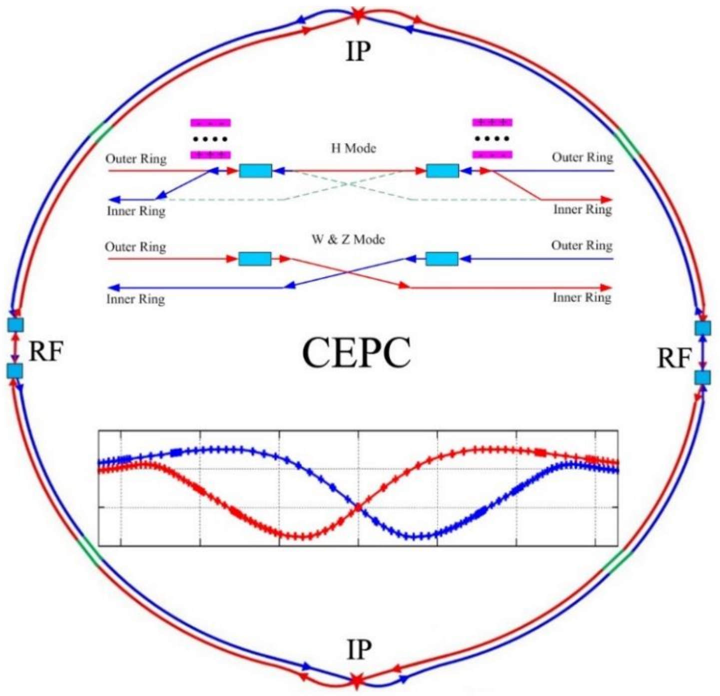
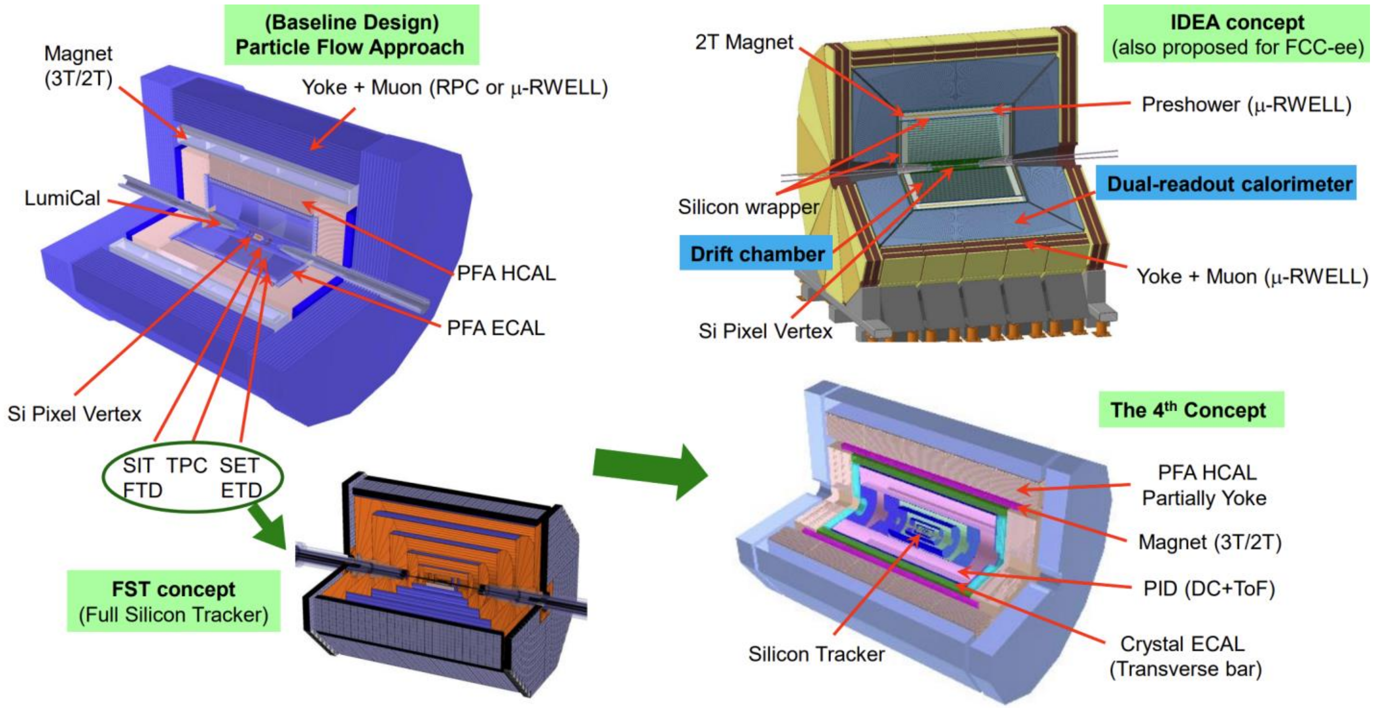
EWK measurements in CEPC

Bo Liu & Zhijun Liang
IHEP, CAS

Introduce to CEPC

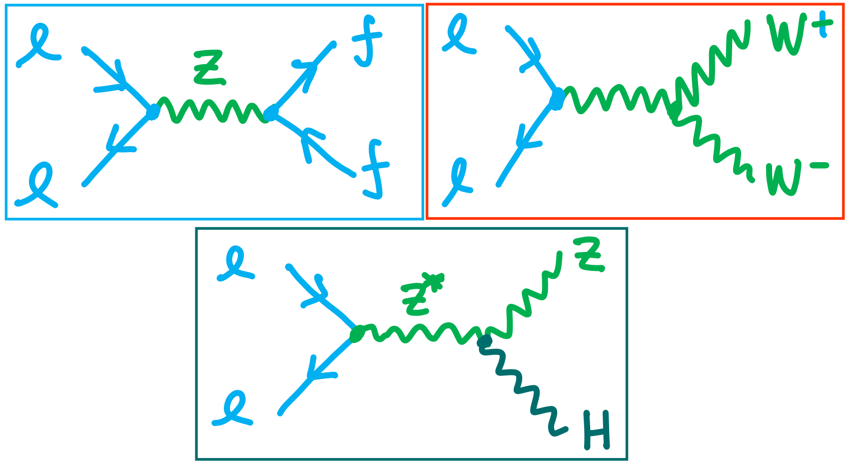
- CEPC is designed as the double ring accelator with length ~100km
- To run with collision energy at 240 GeV, above the ZH production threshold for ~1M Higgs; at the Z pole for ~Tera Z, at the W^+W^- pair, and possible ttbar pair production threshold.
- Four conceptual designes of detectors

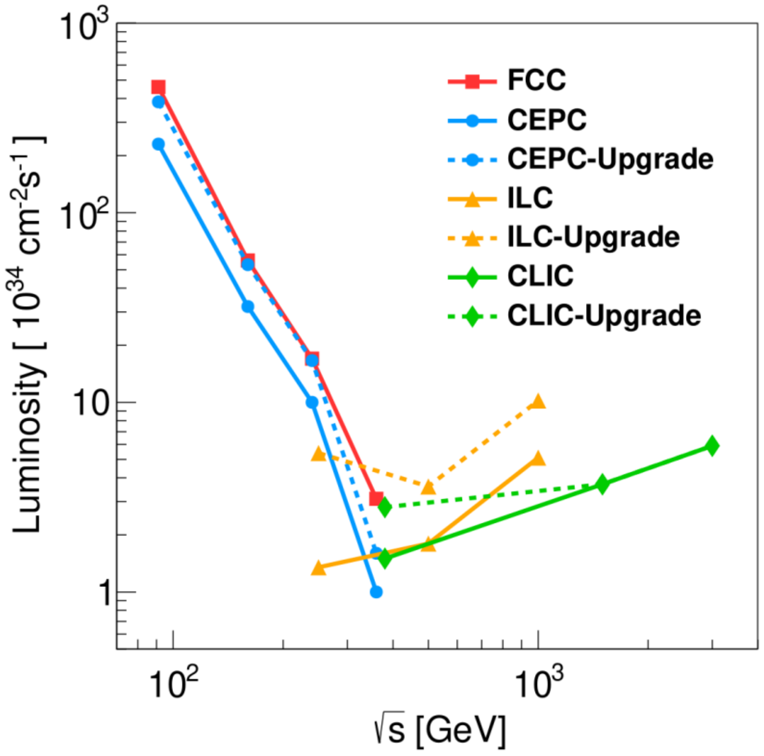




The CEPC program

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 [$\times 10^{34}$ $cm^{-2}s^{-1}$]	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 (50MW)	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

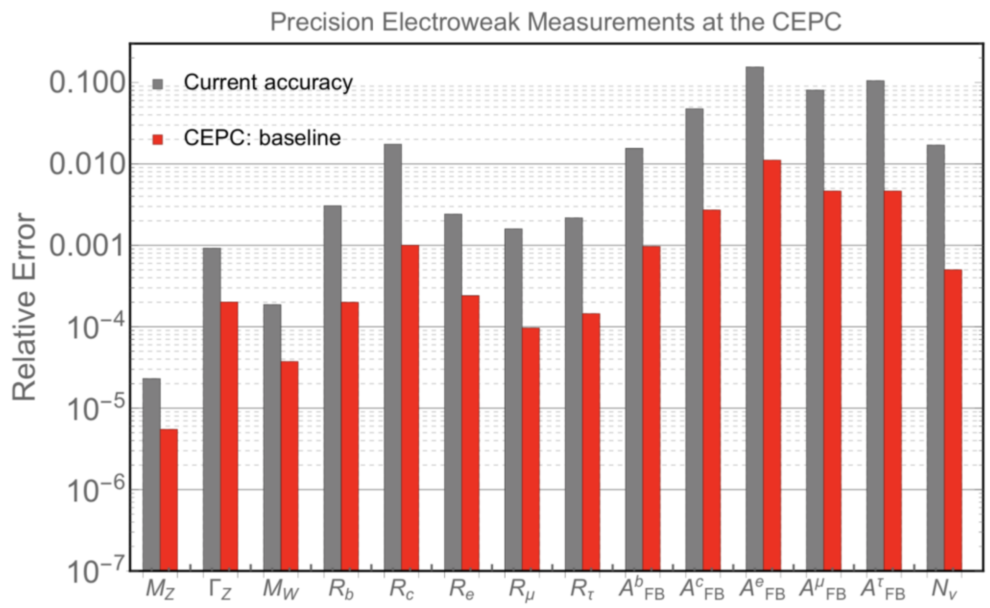




- Updated design with increased luminosity compared to CDR proposal.
  - Comparable with FCC
- New proposed ttbar threshold run

Potential of electroweak measurement in CEPC

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



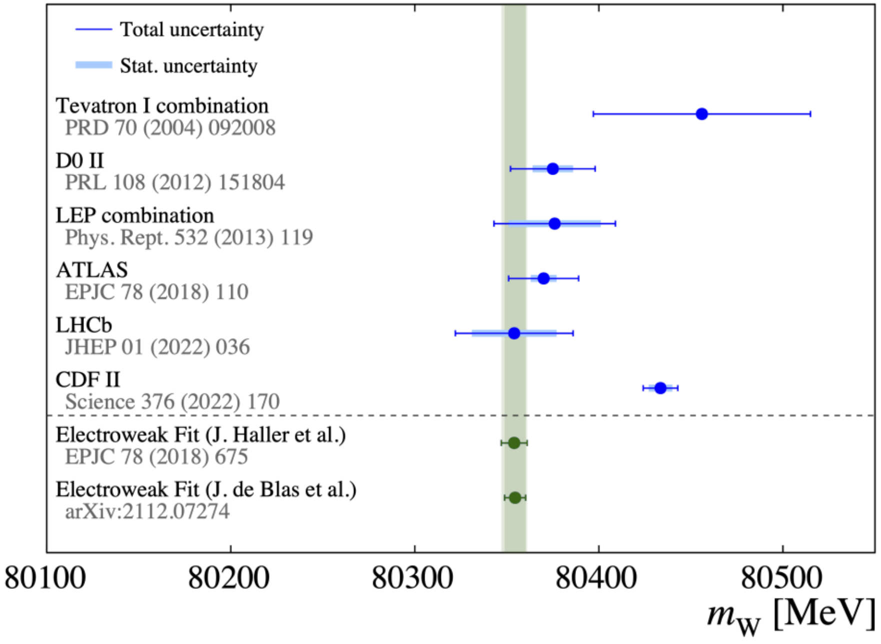
Fundamental constant	δx/x	measurements
α = 1/137.035999139 (31)	1×10^{-10}	$e^\pm$ g_2
G_F = 1.1663787 (6) × 10^{-5} GeV^{-2}	1×10^{-6}	$\mu^\pm$ lifetime
M_Z = 91.1876 ± 0.0021 GeV	1×10^{-5}	LEP
M_W = 80.379 ± 0.012 GeV	1×10^{-4}	LEP/Tevatron/LHC
$\sin^2\theta_W$ = 0.23152 ± 0.00014	6×10^{-4}	LEP/SLD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

- 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.

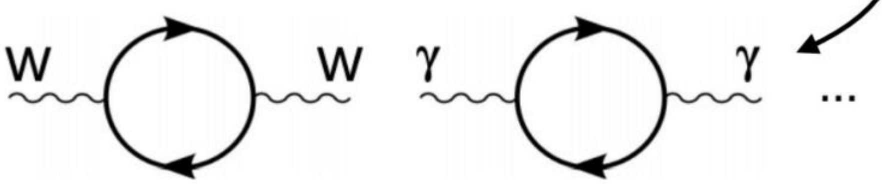
CEPC snowmass white paper: arXiv:2205.08553

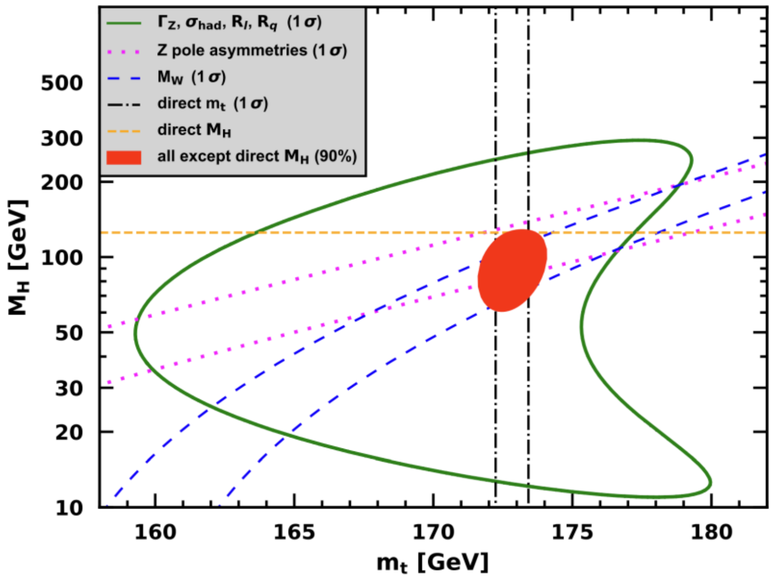
W boson mass measurement

- Key gradient for electrweak 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



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

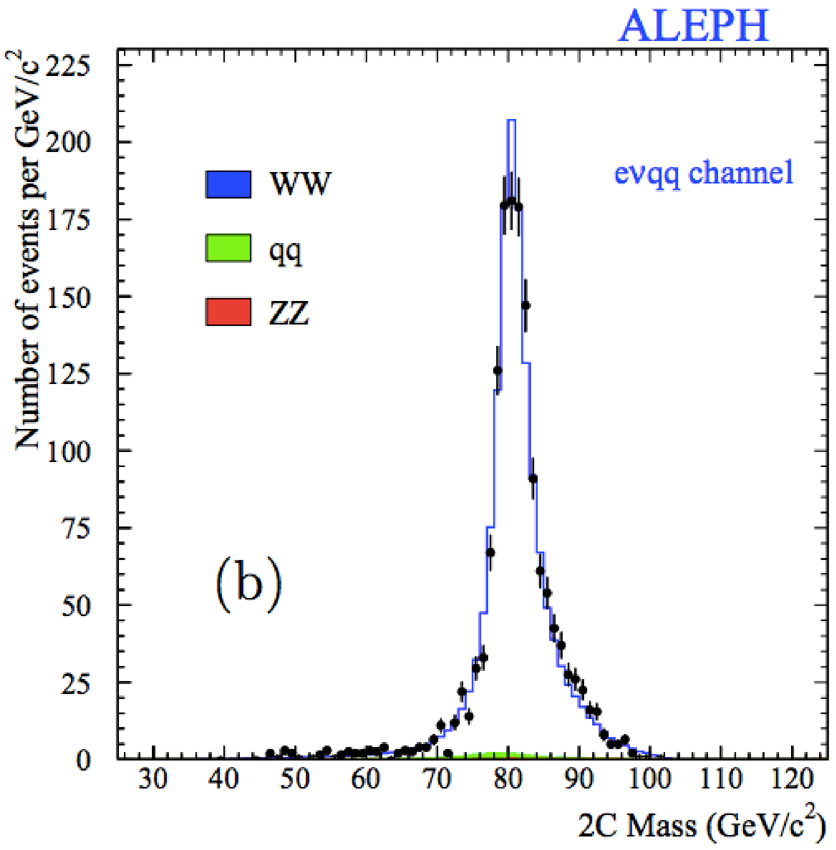




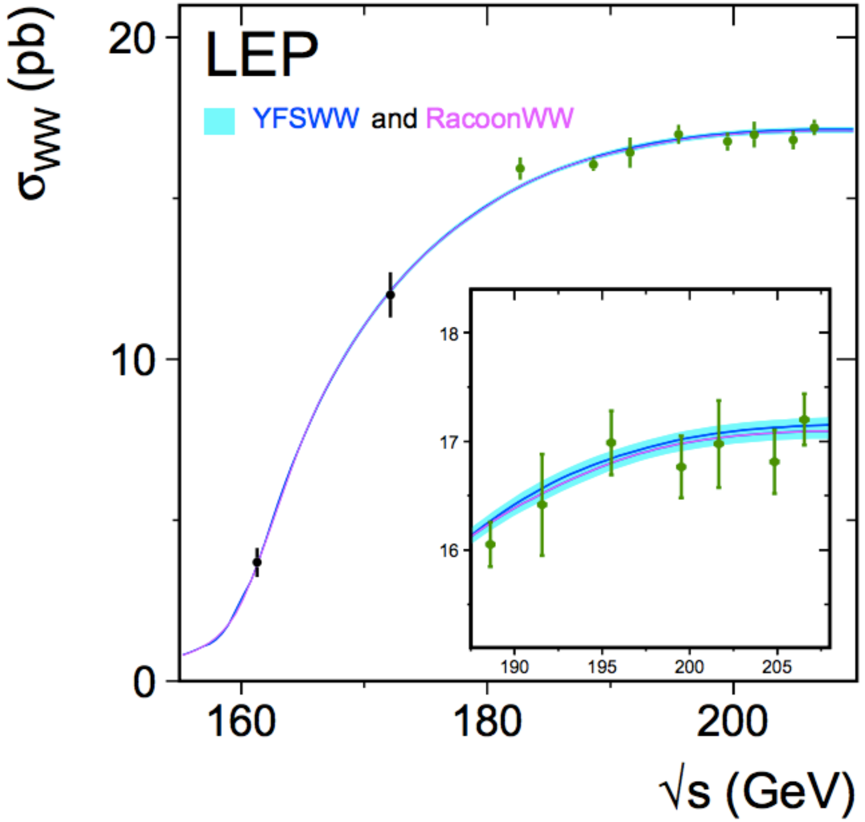
W boson mass measurement

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

Direct measurement
Performed in ZH runs
Precision 2~3 MeV

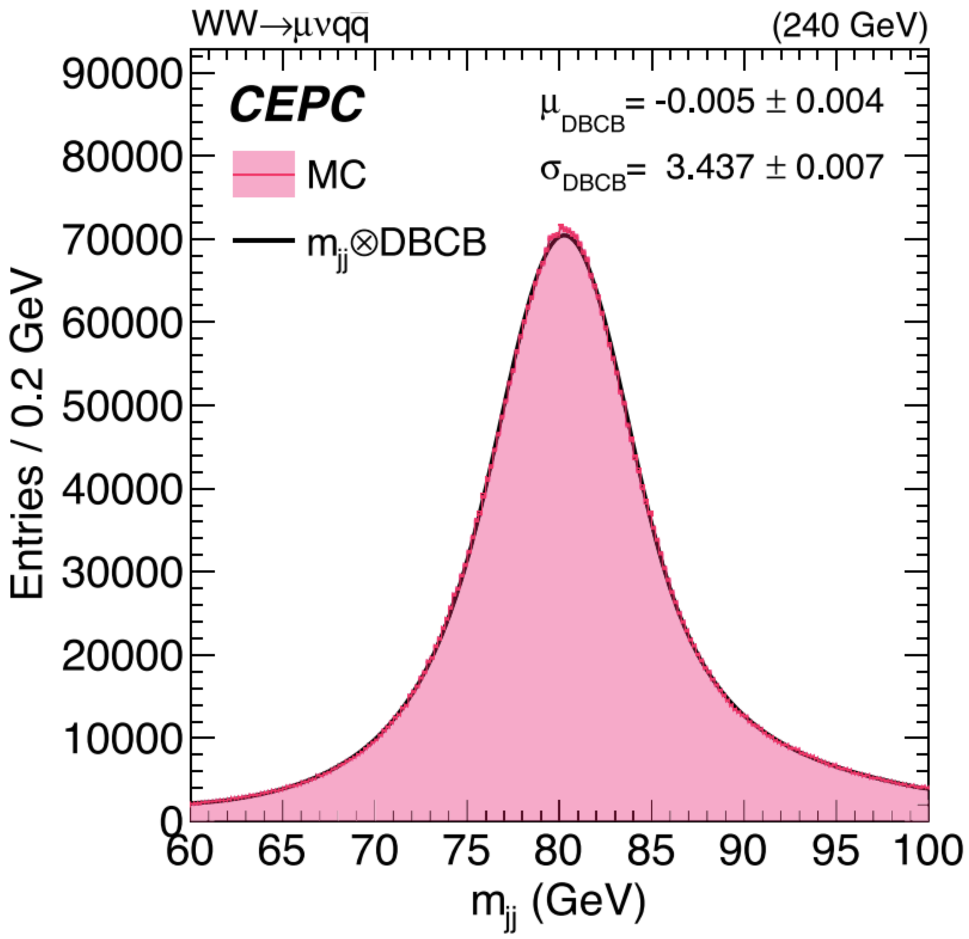


Indirect measurement
Perform WW threshold scan runs (157~172 GeV)
Precision at 1 MeV level



W boson mass measurement

- 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 μvqq event from 5 ab^{-1} from JINST 16 (2021) 07, P07037
- Further studies ongoing

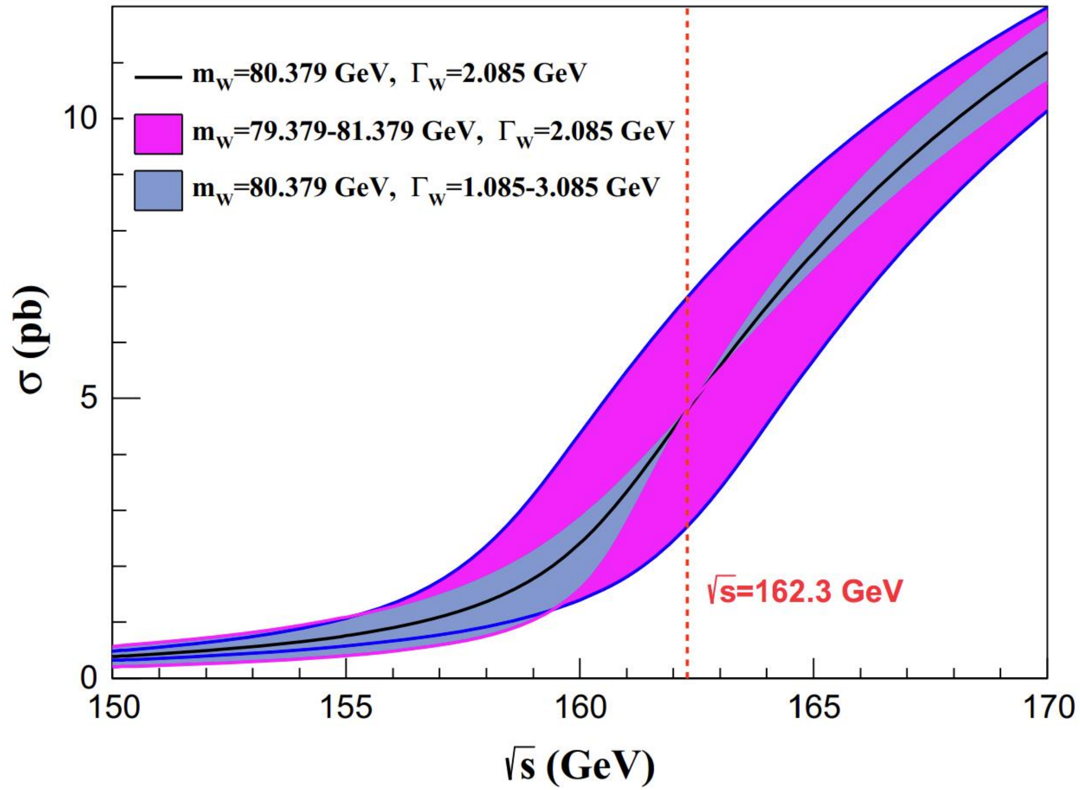


Pei-Zhu Lai *et al.*, JINST 16 (2021) 07, P07037

W boson mass measurement

- 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 (α_{QCD} (m_W) measurement, Br(W→had), CKM $|V_{CS}|$)

E_{cm} (GeV)	Lumiosity (ab^{-1})	Cross section (pb)	Number of WW pairs (M)
161.2	0.2	3.89	0.8
172.0	0.5	12.2	6.1



Peixun Shen *et al.*, Eur. Phys. J. C 80, 66 (2020)

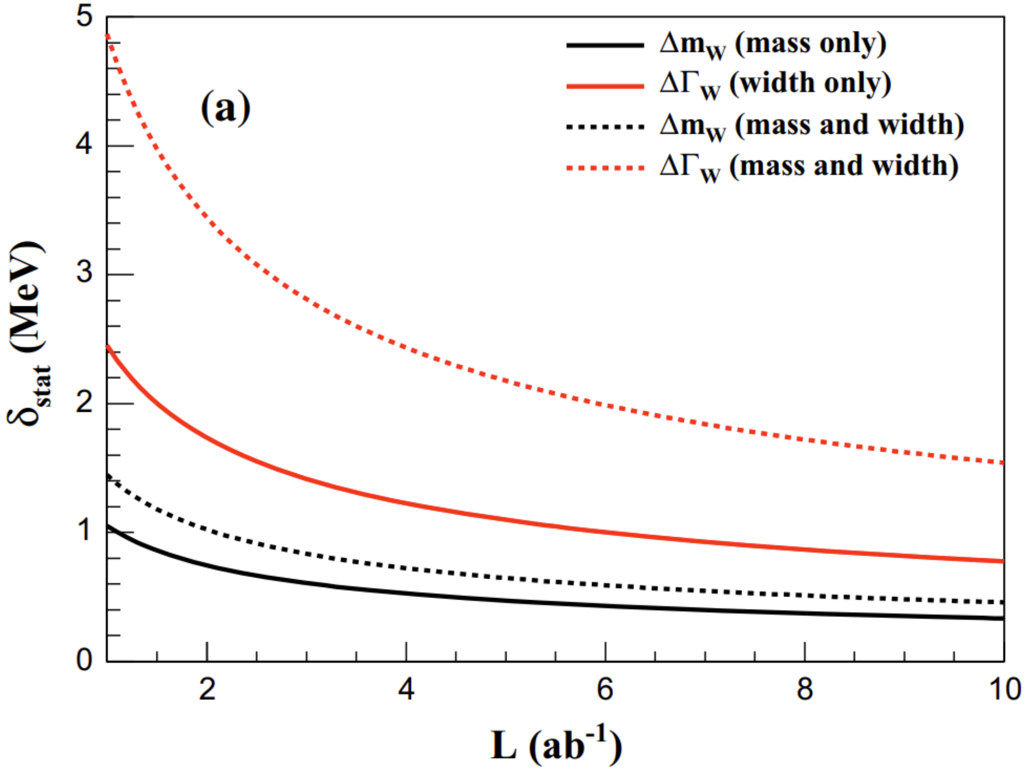
W boson mass measurement

- 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 mW
- Could be further improved with updated calibration method for beam energy
  - With inverse-compton scattering for beam energy calibration, could further reduce systematic uncertainty

Meiyu Si *et al.*, Nucl. Instrum. Meth. A 1026 (2022) 166216,
Guangyi Tang *et al.*, 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

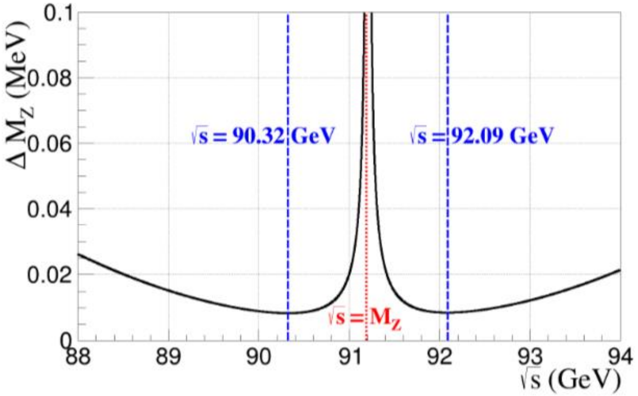
Peixun Shen *et al.*, Eur. Phys. J. C 80, 66 (2020)

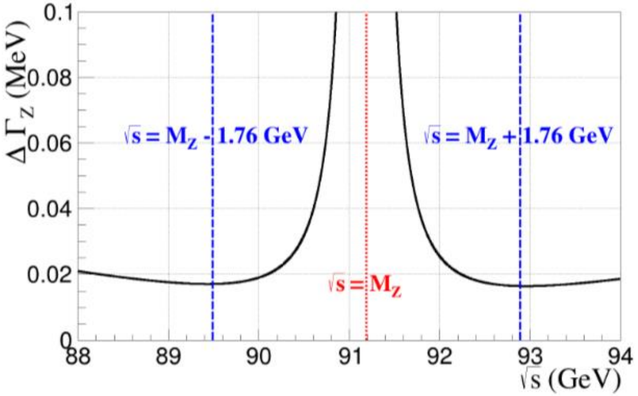


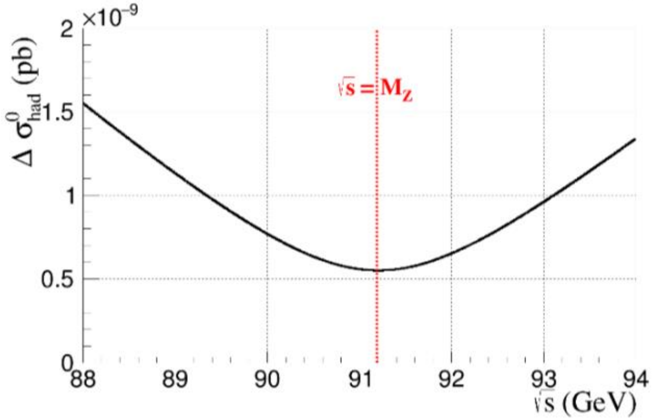
Z boson mass and width measurement

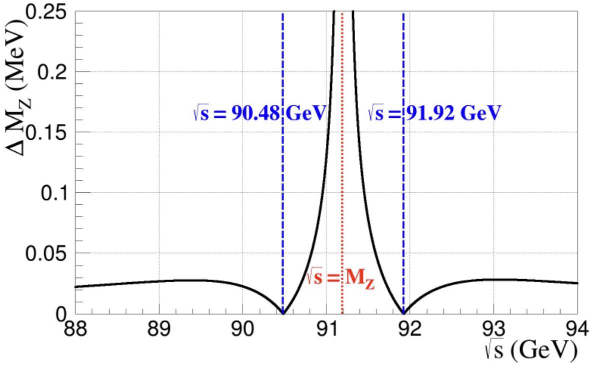
- Tera-Z could help improve m_Z precion by one order of magnitude
- Systematic uncertainty dominant
- Improved energy calibration would further reduce uncertainties

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



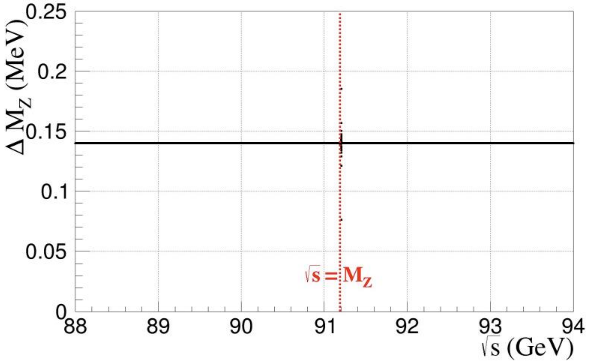






$\Delta E = 0.14$ MeV

Uncertainty of energy scale



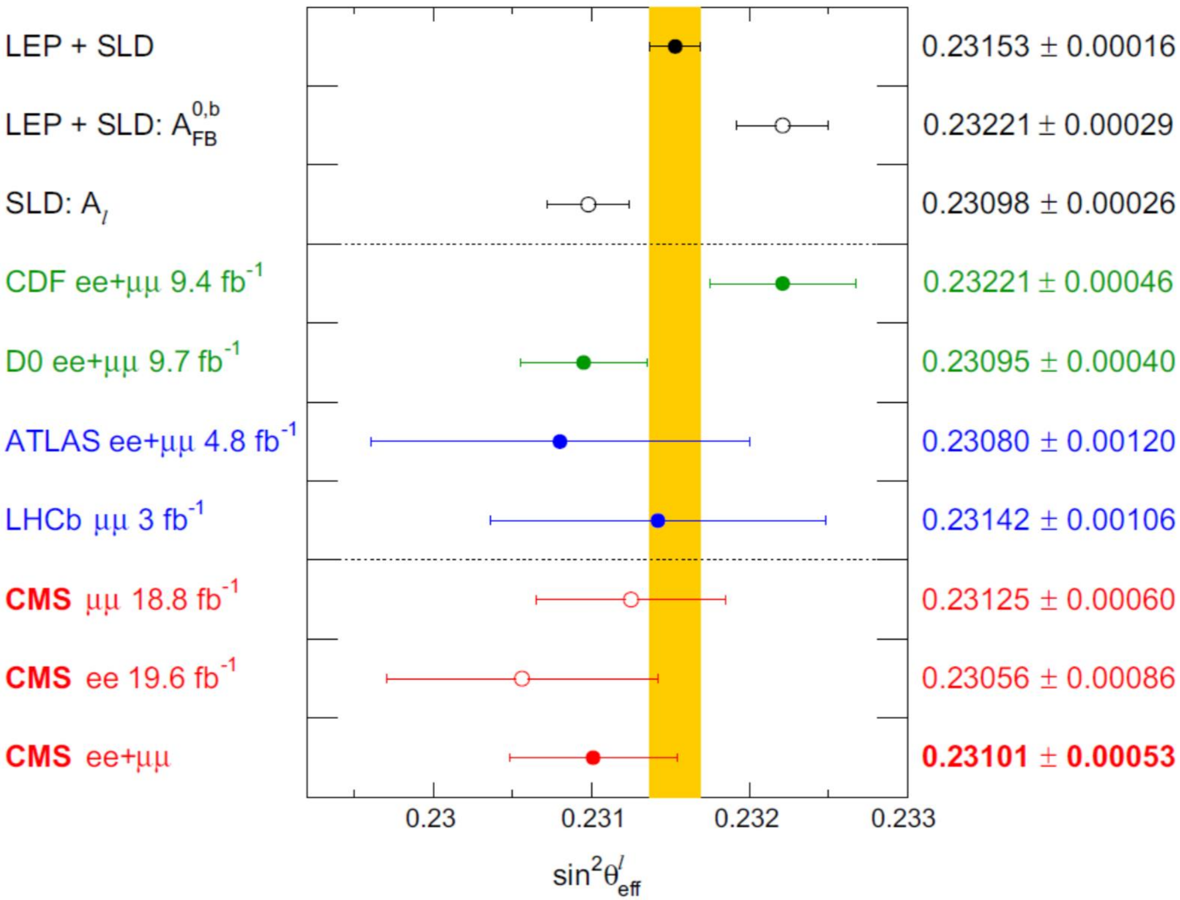
$\Delta\sigma_E = 0.57$ MeV

Uncertainty of energy spread

Weak mixing angle $\sin^2\theta_W$

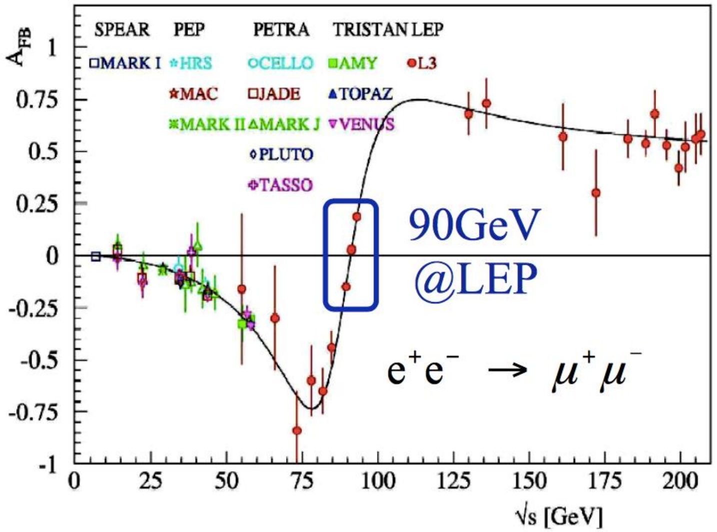
- Key parameter in electroweak sector
  - ~3σ tension between LEP and SLC measurements
  - Experimental syst. much larger than theory syst.

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



- Extract from A_{FB} measurement

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



Weak mixing angle $\sin^2\theta_W$

- 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**

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 …

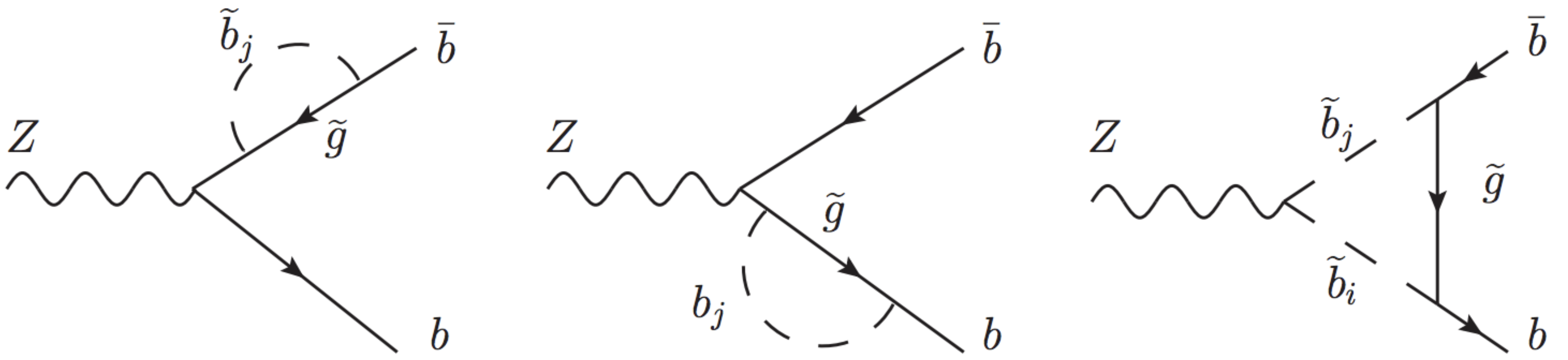
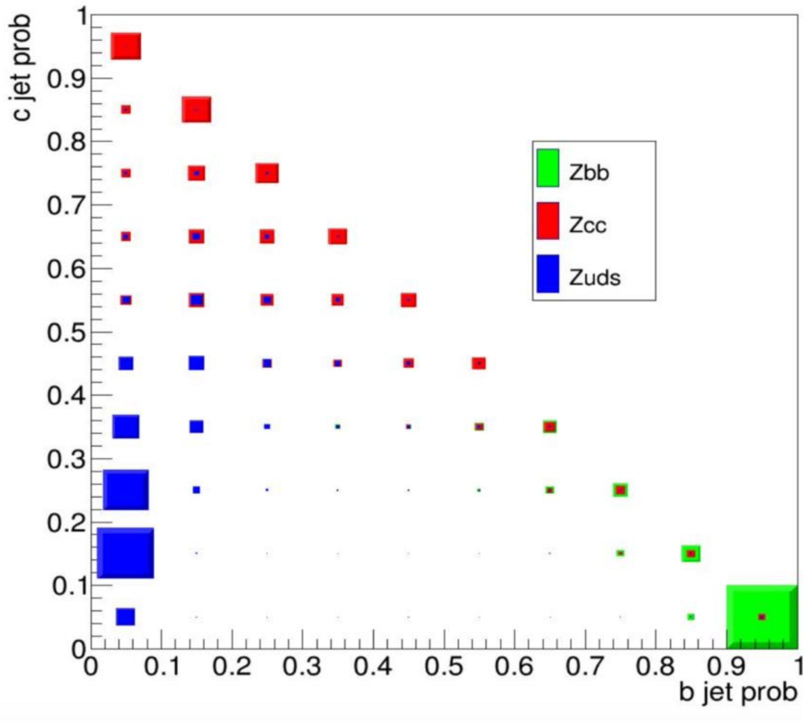


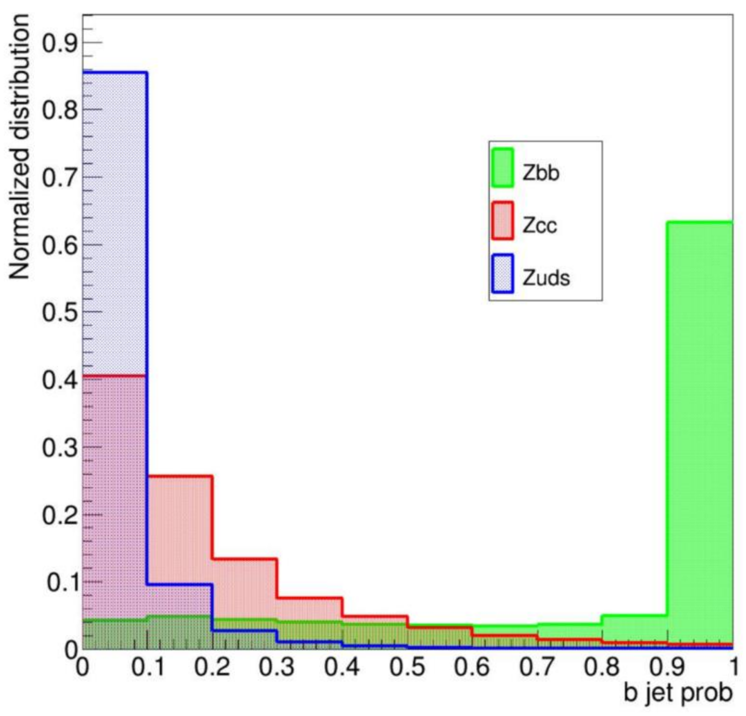
FIG. 1: One-loop Feynman diagrams of gluino correction to $Z \to \bar{b}b$

Wei Su and Jin Min Yang, Phys.Lett.B 757 (2016), 136-141

R^b measurement

- 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 spliting	1
Hemisphere correlation	6
Total	7

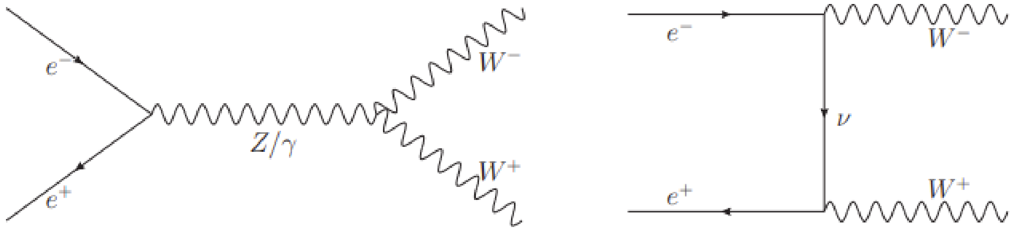
Bo Li *et al.*, Eur. Phys. J. Plus 136, 1 (2021)

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

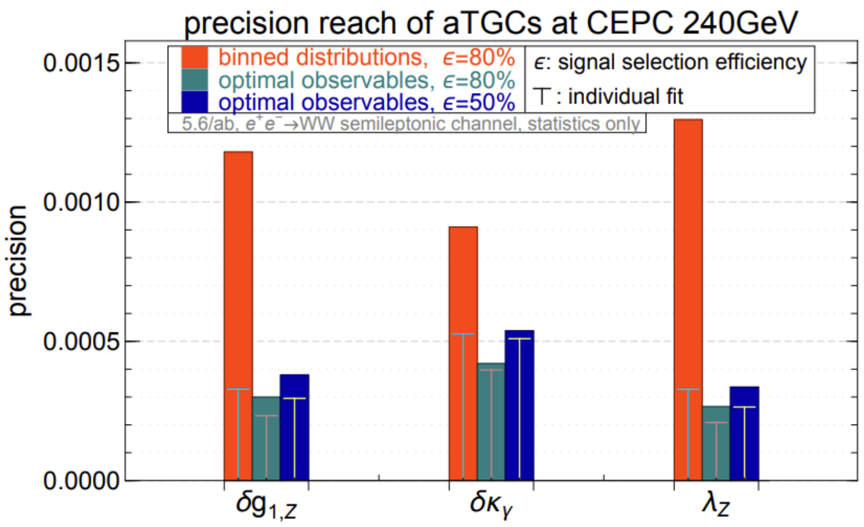
$$\boxed{\delta g_{1,Z}\,,\quad \delta\kappa_\gamma\,,\quad \lambda_Z\,,}\ \boxed{\delta g^{ee}_{Z,L}\,,\quad \delta g^{ee}_{Z,R}\,,\quad \delta g^{e\nu}_{W}\,,\quad \delta_{m_W}}$$

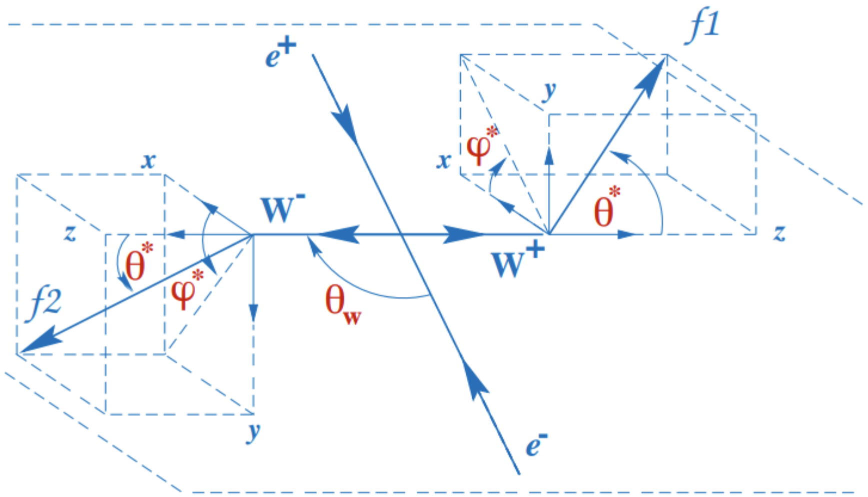
aTGC couplings   gauge couplings modifier



- The optimal observable method explore for this search

(Markus Diehl and Otto Nachtmann, Z. Phys. C 62 (1994) 397–412)





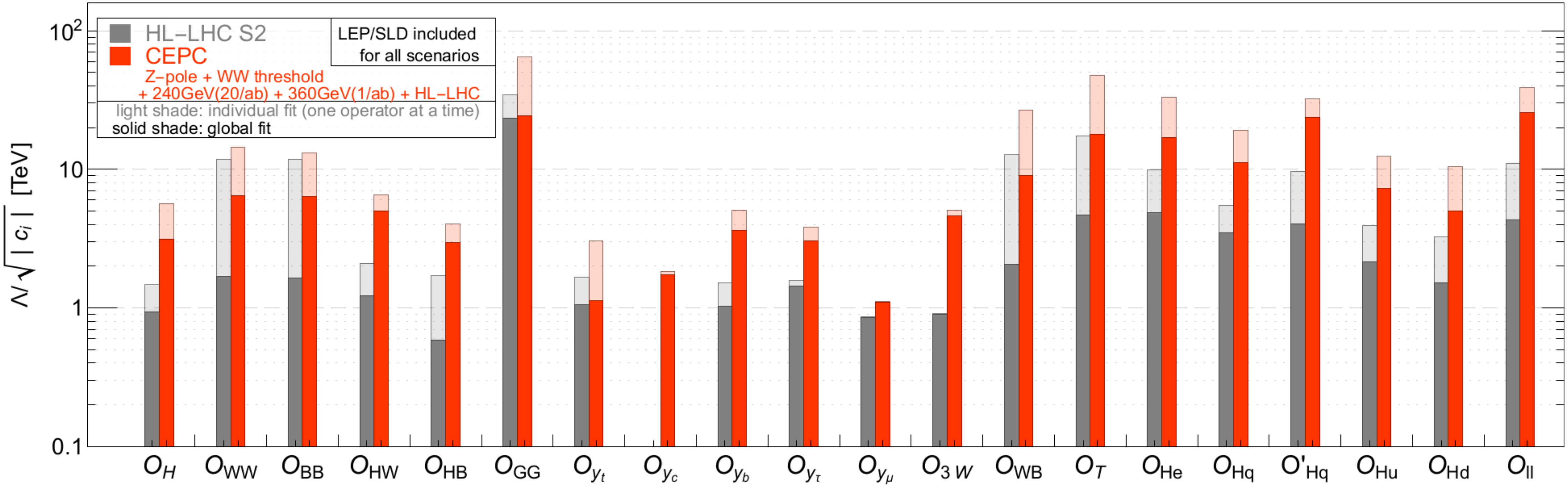
Jorge de Blas *et al.*, JHEP 12 (2019), 117

Global Fit with SMEFT

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

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

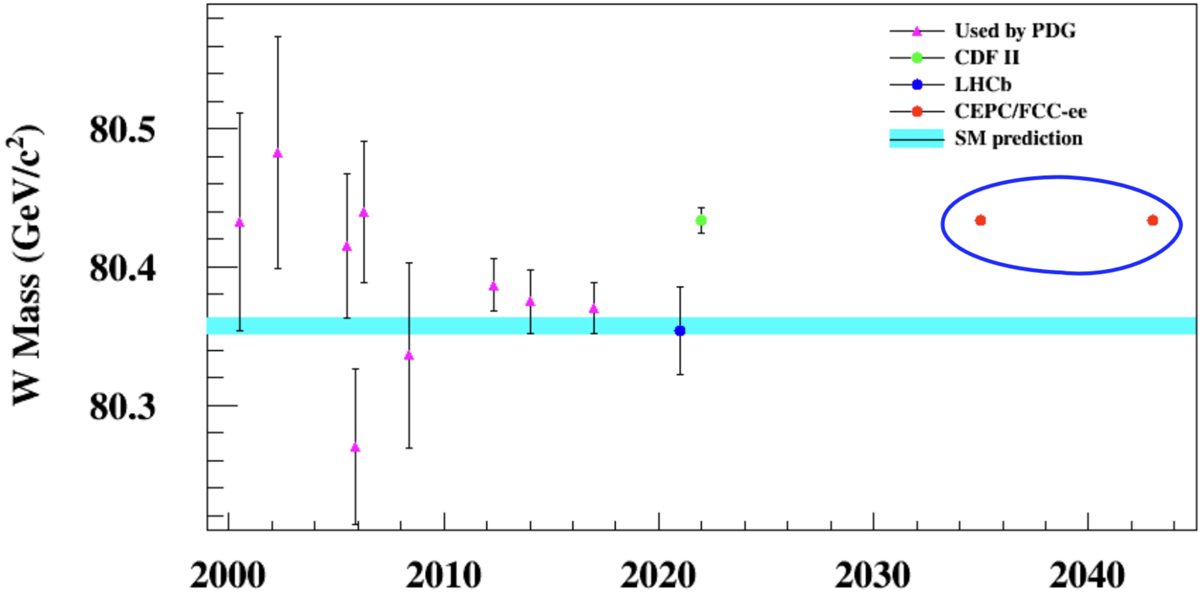
95% CL reach from SMEFT fit



arXiv:2205.08553

Summary

- CEPC is designed to have 100km double ring accelerator
  - Multiple collision energy (from Z pole to ttbar 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



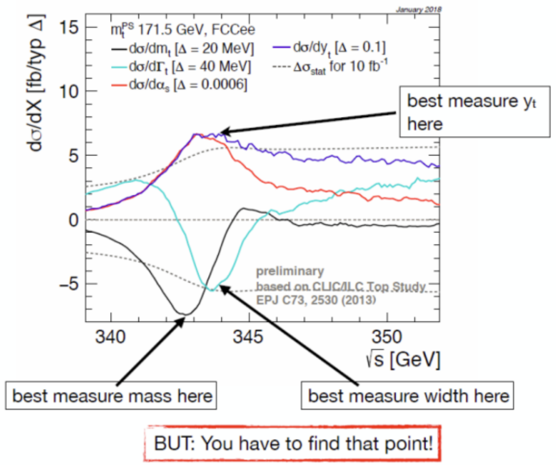
Backup

Top mass

Motivation

- ttbar 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.

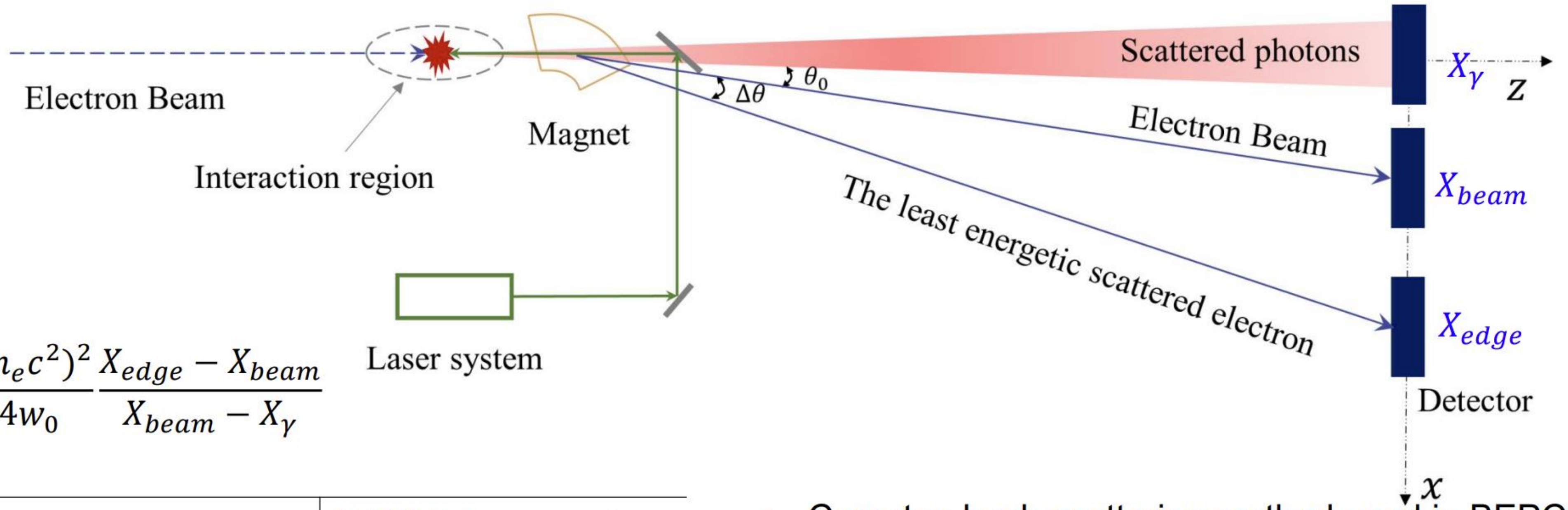
Parameter of interest	Statistical uncertainty
m_t	9.06 MeV
Γ_t	25.86 MeV
α_s	0.000394

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



$$E_{beam} = \frac{(m_e c^2)^2}{4w_0} \frac{X_{edge} - X_{beam}}{X_{beam} - X_\gamma}$$

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

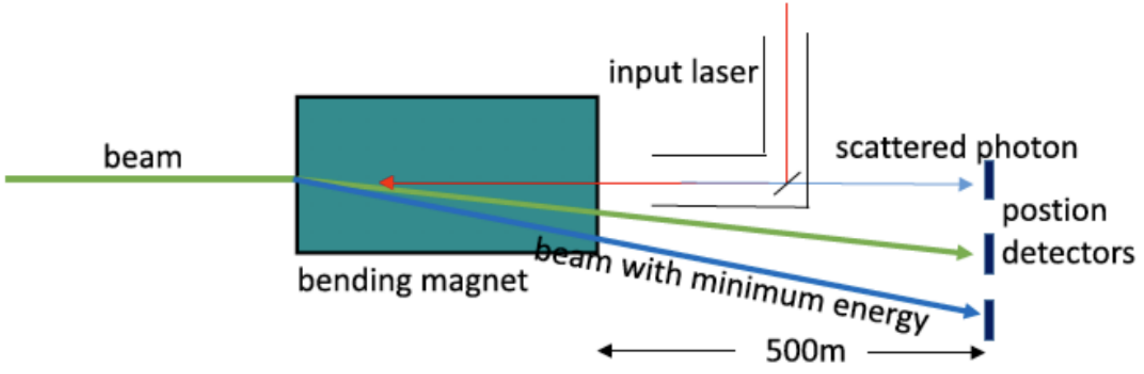
	Higgs mode	Z mode	WW scan	$t\bar{t}$ scan
E_{beam}/GeV	120	45	80	175
X_{edge}/m	6.16352	9.29686	7.10343	5.57276
X_{beam}/m	1.87935	5.00178	2.81903	1.28868
$\delta X_{edge}/m$	2.6× 10^{-5}			
$\delta X_{beam}/m$	6× 10^{-8}			
$\delta E_{beam}/MeV$	1.0	0.3	0.6	1.8

- The statistical uncertainties of beam energy are not included here

doi.10.1063/1.5132975

Beam energy calibration

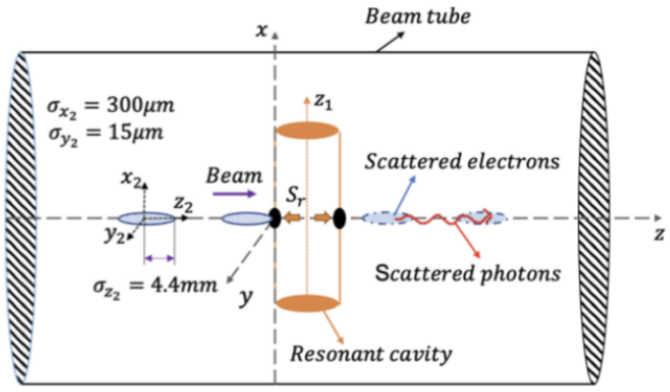
Laser Compton backscattering



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.

Rev. Sci. Instrum. 91 no. 3, (2020) 033109, Nucl. Instrum. Meth. A 1026 (2022) 166216