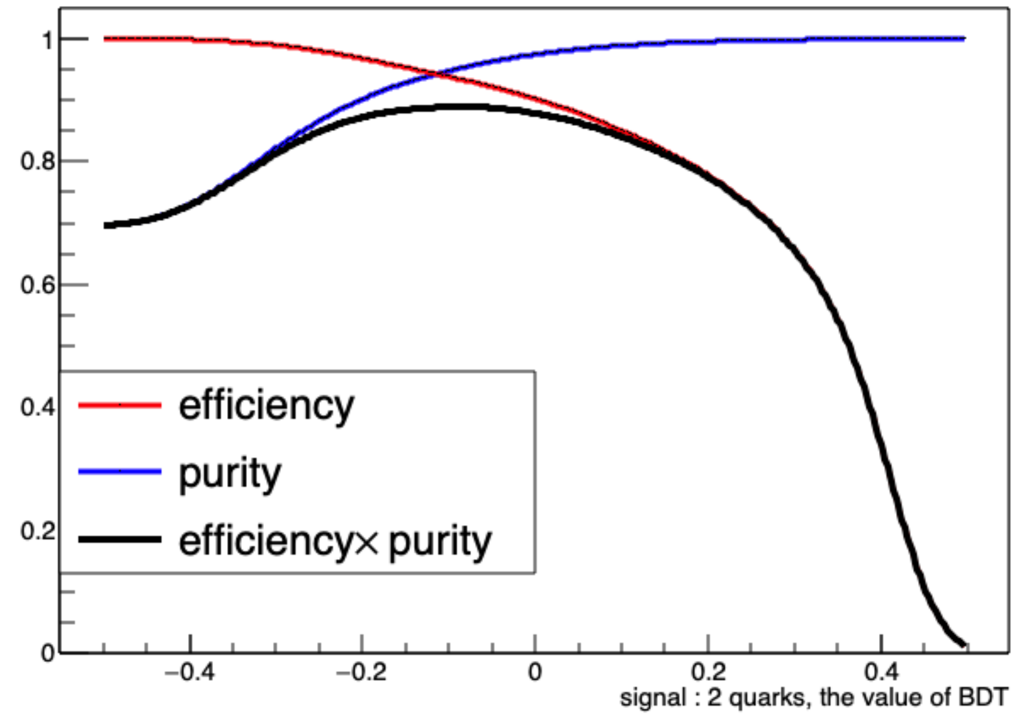
S : B = 1 : (100 ~ 1000)

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

BM2: Preliminary Number of Jet Identification

Yong-Feng Zhu





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)

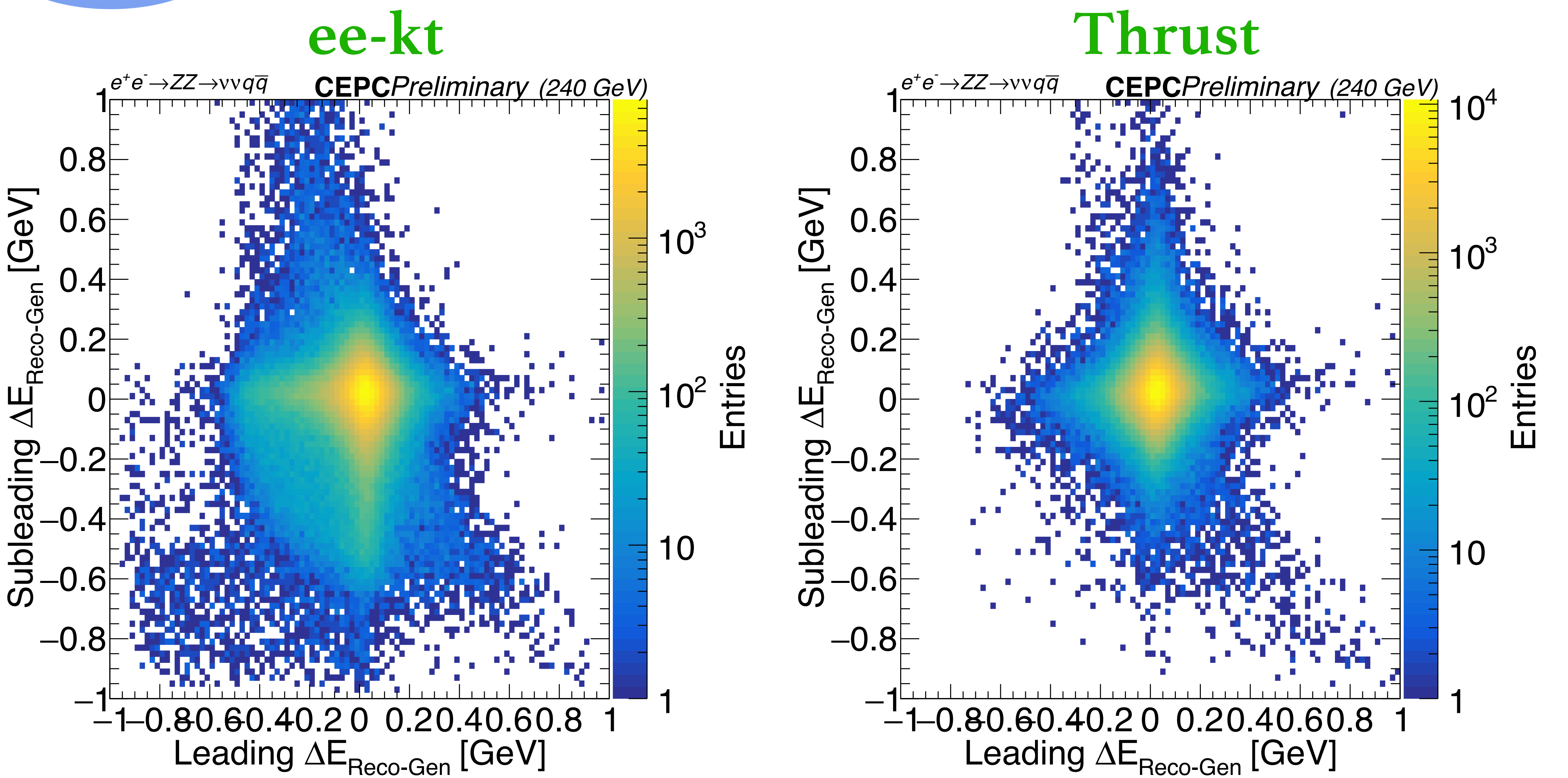
$ZH \to q\bar{q}q\bar{q}$ (4 jets)

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

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

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

BM3: Thrust Jet Clustering Method

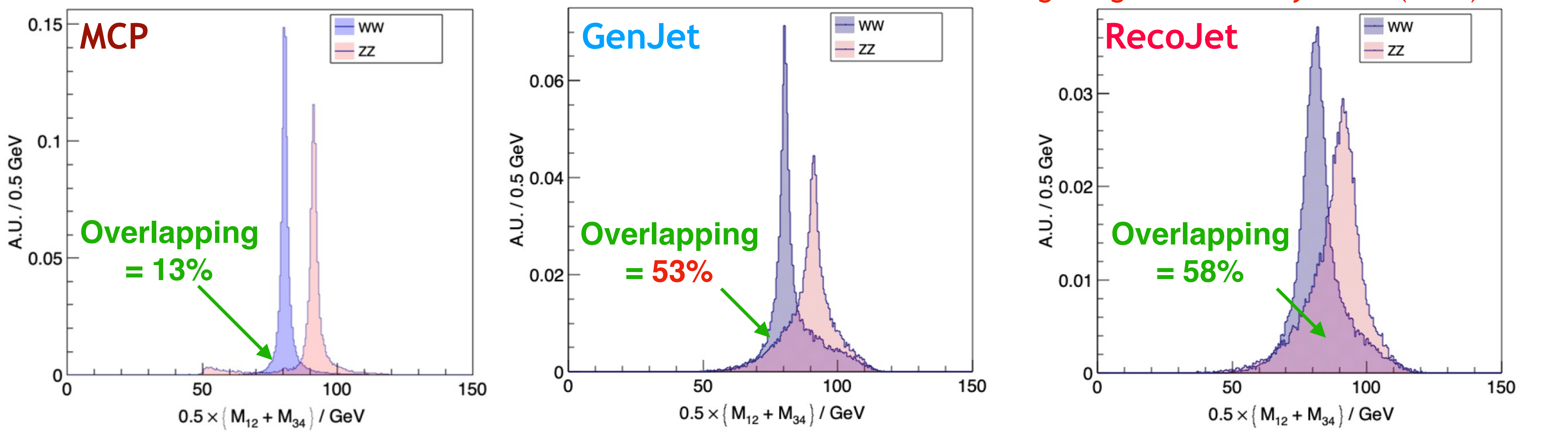


- Identify the 2 jets final-state event with (Efficiency x Purity) = 88.4%, the thrust jet clustering method could be employed.
- After "cleaned" selection, the thrust method has significant tail suppressed → expected to have improvement on jet energy and angular response.

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

BM4: WW & ZZ to 4 Jets Separation

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



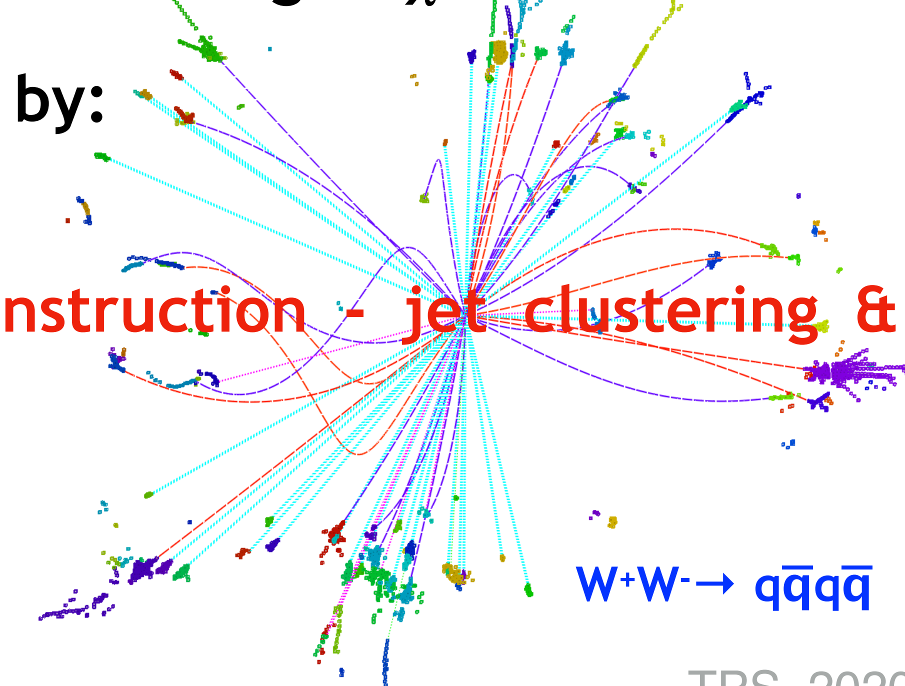
- Low energy jet (20-120 GeV)
- Typical multiplicity could be 10^2.

$$\chi^2 = \frac{|(m_{ij} - m_{boson})|^2 + |(m_{ij} - m_{boson})|^2}{\sigma^2}$$

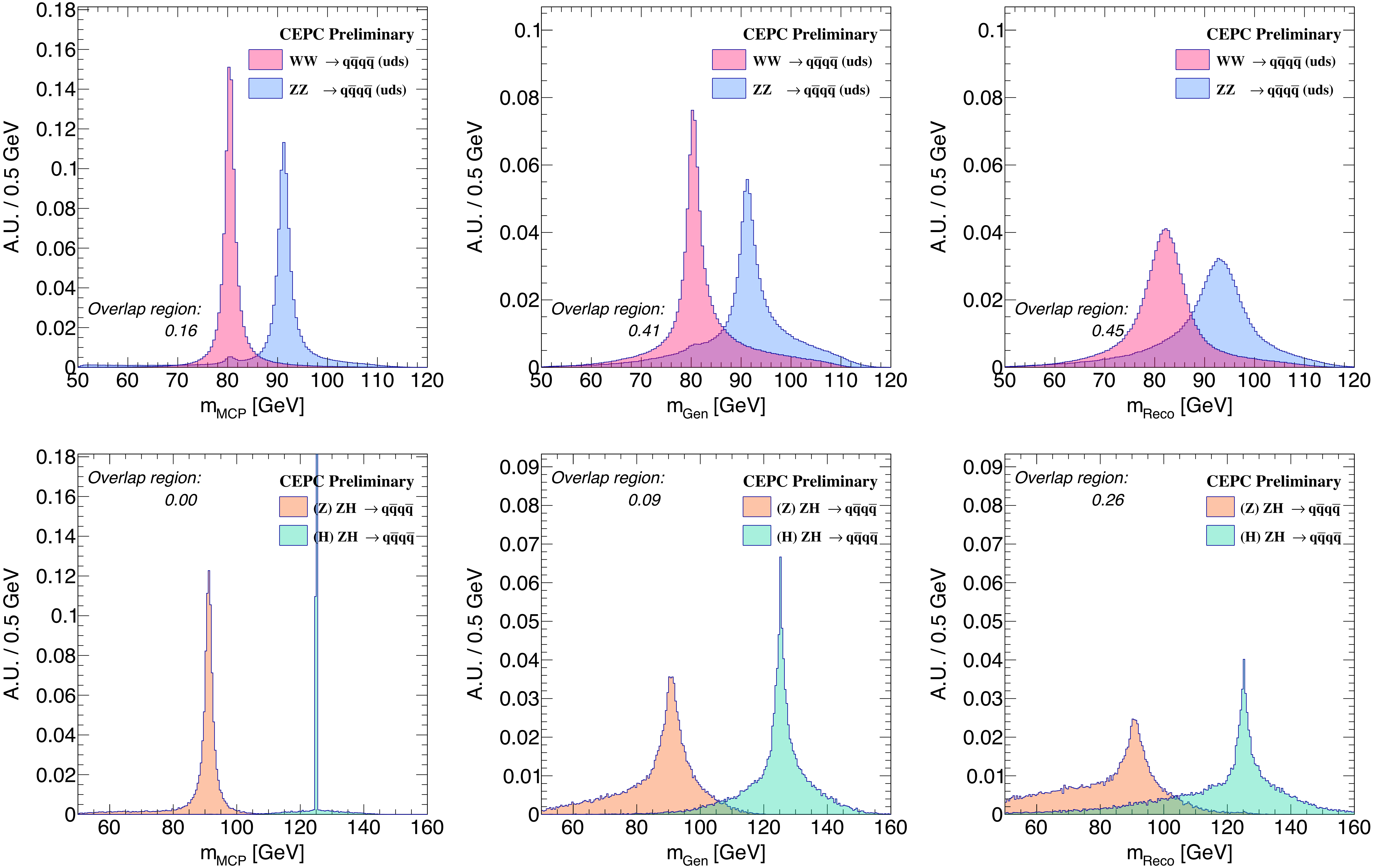
- GenJet and RecoJet are clustered by ee-kt and paired according to χ^2.
- WW & ZZ to 4 jets final-state separation is determined by:
  1. (13%) Intrinsic boson mass/width (10 GeV)
  2. (53%) Wrong jet pairing for color singlet reconstruction - jet clustering & pairing.
  3. (58%) Detector response

40% (1 → 2)

5% (2 → 3)

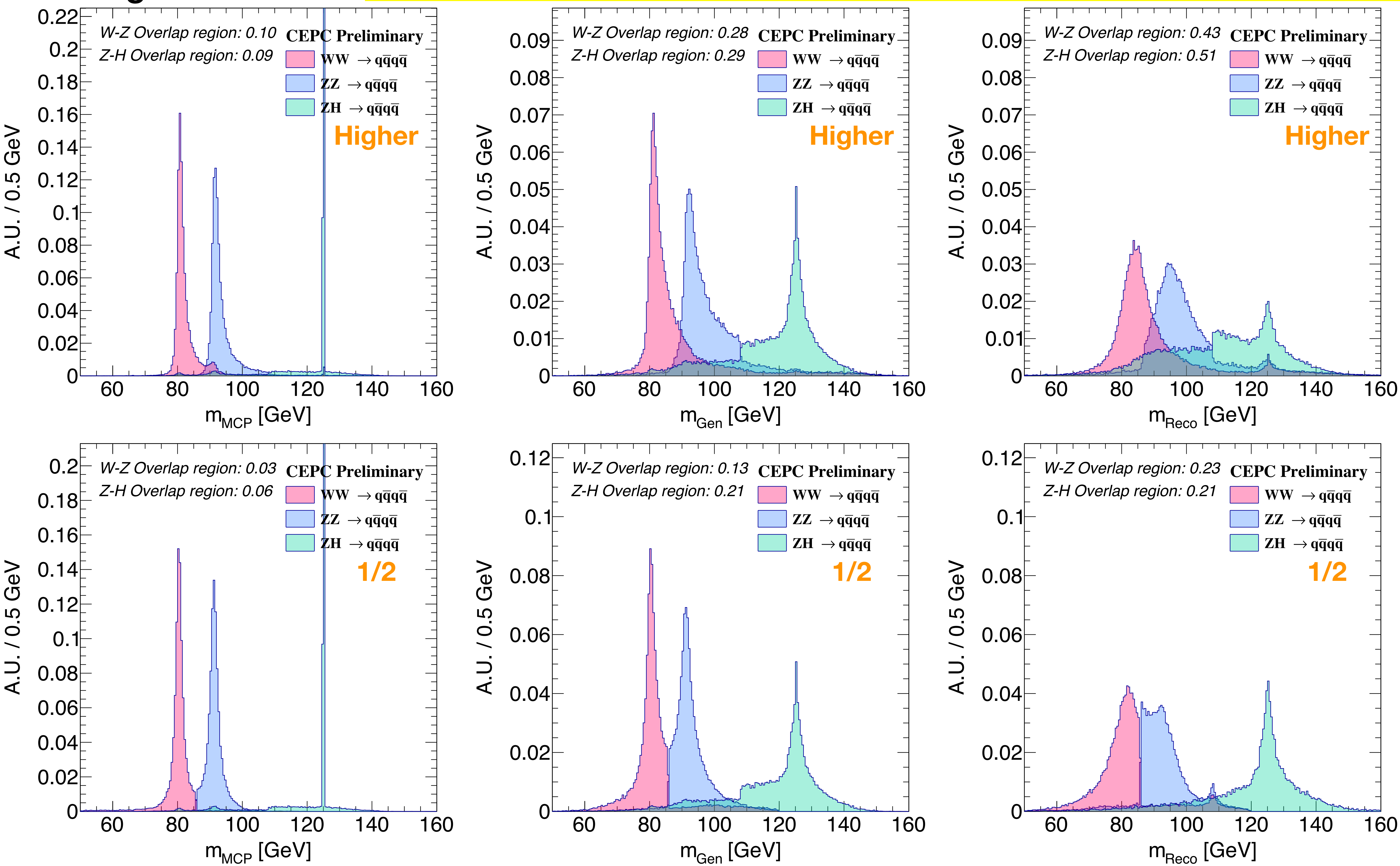


WW, ZZ, and ZH Full Hadronic



Mixing Signal & BKG

WW, ZZ, ZH Full Hadronic Separation



First Row: After reconstructed m1, m2, higher one would be chosen

Second Row: After reconstructed m1, m2, and then (m1 + m2) / 2. (Higgs still chosen the higher one)

BM4:ZH Full Hadronic Identification

- According to the final results, the following estimation could be declared:
  The identified efficiency of ZH signal is 60% with background, 20% ZZ and 10% WW.
  The cross section of ZZ is 5 times amount than ZH, 10 times from WW.

	Efficiency	XS		
WW	10%	10	→	100
ZZ	20%	5	→	100
ZH	60%	1	→	60

Purity → 60/200 = 30%

Efficiency x Purity

60% x 30% = 18%

→

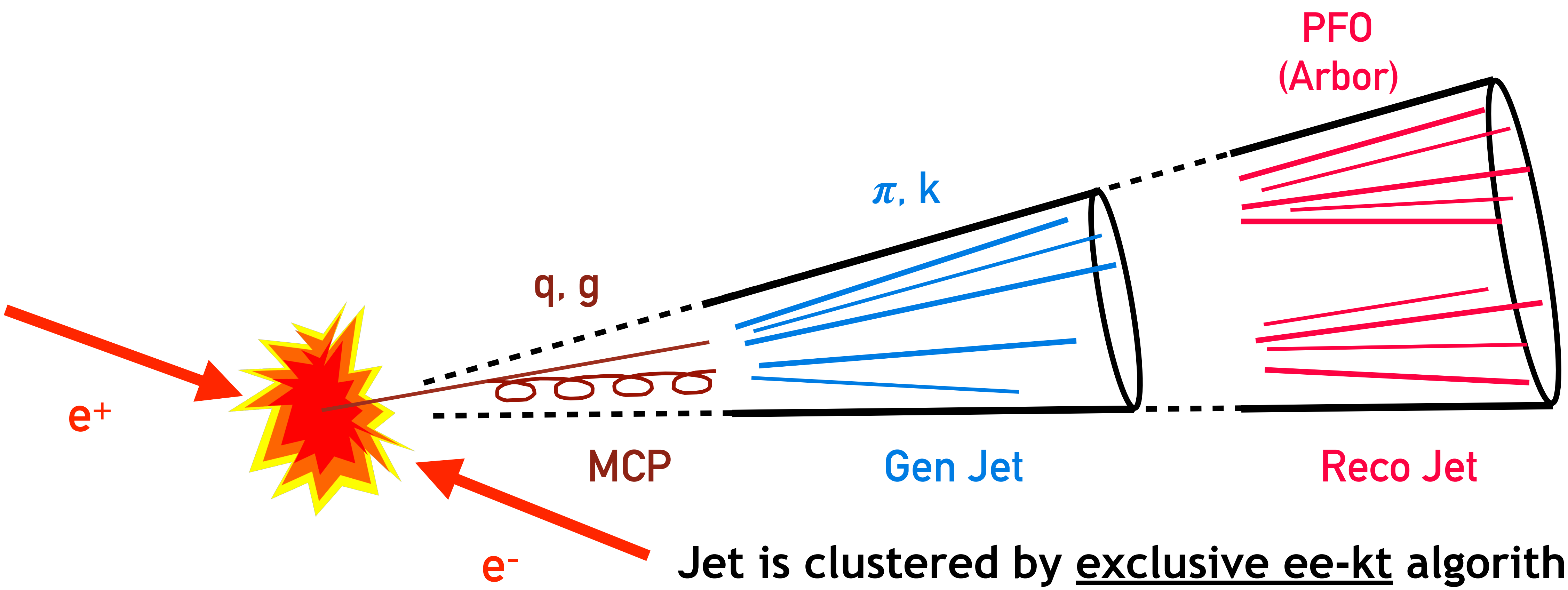
# of ZH = 500,000 in the 5 ab^{-1}

500,000 x 18% = 150,000 could be identified

1 / sqrt(150,000) = 0.25%

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.



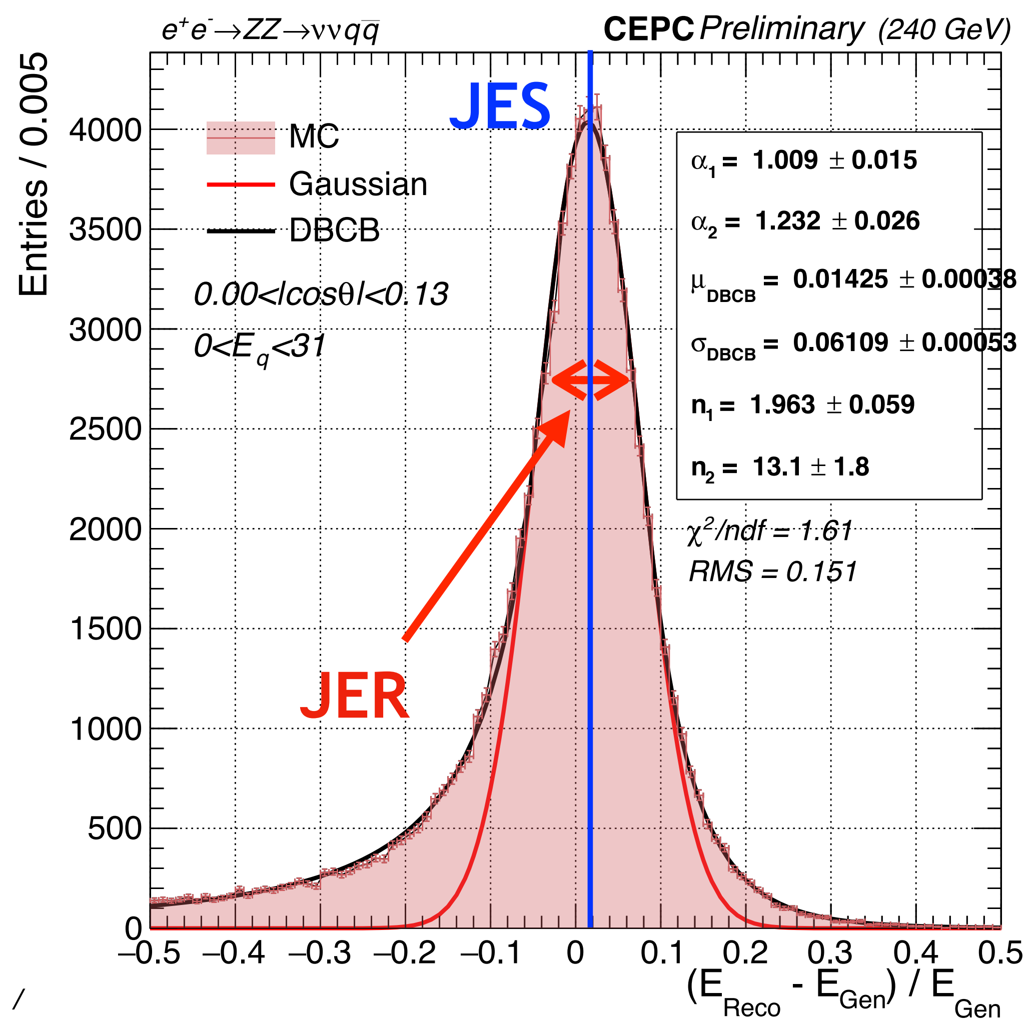
Jet is clustered by exclusive ee-kt algorithm.

Quantify the Performance

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

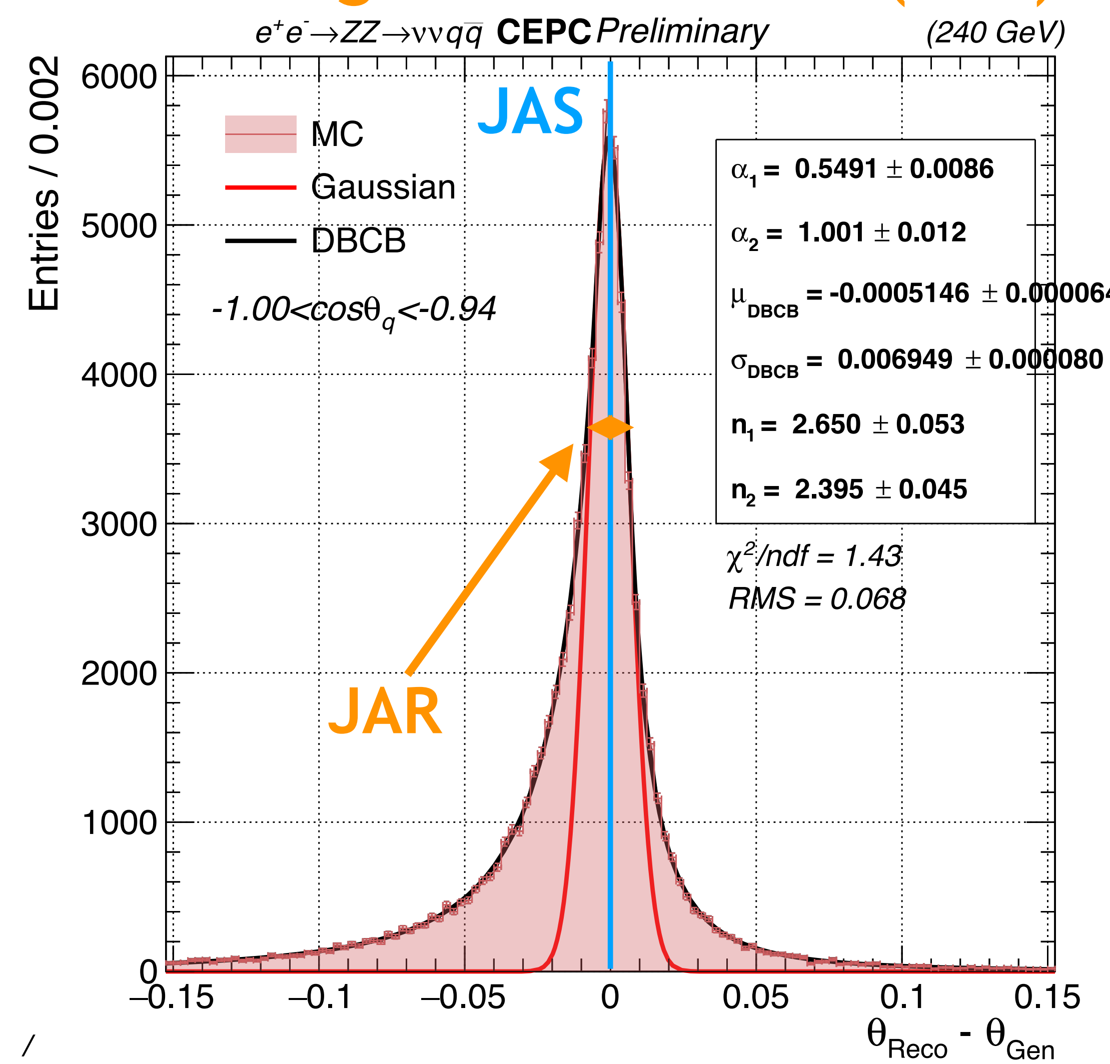
Jet Energy Scale (JES)

Jet Energy Resolution (JER)



Jet Angular Scale (JAS)

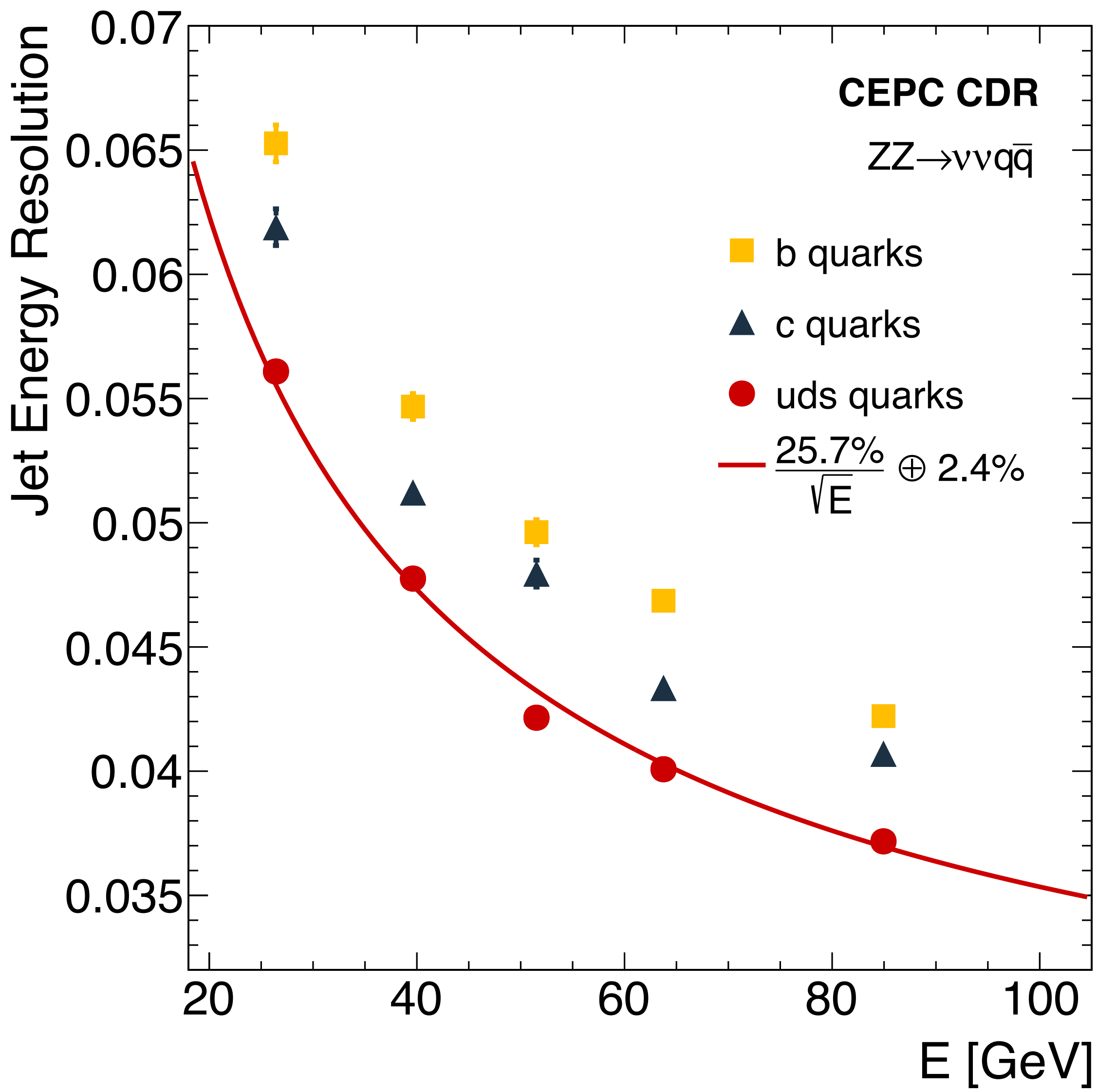
Jet Angular Resolution (JAR)

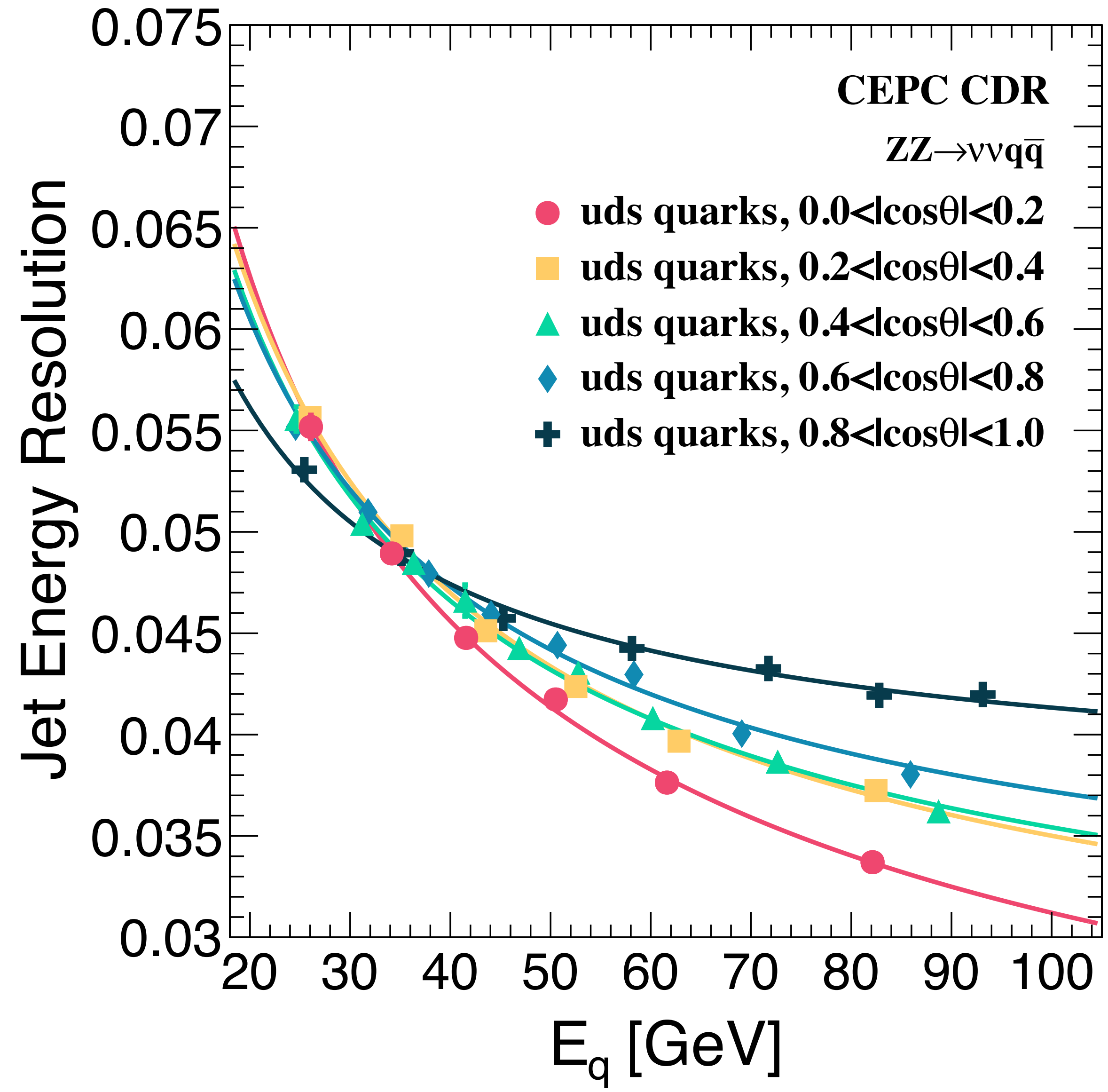


Relative difference : $\dfrac{E_{Reco} - E_{Gen}}{E_{Gen}}$

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

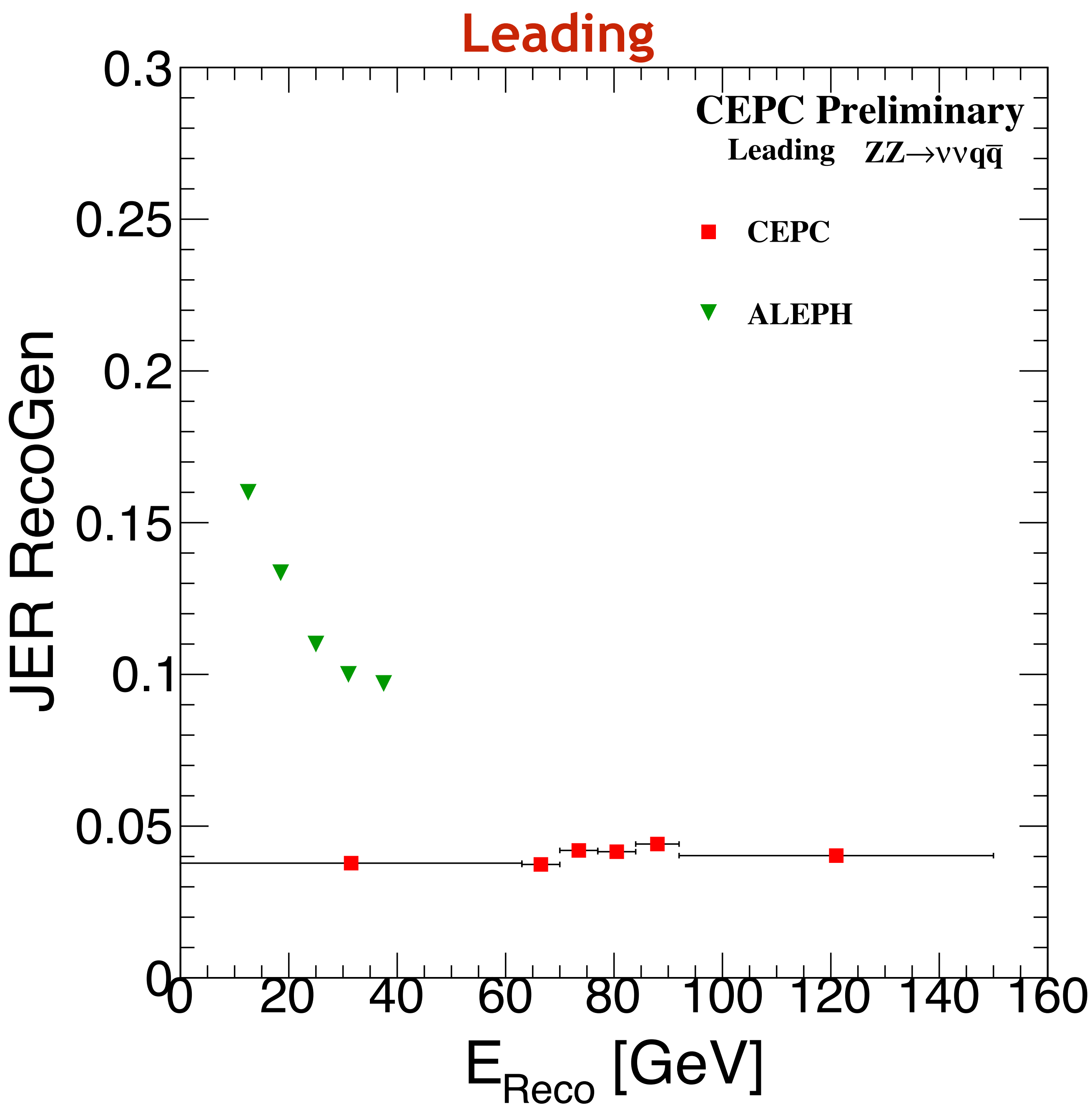
BM3: JER (Reco-Gen)

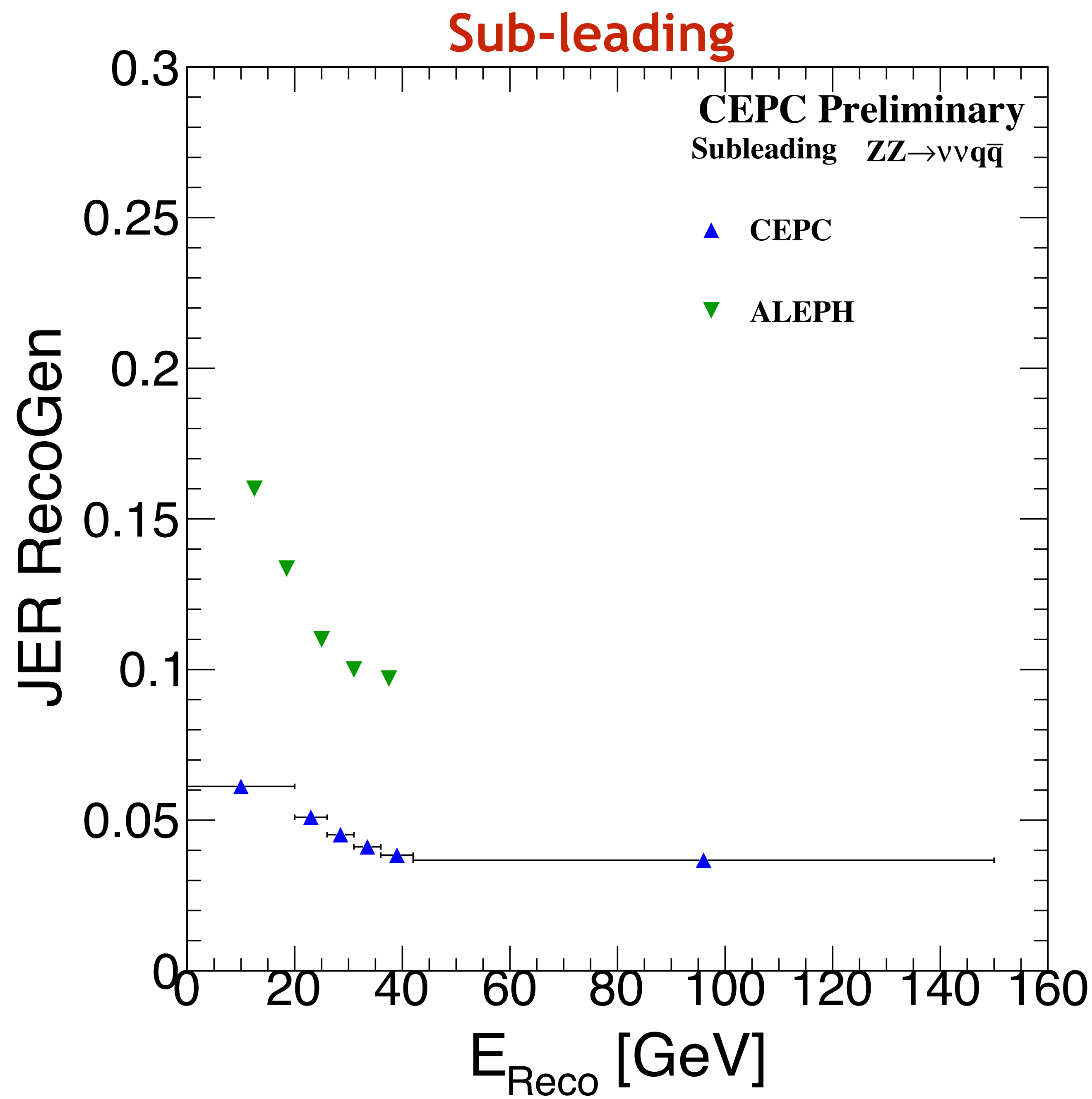




- **JER also depends on jet flavors; the semi-leptonic decay from c- and b-quarks.**
- **For light-flavor jets with high energy and within central region of barrel, JER could reach 3%.**

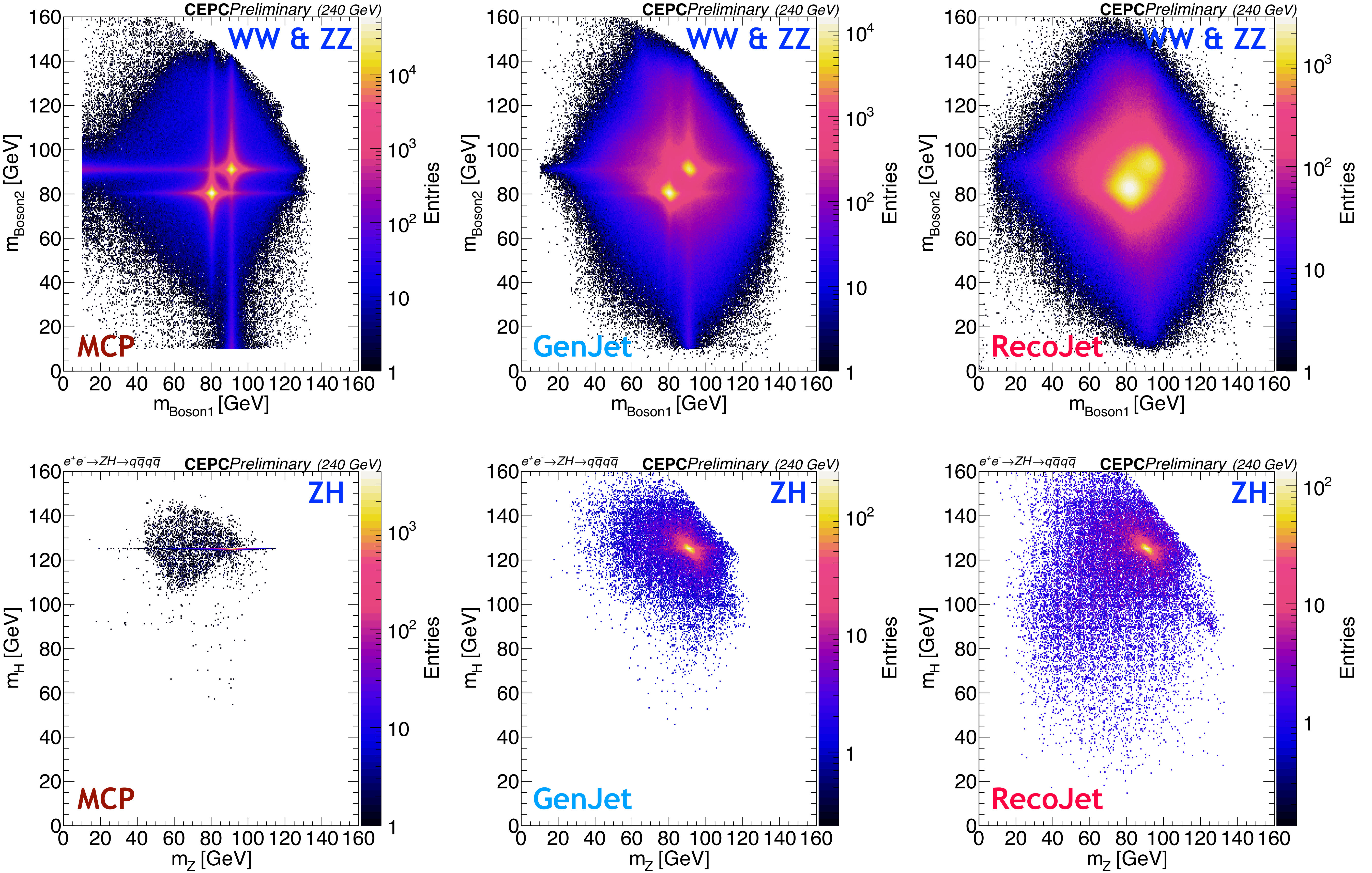
Compare with ALEPH at LEP





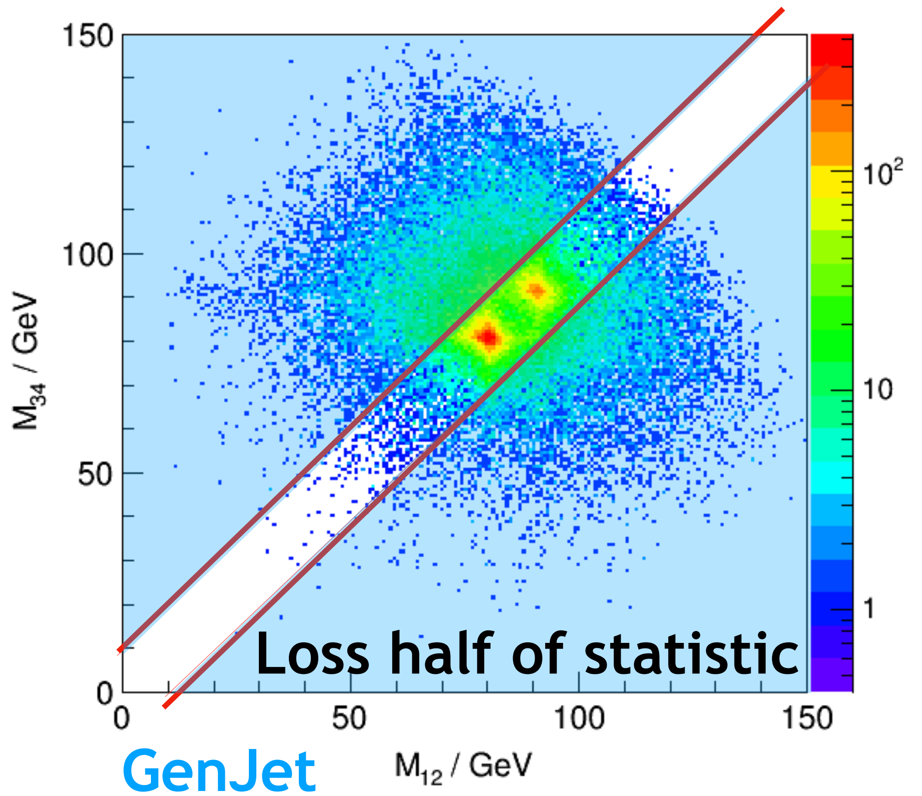
- **Our JER is better than ALEPH.**

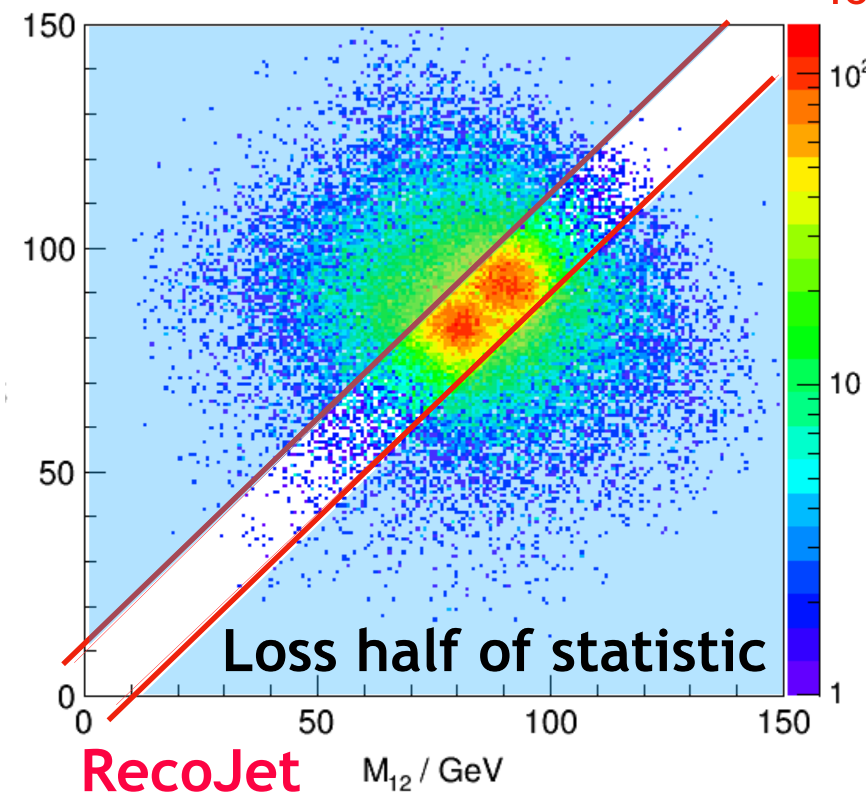
WW & ZZ Full Hadronic

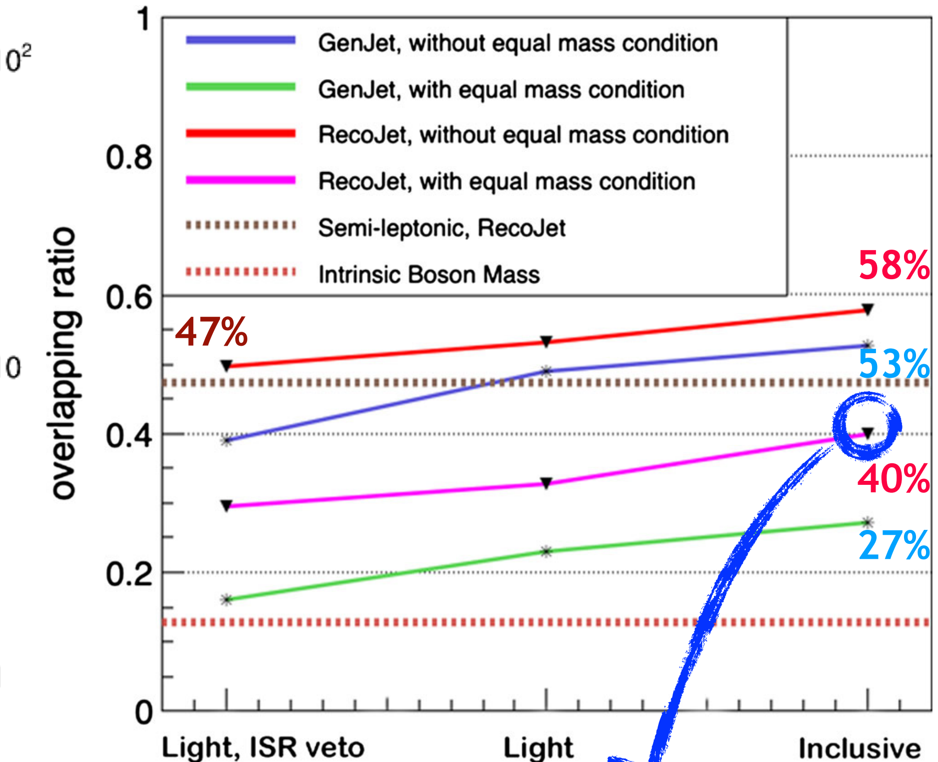


BM4: WW & ZZ to 4 Jets Separation

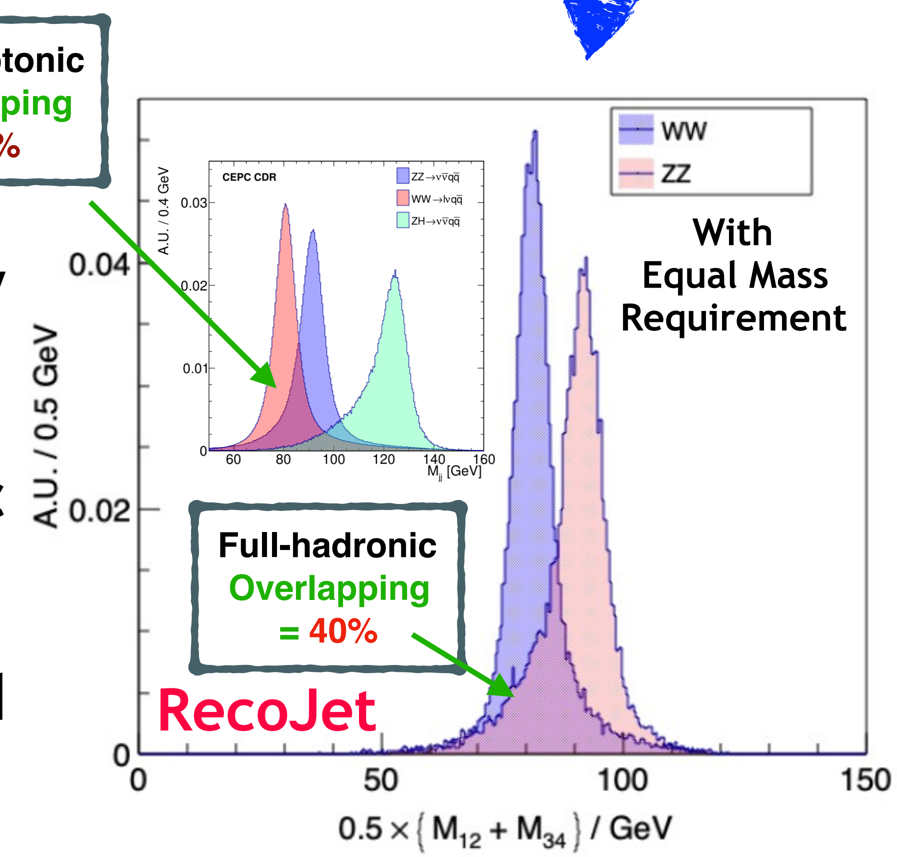
Yong-Feng Zhu—Eur. Phys. J. C (2019) 79:274







- <u>Equal mass requirement</u>: $|M_{12} - M_{34}| < 10$ 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 <u>jet clustering & pairing</u> and control the <u>ISR photon</u> 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. $ZH \rightarrow q\bar{q}q\bar{q}$) - 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.

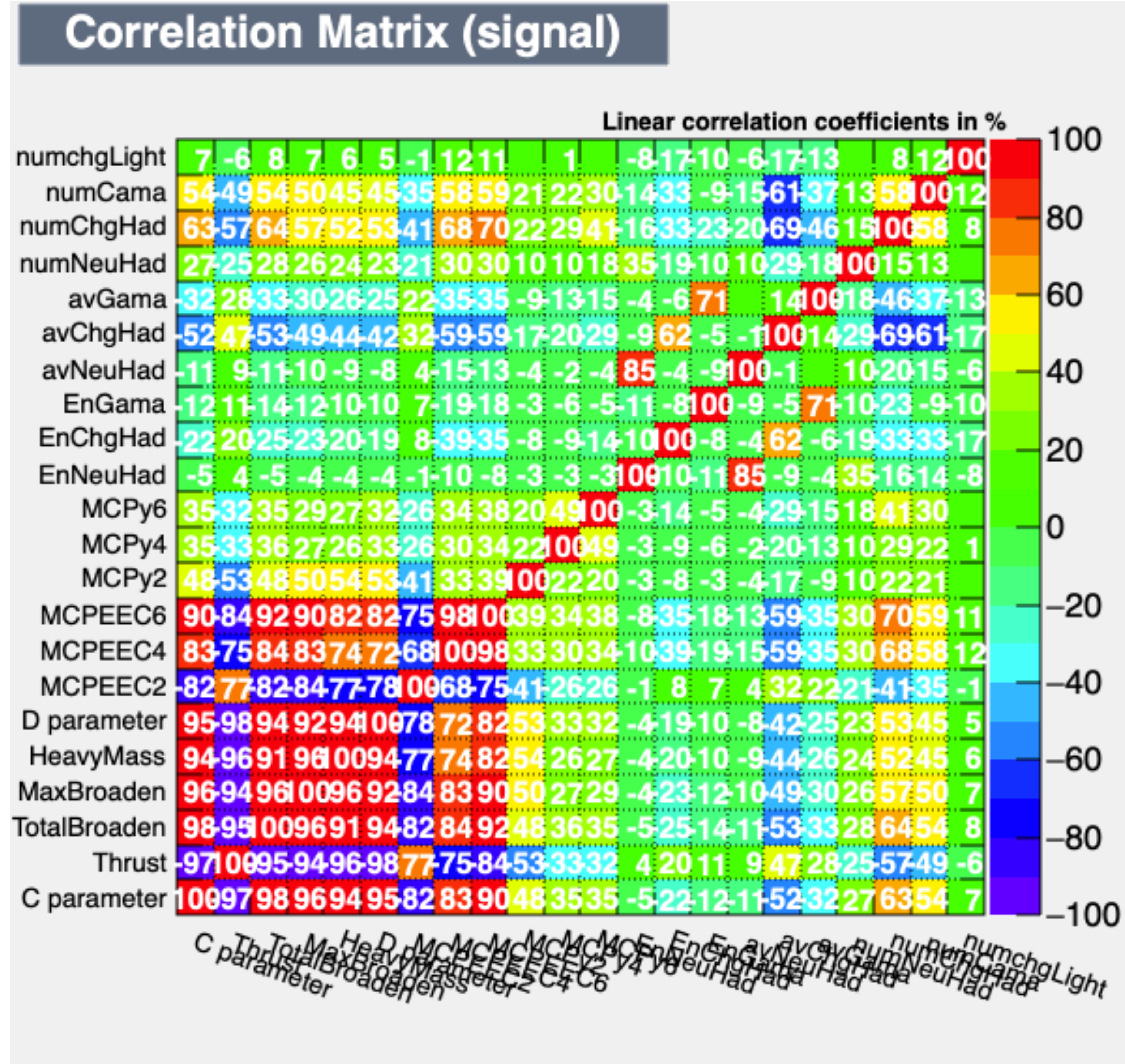
II. **2 jets final-state could be identified with *efficiency×purity* = 88.4%.**
  * Could be clustered by dedicated jet clustering algorithm, thrust.

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.
  * The statistical uncertainty of ZH to full hadronic final-state could be achieved 0.25% after considering the WW and ZZ as bkg.

BM2: Number of Jet Identification

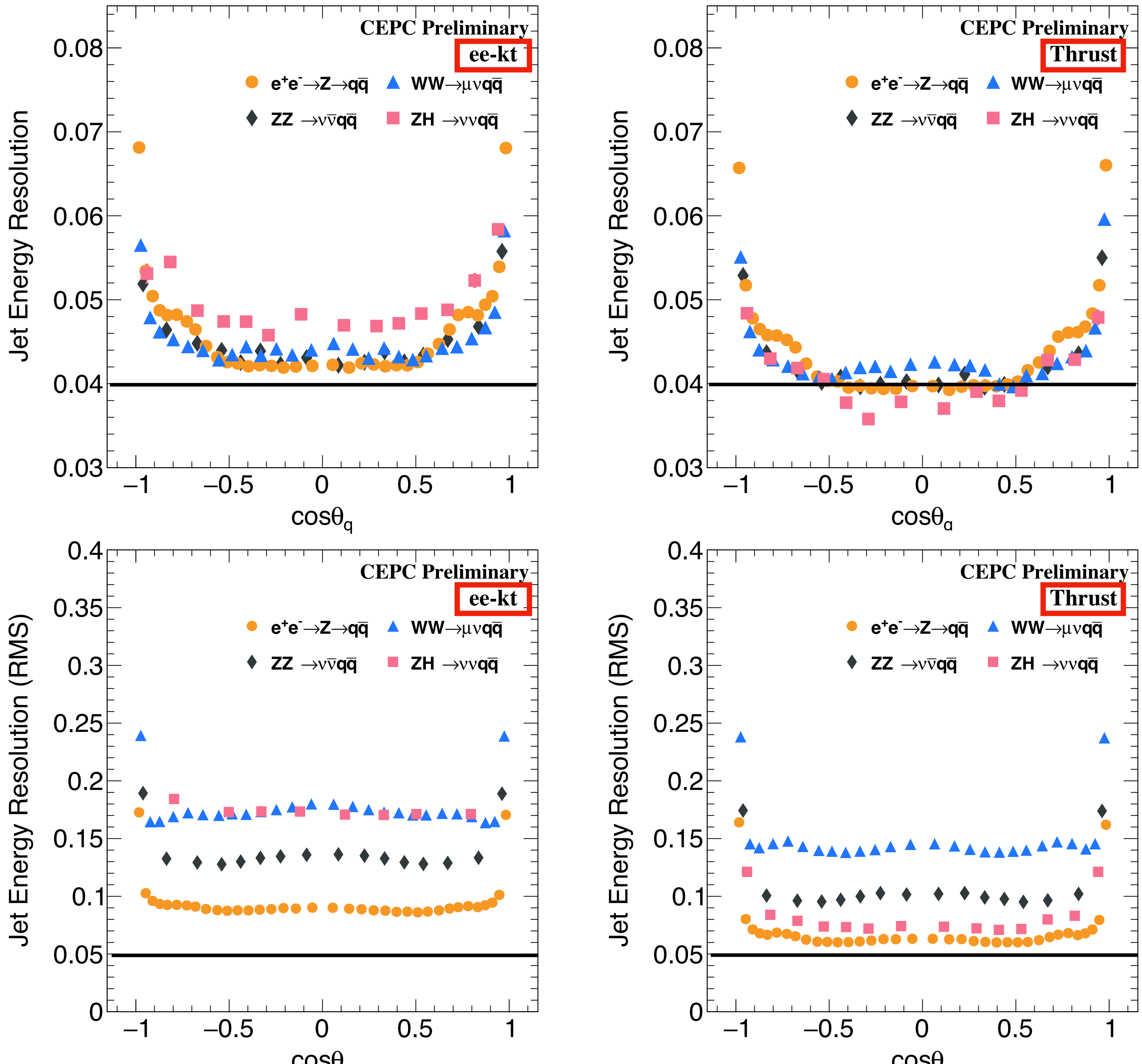
20 Variables	
# of charge lepton	EEC 6
# of γ	EEC 4
# of charge hadron	EEC 2
# of neutro hadron	C parameter
$\bar{E}_{\gamma}$	D parameter
$\bar{E}_{\text{Charge hadron}}$	Heavy Mass
$\bar{E}_{\text{Neutro hadron}}$	Max Broaden
E_{γ}	Total Broaden
$E_{\text{Charge hadron}}$	Thrust
$E_{\text{Neutro hadron}}$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



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

Yong-Feng Zhu

BM3: JER (ee-k_t—Thrust)

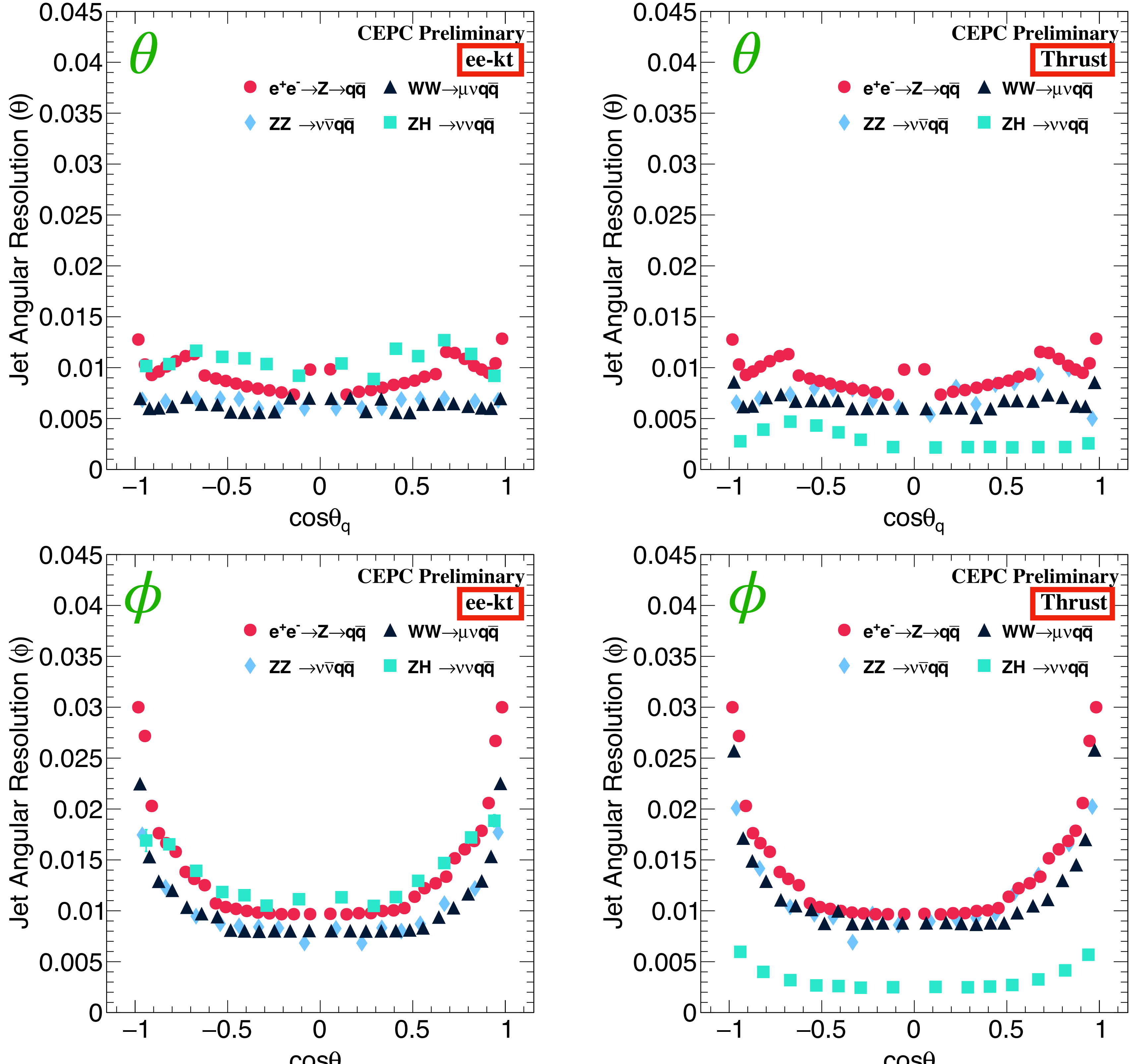


Improved 20% w.r.t ee-kt

Improved 40% w.r.t ee-kt

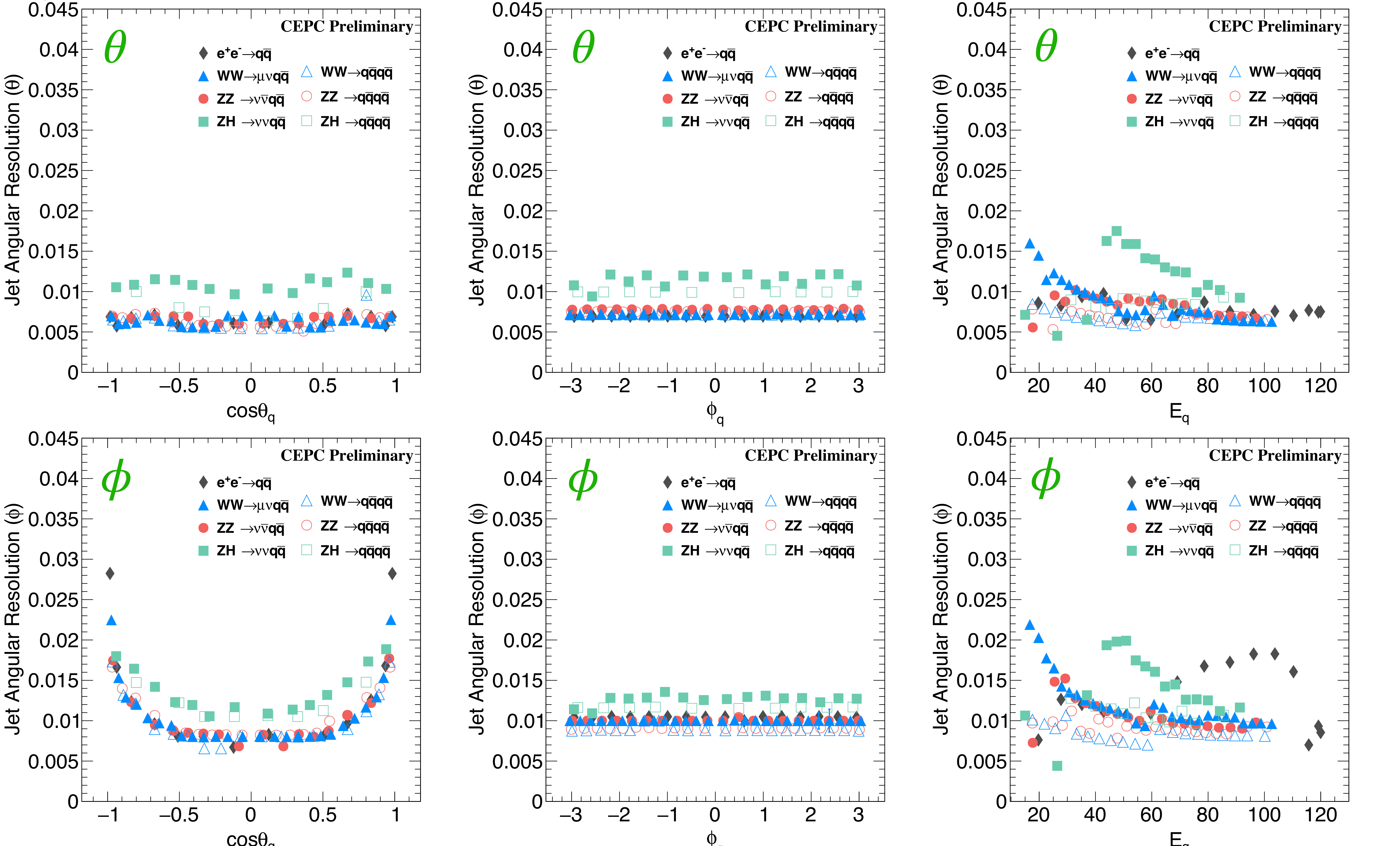
- **Improvement maybe came from <u>boosting the system back to the rest frame with the neutrons' information</u>.**

BM3: JAR (ee-k_t—Thrust)



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

BM3: JAR



- 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.

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}

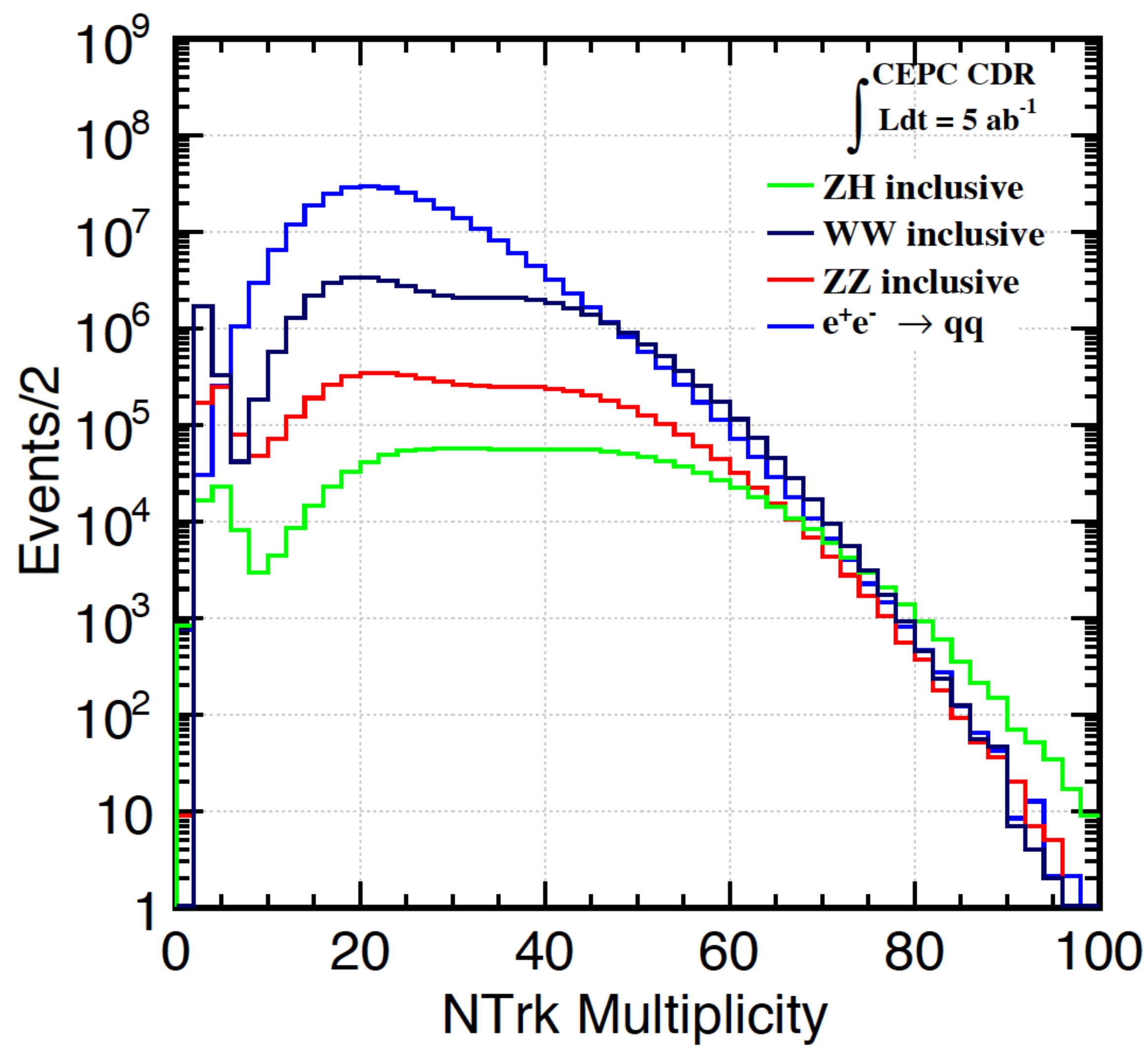
ee-kt jet clustering algorithm

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

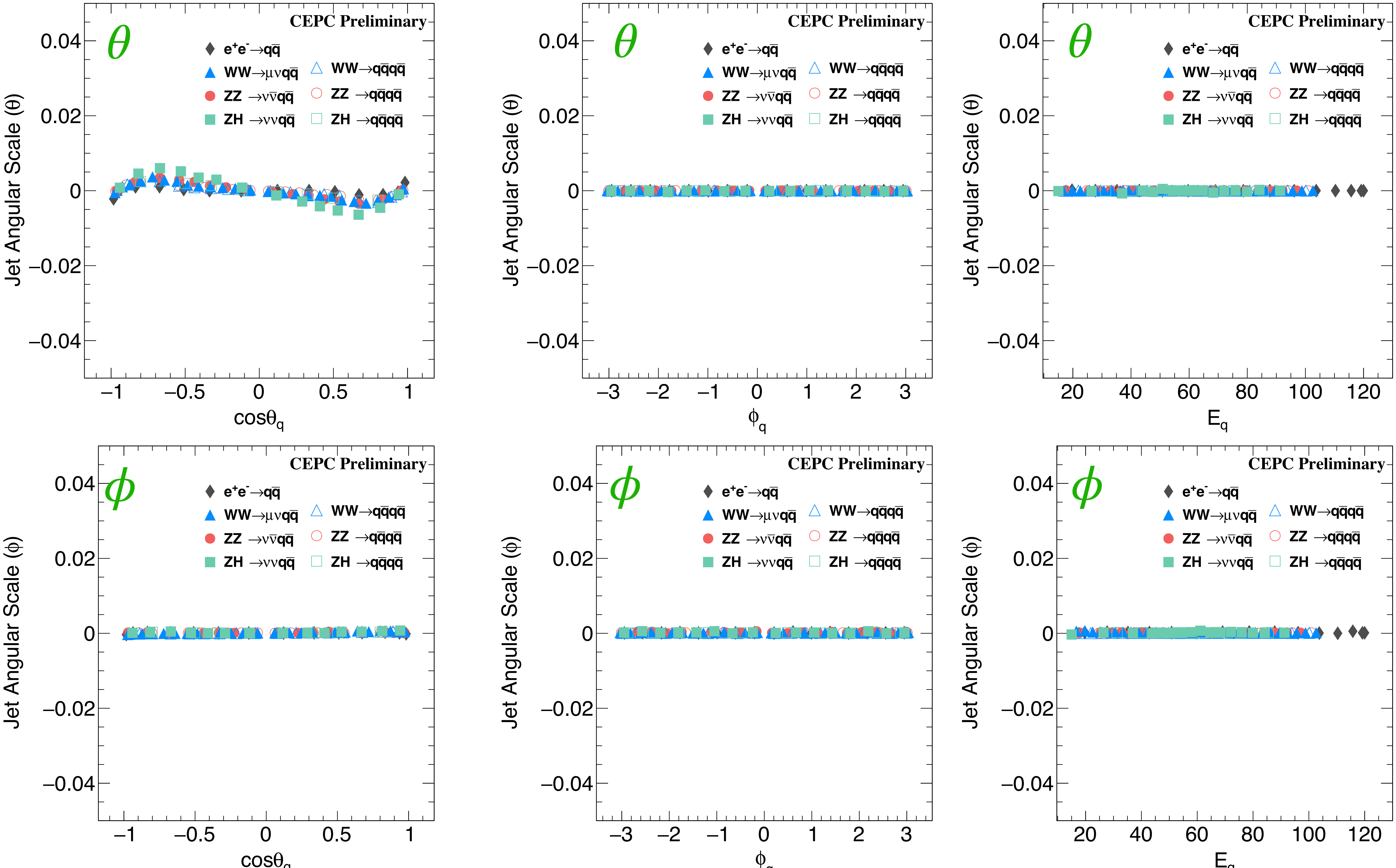
Double-sided Crystal Ball

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

Jet Multiplicity

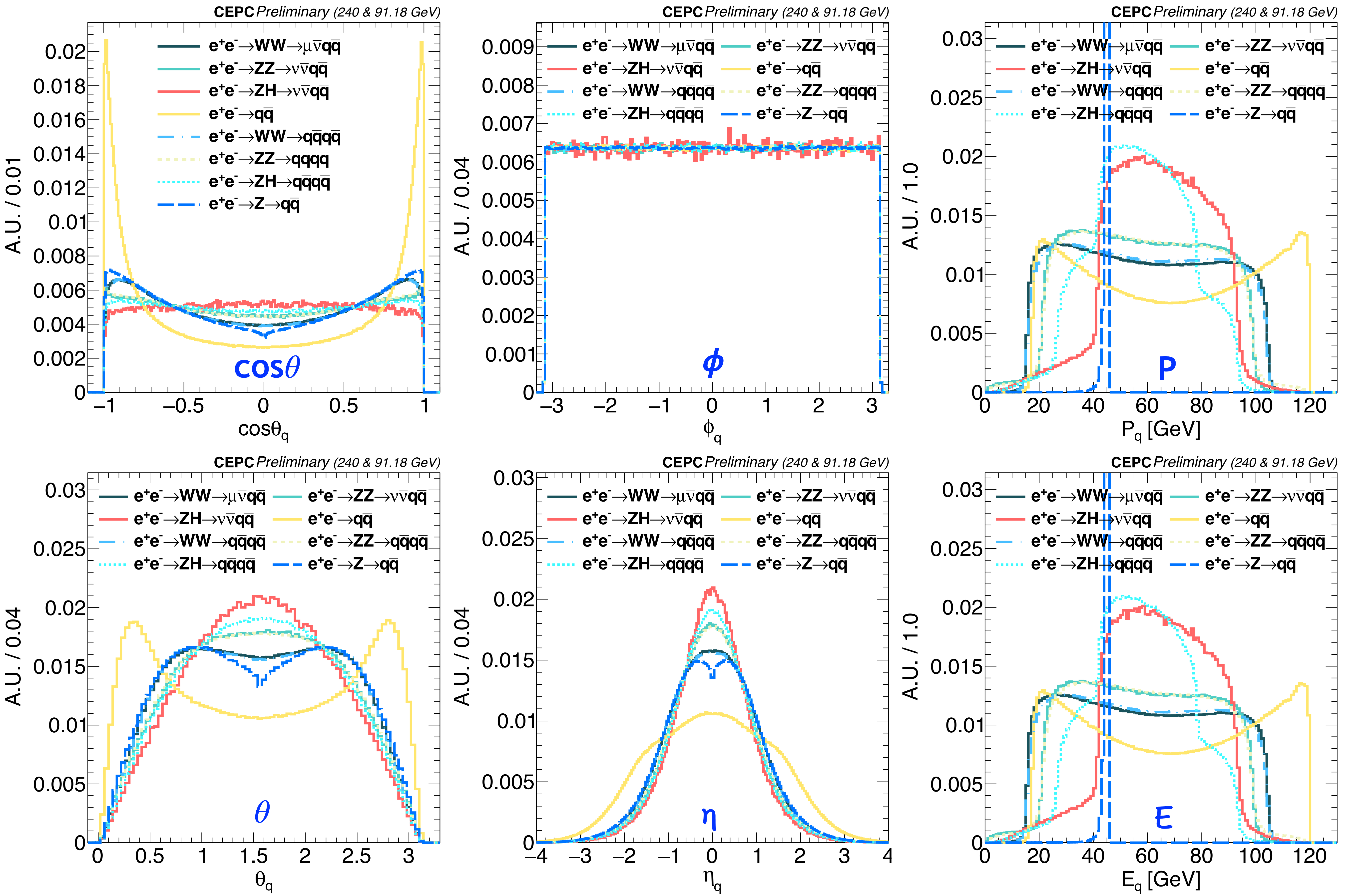


BM3: JAS (Reco-Gen)

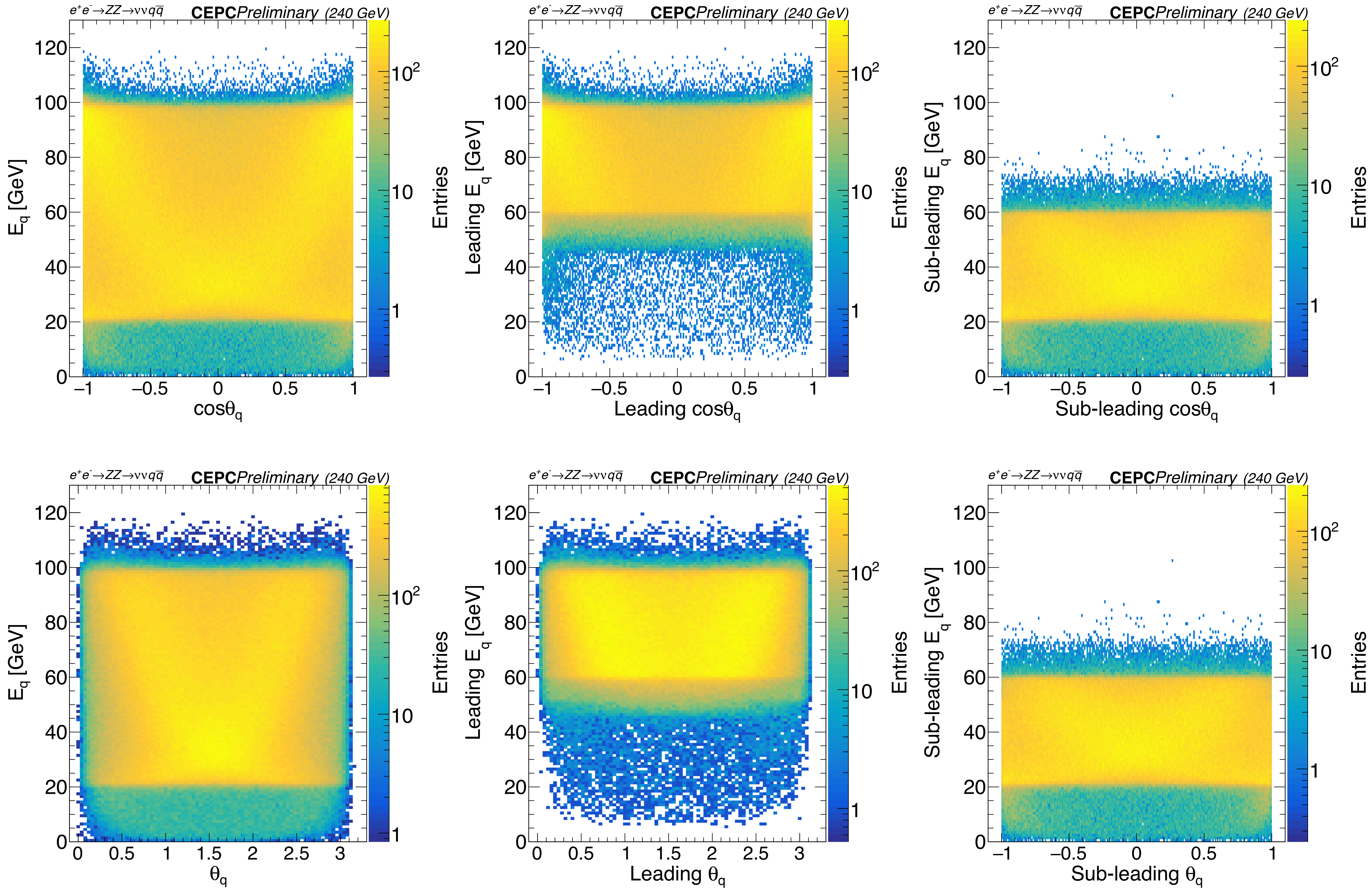


- JAR is around 1% in barrel region; JAS is independent of ϕ and energy.
- The difference between 2 and 4 jets final-state is controlled within 1% level.

Kinematic Summary Plots(Parton level)

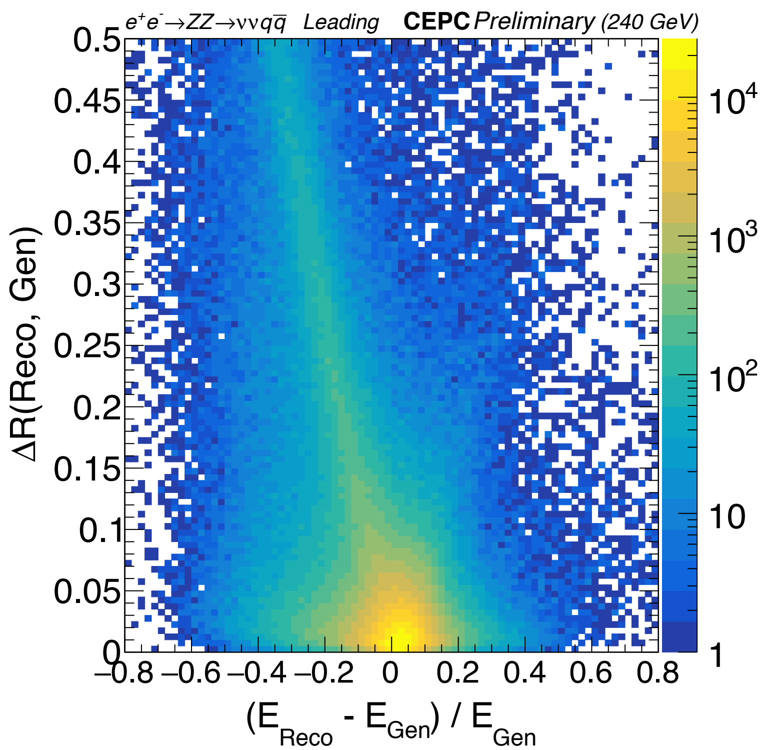


E as the function of the polar angle

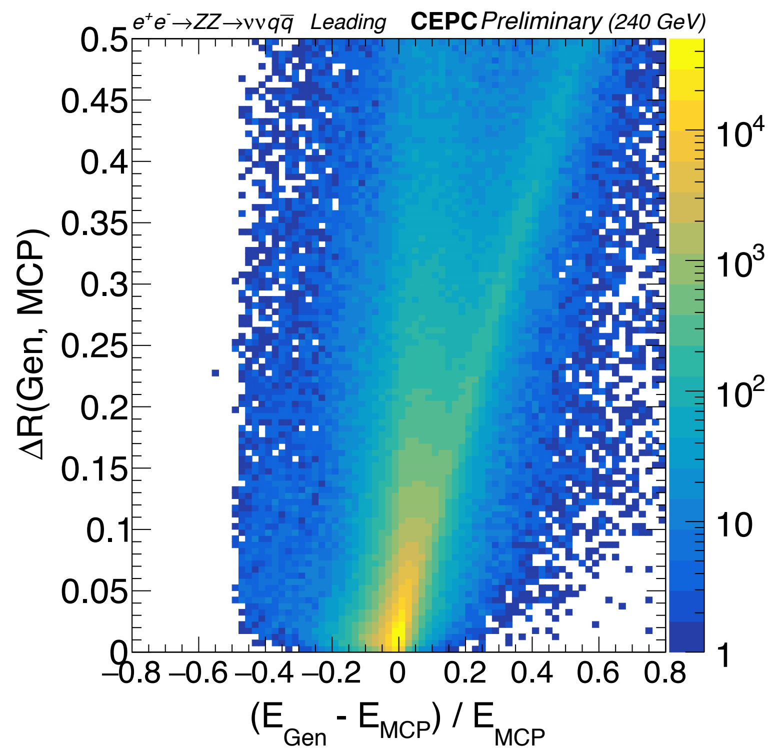


ΔR as the function of ΔE

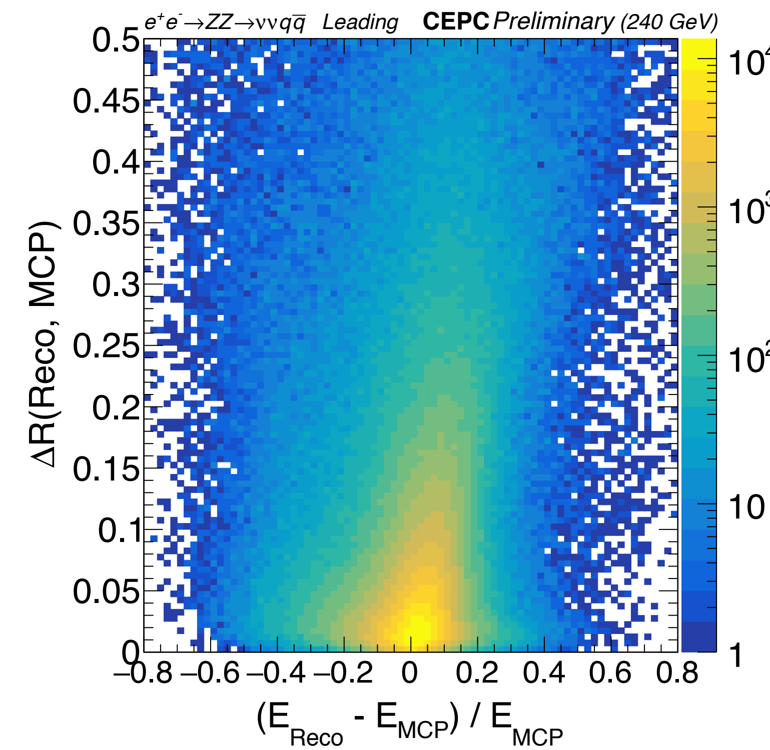
Leading, Gen-MCP



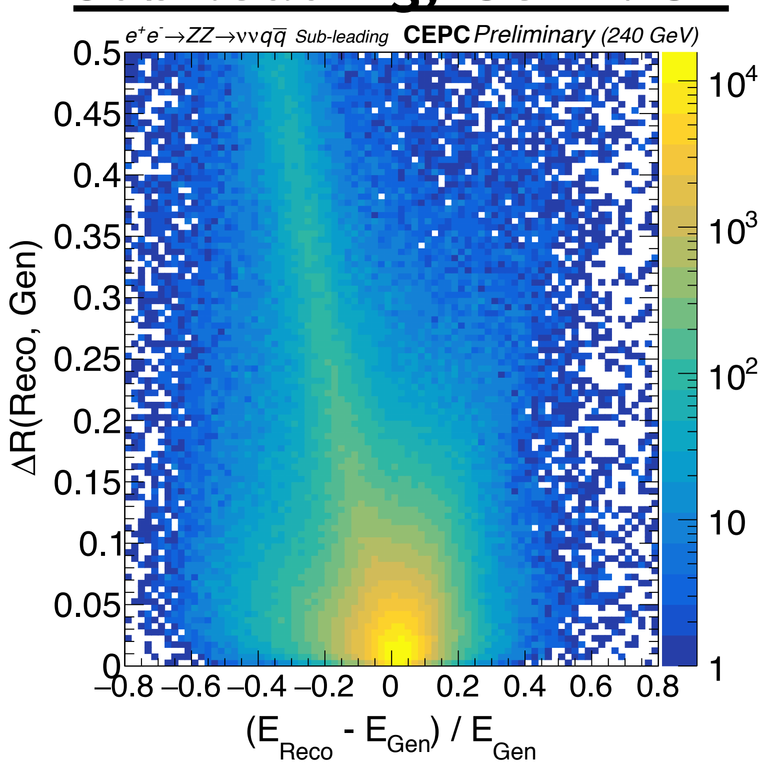
Leading, Reco-Gen



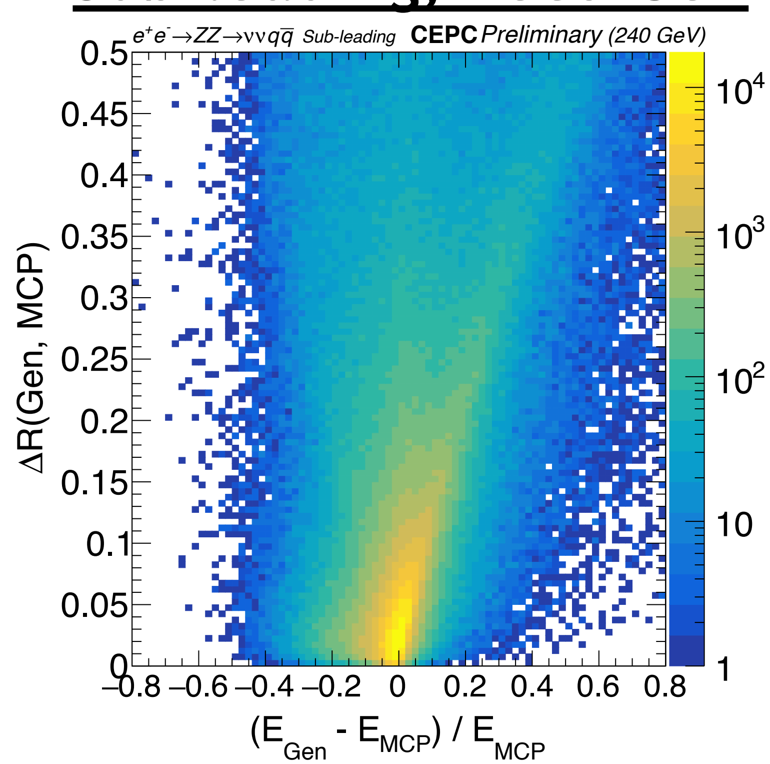
Leading, Reco-MCP



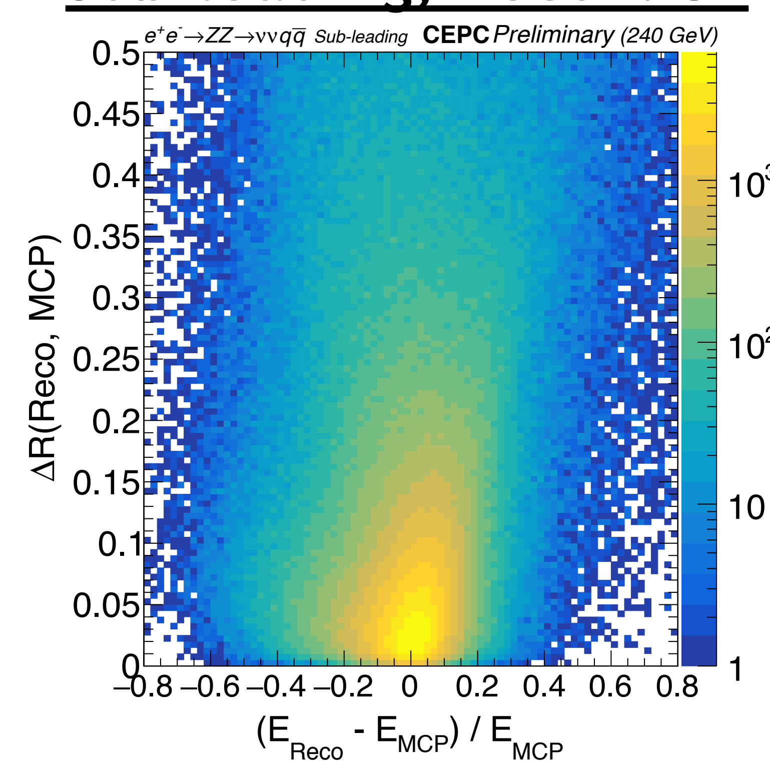
Sub-leading, Gen-MCP



Sub-leading, Reco-Gen



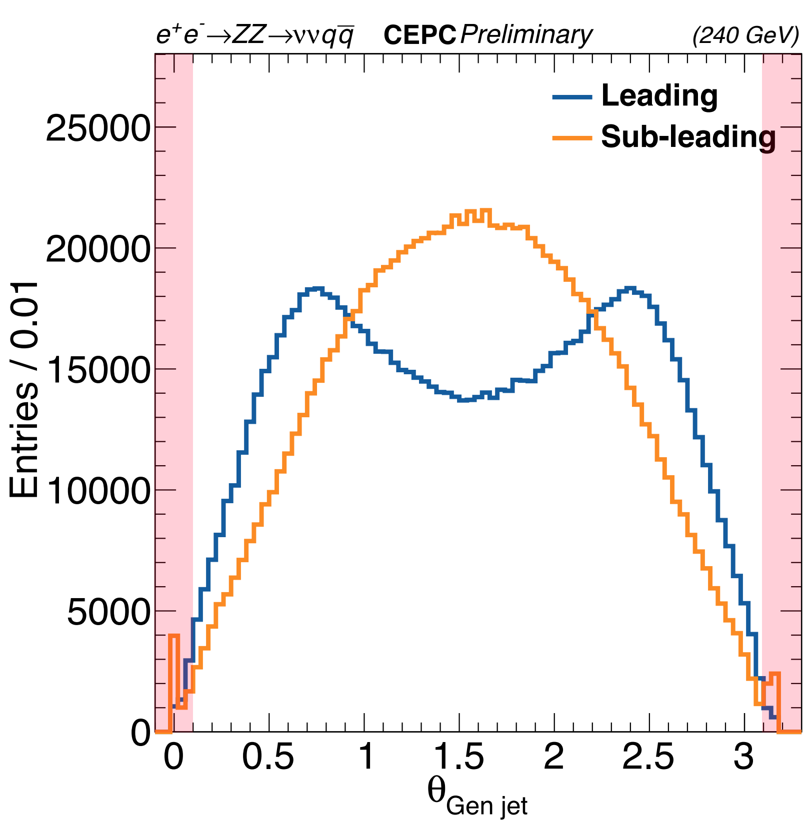
Sub-leading, Reco-MCP

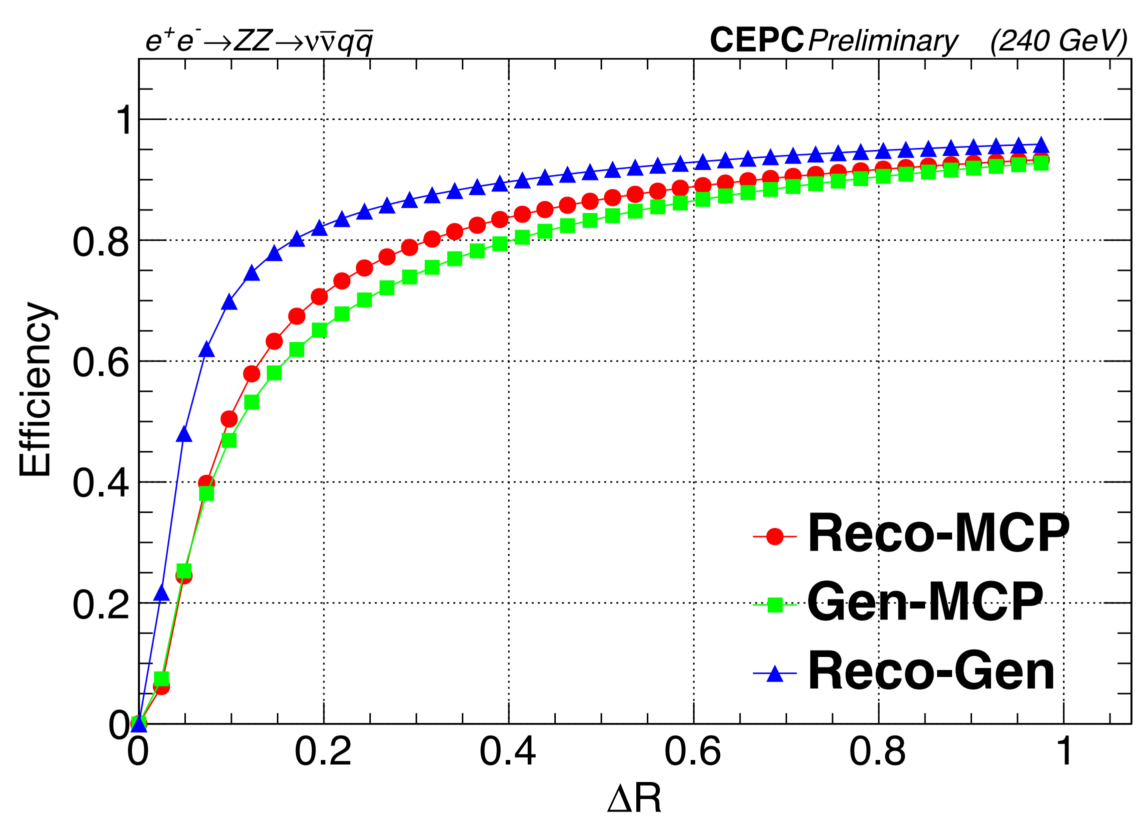


The jet clustering brings a significant uncertainty.

Event Selection

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





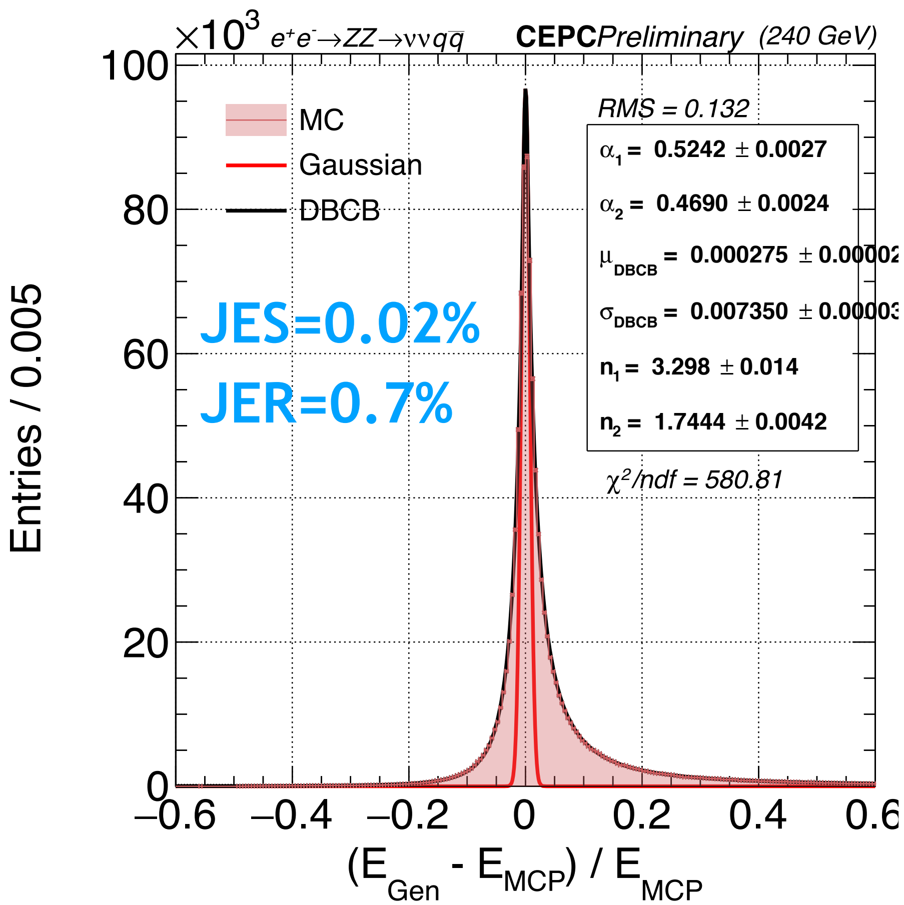
Efficiency=

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

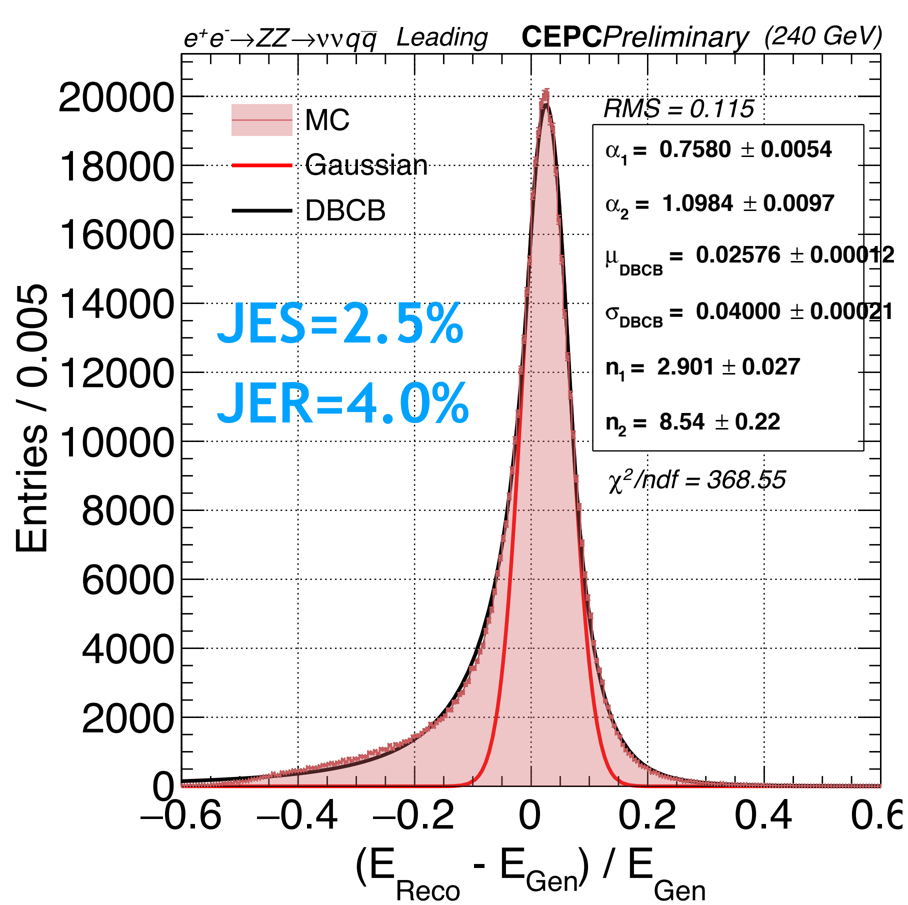
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

Leading JER & JES

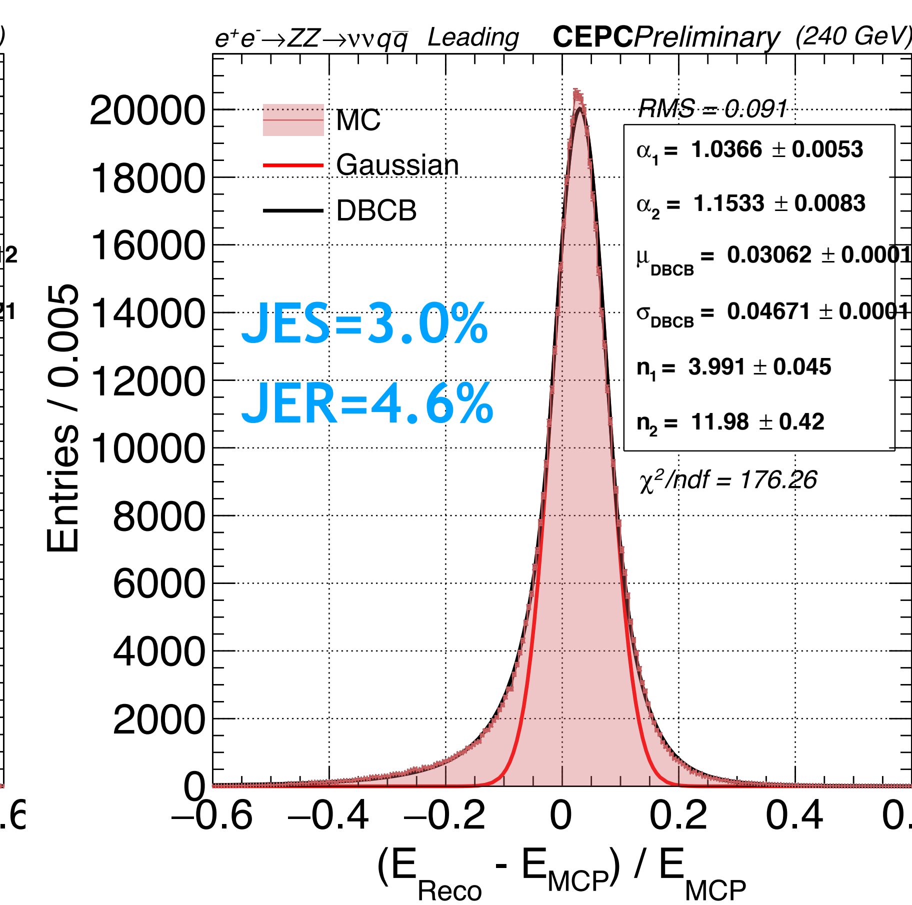
Gen-MCP



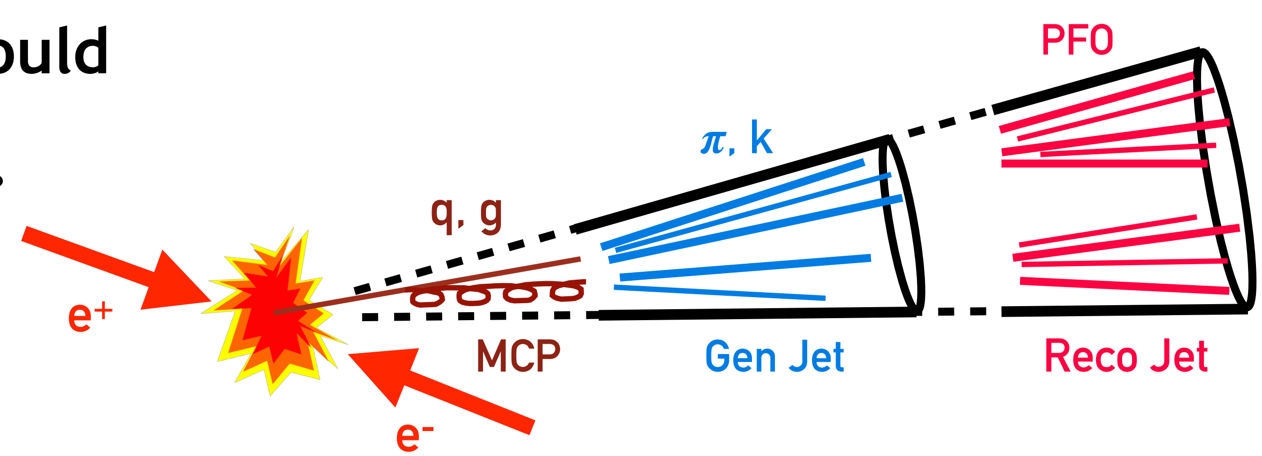
Reco-Gen



Reco-MCP

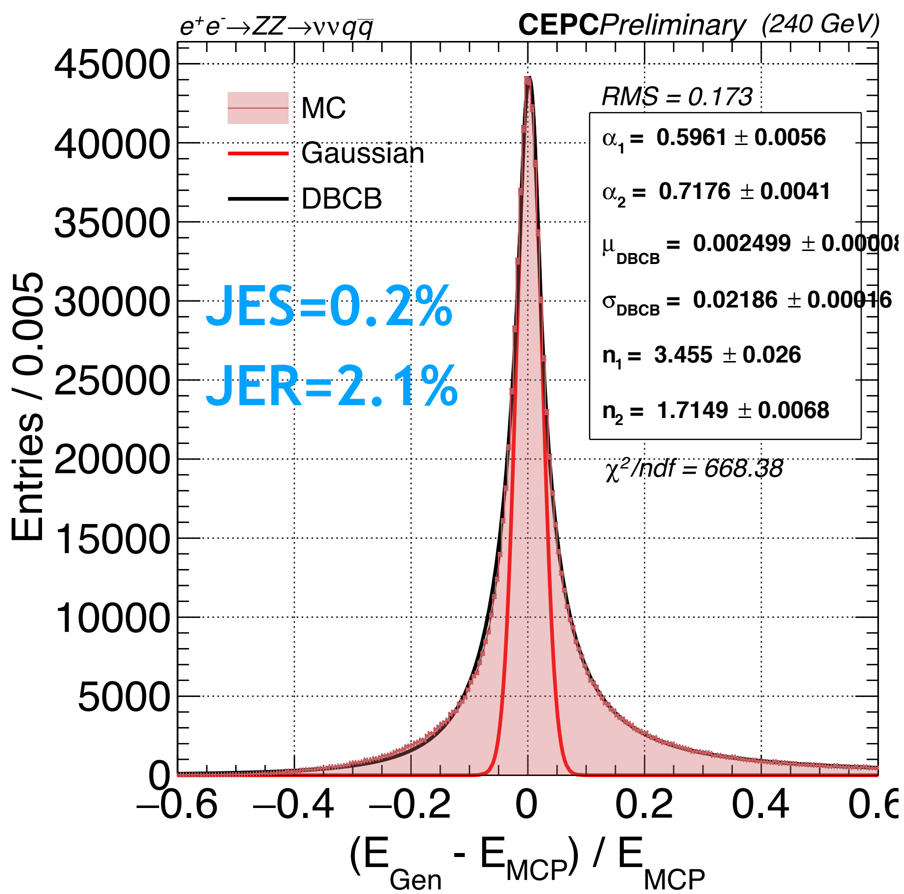


- **JER/JES between Reco jet and MCP would combine the effects of two previous stages.**

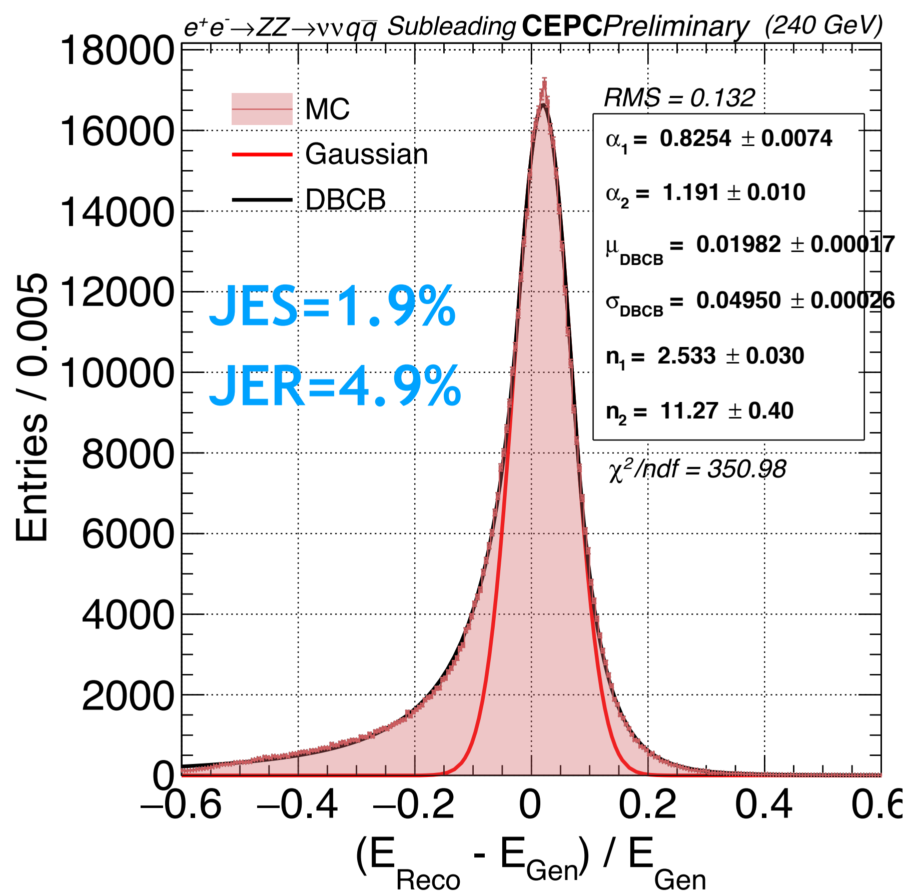


Sub-leading JER & JES

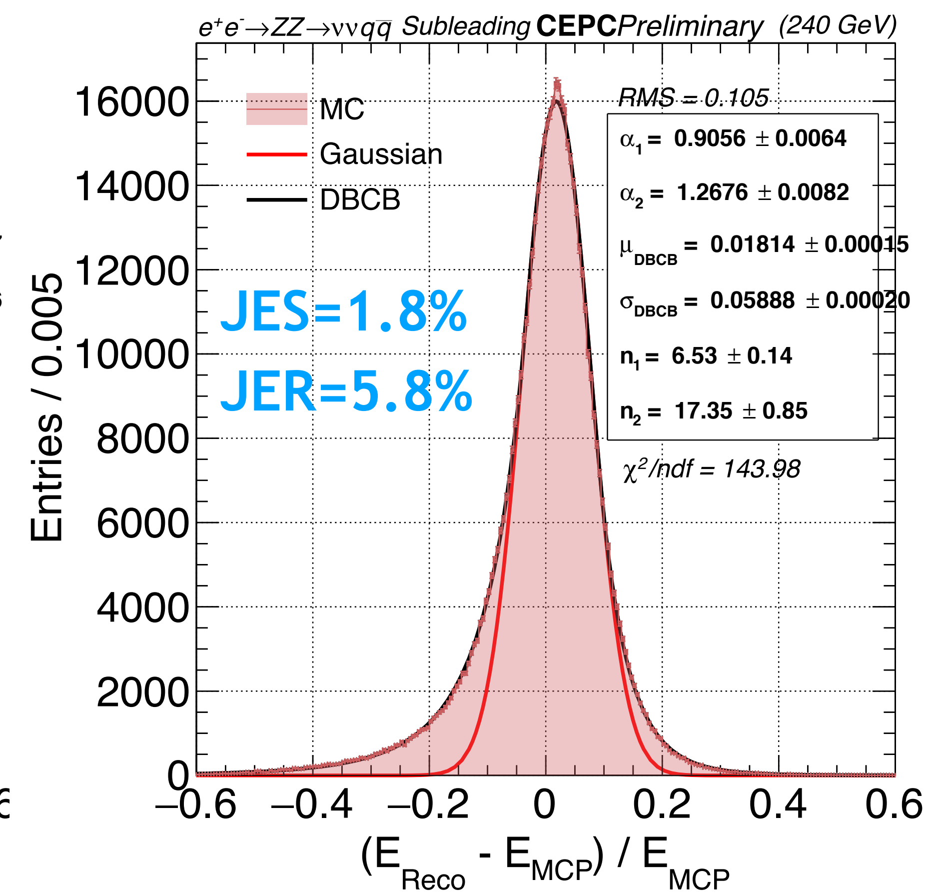
Gen-MCP



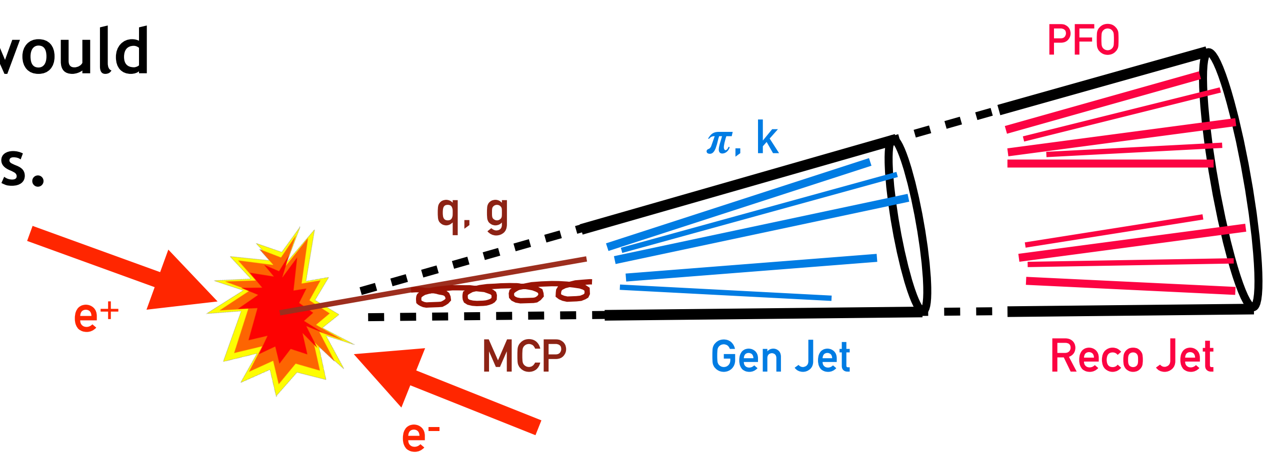
Reco-Gen

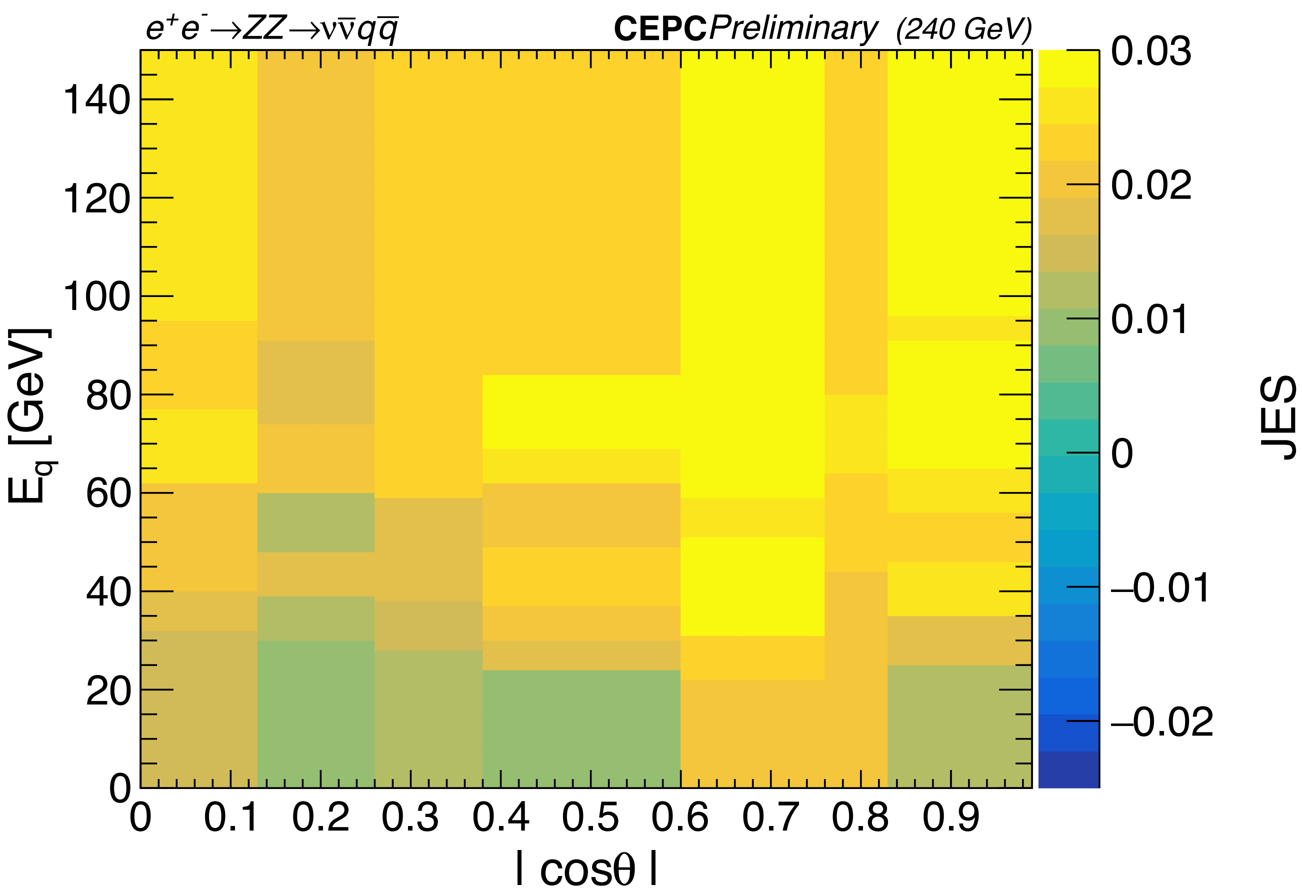


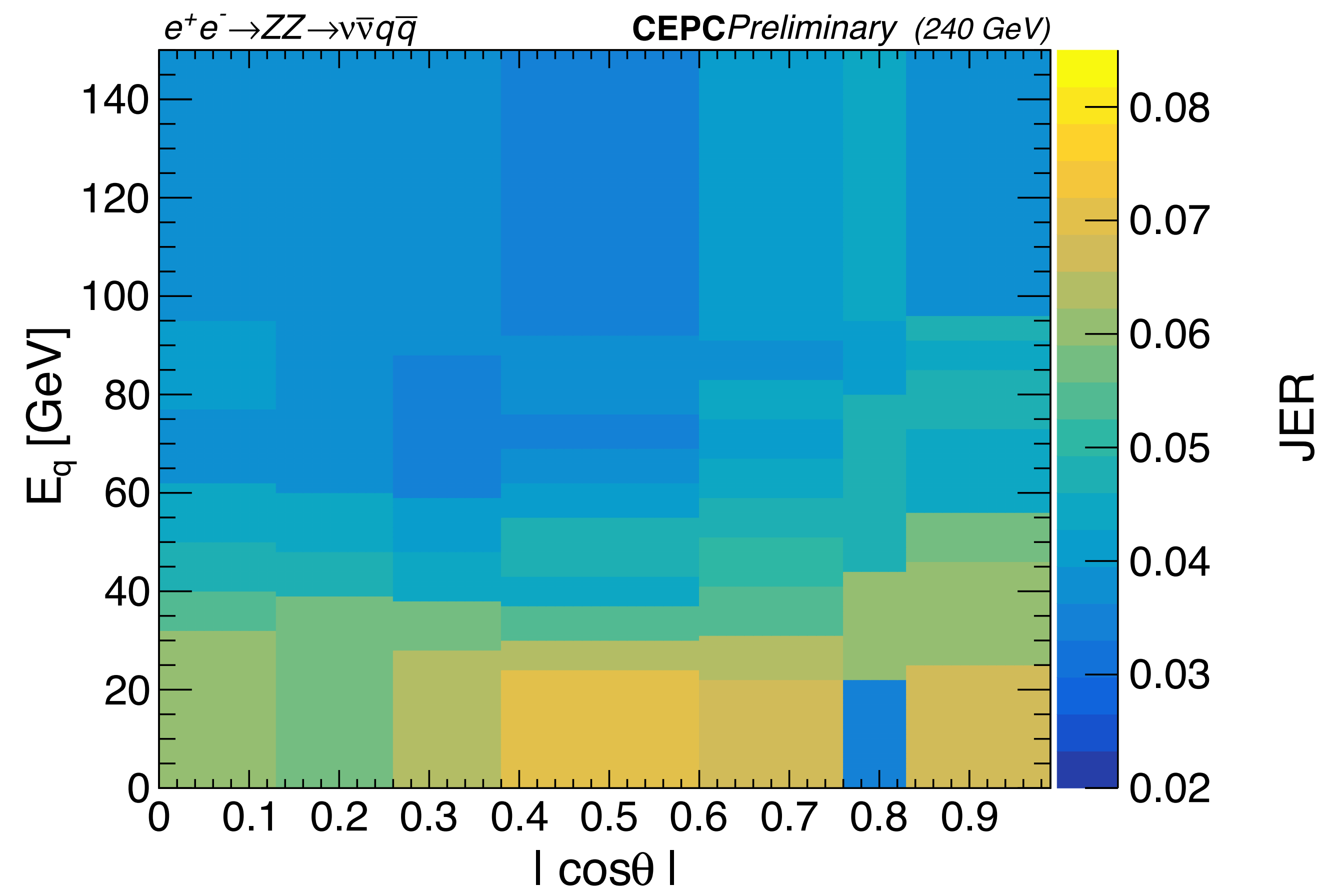
Reco-MCP



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

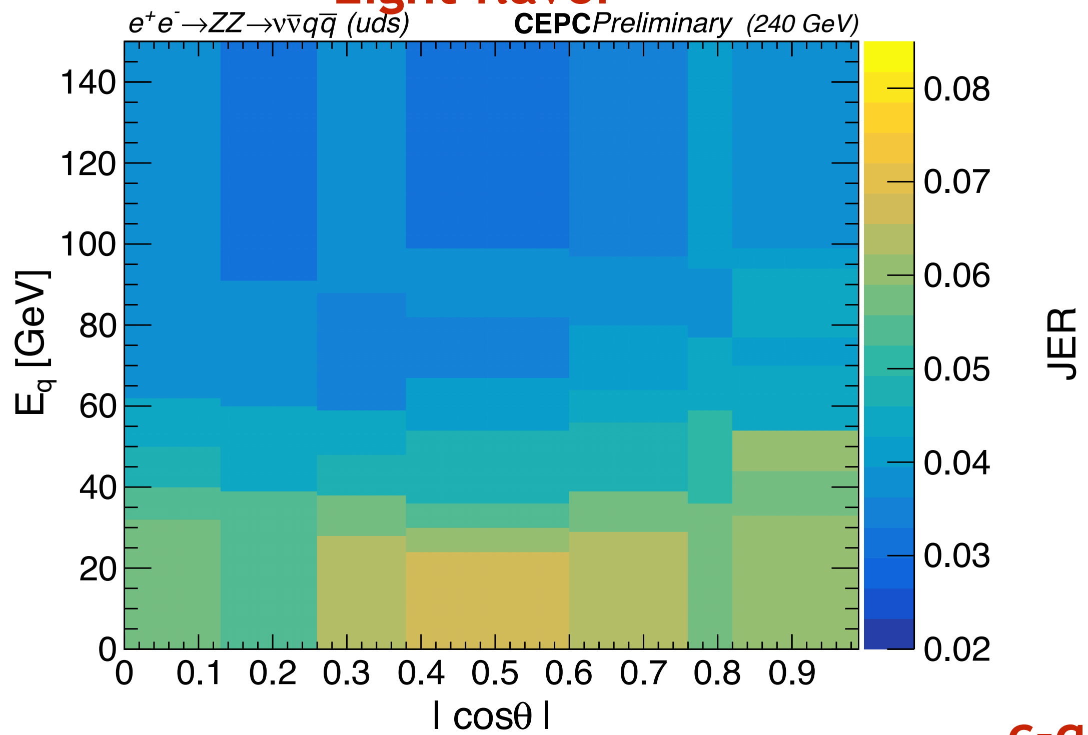



$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$
CEPC Preliminary (240 GeV)
E_q [GeV]
| cosθ |
JES

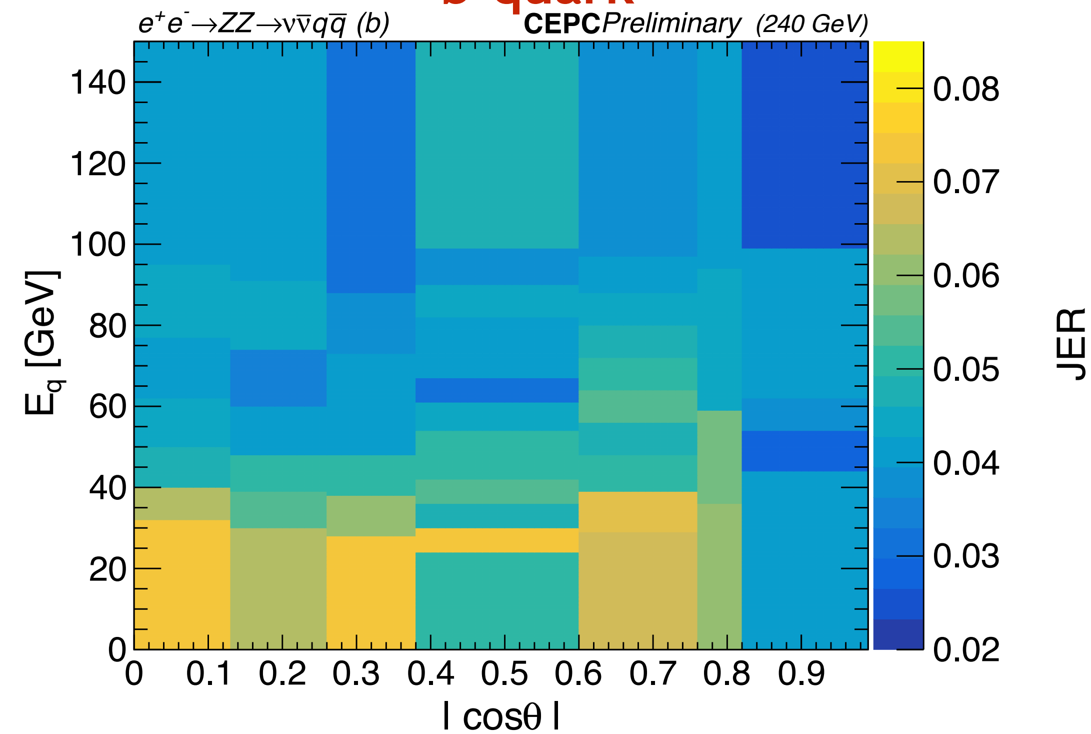

$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$
CEPC Preliminary (240 GeV)
E_q [GeV]
| cosθ |
JER

JER in Phase Space

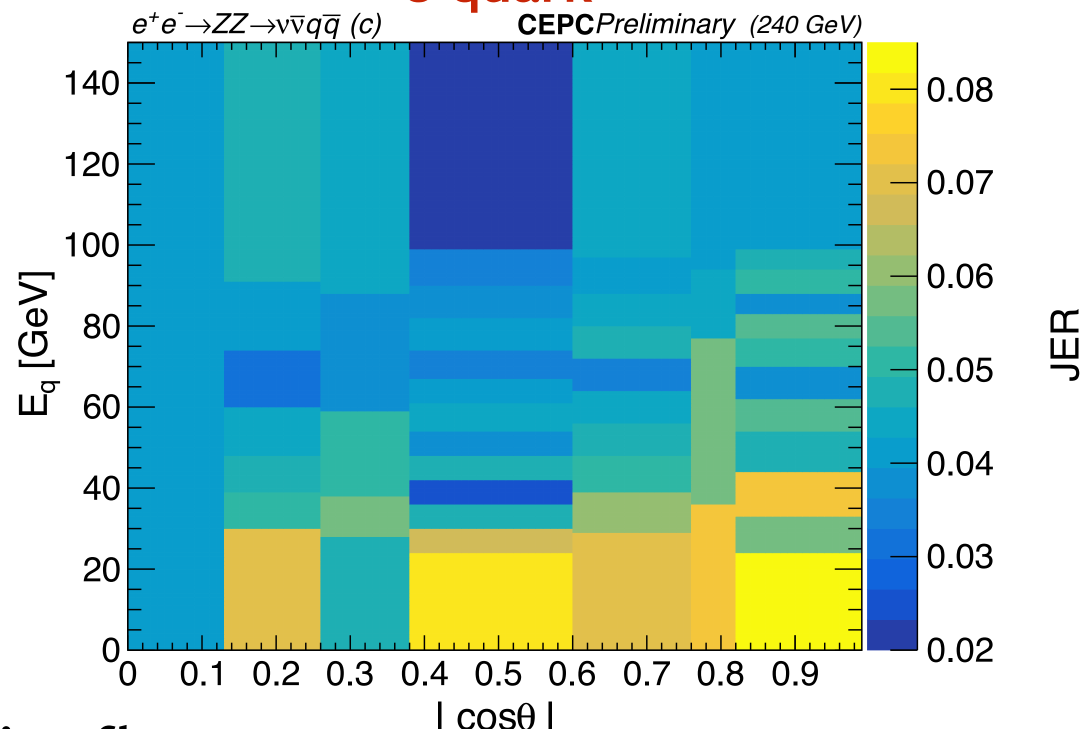
Light flavor



b-quark



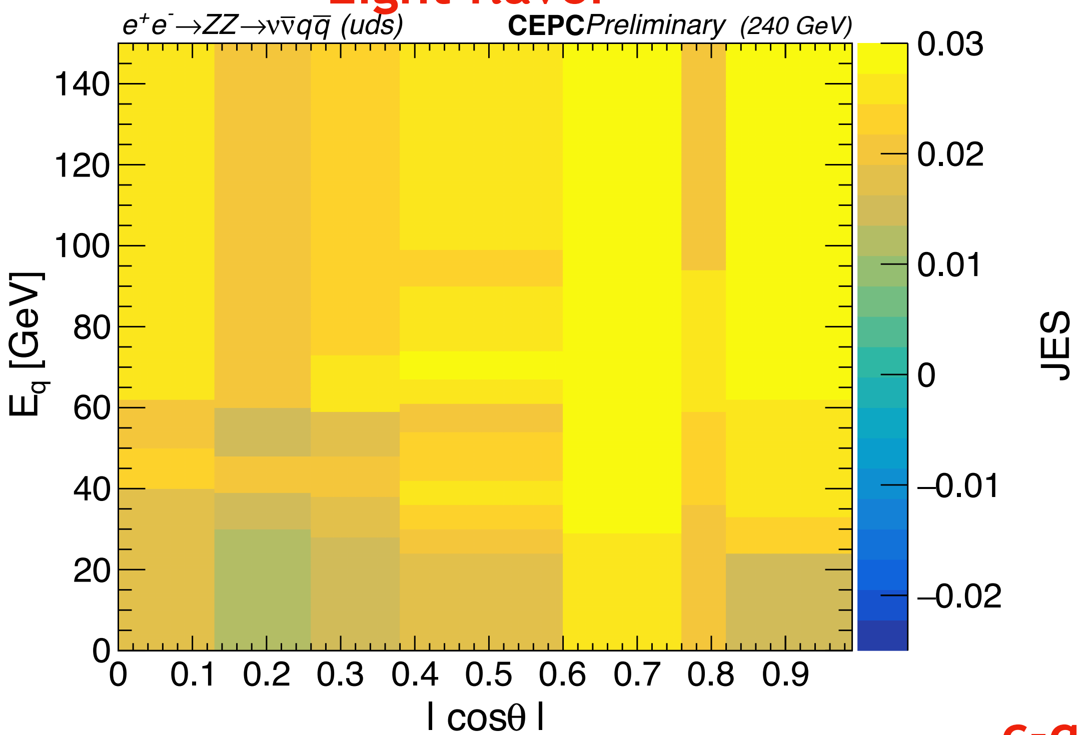
c-quark



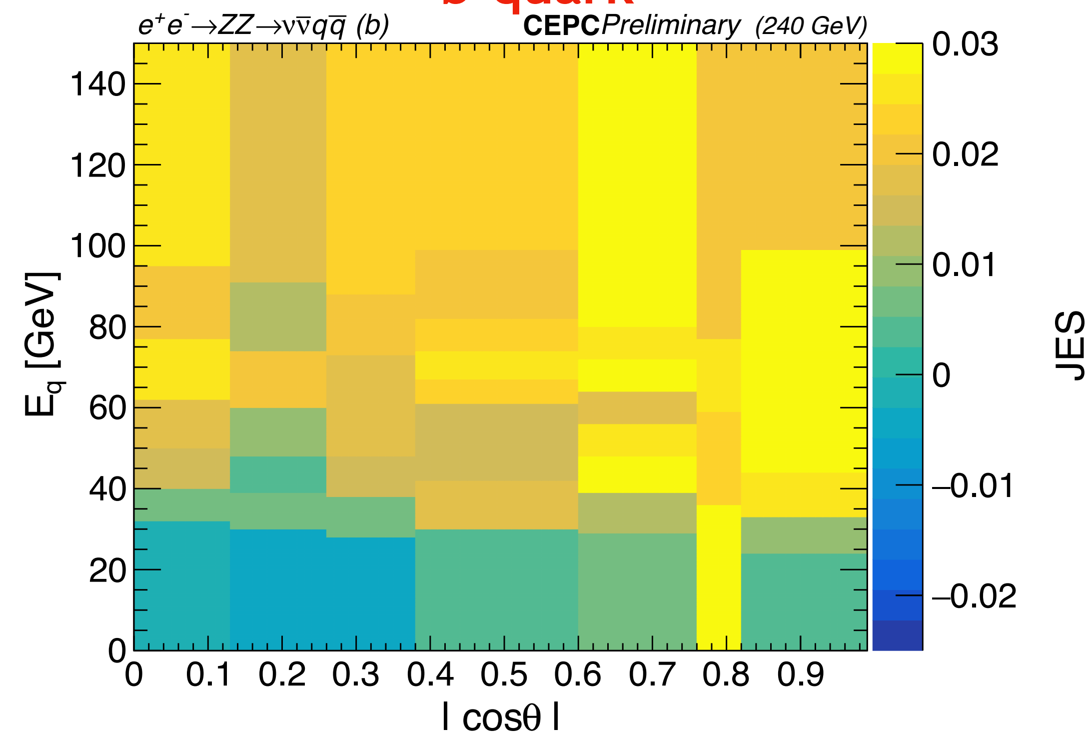
- **JER also depends on the jet flavor.**
- **Higher jet energy and within central region of barrel, JER has impressive performance.**

JES in Phase Space

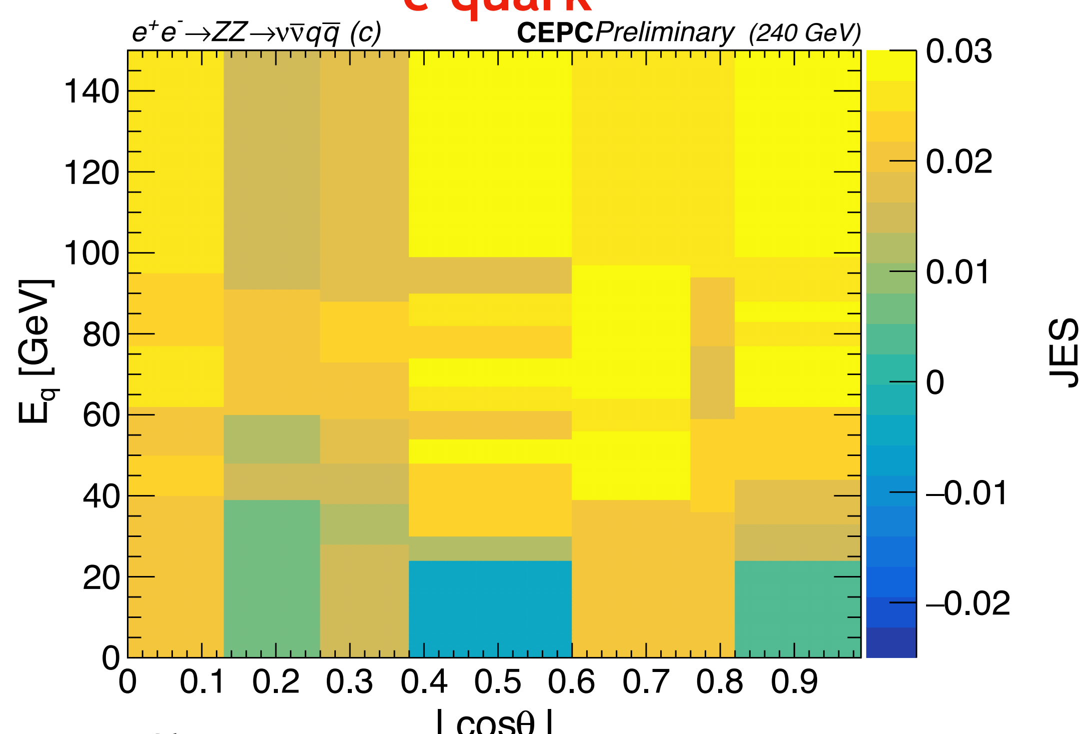
Light flavor



b-quark



c-quark



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