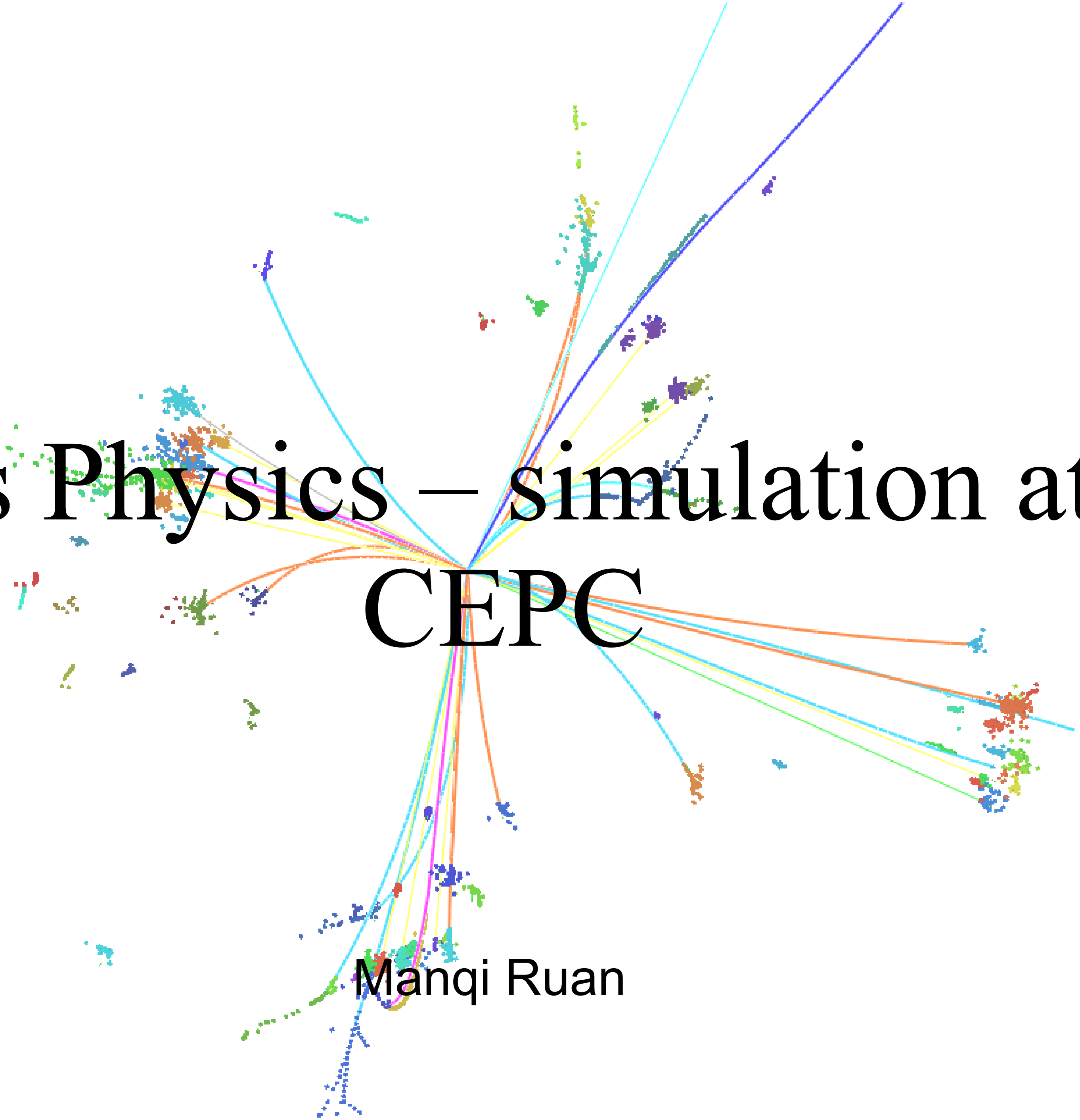
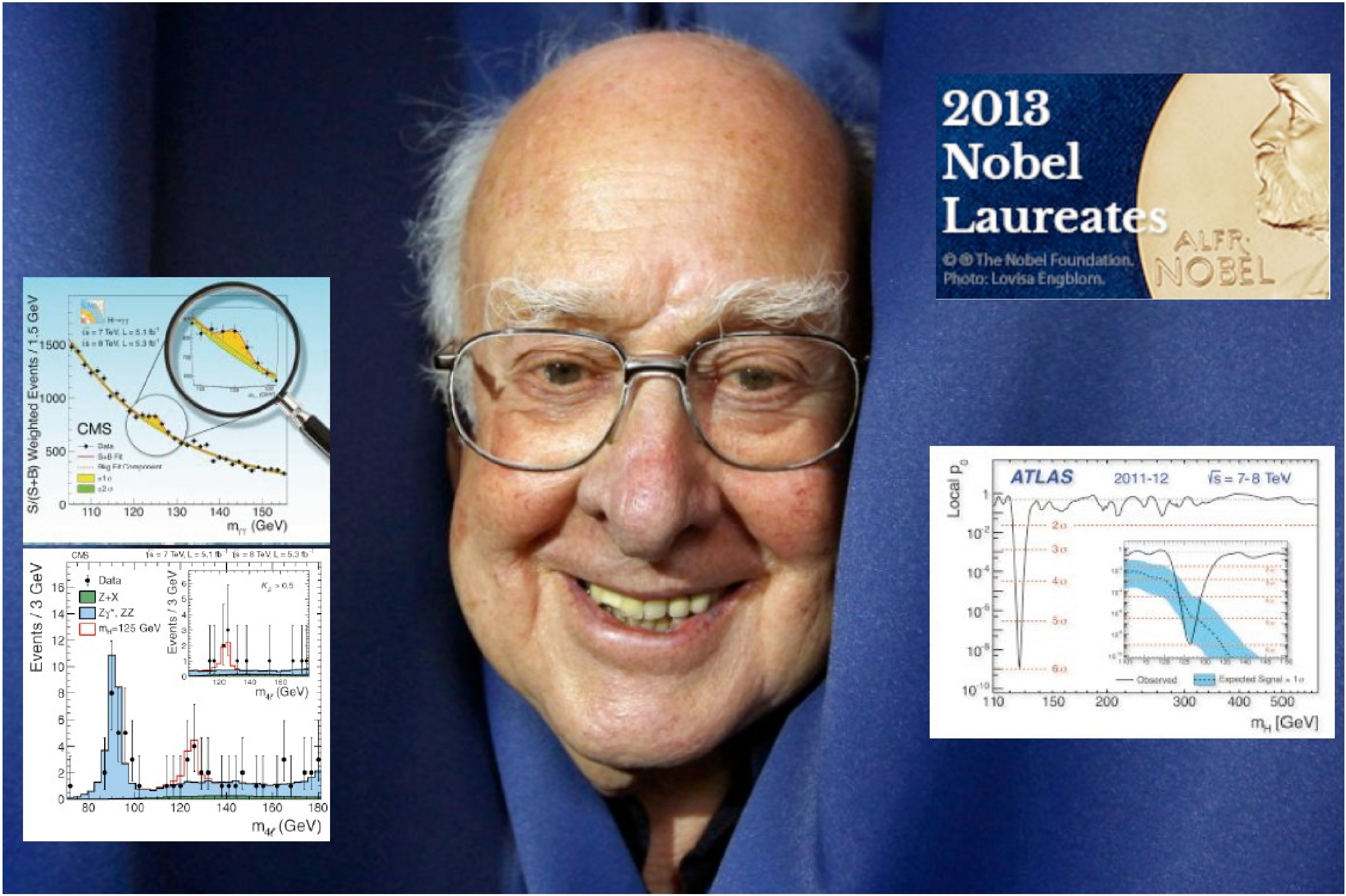
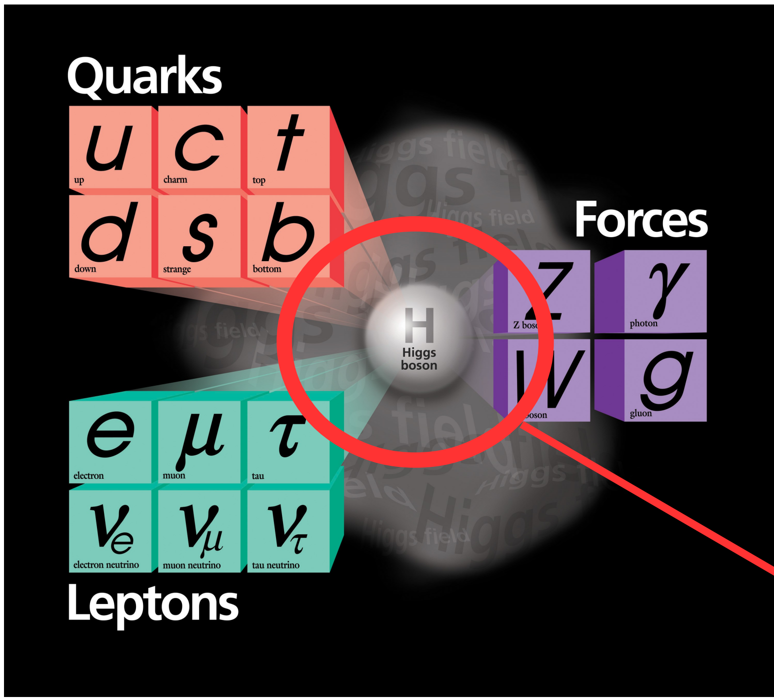
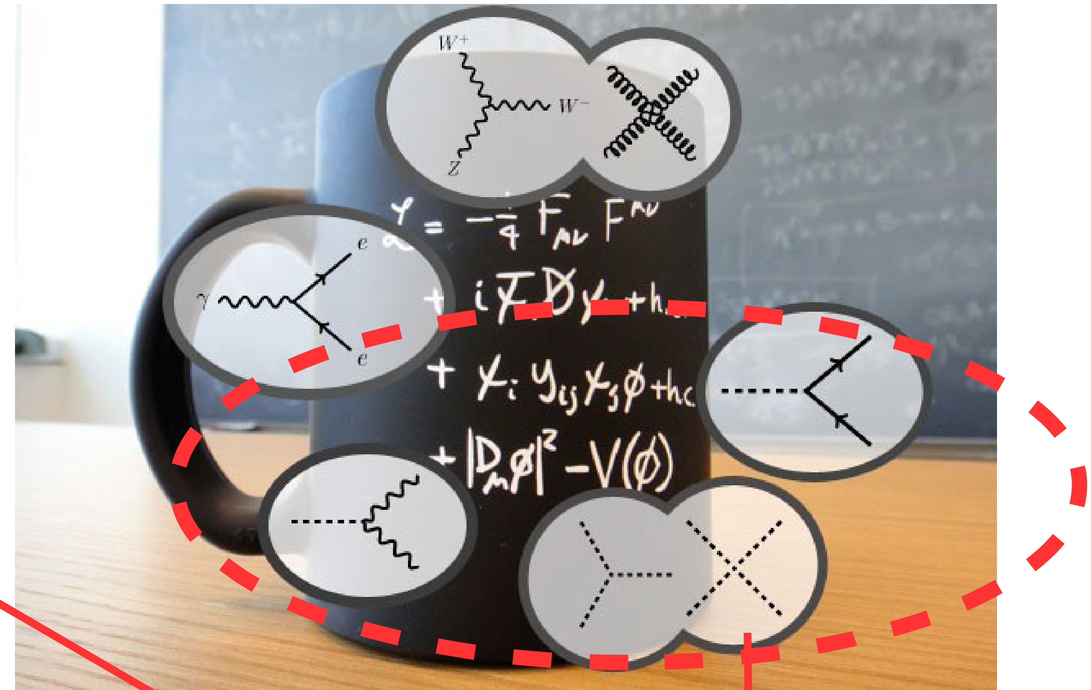
Higgs Physics – simulation at the CEPC

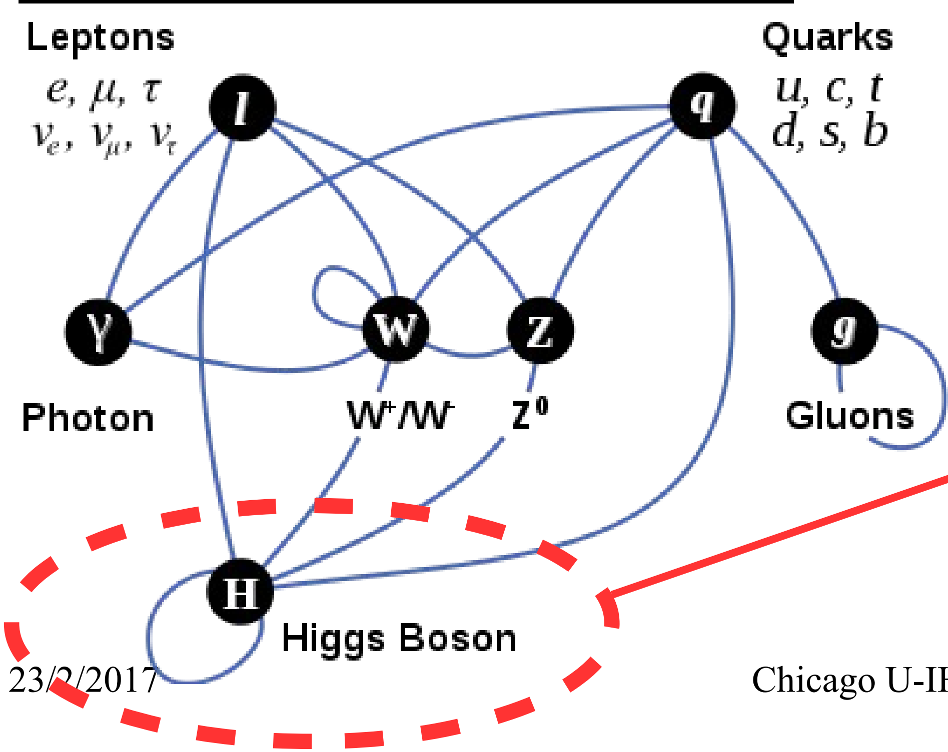


Manqi Ruan


2013
Nobel
Laureates
© ® The Nobel Foundation.
Photo: Lovisa Engblom.
ALFR.
NOBEL
CMS
S/(S+B) Weighted Events / 1.5 GeV
Data
S+B Fit
$m_{\gamma\gamma}$ (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
m_H [GeV]
Observed
Expected Signal ± 1σ


Quarks
u c t
up charm top
d s b
down strange bottom
Forces
Z γ
photon
W g
gluon
H
Higgs boson
e μ τ
electron muon tau
ν_e ν_μ ν_τ
electron neutrino muon neutrino tau neutrino
Leptons


W^+ W^- Z
γ e e
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$


Leptons
e, μ, τ
ν_e, ν_μ, ν_τ
l
Quarks
u, c, t
d, s, b
q
γ
W
Z
g
Photon
W^+/W^-
Z^0
Gluons
H
Higgs Boson

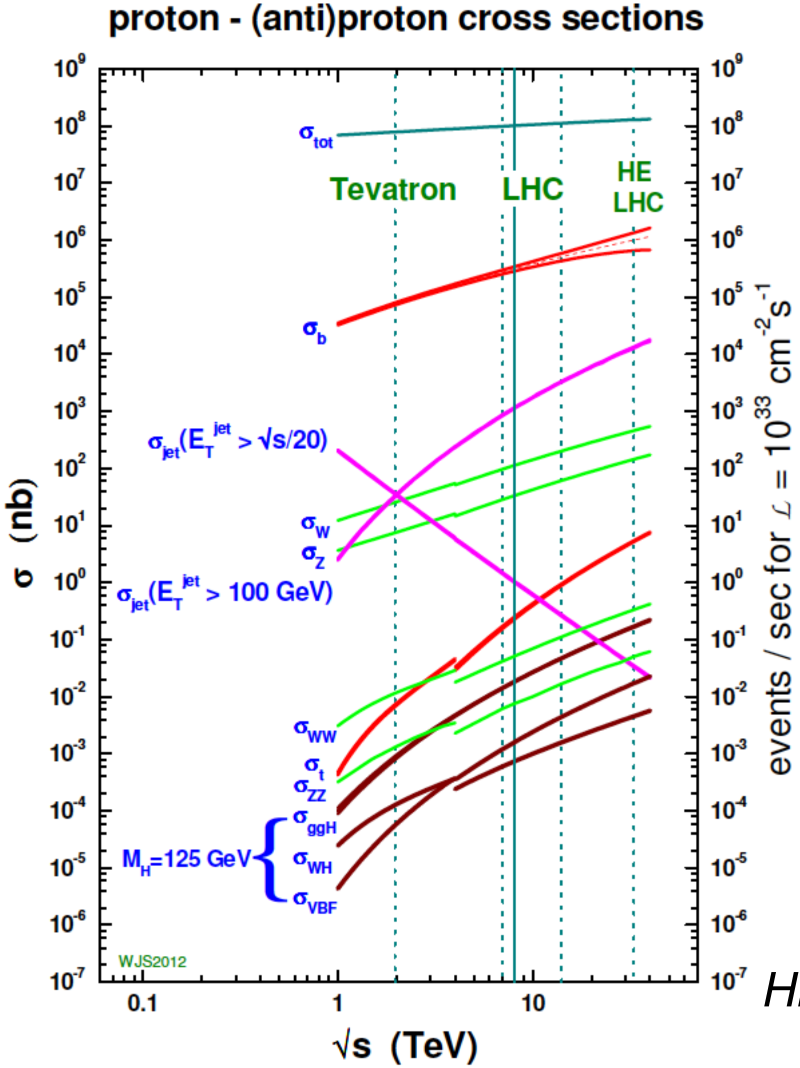

THE HIGGS BOSON
H

Higgs

Mass of electron – size of atom
Mass of u&d quark – stability of proton
Mass of top & Higgs – vacuum stability
Mass of W/Z – strength/range of Weak interaction

Gateway to the unknown...

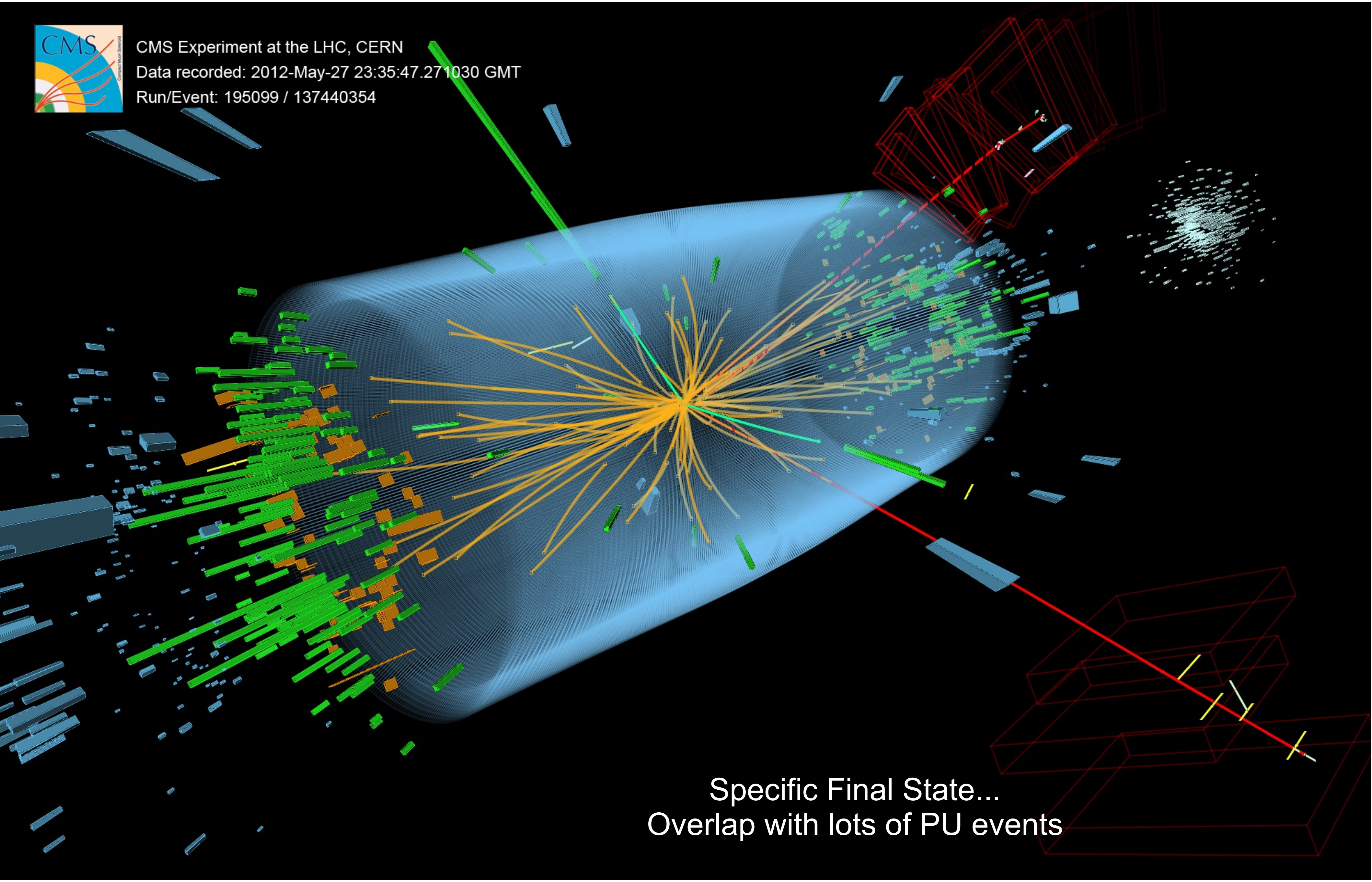
Higgs @ LHC



pp collider:

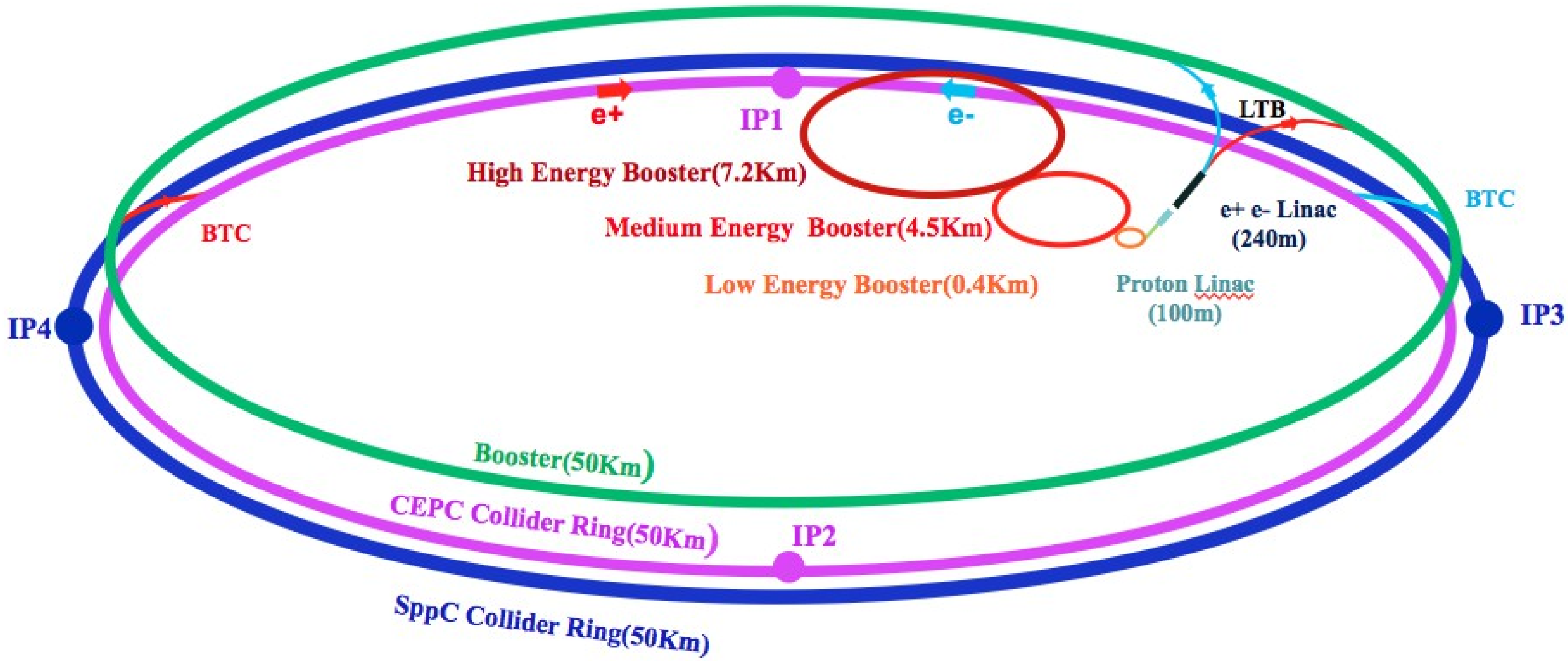
High productivity (~ 1E6 Higgs boson generated at LHC)

Extremely High Background: 1 Higgs boson in 10 Billion events..

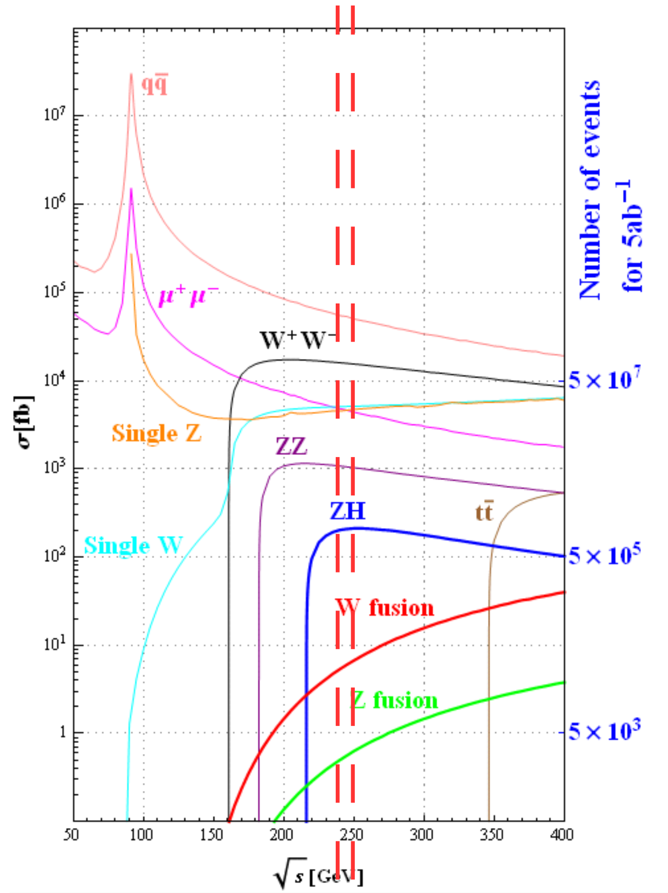

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354
Specific Final State...
Overlap with lots of PU events

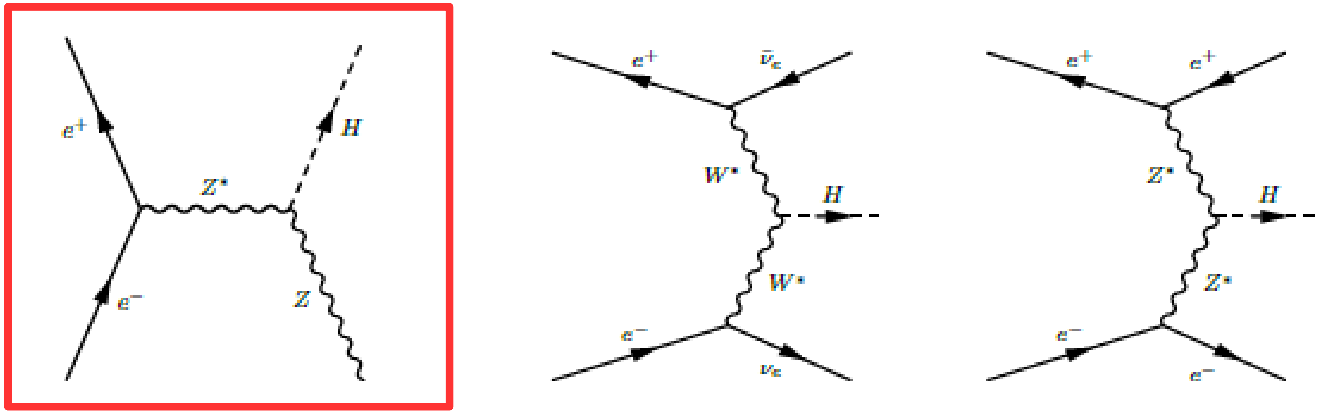
CEPC: a precise Higgs factory

- 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
- CEPC: 1 M Higgs boson + 10 Billion Z bosons...



Higgs @ CEPC



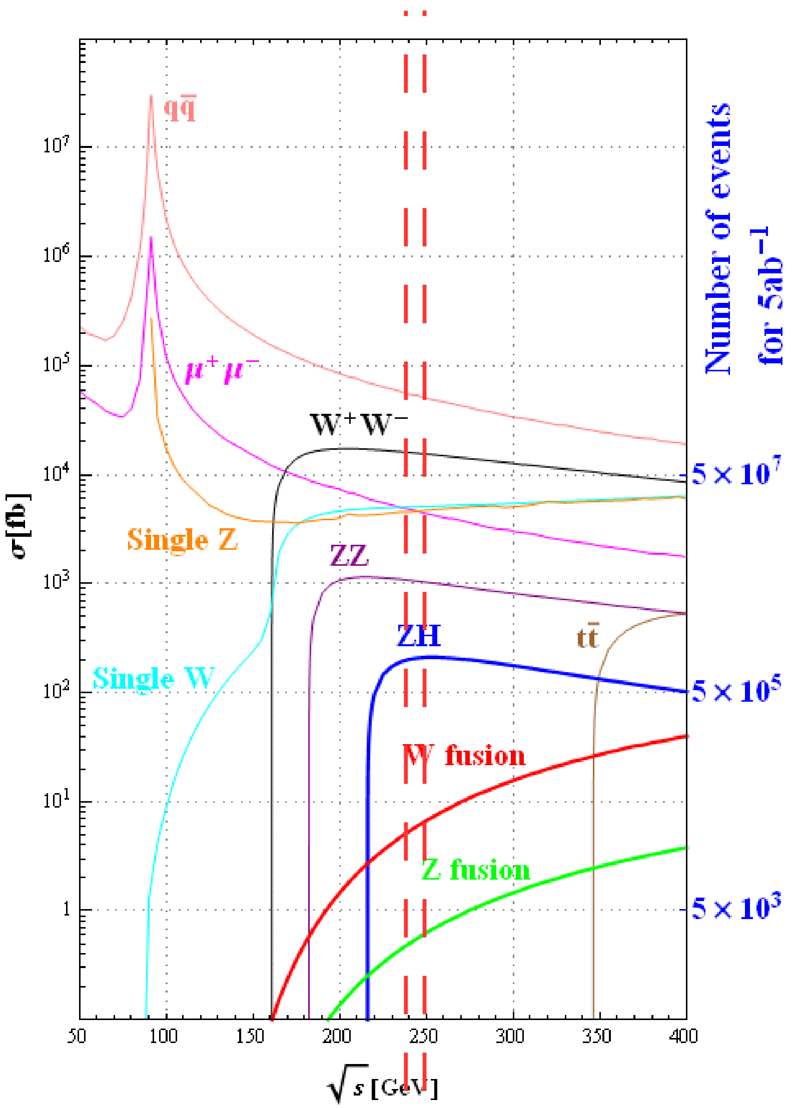


Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

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

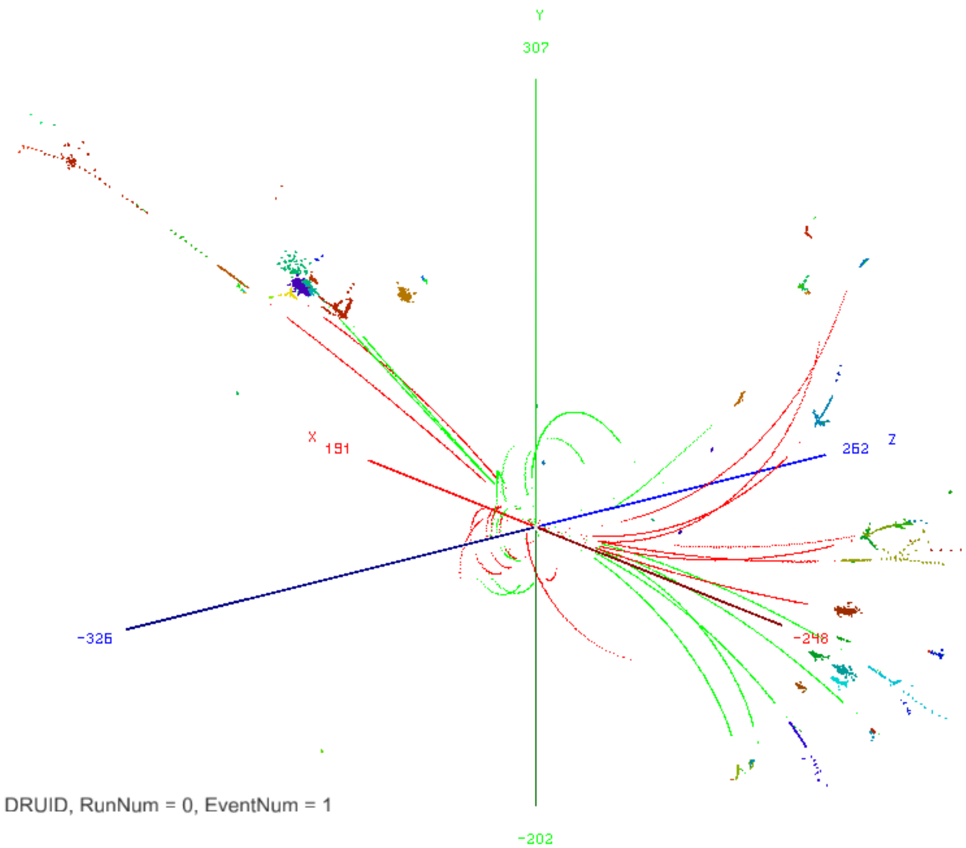
Derive: Absolute Higgs width, branching ratios, couplings

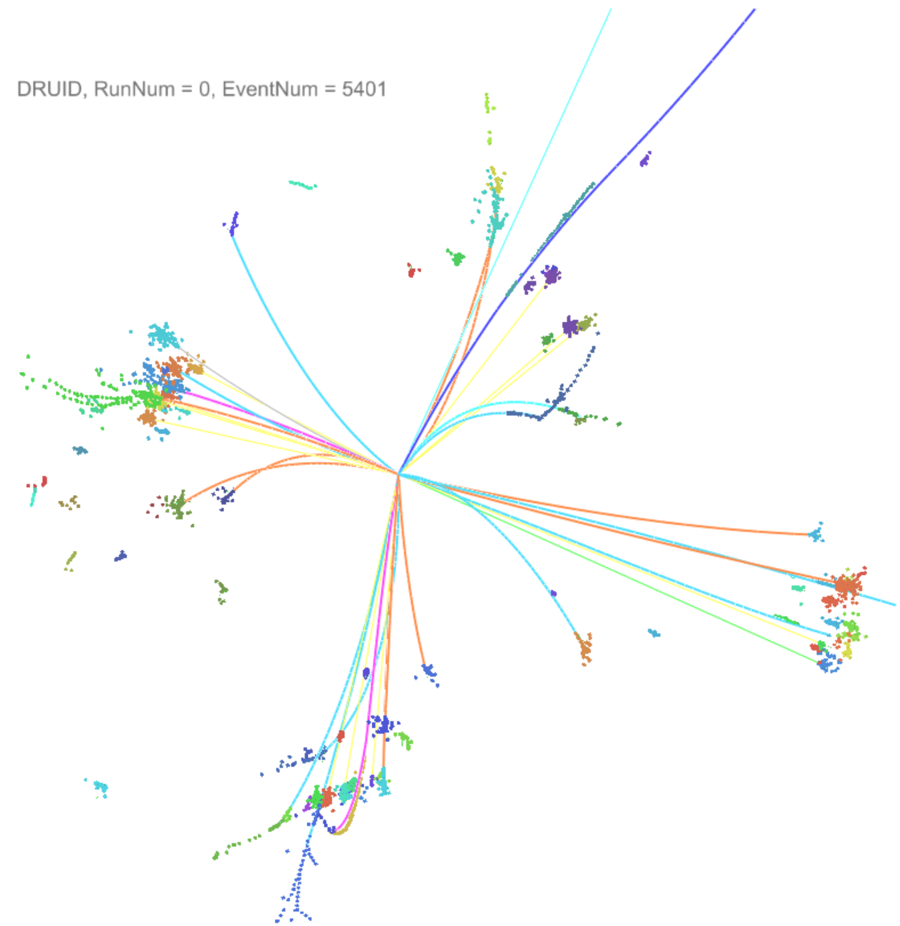
Higgs @ CEPC



Extremely clean;

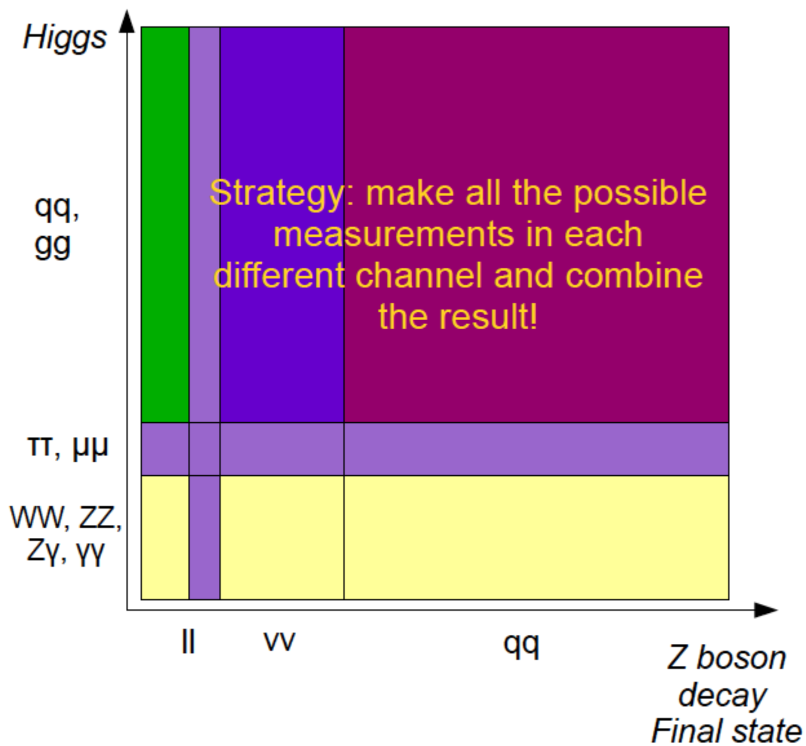
- Absolute measurement to Higgs boson...

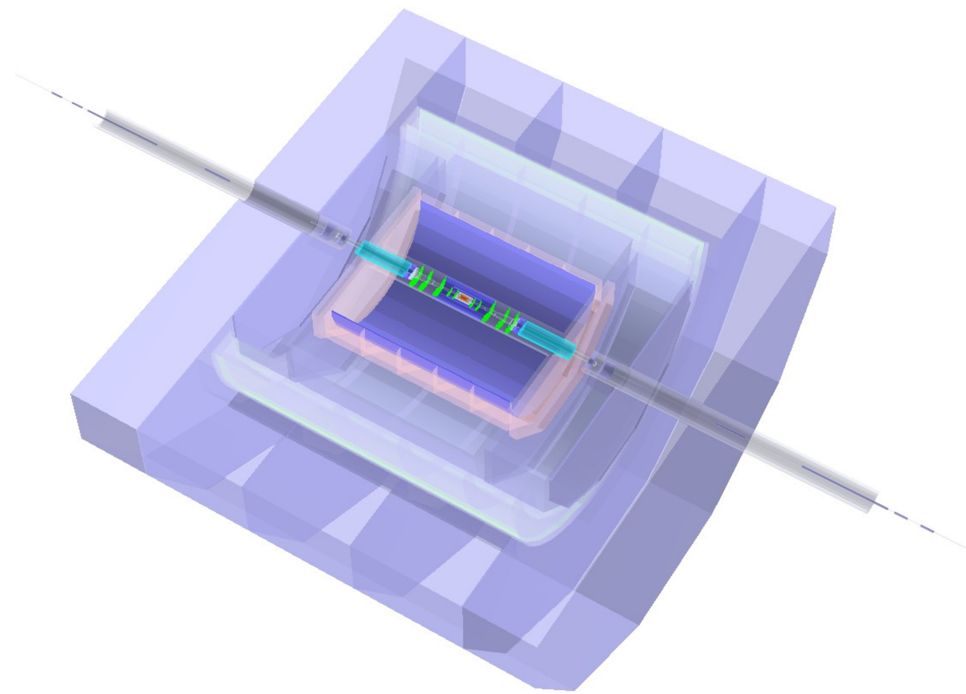




Sim Higgs @ CEPC

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

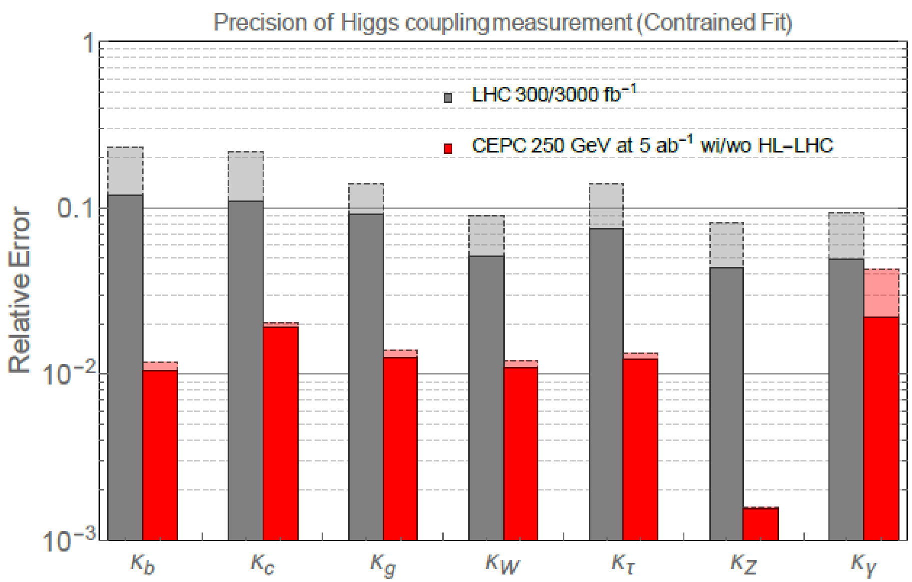
Higgs measurements at CEPC

- Event Rates:
  - $\sigma(AA \rightarrow H \rightarrow BB) \sim g^2(HAA) g^2(HBB)/\Gamma_{total}$
  - Recoil Mass method: absolute measurement of $\sigma(ZH)$ - $g(HZZ)$
  - Absolute measurement to Higgs width and All Higgs couplings

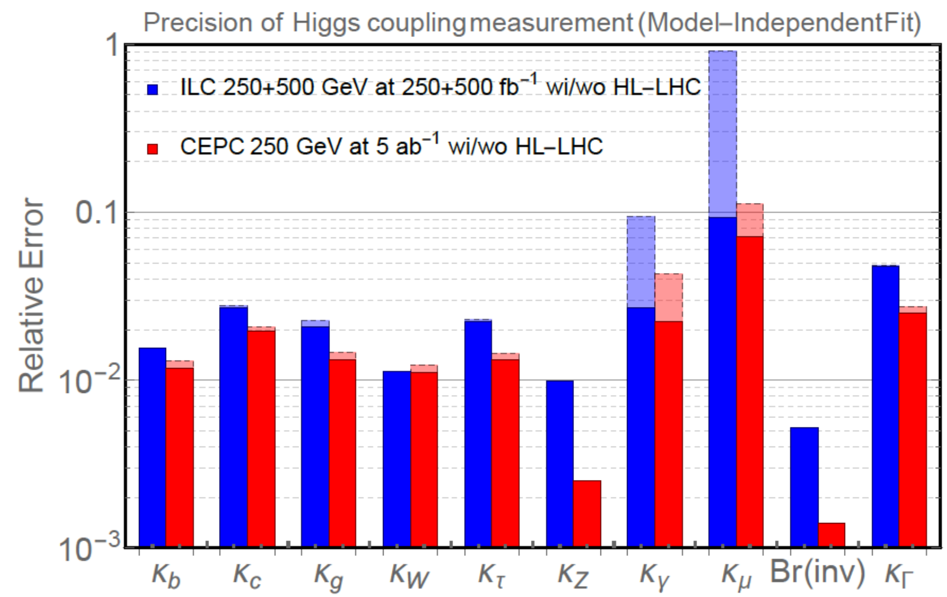
- Differential Distributions

- Higgs rare decay/exotic decays

Higgs analyses at Pre-CDR

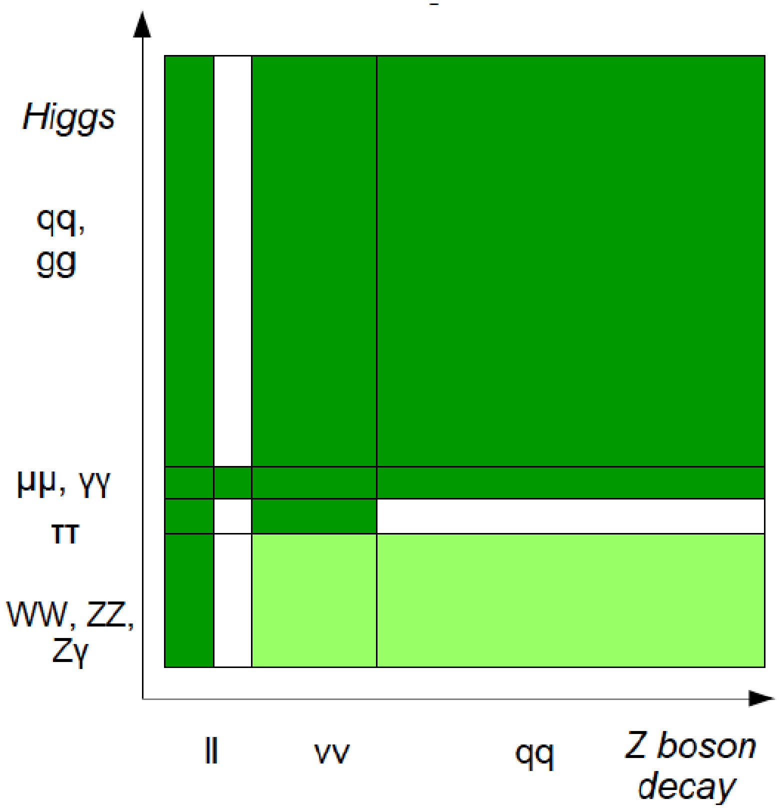


Kappa-framework
model-dependent measurements



Absolute measurements

Status now

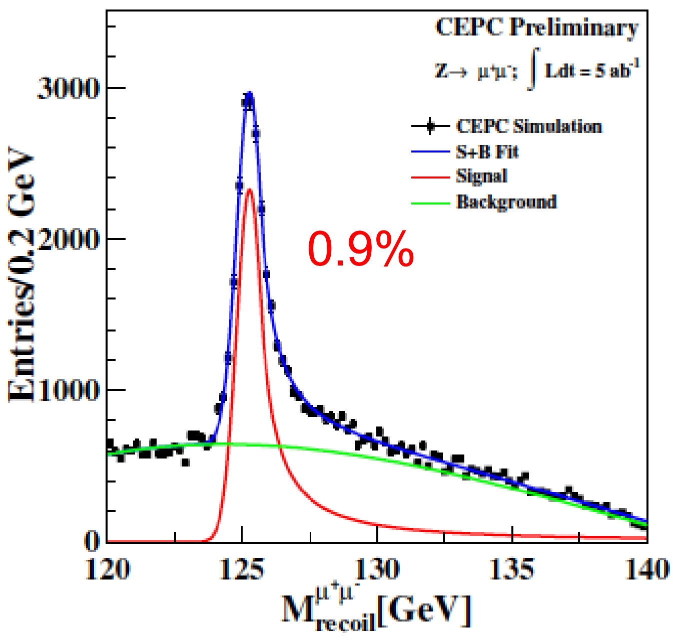


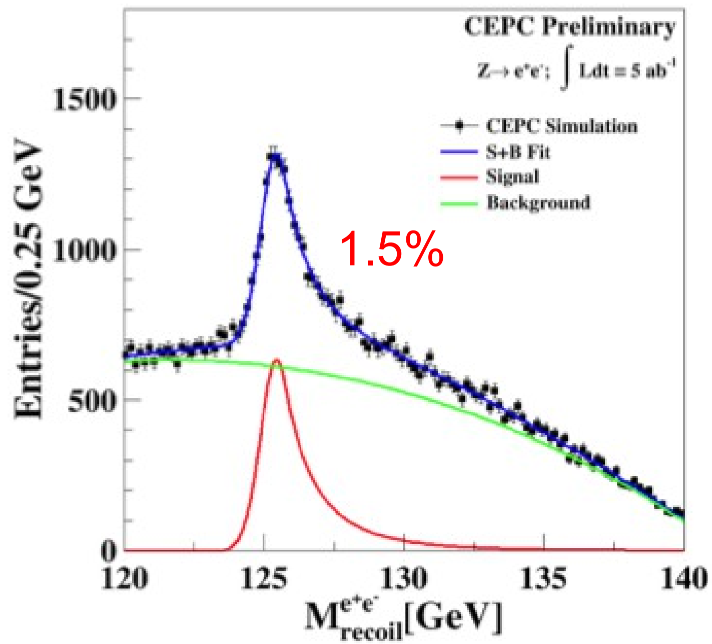
~50 independent analysis at Full Simulation level

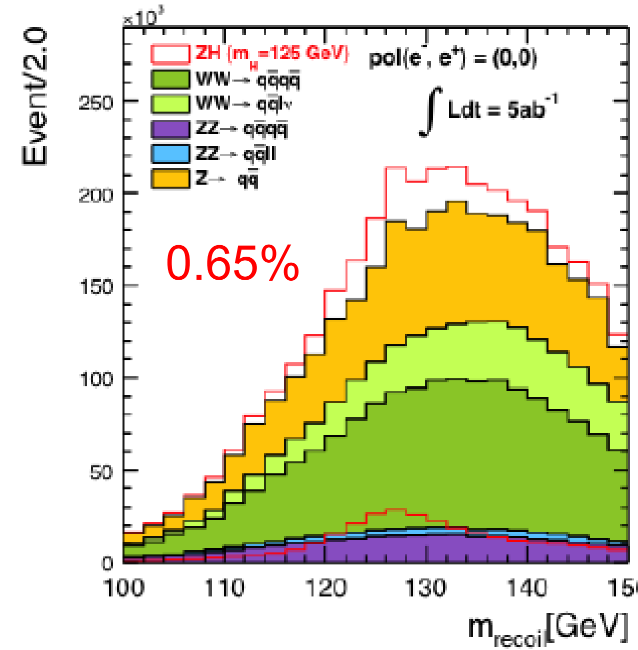
	PreCDR (Jan 2015)	Now (Aug 2016)
σ(ZH)	0.51%	0.50%
σ(ZH)*Br(H→bb)	0.28%	0.21%
σ(ZH)*Br(H→cc)	2.1%	2.5%
σ(ZH)*Br(H→gg)	1.6%	1.2%
σ(ZH)*Br(H→WW)	1.5%	1.0%
σ(ZH)*Br(H→ZZ)	4.3%	4.3%
σ(ZH)*Br(H→ττ)	1.2%	1.0%
σ(ZH)*Br(H→γγ)	9.0%	9.0%
σ(ZH)*Br(H→Zγ)	-	~4 σ
σ(ZH)*Br(H→μμ)	17%	12%
σ(ννH)*Br(H→bb)	2.8%	2.8%
Higgs 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)	$<10^{-3}$	3.0e-4

Model-independent measurement of σ(ZH)

Zhenxing Chen & Yacine Haddad

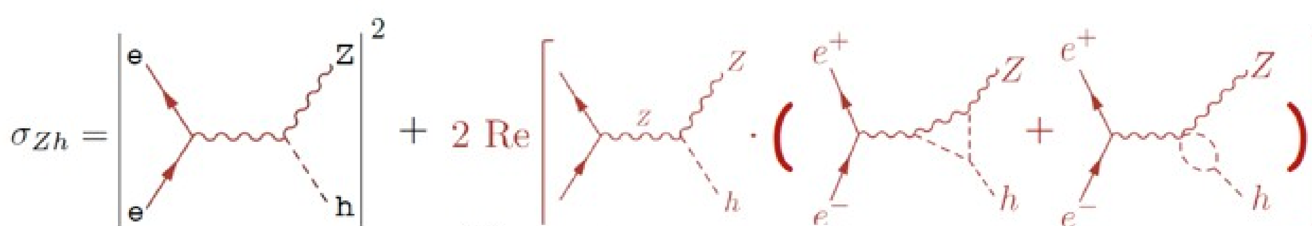






- Recoil mass method. Combined precision:
  $\delta\sigma(ZH)/\sigma(ZH)$ = 0.5% -
  $\delta g(HZZ)/g(HZZ)$ = 0.25%

- Indirect Access to g(HHH)



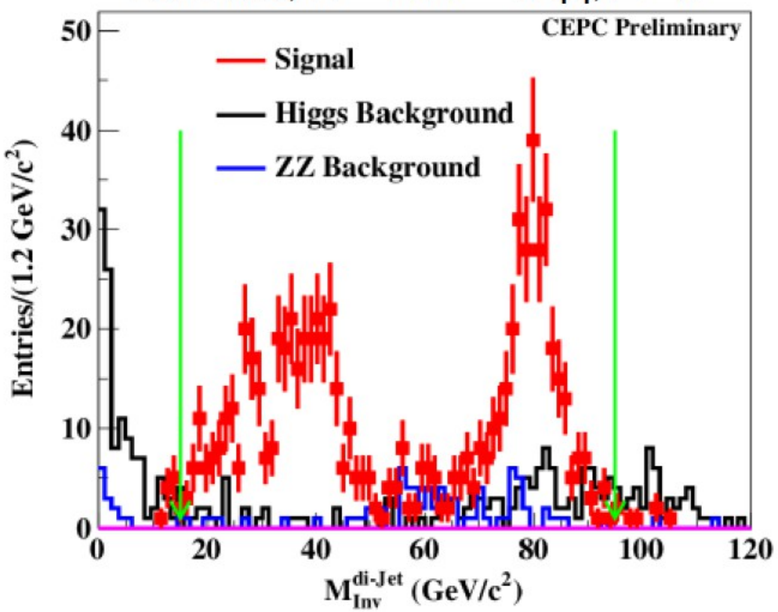
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- *M. McCullough, 1312.3322*

Br(H→WW)

H→WW/ZZ: Portal to Higgs width & perfect test bed for detector/reconstruction performance...

Liao libo, H→WW*→lvqq, Z→ll



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

- Extrapolated from ILC results
- Await for tau finder
- Await for the SM Background simulation
- Full Simulation
- Preliminary result acquired
- Unexplored

- Br(H→WW), Combined accuracy ~ 1.0% from 13 independent full simulation analyses
  - 1.45% at llH, H→WW*→ inc channels, 12 independent channels.
  - *~ 1.7% at vvH, H→WW*→ 4q channel (Preliminary. ILC extrapolation = 2.3%)*
  - 2.3% at qqH, H→WW*→ 2qlv channel (extrapolated from ILC full simulation)
- High efficiency in event reconstruction

Br(H→WW)

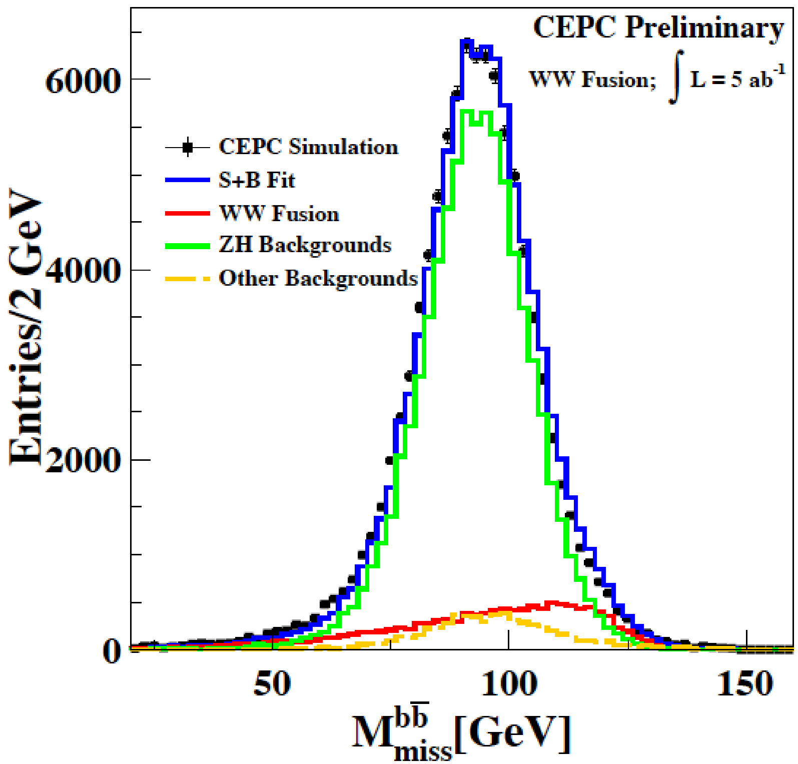
ZH, H->WW*	Yield	Object reconstructed	Isolation	Signal Efficiency	Main Background	Accuracy	Combined
Z(μμ)H(evev)	88	76(86.36%)	61(80.26%)	36(40.91%)	4(ZH)	17.57%	2.68%
Z(μμ)H(μvμv)	89	80(89.89%)	77(96.25%)	52(58.43%)	6(ZH&ZZ)	14.65%	
Z(μμ)H(evμv)	174	157(90.23%)	147(93.63%)	105(60.34%)	0	9.76%	
Z(μμ)H(evqq)	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: 1.1%
- Extrapolation from other ILC channels: 2.2%
- Combined: 1.0%

	Z→ll	tautau	vv	qq
H→WW*→4q	1.45%	3.45k	< 1.9%	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

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

To do: Differential Distributions & Benchmarks for optimization

Benchmarks	Main observables	Key performances	Status
llH, H->X	Higgs recoil spectrum	Lepton Id efficiency, Tracker intrinsic momentum resolution	Well understood
H+X, H->di photon	Event reconstruction efficiency, Higgs invariant mass peak width	Tracker Material, Intrinsic ECAL energy Resolution	
ZH->4 jets,	Br(H->bb, cc, gg)	Jet clustering, PFA: Jet Energy Resolution, Jet Flavor Tagging	Studied at CEPC conceptual Detector (CEPC_v1)
vvH, H->2 jets (optional)	Br(H->bb, cc, gg)	Jet Energy Resolution & Flavor Tagging	
H+X, H->di muon	Event reconstruction efficiency, Higgs invariant mass peak width	Lepton Id efficiency, Tracker intrinsic momentum resolution	
vvH, H->di tau	Efficiency of Tau reconstruction with different tau decay mode	PFA separation, Impact parameter resolution	
qqH, H->invisible	Higgs recoil spectrum	PFA: Jet Energy Resolution	
vvH, H->WW->lvqq	Event Reconstruction Efficiency di-jet mass distribution	PFA, Simultaneous reconstruction of Lepton, Jets and Missing Energy	Studied at different Calorimeter Granularity
WW->lvqq	W mass	Jet Energy resolution & Systematic controls	Full simulation analysis not accomplished yet
Z->tautau	V/A, spectrum function, Branching ratios	Separation & Tracking efficiencies	not started yet

Physics with taus would be essential for the detector optimization...

Summary

- Higgs, portal to unknown
- CEPC, an electron-positron Higgs factory & an precision EW machine
  - o(0.1-1%) level accuracy in absolute measurement of Higgs Branching ratio and couplings
  - Higgs total width measured to 2.8%
  - Good access to SM Higgs rare decays (μμ, γγ, Zγ)
  - Higgs exotic decays, limited to better than 0.1% level
  - EW Program significantly enhance the access to the New Physics
  - Highly complementary to pp machine
- Simulation study: toward a better understanding of its Physics potential
  - Good understanding toward absolute Higgs coupling measurement
  - Toward detector optimization & measurement with detector optimizations

IHEP-CEPC-DR-2015-01

IHEP-EP-2015-01

IHEP-TH-2015-01

Can be downloaded from

http://cepc.ihep.ac.cn/preCDR/volume.html

CEPC-SPPC

Preliminary Conceptual Design Report

Volume I - Physics & Detector

403 pages, 480 authors

The CEPC-SPPC Study Group

March 2015

IHEP-CEPC-DR-2015-01

IHEP-AC-2015-01

CEPC-SPPC

Preliminary Conceptual Design Report

Volume II - Accelerator

328 pages, 300 authors

The CEPC-SPPC Study Group

March 2015

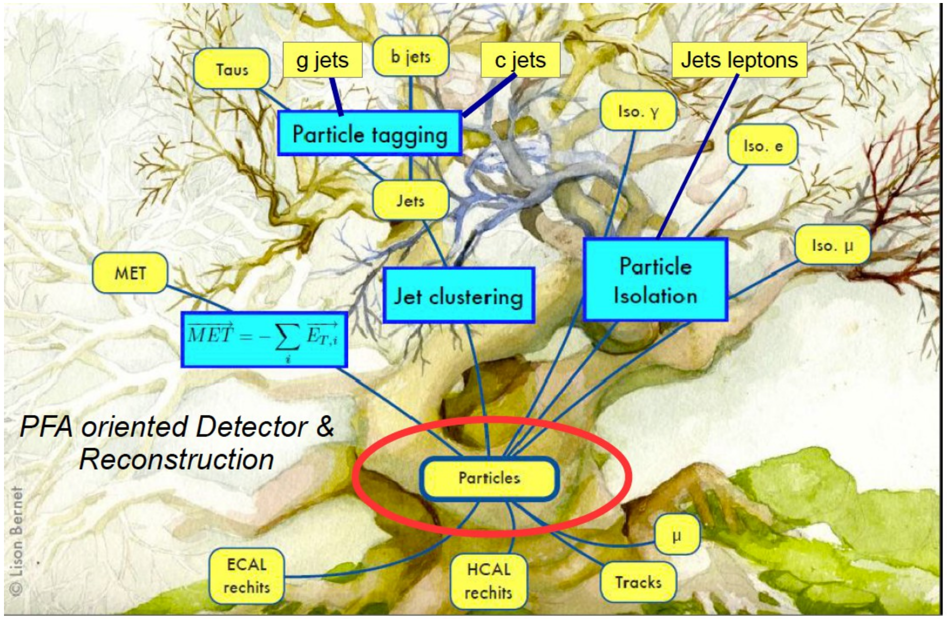
References

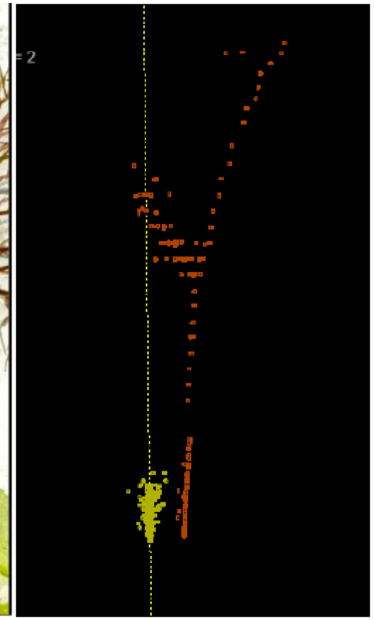
- https://arxiv.org/abs/1601.05352
- https://arxiv.org/abs/1701.07542
- https://arxiv.org/abs/1609.03995
- https://arxiv.org/abs/1505.01008
- https://arxiv.org/abs/1512.06877

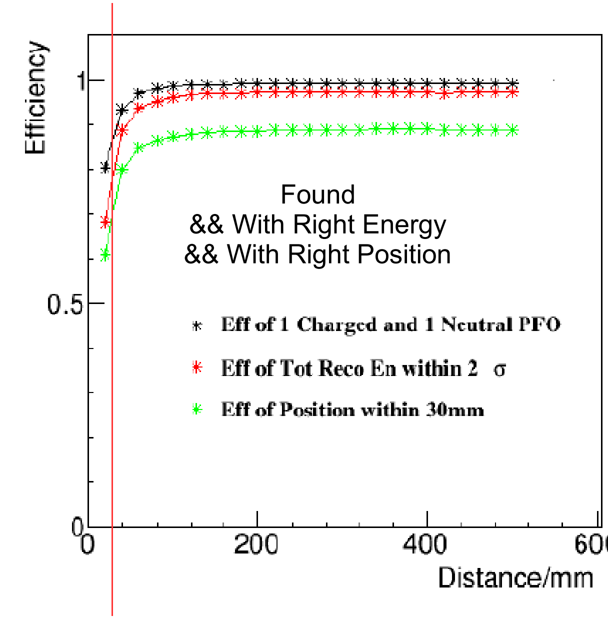
Welcome!

Backup

Detector performance







Acceptance	$\lvert\cos(\theta)\rvert < 0.995$ (from the inner radius of the outmost tracking disk)
Tracking Efficiency	For isolated charged particle with energy > 1GeV: ~100%
Photon Reconstruction Efficiency	For isolated photon with energy > 0.5 GeV: ~100%
Tracker resolution	$\delta(1/P_T) = 2*10^{-5}(\mathrm{GeV}^{-1})$
ECAL intrinsic resolution	$\delta E/E = 16\%/\sqrt{E/GeV} \oplus 0.5\,\%$
HCAL intrinsic resolution	$\delta E/E = 60\%/\sqrt{E/GeV} \oplus 1\,\%$
Jet energy resolution	$\delta E/E = 4\%$
Typical Distance for shower separation	< 3 cm
Lepton identification	For charged particle with Energy >2GeV: Lepton identification efficiency > 99.5%, P(hadron→muon)~P(hadron→electron): 1%
b-tagging	At Z pole samples & eff(b→b)) = 80%, P(uds→b) < 1%, P(c→b) ~ 10%
c-tagging	At Z pole samples & eff(c→c)) = 60%, P(uds→c) = 7%, P(b→c) = 12%

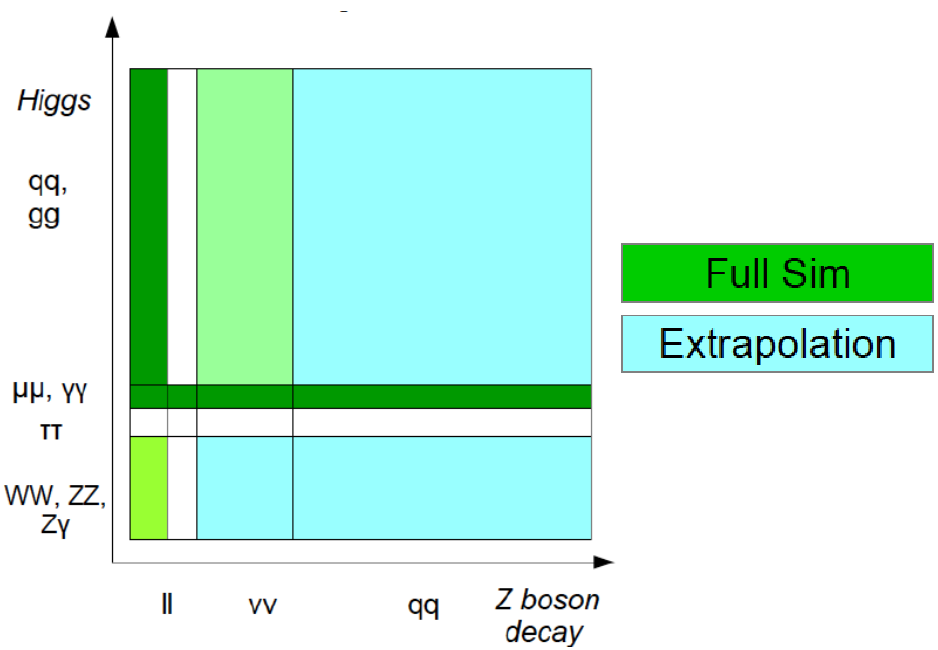
Performance at full reconstruction

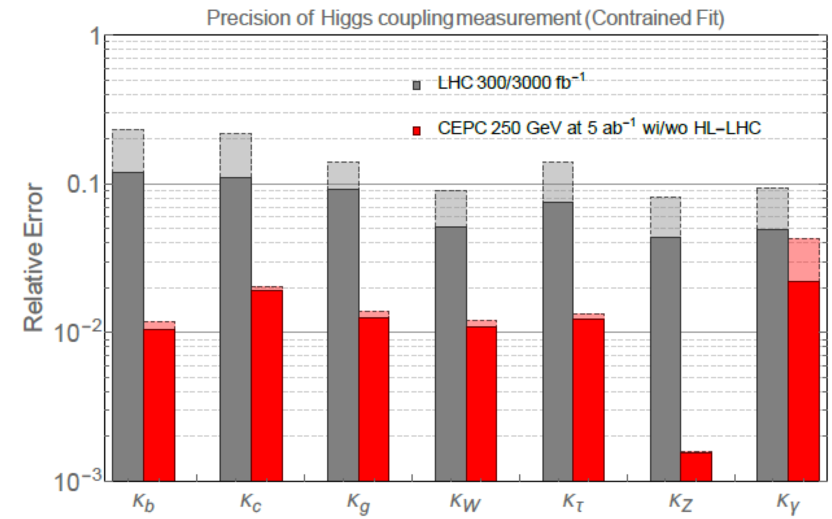
Benchmark separation distance < 3 cm (Testing on 10 GeV Pion + 5 GeV Photon Sample)

Higgs analyses at Pre-CDR

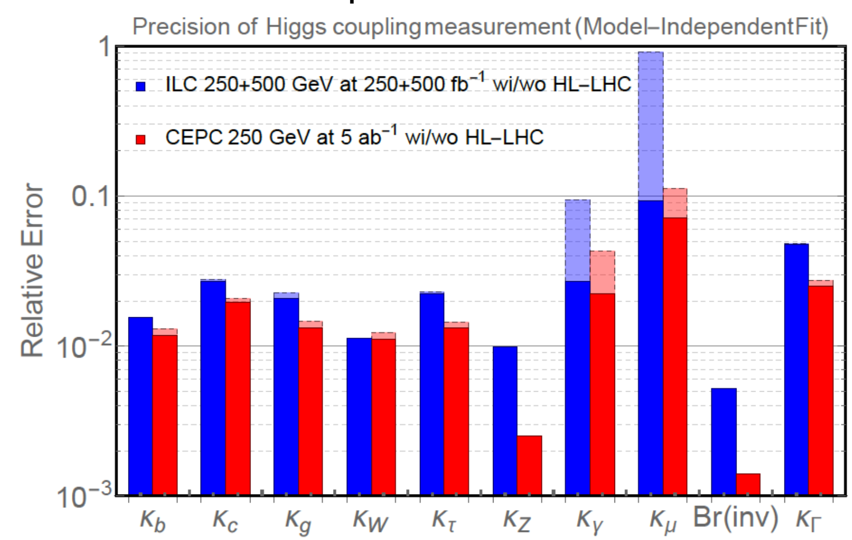
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2}\mathcal{O}_{6,i} \qquad \delta \sim c_i \frac{v^2}{M^2}$$

% precision → M ~ 1 TeV
to new physics → ~ × 10 over LHC





Kappa-framework
model-dependent measurements



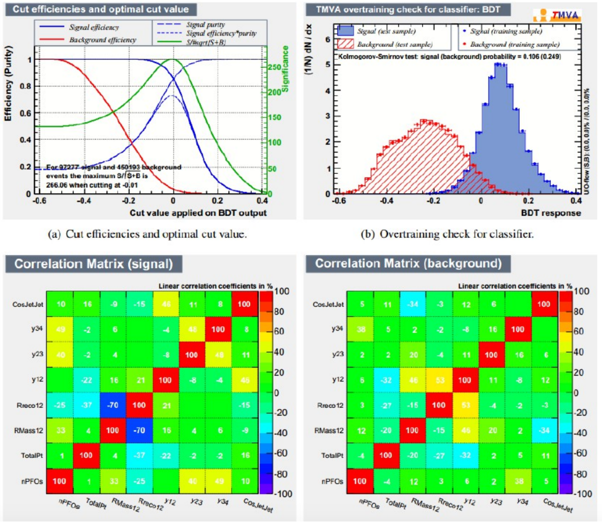
Absolute measurements

Workflow for Br(H->bb, cc, gg) measurements general event selection + Template fit

2. Selection

Cut Definition	*Sig.*	*qq*	*qqnn*	*qqln*	*xxh*
FSClasser output	148955	25M	183687	3698817	63194
$N_{\mathrm{PFO}(E>0.4\mathrm{GeV})} > 20$	148808	23M	163088	3439927	58882
$110 < E_{\mathrm{total}} < 150$	132561	10M	125878	705357	34215
$P_T > 19$	126006	34198	116314	627602	32300
Isolation lepton veto	123586	33775	115867	327206	23773
$100 < M_{\mathrm{inv}} < 135$	117845	9506	10420	162511	21277
$70 < M_{\mathrm{rec}} < 125$	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
$-0.98 < \cos(\theta^{(2\mathrm{jets})}_{\mathrm{included}}) < -0.4$	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

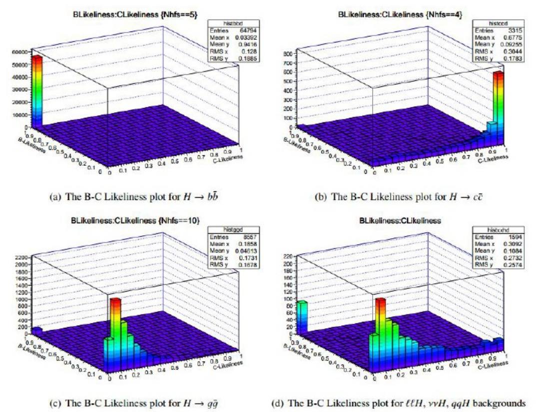
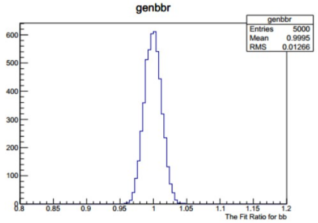

(a) The B-C Likeliness plot for $H \to b\bar{b}$ (b) The B-C Likeliness plot for $H \to c\bar{c}$ (c) The B-C Likeliness plot for $H \to g\bar{g}$ (d) The B-C Likeliness plot for $\ell\ell H$, $\nu\nu H$, qqH backgrounds

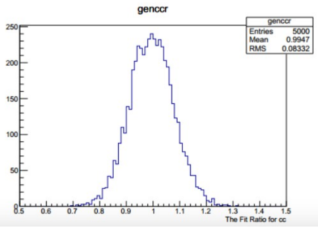
Figure 7: The B-C Likeliness characteristics for Signal and other Higgs Background. The Standard Model Background isn't included in because there is no B-C Likeliness.

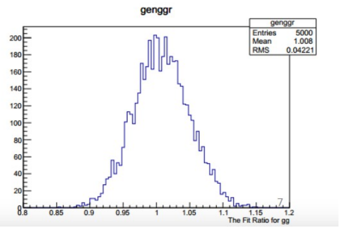
Template fit



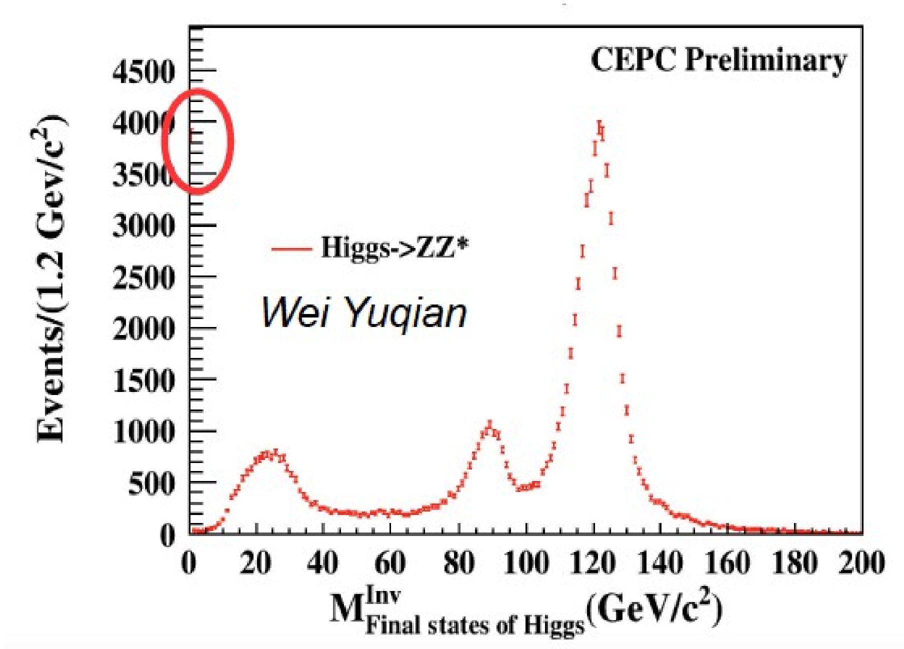
Template: 2000 fb-1
Data: 500 fb-1
Fit Times: 5000

No SM bkg in template fit, since no full simulation





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

- 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), explored at 18 different channels with full simulation (llvvqq, 4lqq, ll4q, 2l4v)
  - 8 Channels has individual accuracy better than 25%: Combined accuracy **~ 5.4%**
  - 8 with accuracy worse than 25 - 50%
  - 2 with accuracy worse than 50% (llH, H→ZZ→4q and vvH, H→ZZ→llvv)
- High efficiency in event reconstruction

Br(H→ZZ)

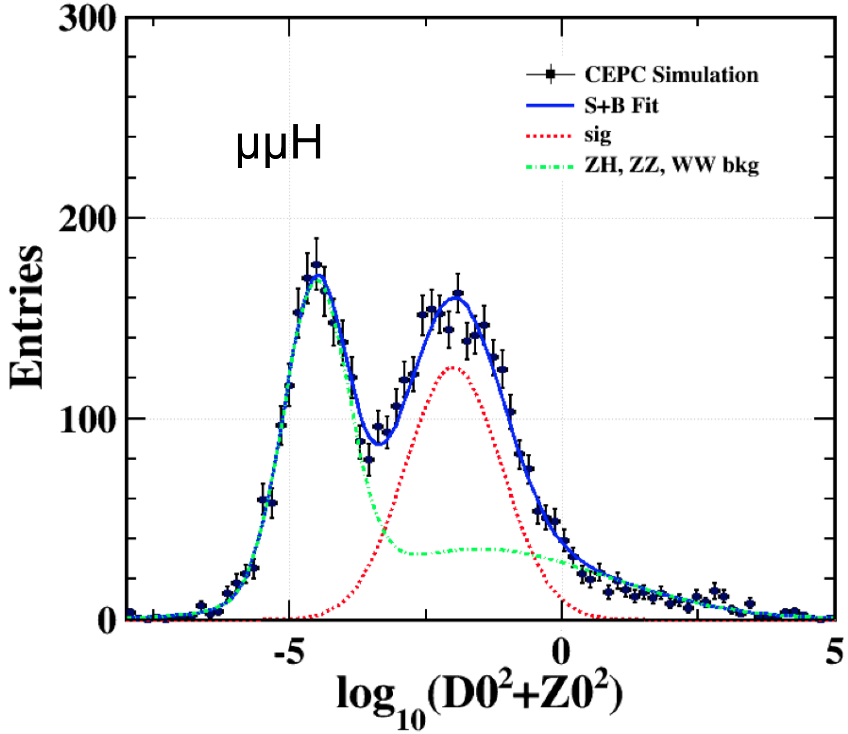
ZZZ*	Yield	Object reconstructed	Signal Efficiency(%)	Main Background	Accuracy (%)	Comments
μμvvqq	128	118	63.3	h->ww&zz_sl	**12.9**	Tau finder would be highly appreciated Reconstructed efficiency of electron need to be improved
μμqqvv	128	125	-	h->bb&zz_sl	>25	
eevvqq	132	91	53.8	h->ww&sze_sl	**15.8**	
eeqqvv	132	88	-	h->bb&zz_sl	>25	
vvμμqq	158	144	61.4	h->t,w&zz_sl	**11.0**	
vvqqμμ	158	149	51.9	h->w,b&zz_sl	**12.9**	
vveeqq	151	118	43.1	h->w&sze_sl	**21.3**	
vvqqee	151	134	-	h->bb&sze_sl	>25	
qqμμvv	135	115	-	h->tt&zz_sl	>25	Compare to ll recoil, qq recoil mass has much worse distinguishing power to SM background
qqvvμμ	135	122	-	h->t,w&zz_sl	>25	
qqeevv	127	107	-	h->tt&sze_sl	>25	
qqvvee	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**	

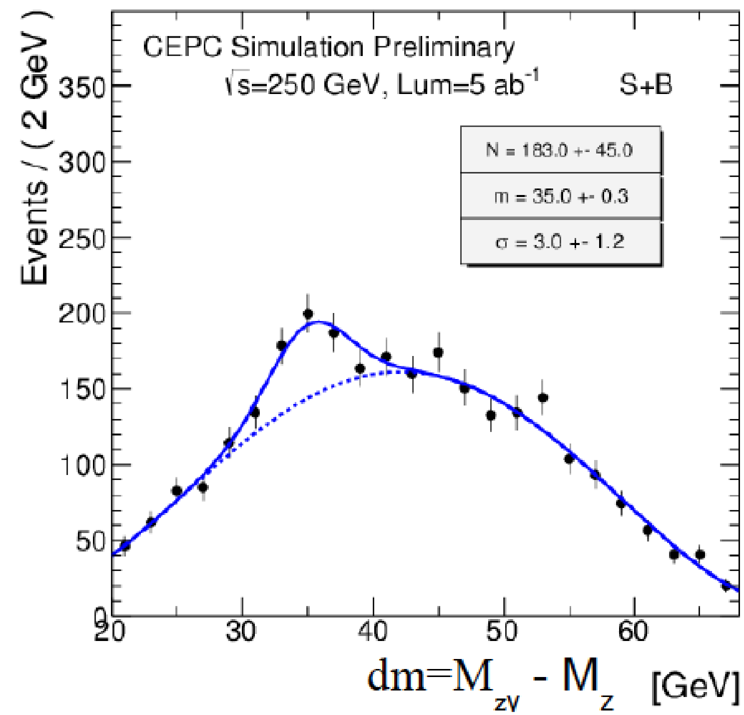
Full Simulation analysis performed on 16 independent channels.
8 Channels acquire accuracy better than 25%.

- Combined accuracy: **5.4%**
- *If electron id efficiency ~ muon id:* ***4.8%***
- ***If tau finder (used for veto) is mature: ??***

TLEP extrapolation**: 4.3%**

Br(H→ττ) & Br(H→Zγ)





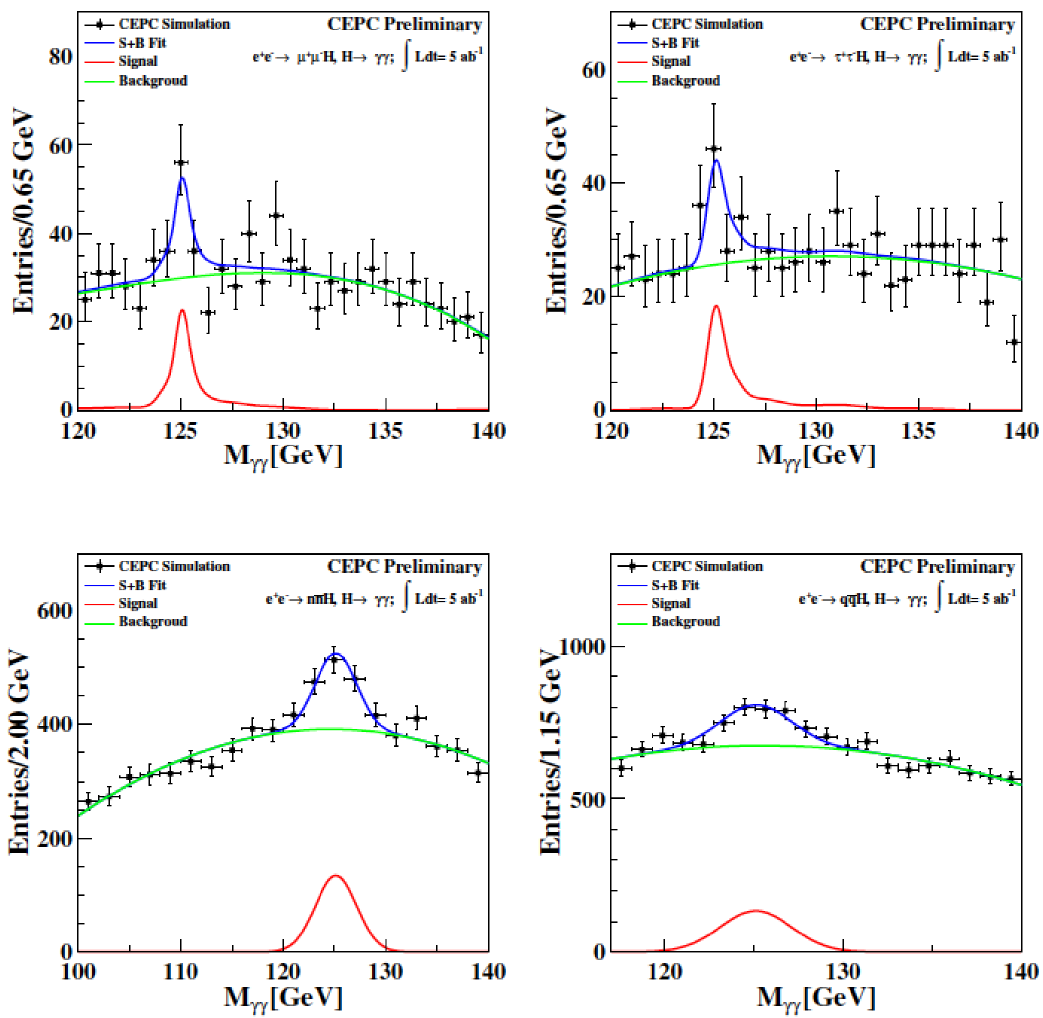
Br(H→ττ): 3% accuracy acquired by mumuH channel; overall accuracy < 1% (Dan Yu)

H→Zγ events: 4σ signal (Weiming Yao)

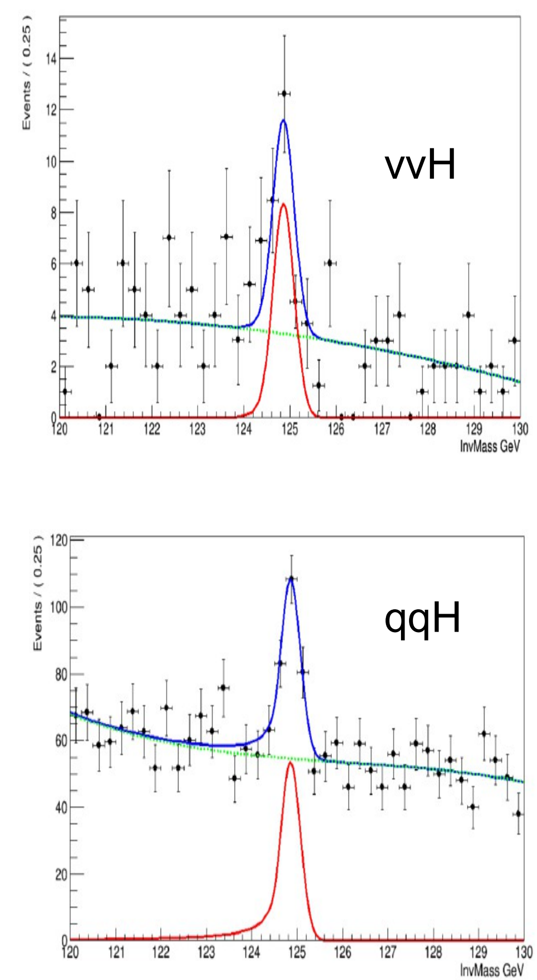
Higgs rare decay

Feng Wang, Jianhuan Xiang, Yitian Li. etc

Binlong Wang, Zhenwei Cui



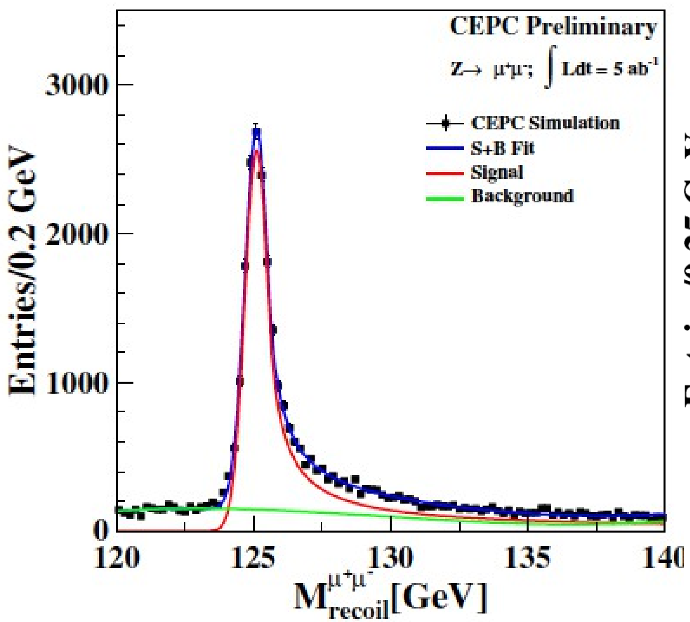
Br(H→γγ): ~10%

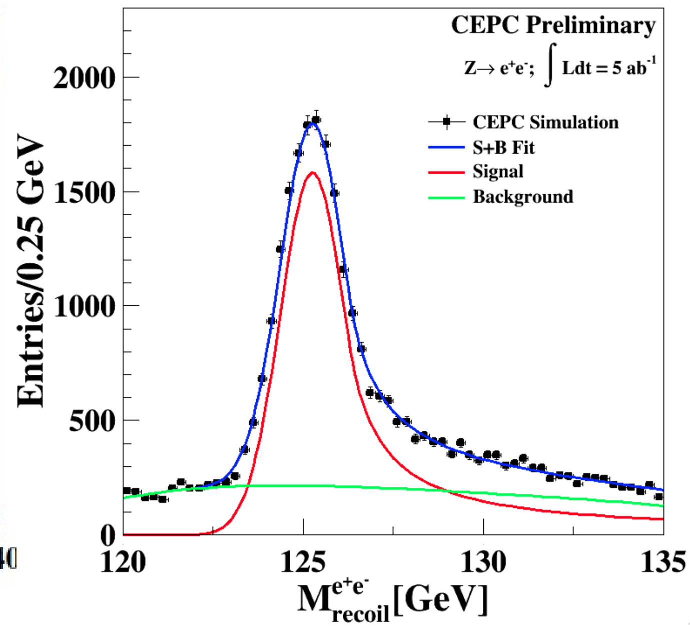


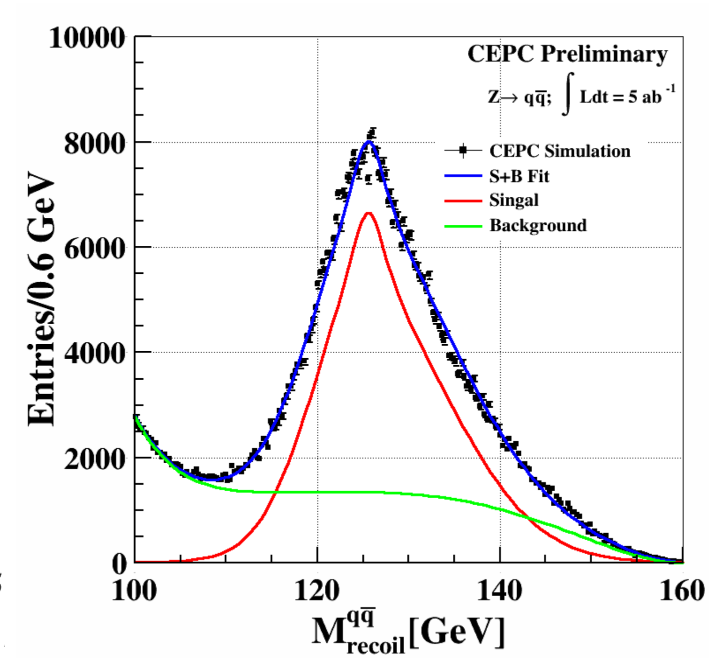
Br(H→μμ): ~12%
(Exclusive analysis)

Exotic: Higgs invisible decays

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





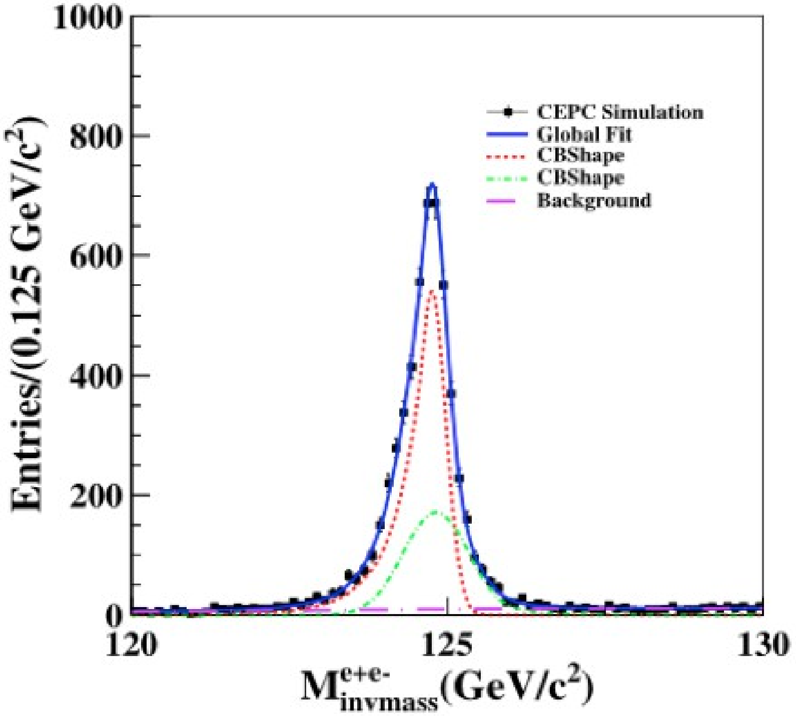


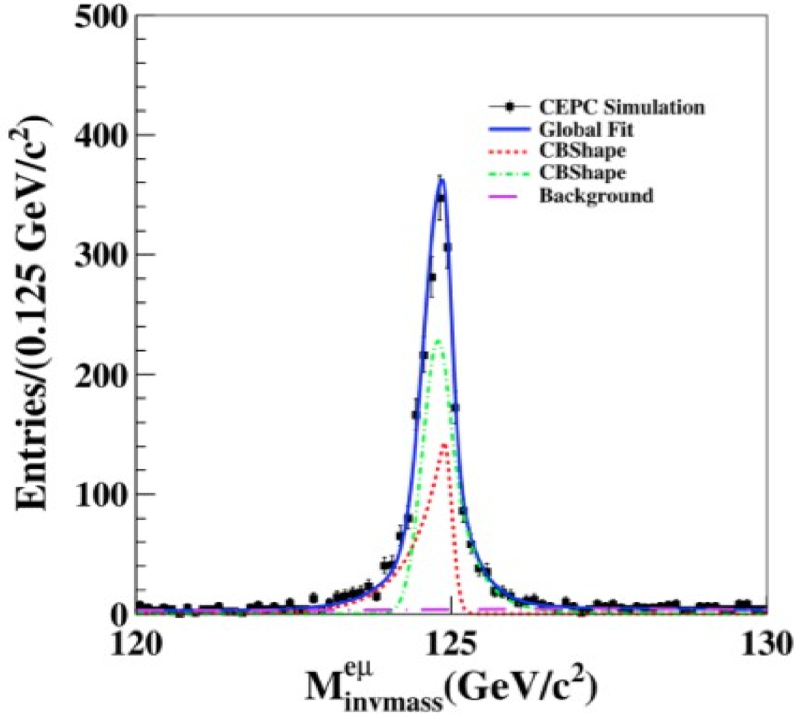
Invisible up limit at CEPC: 0.14% at 95% C.L

Up limit of Br(H→ee) & Br(H→eμ)

Lei Wang

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



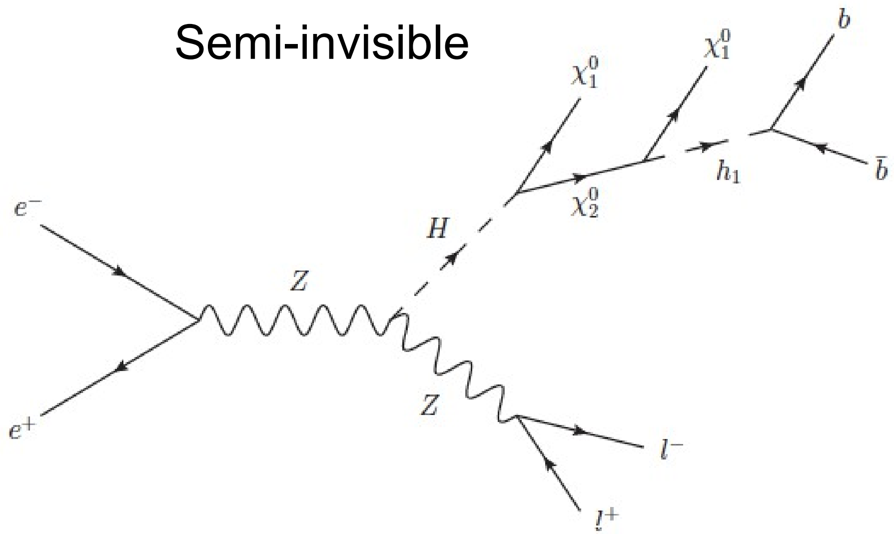


95% up limit: Br(H->ee) = 1.7e-4;
Br(H->emu) = 1.2e-4;

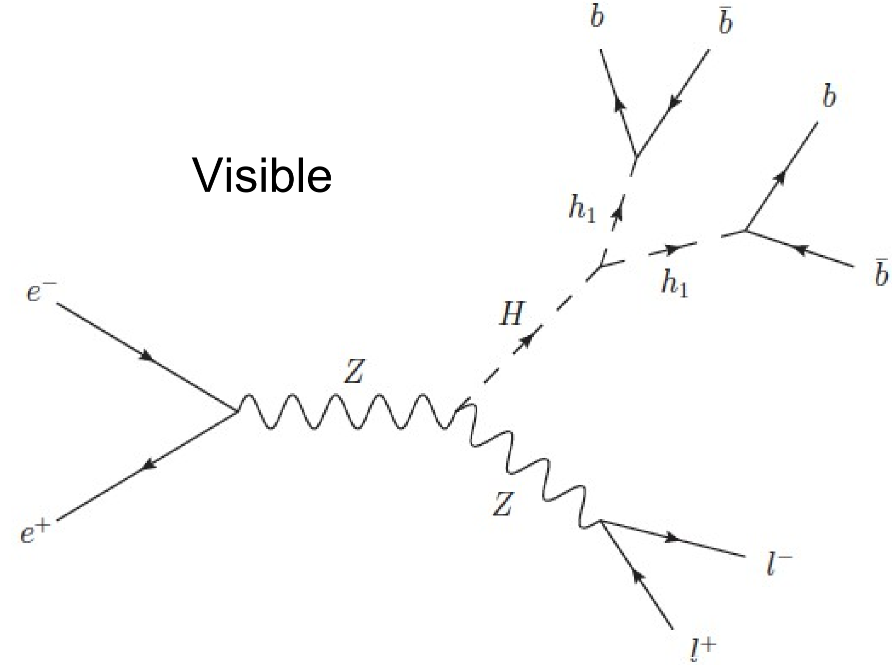
Many updates on the H->exotic with Hadronic final states

H→Exotic, Hadronic

Semi-invisible



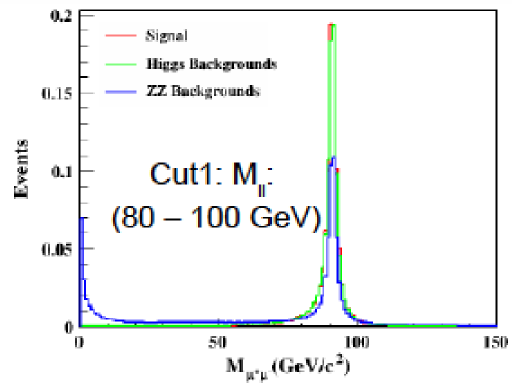
Visible

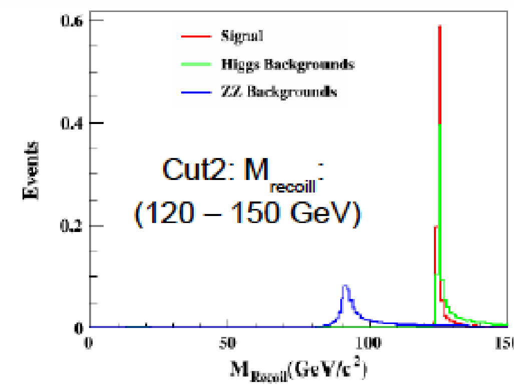


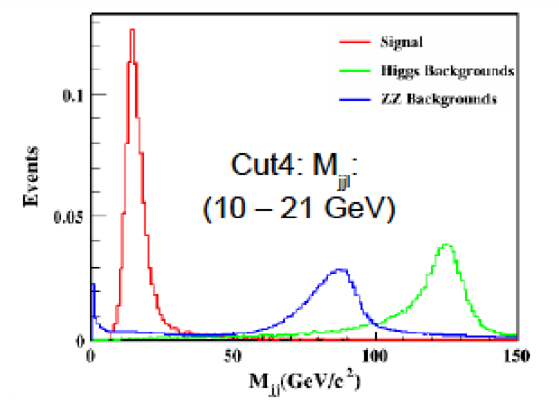
- Typical processes in 2HDM & NMSSM
- Joint efforts by HK Cluster and IHEP
  - Study proposed by T. Liu
  - Main analyzer, Jiawei Wang, Kevin & Zhenxing Chen
- 95% CL up limit ~o(10^{-4}).

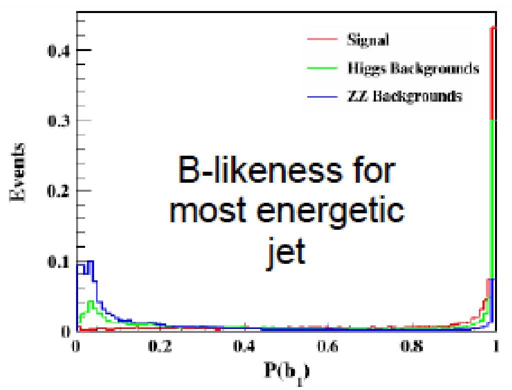
H->Exotic, hadronic

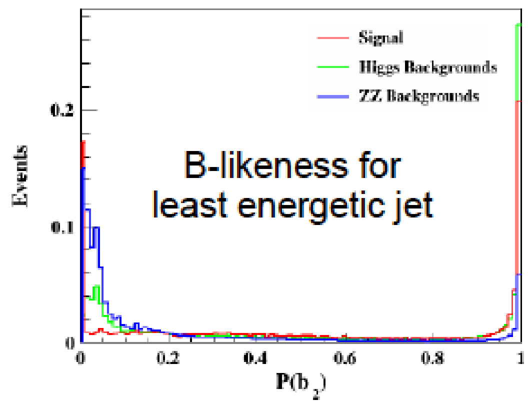
Para: M(LSP) = 0; M(h0) = 15 GeV; M(NLSP) = 20 GeV









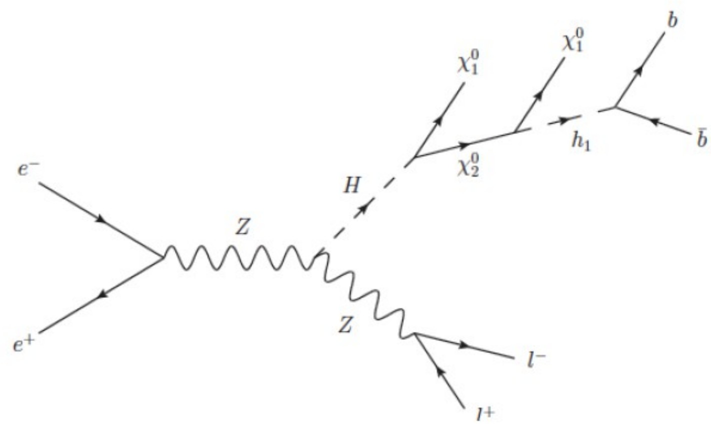


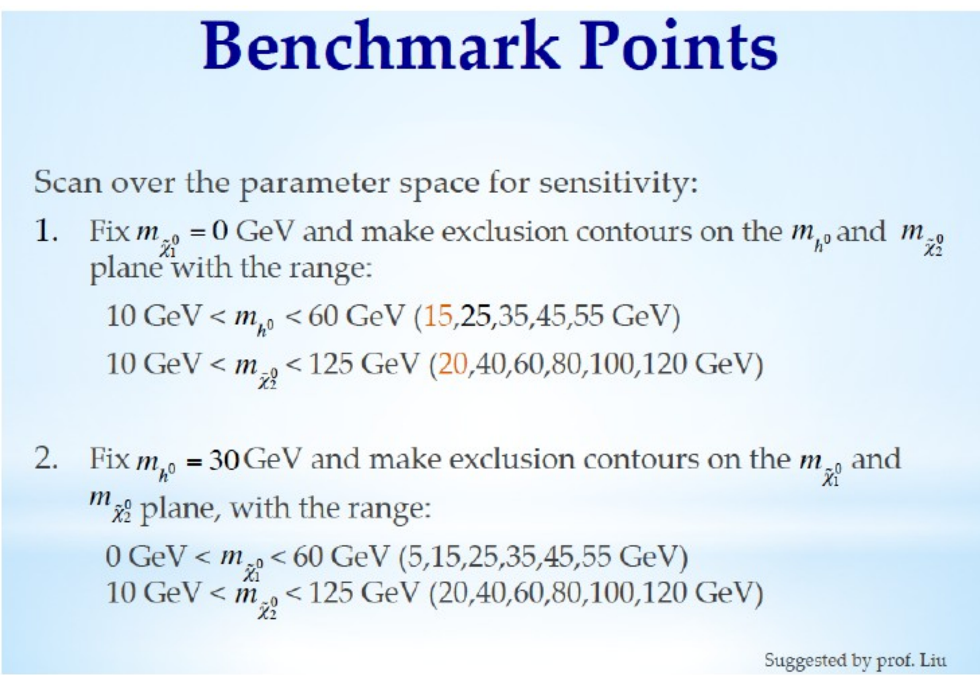
	Object found	Cut 1 m_{ll}	Cut 2 m_{rec}	Cut 3 b likeness	Cut 4 m_{jj}
Signal	17	15	15	12	10
ZH BGs	34093	30732	30030	16026	4
ZZ BGs	538790	281198	30825	4274	20

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)

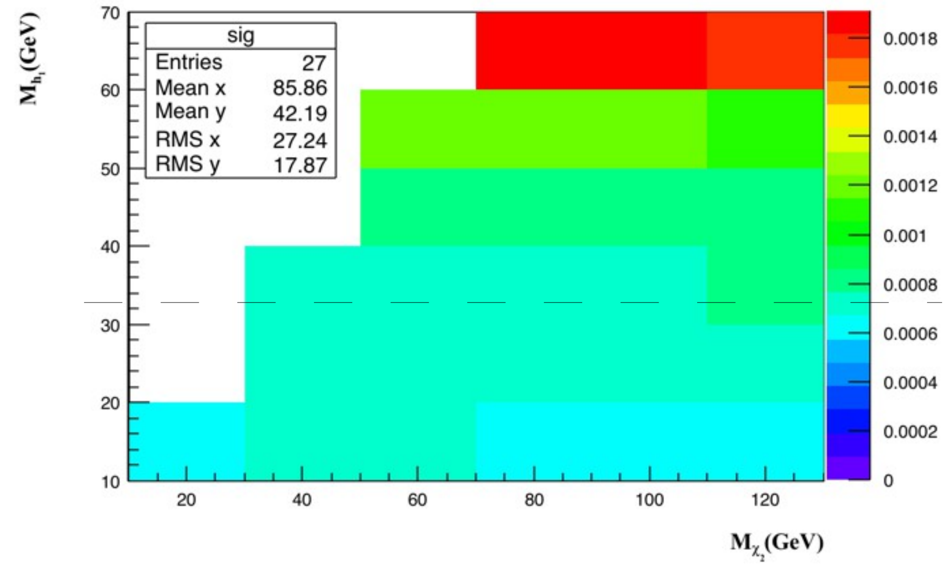
   10 GeV < $m_{\tilde{\chi}_2^0}$ < 125 GeV (20,40,60,80,100,120 GeV)

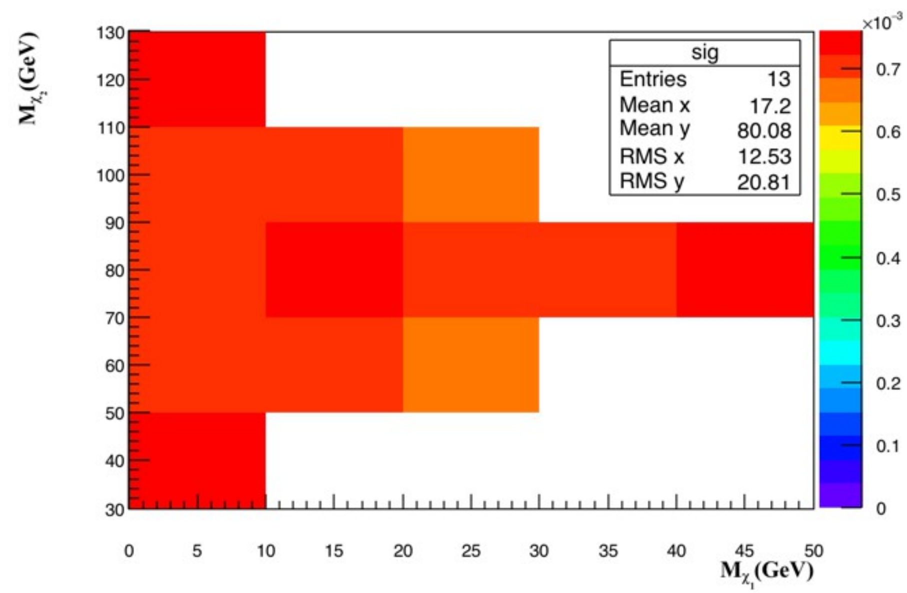
2. Fix $m_{h^0} = 30$ GeV and make exclusion contours on the $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0}$ plane, with the range:

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

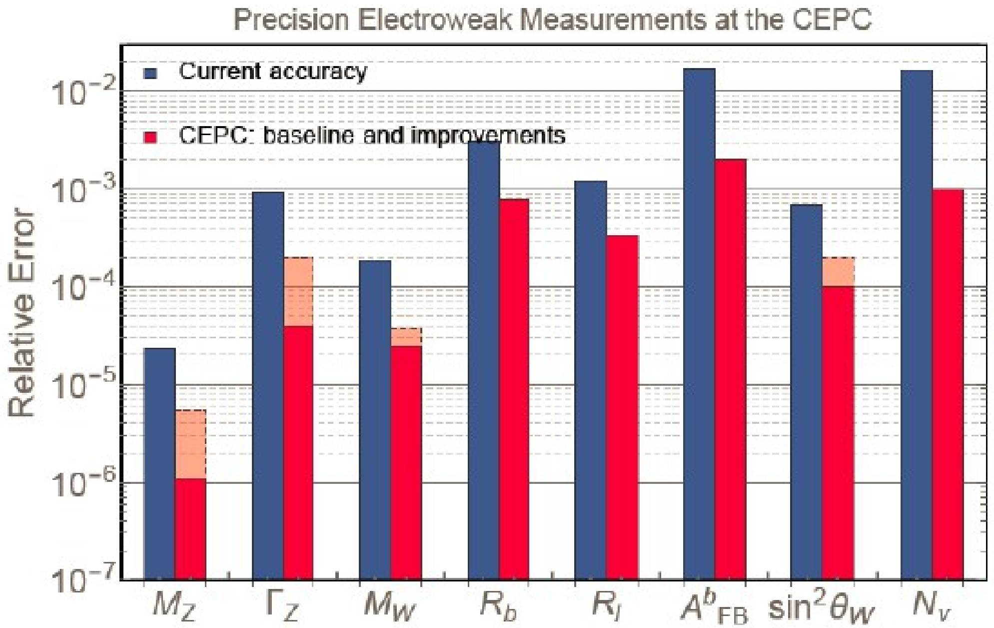
   10 GeV < $m_{\tilde{\chi}_2^0}$ < 125 GeV (20,40,60,80,100,120 GeV)

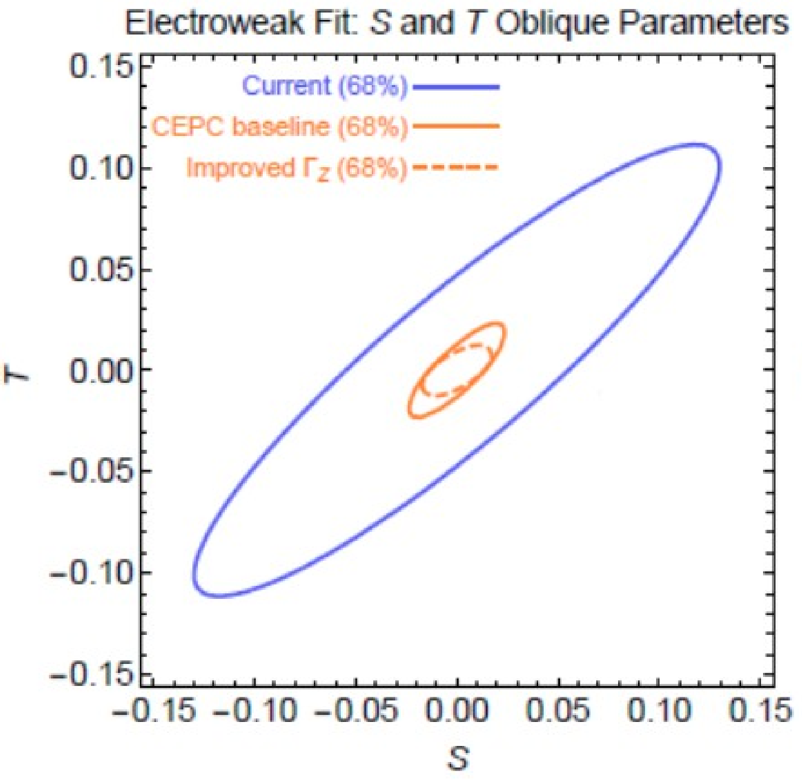
Suggested by prof. Liu





EW Physics

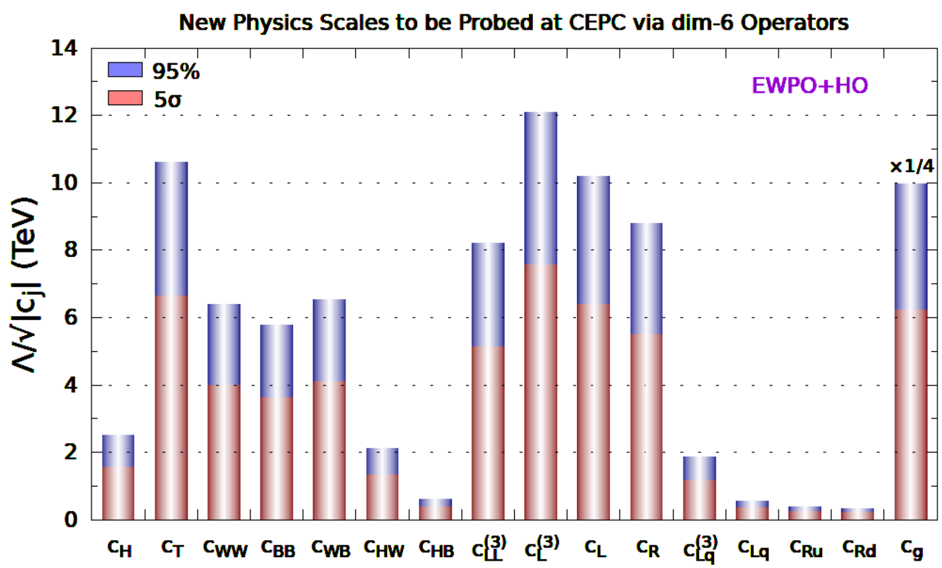




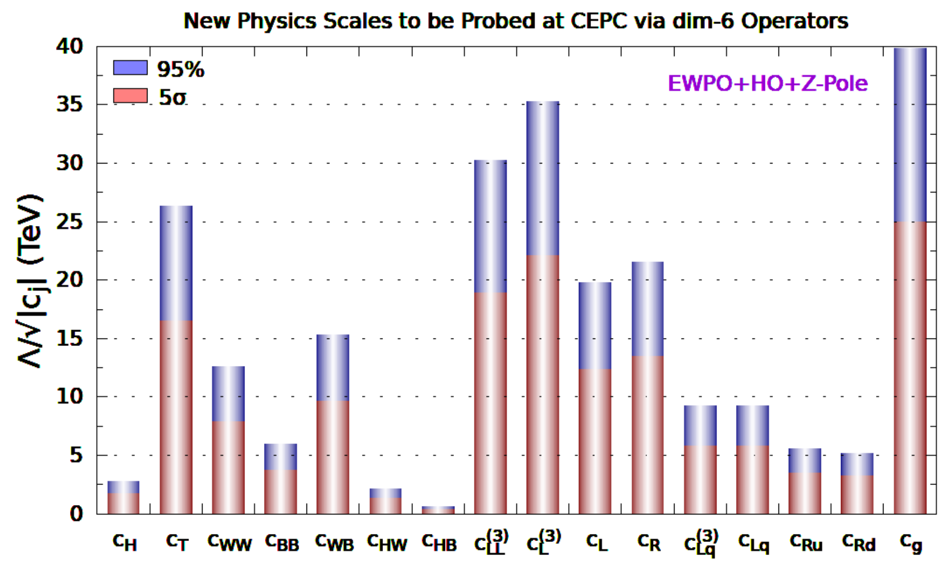
From 10 Billion Z bosons + the data at Higgs runs

New Physics Reach via dim-6 operators

Sensitivities from Existing EWPO & Future HO



Sensitivity from EWPO+HO+Z-Pole



1603.03385

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{ij} \frac{y_{ij}}{\Lambda \sim 10^{14}\mathrm{GeV}} (\bar{L}_i \tilde{\mathbf{H}})(\tilde{\mathbf{H}}^\dagger L_j) + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i \,.$$

Higgs	EW Gauge Bosons	Fermions
$\mathcal{O}_{\mathrm{H}} = \frac{1}{2}(\partial_\mu \lvert\mathbf{H}\rvert^2)^2$	$\mathcal{O}_{\mathrm{WW}} = g^2 \lvert\mathbf{H}\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\mathcal{O}^{(3)}_{\mathrm{L}} = (i\mathbf{H}^\dagger \sigma^a \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
$\mathcal{O}_{\mathrm{T}} = \frac{1}{2}(\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})^2$	$\mathcal{O}_{\mathrm{BB}} = g^2 \lvert\mathbf{H}\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}^{(3)}_{\mathrm{LL}} = (\overline{\Psi}_L \gamma_\mu \sigma^a \Psi_L)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
	$\mathcal{O}_{\mathrm{WB}} = g g' \mathbf{H}^\dagger \sigma^a \mathbf{H} W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\mathrm{L}} = (i\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\Psi}_L \gamma^\mu \Psi_L)$
Gluon	$\mathcal{O}_{\mathrm{HW}} = ig(D^\mu \mathbf{H})^\dagger \sigma^a (D^\nu \mathbf{H}) W^a_{\mu\nu}$	$\mathcal{O}_{\mathrm{R}} = (i\mathbf{H}^\dagger \overleftrightarrow{D}_\mu \mathbf{H})(\overline{\psi}_R \gamma^\mu \psi_R)$
$\mathcal{O}_{\mathrm{g}} = g_s^2 \lvert\mathbf{H}\rvert^2 G^a_{\mu\nu} G^{a\mu\nu}$	$\mathcal{O}_{\mathrm{HB}} = ig'(D^\mu \mathbf{H})^\dagger (D^\nu \mathbf{H}) B_{\mu\nu}$	

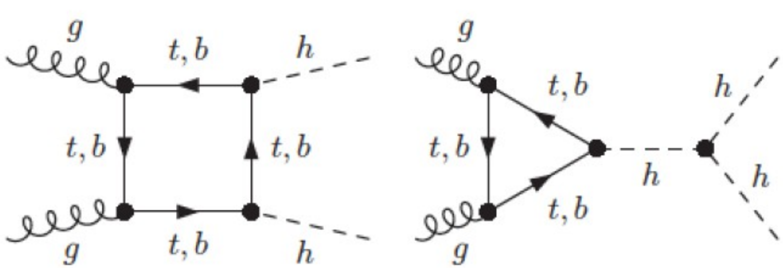
e^+e^- and pp complementary

o($10^{9\text{-}10}$) Higgs at SPPC

Event rates measured at pp collision $\sigma \cdot BR(X \to H \to Y) = \sigma_X \frac{\Gamma_Y}{\Gamma_{tot}}$

e+e- collider: provide anchor for absolute measurement (total width, etc)

pp collision has direct access to g(HHH) & g(Htt) and better access to Higgs rare decays

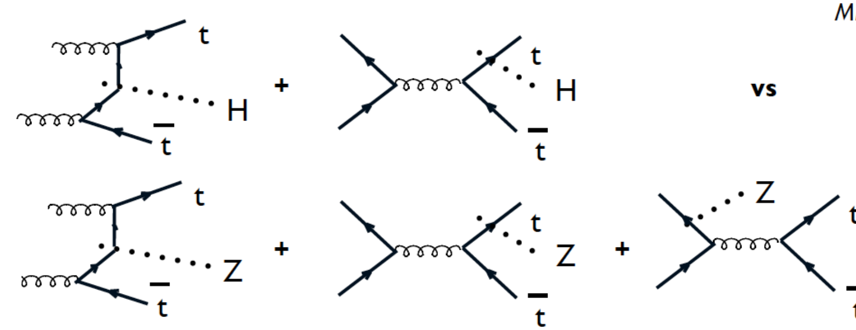


	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

ArXiv: 1310.8361 [hep-ex]

ttH/ttZ as a precision probe of the top Yukawa coupling

MLM, Frederix



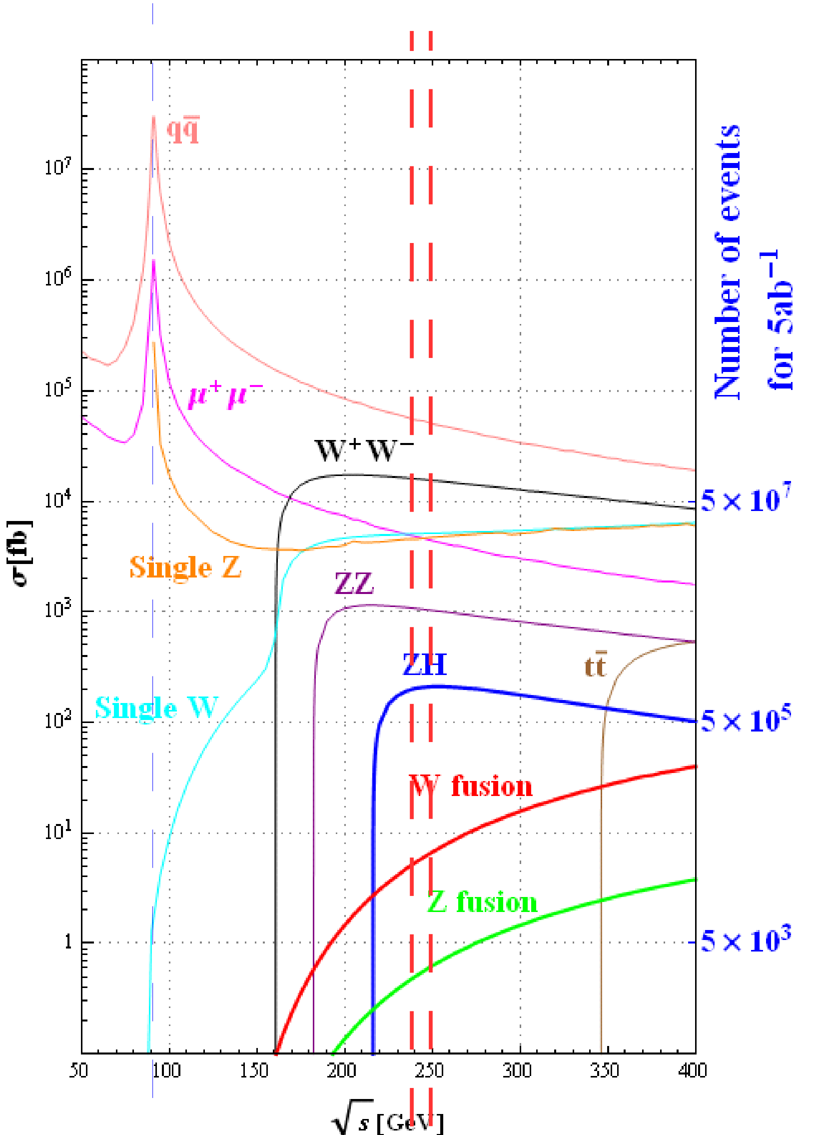
	δσ(ttH)	δσ(ttZ)	δ[σ(ttH)/σ(ttZ)]
14 TeV	± 4.8%	± 5.3%	±0.75%
100 TeV	± 2.7%	± 2.3%	±0.48%

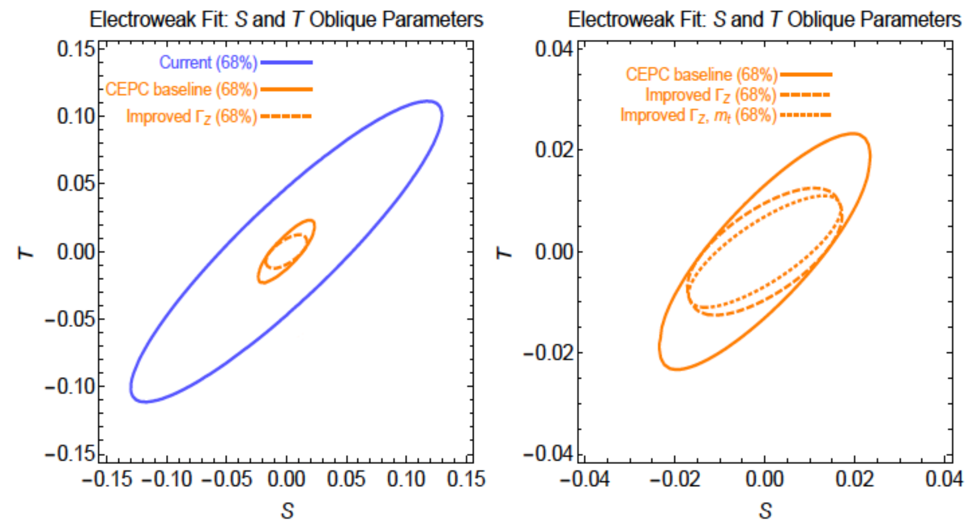
Higgs measurements at electron/positron & proton colliders

	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	10^{9-10}	?	Good access to Higgs rare decay/generation, g(HHH)/g(Htt),

High complementarity between electron-positron & pp colliders

EW@CEPC



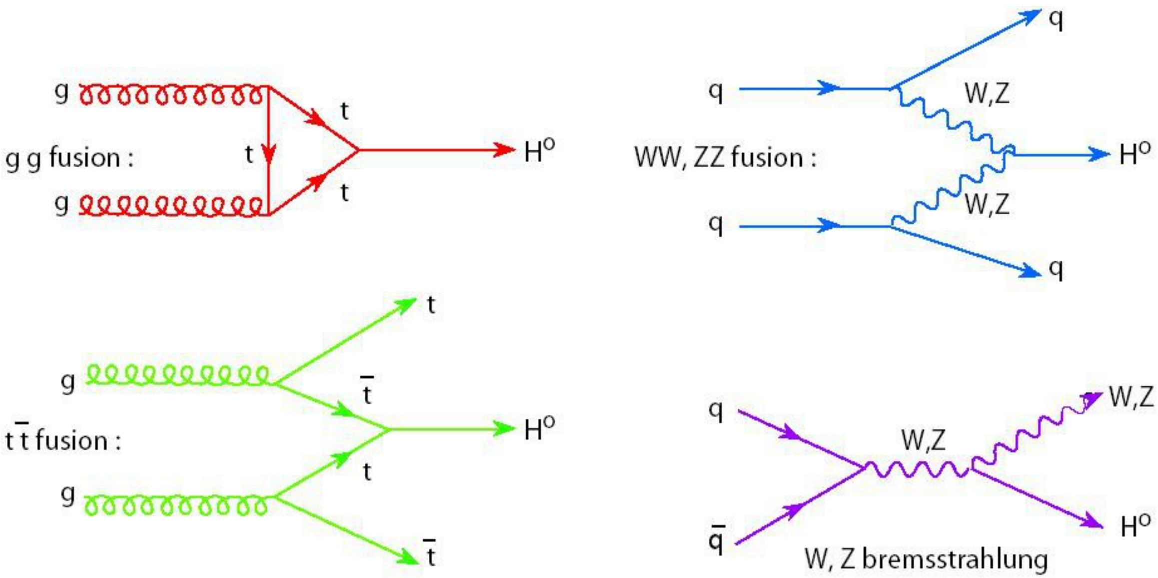


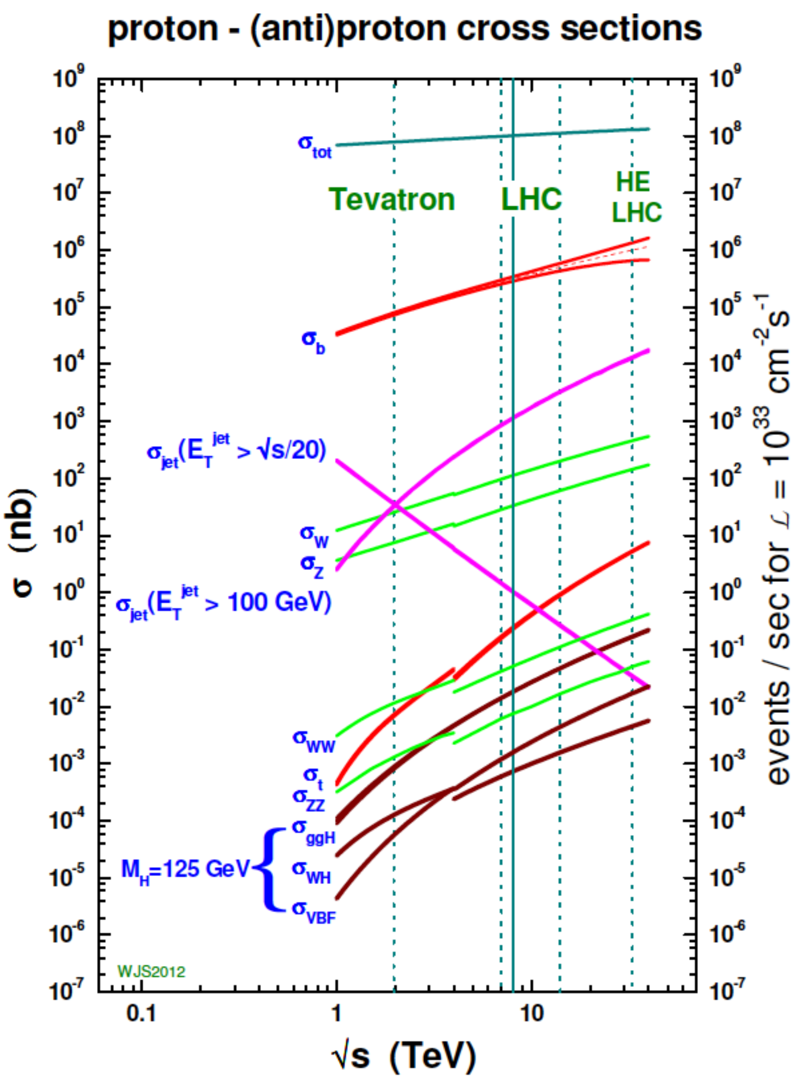
- EW precision measurements with significantly reduced uncertainties:

$$R_b, A_{FB}^b, \sin\theta_W^{eff}, m_Z, m_W, N_\nu \cdots$$

	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [23]	$\pm 1.0 \times 10^{-4}$ [24]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [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]
$\sin^2\theta_{\rm eff}^\ell$	$(23153 \pm 16) \times 10^{-5}$ [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]	$\pm\mathbf{0.007}$

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.

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