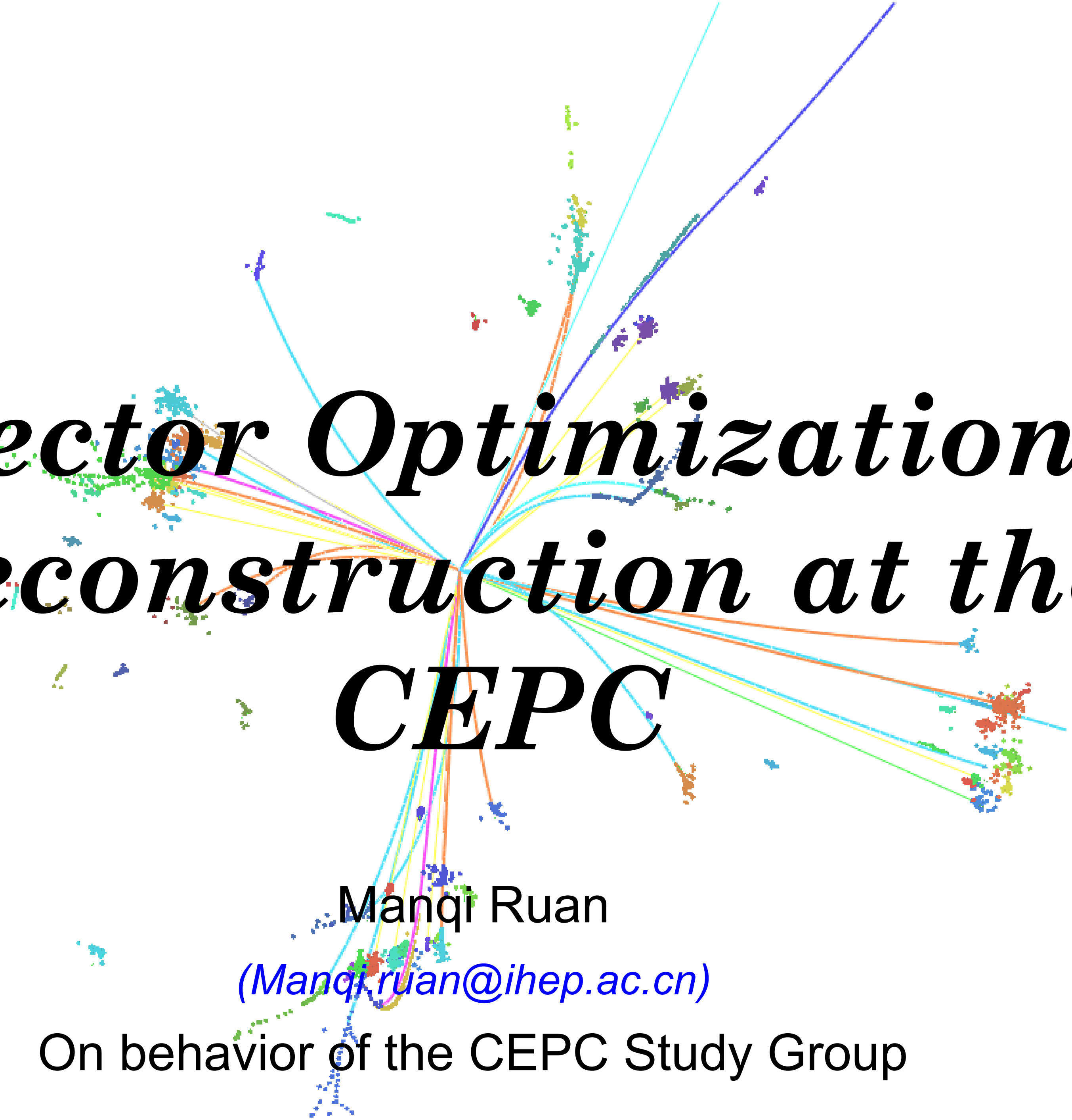


# *Detector Optimization & Reconstruction at the CEPC*

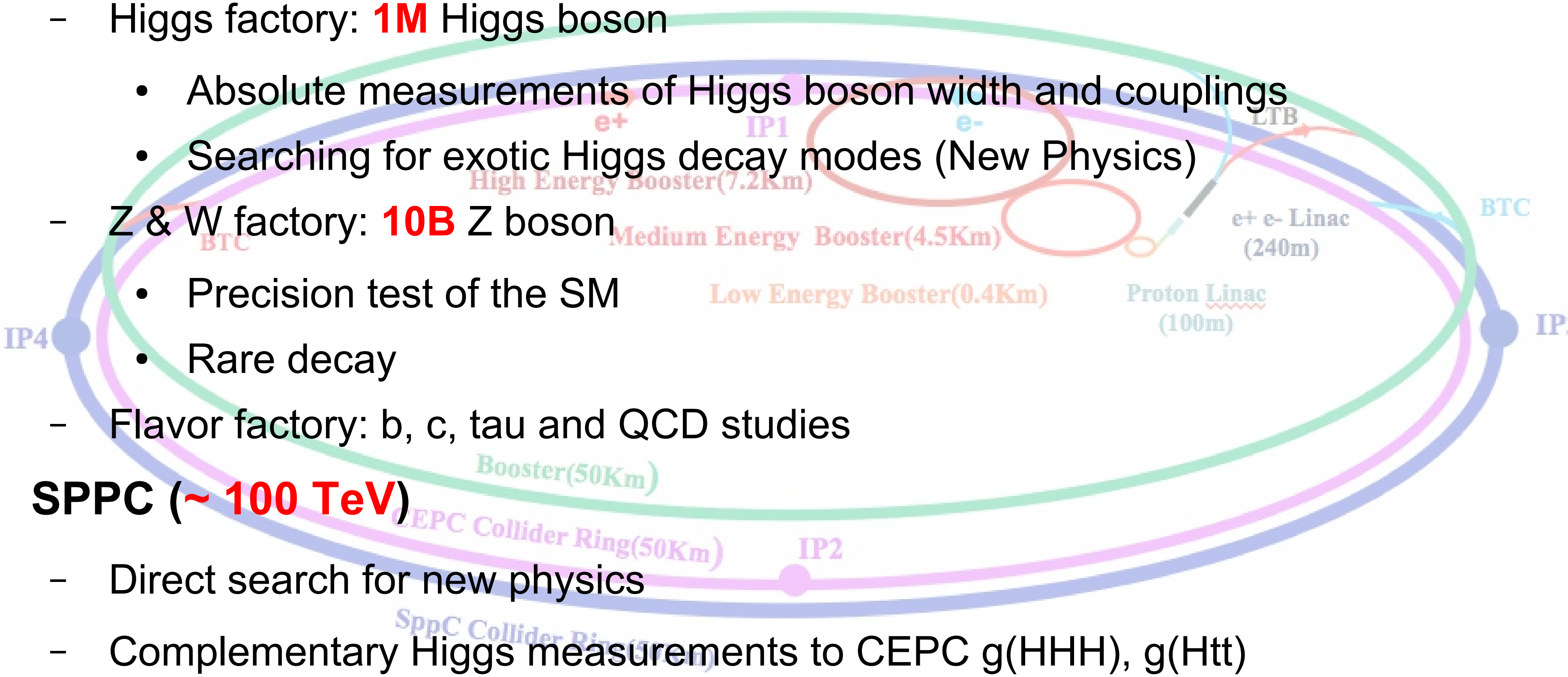
Manqi Ruan

(Manqi.ruan@ihep.ac.cn)

On behavior of the CEPC Study Group

# Science at CEPC-SPPC

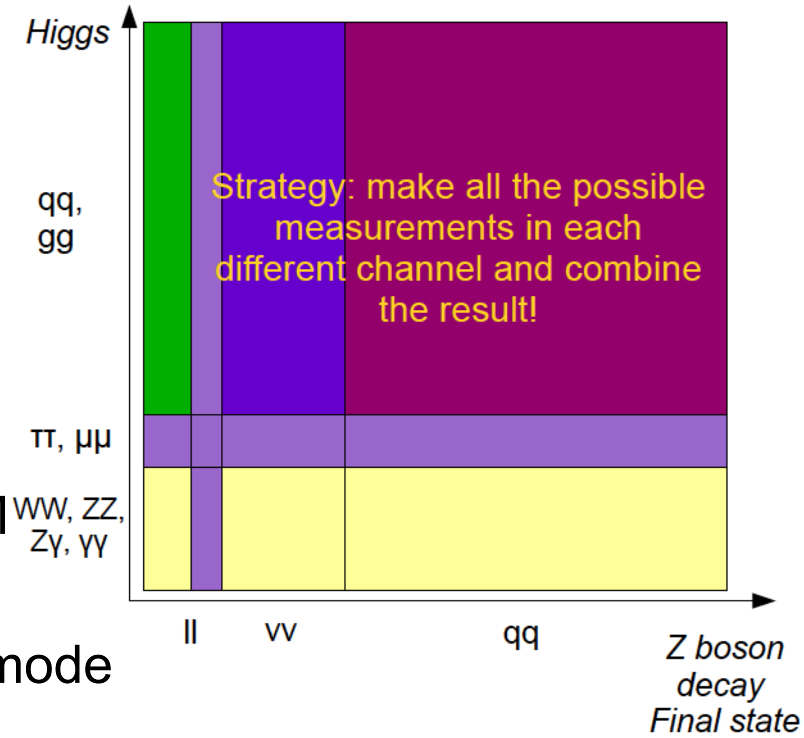
- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **10B** Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor factory: b, c, tau and QCD studies
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**



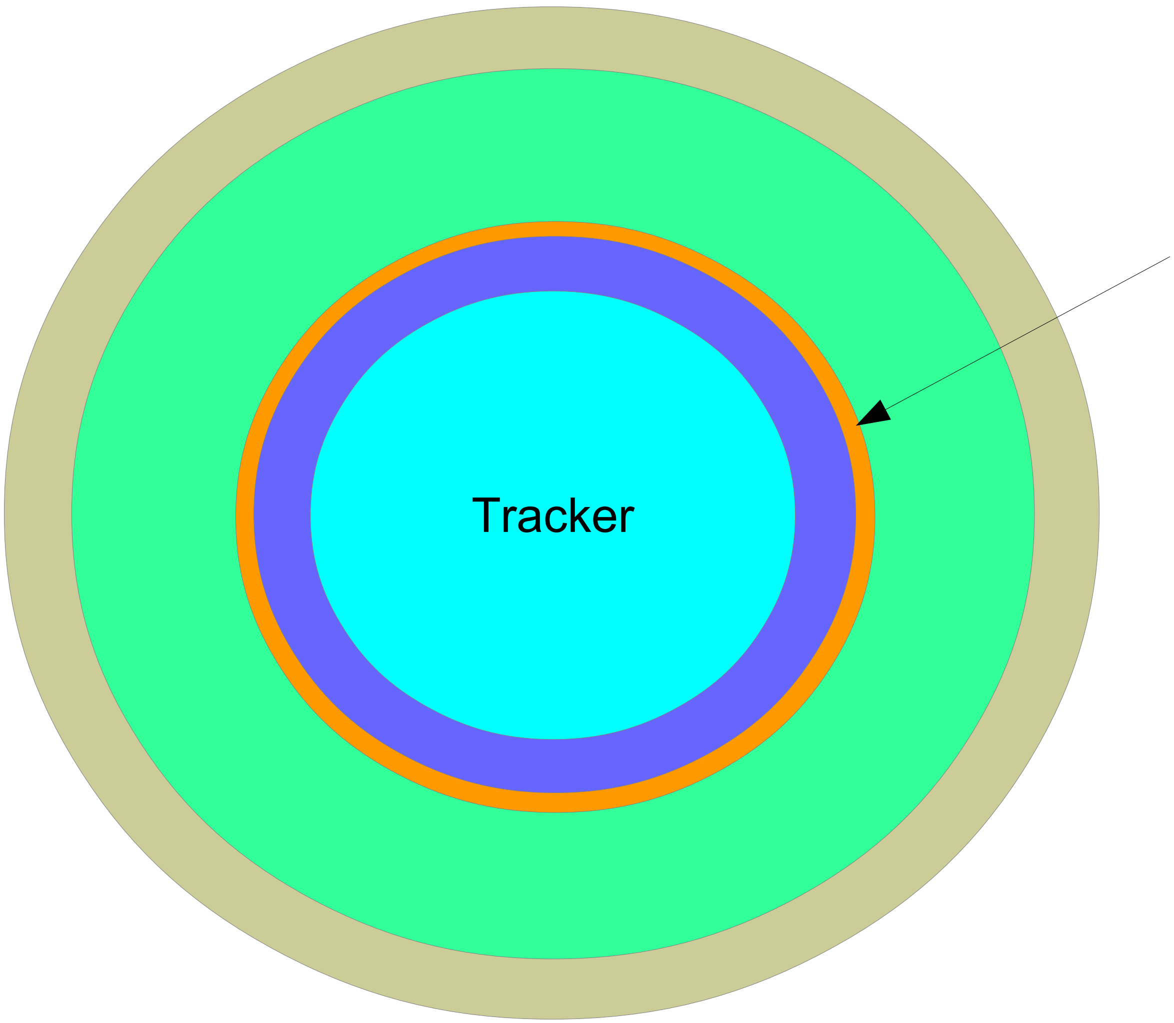

***Complementary***

# Physics requirement

- General Requirements
  - Stable, Systematic Control
  - Hermicity
  - Homogenous
- A Higgs factory:
  - See Higgs
  - Distinguish the Higgs Signal from the SM backgrounds
  - Distinguish the Higgs generation/decay mode
- A Z/factory factory
  - Tag different flavors – particle id (charged P id)



# PFA Oriented concept: A preliminary design




Dedicated ToF
Or
ECAL Layer with TDC
Equipped Chips

delta(T) ~ 50 ps

To balance the efficiency & Purity of time measurement...

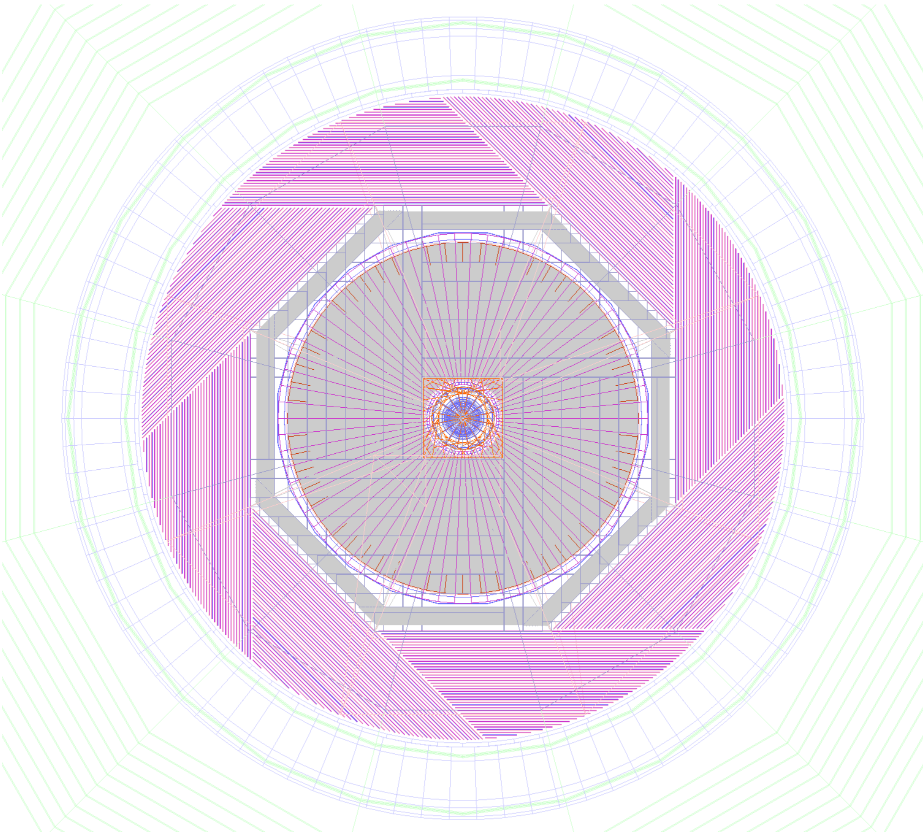
Tracker, TPC: R = 1.8 m

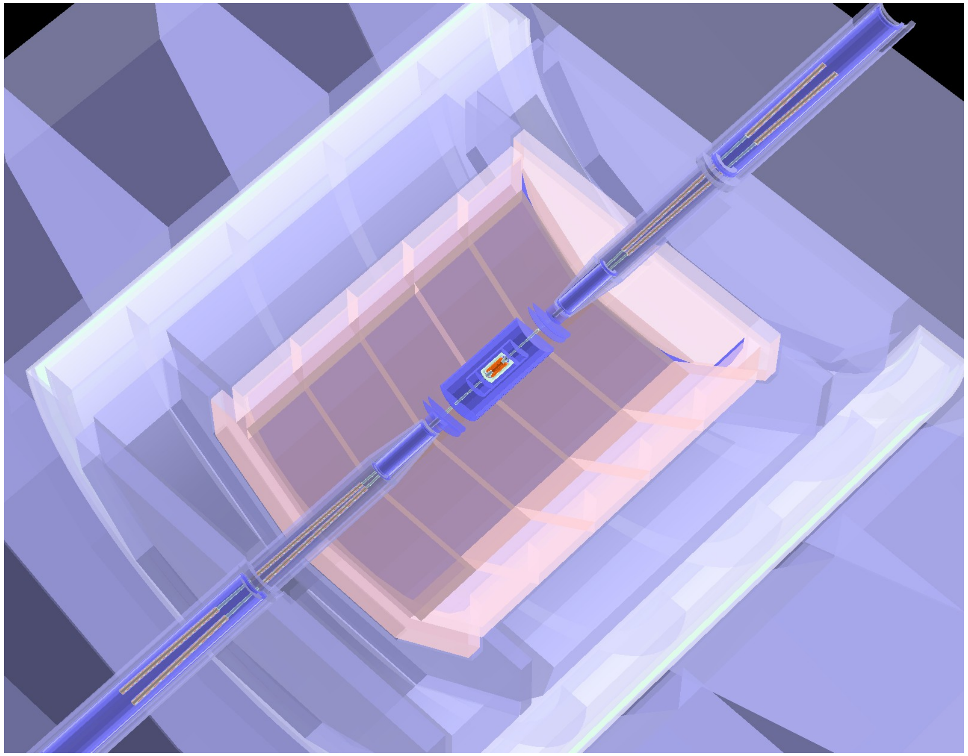
ECAL: 84-90 mm W

HCAL: ~1000 mm Iron

Solenoid (3T) + Yoke

# Reference concept for CEPC CDR



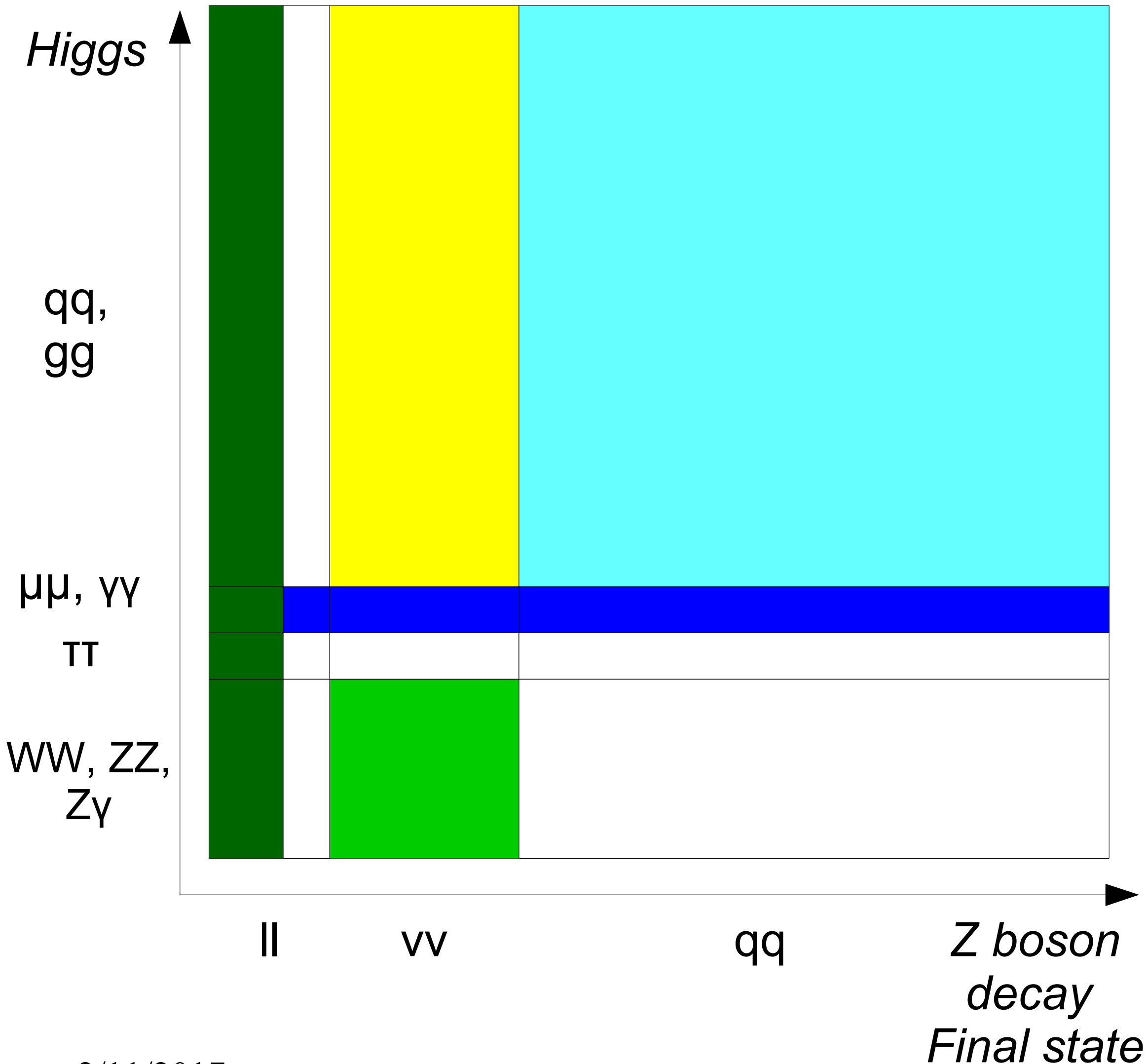


PFA Oriented Design (Reference: ALEPH, SiD & **ILD**). TPC + Si-W ECAL + GRPC HCAL

Geometry optimized at Physics benchmarks
*Smaller B Field (3.5 → 3T), Thinner HCAL (48 → 40Layers), ECAL based ToF (50 ps),*
MDI/Yoke System, etc.

Result based on CEPC-v1(~ ILD), CEPC-v4 (~Optimized), Dedicated geometry sample

# Benchmark measurements




Lepton & Momentum resolution: Br = 6.7%

Flavor Tagging & JER: Br = 14%

Composition of Jet/MET, lepton: Br = 4%

Jet Clustering: Br = 50%

Photon/ECAL: Br = 0.2%

qqH, H->inv. MET & NP: SM Br = 0.1%

EW, Br(tau->X) @ Z pole: Separation

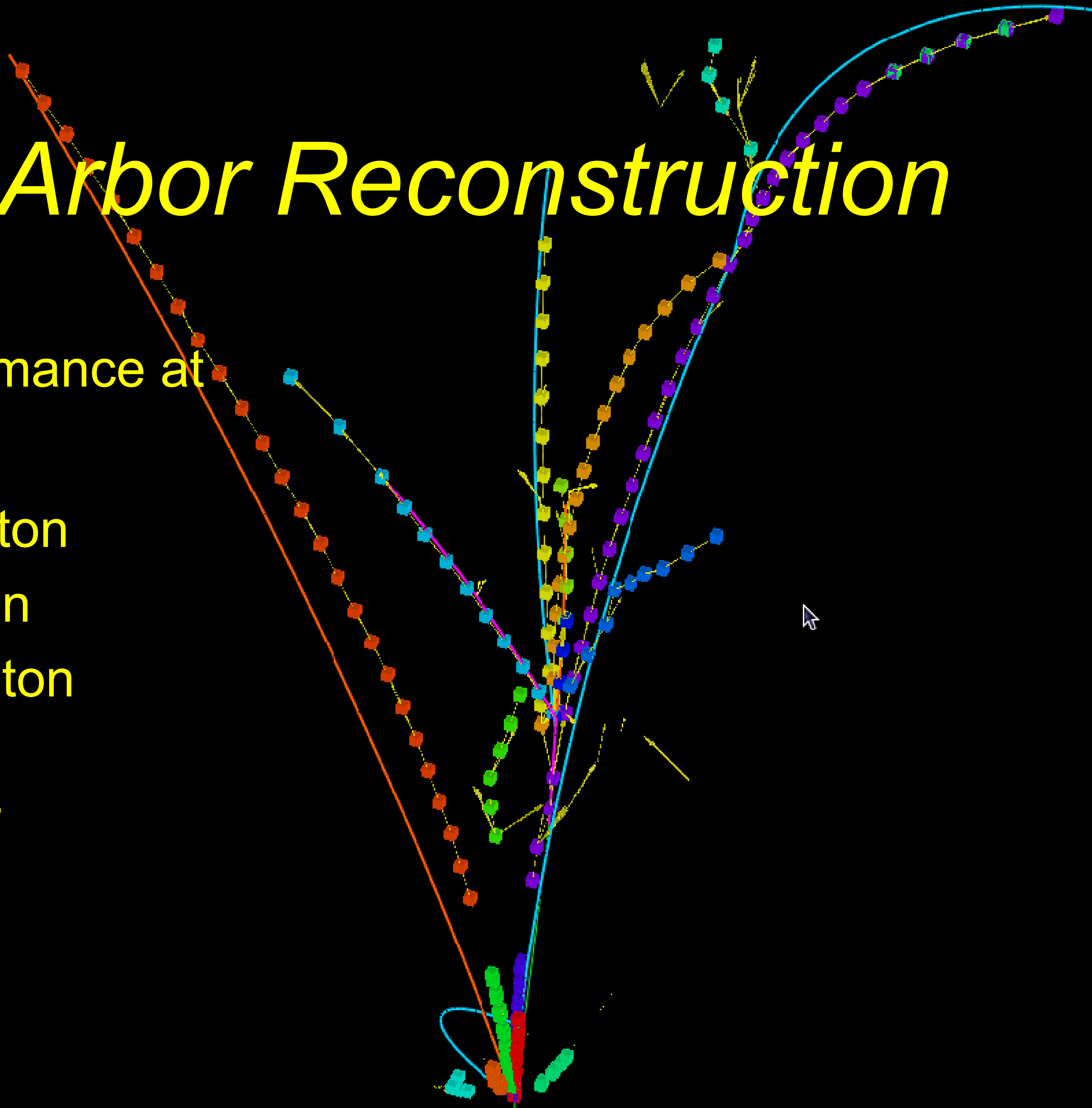
# Parameters

| | CEPC_v1 (~ ILD) | Optimized (Preliminary) | Comments |
|---|---|---|---|
| Track Radius | 1.8 m | >= 1.8 m | Requested by Br(H->μμ) measurement |
| **B Field** | **3.5 T** | **3 T** | **Requested by MDI** |
| **ToF** | **-** | **50 ps** | **Requested by pi-Kaon separation at Z pole** |
| ECAL Thickness | 84 mm | 84(90) mm | 84 mm is optimized on Br(H->γγ) at 250 GeV; 90mm for bhabha event at 350 GeV |
| ECAL Cell Size | 5 mm | 10 – 20 mm | Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation |
| ECAL NLayer | 30 | 20 – 30 | Depends on the Silicon Sensor thickness |
| **HCAL Thickness** | **1.3 m** | **1 m** | - |
| **HCAL NLayer** | **48** | **40** | Optimized on Higgs event at 250 GeV; Margin might be reserved for 350 GeV. |

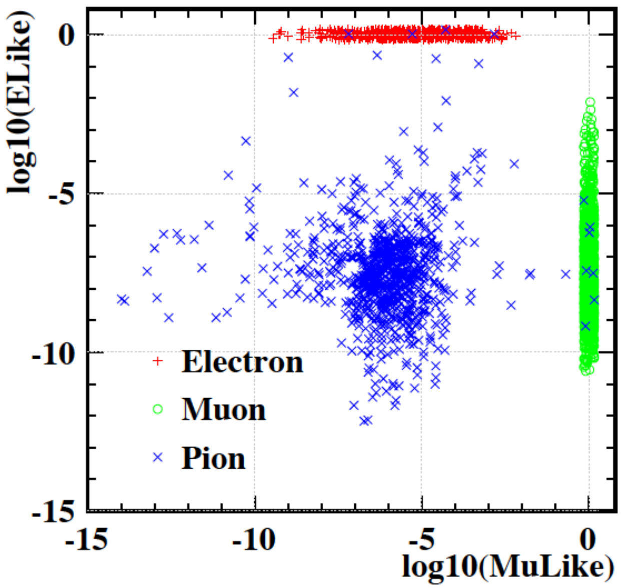
# *Arbor Reconstruction*

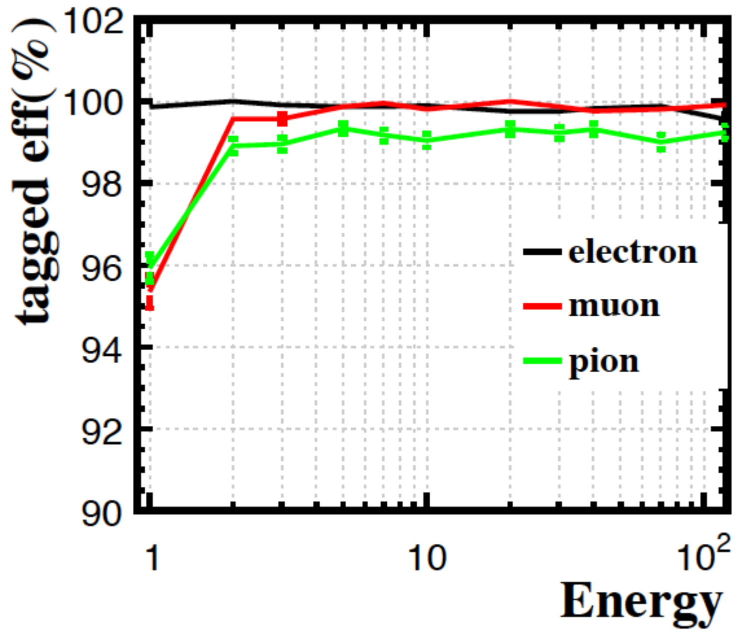
Performance at

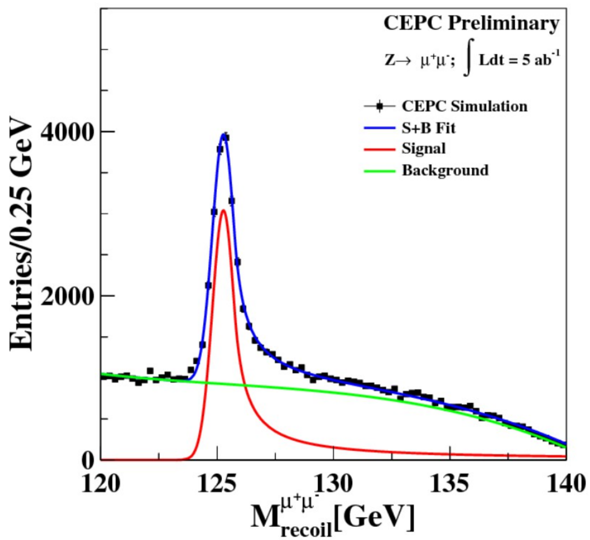
- Lepton
- Kaon
- Photon
- Tau
- JET



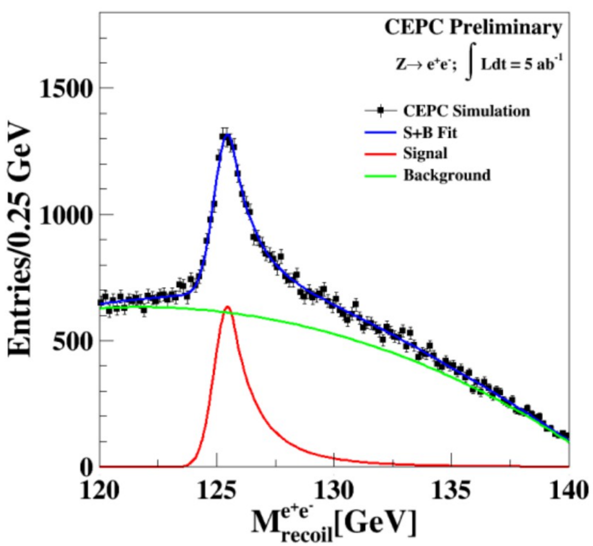
# Lepton



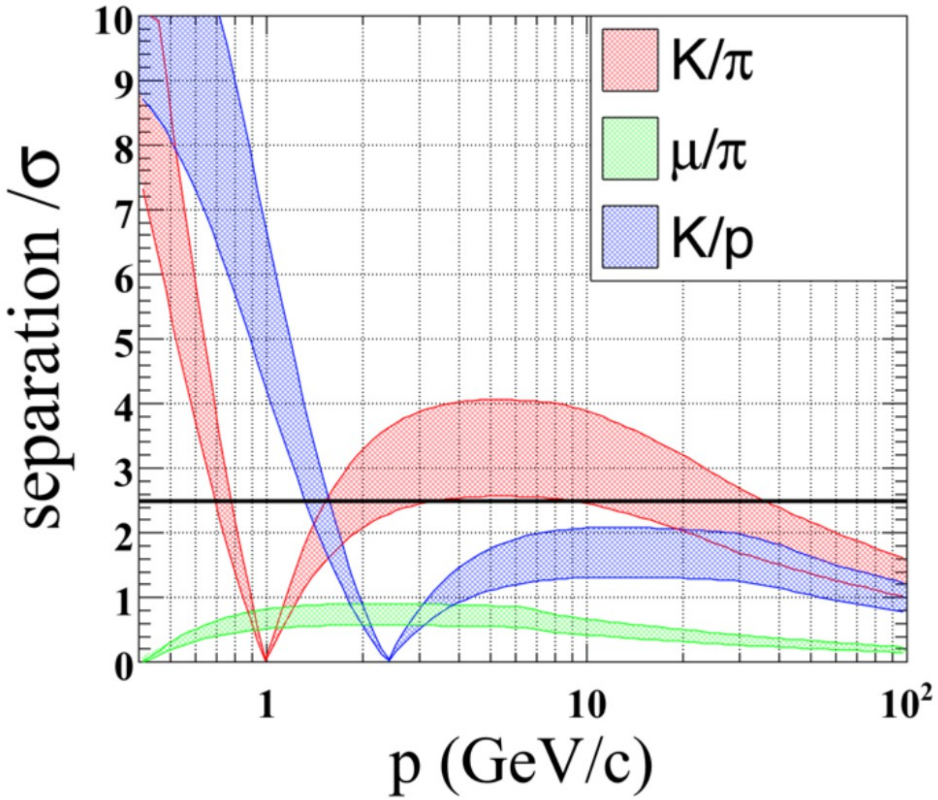

*BDT method using 4 classes of 24 input discrimination variables.*

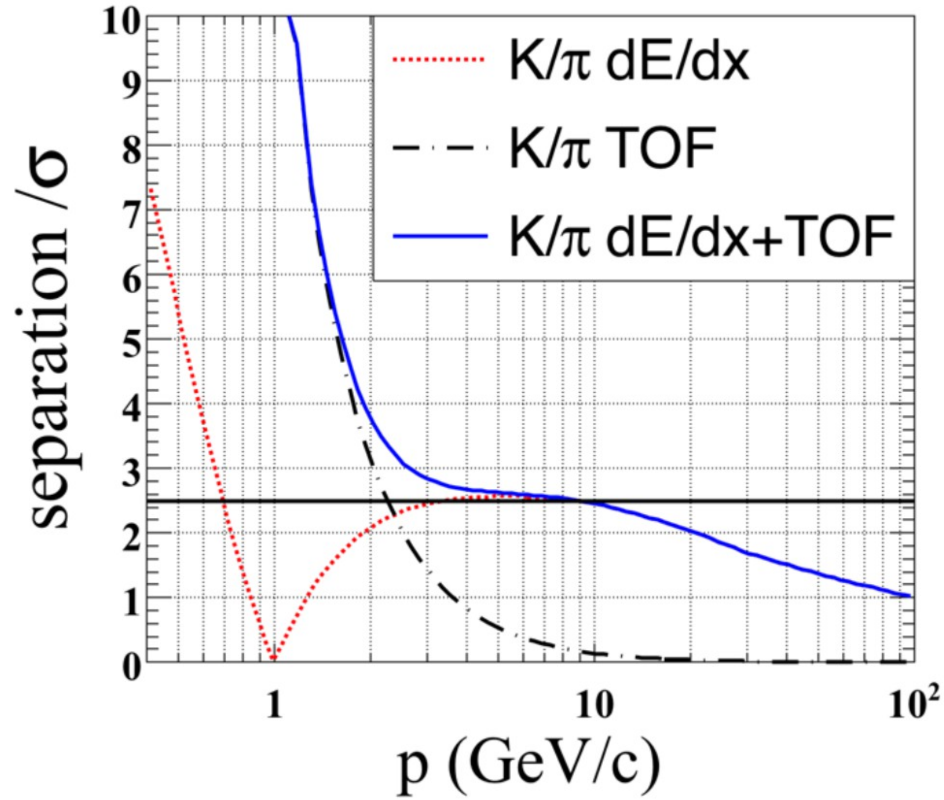



Test performance at: Electron = E_likeness > 0.5 ;
Muon = Mu_likeness > 0.5
Single charged reconstructed particle, for E > 2 GeV:
lepton efficiency > 99.5% && Pion mis id rate ~ 1%


https://link.springer.com/article/10.1140/epjc/s10052-017-5146-5

# Kaon



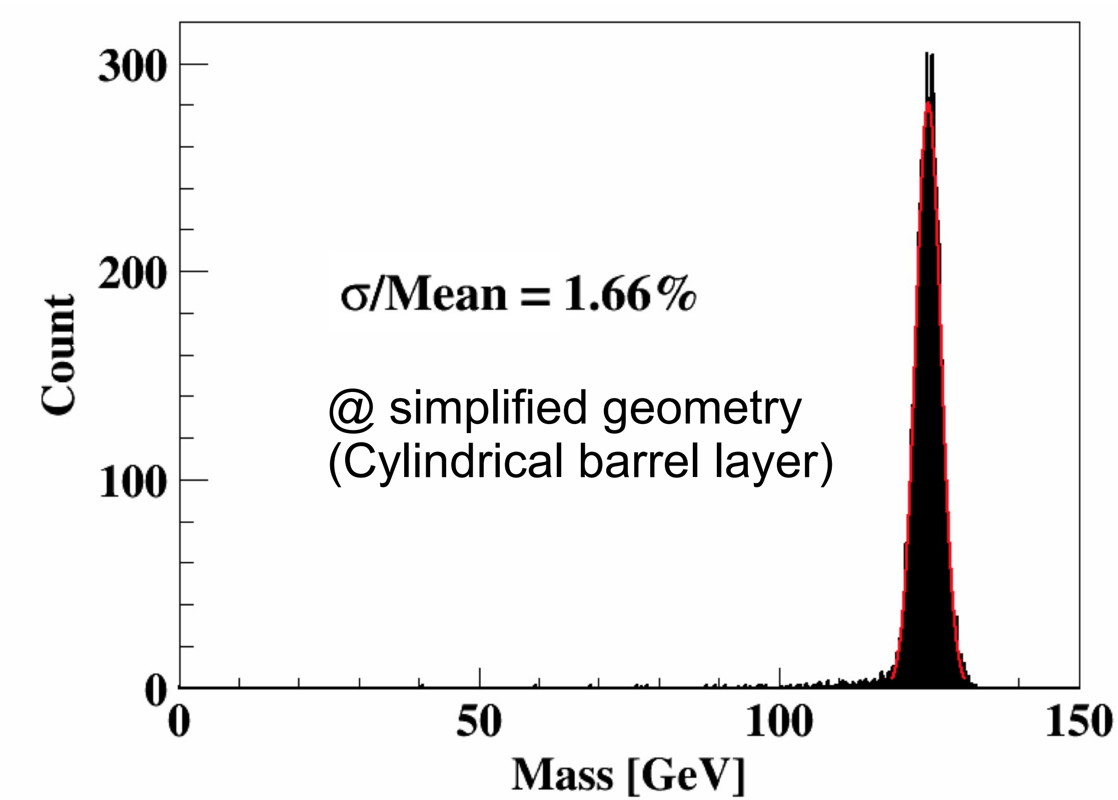



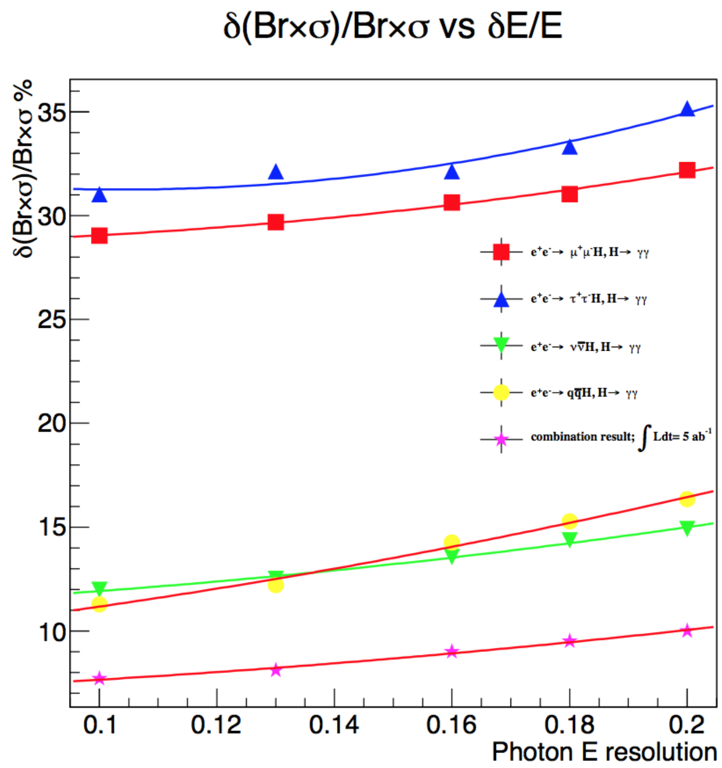

Highly appreciated in flavor physics @ CEPC Z pole
- TPC dEdx + ToF of 50 ps

At inclusive Z pole sample:
- Conservative estimation gives efficiency/purity of 91%/94% (2-20 GeV, 50% degrading +50 ps ToF)
- Could be improved to 96%/96% by better detector/DAQ performance (20% degrading + 50 ps ToF)

More detail in My Talk:
https://agenda.linearcollider.org/event/7645/contributions/40113/attachments/32184/48846/TPC-CEPC-2.pdf

# Photon

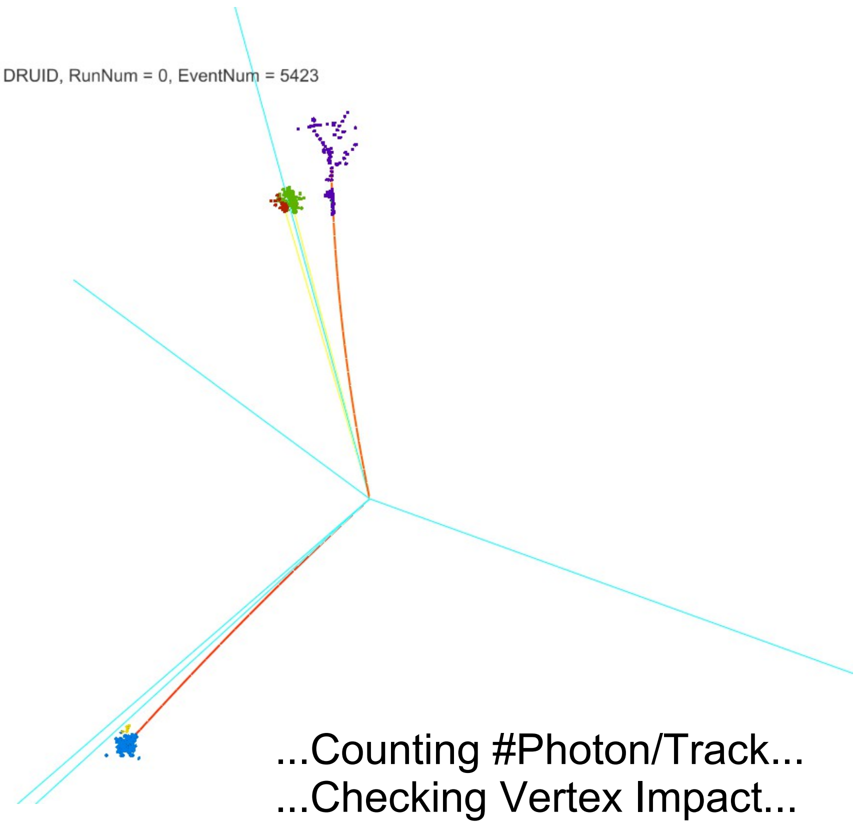


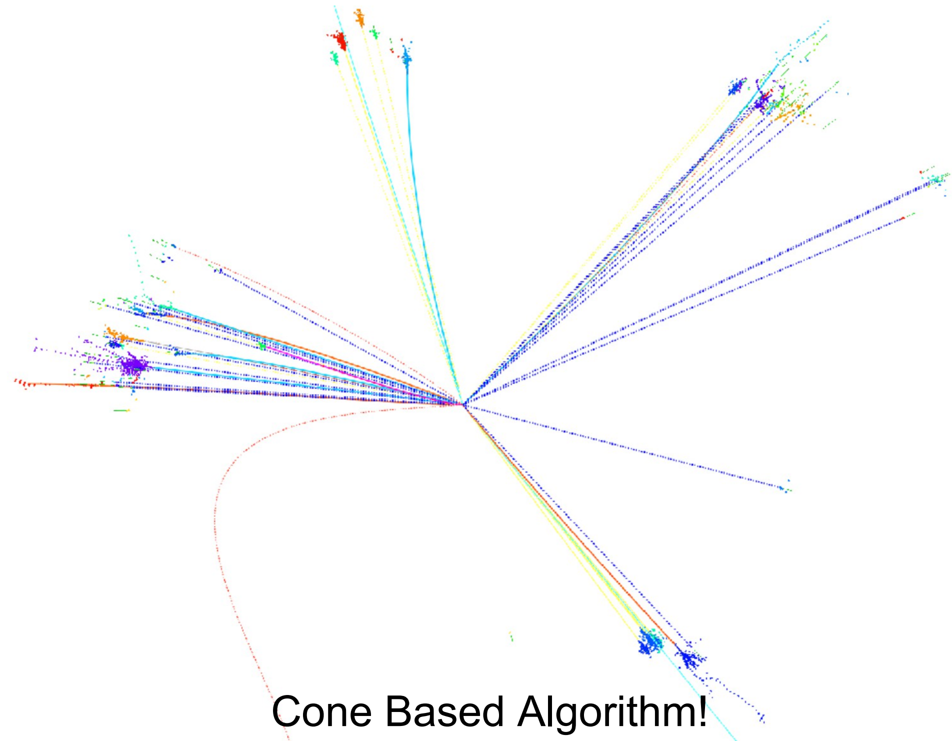

Relative Accuracy: ~ 8.5%

Inhomogeneity degrades the resolution significantly.
Physics requirement: constant term < 1%
Detector geometry defects degrades the mass resolution to **2.2%** (after correction);

# Tau




...Counting #Photon/Track...
...Checking Vertex Impact...

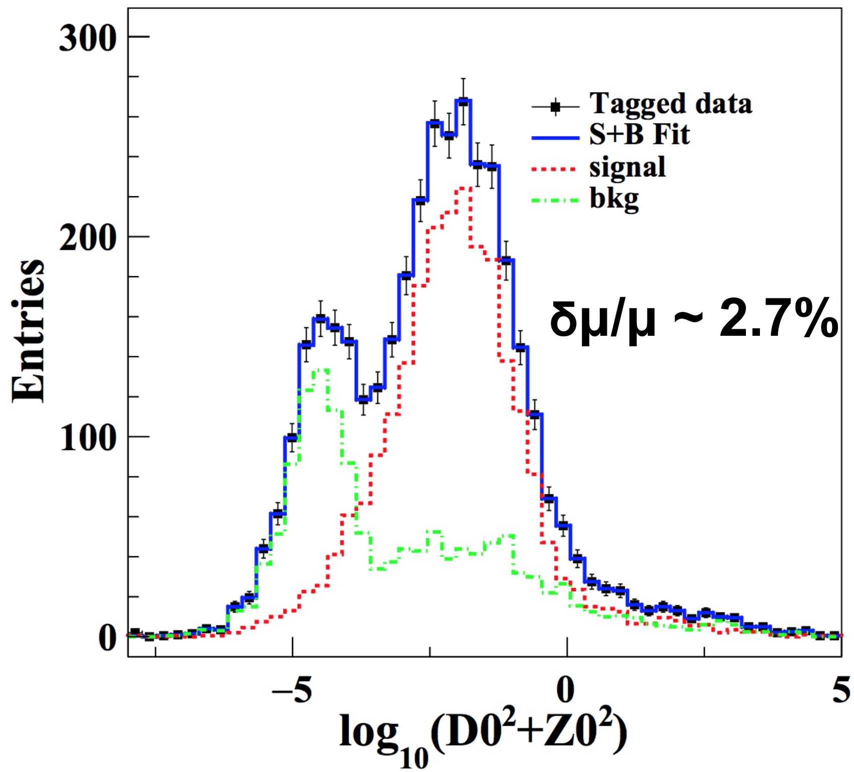


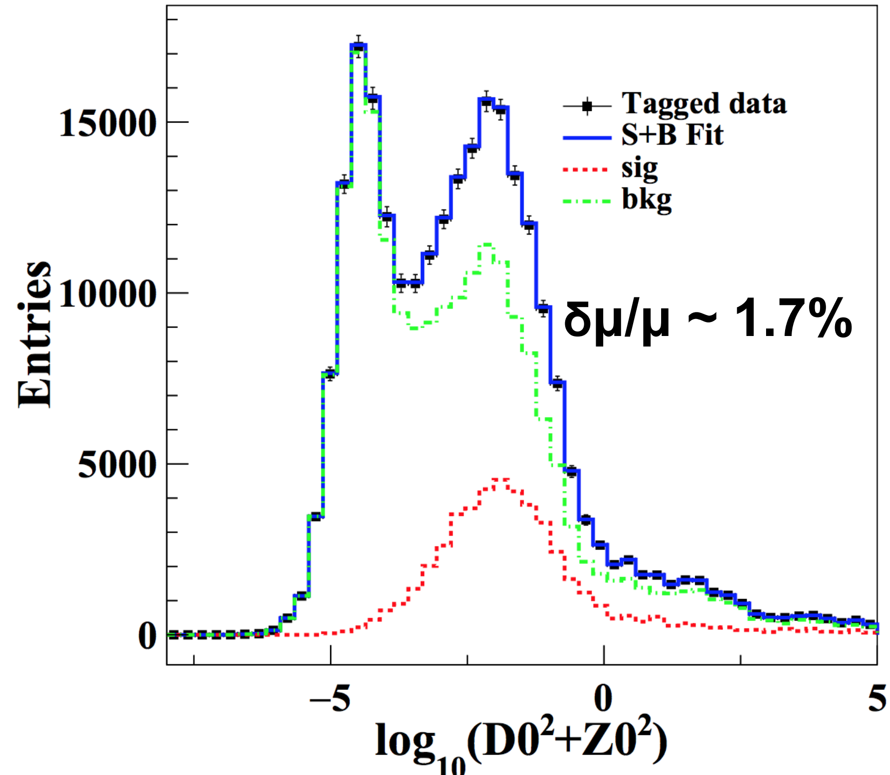
Cone Based Algorithm!
Para. Optimization

- Two catalogues:
  - Leptonic environments: i.e, llττ(ZZ/ZH), ννττ(ZZ/ZH/WW), Z→ττ;
  - Jet environments: i.e, ZZ/ZH→qqττ, WW→qqντ;

*See Dan's presentation for more details*
*https://agenda.linearcollider.org/event/7645/contributions/40070/*

# g(Hττ) measurement: preliminary




- ZH→μμττ
- Extremely Efficient Event Selection
- Signal efficiency of 93% - entire SM background reduced by 5 orders of magnitude

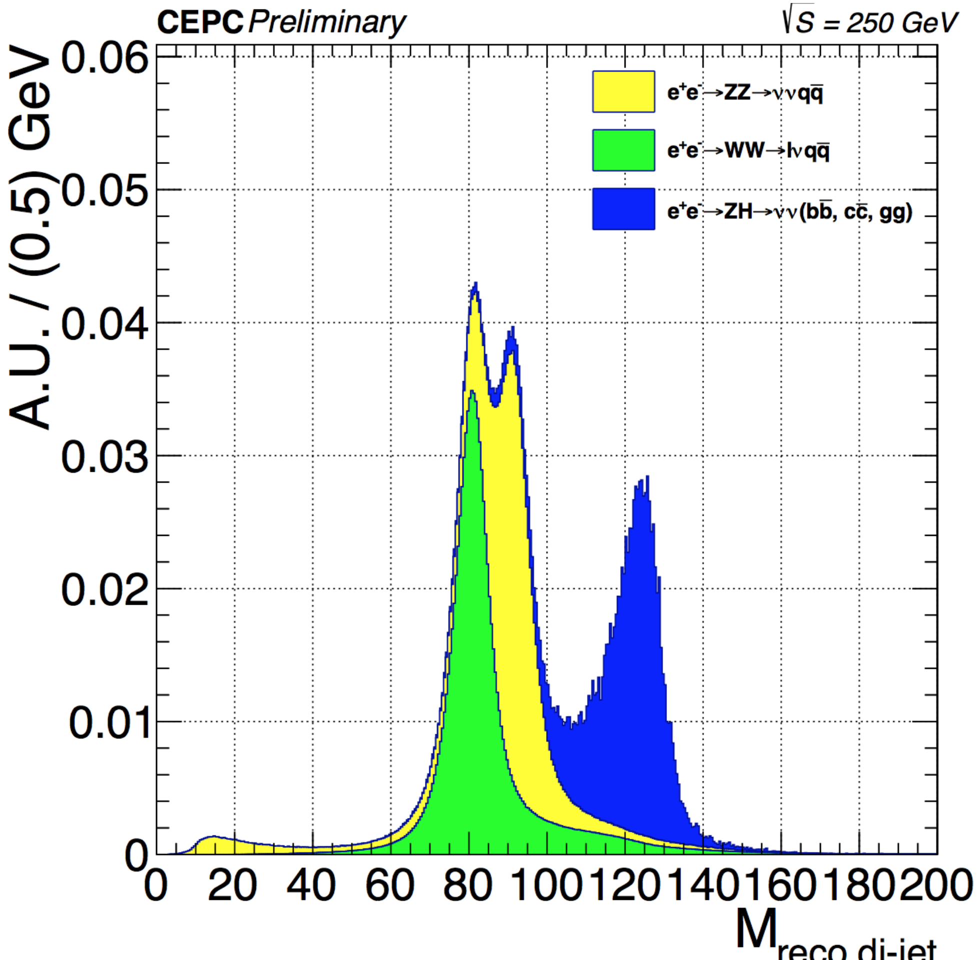
- ZH→qqττ
- Cone based tau finding algorithm, Compromise the efficiency & purity
- Signal efficiency of 51%

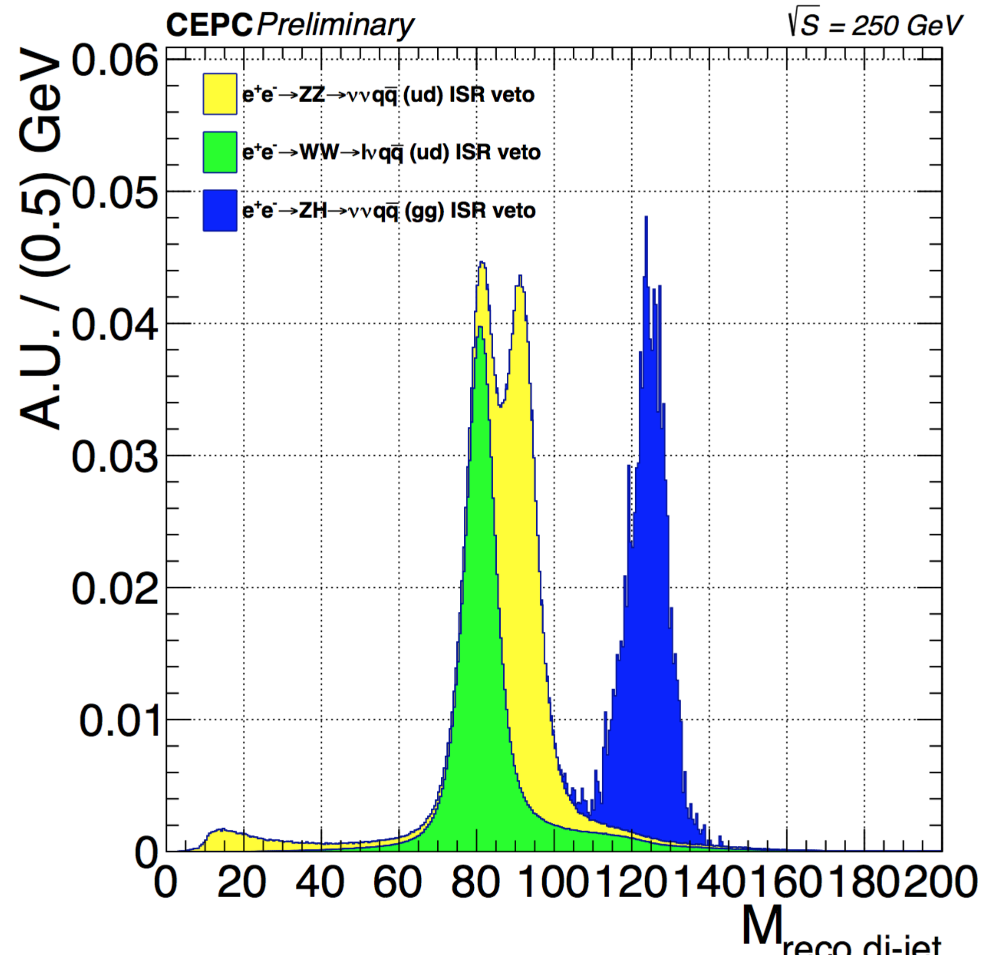
***VTX system, and the understanding of background, is also crucial for this measurement***

# Jets

- Boson Mass Resolution: Separate W, Z and Higgs in hadronic decay mode
  - Essential for Higgs measurement
    - Separate Higgs from Z/W (relatively easy)
    - Separate H→ZZ/WW events (challenging)
  - Appreciated in Triplet Gauge Boson Coupling measurements
    - Separate WW (Signal) from ZZ, ISR return Z, etc.
  - ...
- Jet Clustering & Single jet response
  - To understand the Degrading induced by Jet Clustering, Matching, etc
  - Search for the most suited jet clustering algorithm (Presumably channel dependent) – Understand the Corresponding Systematic
  - ...

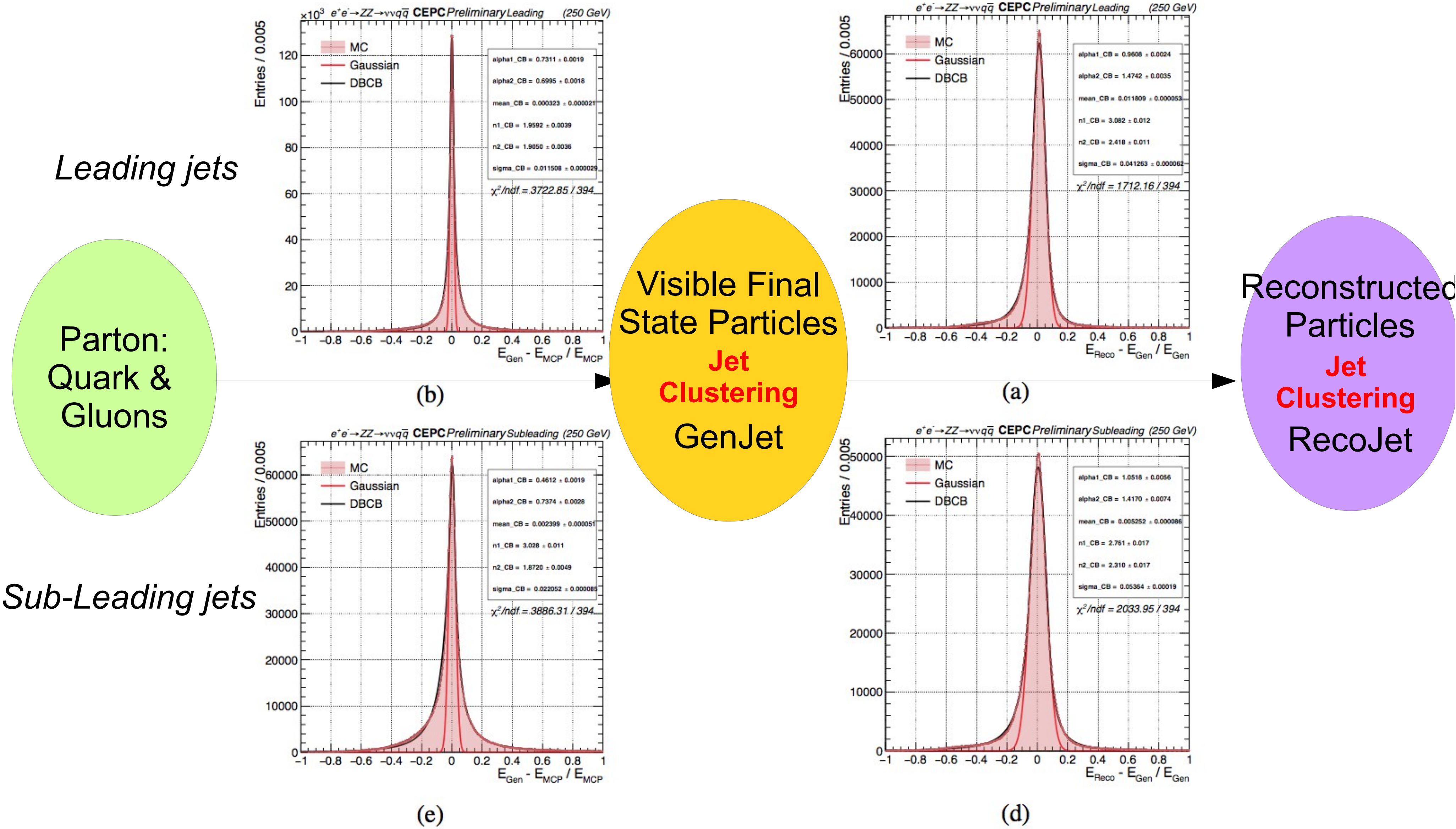
# Separation



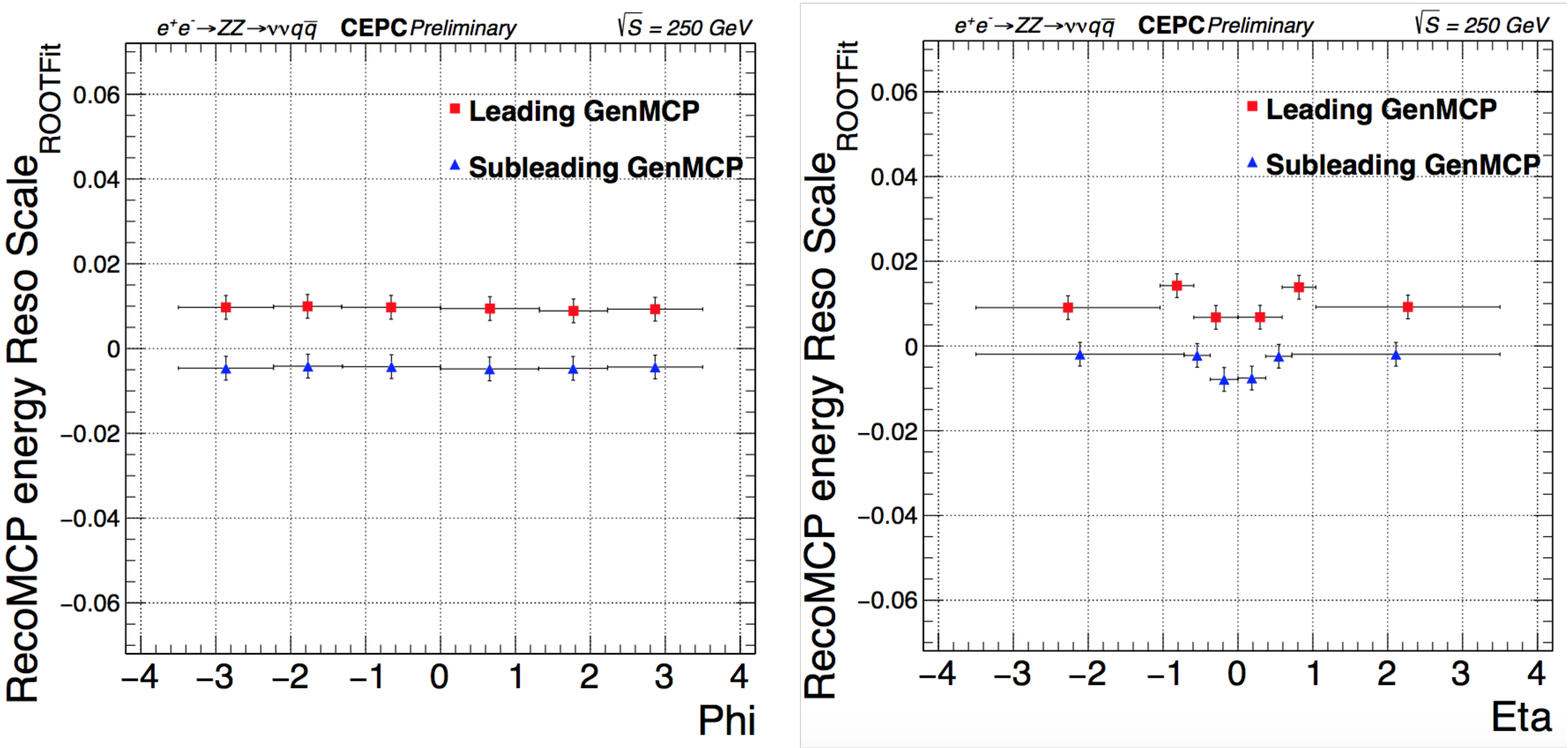

PDF Normalized to unit Area.
Left: Inclusive Samples
Right: Light flavor Sample with Visible ISR Photon Veto

# Impact of Jet Clustering: Significant



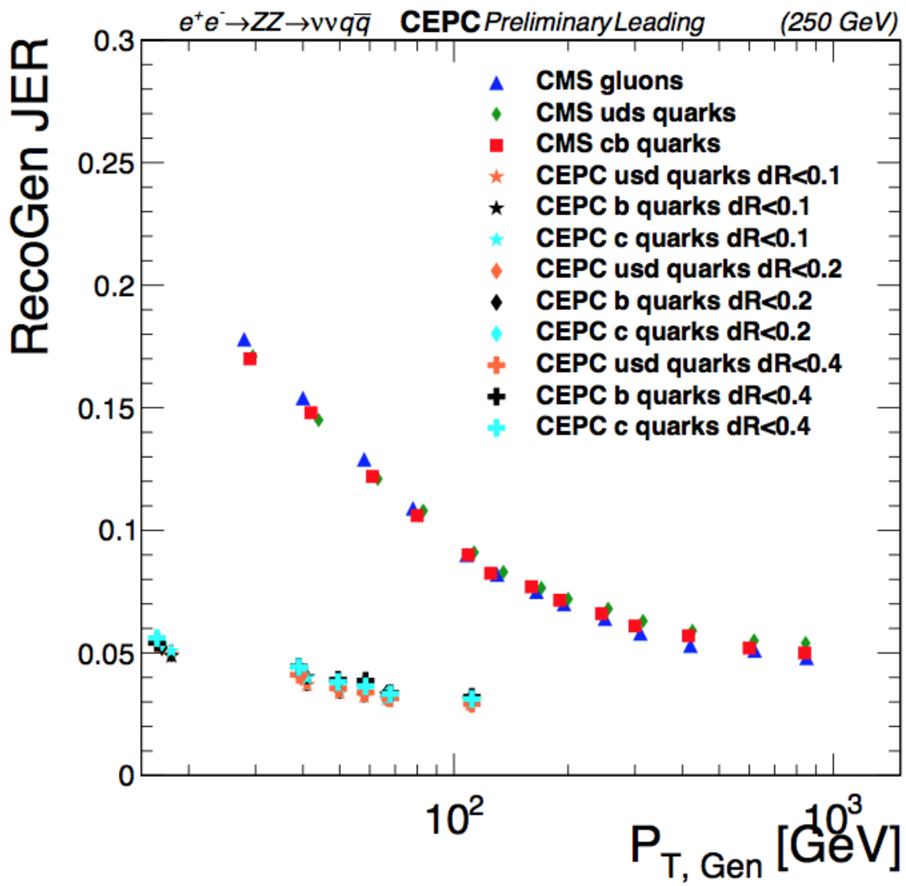

Jet Clustering is Mainly responsible for the tails

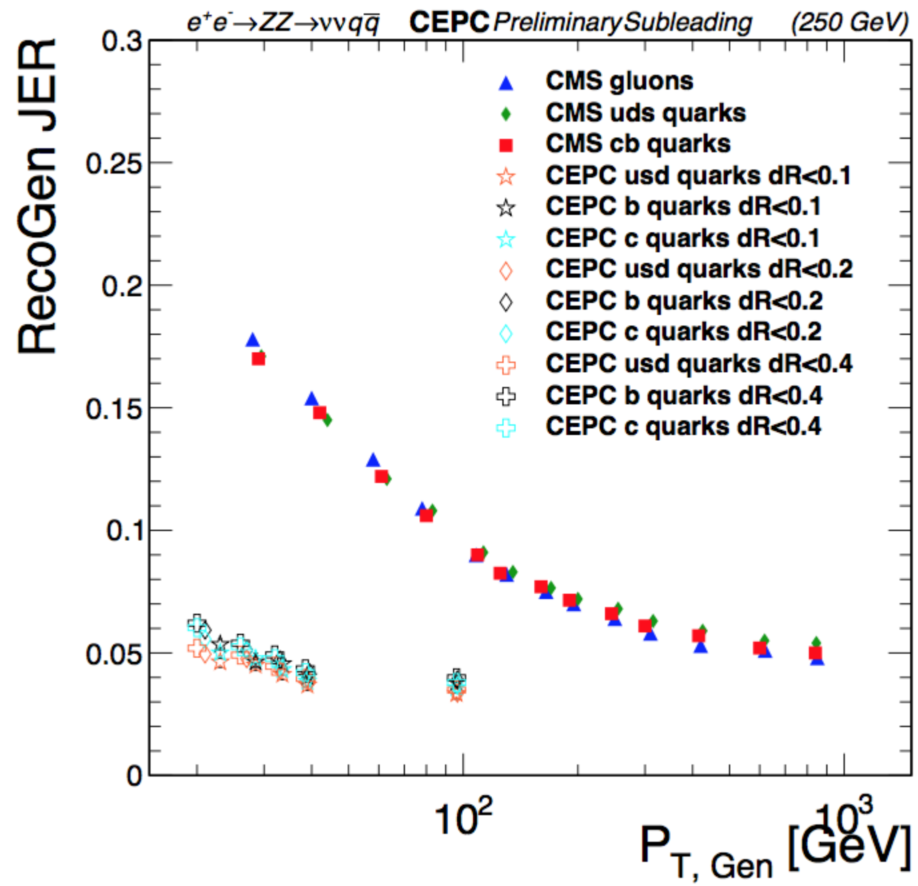
# Jet energy Scale




Amplitude ~ 1%
Large JES observed at Leading Jet (Correlated), and at overlap region (Increasing of Splitting)

# Jet Energy Resolution



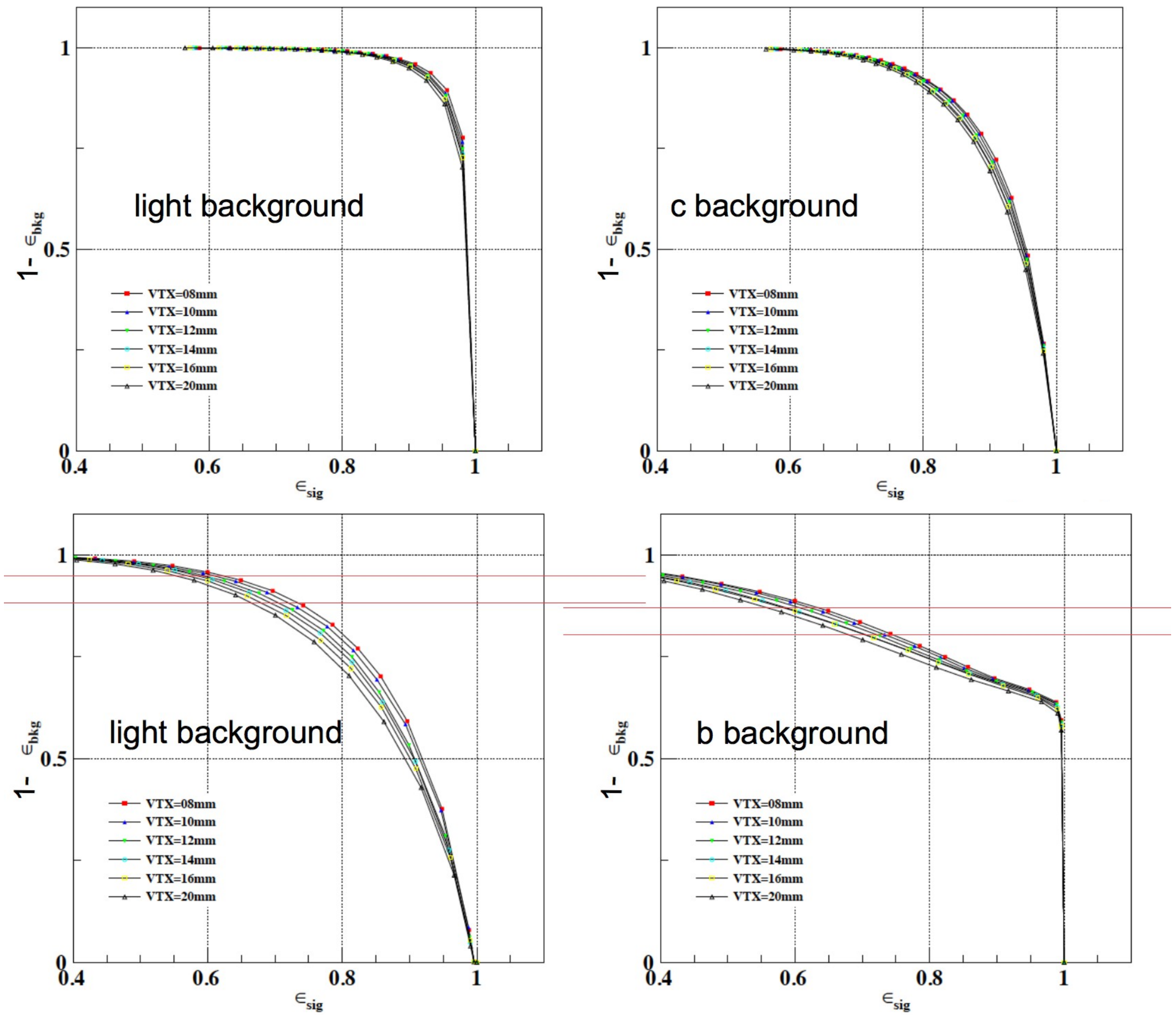




CMS Reference: CMS-JME-13-004,

Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV

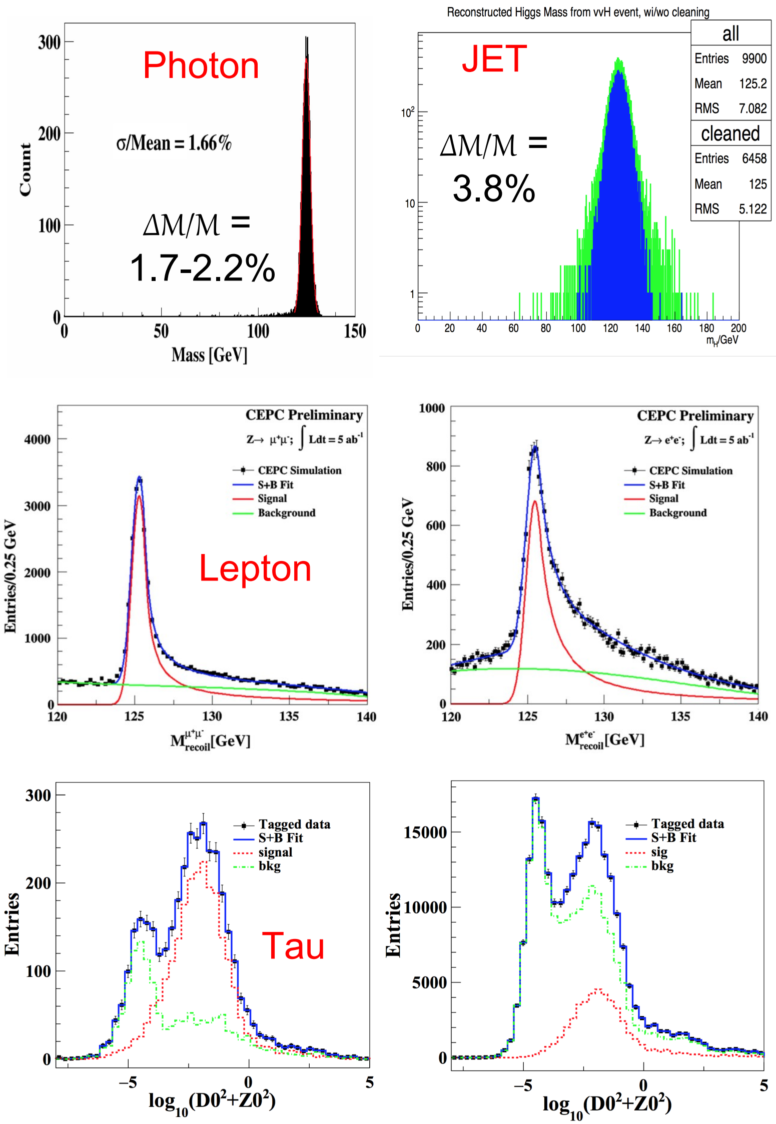
# Flavor Tagging

- LCFIPlus Package
- Typical Performance at Z pole sample:
  - *B-tagging: eff/purity = 80%/90%*
  - *C-tagging: eff/purity = 60%/60%*
- Geometry Dependence of the Performance evaluated




*See Gang's presentation for more details*
*https://agenda.linearcollider.org/event/7645/contributions/40124/*

# PFA Oriented Reconstruction

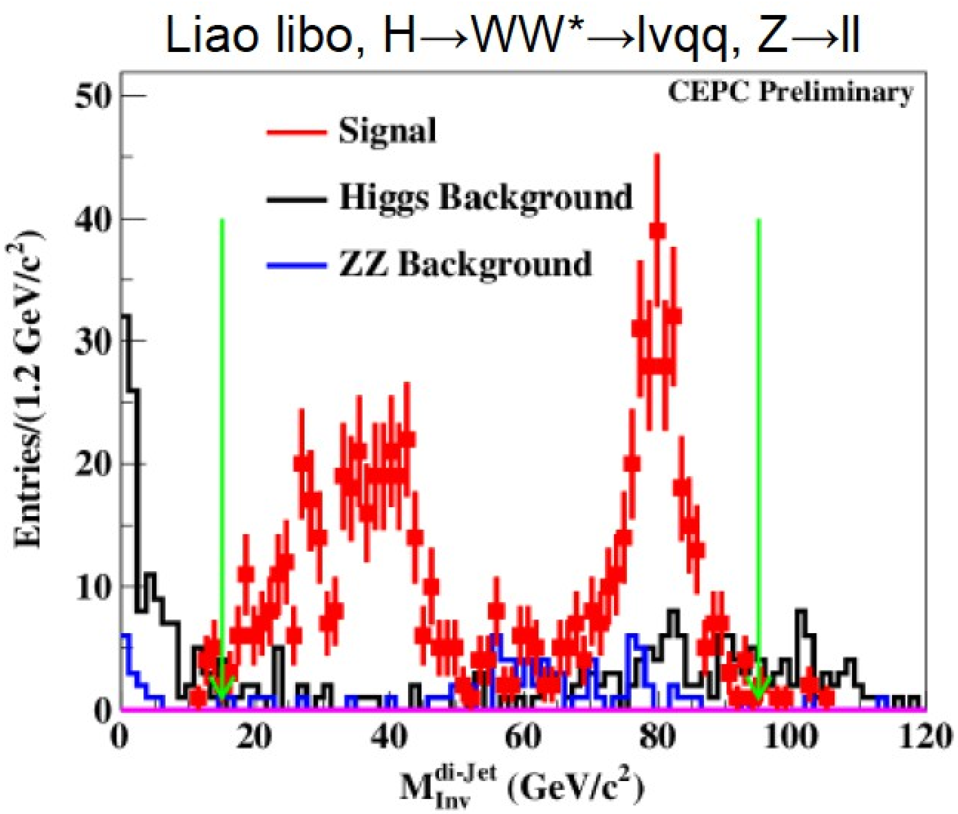


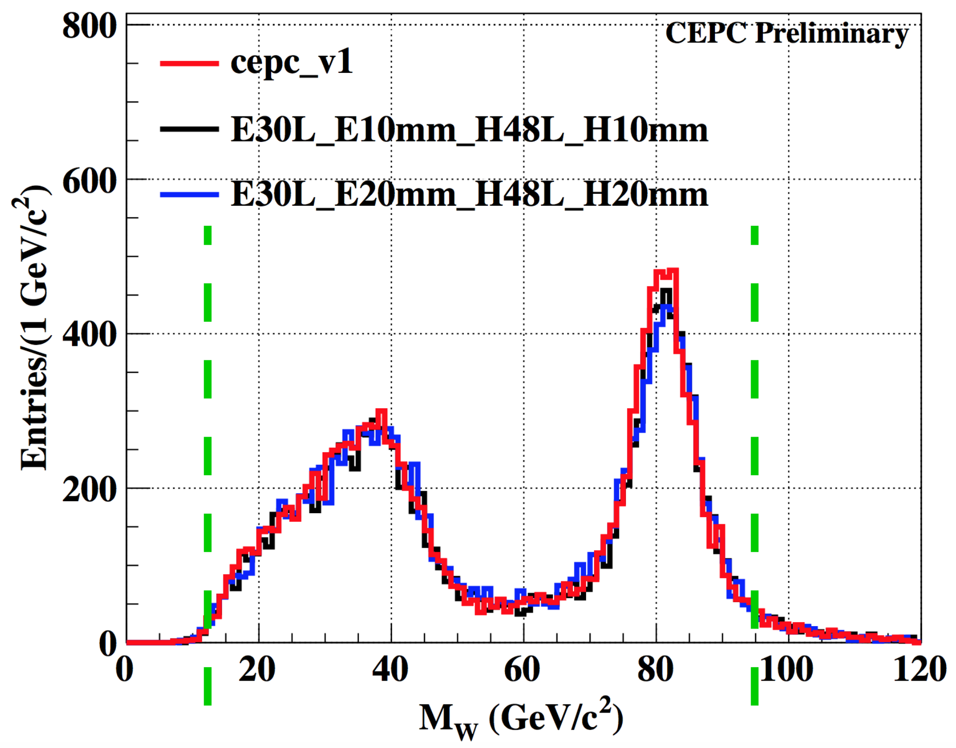

## Example Working Points & Performance for Object identification (Preliminary)

| | Efficiency | Purity | Mis-id Probability from Main Background |
|---|---|---|---|
| Leptons | 99.5 – 99.9% | 99.5 – 99.9% at Higgs Runs(c.m.s = 240 GeV), Energy dependent | $P(\pi^{\pm} \rightarrow leptons) < 1\%$ |
| Photons* | 99.3 – 99.9% | 99.5 – 99.9% at Higgs Runs Energy Dependent | $P(\text{Neutron} \rightarrow \gamma) = 1\text{-}5\%$ |
| Charged Kaons** | 86 – 99% | 90 – 99% at Z pole Runs (c.m.s = 91.2GeV, Track Momentum 2- 20 GeV) | $P(\pi^{\pm} \rightarrow K^{\pm}) = 0.3 - 1.1\%$ |
| b-jets | 80% | 90% at Z pole runs ($Z \rightarrow qq$) | P(uds → b) = 1%<br>P(c → b) = 10% |
| c-jets | 60% | 60% at Z pole runs | P(uds → c) = 5%<br>P(b → c) = 15% |

*Photon*: only considering neutron background and using ToF information*
*Kaon**: Performance Highly depend on DAQ & Geometry*

# Br(H→WW) @ 10mm/20mm Cell size




Br(H→WW) via vvH, H→WW*→lvqq

No lose in the object level efficiency: JER degraded, ~ 5/10% at 10/20 mm

Over all: event reco. efficiency varies ~1%

# Conclusion

- The PFA oriented detector & reconstruction: well established at the CEPC
- Reference detector + Arbor
  - High efficiency & purity for Lepton, Kaon, Photon reconstruction
  - Well established Higgs Signal in Physics benchmarks
  - The Jet energy resolution
    - 2-jets events: efficiently separate W, Z & Higgs: appreciated in TGC & Higgs properties measurements
    - Jet level: |JES| < 1%, JER ~ 3-6%
  - Jet Clustering has significant impact and need to be handled with care
    - To do: detailed study on the 4 jets events (ZH, ZZ, WW)
- Requirement to the Calorimeter
  - High Granularity + **Low Power Consumption** + High Homogeneity

# Backup

# Boson Mass Spectrum

- 2-jets Samples (the majority of events with jets at Higgs operation)
  - Higgs: vvH
  - Z: vvqq and ISR return events
  - W: lvqq events
- Physics effects
  - Intrinsic Width (Z: 2.5 GeV, W: 2 GeV)
  - Neutrinos, especially those induced by heavy flavors
  - ISR photons
  - Interferences*
- Detector effects
  - Acceptance
  - Geometry defects
  - Polar angle dependence

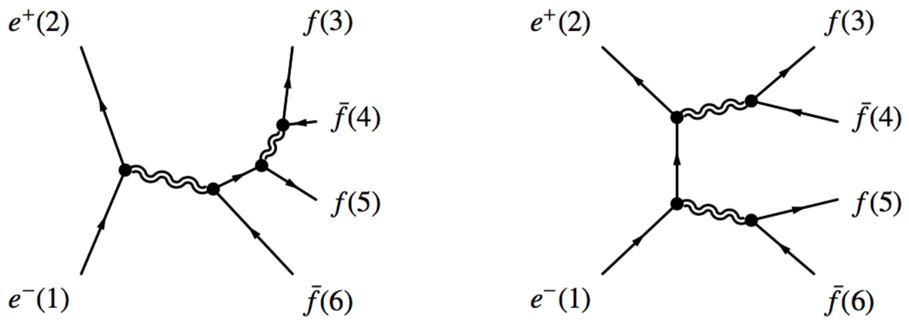
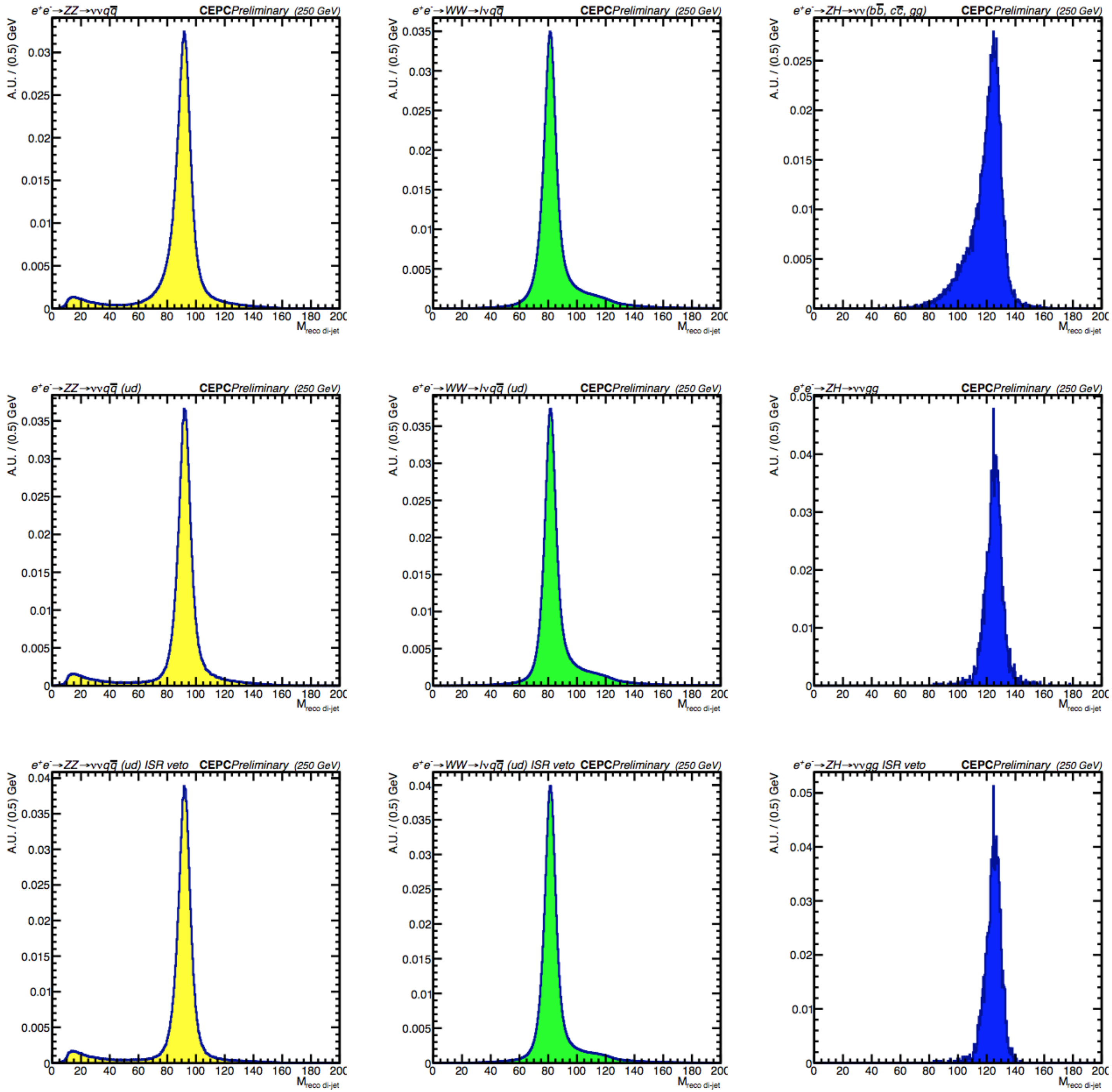



Figure 4: The diagrams for the four fermions processes

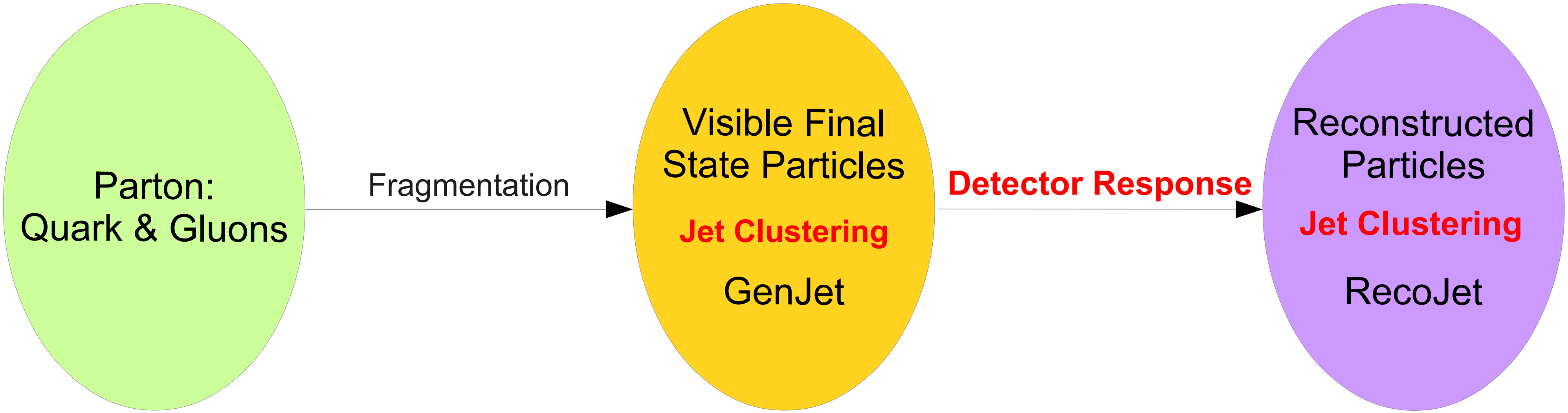



Inclusive sample

Light jet sample

Light jet
+ visible ISR veto

# Jets




- Test on vvqq sample with ee-AntiKt algorithms
- Same Jet Clustering Set up applied for MCParticles & Reconstructed Particles
- *Matching algorithm based on Min. Angle is applied*

# Over all Performance

- Efficiency & Purity at Z pole
  - Statistically: Pion is roughly 8 times w.r.t Kaon, which is 1.4 times more than Protons
  - integrated over 2 – 20 GeV momenta range and the fiducial polar angles

| Condition | | #σ(π-K/K-p) | Efficiency | Purity |
|---|---|---|---|---|
| MCTruth | dEdx only | 3.9/1.5 | 88% | 86% |
| | + TOF | 4.0/3.2 | 98% | 98% |
| 20% degraded | dEdx only | 3.1/1.2 | 81% | 79% |
| | + TOF | 3.3/3.0 | 96% | 96% |
| 50% degraded | dEdx only | 2.4/0.9 | 68% | 68% |
| | + TOF | 2.8/2.9 | 91% | 94% |

Hand waving objective:
To understand the source of degrading, and control it to be less than 20%.

# Key performance: Separation

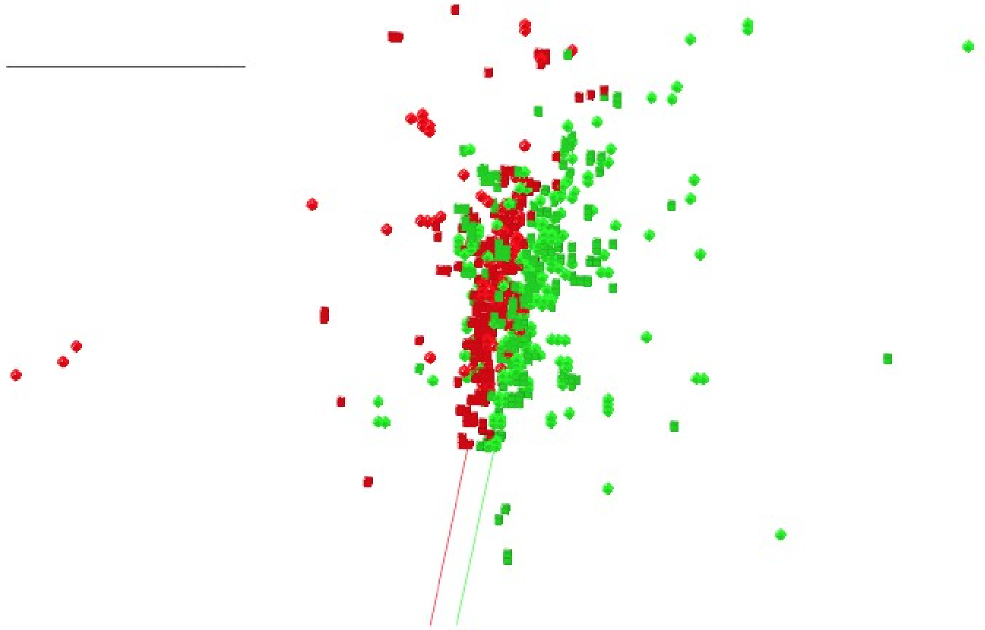
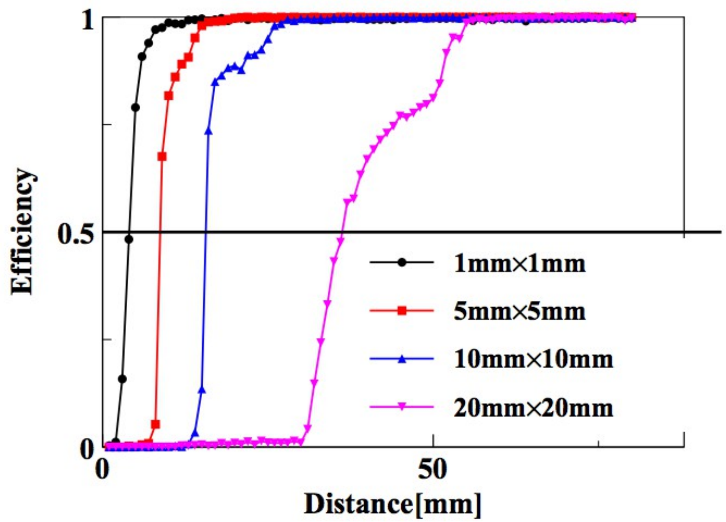
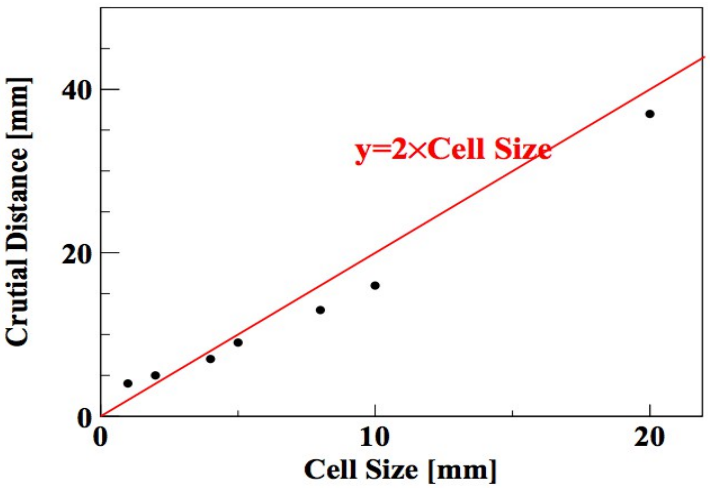


**Figure 11.** Event display of reconstructed di-photon.

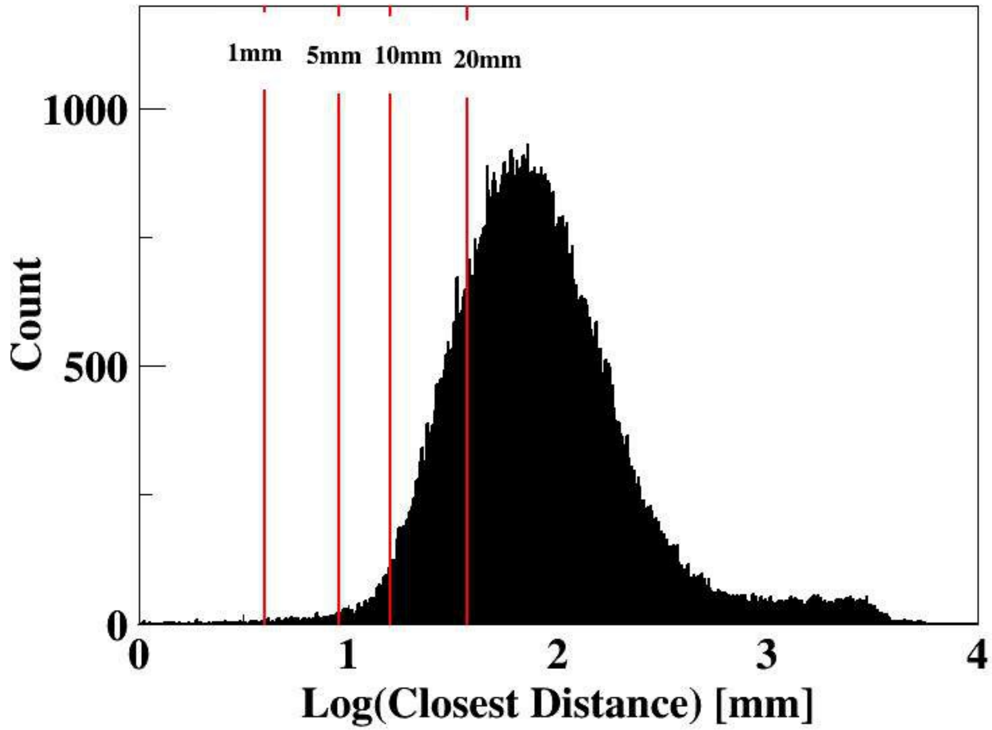
Separation power/Crucial Distance:

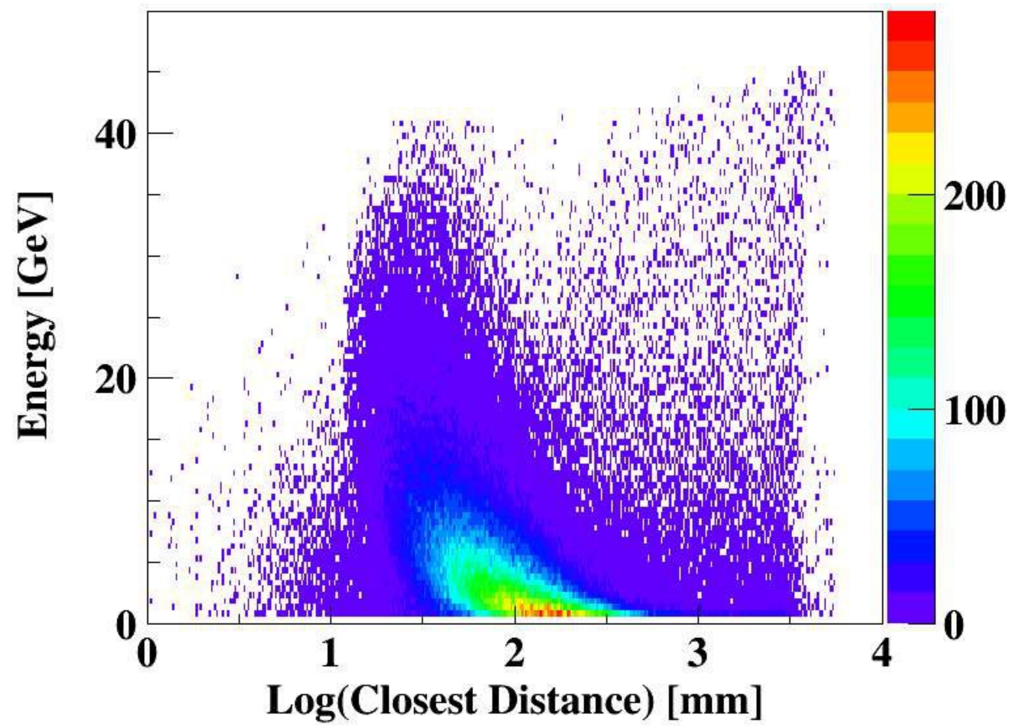
~ 2*Cell with Cell Size <= Moliere Radius;
~ 1 Cell with Cell Size > 1 Moliere Radius.



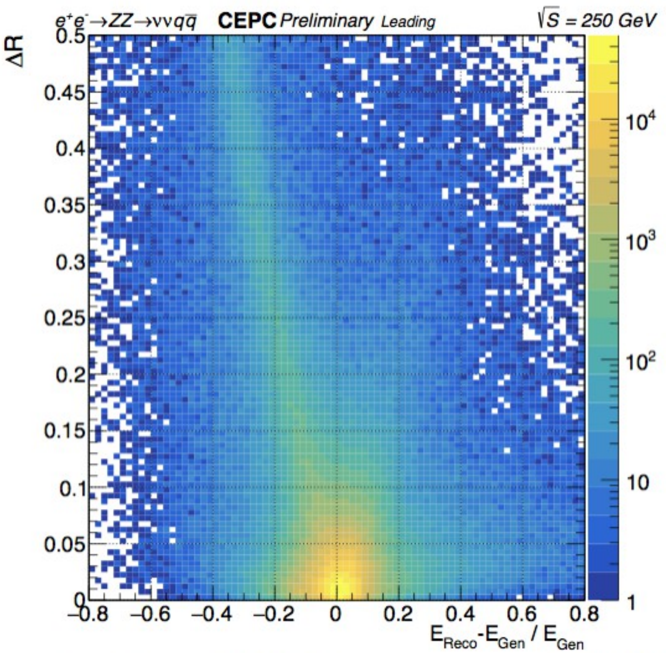
# Impact of Separation: Z->tau tau @ Z pole

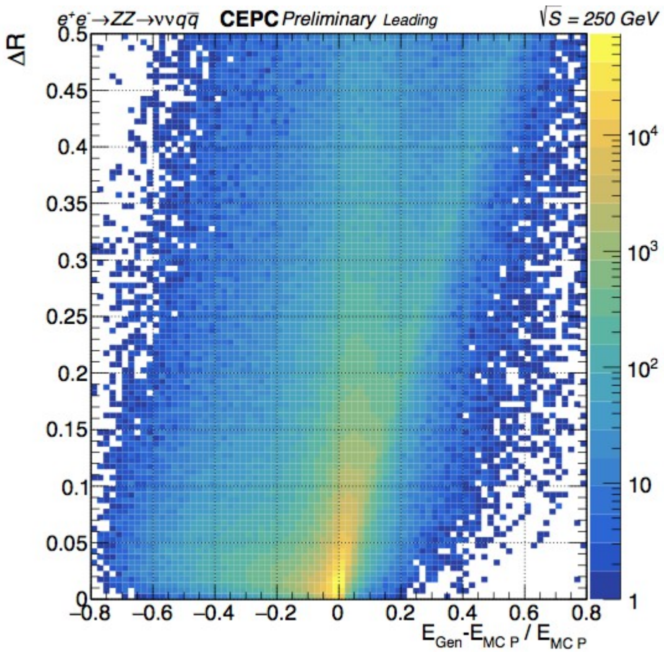


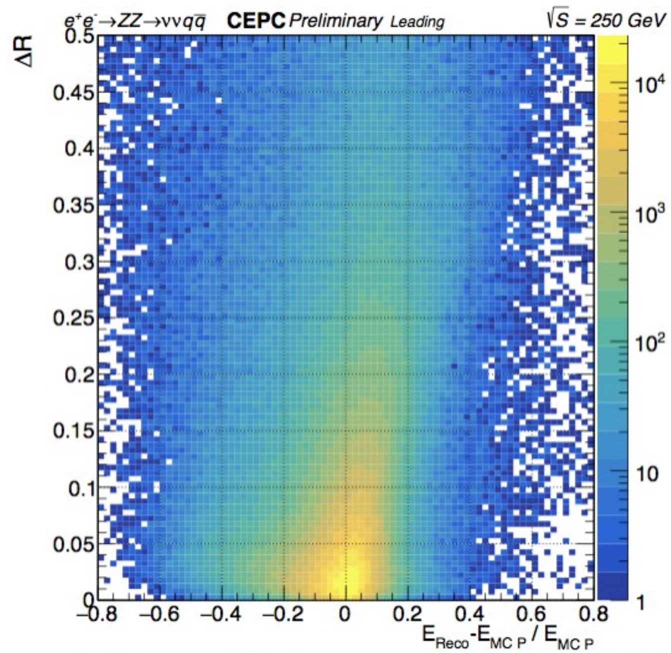



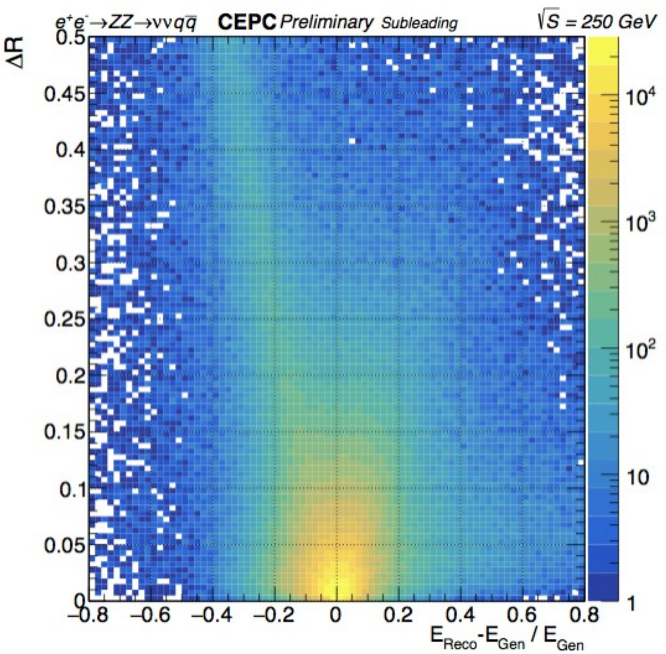

| Cell Size/mm | 1 | 5 | 10 | 20 |
|---|---|---|---|---|
| Crucial Dis/mm | 4 | 9 | 16 | 37 |
| Percentage of potentially overlap photon | 0.07% | 0.4% | 1.7% | 18.6% |

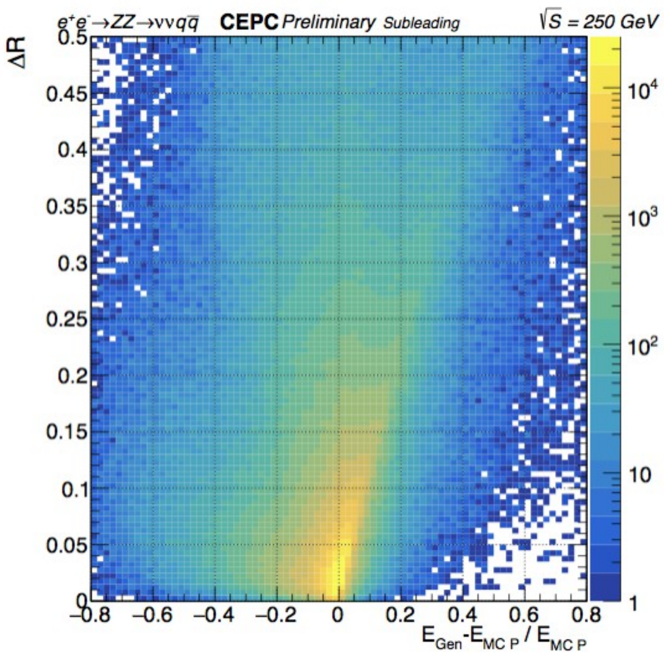
5 -> 20 mm: May severe degrade Tau physics performance
-> to be investigated

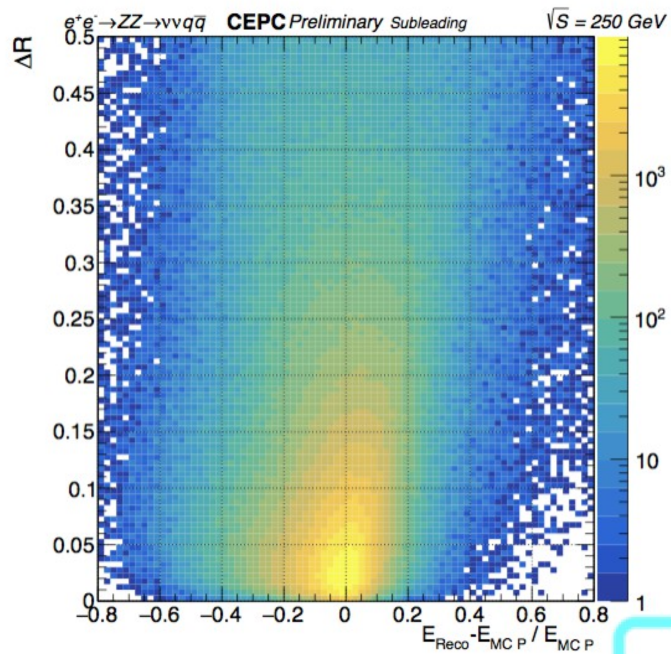

$e^+e^- \to ZZ \to \nu\nu q\bar{q}$ CEPC Preliminary Leading
$\sqrt{S}$ = 250 GeV
ΔR
$E_{Reco}-E_{Gen}$ / $E_{Gen}$

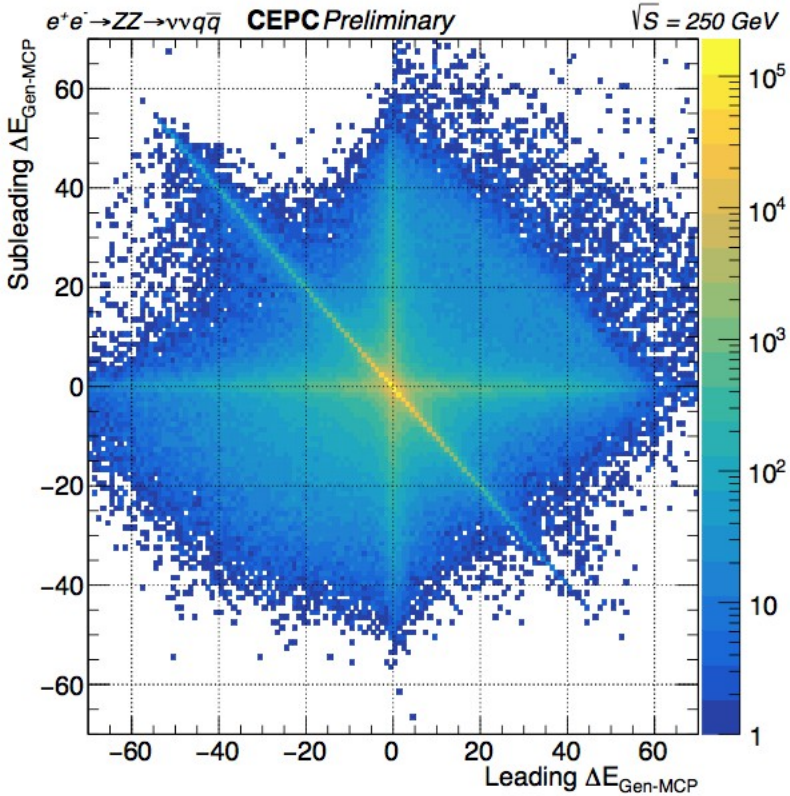

$e^+e^- \to ZZ \to \nu\nu q\bar{q}$ CEPC Preliminary Leading
$\sqrt{S}$ = 250 GeV
ΔR
$E_{Gen}-E_{MC\ P}$ / $E_{MC\ P}$


$e^+e^- \to ZZ \to \nu\nu q\bar{q}$ CEPC Preliminary Leading
$\sqrt{S}$ = 250 GeV
ΔR
$E_{Reco}-E_{MC\ P}$ / $E_{MC\ P}$

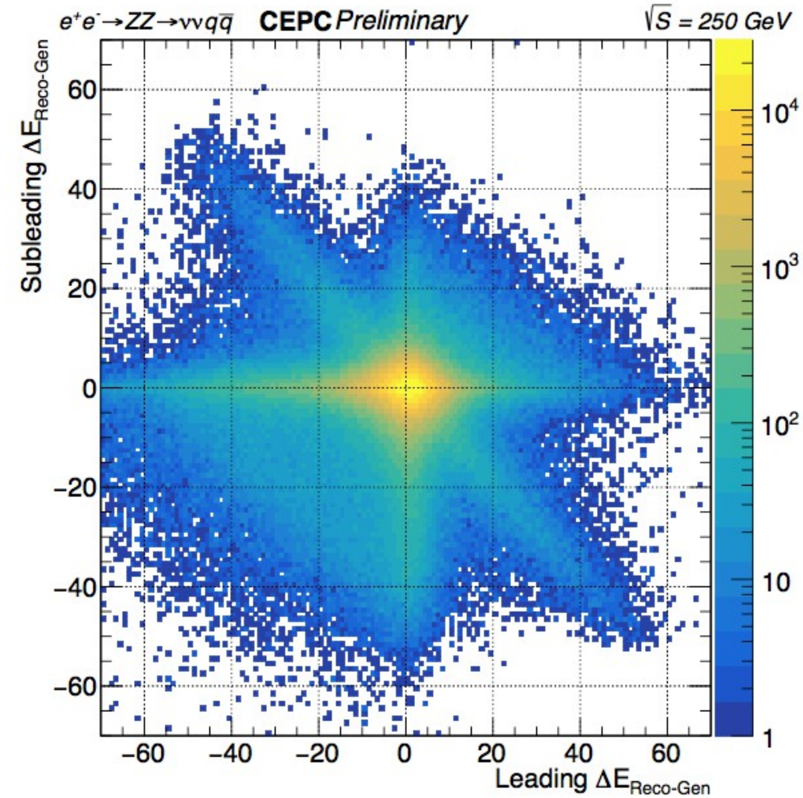

$e^+e^- \to ZZ \to \nu\nu q\bar{q}$ CEPC Preliminary Subleading
$\sqrt{S}$ = 250 GeV
ΔR
$E_{Reco}-E_{Gen}$ / $E_{Gen}$


$e^+e^- \to ZZ \to \nu\nu q\bar{q}$ CEPC Preliminary Subleading
$\sqrt{S}$ = 250 GeV
ΔR
$E_{Gen}-E_{MC\ P}$ / $E_{MC\ P}$

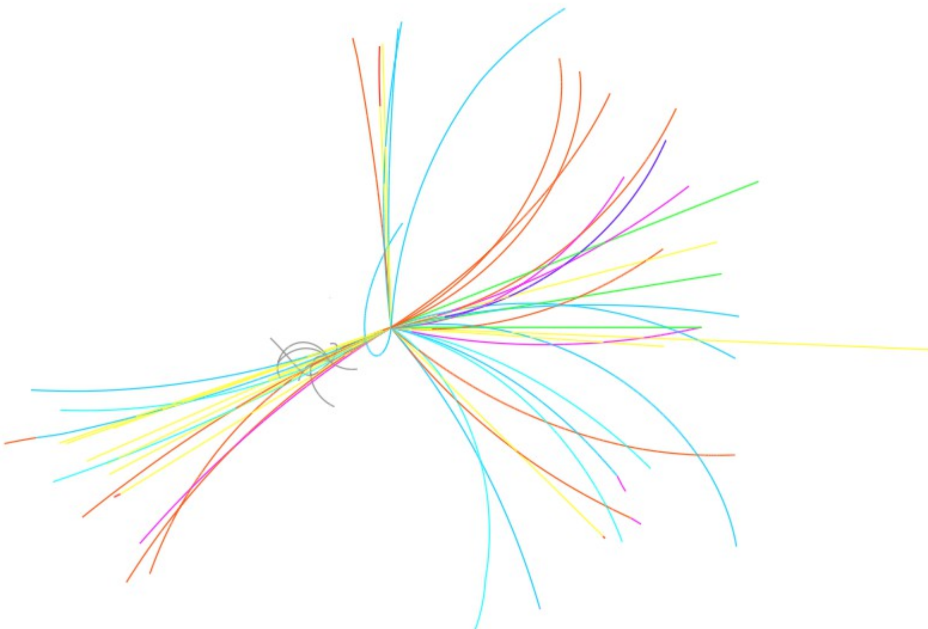

$e^+e^- \to ZZ \to \nu\nu q\bar{q}$ CEPC Preliminary Subleading
$\sqrt{S}$ = 250 GeV
ΔR
$E_{Reco}-E_{MC\ P}$ / $E_{MC\ P}$



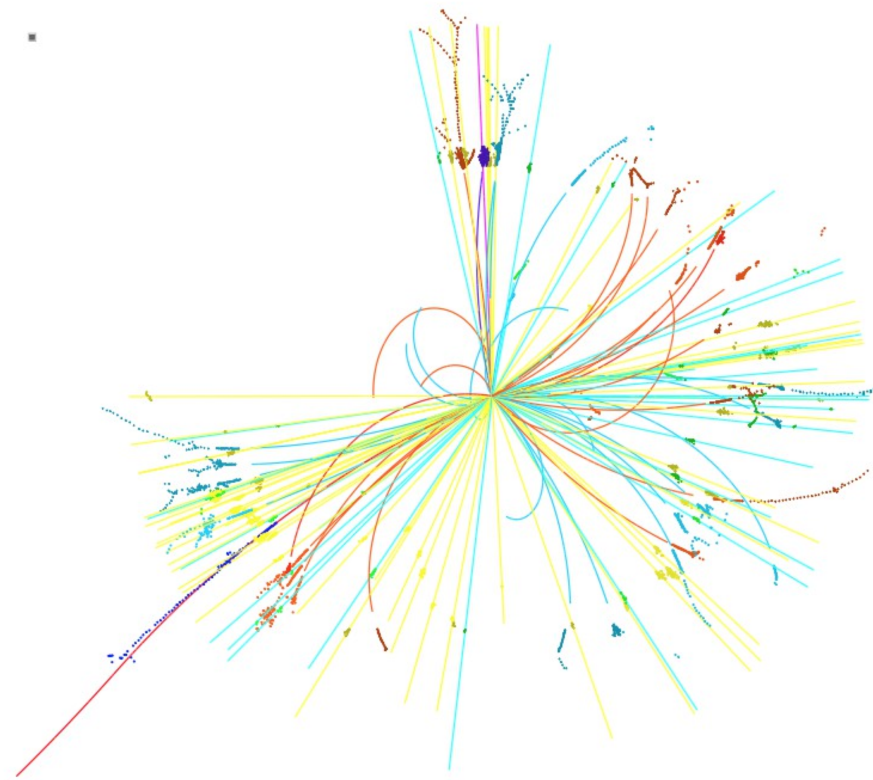
$e^+e^- \to ZZ \to \nu\nu q\bar{q}$
CEPC Preliminary
$\sqrt{S}$ = 250 GeV
Subleading $\Delta E_{Gen-MCP}$
Leading $\Delta E_{Gen-MCP}$

$e^+e^- \to ZZ \to \nu\nu q\bar{q}$
CEPC Preliminary
$\sqrt{S}$ = 250 GeV
Subleading $\Delta E_{Reco-Gen}$
Leading $\Delta E_{Reco-Gen}$



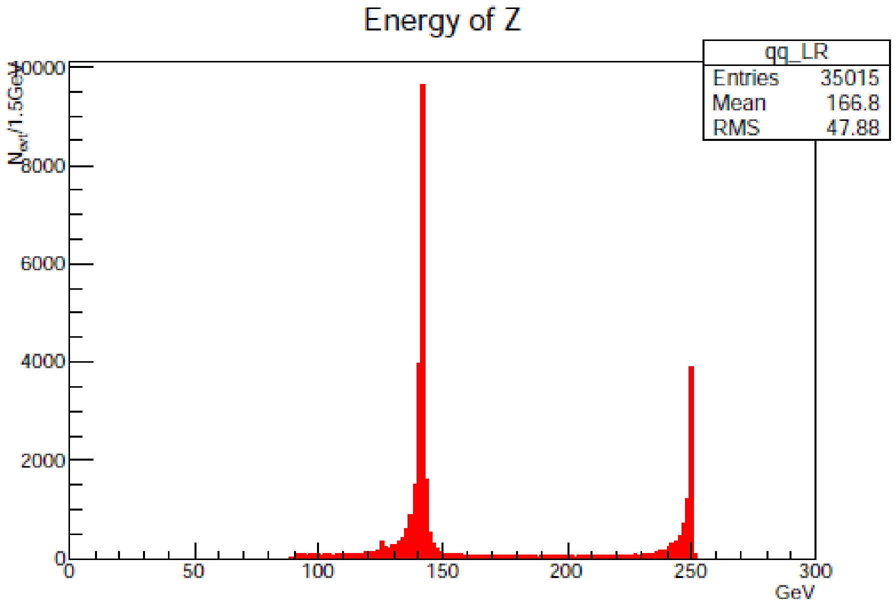
(a)

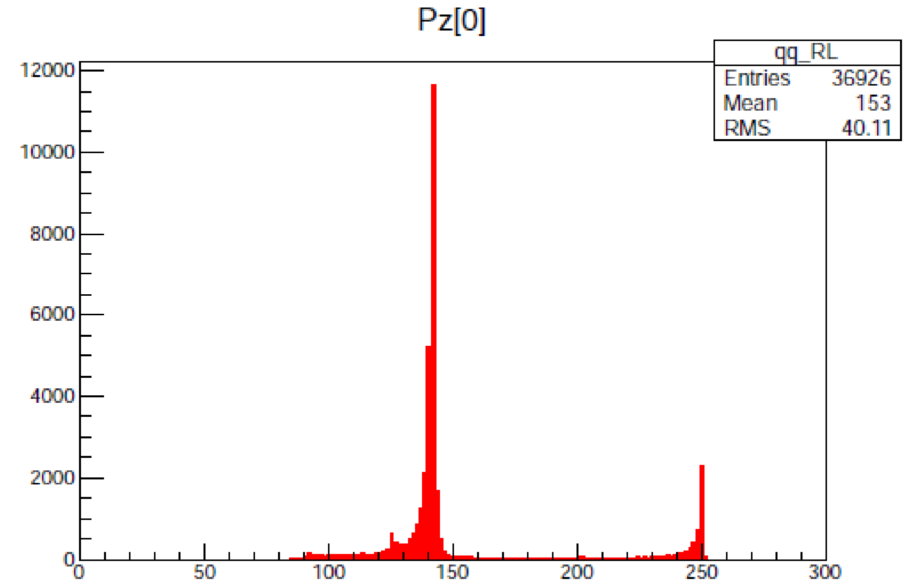


(b)

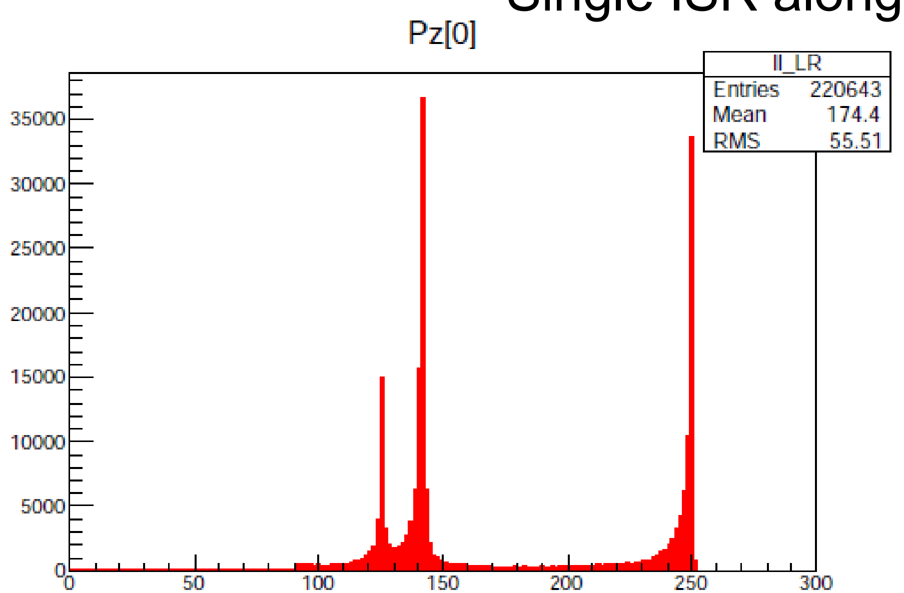
# Z->ff, Energy of Z (SumE of di-fermion)

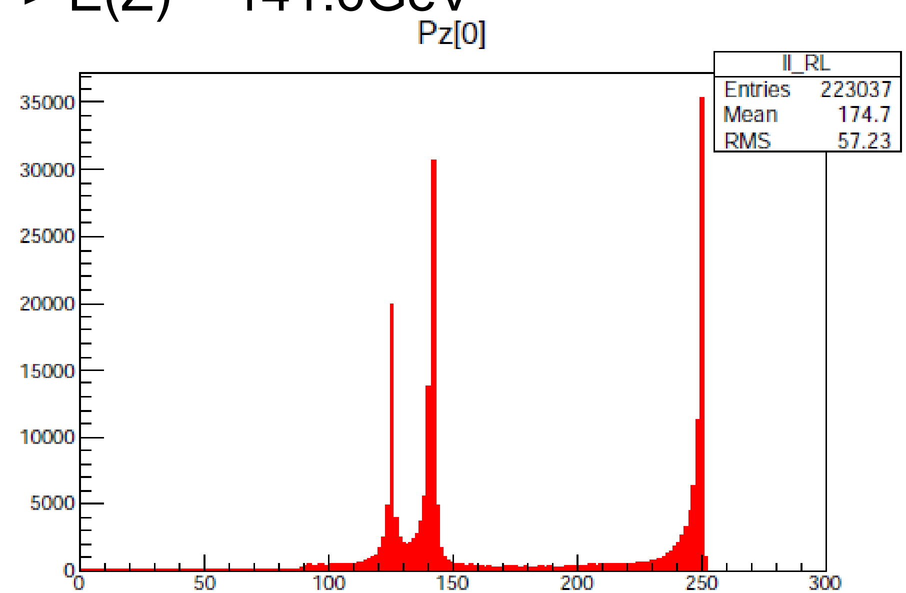
Calorimeter for ILC




Single ISR along Z -> E(Z) = 141.6GeV

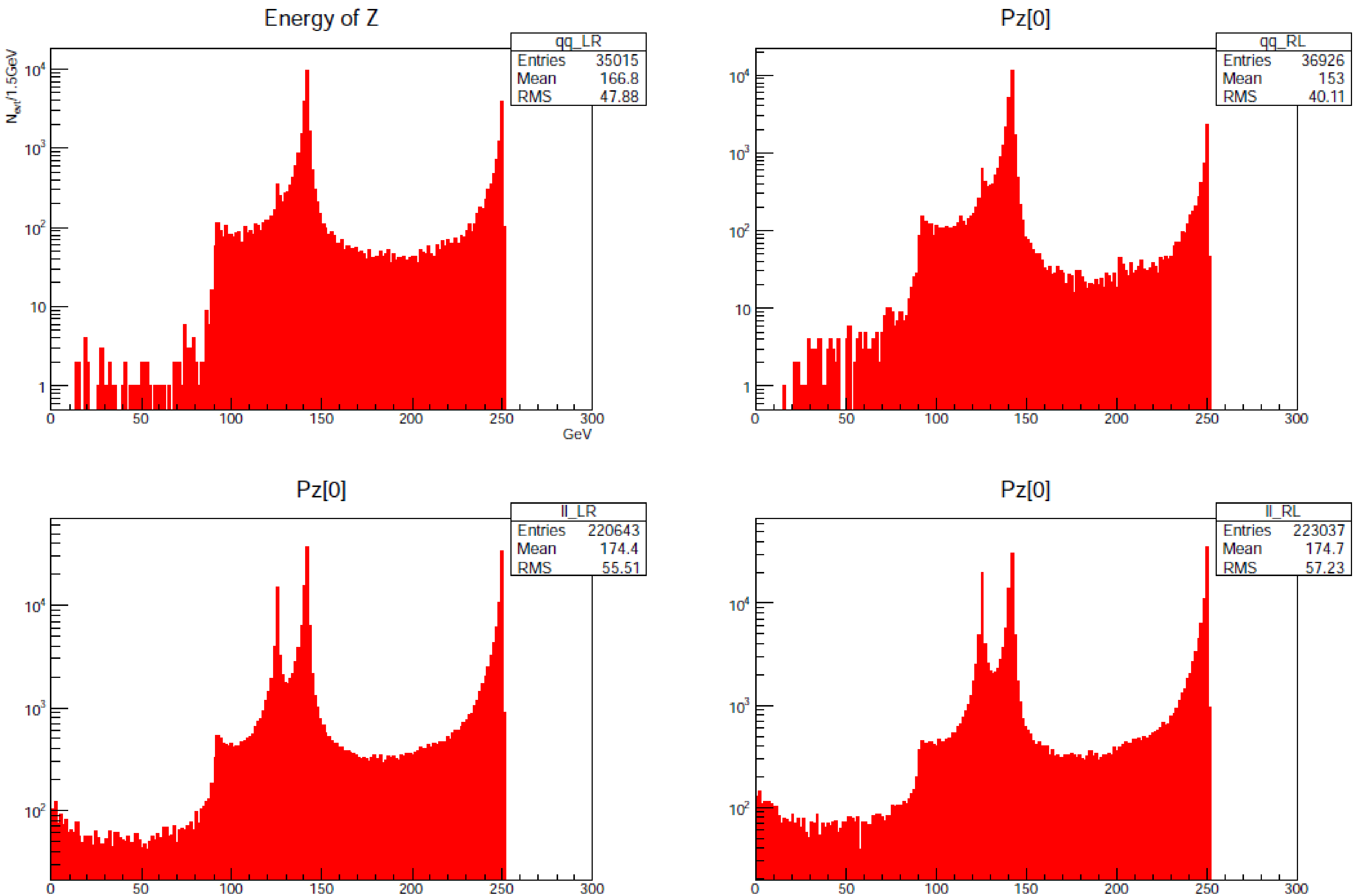





Peak at 125GeV: gamma gamma(ll) event

# Z->ff, Energy of Z (SumE of di-fermion)



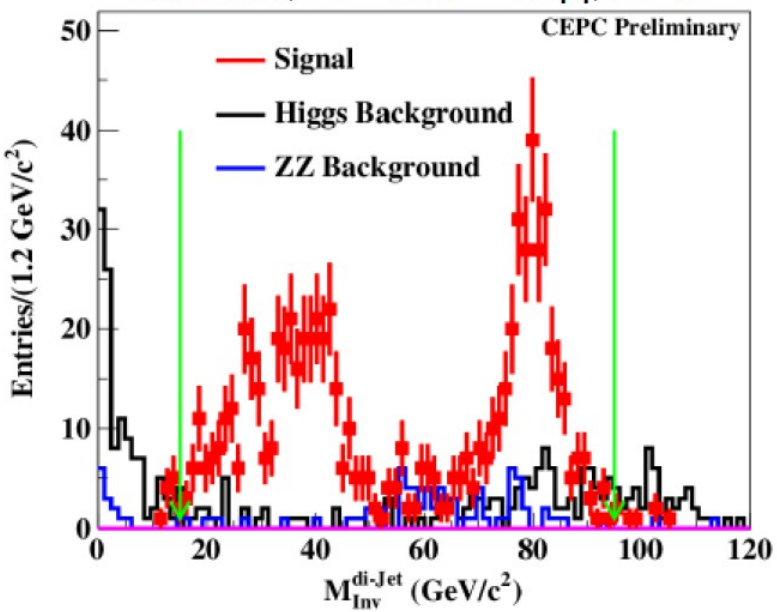
# Parameters

| | CEPC_v1 (~ ILD) | Optimized (Preliminary) | Comments |
|---|---|---|---|
| Track Radius | 1.8 m | >= 1.8 m | Requested by Br(H->μμ) measurement |
| **B Field** | **3.5 T** | **3 T** | **Requested by MDI** |
| **ToF** | **-** | **50 ps** | **Requested by pi-Kaon separation at Z pole** |
| ECAL Thickness | 84 mm | 84(90) mm | 84 mm is optimized on Br(H->γγ) at 250 GeV; 90mm for bhabha event at 350 GeV |
| ECAL Cell Size | 5 mm | 10 – 20 mm | Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation |
| ECAL NLayer | 30 | 20 – 30 | Depends on the Silicon Sensor thickness |
| **HCAL Thickness** | **1.3 m** | **1 m** | - |
| **HCAL NLayer** | **48** | **40** | Optimized on Higgs event at 250 GeV; Margin might be reserved for 350 GeV. |

# Br(H→WW)

*H→WW/ZZ: Portal to Higgs width & perfect test bed for detector/reconstruction performance...*

Liao libo, H→WW*→lvqq, Z→ll



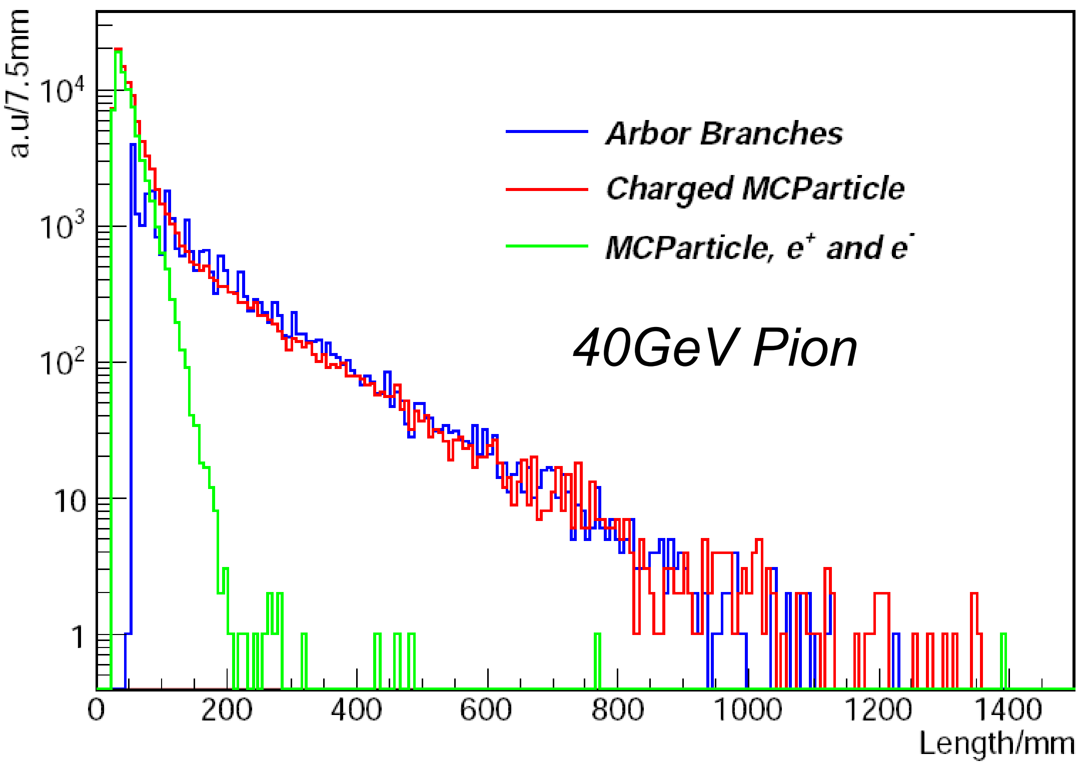

Expected Number of events with different objects

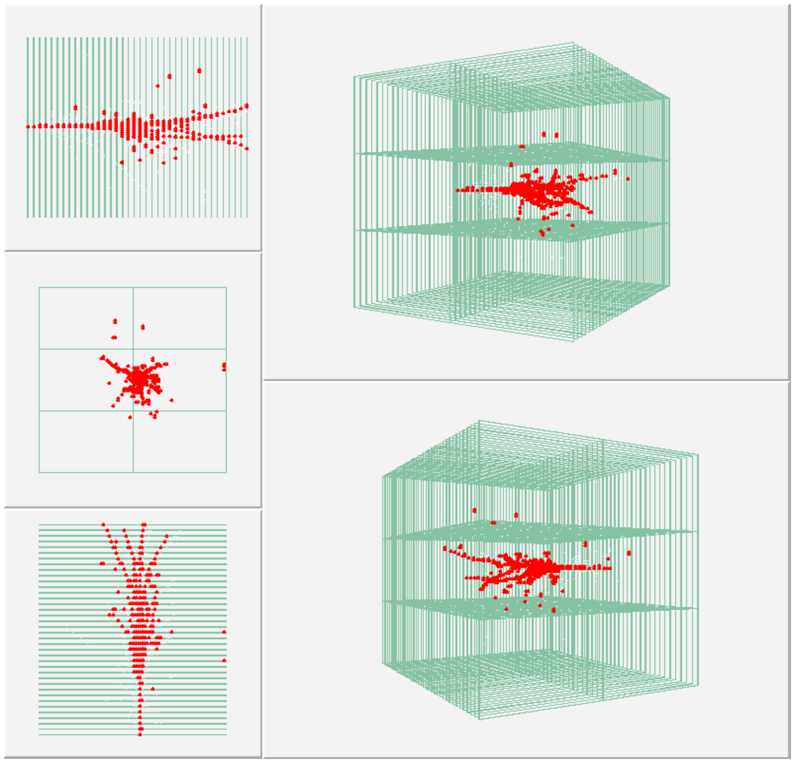
| | Z→ll | tautau | vv | qq |
|---|---|---|---|---|
| H→WW*→4q | 6.91k | 3.45k | 19.74k | 69.1k |
| μvqq | 2.27k | 1.14k | 6.47k | 22.7k |
| evqq | 2.27k | 1.14k | 6.47k | 22.7k |
| eevv | 186 | 93 | 527 | 1.9k |
| μμvv | 186 | 93 | 527 | 1.9k |
| eμvv | 372 | 186 | 1154 | 3.7k |
| X + tau | 3.2k | 1.6k | 9.14k | 32.0k |

Extrapolated from ILC results
Await for tau finder
Await for the SM Background simulation
Full Simulation
Preliminary result acquired
Unexplored

- Br(H→WW), Combined accuracy ~ 1.0% from 13 independent full simulation analyses
  - 1.45% at llH, H→WW*→ inc channels, 12 independent channels.
  - *~ 1.7% at vvH, H→WW*→ 4q channel (Preliminary. ILC extrapolation = 2.3%)*
  - 2.3% at qqH, H→WW*→ 2qlv channel (extrapolated from ILC full simulation)
  - Combined: 1.0%
- High efficiency in event reconstruction

# Validation: Arbor Branch Length

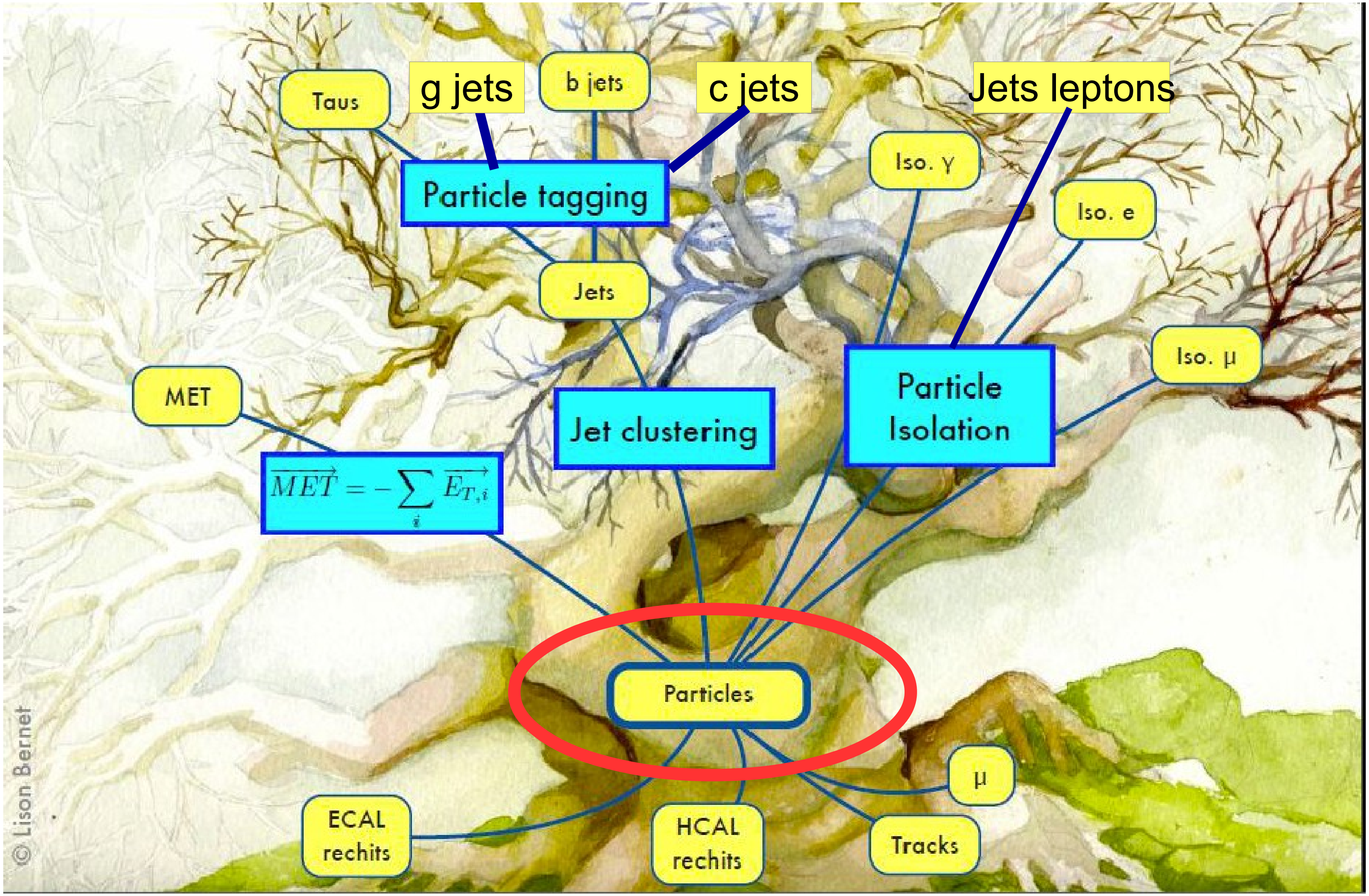


Arbor: successfully tag sub-shower structure

*Samples: Particle gun event at ILD HCAL (readout granularity 1cm$^2$ & layer thickness 2.65cm)*
*Length:*
*Charged MCParticle: spatial distance between generation/end points*
*Arbor branch: sum of distance between neighbor hits*

# PFA Reconstruction




*Requirements at the CEPC: Reconstruct all the physics objects (Lepton, Photon, Kaon, Tau, Jet, MET) efficiently & precisely.*

- $g(H\tau\tau)$ measurement: preliminary
- Jets
- Boson Mass Spectrum
- Separation
- Jets
- Impact of Jet Clustering: Significant
- Jet energy Scale
- Jet Energy Resolution
- Flavor Tagging