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

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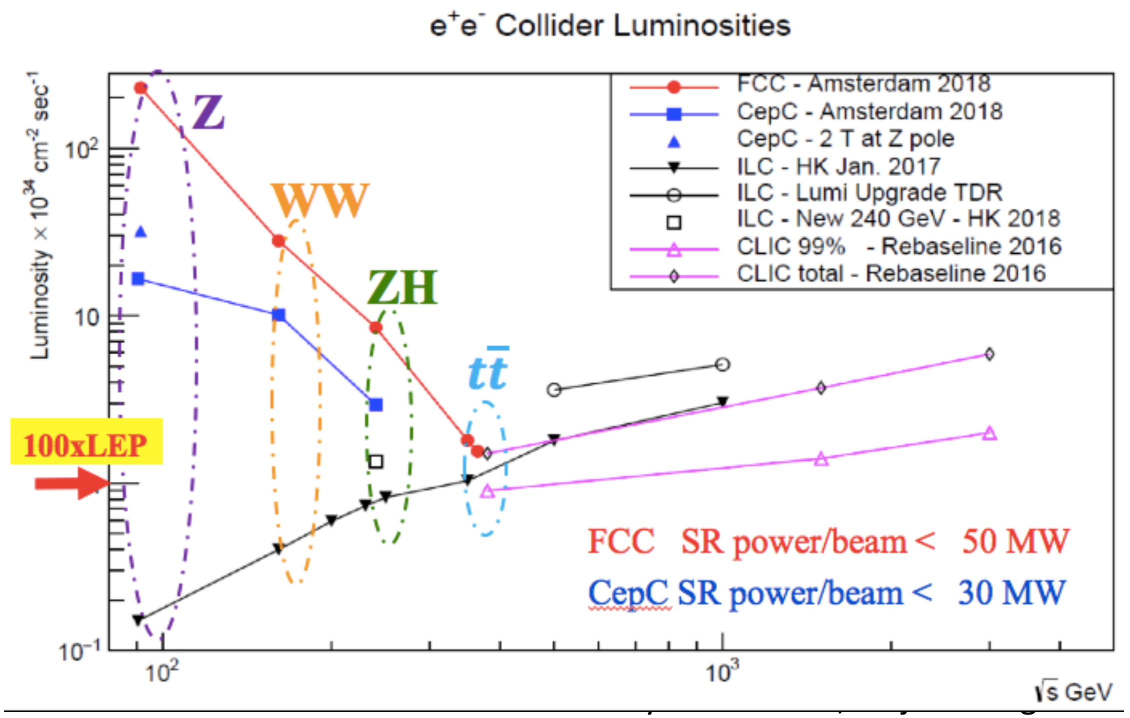
Introduction to CEPC

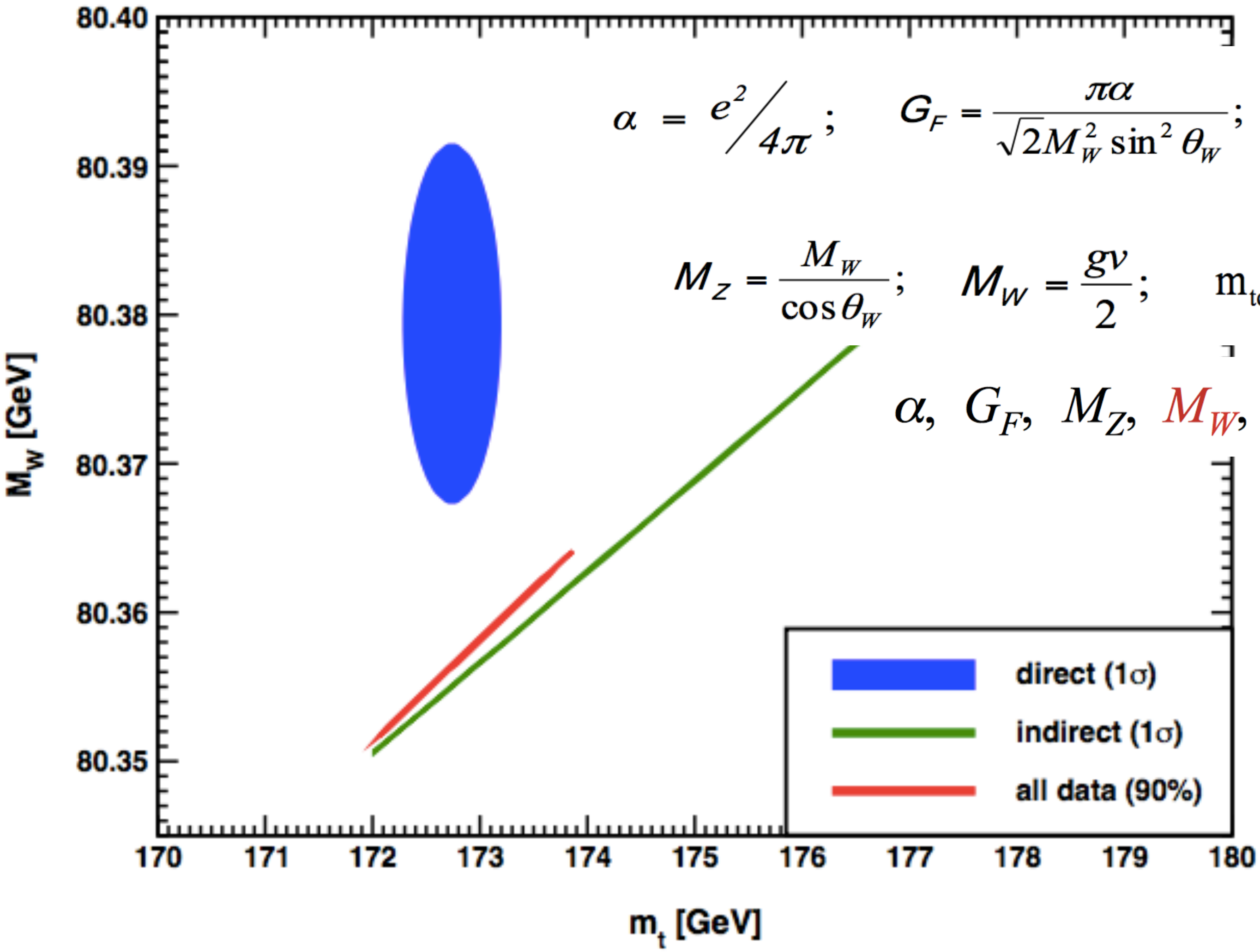
- CEPC is Higgs Factory （ E_{cms}=240GeV，10^6 Higgs)
- CEPC is Z factory(E_{cms}~91GeV) ,electroweak precision physics at Z pole.
  - baseline **L=1.6 X 10^{35} $cm^{-2}s^{-1}$ ，Solenoid =3T, 3X10^{11} Z boson, two years**
  - **L= 3.2 X 10^{35} $cm^{-2}s^{-1}$ ，Solenoid =2T，6X10^{11} Z boson**
- WW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



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

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

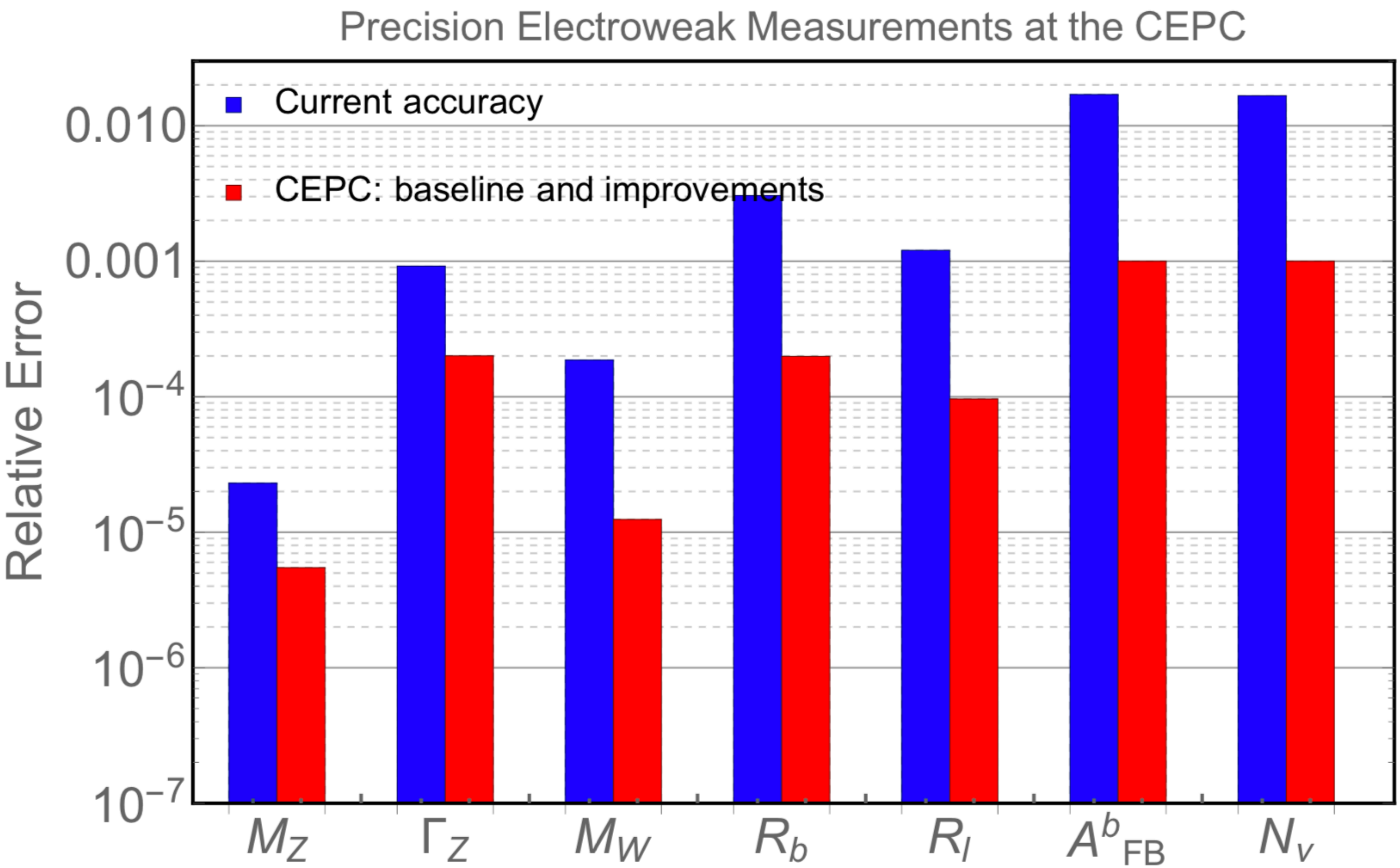
$$\alpha,\ G_F,\ M_Z,\ M_W,\ \sin^2\theta_W,\ m_{top},\ M_H$$

self-consistency Check of SM

Freitas & JE (PDG 2018)

Prospect of CEPC EWK physics

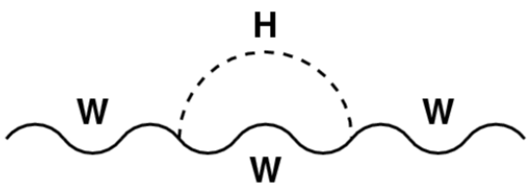
- Expect to have 1~2 order of magnitude better than current precision

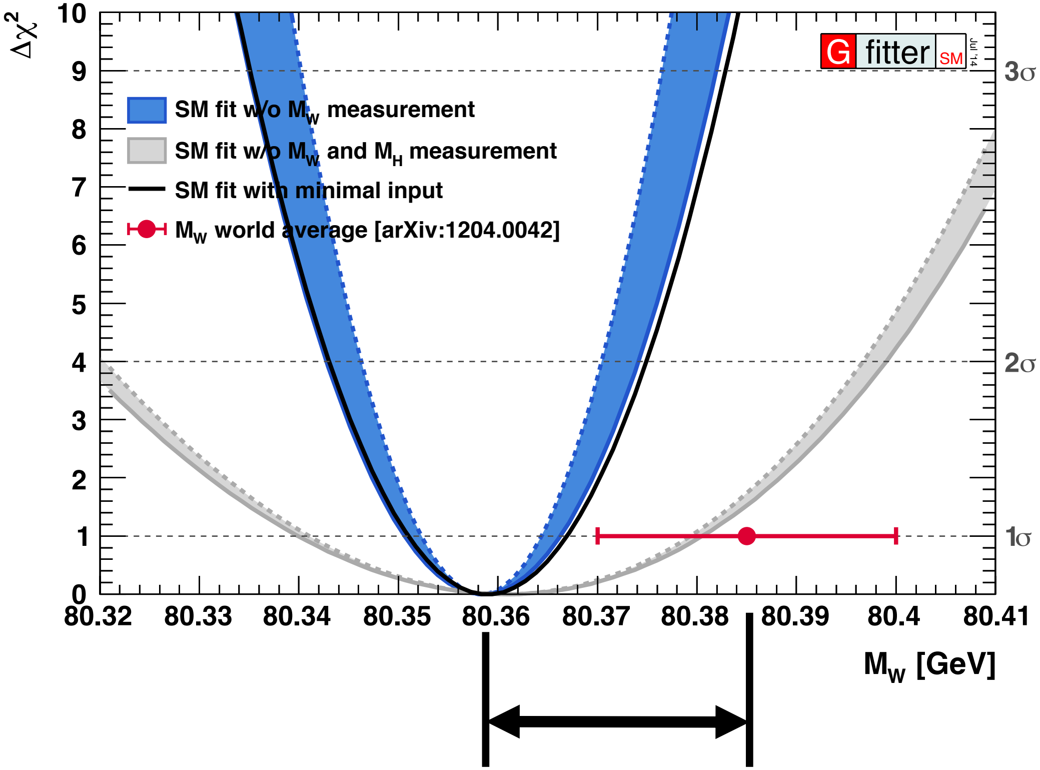


- Introduction to CEPC
- W physics
- Z pole physics

Motivation

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



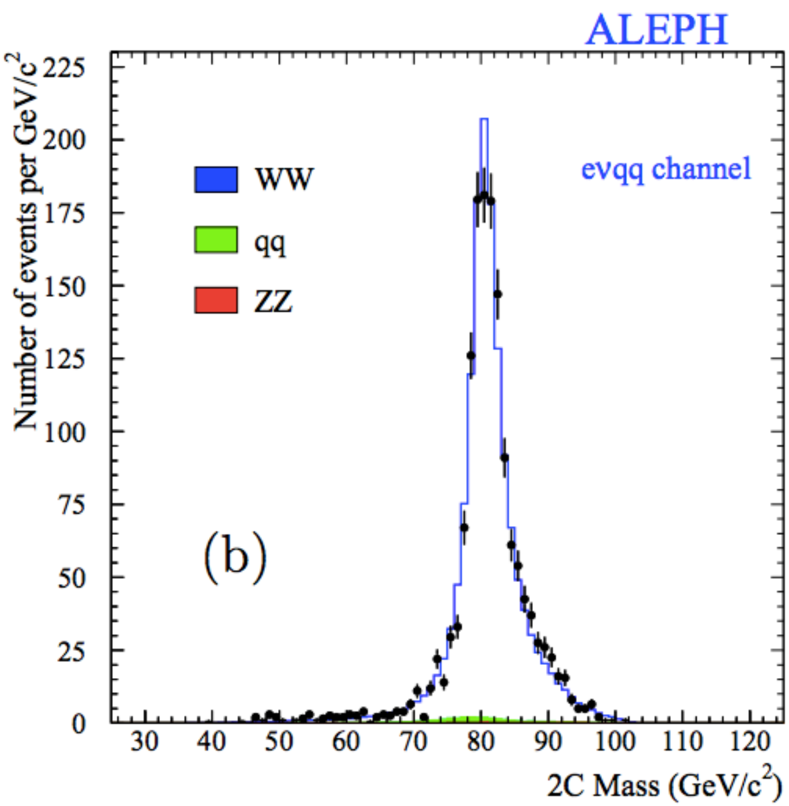


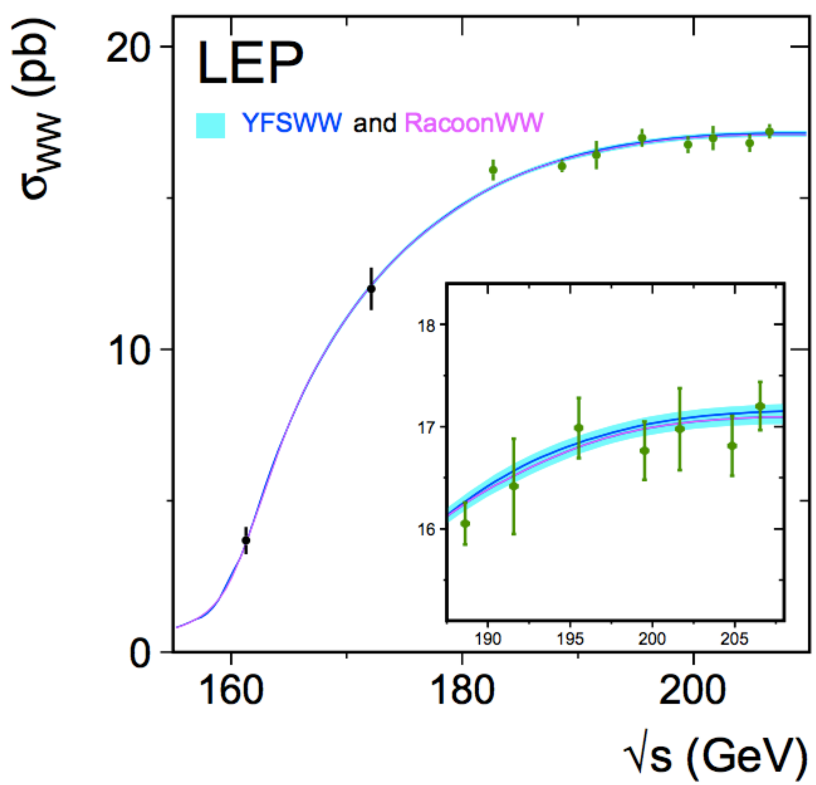
W mass measurement in lepton collider

- 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



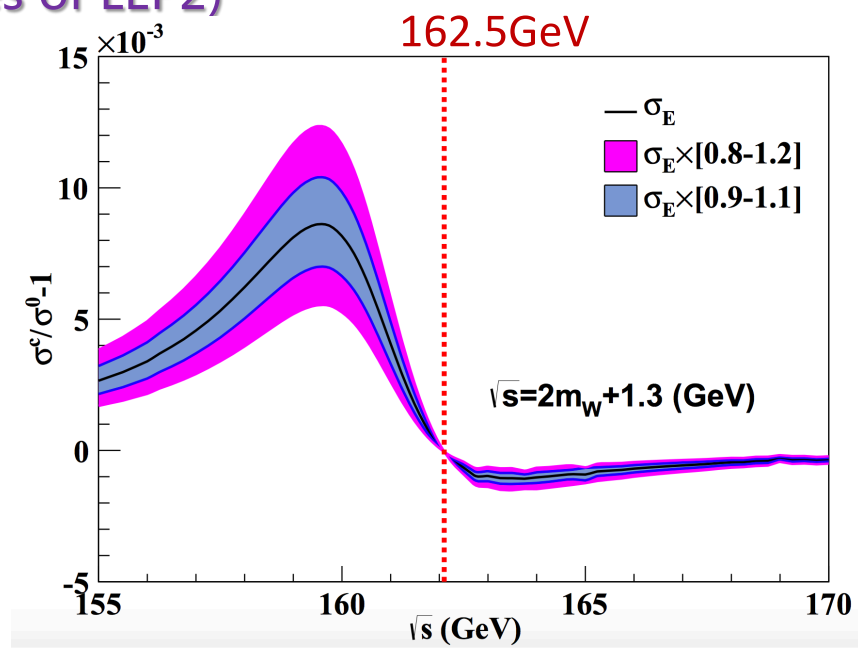


WW threshold scan – CEPC plan

– Collaborate with Fcc-ee for joint Fcc-ee and CEPC publication

- 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 of LEP2)

E_{cm} (GeV)	L (ab^{-1})	Cross section (pb)	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



arXiv.org > hep-ex > arXiv:1812.09855

High Energy Physics – Experiment

Data-taking strategy for the precise measurement of the W boson mass with threshold scan at circular electron positron colliders

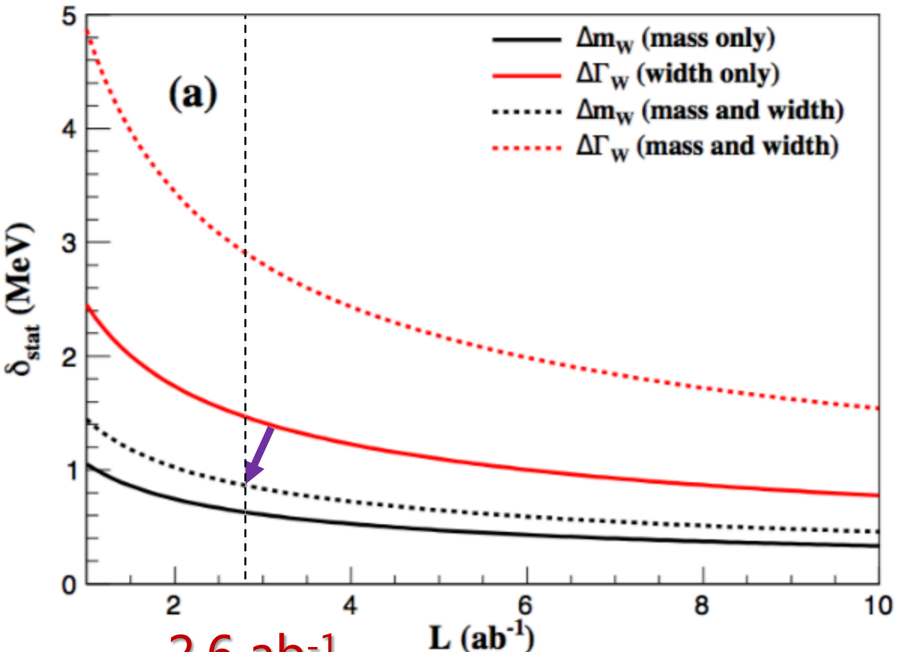
P. X. Shen, P. Azzurri, M. Boonekamp, P. Z. Lai, B. Li, G. Li, H. N. Li, Z. J. Liang, B. Liu, J. M. Qian, L. S. Shi, C. X. Yu

WW threshold scan-systematics unc.

- Expected 1MeV precision in W mass measurement
  - Dominated by statistics uncertainty.
  - Leading syst. (0.5MeV): beam energy syst.

Statistics unc. on W mass Vs Luminosity

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

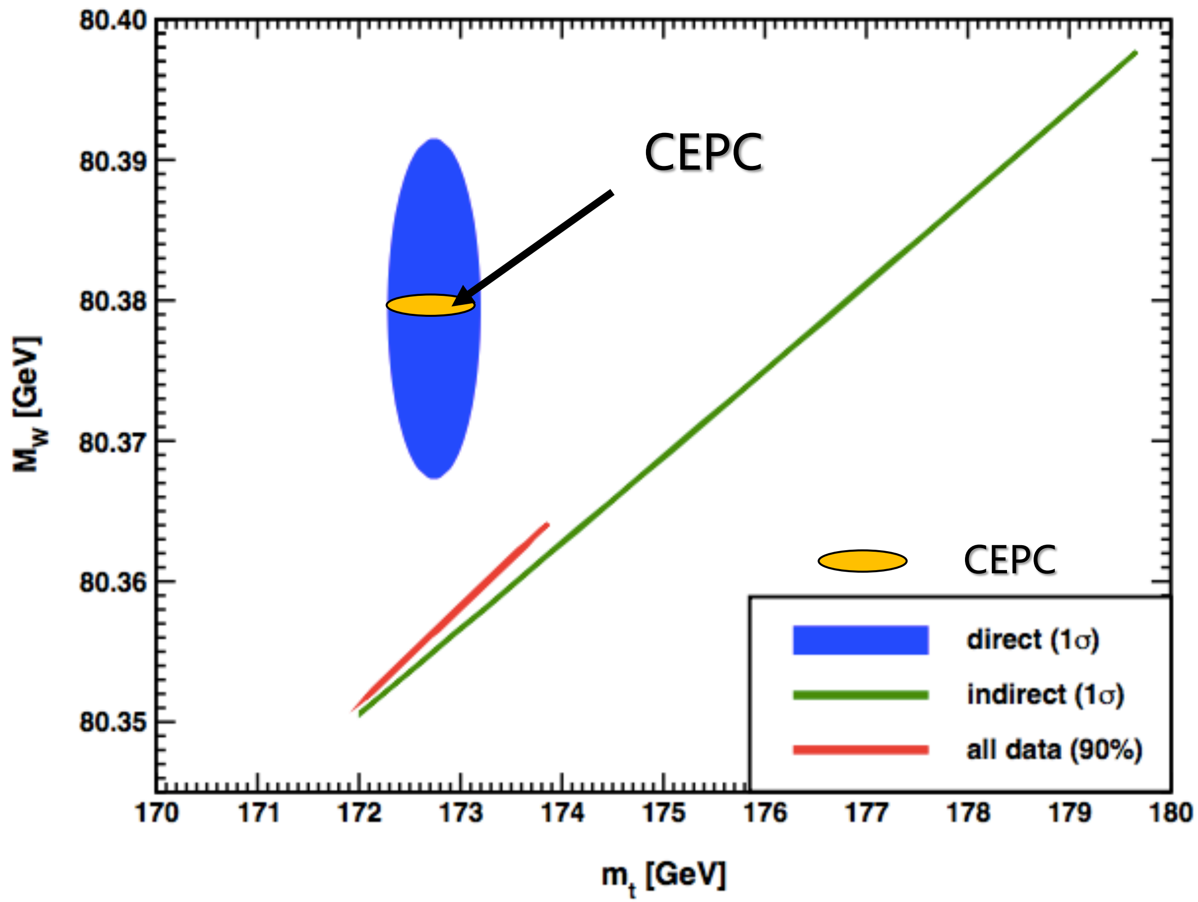


2.6 ab^{-1}

arxiv: 1812.09855

Prospect of CEPC W mass measurement

- CEPC can improve current precision of W mass by one order of magnitude
  - Good physics potential for BSM physics from indirect search



Freitas & JE (PDG 2018)

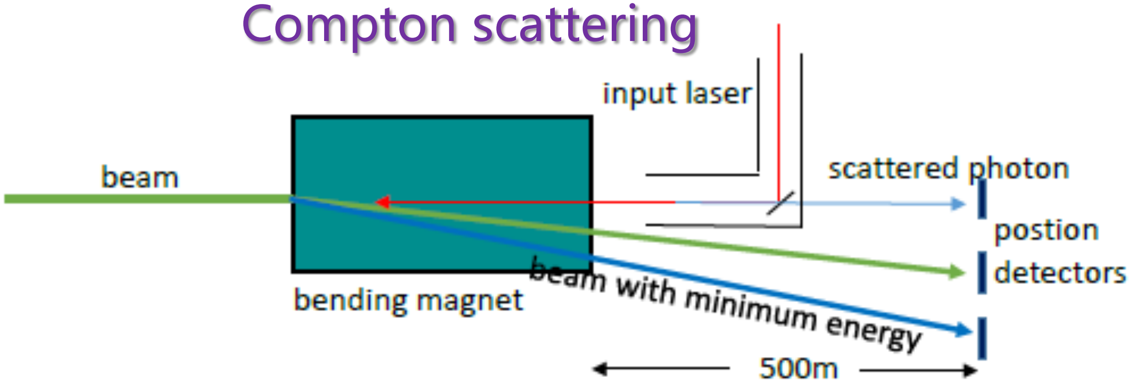
- Introduction to CEPC
- Z pole physics
- W physics

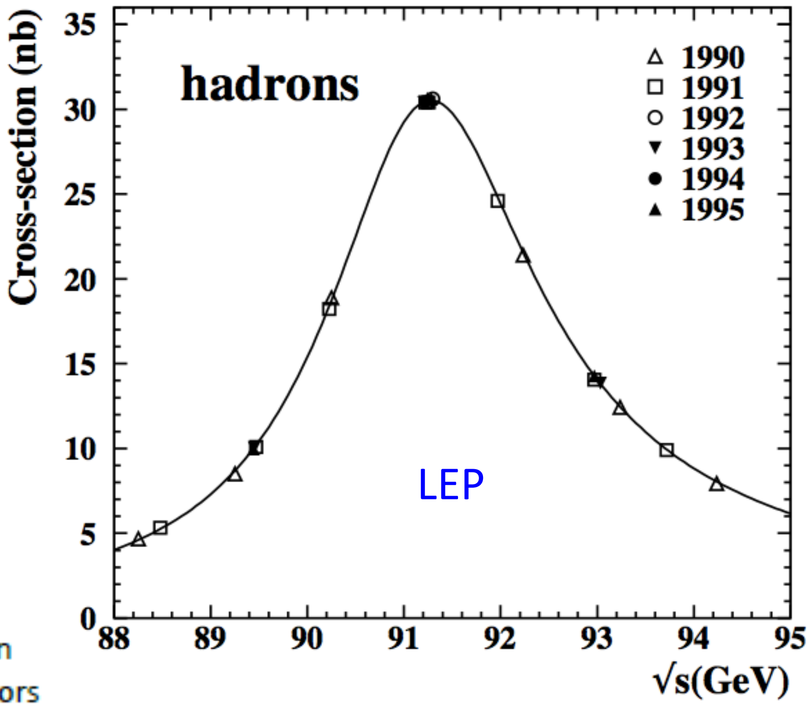
Z mass measurement

- 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



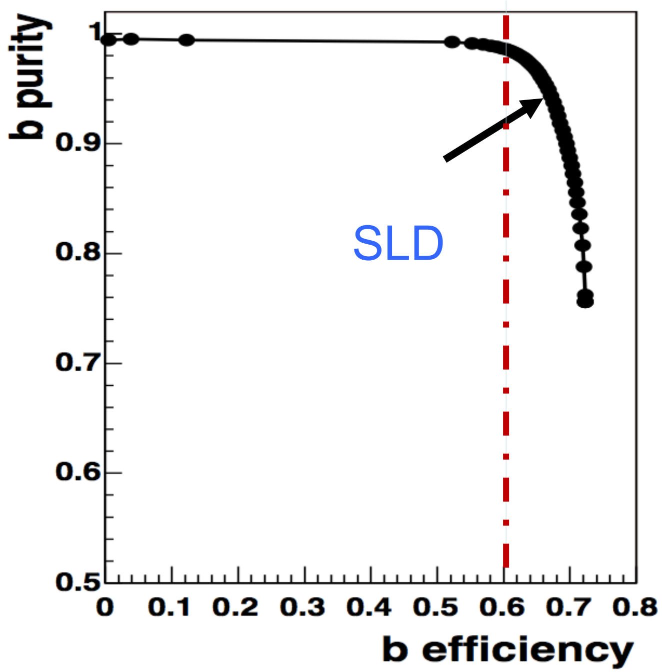


$\frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to had)}$ Branching ratio (R^b)

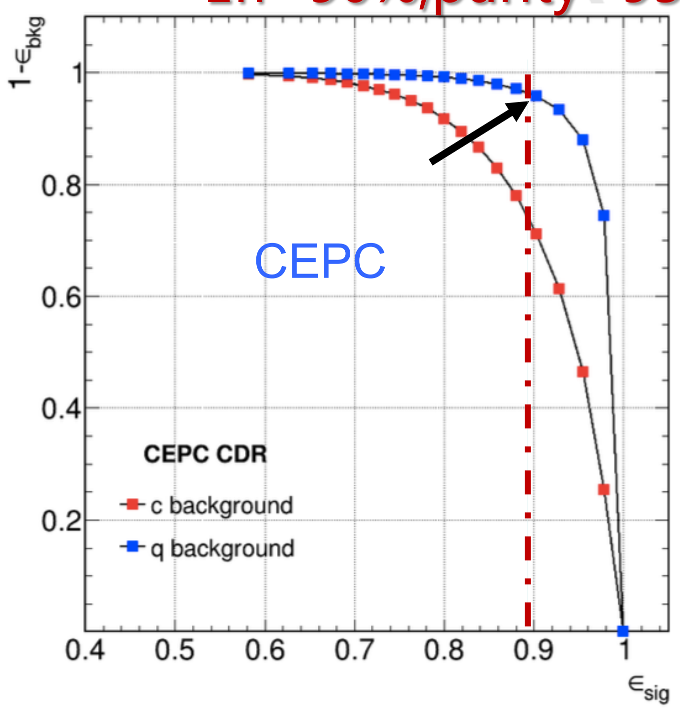
- LEP measurement 0.21594 ±0.00066
  - Syst error : ~0.2%
- CEPC
  - Expected Syst error (0.02%)
  - hemisphere tag correlations depends on b tagging efficiency
  - Expect 20~30% higher B tagging efficiency than SLD
  - Theory uncertainty (gluon splitting ..): need input from theorists

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

Eff=60%,purity~95%

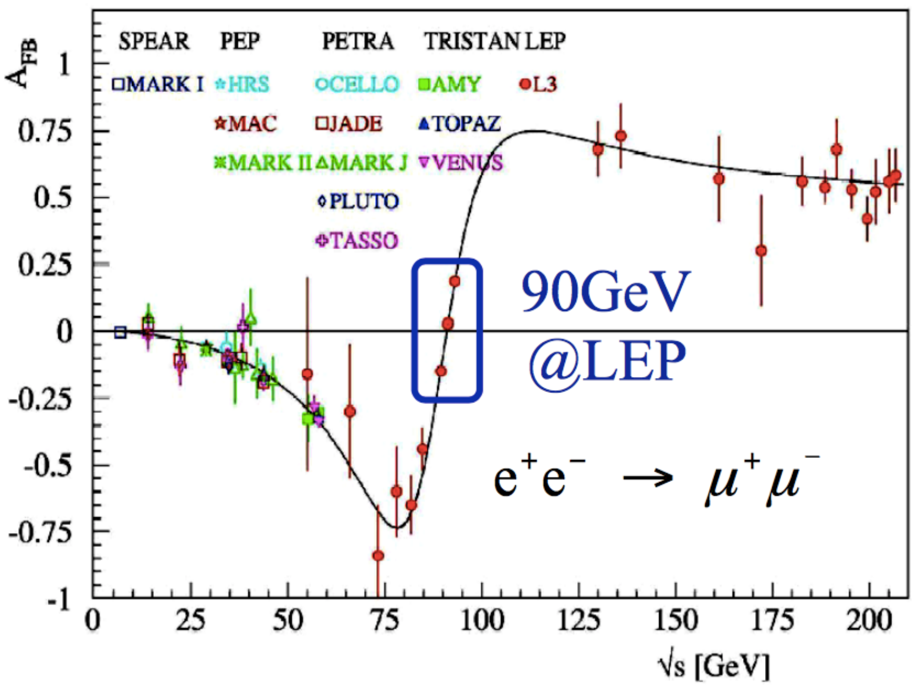


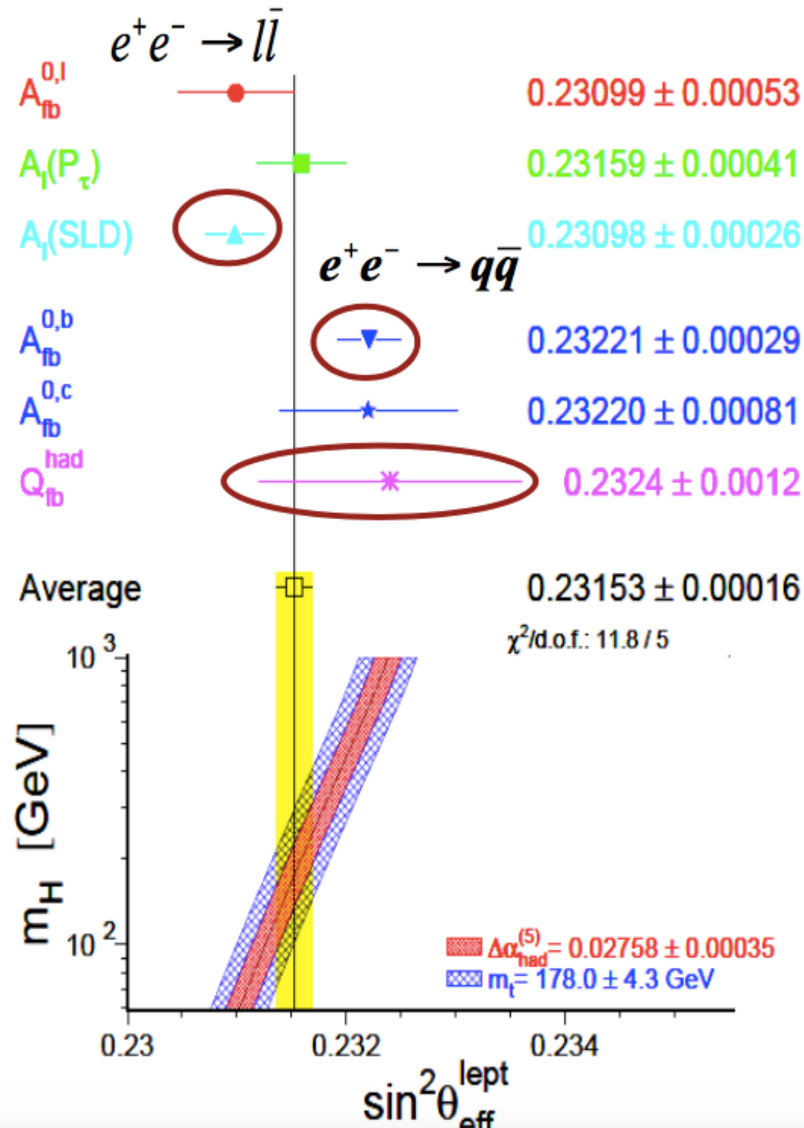
Eff~90%,purity~95%



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

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



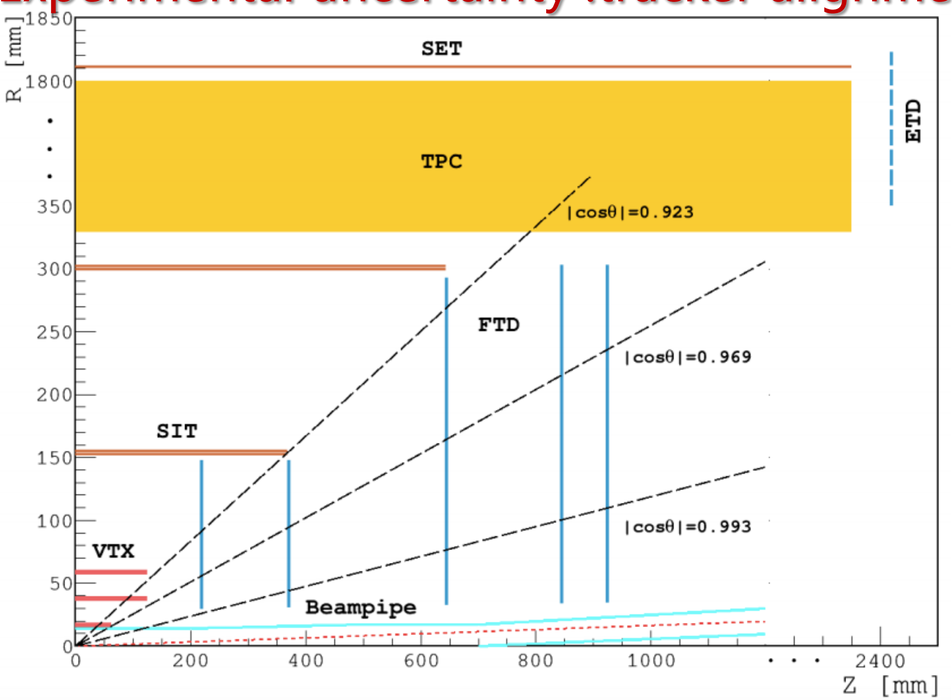


Backward-forward asymmetry in Z->μμ

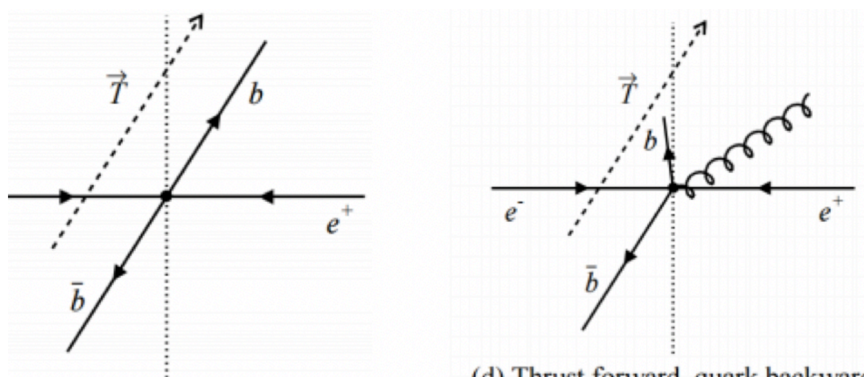
- LEP measurement : 0.0169 +-0.00130
- CEPC expected: +-0.00002
  - CEPC has potential to improve it by a factor of 50 .
    - Acceptance systematics (larger detector coverage, smaller syst.)
- Major systematics (absolute value.)
  - Beam energy systematics ($1e^{-5}$, assuming 100keV E_{beam} unc.)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

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

Experimental uncertainty :tracker alignment



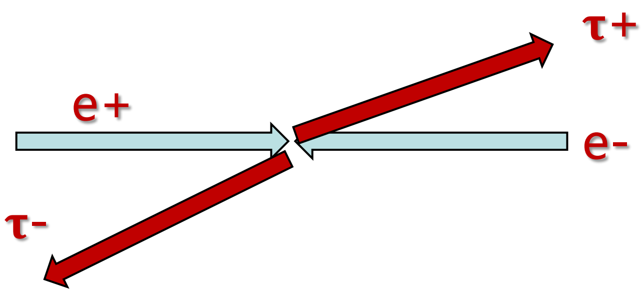
Theory uncertainty: gluon emission



(a) No gluon

(d) Thrust forward, quark backward

A_e and A_τ: tau polarization



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

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

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

- 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

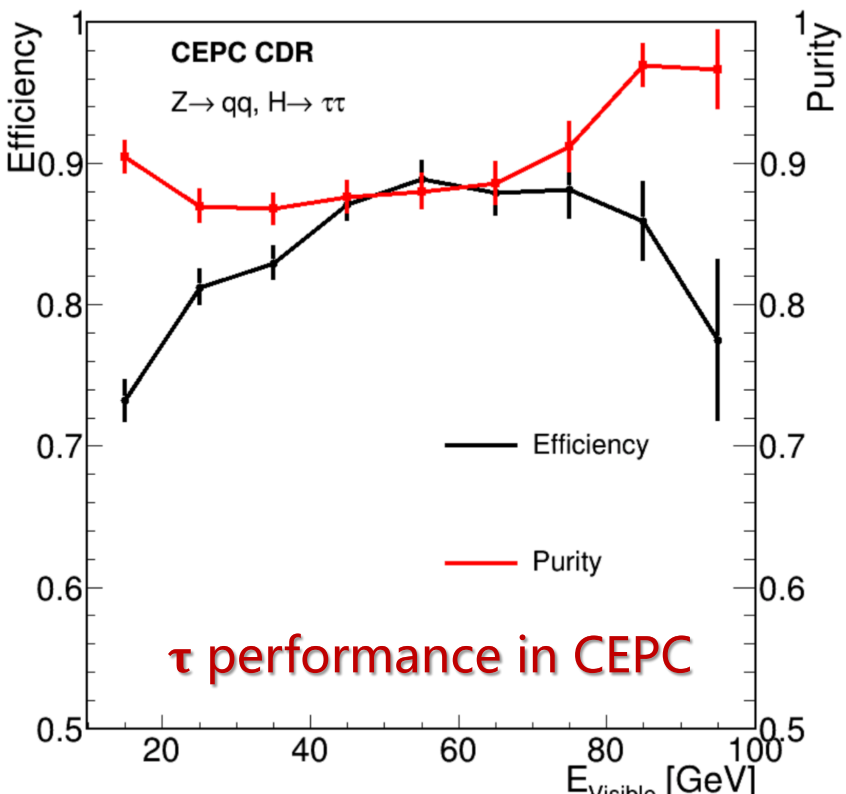
A_{LRFB}, $P_\tau(\cos\theta)$ → A_e and A_τ

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	$1.3X10^{-2}$	$3X10^{-4}$

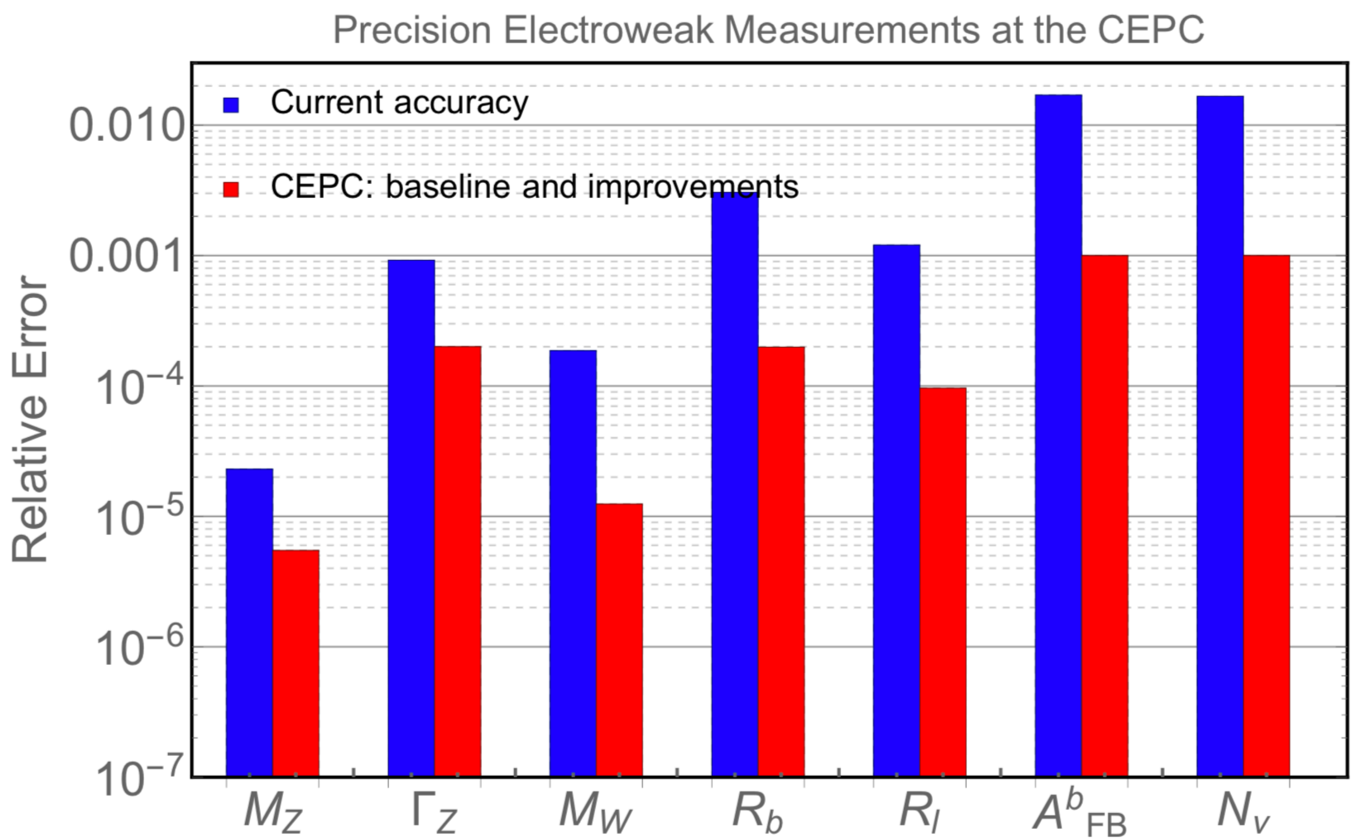
CEPC can improve this by a factor of 50



τ performance in CEPC

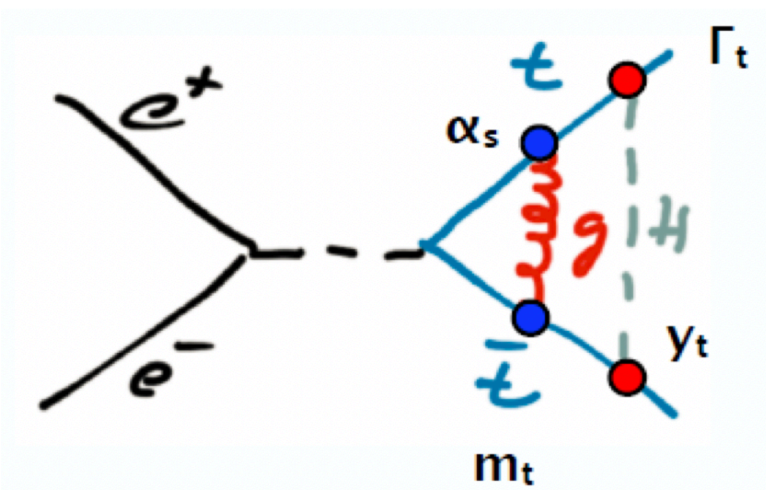
Summary

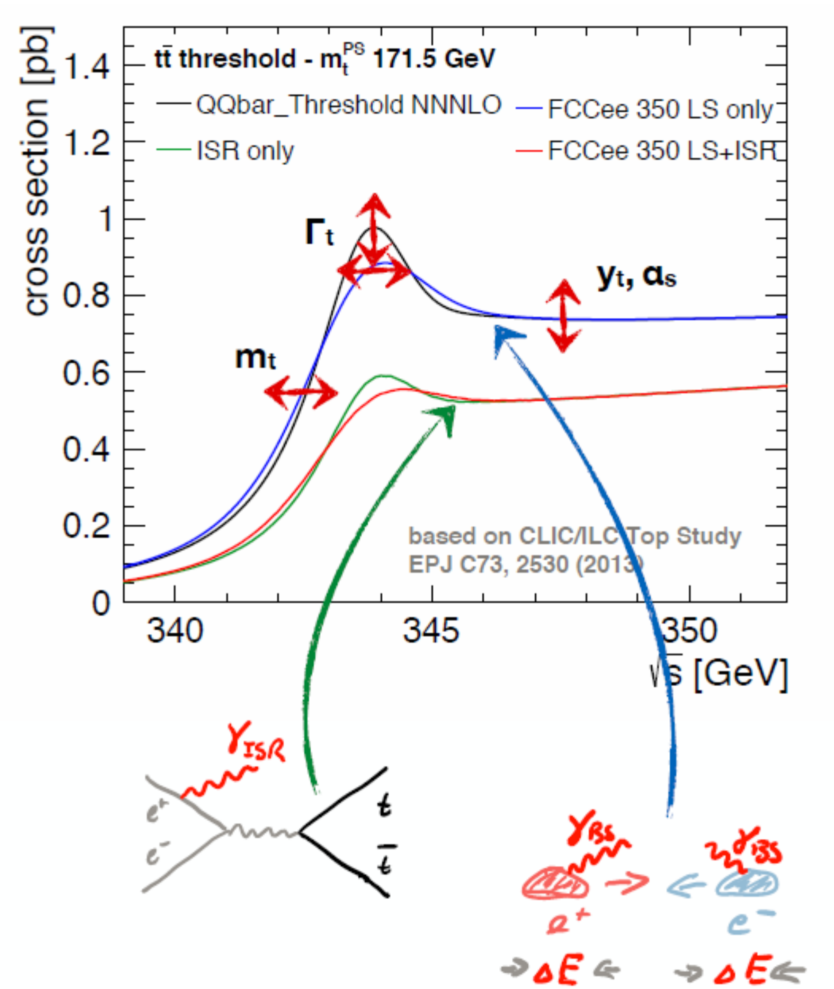
- Potential of electroweak measurement at CEPC
  - 1~2 order of magnitude better than current precision
  - Two years at Z pole: 3(6) X10^{11} Z boson
  - One year WW runs: 10^8 WW pairs (10^7 WW @ 160GeV)



Top threshold scan

- Top threshold scan is not in current CEPC program
- The idea from CLIC
- Top threshold cross-section depends on:
  - top mass
  - top width (lifetime)
  - top-Higgs coupling
  - αQCD



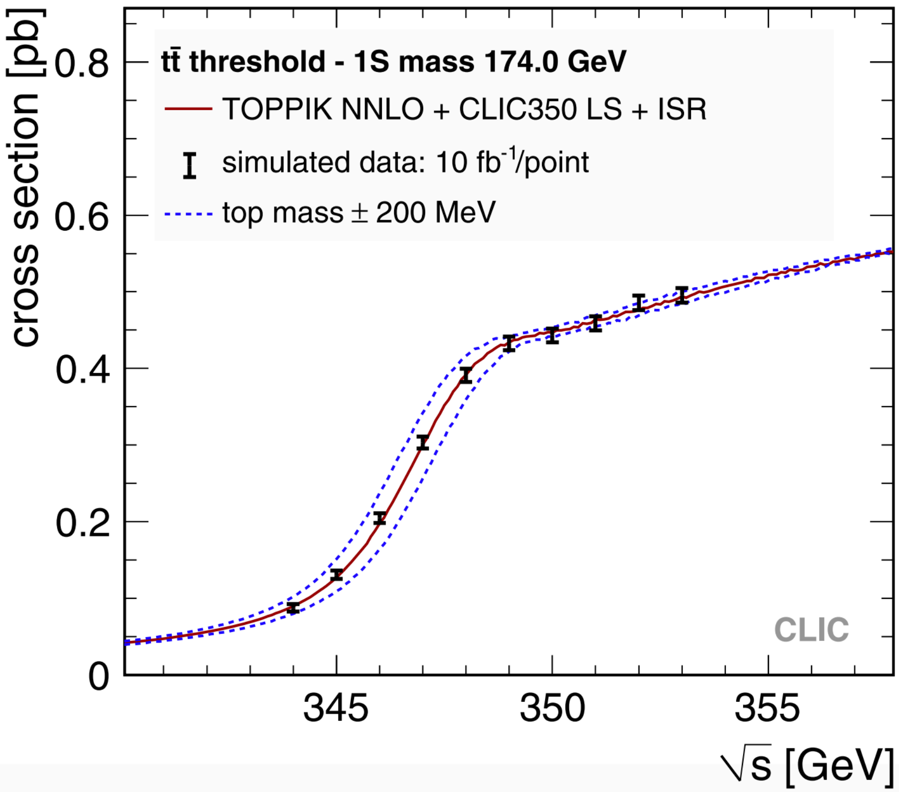


Thanks to discussion and slides from Alain Blondel

Study by Frank Simon (CLIC/ILC study, EPJC 73,(2013)25

Top threshold scan

- CLIC Strategy:
  - Need a rough scan to measure the top mass to 100 MeV. (5-10 fb^{-1})
  - Fix the final scan points
  - since there are four parameters to fix, need at least 4 scan points
    - Scanning range 340GeV ~355GeV
    - Precision can reach 34MeV



CLIC estimation with 100 fb^{-1}

m_t stat. error	34 MeV
m_t theory syst. (1 %/3 %)	5 MeV/8 MeV
α_s stat. error	0.0009
α_s theory syst. (1 %/3 %)	0.0008/0.0022

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.

Discrepancy Due to statistics

doing check on systematics (tracker alignment …)
Plan to work with USTC

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

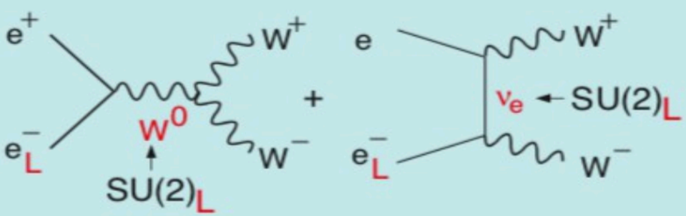
Type	Longitudinal polarized e-	Longitudinal polarized e+	Transverse polarized Beam
CEPC	To be discussed	To be discussed	Yes (Z,WW)
Fcc-ee	No	NO	Yes (Z,WW)
ILC	yes	yes	-

Polarized beam collision: motivation

Any other physics case for polarized beam collision in CEPC?

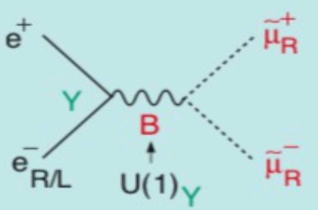
BG Suppression

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



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

Slepton Pair



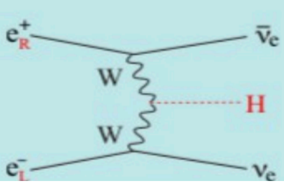
$Y_L = -1/2 : e^-_L$

$Y_R = -1 \quad : e^-_R$

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

Signal Enhancement

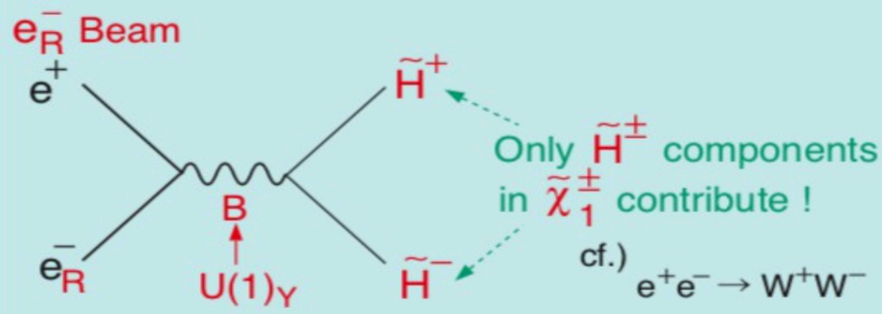
WW-fusion Higgs Prod.



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

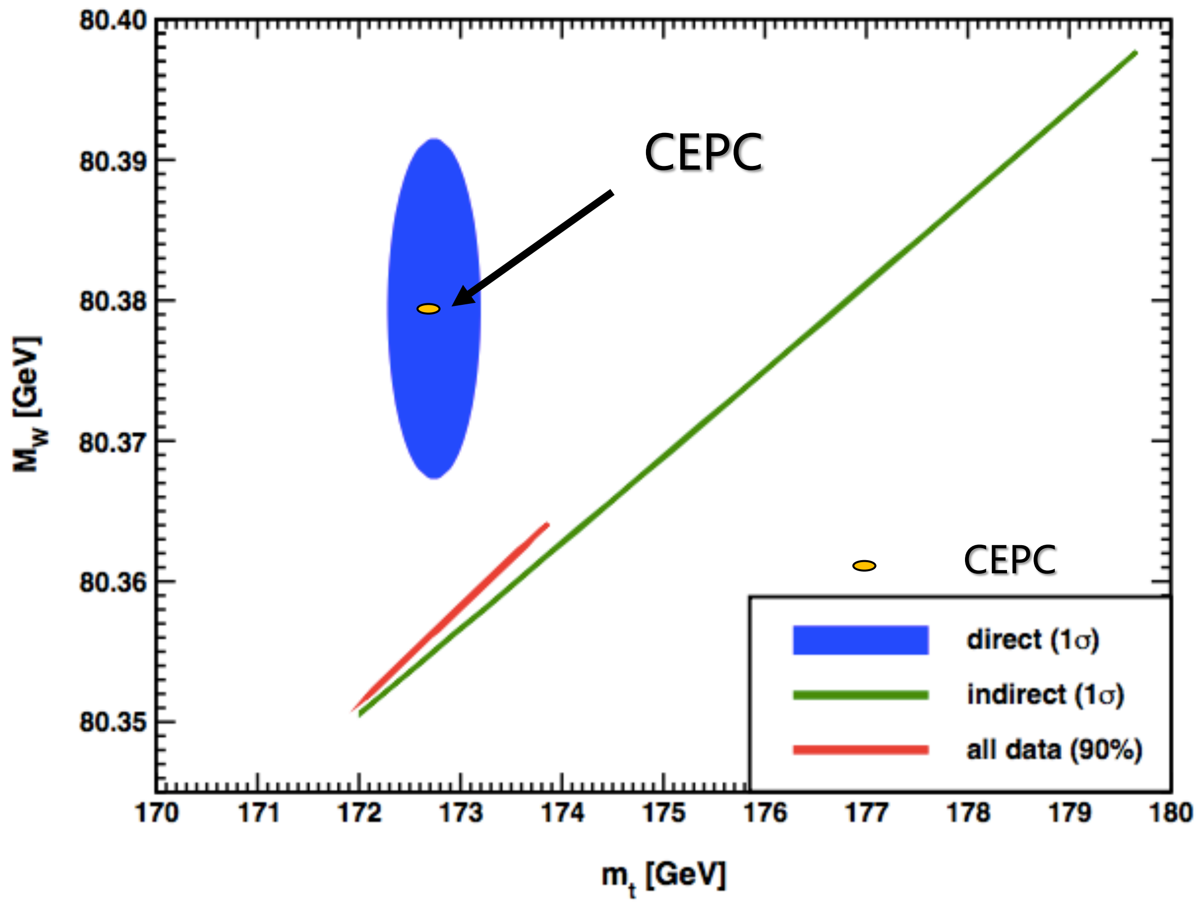
Decomposition

Chargino Pair



$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$, where $\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$

CEPC potential with top threshold scan



Freitas & JE (PDG 2018)

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.

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
$G_F = 1.1663787\,(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$	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

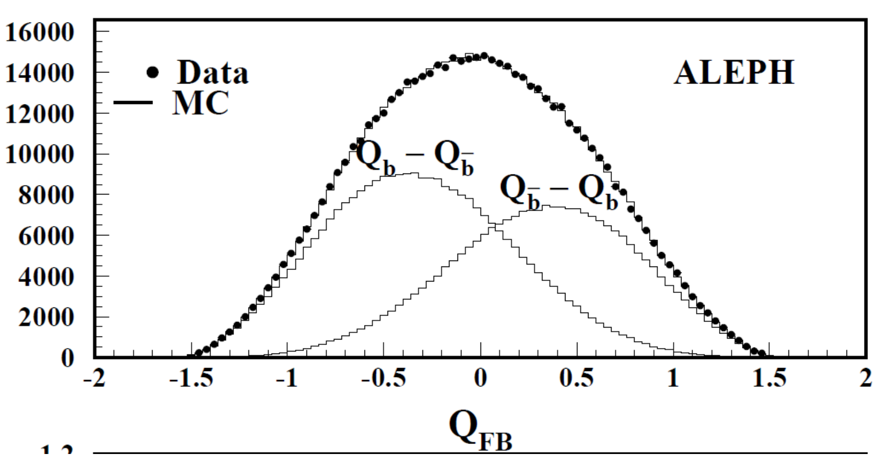
Backward-forward asymmetry

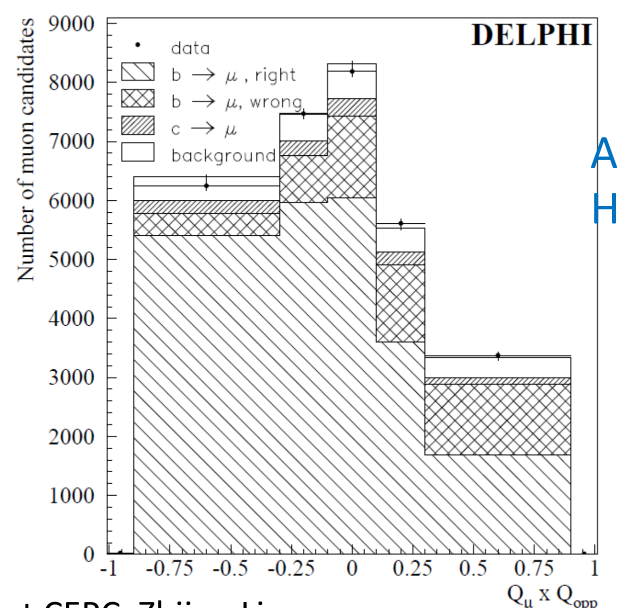
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay (~2%)
    - Select one lepton from b/c decay, and one b jets
    - Select lepton charge (Q_lepton) and jet charge (Q_jet)
  - Method 2: jet charge method using Inclusive b jet (~1.2%)
    - Select two b jets, use event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

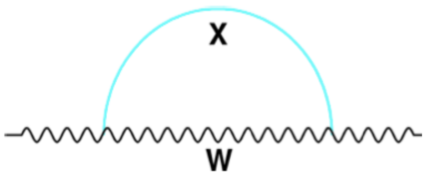


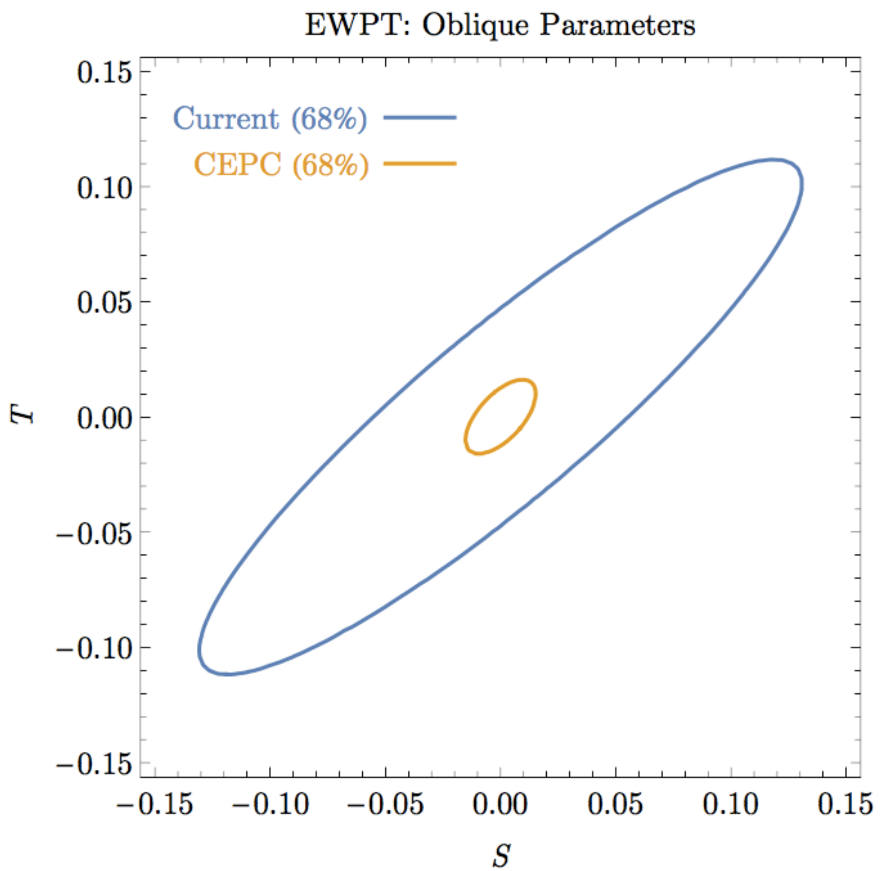


Arxiv: Hep-ex/0403041

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.



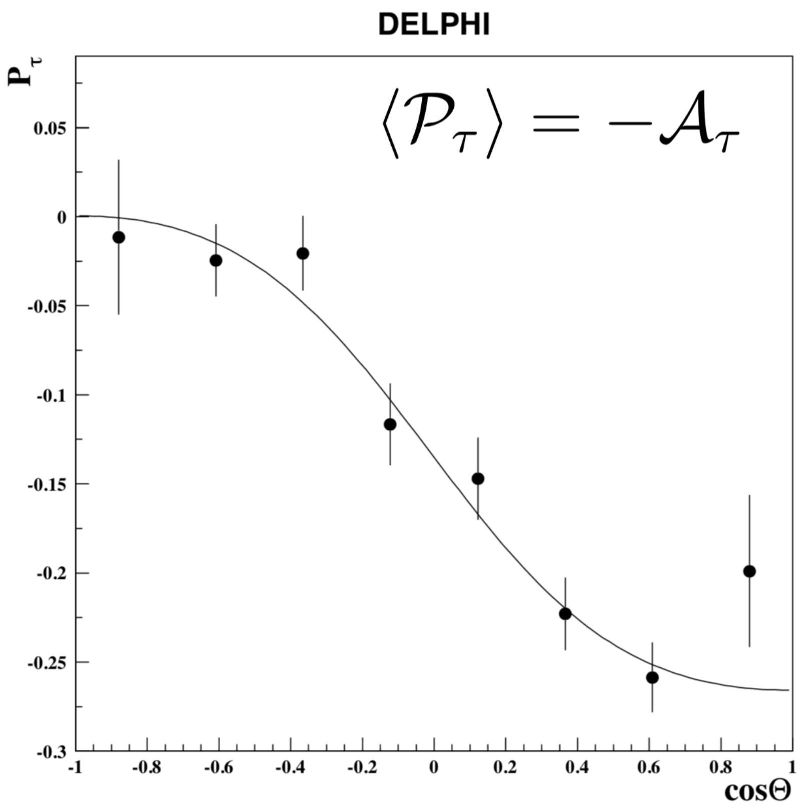


A_e and A_τ in Z →ττ

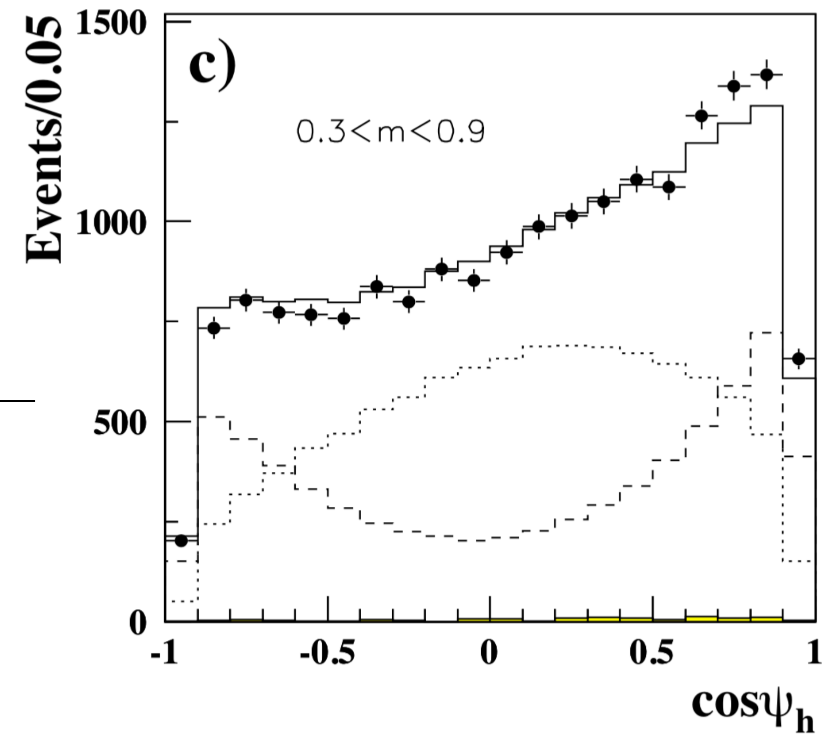
- Tau polarization can be measured through its decay product

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

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



From DELPHI



Eur. Phys. J. C 14, 585-611 (2000)

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

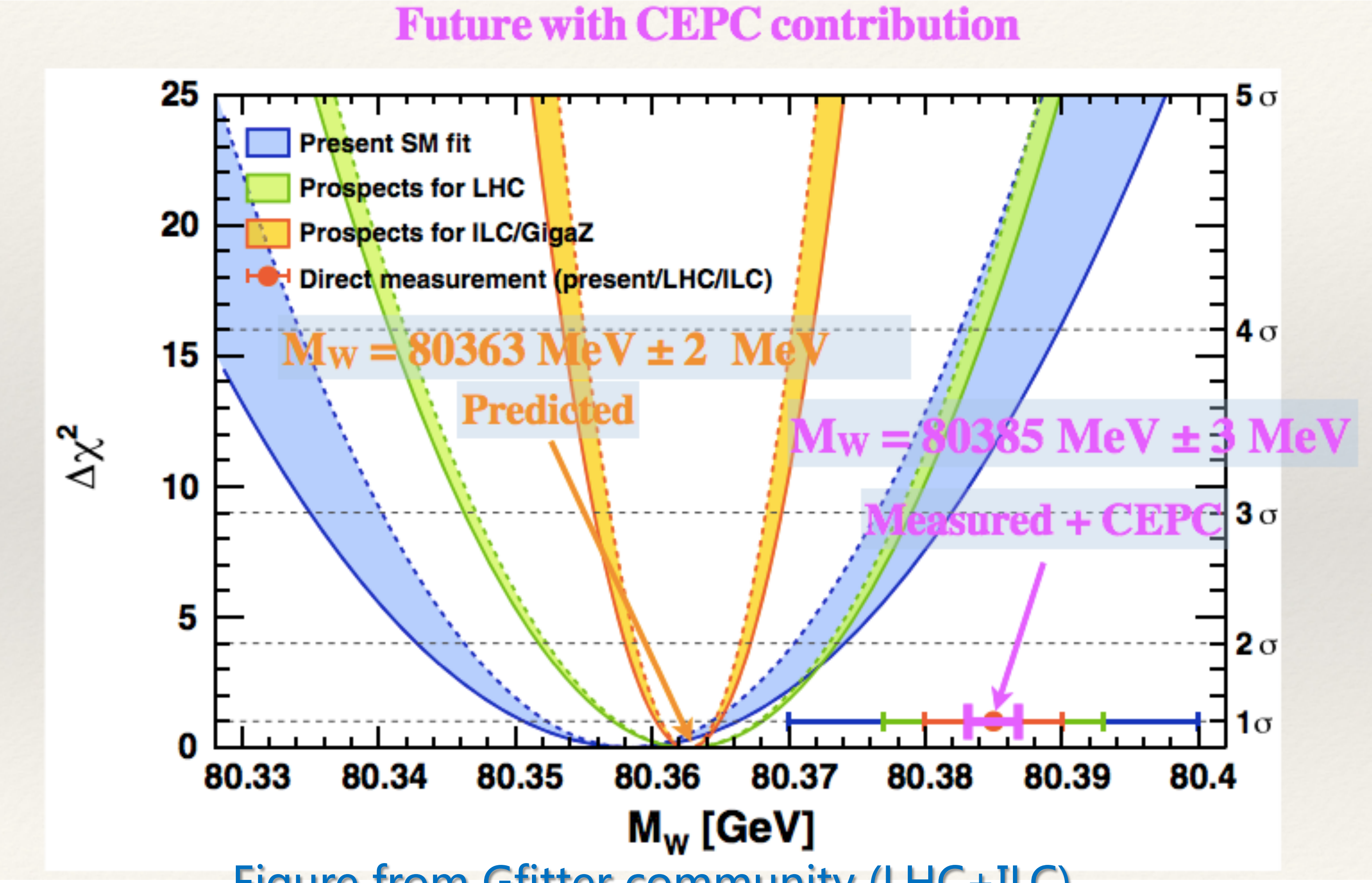


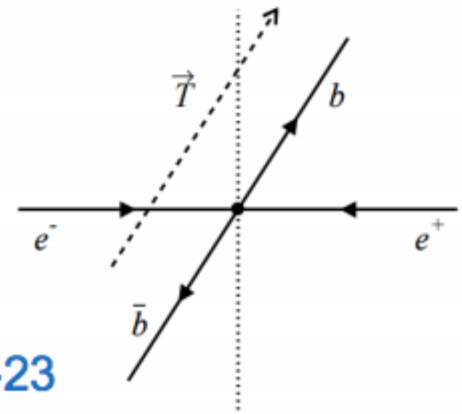
Figure from Gfitter community (LHC+ILC)

Backward-forward asymmetry

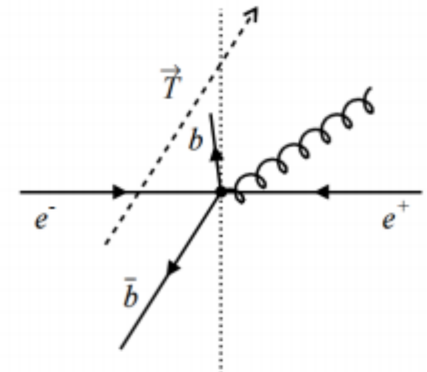
- Uncertainty Afb_b due to QCD correction to Thrust
  - Higher order QCD effect is major systematics

$$A_{FB}^{b\bar{b}}(0)$$

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

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) × 10^{-5} GeV^{-2}	1×10^{-6}	$\mu^{\pm}$ lifetime
$M_Z =$ 91.1876 ± 0.0021 GeV	1×10^{-5}	LEP
$M_W =$ 80.379 ± 0.012 GeV	1×10^{-4}	LEP/Tevatron/LHC
$\sin^2\theta_W =$ 0.23152 ± 0.00014	6×10^{-4}	LEP/SLD
$m_{top} =$ 172.74 ± 0.46 GeV	3×10^{-3}	Tevatron/LHC
$M_H =$ 125.14 ± 0.15 GeV	1×10^{-3}	LHC

Number of neutrino generation (N_ν)

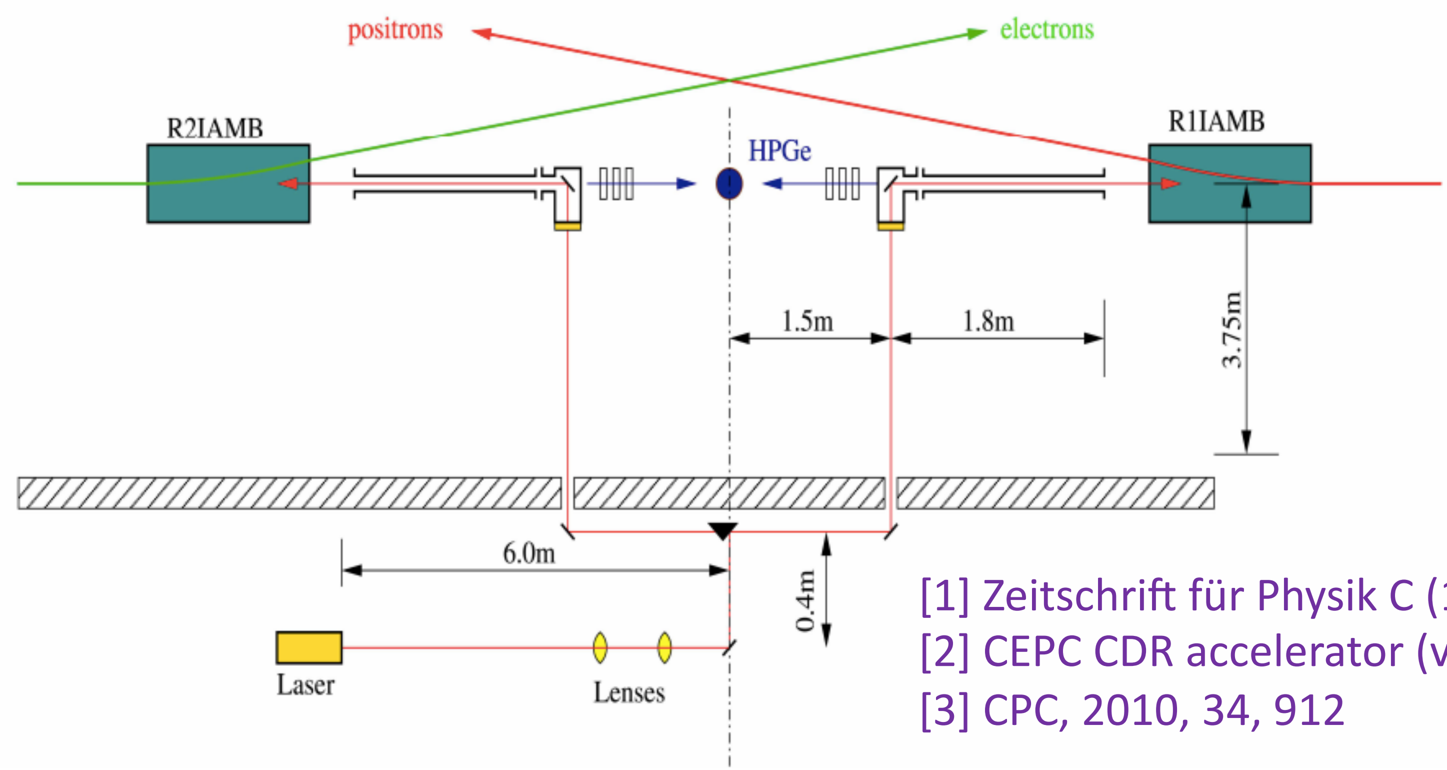
$e^+e^- \to \nu\bar{\nu}\gamma.$

- 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



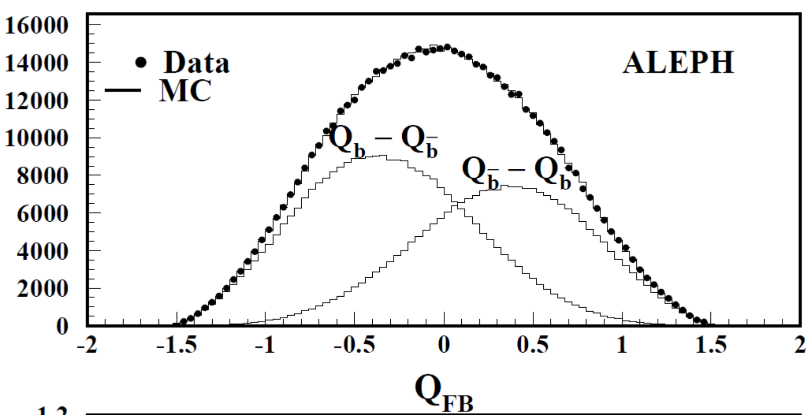
[1] Zeitschrift für Physik C (1995) 45–62.
[2] CEPC CDR accelerator (volume I)
[3] CPC, 2010, 34, 912

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

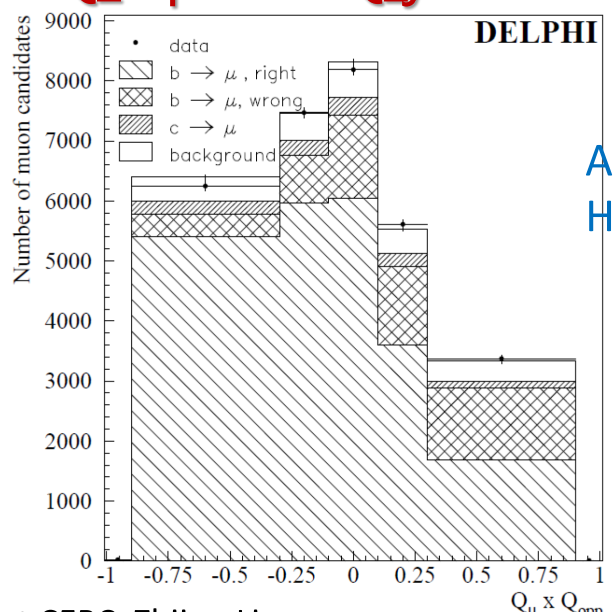
- LEP measurement : 0.1000+-0.0017 (Z peak)
  - Method 1: Soft lepton from b/c decay
    CEPC precision 0.1% ,LEP precision ~2% (stat dominated)
    – Main systematics is B hadron decay branching ratio
  - Method 2: jet charge method , Inclusive b jet (LEP precision 1.2%)
    – use event Thrust to define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

Arxiv:Hep-ex/0107033

Q_F - Q_B in method 2

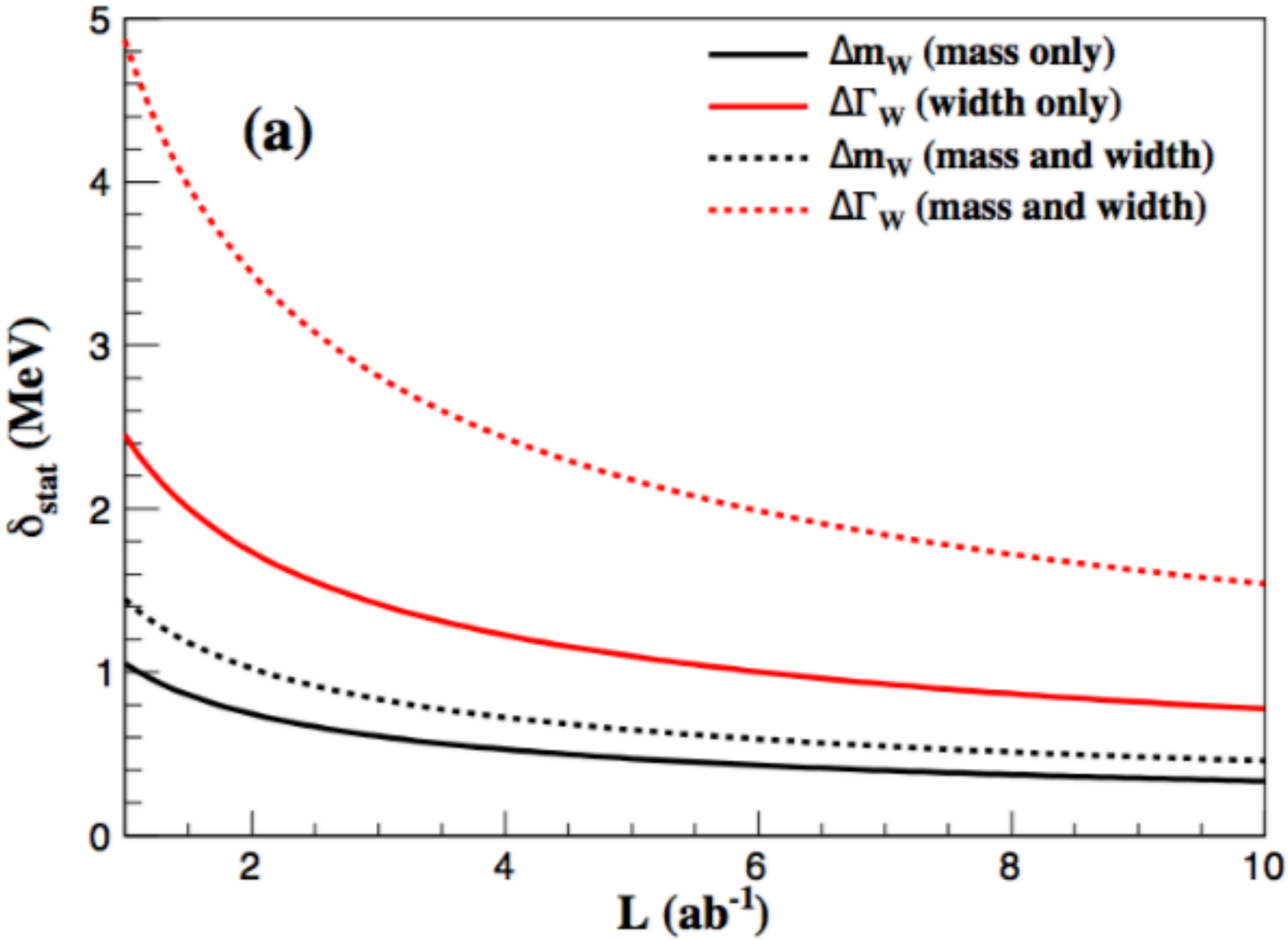


Q_lepton - Q_jet in method 1



Arxiv: Hep-ex/0403041

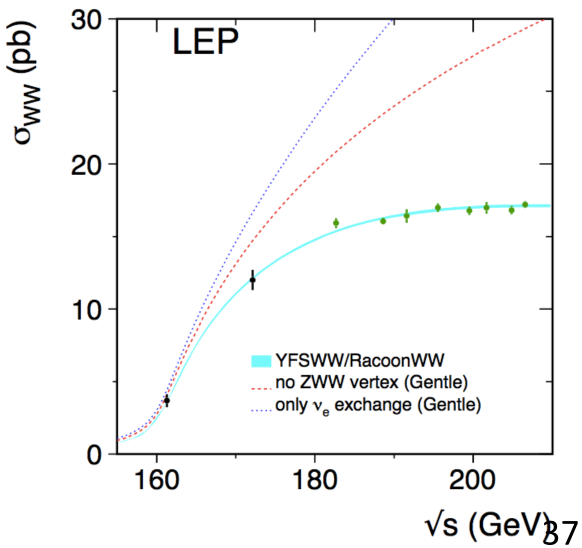
Statistics error on W mass Vs Luminosity



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)