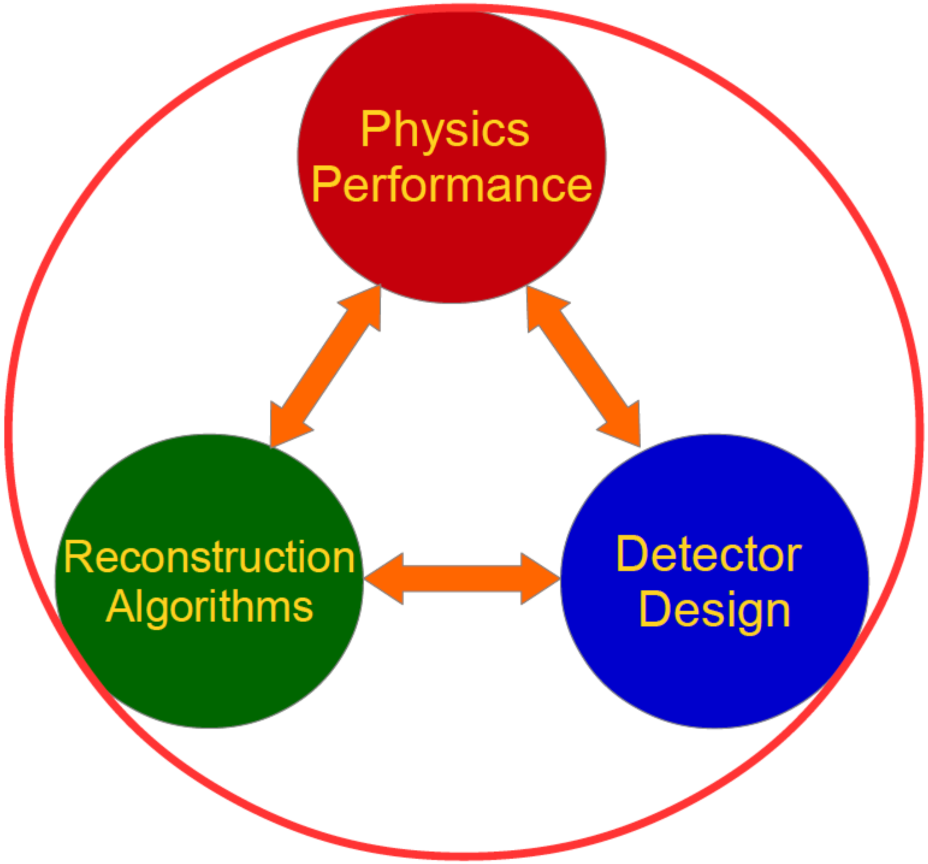
The CEPC Simulation and tools: Software & Performance

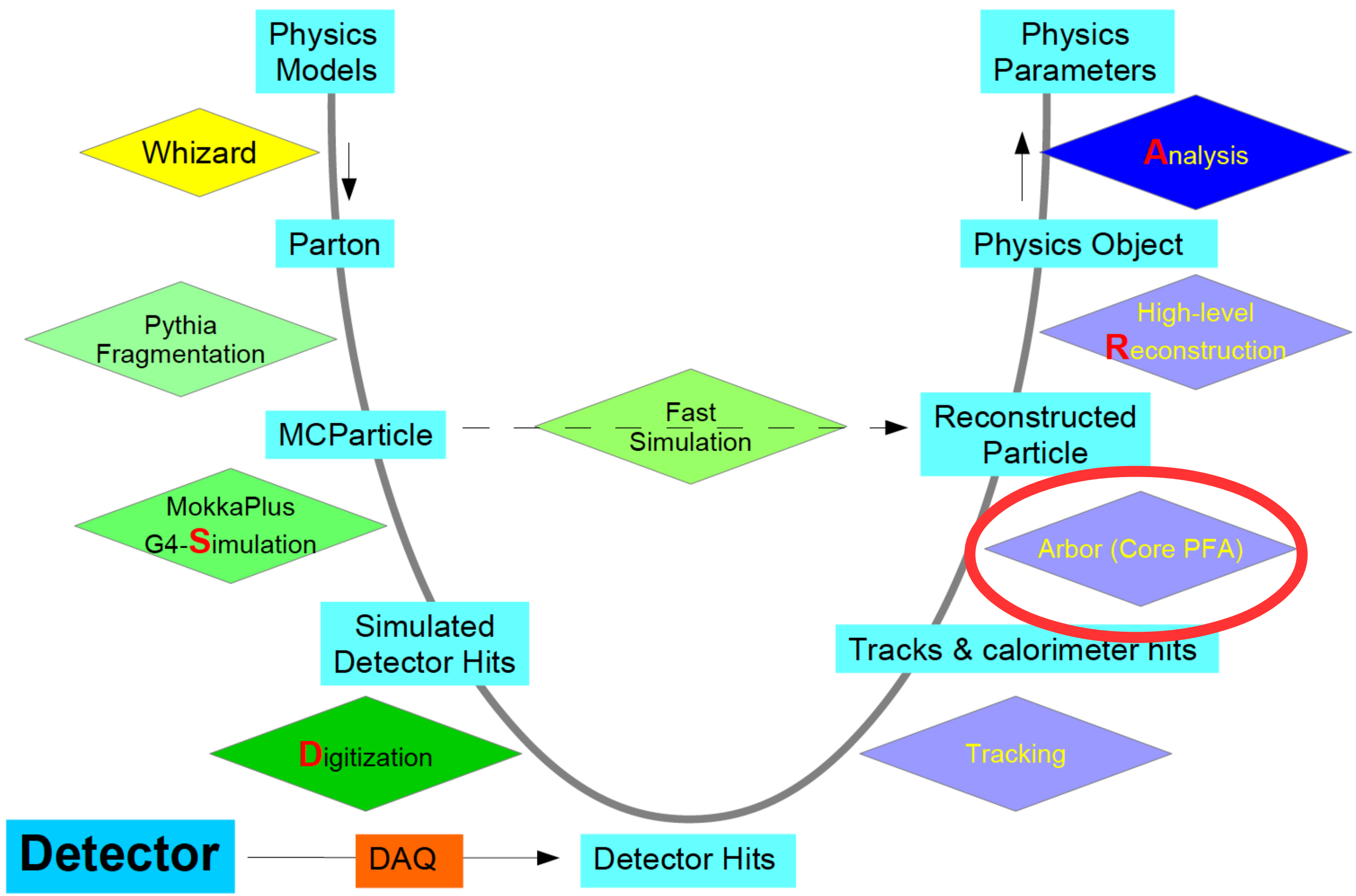
Manqi Ruan

Performance

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



CEPC Baseline Software

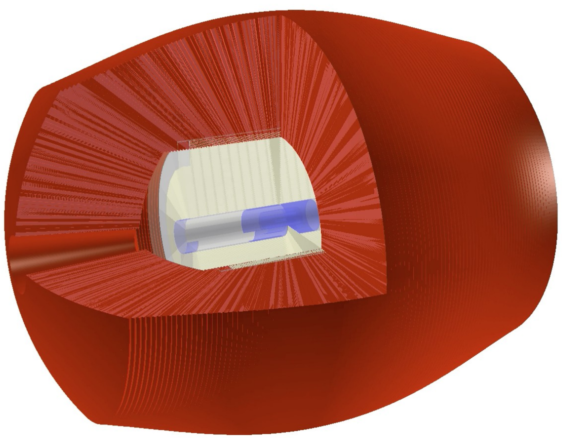


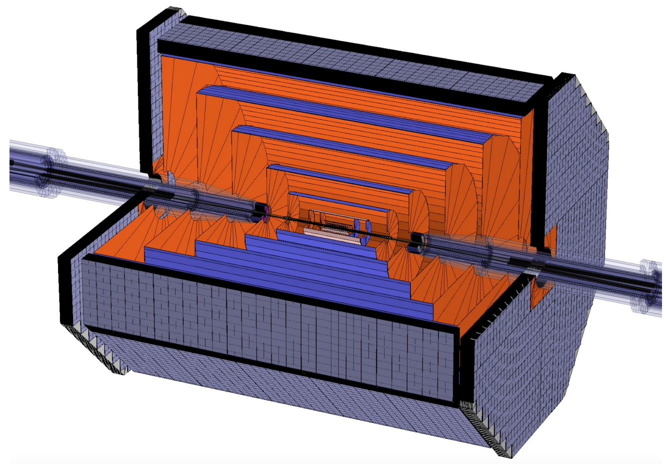
- Generators (Whizard & Pythia)
- Data format & management (LCIO & Marlin)
- Simulation (MokkaC)
- Digitizations
- Tracking
- PFA (Arbor)
- Single Particle Physics Objects Finder (LICH)
- Composed object finder (Coral)
- Tau finder
- Jet Clustering (FastJet)
- Jet Flavor Tagging (LCFIPLus)
- Event Display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

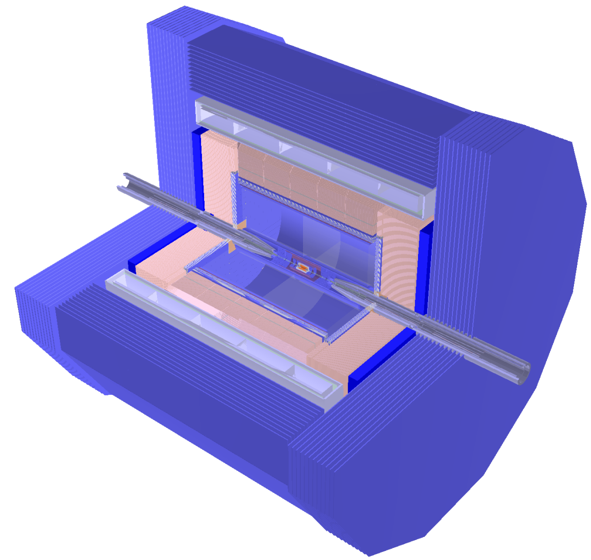
CEPC-SIMU-2017-001,
CEPC-SIMU-2017-002,
(DocDB id-167, 168, 173)

General Software | ILCSoft | ILCSoft + Development | Developments

Status of simulation-performance study

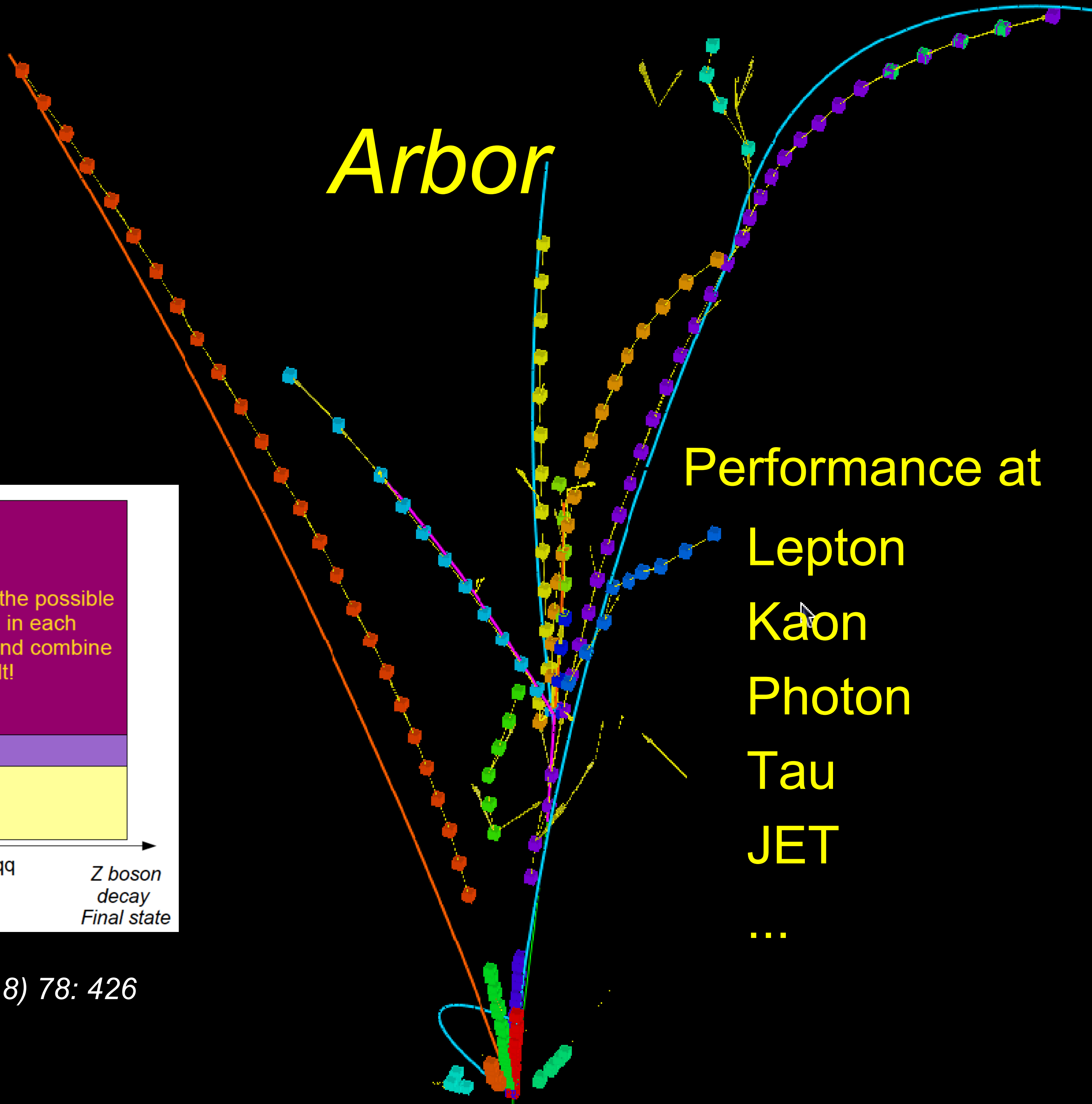


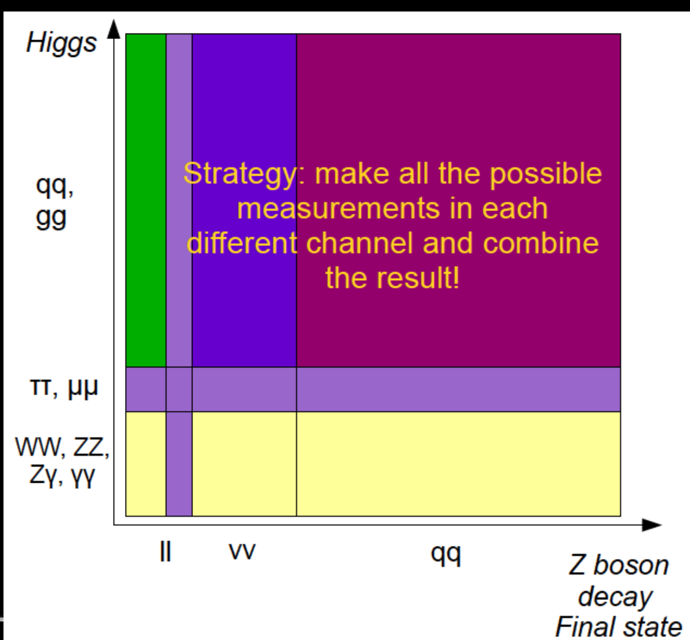




	Geant4-Simulation	Digitization	Reconstruction	Performance-Object	Performance-Benchmark
IDEA					
Full-Silicon					
APODIS					

Arbor



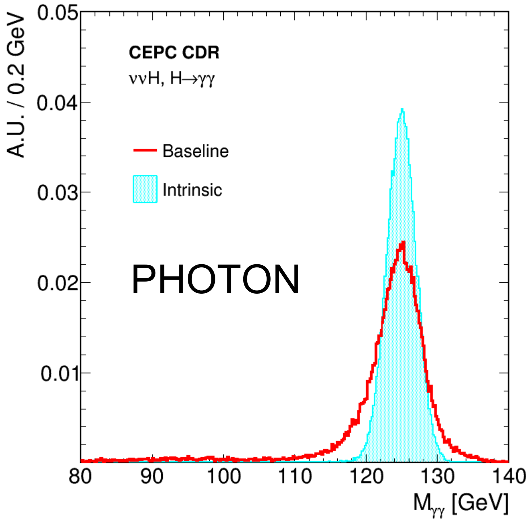


Eur. Phys. J. C (2018) 78: 426

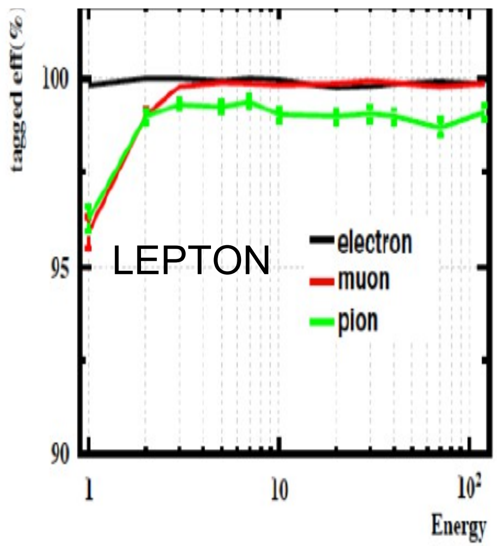
Performance at

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

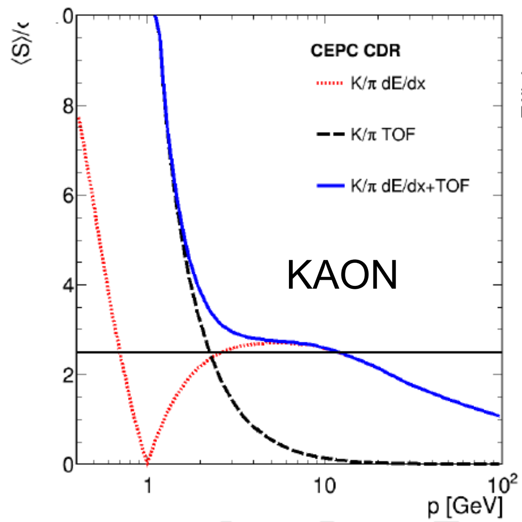
Physics Objects

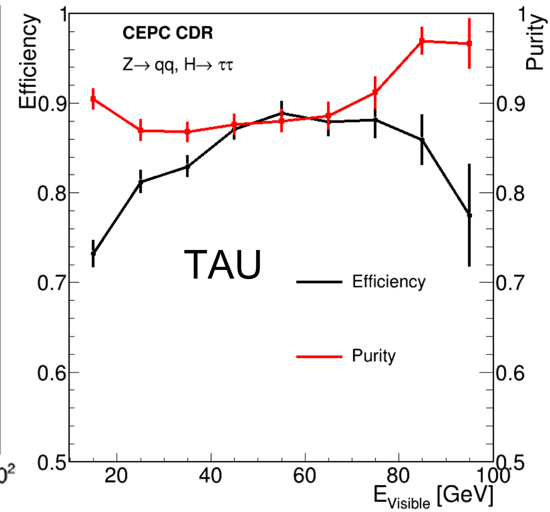


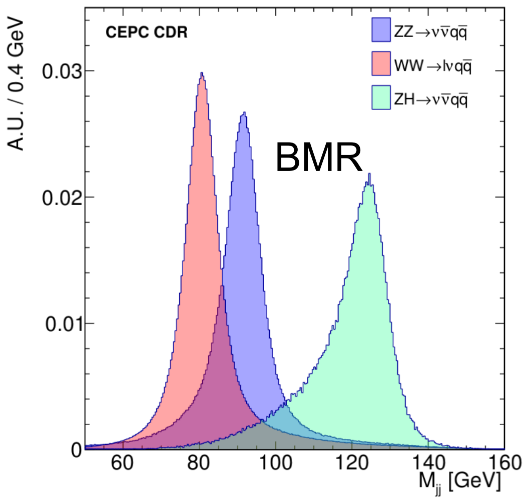
Eur. Phys. J. C (2017) 77: 591

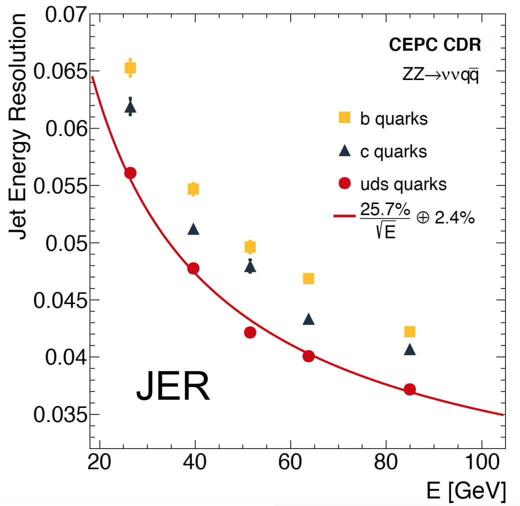


Eur. Phys. J. C (2018) 78:464









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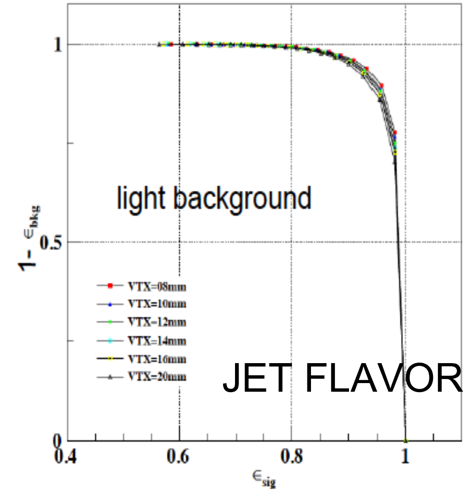
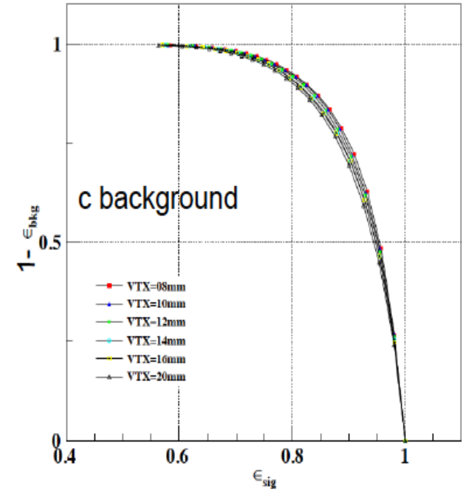
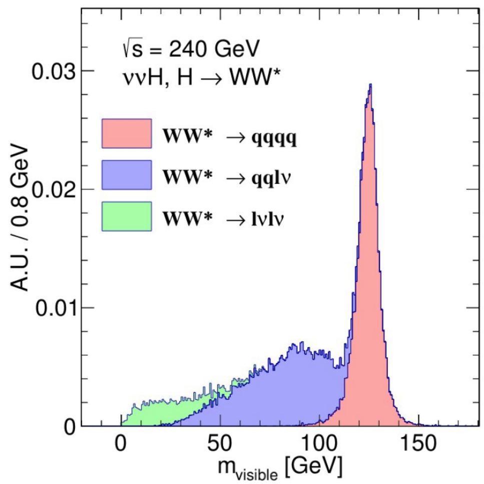
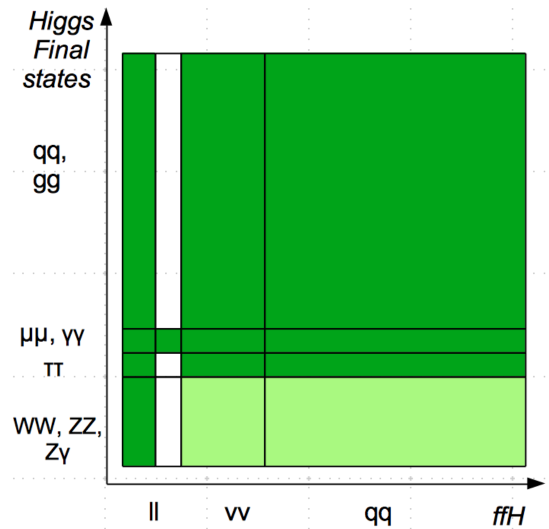
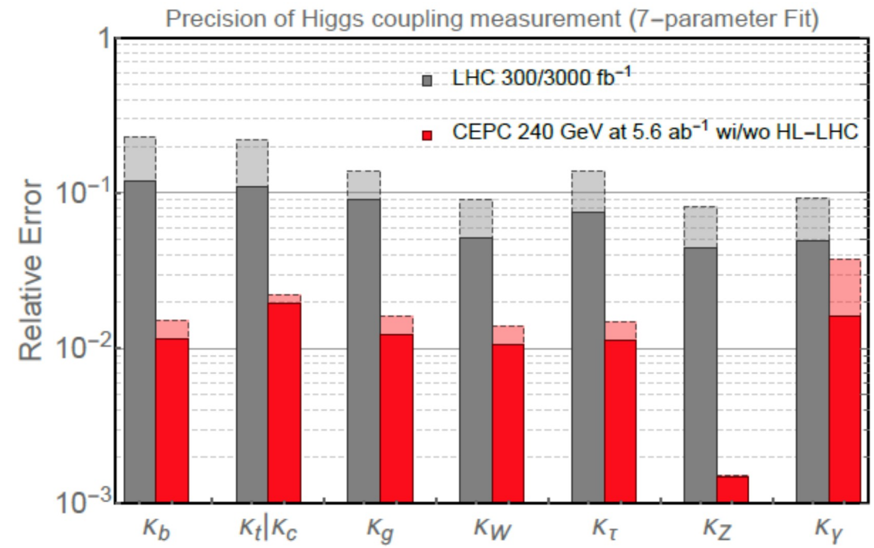


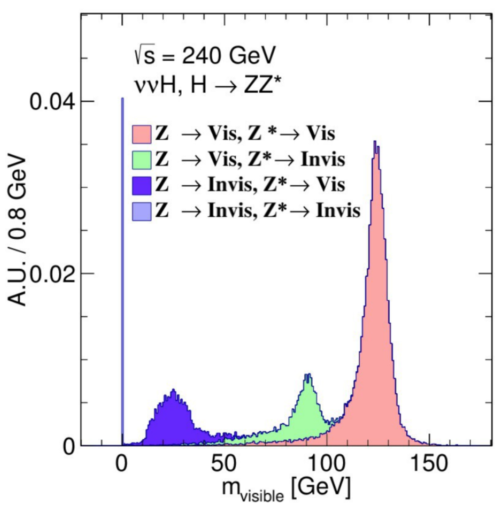


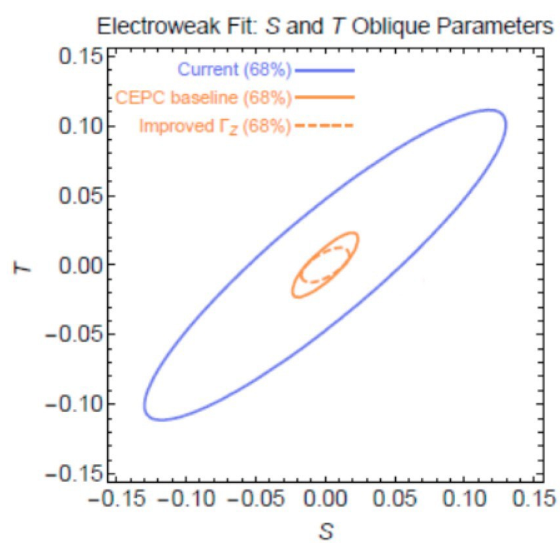
Applied on Higgs physics, et.al





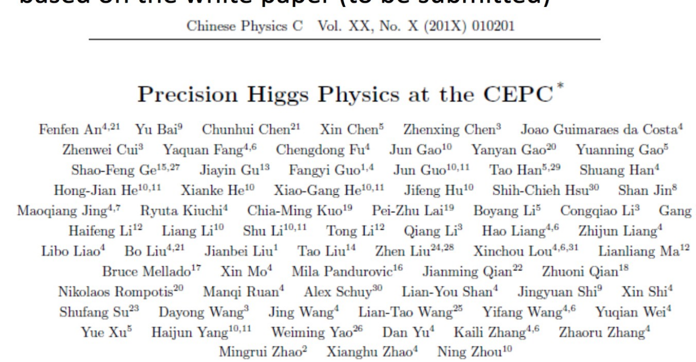






Precision Higgs Physics at CEPC

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

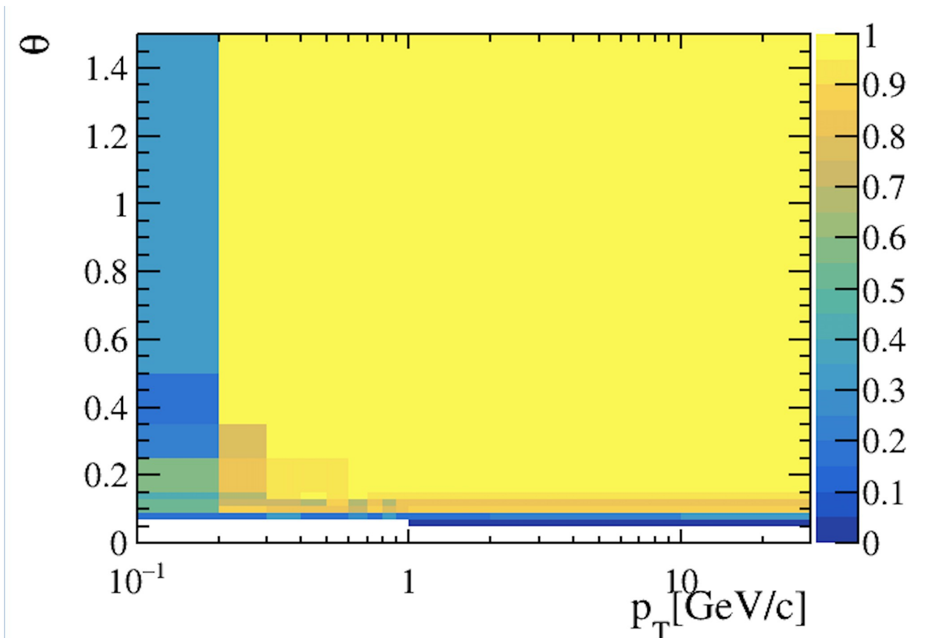

Chinese Physics C Vol. XX, No. X (201X) 010201

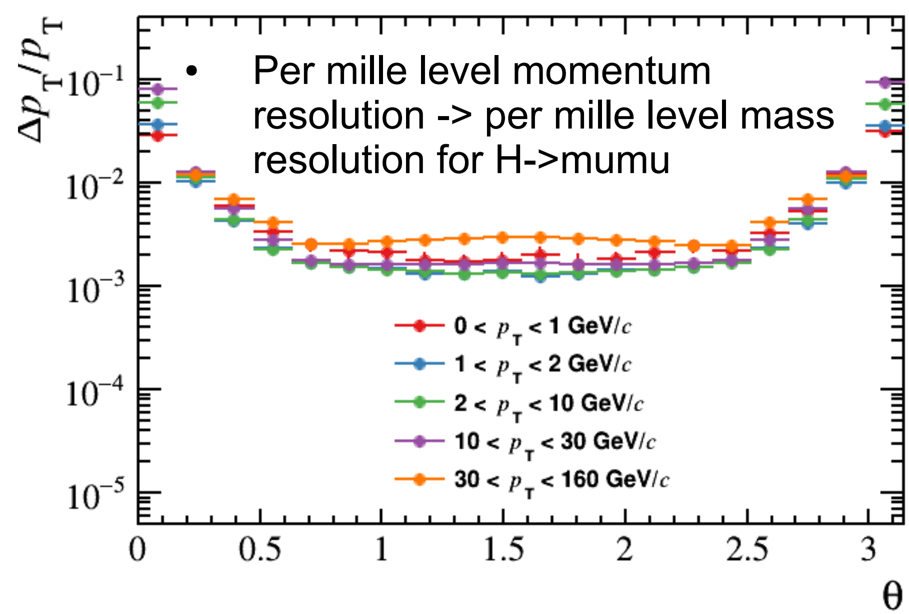
Precision Higgs Physics at the CEPC*

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]

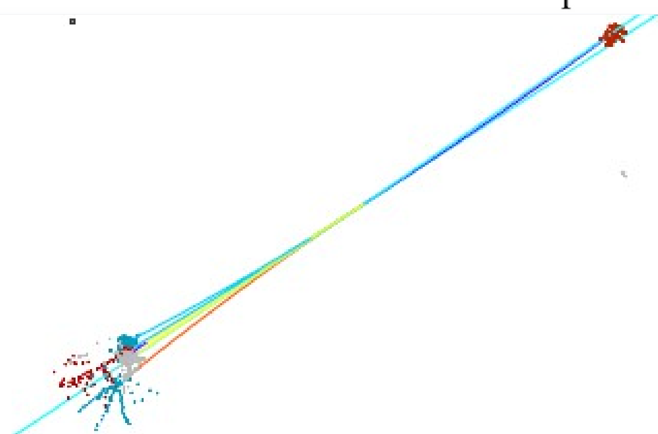
https://arxiv.org/pdf/1810.09037.pdf

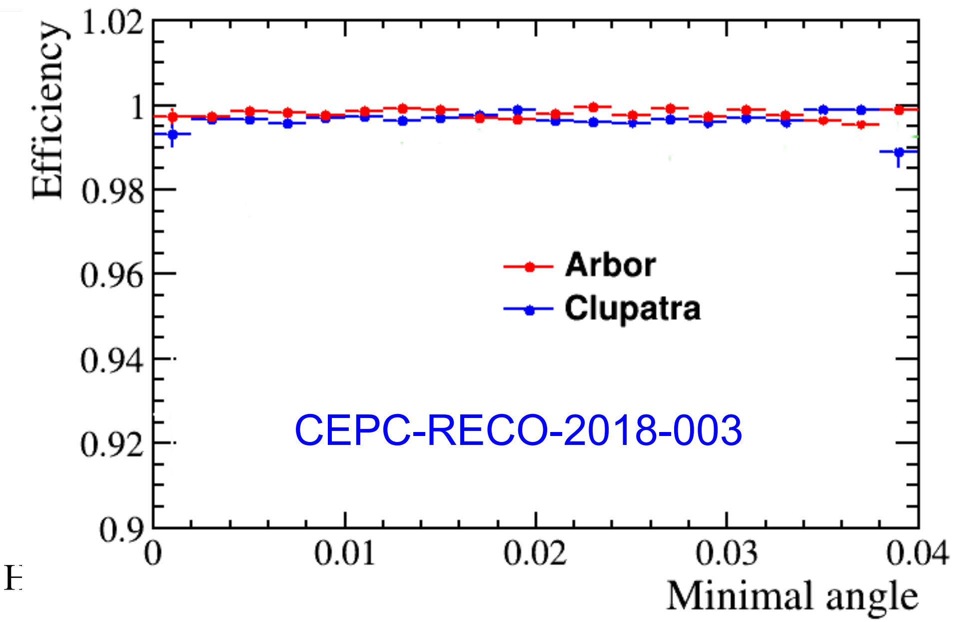
Tracking





- Per mille level momentum resolution -> per mille level mass resolution for H->mumu

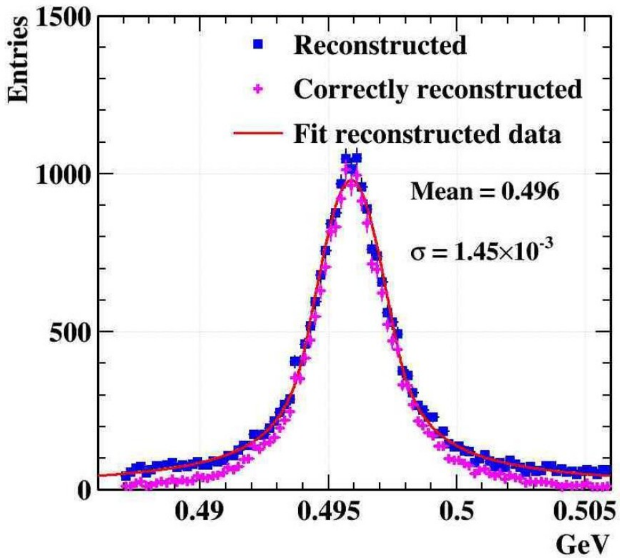


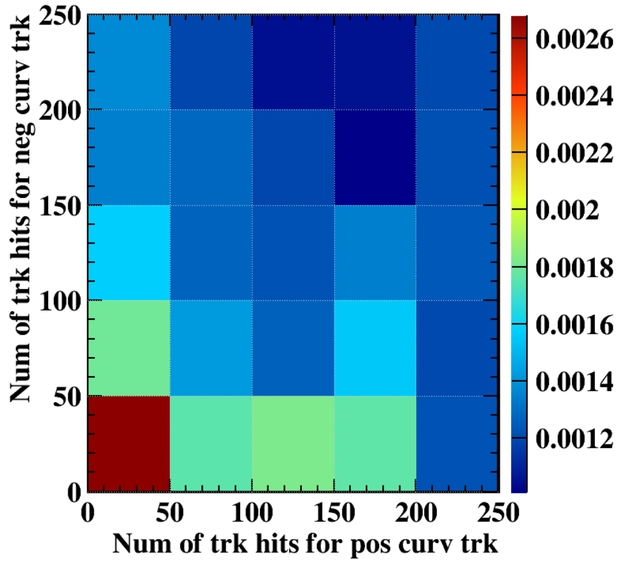


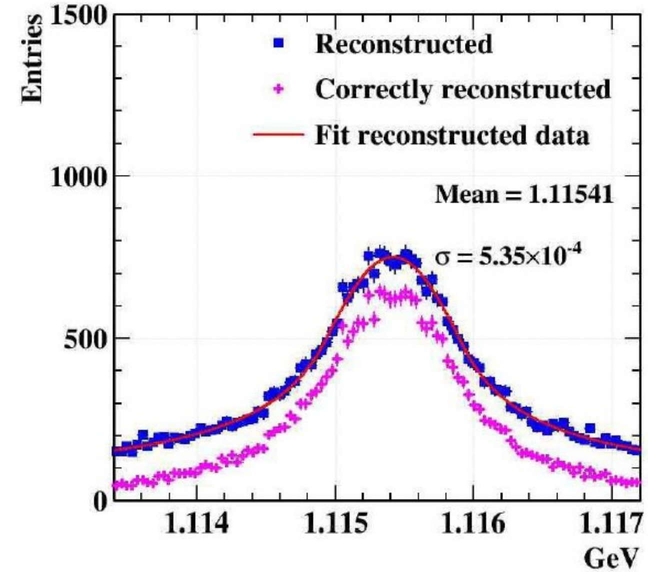
CEPC-RECO-2018-003

Mingrui Zhao. CEPC CDR

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





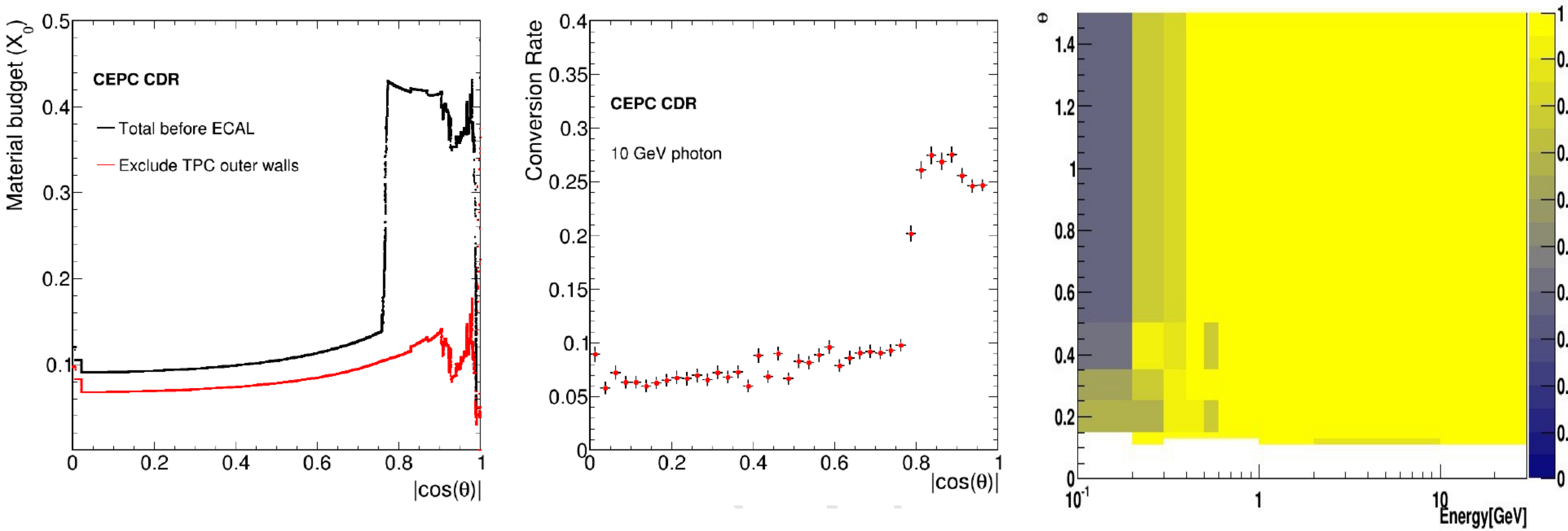


wi/wo perfect PID	Efficiency	Purity	Resolution
K_short	79%/78%	91%/86%	0.28%/0.29%
Lambda	82%/68%	94%/64%	0.043%/0.046%

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

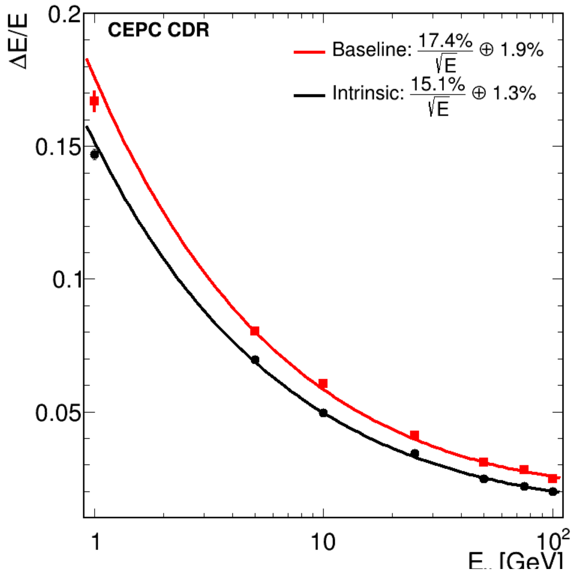
Photons – conversion & efficiency

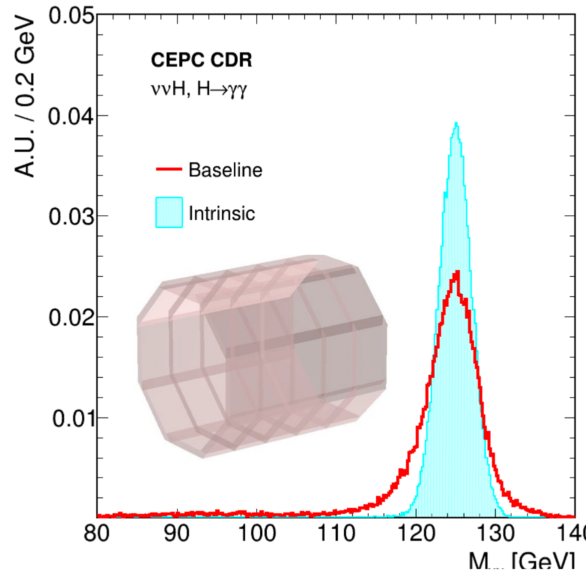


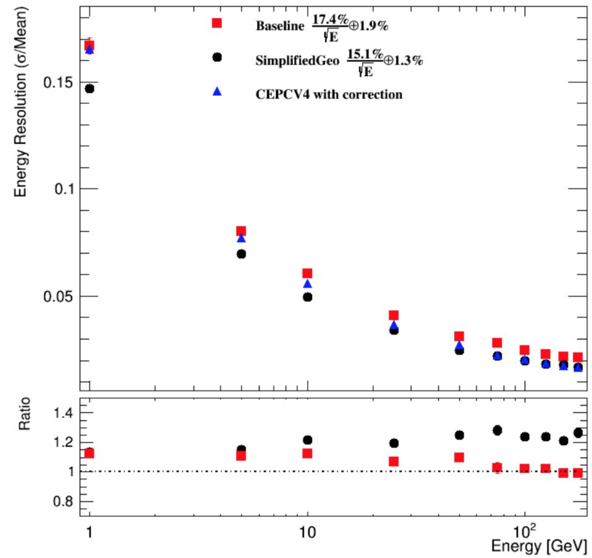
In the barrel region: Roughly 6-10% of the photons converts before reaching the Calorimeter.

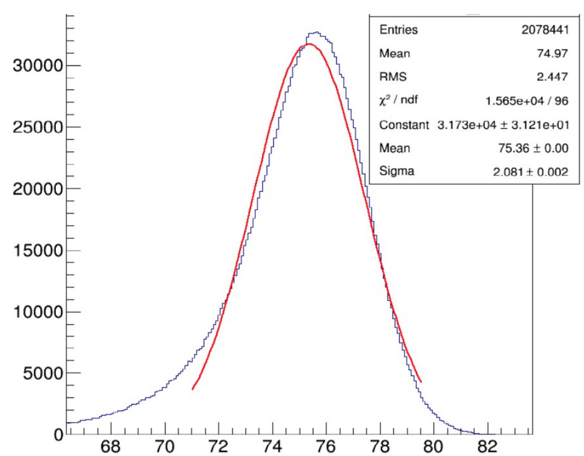
For the unconverted photon: A critical energy of 200 MeV is observed.

Photon: resolution

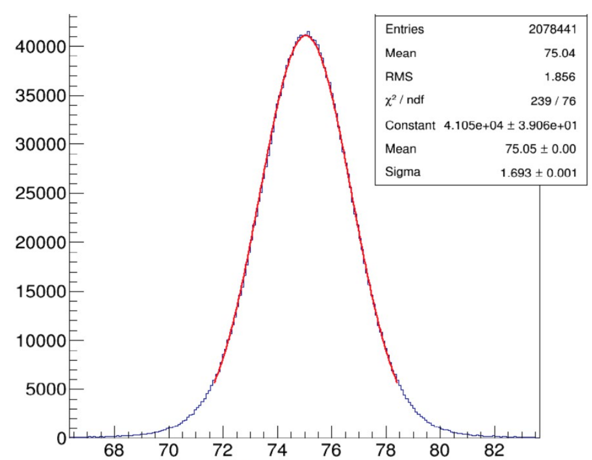








Before correction

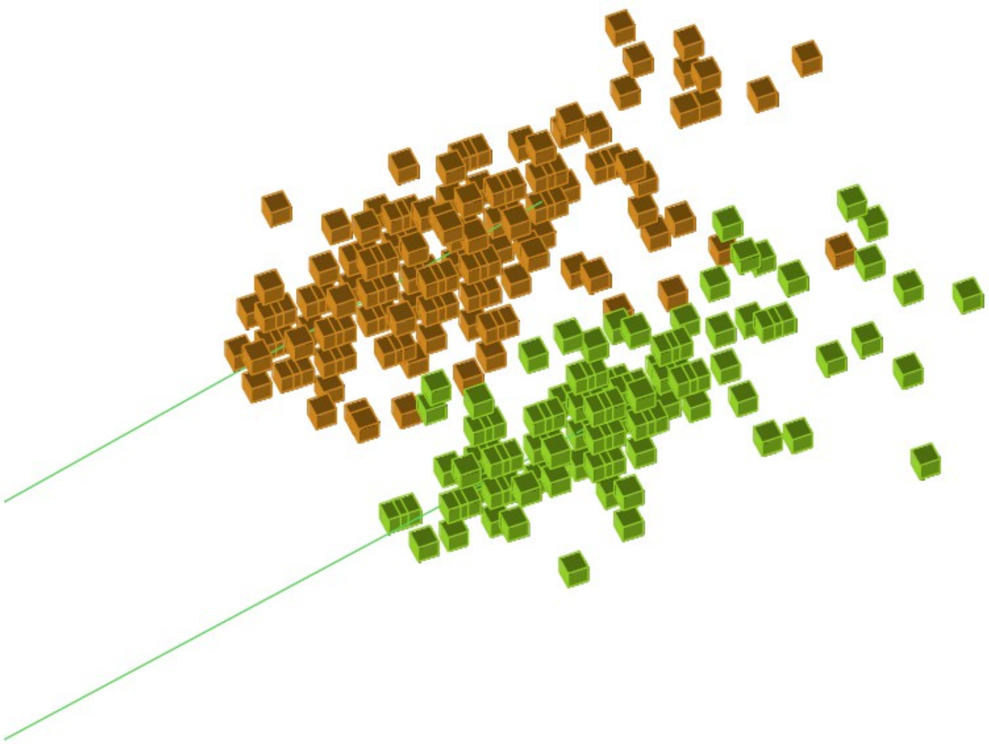


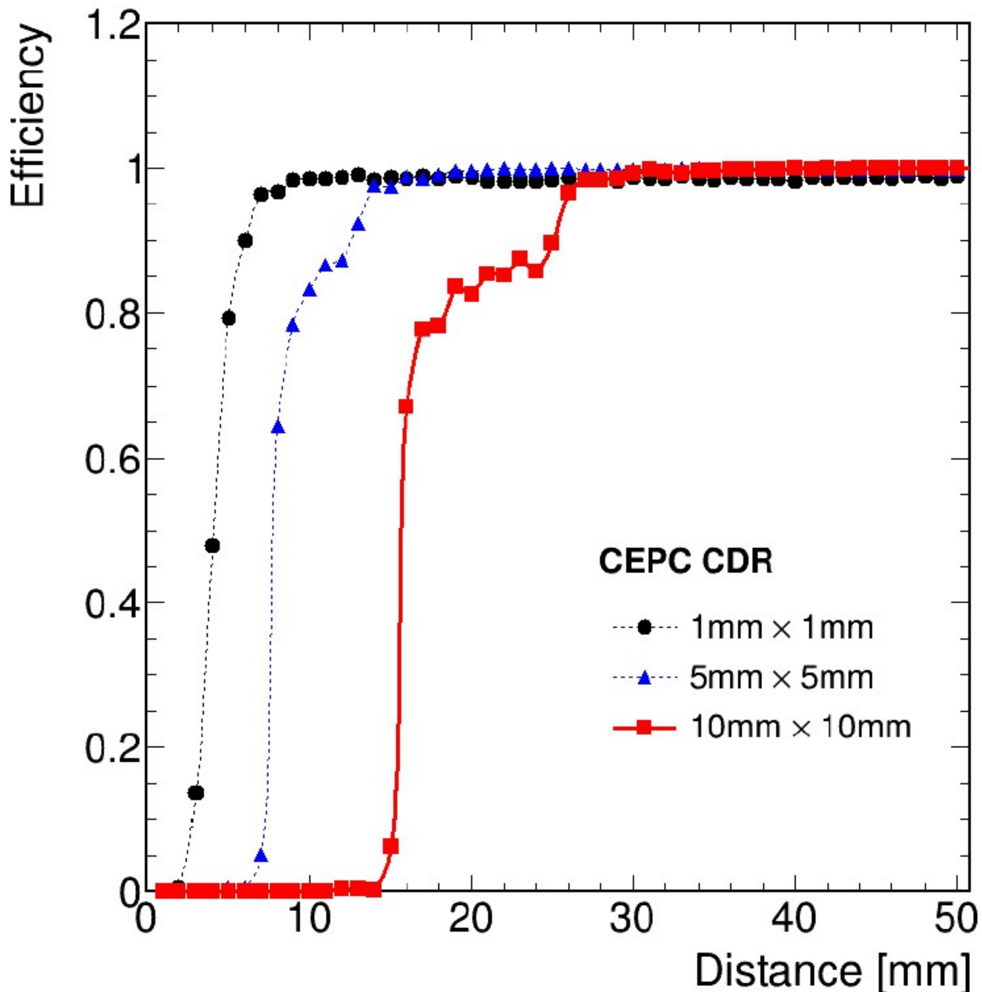
After correction

- 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

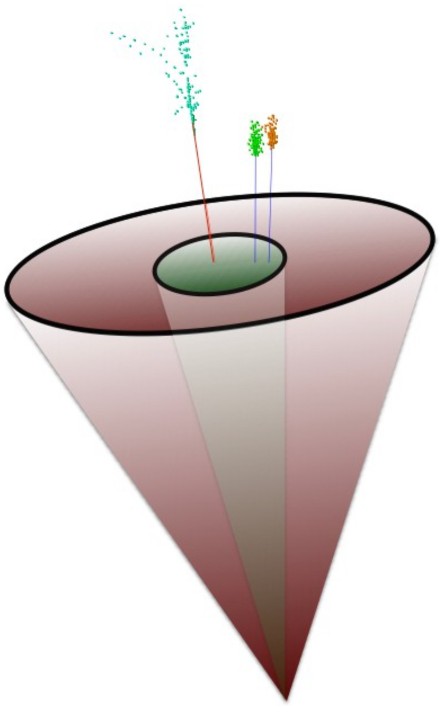


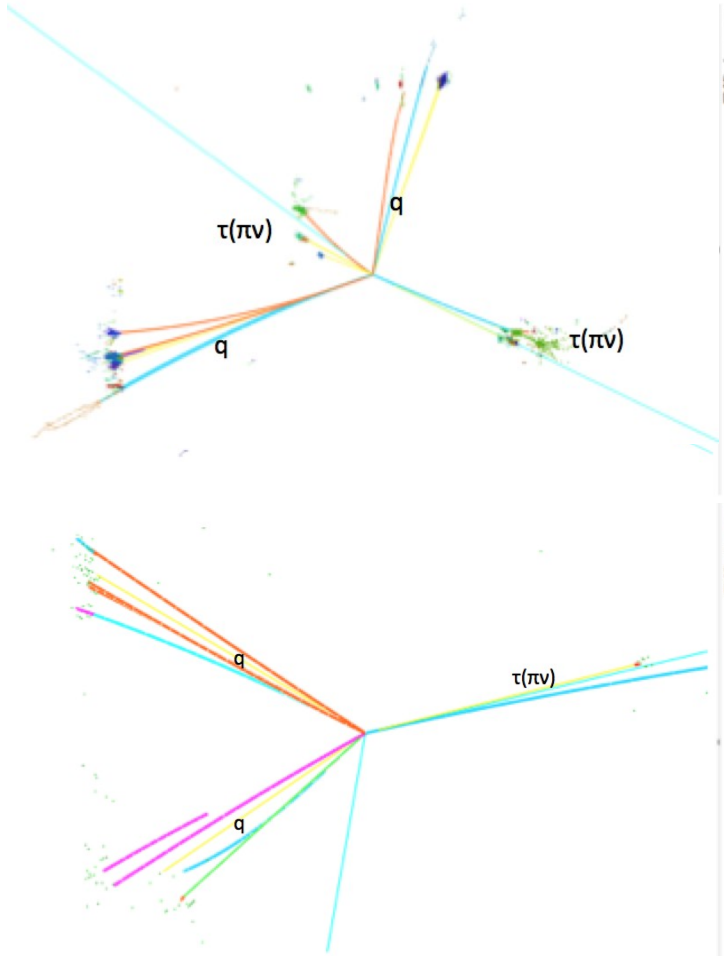


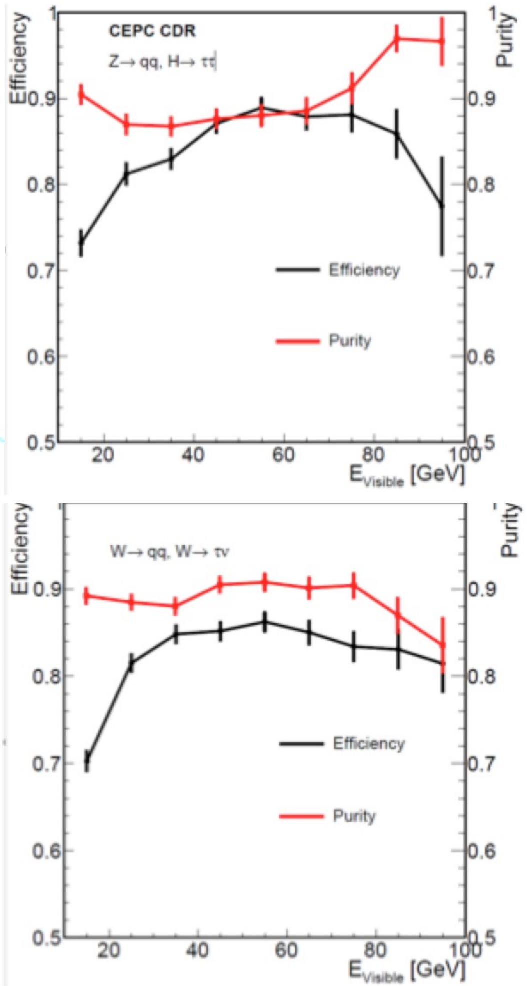
Critical energy to separate an evenly decay π_0: 30 GeV

Hang Zhao. CEPC CDR

Tau finding at hadronic events







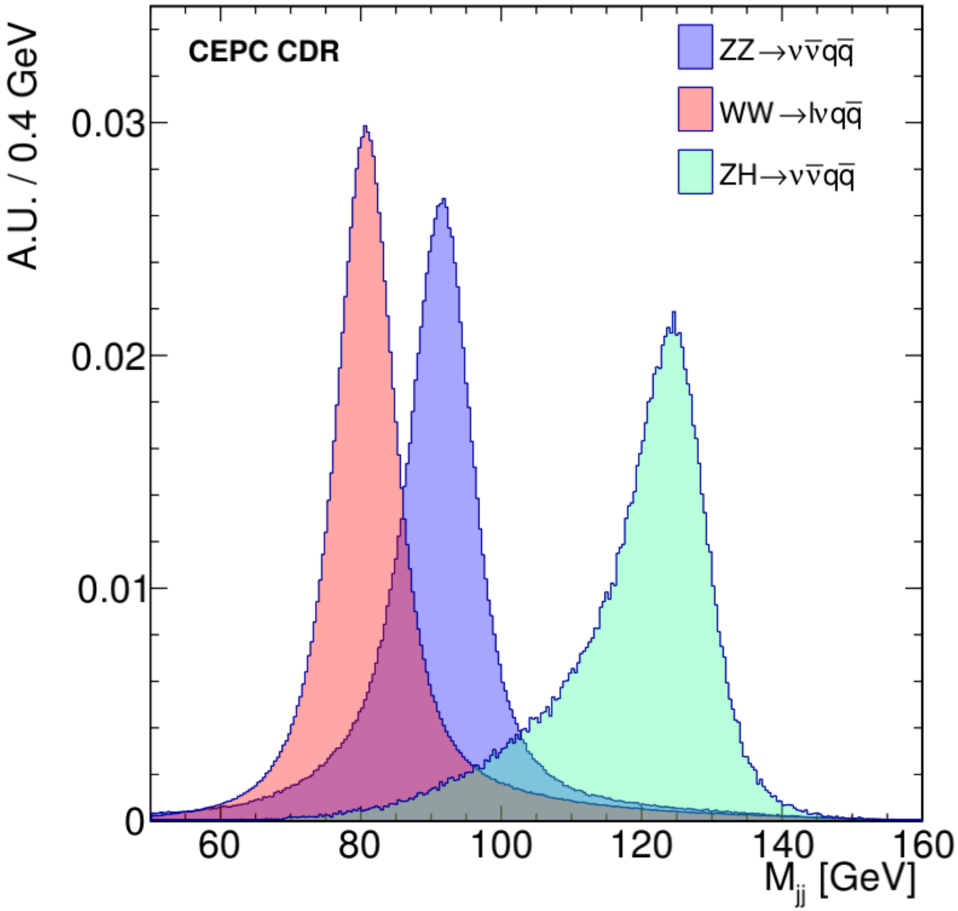
TAURUS (Tau ReconstrUction toolS):
an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

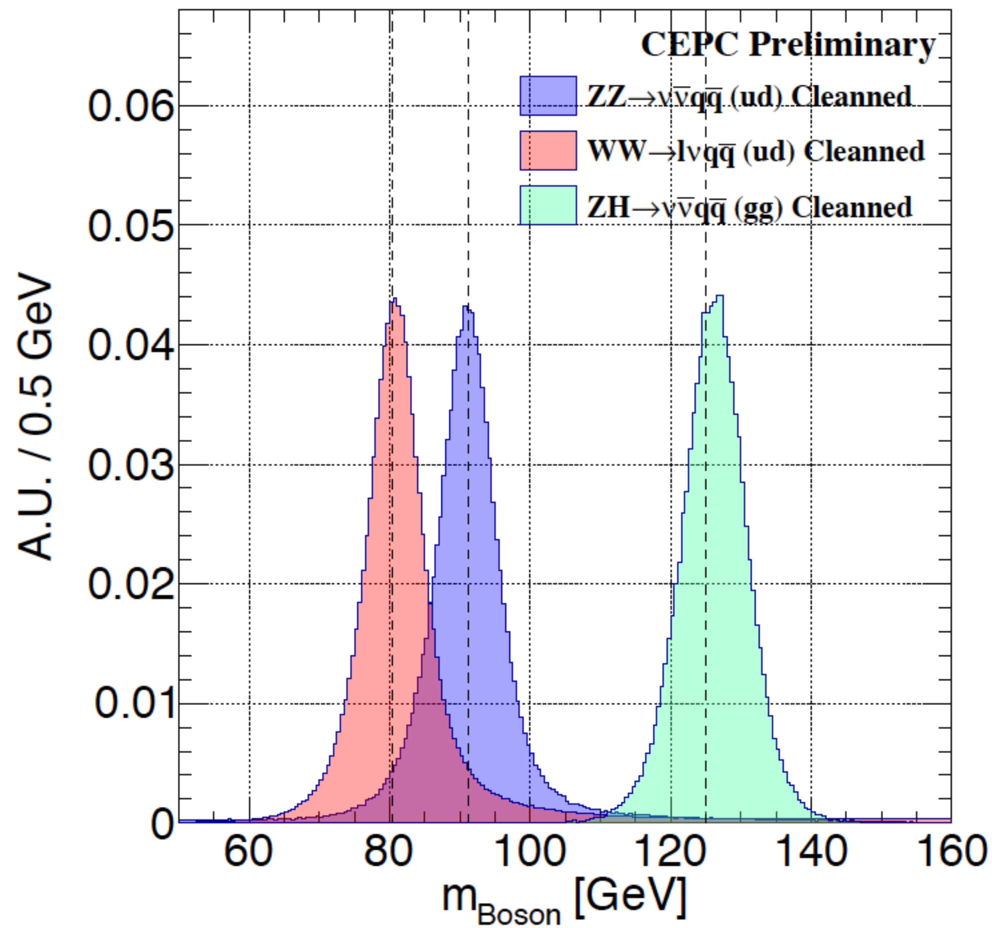
Zhigang Wu, CEPC CDR

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





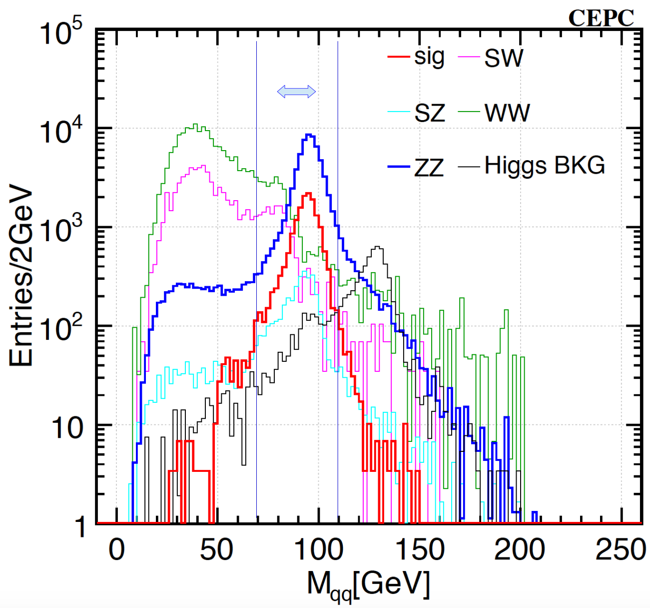
Peizhu Lai & CEPC CDR

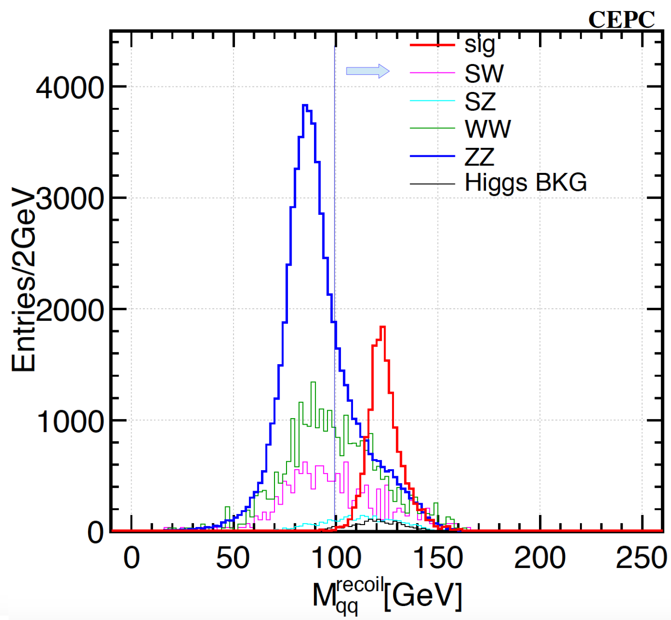
WW sample: using μνqq sample,
Plot: the visible mass without the muon

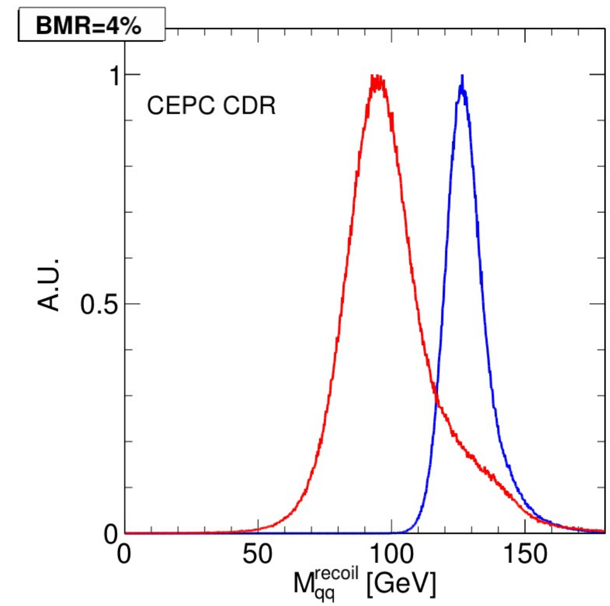
CEPC-RECO-2017-002 (DocDB id-164),
CEPC-RECO-2018-002 (DocDB id-171),

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

An Analysis Example: *g(Hττ)* at qqH



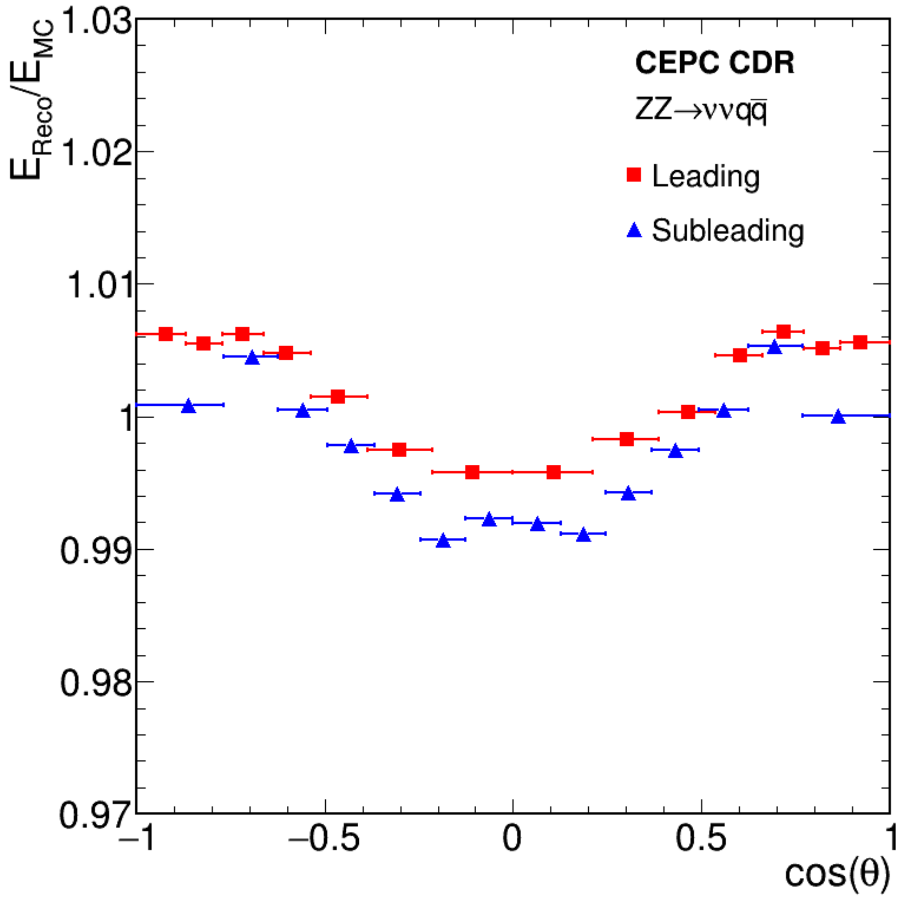


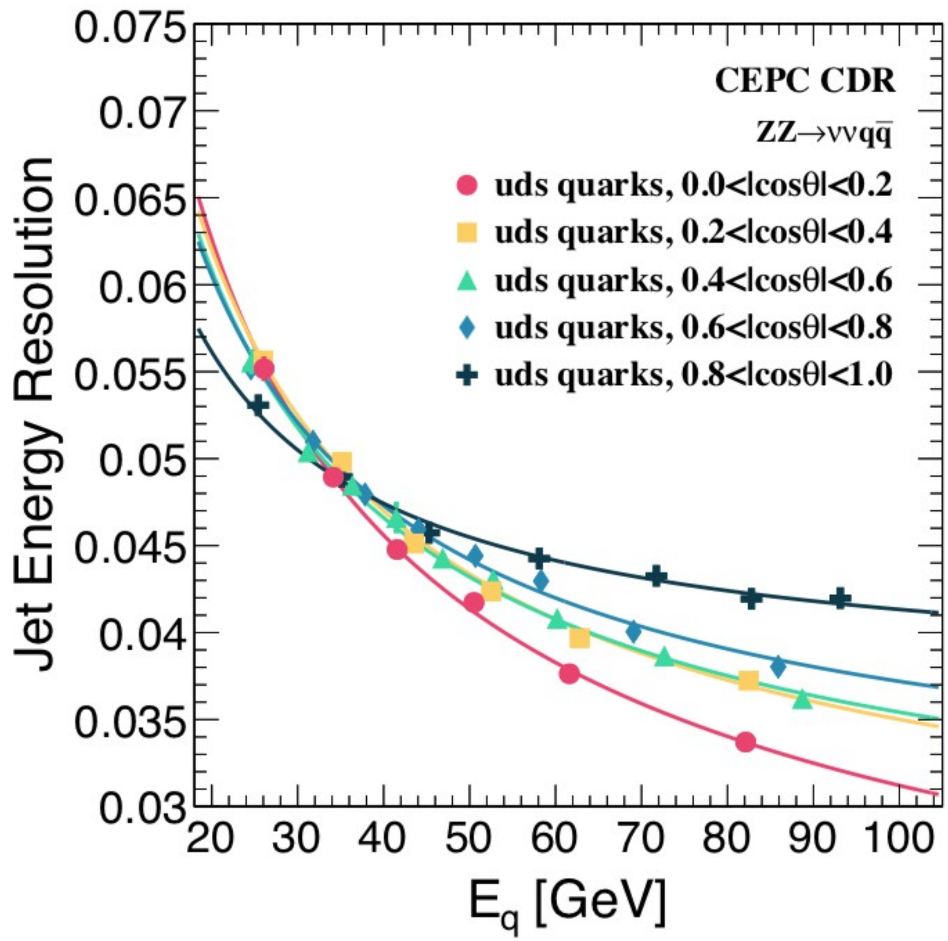


- TAURUS: di-tau system
- The rest particles are identified as the di-jet: to distinguish the ZZ/ZH background & Improves the accuracy by more than a factor of 2: **BMR < 4% (baseline of 3.8%) is crucial**
- Isolated tracks are intensionally defined as tau candidate: be distinguished by the VTX

Dan Yu's thesis

Jet Energy Scale & Resolution

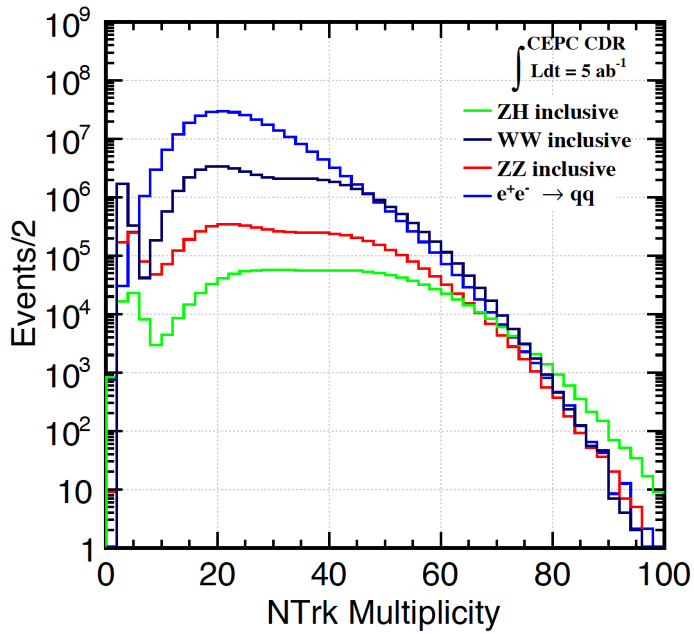


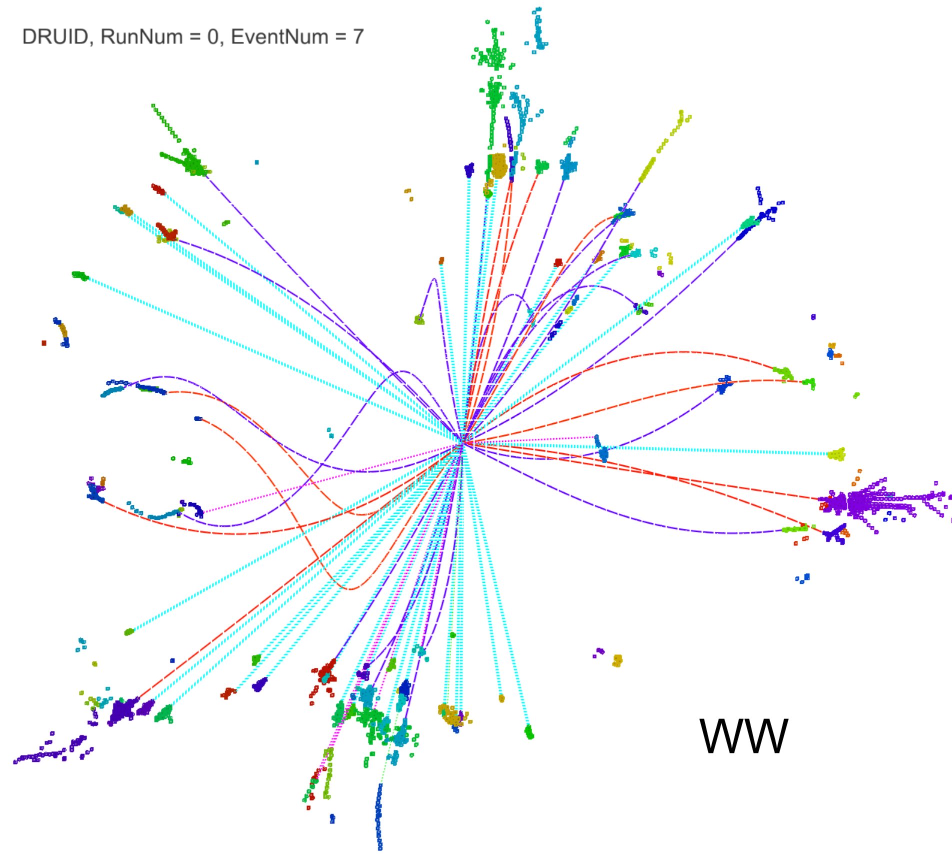


- JES ~ with 1% of the unity (without correction)
- JER ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
- **Both Superior to LHC experiments by 3-4 times**

Peizhu LAI

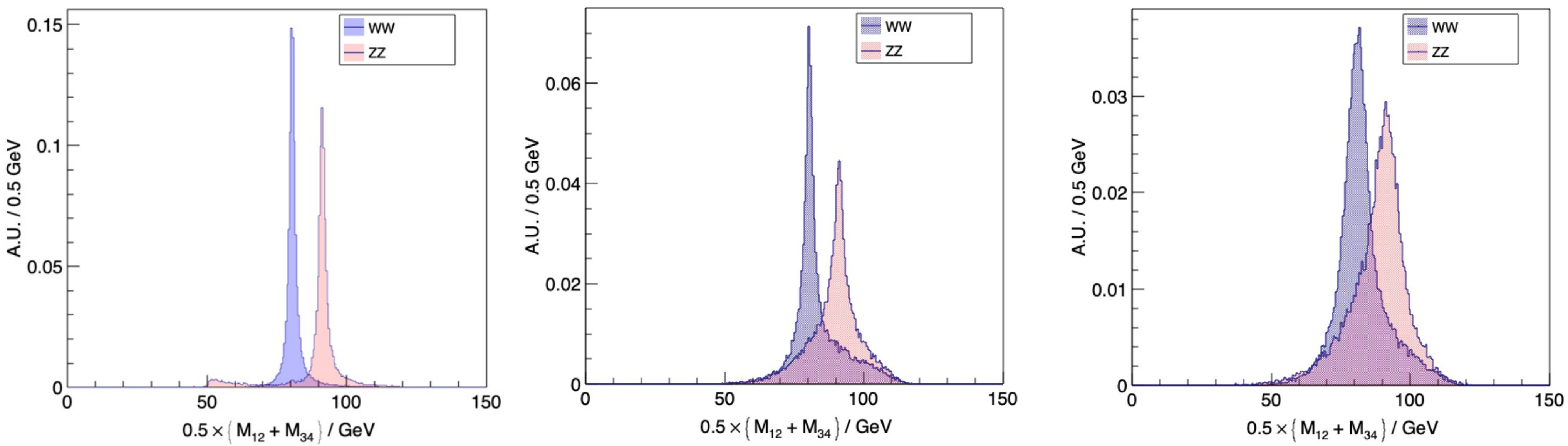
Separation of full hadronic WW-ZZ event





- 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

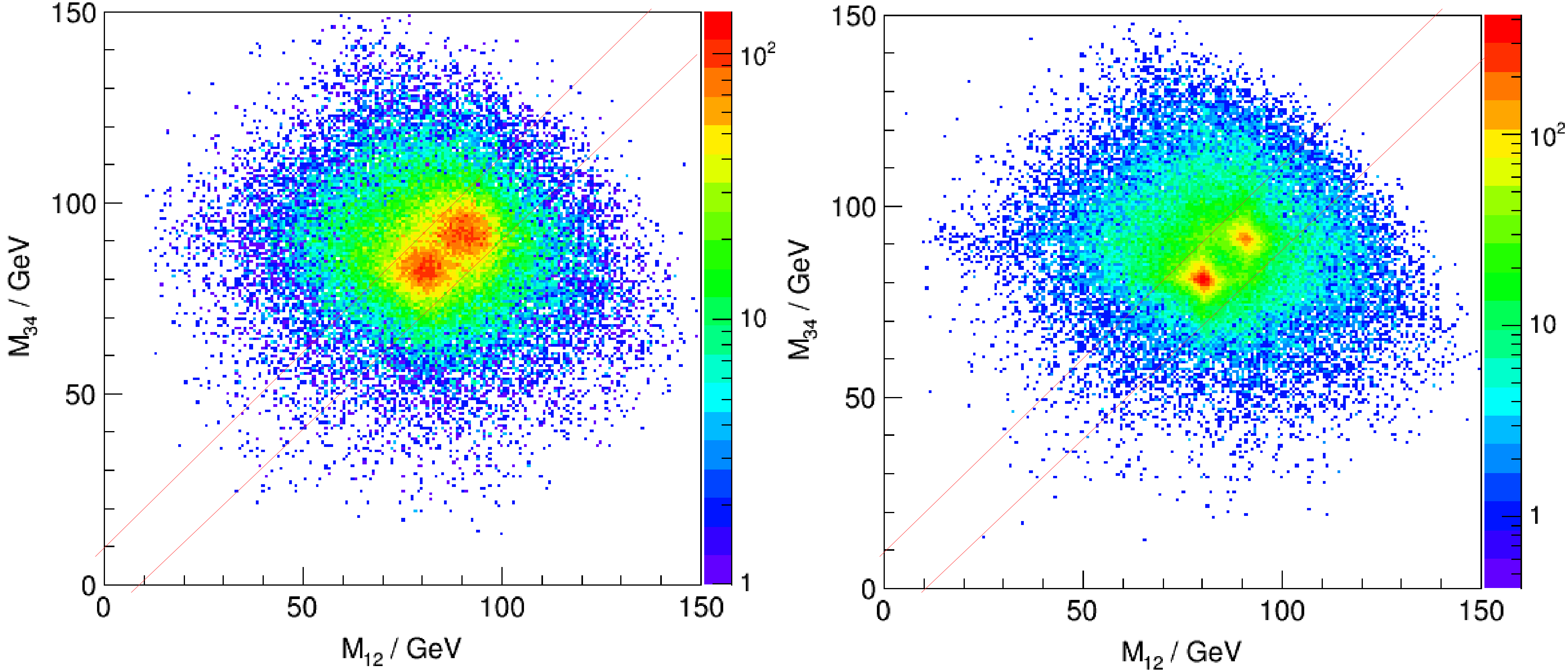
$$overlapping\ ratio = \sum_{bins} min(a_i, b_i)$$

- Final state/MC particles are clustered into Reco/Genjet with ee-kt, and paired according to chi2

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

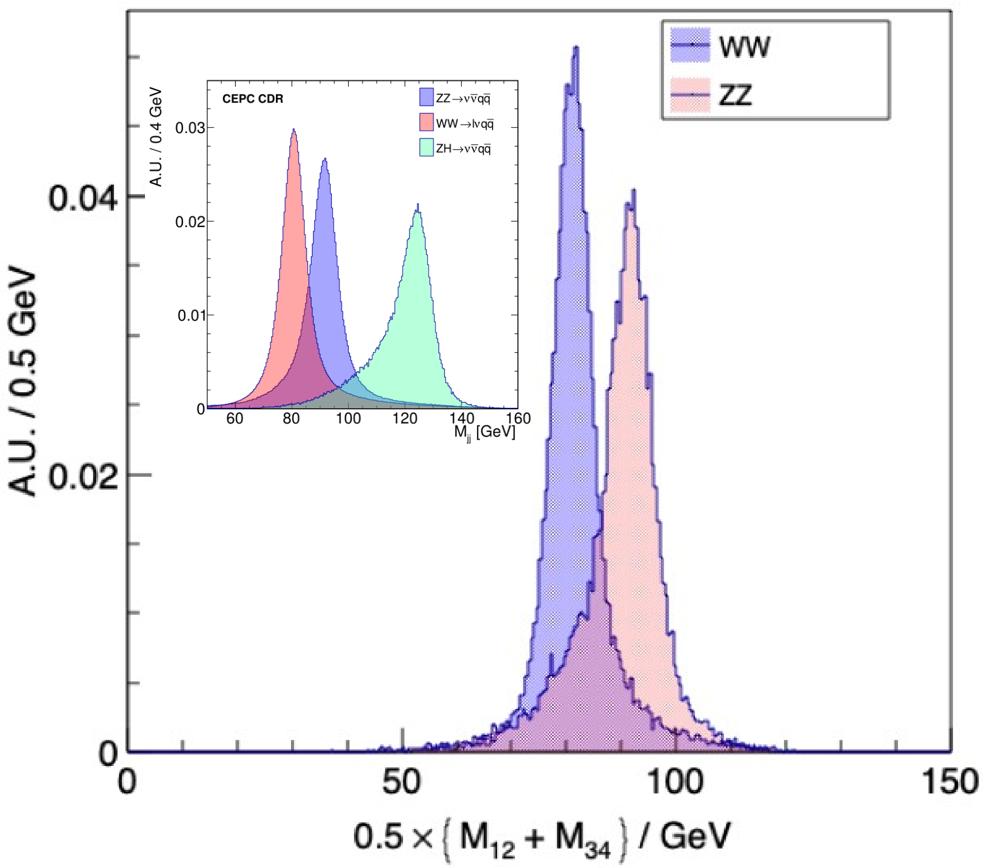
- WW-ZZ Separation at the inclusive sample:
  - Intrinsic boson mass/width - lower limit: Overlapping ratio of 13%
  - + Jet confusion – Genjet: Overlapping ratio of **53%**
  - + Detector response – Recojet: Overlapping ratio of 58%

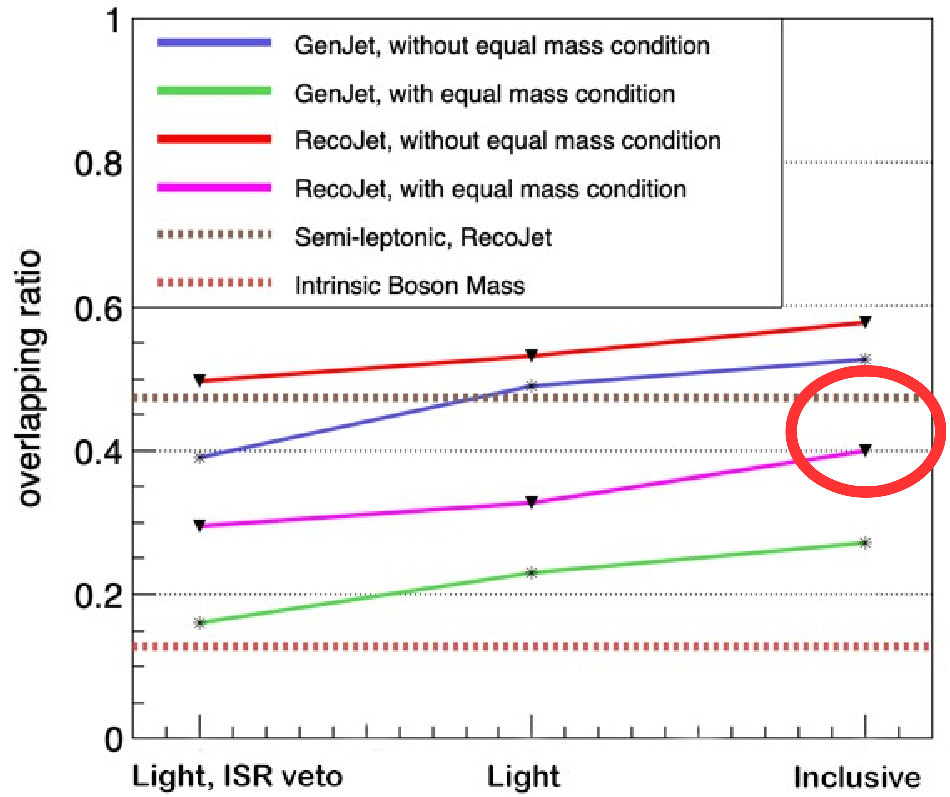
Reconstructed mass of the two di-jet system



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.

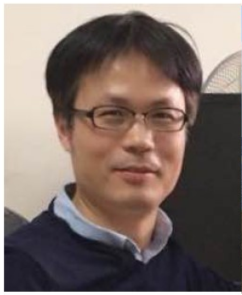
Summary

- 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...

Many Thanks to


C. Fu, Geant 4 & Tracking


X. Zhao, Software & production


Dan, Lepton ID, Tau, PFA

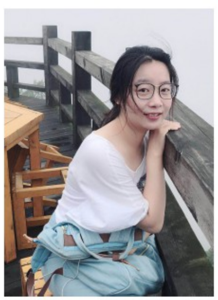

P. Lai, Jet Calibration


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

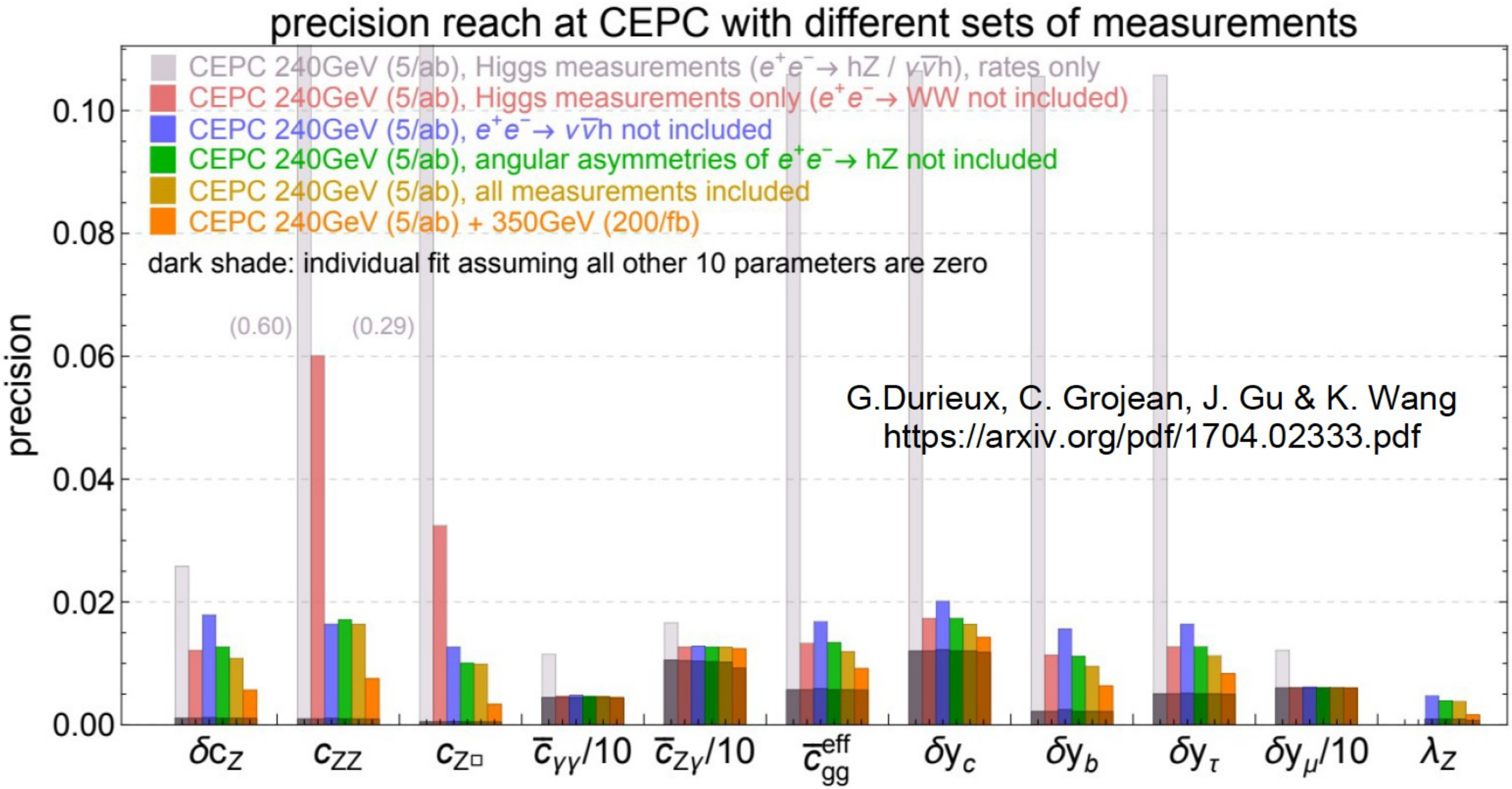

M. Ruan, PFA, Object,...

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

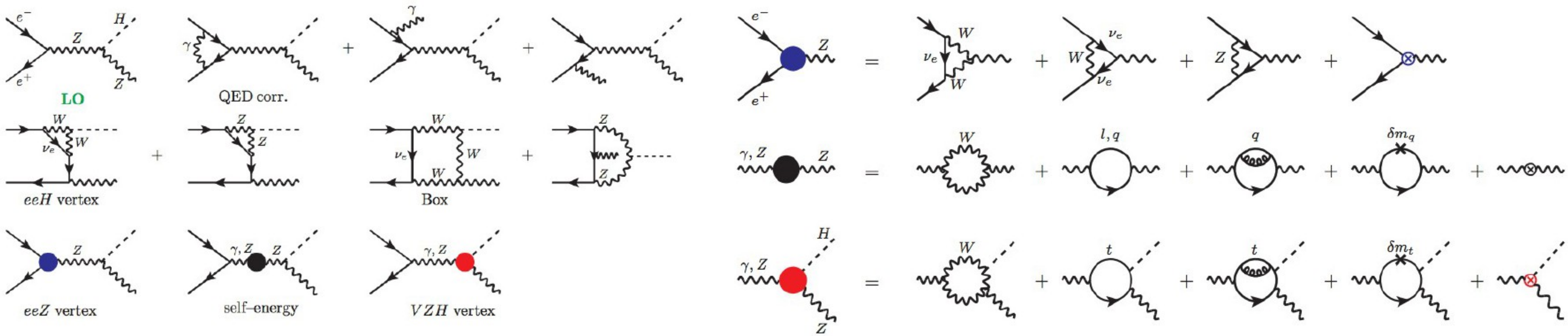
backup

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



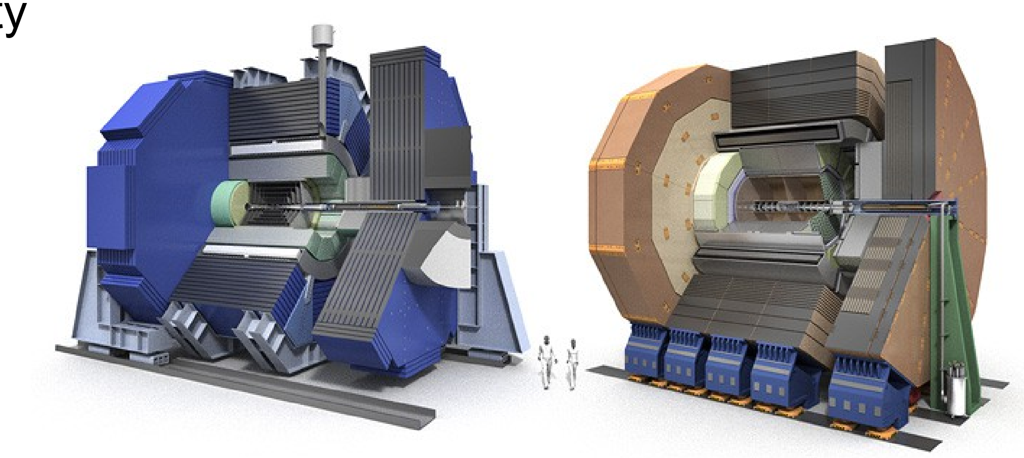
$\sqrt{s}$ (GeV)		LO (fb)	NLO Weak (fb)		NNLO mixed electroweak-QCD (fb)			
		$\sigma^{(0)}$	$\sigma^{(\alpha)}$	$\sigma^{(0)} + \sigma^{(\alpha)}$	$\sigma_Z^{(\alpha\alpha_s)}$	$\sigma_\gamma^{(\alpha\alpha_s)}$	$\sigma^{(\alpha\alpha_s)}$	$\sigma^{(0)} + \sigma^{(\alpha)} + \sigma^{(\alpha\alpha_s)}$
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

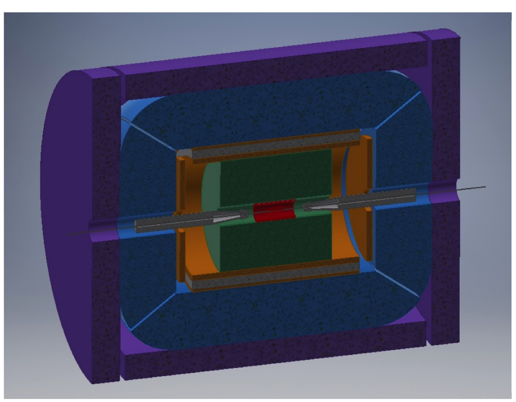
- Correction at 1% level with NNLO calculation.
- Lots of efforts needed to correctly interpret the measurements at CEPC

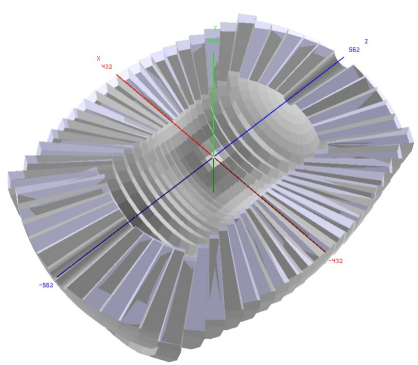
Two classes of Concepts

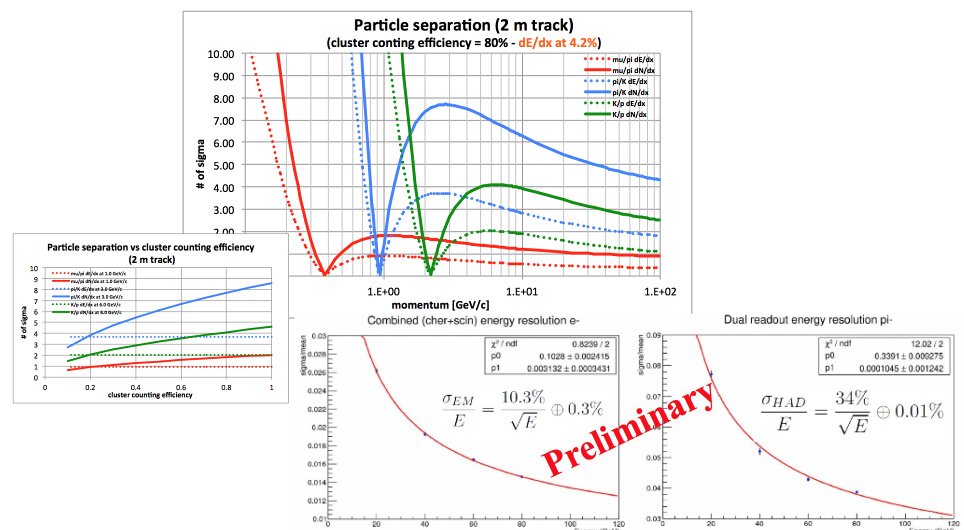
- PFA Oriented concept using High Granularity Calorimeter
  - **+ TPC (ILD-like, Baseline)**
  - + Silicon tracking (SiD-like)



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



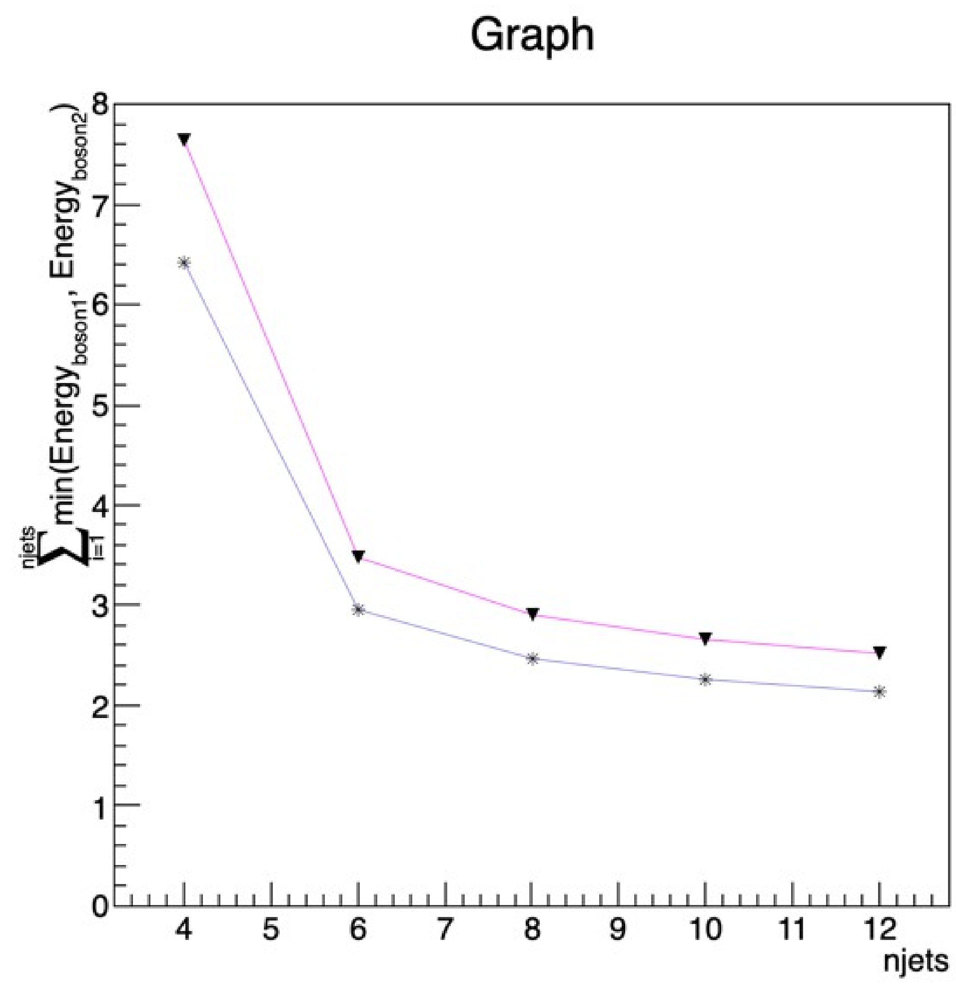




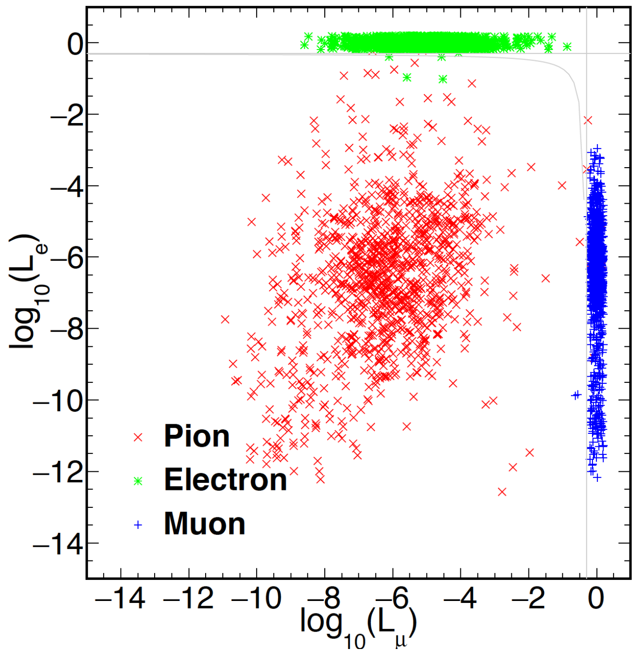
https://indico.ihep.ac.cn/event/6618/

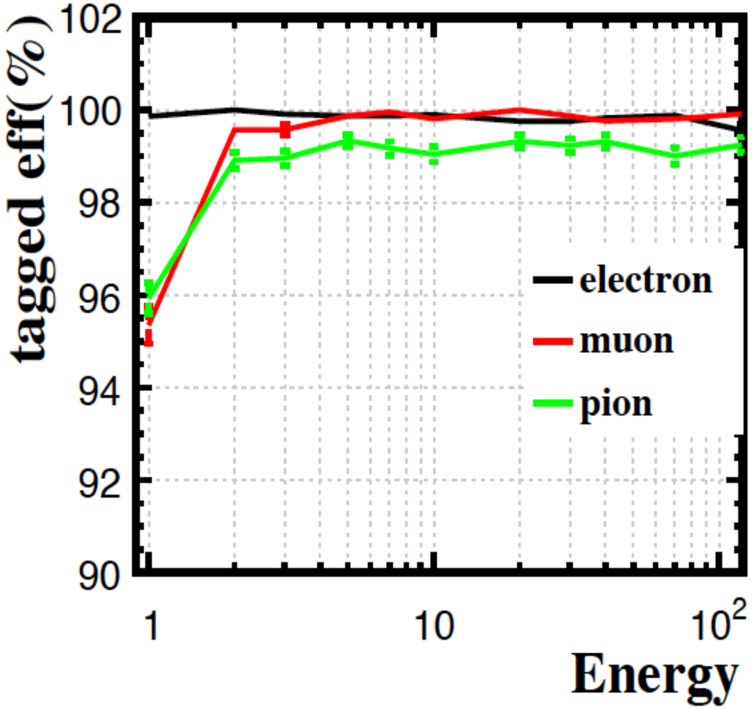
https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=14816

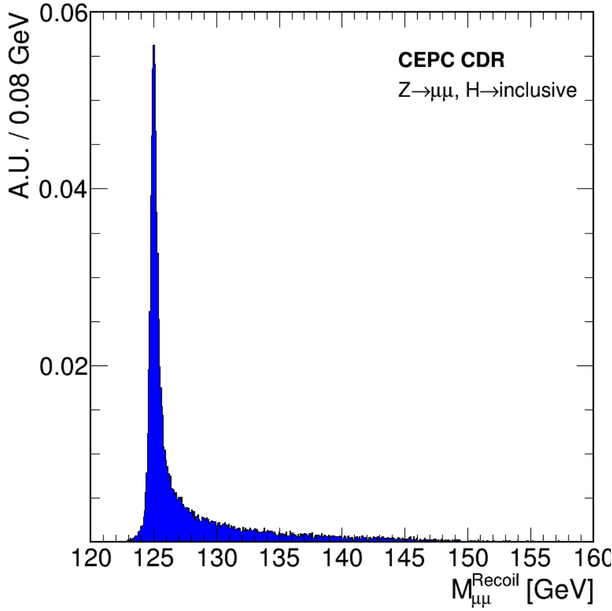
New Hints: N+2 clustering

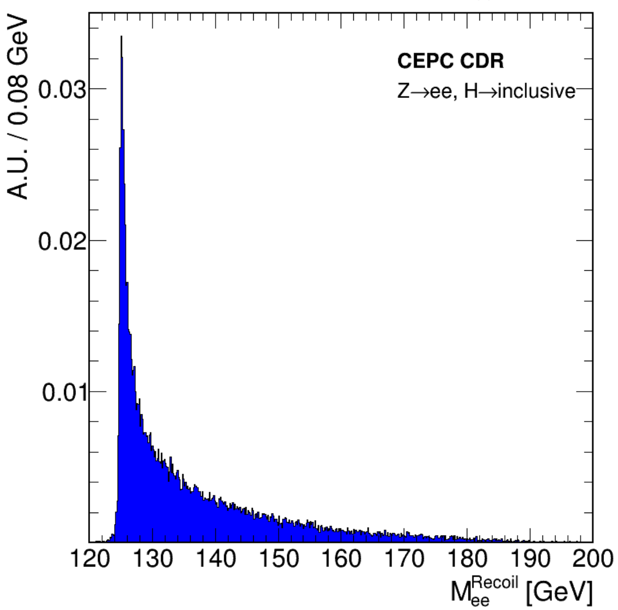


Leptons









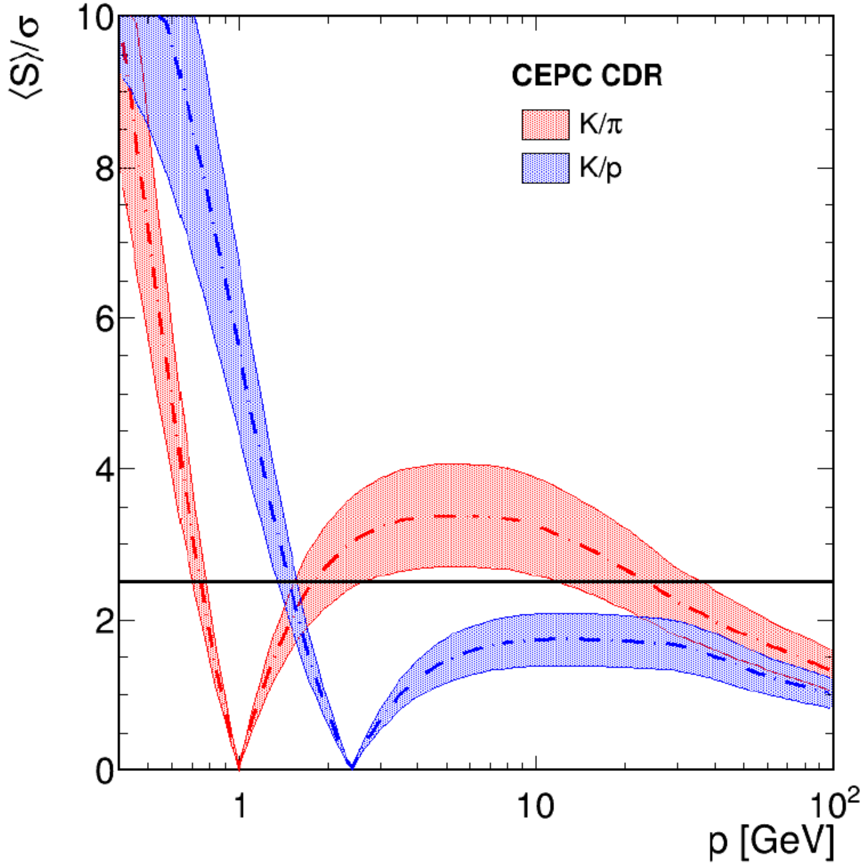
BDT method using 4 classes of 24 input discrimination variables.

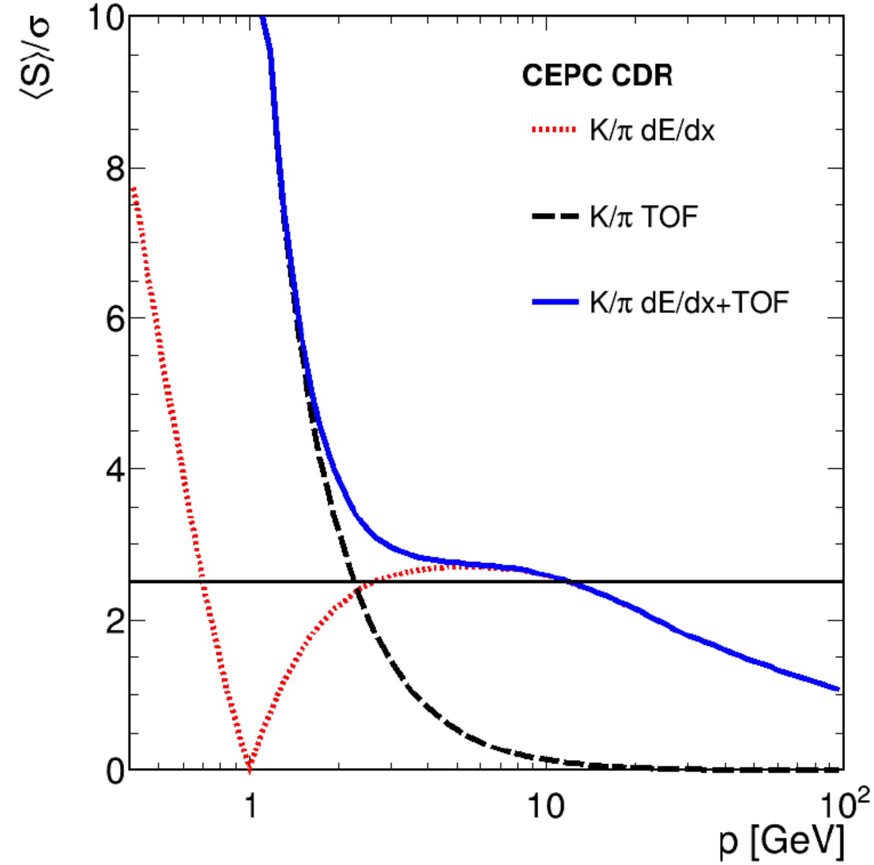
Test performance at: Electron = E_likeness > 0.5 ;
Muon = Mu_likeness > 0.5

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

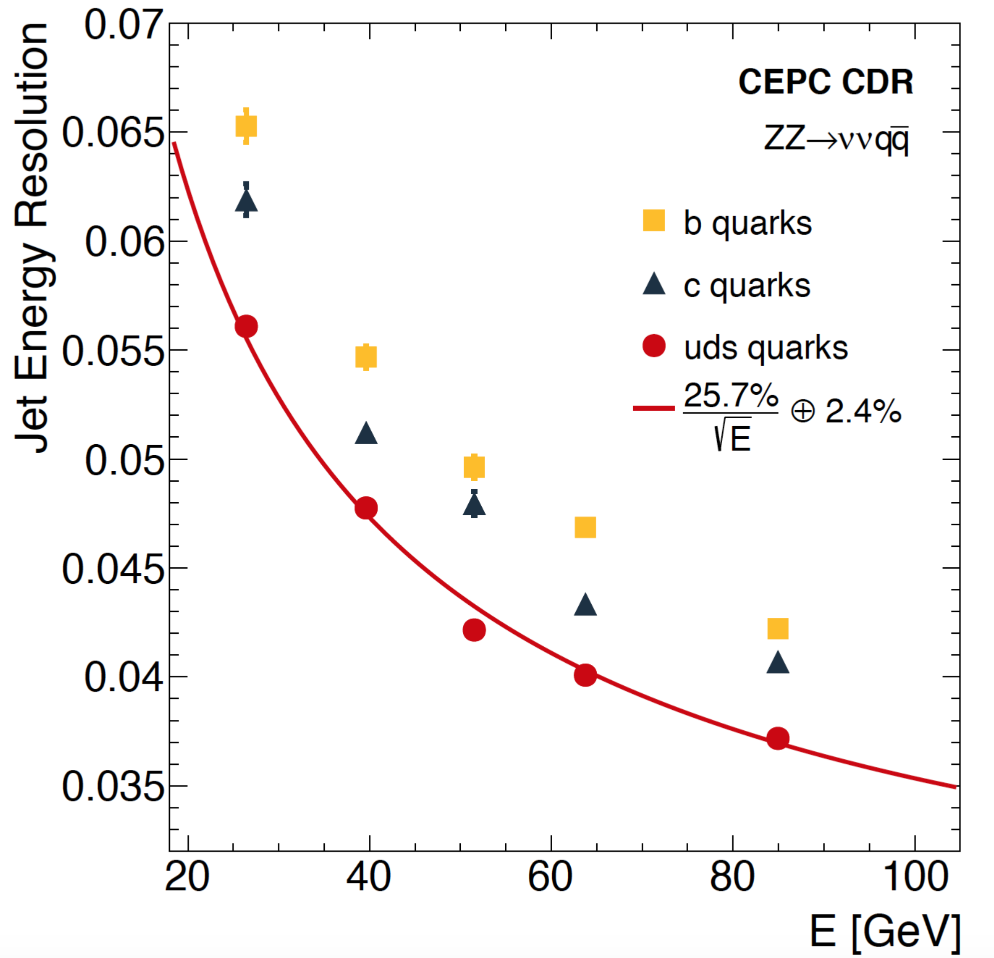
Eur. Phys. J. C (2018) 78:464

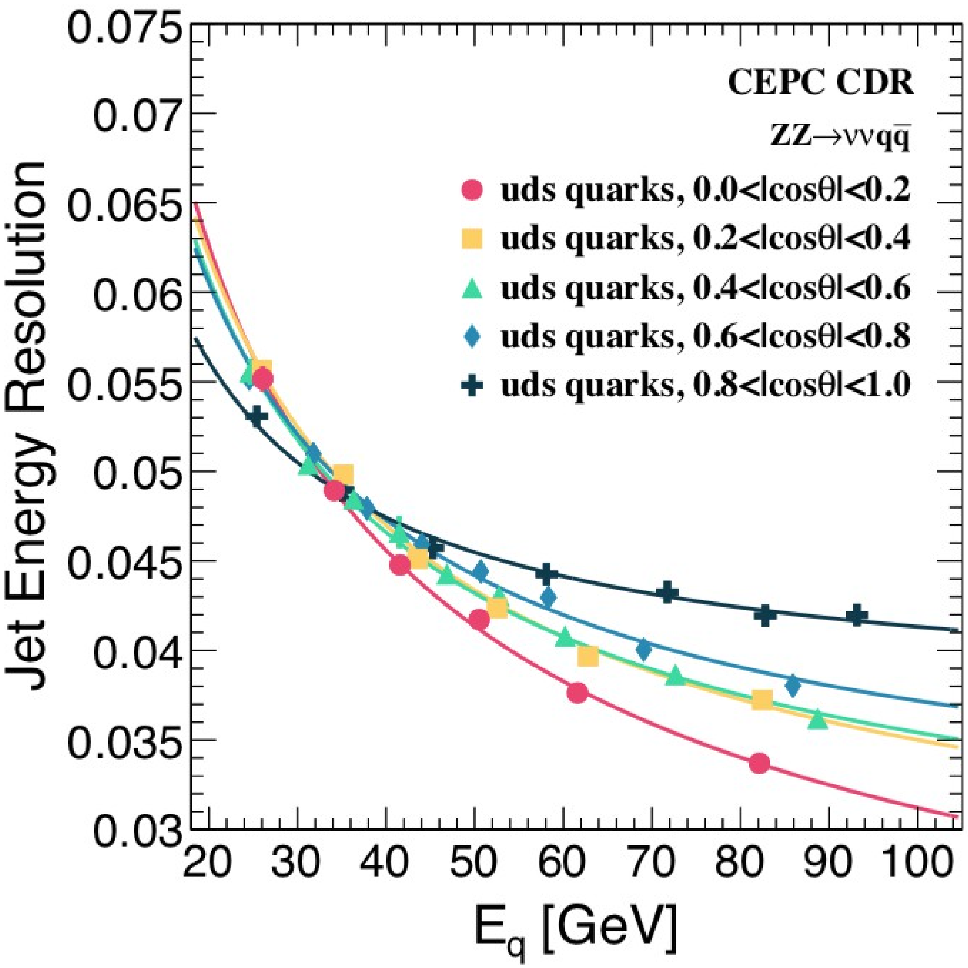
At inclusive Z pole sample:

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

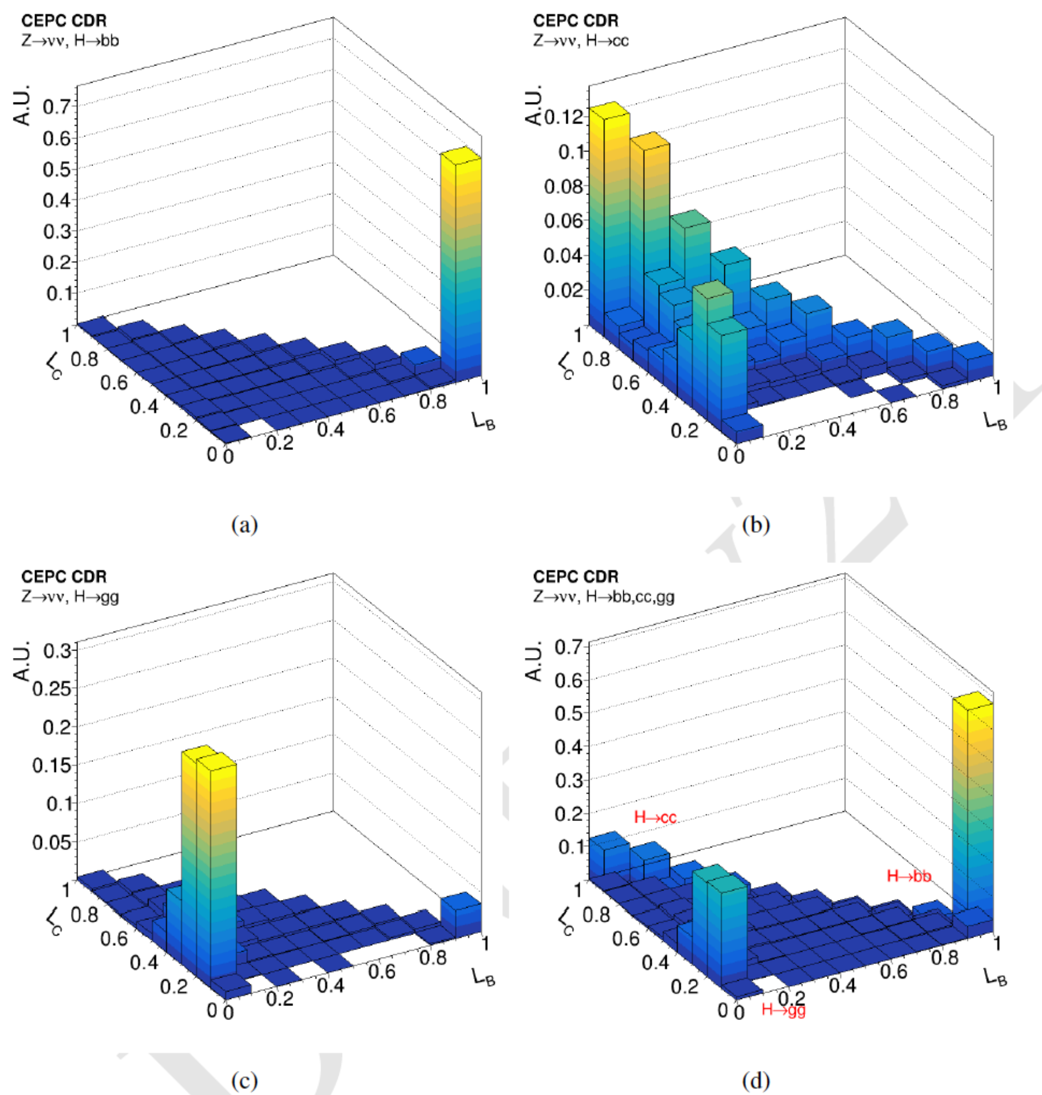




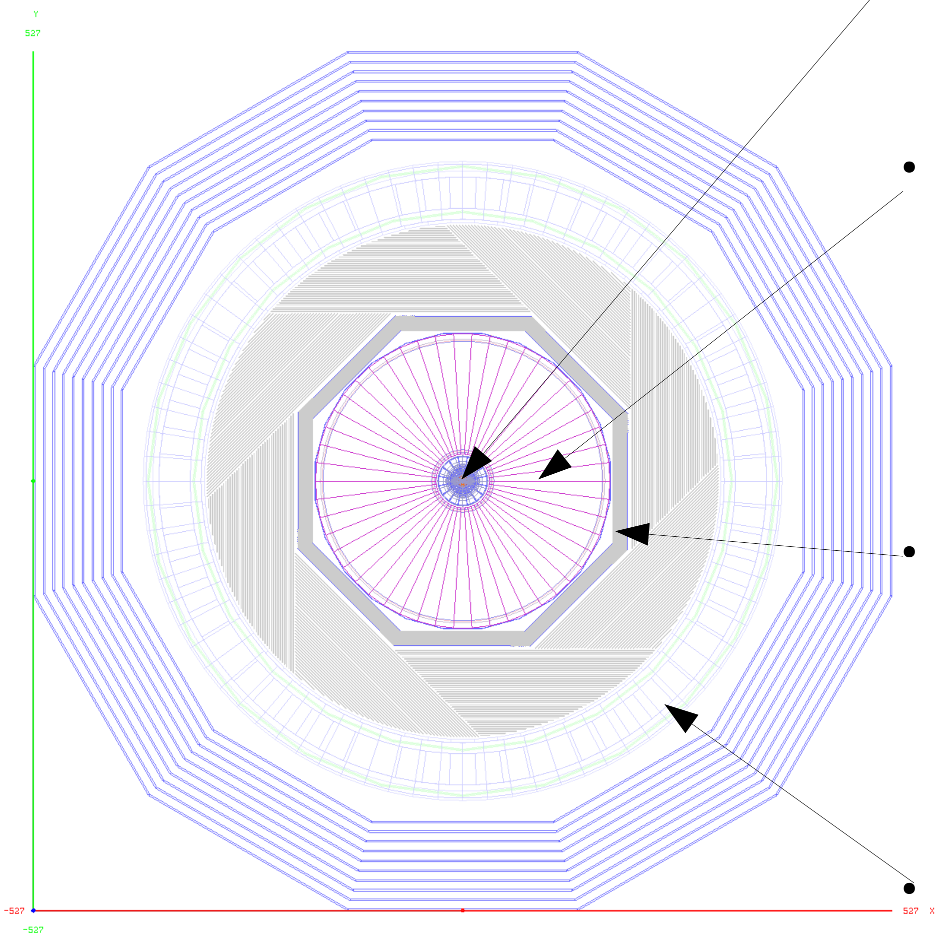
Amplitude ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
Depends on the Flavor, direction and jet energy
Superior to LHC experiments by 3-4 times

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%*

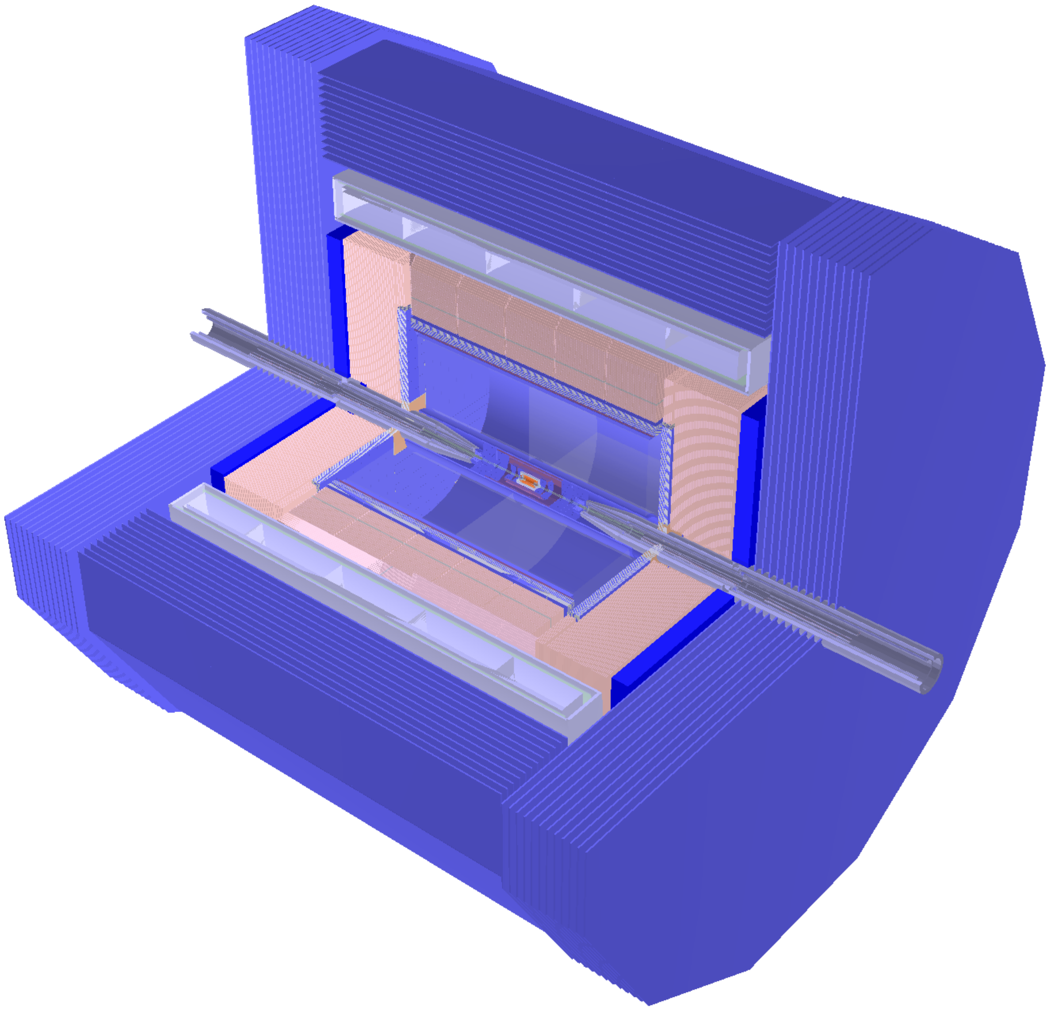


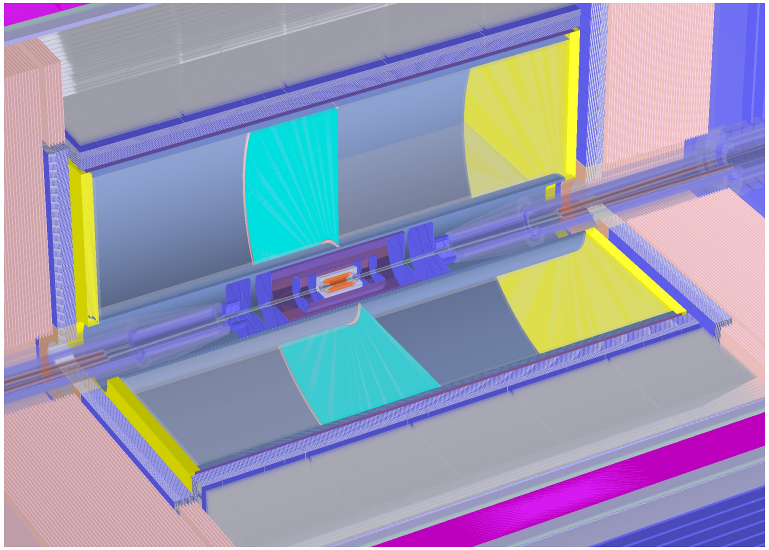
An ILD-like detector at the CEPC

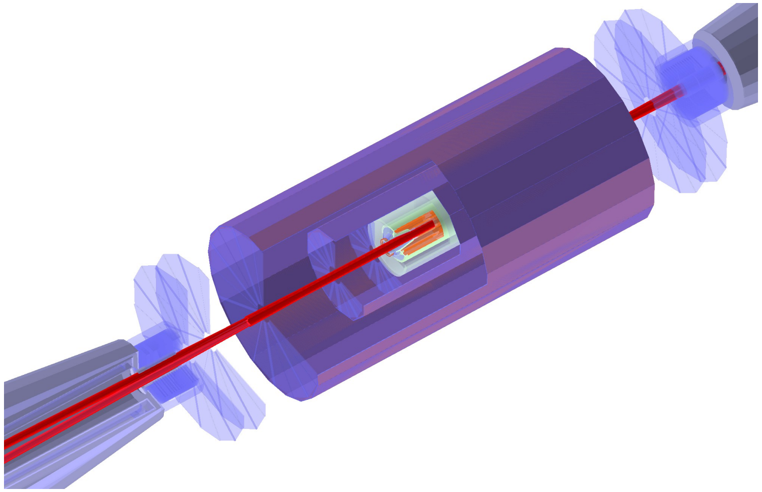


- Different collision environments/rates :
  - MDI design & Implementation: CEPC-SIMU-2017-001
- The CEPC Event rate is significantly higher than linear colliders, charged kaon id can strongly enhance the CEPC flavor physics program
  - TPC Feasibility: JINST-12-P07005 (2017)
  - Pid using TPC dEdx and 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

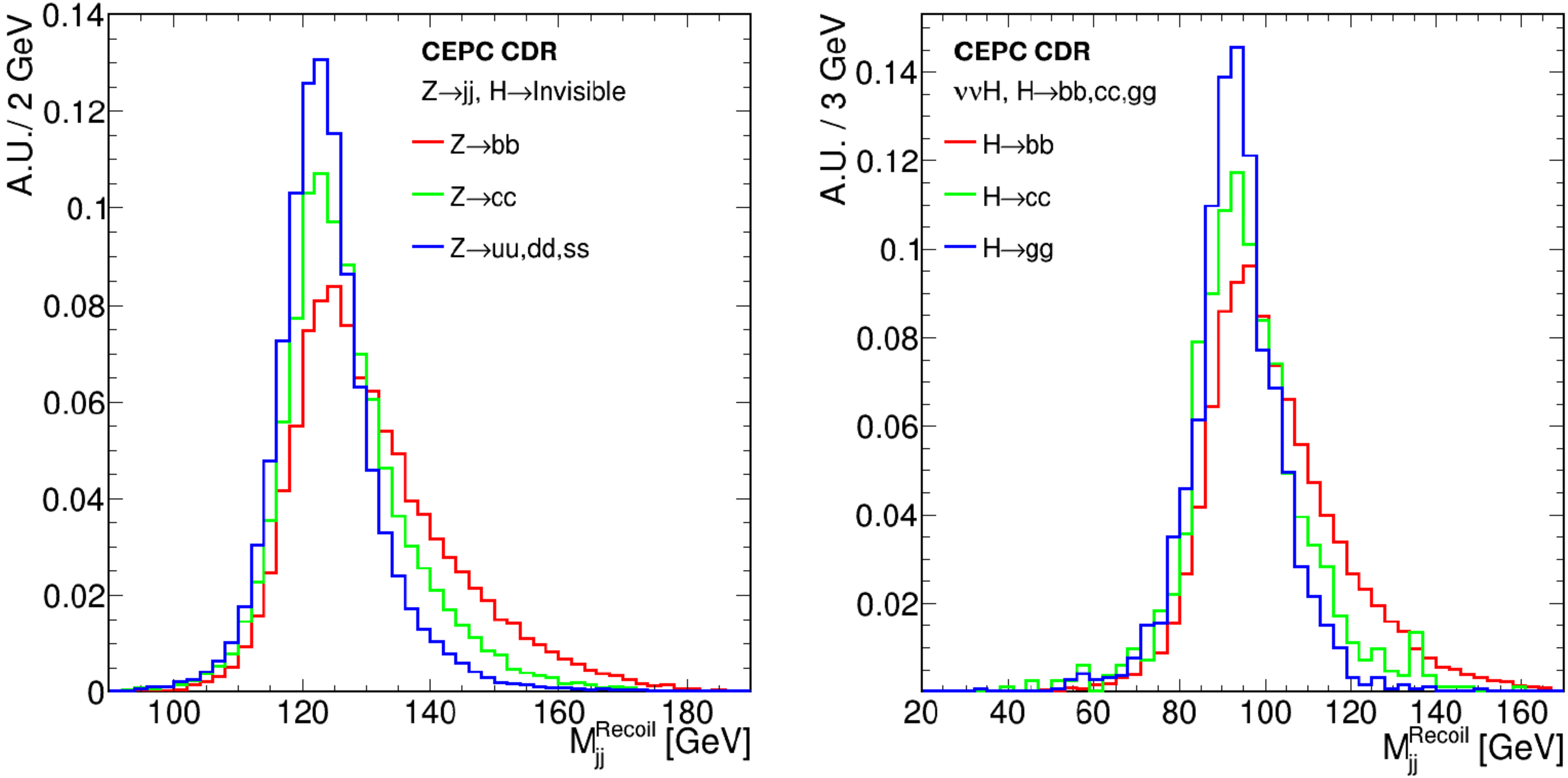
APODIS Geometry





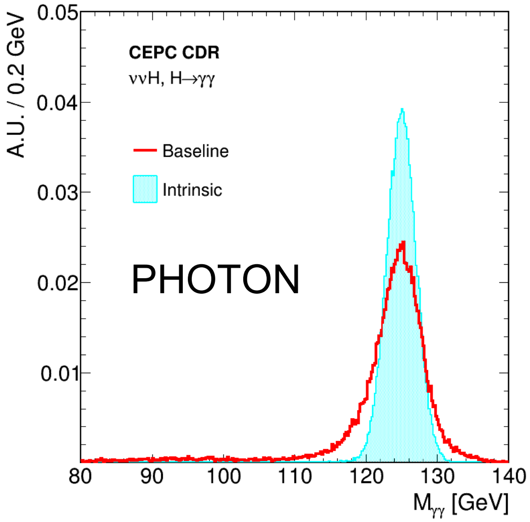


Missing Energy & Momentum

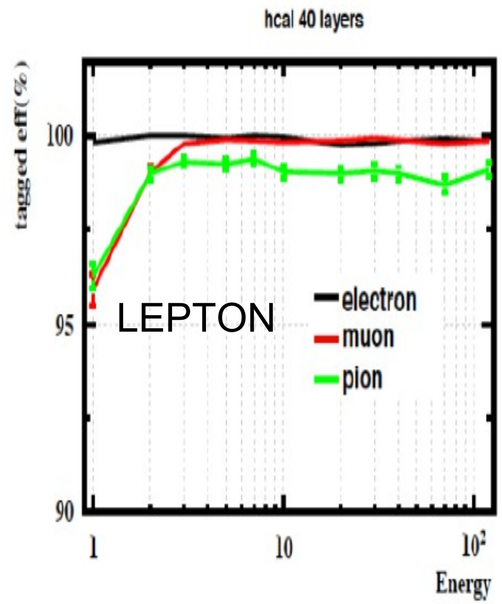


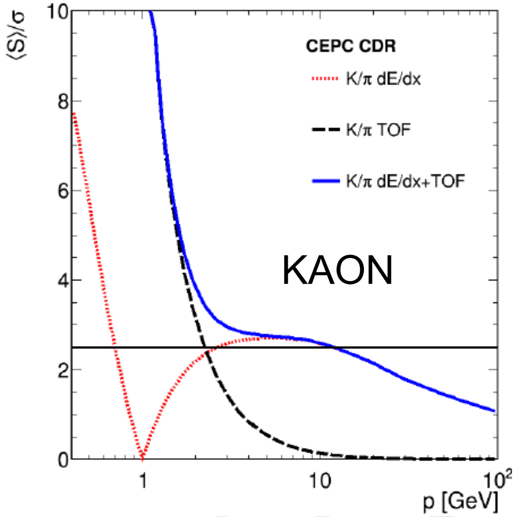
Width of the Light jets: 6GeV/8GeV (Left/Right Plots)

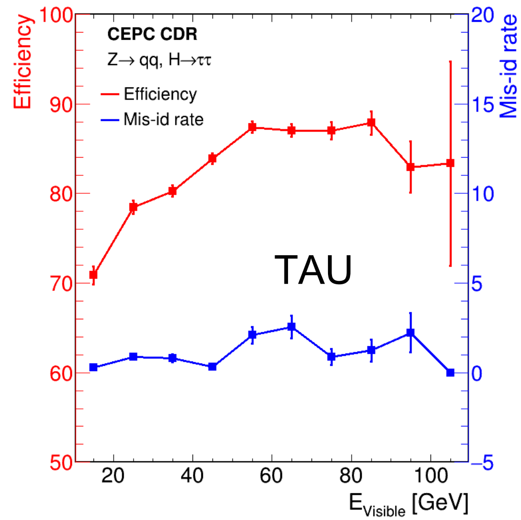
Physics Objects: Tamed

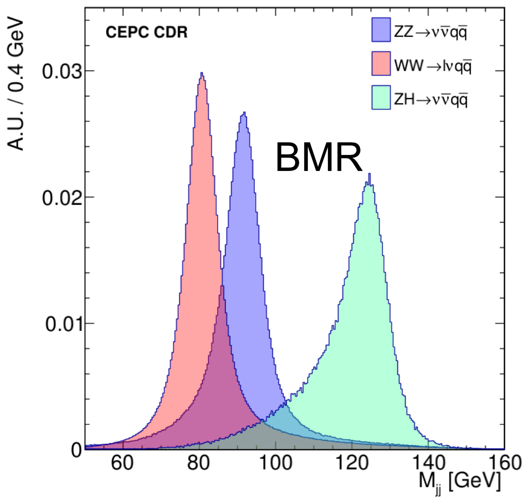


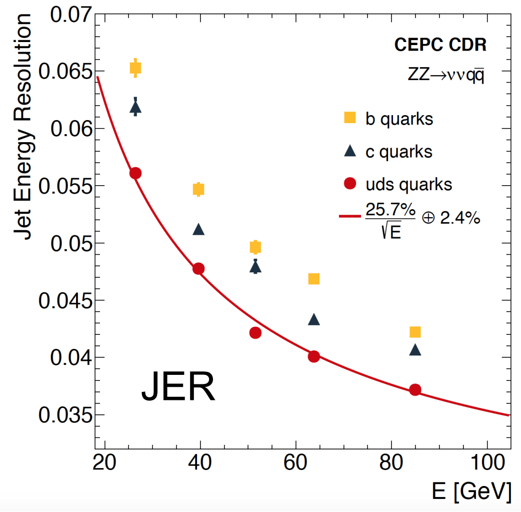
Higgs mass/GeV

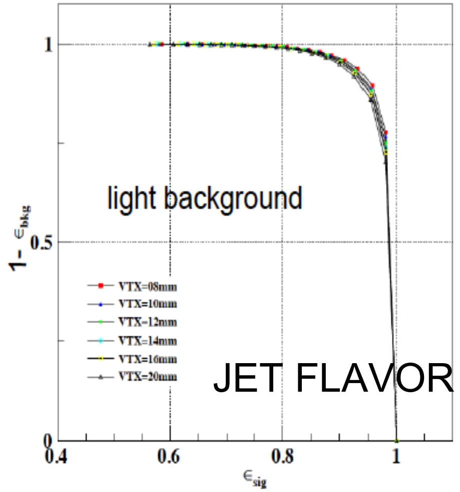


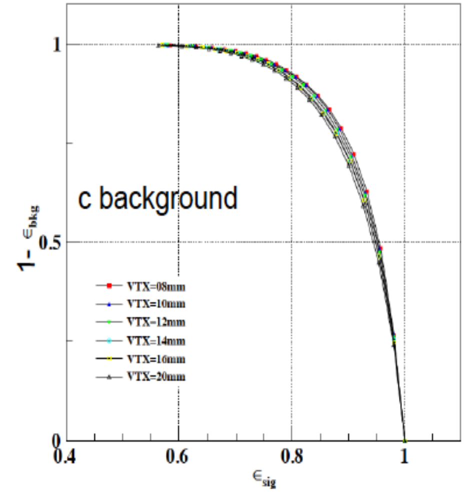




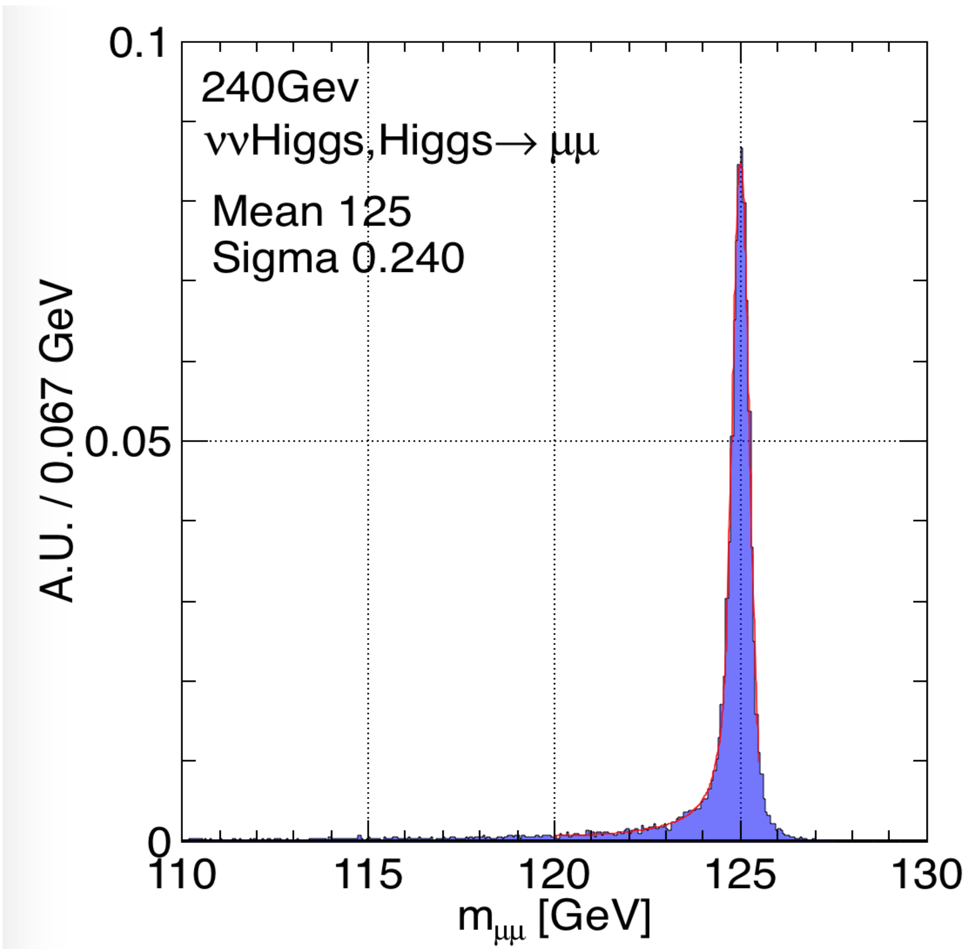


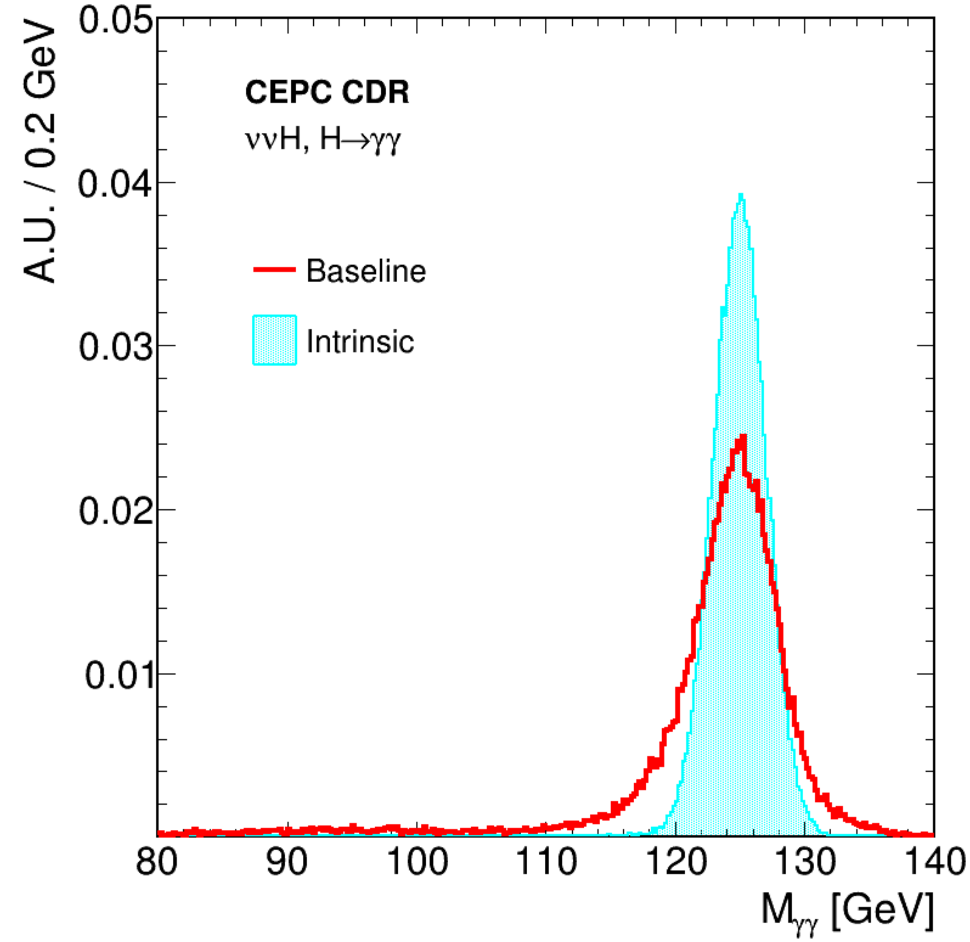






Higgs Signal at APODIS

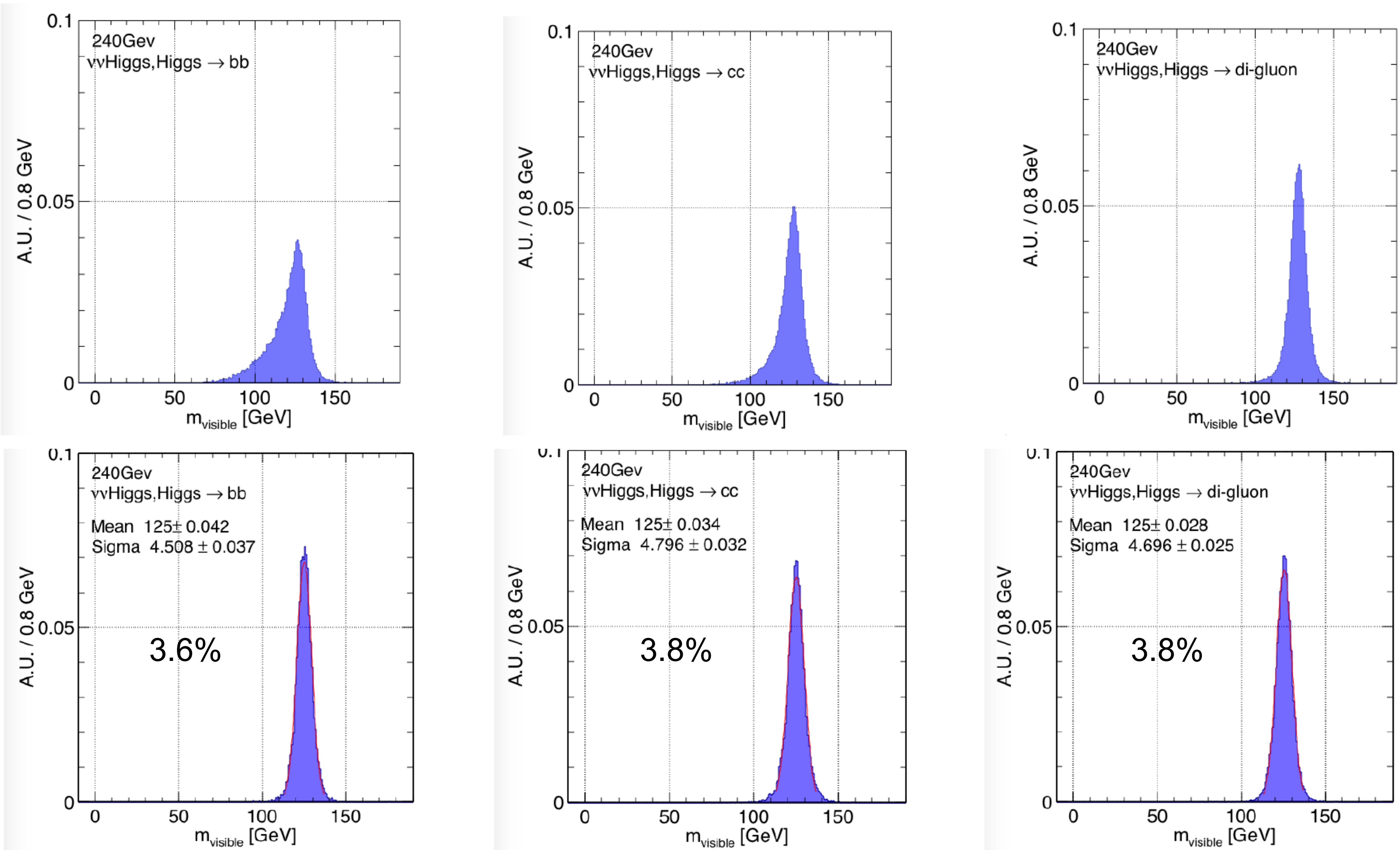




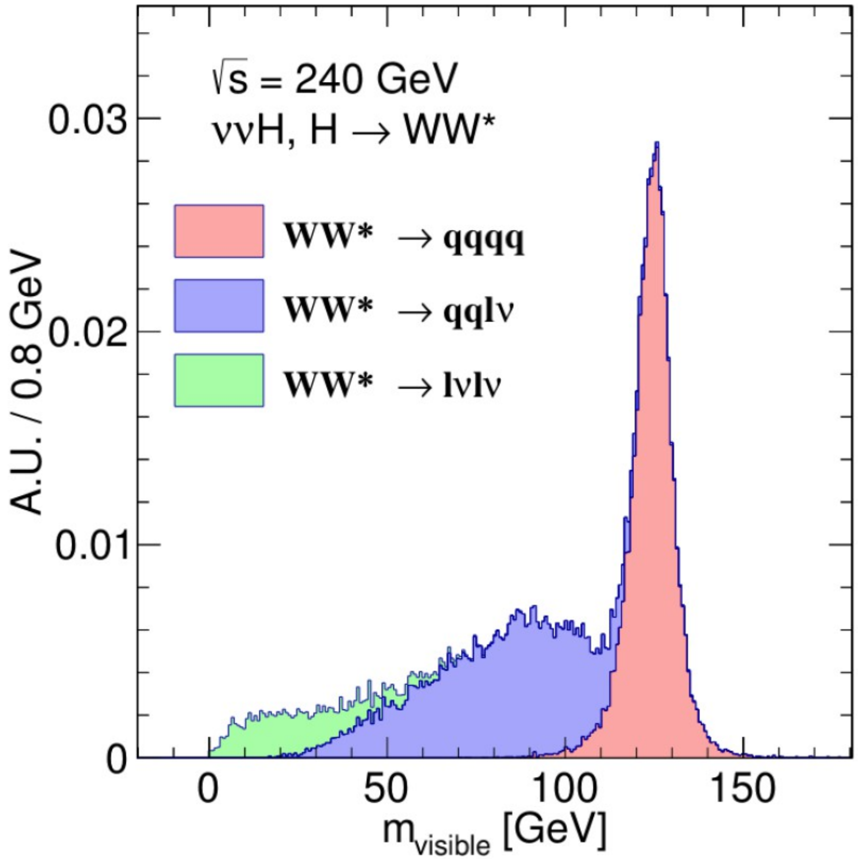
CEPC-RECO-2018-002
CEPC-Doc id 174, 175

Lepton tracks & Photon Clusters

Higgs to bb, cc, gg (Jets)



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



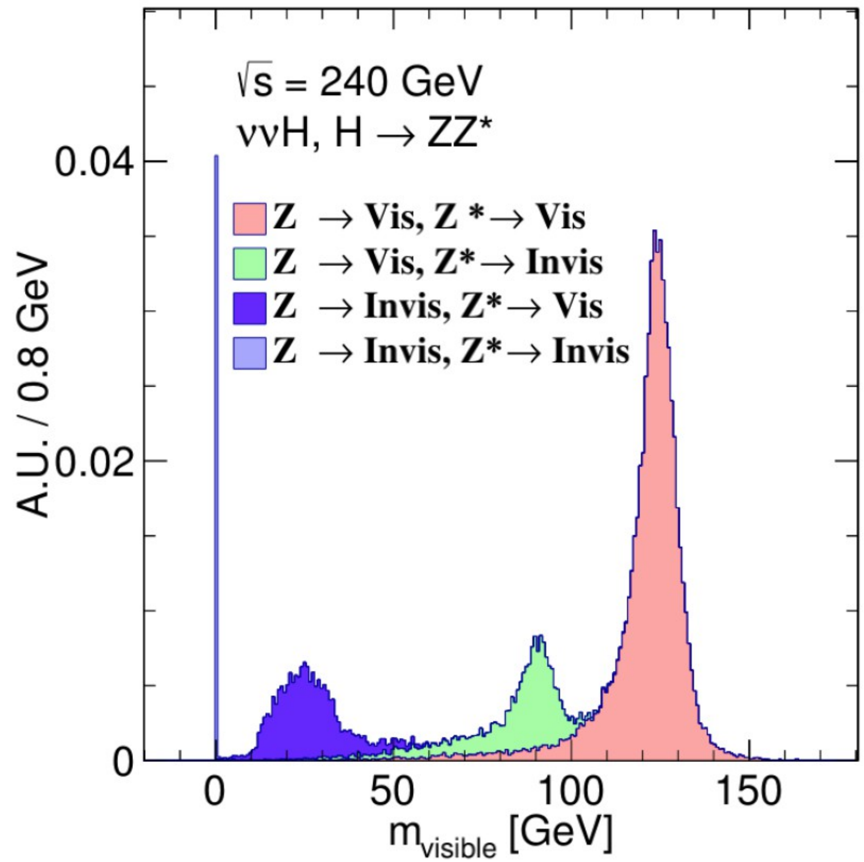
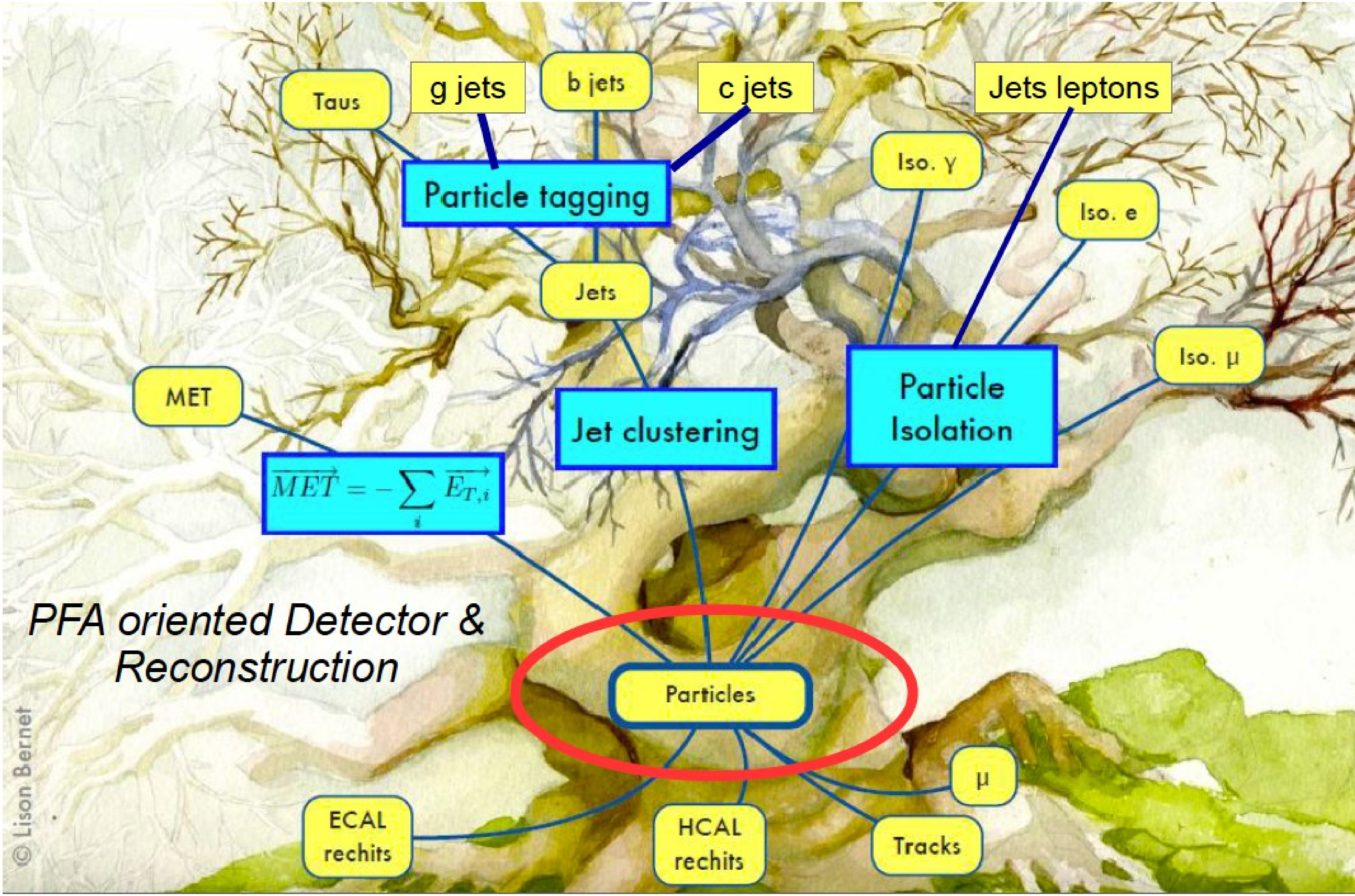


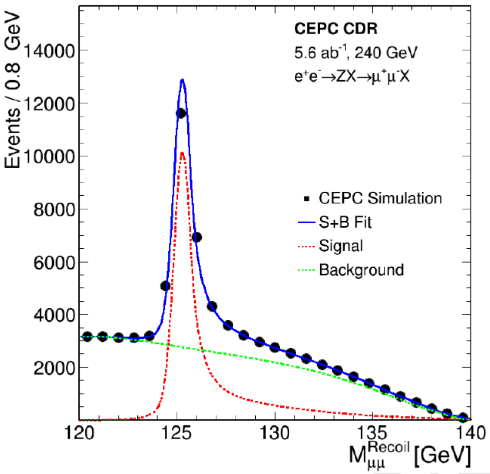
Table 2. Benchmark resolutions ($\sigma/Mean$) of reconstructed Higgs boson mass, comparing to LHC results.

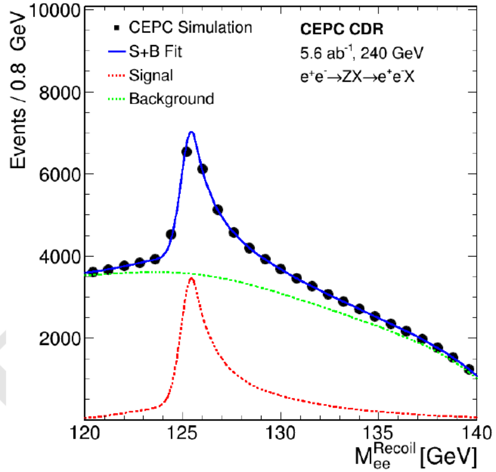
	Higgs→ $\mu\mu$	Higgs→ $\gamma\gamma$.	Higgs→bb
CEPC (APODIS)	0.20%	2.59%[1]	3.63%
LHC (CMS, ATLAS)	~2% [19, 20]	~1.5% [21, 22]	~10% [23, 24]

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

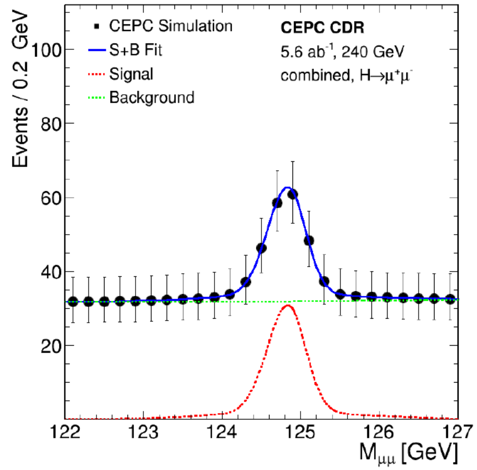

Taus
g jets
b jets
c jets
Jets leptons
Particle tagging
Iso. γ
Iso. e
Jets
Iso. μ
MET
Jet clustering
Particle Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
PFA oriented Detector & Reconstruction
Particles
μ
ECAL rechits
HCAL rechits
Tracks
© Lison Bernet

Higgs benchmark analyses

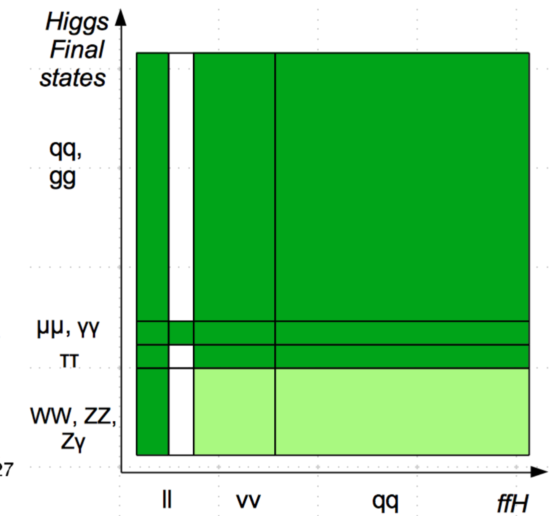


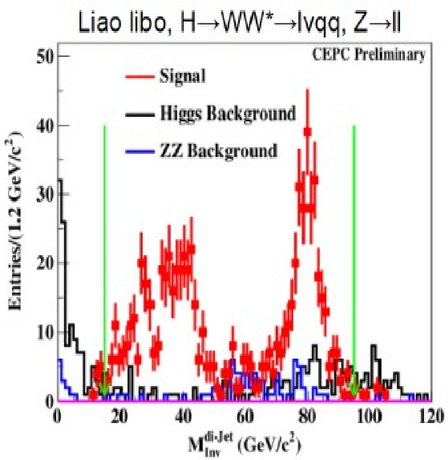


σ(ZH) measurements

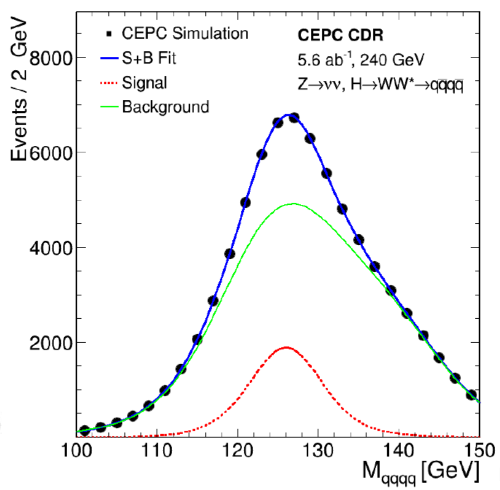


Br(H→μμ)

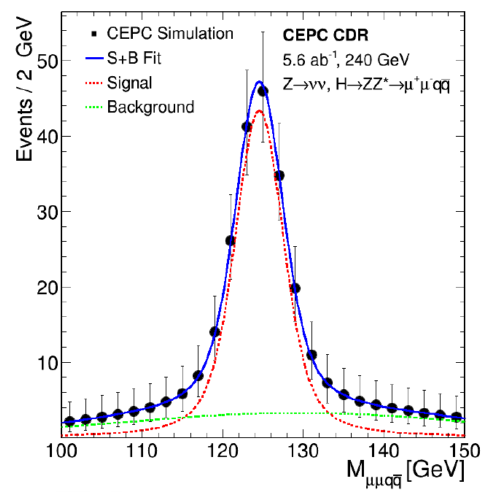




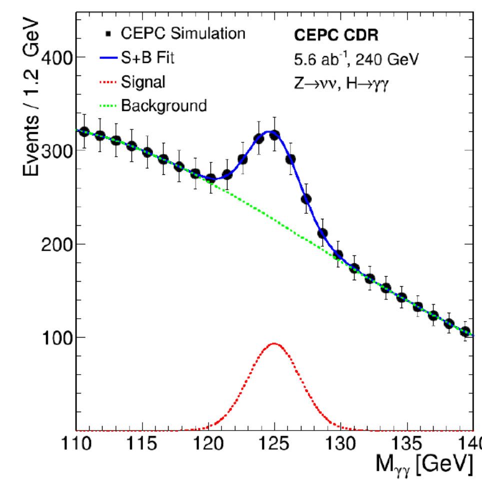
Br(H→WW)



σ(ννH)*Br(H→bb)



Br(H→ττ)



Br(H→γγ) (Asimov)