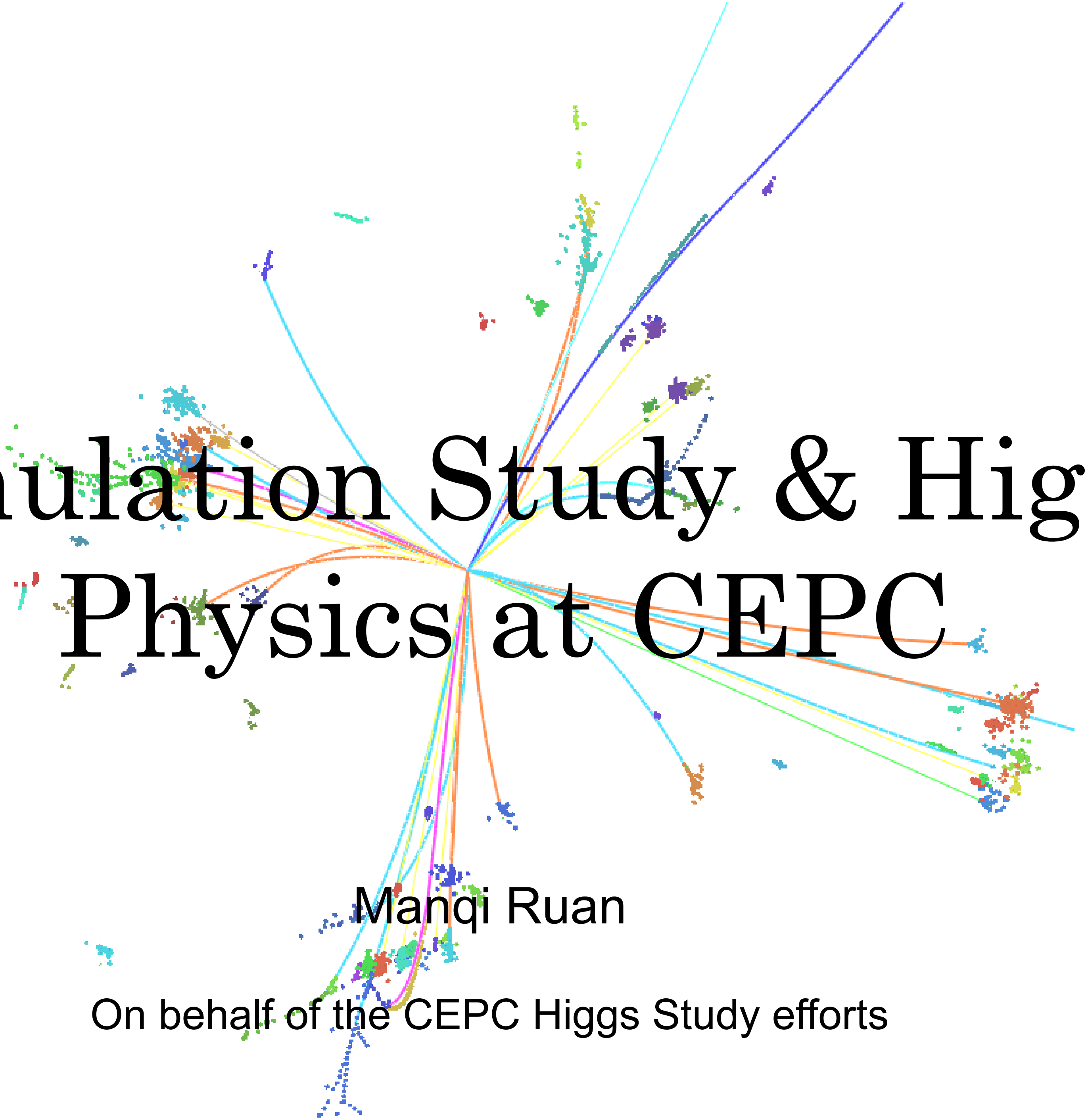
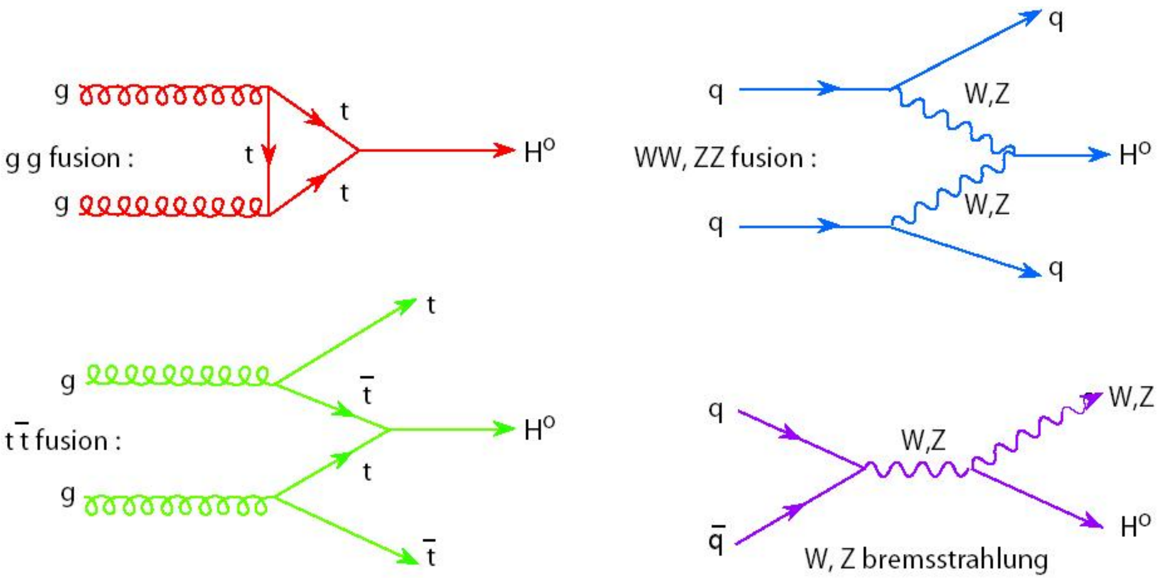
Simulation Study & Higgs Physics at CEPC

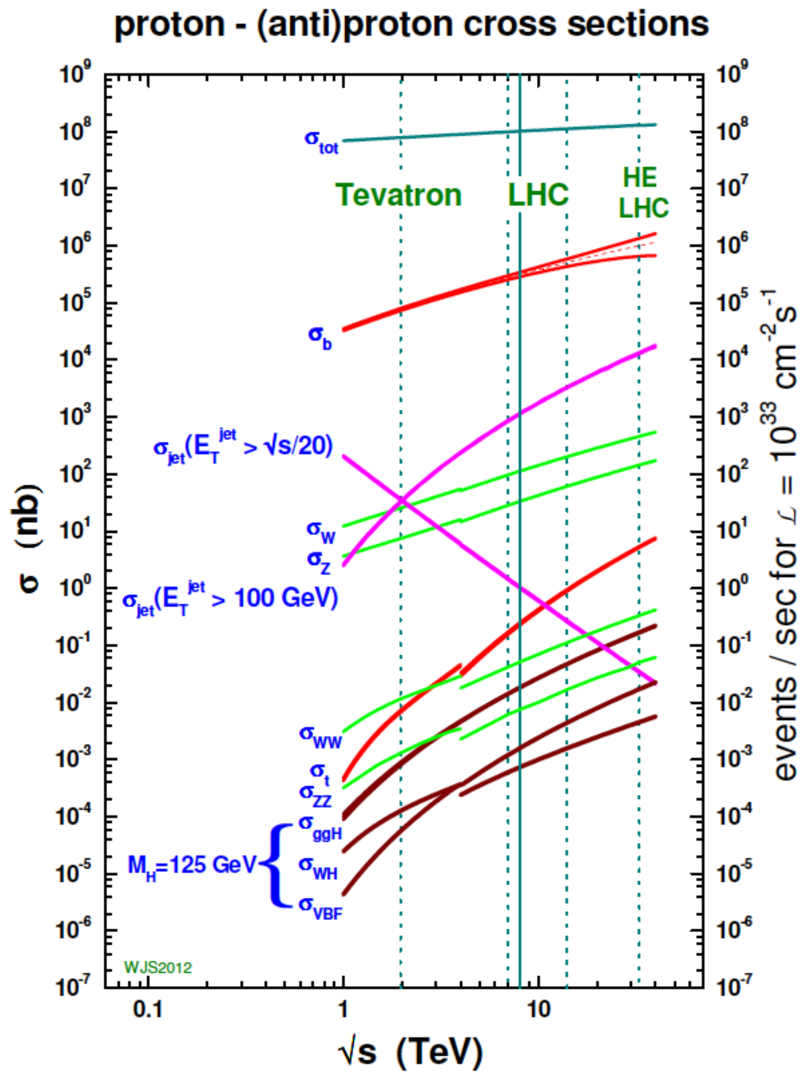


Manqi Ruan

On behalf of the CEPC Higgs Study efforts

Higgs @ LHC

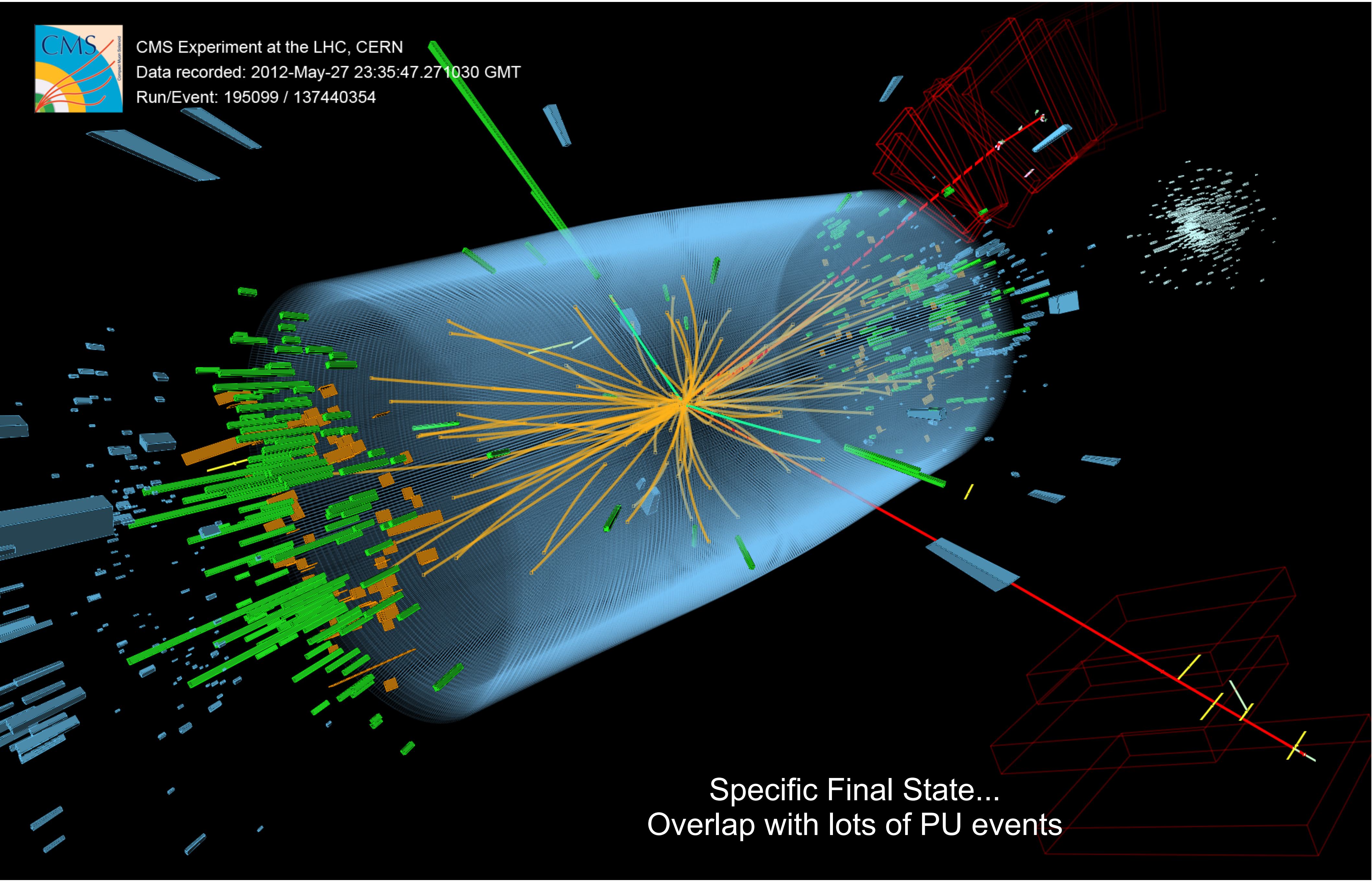




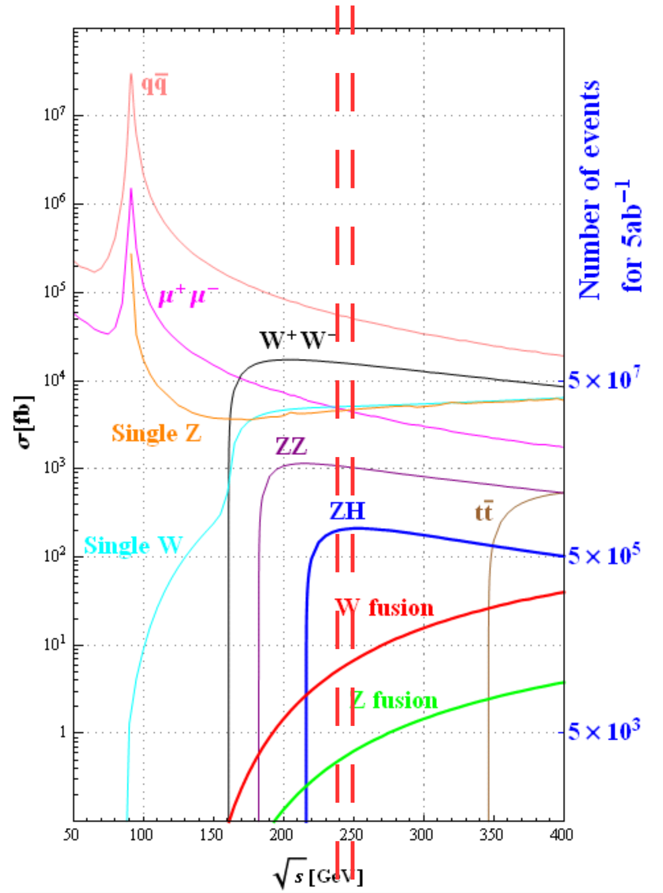
PP collider: High productivity but low finding efficiency
~already 10^6 Higgs in Run 1 data...

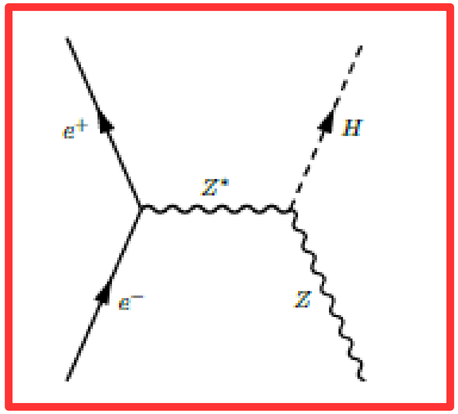
Higgs signal: found via the decay final states.

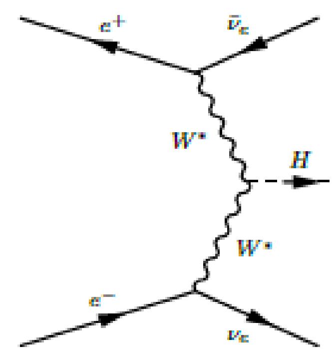
$$\sigma(AA\rightarrow H\rightarrow BB) \sim g^2(HAA)g^2(HBB)/\Gamma_{total}$$

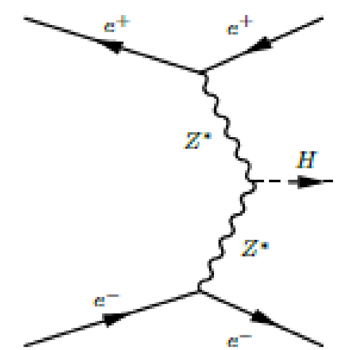

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
Specific Final State...
Overlap with lots of PU events

Higgs @ CEPC







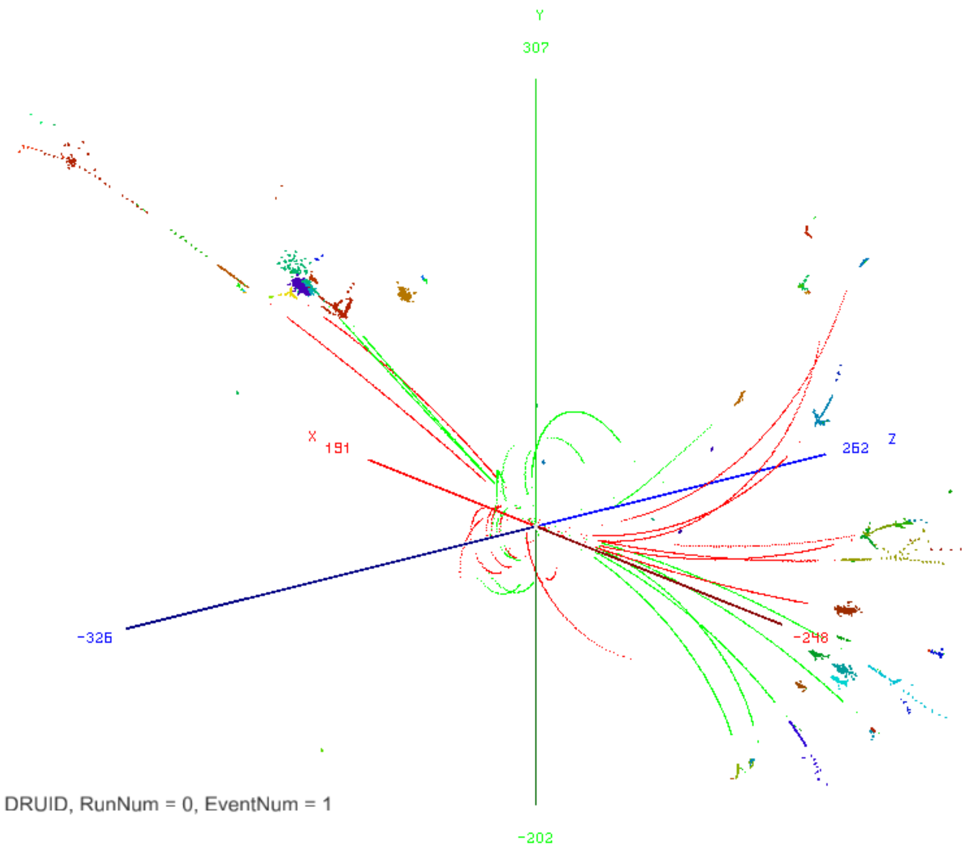


Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

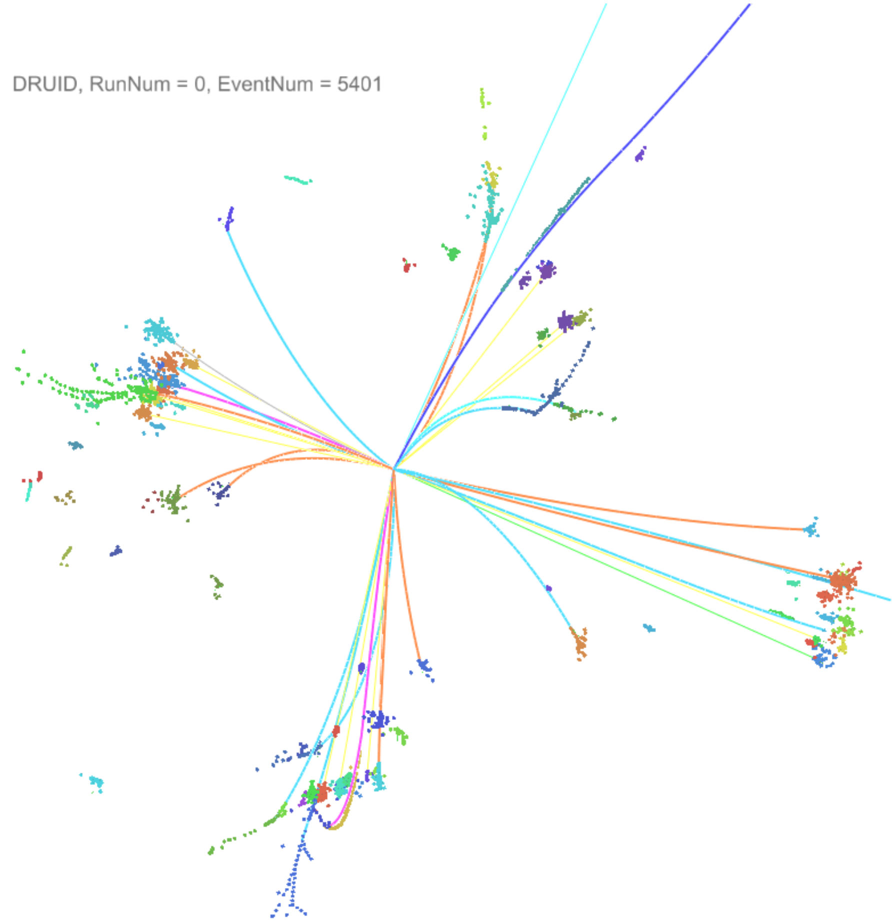
Observables: Higgs mass, CP, σ(ZH), event rates (σ(ZH, vvH)*Br(H->X))

Derive: Higgs width, branching ratios & absolute value of coupling constants

Simulated Higgs Event @ CEPC



~25% of Higgs events



~50% of Higgs events

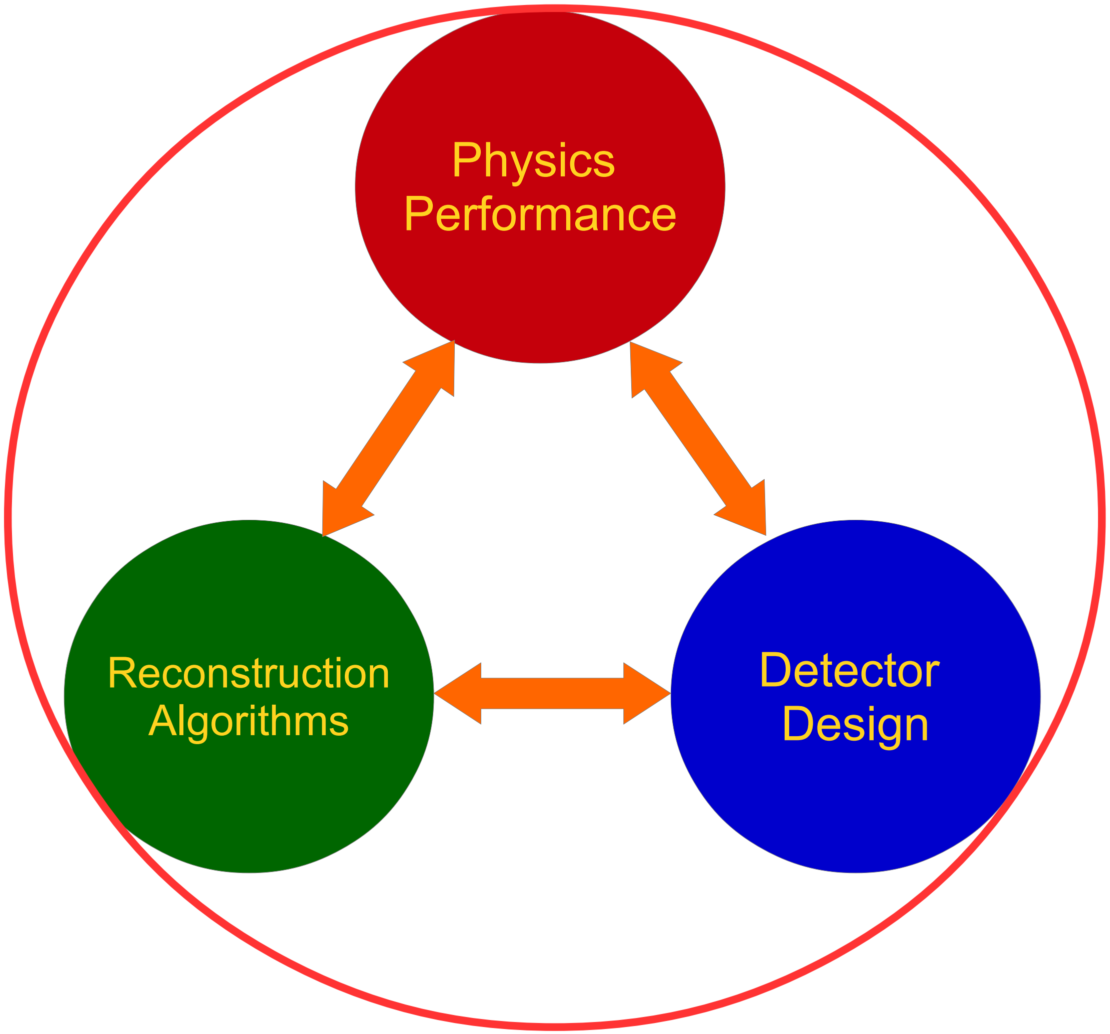
Higgs at e+e- & proton colliders

	Productivity	Finding efficiency	Remarks
LHC	Run 1: 10^6 Run 2/HL: 10^{7-8}	~o(10^{-3})	Lots of Pile Up; Large theoretical/systematic uncertainties. Access to signal strength in major decay channels; Access to g(HHH)/g(Htt).
CEPC	10^6	~o(1)	Absolute measurements in very clean environment; o(0.1%) accuracy on key observable (g(HZZ)); Excellent precision to total width, invisible/exotic decay ratios; Indirect constrain to g(HHH)/g(Htt);
SPPC - FCC-hh	10^{9-10}	> o(10^{-2})??	Good access to Higgs rare decay/generation, g(HHH)/g(Htt),

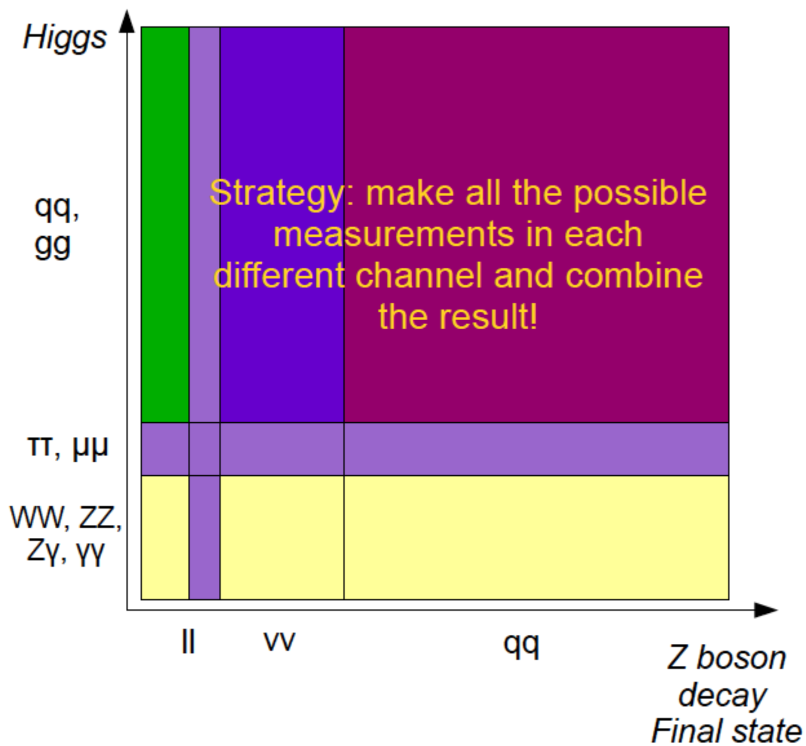
High complementarity between electron-positron & pp colliders

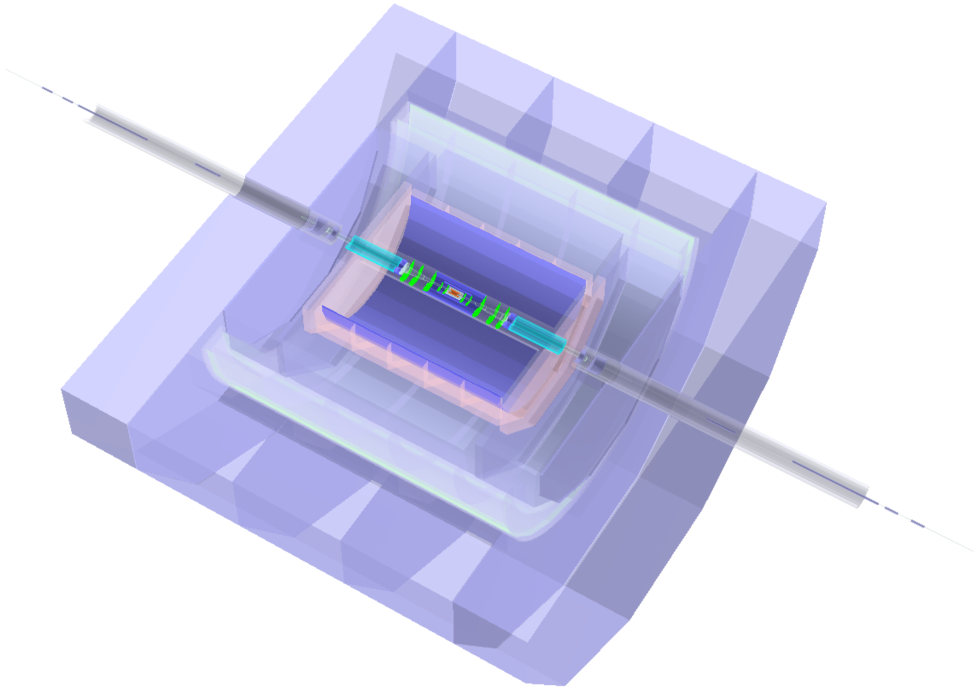
Simulation: Objectives

- **Explore & Demonstrate the Physics Potential**
  - ***Cooperate with Theory/pheon studies***
- **Deliver the optimized detector design**
  - ***Cooperate with machine/Detector hardware design***
- **Develop the mandatory software tools**



CEPC Conceptual detector, developed from ILD

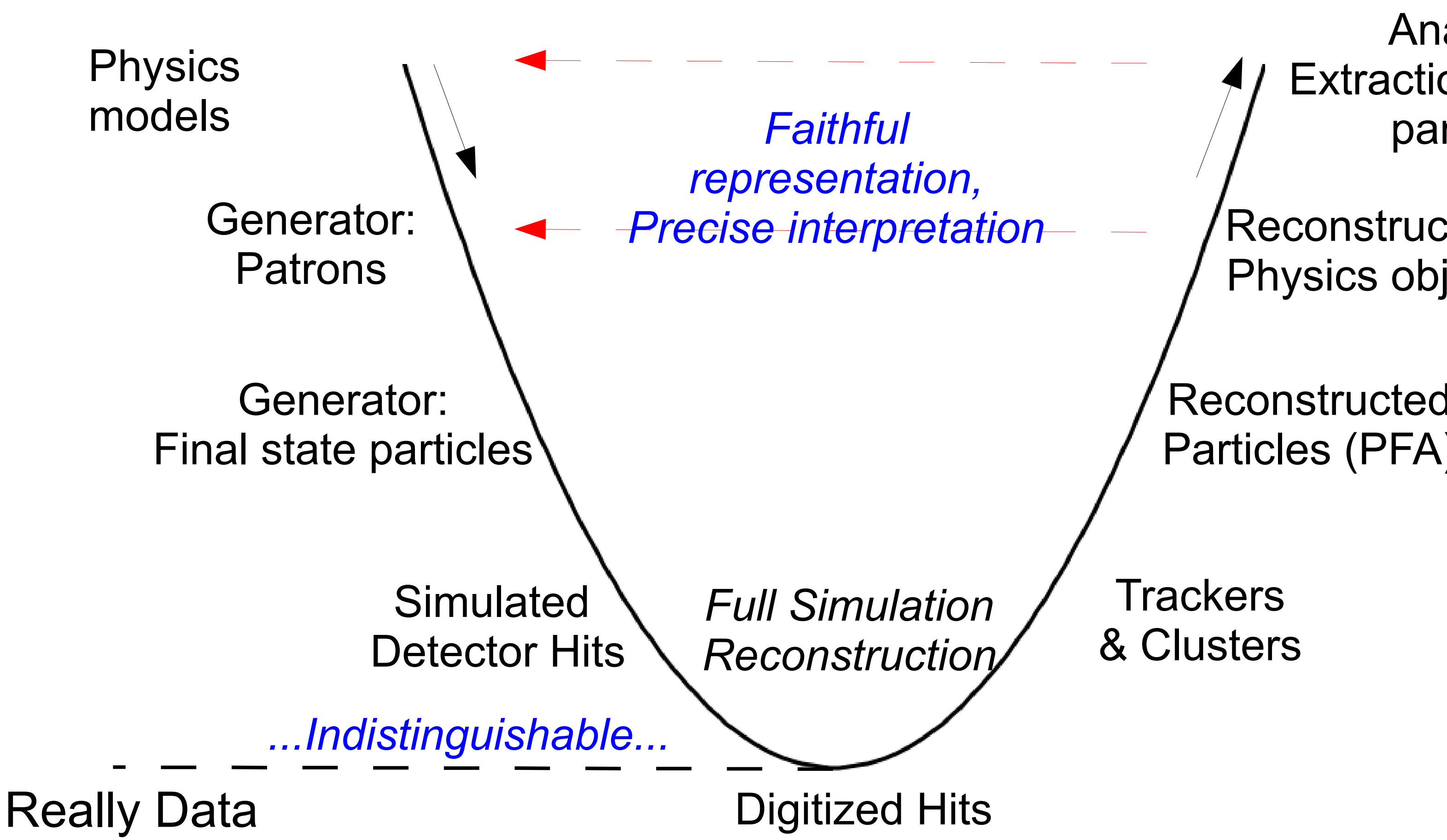




A detector reconstruct all the physics object (lepton, photon, tau, Jet, MET, ...) with high efficiency/precision

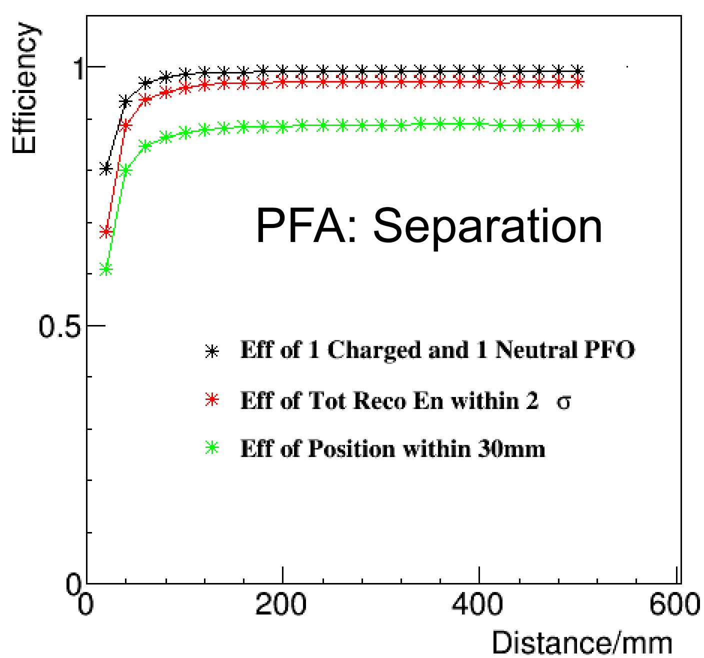
High Precision VTX located close to IP: b, c, tau tagging
High Precision Tracking system: $\delta(1/Pt) \sim 2*10^{-5}(GeV^{-1})$
PFA oriented Calorimeter System (~o(10^8) channels): Tagging, ID, Jet energy resolution, ect

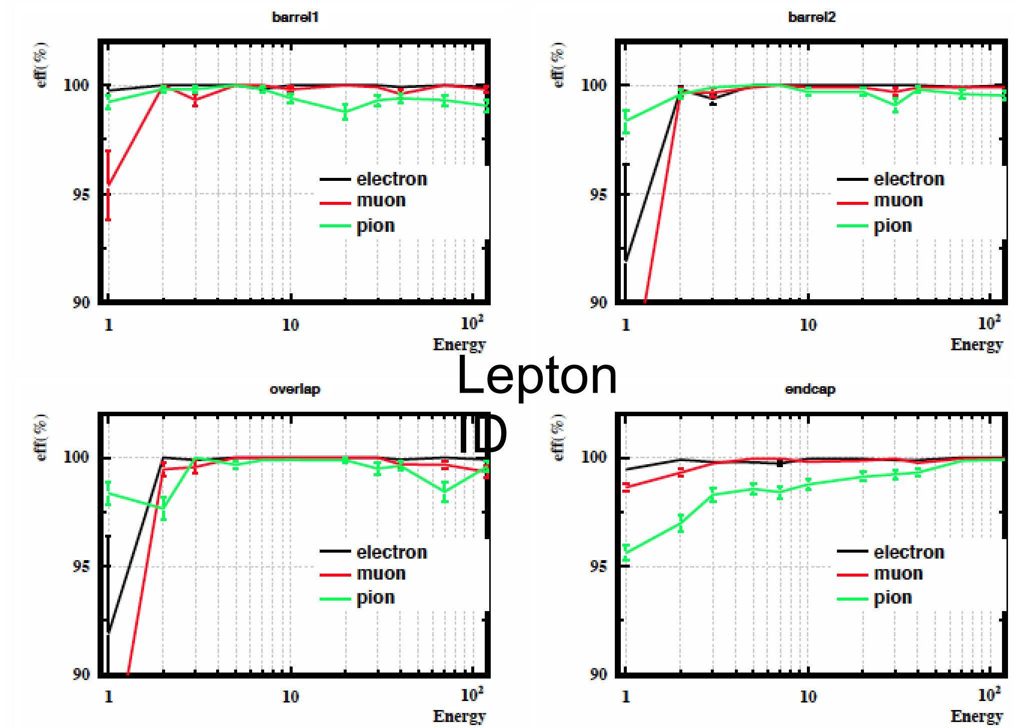
Software Toolkits & information Chain

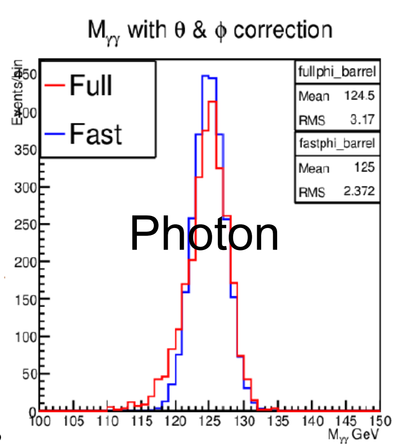


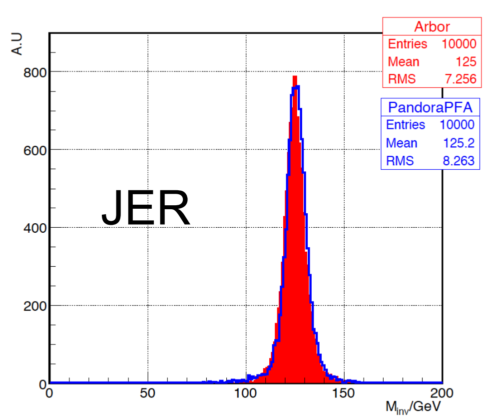
Fully operational;
Many crucial packages (Simulation, Digitization, PFA-PID, Event Displays) developed

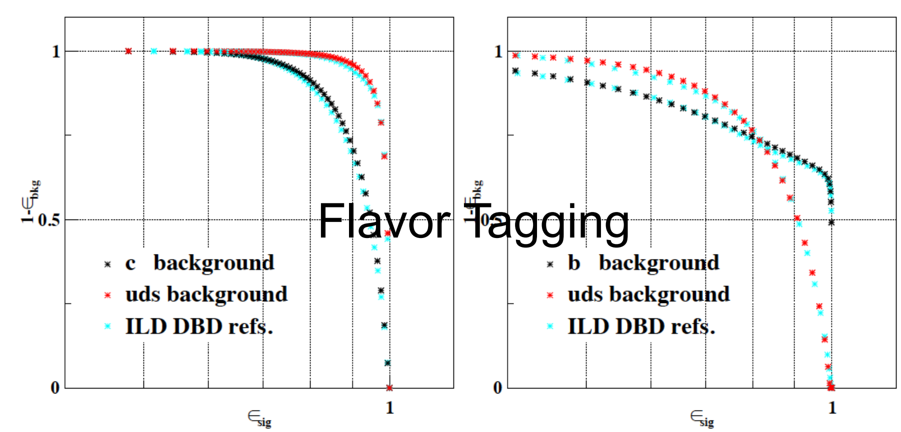
Reconstructions







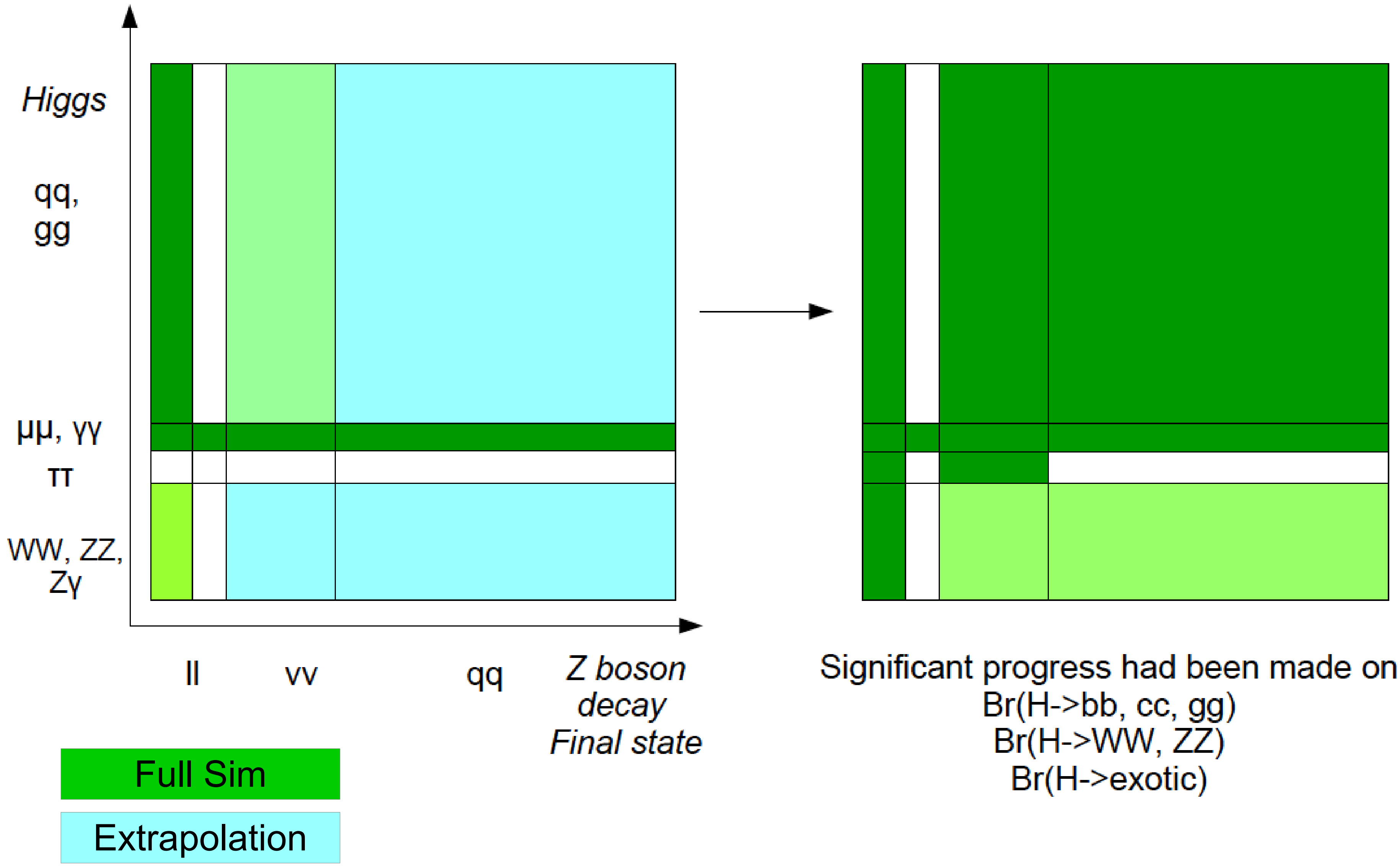




CEPC Higgs program: a sub-set

- Higgs rates: ~ **200** analyses according to composition of physics objects (e, mu, tau, b, c, g, MET):
  - Recoil mass and Xsec measurement via eeH, mumuH and qqH: 3 independent analyses
  - Jets: 4-5 independent analyses
    - σ(eeH, mumuH, vvH, qqH & tautauH)*Br(H->bb, cc, gg)
    - vvH event need to be decoupled into Z->vv and W fusion contributions
  - Simple Objects: 14 – 15 analyses
    - σ(eeH, mumuH, vvH, qqH & tautauH)*Br(H->tautau), Br(H->mumu), Br(H->di photon)
  - Br(H->ZZ/WW/Zgamma): exclude all events with tau...
    - σ(eeH, mumuH, vvH, qqH, tautauH)*Br(H->ZGamma), Z->ee, mumu, tautau, vv, bb, cc, uds, 35 analyses...
    - σ(eeH, mumuH, vvH, qqH, tautauH)*Br(H->WW*), WW*->llvv, lvqq, 4q: **50** analyses
    - σ(eeH, mumuH, vvH, qqH, tautauH)*Br(H->ZZ*), ZZ*->4l, llvv, llqq, vvqq, 4q: **70** analyses
- Higgs exotics: 25 analyses
  - Higgs->invisible: via eeH, mumuH, qqH: 3 ananlyses
  - ZH->llvvbb: 2 analyses
  - Br(Higgs->ee, emu, etau, mutau), 20 analyses
- Higgs Differential Xsec: as for quantum number measurements

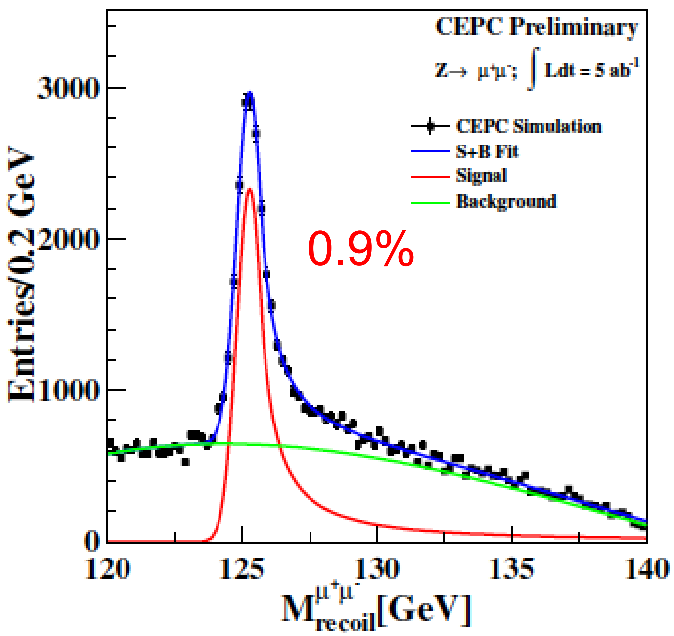
PreCDR→now

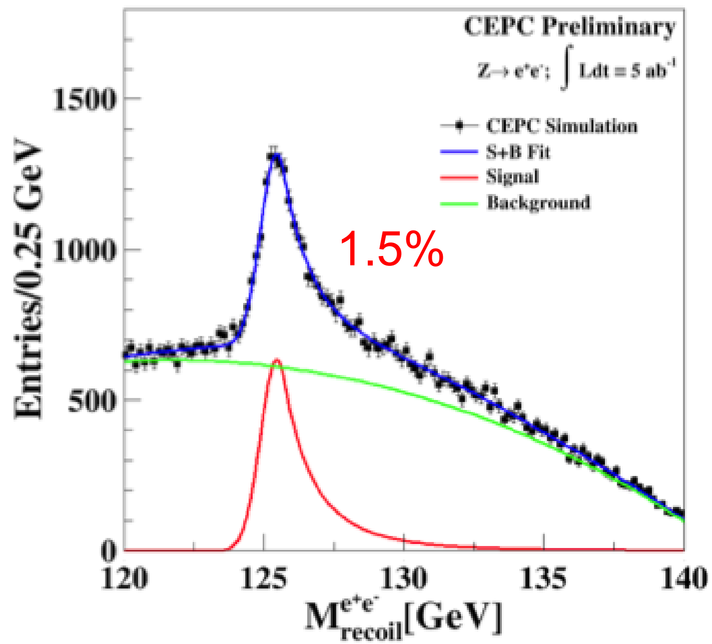


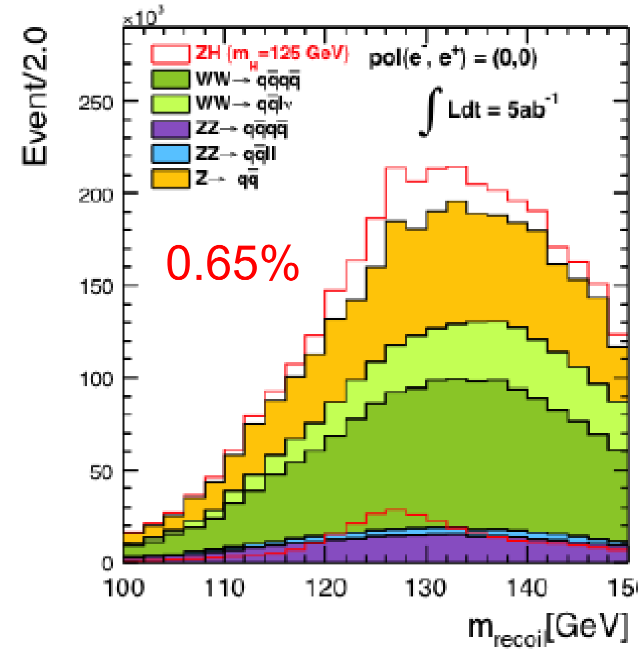
Significant progress had been made on
Br(H->bb, cc, gg)
Br(H->WW, ZZ)
Br(H->exotic)

Model-independent measurement of σ(ZH)

Zhenxing Chen & Yacine Haddad

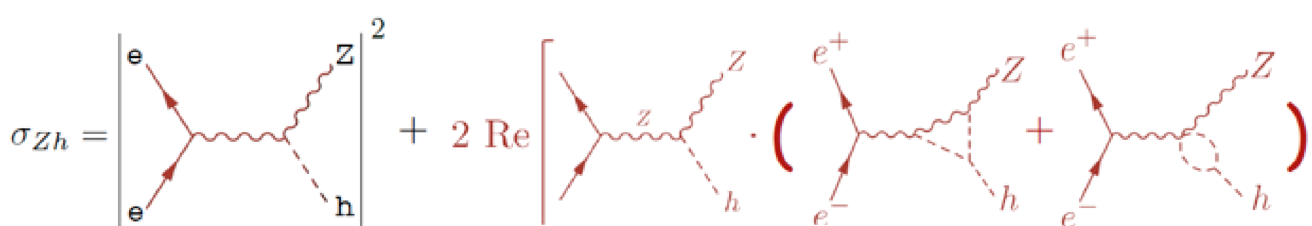






- Recoil mass method. Combined precision:
  δσ(ZH)/σ(ZH) = 0.5% -
  δg(HZZ)/g(HZZ) = 0.25%

- Indirect Access to g(HHH)



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- *M. McCullough, 1312.3322*

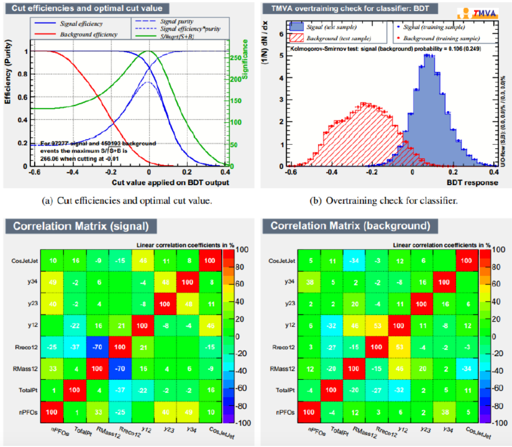
Workflow for Br(H->bb, cc, gg) measurements

Yu Bai,
Boyang,
Hao Liang,
Shuyang Hu,
Zhenxing Chen,
etc

2. Selection

Cut Definition	*Sig.*	*qq*	*qqnn*	*qqln*	*xxh*
FSClasser output	148955	25M	183687	3698817	63194
$N_{PFO(E>0.4GeV)} > 20$	148808	23M	163088	3439927	58882
$110 < E_{total} < 150$	132561	10M	125878	705357	34215
$P_T > 19$	126006	34198	116314	627602	32300
Isolation lepton veto	123586	33775	115867	327206	23773
$100 < M_{inv} < 135$	117845	9506	10420	162511	21277
$70 < M_{rec} < 125$	111886	7521	10045	110426	20458
$0.15 < y_{12} < 1$	111353	7405	9702	101797	19983
$y_{23} < 0.06$	105078	6644	8456	69313	14495
$y_{34} < 0.008$	100117	6504	7878	58532	6899
$-0.98 < \cos(\theta^{(2jets)}_{included}) < -0.4$	97277	5178	5365	33293	6273
BDT > -0.01	76666	344	118	69	1594
Significance	**265.20**				
Efficiency	**51.5%**				

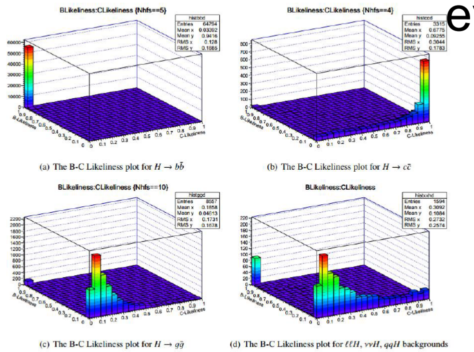
3. BDT & final results



(a) Cut efficiencies and optimal cut value. (b) Overtraining check for classifier.

Flavor tagging

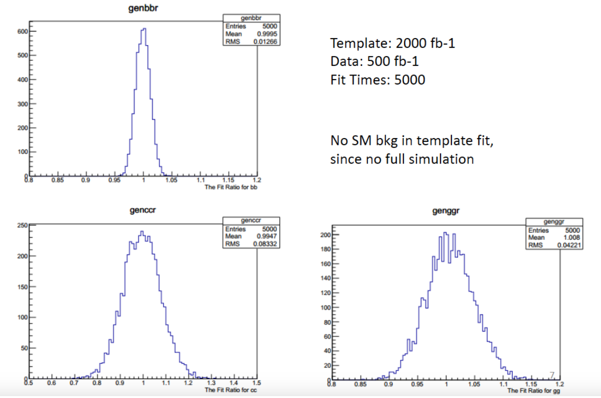
vvH events



(a) The B-C Likeliness plot for $H \to b\bar{b}$ (b) The B-C Likeliness plot for $H \to c\bar{c}$ (c) The B-C Likeliness plot for $H \to gg$ (d) The B-C Likeliness plot for $\ell\ell H$, $\nu\nu H$, qqH backgrounds

Figure 7: The B-C Likeliness characteristics for Signal and other Higgs Background. The Standard

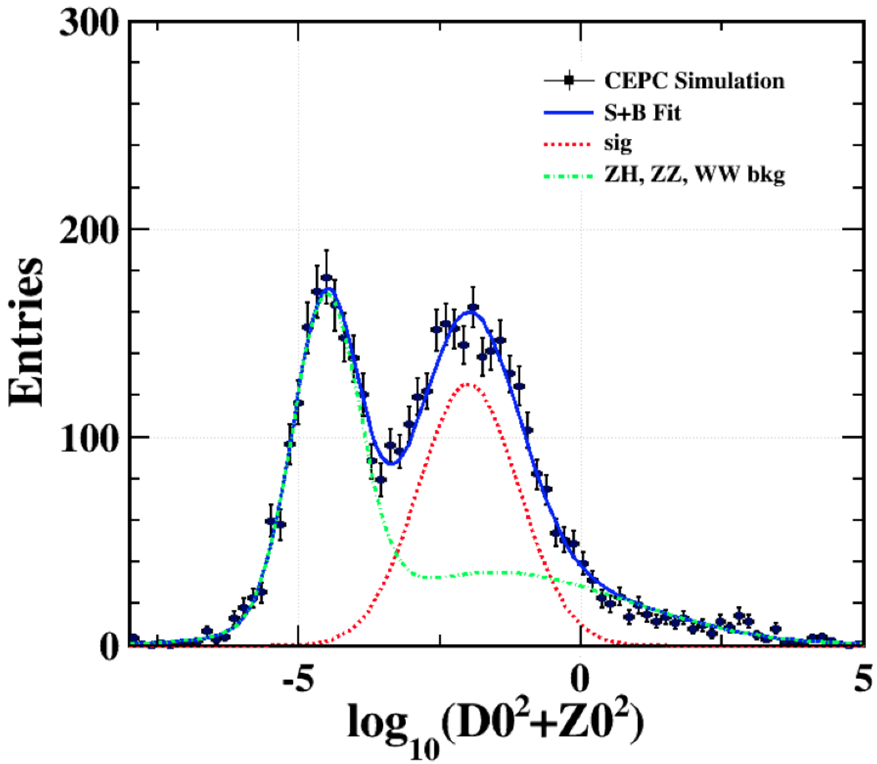
Template fit

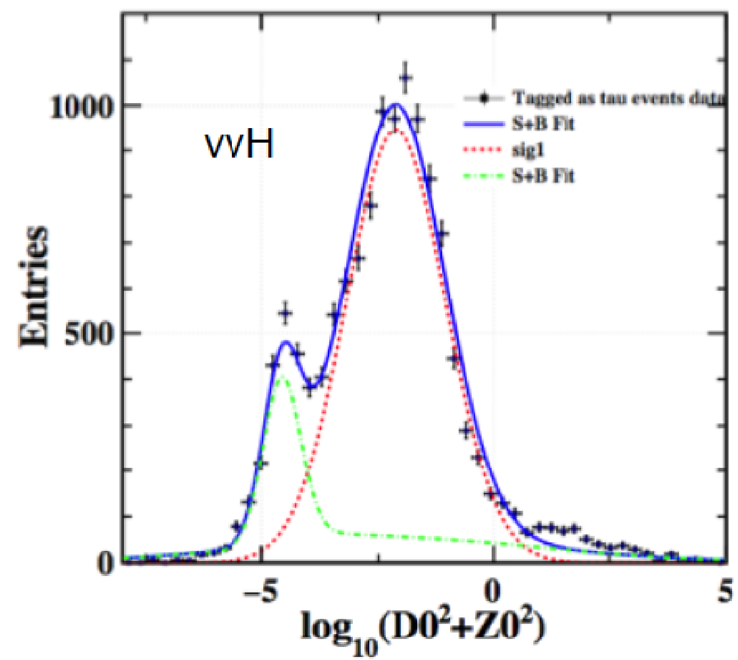


	Rbb		Rcc		Rgg		Comments
	CEPC, 5ab-1	ILC, 250fb-1	CEPC	ILC	CEPC	ILC	
mumuH	0.89%	3.3%	9.5%	22.6%	7.0%	33.0%	Full Simulated Sig + Bkg (Bkg using pre-selection technology)
eeH	1.3%	3.8%	11.8%	26.8%	10.6%	31.3%	
qqH	0.25%	1.5%	12.2%	10.2%	18.8%	13.1%	
vvH	0.4%	2.0%	2.7%	11.0%	1.3%	14.0%	Full Sim Sig + Fast Sim Bkg for event selection; No SM Bkg for Template fit
combined	0.2%	1.0%	2.5%	6.9%	1.3%	8.5%	

Br(H→di tau)

Dan Yu

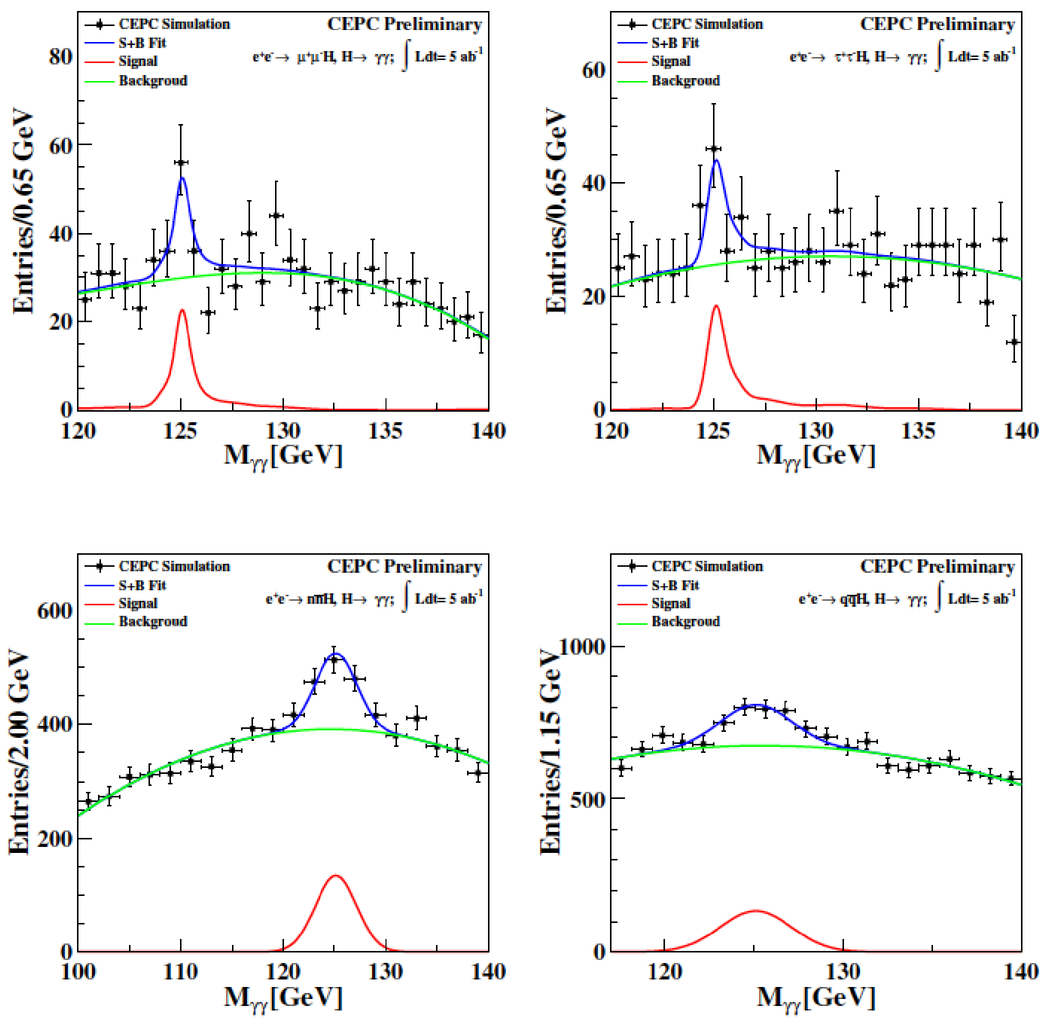




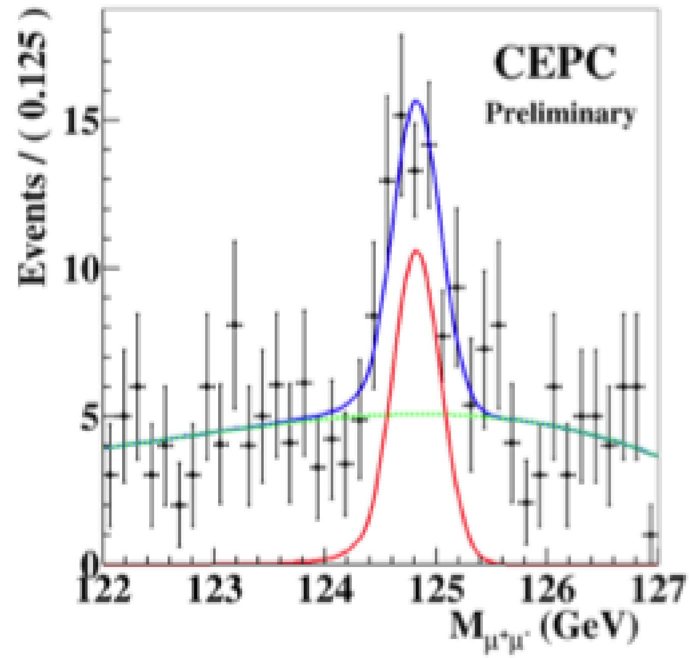
	Status	Accuracy
mumuH	Full Simulated Signal and SM background	3%
eeH	-	
vvH	Full Simulated Signal and Higgs background Await for SM background generation	1%
qqH	Await for tau finder in jet environment	
Combined		< 1%

Higgs rare decay

Feng Wang, Jianhuan Xiang, etc



Binlong Wang, Zhenwei Cui

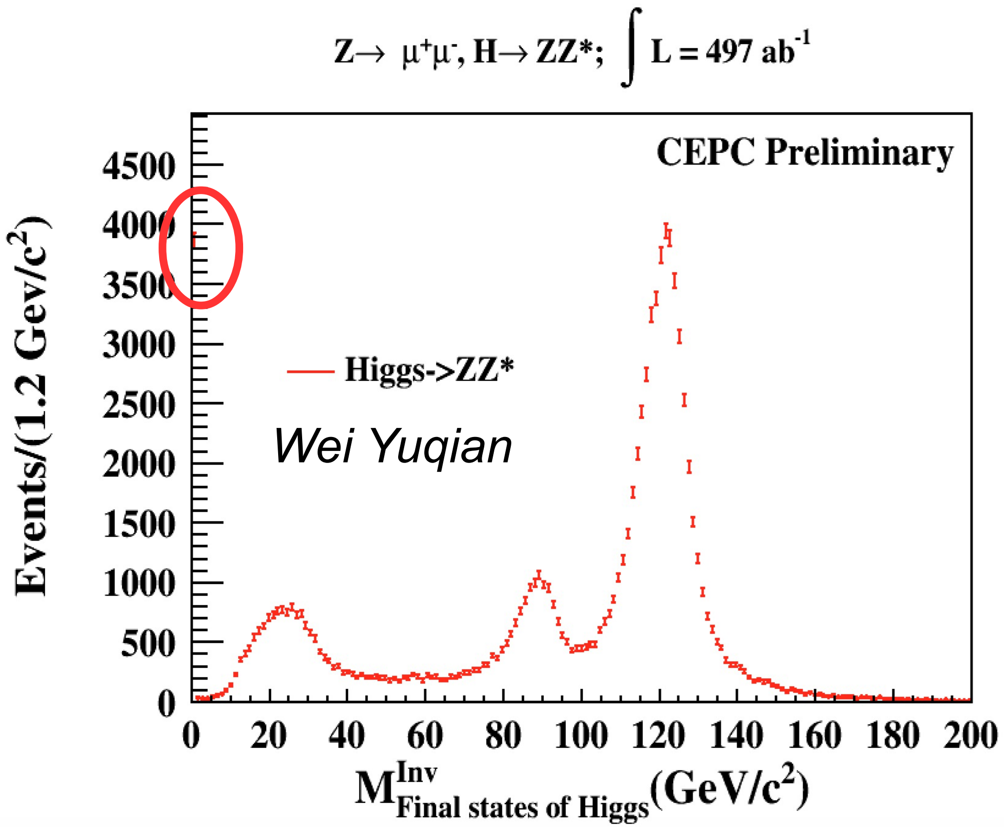


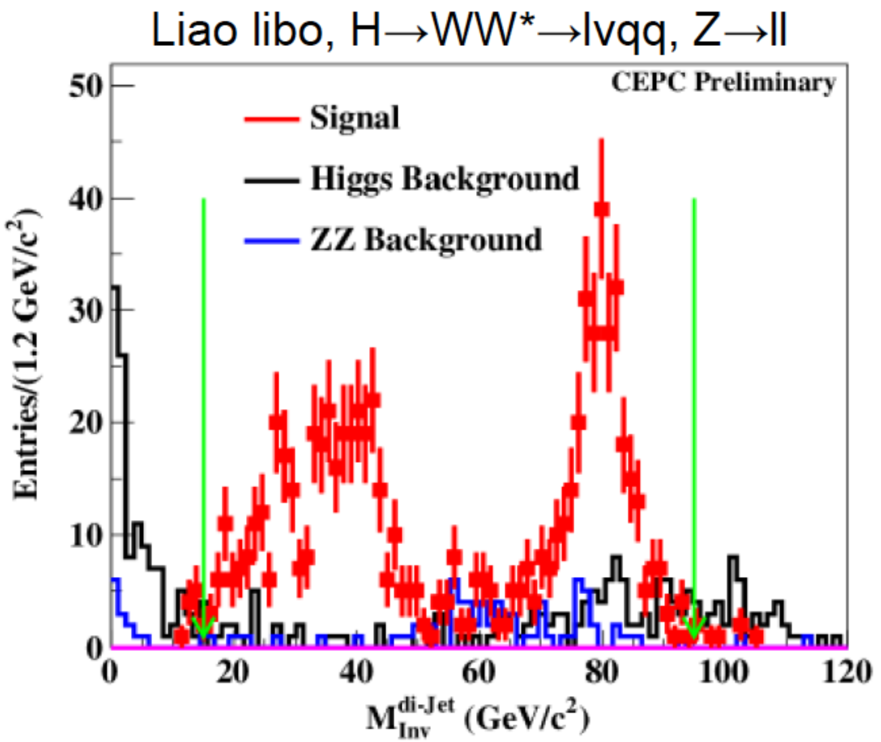
Br(H→γγ):
photon identification efficiency
& ECAL intrinsic resolution

Br(H→μμ):
Muon identification & Track
Momentum resolution

Higgs to ZZ/WW

Portal to Higgs width & perfect test bed for detector/reconstruction performance...





Br(H→WW)

Expected Number of events with different objects

	Z→ll	tautau	vv	qq
H→WW*→4q	6.91k	3.45k	19.74k	69.1k
μvqq	2.27k	1.14k	6.47k	22.7k
evqq	2.27k	1.14k	6.47k	22.7k
eevv	186	93	527	1.9k
μμvv	186	93	527	1.9k
eμvv	372	186	1154	3.7k
X + tau	3.2k	1.6k	9.14k	32.0k

LB. Liao

Purple	Extrapolated from ILC results
Cyan	Await for tau finder
Yellow	Await for the SM Background simulation
Dark green	Full Simulation
Light green	Preliminary result acquired
White	Unexplored

Br(H→WW)

ZH, H->WW*	Yield	Object reconstructed	Isolation	Signal Efficiency	Main Background	Accuracy	Combined
Z(μμ)H(evev)	88	76(86.36%)	61(80.26%)	36(40.91%)	4(ZH)	17.57%	2.68%
Z(μμ)H(μvμv)	89	80(89.89%)	77(96.25%)	52(58.43%)	6(ZH&ZZ)	14.65%	
Z(μμ)H(evμv)	174	157(90.23%)	147(93.63%)	105(60.34%)	0	9.76%	
Z(μμ)H(evqq)	1105	1042(94.30%)	864(82.92%)	663(60.00%)	45(ZH)	4.02%	
Z(μμ)H(μvqq)	1110	1056(95.14%)	988(93.56%)	717(64.59%)	159(ZH&ZZ)	4.13%	
Z(μμ)H(qqqq)	Preliminary						3.0%
Z(ee)H(evev)	91	62(68.13%)	60(96.77%)	22(24.16%)	16(SZ)	28.02%	2.87%
Z(ee)H(μvμv)	82	63(76.83%)	63(100%)	44(53.66%)	24(SZ)	18.74%	
Z(ee)H(evμv)	178	132(74.16%)	124(93.94%)	82(46.07%)	25(ZH&SZ)	12.61%	
Z(ee)H(evqq)	1182	1041(88.07%)	916(87.99%)	621(51.78%)	188(SZ&ZH)	4.62%	
Z(ee)H(μvqq)	1221	1194(97.79%)	1048(87.77%)	684(56.02%)	49(ZH&SZ)	3.96%	
Z(ee)H(qqqq)	Preliminary estimation						3.2%

- Full Simulation on 12 independent channels
  - Very high object reconstruction efficiency
  - Combined result: 1.45%
- Extrapolation from other ILC channels: 1.59%
- Combined: 1.07%

	Z→ll	tautau	vv	qq
H→WW*→4q	1.45%	3.45k	2.3%	69.1k
μvqq		1.14k	6.47k	2.2%
evqq		1.14k	6.47k	
eevv		93	527	1.9k
μμvv		93	527	1.9k
eμvv		186	1154	3.7k
X + tau	3.2k	1.6k	9.14k	32.0k

Br(H→ZZ)

Expected Number of events with different objects

	Z→ll	tautau	vv	qq
H→ZZ*→4q	888	444	3.10k	9.24k
2v + 2q	508	254	1.77k	5.29k
2l + 2q	170	85	596	1.8k
4v	73	36	254	756
2l + 2v	49	24	170	508
4l	8	4	28	86
X + tau	120	60	418	1246

YQ. Wei

More than 2 jets, Await for sophisticated Jet Clustering

Await for tau finder

limited accuracy ~ > 50%

Explored by H->invisible analysis -> Accuracy ~ 40%

Promising channels

Unexplored

Br(H→ZZ)

ZZZ*	Yield	Object reconstructed	Signal Efficiency(%)	Main Background	Accuracy (%)	Comments
μμννqq	128	118	63.3	h->ww&zz_sl	**12.9**	Tau finder would be highly appreciated Reconstructed efficiency of electron need to be improved
μμqqνν	128	125	-	h->bb&zz_sl	>25	
eeννqq	132	91	53.8	h->ww&sze_sl	**15.8**	
eeqqνν	132	88	-	h->bb&zz_sl	>25	
ννμμqq	158	144	61.4	h->t,w&zz_sl	**11.0**	
ννqqμμ	158	149	51.9	h->w,b&zz_sl	**12.9**	
ννeeqq	151	118	43.1	h->w&sze_sl	**21.3**	
ννqqee	151	134	-	h->bb&sze_sl	>25	
qqμμνν	135	115	-	h->tt&zz_sl	>25	Compare to ll recoil, qq recoil mass has much worse distinguishing power to SM background
qqννμμ	135	122	-	h->t,w&zz_sl	>25	
qqeeνν	127	107	-	h->tt&sze_sl	>25	
qqννee	127	123	-	h->t,w&sze_sl	>25	
μμμμqq/qqμμ	43	39	69.8	h->tt&zz_sl	**19.9**	Tau finder & Electron Reconstruction
μμeeqq/qqee	43	39	60.5	h->tt&zz_sl	**21.2**	
eeeeqq/eeqqee	43	33	-	h->tt&sze_sl	>25	
eeμμqq/eeqqμμ	43	41	58.2	h->tt&sze_sl	**19.9**	

Full Simulation analysis performed on 16 independent channels.
8 Channels acquire accuracy better than 25%.

Combined accuracy: **5.4%**

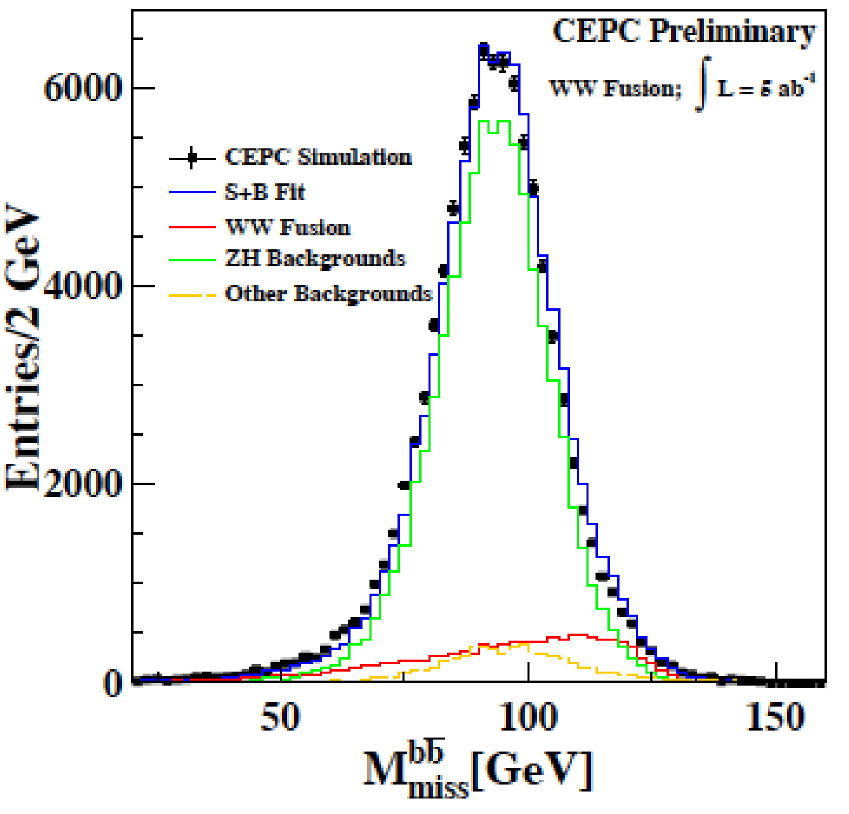
If electron id efficiency ~ muon id: ***4.8%***

TLEP extrapolation**: 4.3%**

σ(vvH)*Br(H→bb), Higgs width

- Relative Accuracy of σ(ZH)*Br(H→bb): 2.8%

- Γ_{total} : determined to:
  - 4.4% from σ(ZH) (~g^2(HZZ)) and σ(ZH)*Br(H→ZZ) (~$g^4(HZZ)/\Gamma_{total}$)
  - 3.3% from σ(ZH)*Br(H→bb), σ(vvH)*Br(H→bb), σ(ZH)*Br(H→WW), σ(ZH)
  - Combined accuracy: 2.6%

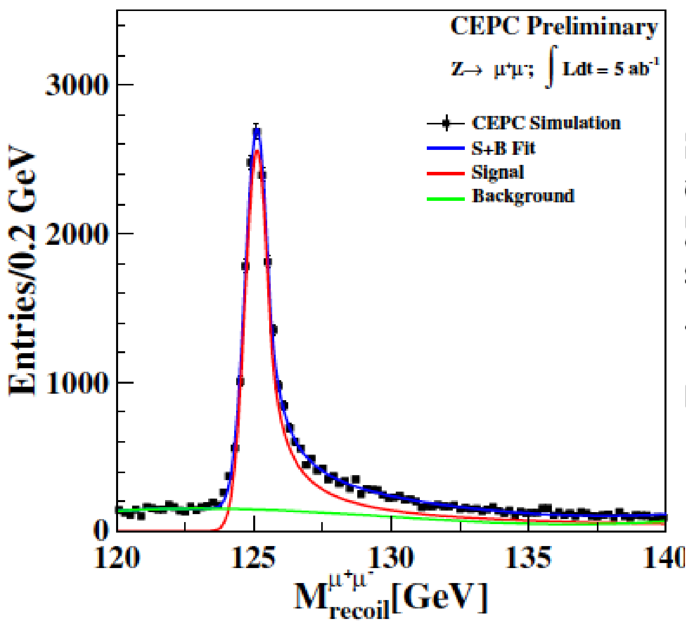


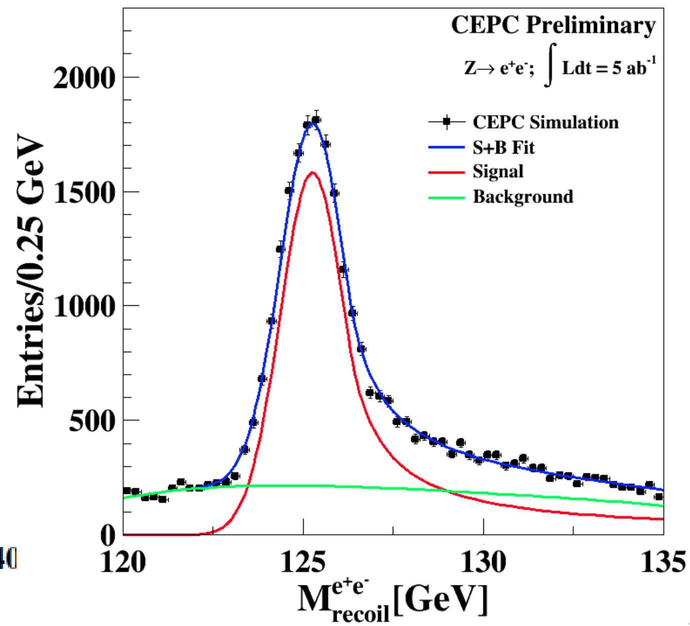
BSM

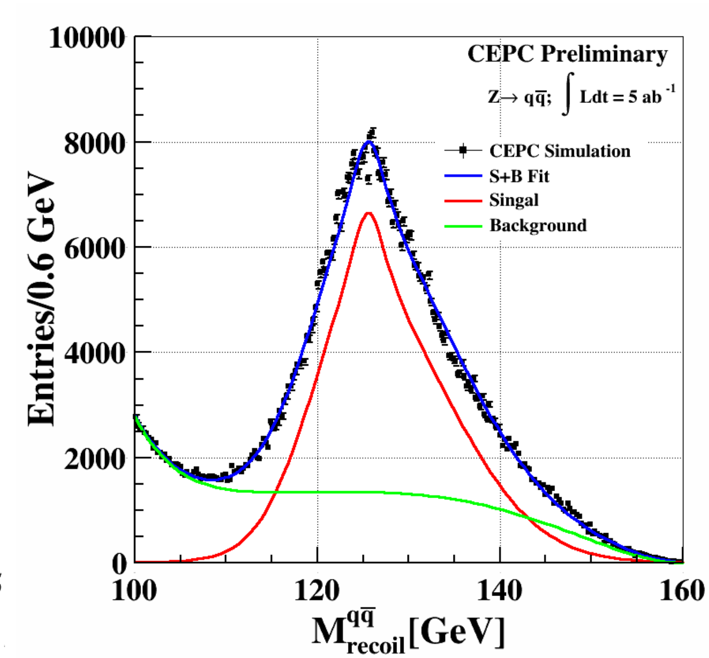
- http://arxiv.org/abs/1312.4992
- http://arxiv.org/abs/1512.06877
- http://indico.ihep.ac.cn/event/5592/contribution/5/material/slides/0.pdf

Higgs invisible decays

*Assuming sigma(ZH)*Br(H->inv) = 200 fb*





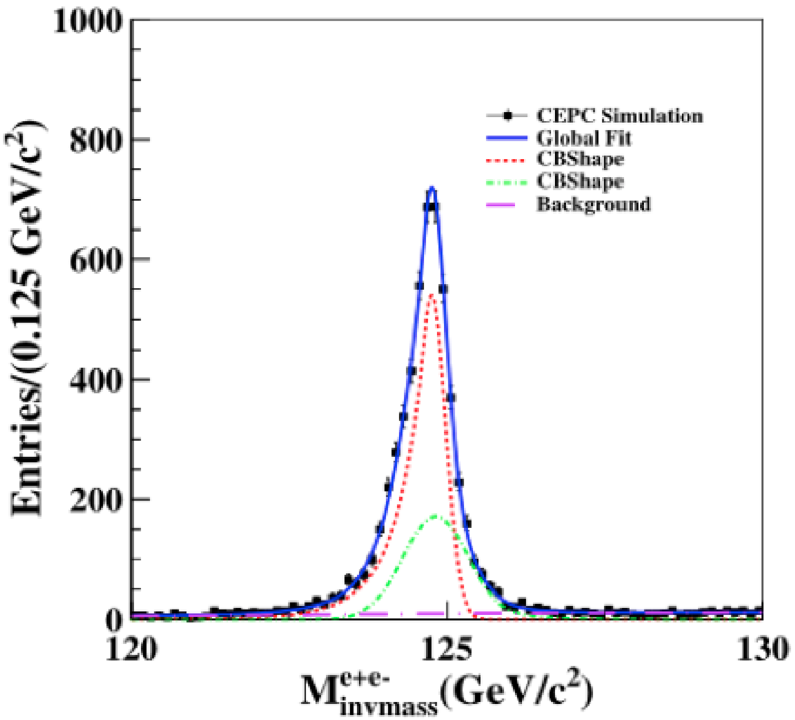


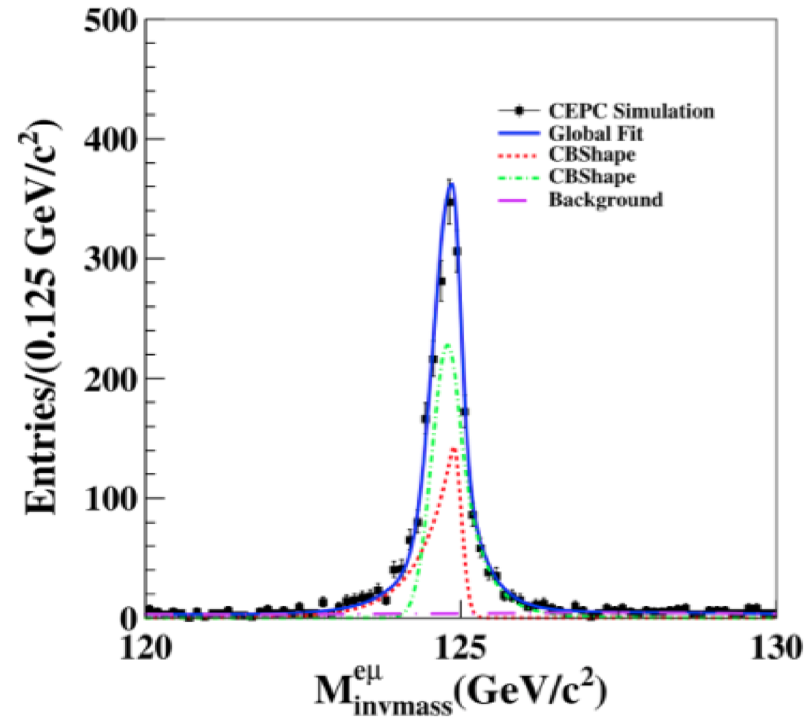
Invisible up limit at CEPC: 0.14% at 95% C.L

Up limit of Br(H→ee) & Br(H→eμ)

Lei Wang

*Assuming sigma(ZH)*Br(H->ee/eμ) = 200 fb*

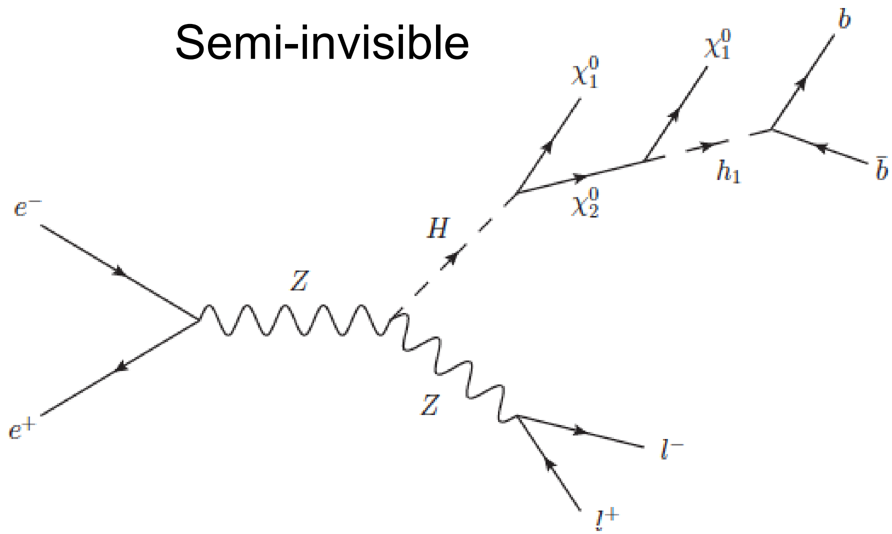




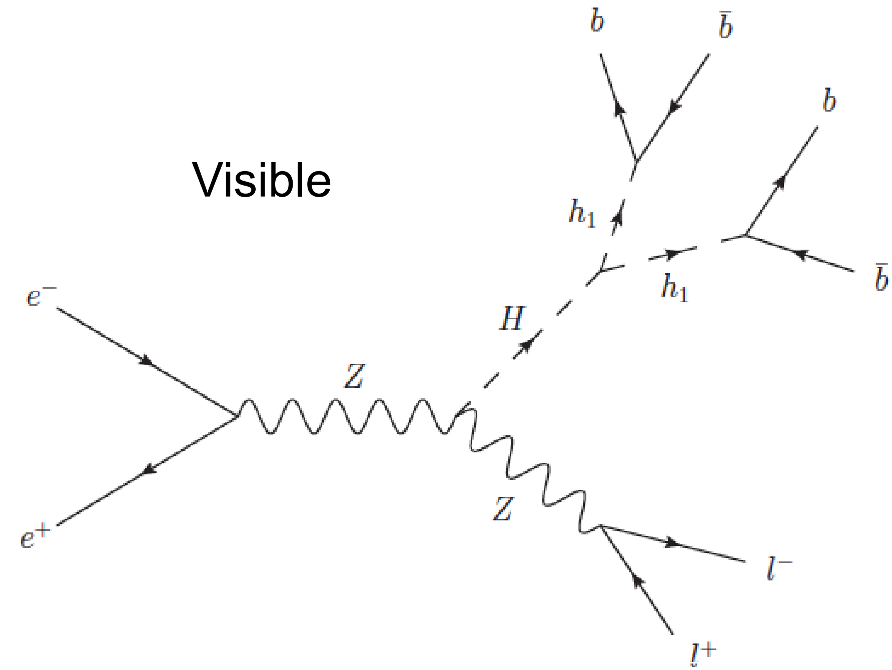
95% up limit: Br(H->ee) = 1.7e-4;
Br(H->emu) = 1.2e-4;

H→Exotic, Hadronic

Semi-invisible



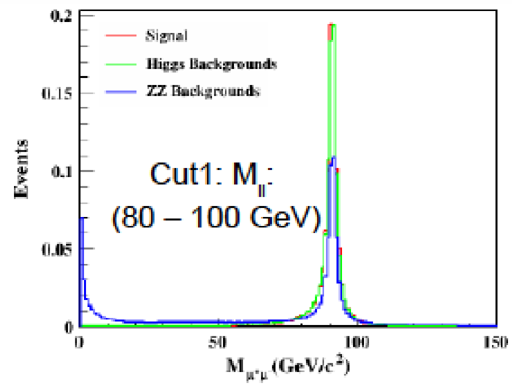
Visible

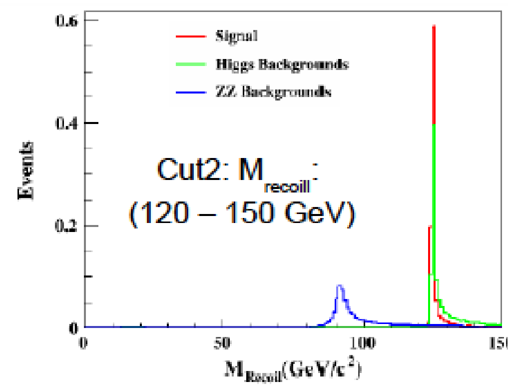


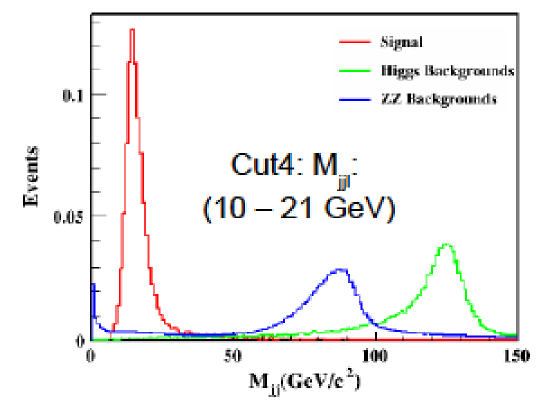
- Typical processes in 2HDM & NMSSM
- Joint efforts by HK Cluster and IHEP
  - Study proposed by T. Liu
  - Main analyzer, Jiawei Wang, Kevin & Zhenxing Chen
- 95% CL up limit ~o(10^{-4}).

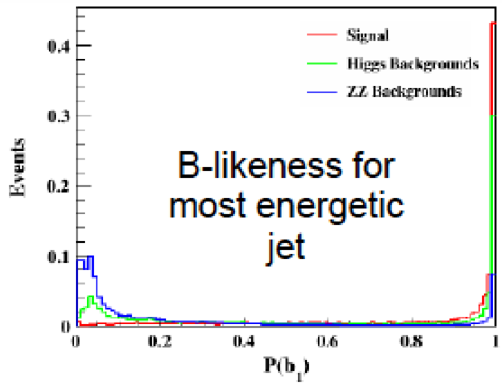
H->Exotic, hadronic

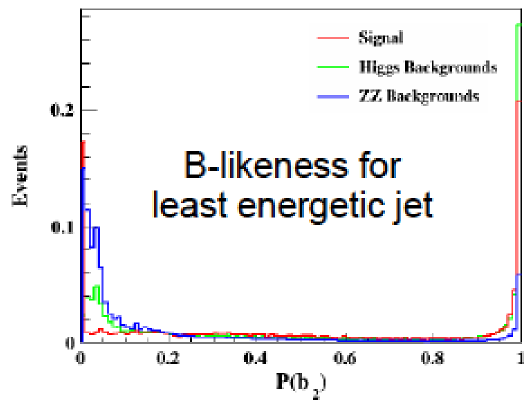
Para: M(LSP) = 0; M(h0) = 15 GeV; M(NLSP) = 20 GeV









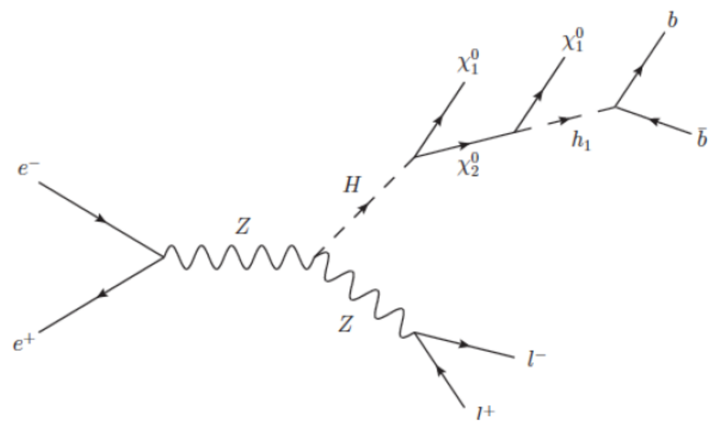


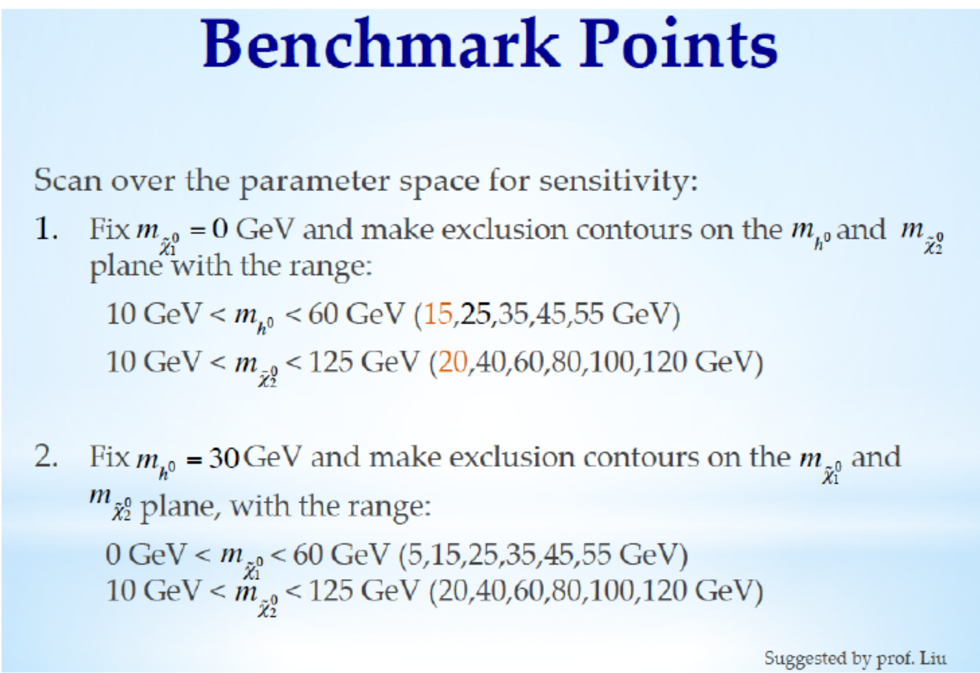
	Object found	Cut 1 m_{ll}	Cut 2 m_{rec}	Cut 3 b likeness	Cut 4 m_{jj}
Signal	17	15	15	12	10
ZH BGs	34093	30732	30030	16026	4
ZZ BGs	538790	281198	30825	4274	20

Cut3: sum(B-likeness) > 0.9

- 95% CL. Uplimt set to be 5E-4; will be significantly improved by including di-electron/tau channel...
- ISR effect not included in the Signal sample. sigma(ZH) refered to SM Xsec of 200 fb. Effect on uplimit setting could be ignored

H→Exotic, Hadronic





Benchmark Points

Scan over the parameter space for sensitivity:

1. Fix $m_{\tilde{\chi}_1^0} = 0$ GeV and make exclusion contours on the m_{h^0} and $m_{\tilde{\chi}_2^0}$ plane with the range:

   10 GeV < m_{h^0} < 60 GeV (15,25,35,45,55 GeV)

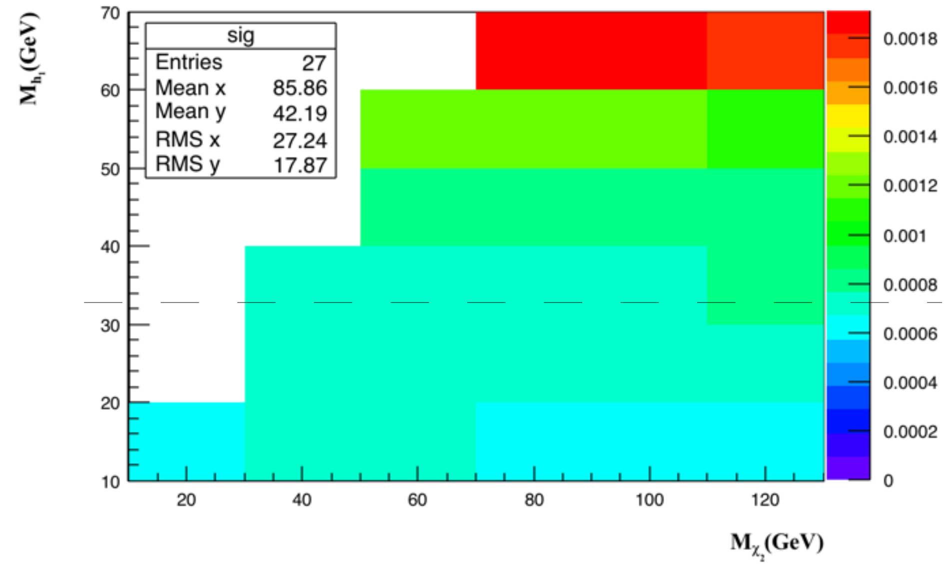
   10 GeV < $m_{\tilde{\chi}_2^0}$ < 125 GeV (20,40,60,80,100,120 GeV)

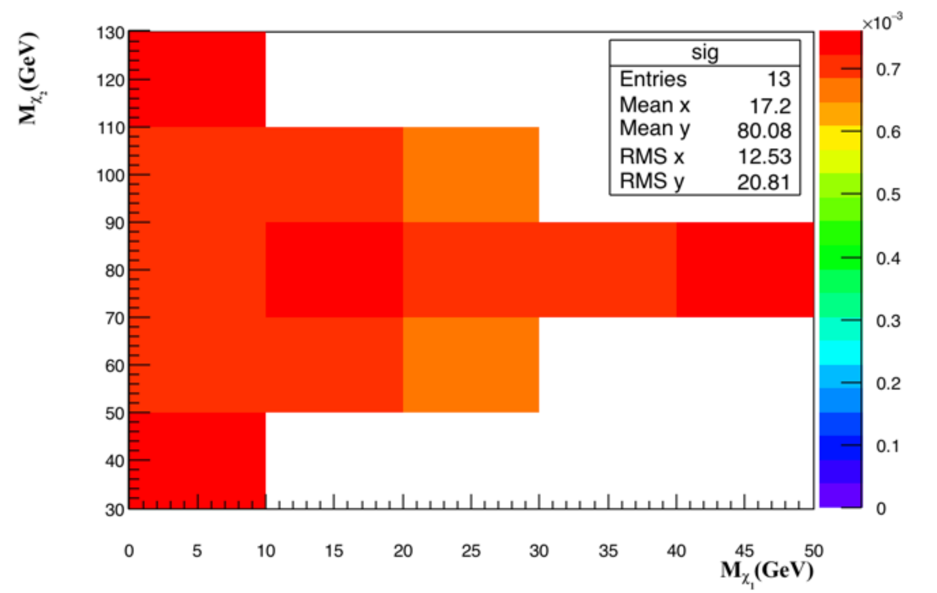
2. Fix $m_{h^0} = 30$ GeV and make exclusion contours on the $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$ plane, with the range:

   0 GeV < $m_{\tilde{\chi}_1^0}$ < 60 GeV (5,15,25,35,45,55 GeV)

   10 GeV < $m_{\tilde{\chi}_2^0}$ < 125 GeV (20,40,60,80,100,120 GeV)

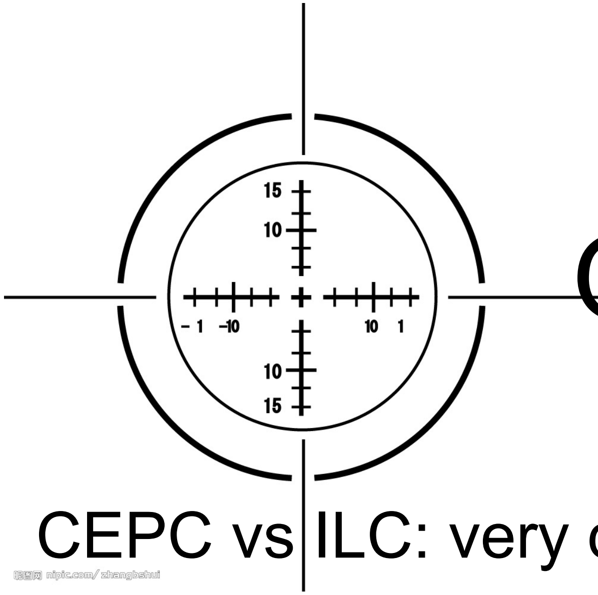
Suggested by prof. Liu





PreCDR→now

	PreCDR (Jan 2014)	Now (July 2015)
σ(ZH)	0.51%	0.50%
σ(ZH)*Br(H→bb)	0.28%	0.21%
σ(ZH)*Br(H→cc)	2.1%	2.5%
σ(ZH)*Br(H→gg)	1.6%	1.3%
σ(ZH)*Br(H→WW)	1.5%	1.1%
σ(ZH)*Br(H→ZZ)	4.3%	4.3%
σ(ZH)*Br(H→ττ)	1.2%	1.0%
σ(ZH)*Br(H→γγ)	9.0%	9.0%
σ(ZH)*Br(H→μμ)	17%	17%
σ(vvH)*Br(H→bb)	2.8%	2.8%
Higgs Mass/MeV	5.9	5.0
σ(ZH)*Br(H→inv)	95%. CL = 1.4e-3	1.4e-3
Br(H→ee/emu)	-	1.7e-4/1.2e-4
Br(H→bbχχ, 4b)	$<10^{-3}$	Br(H→bbχχ) < 3e-4



Optimization

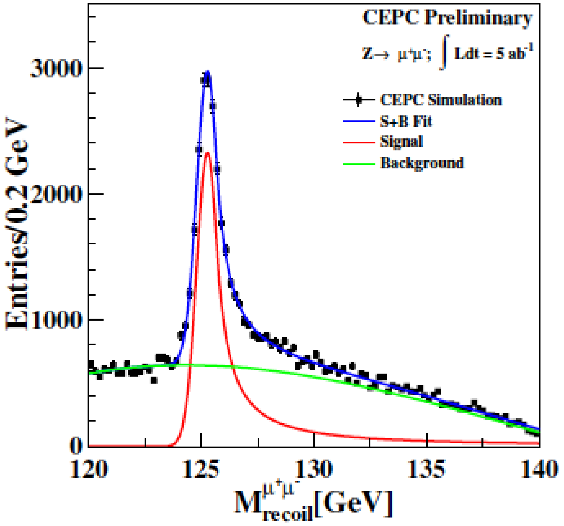
- CEPC vs ILC: very different collision environment

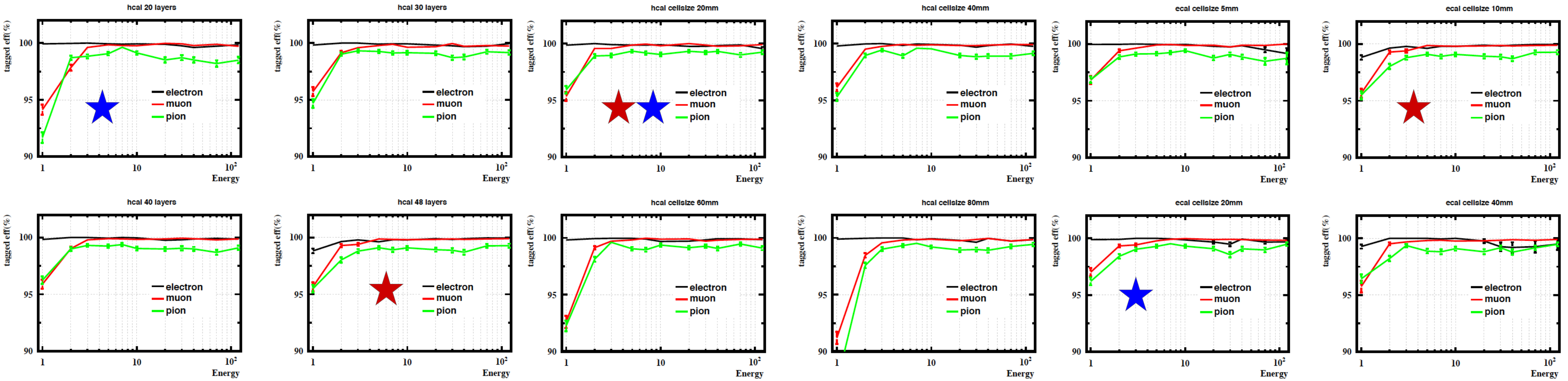
- The performance:
  - wi/wo active cooling?
  - At different tracker radius & B-Field?
  - Realistic MDI design that satisfy the Radiation & Luminosity Constrain
  - Feasibility of different technologies?
  - …
  - How to measure the beam energy to an accuracy of 1e-5?

LICH: lepton id at arbitrary granularity...

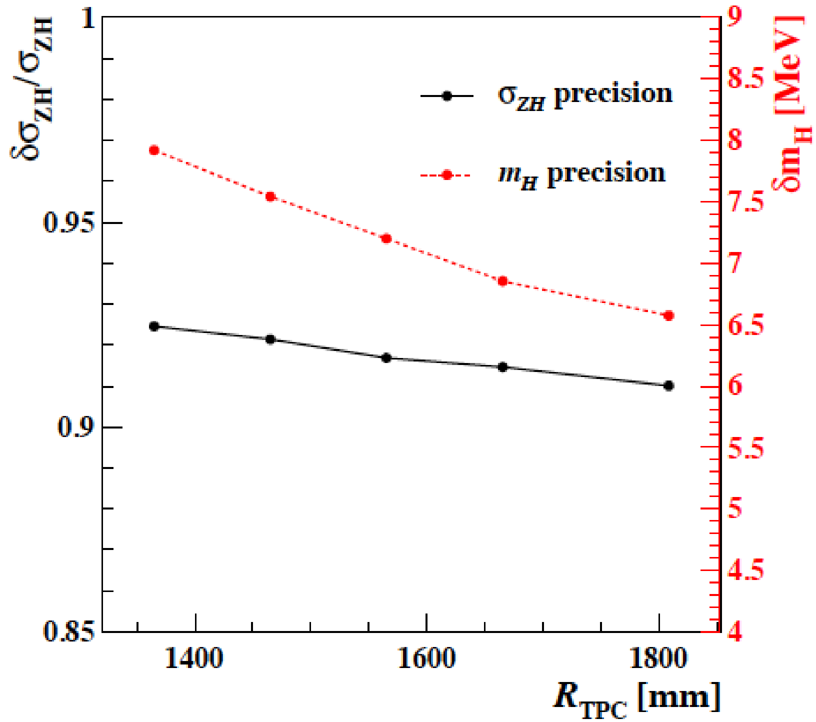
Table 3 $\mu\mu H$ events muon pid efficiency

	Geom 1	Geom 2	Geom 3
ECAL N layers	30	30	20
ECAL cell size	10	20	20
HCAL N layers	48	48	20
HCAL cell size	10	20	20
$\mu\mu H$ efficiency (%)	97.99 ± 0.44	96.48 ± 0.58	95.17 ± 0.73
# channels compare to ILD:			
ECAL	1/4	1/16	1/24
HCAL	1	1/4	1/10



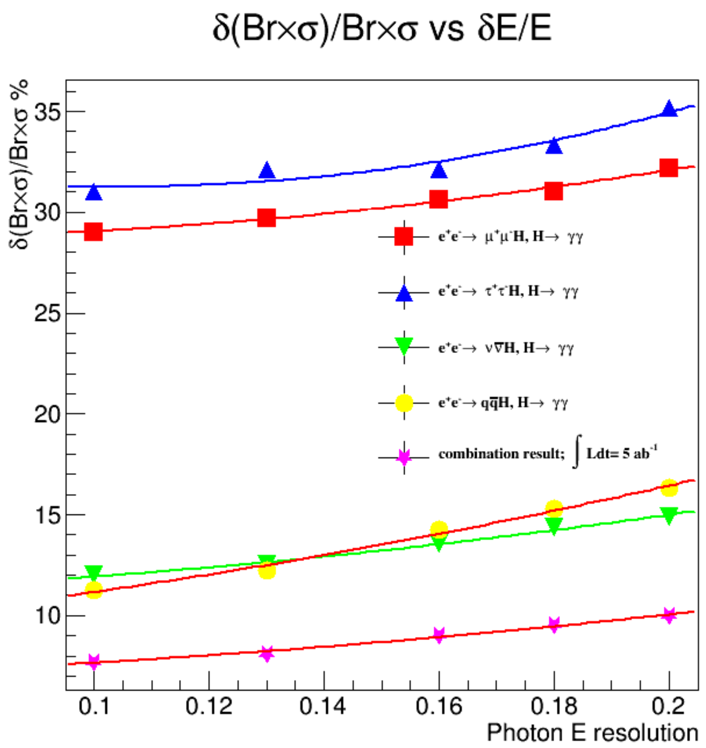


TPC Radius & ECAL resolution



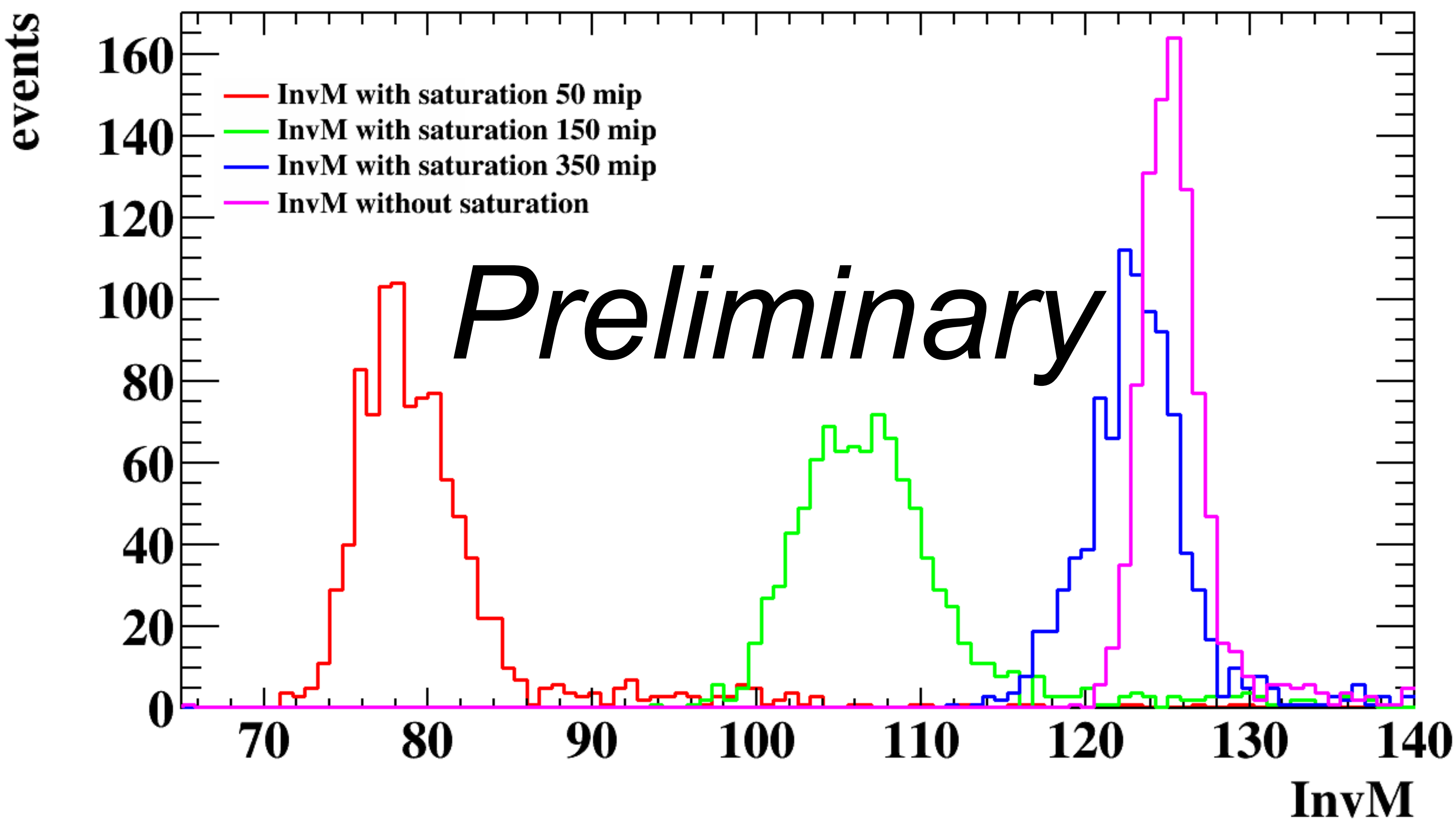
$$\delta m_H = 36.286 \times (1 + 0.092 \times e^{-1.820 \cdot R_{TPC}}) \text{MeV}.$$

$$\frac{\delta\sigma_{ZH}}{\sigma_{ZH}} = 0.485 \times (1 + e^{-0.094 \cdot R_{TPC}})$$

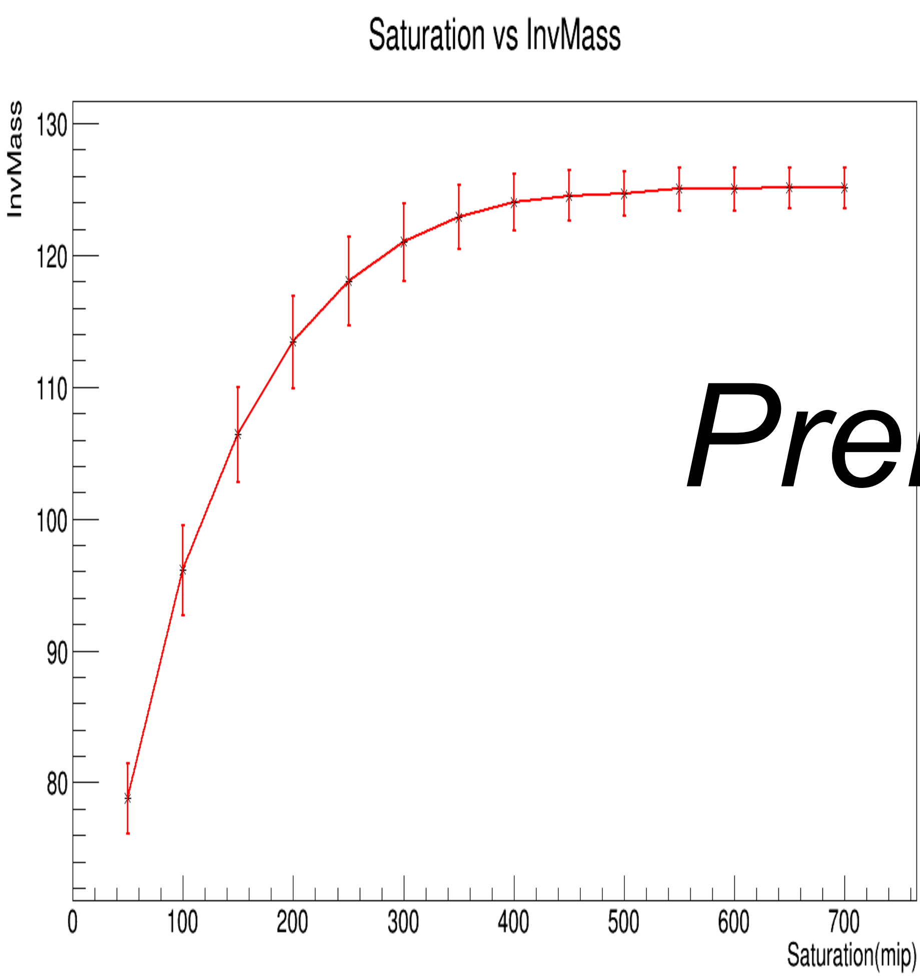


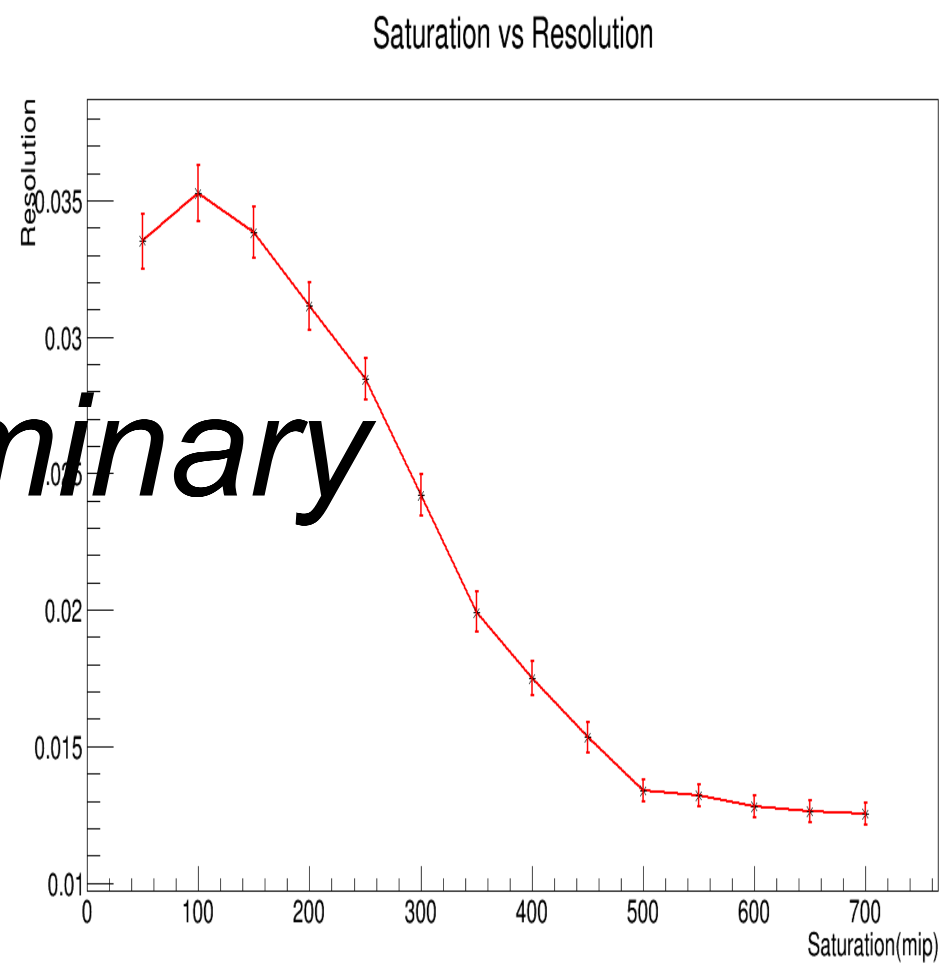
H->di photon branching ratio measurement

ECAL dynamic range: H→di photon measurement



ECAL dynamic range: H→di photon measurement





Preliminary

At 10 mm Cell Size: Require the Dynamic range of at least 1k MIP...

Summary

- CEPC Physics Program
  - σ(ZH), invisible/exotic branching ratios, Total Width, absolute couplings
  - Numerous individual analysis, different requirements on the detector/reconstruction

- Significant Progress since PreCDR, especially to Higgs width/exotic decays
- High Reconstruction Performance for Physics Objects

- Long to do list
  - Polish existing analysis
  - Dedicated reconstruction algorithms: tau finder & jet clustering
  - Extend the physics analysis to Differential Distributions
  - **Iterate with Detector Design/Optimization**

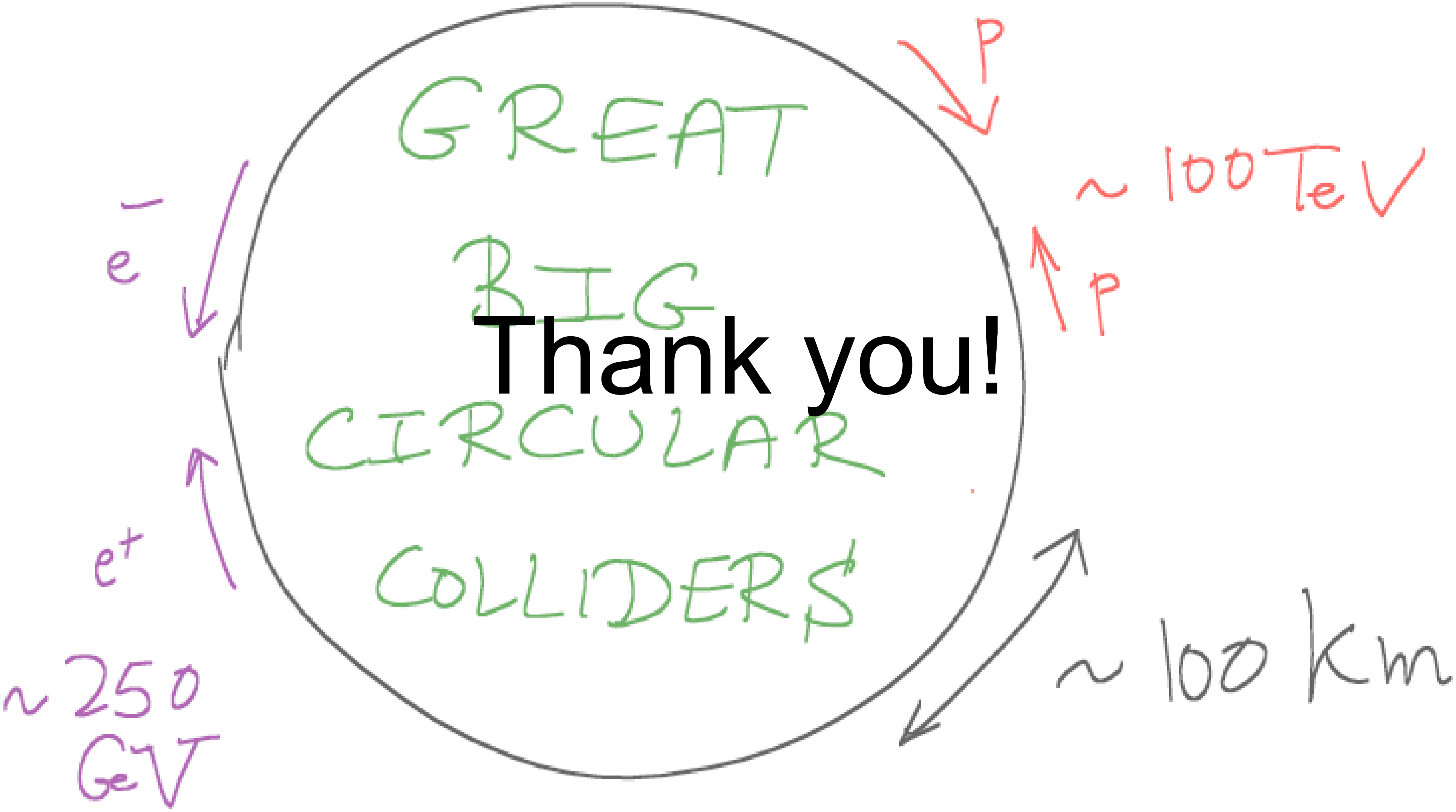
- New ideas & proposals are welcome

Meeting & References

- Regular CEPC Software-Analysis meeting: every four months
  - Aug 29-31, http://indico.ihep.ac.cn/event/6253/

- Higgs exotic decays & Differential distributions...
  - http://arxiv.org/abs/1312.4992
  - http://arxiv.org/abs/1512.06877
  - http://indico.ihep.ac.cn/event/5592/contribution/5/material/slides/0.pdf

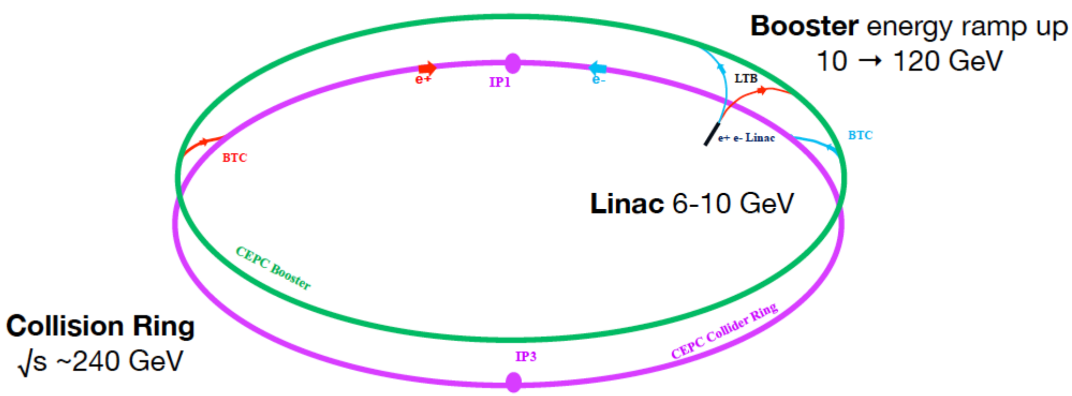
- ICHEP reports:
  - http://indico.cern.ch/event/432527/contributions/1071856/attachments/1321305/1981584/ICHEP2016zhijunv2.pdf
  - http://indico.cern.ch/event/432527/contributions/1072435/attachments/1321203/1981368/ICHEP_CEPC_chenzx.pdf
  - http://indico.cern.ch/event/432527/contributions/1071514/attachments/1321190/1981507/ICHEP_HiggsPhysics_at_CEPC_18.pdf

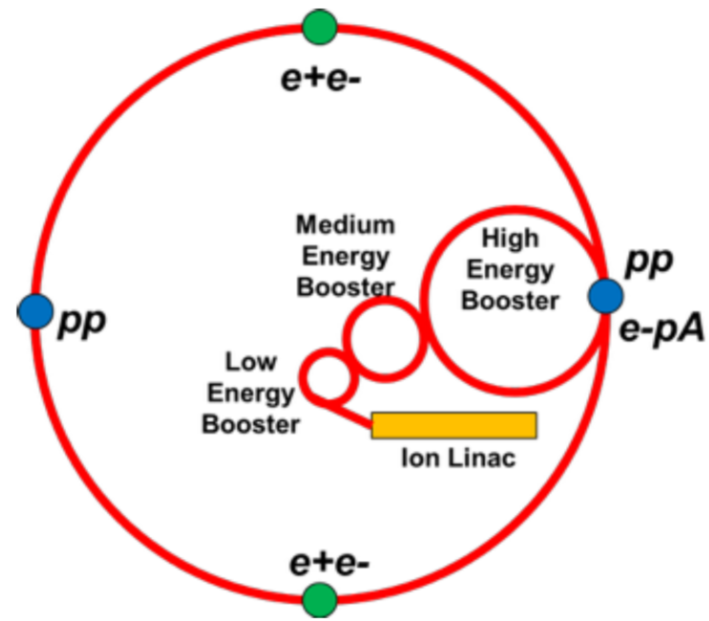


Thank you!

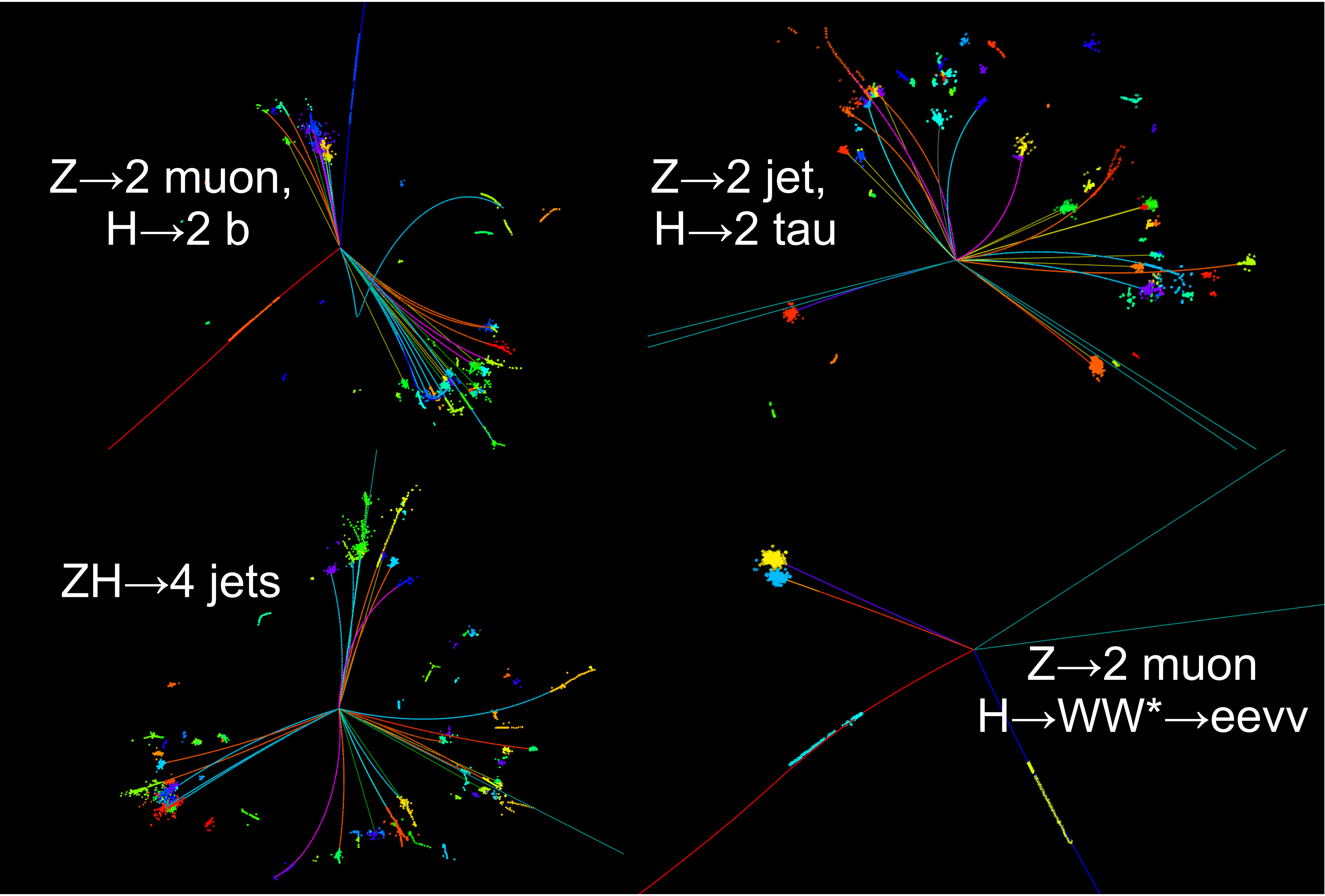
Backup

CEPC-SPPC





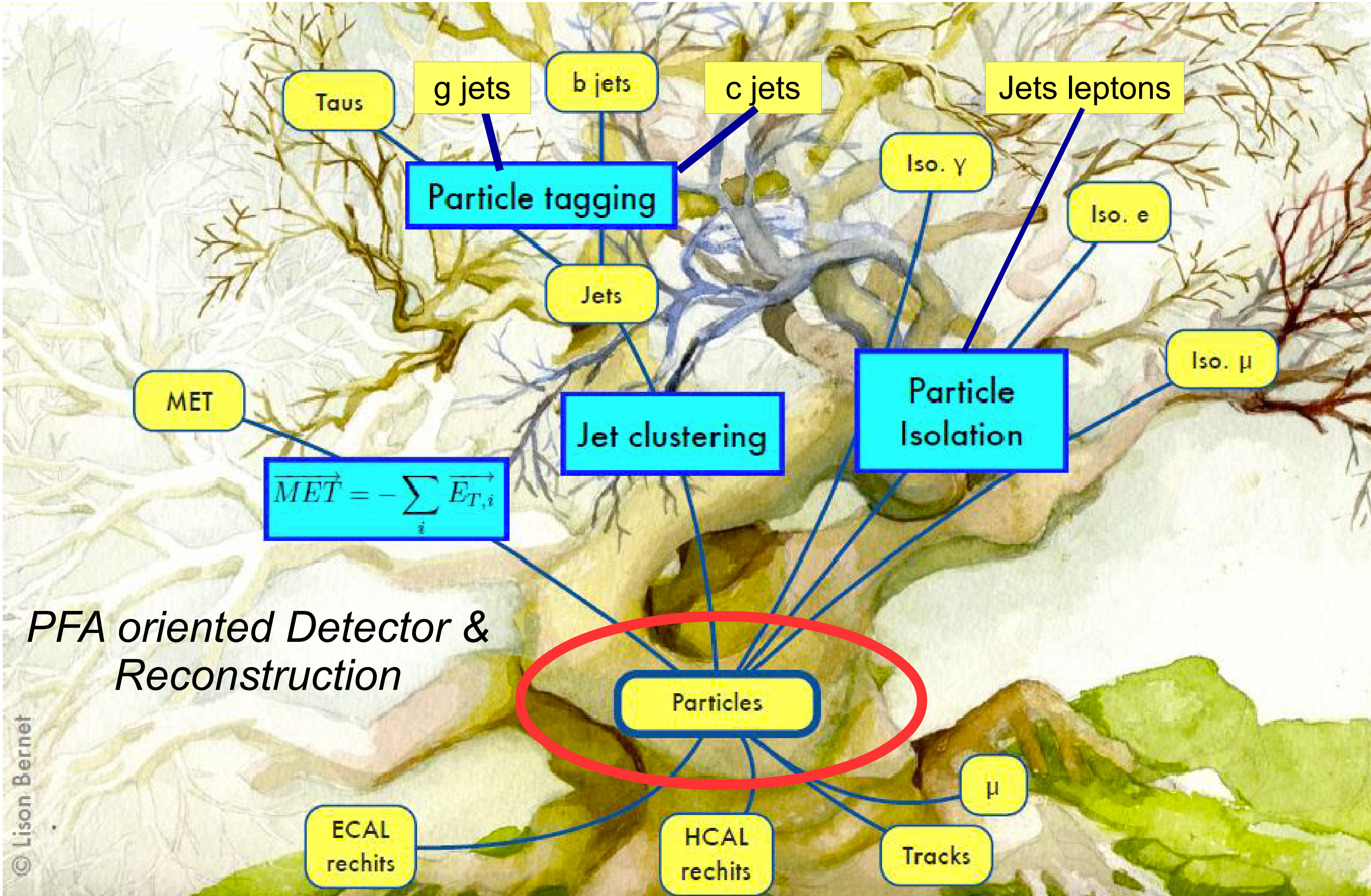
- Electron-positron collision phase
  - Higgs factory: collision at ~240 - 250 GeV center-of-mass energy, Instant luminosity ~ $2*10^{34}$ $cm^{-2}s^{-1}$, 1M clean Higgs event at 2 IP over 10 years
  - Z pole operation for precise EW measurement
- Proton-Proton collision phase
  - center-of-mass energy constrained by tunnel circumference and high-field dipole
  - Peak luminosity ~ $1*10^{35}$ $cm^{-2}s^{-1}$ (*ArXiv: 1504.06108, discussion on needed Luminosity*)
- Tunnel circumference: 54 km in the baseline design. Longer tunnel to be evaluated.


Z→2 muon,
H→2 b
Z→2 jet,
H→2 tau
ZH→4 jets
Z→2 muon
H→WW*→eevv

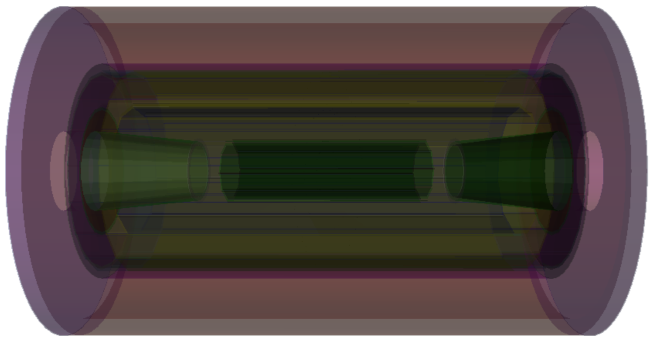
CEPC Higgs measurements: Team

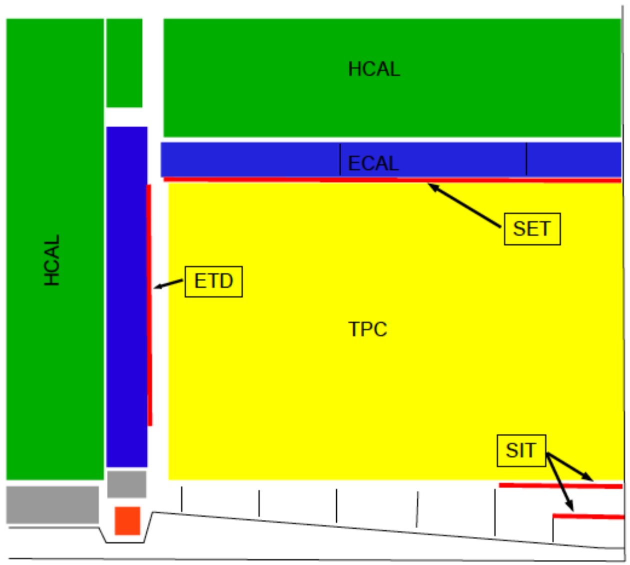
- Higgs rates: ~ **200** analyses according to composition of physics objects (e, mu, tau, b, c, g, MET):
  - Recoil mass and Xsec measurement via eeH, mumuH and qqH:
    - IHEP & PKU, ZX. Chen
  - Jets: 4-5 independent analyses
    - SETU, SJTU & IHEP, 401. Y.Bai, ZX Chen, etc
  - Simple Objects: 14 – 15 analyses
    - PKU(ZW Cui), Chicago University (YT Li, JH Xiang), etc
  - Br(H->ZZ/WW/Zgamma): exclude all events with tau...
    - H->ZZ: IHEP, YQ. Wei
    - H->WW: IHEP & SJTU: LB. Liao, etc
  - Br(H->di tau): IHEP & LLR, D. Yu
- Higgs exotics: 25 analyses
  - Higgs->invisible: IHEP & PKU: X. Mo & ZX. Chen
  - ZH->llvvbb: Hongkong (JW. Wang)
  - Br(Higgs->ee, emu, etau, mutau), PKU (L. Wang & ZW. Cui)
- Higgs Differential Xsec: as for quantum number measurements

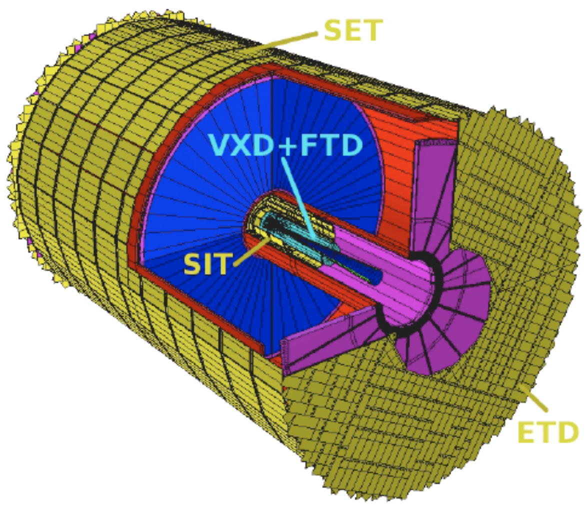
>10 active analyzers


Taus
g jets
b jets
c jets
Jets leptons
Particle tagging
Iso. γ
Iso. e
Jets
Iso. μ
MET
Jet clustering
Particle Isolation
$\overrightarrow{MET} = -\sum_i \overrightarrow{E_{T,i}}$
PFA oriented Detector & Reconstruction
Particles
© Lison Bernet
μ
ECAL rechits
HCAL rechits
Tracks

Vertex & Silicon Tracking at ILD



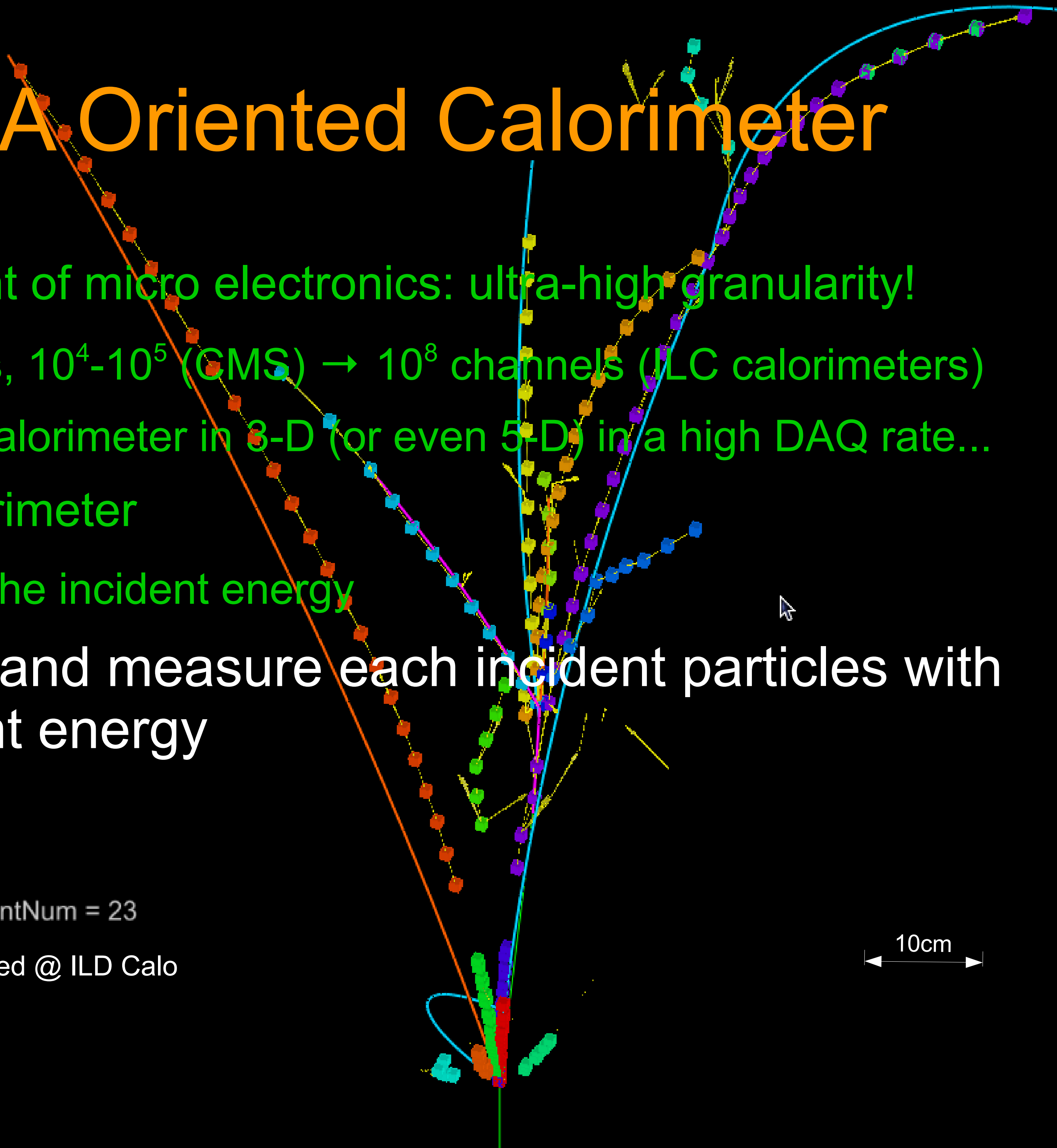




- VTX: Inner most layer Radius: ~15 mm, Spatial resolution: ~ 5 μm
- Massive usage of silicon pixel/strips in the tracking system & VTX: ensures good accuracy in Impact parameter & momentum measurement

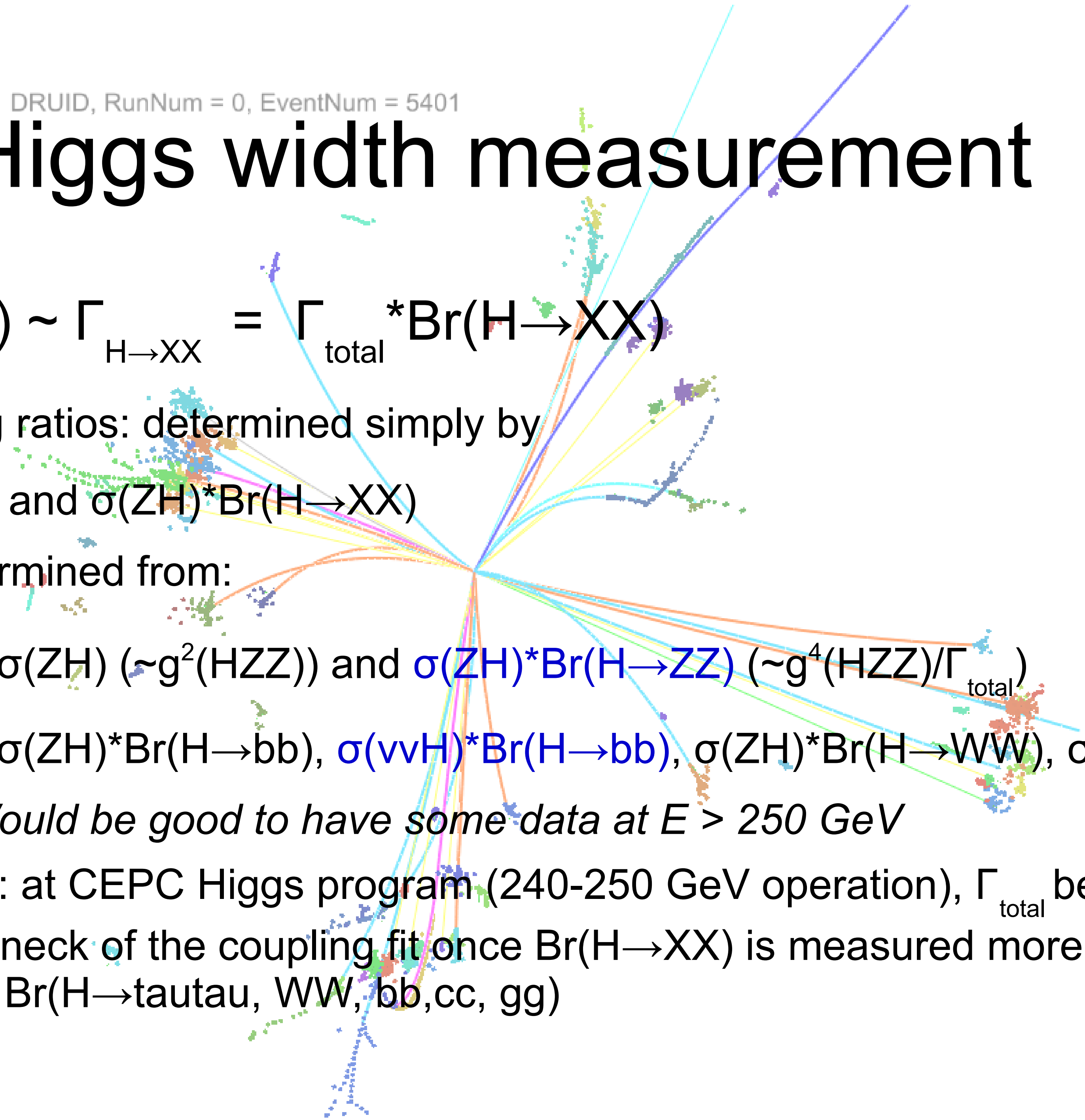
PFA Oriented Calorimeter

- Development of micro electronics: ultra-high granularity!
  - #channels, 10^4-10^5 (CMS) → 10^8 channels (ILC calorimeters)
  - Imaging calorimeter in 3-D (or even 5-D) in a high DAQ rate...
- Role of calorimeter
  - Measure the incident energy
  - Identify and measure each incident particles with sufficient energy



DRUID, RunNum = 0, EventNum = 23

20 GeV Klong reconstructed @ ILD Calo



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) ($\sim g^2(HZZ)$) and σ(ZH)*Br(H→ZZ) ($\sim g^4(HZZ)/\Gamma_{total}$)
  - From σ(ZH)*Br(H→bb), σ(ννH)*Br(H→bb), σ(ZH)*Br(H→WW), σ(ZH)
    - *Would be good to have some data at E > 250 GeV*
- Therefore: at CEPC Higgs program (240-250 GeV operation), Γ_{total} become the bottle neck of the coupling fit once Br(H→XX) is measured more precisely: Br(H→tautau, WW, bb,cc, gg)

Result

$$\Gamma_h \propto g_Z^2 \frac{\sigma_Z^{inc}\sigma_{Wb}}{\sigma_{ZW}\sigma_{Zb}}$$ WW method

$$\Gamma_h = \frac{(g_A^2)^2}{(g_A^2 g_A^2/\Gamma_h)} \propto g_A^2 \frac{\sigma_A^{inc}}{\sigma_{AA}};$$ ZZ method

O_1	σ_{ZH}	0.5% from pre-CDR
O_2	$\sigma_{ZZ} = \sigma_{ZH}$ x Br(H -> ZZ*)	4.3% extrapolated from TLEP
O_3	$\sigma_{Wb} = \sigma_{\nu\nu H}$ x Br(H -> bb)	~~2.8% from pre-CDR~~
O_4	$\sigma_{ZW} = \sigma_{ZH}$ x Br(H -> WW*)	1.38% latest result from Libo's work combined with the result extrapolated from ILC result ~~(1.5% at PreCDR)~~
O_5	$\sigma_{Zb} = \sigma_{ZH}$ x Br(H -> bb)	0.28% from pre-CDR

Up to date Full Simulation

→ Improved to 1.1%

Total Higgs width relative precision

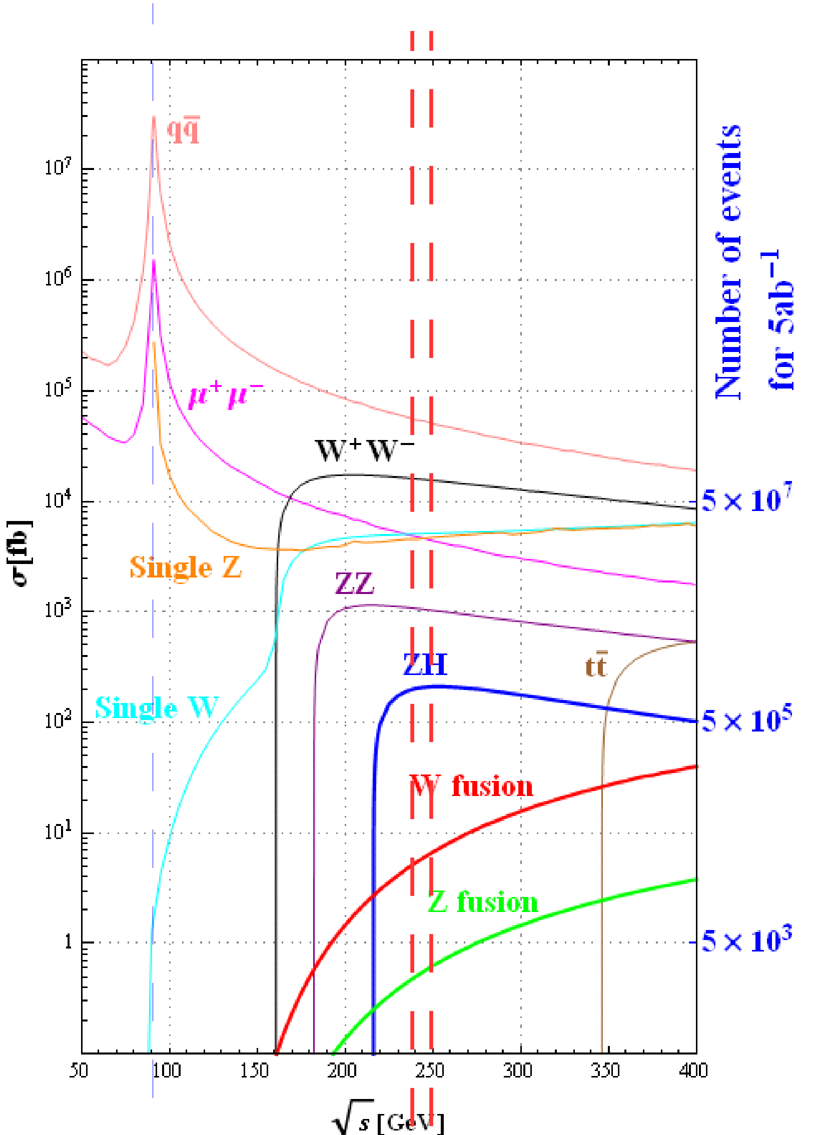
ww method	~~3.3%~~
zz method	4.4%

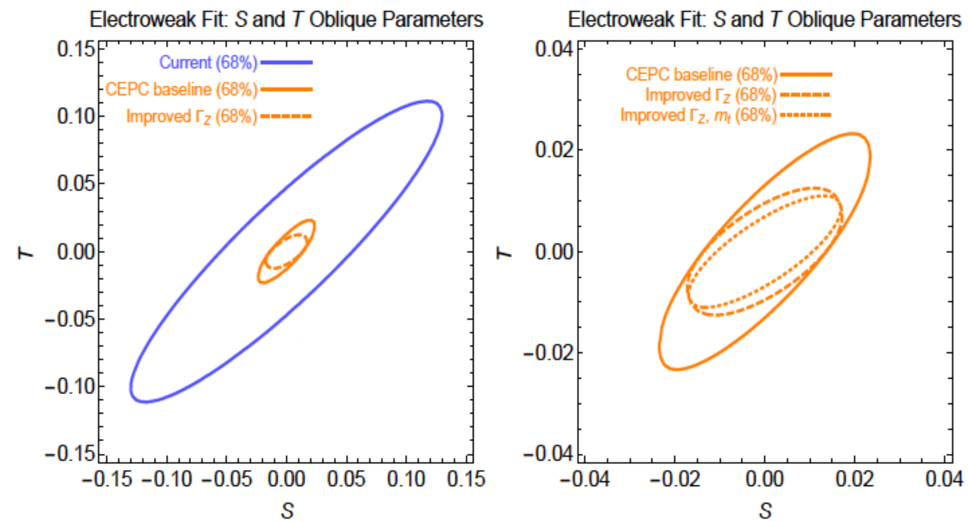
→ Improved to 3.2%

Yuqian Wei

Combined Accuracy: 2.6% on Absolute Higgs width

EW@CEPC





- EW precision measurements with significantly reduced uncertainties:

$$R_b, A^b_{FB}, \sin\theta^{eff}_W, m_Z, m_W, N_\nu \cdots$$

	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [23]	$\pm 1.0 \times 10^{-4}$ [24]
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [25]	$\pm 4.7 \times 10^{-5}$ [26]
m_Z [GeV]	91.1875 ± 0.0021 [27]	$\pm\mathbf{0.0005}$
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [28] $\pm 0.5_{\rm th}$ [26]	$\pm 0.2_{\rm exp} \pm 0.5_{\rm th}$ [29, 30]
m_h [GeV]	125.14 ± 0.24 [26]	$< \pm 0.1$ [26]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [23] $\pm 0.004_{\rm th}$ [31]	$(\pm\mathbf{3}_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [31]
$\sin^2\theta^\ell_{\rm eff}$	$(23153 \pm 16) \times 10^{-5}$ [27]	$(\pm\mathbf{2.3}_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [32]
Γ_Z [GeV]	2.4952 ± 0.0023 [27]	$(\pm\mathbf{5}_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [33]
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.21629 ± 0.00066 [27]	$\pm\mathbf{1.7} \times 10^{-4}$
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.767 ± 0.025 [27]	$\pm\mathbf{0.007}$

Reconstruction

Table 3.4 Expected performance of CEPC detector at object level (within geometry acceptance). For the flavor tagging, the b/c tagging efficiency should preserve a purity of 80% at Z pole sample with hadronic final states

Tracking: Kalman Fitter based Clupatra (ILC tool)	Charged particle tagging efficiency ($E > 10$ GeV)	99.5%	>99%
Arbor	Muon identification efficiency ($E > 10$ GeV)	98.5%	99%
	Electron identification efficiency ($E > 10$ GeV)	99.5%	99%
	Photon tagging efficiency ($E > 1$ GeV)	95%	99% for E>5GeV γ
	Neutral Hadron tagging efficiency ($E > 5$ GeV)	90%	NAN
	Jet Energy resolution	3 - 4%	4%
Flavor tagging: LCFIPlus (ILC tool)	b-tagging efficiency	90%	87%
	c-tagging efficiency	60%	40%

- Fully validated reconstruction chain
- PFA oriented: object finding efficiency & Jet Energy Resolution

SM Lagrangian

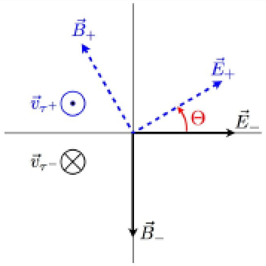
$$
\begin{aligned}
\mathcal{L} \; = \; & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.}) && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.}) && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu \phi)} D^\mu \phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \qquad (1)
\end{aligned}
$$

Higgs CP Phase in $h \to \tau^+\tau^-$ Decay

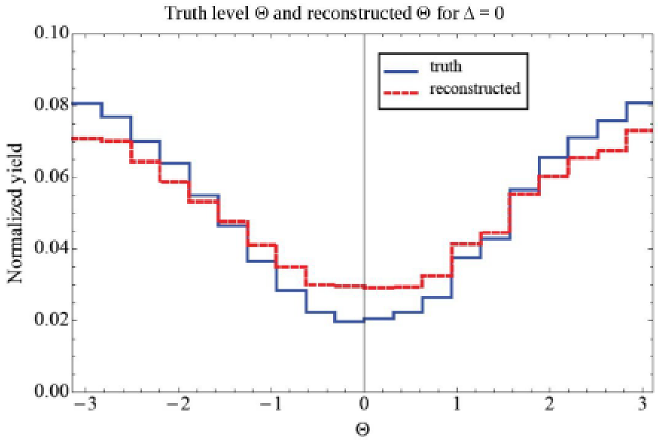
1308.1094

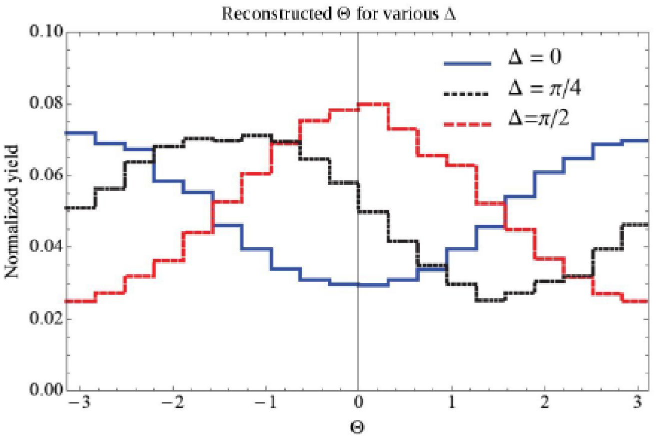
Θ Angle

$$\Theta \equiv \text{sgn}\left[\vec{v}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+)\right] \arccos\left(\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+||\vec{E}_-|}\right)$$



Differential Distribution





Precision Measurement @ CEPC

CEPC preCDR

Colliders	LHC	HL-LHC	CEPC1	CEPC5	CEPC10
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

Enhancement from M_Z & M_W @ CEPC

Observables	Relative Error	
	Current	CEPC
M_Z	2.3×10^{-5}	$5.5 \times 10^{-6} \sim 1.1 \times 10^{-5}$
M_W	1.9×10^{-4}	**3.7×10^{-5}** $\sim 6.2 \times 10^{-5}$

Table: The M_Z and M_W @ CEPC [Z.Liang, "Z & W Physics @ CEPC"].

Scheme-Independent Analysis

$\frac{\Lambda}{\sqrt{c_i}}$ [TeV]	$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_L^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
HO+EWPO	2.74	10.6	6.38	5.78	6.53	2.15	0.603	8.57	12.1	10.2	8.78	1.85	0.565	0.391	0.337	39.8
$+M_Z$	2.74	**10.7**	6.38	5.78	**6.54**	2.15	0.603	**8.61**	12.1	10.2	8.78	1.85	0.565	0.391	0.337	39.8
$+M_W$	2.74	**21.0**	6.38	5.78	**10.4**	2.15	0.603	**15.5**	**16.4**	10.2	8.78	1.85	0.565	0.391	0.337	39.8
$+M_{Z,W}$	2.74	**23.7**	6.38	5.78	**11.6**	2.15	0.603	**17.4**	**18.1**	10.2	8.78	1.85	0.565	0.391	0.337	39.8

Table: Impacts of the projected M_Z and M_W measurements at CEPC on the reach of new physics scale $\Lambda/\sqrt{|c_j|}$ (in TeV) at 95% C.L. The Higgs observables (including $\sigma(\nu\bar{\nu}h)$ at 350 GeV) and the existing electroweak precision observables are always included in each row. The differences among the four rows arise from whether taking into account the measurements of M_Z and M_W or not. The second (third) row contains the measurement of M_Z (M_W) alone, while the first (last) row contains none (both) of them. We mark the entries of the most significant improvements from M_Z / M_W measurements in red color.

1603.03385

Enhancement from Z-Pole Observables @ CEPC

N_ν	$A_{FB}(b)$	R^b	R^μ	R^τ	$\sin^2\theta_w$
1.8×10^{-3}	1.5×10^{-3}	8×10^{-4}	5×10^{-4}	5×10^{-4}	1×10^{-4}

Table: The Z-pole measurements at CEPC [Z.Liang, "Z & W Physics @ CEPC"].

Z-Pole Observables are **IMPORTANT** for New Physics Scale Probe

$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_L^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
2.74	23.7	6.38	5.78	11.6	2.15	0.603	17.4	18.1	10.2	8.78	1.85	0.565	0.391	0.337	39.8
2.74	23.7	6.38	5.78	11.6	2.15	0.603	**17.5**	**18.3**	**10.5**	8.78	1.85	0.565	0.391	0.337	39.8
2.74	24.0	**8.32**	5.80	**12.2**	2.15	0.603	**20.7**	**23.0**	**12.5**	**13.0**	2.08	**1.62**	0.391	**3.97**	39.8
2.74	24.0	8.33	5.80	12.2	2.15	0.603	20.7	23.0	12.5	13.0	**7.90**	**7.89**	**3.55**	4.05	39.8
2.74	24.0	8.54	5.80	12.2	2.15	0.603	20.7	23.4	**14.4**	**14.0**	8.63	8.62	4.88	**4.71**	39.8
2.74	24.0	8.75	5.80	12.3	2.15	0.603	20.7	23.7	15.8	14.9	**9.21**	**9.21**	5.59	5.17	39.8
2.74	**26.3**	**12.6**	**5.93**	**15.3**	2.15	0.603	**30.2**	**35.2**	**19.8**	**21.6**	9.21	9.21	5.59	5.17	39.8

Table: Impacts of the projected Z-pole measurements at the CEPC on the reach of new physics scale $\Lambda/\sqrt{|c_j|}$ (in TeV) at 95% C.L. For comparison, the first row of this table repeats the last row of Table ??, as our starting point of this table. For the $(n+1)$-th row, the first n observables are taken into account. In addition, the estimated M_Z and M_W measurements at the CEPC, the Higgs observables (HO), and the existing electroweak precision observables (EWPO) are always included for each row. The entries with major enhancements of the new physics scale limit are marked in red color.

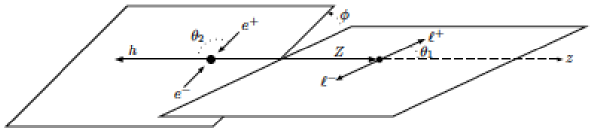
A factor of 2 enhancement from Z-Pole Observables

Angular Observable in Higgsstrahlung

1512.06877

CP violating dim-6 operators

$$
\begin{aligned}
&\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi) && \mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu} \\
&\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi) && \mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu} \\
&\mathcal{O}^{(1)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell) && \mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W^I_{\mu\nu}B^{\mu\nu} \\
&\mathcal{O}^{(3)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\gamma^\mu\tau^I\ell) && \mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu} \\
&\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e\gamma^\mu e) && \mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu} \\
&\mathcal{O}_{4L} = (\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell) && \mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}
\end{aligned}
$$



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\phi\,\mathrm{d}\cos\theta_1\,\mathrm{d}\cos\theta_2}$$

Observables

$$\sigma(s) \qquad \mathcal{A}_{\theta_1} \equiv \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos(2\theta_1))\,\frac{d\sigma}{d\cos\theta_1}$$

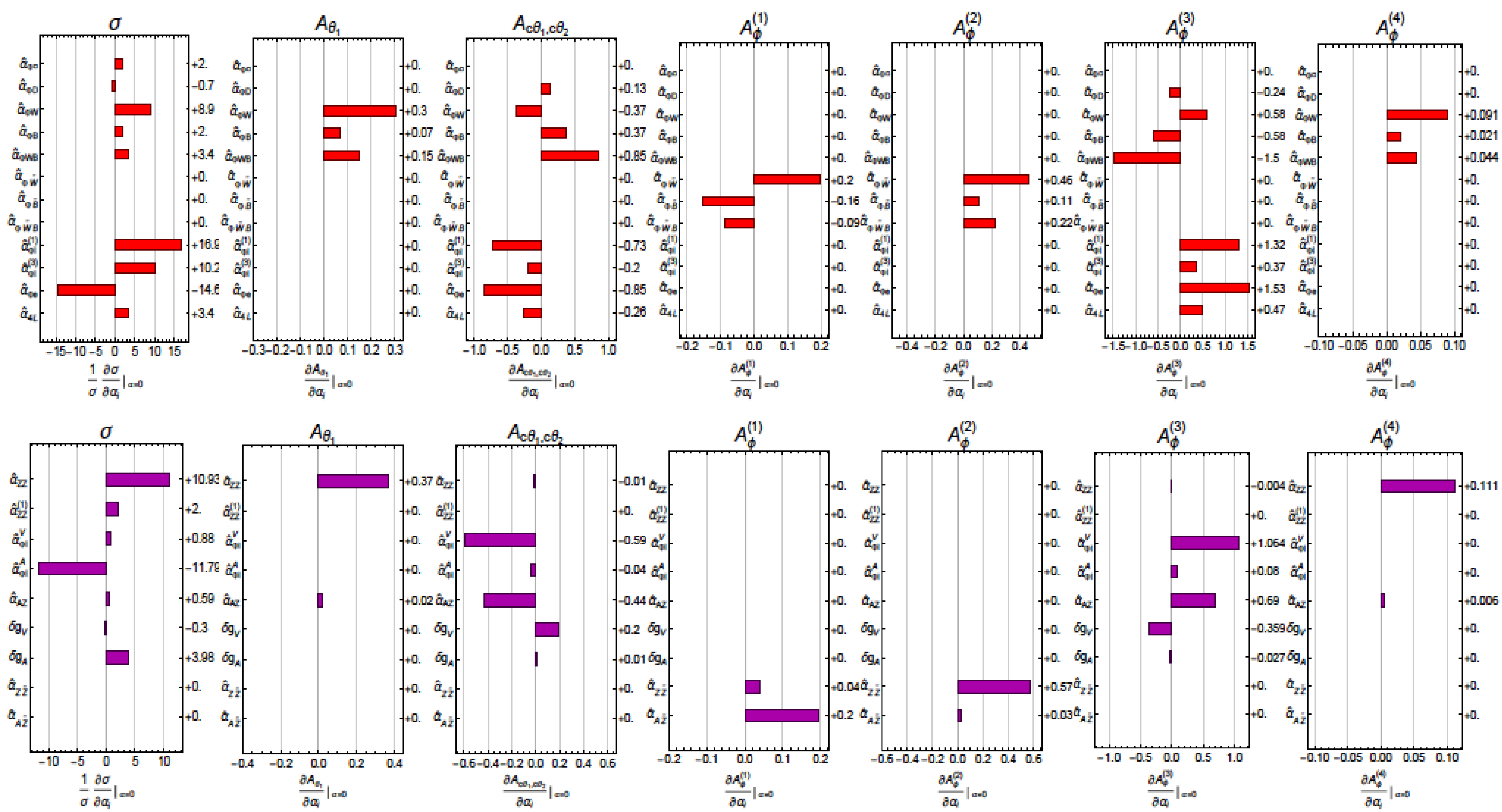
$$\mathcal{A}^{(1)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\sin\phi)\,\frac{d\sigma}{d\phi} \qquad \mathcal{A}^{(2)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\sin(2\phi))\,\frac{d\sigma}{d\phi}$$

$$\mathcal{A}^{(3)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\cos\phi) \qquad \mathcal{A}^{(4)}_\phi \equiv \frac{1}{\sigma}\int_0^{2\pi} d\phi\,\mathrm{sgn}(\cos(2\phi))\,\frac{d\sigma}{d\phi}$$

$$\mathcal{A}_{c\theta_1,c\theta_2} \equiv \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\mathrm{sgn}(\cos\theta_2)\frac{d^2\sigma}{d\cos\theta_1\,d\cos\theta_2}$$

Angular Observable in Higgsstrahlung

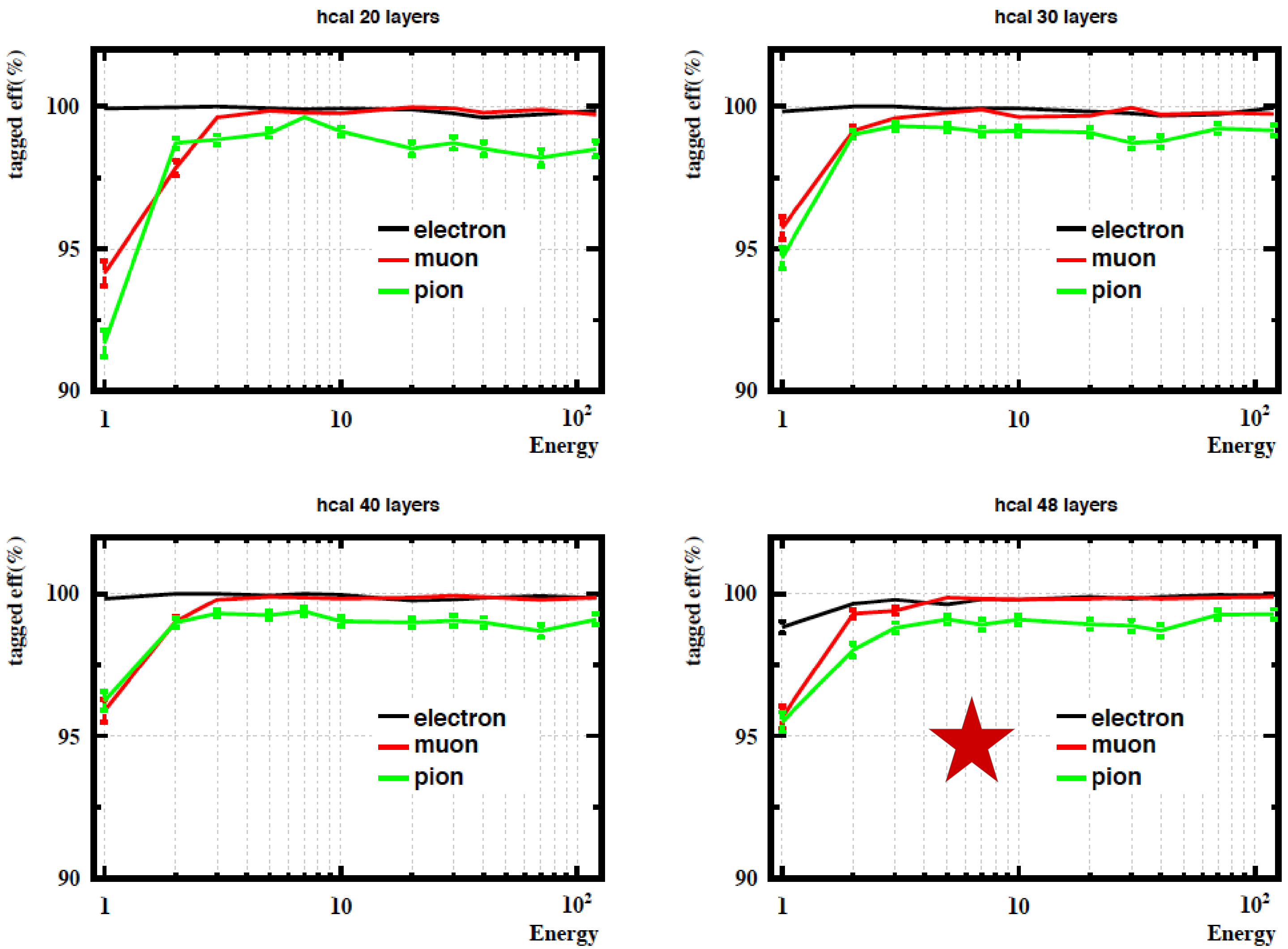
1512.06877



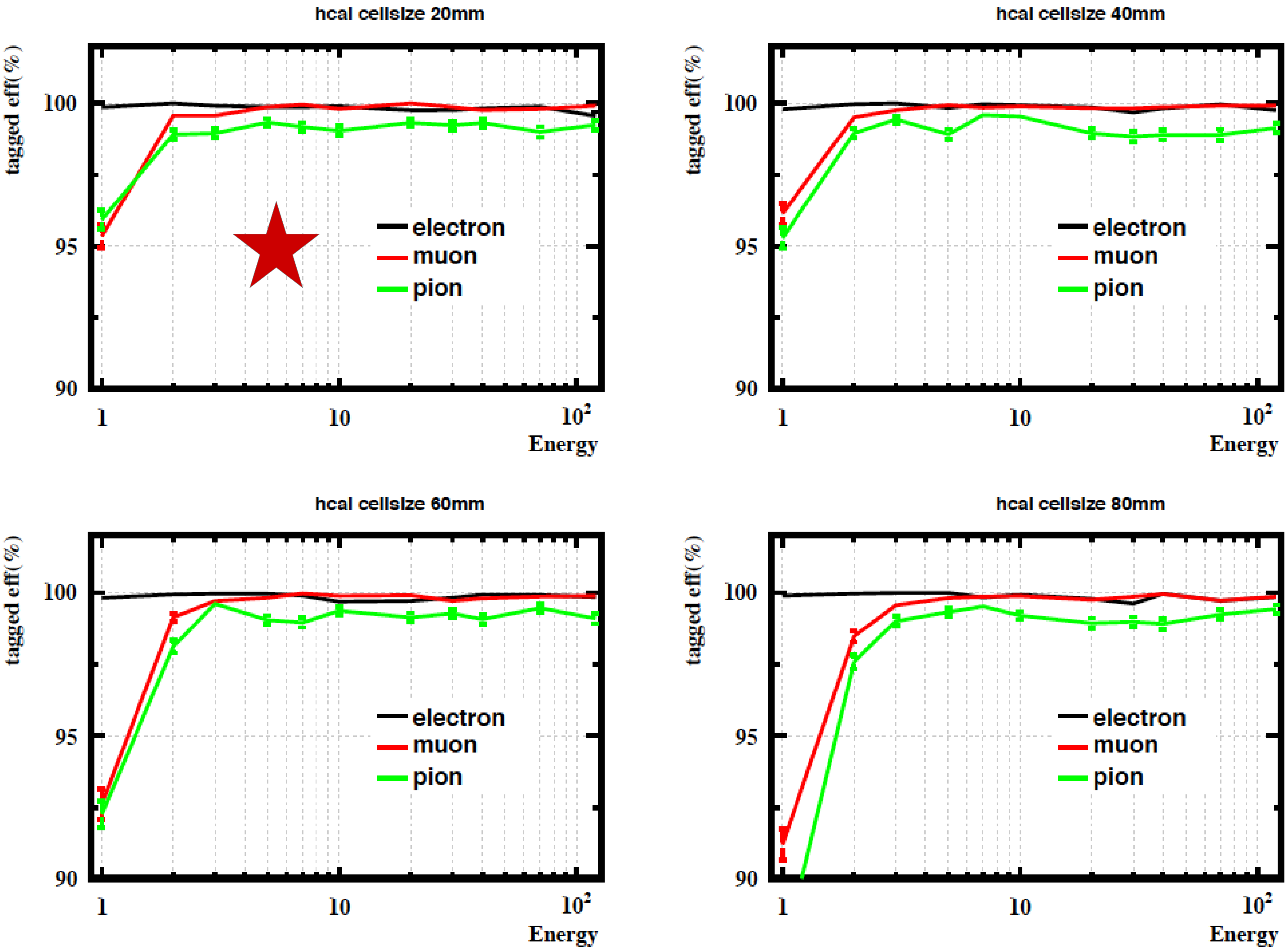
	$\hat{\alpha}_{ZZ}$	$\hat{\alpha}^{(1)}_{ZZ}$	$\hat{\alpha}^{V}_{\Phi\ell}$	$\hat{\alpha}^{A}_{\Phi\ell}$	$\hat{\alpha}_{AZ}$	δg_V	δg_A	$\hat{\alpha}_{Z\tilde{Z}}$	$\hat{\alpha}_{A\tilde{Z}}$
rate	0.00064	0.0035	0.0079	0.00059	0.012	0.023	0.0018	∞	∞
angles	0.016	∞	0.0058	0.078	0.0087	0.017	0.23	0.012	0.036
total	0.00064	0.0035	0.0047	0.00059	0.0070	0.014	0.0018	0.012	0.036


Higgs...

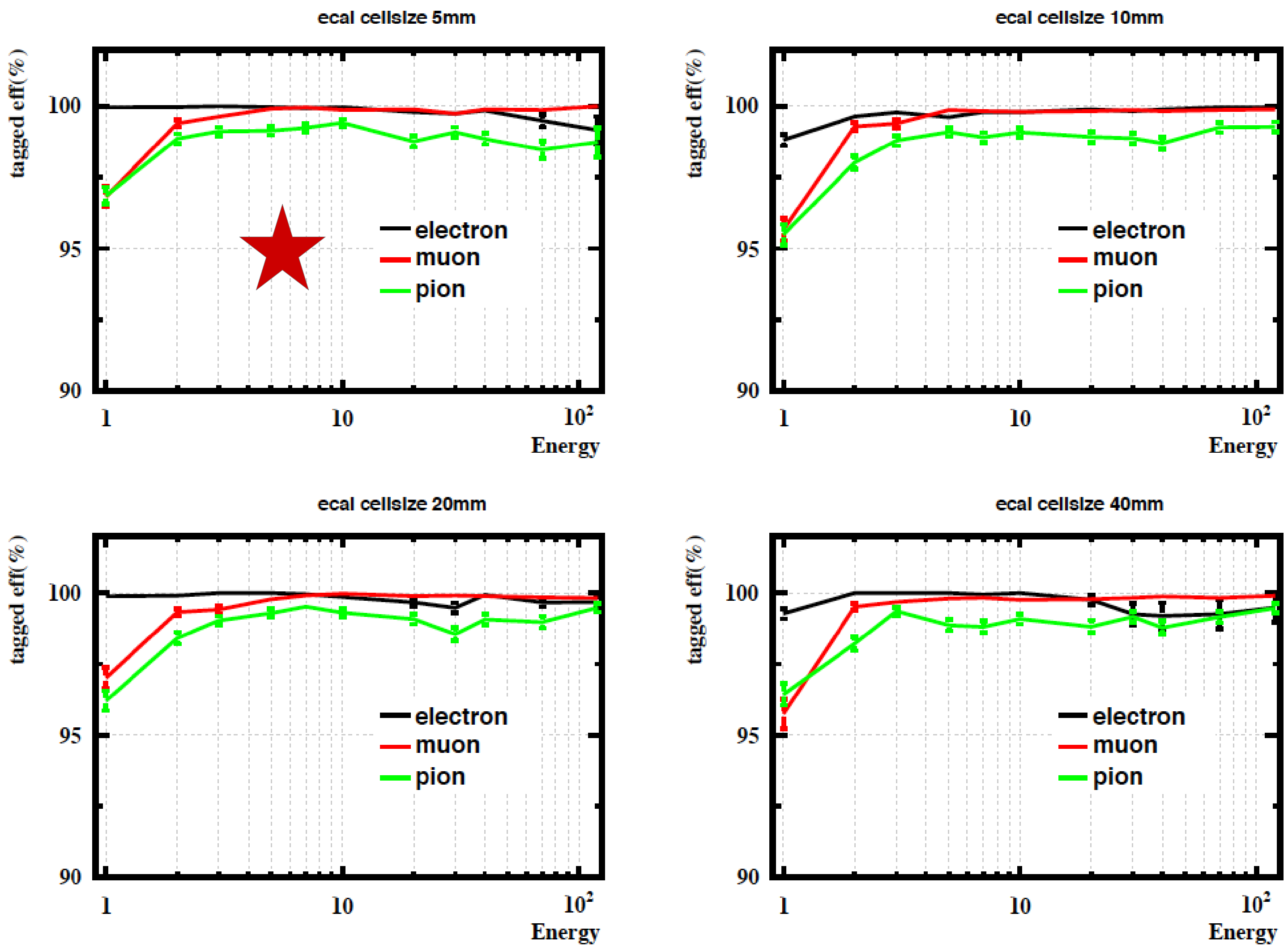
LICH: different HCAL layer



LICH: different HCAL cell size



LICH: different ECAL Cell size



LICH: different ECAL Layers

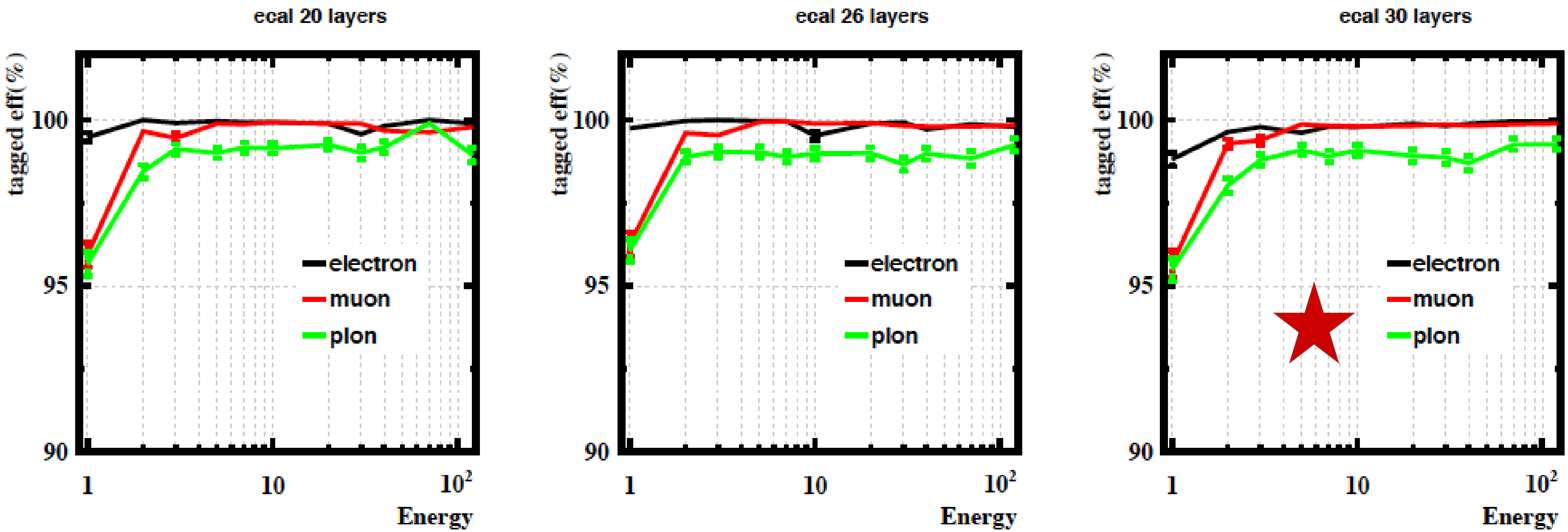


Table 3 $\mu\mu H$ events muon pid efficiency

	Geom 1	Geom 2	Geom 3
ECAL N layers	30	30	20
ECAL cell size	10	20	20
HCAL N layers	48	48	20
HCAL cell size	10	20	20
$\mu\mu H$ efficiency (%)	97.99 ± 0.44	96.48 ± 0.58	95.17 ± 0.73

channels compare to ILD:

ECAL	1/4	1/16	1/24
HCAL	1	1/4	1/10