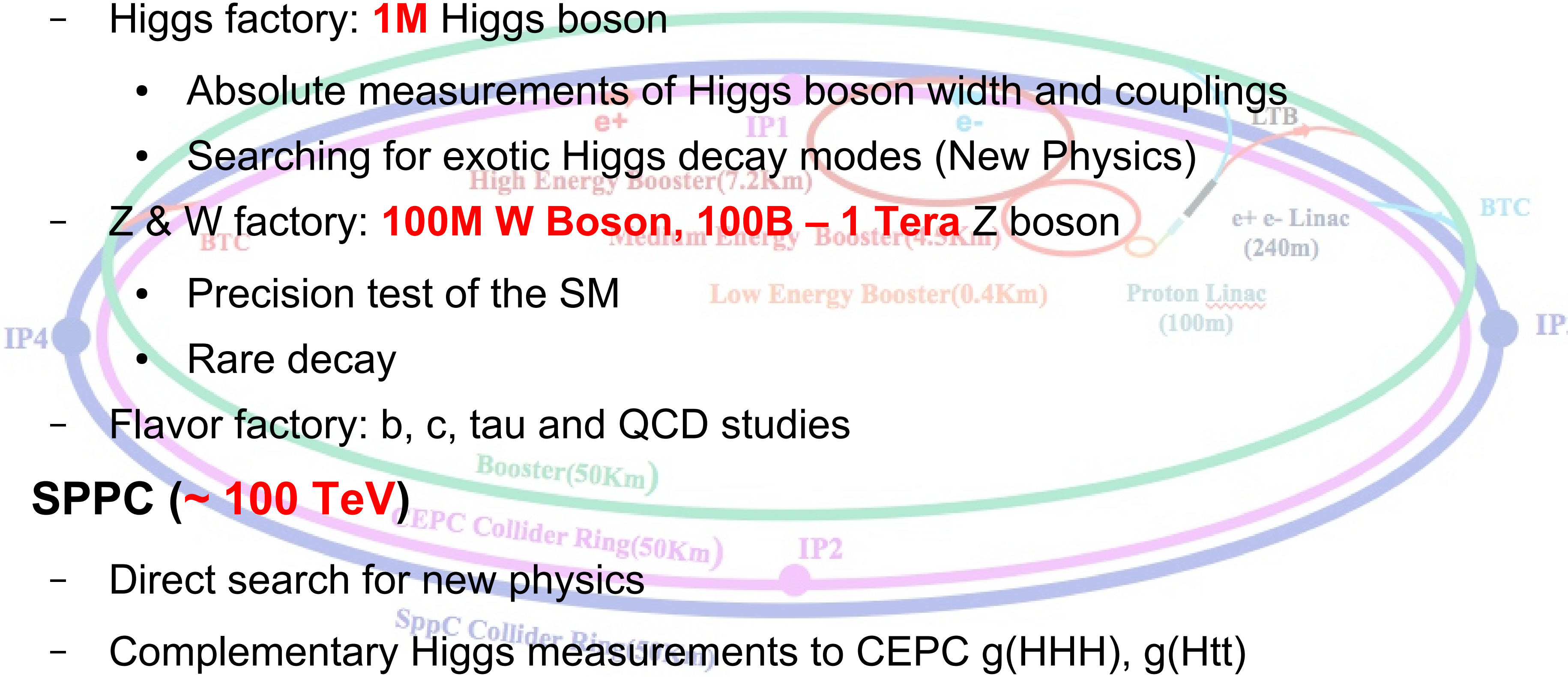
Requirement & performance: CEPC CDR baseline, and the key questions to the future

Manqi Ruan

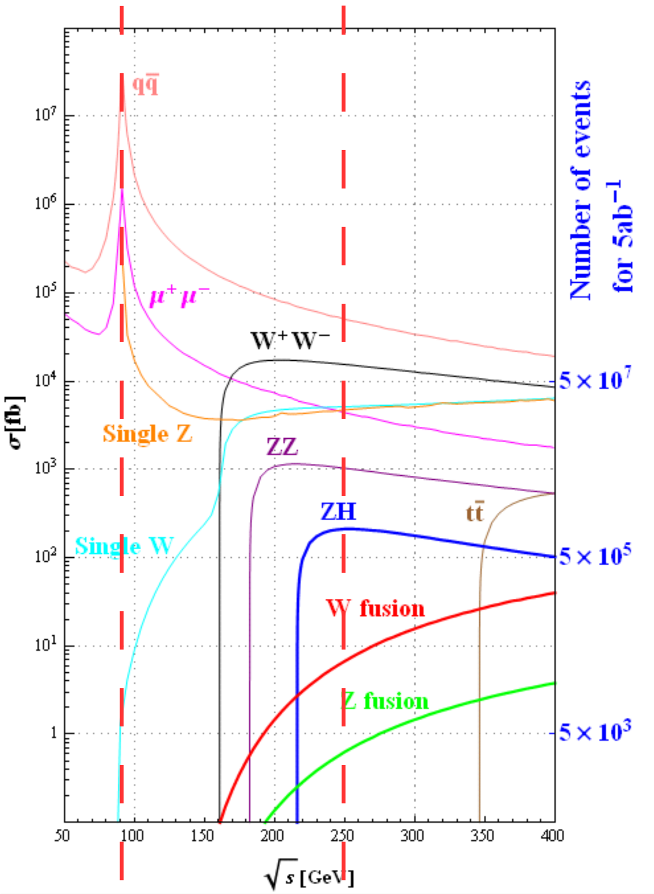
Science at CEPC-SPPC

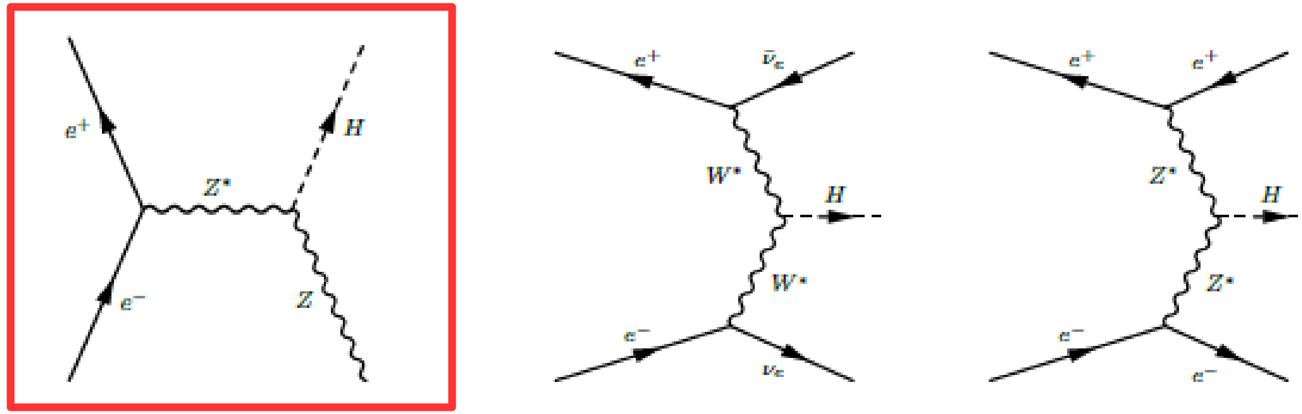
- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **100M W Boson, 100B – 1 Tera** Z boson
    - Precision test of the SM
    - 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

Higgs @ CEPC





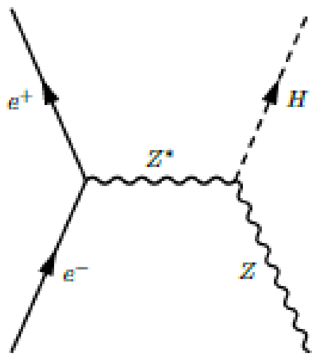
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

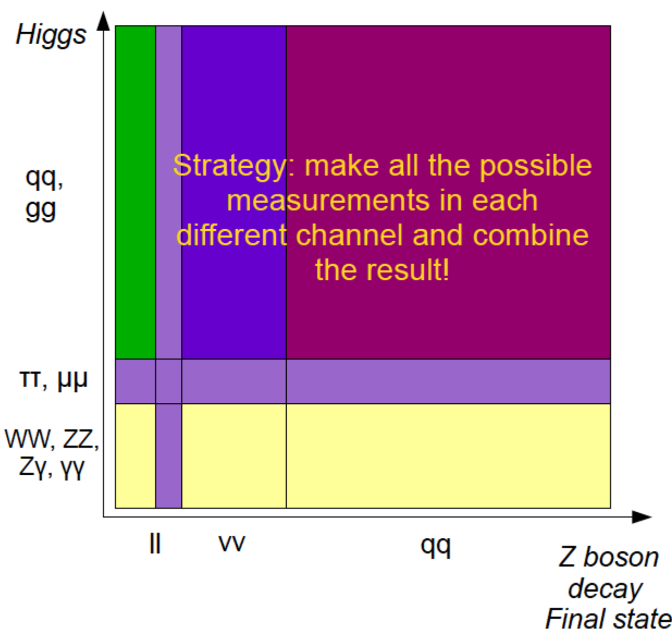
S/B ~ 1:100 - 1000

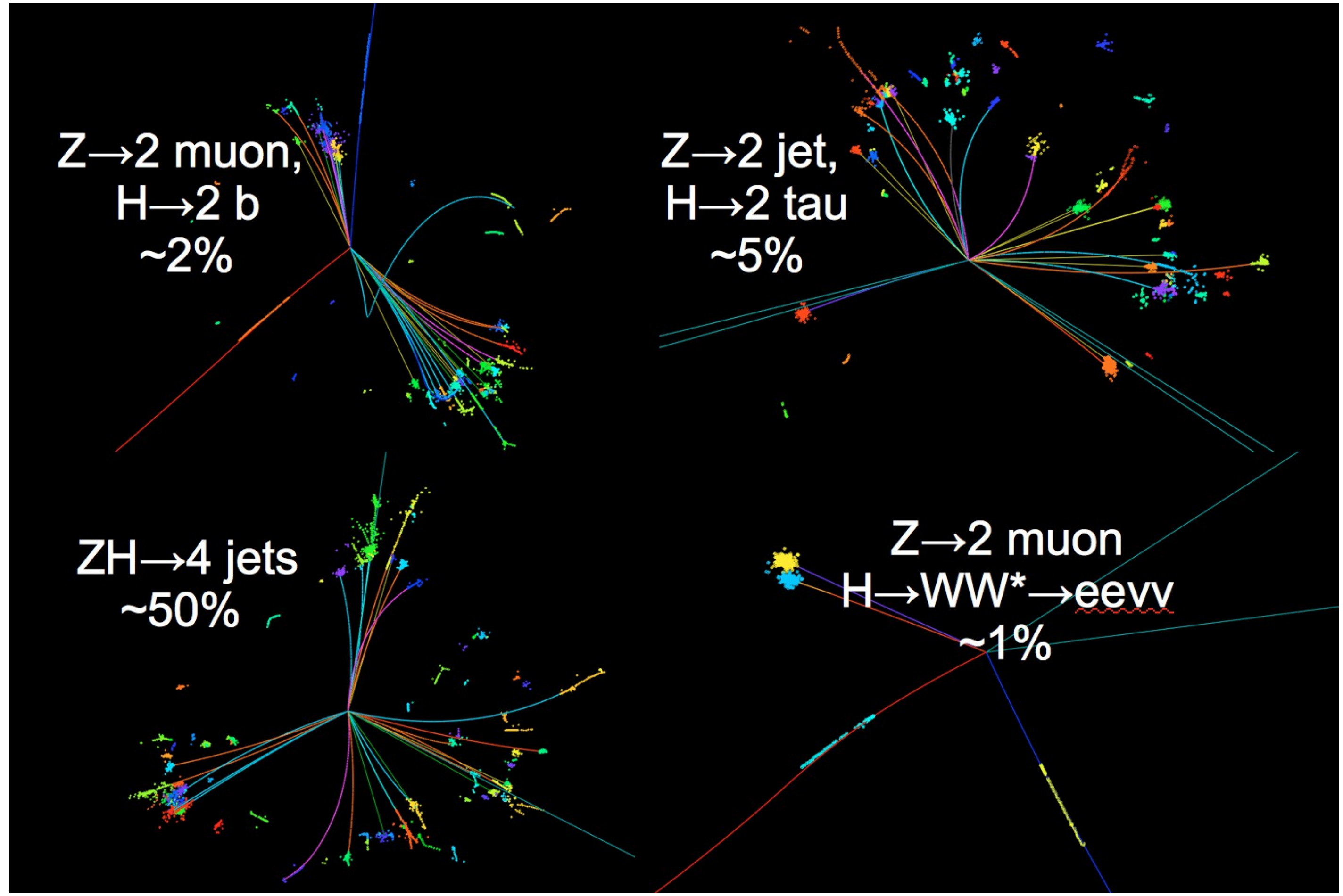
Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, νvH)*Br(H→X)), Diff. distributions

Derive: Absolute Higgs width, branching ratios, couplings

Physics Requirements







Detector:

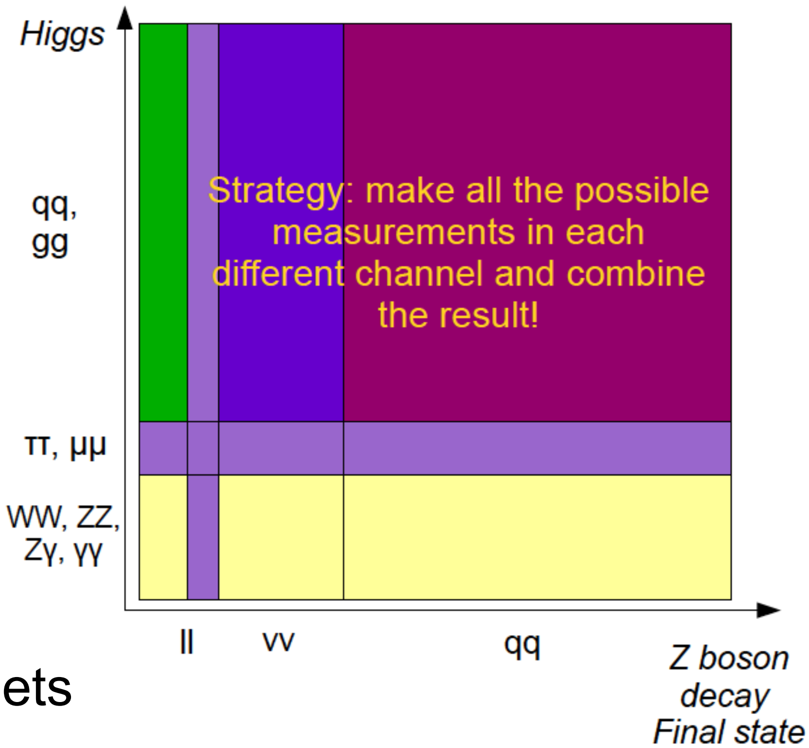
- To reconstruct all the physics objects with high efficiency, purity & resolution
- Homogenous & Stable enough to control the systematic

Requirements on the physics object

- Low-level
  - VTX: allows a precise flavor tagging & b/c-baryon reconstruction
  - Tracks;
    - threshold < 150 MeV (for D*, K* cascade reconstruction),
    - momentum resolution < 0.1% for H->mumu reconstruction
  - Clusters;
    - Ensure pi0 reconstruction at Z->tautau, Z pole, and potentially high energy runs
- Final State Particle
  - Lepton: Isolated, high energy muon/electrons: eff > 99% && mis-id < 1% for the Higgs recoil
  - Photon;
  - Charged/Neutral Hadrons;
- High Level Objects
  - Simple composited: Pi0, Ks, converted photons;
  - Tau;
  - Jets – Massive bosons fragment into jets: **BMR < 4%**

Jets at the Higgs Signal

- SM Higgs
  - **0 jets: 3%**
    - Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)
  - **2 jets: 30%**
    - Z→qq, H→0 jets.
    - Z→ll, νν; H→2 jets.
    - Z→ll, νν; H→WW/ZZ→semi-leptonic.
  - **4 jets: 59%**
    - Z→qq, H→2 jets.
    - Z→ll, νν; H→WW/ZZ→4 jets.
  - **6 jets: 8%**
    - Z→qq, H→WW/ZZ→4 jets.



- 97% of the SM Higgsstrahlung Signal involves Jets

Jets at the Higgs Signal

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    - Z→qq, H→0 jets.
    - Z→ll, νν; H→2 jets.
    - Z→ll, νν; H→WW/ZZ→semi-leptonic.

- 1/3 of the Higgs events
  - Access to all SM Higgs decay modes
  - Doesn't need color singlet identification: at most 1 color singlet thus naturally identified

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  - **4 jets: 59%**
    - Z→qq, H→2 jets.
    - Z→ll, νν; H→WW/ZZ→4 jets.
  - **6 jets: 8%**
    - Z→qq, H→WW/ZZ→4 jets.

- 2/3 of the Higgs events
  - Dominate statistic of H→bb, cc, gg, WW, ZZ, Zγ
  - Color singlet identification – **potentially a leading systematic, huge impact**

- 2/3 of the events need to group the final state particles into Color-Singlet: currently via Jet Clustering-Matching (analyzed in WW/ZZ separation study ~ 50% of 4-jets event have correct pairing)

Physics benchmarks

- Higgs measurement with 2-jet event
  - qqH, Higgs→$\tau\tau$;
    - Percentage level accuracy, sensitive probe to NP
  - qqH, Higgs→invisible;
    - Key measurement for the DM search, significant advantage V.S. LHC
  - vvH, H→bb (W fusion Xsec measurement)
    - Key input & Bottleneck for the Higgs width measurement – limitation for Higgs couplings to major decay modes (bb, gg, WW, ZZ, tautau)

- Full Simulation analyses at baseline Detector
- Dedicated Fast simulation tool developed, and validated on Full Simulation result

Key physics performance: BMR

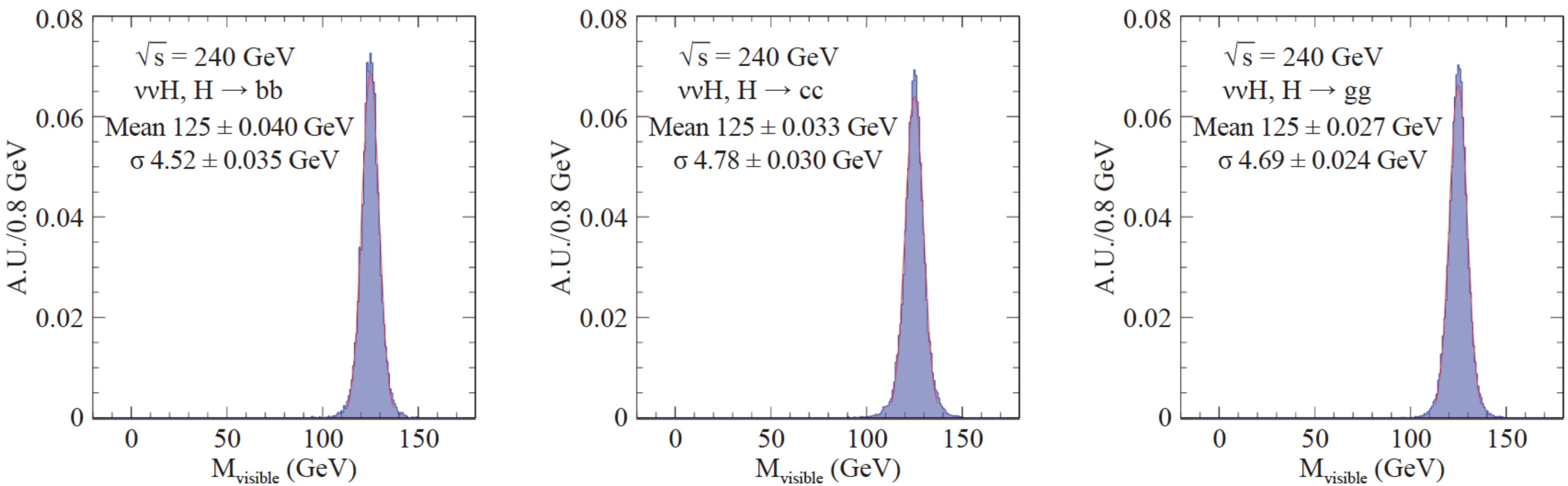
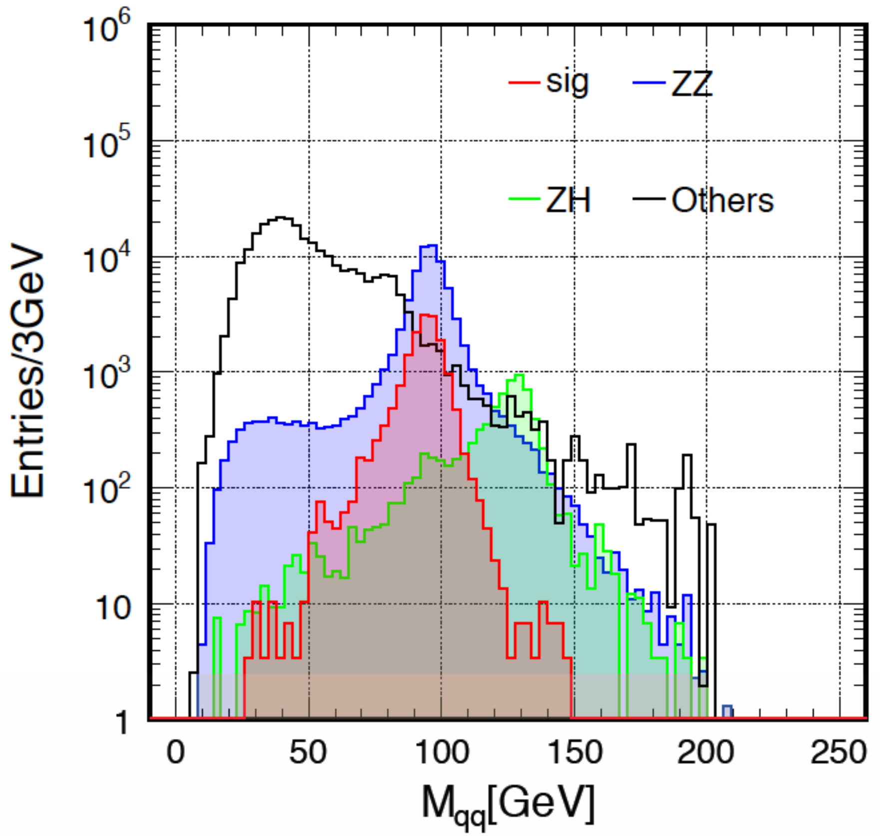
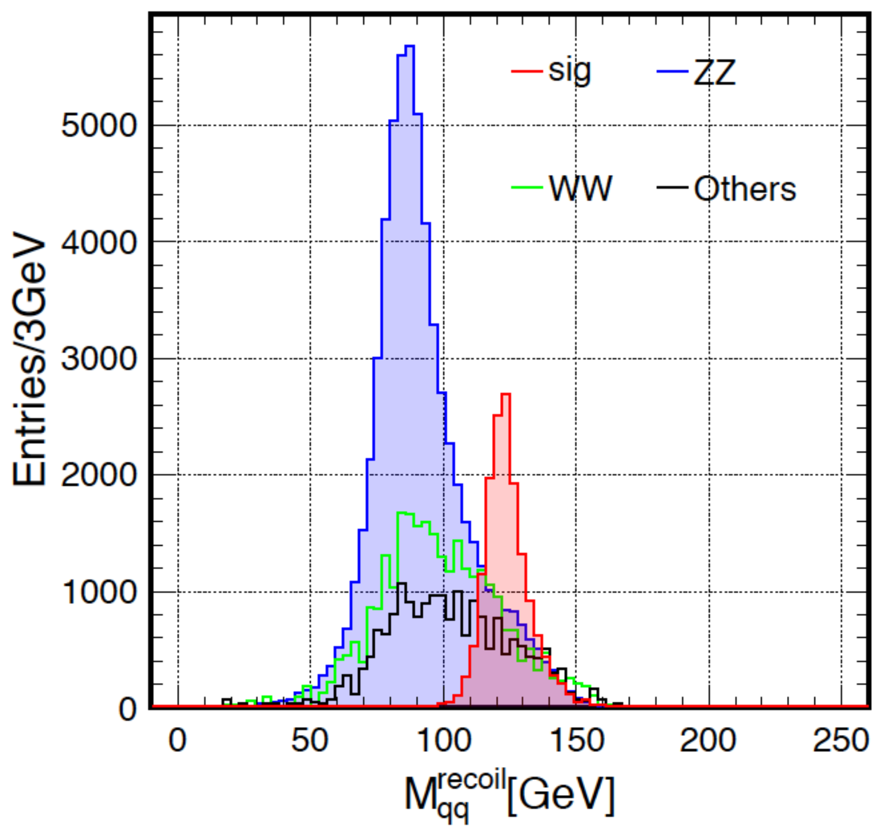


Fig. 8. (color online) Distributions of the reconstructed total visible invariant mass for $H \to bb, cc, gg$ events after event cleaning and fitted by Gaussian functions. The resolutions (sigma/mean) of the fitted results are 3.63% (*bb*), 3.82% (*cc*), and 3.75% (*gg*).

- Boson Mass resolution:
  - Characterized by the Higgs mass resolution with di-gluon final state
- Baseline reaches a BMR of 3.8%
- Fast Simulation: extract 4 momentum of the hadronic system (di-jet), smear its energy according to BMR (jet direction precision ~ 1%, negligible w.r.t energy reconstruction)

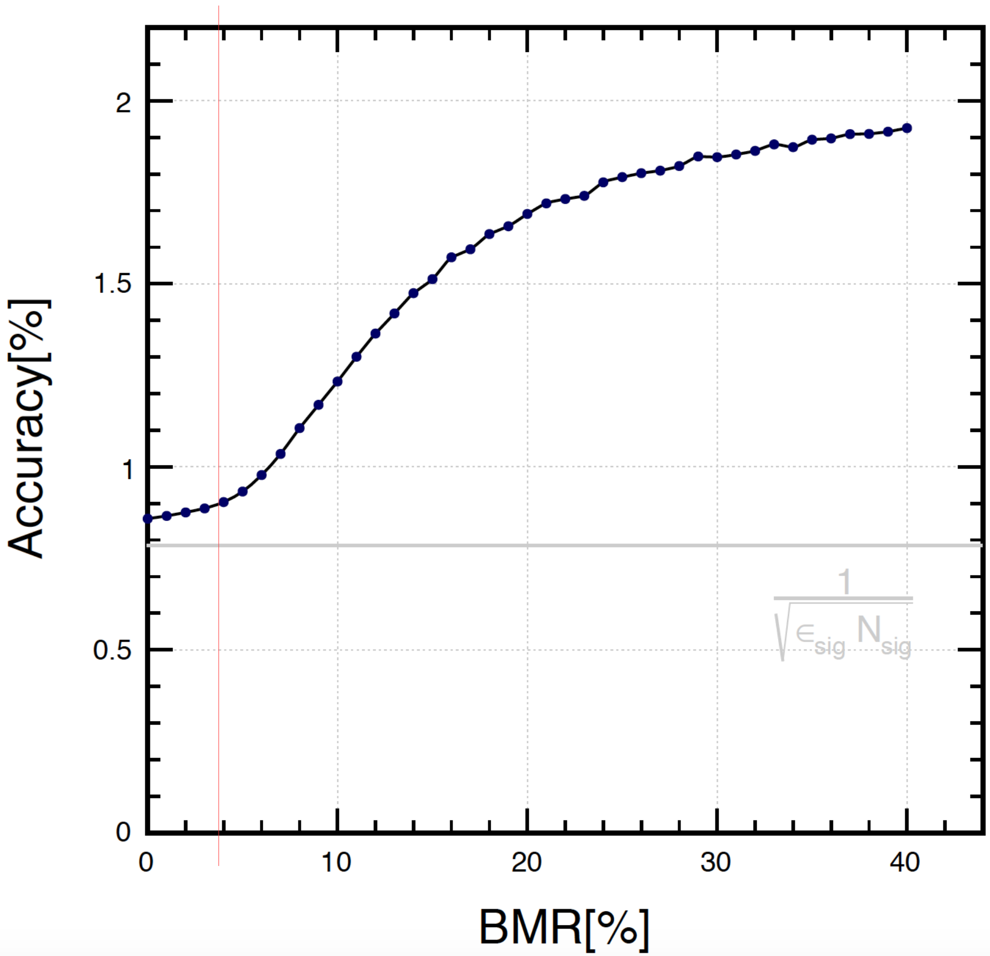
qqH, H->tautau

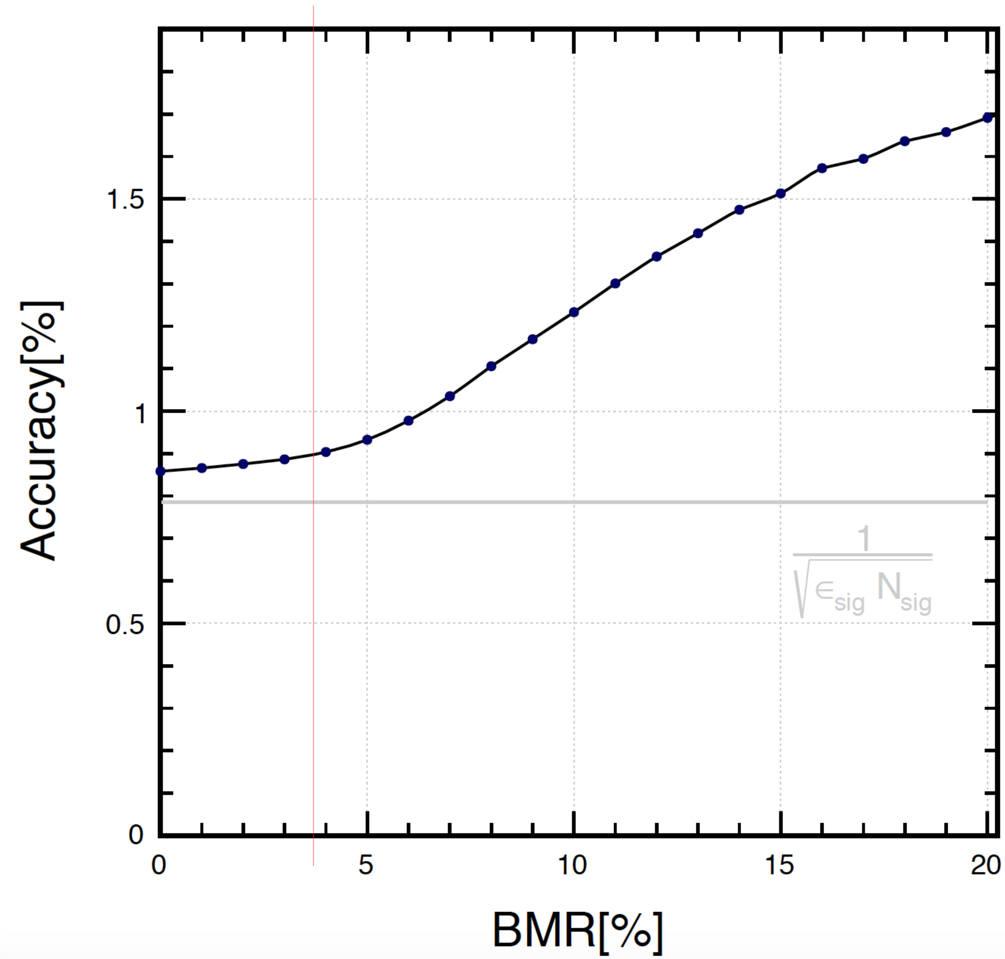




- The recoil mass of the di-jet system is essential for the separation of ZZ background

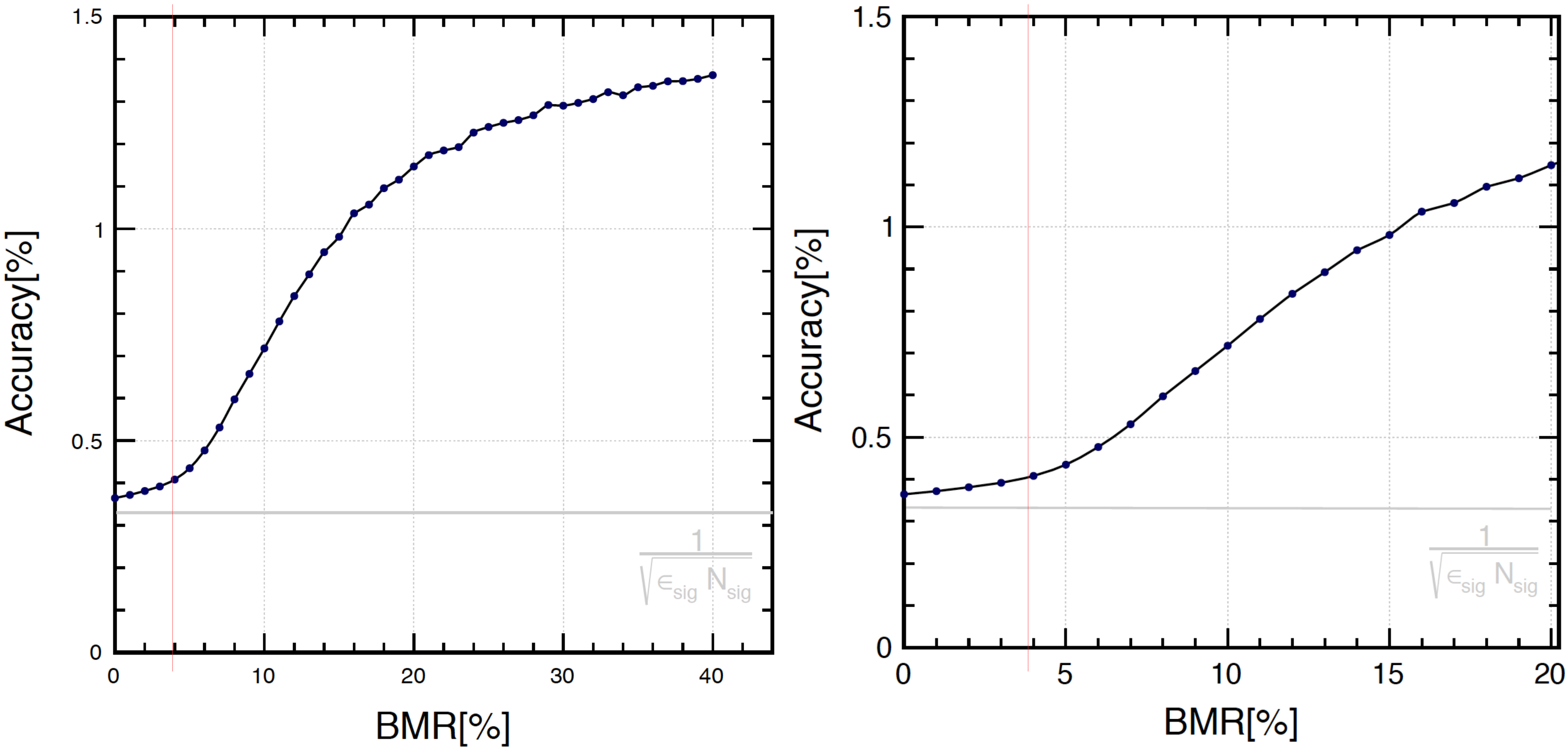
qqH, H->tautau





- Considering Only ZZ background and Normalize according to full sim result (efficiency, statistics, accuracy ~ 0.9% at BMR = 3.8%)

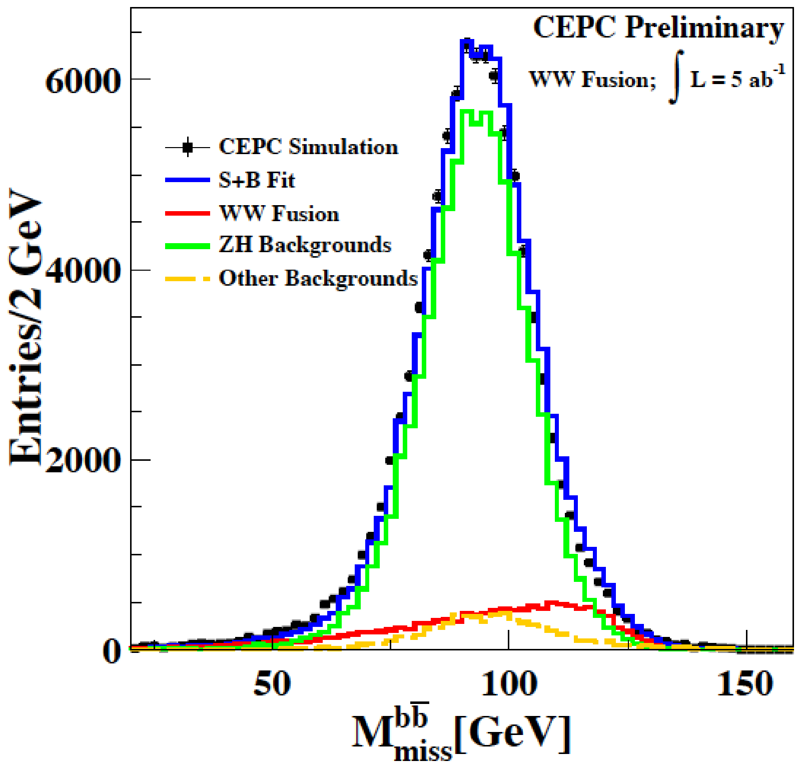
qqH, H->invisible



- Similar behavior as the ZZ is the major background
- *Y axis: accuracy at sigma(ZH)*Br(H->inv) = 100 fb*

vvH, H->bb & total width

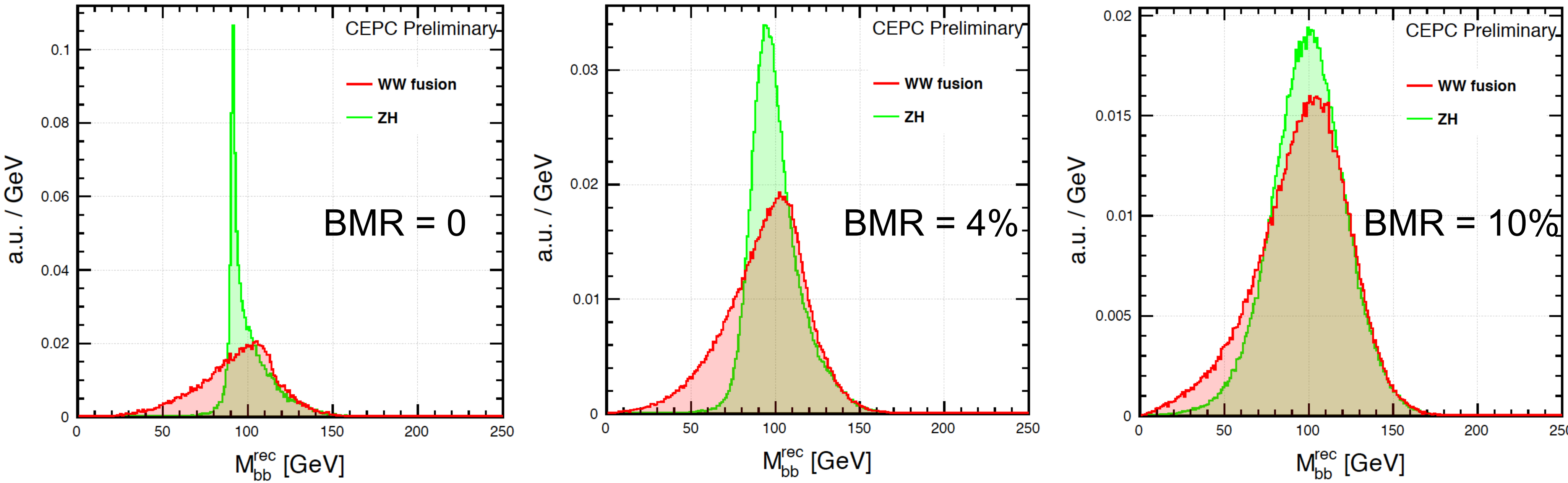
- $g^2(HXX) \sim \Gamma_{H\to XX} = \Gamma_{total} * Br(H\to XX)$
- Branching ratios: determined simply by
  - σ(ZH) and σ(ZH)*Br(H→XX)
- Γ_{total}: determined from:
  - From σ(ZH) (~g^2(HZZ)) and σ(ZH)*Br(H→ZZ) (~$g^4(HZZ)/\Gamma_{total}$)
  - From σ(ZH)*Br(H→bb), σ(vvH)*Br(H→bb), σ(ZH)*Br(H→WW), σ(ZH)



A combined accuracy of 2.8% for the Higgs total width measurements; dominated by W fusion measurement (with accuracy of 2.6%)

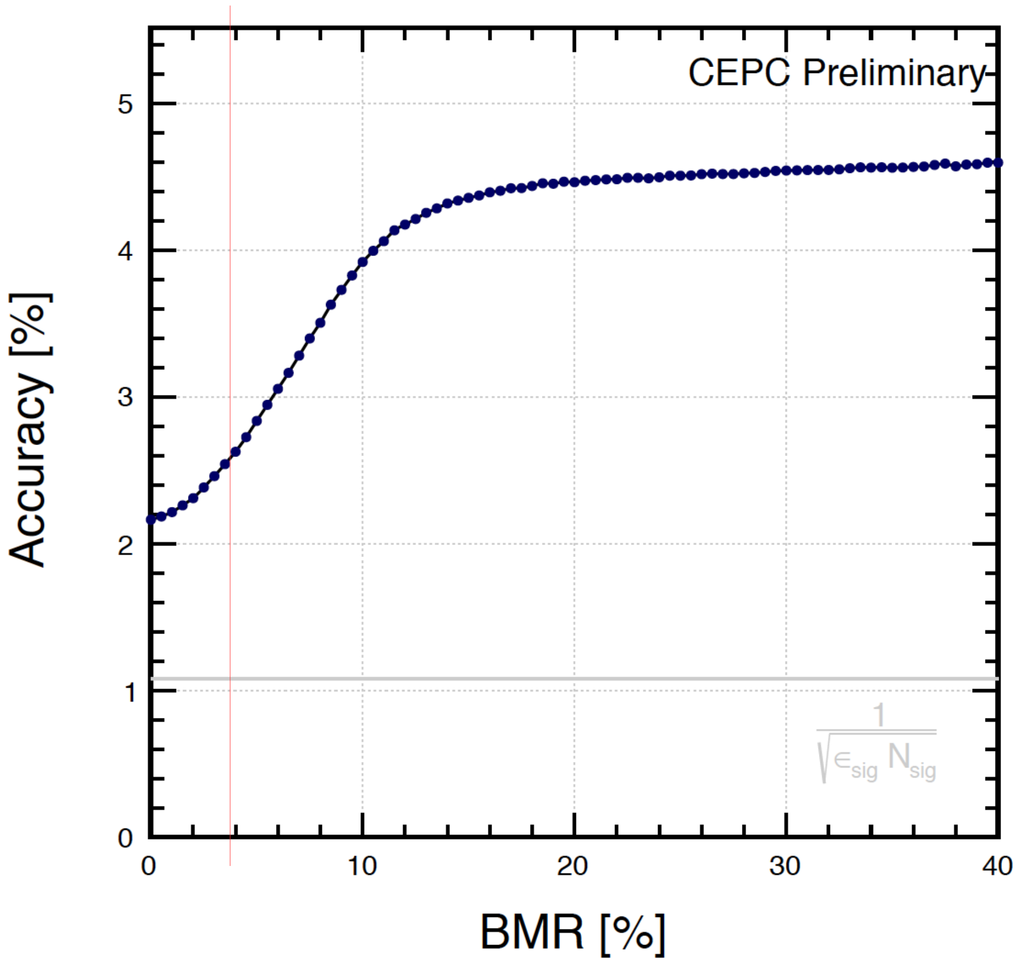
σ(vvH)*Br(H->bb): major background are ZZ and ZH (Z->vv)

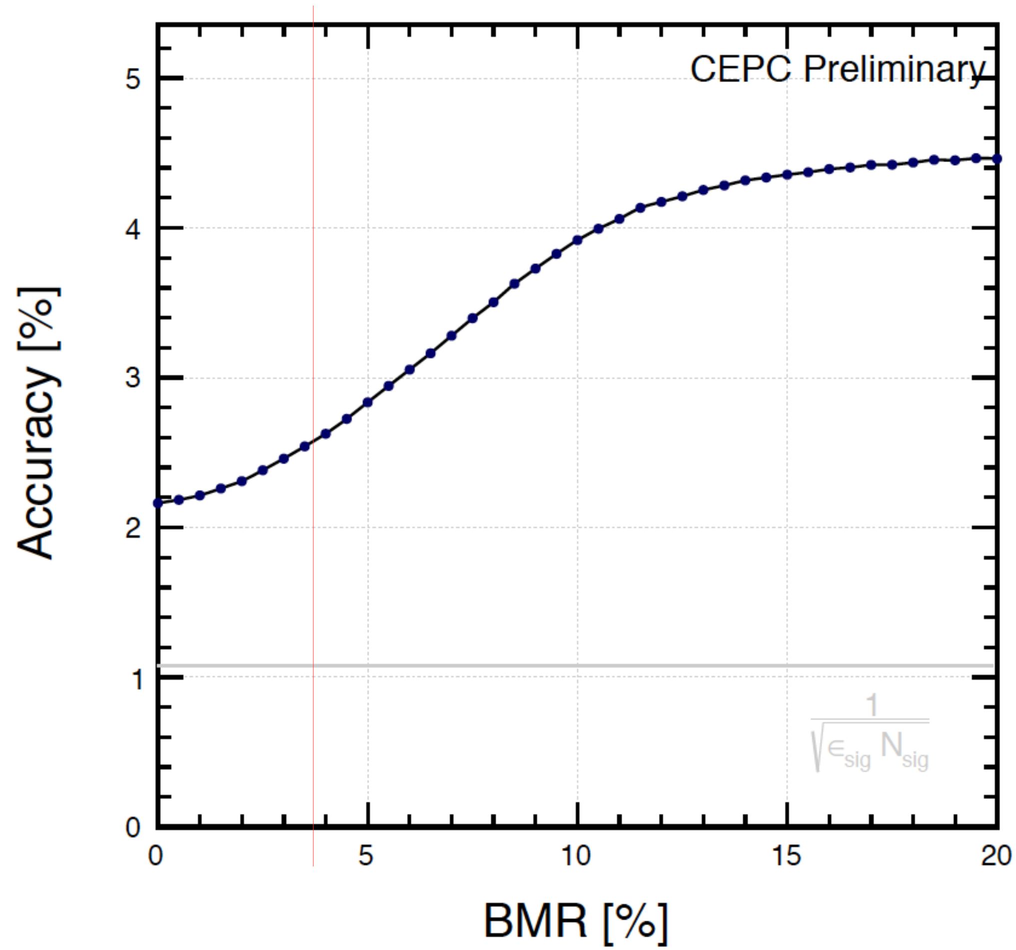
Recoil mass PDF at different BMR



PS: at 240 GeV center of mass energy, the Xsec of ZH, Z->vv is 7 times larger than The W fusion (40/5.4 fb)

vvH, H->bb





- Similar behavior as the ZZ is the major background
- *Y axis: accuracy at sigma(ZH)*Br(H->inv) = 100 fb*

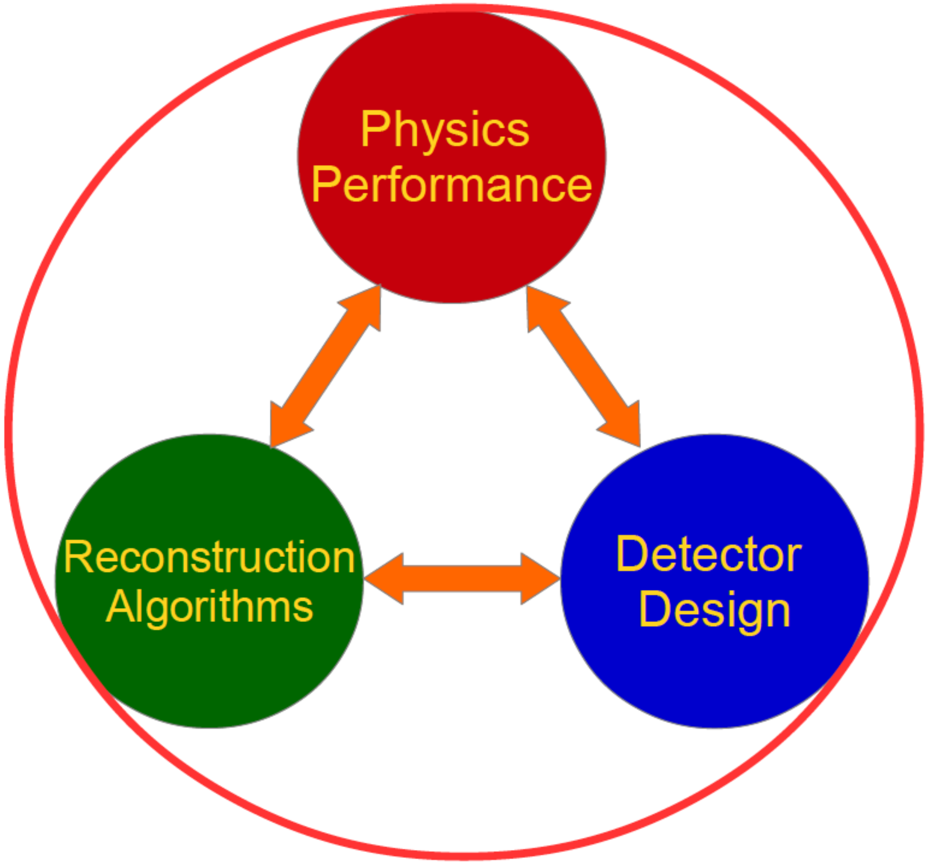
2-jet Higgs benchmarks at 240 GeV

	BMR = 2%	4%	6%	8%
σ(vvH, H→bb)	2.3%	2.6%	3.0%	3.4%
σ(qqH, H→inv)	0.38%	0.4%	0.5%	0.6%
σ(qqH, H→ττ)	0.85%	0.9%	1.0%	1.1%

- From qqH, H->inv/tautau: BMR < 4%
- From W fusion: should pursue better BMR even up to 2%...

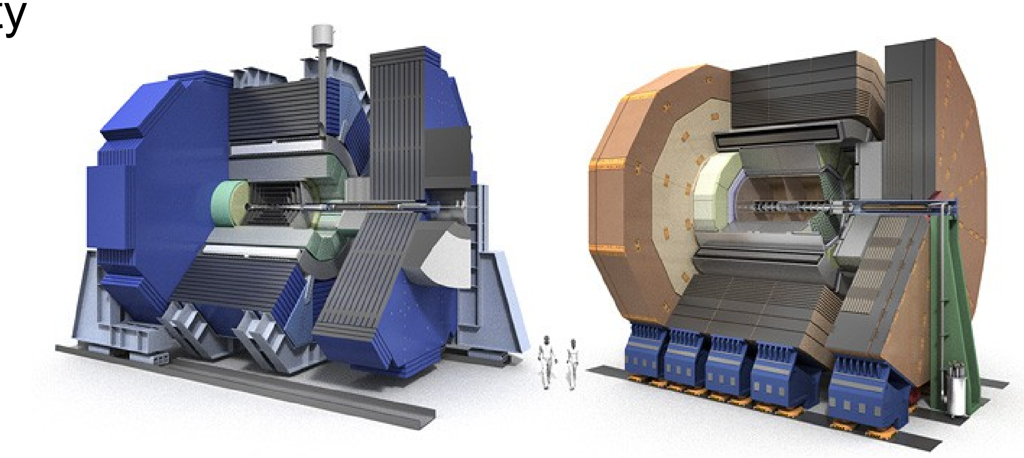
Performance at the CDR baseline

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

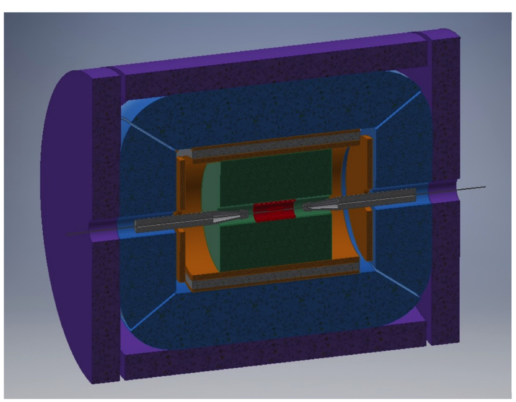


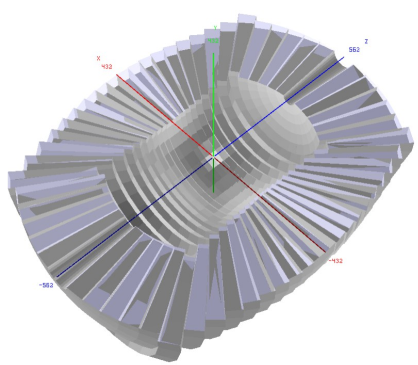
Two classes of Concepts

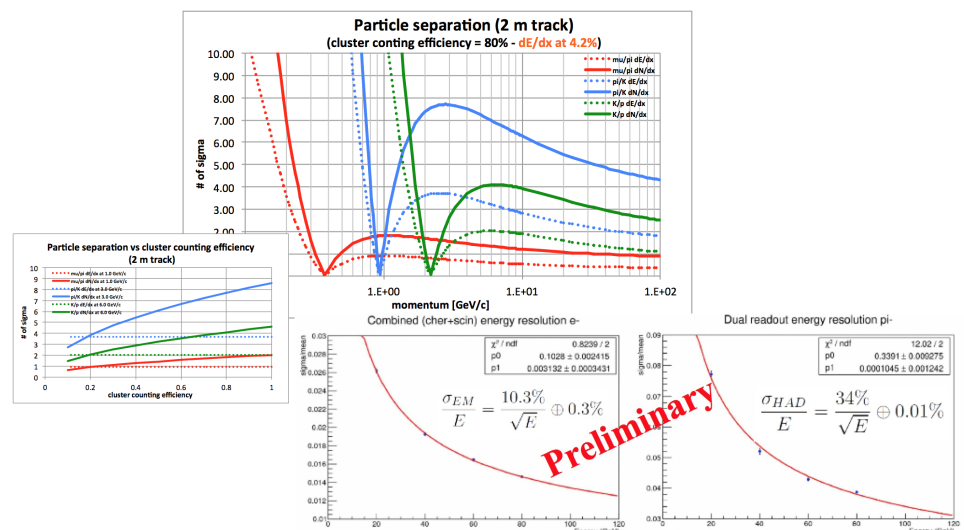
- PFA Oriented concept using High Granularity Calorimeter
  - **+ TPC (ILD-like, Baseline)**
  - + Silicon tracking (SiD-like)



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



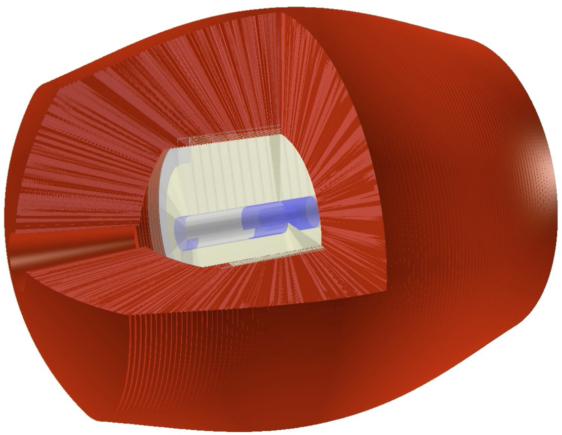


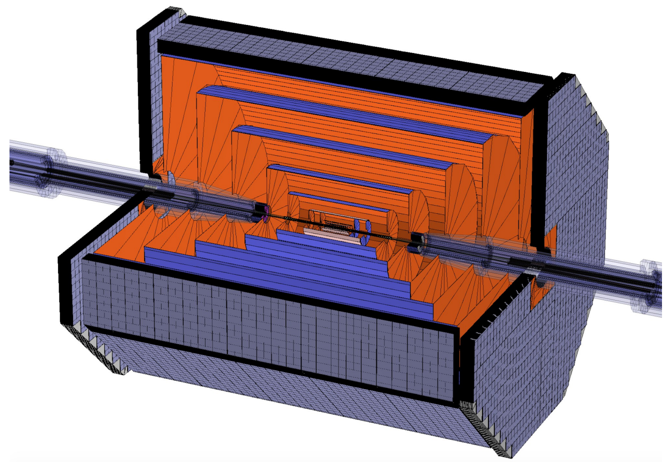


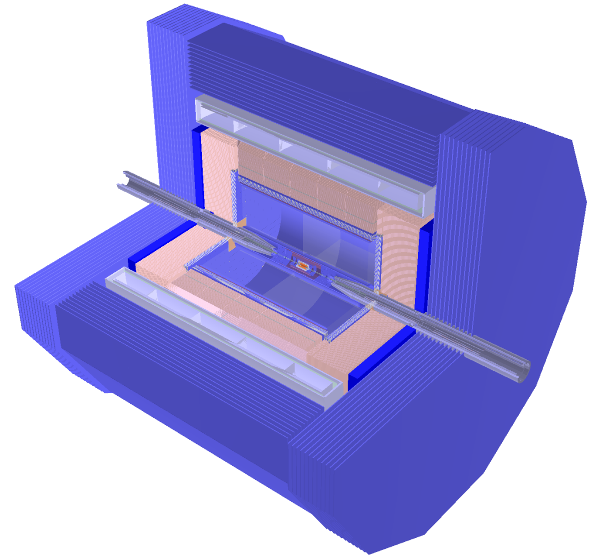
https://indico.ihep.ac.cn/event/6618/

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

Status of simulation-performance study

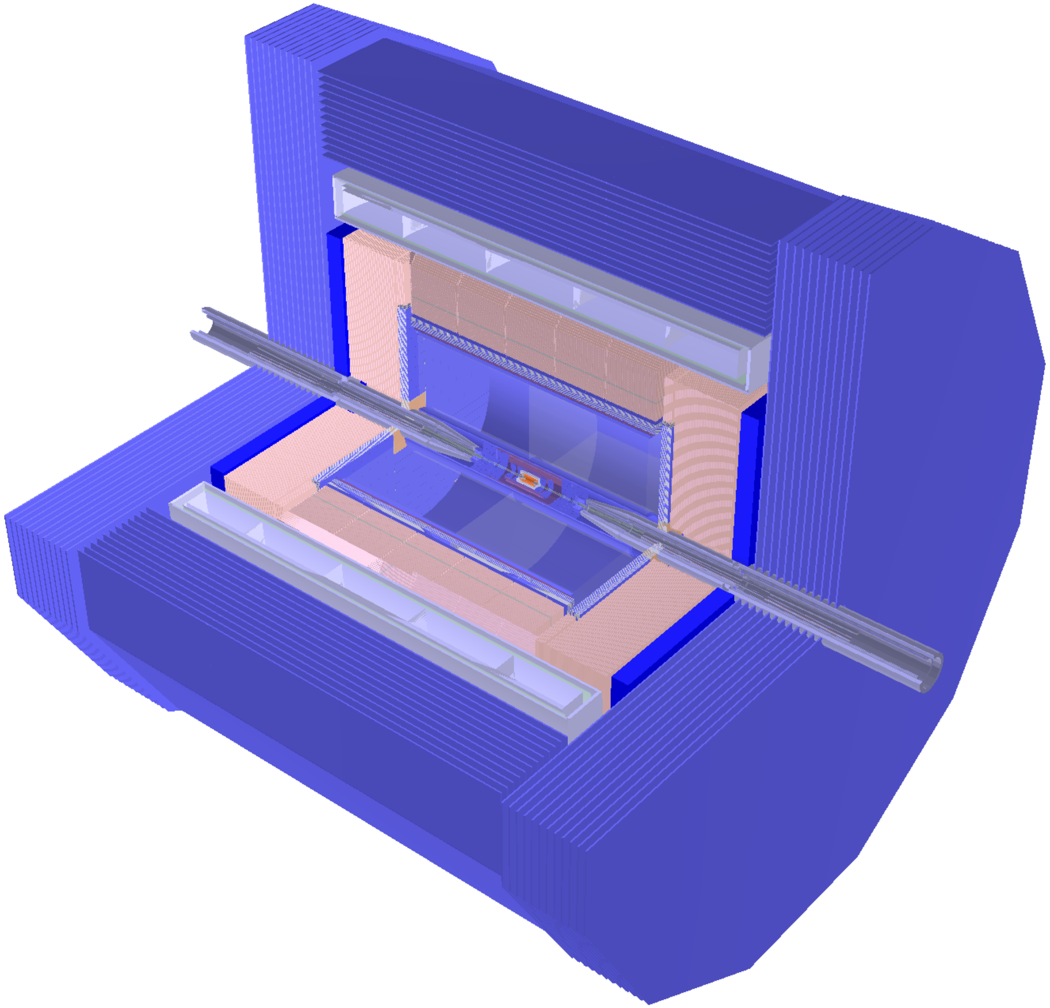


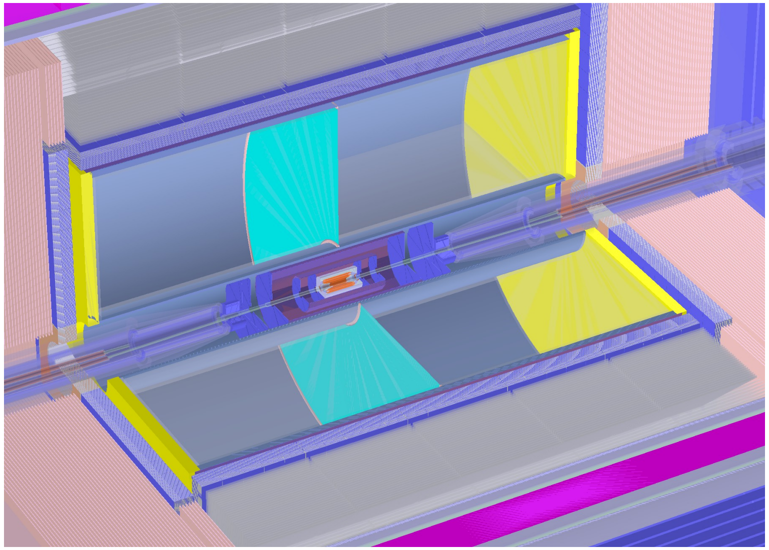


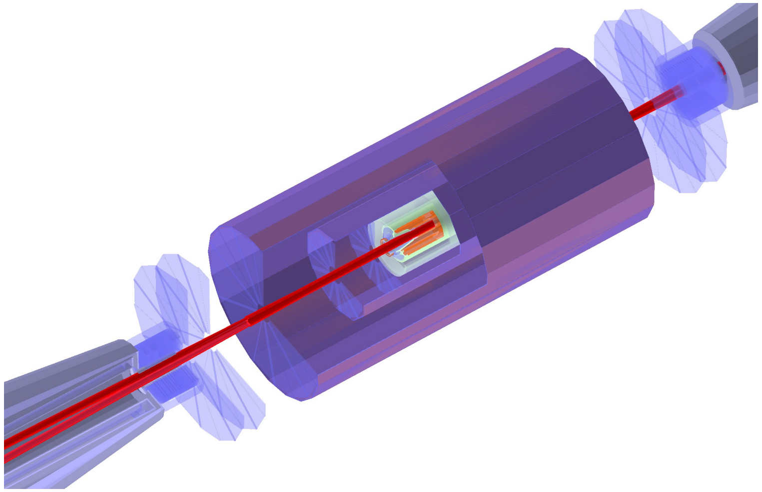


	Geant4-Simulation	Digitization	Reconstruction	Performance-Object	Performance-Benchmark
IDEA					
Full-Silicon					
APODIS					

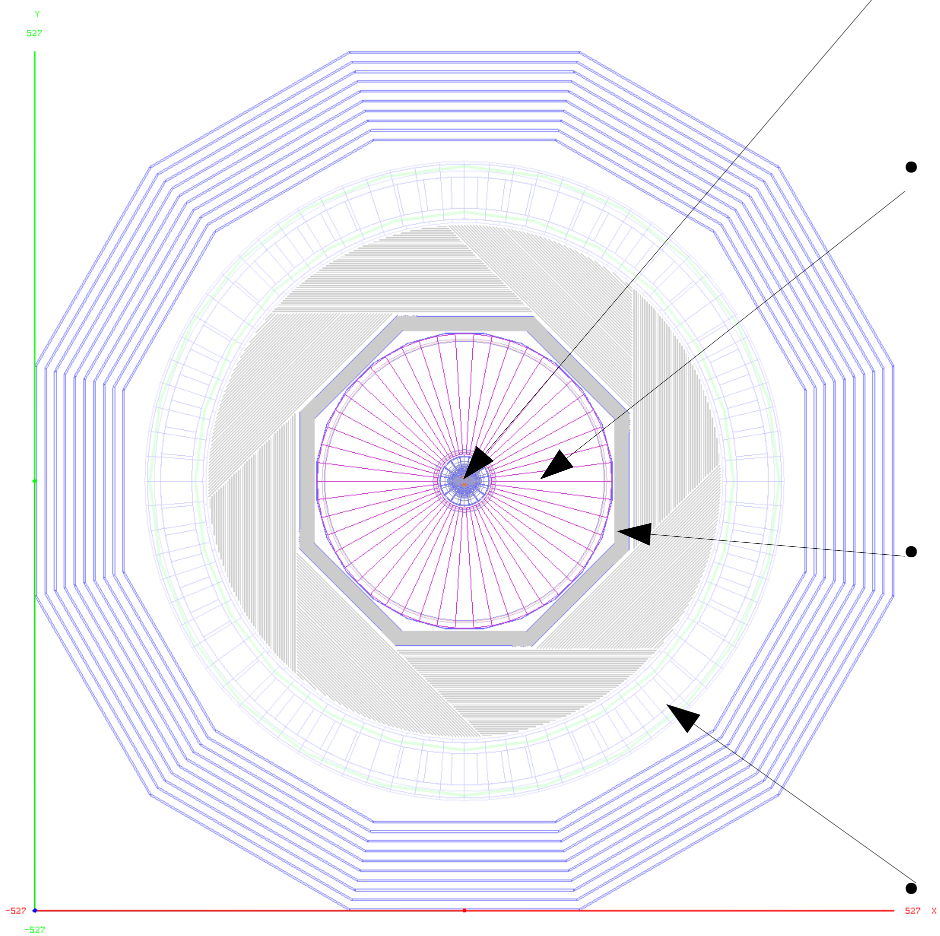
CEPC Baseline Detector





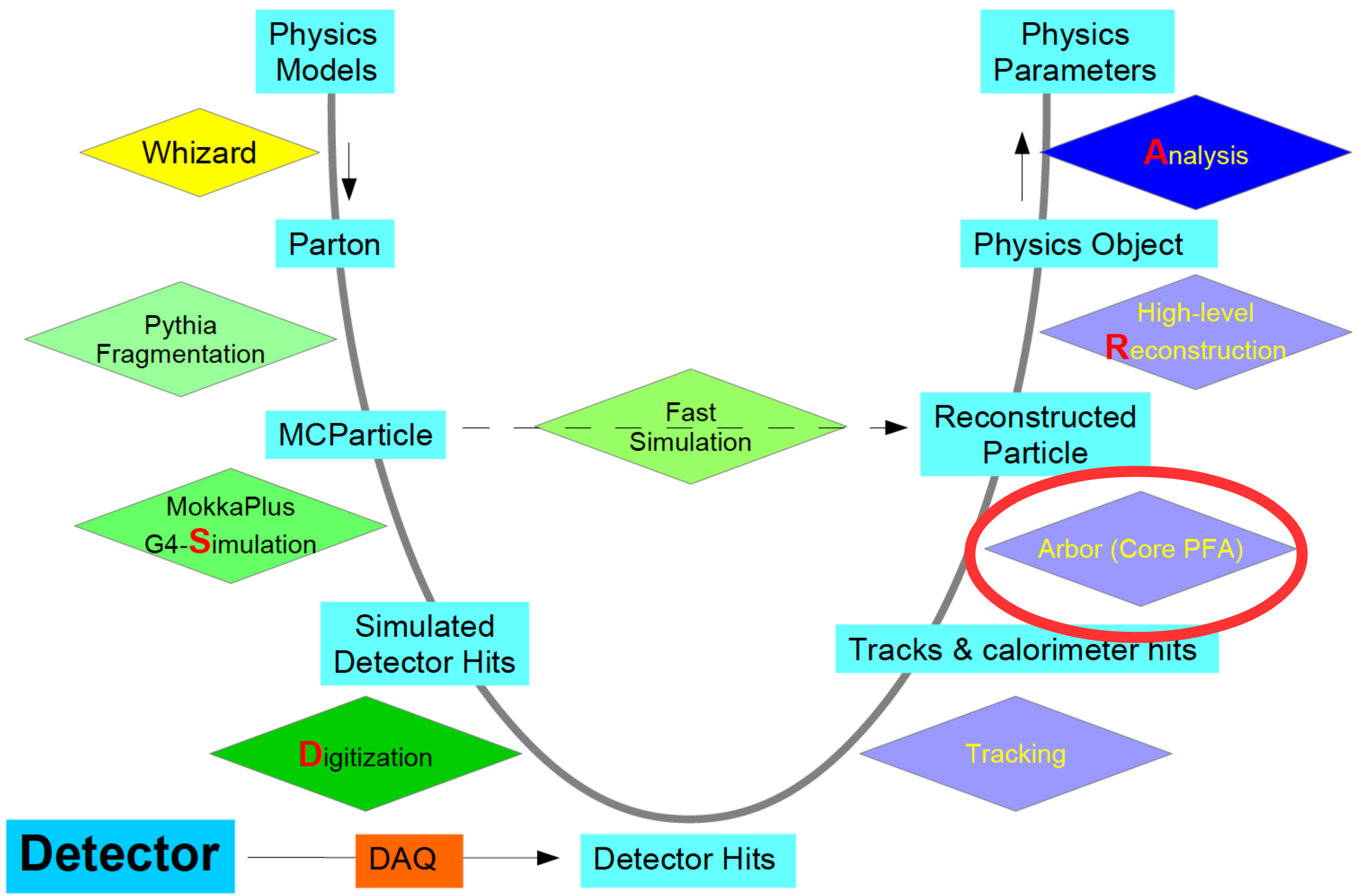


An ILD-like detector at the CEPC



- 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

CEPC Baseline Software

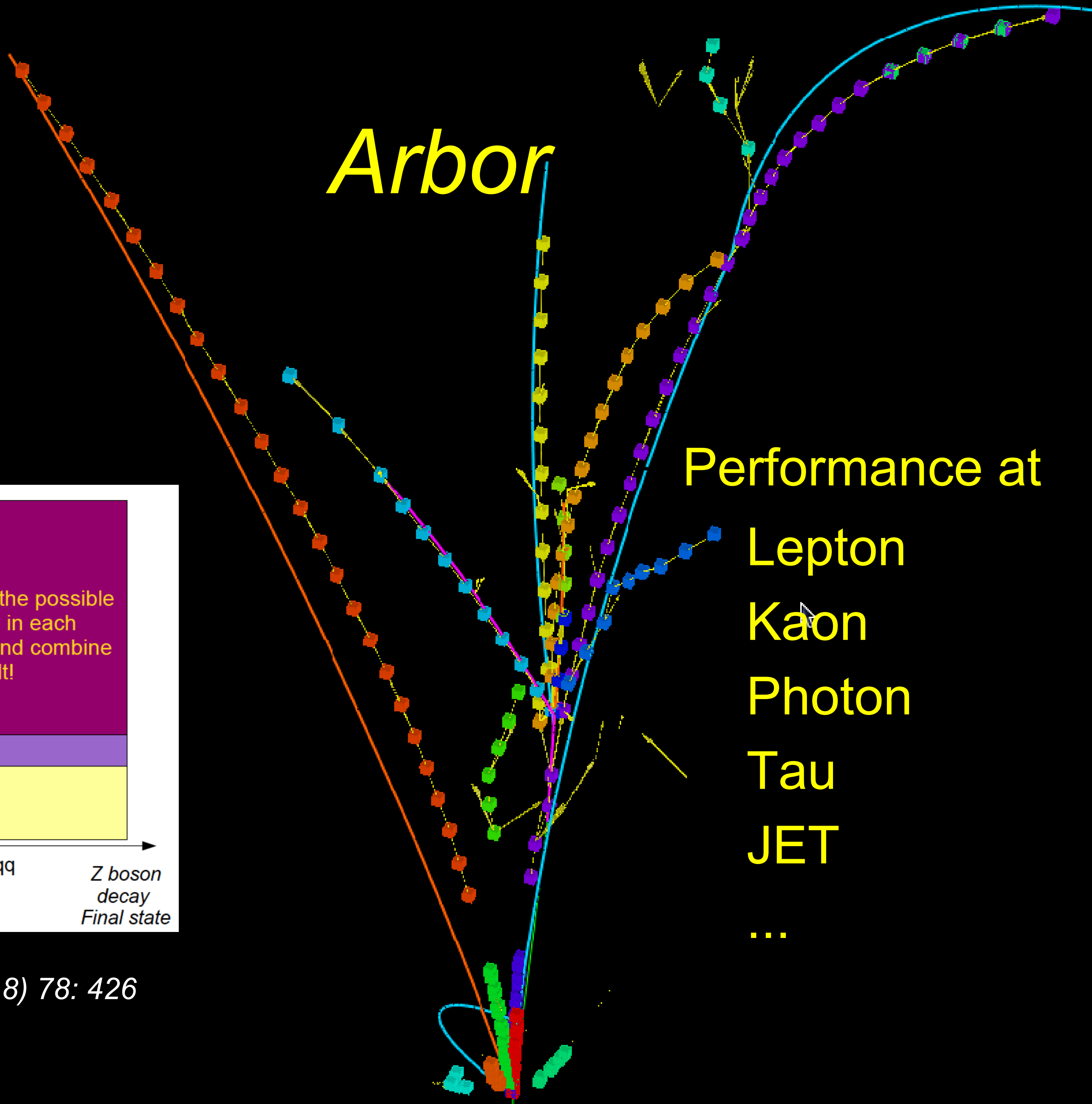


- Generators (Whizard & Pythia)
- Data format & management (LCIO & Marlin)
- Simulation (MokkaC)
- Digitizations
- Tracking
- PFA (Arbor)
- Single Particle Physics Objects Finder (LICH)
- Composed object finder (Coral)
- Tau finder
- Jet Clustering (FastJet)
- Jet Flavor Tagging (LCFIPLus)
- Event Display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

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

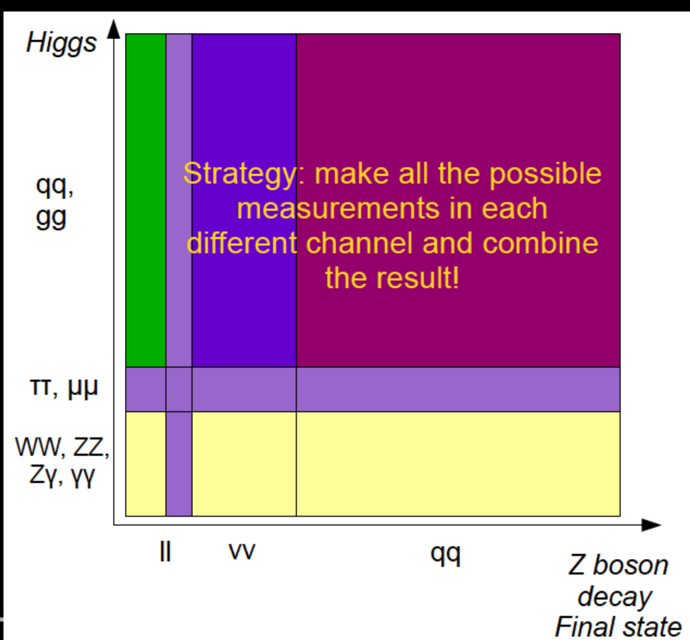
General Software | ILCSoft | ILCSoft + Development | Developments

Arbor



Performance at

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



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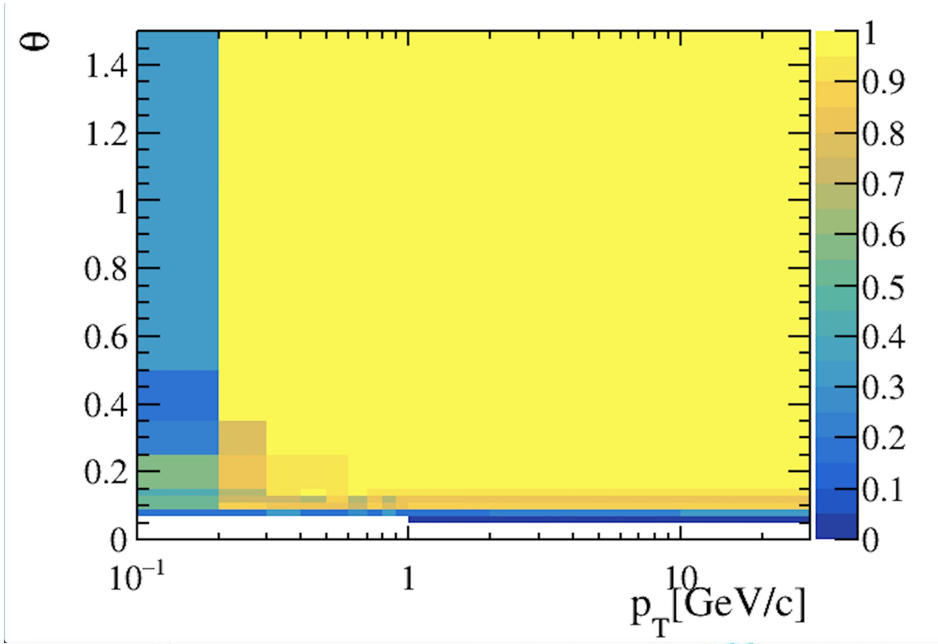
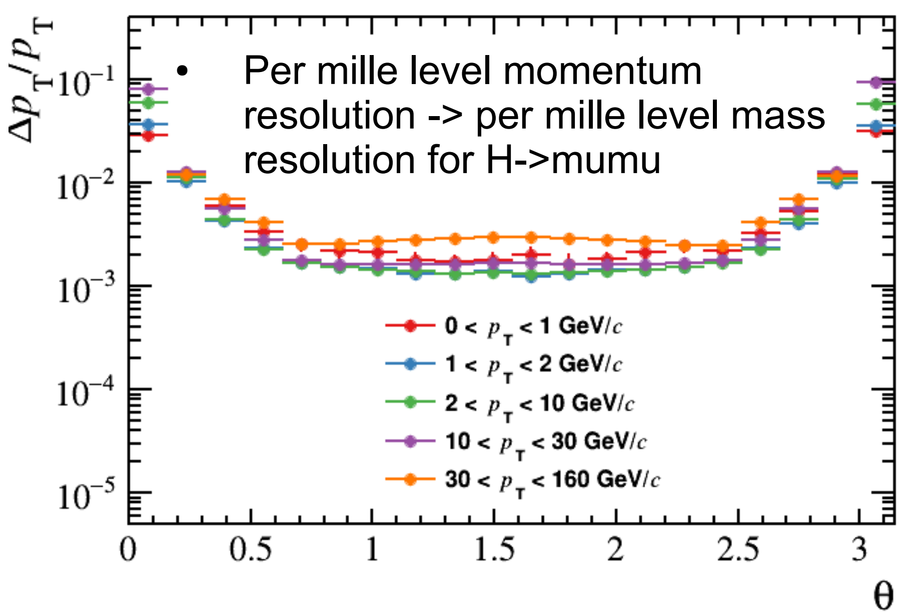
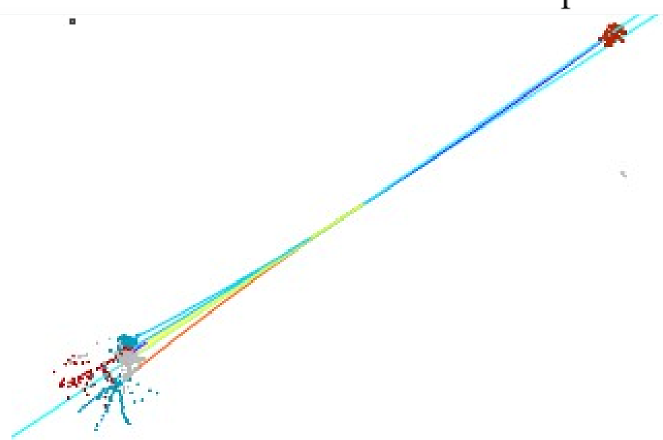
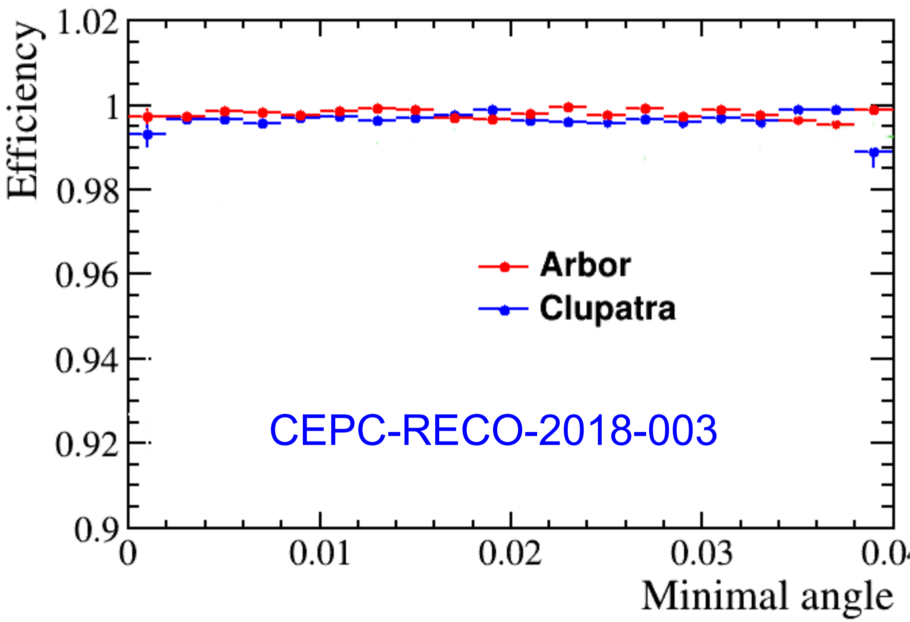
Tracking



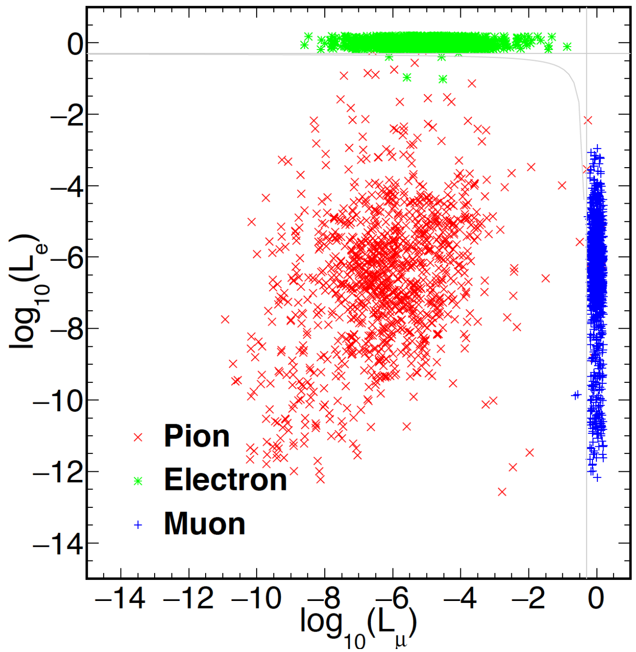


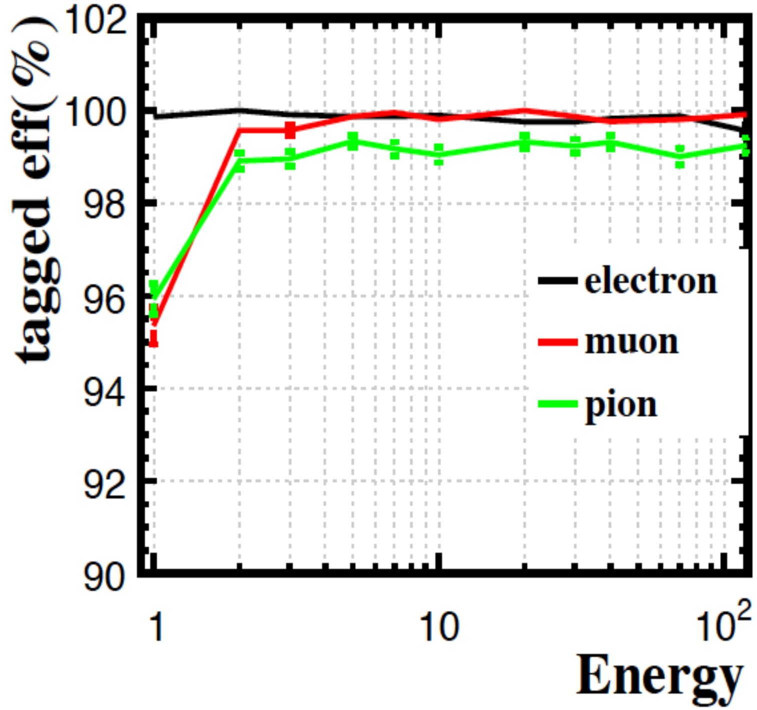


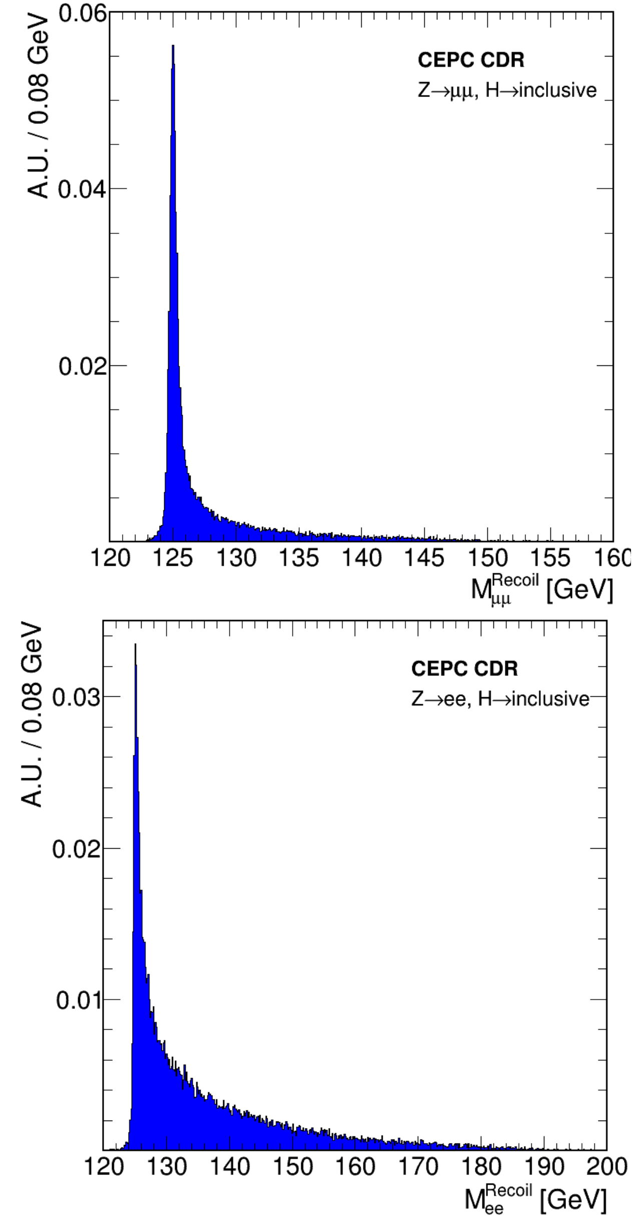
Mingrui Zhao. CEPC CDR



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%

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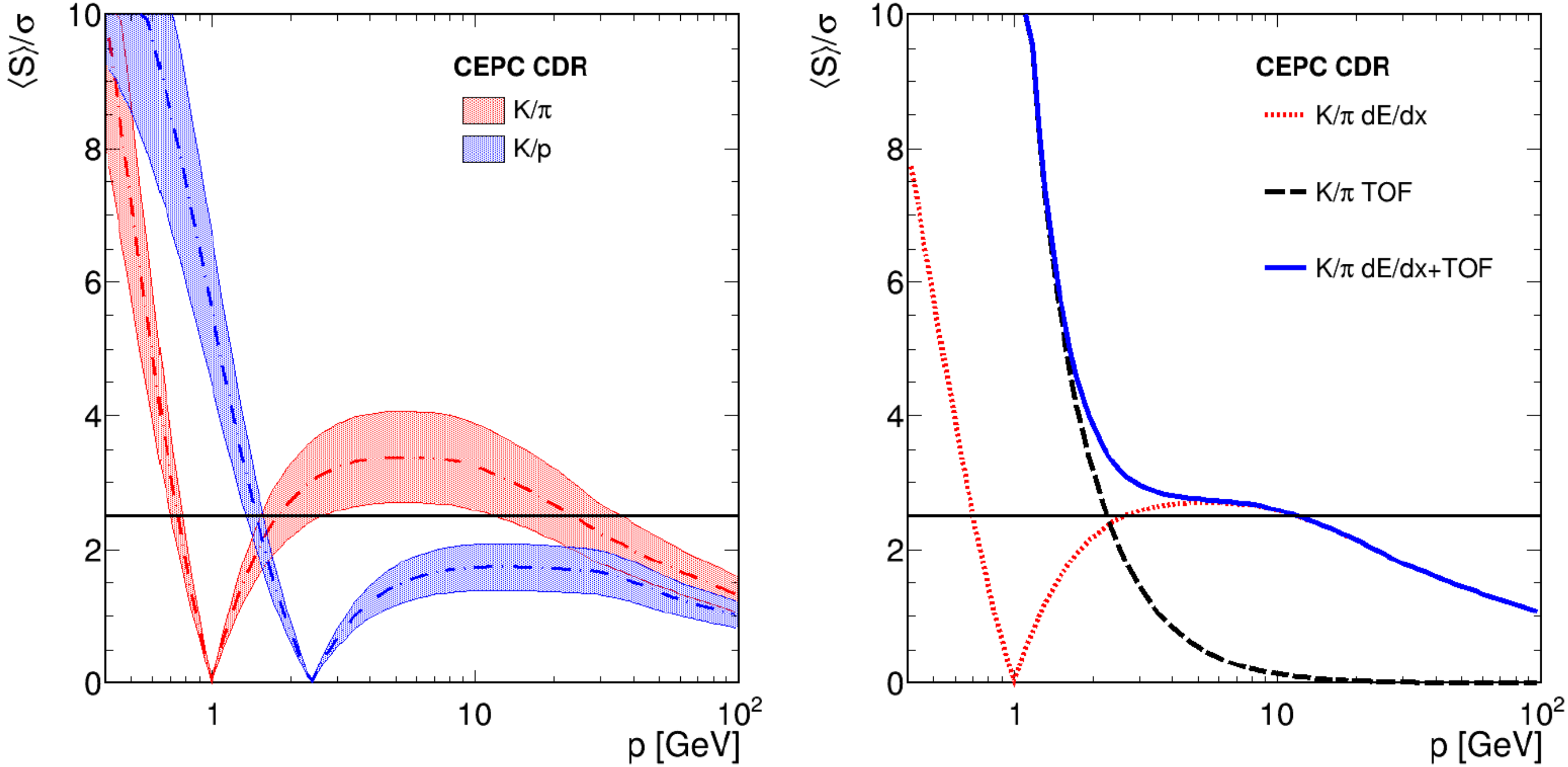
Kaon



Highly appreciated in flavor physics @ CEPC Z pole

- TPC dEdx + ToF of 50 ps

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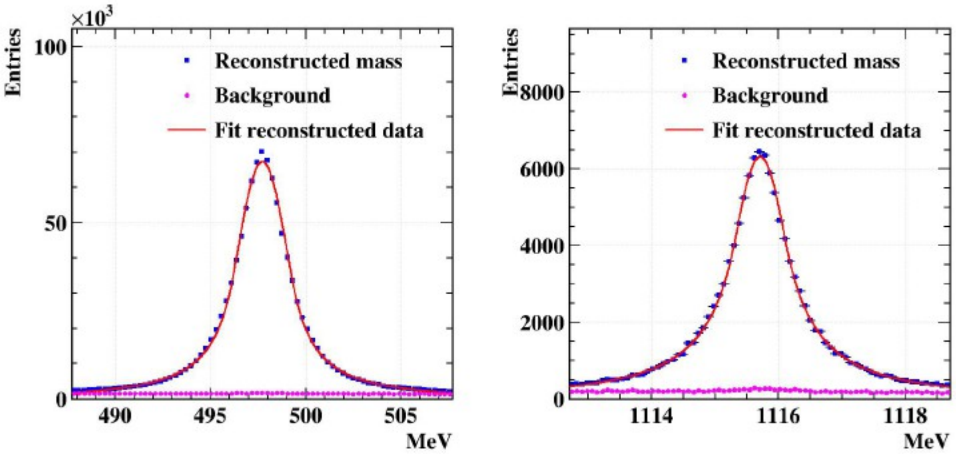
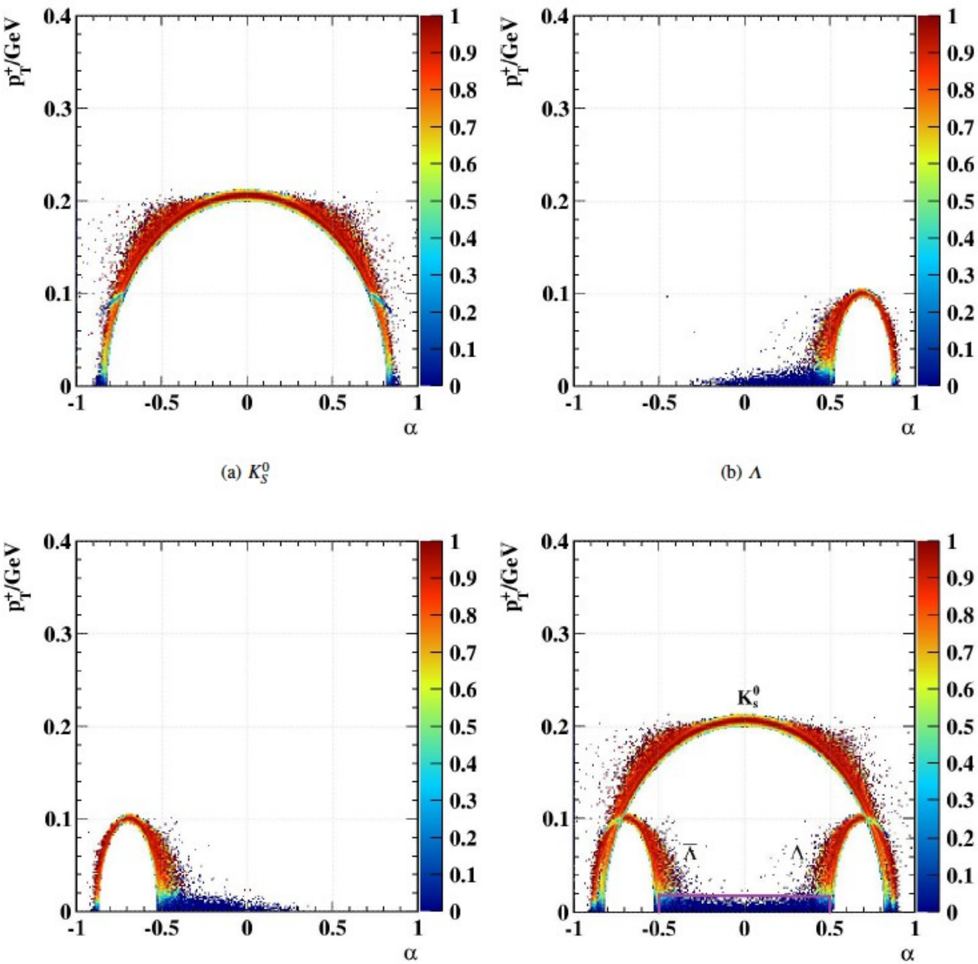
At inclusive Z pole sample:

- 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)

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



(a) K_S^0. (b) Λ.



(a) K_S^0 (b) Λ (c) $\bar{\Lambda}$ (d) All 3 particles

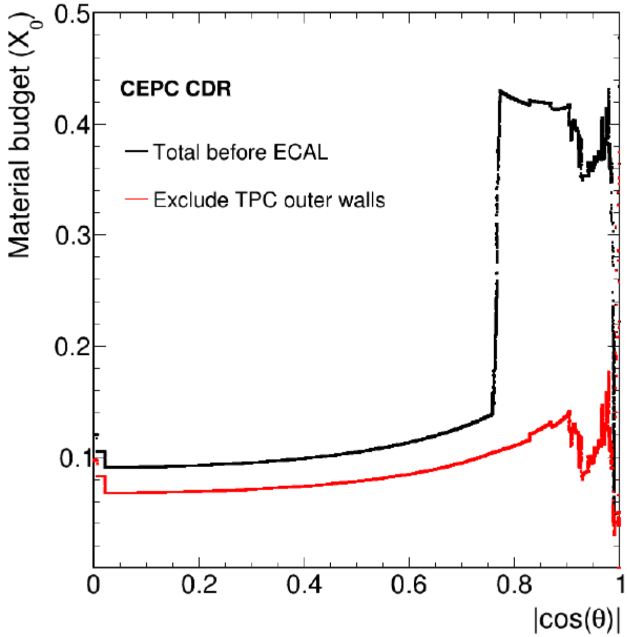
Table 3: K_S^0 and Λ reconstruction performance.

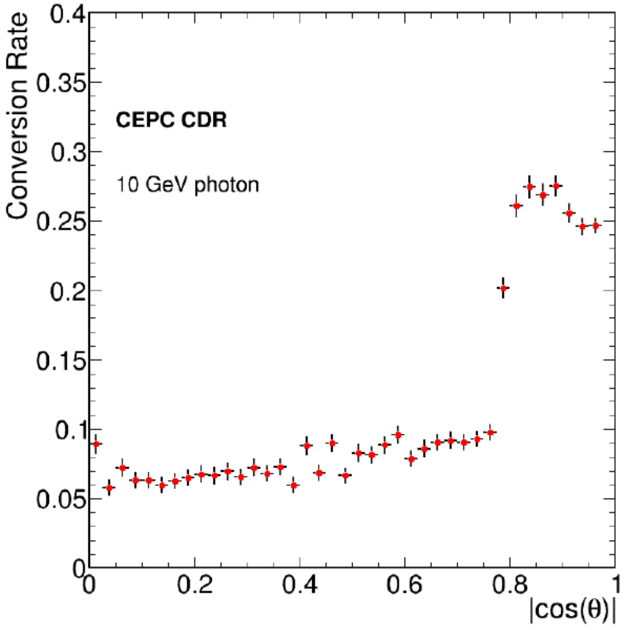
Particle	K_S^0	Λ
ε_R	79.7%	65.1%
ε_T	39.8%	25.5%
P	89.7%	87.9%
$\varepsilon_R \cdot P$	0.715	0.572
$\varepsilon_T \cdot P$	0.357	0.224

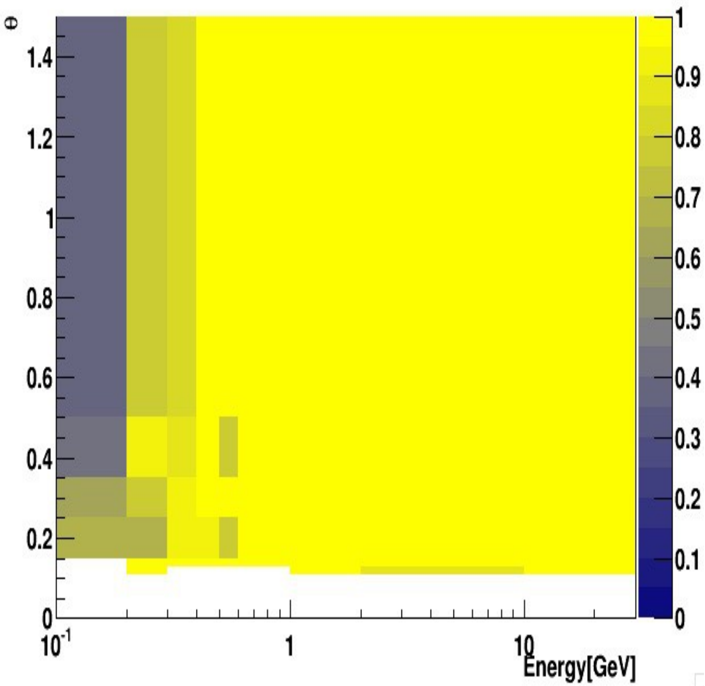
Taifan Zhen

Statistic uncertainty of the mass/life time ~ 1 keV/0.3 ps

Photons – conversion & efficiency



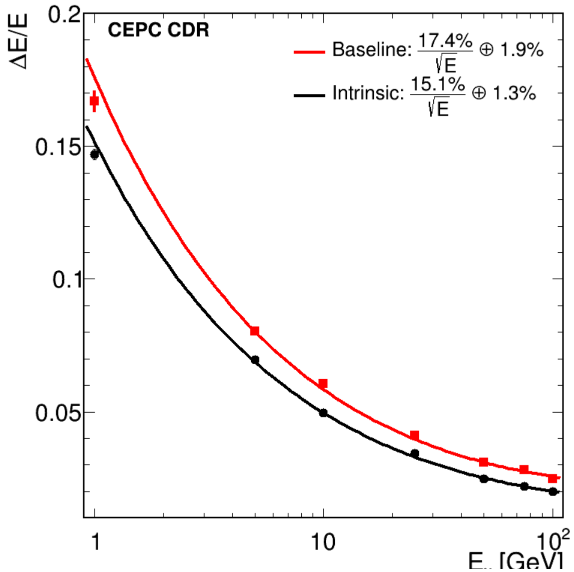


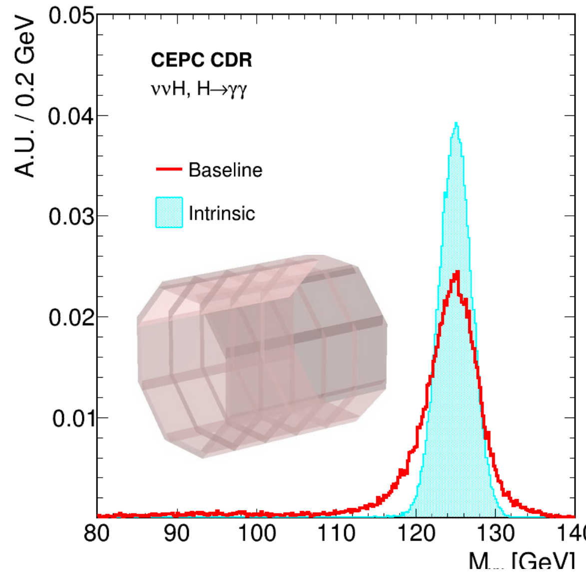


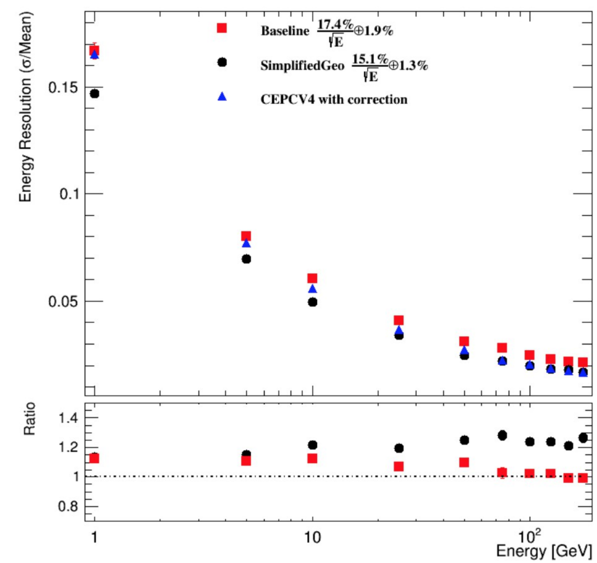
In the barrel region: Roughly 6-10% of the photons converts before reaching the Calorimeter.

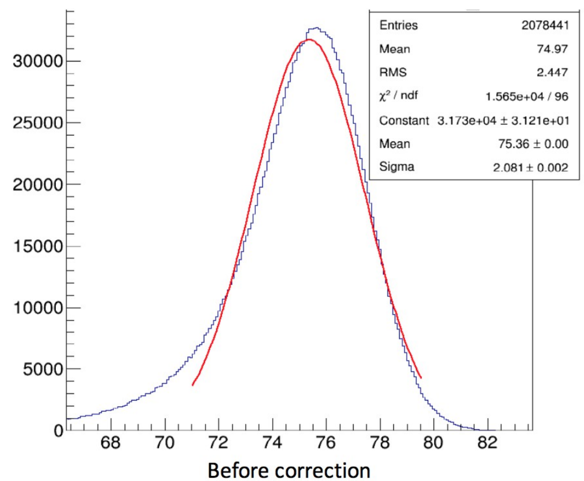
For the unconverted photon: A critical energy of 200 MeV is observed.

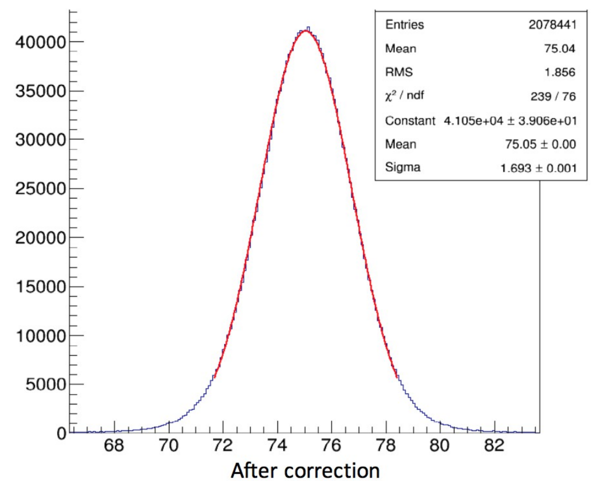
Photon: resolution







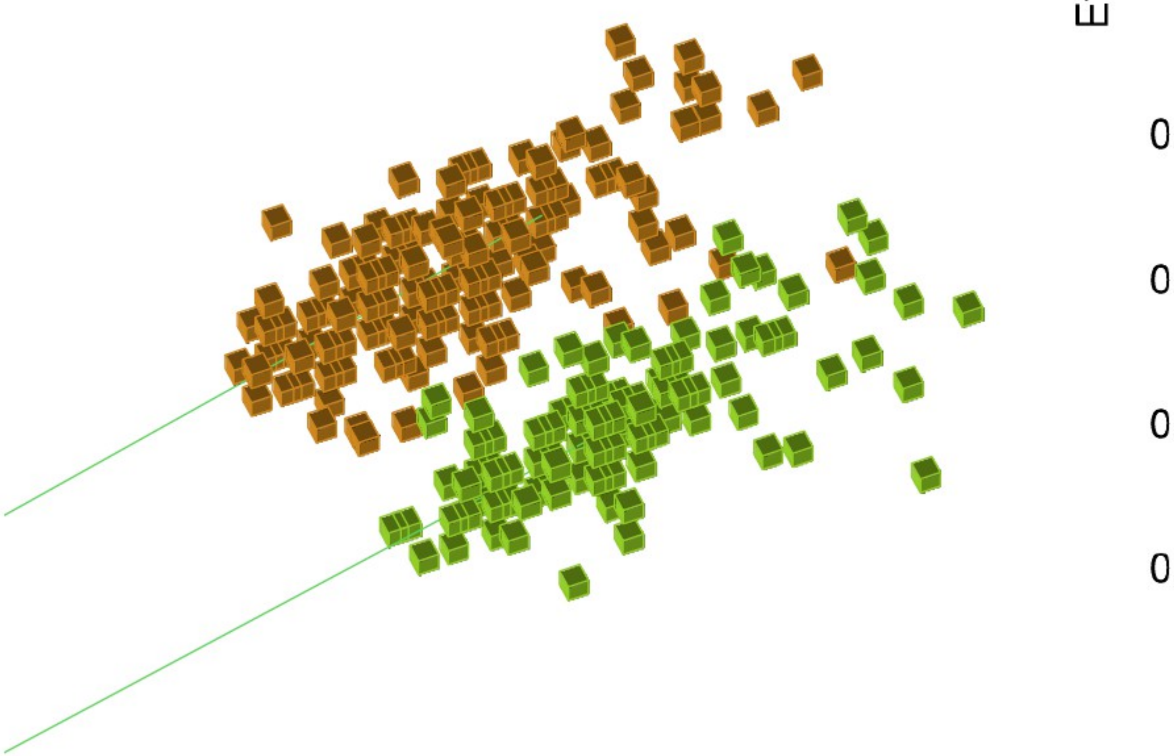


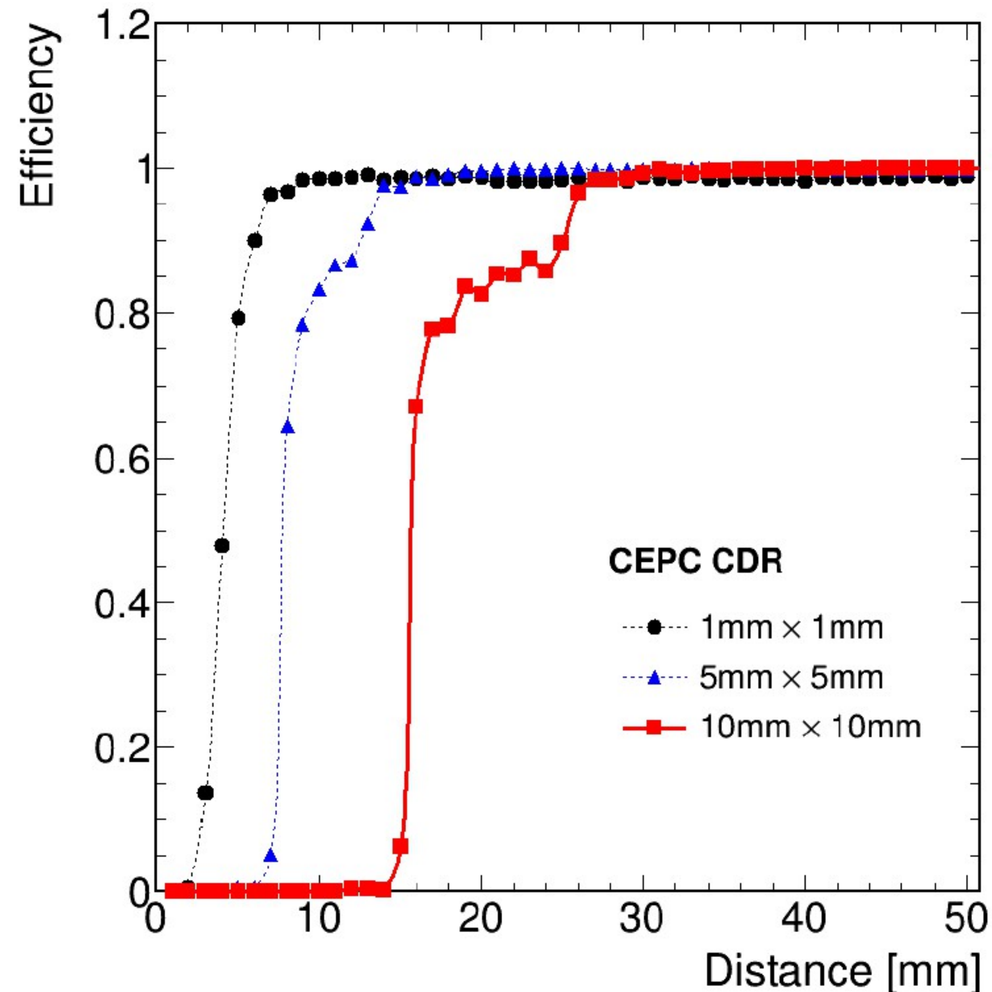


- A Higgs mass resolution of 1.7/2.5% is achieved in the Higgs to di-photon final states with simplified/baseline geometry
- The geometry defects correction could be efficiently corrected (Preliminary)

Yuqiao Shen & CEPC CDR

Clustering - Separation

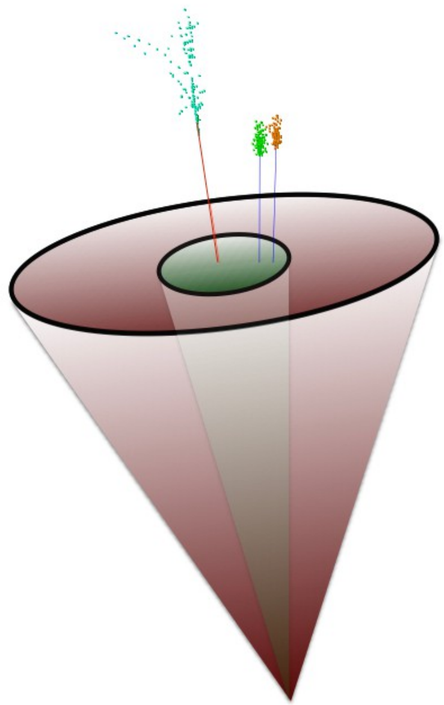


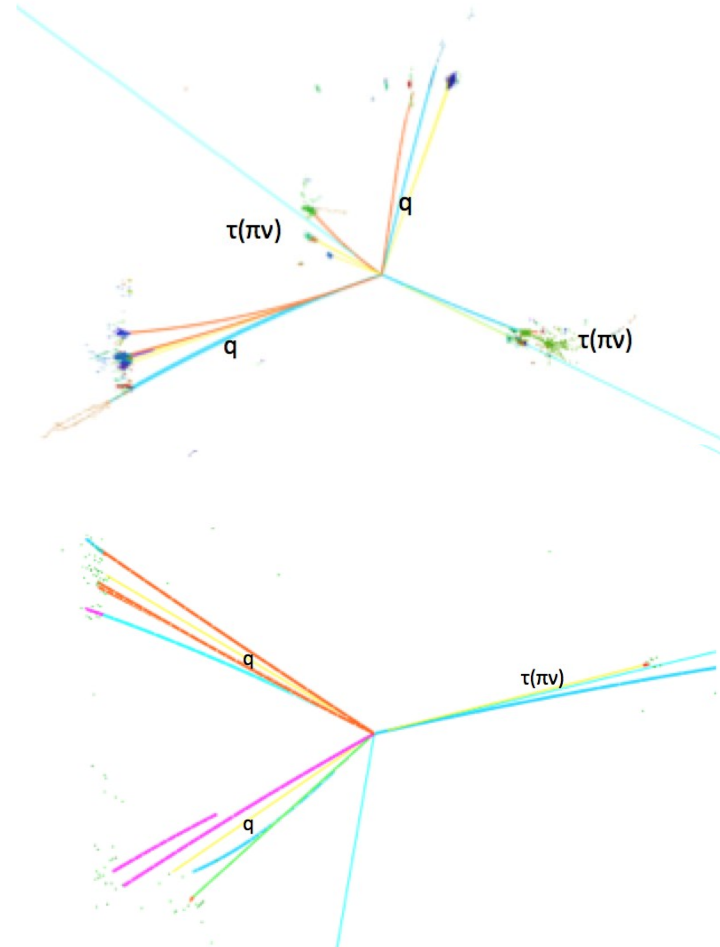


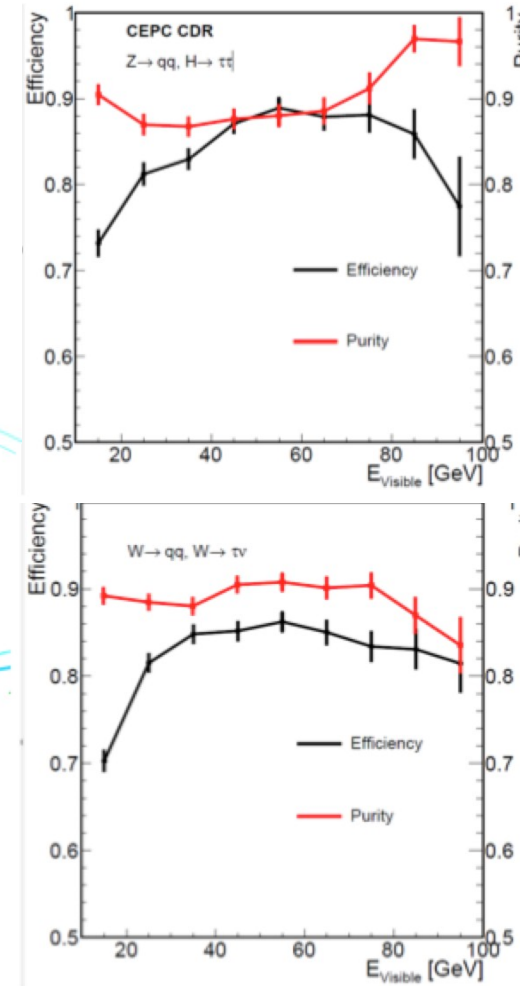
Critical energy to separate an evenly decay π_0: 30 GeV

Hang Zhao. CEPC CDR

Tau finding at hadronic events



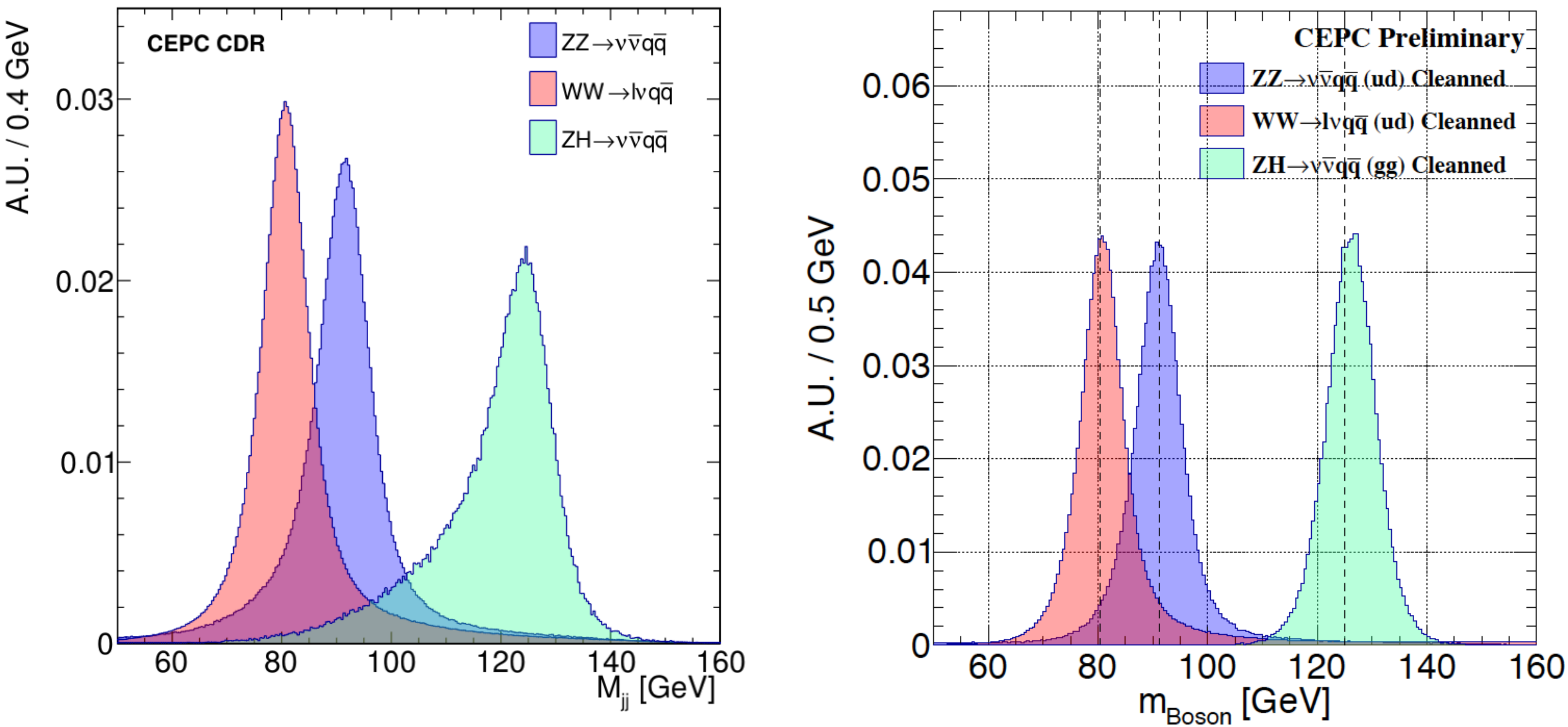




TAURUS (Tau ReconstrUction toolS):
an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

Zhigang Wu, CEPC CDR

JETS: BMS of 3.8% reached, enables Massive Boson Separation

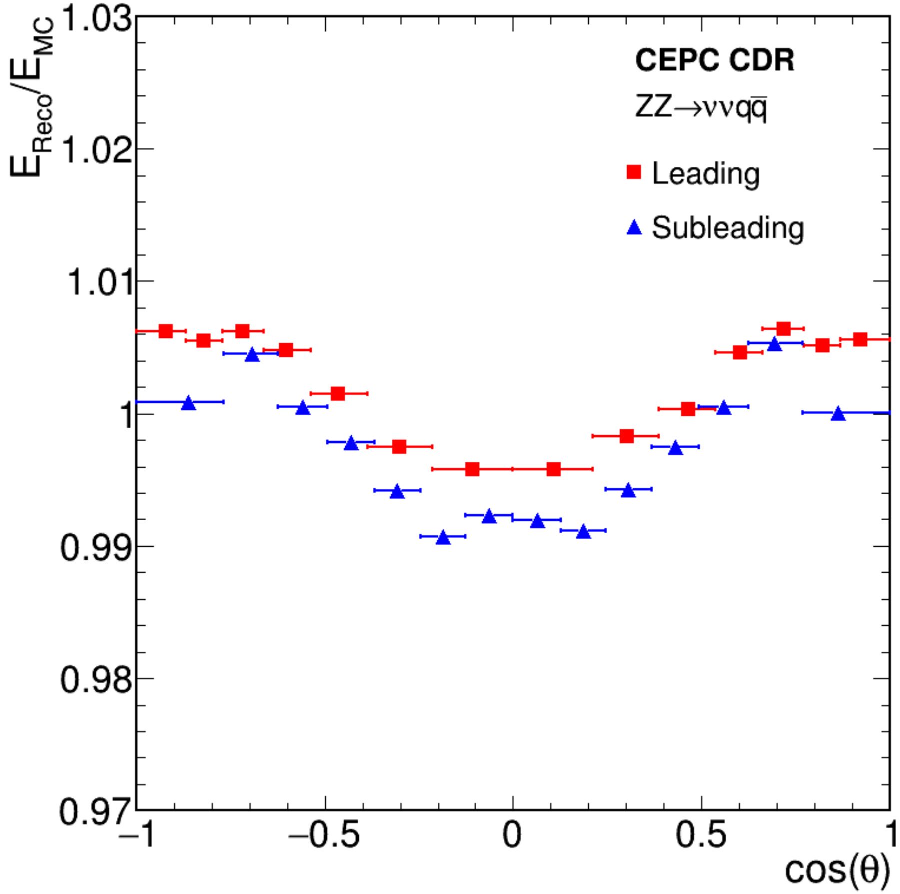


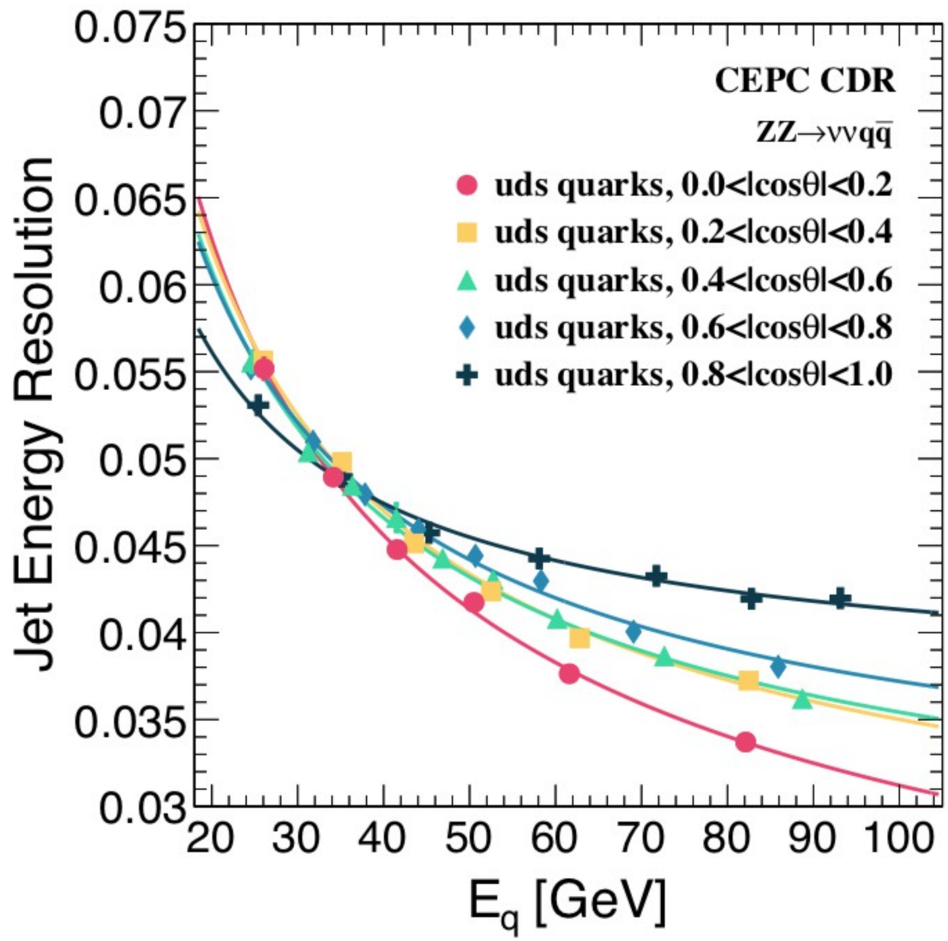
Peizhu Lai & CEPC CDR

WW sample: using μvqq 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

Jet Energy Scale & Resolution

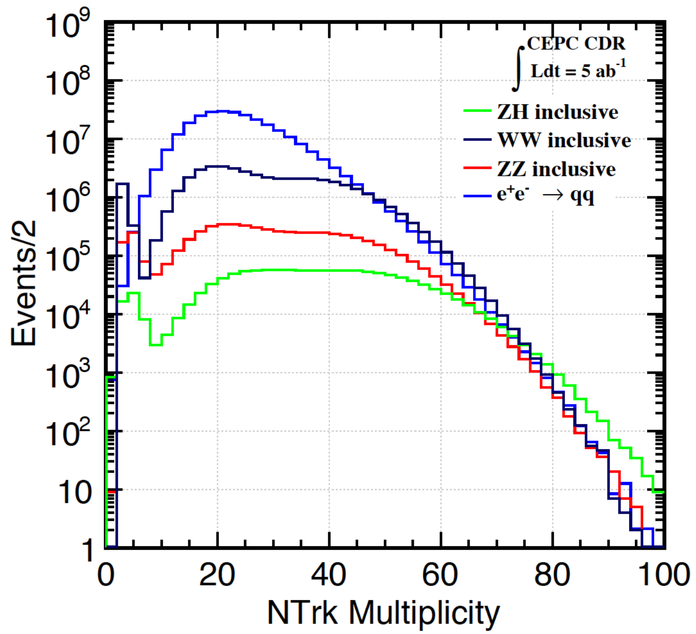


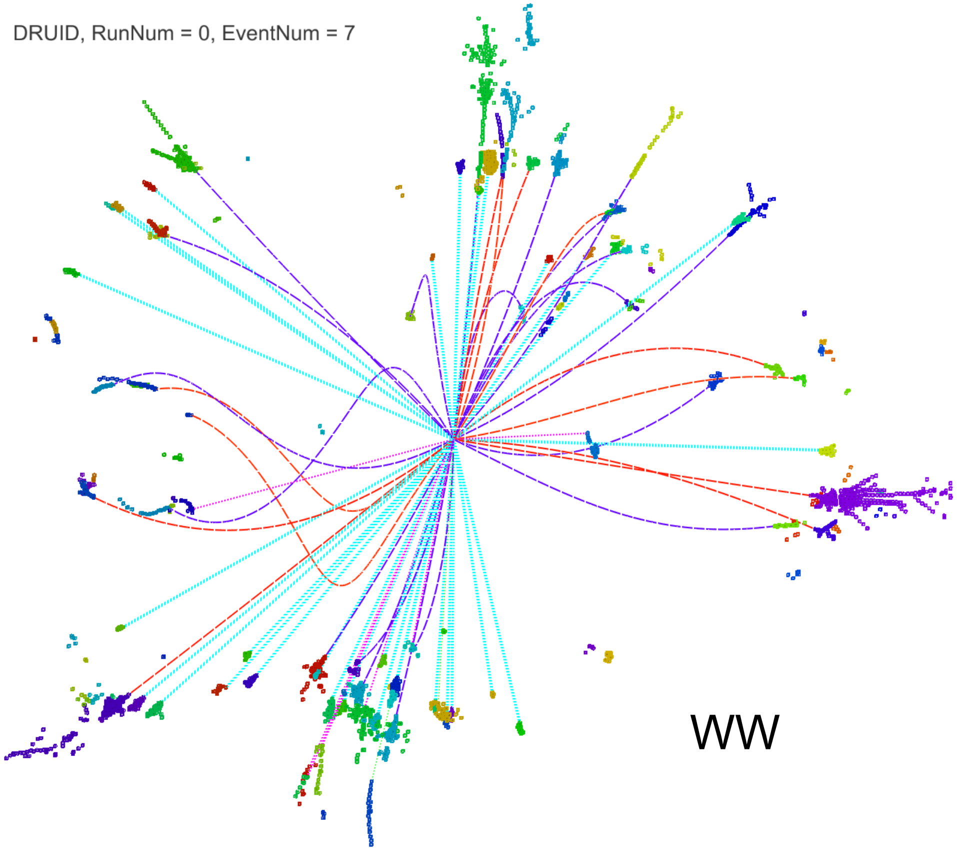


- JES ~ with 1% of the unity (without correction)
- JER ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
- **Both Superior to LHC experiments by 3-4 times**

Peizhu LAI

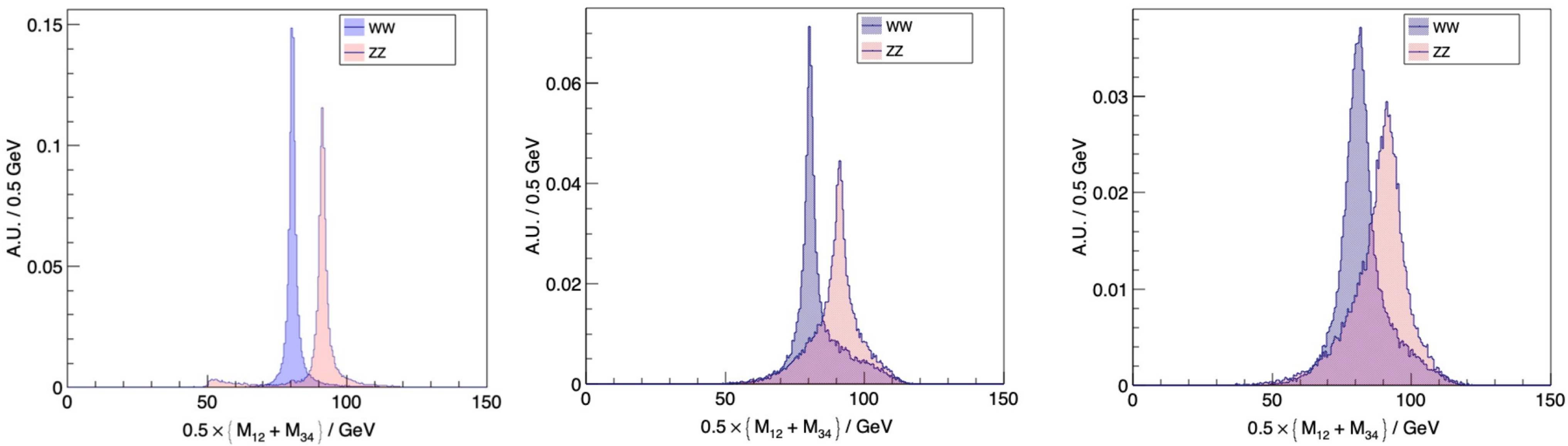
Separation of full hadronic WW-ZZ event





- 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

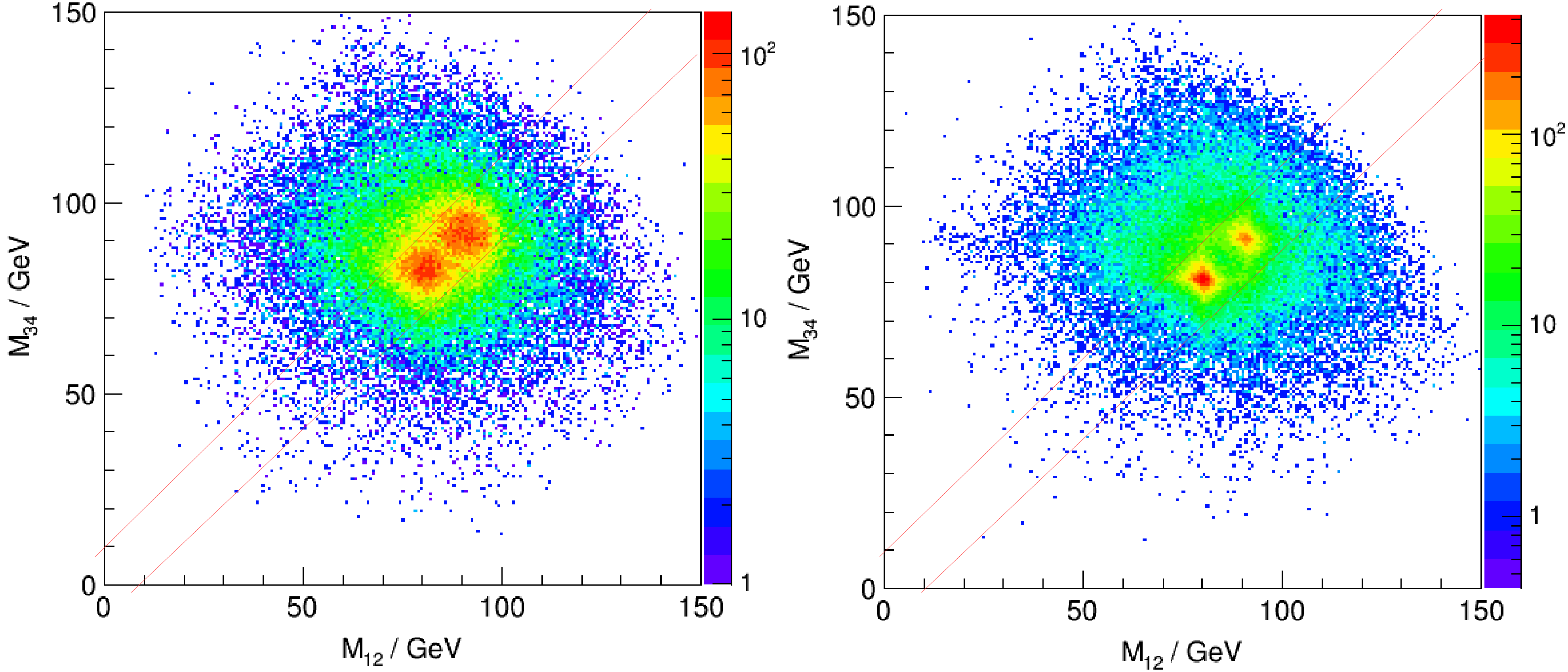


- Separation be characterized by
- Final state/MC particles are clustered into Reco/Genjet with ee-kt, and paired according to chi2
- WW-ZZ Separation at the inclusive sample:
  - Intrinsic boson mass/width - lower limit: Overlapping ratio of 13%
  - \+ Jet confusion – Genjet: Overlapping ratio of **53%**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

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

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

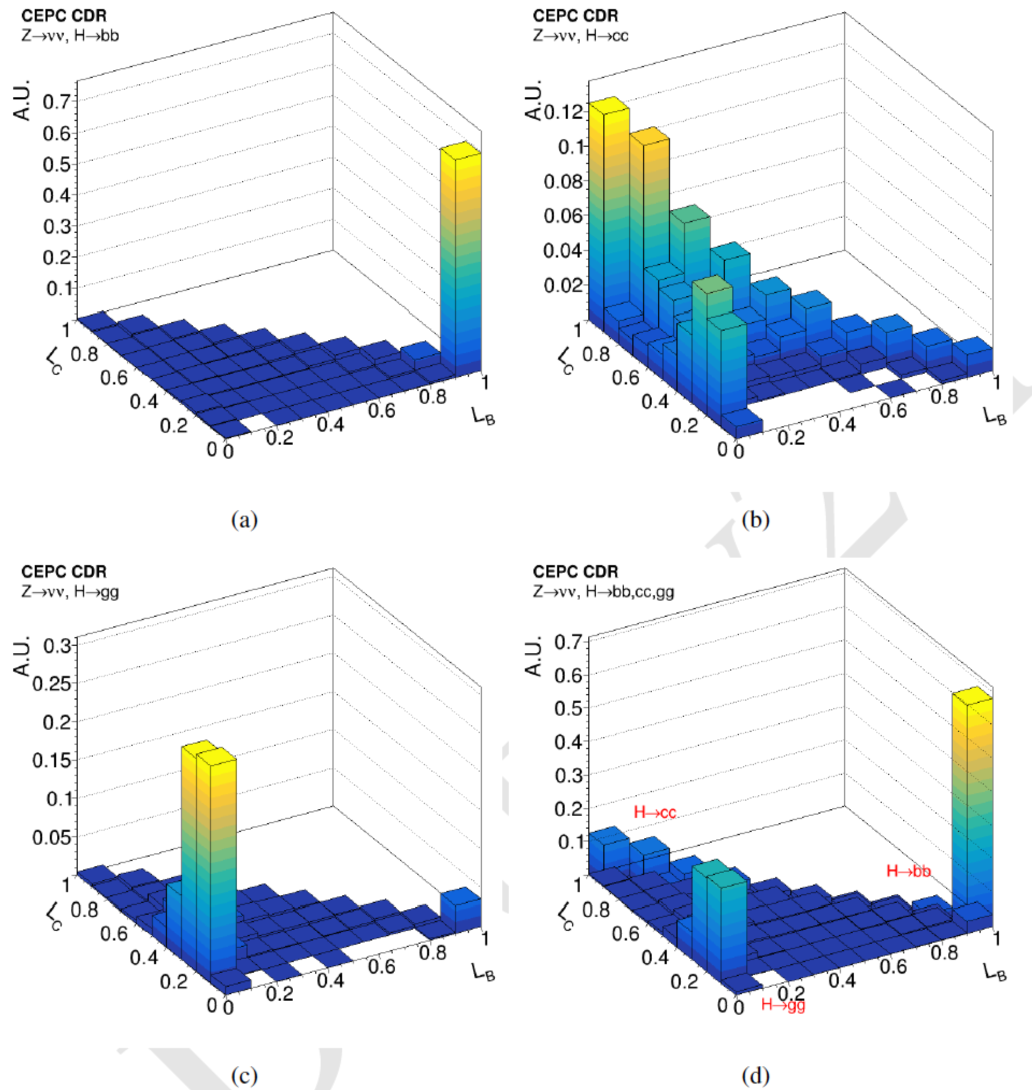
Reconstructed mass of the two di-jet system



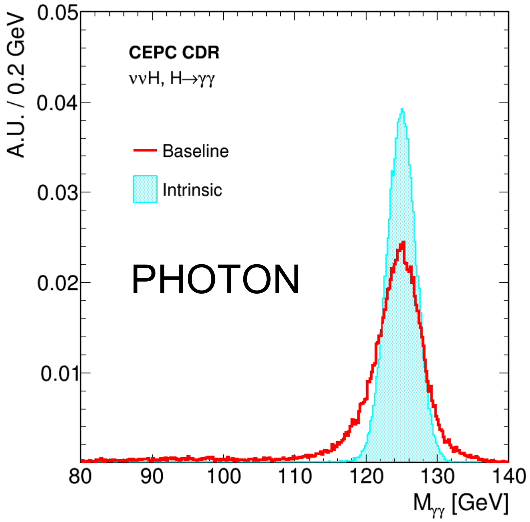
Equal mass condition |M12 – M34| < 10 GeV: At the cost of half the statistic, the overlapping ratio can be reduced from 58%/53% to 40%/27% for the Reco/Genjet

Flavor Tagging

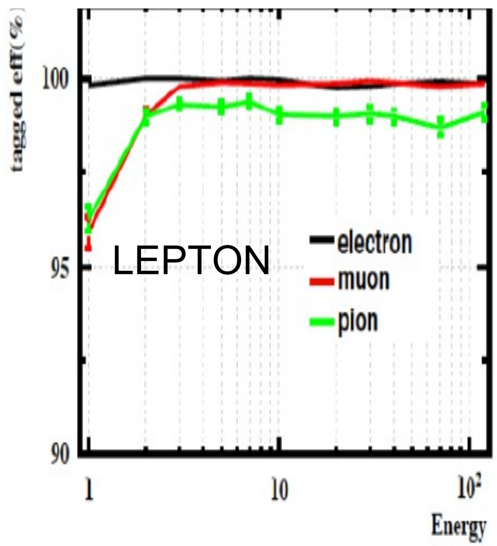
- Using LCFIPlus Package from ilcsoft
- At Higgs->2 jet samples:
  - *Clear separation between different decay modes*
- Typical Performance at Z pole sample:
  - *B-tagging: eff/purity = 80%/90%*
  - *C-tagging: eff/purity = 60%/60%*



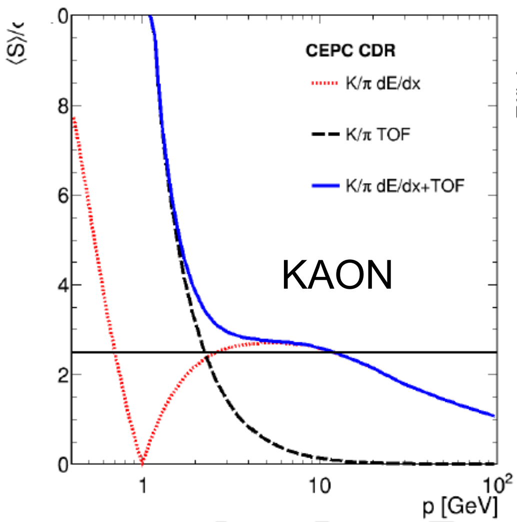
Physics Objects

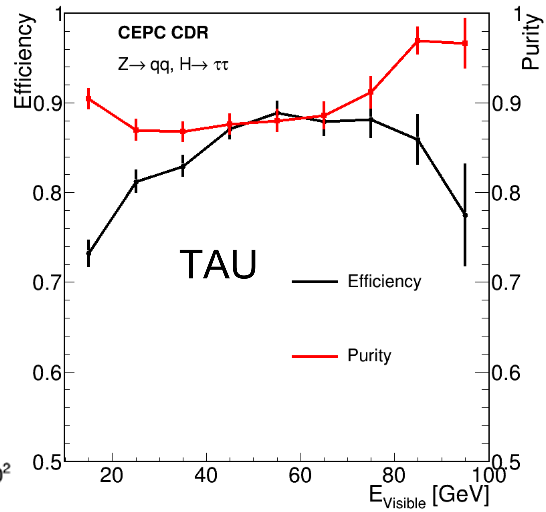


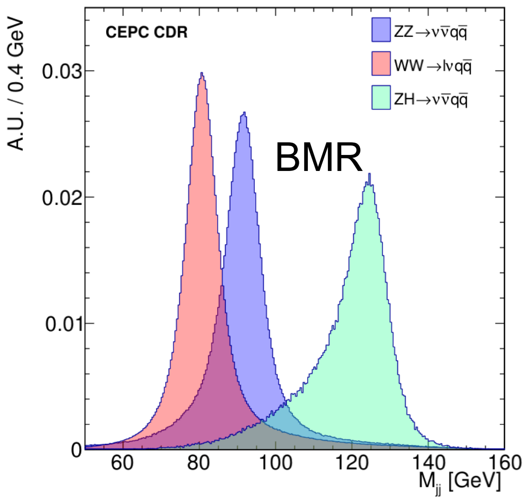
Eur. Phys. J. C (2017) 77: 591

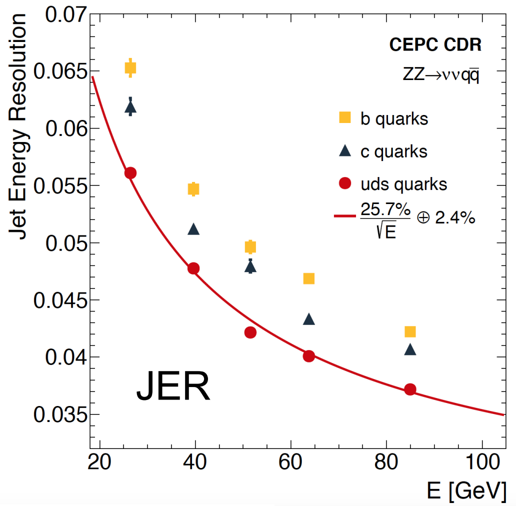


Eur. Phys. J. C (2018) 78:464

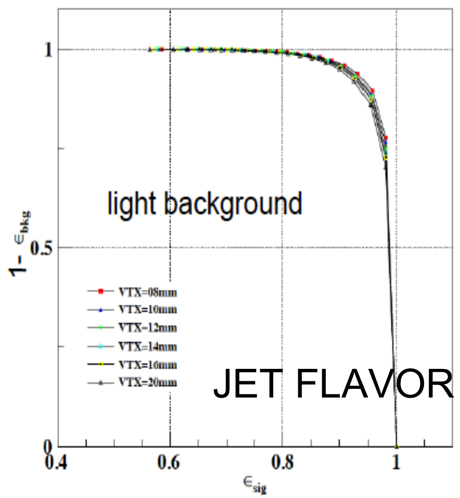


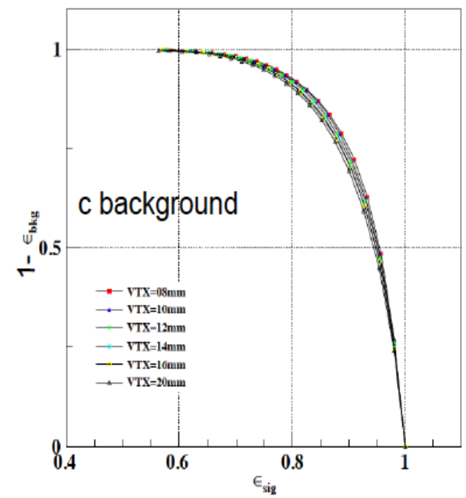




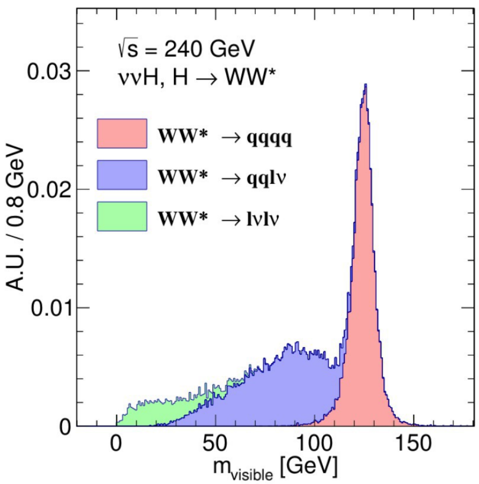


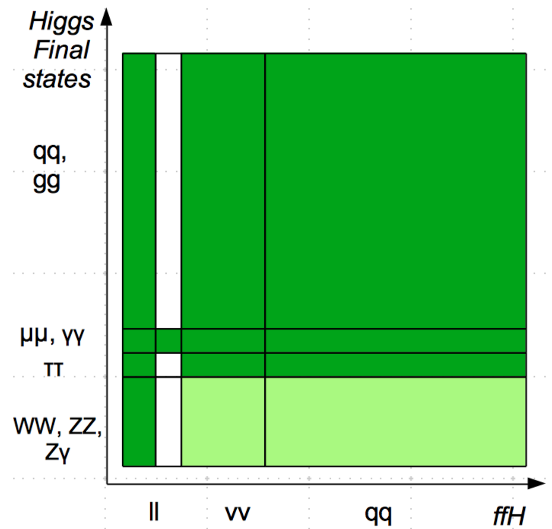
Eur. Phys. J. C (2018) 78: 426

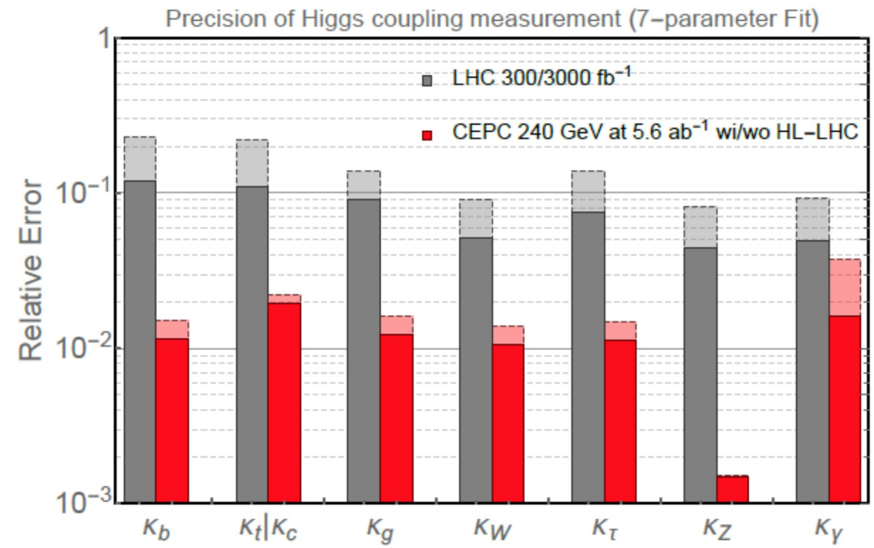


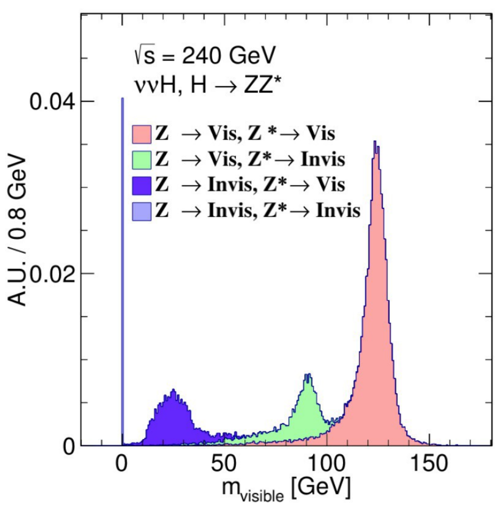


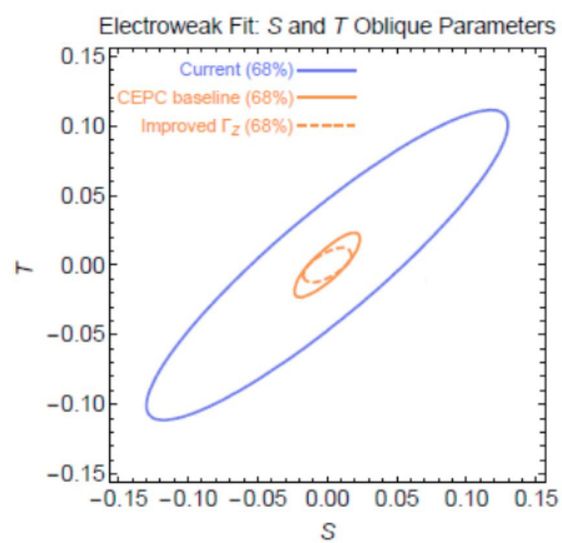
Applied on Higgs physics, et.al











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

Requirements on the physics object

- Low-level
  - VTX: allows a precise flavor tagging & b/c-baryon reconstruction
  - Tracks;
    - threshold < 150 MeV (for D*, K* cascade reconstruction),
    - momentum resolution < 0.1% for H->mumu reconstruction
  - Clusters;
    - ensures pi0 reconstruction at Z->tautau, Z pole, and potentially high energy runs
- Final State Particle
  - Lepton: Isolated, high energy muon/electrons: eff > 99% && mis-id < 1% for the Higgs recoil
  - Photon;
  - Charged/Neutral Hadrons;
- High Level Objects
  - Simple composited: Pi0, Ks/Lambda, converted photons;
  - Tau;
  - Jets – Massive bosons fragment into jets: **BMR < 4%**

Key questions: quantification & control

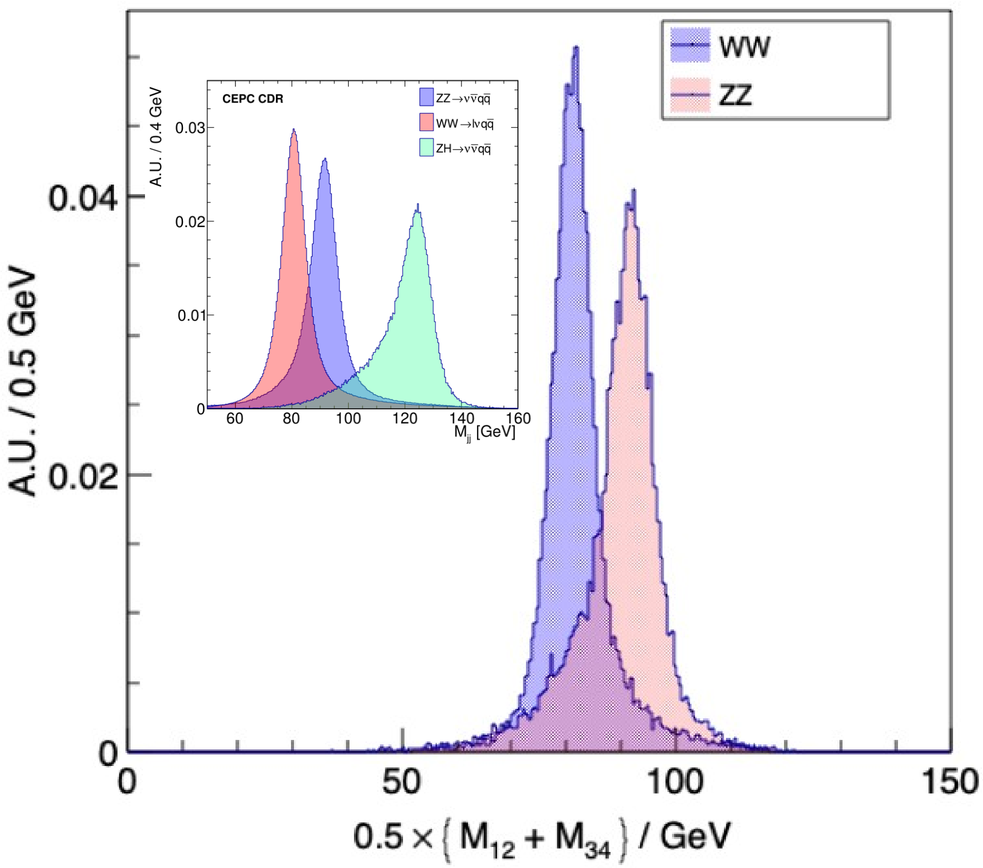
- Flavor Physics:
  - The physics impact of lowing the thresholds (Pt/energy for charged tracks/photons): essential for flavor physics
  - Object finding inside the jets (for the flavor physics), i.e., tau finding inside a b-jet
  - Requirement for the VTX reconstruction
- Jet Clustering & Color singlet: QCD, Higgs & EW
  - How to count, and match precisely the final state jets
  -
- Further optimization: Optimal configuration
- Requirement on the stability & monitoring: EW precisions
- *Many questions can start with CDR sample analysis!*

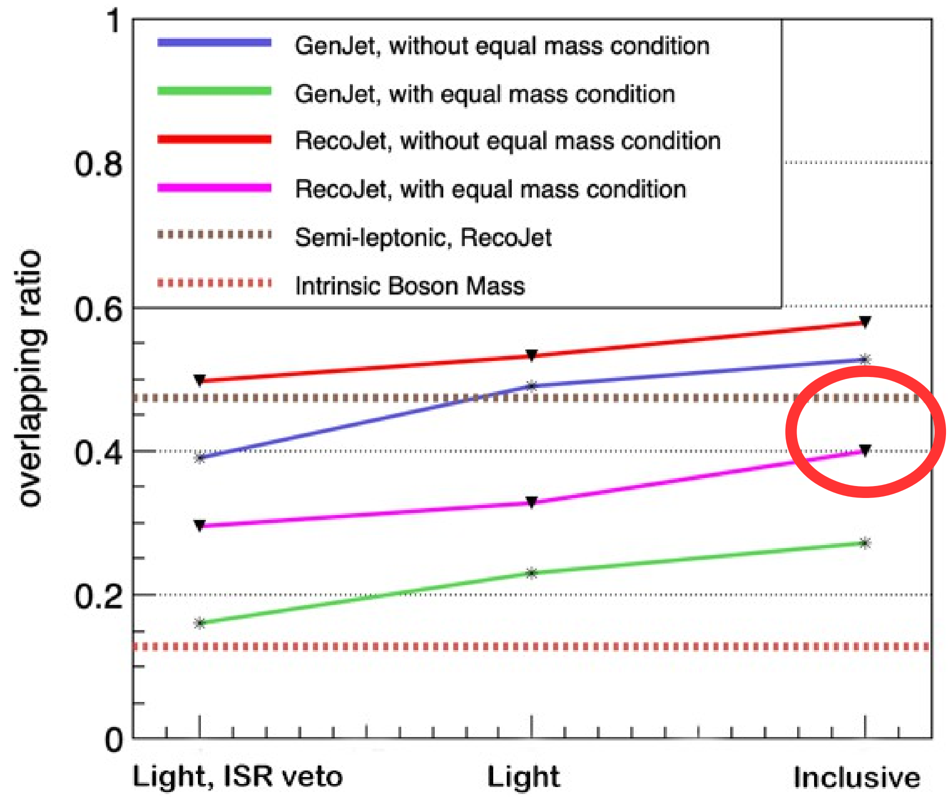
Summary

- 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
- CEPC baseline fulfills the physics requirements – especially for the Higgs measurements, a reasonable starting point for future performance & optimization study
  - All key physics objects tamed
  - Clear Higgs signature in all SM Higgs decay modes
  - 0.1% – 1% relative error in Higgs coupling measurements
- Future works:
  - To quantify more precisely the requirement on EW, QCD & Flavor: **Digest the CDR samples...**
  - Specify more benchmarks, and investigate into more innovative designs
  - Your input & contribution

backup

Separation of full hadronic WW-ZZ event





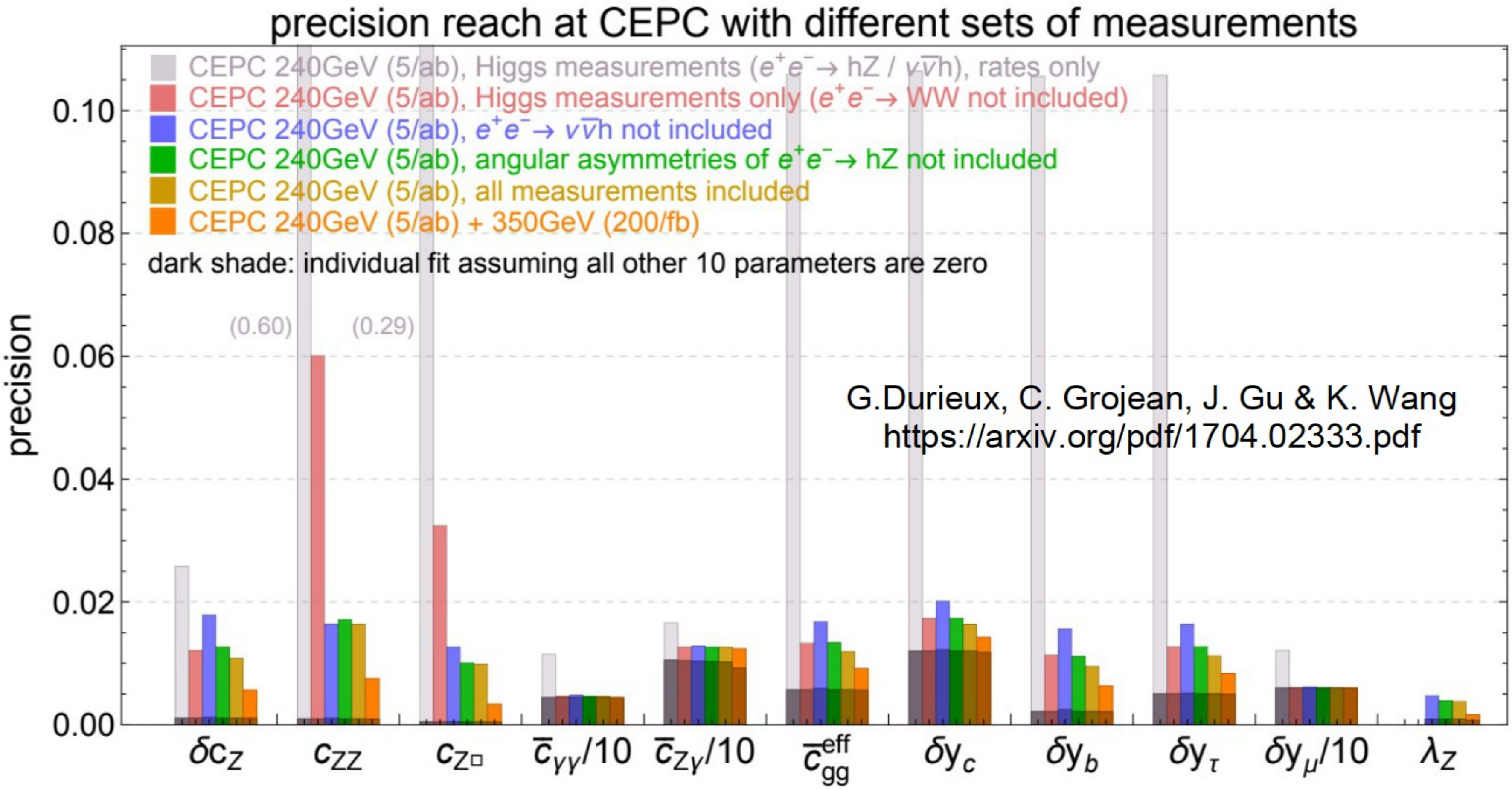
The CEPC Baseline could separate efficiently the WW-ZZ with full hadronic final state.

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

Quantified by differential overlapping ratio.

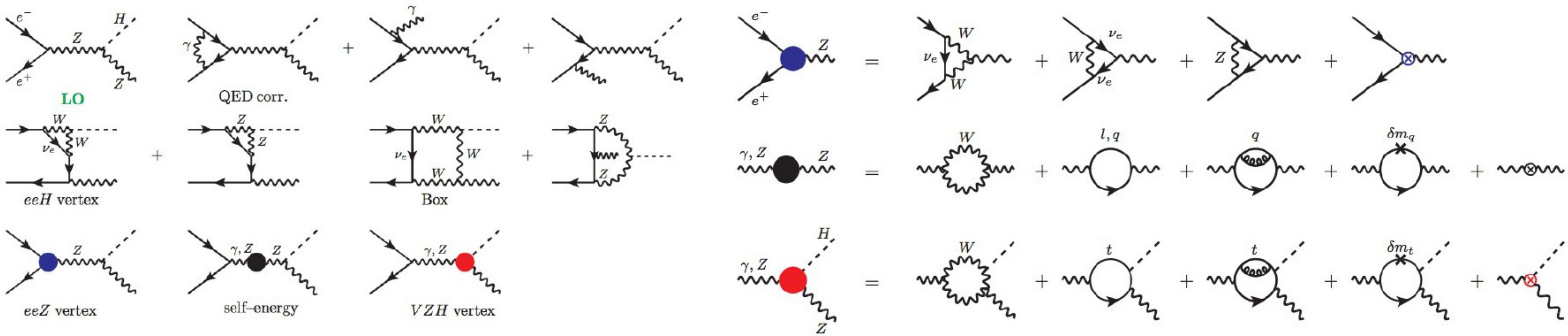
Control of ISR photon/neutrinos from heavy flavor jet is important.

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)

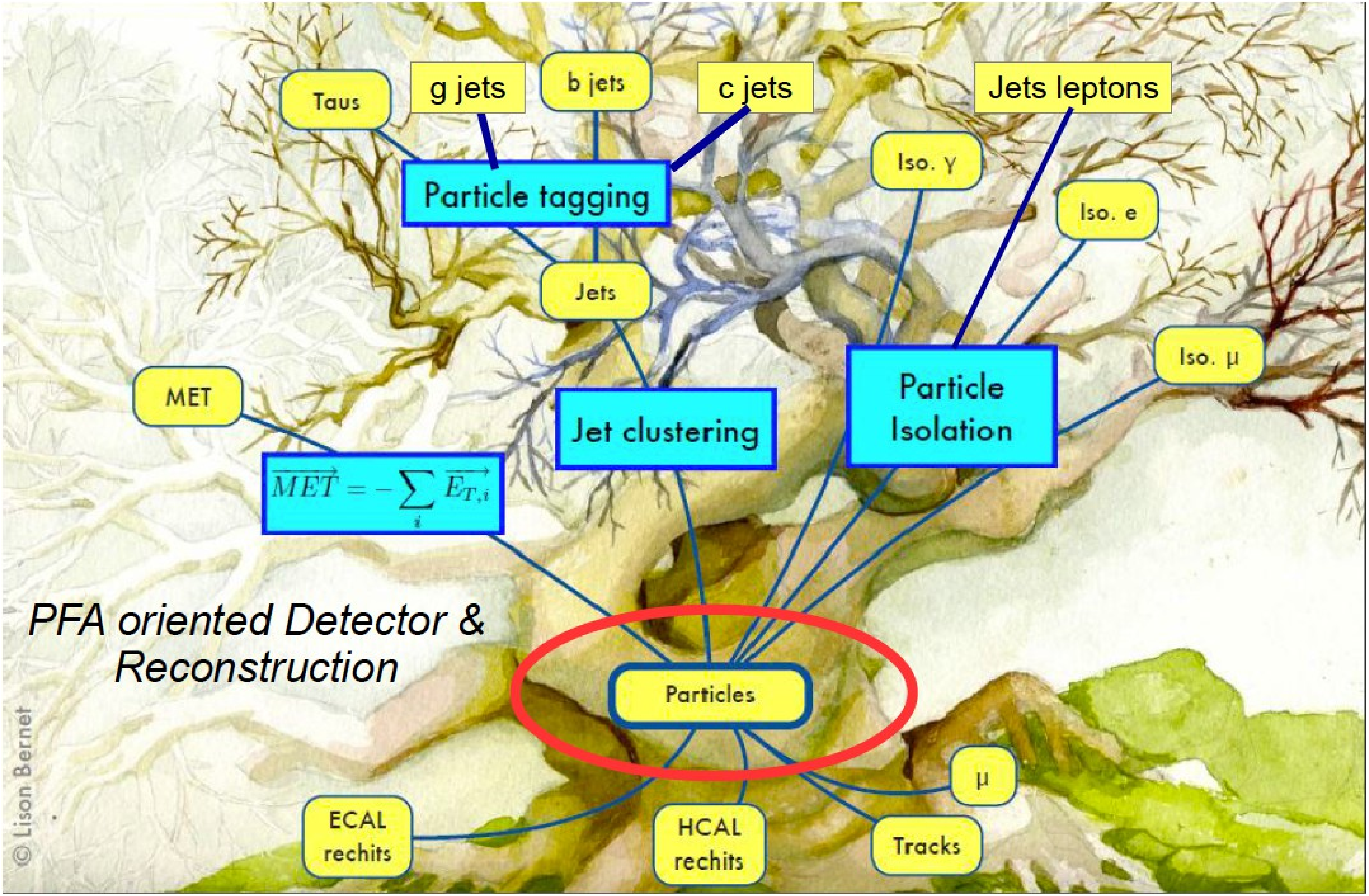
Pheno-studies: High order corrections



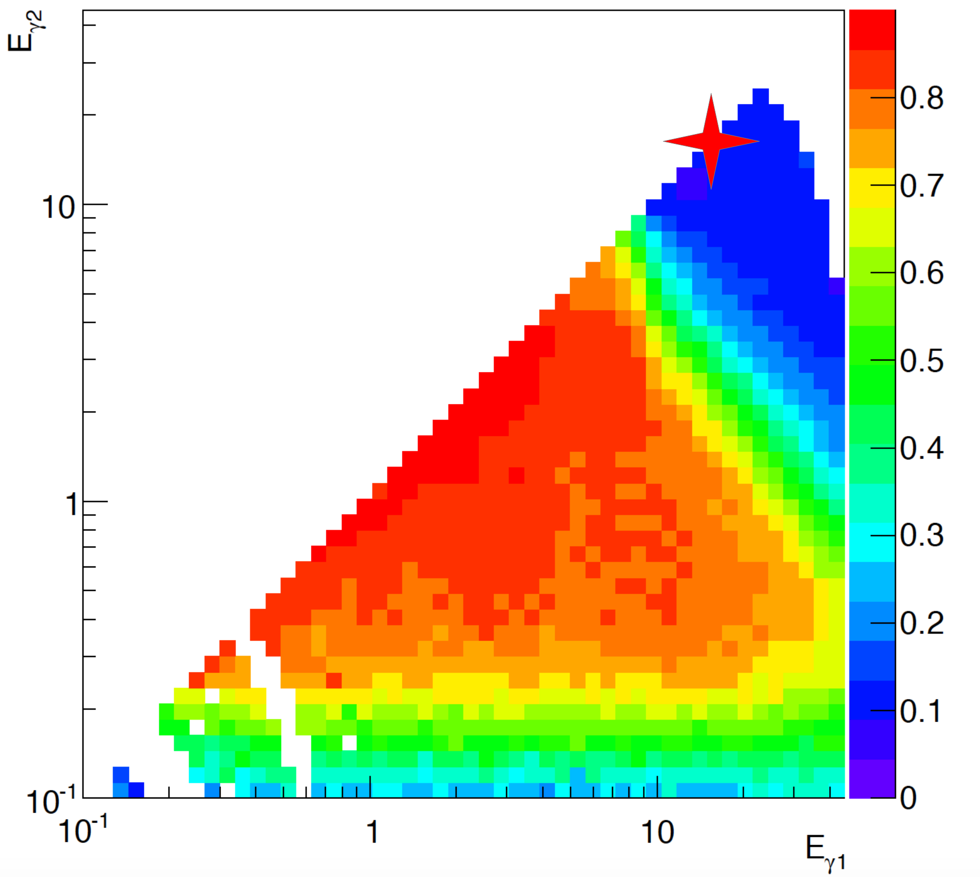
$\sqrt{s}$ (GeV)		LO (fb)	NLO Weak (fb)		NNLO mixed electroweak-QCD (fb)			
		$\sigma^{(0)}$	$\sigma^{(\alpha)}$	$\sigma^{(0)}+\sigma^{(\alpha)}$	$\sigma_Z^{(\alpha\alpha_s)}$	$\sigma_\gamma^{(\alpha\alpha_s)}$	$\sigma^{(\alpha\alpha_s)}$	$\sigma^{(0)}+\sigma^{(\alpha)}+\sigma^{(\alpha\alpha_s)}$
240	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

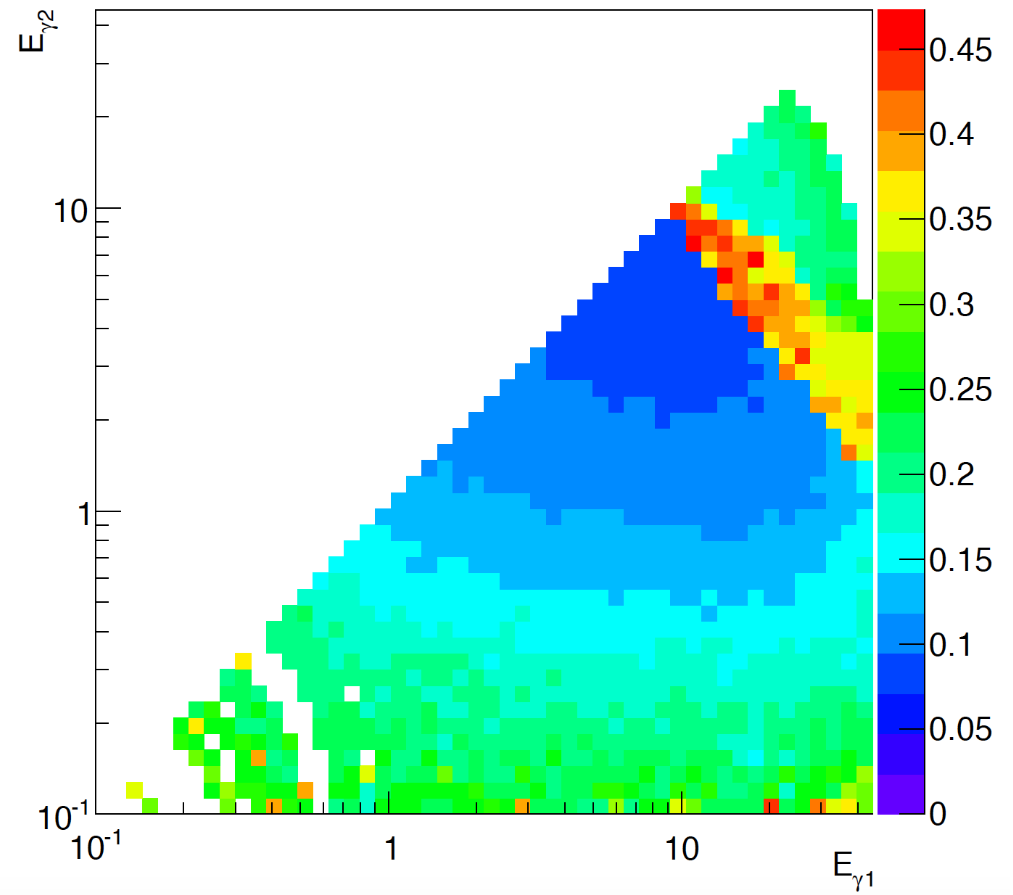
Q.Sun, et.al
https://arxiv.org/pdf/1609.03995.pdf

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


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

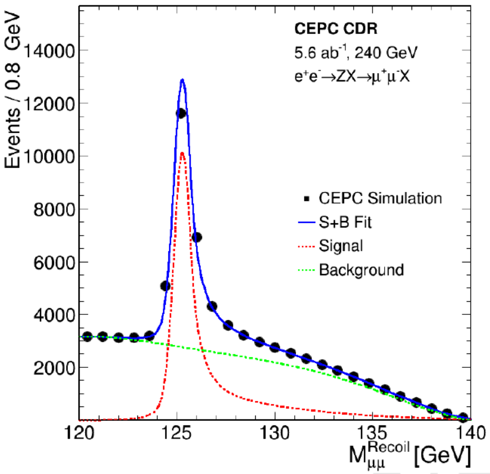
Pi0: efficiency & mass resolution (Preliminary)

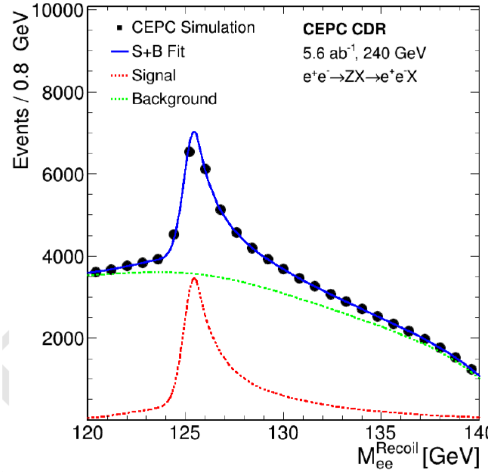




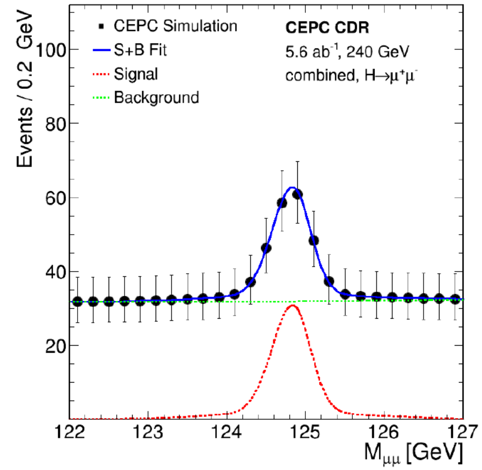
Arbor parameter & Photon Id - parameters need further optimization...

Higgs benchmark analyses

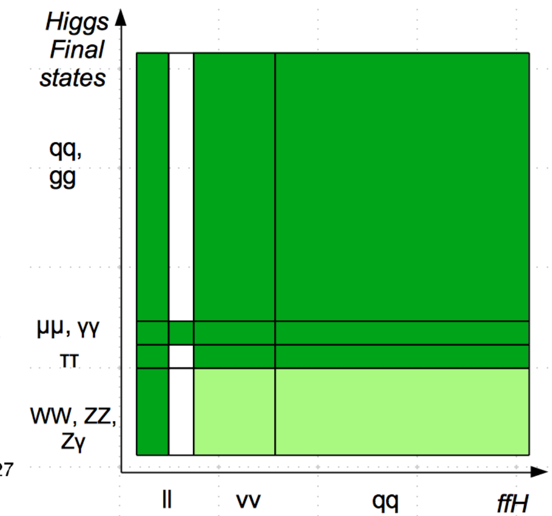


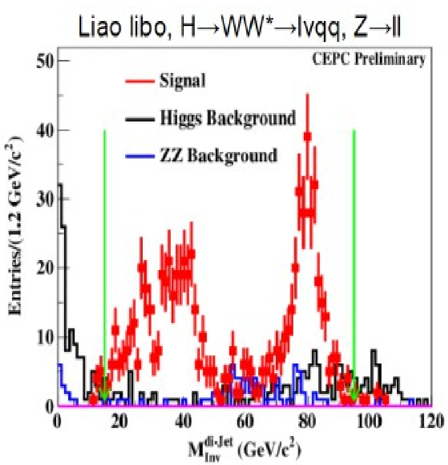


σ(ZH) measurements

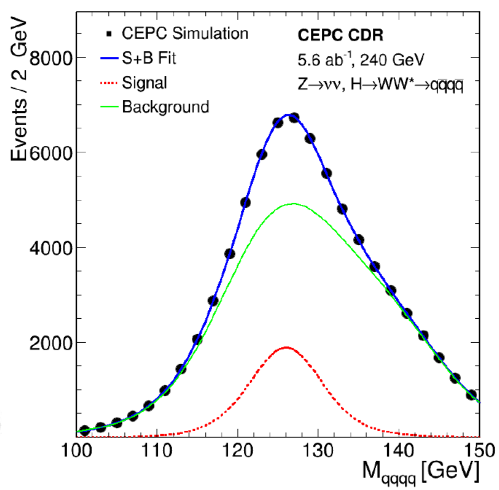


Br(H→μμ)

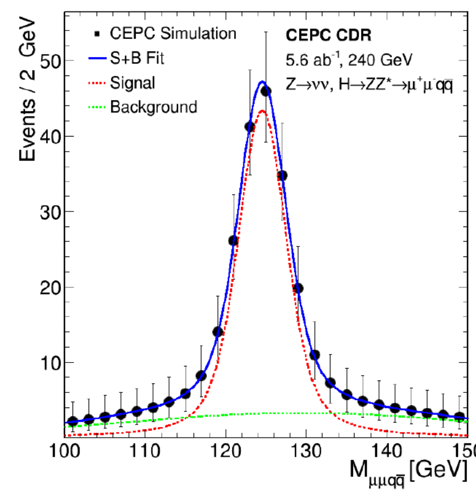




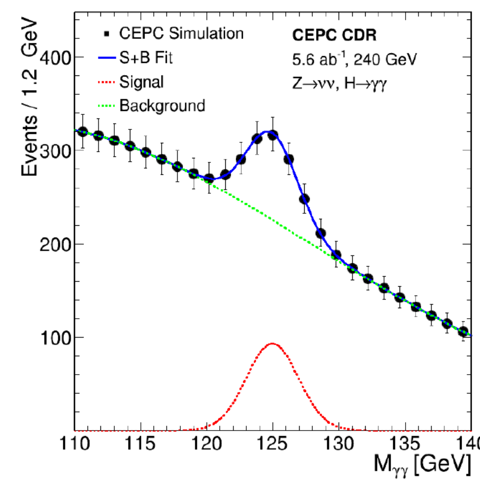
Br(H→WW)



σ(ννH)*Br(H→bb)



Br(H→ττ)



Br(H→γγ) (Asimov)