W Mass Measurements at CEPC

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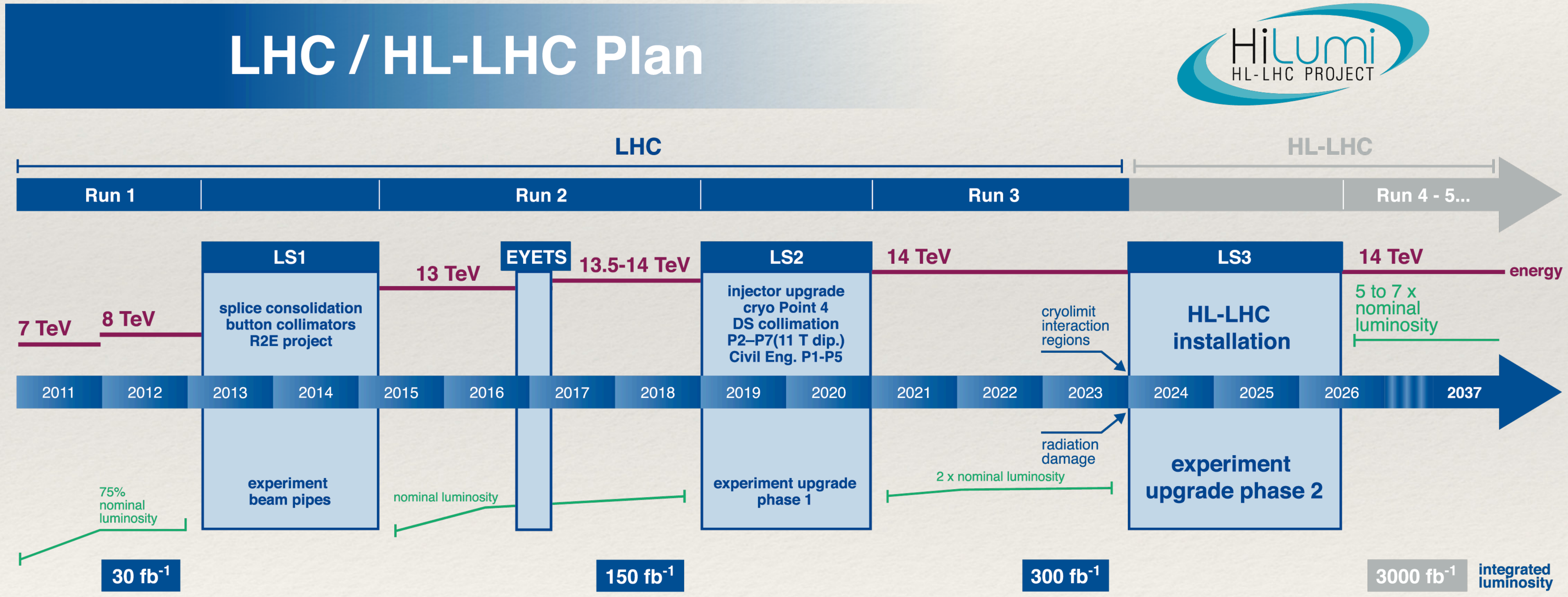
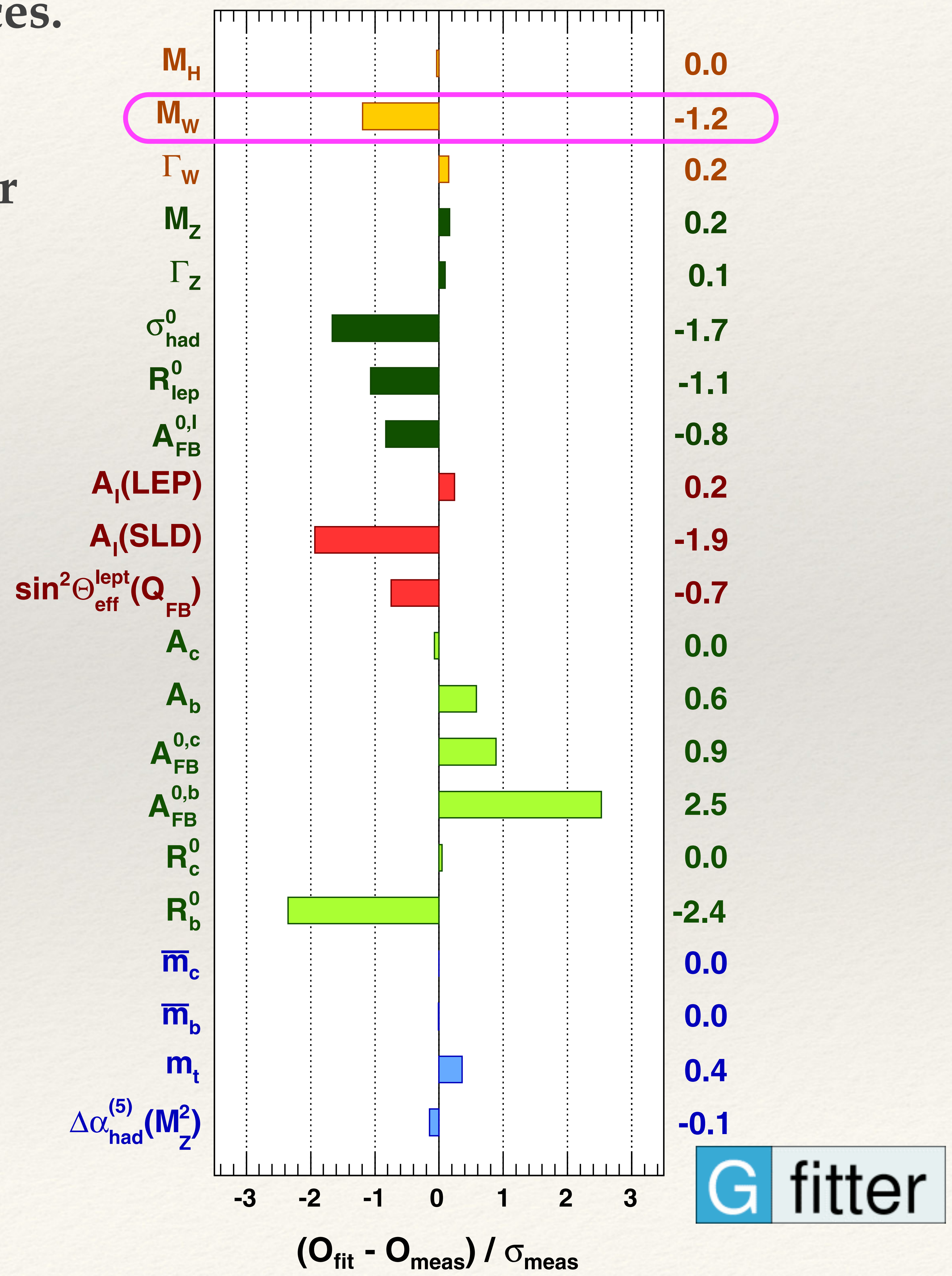
Precisely measure SM properties

- Precisely measure SM properties, compare with SM predictions, looking for differences.
- The differences can come from contributions of new particles.
- Given a particular new theoretical model, the difference can be translated to the upper limits of the new theory.



If LHC do not go above 14 TeV, SM precision measurements will also become more important programs at LHC!

Pull plot of SM global fit



The W mass measurements

- The Standard Model (SM) predicts a relationship between the W boson mass and other parameters of electroweak theory:

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\,\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

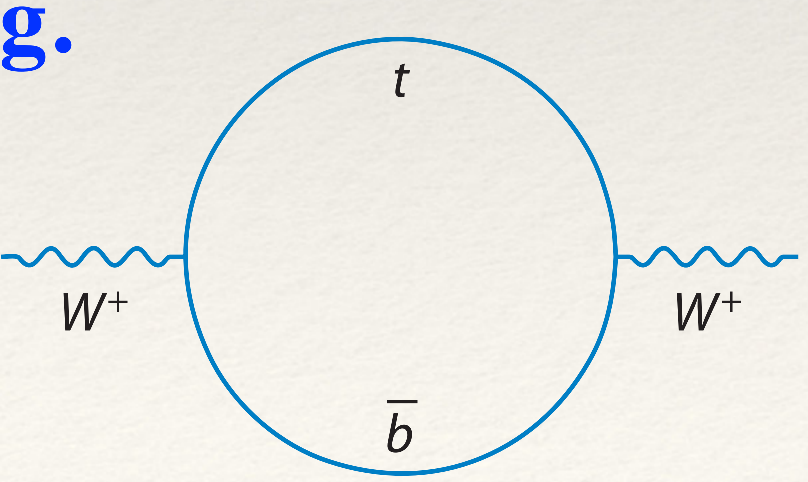
- Contributions to MW through radiative corrections **Δr**.

- Precisely test the electroweak theory at the loop level.
  - In case of SM, the precise W mass and top mass measurements can predict the SM Higgs boson mass.
  - By comparing the prediction and direct W mass measurement, we can know how good is the SM prediction. If disagreement is big, we can infer contributions from theories beyond SM

W mass related to Top quark mass:

$$\Delta r \propto M_t^2$$

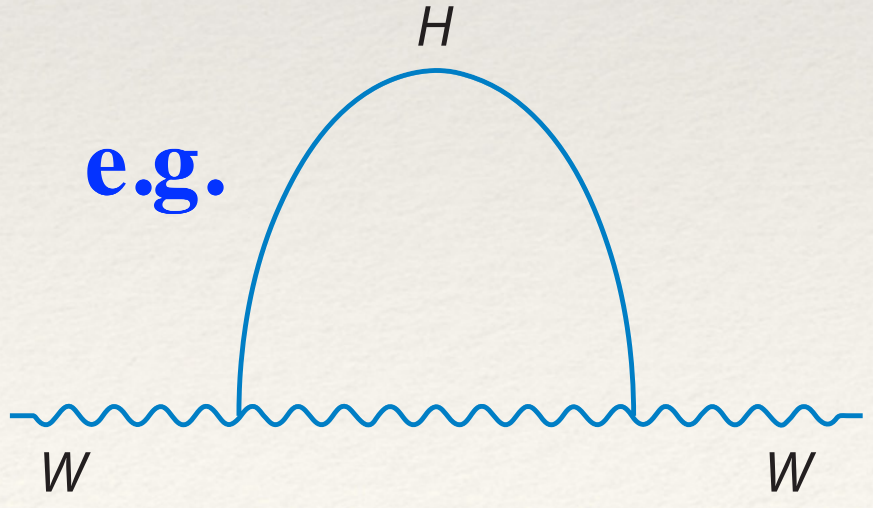
e.g.



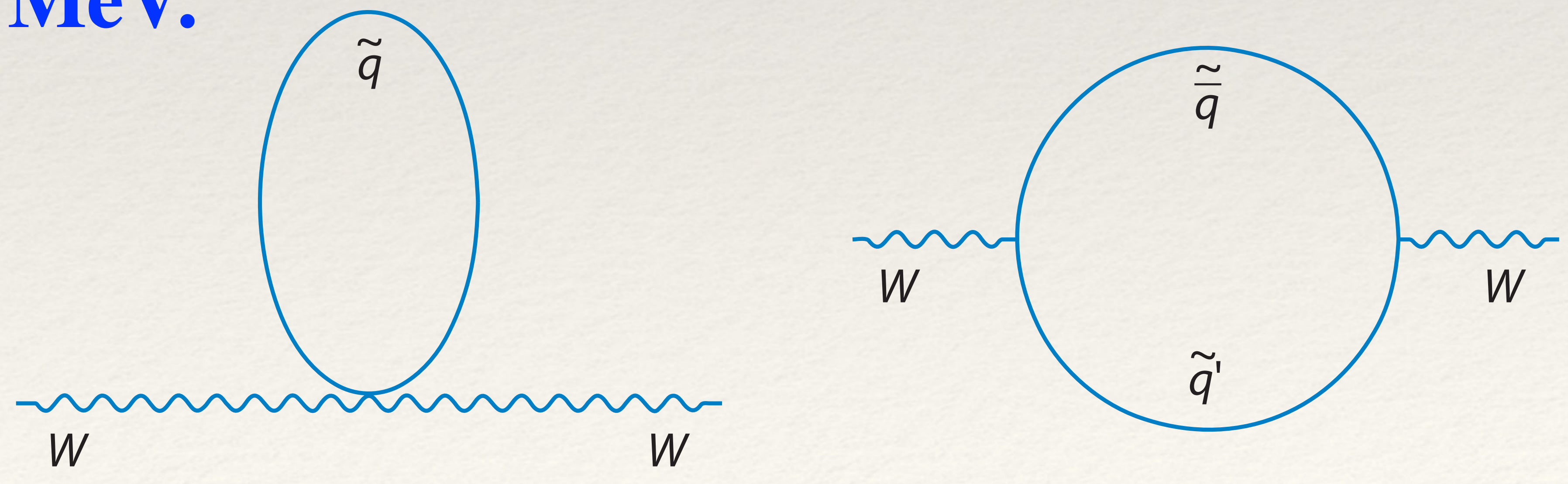
W mass related to SM Higgs mass:

$$\Delta r \propto \ln M_H$$

e.g.



Beyond SM, contribution from SUSY particles can induce a total radiative correction to M_W of 100 to 200 MeV.



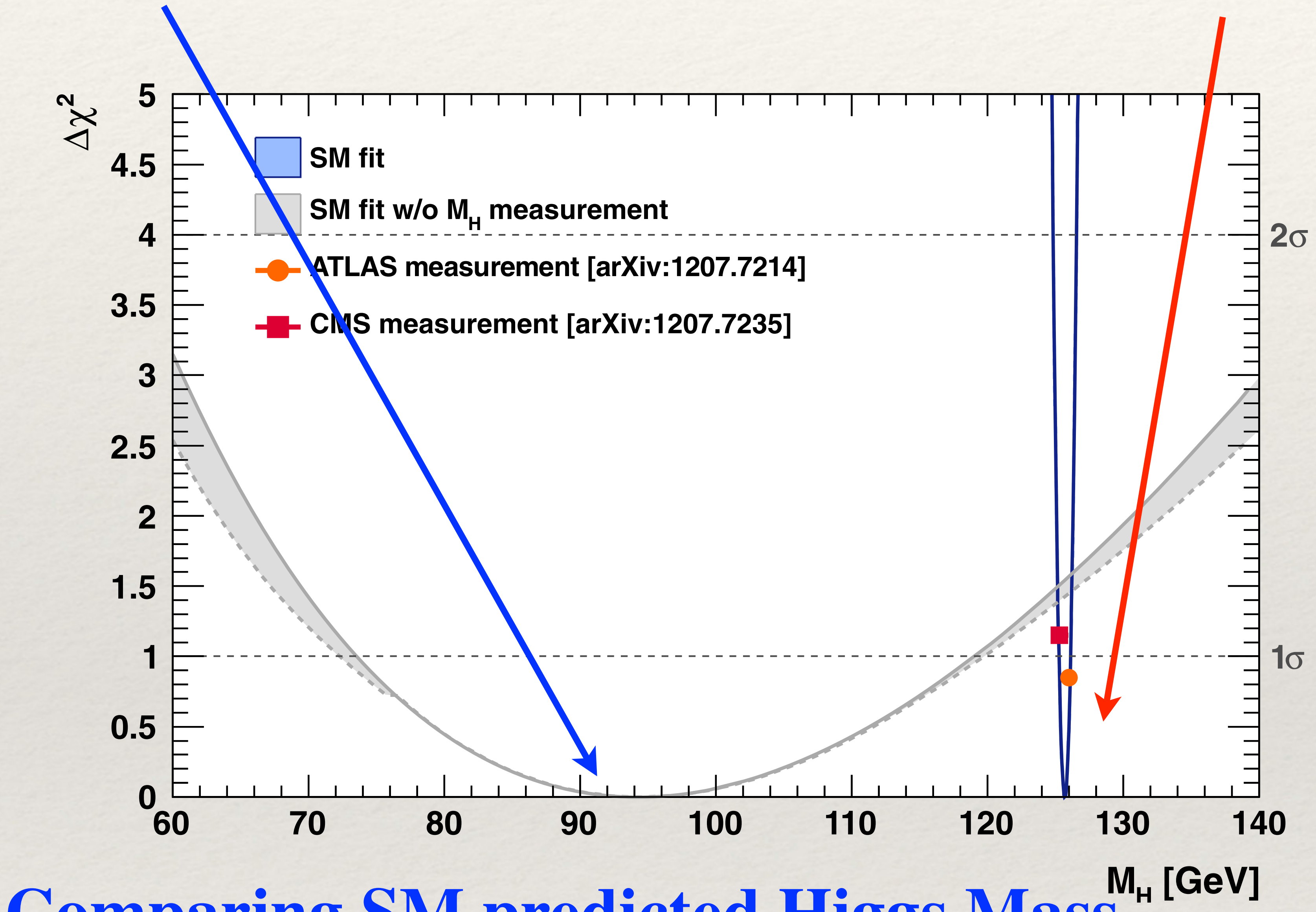
The W mass measurements

$M_H = 94\ \text{GeV}\,^{+25\ \text{GeV}}_{-22\ \text{GeV}}$

Predicted

$M_H = 125.7\ \text{GeV} \pm 0.4\ \text{GeV}$

Measured



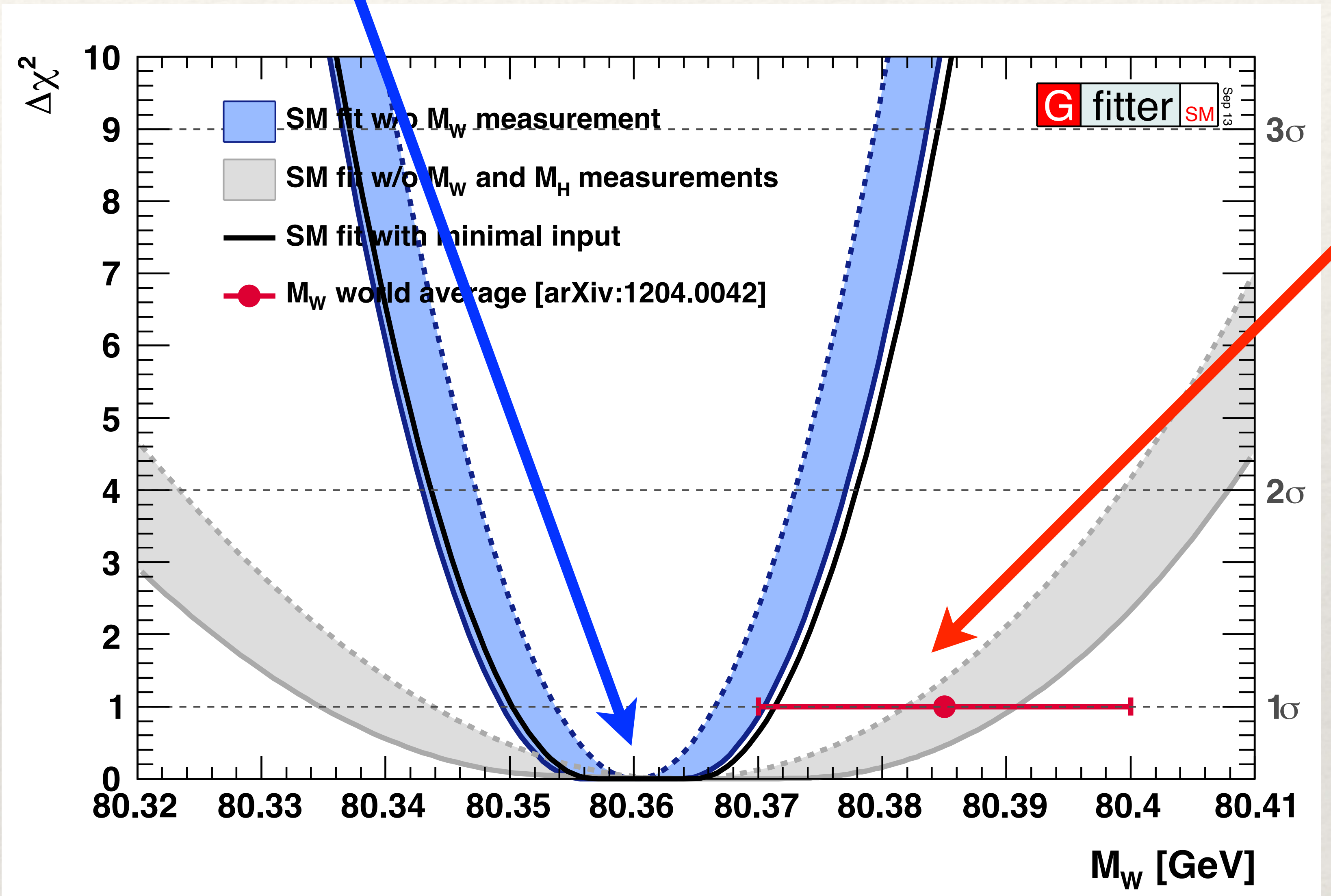
Comparing SM predicted Higgs Mass with directly measured value. A difference of ~1.3 sigma.

$M_W = 80356\ \text{MeV} \pm 8\ \text{MeV}$

Predicted

$M_W = 80385\ \text{MeV} \pm 15\ \text{MeV}$

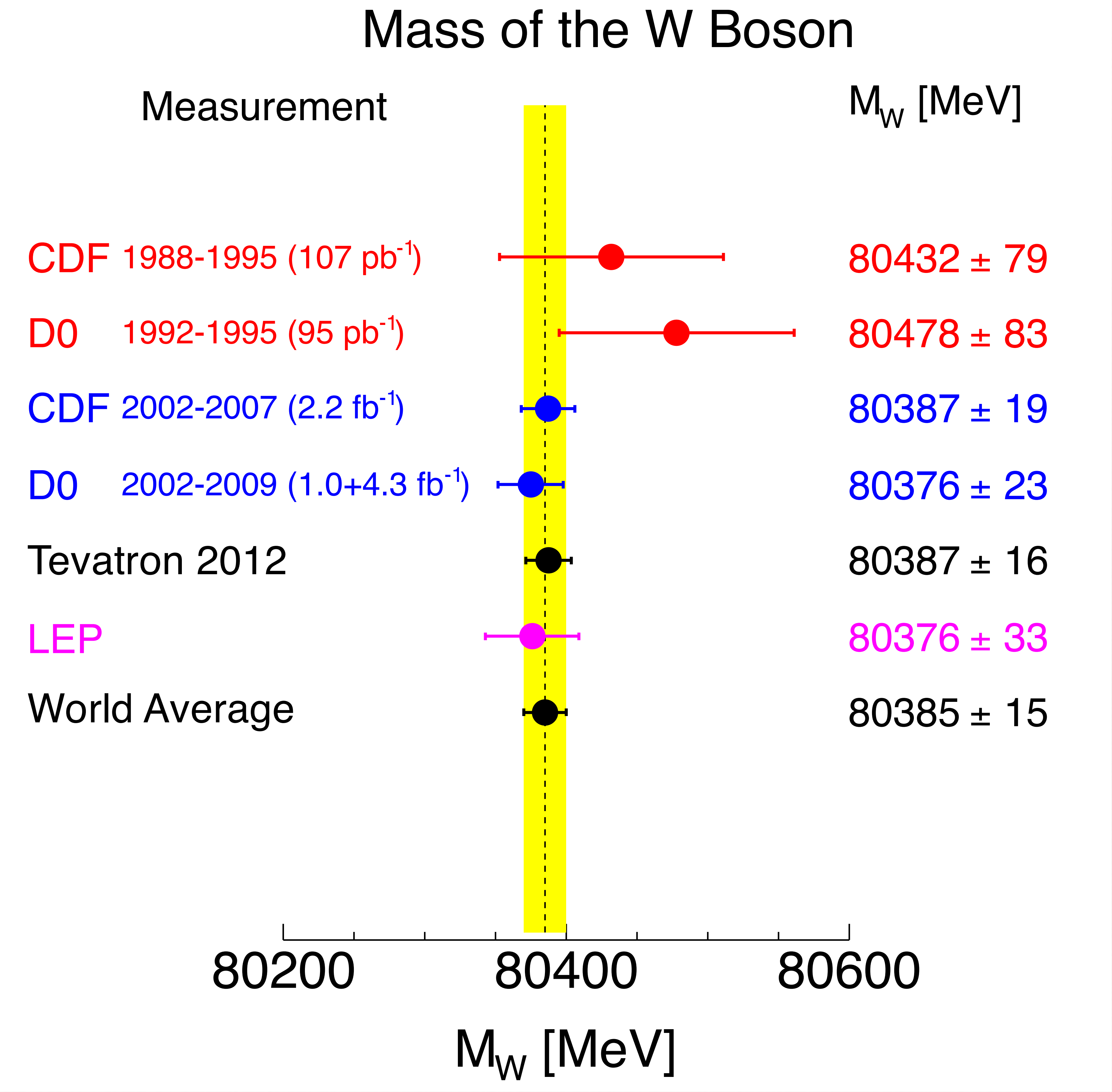
Measured

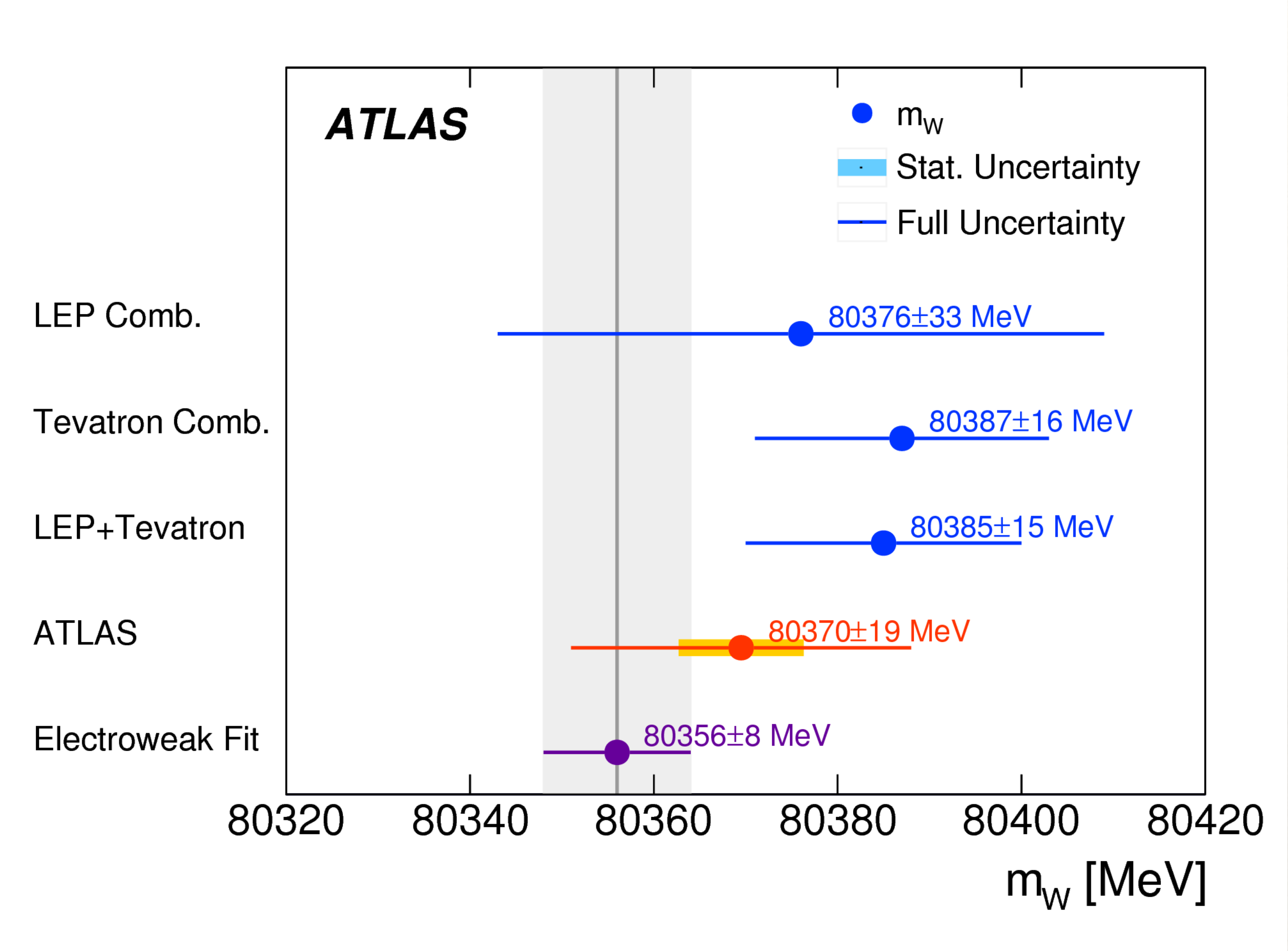


A ~1.3 sigma difference between the two M_W central values.

The difference can come from new particles interacting with the SM bosons (Higgs, W, Z).
Giving a particular new theoretical model, the difference can be translated to the upper limits of the new theory.

Current Results



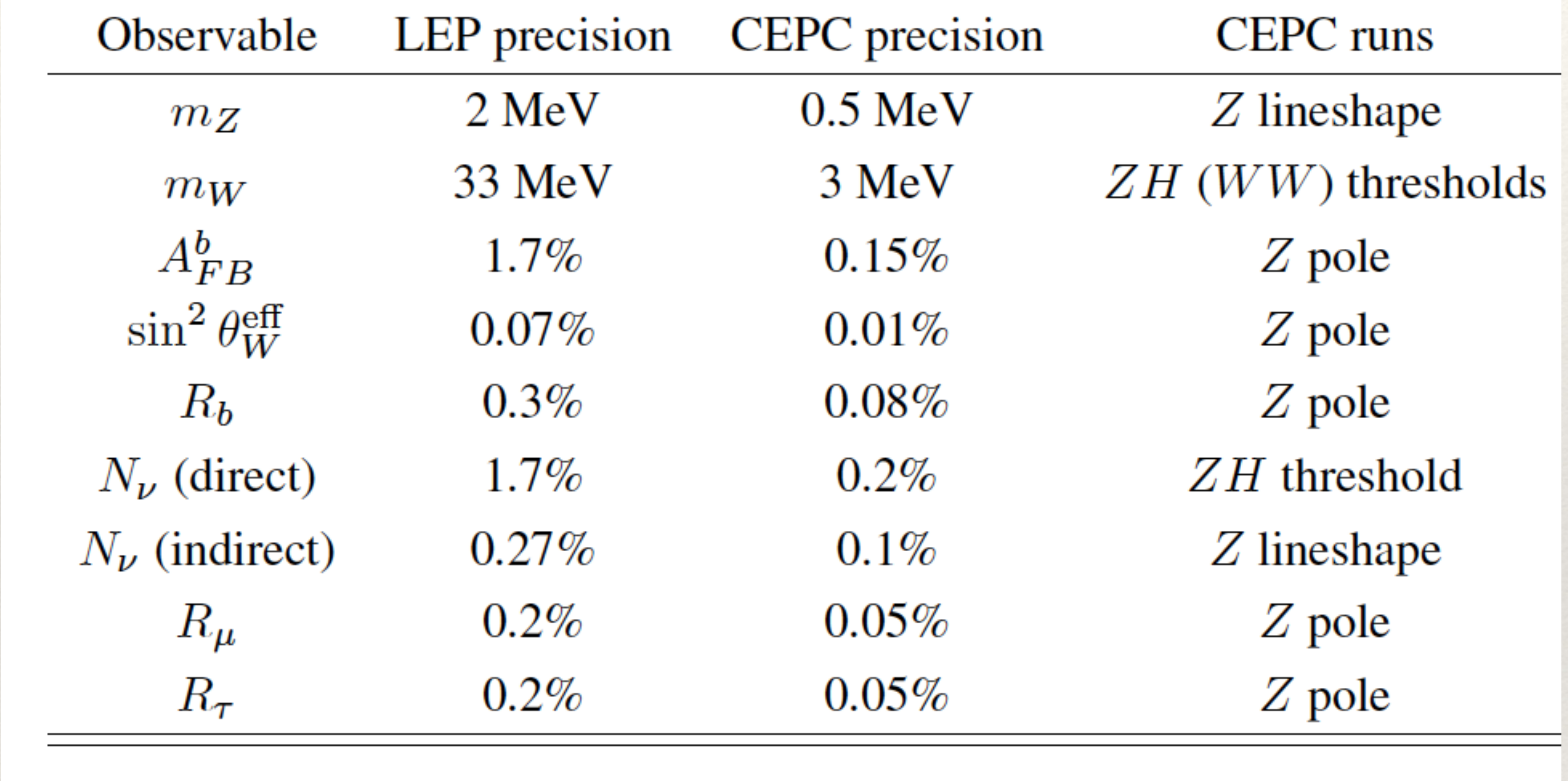


Including the new ATLAS results, the new world average should be around 80379 +- 12 MeV [Not official, based on self-running the combination codes.]

The CEPC efforts

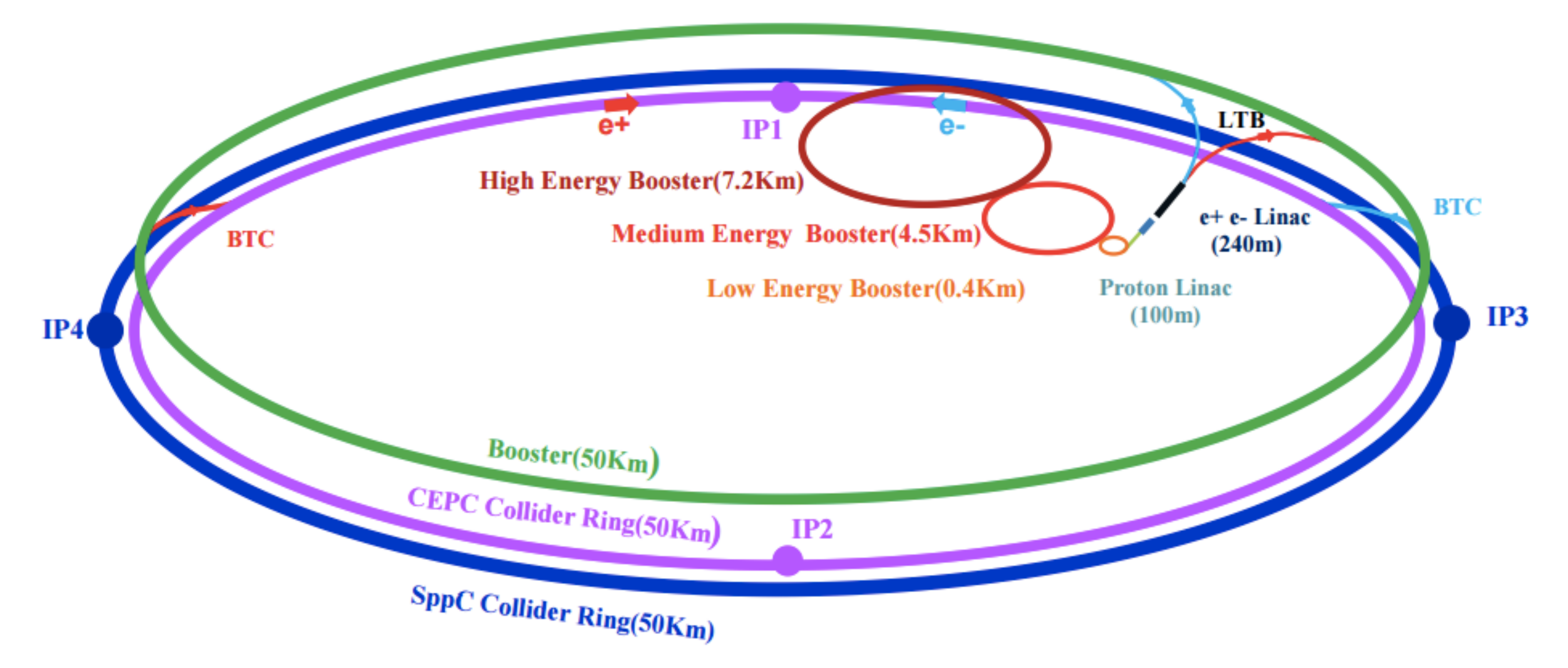
- **CEPC is an ideal instrument for EW precision measurements**

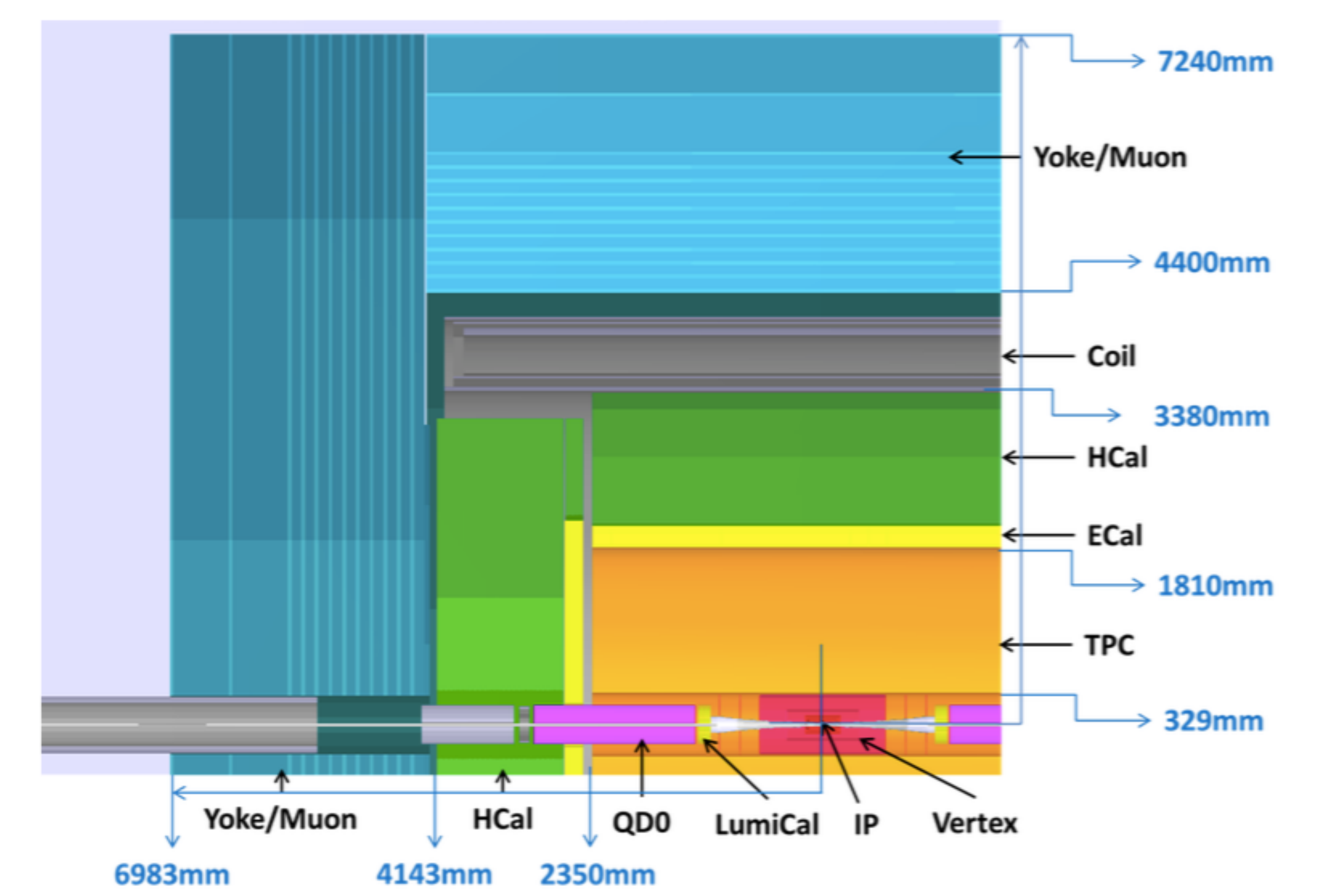
CEPC Pre-CDR



Observable	LEP precision	CEPC precision	CEPC runs
m_Z	2 MeV	0.5 MeV	Z lineshape
m_W	33 MeV	3 MeV	ZH (WW) thresholds
A^b_{FB}	1.7%	0.15%	Z pole
$\sin^2\theta^{\mathrm{eff}}_W$	0.07%	0.01%	Z pole
R_b	0.3%	0.08%	Z pole
N_ν (direct)	1.7%	0.2%	ZH threshold
N_ν (indirect)	0.27%	0.1%	Z lineshape
R_μ	0.2%	0.05%	Z pole
R_τ	0.2%	0.05%	Z pole

- **The goal for CEPC on W mass:**
  - **To reduce the world average uncertainty from current 15 MeV (12 MeV) to 2-3 MeV or even smaller**

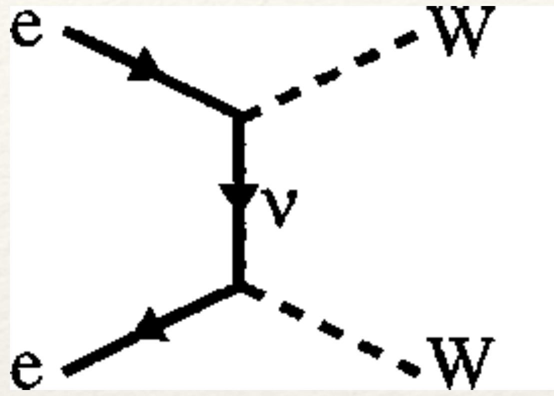




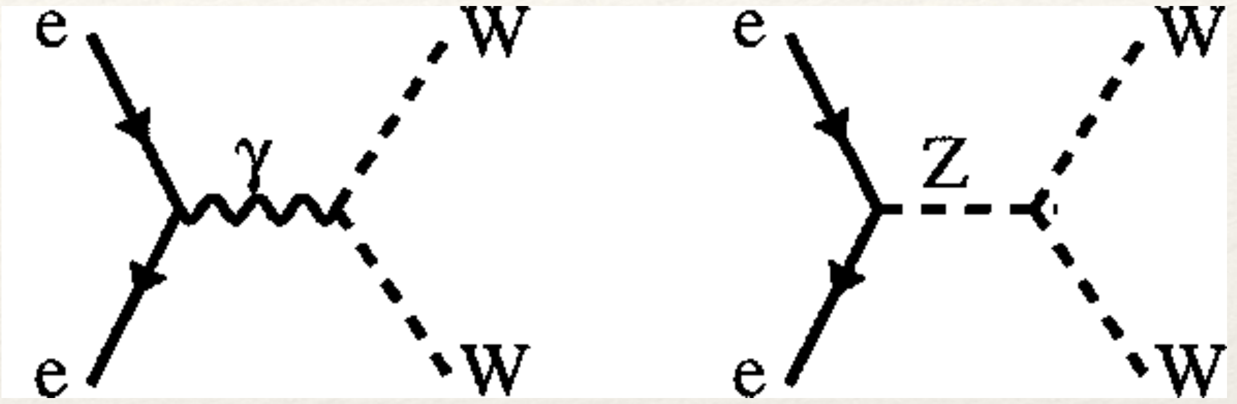
The CEPC efforts

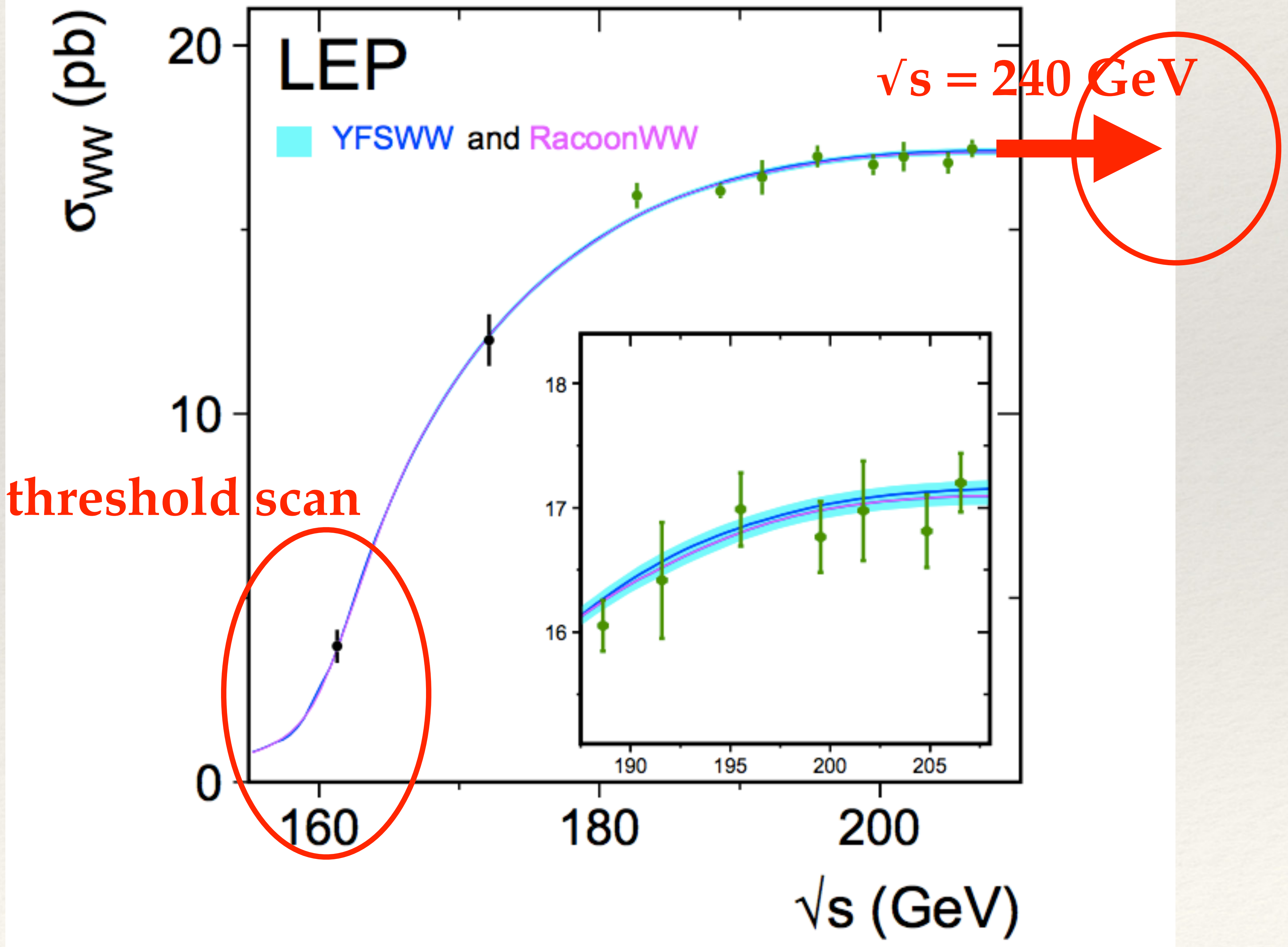
- Two methods, following LEP experiences:
  - Threshold scan:
    - Measure the W mass by measuring the WW cross-section
    - The cross-section is directly related to the W mass around WW threshold (~160 GeV)
  - Direct measurements
    - Directly reconstruct W boson decays: WW->lνqq, WW->qqqq
    - Compare data to MC with known W mass and width to extract the results: maximum likelihood fits to the data.

t-channel neutrino exchange



s-channel gamma/Z* exchange





direct measure

√s = 240 GeV

threshold scan

The threshold scan method

The threshold scan method

- Threshold scan:
  - Measure the W mass by measuring the WW cross-section
  - The cross-section is directly related to the W mass around WW threshold (~160 GeV):

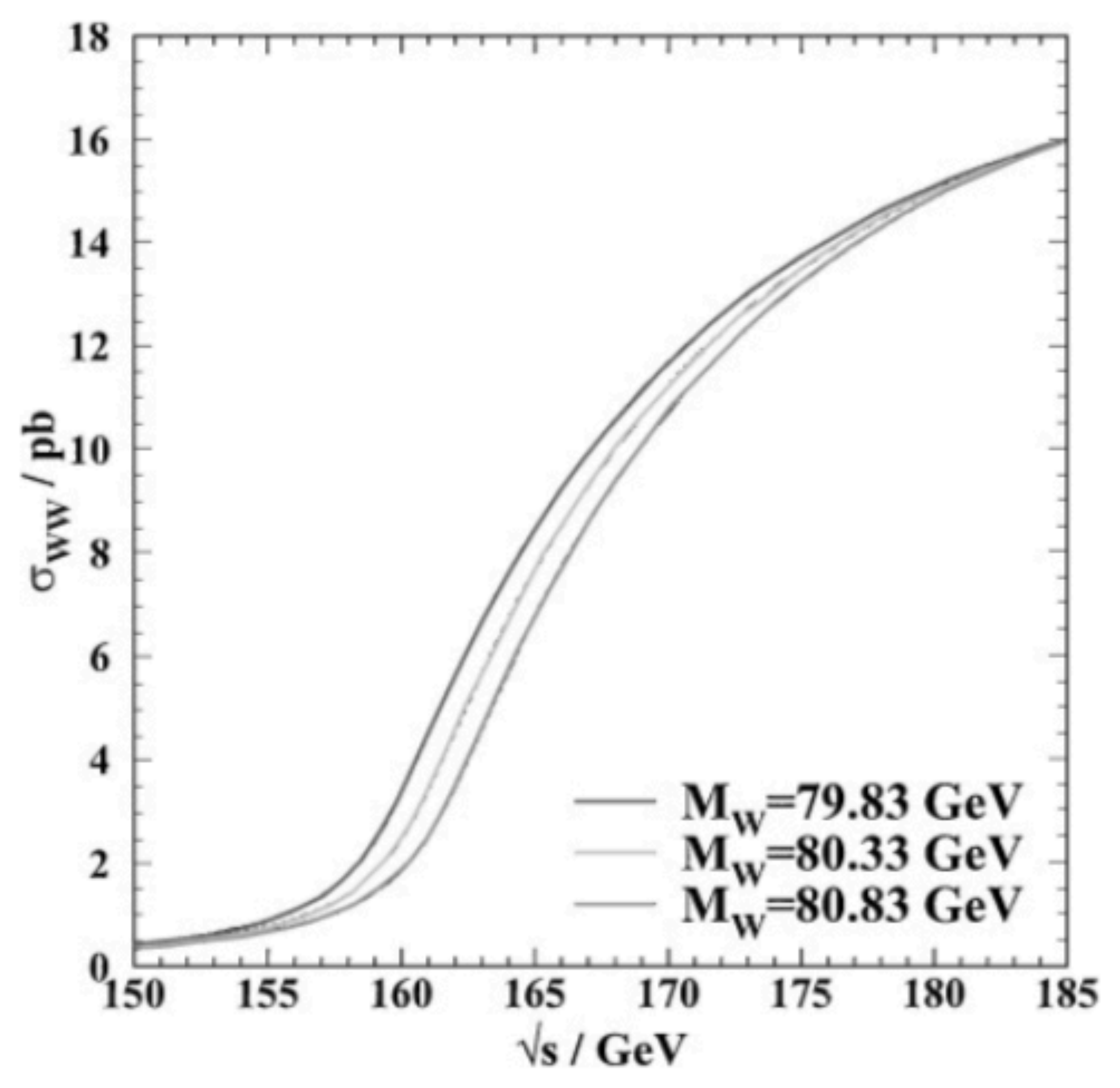
$$\sigma_{WW} \propto \beta = \sqrt{1 - 4m_W^2/s}$$

β: velocity of W boost

√s : center of mass energy

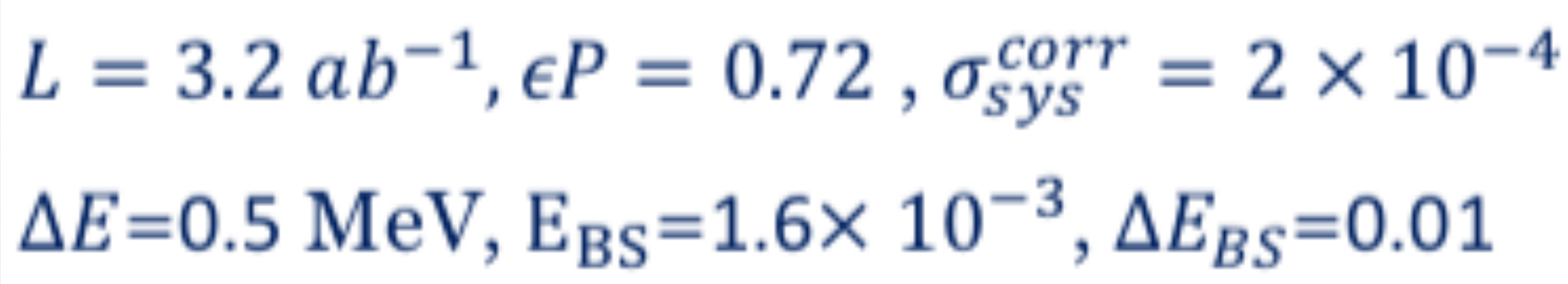
- Precision is limited by data statistics:
  - Other systematics such as hadronisation and fragmentation, radiative corrections, final state interactions are all negligible w.r.t. statistical uncert.
- Require high beam energy precision : 0.5 MeV
- Robust method, can achieve high precision, but:
  - Require dedicated runs at WW threshold.

The cross-sections curves are significantly separated for different W mass values at the WW threshold



Data taking scheme

- Only measure W mass? Or both W mass and width?
  - Measure only the W mass: One √s scan point is sufficient
  - Measure both the W mass and W width: At least 2 √s scan points
- A detailed data taking scheme has been studied:
  - Assuming:



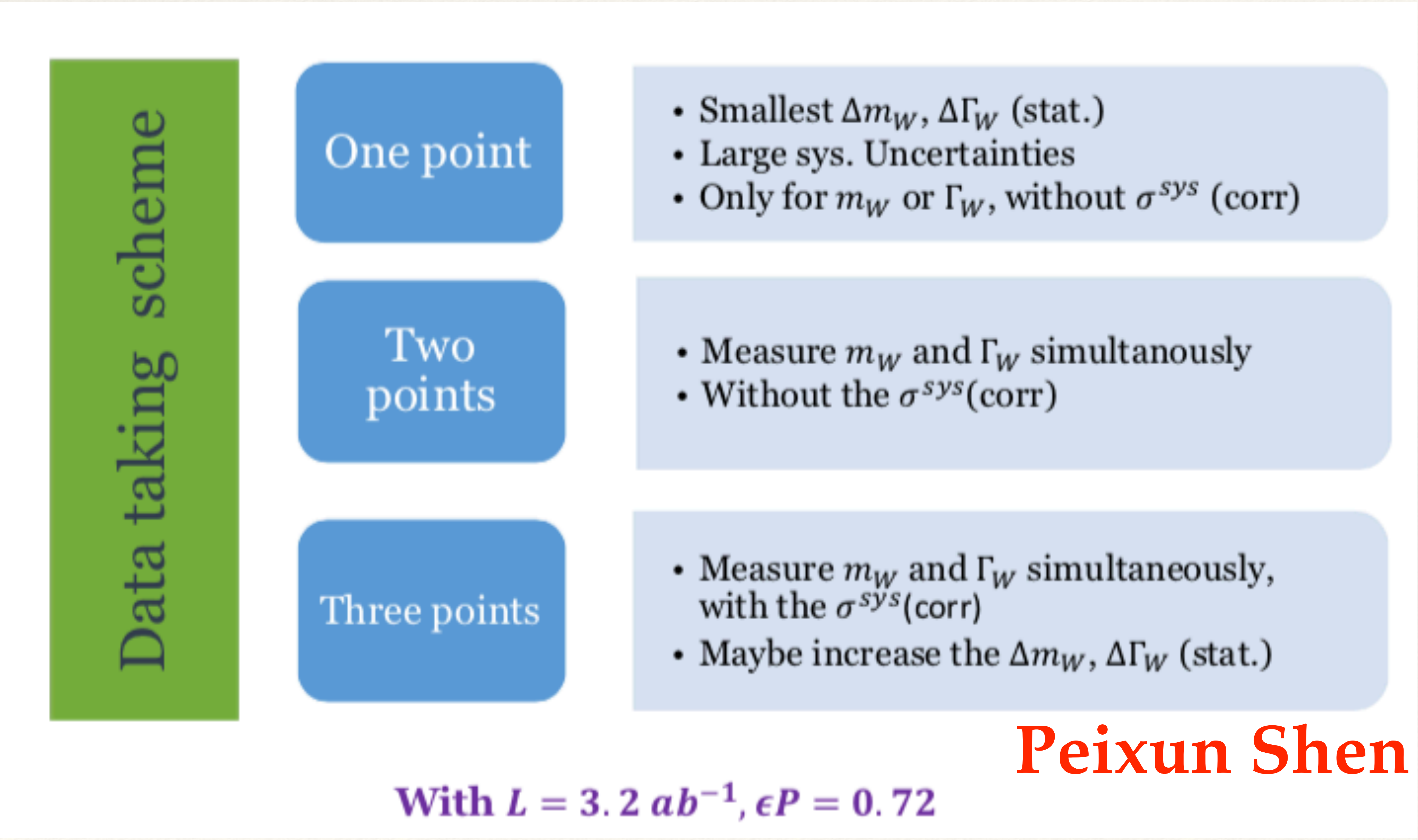
$L = 3.2\ ab^{-1}, \epsilon P = 0.72\ , \sigma_{sys}^{corr} = 2 \times 10^{-4}$

ΔE=0.5 MeV, E_{BS}=1.6× 10^{-3}, ΔE_{BS}=0.01

  - Evaluated up to 3 √s scan points
  - Based on GENTLE package, including ISR, EW, QCD corrections.
  - Considering both statistical uncert. and systematic uncert. (and their correlations).

Data taking scheme/Expected precision

- A summary of the conclusions:
  - Detailed studies are reported in dedicated talk by Peixun.



Data taking scheme

One point
- Smallest Δm_W, $\Delta\Gamma_W$ (stat.)
- Large sys. Uncertainties
- Only for m_W or Γ_W, without σ^{sys} (corr)

Two points
- Measure m_W and Γ_W simultanously
- Without the σ^{sys}(corr)

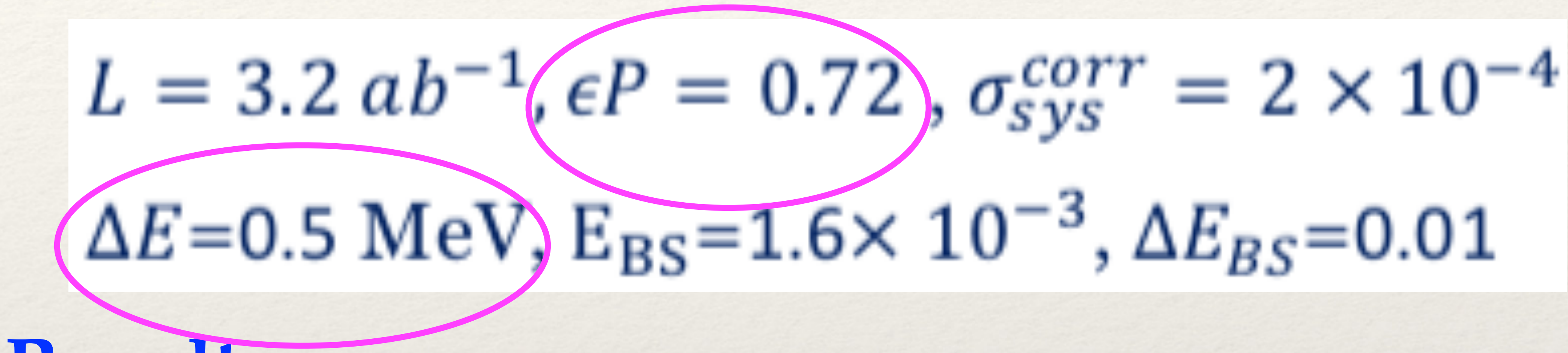
Three points
- Measure m_W and Γ_W simultaneously, with the σ^{sys}(corr)
- Maybe increase the Δm_W, $\Delta\Gamma_W$ (stat.)

Peixun Shen

With $L = 3.2\ ab^{-1}$, $\epsilon P = 0.72$

Assuming:

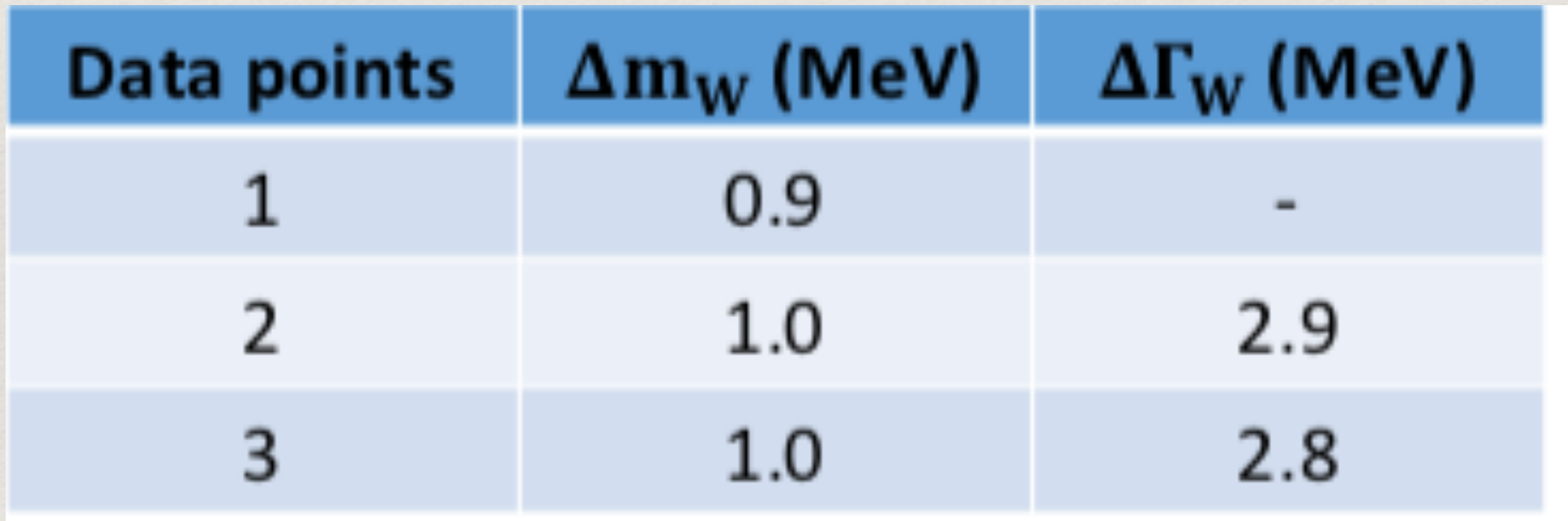
$$\delta M_W = \sqrt{\sigma_{WW}}\left|\frac{\partial M_W}{\partial \sigma_{WW}}\right|\frac{1}{\sqrt{L\epsilon P}}$$



$L = 3.2\ ab^{-1}$, $\epsilon P = 0.72$, $\sigma_{sys}^{corr} = 2\times10^{-4}$

ΔE=0.5 MeV, $\mathrm{E_{BS}}$=1.6× 10^{-3}, ΔE_{BS}=0.01

Results:



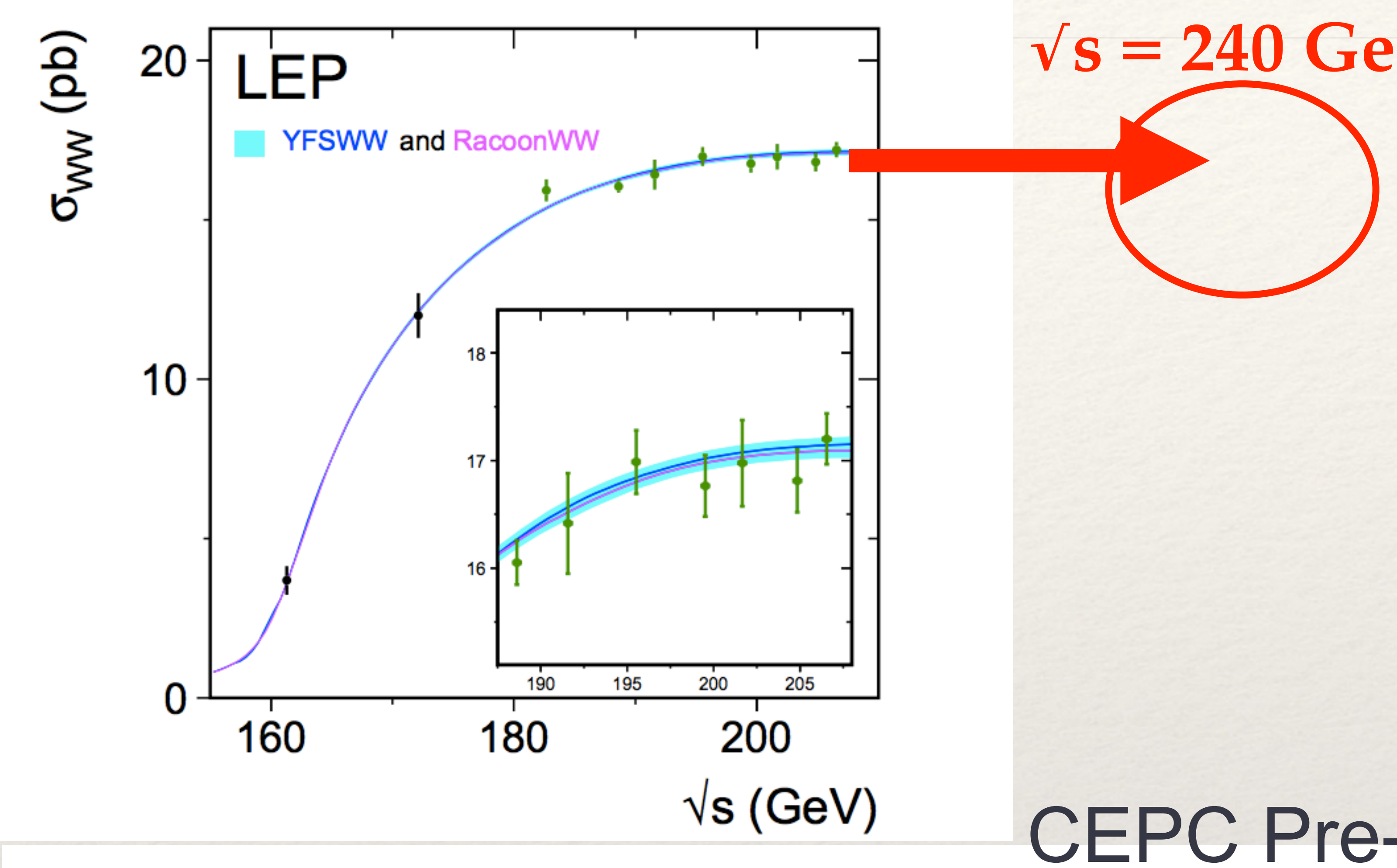
Data points	Δm_W (MeV)	$\Delta\Gamma_W$ (MeV)
1	0.9	-
2	1.0	2.9
3	1.0	2.8

- Beam energy uncertainty is an essential contribution to the precision
- High efficiency and purity is a key factor to have high precision

Direct reconstruction of M_W

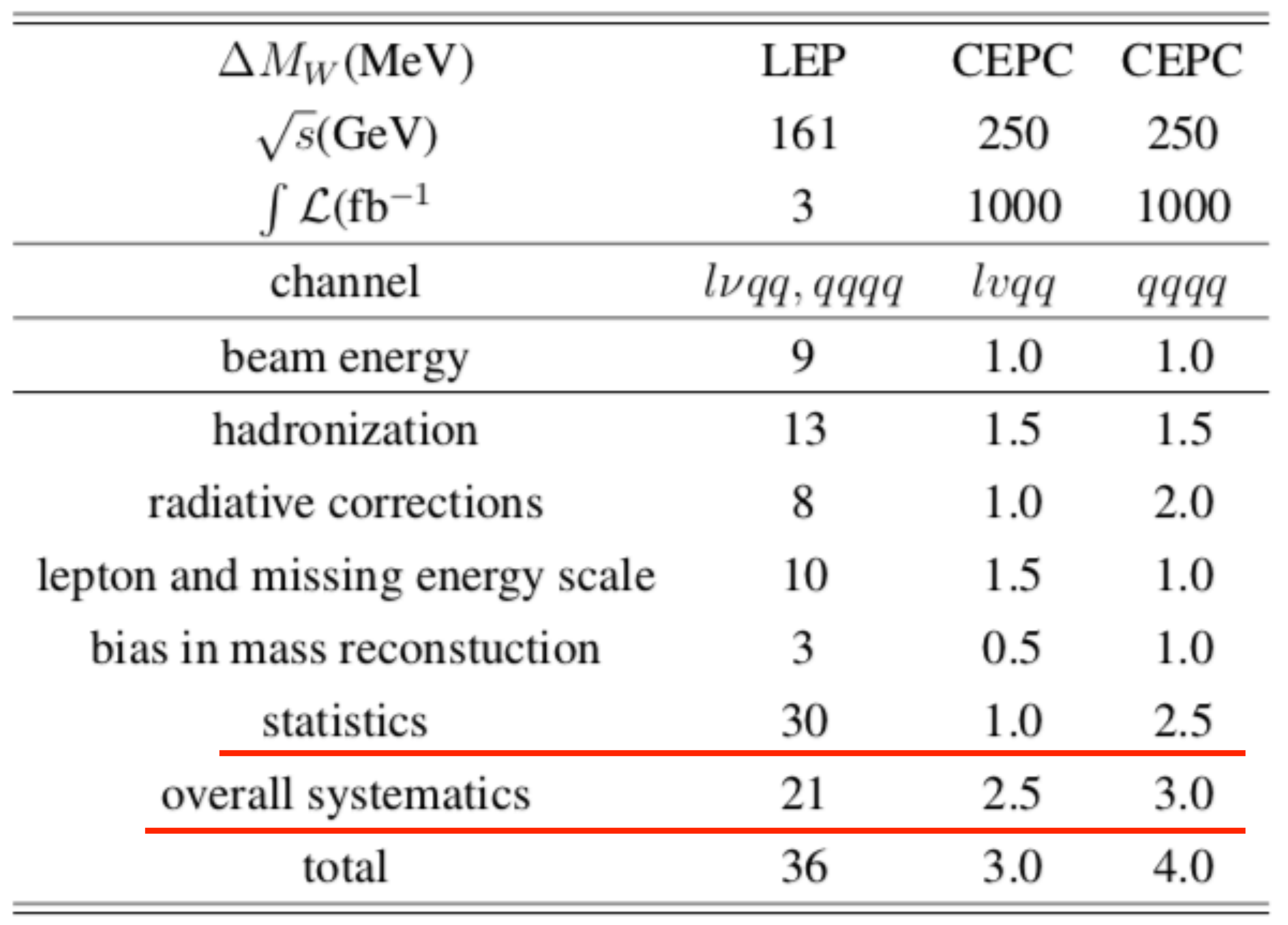
Direct reconstruction of M_W

- Direct measurements
  - Directly reconstruct W boson decays: WW->lνqq, WW->qqqq
  - Compare data to MC with known W mass and width to extract the results: Unbinned maximum likelihood fits to the data.
- Do not need dedicated runs at WW threshold
- Measurements using ZH runs at √s = 240 GeV
  - Big statistics: 1000 fb-1 (vs. 3.2 ab-1 for WW threshold scan)
- Lower requirements on beam energy uncertainty
- But a much complicated analysis:
  - A full reconstruction of the W boson
  - All sorts of systematic uncertainties need to be understood and they are big!



direct measure
√s = 240 GeV

CEPC Pre-CDR

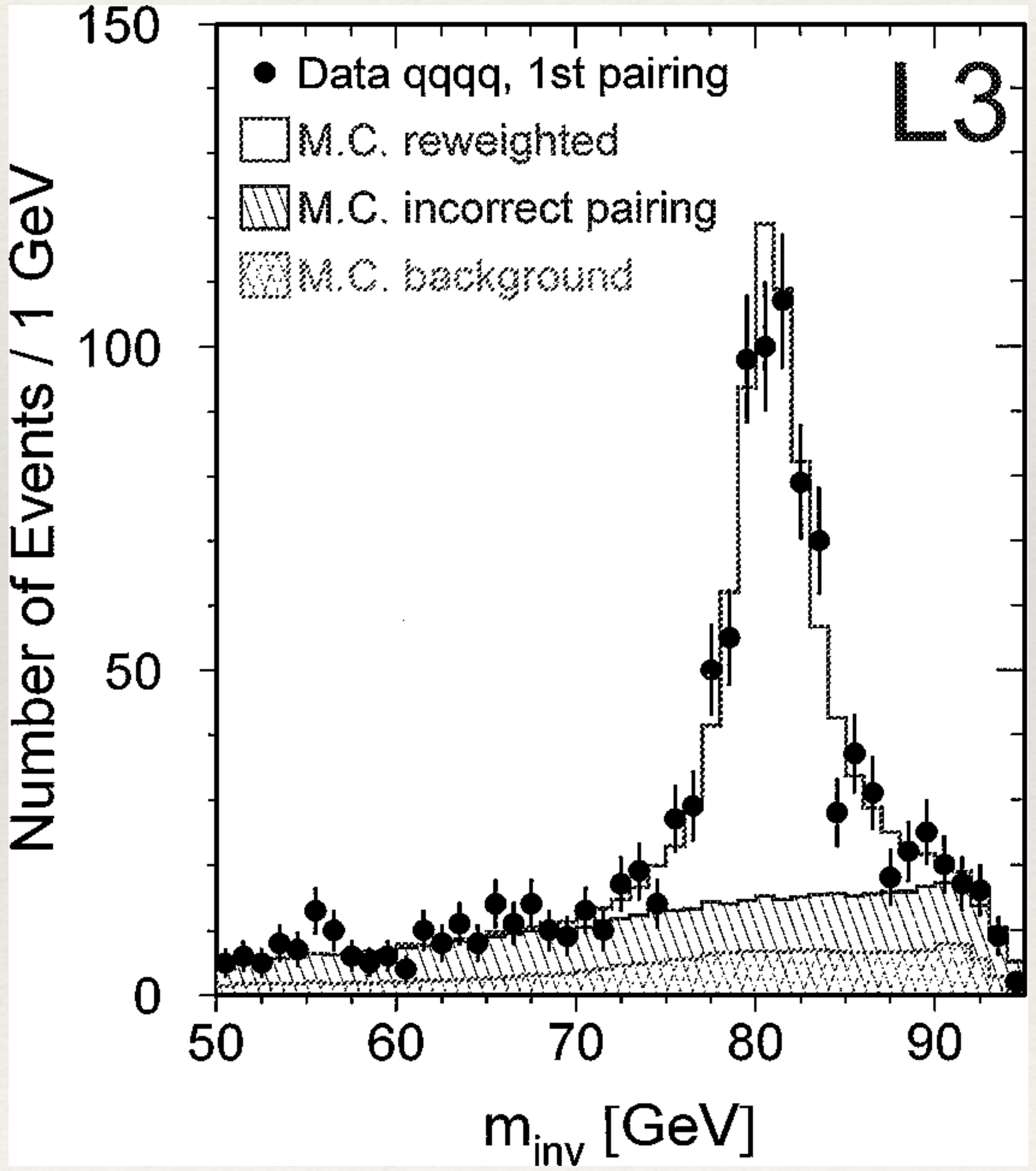


ΔM_W(MeV)	LEP	CEPC	CEPC
$\sqrt{s}$(GeV)	161	250	250
$\int \mathcal{L}$(fb^{-1}	3	1000	1000
channel	$l\nu qq, qqqq$	$l\nu qq$	$qqqq$
beam energy	9	1.0	1.0
hadronization	13	1.5	1.5
radiative corrections	8	1.0	2.0
lepton and missing energy scale	10	1.5	1.0
bias in mass reconstuction	3	0.5	1.0
statistics	30	1.0	2.5
overall systematics	21	2.5	3.0
total	36	3.0	4.0

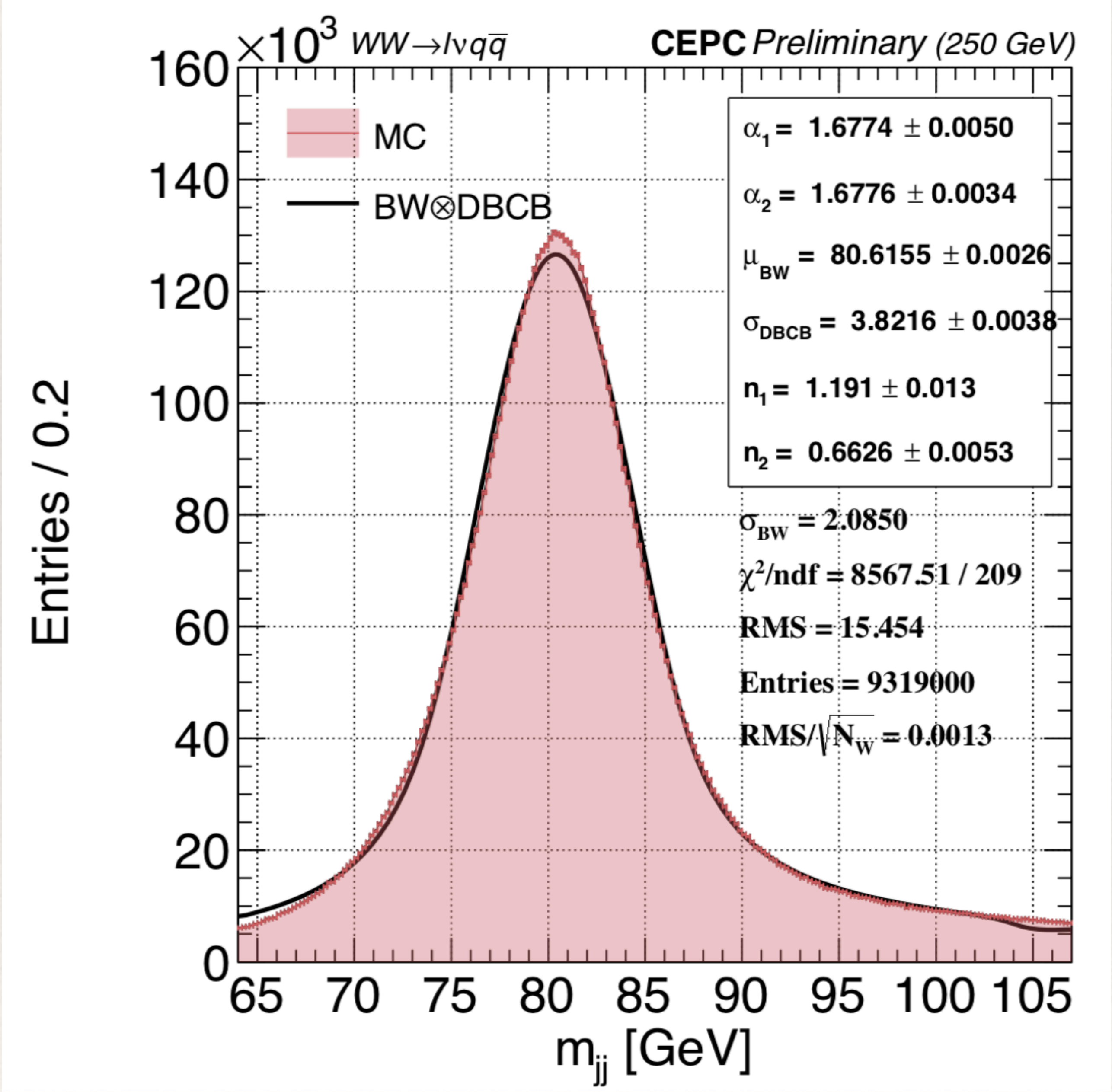
Mass Reconstruction

- Reconstruct the W boson invariant mass directly from the W decay products
- For WW->lνqq
  - A 2-jet pair, and a lepton + MET
- For WW->qqqq
  - Complicated by combinatorial ambiguities of jet pairing from two W decays.
    - W mass value can be used as an estimator to find the best combination
    - Remaining incorrect pairing treated as background (10 - 15% for LEP experiments)

WW->qqqq

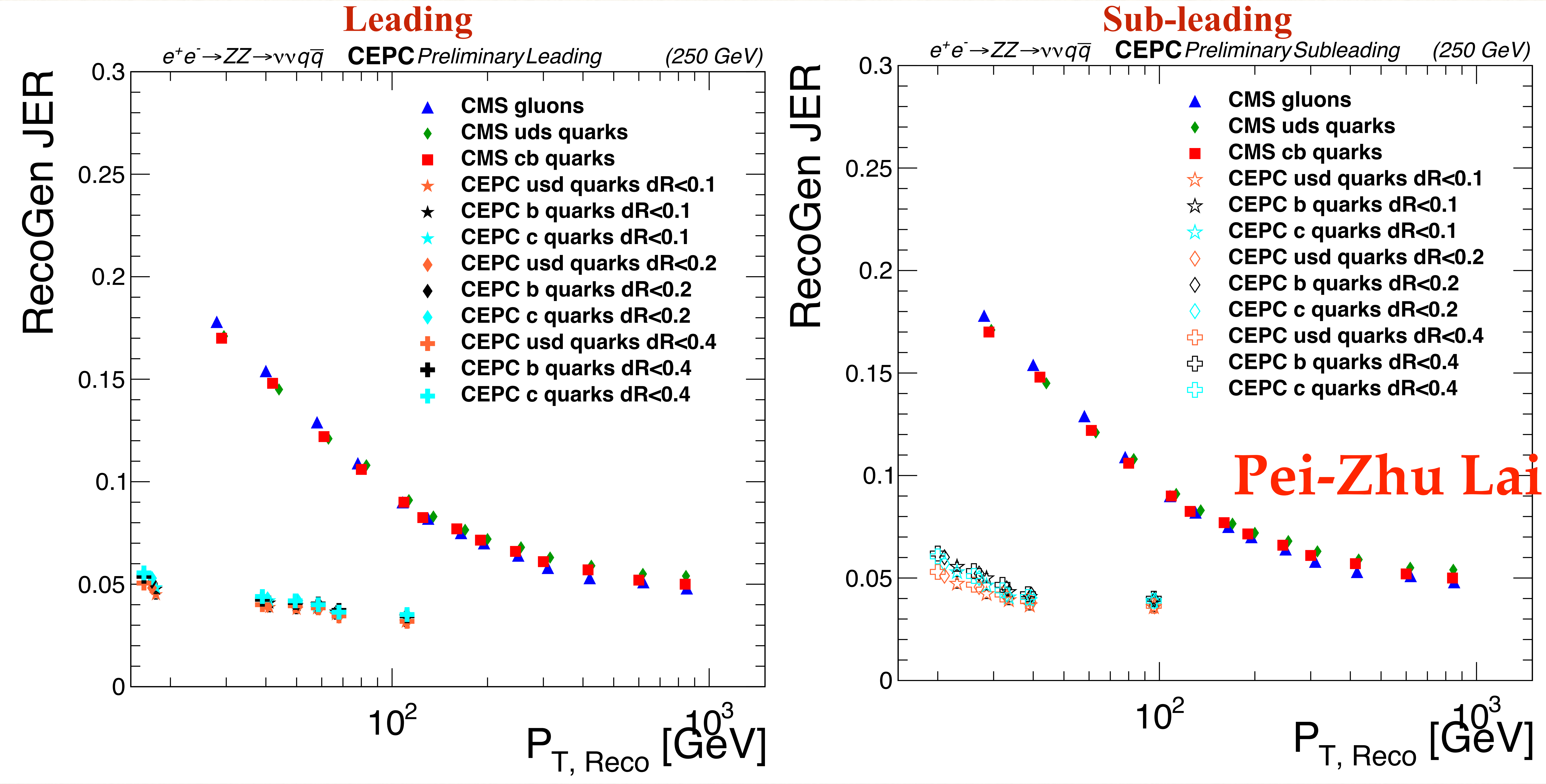


WW->lνqq



Pei-Zhu Lai

Jet Energy Resolution



- **Not a fair comparison, i.e. LHC has huge pileups, but it clearly shows the cleanness of the CEPC environment!**

Kinematic Fit

- **Di-jet mass resolution is mainly determined by the precision of jet energy reconstruction.**
- **Kinematic constraints can substantially improve the mass resolution**
- **Energy and momentum conservation:**
  - **with known CEPC center-of-mass energy**
  - **total momentum equals zero**
- **LEP experiments show a 50% to 80% improvements of the di-jet mass resolution!**
  - **before kin-fit: 8 - 9 GeV**
  - **after kin-fit: 2.9 GeV for lνqq; 1.7 GeV for qqqq**

- **For WW->qqqq:**
  - **4-C (constraints) fit:**
    - **both energy and momentum conservation**
    - **yields two reco. masses (M_{rec1}, M_{rec2})**
  - **or 5-C fit:**
    - **4-C + requirement of $M_{rec1} = M_{rec2}$**
    - **yields one reco. mass**
- **For WW->lνqq:**
  - **2-C fit:**
    - **because the neutrino from leptonic W decay removes 3 degrees of freedom.**

Extracting W mass and width

- Using reco. W boson invariant mass, two methods can be used to extract the W mass and width results:
  - Monte-Carlo reweighting and Convolution method.
- Monte-Carlo reweighting (templates fit):
  - Compare data W inv. mass spectrum to MC spectra (templates) corresponding to different values of true W mass.
  - Using a maximum likelihood method to find the best match ==> gives the W mass and width results.
  - Very straight-forward to operate:
    - All systematic effects are implicitly included in the MC templates.
      - such as detector resolution, ISR, selection efficiency, etc.
  - used by ALEPH, L3, OPAL, D0, CDF, ATLAS

Extracting W mass and width

- **Convolution method (Sig.+bkg. line shape fit):**
  - **Construct signal PDF:**

$$P_s(m_W, \Gamma_W, m_{i,\mathrm{rec}}) = S(m_W, \Gamma_W, m_i, s') \otimes ISR(s', s) \otimes R(m_i, m_{i,\mathrm{rec}}).$$

  - **where, S is the true mass distribution, ISR is radiation function, and R is the detector resolution function.**
  - **Fit S+B function to the data spectrum to extract the W mass and width**

$$f_s P_s(m_W, \Gamma_W, m_{i,\mathrm{rec}}) + f_b P_b(m_{i,\mathrm{rec}})$$

  - **Easier to understand, but require various approximations/assumptions (e.g. resolution often assumed to be Gaussian), additional systematic due to choice of fitting function needs to be considered**
  - **Used by DELPHI**

Systematic Uncertainties

- The major systematic uncert. of a "typical" LEP experiment is shown on the right side.
- ISR, fragmentation, four-fermion interference:
    - limited by MC statistics used to determine them.
- "Fit procedure" includes selection efficiencies and accepted backgrounds.
- "Detector effects" (biggest for lνqq):
    - energy scales, resolutions, modelings, etc.
- Color-Reconnection and Bose-Einstein correlation (CR/BE), largest for qqqq:
    - Quarks from the two Ws can "talk" to each other: W decay distance $1/\Gamma_W$ ~ 0.1 fm is much smaller than fragmentation radius $1/\lambda_{QCD}$ ~ 1 fm
    - Differences from different theory models are quoted, and they are big. ==> do we have better models nowadays?

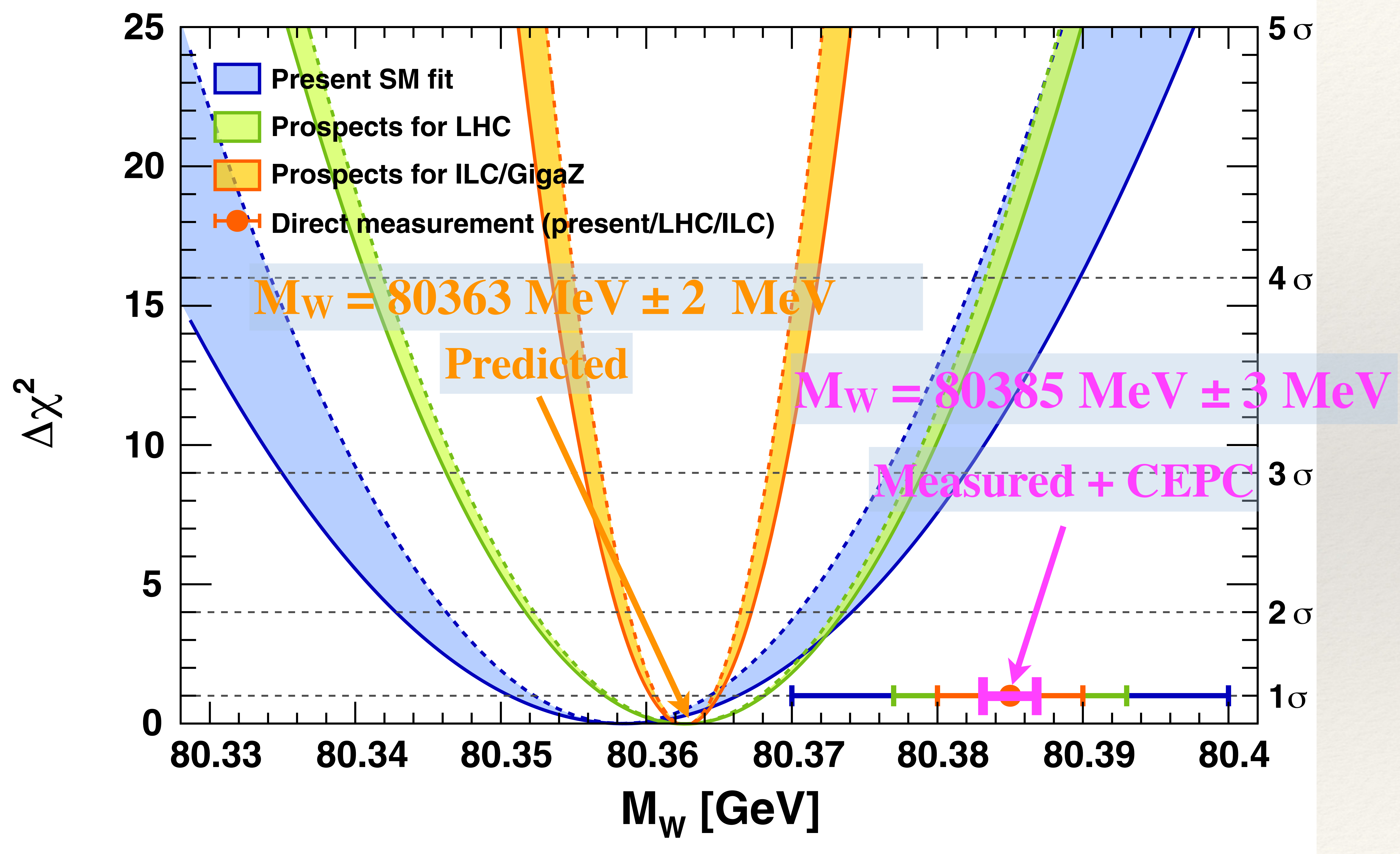
Systematic uncertainties on W mass from direct reconstruction for a "typical" LEP experiment

	Uncertainty (MeV)	
Systematic	$q\bar{q}\ell\bar{\nu}$	$q\bar{q}q\bar{q}$
Initial-state radiation	10	10
Four-fermion	10	10
Fragmentation	25	30
Detector effects	30	30
Fit procedure	20	20
Subtotal	46	49
Beam energy	17	17
CR/BE	—	60
Total	49	79

Douglas A. Glenzinski Ulrich Heintz
Annu. Rev. Nucl. Part. Sci. 2000. 50:207–48

Expectation in the future

Future with CEPC contribution



- Borrow the figure from GFitter for LHC+ILC:
  - Assume ILC gives similar improvements as CEPC on the "predicted values"
  - Assume the directly measured central value does not change in the future
- **A possible 4 to 5-sigma "bug" can be found in SM with the CEPC efforts!!!**

People Working on this project

- PhD Students, and who are practically working:
  - Peixun Shen (Nankai U.), Pei-Zhu Lai (NCU)
- Supervisors, Conveners, Experts, who are contributing ideas and mentoring:
  - Gang Li (IHEP), Zhijun Liang (IHEP), Manqi Ruan (IHEP), Bo Liu (IHEP), Chai-Ming Kuo (NCU), Maarten Boonekamp (CEA Saclay), Hengne Li (SCNU/UVa)
- **Welcome more collaborators contributing to this exciting project!**