中國科學院高能物理研究所
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Z pole Physics overview

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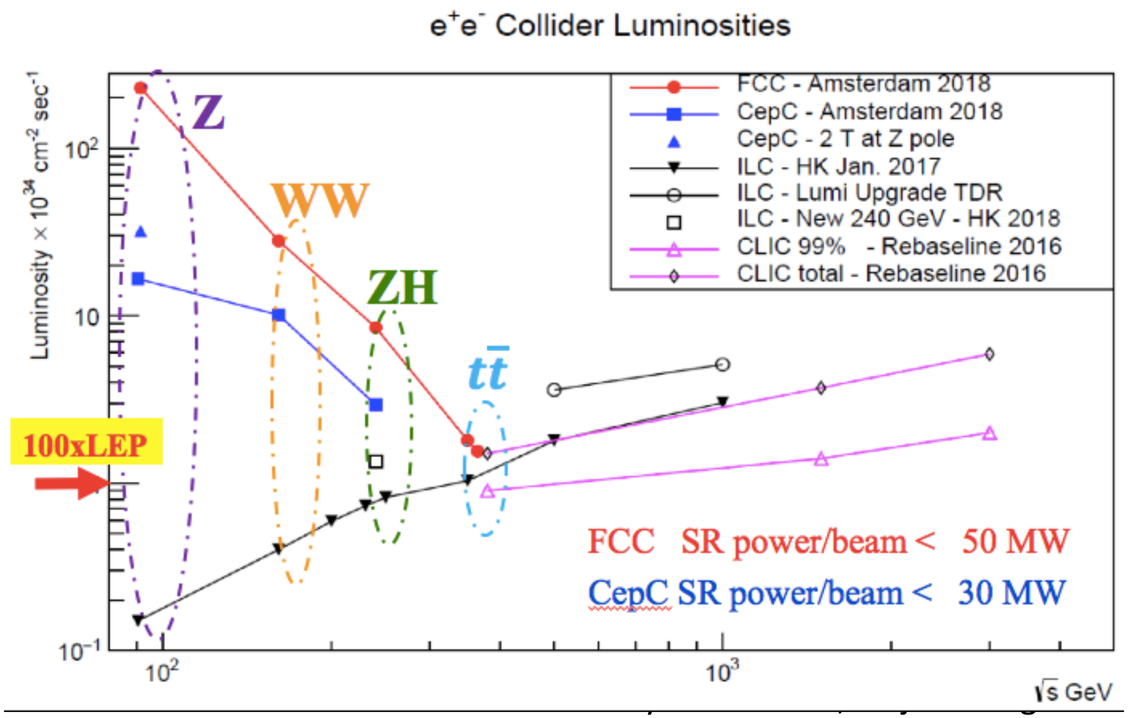
Introduction to CEPC

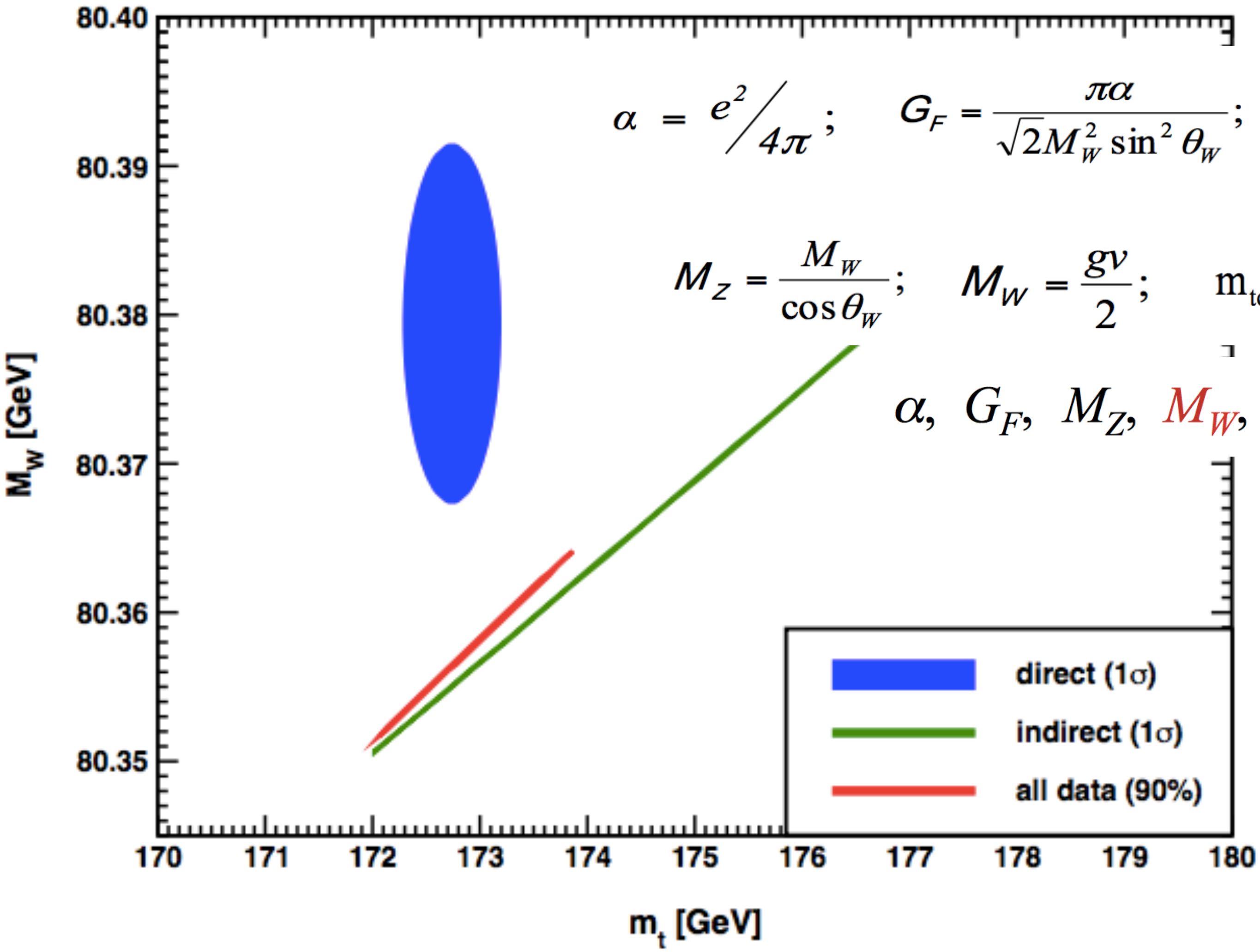
- CEPC is Higgs Factory (E_{cms}=240GeV , 10^6 Higgs)
- CEPC is Z factory(E_{cms}~91GeV) ,electroweak precision physics at Z pole.
  - **baseline L=1.6 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =3T, 3X10^{11} Z boson, two years**
  - **L= 3.2 X 10^{35} $cm^{-2}s^{-1}$, Solenoid =2T , 6X10^{11} Z boson**
-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



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

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

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

self-consistency Check of SM

Freitas & JE (PDG 2018)

Motivation for CEPC electroweak physics

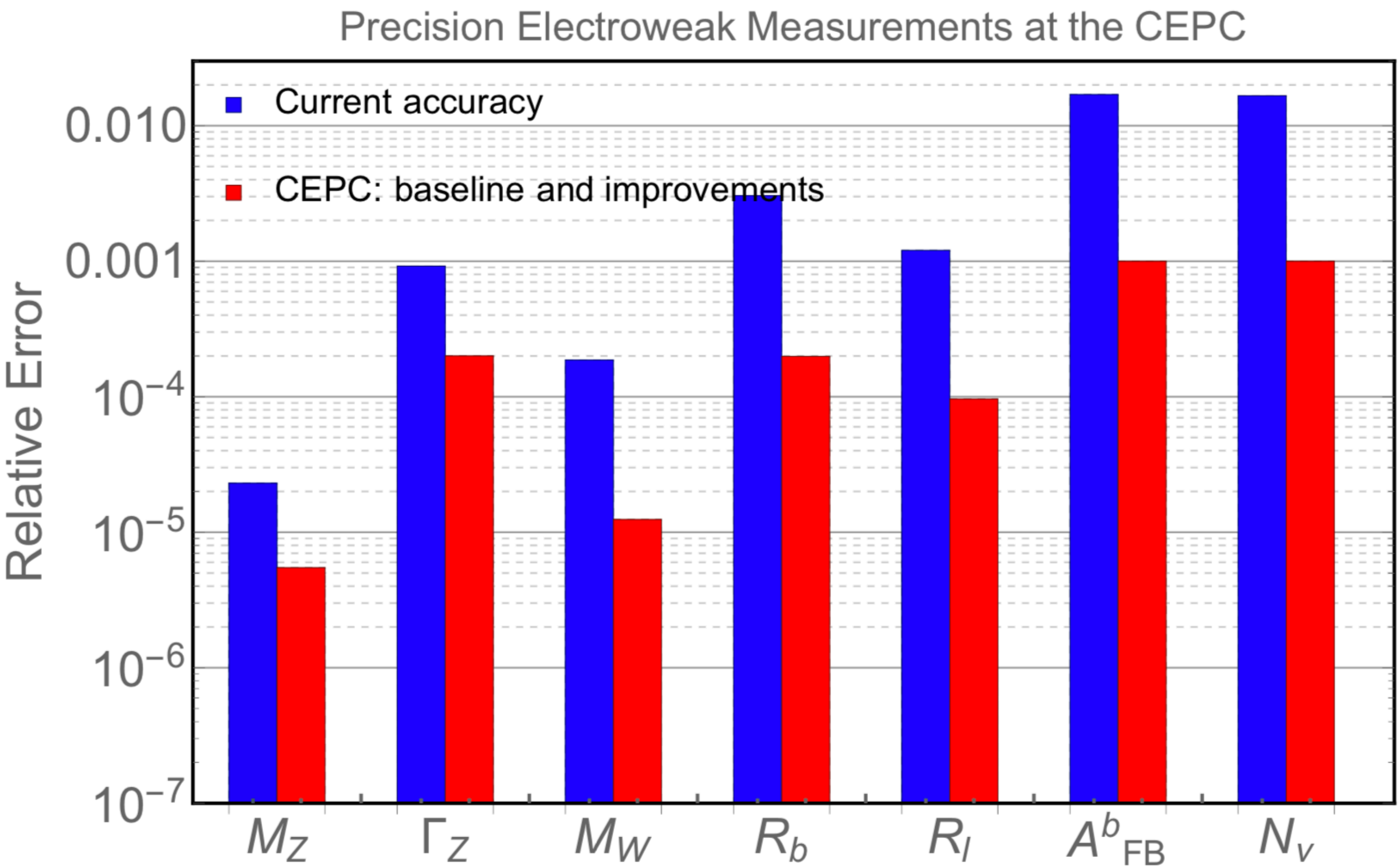
- need more precision in
  - W mass, Top mass and weak mixing angle
- CEPC can provide more precise measurement

From PDG2018

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

Prospect of CEPC EWK physics

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

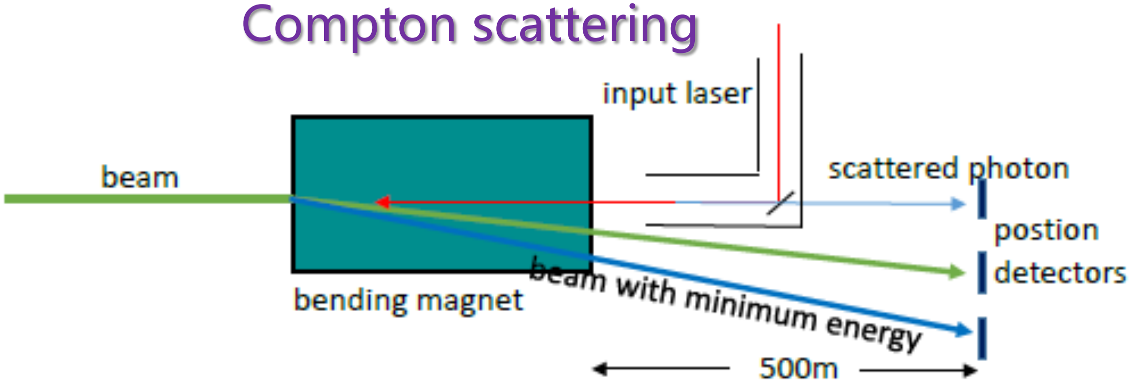


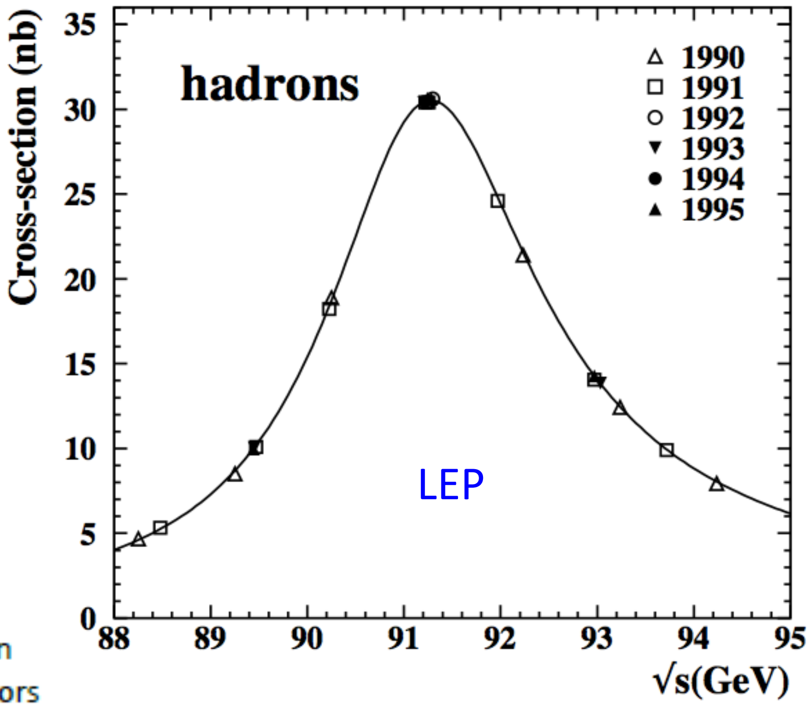
Z mass measurement

- LEP precision ： 91.1876±0.0021 GeV
- CEPC goal : 0.5 MeV (CDR) → 0.1MeV (TDR)
  - Beam energy uncertainty is major systematics
    - Resonant depolarization approach by LEP → <0.1MeV
    - Compton scattering → <0.3 MeV

	Z pole (91GeV)	WW (160GeV)	ZH (240GeV)
Resonant Depolarization	0.1MeV	0.5 MeV	NA
Compton Scattering	0.3MeV	0.6MeV	1.0 MeV

Compton scattering



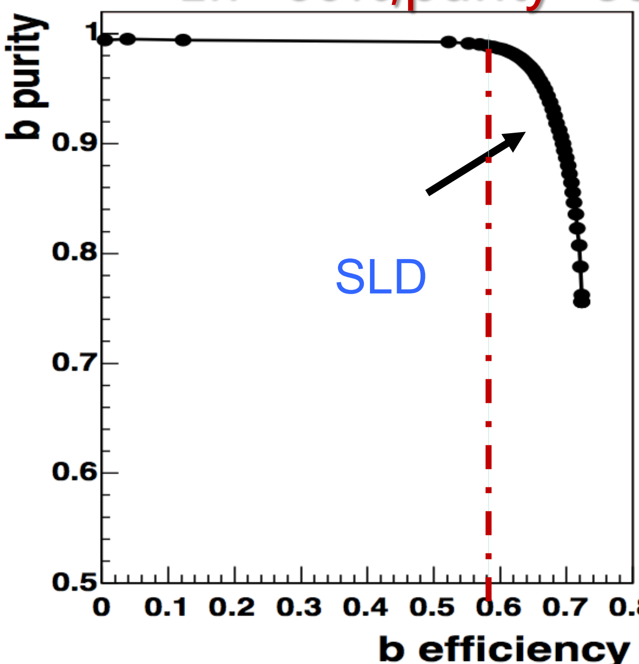


$\frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to had)}$ Branching ratio (R^b)

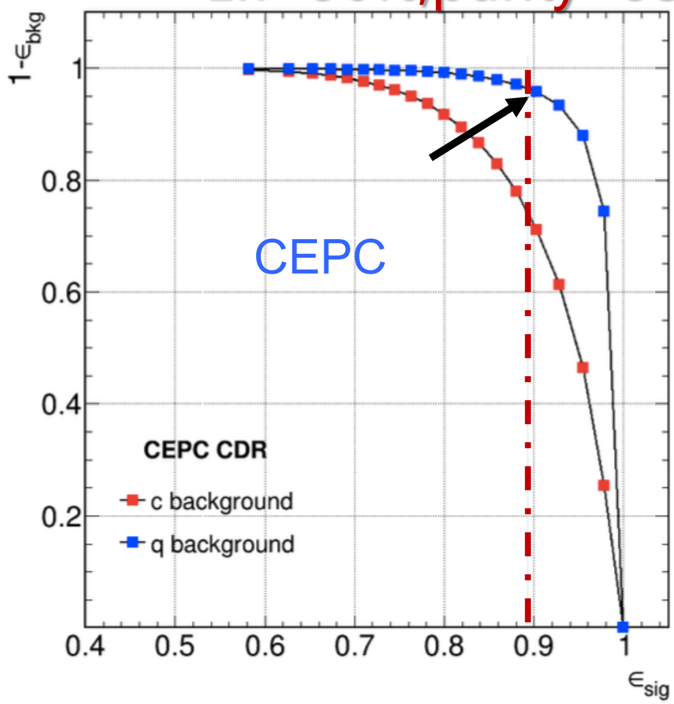
- LEP measurement 0.21594 ±0.00066
  - Syst error : ~0.2%
- CEPC
  - Expected Syst error (0.02%)
  - hemisphere tag correlations depends on b tagging efficiency
  - Expect 20~30% higher B tagging efficiency than SLD
  - Theory uncertainty (gluon splitting ..): need input from theorists

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

Eff=60%,purity~95%



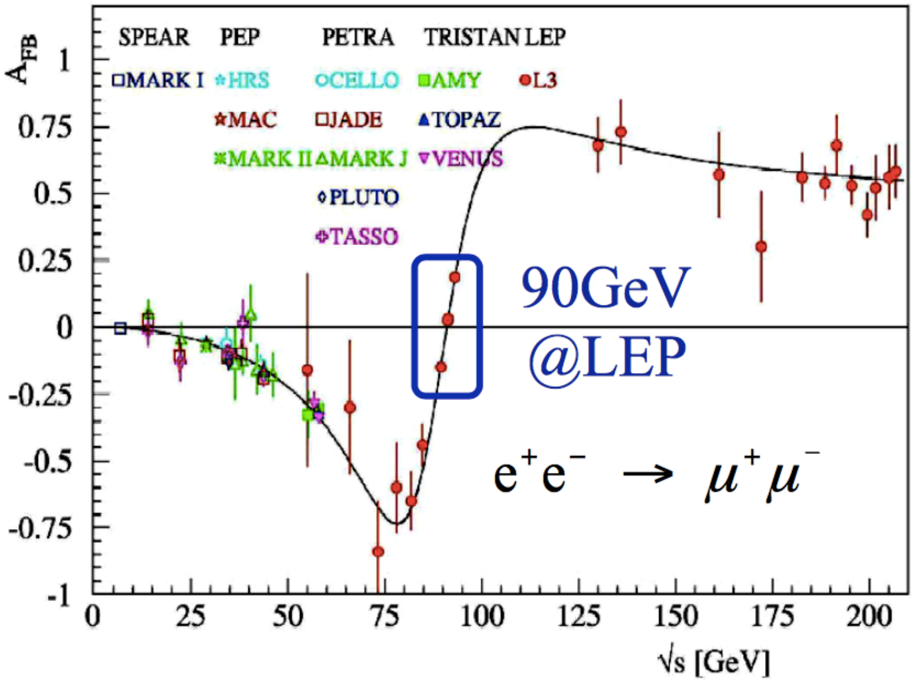
Eff~90%,purity~95%

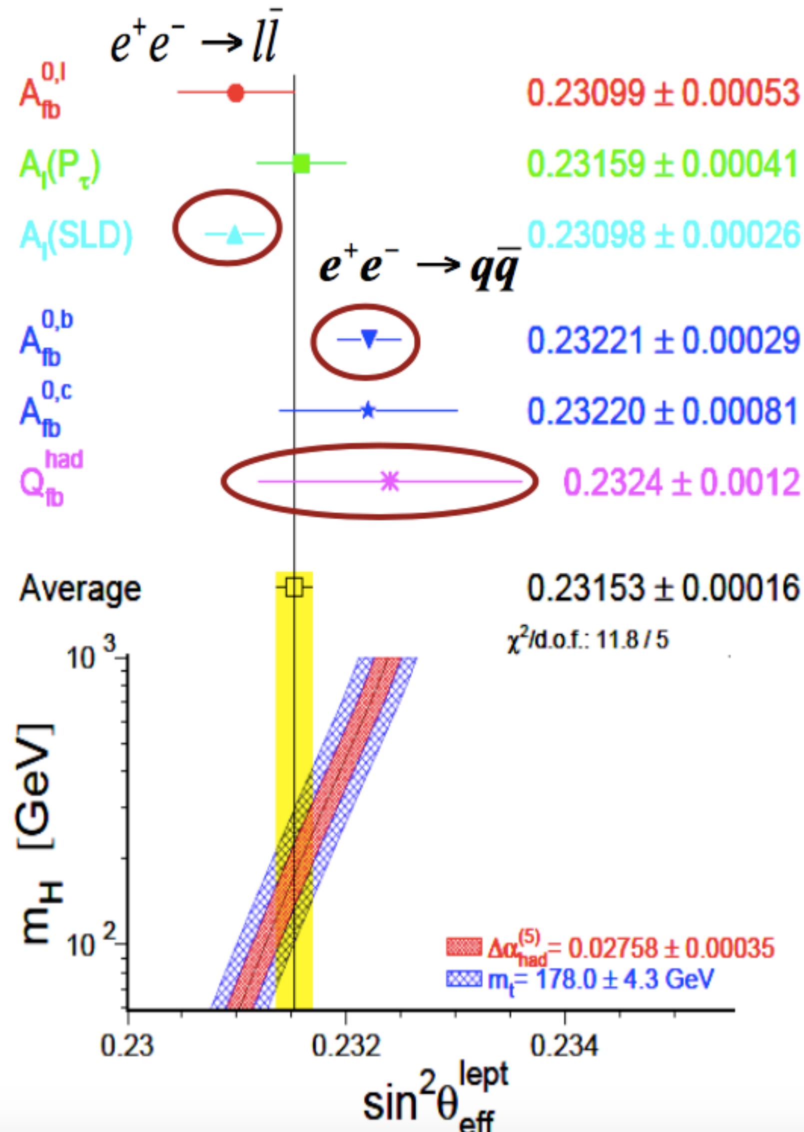


More details in Bo Li's talk

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

- Some tension between SLD and LEP results (~3σ)
  - Remain a puzzle for ~10 years



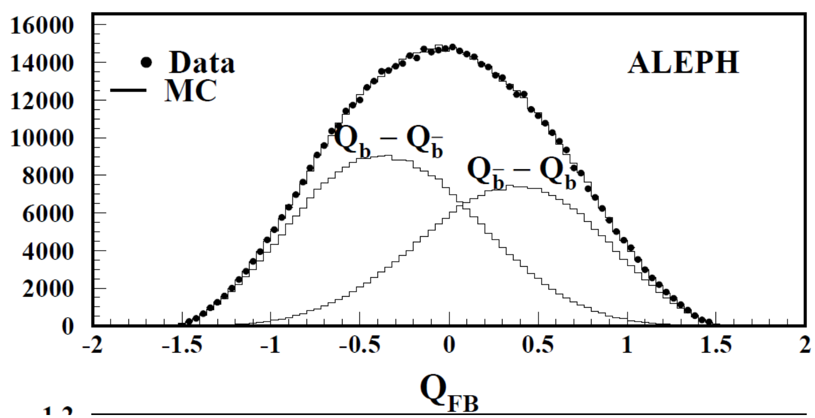


Backward-forward asymmetry $A_{FB}^{0,b}$

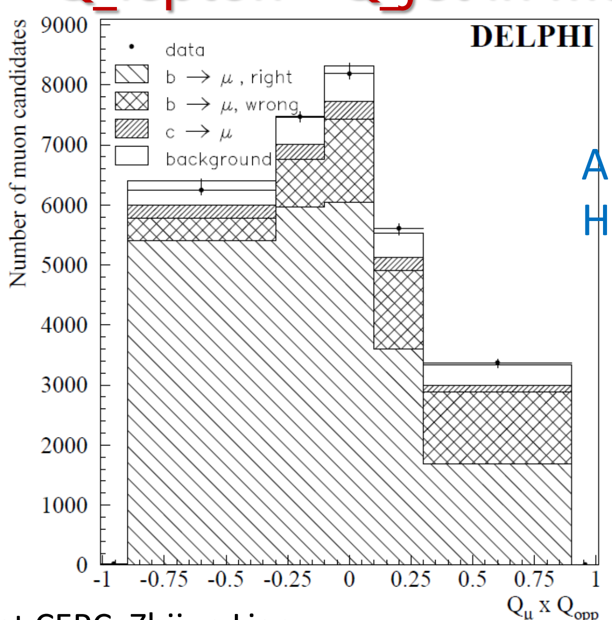
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay
    CEPC precision 0.1% ,LEP precision ~2% (stat dominated)
    - Main systematics is B hadron decay branching ratio
  - Method 2: jet charge method , Inclusive b jet (LEP precision 1.2%)
    - use event Thrust to define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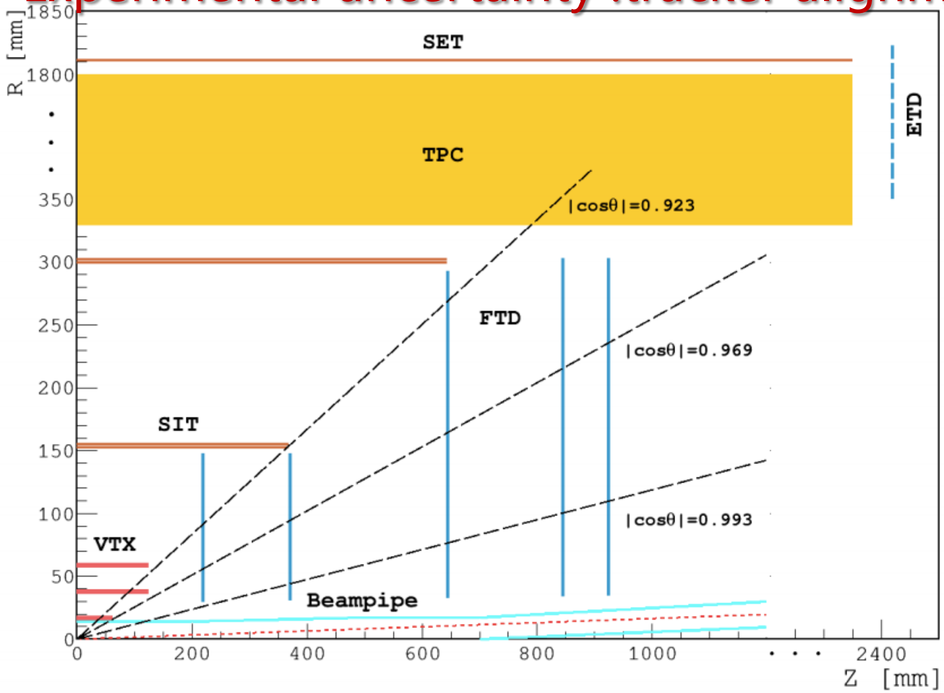
Backward-forward asymmetry in Z->μμ

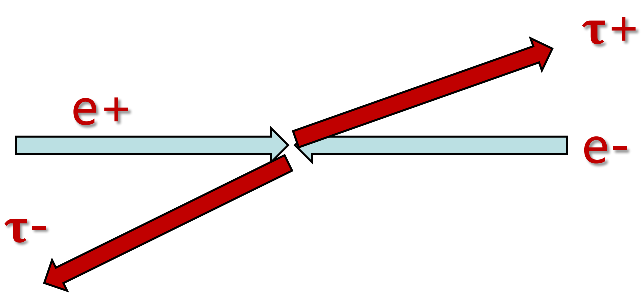
$A_{FB}^{(0,\mu)}$

- LEP measurement : 0.0169 +-0.00130
- CEPC expected: +-0.00002
  - CEPC has potential to improve it by a factor of 50 .
    - Acceptance systematics (larger detector coverage, smaller syst.)
- Major systematics (absolute value.)
  - Beam energy systematics ($1e^{-5}$, assuming 100keV E_{beam} unc.)
  - Tracker alignment and Muon angular resolution ($1e^{-5}$ level)

Experimental uncertainty :tracker alignment



A_e and A_τ: tau polarization



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

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

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

- Weak mixing angle
  - extracted from A_e and A_τ using tau polarization: more precise

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

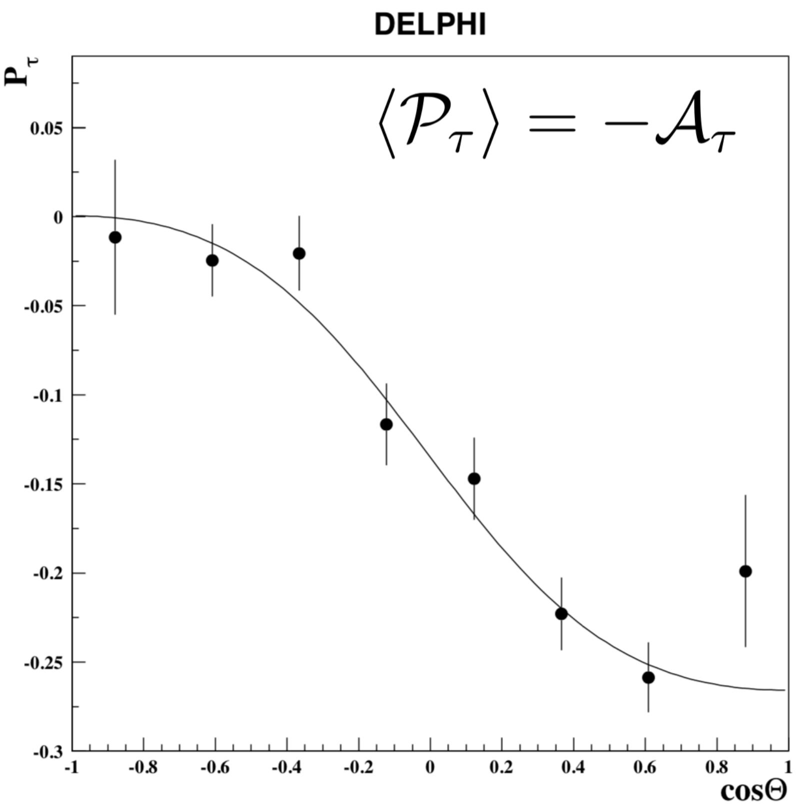
$A_{\rm LRFB}$, $P_\tau(\cos\theta)$ → A_e and A_τ

A_e and A_τ in $Z \to \tau\tau$

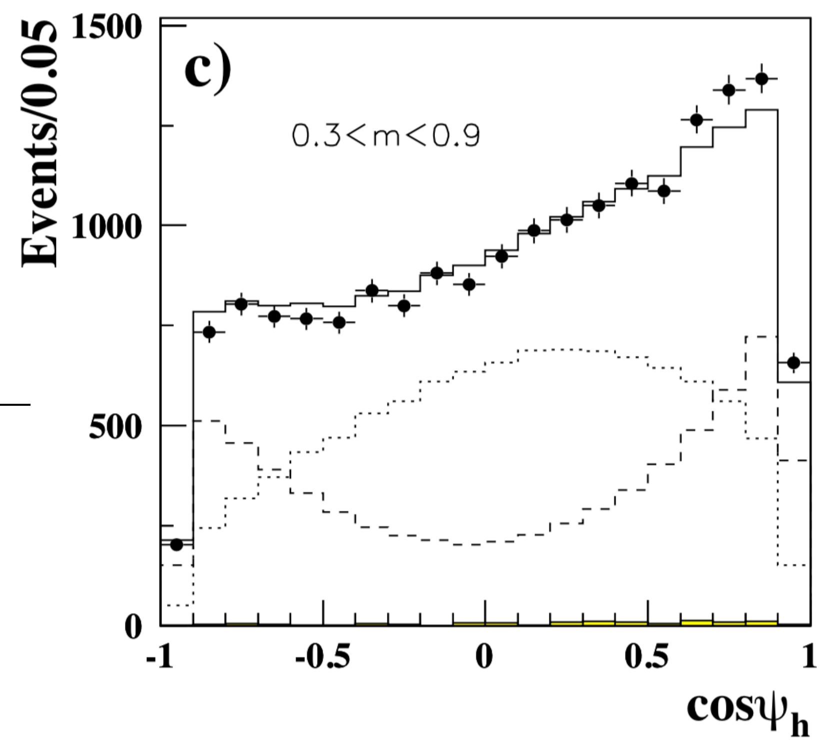
- Tau polarization can be measured through its decay product

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

A_{LRFB}, $P_\tau(\cos\theta)$ → A_e and A_τ



From DELPHI



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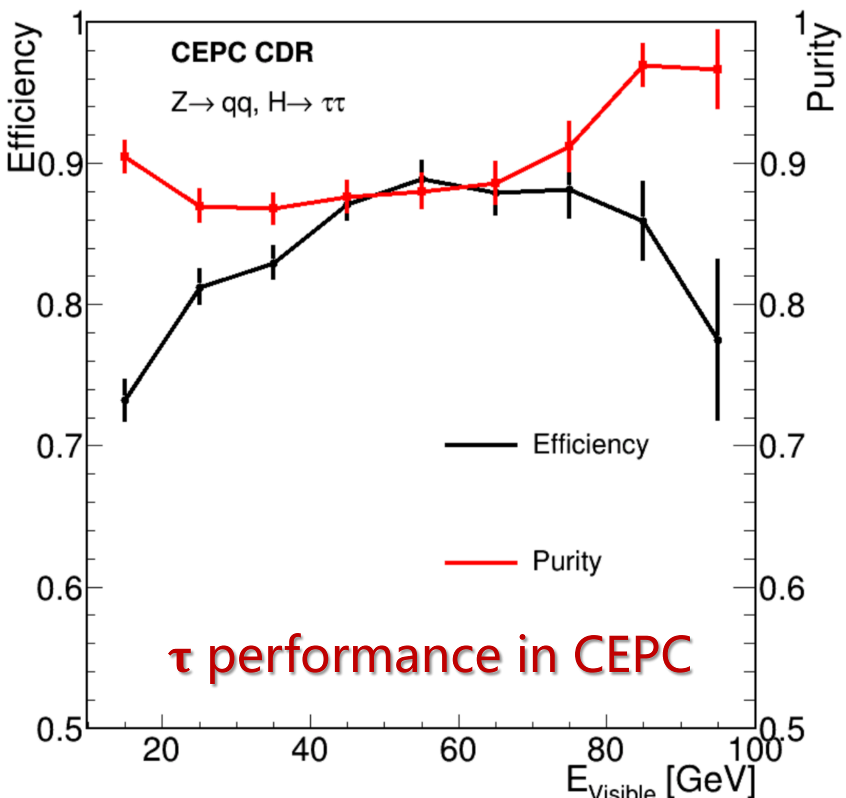
A_e and A_τ in Z →ττ: systematics

- Current precision
  - A_e : **0.1515±0.0019 (PDG)**
  - A_τ : **0.143±0.004 (PDG)**
- CEPC expected :
  - A_τ Key systematics is from EM scale, and **τ** identification
  - A_e limited by statistics

Relative unc.	current PDG Precision	CEPC Precision
A_τ	$2.8X10^{-2}$	$5X10^{-4}$
A_e	$1.3X10^{-2}$	$3X10^{-4}$

CEPC can improve this by a factor of 50



τ performance in CEPC

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	2.1 MeV	0.5 MeV	Z pole	8 ab^{-1}
Γ_Z	2.3 MeV	0.5 MeV	Z pole	8 ab^{-1}
$A_{FB}^{0,b}$	0.0016	0.0001	Z pole	8 ab^{-1}
$A_{FB}^{0,\mu}$	0.0013	0.00005	Z pole	8 ab^{-1}
$A_{FB}^{0,e}$	0.0025	0.00008	Z pole	8 ab^{-1}
$\sin^2\theta_W^{\text{eff}}$	0.00016	0.00001	Z pole	8 ab^{-1}
R_b^0	0.00066	0.00004	Z pole	8 ab^{-1}
R_μ^0	0.025	0.002	Z pole	8 ab^{-1}
m_W	33 MeV	1 MeV	WW threshold	2.6 ab^{-1}
m_W	33 MeV	2–3 MeV	ZH run	5.6 ab^{-1}
N_ν	1.7%	0.05%	ZH run	5.6 ab^{-1}

Beam polarization for Z pole ?

- What is Polarized beam collision ?
  - Usually mean longitudinal polarized beam for physics

Type	Polarized beam collision	Beam energy measurement
Polarized Type	Longitudinal polarized	Transverse polarized
Fraction of polarization	>30% (50%)	5~10% is enough

Type	Longitudinal polarized e-	Longitudinal polarized e+	Transverse polarized Beam
CEPC	To be discussed	To be discussed	Yes (Z,WW)
Fcc-ee	No	NO	Yes (Z,WW)
ILC	yes	yes	-

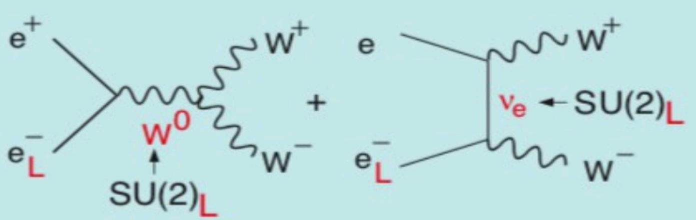
Polarized beam collision: motivation

Any other physics case for polarized beam collision in CEPC?

BG Suppression

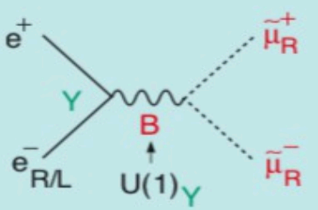
From ILC

W^+W^- (Largest SM BG in SUSY searches)



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton Pair

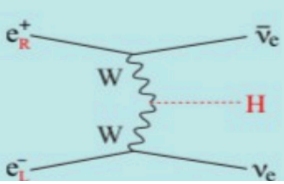


$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

WW-fusion Higgs Prod.

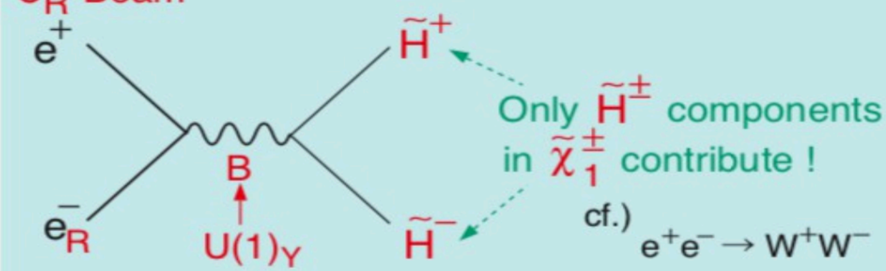


	ILC
Pol (e-)	-0.8
Pol (e+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Signal Enhancement

Chargino Pair

e^-_R Beam



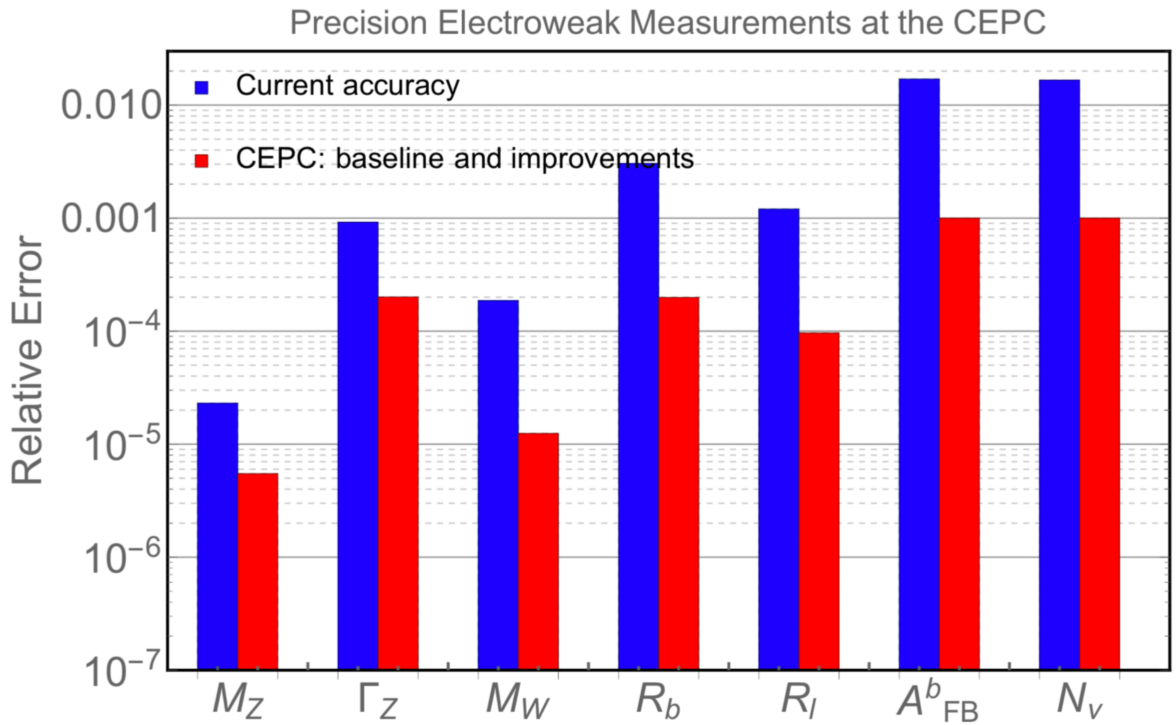
$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$

$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$

Decomposition

Summary

- Potential of electroweak measurement at CEPC
  - 1~2 order of magnitude better than current precision
  - **Two years at Z pole: 3(6) X10^{11} Z boson**
  - **One year WW runs: 10^8 WW pairs (10^7 WW @ 160GeV)**
- Polarized beam collision is under study



Electroweak global fit

- Review of the key electroweak constant

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	
$M_Z = 91.1876 \pm 0.0021$ GeV	1×10^{-5}	LEP	Z pole
$M_W = 80.379 \pm 0.012$ 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
$m_{top} = 172.74 \pm 0.46$ GeV	3×10^{-3}	Tevatron/LHC	
$M_H = 125.14 \pm 0.15$ GeV	1×10^{-3}	LHC	ZH runs

From PDG2018

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.

doing check on systematics (tracker alignment ...)

Discrepancy Due to statistics

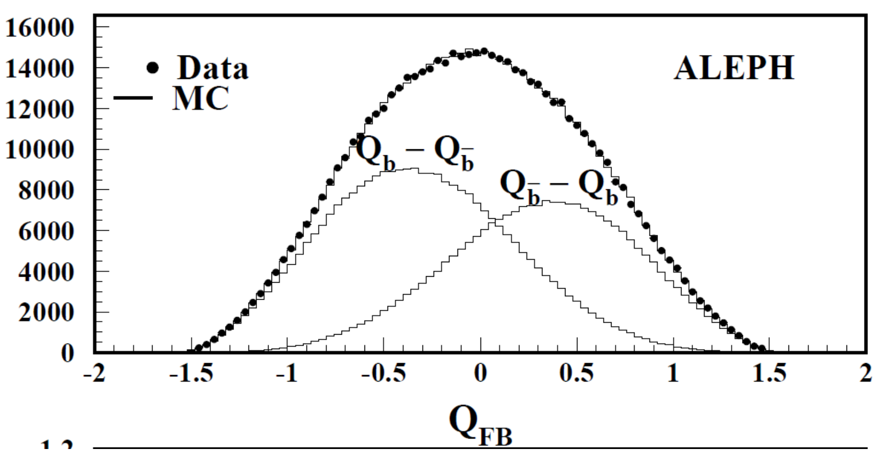
Backward-forward asymmetry

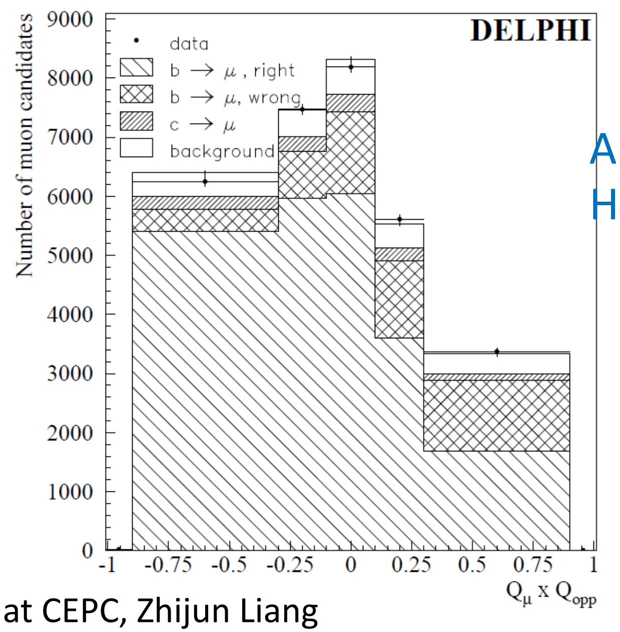
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay (~2%)
    - Select one lepton from b/c decay, and one b jets
    - Select lepton charge (Q_lepton) and jet charge (Q_jet)
  - Method 2: jet charge method using Inclusive b jet (~1.2%)
    - Select two b jets, use event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

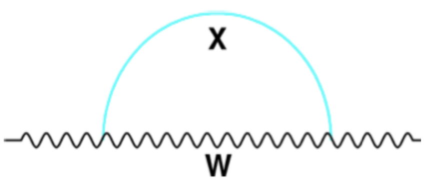


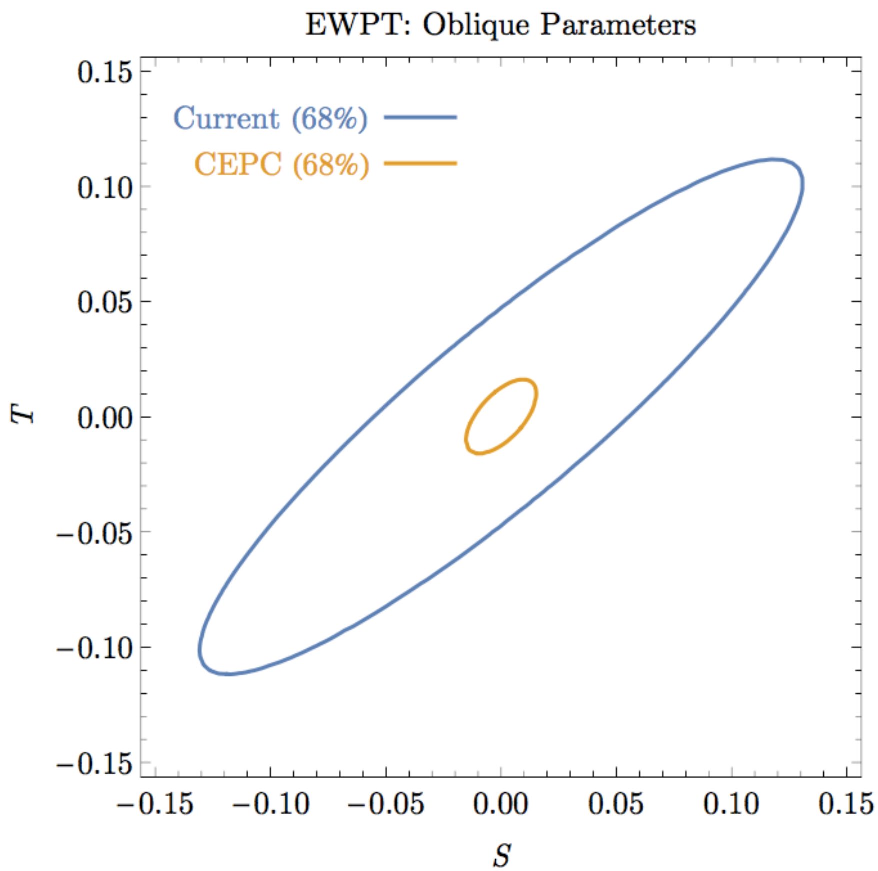


Arxiv: Hep-ex/0403041

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.





A_e and A_τ in Z →ττ

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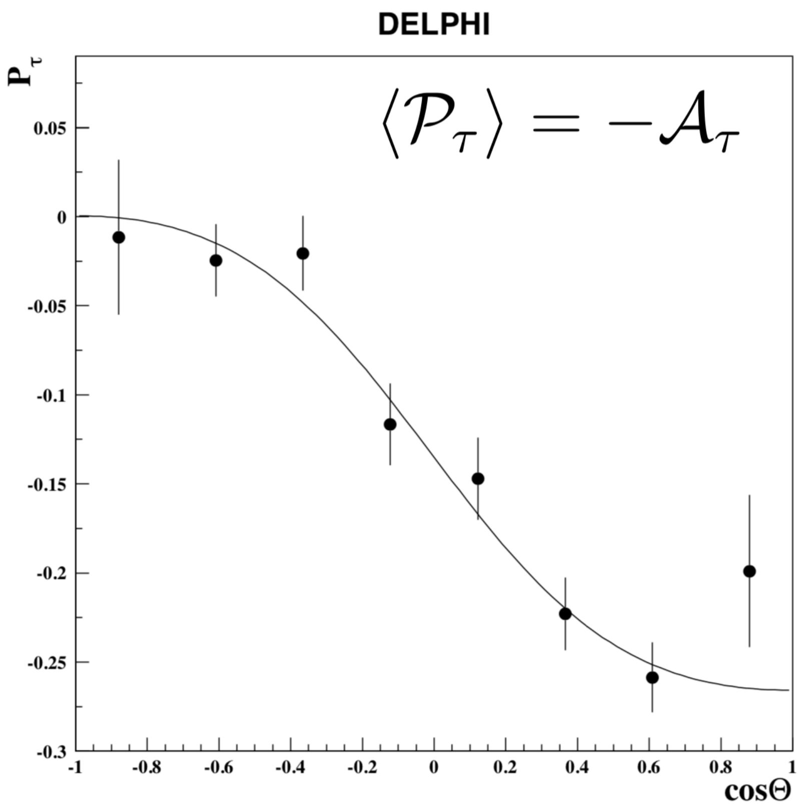
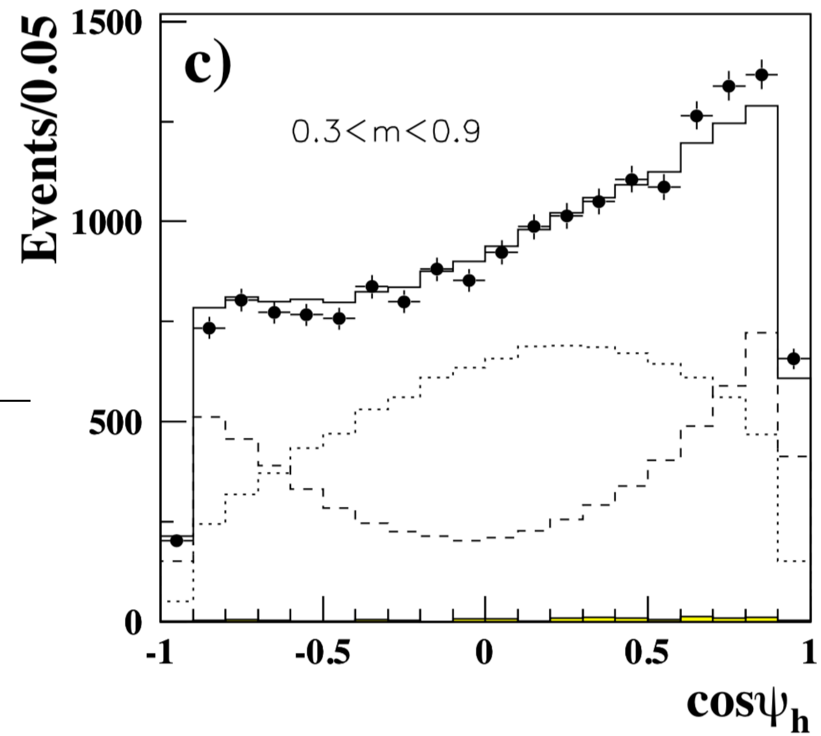


From DELPHI



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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

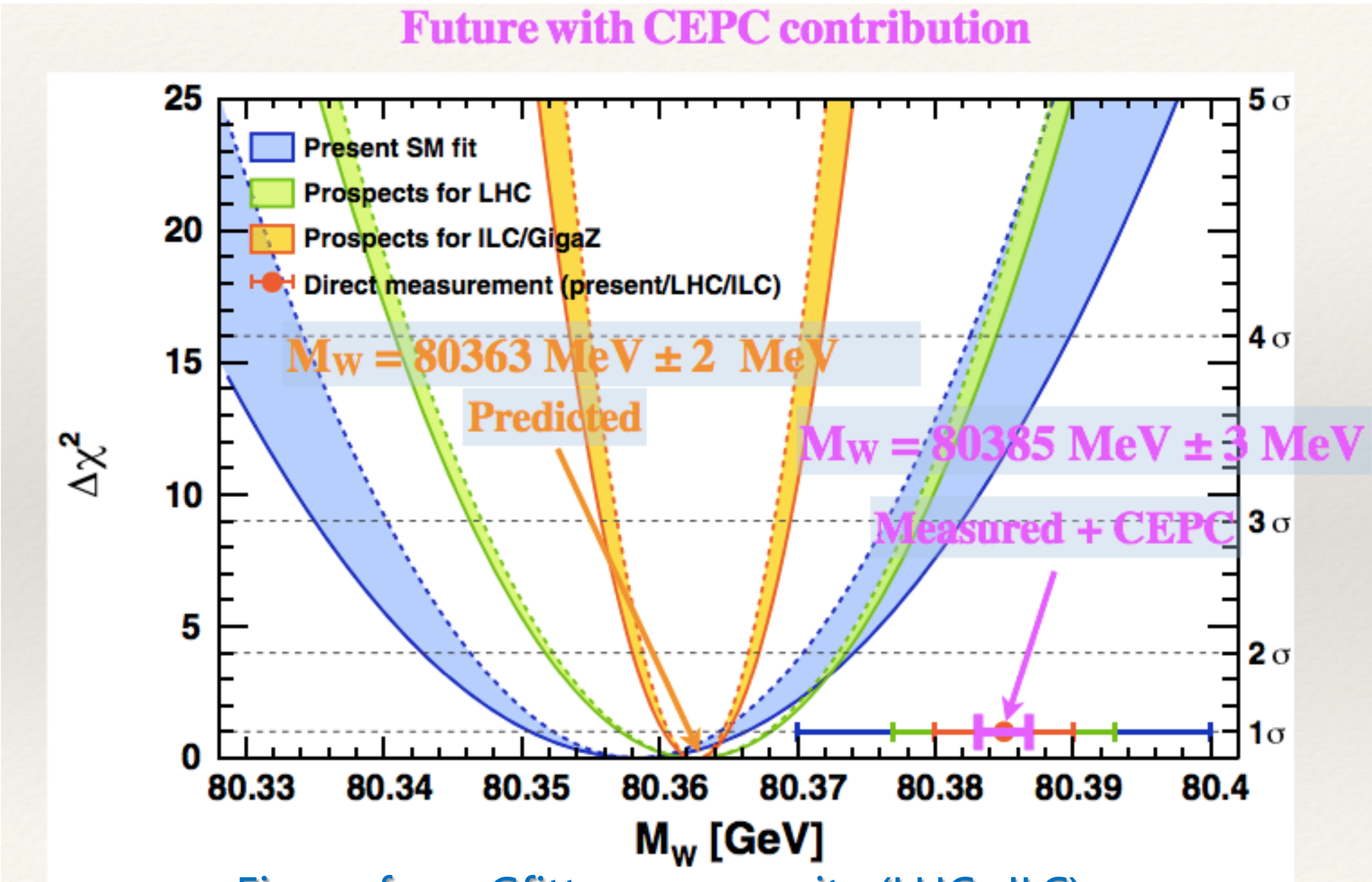

Figure from Gfitter community (LHC+ILC)

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

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Number of neutrino generation (N_ν)

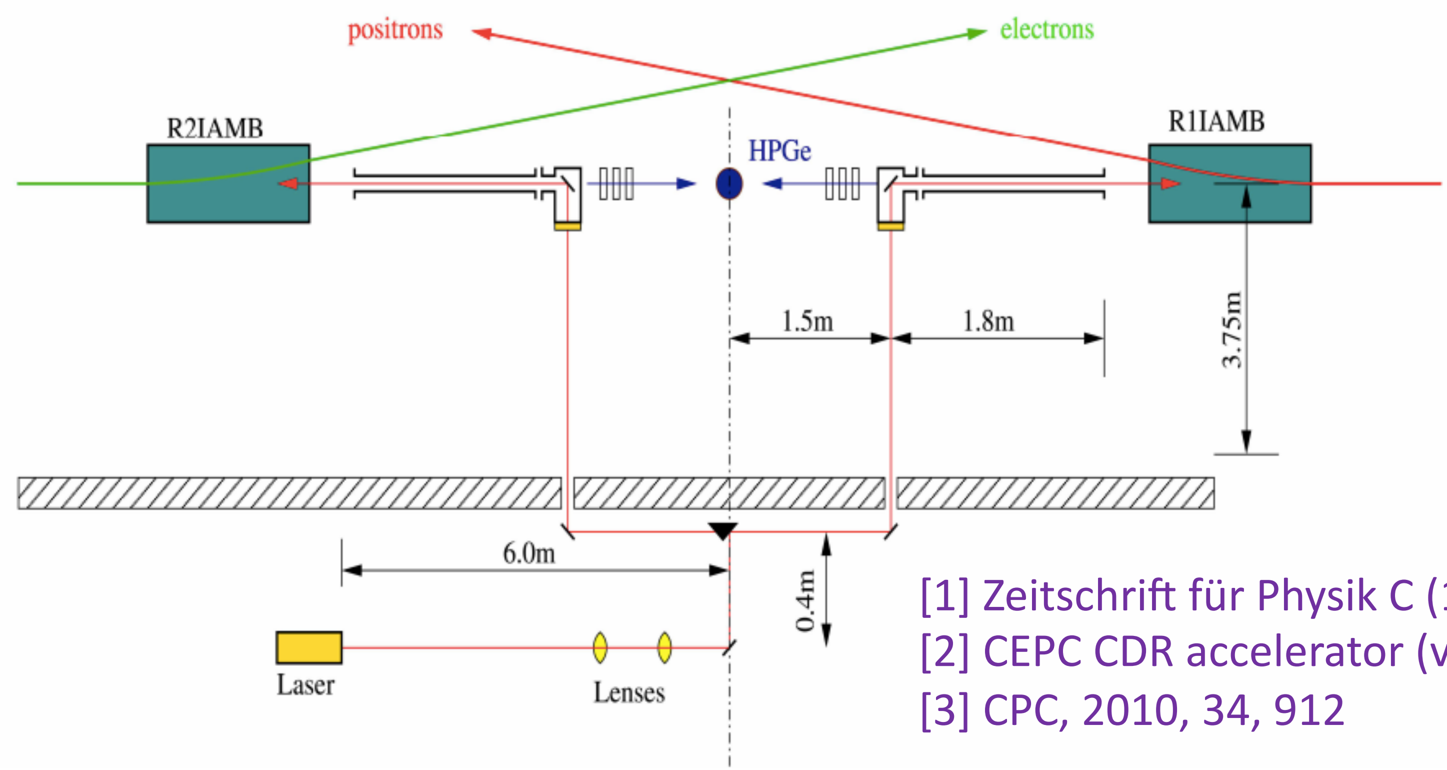
$$e^+e^- \to \nu\bar{\nu}\gamma.$$

- 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

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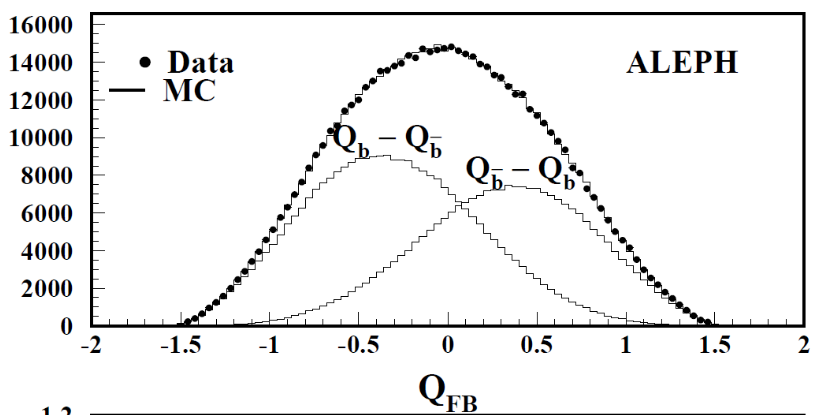
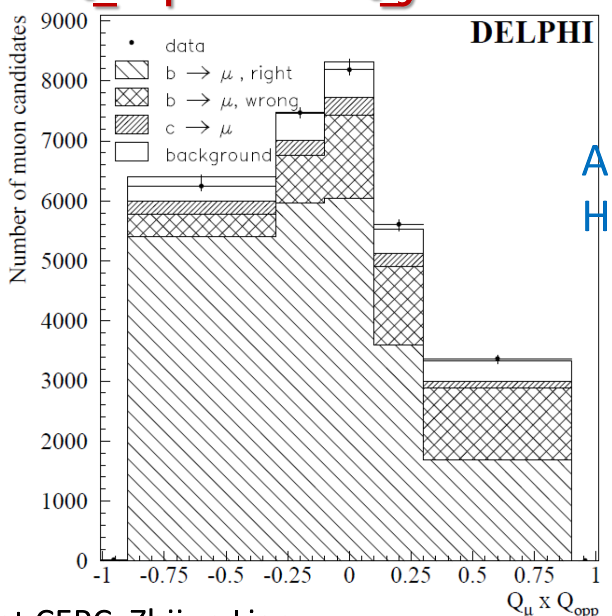
Arxiv:Hep-ex/0107033

Q_F - Q_B in method 2

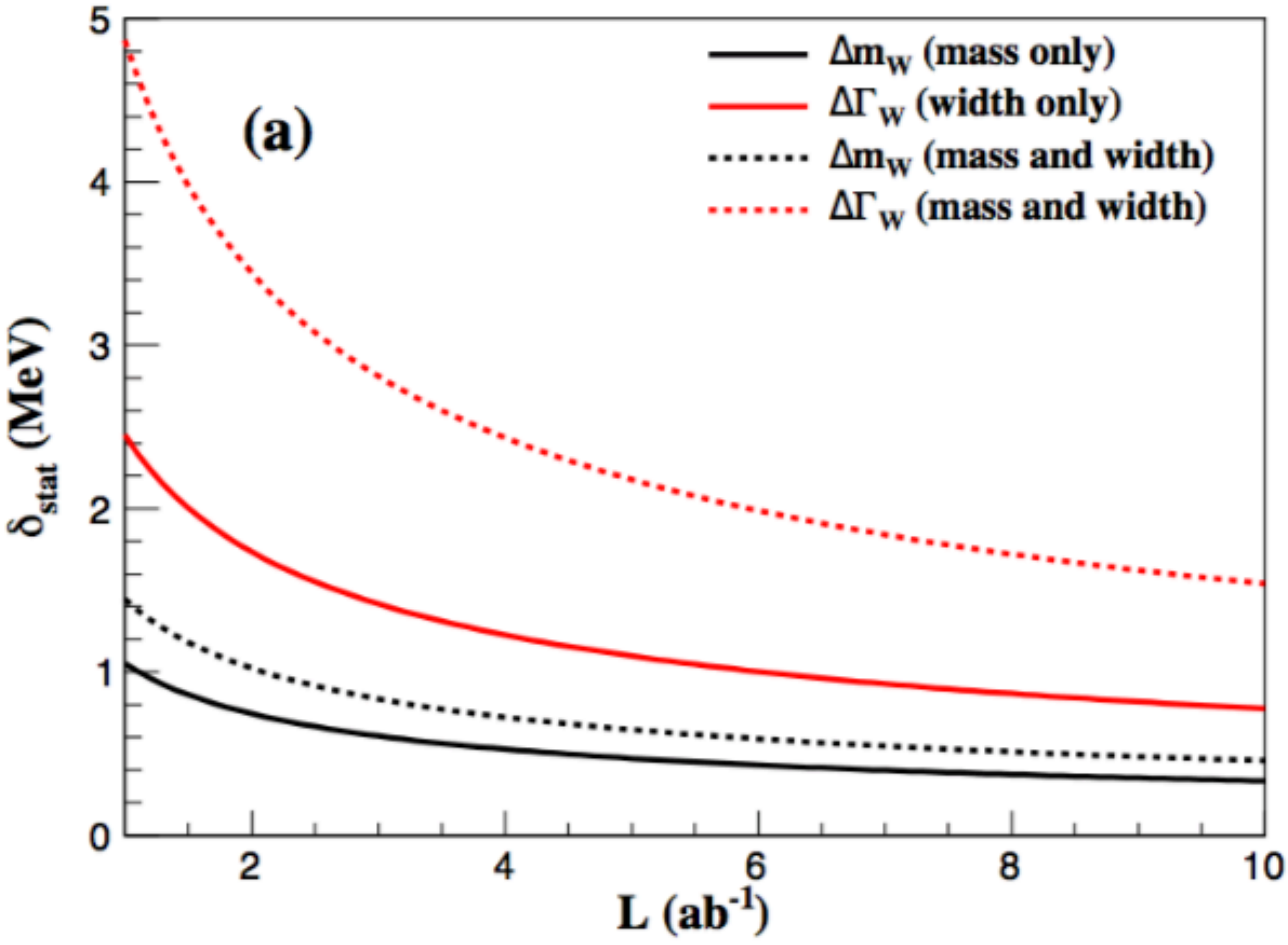


Q_lepton - Q_jet in method 1



Arxiv: Hep-ex/0403041

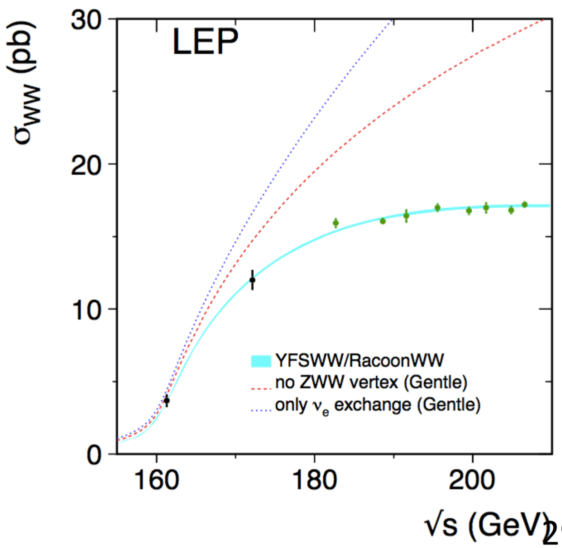
Statistics error on W mass Vs Luminosity



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



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)