Standard Model and Beyond

Kiwoon Choi

The IBS Center for Theoretical Physics of the Universe, South Korea

ib**S** Institute for
Basic Science

Outline

 * Where are we now?

* Precision BEH boson physics for singlet-extended SUSY

(NMSSM, μνSSM, nMSSM, S-MSSM, ...)

* New approach for the precision measurement of

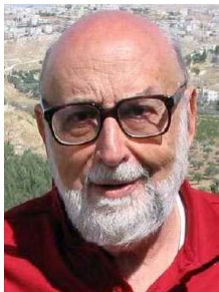the W boson and top quark masses

With the discovery of the Brout-Englert-Higgs (BEH) boson by the ATLAS & CMS, the Standard Model (SM) of particle physics is completed!
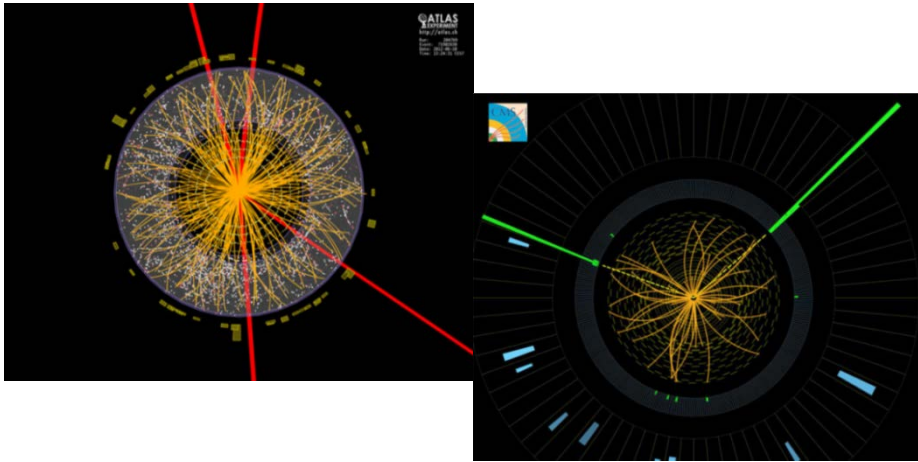
Here, at last!

➔

Nobel Prize in Physics 2013

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

This is indeed a tremendous achievement of the LHC Run 1, although we couldn't see yet any sign of new physics in the data.

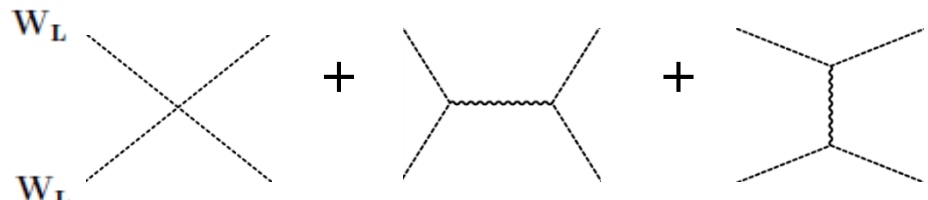The SM can work in principle up to high scales near the Planck scale.

The existing observational evidences for new physics (ν-mass, dark matter, baryon asymmetry, inflation) also do not clearly tell us where is the next scale.

So the next scale of new physics can be anywhere in between the LHC scale **(TeV)** and very high scales **($10^{12} - 10^{15}$ TeV)** near the Planck scale.

This is in contrast to the past, in which our theory always showed a clear indication of nearby new physics scale.

* Massive weak gauge bosons without the BEH boson

$$\mathcal{L}_{W_L/Z_L} = \left(1 + \frac{\theta^2}{v^2} + ...\right) D_\mu \theta D^\mu \theta \quad \left(\partial^\mu \theta = W_L^\mu, Z_L^\mu, \; v = 174 \text{ GeV} \sim \frac{M_{W,Z}}{g_{1,2}}\right)$$
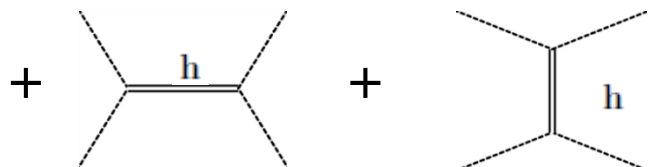

$$\mathcal{A} \sim \frac{E^2}{v^2} \leq 16\pi$$

(Unitarity Bound)

➔   New physics at $E \leq 4\sqrt{\pi} v \sim 1 \text{ TeV}$

$$\mathcal{L}_{BEH} = D_\mu \phi^\dagger D^\mu \phi = \left(1 + \frac{h}{v}\right)^2 \left(1 + \frac{\theta^2}{v^2} + ...\right) D_\mu \theta D^\mu \theta + \frac{1}{2}\partial_\mu h \partial^\mu h$$
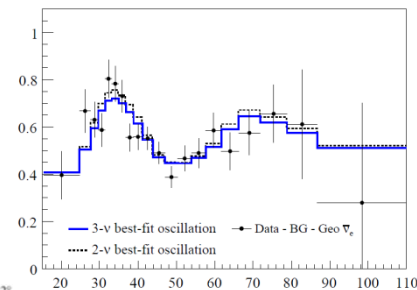

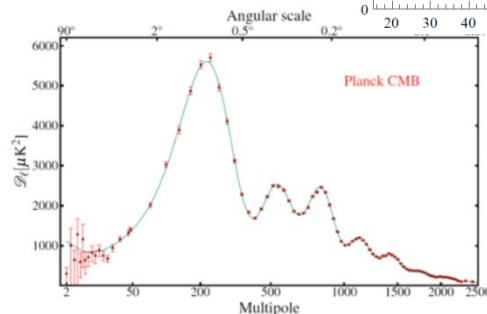$$\mathcal{A} \sim \frac{m_h^2}{v^2} \leq 16\pi$$
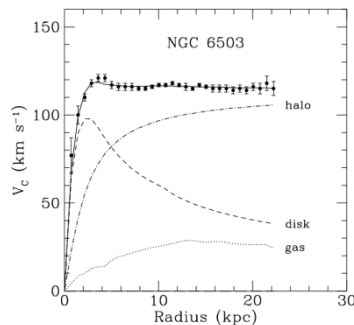
➔ $m_h \leq 4\sqrt{\pi} v \sim 1 \text{ TeV}$ Lee, Quigg, Thacker '77

Although we don't have such no-lose theorem for a nearby next scale anymore, obviously the SM can not be the final story as we have ample observational evidences for Beyond SM (BSM) physics:
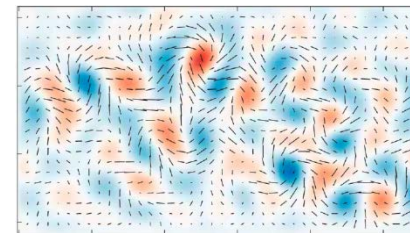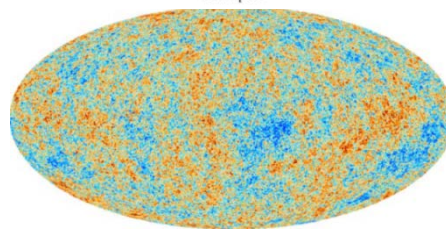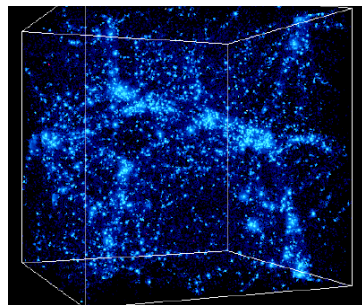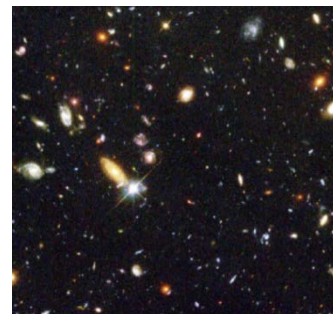
* Neutrino masses

* Dark matter

* Inflation

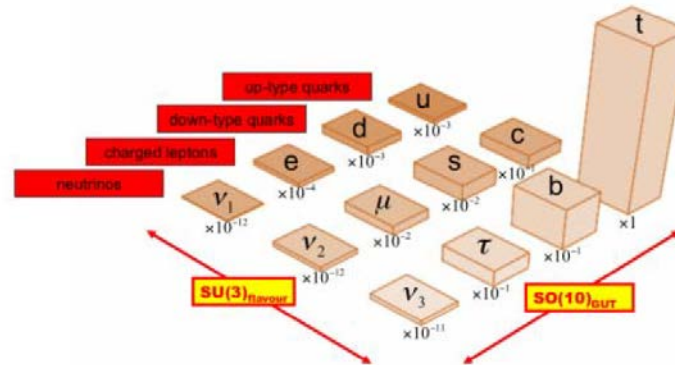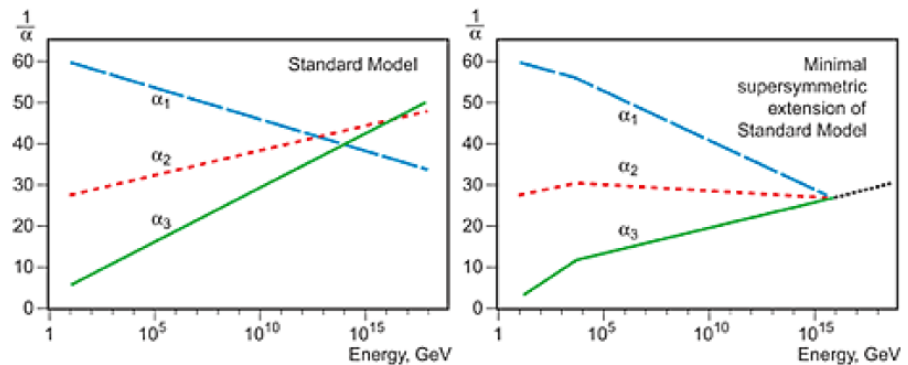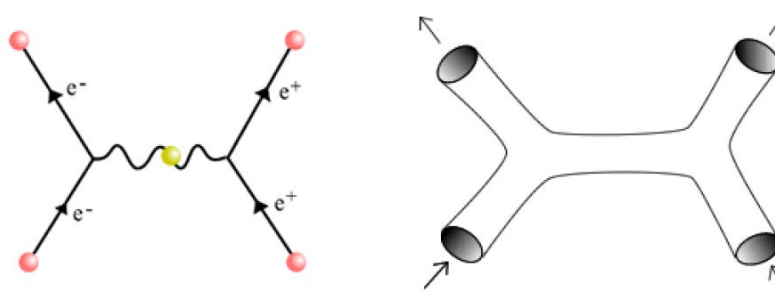* Matter-antimatter asymmetry

SM can not address

* Origin of the 3 flavors and their mass hierarchy:

* Unification of all forces:

* Quantum gravity:

There are also the naturalness problems associated with the mass scales and CP violation in the SM, which have motivated us to speculate about new physics which may solve the problems.
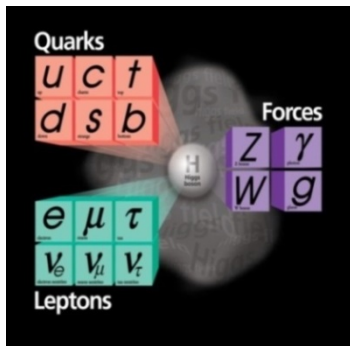
$$\mathcal{L}_{\mathrm{SM}}(\Lambda_{\mathrm{SM}}) = -\frac{1}{4\mathrm{g}^2}\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} + \frac{\theta}{32\pi^2}\mathbf{F}_{\mu\nu}\tilde{\mathbf{F}}^{\mu\nu} + \mathrm{i}\bar{\psi}\gamma^\mu\mathbf{D}_\mu\psi + \mathbf{D}_\mu\phi^\dagger\mathbf{D}^\mu\phi$$

$$+ \left(\mathbf{y}\phi\bar{\psi}_\mathbf{L}\psi_\mathbf{R} + \mathrm{h.c}\right) - \left(\mathbf{m}_\phi^2|\phi|^2 + \lambda|\phi|^4\right)$$

Two mass scales:

"Explicit (observable) BEH boson mass m_ϕ"

"Implicit (not yet observable) cutoff scale Λ_{SM}"

Two CP-violating angles:

"Kobayashi-Maskawa phase δ_{KM}"

"QCD vacuum angle θ_{QCD}"

A. Weiler, MC4BSM 2014

* Gauge hierarchy problem on the mass scales in the SM:

Unless there is some physics to distinguish m_ϕ and Λ_{SM} ,

$$\frac{m_\phi^2}{\Lambda_{SM}^2} \ll 1 \quad \text{is unnatural.}$$

➔ New physics (SUSY, Compositeness, ..) near m_ϕ ?

Although not as definite as the unitarity argument, this has been the argument most frequently used to motivate new physics near the weak scale.

* Strong CP problem on the CP-violating angles in the SM:

$$\frac{\theta_{QCD}}{\delta_{KM}} < 10^{-10} \quad \text{is unnatural}$$ ➔ New physics (axion, ...) to suppress θ_{QCD}?

Naturalness problems:

Natural

Highly
Unnatural

No obvious conflict with the known
physical principles, but unnatural
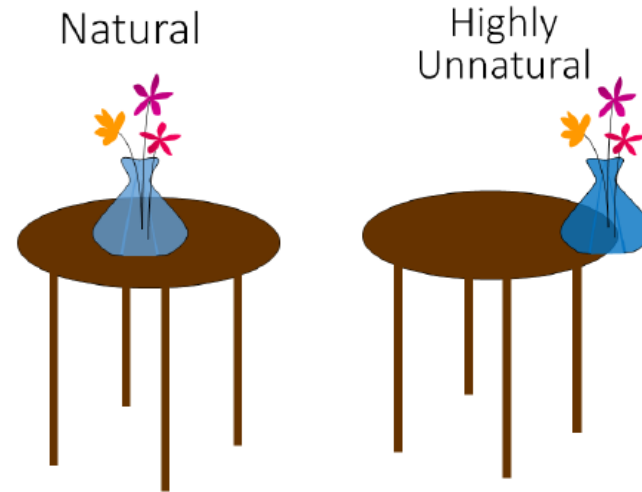
M. Strassler '13

In any case, the visible part (SM) does not represent the full table.
Then there may be an extension (not visible yet) of the table making
the vase (BEH boson) look natural.

.

Natural with
an extension of table
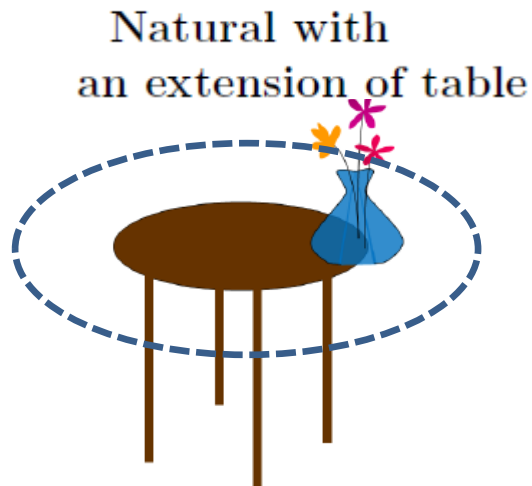
In fact, this has been the situation of "the SM and Beyond" for many years, even before the LHC experiments began.

The discovery of the elementary scalar boson at LHC Run1 confirmed that the hierarchy problem is indeed there:
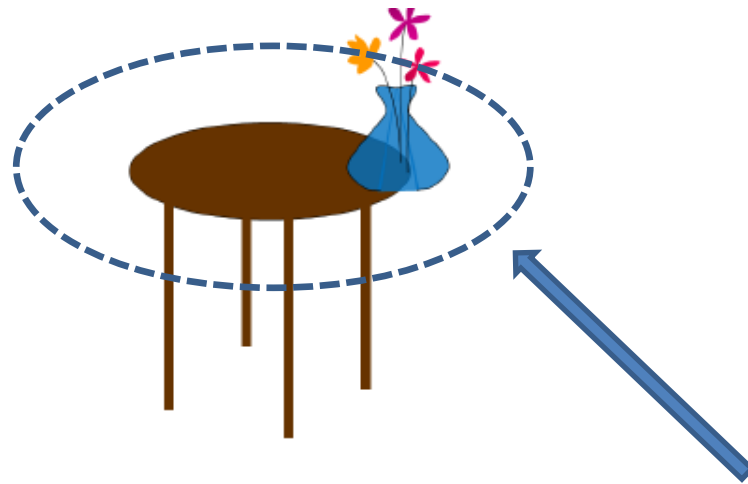
We should examine more extensively if there is **new physics** making the BEH boson natural.

What can we do?

* Precision test of the SM:

Search for the deviation of SM particle properties from the SM predictions:

Precision measurement of the BEH boson, EW gauge bosons, top, ...

$$\frac{|\phi|^2|D_\mu\phi|^2}{\Lambda_1^2}, \quad \frac{|\phi|^6}{\Lambda_2^2}, \quad \frac{|\phi|^2 F^{\mu\nu}F_{\mu\nu}}{\Lambda_3^2}, \quad \frac{|\phi|^2 \bar\psi_L \phi \psi_R}{\Lambda_4^2}, \quad \frac{\phi^\dagger D_\mu \psi \bar\psi \gamma^\mu \psi}{\Lambda_5^2}, \quad \cdots$$

EDMs, (g-2), Flavor changing processes, p-decays, ...

$$\frac{\bar\psi \sigma_{\mu\nu} \phi \psi F^{\mu\nu}}{\Lambda_6^2}, \quad \frac{\bar\psi\psi\bar\psi\psi}{\Lambda_7^2}, \quad \cdots$$

Neutrino oscillations, ν-less double beta decays, ...

$$\frac{\phi \ell \phi \ell}{\Lambda_8}, \cdots$$

Many of these precision tests can give a key information on the next scale, however often the connection between the precision observables and the new physics scale involves highly model-dependent factors:

1/Λ^N = Loop factors

× Small couplings

× Approximate symmetries (flavor, CP, custodial,..)

× **(1/New physics scale)^N**

So new physics scale can be much lower than the scale Λ what we measure through precision physics:

Flavor violations: 1 TeV – 10^5 TeV

EDMs: 1 TeV – 10^2 TeV

Neutrino masses: 1 TeV – 10^{12} TeV

* Search for new particles

This needs a guide.

At the moment, the best motivated new particles are those associated with dark matter or those predicted by the solutions of the naturalness problems:

SUSY partners

Additional BEH bosons

WIMP dark matter

Axions

Companions of composite BEH boson

Dark gauge bosons

Kaluza-Klein exitations of extra dim

.....

So there are many different routes toward new physics, and it is true that new physics can appear anywhere in these approaches.

Among those approaches, at this moment **precision BEH boson physics** is particularly interesting and promising:

* This is a new world.

* Excellent portal to new physics:

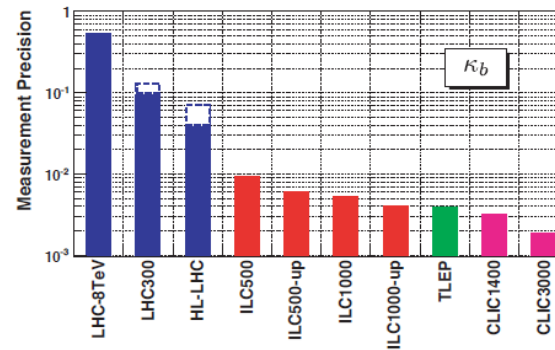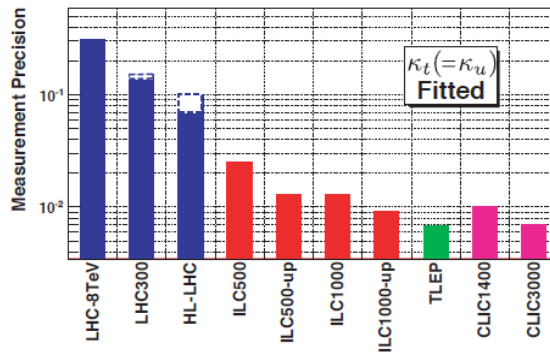$|\phi|^2$ = Lowest dimensional gauge invariant operator in the SM

➔ $|\phi|^2 \mathcal{O}_{\mathrm{NP}}$, ...

* There may be additional scalar bosons near the weak scale.

...

Expected precision of the BEH boson coupling measurements

$$\kappa_i = \frac{g_{hii}}{g_{hii}(\mathrm{SM})}$$ = BEH boson coupling in the unit of the SM value
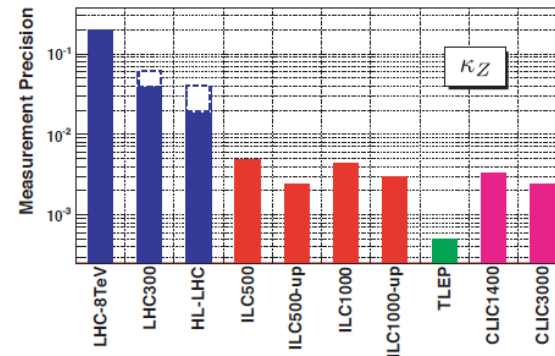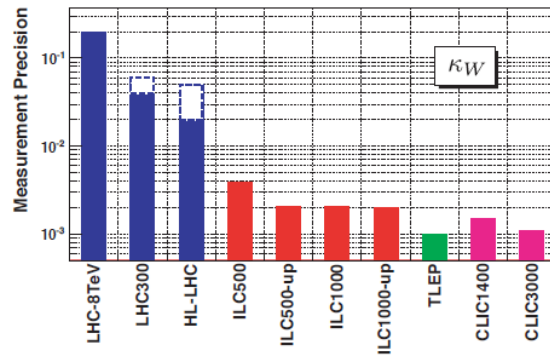
Higgs working group report, arXiv:1310.8361

Excellent probe of new physics at TeV scale, which couples dominantly to the BEH boson:

$$\kappa_i - 1 \sim \frac{v^2}{m_{NP}^2} \sim \mathrm{few}\,\%$$

Precision BEH boson physics for Singlet-extended SUSY

Additional singlet $\mathbf{S} = (\mathbf{s} + \mathbf{ia}, \tilde{\mathbf{s}})$ with $\mathbf{W} = \lambda \mathbf{SH_u H_d} + ...$

* Less fine-tuning for the EWSB:
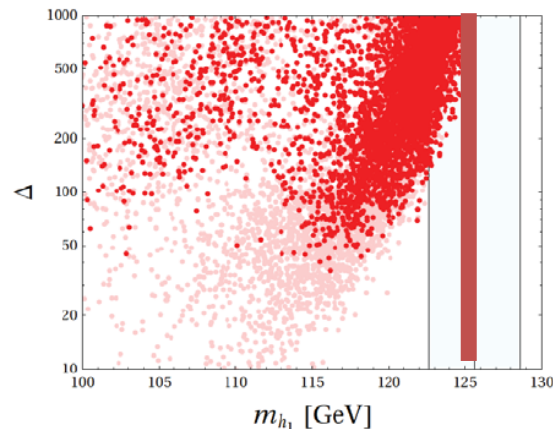
"BEH boson mass" vs "Scalar top mass" and "Fine tuning"

$$\mathbf{m_h^2} = \mathbf{m_Z^2} \cos^2 2\beta + \left(\frac{3\mathbf{y_t^2 m_t^2}}{4\pi^2} \ln\left(\frac{\mathbf{m_{\tilde{t}}}}{\mathbf{m_t}}\right) + ... \right) + \lambda^2 \mathbf{v}^2 \sin^2 2\beta + \left(\mathbf{m_h^2} - \mathbf{m_s^2}\right) \sin^2 \theta + ...$$

$$= (125 \text{ GeV})^2 \text{ with lighter scalar top, so with less fine-tuning}$$
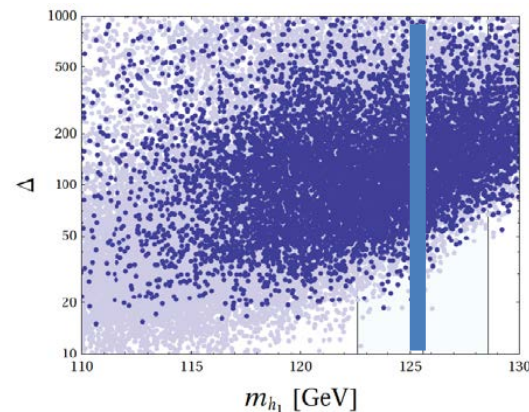
Kaminska, Ross
& Schmidt-Hoberg '13

MSSM: $1/\Delta \sim 0.1\%$ Singlet-extension: $1/\Delta \sim$ few $\%$

* Rich structure of the BEH boson couplings

KC et al, arXiv:1211.0875; Cheung et al, arXiv:1302.0314; Barbieri et al, arXiv:1304.3670; Badziak et al, arXiv:1304.5437

CP-even BEH bosons in mass eigenstates:

$$\mathbf{h} = c_{\theta_1}c_{\theta_2}\hat{\mathbf{h}} - s_{\theta_1}\hat{\mathbf{H}} - c_{\theta_1}s_{\theta_2}\hat{\mathbf{s}} \quad = \text{SM-like 125 GeV boson}$$

$$\mathbf{s} = \left(c_{\theta_2}c_{\theta_3} - s_{\theta_1}s_{\theta_2}s_{\theta_3}\right)\hat{\mathbf{s}} + \left(s_{\theta_2}c_{\theta_3} + s_{\theta_1}s_{\theta_3}c_{\theta_2}\right)\hat{\mathbf{h}} + s_{\theta_3}c_{\theta_1}\hat{\mathbf{H}}$$

$$\mathbf{H} = \left(c_{\theta_1}c_{\theta_3} - s_{\theta_3}c_{\theta_2}\right)\hat{\mathbf{H}} + \left(s_{\theta_1}c_{\theta_2}c_{\theta_3} - s_{\theta_2}s_{\theta_3}\right)\hat{\mathbf{h}} - \left(s_{\theta_3}c_{\theta_2} + s_{\theta_1}s_{\theta_2}c_{\theta_3}\right)\hat{\mathbf{s}}$$
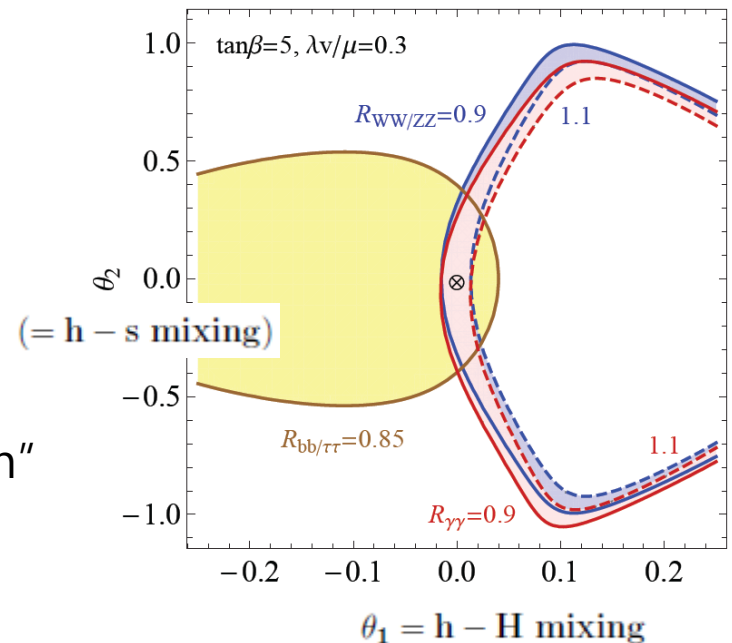
Couplings of the 125 GeV boson:

$$\kappa_{W,Z} = c_{\theta_1}c_{\theta_2}, \quad \kappa_t = c_{\theta_1}c_{\theta_2} + s_{\theta_1}\cot\beta,$$

$$\kappa_b = \kappa_\tau = c_{\theta_1}c_{\theta_2} - s_{\theta_1}\tan\beta,$$

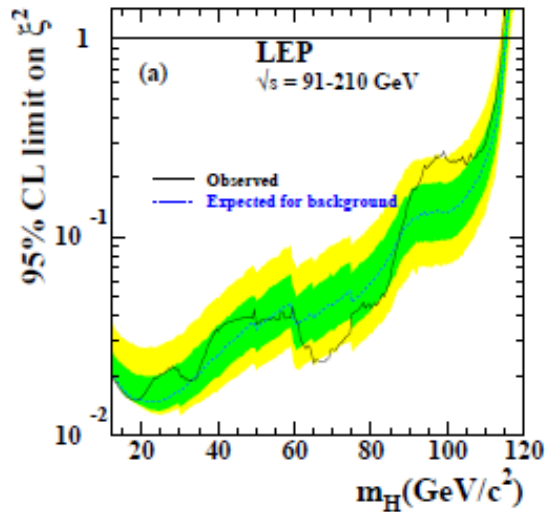$$\kappa_\gamma \simeq 1 + 0.2\frac{\lambda v}{\mu}\tan\theta_2$$

With "s" and "H" near TeV,

the couplings of the 125 GeV boson "h"
can be substantially modified.

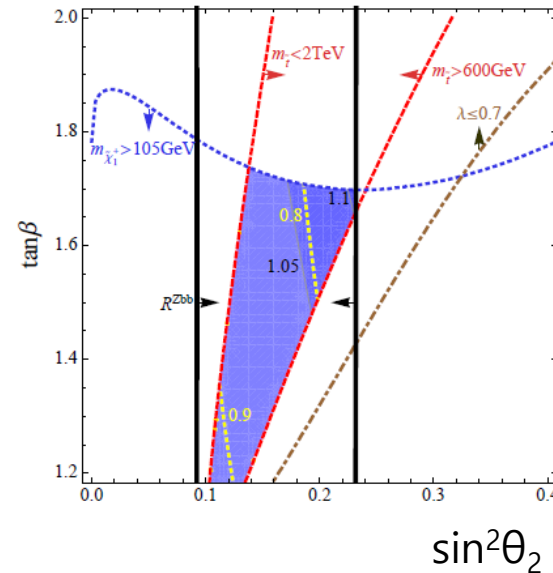*** 98 GeV singlet-like boson "s" at LEP?**   Belanger et. al, arXiv:1210.1976
KC et al, arXiv:1308.4447

$$R(e^+e^- \to Z\,s \to Z b\bar{b}) \sim \sin^2\theta_2 \quad \sim 0.1 - 0.25$$

$\sin^2\theta_2$

($\theta_2 = h - s$ mixing)

* Exotic decays of the BEH boson?

$$h \to aa,\ ss\ aZ,\ \tilde{s}\tilde{s}$$

There can be a variety of opportunities in the precision BEH boson physics!

New approach for the precision measurement of the W and top masses: W.S. Cho, arXiv:1408:xxxx; Cho, KC, Lim, Park, in preparation

W boson mass measurement:
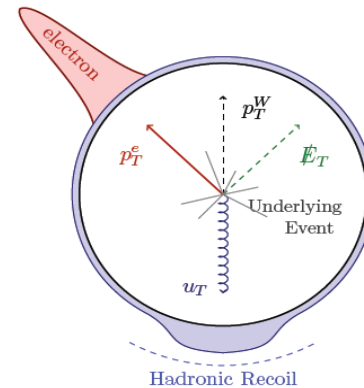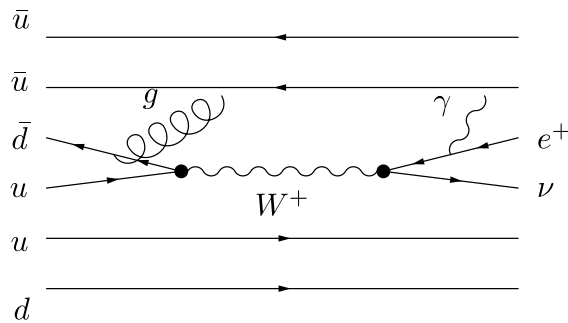
Template fit of

$$M_T = \sqrt{2P_T^l P_T^\nu (1 - \cos(\phi^l - \phi^\nu))}$$

P_T^l

P_T^ν distributions

New approach:

In the existing approach, $\{P_z^\ell\}$ are not used at all.

In the new approach, we utilize $\{P_z^\ell\}$ and construct

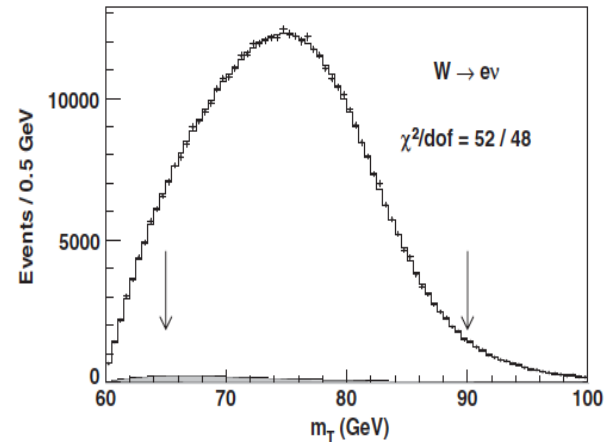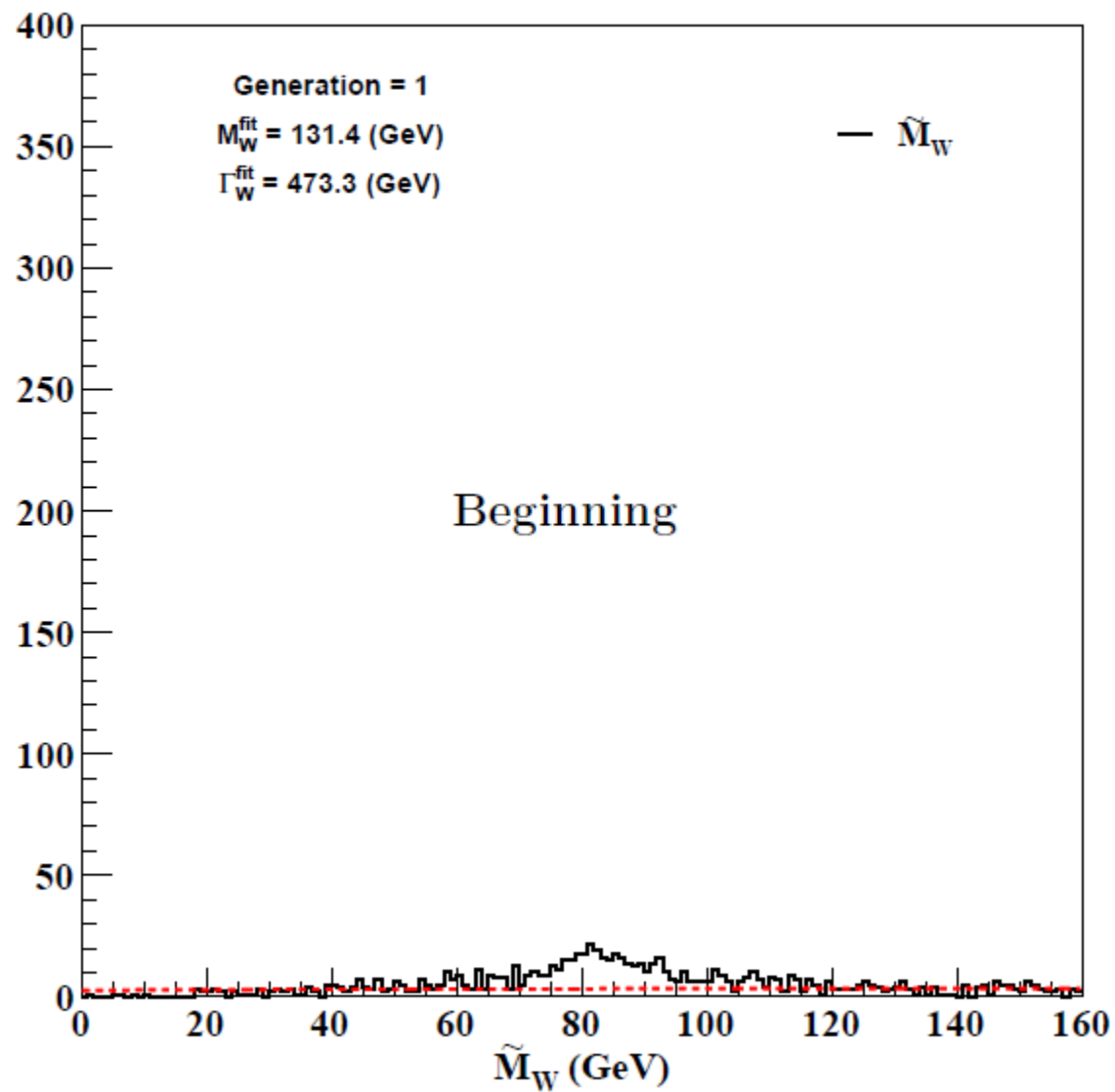### the Collectively Optimized invariant-Mass (COM):

$$\tilde{M}_W^2 = \left(P_\mu^\ell + \tilde{P}_\mu^\nu\right)^2 = 2P_T^\ell P_T^\nu \left(\cosh(\eta_\ell - \tilde{\eta}_\nu) - \cos(\phi_\ell - \phi_\nu)\right)$$

$\{\tilde{\eta}_\nu\}$ = Neutrino rapidity reconstructed by
collective stochastic optimization process
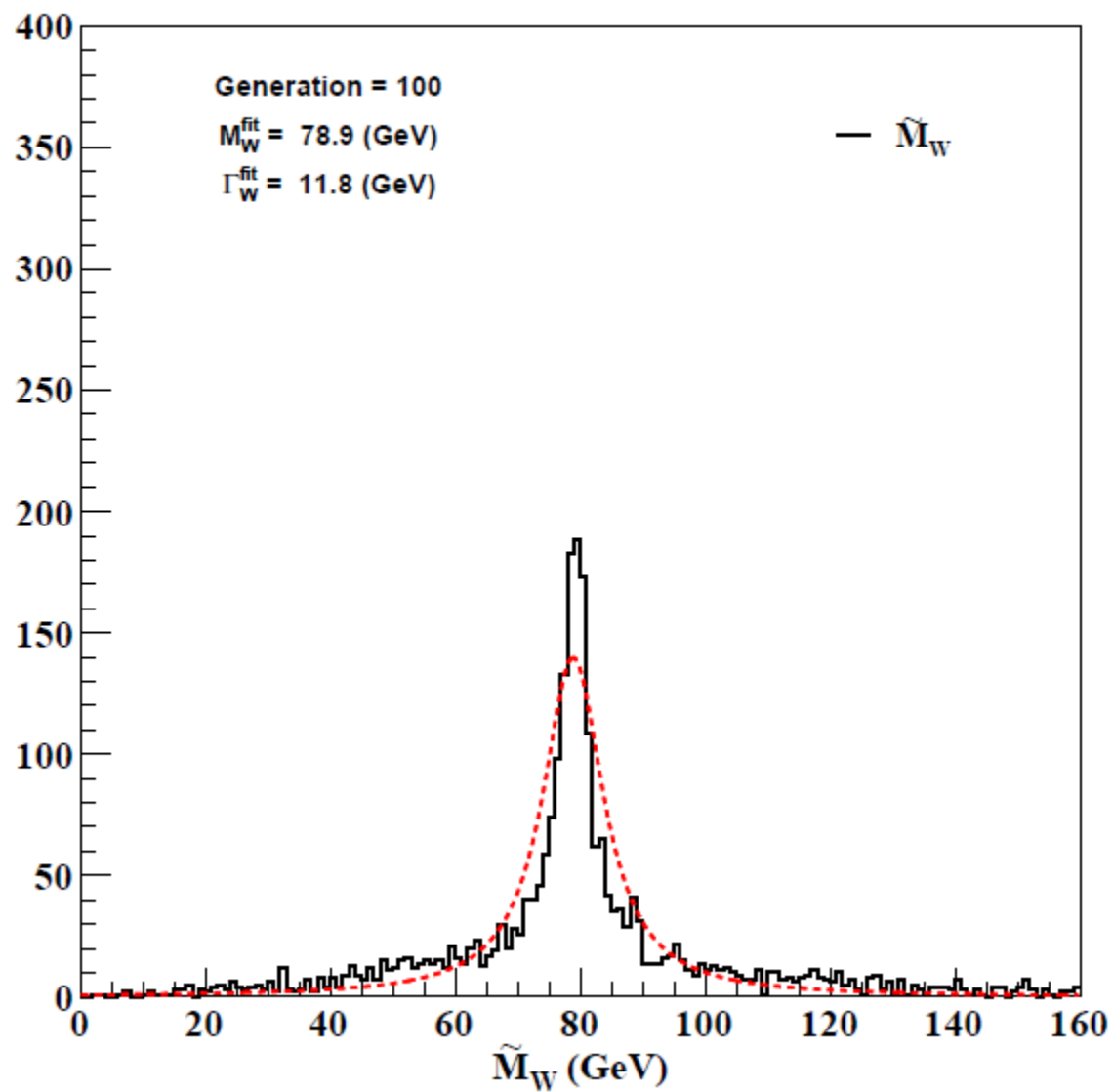through a genetic algorithm

Collective stochastic optimization process

1) For a given N_E W-boson events, begin with N_S samples of random distribution of $\{\tilde{\eta}_\nu\}$: $N_E \times N_S$ matrix-valued initial configuration

2) Apply for a genetic algorithm with a target distribution of $\tilde{M}_W^2$ (COM) taking the Breit-Wigner form.

- Define a distance between the sample and target distributions,

    e.g. likelyhood, or relative entropy, or χ^2

  and then find the optimal target distribution for each sample distribution, which

  is minimizing the distance between the sample and target.

- Make a ranking of the sample distributions based on the distance between the sample and target, and throw away the bottom half.

- Implement a genetic evolution (selection, mating, reproduction) to regenerate the missing half of the sample distributions.

3) Repeat the above genetic algorithm: A process of acquiring information to arrive at the correct final Breit-Wigner distribution of the W-boson mass.

Preliminary test for 10 independent sets of 200 events

After 100 evolutions

Generation = 100

M_W^{fit} = 78.9 (GeV)

Γ_W^{fit} = 11.8 (GeV)

$\tilde{M}_W$

$\tilde{M}_W$ (GeV)

After 500 evolutions

Generation = 500

$M_W^{fit} =$ 79.1 (GeV)

$\Gamma_W^{fit} =$ 6.7 (GeV)

$\tilde{M}_W$

After 2000 evolutions

Generation = 2000

M_W^{fit} = 79.3 (GeV)

Γ_W^{fit} = 4.7 (GeV)

$\tilde{M}_W$
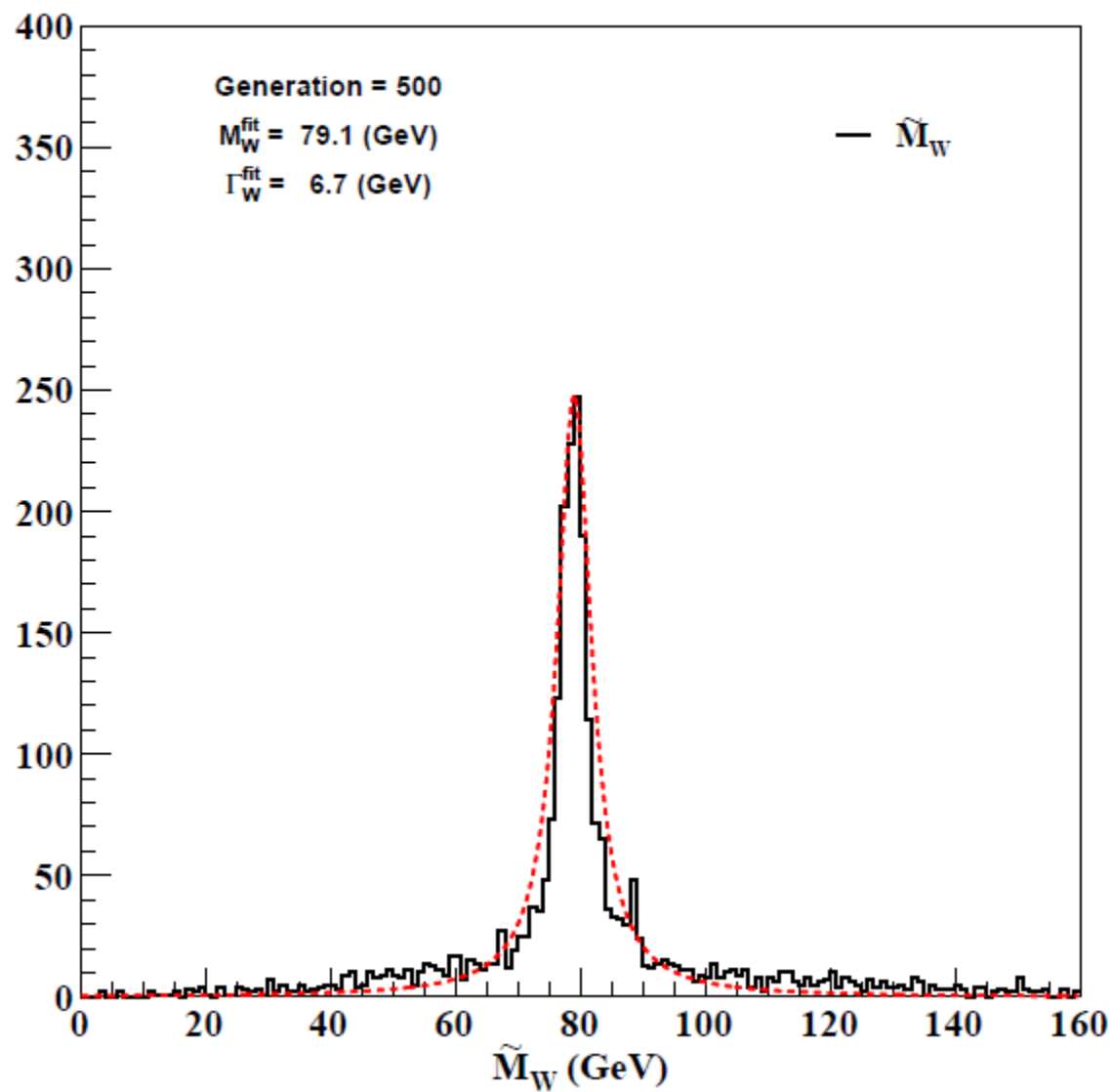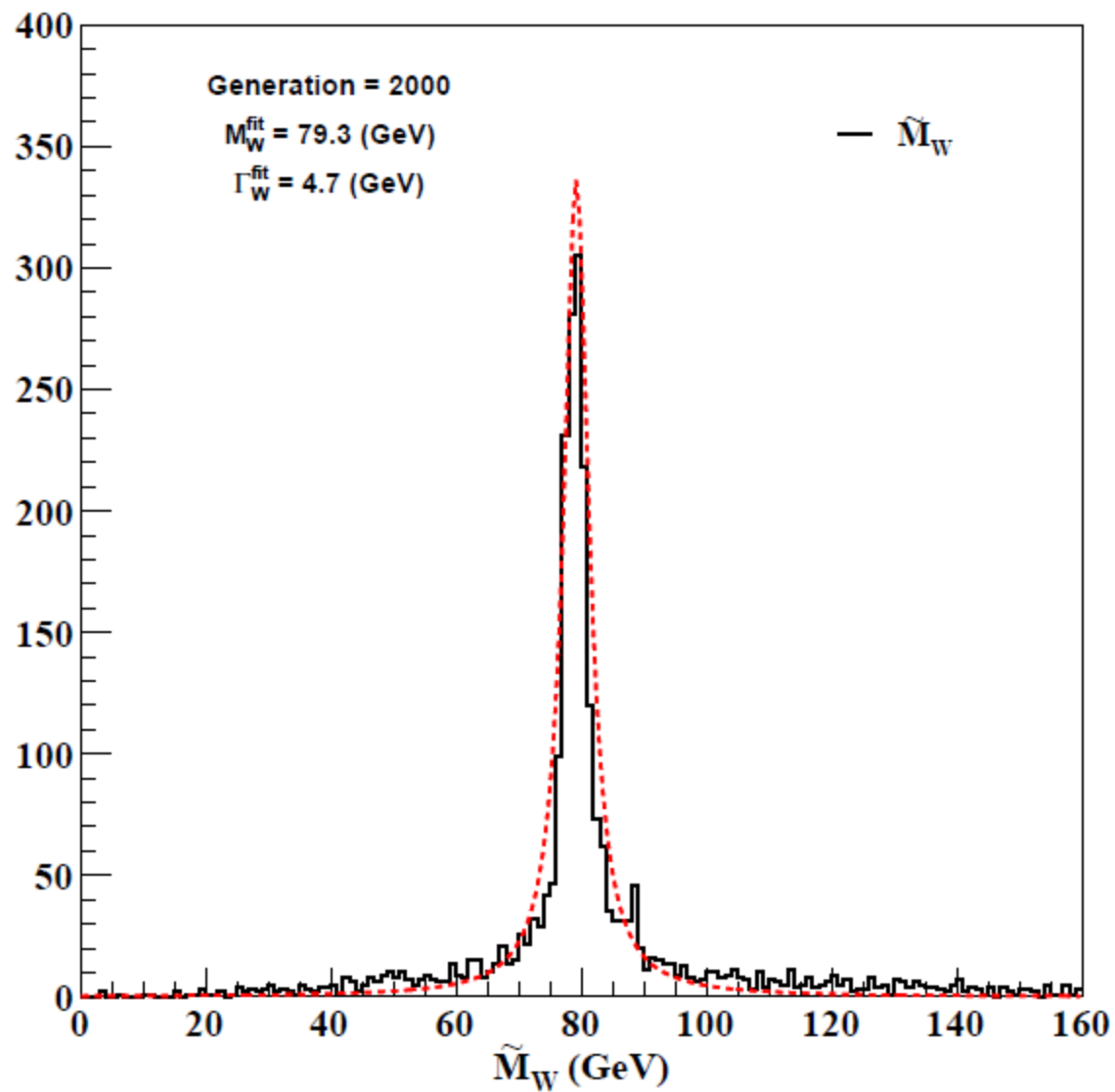
There are a lots of room to improve this preliminary test of the idea.

This approach has a good potential to reduce various systematic uncertainties:

  * COM is Lorentz-invariant, so less sensitive to PDF and P_T^W .

  * Peak position of the COM distribution is likely to be insensitive to the detector resolution

➔   We may be able to significantly improve the accuracy of the W-boson mass determination with this new approach.

A similar approach can be applied for the top mass determination, which can reduce also the combinatoric ambiguities.

(For details, WS Cho, arXiv: 1408.xxxx and Cho, KC, Lim, Park, in preparation)

Conclusion

* Both the available observational evidences for new physics and
the theoretical structure of the SM allow that the next scale can be
anywhere between TeV and a very high scale near the Planck scale.

* During the last several decades, the gauge hierarchy problem has been
the major motivation for speculating about new physics near the weak
scale, and the discovery of elementary BEH boson confirmed that the
hierarchy problem is indeed there.

Therefore we have to examine carefully if there is a new physics
making the BEH boson natural.

* There are many different routes to approach to new physics, and we now have a new blue ocean: Precision BEH boson physics.

* The collectively optimized mass (COM) variable may allow us to determine the W and top masses more accurately, which will be greatly useful for searching for new physics.