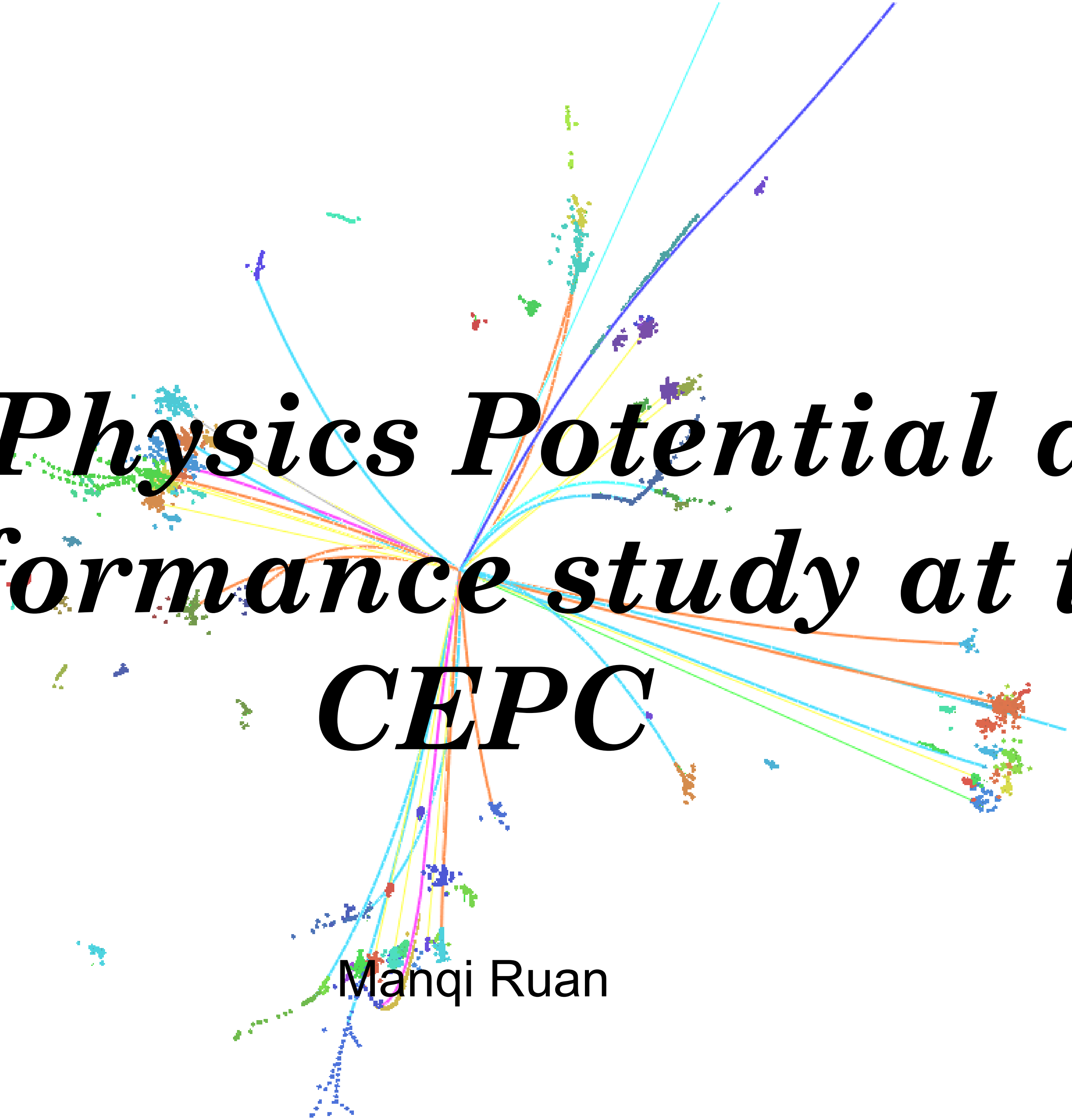
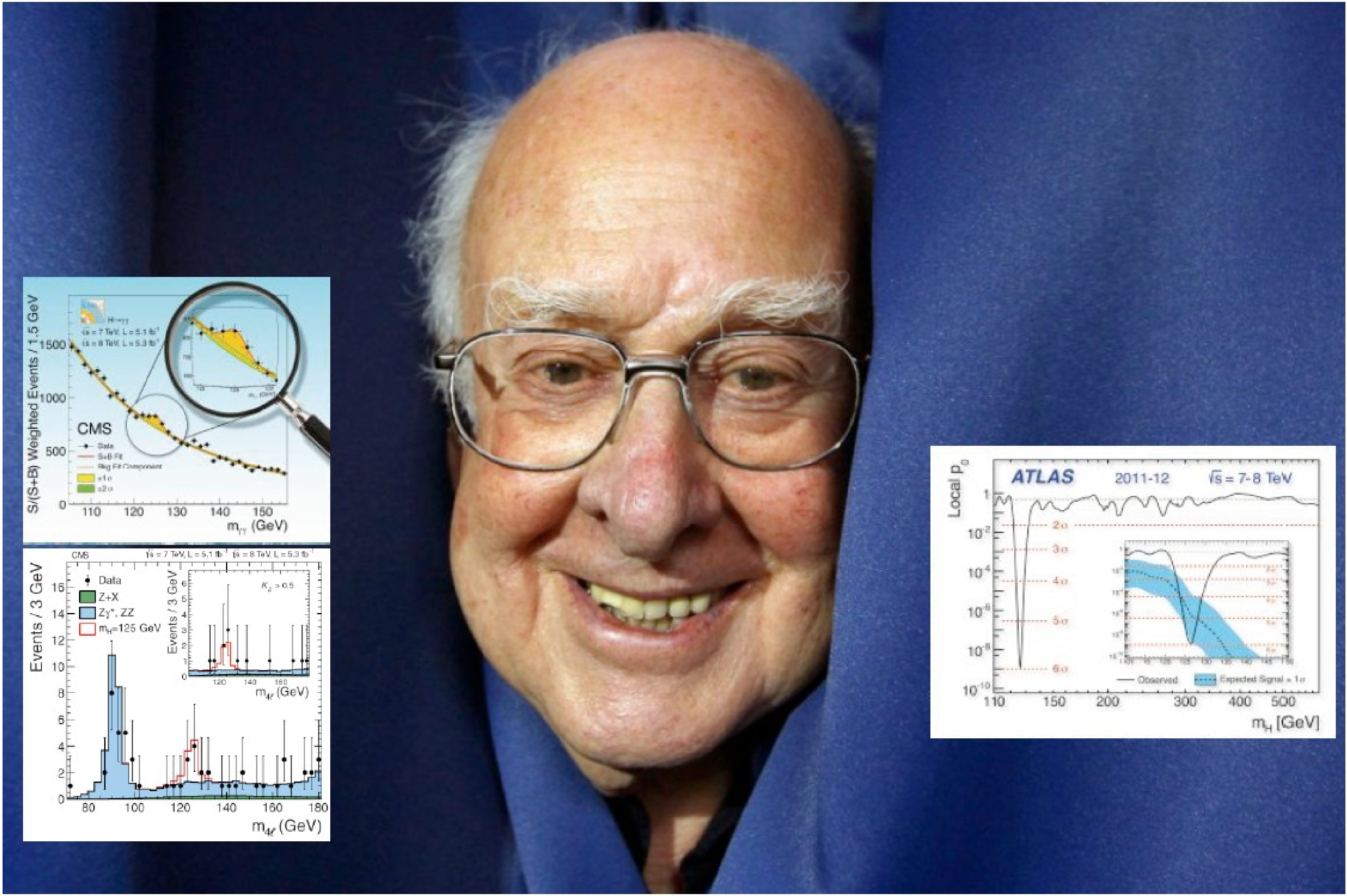


The Physics Potential and Performance study at the CEPC

Manqi Ruan



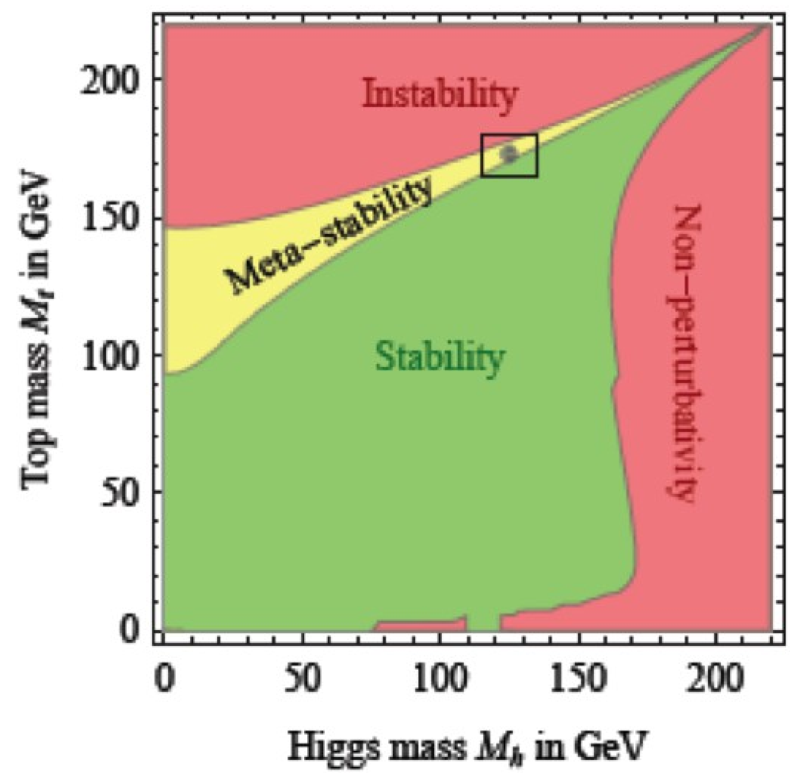
CMS
S/(S+B) Weighted Events / 1.5 GeV
Data
S+B Fit
Bkg Fit Component
$m_{\gamma\gamma}$ (GeV)
Events / 3 GeV
Data
Z+X
Zγ*, ZZ
m_H=125 GeV
$m_{4\ell}$ (GeV)
ATLAS
2011-12
$\sqrt{s}$ = 7-8 TeV
Local p_0
Observed
Expected Signal ± 1σ
m_H [GeV]

SM is **NOT** the end of story...

- Hierarchy: From neutrinos to the top mass, masses differs by 13 orders of magnitude
- Naturalness: Fine tuning of the Higgs mass
- Masses of Higgs and top quark: meta-stable of the vacuum
- Unification?
- Dark matter candidate?
- Not sufficient CP Violation for Matter & Antimatter asymmetry

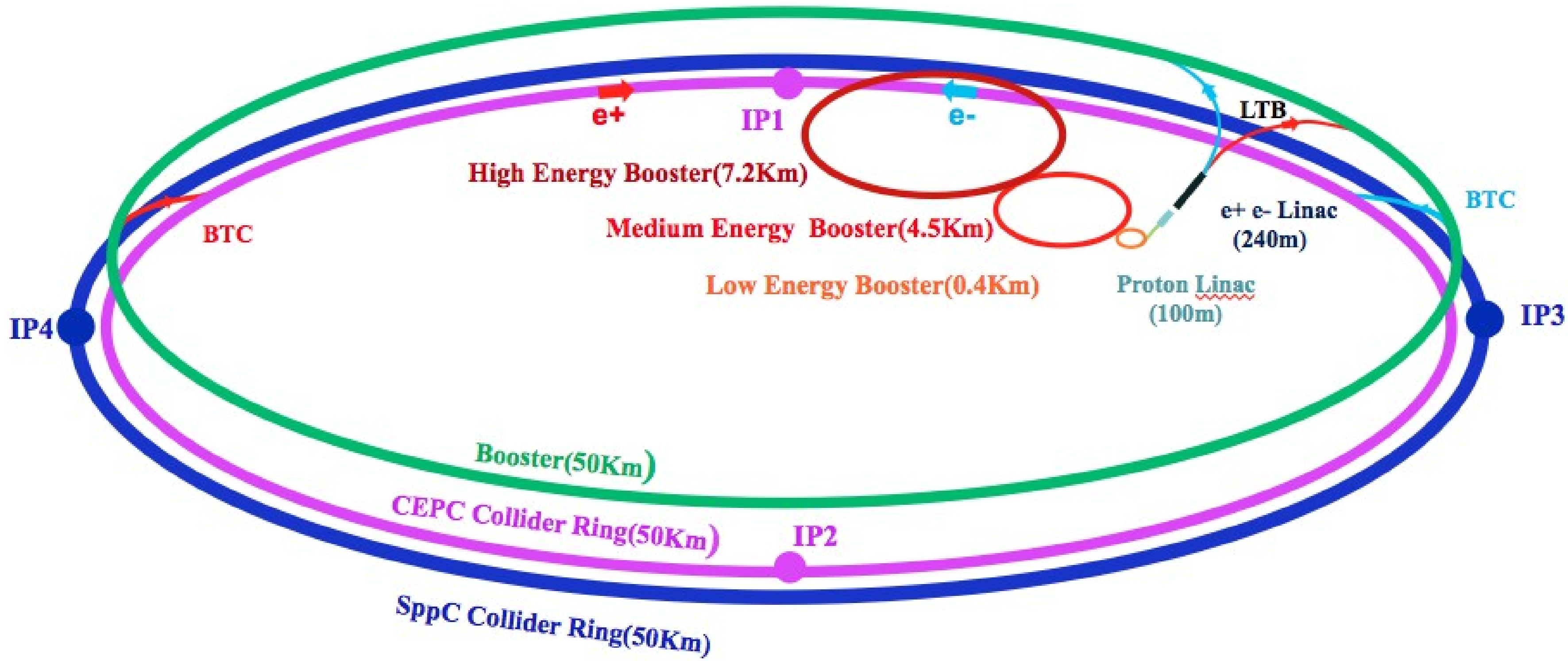
- **Most issues related to Higgs**

$$m_H^2 = 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}933{,}023$$
$$-36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}917{,}398$$
$$= (125\ \text{GeV})^2\ !\ ?$$



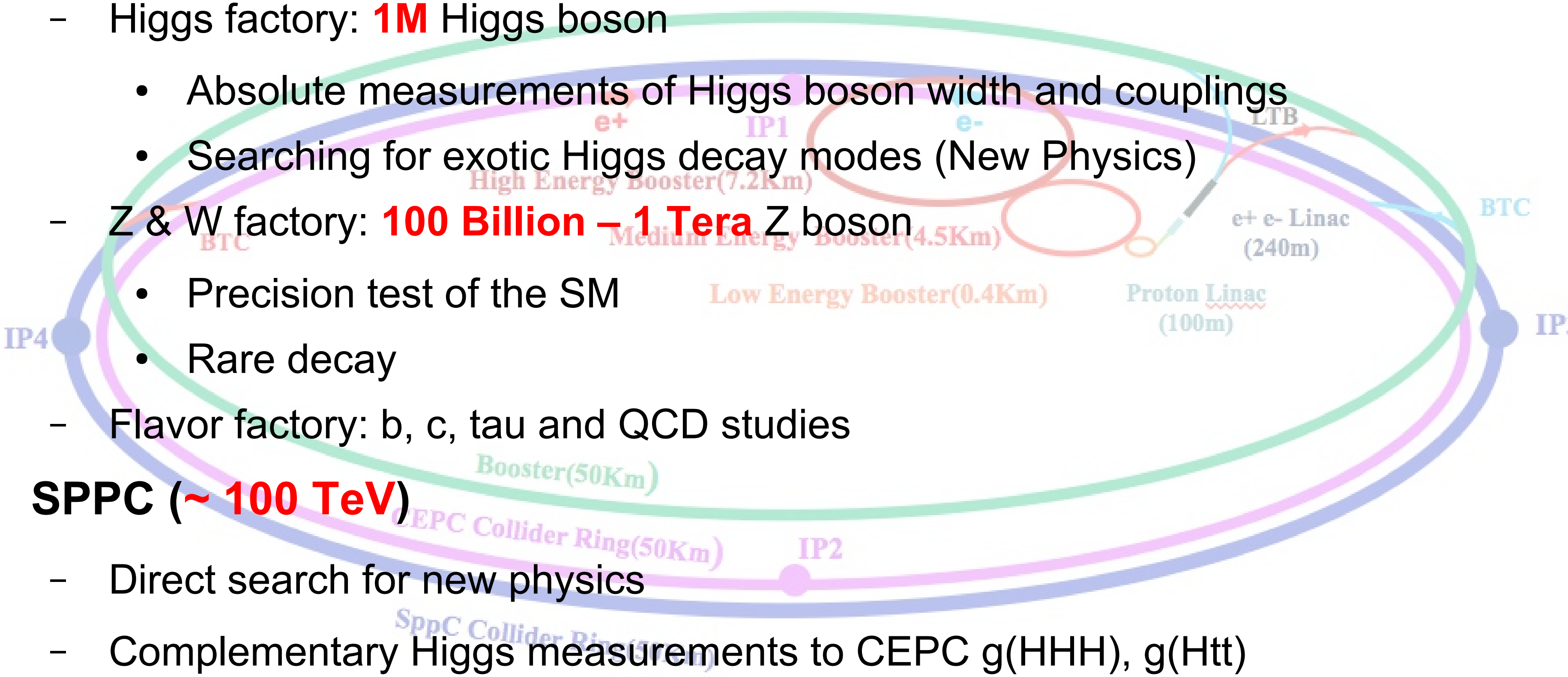
Key: a precise Higgs factory

- Higgs mass ~ 125 GeV, it is possible to build a Circular e+e- Higgs factory (CEPC), followed by a proton collider (SPPC) in the same tunnel
- Looking for Hints (from Higgs) at CEPC → direct search at SPPC



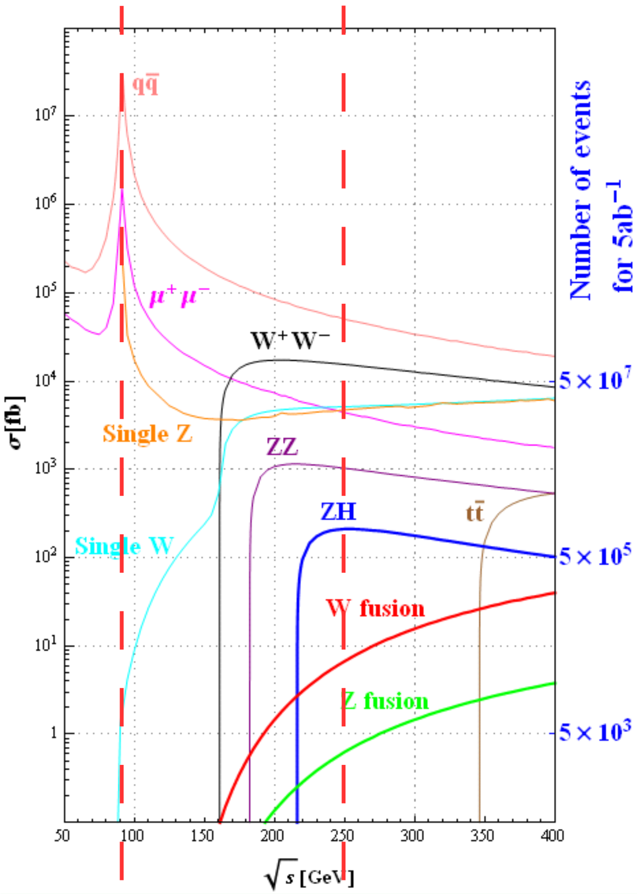
Science at CEPC-SPPC

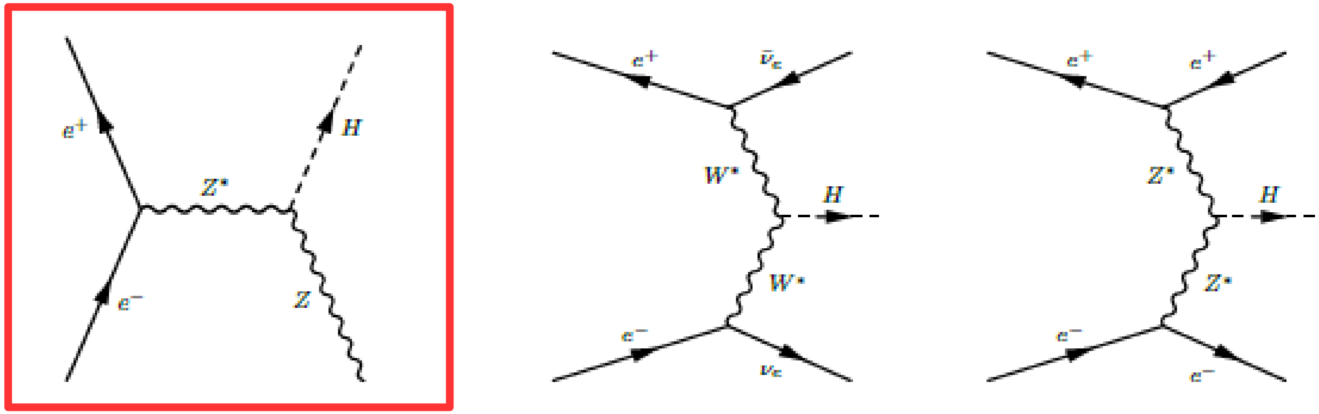
- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **100 Billion – 1 Tera** Z boson
    - Precision test of the SM
    - Rare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





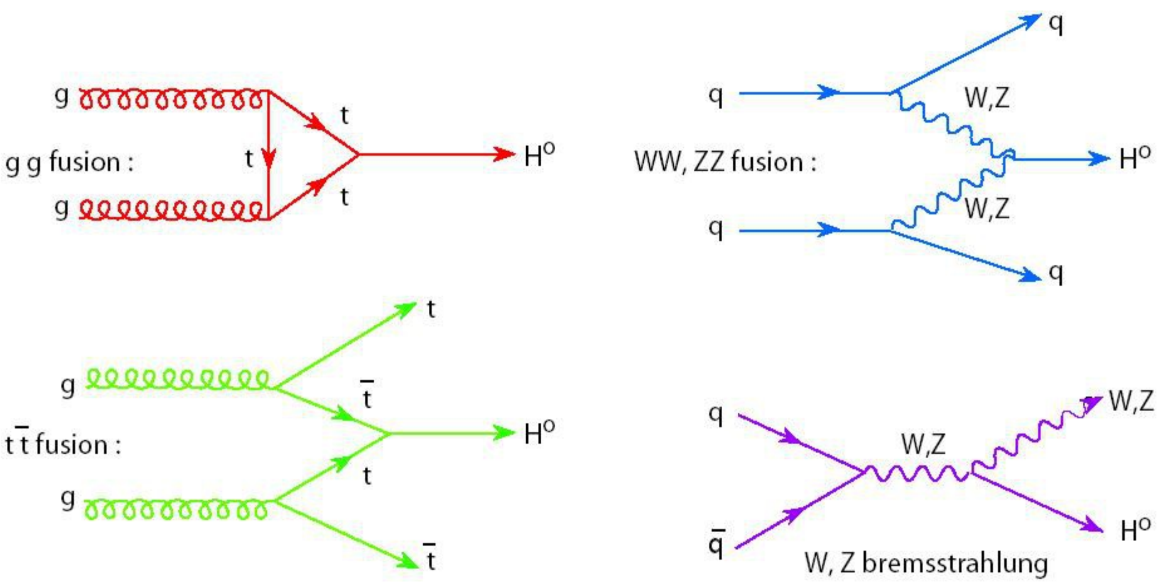
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

S/B ~ 1:100 - 1000

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

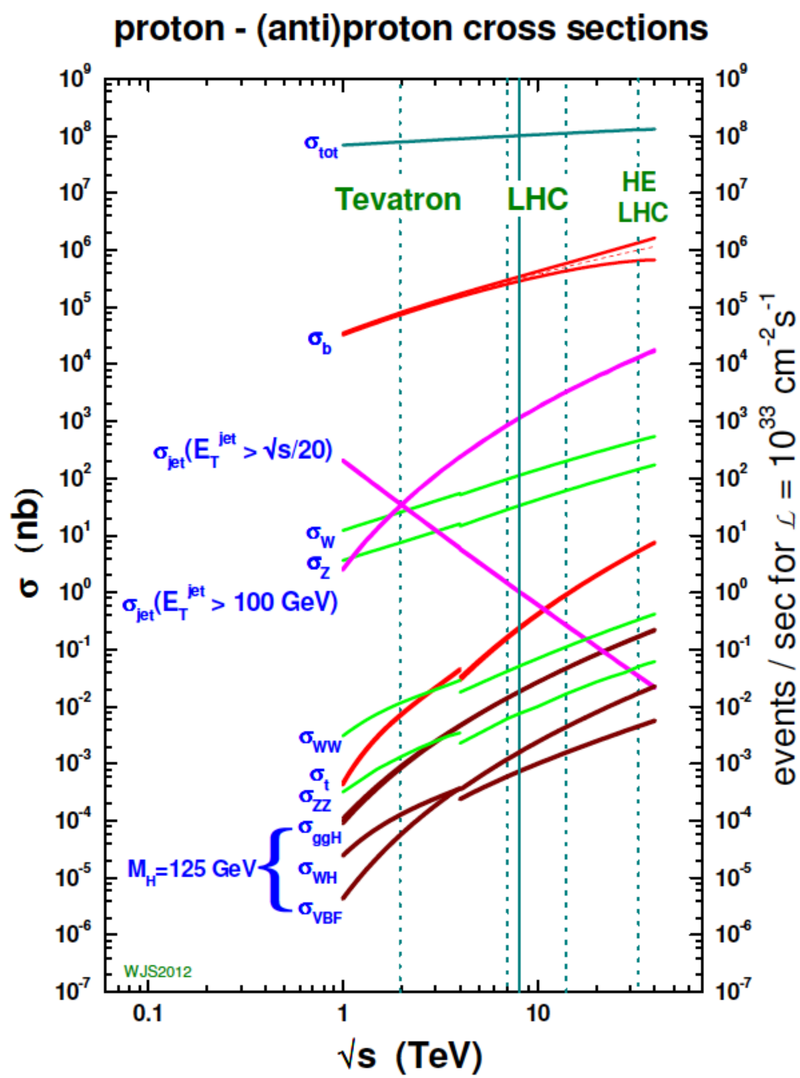
Derive: Absolute Higgs width, branching ratios, couplings

Higgs @ LHC

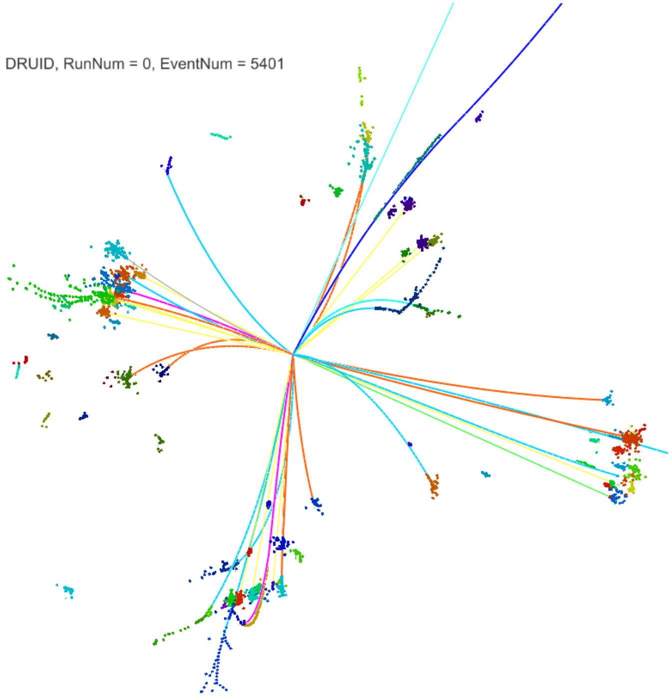


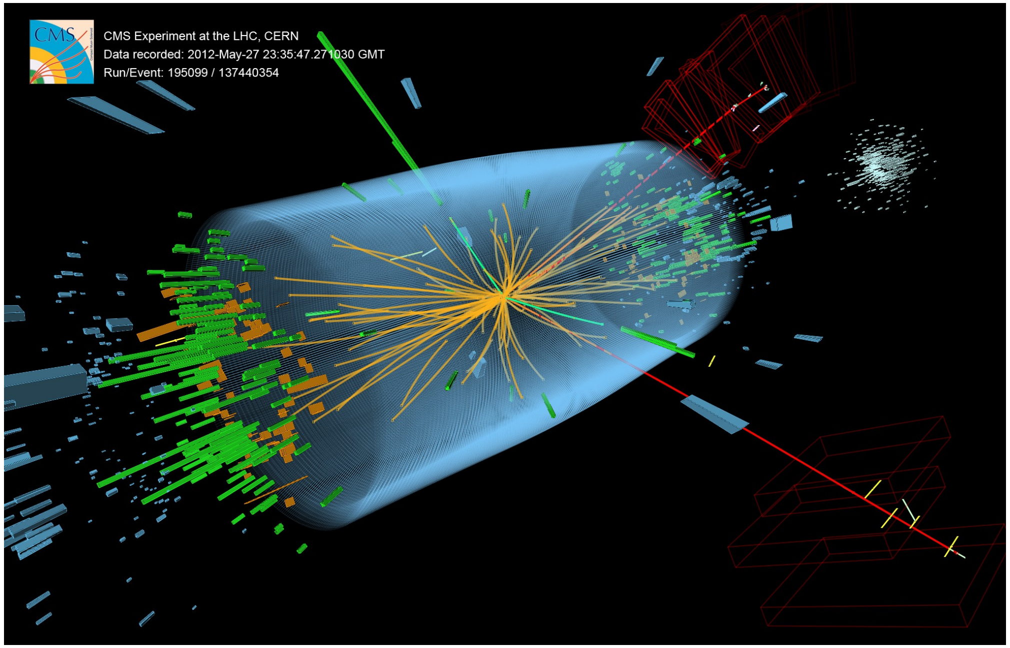
S/B ~ 1:1E10 !!!

$$\sigma(AA \to H \to BB) \sim g^2(HAA)g^2(HBB)/\Gamma_{total}$$



Higgs measurement at e+e- & pp

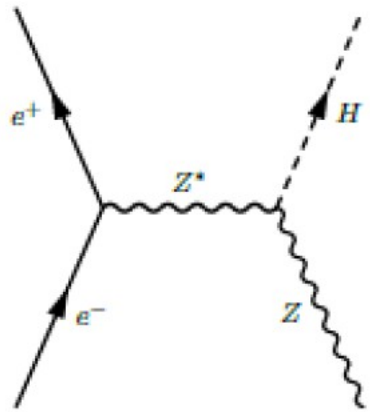


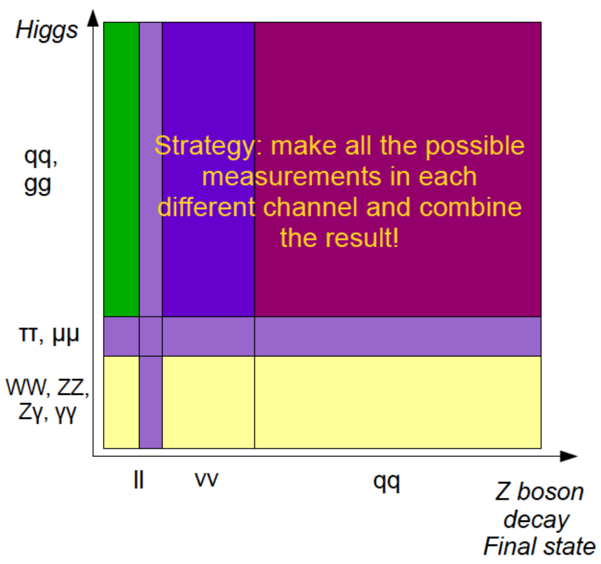


	Yield	efficiency	Comments
LHC	Run 1: 10^6 Run 2/HL: $10^{7\text{-}8}$	$\sim o(10^{-3})$	High Productivity & High background, Relative Measurements, Limited access to width, exotic ratio, etc, Direct access to g(ttH), and even g(HHH)
CEPC	10^6	$\sim o(1)$	Clean environment & Absolute measurement, Percentage level accuracy of Higgs width & Couplings

Complementary

Principle of the detector design

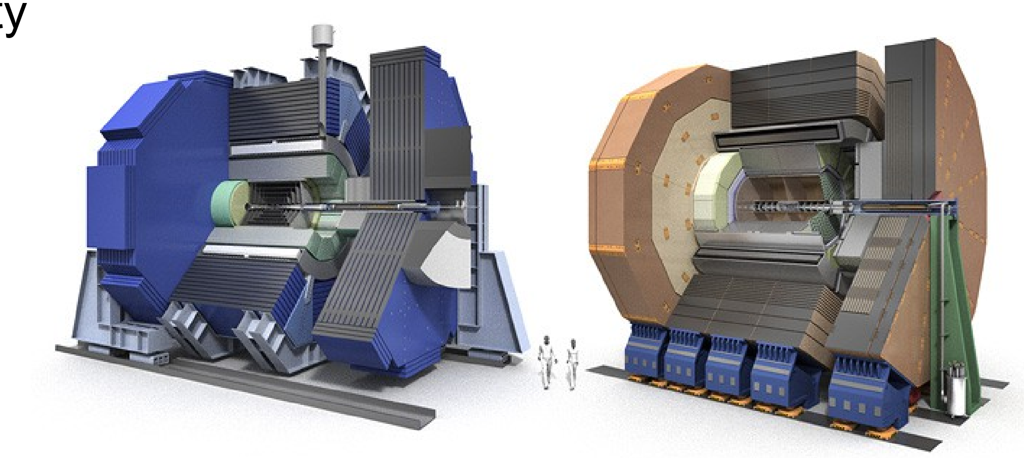




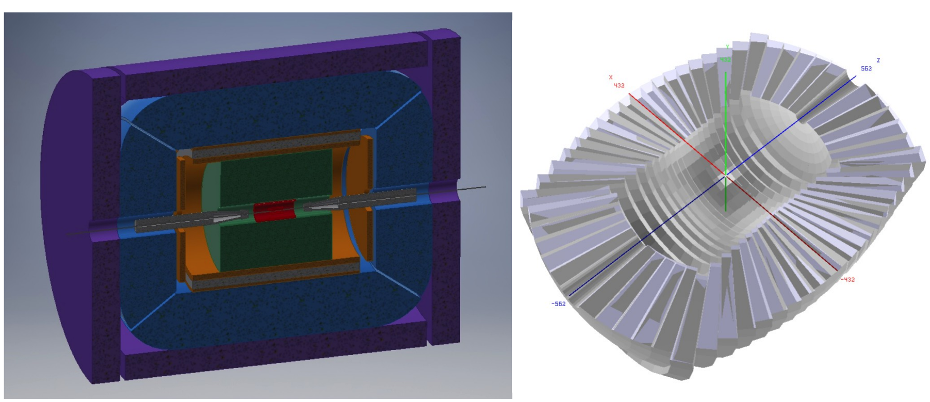
- Performance: Precisely reconstruct all the physics objects:
  - lepton, photon, tau, Jet, MET, Jet Flavor-Charge, and Charged Kaon
- Technical: Operational & Tolerable systematic uncertainty
  - Stability, Homogeneity, Robustness, Cost, Integration, In-situ monitoring
- Minimal requirements:
  - Lepton recoil at llH
  - Jet recoil at qqH
- Essential for the Higgs model-independent analysis, especially, the Higgs inclusive cross section, the Higgs width, the Higgs invisible, Higgs exotic...

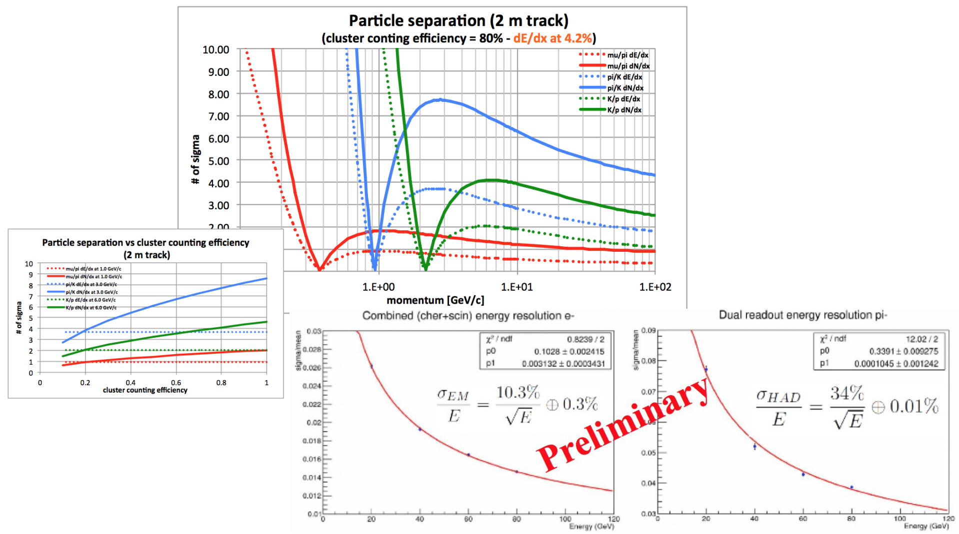
Two classes of Detector Concepts

- 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

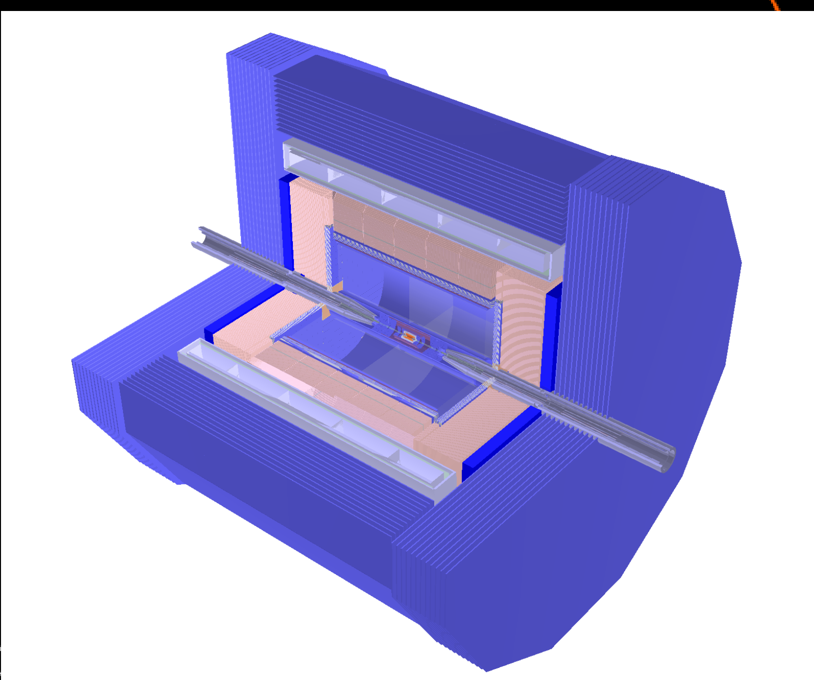


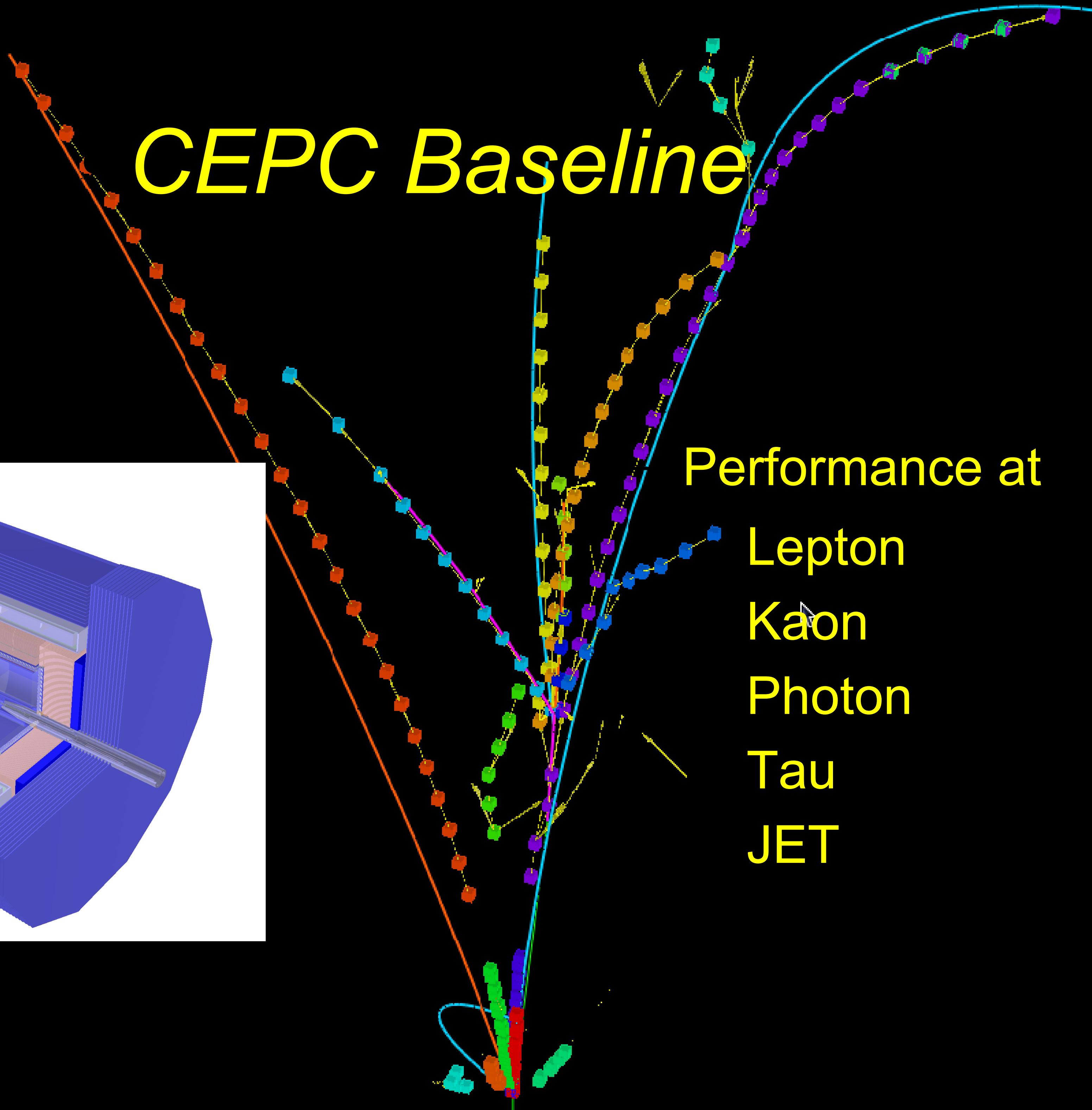


https://indico.ihep.ac.cn/event/6618/

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

CEPC Baseline

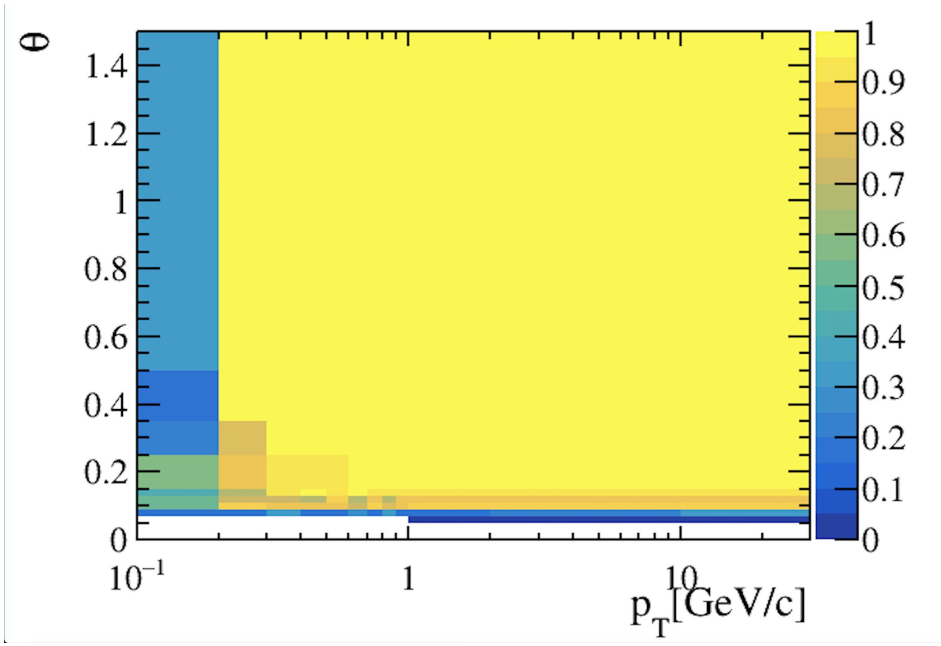


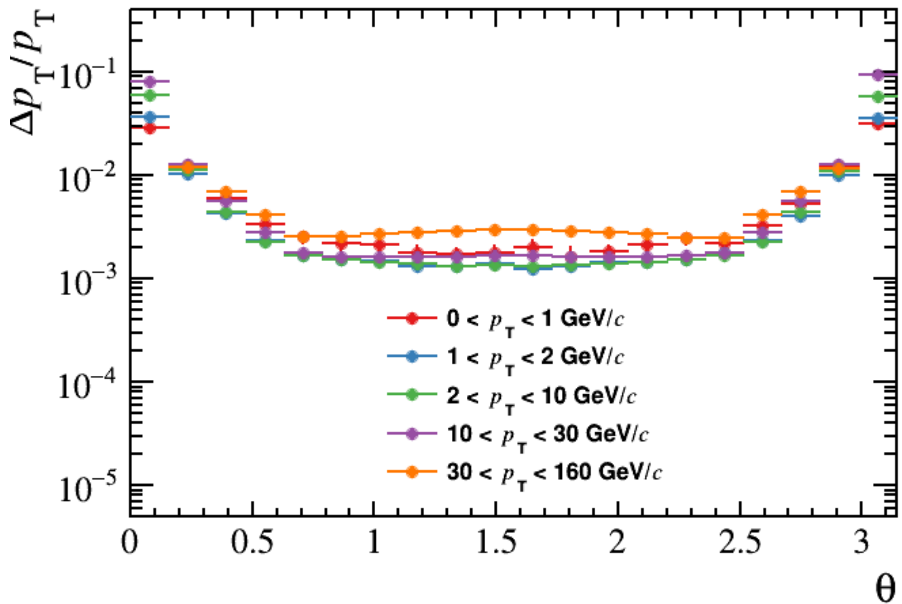


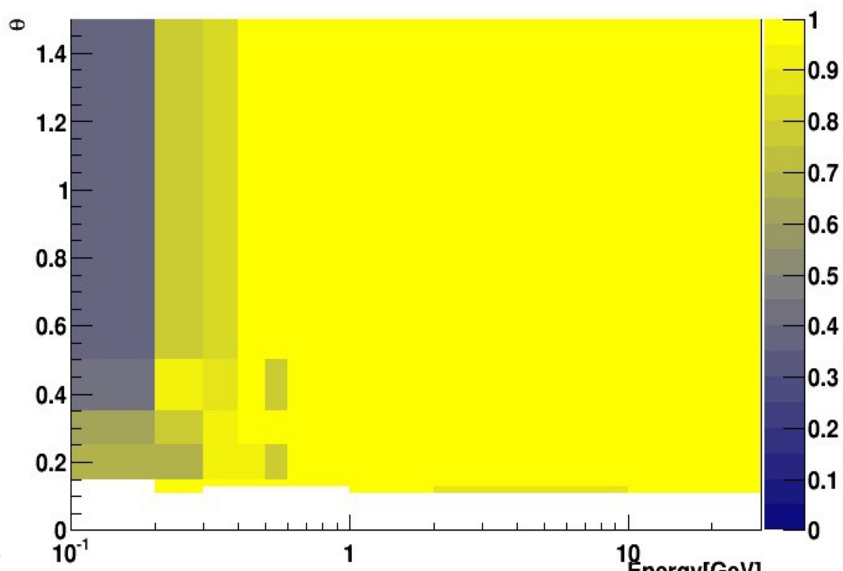
Performance at

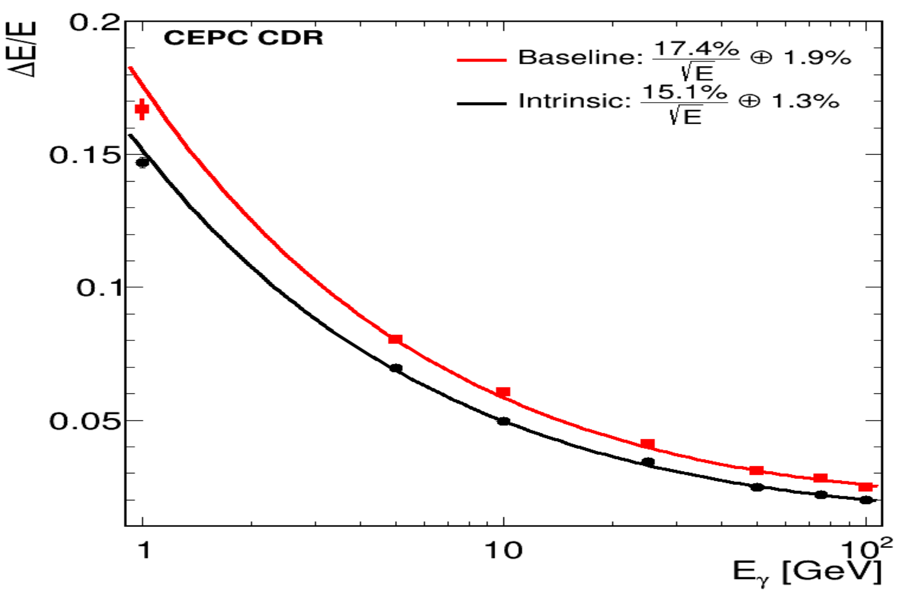
- Lepton
- Kaon
- Photon
- Tau
- JET

Tracking & ECAL



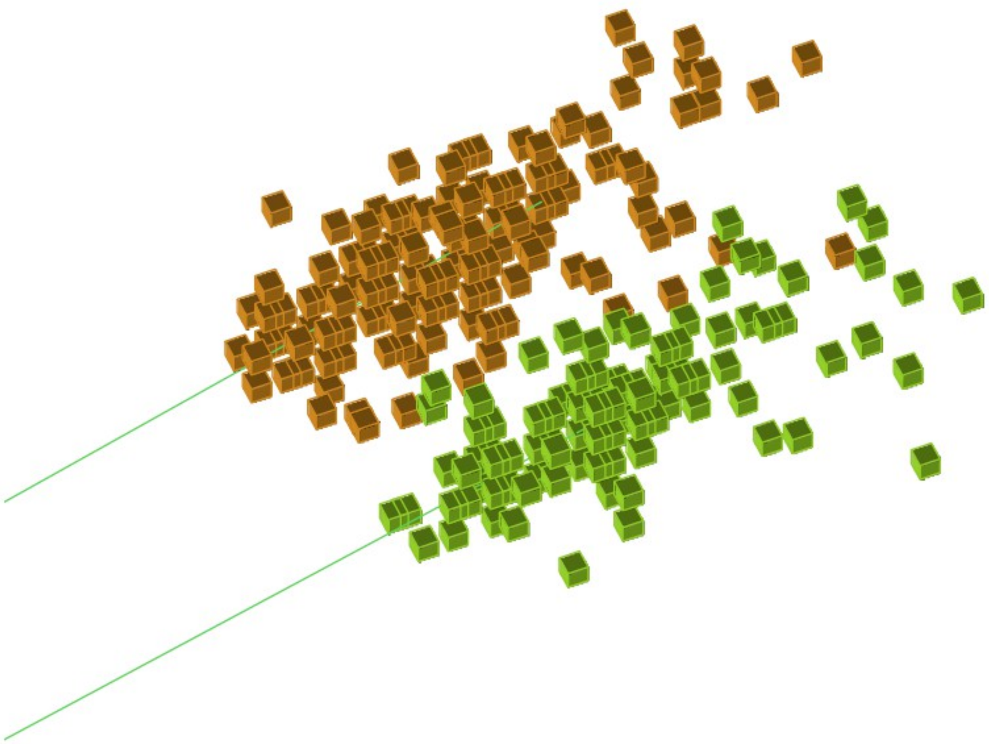


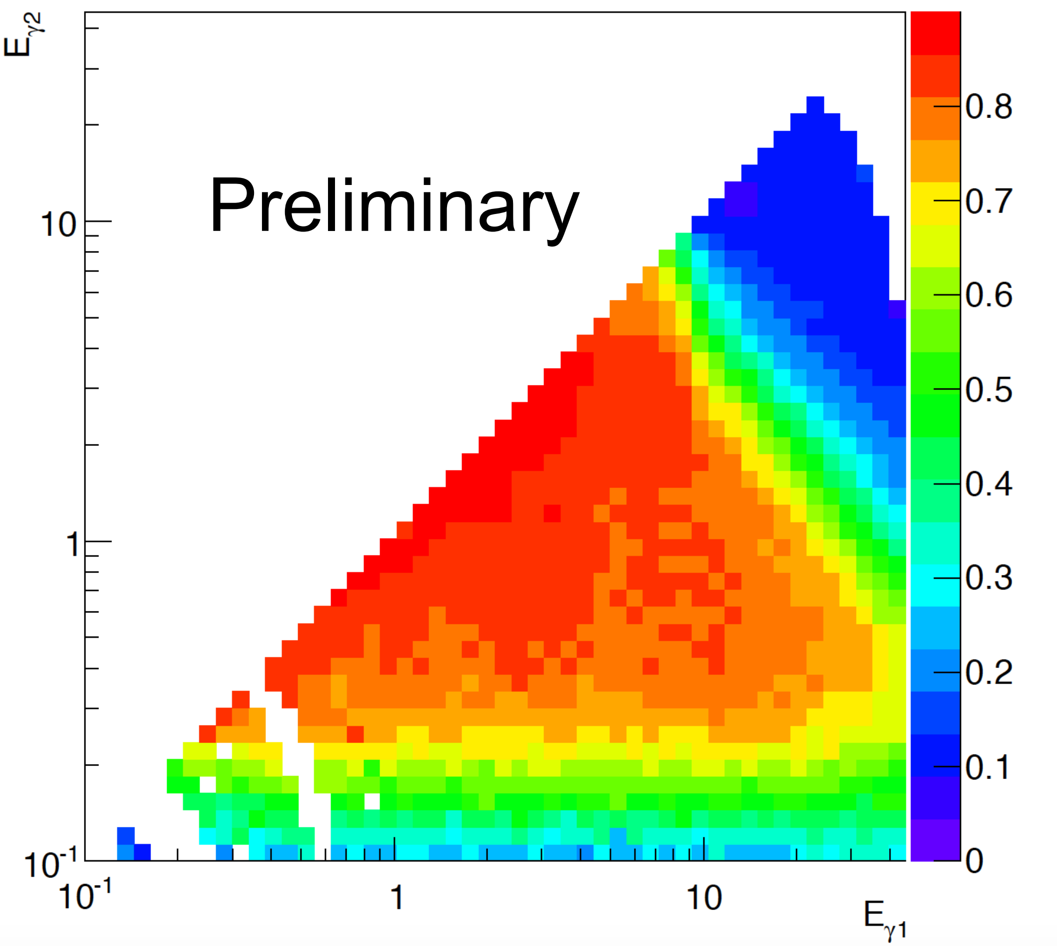




19 itte

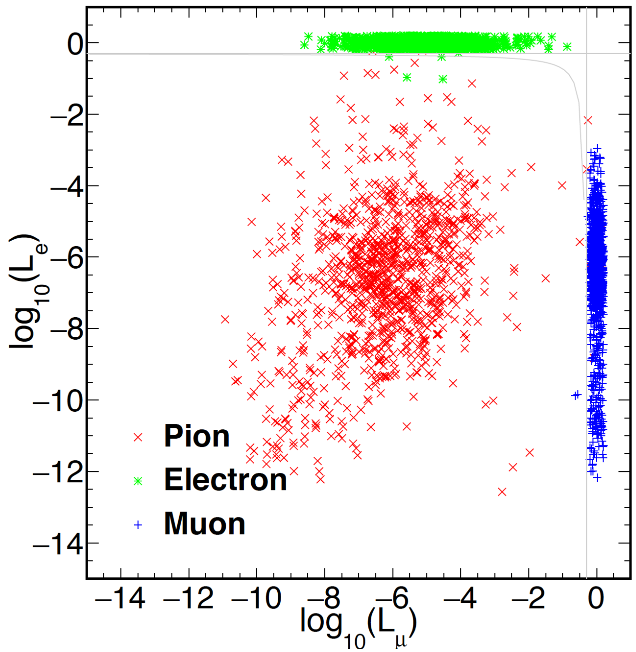
Clustering - Separation

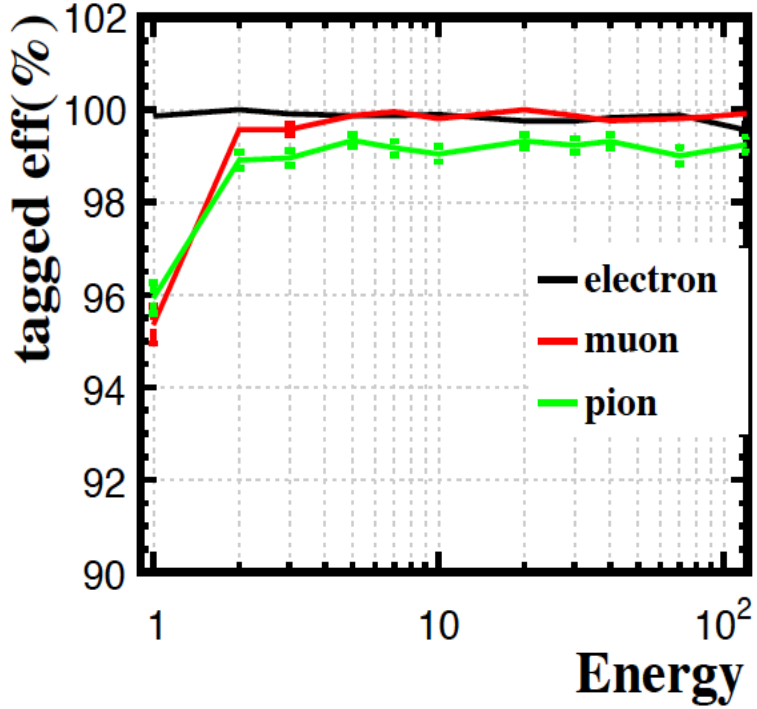


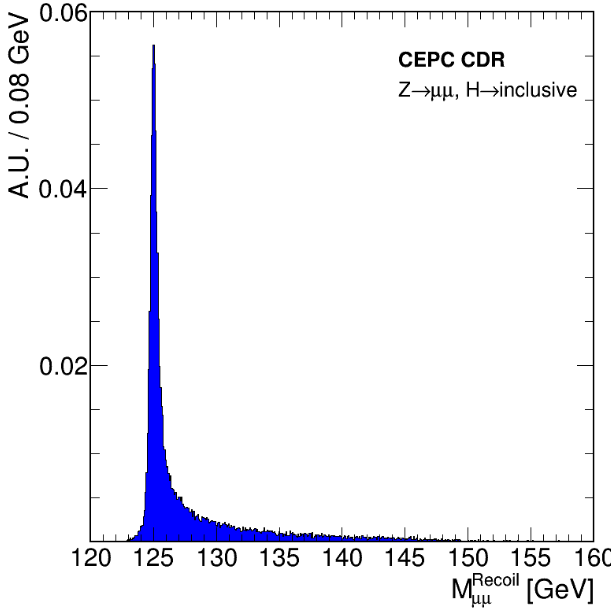


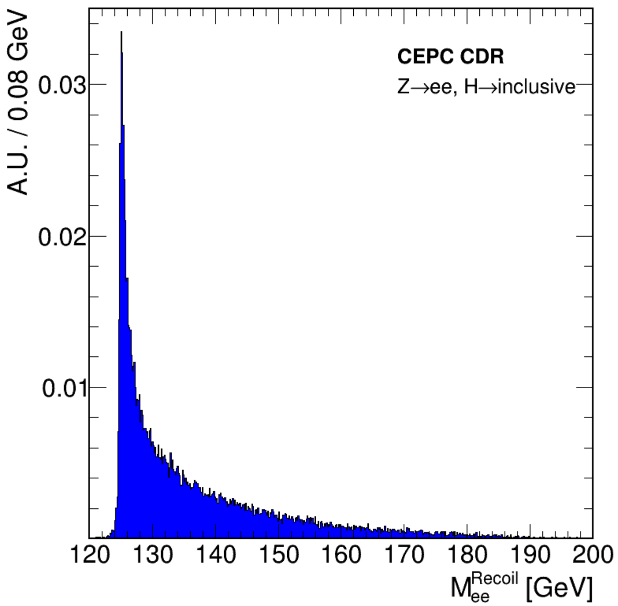
π_0 reconstruction efficiency

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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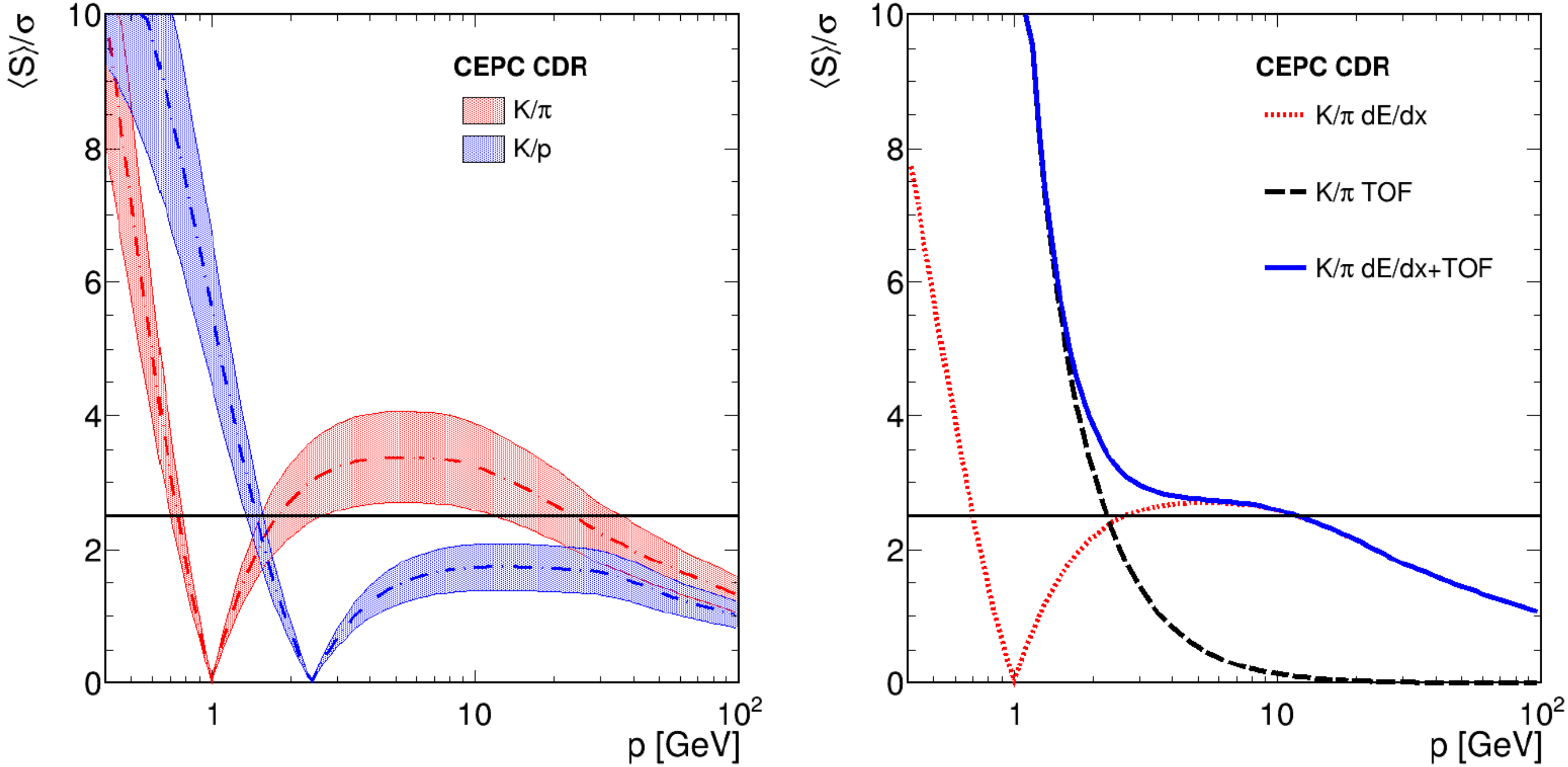
Kaon



Highly appreciated in flavor physics @ CEPC Z pole

TPC dEdx + ToF of 50 ps

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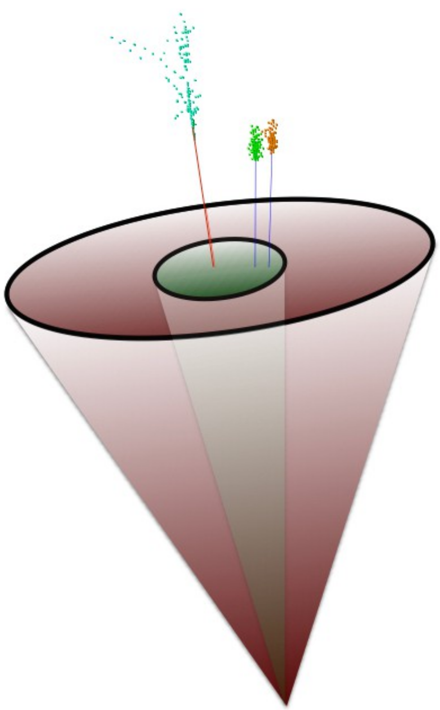
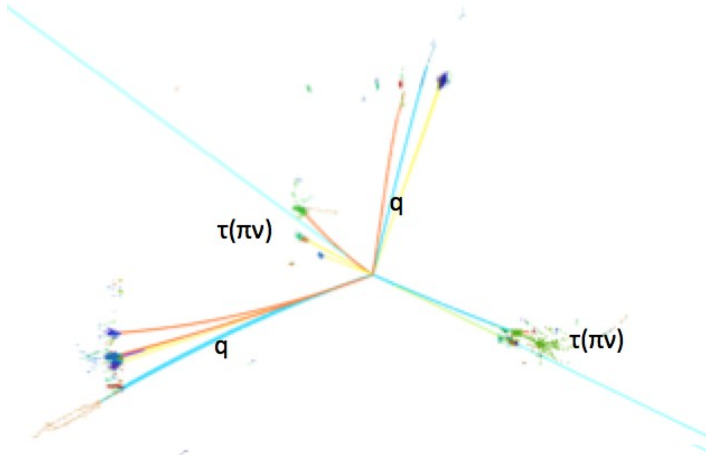
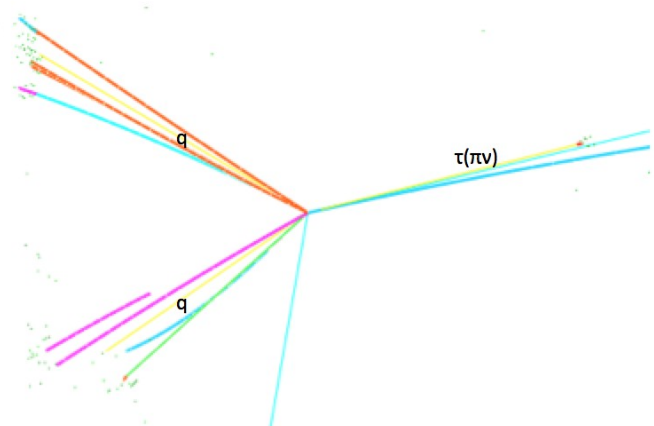
At inclusive Z pole sample:

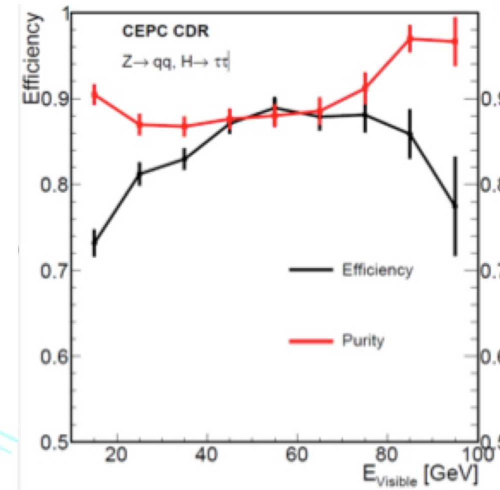
- Conservative estimation gives efficiency/purity of 91%/94% (2-20 GeV, 50% degrading +50 ps ToF)
- Could be improved to 96%/96% by better detector/DAQ performance (20% degrading + 50 ps ToF)

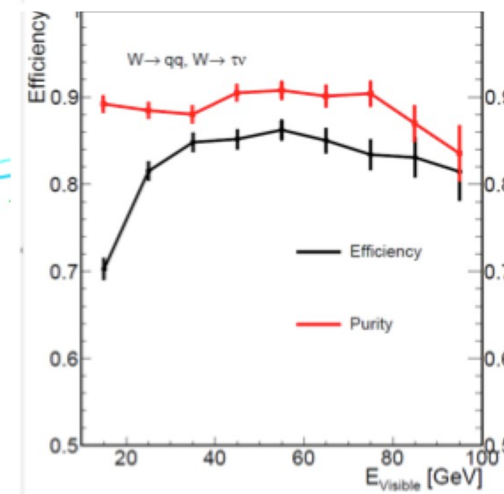
Tau finding at hadronic events







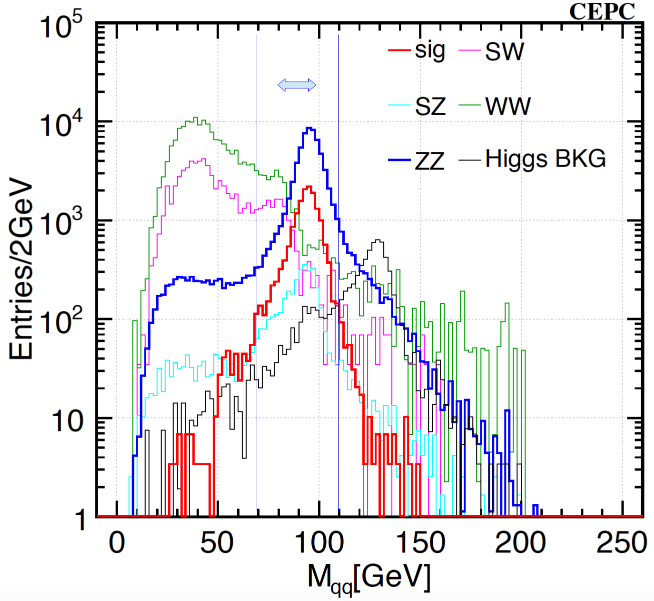


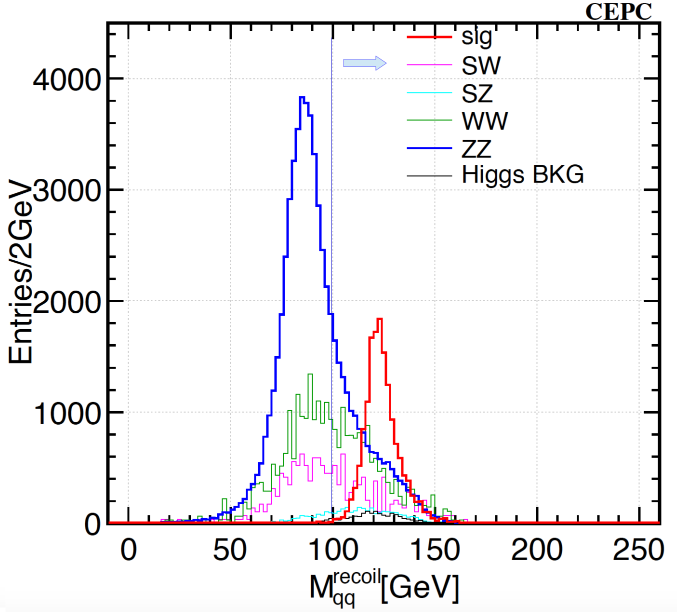


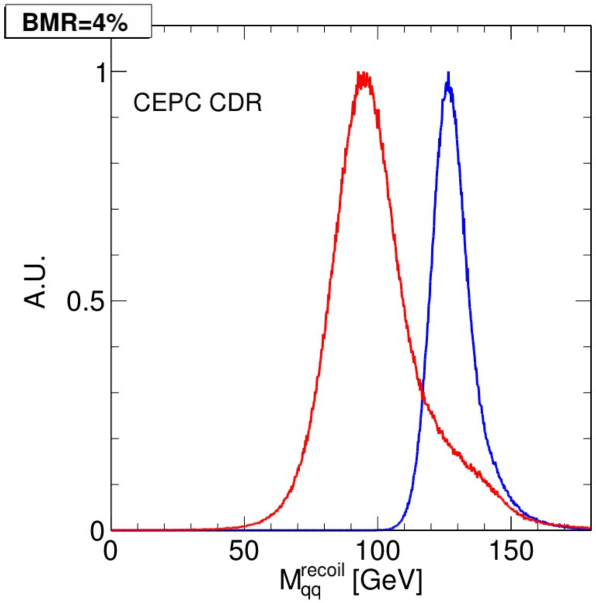
TAURUS (Tau ReconstrUction toolS):
an overall efficiency*purity higher than 70% is achieved for qqττ, and qqτν events

Zhigang Wu, CEPC CDR

An Analysis Example: *g(Hττ)* at qqH



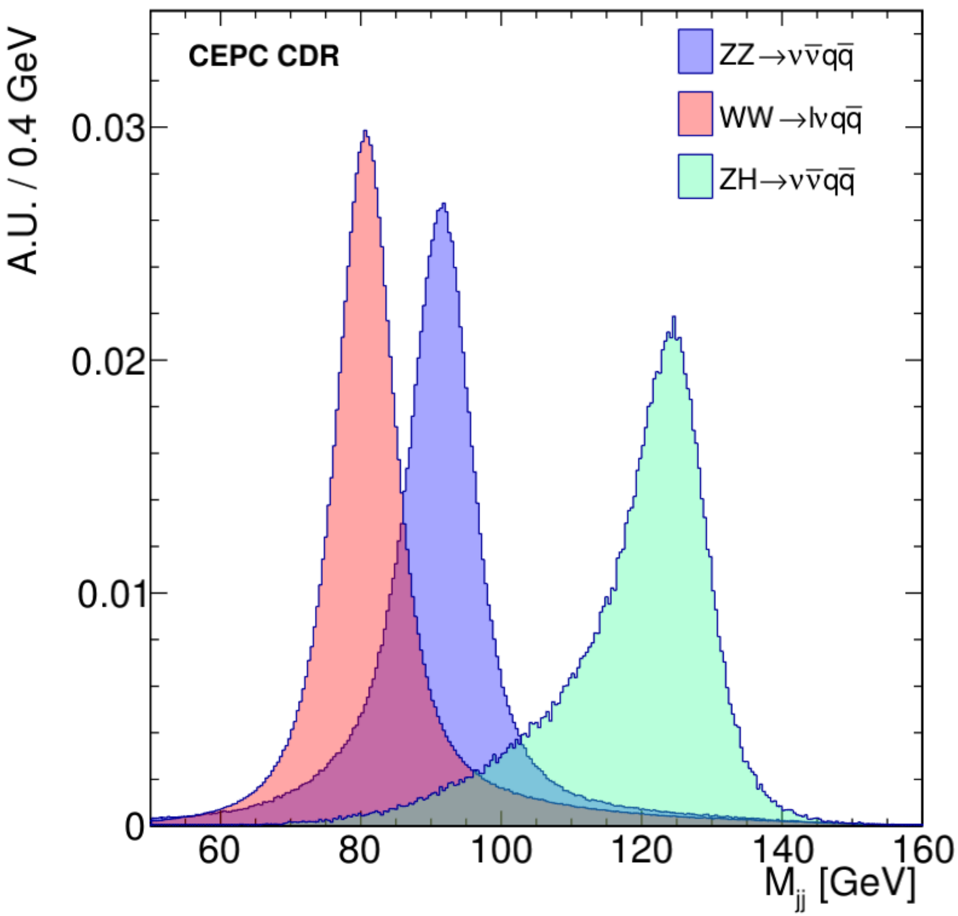


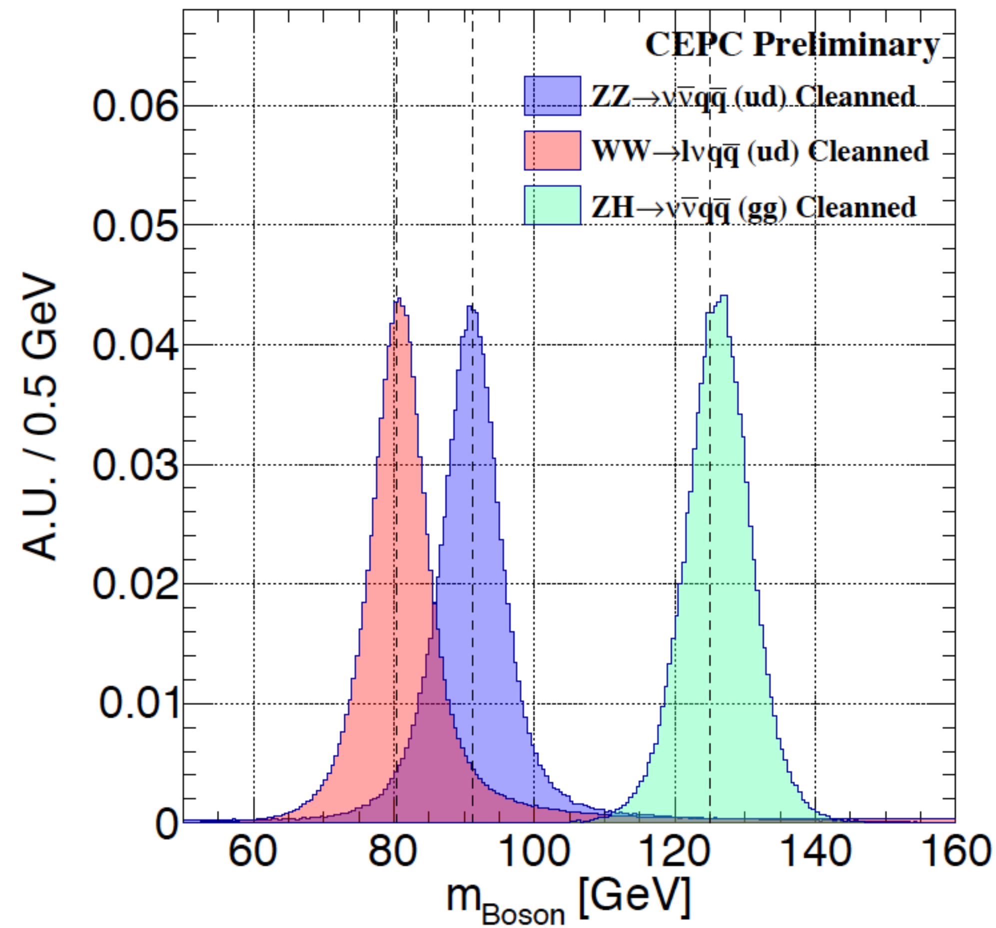


- TAURUS: di-tau system
- The rest particles are identified as the di-jet: to distinguish the ZZ/ZH background & Improves the accuracy by more than a factor of 2: **BMR < 4% (baseline of 3.8%) is crucial**
- Isolated tracks are intensionally defined as tau candidate: be distinguished by the VTX

Dan Yu's thesis

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),

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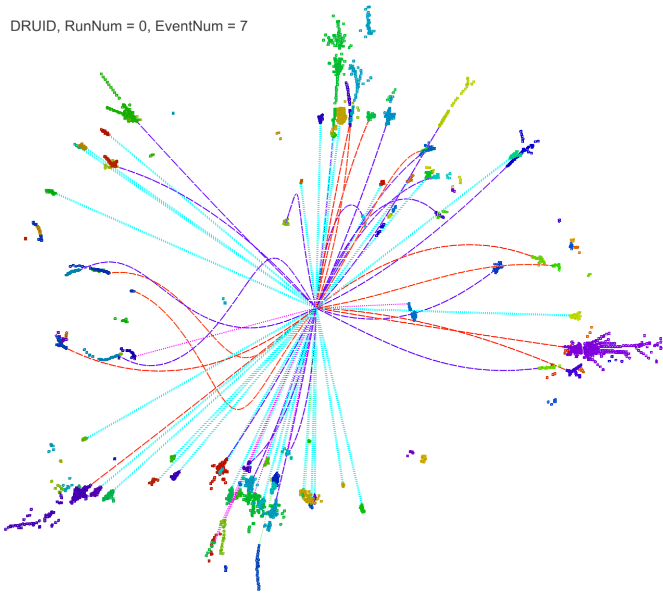
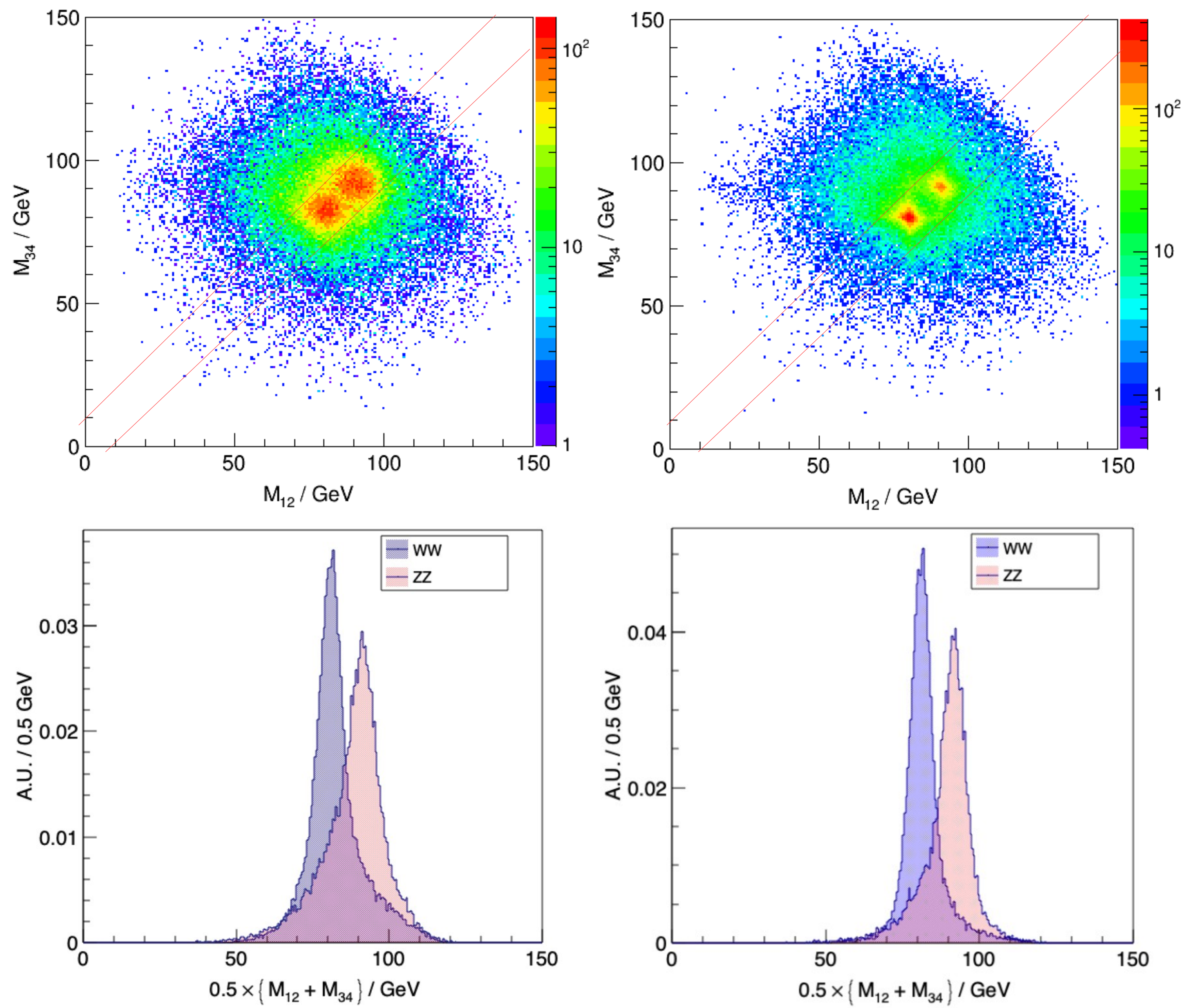
Separation at full hadronic WW-ZZ events





Separation performance dominated by the identification of color-singlet:

Jet Clustering & Matching algorithm

Physics Objects

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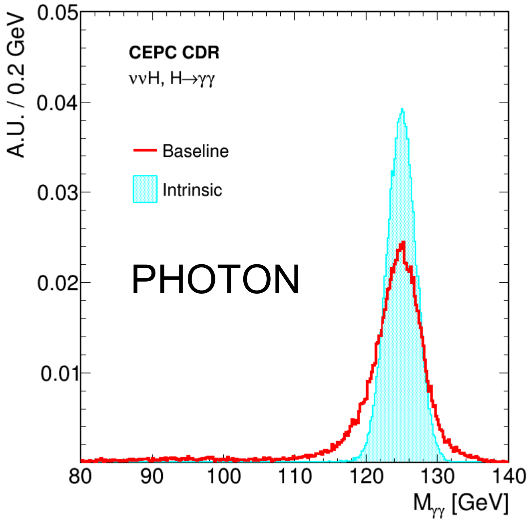

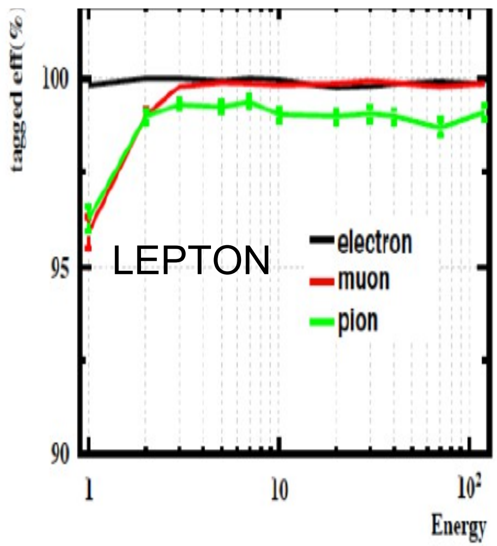

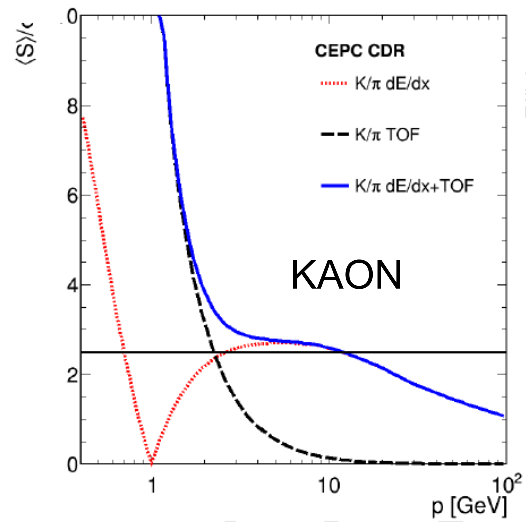

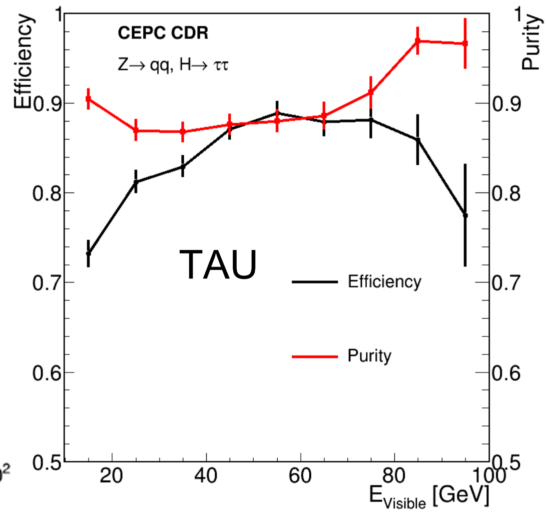

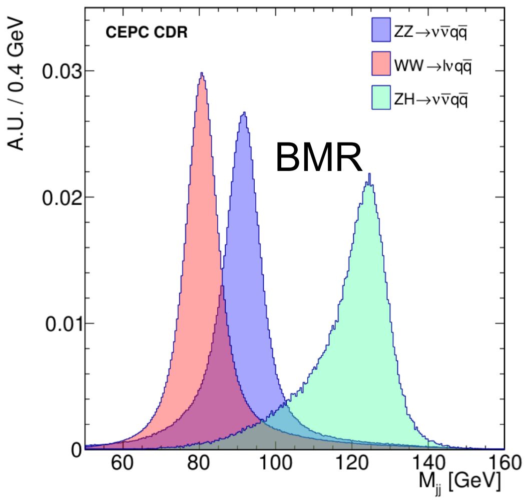

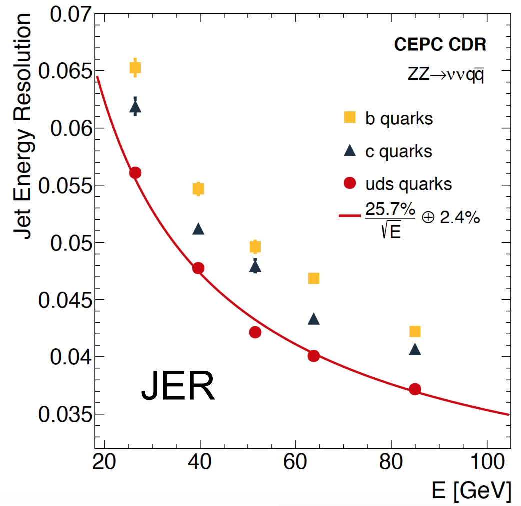

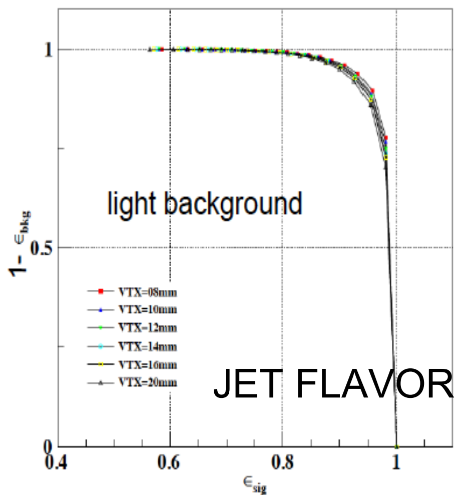

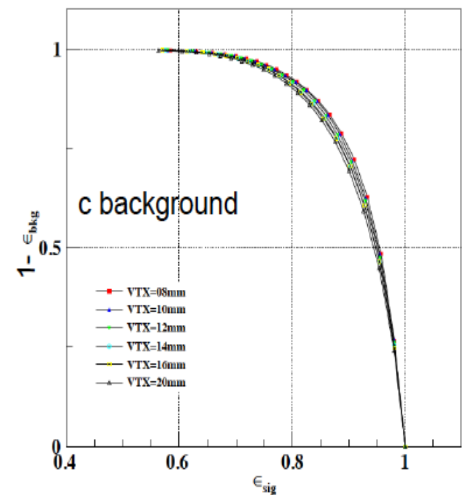

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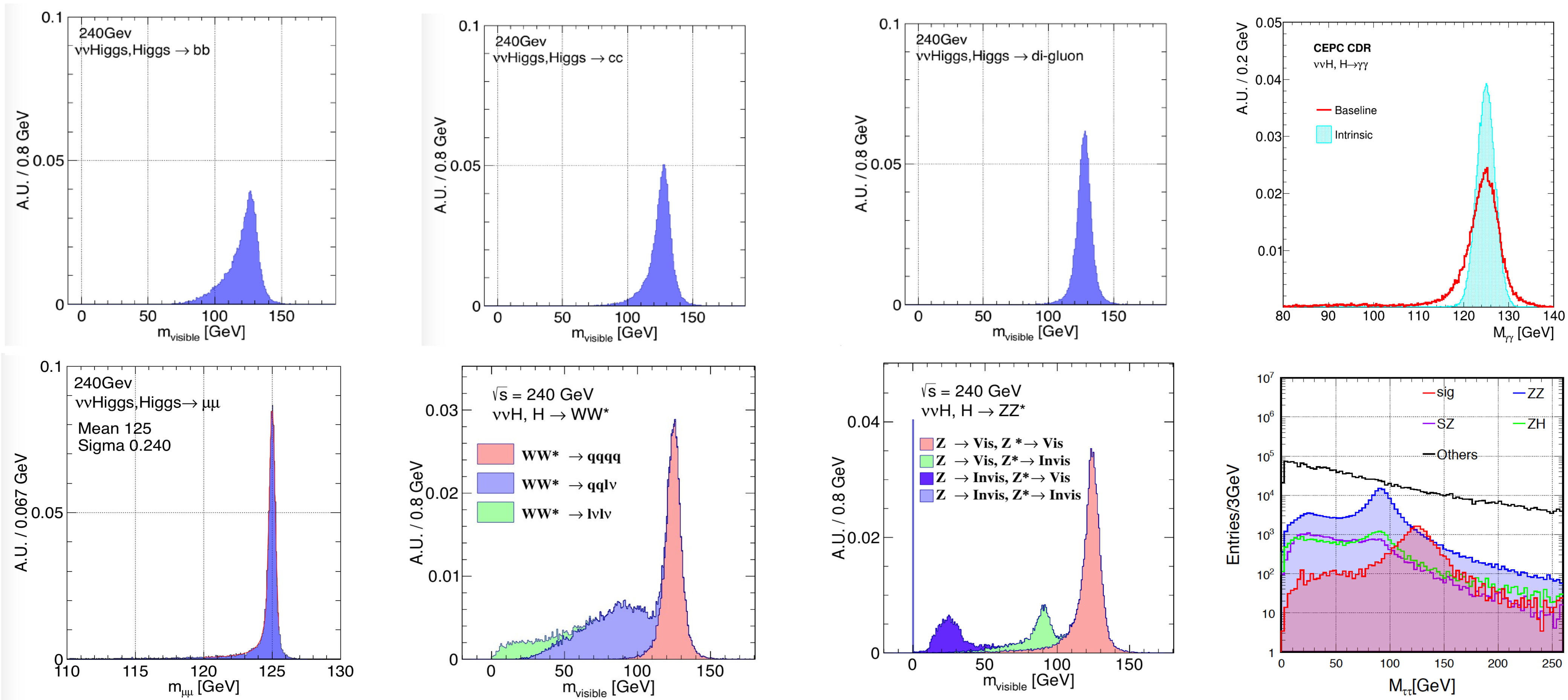
Higgs Signals



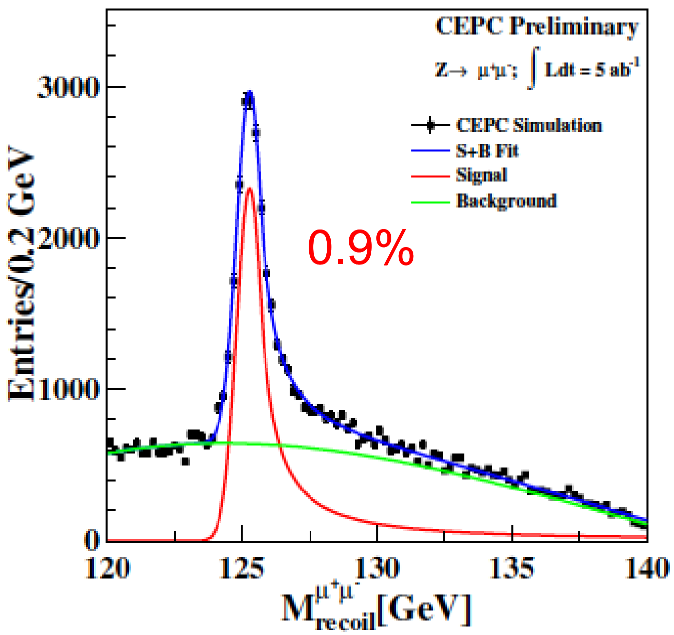
Clear Higgs Signature in all SM decay modes

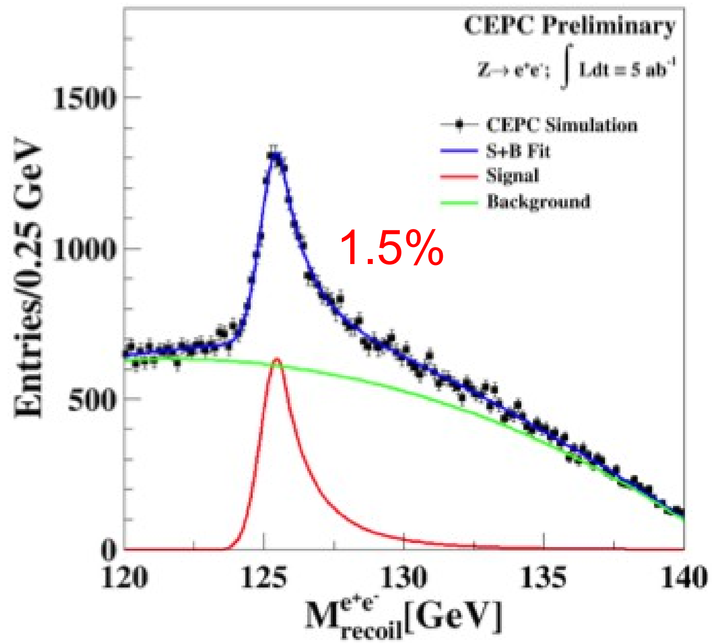
Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

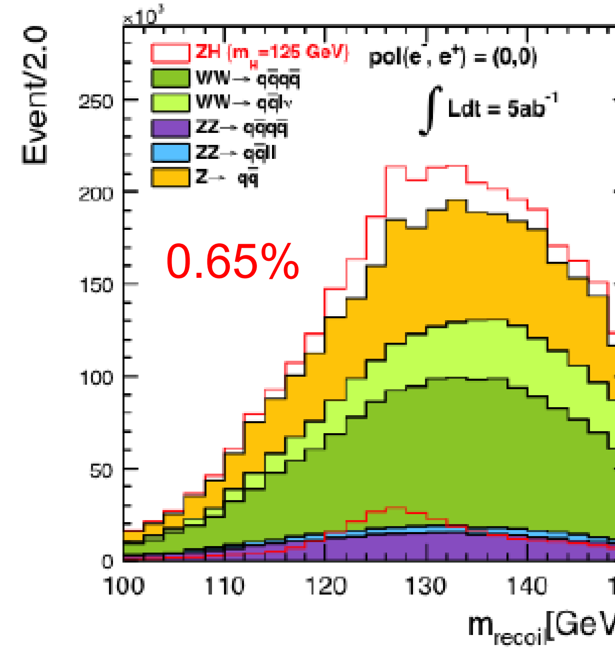
Right corner: di-tau mass distribution at qqH events using collinear approximation

Model-independent measurement of σ(ZH)

Zhenxing Chen & Yacine Haddad



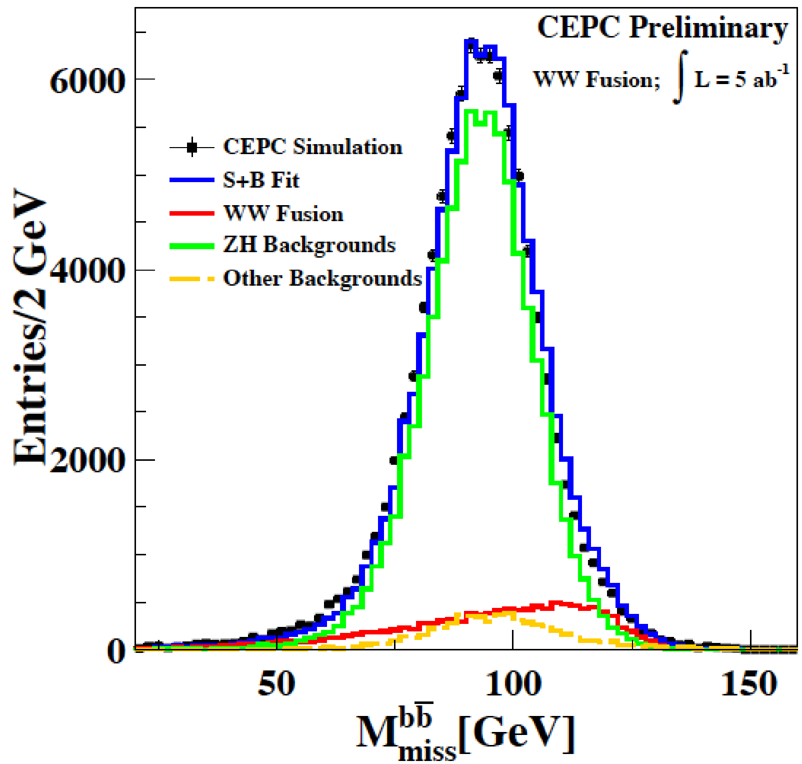




- Recoil mass measurement: Combined precision:
  δσ(ZH)/σ(ZH) = 0.5% - δg(HZZ)/g(HZZ) = 0.25%

Higgs width measurement

- $g^2(HXX) \sim \Gamma_{H\to XX} = \Gamma_{total}{*}Br(H\to XX)$
- 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)

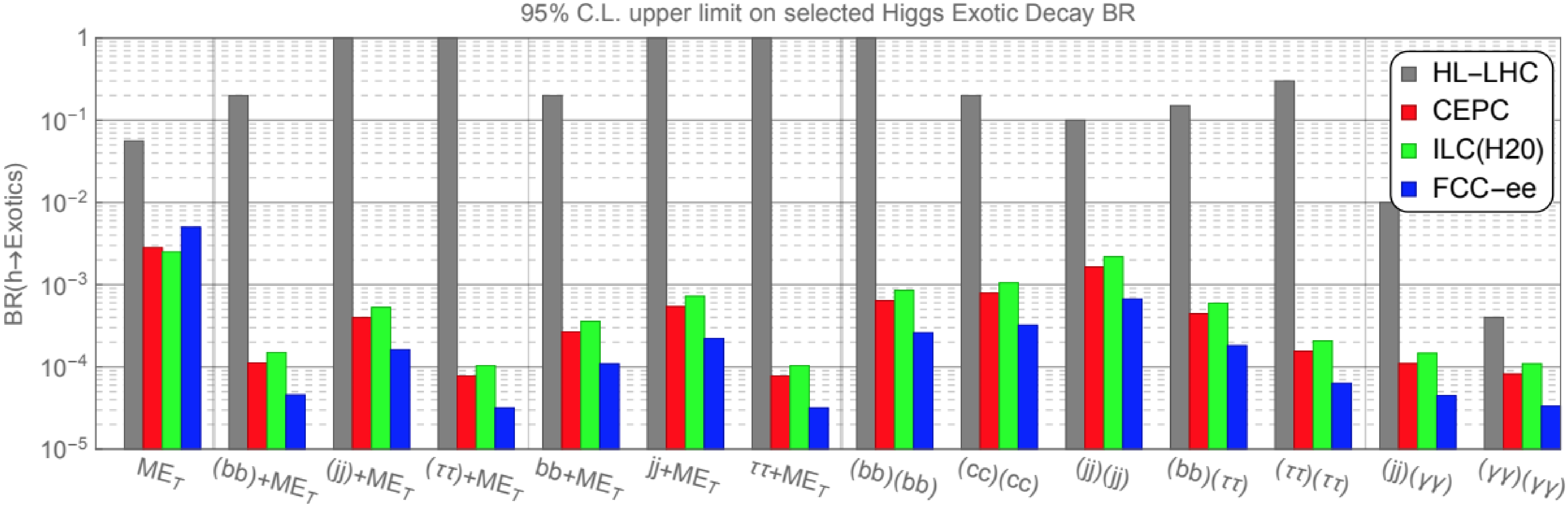


Br(H->ZZ): relative error of 6.9% achieved with ZH->ZZZ*->vv(Z)llqq(H) final states. Extrapolation of TLEP result leads to 4.3% relative error

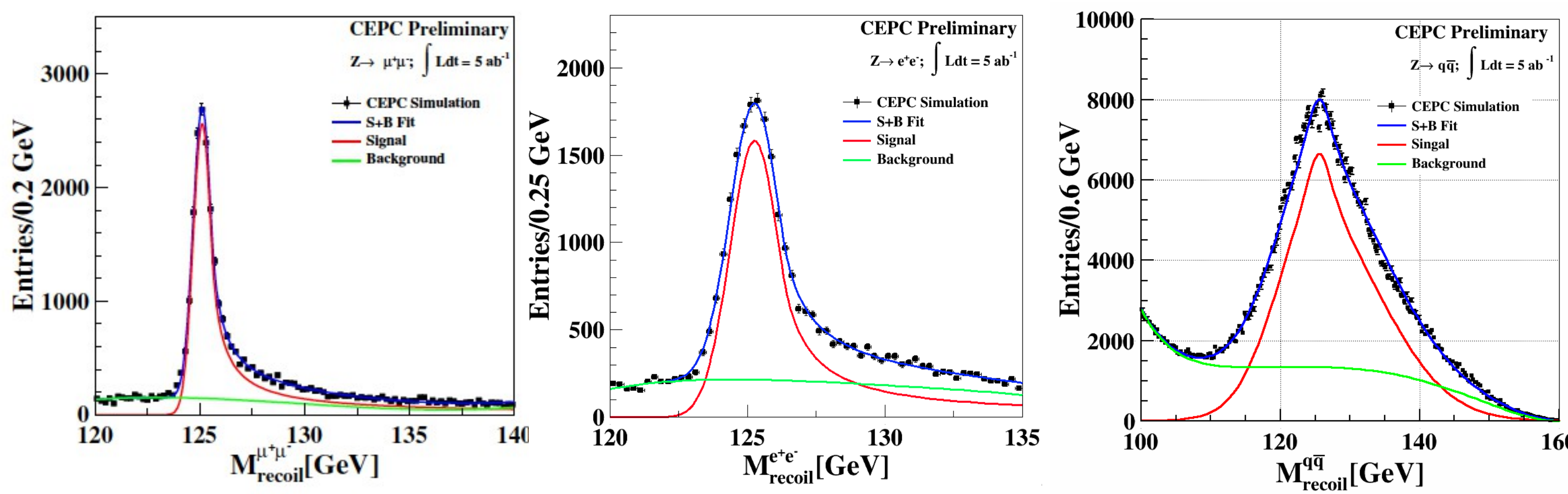
σ(vvH)*Br(H->bb): relative error of 2.8%

A combined accuracy of 2.8% for the Higgs total width measurements

Higgs exotic decays

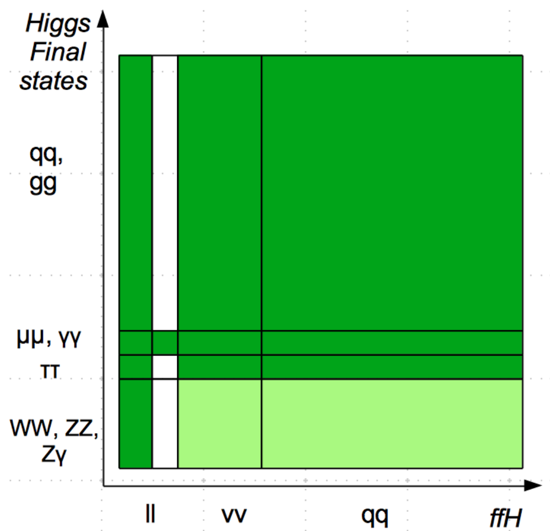


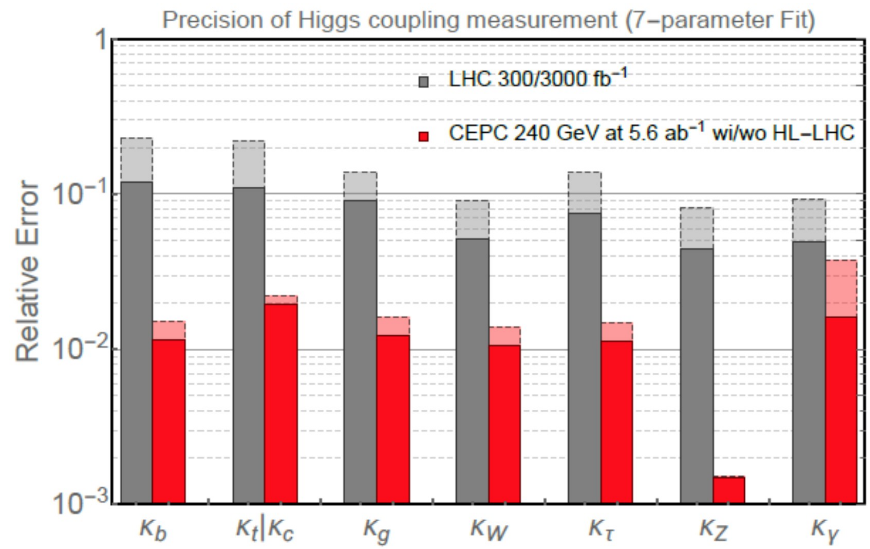
Invisible up limit at CEPC: 0.28% at 95% C.L

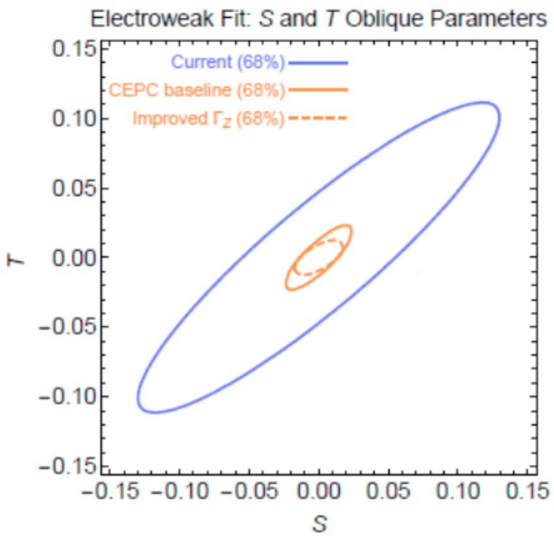


*Assuming σ(ZH)*Br(H->inv) = 200 fb*

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)

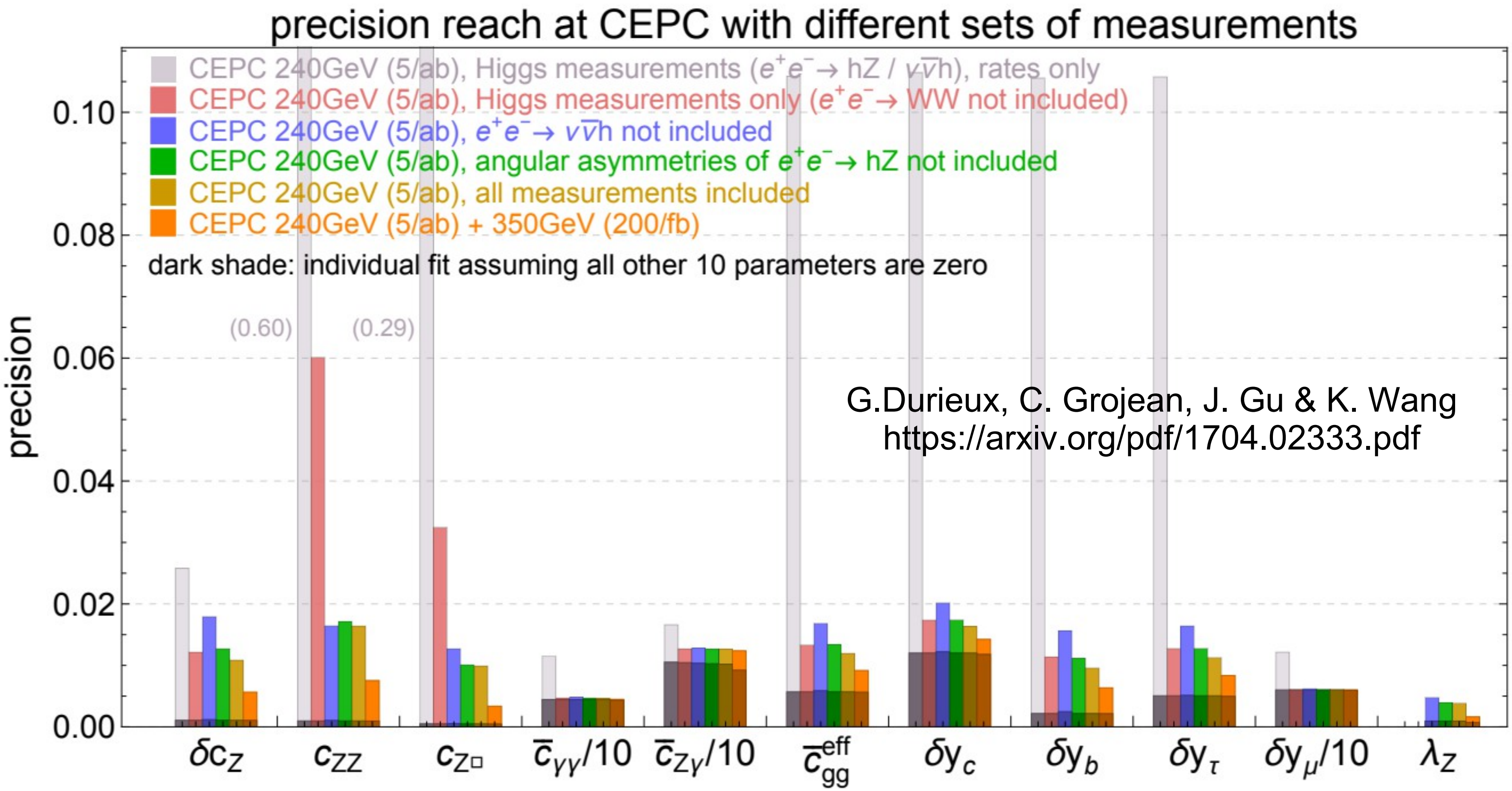
Chinese Physics C Vol. XX, No. X (201X) 010201

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

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)

Summary

- CEPC, a super Higgs/W/Z factory
- Physics Potential
  - Higgs:
    - Absolute determination of Higgs couplings, width...
    - 1 order of magnitude improvement w.r.t HL-LHC (Signal Strength)
    - Exotic decay: 2-3 orders of magnitude better than HL-LHC
  - EW: boost by at least 1 order of magnitude
  - Rich program on Flavor physics
- Performance at the baseline design
  - High efficiency/accuracy reconstruction of all key physics objects
  - Clear Higgs signature in all SM Higgs decay modes
  - Clear distinguish between the Signal and SM backgrounds
  - Fulfills the physics requirements of the CEPC Higgs operation

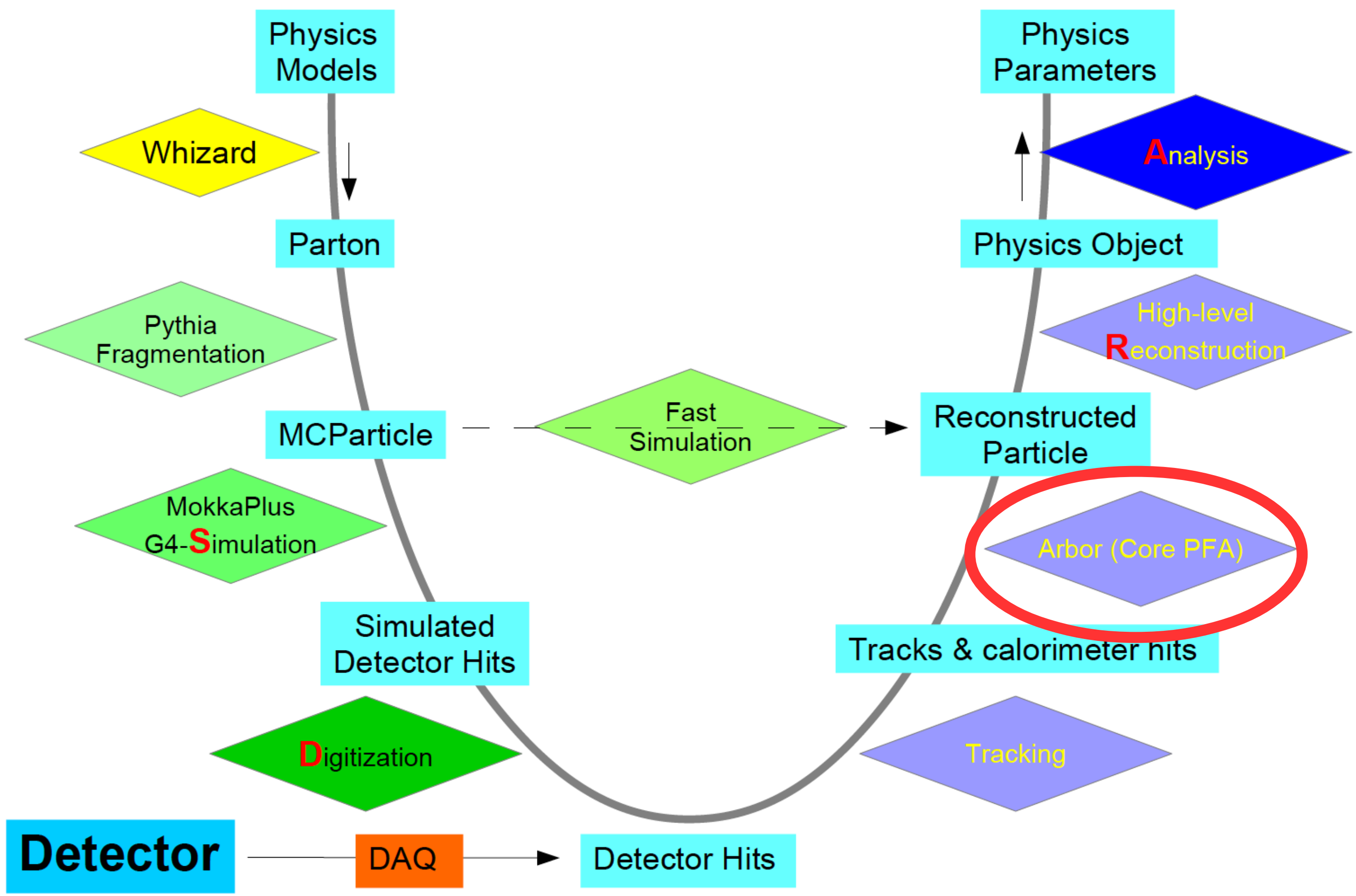
Summary

- CDR in finalization: long to do list towards the TDR
  - Physics Potential study:
    - Pheno Study & Systematic control
    - Higgs Differential measurements
    - QCD, Flavor, EW...
    - *Dedicated discussion on July 1-5th, at Peking University of Beijing*
  - Detector design & optimization:
    - Lots of efforts needed, to bridging the CDR design to TDR & construction: especially the integration & systematic controls
    - Multiple IP: new ideas are always welcome
  - Software, Reconstruction, Algorithms, Analysis tools...

- **You ideas, supports & participations are essential!**

backup

The Simu-Reco Chain at CEPC

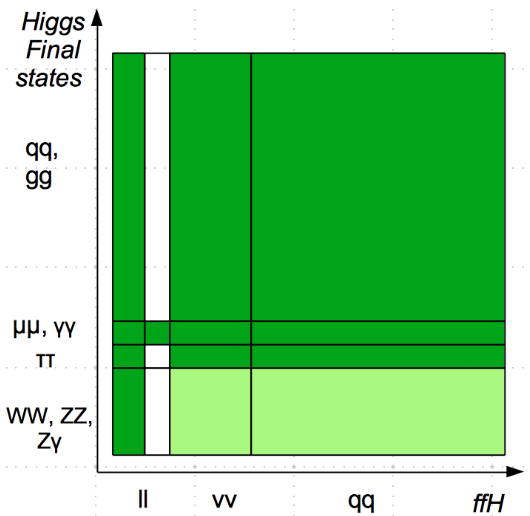


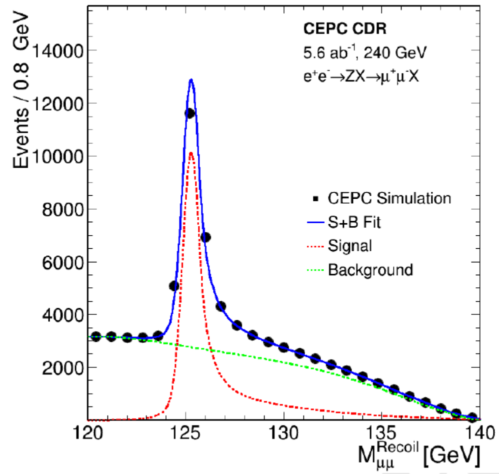
- Generators (Whizard & Pythia)
- Data format & management (LCIO & Marlin)
- Simulation (MokkaC)
- Digitizations
- Tracking
- PFA (Arbor)
- Single Particle Physics Objects Finder (LICH)
- Composed object finder (Coral)
- Tau finder
- Jet Clustering (FastJet)
- Jet Flavor Tagging (LCFIPLus)
- Event Display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

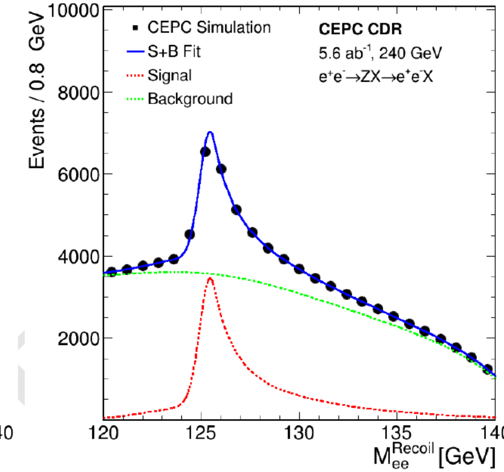
CEPC-SIMU-2017-001,
CEPC-SIMU-2017-002,
(DocDB id-167, 168, 173)

General Software | ILCSoft | ILCSoft + Development | Developments

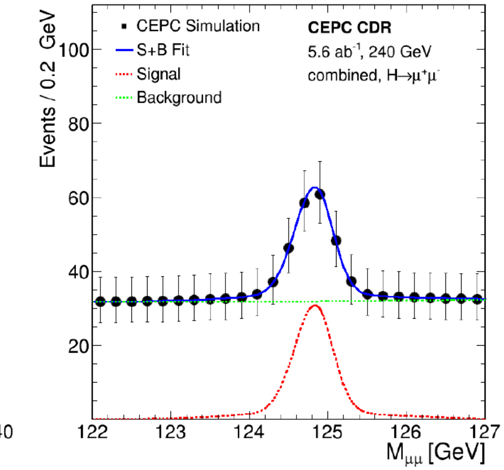
Higgs benchmark analyses



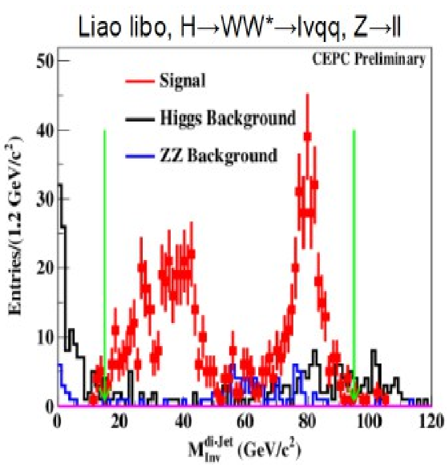




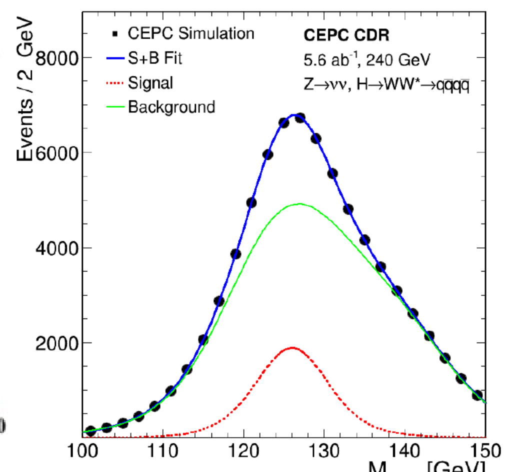
σ(ZH) measurements



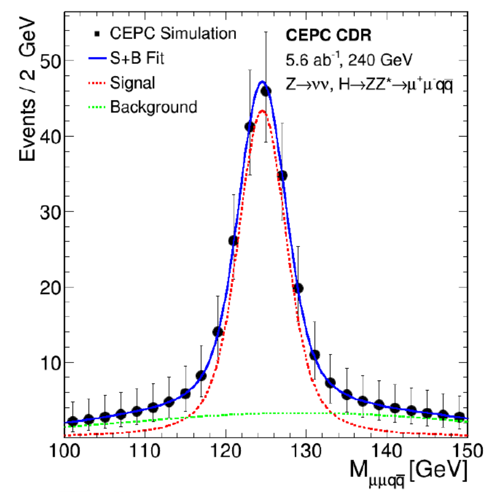
Br(H→μμ)



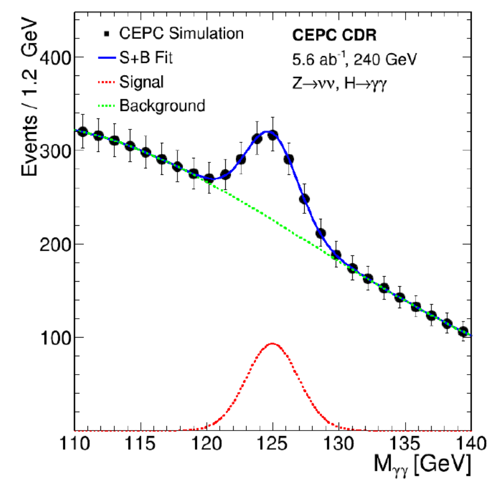
Br(H→WW)



σ(ννH)*Br(H→bb)

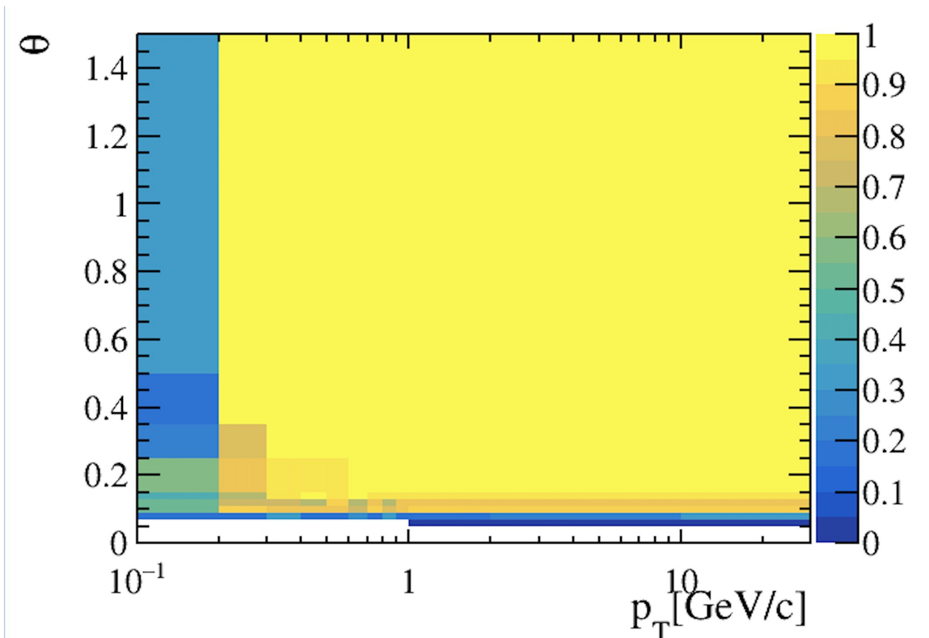


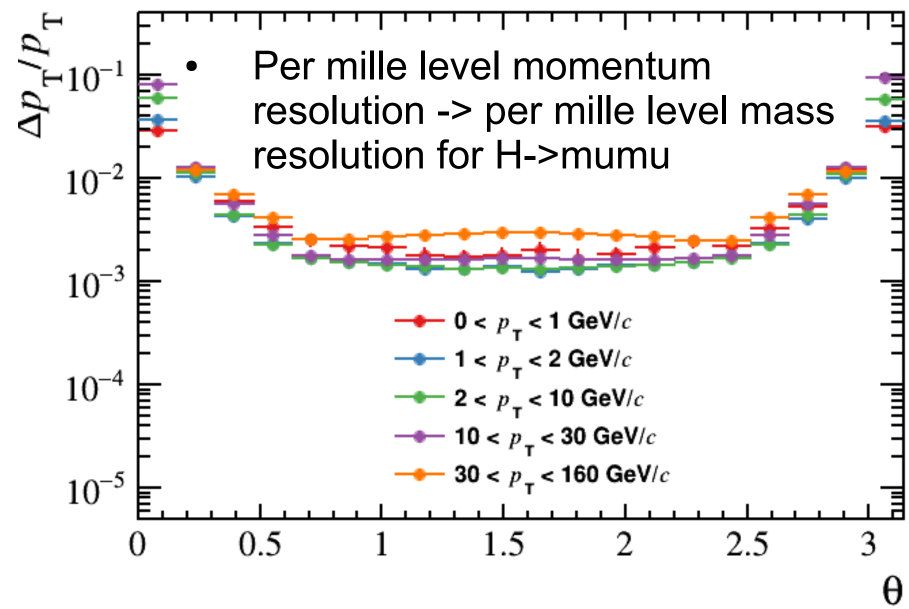
Br(H→ττ)

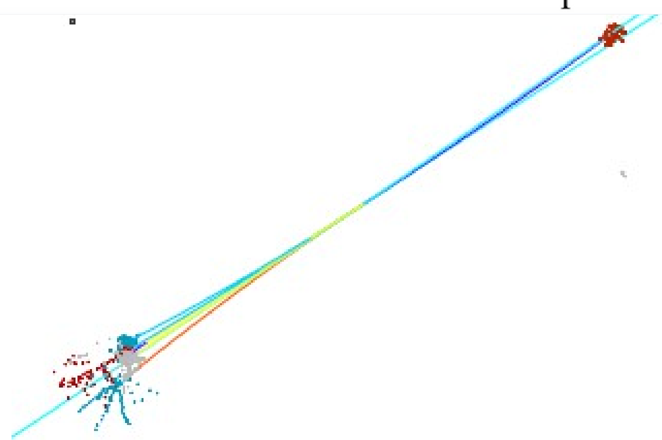


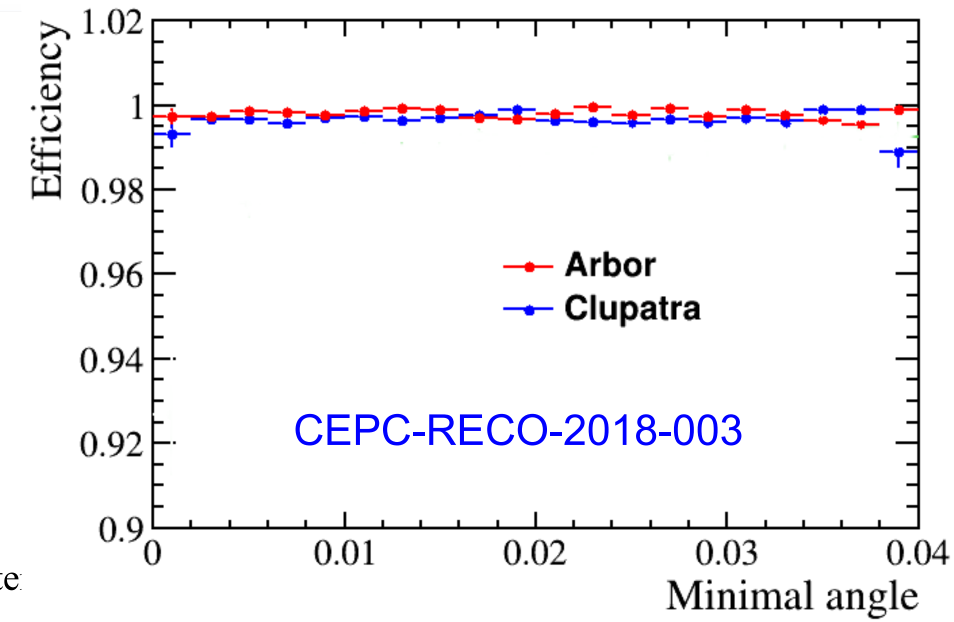
Br(H→γγ) (Asimov)

Tracking



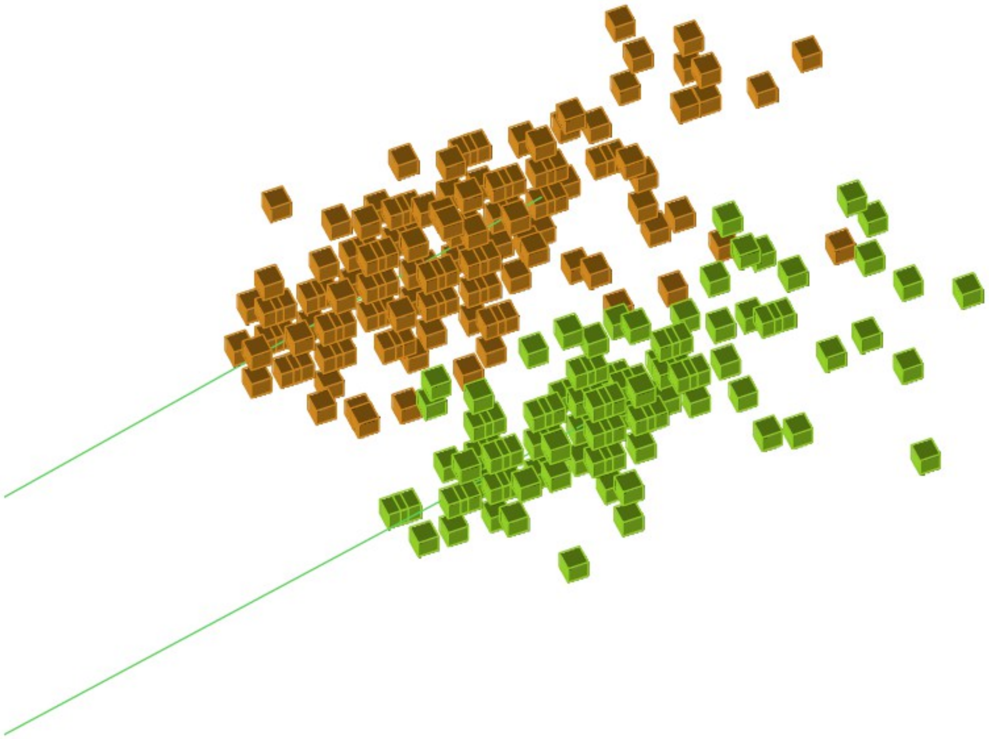


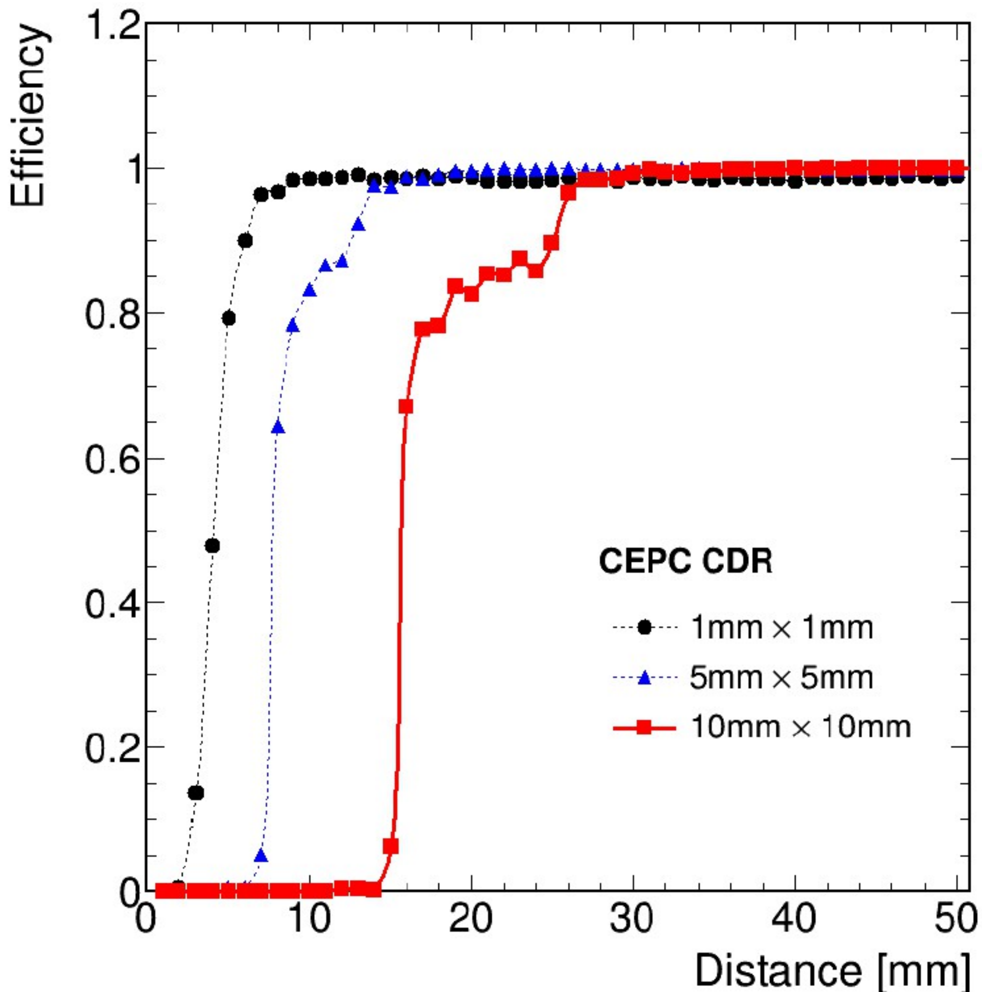




Mingrui Zhao. CEPC CDR

Clustering - Separation

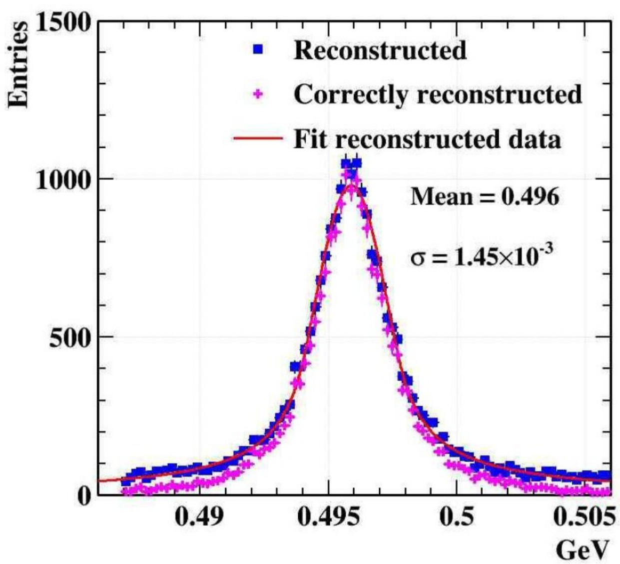


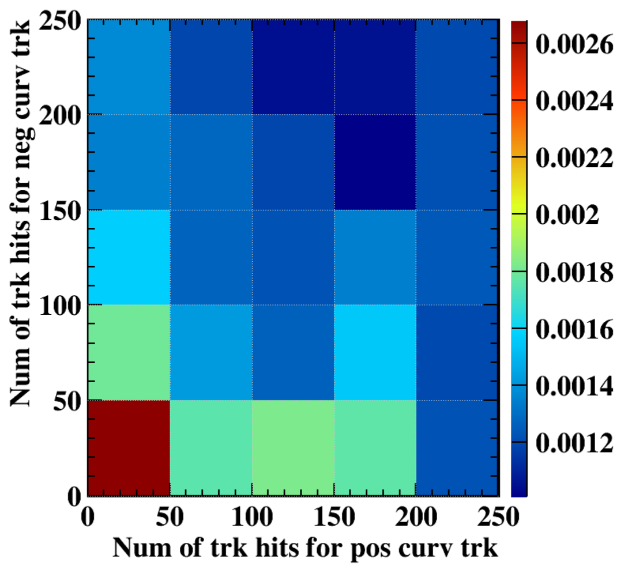


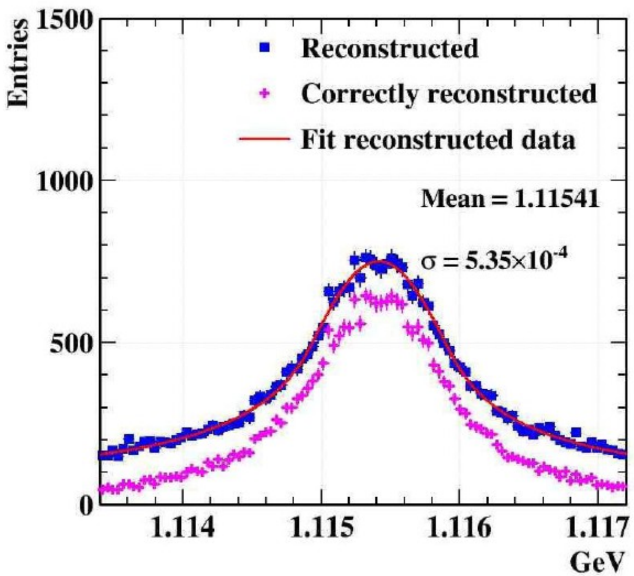
Critical energy to separate an evenly decay π_0: 30 GeV

Hang Zhao. CEPC CDR

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





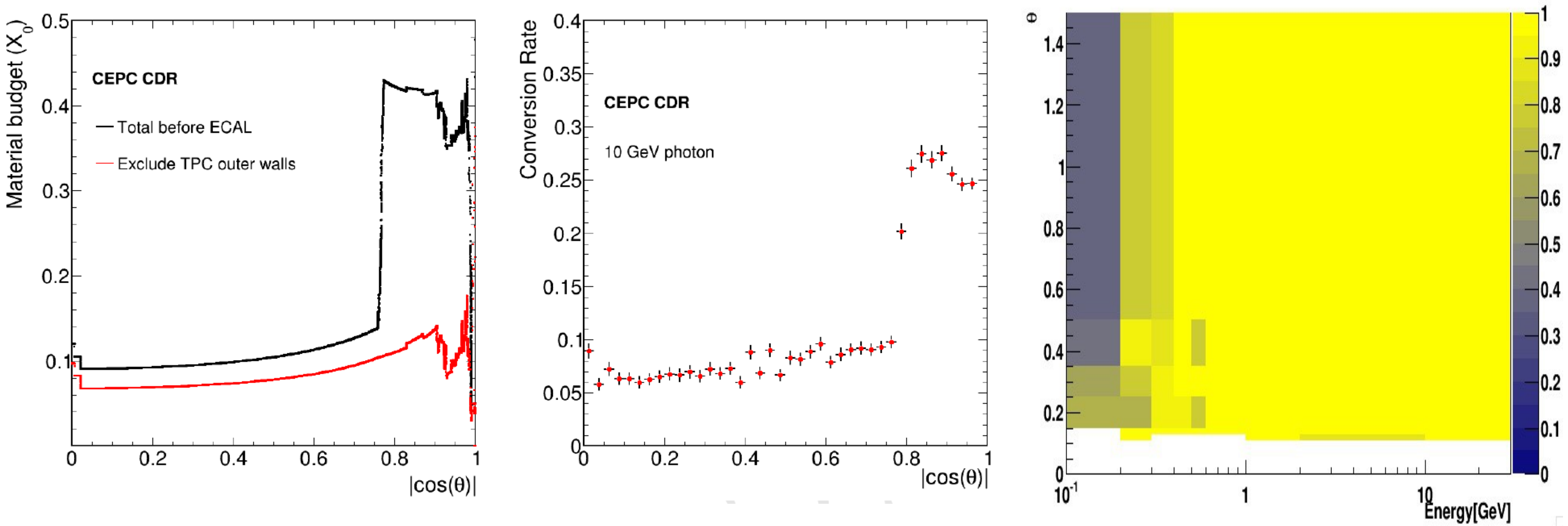


wi/wo perfect PID	Efficiency	Purity	Resolution
K_short	79%/78%	91%/86%	0.28%/0.29%
Lambda	82%/68%	94%/64%	0.043%/0.046%

Efficiency = Correctly reconstructed Ks(Λ)/Ks(Λ) with 2 tracks reconstructed
Purity = Correctly reconstructed Ks(Λ)/All reconstructed Ks(Λ)

Perfect PID = Perfect identification of pions, charged kaons, and (anti-)protons

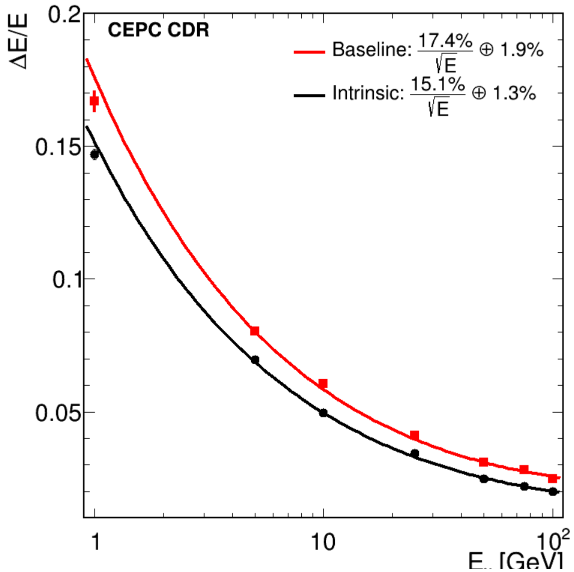
Photons – conversion & efficiency

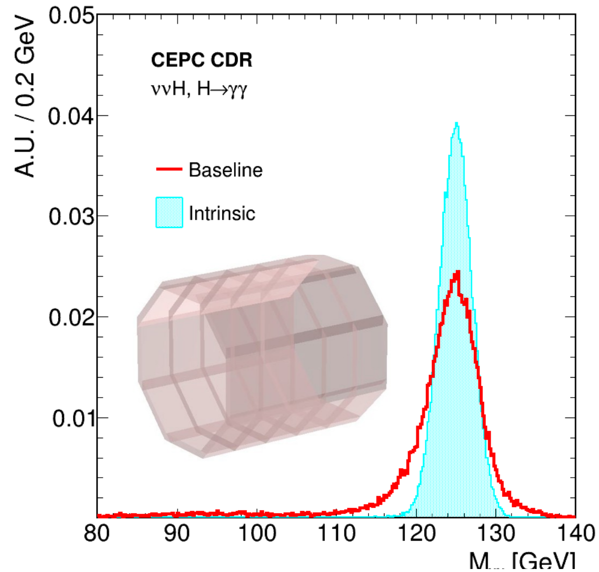


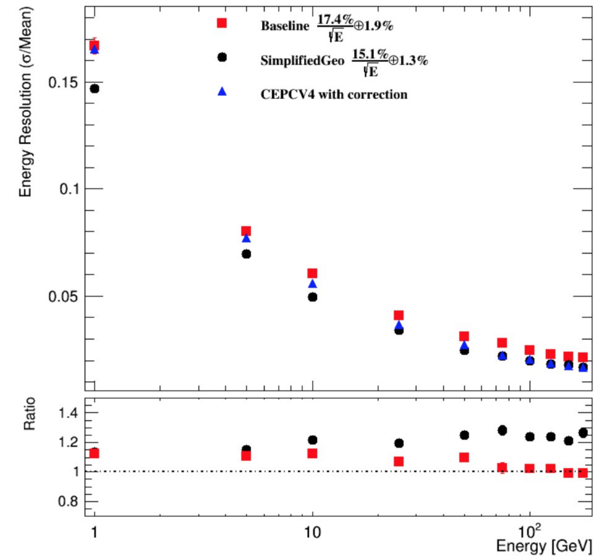
In the barrel region: Roughly 6-10% of the photons converts before reaching the Calorimeter.

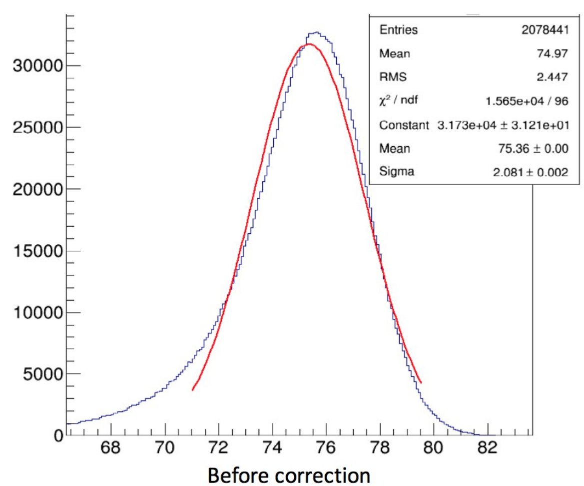
For the unconverted photon: A critical energy of 200 MeV is observed.

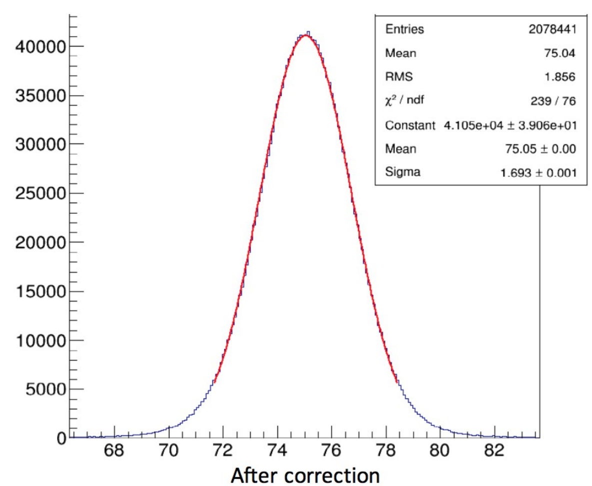
Photon: resolution







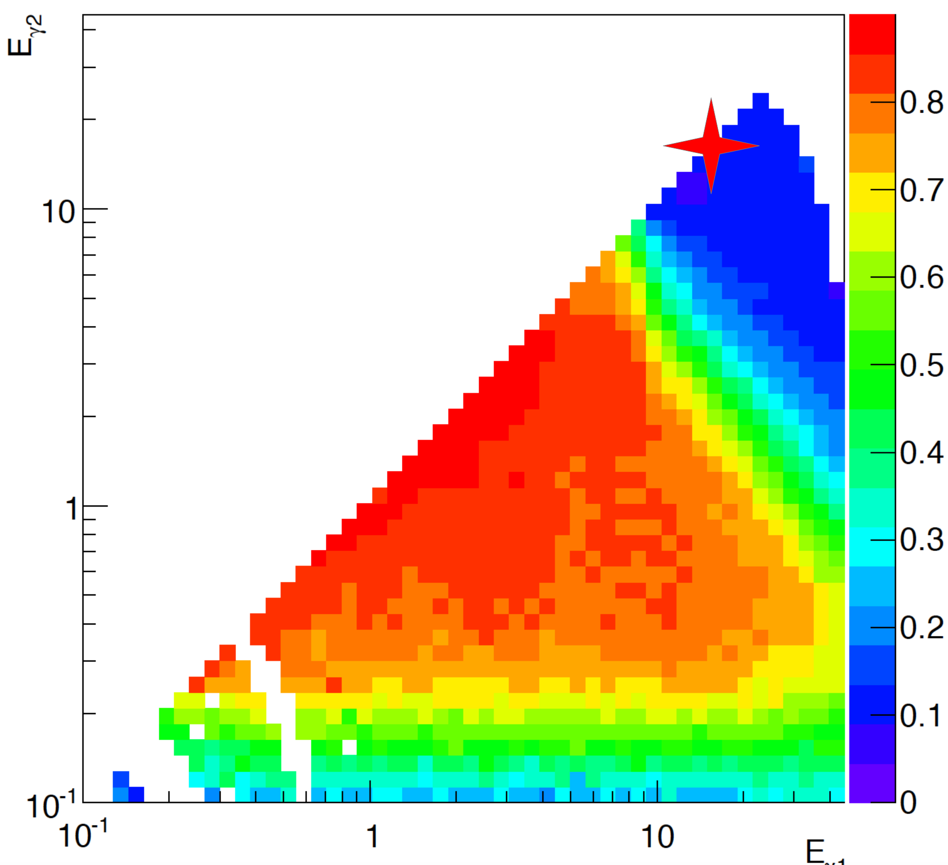


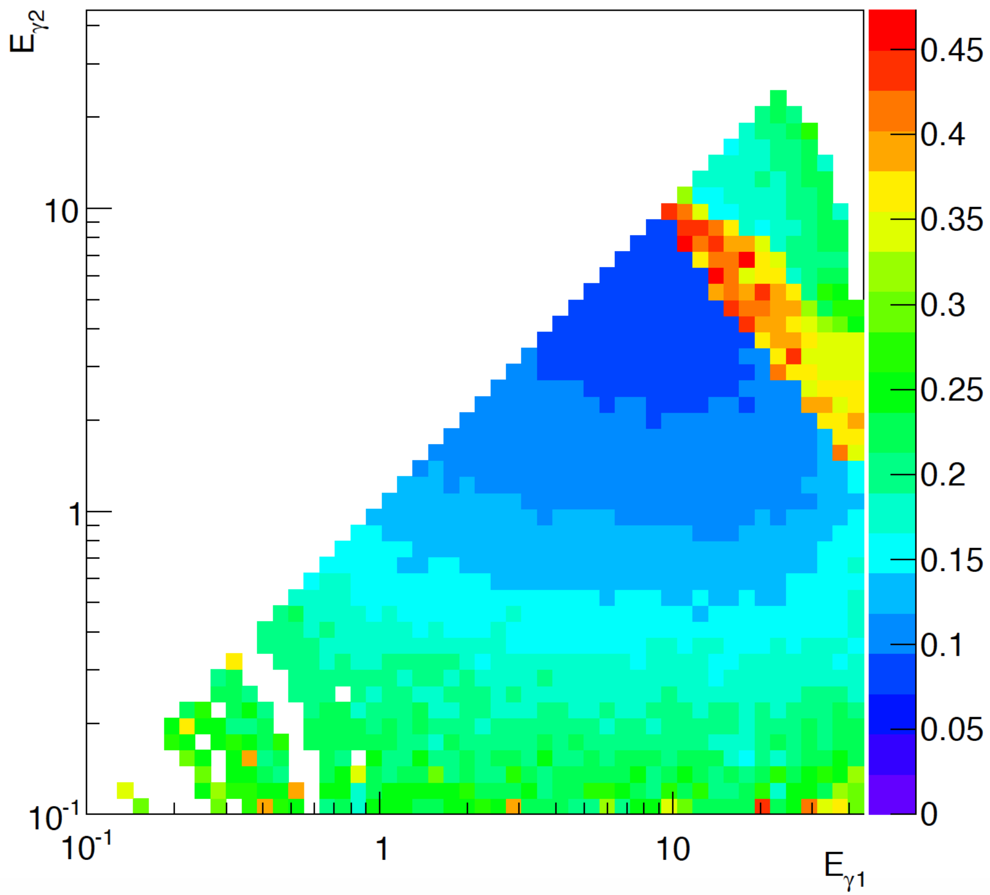


- A Higgs mass resolution of 1.7/2.5% is achieved in the Higgs to di-photon final states with simplified/baseline geometry
- The geometry defects correction could be efficiently corrected (Preliminary)

Yuqiao Shen & CEPC CDR

Pi0: efficiency & mass resolution (Preliminary)



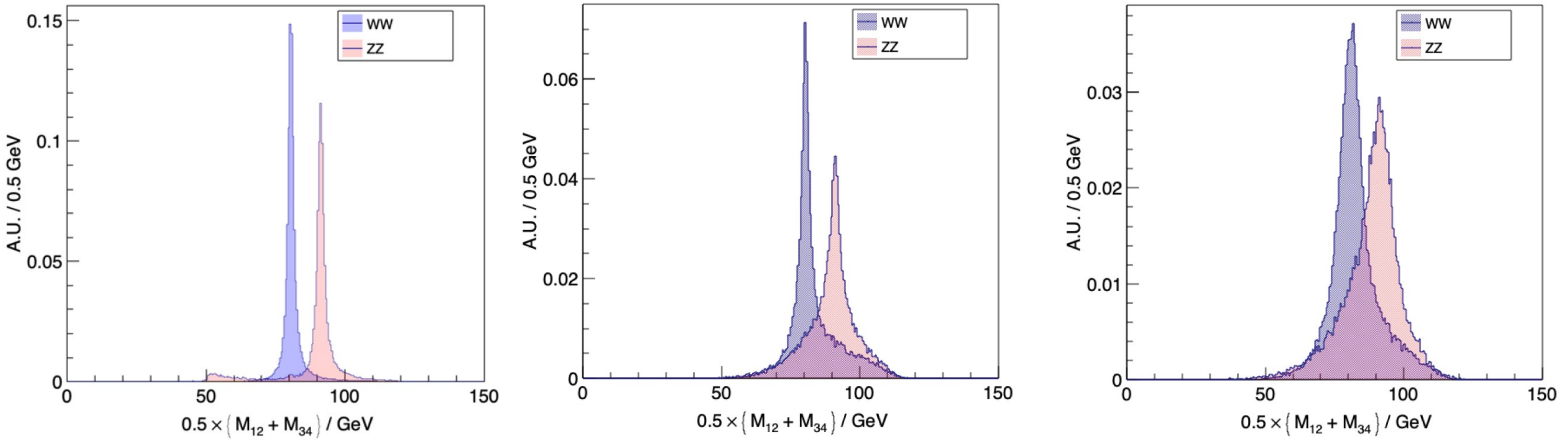


Arbor parameter & Photon Id - parameters need further optimization...

Jets – color singlet

- Boson Mass Resolution: Total reconstructed mass of hadronic events
  - 3.8% at baseline (benchmarked with vvH, H→gluons process)
  - Applied to event with one color singlet fragments into jets
    - W, Z, H signal separation at lvqq, ll(vv)+qq events (Appreciated in Triplet Gauge Boson Coupling measurements)
    - Analysis of qqH, Higgs decays into non-jet final states, for example, qqH, H→taus, inv, photons, muons...
    - ...
- Single Jet Response (Jet energy scale/resolution)
  - Differential measurements with jet directions
  - Applied to events with more than one color singlet fragment into jets
    - WW/ZZ/ZH event separation in 4-jet final state
    - ...

Jet confusion: the leading term



- Separation be characterized by

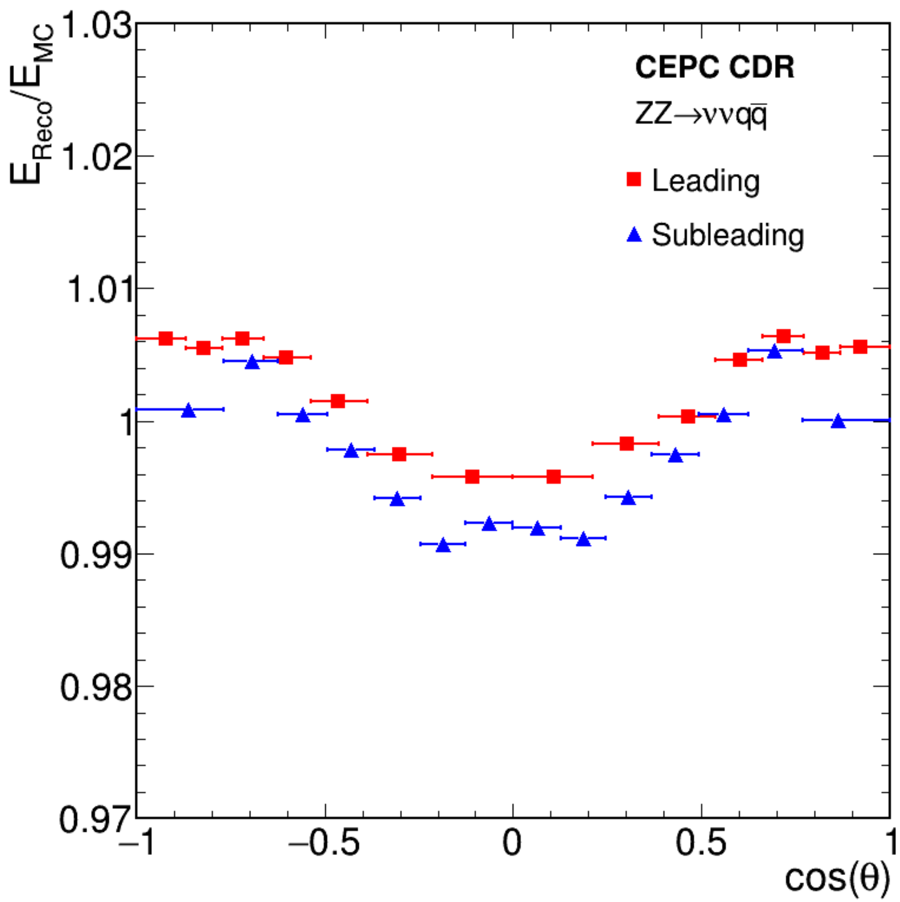
$$overlapping\ ratio = \sum_{bins} min(a_i, b_i)$$

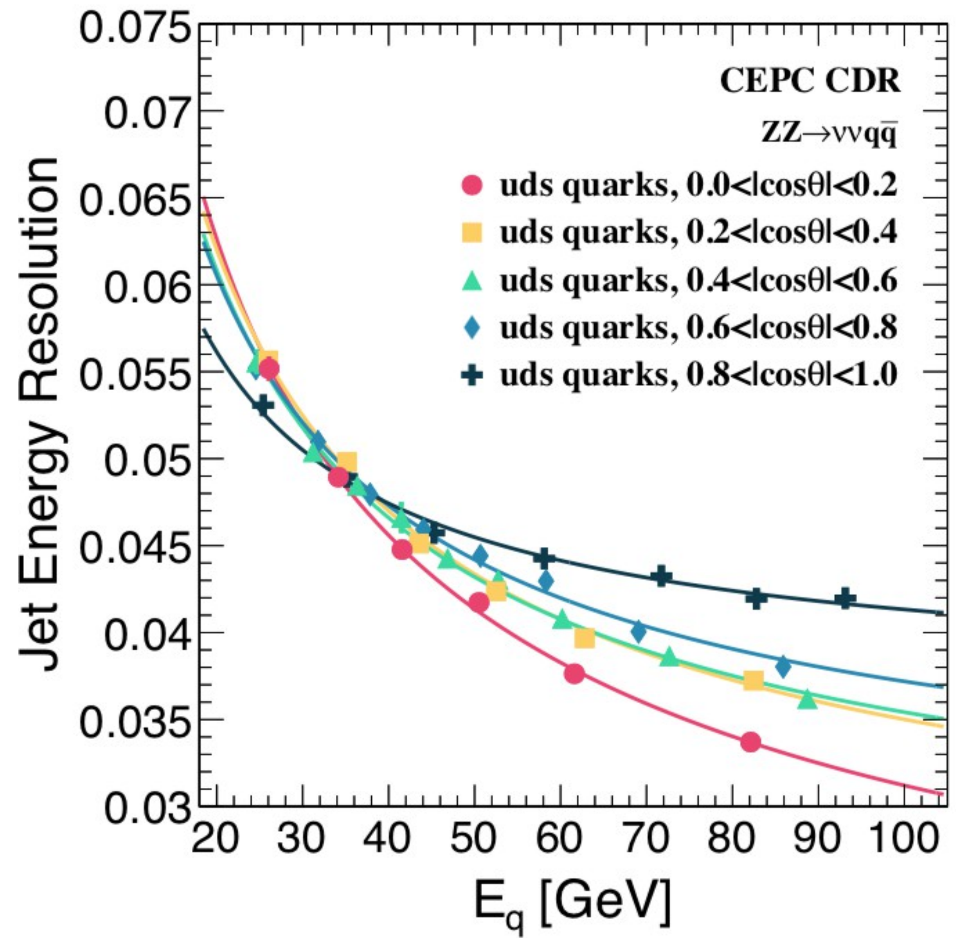
- Final state/MC particles are clustered into Reco/Genjet with ee-kt, and paired according to chi2

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

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

Jet Energy Scale & Resolution

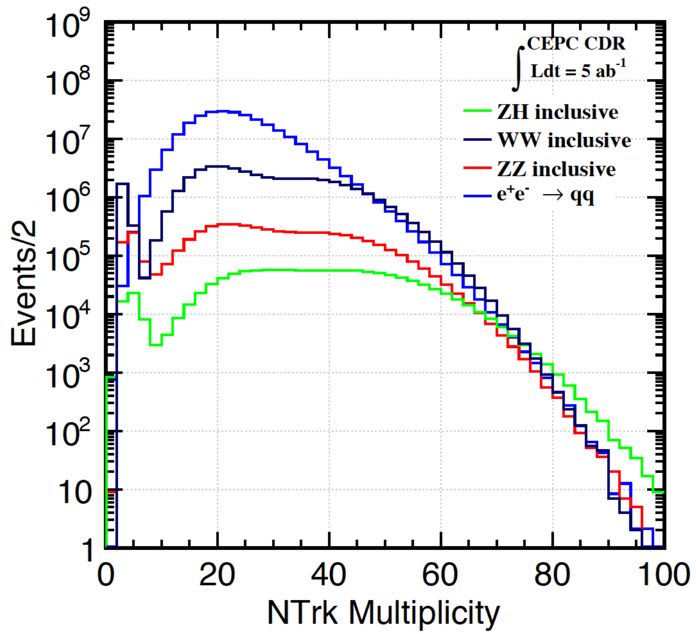


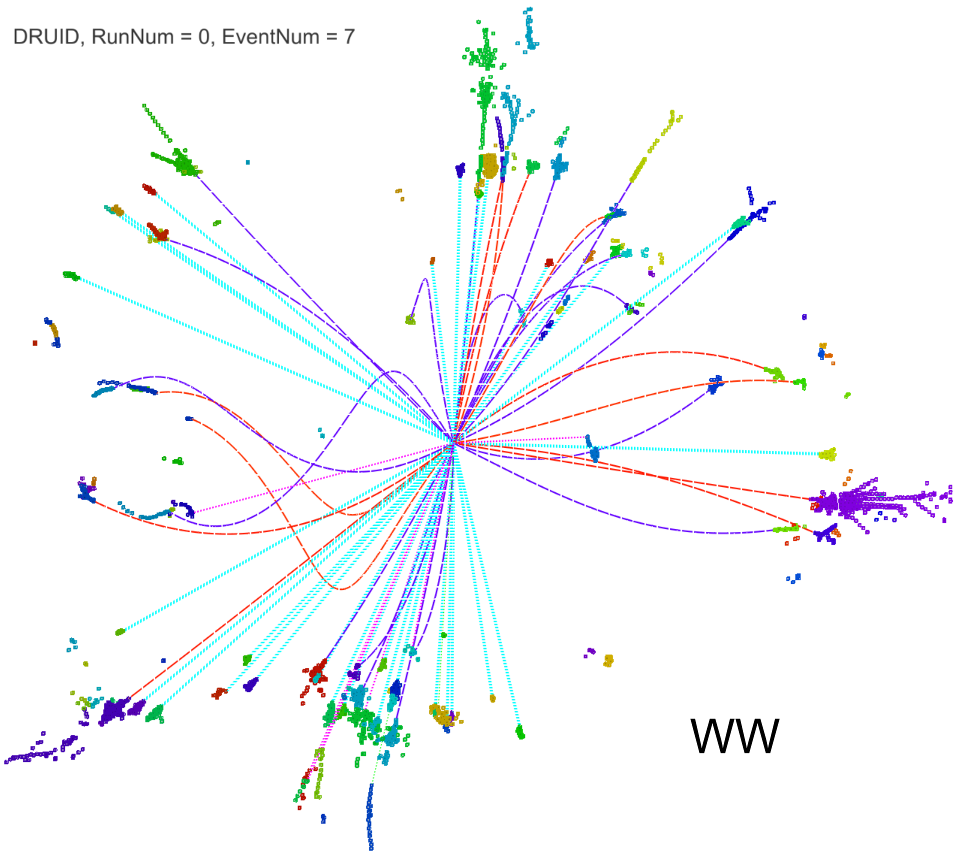


- JES ~ with 1% of the unity (without correction)
- JER ~ 3.5% - 5.5% for E ~ 20 – 100 GeV Jets
- **Both Superior to LHC experiments by 3-4 times**

Peizhu LAI

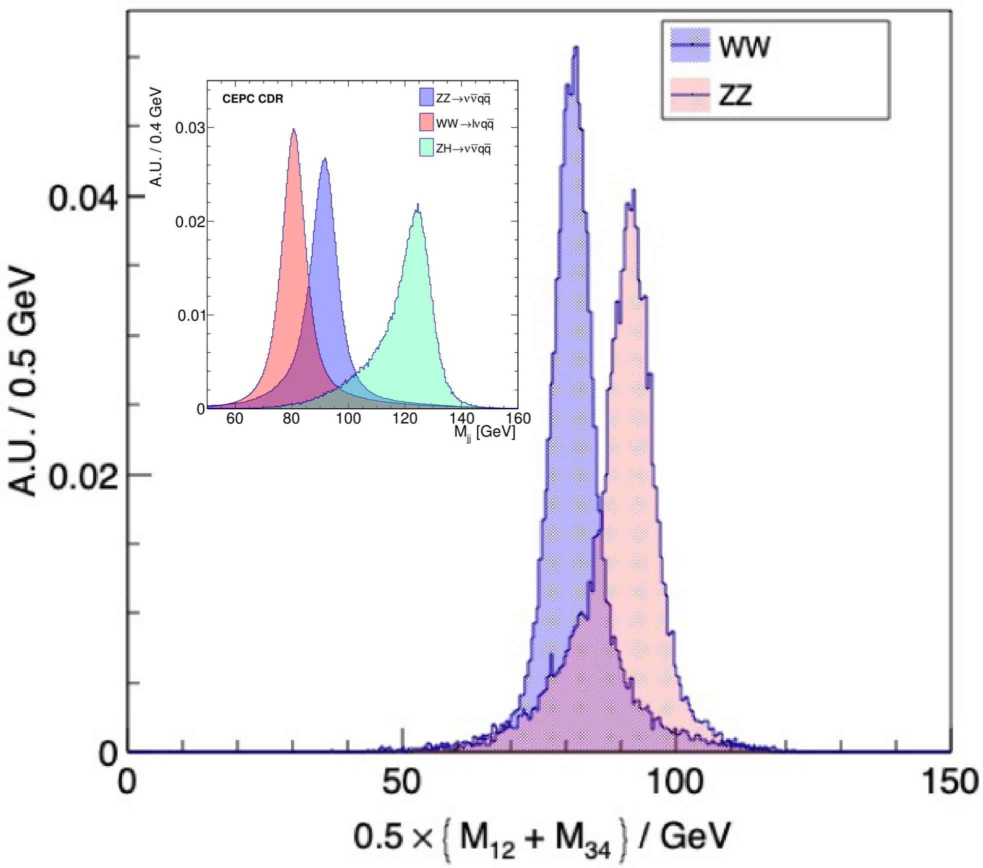
Separation of full hadronic WW-ZZ event

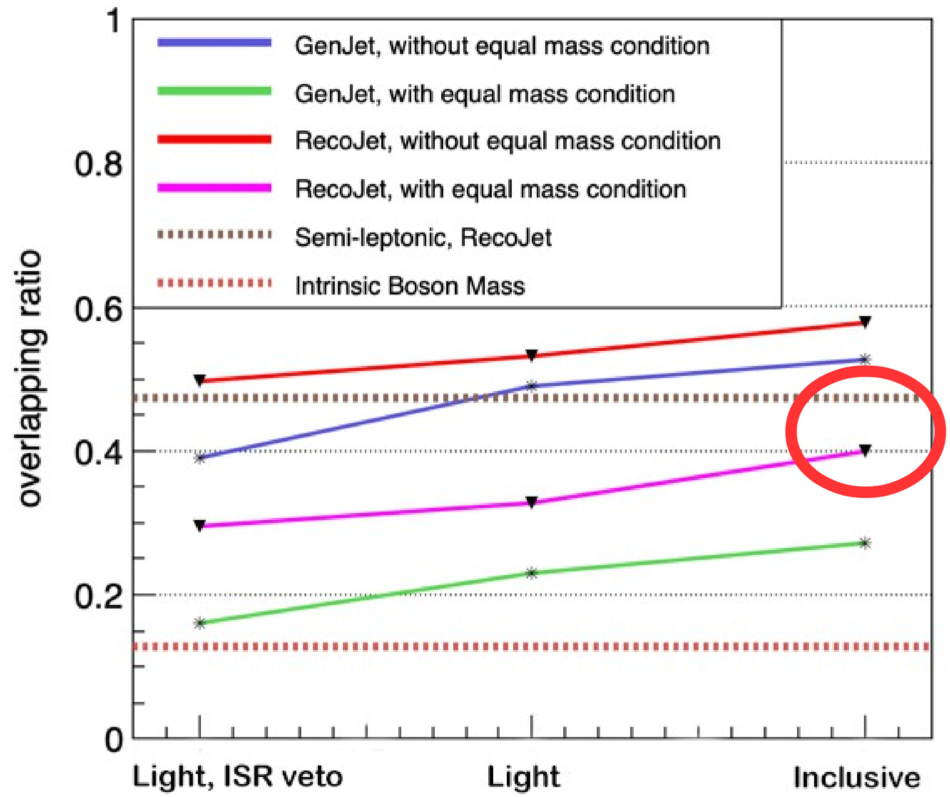




- Low energy jets! (20 – 120 GeV)
- Typical multiplicity ~ o(100)
- WW-ZZ Separation: determined by
  - Intrinsic boson mass/width
  - Jet confusion from color single reconstruction – jet clustering & pairing
  - Detector response

Separation of full hadronic WW-ZZ event





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

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

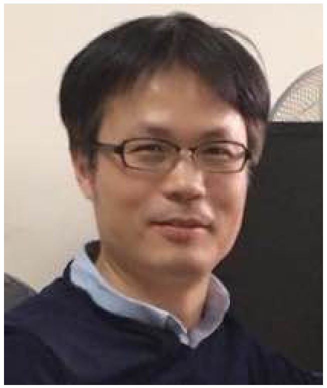
Quantified by differential overlapping ratio.

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

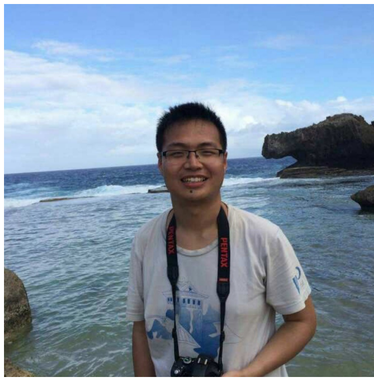
Summary

- The Particle Flow oriented detector is well established and serves as the baseline detector for the CEPC CDR studies
  - High efficiency/accuracy reconstruction of all key physics objects;
  - Clear Higgs signature in all SM Higgs decay mode
  - **Mature software/reconstruction tool/team**
- APODIS, 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
  - Iterate with hardware studies
- Todo:
  - Physics study, especially flavor tagging & EW measurements (τ leptons)
  - Towards the TDR, Integration, Sub detector modeling, Systematic Studies

软件队伍



成栋：几何及寻迹



新人：赵祥虎
软件-计算

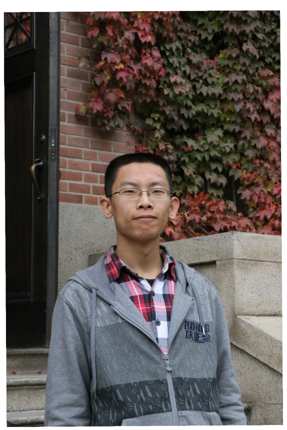
于丹：轻子甄别
PFA，tau

新人：赖培筑
喷注

安芬芬：
Pid，软件

吴志刚
顶点优化

徐音：几何

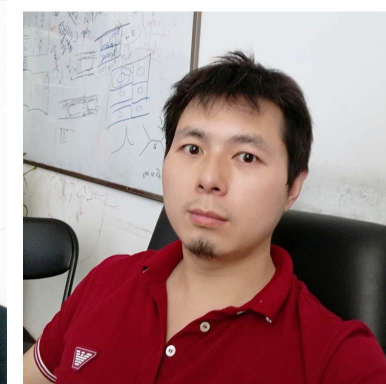


赵明锐：寻迹，
软件

李刚：产生子，
喷注味道甄别

赵航：PFA，
量能器优化

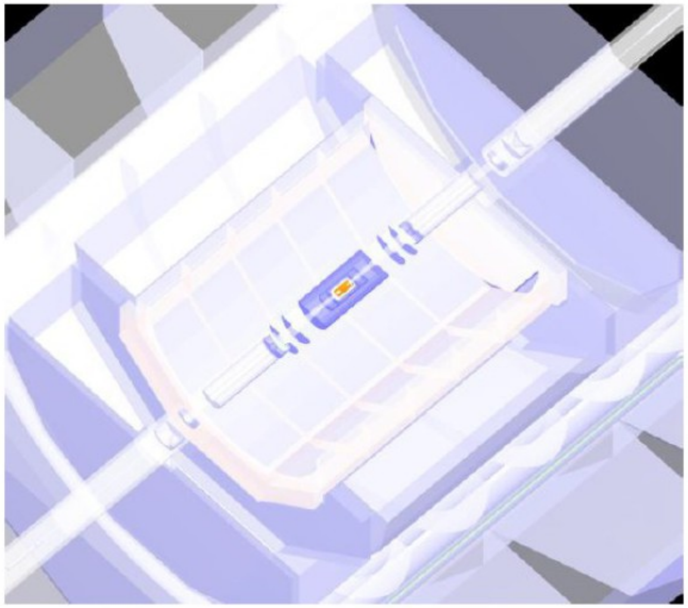
李亮：轻子

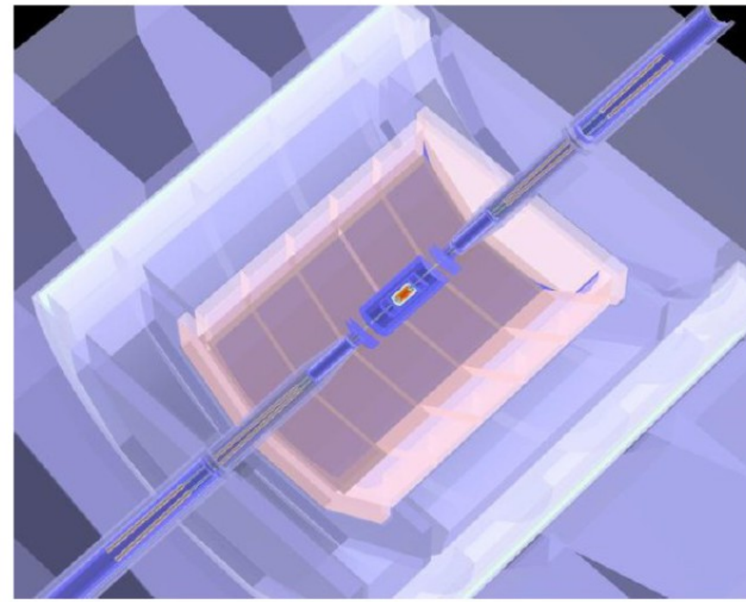


曼奇：探测器设计
软件，分析

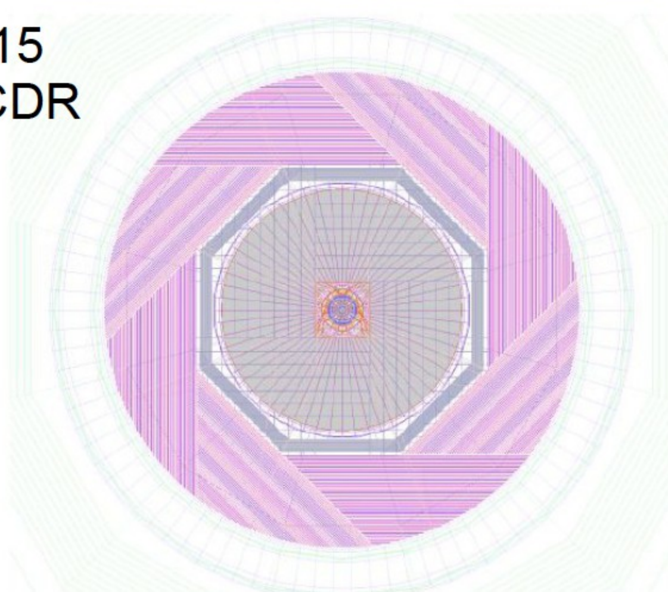
Benchmark detector for CDR: APODIS

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





2015
PreCDR



2017
CDR

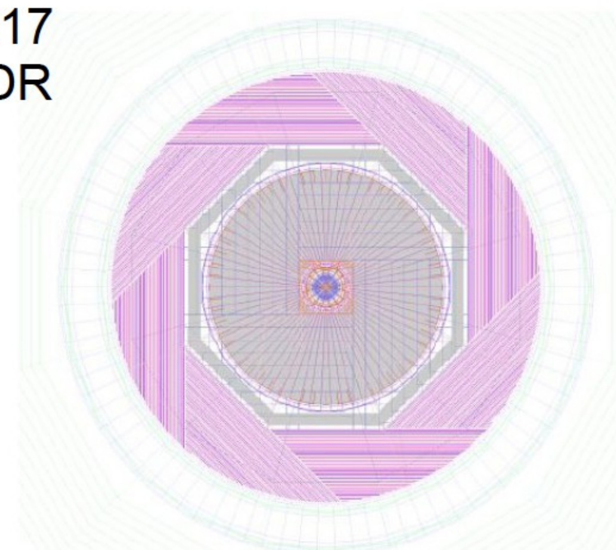
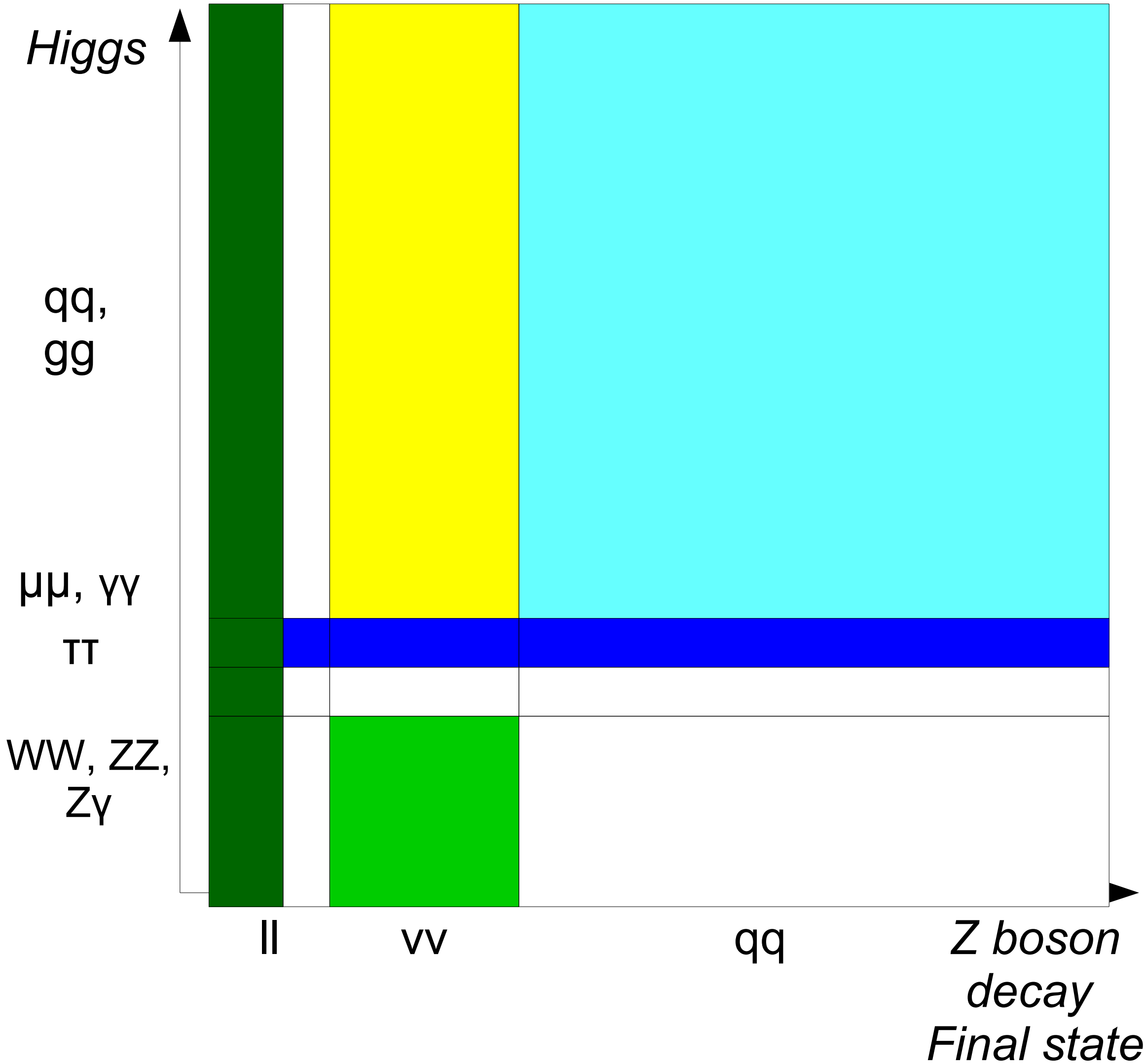


Table 9 Cut Flow of MC sample for $qqH \to \tau\tau$ selection on signal and inclusive SM backgrounds

	$qqH\tau\tau$	qqH inclusive bkg	ZH inclusive bkg	ZZ	WW	single$W$	single$Z$	$2f$
total generated (scaled to 5 ab^{-1})	45597	678158	357249	5711445	44180832	17361538	7809747	418595861
1st preselection	45465	677854	310245	5039286	42425195	1267564	1398362	148401031
2nd preselection	45145	174650	226059	293306	12452091	125735	117306	547402
$N_{\tau^+} > 0, N_{\tau^-} > 0$	24674	7342	33721	93955	723989	33887	54386	103642
$20GeV < M_{\tau^+\tau^-}$ < 120GeV	24284	6290	32344	88245	597480	24927	36039	56615
$70GeV < M_{qq}$ <110GeV	22937	2103	4887	65625	21718	738	1893	556
$100GeV < M_{qq}^{Rec}$ <170GeV	22703	2045	4524	23789	13154	315	306	193
efficiency	49.97%	0.31%	1.26%	0.41%	0.04%	<0.01%	<0.01%	$< 0.01\%$

Benchmark measurements



Lepton & Momentum resolution: Br = 6.7%

Flavor Tagging & JER: Br = 14%

Composition of Jet/MET, lepton: Br = 4%

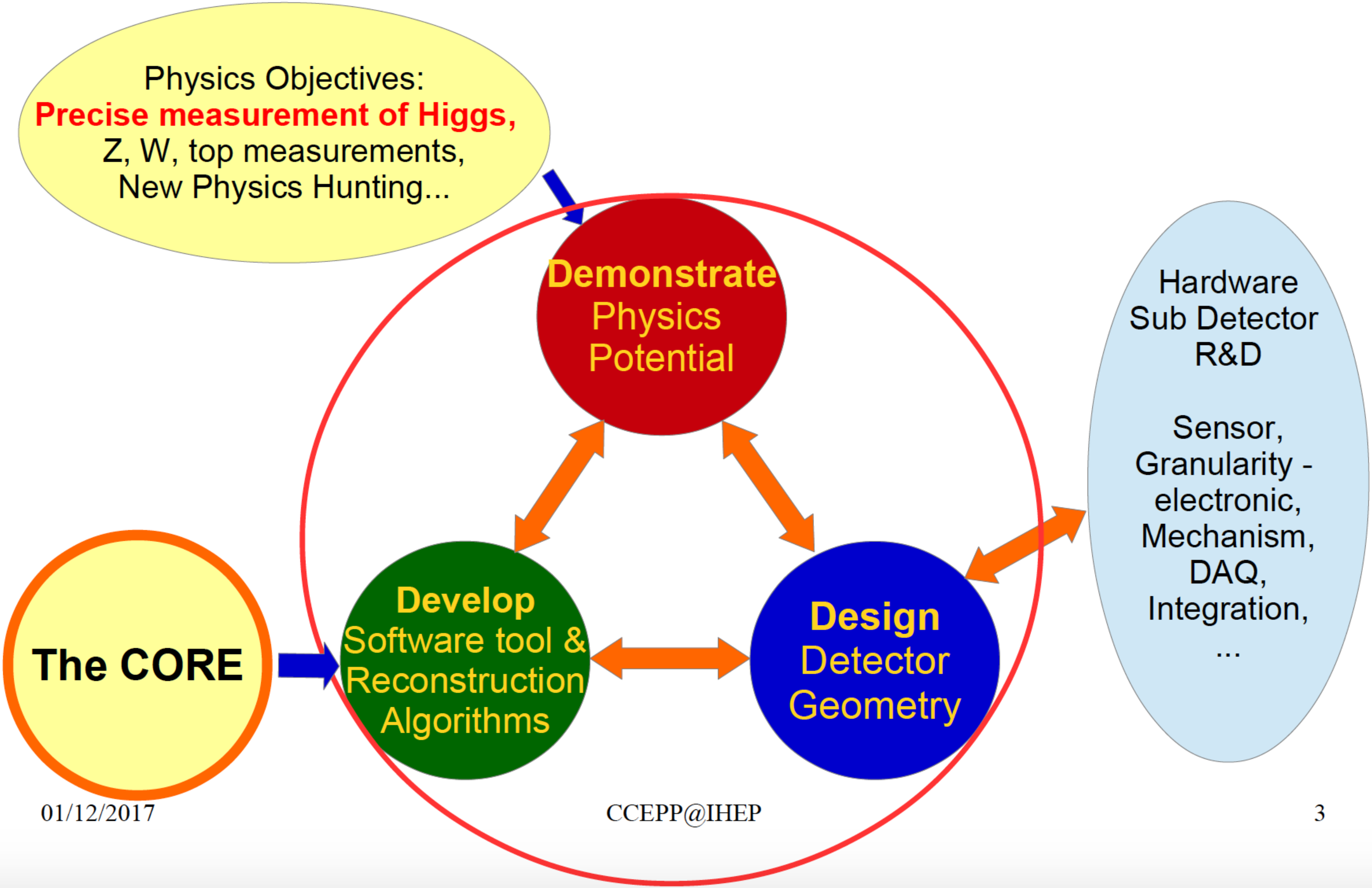
Jet Clustering: Br = 50%

Photon/ECAL: Br = 0.2%

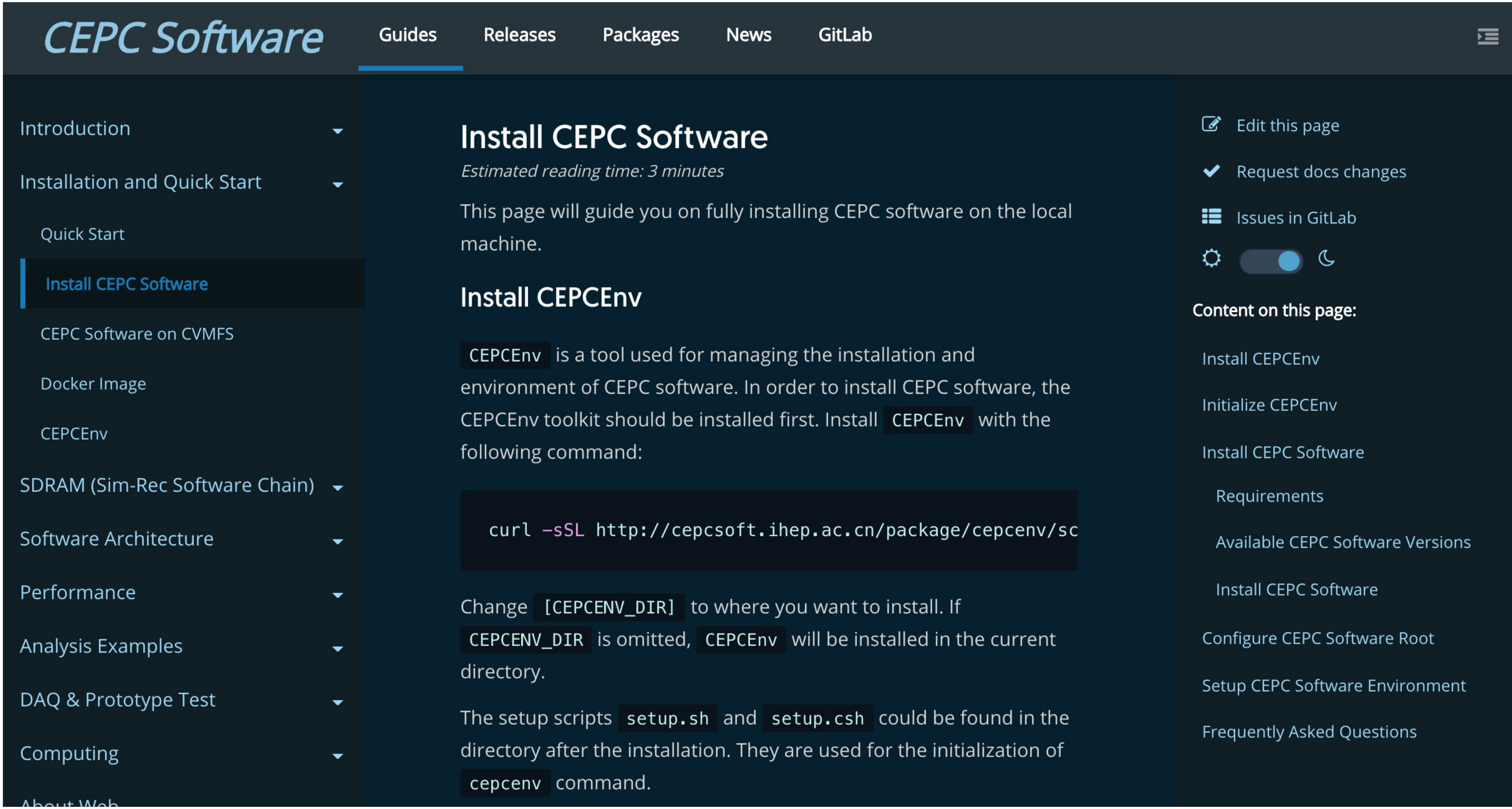
qqH, H->inv. MET & NP: SM Br = 0.1%

EW, Br(tau->X) @ Z pole: Separation

Key SOFT ingredients

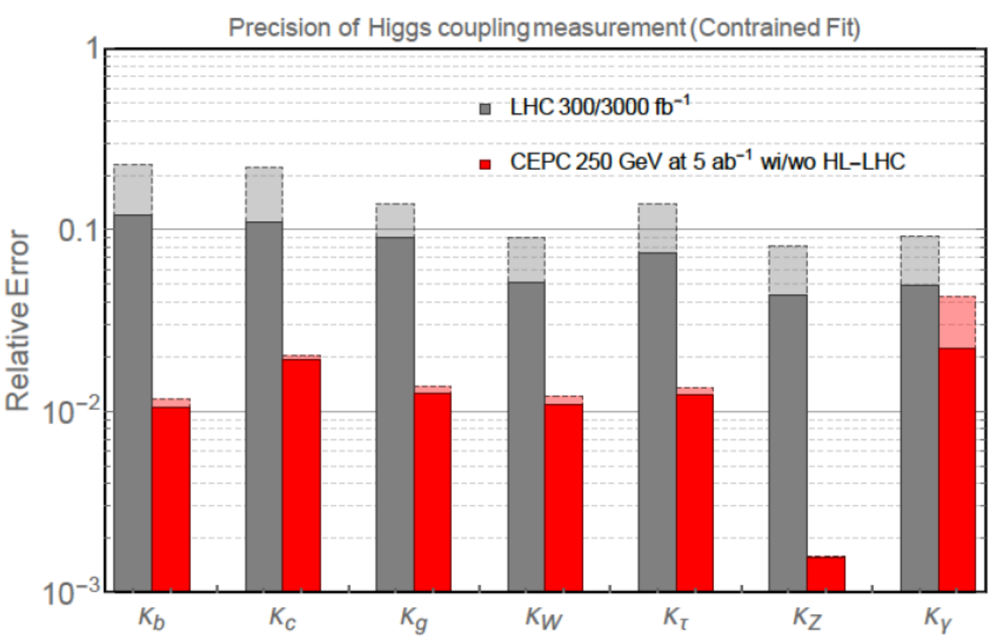


http://cepcsoft.ihep.ac.cn/

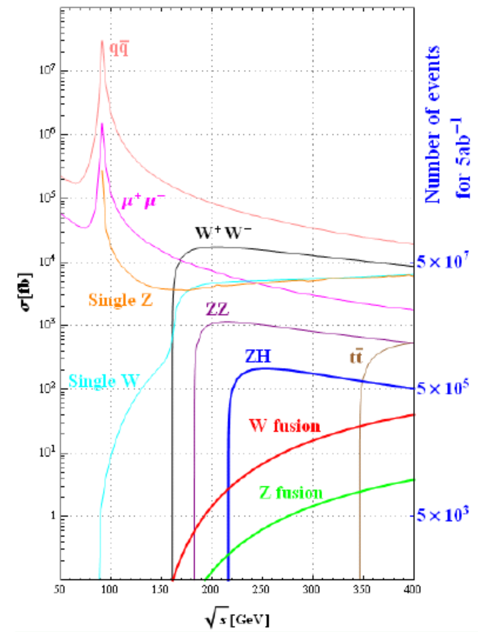


5 commands & you got the cepcsoft installed on an SL6 machine

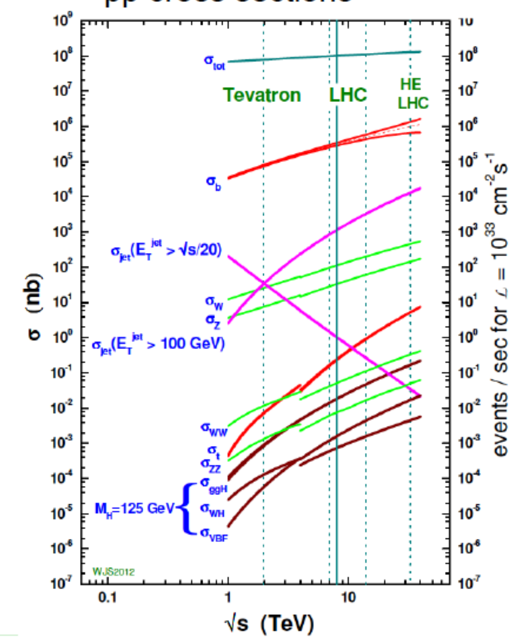
Higgs measurement at e+e- & pp



e+e- cross sections



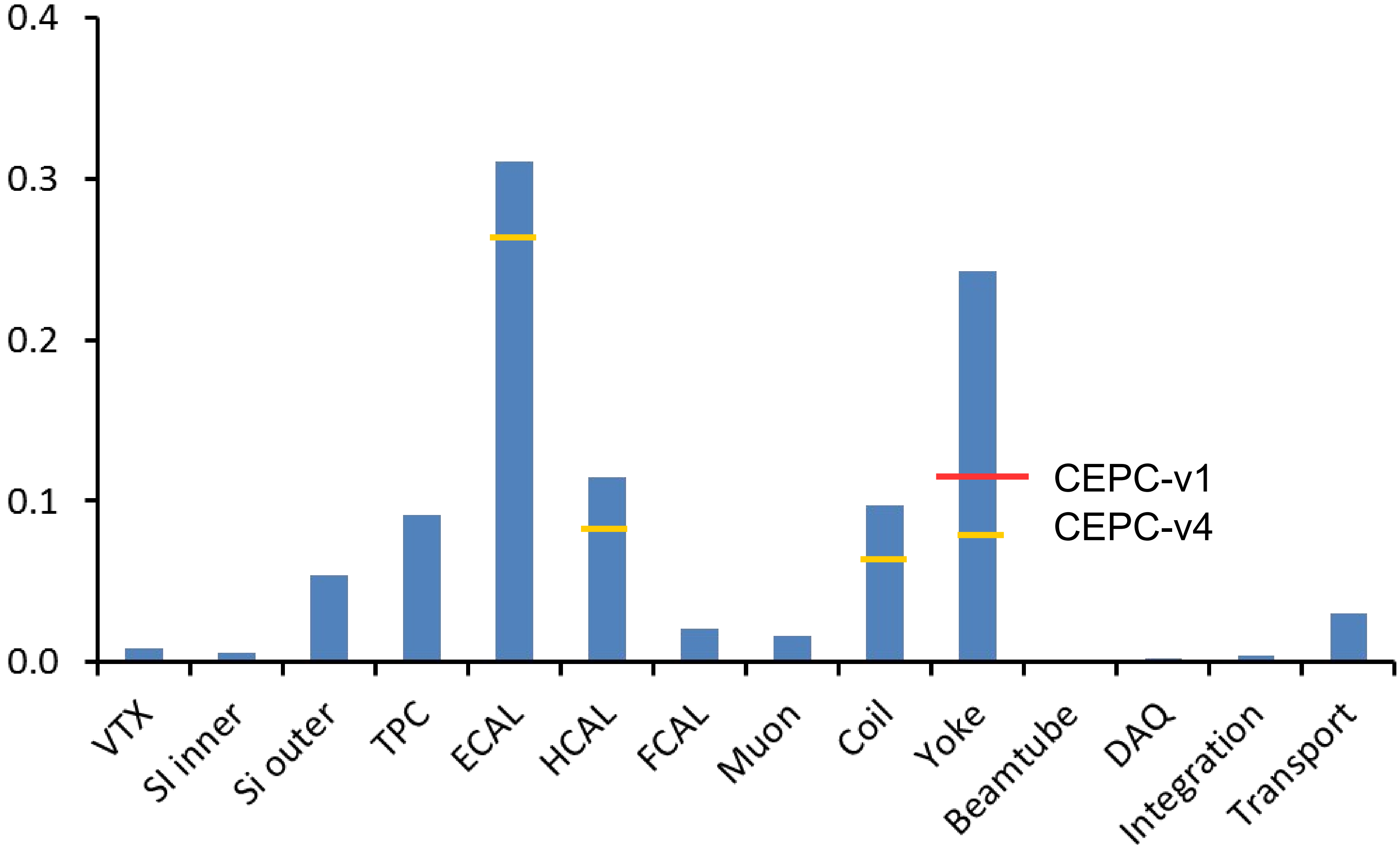
pp cross sections



	Yield	efficiency	Comments
LHC	Run 1: 10^6 Run 2/HL: 10^{7-8}	~o(10^{-3})	High Productivity & High background, Relative Measurements, Limited access to width, exotic ratio, etc, Direct access to g(ttH), and even g(HHH)
CEPC	10^6	**~o(1)**	Clean environment & Absolute measurement, Percentage level accuracy of Higgs width & Couplings

Example Working Points & Performance for Object identification (Preliminary)

	Efficiency	**Purity**	**Mis-id Probability from Main Background**
Leptons	99.5 – 99.9%	99.5 – 99.9% at Higgs Runs(c.m.s = 240 GeV), Energy dependent	$P(\pi^{\pm} \rightarrow leptons) < 1\%$
Photons*	99.3 – 99.9%	99.5 – 99.9% at Higgs Runs Energy Dependent	$P(\text{Neutron} \rightarrow \gamma) = 1\text{-}5\%$
Charged Kaons**	86 – 99%	90 – 99% at Z pole Runs (c.m.s = 91.2GeV, Track Momentum 2- 20 GeV)	$P(\pi^{\pm} \rightarrow K^{\pm}) = 0.3 - 1.1\%$
b-jets	80%	90% at Z pole runs ($Z \rightarrow qq$)	$P(\text{uds} \rightarrow \text{b}) = 1\%$ $P(\text{c} \rightarrow \text{b}) = 10\%$
c-jets	60%	60% at Z pole runs	$P(\text{uds} \rightarrow \text{c}) = 5\%$ $P(\text{b} \rightarrow \text{c}) = 15\%$


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