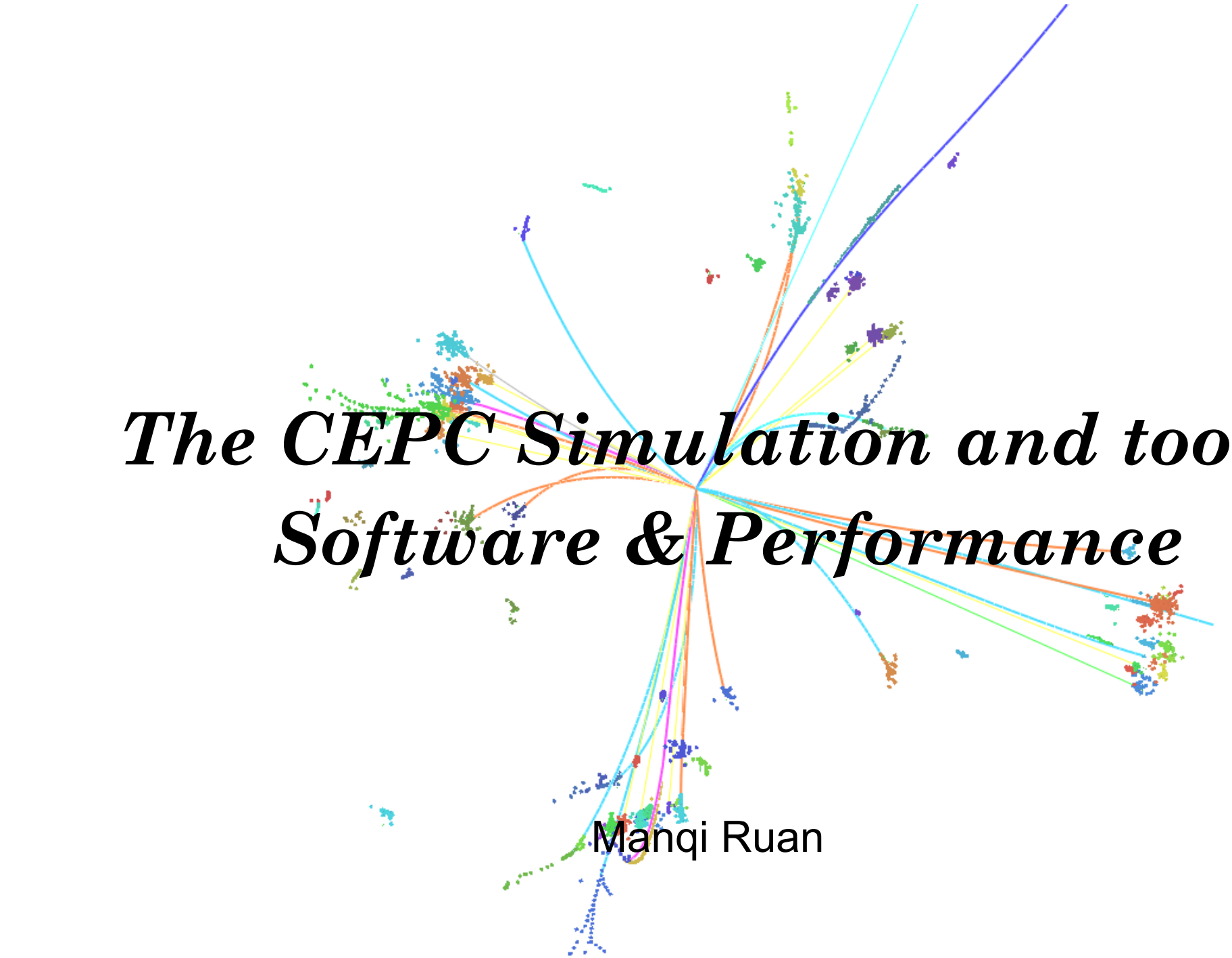
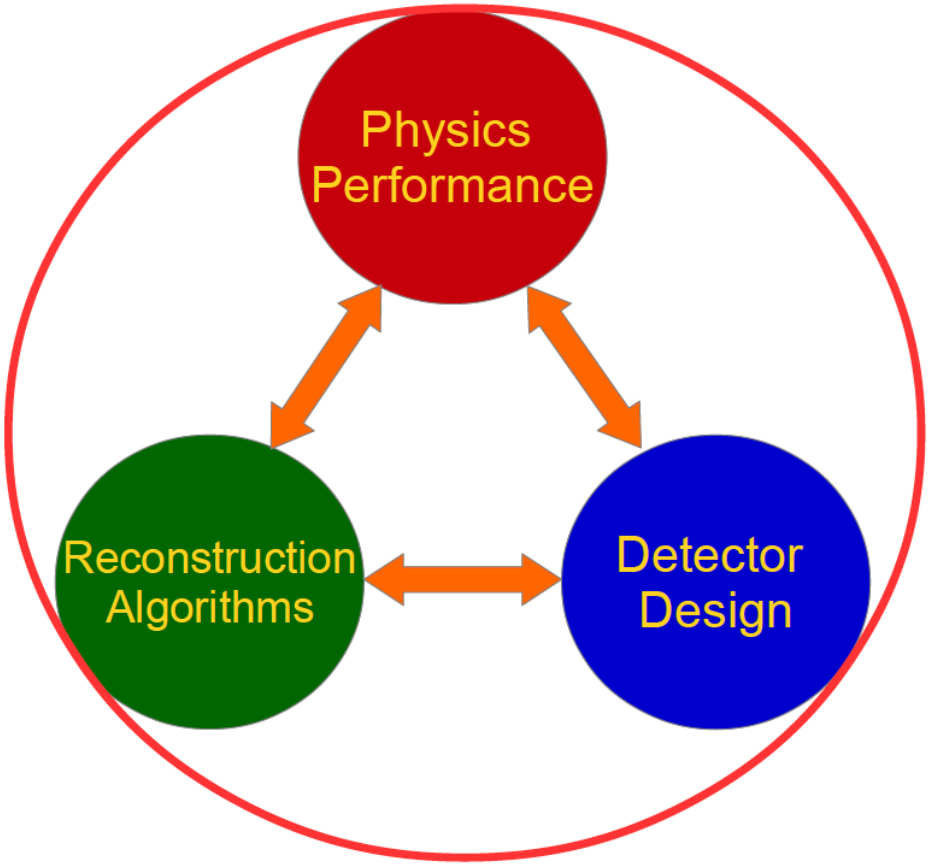


The CEPC Simulation and tools: Software & Performance

Manqi Ruan

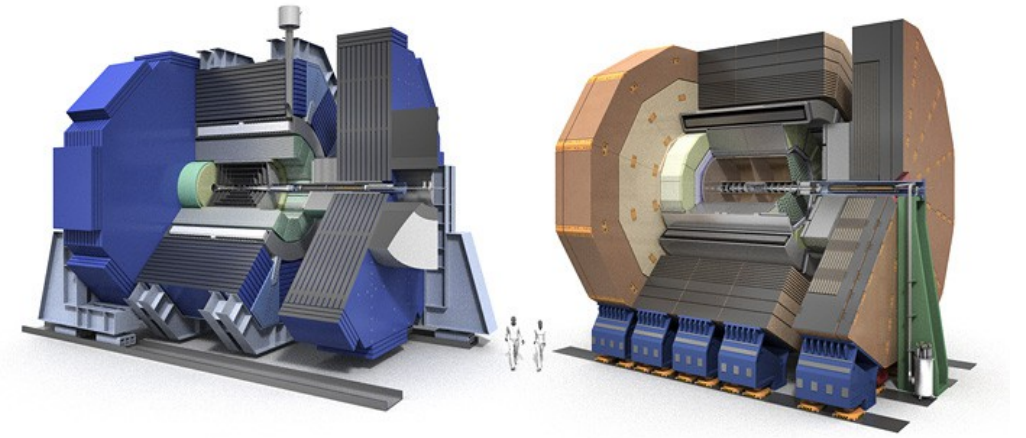
Performance

- Determined by
  - Detector design
  - Reconstruction algorithm
- Characterized at
  - **Physics Objects**
  - Higgs Signal
  - Benchmark Physics Analyses

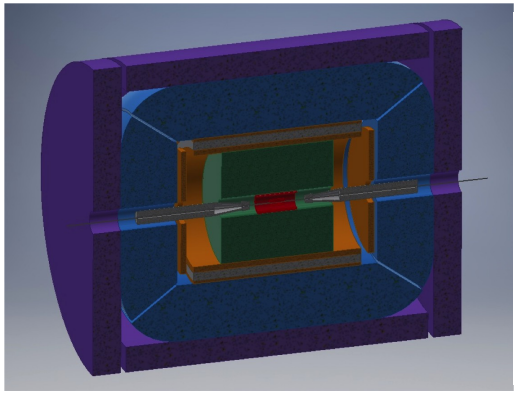


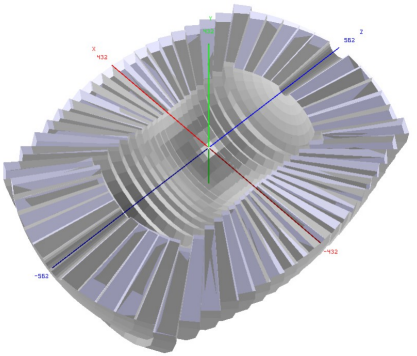
Two classes of Concepts

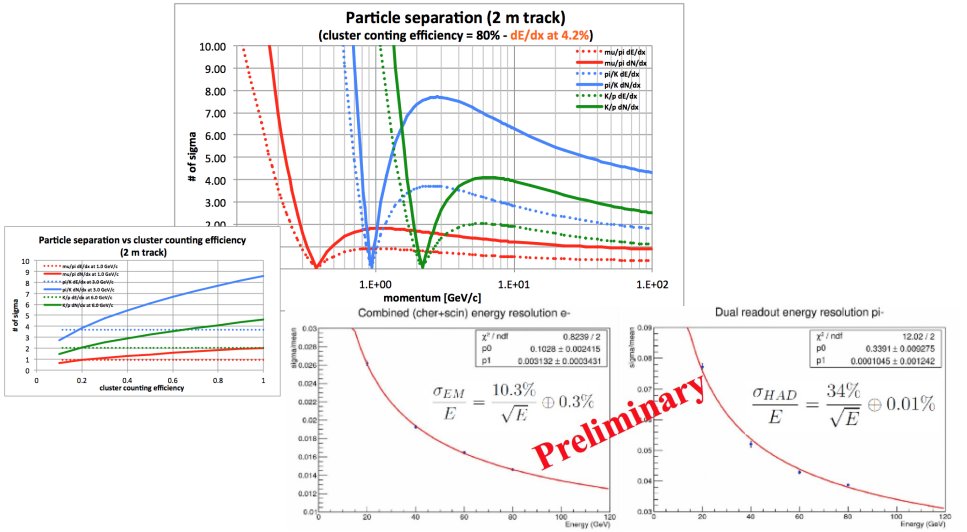
- PFA Oriented concept using High Granularity Calorimeter
  - **+ TPC (ILD-like, Baseline)**
  - + Silicon tracking (SiD-like)



- Low Magnet Field Detector Concept (IDEA)
  - Wire Chamber + Dual Readout Calorimeter



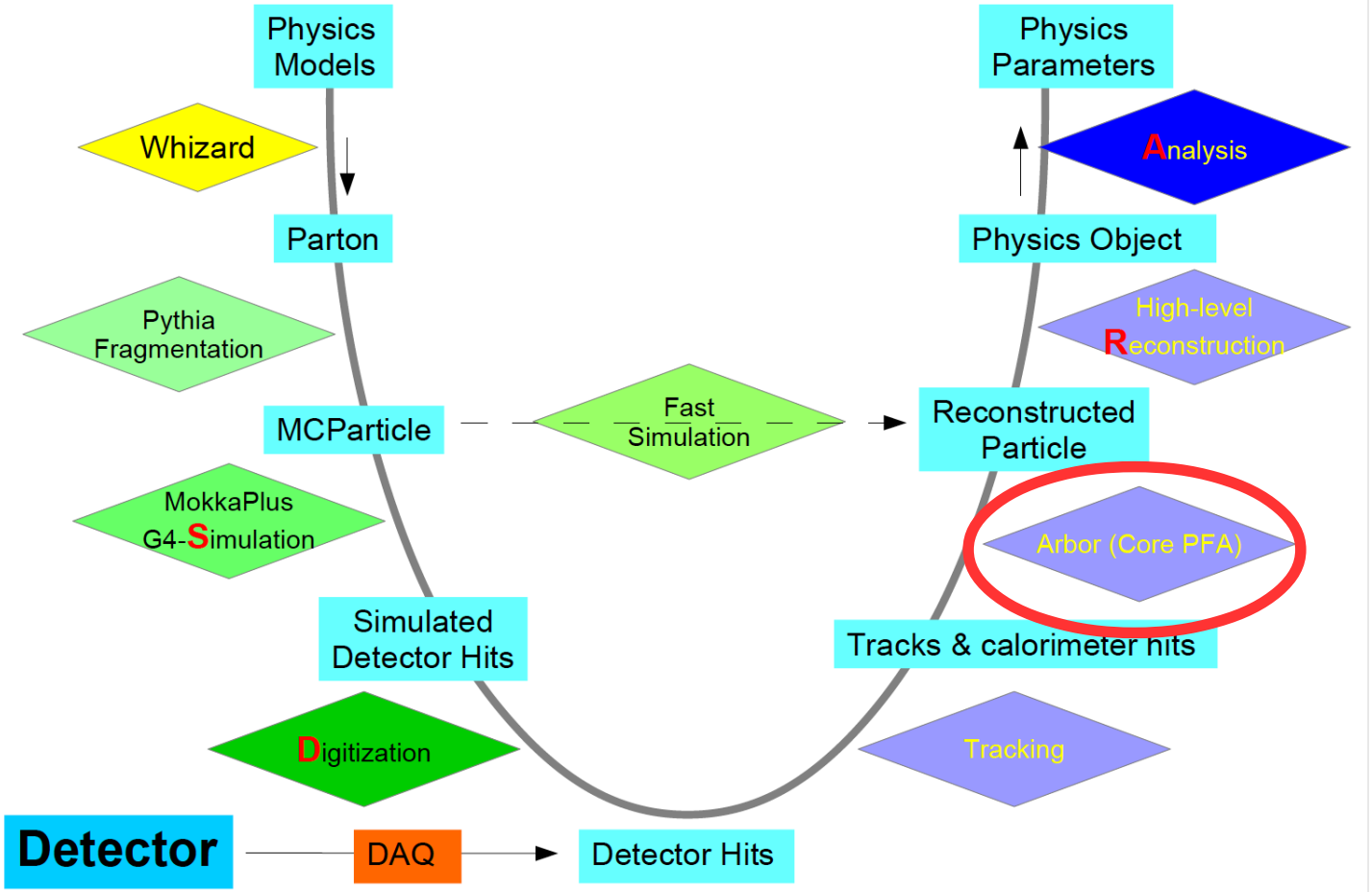




https://indico.ihep.ac.cn/event/6618/

https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=14816

CEPC Baseline Software

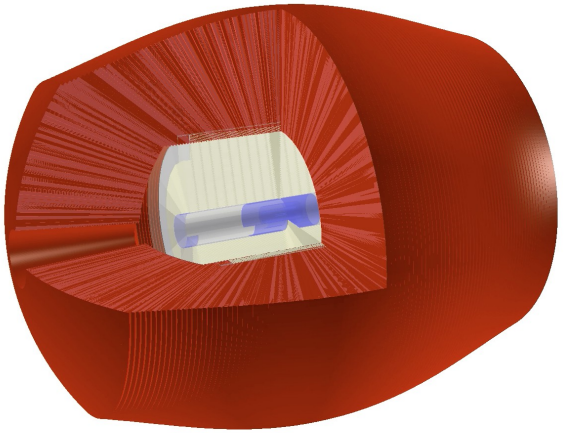


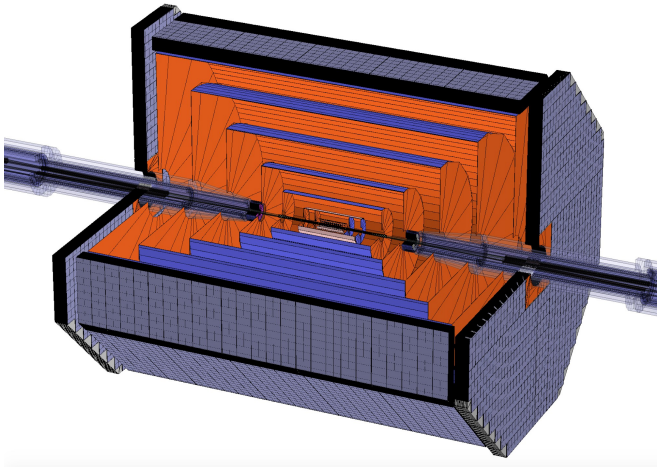
Generators (Whizard & Pythia)
Data format & management (LCIO & Marlin)
Simulation (MokkaC)
Digitizations
Tracking
PFA (Arbor)
Single Particle Physics Objects Finder (LICH)
Composed object finder (Coral)
Tau finder
Jet Clustering (FastJet)
Jet Flavor Tagging (LCFIPLus)
Event Display (Druid)
General Analysis Framework (FSClasser)
Fast Simulation (Delphes + FSClasser)

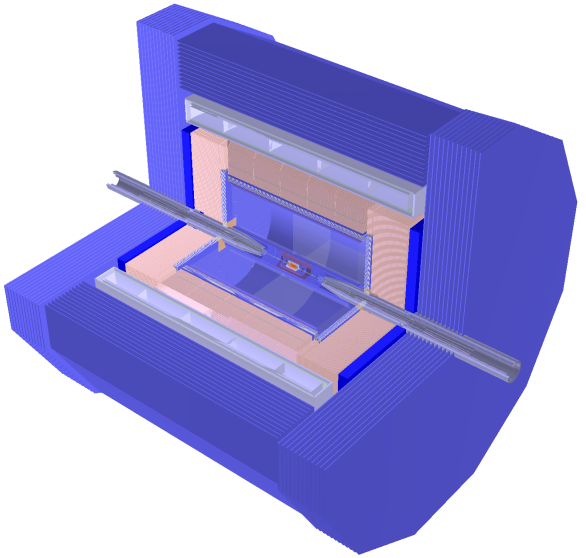
CEPC-SIMU-2017-001,
CEPC-SIMU-2017-002,
(DocDB id-167, 168, 173)

General Software | ILCSoft | ILCSoft + Development | Developments

Status of simulation-performance study

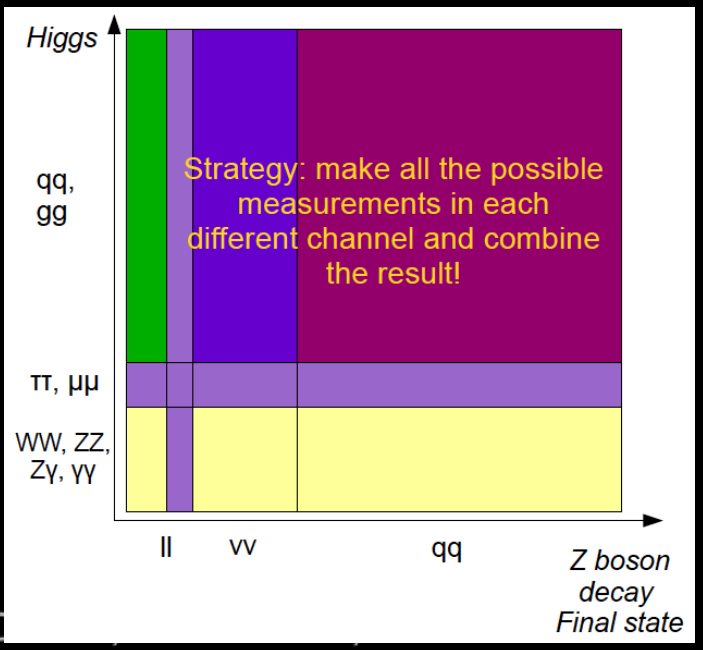






	Geant4-Simulation	Digitization	Reconstruction	Performance-Object	Performance-Benchmark
IDEA					
Full-Silicon					
APODIS					

Arbor



Performance at

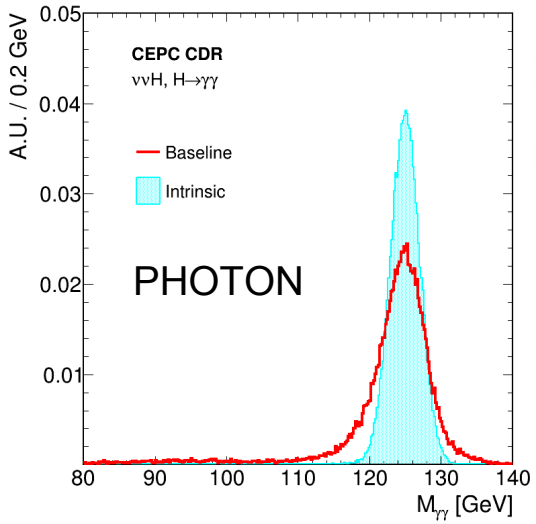
- Lepton
- Kaon
- Photon
- Tau
- JET
- ...

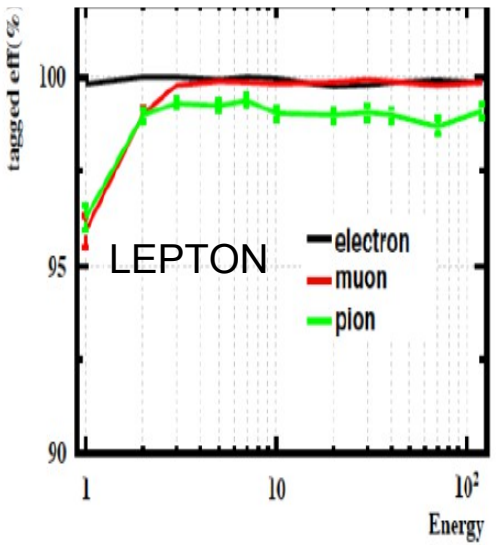
Eur. Phys. J. C (2018) 78: 426

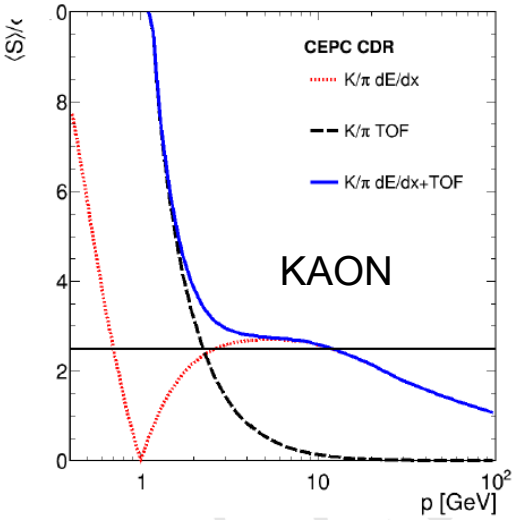
Physics Objects

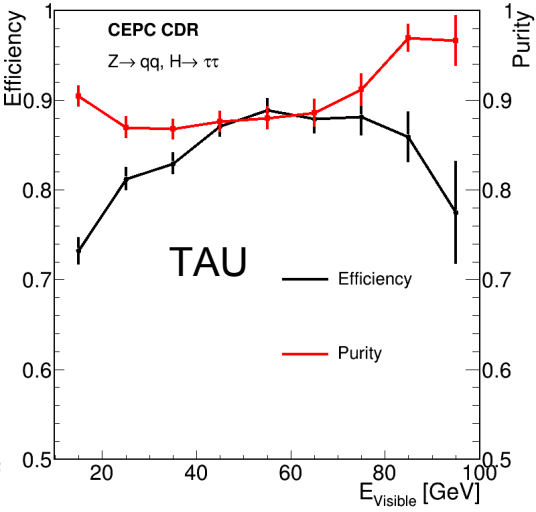
Eur. Phys. J. C (2017) 77: 591

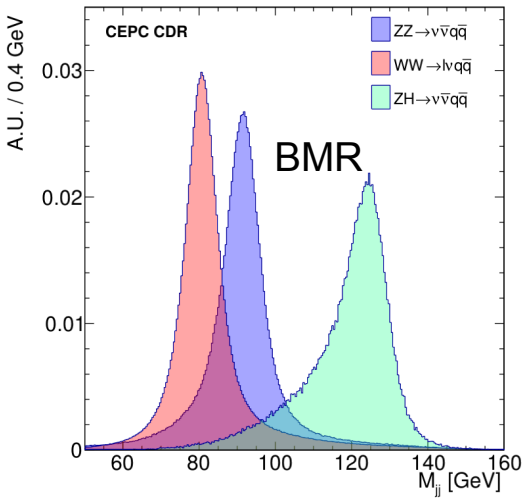
Eur. Phys. J. C (2018) 78:464

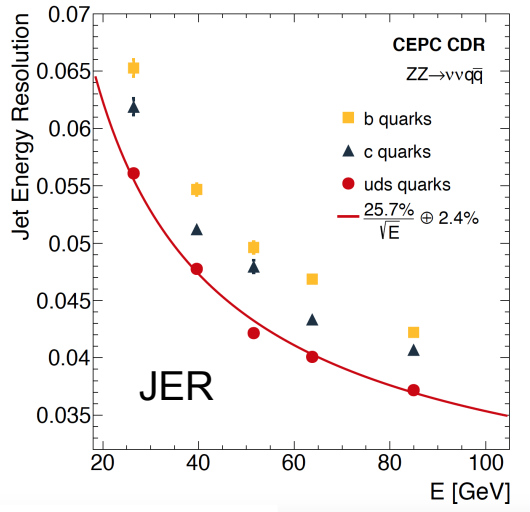


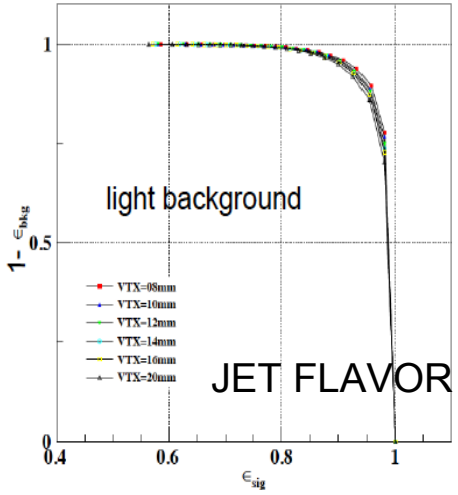


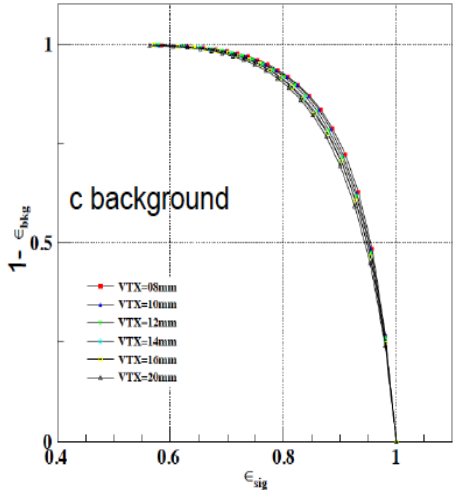






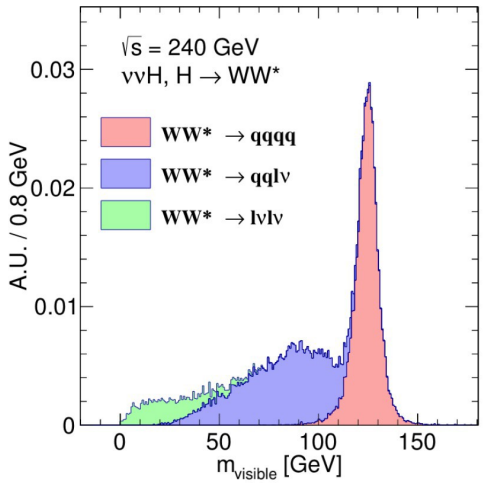


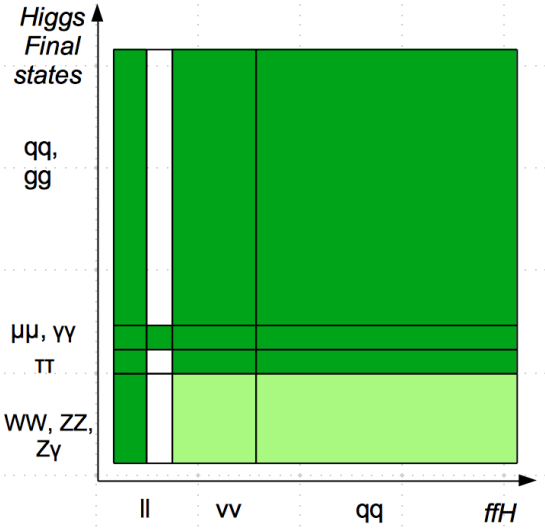


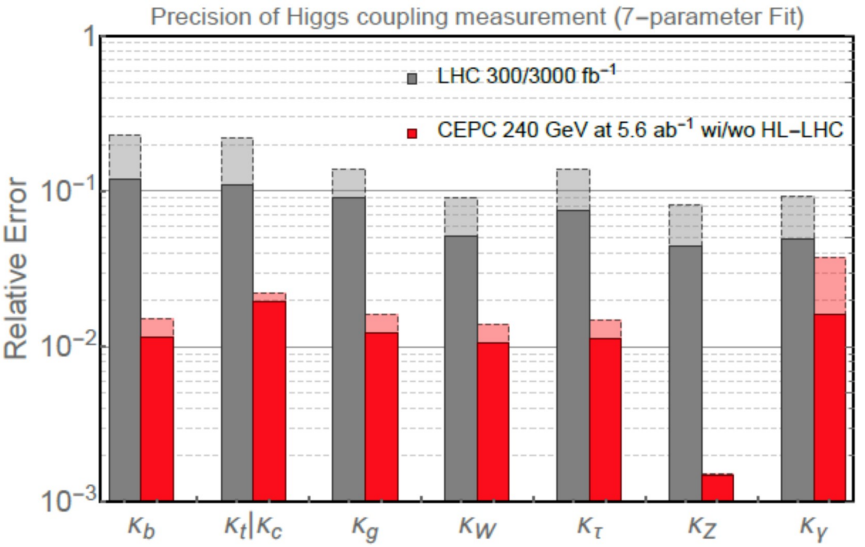


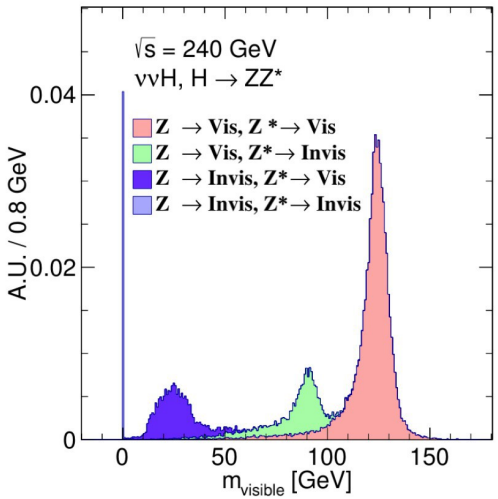
Eur. Phys. J. C (2018) 78: 426

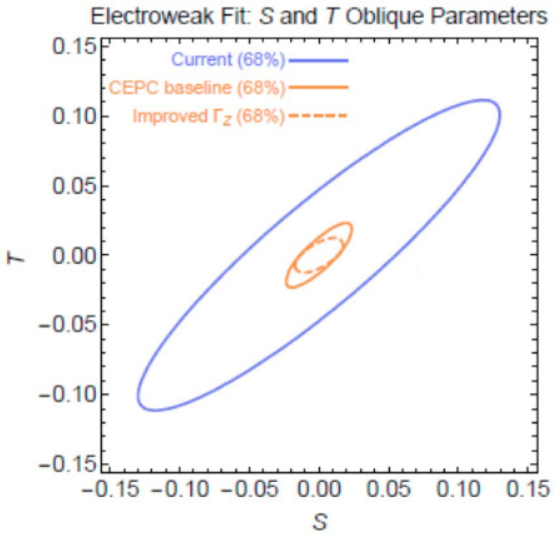
Applied on Higgs physics, et.al











Precision Higgs Physics at CEPC

Initial assessments of Higgs physics potential at the CEPC based on the white paper (to be submitted)

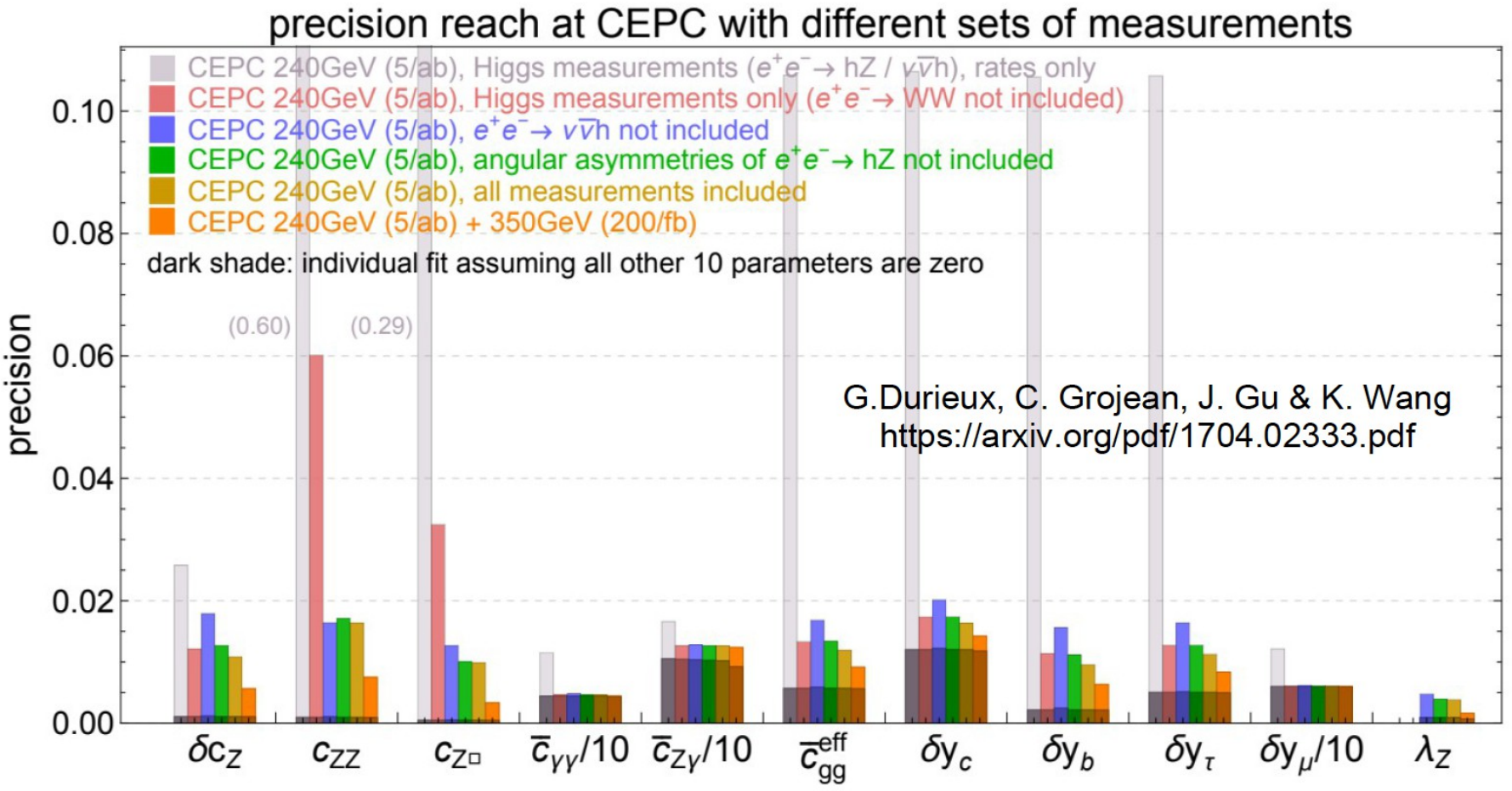
Chinese Physics C Vol. XX, No. X (201X) 010201

Precision Higgs Physics at the CEPC*

Fenfen An[4,21] Yu Bai[9] Chunhui Chen[21] Xin Chen[5] Zhenxing Chen[3] Joao Guimaraes da Costa[4] Zhenwei Cui[3] Yaquan Fang[4,6] Chengdong Fu[4] Jun Gao[10] Yanyan Gao[20] Yuanning Gao[5] Shao-Feng Ge[15,27] Jiayin Gu[13] Fangyi Guo[1,4] Jun Guo[10,11] Tao Han[5,29] Shuang Han[4] Hong-Jian He[10,11] Xianke He[10] Xiao-Gang He[10,11] Jifeng Hu[10] Shih-Chieh Hsu[30] Shan Jin[8] Maoqiang Jing[4,7] Ryuta Kiuchi[4] Chia-Ming Kuo[19] Pei-Zhu Lai[19] Boyang Li[5] Congqiao Li[3] Gang Li[4] Haifeng Li[12] Liang Li[10] Shu Li[10,11] Tong Li[12] Qiang Li[3] Hao Liang[4,6] Zhijun Liang[4] Libo Liao[4] Bo Liu[4,21] Jianbei Liu[1] Tao Liu[14] Zhen Liu[24,28] Xinchou Lou[4,6,31] Lianliang Ma[12] Bruce Mellado[17] Xin Mo[4] Mila Pandurovic[16] Jianming Qian[22] Zhuoni Qian[18] Nikolaos Rompotis[20] Manqi Ruan[4] Alex Schuy[30] Lian-You Shan[4] Jingyuan Shi[9] Xin Shi[4] Shufang Su[23] Dayong Wang[3] Jing Wang[4] Lian-Tao Wang[25] Yifang Wang[4,6] Yuqian Wei[4] Yue Xu[5] Haijun Yang[10,11] Weiming Yao[26] Dan Yu[4] Kaili Zhang[4,6] Zhaoru Zhang[4] Mingrui Zhao[2] Xianghu Zhao[4] Ning Zhou[10]

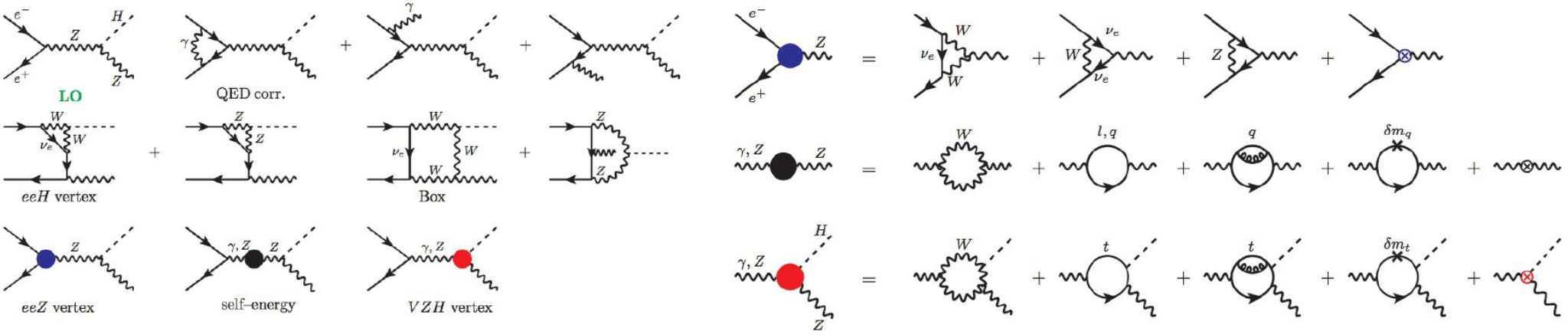
https://arxiv.org/pdf/1810.09037.pdf

Pheno-studies: EFT & Physics reach



The Physics reach could be largely enhanced if the EW measurements is combined With the Higgs measurements (in the EFT)

Pheno-studies: High order corrections

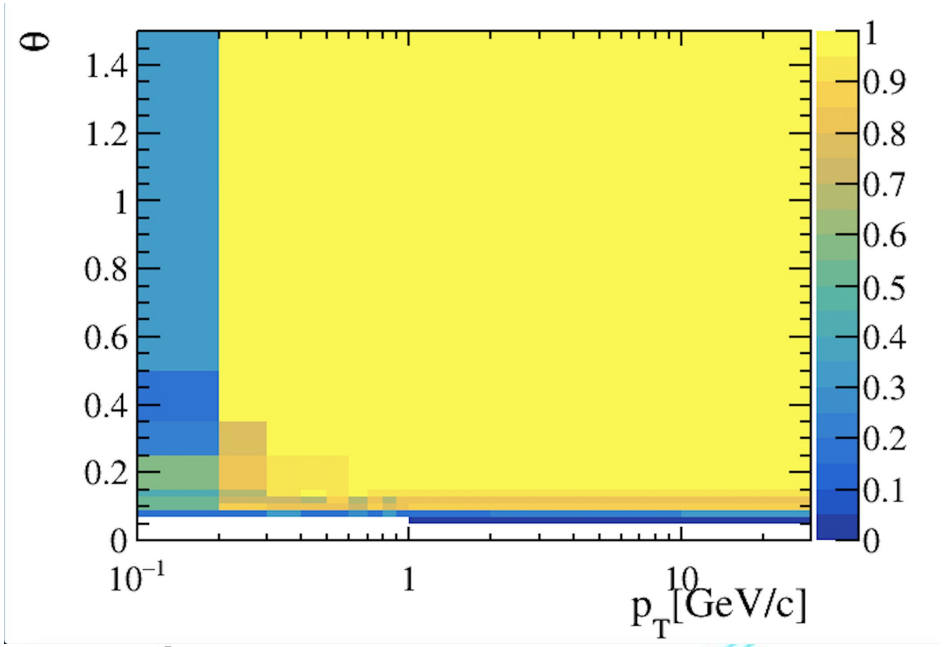


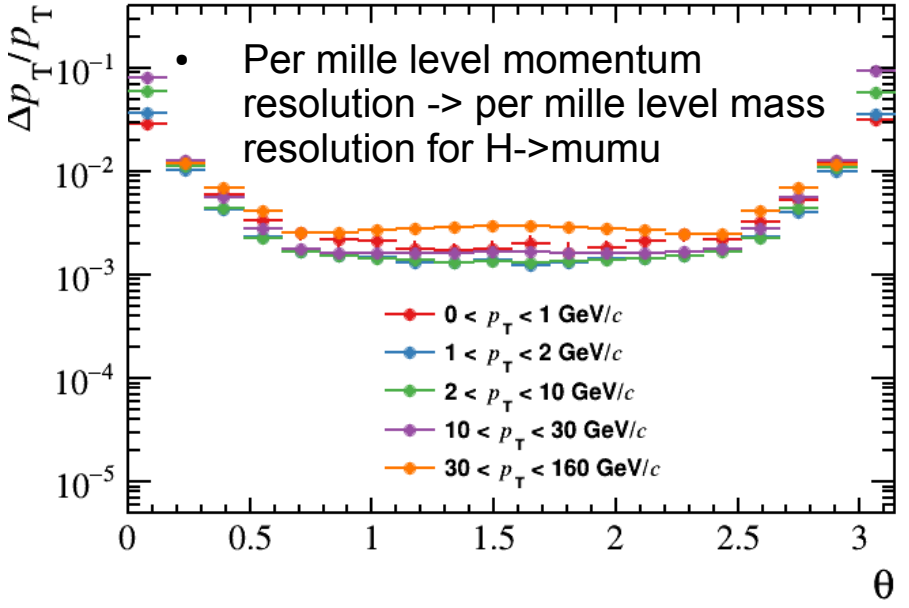
$\sqrt{s}$ (GeV)		LO (fb)	NLO Weak (fb)		NNLO mixed electroweak-QCD (fb)			
		$\sigma^{(0)}$	$\sigma^{(\alpha)}$	$\sigma^{(0)}+\sigma^{(\alpha)}$	$\sigma_Z^{(\alpha\alpha_s)}$	$\sigma_\gamma^{(\alpha\alpha_s)}$	$\sigma^{(\alpha\alpha_s)}$	$\sigma^{(0)}+\sigma^{(\alpha)}+\sigma^{(\alpha\alpha_s)}$
240	Total	**223.14**	6.64	229.78	2.42	0.008	2.43	232.21
	L	88.67	3.18	91.86	0.96	0.003	0.97	92.82
	T	134.46	3.46	137.92	1.46	0.005	1.46	139.39
250	Total	**223.12**	6.08	229.20	2.42	0.009	2.42	231.63
	L	94.30	3.31	97.61	1.02	0.004	1.02	98.64
	T	128.82	2.77	131.59	1.40	0.005	1.40	132.99

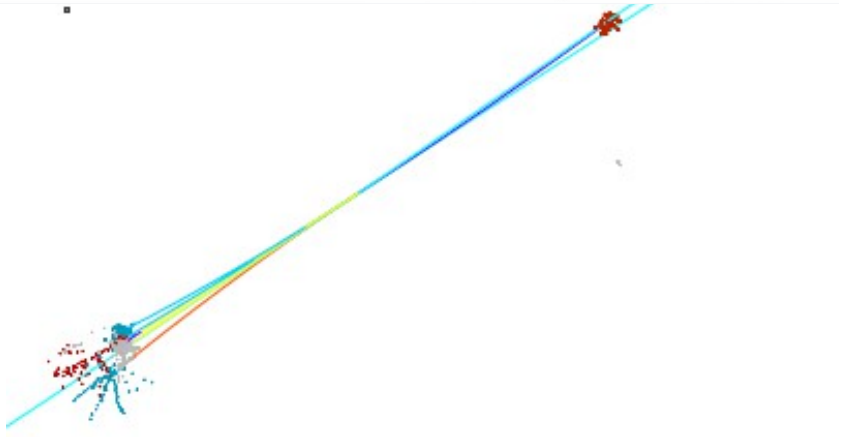
Q.Sun, et.al
https://arxiv.org/pdf/1609.03995.pdf

- Correction at 1% level with NNLO calculation.
- Lots of efforts needed to correctly interpret the measurements at CEPC

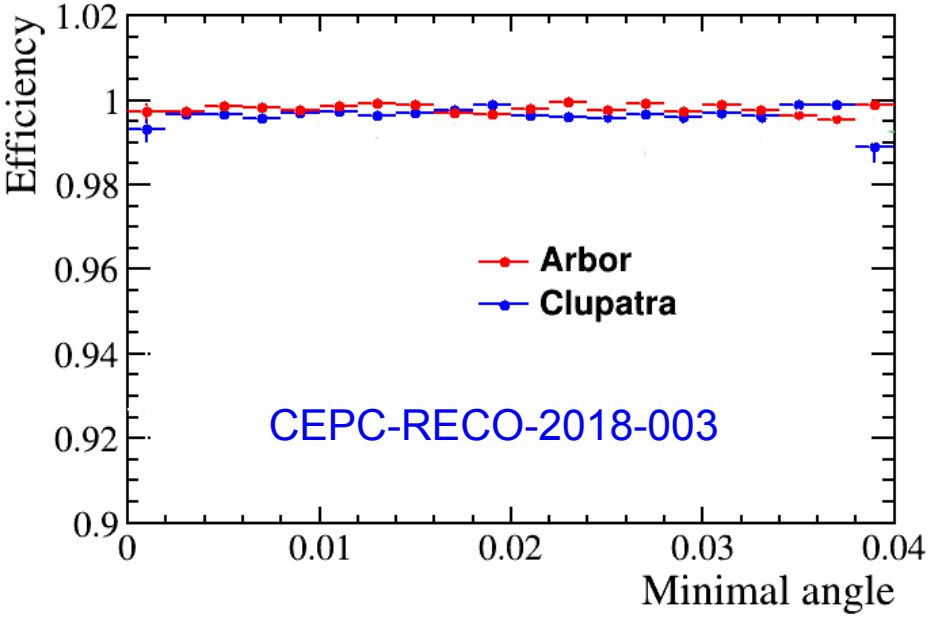
Tracking



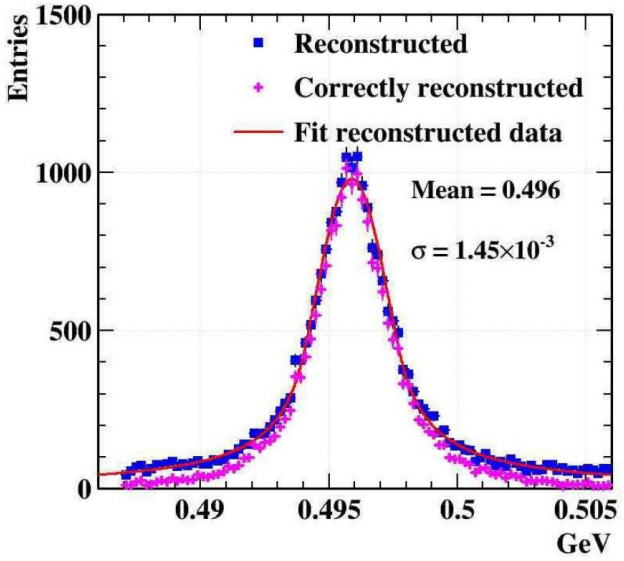


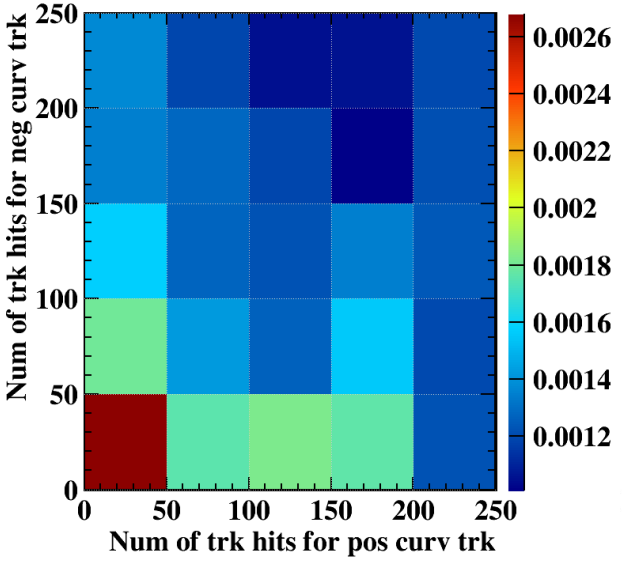


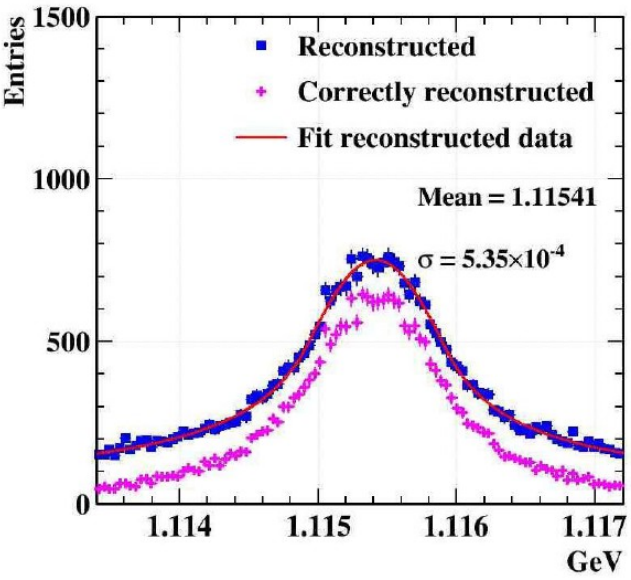
Mingrui Zhao. CEPC CDR



Reconstruction of Ks(Λ) at Z pole (Preliminary)





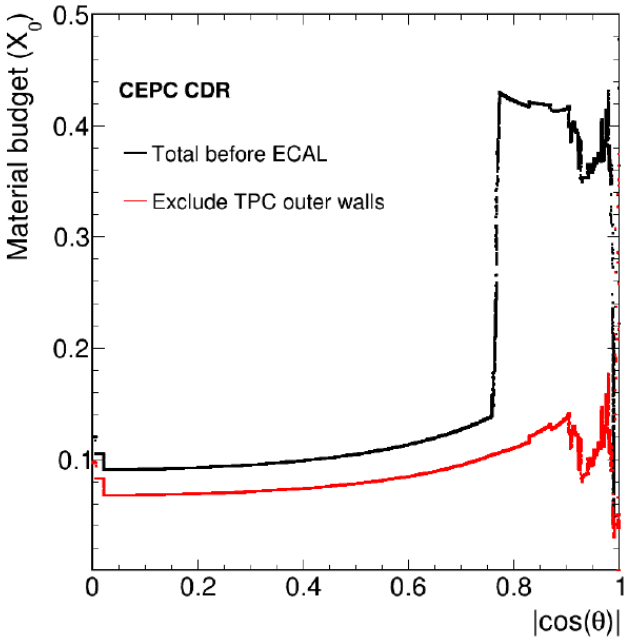


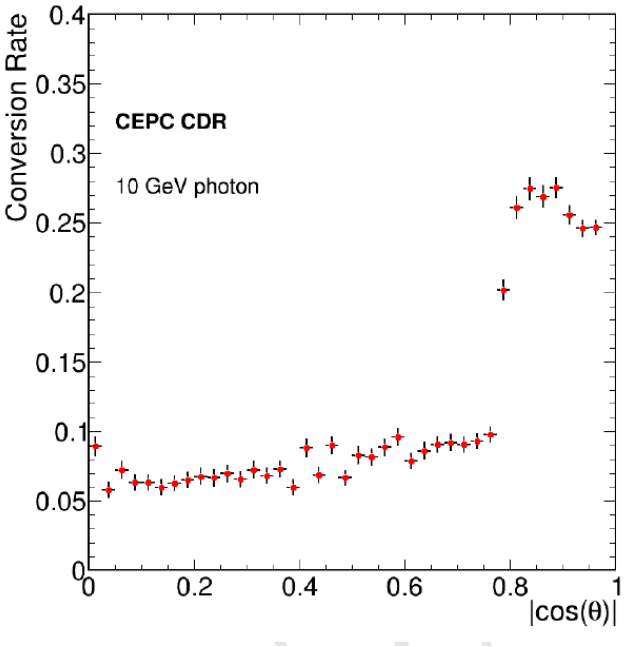
wi/wo perfect PID	Efficiency	Purity	Resolution
K_short	79%/78%	91%/86%	0.28%/0.29%
Lambda	82%/68%	94%/64%	0.043%/0.046%

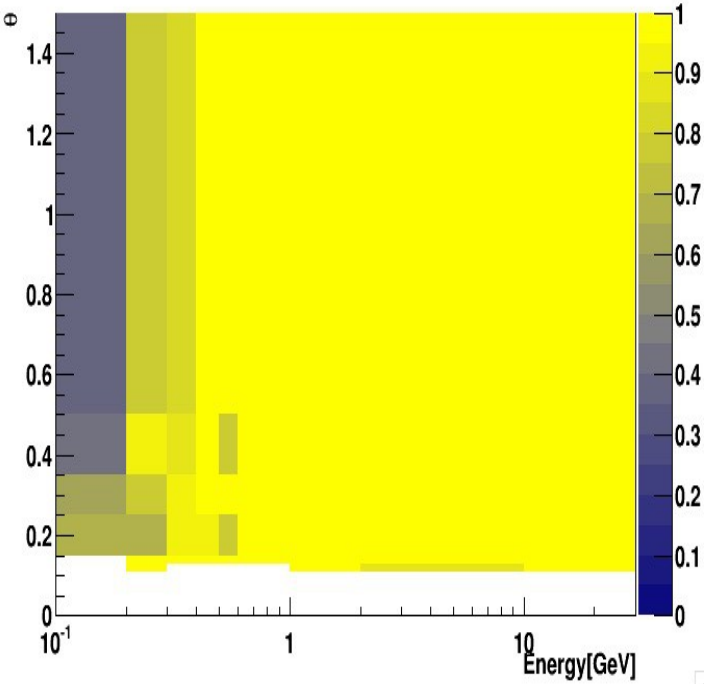
Efficiency = Correctly reconstructed Ks(Λ)/Ks(Λ) with 2 tracks reconstructed
Purity = Correctly reconstructed Ks(Λ)/All reconstructed Ks(Λ)

Perfect PID = Perfect identification of pions, charged kaons, and (anti-)protons

Photons – conversion & efficiency



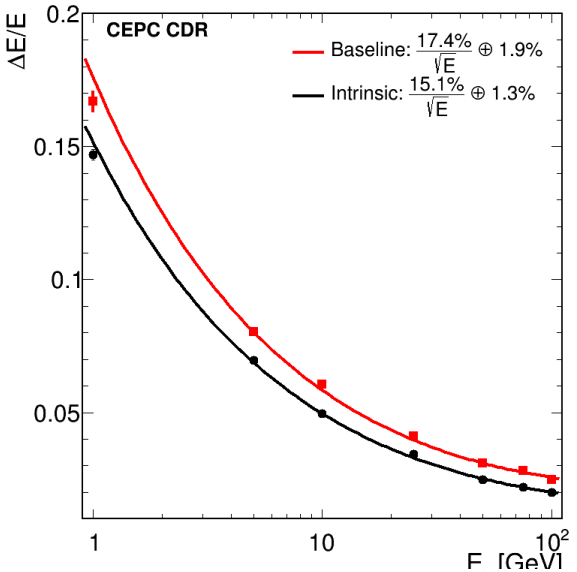


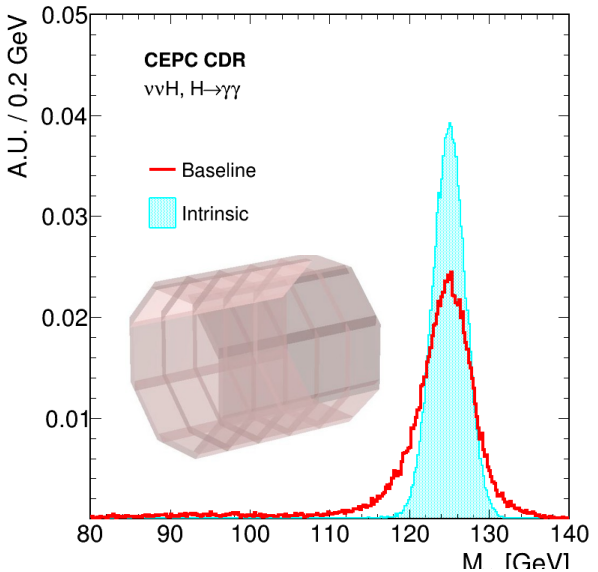


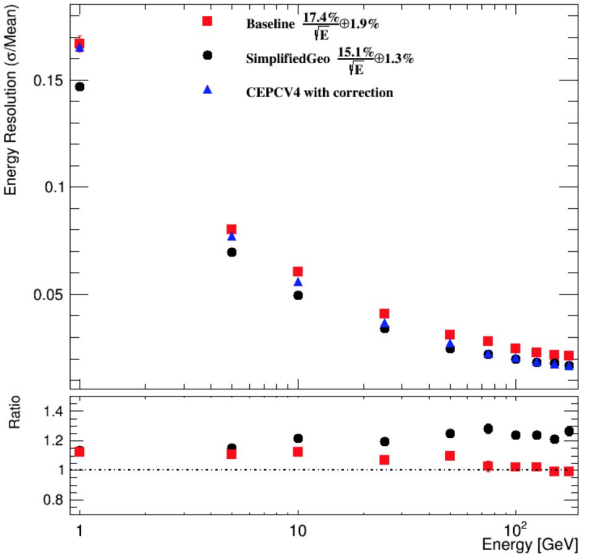
In the barrel region: Roughly 6-10% of the photons converts before reaching the Calorimeter.

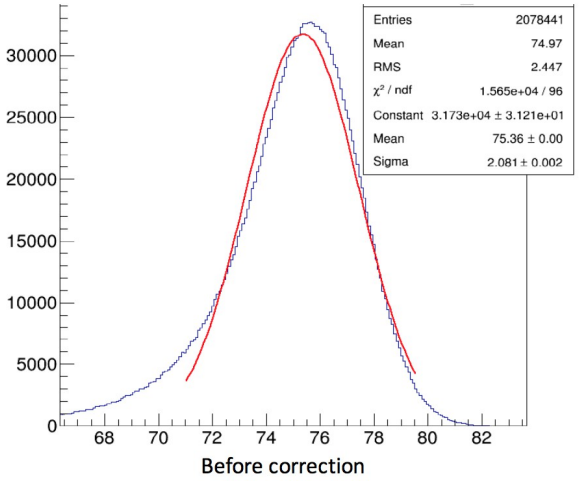
For the unconverted photon: A critical energy of 200 MeV is observed.

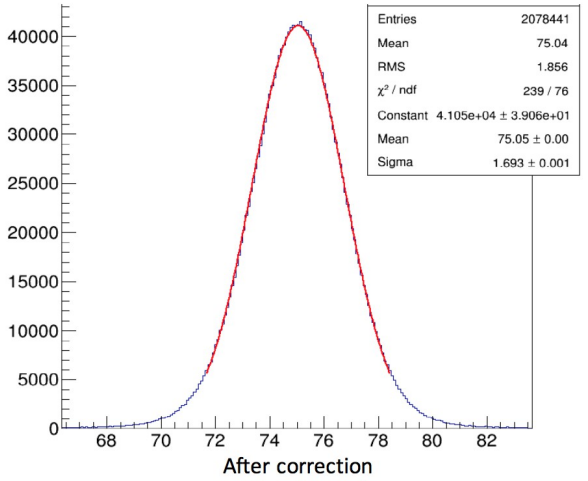
Photon: resolution







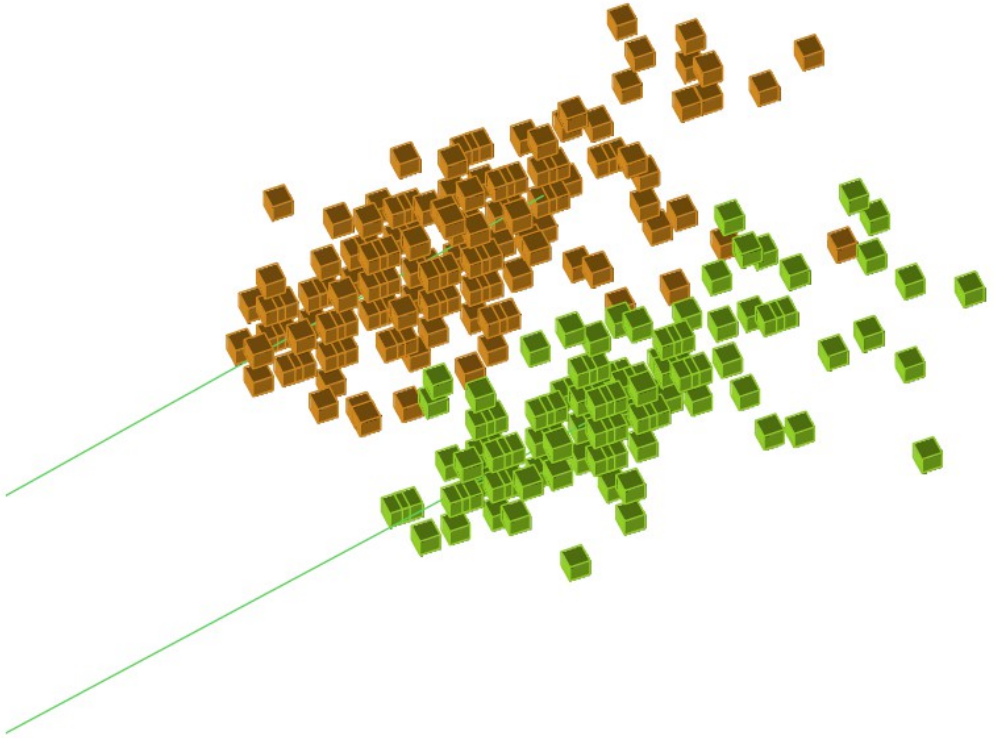


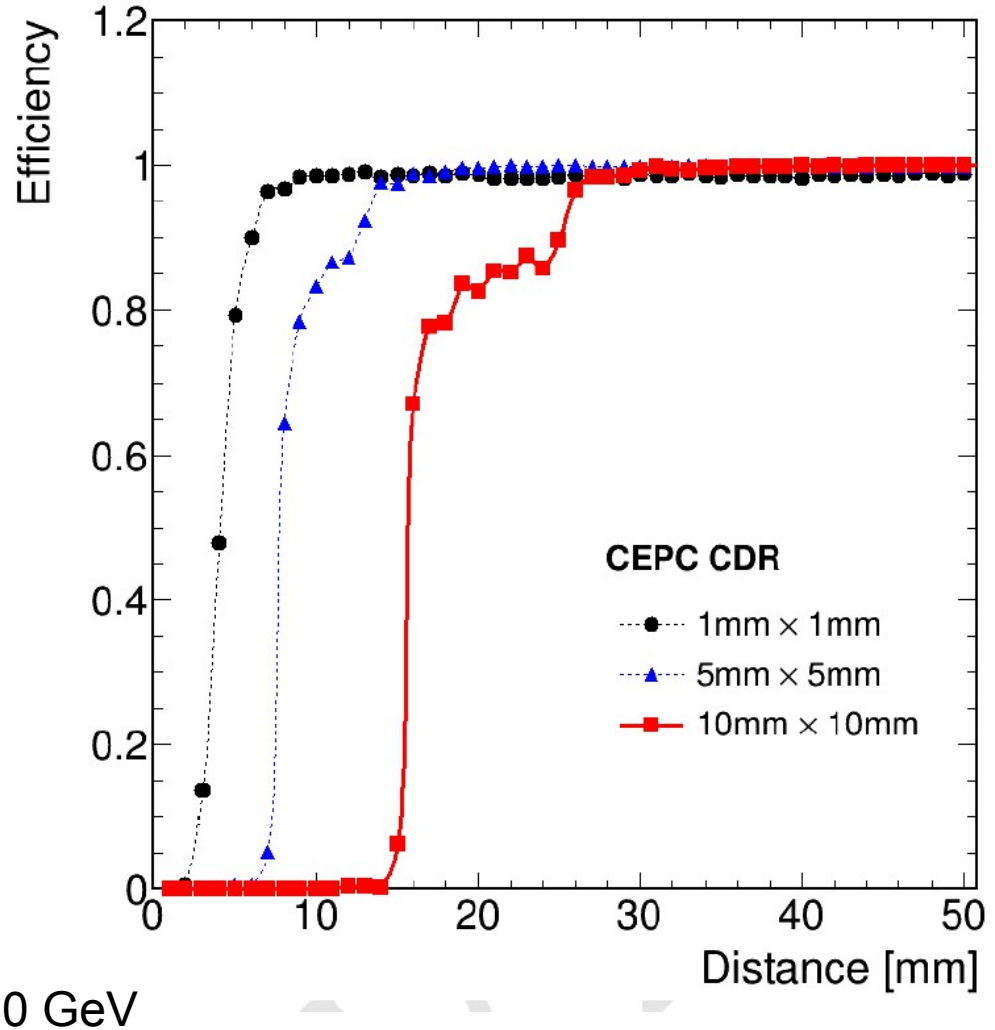


- A Higgs mass resolution of 1.7/2.5% is achieved in the Higgs to di-photon final states with simplified/baseline geometry
- The geometry defects correction could be efficiently corrected (Preliminary)

Yuqiao Shen & CEPC CDR

Clustering - Separation

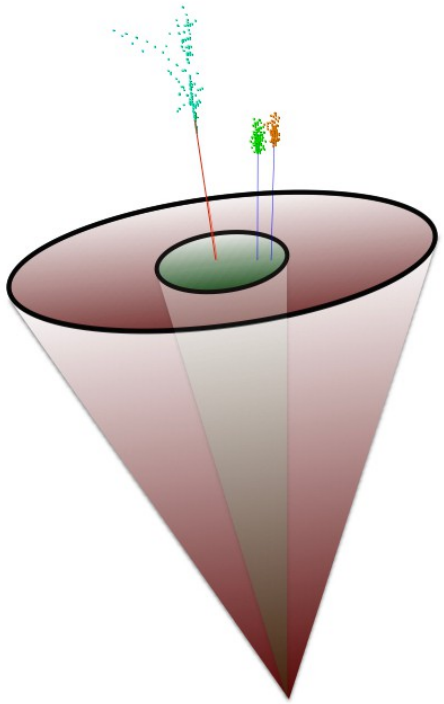


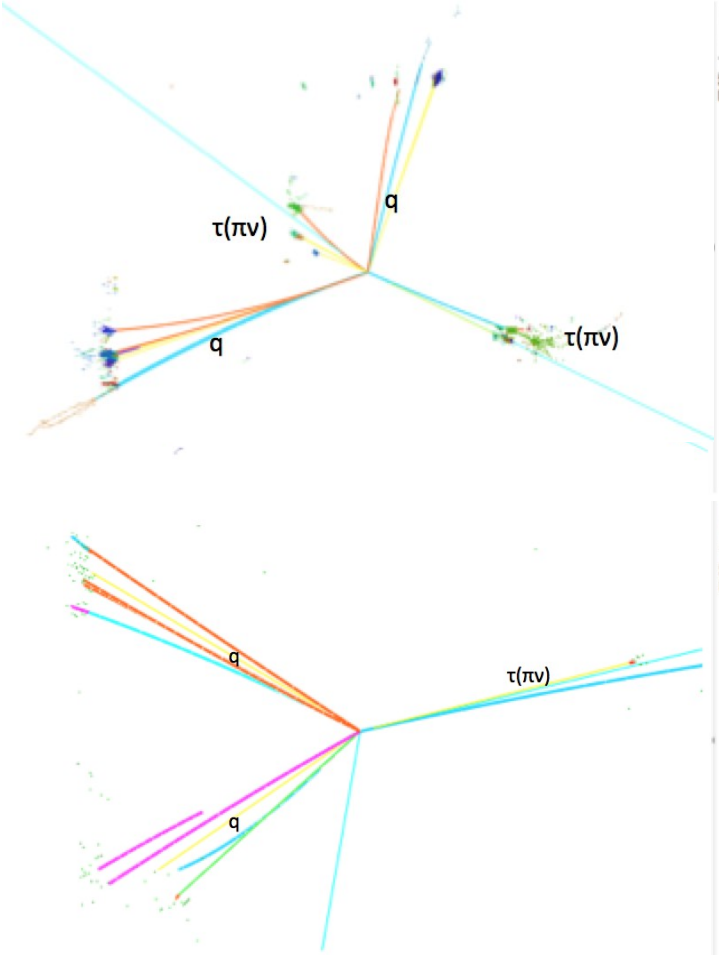


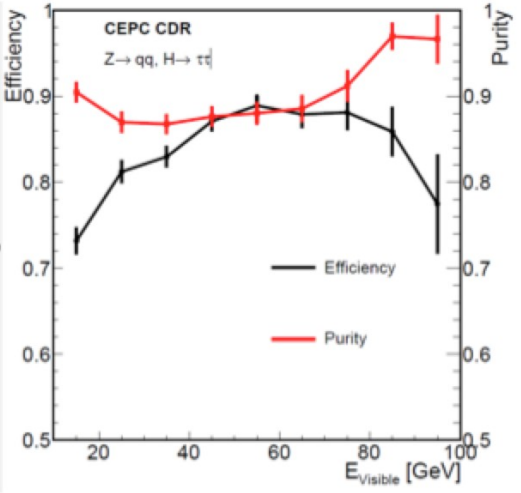
Critical energy to separate an evenly decay π_0: 30 GeV

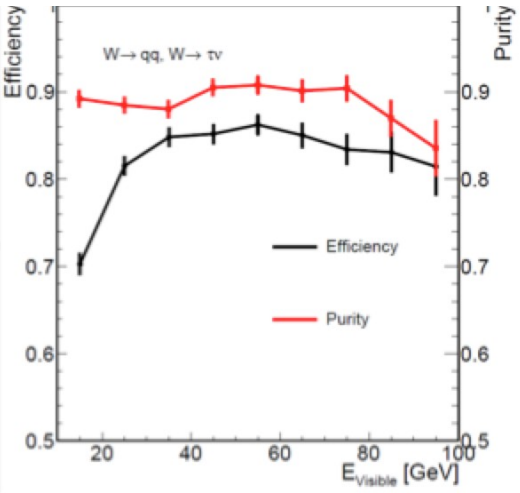
Hang Zhao. CEPC CDR

Tau finding at hadronic events









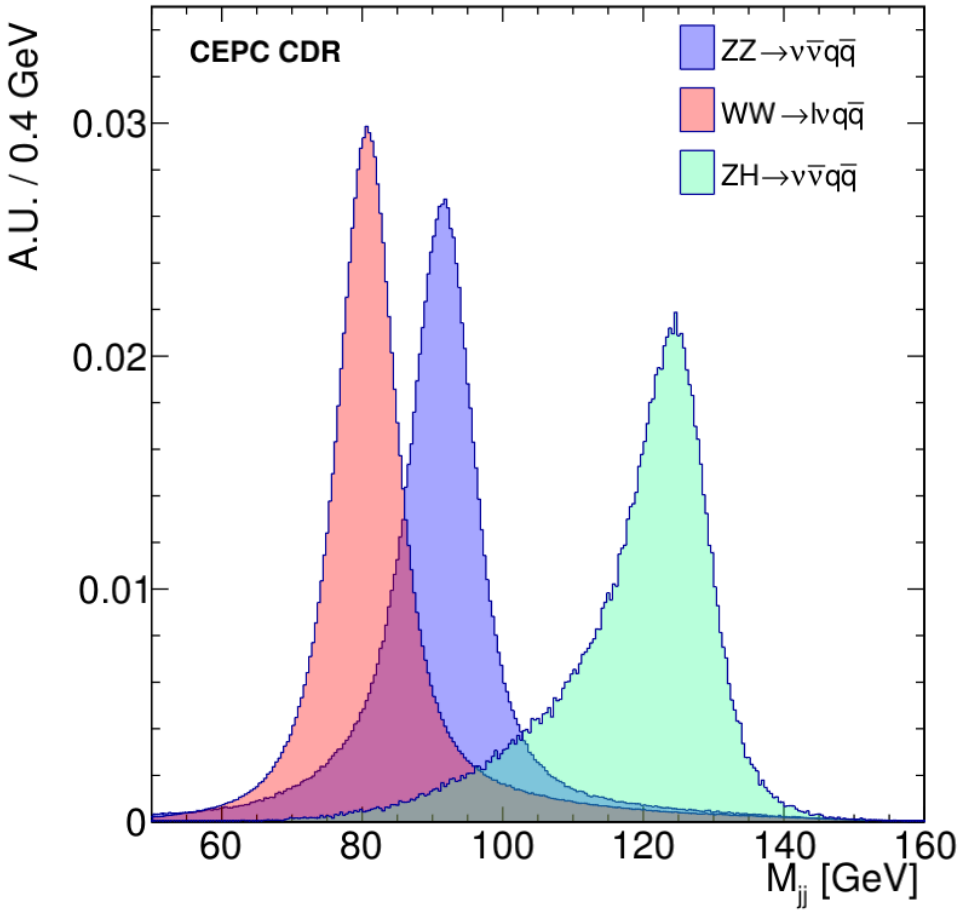
TAURUS (Tau ReconstrUction toolS):
an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

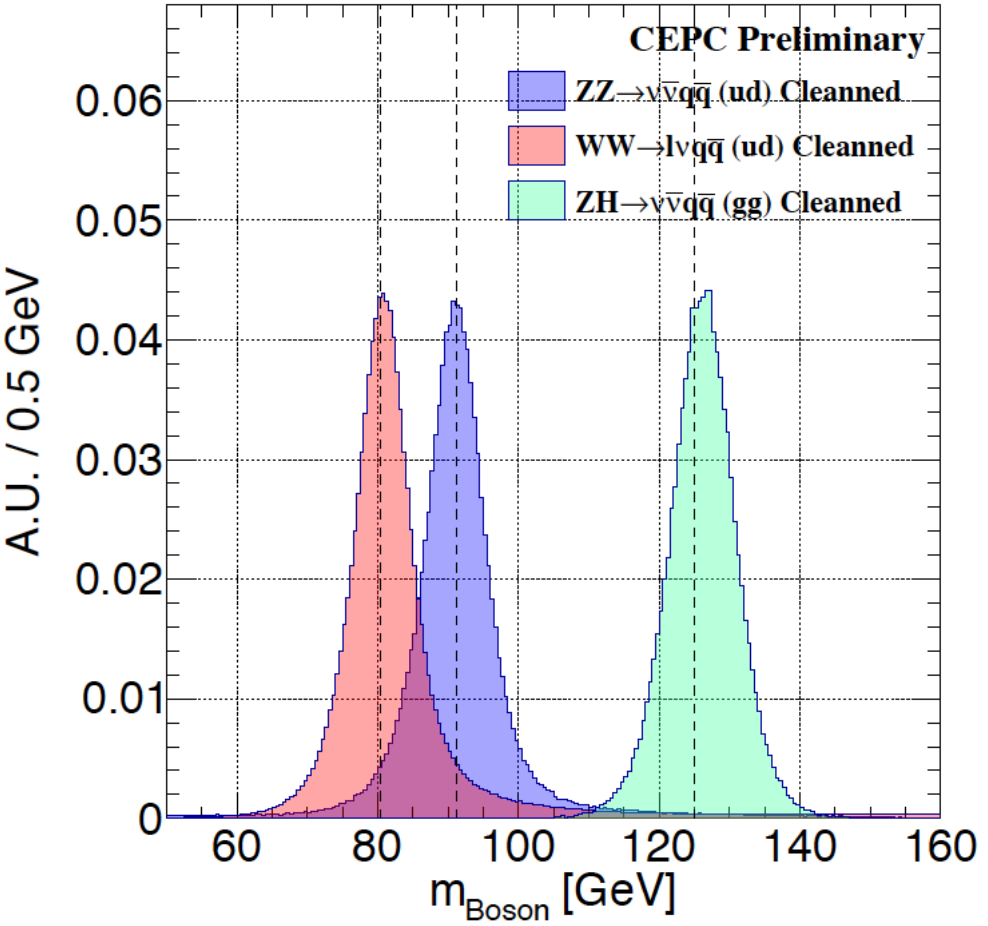
Zhigang Wu, CEPC CDR

Jets – color singlet

- Boson Mass Resolution: Total reconstructed mass of hadronic events
  - 3.8% at baseline (benchmarked with vvH, H→gluons process)
  - Applied to event with one color singlet fragments into jets
    - W, Z, H signal separation at lvqq, ll(vv)+qq events (Appreciated in Triplet Gauge Boson Coupling measurements)
    - Analysis of qqH, Higgs decays into non-jet final states, for example, qqH, H→taus, inv, photons, muons...
    - ...
- Single Jet Response (Jet energy scale/resolution)
  - Differential measurements with jet directions
  - Applied to events with more than one color singlet fragment into jets
    - WW/ZZ/ZH event separation in 4-jet final state
    - ...

Massive Boson Separation

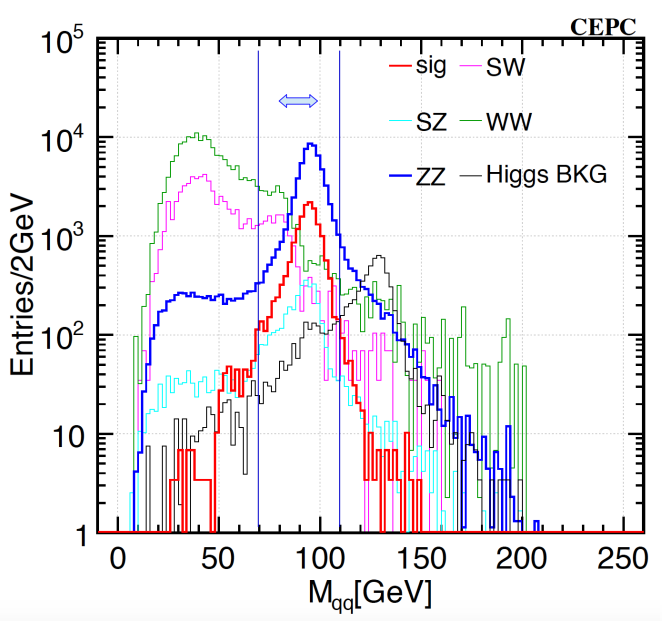


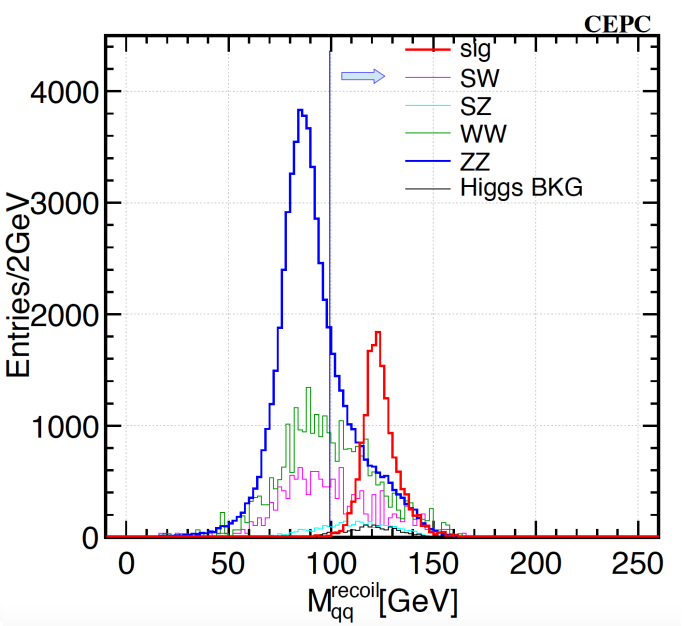


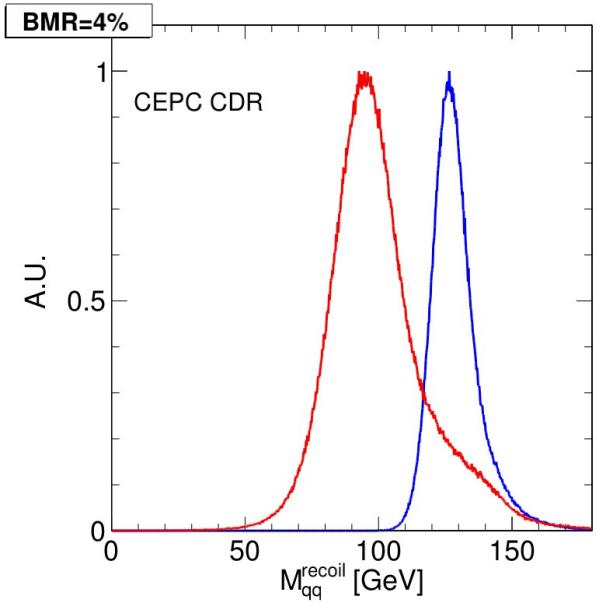
Peizhu Lai & CEPC CDR *WW sample: using μνqq sample, Plot: the visible mass without the muon*

CEPC-RECO-2017-002 (DocDB id-164),
CEPC-RECO-2018-002 (DocDB id-171),
Eur. Phys. J. C (2018) 78: 426

An Analysis Example: *g(Hττ)* at qqH



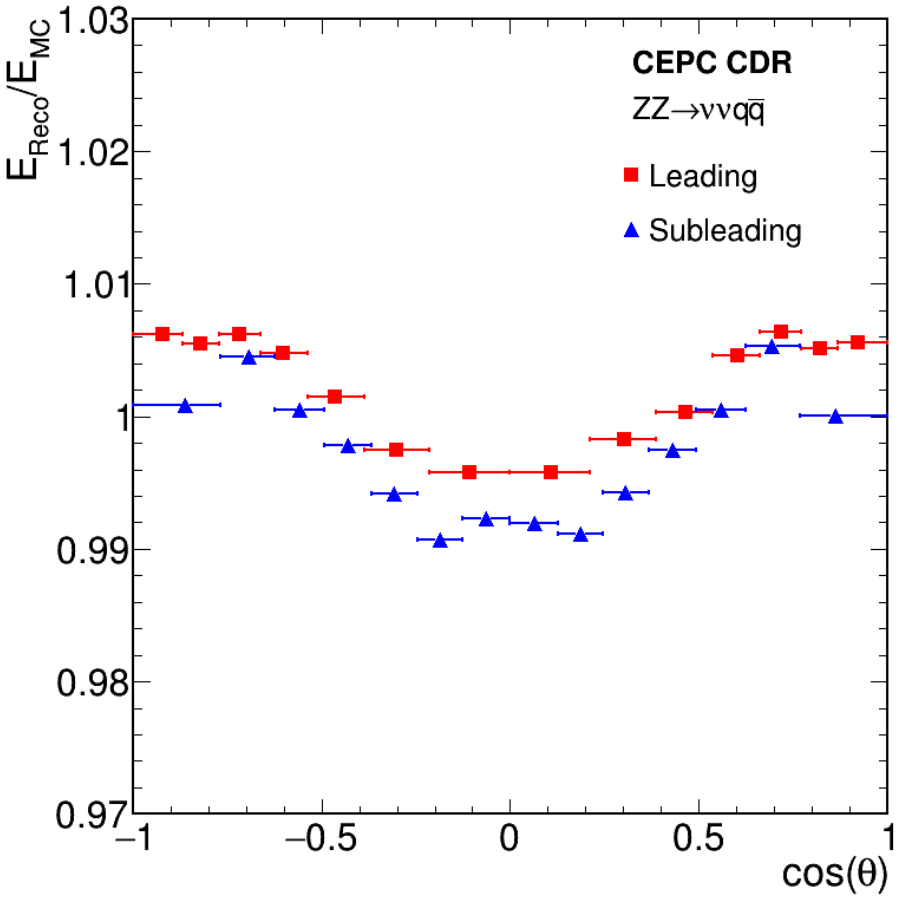


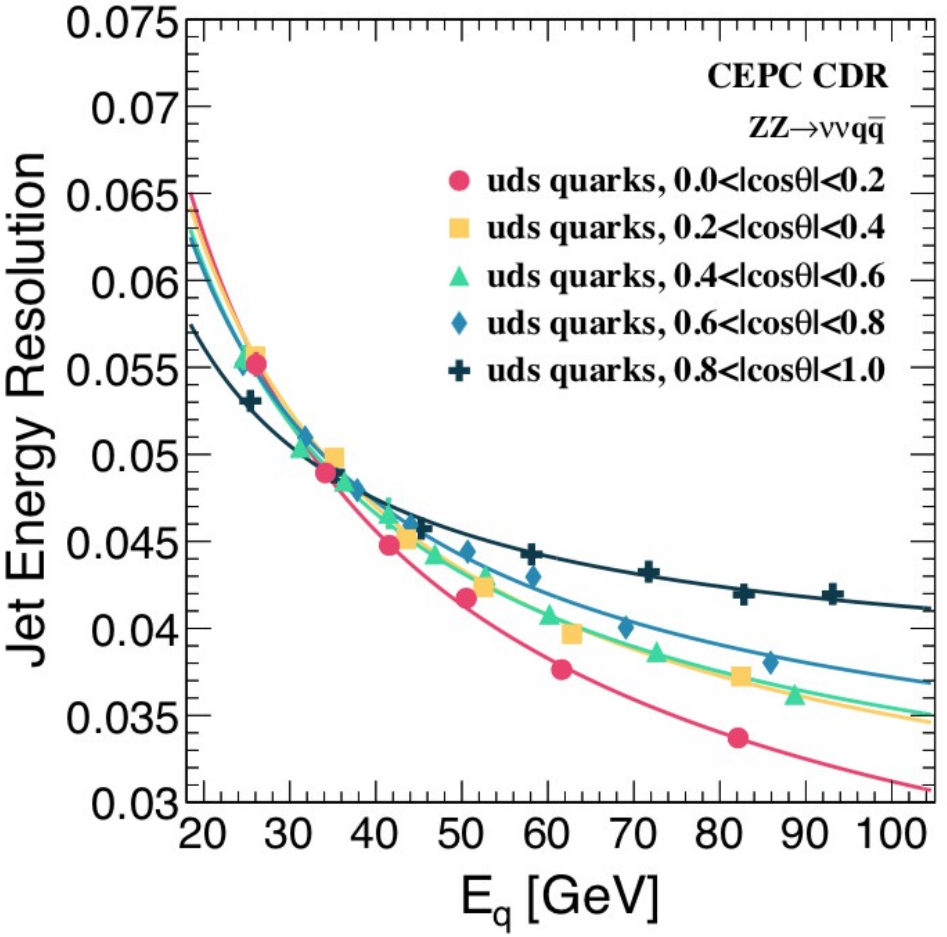


- TAURUS: di-tau system
- The rest particles are identified as the di-jet: to distinguish the ZZ/ZH background & Improves the accuracy by more than a factor of 2: **BMR < 4% (baseline of 3.8%) is crucial**
- Isolated tracks are intensionally defined as tau candidate: be distinguished by the VTX

Dan Yu's thesis

Jet Energy Scale & Resolution

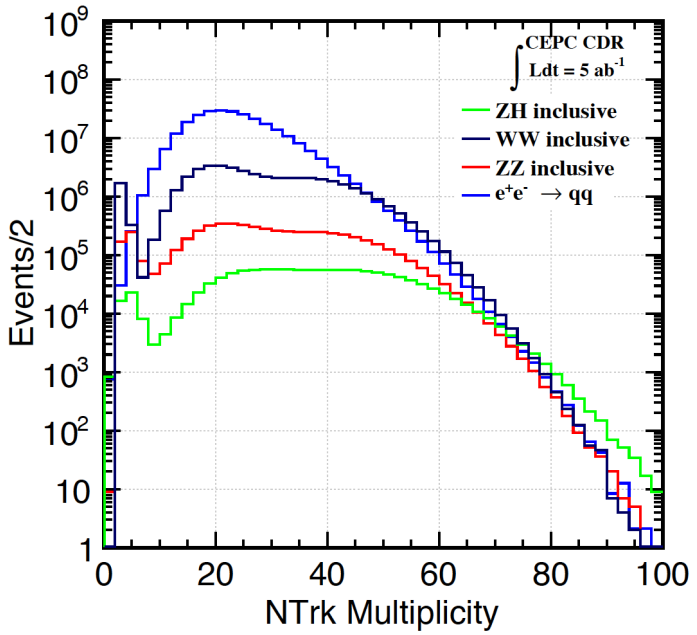


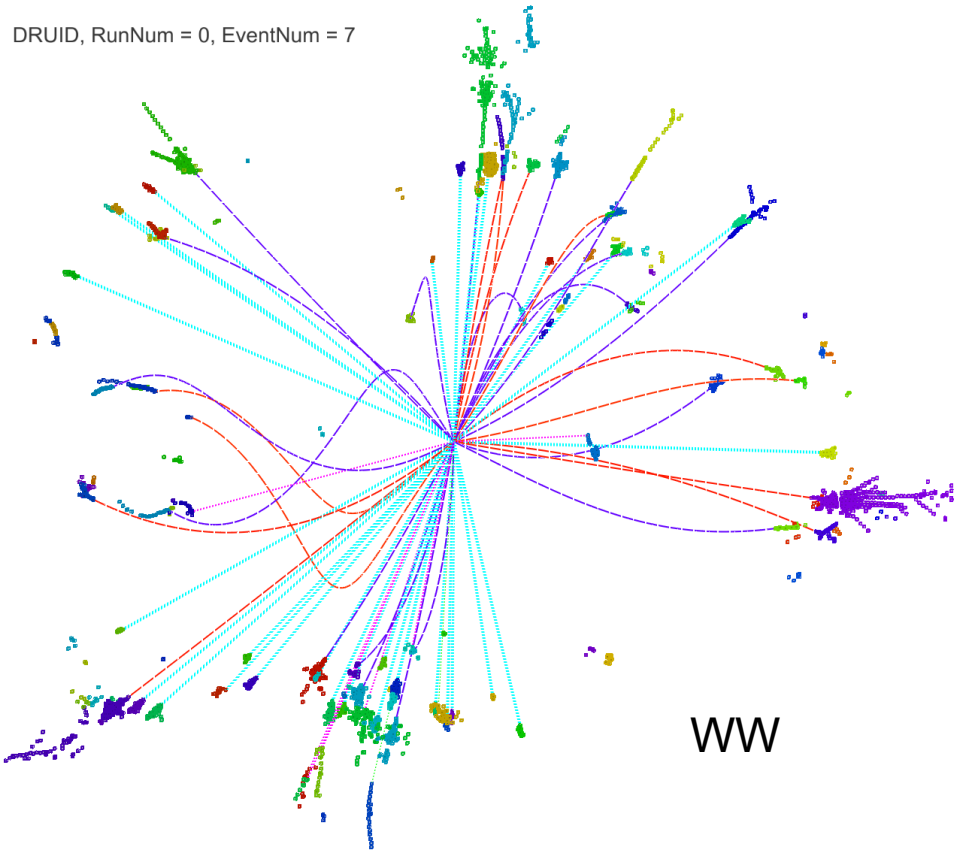


- JES ~ with 1% of the unity (without correction)
- JER ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
- **Both Superior to LHC experiments by 3-4 times**

Peizhu LAI

Separation of full hadronic WW-ZZ event

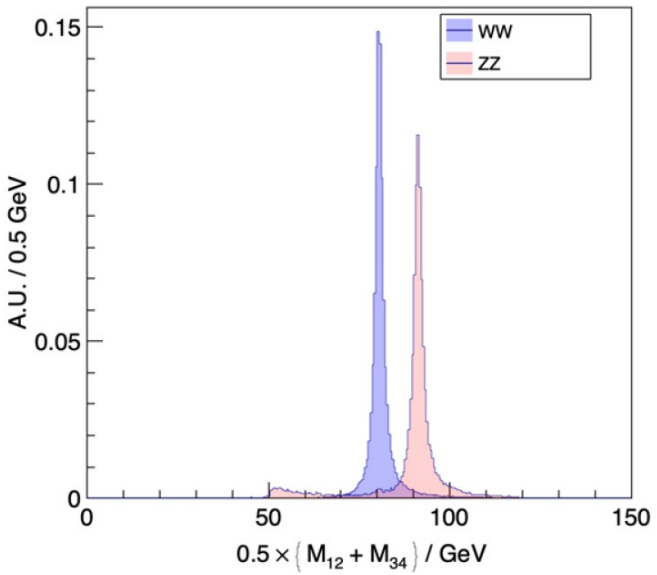


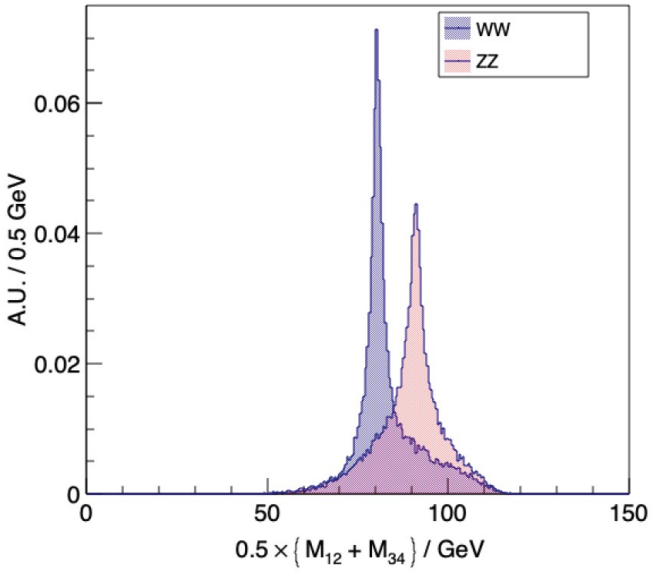


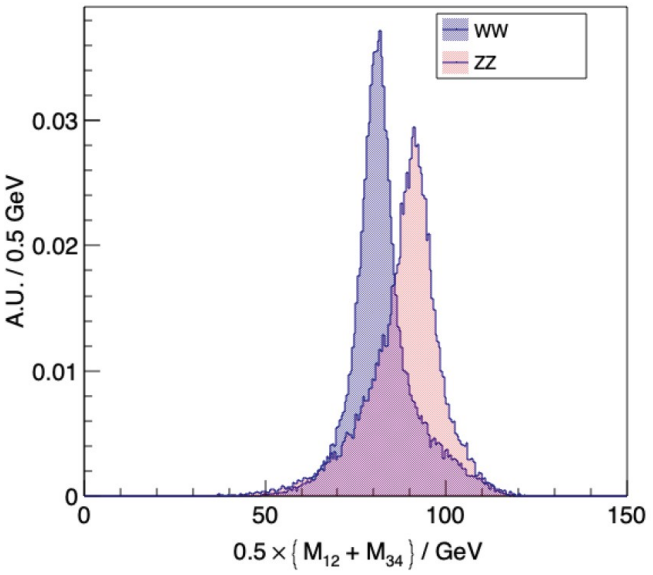
WW

- Low energy jets! (20 – 120 GeV)
- Typical multiplicity ~ o(100)
- WW-ZZ Separation: determined by
  - Intrinsic boson mass/width
  - Jet confusion from color single reconstruction – jet clustering & pairing
  - Detector response

Jet confusion: the leading term





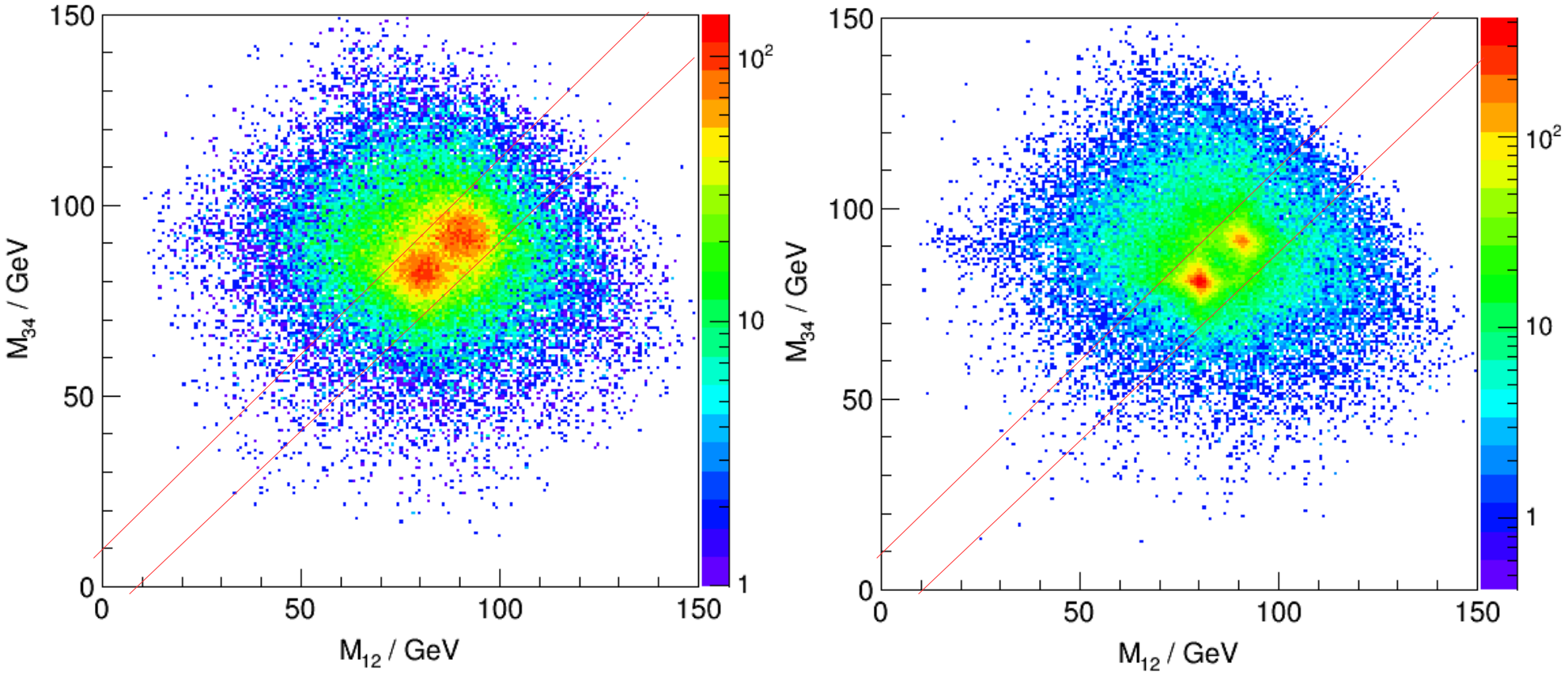


- Separation be characterized by
- Final state/MC particles are clustered into Reco/Genjet with ee-kt, and paired according to chi2
- WW-ZZ Separation at the inclusive sample:
  - Intrinsic boson mass/width - lower limit: Overlapping ratio of 13%
  - + Jet confusion – Genjet: Overlapping ratio of **53%**
  - + Detector response – Recojet: Overlapping ratio of 58%

$$overlapping\ ratio = \sum_{bins} min(a_i, b_i)$$

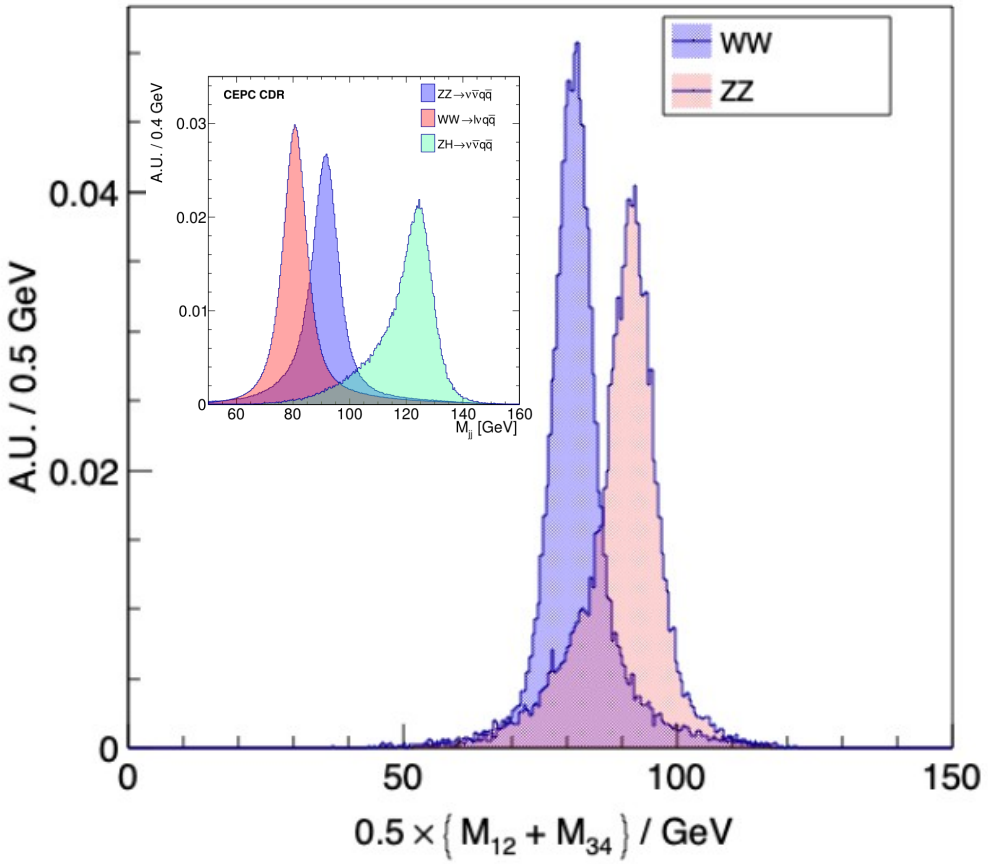
$$\chi^2 = \frac{(M_{12}-M_B)^2+(M_{34}-M_B)^2}{\sigma_B^2}$$

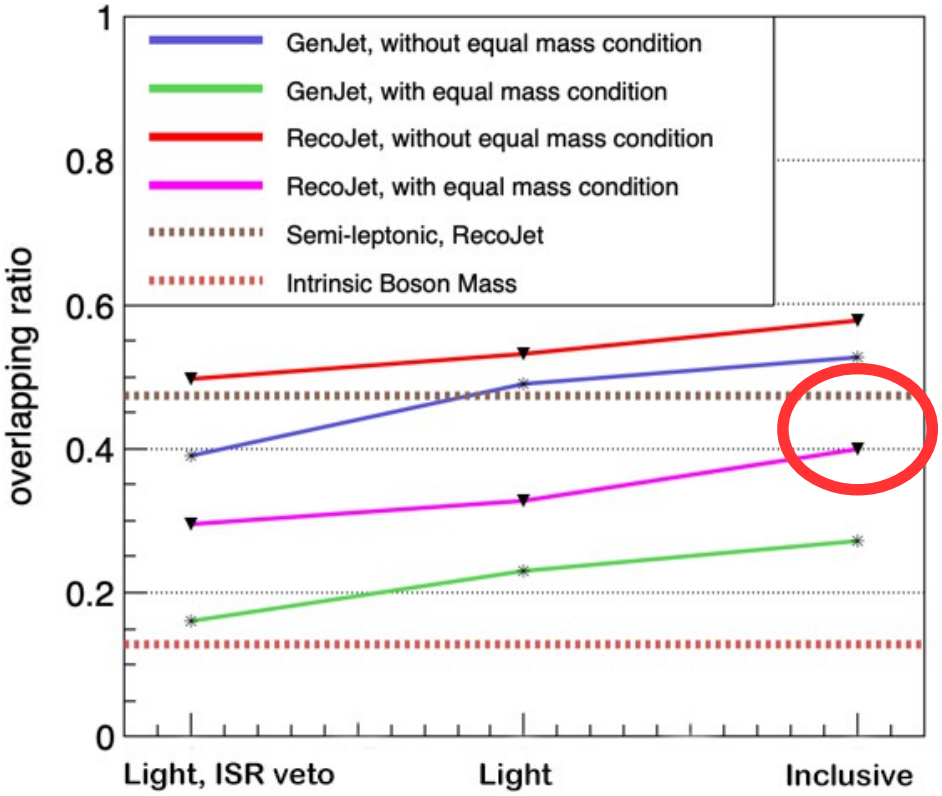
Reconstructed mass of the two di-jet system



Equal mass condition |M12 – M34| < 10 GeV: At the cost of half the statistic, the overlapping ratio can be reduced from 58%/53% to 40%/27% for the Reco/Genjet

Separation of full hadronic WW-ZZ event





The CEPC Baseline could separate efficiently the WW-ZZ with full hadronic final state.

Critical to develop color singlet reconstruction: improve from the naive Jet clustering & pairing.

Quantified by differential overlapping ratio.

Control of ISR photon/neutrinos from heavy flavor jet is important.

Summary

- CEPC, a super Higgs/W/Z factory, requires high **efficiency, purity,** and **precision** reconstruction of all key physics objects
  - Tracker & Calorimeter intrinsic resolution: better is better!
  - BMR < 4% is crucial: di-jet recoil mass at qqH events
- Performance of the CEPC baseline fulfills the physics requirements
  - All key physics objects tamed
    - Tracks, Clusters
    - Charged Particle & identification
    - Leptons, photons
    - Composited objects
      - Ks/Λ
      - Tau
      - Jets: WW-ZZ separation
  - Clear Higgs signature in all SM Higgs decay modes
  - 0.1% – 1% relative error in Higgs coupling measurements

Summary

- To do
  - Generator: understand the current theoretical error & roadmap to its control
  - Simulation: novel framework that supports parallel computing
  - **Reconstruction – Optimization:**
    - Enhance the engagement-iteration with the detector design
    - Jet, **vertex**-jet flavor, gluon jet, and **color singlet**
    - Machine learning...
  - Analysis:
    - Iterates with physics reach study
    - Data driven method for systematic control...
- Wishlist & Perspective for future collaboration
  - Common software: simulation framework and reconstruction algorithm/toolkits
  - Common samples: start from generator samples
  - Common toolkits/repositories to other tech. Challenges: integration, cooling, etc

Many Thanks to

C. Fu, Geant 4 & Tracking

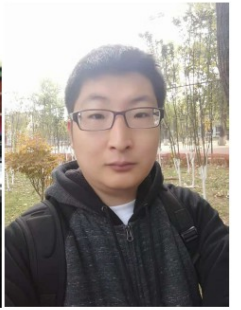
X. Zhao, Software & production

Dan, Lepton ID, Tau, PFA

P. Lai, Jet Calibration

F. An, Pid & Flavor

Z. Wu, VTX Optimization


H. Liang, Generator

Y. Wang, Calo optimization

Y. Shen, Photon

M. Zhao, Tracking, TPC,

G. Li, Generator & Flavor tagging

H. Zhao, Calo Optimization & PFA

Y. Zhu, Jet Clustering

T. Zhen, K_short & Lambda

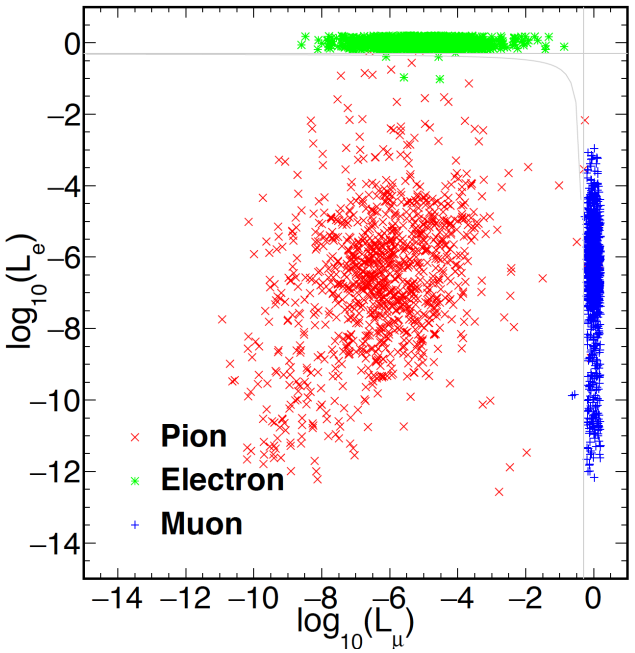
M. Ruan, PFA, Object,...

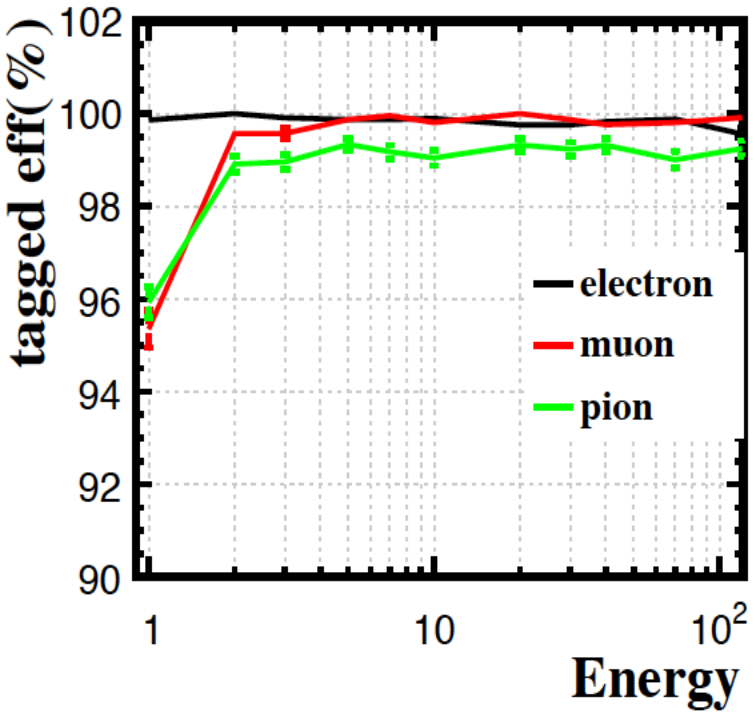
See also:

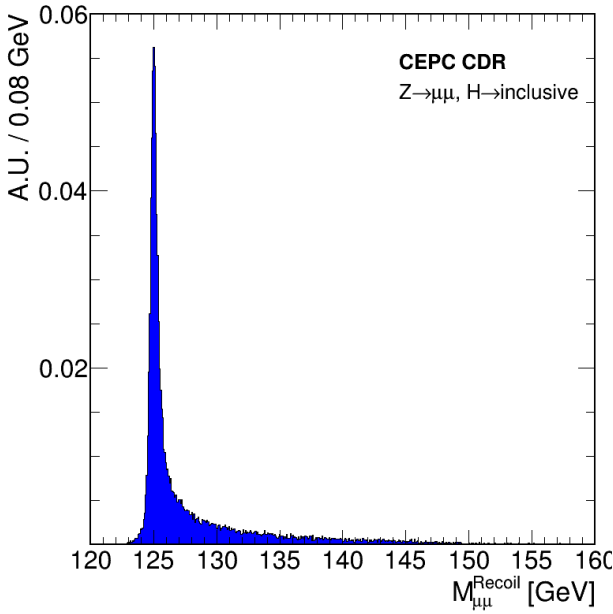
Xianghu Zhao & Mingrui Zhao's talks on Software/production
Taifan Zhen's talk on Ks & Λ reconstruction
Hao Liang & Fenfen An's talks on Higgs/Flavor benchmark analysis
YueXin Wang's Poster on Alternative Calorimeter study

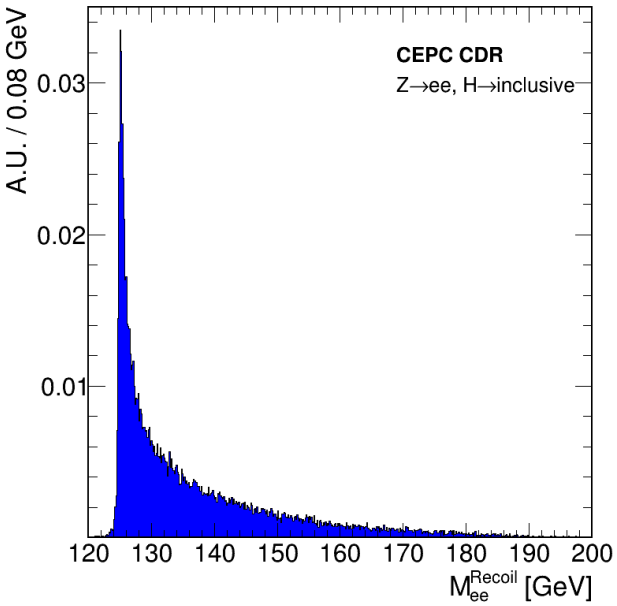
backup

Leptons







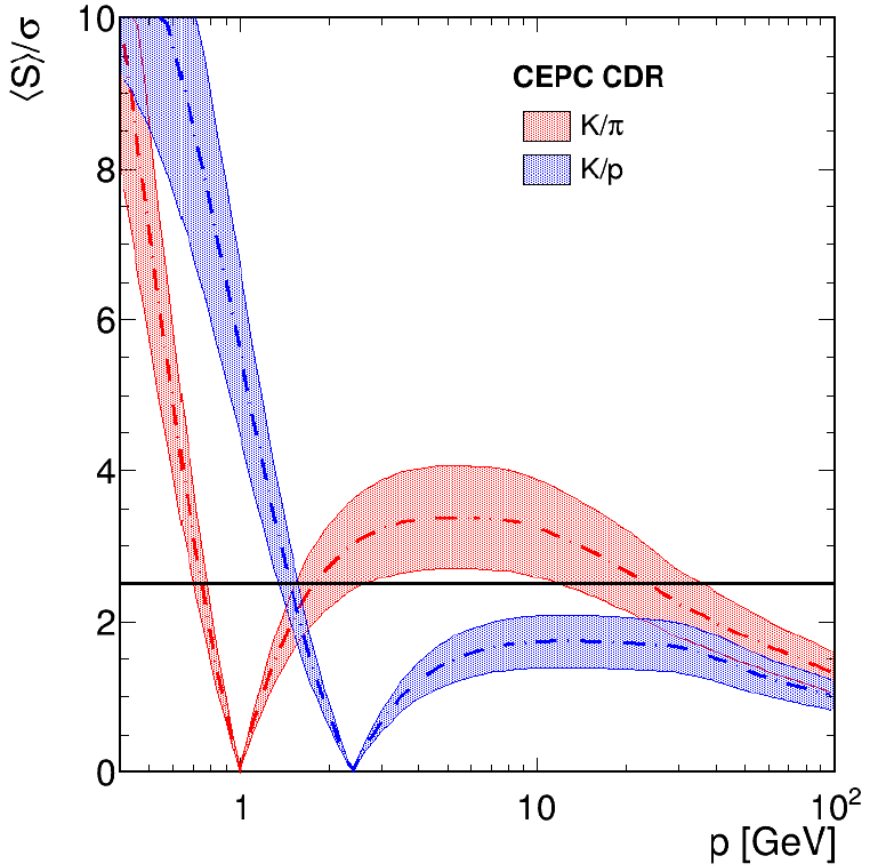


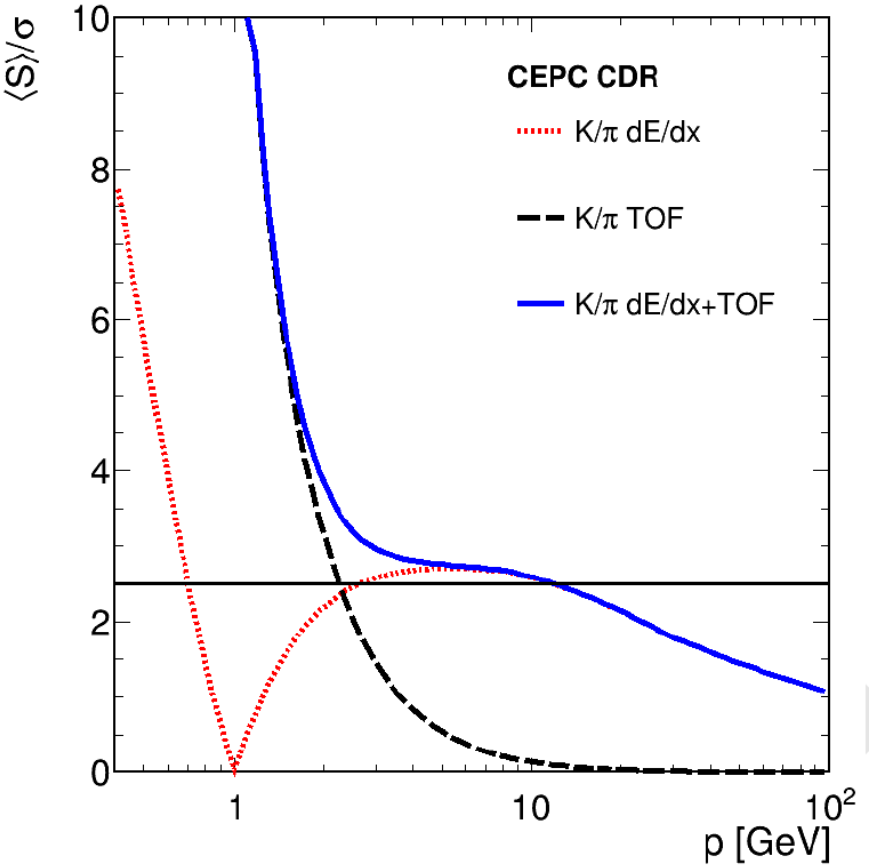
BDT method using 4 classes of 24 input discrimination variables.

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%

Eur. Phys. J. C (2017) 77: 591

Kaon





Highly appreciated in flavor physics @ CEPC Z pole

TPC dEdx + ToF of 50 ps

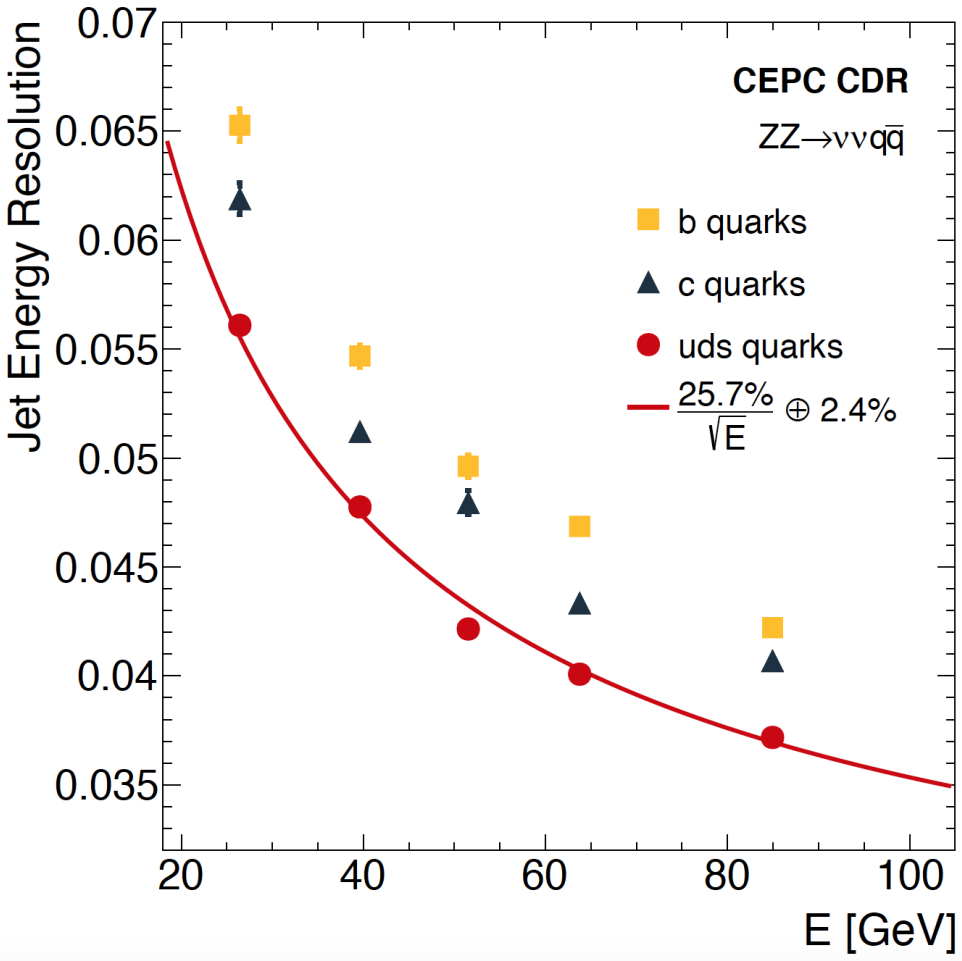
Eur. Phys. J. C (2018) 78:464

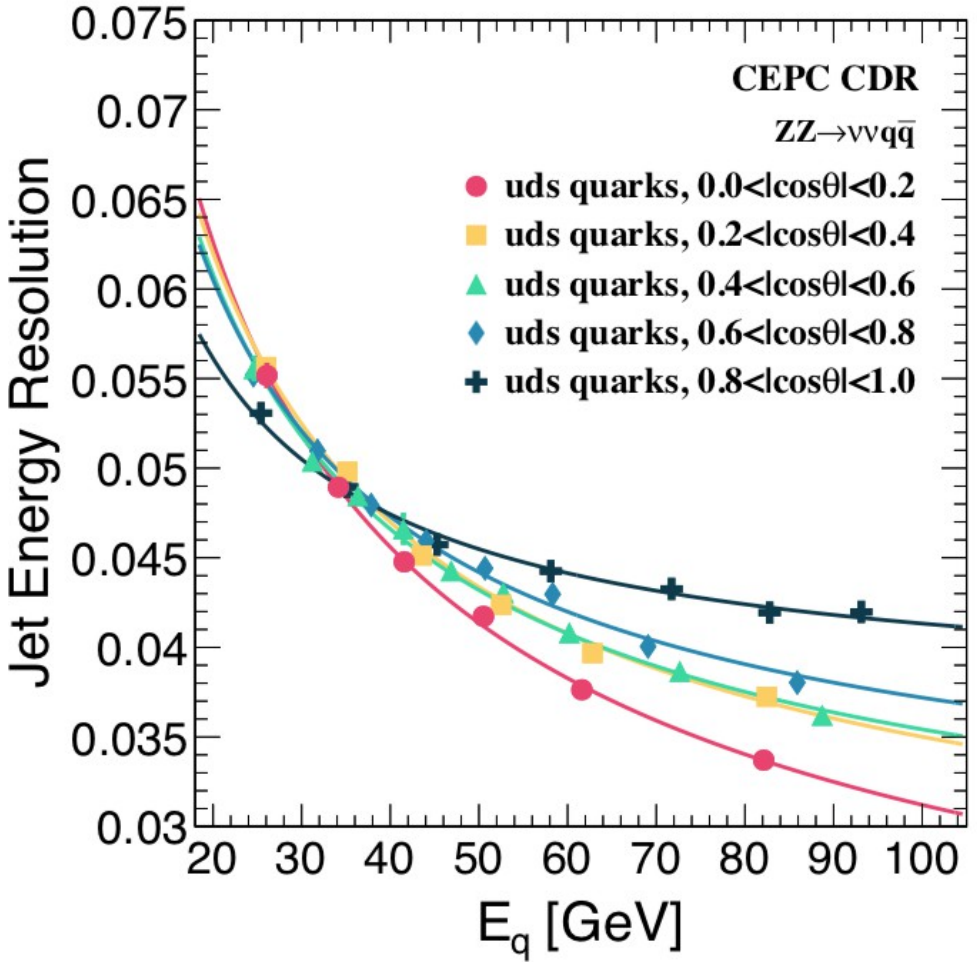
At inclusive Z pole sample:

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)

Jet Energy Resolution

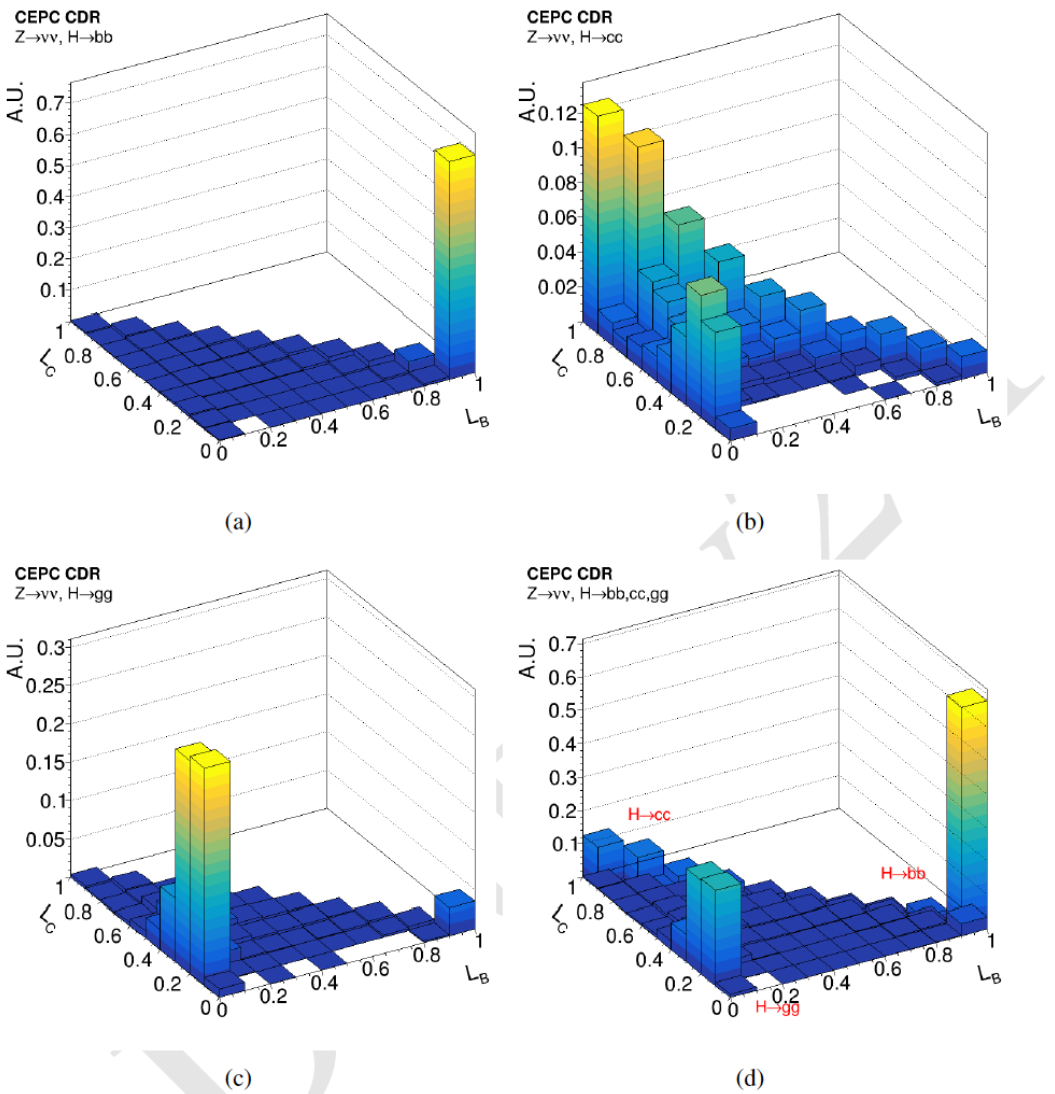




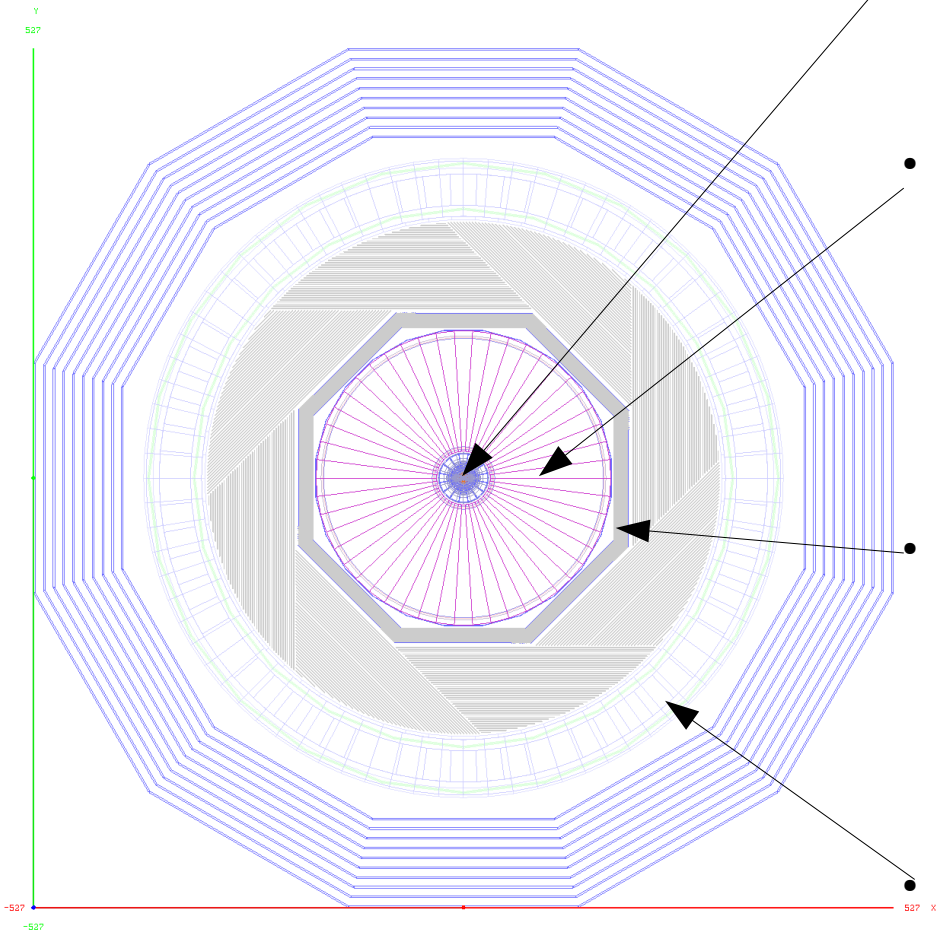
Amplitude ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
Depends on the Flavor, direction and jet energy
Superior to LHC experiments by 3-4 times

Flavor Tagging

- Using LCFIPlus Package from ilcsoft
- At Higgs->2 jet samples:
  - *Clear separation between different decay modes*
- Typical Performance at Z pole sample:
  - *B-tagging: eff/purity = 80%/90%*
  - *C-tagging: eff/purity = 60%/60%*

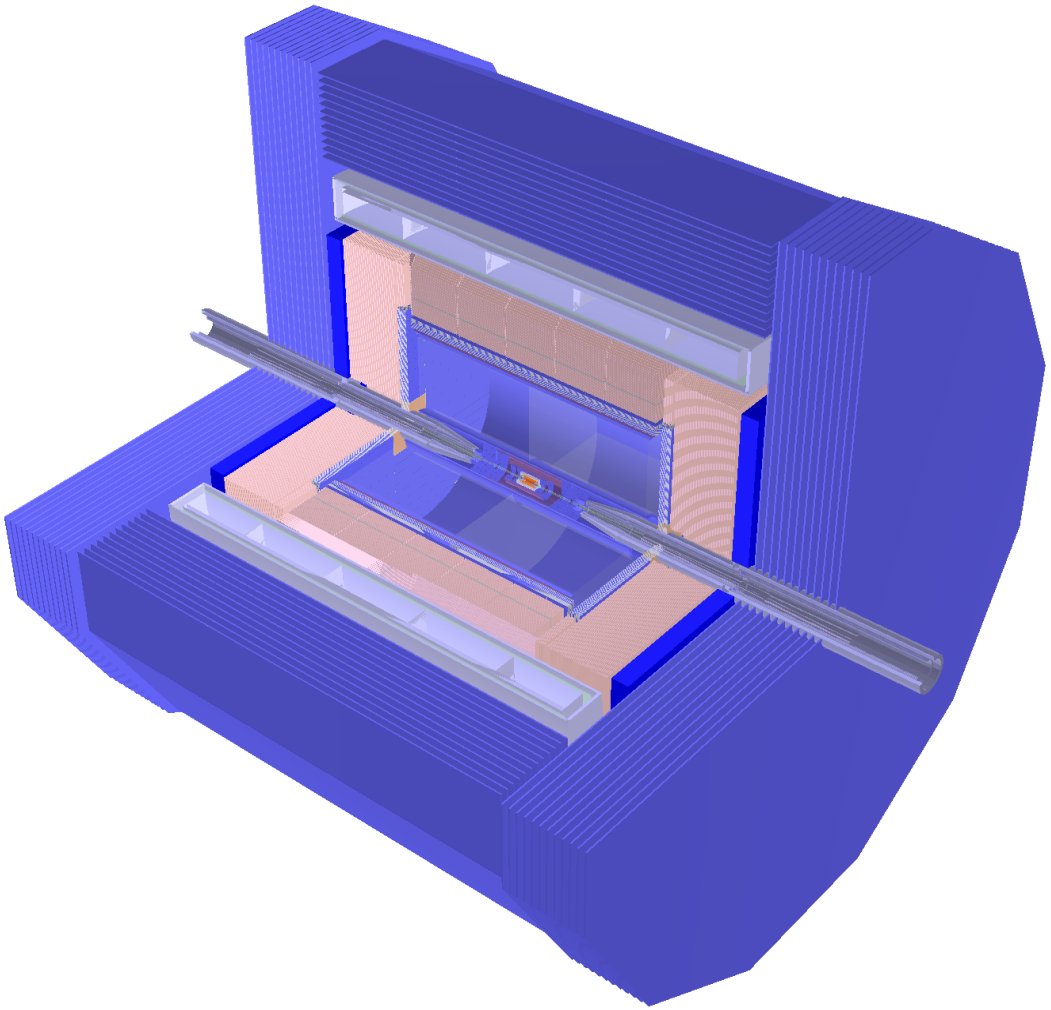


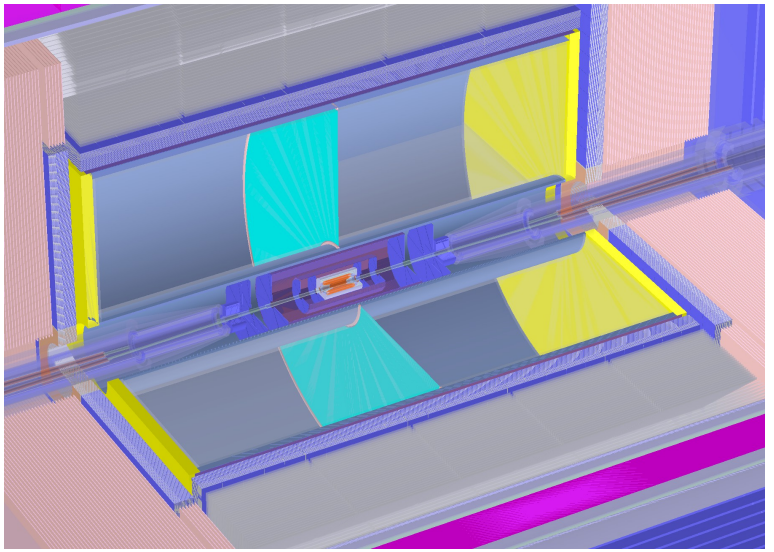
An ILD-like detector at the CEPC

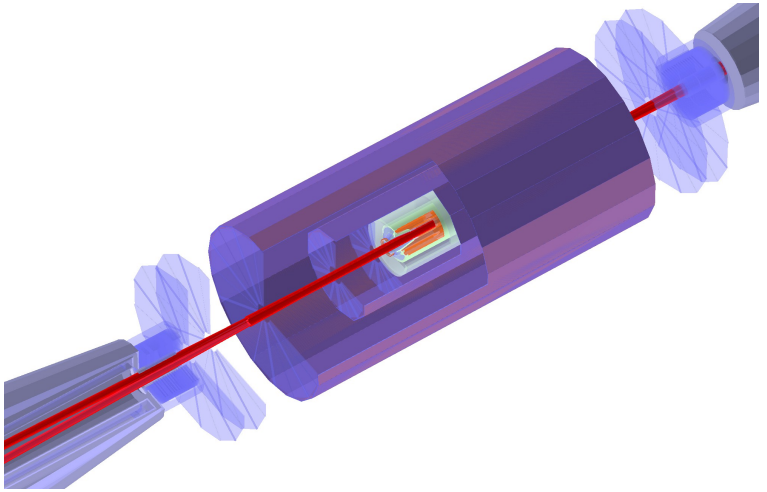


- Different collision environments/rates :
  - MDI design & Implementation: CEPC-SIMU-2017-001
- The CEPC Event rate is significantly higher than linear colliders, charged kaon id can strongly enhance the CEPC flavor physics program
  - TPC Feasibility: JINST-12-P07005 (2017)
  - Pid using TPC dEdx and ToF: Eur. Phys. J. C (2018) 78:464
- No power pulsing at CEPC detector
  - A significant reduction of the readout channel, especially the Calorimeter Granularity: JINST-13-P03010 (2018)
  - HCAL Optimization
- 3 Tesla Solenoid: requested by the Accelerator/MDI

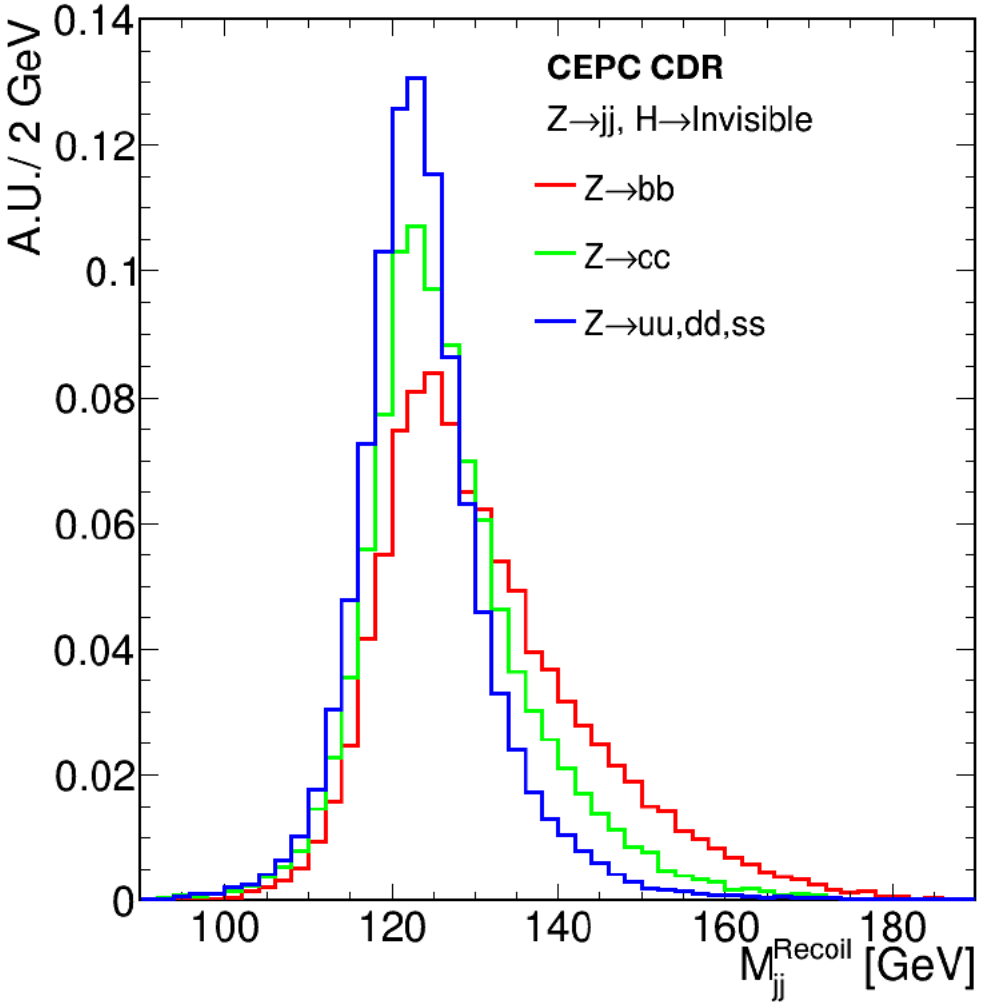
APODIS Geometry

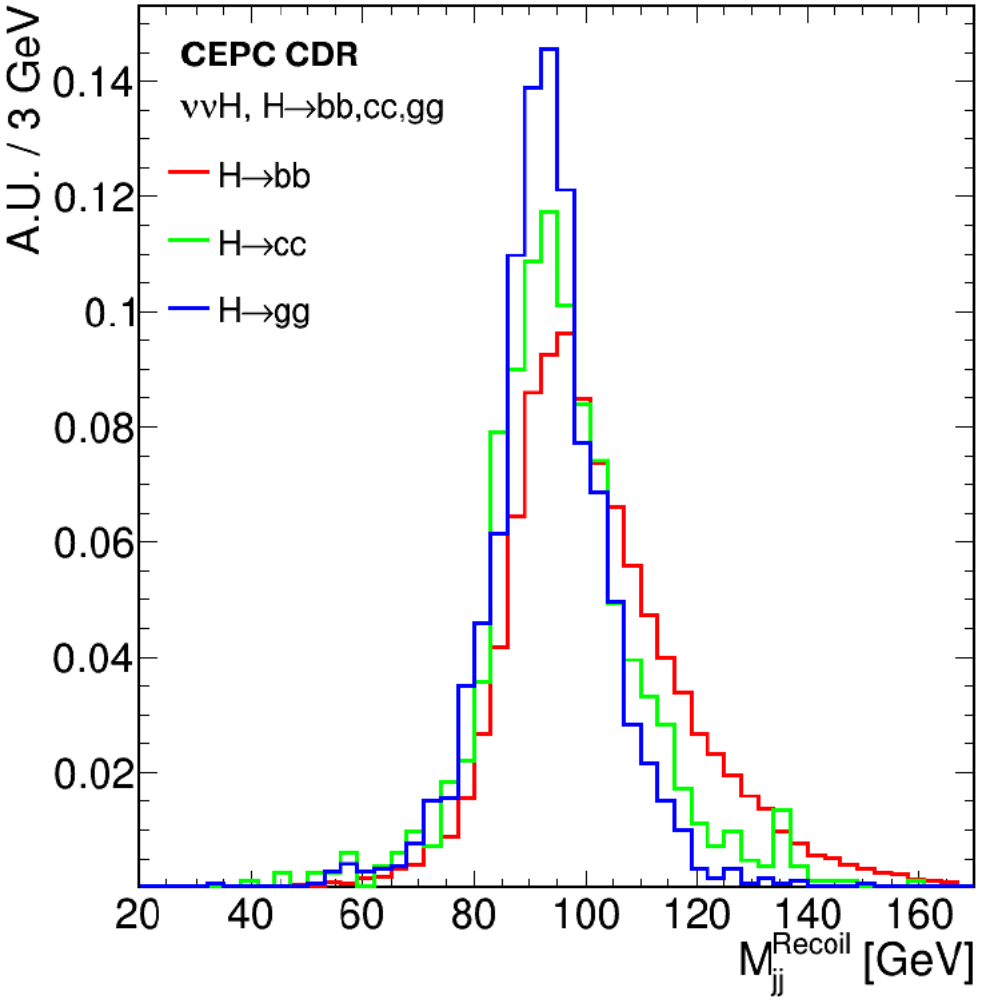






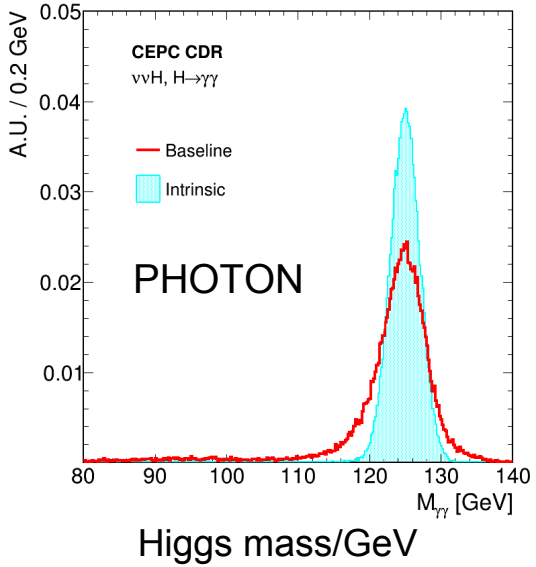
Missing Energy & Momentum

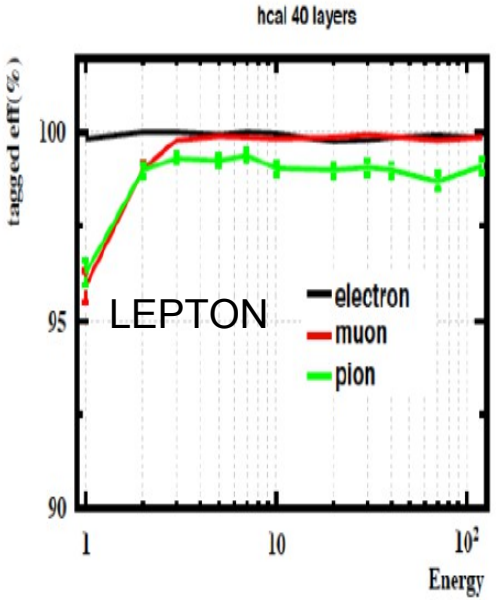


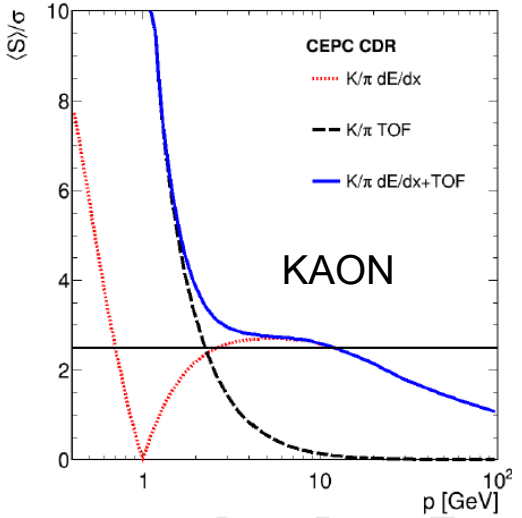


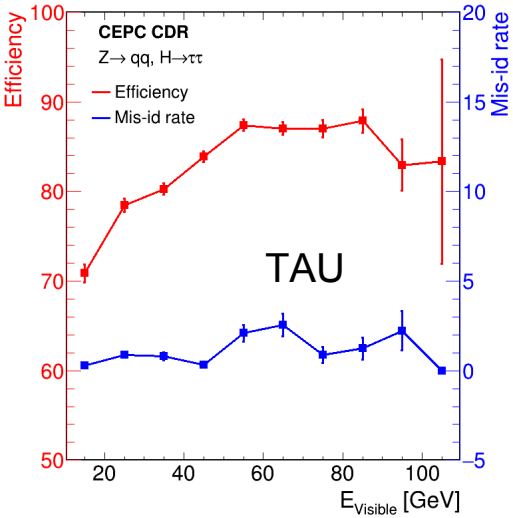
Width of the Light jets: 6GeV/8GeV (Left/Right Plots)

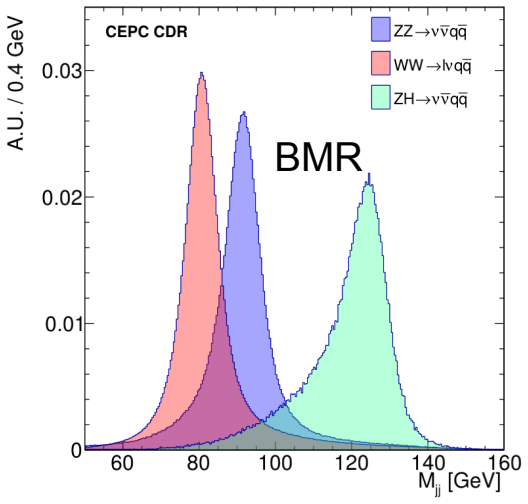
Physics Objects: Tamed

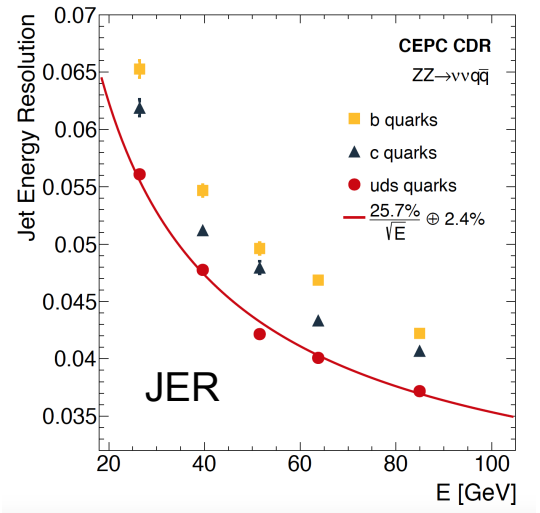


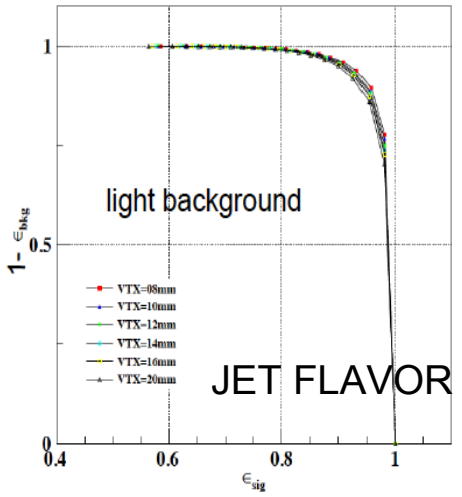


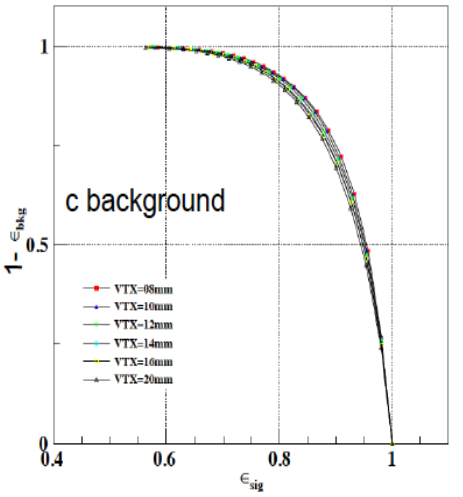




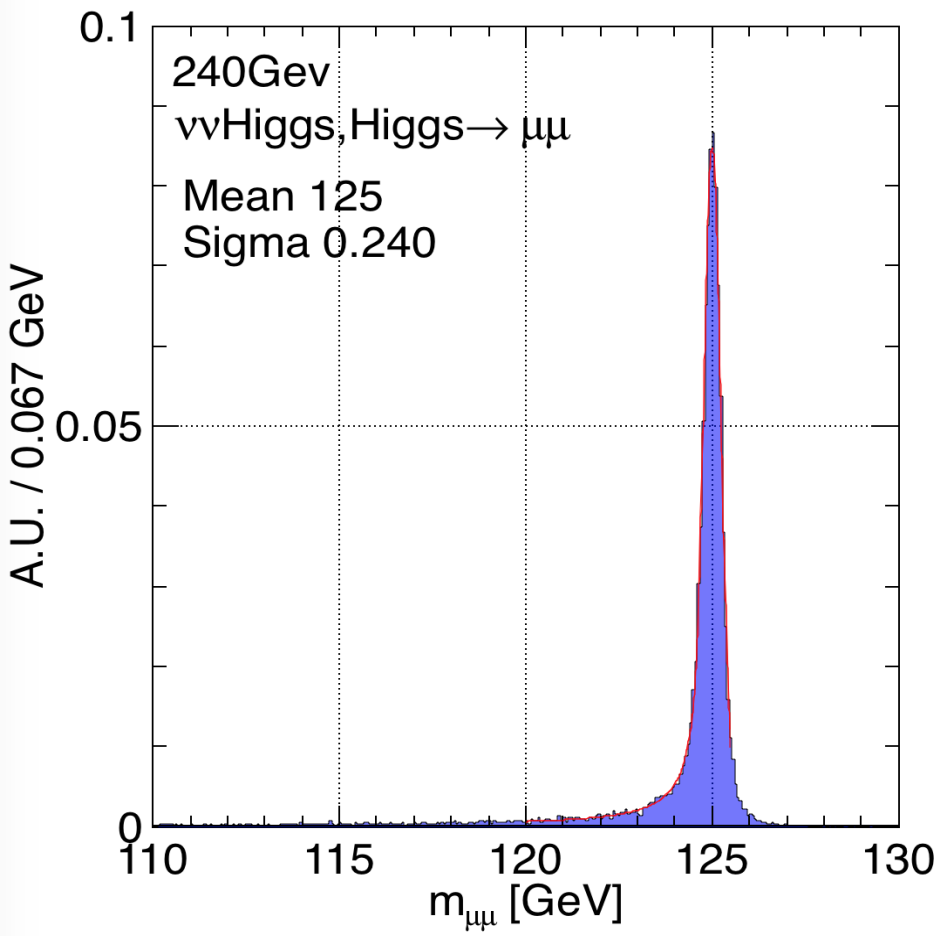


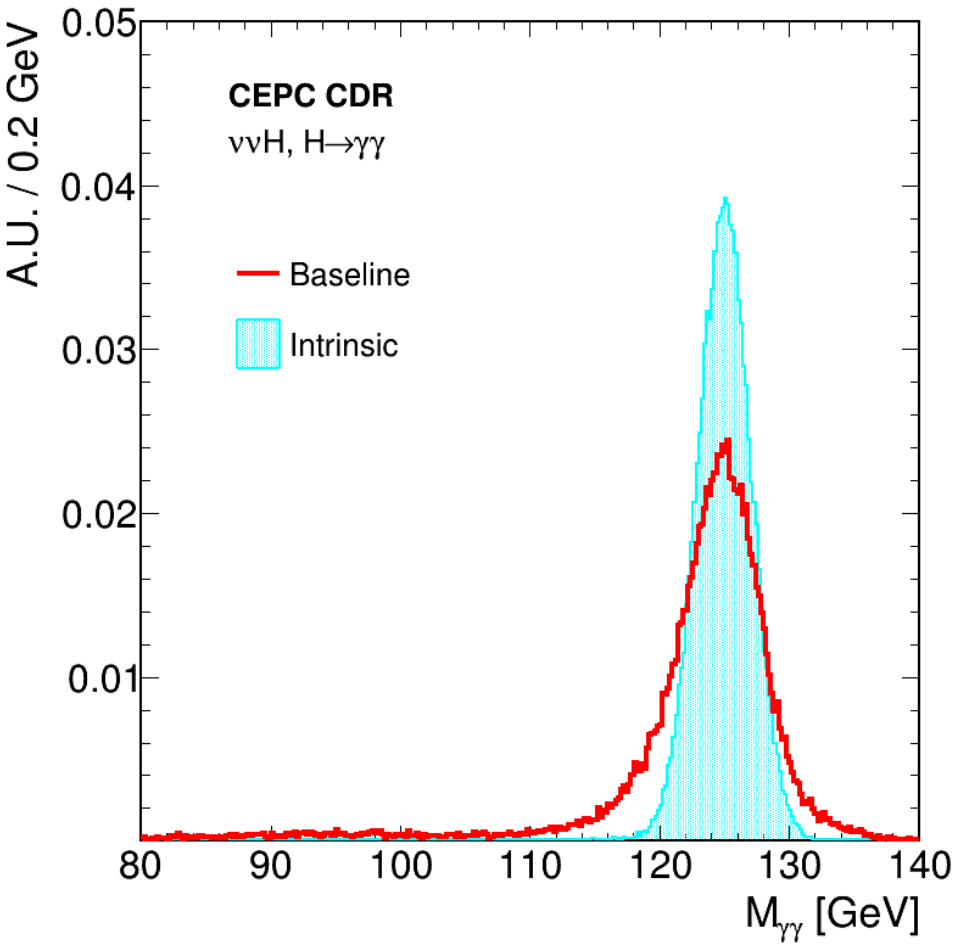






Higgs Signal at APODIS

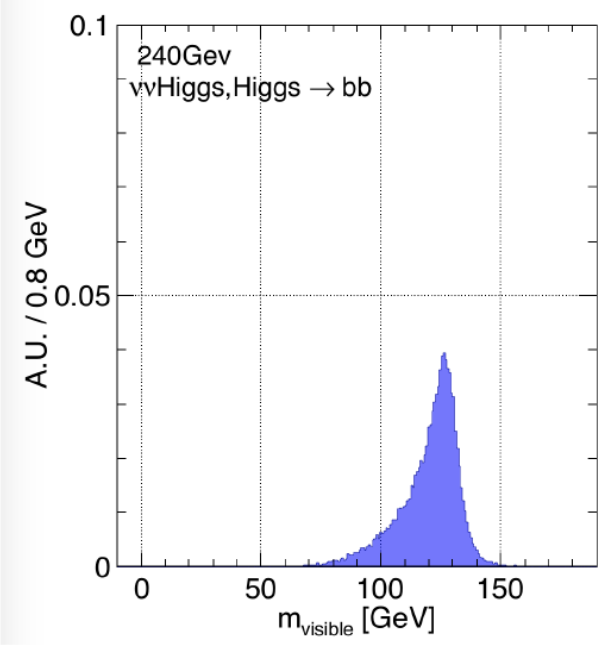


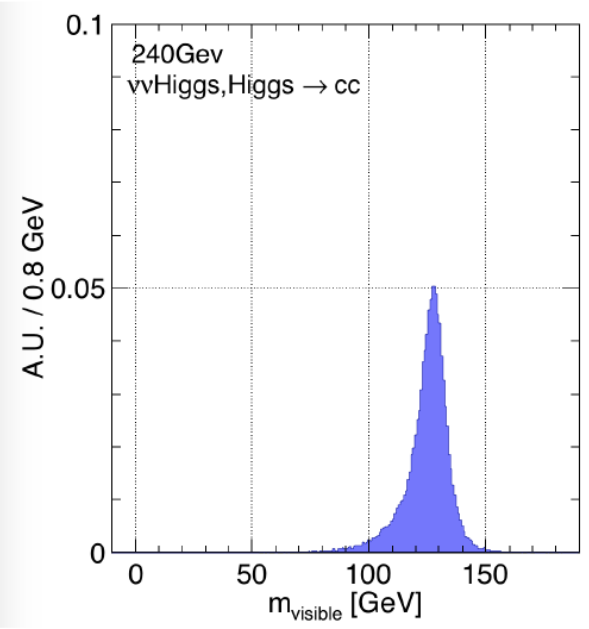


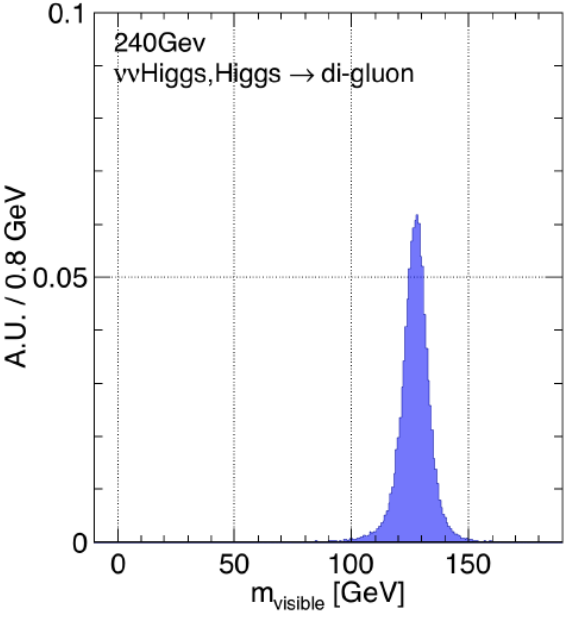
CEPC-RECO-2018-002
CEPC-Doc id 174, 175

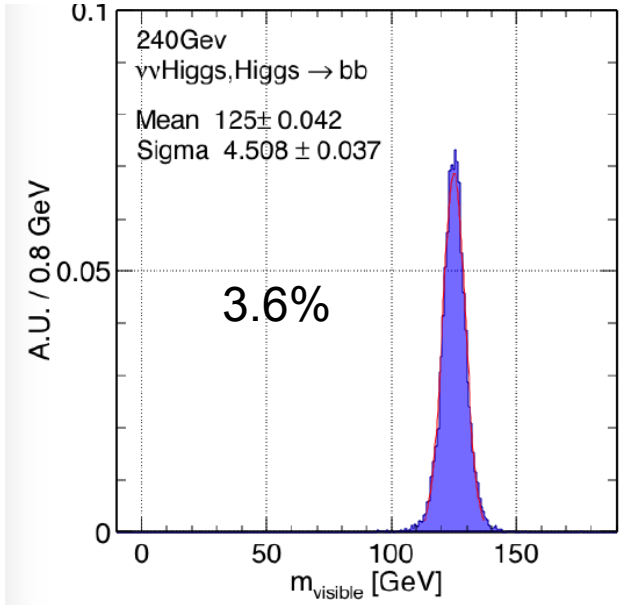
Lepton tracks & Photon Clusters

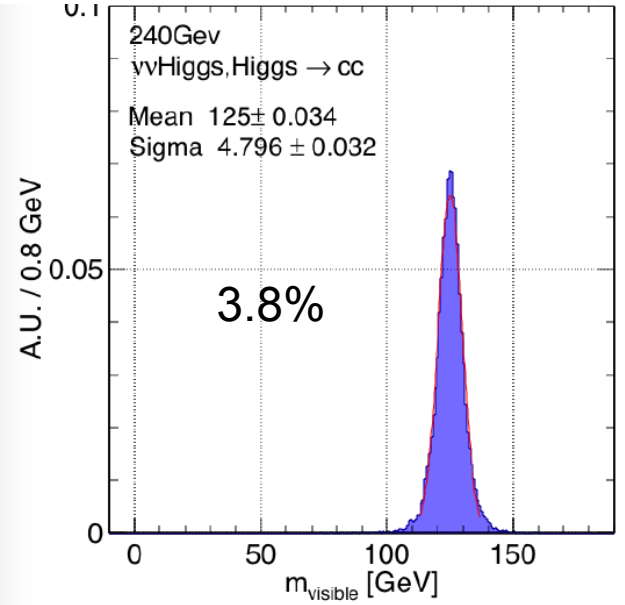
Higgs to bb, cc, gg (Jets)

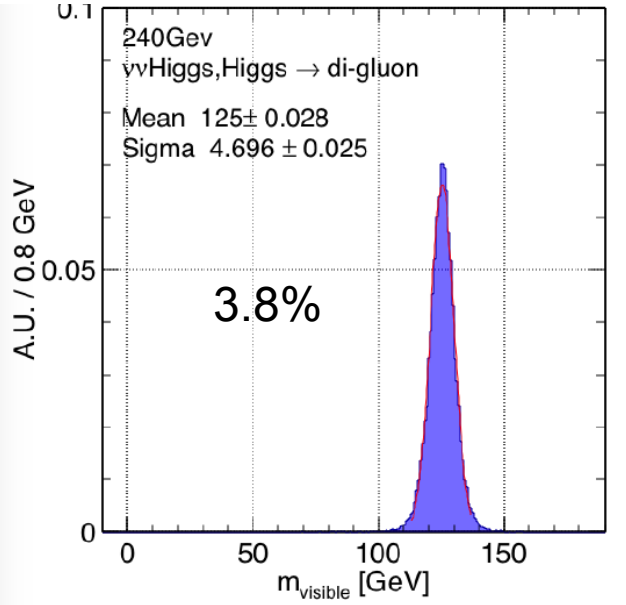




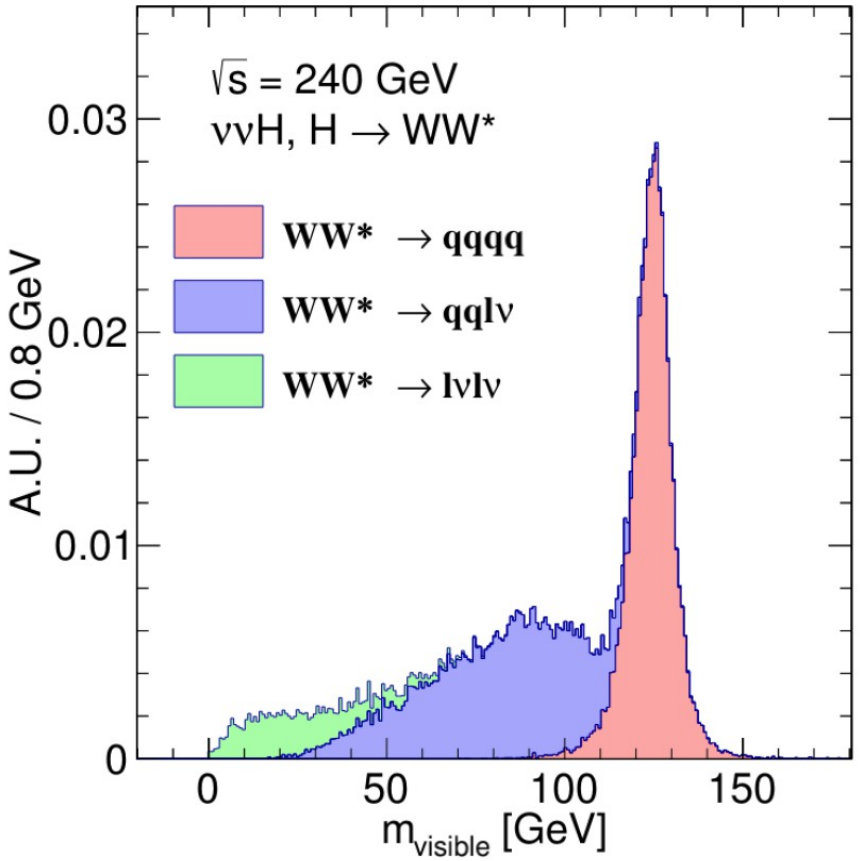








Higgs to WW, ZZ (Jets + leptons + neutrinos)



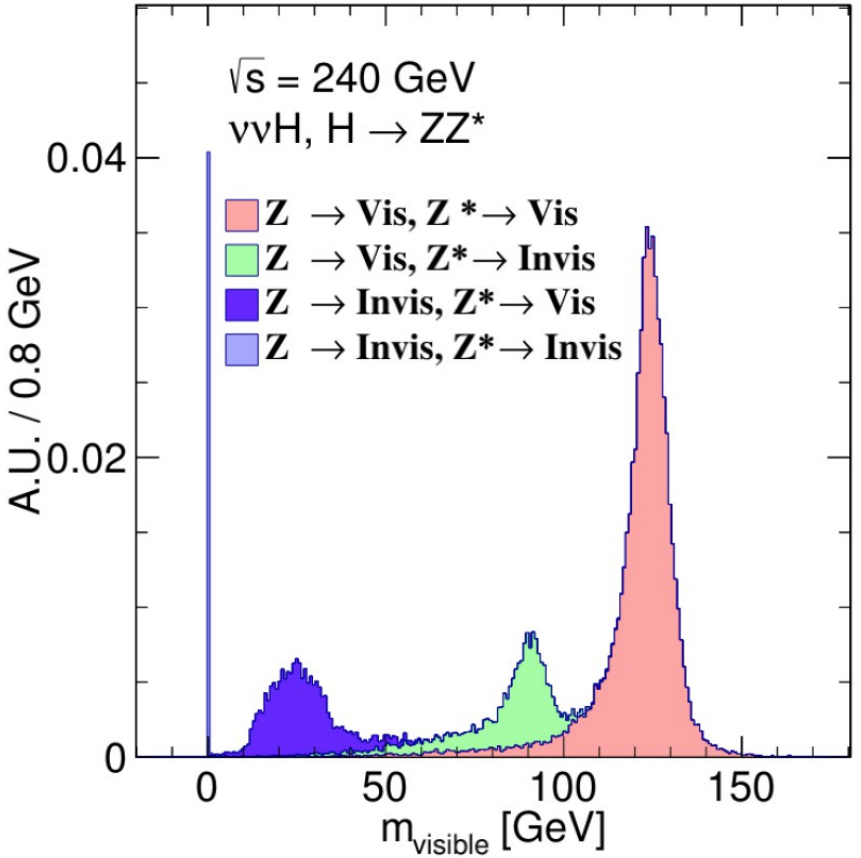
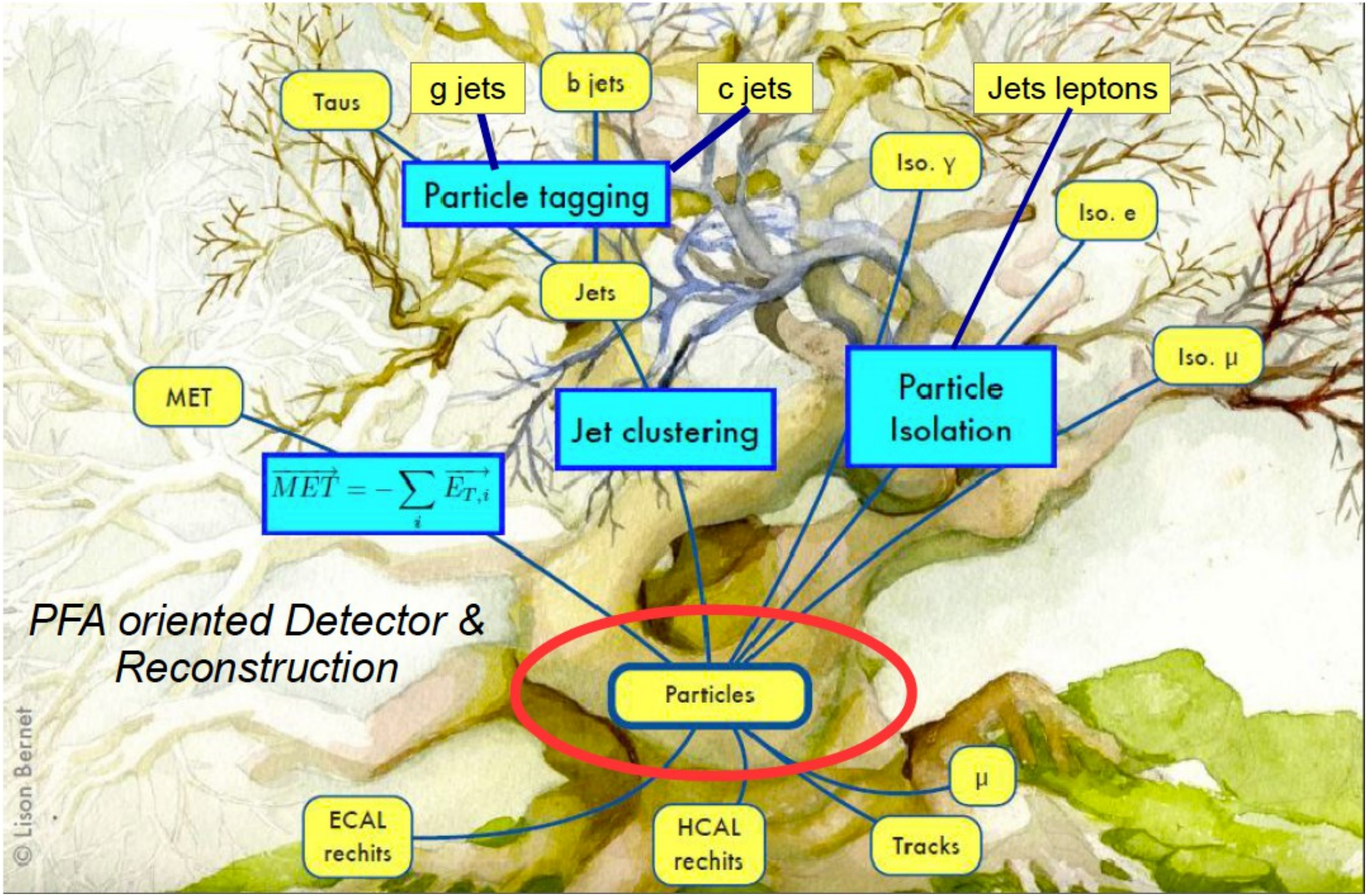


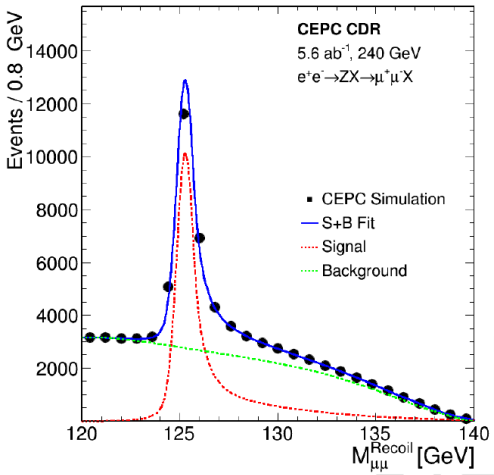
Table 2. Benchmark resolutions ($\sigma/Mean$) of reconstructed Higgs boson mass, comparing to LHC results.

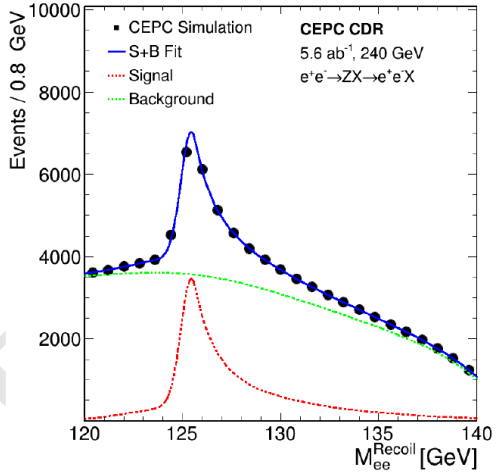
	Higgs→ $\mu\mu$	Higgs→ $\gamma\gamma$.	Higgs→bb
CEPC (APODIS)	0.20%	2.59%[1]	3.63%
LHC (CMS, ATLAS)	∼2% [19, 20]	∼1.5% [21, 22]	∼10% [23, 24]

[1] primary result without geometry based correction and fine-tuned calibration. https://arxiv.org/abs/1806.04992

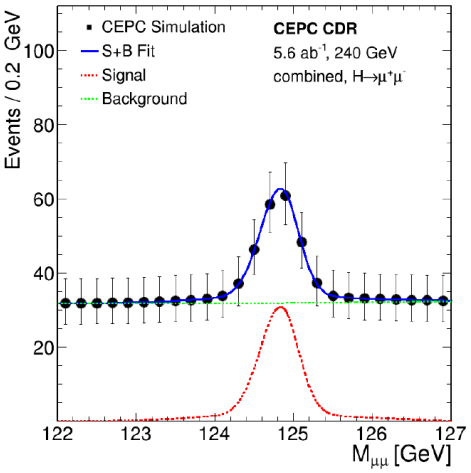

Taus
g jets
b jets
c jets
Jets leptons
Particle tagging
Iso. γ
Iso. e
Jets
Iso. μ
MET
Jet clustering
Particle Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
PFA oriented Detector & Reconstruction
Particles
μ
ECAL rechits
HCAL rechits
Tracks
© Lison Bernet

Higgs benchmark analyses

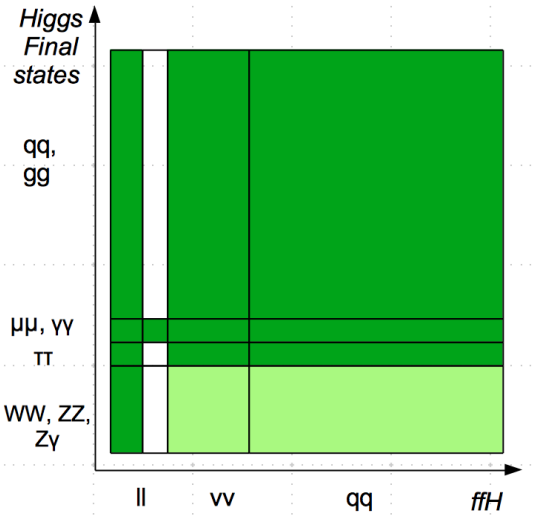


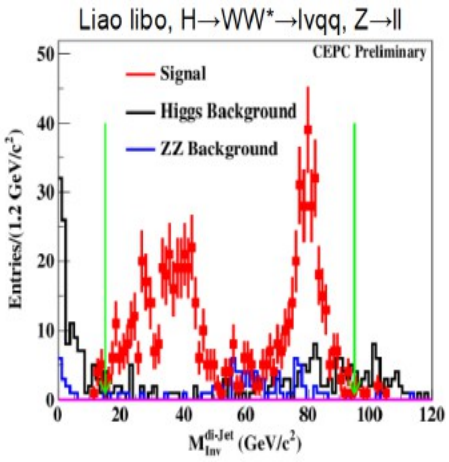


σ(ℤH) measurements

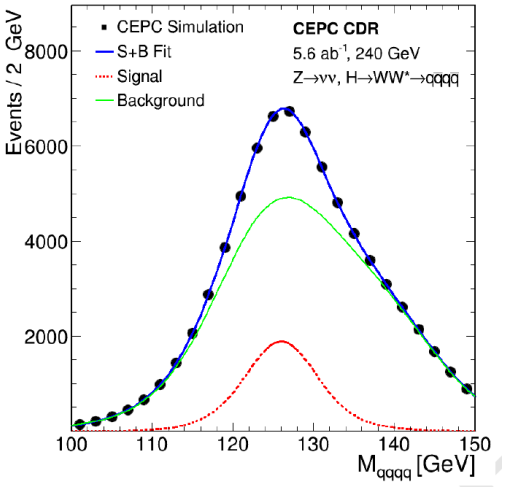


Br(H→μμ)

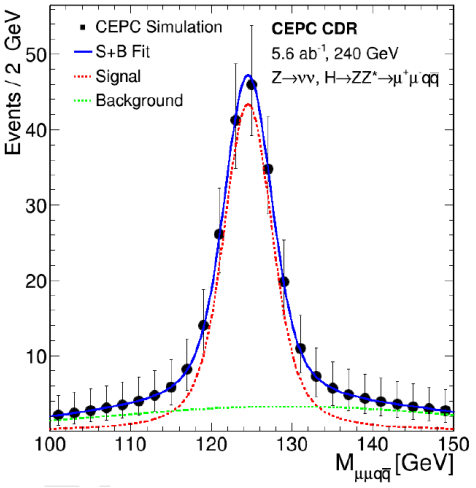




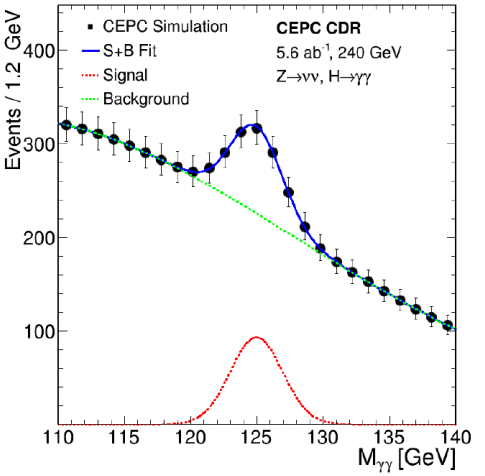
Br(H→WW)



σ(νvH)*Br(H→bb)



Br(H→ττ)



Br(H→γγ) (Asimov)