Differential Jet Performance

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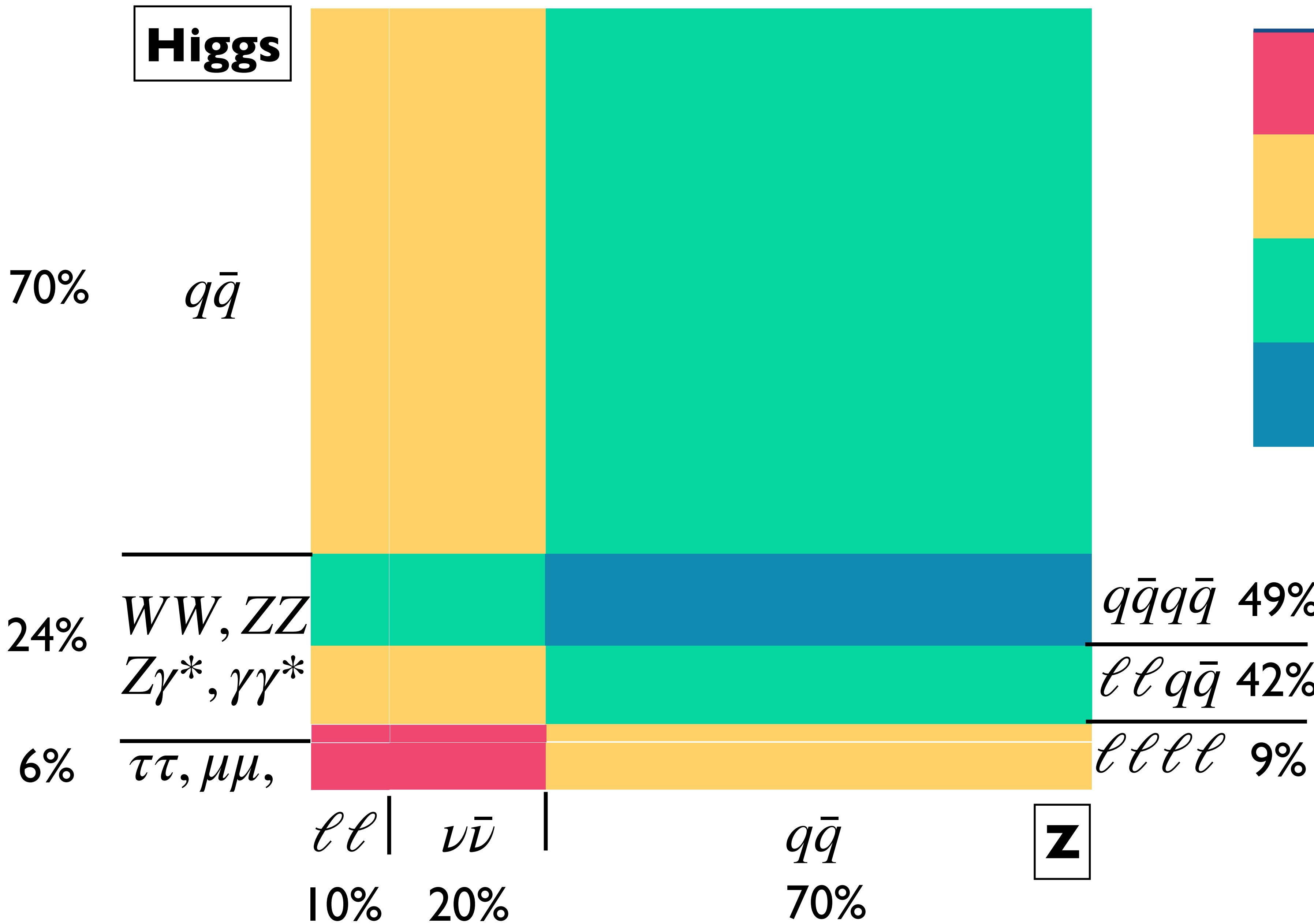
On the behalf of the CEPC Collaboration

Online mini-workshop, National Central University (NCU), Chung-li Taiwan

July 23, 2020

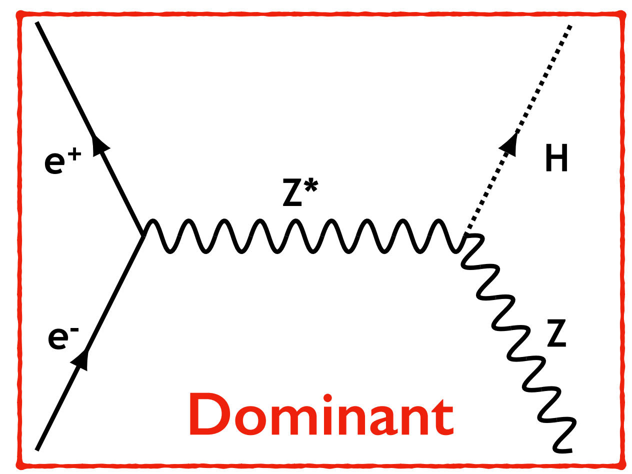
Jets at the Higgs Signal

Higgsstrahlung(ZH) BR Pizza



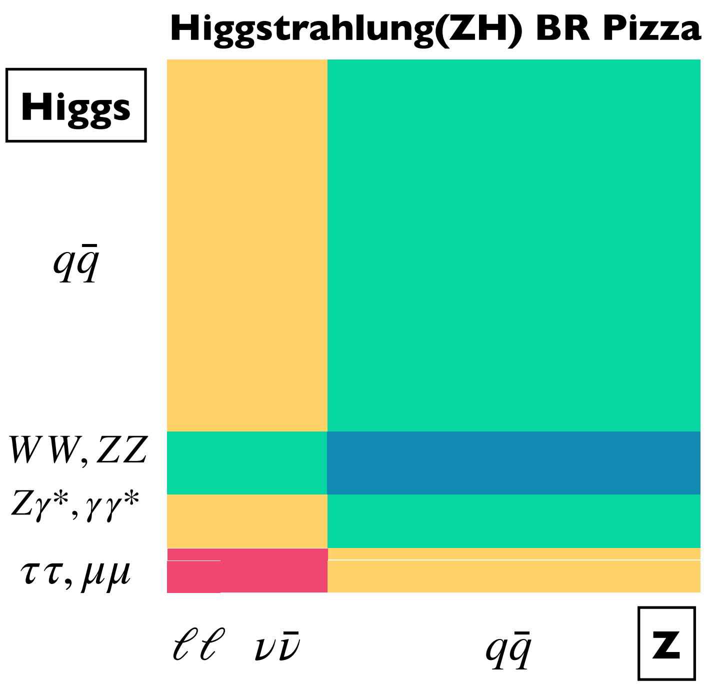
# of jets	Probability
0	2.44%
2	29.73%
4	59.58%
6	8.23%

~ 97% with Jets



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

Jets at the Higgs Signal



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- Major SM Higgs decay mode.
- One color singlet could be identified. (Z or Higgs boson)

2/3 of ZH events
- ZH→$q\bar{q}q\bar{q}$ is dominant.
- Wrong jet pairing is a major uncertainty.

  (Potential huge impact)

- **2/3** of ZH events need dedicated **color-singlet identification** (Z, W, H, γ^*) → Via jet **clustering** and **pairing**.
- **Jet clustering** is also essential for differential & EW precision measurements (e.g. TGCs).

Physical Benchmarks

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BM2: Jet energy and angular differential response

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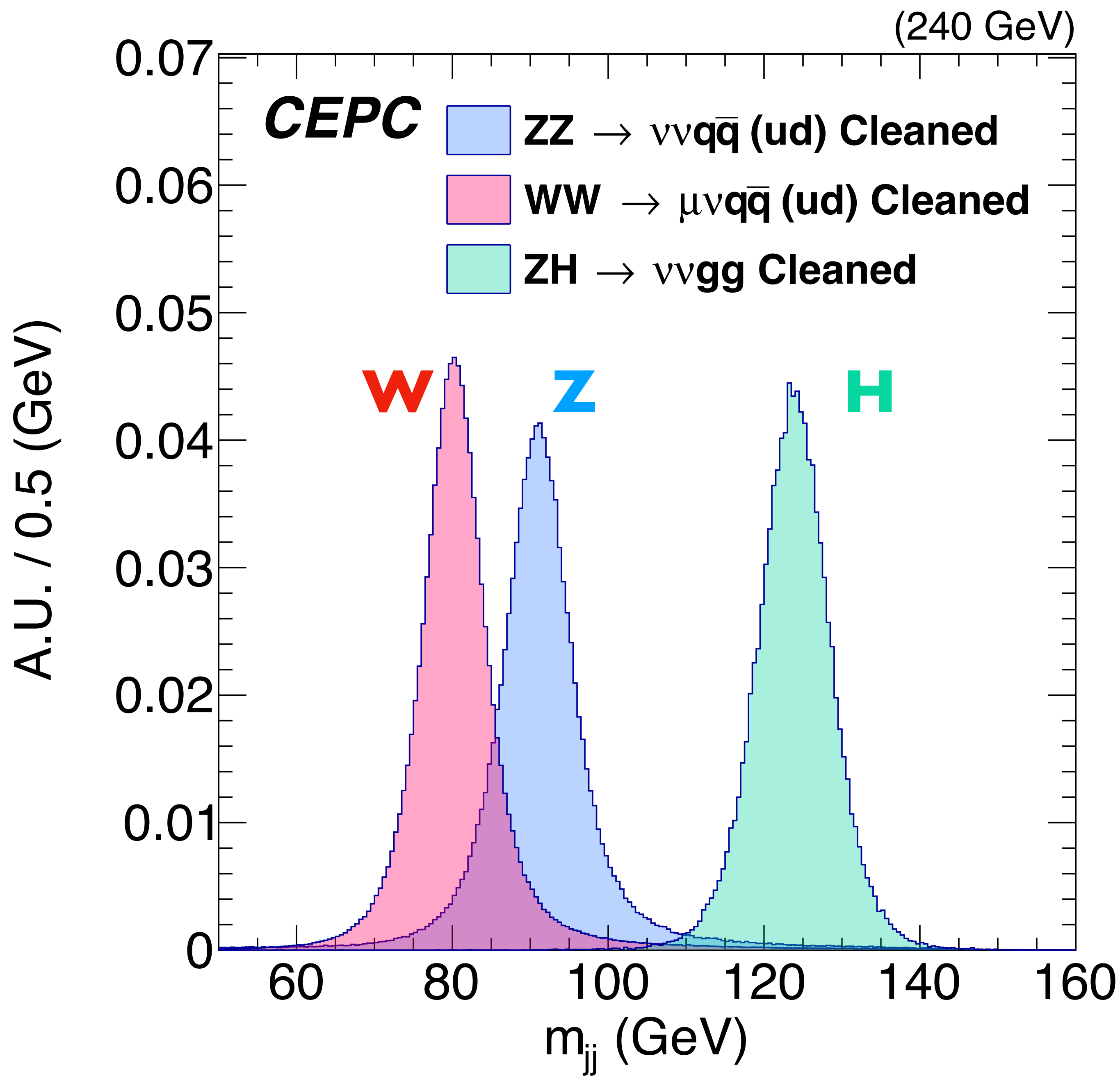
BM1: Massive Boson Mass Resolution



- W-, Z-, and Higgs-boson dijet masses are **well separated** at CEPC.
- Z- and W-boson could be separated ≈ **2σ**.
- **Higgs Boson Mass Resolution = 3.8%** is reached the CEPC baseline.

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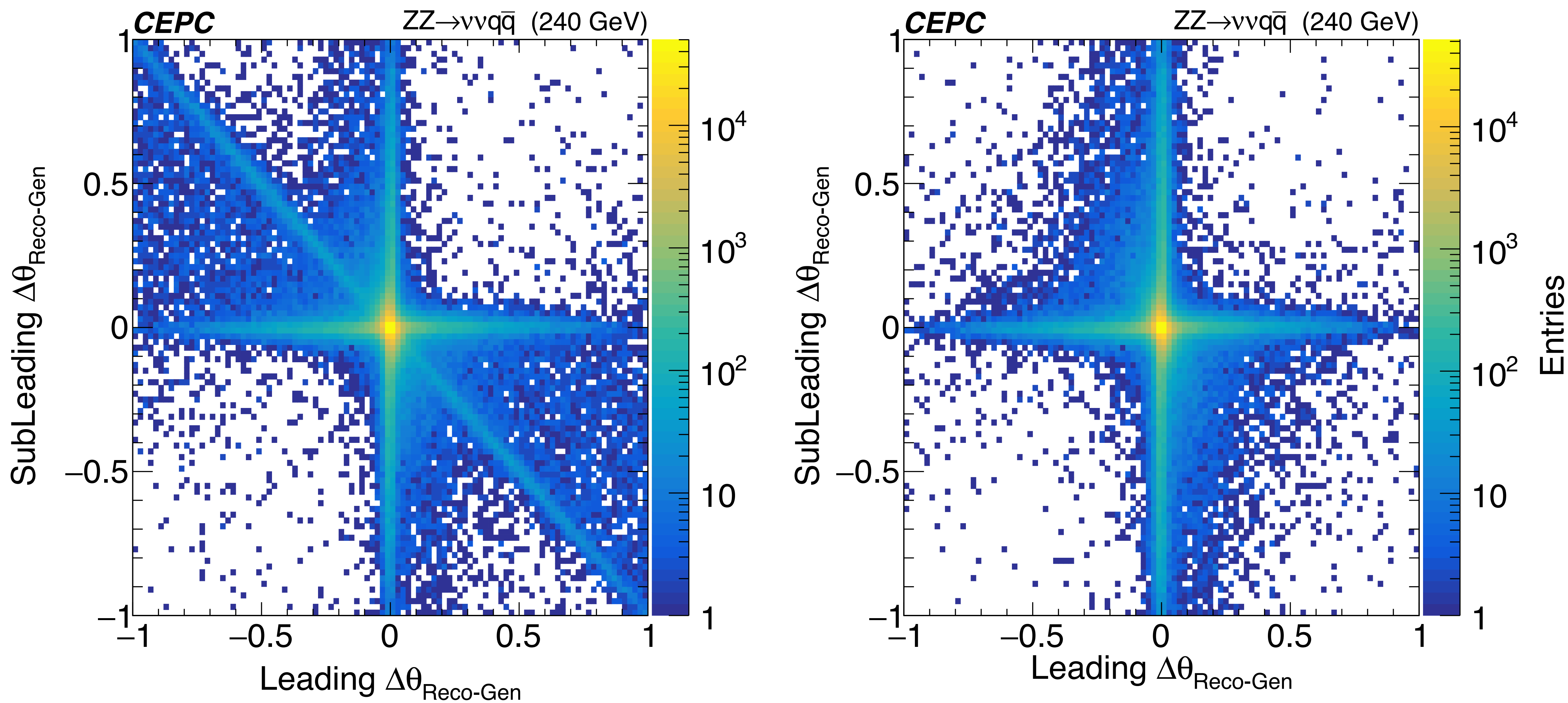
BM2: Jet energy and angular differential response

Matching RecoJet & GenJet

Poor Matching

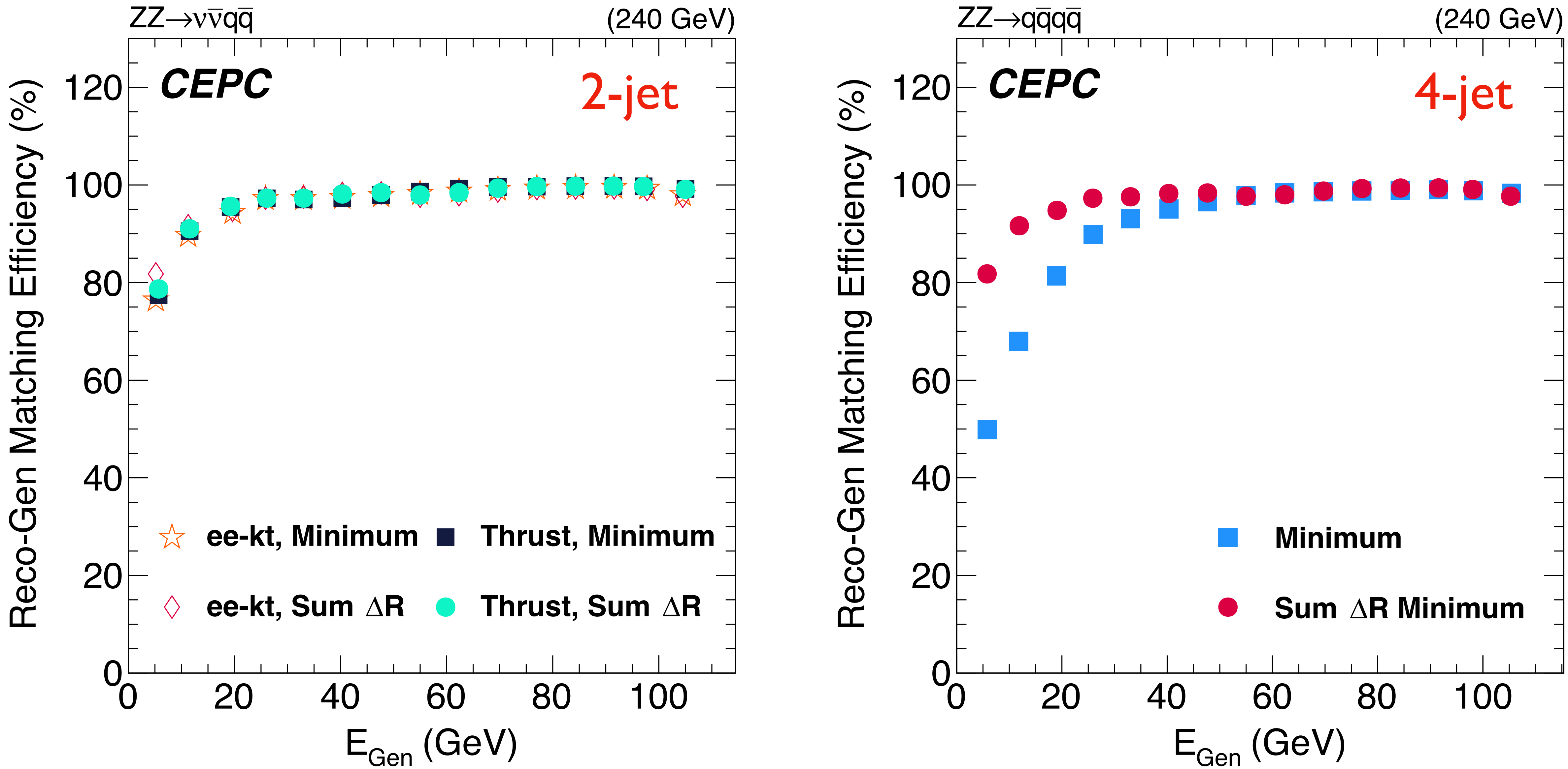
Good Matching



- Two matching methods are studied:
  I. Matching energetic RecoJet to minimum ΔR GenJet.
  II. Minimum combination ΔR ($=\sqrt{\Delta\theta^2+\Delta\phi^2}$) of RecoJet and GenJet. (Adopted)

$$Matching\ Efficiency \equiv \frac{N_{\Delta R<0.4}}{N}$$

Matching RecoJet & GenJet



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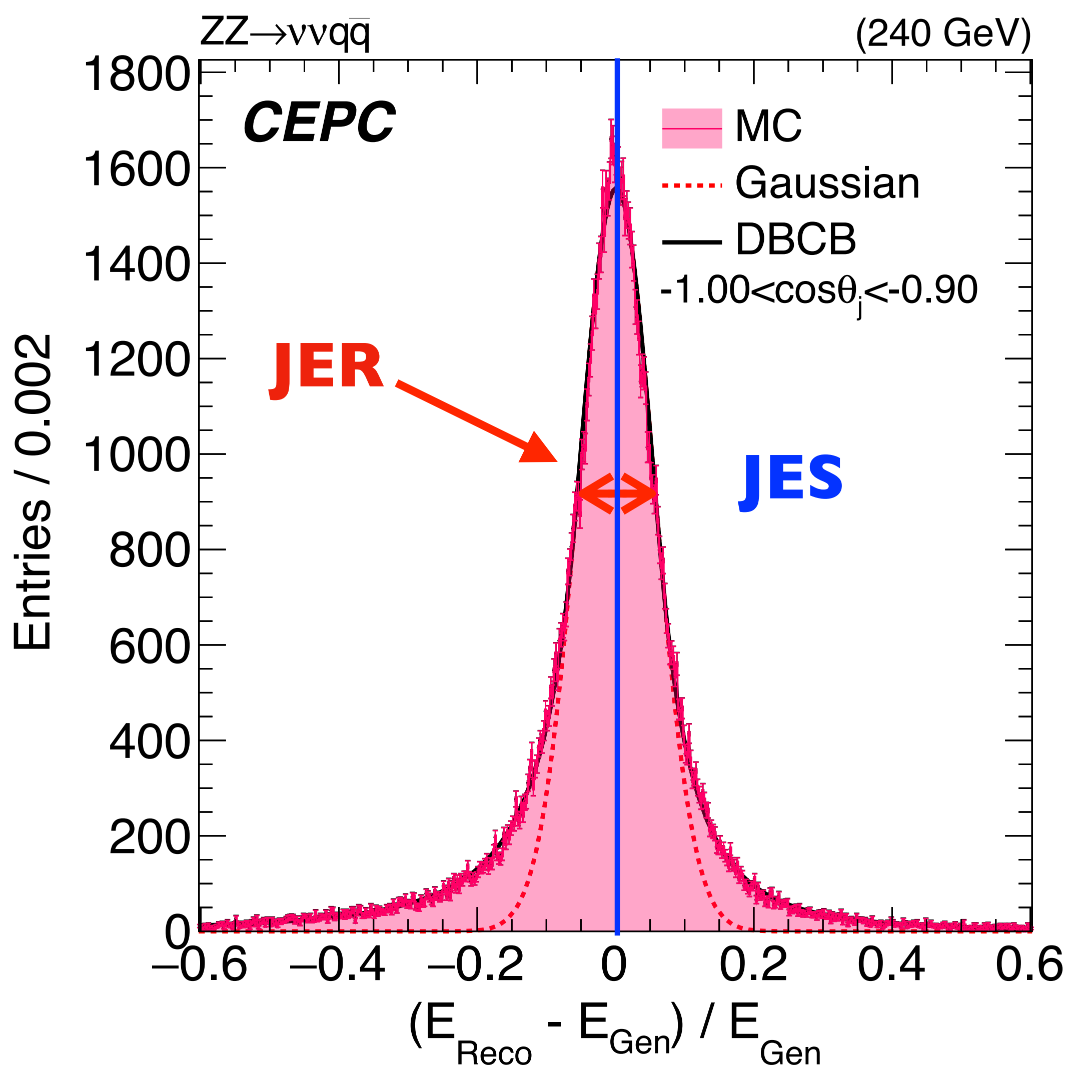
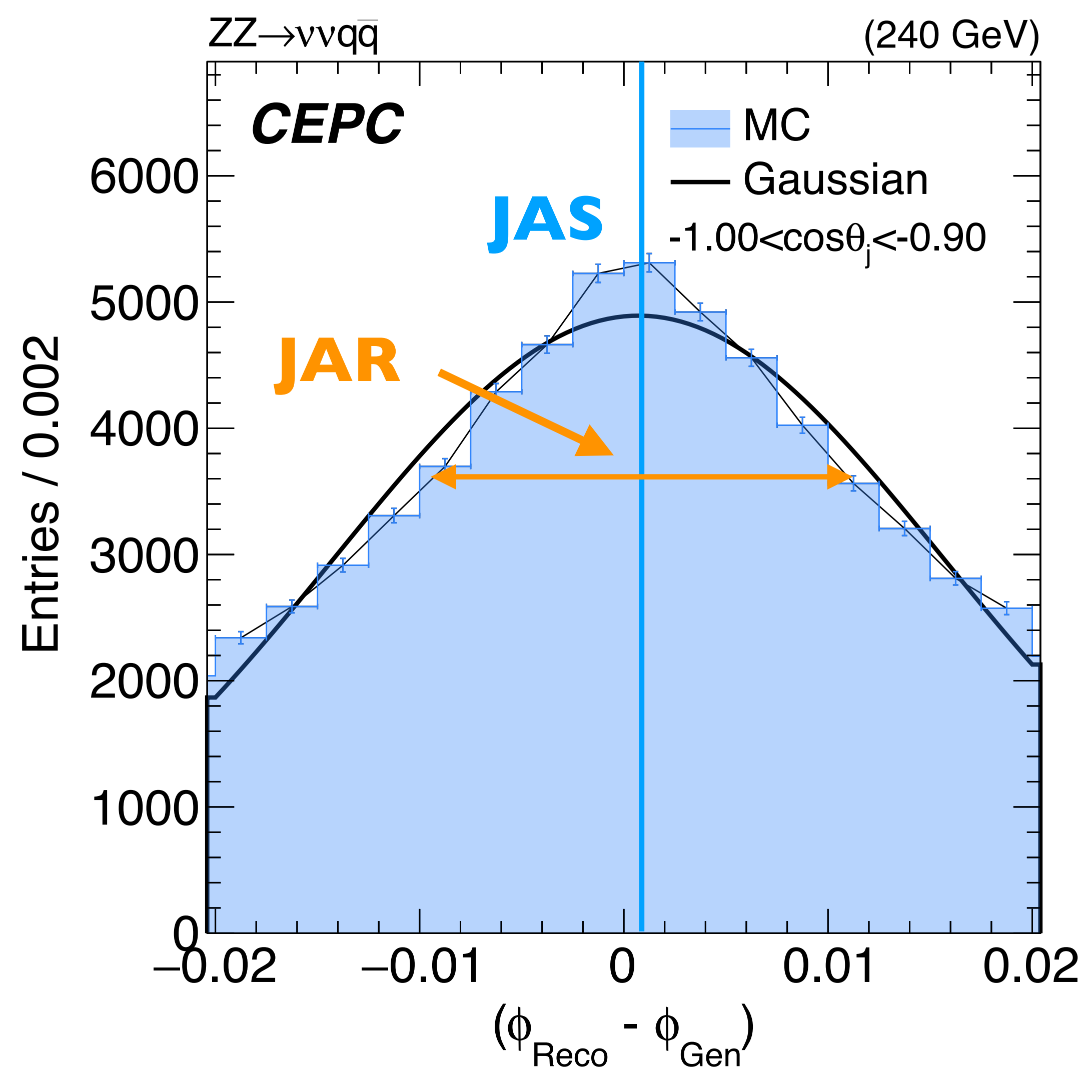
Quantify the Performance

- Double-sided crystal ball (DBCB) function is used to extract energy resolution/scale; Gaussian is used to extracted angular (θ, ϕ) resolution/scale.

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



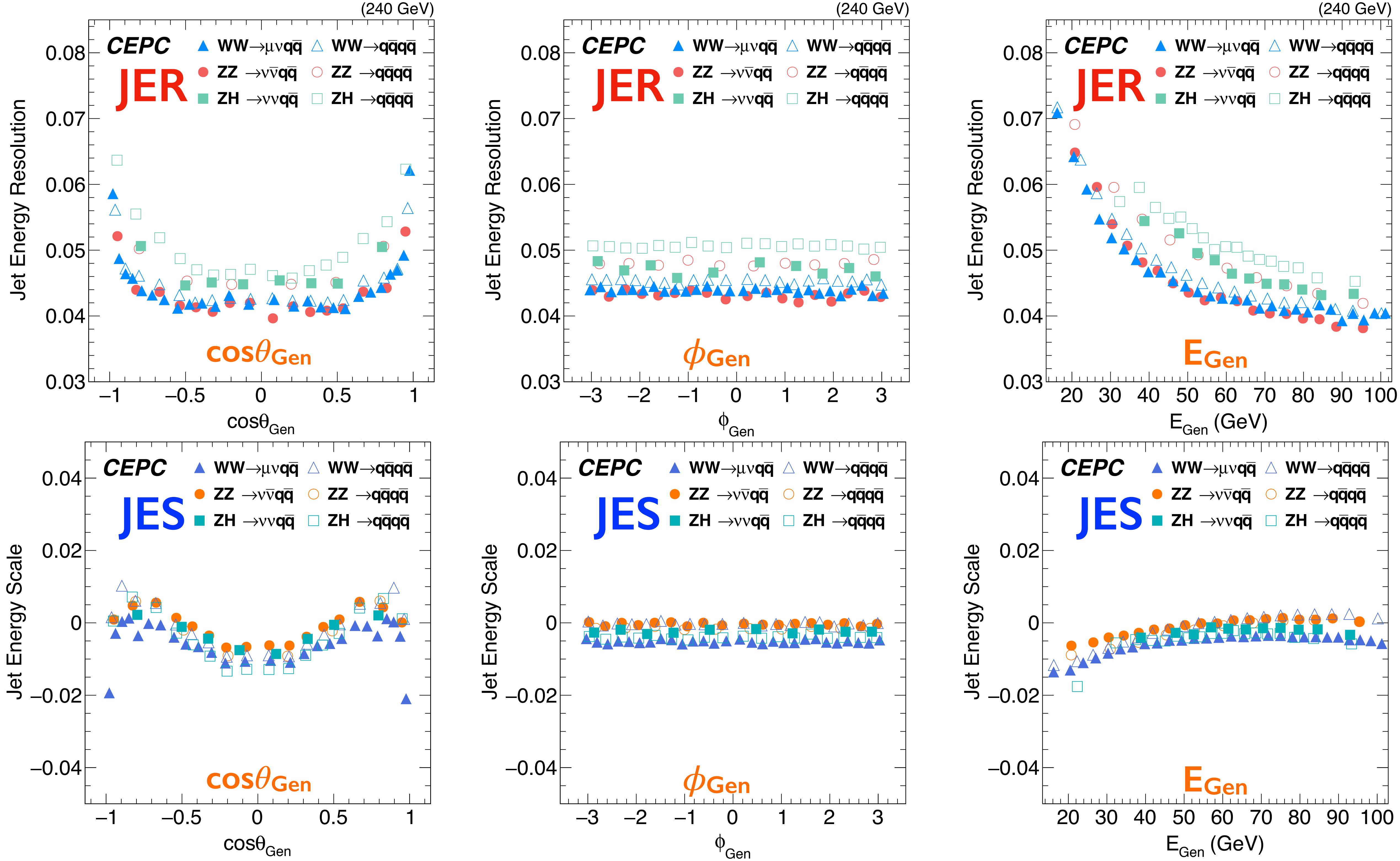
Jet Angular Resolution (JAR)
Jet Angular Scale (JAS)



Energy Relative Difference : $\dfrac{E_{RecoJet} - E_{GenJet}}{E_{GenJet}}$

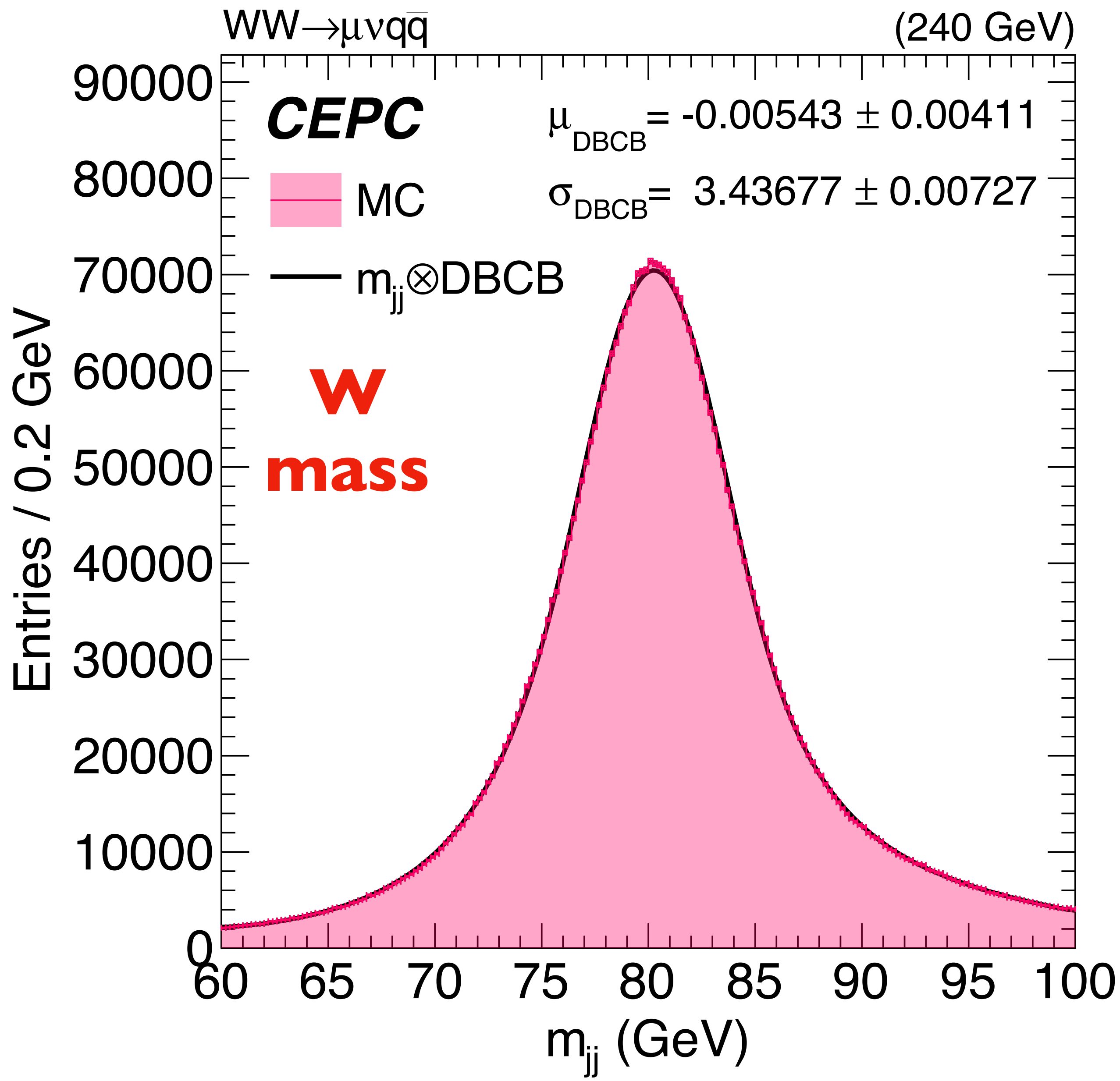
Angular Difference : $\phi_{RecoJet} - \phi_{GenJet}$

BM3: JER & JES (Reco-Gen)



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

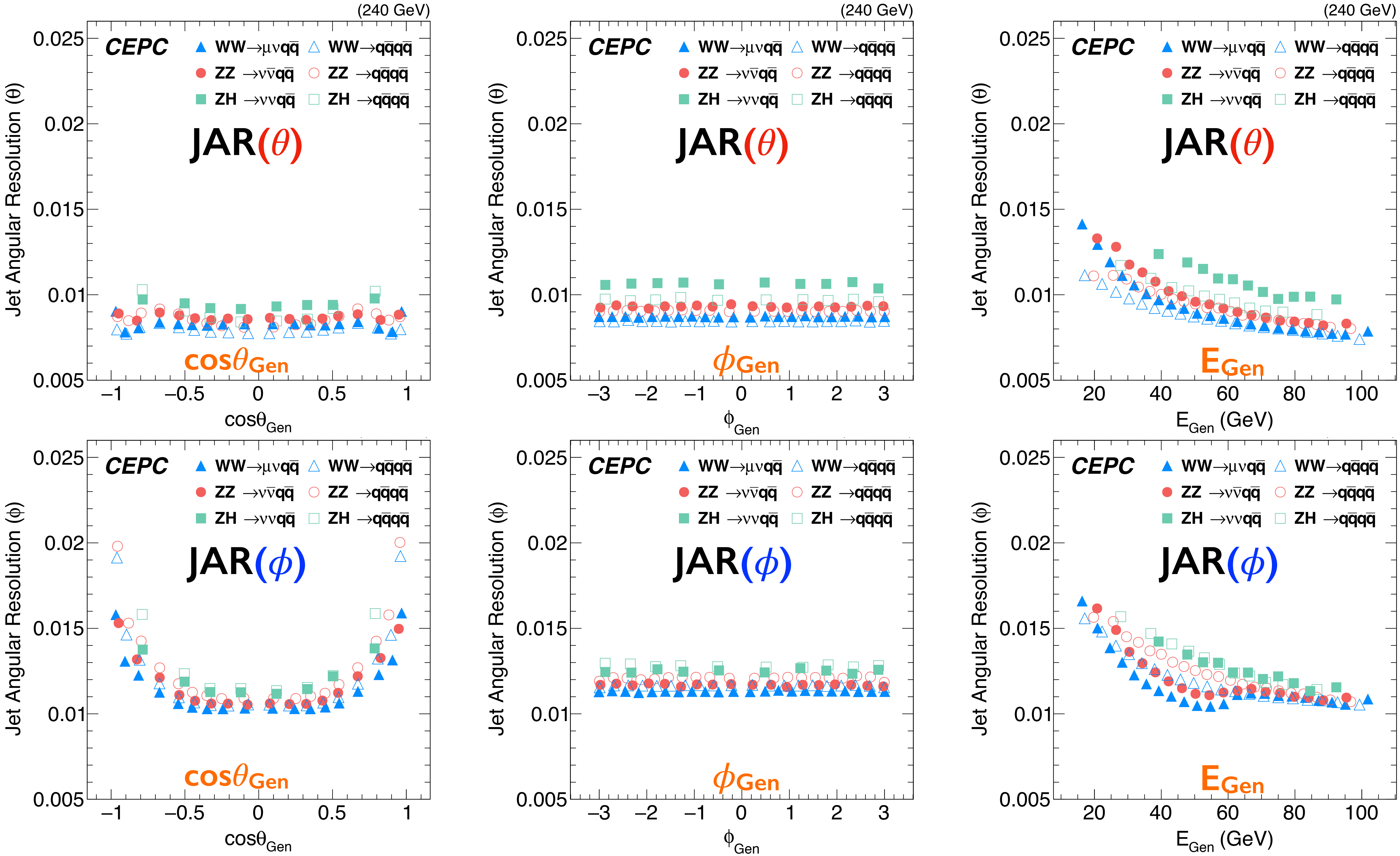
BM3: JES Calibration



Challenge but Important!

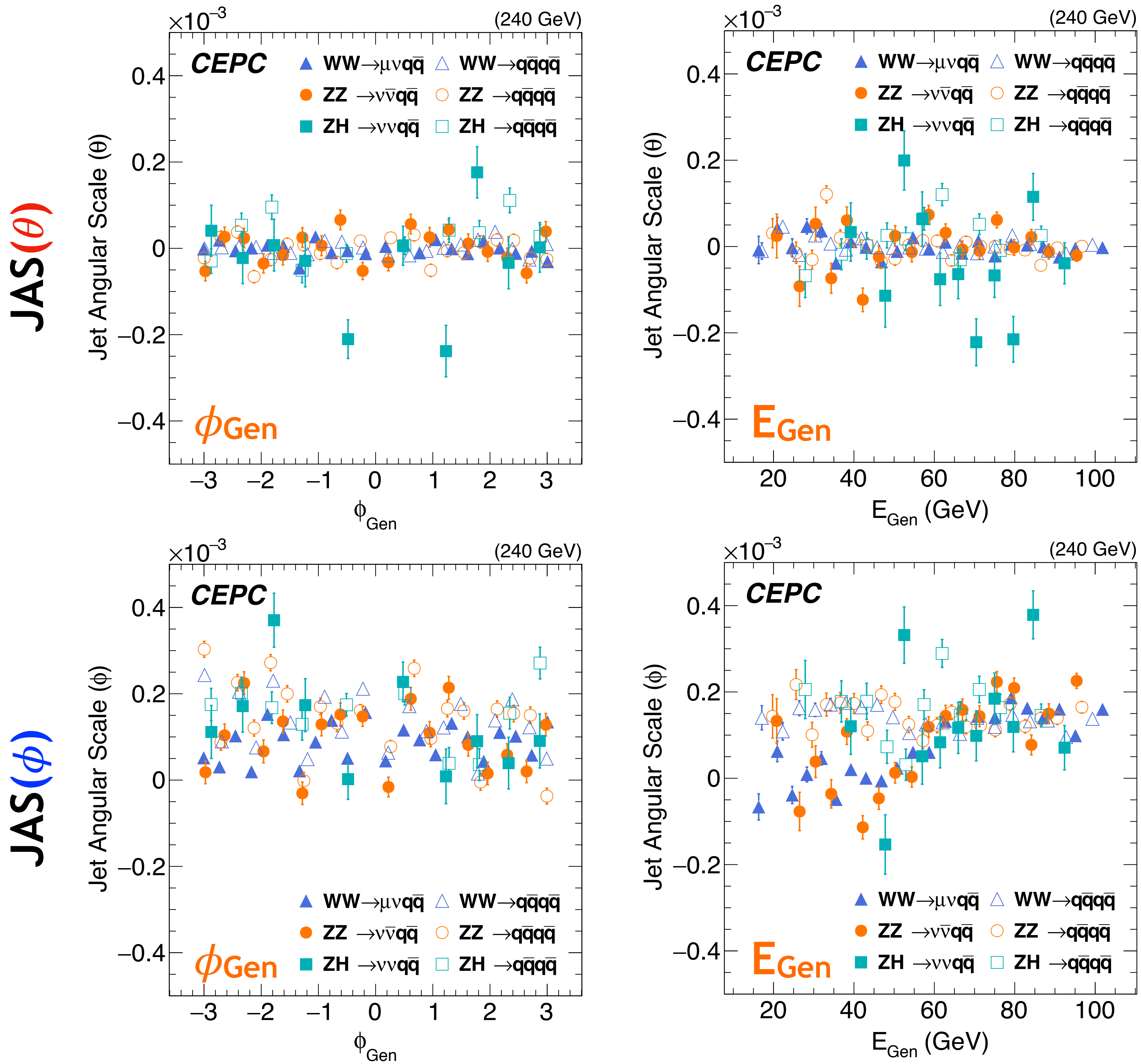
- Multi-differential JES calibration (cosθ, energy, flavor tagging).
- Preliminary W-boson mass uncertainty already at **very small level**.
- Further control the systematic using differential information?

BM3: JAR (Reco-Gen)



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

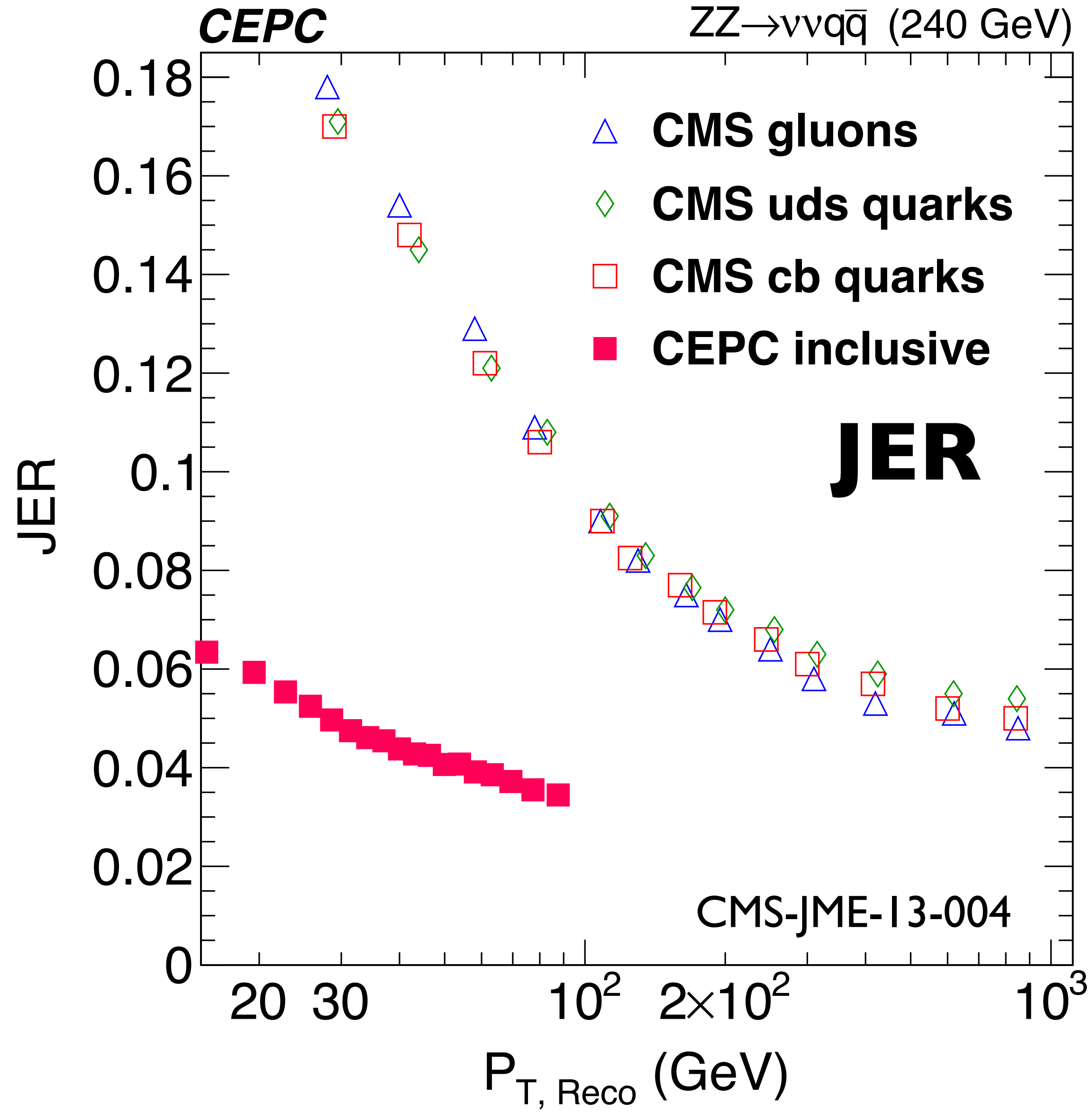
BM3: JAS (Reco-Gen)

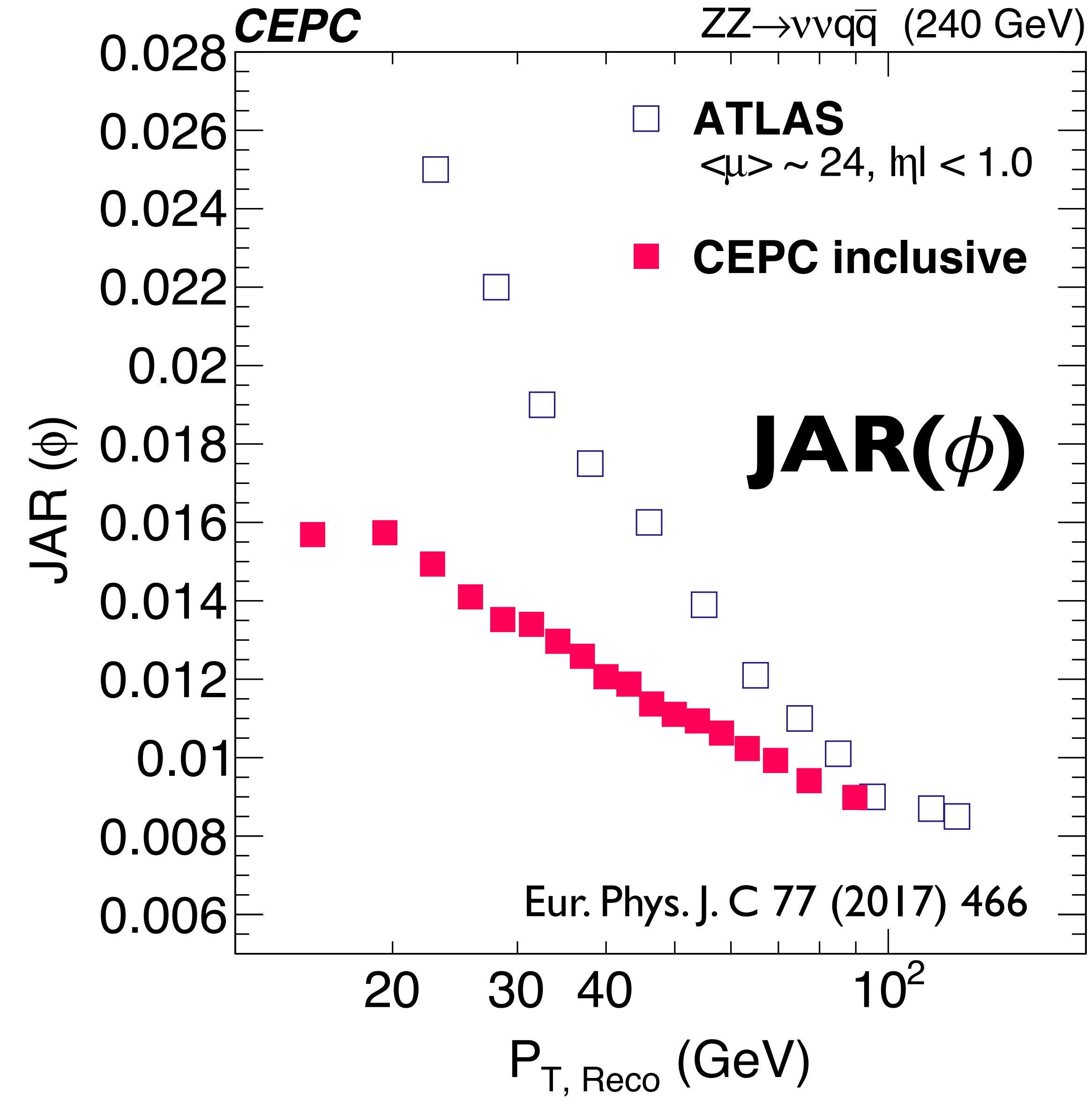


■ JAS(θ) is controlled to be near **0.02%** and JAS(ϕ) is around **0.04%**.

■ RMS of JAS(θ) and JAS(ϕ) is around **10^{-5}**.

Compare to CMS & ATLAS at LHC





- **JER** at CEPC is better than **CMS** as it should be; **3-4 times** better in the same pT region.
- **JAR(ϕ)** at CEPC is better than **ATLAS** as it should be; **1.0-1.6 times** better in the same pT region.

- Free from: QCD Background, Underlying Event, Pile Up.
- Benefit from: PFA (Arbor), Fine-segments of Calorimeter

Physical Benchmarks

# of jets	Probability
0	2.44%
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BM3: # of jet identification & thrust based algorithm

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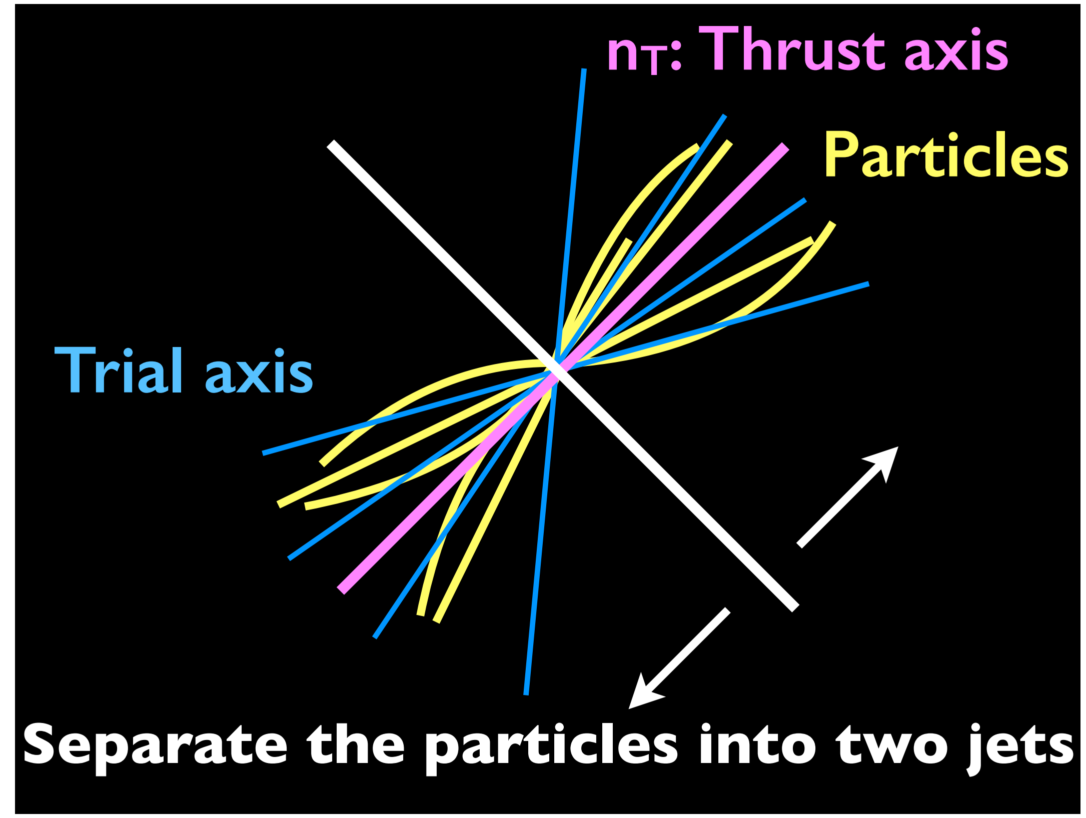
(Potential huge impact)

- **2/3** of ZH events need dedicated **color-singlet identification** (Z, W, H, γ^*) → Via jet **clustering** and **pairing**.
- **Jet clustering** is also essential for differential & EW precision measurements (e.g. TGCs).

BM2: Thrust Jet Clustering Method

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

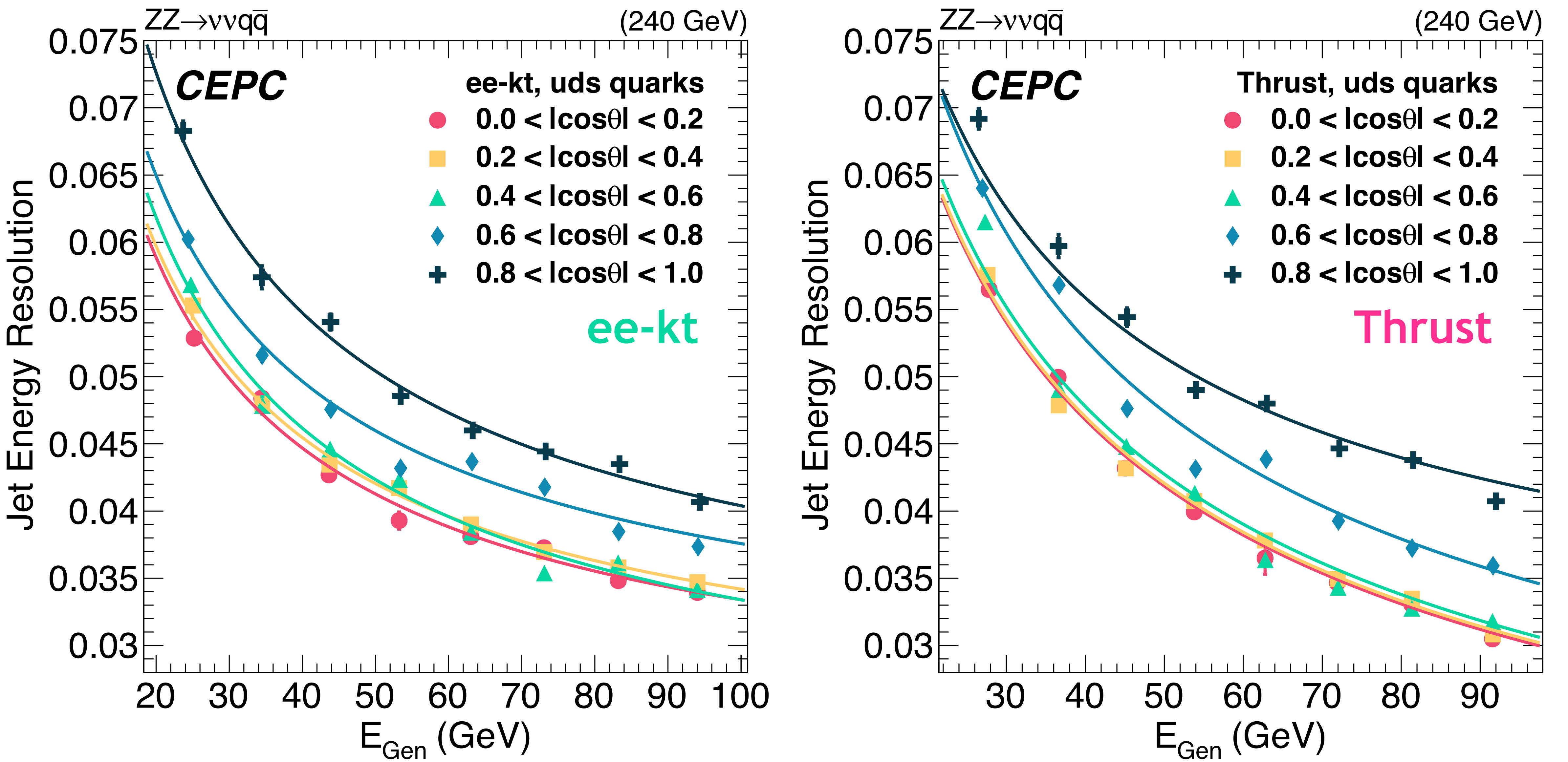


P_i or P_j : Momentum of each particle

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

- Thrust is one kind of event-shape variable.
- The nature of the clustering idea for the **single boson to 2-jet events**.
  1. Boosting the system back to the rest frame.
  2. Find out a vector in the θ and ϕ phase space with highest momentum flux.
  3. Divide the system into 2 hemispheres with the thrust axis, and each identified as a jet. (Only applicable to **2 jets event**)

BM3: JER (ee-kt—Thrust)

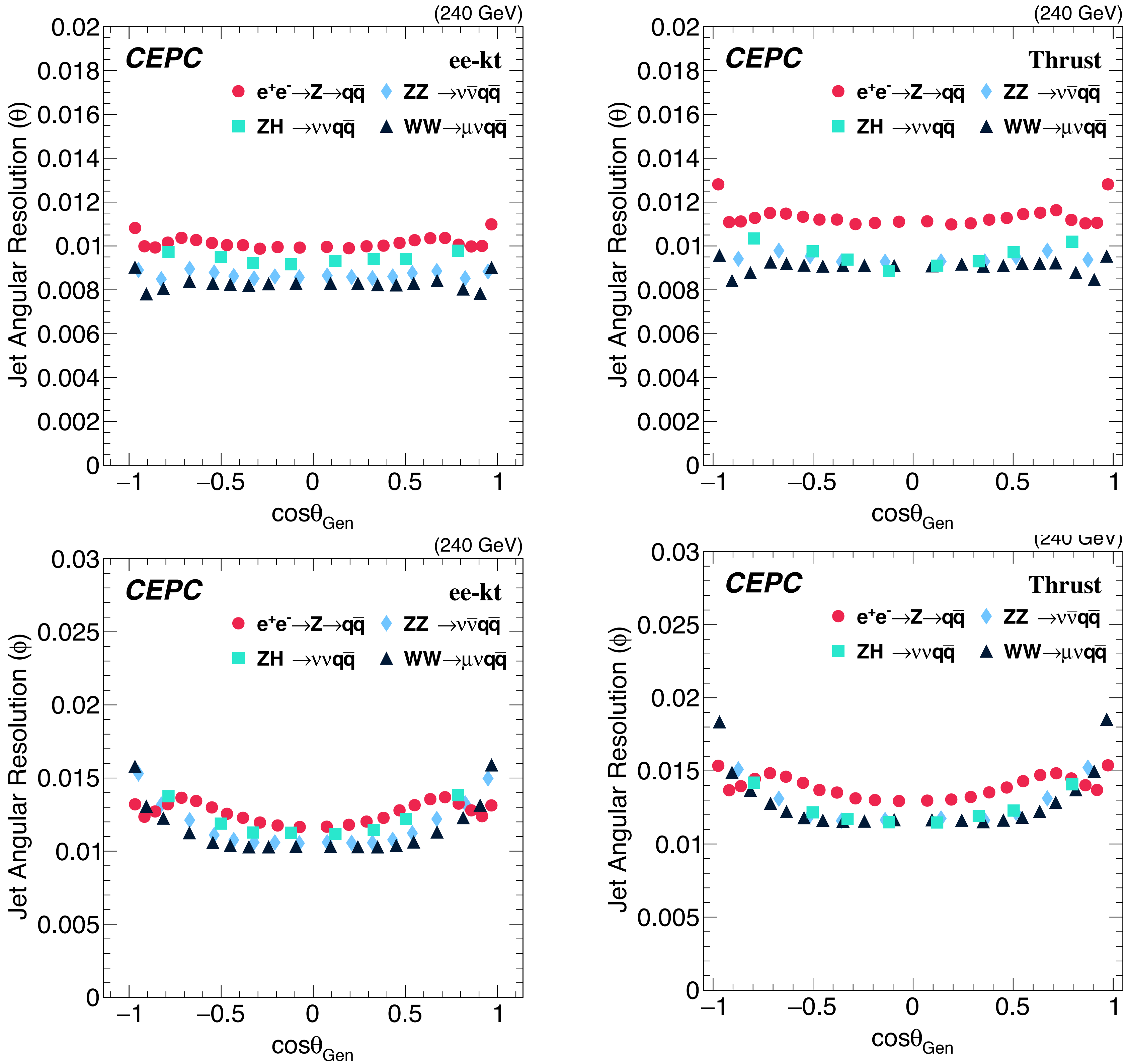


- The improvement brought from thrust based algorithm is significant at high energy region (**E_j > 60 GeV**) and central detector region (**$|\cos\theta_j|$ < 0.6**).
- Improvement comes from boosted object separation in thrust based algorithm.

BM3: JAR (ee-kt—Thrust)

JAR(θ)

JAR(ϕ)



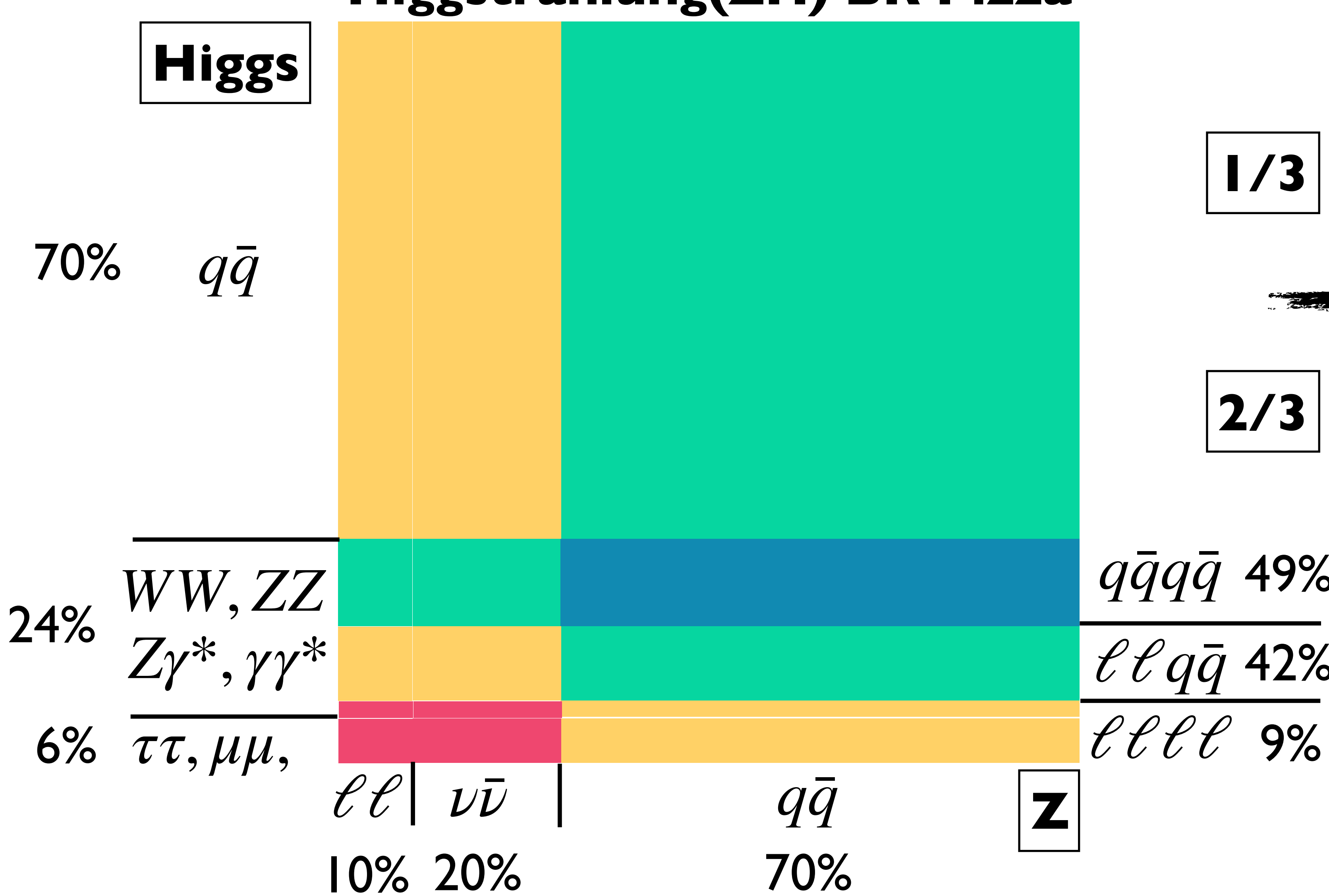
■ Both of jet θ and ϕ angular resolution are degraded by thrust method around 10%.

Summary(1/2)

- **Jets are crucial for the CEPC Higgs physics and EW physics**
  - 97% of ZH events involve jets
  - **1/3** of ZH events come from only 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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Summary(2/2)

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

- 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%.

- All of the dominant jet processes have been studies.

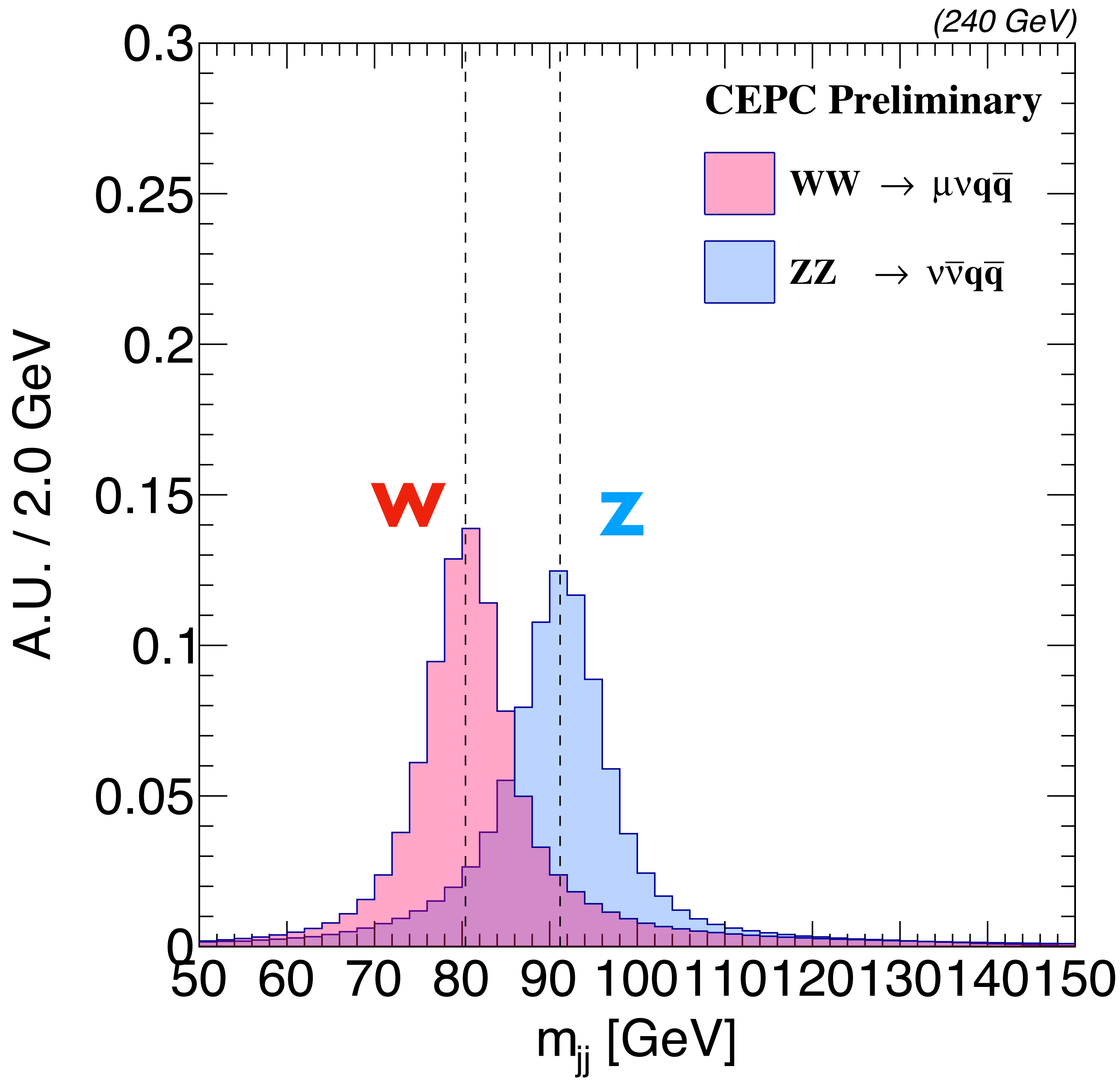
III. 2-jet final-states could be identified with *efficiency×purity* = 88.4%.

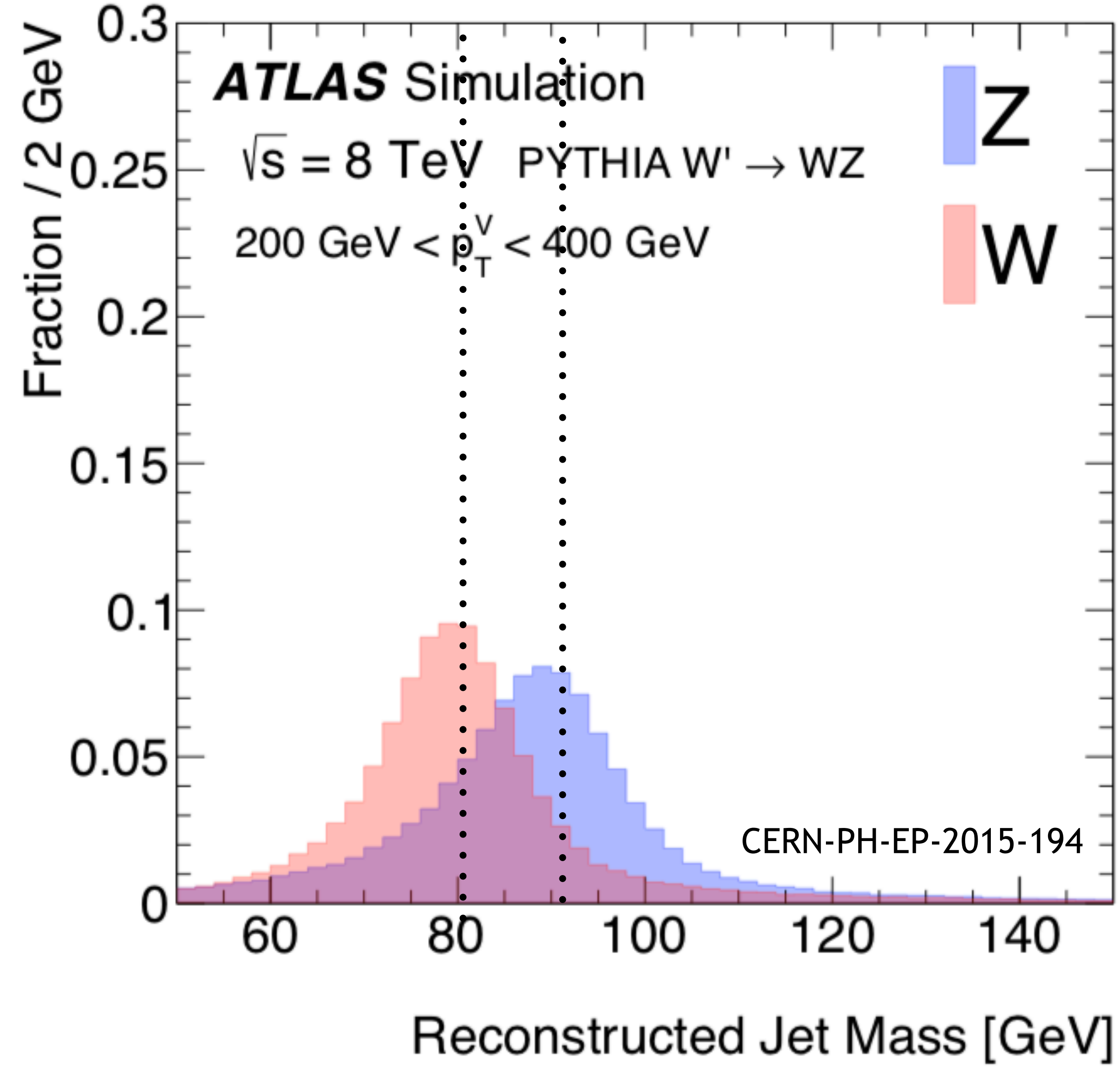
- Have designed a dedicatedly algorithm, thrust based algorithm.
- JER is improved ~10% in $|\cos\theta_j| < 0.6$; JAR is degraded ~10%.

Thank for your attention

Back up

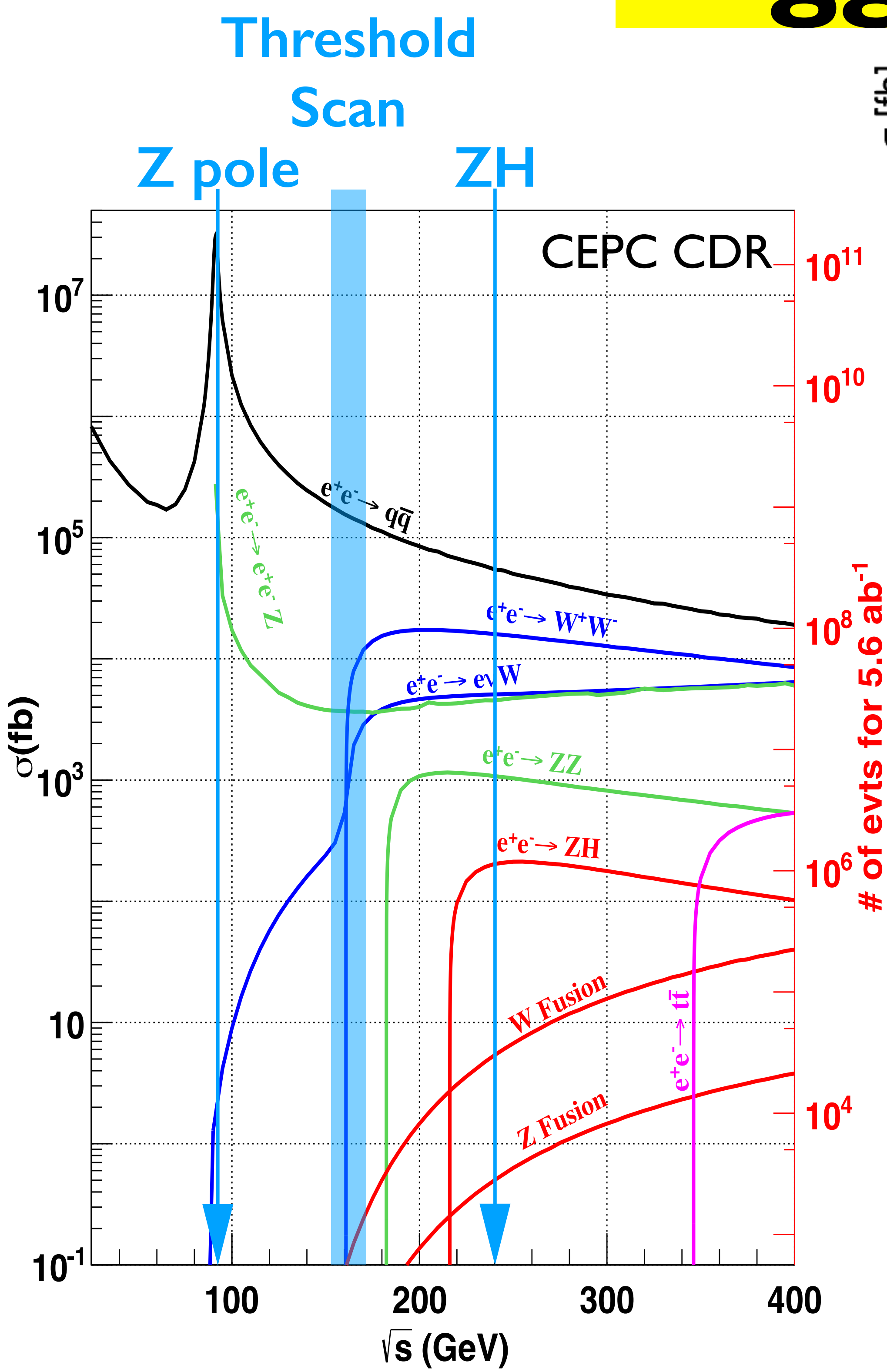
BM1: Massive Boson Mass Resolution

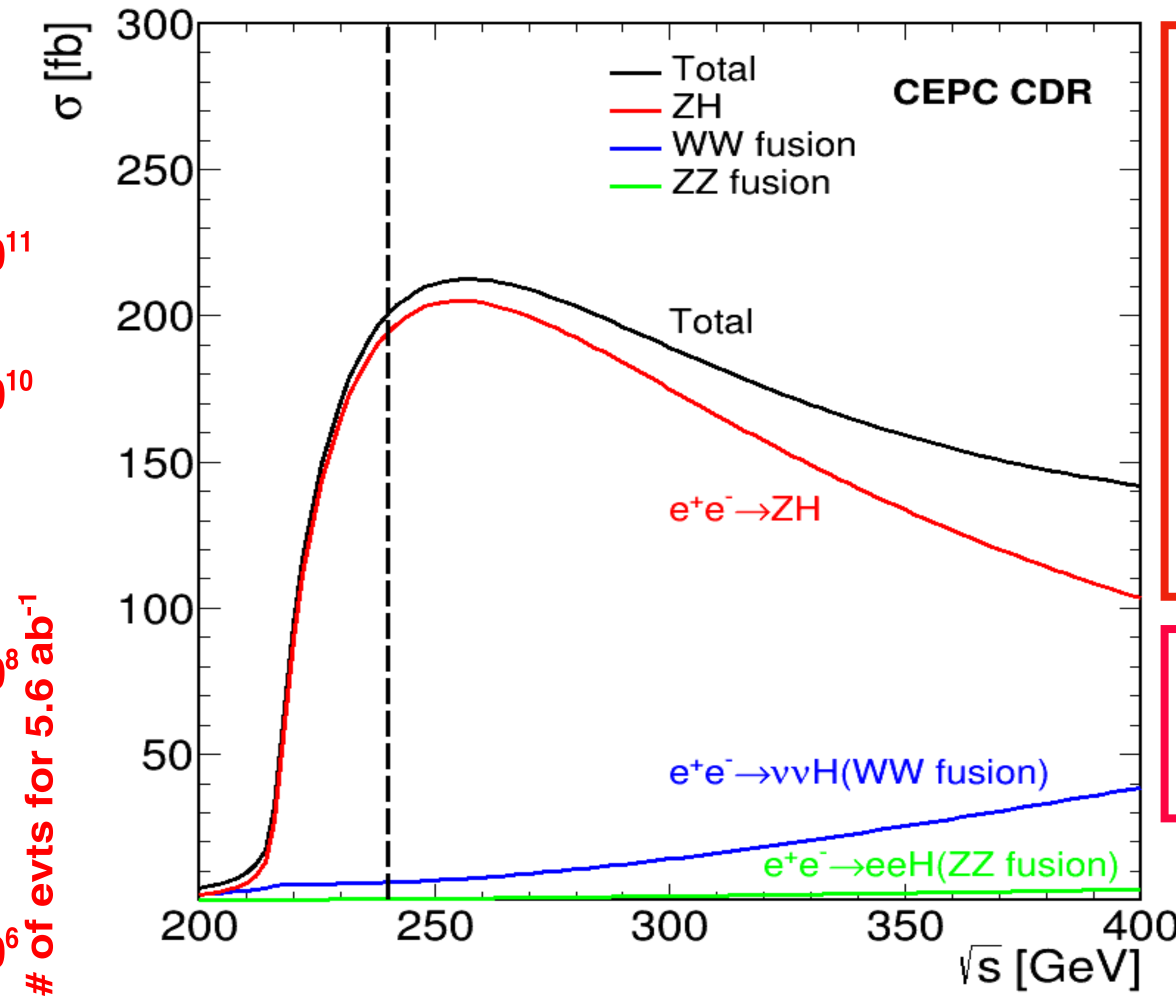


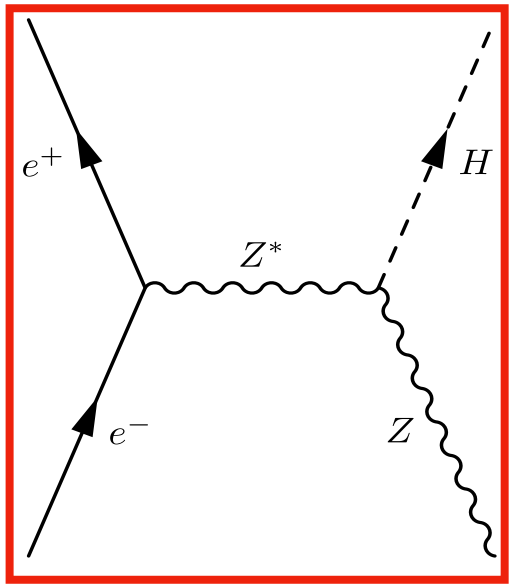


- The separation of Z- and W-boson at CEPC is better than ATLAS as it should be.
  → Better collision environment and dedicatedly designed PFA and detector.

Higgs Production at CEPC







S : B =
1 : (100 ~ 1000)

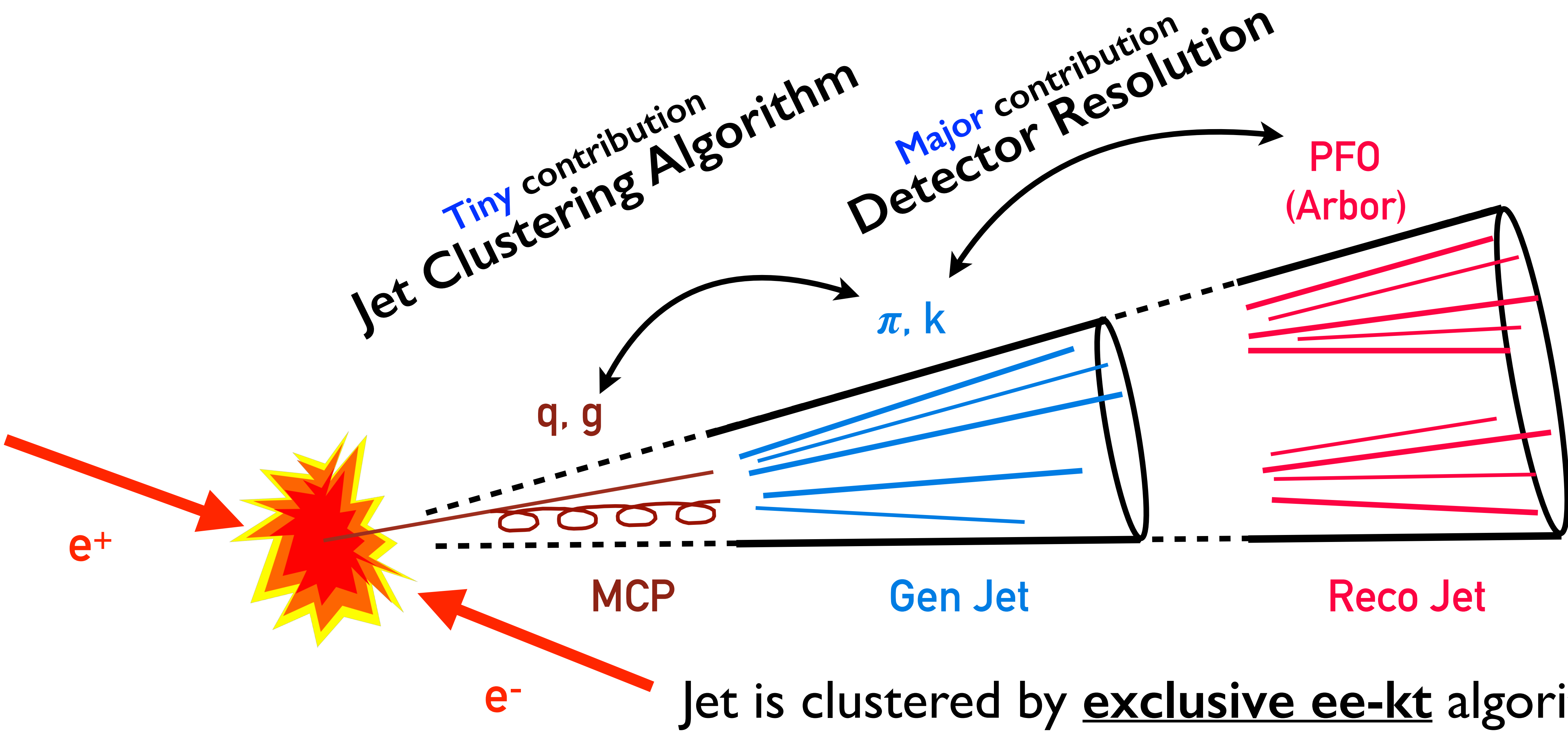
Process	Cross section(fb)	Events in 5.6 ab^{-1}
$e^+e^-\to ZH$	196.2	1.10×10^6
$e^+e^-\to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^-\to e^+e^-H$	0.28	1.57×10^3
Total	203.7	1.14×10^6

- Observables: Higgs mass, **σ(ZH)**, event rate (σ(ZH, ννH) x Br(H→X)), Diff.

→ **Absolute Higgs width**, branching ratio, **couplings**

Objects Definition

- **MCPs** represents initial parton of MC quark. The original state of quark.
- **GenJets** are all MC particles grouped with cτ > 1cm except neutrinos 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.

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

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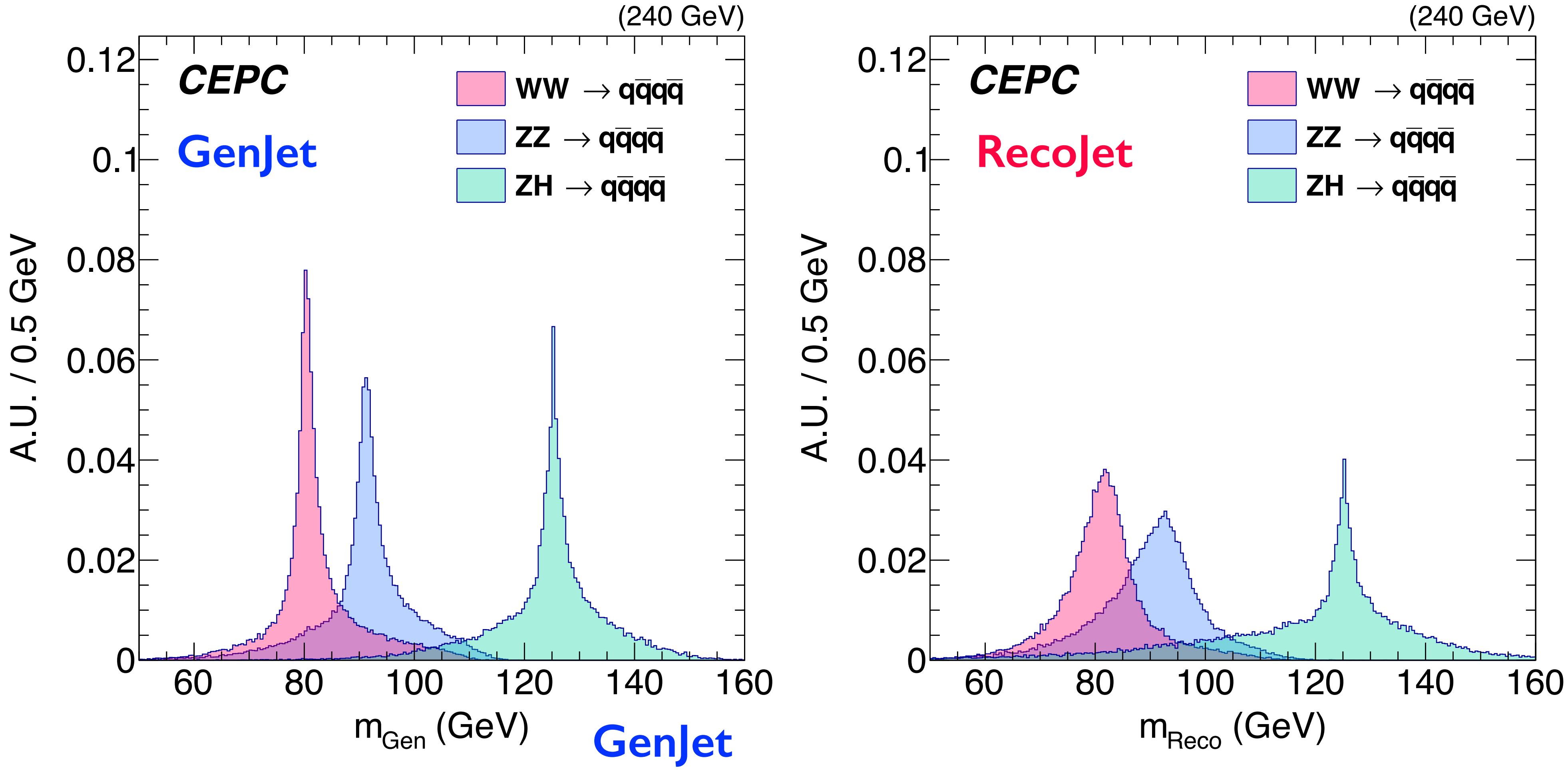
BM4: WW, ZZ, ZH to 4-jet Separation



GenJet

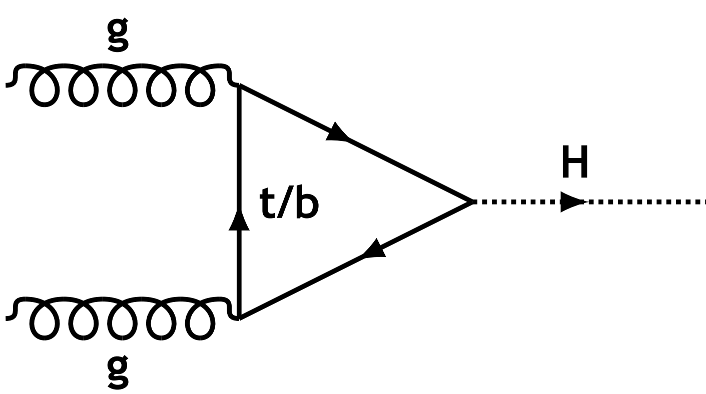
Sample \ Assignment(%)	WW	ZZ	ZH
WW	63.24	18.95	17.81
ZZ	16.09	57.89	26.02
ZH	9.99	13.84	76.17

RecoJet

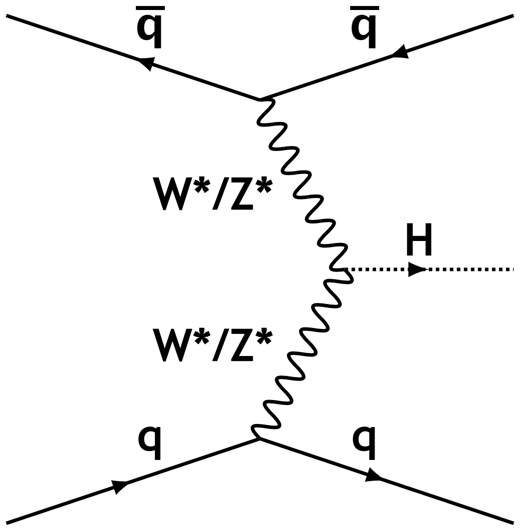
Sample \ Assignment(%)	WW	ZZ	ZH
WW	64.98	19.07	15.94
ZZ	26.51	50.54	22.96
ZH	20.29	22.93	56.77

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

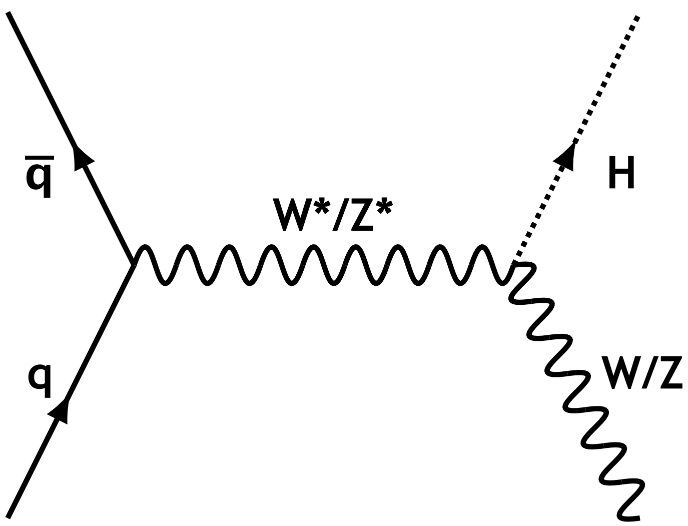
Higgs Production @ Hadron Collider



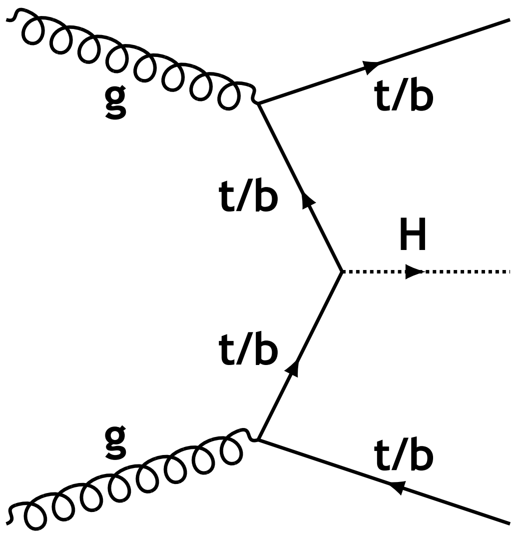
ggF
Gluon-gluon Fusion



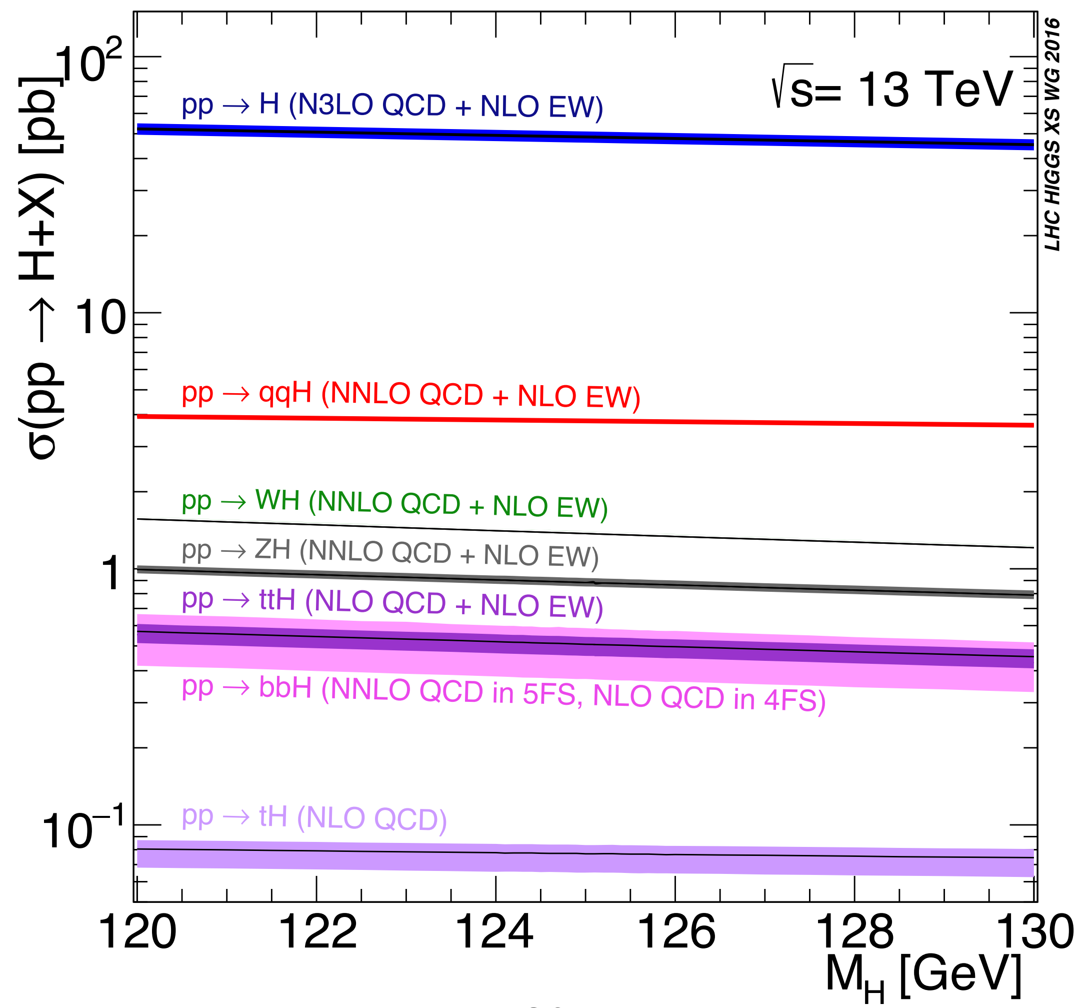
VBF
Vector boson fusion



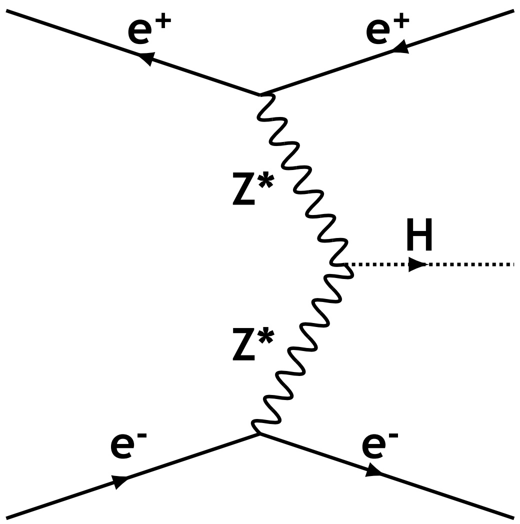
WH/ZH
Associated vector boson fusion



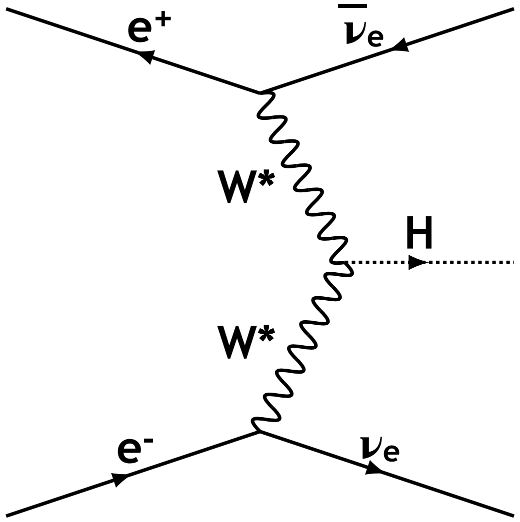
ttH
Associated top-quark pair production



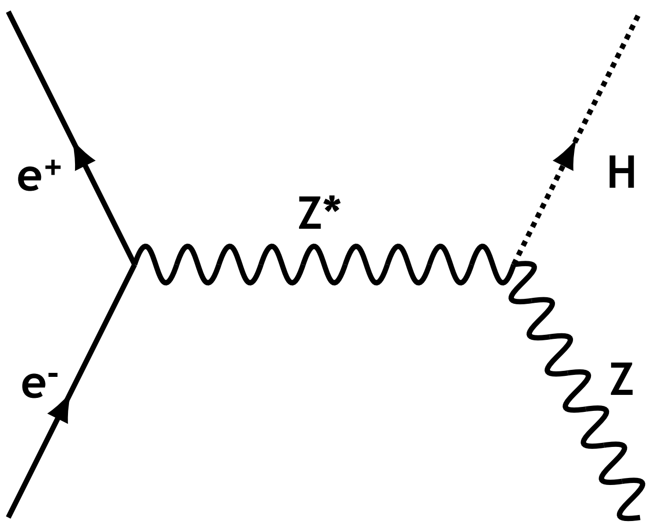
Higgs Production @ Lepton Collider



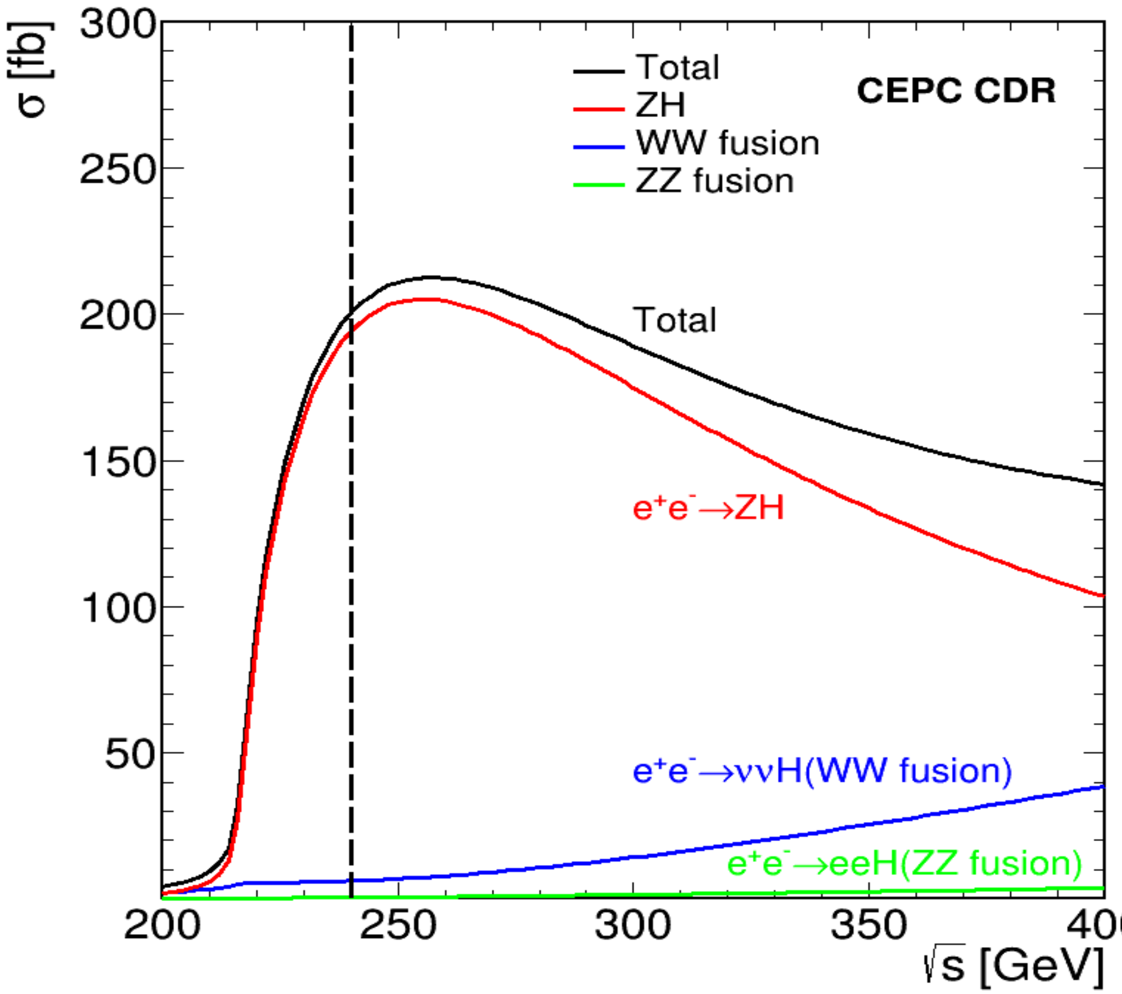
e^+e^-**H**
Z Fusion



$\nu_e\bar{\nu}_e$**H**
W fusion



ZH
Associated vector boson fusion



SM Production @ Lepton Collider

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Higgs boson production, cross section in fb		
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$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^- \to ZH$	0.28	1.57×10^3
Total	203.7	1.14×10^6

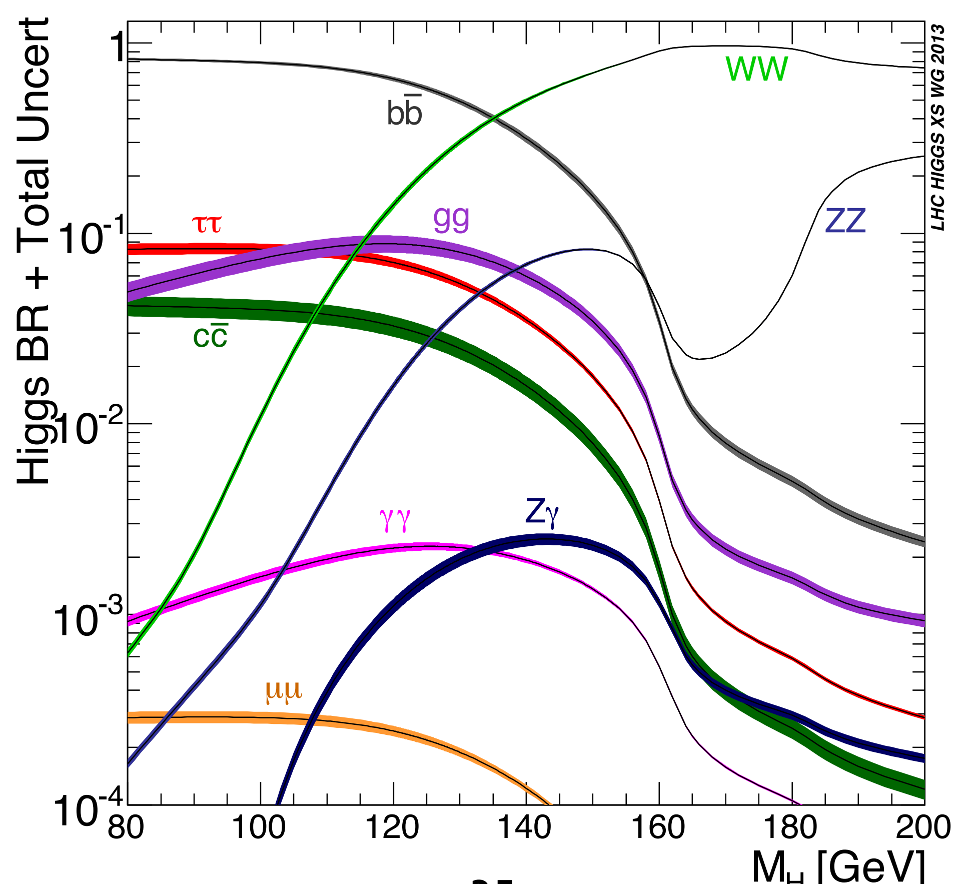
Background production, cross section in pb		
$e^+e^- \to e^+e^+(\gamma)$ (Bhabha)	930	5.2×10^9
$e^+e^- \to q\bar{q}(\gamma)$	54.1	3.0×10^8
$e^+e^- \to \mu^+\mu^-(\gamma)$ [or $\tau^+\tau^-(\gamma)$]	5.3	3.0×10^7
$e^+e^- \to WW$	16.7	9.4×10^7
$e^+e^- \to ZZ$	1.1	6.2×10^6
$e^+e^- \to e^+e^-ZZ$	4.54	2.5×10^7
$e^+e^- \to e^+\nu W^-/e^-\bar{\nu}W^+$	5.09	2.6×10^7

$Z \to \ell^+\ell^-$: **10%**
$Z \to \nu\nu$: **20%**
$Z \to q\bar{q}$: **70%**

$W \to \ell\nu$: **30%**
$W \to q\bar{q}$: **70%**

Higgs Decay Modes

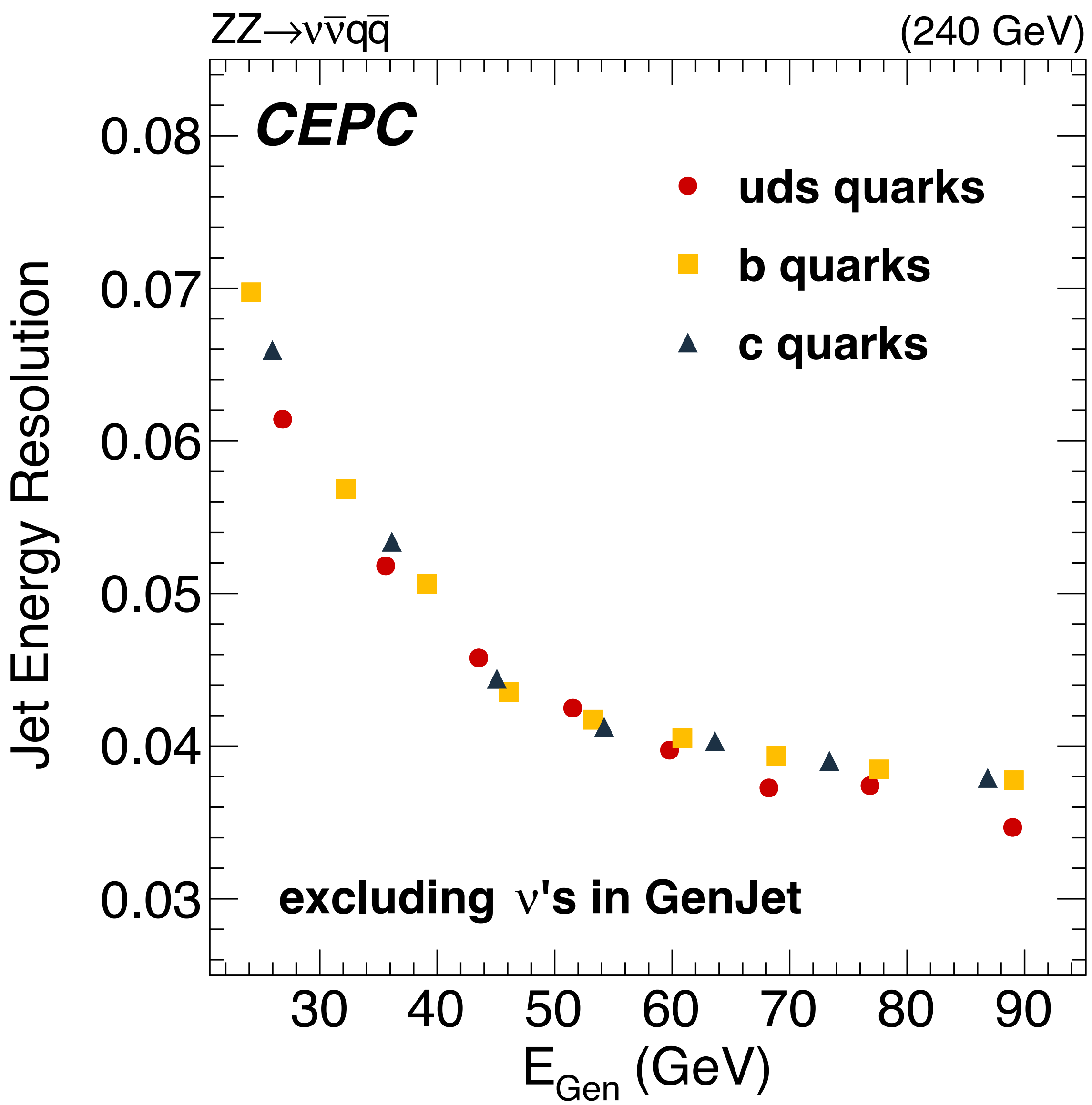
Decay mode	Branching ratio	Relative uncertainty (%)
$H \to b\bar{b}$	57.7%	(+3.2, -3.3)
$H \to c\bar{c}$	2.91%	(+12, -12)
$H \to gg$	8.57%	(+10, -10)
$H \to \tau^+\tau^-$	6.32%	(+5.7, -5.7)
$H \to \mu^+\mu^-$	2.19×10^{-4}	(+6.0, -5.9)
$H \to WW^*$	21.5%	(+4.3, -4.2)
$H \to ZZ^*$	2.64%	(+4.3, -4.2)
$H \to \gamma\gamma$	2.28×10^{-3}	(+5.0, -4.9)
$H \to Z\gamma$	1.53×10^{-3}	(+9.0, -8.8)
Γ_H	4.07 MeV	(+4.0, -4.0)

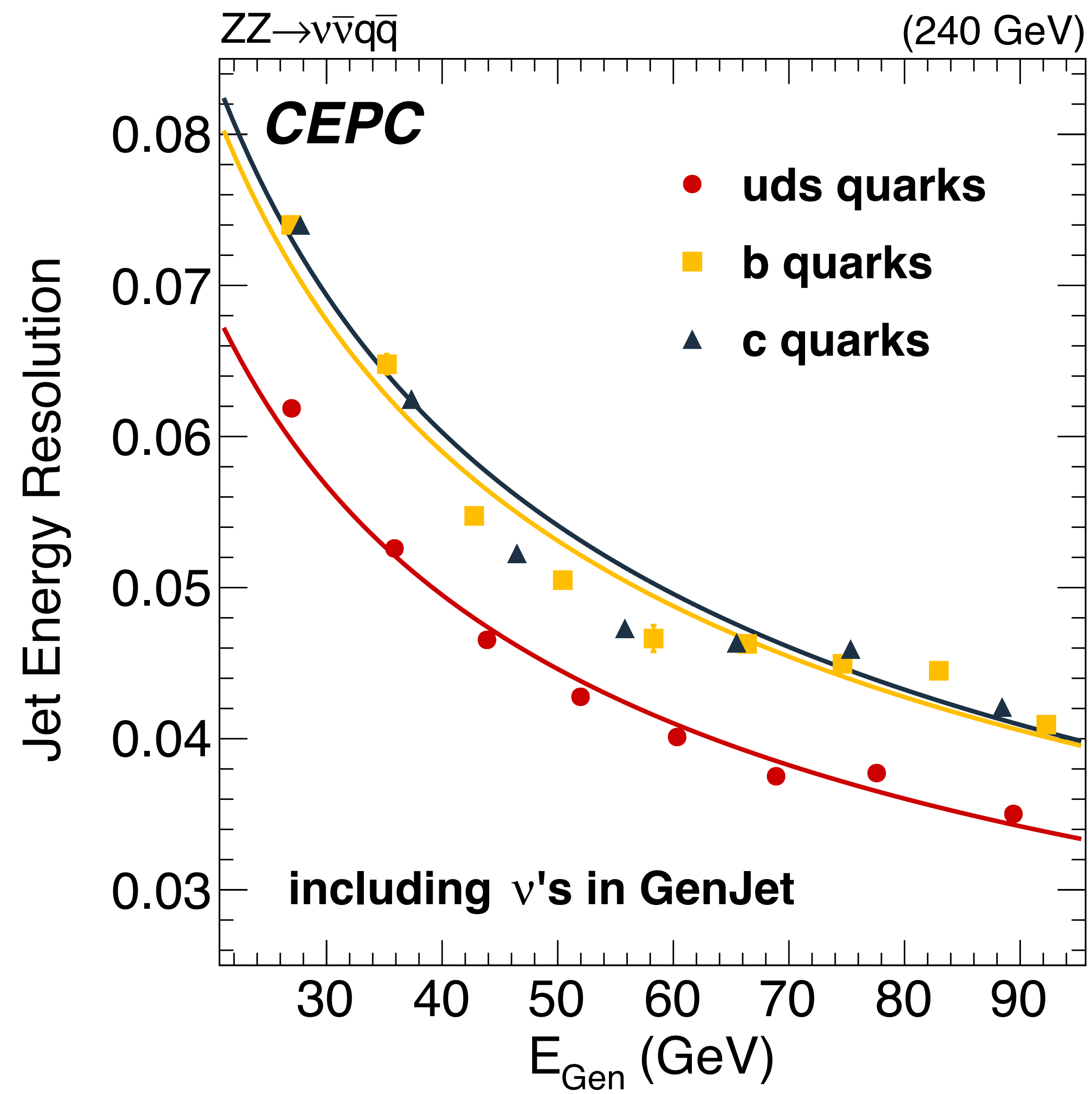


Physics Object Performances

- **Leptons**: Above 2 GeV, the reconstruction efficiency > 99.5% with misidentification rate < 1%; A relative mass resolution 0.19% of $H \to \mu^+\mu^-$.
- **Photons**: Above 5 GeV, the reconstruction efficiency ~ 100% with no misidentification rate from hadronic jet; A relative mass resolution 2.5% of $H \to \gamma\gamma$
- **τ-leptons**: The reconstruction efficiency ~80% with a purity ~90% measured from $ZH \to \tau\tau q\bar{q}$ event at $\sqrt{s} = 240\ GeV$.
- **Jet flavor tagging**: The b-tagging efficiency/purity of 80%/90% and c-tagging efficiency/purity 60%/60% are extracted from $Z \to q\bar{q}$ at Z-pole.
- $K^{\pm}$: K/π separation 2σ with proposed ToF, achieving the accumulated efficiency/purity of 95%/95% for kaons ID in $Z \to q\bar{q}$ from momentum 2~20 GeV.

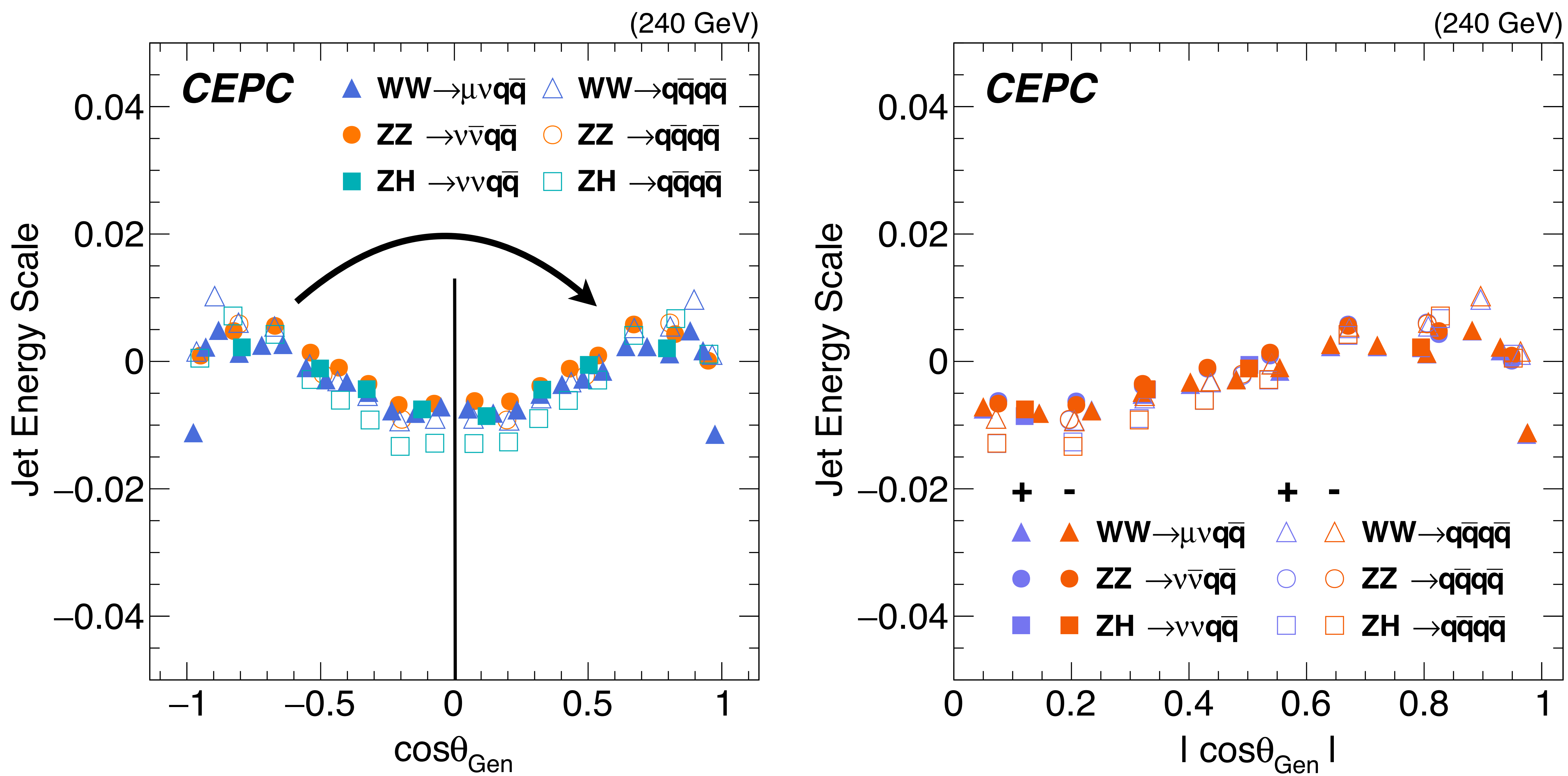
BM3: JER (Reco-Gen)





- JER depends on the jet flavors since the semi-leptonic decay of heavy flavor jet.
  → **Consistent JER when excluding neutrinos in GenJets**
- For light-flavor jets with higher energy (E_j~90), JER could reach **3.4%**.

BM3: JES Symmetry (Reco-Gen)



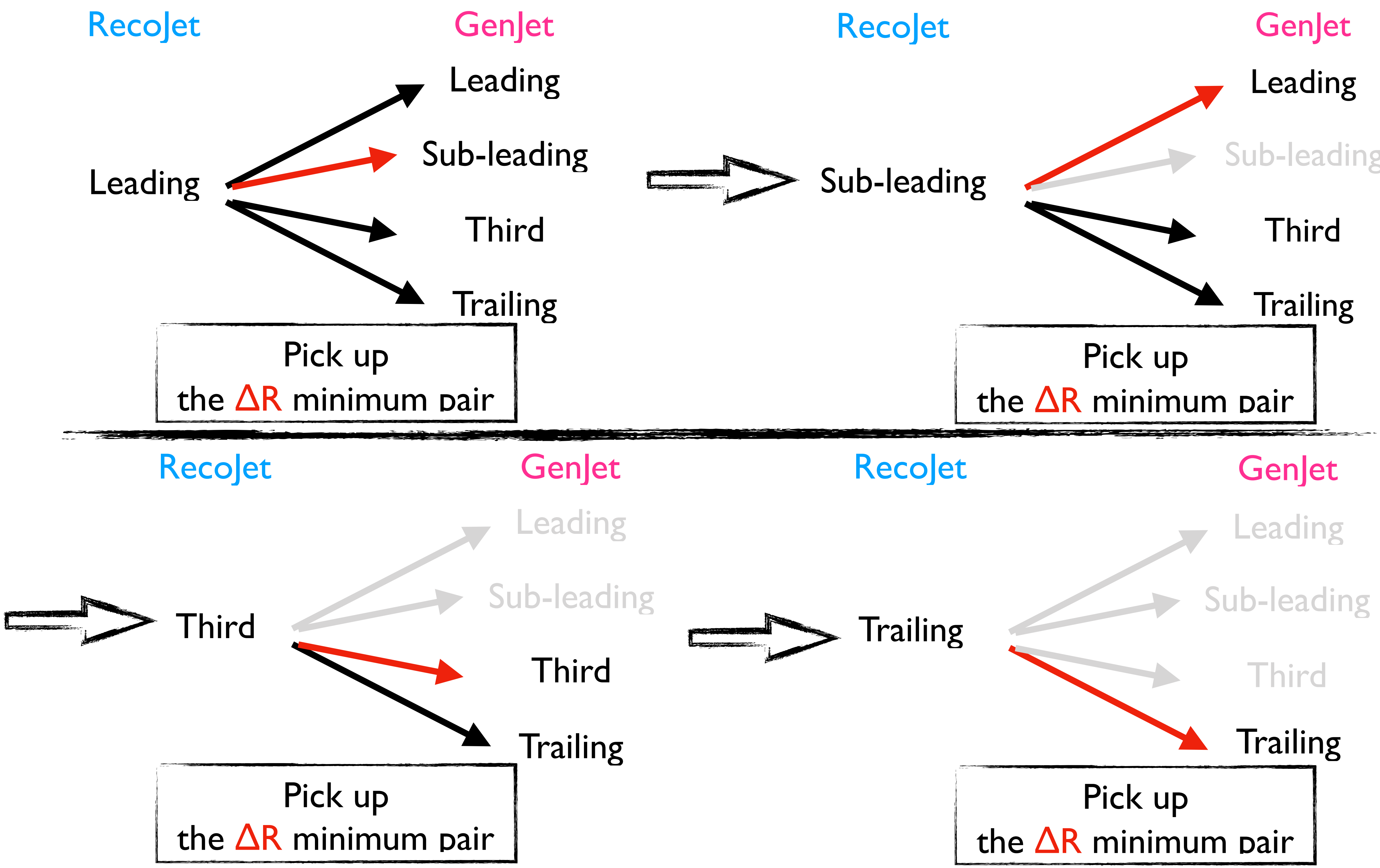
- The results show very nice agreement between $\cos\theta > 0$ and $\cos\theta < 0$

Double-sided Crystal Ball Function

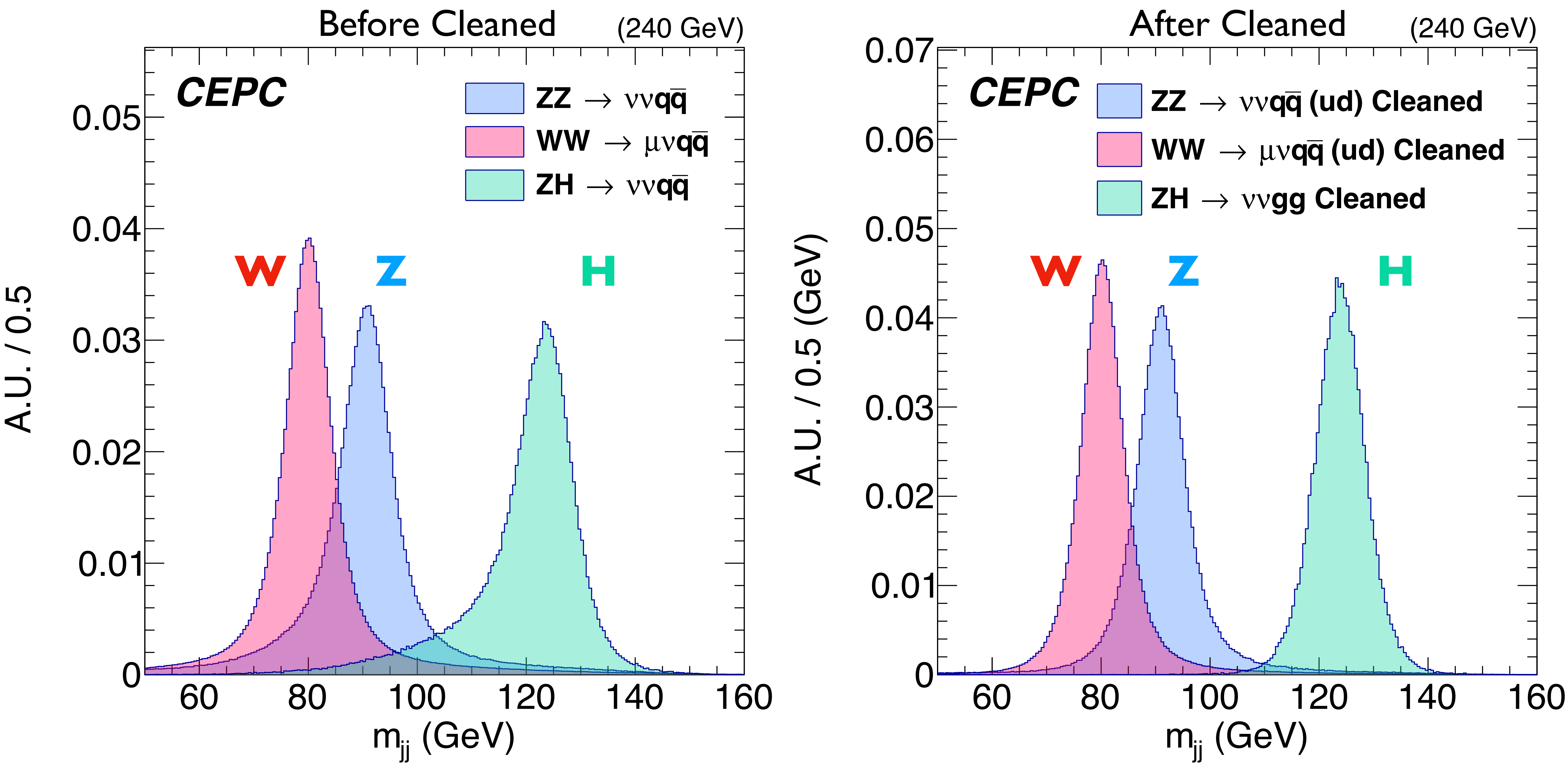
$$f(x|\alpha_1,\alpha_2,n_1,n_2,\bar{x},\sigma) = \begin{cases} \left(\frac{n_1}{|\alpha_1|}\right)^{n_1} e^{-\frac{|\alpha_1|^2}{2}} \left(\frac{n_1}{|\alpha_1|} - |\alpha_1| - \frac{x-\bar{x}}{\sigma}\right)^{-n_1} & \frac{x-\bar{x}}{\sigma} < -\alpha_1 \\ e^{-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2}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

Minimum Matching Method

- Only 1.28% of events have dR < 0.4 between Lead RecoJet to more than 2 GenJets; 1.79% for Sub-leading one; 0.7% for Third one.
- When #($\Delta R_{Reco\text{-}Gen}$<0.4) > 2, matched GenJet is decided by |ΔE/E|.



BM1: Massive Boson Mass Resolution

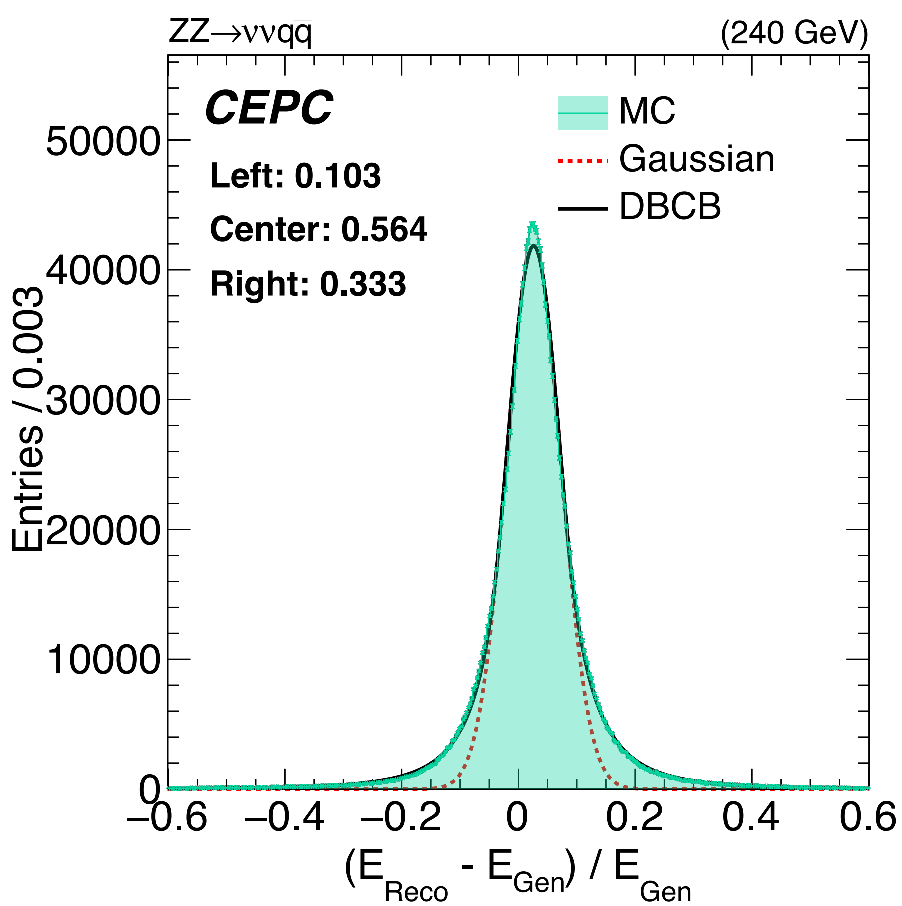


- W-, Z-, and Higgs-boson dijet masses are **well separated** at CEPC.
- After cleaned, Z- and W-boson could be separated ≈ **2σ**.
- **Higgs Boson Mass Resolution = 3.8%** is reached the CEPC baseline.

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

BM3: JER, JAR(θ), and JAR(ϕ) Cover Fraction

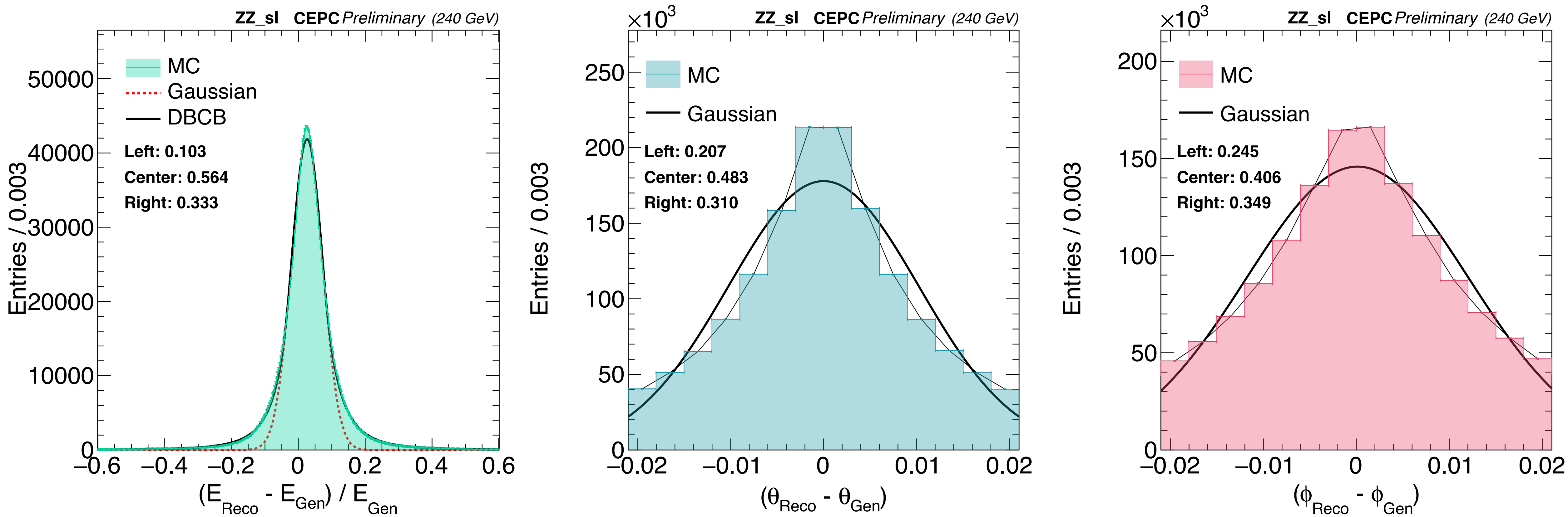
Operation mode	Process	JER(%)	JAR(θ) (%)	JAR(ϕ) (%)
Z	$e^+e^- \to Z \to q\bar{q}$	57.6	52.5	44.7
H	$e^+e^- \to Z\gamma \to q\bar{q}\gamma$	56.2	51.0	47.9
	$e^+e^- \to WW \to \mu\nu q\bar{q}$	49.1	46.7	46.9
	$e^+e^- \to WW \to q\bar{q}q\bar{q}$	58.2	50.9	49.9
	$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$	56.4	48.3	40.6
	$e^+e^- \to ZZ \to q\bar{q}q\bar{q}$	61.4	47.9	48.3
	$e^+e^- \to ZH \to \nu\bar{\nu}(q\bar{q}$ or $gg)$	62.5	44.1	48.5
	$e^+e^- \to ZH \to q\bar{q}(q\bar{q}$ or $gg)$	63.3	43.5	44.8
		~60%	~50%	~50%



Cover Fraction: $= \dfrac{N_{\sigma\ covered}}{N}$

- The cover fraction is close to a Gaussian distribution, **68%**.
  → **Well-controlled tail**

BM3: JER, JAR(θ), and JAR(ϕ) Cover Fraction



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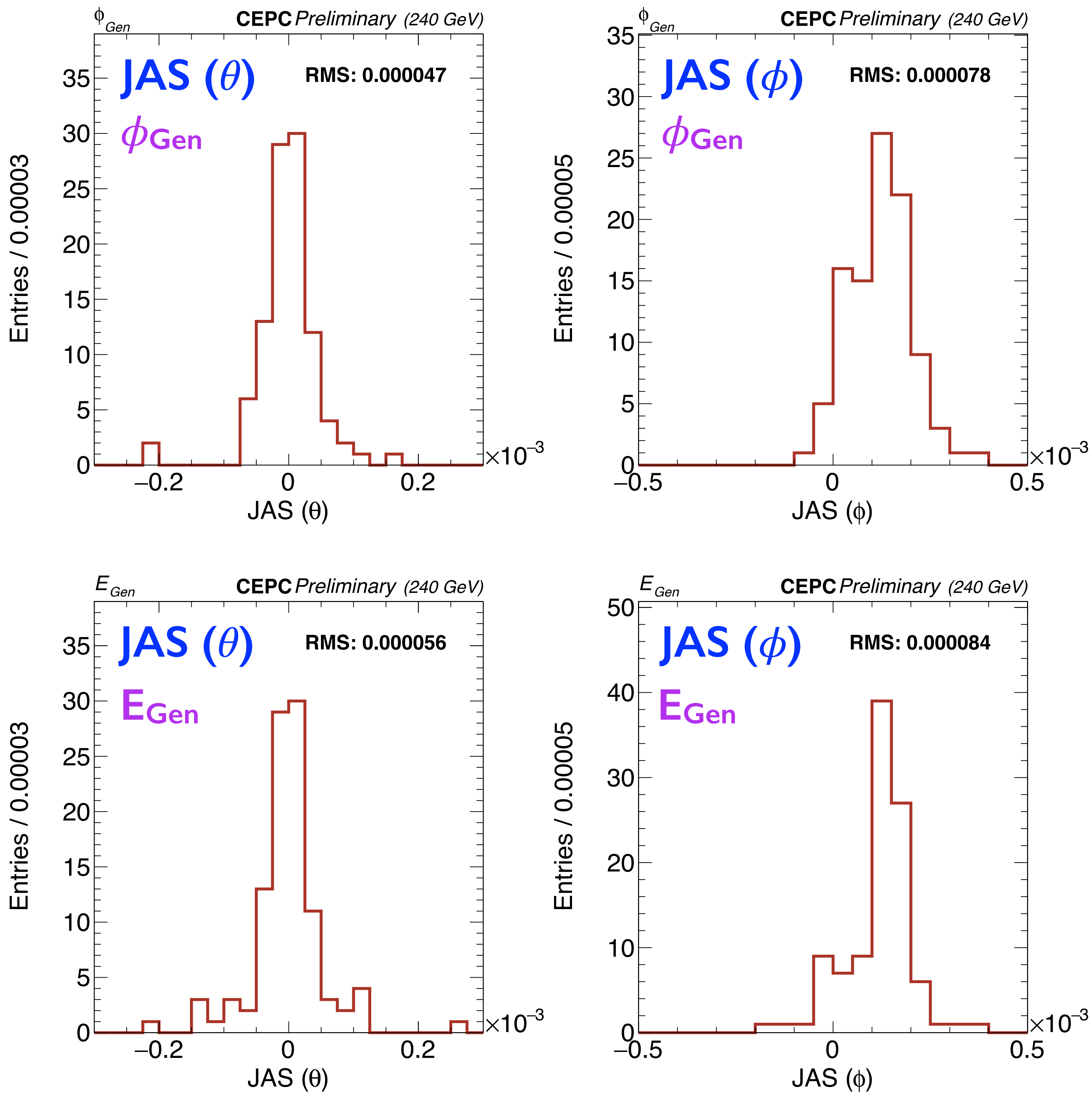
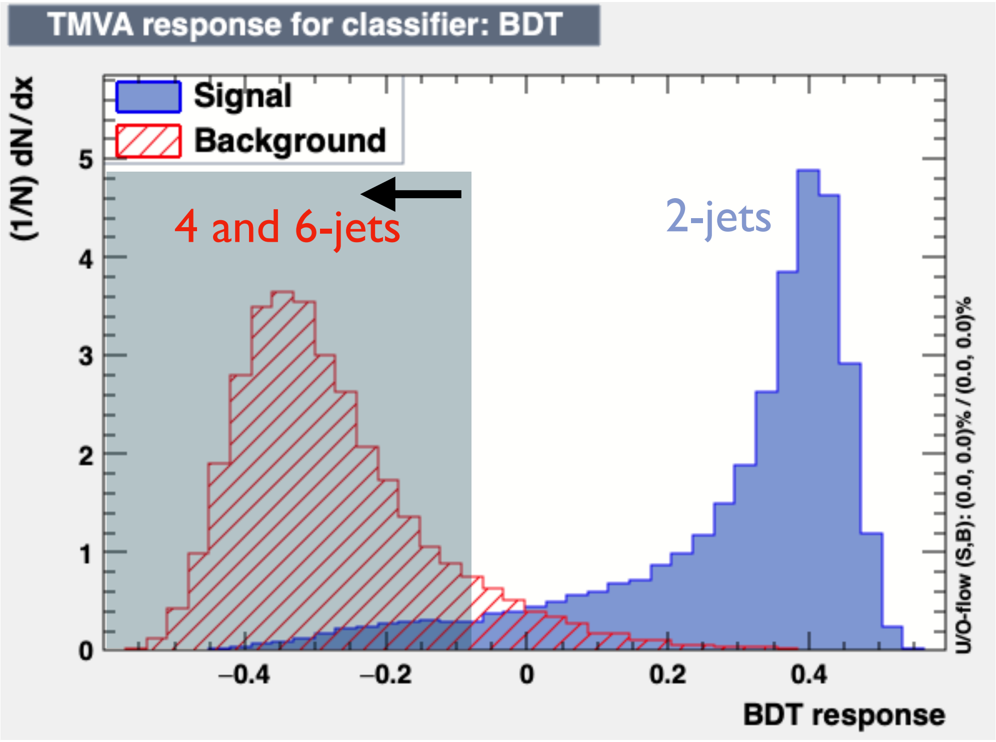
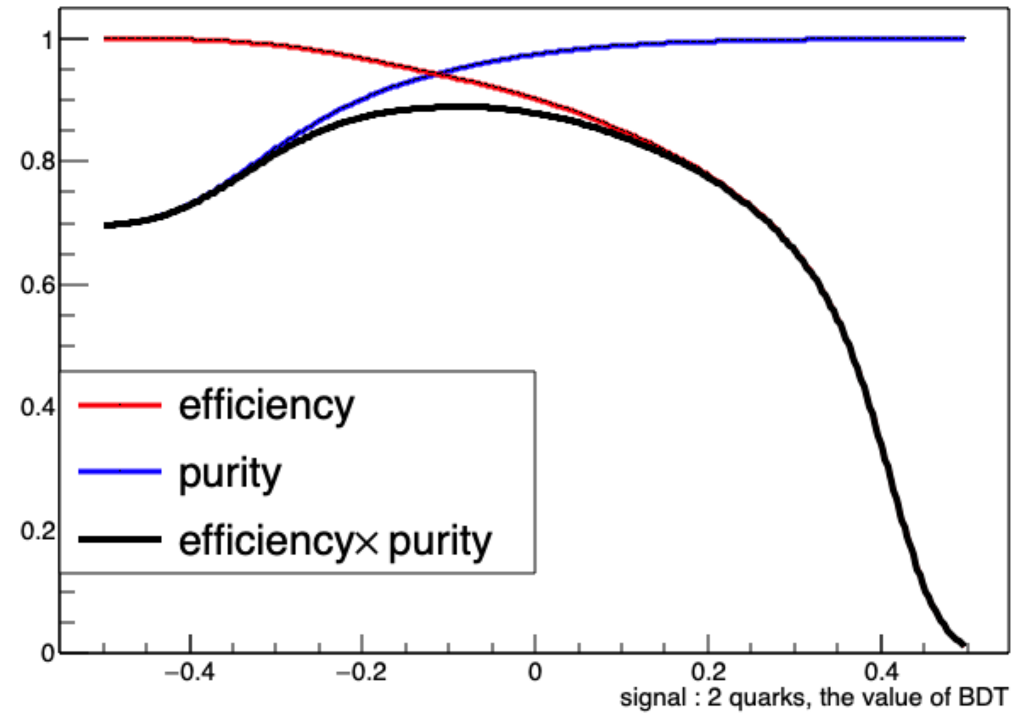
	$e^+e^- \to WW \to q\bar{q}q\bar{q}$	58.2	50.9	49.9
	$e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$	56.4	48.3	40.6
	$e^+e^- \to ZZ \to q\bar{q}q\bar{q}$	61.4	47.9	48.3
	$e^+e^- \to ZH \to \nu\bar{\nu}(q\bar{q}$ or $gg)$	62.5	44.1	48.5
	$e^+e^- \to ZH \to q\bar{q}(q\bar{q}$ or $gg)$	63.3	43.5	44.8

JAS Projection



BM2: Preliminary Number of Jet Identification





Samples:

$$e^+e^- \to q\bar{q} \text{ (2 jets)}$$
$$ZZ \to q\bar{q}q\bar{q} \text{ (4 jets)}$$
$$W^+W^- \to q\bar{q}q\bar{q} \text{ (4 jets)}$$
$$ZH \to q\bar{q}q\bar{q} \text{ (4 jets)}$$
$$ZH \to q\bar{q}H \to q\bar{q}q\bar{q}q\bar{q} \text{ (6 jets)}$$

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.

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}

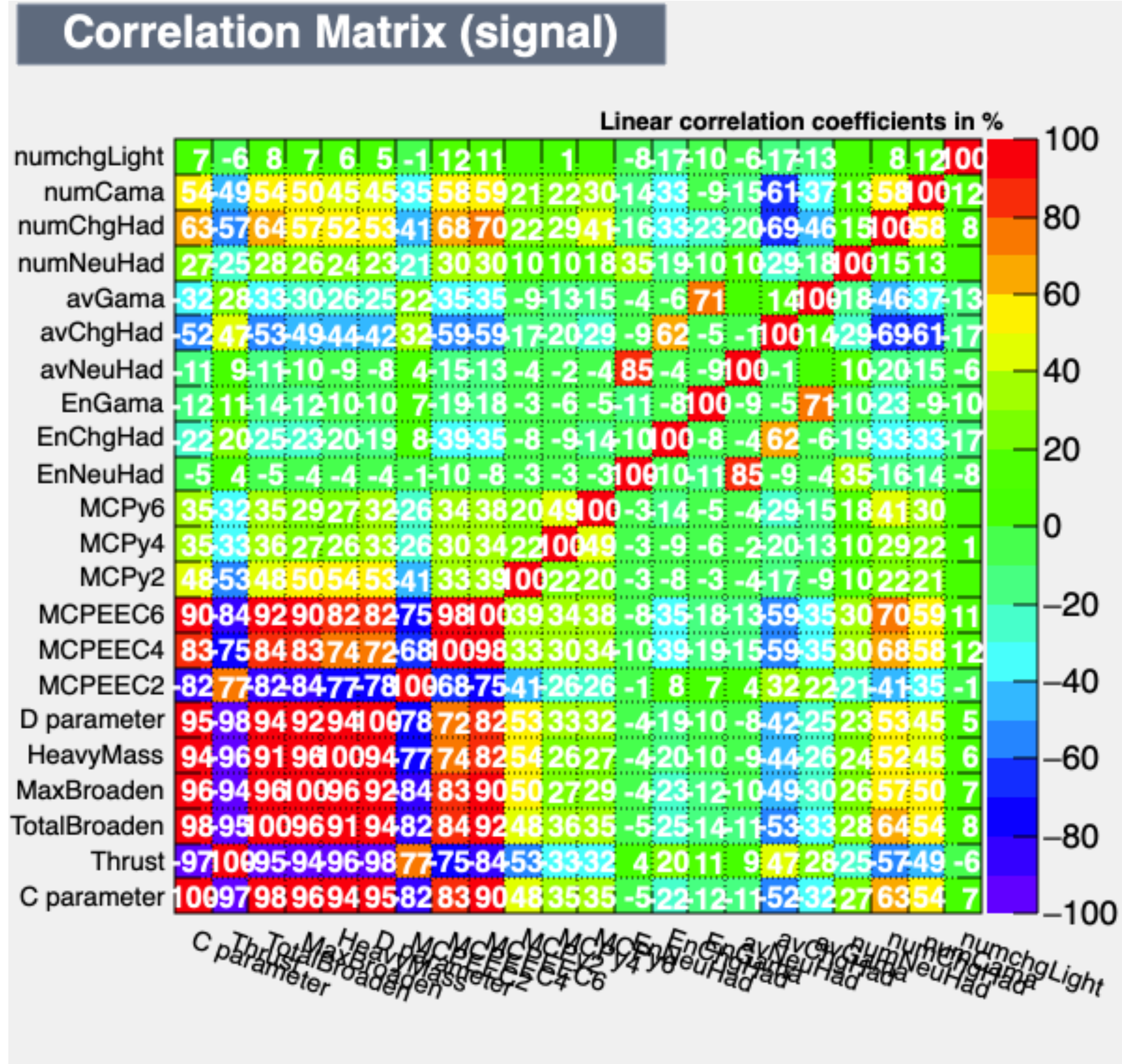
ee-kt jet clustering algorithm

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

BM2: Number of Jet Identification

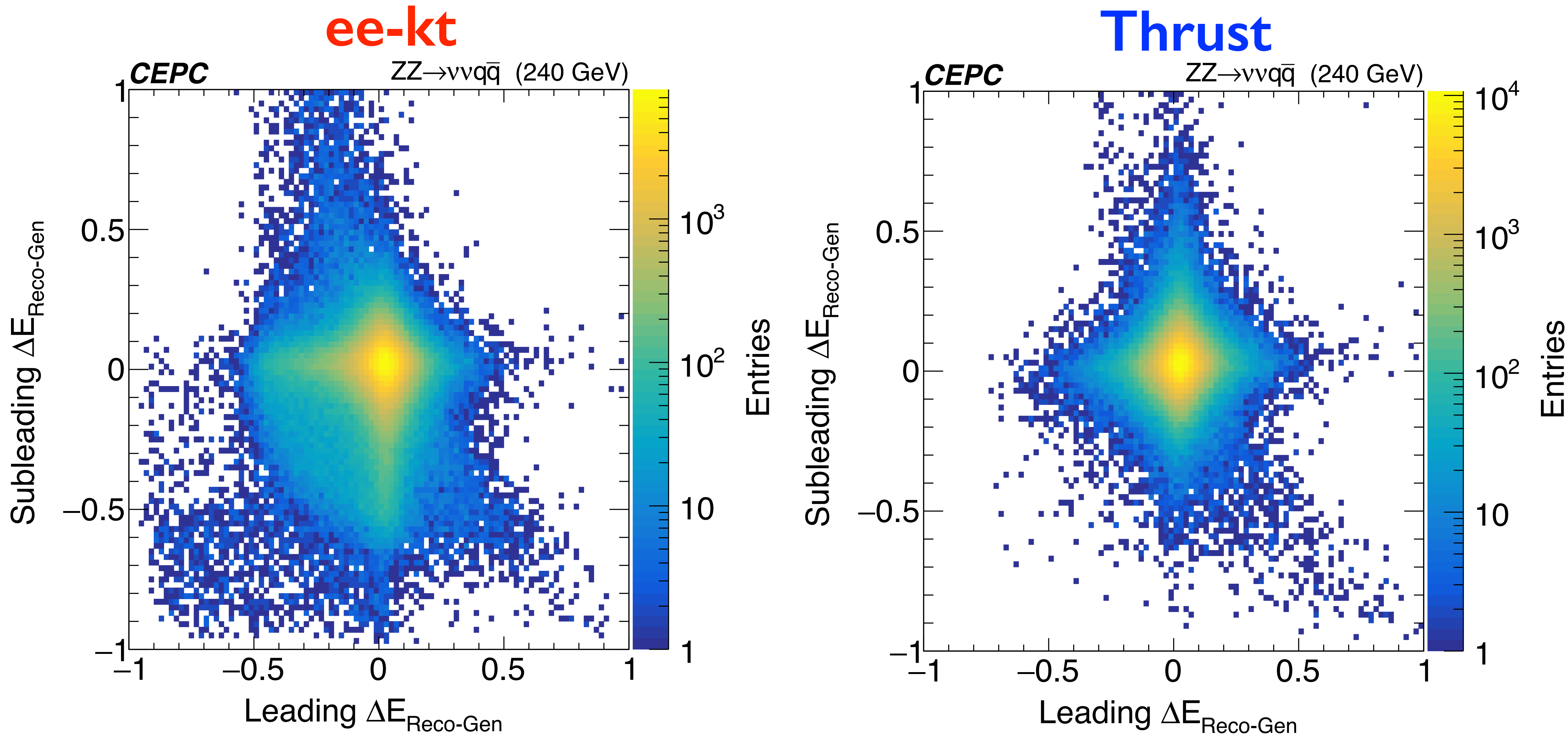
20 Variables

# 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.**

BM3: Thrust Jet Clustering Method

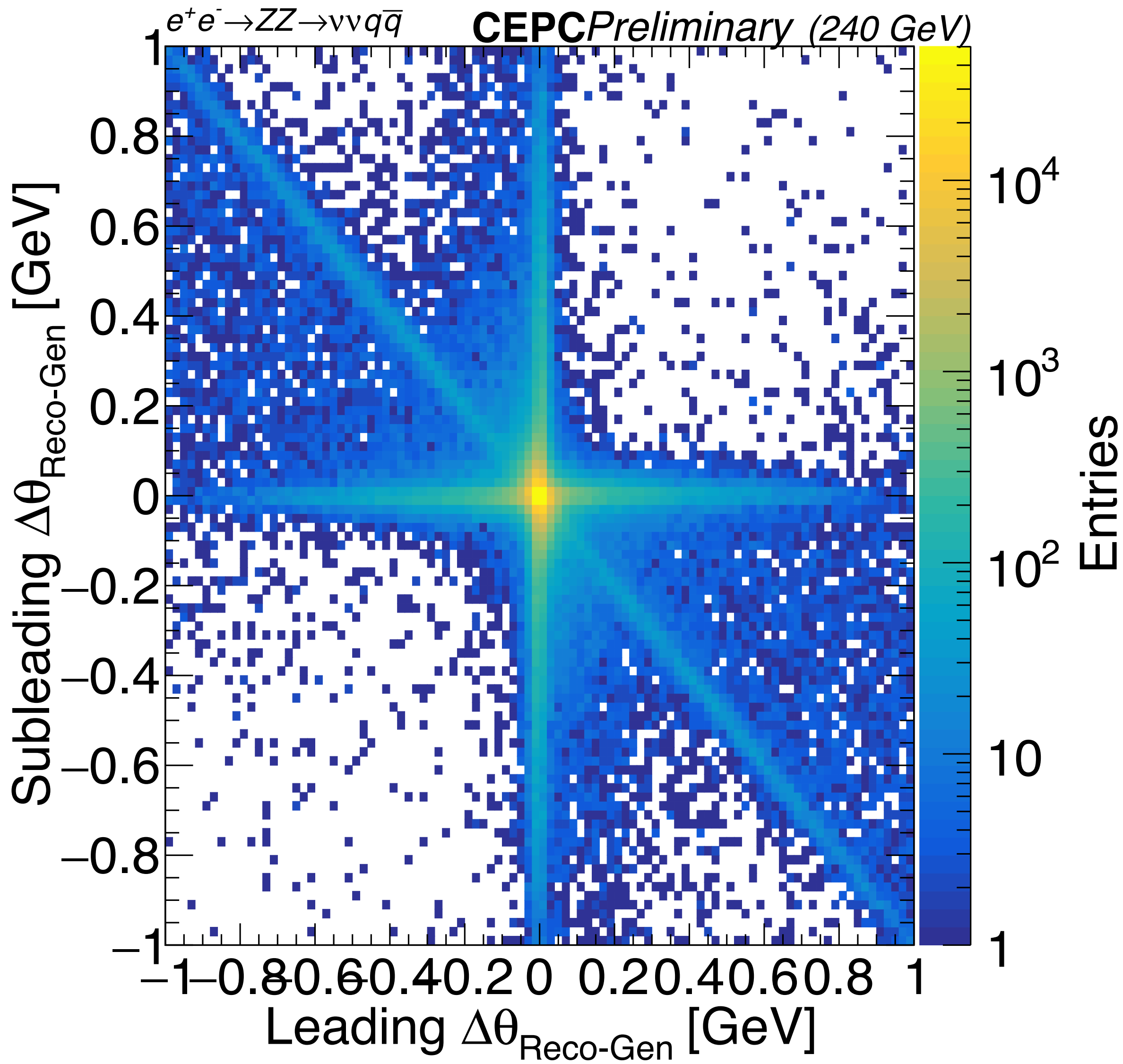


- Identify the 2 jets event with (efficiency x purity) = **88.4%**
  → The thrust jet clustering method
- After "cleaned" selection, the thrust method has **suppressed the tail significantly**
  → Expected to have improvement on jet energy and angular response.

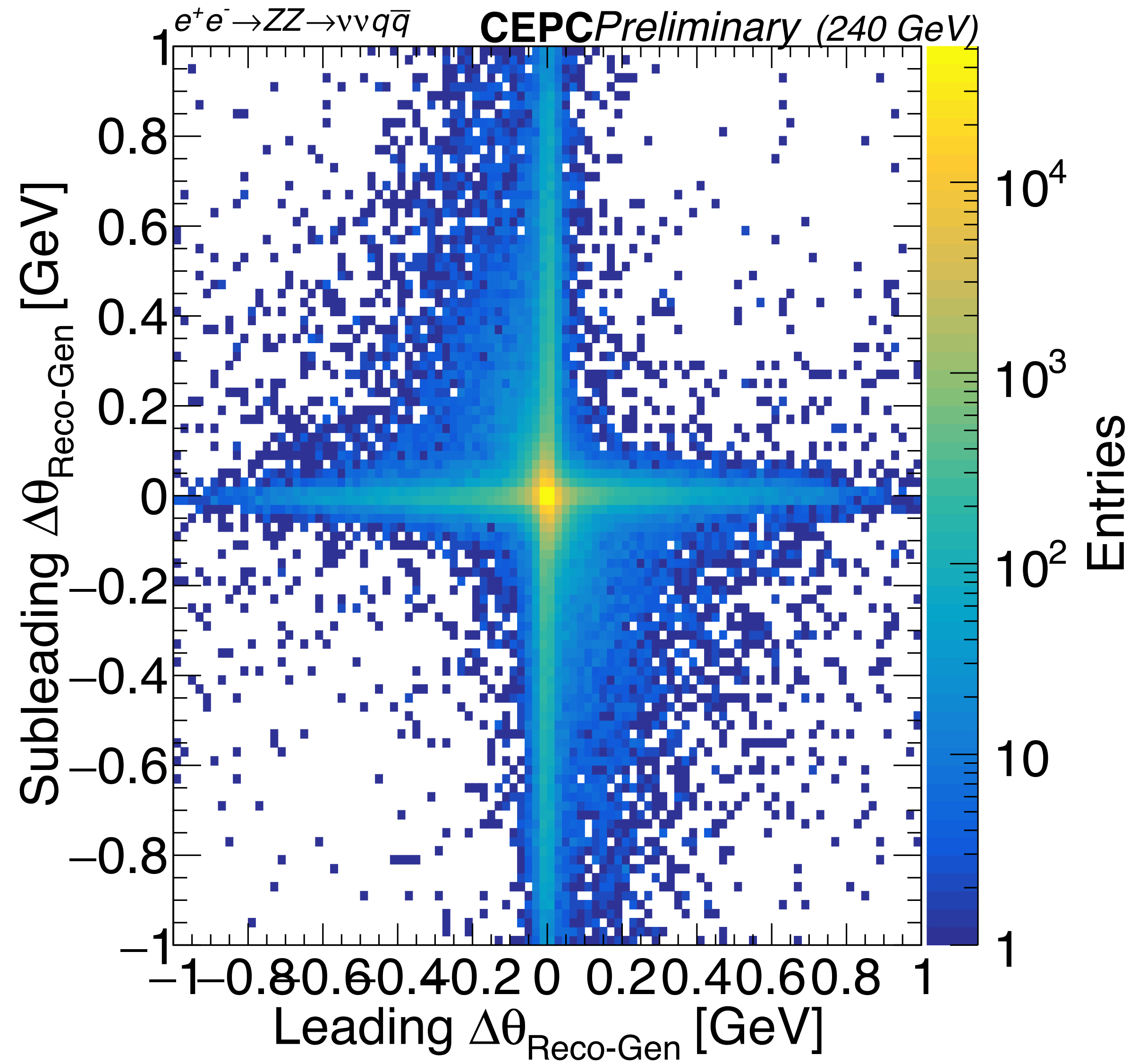
Cleaned: Select the light flavor jet event with low energy ISR, low energy neutrino inside jet, and within $|\cos\theta| < 0.85$.

Matching Impact

Energy Matching

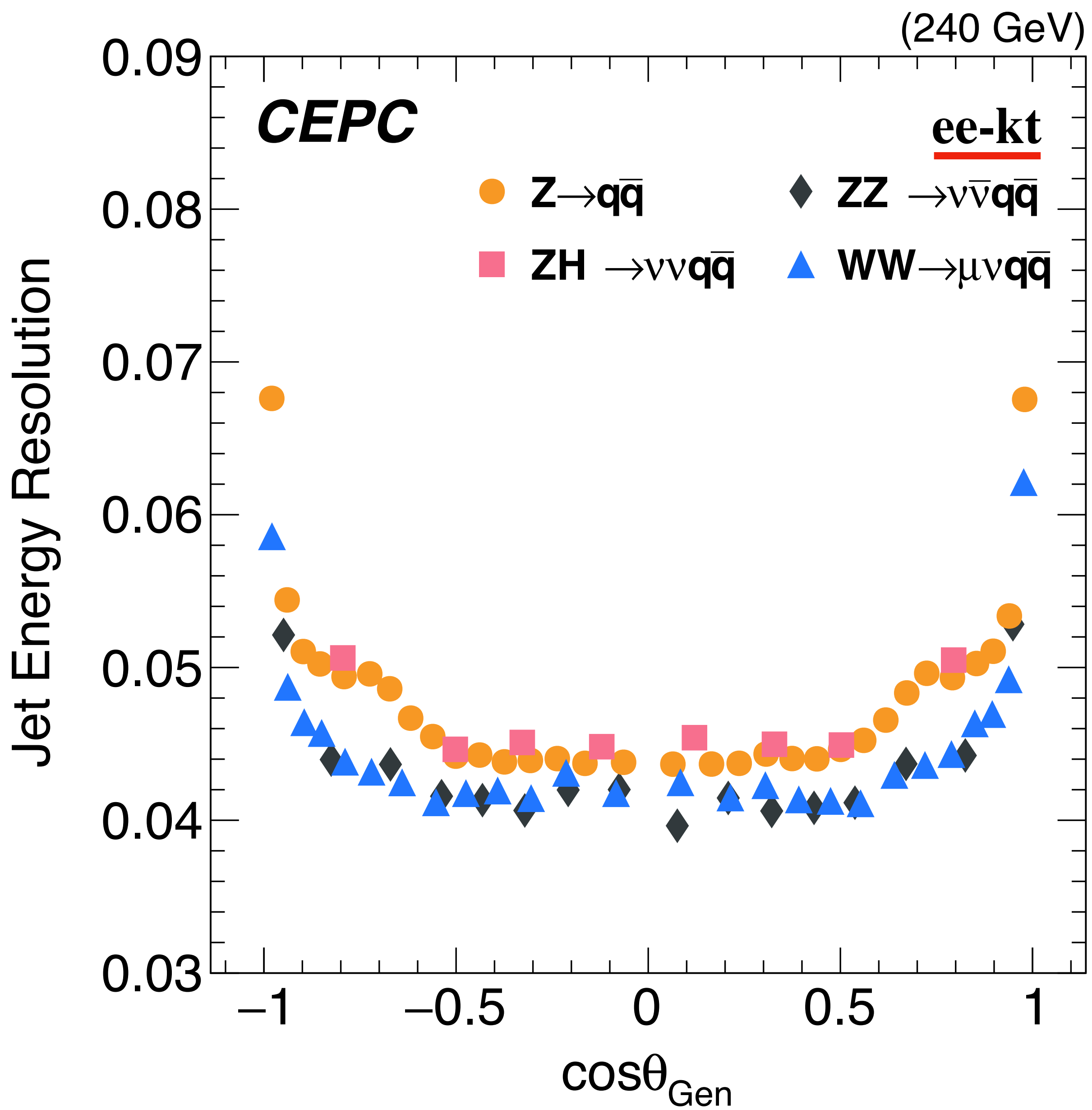


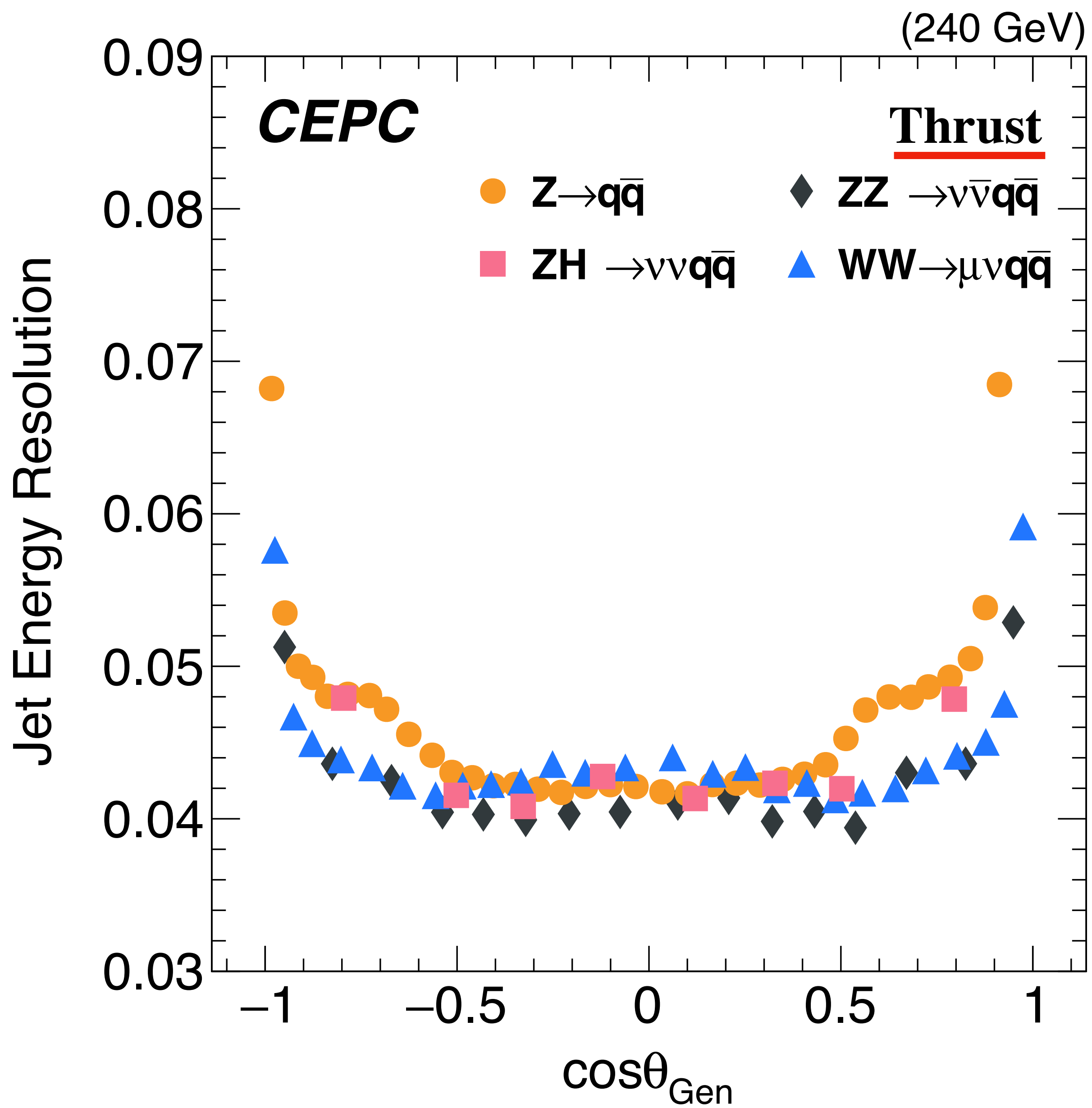
ΔR Matching



Both after being applied the cleaned selection

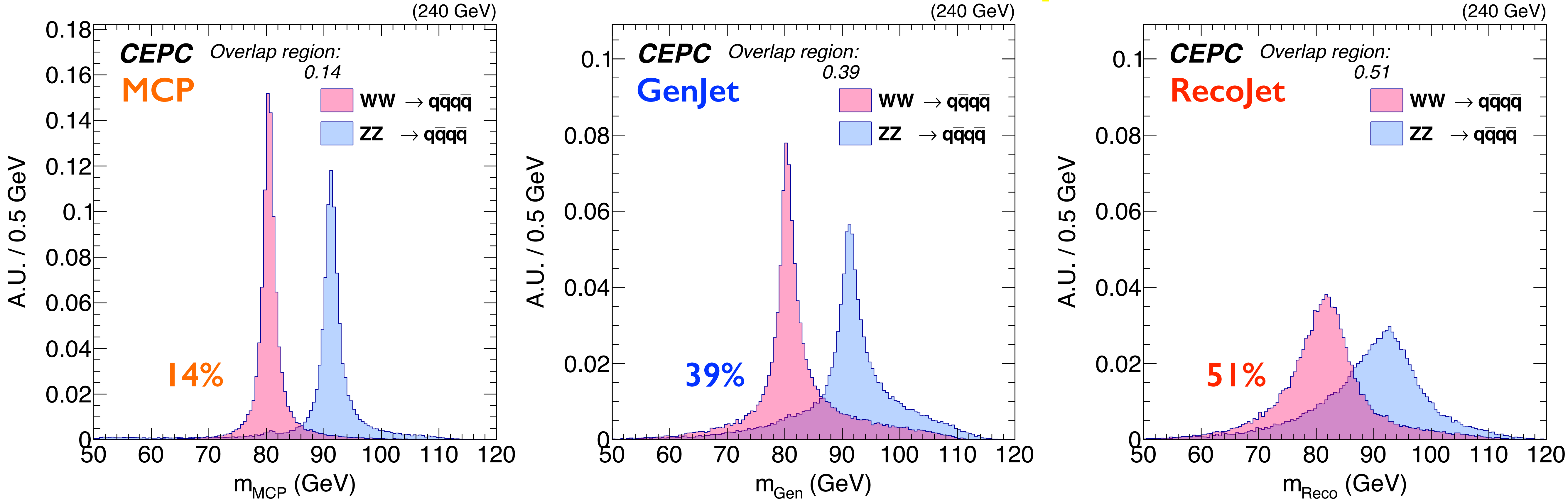
BM3: JER (ee-kt—Thrust)





- ZH and Z-pole processes are improved **~10%** in $|\cos\theta|$ <0.5, while ZZ and WW are degraded by thrust based algorithm. (**Need more investigation**)

BM4: WW & ZZ to 4-jet Separation



$$\chi^2 = |(m_1 - m_{boson})| + |(m_2 - m_{boson})|$$

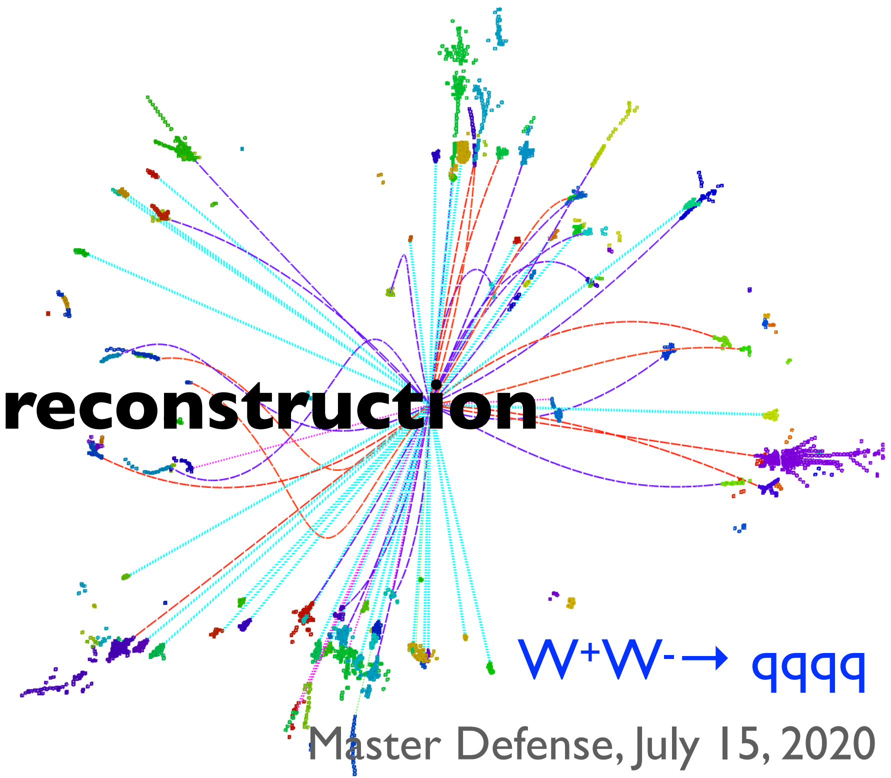
- E_j ~ (20~120 GeV) → Low energy
- Typical multiplicity → Up to 10^2
- Jets are clustered by ee-kt and paired by χ^2.
- Separation of WW & ZZ to 4 jets is determined by:

25%

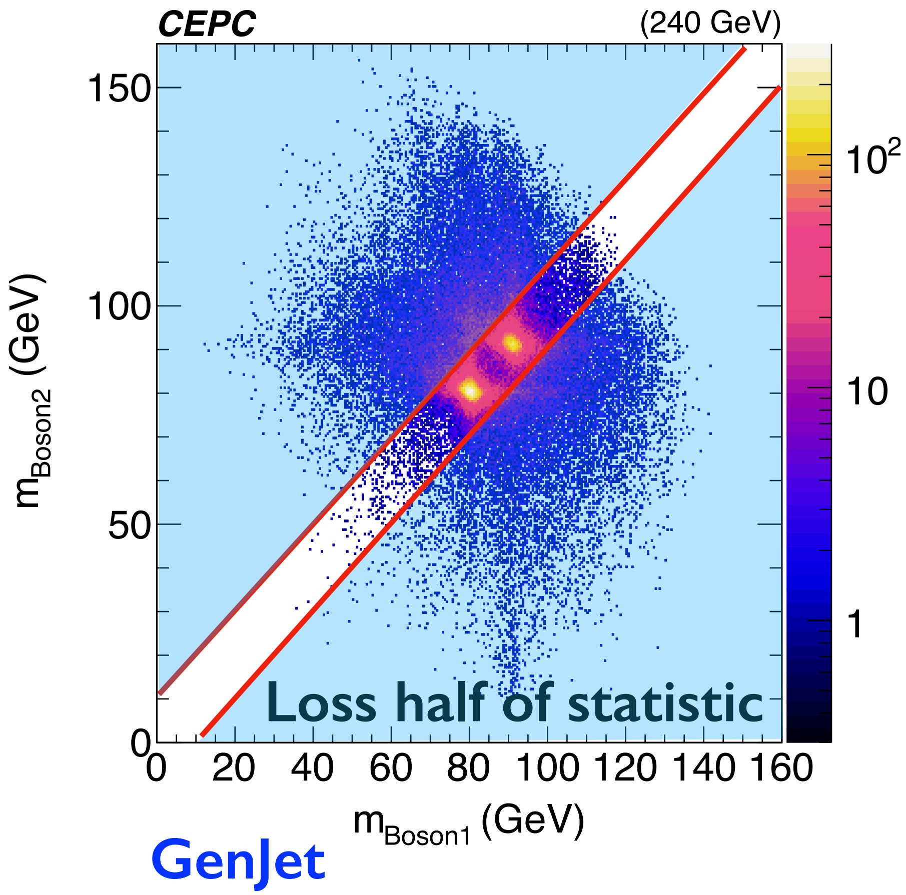
1. (14%) Intrinsic boson mass/width (10 GeV)
2. **(39%) Wrong jet pairing for color singlet reconstruction**
   → Jet Clustering & Pairing

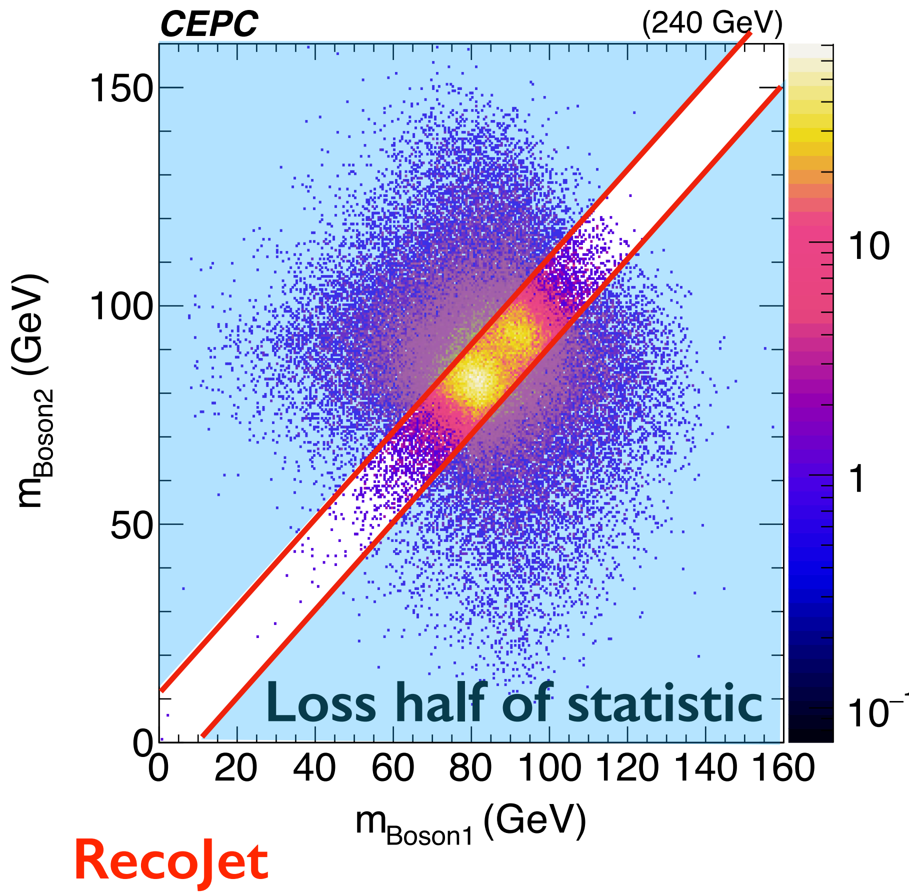
12%

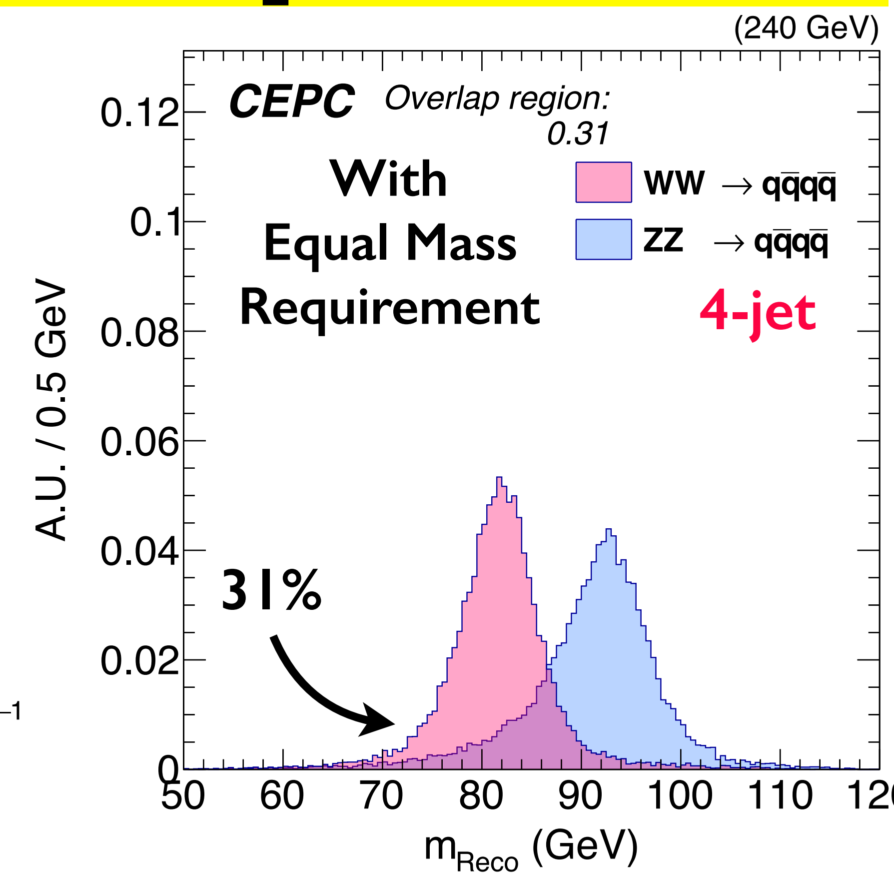
3. (51%) Detector response



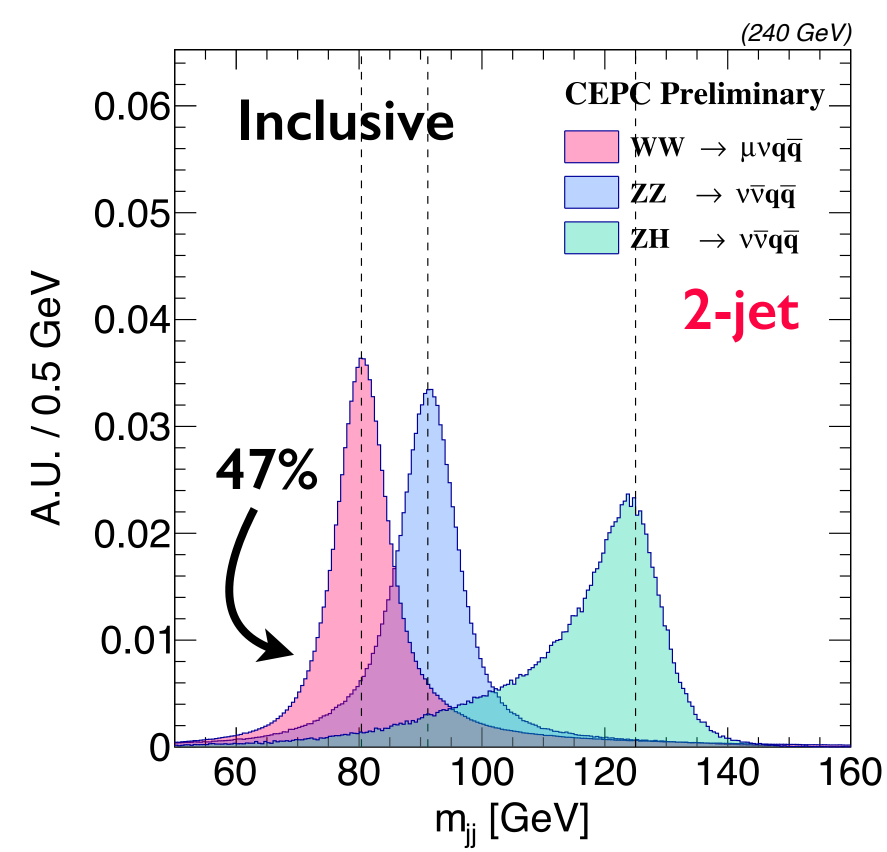
BM4: WW & ZZ to 4-jet Separation







- **Equal mass requirement**: $|M_{12} - M_{34}| < 10$ GeV
  - Cost half of the statistic.
  - Overlapping region can be reduced from 51%/39% to 31%/15% for the RecoJet/GenJet.
- **CEPC baseline could separate WW & ZZ with full hadronic final-state**
- Need to improve the naive jet pairing method.



ZH Full Hadronic Statistical Uncertainty

- 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%

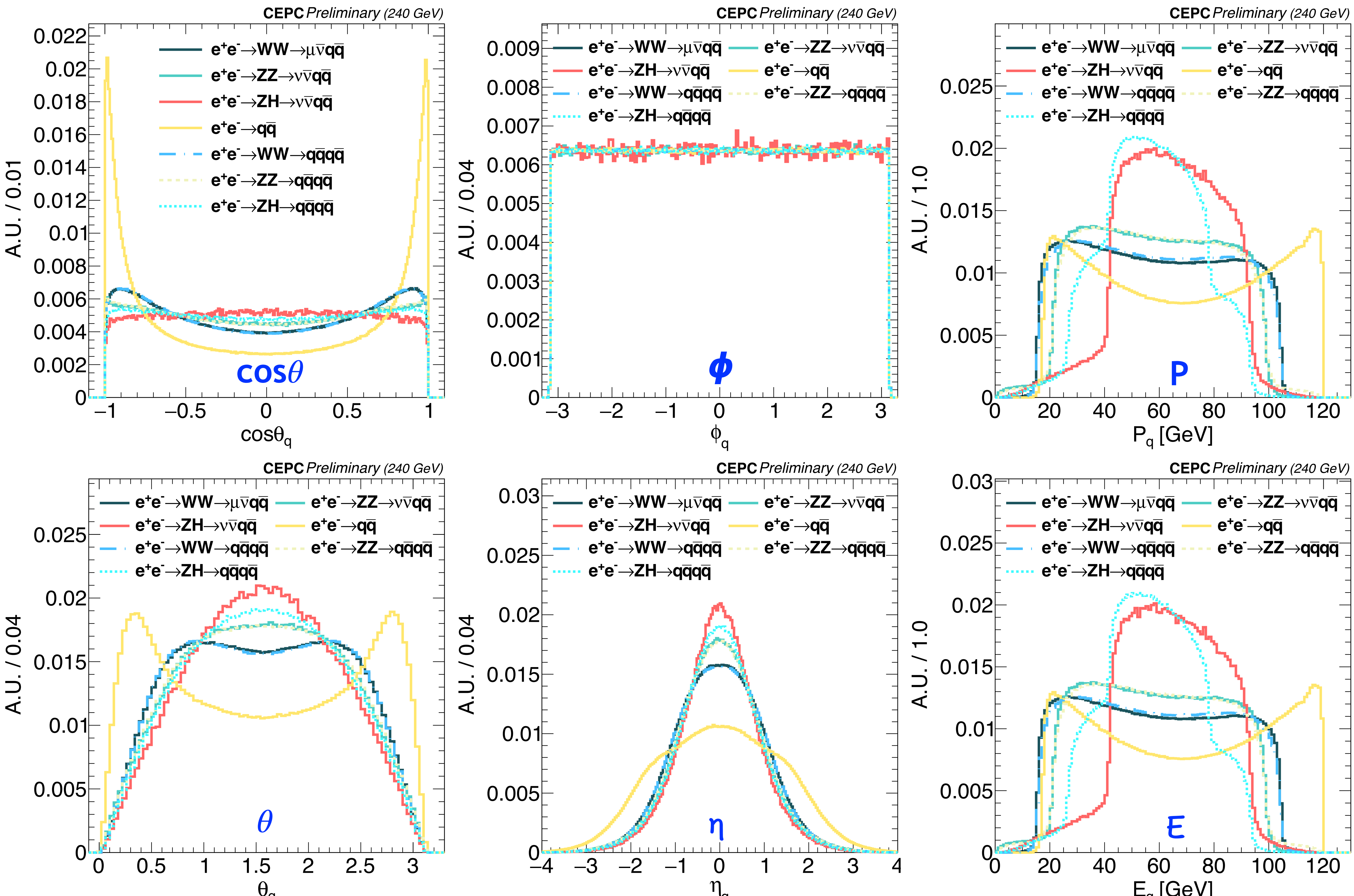
→

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

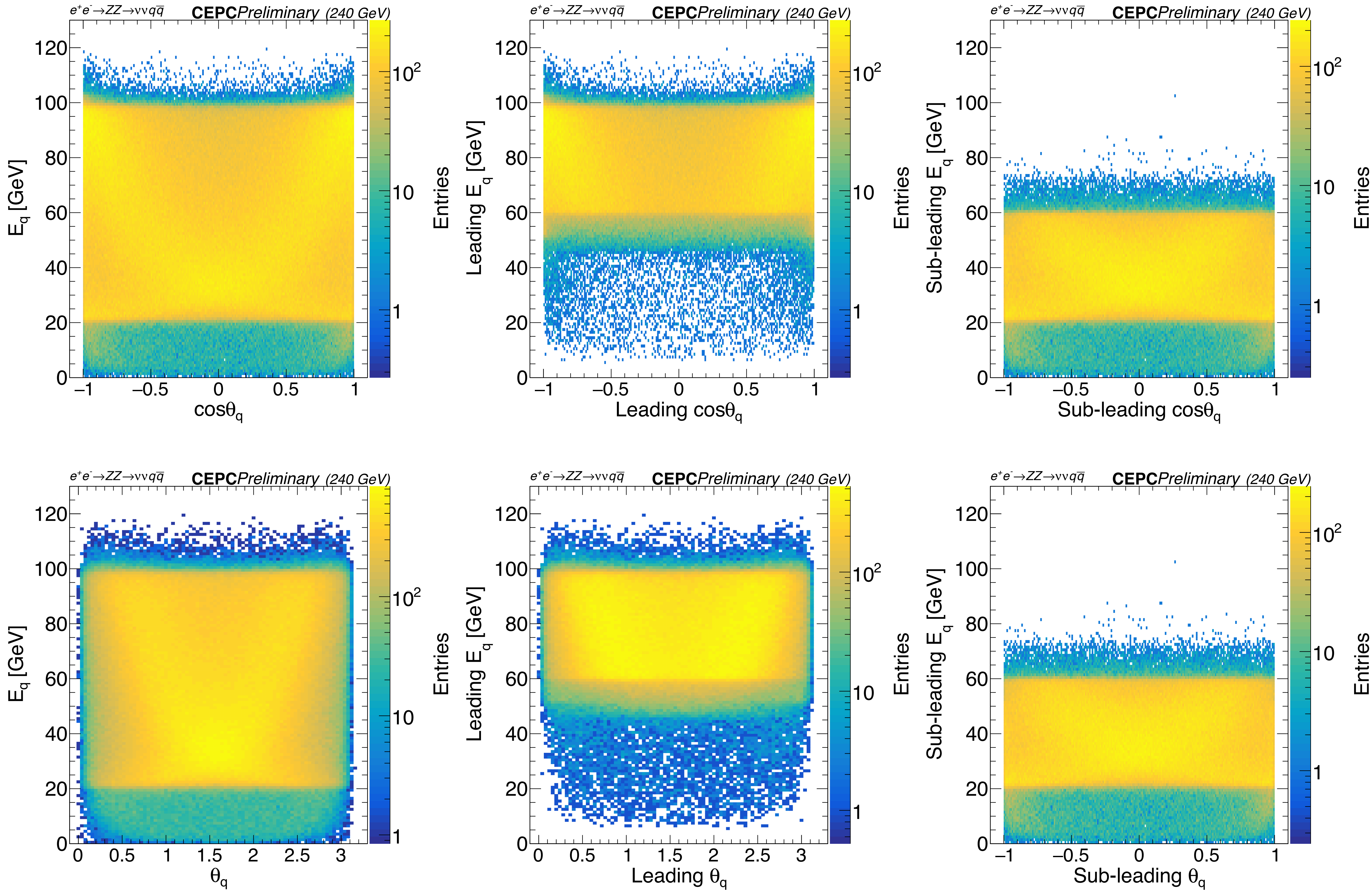
500,000 x 18% = 150,000 could be identified

1 / sqrt(150,000) = 0.25%

Kinematic Summary Plots(Parton level)

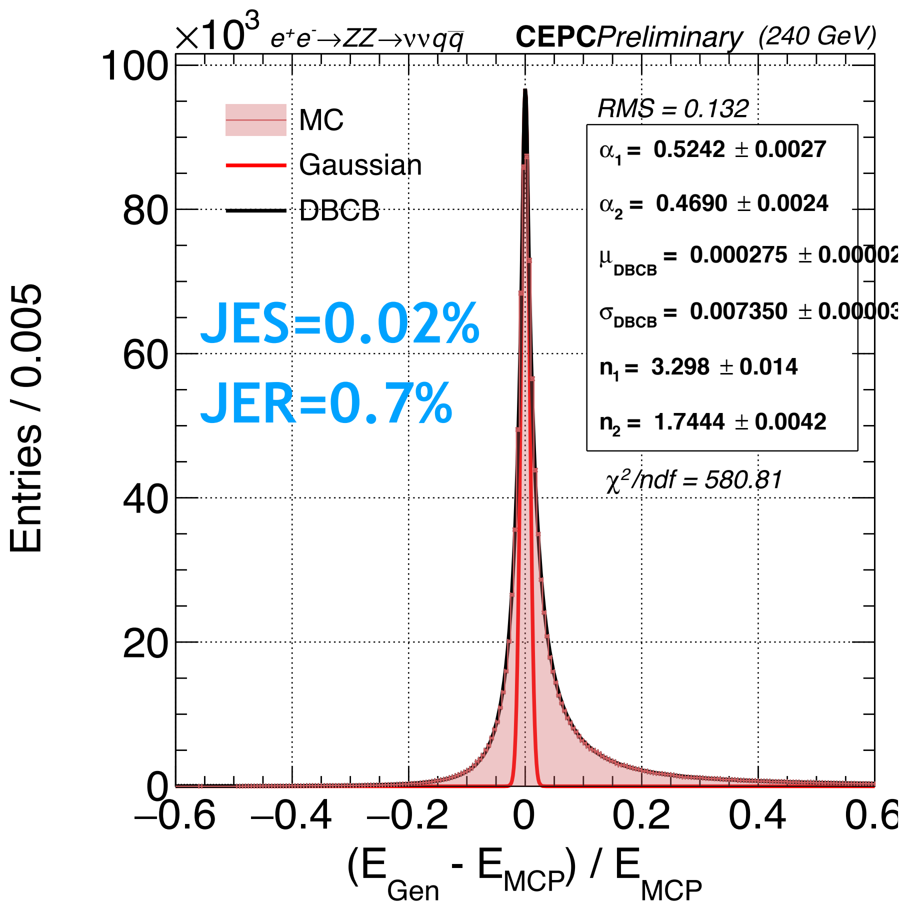


E as a Function of the Polar Angle

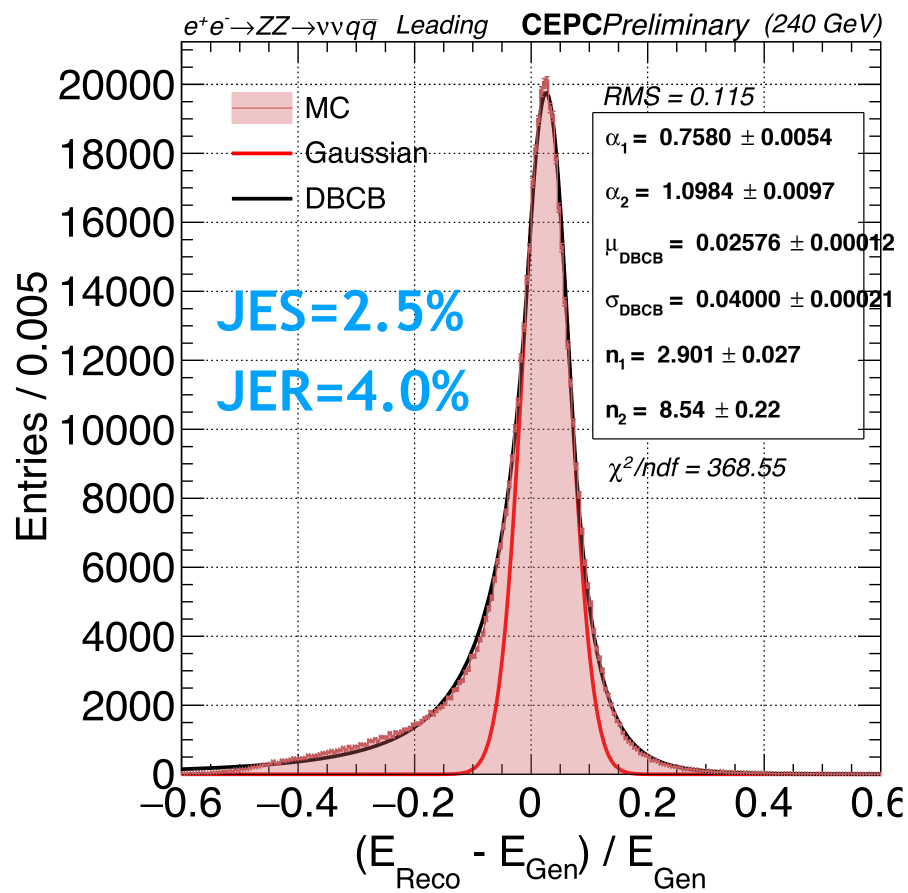


Leading JER & JES

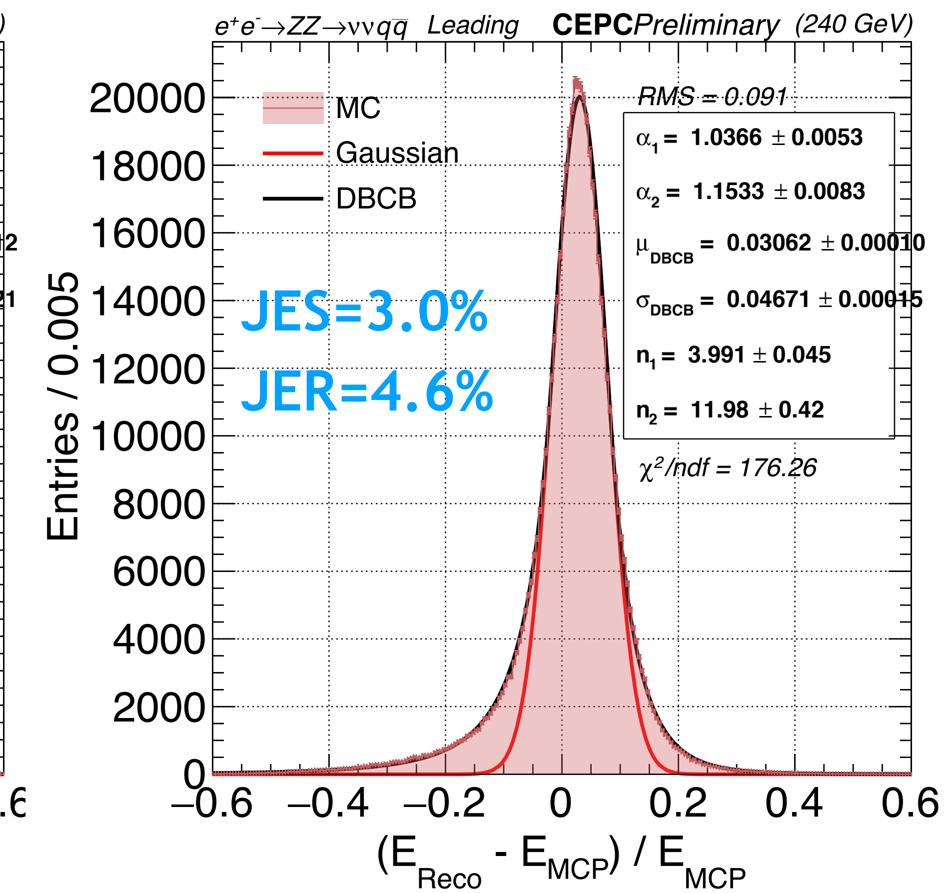
Gen-MCP



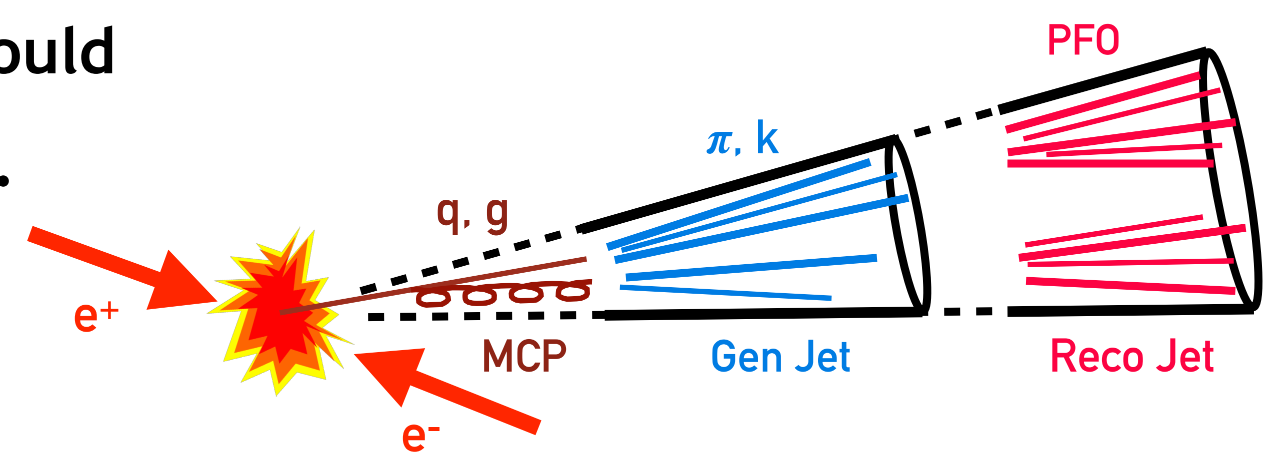
Reco-Gen



Reco-MCP

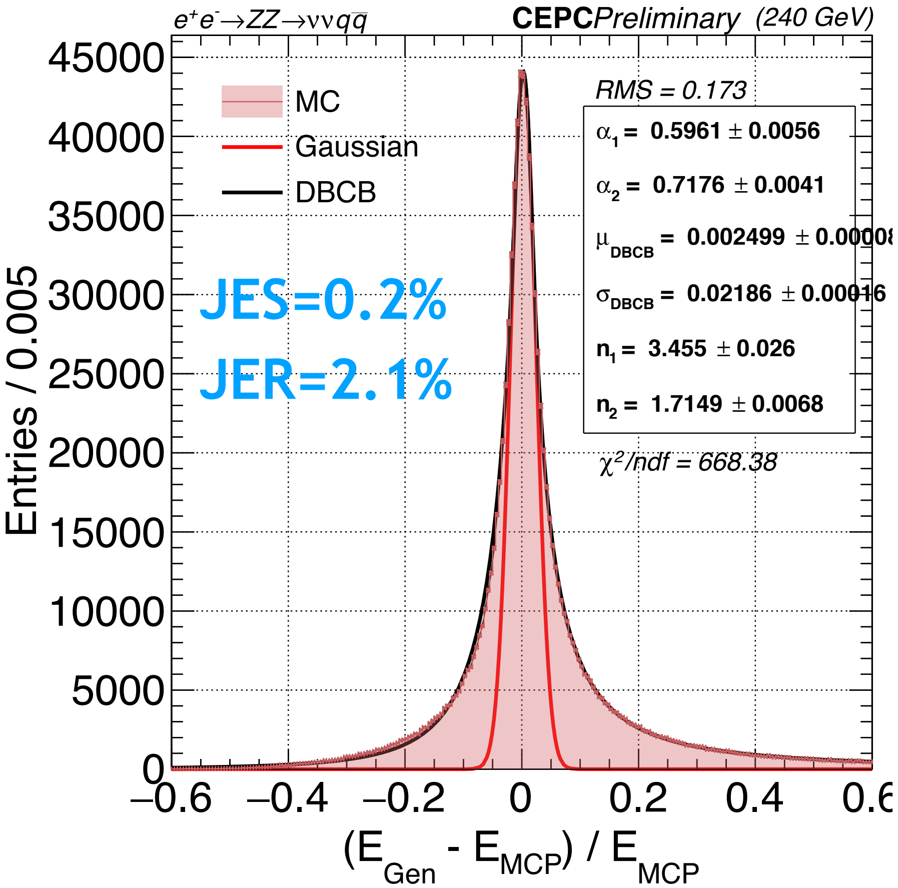


- JER/JES between Reco jet and MCP would combine the effects of two previous stages.

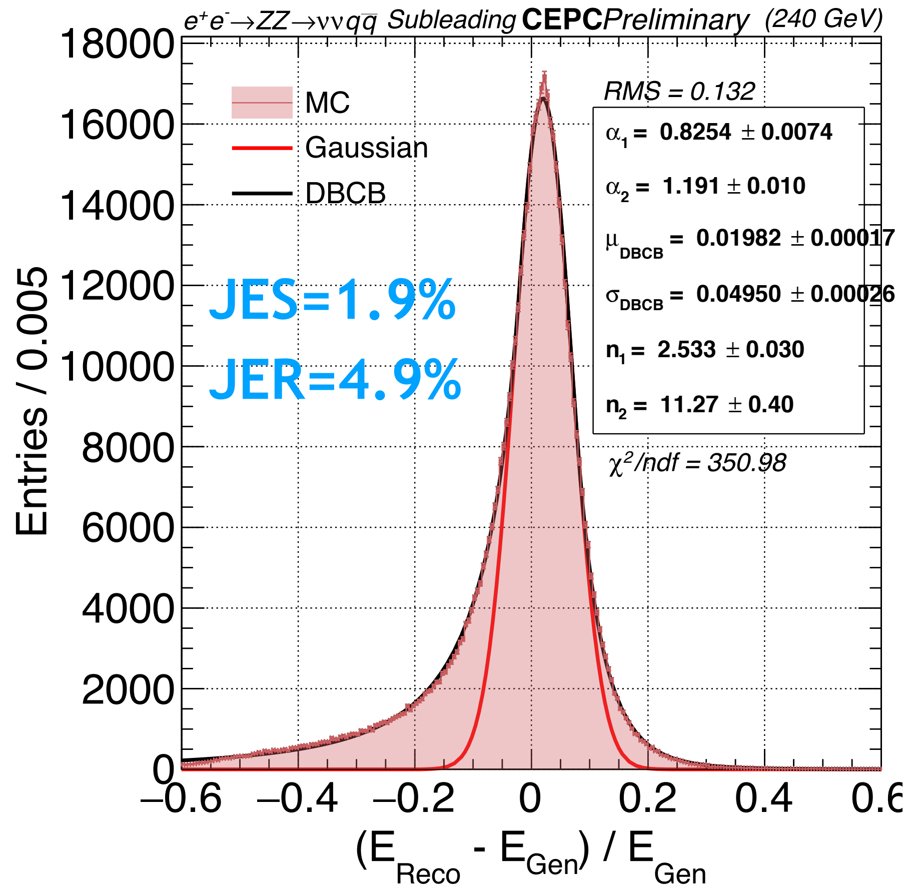


Sub-leading JER & JES

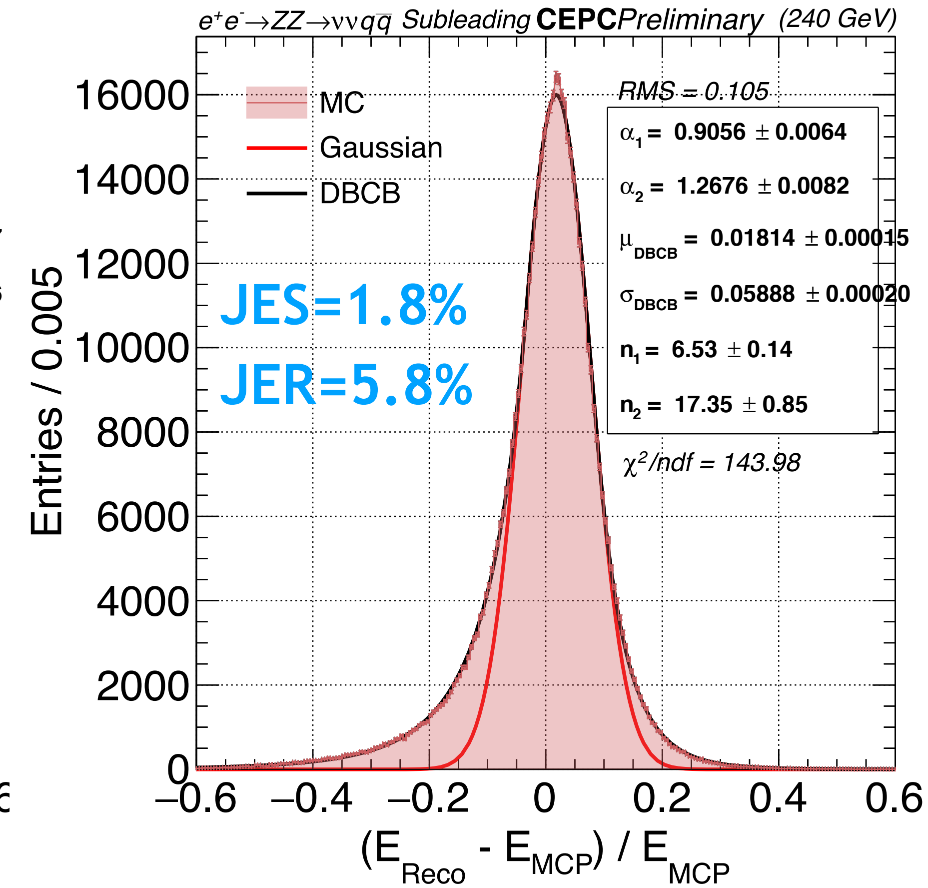
Gen-MCP



Reco-Gen



Reco-MCP



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