EW Physics at the CEPC

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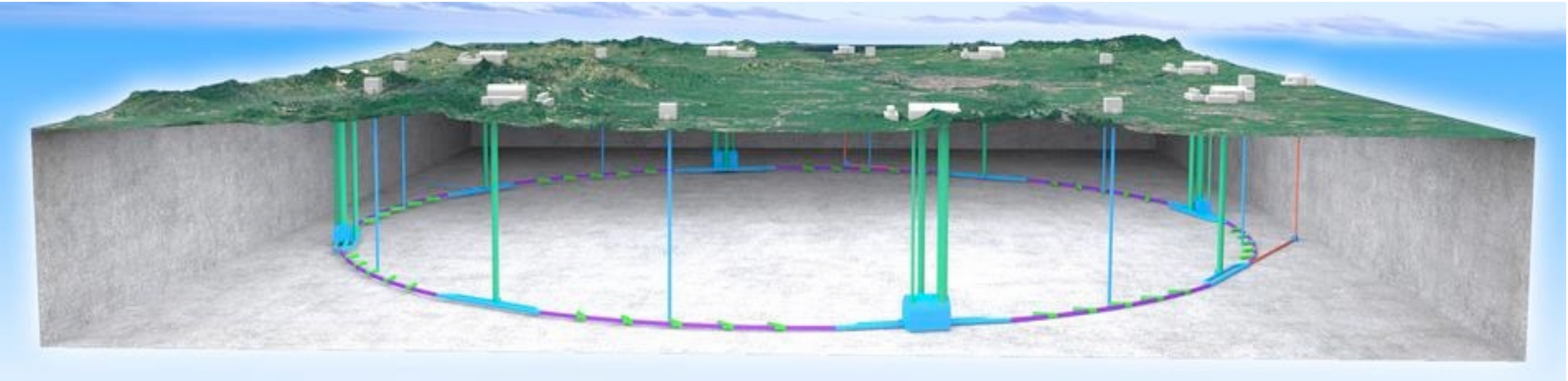
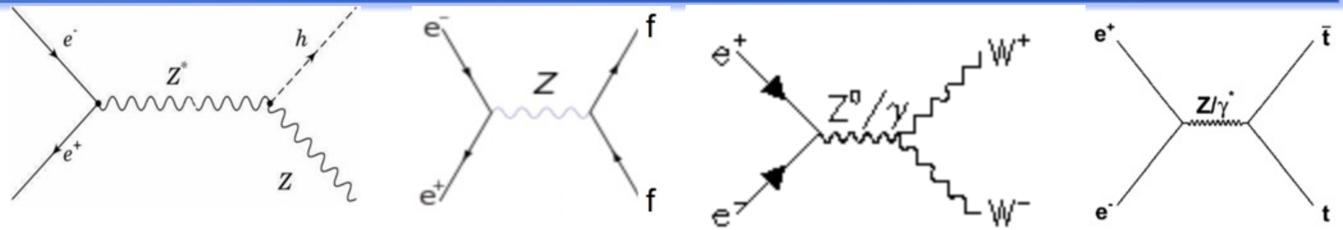
The 2024 International Workshop on the Circular Electron Positron Collider



CEPC physics program

An extremely versatile machine with a broad spectrum of physics opportunities

→ Far beyond a Higgs factory



Operation mode			ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]			~240	~91.2	~160	~360
Run time [years]			10	2	1	5
CDR (30 MW)		L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**3**	**32**	**10**	-
		$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	-
		Event yields [2 IPs]	1×10^{6}	7×10^{11}	2×10^{7}	-
Run Time [years]			10	2	1	~5
Latest	30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**191.7**	**26.6**	**0.8**
		$\int L\,dt$ [ab^{-1}, 2 IPs]	20	96	7	1
		Event yields [2 IPs]	4×10^{6}	4×10^{12}	5×10^{7}	5×10^{5}

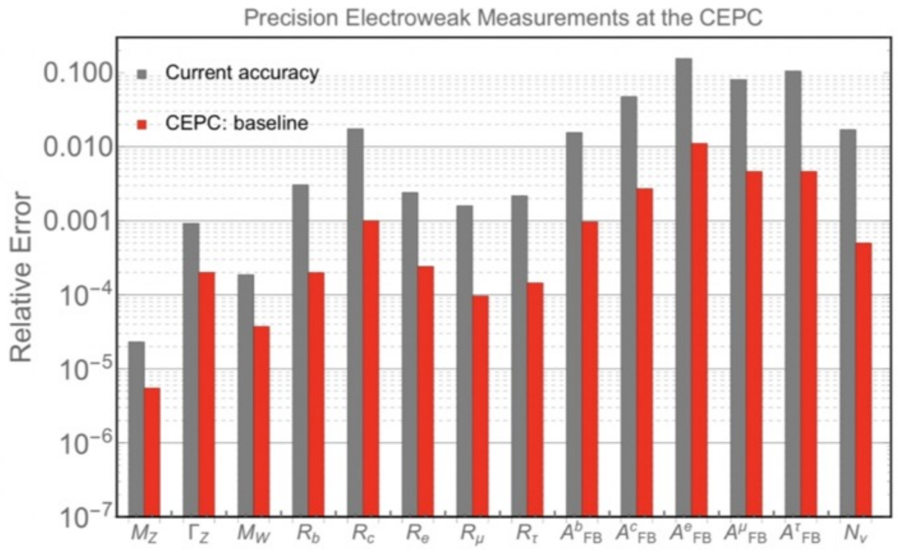
- ❖ **First 10 year operation**
  - ▶ **Higgs factory**
  - ▶ **low-lumi Z (20% of high-lumi Z)**
    - **Detector calibration and alignment**
    - **Physics with Giga-Z**
- ❖ **2 year of high-lumi Z factory operation**
- ❖ **1 year of WW threshold scan**
- ❖ **5 year of ttbar runs**

Both 50 MW and $t\bar{t}$ modes are currently considered as CEPC upgrades.

EWK precision measurements (ZH, Z pole, WW runs)

Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z\to\tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z\to\mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z\to\tau\tau$)	tau decay model
ΔA_b	0.02 [37, 56]	20×10^{-5} (3×10^{-5})	Z pole	QCD effects
ΔA_c	0.027 [37, 56]	30×10^{-5} (6×10^{-5})	Z pole	QCD effects
$\Delta\sigma_{had}$	37 pb [37–41]	2 pb (0.05 pb)	Z pole	lumiosity
δR_b^0	0.003 [37, 57–61]	0.0002 (5×10^{-6})	Z pole	gluon splitting
δR_c^0	0.017 [37, 57, 62–65]	0.001 (2×10^{-5})	Z pole	gluon splitting
δR_e^0	0.0012 [37–41]	2×10^{-4} (3×10^{-6})	Z pole	E_{beam} and t channel
δR_μ^0	0.002 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δR_τ^0	0.017 [37–41]	1×10^{-4} (3×10^{-6})	Z pole	E_{beam}
δN_ν	0.0025 [37, 66]	2×10^{-4} (3×10^{-5})	ZH run ($\nu\nu\gamma$)	Calo energy scale

CEPC snowmass input: https://arxiv.org/abs/2205.08553

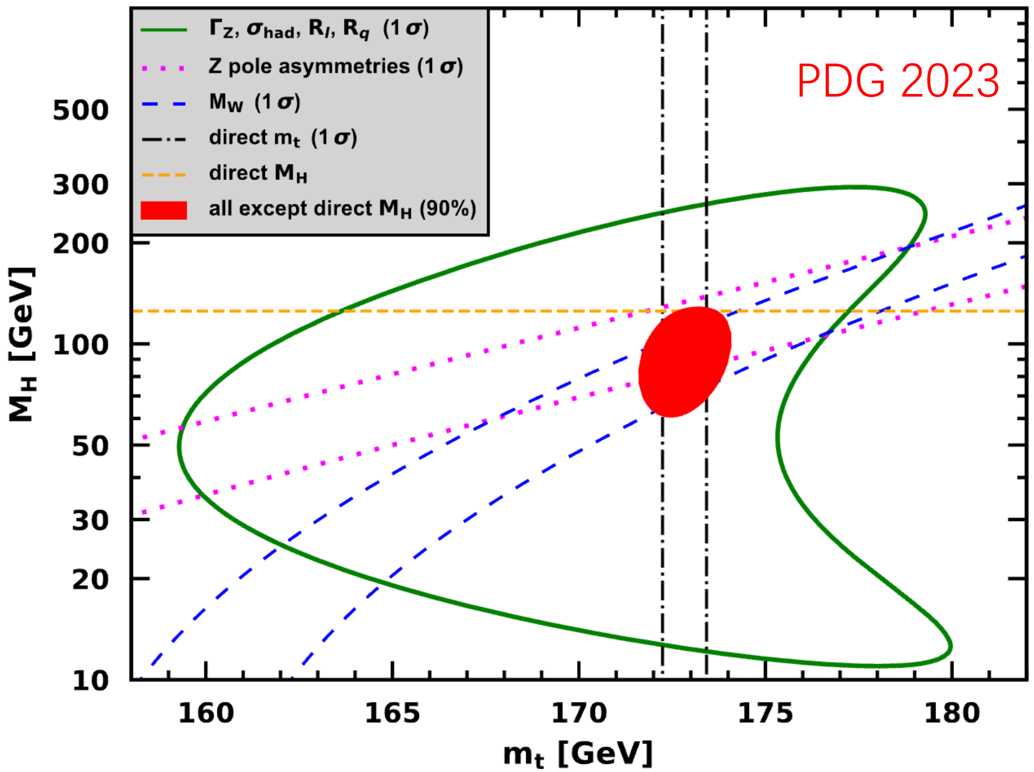


CEPC is expected to improve the current precision by 1-2 orders of magnitude, offering a great opportunity to test the consistency of the SM.

The status of electroweak global fit

❖7 key observables in electroweak global fit

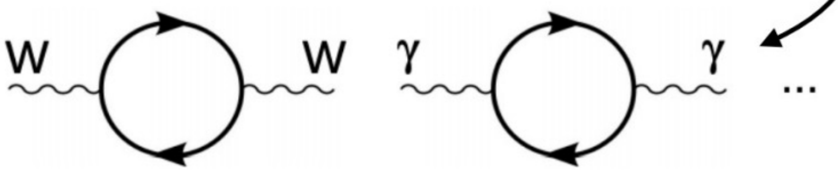
- ▶ Consistency study of the standard model electroweak section
- ▶ Need CEPC Z pole and WW runs : Precise measurements on EWK observables.



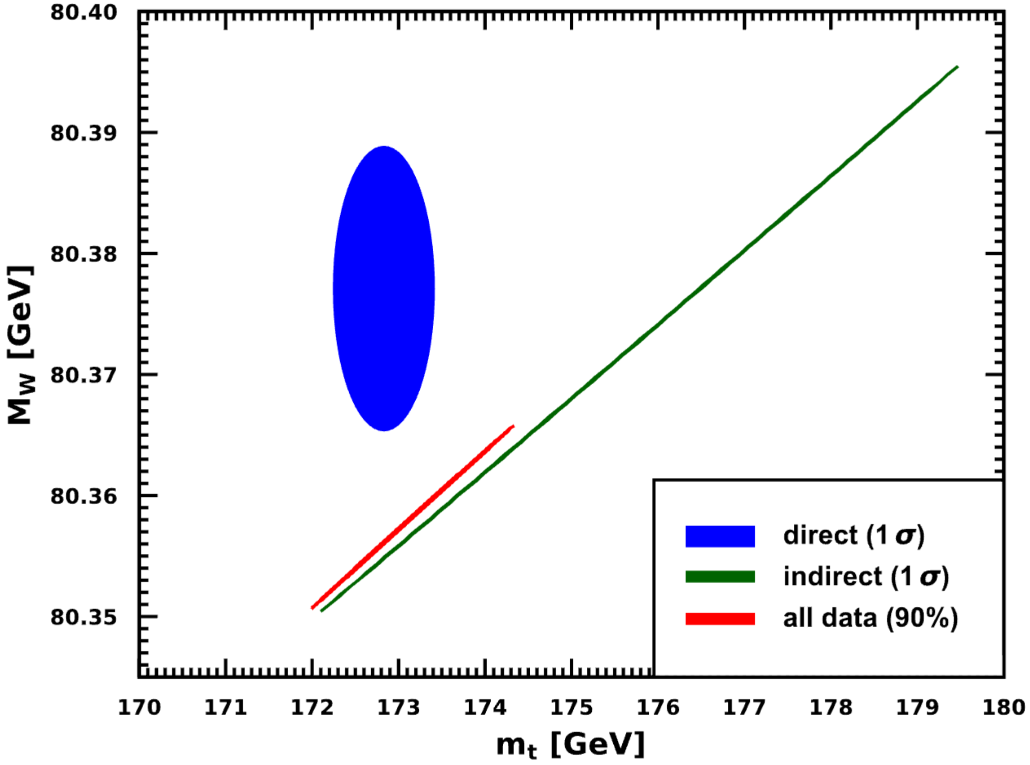
Fundamental constant	δx/x	measurements
$\alpha = 1/137.035999139\ (31)$	1×10^{-10}	$e^{\pm}\ g_2$
$G_F = 1.1663787\ (6) \times 10^{-5}\ \mathrm{GeV}^{-2}$	1×10^{-6}	$\mu^{\pm}$ lifetime
$M_Z = 91.1876 \pm 0.0021$ GeV	1×10^{-5}	LEP
$M_W = 80.379 \pm 0.012$ GeV	1×10^{-4}	LEP/Tevatron/LHC
$\sin^2\theta_W = 0.23152 \pm 0.00014$	6×10^{-4}	LEP/SLD
$m_{top} = 172.74 \pm 0.46$ GeV	3×10^{-3}	Tevatron/LHC
$M_H = 125.14 \pm 0.15$ GeV	1×10^{-3}	LHC

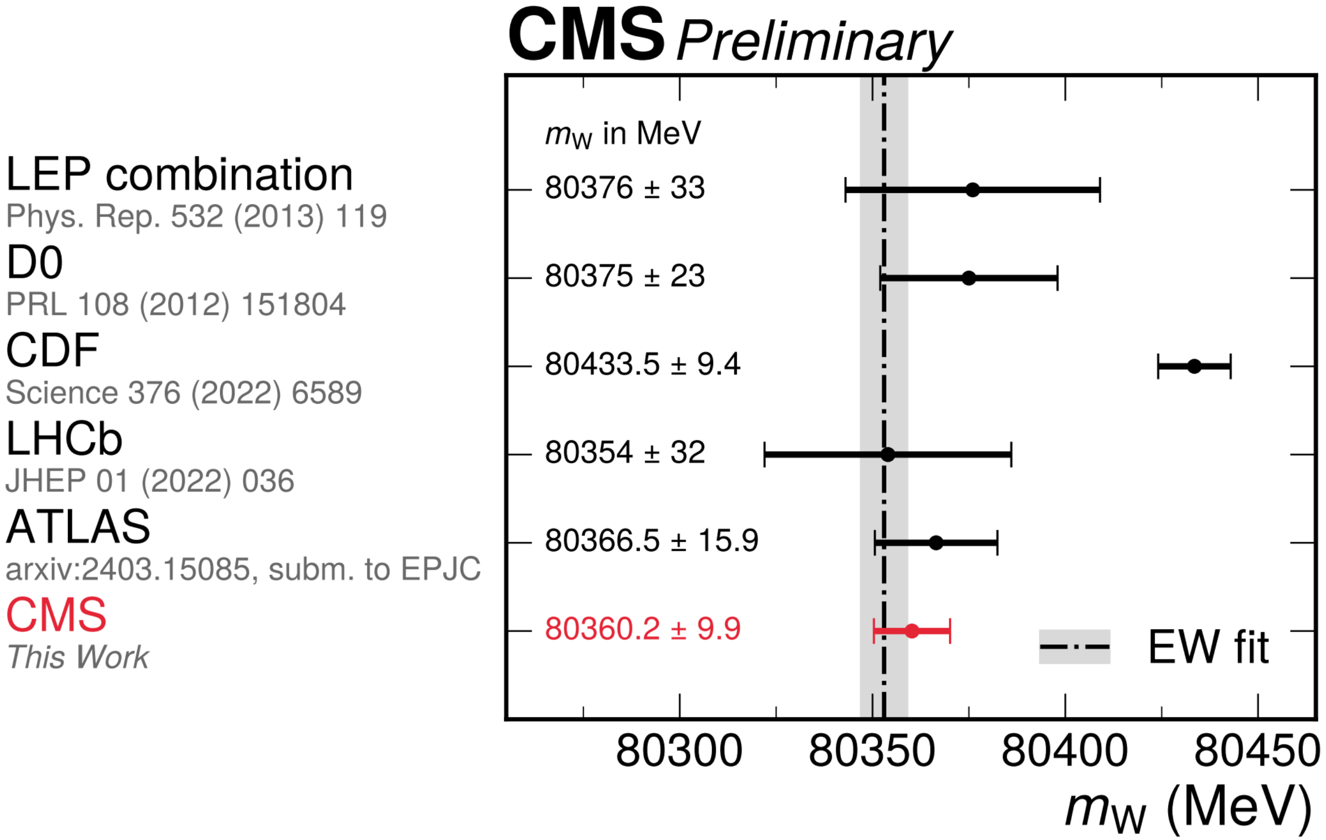
W mass measurement

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

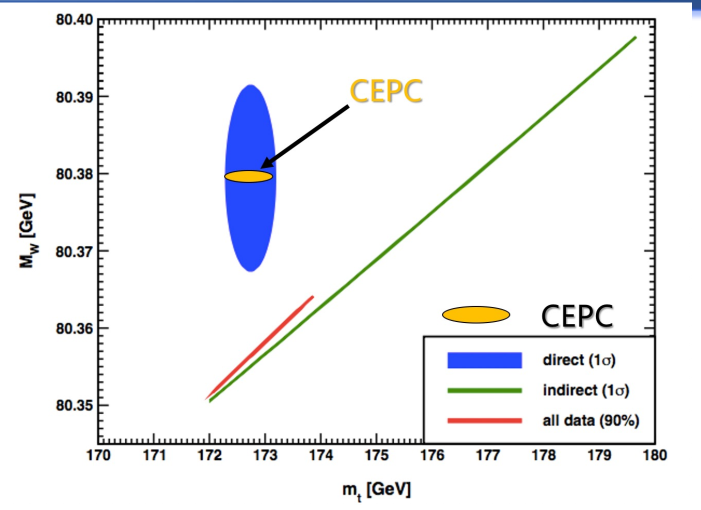


- ❖ **m_W is a key observable to test SM consistency**
  - ▶ Latest CMS result in tension with CDF
  - ▶ m_W Measurement at future collider is essential





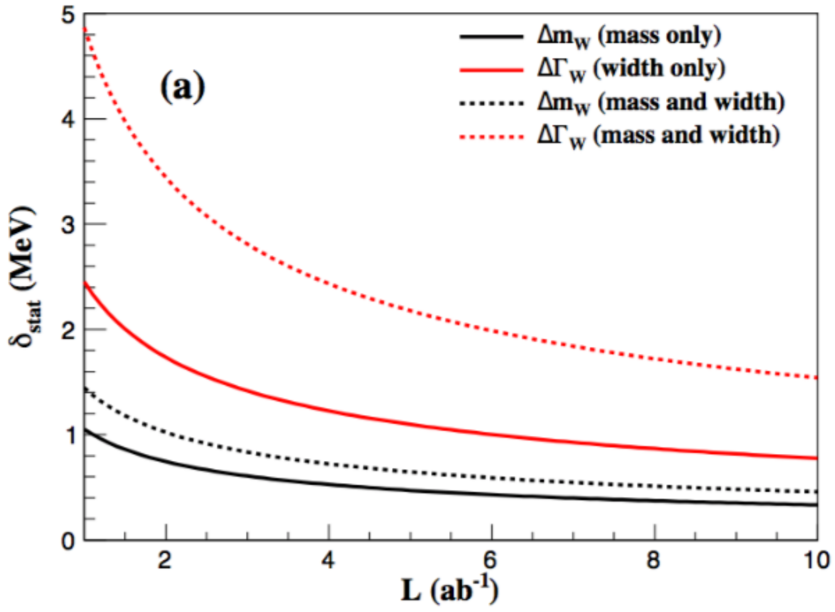
Prospect of W mass measurement at CEPC (WW threshold runs)

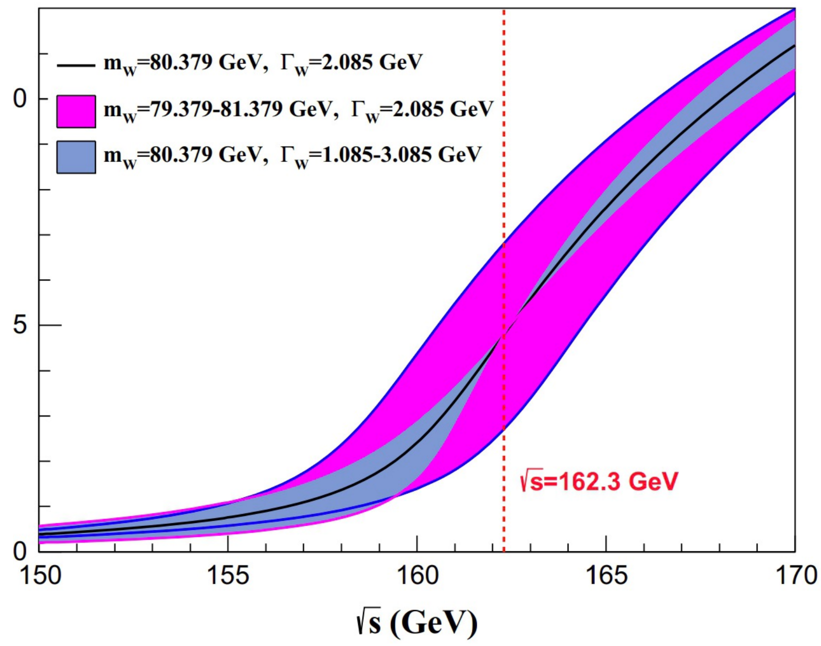


❖ Expect to reach below 1MeV precision on W mass

- Four energy scan points:
  - 157.5, 161.5, 162.5(W mass, W width measurements)
  - 172.0 GeV (αQCD (mW), Br (W->had) , CKM |Vcs|)

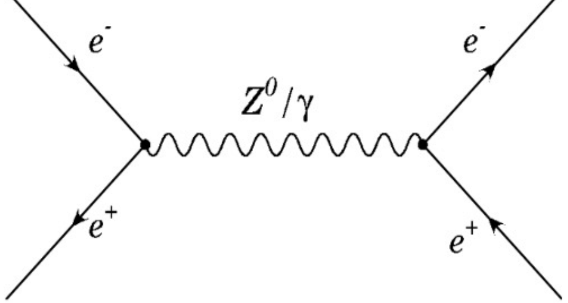
Observable	m_W	Γ_W
Source	Uncertainty (MeV)	
Statistics	0.8	2.7
Beam energy	0.4	0.6
Beam spread	–	0.9
Corr. syst.	0.4	0.2
Total	1.0	2.8



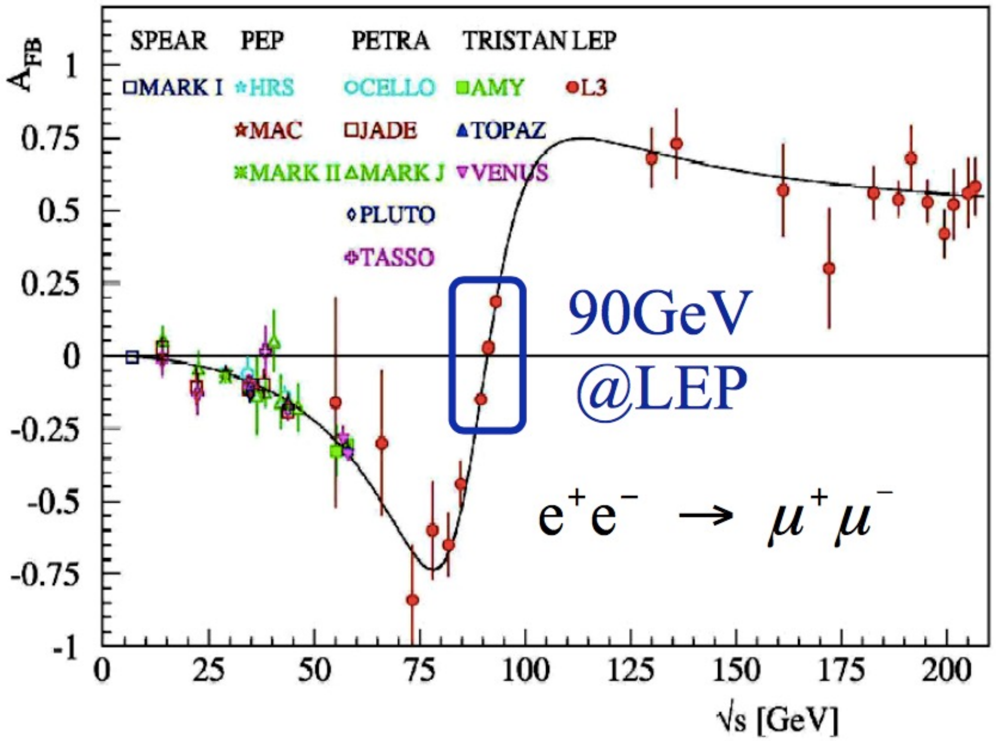


P.X.Shen, P.Azzuri , G.Li et,al,
Eur.Phys.J.C 80 (2020) 1, 66
Joint study of CEPC/Fcc-ee

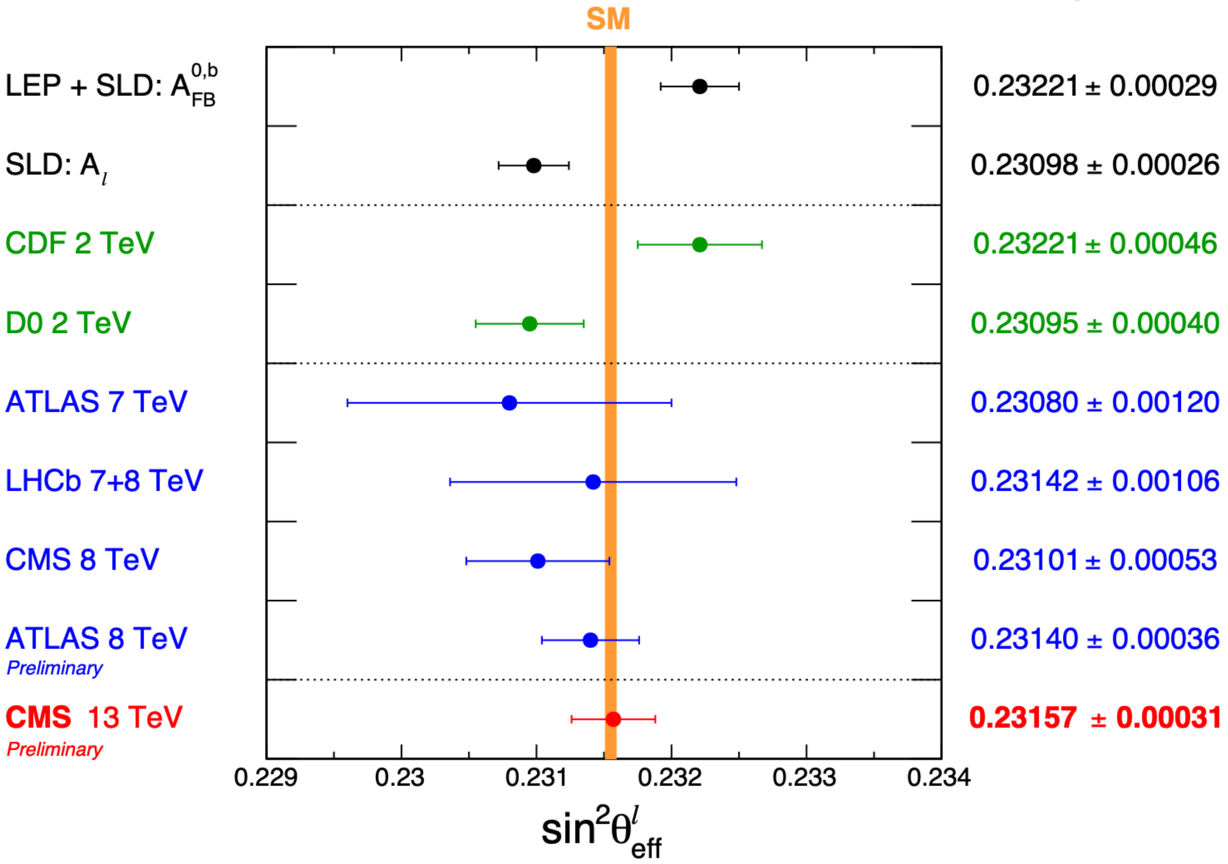
Weak mixing angle measurements ($Sin^2\theta_W$)



- **Weak mixing angle measurement is well motivated**
  - ▶ ~3σ tension between LEP and SLC measurements
  - ▶ LHC results can reach similar precision level now



CMS 2024 update
CMS PAS SMP-22-010



Weak mixing angle measurements at CEPC (A_{FB})

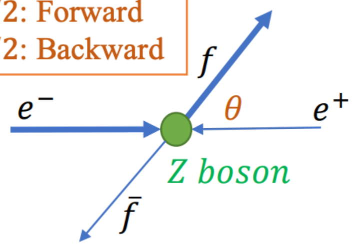
- **Study of off-peak runs for weak mixing angle measurements.**

Table 2. Sensitivity S of different final state particles.

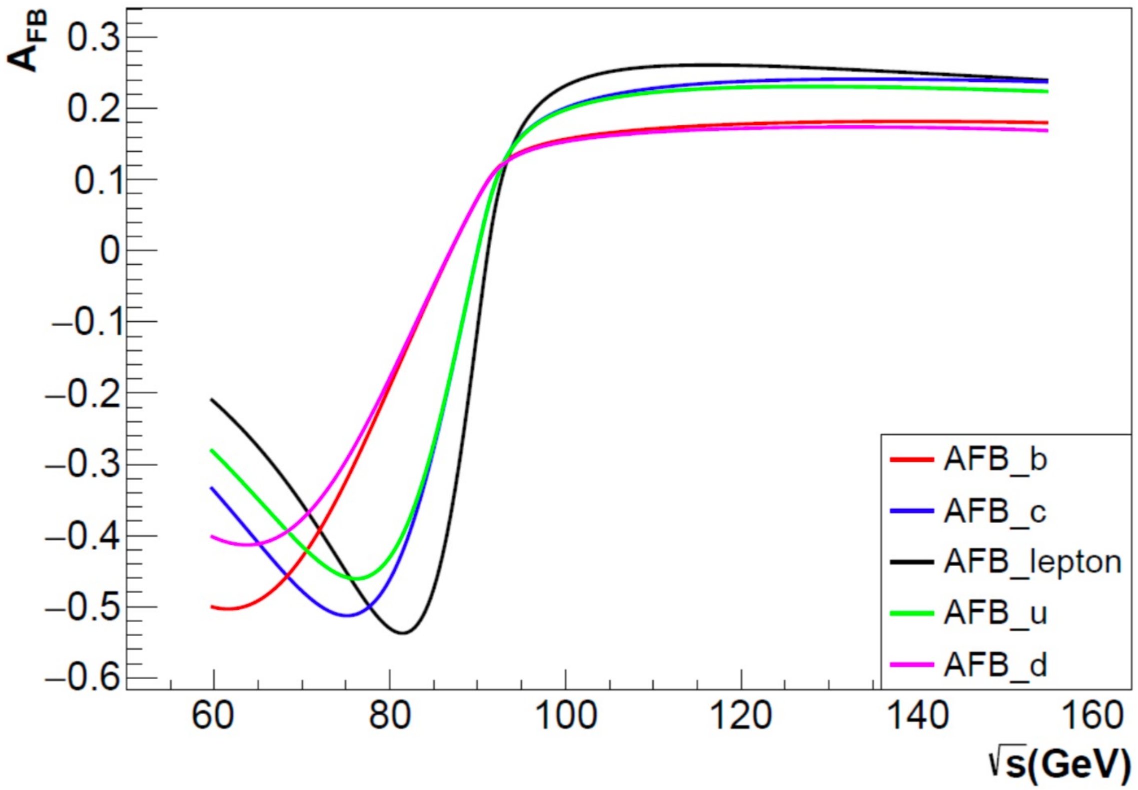
$\sqrt{s}$/GeV	S of $A_{FB}^{e/\mu}$	S of A_{FB}^{d}	S of A_{FB}^{u}	S of A_{FB}^{s}	S of A_{FB}^{c}	S of A_{FB}^{b}
70	0.224	4.396	1.435	4.403	1.445	4.352
75	0.530	5.264	2.598	5.269	2.616	5.237
92	1.644	5.553	4.200	5.553	4.201	5.549
105	0.269	4.597	1.993	4.598	1.994	4.586
115	0.035	3.956	1.091	3.958	1.087	3.942
130	0.027	3.279	0.531	3.280	0.520	3.261

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

$\theta < \pi/2$: Forward
$\theta > \pi/2$: Backward



Chinese Phys. C **47** 123002



Weak mixing angle at CEPC (from $P\tau$ measurement)

Chinese Phys. C **47** 123002

- The only channel for which the polarization can be determined

$$P_\tau = \frac{d(\sigma_r - \sigma_l)}{d\cos\theta} \Big/ \frac{d(\sigma_r + \sigma_l)}{d\cos\theta}$$

- $P_\tau = P_\tau(\cos\theta\,, \sin^2\theta_{eff})$

- Measurement of P_τ rely on the kinematic spectrum of different tau decay modes.

- Statistical: 2.15×10^{-6} (one month data)
- Systematic: $\mathcal{O}(10^{-4})$ for LEP

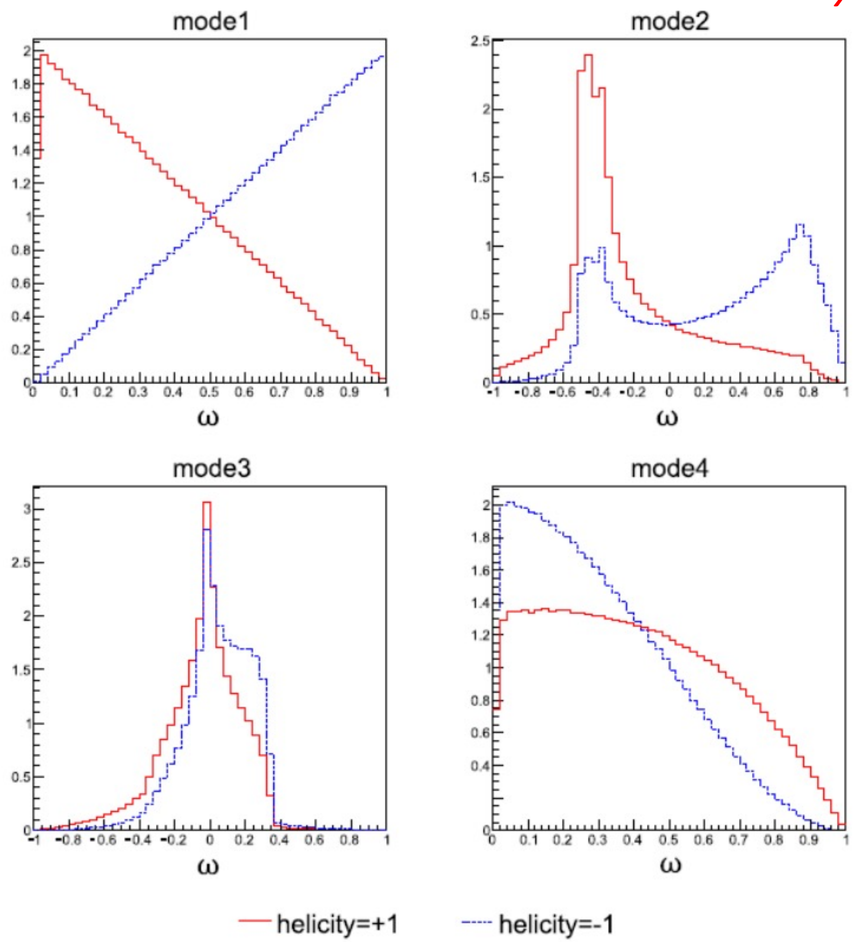


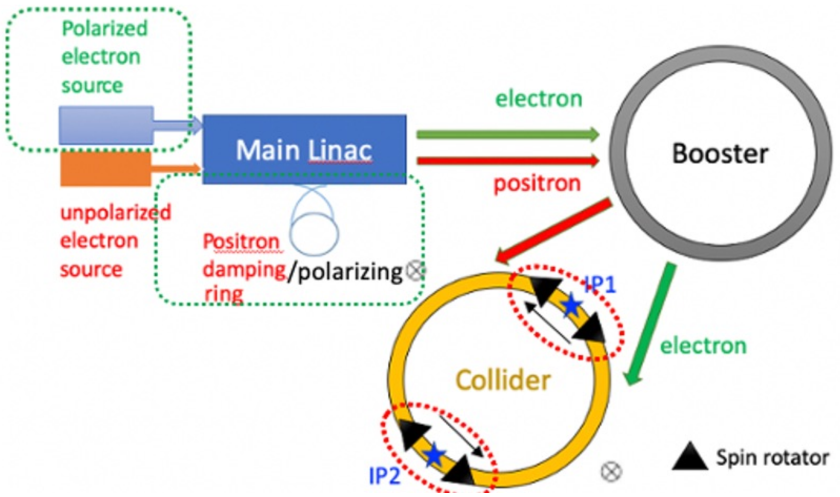
Fig. 5. (color online) Kinematic spectrum of different tau decay modes. The red solid line and blue dashed line represent the kinematic spectrum of taus with *helicity* = +1 and −1, respectively. All the spectra are generated using PYTHIA8 generator and tauola interface.

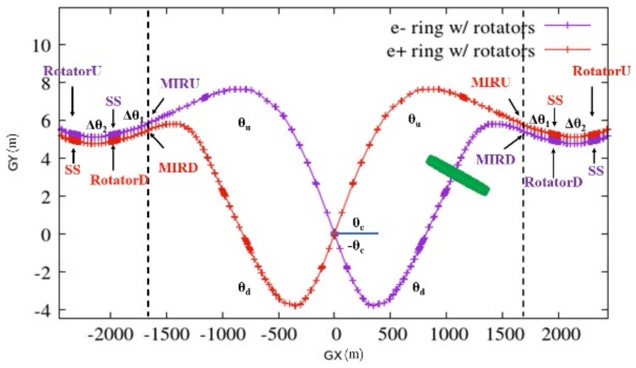
Weak mixing angle at CEPC (from A_{LR} measurement)

❖Potential to have longitudinal beam polarization in CEPC baseline design

Polarized beams @ CEPC: longitudinal polarization

- Weak mixing angle from A_{FB}, A_{LR} @ Z-pole A_{FB} @ CEPC: CPC 47, (2023) 123002
  - A_{FB} -> **nonzero** longitudinal polarization introduces sys. uncertainty -> **keep $|P_z^{e+}|\&|P_z^{e-}| < 10^{-5}$ by depolarizer** (Wilkinson, FCC EPOL Workshop 2022)
  - A_{LR} -> Large P_z^{e-} (SLD: Physics Report Vol 427, No 5-6 (2006))
    - **50%~70% P_z^{e-}** for all colliding e- bunches is attainable at **nominal luminosity & lifetime**
  - Very precise measurement of longitudinal polarization at IPs (**accuracy ~ 10^{-5} to match the large stats**)
    - ~30% P_z^{e+} for a fraction of e+ bunches is attainable, could help relax requirement on polarimetry (Blondel, Physics Letter B 202, 1988)





- Solenoid spin rotators around each IP **(~500 T·m per IP per ring)**

(Xia et al, RDTM 6, 490, 2022)

Weak mixing angle measurements ($Sin^2\theta_W$)

- **CEPC has potential to improve it by two order of magnitudes**

Experiment	Stat. (10^{-5})	Syst. (10^{-5})	Theory unc. (PDF+QCD) (10^{-5})	Total unc. (10^{-5}) $\delta sin^2\theta_W$
LEP	29	~ 1	~0	29
Tevatron	27	5	18	33
ATLAS 8TeV (ATL-CONF-2018-037)	21	16	24	36
CMS 13TeV (SMP-22-01)	10	15	9	27
CEPC (2205.08553)	~0.2	~0.2	~0	~0.3
Theory prediction			~4	~4

R^b measurement

$$\frac{\Gamma(\mathrm{Z} \to \mathrm{b\bar{b}})}{\Gamma(\mathrm{Z} \to \mathrm{had})}$$

- At LEP measurement 0.21594 ±0.00066
- CEPC aim to improve the precision by a factor 10~20 (0.02%)
- R^b measurement is sensitive to New physics models (SUSY)
  - SUSY predicts corrections to Z→ bb vertex
  - Through gluino and chargino loop …

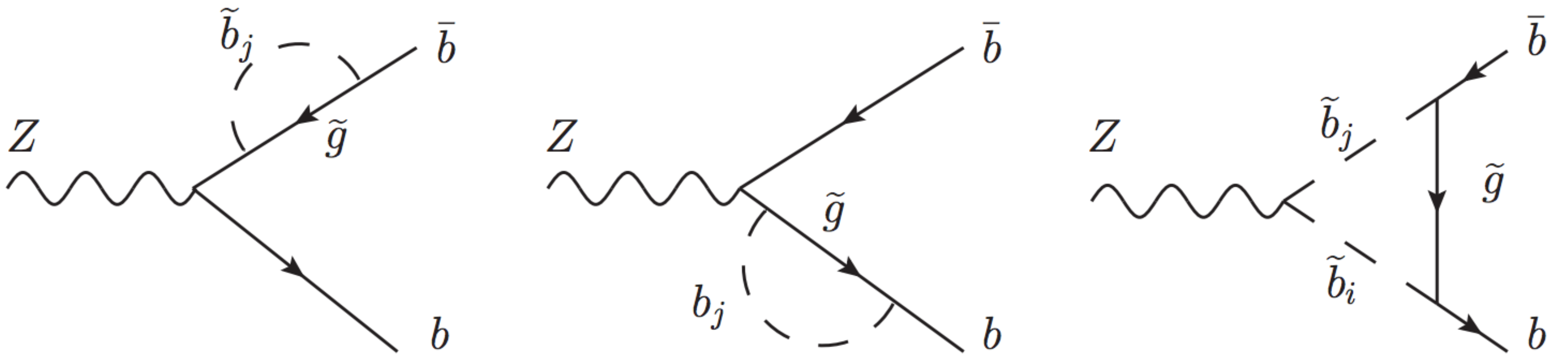


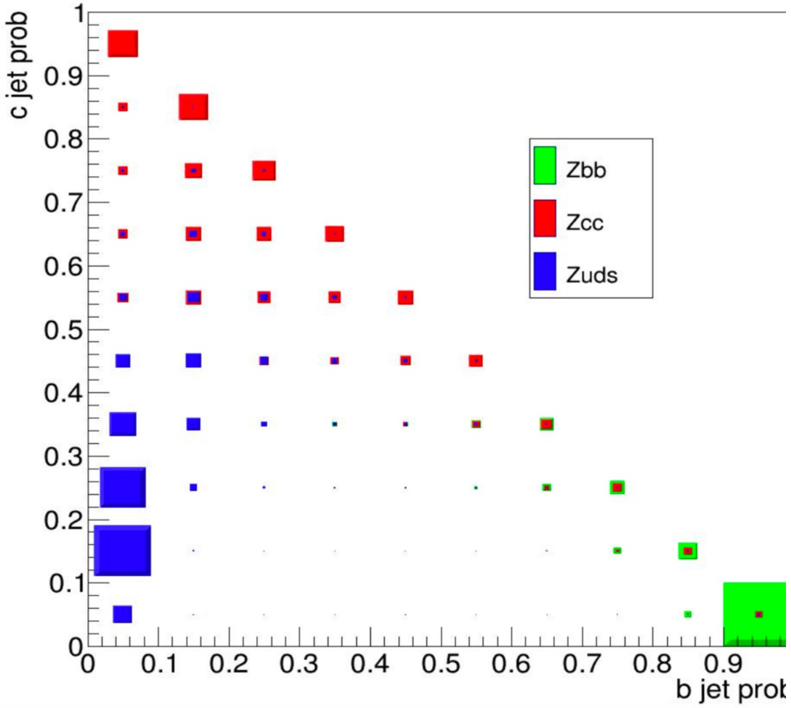
FIG. 1: One-loop Feynman diagrams of gluino correction to $Z \to \bar{b}b$

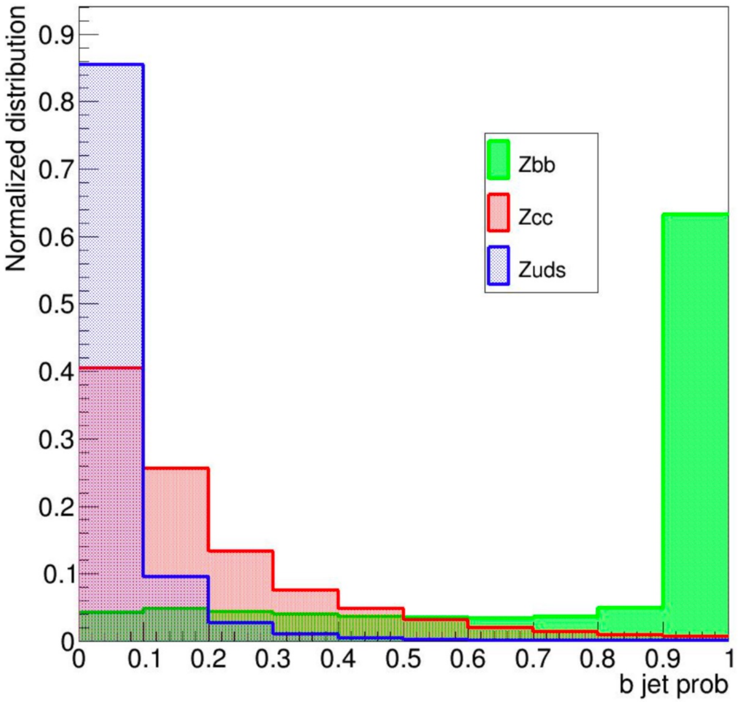
1601.07758

R^b measurement (2)

- Expected to be 20~50 times better than LEP measurements
  - With 95% purity working points, efficiency > 70% in CEPC (~30% for LEP)
  - 1D and 2D template fit for b tagging probability
- A global analysis method is developed to reduce impact from correlations between jet pairs. Method is under validation

Eur. Phys. J. Plus 136, 1 (2021)





Error source	ΔR^b (10^{-5})
Statistics	1
Tracking resolution	1
Charm modeling	3
Gluon spliting	1
Hemisphere correlation	6
Total	7

1

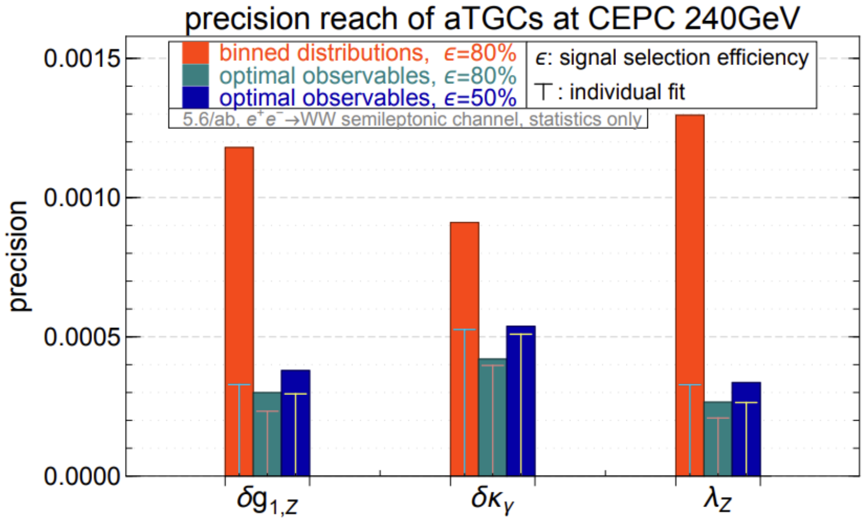
Search for aTGCs with ee→WW

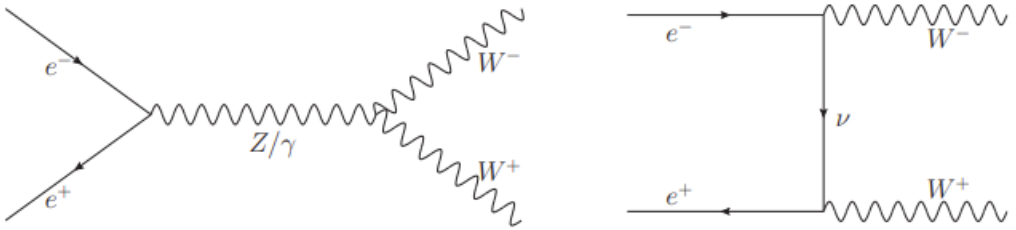
- Measurement of ee→WW process provides important constraints on various new physics contributions
- 7 parameters considered for further EFT studies

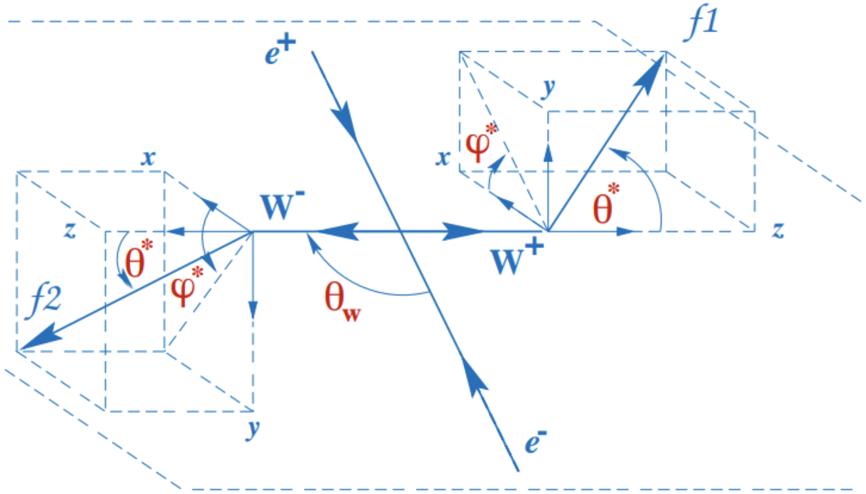
$$\delta g_{1,Z}\,,\quad \delta\kappa_\gamma\,,\quad \lambda_Z\,,\quad \delta g^{ee}_{Z,L}\,,\quad \delta g^{ee}_{Z,R}\,,\quad \delta g^{e\nu}_{W}\,,\quad \delta_{m_W}$$

aTGC couplings　　　gauge couplings modifier

- The optimal observable method explore for this search
  (Z. Phys. C 62 (1994) 397–412)

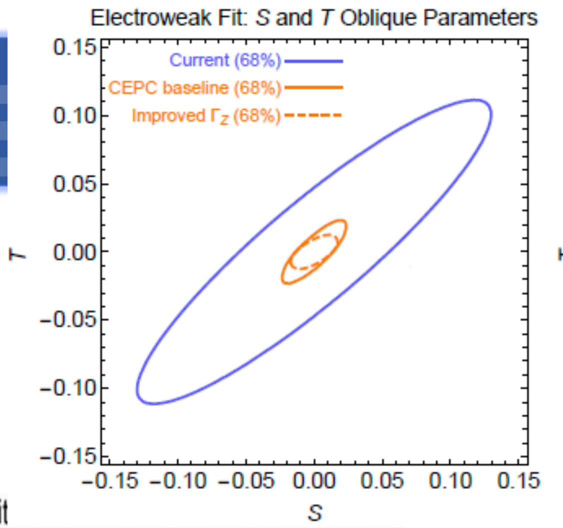




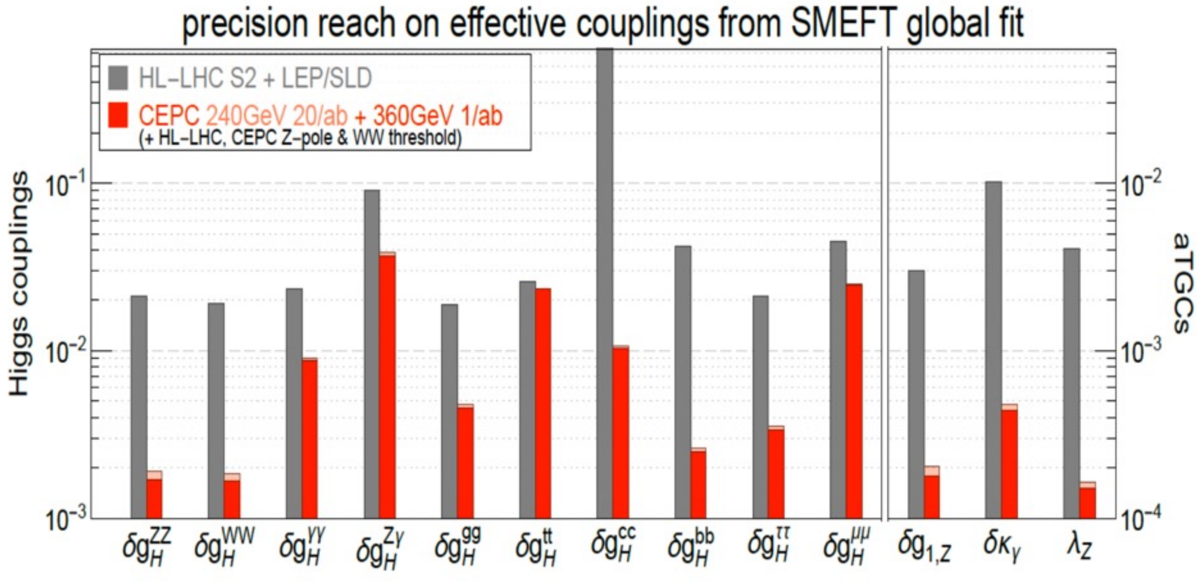


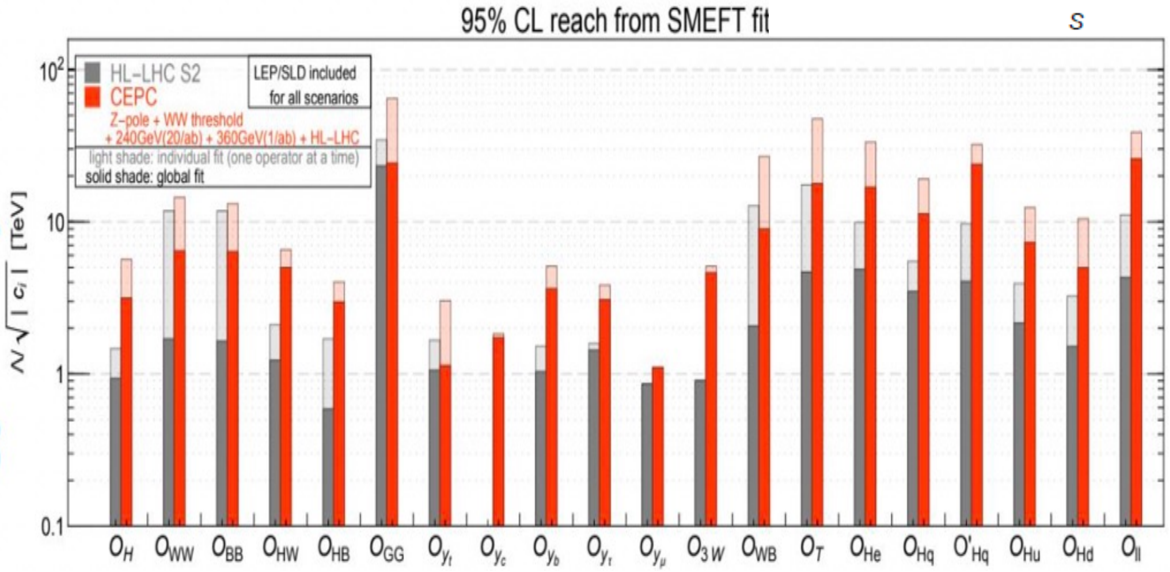
arXiv:1907.04311

Global fit with SMEFT: new physics constrains



$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$





CEPC has potential to reveal new physics @10 TeV by combining Higgs, EWK and top measurements → power of precision

Summary

- Unprecedented luminosity in CEPC provides chance to test the SM EWK sector in a more precise way
  - Expected 1-2 order of magnitude better than current precision
  - Would help to solve puzzles in current measurements
- CEPC Electroweak white paper preparation is on-going
  - Aiming to have a first draft by the end of the year
  - Your input is important, please consider to join us
- For the first 10 years CEPC operation, especially low-lumi Z runs
  - Physics goal needs to be refined.