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 conceptual design report

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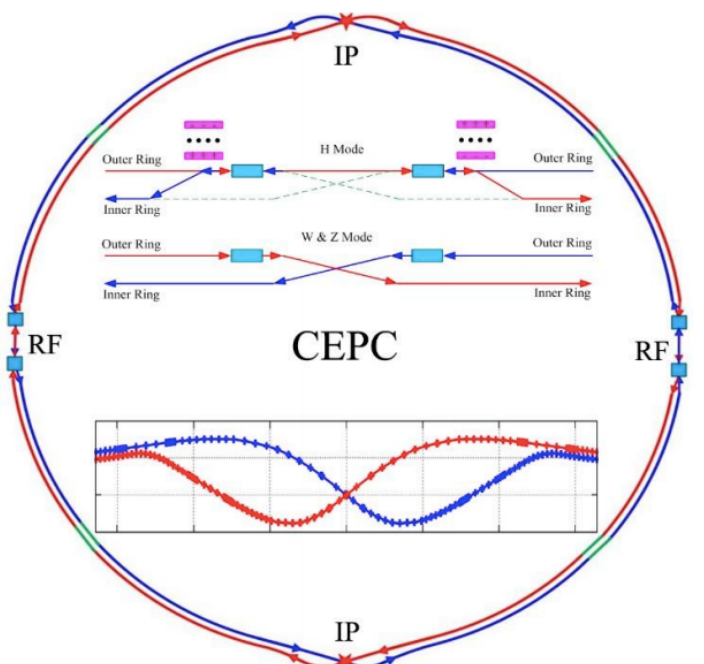
Conceptual design report review meeting , Sep 15th 2018

Outline

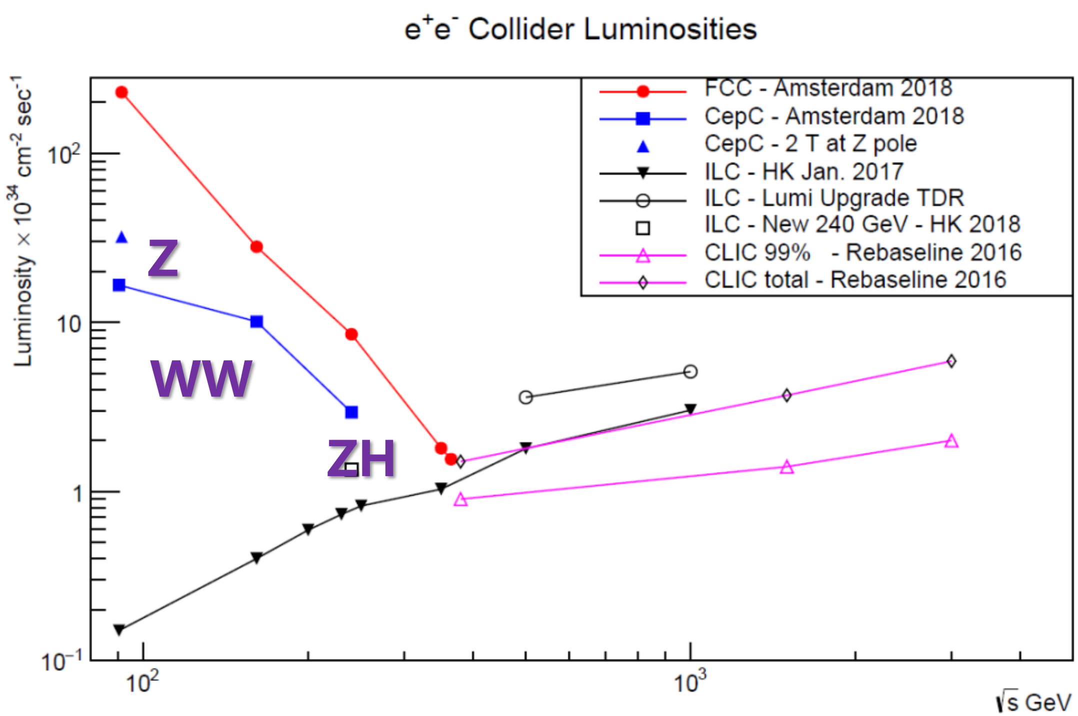
- Introduction to CEPC
- W physics
- Z pole physics

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 =2T, 3X10^{11} Z boson
  - L= 3.2 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =3T , 6X10^{11} Z boson
  - **Assuming Z cross section with ISR correction : 32 nb**
- WW threshold scan runs (~160GeV) are also expected.
  - Total luminosity 2.5 ab^{-1} ,**14M WW events**

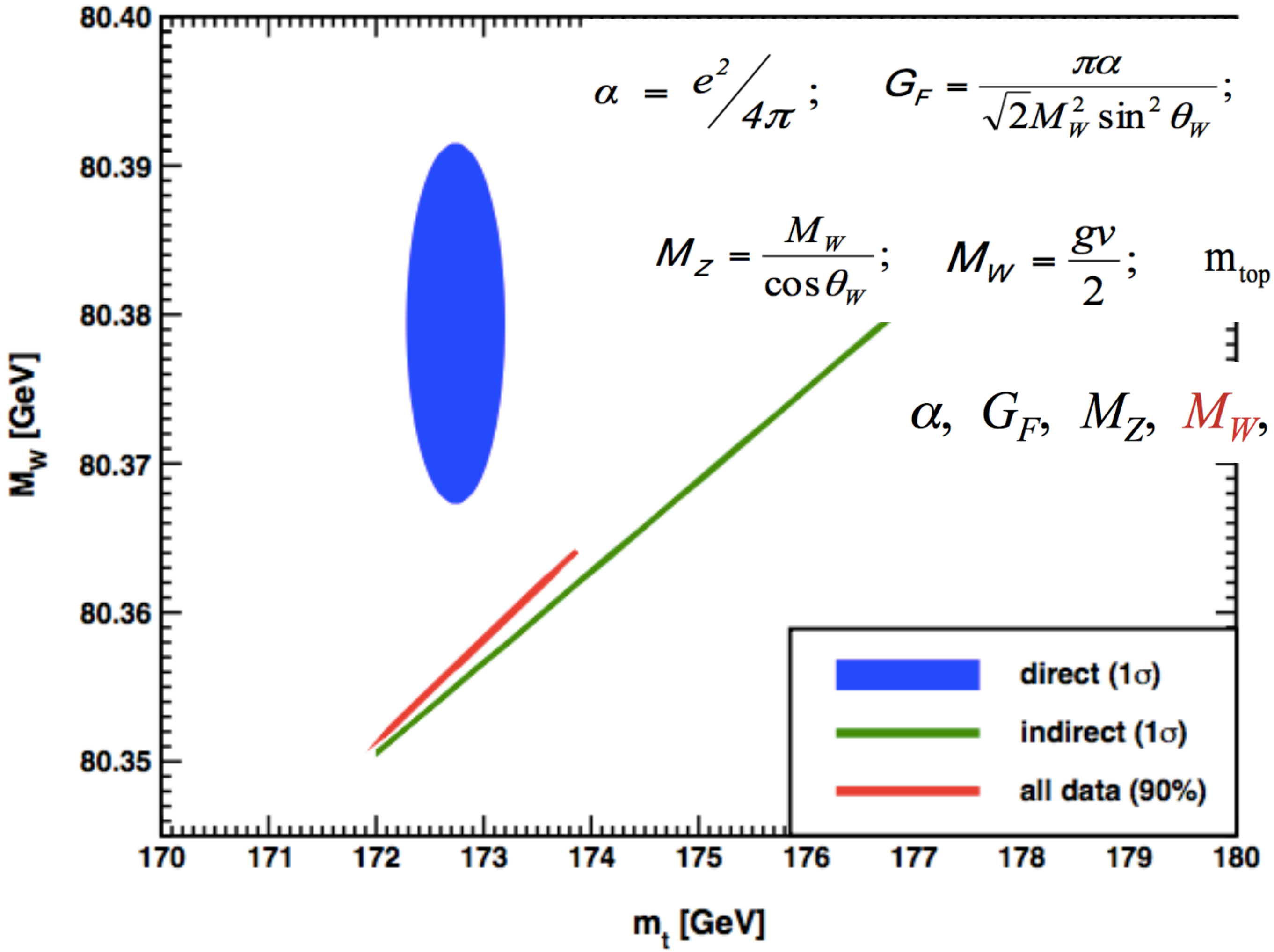


Electrow



Status of electroweak global fit

- Small tension in top mass and W mass.(2σ)
  - Between direct measurement and EWK fit



$$\alpha = e^2/4\pi; \quad G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W}; \quad \sin^2\theta_W = \frac{e^2}{g^2} = 1 - \frac{M_W^2}{M_Z^2};$$

$$M_Z = \frac{M_W}{\cos\theta_W}; \quad M_W = \frac{gv}{2}; \quad m_{top}; \quad m_H = 2v\sqrt{\lambda}$$

$$\alpha,\ G_F,\ M_Z,\ M_W,\ \sin^2\theta_W,\ m_{top},\ M_H$$

self-consistency Check of SM

Freitas & JE (PDG 2018)

Motivation of W mass measurement

- Small tension in W mass in EWK fit may indicate new physics
- Precision measurement is important
    - It constrain new physics beyond the standard model.
    - Eg: Radiative corrections of the W or Z boson is sensitive to new physics

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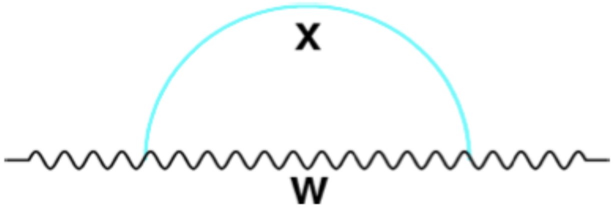
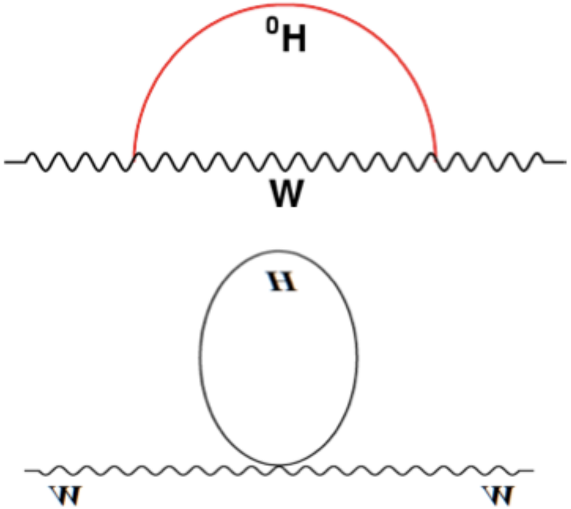
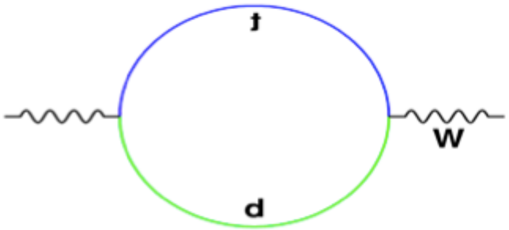




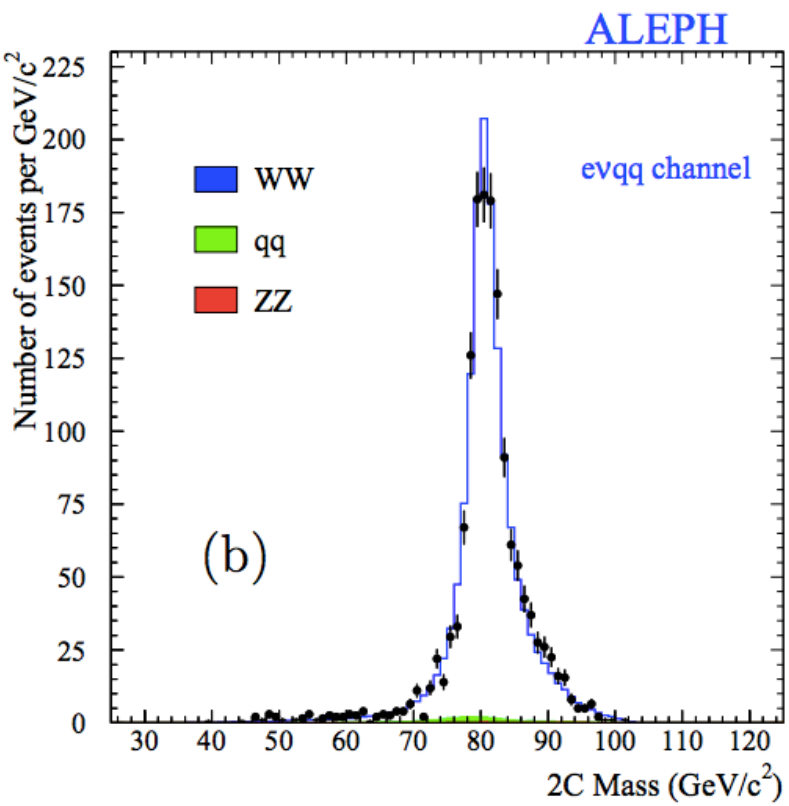


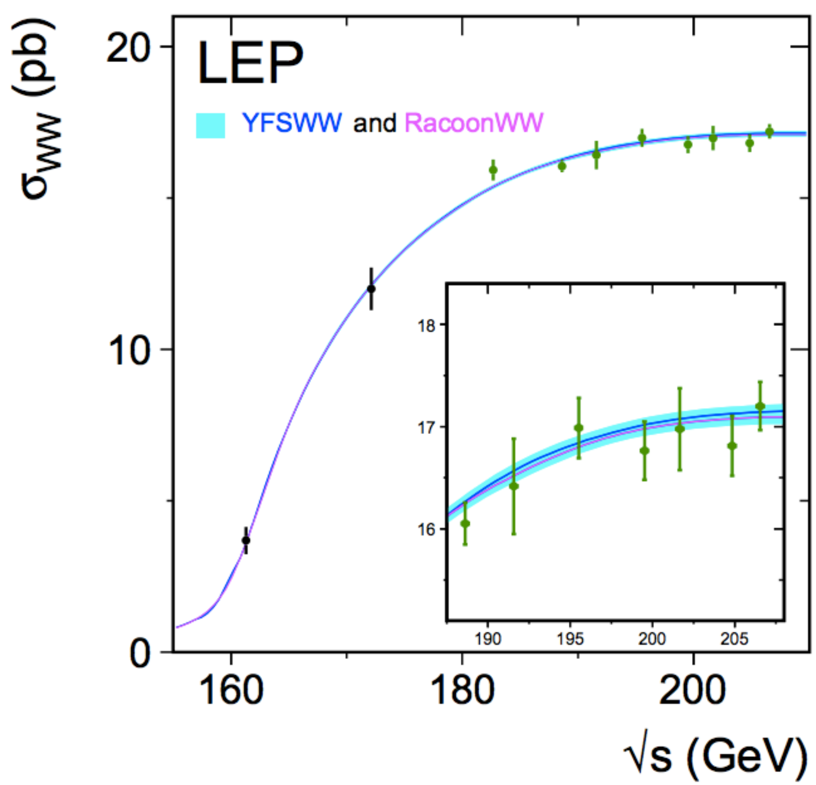
W mass measurement in lepton collider

- 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

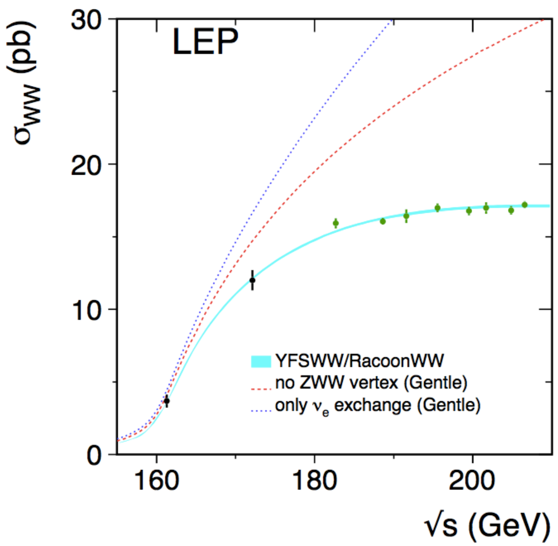




WW threshold scan – CEPC plan

- WW threshold scan running proposal
  - Assuming one year data taking in WW threshold (2.5 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

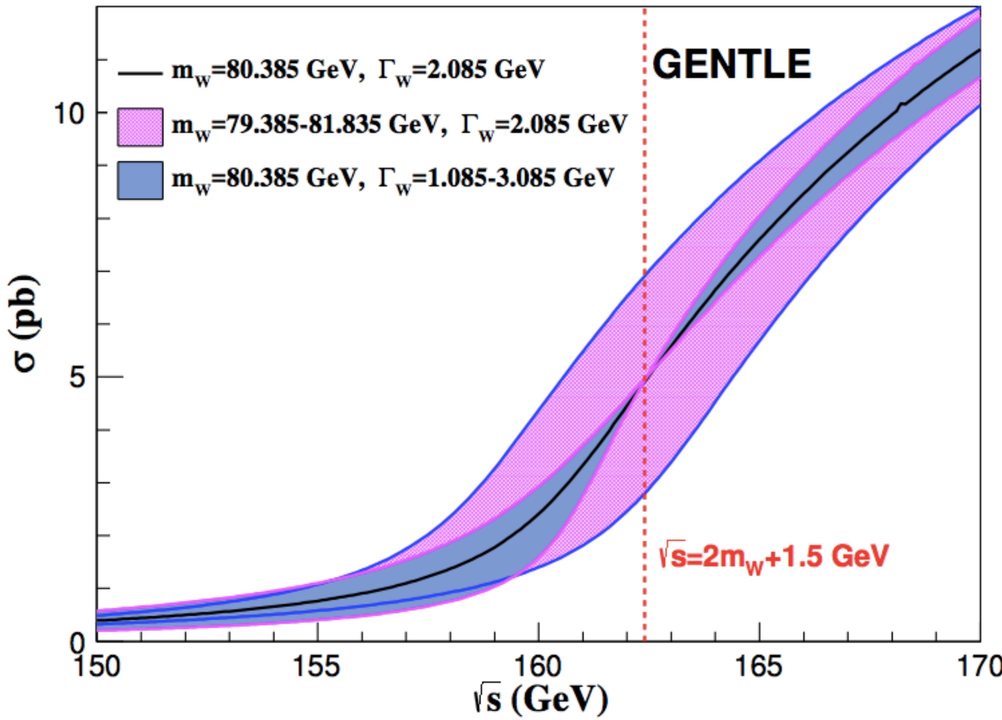
E_{cm} (GeV)	Lumiosity (ab^{-1})	Cross section (pb)	Number of WW pairs (M)
157.5	0.5	1.25	0.6
161.5	0.2	3.89	0.8
162.5	1.3	5.02	6.5
172.0	0.5	12.2	6.1



WW threshold scan-systematics unc.

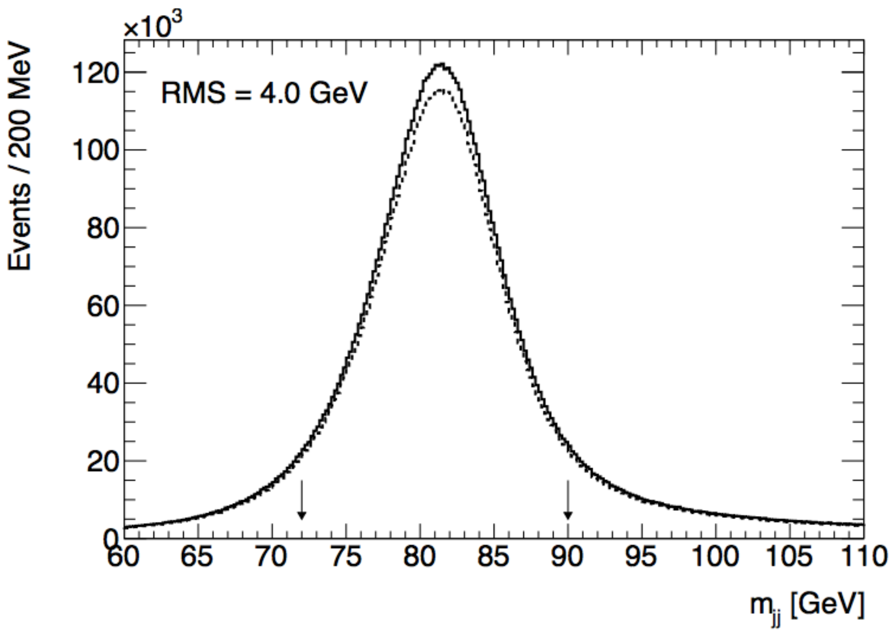
- Consider the beam spread unc. (EBS),beam energy unc. , signal efficiency, cross section unc. and background
- Expected 1MeV precision
  - Dominated by statistics uncertainty: 1MeV
  - Leading syst. (0.5MeV): beam energy syst.

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



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)
  - Calibrate JES with Tera-Z (Z->jj)



Collider	LEP	CEPC
$\sqrt{s}$ (GeV)	180–203	240
$\int \mathcal{L}dt$	2.6 fb^{-1}	5.6 ab^{-1}
Channels	$\ell\nu qq, qqqq$	$\ell\nu qq$
Source	Uncertainty (MeV)	
Statistics	25	1.0
Beam energy	9	1.0
Hadronization	13	1.5
Radiative corrections	8	1.0
Detector effects	10	1.5
Total	33	3.0

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

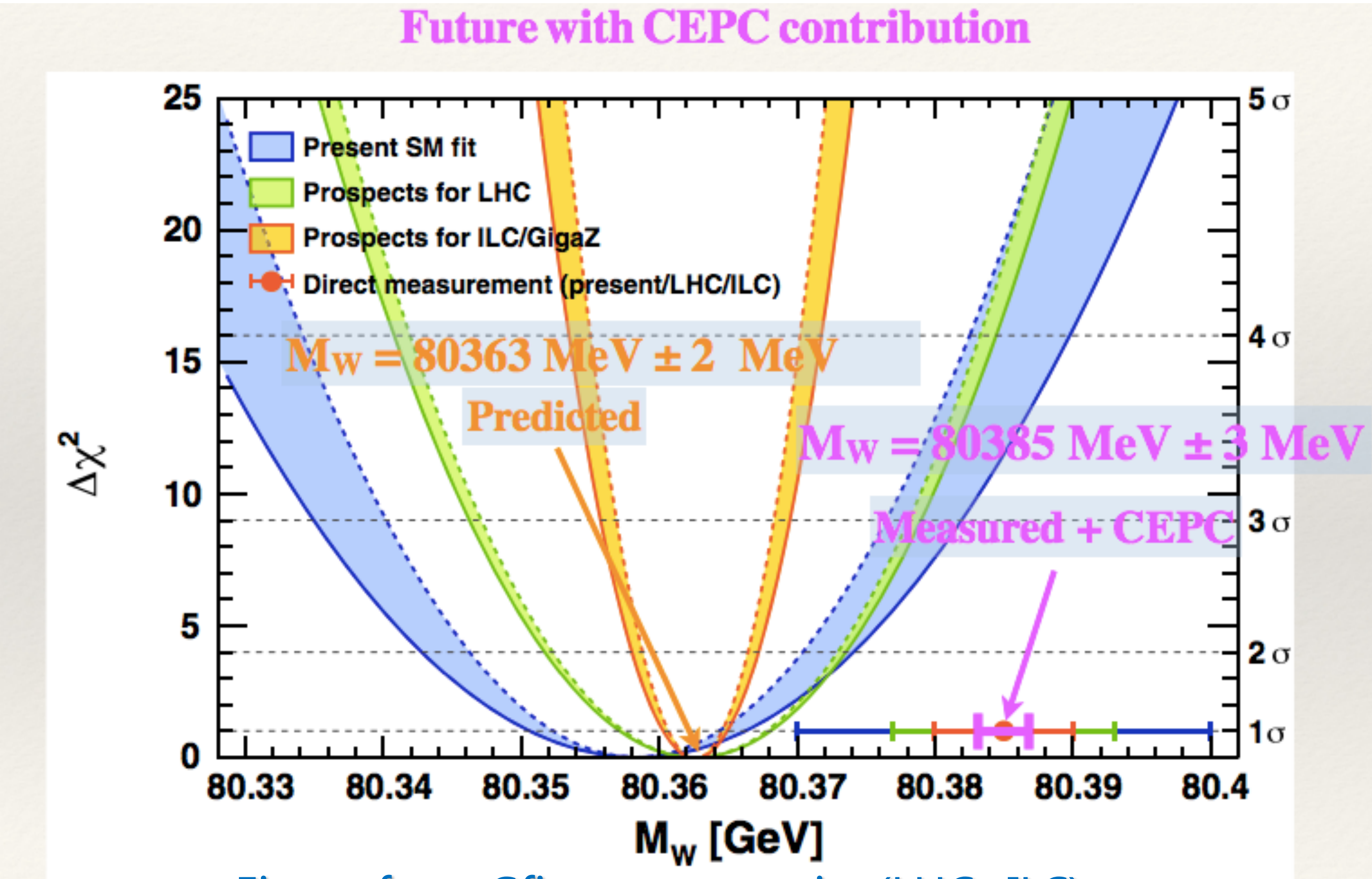
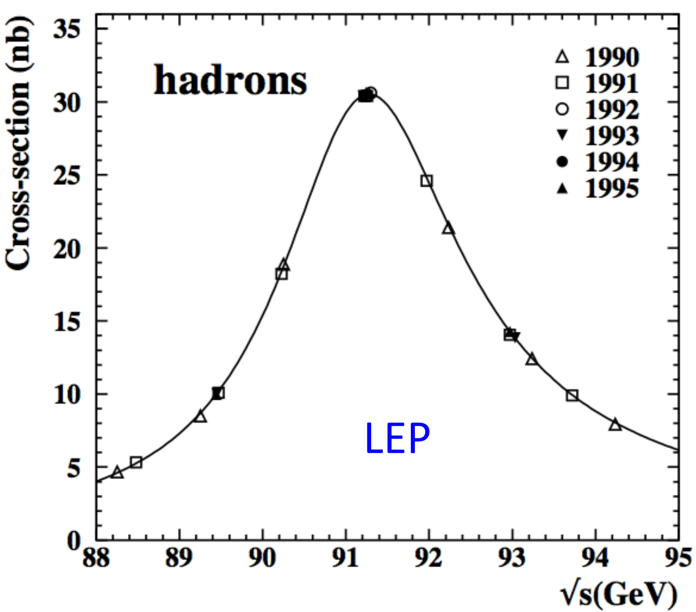


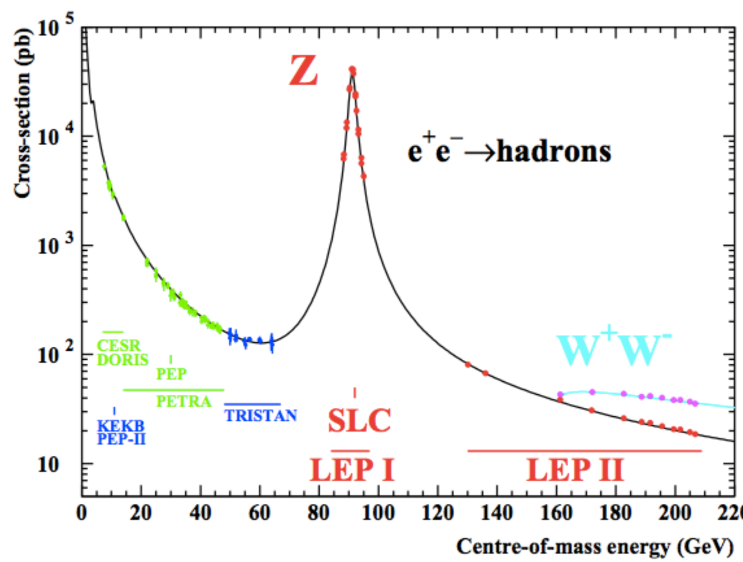
Figure from Gfitter community (LHC+ILC)

- Introduction to CEPC
- W physics
- Z pole physics

Z mass measurement

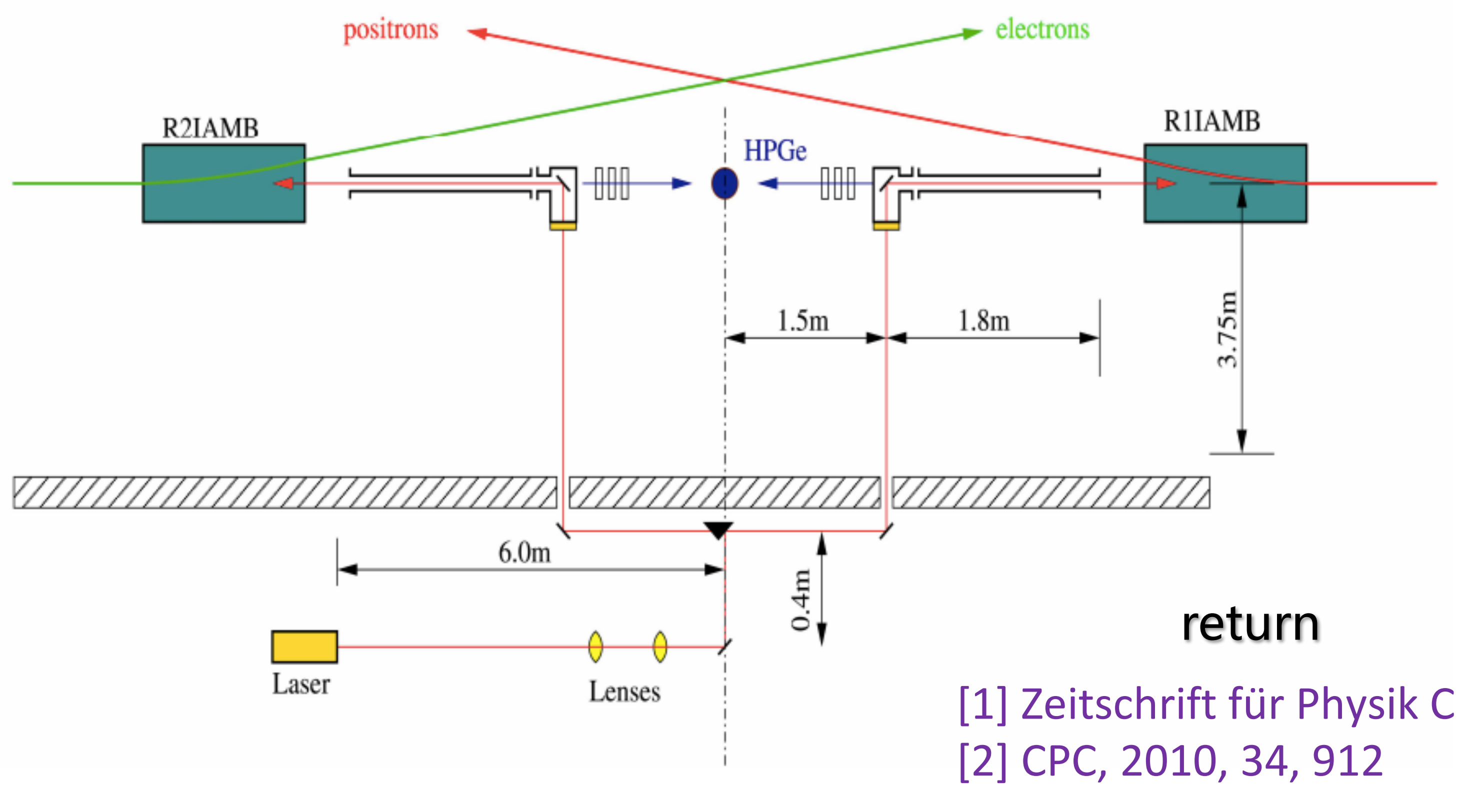
- LEP measurement : 91.1876±0.0021 GeV
- CEPC possible goal: 0.5 MeV
  - Z threshold scan runs is needed to achieve high precision.
  - Syst uncertainty: ~0.5 MeV
    - Beam energy uncertainty is major systematics
      - Resonant depolarization approach by LEP → <0.5MeV
      - Luminosity measurement → <0.1~0.2 MeV
  –





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] → 1~2MeV
    - Radiation return , Z(μμ)γ events → 2~3Me



return

[1] Zeitschrift für Physik C (1995) 45–62.
[2] CPC, 2010, 34, 912

Number of neutrino generation (N_ν)

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

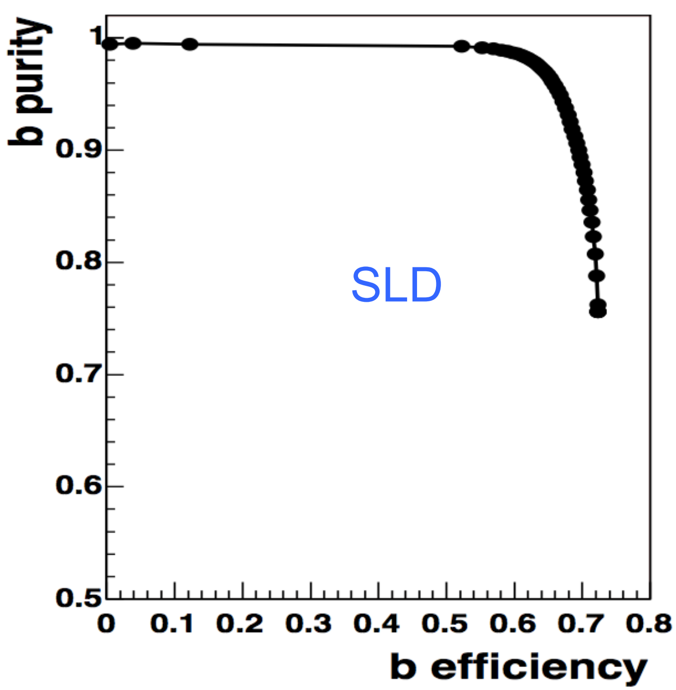
- LEP measurement :
  - Indirect measurement (Z line shape method): 2.984+-0.008
  - Direct measurement (neutrino counting method): 2.92+-0.05
    - Stat error (1.7%), Syst error (1.4%)
- CEPC measurement :
  - Focus on direct measurement, Expected Syst error (0.2%)
  - High granularity in calorimeter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

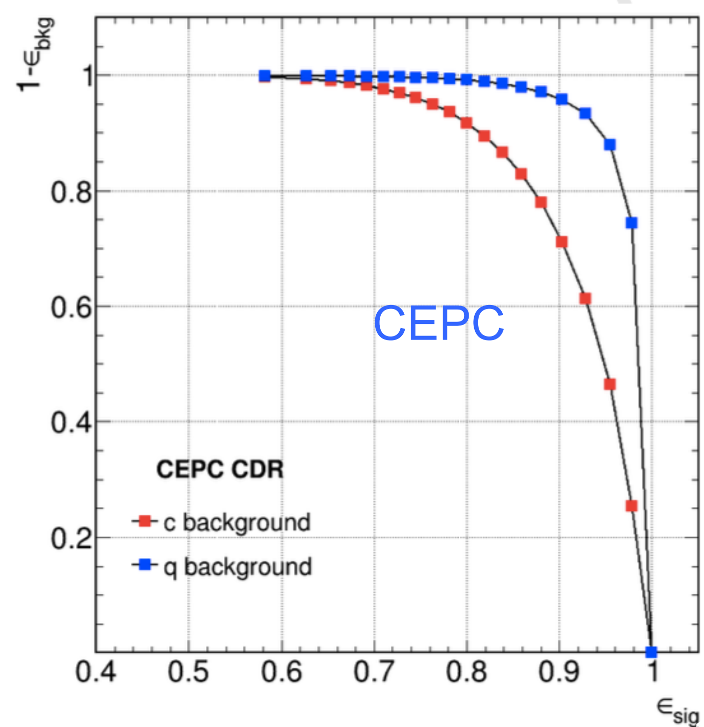
Systematics source	LEP	CEPC
Photon Trigger efficiency	~0.5%	-
Photon Identification efficiency	~0.5%	<0.1%
Calorimeter energy scale	0.3~0.5%	<0.2%

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

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

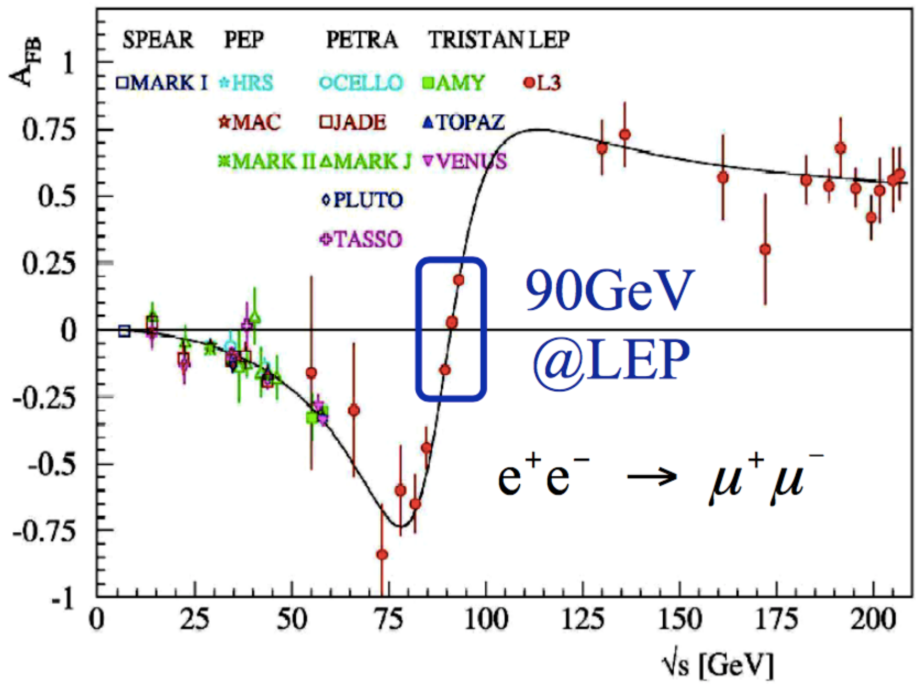
- LEP measurement 0.21594 ±0.00066
  - Syst error : ~0.2%
    - Major systematics is hemisphere tag correlations
- CEPC
  - Expected Syst error (0.02%)
  - hemisphere tag correlations depends on b tagging efficiency
  - Expect 10~15% higher B tagging efficiency than SLD

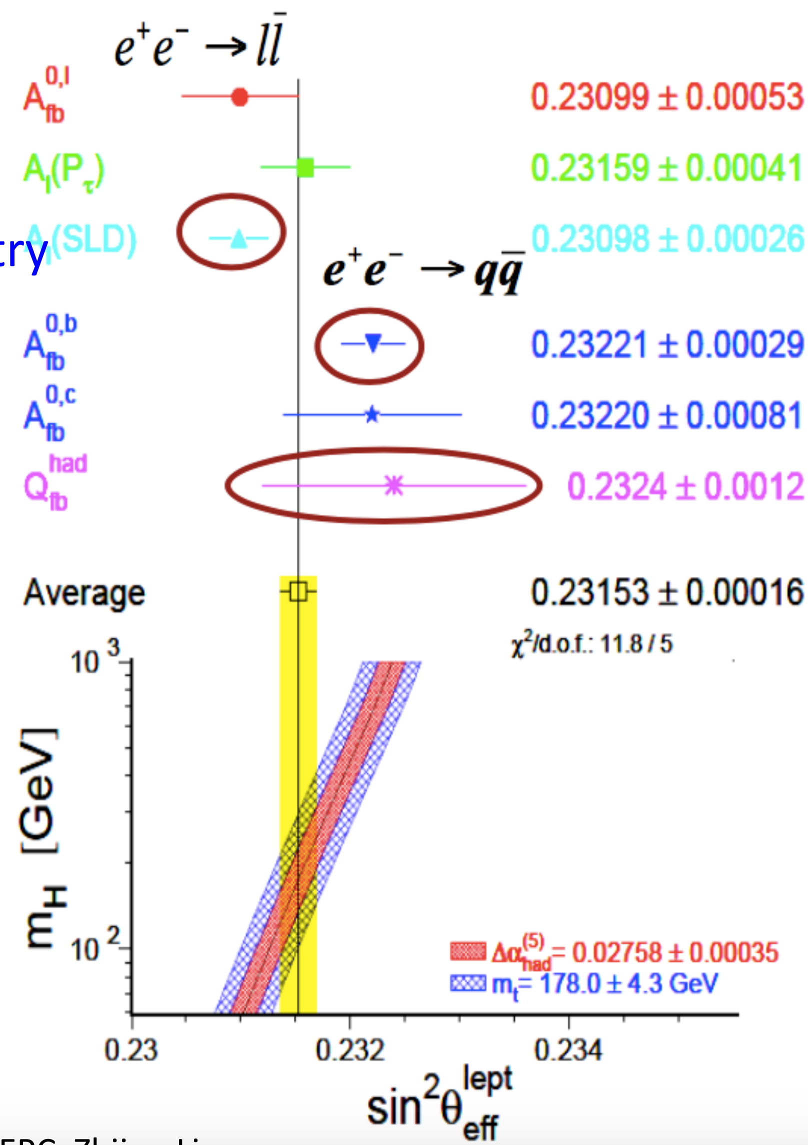




Weak mixing angle $\sin^2\theta_{eff}^{lept}$

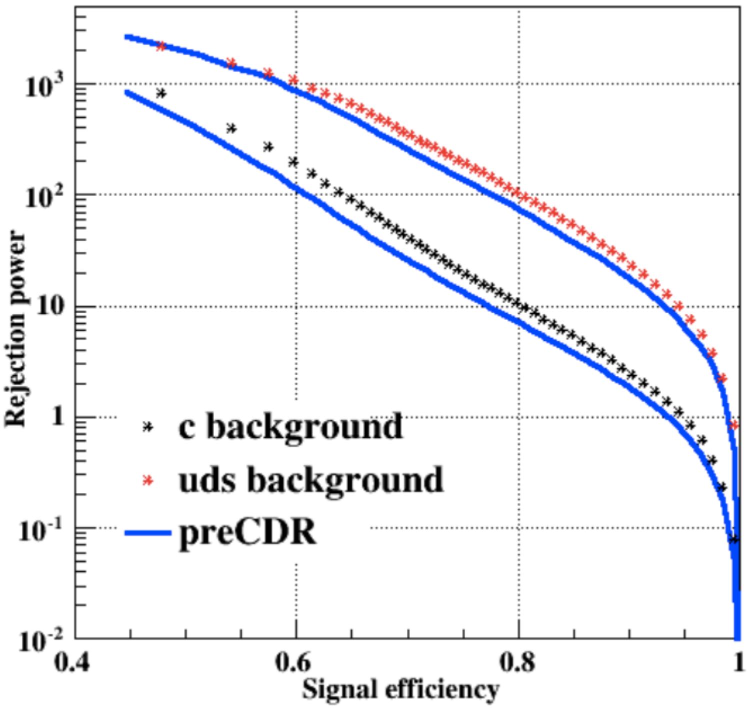
- Some tension between SLD and LEP results (~3σ)
  - Remain a puzzle for ~10 years
- CEPC
  - Aim for 0.002% precision
    - Input from Backward-forward asymmetry





Weak mixing angle with Z->bb

- LEP/SLD measurement: **0.23153 ± 0.00016**
  - Stat unc and Systematics Unc. Have similar contribution
- CEPC benefits from latest pixel technique
  - Expected Stat Unc. is neglectable
  - Syst. Unc.: 10 times better than LEP
  - Use 95% purity working points
    - 15% higher efficiency than SLD



Improvement compared to LEP results	CEPC
A_{FB} (Z->ee)	30
A_{FB} (Z->μμ)	20-30
A_{FB} (Z->ττ)	NA
A_{FB} (Z->bb)	10
Weak mixing angle	70

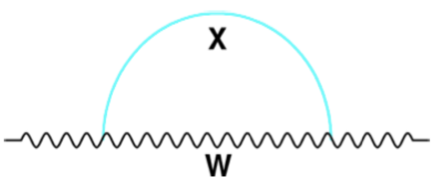
Prospect of CEPC EWK physics

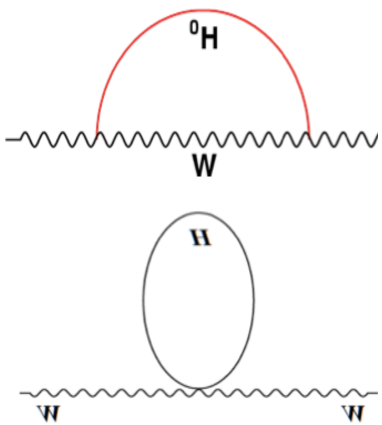
- Expect to have one order of magnitude better than current precision

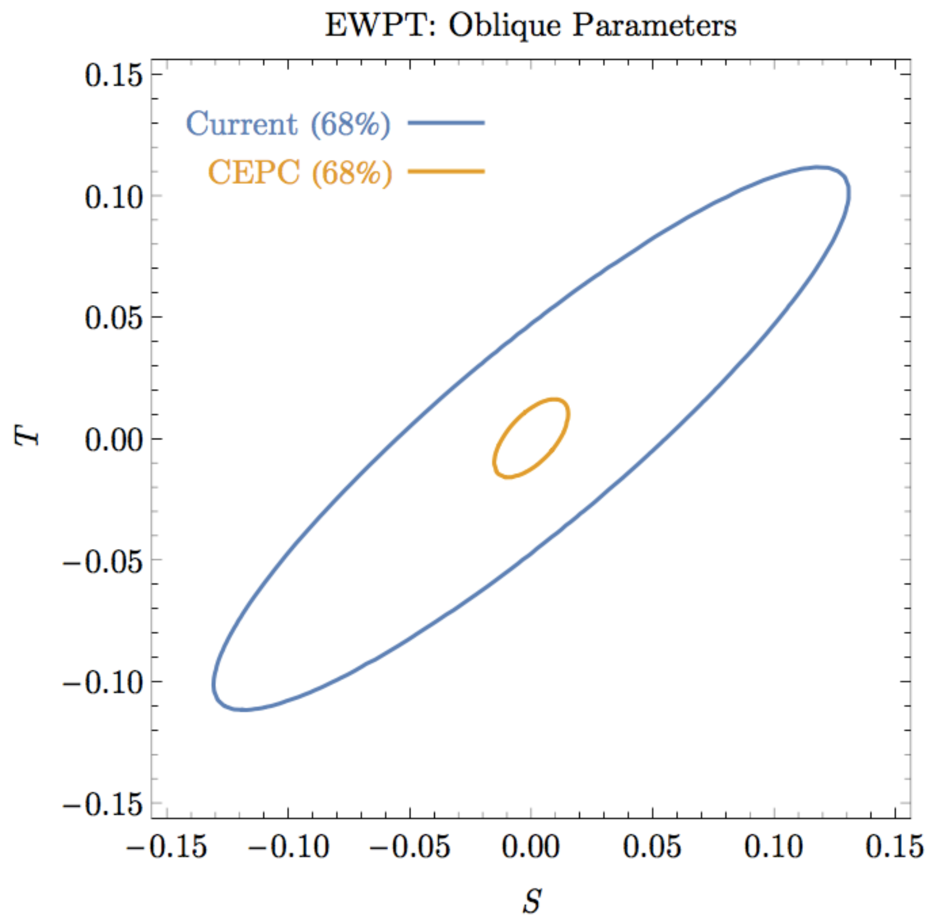
Observable	LEP precision	CEPC precision	CEPC runs	CEPC $\int \mathcal{L}dt$
m_Z	2 MeV	0.5 MeV	Z pole	8 ab^{-1}
$A_{FB}^{0,b}$	1.7%	0.1%	Z pole	8 ab^{-1}
$A_{FB}^{0,\mu}$	7.7%	0.3%	Z pole	8 ab^{-1}
$A_{FB}^{0,e}$	17%	0.5%	Z pole	8 ab^{-1}
$\sin^2 \theta_W^{\text{eff}}$	0.07%	0.001%	Z pole	8 ab^{-1}
R_b	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}

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.







Summary

- Potential of electroweak measurement at CEPC
  - Expect 1~2 order of magnitude better than current precision
  - Key issue
    - Beam energy measurement (Z/W mass)
    - Luminosity measurement (Z/W mass)
    - Jet energy scale and resolution (W mass)
    - Impact parameter and b tagging performance
      - Weak mixing angle, R^b
    - Photon energy scale uncertainty
      - Number of neutrino generation, R^{mu}

Acknowledgment

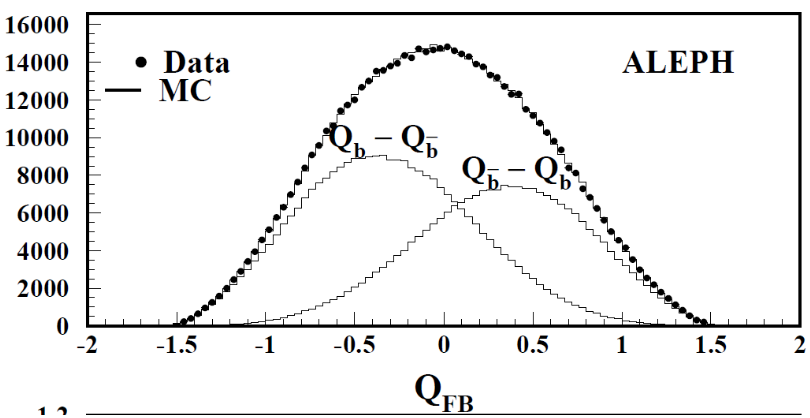
- Thanks for hard work from current team.
  - Editors
    - Maarten Boonekamp (CEA Saclay), Fuivio Piccinini (INFN)
  - PhD Students, and who are practically working:
  - Peixun Shen (Nankai.), Pei-Zhu Lai (NCU), Mengran Li (IHEP), Bo Li(Yantai U. U), Bo Liu (IHEP)
  - Supervisors, Conveners, Experts, who are contributing ideas :
  - Chai-Ming Kuo (NCU), Zhijun Liang (IHEP), Gang Li (IHEP), Manqi Ruan (IHEP), Hengne Li (SCNU/UVa), Liantao Wang (Chigago)

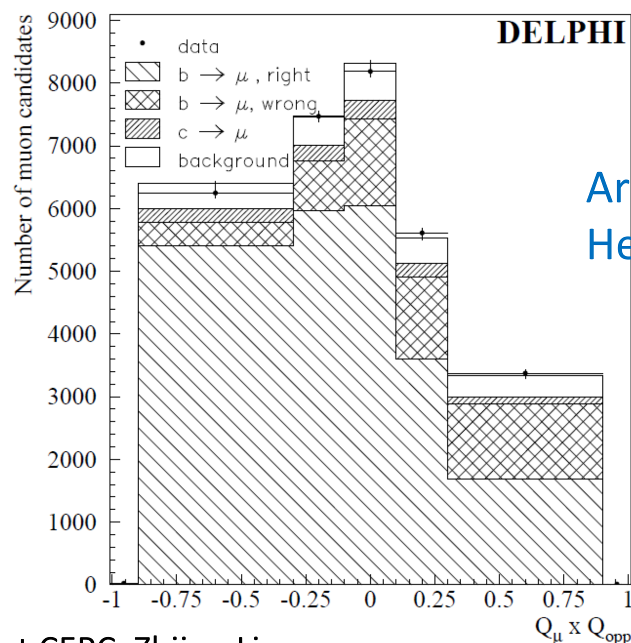
Backward-forward asymmetry

- 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

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

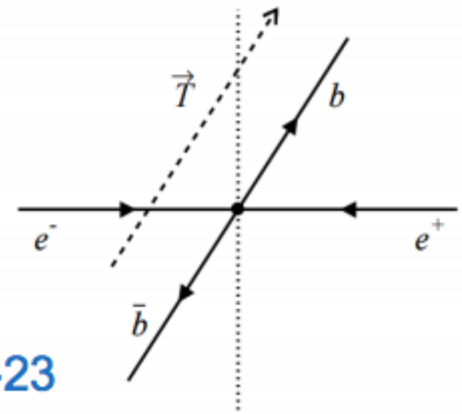
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay (~2%)
  - Method 2: jet charge method using Inclusive b jet (~1.2%)
  - Method 3: D meson method (>8%, method)
- CEPC
  - Focus more on method 2 (inclusive b jet measurement)
  - Expected Systematics (0.15%) :

Uncertainty	LEP	CEPC	Things to improve
hemisphere tag correlations for b events	1.2%	0.1%	Higher b tagging efficiency
QCD and thrust axis correction	0.7%	0.1%	

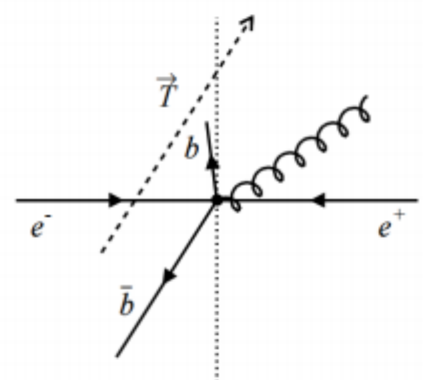
Backward-forward asymmetry $A_{FB}^{b\bar{b}}(0)$

- 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

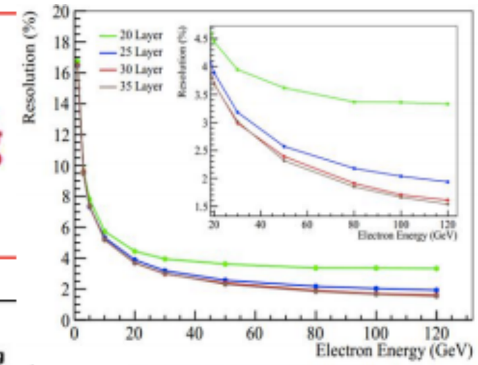
CEPC detector (2)

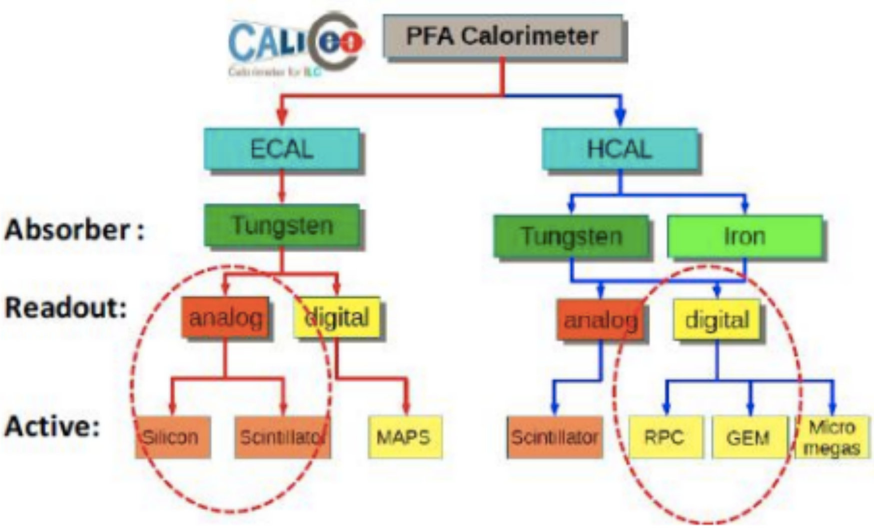
- Calorimeters:
  - Concept of Particle Flow Algorithm (PFA) based
  - EM calorimeter energy resolution: $\sigma_E/E \sim 0.16/\sqrt{E}$
  - Had calorimeter energy resolution: $\sigma_E/E \sim 0.5/\sqrt{E}$
  - Expected jet energy resolution : $\sigma_E/E \sim 0.3/\sqrt{E}$

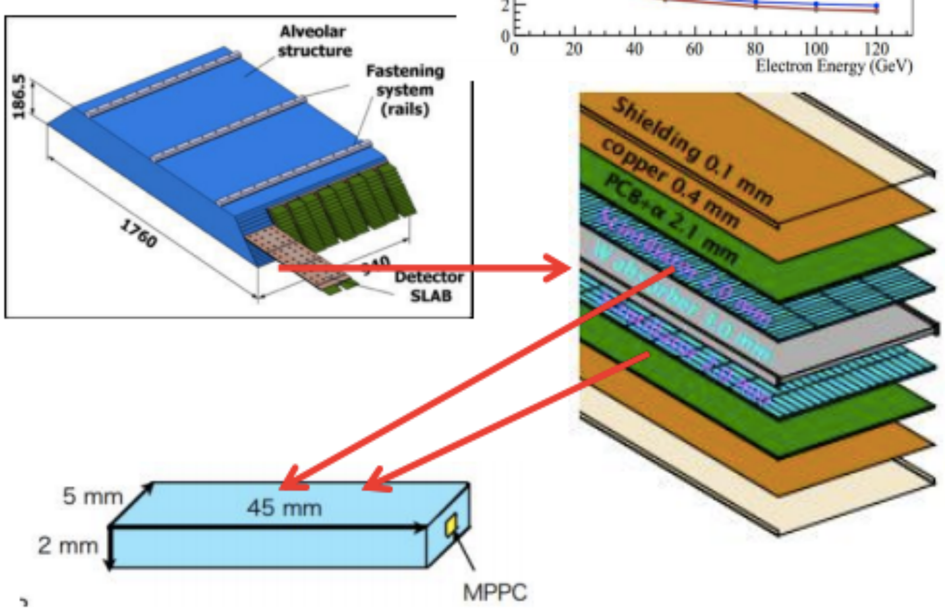
- Jet energy (Higgs self-coupling, W/Z separation)
  - ~1/2 resolution (wrt LHC)

$$\sigma_E / E = 0.3/\sqrt{E(GeV)}$$

less demanding at CEPC







ECAL: Scintillator + W + Scintillator

Motivation of W mass measurement

- CEPC have very good potential in electroweak physics.
- Precision measurement is important
  - It constrain new physics beyond the standard model.
  - Eg: Radiative corrections of the W or Z boson is sensitive to new physics

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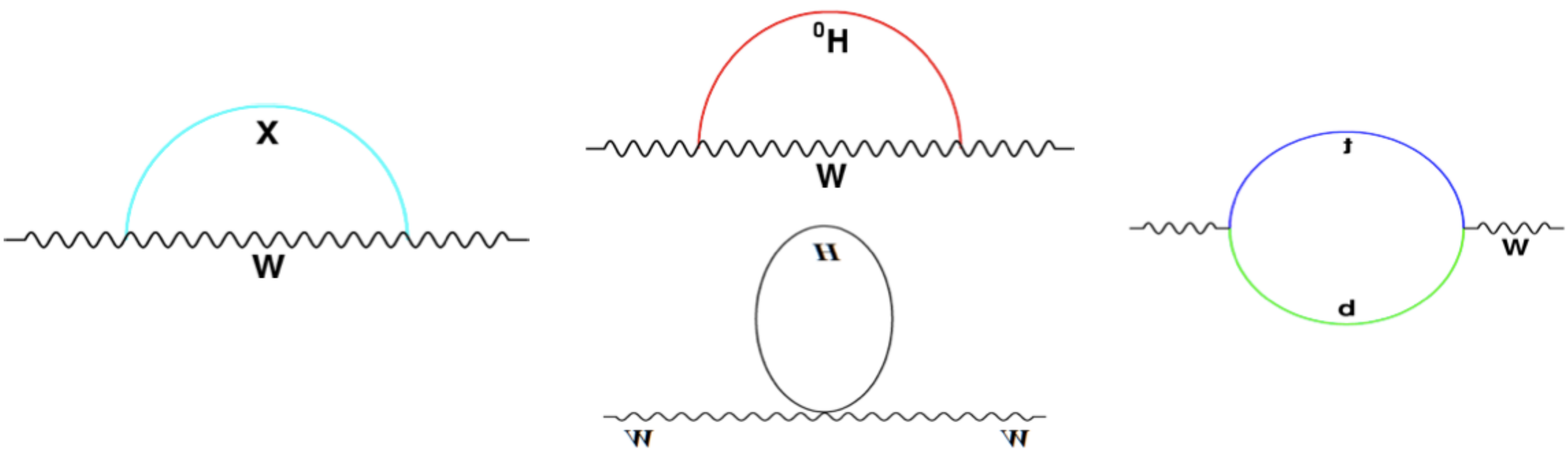
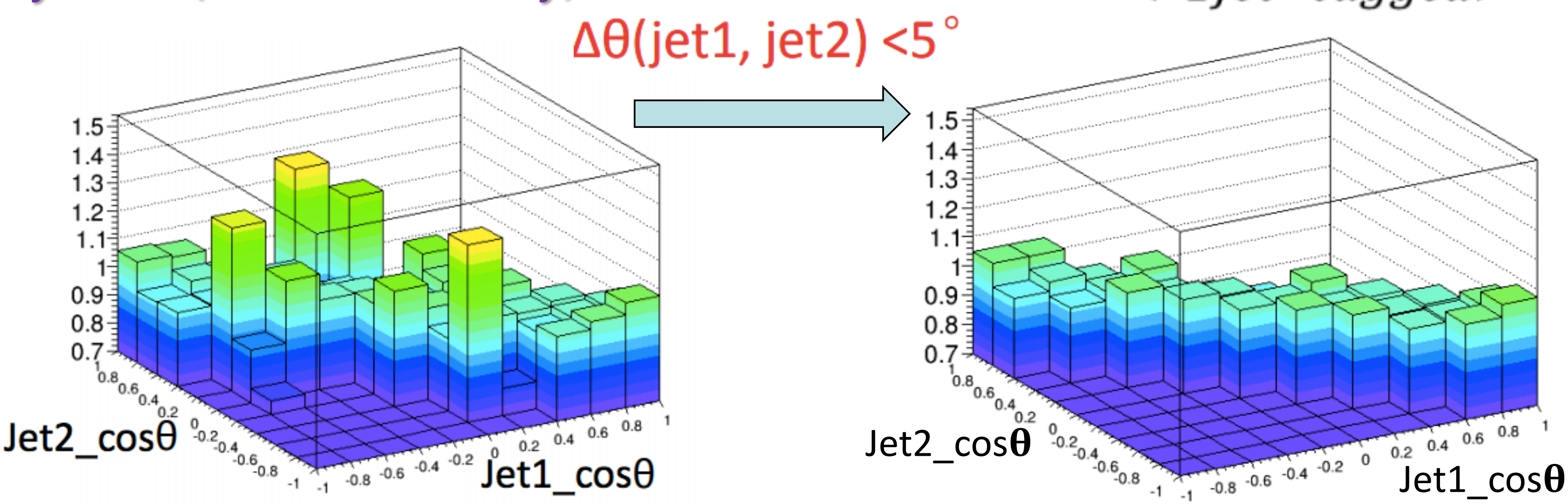


R^b : hemisphere tag correlations

- Study hemisphere b tag correlations systematics with full simulation
- Two ways to reduce correlations factor -> reducing systematics
  - Using tighter cuts to choose Z->bb events
  - Use different B jet tagger (soft muon tag Vs impact parameter)
  - Correlations factors c_b need to be reduced below 0.01%

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

By Bo Li (Yantai University)

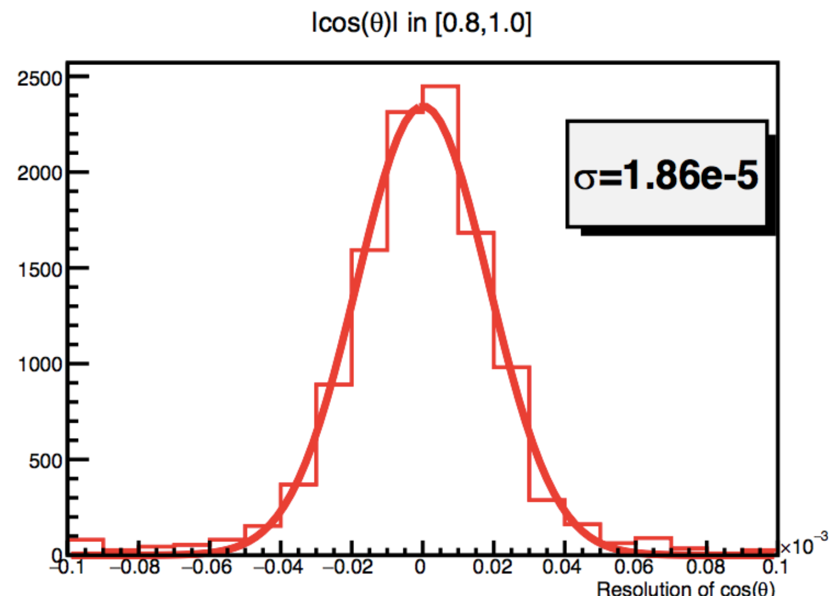


Backward-forward asymmetry in Z->μμ

- 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

Open issue

- Tools needed:
  - Soft muon b jet tagger is needed for R_b measurement
  - Jet charge reconstruction is need for Afb_b
- Analyses to be covered
  - Afb_b , Afb_e measurements
    - Key input to weak mixing angle measurement
  - W->jj branching ratio and alpha_QCD
  - Z->ll off-peak runs design and alpha_QED measurements

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

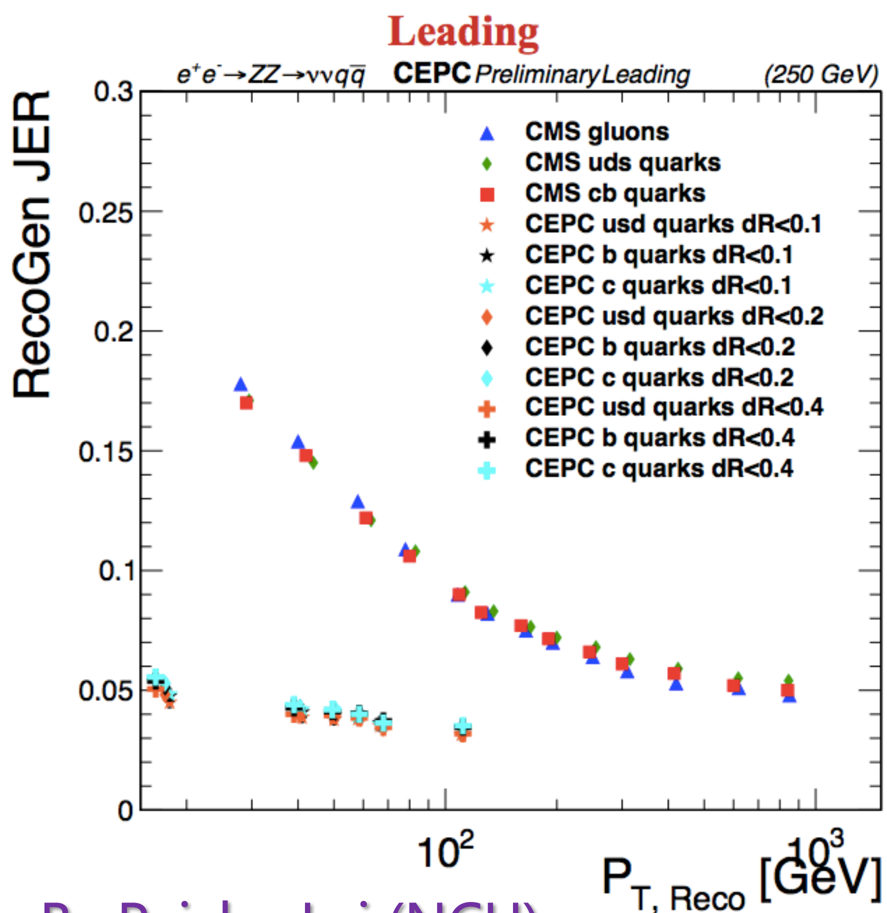
Motivation for CEPC electroweak physics

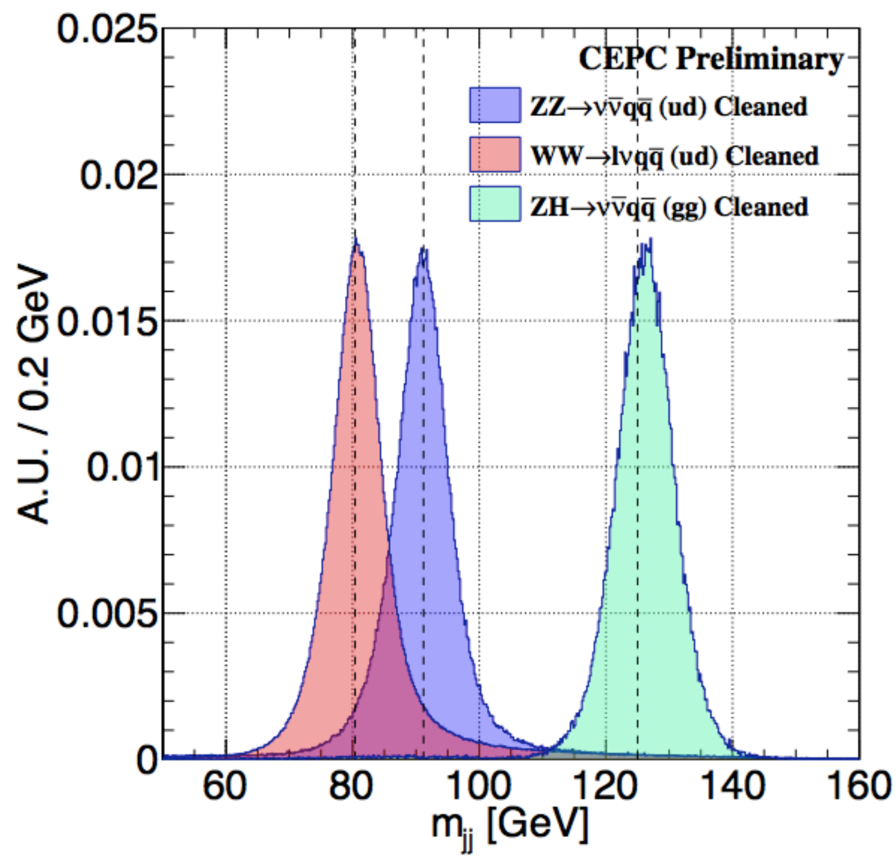
- need more precision in
  - W mass, Top mass and weak mixing angle
- CEPC can provide more precise measurement for
  - W/Z and Higgs mass and weak mixing angle

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.





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