

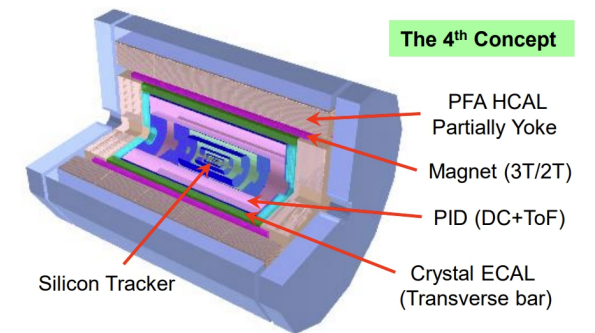
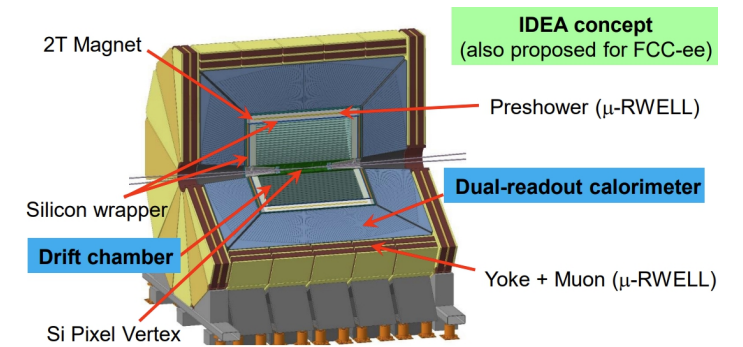
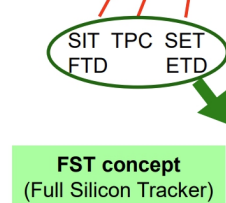
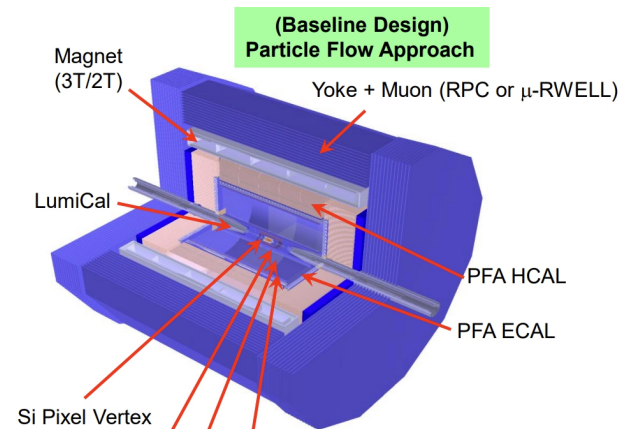
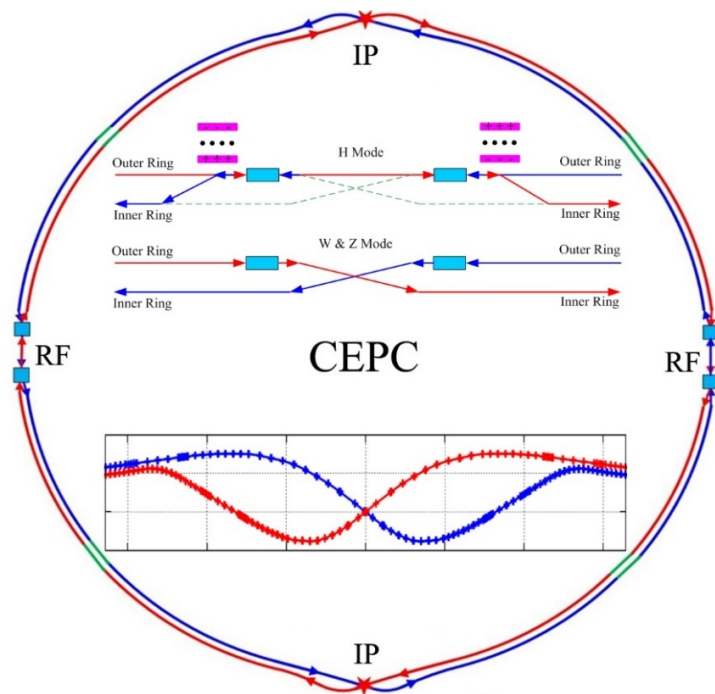
EWK measurements in CEPC

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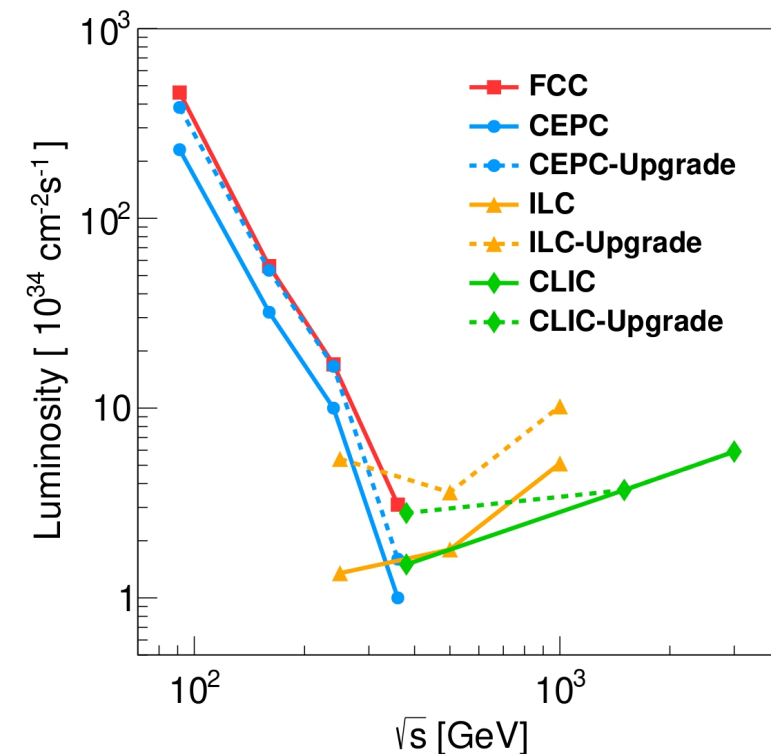
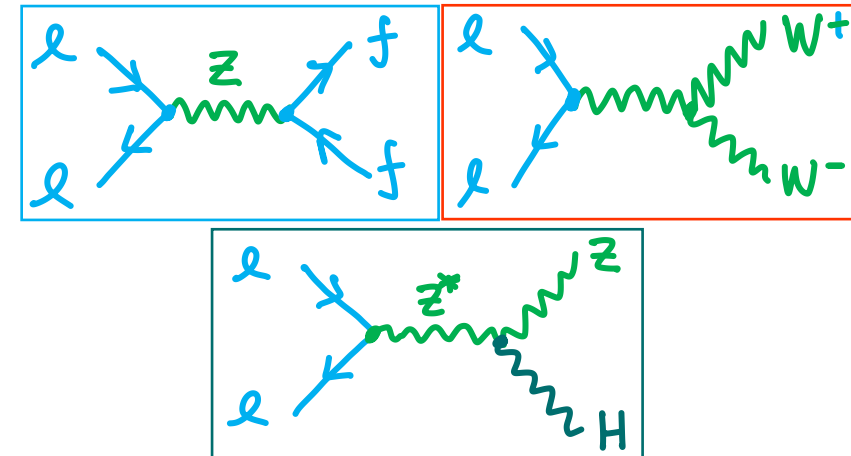
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- CEPC is designed as the double ring accelerator with length ~100km
- To run with collision energy at 240 GeV, above the **ZH** production threshold for ~1M Higgs; at the **Z pole** for ~Tera Z, at the **W^+W^- pair**, and possible **$ttbar$ pair** production threshold.
- Four conceptual designs of detectors



CEPC Operation mode		ZH	Z	W ⁺ W ⁻	ttbar
\sqrt{s} [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	-
CDR (30MW)	L / IP [$\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	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 (50MW)	L / IP [$\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	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

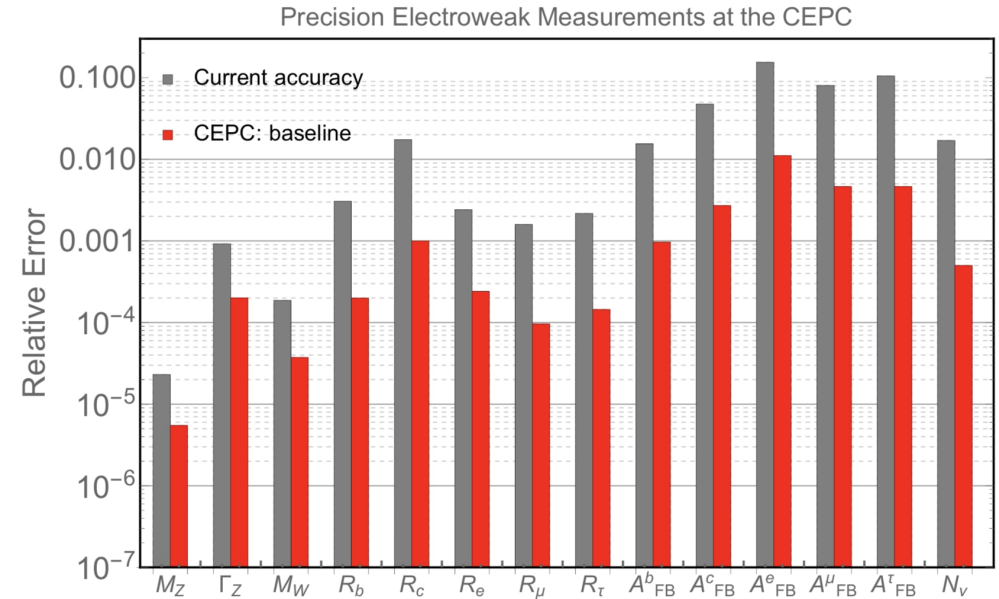
- Updated design with increased luminosity compared to CDR proposal.
 - Comparable with FCC
- New proposed ttbar threshold run



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	tt threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z \rightarrow \tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]	3.5×10^{-5} (3.0×10^{-5})	Z pole ($Z \rightarrow \mu\mu$)	point-to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]	7.0×10^{-5} (1.2×10^{-5})	Z pole ($Z \rightarrow \tau\tau$)	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	luminosity
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

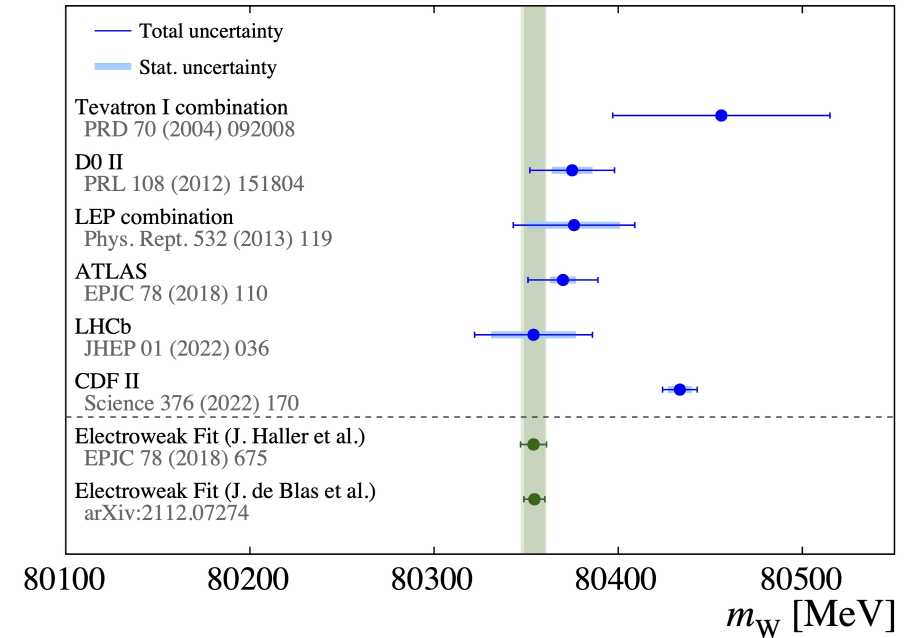
- With increased luminosity, CEPC expect to have 1~2 order of magnitude better than current precision
- Great opportunity to test the consistency of SM EWK sector.

CEPC snowmass white paper: arXiv:2205.08553

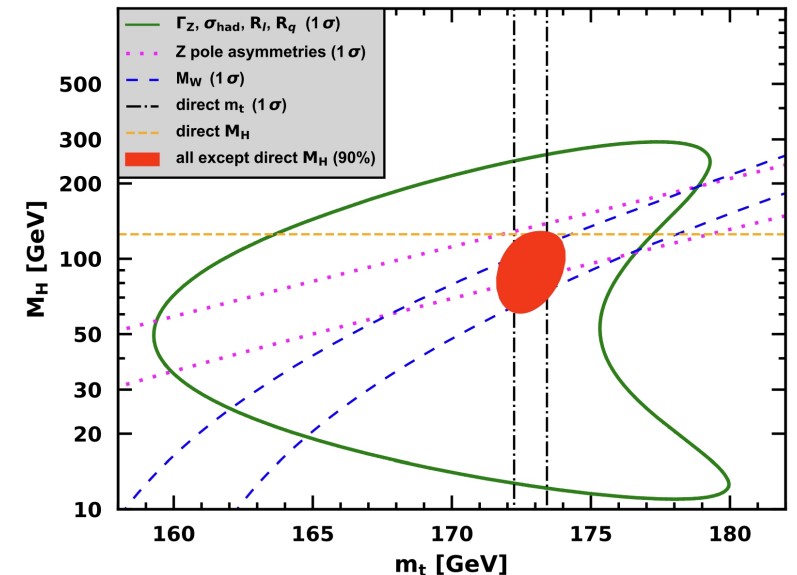
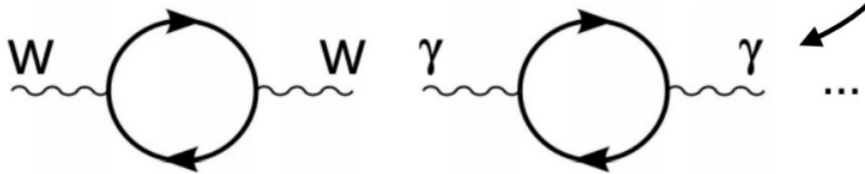


Fundamental constant	$\delta x/x$	measurements
$\alpha = 1/137.035999139$ (31)	1×10^{-10}	e^+g_2
$G_F = 1.1663787(6) \times 10^{-5} \text{ GeV}^{-2}$	1×10^{-6}	μ^+ lifetime
$M_Z = 91.1876 \pm 0.0021 \text{ GeV}$	1×10^{-5}	LEP
$M_W = 80.379 \pm 0.012 \text{ GeV}$	1×10^{-4}	LEP/Tevatron/LHC
$\sin^2\theta_W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

- Key gradient for electroweak sector
- Very important role to test the SM consistency
 - Predictable with given EWK parameters
- Observed 7σ deviation wrt SM predictions
- Difficult to reach to same level of precision at LHC
- Next generation ee collider is essential

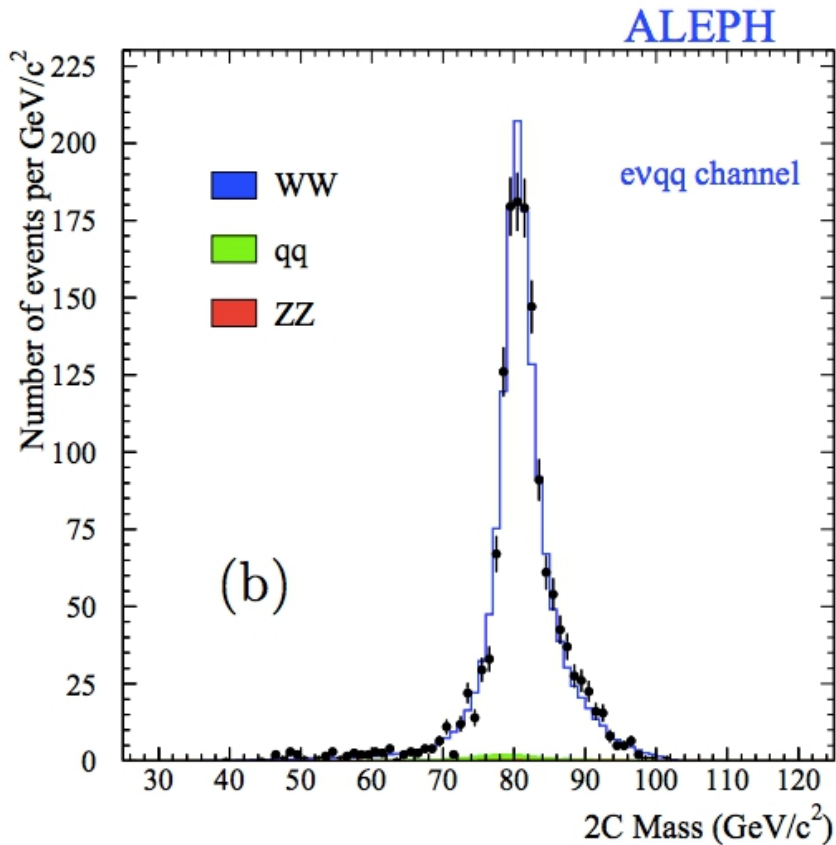


$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi\alpha}{\sqrt{2}G_F} (1 + \Delta)$$

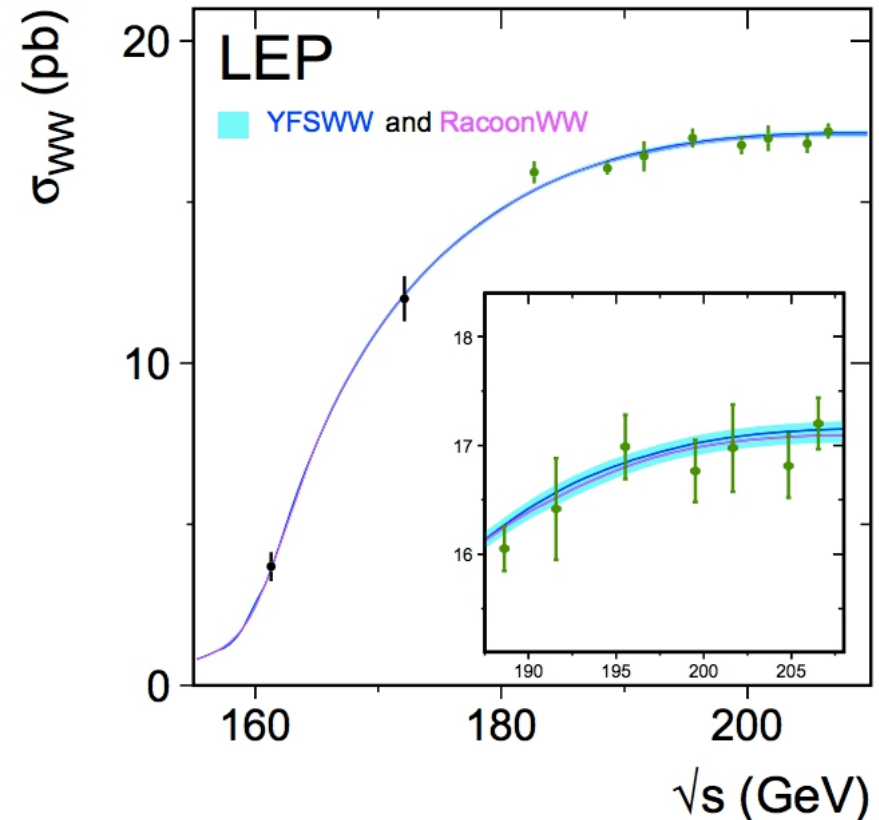


- Two approaches for W boson mass measurement at lepton collider (from LEP)

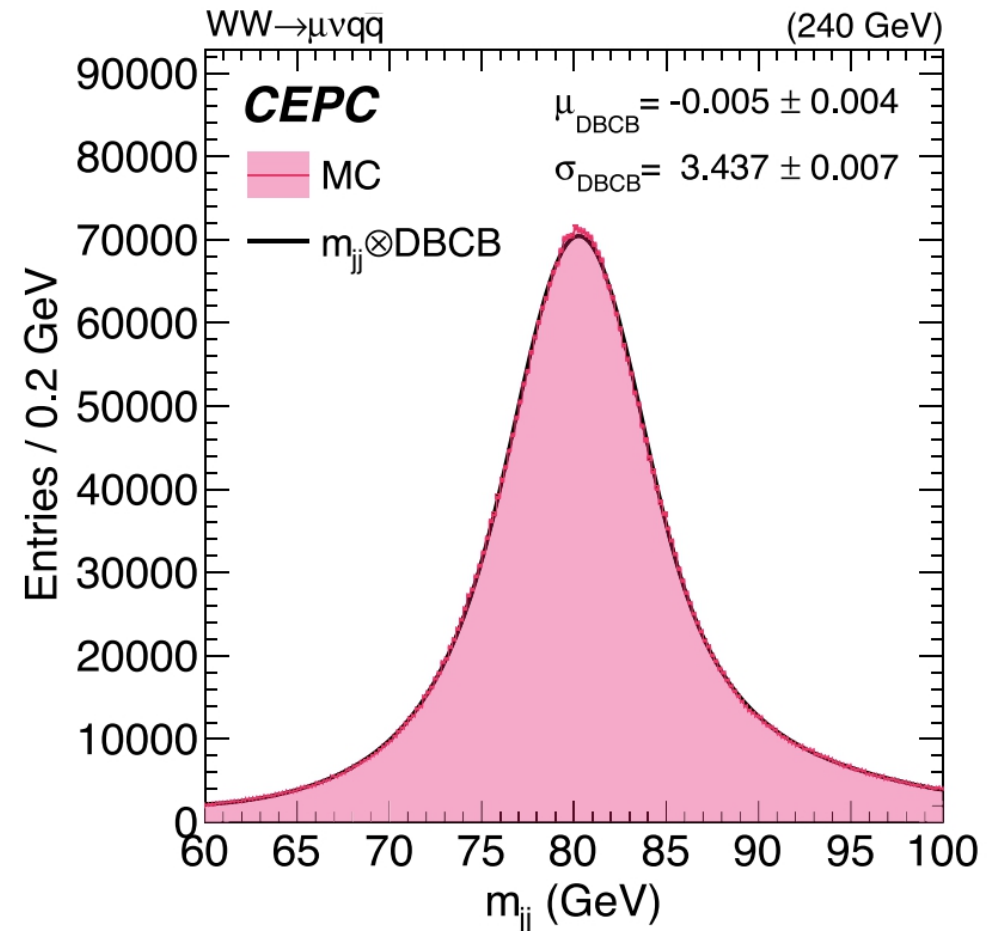
Direct measurement
 Performed in ZH runs
 Precision 2~3 MeV



Indirect measurement
 Perform WW threshold scan runs (157~172 GeV)
 Precision at 1 MeV level



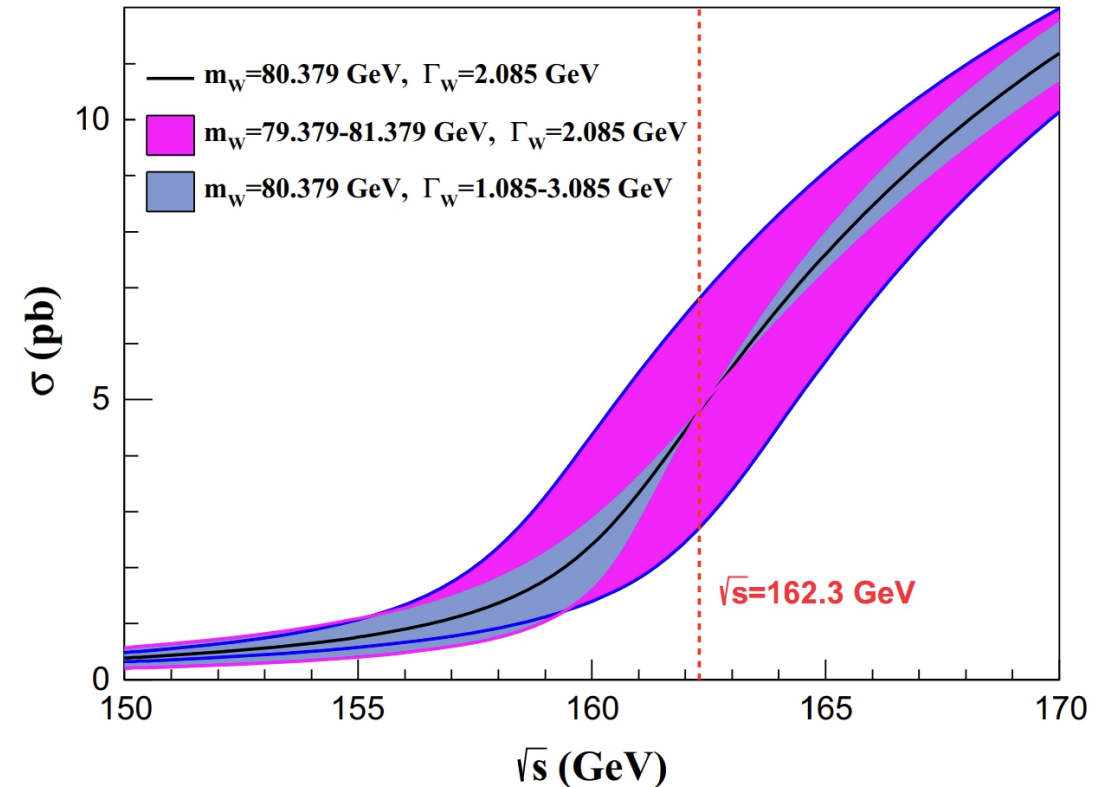
- Perform measurement in ZH run
- Expected 2-3 MeV uncertainty on W boson mass using two $lvqq$ process at 240 GeV
- About <10 MeV achieved with only $\mu\nu qq$ event from 5 ab^{-1} from [JINST 16 P07037](#)
- Further studies ongoing



JINST 16 P07037

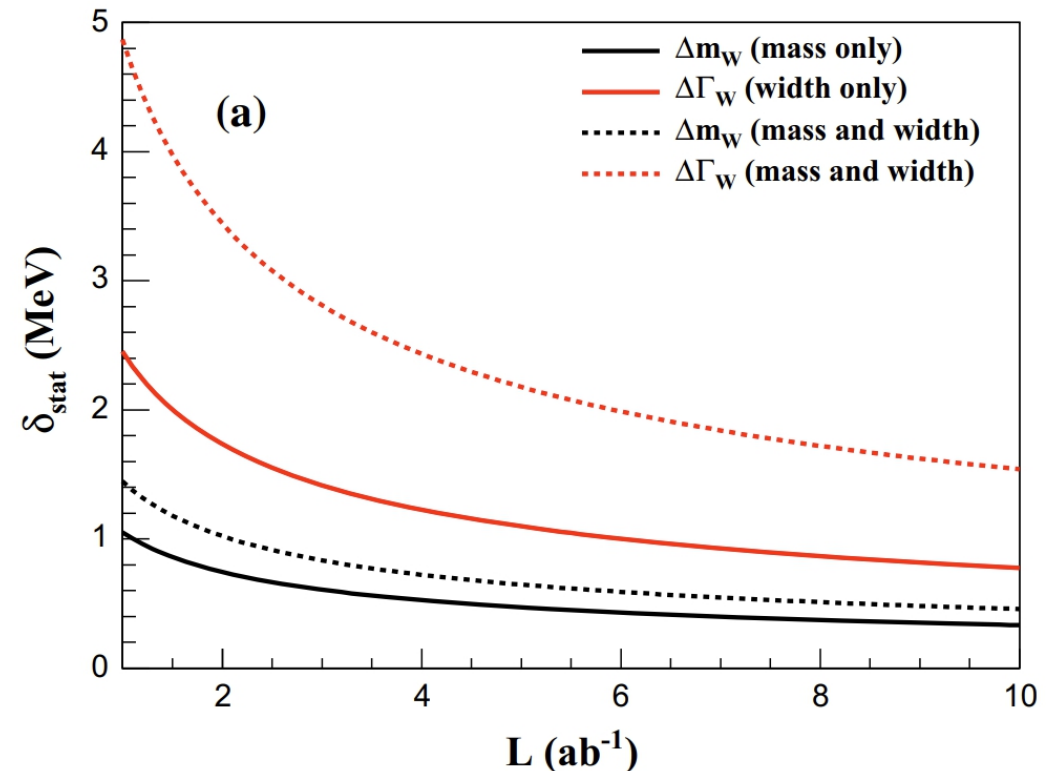
- Joint effort of CEPC/FCC-ee to optimize WW threshold scan data taking strategy
- Assuming 1 year data taking with 2.6 ab^{-1} luminosity (update design propose x2)
- Four points proposed
 - 157.5 GeV, 161.5 GeV and 162.5 GeV (W mass, W width measurement)
 - 172.0 GeV ($\alpha_{\text{QCD}}(m_W)$ measurement, $\text{Br}(W \rightarrow \text{had})$, CKM $|V_{\text{CS}}|$)

E_{cm} (GeV)	Luminosity (ab^{-1})	Cross section (pb)	Number of WW pairs (M)
157.5	0.5	1.25	0.6
161.2	0.2	3.89	0.8
162.3	1.3	5.02	6.5
172.0	0.5	12.2	6.1



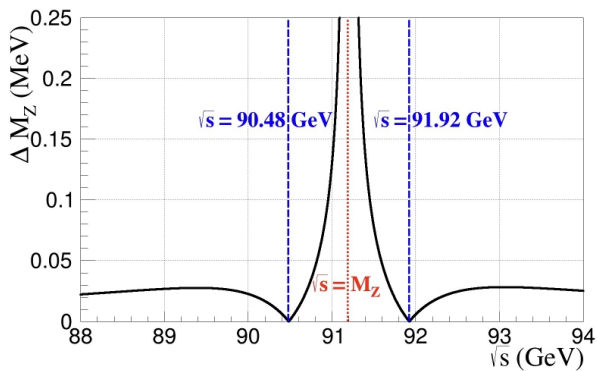
- Joint effort of CEPC/FCC-ee to optimize WW threshold scan data taking strategy
- Assuming 1 year data taking with 2.6 ab^{-1} luminosity (updated design propose x2)
- Expected to reach 1 MeV precision for m_W
- Could be further improved with updated calibration method for beam energy
 - With inverse-compton scattering for beam energy calibration, could further reduce systematic uncertainty (Nucl. Instrum. Meth. A 1026 (2022) 166216, Rev. Sci. Instrum. 91 no. 3, (2020) 033109)

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



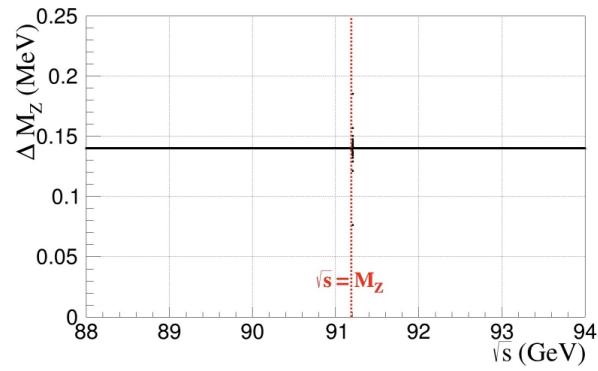
- Tera-Z could help improve m_Z precision by one order of magnitude
- Systematic uncertainty dominant
- Improved energy calibration would further reduce uncertainties

Parameter	δ_{stat}	δ_{total}
M_Z (KeV)	7	66
Γ_Z (KeV)	13	126
σ_{had}^0 (pb)	0.09	1.73



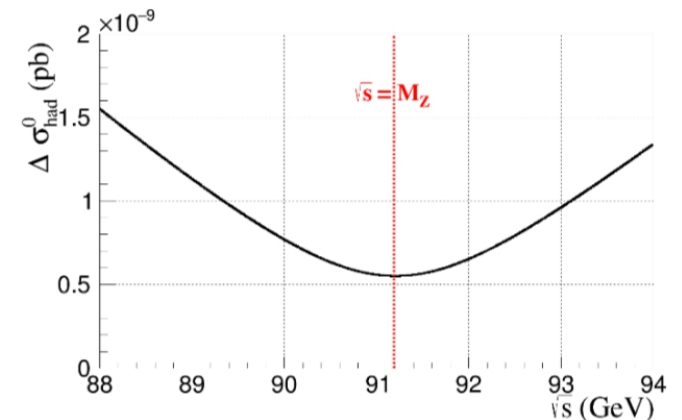
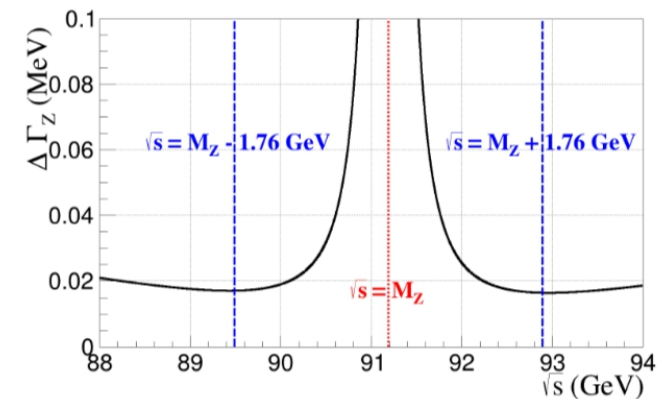
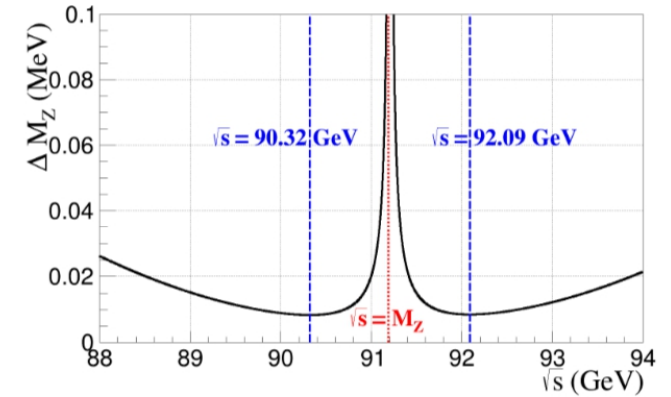
$\Delta E = 0.14$ MeV

Uncertainty of **energy scale**



$\Delta\sigma_E = 0.57$ MeV

Uncertainty of **energy spread**

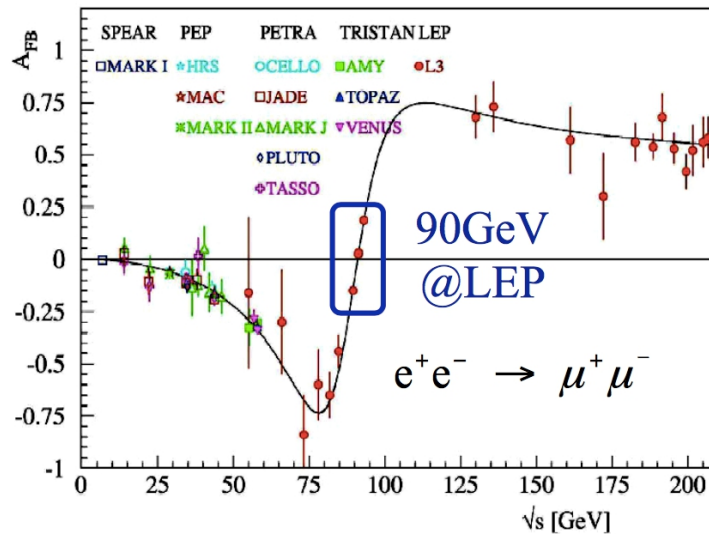


- Key parameter in electroweak sector
 - $\sim 3\sigma$ tension between LEP and SLC measurements
 - Experimental syst. much larger than theory syst.

	$\text{Sin}^2\theta_W$
LEP	0.23221 ± 0.00029
SLC	0.23098 ± 0.00026
Theory	0.23121 ± 0.00004

- Extract from A_{FB} measurement

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



LEP + SLD
LEP + SLD: $A_{FB}^{0,b}$
SLD: A_l

CDF $ee+\mu\mu$ 9.4 fb^{-1}

D0 $ee+\mu\mu$ 9.7 fb^{-1}

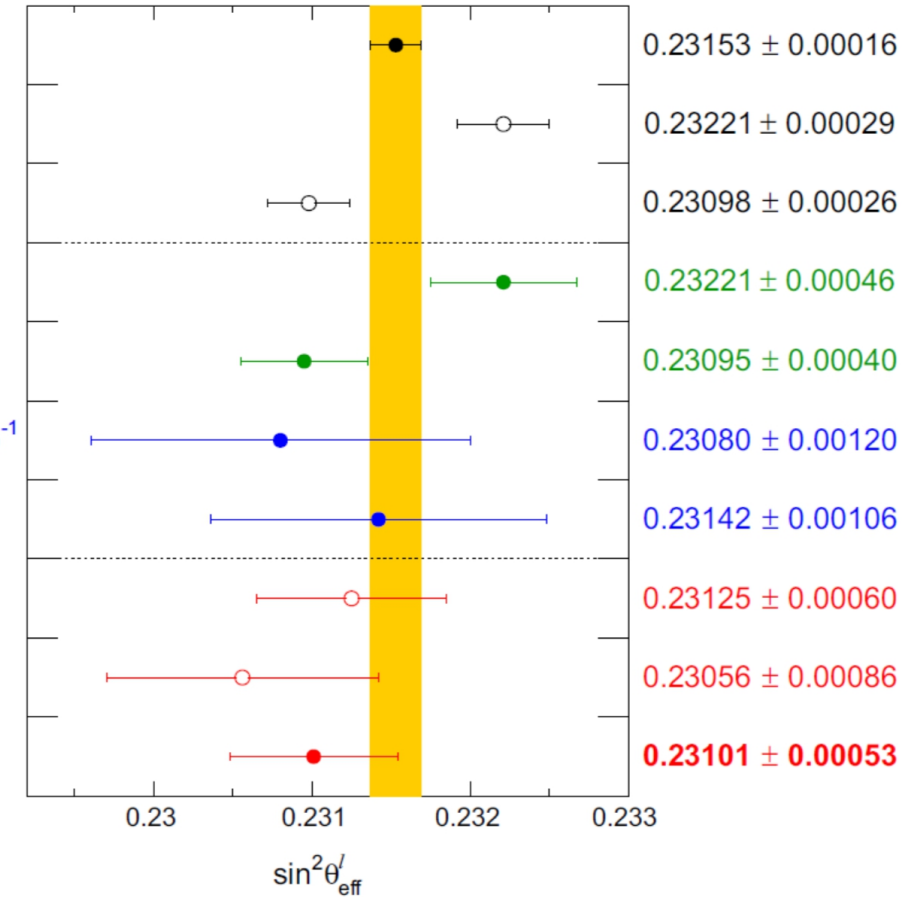
ATLAS $ee+\mu\mu$ 4.8 fb^{-1}

LHCb $\mu\mu$ 3 fb^{-1}

CMS $\mu\mu$ 18.8 fb^{-1}

CMS ee 19.6 fb^{-1}

CMS $ee+\mu\mu$



- Stat. Unc. dominated in LEP and Tevatron measurements
- Syst. Unc. (PDF) will become dominated systematics for LHC measurements
- CEPC has potential to improve $\sin^2\theta_W$ by **two order** of magnitudes
- Theory unc. is about 4×10^{-5} level with two loop calculation

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
LHC 8TeV	36	18	35	53
LHC 13TeV By Projection	~15	> 20	> 25	~ 20
CEPC By LEP Projection	~0.2	~0.2	4 (Today)	~0.3

- 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 $Z \rightarrow b\bar{b}$ vertex
 - Through gluino and chargino loop ...

$$\frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma(Z \rightarrow \text{had})}$$

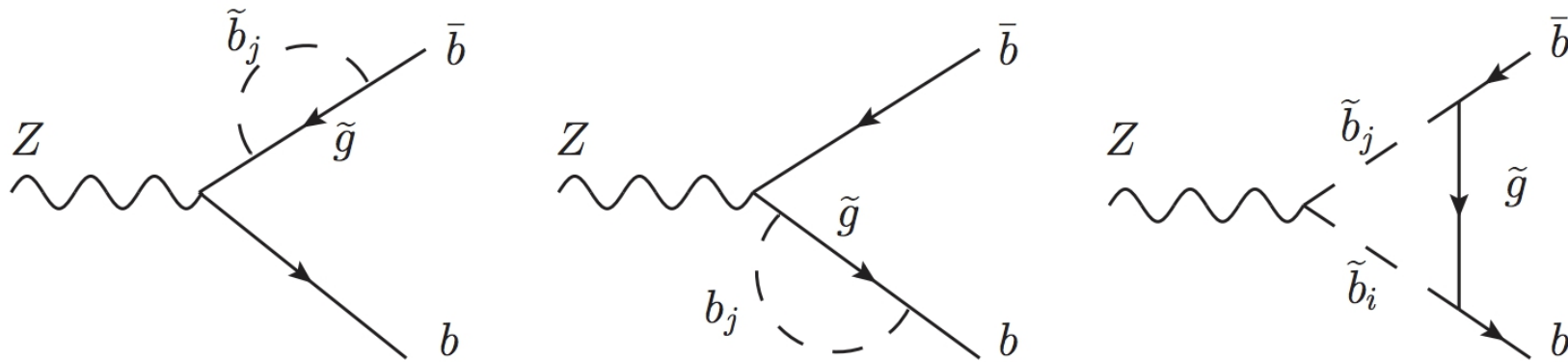
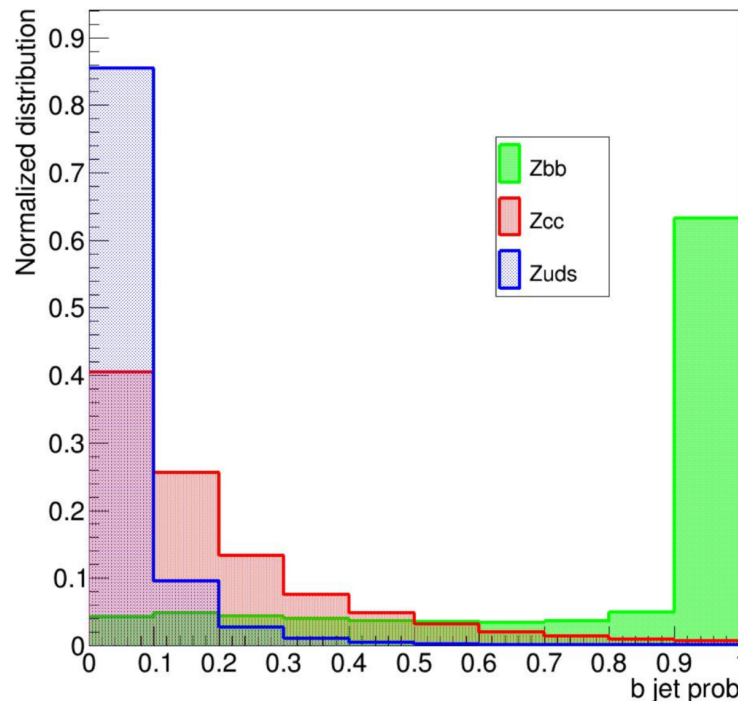
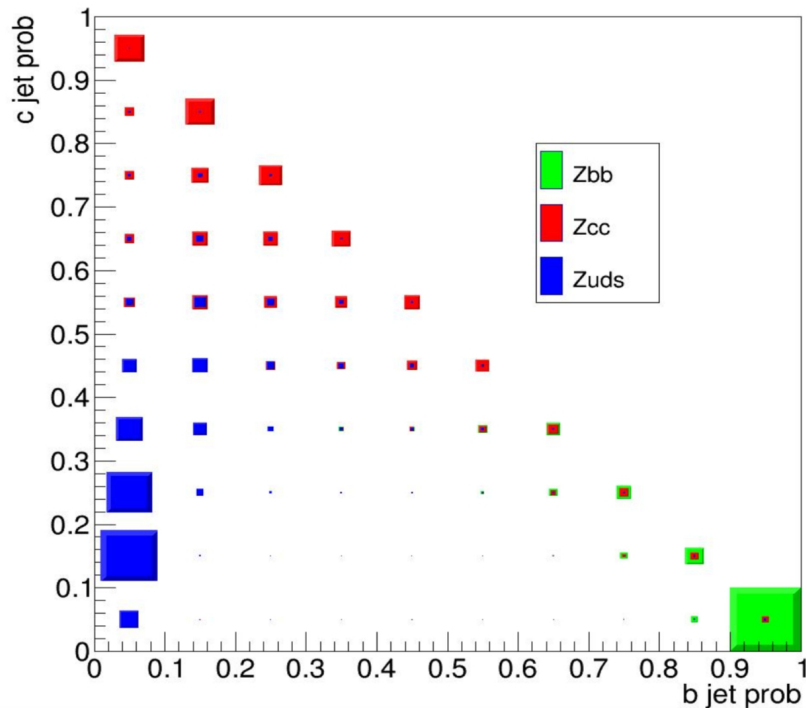


FIG. 1: One-loop Feynman diagrams of gluino correction to $Z \rightarrow \bar{b}b$

- 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



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

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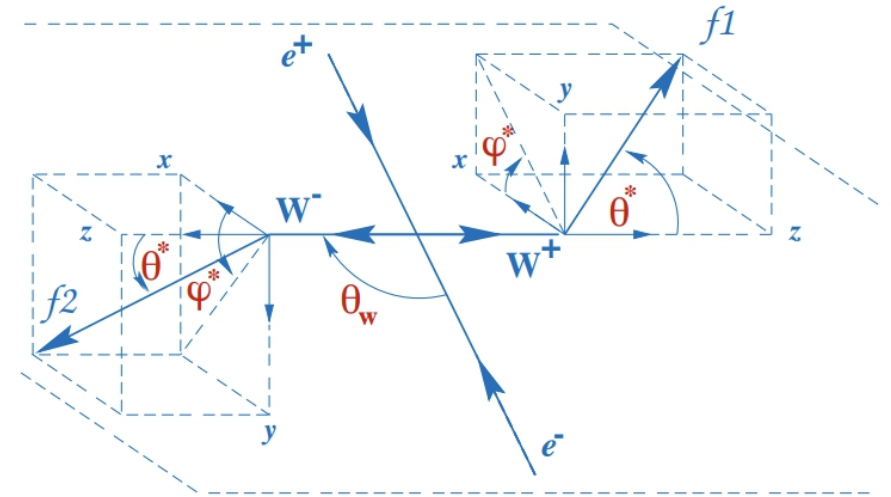
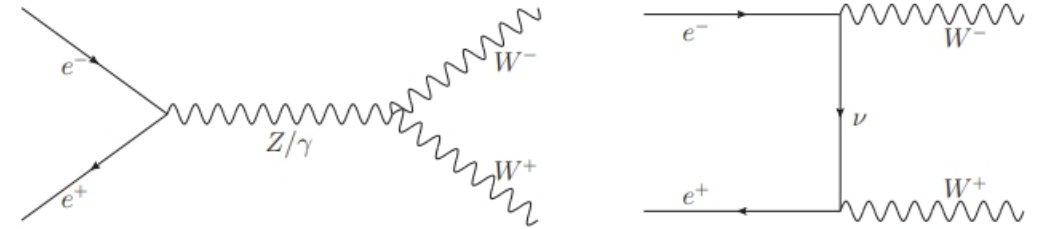
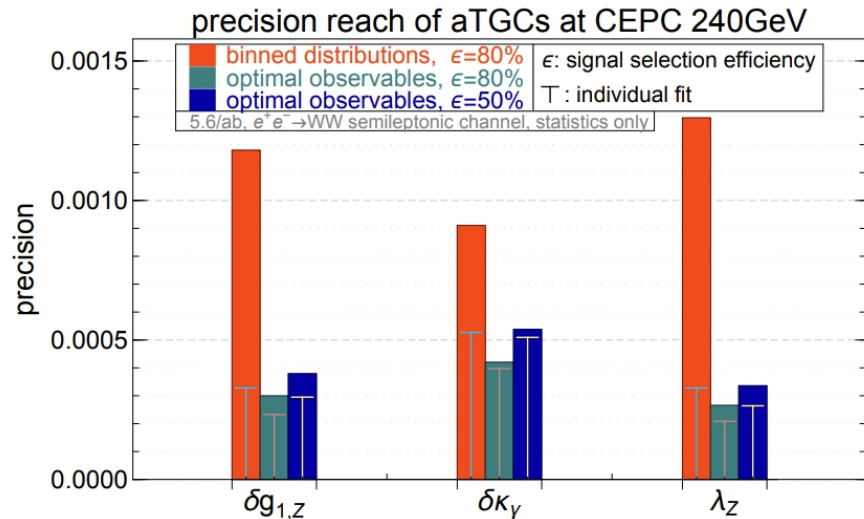
- Measurement of $ee \rightarrow WW$ process provides important constraints on various new physics contributions
- 7 parameters considered for further EFT studies

$$\delta g_{1,Z}, \delta \kappa_\gamma, \lambda_Z, \delta g_{Z,L}^{ee}, \delta g_{Z,R}^{ee}, \delta g_W^{e\nu}, \delta m_W$$

aTGC couplings

gauge couplings modifier

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

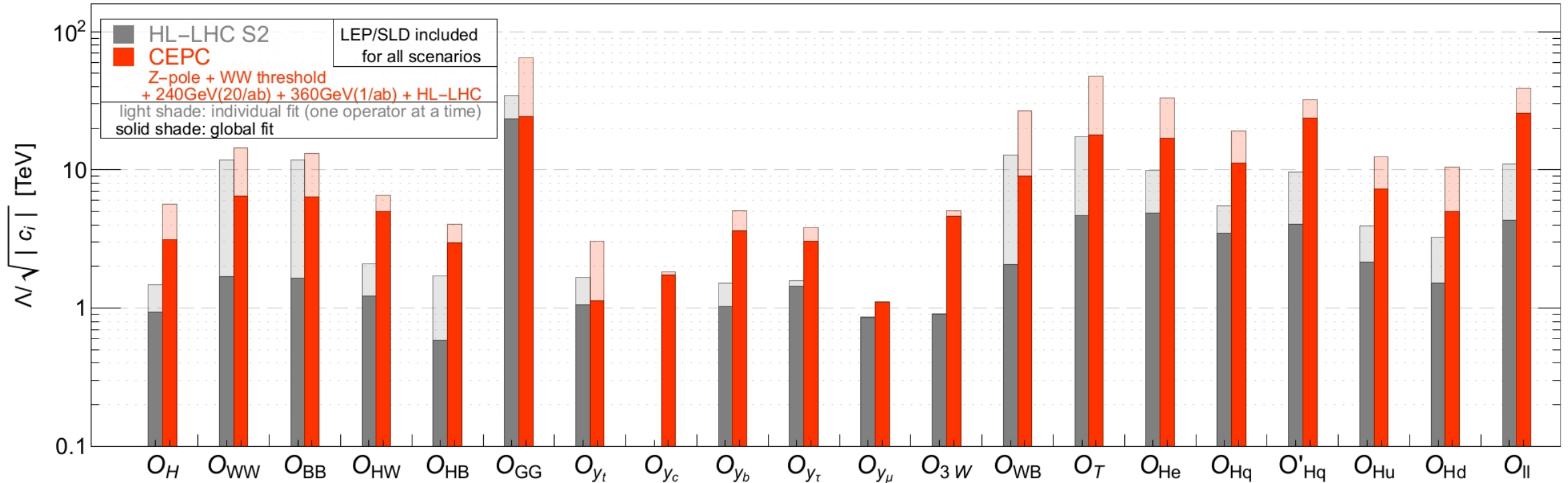


arXiv:1907.04311

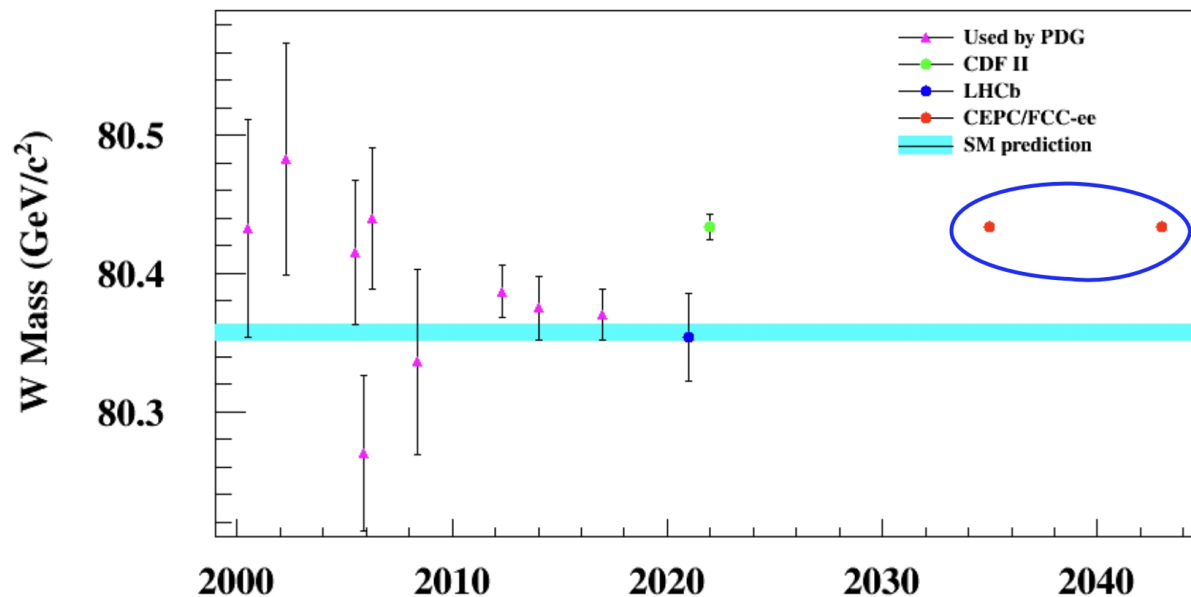
- Combined measurement from EWK and Higgs properties to constrain higher dimension operators in SMEFT

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

95% CL reach from SMEFT fit



- CEPC is designed to have 100km double ring accelerator
 - Multiple collision energy (from Z pole to $t\bar{t}$ threshold) proposed for various physics motivations
- Unprecedented luminosity 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



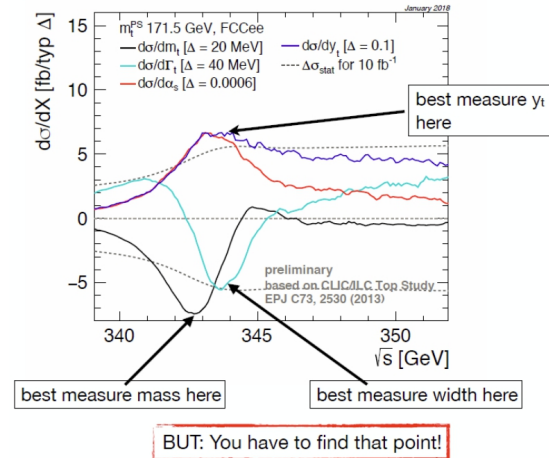
Backup



Motivation

- $t\bar{t}$ threshold scan is made against \sqrt{s} and cross section, which is direct observable.
- It brings measurements of such parameters:
 - Top mass
 - Top width
 - Top Yukawa coupling
 - α_s (strong coupling)

Eur. Phys. J. C (2013) 73:2530



Expected precision

- With the CEPC setup, limited to the total luminosity of 100 fb^{-1} , top quark mass, width and α_s are measured individually at their optimal energy points.

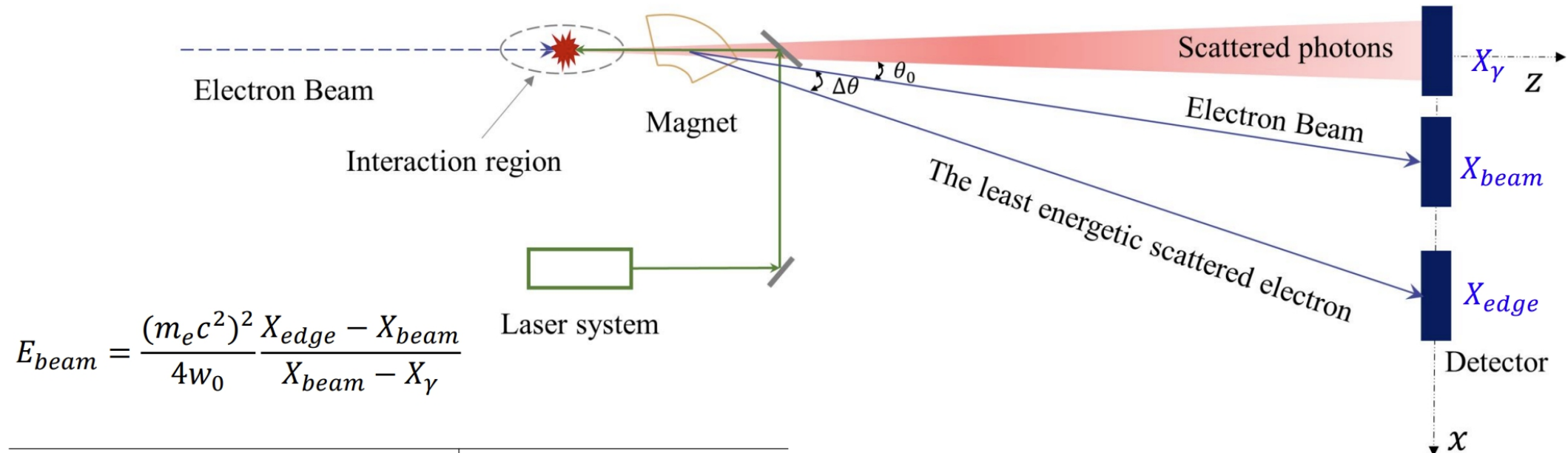
Parameter of interest	Statistical uncertainty
m_t	9.06 MeV
Γ_t	25.86 MeV
α_s	0.000394

CLIC results:

POI	Stat. uncertainty
m_t	34 MeV
Γ_t	
α_s	0.0009

Laser-Compton Method of calibration of beam energy

- **Method:** Compton back-scattering combining a bending magnet



Electron beam		Nd:YAG Laser system	
Energy (GeV)	120	λ (nm)	532
N_e	15×10^{10}	Energy(J)	0.1
Collision angle α	~ 2.35 mrad		
Compton scattering cross section	202 mb		

- Compton back-scattering method used in BEPC by measuring the energy of scattered photons with accuracy is 2×10^{-5} .

<https://doi.org/10.1016/j.nima.2011.08.050>

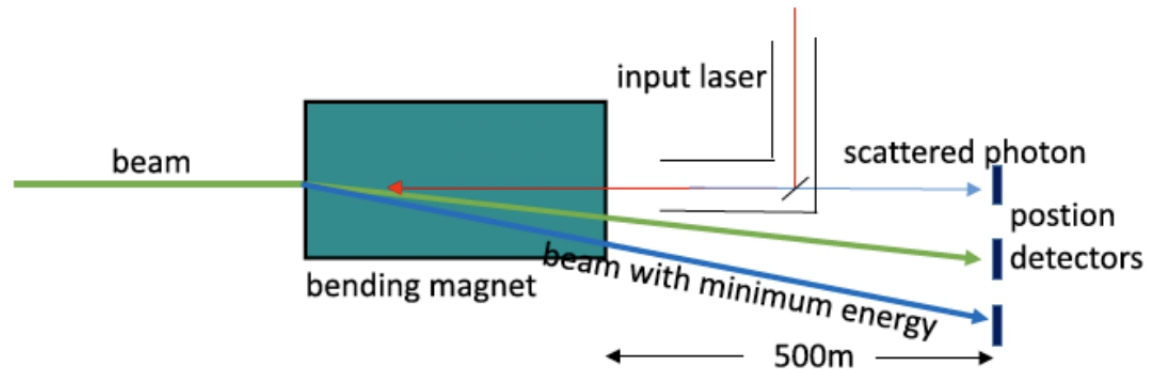
- The technique is “non-destructive”: $\sim 10^6$ Compton scattered particles in one collision.

Comparison of the key parameters for different models in CEPC

	Higgs mode	Z mode	WW scan	$t\bar{t}$ scan
E_{beam}/GeV	120	45	80	175
X_{edge}/m	6.16352	9.29686	7.10343	5.57276
X_{beam}/m	1.87935	5.00178	2.81903	1.28868
$\delta X_{edge}/m$		2.6×10^{-5}		
$\delta X_{beam}/m$		6×10^{-8}		
$\delta E_{beam}/MeV$	1.0	0.3	0.6	1.8

- The statistical uncertainties of beam energy are not included here

Laser Compton backscattering

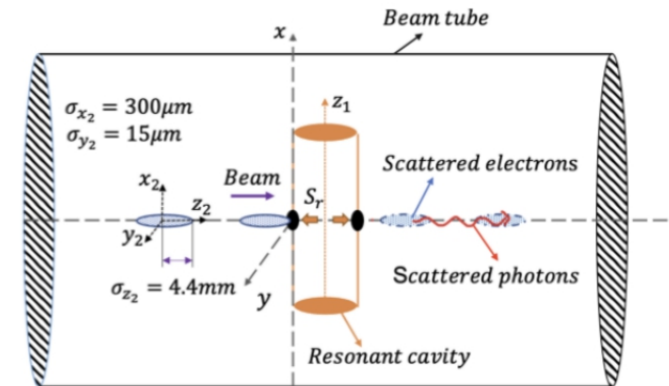


With some proper corrections, the beam energy uncertainty of the Higgs mode is around **2 MeV**.

Independent extraction device.

Separately detect the positions of scattered electrons, scattered photons and unscattered beams.

Microwave-beam Compton backscattering



Simple model of cavity and beam

Use synchrotron radiation lead wire.

Detection of the maximum energy of scattered photons by a HPGe detector.

If the beam energy is calibrated within 10MeV, it will be interesting and worth doing.