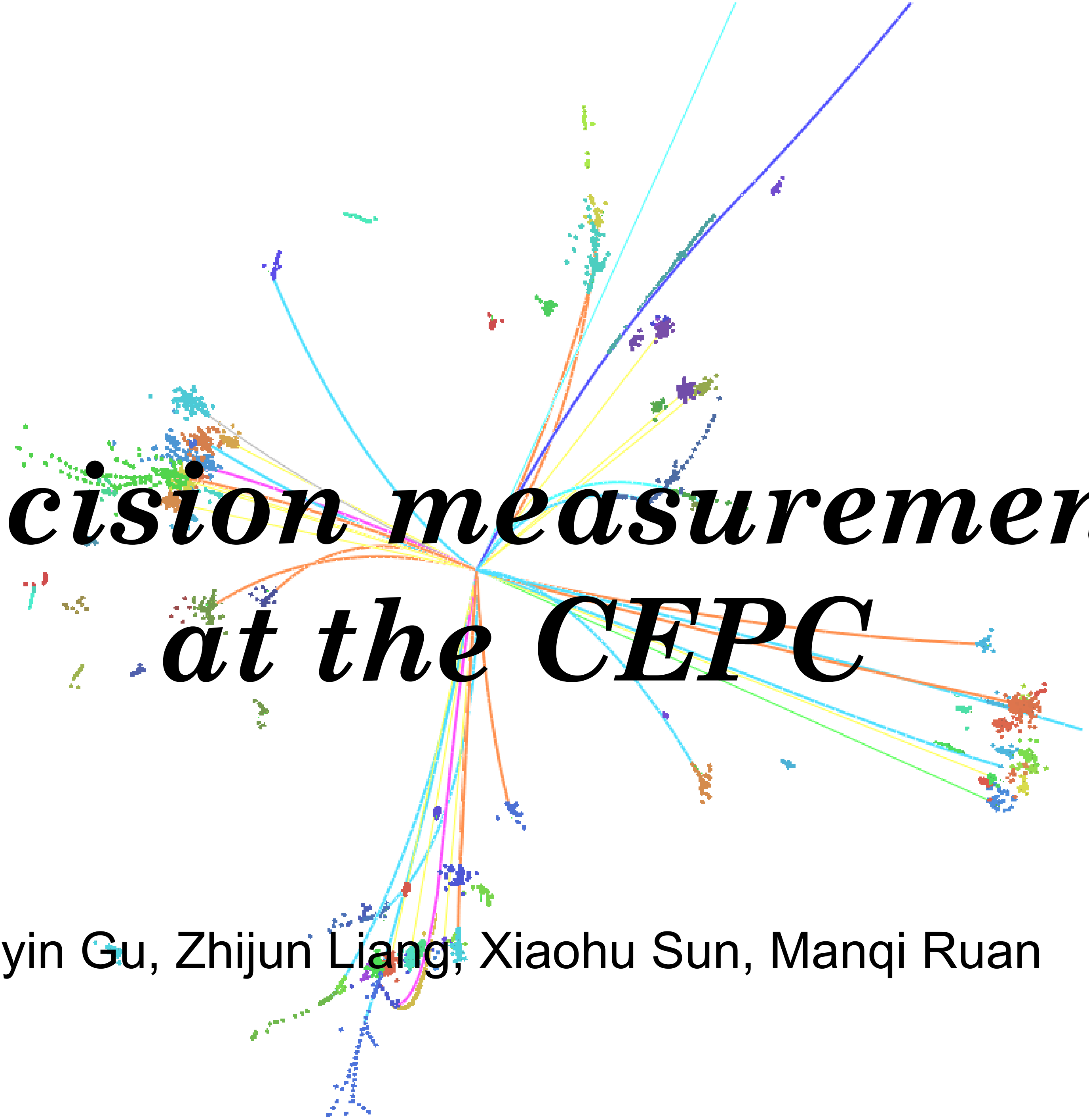
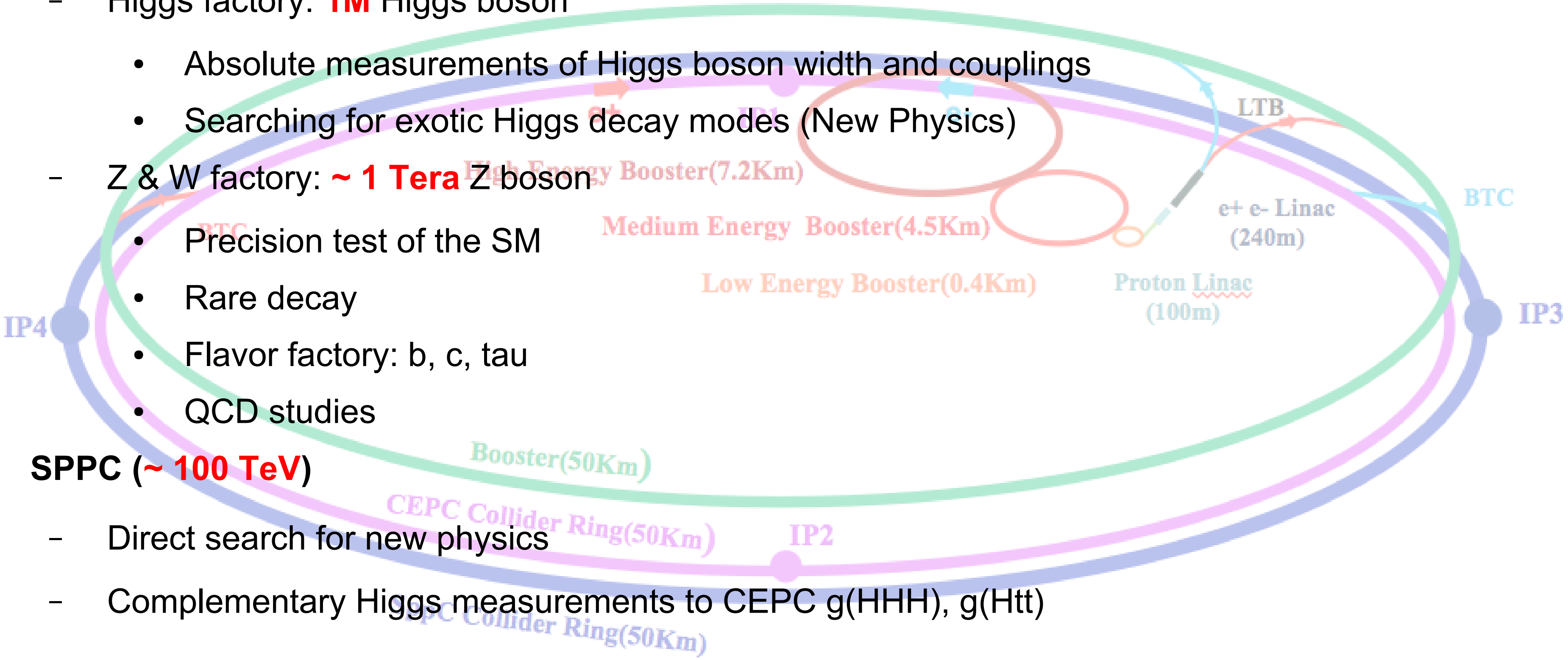
Precision measurements at the CEPC



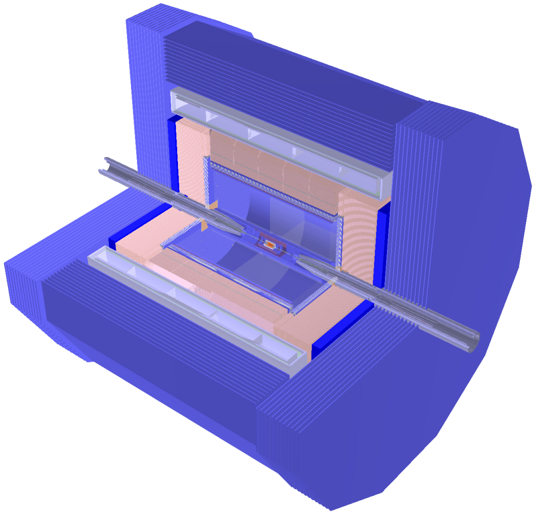
Jiayin Gu, Zhijun Liang, Xiaohu Sun, Manqi Ruan

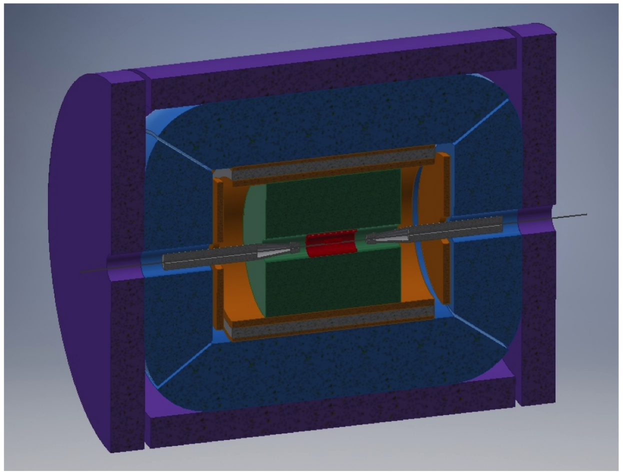
Key figures of the CEPC @ CDR

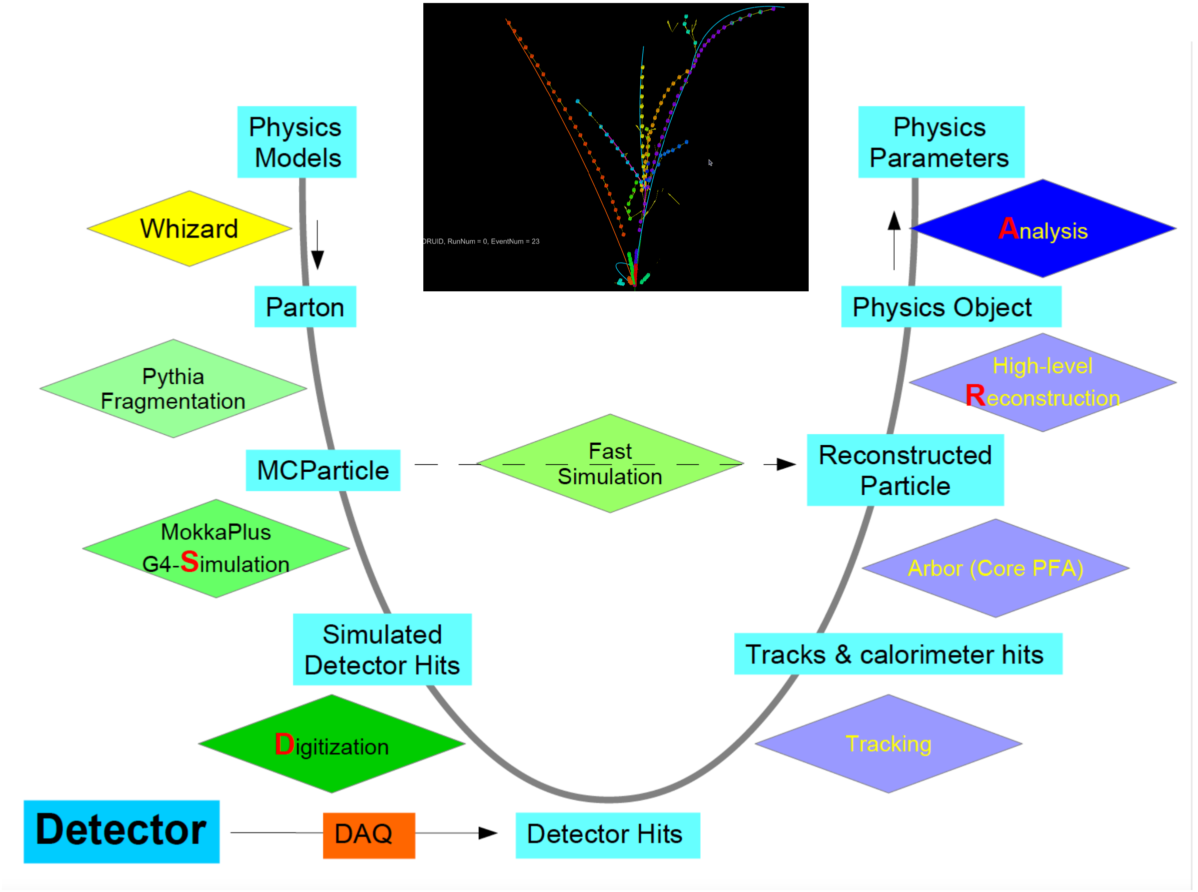
- **Tunnel ~ 100 km**
- **CEPC (90 – 240 GeV)**
  - Higgs factory: **1M** Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: **~ 1 Tera** Z boson
    - Precision test of the SM
    - Rare decay
    - Flavor factory: b, c, tau
    - QCD studies
- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...
- **Heavy ion, e-p collision...**



Detector & Software







Physics Models

Whizard

Parton

Pythia Fragmentation

MCParticle

MokkaPlus G4-Simulation

Simulated Detector Hits

Digitization

Detector

DAQ

Detector Hits

Tracking

Tracks & calorimeter hits

Arbor (Core PFA)

Reconstructed Particle

Fast Simulation

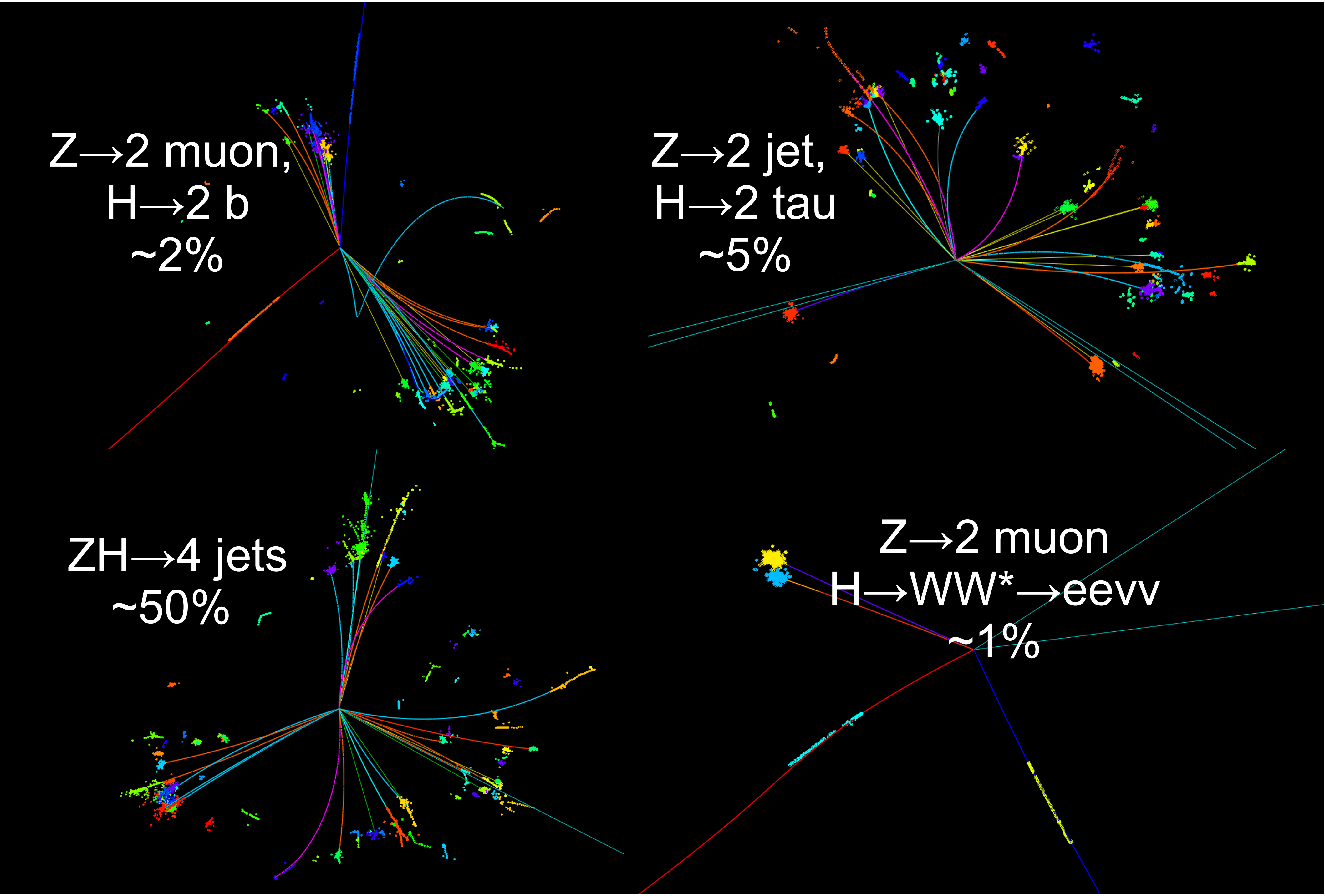
High-level Reconstruction

Physics Object

Analysis

Physics Parameters

Full simulation reconstruction Chain with Arbor, iterating/validation with hardware studies



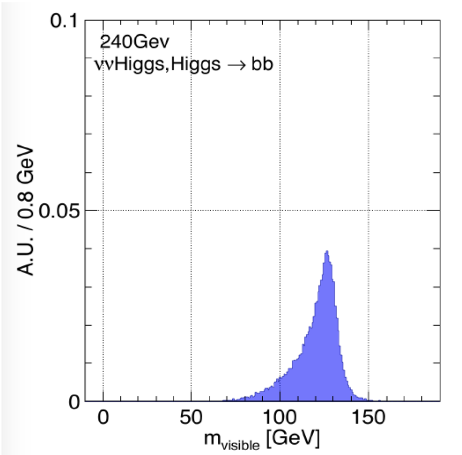
Z→2 muon,
H→2 b
~2%

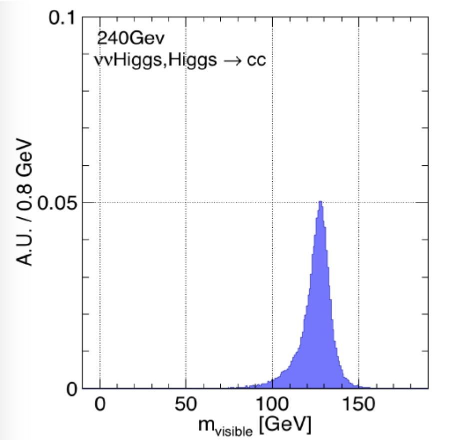
Z→2 jet,
H→2 tau
~5%

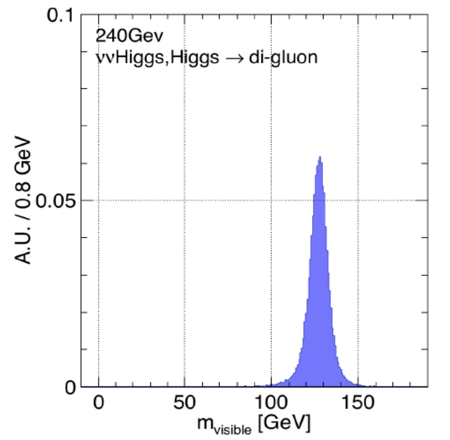
ZH→4 jets
~50%

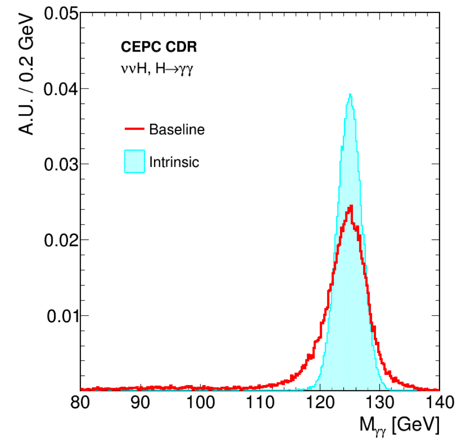
Z→2 muon
H→WW*→eevv
~1%

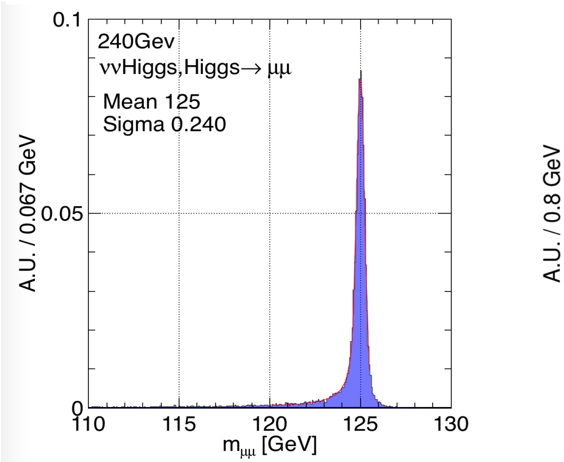
Reconstructed Higgs Signatures

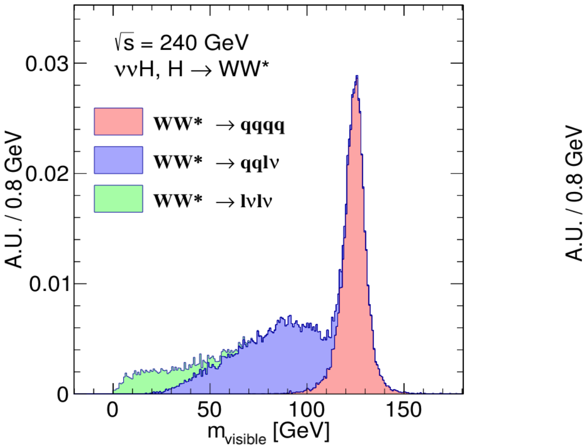


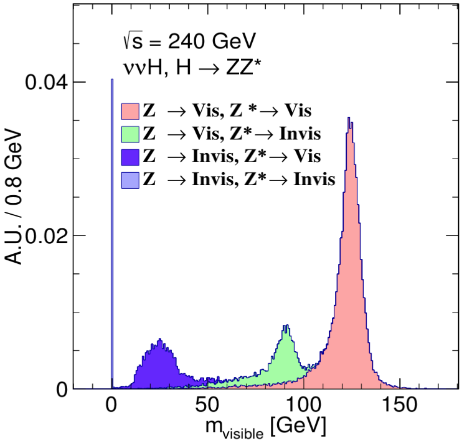


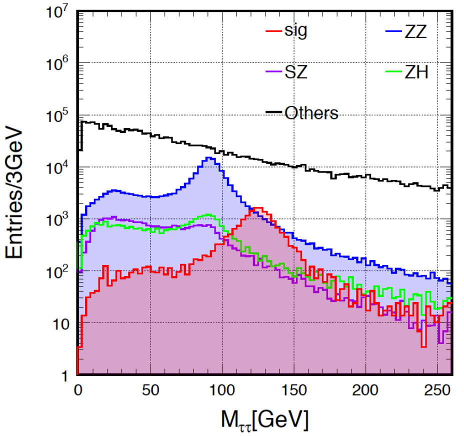










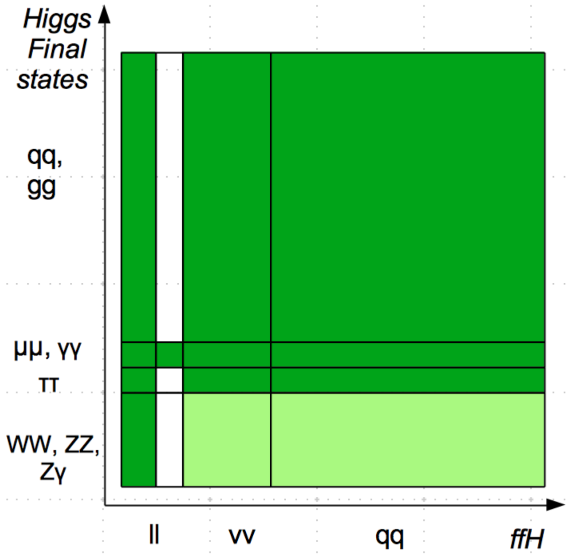


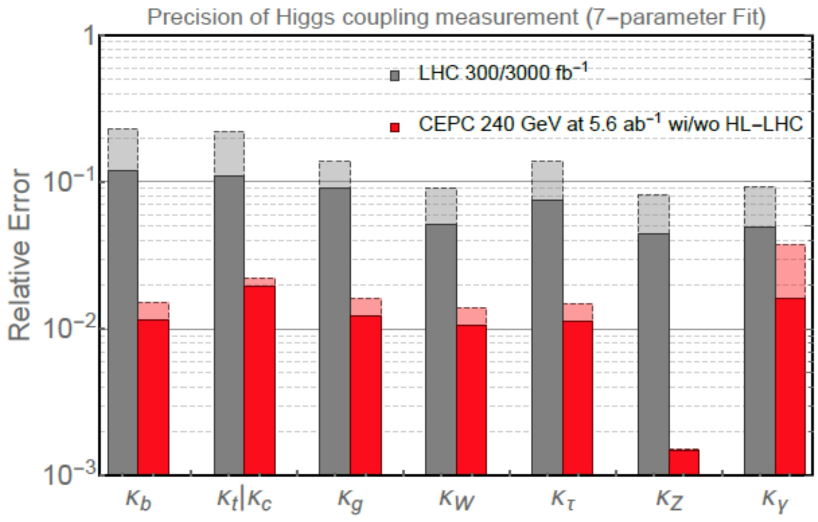
Clear Higgs Signature in all SM decay modes

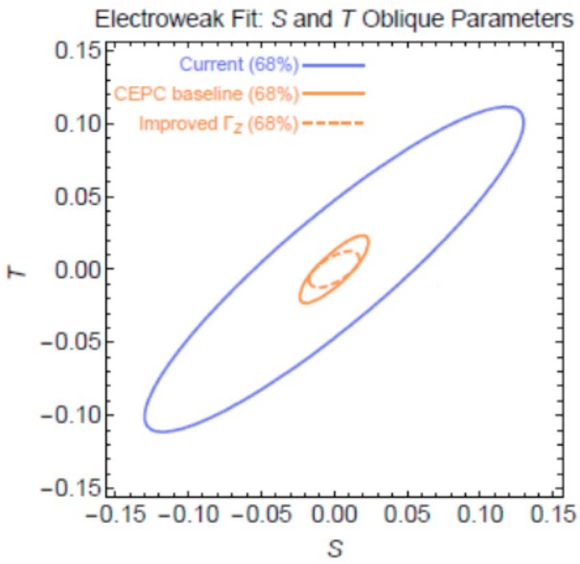
Massive production of the SM background (2 fermion and 4 fermions) at the full Simulation level

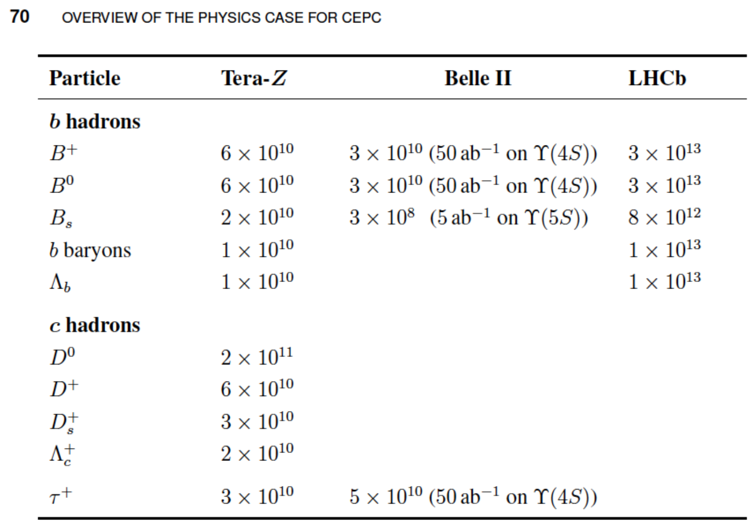
Right corner: di-tau mass distribution at qqH events using collinear approximation

Excellent physics potential



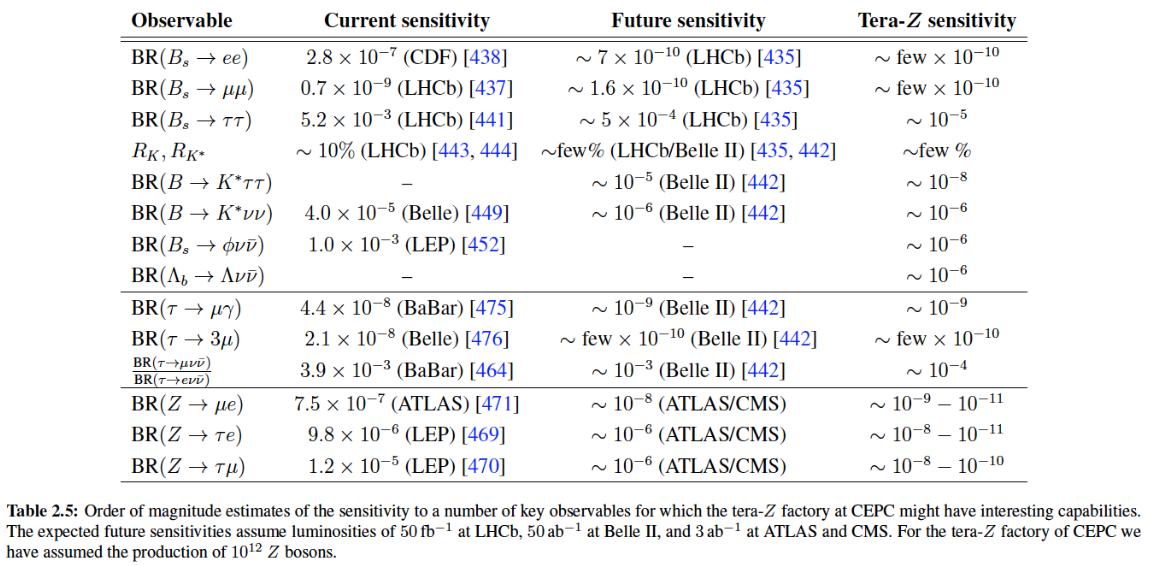






70 OVERVIEW OF THE PHYSICS CASE FOR CEPC

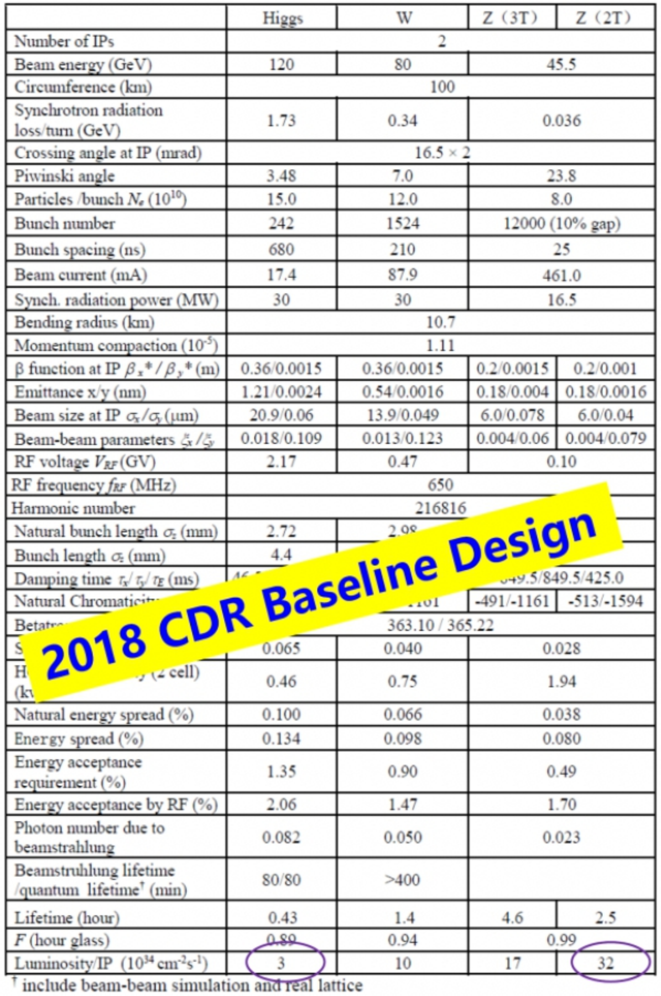
Particle	Tera-Z	Belle II	LHCb
b hadrons			
B^+	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	



Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
BR($B_s \to ee$)	2.8×10^{-7} (CDF) [438]	$\sim 7 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
BR($B_s \to \mu\mu$)	0.7×10^{-9} (LHCb) [437]	$\sim 1.6 \times 10^{-10}$ (LHCb) [435]	$\sim$ few $\times 10^{-10}$
BR($B_s \to \tau\tau$)	5.2×10^{-3} (LHCb) [441]	$\sim 5 \times 10^{-4}$ (LHCb) [435]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim$ 10% (LHCb) [443, 444]	~few% (LHCb/Belle II) [435, 442]	~few %
BR($B \to K^*\tau\tau$)	–	$\sim 10^{-5}$ (Belle II) [442]	$\sim 10^{-8}$
BR($B \to K^*\nu\nu$)	4.0×10^{-5} (Belle) [449]	$\sim 10^{-6}$ (Belle II) [442]	$\sim 10^{-6}$
BR($B_s \to \phi\nu\bar{\nu}$)	1.0×10^{-3} (LEP) [452]	–	$\sim 10^{-6}$
BR($\Lambda_b \to \Lambda\nu\bar{\nu}$)	–	–	$\sim 10^{-6}$
BR($\tau \to \mu\gamma$)	4.4×10^{-8} (BaBar) [475]	$\sim 10^{-9}$ (Belle II) [442]	$\sim 10^{-9}$
BR($\tau \to 3\mu$)	2.1×10^{-8} (Belle) [476]	$\sim$ few $\times 10^{-10}$ (Belle II) [442]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau\to\mu\nu\bar{\nu})}{\mathrm{BR}(\tau\to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [464]	$\sim 10^{-3}$ (Belle II) [442]	$\sim 10^{-4}$
BR($Z \to \mu e$)	7.5×10^{-7} (ATLAS) [471]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
BR($Z \to \tau e$)	9.8×10^{-6} (LEP) [469]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
BR($Z \to \tau\mu$)	1.2×10^{-5} (LEP) [470]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Table 2.5: Order of magnitude estimates of the sensitivity to a number of key observables for which the tera-Z factory at CEPC might have interesting capabilities. The expected future sensitivities assume luminosities of 50 fb^{-1} at LHCb, 50 ab^{-1} at Belle II, and 3 ab^{-1} at ATLAS and CMS. For the tera-Z factory of CEPC we have assumed the production of 10^{12} Z bosons.

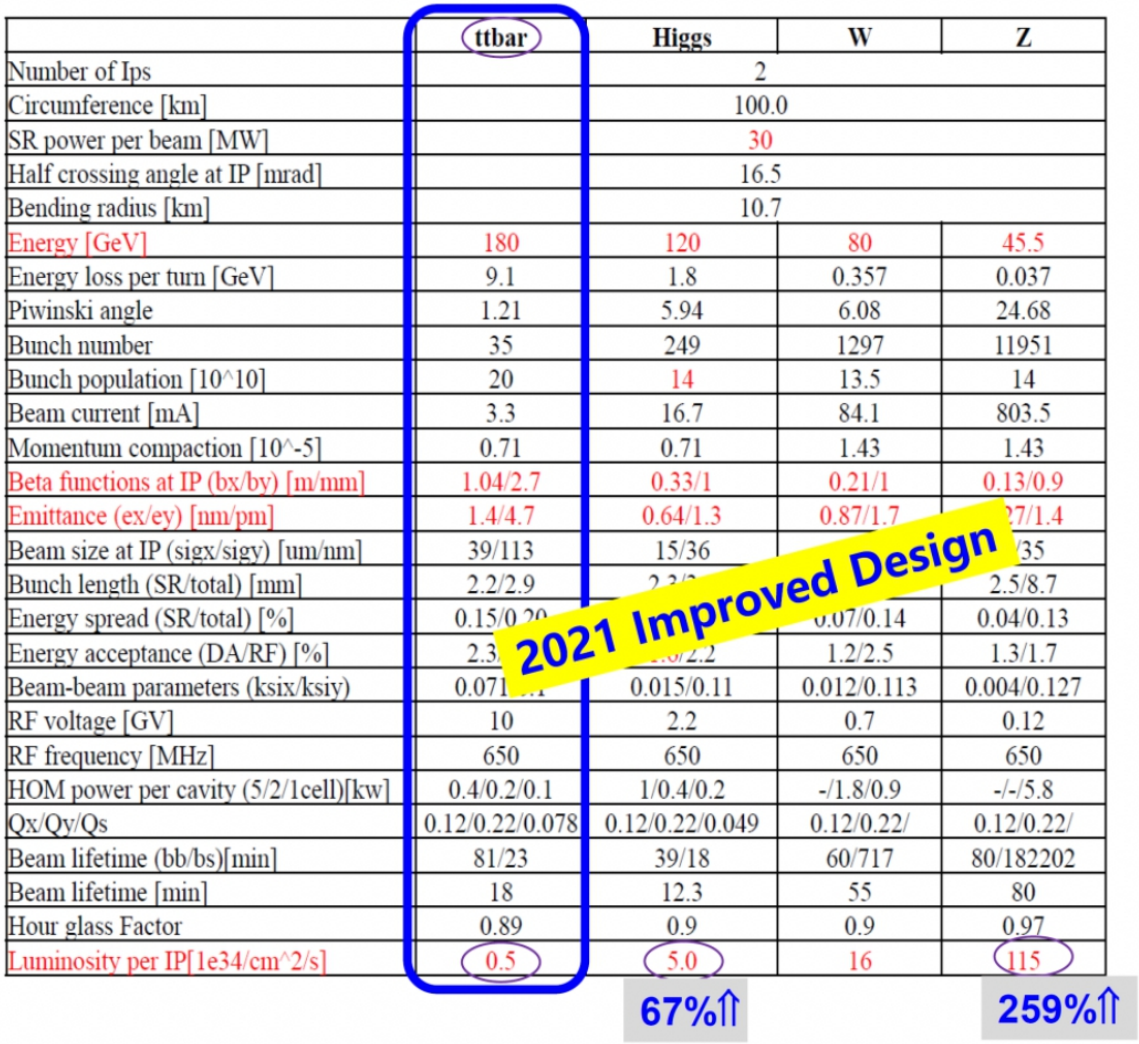
CEPC Accelerator TDR Design



2018 CDR Baseline Design

	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	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (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 x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	2.98	[illegible]	[illegible]
Bunch length σ_z (mm)	4.4	[illegible]	[illegible]	[illegible]
Damping time $\tau_x/\tau_y/\tau_E$ (ms)	[illegible]	[illegible]	849.5/849.5/425.0	
Natural Chromaticit[illegible]	[illegible]	[illegible]1161	-491/-1161	-513/-1594
Betatr[illegible]	363.10 / 365.22			
S[illegible]	0.065	0.040	0.028	
H[illegible] (2 cell) (k[illegible]	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime[†] (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

[†] include beam-beam simulation and real lattice



2021 Improved Design

	ttbar	Higgs	W	Z
Number of Ips		2		
Circumference [km]		100.0		
SR power per beam [MW]		30		
Half crossing angle at IP [mrad]		16.5		
Bending radius [km]		10.7		
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	[illegible]7/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36	[illegible]	[illegible]/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/[illegible]	[illegible]	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	[illegible]	0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3/[illegible]	[illegible]/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071/[illegible]	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

67%⇑

259%⇑

CEPC TDR Parameters - 50MW upgrade

	ttbar	Higgs	W	Z
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	50			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Bunch number	58	415	2162	19918
Bunch spacing [ns]	2640	385	154	15 (10% gap)
Bunch population [10^{10}]	20	14	13.5	14
Beam current [mA]	5.5	27.8	140.2	1339.2
Momentum compaction [10^{-5}]	0.71	0.71	1.43	1.43
Beta functions at IP (βx/βy) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (εx/εy) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	0.27/1.4
Betatron tune ν_x/ν_y	445.10/445.22	445.10/445.22	266.10/267.22	266.10/267.22
Beam size at IP (σx/σy) [um/nm]	39/113	15/36	13/42	6/35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20	0.10/0.17	0.07/0.14	0.04/0.13
Damping time (ms)	14/14/7	44/44/22	156/156/78	849.5/849.5/425.0
Energy acceptance (DA/RF) [%]	2.3/2.6	1.7/2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ξx/ξy)	0.071/0.1	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
Longitudinal tune νs	0.078	0.049	0.062	0.035
Luminosity per IP[10^{34}/cm^2/s]	0.83	8.3	26.6	191.7

From Prof. J. Gao

CEPC: operation scenario

- CEPC emphasize on the Higgs factory & Z factory

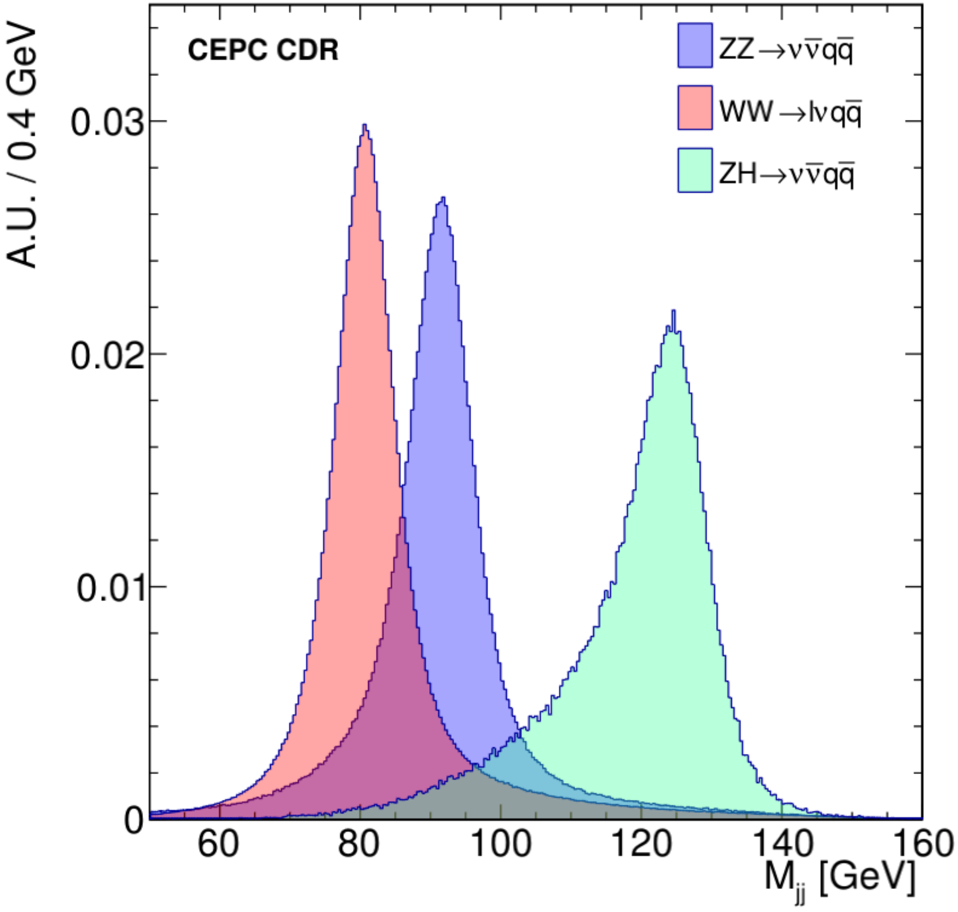
- Upgradable:
  - In energy: to 360 GeV
  - In SR beam power: 30 to 50 MW

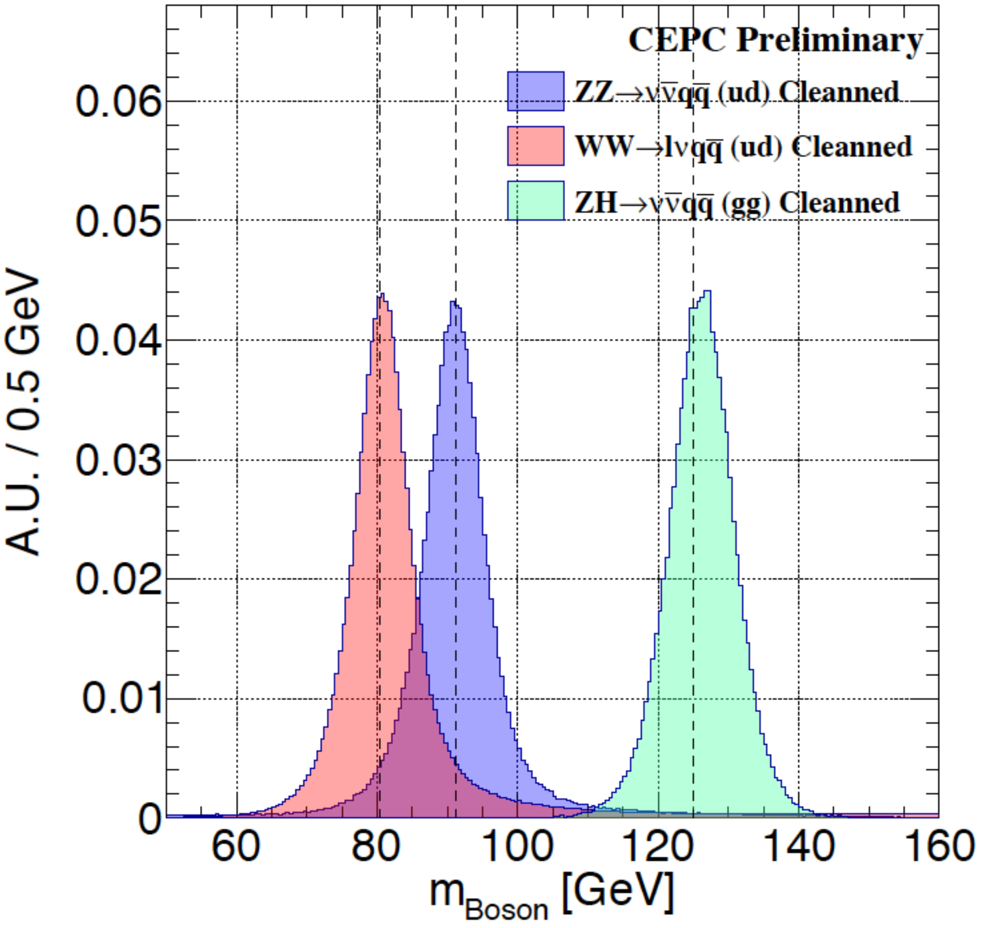
- Tentative Operation Plan & Yields (2 IP, with 50 MW)
  - 2 year in Z: 100 ab^{-1}, 4 Tera Z Boson
  - 1 year in W: 6 ab^{-1}, ~ 100 Million WW events
  - 10 year in Higgs: 20 ab^{-1}, 4 Million Higgs
  - ~ 5 years at top: 1 ab^{-1}, 0.5 Million ttbar events, 150 k Higgs

Anticipated Higgs precisions at 20 + 1 iab

	240GeV, 20ab^{-1}	360GeV, 1ab^{-1}		
	ZH	ZH	vvH	eeH
any	**0.26%**	**1.4%**	****	\\
$\mathrm{H} \rightarrow \mathrm{bb}$	**0.14%**	**0.9%**	**1.1%**	4.3%
$\mathrm{H} \rightarrow \mathrm{cc}$	**2.02%**	**8.8%**	**16%**	20%
$\mathrm{H} \rightarrow \mathrm{gg}$	**0.81%**	**3.4%**	**4.5%**	12%
$\mathrm{H} \rightarrow \mathrm{WW}$	**0.53%**	**2.8%**	**4.4%**	6.5%
$\mathrm{H} \rightarrow \mathrm{ZZ}$	**4.17%**	**20%**	**21%**	
$\mathrm{H} \rightarrow \tau\tau$	**0.42%**	**2.1%**	**4.2%**	7.5%
$\mathrm{H} \rightarrow \gamma\gamma$	**3.02%**	**11%**	**16%**	
$\mathrm{H} \rightarrow \mu\mu$	**6.36%**	**41%**	**57%**	
$\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \rightarrow \mathrm{inv.})$	**0.07%**	****	****	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow Z\gamma)$	**8.5%**	**35%**	****	
Width	**1.73%**	**1.10%**		

Massive Boson Separation





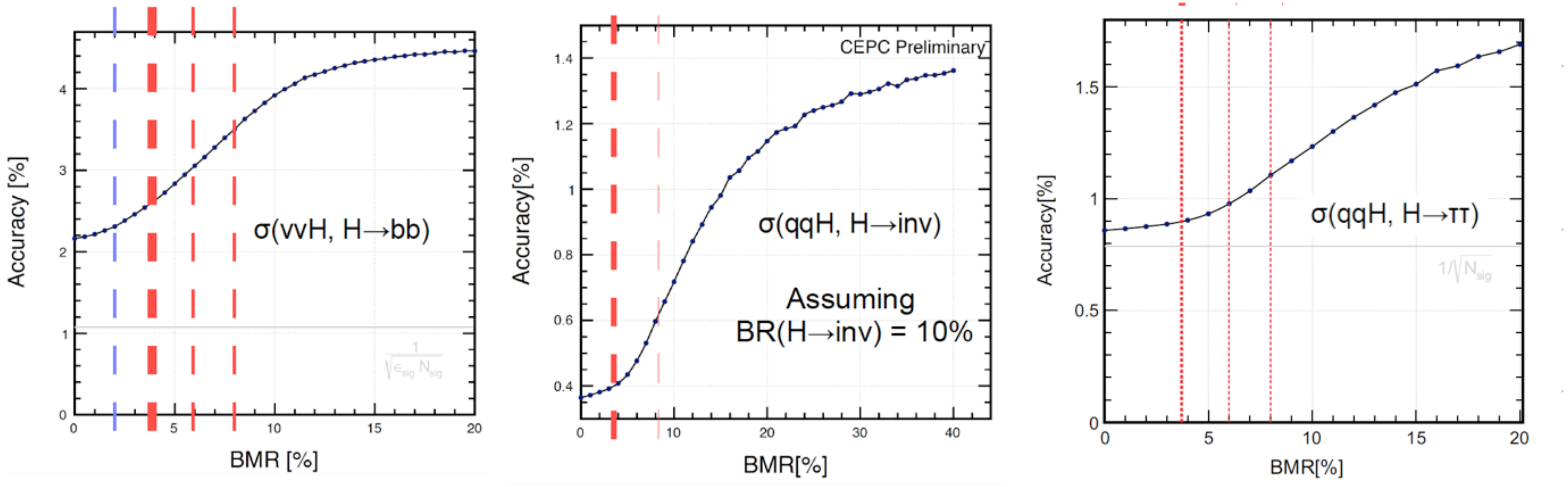
Peizhu Lai & CEPC CDR

WW sample: using μvqq sample,
Plot: the visible mass without the muon

CEPC-RECO-2017-002 (DocDB id-164),
CEPC-RECO-2018-002 (DocDB id-171),

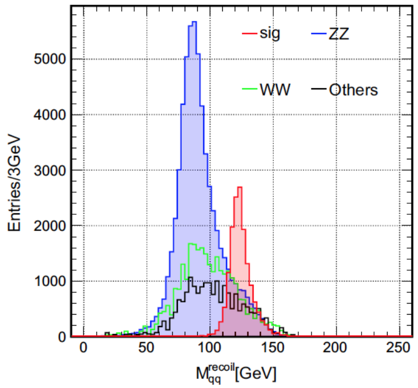
Eur. Phys. J. C (2018) 78: 426

BMR V.S. benchmark accuracy

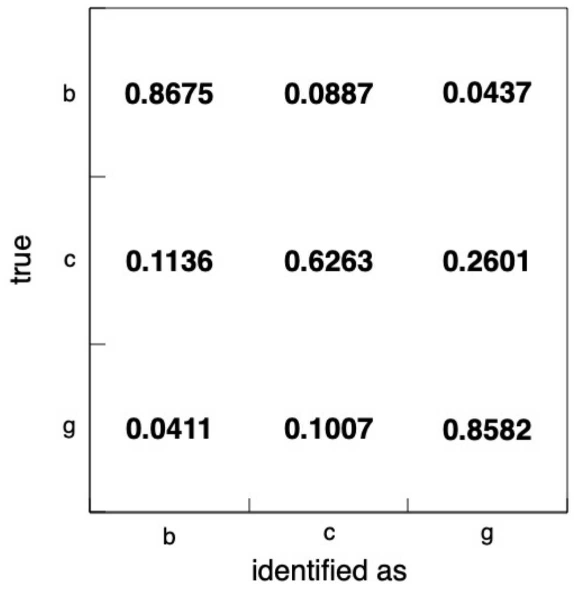


- Boson Mass Resolution: relative mass resolution of vvH, H→gg events
  - Free of Jet Clustering
  - Be applied directly to the Higgs analyses
- The CEPC baseline reaches 3.8%

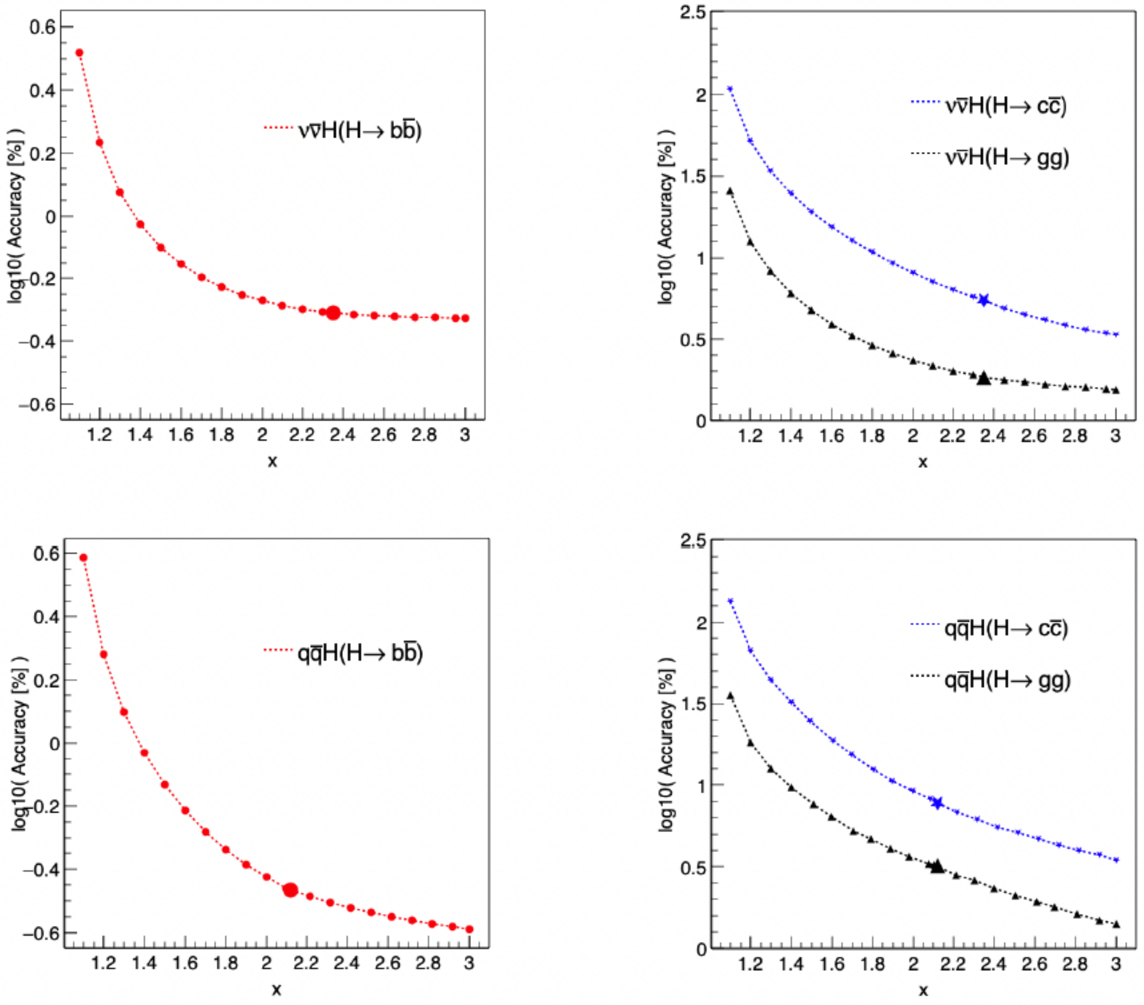
	BMR = 2%	4%	6%	8%
σ(vvH, H→bb)	2.3%	2.6%	3.0%	3.4%
σ(vvH, H→inv)	0.38%	0.4%	0.5%	0.6%
σ(qqH, H→ττ)	0.85%	0.9%	1.0%	1.1%



Jet Flavor Tagging for Higgs measurement: good & significant potential to improve



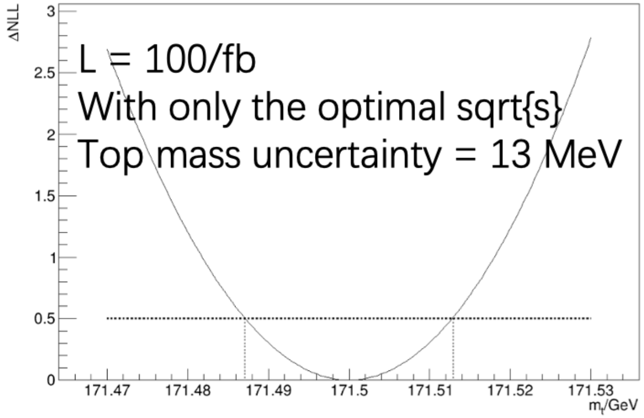
true \ identified as	b	c	g
b	0.8675	0.0887	0.0437
c	0.1136	0.6263	0.2601
g	0.0411	0.1007	0.8582



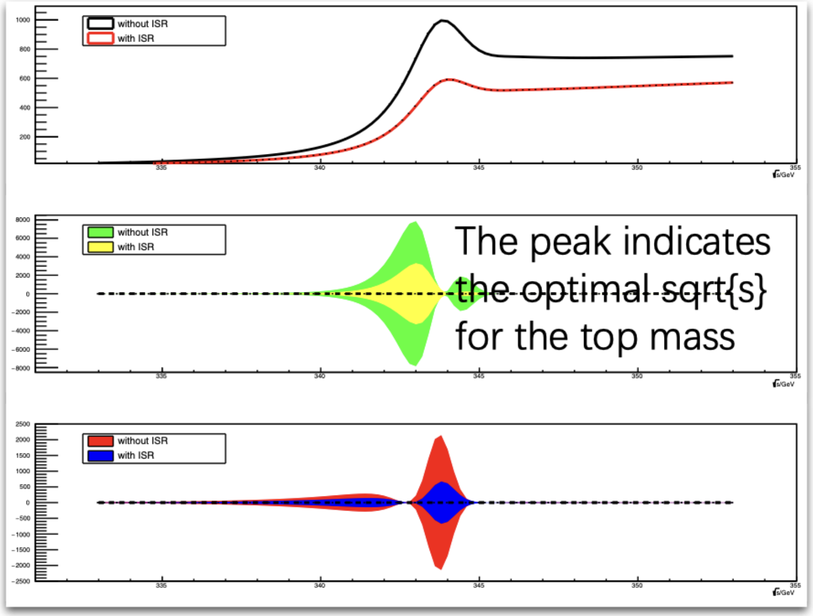
Compared to Baseline, Ideal FT improve the H->bb, cc, gg Measurements significantly. Especially at qqH channel. (up to 2 times.)

Top property measurement

- 360 GeV runs open a door to measure top properties in high precision that hadron colliders cannot reach
- Currently we study the top mass and width measurements using the tt threshold method at ~360 GeV
  - One order of magnitude better precision than the hadron collider is expected
  - A single run at the energy where the tt xsection varies most largely in a given top mass range is found to provide the best performance
  - A quick energy scan with low luminosity to find the optimal energy point before data taking with the full luminosity is proposed
  - More studies are ongoing for the simultaneous measurements of the top mass, width and alpha_S



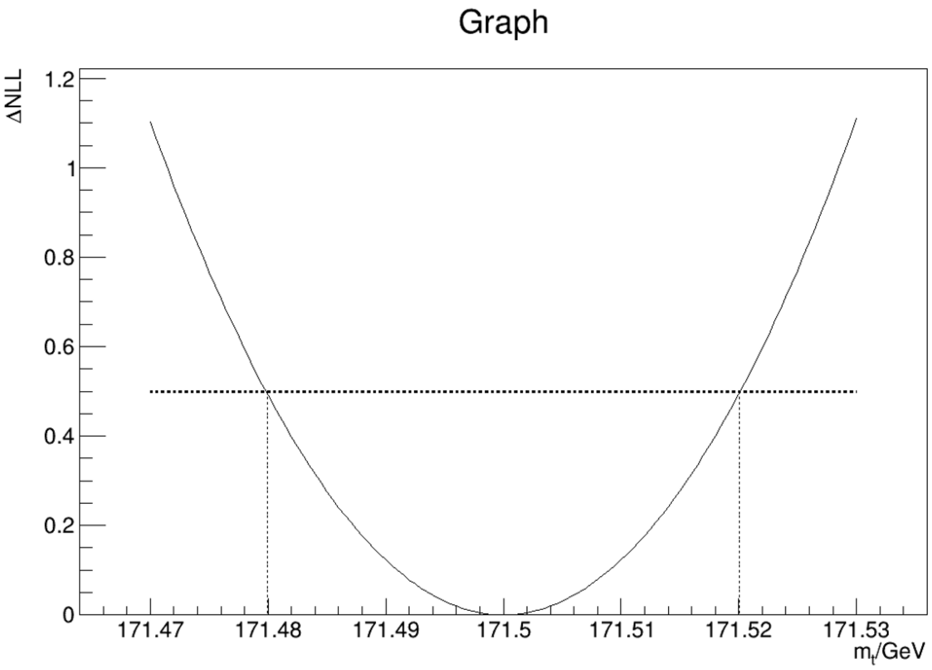
L = 100/fb
With only the optimal sqrt{s}
Top mass uncertainty = 13 MeV



The peak indicates the optimal sqrt{s} for the top mass

Top mass measurement: different schemes

8 $\sqrt{s}$ scheme
$=\{340,341,342,342.5,343,343.5,344.5,345\}$



12.5fb^{-1} per point $\sigma(m_t)$:-0.0200625 0.0200625

scheme	8 points	6 points	4 points	1 point
$\sigma(m_t)$/ MeV	20.06	17.56	14.93	12.93

We incorporate Luminosity Spectrum(LS) by a simple Gaussian function with CEPC LS (~0.5GeV, provided by Yiwei Wang) as the energy resolution at the moment.

Statistical Uncertainty ~ 10 - 20 MeV
With 1/10 of the data.

Input: EWPO @ future e+e-

[1905.03764]

[1907.04311]

[1908.11299]

[2106.13885]

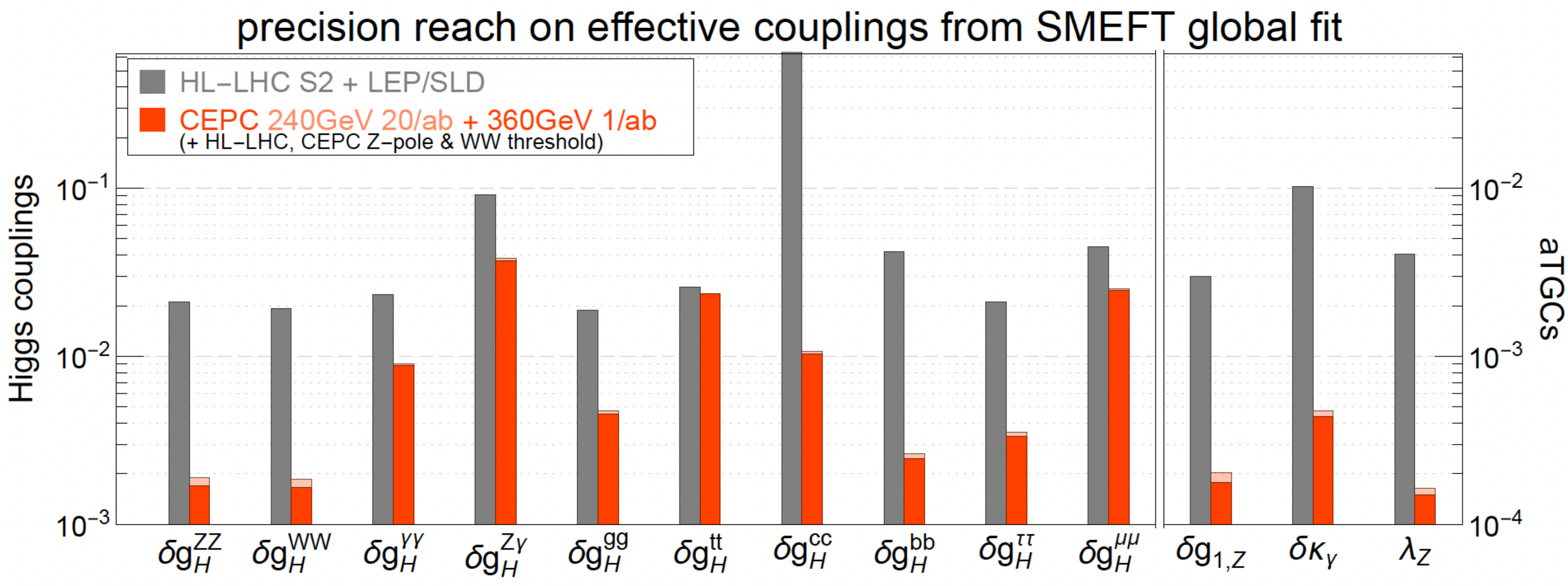
	ILC250 (ra. re.)	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha^{-1}$	0.0178*		3.8(1.2)x10^{-3}	0.0178*	0.0178*
Δm_W / MeV	2.4(0.5)		0.25(0.3)	1	
Δm_Z / MeV	2.1*		0.004(0.1)	0.1	2.1
Δm_H / MeV	14		2.5(2)	5.9	78
$\Delta\Gamma_W$ / MeV	2		1.2(0.3)	2.8	
$\Delta\Gamma_Z$ / MeV	2.3*	(1)	0.025(0.004)	0.025	2.3
ΔA_e	14(4.5)x10^{-5}	1.5(8)x10^{-5}	0.7(2)x10^{-5}	0.000015	0.00064
ΔA_μ	82(4.5)x10^{-5}	3(8)x10^{-5}	2.3(2.2)x10^{-5}	0.00045	0.0040
ΔA_τ	86(4.5)x10^{-5}	3(8)x10^{-5}	0.5(20)x10^{-5}	0.000070	0.0057
ΔA_b	53(35)x10^{-5}	9(51)x10^{-5}	2.4(21)x10^{-5}	22x10^{-5}	0.0038
ΔA_c	140(25)x10^{-5}	20(50)x10^{-5}	20(15)x10^{-5}	0.0020	0.0020
$\Delta\sigma_{had}$	t.b.u.	t.b.u.	4 pb	5 pb	37 pb*
δR_e	0.0011	0.00054	0.0003	0.0006	0.0027
δR_μ	0.0011	0.00028	0.00005	0.0001	0.0027
δR_τ	0.0011	0.00045	0.0001	0.0002	0.006
δR_b	0.0011	0.00070	<0.0003	0.0002	0.0018
δR_c	0.0050	0.0030	0.0015	0.0011	0.0056

Δ: absolute error
δ: relative error

*: from current data

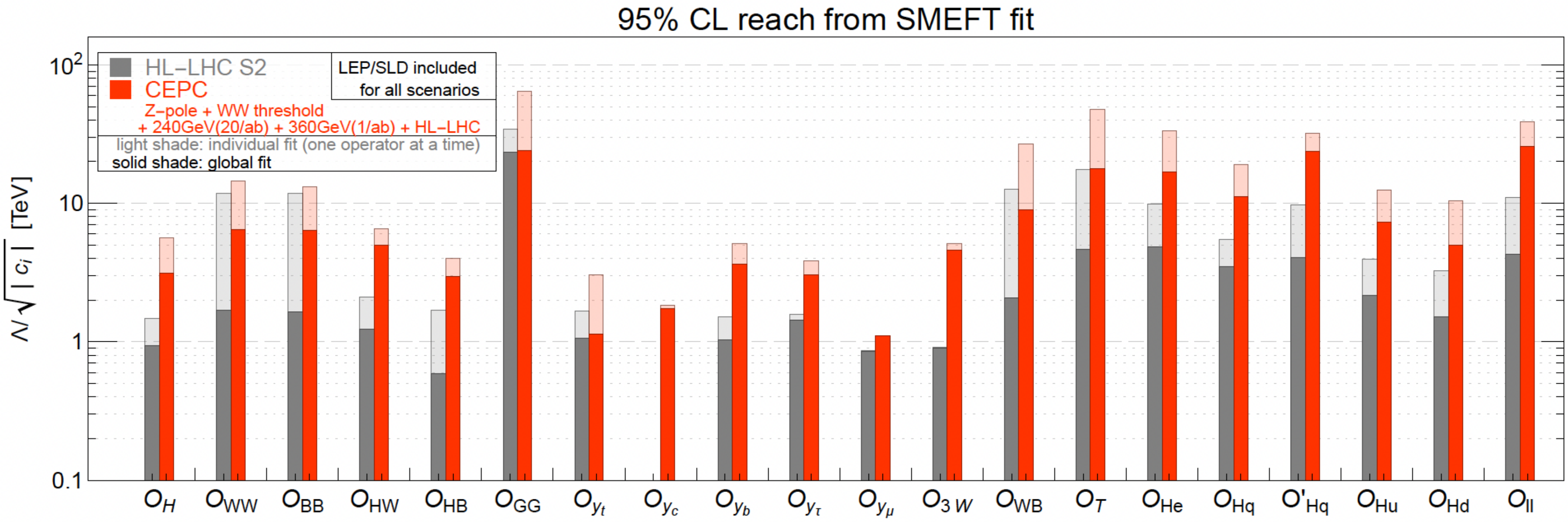
breakdown for CEPC and CLIC yet to be done

SMEFT global fit (effective coupling precision)



- 28-parameter fit projected on Higgs couplings and anomalous triple gauge couplings.
- $\delta g_H^{ZZ} \approx \delta g_H^{WW}$ from theoretical constraints (gauge invariance & custodial symmetry) and EW measurements.
- Non-negligible improvement from a small data sample at 360 GeV.

SMEFT global fit (reach on new physics scale)



- 20-parameter fit (assuming flavor universality in gauge-fermion couplings).
- See next page for the operator basis.

Summary

- CEPC, a precision & upgradable Higgs/W/Z factory, and a Discover machine!
  - 4 M Higgs, 100 Million – 1 Billion W, 1 Million Top, and 4 Tera Z.
  - For Higgs precision measurements, secures the precisions ~ 1 order of magnitude better compared to HL-LHC
  - Boost the precision on EW, etc, by at 1-2 orders of magnitudes.
  - Top mass be measured to an statistical uncertainty accuracy of ~o(10) MeV
  - ...
- Lots of challenges:
  - Beam energy calibration,
  - Beam polarization,
  - Luminosity Spectrum,
  - Luminosity Measurements,
  - Theoretical uncertainties...
  - ...

Backup

Challenge: Beam condition

- Beam energy calibration
  - ~ 0.1 MeV at Z pole
  - ~ sub MeV at W threshold
  - ~ MeV at Higgs operation
  - ...with nature beam energy spread of ~ o(1E-3)

- Beam polarization monitoring
  - Transverse... (essential for the Resonance depolarization Method) and even longitudinal...

- Beam Luminosity Spectrum Monitoring, especially at top

D6 operators

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{q}_L H u_R + \mathrm{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{q}_L H d_R + \mathrm{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{l}_L H e_R + \mathrm{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

- SILH’ basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH’ basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$) (used here)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)