中國科學院高能物理研究所

Institute of High Energy Physics Chinese Academy of Sciences

Electroweak Physics at CEPC

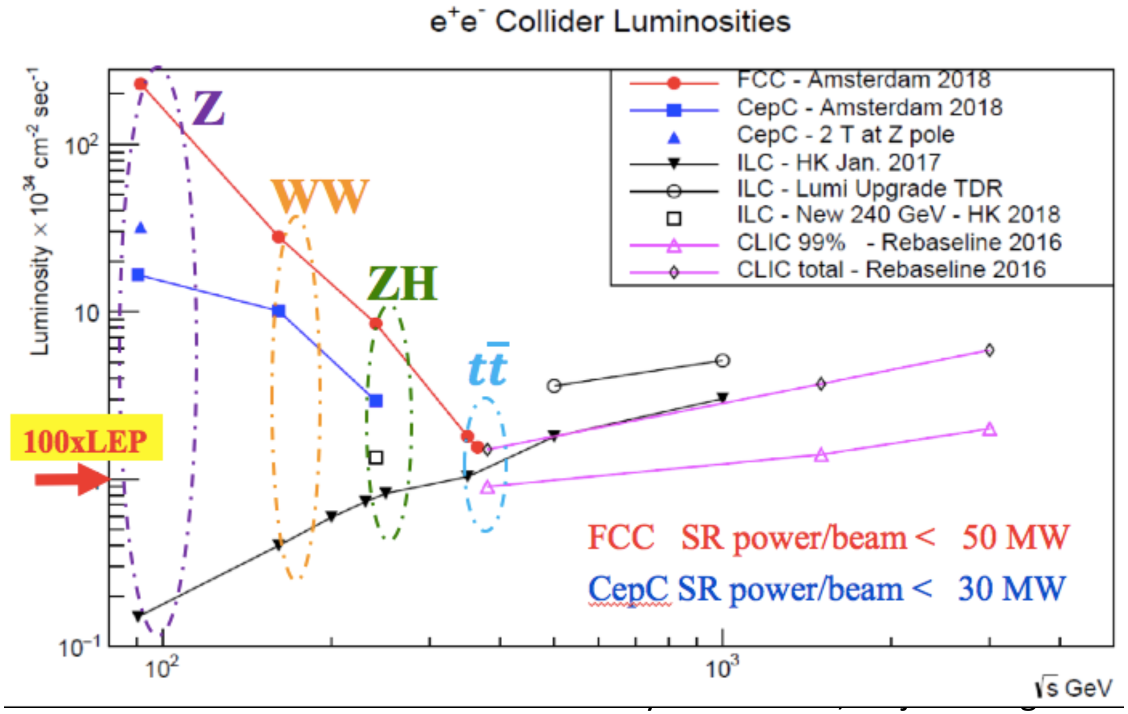
Zhijun Liang

Institute of High Energy Physics ,
Chinese Academy of Science

Conceptual design report review meeting , Sep 15th 2018

Introduction to CEPC

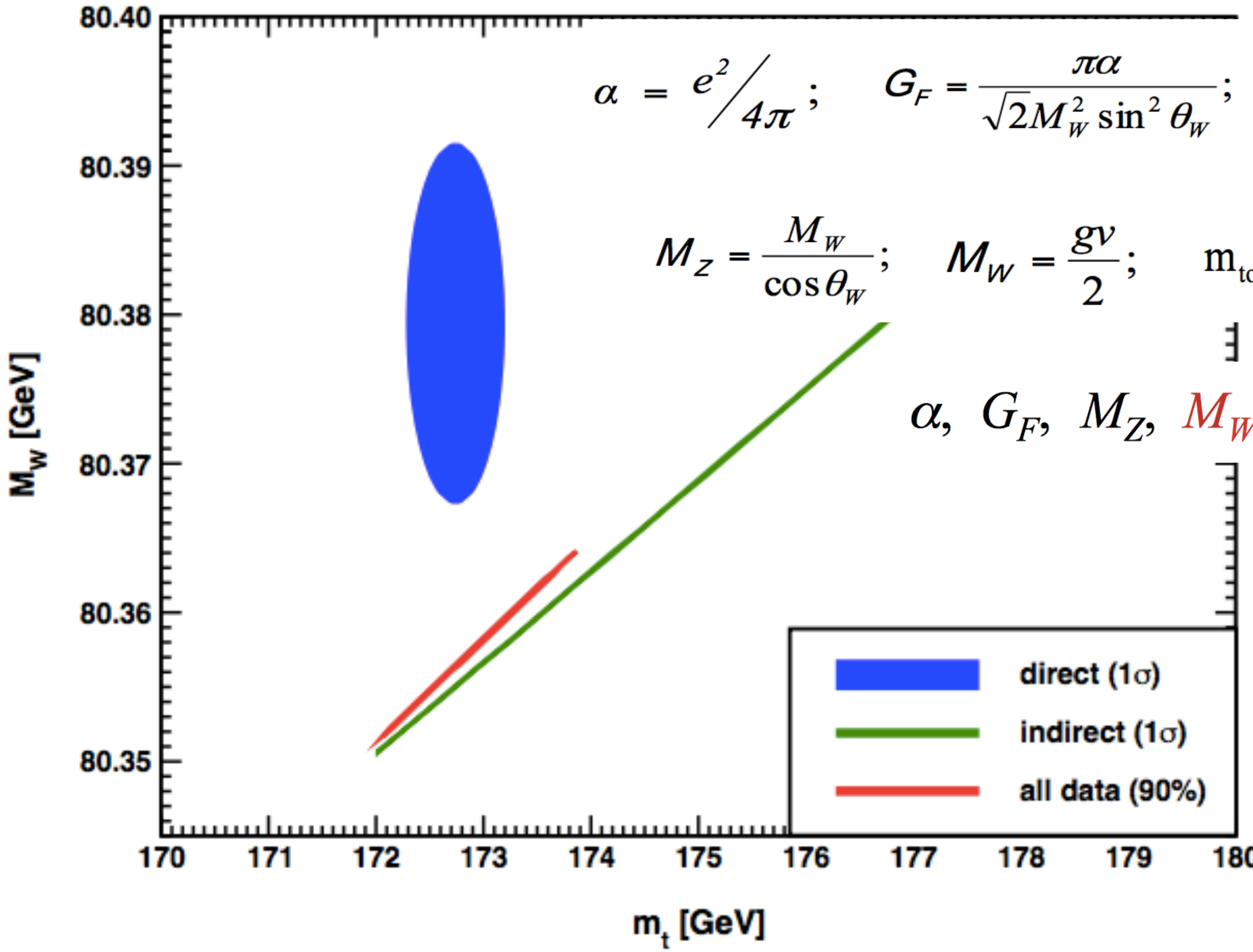
- CEPC is Higgs Factory (E_{cms}=240GeV , 10^6 Higgs)
- CEPC is Z factory(E_{cms}~91GeV) ,electroweak precision physics at Z pole.
  - **baseline** L=1.6 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =3T, 3X10^{11} Z boson, two years
  - L= 3.2 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =2T , 6X10^{11} Z boson
  - **Assuming 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

Status of electroweak global fit

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



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

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

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

self-consistency
Check of SM

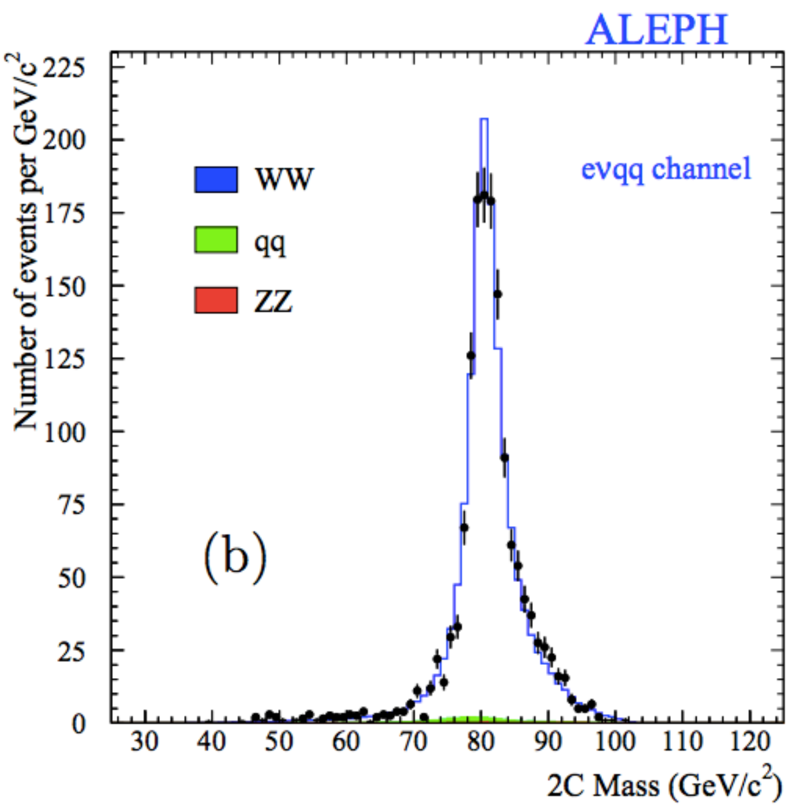
Freitas & JE (PDG 2018)

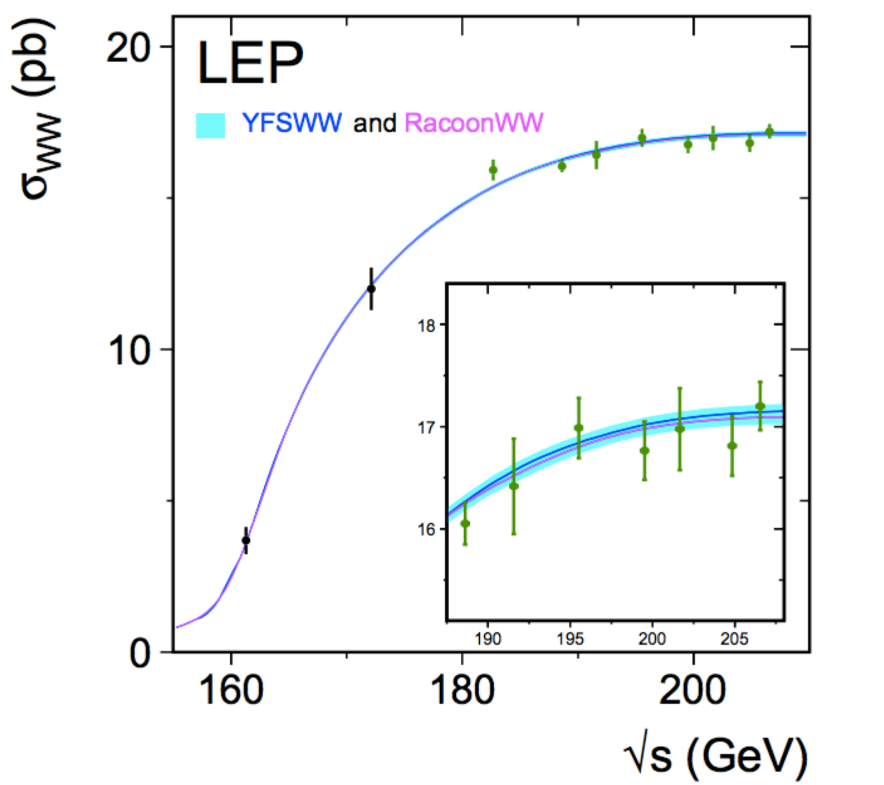
W mass measurement in lepton collider

- 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

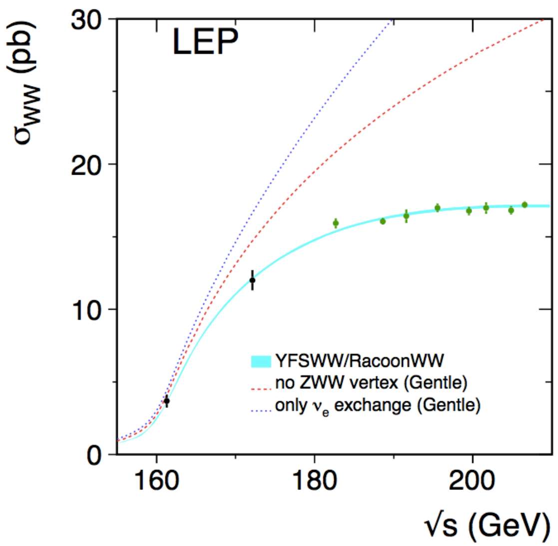




WW threshold scan – CEPC plan

- 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

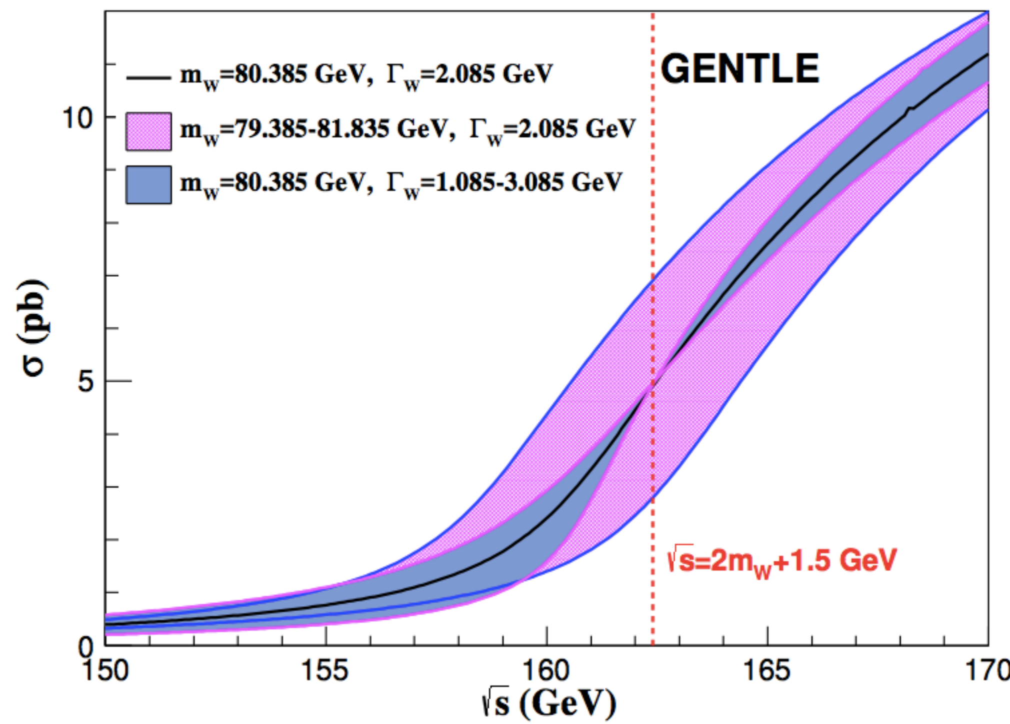
E_{cm} (GeV)	Lumiosity (ab^{-1})	Cross section (pb)	Number of WW pairs (M)
157.5	0.5	1.25	0.6
161.5	0.2	3.89	0.8
162.5	1.3	5.02	6.5
172.0	0.5	12.2	6.1



WW threshold scan-systematics unc.

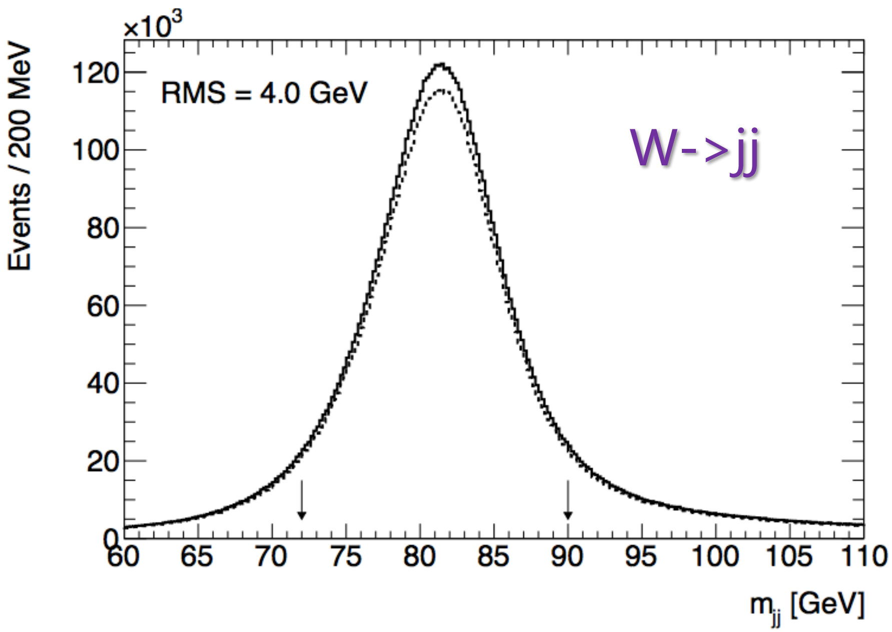
- Consider the beam spread unc. (EBS),beam energy unc. , signal efficiency, cross section unc. and background
- Expected 1MeV precision
  - Dominated by statistics uncertainty: 1MeV
  - Leading syst. (0.5MeV): beam energy syst.

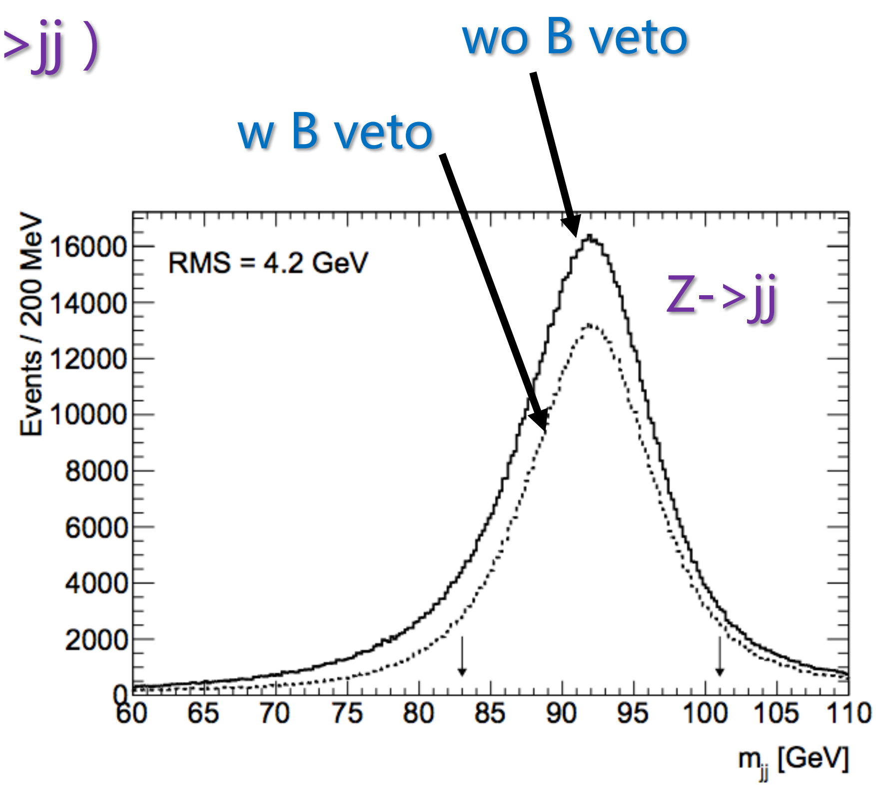
Observable	m_W	Γ_W
Source	Uncertainty (MeV)	
Statistics	0.8	2.7
Beam energy	0.4	0.6
Beam spread	–	0.9
Corr. syst.	0.4	0.2
Total	1.0	2.8



W mass direct measurement

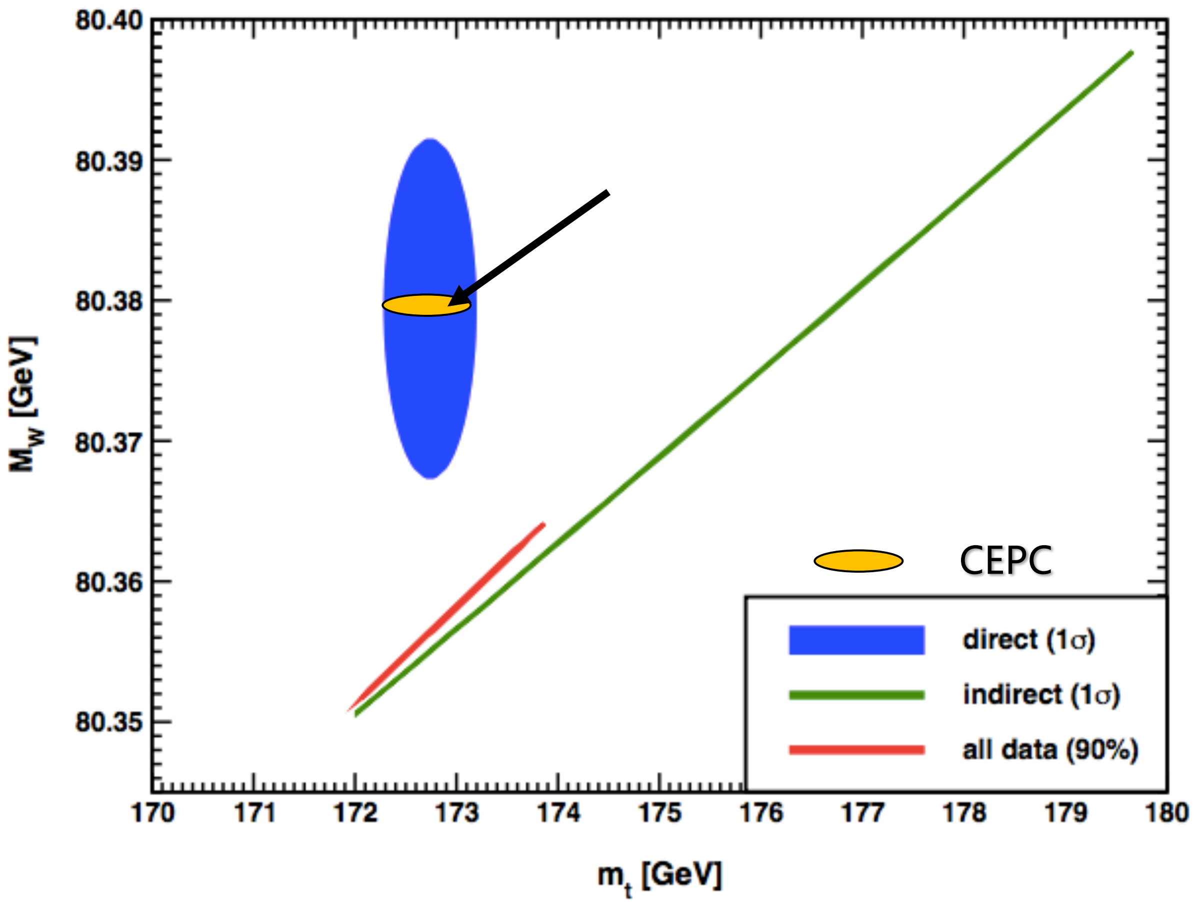
- Reconstruct di-jet mass from WW->lvqq events in ZH run
  - Not affect by beam energy uncertainty
  - Major systematics is Jet energy scale (JES) uncertainty (2~3 MeV)
    - Mainly from Jet flavor composition and jet flavor response
  - Calibrate JES with Tera-Z (Z->jj)





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

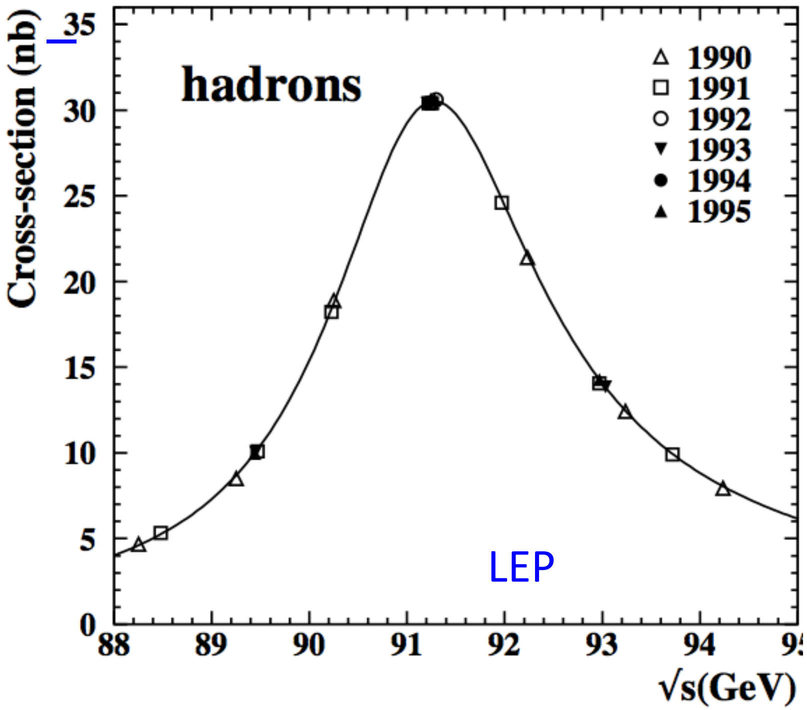


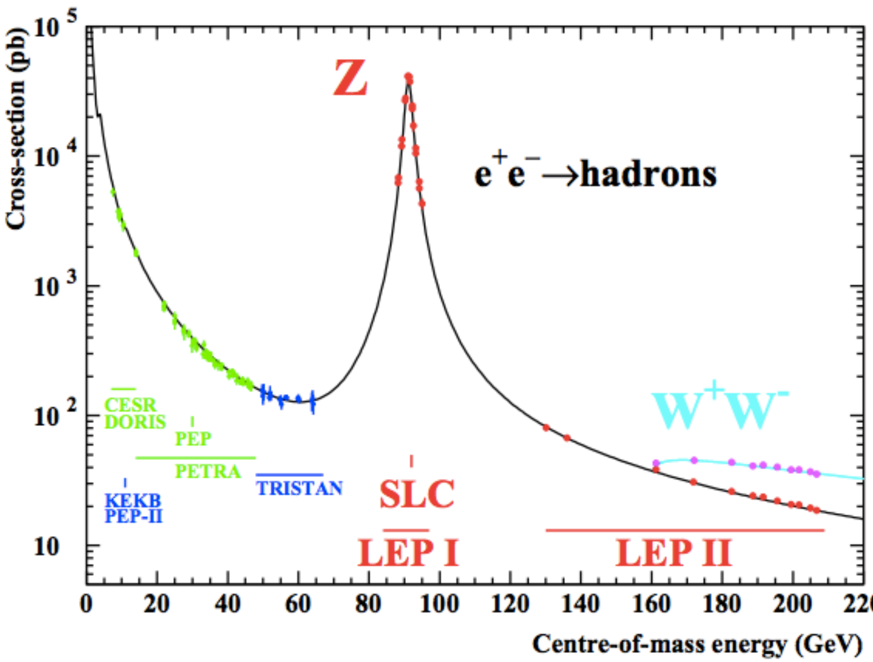
Freitas & JE (PDG 2018)

- Introduction to CEPC
- W physics
- Z pole physics

Z mass measurement

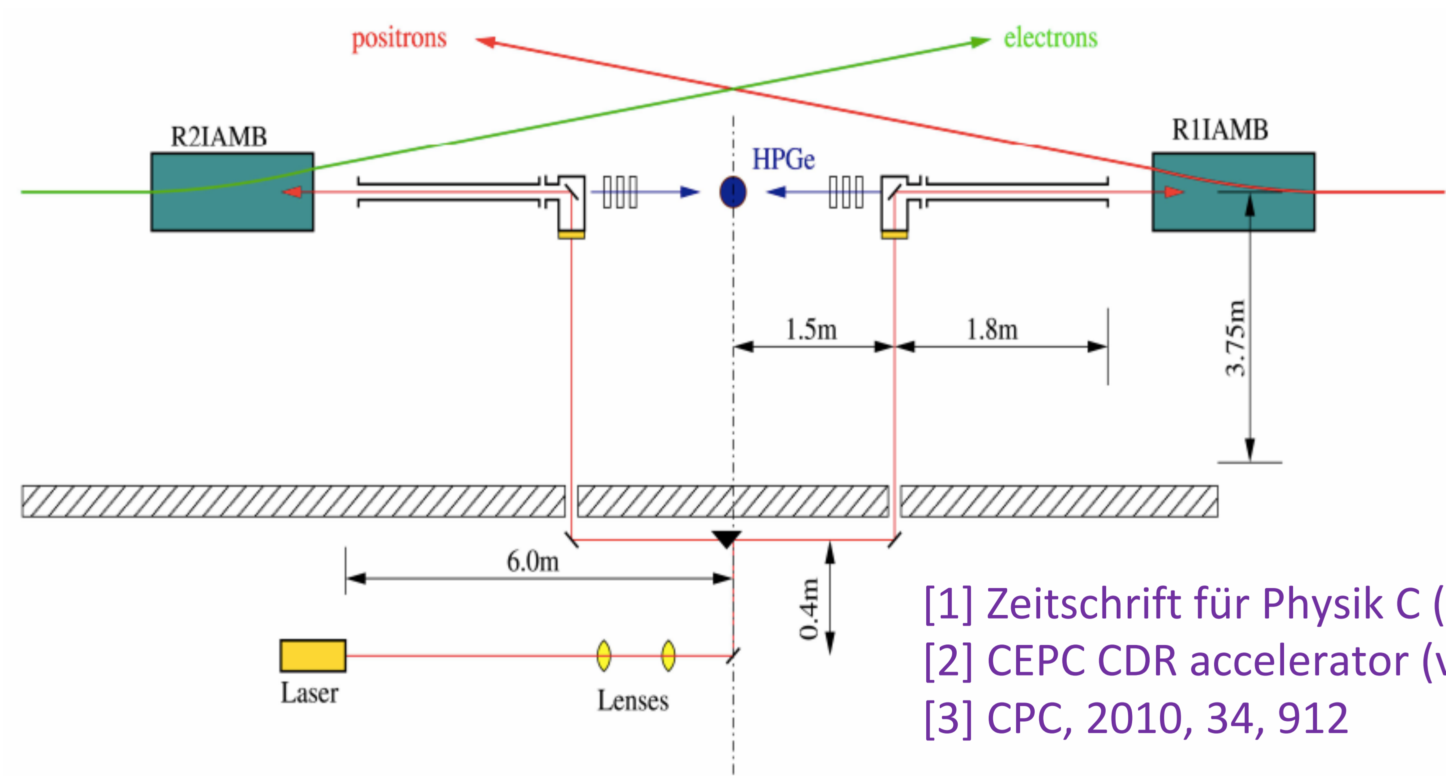
- LEP measurement : 91.1876±0.0021 GeV
- CEPC possible goal: 0.5 MeV
  - Z threshold scan runs is needed to achieve high precision.
  - Syst uncertainty: ~0.5 MeV
    - Beam energy uncertainty is major systematics
      - Resonant depolarization approach by LEP → <0.5MeV
      - Luminosity systematics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

Number of neutrino generation (N_ν)

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

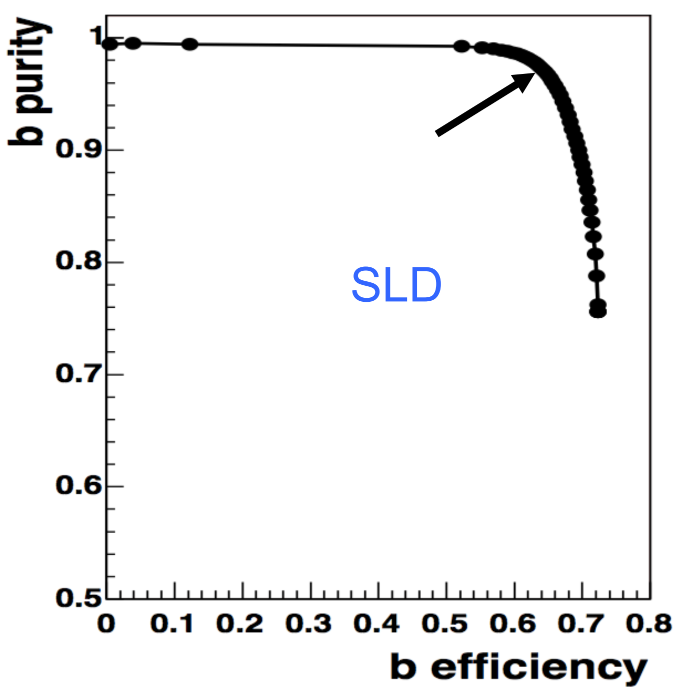
- LEP measurement :
  - Indirect measurement (Z line shape method): 2.984+-0.008
  - Direct measurement (neutrino counting method): 2.92+-0.05
    - Stat error (1.7%), Syst error (1.4%)
- CEPC measurement :
  - Focus on direct measurement, Expected Syst error (~0.2%)
  - High granularity in calorimeter 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

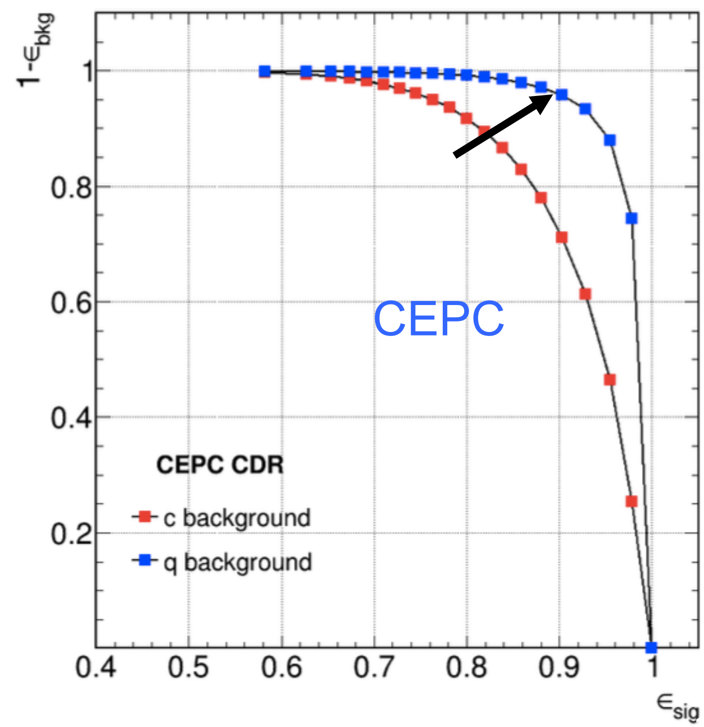
Systematics source	LEP	CEPC
Photon trigger and Identification efficiency	~0.5%	<0.1%
Calorimeter energy scale	0.3~0.5%	<0.2%

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

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

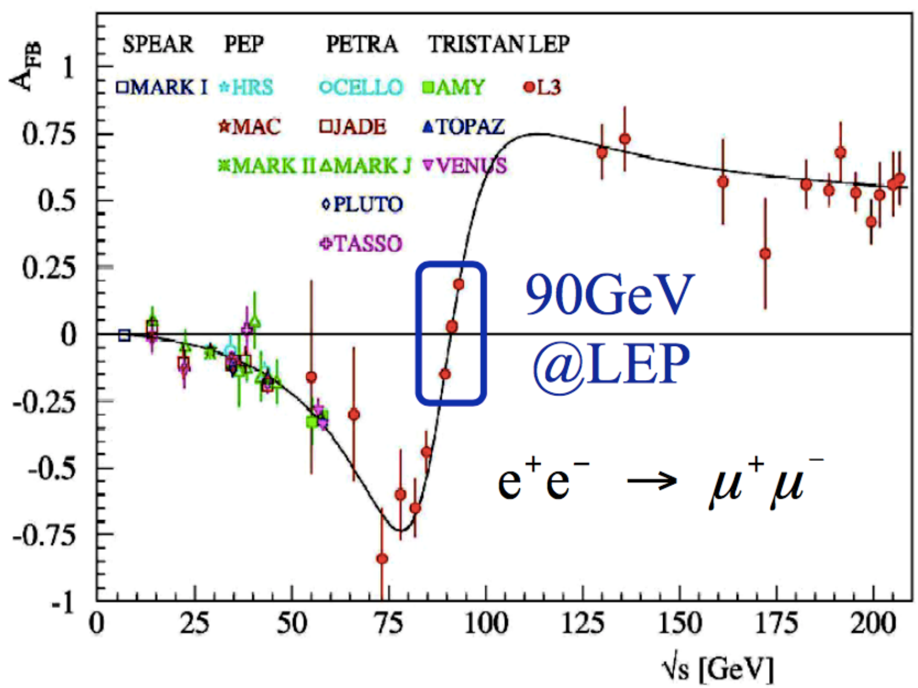
- LEP measurement 0.21594 ±0.00066
  - Syst error : ~0.2%
    - Major systematics is hemisphere tag correlations
- CEPC
  - Expected Syst error (0.02%)
  - hemisphere tag correlations depends on b tagging efficiency
  - Expect 20~30% higher B tagging efficiency than SLD

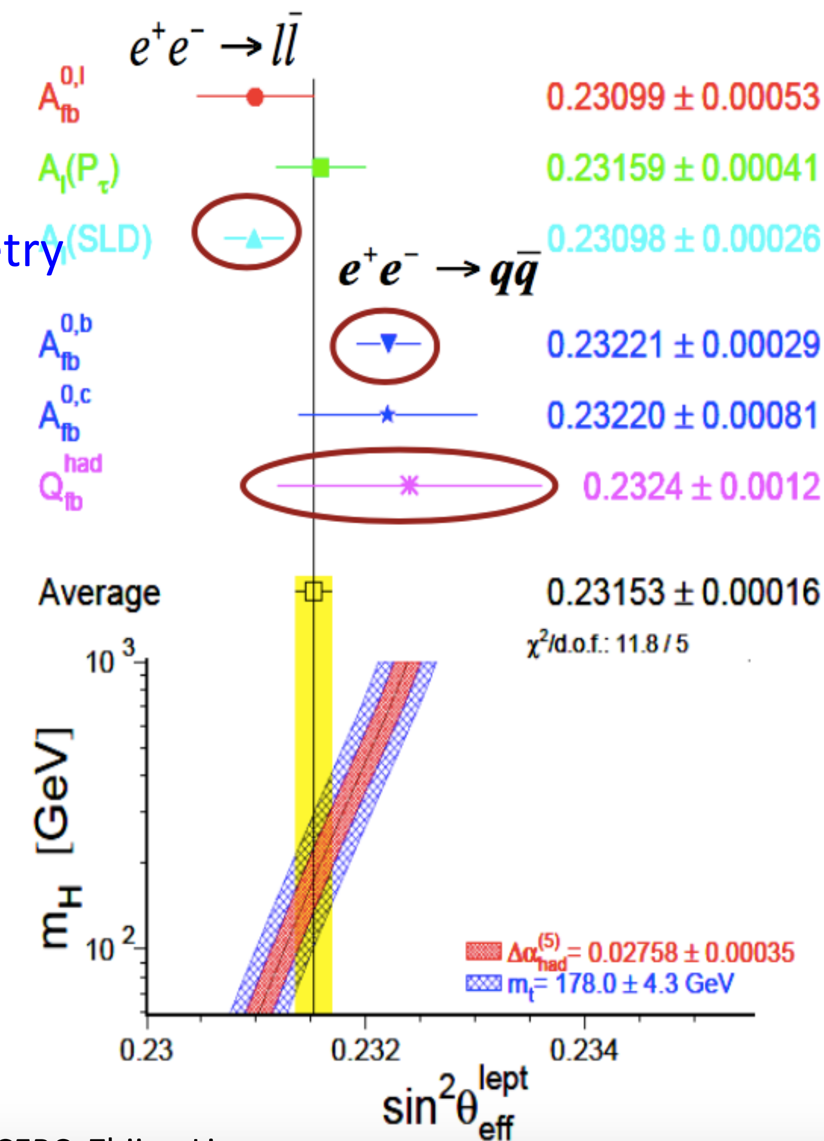




Weak mixing angle $\sin^2\theta_{eff}^{lept}$

- 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

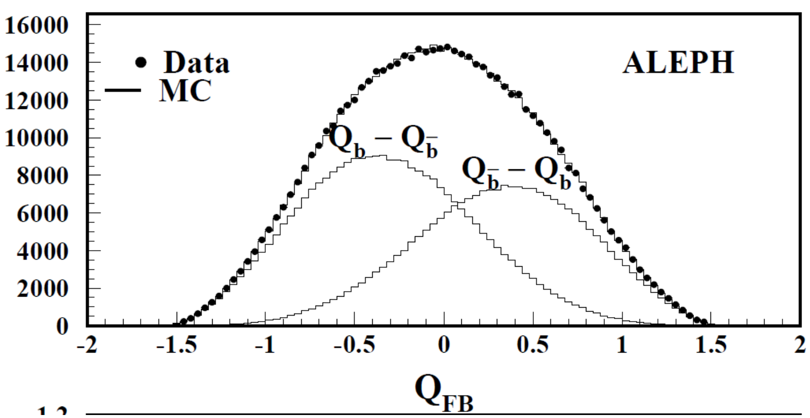
$A_{FB}^{0,b}$

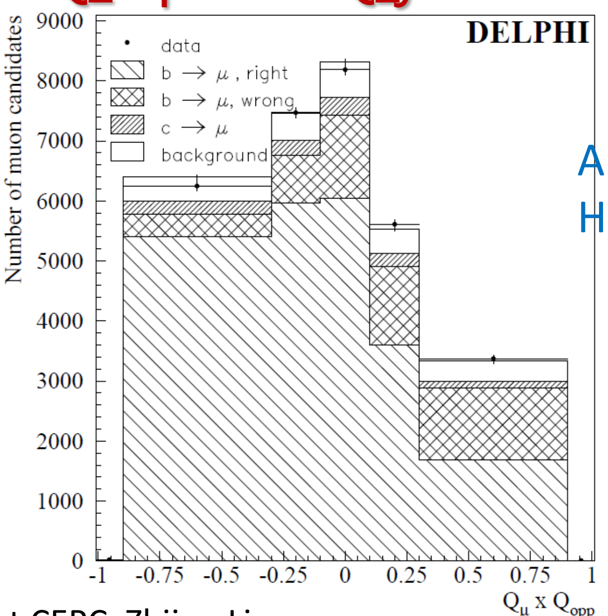
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay
    CEPC precision 0.1% ,LEP precision ~2% (stat dominated)
    – Main systematics is B hadron decay branching ratio
  - Method 2: jet charge method , Inclusive b jet (LEP precision 1.2%)
    – use event Thrust to define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

Q_lepton - Q_jet in method 1

Arxiv:Hep-ex/0107033

Q_F - Q_B in method 2



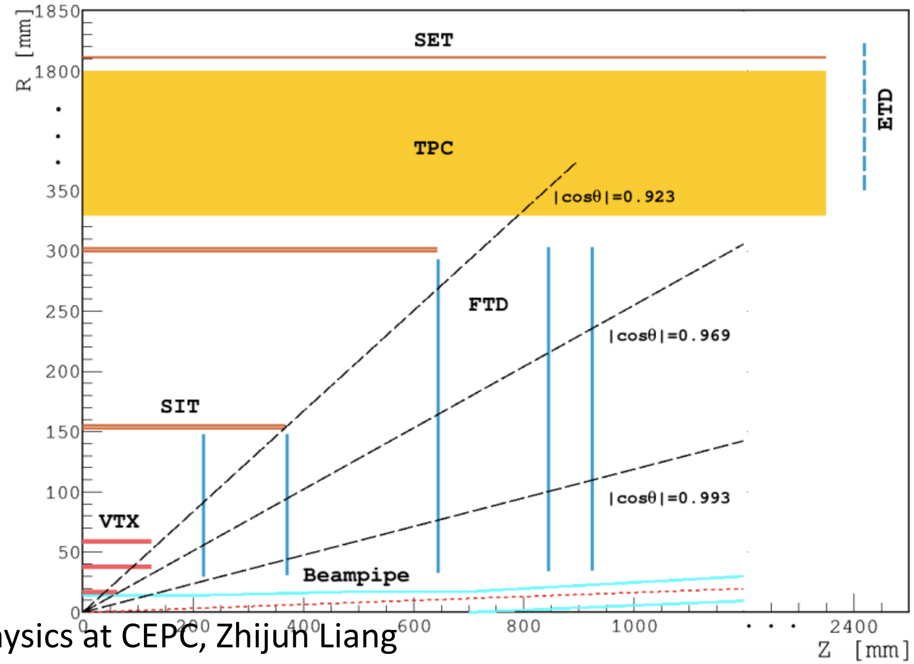


Arxiv:
Hep-ex/0403041

Backward-forward asymmetry in Z->μμ

- LEP measurement : 1.69% +-0.13% (PDG fit)
- CEPC has potential to improve it by a factor of 20~30 .
  - muon angular resolution(~0.1%)
  - 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)
    - 0.1% systematics for AFB

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



Weak mixing angle

- LEP/SLD measurement: **0.23153 ± 0.00016**
  - Stat unc and Systematics Unc. have similar contribution
- CEPC benefits from latest pixel technology and large statistics

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 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.

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}

Acknowledgment

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

FCC-ee: Theory calculations

- **Today**

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

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

- **With FCC-ee**

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

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

- **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

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

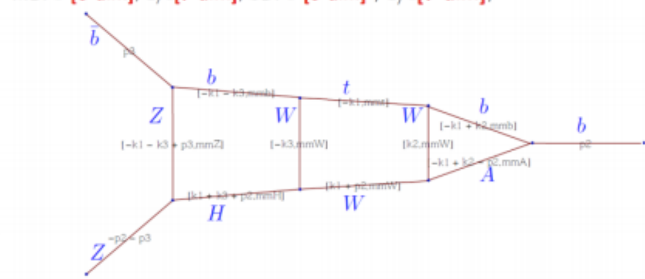
Genuine virtual loops (aITALC, qgraf, FeynArts).

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

J. Gluza
(supported by FCC)

such as:

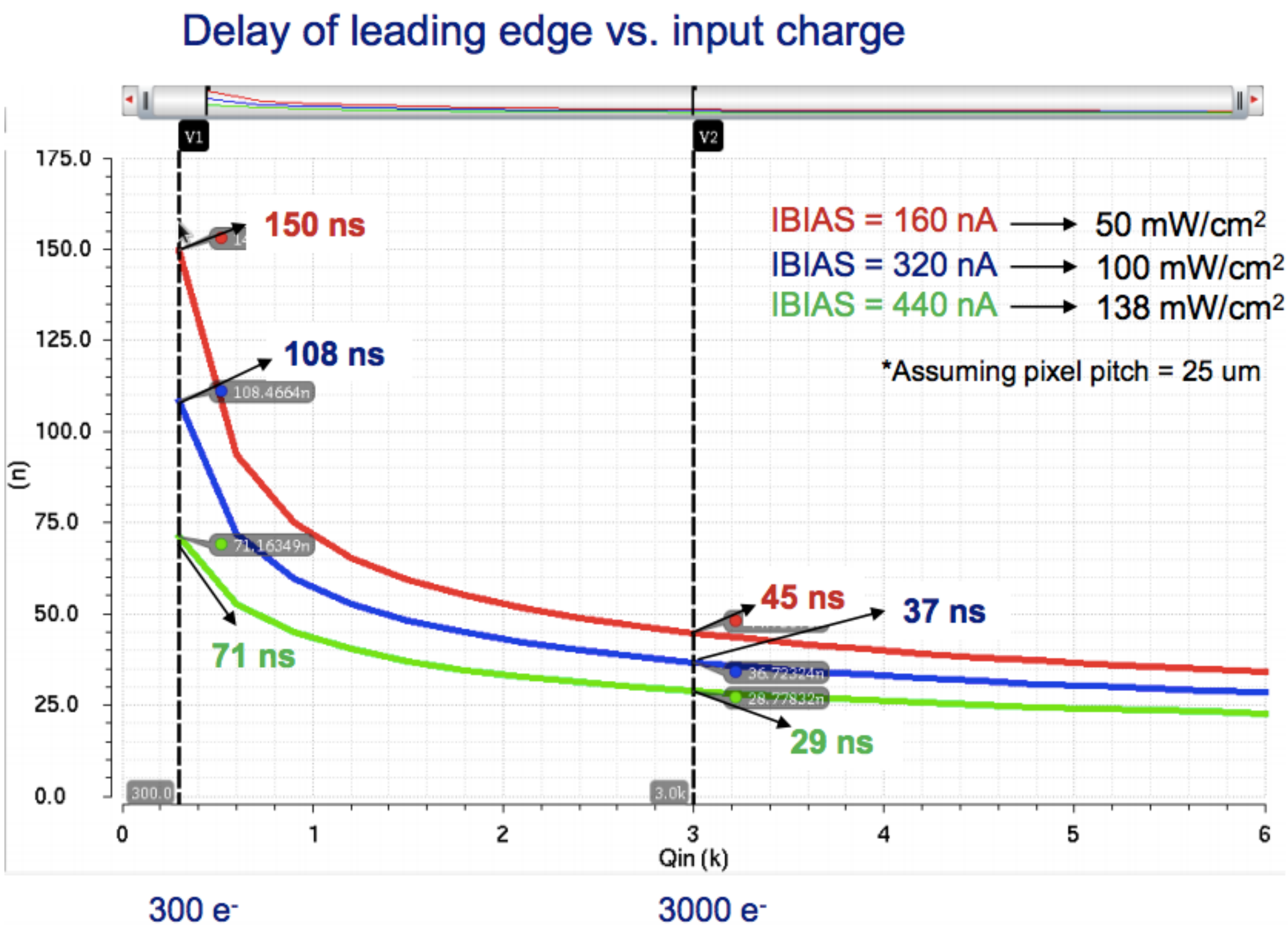
MB: ϵ^0[8-dim], $1/\epsilon$[7-dim]; SD: ϵ^0[8-dim], $1/\epsilon$[7-dim];



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

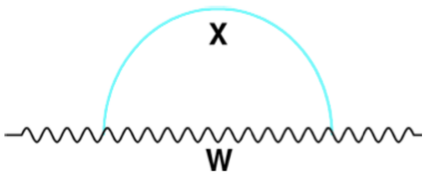
Time walk Vs power consumption in pixel

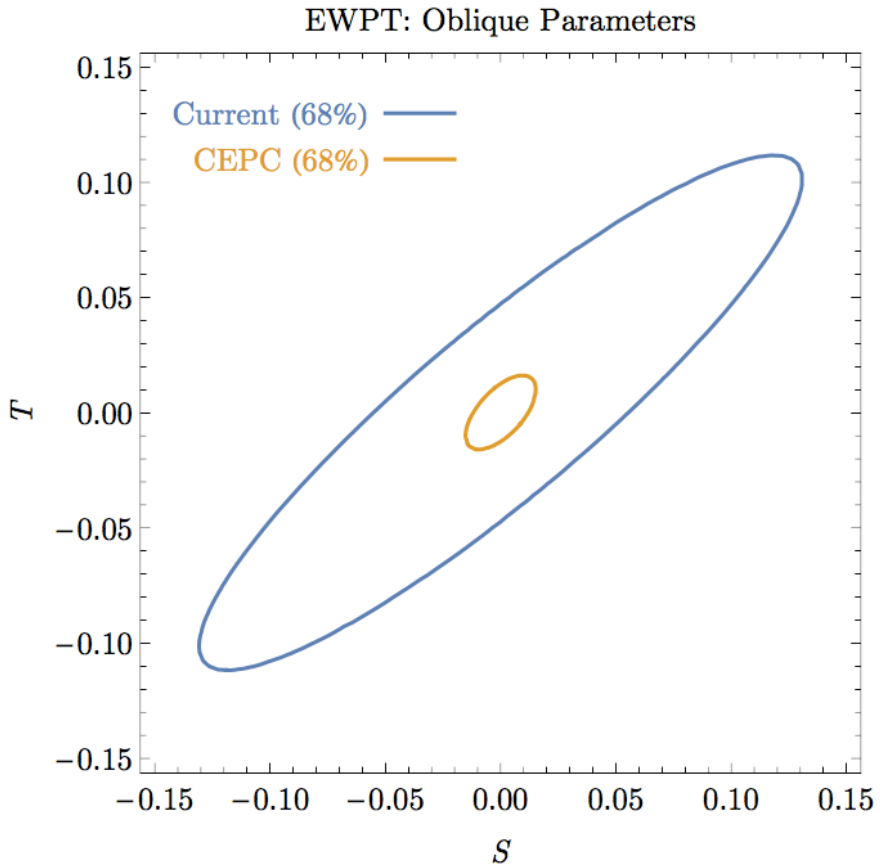
- In MOST2 R & D project lead by Joao,
  - We are planning to build a vertex detector prototype
  - Aim to have faster readout time, more optimized for Z pole physics



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

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  - 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
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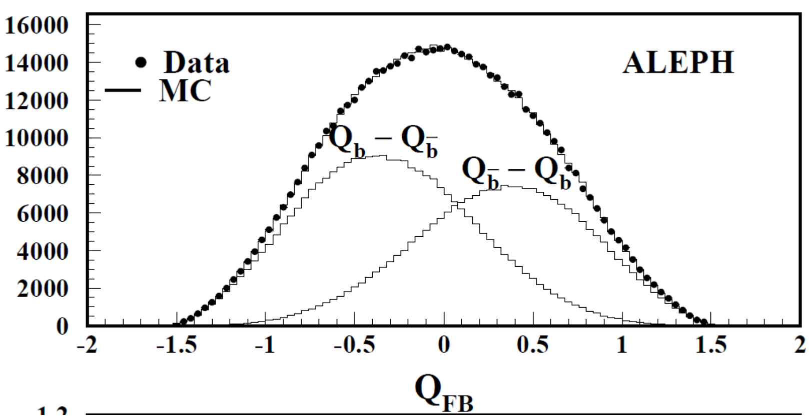
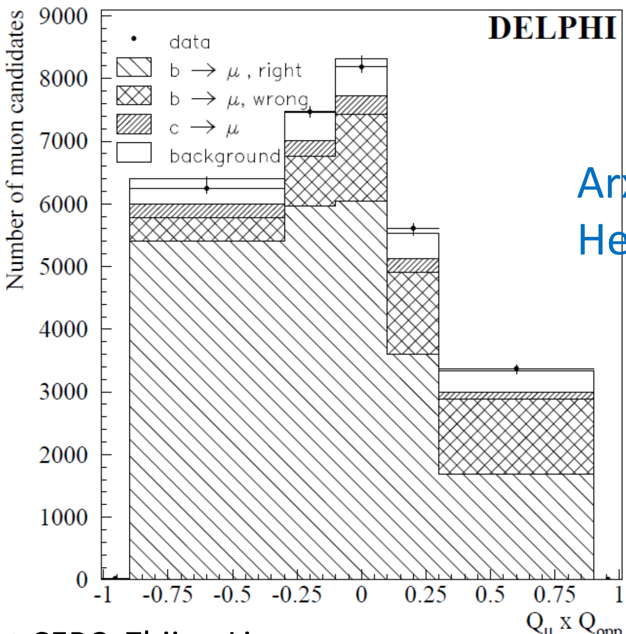
Arxiv:Hep-ex/0107033

Q_F - Q_B in method 2





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Prospect of CEPC W mass measurement

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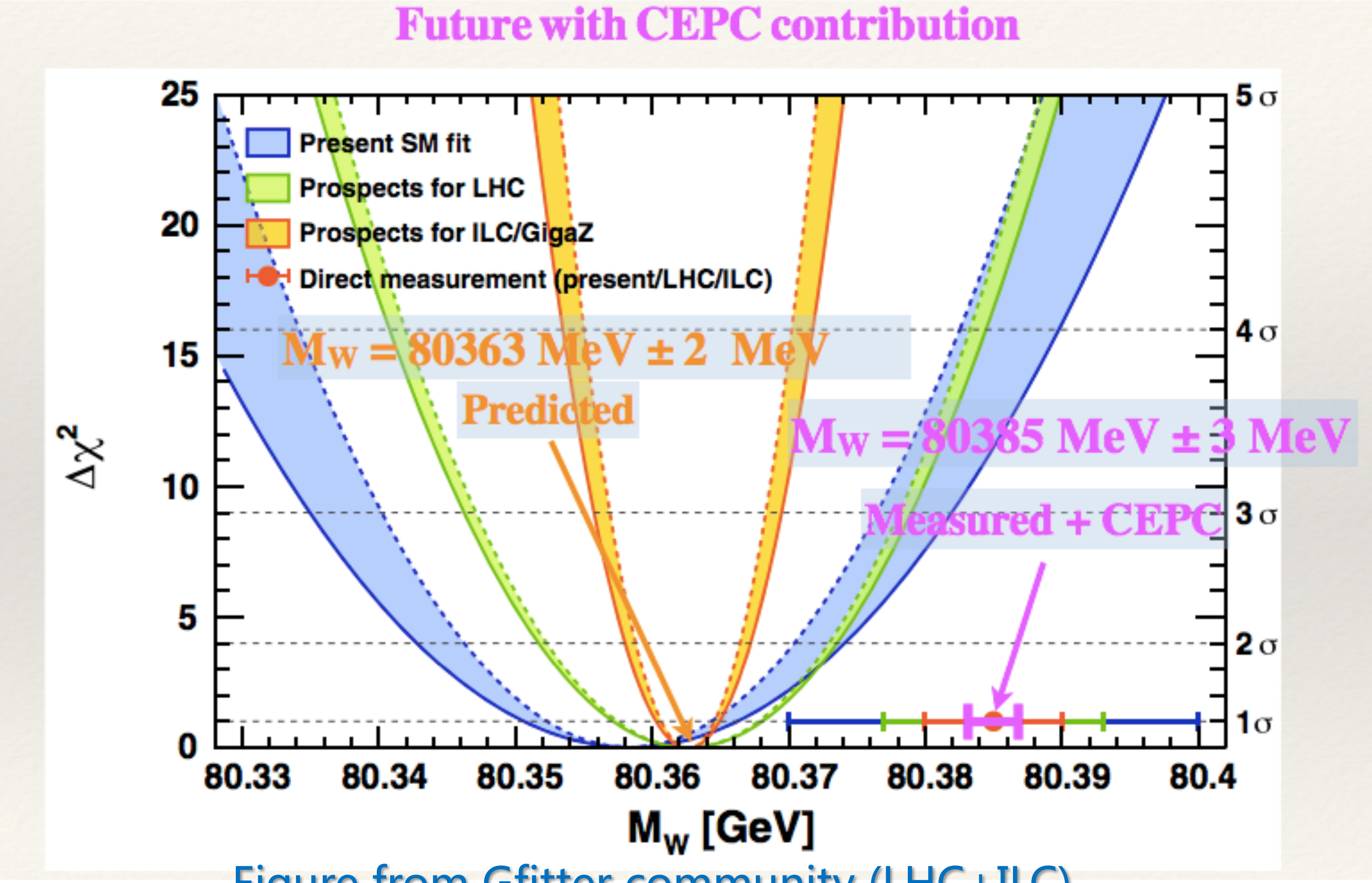
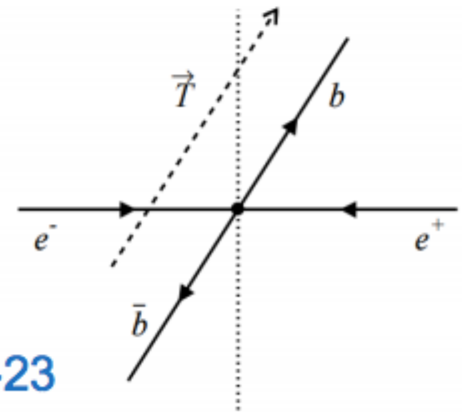


Figure from Gfitter community (LHC+ILC)

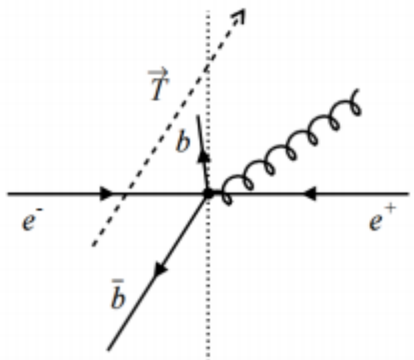
Backward-forward asymmetry $A_{FB}^{b\bar{b}}(0)$

- 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

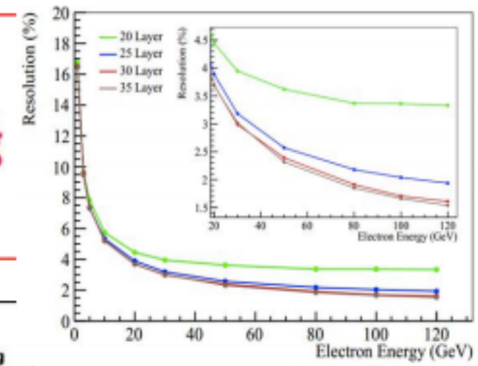
CEPC detector (2)

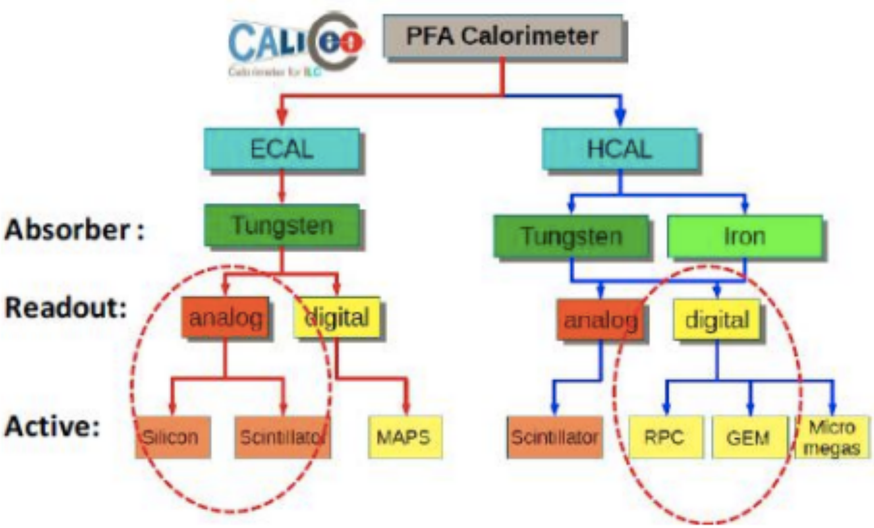
- Calorimeters:
  - Concept of Particle Flow Algorithm (PFA) based
  - EM calorimeter energy resolution: $\sigma_E/E \sim 0.16/\sqrt{E}$
  - Had calorimeter energy resolution: $\sigma_E/E \sim 0.5/\sqrt{E}$
  - Expected jet energy resolution : $\sigma_E/E \sim 0.3/\sqrt{E}$

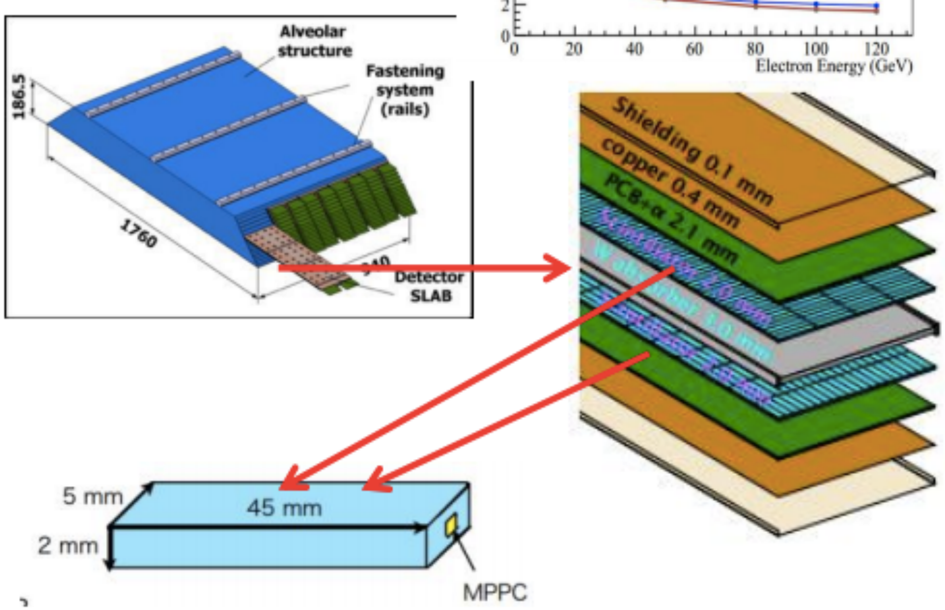
- Jet energy (Higgs self-coupling, W/Z separation)
  - ~1/2 resolution (wrt LHC)

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

less demanding at CEPC







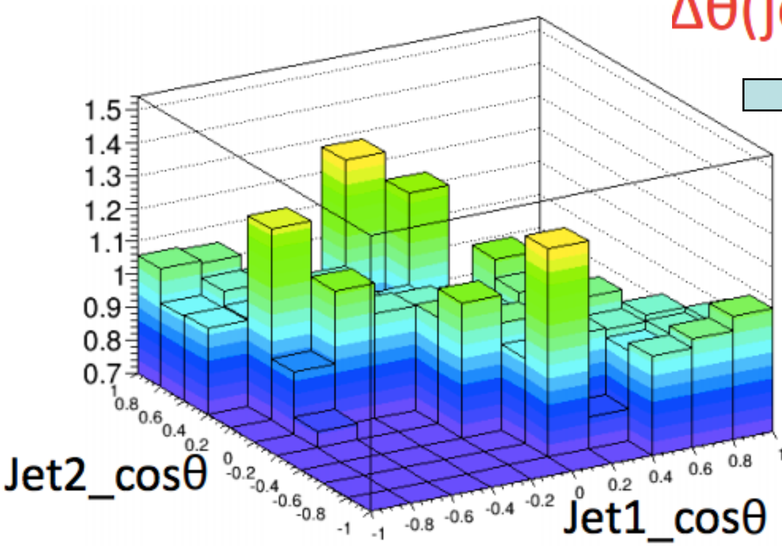
ECAL: Scintillator + W + Scintillator

R^b : hemisphere tag correlations

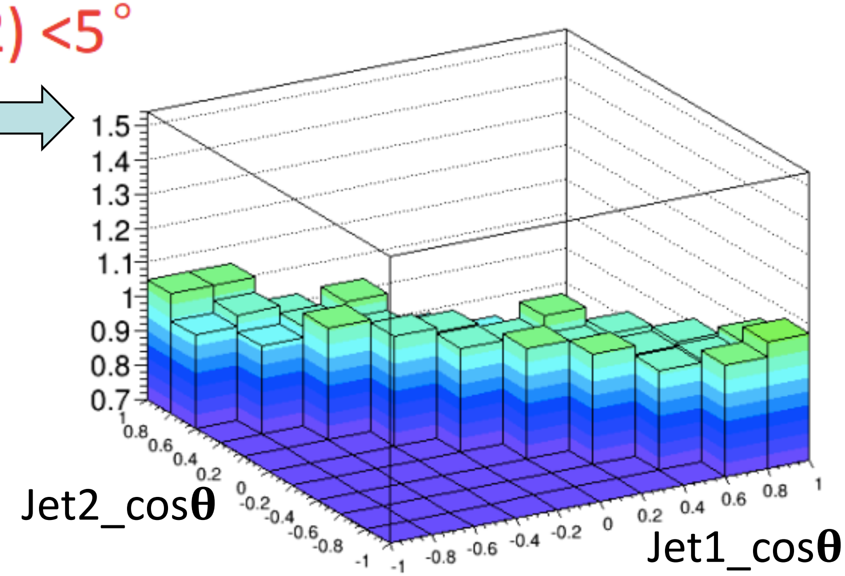
- Study hemisphere b tag correlations systematics with full simulation
- Two ways to reduce correlations factor -> reducing systematics
  - Using tighter cuts to choose Z->bb events
  - Use different B jet tagger (soft muon tag Vs impact parameter)
  - Correlations factors c_b need to be reduced below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

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

By Bo Li (Yantai University)



Δθ(jet1, jet2) <5°

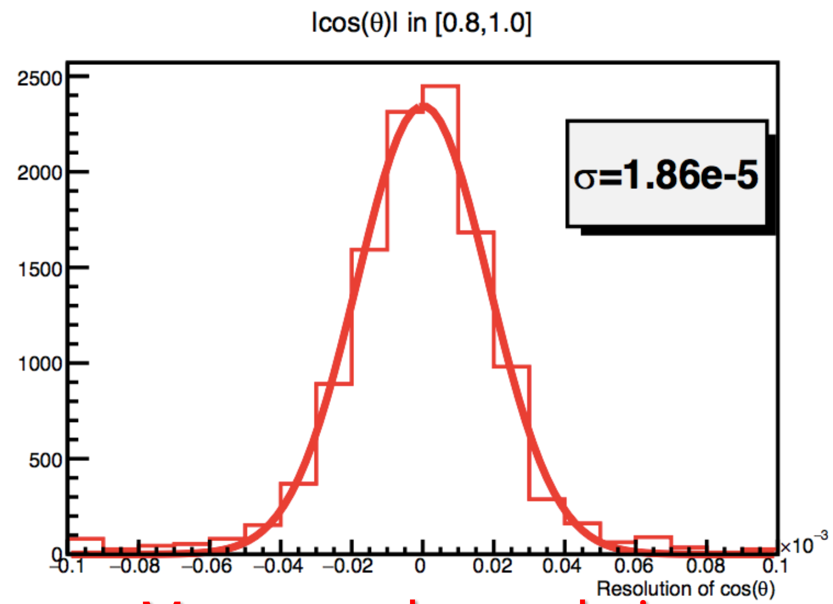


Backward-forward asymmetry in Z->μμ

- 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

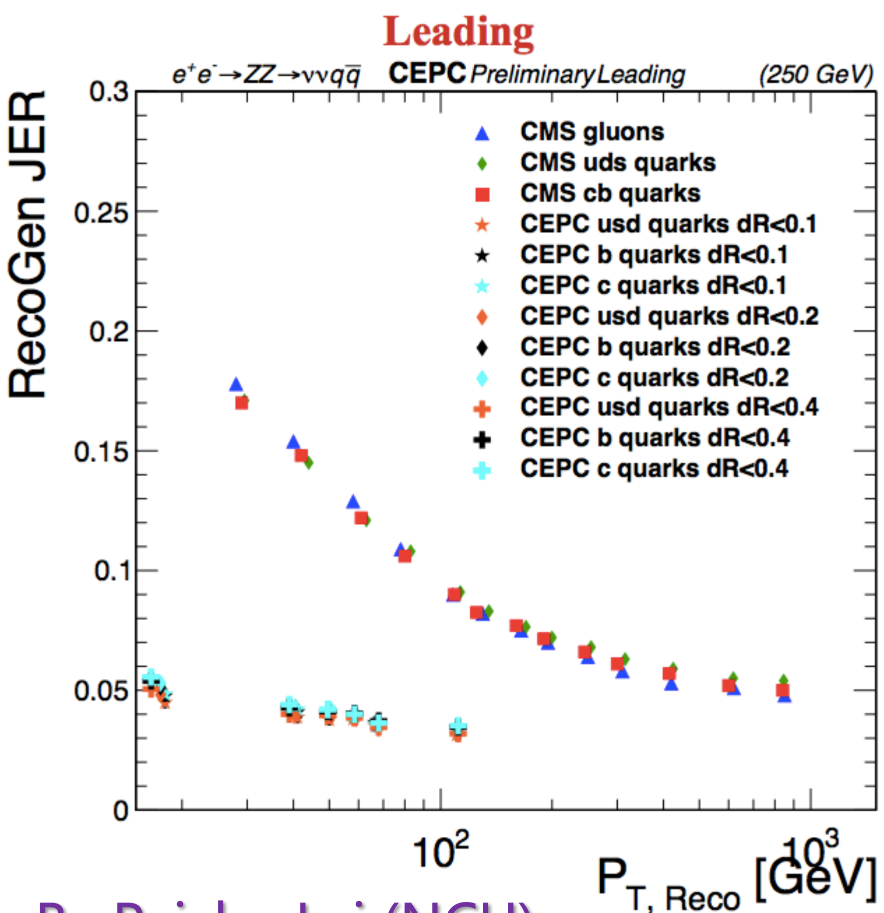
Motivation for CEPC electroweak physics

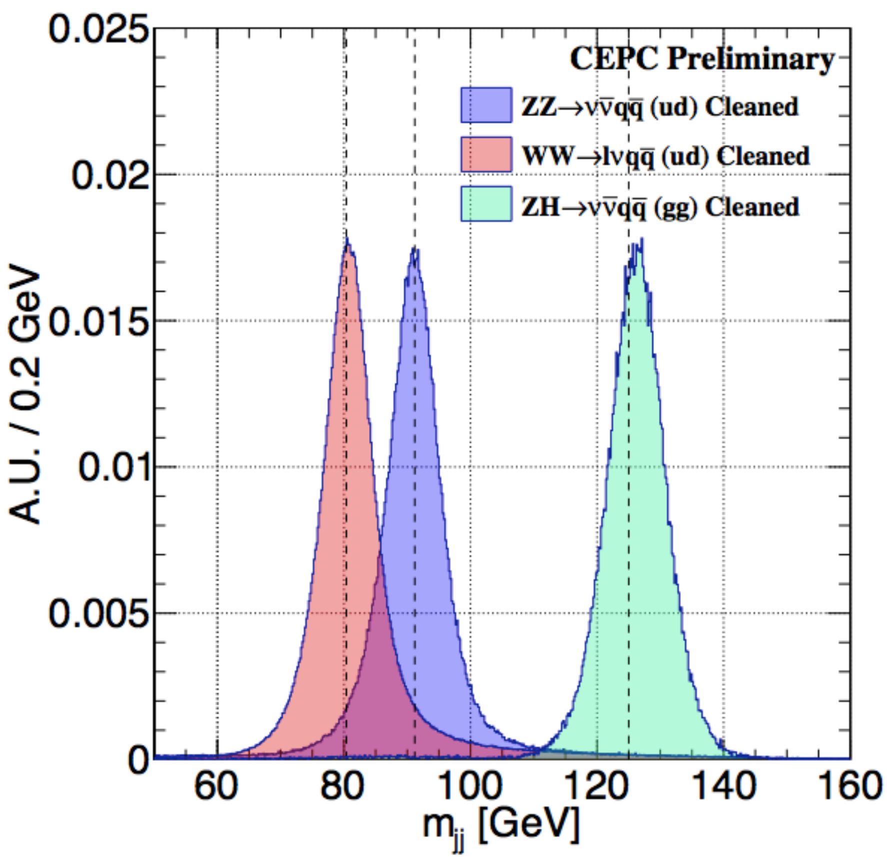
- need more precision in
  - W mass, Top mass and weak mixing angle
- CEPC can provide more precise measurement for
  - W/Z and Higgs mass and weak mixing angle

Fundamental constant	δx/x	measurements
$\alpha = 1/137.035999139\ (31)$ From PDG2018	1×10^{-10}	$e^{\pm}\ g_2$
$G_F = 1.1663787\ (6) \times 10^{-5}\ \text{GeV}^{-2}$	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)