CEPC Physics and Performance

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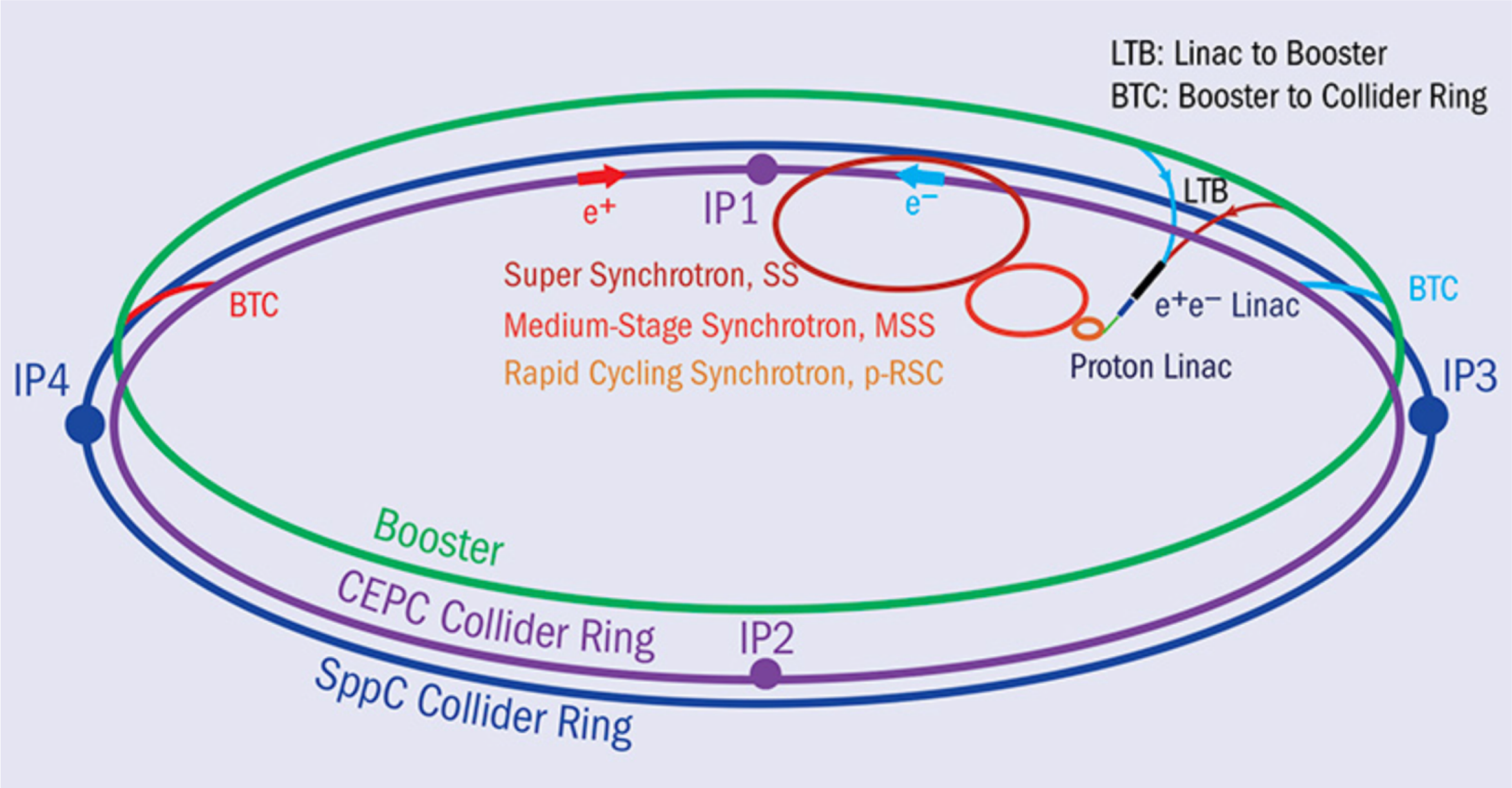
Outline

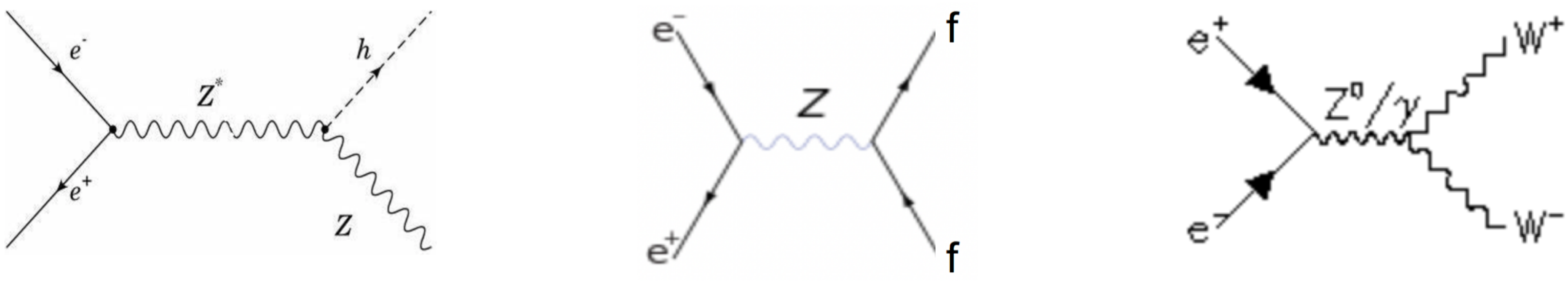
- CEPC physics program
- CEPC detector performance
  - Reconstruction and identification
- CEPC physics studies
  - Higgs physics
  - Electroweak physics
- Summary

The CEPC Project

- A 100-km Circular Electron-Positron Collider (CEPC) serving as a factory of bosons: Higgs, Z, W
- Upgradable to a 100-TeV proton-proton collider



CEPC Physics Program



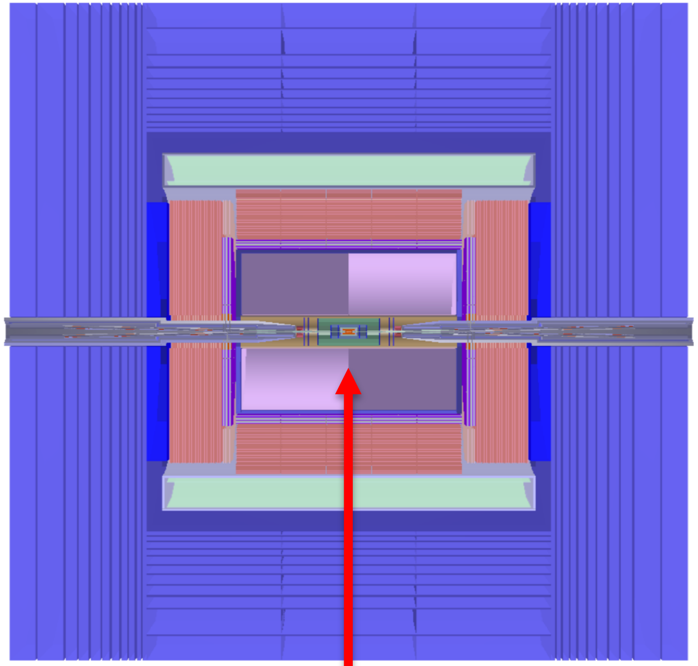
Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)

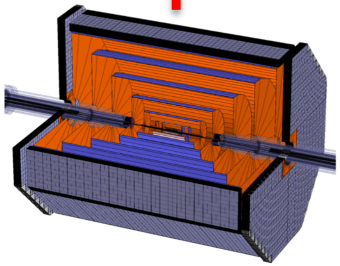
- The centerpiece: precise measurement of the Higgs boson properties (width, couplings, mass …)
- Precision tests of SM: electroweak physics, flavor physics, QCD
- Searching for exotic or rare decays of H, Z, B and tau
- …

CEPC Detector Concepts

Baseline : PFA approach
(derived from ILD)

Silicon + TPC (B=3T)
+ PFA-ECAL&HCAL + Muon

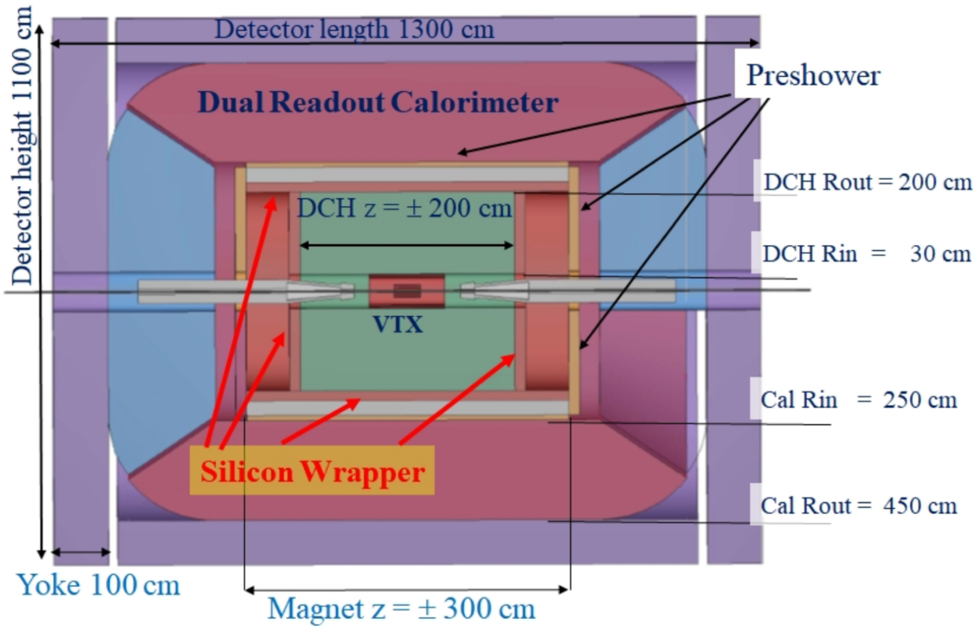




Another tracking
option with full-silicon

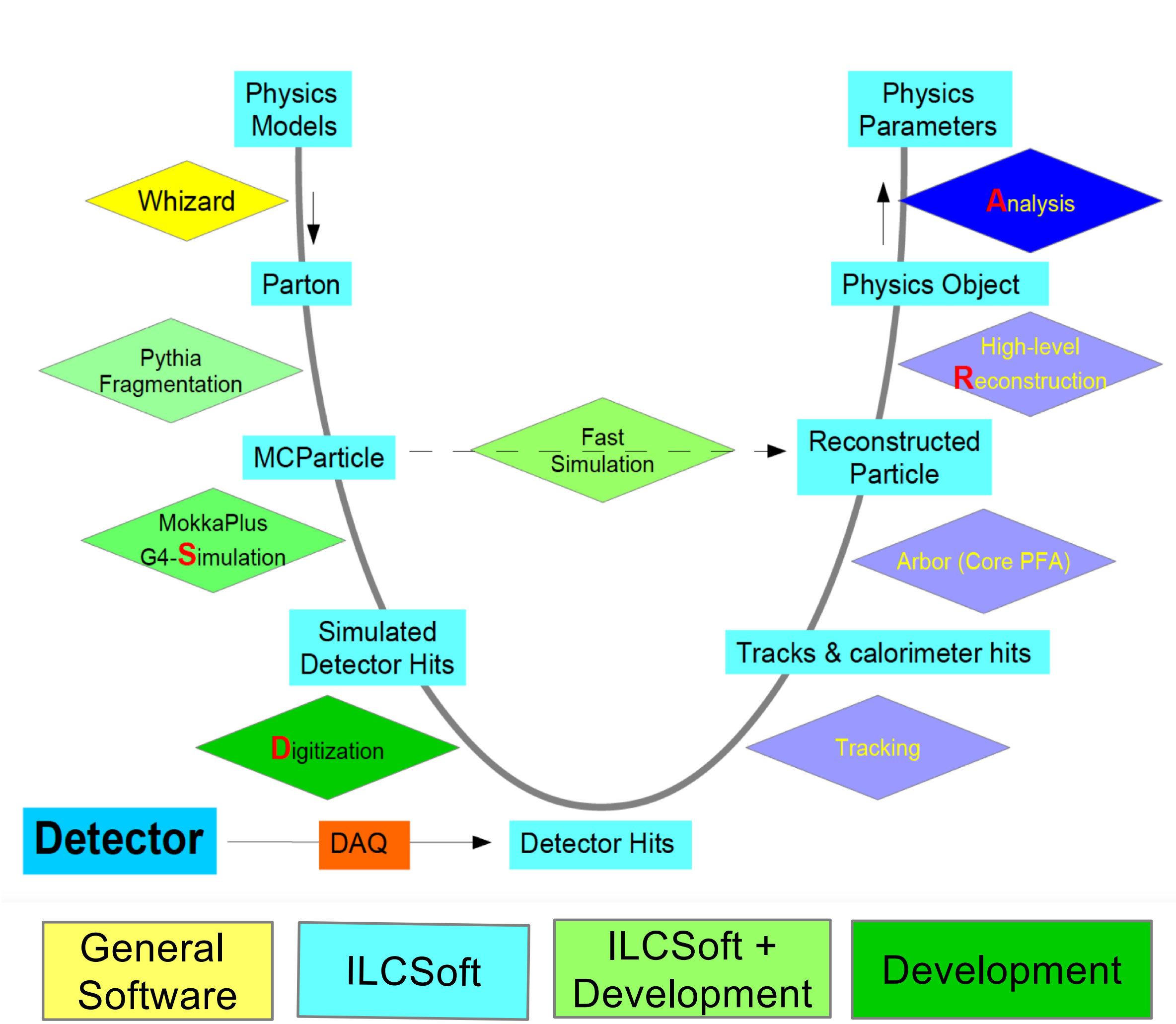
Alternative : IDEA
(low magnetic field)

Silicon + Drift Chamber (B=2T)
+ Dual-readout calorimeter + Muon



Calorimeter outside the coil

Simulation and Reconstruction



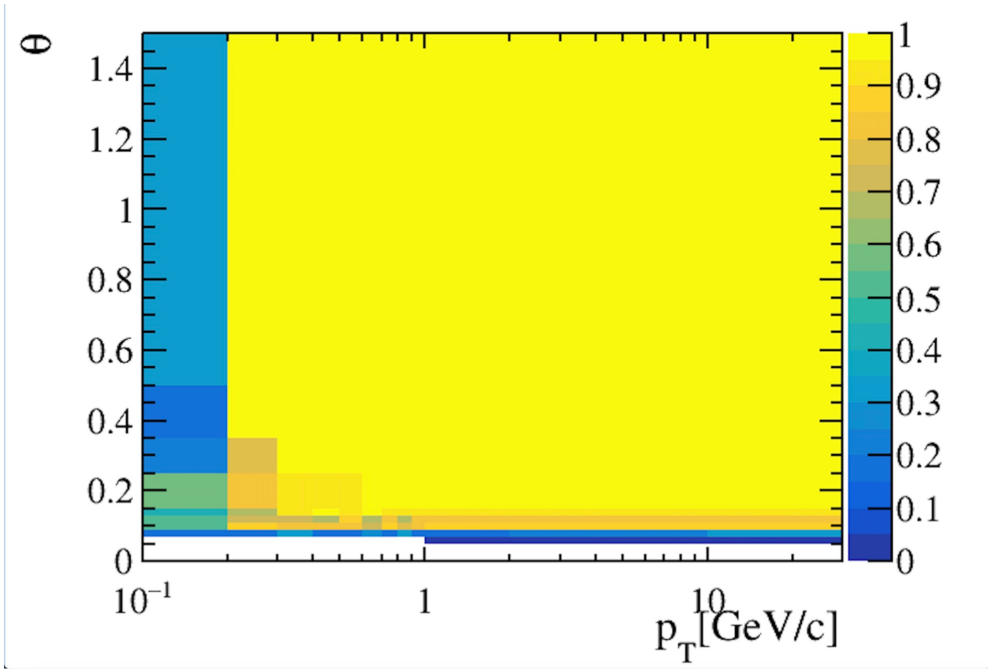
Generators (Whizard & Pythia)
Data format & management (LCIO & Marlin)
Simulation (MokkaC)
Digitization
Tracking
PFA (Arbor)
Single Particle Physics Objects Finder (LICH)
Composed object finder (Coral)
Tau finder
Jet Clustering (FastJet)
Jet Flavor Tagging (LCFIPLus)
Event Display (Druid)
General Analysis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

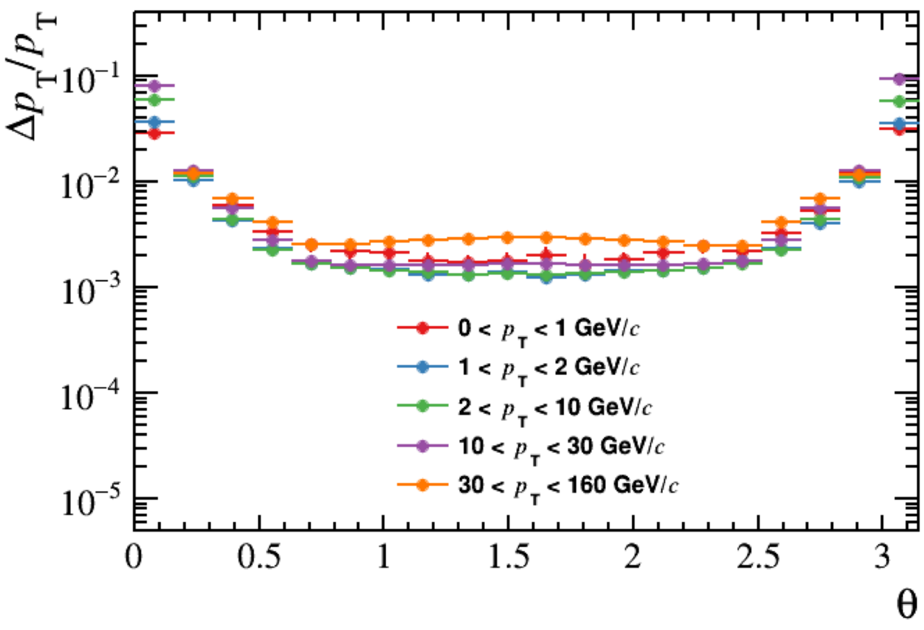
New effort: A software framework based on Gaudi, CSS etc. is under development !

Baseline Detector Performance

- Tracking
- Lepton identification
- Photon reconstruction
- Tau identification
- Kaon identification
- Boson mass resolution
- Jet reconstruction
- Jet flavor tagging

Tracking

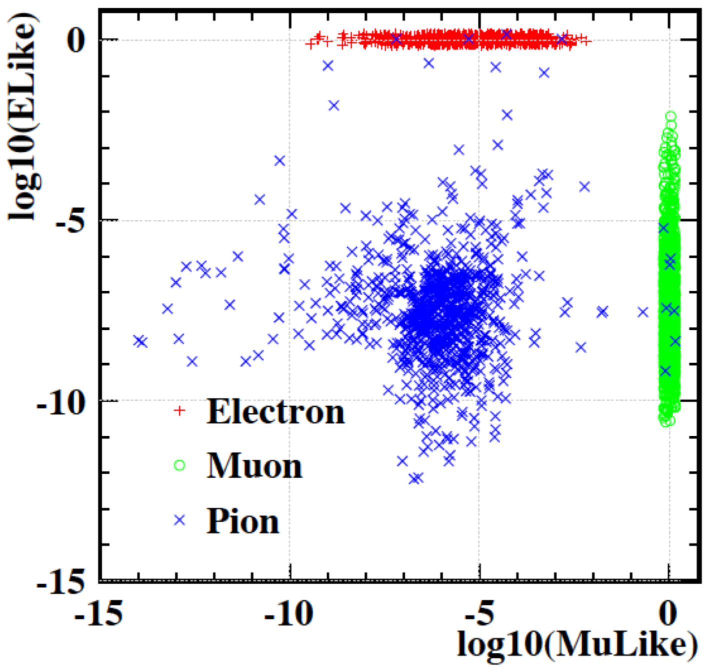


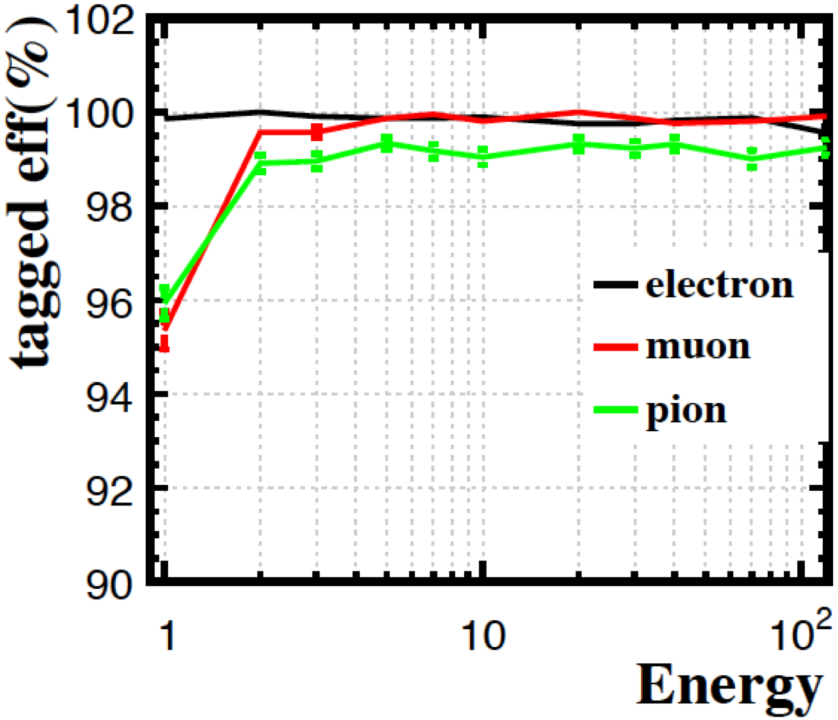


- Highly efficient for pT > 200 MeV
- Good momentum resolution fulfilling the H→$\mu\mu$ requirement

Lepton Identification

- A BDT-based lepton ID algorithm (LICH) has been developed exploiting the high granularity of the PFA calorimetry system (combined with dE/dx from the tracker).
- Lepton ID efficiency > 99.5% with mis-ID rate ~ 1% for p>2GeV

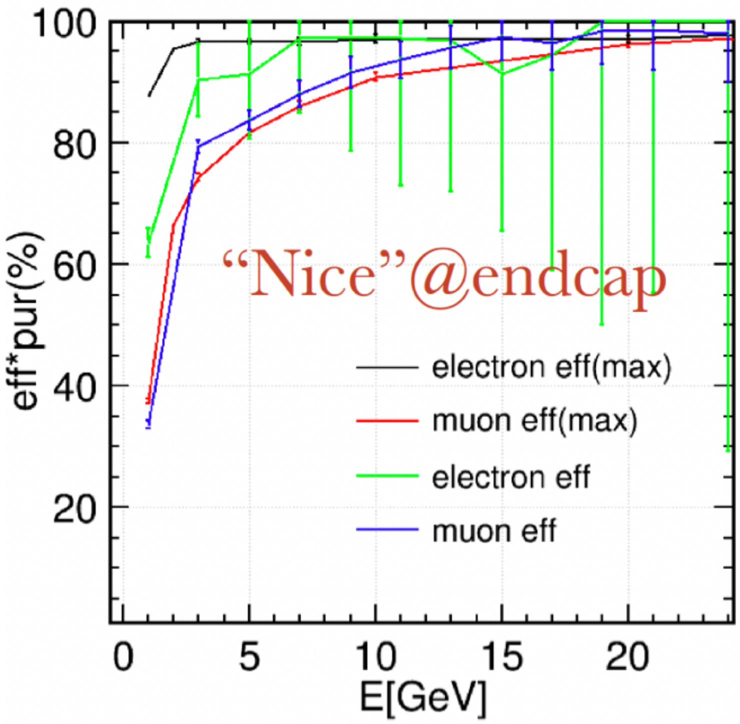


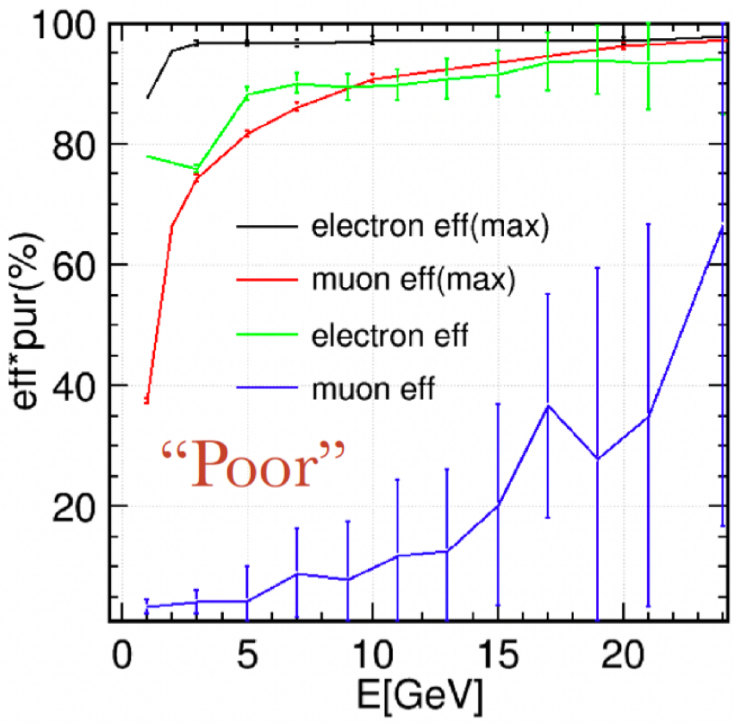


Eur. Phys. J. C (2017) 77: 591

Lepton ID inside Jets

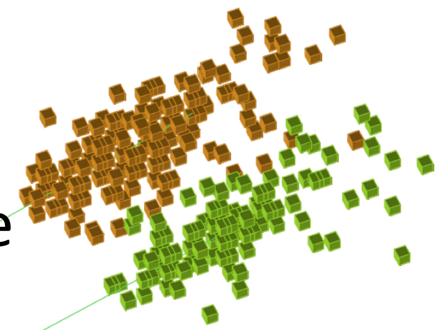
- Performance of lepton ID in good/poor calorimeter clusters, in comparison with that extrapolated from the isolated case.
- An indicator of clustering performance.

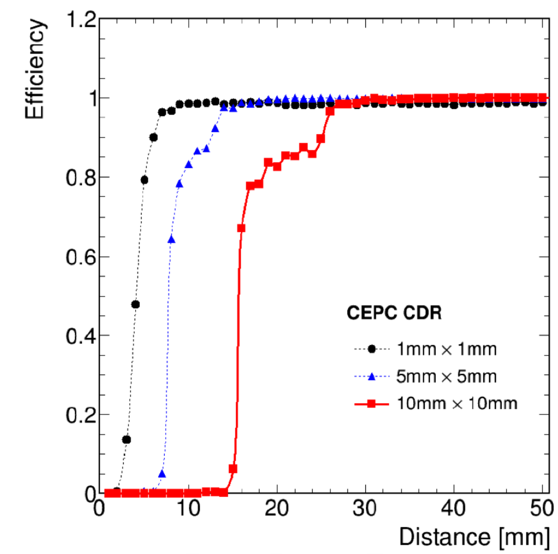


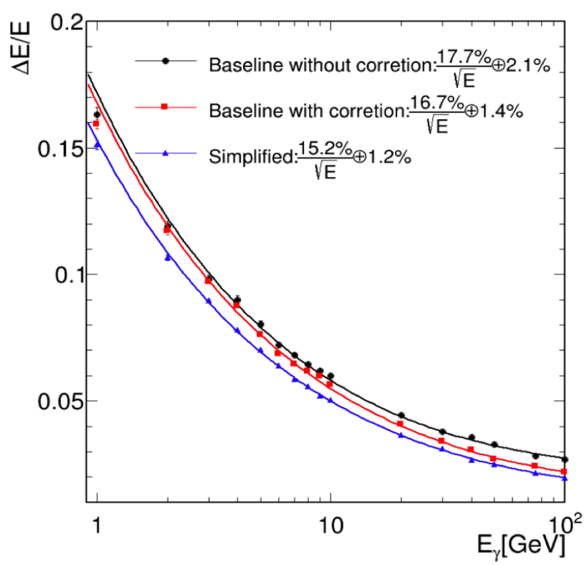


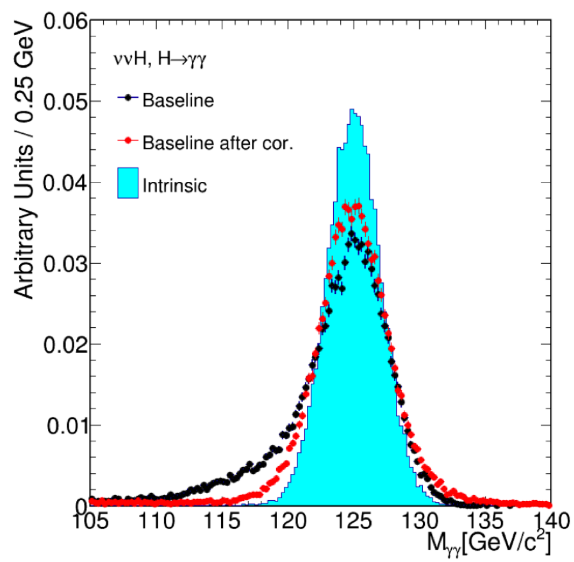
Photon Reconstruction

- Capability of separating close-by photons heavily depends on ECAL cell-size.
- Baseline detector can separate the two photons from a pi0 decay with energy up to 30 GeV.



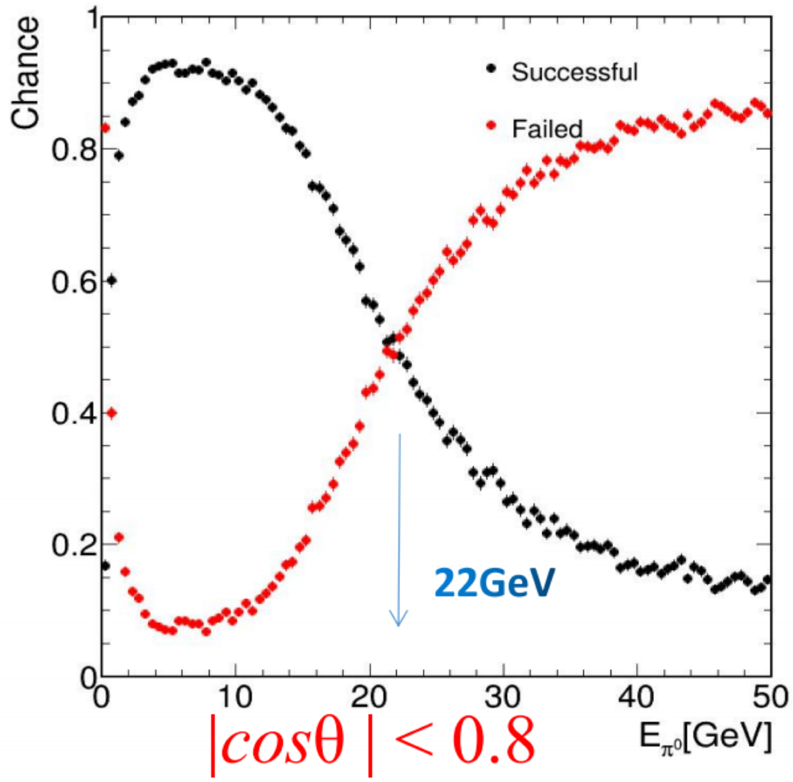


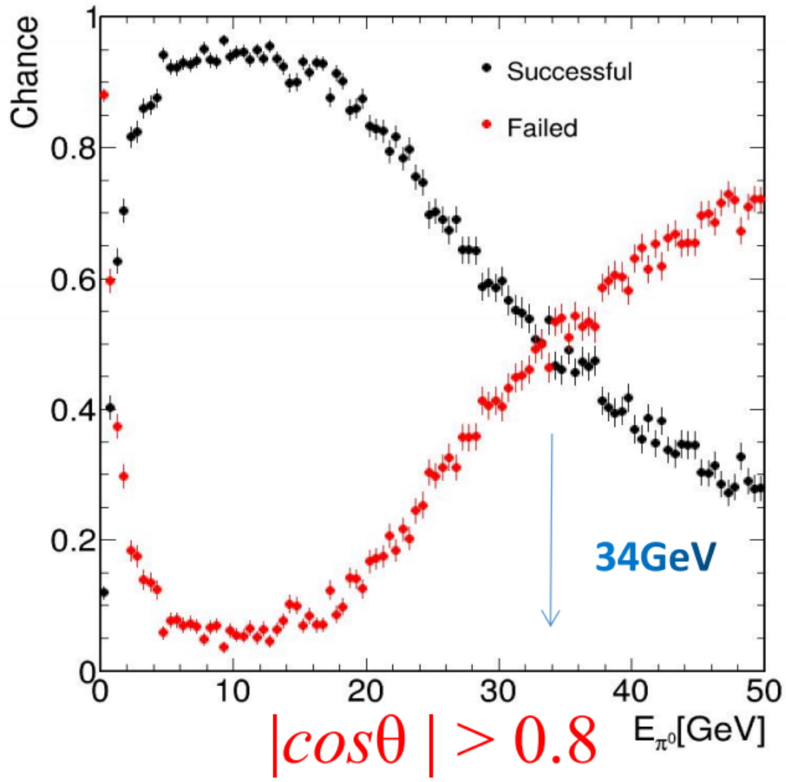




- Photon energy resolution is improved when correcting for ECAL geometry defects.
- A Higgs mass resolution of 2.2% is achieved in $H \rightarrow \gamma\gamma$.

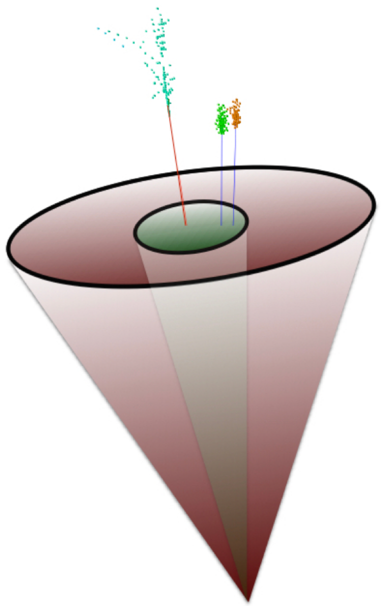
π^0 reconstruction

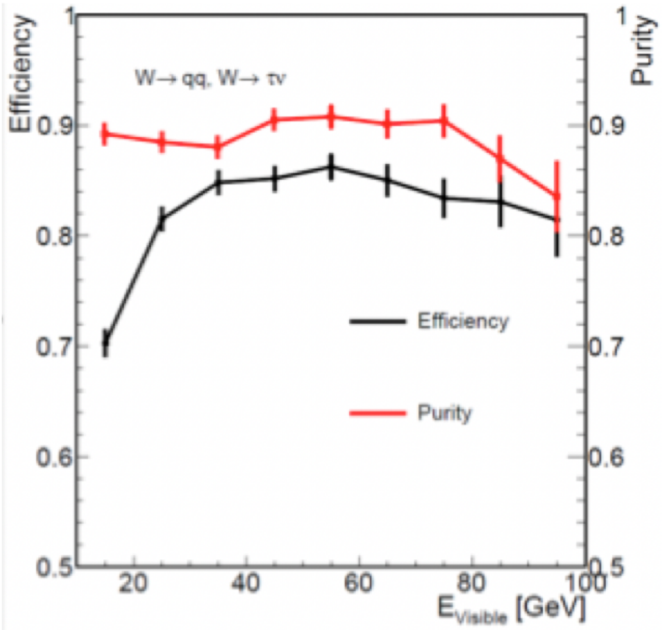


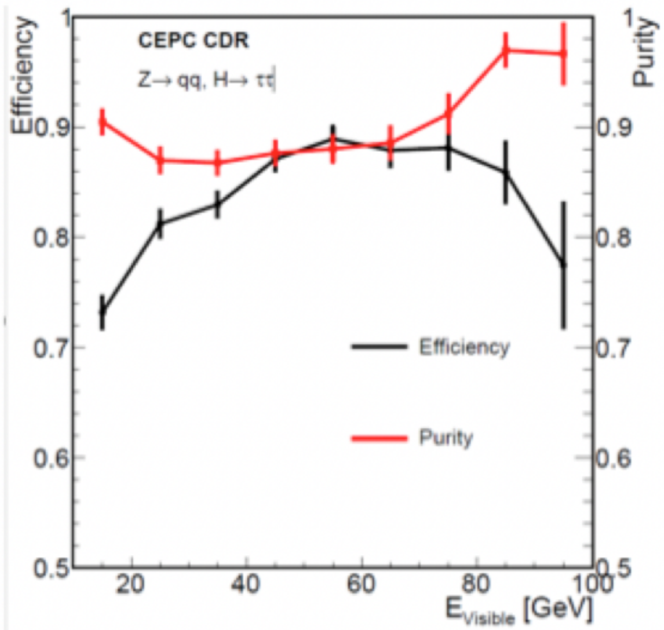


- Better performance in endcaps due to larger spatial separation between the two decay photons

Tau Identification



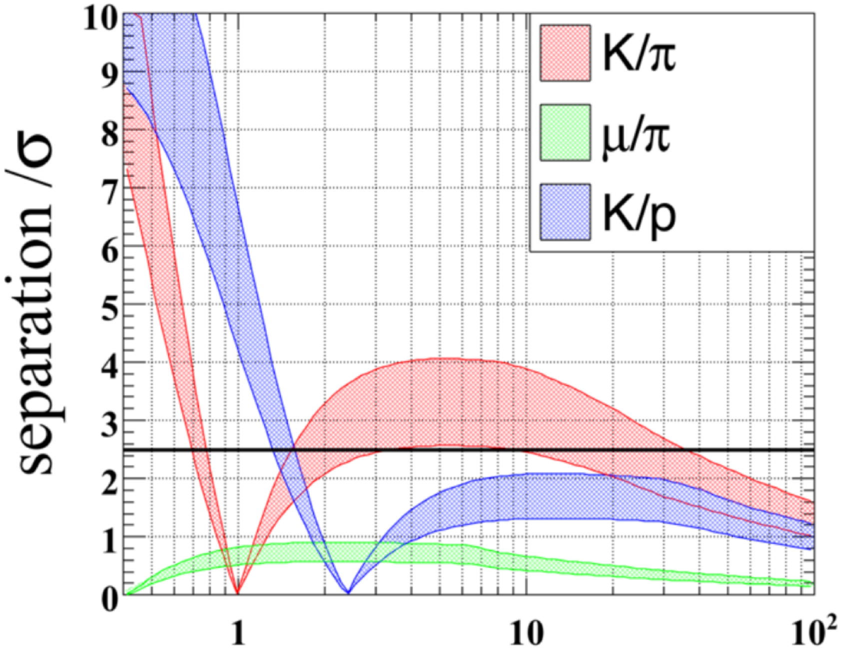




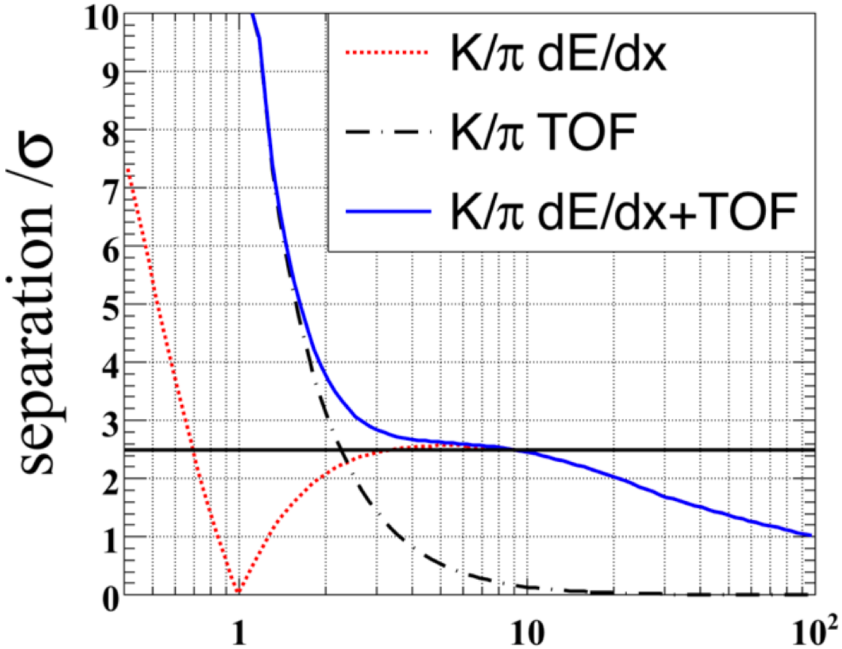
- Double-cone based Tau ID algorithm has been developed for TAURUS (Tau ReconstrUction toolS)
- An efficiency*purity higher than 70% is achieved for qqττ and qqτν events

Kaon Identification

dE/dx alone



dE/dx + TOF (50ps resolution)

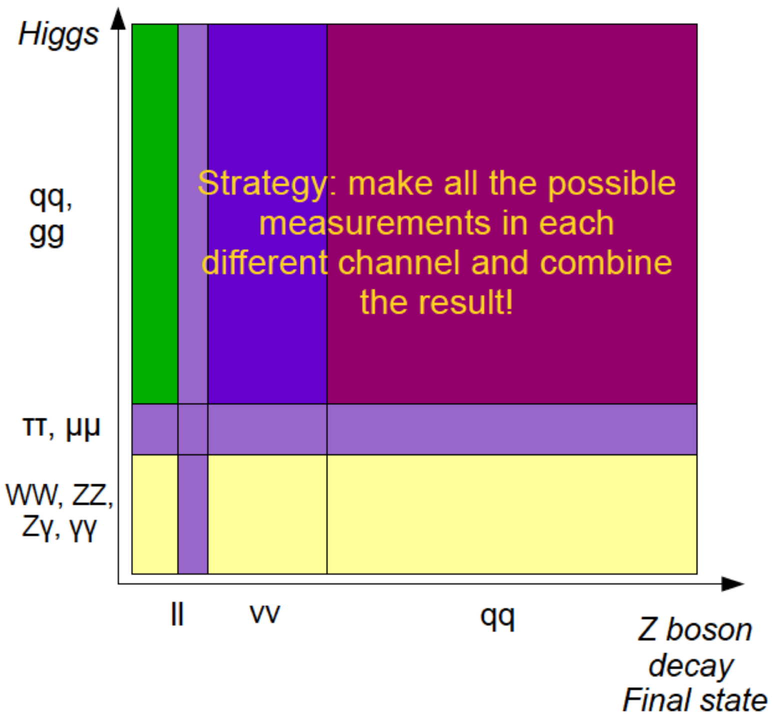


Eur. Phys. J. C (2018) 78:464

- > 2-σ pi/K separation could be achieved for p<20GeV, resulting in Kaon efficiency/purity of 91%/94% in the inclusive Z sample.
- Important for flavor physics. Could also help with jet flavor and charge determination.

Jets

- Jets are important physics objects: 97% of HZ events have jets in their final states
  - 1/3 of them have only 2 jets
  - The rest have > 2 jets



- For 2-jet events
  - the 2 jets came from either Z or H decays
  - Can calculate the visible mass of the 2-jet system without reconstructing jets → boson mass
  - Then use boson mass resolution to quantify performance of 2-jet event reconstruction.
- Jet clustering/reconstruction is required for >2-jet events and differential measurements.

Boson Mass Resolution (BMR)

- With a standard cleaning procedure implemented to control the effect of ISR photon, neutrinos generated in Higgs decays, and detector acceptance, a consistent BMR is observed for different Higgs di-jet decay channels: ~3.7%

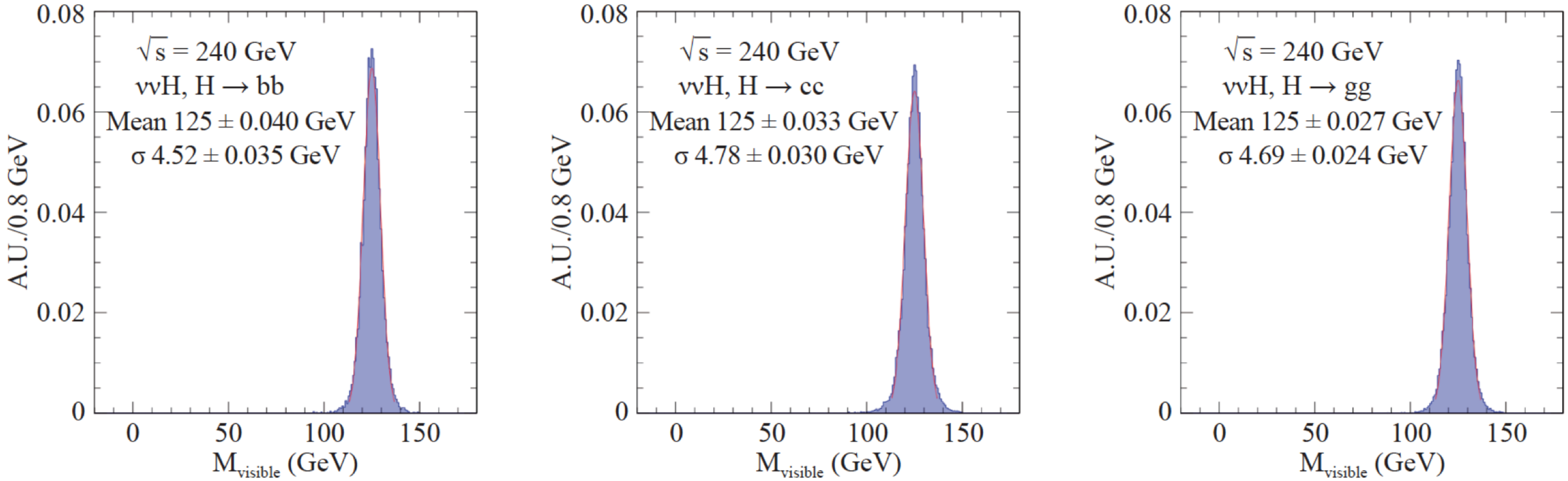
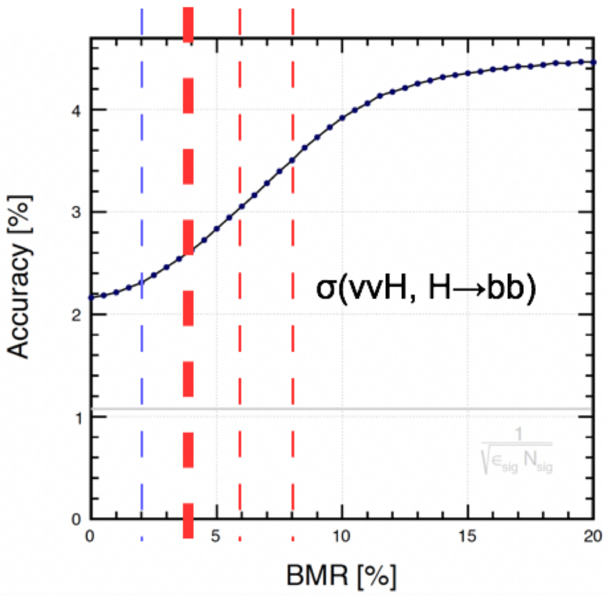
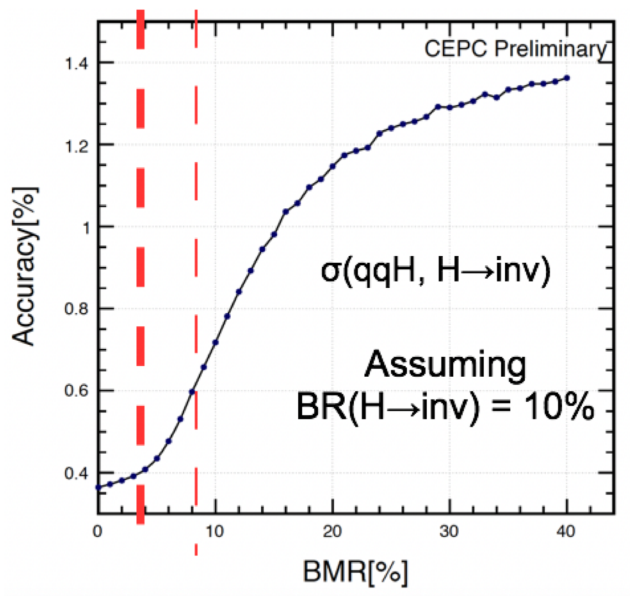
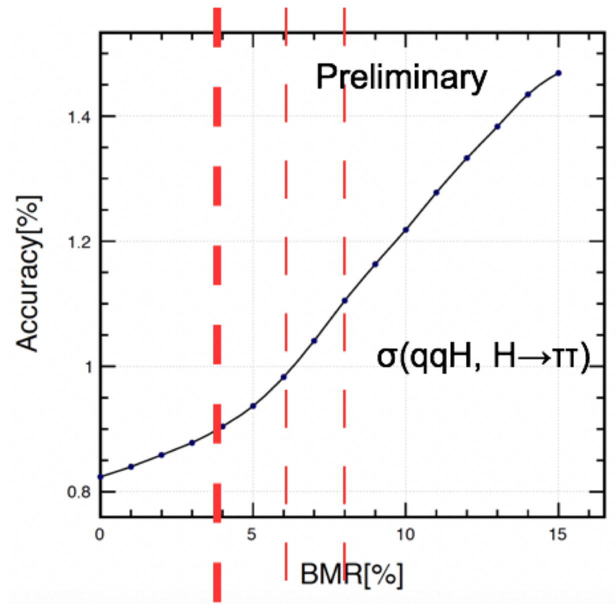


Fig. 8. (color online) Distributions of the reconstructed total visible invariant mass for $H \to bb, cc, gg$ events after event cleaning and fitted by Gaussian functions. The resolutions (sigma/mean) of the fitted results are 3.63% (*bb*), 3.82% (*cc*), and 3.75% (*gg*).

BMR Requirement



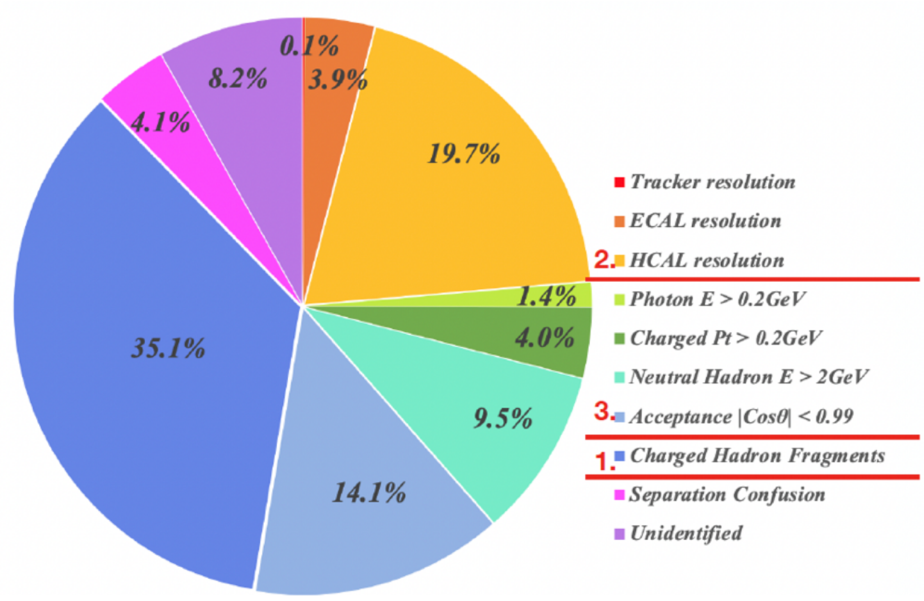




- BMR<4% is required from those benchmark processes
- CPEC baseline detector can meet this requirement
- BMR (free of jet clustering): an important performance parameter and a good figure of merit for optimizing detector(calorimeters) design

Breaking Down BMR

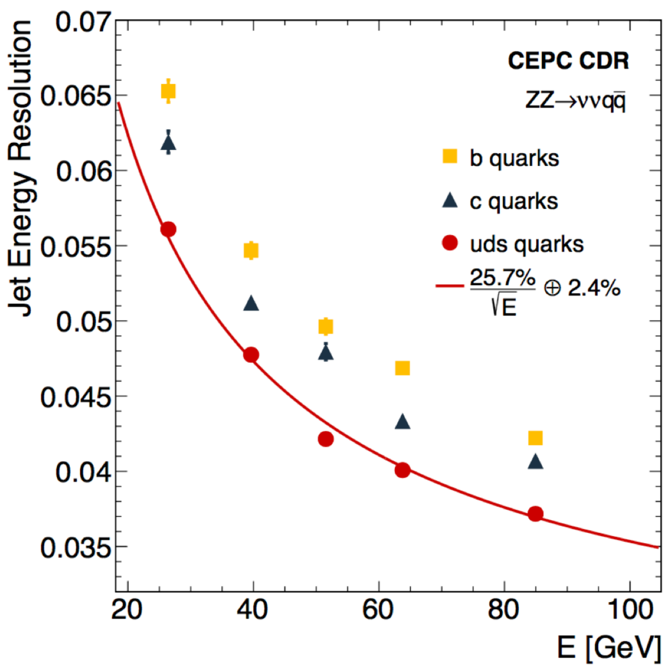
- Sources contributing to BMR include imperfect response of sub-detectors and various confusions in PFA
- A fast simulation was set up to quantify contributions from the individual sources
  - The leading factor: charged hadron fragments
  - And sub-leading: HCAL energy resolution

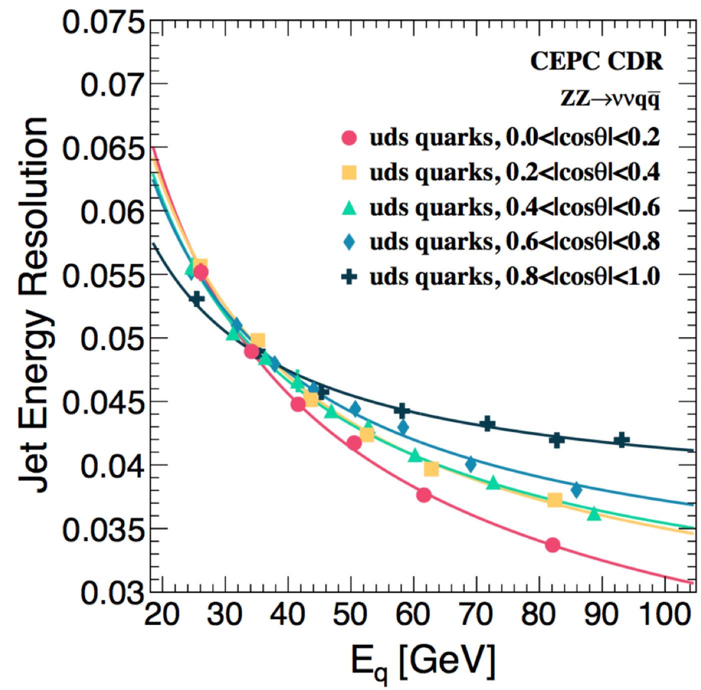


Suggesting the directions for detector and algorithm optimization

Jet Reconstruction

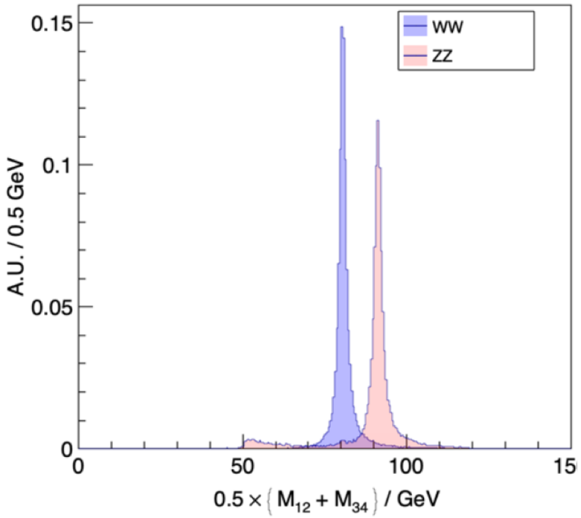
- Jets are reconstructed with the exclusive ee kt algorithm.
- Jet energy resolution shows jet flavour dependence.
- Energy resolution of light-flavour jets could reach 3% at ~ 100 GeV in a central barrel region.



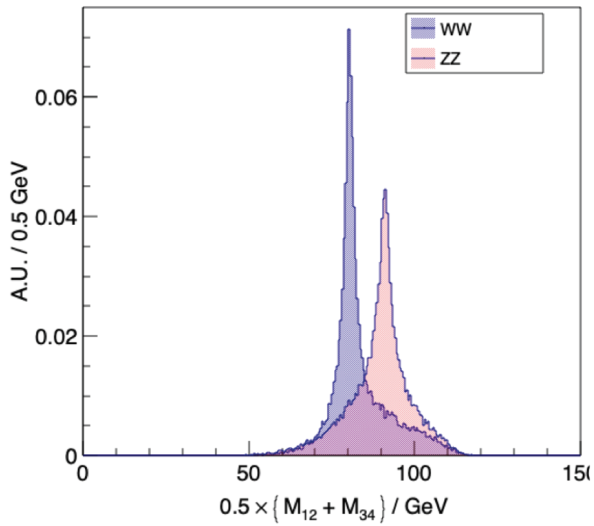


WW/ZZ→4jets Separation

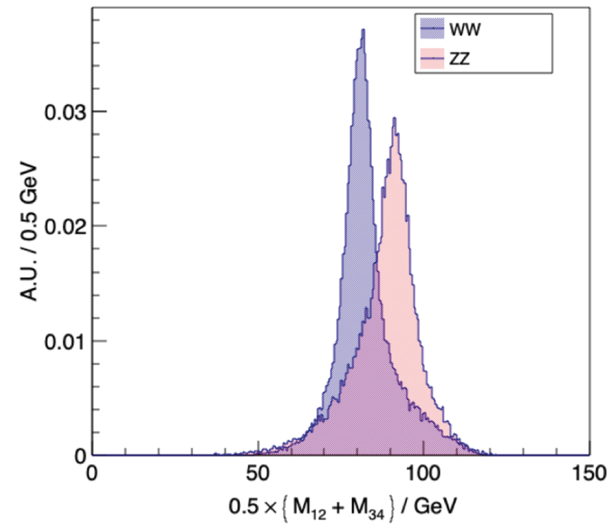
$$\chi^2 = \frac{(M_{12}-M_B)^2+(M_{34}-M_B)^2}{\sigma_B^2}$$



Intrinsic boson width



Truth jets

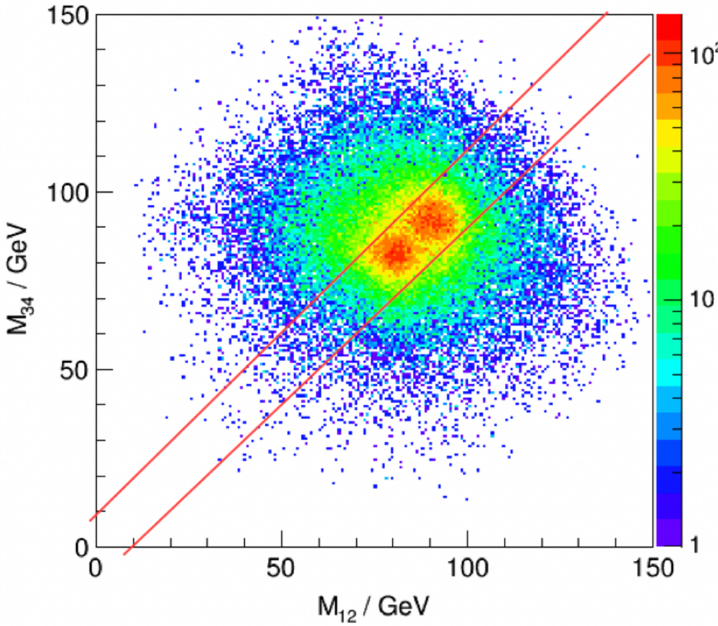


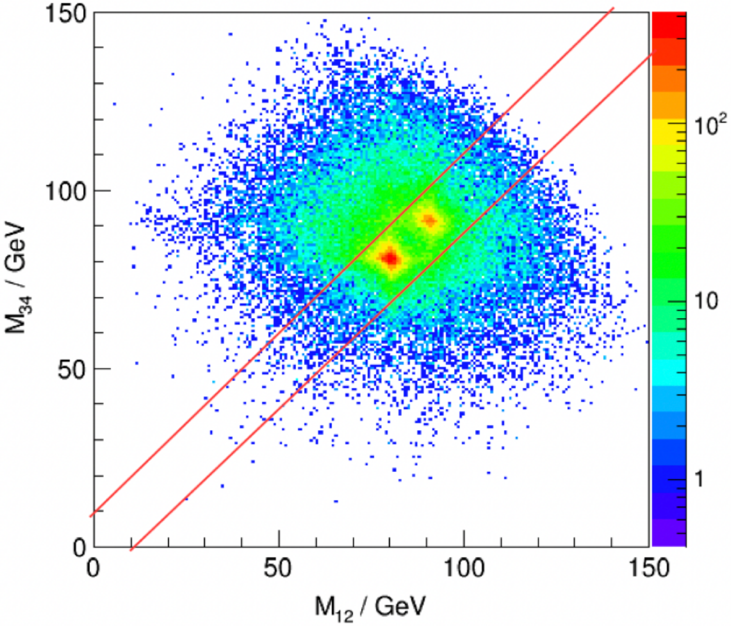
Reconstructed jets

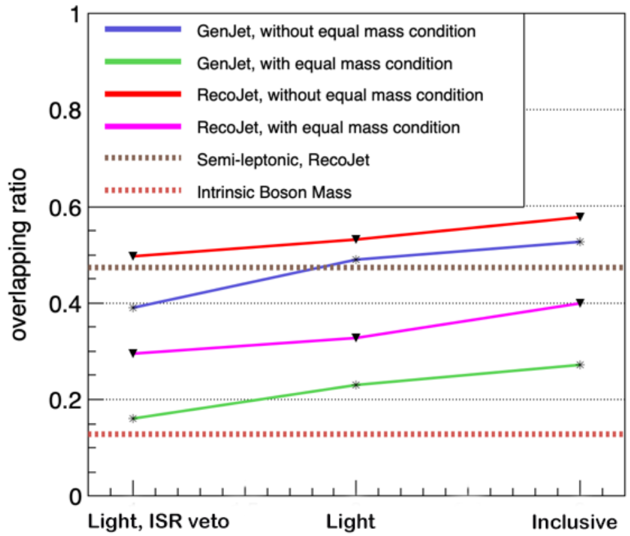
Intrinsic boson width :	13%	Overlapping ratio
+ Jet clustering & pairing :	53%	
+ Detector resolution:	58%	

- Jet clustering and pairing is the dominant factor confusing multi-jet events. It's critical to develop better algorithms.
- kinematic fit with extra constraints could also help.

One Example



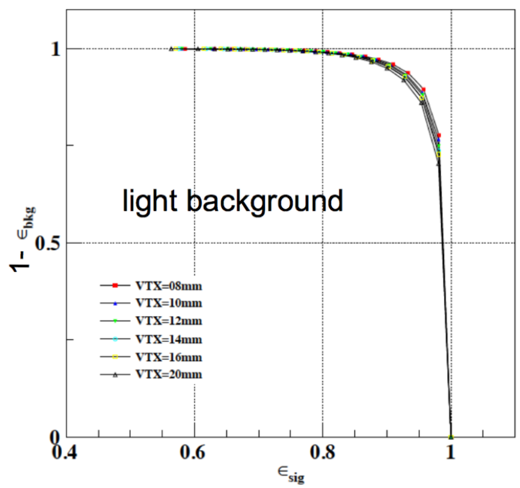


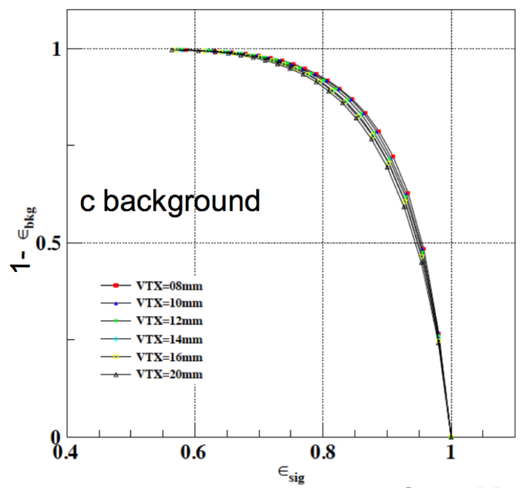


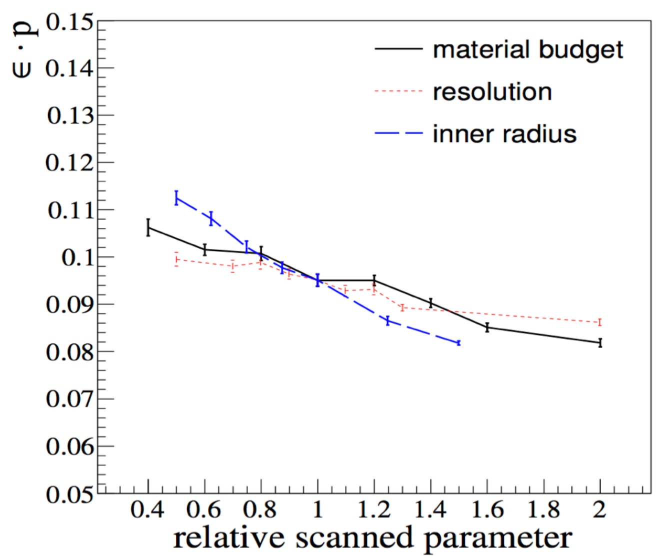
- imposing equal mass constrain of |M12 – M34| < 10 GeV can enhance separation of 4jet events significantly, but at the cost of halved statistics.

Jet Flavor Tagging

- LCFI+ package used
- Typical Performance at Z pole
  - B-tagging: eff/purity = 80%/90%
  - C-tagging: eff/purity = 60%/60%

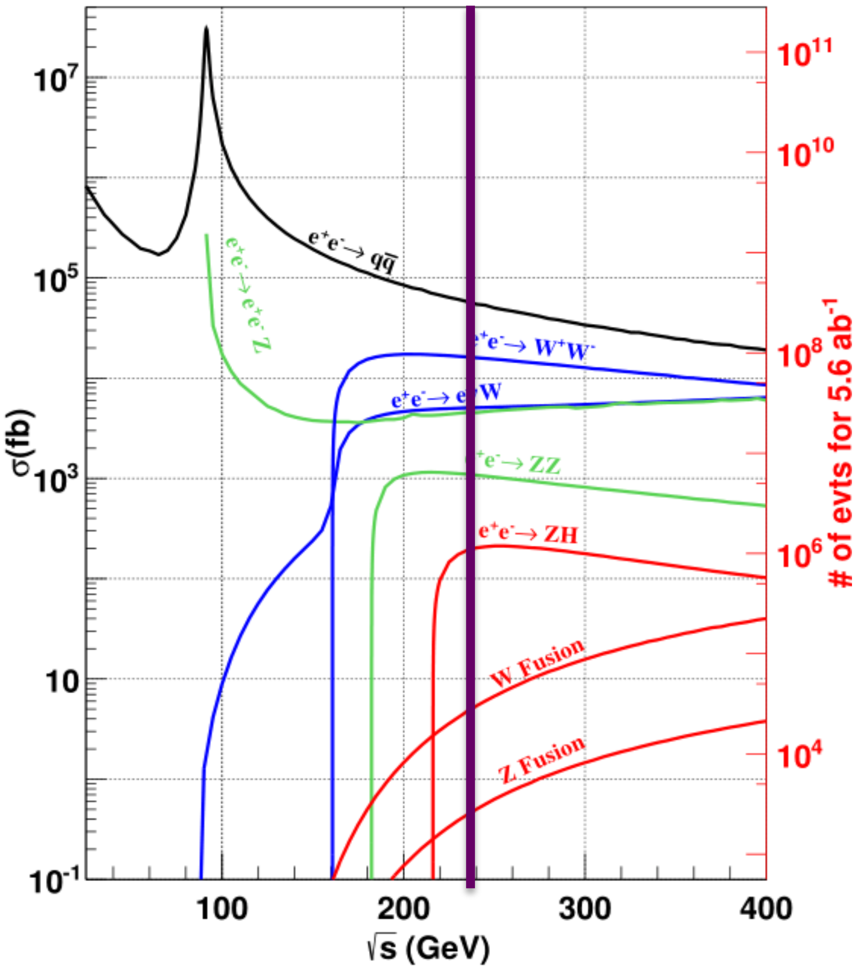






- Jet flavor tagging performance was evaluated for varied vertex detector parameters
  - Reducing inner radius is much more significant than pushing up position resolution.

Higgs Production @ 240 GeV

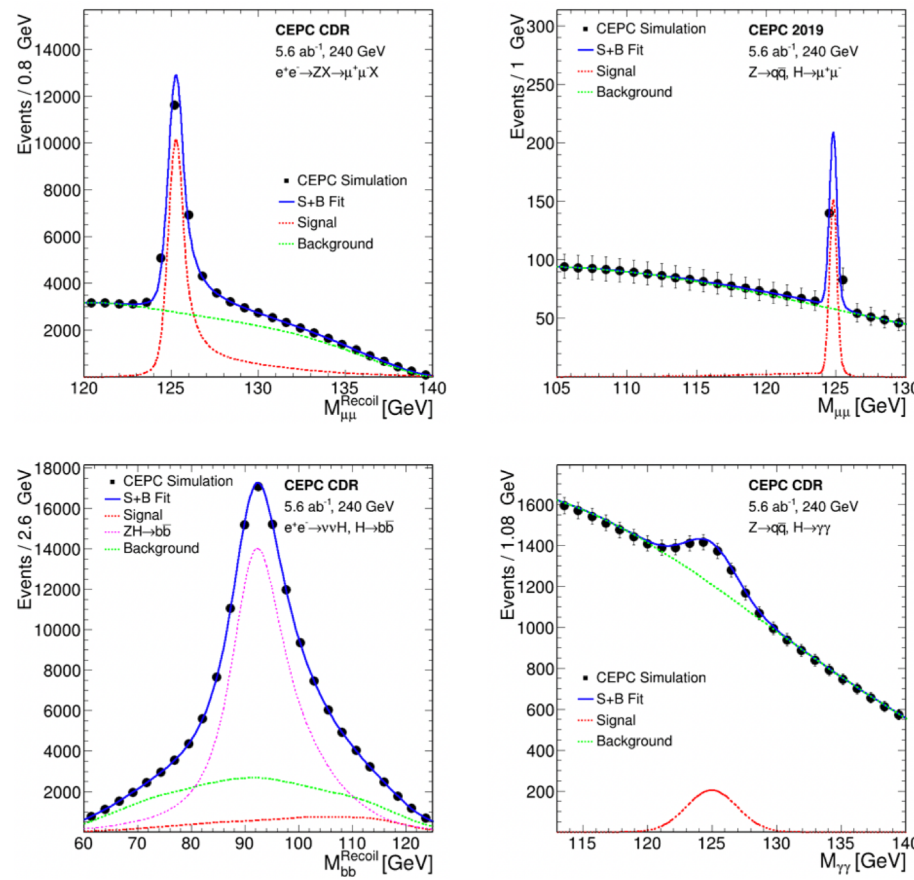


Process	Cross section	Events in 5.6 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	196.2	1.10×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^- \to e^+e^- H$	0.28	1.57×10^3
Total	203.7	1.14×10^6

- A large clean sample of Higgs events (S/B ~1: 500-1000) at 240 GeV allows for a precision Higgs physics program.

CDR Results and Improvements

$(240\text{GeV}, 5.6\text{ab}^{-1})$	CDR	2019.09
$\sigma(ZH)$	**0.50%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$	**0.27%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{cc})$	**3.3%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{gg})$	**1.3%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{WW})$	**1.0%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mathrm{ZZ})$	**5.1%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \tau\tau)$	**0.8%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \gamma\gamma)$	**6.8%**	**5.4%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to \mu\mu)$	**17%**	**12%**
$\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb})$	**3.0%**	
$\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \to \mathrm{inv.})$	**0.41%**	**0.2%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \to Z\gamma)$	**16%**	
Width	**2.8%**	
Mass	**5.9 MeV**	



$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)} \to 5.1\% \to 2.8\%$$

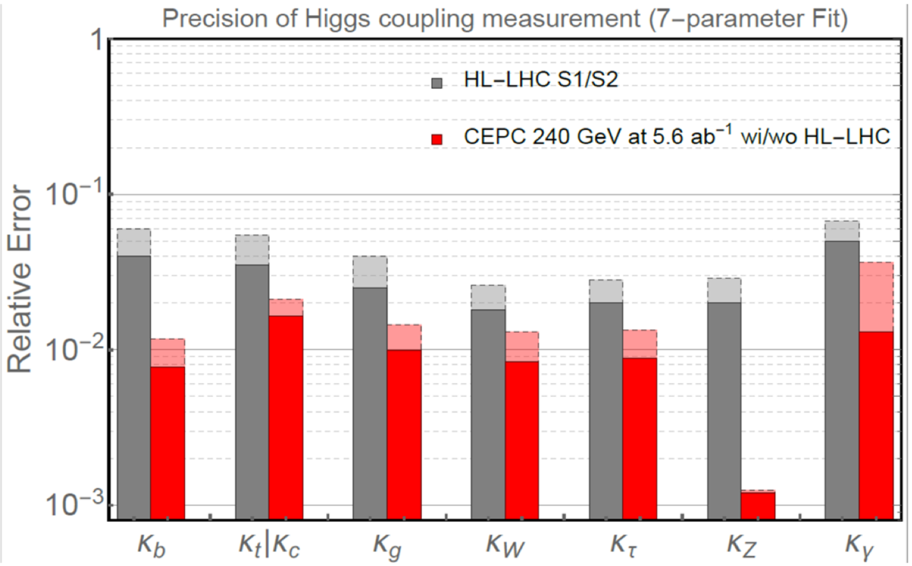
$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b})}{\mathrm{BR}(H \to b\bar{b}) \cdot \mathrm{BR}(H \to WW^*)} \to 3.0\%$$

Published: $\sigma(ZH)$:1601.05352, bb/cc/gg: 1905.12903, $\tau\tau$:1903.12327……

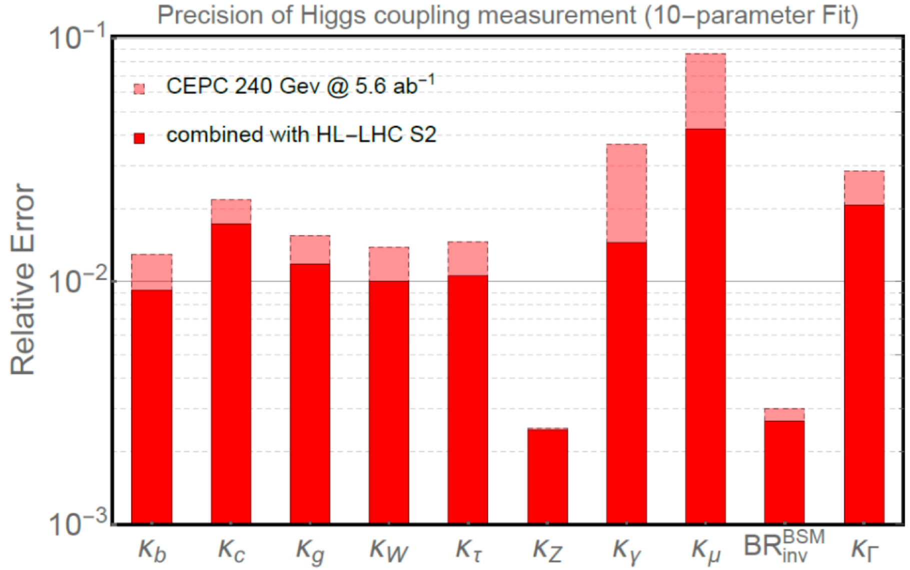
Higgs Couplings

- Using updated HL-LHC projections in comparison and combination

Constrained 7-parameter fit



10-parameter fit with floating total width



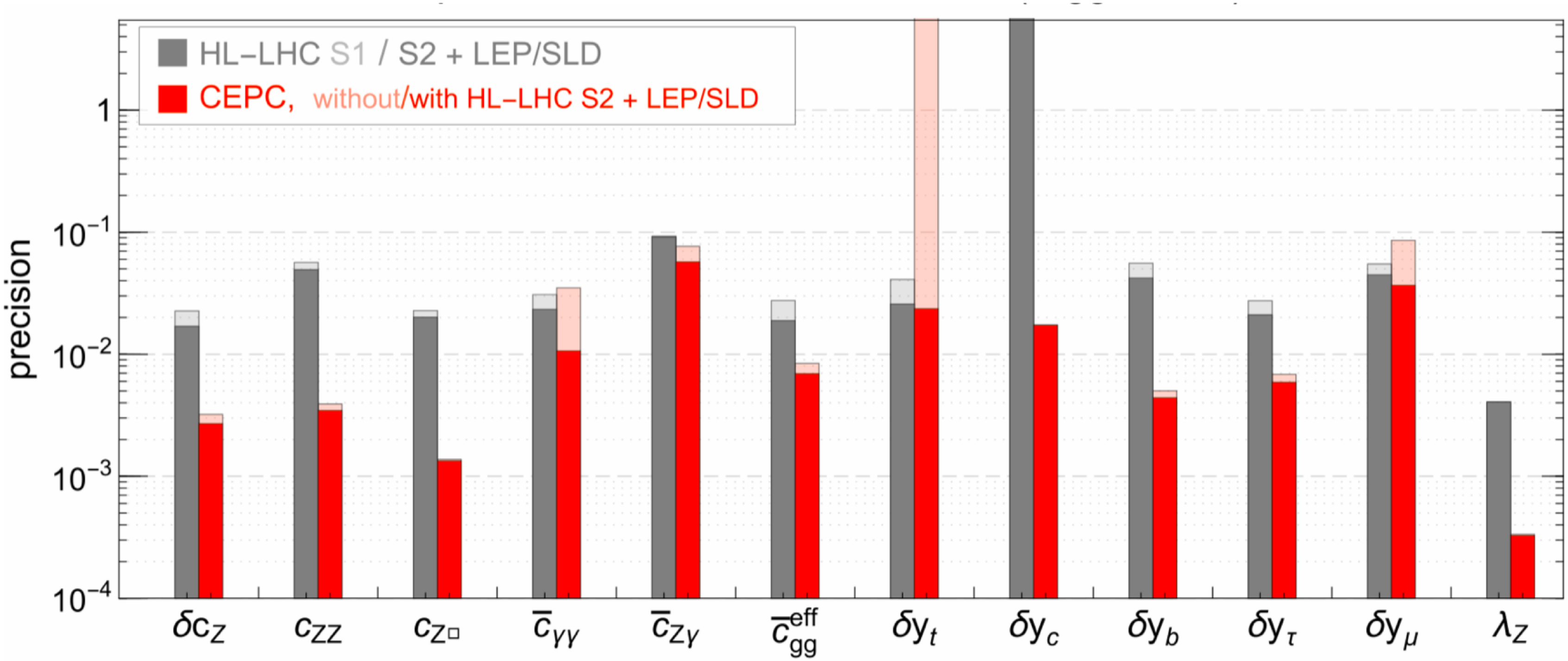
$$\kappa_f = \frac{g(hff)}{g(hff;\mathrm{SM})}, \ \kappa_V = \frac{g(hVV)}{g(hVV;\mathrm{SM})}$$

CEPC: ~1% precision (κ_Z ~0.16%)

Probing BSM with Precision

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

EFT fit with Higgs basis



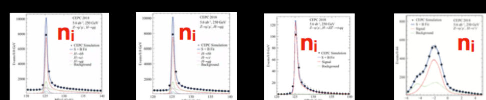
A New Global Analysis Approach

We possess what the LHC lacks（人无我有）

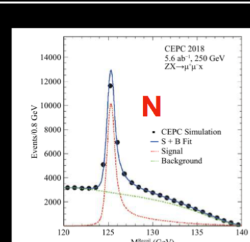
- Tagging method, absolute/model-independent
- All Higgs decays accessible except e and uds
- Multinomial distribution: statistical constraint
- Two types of backgrounds
  - Higgs background (crosstalk)
  - non-Higgs background (enlarge the stat. unc. of n_i)

$$B_i = \frac{n_i/\epsilon_{ii}}{N}$$

B_i =



+ … …



non-Higgs background
— subtracted with fitting
— but enlarges σ_{n_i}

Solve N_i by minimizing the χ^2 with constraint

$$\chi^2 = \sum_i \frac{(\sum \epsilon_{ij} N_j - n_i)^2}{\sigma^2_{n_i}} + \frac{(\sum_l N_l - N)^2}{\sigma^2_N}$$

Higgs -> cc, bb, mm, tt, gg, aa, aZ, ZZ, WW
1 2 3 4 5 6 7 8 9

$$\begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \\ n_7 \\ n_8 \\ n_9 \end{pmatrix} = \begin{pmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} & \epsilon_{14} & \epsilon_{15} & \epsilon_{16} & \epsilon_{17} & \epsilon_{18} & \epsilon_{19} \\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23} & \epsilon_{24} & \epsilon_{25} & \epsilon_{26} & \epsilon_{27} & \epsilon_{28} & \epsilon_{29} \\ \epsilon_{31} & \epsilon_{32} & \epsilon_{23} & \epsilon_{34} & \epsilon_{35} & \epsilon_{36} & \epsilon_{37} & \epsilon_{38} & \epsilon_{39} \\ \epsilon_{41} & \epsilon_{42} & \epsilon_{33} & \epsilon_{44} & \epsilon_{45} & \epsilon_{46} & \epsilon_{47} & \epsilon_{48} & \epsilon_{49} \\ \epsilon_{51} & \epsilon_{52} & \epsilon_{43} & \epsilon_{54} & \epsilon_{55} & \epsilon_{56} & \epsilon_{57} & \epsilon_{58} & \epsilon_{59} \\ \epsilon_{61} & \epsilon_{62} & \epsilon_{53} & \epsilon_{64} & \epsilon_{65} & \epsilon_{66} & \epsilon_{67} & \epsilon_{68} & \epsilon_{69} \\ \epsilon_{71} & \epsilon_{72} & \epsilon_{63} & \epsilon_{74} & \epsilon_{75} & \epsilon_{76} & \epsilon_{77} & \epsilon_{78} & \epsilon_{79} \\ \epsilon_{81} & \epsilon_{82} & \epsilon_{73} & \epsilon_{84} & \epsilon_{85} & \epsilon_{86} & \epsilon_{87} & \epsilon_{88} & \epsilon_{89} \\ \epsilon_{91} & \epsilon_{92} & \epsilon_{83} & \epsilon_{94} & \epsilon_{95} & \epsilon_{96} & \epsilon_{97} & \epsilon_{98} & \epsilon_{99} \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \\ N_5 \\ N_6 \\ N_7 \\ N_8 \\ N_9 \end{pmatrix}$$

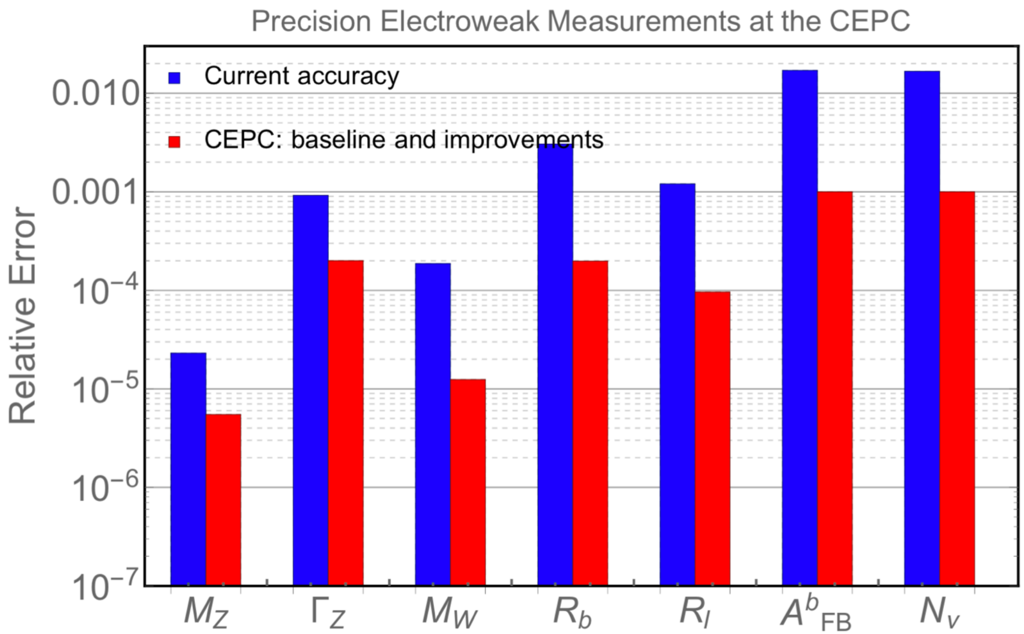
Neglect e and uds decays — constraint feasible

$$\sum_i N_i = N^{tag} \text{ or } \sum_i B_i = 1 \qquad B_i = \frac{N_i}{N}$$

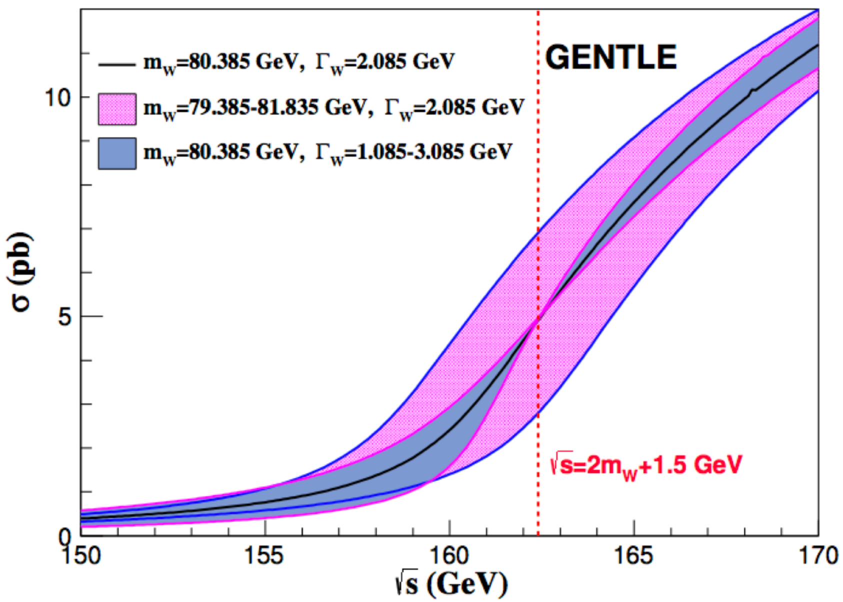
See the talk by P. Shen and G. Li at the CEPC physics workshop, 2019/07/01-05, PKU, for more details .

Electroweak Physics

Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158–172	10	1	2.6	2×10^7 (†)



Precision observables at Z pole



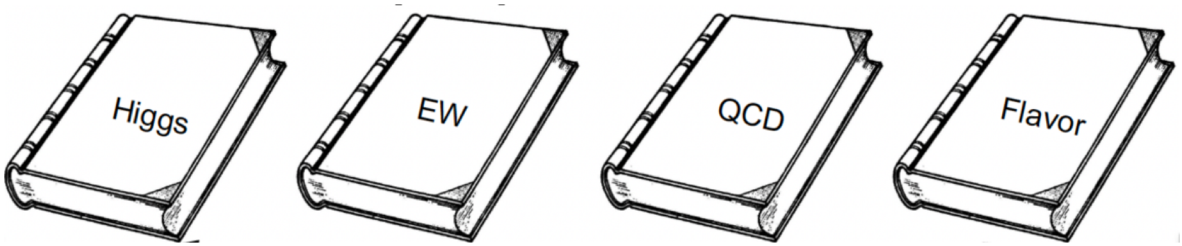
W mass using threshold scan technique.
Expected $\sigma(M_W)$ ~ 1MeV

A big challenge for beam energy calibration !

Post-CDR Planning

- Dedicated workshops and discussions for planning for TDR
- More to happen in the coming IAS HKUST HEP event

To deliver full CEPC physics white papers by the end of 2020



- Fully explore detector performance in physics analysis
- Enhance existing analyses by use of full kinematic information, MAV techniques, global analysis approaches.
- Go deeper and wider: differential measurement, Spin/CP, BSM search

Summary

- CEPC is a factory of H/Z/W bosons with a clean environment
- Huge physics potential
  - Higgs, EWK, Flavor, QCD
- Performance of the baseline detector can meet requirements from Higgs physics program
- A lot of work ahead from CDR to TDR
  - full exploitation of CEPC physics potential, particularly on flavor and QCD
  - Detector optimization based on performance studies, especially for Z pole operation
  - Software, reconstruction/Identification, analysis tools

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- Back up