Detector Optimization study of the CEPC

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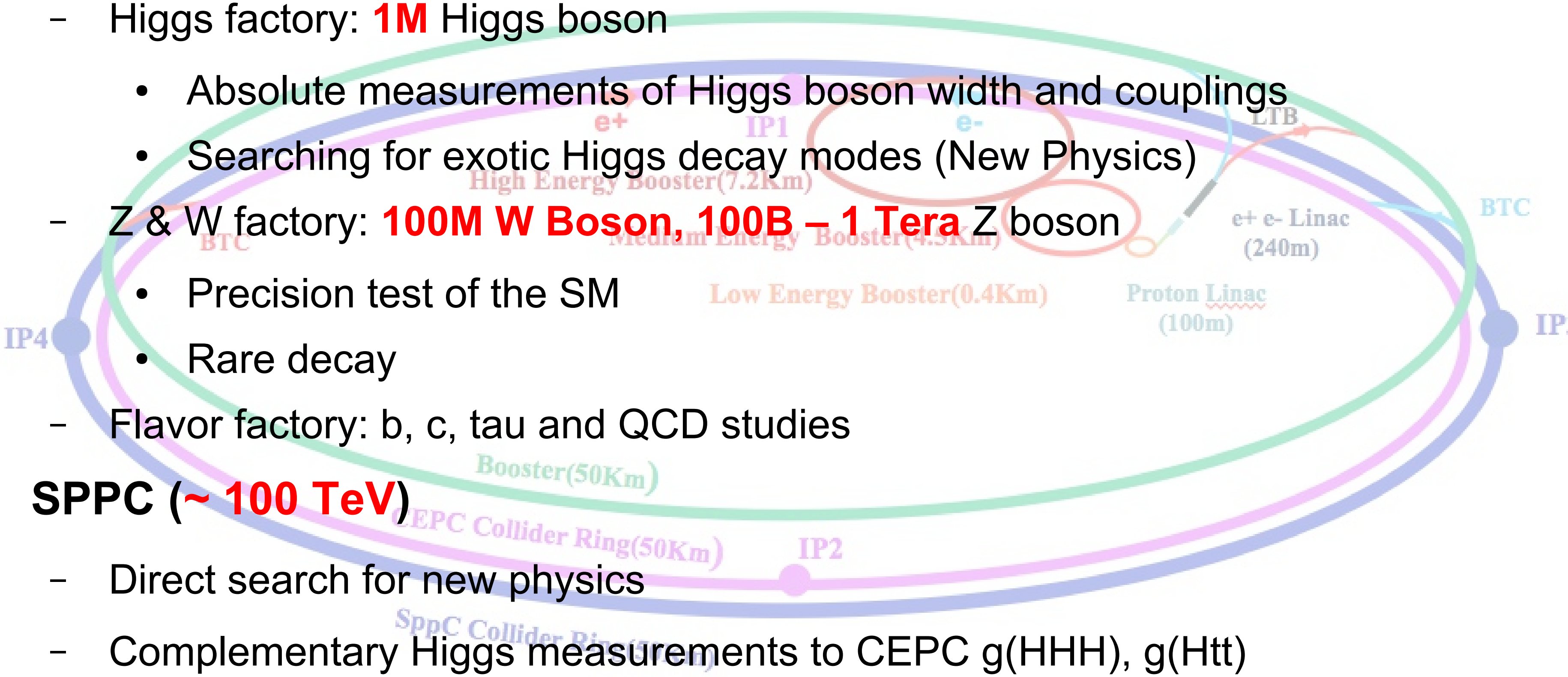
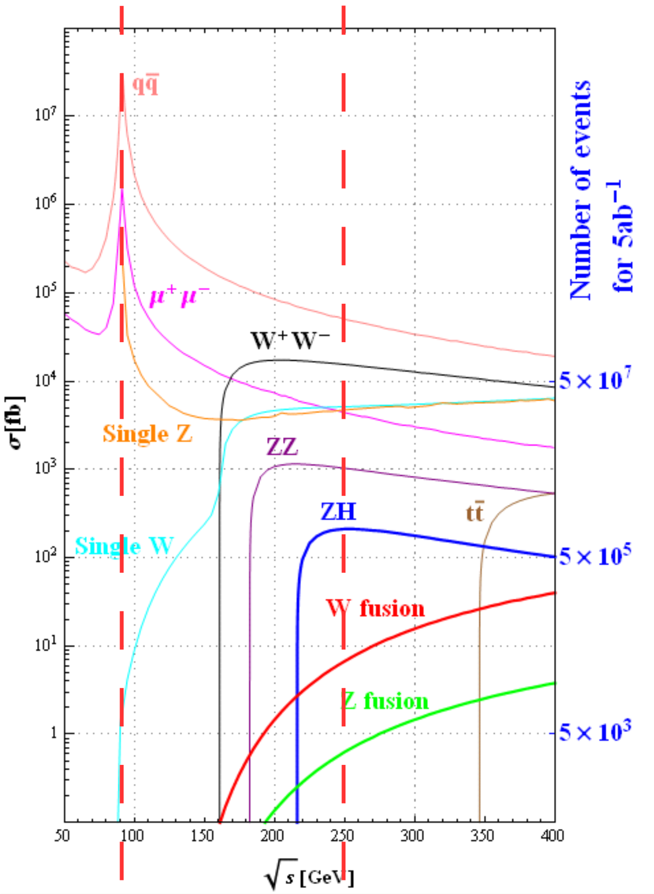
Science at CEPC-SPPC

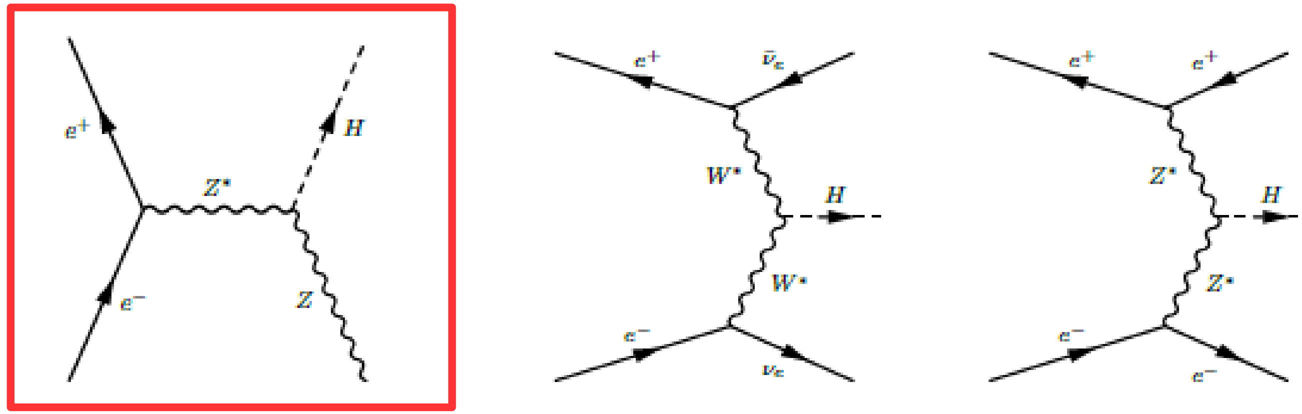
- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **100M W Boson, 100B – 1 Tera** Z boson
    - Precision test of the SM
  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





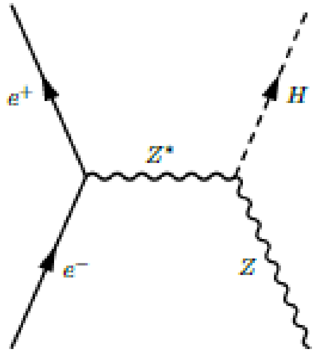
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

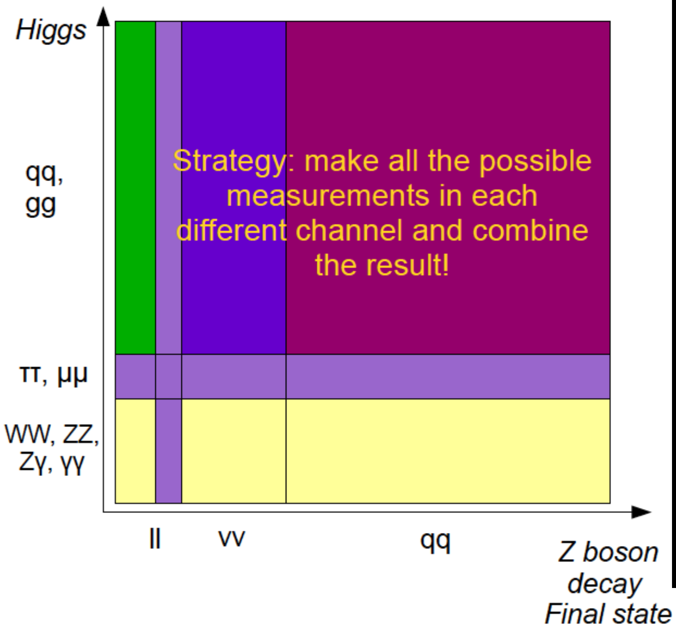
S/B ~ 1:100 - 1000

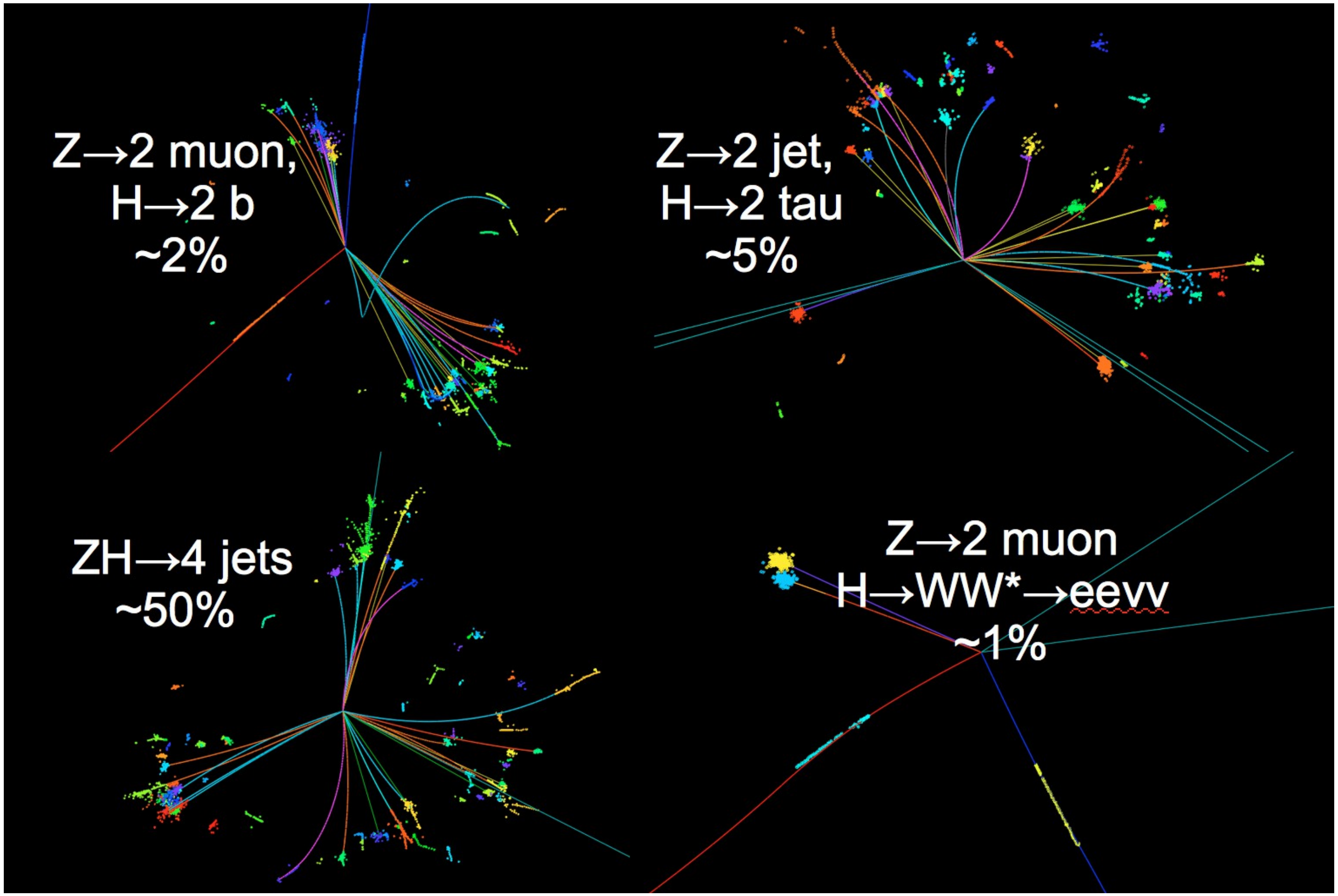
Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, vvH)*Br(H→X)), Diff. distributions

Derive: Absolute Higgs width, branching ratios, couplings

Physics Requirements







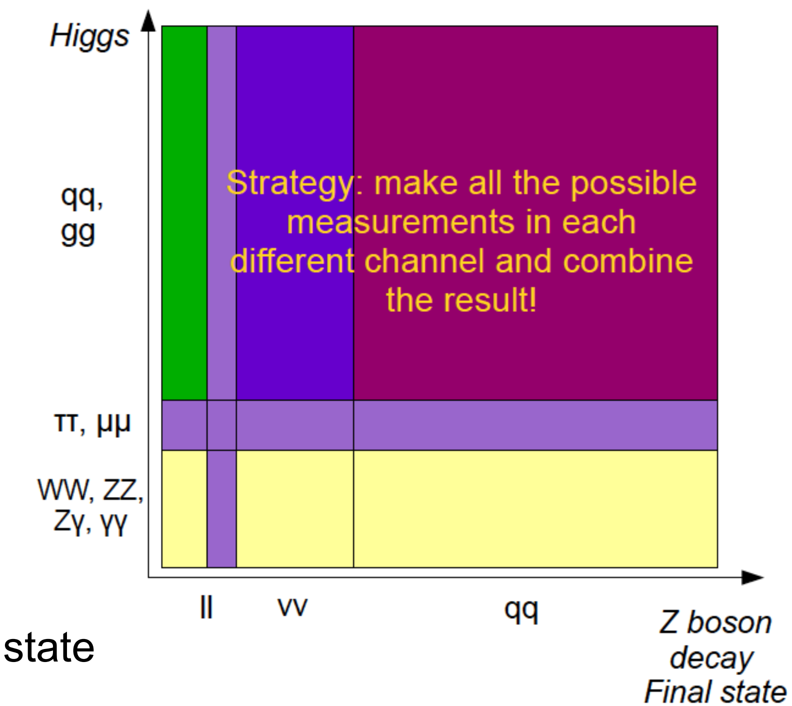
Detector:

To reconstruct all the physics objects with **high efficiency, purity & resolution**

Homogenous & Stable enough to control the systematic

Jets at the Higgs Signal

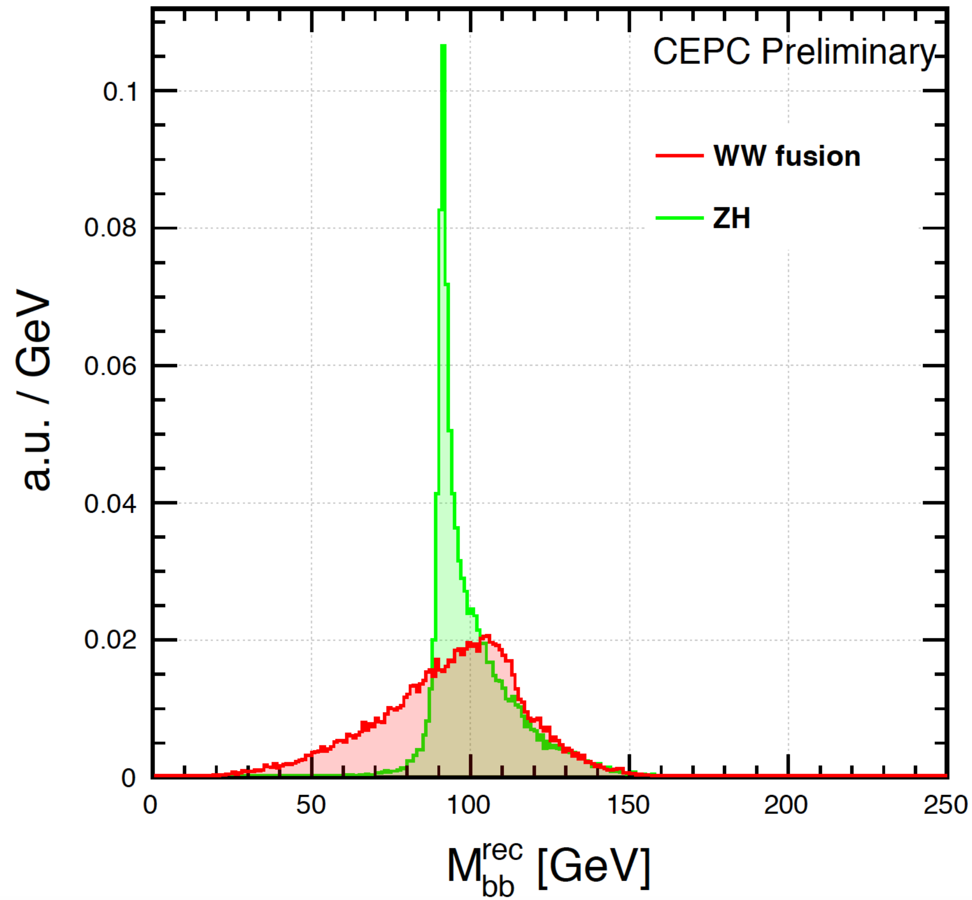
- SM Higgs
  - ***0 jets: 3%:*** *Z→ll, νν (30%); H→0 jets (~10%, ττ, μμ, γγ, γZ/WW/ZZ→leptonic)*
  - ***2 jets: 32%***
    - *Z→qq, H→0 jets. 70%*10% = 7%*
    - *Z→ll, νν; H→2 jets. 30%*70% = 21%*
    - *Z→ll, νν; H→WW/ZZ→semi-leptonic. 3.6%*
  - ***4 jets: 55%***
    - *Z→qq, H→2 jets. 70%*70% = 49%*
    - *Z→ll, νν; H→WW/ZZ→4 jets. 30%*15% = 4.5%*
  - ***6 jets: 11%***
    - *Z→qq, H→WW/ZZ→4 jets. 70%*15% = 11%*



- **97%** of the SM Higgsstrahlung Signal has Jets in the final state
- **1/3** has only 2 jets: be described by the mass resolution of the hadronic decay boson (**BMR**)
- **2/3** need color-singlet identification: grouping the hadronic final sate particles into color-singlets
- Jet is important for EW measurements & jet clustering is essential for **differential** measurements

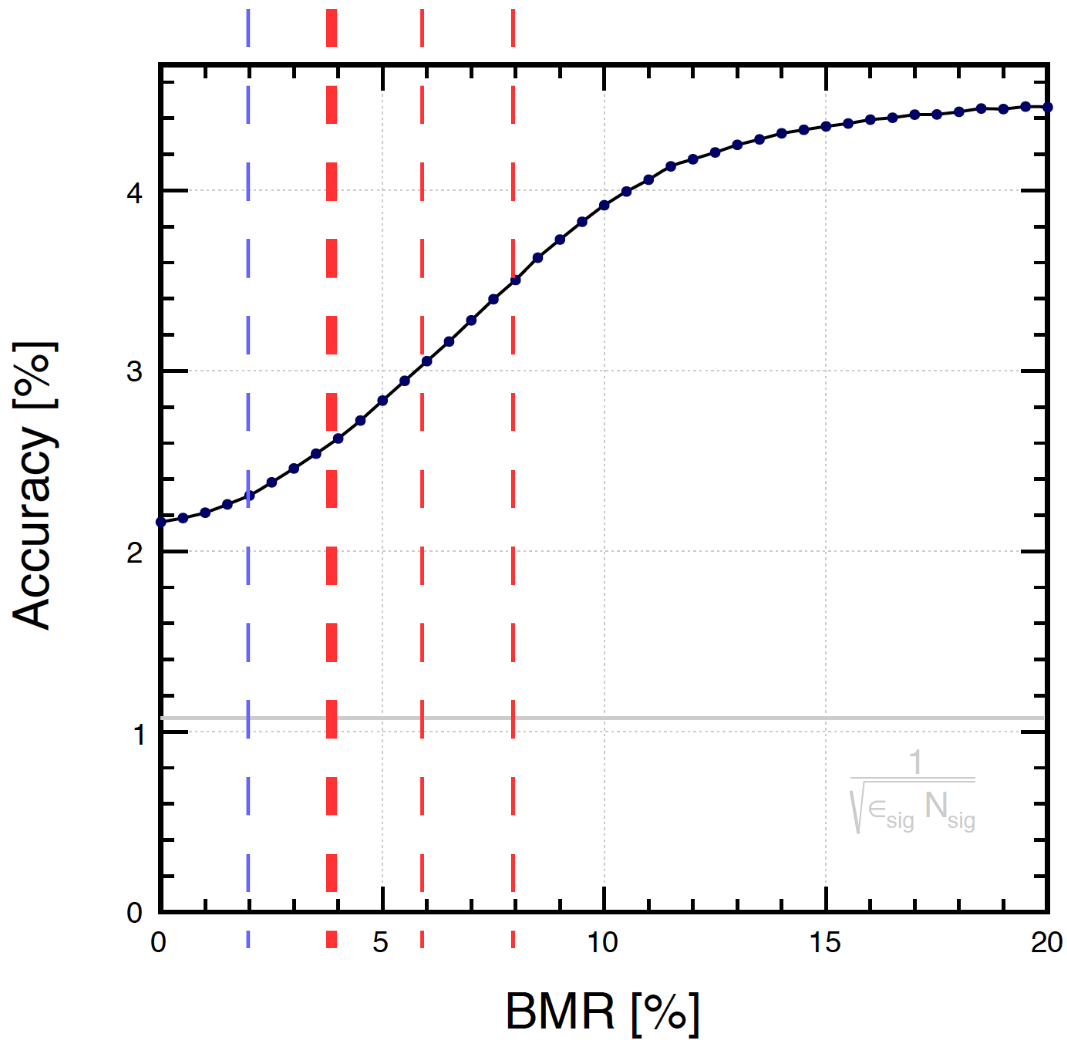
1^{st} Benchmark: σ(vvH, H→bb) ~ Higgs width

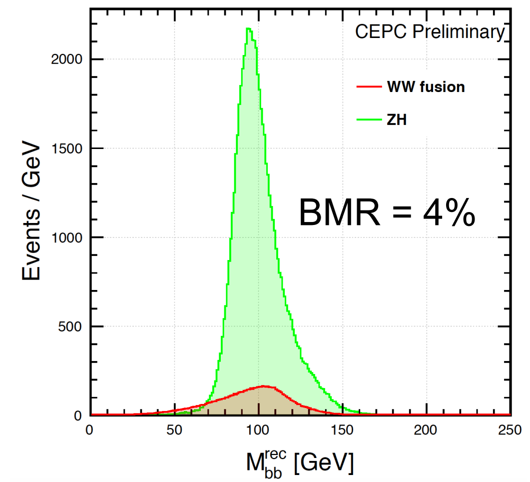
- $g^2(HXX) \sim \Gamma_{H\to XX} = \Gamma_{total} * Br(H\to XX)$
- Γ_{total} : determined by combining:
  - 1^{st}, σ(ZH) (~g^2(HZZ)), σ(ZH, H→ZZ) (~$g^4(HZZ)/\Gamma_{total}$)
  - 2^{nd}, σ(ZH, H→bb), σ(ZH, H→WW), σ(ZH), σ(vvH$|_{w\ fusion}$, H→bb), (bb can be replaced by X)
  - The 2nd method dominant the accuracy
- Critical to identify the W fusion events from the Higgsstrahlung ones with vvH final state: rely on the recoil mass agains the Higgs (and the Higgs direction).

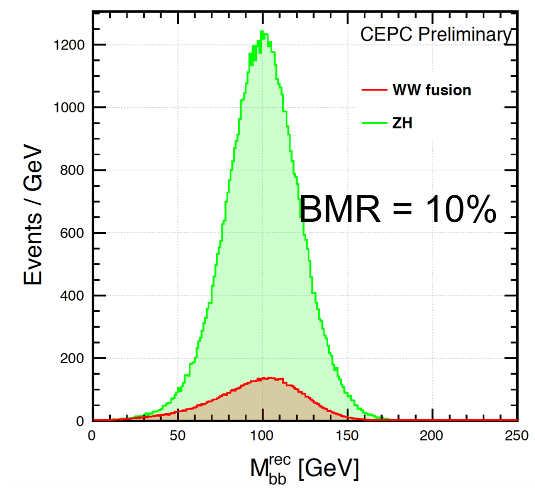


Hao Liang

σ(vvH, H→bb): Accuracy V.S. BMR



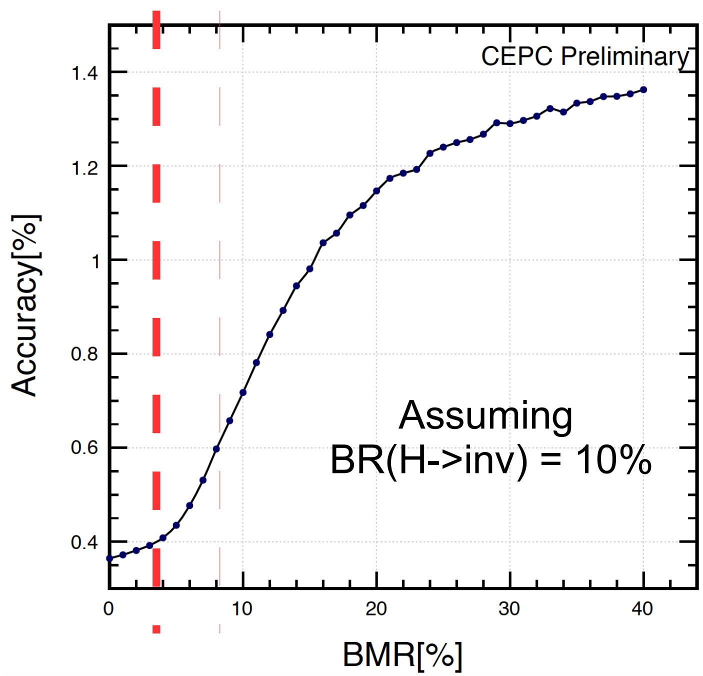


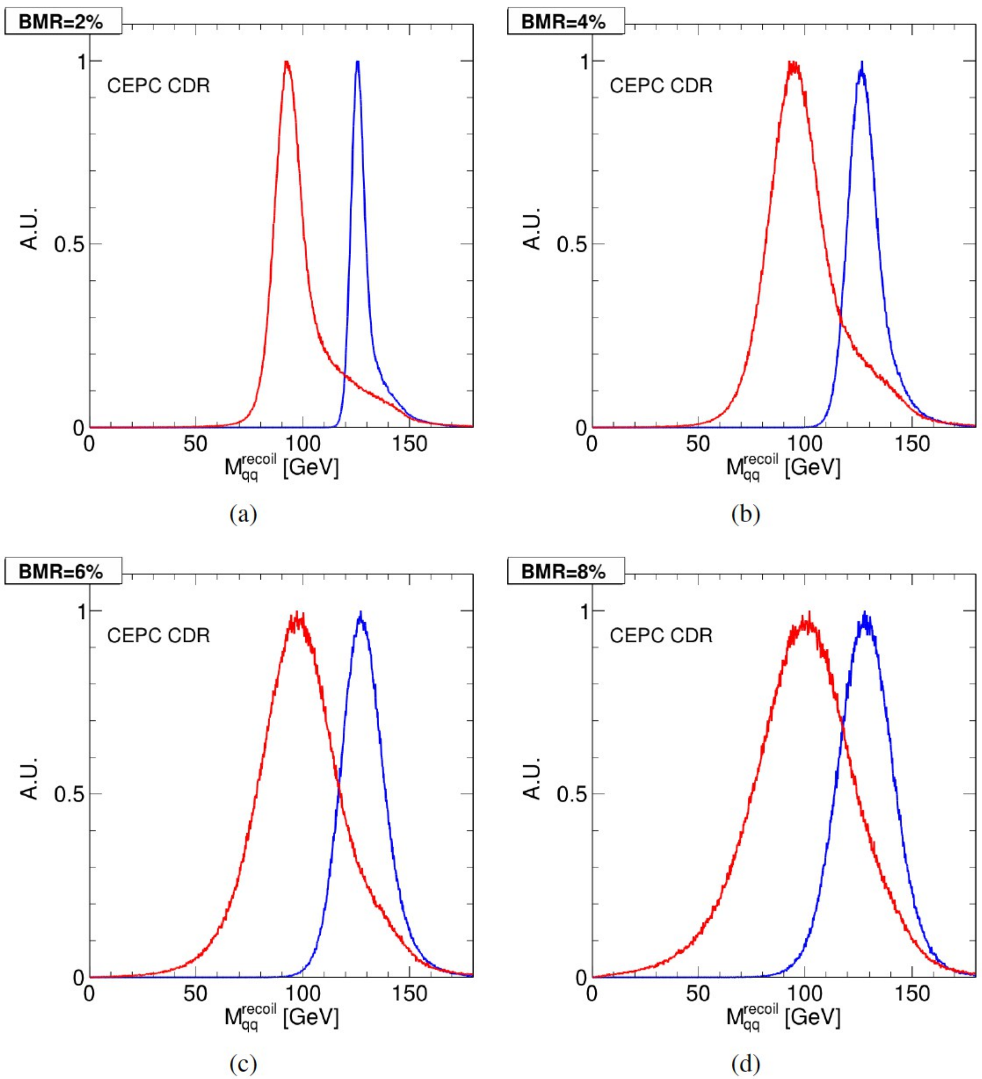


If the BMR degrades from 4% to 6/8%: the Higgs width measurement degrades by 20/40%
improves to 2%: the width measurement will improve by 15%

2nd Benchmark: qqH, H→invisible

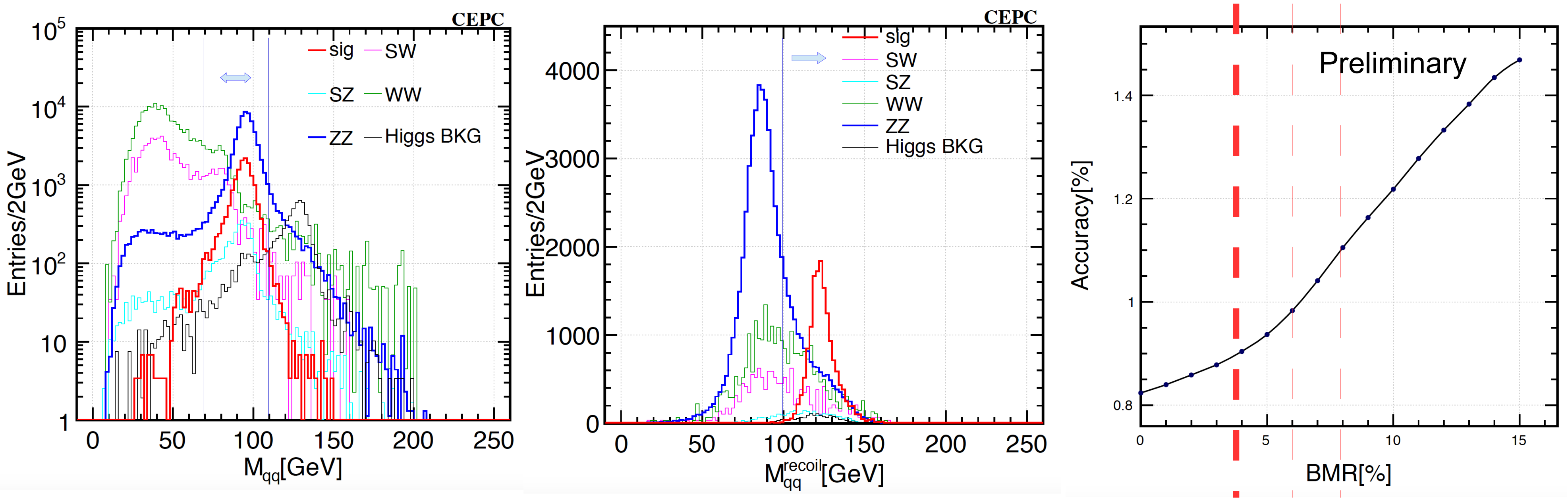
- Portal to DM...
- qqH dominants the precision & rely on the recoil mass to separate the ZZ bkg
- Essential for qqH analysis, especially H→non jet final state





If the BMR degrades from 4% to 6/8%: the Higgs invisible measurement degrades by 20/50%

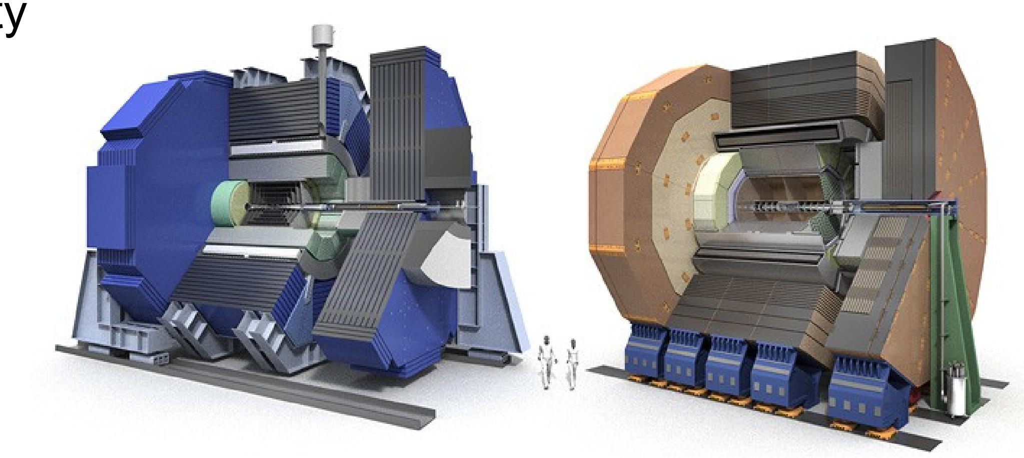
3rd Benchmark: g(Hττ) at qqH



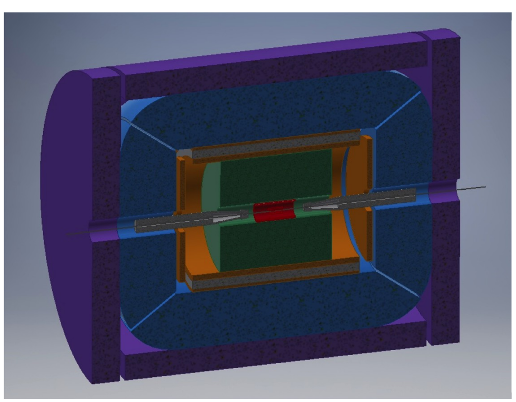
- TAURUS: di-tau system identification
- The rest particles are identified as the di-jet: to distinguish the ZZ/ZH background & Improves the accuracy by more than a factor of 2: **BMR < 4% (baseline of 3.8%) is crucial**
- Isolated tracks are intensionally defined as tau candidate: be distinguished by the VTX
- Relative accuracy of 0.9% at 5.6 ab^{-1} integrated luminosity, dominate the combined accuracy (0.8%)
- Changing BMR from 4% to 6/10%, the Accuracy degrades by 10/20%

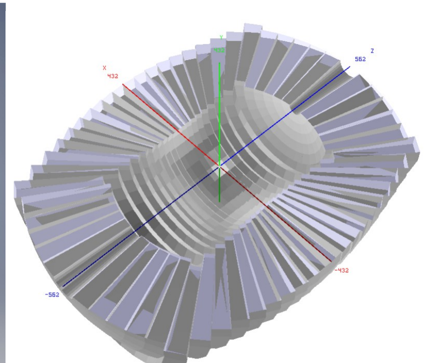
Two classes of Concepts

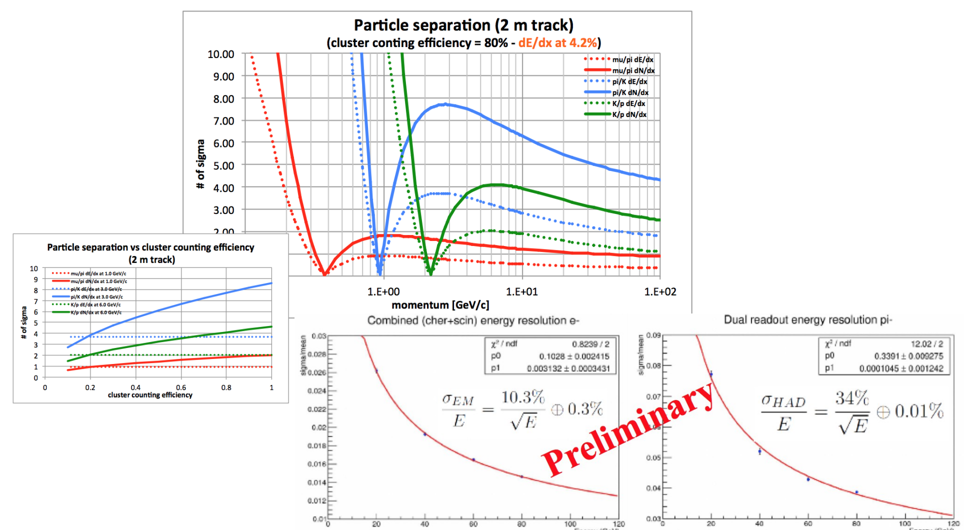
- PFA Oriented concept using High Granularity Calorimeter
  - **+ TPC (ILD-like, Baseline)**
  - + Silicon tracking (SiD-like)



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



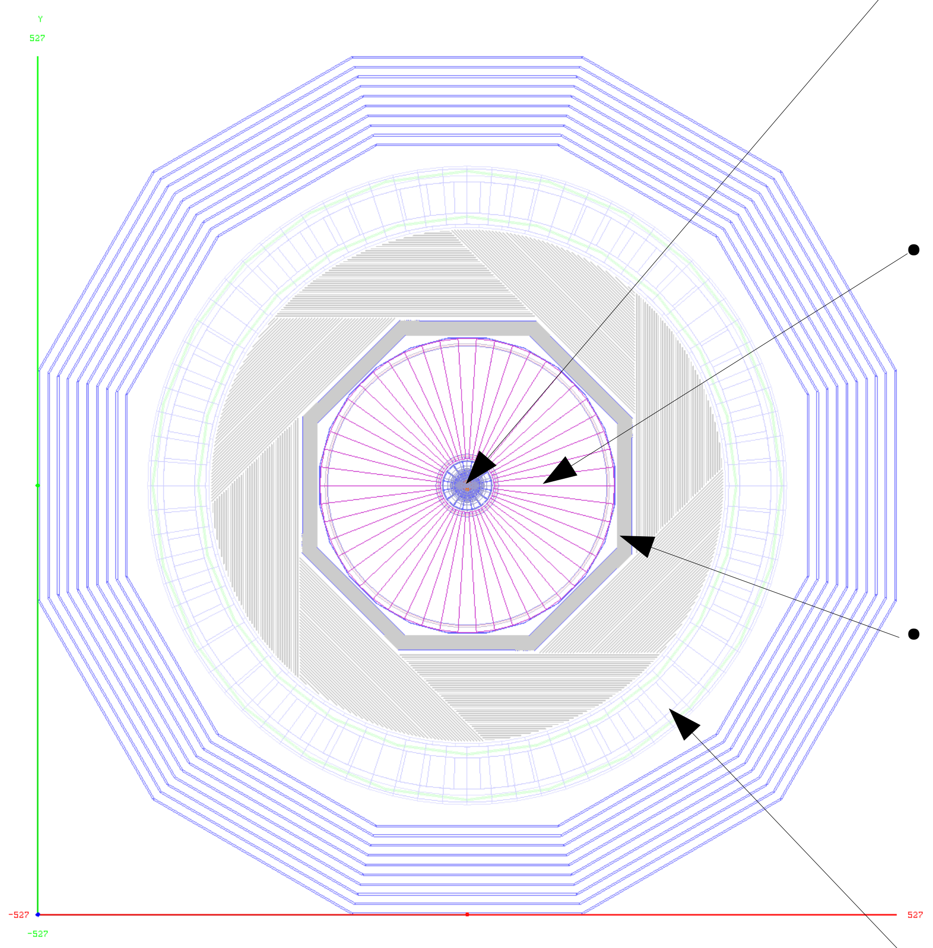




https://indico.ihep.ac.cn/event/6618/

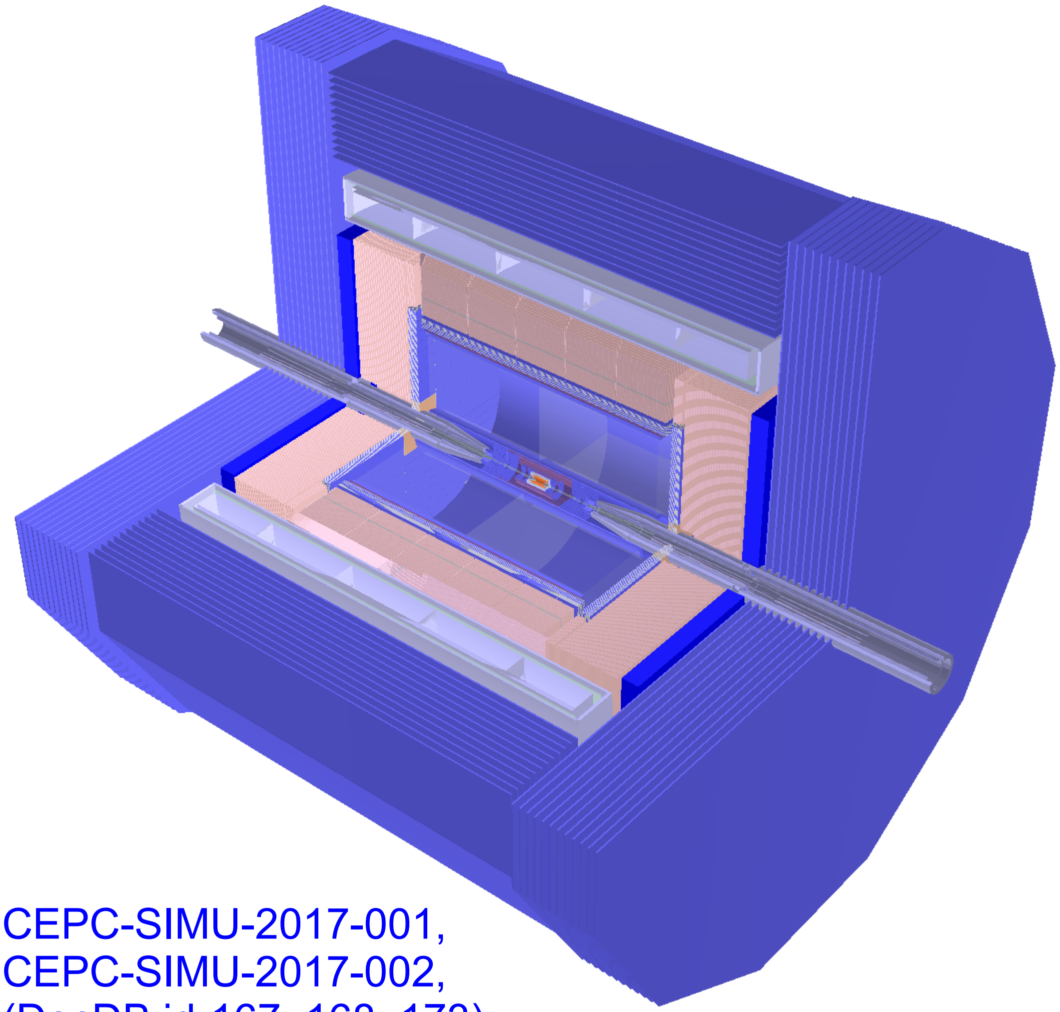
https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=14816

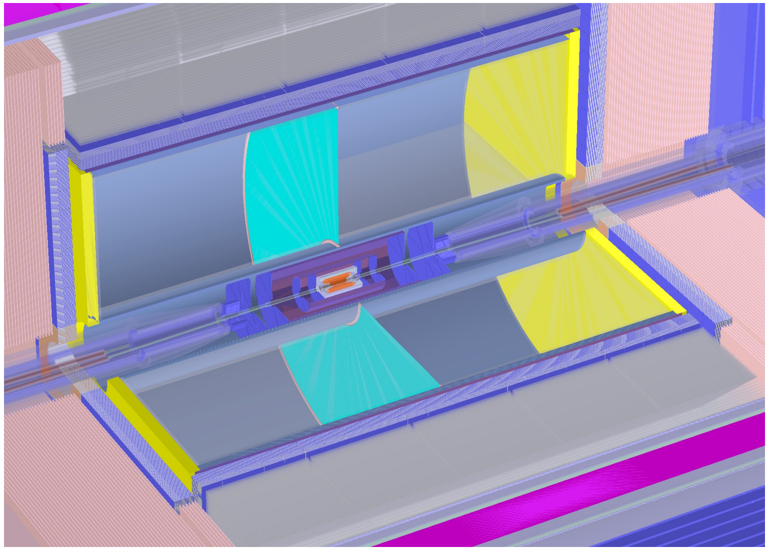
The CEPC baseline: Optimized from the ILD

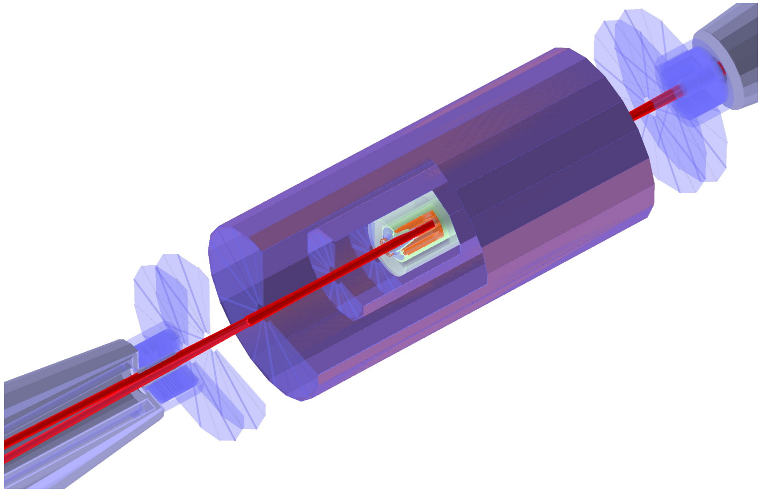


- Different collision environments/rates :
  - MDI design & Implementation: CEPC-SIMU-2017-001
  - Vertex optimization: JINST-13-T09002 (2018)
- The CEPC Event rate is significantly higher than linear colliders, charged kaon id can strongly enhance the CEPC flavor physics program
  - TPC Feasibility: 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

Baseline Geometry

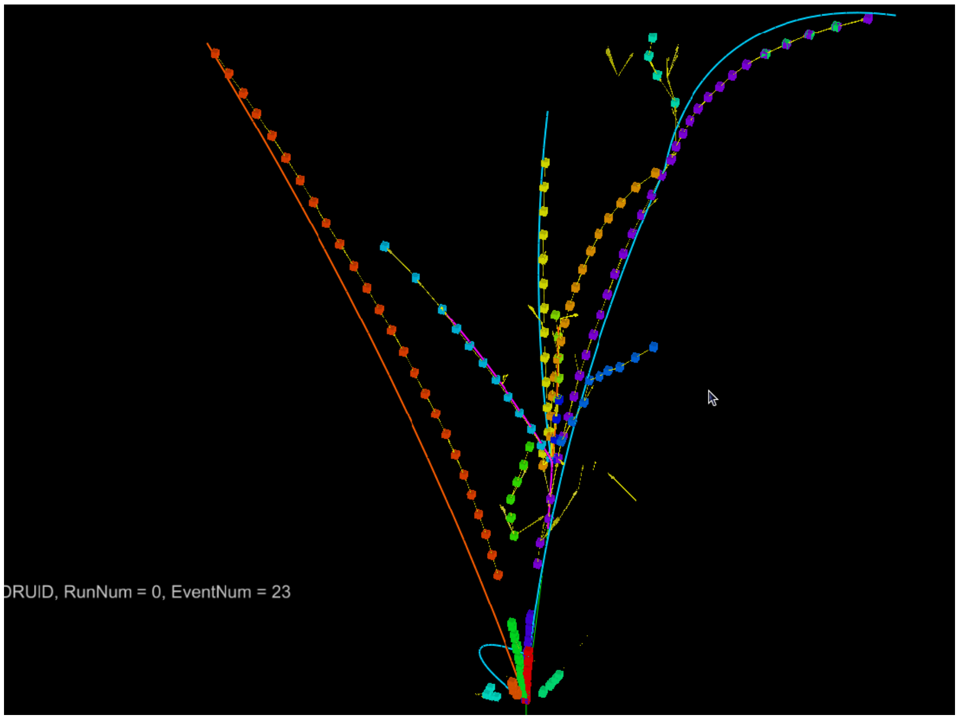


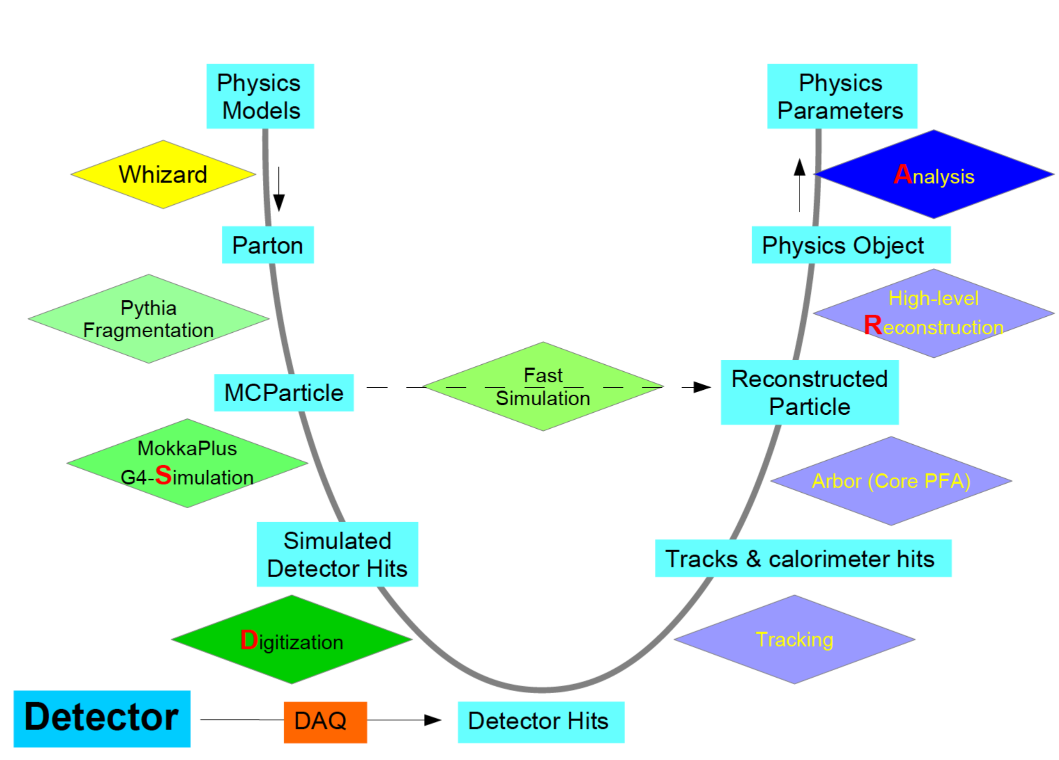




CEPC-SIMU-2017-001,
CEPC-SIMU-2017-002,
(DocDB id-167, 168, 173)

Software & Reconstruction

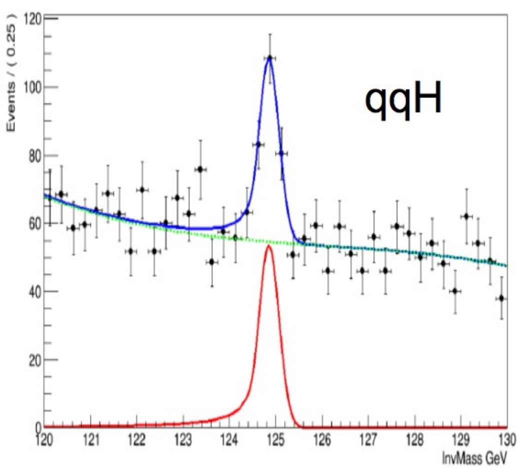


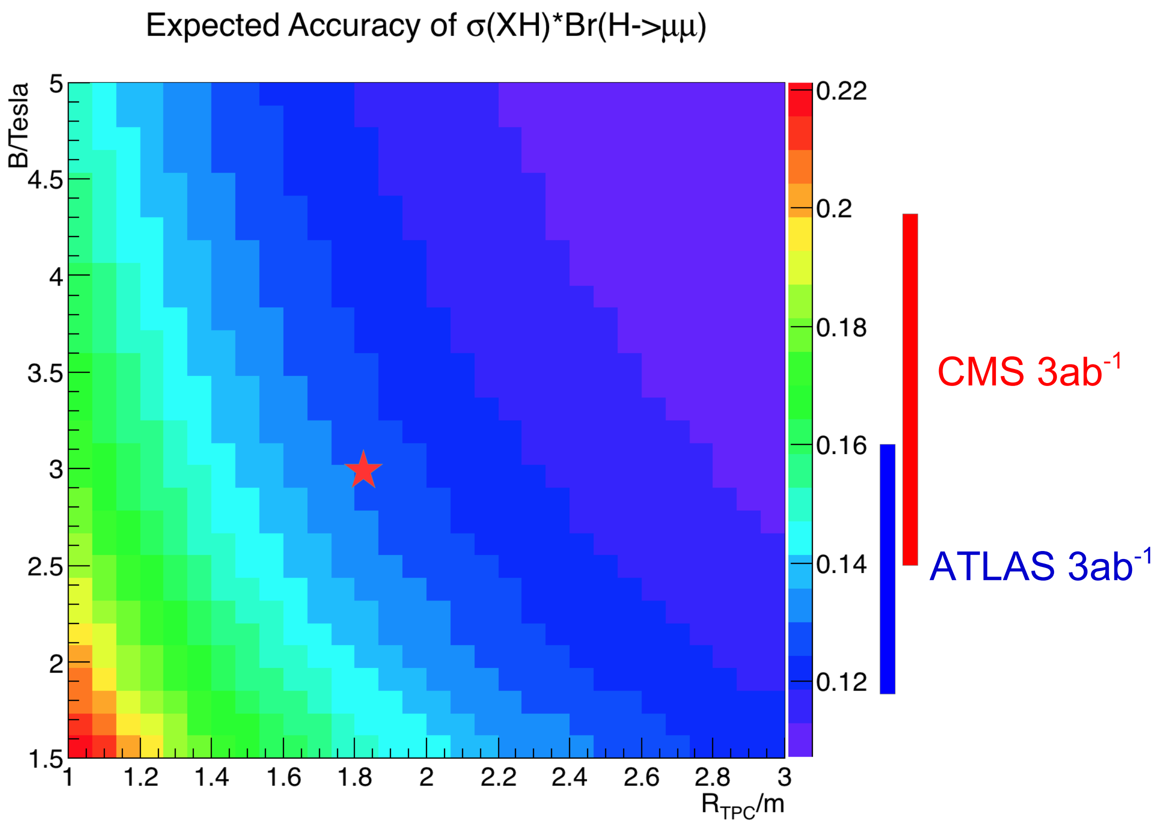


Starting from the ilcsoft & replace all the PFA/high-level reconstruction algorithms.

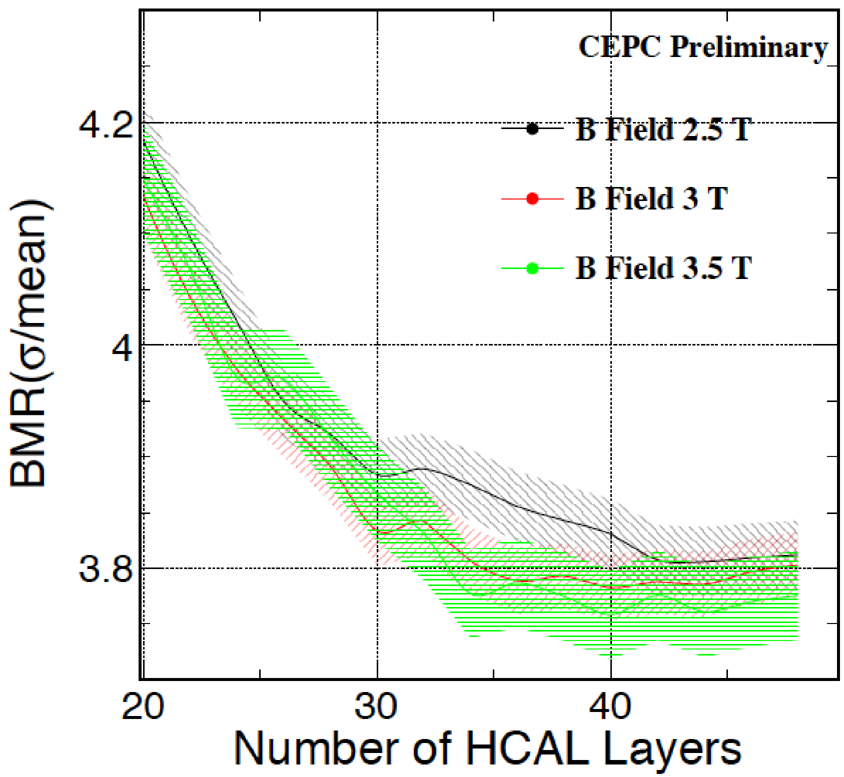
Tracker Radius: the optimized value

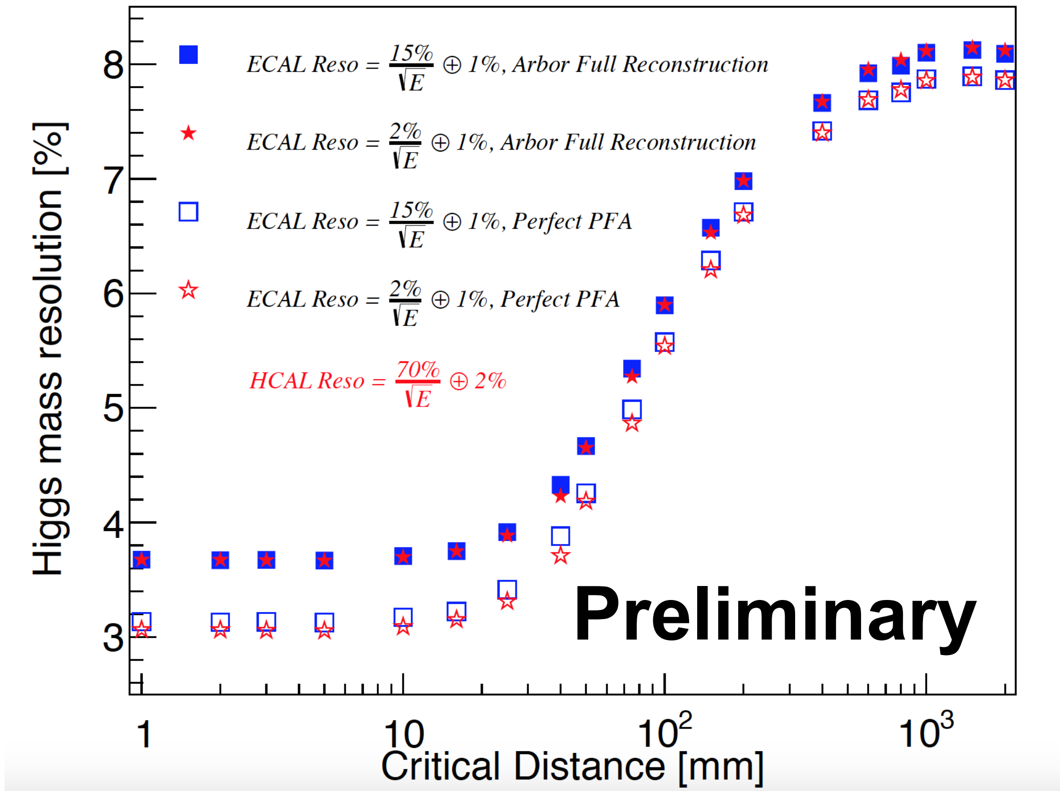
- Detector cost is sensitive to tracker radius, however, I recommend TPC radius >= 1.8m:
  - Better separation & JER
  - Better dEdx
  - **Better (H->di muon) measurement**





Calorimeter optimization: B-Field, HCAL thickness, and ECAL Separation power



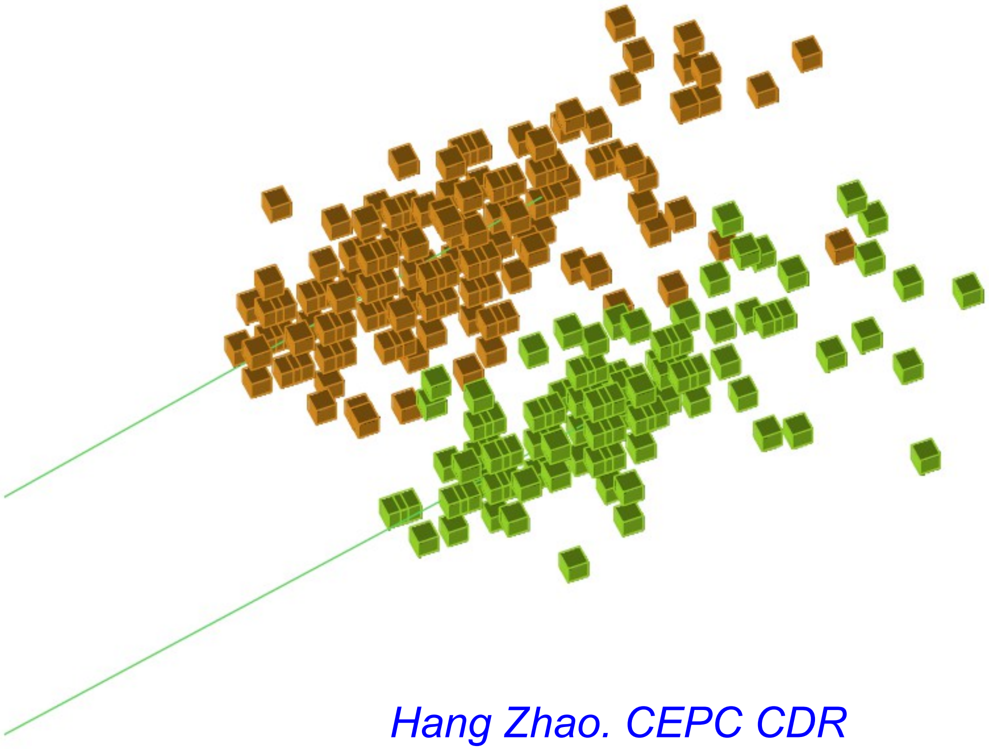


HCAL #Layer: 40

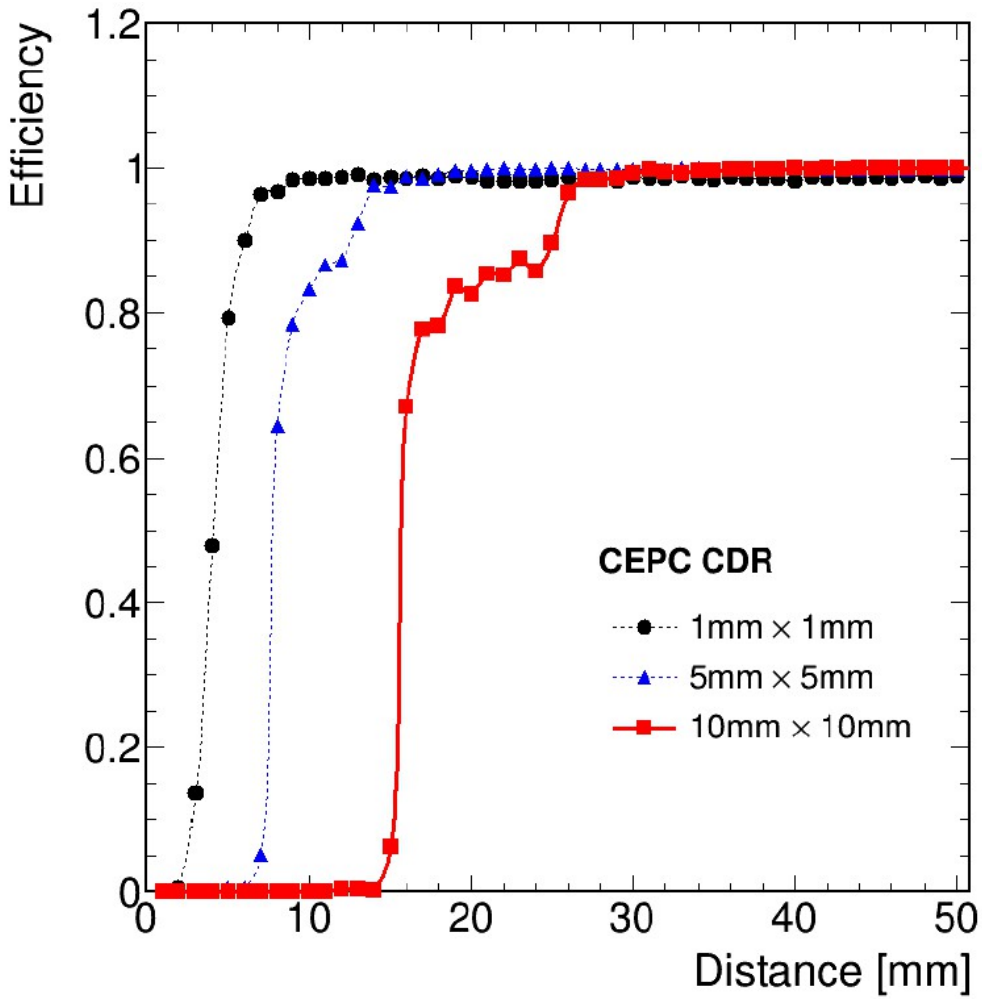
B-Field: No significant degrading at 3 T, Comparing to 3.5 T

Separation power: Better than 20 mm is required

Clustering - Separation



Hang Zhao. CEPC CDR



10 mm Cell Size gives 16 mm Critical Separation distance: a good choice

Critical energy to separate an evenly decay π_0: 30 GeV

Validation on Full Simulation

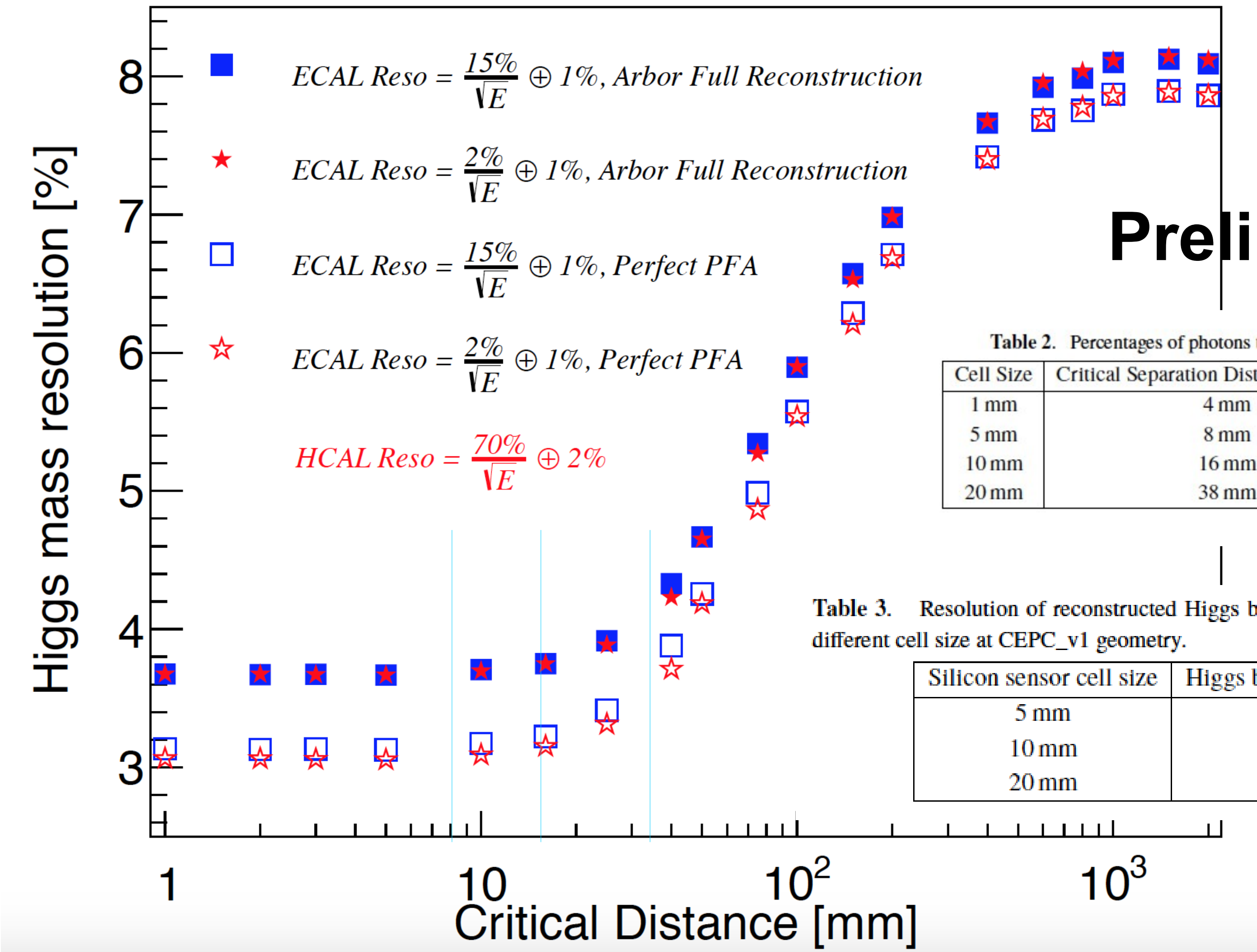


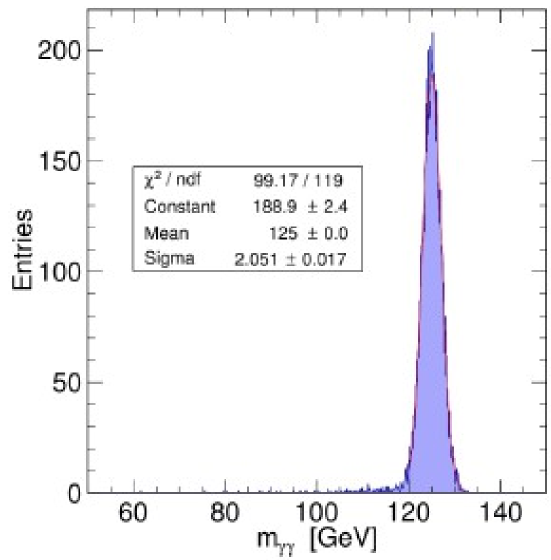
Table 2. Percentages of photons that would be polluted by neighbor particles

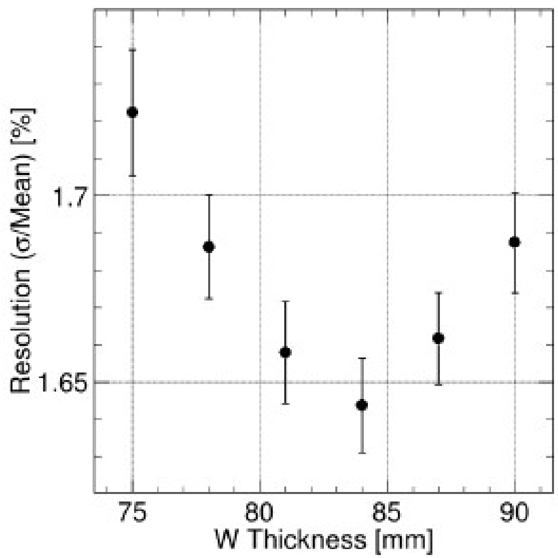
Cell Size	Critical Separation Distance with Arbor	Percentage of $Z \to \tau^+\tau^-$
1 mm	4 mm	0.07%
5 mm	8 mm	0.30%
10 mm	16 mm	1.70%
20 mm	38 mm	19.6%

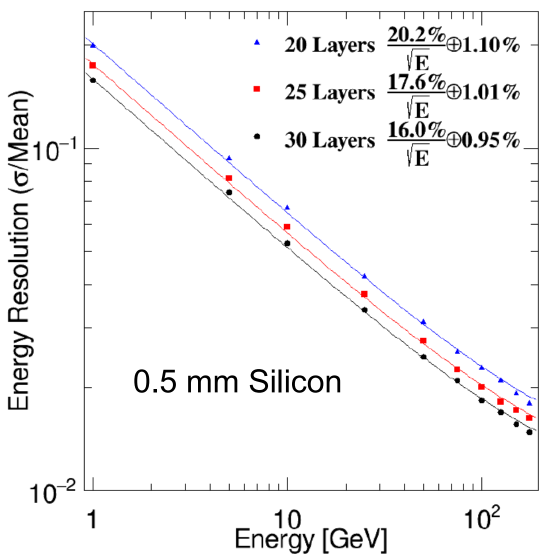
Table 3. Resolution of reconstructed Higgs boson mass through $\nu\nu$Higgs, Higgs $\to$ gluons events with different cell size at CEPC_v1 geometry.

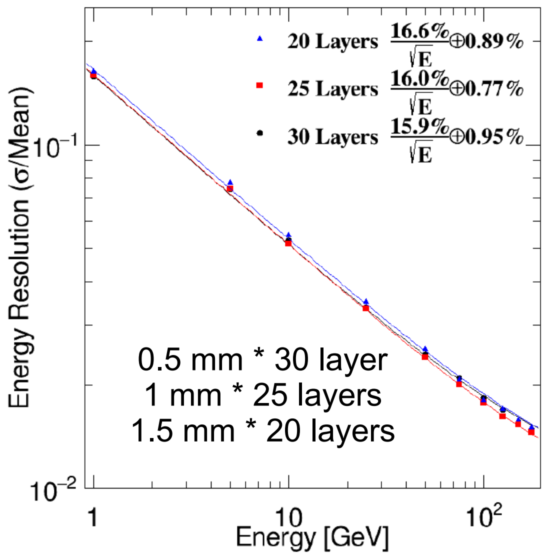
Silicon sensor cell size	Higgs boson mass resolution (Statistic error only)
5 mm	3.74 ± 0.02%
10 mm	3.75 ± 0.02%
20 mm	3.93 ± 0.02%

ECAL Longitudinal Structure









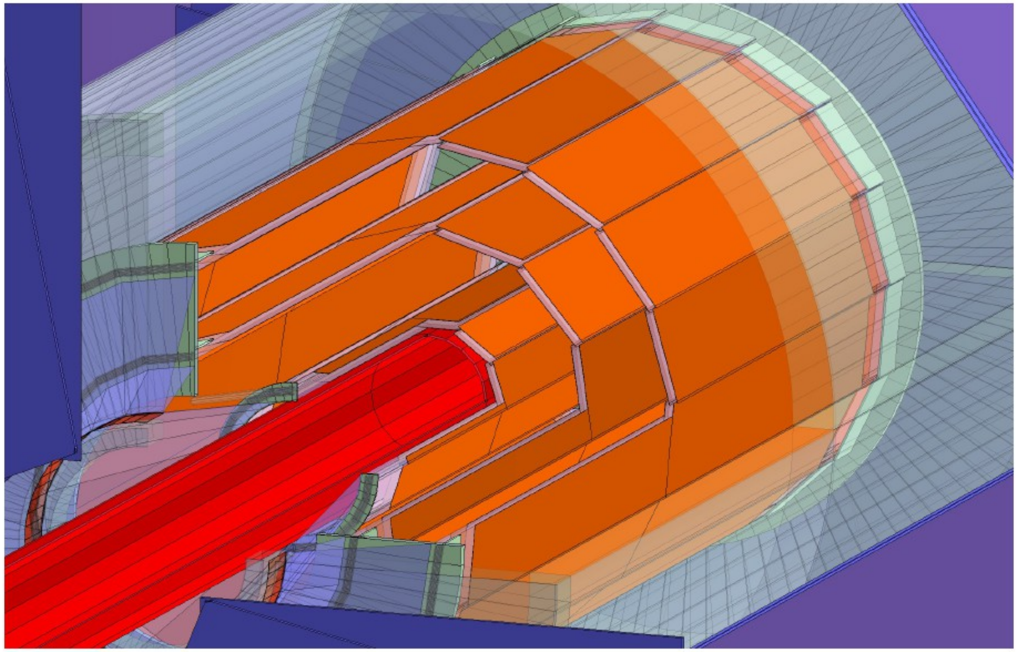
Optimized ECAL thickness

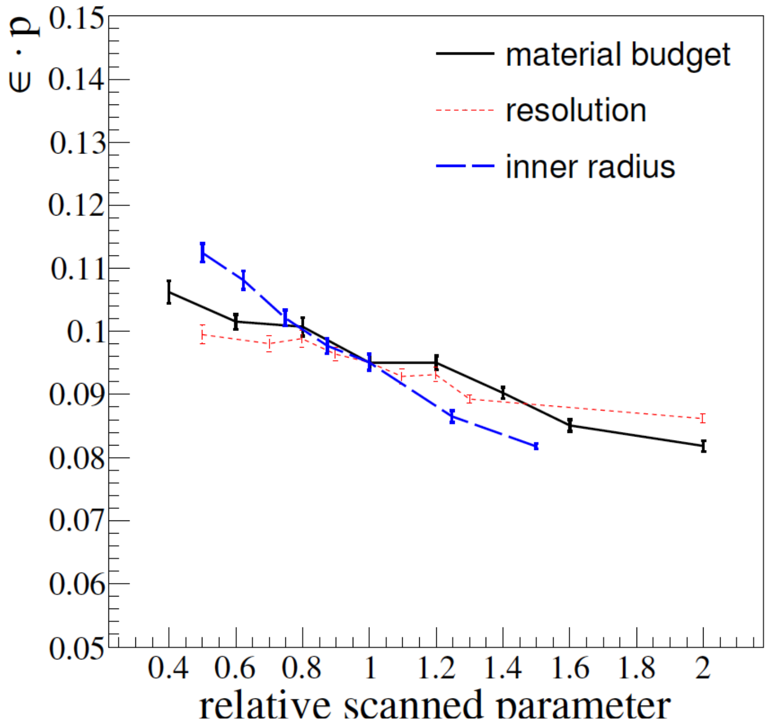
ECAL W thickness: 84 mm

Using thicker Wafer: the ECAL Energy Resolution Can be improved

https://arxiv.org/abs/1712.09625

VTX Optimization on H→bb, **cc**, ττ





$$\epsilon \cdot p = 0.095(1 - 0.14\frac{\Delta x_{\text{material}}}{x_{\text{material}}})(1 - 0.09\frac{\Delta x_{\text{resolution}}}{x_{\text{resolution}}})(1 - 0.23\frac{\Delta x_{\text{radius}}}{x_{\text{radius}}})$$

- Closer > Lighter > Preciser

Wu_2018_J._Inst._13_T09002

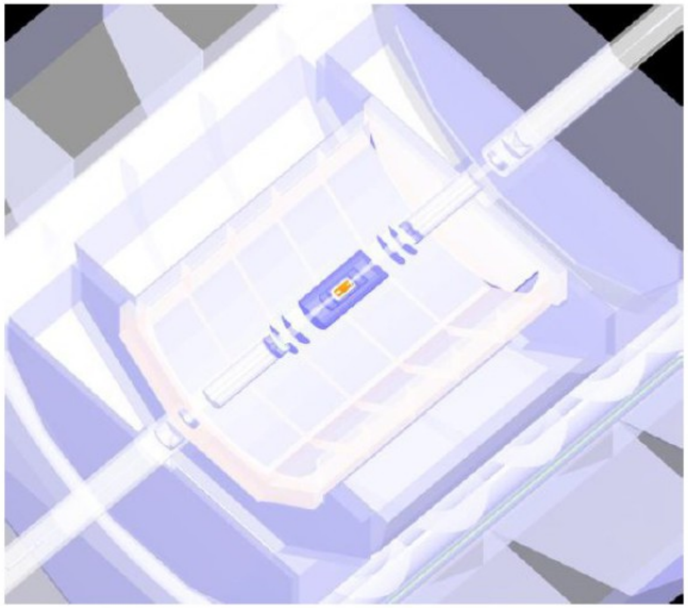
Optimized Parameters

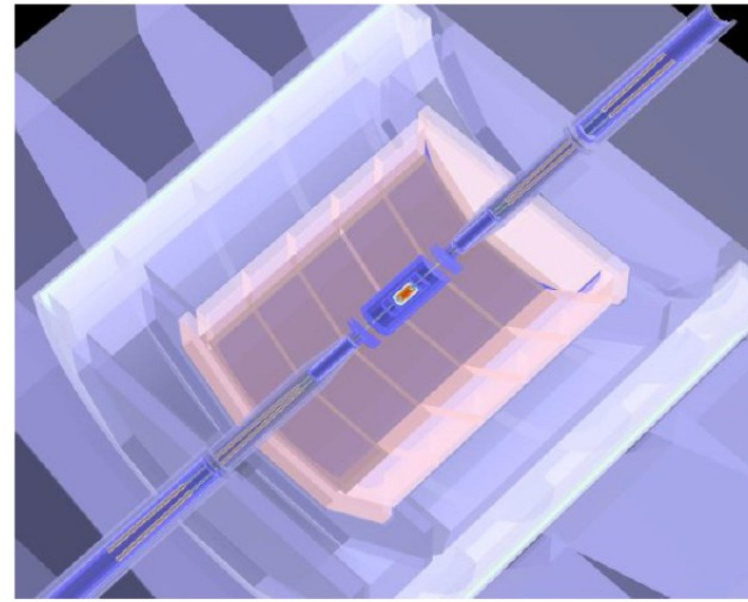
	CEPC_v1 (~ ILD)	APODIS (Optimized)	Comments
Track Radius	1.8 m	>= 1.8 m	Requested by Br(H->di muon) measurement
B Field	**3.5 T**	**3 T**	**Requested by MDI**
ToF	**-**	**50 ps**	**Requested by pi-Kaon separation at Z pole**
ECAL Thickness	84 mm	84(90) mm	84 mm is optimized on Br(H->di photon) at 250 GeV; 90mm for bhabha event at 350 GeV
ECAL Cell Size	5 mm	10 mm	Passive cooling request ~ 20 mm.
ECAL NLayer	30	30	Depends on the Silicon Sensor thickness
HCAL Thickness	**1.3 m**	**1 m**	-
HCAL NLayer	**48**	**40**	Optimized on Higgs event at 250 GeV; Margin might be reserved for 350 GeV.

Vertex: needs extra boundary conditions from dedicated MDI/Machine background analyses.

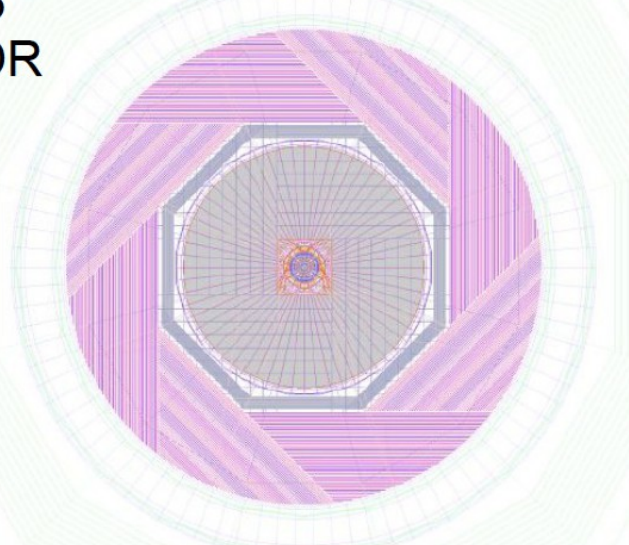
Benchmark detector for CDR: APODIS

(A PFA Oriented Detector for HIggS factory. a.k.a CEPC_v4)

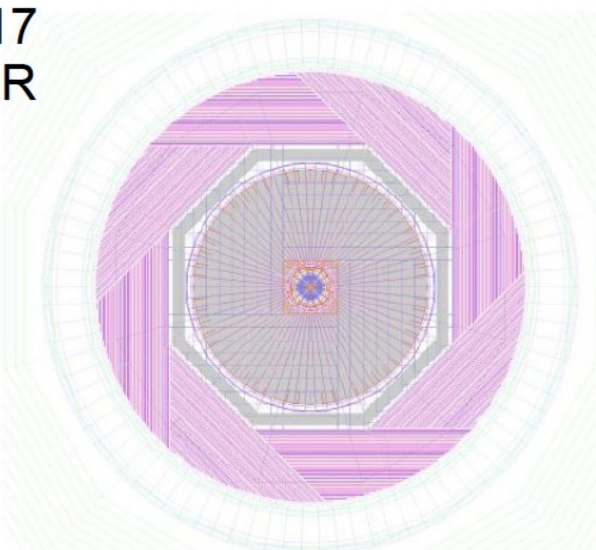




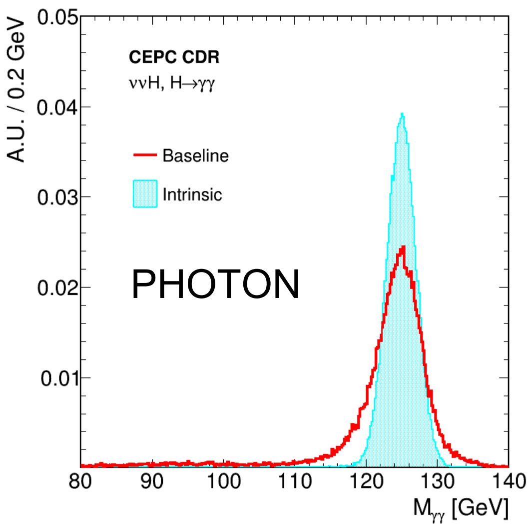
2015
PreCDR



2017
CDR



Physics Objects



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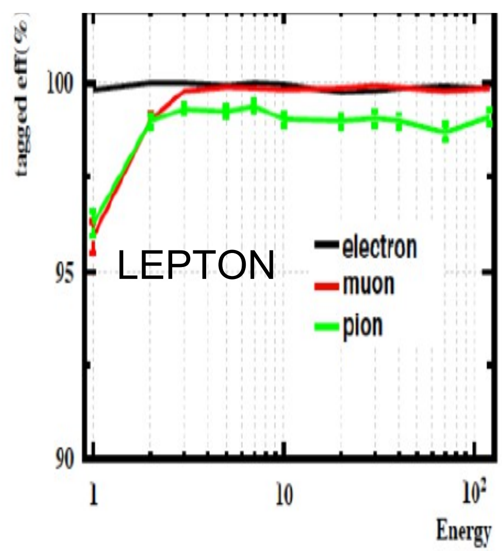

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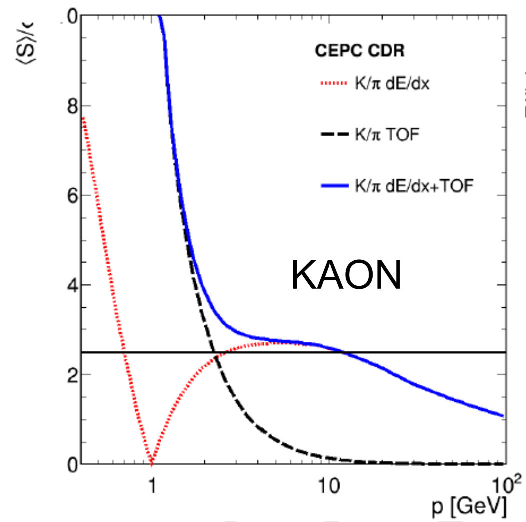

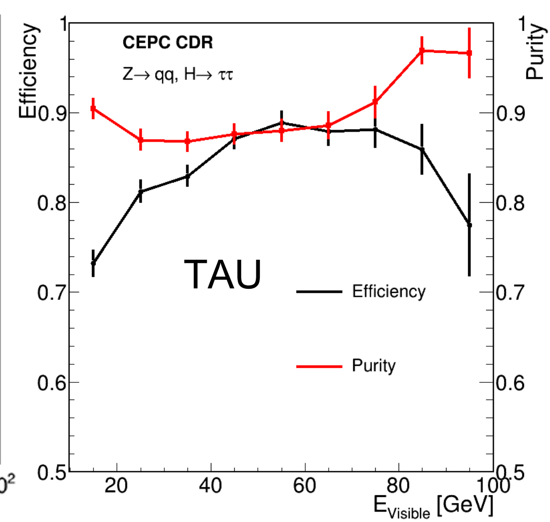

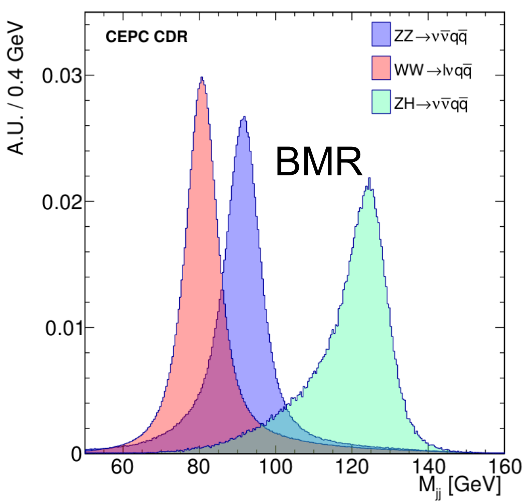

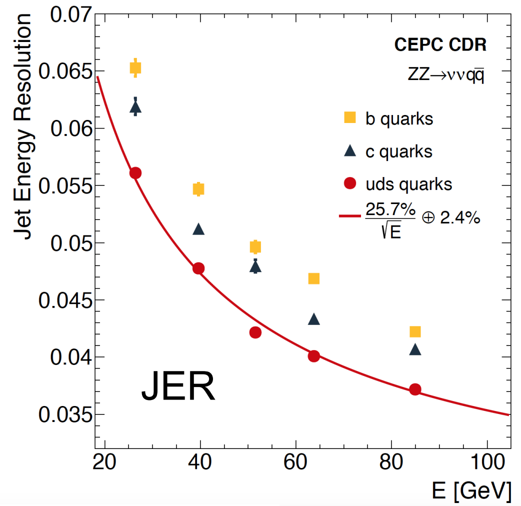

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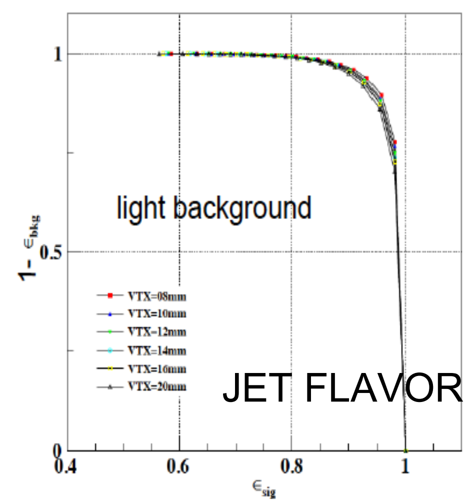
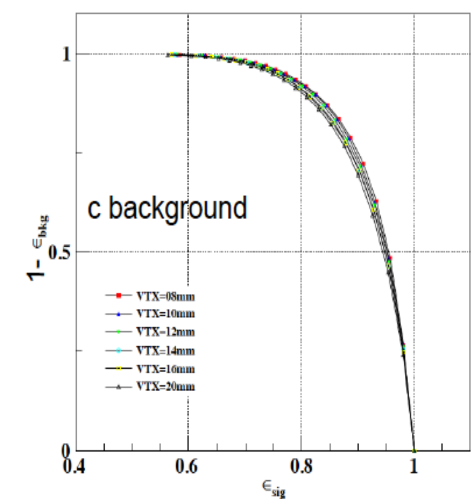
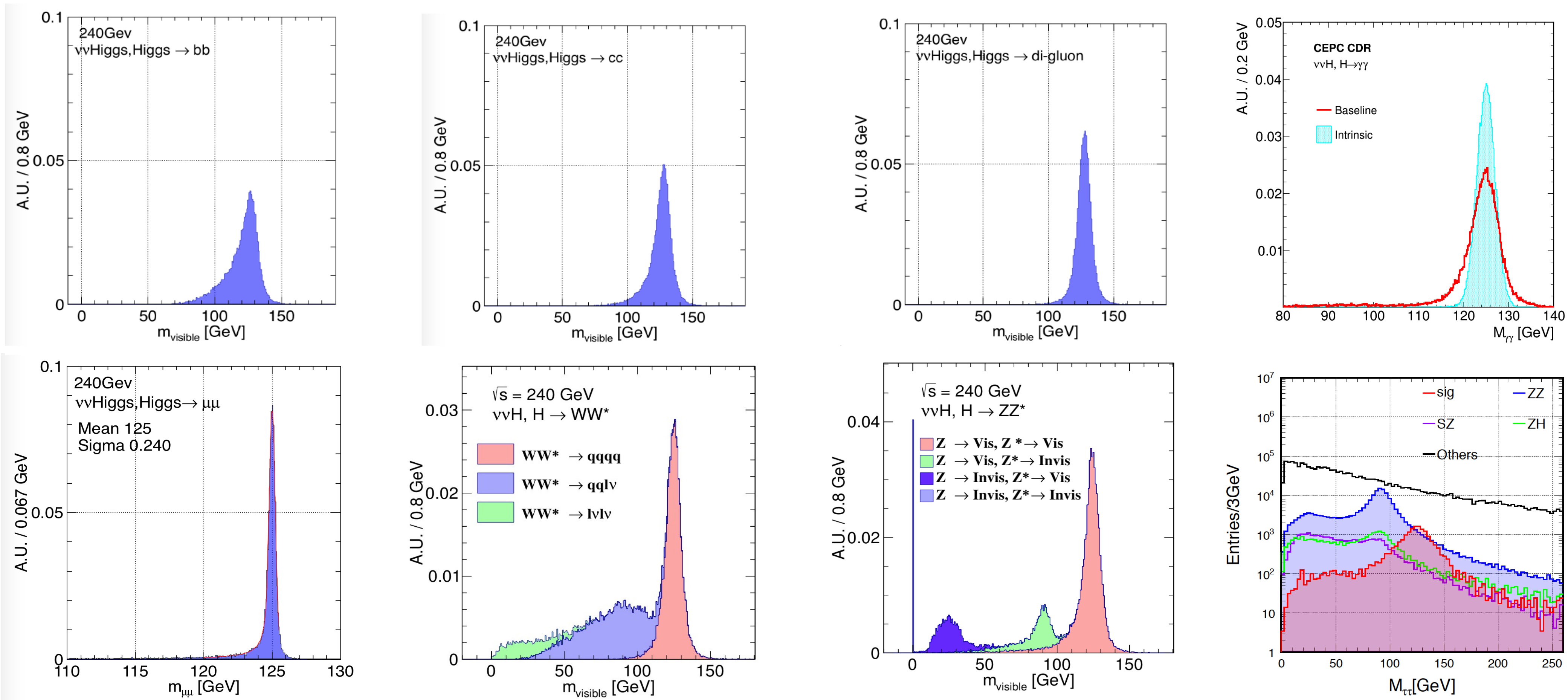




Reconstructed Higgs Signatures

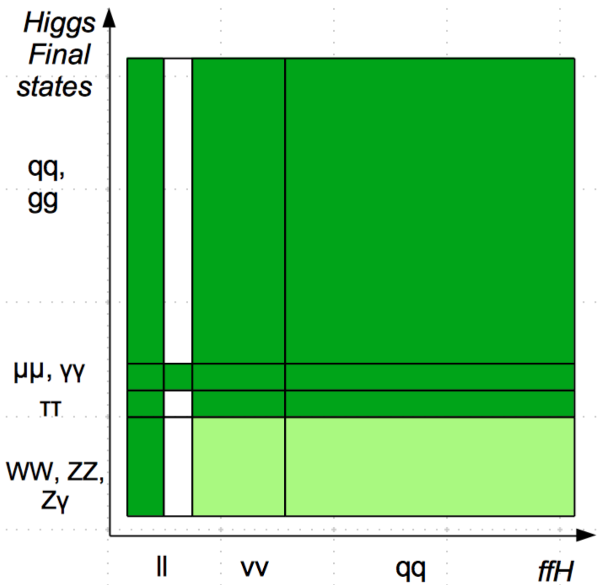


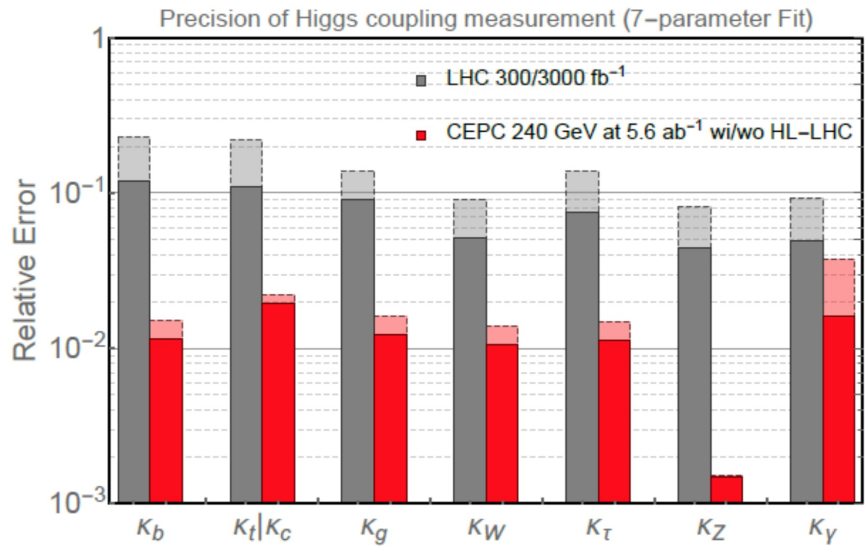
Clear Higgs Signature in all SM decay modes

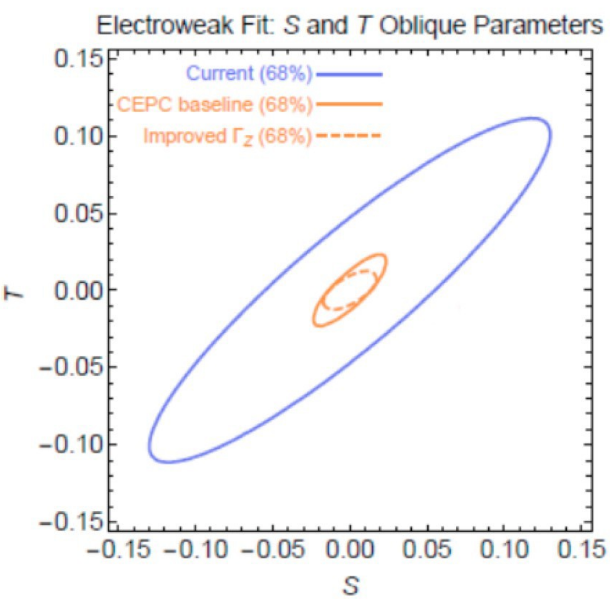
Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

Right corner: di-tau mass distribution at qqH events using collinear approximation

Applied to physics potential study







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*

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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]
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Bruce Mellado[17] Xin Mo[4] Mila Pandurovic[16] Jianming Qian[22] Zhuoni Qian[18]
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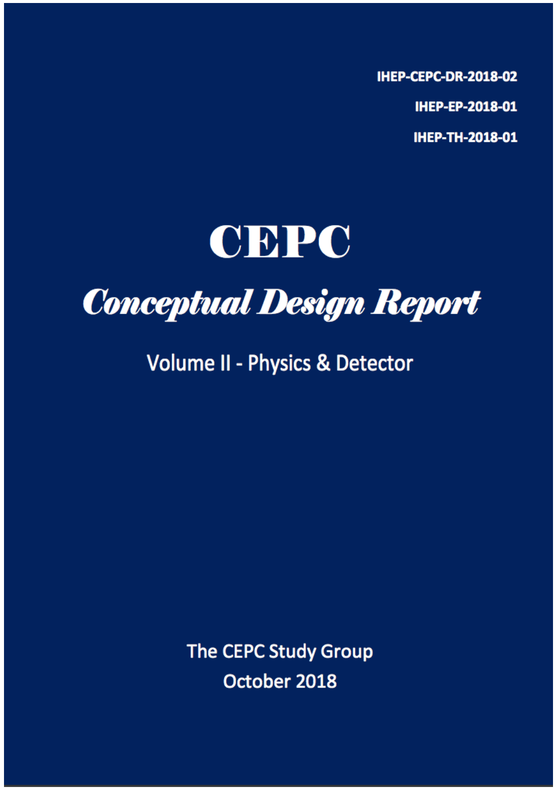
Shufang Su[23] Dayong Wang[3] Jing Wang[4] Lian-Tao Wang[25] Yifang Wang[4,6] Yuqian Wei[4]
Yue Xu[5] Haijun Yang[10,11] Weiming Yao[26] Dan Yu[4] Kaili Zhang[4,6] Zhaoru Zhang[4]
Mingrui Zhao[2] Xianghu Zhao[4] Ning Zhou[10]

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

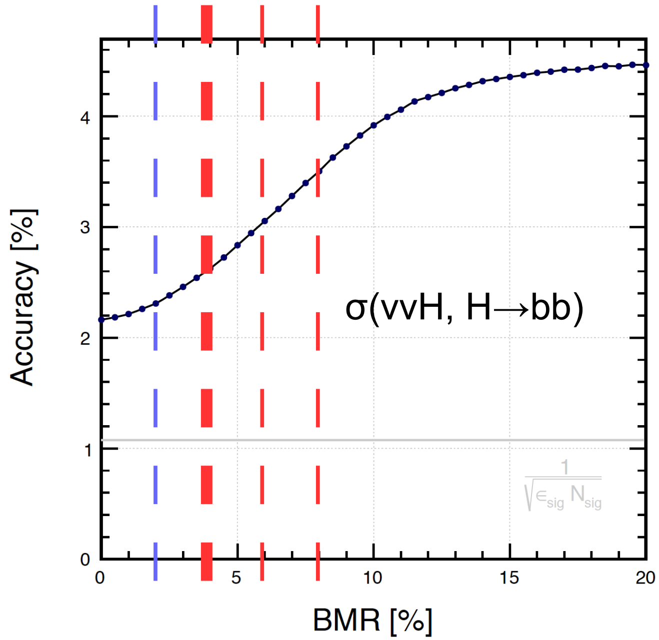


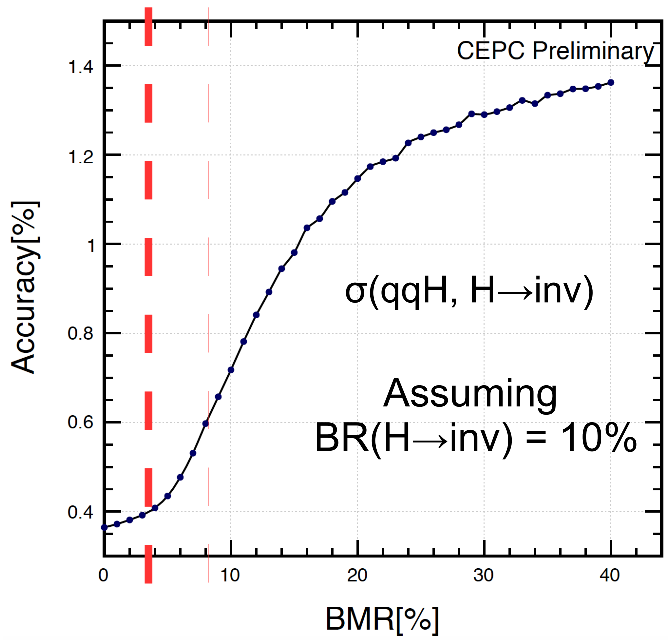
Summary

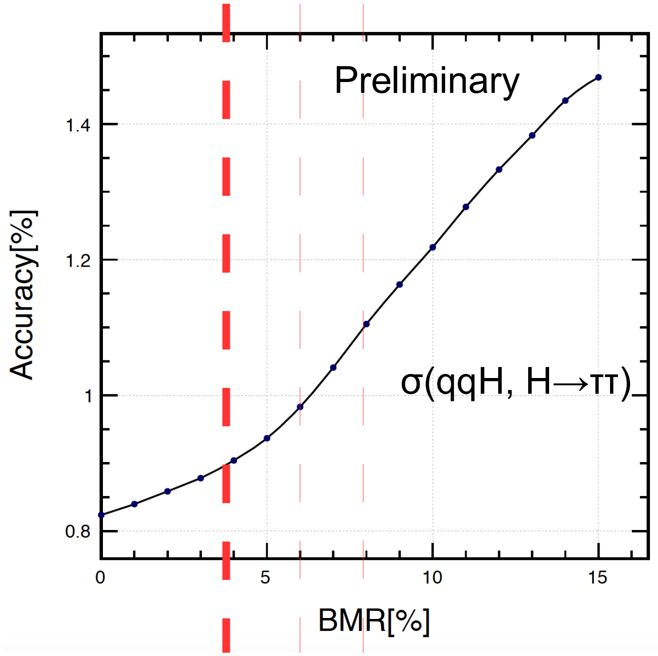
- The Particle Flow oriented detector is chosen as the baseline detector for the CEPC CDR
  - High efficiency/accuracy reconstruction of all key physics objects
  - Baseline achieves the BMR ~ 3.8%, fulfills the requirement of BMR < 4%
  - Clear Higgs signature in all SM Higgs decay mode
- Baseline detector is optimized for the CEPC collision environments
  - Significantly reduced B-Field (15%), #readout channels (75% in ECAL) & HCAL layer-thickness (20%) & cost (15%/30% w.r.t CEPC-v1/ILD)
  - Same Higgs performance & enhanced Pid Performance
- Todo:
  - To model precisely sub-detector response - Dedicated Digitizer
  - Quantify the requirements of sub-detector homogeneity, stability, etc
  - Integration on DAQ, Cooling & Mechanics
  - New ideas

backup

Requirement from benchmark analysis: BMR < 4%



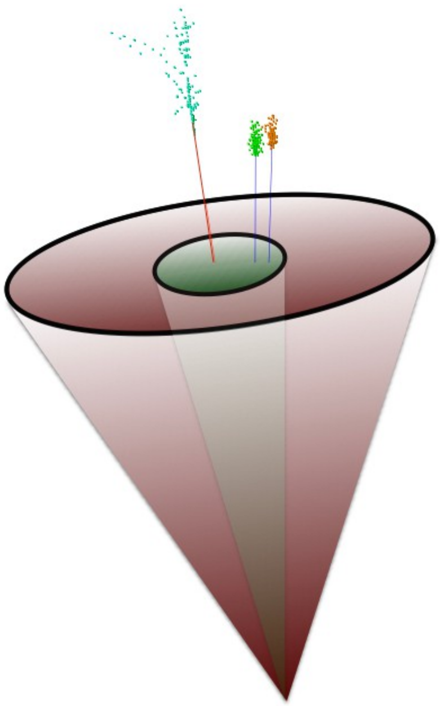


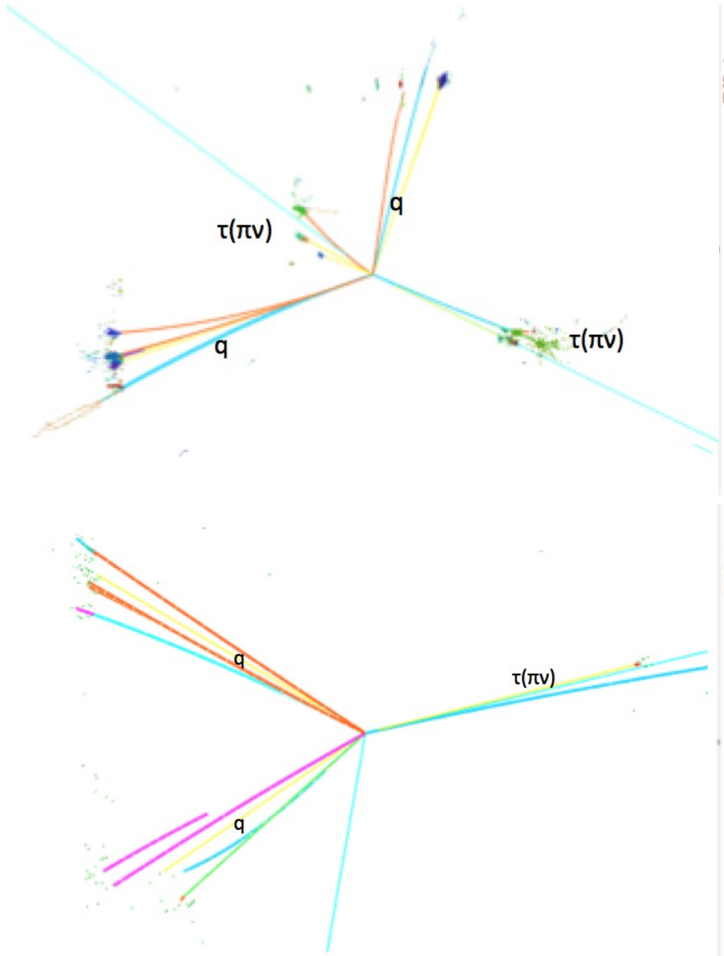


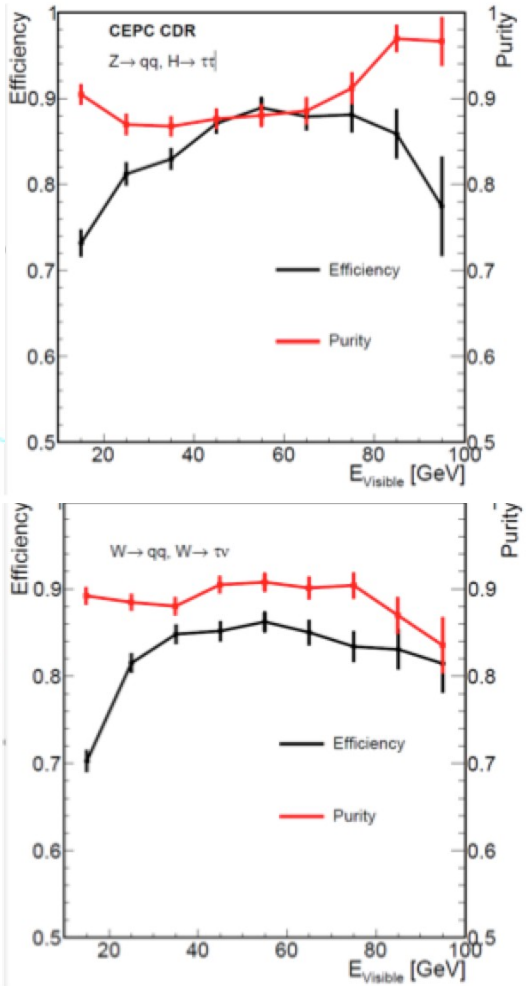
- Boson Mass Resolution: relative mass resolution of vvH, H→gg events
  - Free of Jet Clustering
  - Be applied directly to the Higgs analyses
- The CEPC baseline reaches 3.8%

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

Tau finding at hadronic events



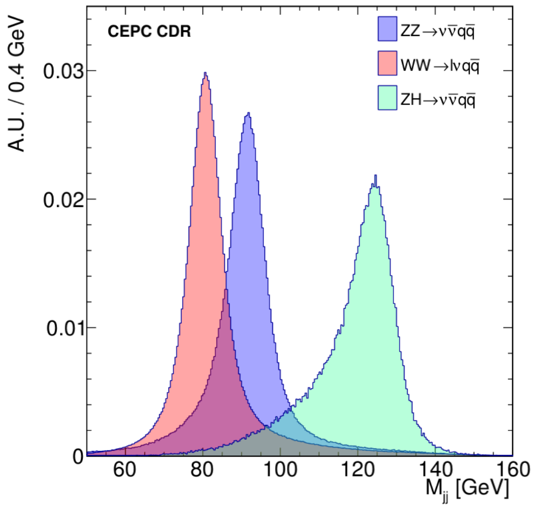


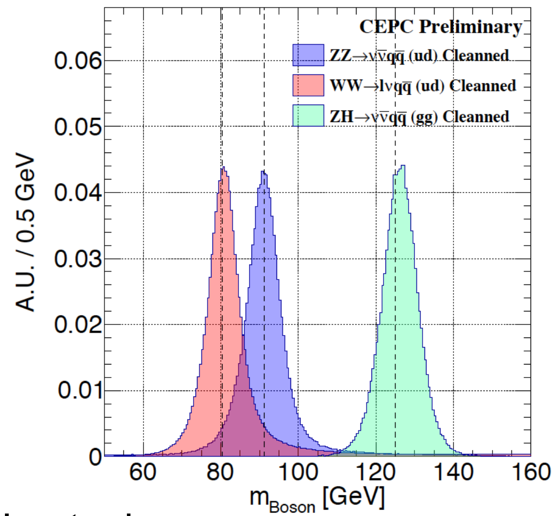


TAURUS (Tau ReconstrUction toolS):
an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

Zhigang Wu, CEPC CDR

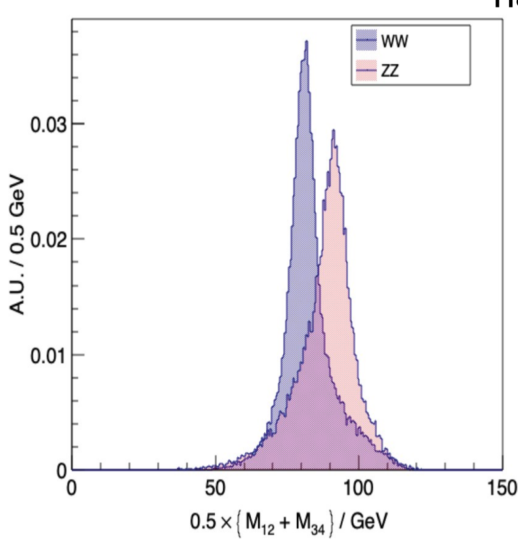
Massive Boson Separation



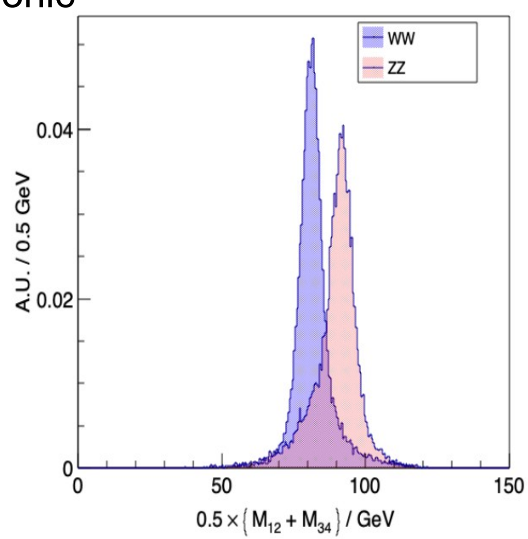


Semi-Leptonic

hadronic



Inclusive



Cleaned

- With BMR of 3.8%, the baseline detector efficiently separate the W, Z & Higgs boson at semi-leptonic and hadronic events
- Identification & Cleaning of physics effects significantly improves the separation
  - *Heavy Flavor Jets*
  - *ISR*
  - *Acceptance*
  - *Equal mass condition ...*
- The Jet Confusions: failure of identify individual color singlet, dominant the hadronic WW-ZZ separation performance at the CEPC baseline – better Color Singlet identification algorithms are needed

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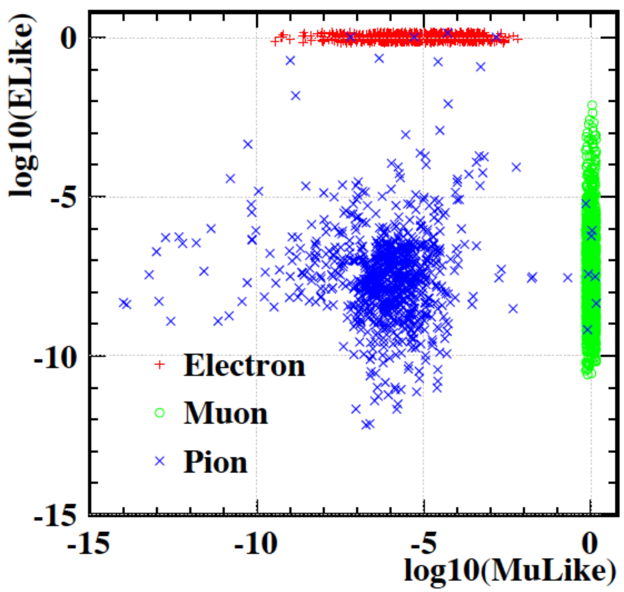
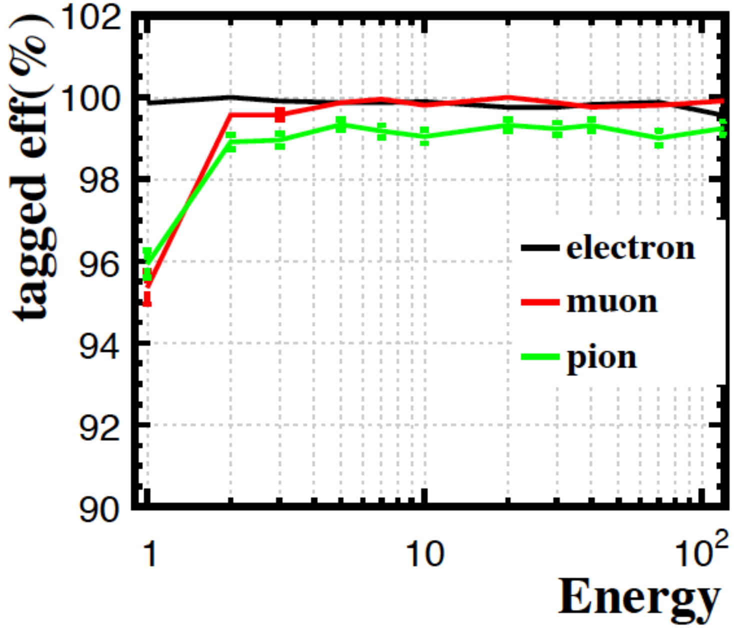
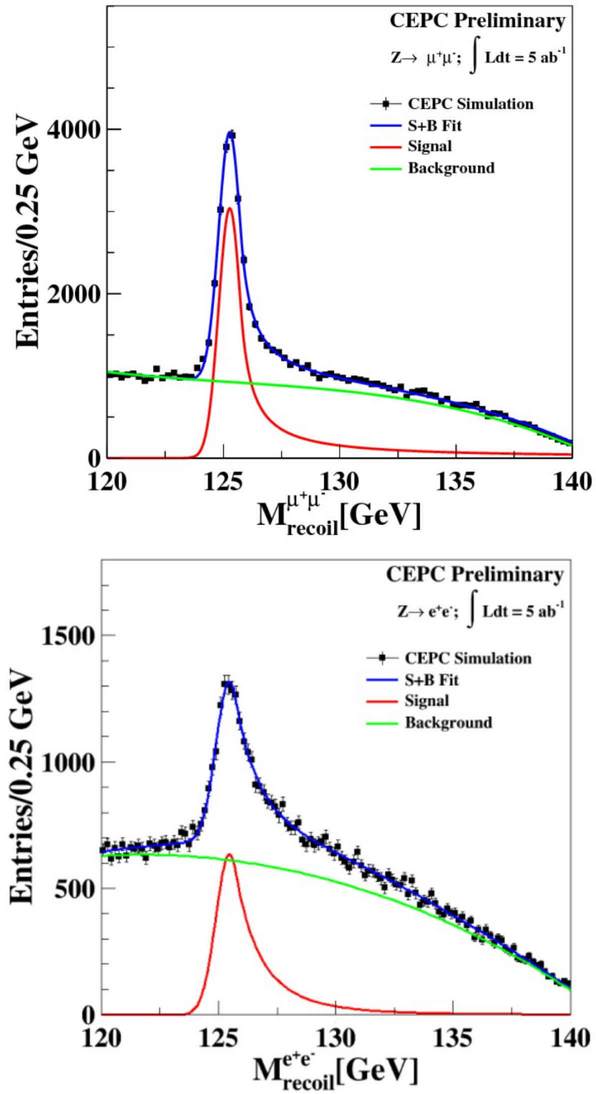
Lepton





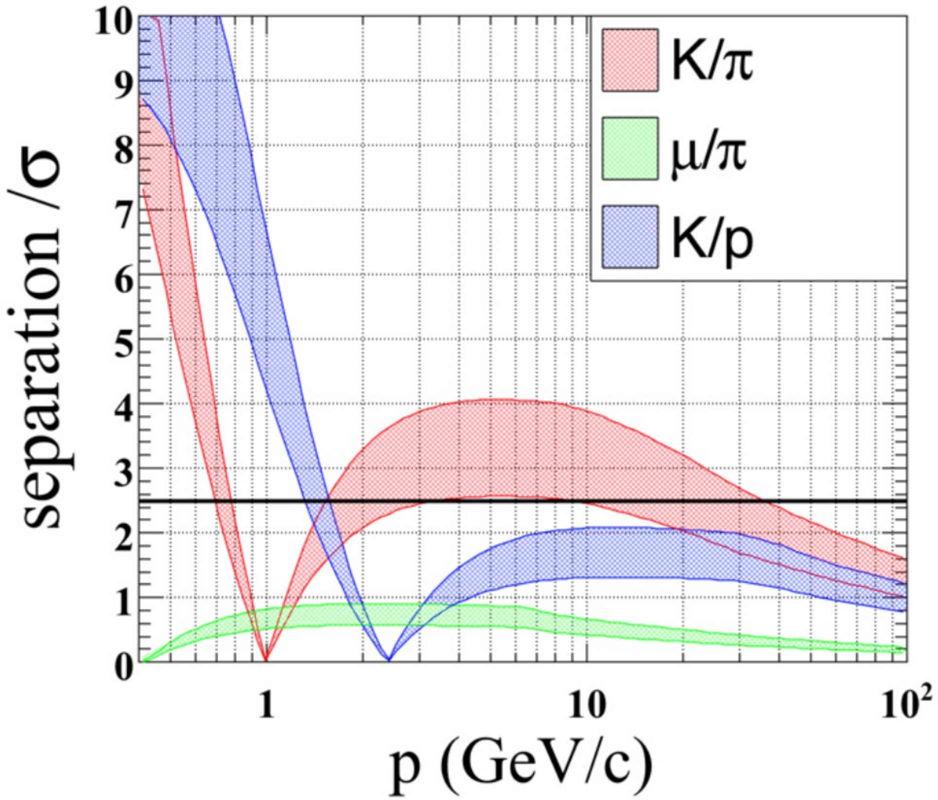


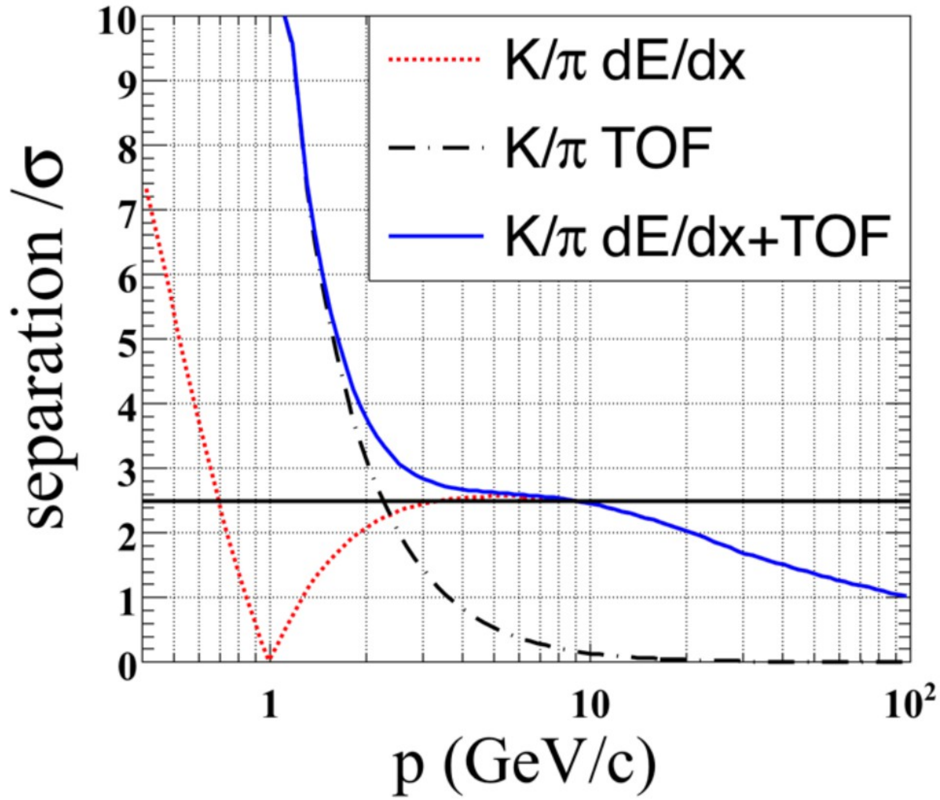
BDT method using 4 classes of 24 input discrimination variables.

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%

https://link.springer.com/article/10.1140/epjc/s10052-017-5146-5
CEPC-DocDB-id:148

Kaon





Highly appreciated in flavor physics @ CEPC Z pole

TPC dEdx + ToF of 50 ps

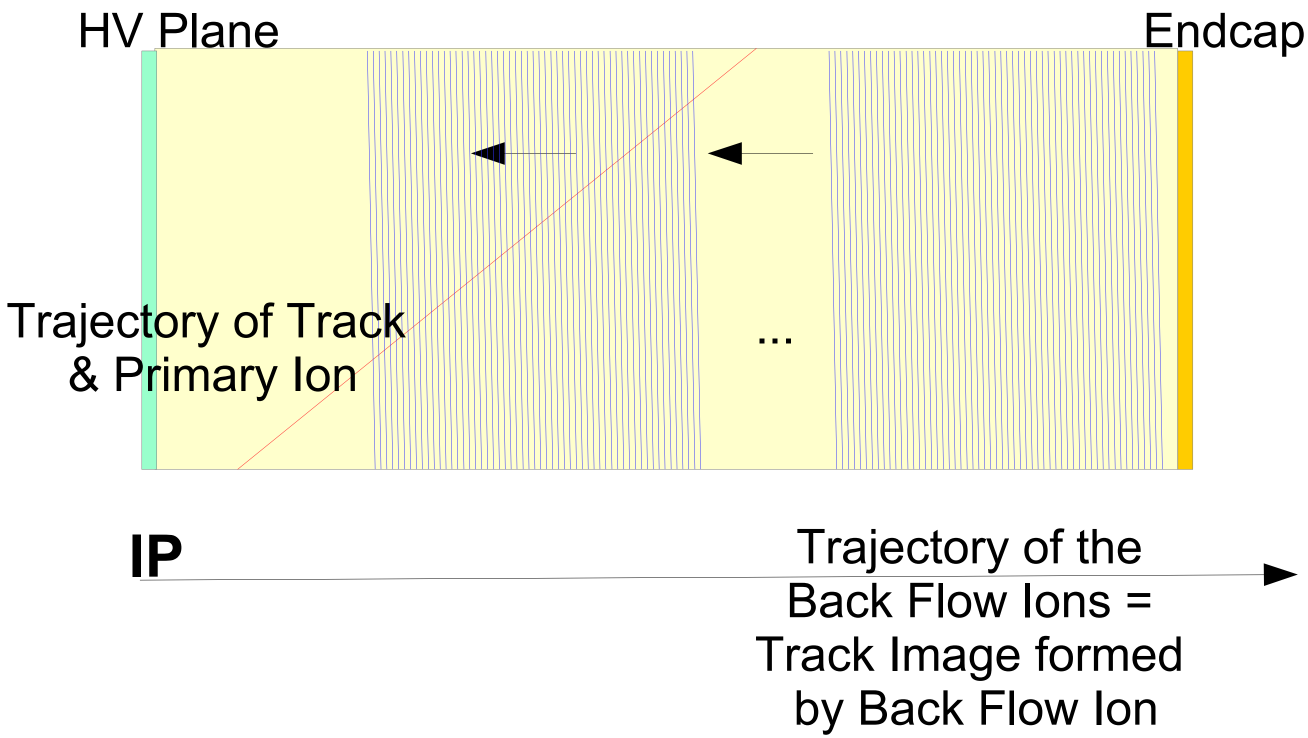
At inclusive Z pole sample:

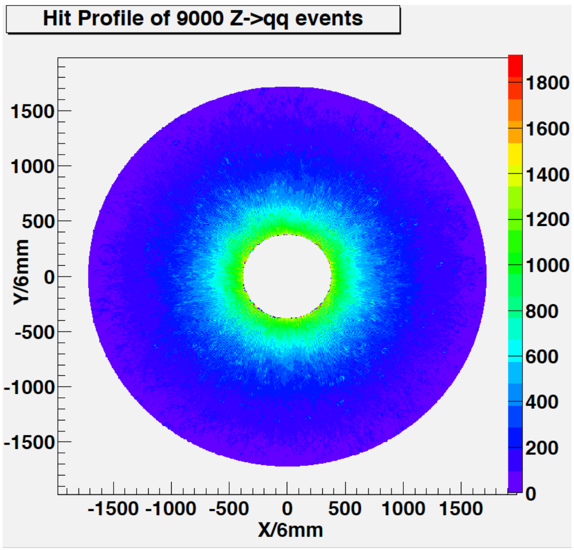
Conservative estimation gives efficiency/purity of 91%/94% (2-20 GeV, 50% degrading +50 ps ToF)

Could be improved to 96%/96% by better detector/DAQ performance (20% degrading + 50 ps ToF)

CEPC-DocDB-id: 172
https://arxiv.org/abs/1803.05134
EPJC Accepted

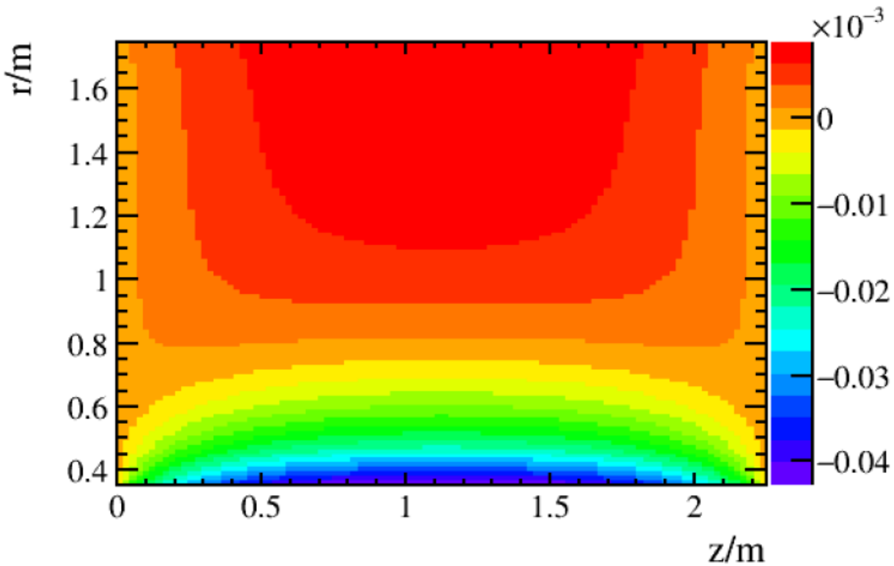
Feasibility of TPC at Z pole

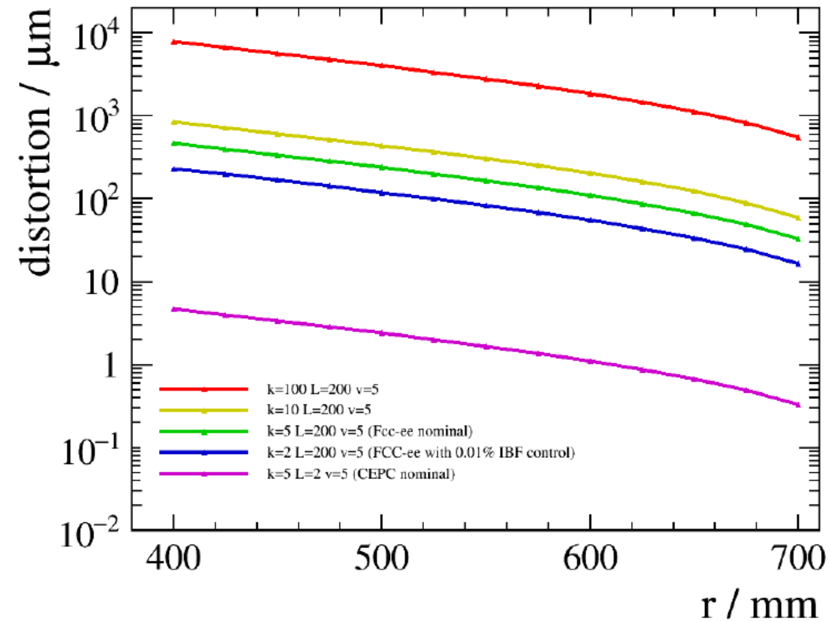




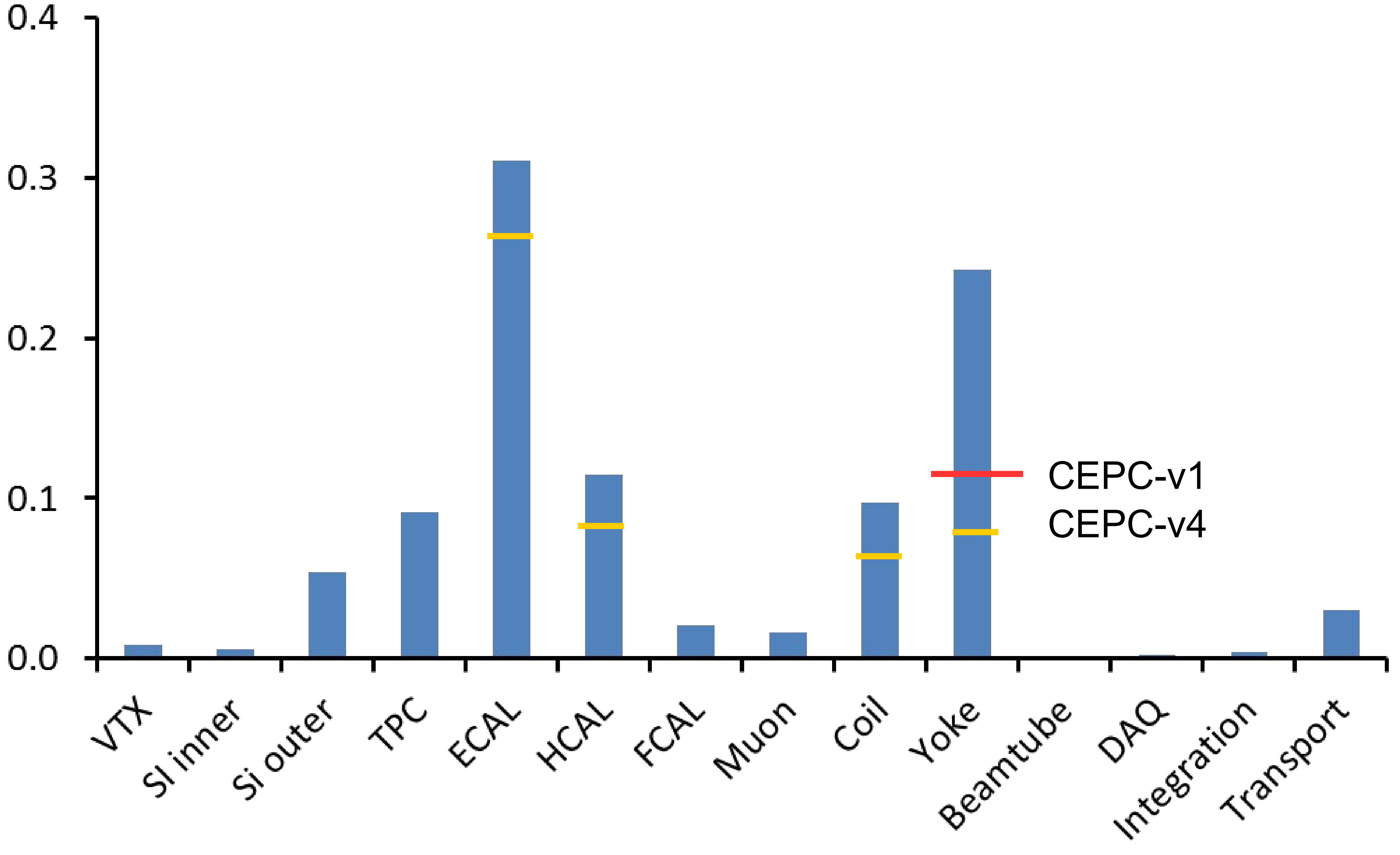
- 600 Ion Disks induced from Z->qq events at 2E34cm^{-2}s^{-1}
- Voxel occupancy & Charge distortion from **Ion Back Flow** (IBF)
- Cooperation with CEA & LCTPC

TPC Feasibility





- Conclusion (JINST_12_P07005, CEPC-DocDB-id-147):
  - Voxel occupancy ~ (10^-4 – 10^-6) level, safe
  - **Safe for CEPC If the ion back flow be controlled to per mille level** (k = 5) -
    - The charge distortion at ILD TPC would be one order of magnitude then the intrinsic resolution (L = 2E34 $cm^{-2}s^{-1}$)
    - TPC usage is not limited by the Physics Hits;
    - Beam background needs further investigation (a priori not the dominant source at Z pole)


0.4
0.3
0.2
0.1
0.0
CEPC-v1
CEPC-v4
VTX
SI inner
Si outer
TPC
ECAL
HCAL
FCAL
Muon
Coil
Yoke
Beamtube
DAQ
Integration
Transport