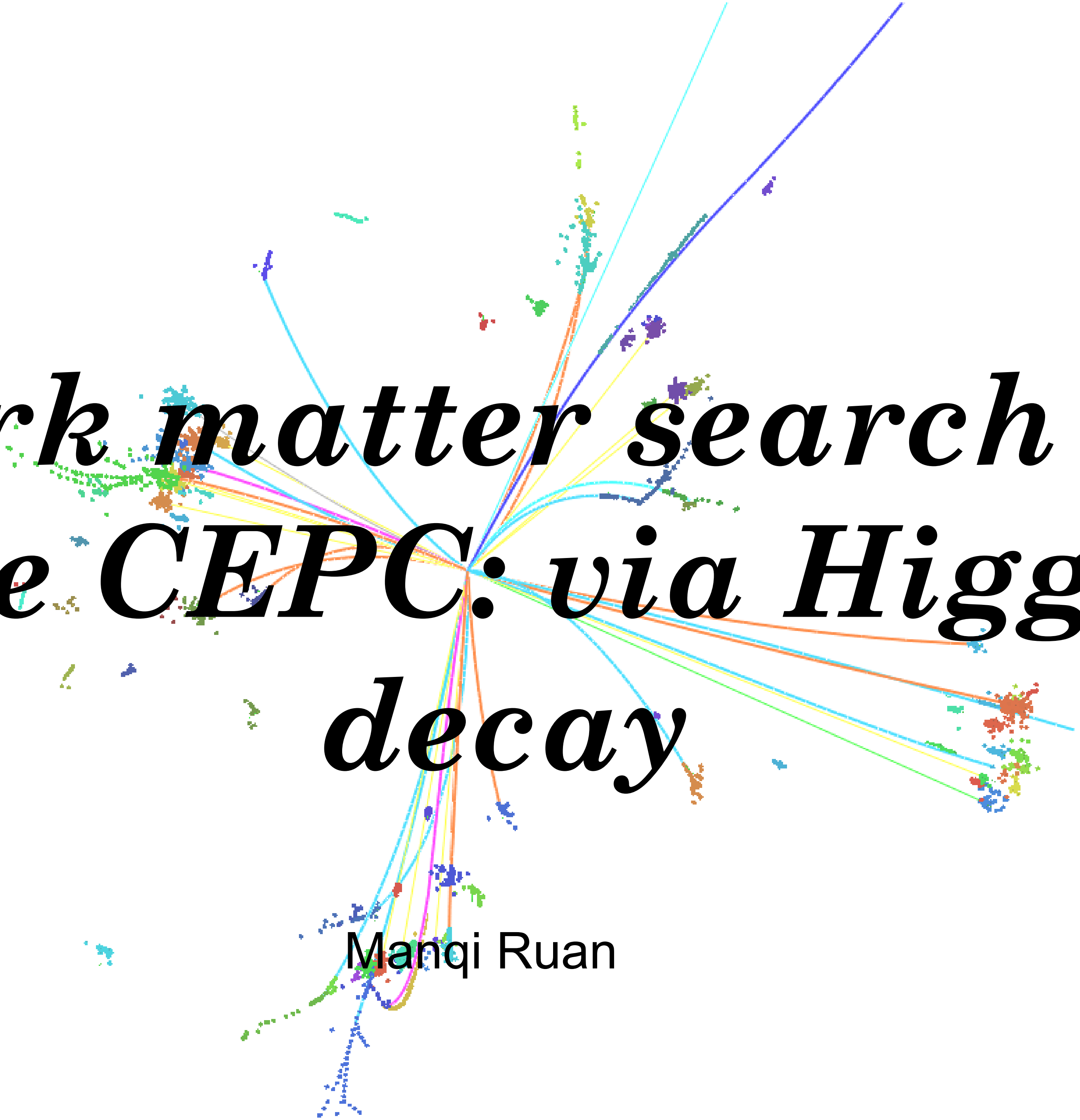
Dark matter search at the CEPC: via Higgs decay



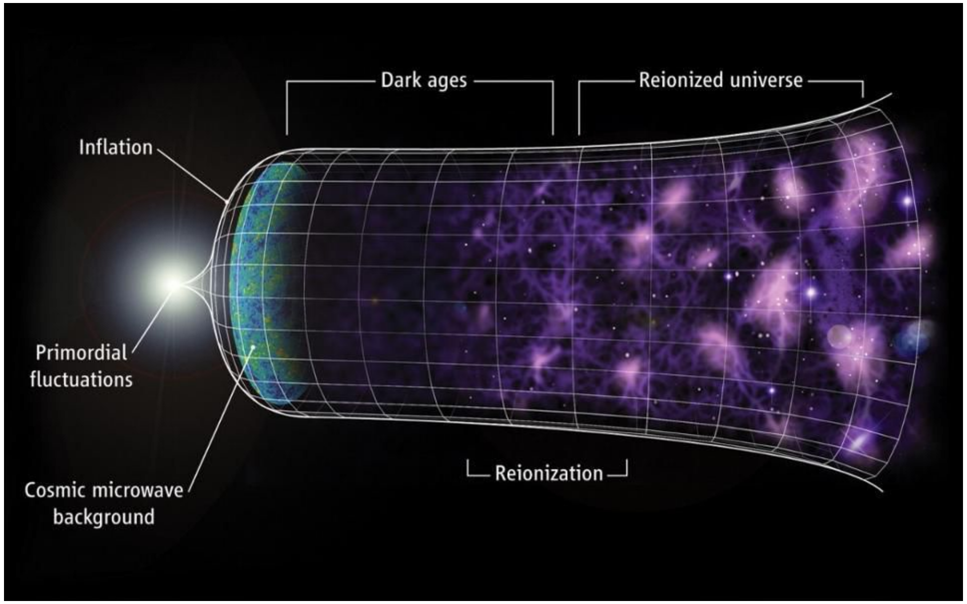
Manqi Ruan

Higgs: linked to many known unknowns of the SM

- Hierarchy: From neutrinos to the top mass, masses differs by 13 orders of magnitude

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

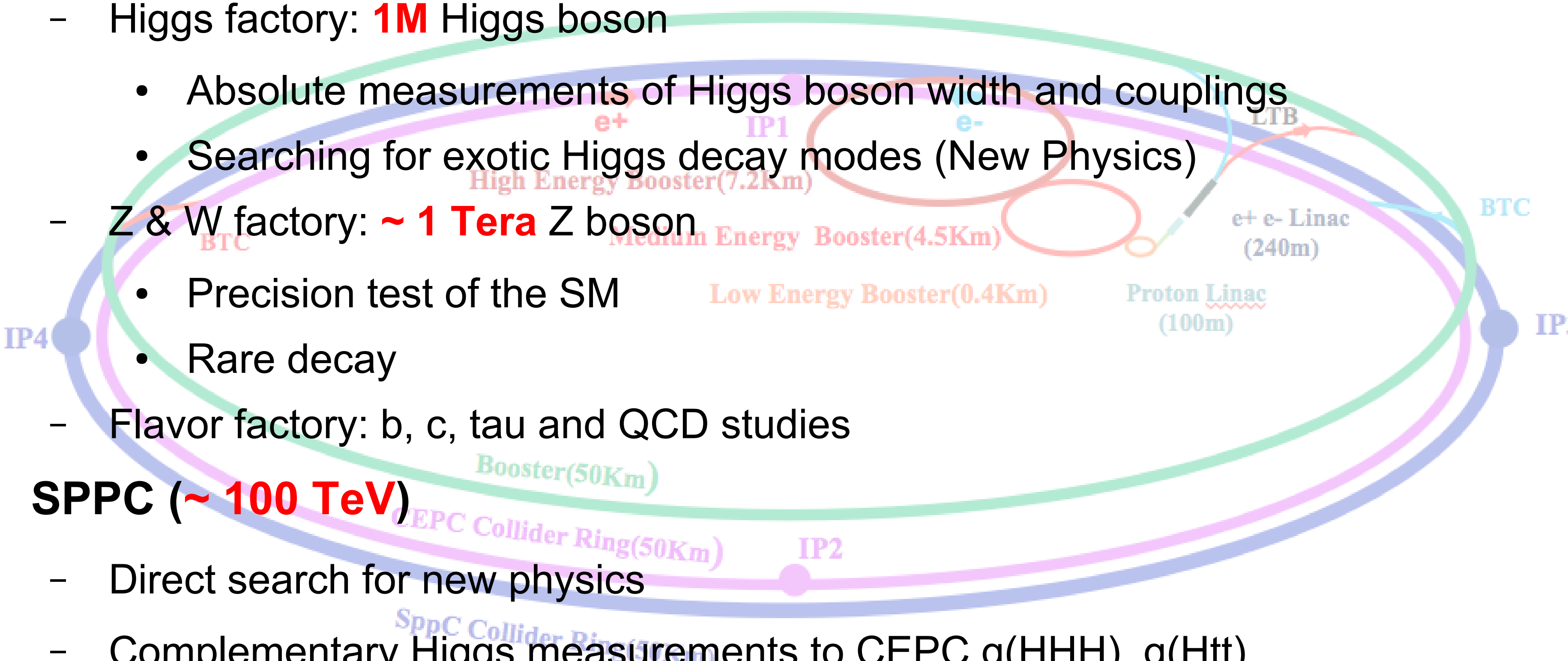
- Naturalness: Fine tuning of the Higgs mass
- Masses of Higgs and top quark: meta-stable of the vacuum
- Unification?
- Dark matter candidate?
- Not sufficient CP Violation for Matter & Antimatter asymmetry



- **Most issues related to Higgs**

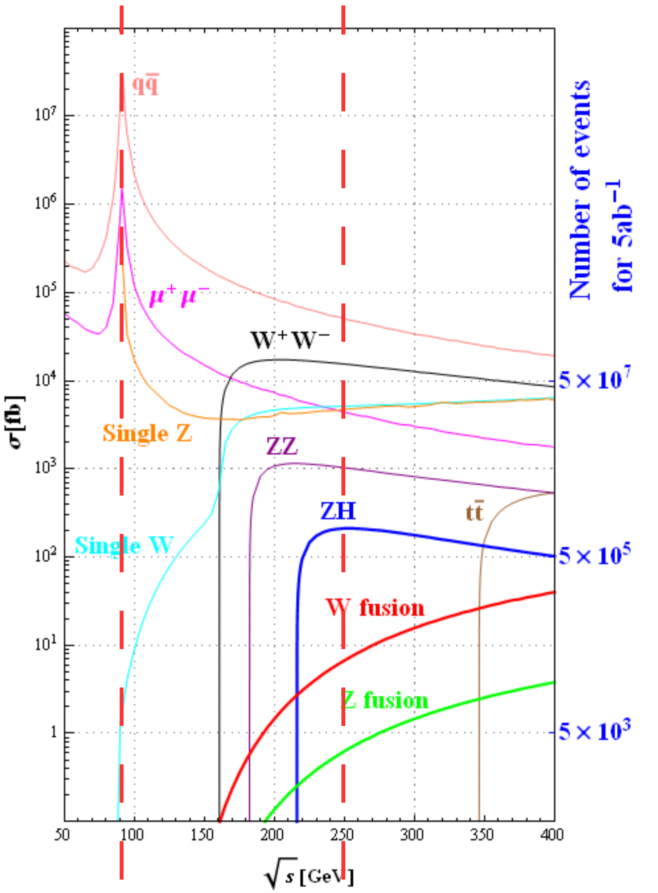
Science at CEPC-SPPC

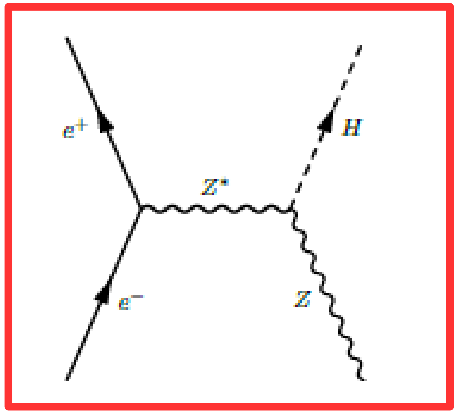
- **Tunnel ~ 100 km**
- **CEPC (90 – 250 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 1 Tera** Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor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

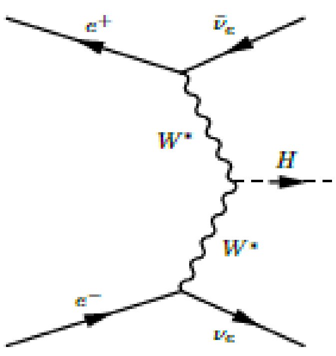


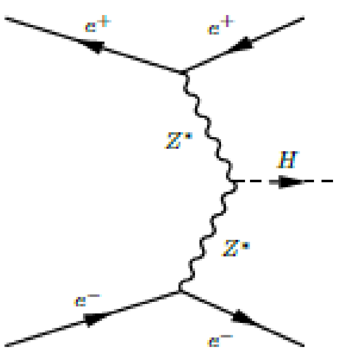
Complementary

Higgs @ CEPC







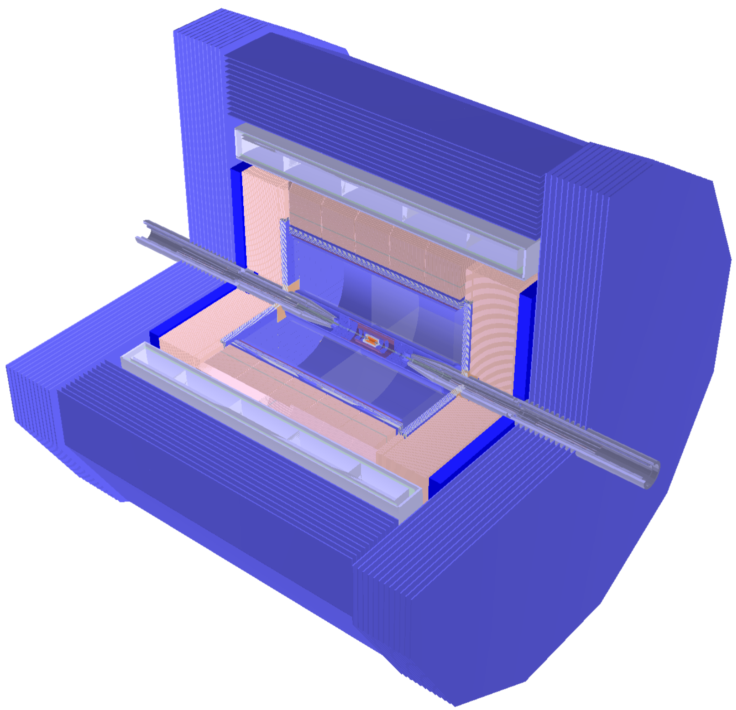


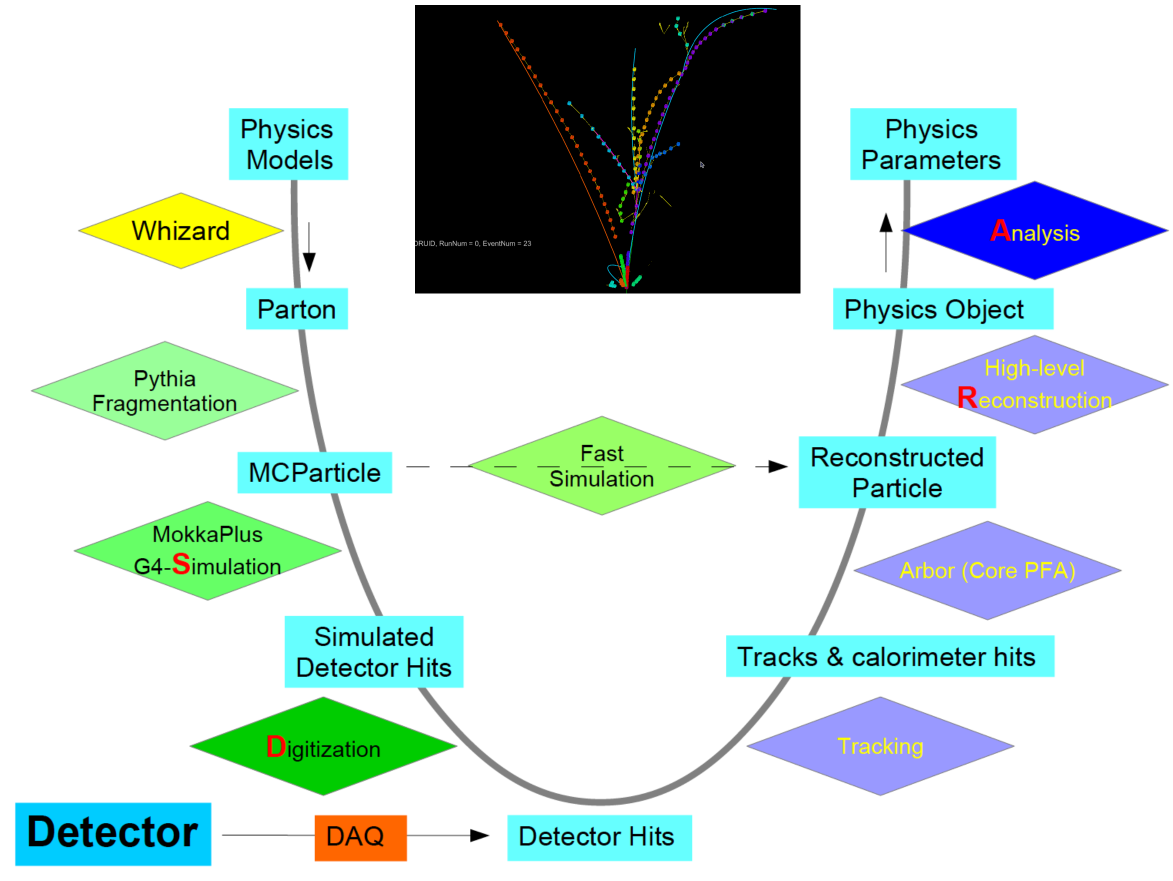
Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \to e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6

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

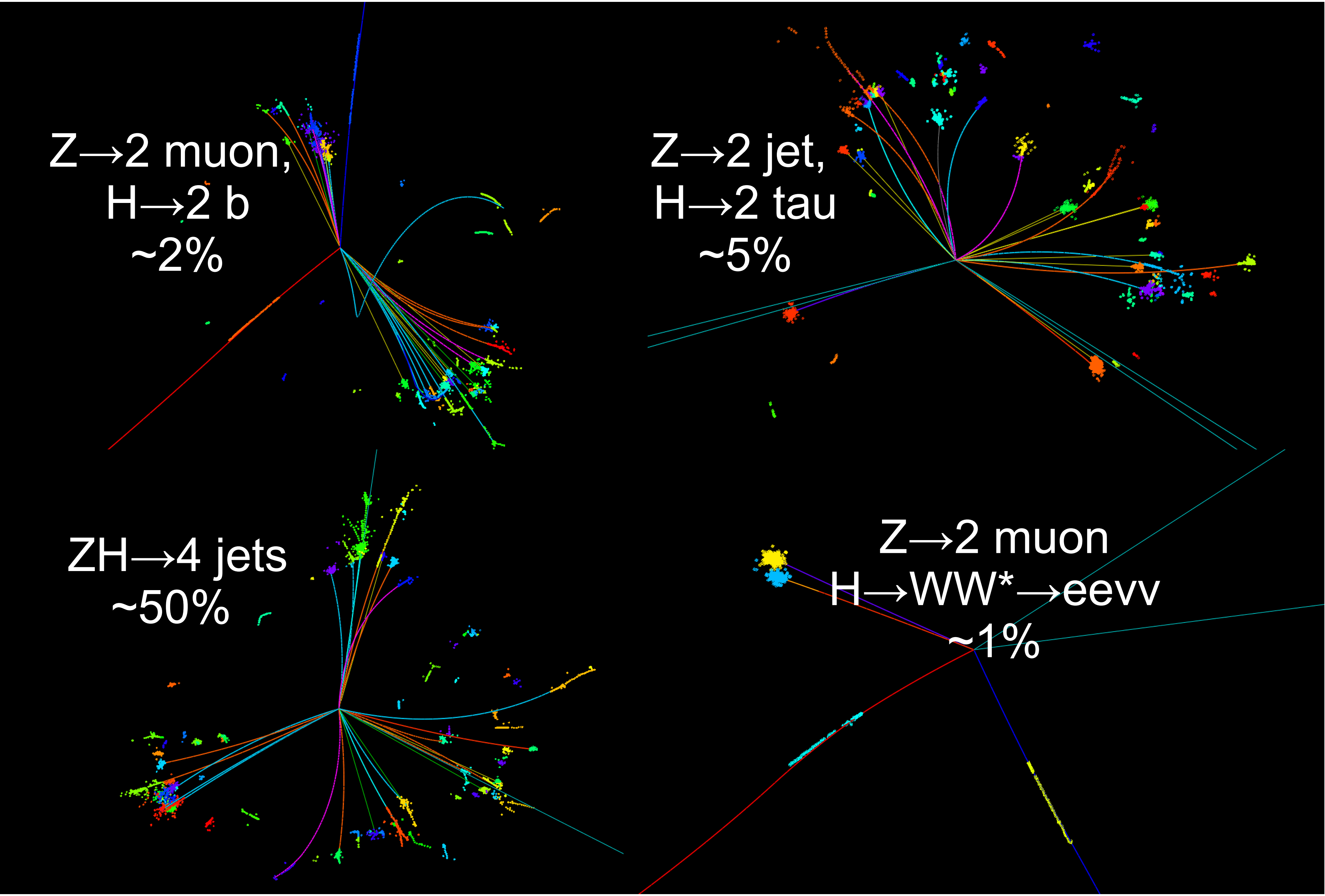
Derive: Absolute Higgs width, branching ratios, couplings

Software & Reconstruction

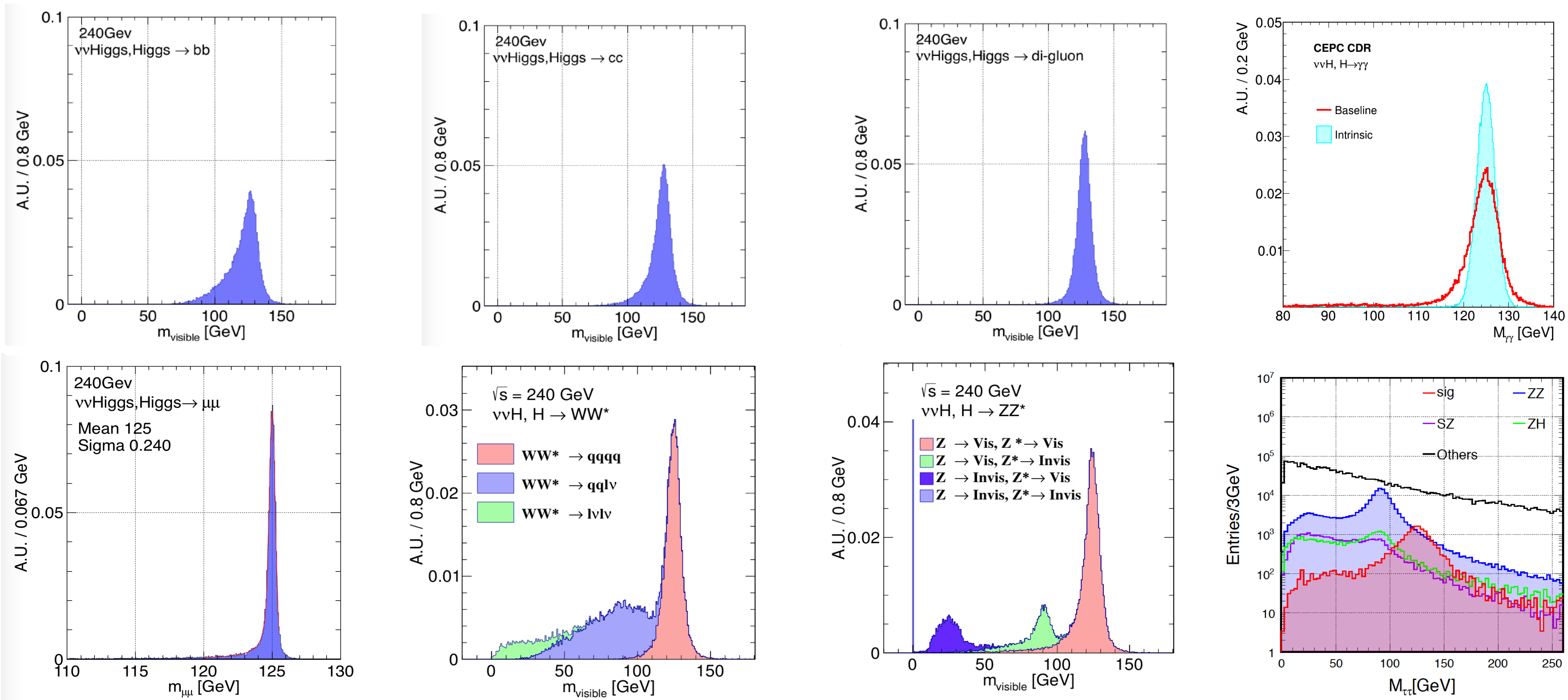




Starting from the ilcsoft & rewriting all the PFA/high-level reconstruction algorithms.


Z→2 muon,
H→2 b
~2%
Z→2 jet,
H→2 tau
~5%
ZH→4 jets
~50%
Z→2 muon
H→WW*→eevv
~1%

Reconstructed Higgs Signatures



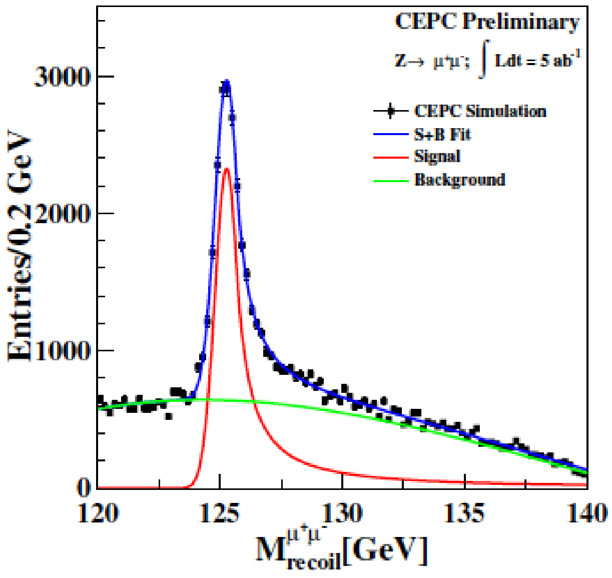
Clear Higgs Signature in all SM decay modes

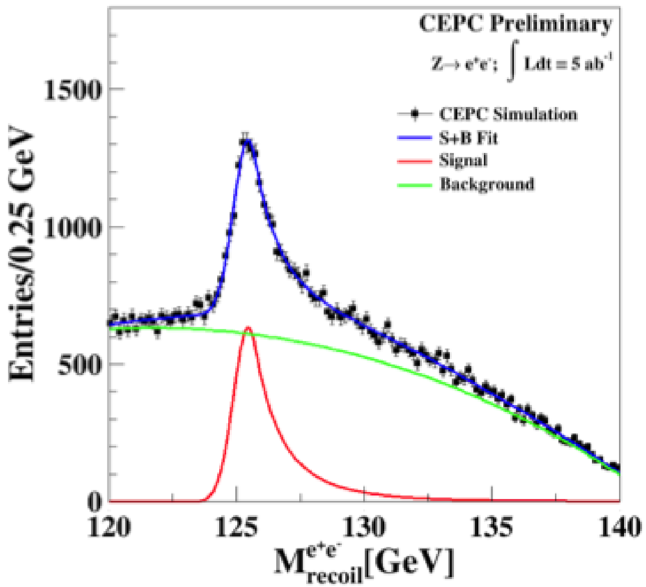
Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

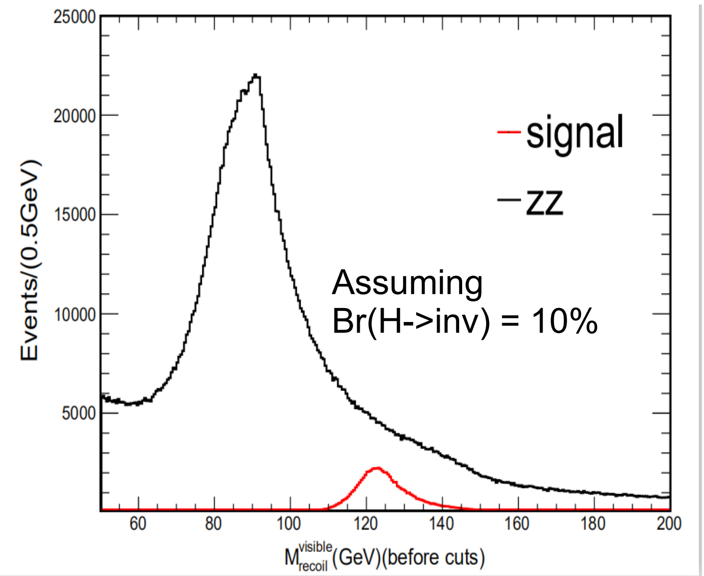
Right corner: di-tau mass distribution at qqH events using collinear approximation

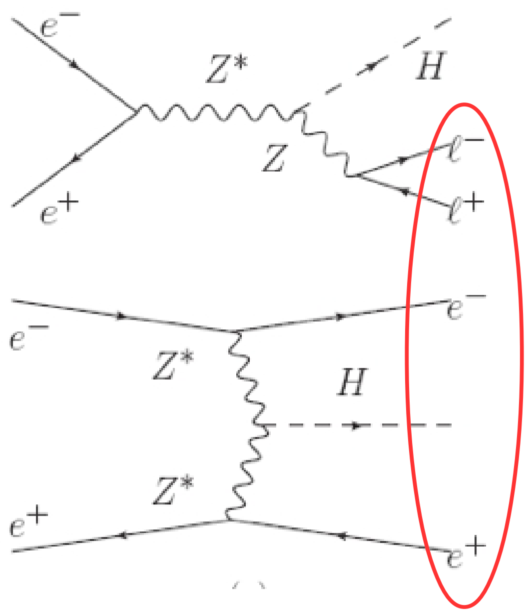
Recoil mass method at ZH: Probing DM

Recoil mass spectrum for σ(ZH) measurement, inclusive Z decay









- Key performance.
  - Lepton id & Tracker resolution, Beam energy spread control;
  - Reconstruction of the Hadronic System, i.e., the jets

After the full event selection

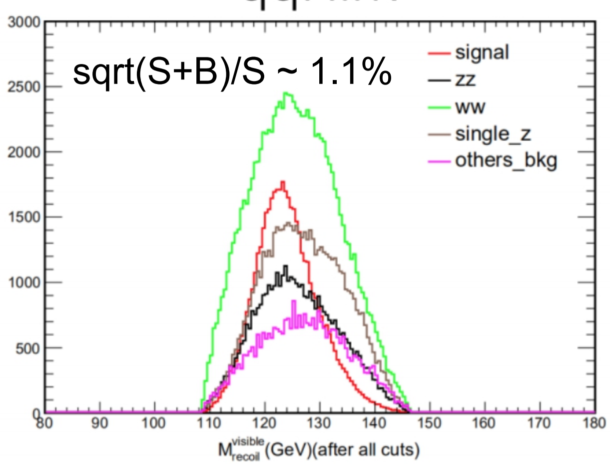
Table 3. Yields for backgrounds and $ZH(Z \to qq, H \to \text{inv})$ signal at the CEPC, with $\sqrt{s}$ = 240 GeV, BR($H \to$ inv) = 10%, and integrated luminosity of 5.6 ab^{-1}.

Process	qqH_inv	2f	single_w	single_z	szorsw	zz	ww	zzorww	ZH_visible	total_bkg	Significance
Total generated	76614	801152072	19517400	9072952	1397088	6389432	50826216	20440840	1140496	909936496	2.54
100 GeV< $M_{\text{recoil}}^{\text{visible}}$ <150 GeV	73800	47294924	1388875	822729	229217	507567	1752827	658204	97387	52751730	10.16
18 GeV< $P_{\text{T}}^{\text{visible}}$ <60 GeV	67115	9165311	1000762	269328	152273	282630	1294265	462029	79965	12706563	18.81
90 GeV< E_{visible} <117 GeV	63912	5748712	595697	223049	92958	231058	785392	272518	33705	7983089	22.59
85 GeV< M_{visible} <102 GeV	53786	605791	238191	148850	39280	135641	392277	113043	18284	1691357	41.14
$\Delta\phi_{\text{dijet}} < 175°$	51911	390077	230273	141494	38359	129135	379931	109735	17395	1436399	43.06
30 GeV< P_{visible} <58 GeV	48572	241510	148607	69457	24393	46807	226883	74781	13466	845904	52.32
$N_{\text{charged}} > 5, E_{\text{charged}} > 1$GeV	47772	7986	18399	62990	6	43728	121365	4110	11699	270283	89.36
M_T <95 GeV	46589	7111	11044	59815	1	41180	104784	3126	11111	238172	92.58
Efficiency	60.81%	0.00%	0.06%	0.66%	0.00%	0.64%	0.21%	0.02%	0.97%	0.03%	

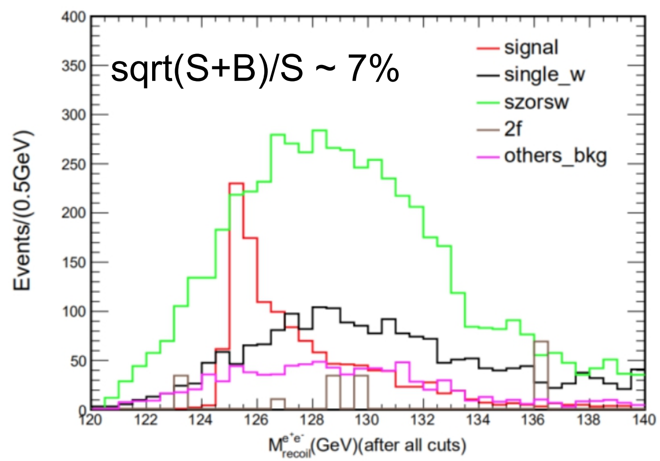
Expected Accuracy at Br(H->inv) = 10%

~ o(1)%

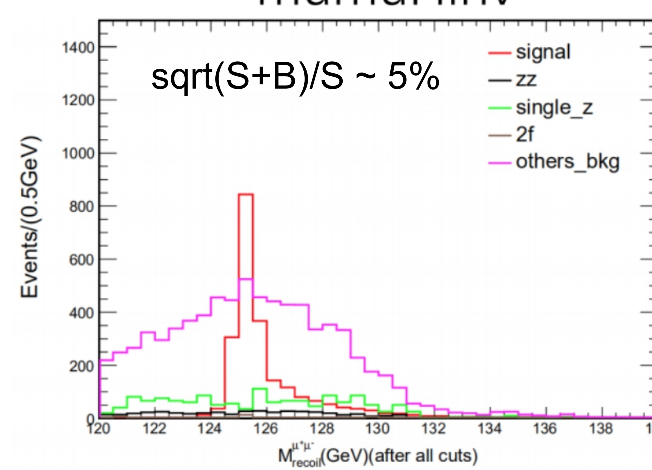
qqHinv



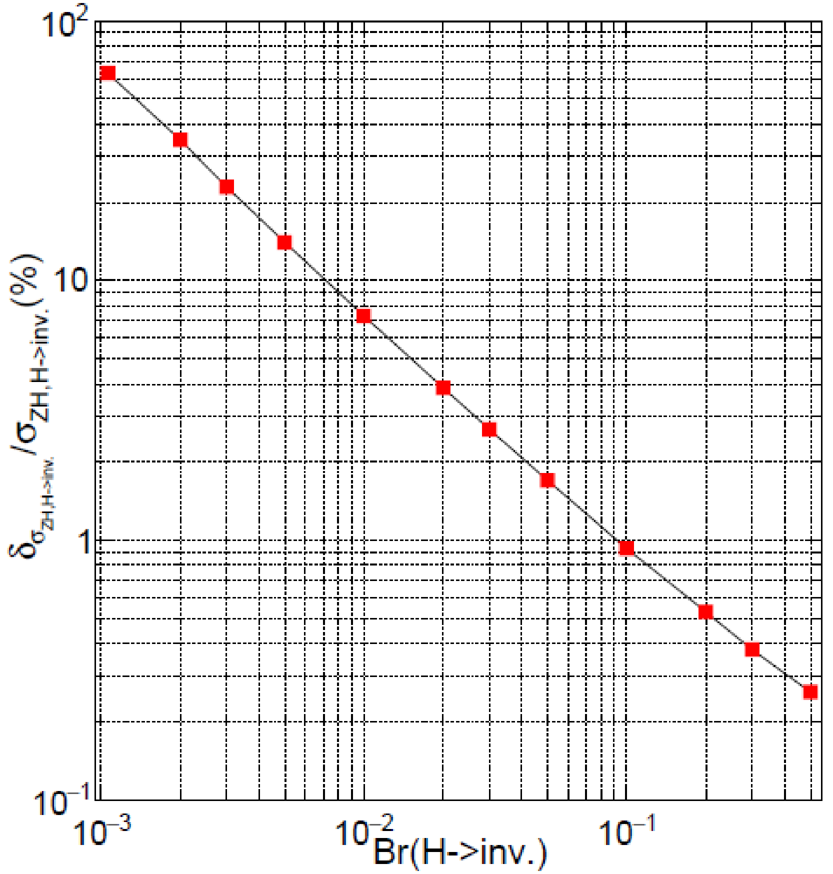
eeHinv



mumuHinv



Up limited setting



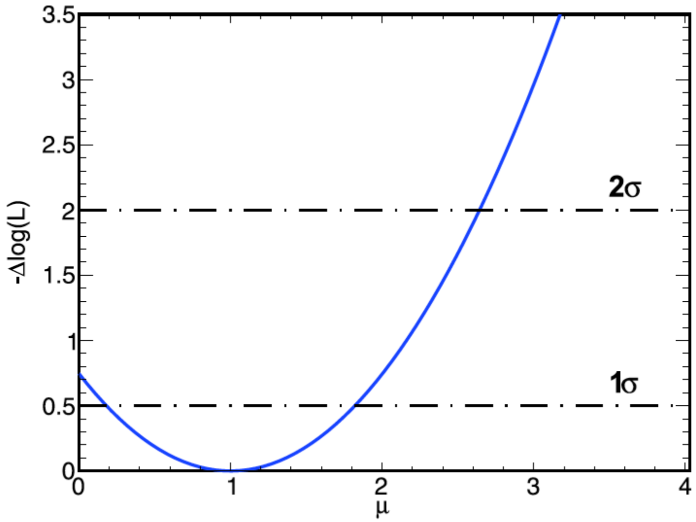


Fig. 5. (color online) The μ distribution from the likelihood profile, where the horizontal dash-dotted lines indicate the location of the approximately 68%, 95% CL interval, which corresponds to $-\Delta\log(L) = 0.5$, 2 on the y-axis.

Table 6. Expected precision of the measurement of BR($H \to$ inv) and the 95% CL upper limit on BR($H \to$ inv) for the dataset 5.6 ab^{-1}.

ZH final states	Precision of BR($H \to$ inv)×100 (%)	Upper limit on BR($H \to$ inv) (%)
$Z \to e^+e^-$, $H \to$ inv	45.37	1.08
$Z \to \mu^+\mu^-$, $H \to$ inv	23.57	0.55
$Z \to q\bar{q}$, $H \to$ inv	9.54	0.27
Combination	8.68	0.26

Key performance: reconstruction of Hadronic system

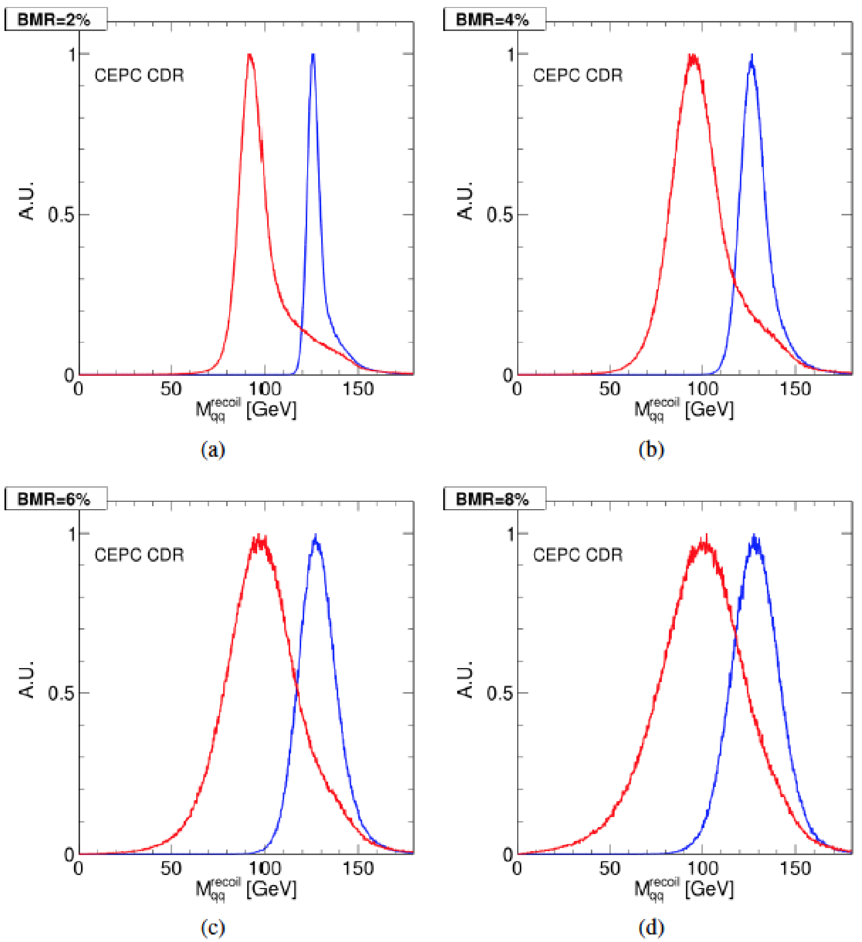


Figure 3.7: The dijet recoil mass distributions of the $ZZ \to \nu\bar{\nu}q\bar{q}$ (red) and $ZH \to q\bar{q}H$ (blue) events for different BMR values. The invisible Higgs boson decays are considered. All distributions are normalized to unit height.

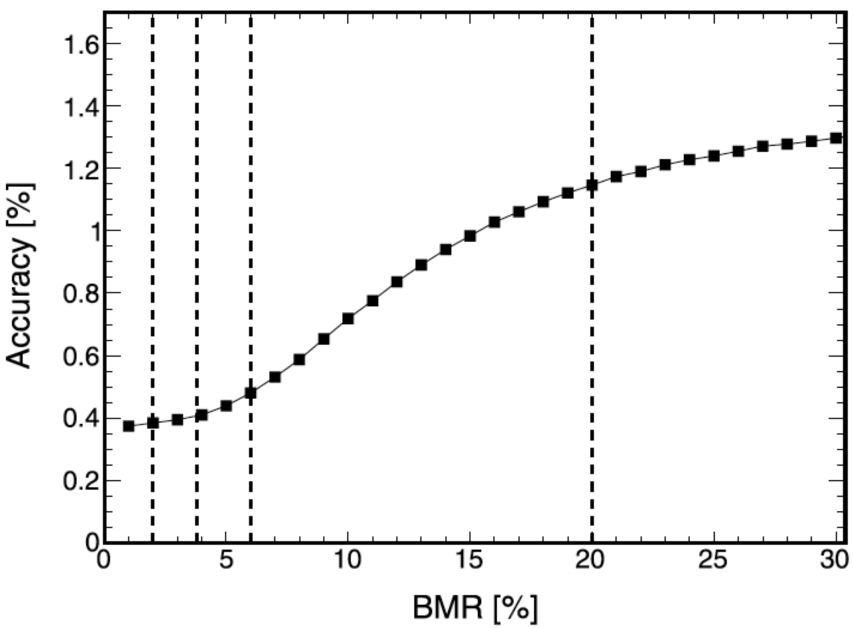
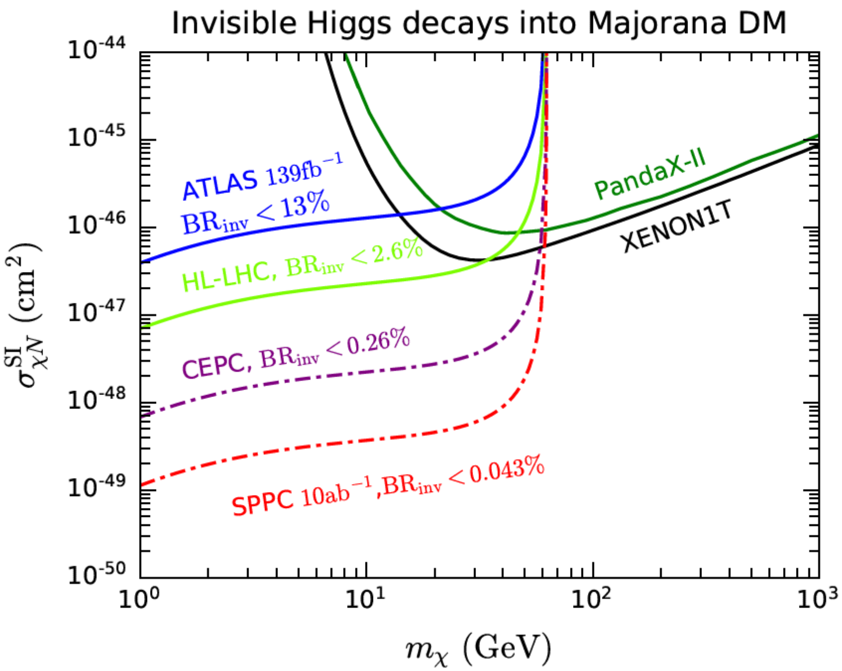
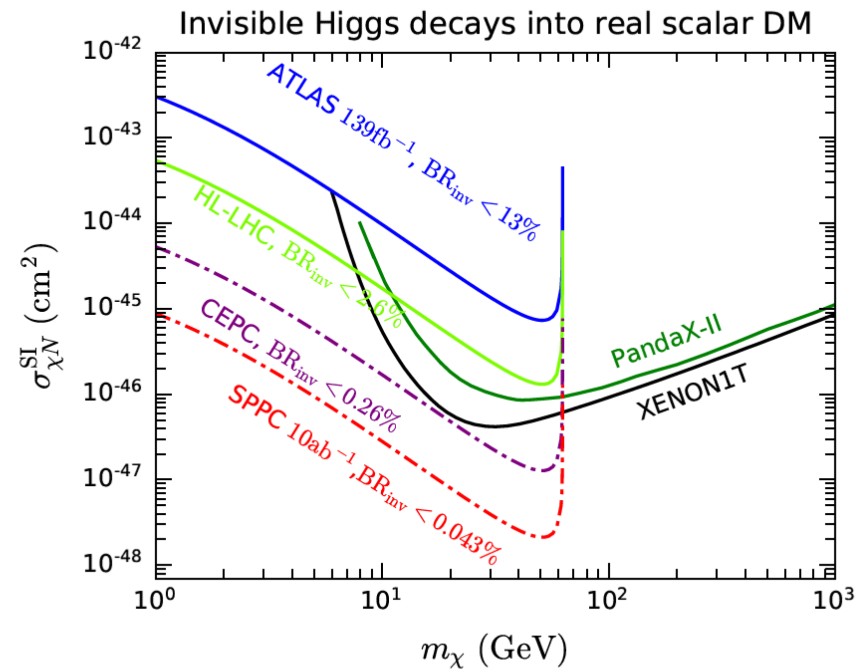


Fig. 6. Accuracy of the qqH ($H \to$ inv) channel vs. BMR, for the background of $ZZ(Z \to qq, Z \to$ inv). The dashed vertical lines show the accuracy at BMR is 2%, 3.8%, 6%, and 20%, assuming BR($H \to$ inv) = 10%.

Interpretation at Higgs Portal model





Plots by W. Song

References:

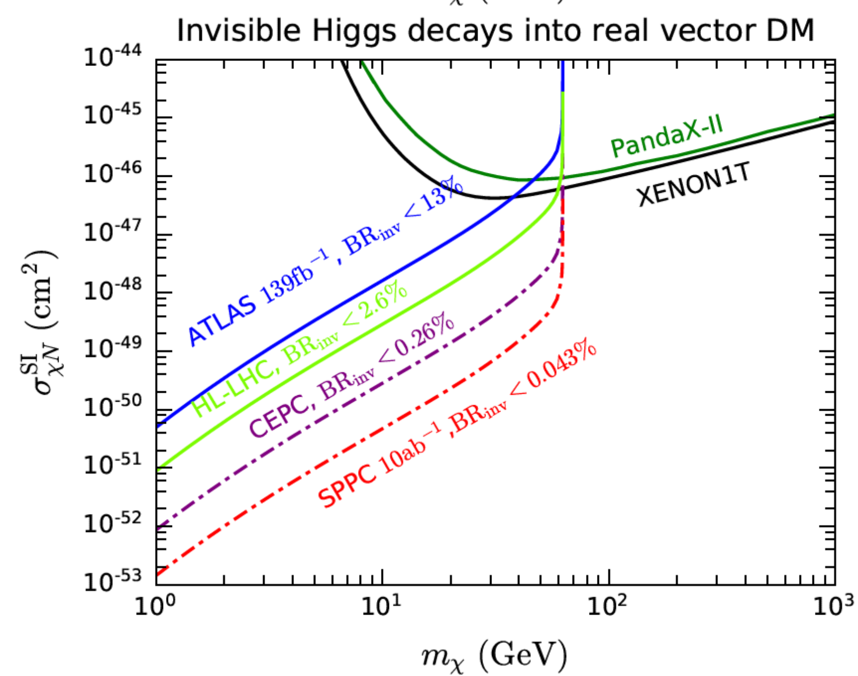
Higgs Portal: Physics Reports 842 (2020) 1–180

LHC result: ATLAS-CONF-2020-008

HL-LHC: https://arxiv.org/abs/1905.03764

CEPC: Chinese Physics C, 44, 12, 123001 (2020)

SPPC: scaled from FCC-hh, J. High Energ. Phys(01). 139 (2020)



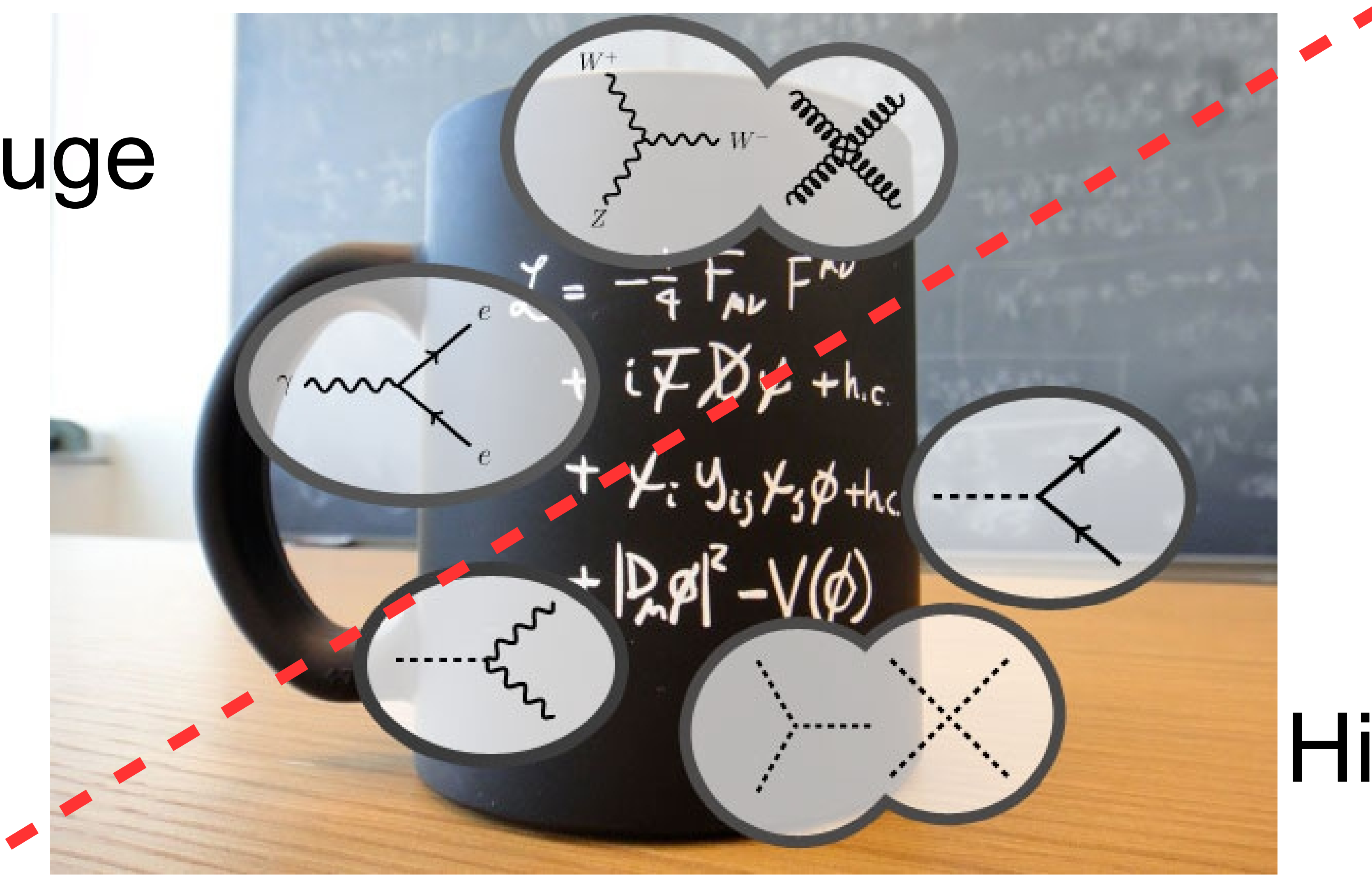
Conclusion

- The CEPC, an electron positron Higgs factory, is an excellent probe for dark matter search via Higgs Portal
  - Giving a Branching ratio of 10%, the H->invisible signal can be determined to a relative accuracy of 1%.
  - The 95% C.L. up limit of Br(H->inv) can be set to 0.26%
- The recoil mass method, especially via the qqH channel, requires
  - A good reconstruction of the hadronic decayed Z boson is essential: the Boson mass resolution is required to be better than 4%.
- From LHC, to HL-LHC, to CEPC (electron positron Higgs factory with Higgs Yield ~ 1 Million), and to the SPPC (proton collider with 100 TeV c.m.s energy) in the far future, the up limit can be improved by ~1 order of magnitude in each step.

Back up

The Higgs field: one of the two pillars of the SM

Gauge

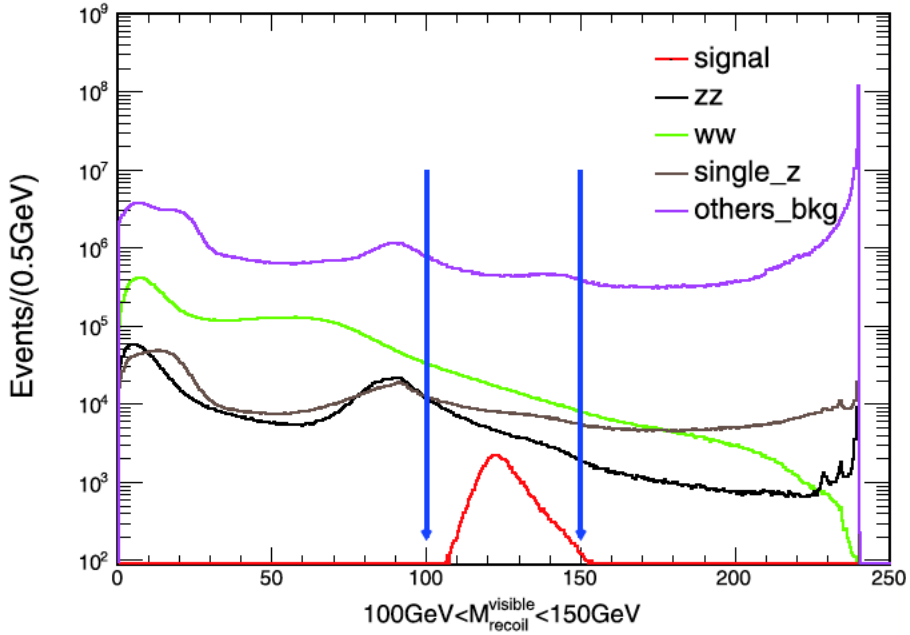


Higgs

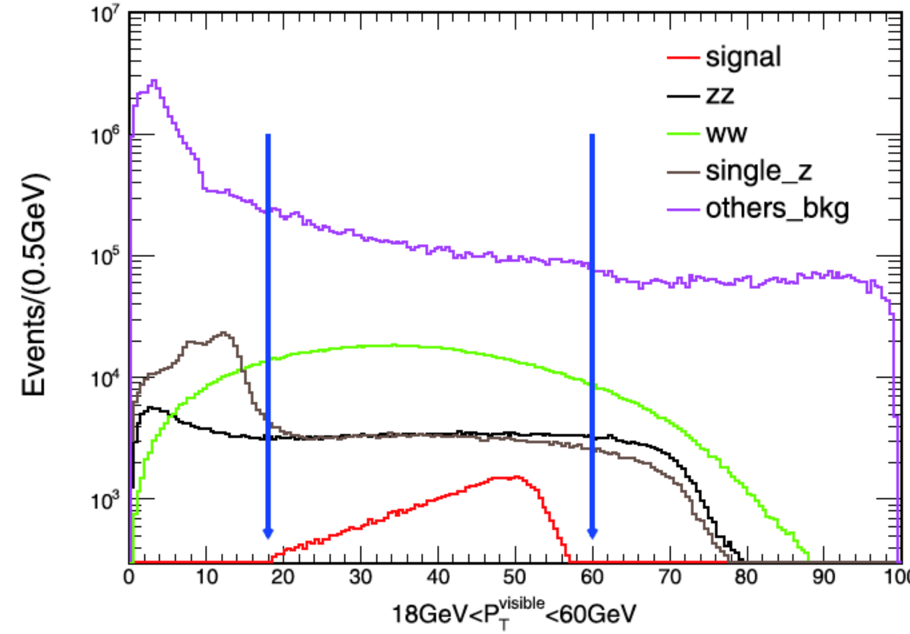
CEPC CDR Parameters

D. Wang

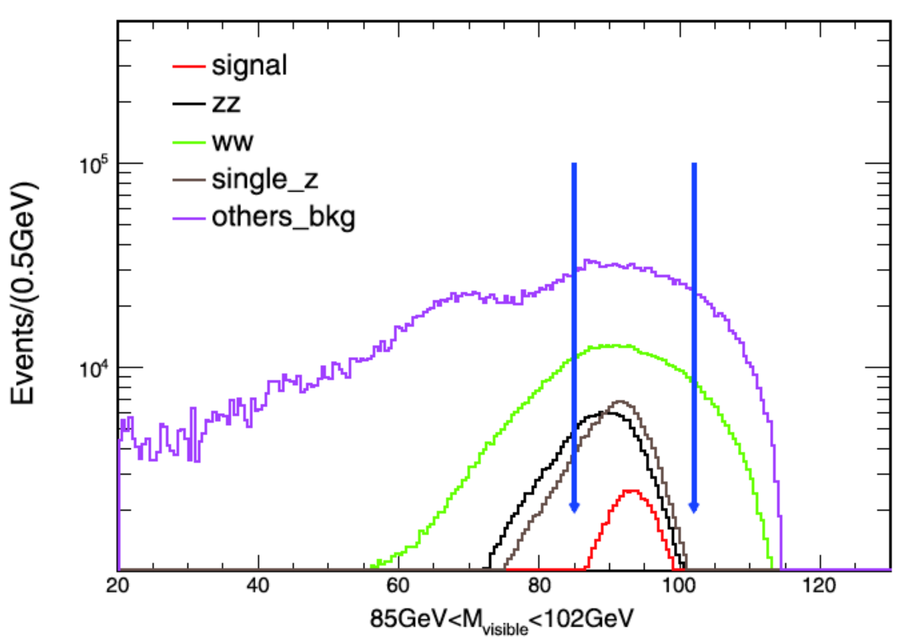
	Higgs	*W*	*Z* (3T)	*Z* (2T)
Number of IPs	2			
Beam energy (GeV)	**120**	**80**	**45.5**	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	**242 (0.68μs)**	**1524 (0.21μs)**	**12000 (25ns+10%gap)**	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	**30**	**30**	**16.5**	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	**0.36/0.0015**	**0.36/0.0015**	**0.2/0.0015**	**0.2/0.001**
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
HOM power/cavity (2 cell) (kw)	0.54	0.75	**1.94**	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	**1.35**	**0.4**	**0.23**	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.1	0.05	0.023	
Lifetime _simulation (min)	100			
Lifetime (hour)	**0.67**	**1.4**	**4.0**	**2.1**
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP L ($10^{34}cm^{-2}s^{-1}$)	**2.93**	**10.1**	**16.6**	**32.1**


signal
zz
ww
single_z
others_bkg
Events/(0.5GeV)
100GeV<$M_{recoil}^{visible}$<150GeV

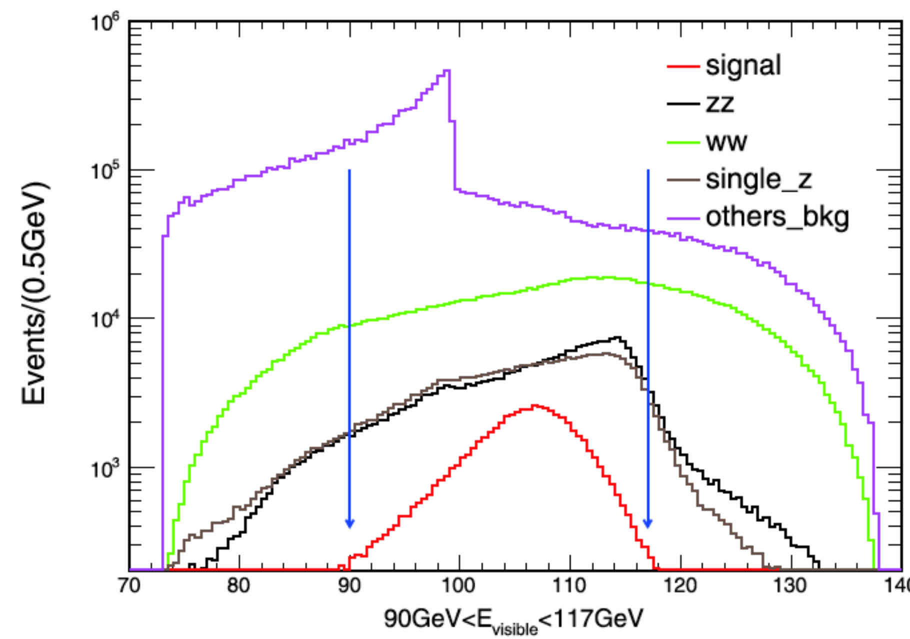
(a)


signal
zz
ww
single_z
others_bkg
Events/(0.5GeV)
18GeV<$P_T^{visible}$<60GeV

(b)


signal
zz
ww
single_z
others_bkg
Events/(0.5GeV)
85GeV<$M_{visible}$<102GeV

(c)


signal
zz
ww
single_z
others_bkg
Events/(0.5GeV)
90GeV<$E_{visible}$<117GeV

(d)

Collider	95% CL upper bound on				
	BR_{inv} [%]			BR_{unt} [%]	
	Direct	kappa-3	BR_{inv} only	kappa-3	BR_{unt} only
HL-LHC	2.6	1.9	1.9	4.0	3.6
HL-LHC + HE-LHC(S_2')		1.5	1.5	2.4	1.9
FCC-hh	0.025	0.024	0.024	1.0	0.36
HL-LHC + LHeC	2.3	1.1	1.1	1.3	1.3
HL-LHC + CEPC	0.3	0.27	0.26	1.1	0.49
HL-LHC + $FCC\text{-}ee_{240}$	0.3	0.22	0.22	1.2	0.62
HL-LHC + $FCC\text{-}ee_{365}$		0.19	0.19	1.0	0.54
HL-LHC + ILC_{250}	0.3	0.26	0.25	1.8	0.85
HL-LHC + ILC_{500}		0.23	0.22	1.4	0.55
HL-LHC + ILC_{1000}		0.22	0.20	1.4	0.43
HL-LHC + $CLIC_{380}$	0.69	0.63	0.56	2.7	1.0
HL-LHC + $CLIC_{1500}$		0.62	0.40	2.4	0.51
HL-LHC + $CLIC_{3000}$		0.62	0.30	2.4	0.33

Table 14. Expected upper limits on the invisible and untagged BRs of the Higgs boson. The SM decay, $H \to 4\nu$, has been subtracted as a background. Given are the values of the direct searches using missing (transverse) momentum searches, the constraint derived from the coupling fit (see table 5) in the kappa-3 scenario, and the result from a fit in the κ framework where only modifications of BR_{inv} are allowed. The last two columns show the corresponding information for untagged BR of the Higgs, BR_{unt}. For all fits the direct search for invisible decays is included.