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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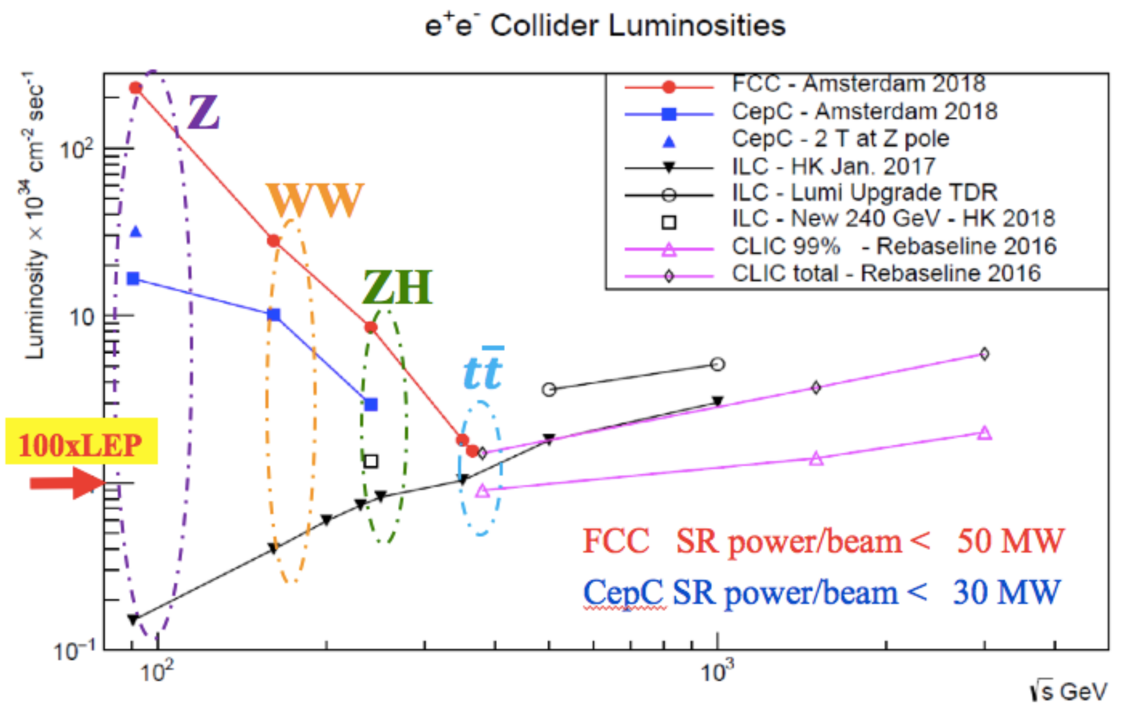
Institute of High Energy Physics ,
Chinese Academy of Science

KAIST-KAIX workshop for Future Particle Accelerators

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

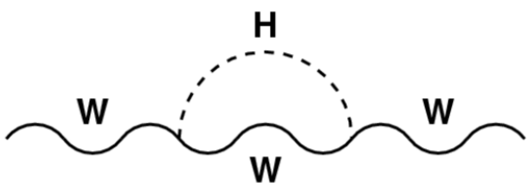
- Review of the key electroweak constant
  - Beam energy systematics is dominant systematics on M_Z, M_W
  - Beam energy measurement is the key to Z pole and WW physics

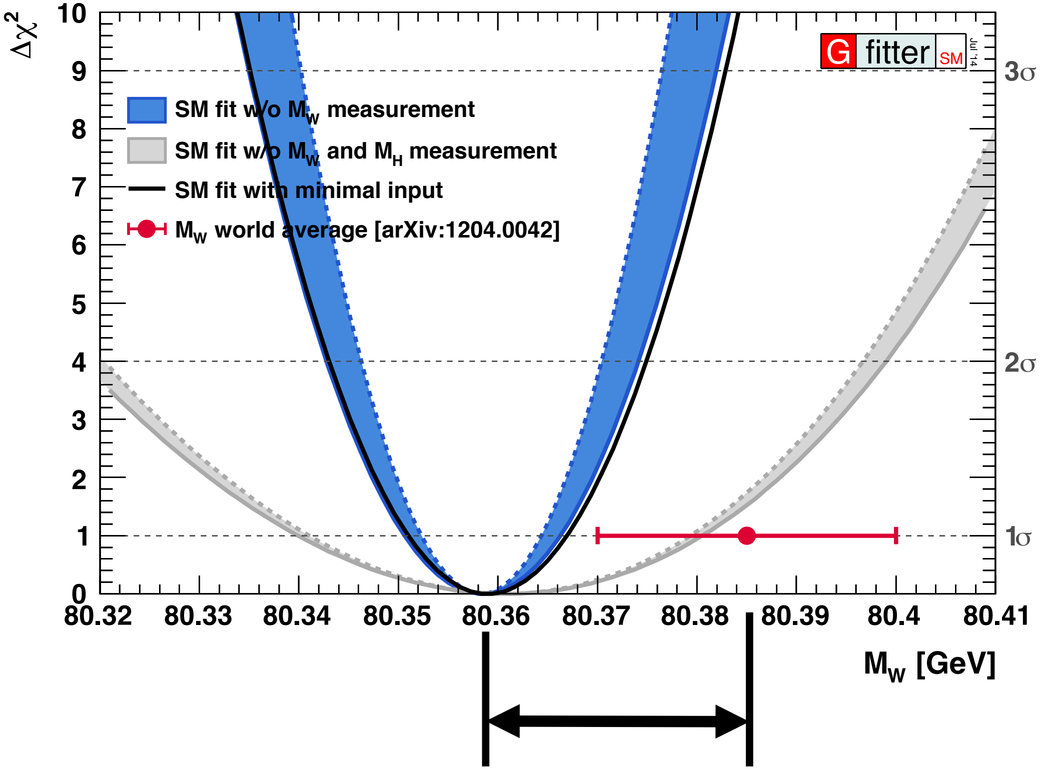
Fundamental constant	δx/x	measurements	
$\alpha = 1/137.035999139\,(31)$	1×10^{-10}	$e^{\pm}\ g_2$	Z pole
$G_F = 1.1663787\,(6)\times10^{-5}\ \mathrm{GeV}^{-2}$	1×10^{-6}	$\mu^{\pm}$ lifetime	
$M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$	1×10^{-5}	LEP	Z pole
$M_W = 80.379 \pm 0.012\ \mathrm{GeV}$	1×10^{-4}	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



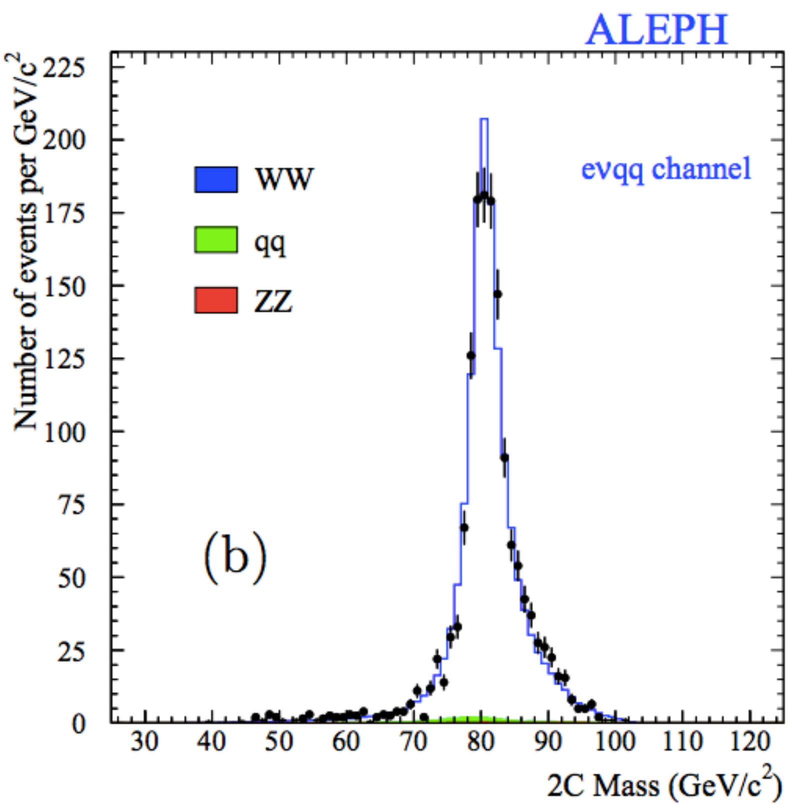


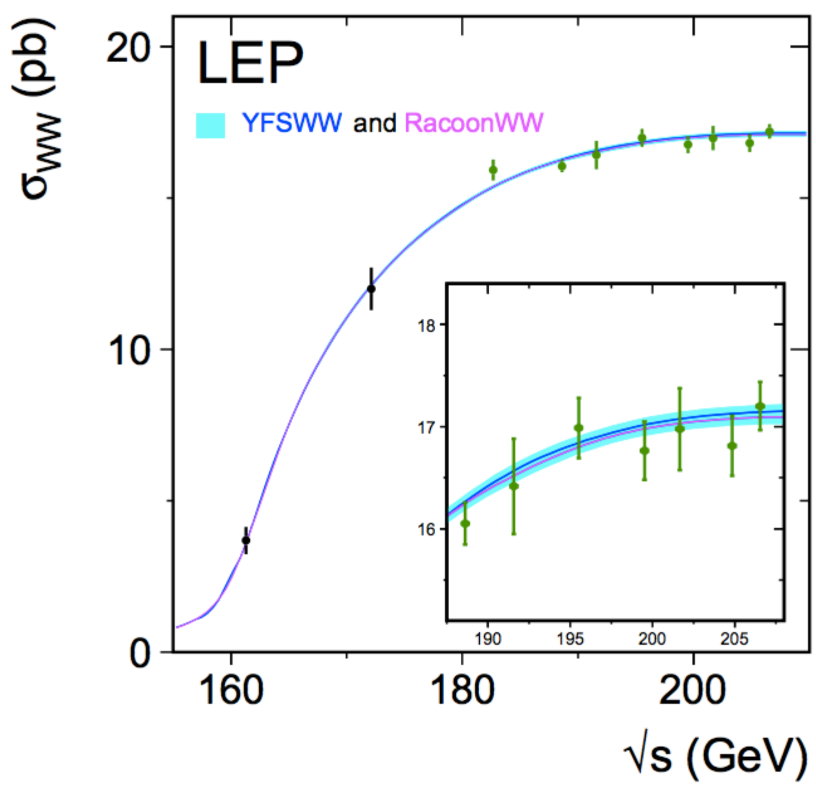
W mass measurement in lepton collider

- Two approaches to measure W mass at lepton collider:

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

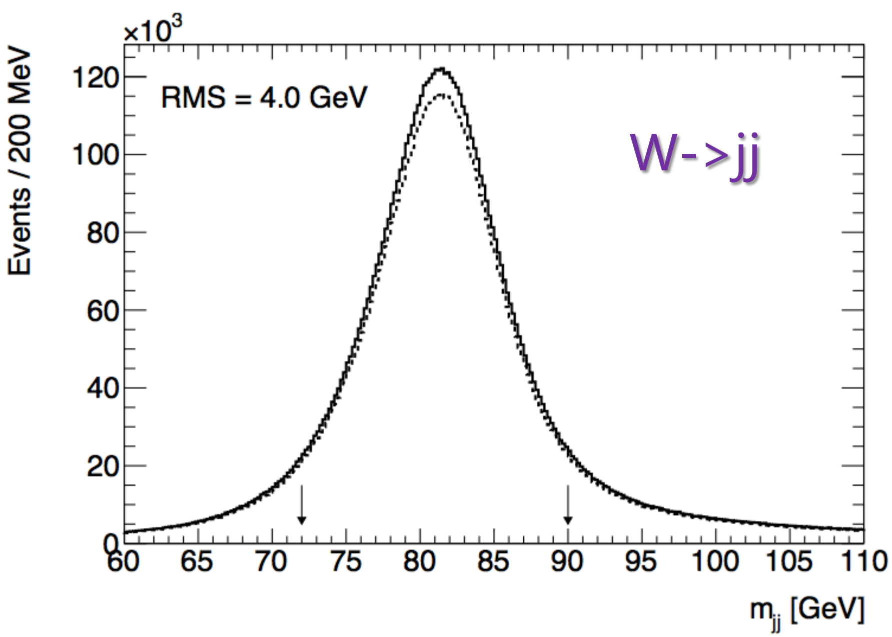
WW threshold scan
WW threshold runs (157~172GeV)
Expected Precision 1MeV level

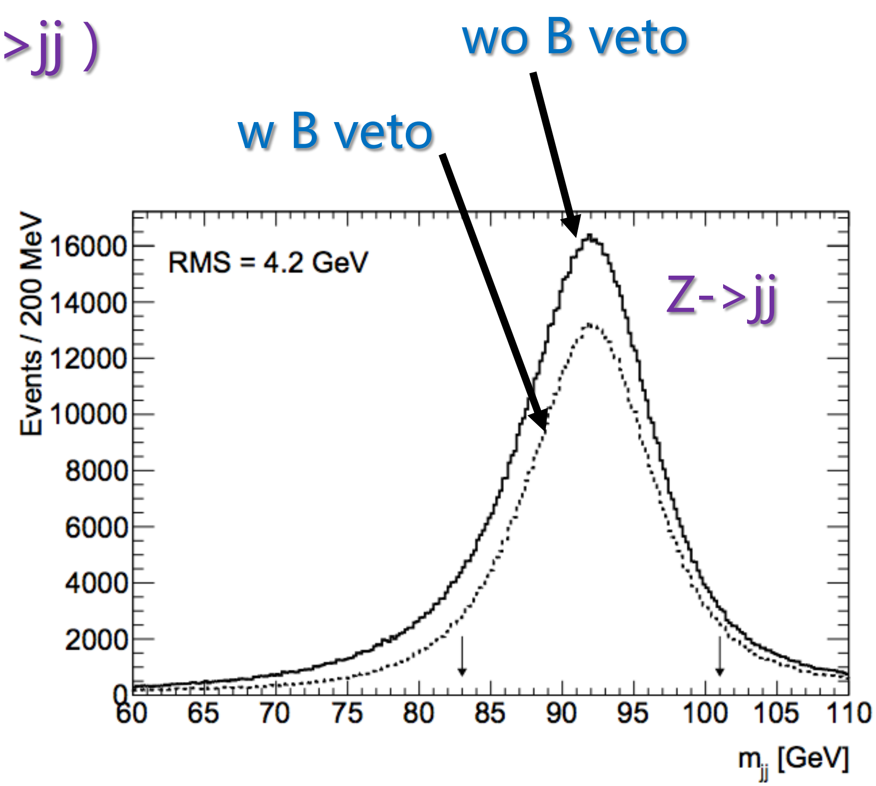




W mass direct measurement

- 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)

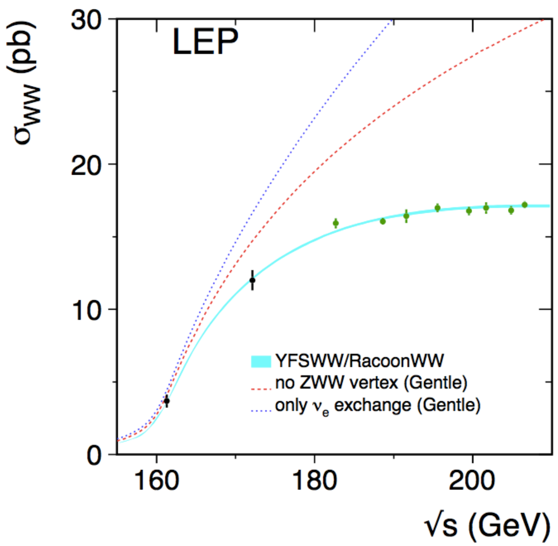




WW threshold scan – CEPC plan

- 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

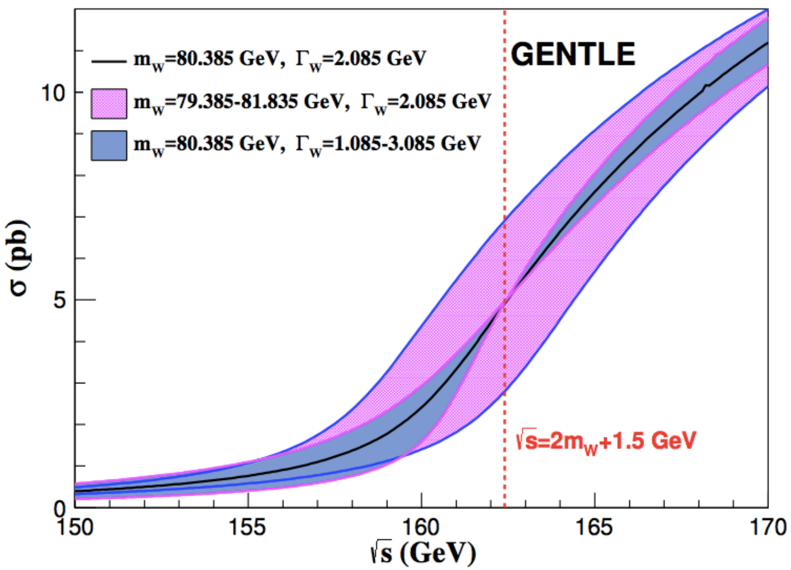
E_{cm} (GeV)	Lumiosity (ab^{-1})	Cross section (pb)	Number of WW pairs (M)
157.5	0.5	1.25	0.6
161.5	0.2	3.89	0.8
162.5	1.3	5.02	6.5
172.0	0.5	12.2	6.1



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.
- Plan to have a joint CEPC-Fcc(ee) paper on WW threshold scan.

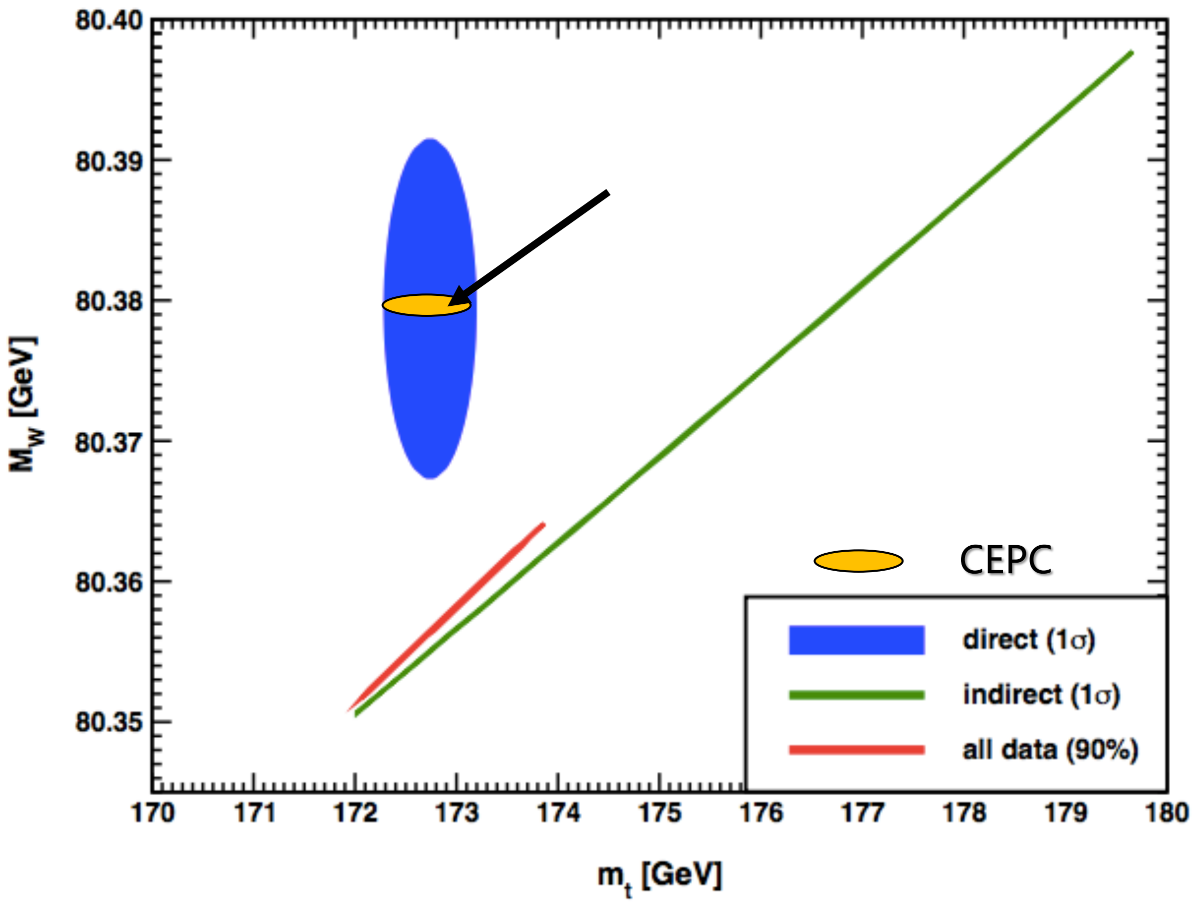
Observable	m_W	Γ_W
Source	Uncertainty (MeV)	
Statistics	0.8	2.7
Beam energy	0.4	0.6
Beam spread	–	0.9
Corr. syst.	0.4	0.2
Total	1.0	2.8



Paolo Azzuri et al. arxiv: 1703.01626v1

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

Prospect of CEPC EWK physics

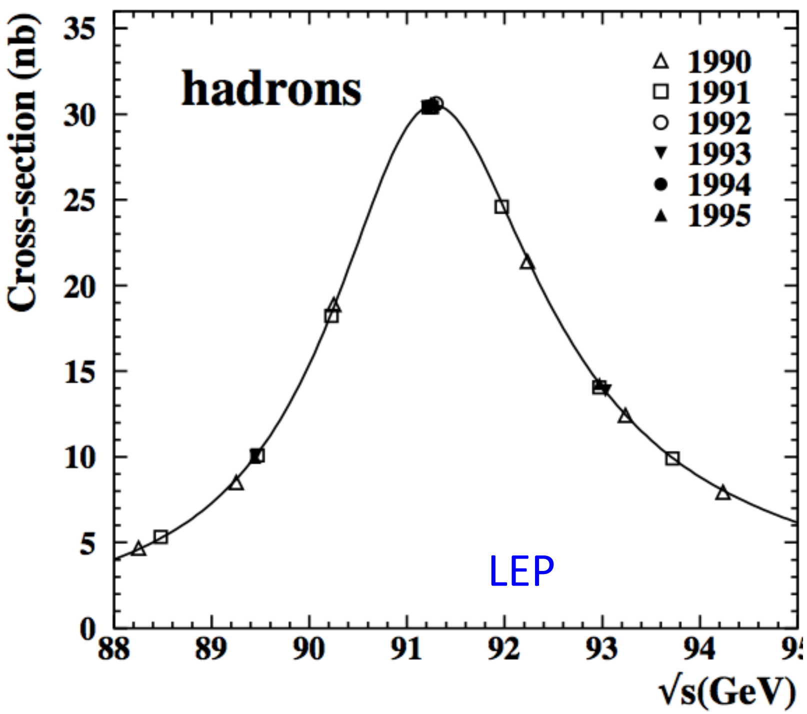
- Expect to have 1~2 order of magnitude better than current precision

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}
$\sin^2\theta_W^{\text{eff}}$	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}

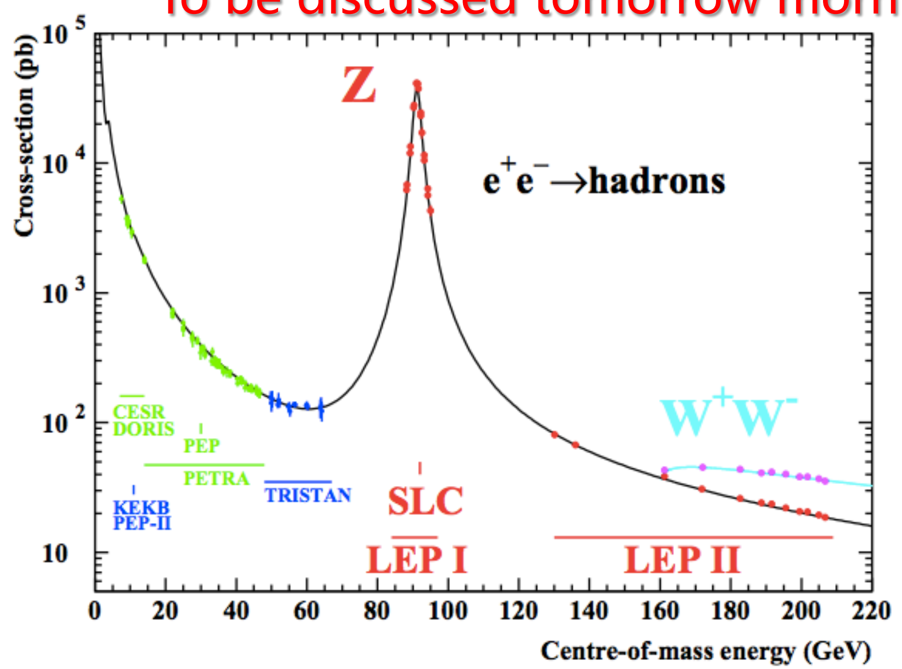
Table 11.9: The expected precision in a selected set of EW precision measurements in CEPC and the comparison with the precision from LEP experiments. The CEPC accelerator running mode and total integrated luminosity expected for each measurement are also listed.

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
  -



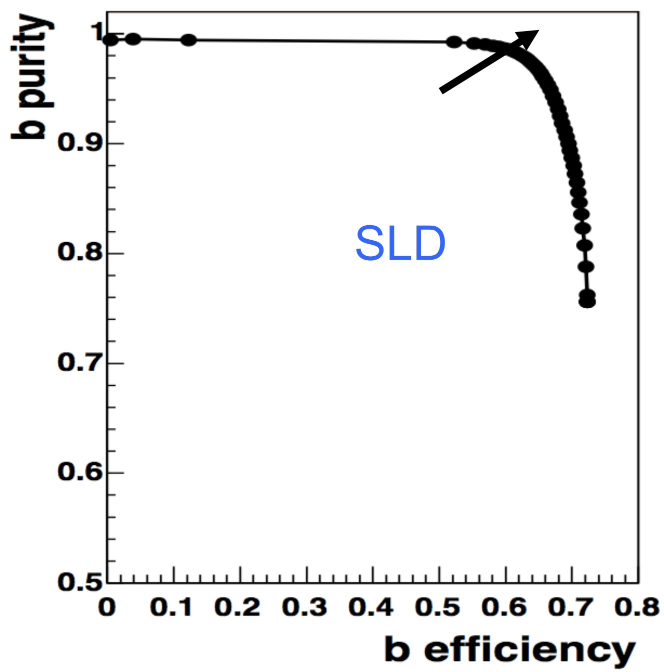
To be discussed tomorrow morning

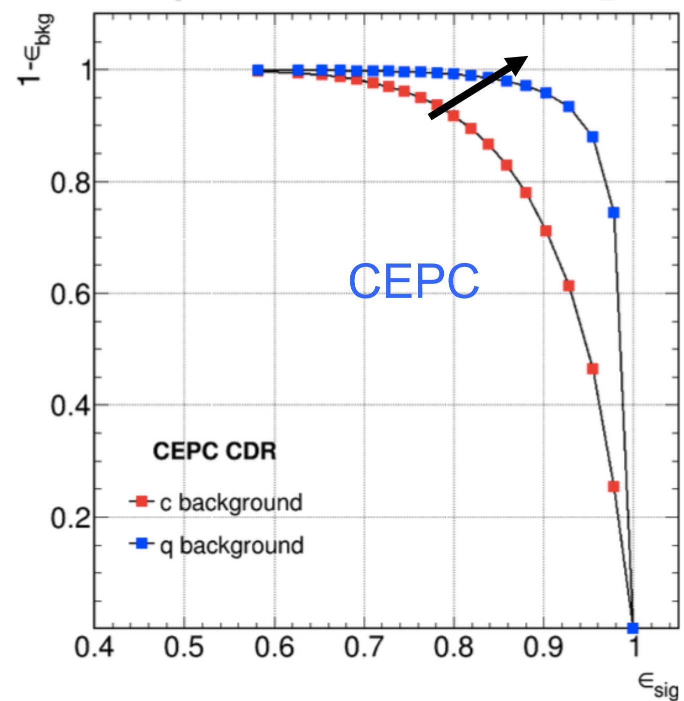


$\frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to had)}$ Branching ratio (R^b)

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

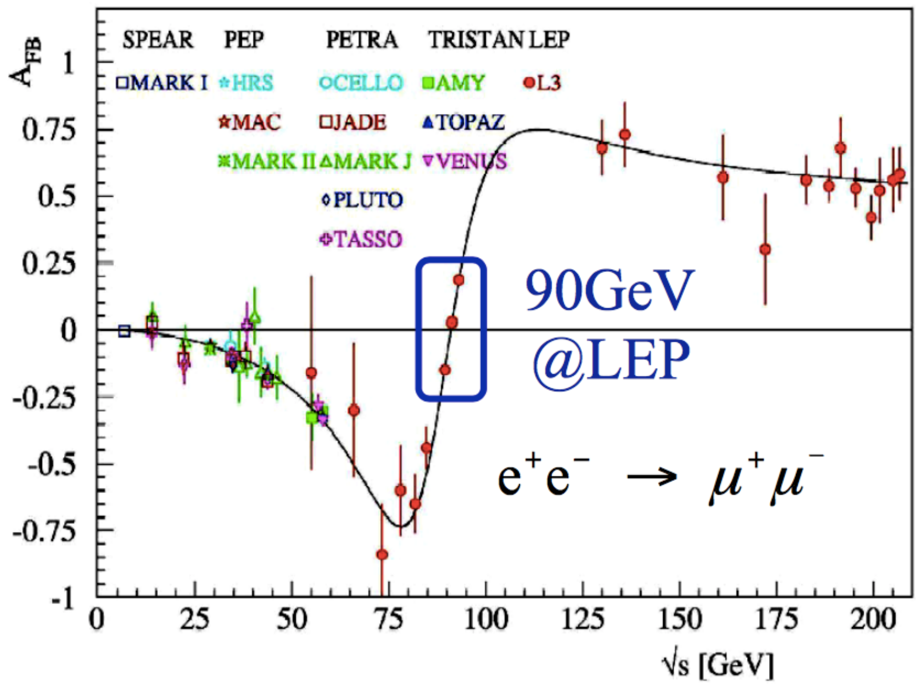
- LEP measurement 0.21594 ±0.00066
  - Syst error : ~0.2%
    - Major systematics is hemisphere tag correlations
- CEPC
  - Expected Syst error (0.02%)
  - hemisphere tag correlations depends on b tagging efficiency
  - Expect 20~30% higher B tagging efficiency than SLD
  - Theory uncertainty (gluon splitting ..): need input from theorists

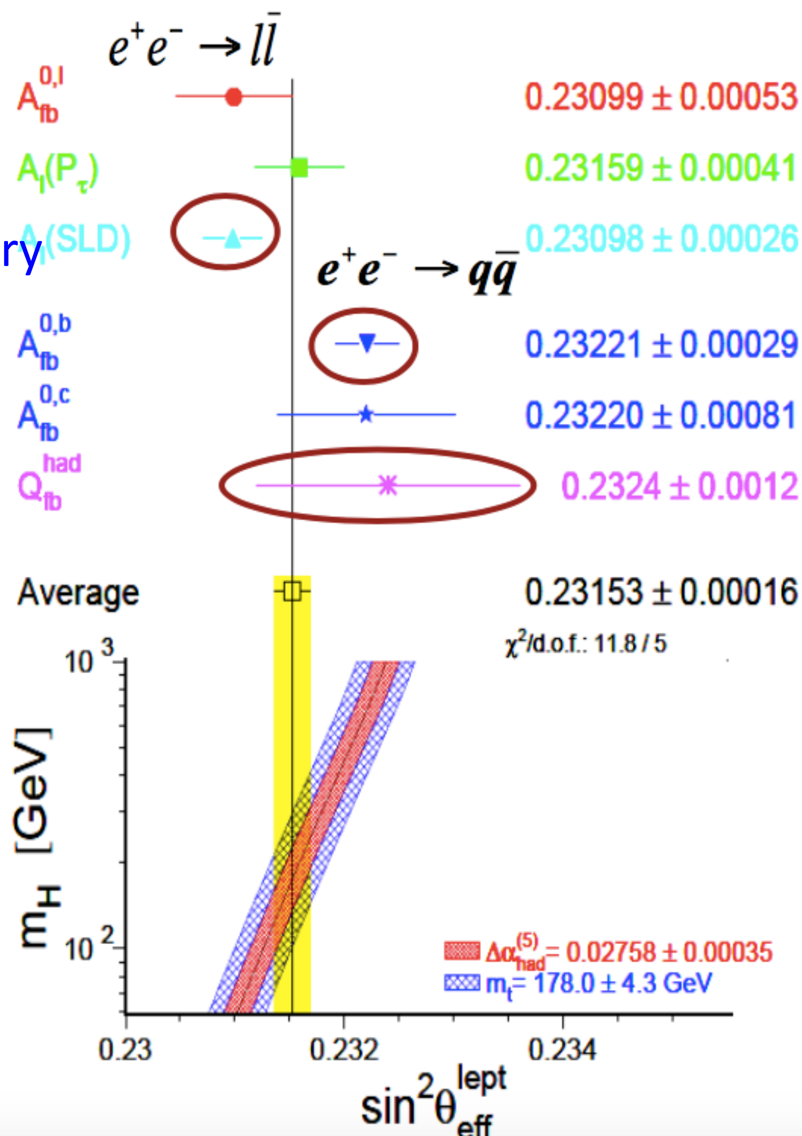




Weak mixing angle $\sin^2\theta_{eff}^{lept}$

- 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



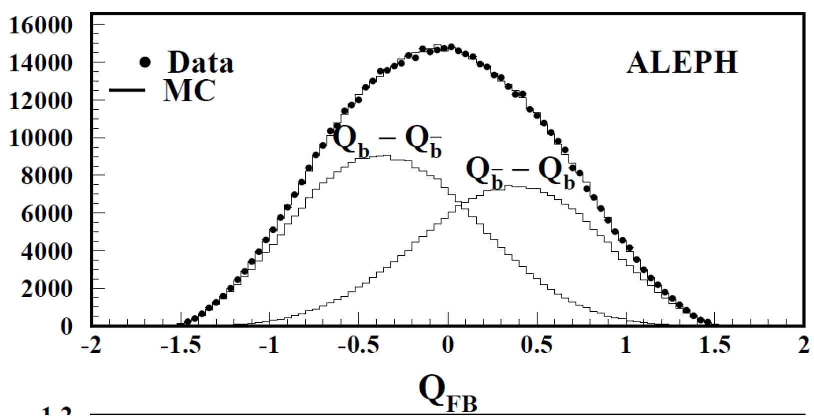


Backward-forward asymmetry $A_{FB}^{0,b}$

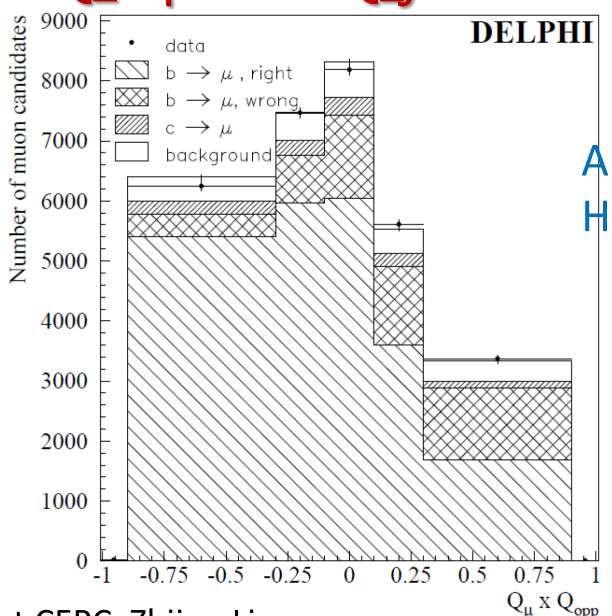
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay
    CEPC precision 0.1% ,LEP precision ~2% (stat dominated)
    - Main systematics is B hadron decay branching ratio
  - Method 2: jet charge method , Inclusive b jet (LEP precision 1.2%)
    - use event Thrust to define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

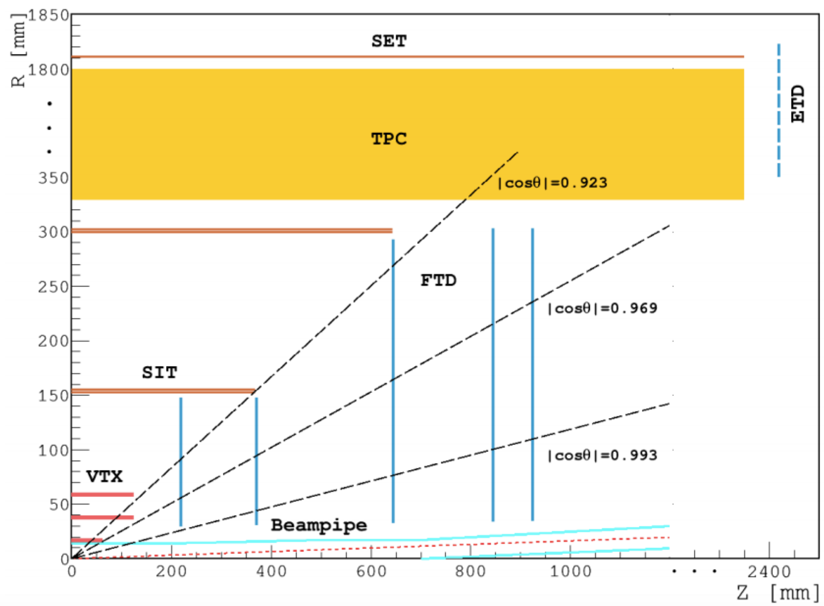


Arxiv: Hep-ex/0403041

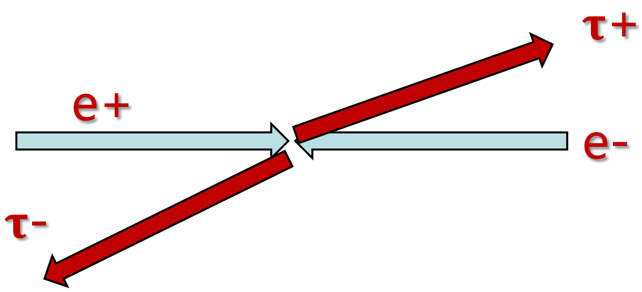
Backward-forward asymmetry in Z->μμ

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

- LEP measurement : 0.0169 +-0.00130
- CEPC expected: +-0.00005
- CEPC has potential to improve it by a factor of 20~30 .
  - Acceptance systematics (larger detector coverage, smaller syst.)
  - The precision of beam energy measurement
- Major systematics
  - Beam energy systematics ($5e^{-5}$)
  - 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 expected precision in CEPC
  - Direct measurement using Z ->ττ events is more precise
  - τ polarization information is the key

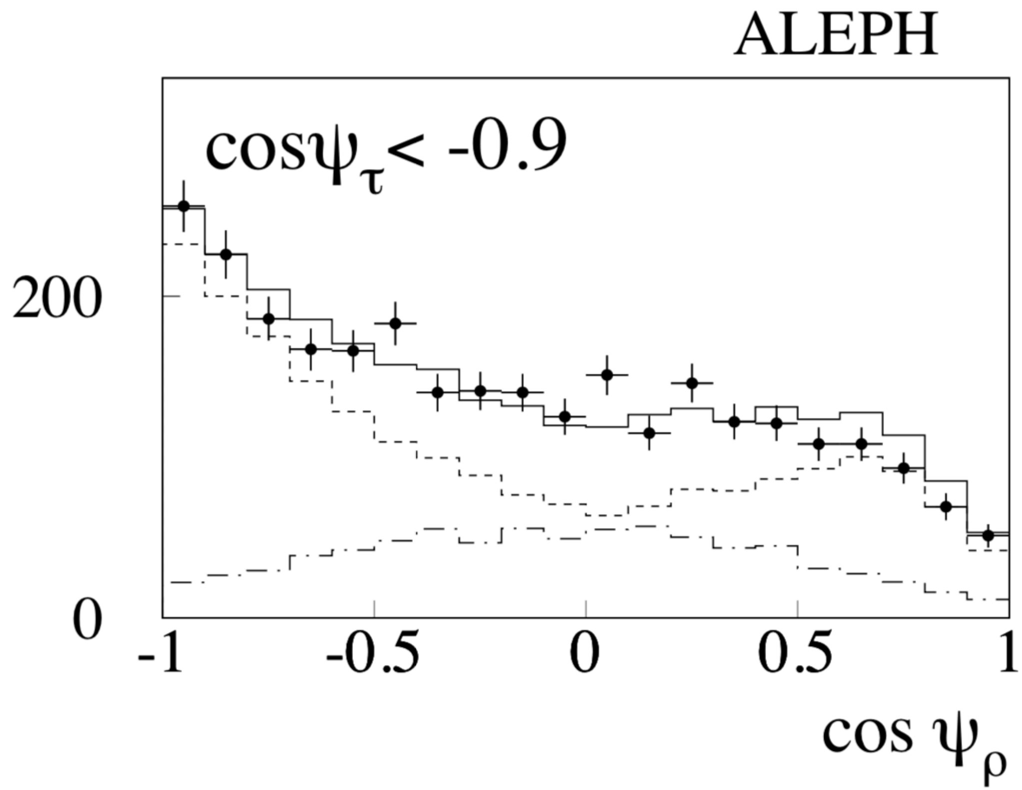
Precision (relative uncertainty)	A_e	A_τ
Direct measurement from Z ->ττ τ polarization analysis	0.0003	0.0005
A_{FB} from Z ->ee and Z ->ττ (indirect measurement)	0.003	0.006

A_e and A_τ in $Z \rightarrow \tau\tau$

- 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 (%)
$\tau \rightarrow e\nu_e\nu_\tau$	18434	89.4 ± 0.1
$\tau \rightarrow \mu\nu_\mu\nu_\tau$	19811	94.3 ± 0.1
$\tau \rightarrow \pi/K\nu_\tau$	14850	73.2 ± 0.1
$\tau \rightarrow \rho\nu_\tau$	26548	75.4 ± 0.1
$\tau \rightarrow a_1\nu_\tau$	9446	53.2 ± 0.2



From ALEPH

Eur.Phys.J.C20:401-430,2001

A_e and A_τ in $Z \to \tau\tau$: systematics

- Key systematics is from EM scale, and τ identification
- A_τ : stat +- 0.00015 (scale from LEP), total unc., 0.0005
- A_e : stat +-0.0003 (scale from LEP), Total unc. , 0.0003

	A_e						
Systematic effect	h	ρ	$3h$	$h2\pi^0$	e	μ	acol
tracking	0.04	-	-	-	-	0.05	-
non-τ background	0.13	0.08	0.02	0.07	1.23	0.24	0.24
modelling	-	-	0.40	0.40	-	-	-
TOTAL	0.13	0.08	0.40	0.41	1.23	0.24	0.24

Eur.Phys.J.C20:401-430,2001

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

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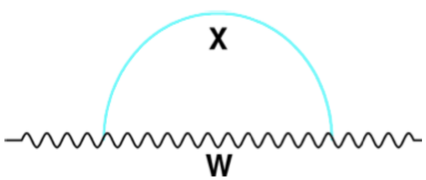
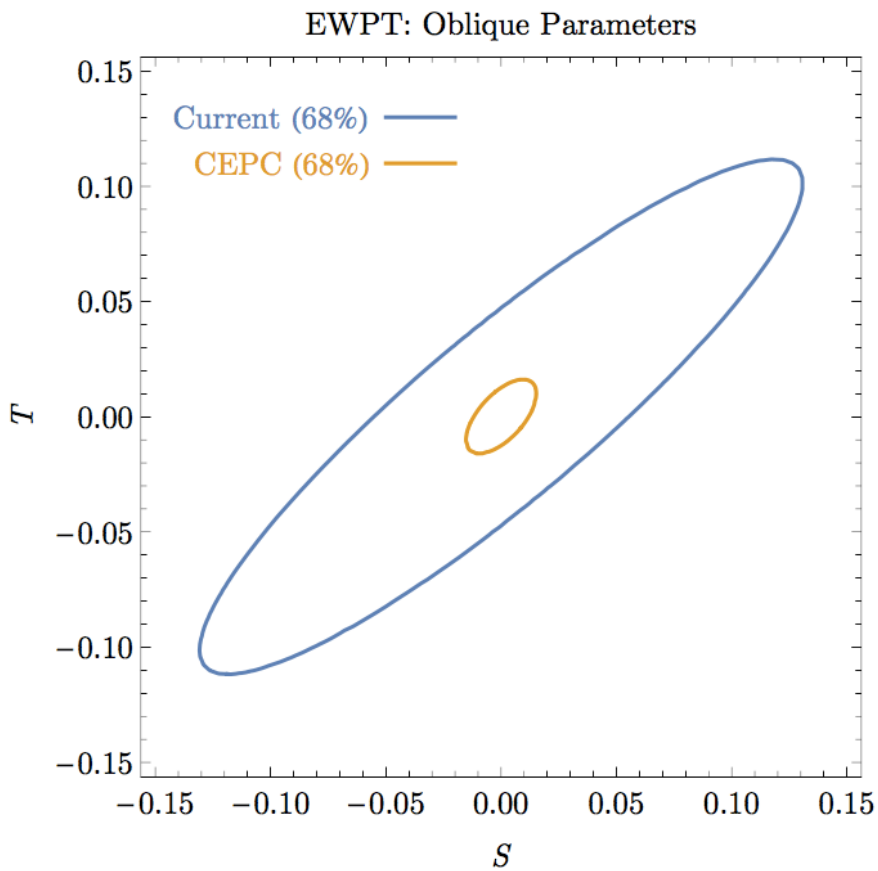
Table 11.9: The expected precision in a selected set of EW precision measurements in CEPC and the comparison with the precision from LEP experiments. The CEPC accelerator running mode and total integrated luminosity expected for each measurement are also listed.

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.



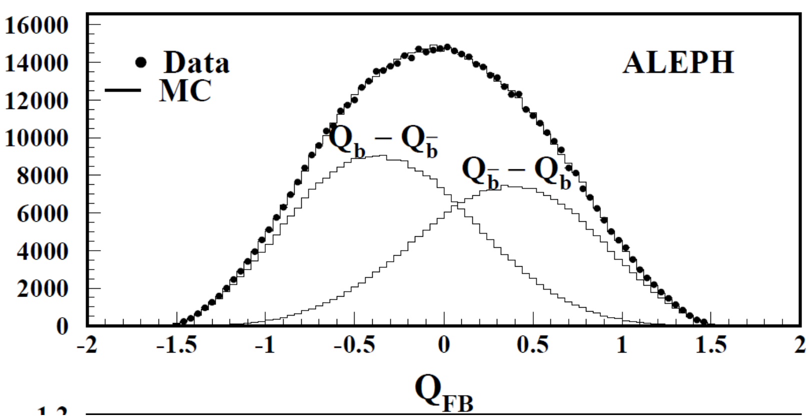


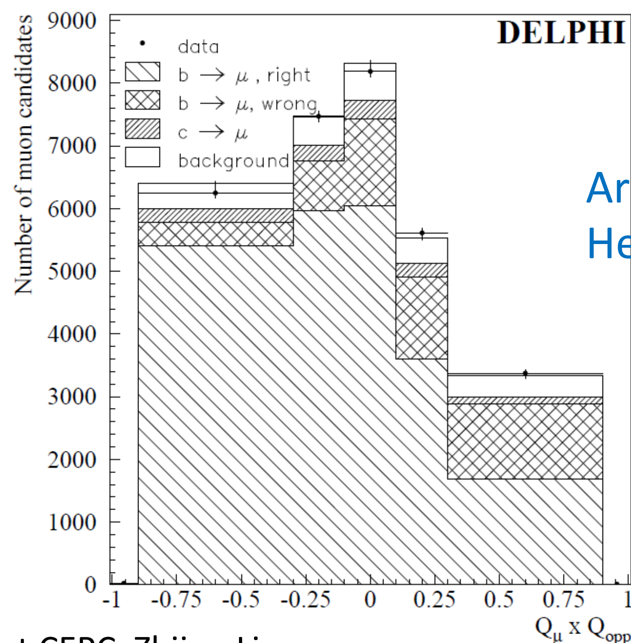
Backward-forward asymmetry

- 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





Arxiv: Hep-ex/0403041

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

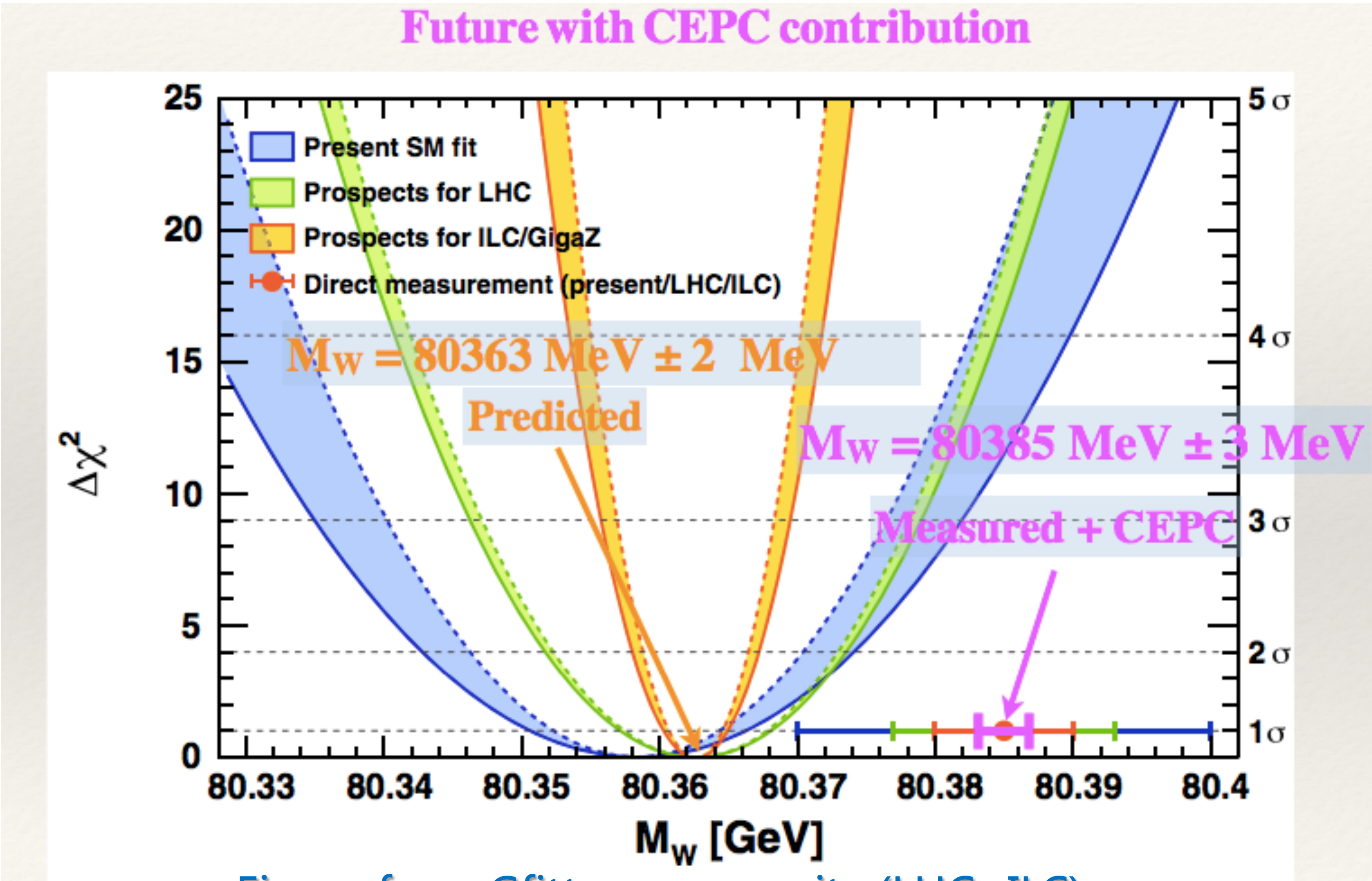
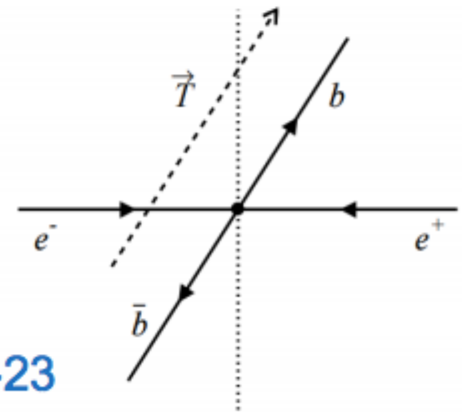


Figure from Gfitter community (LHC+ILC)

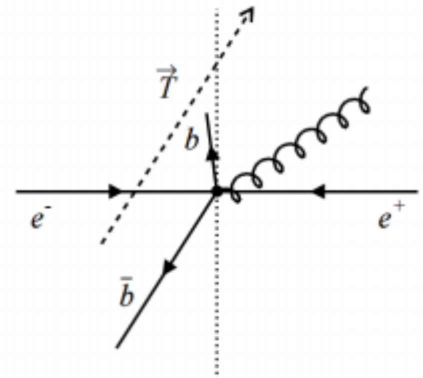
Backward-forward asymmetry $A_{FB}^{b\bar{b}}(0)$

- 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

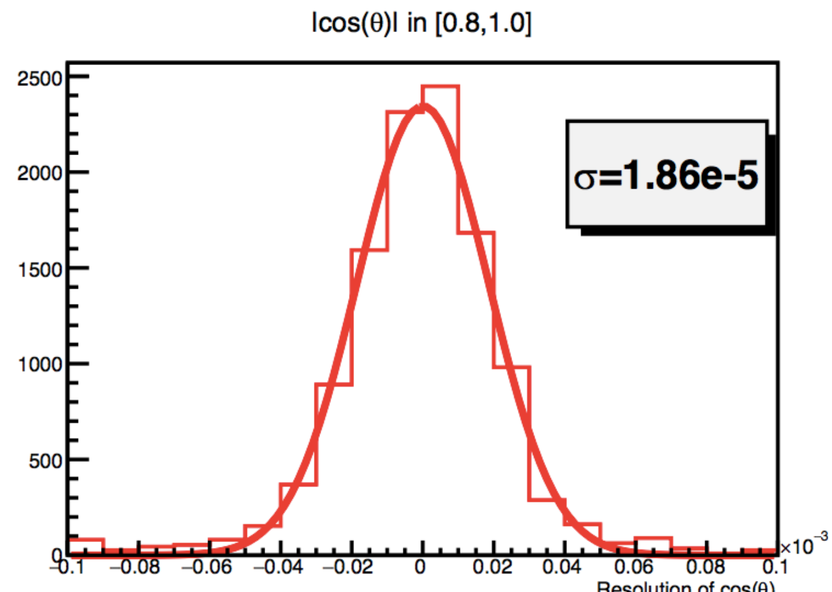
Error source	C_{QCD}^{quark} (%)		$C_{QCD}^{part,T}$ (%)	
	$b\bar{b}$	$c\bar{c}$	$b\bar{b}$	$c\bar{c}$
Theoretical error on m_b or m_c	0.23	0.11	0.15	0.08
$\alpha_s(m_Z^2)$ (0.119 ± 0.004)	0.12	0.16	0.12	0.16
Higher order corrections	0.27	0.66	0.27	0.66
Total error	0.37	0.69	0.33	0.68

Backward-forward asymmetry in Z->μμ

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

- 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

By Mengran Li (IHEP)



Muon angular resolution

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

Number of neutrino generation (N_ν)

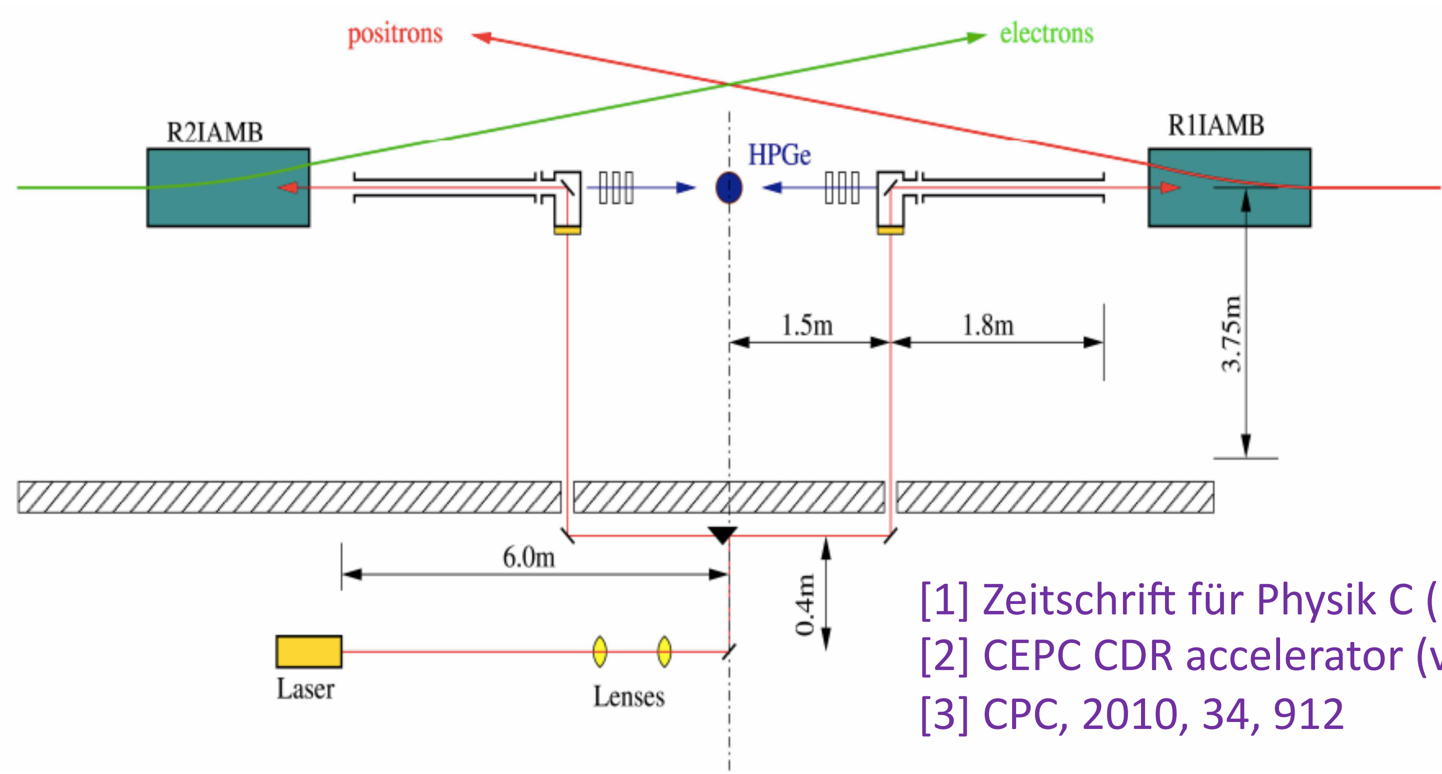
$e^+e^- \to \nu\bar{\nu}\gamma.$

- 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%

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