中国科学院高能物理研究所

Institute of High Energy Physics Chinese Academy of Sciences

Electroweak Physics at CEPC

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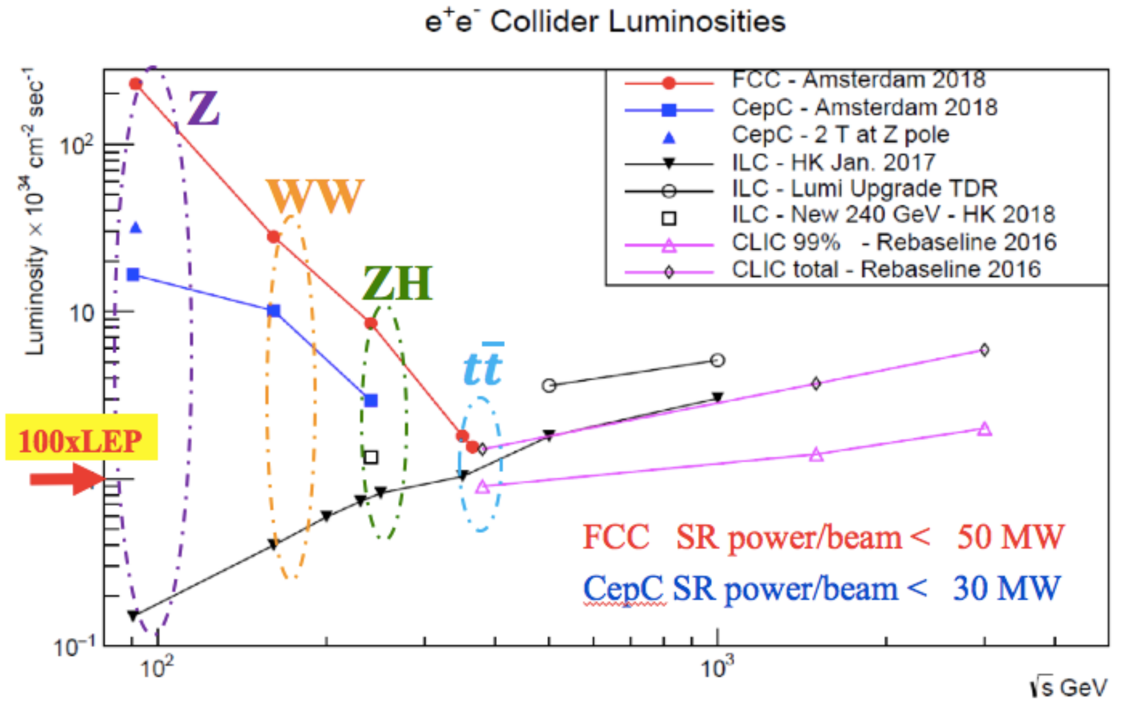
Introduction to CEPC

- CEPC is Higgs Factory （E_{cms}=240GeV，10^6 Higgs)
- CEPC is Z factory(E_{cms}~91GeV) ,electroweak precision physics at Z pole.
  - **baseline** L=1.6 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =3T, 3X10^{11} Z boson, two years
  - L= 3.2 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =2T，6X10^{11} Z boson
  - **Assuming Z cross section with ISR correction : 32 nb**
- WW threshold scan runs (~160GeV) are also expected.
  - One year, Total luminosity 2.6 ab^{-1} **14M WW events**



From F. Bedeschi

Electroweak global fit

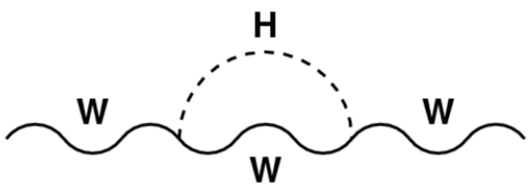
- Review of the key electroweak constant
  - Beam energy systematics is dominant systematics on M_Z, M_W
  - Beam energy measurement is the key to Z pole and WW physics

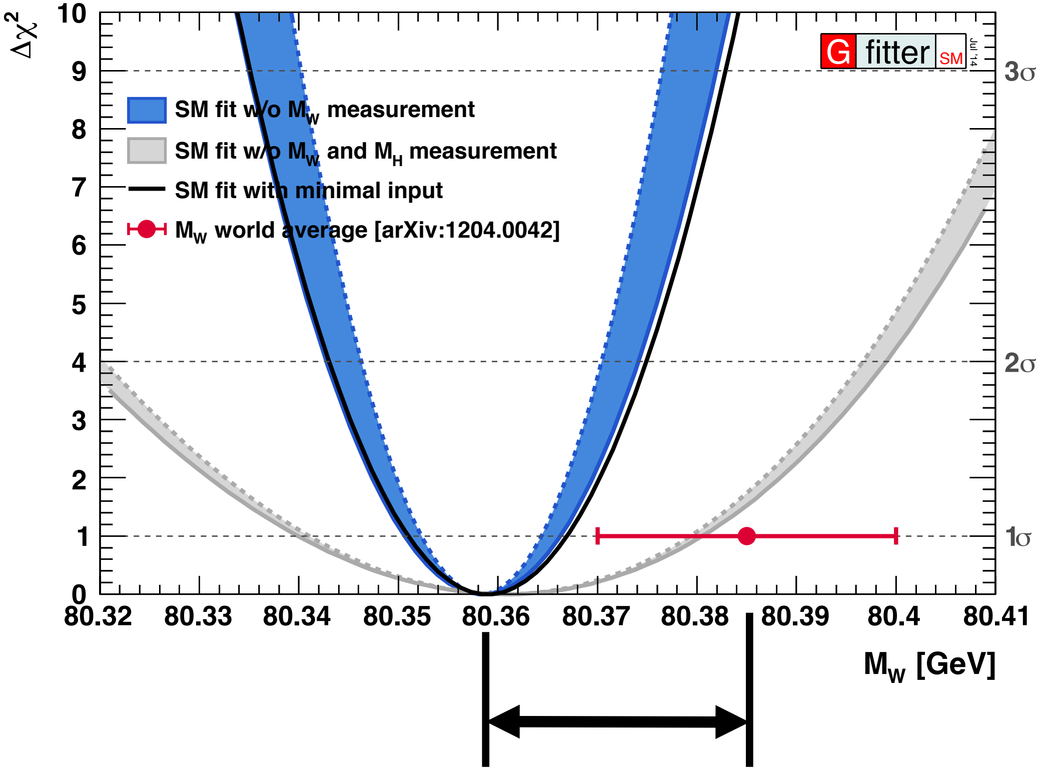
Fundamental constant	δx/x	measurements	
$\alpha = 1/137.035999139\ (31)$	1×10^{-10}	$e^{\pm}\ g_2$	Z pole
$G_F = 1.1663787\ (6) \times 10^{-5}\ \mathrm{GeV}^{-2}$	1×10^{-6}	$\mu^{\pm}$ lifetime	
$M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$	1×10^{-5}	LEP	Z pole
$M_W = 80.379 \pm 0.012\ \mathrm{GeV}$	1×10^{-4}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

From PDG2018

Motivation

- Small tension in weak mixing angle and W mass.(2σ)
  - Between direct measurement and EWK fit prediction
  - Indirect search for new physics



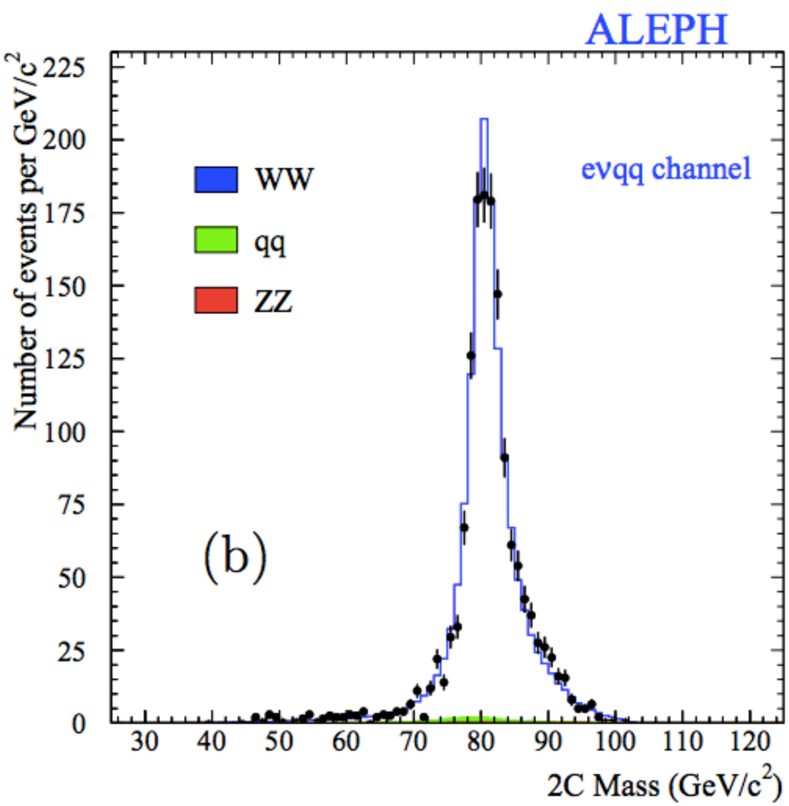


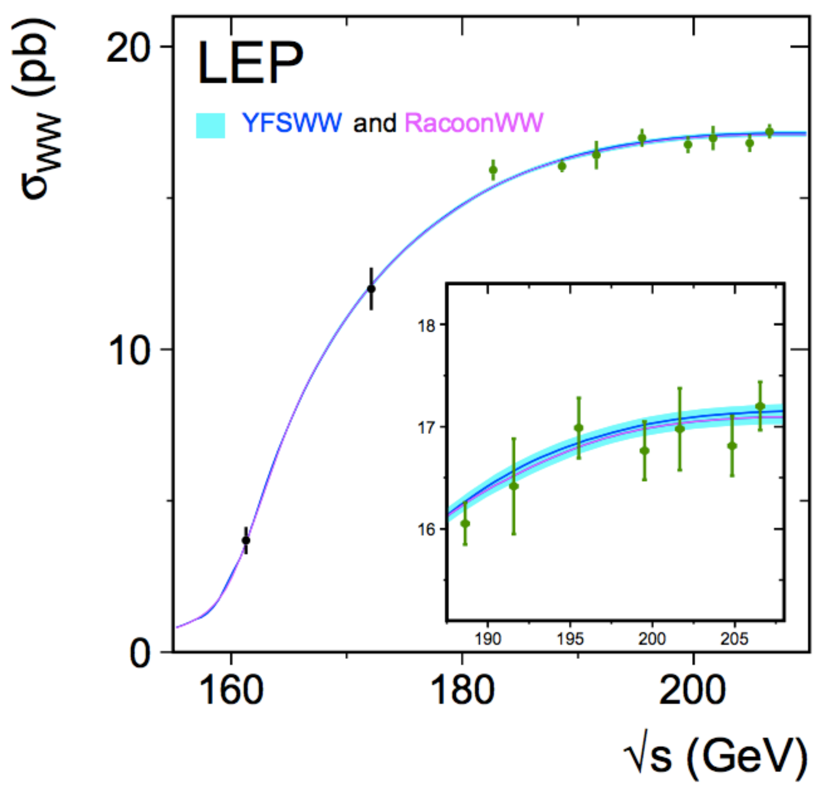
W mass measurement in lepton collider

- Two approaches to measure W mass at lepton collider:

Direct measurement
performed in ZH runs (240GeV)
Precision 2~3MeV

WW threshold scan
WW threshold runs (157~172GeV)
Expected Precision 1MeV level



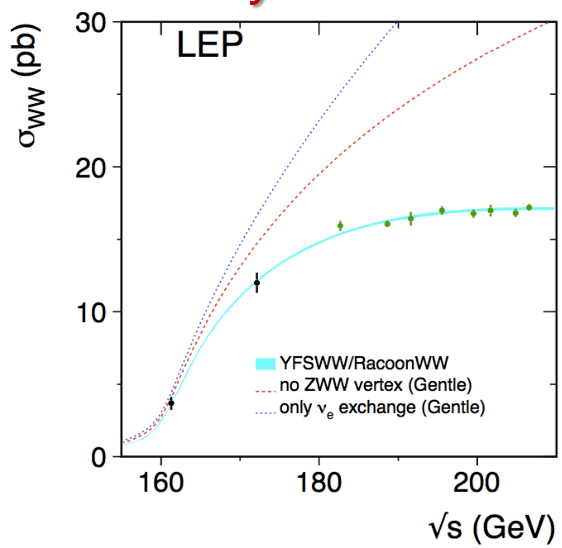


WW threshold scan – CEPC plan

- WW threshold scan running proposal
  - Assuming one year data taking in WW threshold (2.6 ab^{-1})
  - Four energy scan points:
    - 157.5, 161.5, 162.5(W mass, W width measurements)
    - 172.0 GeV (α_{QCD} (m_W) measurement, Br (W->had) , CKM |Vcs|)
    - 14M WW events in total
      - 400 times larger than LEP2 comparing WW runs

E_{cm} (GeV)	Lumiosity (ab^{-1})	Cross section (pb)	Number of WW pairs (M)
157.5	0.5	1.25	0.6
161.5	0.2	3.89	0.8
162.5	1.3	5.02	6.5
172.0	0.5	12.2	6.1

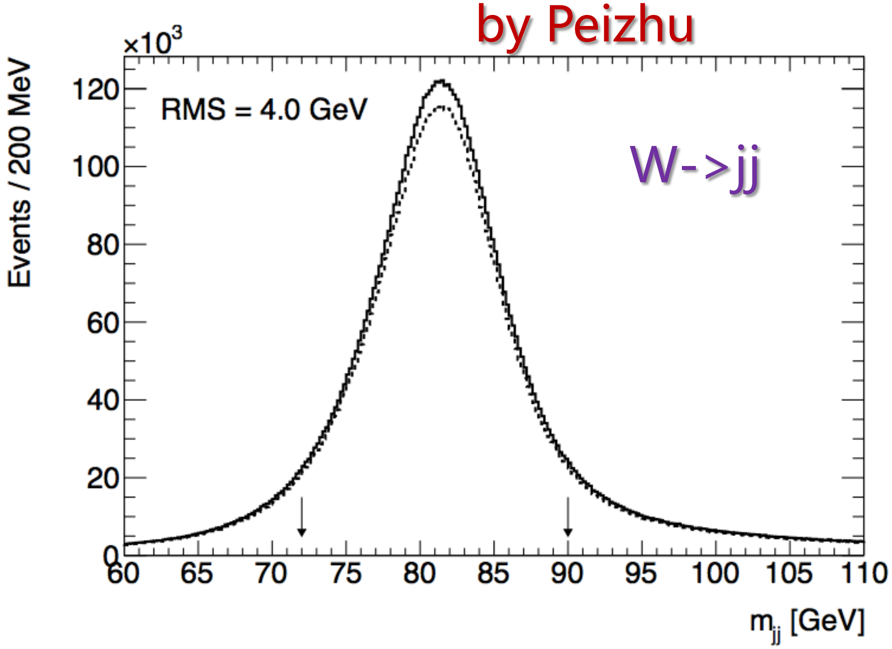
In talk by Peixun



W mass direct measurement

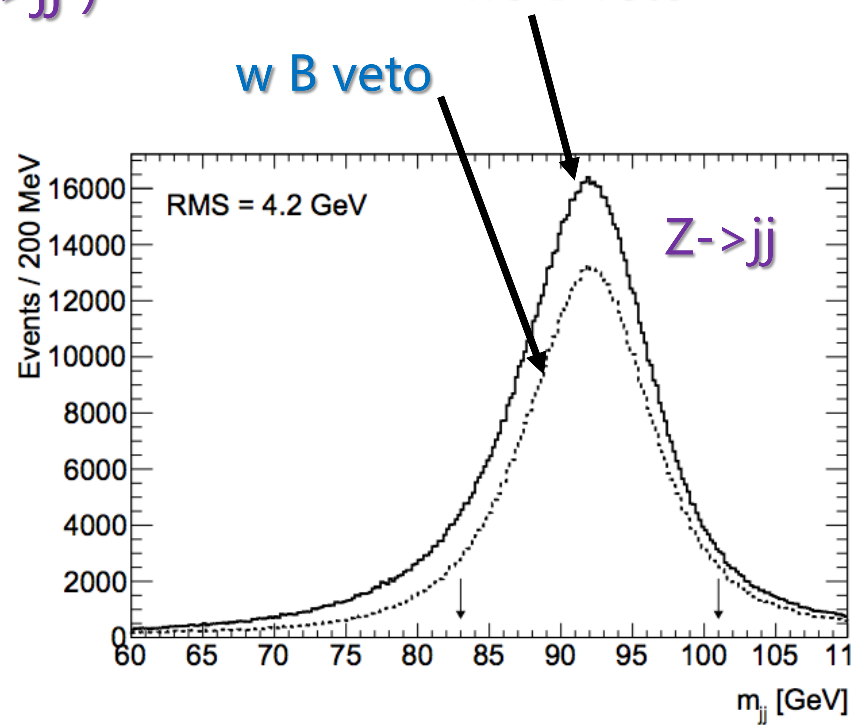
- Reconstruct di-jet mass from WW->lvqq events in ZH run
  - Not affect by beam energy uncertainty
  - Major systematics is Jet energy scale (JES) uncertainty (2~3 MeV)
    - Mainly from Jet flavor composition and jet flavor response
  - Calibrate JES with Tera-Z (Z->jj)

by Peizhu



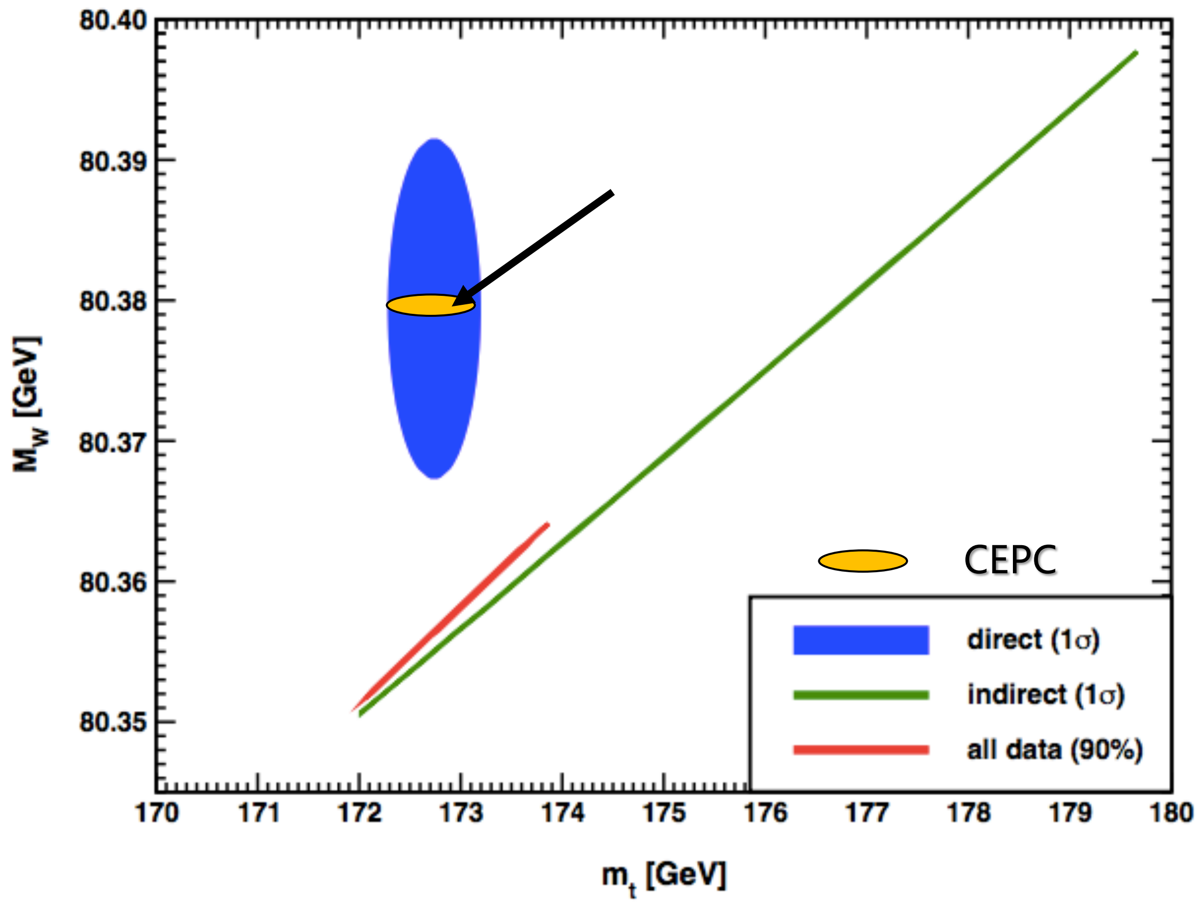
wo B veto

w B veto



Prospect of CEPC W mass measurement

- CEPC can improve current precision of W mass by one order of magnitude
  - A possible BSM physics can be discovered in the future



Freitas & JE (PDG 2018)

- Introduction to CEPC
- W physics
- Z pole physics

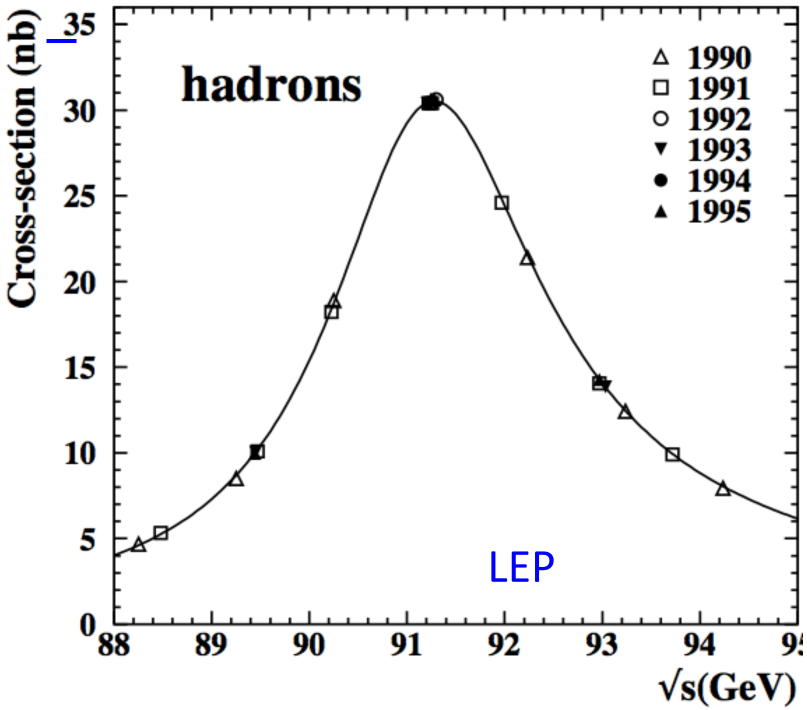
CEPC EWK input to ECFA

	Γ_Z	σ_{had}		A_e (τ pol)	A_τ (τ pol)
CEPC	0.5 MeV	0.005 nb		0.0003	0.0005
FCC-ee	0.1 MeV	0.005 nb		–	–
	R_e	R_μ	R_τ	R_b	R_c
CEPC	0.0003	0.0001	0.0002	0.0002	0.001
FCC-ee	0.0003	0.00005	0.0001	0.0003	0.0015
	$A_{\text{FB}}^{0,e}$	$A_{\text{FB}}^{0,\mu}$	$A_{\text{FB}}^{0,\tau}$	$A_{\text{FB}}^{0,b}$	$A_{\text{FB}}^{0,c}$
CEPC	0.005	0.003	0.005	0.001	0.003
FCC-ee	–	–	–	–	–
(fitted)	A_e	A_μ	A_τ	A_b	A_c
CEPC	0.0003	0.003	0.0005	0.001	0.003
FCC-ee	0.0001	0.00015	0.0003	0.003	0.008

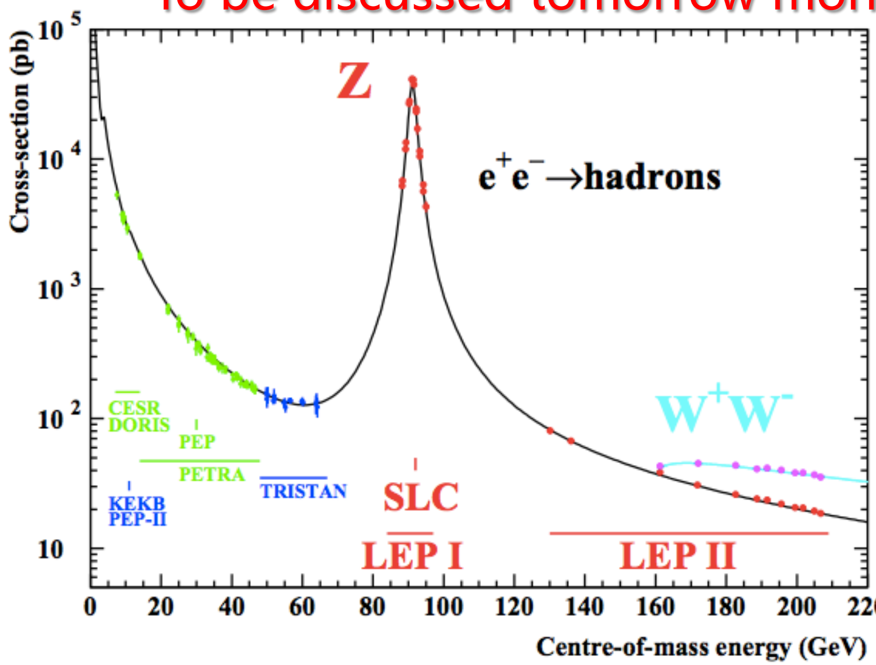
Table 1: A comparison of CEPC and FCC-ee Z-pole inputs. All uncertainties are relative **(normalized to 1)** except for Γ_Z and σ_{had}. "τ pol" denotes that the measurement is from τ polarization in $Z \to \tau^+\tau^-$. The 5 fitted asymmetry observables ($A_{e,\mu,\tau,b,c}$) are derived from a simutanous fit of all the $A_{\text{FB}}^{0,}$ observables as well as the A_e and A_τ from τ polarization.

Z mass measurement

- LEP measurement : 91.1876±0.0021 GeV
- CEPC possible goal: 0.5 MeV (CDR) → 0.1MeV (TDR)
  - Z threshold scan runs is needed to achieve high precision.
  - Syst uncertainty: ~0.5 MeV
    - Beam energy uncertainty is major systematics
      - Resonant depolarization approach by LEP → <0.1MeV
      - Luminosity systematics → <0.1 MeV



To be discussed tomorrow morning

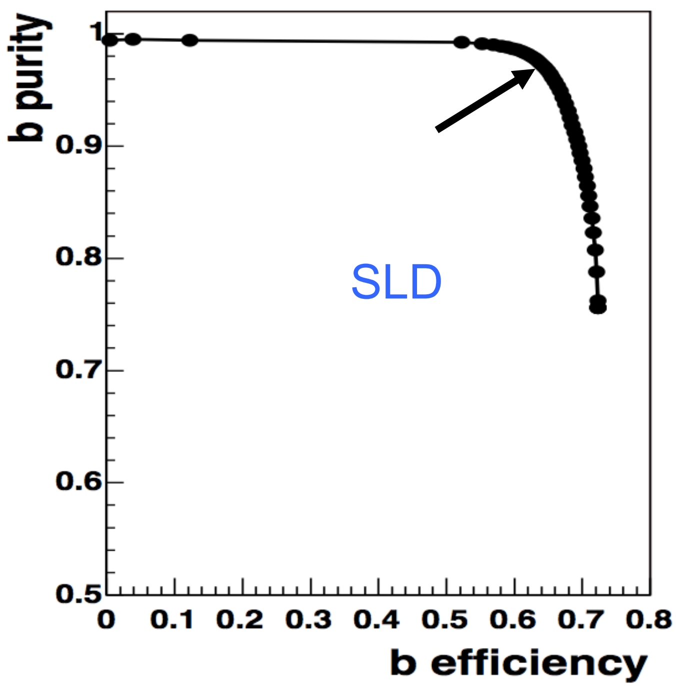


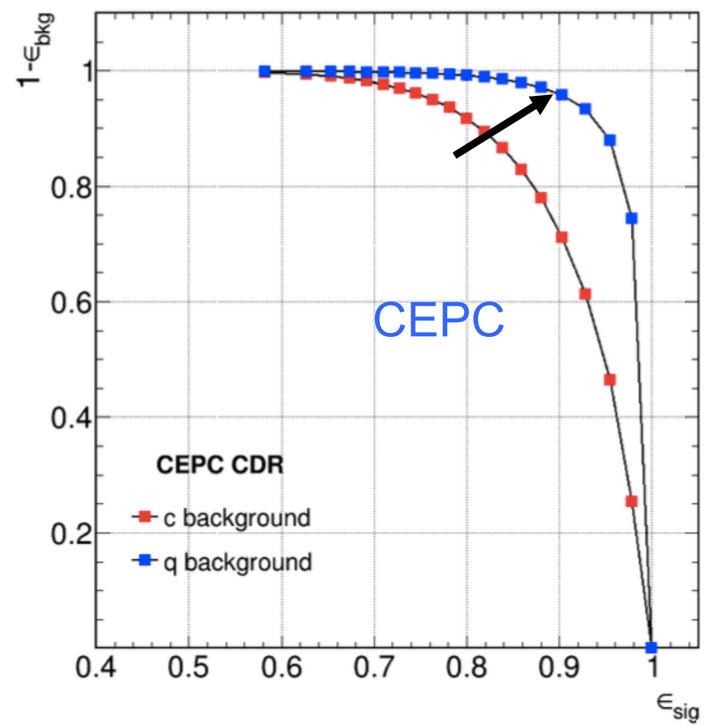
$\frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to had)}$ Branching ratio (R^b)

$$C_b = \frac{\varepsilon_{2jet-tagged}}{(\varepsilon_{1jet-tagged})^2}$$

- LEP measurement 0.21594 ±0.00066
  - Syst error : ~0.2%
    - Major systematics is hemisphere tag correlations
- CEPC
  - Expected Syst error (0.02%)
  - hemisphere tag correlations depends on b tagging efficiency
  - Expect 20~30% higher B tagging efficiency than SLD

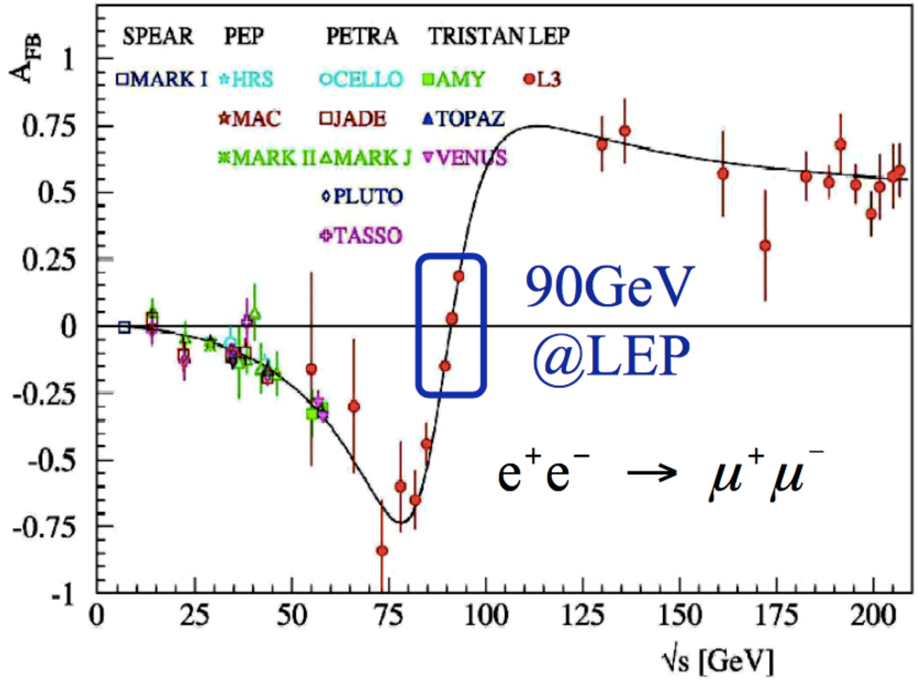
To be discussed
In talk by Li Bo

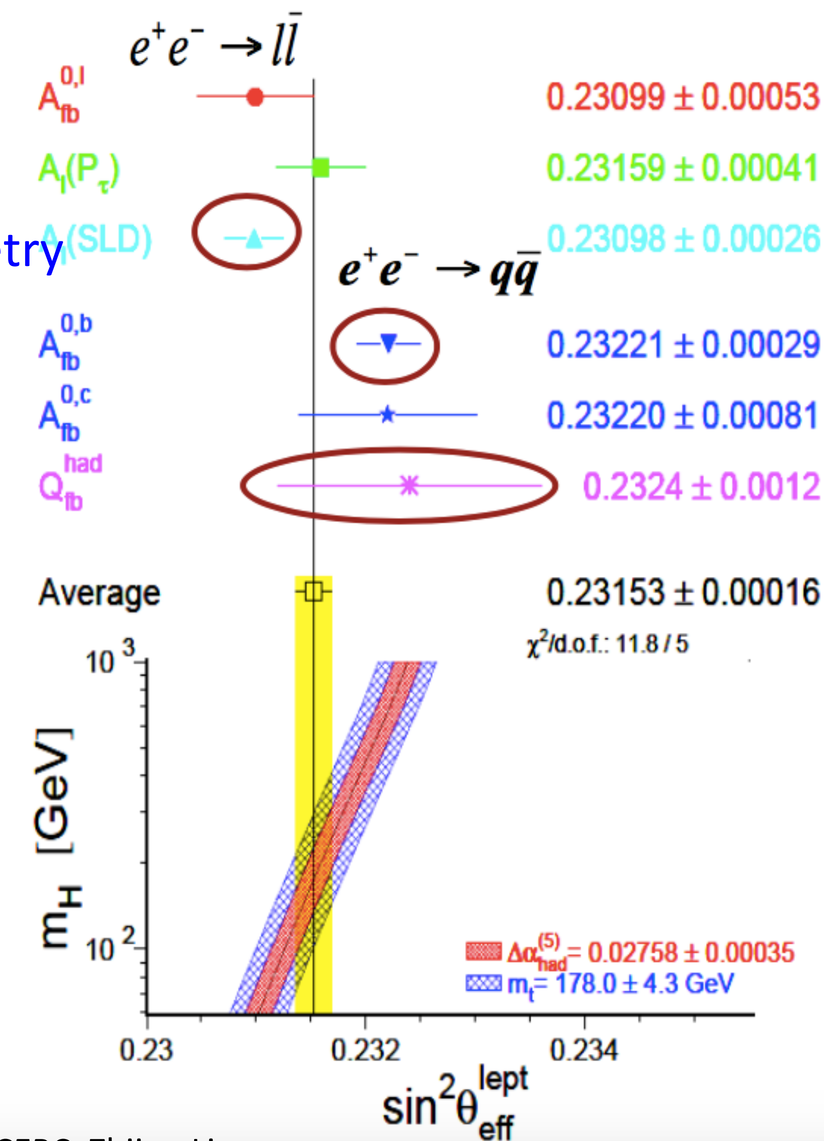




Weak mixing angle $\sin^2\theta_{eff}^{lept}$

- Some tension between SLD and LEP results (~3σ)
  - Remain a puzzle for ~10 years
- CEPC
  - Aim for 0.002% precision
    - Input from Backward-forward asymmetry





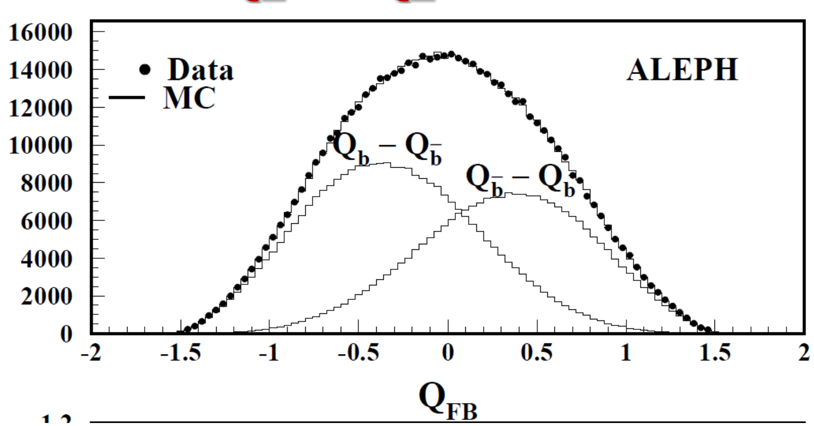
Backward-forward asymmetry

$A_{FB}^{0,b}$

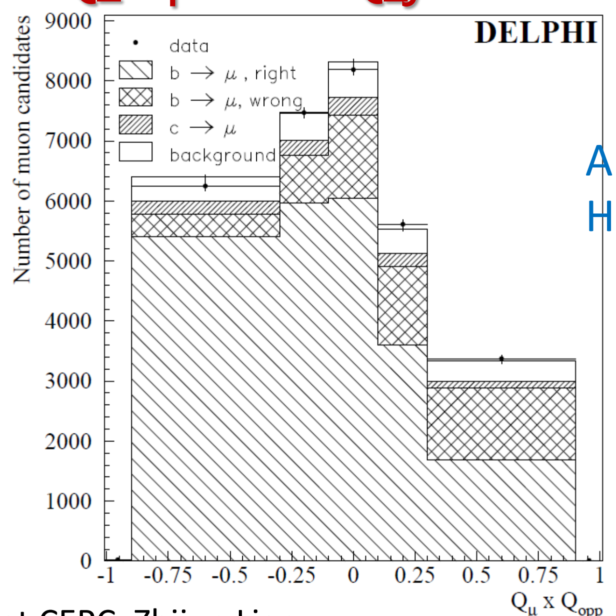
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay
    CEPC precision 0.1% ,LEP precision ~2% (stat dominated)
    - Main systematics is B hadron decay branching ratio
  - Method 2: jet charge method , Inclusive b jet (LEP precision 1.2%)
    - use event Thrust to define the forward and background
    - Use jet charge difference (Q_F - Q_B)

Arxiv:Hep-ex/0107033

Q_F - Q_B in method 2



Q_lepton - Q_jet in method 1



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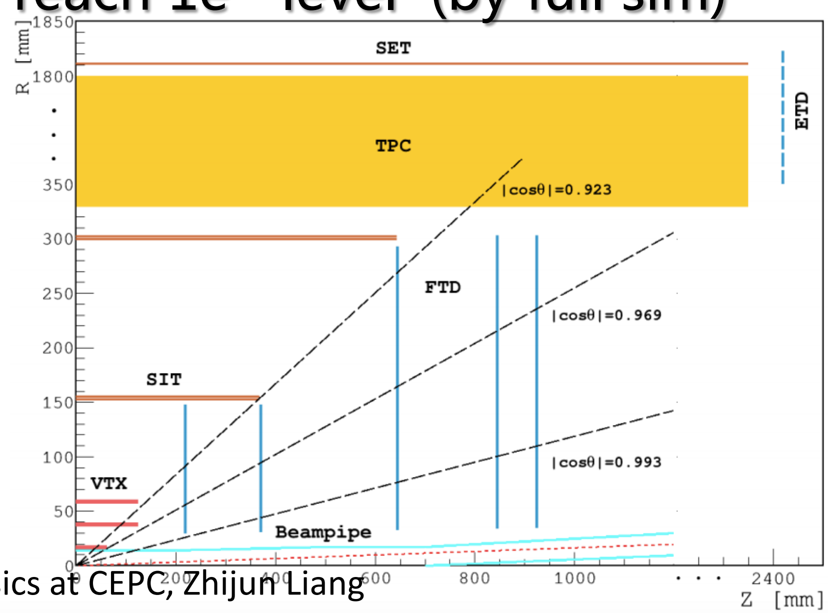
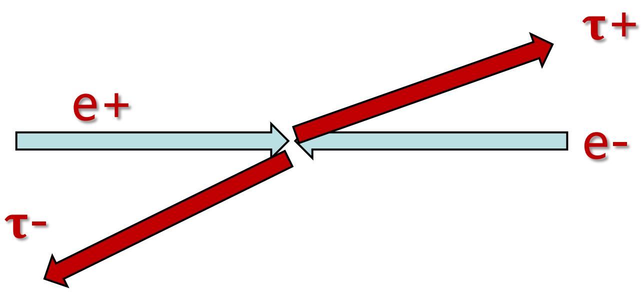
Backward-forward asymmetry in Z->μμ

$A_{FB}^{(0,\mu)}$

- LEP measurement : 0.0169 +-0.00130
- Fcc-ee: +- 0.0000025
- CEPC: +-0.00005
- CEPC has potential to improve it by a factor of 20~30 .
  - Acceptance systematics (larger detector coverage, smaller syst.)
  - Tracker alignment systematics (to be answered in TDR)
  - The precision of beam energy measurement
- Full simulation studies to understand muon angular resolution
  - Muon angular resolution can reach 1e^{-5} level (by full sim)



A_e and A_τ measurements



$$A_{\rm FB} = \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}}$$

$$A_{\rm LR} = \frac{\sigma_{\rm L} - \sigma_{\rm R}}{\sigma_{\rm L} + \sigma_{\rm R}} \frac{1}{\langle|\mathcal{P}_{\rm e}|\rangle}$$

$$A_{\rm LRFB} = \frac{(\sigma_{\rm F} - \sigma_{\rm B})_{\rm L} - (\sigma_{\rm F} - \sigma_{\rm B})_{\rm R}}{(\sigma_{\rm F} + \sigma_{\rm B})_{\rm L} + (\sigma_{\rm F} + \sigma_{\rm B})_{\rm R}} \frac{1}{\langle|\mathcal{P}_{\rm e}|\rangle}$$

- A_e and A_τ using polarization info

(derived)	A_e	A_μ	A_τ	A_b	A_c
CEPC	0.0025	0.0039	0.0056	0.0027	0.0039
FCC-ee	0.0001	0.00015	0.0003	0.003	0.008

- A_e and A_τ with polarization info (from tau or from beam)

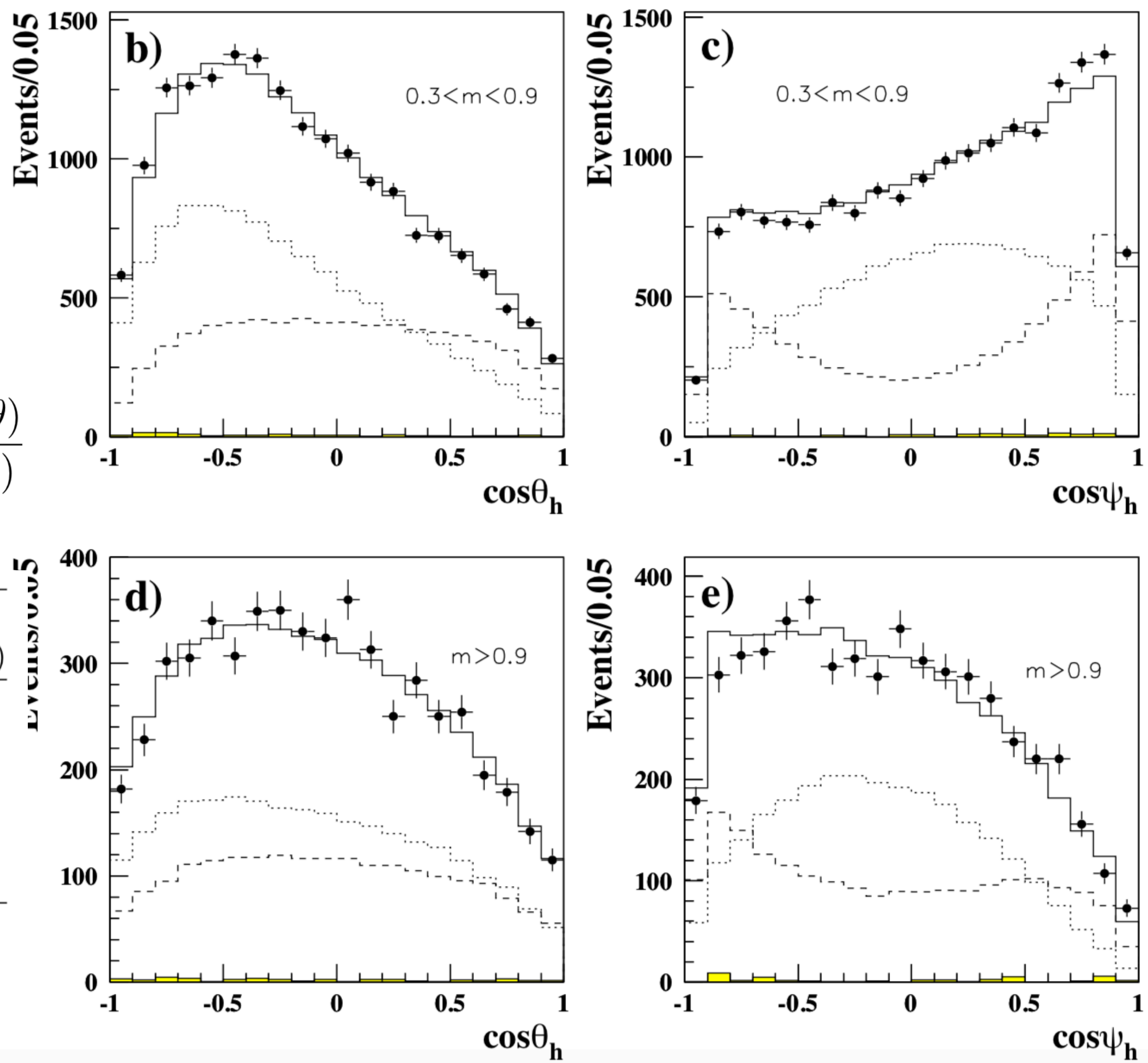
(fitted)	A_e	A_μ	A_τ	A_b	A_c
CEPC	0.0003	0.003	0.0005	0.001	0.003
FCC-ee	0.0001	0.00015	0.0003	0.003	0.008

A_e and A_τ in Z->ττ

- Tau polarization can be measured through its decay product

$$P_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + \mathcal{A}_e(2\cos\theta)}{(1+\cos^2\theta) + \frac{4}{3}\mathcal{A}_{fb}(2\cos\theta)}$$

τ decay mode	Number selected decays	Purity of the samples (%)
$\tau \to e\nu_e\nu_\tau$	18434	89.4 ± 0.1
$\tau \to \mu\nu_\mu\nu_\tau$	19811	94.3 ± 0.1
$\tau \to \pi/K\nu_\tau$	14850	73.2 ± 0.1
$\tau \to \rho\nu_\tau$	26548	75.4 ± 0.1
$\tau \to a_1\nu_\tau$	9446	53.2 ± 0.2



A_e and A_τ in Z->ττ: systematics

- Key systematics is from EM scale, and **τ** identification

	A_τ						
Source	h	ρ	$3\,h$	$h\,2\pi^0$	e	μ	Incl. h
selection	-	0.01	-	-	0.14	0.02	0.08
tracking	0.06	-	0.22	-	-	0.10	-
ECAL scale	0.15	0.11	0.21	1.10	0.47	-	-
PID	0.15	0.06	0.04	0.01	0.07	0.07	0.18
misid.	0.05	-	-	-	0.08	0.03	0.05
photon	0.22	0.24	0.37	0.22	-	-	-
non-τ back.	0.19	0.08	0.05	0.18	0.54	0.67	0.15
τ BR	0.09	0.04	0.10	0.26	0.03	0.03	0.78
modelling	-	-	0.70	0.70	-	-	0.09
MC stat	0.30	0.26	0.49	0.63	0.61	0.63	0.26
TOTAL	0.49	0.38	1.00	1.52	0.96	0.93	0.87

Impact of Polarized beam collision

- A_e is obtained from Z->$\tau\tau$
  - Fcc-ee expected precision : 0.0001
  - CEPC expected precision : 0.0003
  - CEPC expected precision (with polarized beam) : 0.0001
    - limited by statistics , a factor of 2~3 worse than Fcc
    - By using polarized beam collision, A_e precision can improve by 3
- A_μ
  - Fcc-ee expected precision : 0.00015
  - CEPC expected precision : 0.003
  - CEPC expected precision (with polarized beam) : 0.0003
  - By using polarized beam collision, A_e precision can improve by 10

Summary

- Potential of electroweak measurement at CEPC
  - Expect 1~2 order of magnitude better than current precision
  - Key issue (already addressed in CDR)
    - Jet energy scale and resolution (W mass)
    - Luminosity measurement (Z/W mass)
    - Impact parameter and b tagging performance
      - Weak mixing angle, R^b
  - Key issue (To be address or to be improved in TDR)
    - Beam energy measurement (Z/W mass)
    - Detector readout time and Pileup issue is the key for Missing energy (Number of neutrino generation)
    - Photon energy scale uncertainty
      - Number of neutrino generation, R^{mu}

Prospect of CEPC EWK physics

- Expect to have 1~2 order of magnitude better than current precision

Observable	LEP precision	CEPC precision	CEPC runs	CEPC $\int \mathcal{L}dt$
m_Z	2 MeV	0.5 MeV	Z pole	8 ab^{-1}
$A_{FB}^{0,b}$	1.7%	0.1%	Z pole	8 ab^{-1}
$A_{FB}^{0,\mu}$	7.7%	0.3%	Z pole	8 ab^{-1}
$A_{FB}^{0,e}$	17%	0.5%	Z pole	8 ab^{-1}
$\sin^2\theta_W^{\mathrm{eff}}$	0.07%	0.001%	Z pole	8 ab^{-1}
R_b	0.3%	0.02%	Z pole	8 ab^{-1}
R_μ	0.2%	0.01%	Z pole	8 ab^{-1}
N_ν	1.7%	0.05%	ZH runs	5.6 ab^{-1}
m_W	33 MeV	2–3 MeV	ZH runs	5.6 ab^{-1}
m_W	33 MeV	1 MeV	WW threshold	2.6 ab^{-1}

Table 11.9: The expected precision in a selected set of EW precision measurements in CEPC and the comparison with the precision from LEP experiments. The CEPC accelerator running mode and total integrated luminosity expected for each measurement are also listed.

FCC-ee: Theory calculations

- **Today**

$$
\begin{aligned}
m_W = \quad & 80.3584 \quad \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \\
& \qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{\text{theory}} \text{ GeV} \\
= \quad & 80.358 \quad \pm 0.008_{\text{total}} \text{ GeV},
\end{aligned}
$$

$$m_W^{\text{direct}} = 80.385 \pm 0.015 \text{ GeV}$$

- **With FCC-ee**

$$
\begin{aligned}
m_W = \quad & 80.3584 \quad \pm 0.0002_{m_{top}} \pm 0.0001_{m_Z} \pm 0.0005_{\alpha_{QED}} \\
& \qquad \pm 0.0002_{\alpha_S} \pm 0.0000_{m_H} \pm 0.0040_{\text{theory}} \text{ GeV} \\
= \quad & 80.3584 \quad \pm 0.0006_{\text{exp}} \pm 0.0040_{\text{theory}} \text{ GeV},
\end{aligned}
$$

$$m_W^{\text{direct}} = 80.385 \pm 0.0006 \text{ GeV}$$

- **Theory R&D**

Conclusion from Precision Calculations Mini-Workshop in January 2018:
The necessary theoretical work is doable in 5-10 years perspective, due to steady progress in methods and tools, including the recent completion of NNLO SM corrections to EWPOS. This statement is conditional to a strong support by the funding agencies and the overall community. Appropriate financial support and training programs for these precision calculations are mandatory.

Theory development

J. Gluza
(supported by FCC)

Look into the future. Bookkeeping with three loops

$Z \to b\bar{b}$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \to^{A} 7 \to^{B}$ **5**	$211 \to^{A} 84 \to^{B}$ **50**
Number of diagrams	15	$2383 \to^{A,B}$ **1114**	$490387 \to^{A,B}$ **120187**
Fermionic loops	0	371	116091
Bosonic loops	15	2012	374296
Planar	1T/15D	13T/2250D	186T/426753D
Non-planar	0	1T/133D	25T/63634D

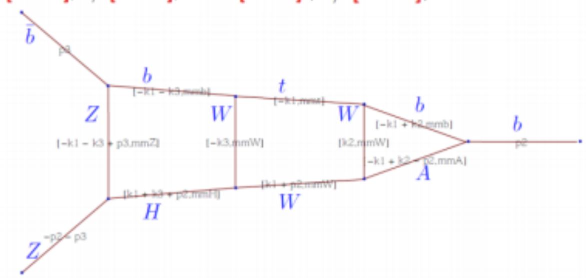
$Z \to e^+e^-, \ldots$			
Number of topologies	1 loop	2 loops	3 loops
	1	$14 \to^{A} 7 \to^{B}$ **5**	$211 \to^{A} 84 \to^{B}$ **50**
Number of diagrams	14	$2012 \to^{A,B}$ **880**	$397690 \to^{A,B}$ **91271**
Fermionic loops	0	301	92397
Bosonic loops	14	1711	305293
Planar	1	13	186
Non-planar	0	1	25

Genuine virtual loops (aITALC, qgraf, FeynArts).

(A) - no tadpoles, no product of lower loops, (B) - symmetry included 19 / 46

such as:

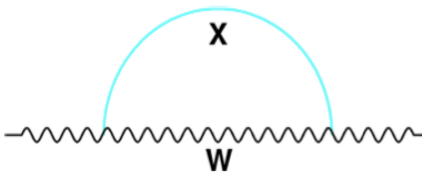
MB: ϵ^0[8-dim], $1/\epsilon$[7-dim]; SD: ϵ^0[8-dim] , $1/\epsilon$[7-dim];

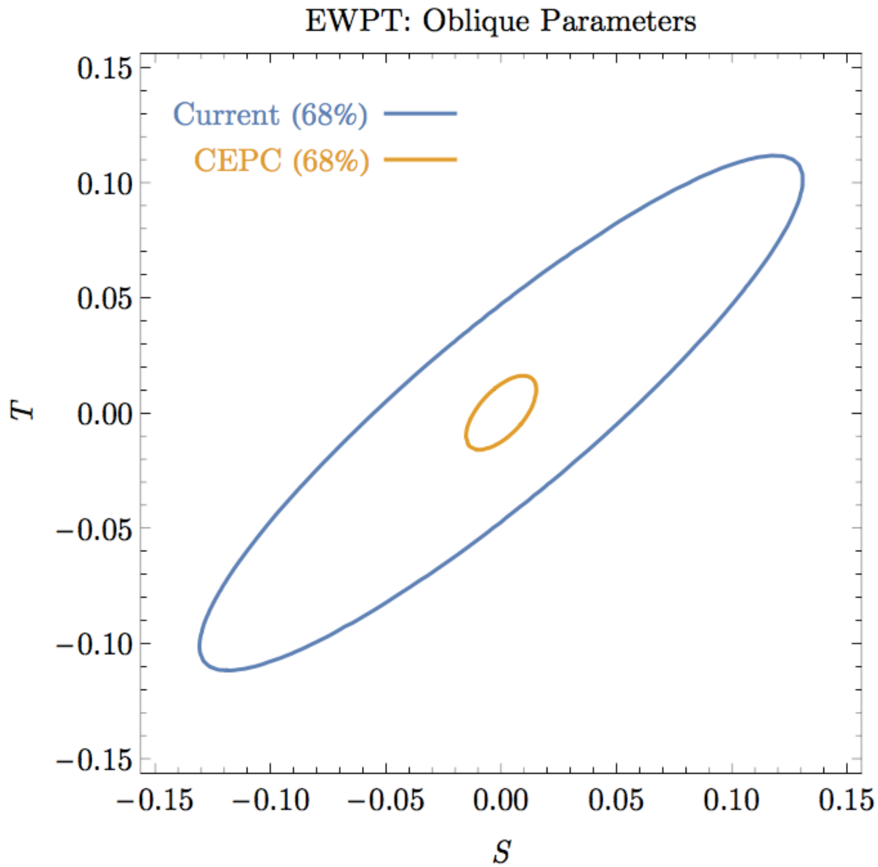


«FCC-ee is not for the faint-hearted !»

Constraint to new physics

- Oblique parameter S,T,U : corrections to gauge-boson self-energies
  - S and T (U) correspond to dimension 6 (8) operators
- Constraint to Oblique parameter from CEPC EWK measurements will be about one order of magnitude better than current constraint.



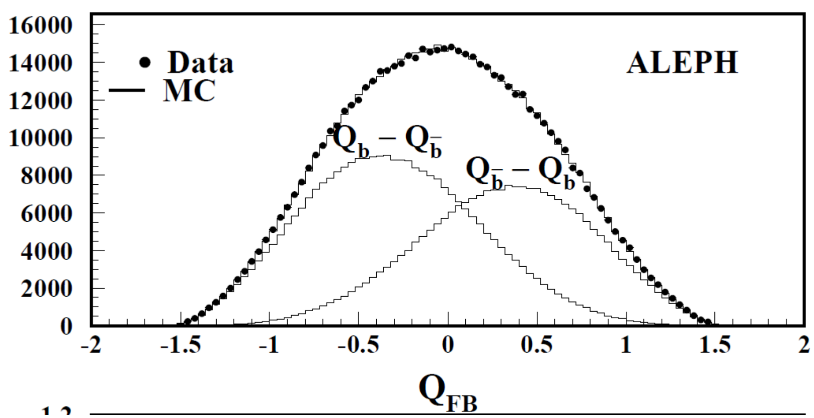


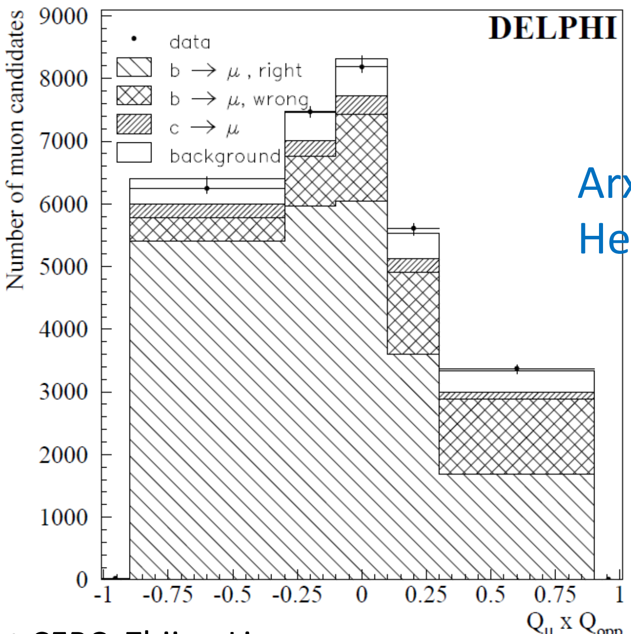
Backward-forward asymmetry

- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay (~2%)
    - Select one lepton from b/c decay, and one b jets
    - Select lepton charge (Q_lepton) and jet charge (Q_jet)
  - Method 2: jet charge method using Inclusive b jet (~1.2%)
    - Select two b jets
    - use event Thrust to define the forward and background
    - Use jet charge difference (Q_F - Q_B) Q_lepton - Q_jet in method 1

Arxiv:Hep-ex/0107033

Q_F - Q_B in method 2





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Prospect of CEPC W mass measurement

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  - A possible BSM physics can be discovered in the future

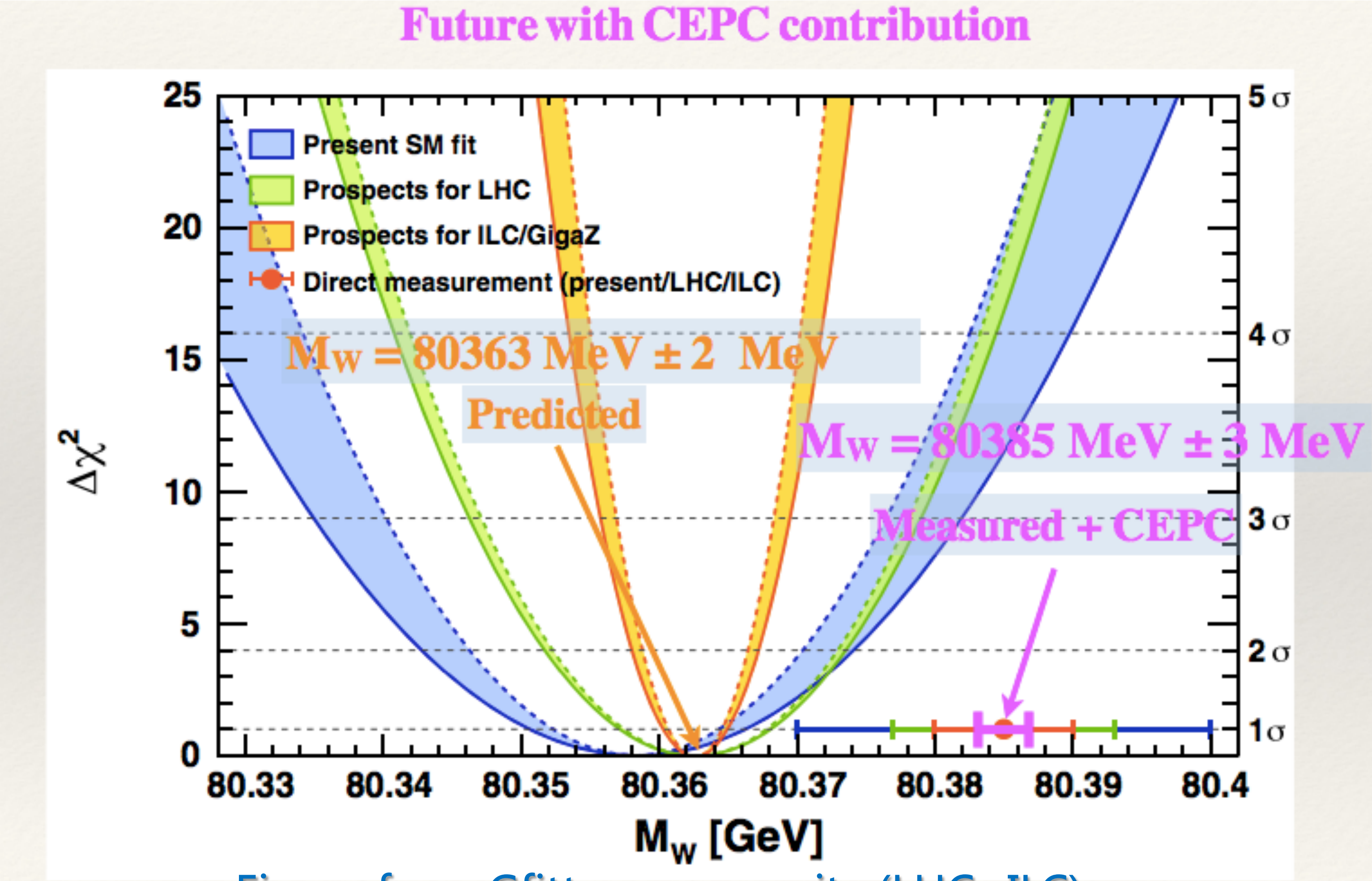
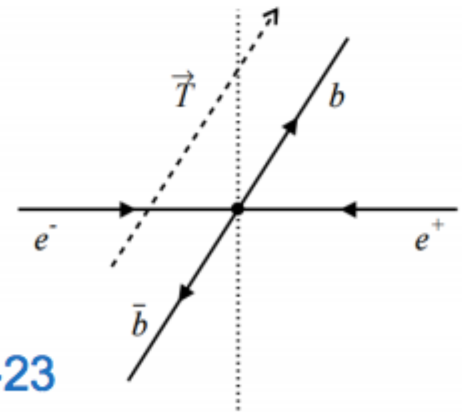


Figure from Gfitter community (LHC+ILC)

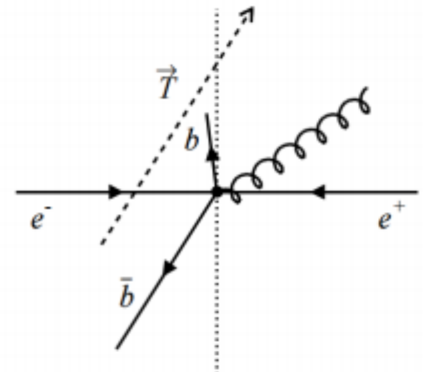
Backward-forward asymmetry $A_{FB}^{b\bar{b}}(0)$

- Uncertainty Afb_b due to QCD correction to Thrust
  - Higher order QCD effect is major systematics

CERN-EP/98-23



(a) No gluon



(d) Thrust forward, quark backward

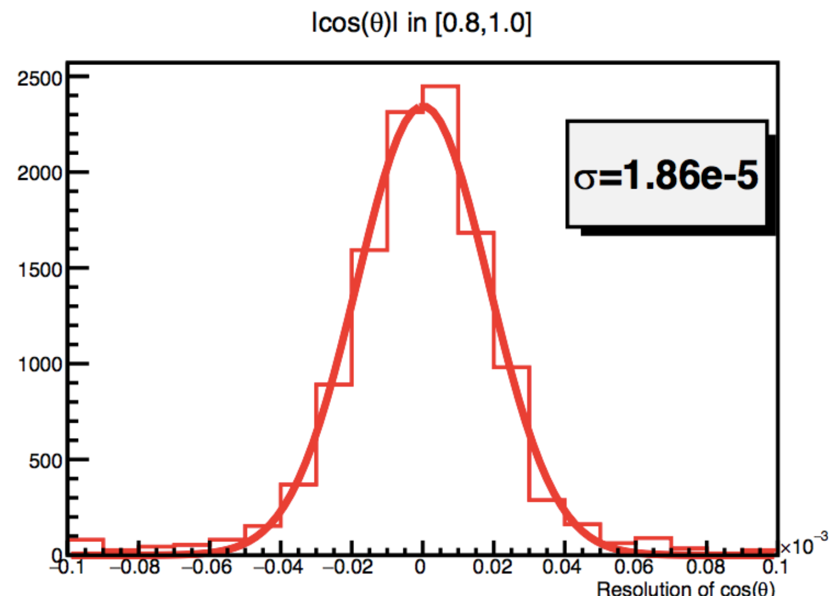
Error source	$C_{\rm QCD}^{\rm quark}$ (%)		$C_{\rm QCD}^{\rm part,T}$ (%)	
	$b\bar{b}$	$c\bar{c}$	$b\bar{b}$	$c\bar{c}$
Theoretical error on m_b or m_c	0.23	0.11	0.15	0.08
$\alpha_s(m_Z^2)$ (0.119 ± 0.004)	0.12	0.16	0.12	0.16
Higher order corrections	0.27	0.66	0.27	0.66
Total error	0.37	0.69	0.33	0.68

Backward-forward asymmetry in Z->μμ

- LEP measurement : 1.69% +-0.13%(PDG fit)
- CEPC aim to improve it by a factor of 20~30 .
  - muon angular resolution and acceptance
  - the precision of beam energy measurement
- Full simulation studies to understand muon angular resolution
  - Muon angular resolution can reach 1e-4 to 1e-5 level

$$A_{FB}^{(0,\mu)}$$

By Mengran Li (IHEP)



Muon angular resolution

WW threshold scan – physics goal

- Statistics is enough for Branching ratio measurement Br (W->had) and αQCD (mW) measurements.
- Statistics uncertainty is one of the limiting factor for W mass and W width measurement with CEPC one year running plan (2.5 fb^{-1})

Energy (GeV)	Systematics	Statistics uncertainty	limiting factor
W mass	1MeV Beam energy	1.0 MeV	/
W width	1 MeV	3.2 MeV	Statistics
Br (W->had) & α_{QCD} (mW)	10^{-4}	10^{-4}	/

Weak mixing angle (2)

- Comparison with Fcc-ee on weaking mixing angle measurement
  - Expect 1~2 order magnitude better than LEP results
  - consistent with FCC-ee prediction

Improvement compared to LEP results	CEPC	FCC-ee (Paolo's talk in CEPC Roma workshop)
A_{FB} (Z->ee)	30	50
A_{FB} (Z->μμ)	20-30	30
A_{FB} (Z->ττ)	NA	15
A_{FB} (Z->bb)	10	5
Weak mixing angle	70	100

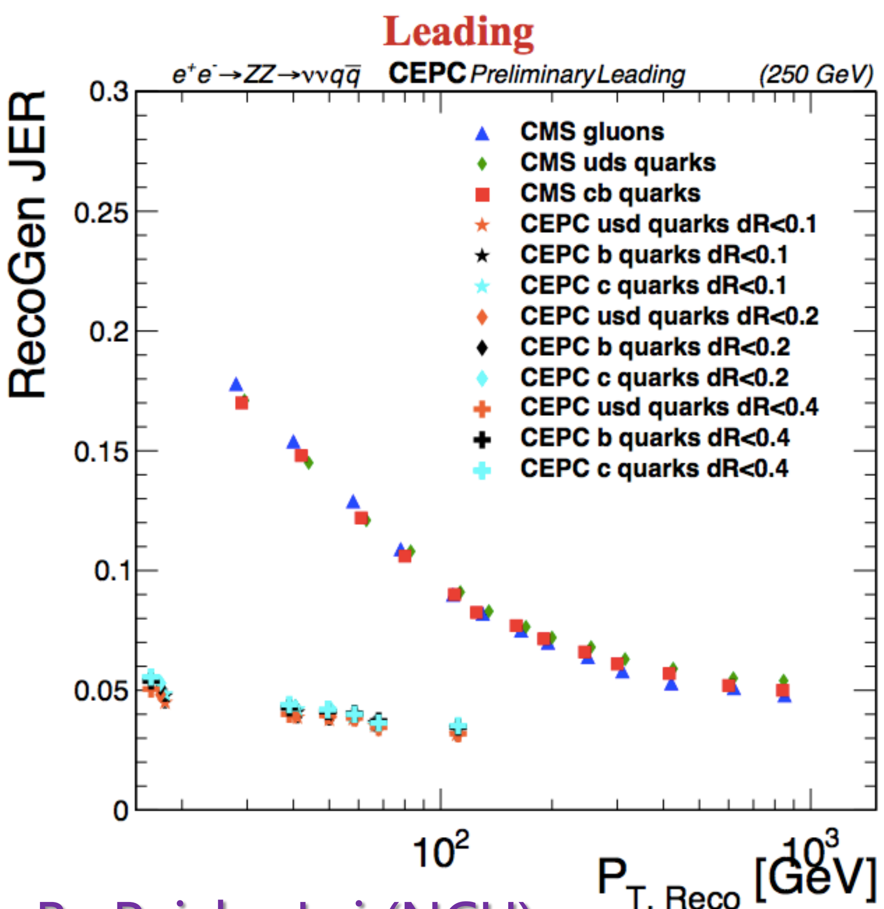
Motivation for CEPC electroweak physics

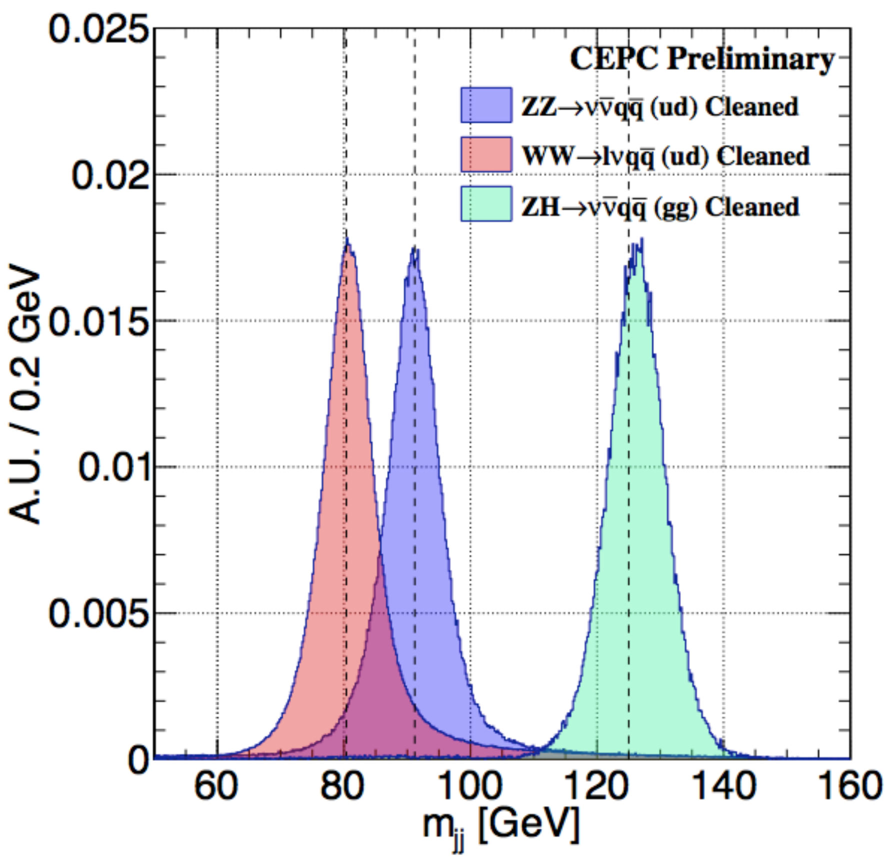
- need more precision in
  - W mass, Top mass and weak mixing angle
- CEPC can provide more precise measurement for
  - W/Z and Higgs mass and weak mixing angle

Fundamental constant	δx/x	measurements
$\alpha = 1/137.035999139\ (31)$ From PDG2018	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 direct measurement

- The Z, W, and Higgs bosons can be well separated in CEPC.
- Benefitted from excellent jet energy resolution and PFA based calorimeter
- Possible to measure W mass from direct di-jet mass reconstruction.





By Peizhu Lai (NCU)

Number of neutrino generation (N_ν)

$e^+e^- \to \nu\bar{\nu}\gamma.$

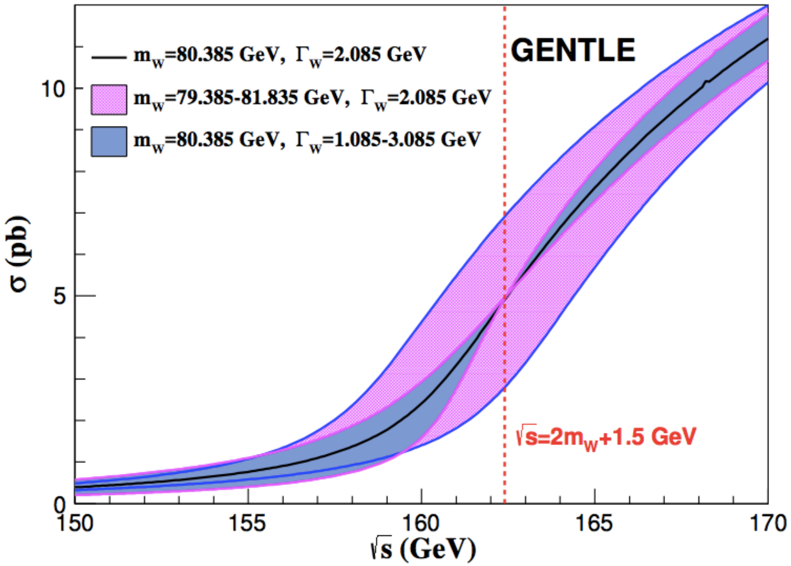
- LEP measurement :
  - Indirect measurement (Z line shape method): 2.984+-0.008
  - Direct measurement (neutrino counting method): 2.92+-0.05
    - Stat error (1.7%), Syst error (1.4%)
- CEPC measurement :
  - Focus on direct measurement, Expected Syst error (~0.2%)
  - High granularity in calorimeter can help photon identification
  - Detector readout time and Pileup is also key for Missing energy
  - Need focus on improving photon energy scale in next step

Systematics source	LEP	CEPC
Photon trigger and Identification efficiency	~0.5%	<0.1%
Calorimeter energy scale	0.3~0.5%	<0.2%

WW threshold scan-systematics unc.

- Consider the beam spread unc. (EBS),beam energy unc. , signal efficiency, cross section unc. and background
- Expected 1MeV precision
  - Dominated by statistics uncertainty: 1MeV
  - Leading syst. (0.5MeV): beam energy syst.
- Working with Paolo Azzuri and Maarten Boonekamp for systematics study
- Plan to have a joint CEPC-Fcc(ee) paper on WW threshold scan.

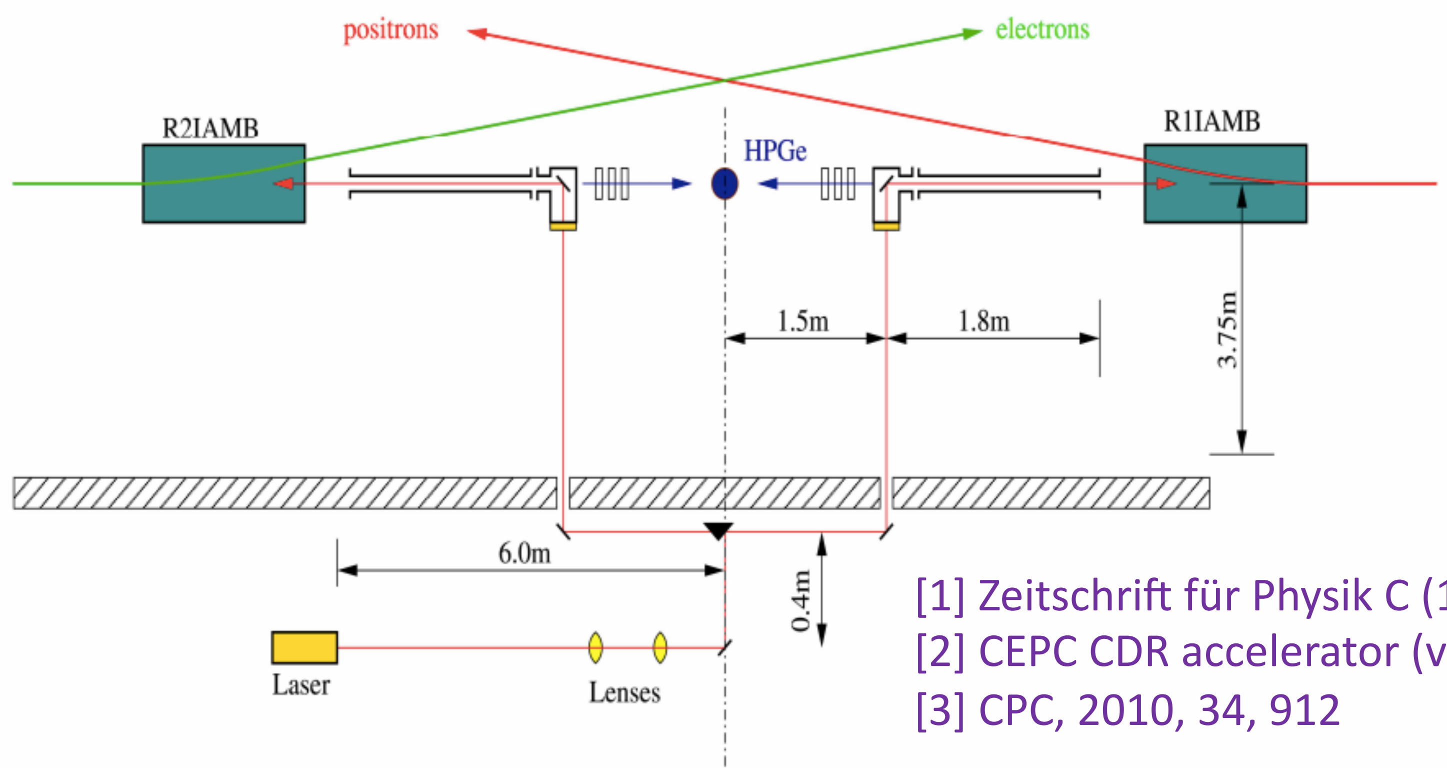
Observable	m_W	Γ_W
Source	Uncertainty (MeV)	
Statistics	0.8	2.7
Beam energy	0.4	0.6
Beam spread	–	0.9
Corr. syst.	0.4	0.2
Total	1.0	2.8



Paolo Azzuri et al. arxiv: 1703.01626v1

Z mass measurement（2）

- Syst uncertainty: ~0.5 MeV
  - Beam energy uncertainty is major systematics
    - Resonant depolarization approach by LEP [1] → <0.5MeV
    - Compton backscattering [2] → 2~5 MeV
    - Radiation return , Z(μμ)γ events → 2~5MeV



[1] Zeitschrift für Physik C (1995) 45–62.
[2] CEPC CDR accelerator (volume I)
[3] CPC, 2010, 34, 912