W Mass Measurements in Future Lepton Collider

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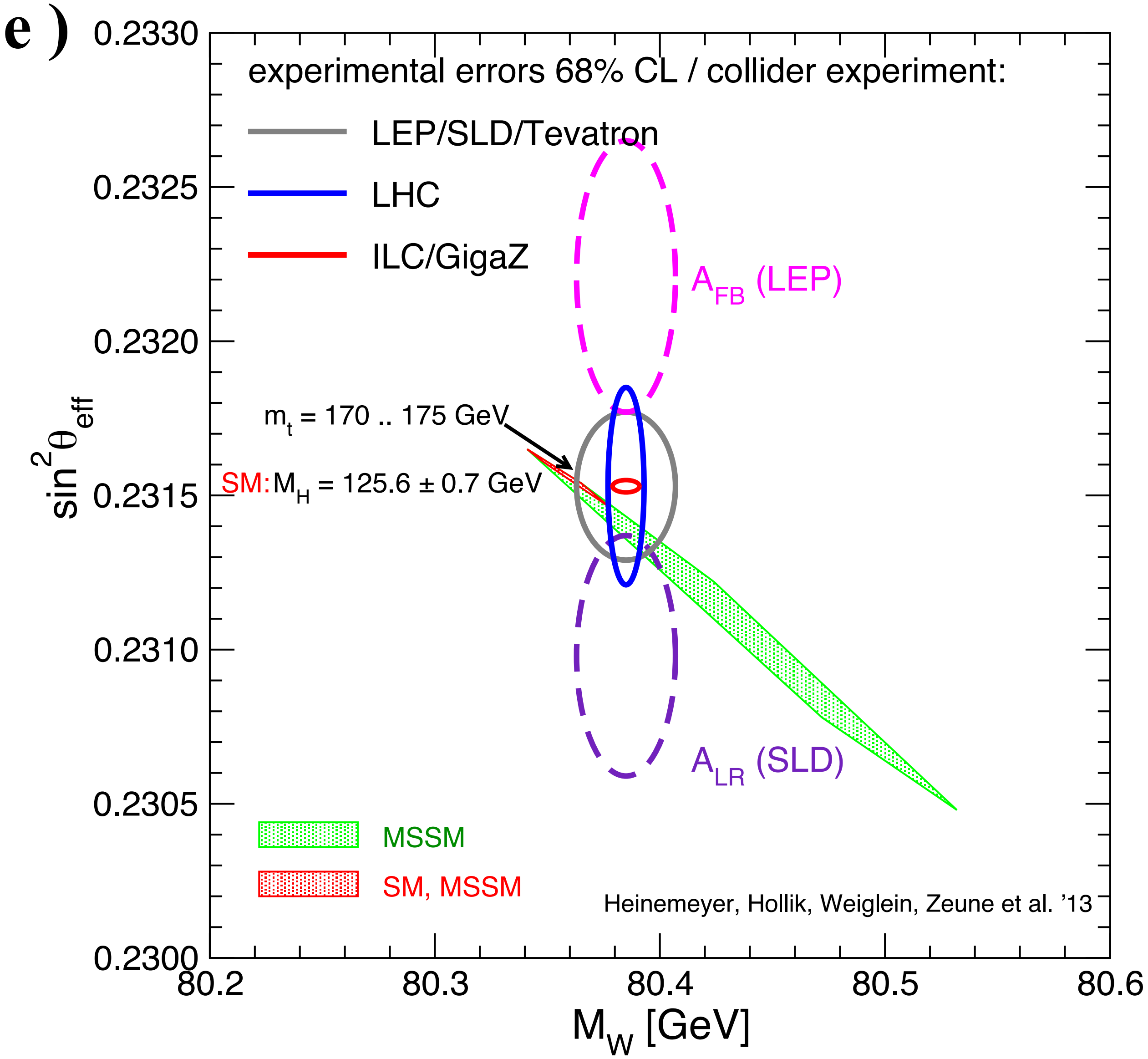
Outline

- Motive of W mass measurements
  - The newest results and worldwide average
- WW production and decay
- The ways to measure W mass
  - Benefit of each way
  - Running plan for each way
  - Uncertainties for each way
- Prospect of W mass measurement
- Conclusion

Motive of W Mass Measurement

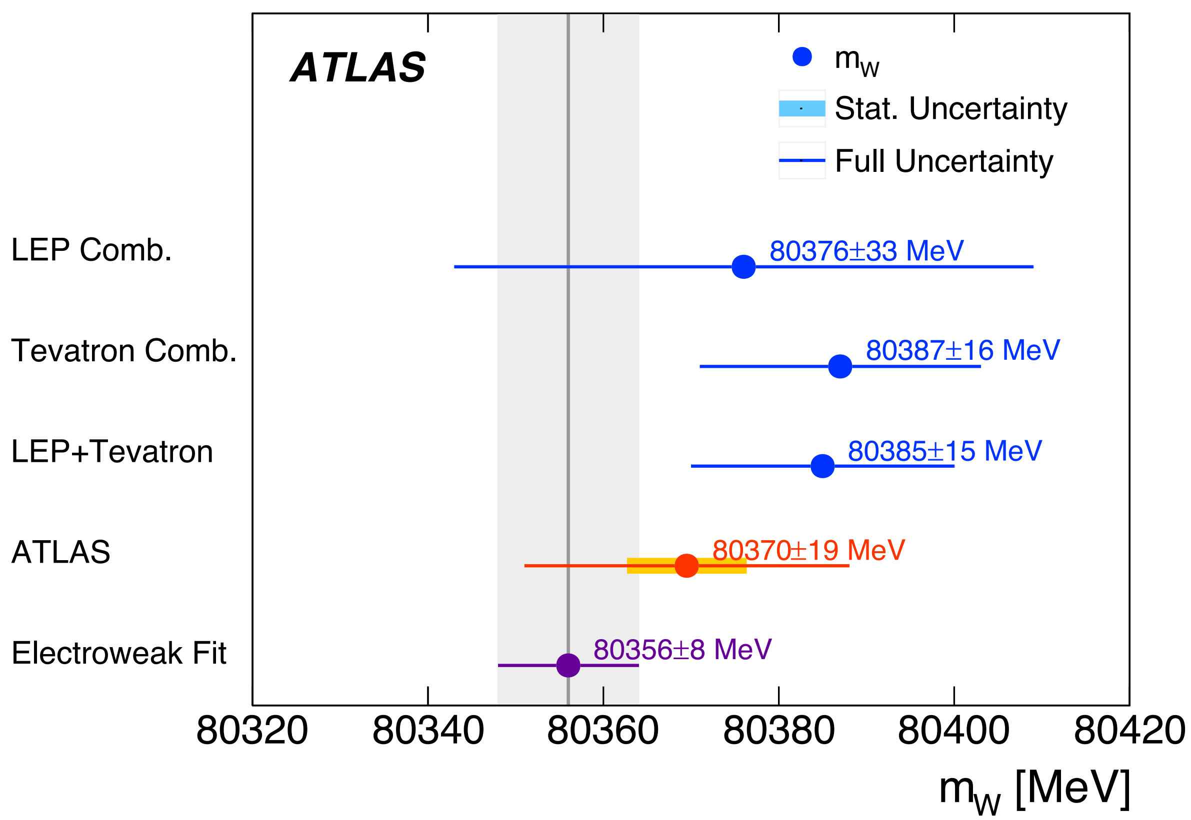
- **Preparing a next microscope.**
- **Developing in important tools for indirect information on new physics.**
  - **Discovery can be better prepared if we know where to look**
  - **Once a new state is discovered, it would need a framework to build the full picture (e.g. test the New Standard Model, give indications where other state could be)**

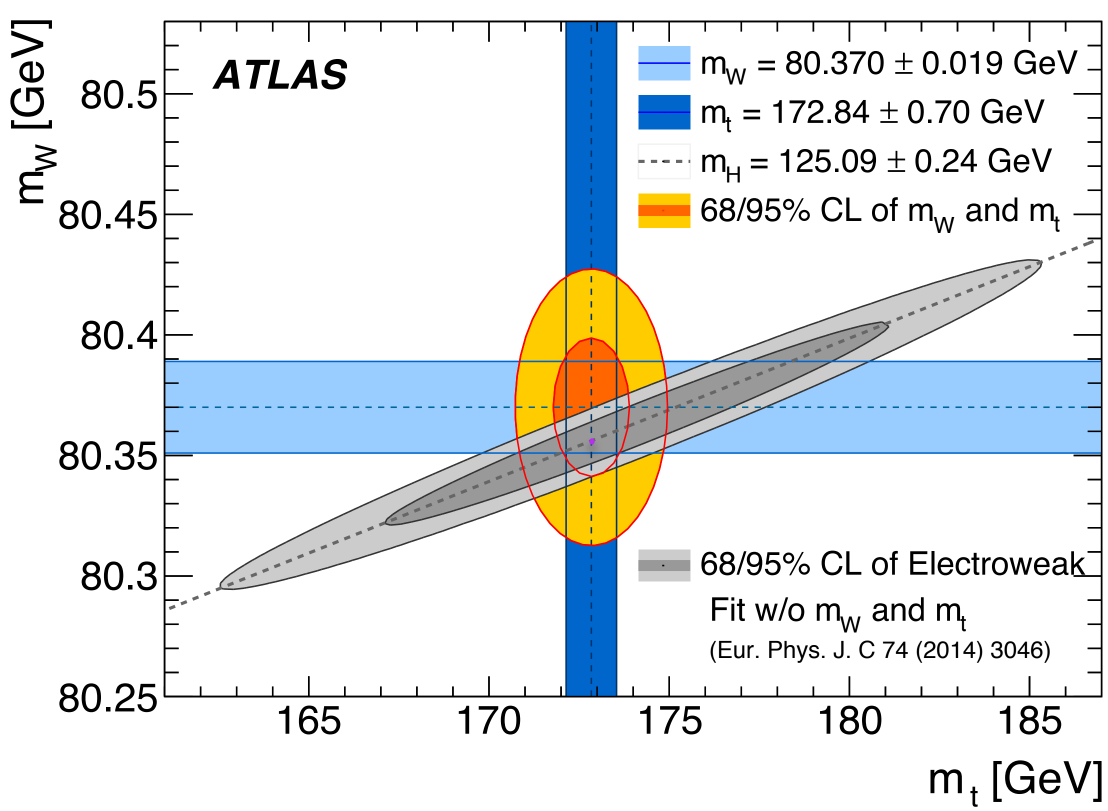


Ref. [1]

Motive of W Mass Measurement

- **More precise measurement of W mass could lead to more precise weak mixing angle. Weak mixing angle describes the rotation of the original W^0 and B^0 vector states into the observed γ and Z boson as the results of spontaneous symmetry breaking. (test Higgs mechanism)**
- **It constrains a new physics beyond the Standard Model.**
- **Electroweak radiative corrections of W or Z boson is sensitive to new physics.**
- **Current results** $\sin^2\theta_W = 0.23153 \pm 0.00016$



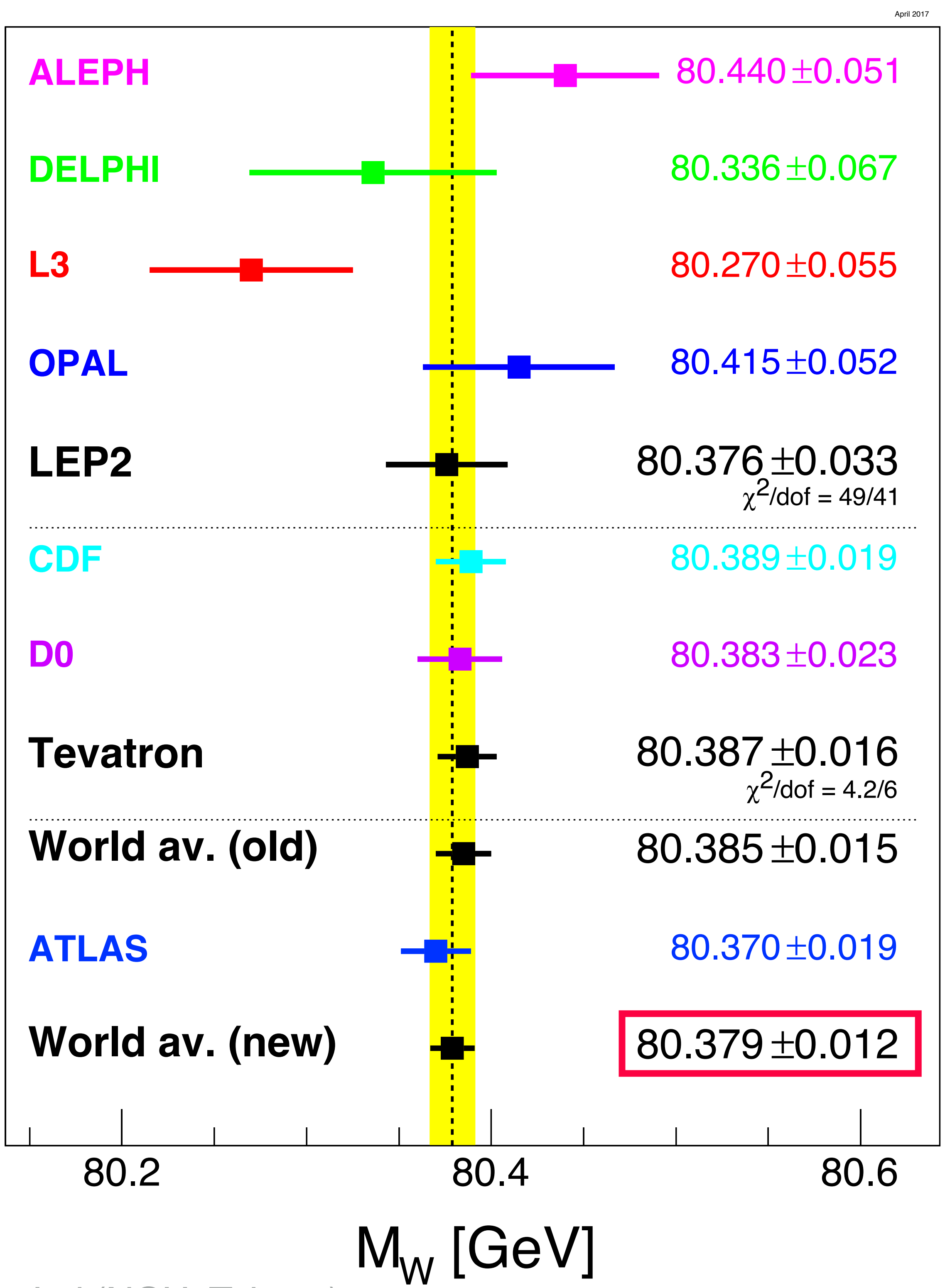


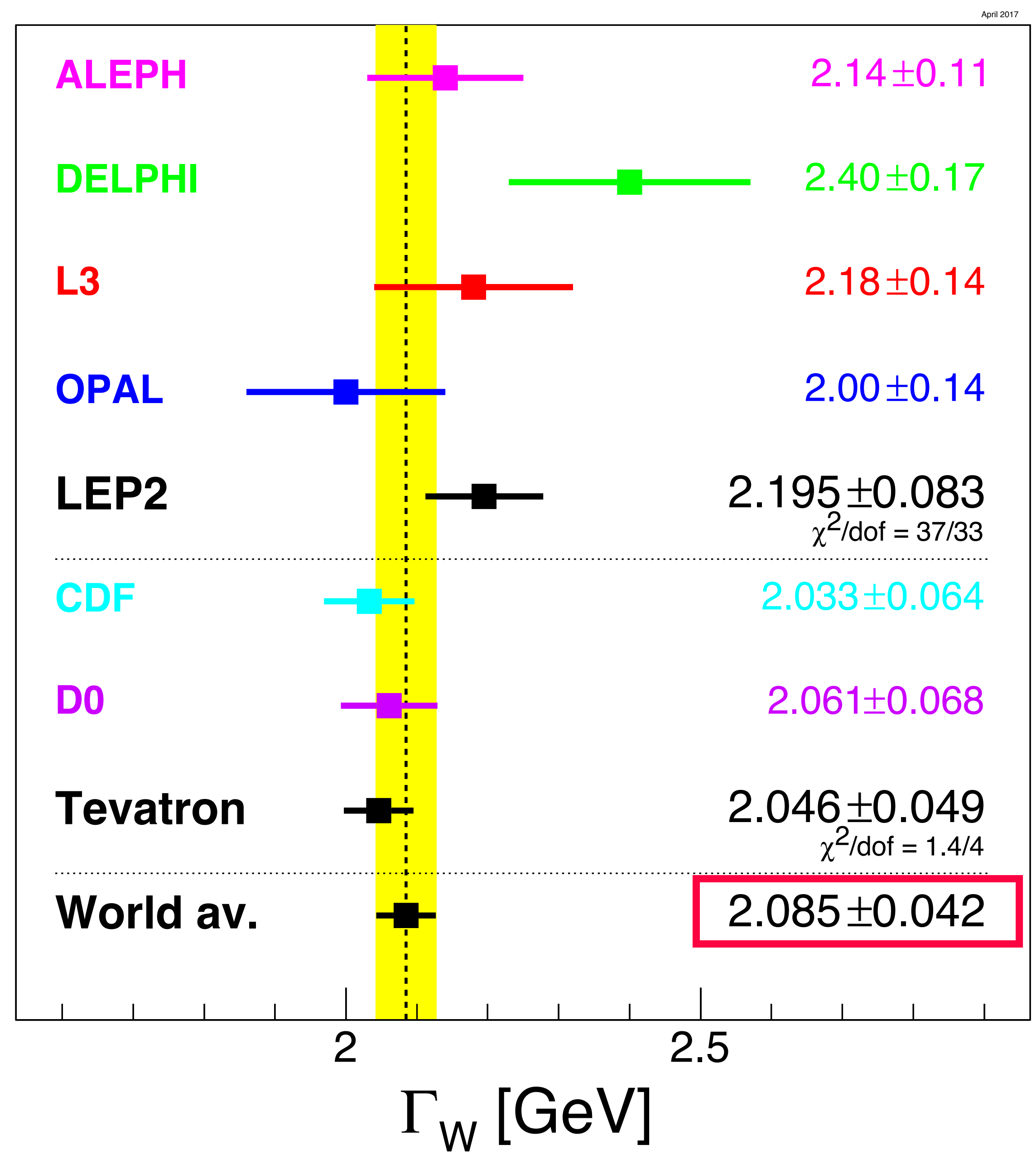
$$\frac{m_W}{m_Z} = \cos\theta_W$$

Ref. [2]

Motive of W Mass Measurement

- The uncertainty of current W mass measurement is around 12 MeV.

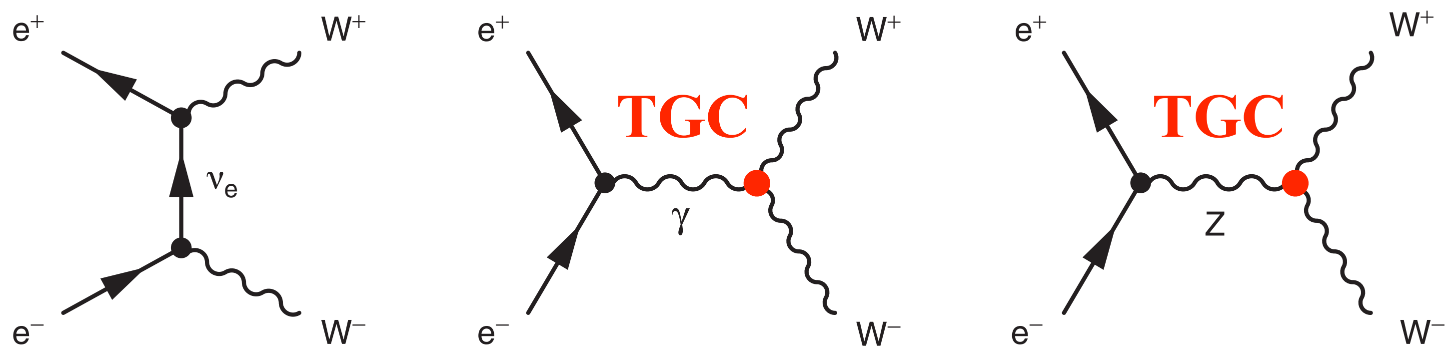


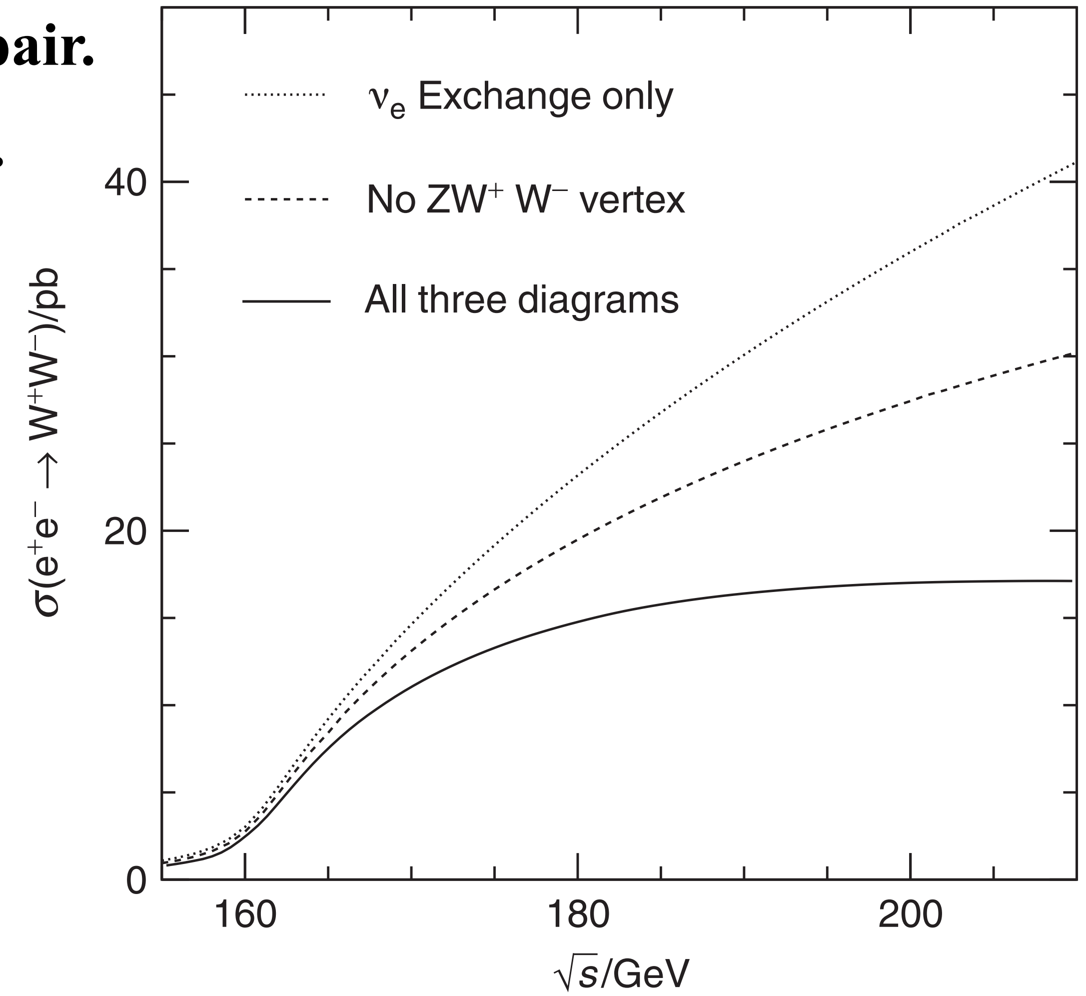


Ref. [3]

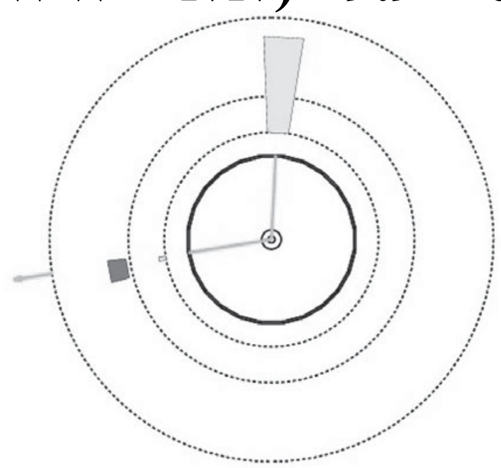
WW Production & Decay

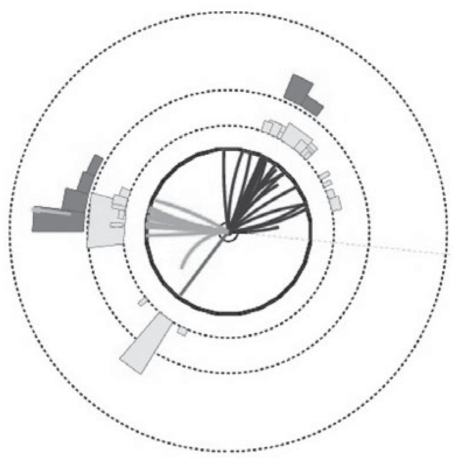
- In the e^+e^- machine, W boson is mainly produced in a pair.
- Can produce W^+W^- with center-of-mass, $\sqrt{s} > 161$ GeV.

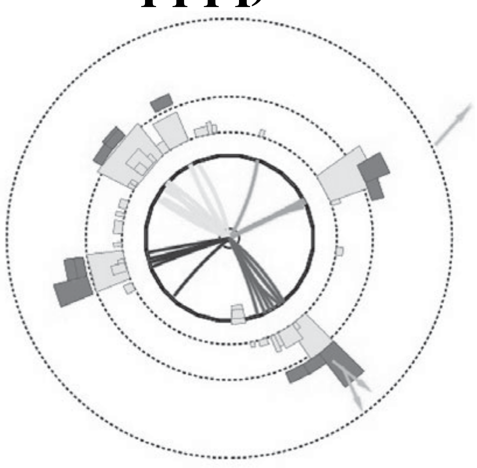




(Fully Leptonic)	(Semi Leptonic)	(Fully Hadronic)
$Br(WW \to l\nu l\nu) = 9.9 \pm 0.3\%$	$Br(WW \to l\nu q\bar{q}) = 43.2 \pm 0.8\%$	$Br(WW \to q\bar{q}q\bar{q}) = 46.9 \pm 0.8\%$





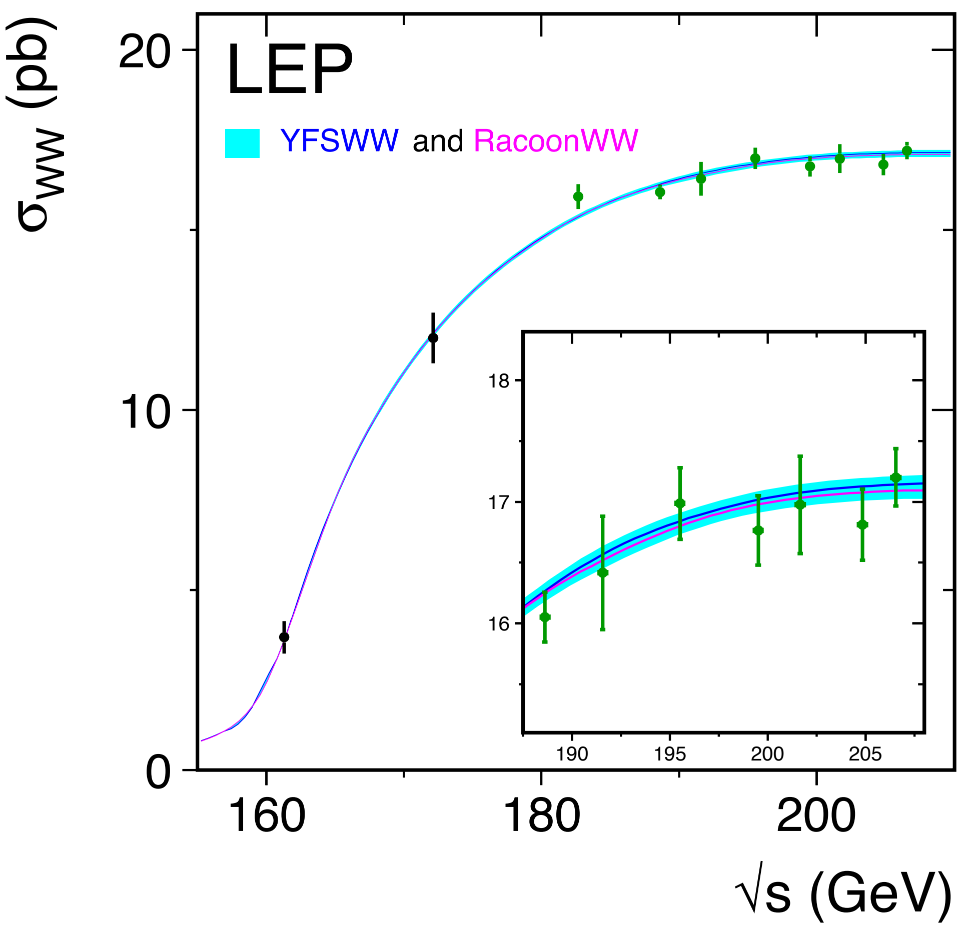


Ref. [4]

Two Ways for W-boson Mass Measurement

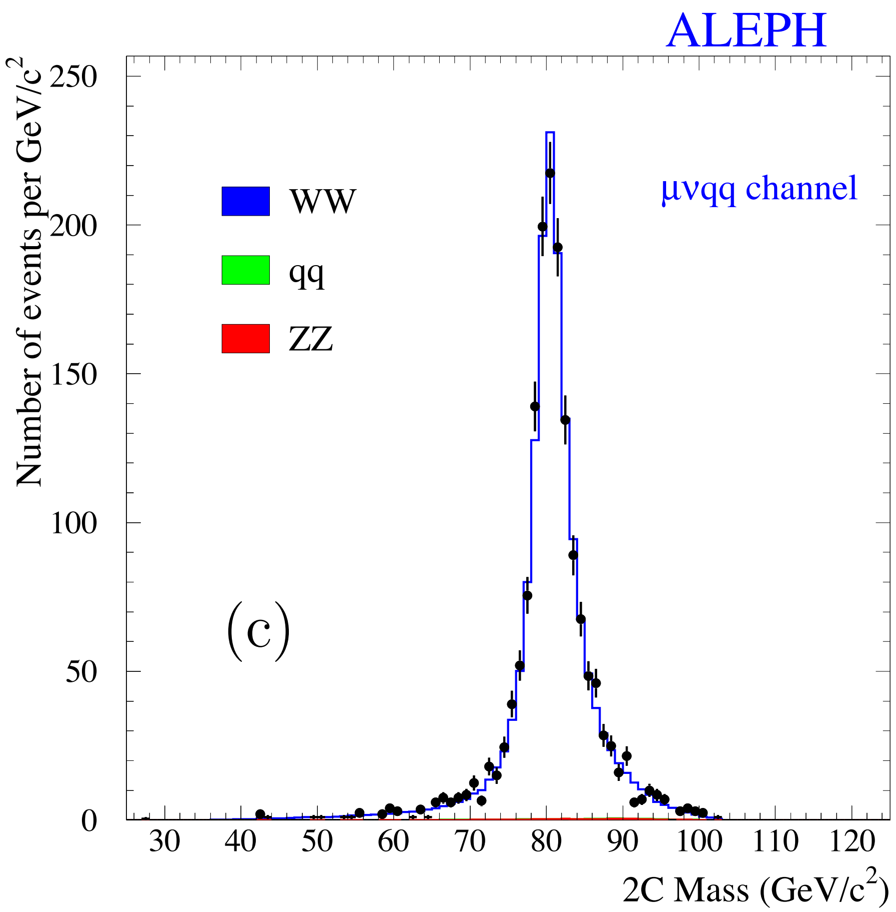
WW Threshold Scan

- WW threshold runs (157~172 GeV)
- Expected precision 1 MeV at CEPC



Direct Measurement

- Performed in ZH runs (240 GeV)
- Expected precision 2~3 MeV at CEPC



Operation mode	$\sqrt{s}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^6
Z	91.2	32 (*)	2	16	7×10^{11}
W^+W^-	158-172	10	1	2.6	2×10^7

Ref. [5, 6]

Benefit of WW Threshold Scan

1. **WW production threshold is very sensitive to m_W, m_W can be measured from threshold scans.**
2. **The threshold scan method suffered from large statistical uncertainty at LEP (about 200 MeV).**
3. **CEPC can provide a 4-point threshold scan with 2.6 ab^{-1} integral luminosity.**
4. **Strong rely on stability of beam energy.**

Ref. [7]

WW Threshold Scan(Systematics Uncertainty)

- Consider the beam spread uncertainty (E_{BS}), beam energy uncertainty, signal efficiency, cross section uncertainty, and background uncertainty.

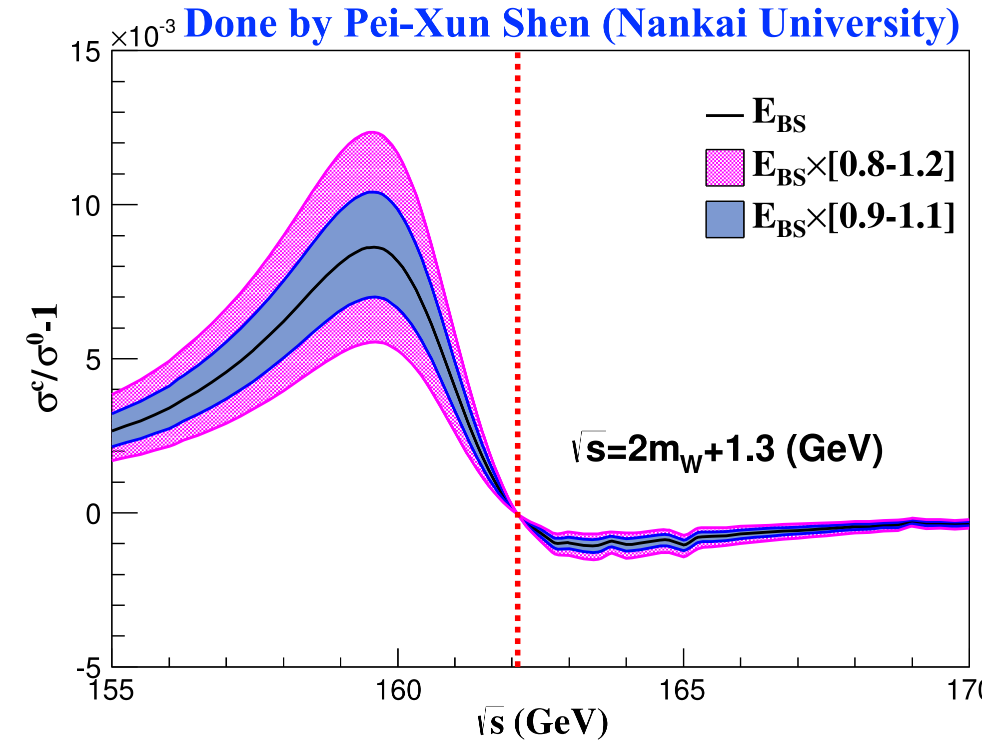
✱ **With E_{BS}, the σ_{WW} becomes:**

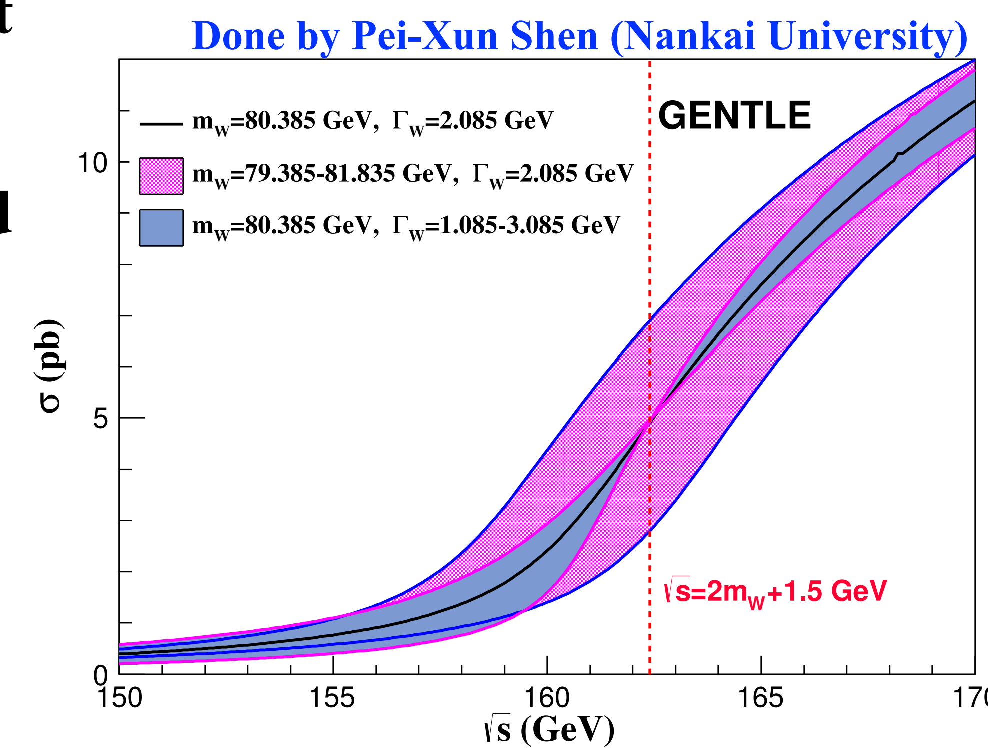
$$\sigma_{WW}(E) = \int_0^{\infty} \sigma_{WW}(E') \times G(E, E')\, dE'$$

$$\approx \int_{E-6\sqrt{2}\Delta E_{BS}}^{E-6\sqrt{2}\Delta E_{BS}} \sigma(E') \times \frac{1}{\sqrt{2\pi}\sqrt{2}E_{BS}} e^{\frac{-(E-E')^2}{2(\sqrt{2}E_{BS})^2}}\, dE'$$

✱ **$E_{BS} + \Delta E_{BS}$ is used in the simulation, and E_{BS} is for the fit formula.**

✱ **The m_W insensitive ΔE_{BS} to when taking data around 162.2 GeV.**

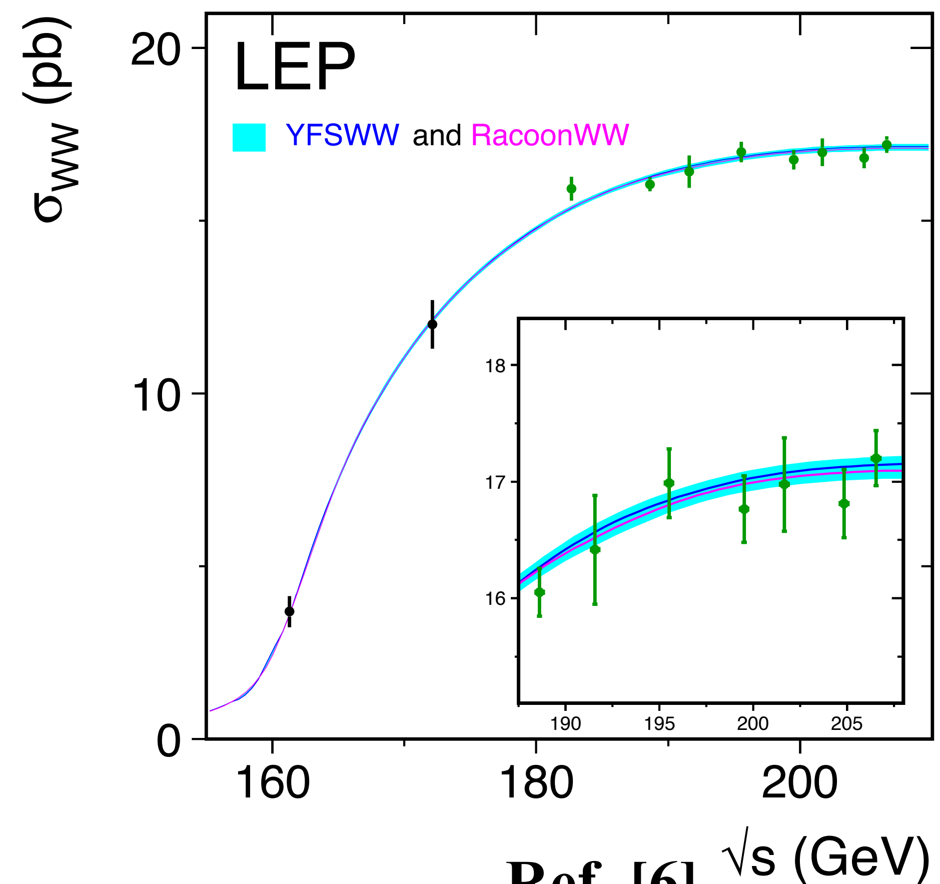




WW Threshold Scan(running plan)

- **WW threshold scan running proposal:**
  - **Assuming one year data taking in WW threshold (2.6 ab^{-1})**
  - **Four center-of-mass energy scan points:**
    - **157.5, 161.5, 162.5 (W mass, W width measurements)**
    - **172.0 GeV (α_{QCD} (m_W) measurements, Br(W→had), CKM $|V_{CS}|$)**
    - **16M WW events will be collected in total threshold scan data. (Amount of W is 400 times larger than LEP2 during threshold scan runs)**

E_{cm}(GeV)	Lumi(ab^{-1})	XS(pb)	Number of WW pairs(10^6)
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	0.6	12.2	6.1



Ref. [6]

WW Threshold Scan(Uncertainty)

- **Statistics is enough for branching ratio measurement Br(W→had) and α_{QCD} (m_W) measurements.**
- **Statistics uncertainty is one of the limiting factor for W mass and W width measurement with CEPC one year running plan. (2.6 ab^{-1})**
- **According to the CDR, the total uncertainty of WW threshold scan manner is expected to be 1 MeV at CEPC.**

Observable	m_W	Γ_W	
Source	Uncertainty (MeV)		
Statistics	0.8	2.7	
Beam energy	0.4	0.6	→ **accelerator**
Beam spread	—	0.9	→ **accelerator**
Corr. Syst.	0.4	0.2	→ **Lumi unc. & signal effi. & theory XS unc.**
Total	1.0	2.8	

Ref. [7]

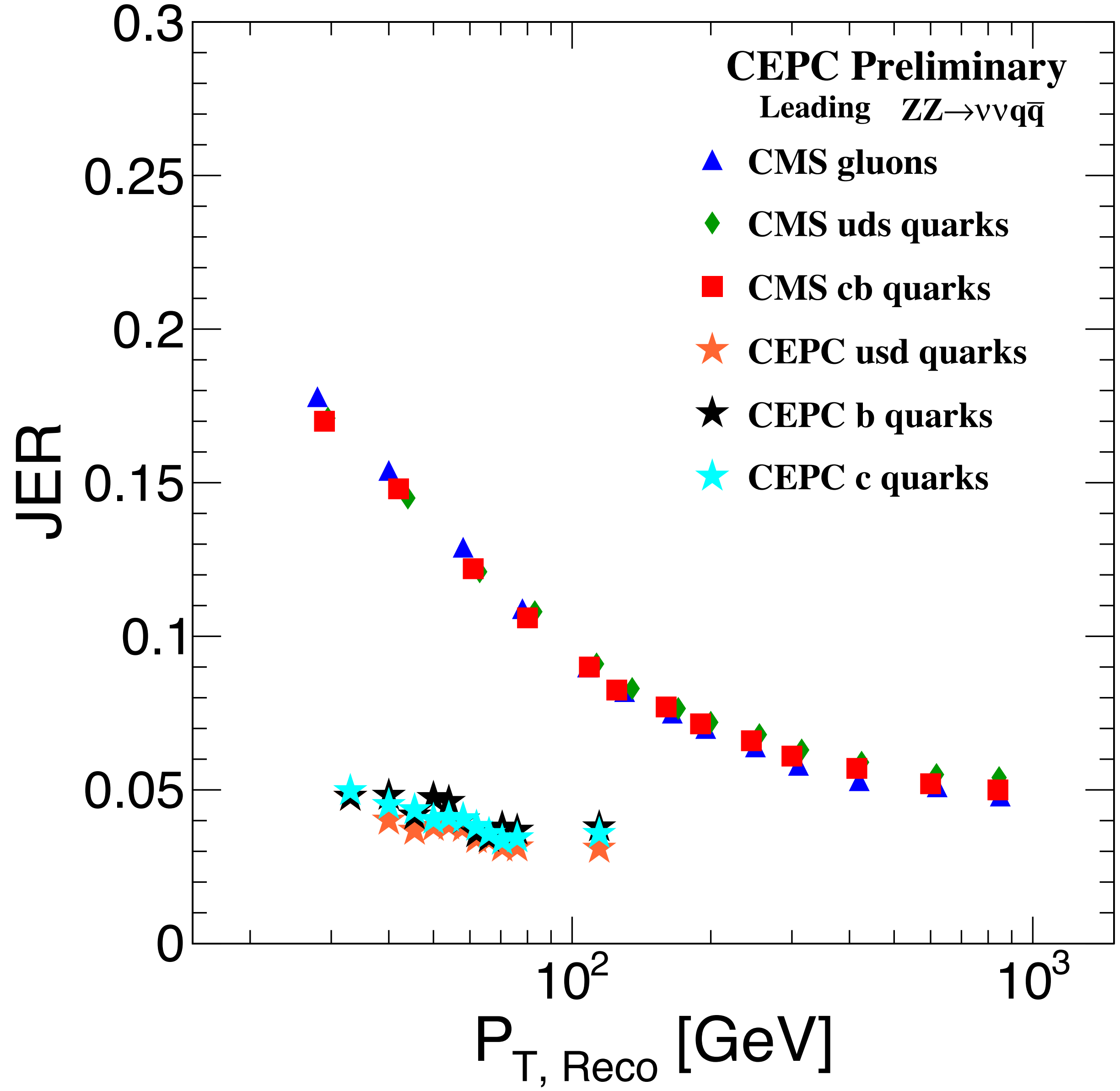
Benefit of Direct Measurement

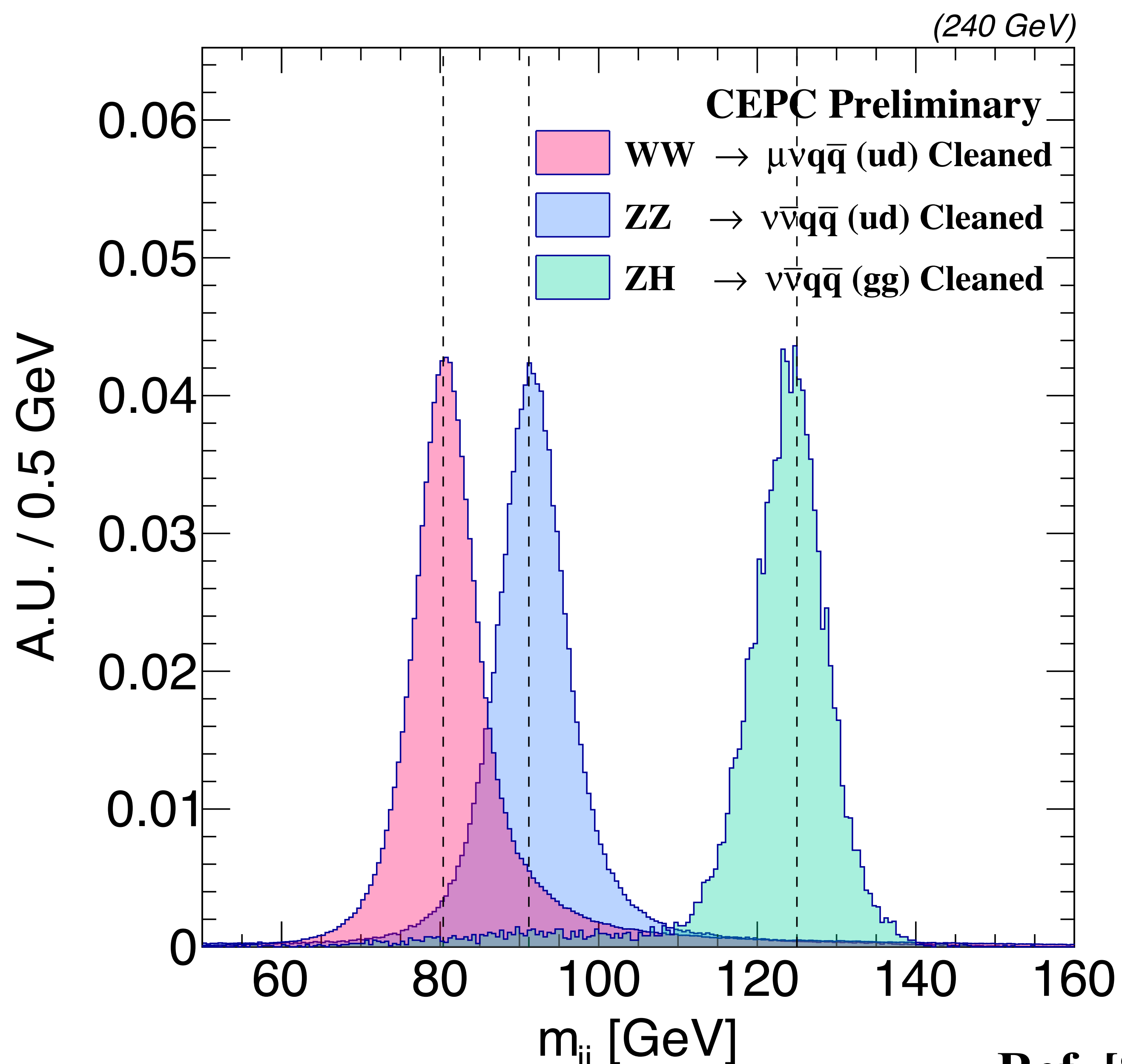
1. **No dedicated run is needed: all the measurements can be done in ZH runs with $\sqrt{s}$ = 240 GeV. It also represents that this method has a lower requirement for accelerator performance.**
2. **Not affect by beam energy uncertainty.**
3. **Semi-leptonic channel has more statistic than fully leptonic channel.**
4. **Provide a better measurement than threshold scans at LEP.**
5. **Main challenge is to handle the uncertainty due to QED radiation. It can be reduced to the 1 MeV level by using 1000 fb^{-1}.**

Ref. [7]

W Mass Direct Measurement

- Benefited by excellent jet energy resolution and PFA oriented detector.
- The W, Z, and Higgs bosons in dijet final state can be well separated in CEPC.
- It is possible to measure W mass from direct dijet mass reconstruction.

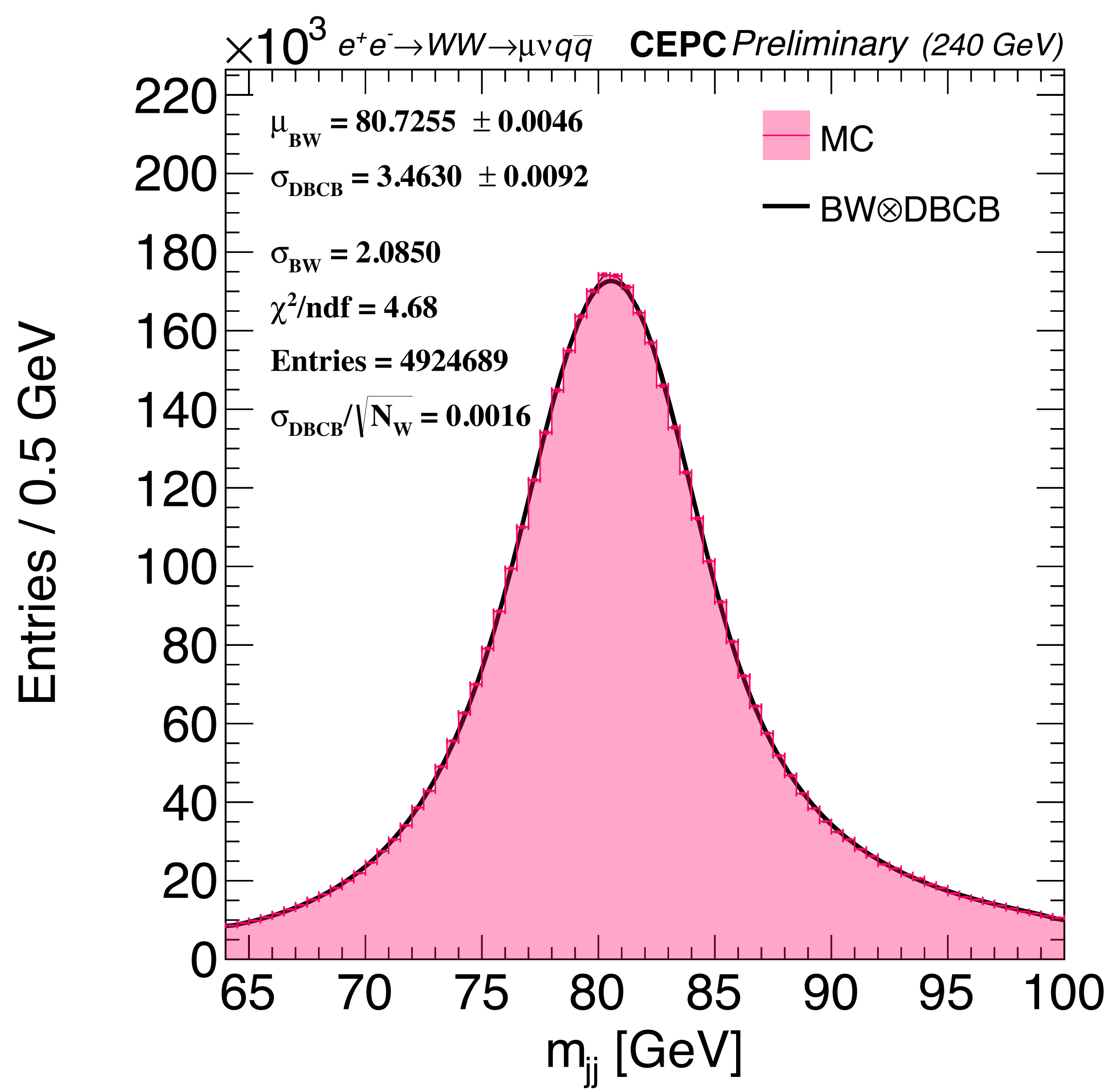




Ref. [8]

W Mass Direct Measurement

- **Reconstruct dijet mass from WW→$\mu\nu$qq process in ZH run.**
  - **Major systematic is from jet energy scale (JES) uncertainty (2~3 MeV)**
    - **Main uncertainty is from jet flavor composition and jet flavor response.**
  - **Calibrate JES with Tera-Z (Z→qq).**



Direct Measurement(Uncertainty)

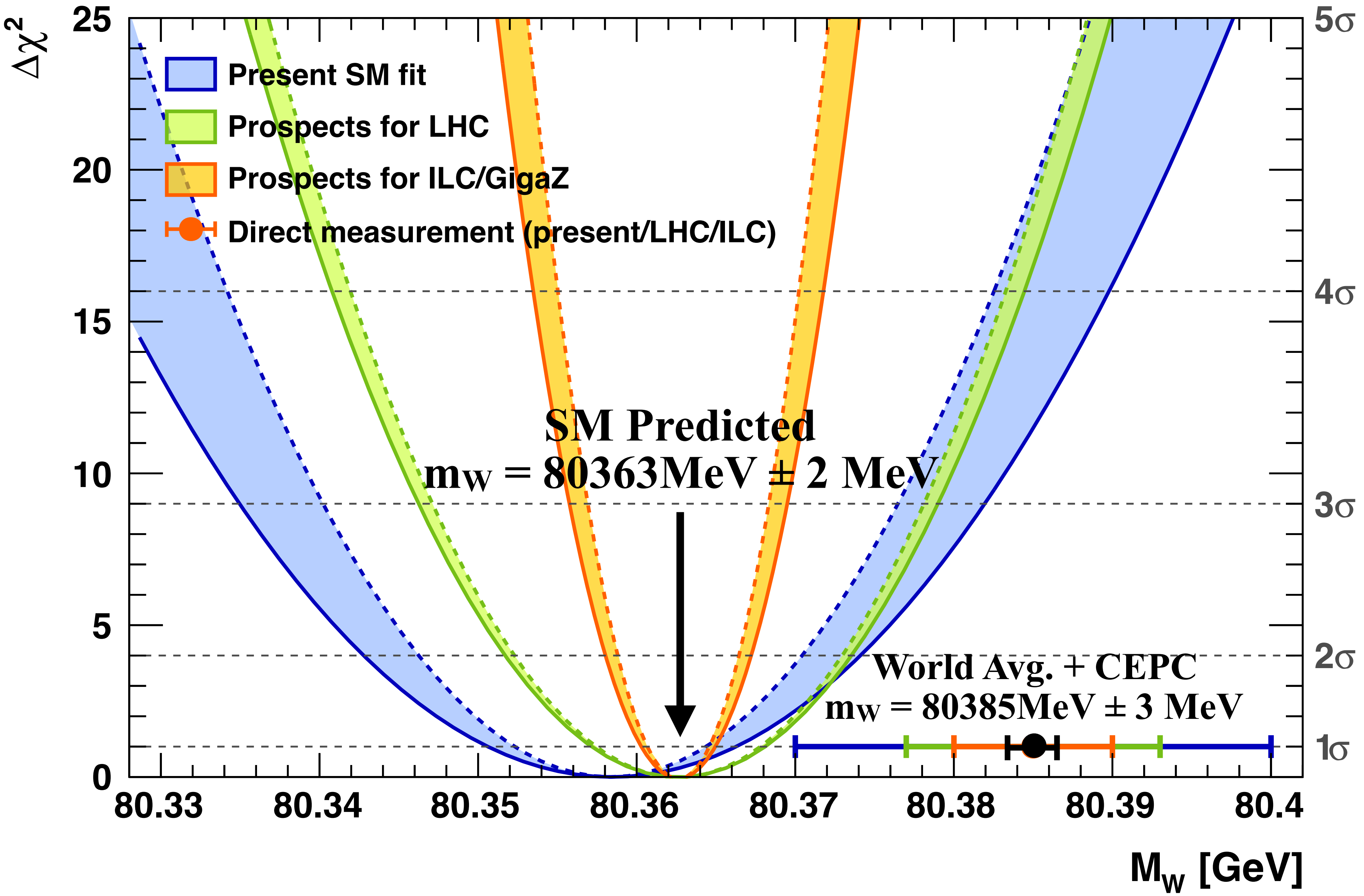
- **After calibration, the major systematics, jet energy scale uncertainty is expected to be reduced to 1.5 MeV.**
- **The total uncertainty of direct W mass measurement is expected to be 3 MeV at CEPC.**

Collider	LEP	CEPC	
$\sqrt{s}$ (GeV)	180-203	240	
$\int \mathcal{L}dt$	2.6 fb^{-1}	5.6 ab^{-1}	
Channels	$l\nu q\bar{q}$, $q\bar{q}q\bar{q}$	$l\nu q\bar{q}$	
Source	**Uncertainty (MeV)**		
Statistics	25	1.0	
Beam energy	9	1.0	→ **accelerator**
Hadronization	13	1.5	→ **theory**
Radiative corrections	8	1.0	→ **theory**
Detector effects	10	1.5	→ **jet flavor response**
Total	33	3.0	

Ref. [7]

Prospect of W Mass Measurement at CEPC

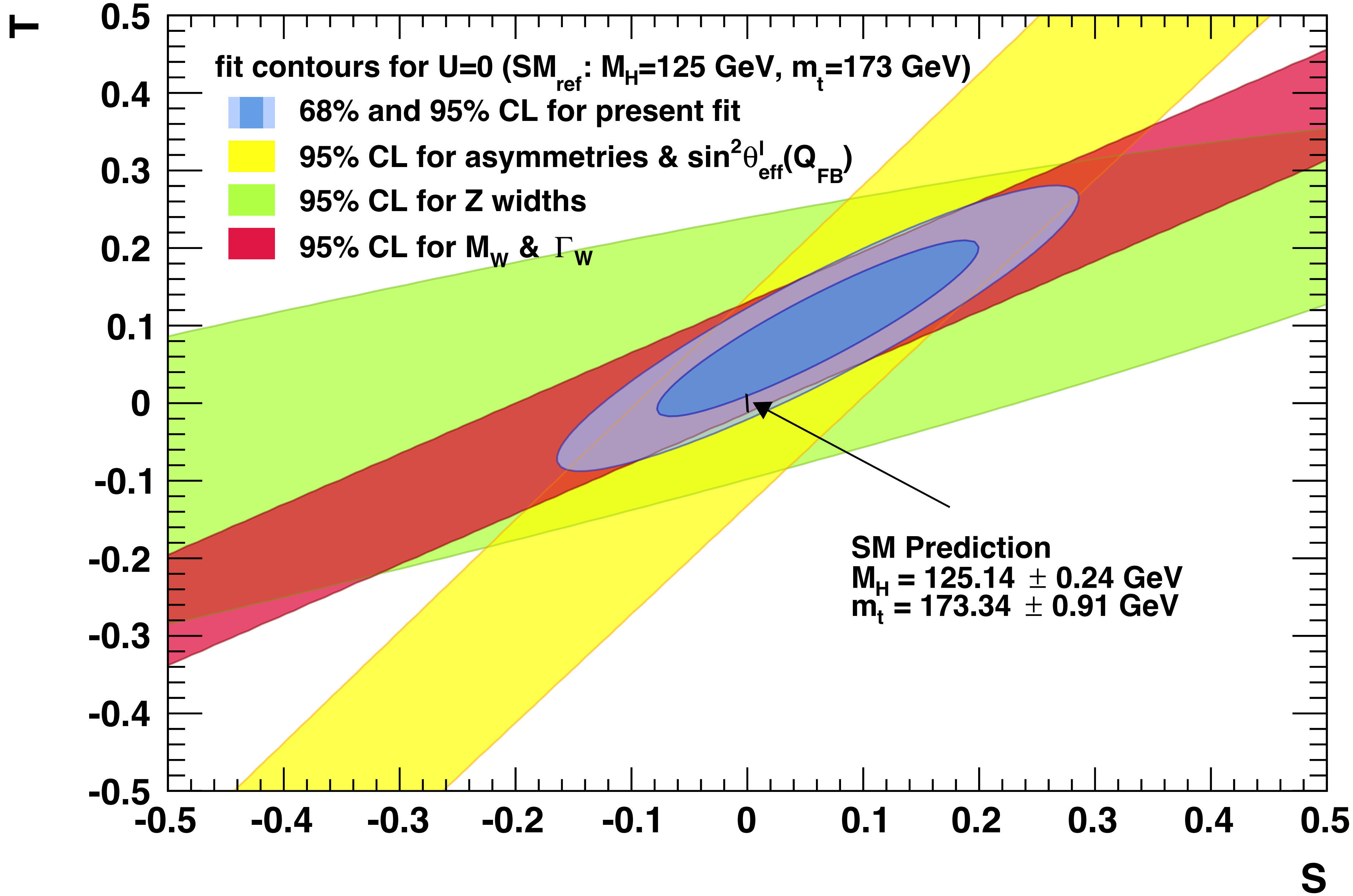
- **CEPC can improve current precision of W mass by one order of magnitude.**
  - **A possible BSM physics can be discovered in the future.**



Ref. [1]

Prospect of W Mass Measurement at CEPC

- **CEPC can improve current precision of W mass by one order of magnitude.**
  - **A possible BSM physics can be discovered in the future.**
  - **Oblique parameter, U is only constrained by the W mass and its total width.**



Ref. [1]

Conclusion

- **The excellent performance of the ILC, CEPC, FCC-ee colliders with clean, advantageous kinematics of e^+e^- annihilation events offer a high precision to explore and probe the new physics.**

ΔM_W [MeV]	LEP2	ILC	ILC	ILC	CEPC	FCC-ee	CEPC
$\sqrt{s}$ [GeV]	172-209	250	350	500	160	160	240
$\mathcal{L}$ [fb^{-1}]	3.0	500	350	1000	2.6 ab^{-1}	10 ab^{-1}	5.6 ab^{-1}
$P(e^-)$ [%]	0	80	80	80	WW threshold	WW threshold	Direct measurement
$P(e^+)$ [%]	0	30	30	30			
beam energy	9	0.8	1.1	1.6	0.6	—	1.0
luminosity spectrum	N/A	1.0	1.4	2.0	—	—	—
hadronization	13	1.3	1.3	1.3	—	—	1.5
radiative corrections	8	1.2	1.5	1.8	—	—	1.0
detector effects	10	1.0	1.0	1.0	—	—	1.5
other systematics	3	0.3	0.3	0.3	0.2	—	—
total systematics	21	2.4	2.9	3.5	0.6	—	2.5
statistical	30	1.5	2.1	1.8	0.8	0.3	1.0
total	36	2.8	3.6	3.9	1.0	1.0	3.0

Ref. [1, 7, 9]

Thank for your attention

Reference

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[2] Measurement of the W-boson mass in pp collisions at $\sqrt{s}$=7TeV with the ATLAS detector

[3] Mass and Width of the W Boson, http://pdg.lbl.gov/2018/reviews/rpp2018-rev-w-mass.pdf

[4] Thomson, Mark Modern particle physics 2013 2013

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[6] Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP, arXiv:1302.3415

[7] CEPC Conceptual Design Report Volume II - Physics & Detector

[8] CMS-JME-13-004, CERN-PH-EP "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV"

[9] ICHEP 2018 Seoul Electroweek physics at FCC-ee, https://indico.cern.ch/event/686555/contributions/2975646/attachments/1681638/2701907/FCCee_ew_Lesiak.pdf

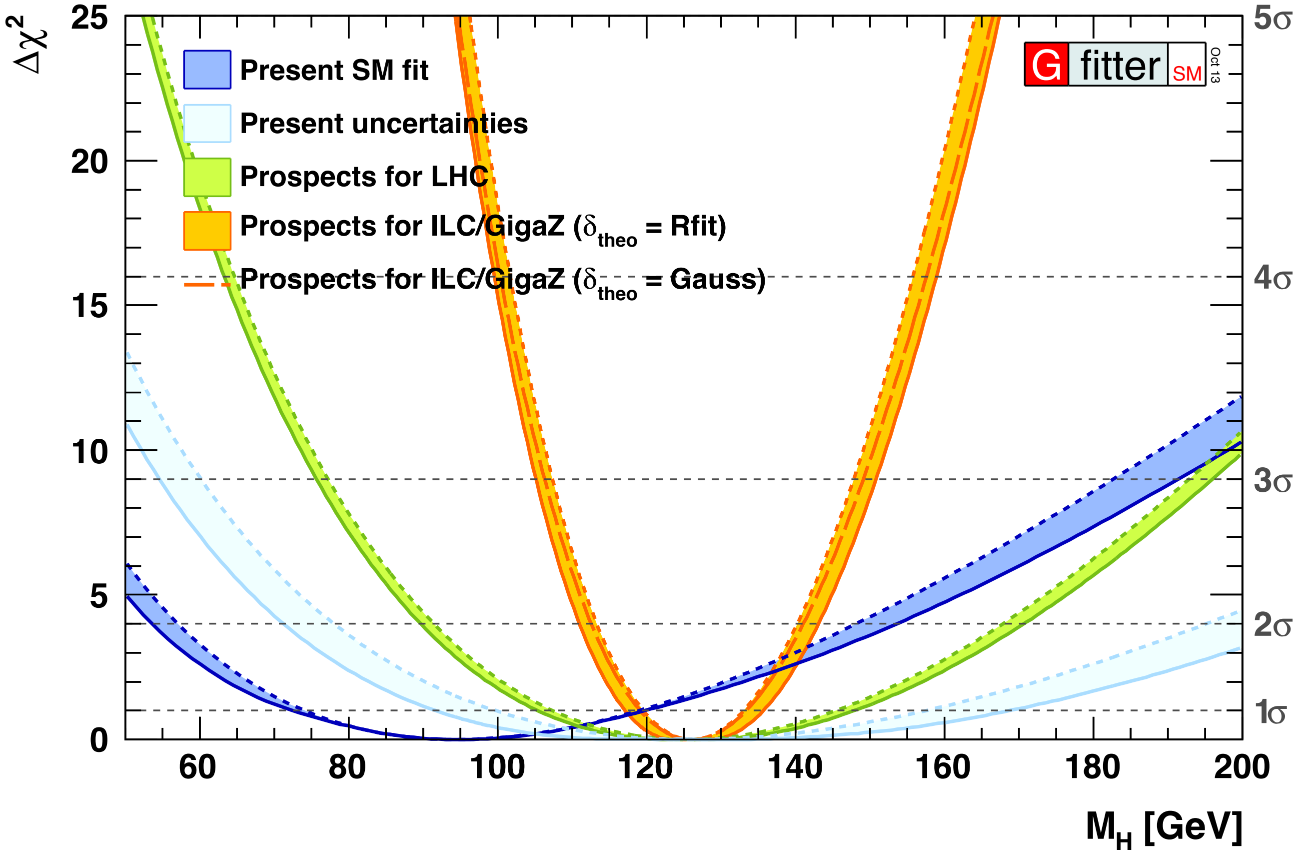
Back up

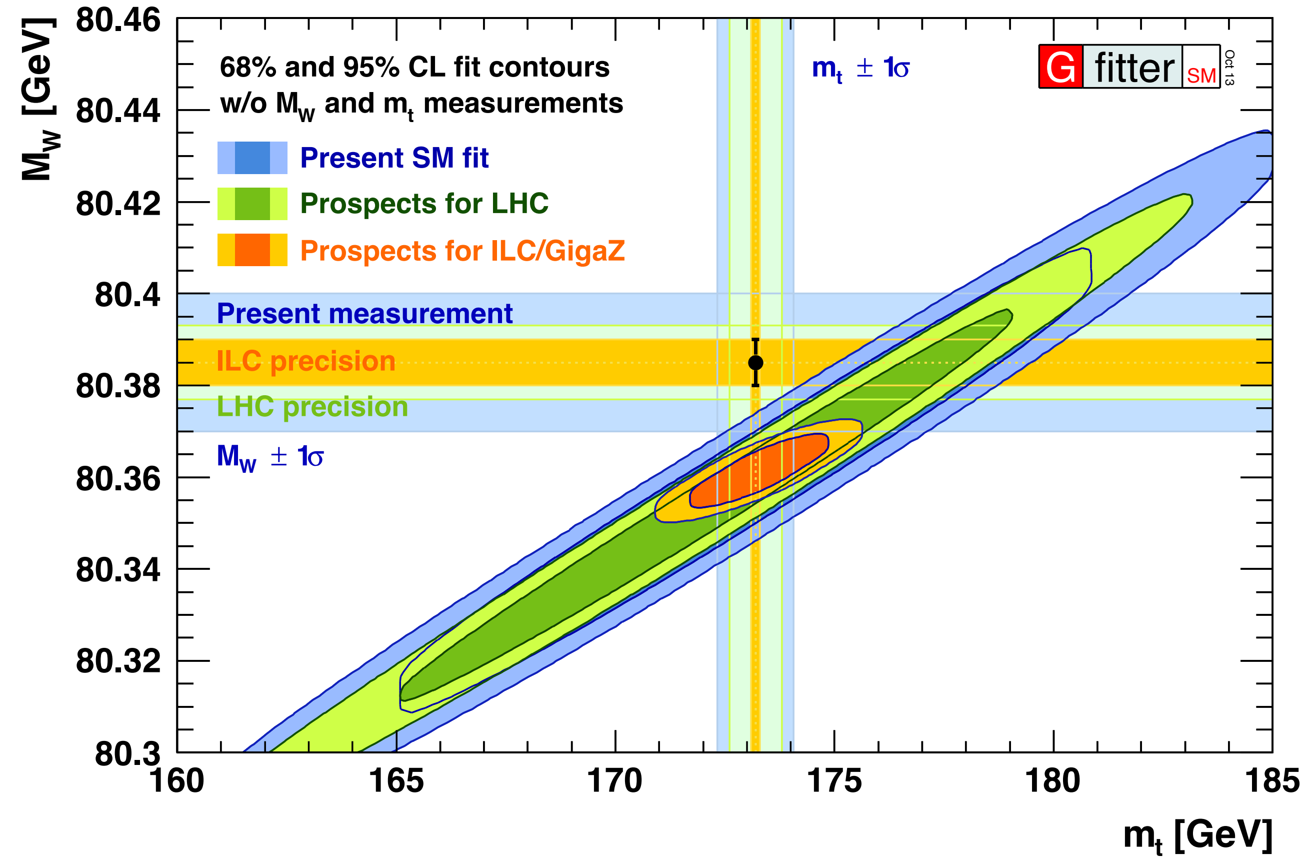
Two Ways for W-boson Mass Measurement

	Higgs	W	Z (3T)	Z (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	3.48	7	23.8	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
No. of particles/bunch $N_e (10^{10})$	15	12	8	
Beam current (mA)	17.4	87.9	461	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
β function at IP: β_x^* (m)	0.36	0.36	0.2	0.2
β_y^* (m)	0.0015	0.0015	0.0015	0.001
Emittance: x (nm)	1.21	0.54	0.18	0.18
y (nm)	0.0024	0.0016	0.004	0.0016
Beam size at IP: σ_x (μm)	20.9	13.9	6.0	6.0
σ_y (μm)	0.06	0.049	0.078	0.04
Beam-beam parameters: ξ_x	0.018	0.013	0.004	0.004
ξ_y	0.109	0.123	0.06	0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.1	
RF frequency f_{RF} (MHz)	650			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	4.4	5.9	8.5	
Natural energy spread (%)	0.1	0.066	0.038	
Energy spread (%)	0.134	0.098	0.08	
Photon number due to beamstrahlung	0.082	0.05	0.023	
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

Ref. [7]

Motive of W Mass Measurement





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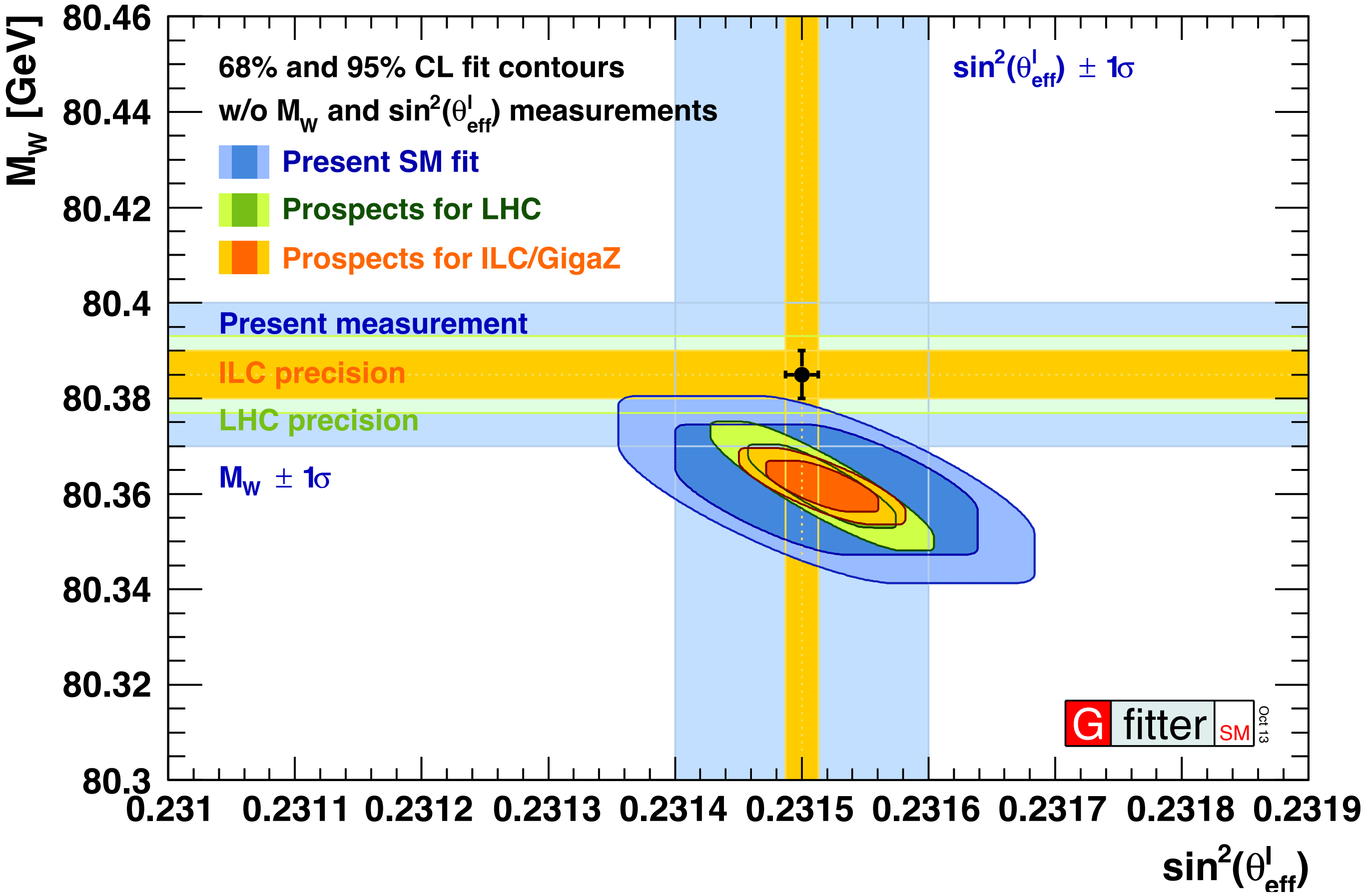
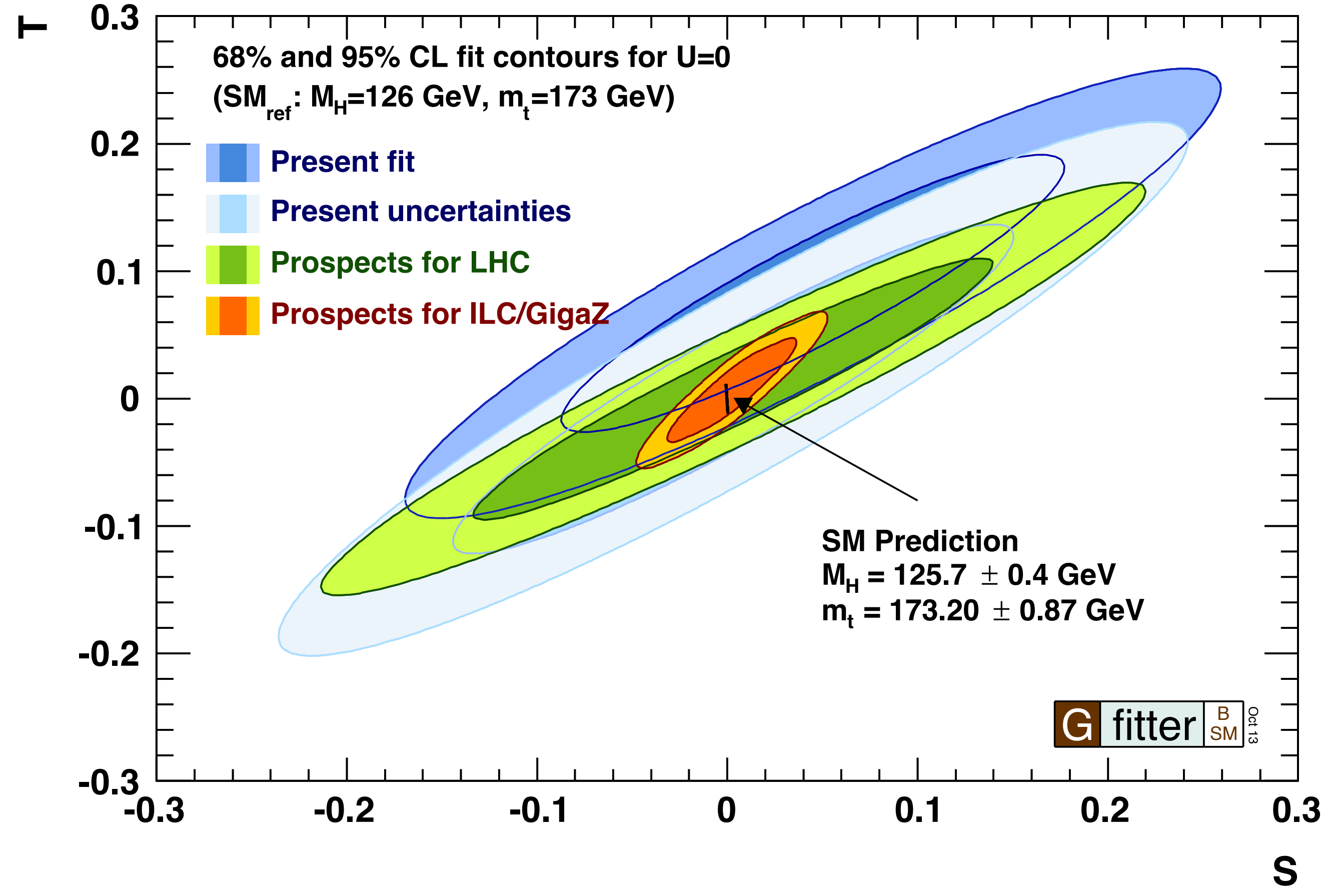
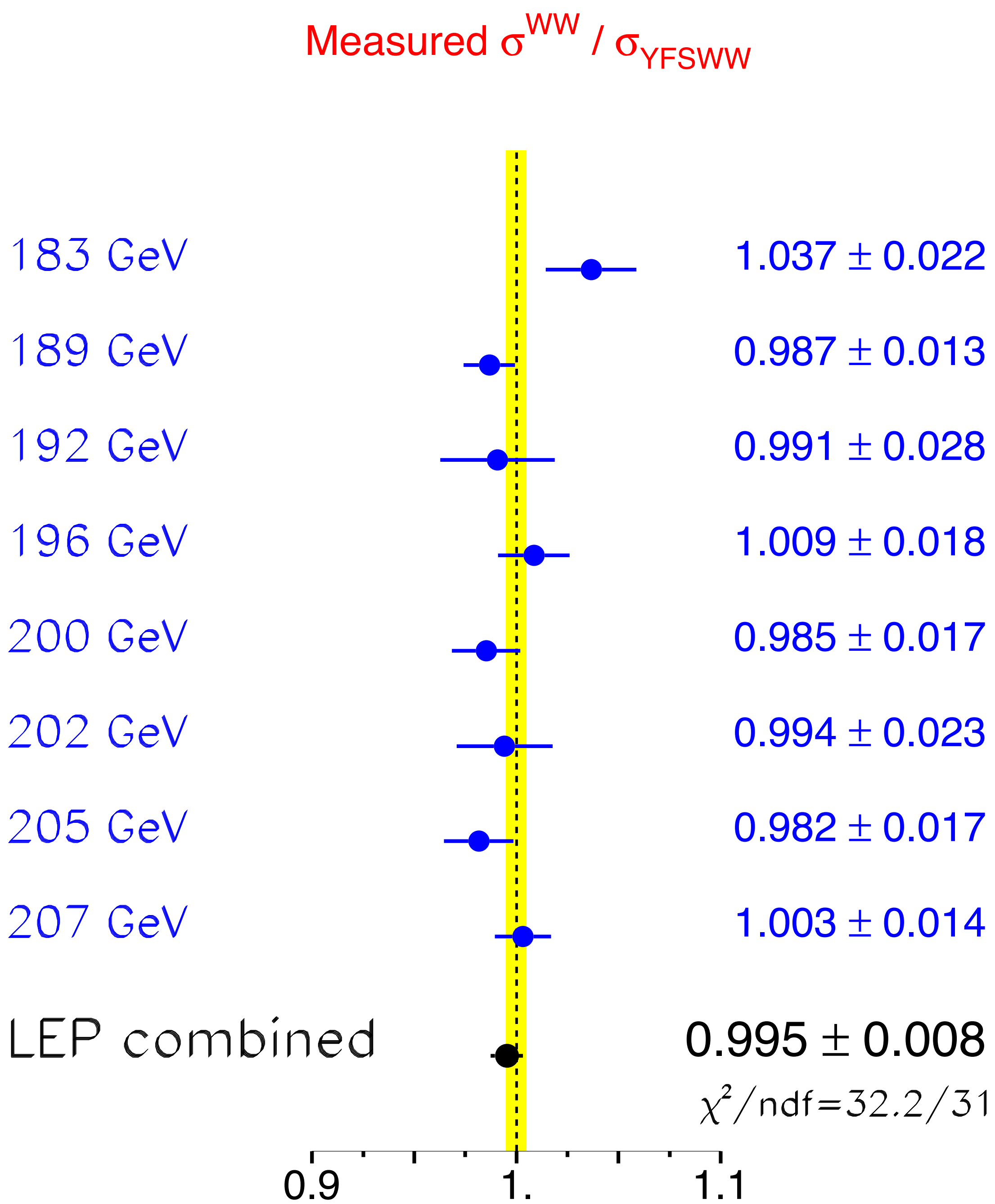
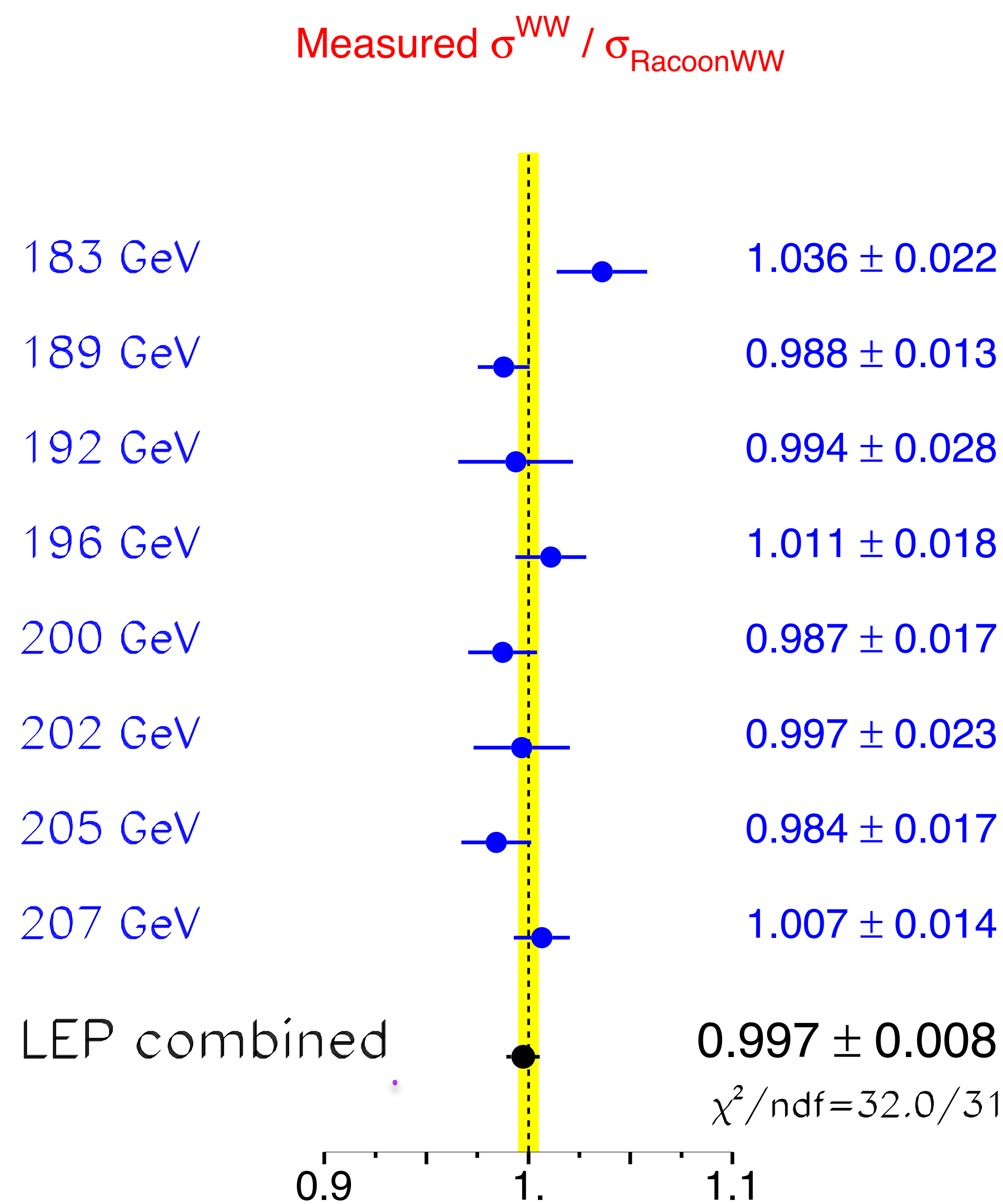




Ref. [1]

Motive of W Mass Measurement

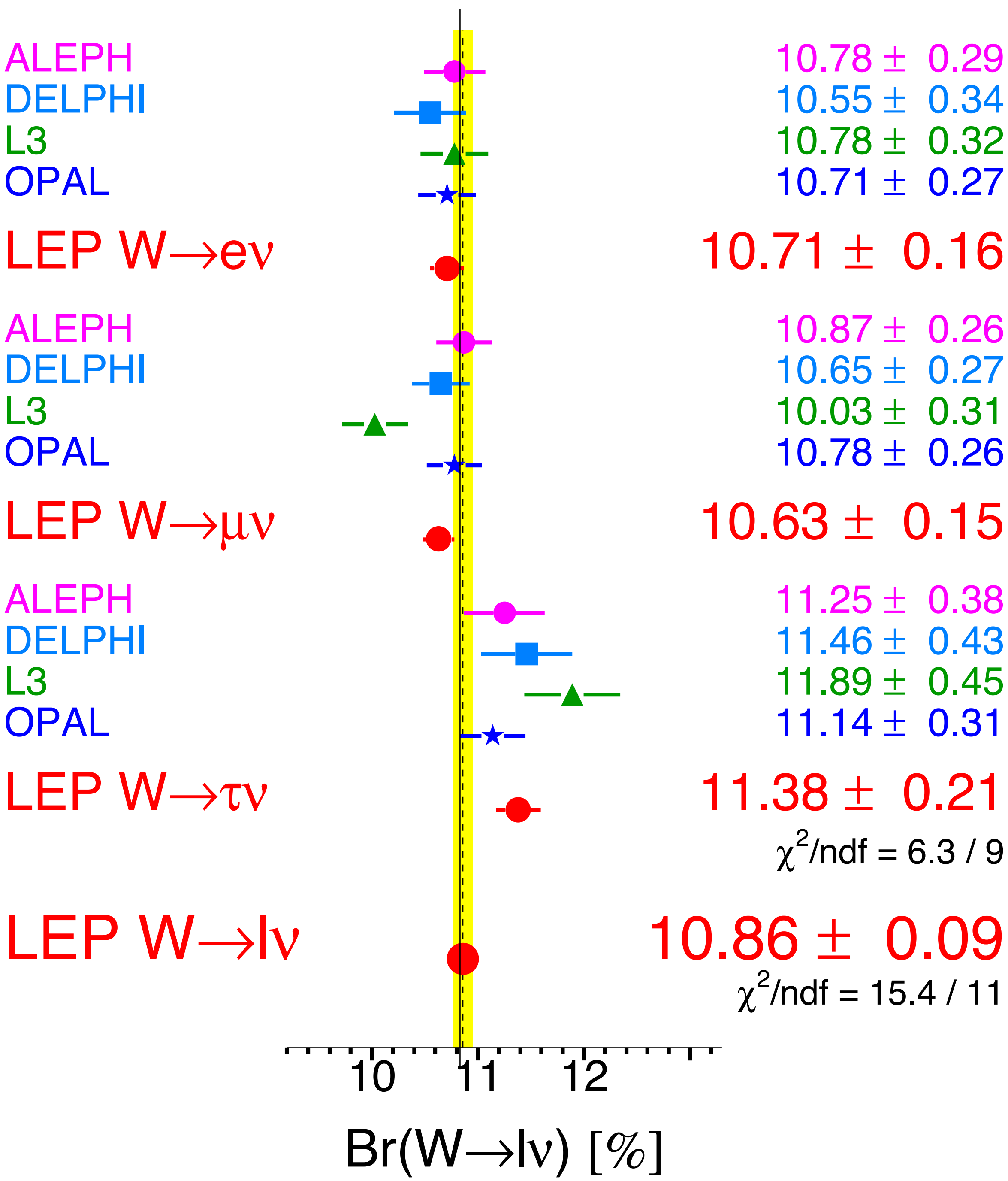




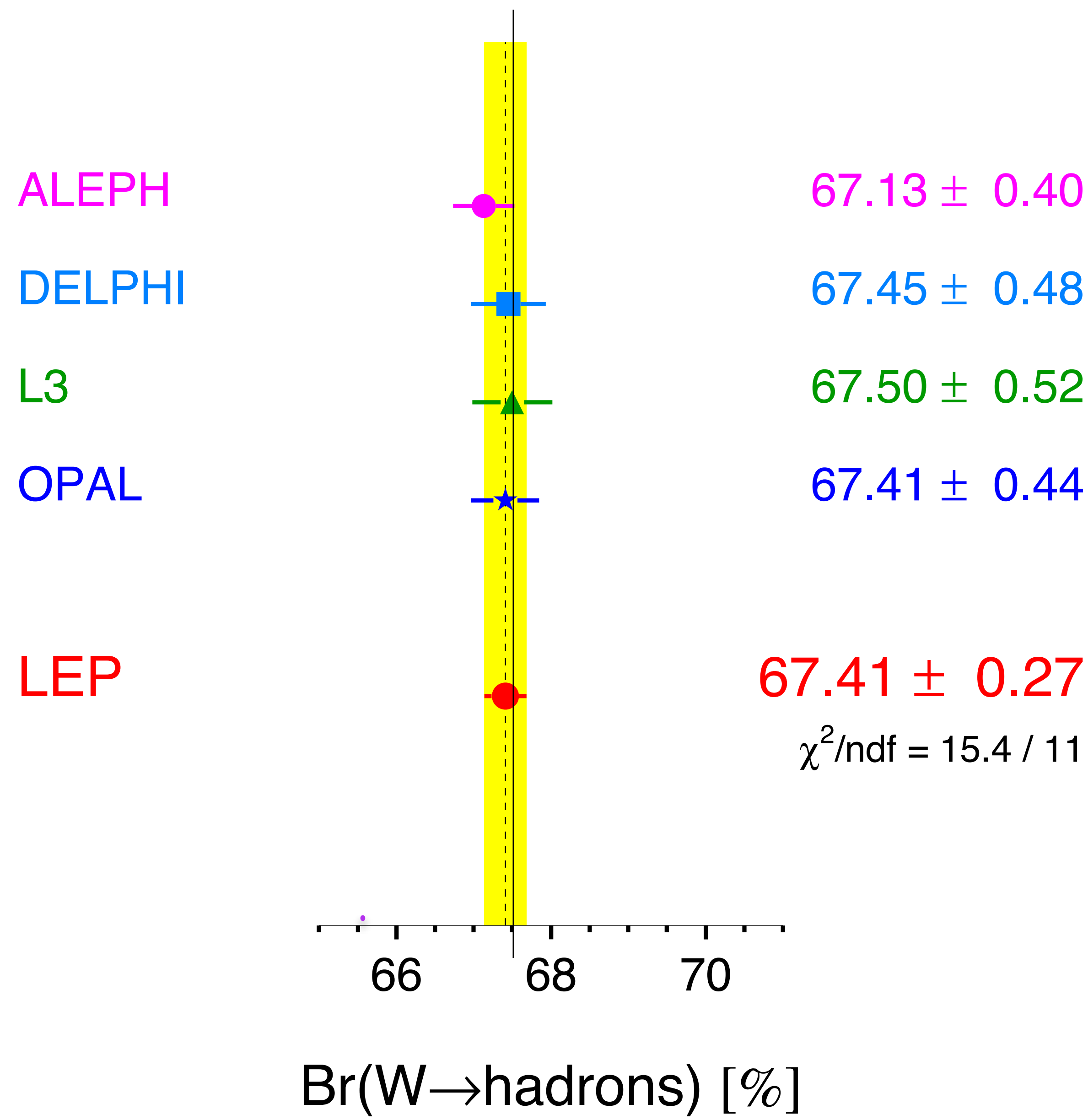
Ref. [3]

Motive of W Mass Measurement

W Leptonic Branching Ratios



W Hadronic Branching Ratio



Ref. [3]

Benefit of Direct Measurement

ΔM_W(MeV)	LEP	CEPC
√s(GeV)	161	250
∫L(fb-1)	3	1000
Channel	lvqq, qqqq	lvqq
Beam energy	9	1.0
Hadronization	13	1.5
Radiative corrections	8	1.0
Lepton and missing energy scale	10	1.5
Bias in mass reconstruction	3	0.5
Statistics	30	1.0
Overal systematics	21	2.5
Total	36	3.0

Ref. [7]

Select the Final State($\mu\nu q\bar{q}$)

V1($WW \to \mu\nu q\bar{q}$)	# of event	Efficiency	Efficiency w.r.t. previous
Tot # of event	5799018	—	—
nTrack > 7	5772755	99.6%	—
Muon Selection	4846986	83.5%	84.0%
Detector acceptance $\lvert\cos(\theta_\mu)\rvert < 0.995$	4846986	83.5%	100%
Pt_{Miss} > 10 GeV	4651878	80.2%	96.0%
Visible mass > 0.5*√s	4323619	74.5%	92.9%
Two jets b-tag score < 0.5	4024306	69.4%	93.1%
Two jets c-tag score < 0.6	2801400	48.3%	69.6%

Summary

m_W (GeV)	m_Z (GeV)	m_H (GeV)	Jets / PFOs	wi/wo Clean	wi/wo Cali
82.66 ± 3.54	93.69 ± 3.89	127.48 ± 4.93	Jets	0	0
82.79 ± 3.34	93.95 ± 3.48	127.31 ± 4.54	Jets	1	0
80.72 ± 3.46	91.67 ± 3.77	125.02 ± 5.11	Jets	0	1
80.82 ± 3.23	91.76 ± 3.39	124.39 ± 4.39	Jets	1	1
82.63 ± 3.53	93.69 ± 3.89	127.57 ± 4.80	PFOs	0	0
82.77 ± 3.32	93.90 ± 3.54	127.83 ± 4.50	PFOs	1	0