Jet Response at CEPC

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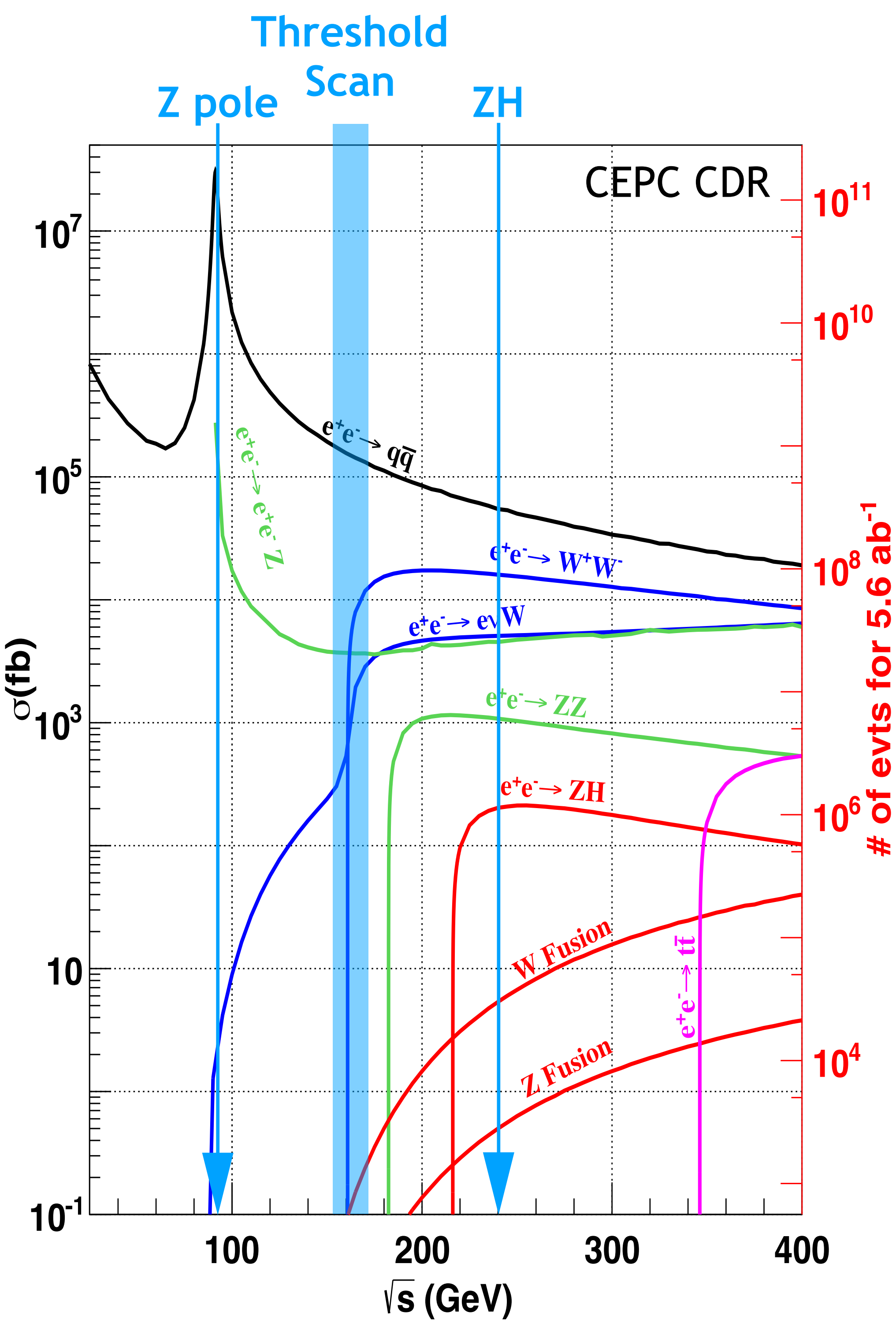
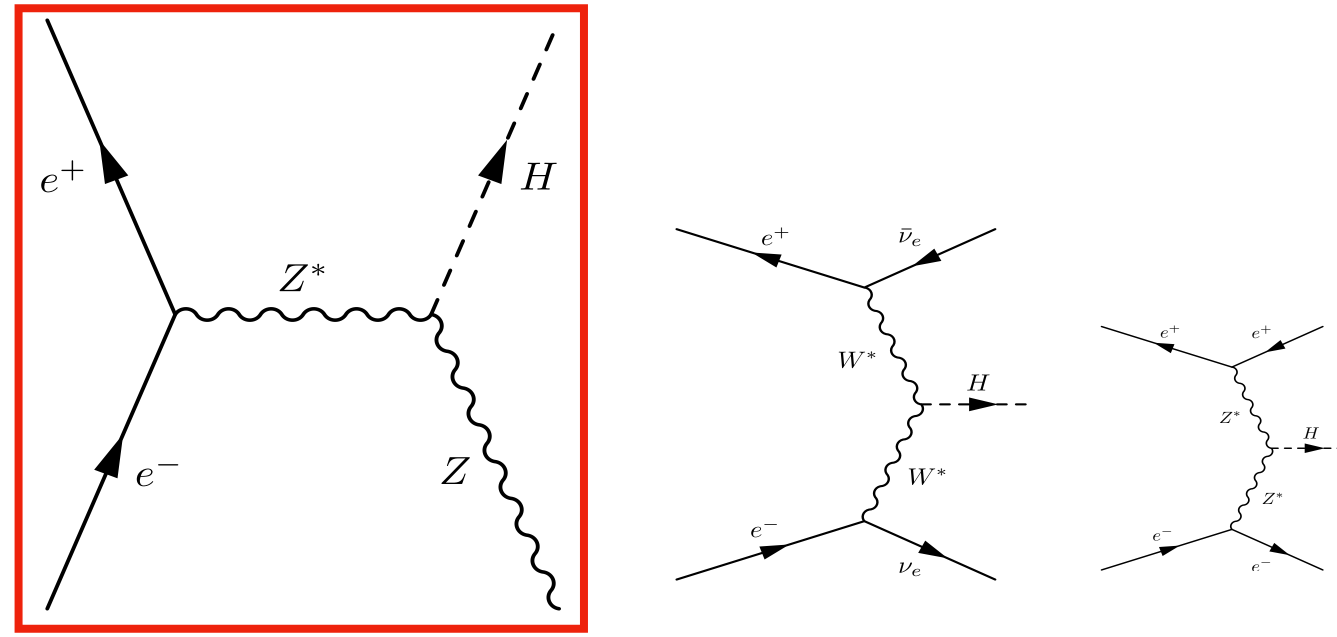
Outline

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

Higgs Production at CEPC



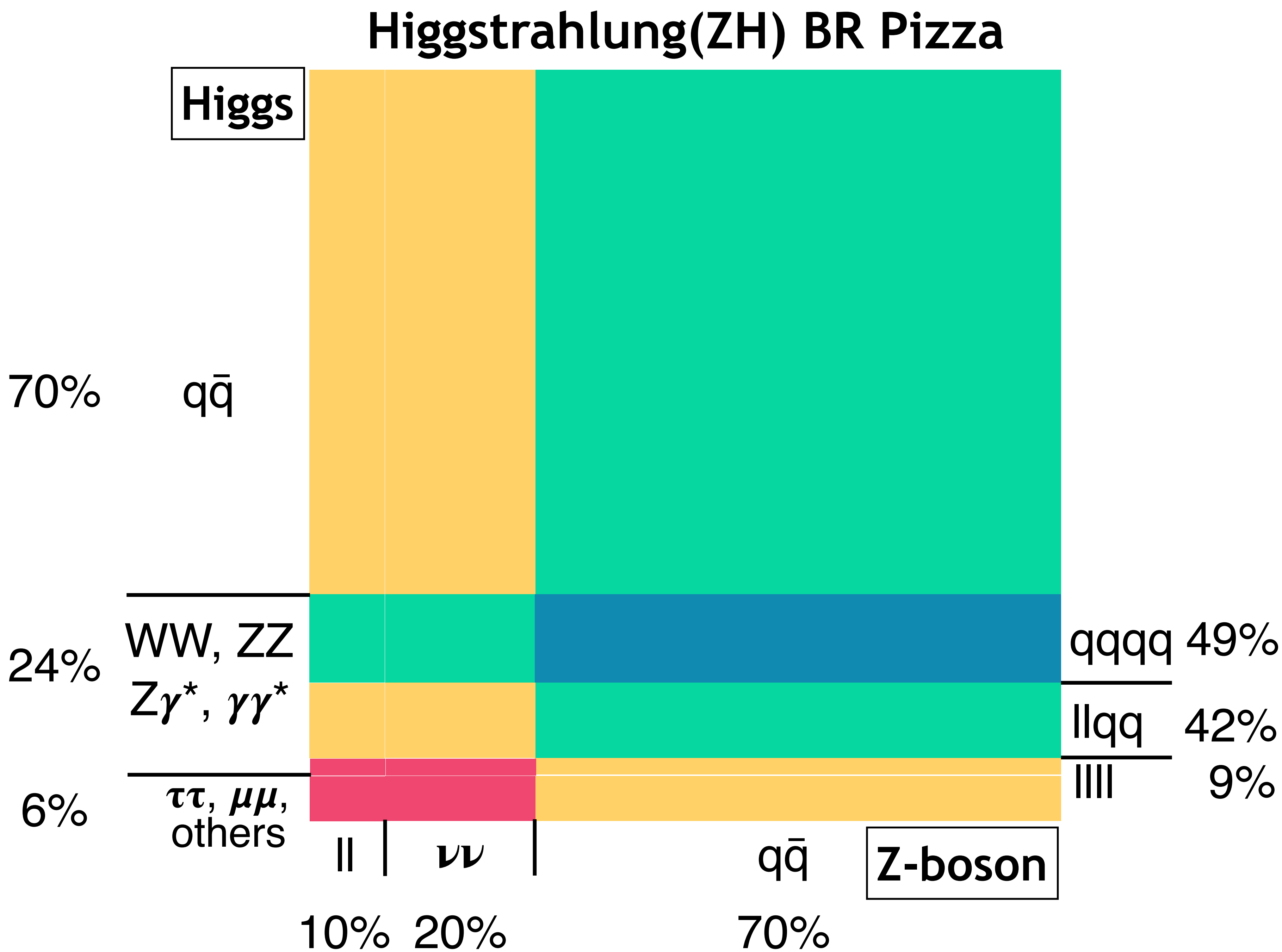


Process	Cross section(fb)	Events in 5.6 ab^{-1}
$e^+e^- \to ZH$	196.2	1.10×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^- \to e^+e^- H$	0.28	1.57×10^3
Total	203.7	1.14×10^6

S : B = 1 : (100 ~ 1000)

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

Jets at the Higgs Signal

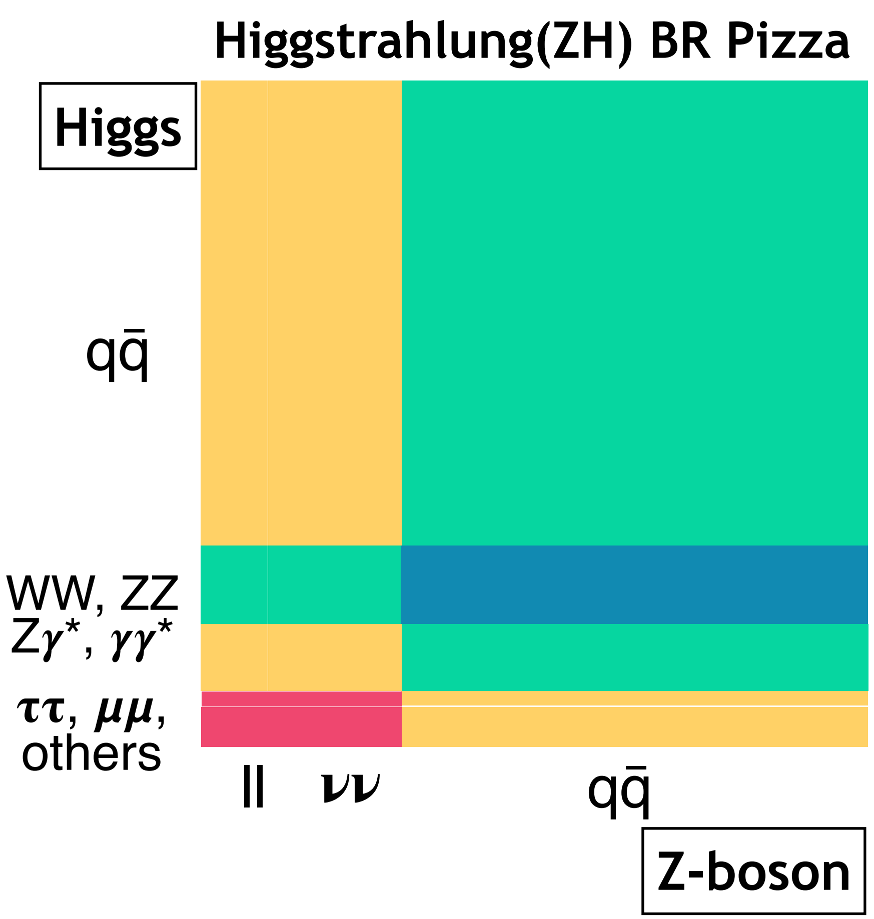


# of jets	Probability
0	2.44%
2	29.73%
4	59.58%
6	8.23%

~ 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 $ZH \rightarrow q\bar{q}q\bar{q}$.
- 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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BM3: Jet energy and angular differential response

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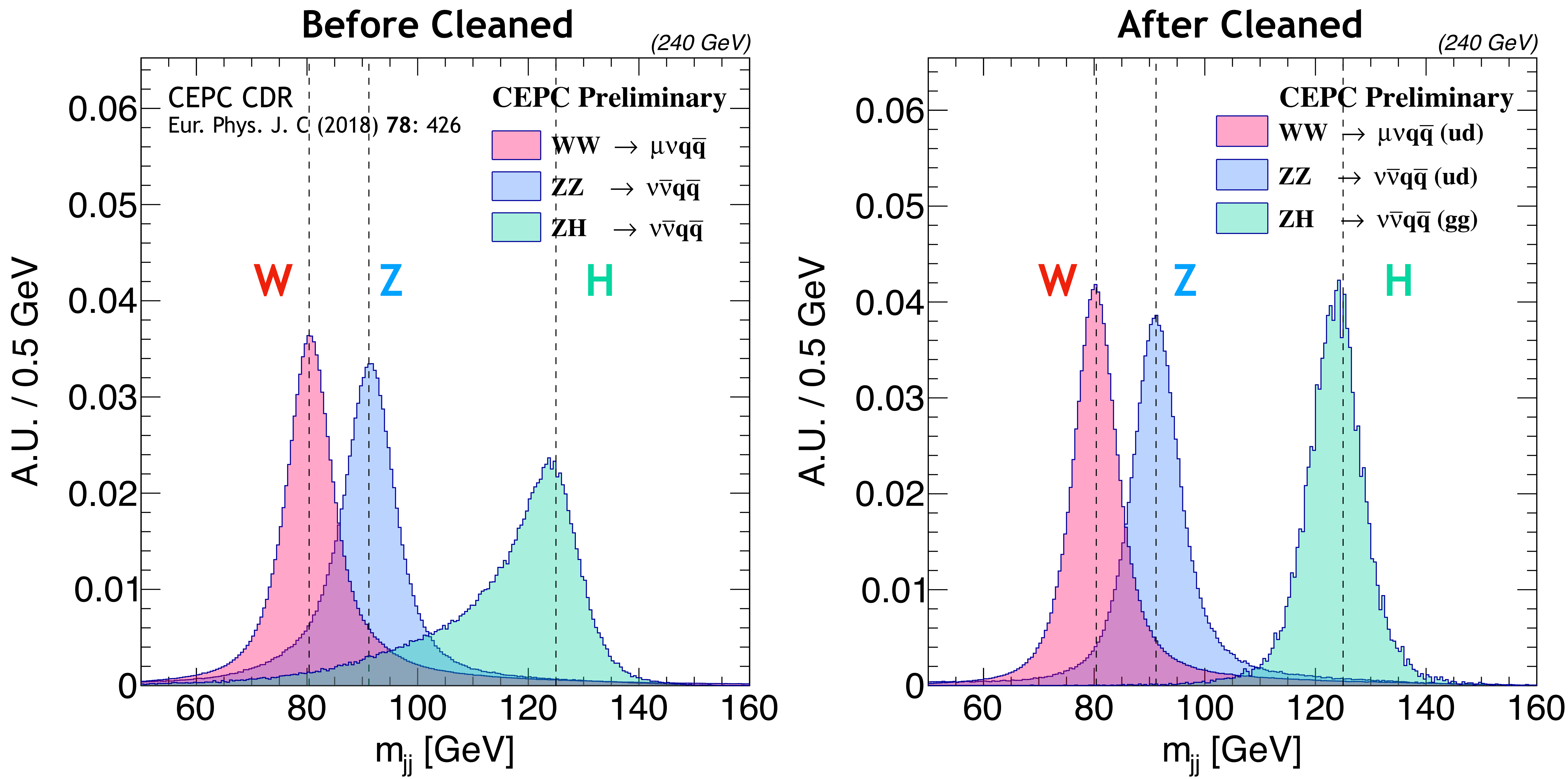
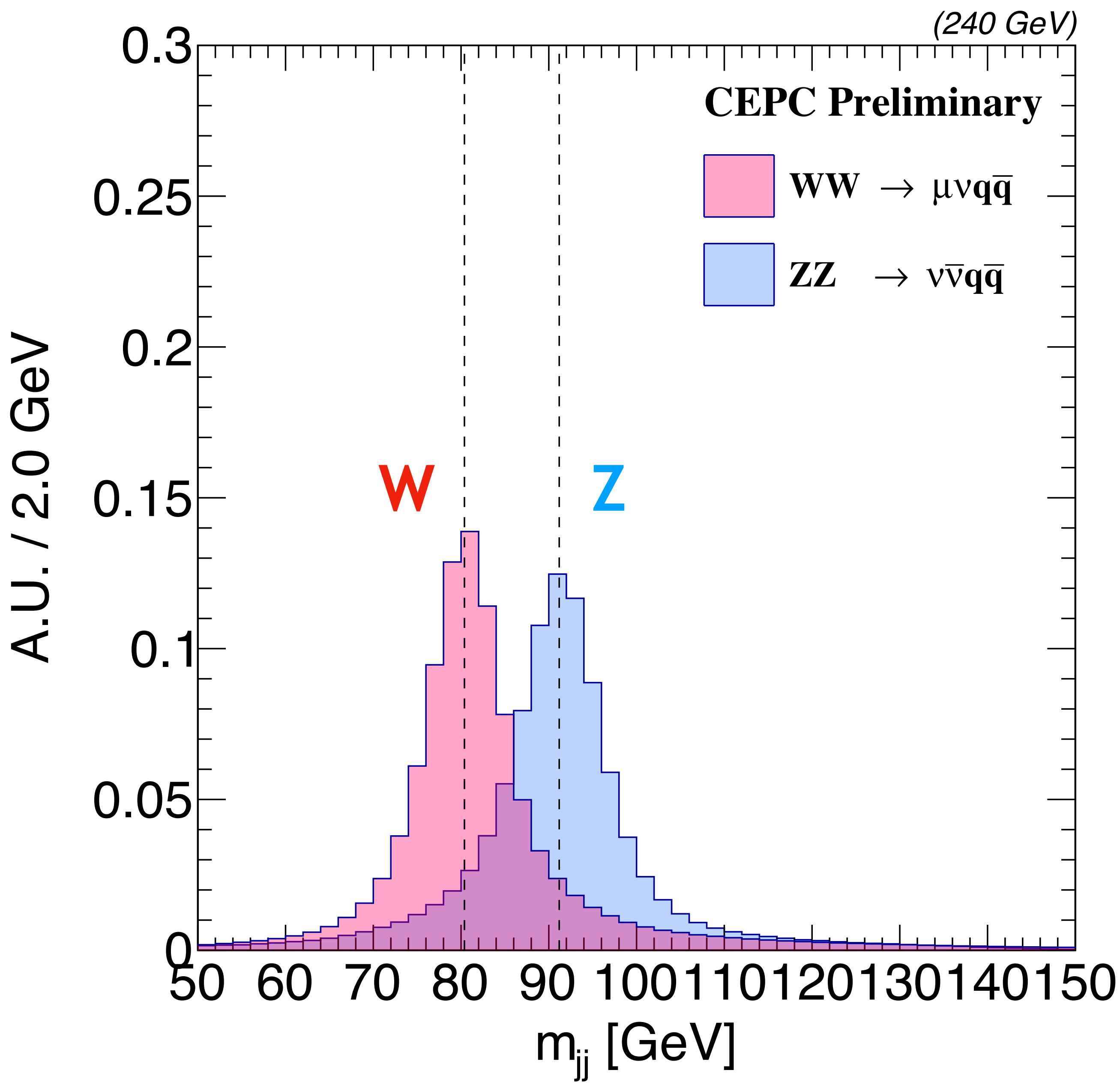
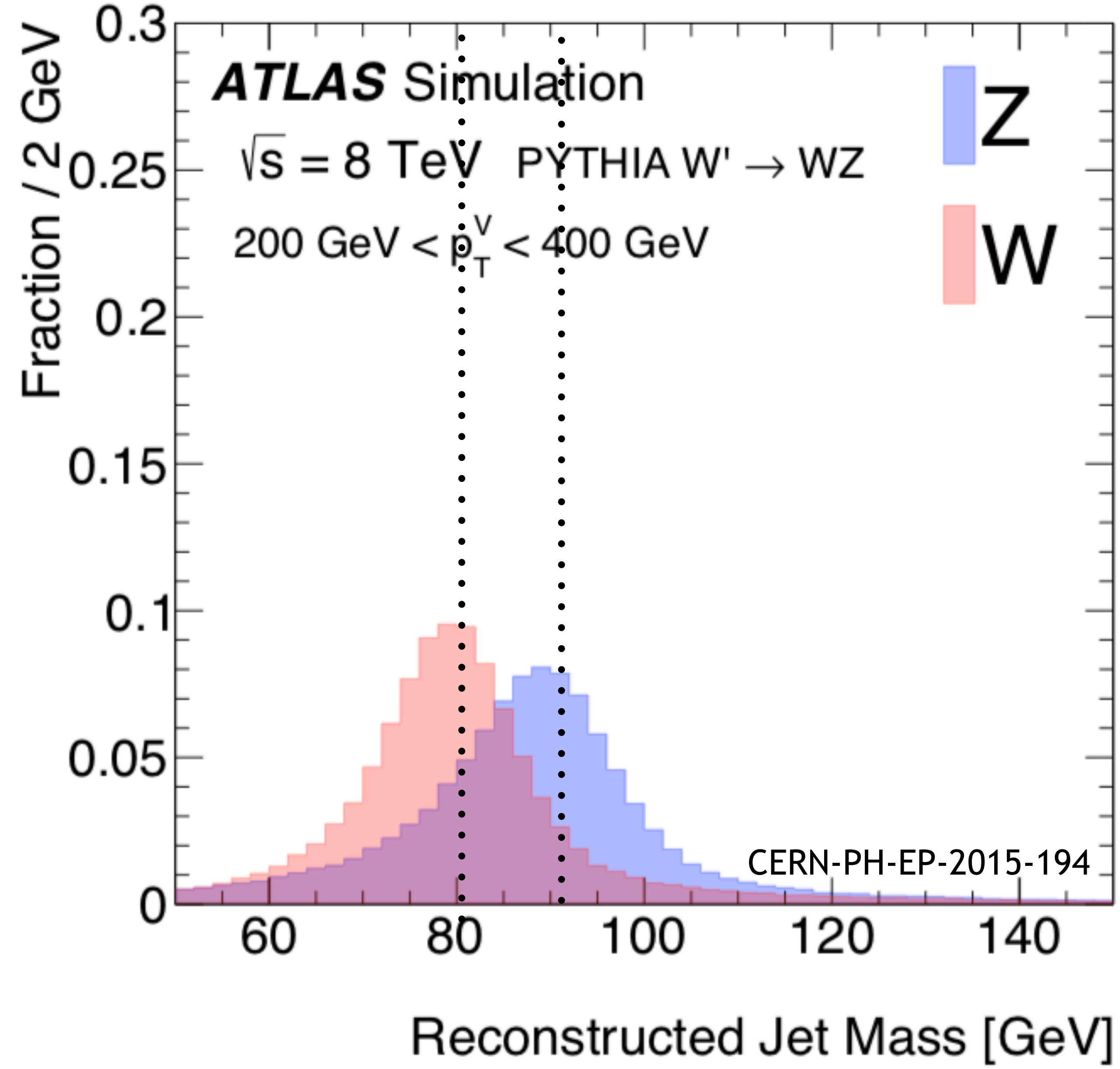


- **W-, Z-, and Higgs-boson masses in dijet final state can be well separated at CEPC.**
- **After cleaned, Z- and W-boson could be separated ≈ 2σ, and the Higgs Boson Mass Resolution = 3.8% achieving the CEPC baseline.**

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

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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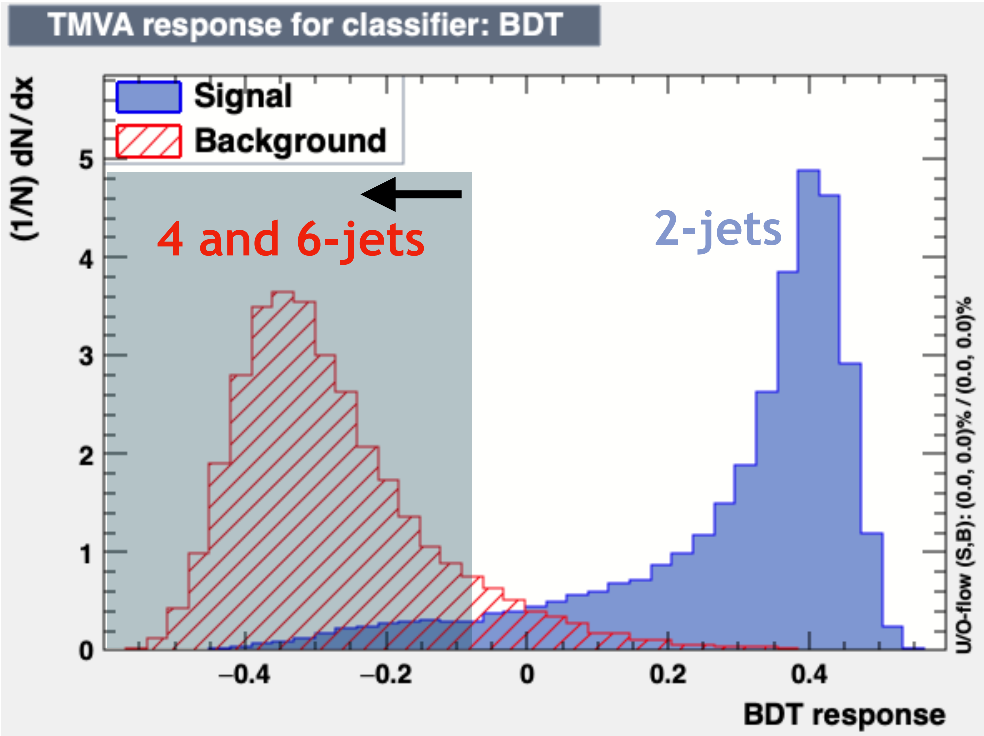
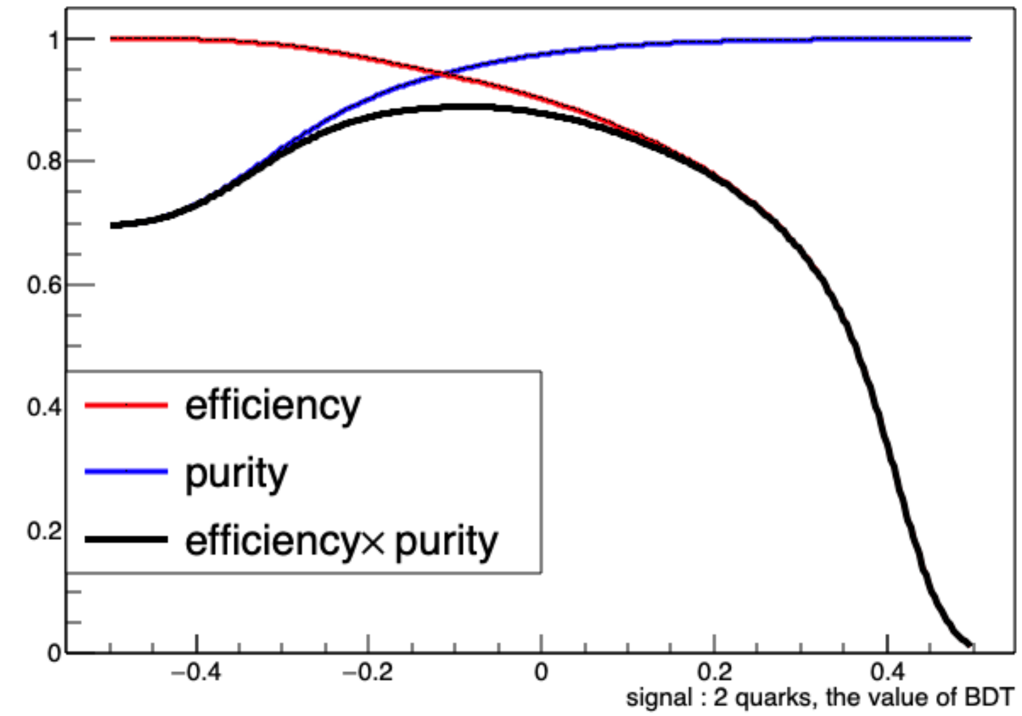
BM2: Preliminary Number of Jet Identification

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)

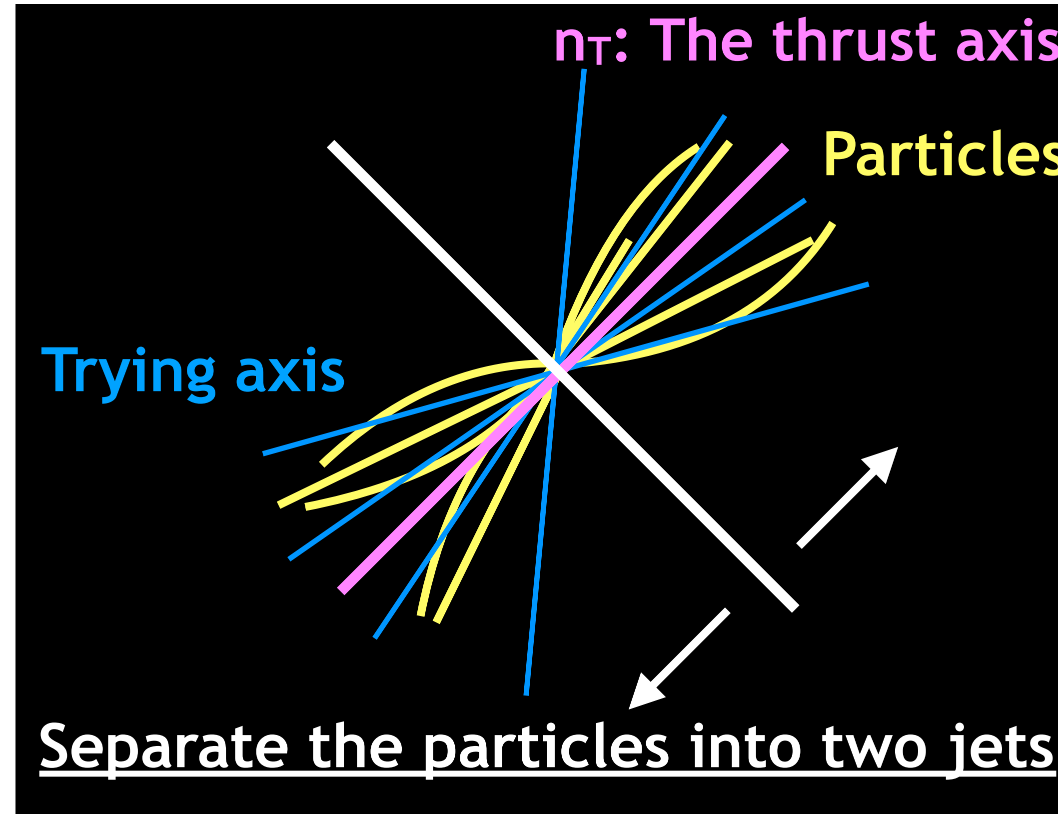
$ZH \to q\bar{q}H \to qqqqqq$ (6 jets)

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.

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 efflux.
  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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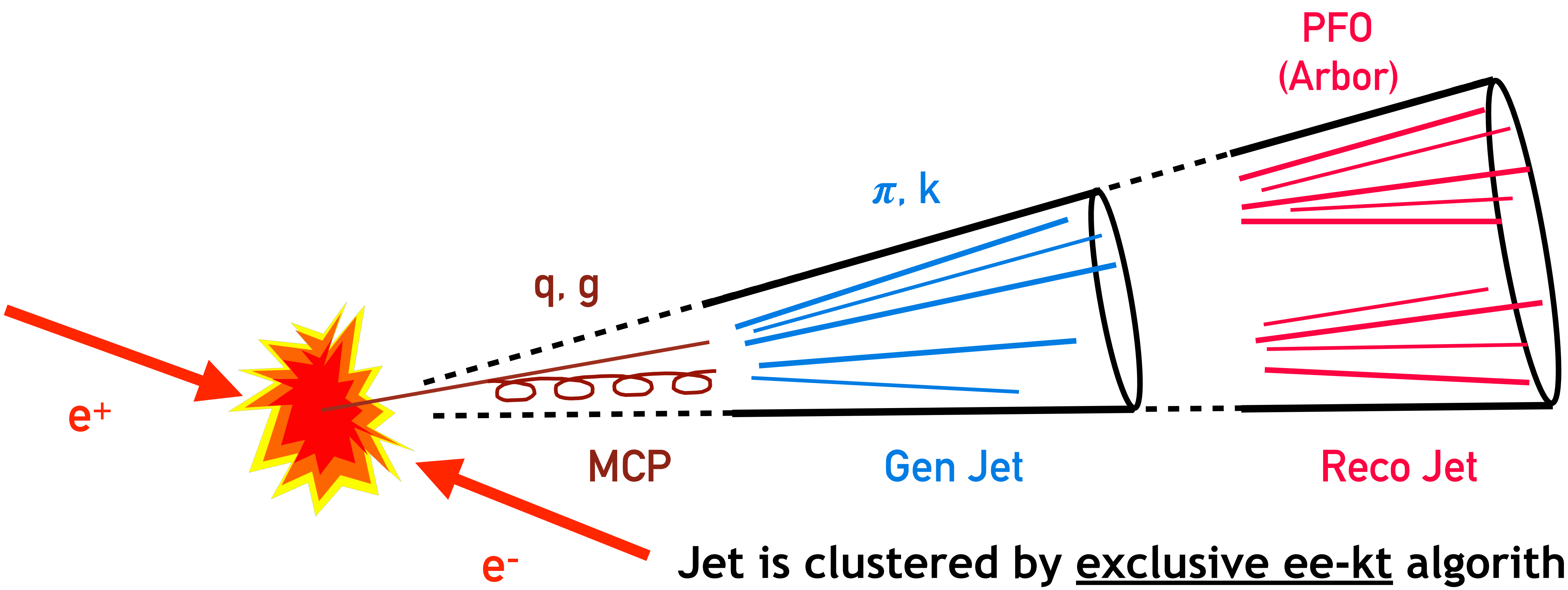
- **Jet clustering is also essential for differential & EW precision measurements (e.g. TGCs).**

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 cτ > 1 cm through exclusive ee-kt jet clustering algorithm.
- **RecoJets** are grouped with the particle flow objects by exclusive ee-kt jet clustering algorithm.

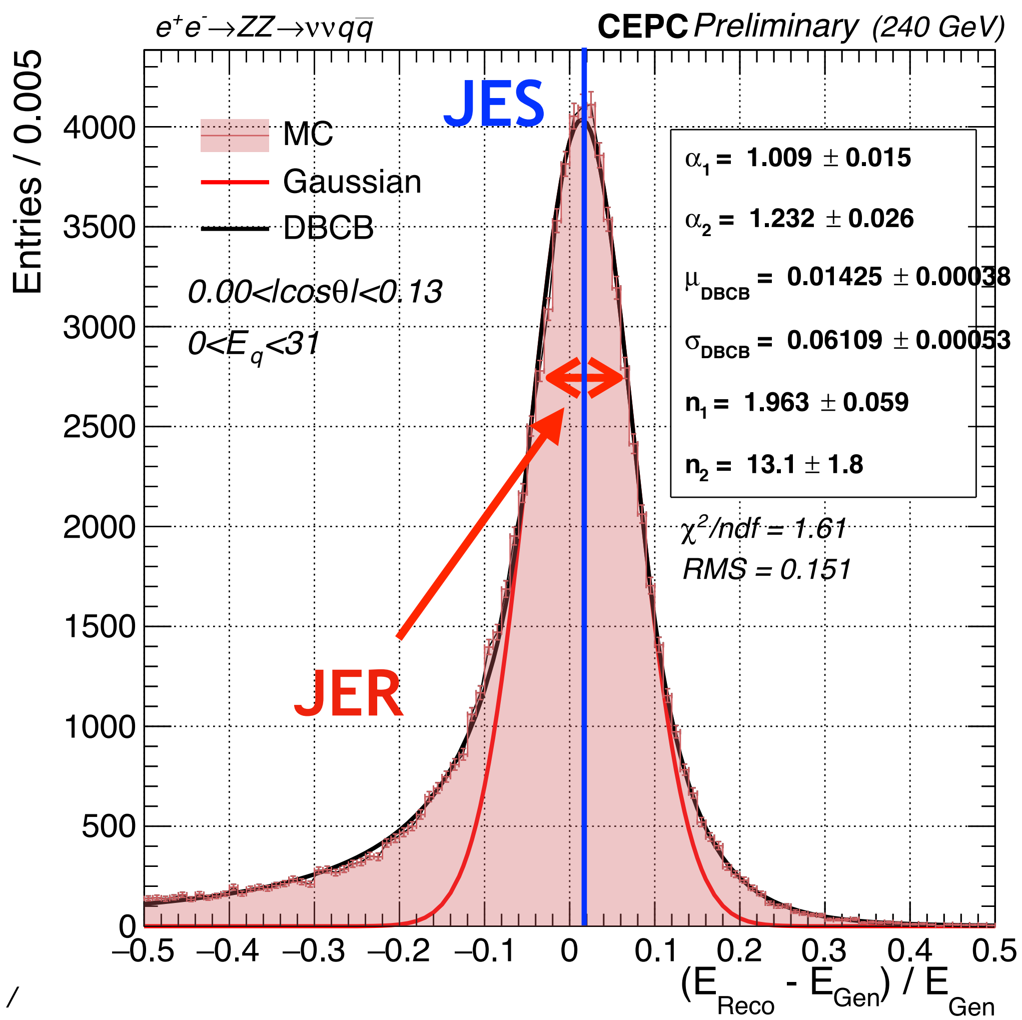


Jet is clustered by exclusive ee-kt algorithm.

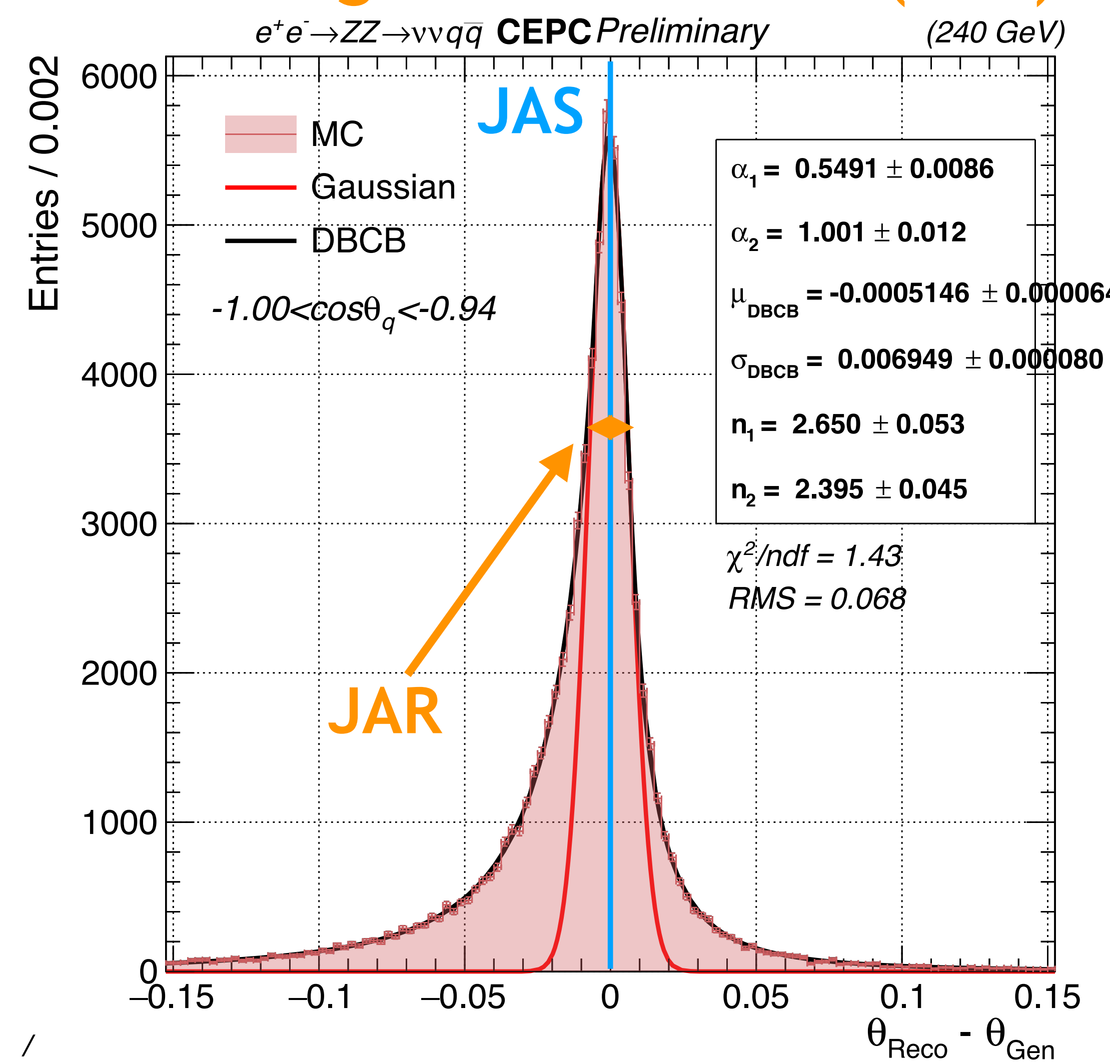
Quantify the Performance

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

Jet Energy Scale (JES)
Jet Energy Resolution (JER)



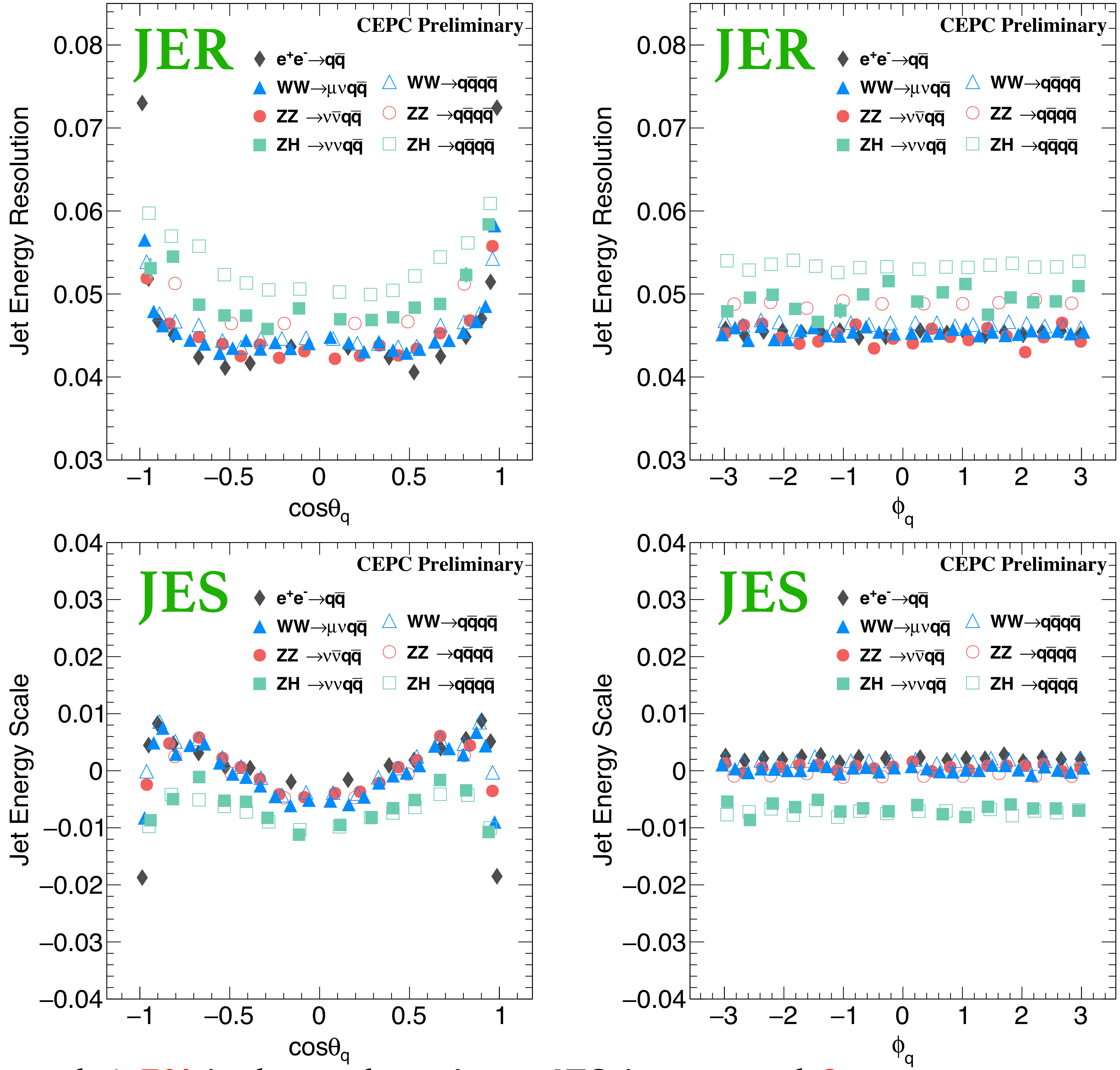
Jet Angular Scale (JAS)
Jet Angular Resolution (JAR)



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

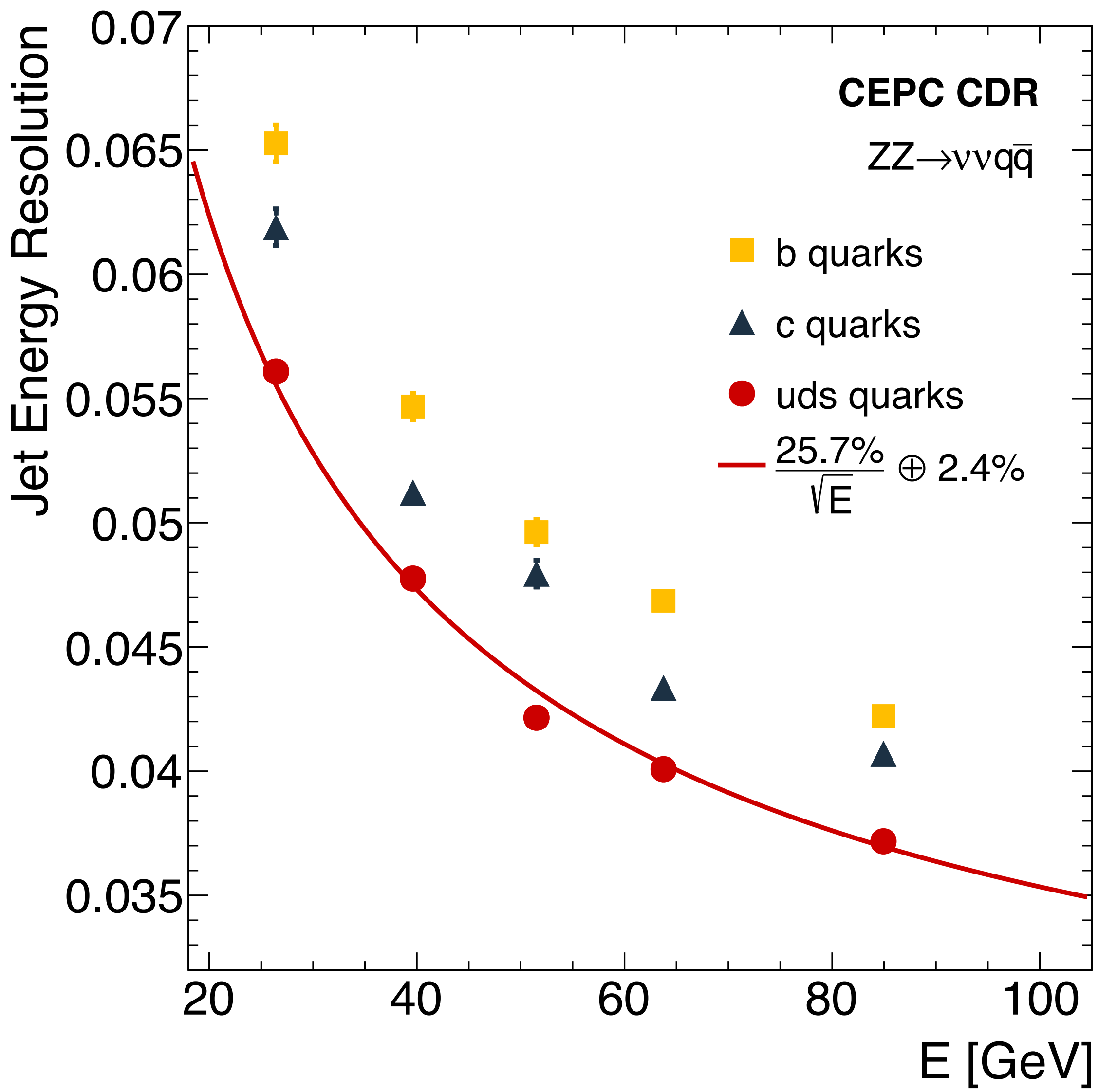
Difference : $\theta_{Reco} - \theta_{Gen}$

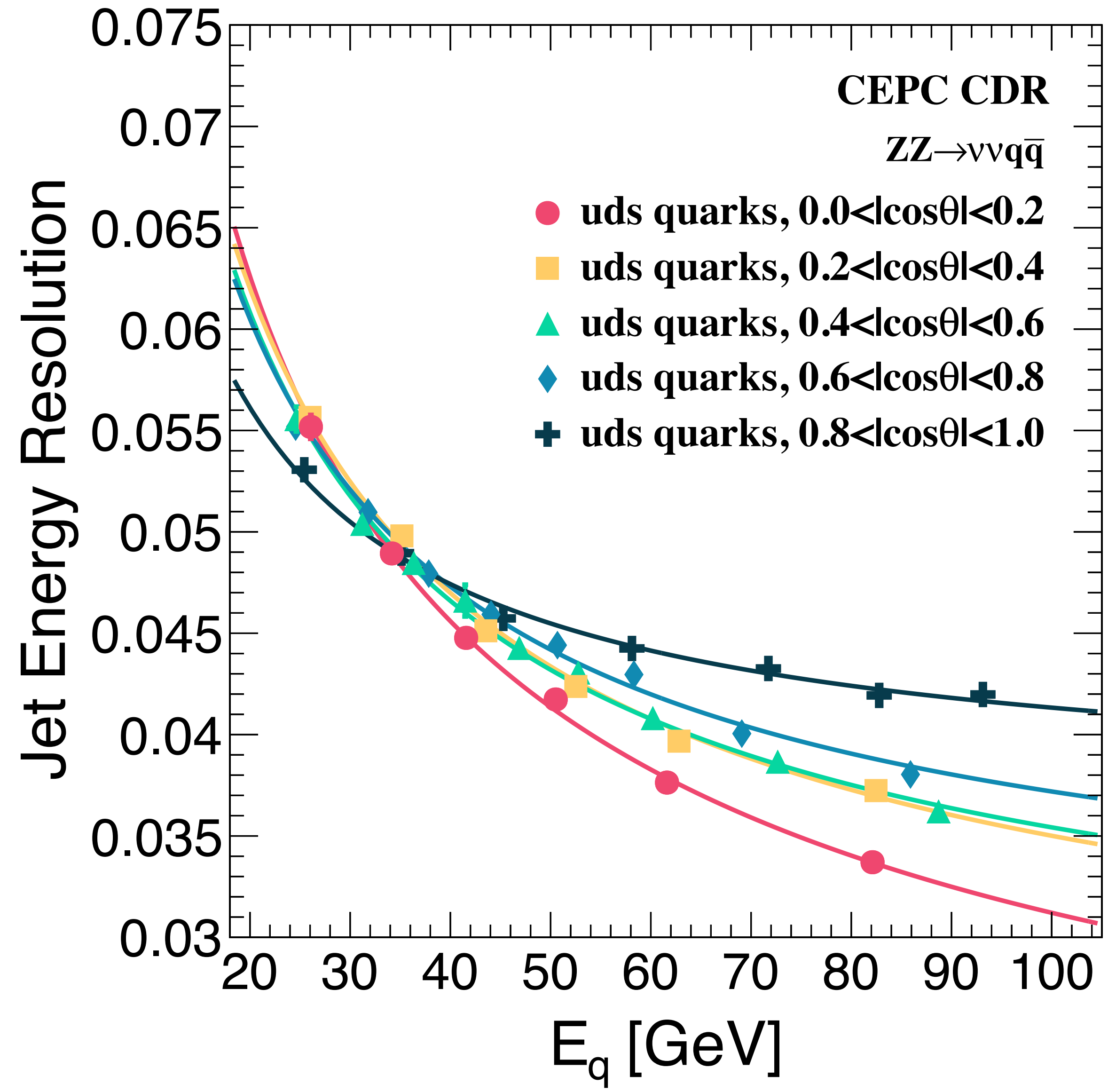
BM3: JER & JES (Reco-Gen)



- 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.

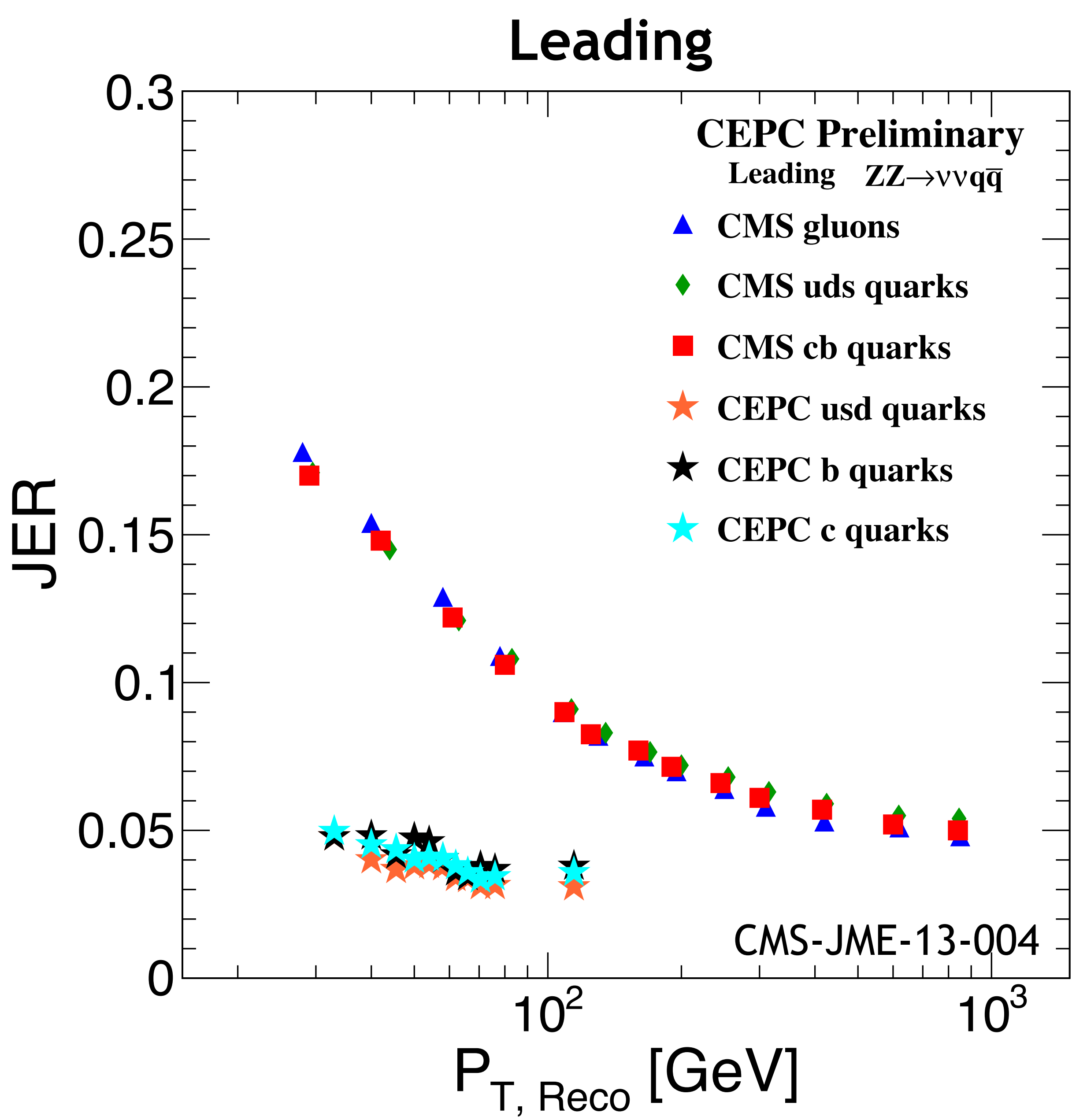
BM3: JER (Reco-Gen)

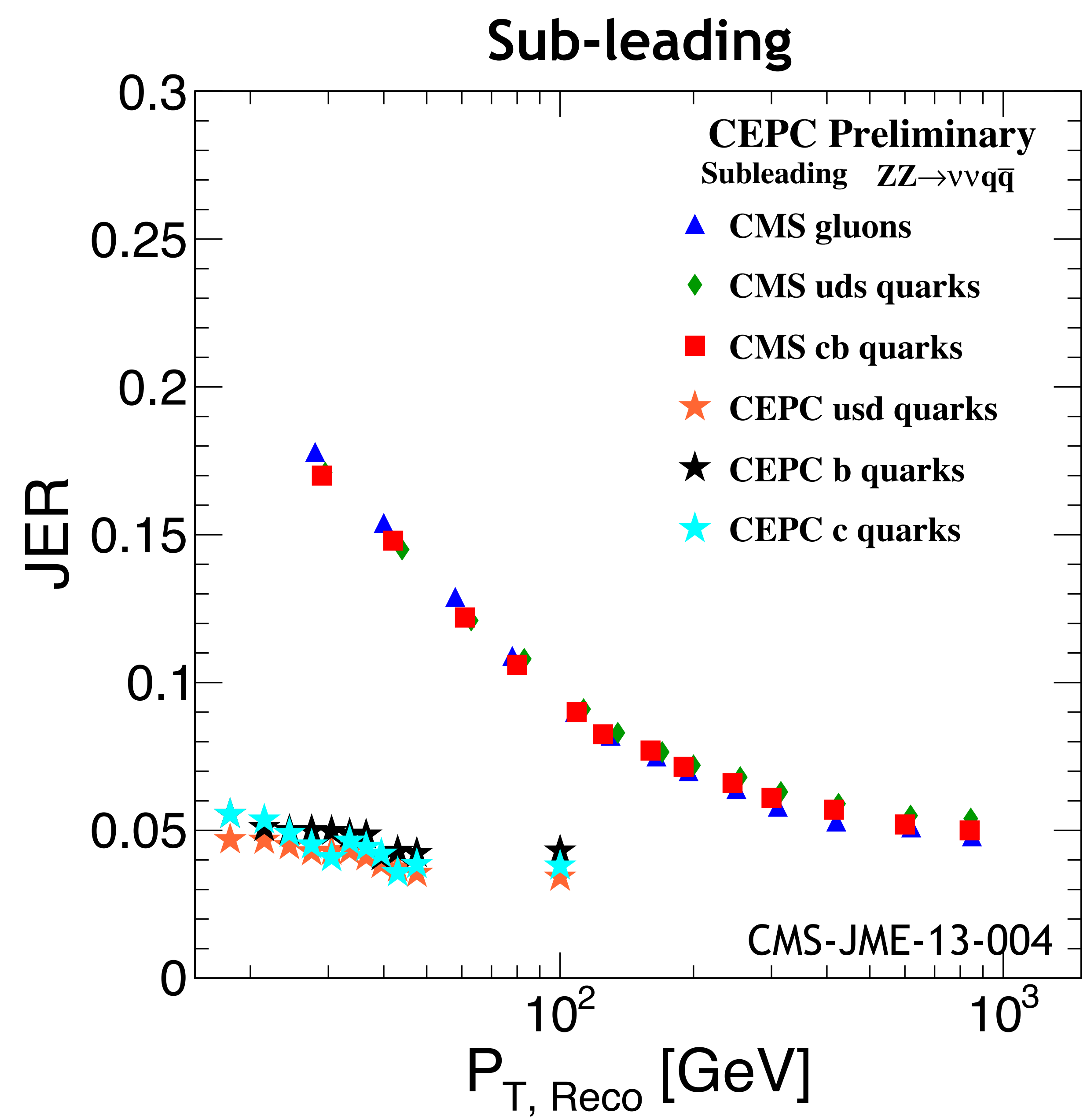




- **JER also depends on jet flavors.**
- **For light-flavor jets with high energy and within central region of barrel, JER could reach 3%.**

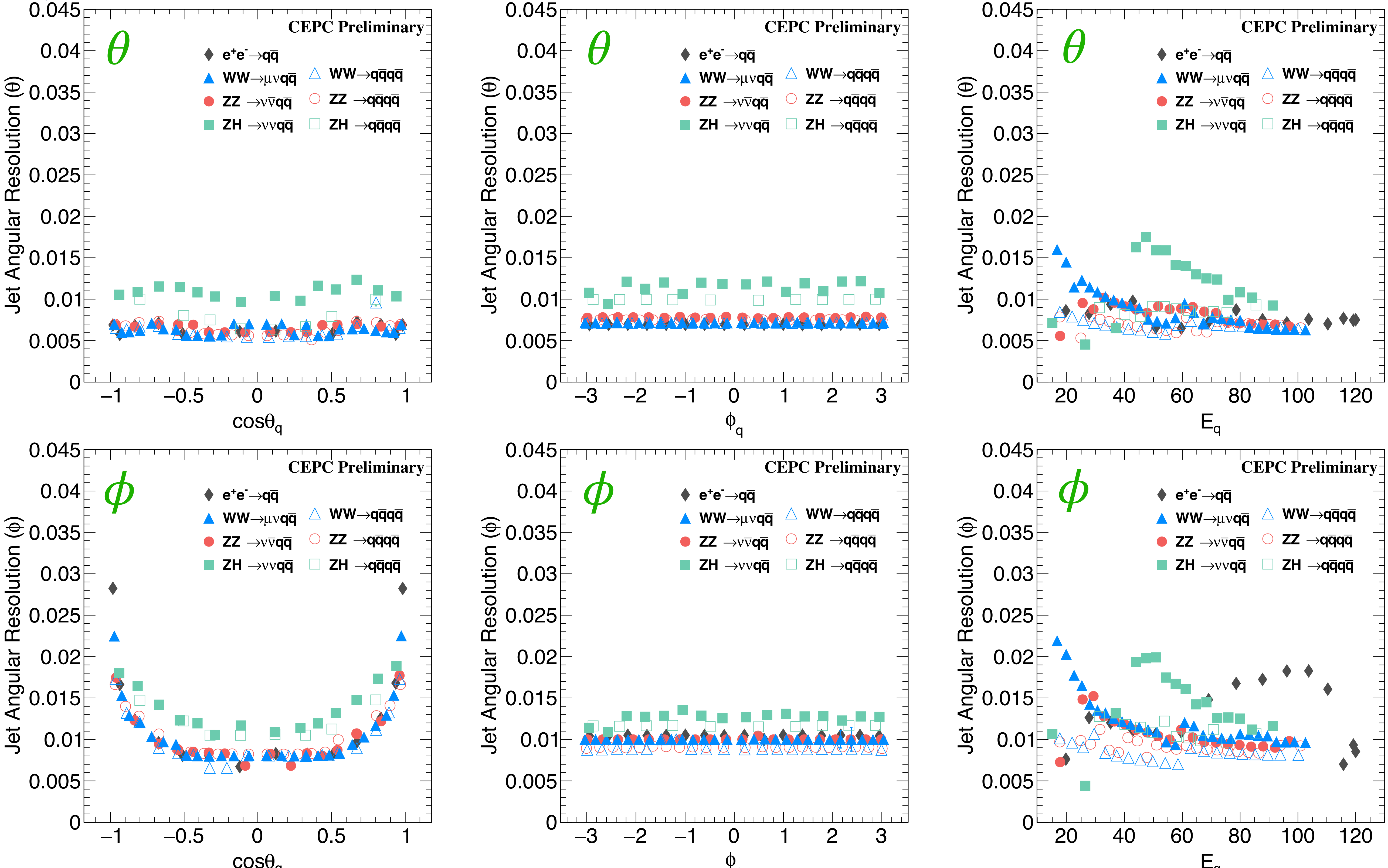
Compare to CMS at LHC





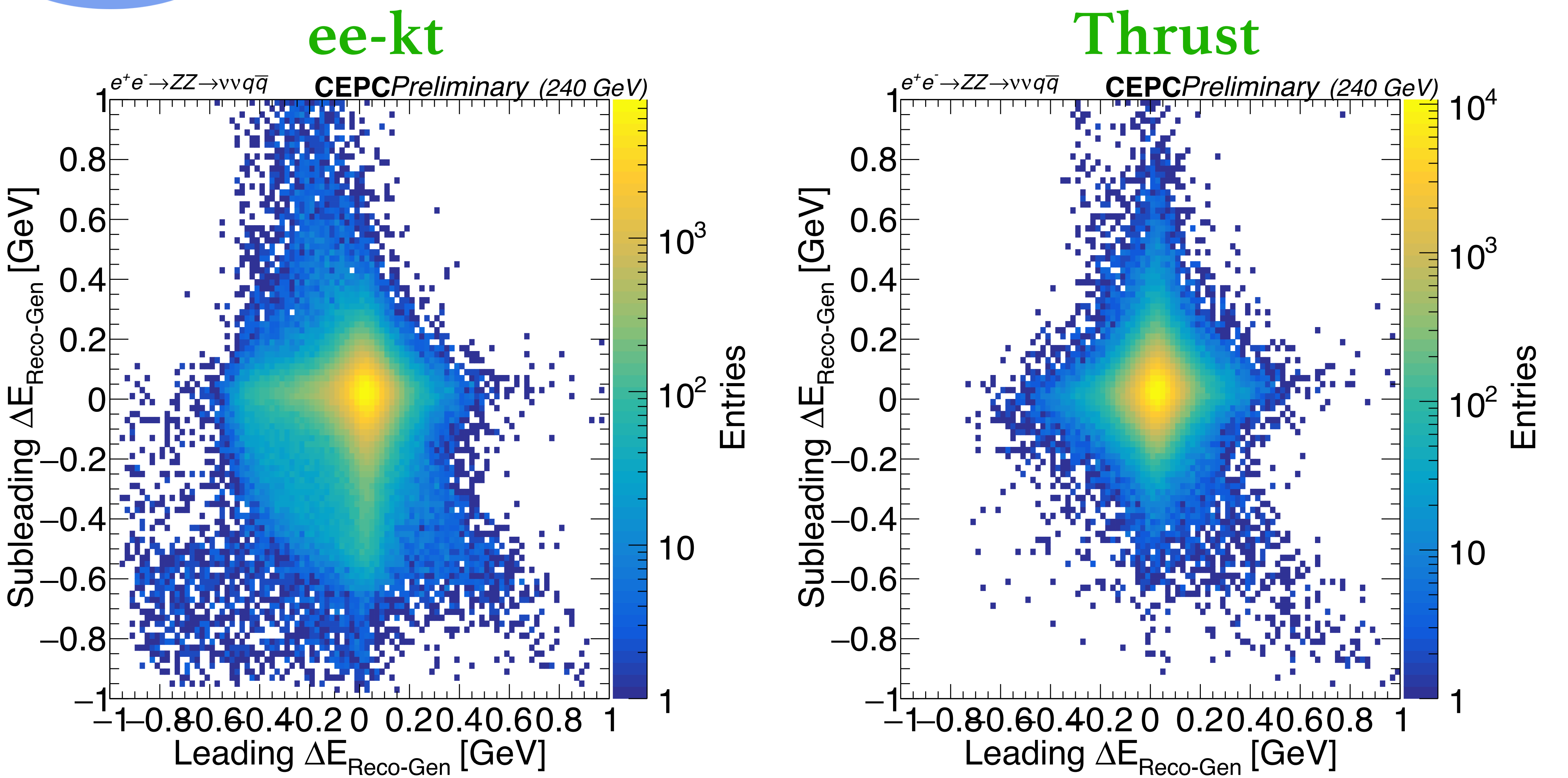
- JER at CEPC is better than CMS as it should be; 2-4 times better in the same energy region.

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.

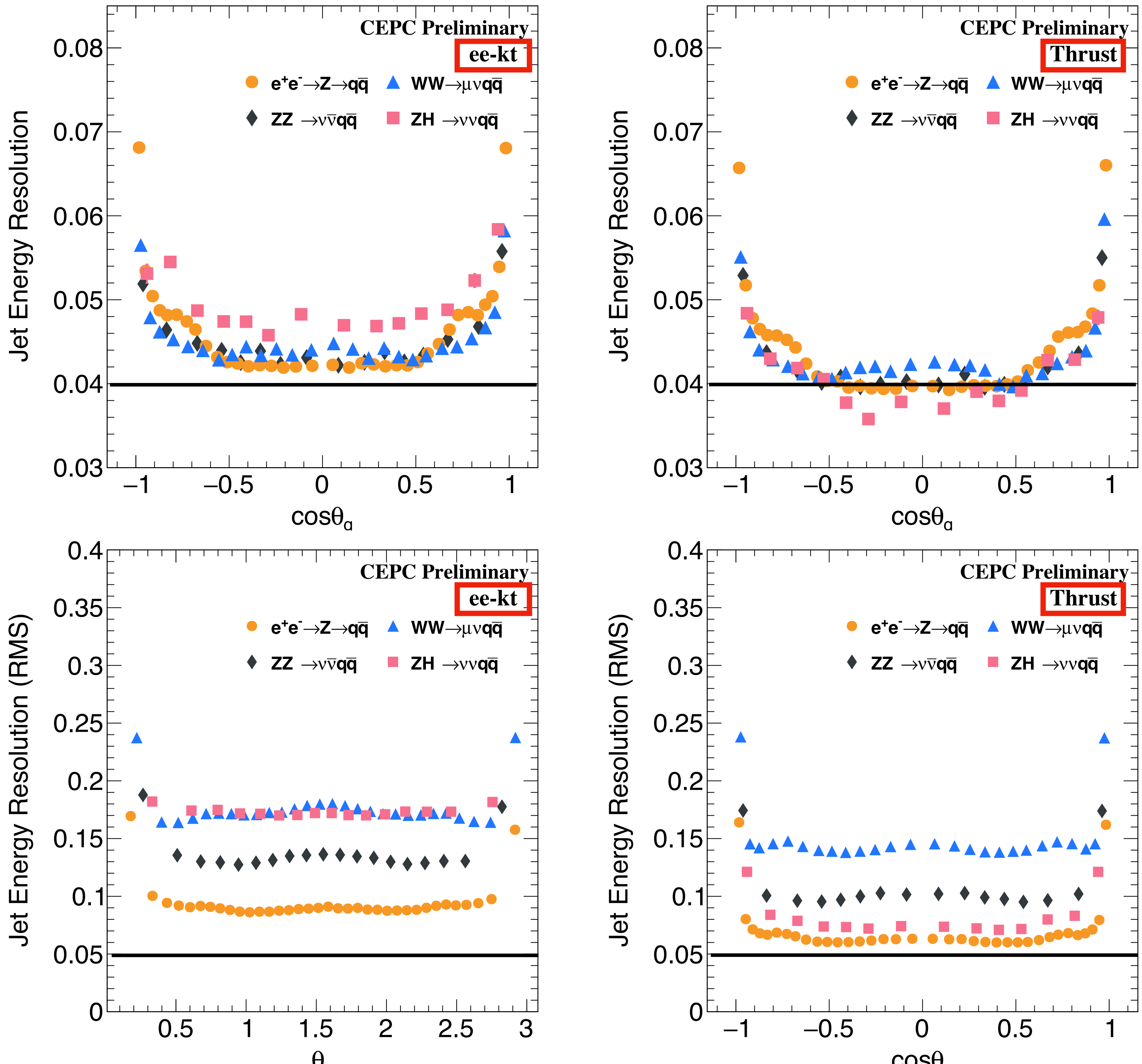
BM3: Thrust Jet Clustering Method



- **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 |cosθ| < 0.85.

BM3: JER (ee-kt—Thrust)

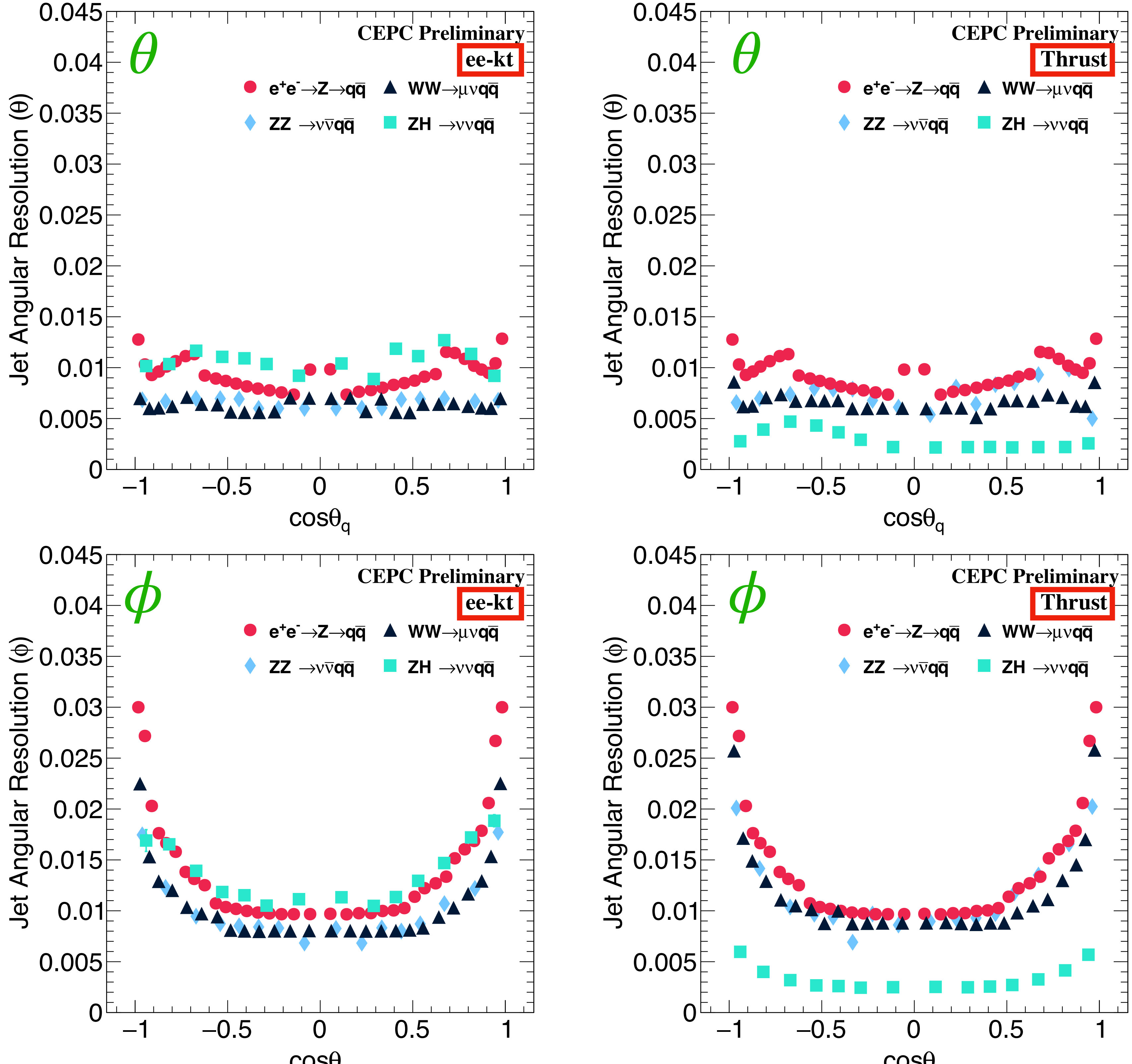


Improved 20% w.r.t ee-kt

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

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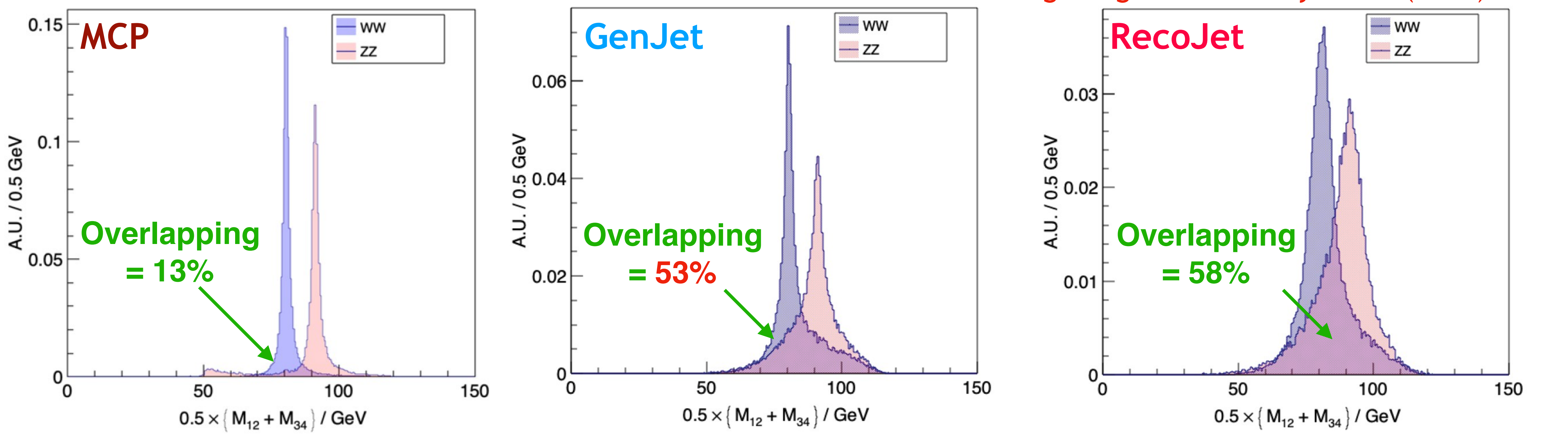
BM4: WW & ZZ to 4 Jets Separation

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



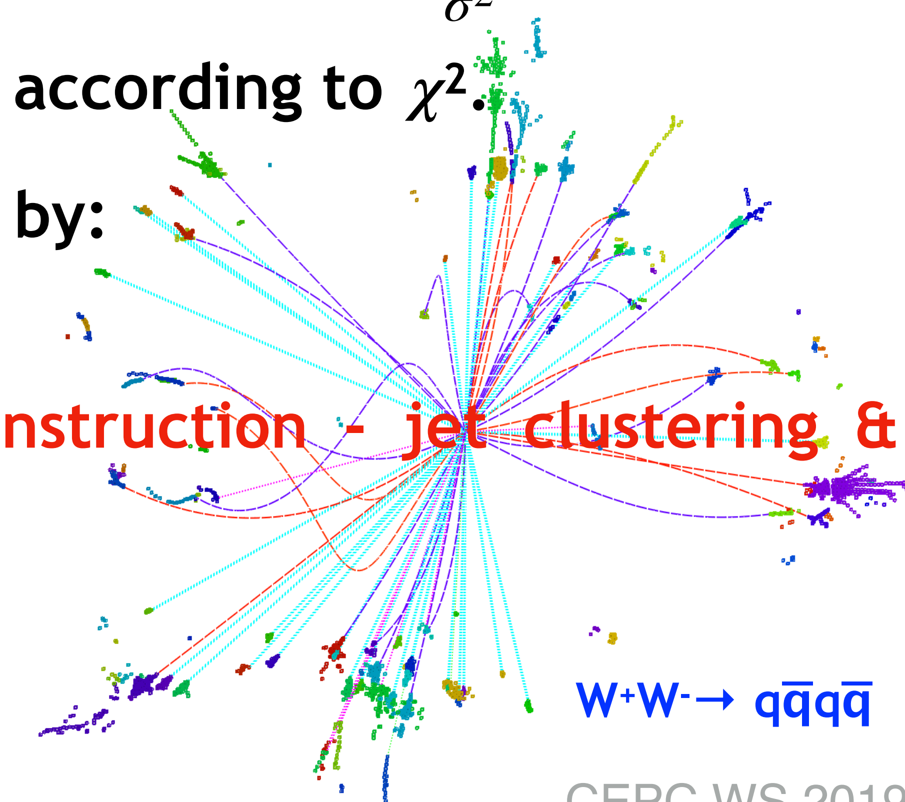
- Low energy jet (20-120 GeV)
- Typical multiplicity could be 10^2.

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

- 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%

5%



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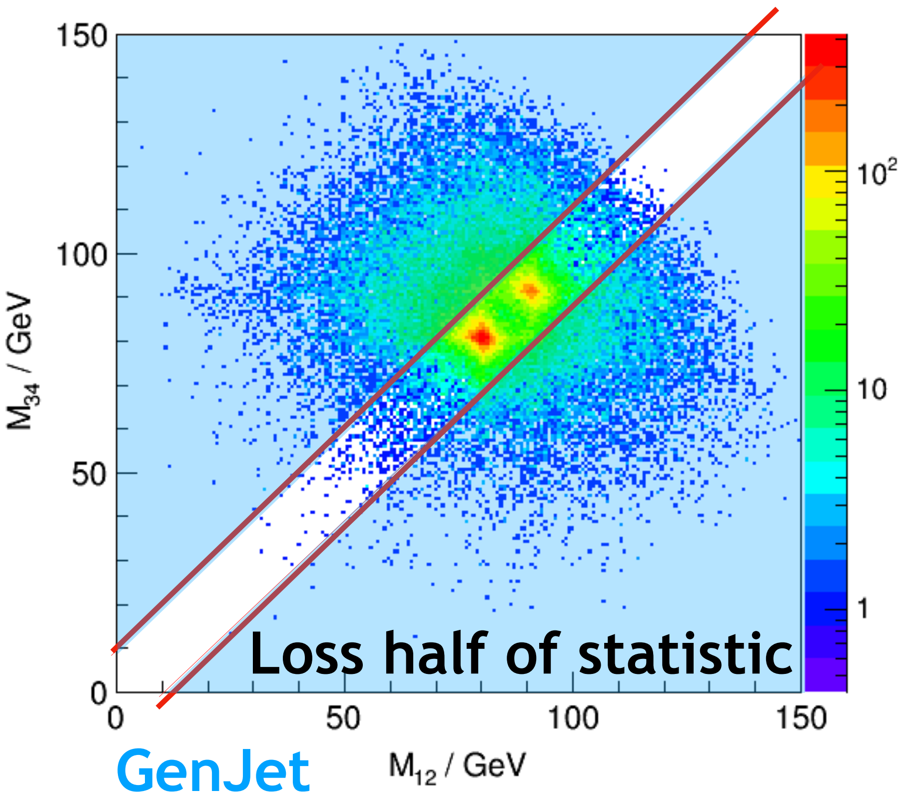
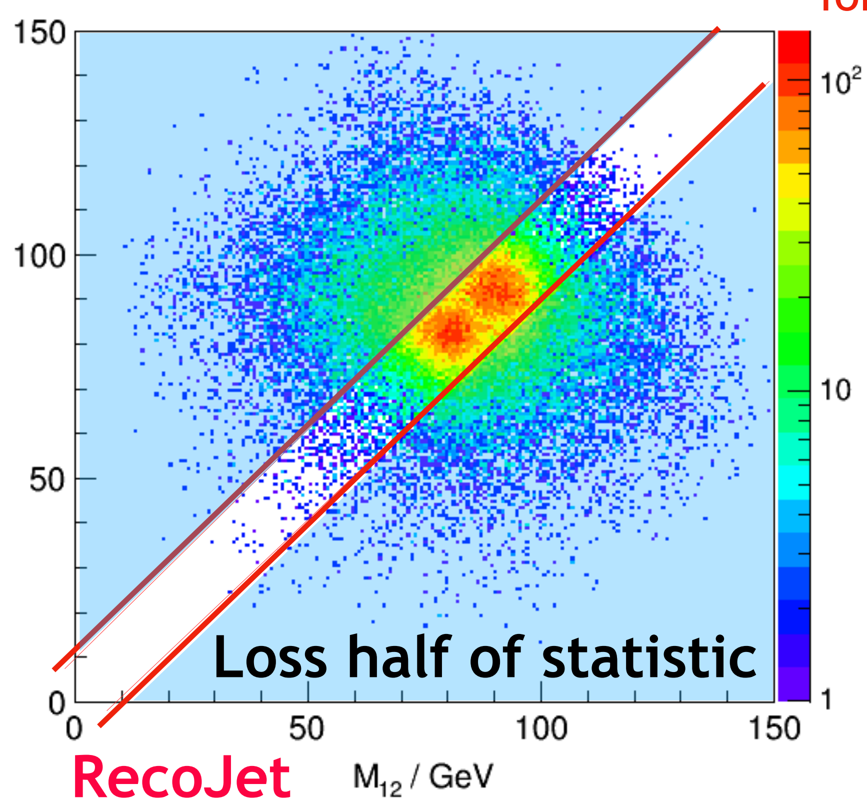
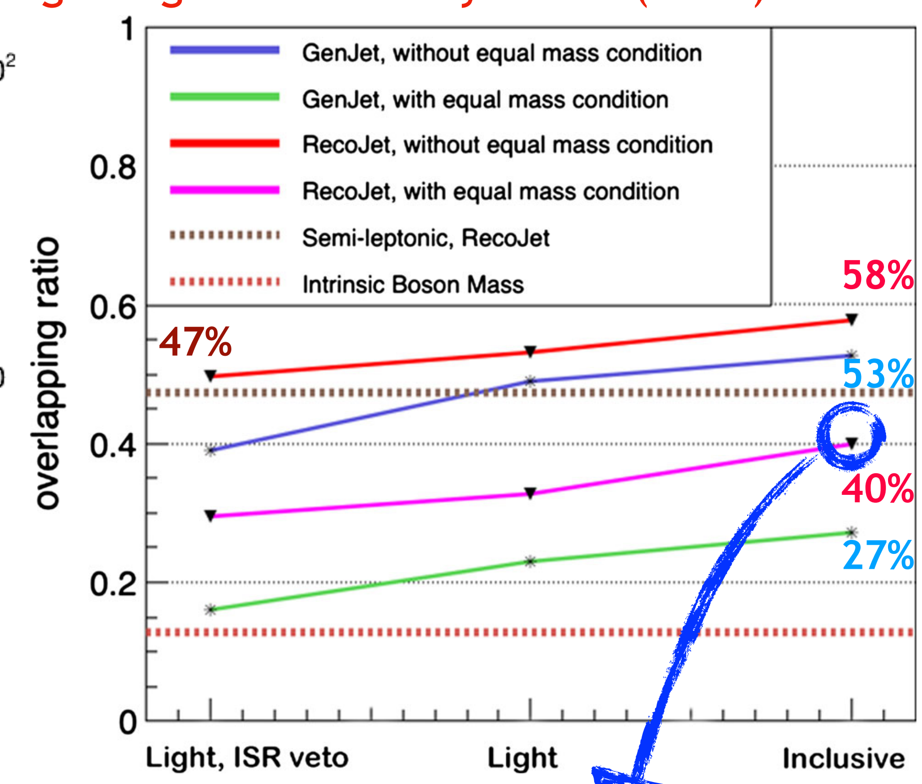
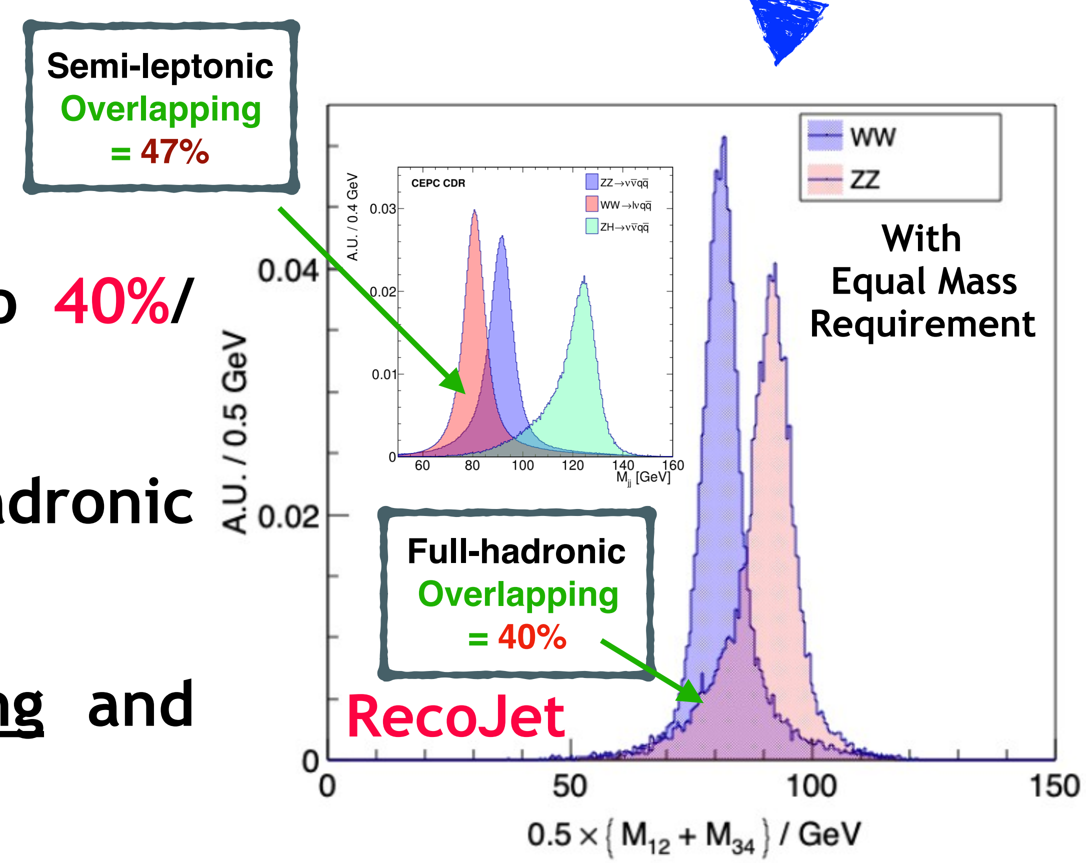






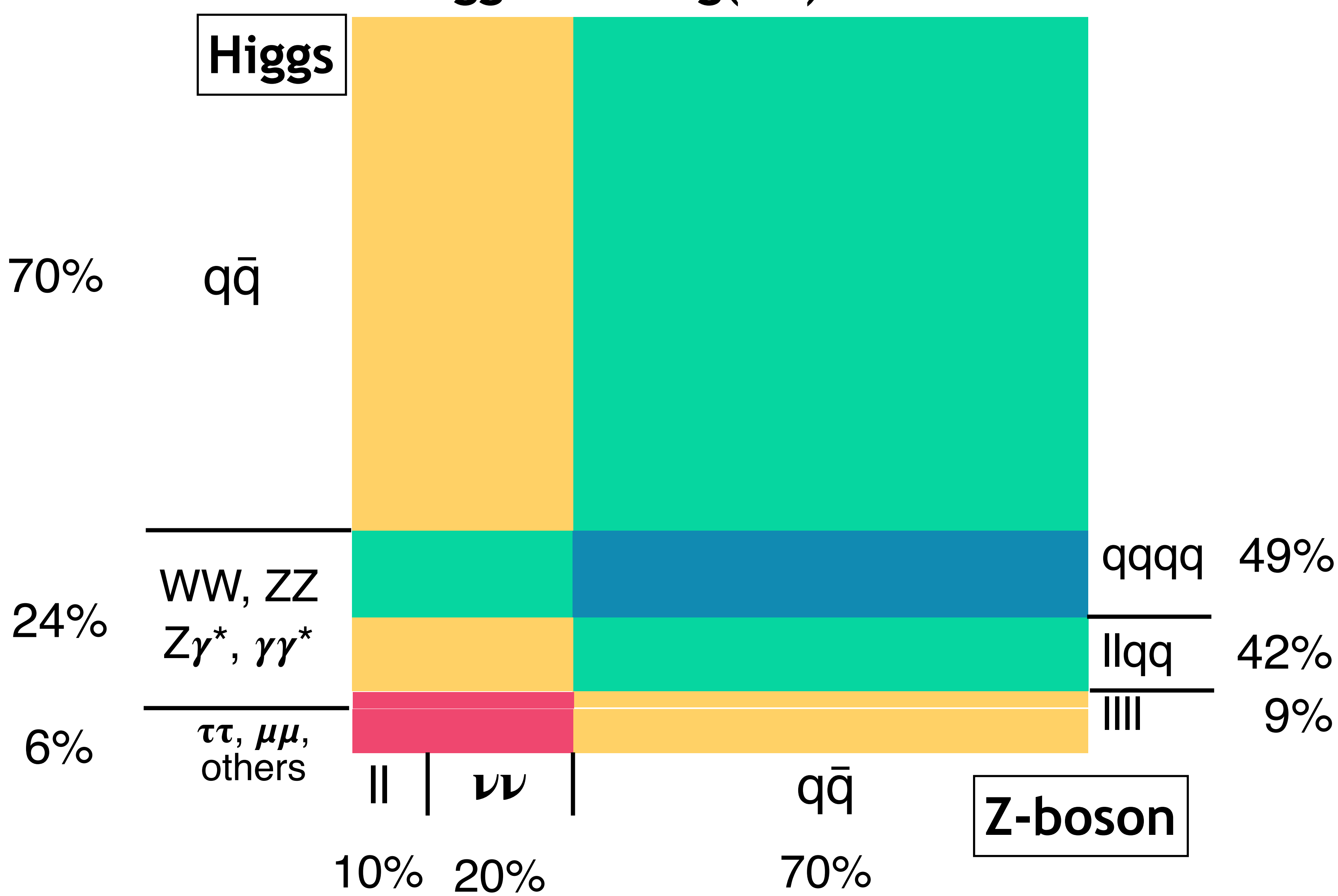


- Equal mass requirement: $|M_{12} - M_{34}| < 10$ GeV
  - Cost half of the statistic.
  - Overlapping can be reduced from 58%/53% to 40%/27% for the RecoJet/GenJet.
- CEPC baseline could separate WW & ZZ with full hadronic final-state.
- Improve from the naive jet clustering & pairing and control the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

Summary(1/2)

- **Jets are crucial for the CEPC Higgs physics**
  - 97% of ZH events evolve 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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2/3

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

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

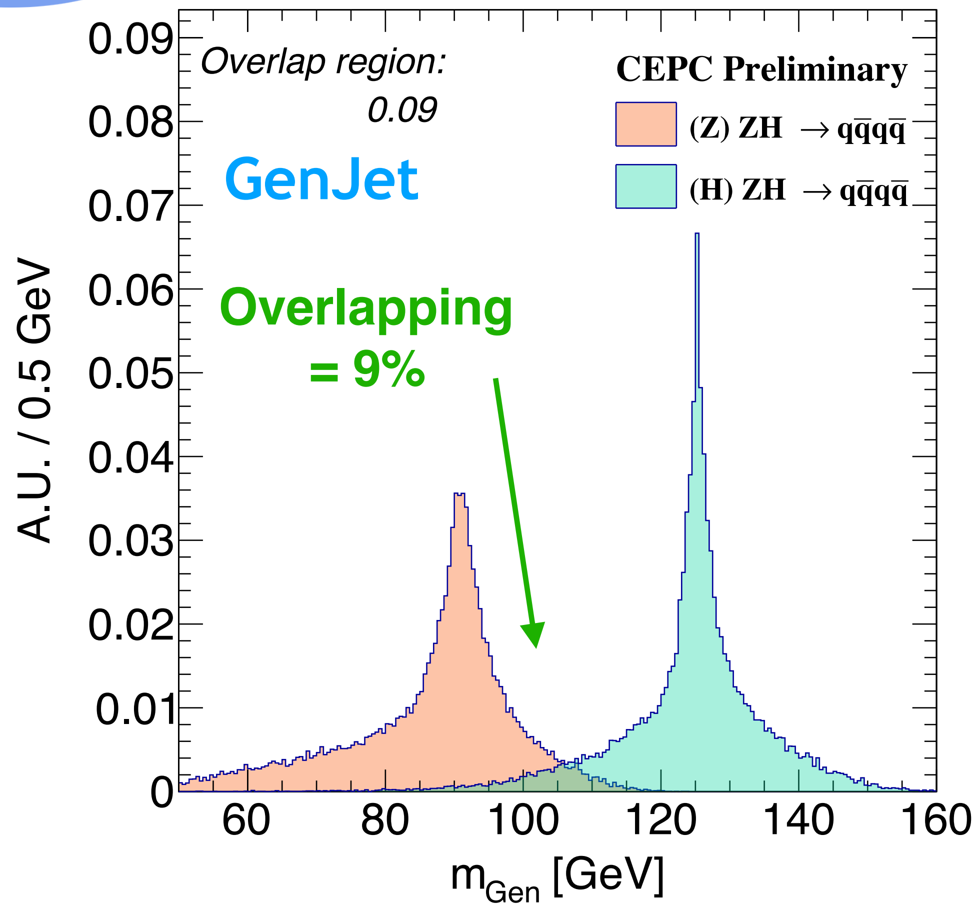
III. **Single Jet — JER ~ 3-5% & JAR ~ 1%.**
   - Thrust clustering method is recommended for two jets final-state. It improves the JER 20%, 40% on tail (RMS), **and** JAR 20%.

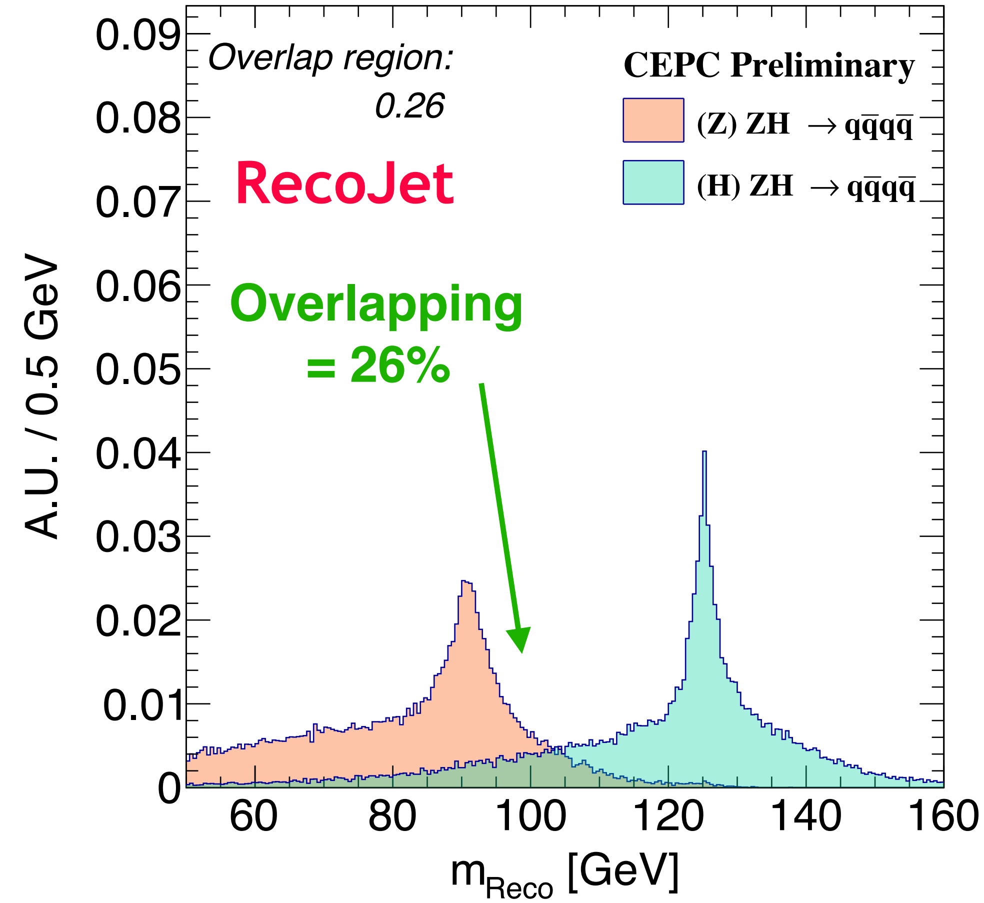
IV. **Need a better color-singlet identification algorithm for full hadronic.**
   - Wrong jet pairing is the dominant effect to induce overlapping in full hadronic WW-ZZ separation.
   - Equal mass requirement could reduce the overlap region to be better than semi-leptonic, but very costly.
   - Physical impact is needed to be controlled, ISR photon.

Thank for your attention

Back up

BM4: WW, ZZ, ZH to 4 Jets Separation





GenJet

Sample \ ID Efficiency(%)	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 \ ID Efficiency(%)	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 still employed.

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

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

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	**Purity**	
ZZ	20%	5	→	100	→	60/200 = 30%
ZH	60%	1	→	60		

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%

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  - 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.

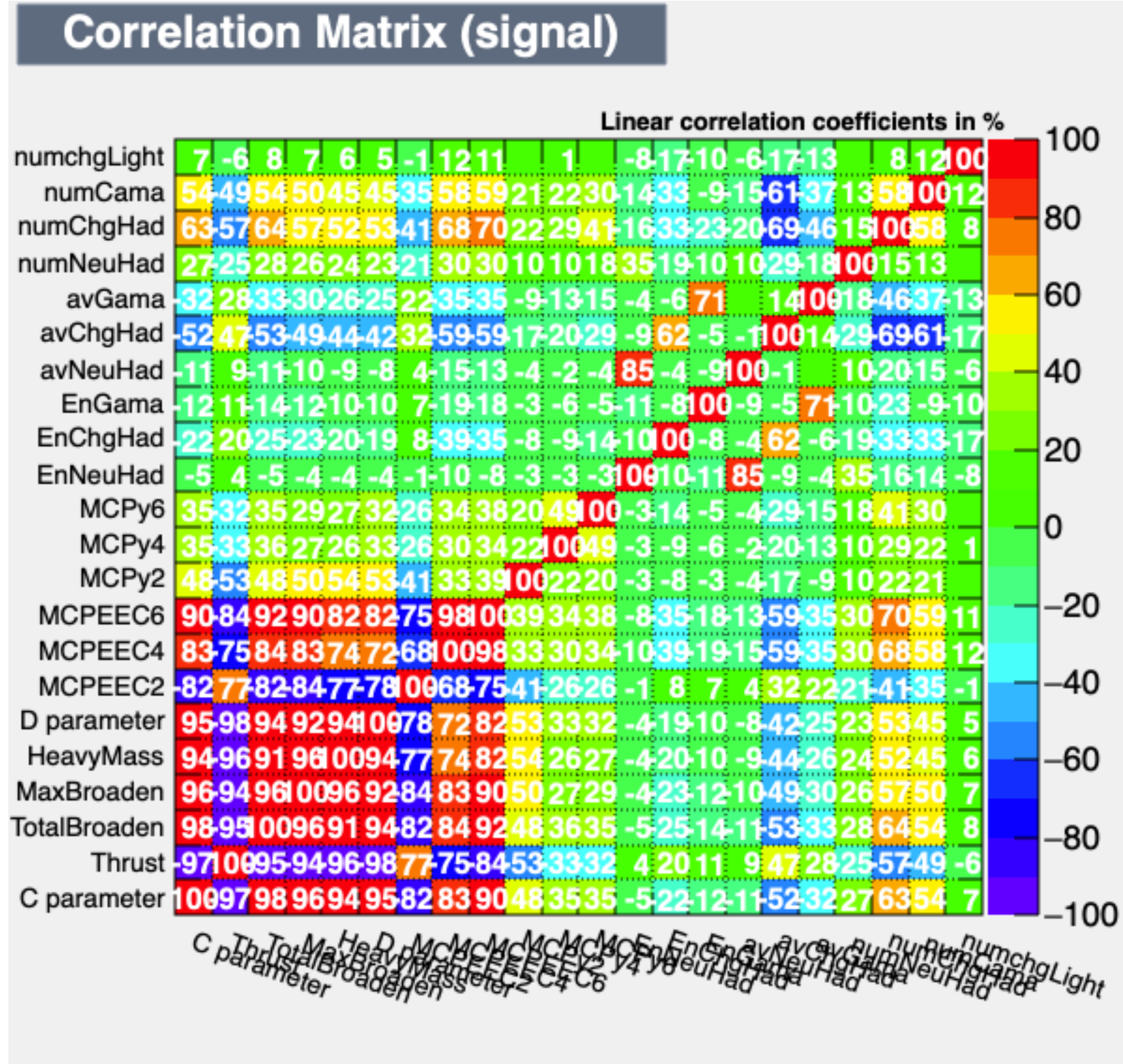
III. **Single Jet — JER ~ 3-5% & JAR ~ 1%.**
   - ✱ Thrust clustering method is recommended for two jets final-state. It could improve the JER 20%, 40% on tail (RMS), and JAR 20%.

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.
   - ✱ 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

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}

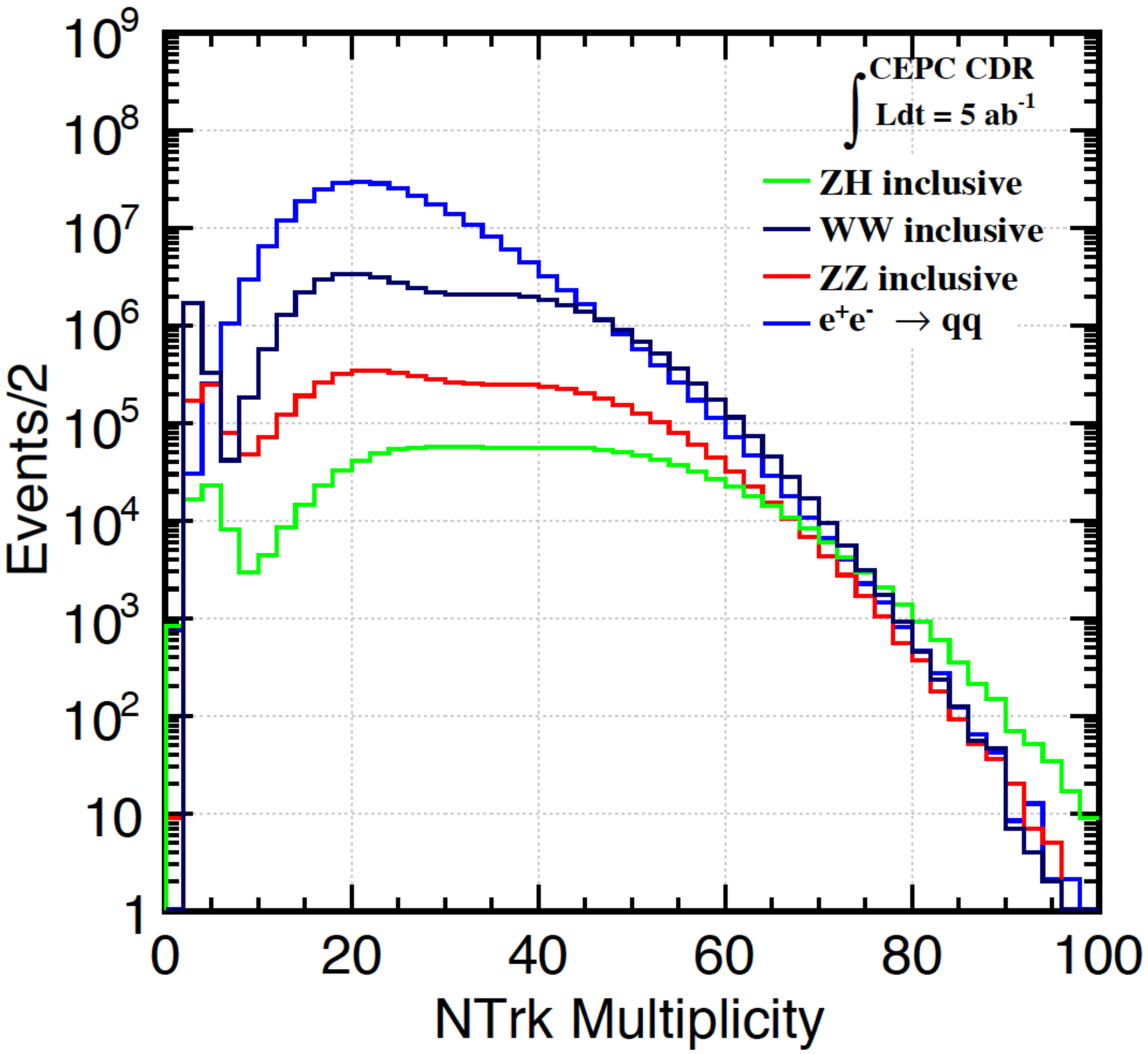
ee-kt jet clustering algorithm

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

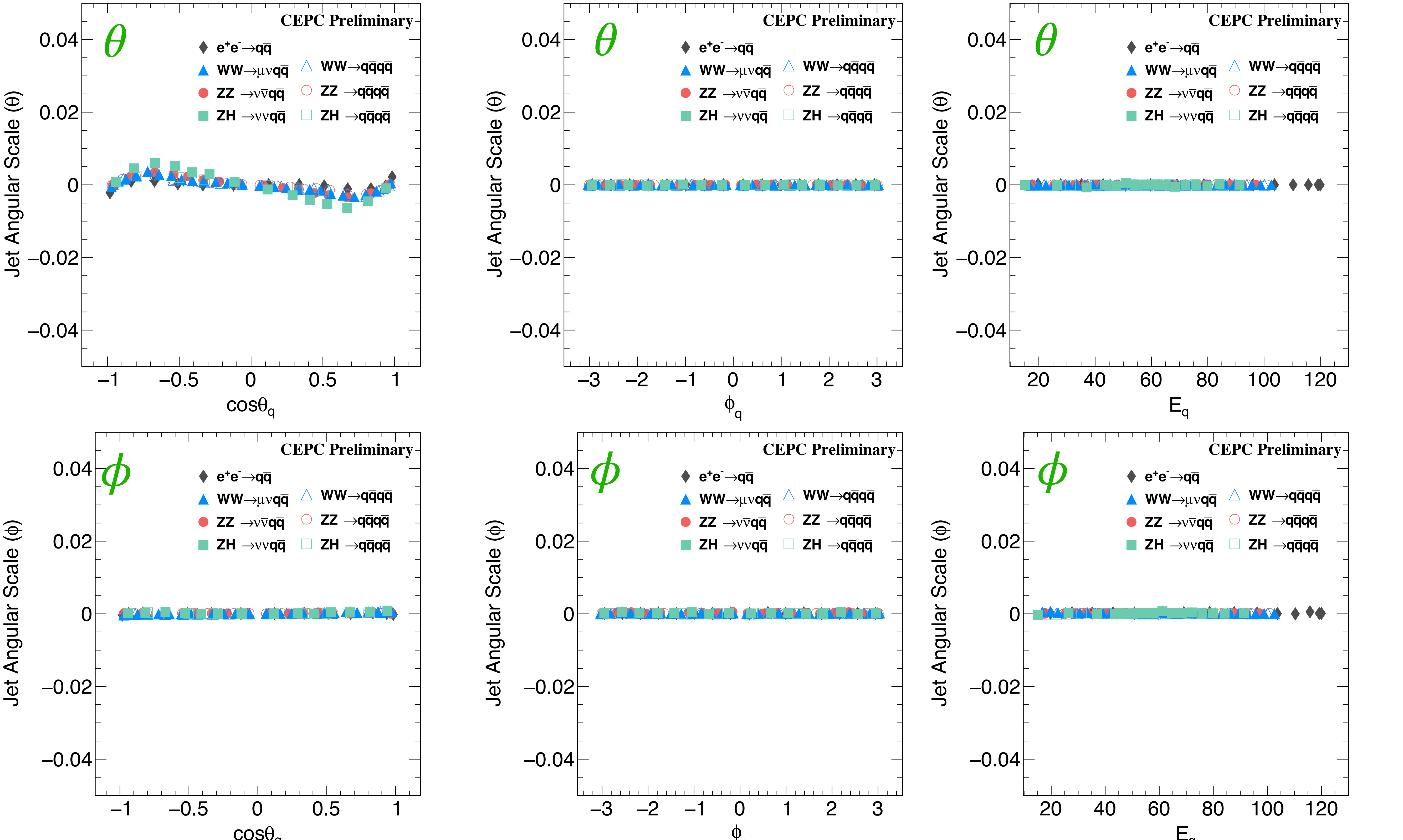
Double-sided Crystal Ball

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

Jet Multiplicity

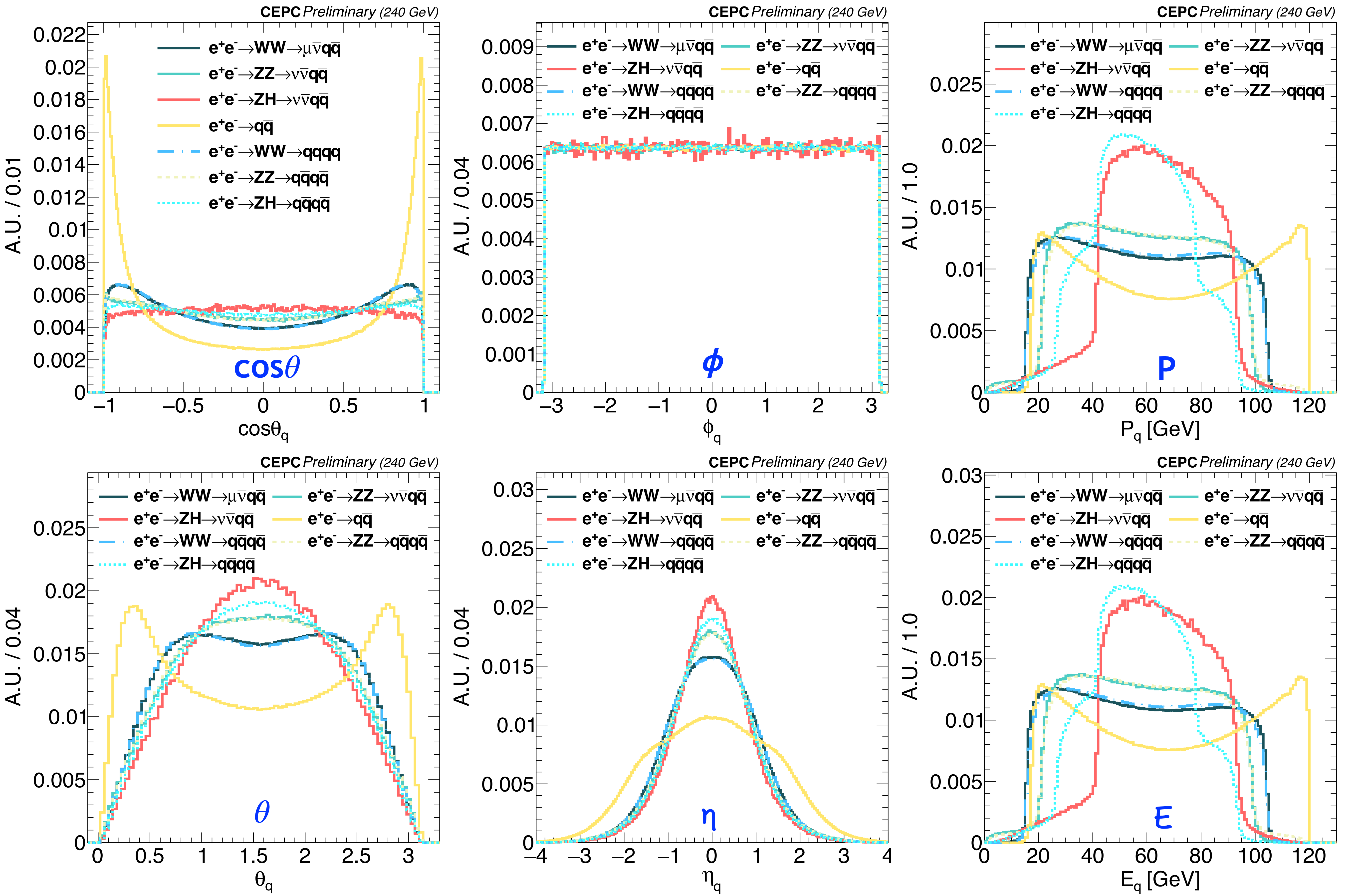


BM3: JAS (Reco-Gen)

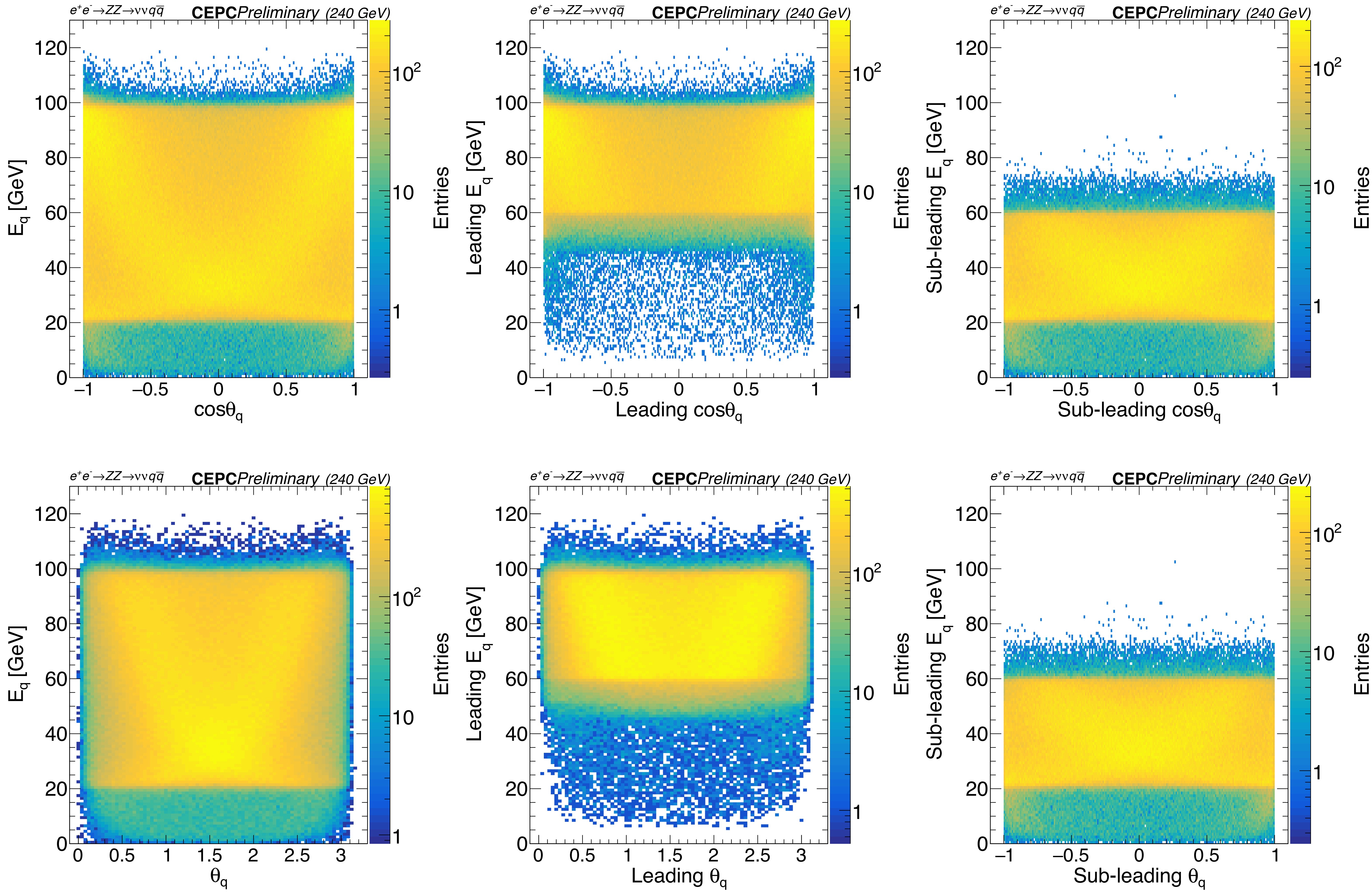


- JAR is around 1% in barrel region; JAS is independent of ϕ and energy.
- The difference between 2 and 4 jets final-state is controlled within 1% level.

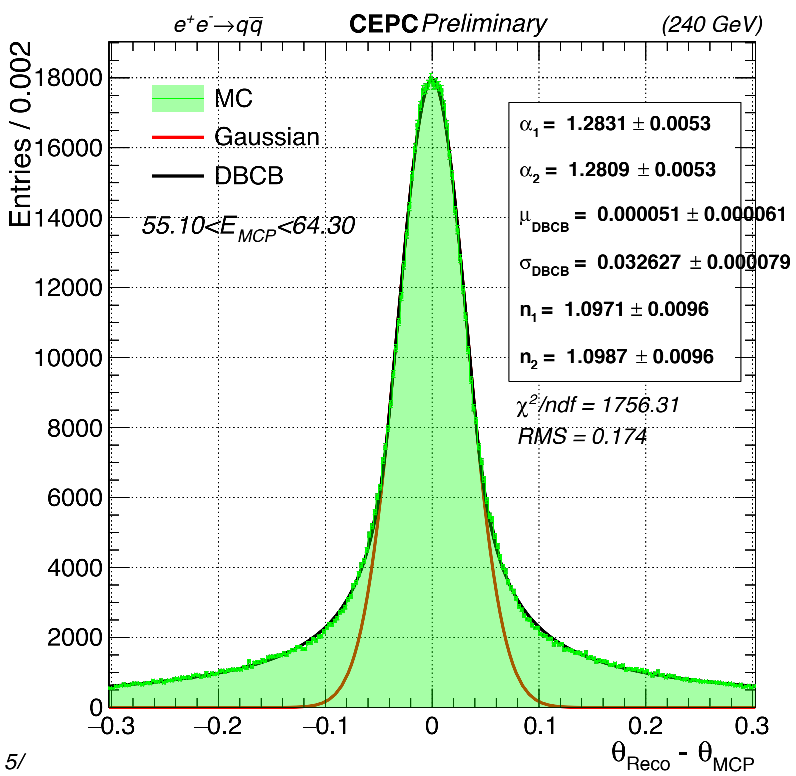
Kinematic Summary Plots(Parton level)

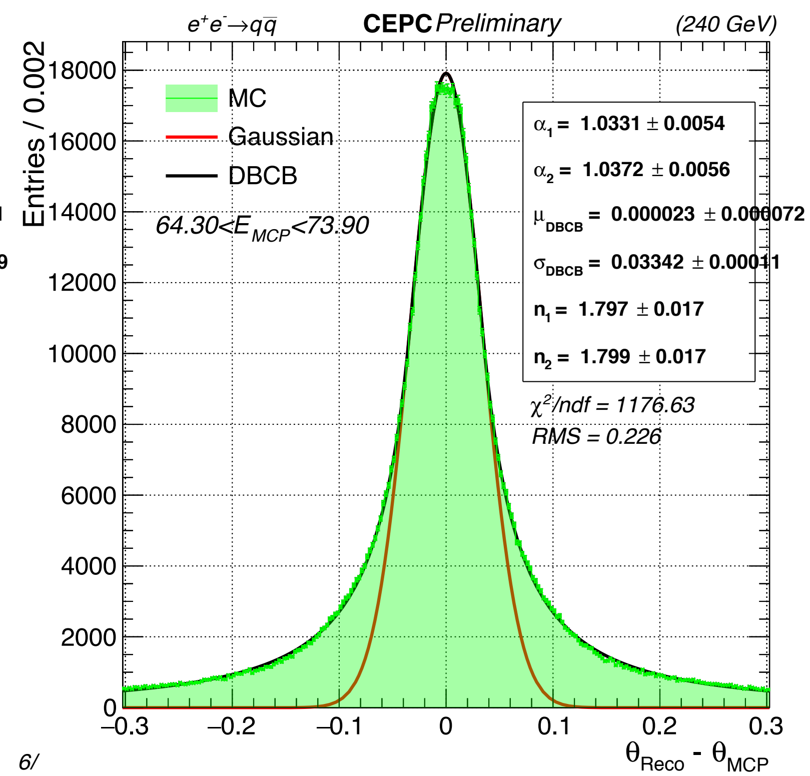


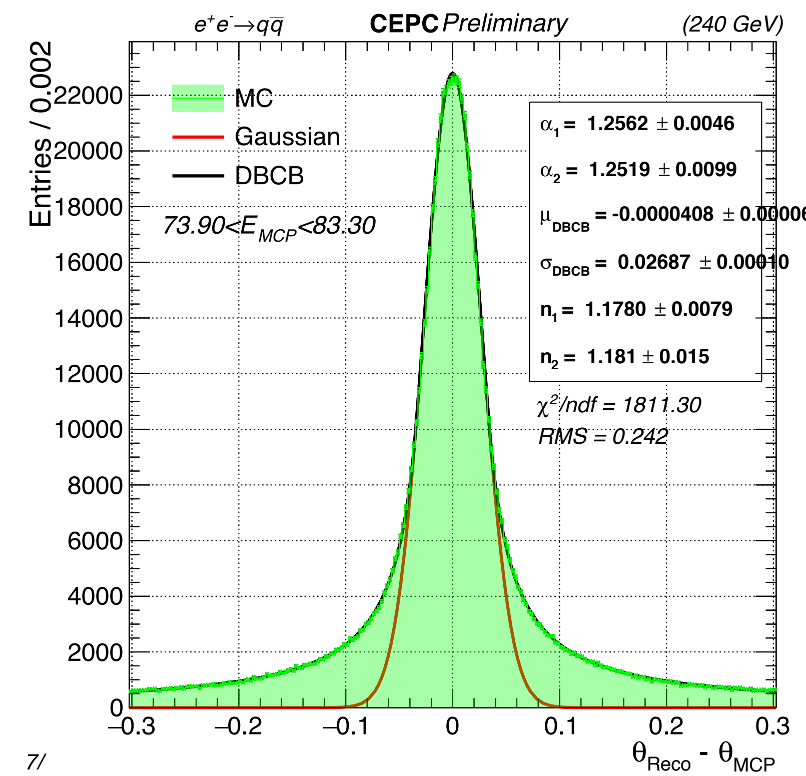
E as the function of the polar angle

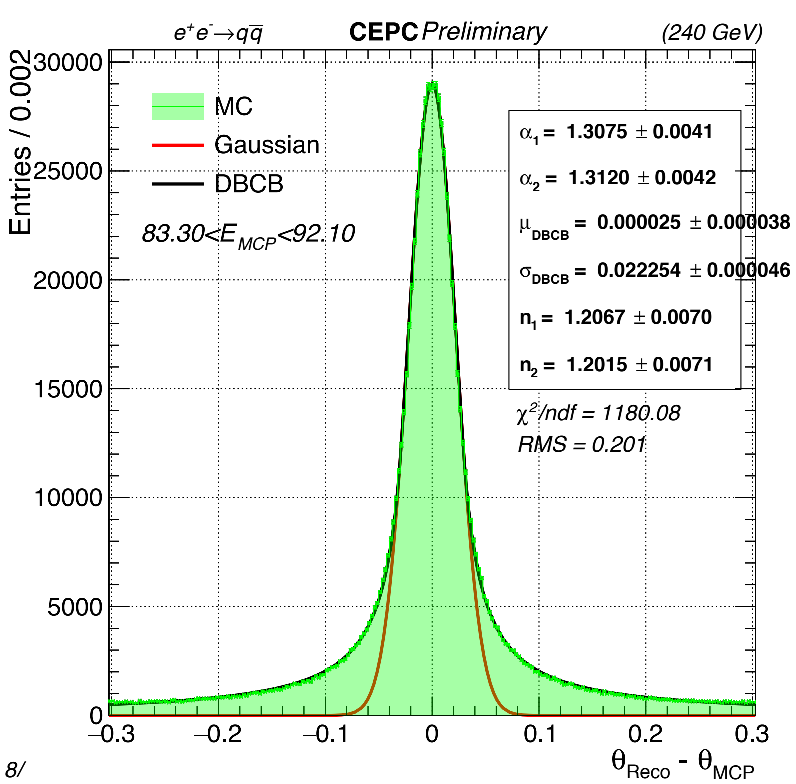


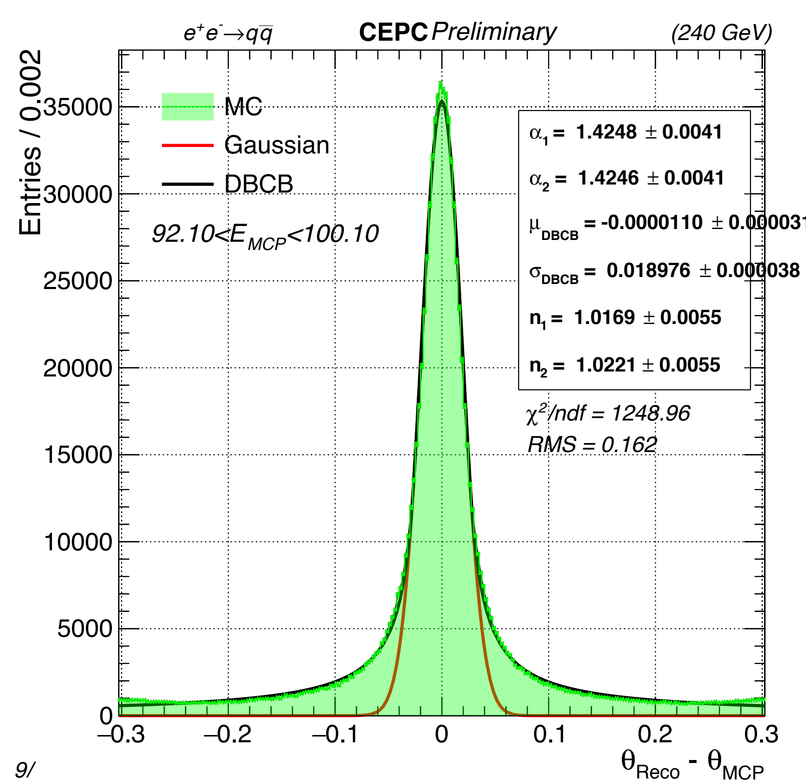
JAR(Reco-MCP)

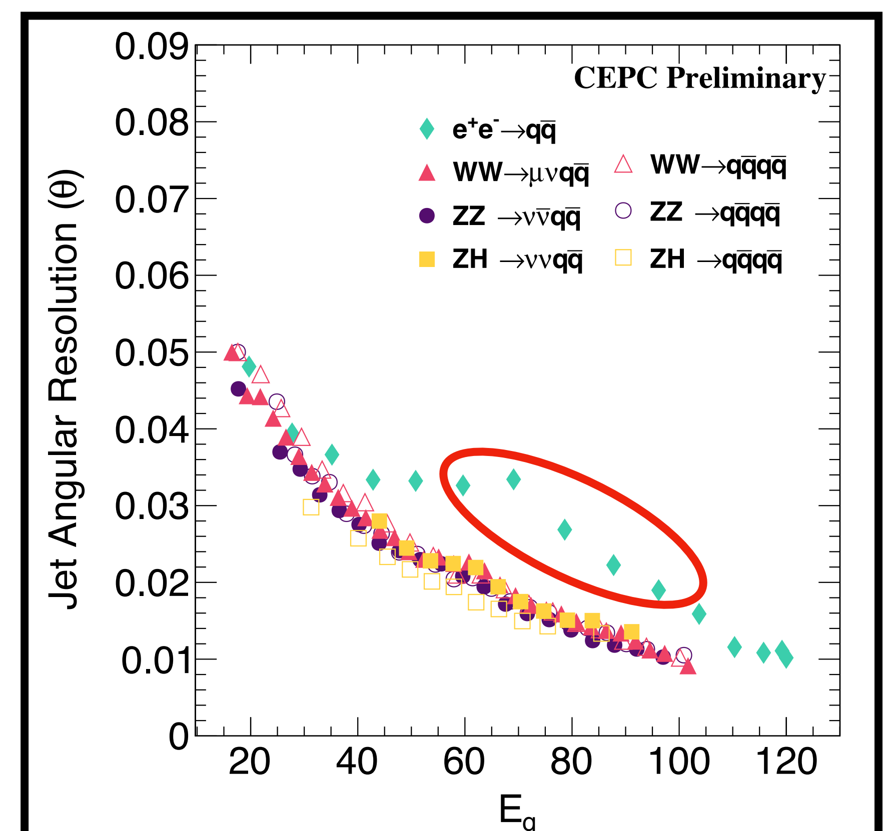

e+e−→qq̄
CEPC Preliminary
(240 GeV)
MC
Gaussian
DBCB
55.10<E_MCP<64.30
α1 = 1.2831 ± 0.0053
α2 = 1.2809 ± 0.0053
μDBCB = 0.000051 ± 0.000061
σDBCB = 0.032627 ± 0.000079
n1 = 1.0971 ± 0.0096
n2 = 1.0987 ± 0.0096
χ2/ndf = 1756.31
RMS = 0.174
Entries / 0.002
θReco - θMCP
5/


e+e−→qq̄
CEPC Preliminary
(240 GeV)
MC
Gaussian
DBCB
64.30<E_MCP<73.90
α1 = 1.0331 ± 0.0054
α2 = 1.0372 ± 0.0056
μDBCB = 0.000023 ± 0.000072
σDBCB = 0.03342 ± 0.00011
n1 = 1.797 ± 0.017
n2 = 1.799 ± 0.017
χ2/ndf = 1176.63
RMS = 0.226
Entries / 0.002
θReco - θMCP
6/


e+e−→qq̄
CEPC Preliminary
(240 GeV)
MC
Gaussian
DBCB
73.90<E_MCP<83.30
α1 = 1.2562 ± 0.0046
α2 = 1.2519 ± 0.0099
μDBCB = -0.0000408 ± 0.000068
σDBCB = 0.02687 ± 0.00010
n1 = 1.1780 ± 0.0079
n2 = 1.181 ± 0.015
χ2/ndf = 1811.30
RMS = 0.242
Entries / 0.002
θReco - θMCP
7/

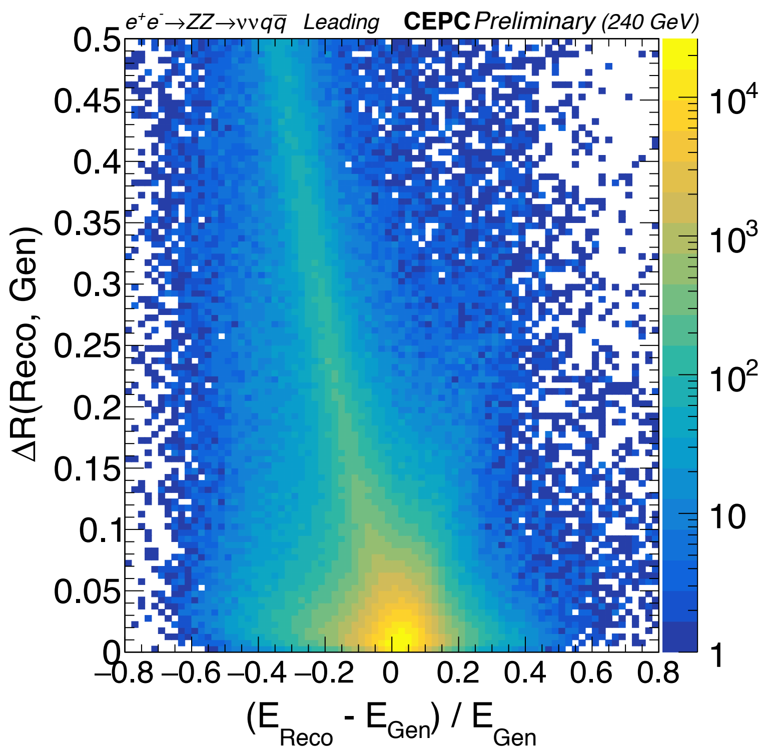

e+e−→qq̄
CEPC Preliminary
(240 GeV)
MC
Gaussian
DBCB
83.30<E_MCP<92.10
α1 = 1.3075 ± 0.0041
α2 = 1.3120 ± 0.0042
μDBCB = 0.000025 ± 0.000038
σDBCB = 0.022254 ± 0.000046
n1 = 1.2067 ± 0.0070
n2 = 1.2015 ± 0.0071
χ2/ndf = 1180.08
RMS = 0.201
Entries / 0.002
θReco - θMCP
8/


e+e−→qq̄
CEPC Preliminary
(240 GeV)
MC
Gaussian
DBCB
92.10<E_MCP<100.10
α1 = 1.4248 ± 0.0041
α2 = 1.4246 ± 0.0041
μDBCB = -0.0000110 ± 0.000031
σDBCB = 0.018976 ± 0.000038
n1 = 1.0169 ± 0.0055
n2 = 1.0221 ± 0.0055
χ2/ndf = 1248.96
RMS = 0.162
Entries / 0.002
θReco - θMCP
9/

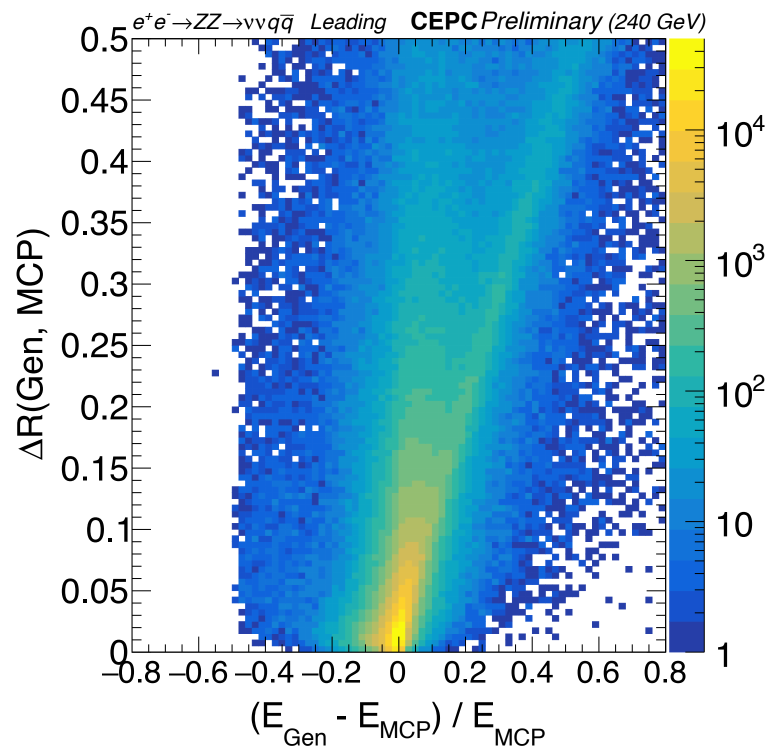

CEPC Preliminary
e+e−→qq̄
WW→μνqq̄
WW→qq̄qq̄
ZZ →νν̄qq̄
ZZ →qq̄qq̄
ZH →ννqq̄
ZH →qq̄qq̄
Jet Angular Resolution (θ)
Eq

ΔR as the function of ΔE

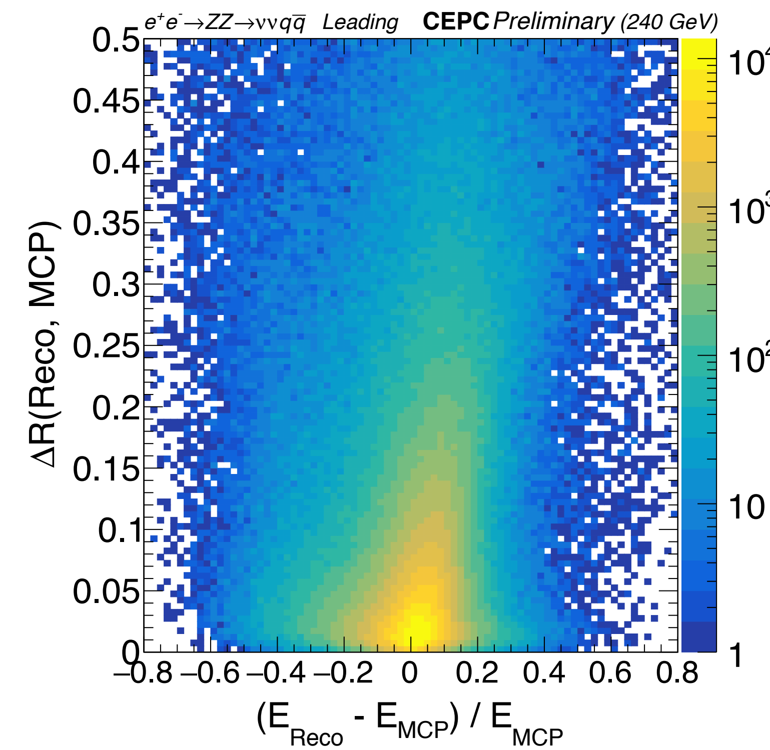
Leading, Gen-MCP



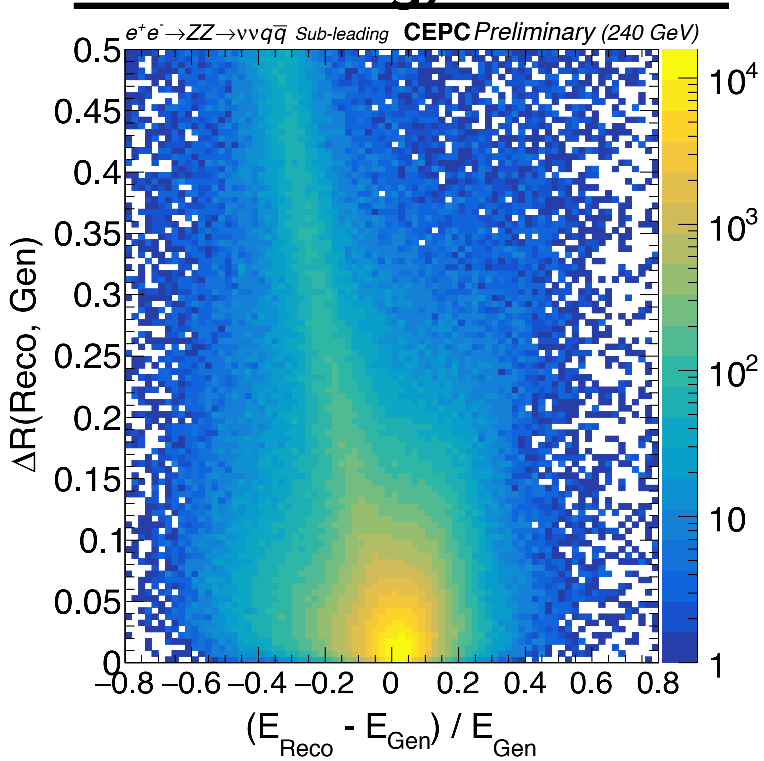
Leading, Reco-Gen



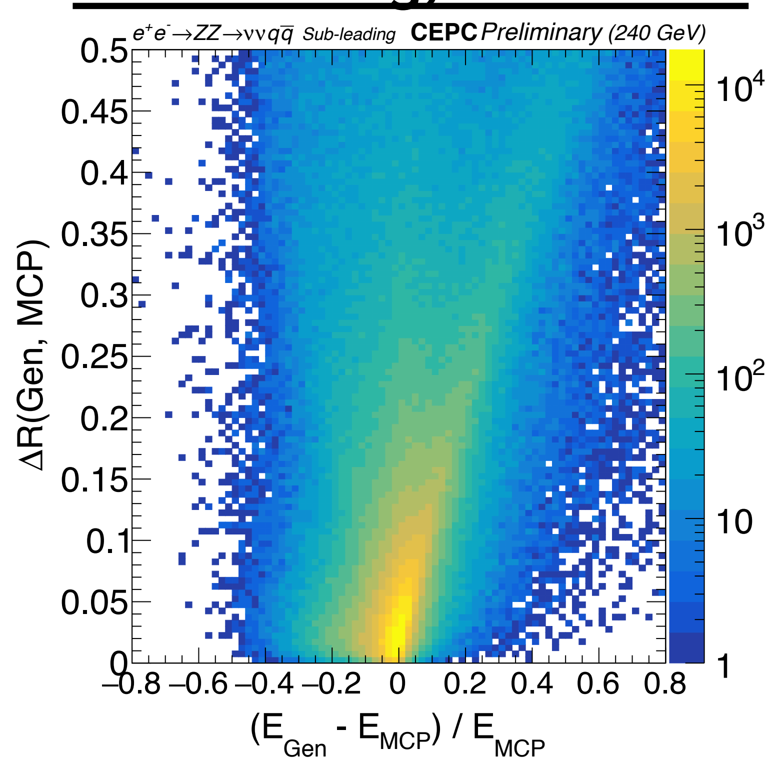
Leading, Reco-MCP



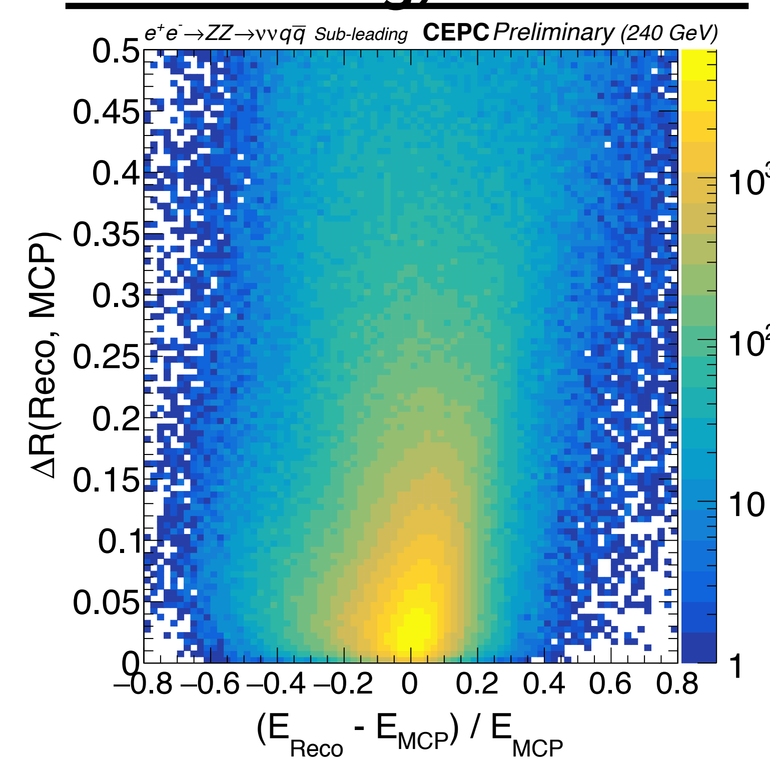
Sub-leading, Gen-MCP



Sub-leading, Reco-Gen



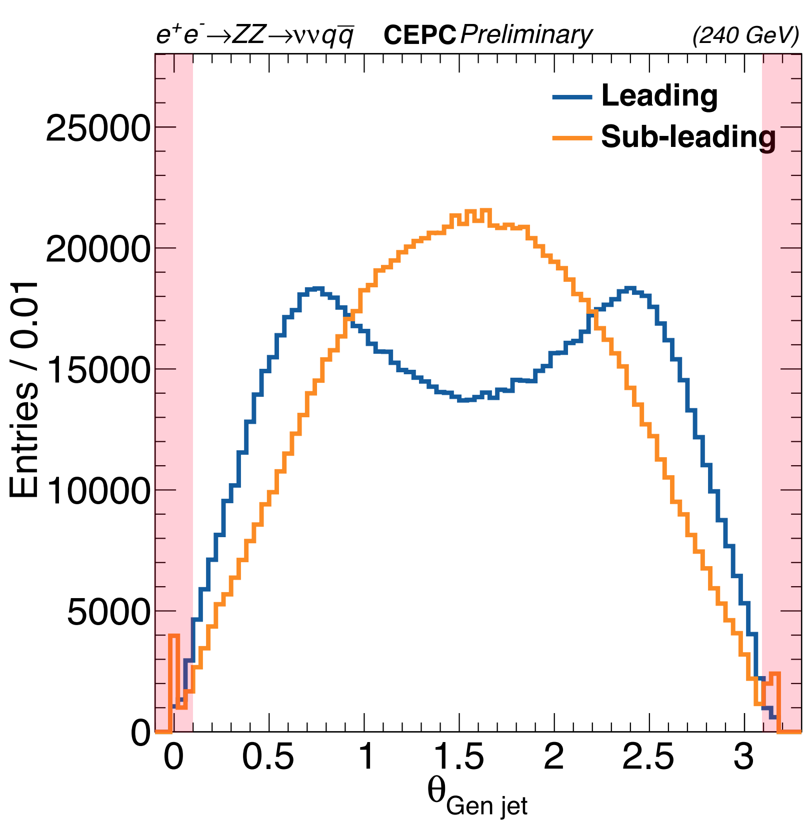
Sub-leading, Reco-MCP

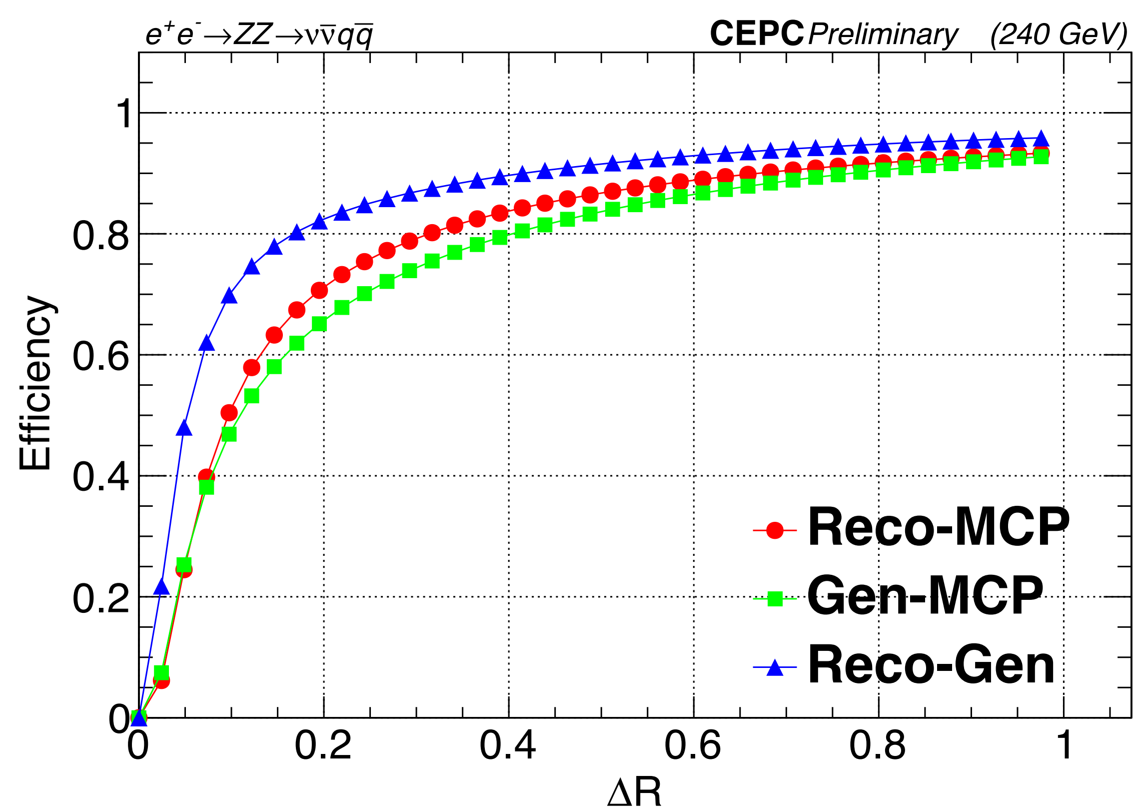


The jet clustering brings a significant uncertainty.

Event Selection

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





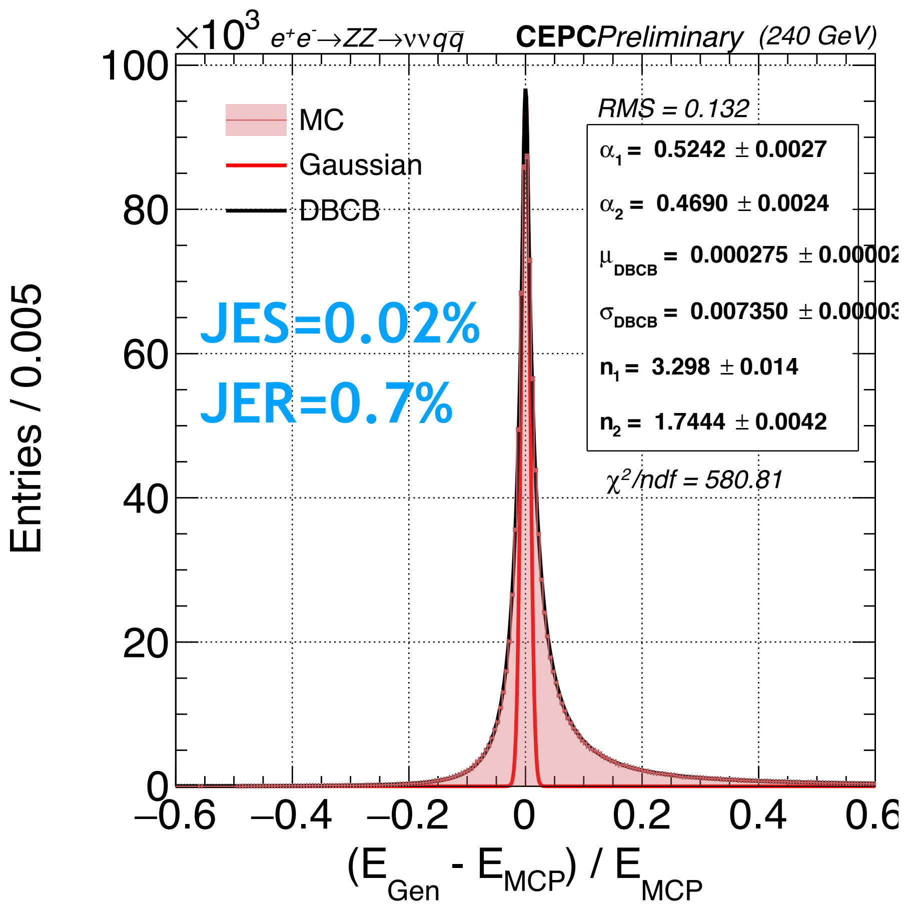
Efficiency=

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

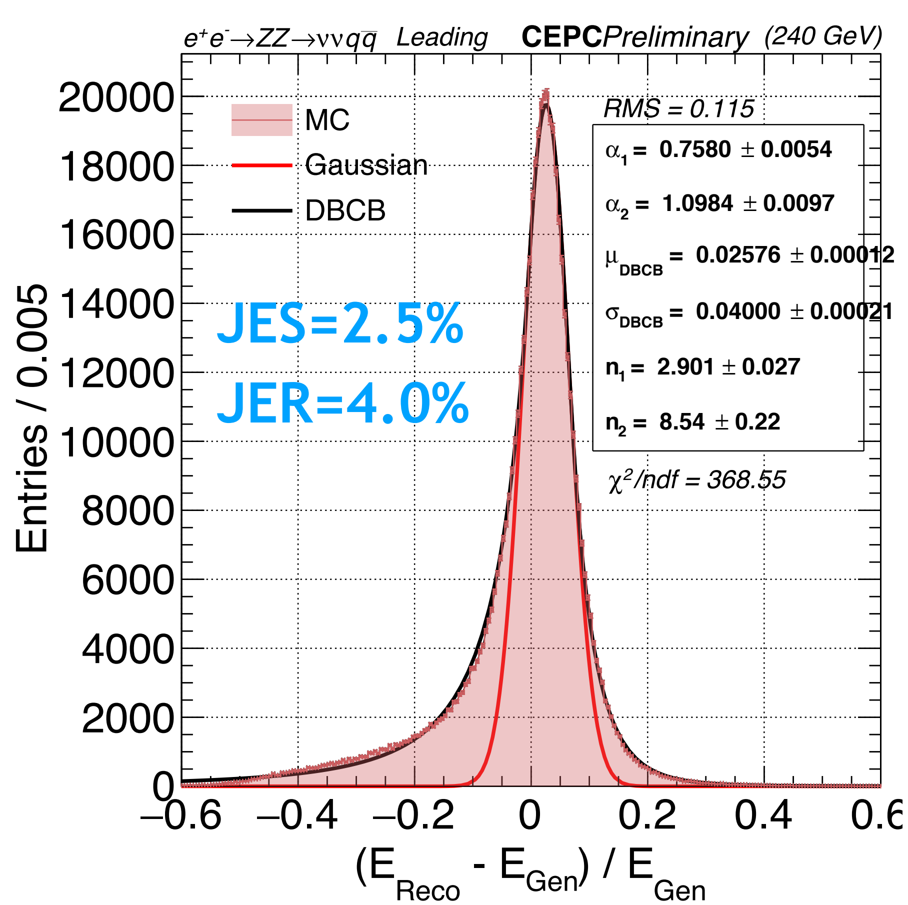
$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

Leading JER & JES

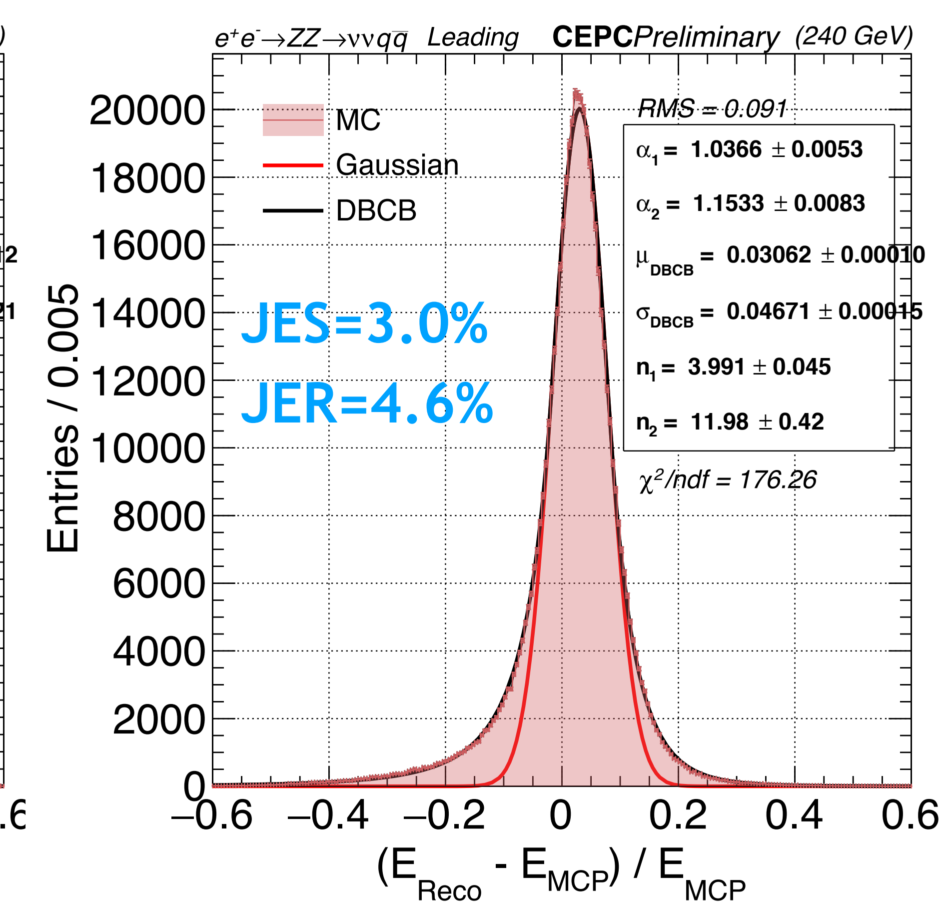
Gen-MCP



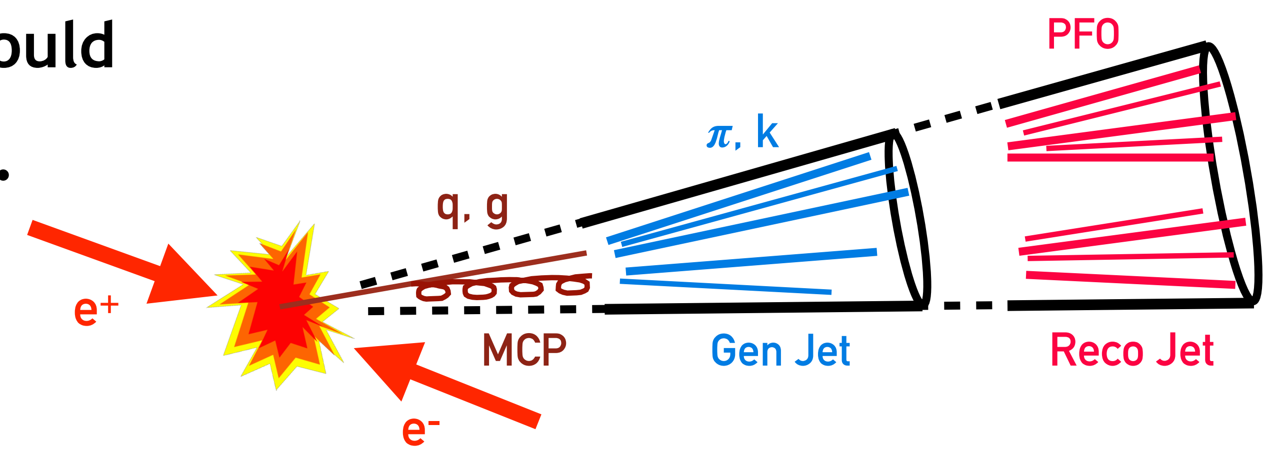
Reco-Gen



Reco-MCP

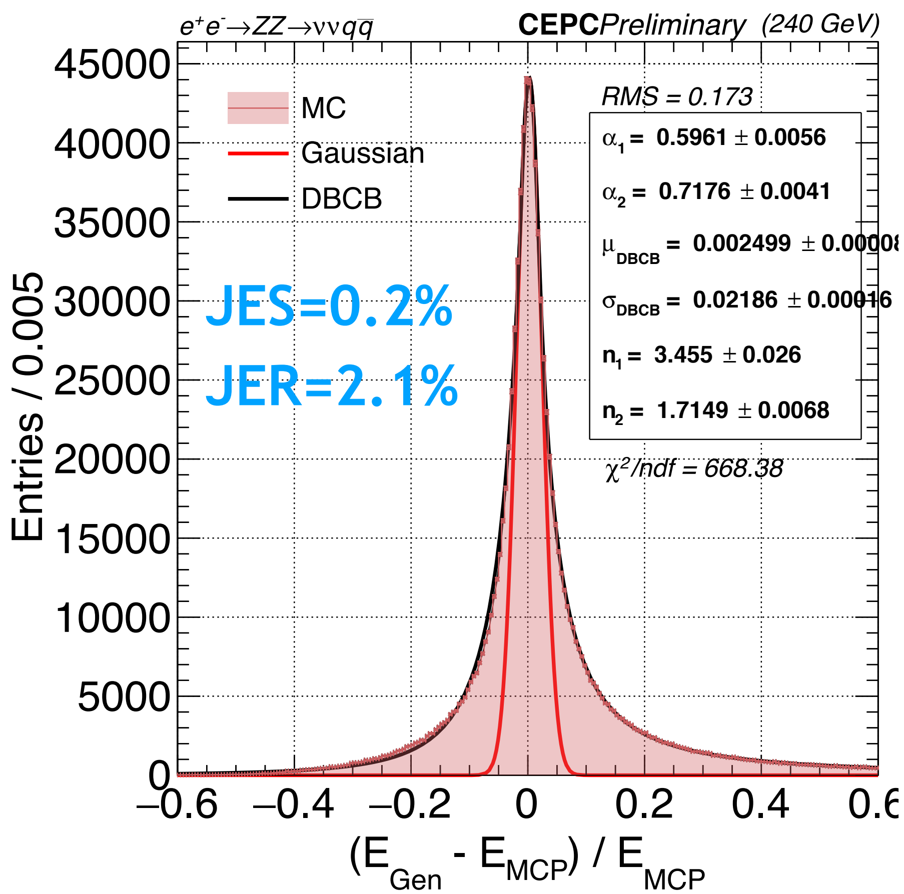


- JER/JES between Reco jet and MCP would combine the effects of two previous stages.

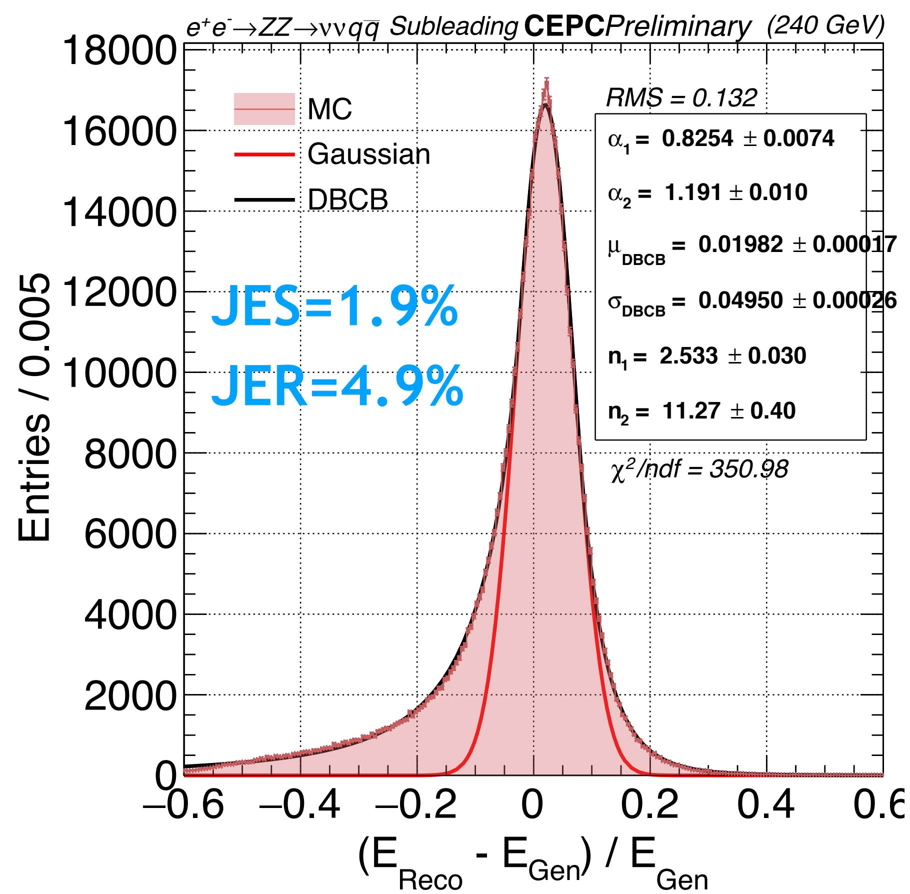


Sub-leading JER & JES

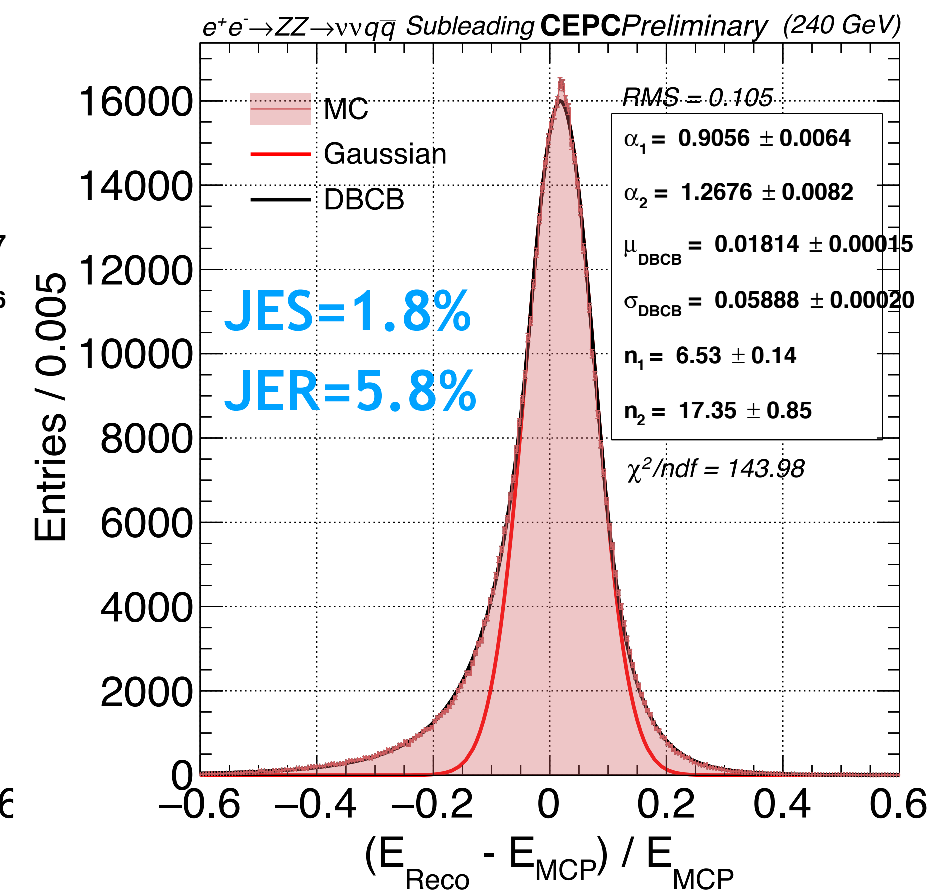
Gen-MCP



Reco-Gen

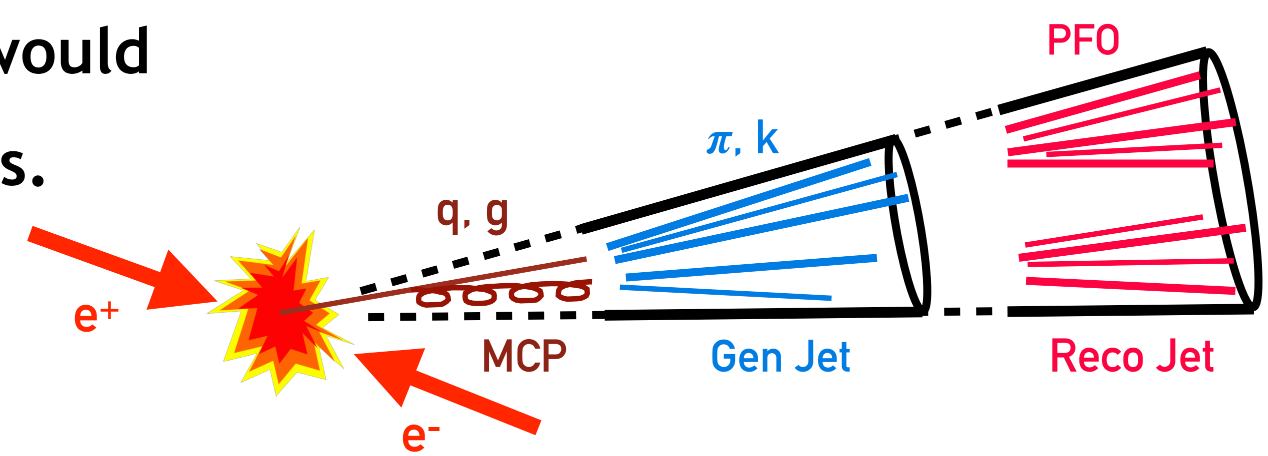


Reco-MCP



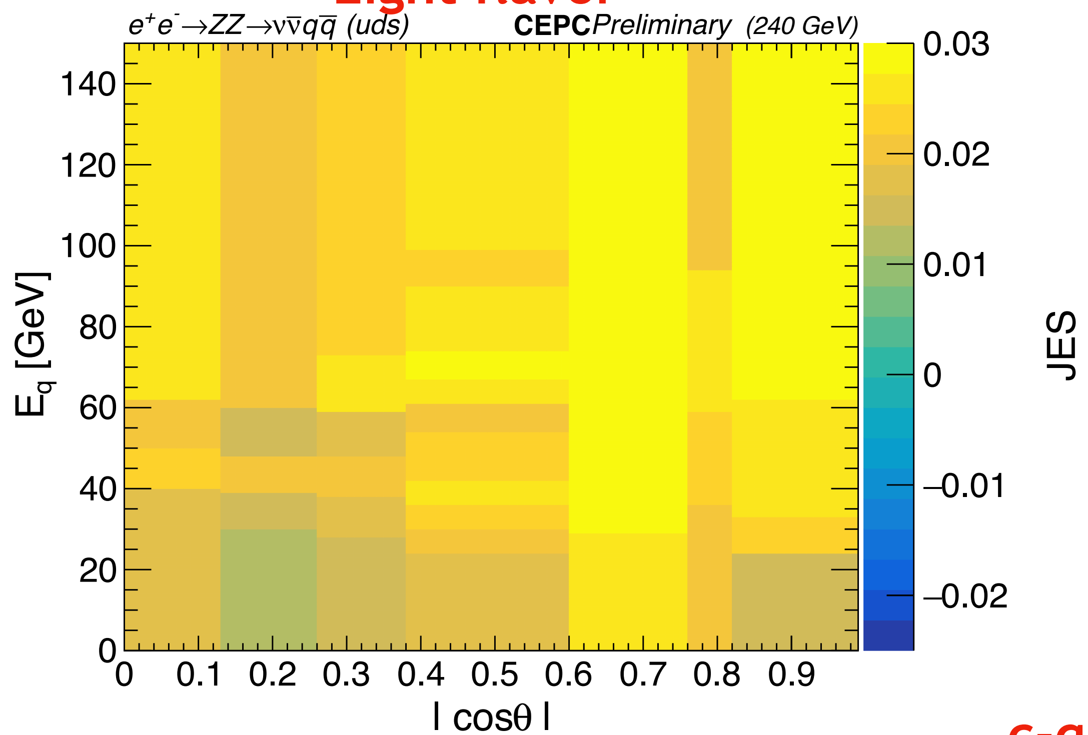
MCP **Gen jet** **Reco jet**

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

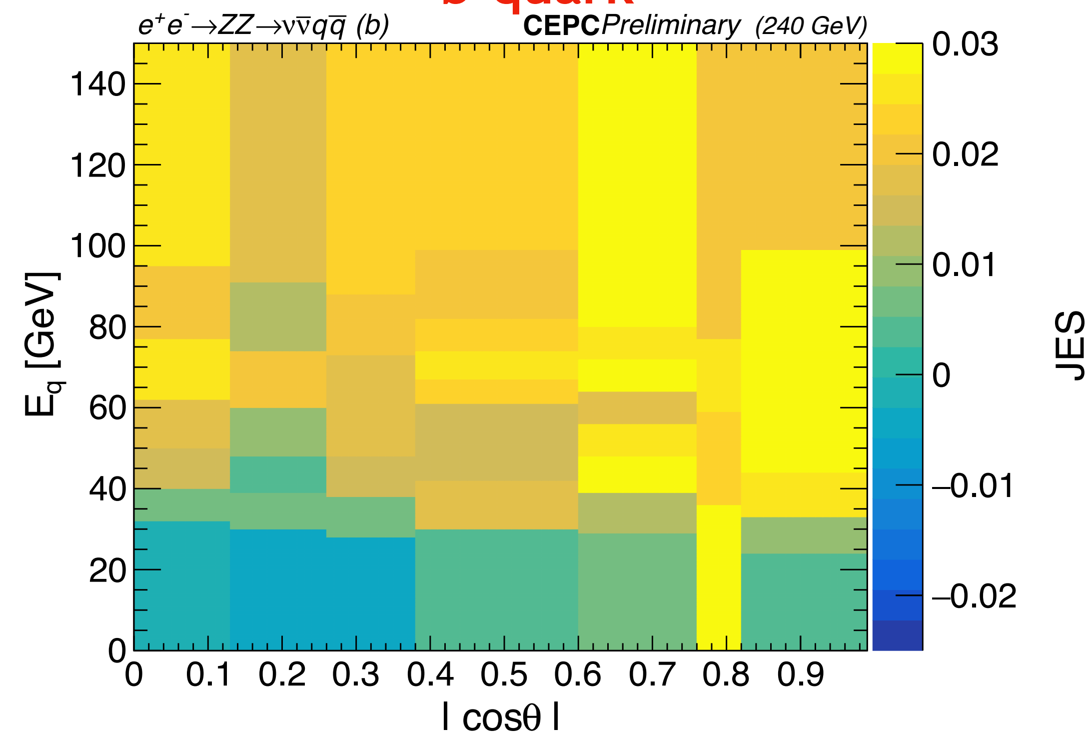


JES in Phase Space

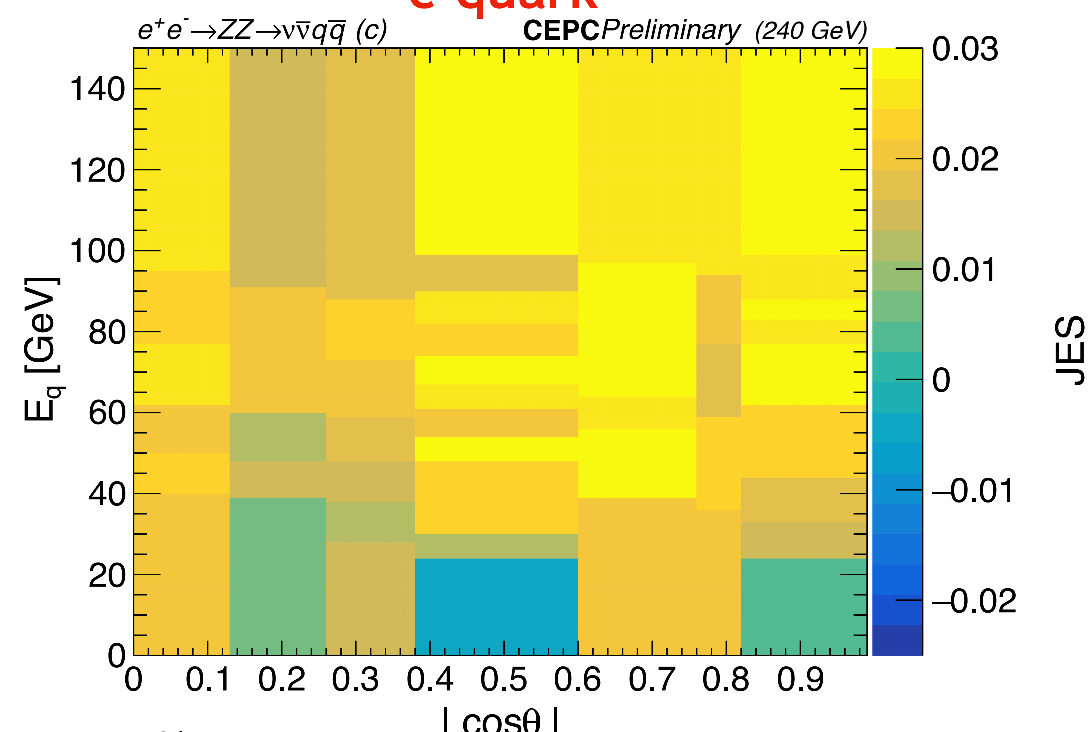
Light flavor



b-quark



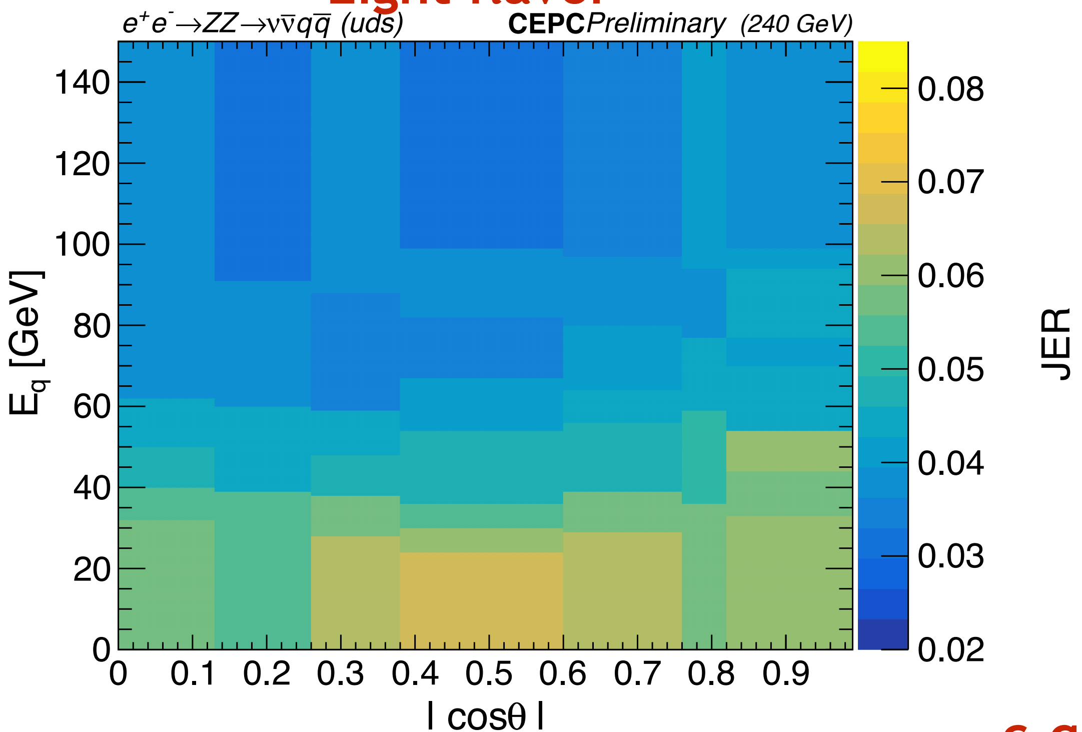
c-quark



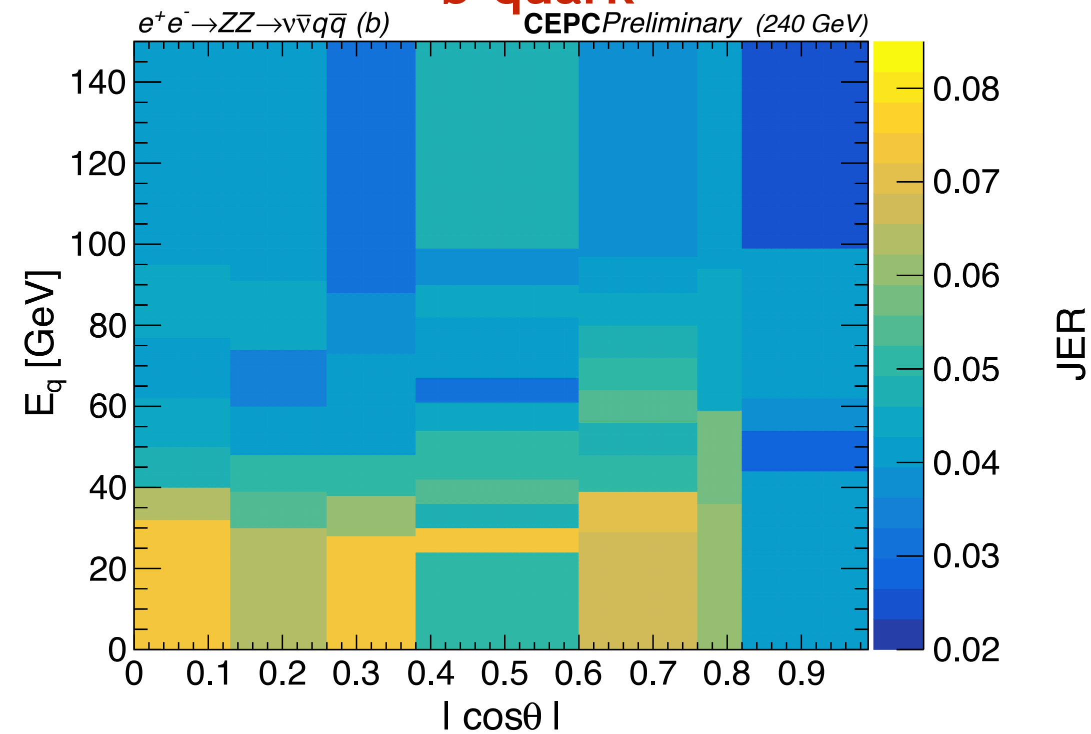
- **JES also depends on the jet flavor.**
- **Light flavor jet has higher energy deviation.**

JER in Phase Space

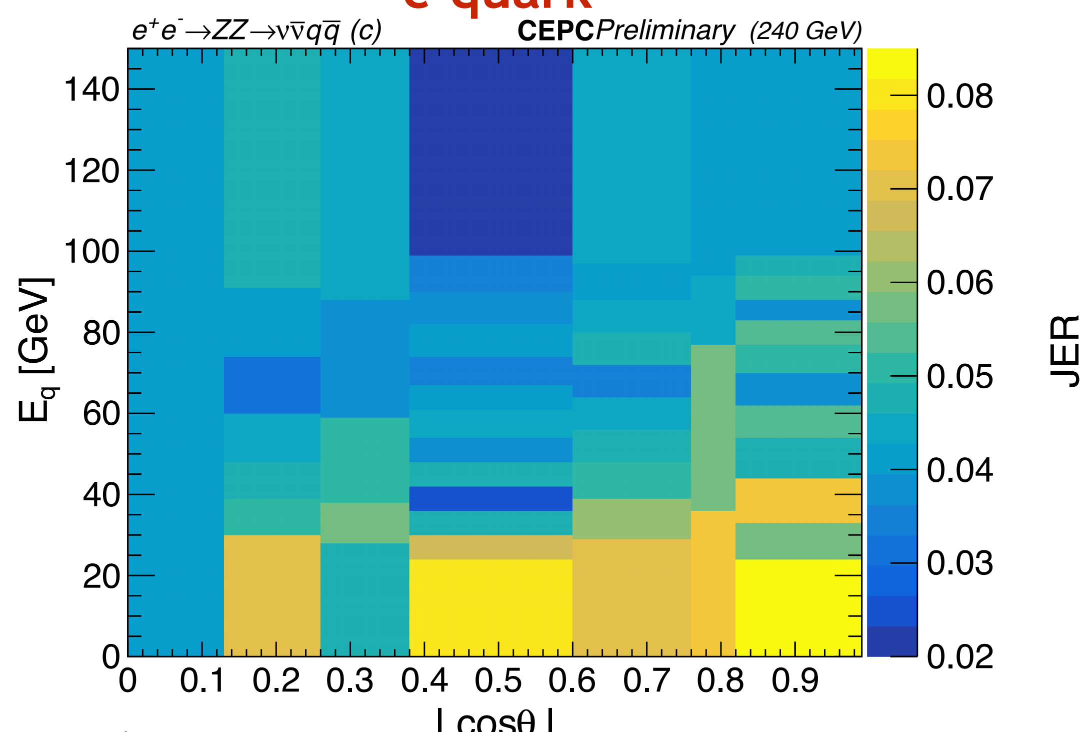
Light flavor



b-quark

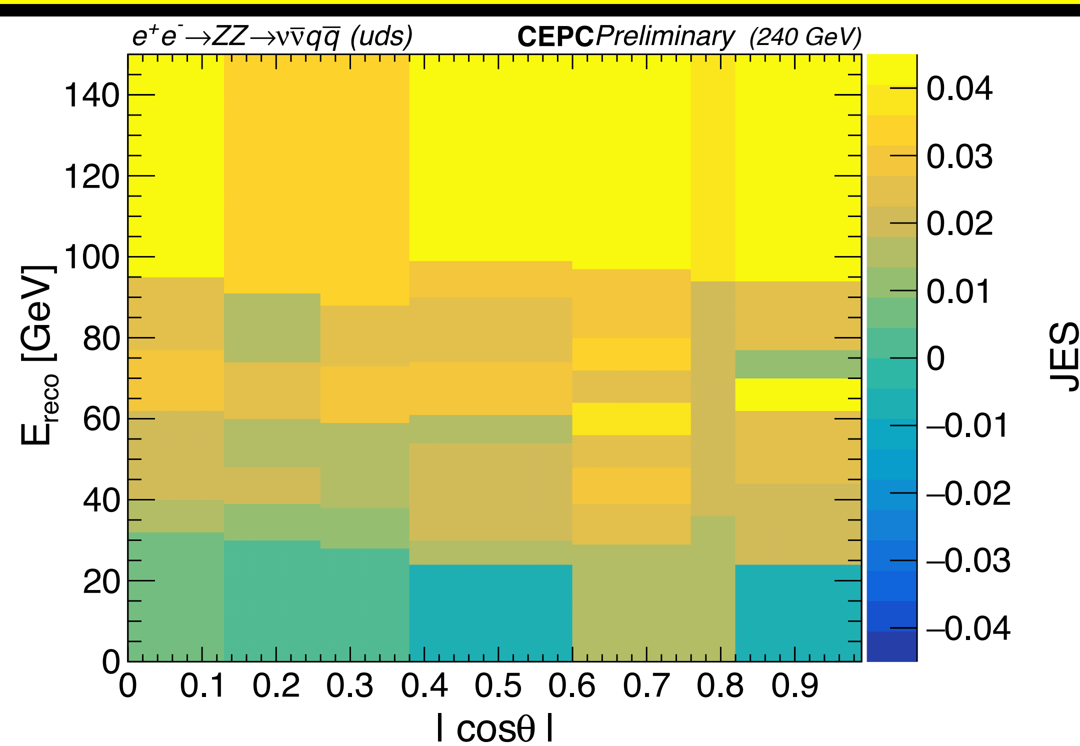


c-quark

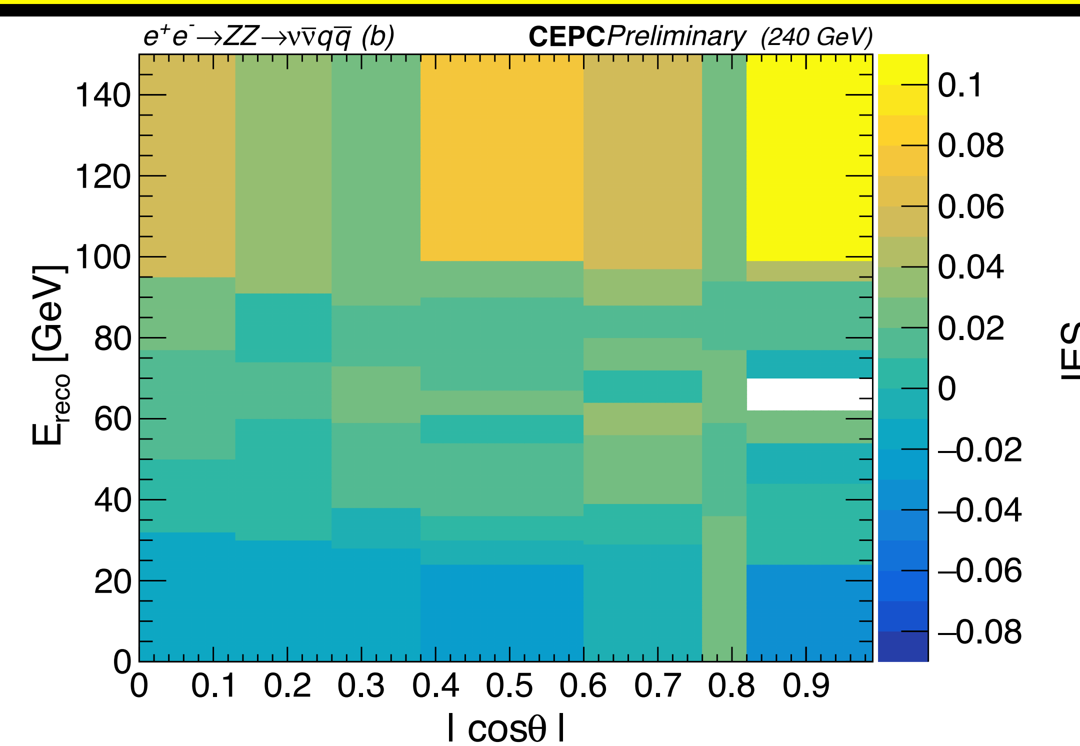


- **JER also depends on the jet flavor.**
- **Higher jet energy and within central region of barrel, JER has impressive performance.**

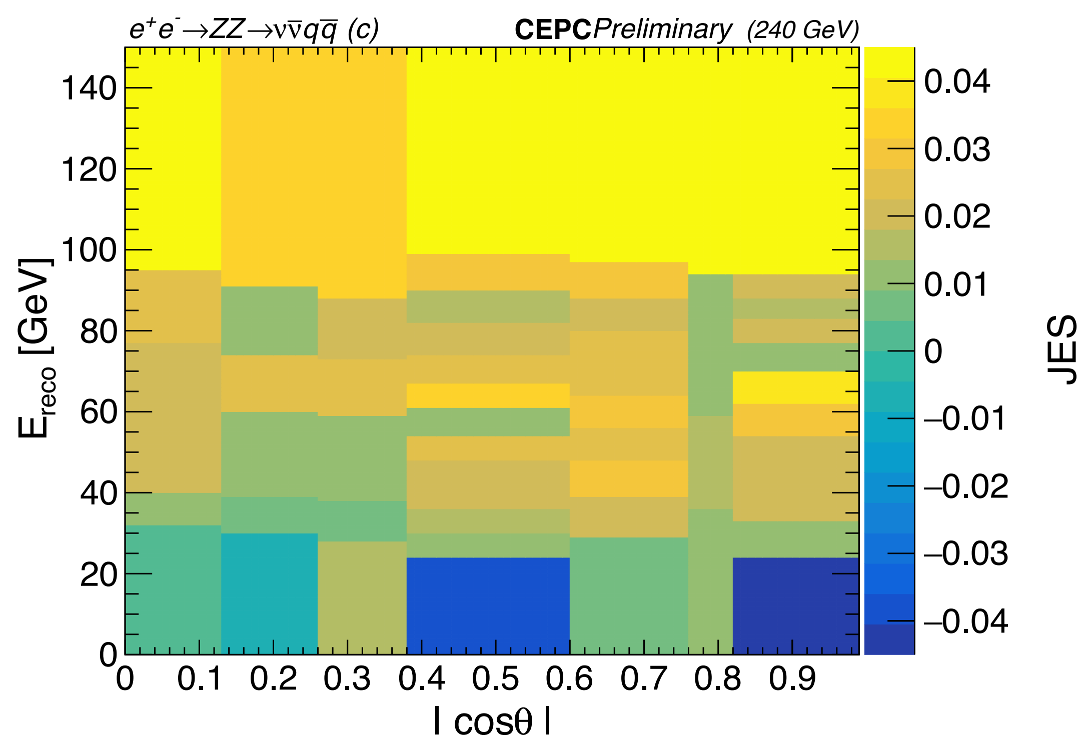
JES



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

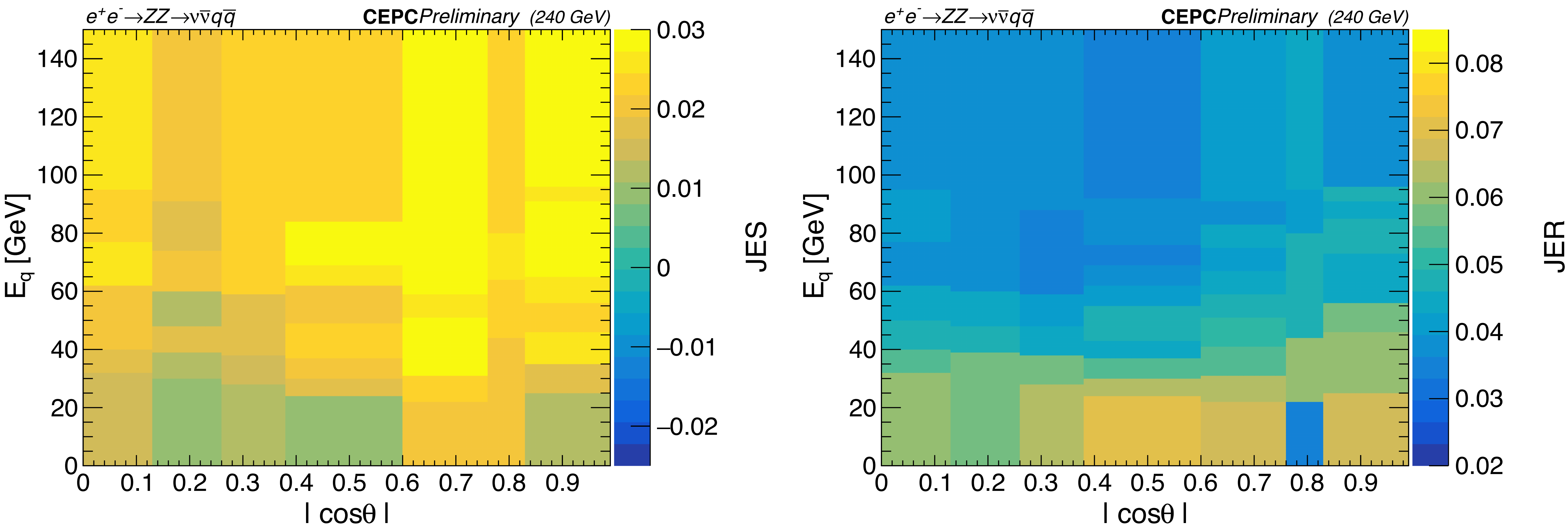


$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$ (b)
CEPC *Preliminary* (240 GeV)
E_{reco} [GeV]
| cosθ |
JES



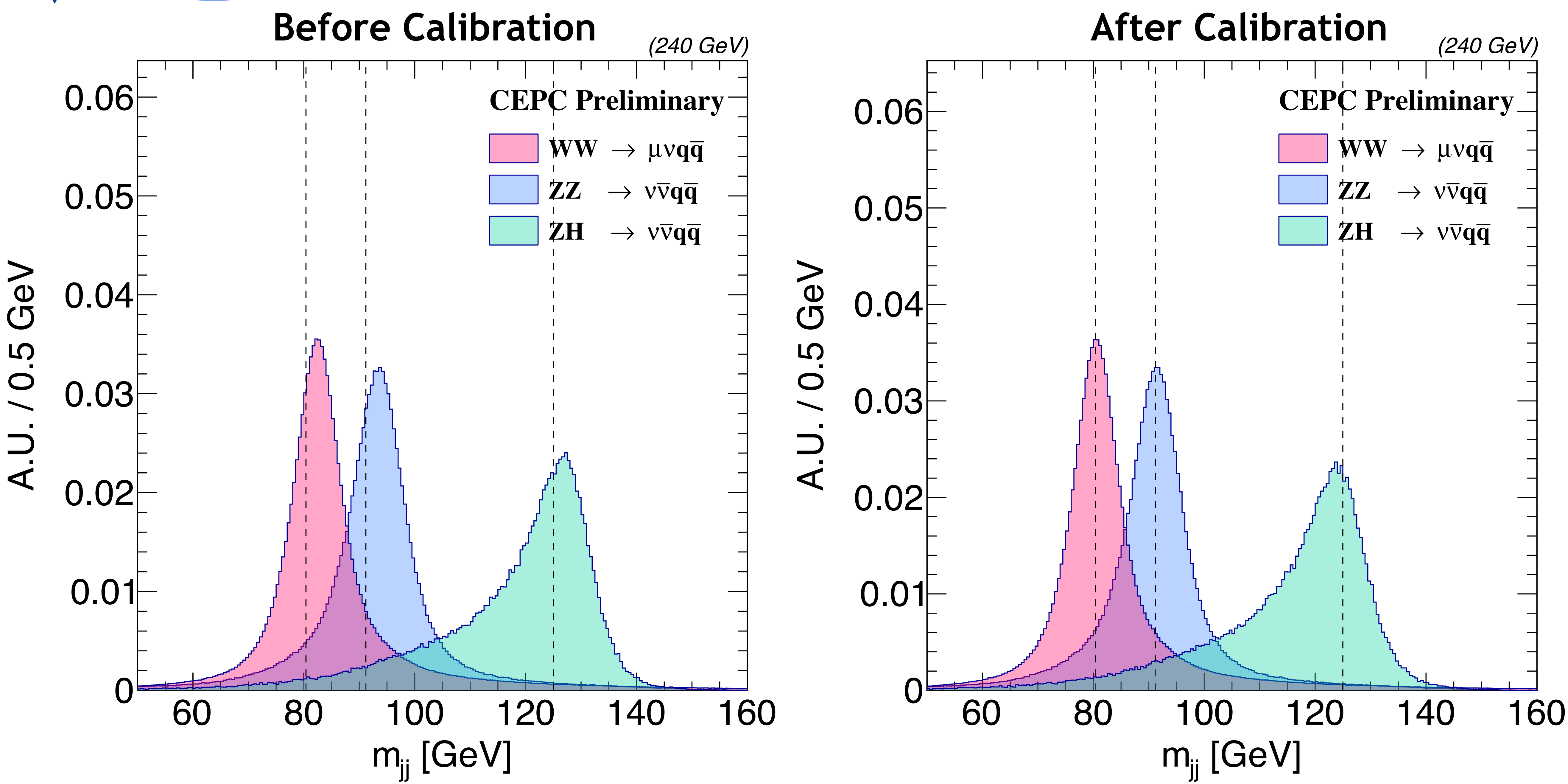
$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$ (c)
CEPC *Preliminary* (240 GeV)
E_{reco} [GeV]
| cosθ |
JES

JER & JES



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



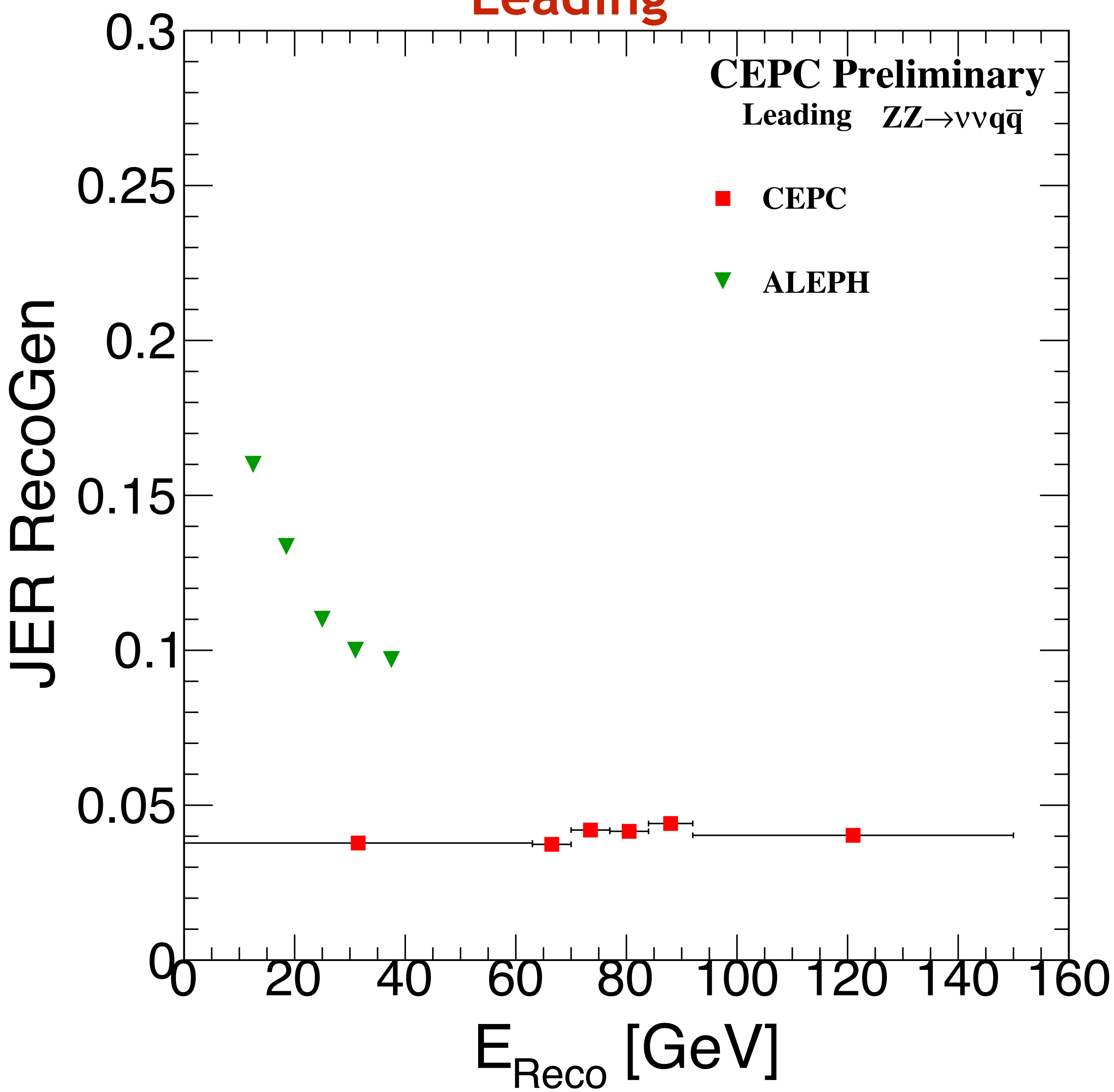
- **Since the double-counting effect, jet energy would be overestimated.**
- **According to MC true energy and cosθ distribution, JES can be used to calibrate the dijet invariant mass back to the value we put into simulation.**
- **After calibration, boson mass resolution is improved about 1%.**

Summary

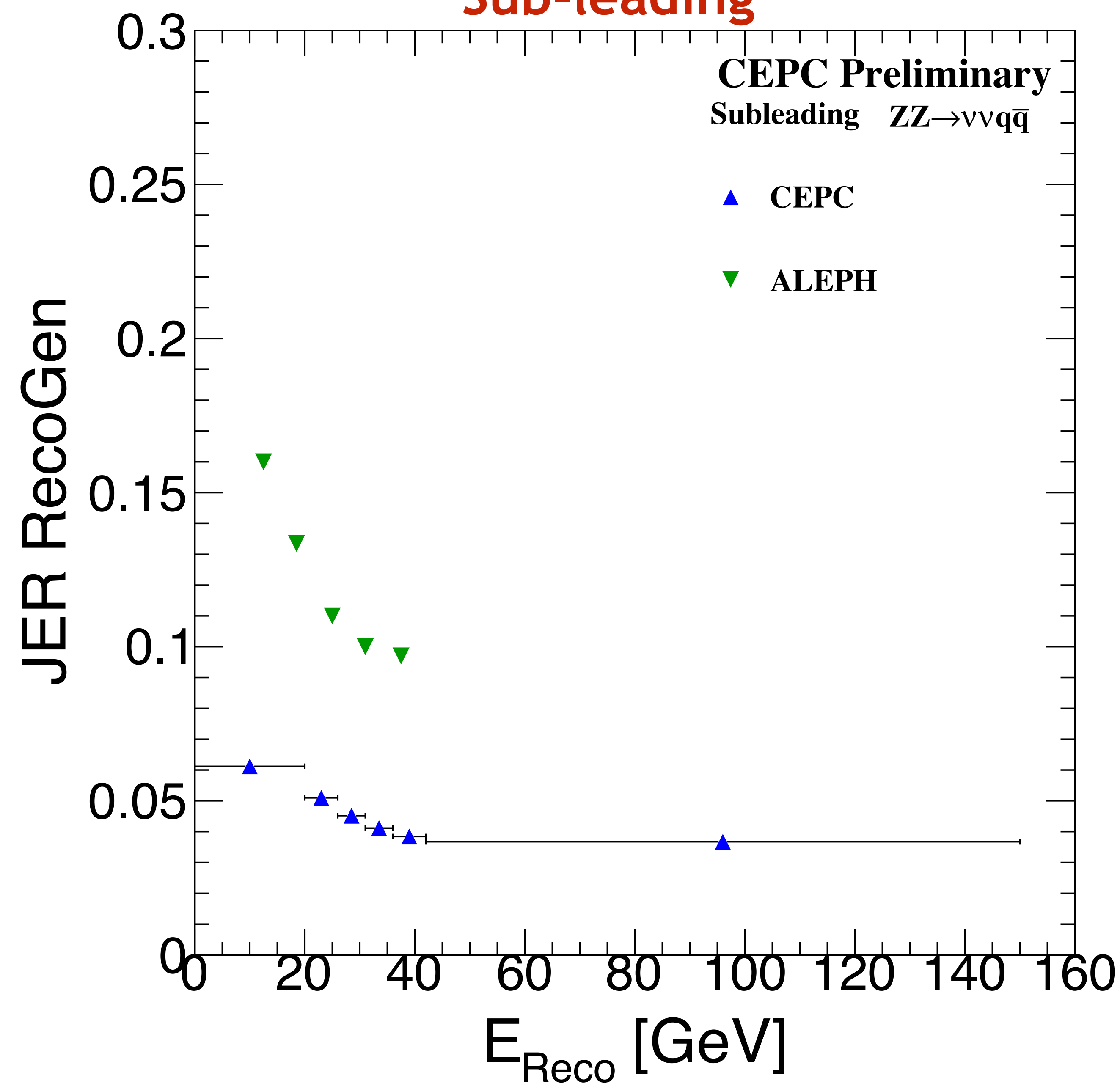
m_W (GeV)	m_Z (GeV)	m_H (GeV)	Jets / PFOs	wi/wo Clean	wi/wo Cali
82.66 ± 3.54	93.69 ± 3.89	127.48 ± 4.93	Jets	0	0
82.79 ± 3.34	93.95 ± 3.48	127.31 ± 4.54	Jets	1	0
80.72 ± 3.46	91.67 ± 3.77	125.02 ± 5.11	Jets	0	1
80.82 ± 3.23	91.76 ± 3.39	124.39 ± 4.39	Jets	1	1
82.63 ± 3.53	93.69 ± 3.89	127.57 ± 4.80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

Compare with ALEPH at LEP

Leading



Sub-leading



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