Physics requirements and detector concepts

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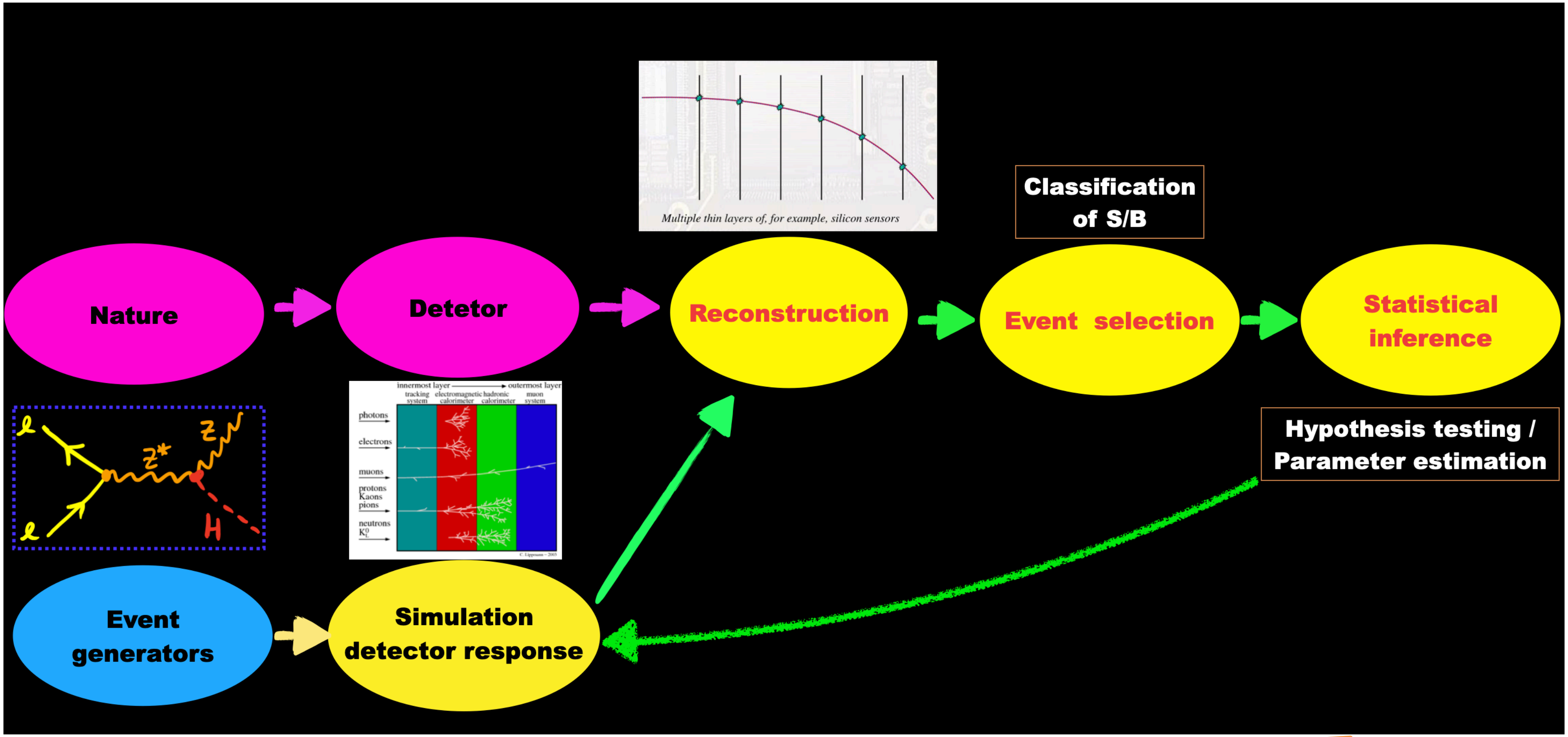
CEPCSW tutorial

IHEP, 2020-09-17

Outline

- Introduction
- Physics study at CEPC
- Requirements
- CEPC soft to new CEPCSW
- Summary

Introduction: experiment procedure



Green loop is the main activity at R&D stage
Yellow ellipses related with software

Introduction: comment on detector and software performances

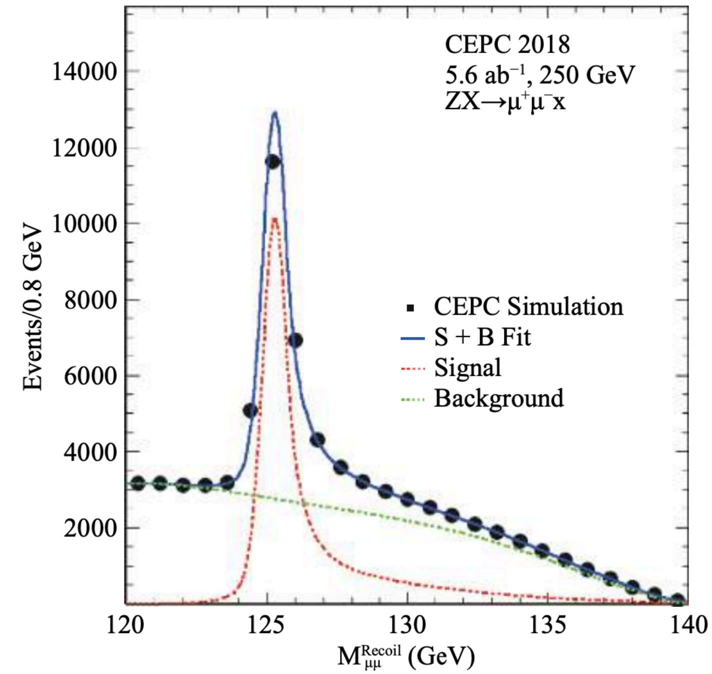
Resolution of instrument

$$\hat{\sigma}_m = \frac{\hat{\sigma}}{\sqrt{n}}$$

Stat. uncertainty

Statistics

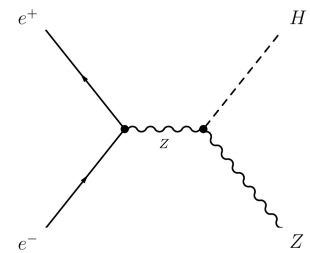
6.5 MeV with 18k signals

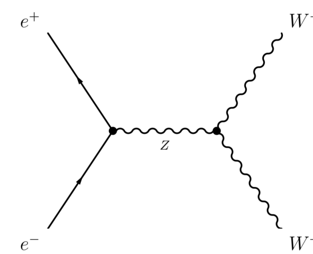


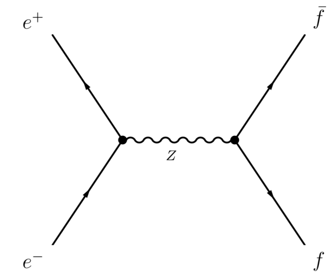
Conclusion: if resolution doubles, at least 4-times of statistics needed to compensate it.

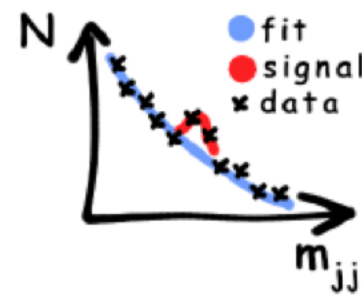
Two ways to go beyond SM
direct searches/precision measurements

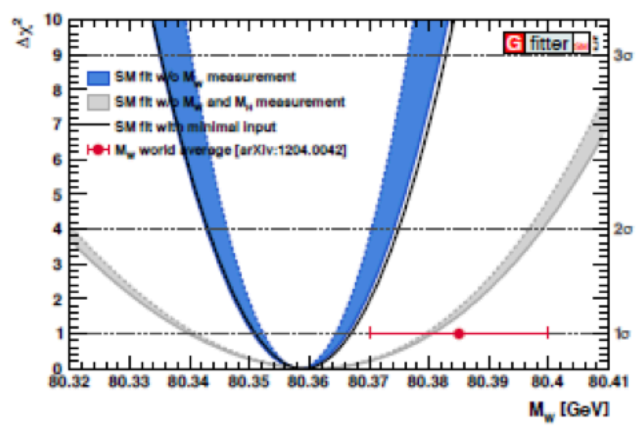
- Higgs : mass, width, production, decay couplings, quantum numbers, …
- W: mass, width, and TGC
- Z: Rb, Afb, …
- Flavor physics







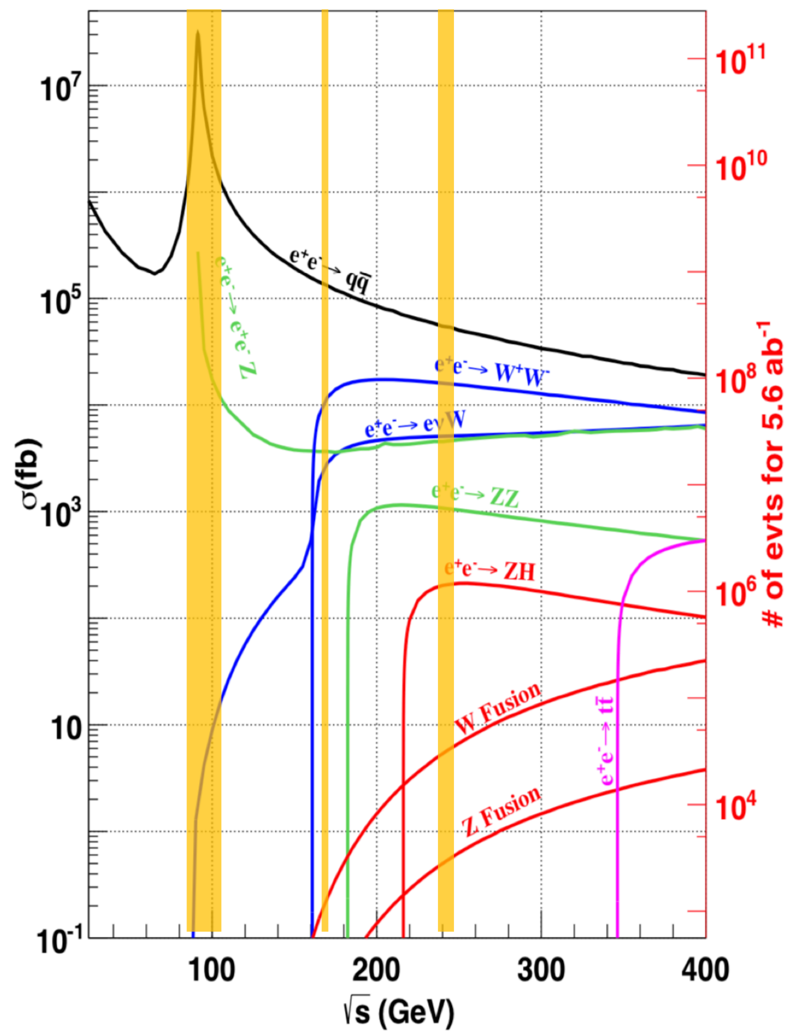




Physics at CEPC

- ✓ CEPC dedicated Higgs precision and probing BSM with Higgs as a portal, as well as precision electroweak test, QCD, and flavor physics – the natural expansion and tradition of BES
- ✓ CEPC is going to deliver more than 1 M Higgs events, 10^8 WW pairs, and almost 10^{12} Z bosons

Operation mode	Z factory	W threshold scan	Higgs factory
$\sqrt{s}$ (GeV)	91.2	158 - 172	240
L ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	16-32	10	3
Running time (years)	2	1	7
Integrated Luminosity (ab^{-1})	8 - 16	2.6	5.6
Higgs yield	-	-	10^6
W yield	-	10^7	10^8
Z yield	10^{11-12}	10^9	10^9



Benchmarks for performance

Physics process	Measurands	Critical detector	Required performance
$ZH \to l^+l^-X$	m_H, σ_{ZH}	Tracker	$\Delta(1/P_T) = 2\times10^{-5} \oplus \frac{10^{-3}}{P(GeV)\sin^{\frac{3}{2}}\theta}$
$H \to \mu^+\mu^-$	$B(H \to \mu^+\mu^-)$		
$H \to b\bar{b}, c\bar{c}, gg$	$B(H \to b\bar{b}, c\bar{c}, gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(GeV)\sin^{\frac{3}{2}}\theta}(\mu m)$
$H \to q\bar{q}, W^+W^-, ZZ$	$B(H \to q\bar{q}, W^+W^-, ZZ)$	Calo	$\sigma_E^{jet} = 3 \sim 4\% \ @100\,GeV$
$H \to \gamma\gamma$	$B(H \to \gamma\gamma)$	ECAL	$\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E(GeV)}} \oplus 0.01$

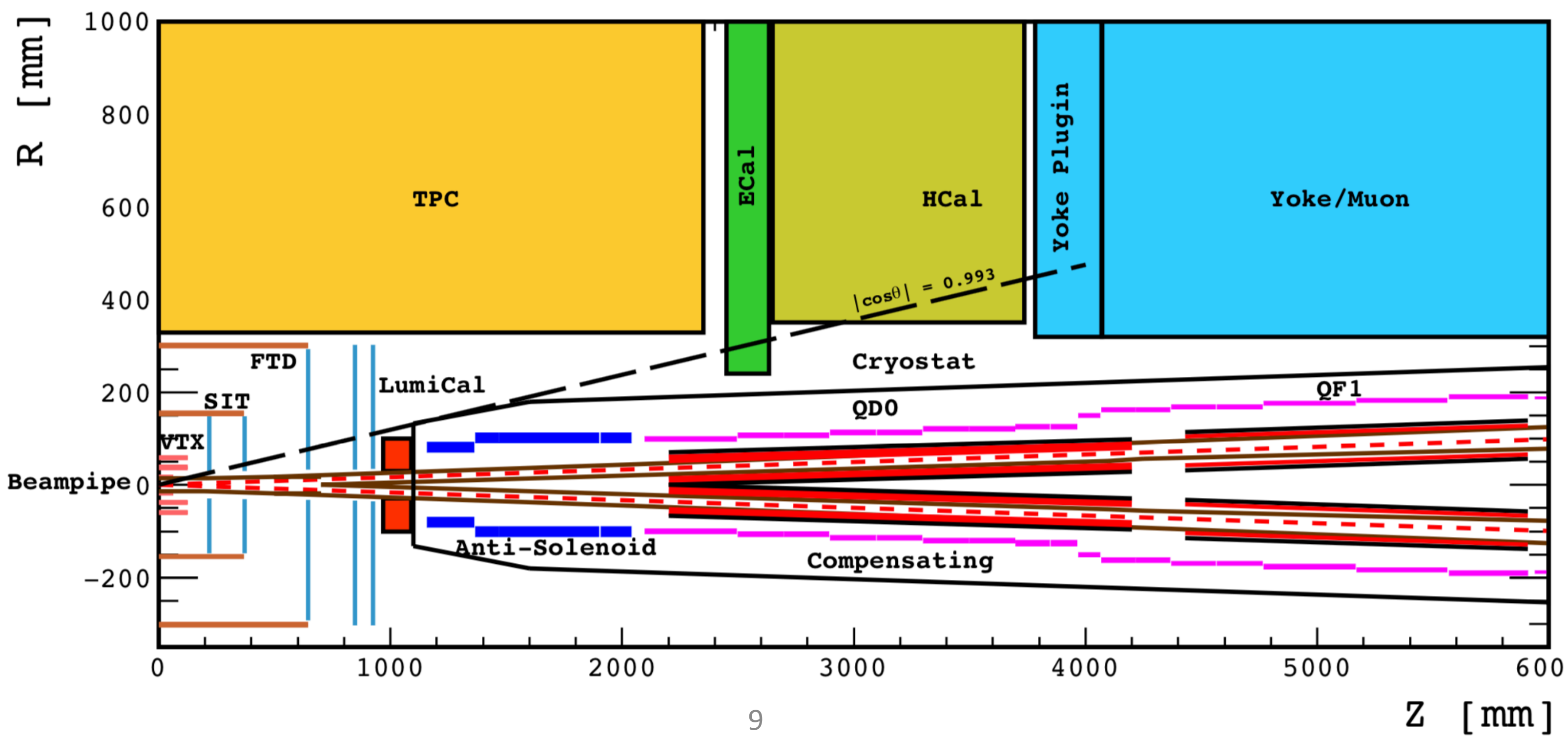
- Many flavor studies need excellent particle identification, which also benefits to jet physics

Experiment conditions

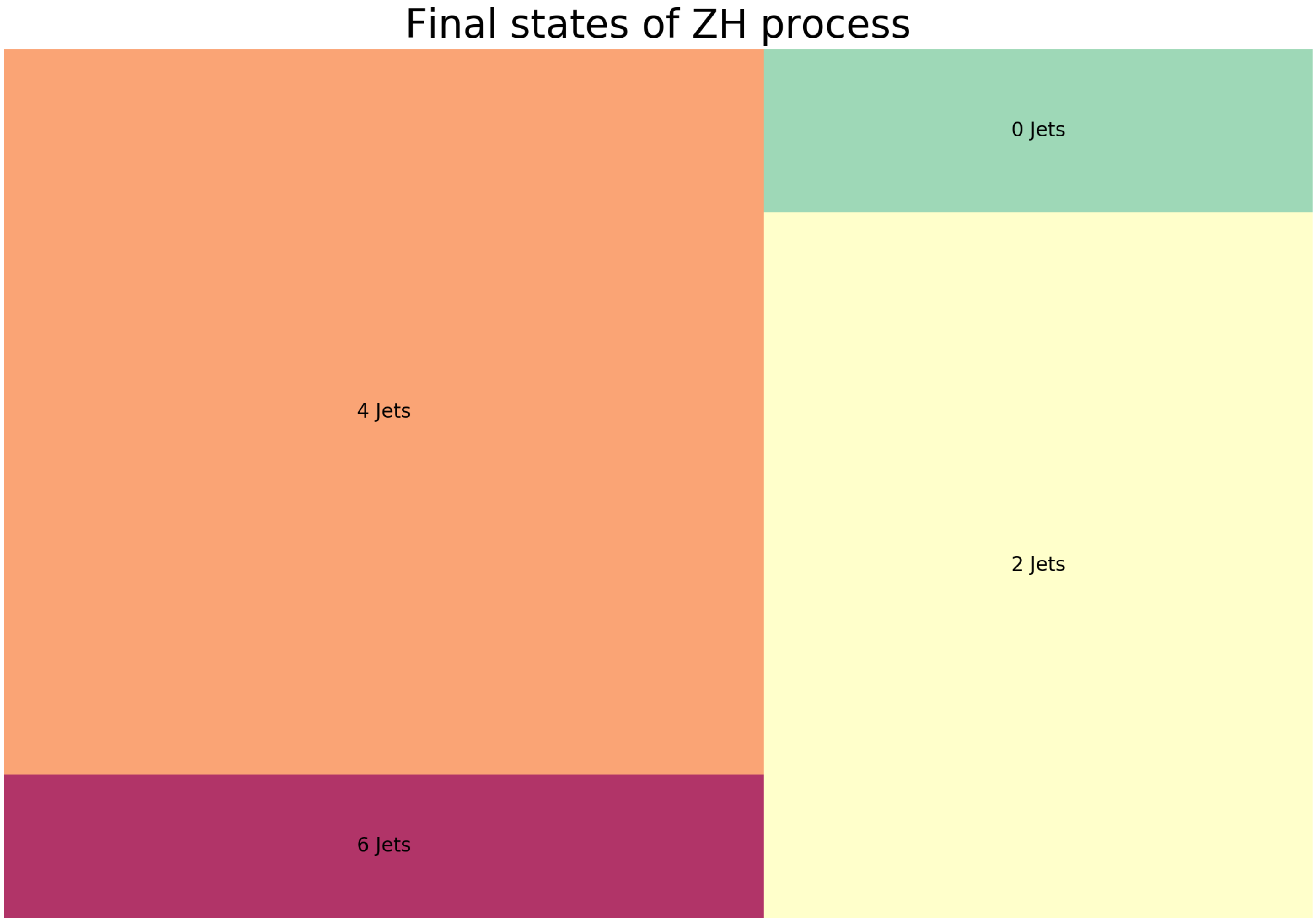
CEPC design supposed to deliver more luminosities at all energies Constraint from machine

- double ring
- cross angle: 33 mrad
- L* = 2.2 m, QD0, QF1 inside detector
- Backgrounds : pair production& off-beam particles
- Luminosity measurement very challenge, Stringent requirements on detector design

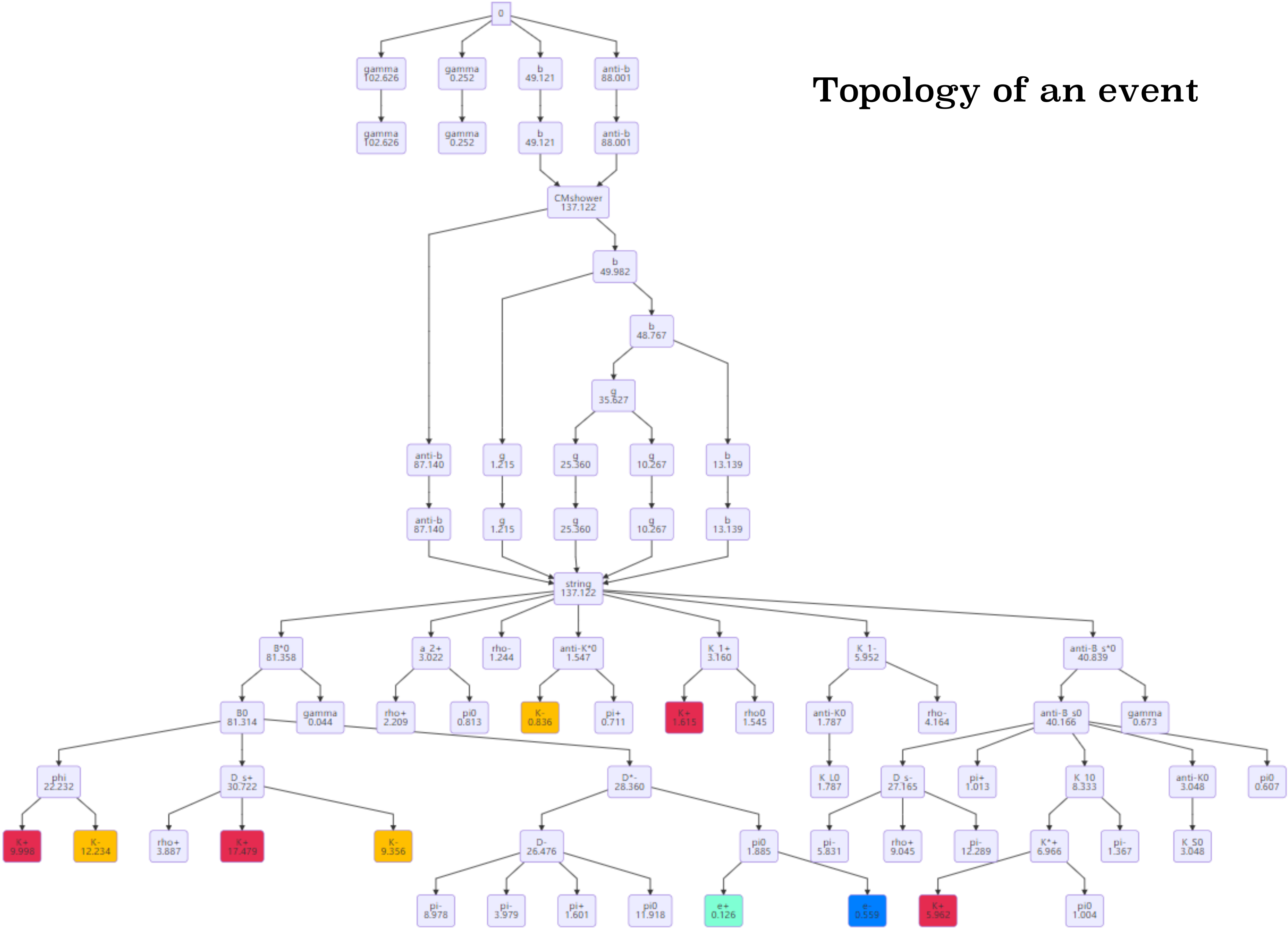
	H (240)	**W** (160)	**Z** (91)
Hit Density [hits/cm^2·BX]	2.4	2.3	0.25
TID [MRad/year]	0.93	2.9	3.4
NIEL [10^{12} 1 MeV n_{eq}/cm^2·year]	2.1	5.5	6.2



Physics objects:
leptons, photons, jets, missing energy

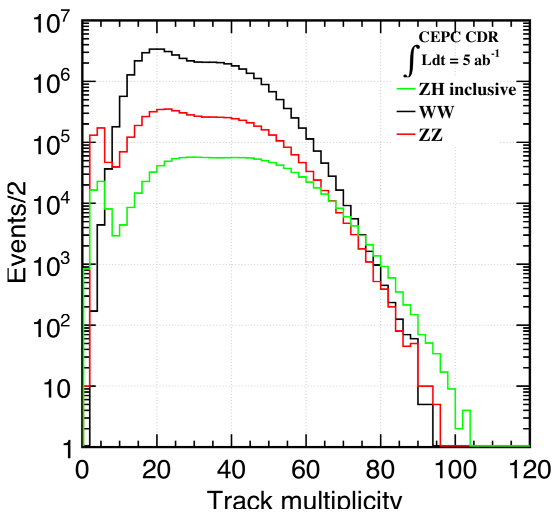


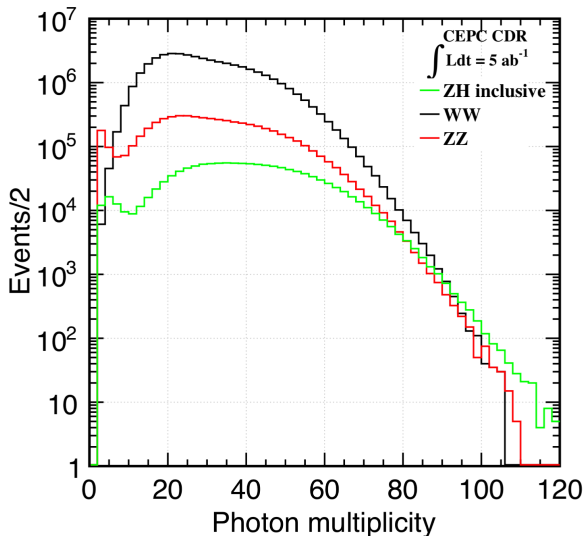
Topology of an event

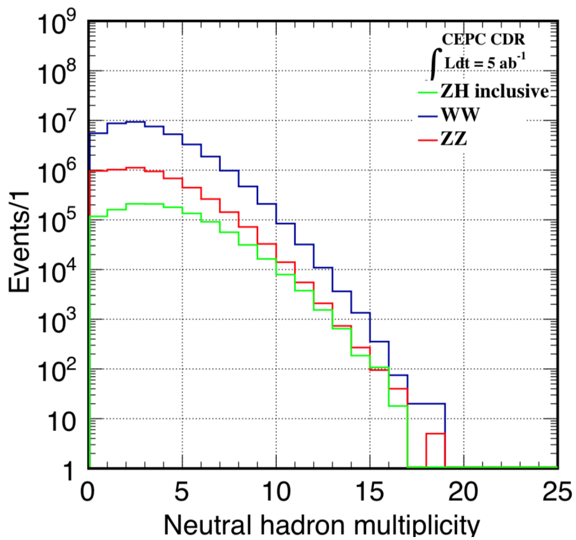


Multiplicities of typical events

- Averaged multiplicities of the charged tracks and photons ~ 30, but the maximum to 100, which carry most of the energy of an event
- Neutral hadrons ~ 10% of the energy





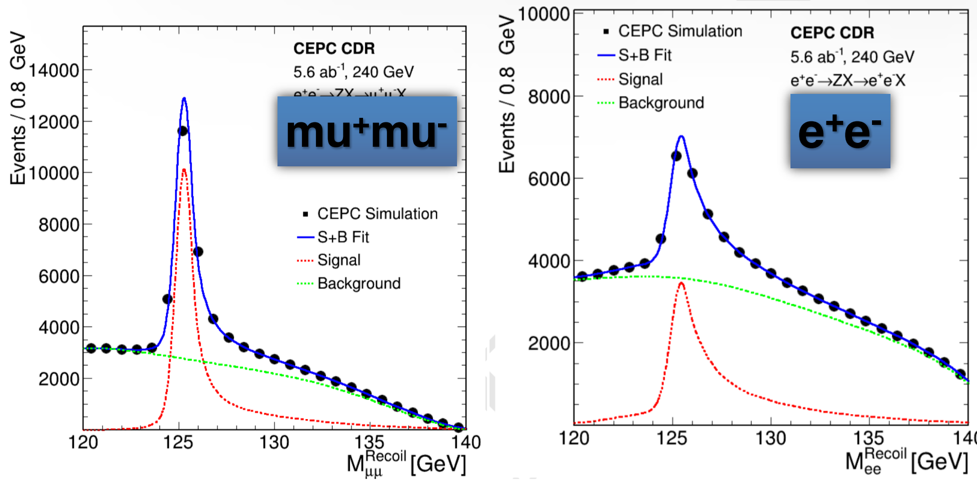


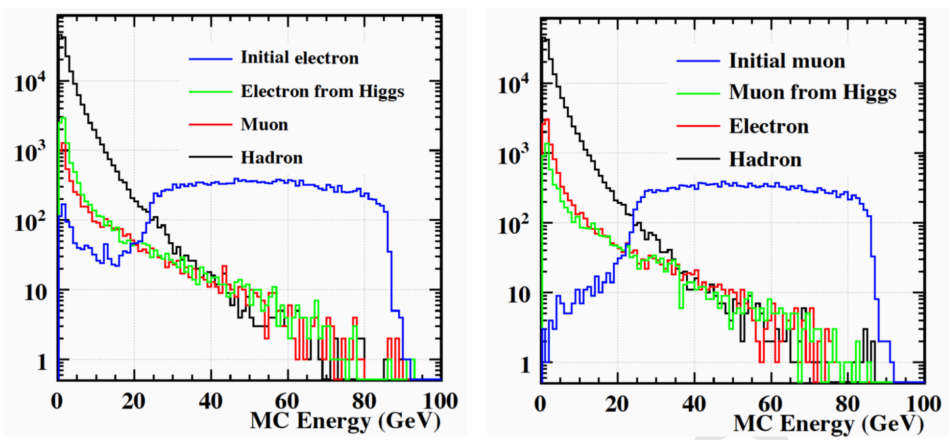
Leptons: tracking & ID

- ☑ Leptons extremely important for the model independent study of Higgs
- ☑ The momenta greater than 15 GeV
- ☑ High tracking efficiency, good lepton ID, and good resolution preferred

$$\hat{\sigma}_m = \frac{\hat{\sigma}}{\sqrt{n}}$$

$$e^+e^- \to ZH \to \mu^+\mu^-(e^+e^-) + inclusive$$

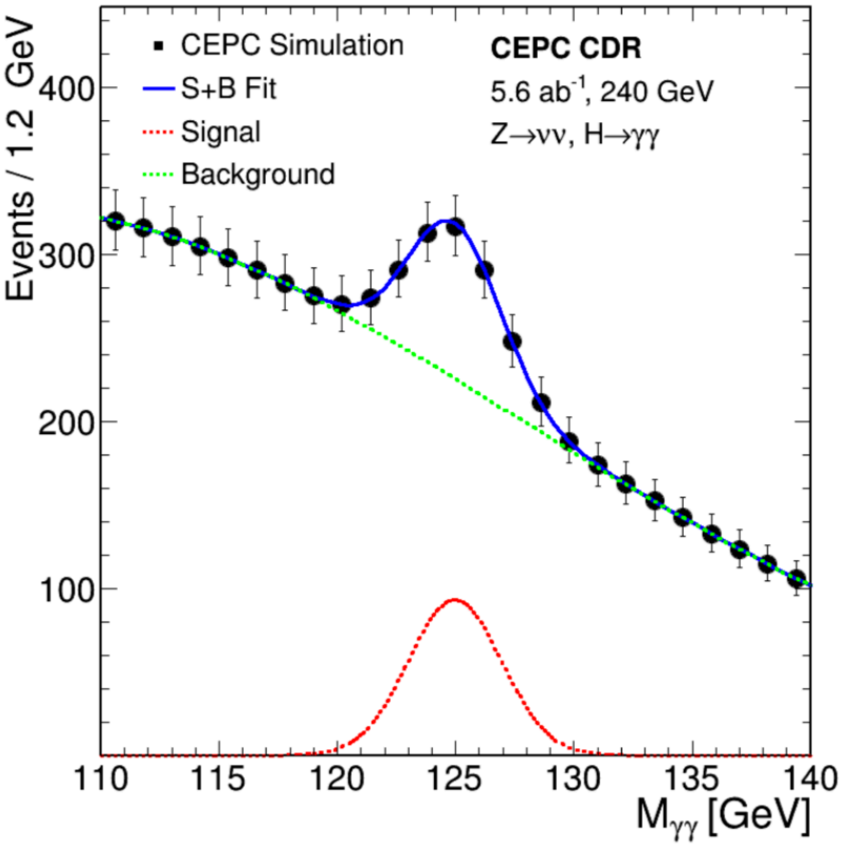




Photons

- Photon energy resolution is key issue for Higgs di-photon measurement, as well as π^0 and ISR photon tagging

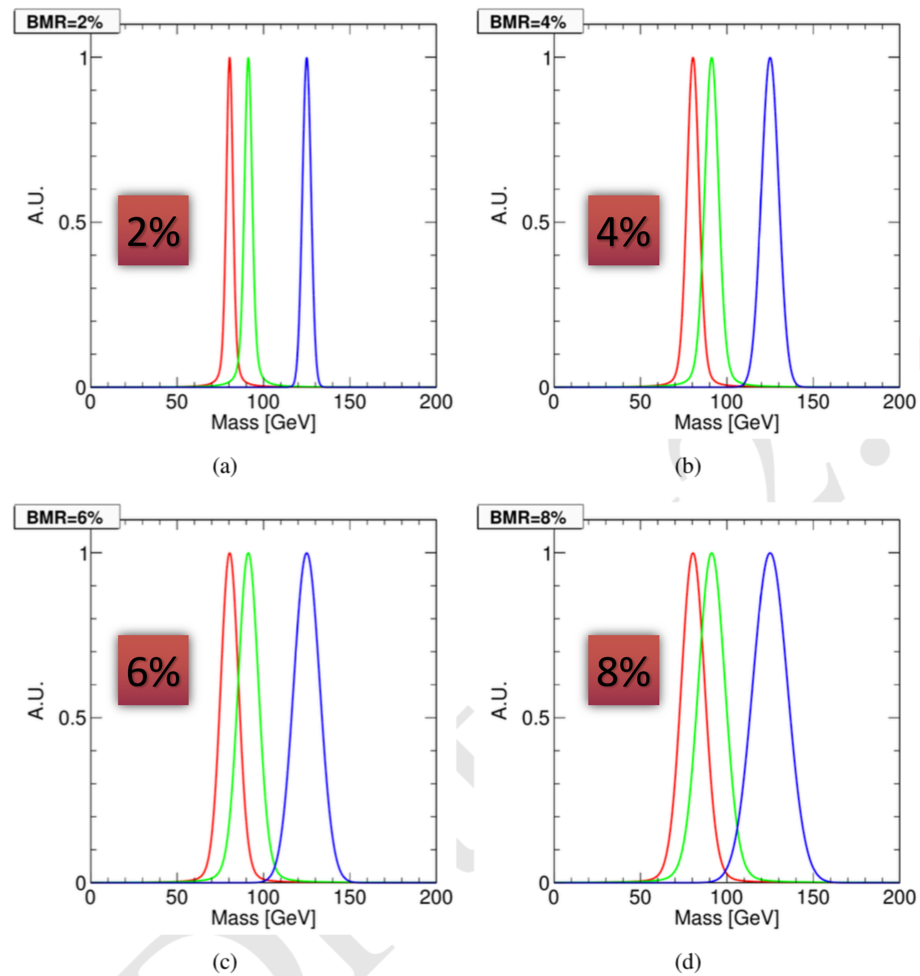
- Simulation shows $20\%/E^{1/2}$ is minimum requirement for Higgs to di-photon study.



Jets

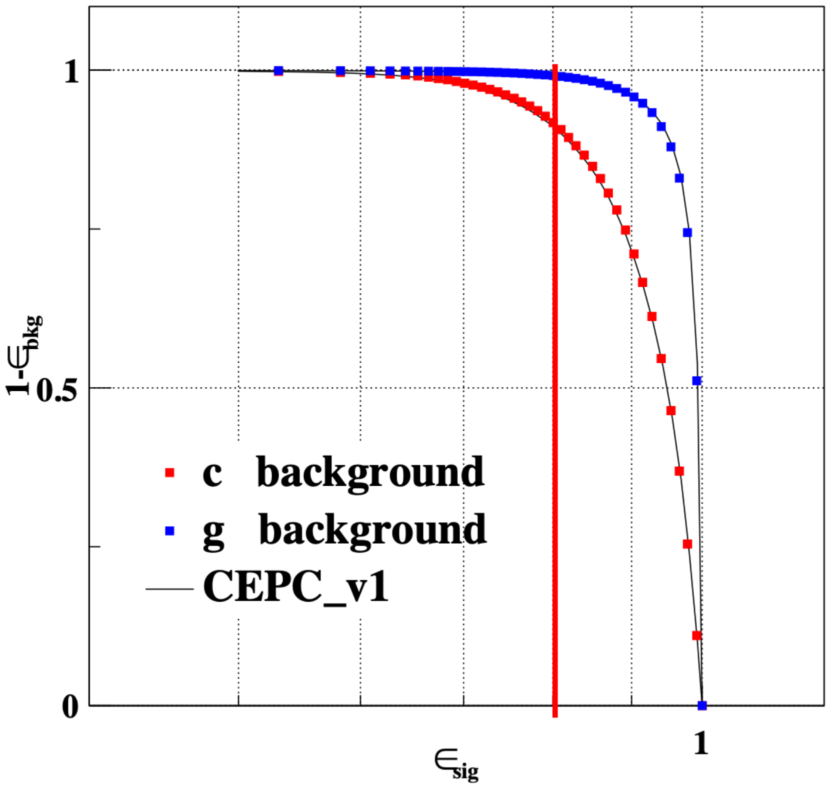
- Jet energy resolution (JER) is essential for boson reconstruction, left plots demonstrate the importance of boson mass resolution

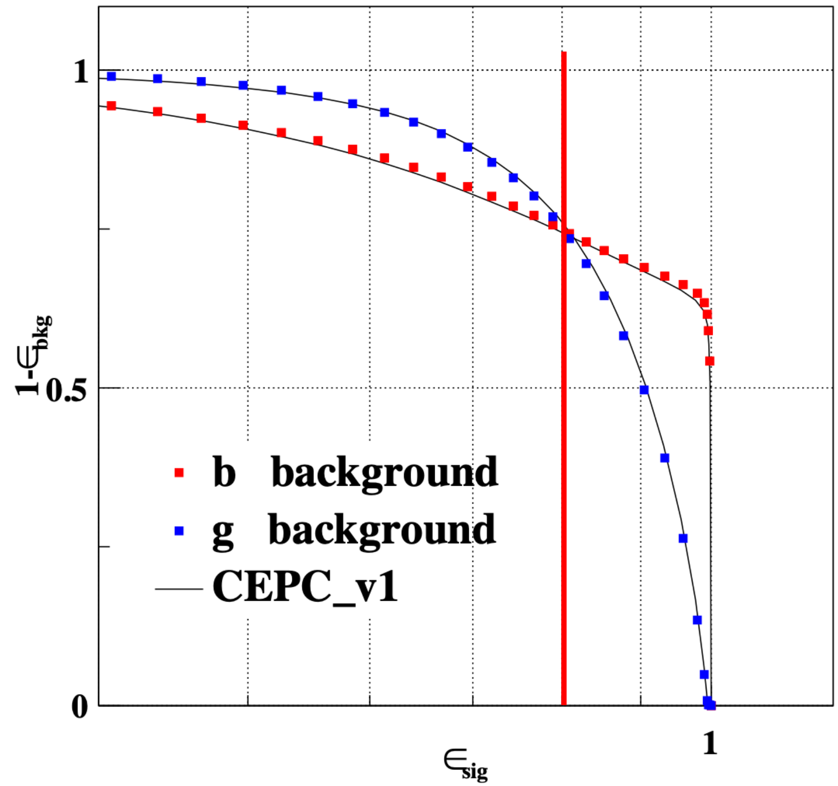
- 4% is minimum requirement for W&Z boson separation



(a) (b) (c) (d)

Jet ID





Receiver Operating Characteristic Curve (ROC)

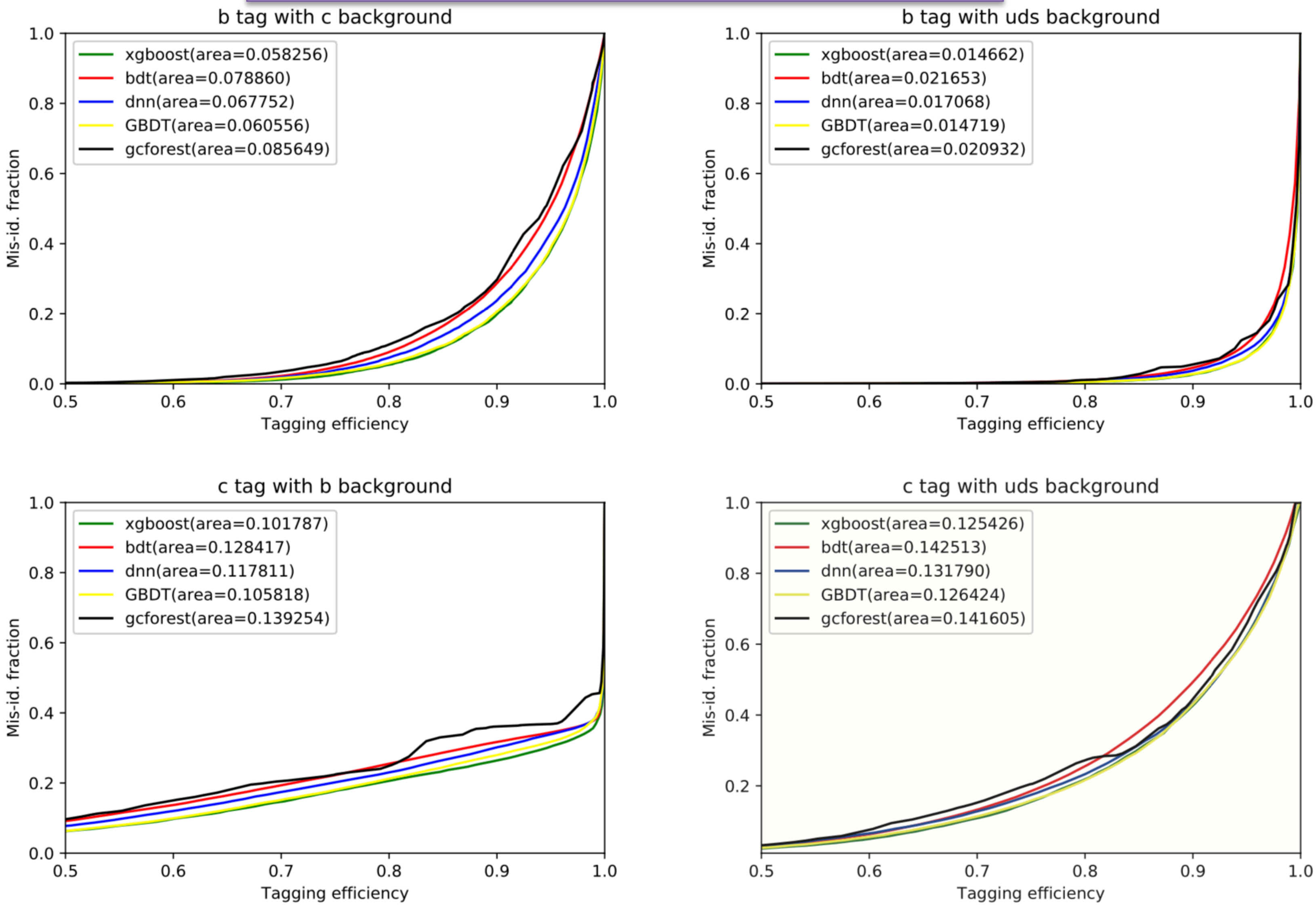
80% b-tagging eff. : Reject 90% c and 99% o jets

80% c-tagging eff. : Reject 75% b and 75% o jets

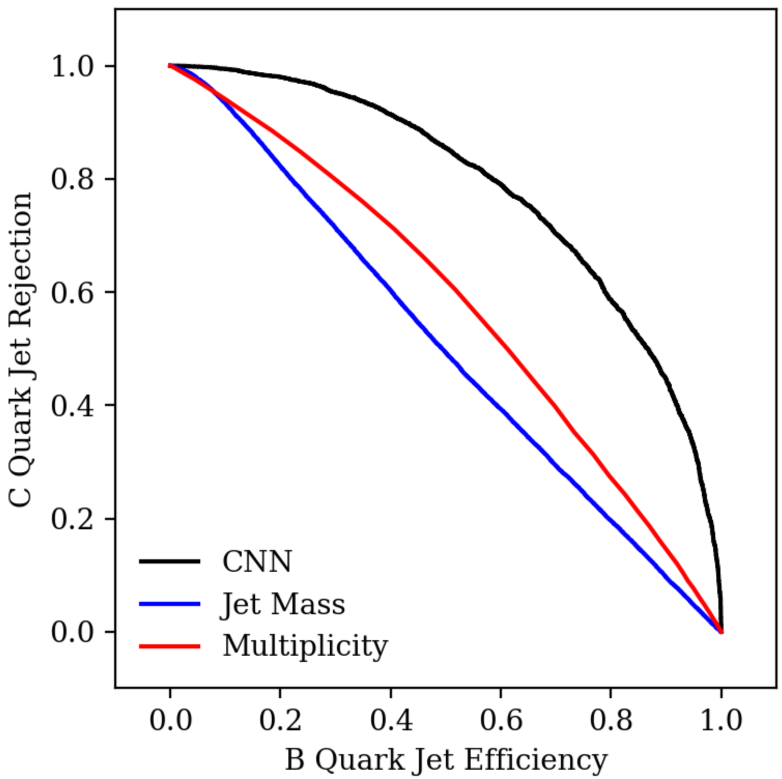
Tag efficiency vs. mis-identification

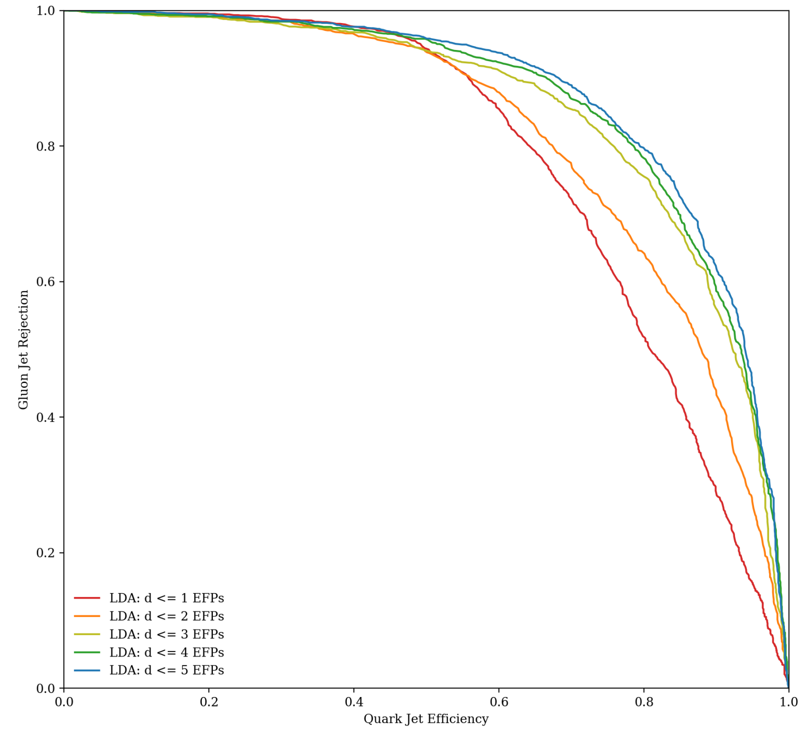
AUC: the smaller the better

xgboost



Trying more inputs with energy flow polynomial and CNN/DNN





Physics requirements

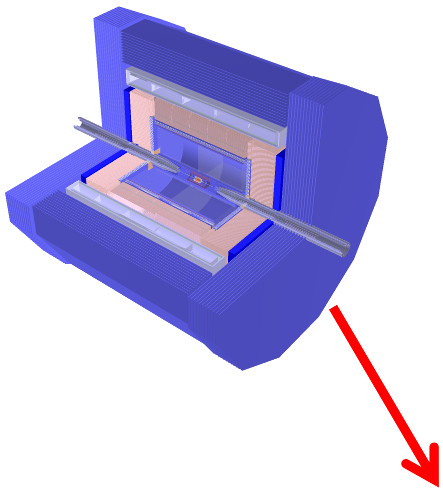
- **Robustness and efficiency : record all physics events/objects in a noisy environment**
- **Ultimate goal: trace the whole cascade topology of a physics event, for example, jet substructure!**
- **Excellent resolution and efficiency to reconstruct physics objects**
- **Luminosity/beam energy calibration to meet physics goal**
  - **Luminosity: ~ 0.1% at 240 GeV and ~0.01% at 91 GeV**
  - **E beam: ~1 MeV at 240 GeV and ~0.1MeV at 91 GeV**
- **Highly hermetic coverage**
- **PID: lepton/jet/hadron identification with high efficiency and rejection power**

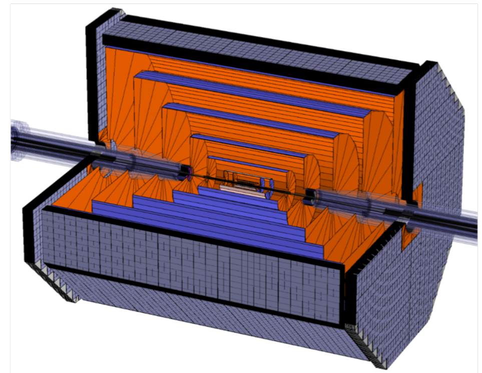
CEPC PFA detector concepts

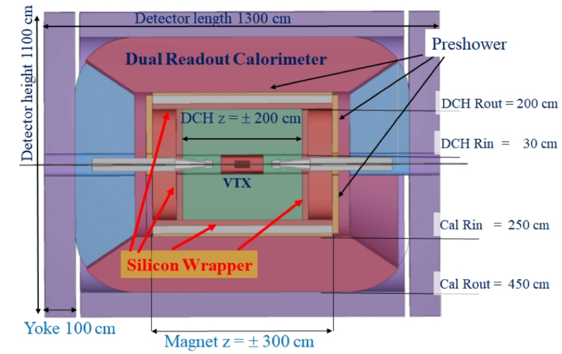
Particle flow: make use of the optimal sub-detector information in reconstruction and a high granularity calorimetry system required

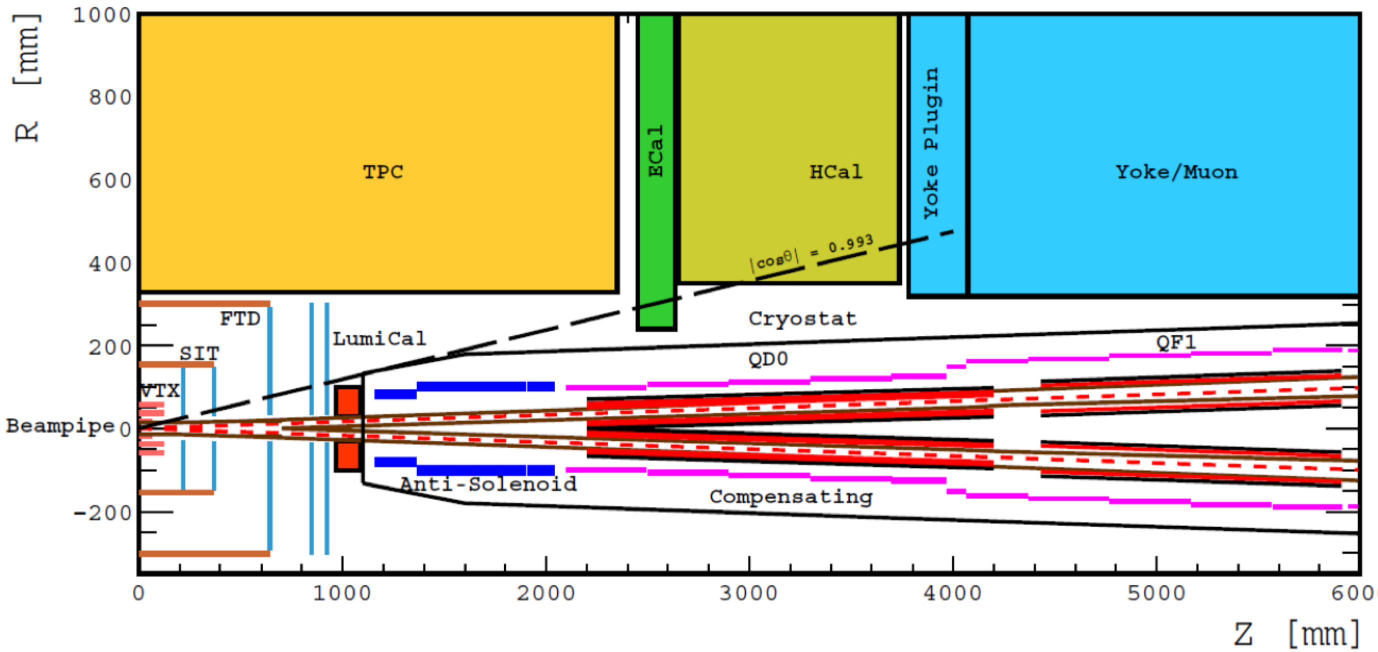
Charged tracks	~60%	Tracker	Negligible
Photons	~30%	Ecal	$0.11^2 E_{jet}$
Neutral hadron	~10%	Ecal+Hcal	$0.16^2 E_{jet}$
Conclusion	Required for 30%/sqrt(E)		$0.20^2 E_{jet}$

CEPC: Detector Concepts







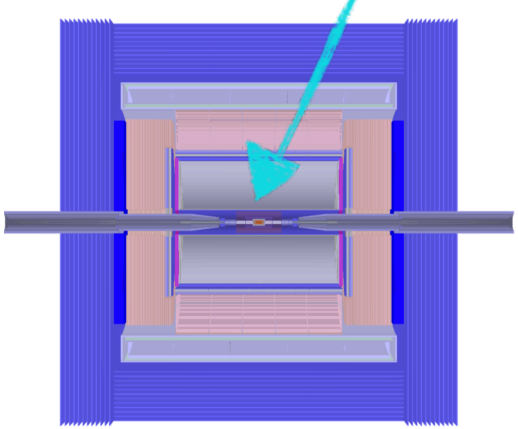


MDI of baseline

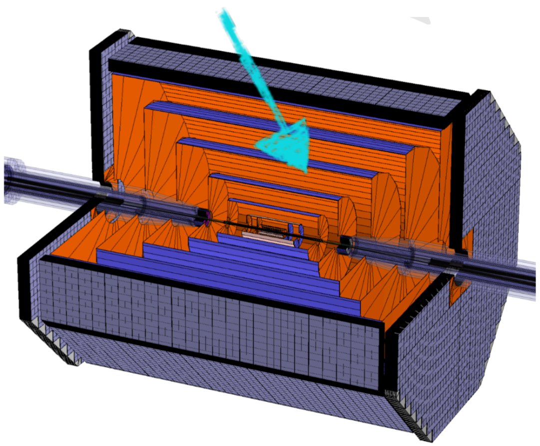
CEPC detector concepts

- Three detector concepts proposed
  - Silicon tracker + TPC + PFA calo - used for full simulation performance study
  - Full silicon tracker + PFA calo
  - Silicon + Drift Chamber + DR calo

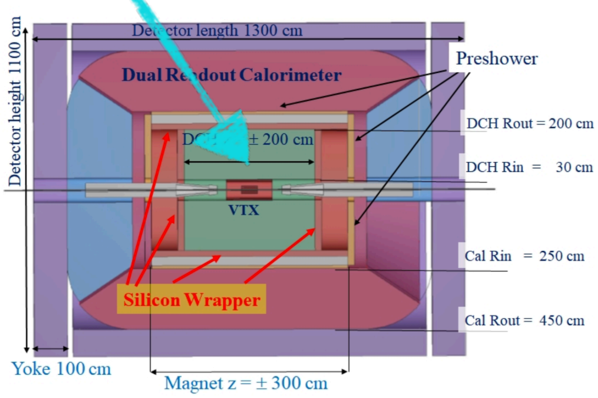
TPC



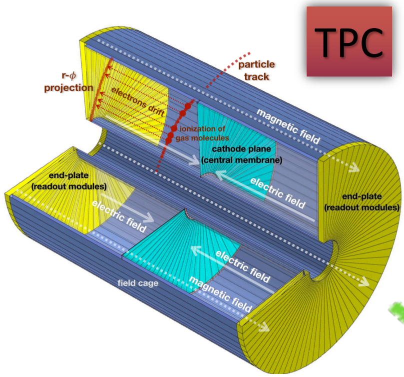
Silicon

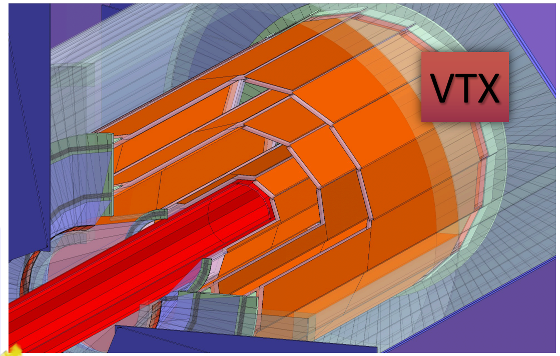


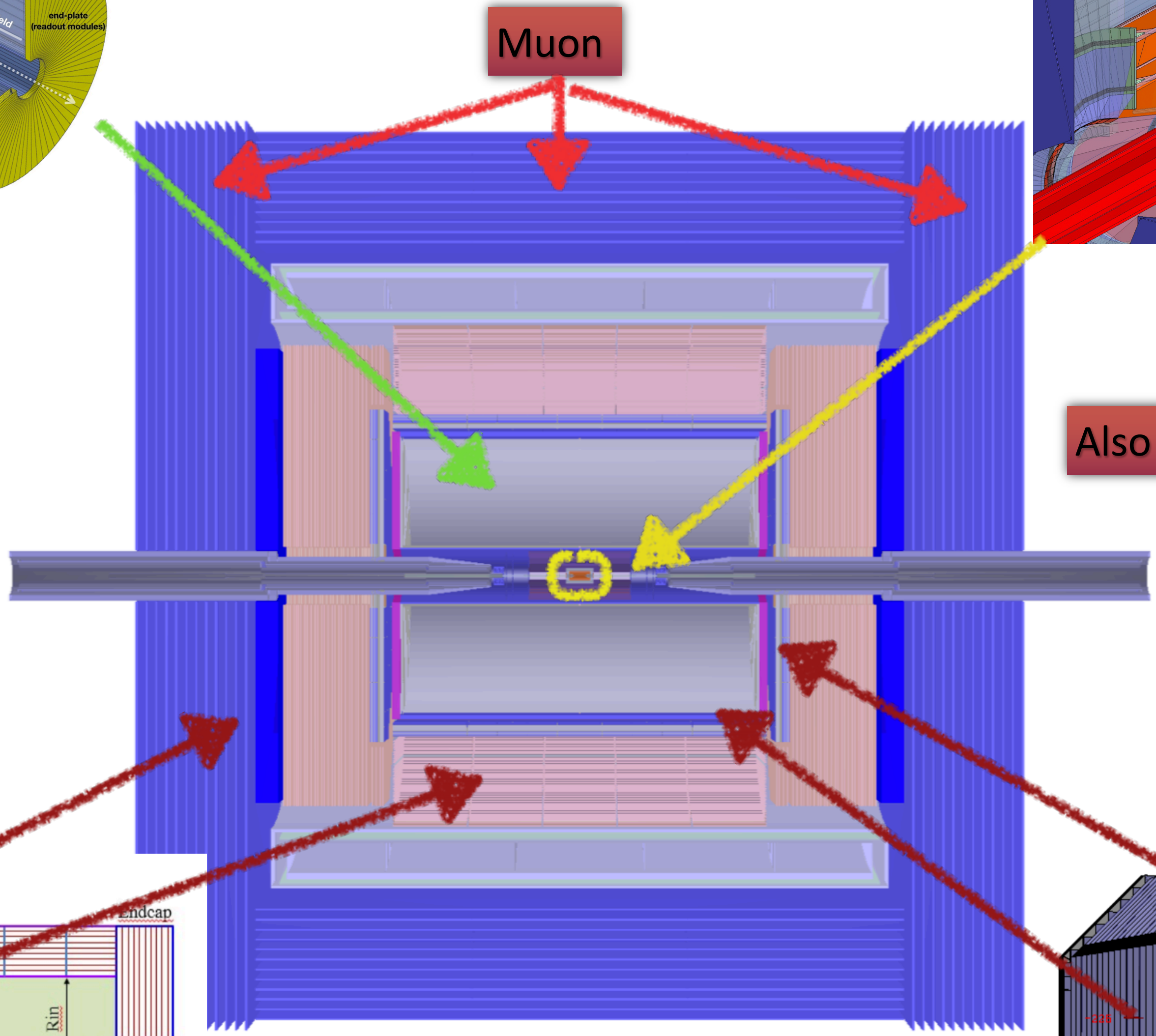
Drift chamber



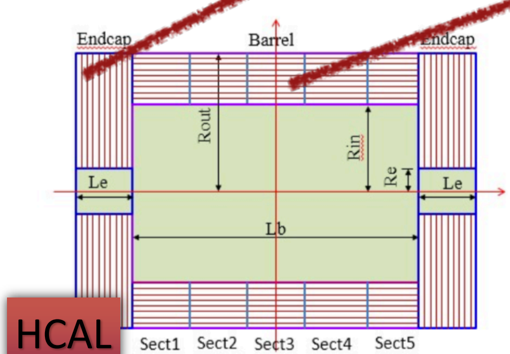
Baseline design

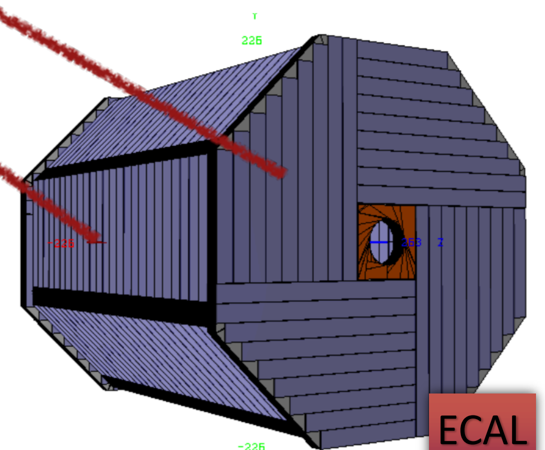






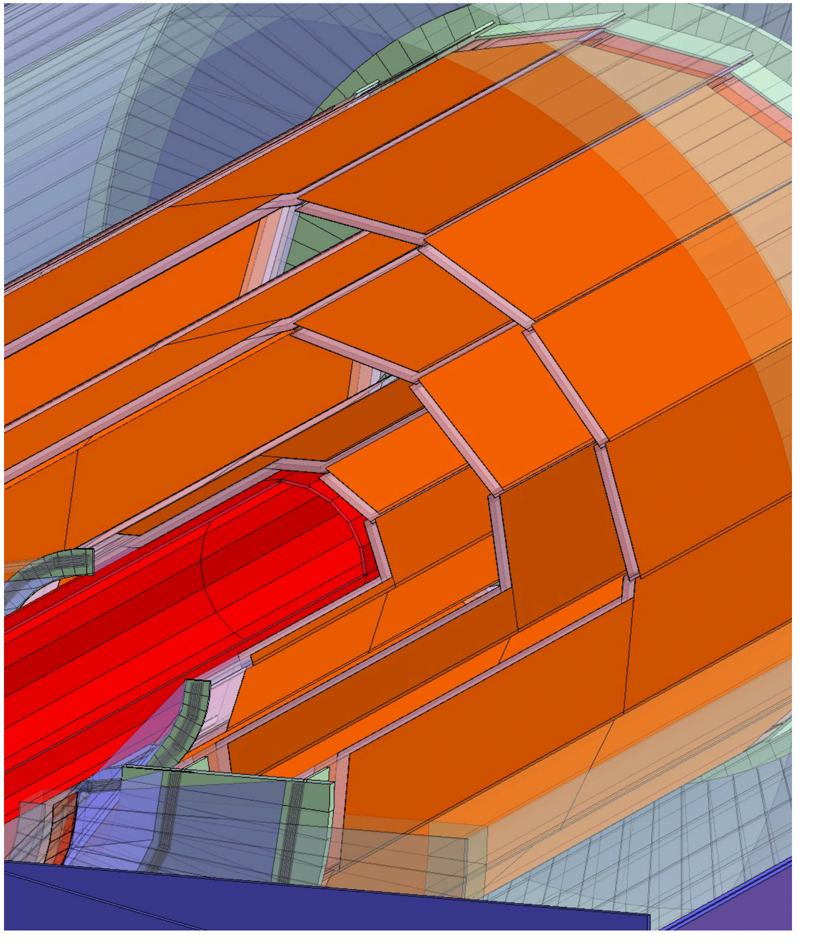
Also silicon tracker





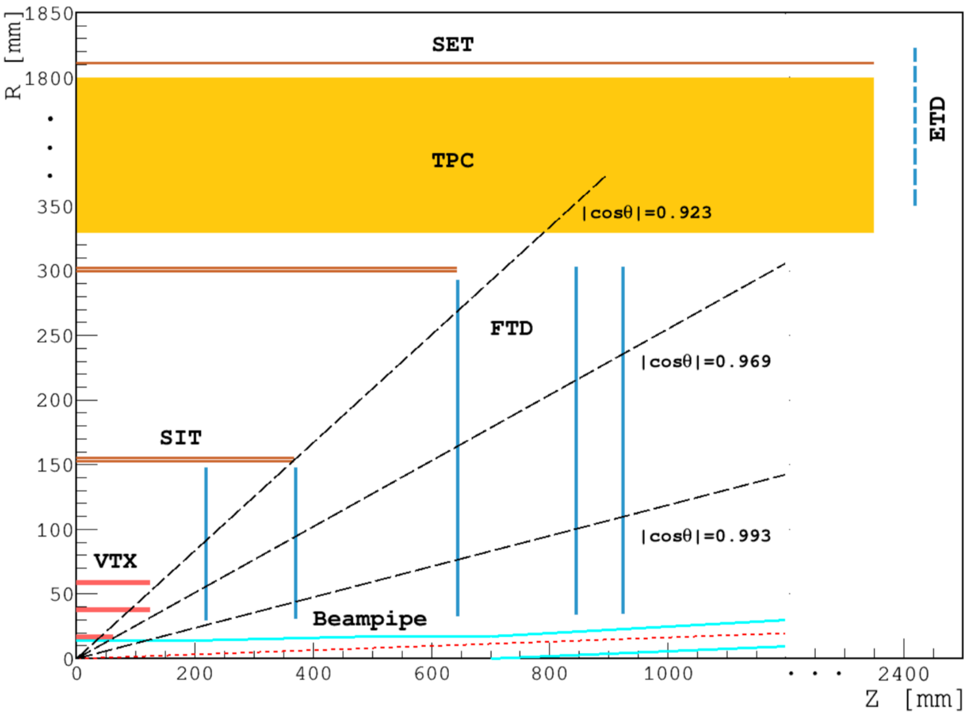
Silicon Vertex

- Three double layer pixel detector
- Rin = 16 mm
- Best single point resolution 3 microns
- Material 0.15%X_0 per layer
- Impact parameter resolution

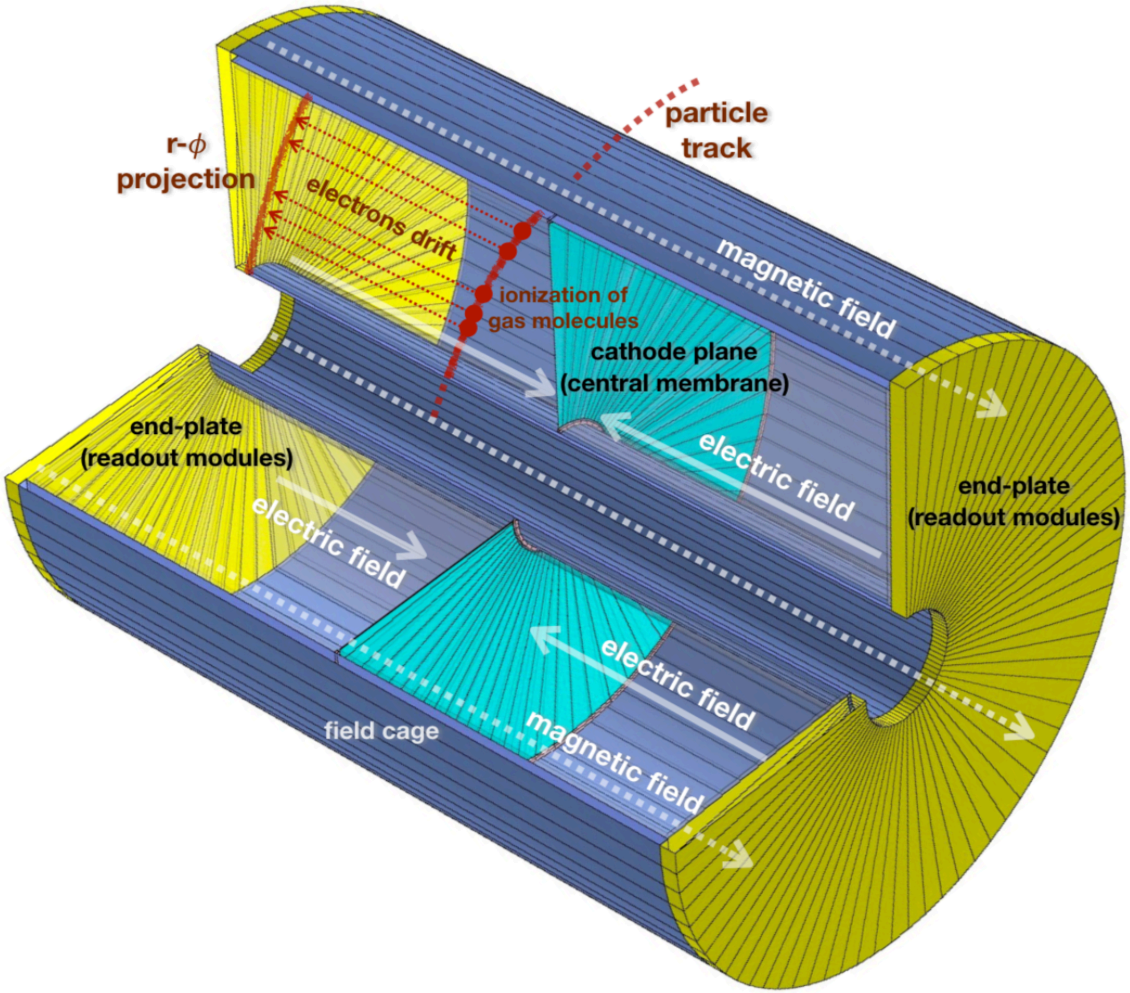


Silicon tracker

- **SIT: Silicon inner tracker**
- **SET: Silicon external tracker**
- **FTD: Forward tracking disk**
- **ETD: End-cap tracking disk**
- **See more details in Meng's talk**



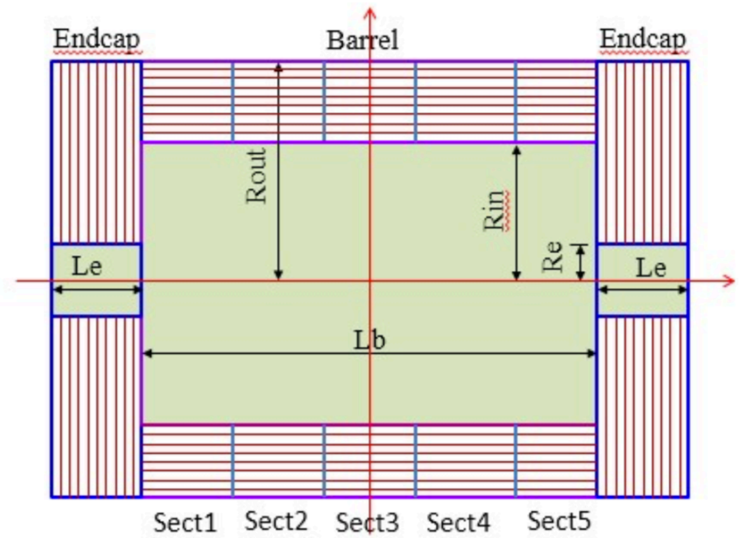
- Rin = 0.3 mm
- Rout =1.8 m
- Half Z = 2.35 m
- Low material budget only 1%X0 in the central part
- Provide up to 220 points of 100 micron precision for tracking reconstruction and dE/dx for PID

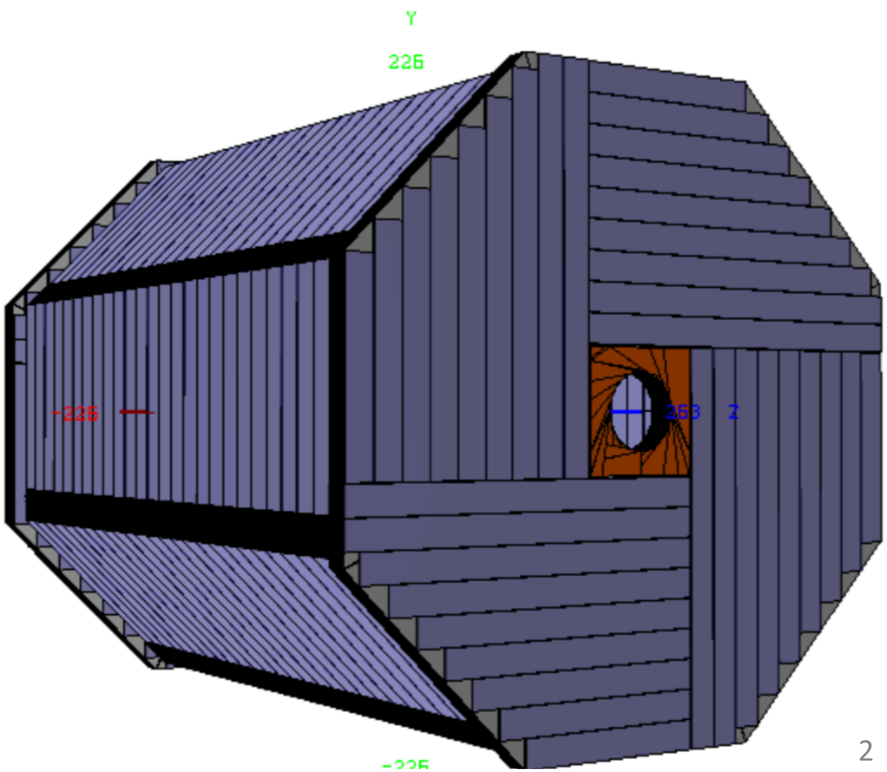


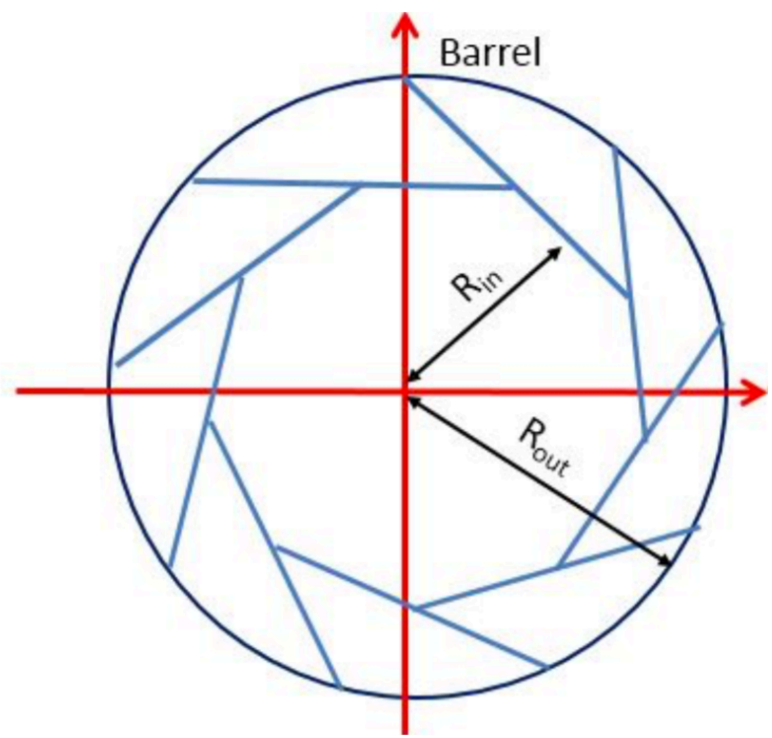
Time project Chamber

Calorimeter: key of PFA concept

- Ecal baseline
  - 30 layers
  - Cell size:
  - 24 X_0
- Hcal baseline
  - 40 layers

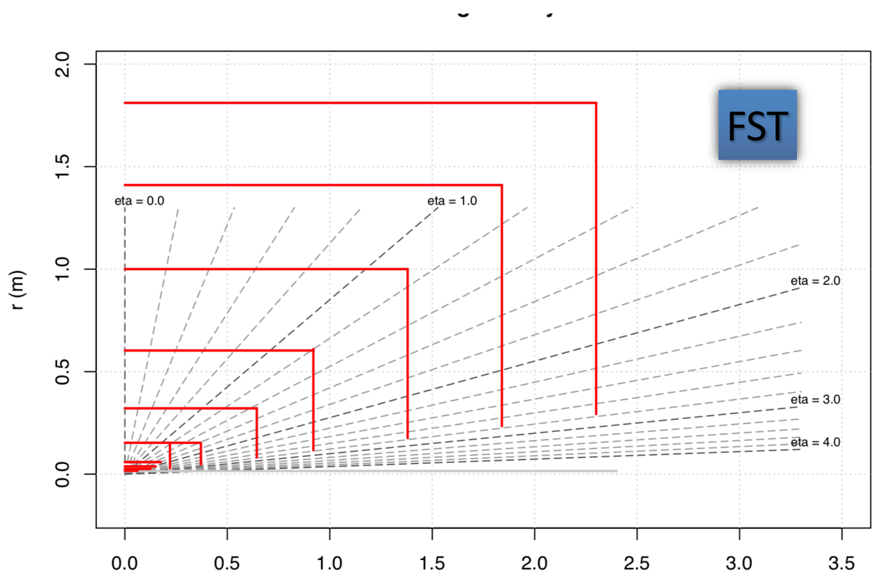


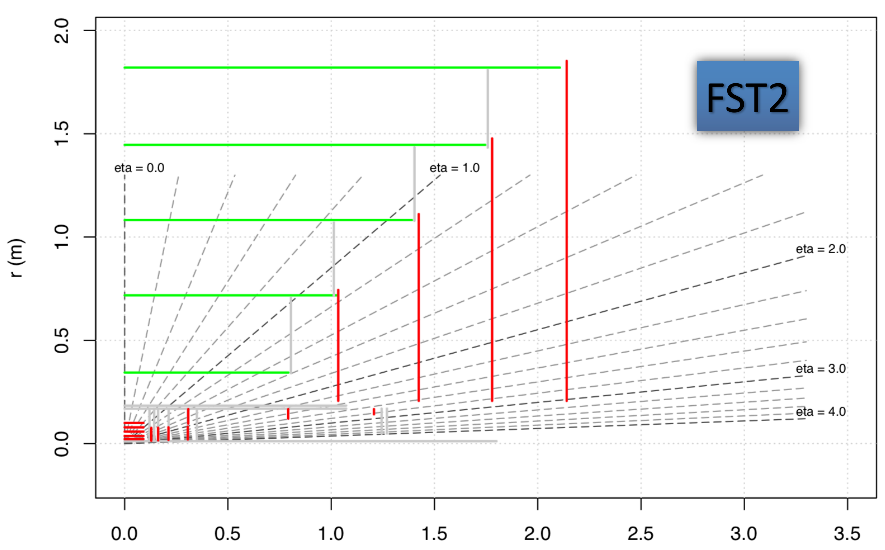


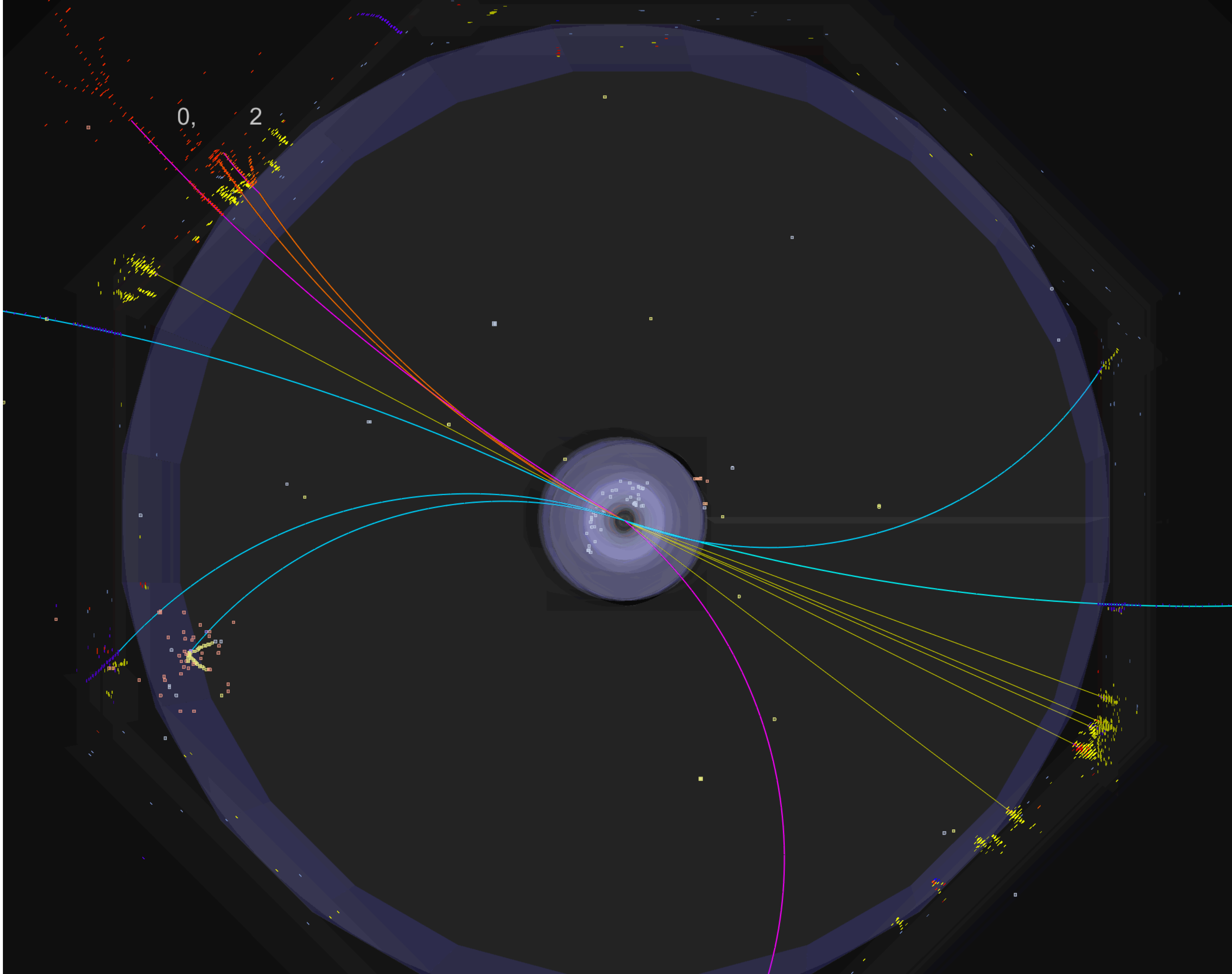


Full Silicon tracker options

- Same calorimeters
- FST: expand SIT to TPC volume, more expensive
- FST2: inspired by SID
- Double strip layer for FST and single layer for FST2



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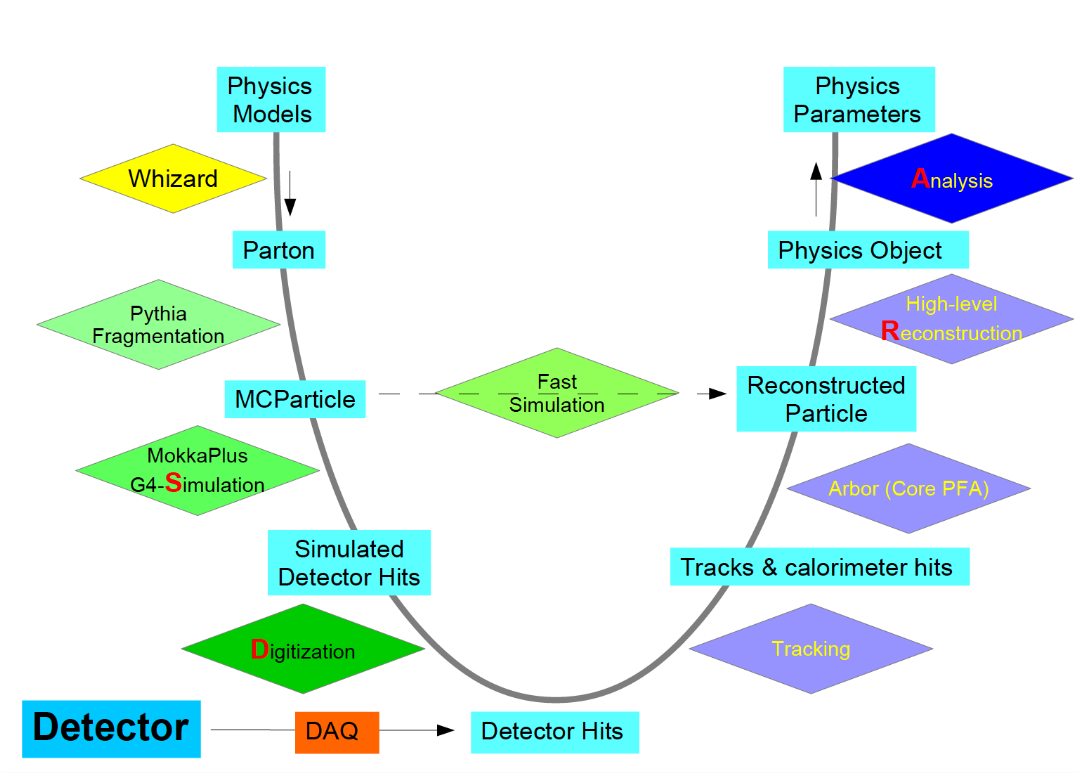
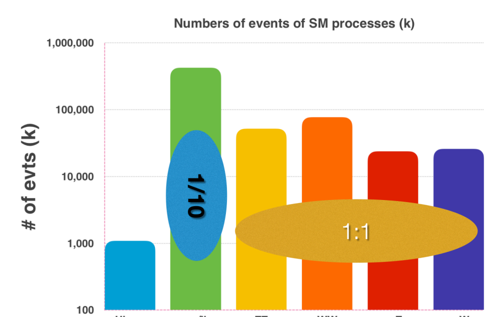
From CEPCsoft to new CEPCSW

CEPC baseline software — http://cepcsoft.ihep.ac.cn/



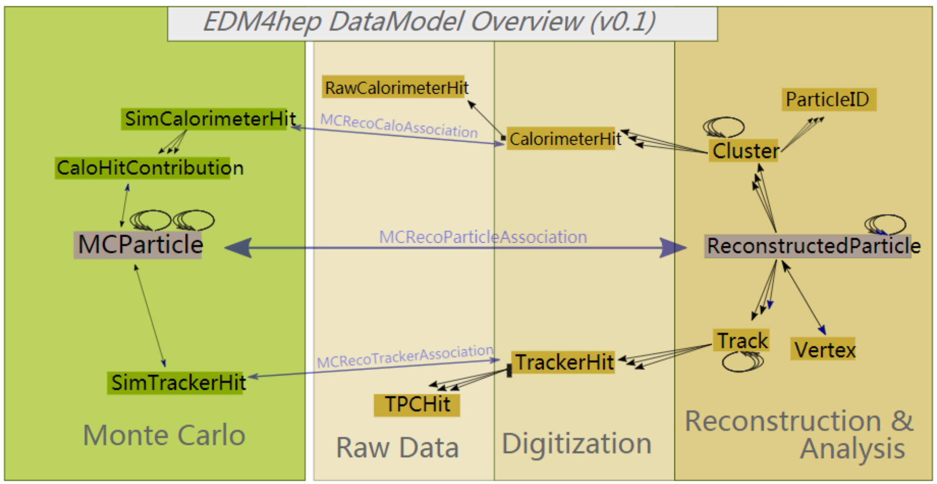
Generators (Whizard & Pythia)
Data format & management (LCIO & Marlin)
Simulation (MokkaC)
Digitizations
Tracking
PFA (Arbor)
Single Particle Physics Objects Finder (LICH)
Composed object finder (Coral)
Tau finder
Jet Clustering (FastJet)
Jet Flavor Tagging (LCFIPLus)
Event Display (Druid)
General Analysis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

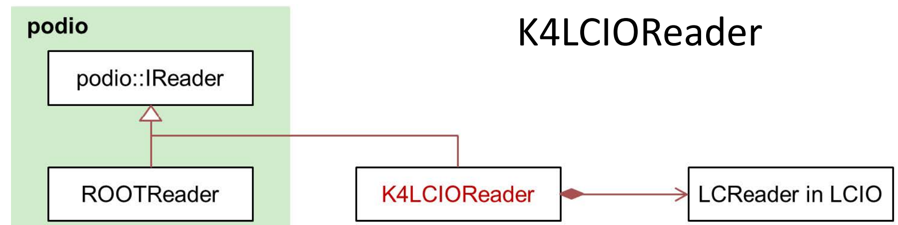
- Using for performance study and physics simulation
- A complete set of full simulated samples at 240 GeV and
- Others at alternative energy points



CEPC Software Prototype

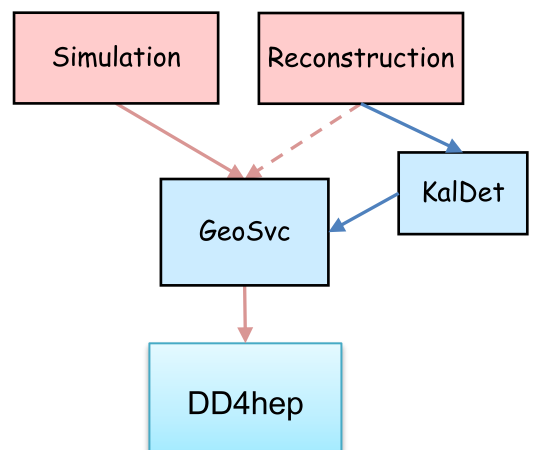
- EDM4Hep: official and common event data model in Kep4Hep
  - V0.1 has been released and performed in CEPCSW
  - Close to plcio





- Unified geometry service
  - Interfaced to DD4Hep
  - Used by simulation and reconstruction
  - To keep compatible during migration,

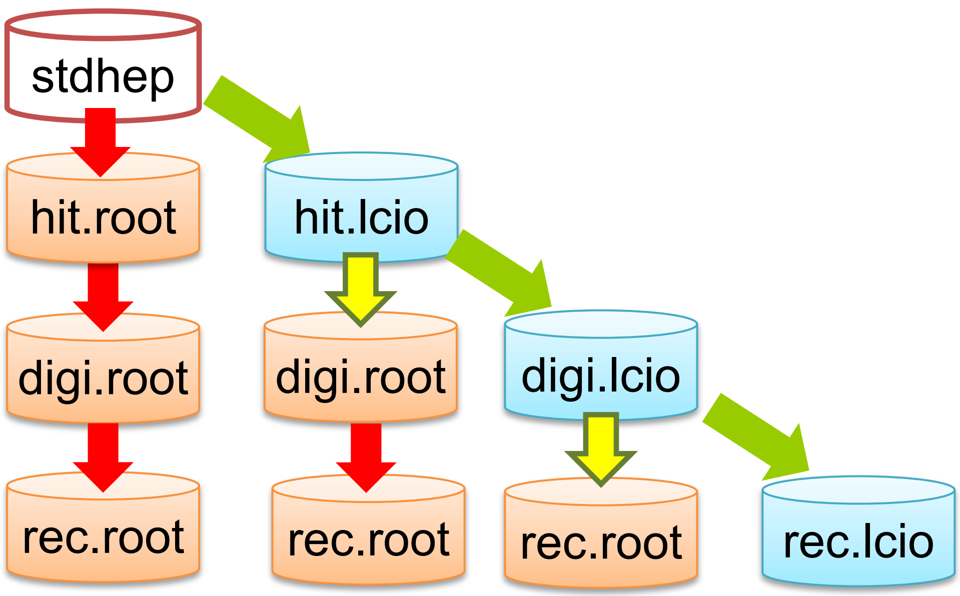
KalDet is kept but the underlying geometry information is from GeoSvc



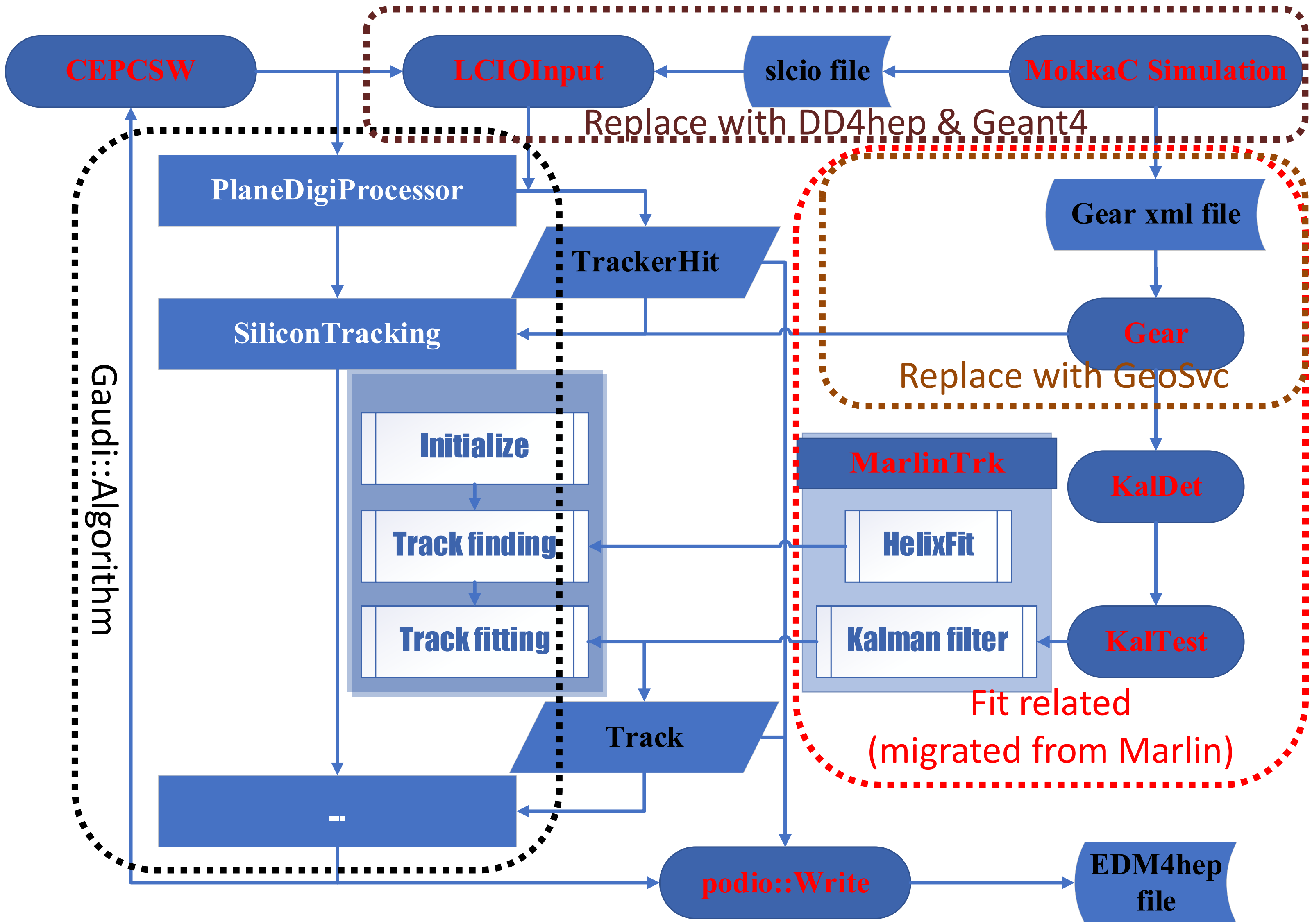
Roadmap for porting Sim/Digi/Rec

- To porting Sim/Digi/Rec in parallel, two major development branches
  - One is based on the LCIO reader and only update the I/O and EDM parts in the algorithms. The output is EDM4Hep.
  - The other based on the DD4hep. All the I/O and EDM is EDM4hep.

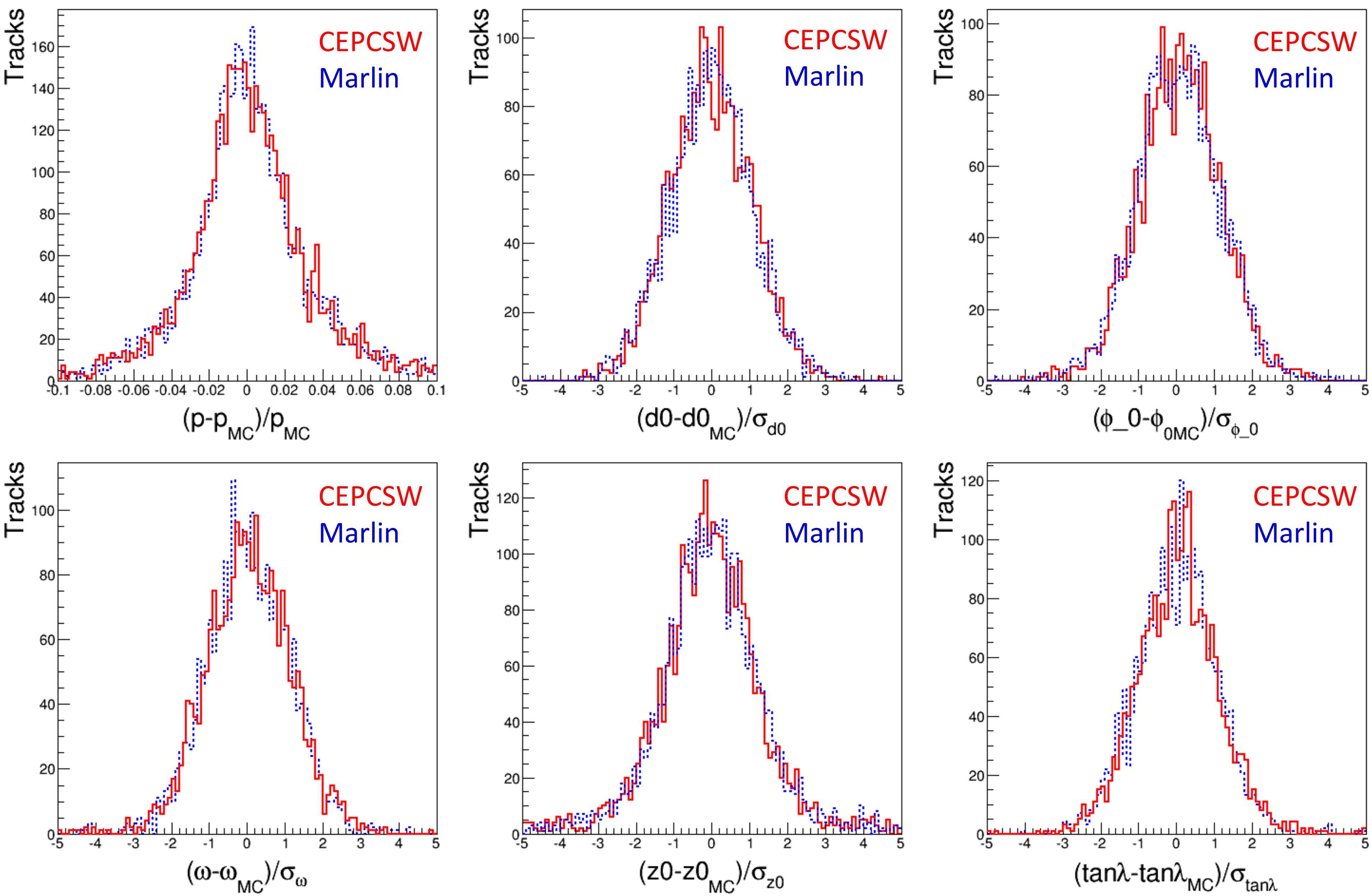
- **The Green arrows:**
  - LCIO+Mokka+Marlin
- **The Yellow arrows:**
  - Input: LCIO
  - Output: EDM4hep
- **The Red arrows:**
  - EDM4hep+DD4hep



CEPCSW Silicon Tracking Flow



Two ways: CEPCSW+LCIO&Gear, fully CEPCSW

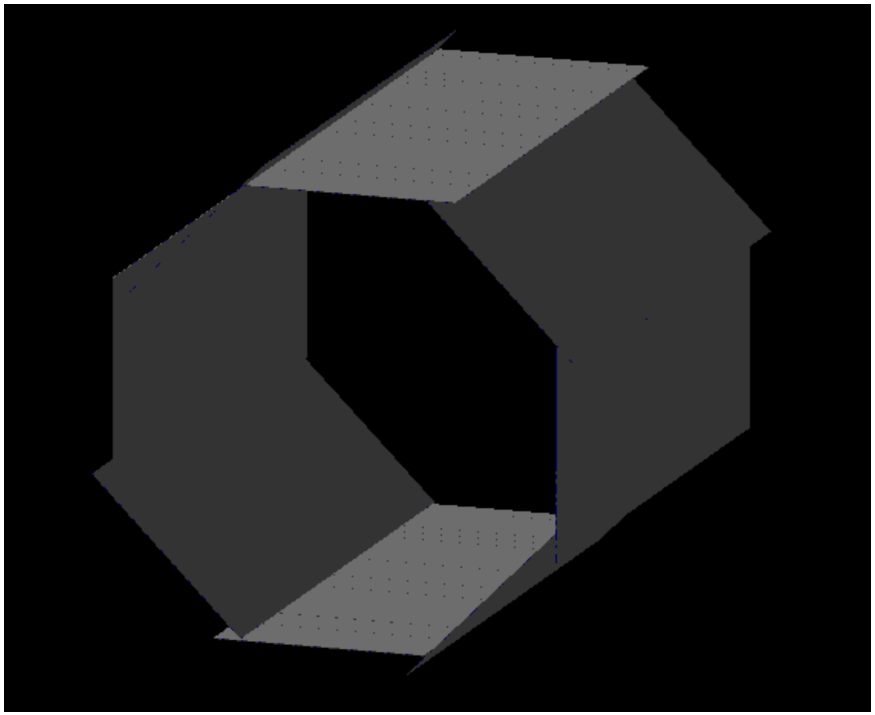

Tracks
CEPCSW
Marlin
(p-p_MC)/p_MC
(d0-d0_MC)/σ_d0
(φ_0-φ_0MC)/σ_φ_0
(ω-ω_MC)/σ_ω
(z0-z0_MC)/σ_z0
(tanλ-tanλ_MC)/σ_tanλ

Porting ECAL simulation into CEPCSW

- Status: SiW-ECAL is available in the CEPCSW
- The detector description is available for both simulation and reconstruction.
  - DD4hep version is from Chengdong.
  - Detector parameters (XML based compact file): Detector/DetCEPCv4/compact
  - Detector constructors (C++ based): Detector/DetCEPCv4/src/calorimeter/
    - SEcal05_Barrel, SEcal05_Endcaps, SEcal05_ECRing
- Detector response simulation for ECAL is done.
  - Package Simulation/DetSimSD is created for geant4 simulation.
    - CalorimeterSensDetTool: integrated with Gaudi
    - CaloSensitiveDetector: integrated with Geant4
    - DDG4SensitiveDetector: integrated with DDG4 to get VolumeID/CellID
- EDM4hep based calo hit objects and McTruth info are saved.
  - SimCalorimeterHitCollection (cellID, energy, position…)
  - CaloHitContributionCollection (Particles'PDG, energy, time, position…)

The detector could be visualized in G4

- One layer (Si+W+Si) is shown



Logical volume: EcalBarrel_alveolus_layer0

- 8 staves
- 5 modules per stave
- 5 towers per modules

magicwafer

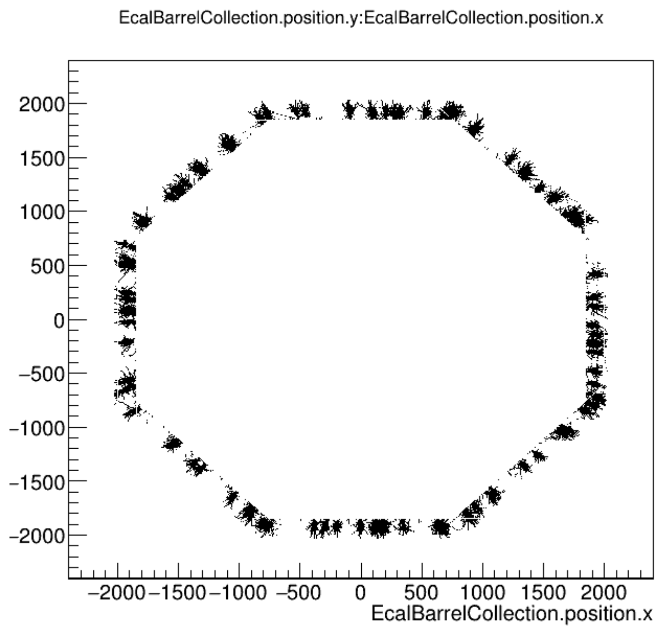
Note: other wafers in this layer are not displayed.

wafer

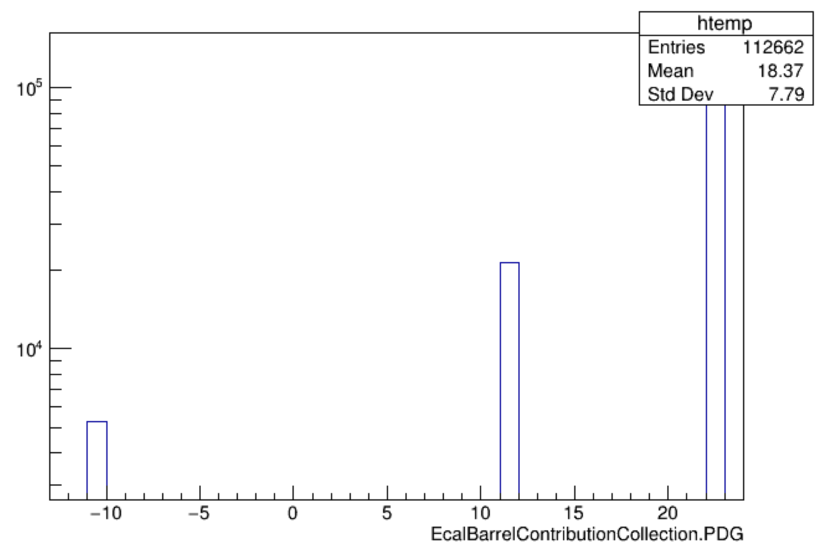
One sensitive layer in a tower

The detector responses (barrel)

- All the information are stored in ROOT for further validation.
  - 6 collections are saved
    - EcalBarrelCollection, EcalBarrelContributionCollection
    - EcalEndcapsCollection, EcalEndcapsContributionCollection
    - EcalEndcapRingCollection, EcalEndcapRingContributionCollection



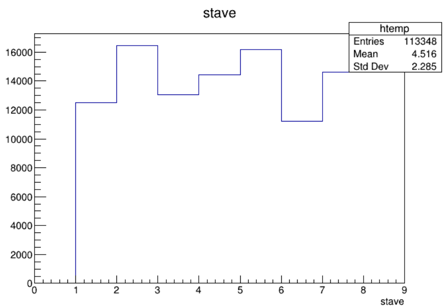
Hit position (x:y)



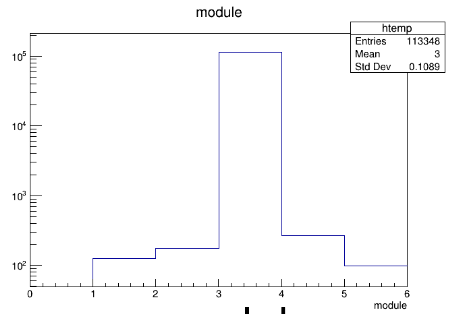
MC particle contribution (PDG: e+, e-, gamma)

Gamma, 1GeV, theta=90deg, phi=[0,360deg], 100 events , No B-field

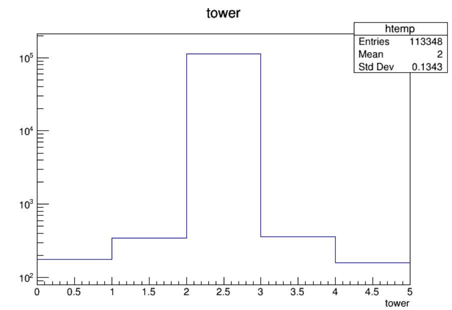
ID distribution (barrel)



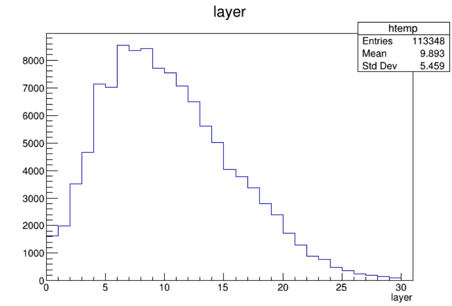
stave



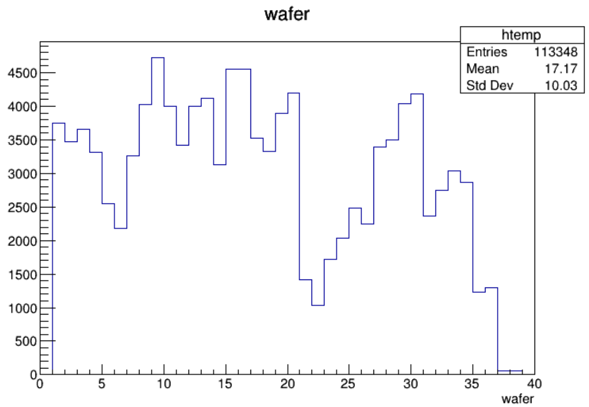
module



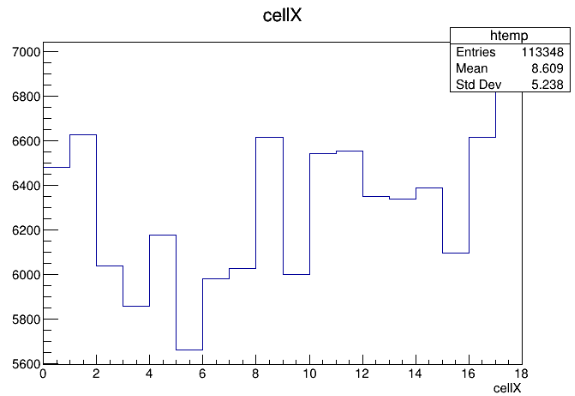
tower



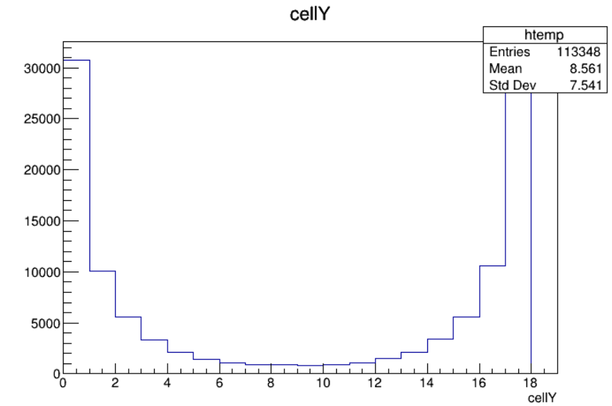
layer



wafer



cellX



cellY

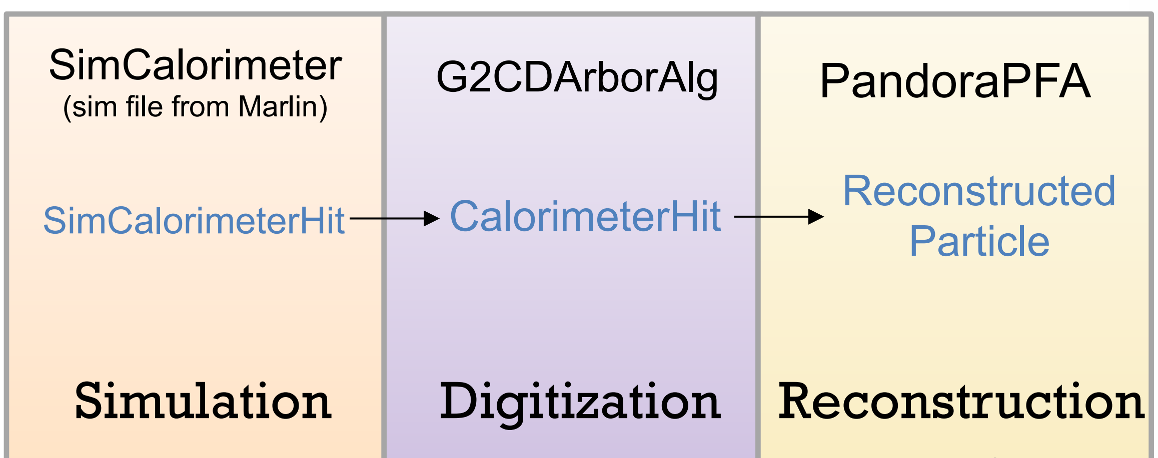
The ID is based on VolumeID (detector) and CellID (segmentation) in DD4hep.

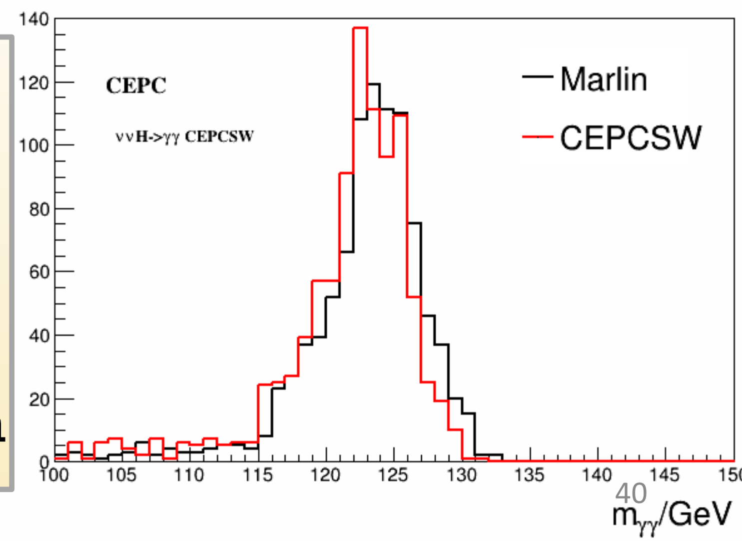
Problem: the ID definitions are not same for CEPCSW and Mokka.

Need further studies. See issue: https://github.com/cepc/CEPCSW/issues/5

Migration of calorimeter digitization

- Calorimeter digitization algorithm (G2CDArbor) was migrated from Marlin to CEPCSW
  - Use EDM4Hep event data model
  - Comparison of reconstructed results between Marlin and CEPCSW
    - **ECAL**: slight difference might be caused by different configuration parameters and version of PandoraPFA. Further check is in progress
    - **HCAL**: to be validated



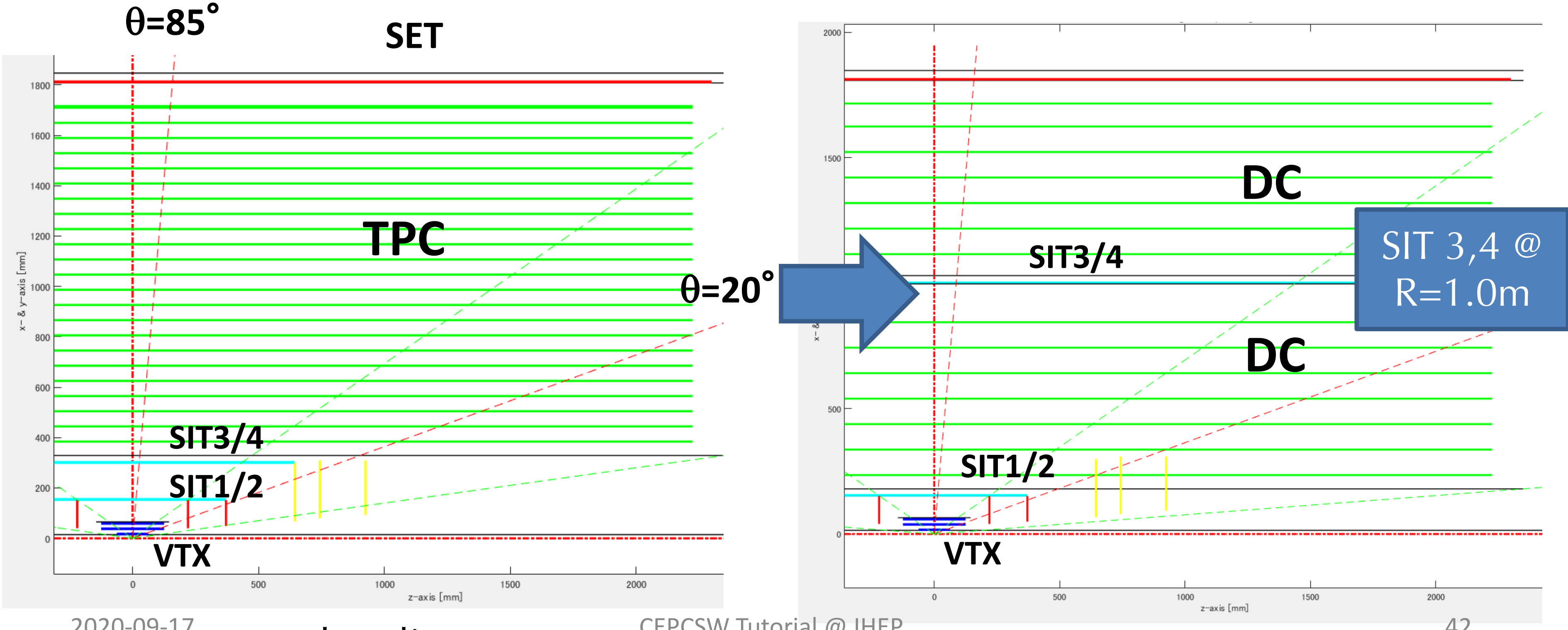


Motivation for Silicon + Drift Chamber Tracker

- Explore a different tracker option for CEPC, our own design
- Capable for both tracking and PID (flavor, JES, jet flavor tagging ,...)
- Combine the Silicon technology (strip, CMOS) and
  Drift chamber technology (dE/dx, cluster counting, ...)
- Provide concrete platform to integrate smaller crystal ECAL
- Open path for better particle ID with future timing layer (LGAD) between SDT and crystal ECAL

CEPC Silicon + Drift Chamber Tracker

- Based on the baseline Silicon + TPC
- Replace TPC layers with two drift chamber layers
  - SIT 3&4 at R~1.0m / larger cell size of DC than TPC



The goal and plan of this tutorial
For developers, for detector study, for software

10:30 - 12:00	Software basics	
	10:30	**Software ABC: linux, git, root, and GEANT4** *1h30'* Speaker: Xin Shi (IHEP)
12:00 - 14:00	Lunch break	
14:00 - 16:00	Detector Simulation	
	14:00	**Introduction to CEPCSW** *1h0'* Speaker: Dr. Jiaheng Zou (高能所)
	15:00	**DD4HEP: detector description** *1h0'* Speaker: Chengdong FU (IHEP)
16:00 - 16:30	Break	
16:30 - 18:10	Detector simulation	
	17:05	**Simulation of a simple detector in CEPCSW** *1h0'* Speaker: Dr. Tao LIN (高能所)

Friday, 18 September 2020

08:00 - 10:20	CEPC Detector	
	09:00	**CEPC tracker system** *40'* Speaker: Dr. Hongbo ZHU (IHEP)
	09:40	**Tracking reconstruction** *40'* Speaker: Ms. Yao Zhang (Institute of high energy physics, Beijing China)
10:20 - 10:40	Break	
10:40 - 12:10	CEPC detector	
	10:45	**CEPC Calorimeters** *40'* Speaker: Dr. Yong Liu (Institute of High Energy Physics)
	11:25	**Calorimeter reconstruction** *40'* Speaker: 文兴 方 (高能所)
12:10 - 14:00	Break	
14:00 - 16:00	CEPC detector: Questions & Answers	

Summary

- **CEPCSOFT supported preCDR & CDR studies, still supporting detector some R&D.**
- **The CEPC new software under developing with lots of modern software technologies: DD4hep, new tracking software, particle flow algorithms, machine learning, ….**
- **R&D of new detector concepts and the optimization with physics benchmarks is the main tasks of our software, as well as the software itself.**
- **Development of new detectors and its software are challenging and full of senses of achievement.**