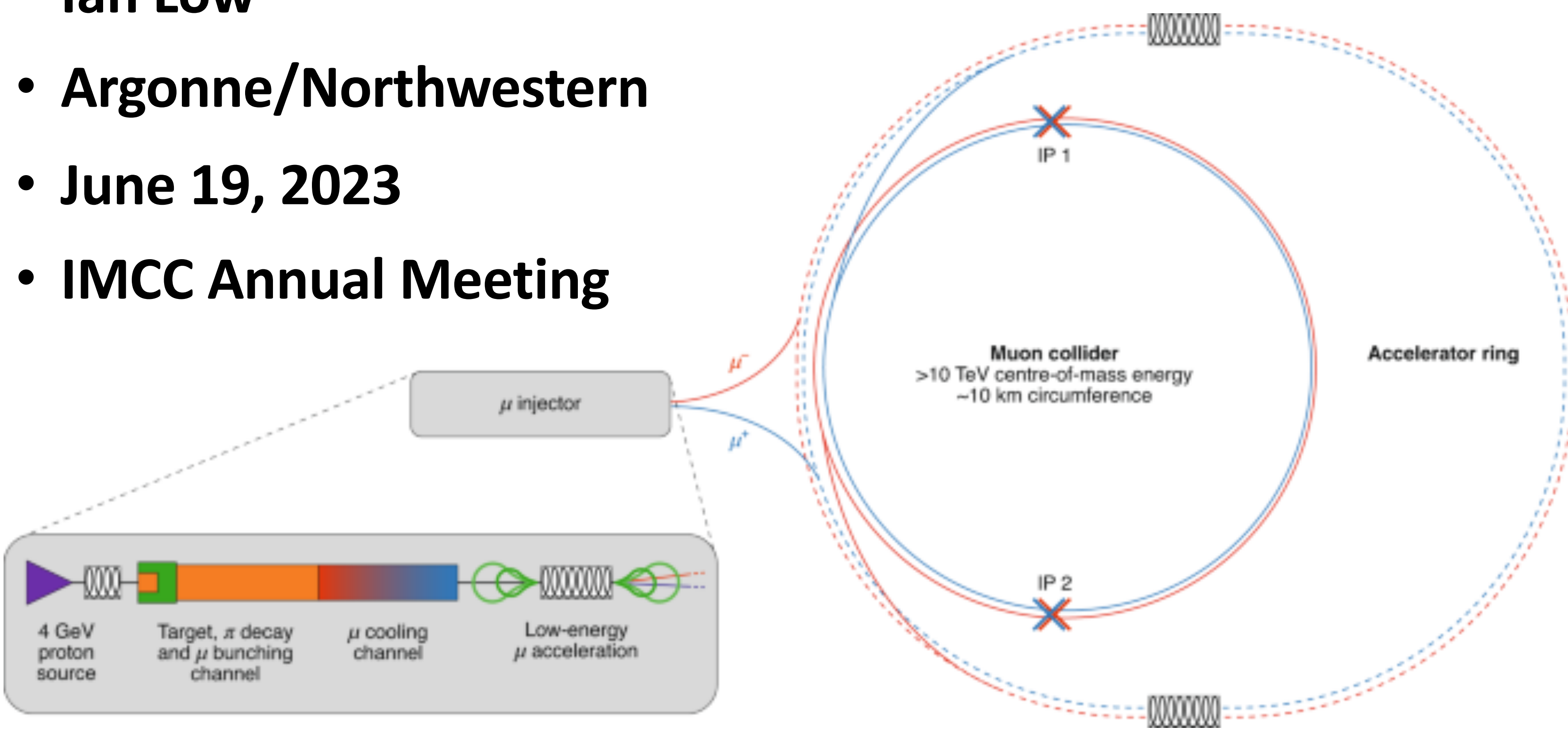
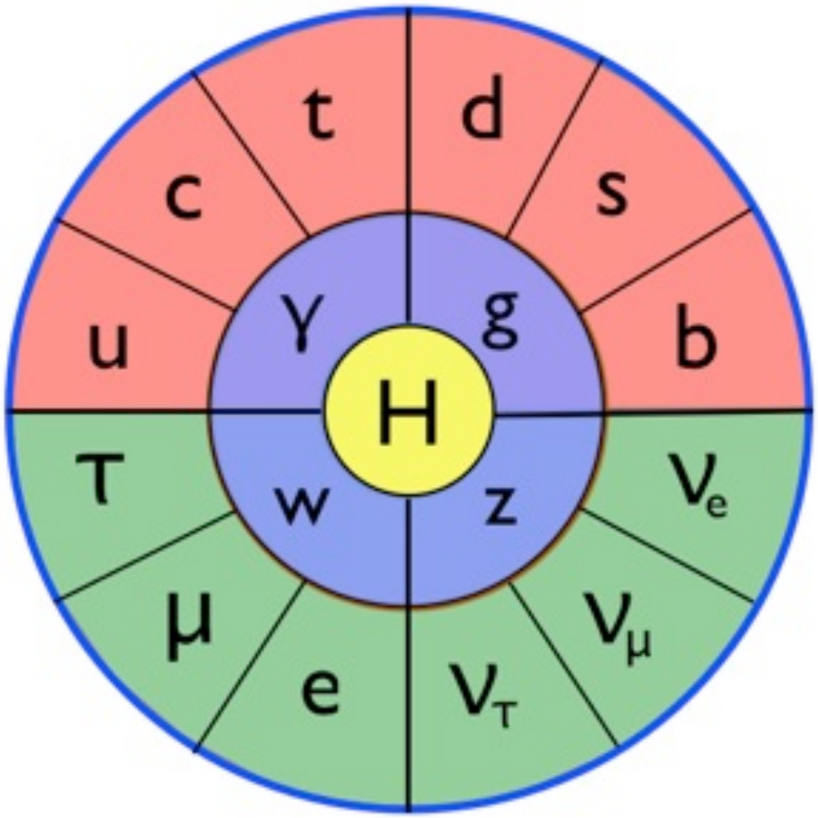
Vision for Physics at the Muon Collider

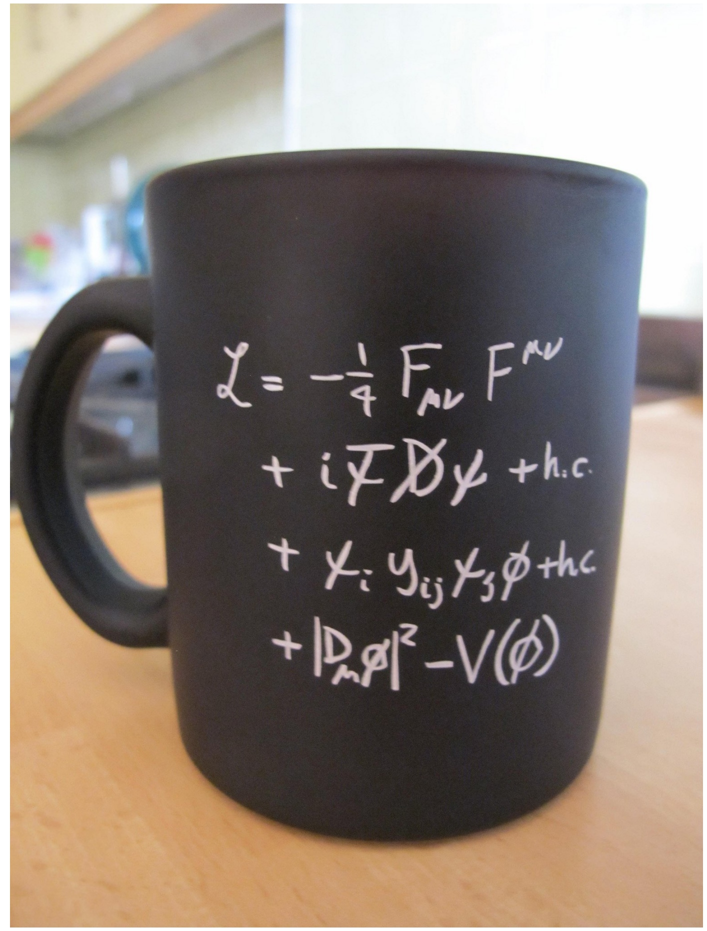
International
MUON Collider
Collaboration

- **Ian Low**
- **Argonne/Northwestern**
- **June 19, 2023**
- **IMCC Annual Meeting**



The Standard Model is UV-complete after the discovery of the Higgs:





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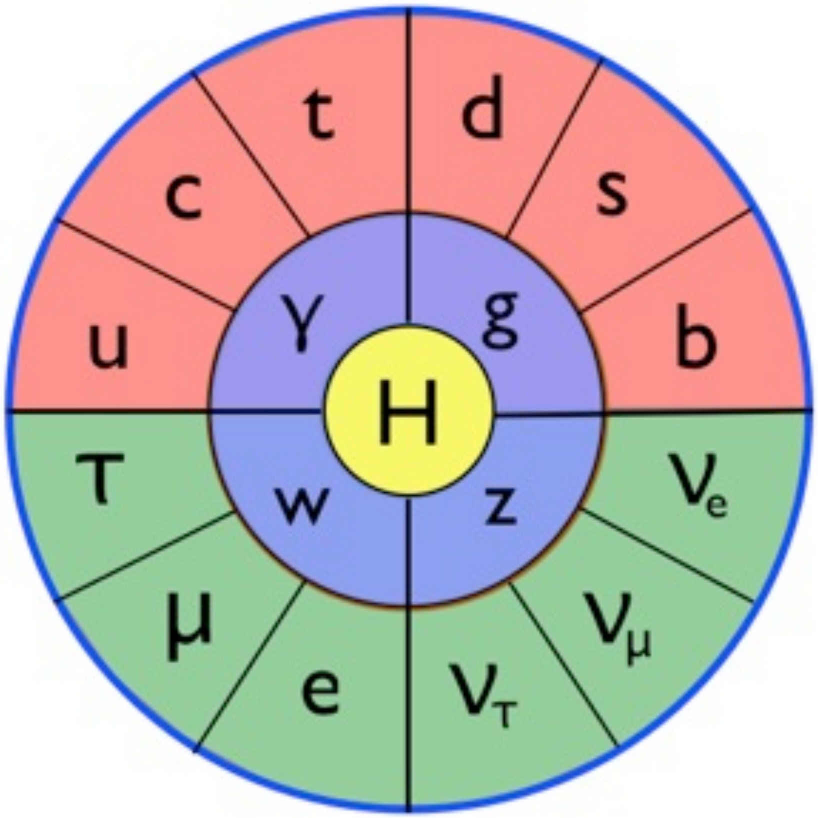

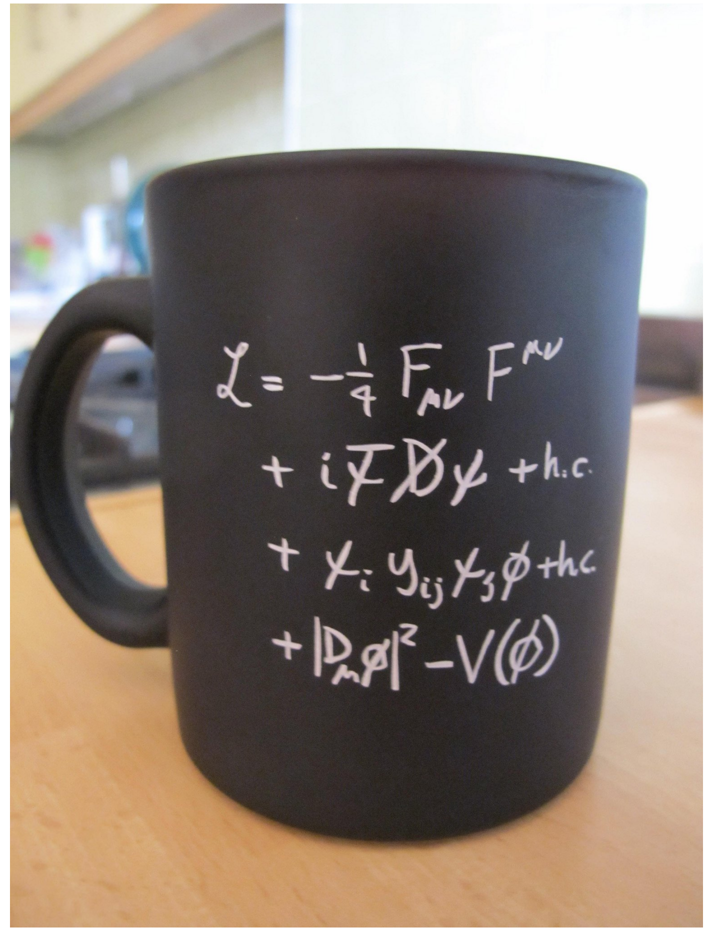

Why a 10 TeV Muon Collider then?

A reminder:

throughout the course of history, UV completion always fails to predict the completeness of the theory!

- QED (photons+electrons) is UV-complete. But physics didn’t stop there.
- QCD (gluons+quarks) is UV-complete. Again physics didn’t stop there.
- SM with one generation of fermion is UV-complete. “WHO ORDERED THAT?”

Why a 10 TeV Muon Collider?

- Questions unanswered
- Predictions untested
- A New Regime of Quantum Field Theories
- Strong Synergies with the Neutrino Frontier

Questions unanswered

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What is the Higgs made of?

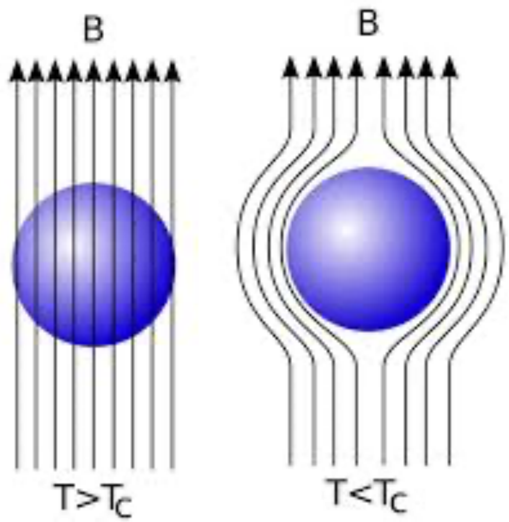
A physics Ph.D could rephrase the question in a slightly more sophisticated fashion:

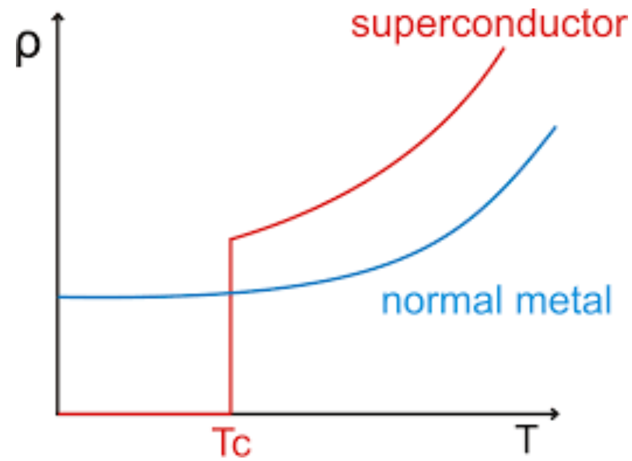
What is the microscopic theory that gives rise to the Higgs boson and its potential?

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

Our colleagues in condensed matter physics are very used to asking, and studying, this kind of questions.

One of the most beautiful examples is the superconductivity discovered in 1911:





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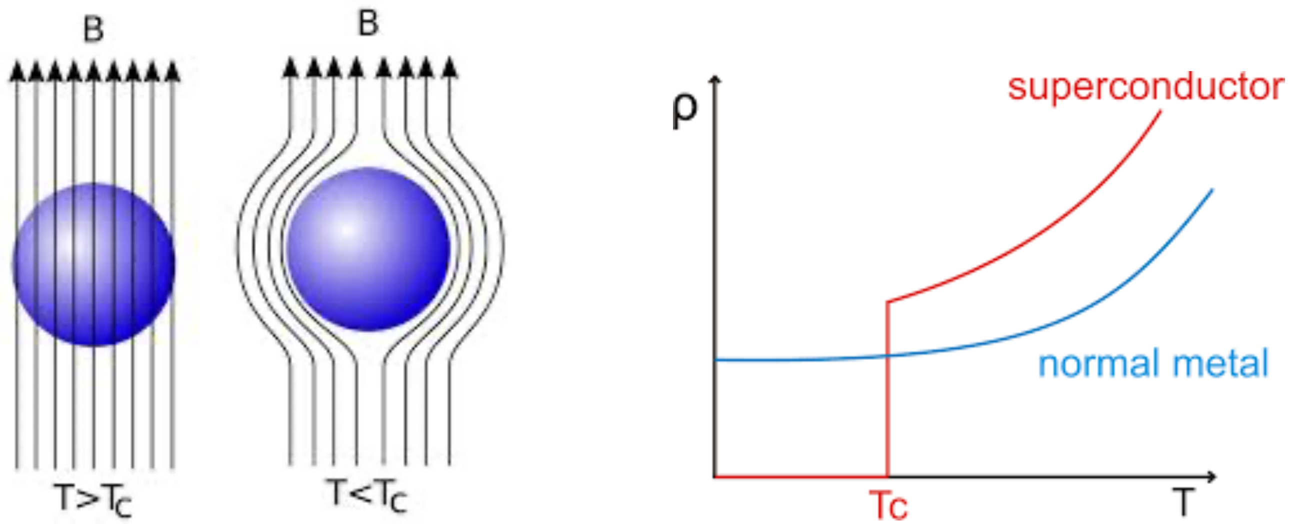

Ginzburg-Landau theory from 1950 offered a **macroscopic** (ie effective) theory for conventional superconductivity,

$$V(\Psi) = \alpha(T)|\Psi|^2 + \beta(T)|\Psi|^4 \qquad \alpha(T) \approx a^2(T - T_c) \qquad \text{and} \qquad \beta(T) \approx b^2$$

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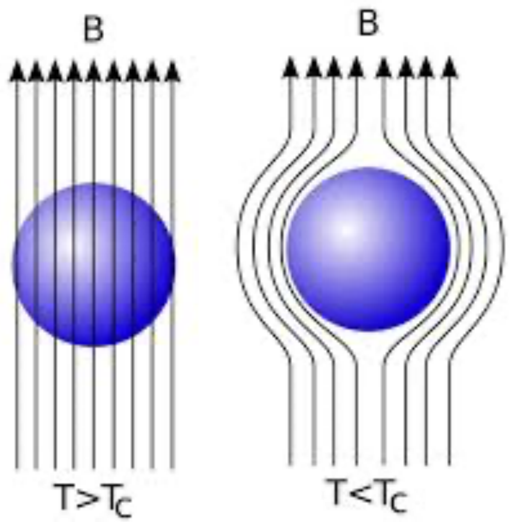

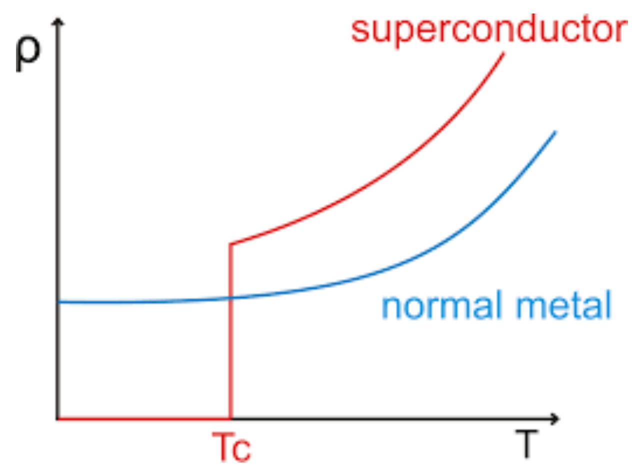

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What is the **microscopic** origin of the Ginzburg-Landau potential for superconductivity?

In 1957 Bardeen, Cooper and Schrieffer provided the **microscopic** (fundamental) theory that allows one to

1) interpret $|\Psi|^2$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

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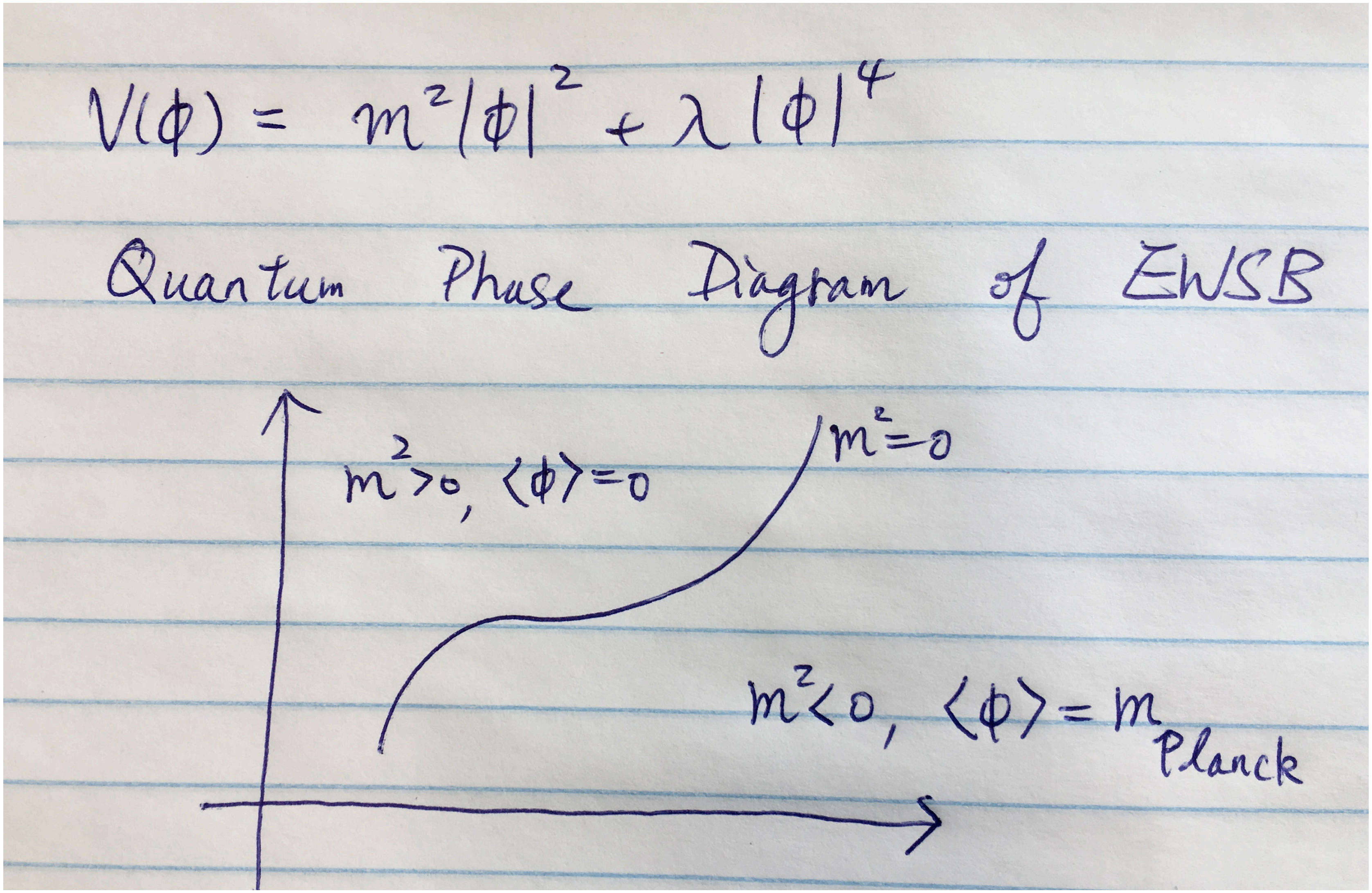
1) interpret $|\Psi|^2$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

We do not have the corresponding **microscopic** theory for the Higgs boson.

In fact, we have NOT even measured the Ginzburg-Landau potential of the Higgs!

The question can be reformulated in terms of **Quantum Criticality**:



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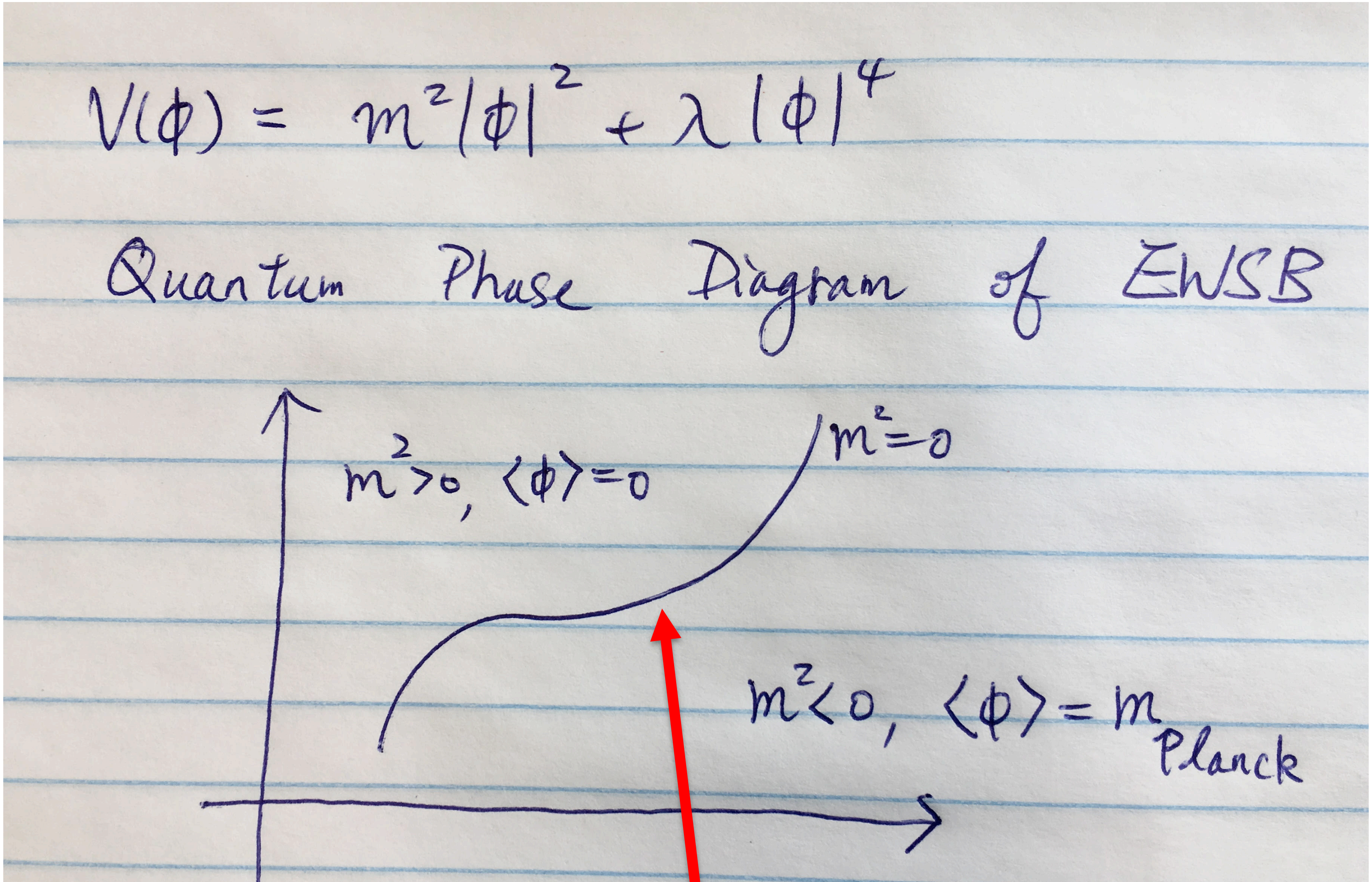


Mh=125 GeV. We are sitting extremely close to the criticality. **WHY??**

One appealing possibility – the critical line is selected dynamically.

This is the analogy of BCS theory for electroweak symmetry breaking. It goes by the name of "technicolor," which is strongly disfavored experimentally.

"The Universe is not a piece of crappy metal!"

by a prominent HEP theorist.

Every day we don’t observe any signs of new physics, the mystery deepens and the plot thickens:

Why are we sitting close to the critical line of EWSB??

An esteemed condensed matter colleague once told me “I have a microscopic theory for EWSB!”

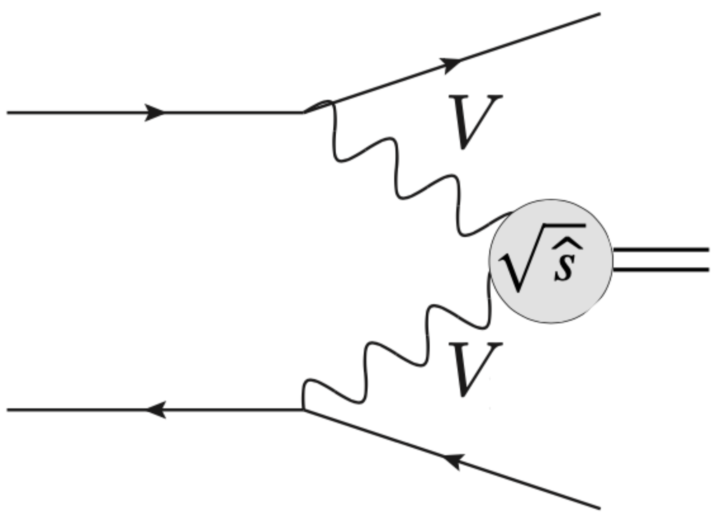
I asked him “So tell me, do you have Higgs and nothing else?”

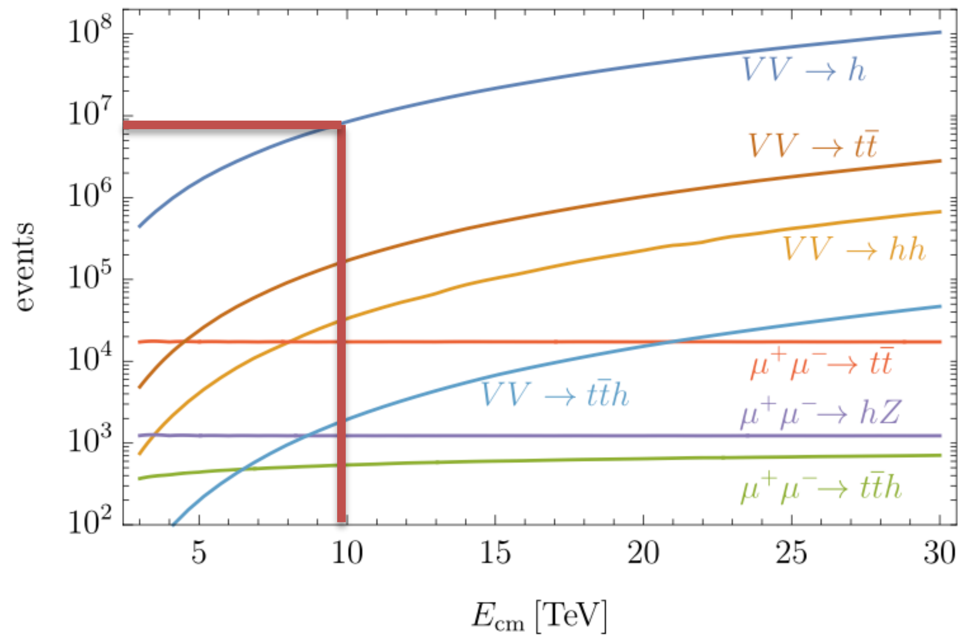
Then he shut up…

EWSB is the most exotic state of quantum criticality.

It is a somewhat embarrassing realization that, after 40 years, our understanding of the electroweak symmetry breaking is still at the level of Ginzburg-Landau level!

A 10 TeV muon collider would be a super-Higgs factory, producing ~ 10 million Higgs bosons with 10 /ab:





(By comparison, an “ordinary” Higgs factory produces ~ 1 million Higgses.)

There is a rich program to understand the *microscopic* nature of the Higgs:

- Deviations in h125 coupling structure.

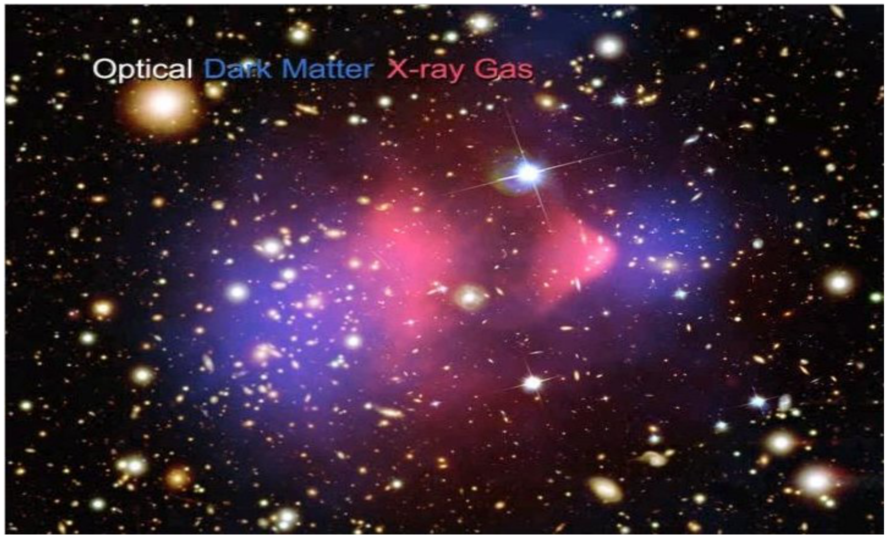
- Rare and new decay channels of h125.

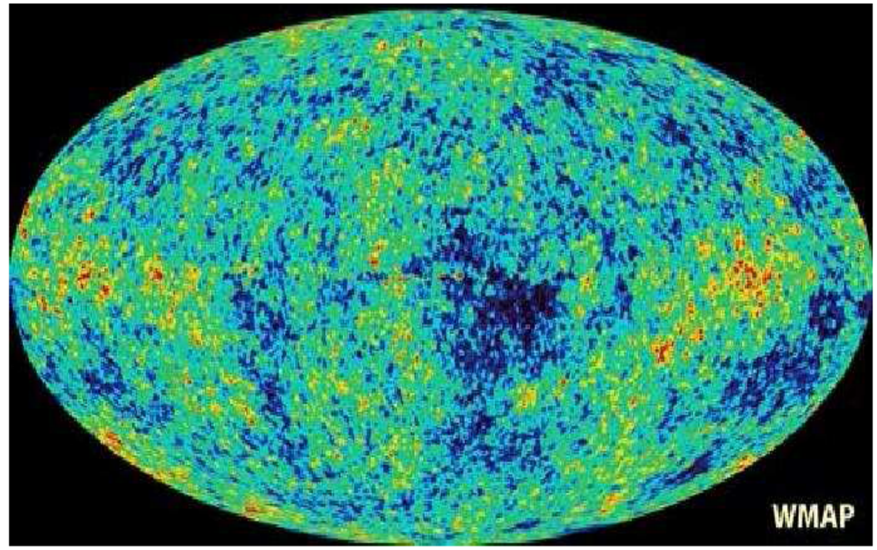
- Partners of the SM top quark that couple significantly to h125.

- Additional Higgs bosons.

Some excellent empirical questions SM cannot answer:

- Dark matter/Dark sector:





We (most people) are convinced about the existence of dark matter. What is it??

In principle, a high energy collider could produce dark matter particles with mass around E_{CM} /2.

For the simplest WIMP scenarios, the thermal target is well above 1 TeV:

Thermal targets

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
$(1,3,\epsilon)$	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
$(1,5,\epsilon)$	Dirac	6.6 TeV
(1,7,0)	Majorana	48.8 TeV
$(1,7,\epsilon)$	Dirac	16 TeV

Correct relic abundance
⇒ Thermal targets

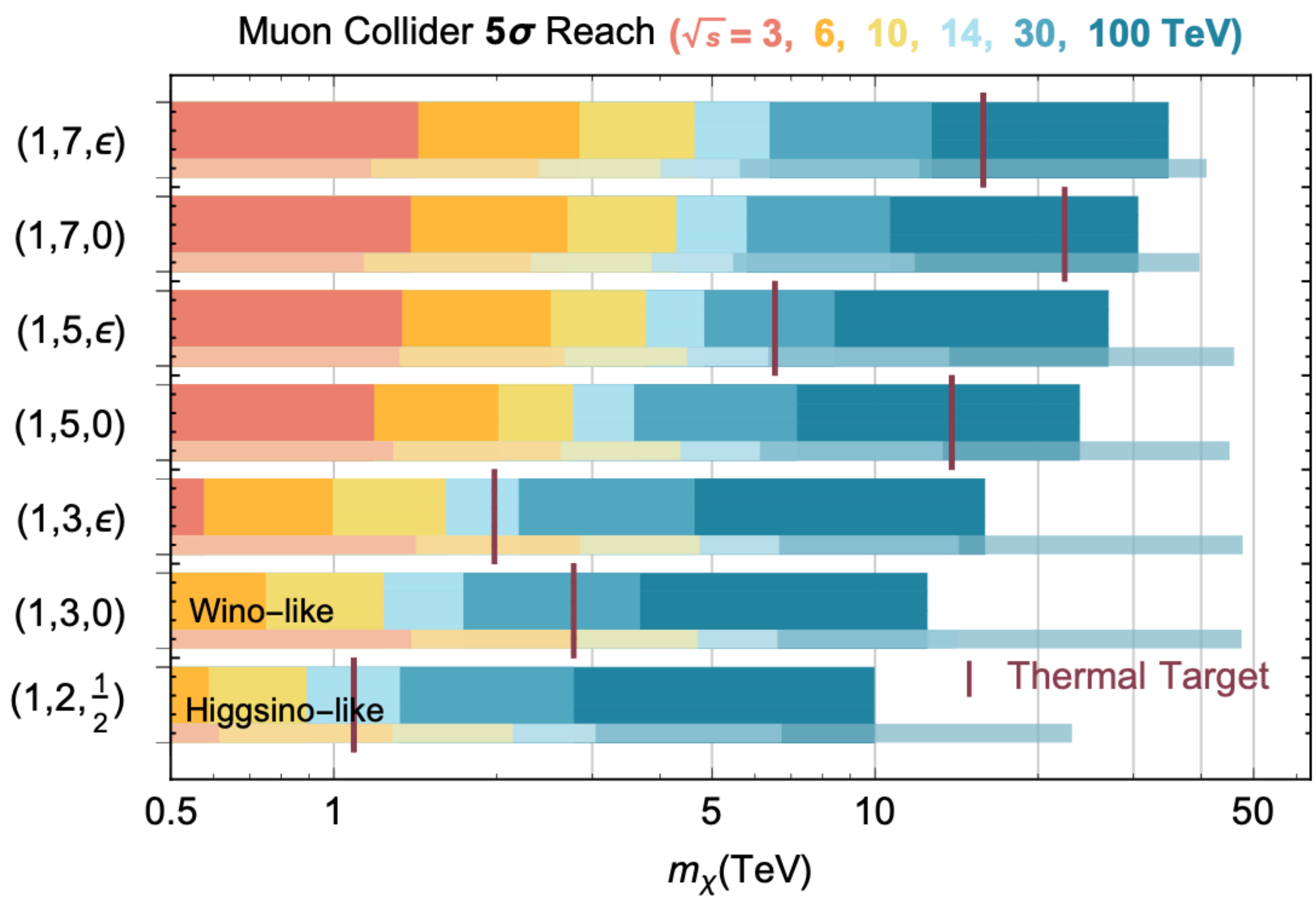
Reach up to thermal target
≈
complete coverage for WIMP candidate

Mitridate, Redi, Smirnov, Strumia, 1702.01141

S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D. Redigolo, L. Vittorio, 2107.09688

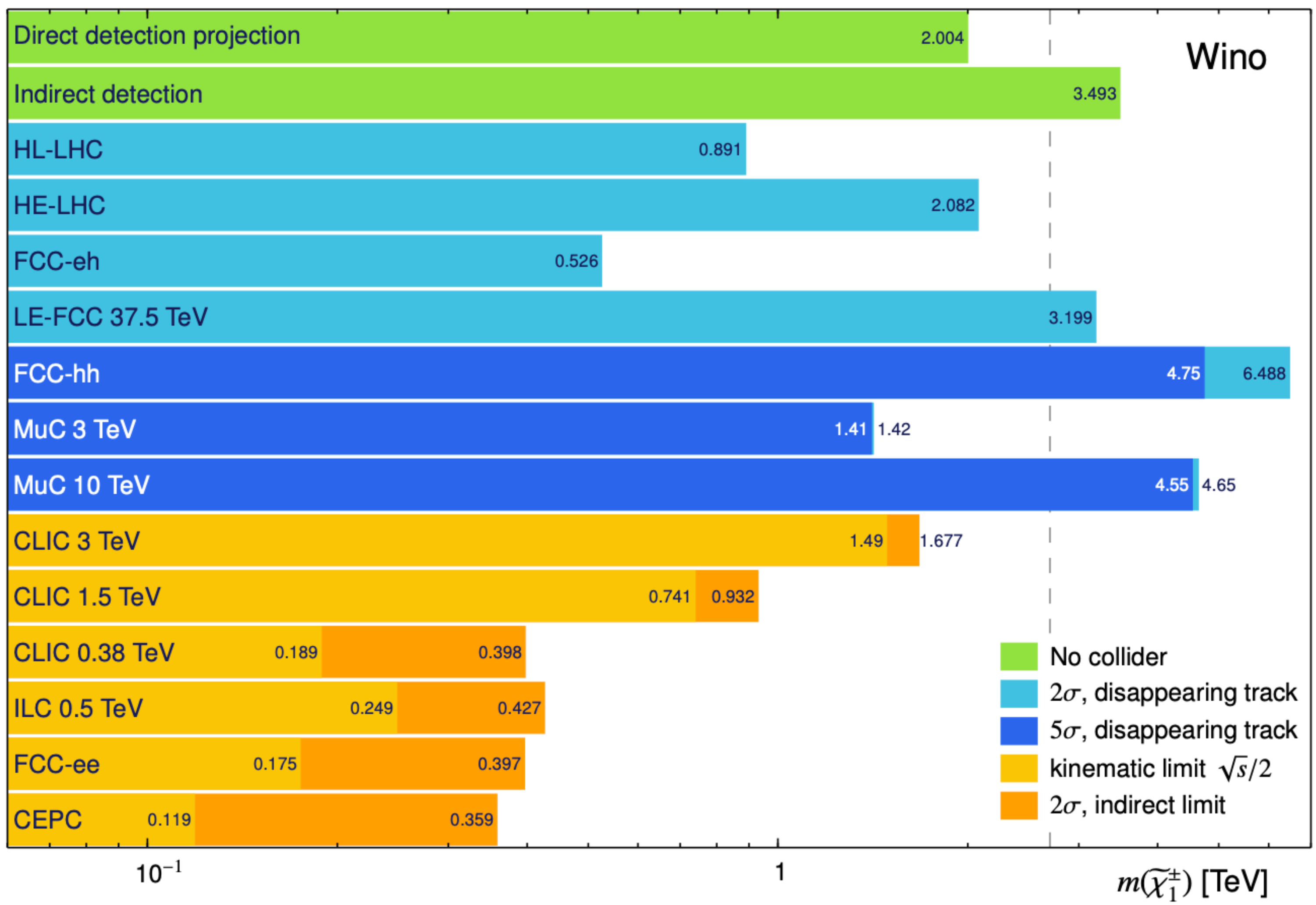
Slide from L.-T. Wang

Preliminary study of searching for "minimal" WIMPs:



T. Han, Z. Liu, L.-T. Wang, X. Wang: 2009.11287

Dedicated study using disappearing tracks on Wino/Bino:



R. Capdevilla, F. Meloni, R. Simoniello, J. Zurita: 2102.11292

Predictions untested

Another reminder: the SM Higgs boson is very special:

Couplings to massive gauge bosons → $$\left(\frac{2m_W^2}{v}\,h\,W_\mu^+W^{-\mu} + \frac{m_Z^2}{v}\,h\,Z_\mu Z^\mu\right)$$

Couplings to massless gauge bosons →

$$+c_g\frac{\alpha_s}{12\pi v}h\,G_{\mu\nu}^a G^{a\,\mu\nu} + c_\gamma\frac{\alpha}{8\pi v}h\,F_{\mu\nu}F^{\mu\nu} + c_{Z\gamma}\frac{\alpha}{8\pi v s_w}\,h\,F_{\mu\nu}Z^{\mu\nu}$$

$$c_g^{(SM)}(125\text{ GeV}) = 1\ , \qquad c_\gamma^{(SM)}(125\text{ GeV}) = -6.48\ , \qquad c_{Z\gamma}^{(SM)}(125\text{ GeV}) = 5.48\ .$$

Couplings to fermions → $$\sum_f \frac{m_f}{v}h\bar{f}f$$

Self-couplings → $$\frac{1}{2}m_h^2h^2 + \frac{m_h^2}{v}h^3 + \frac{2m_h^2}{v^2}h^4$$

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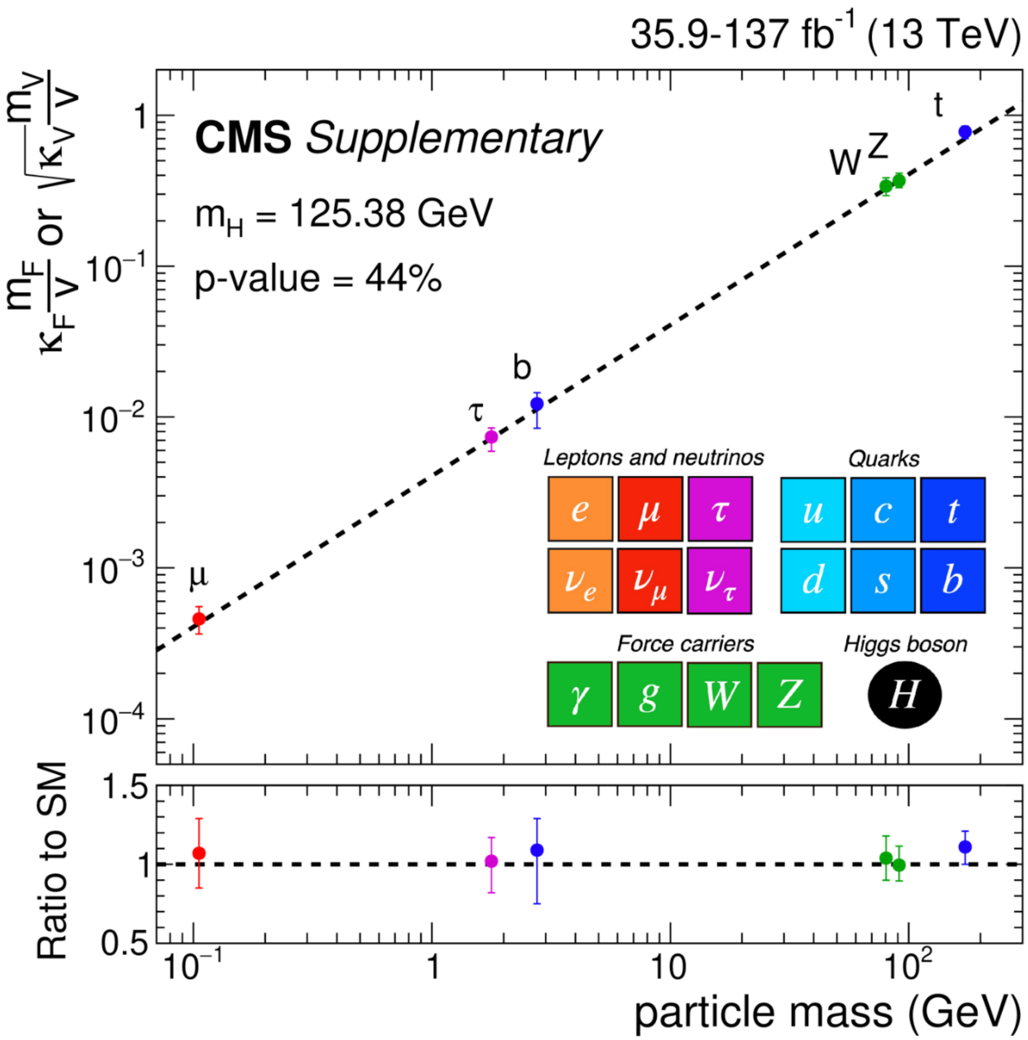
A non-trivial prediction:

There is no free parameters (once all masses are measured)!

- **Prioritize couplings which have yet to be established experimentally:**

We need to keep pursuing Yukawa couplings to 1st and 2nd generation fermions.



Muon collider offers some promise in direct measurements from Higgs decays:

Fit Result [%]

	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

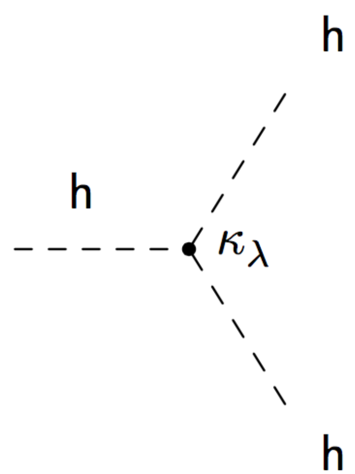
Table 3: Results of a 10-parameter fit to the Higgs couplings in the κ-framework, based on the attainable precision in each on-shell Higgs production and decay channel listed in Table 2. Additionally, we include the effects of adding data sets projected from the HL-LHC and a 250 GeV e^+e^- Higgs factory. One should keep in mind that a muon collider will also strongly constrain Higgs properties via off-shell measurements, which are not included here.

Muon Smasher's Guide: 2103.14043

In addition to Yukawas, there are two important classes of Higgs couplings that have yet to be established <u>experimentally</u>:

- Higgs self-couplings:

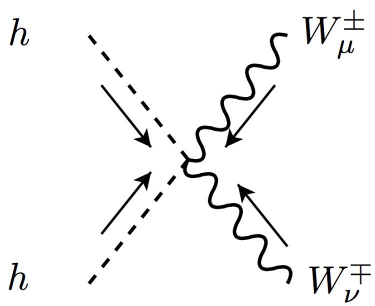
  This can be measured in the double-Higgs production



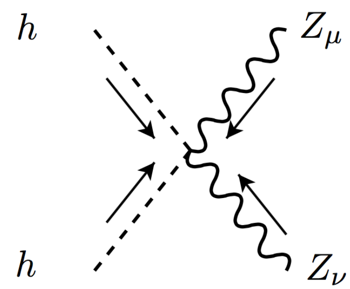
It is difficult to measure at the LHC, but experimental colleagues are making some progress.

- The second class of coupling, however, is still largely missing from the picture -- the HHVV coupling

$$D_\mu H^\dagger D^\mu H \;\supset\; g^2 h^2 V_\mu V^\mu$$



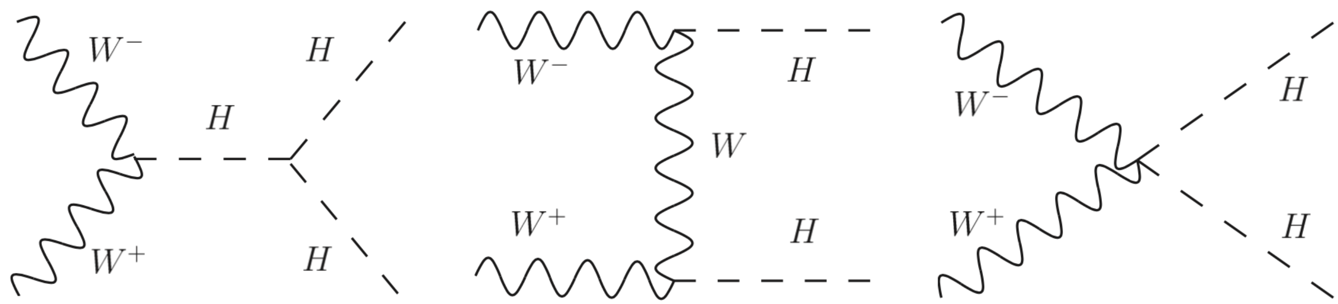
$$\frac{i}{2} g^2 g_{\mu\nu}$$



$$\frac{i}{2} \frac{g^2}{\cos^2\theta_W} g_{\mu\nu}$$

This is a prediction of gauge invariance!

- At a lepton collider, both the trilinear and quartic couplings can be probed in double Higgs production through VBF:



(a) (b) (c)

Notice the process is sensitive to **both** HHH and WWHH couplings!

- Using the M_{HH} shape information, it is possible to constrain both couplings at the same time:

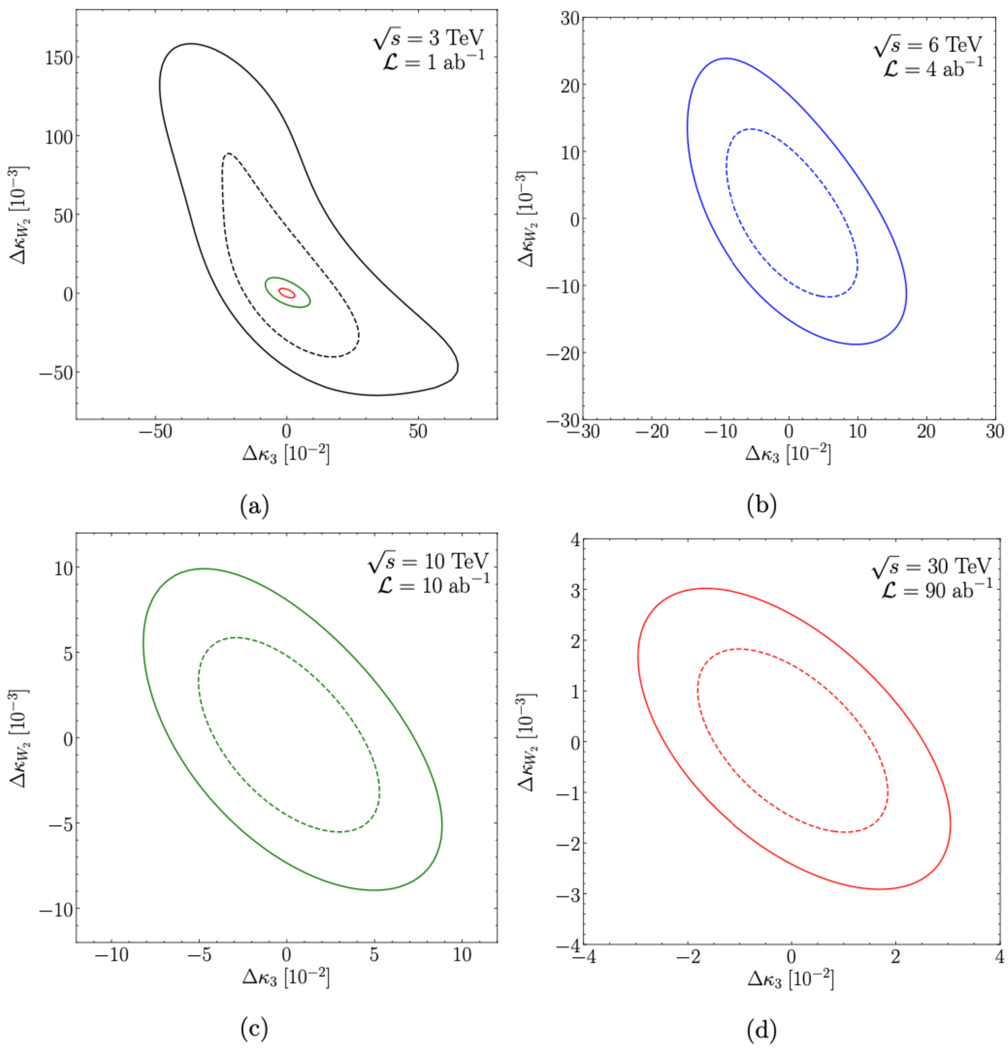
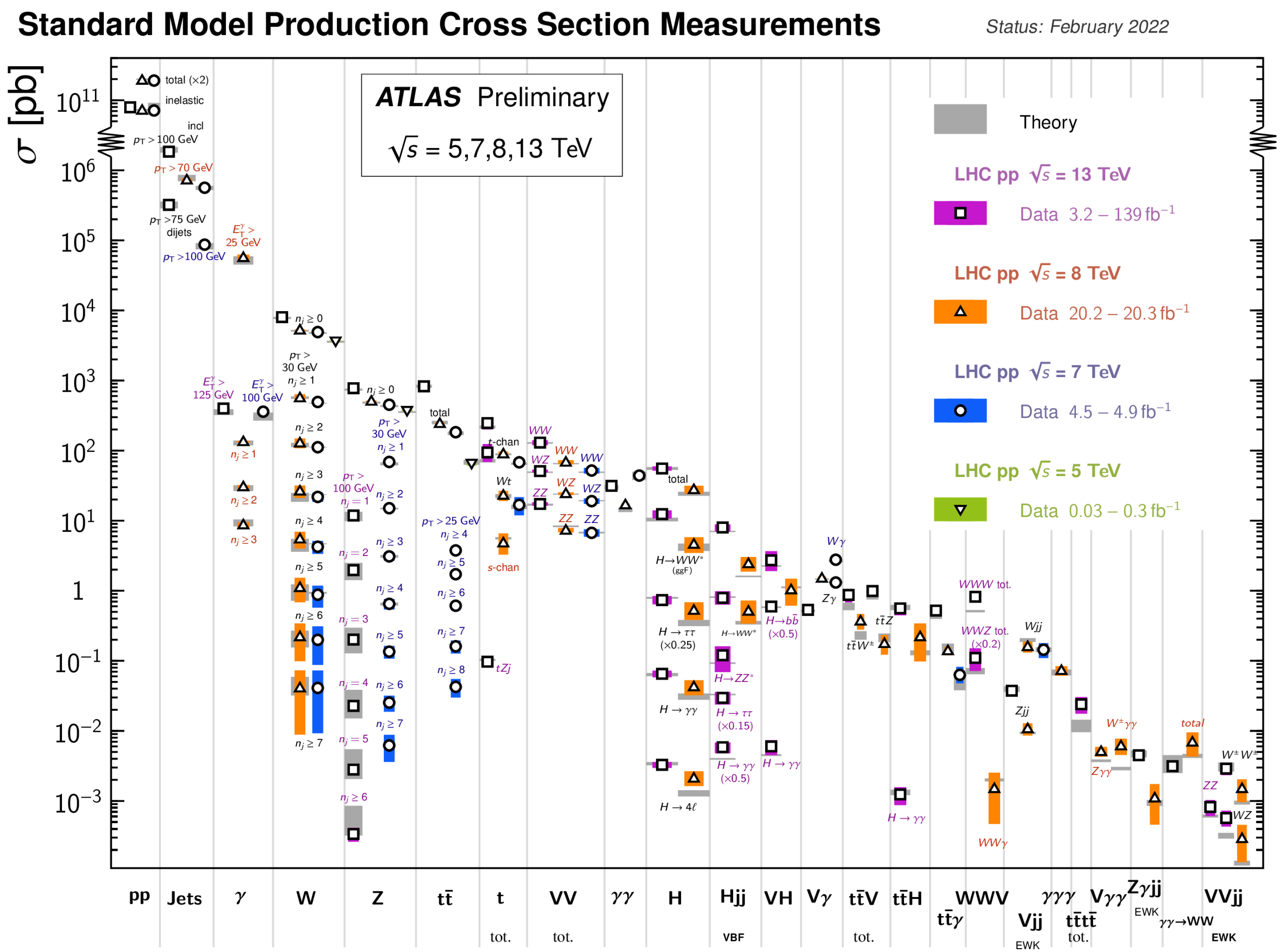


Figure 7: Correlated bounds with 95% C.L. (solid) and 68% C.L. (dashed) in the $\Delta\kappa_{W_2}$-$\Delta\kappa_3$ plane for $\sqrt{s} = 3, 6, 10, 30$ TeV, respectively. In (a), inner ellipses (solid) include the 95% C.L. results for 10 TeV and 30 TeV for comparison.

T. Han, D. Liu, IL, X. Wang: 2008.12204

Our experimental colleagues have been systematically testing SM by going to higher multiplicities:

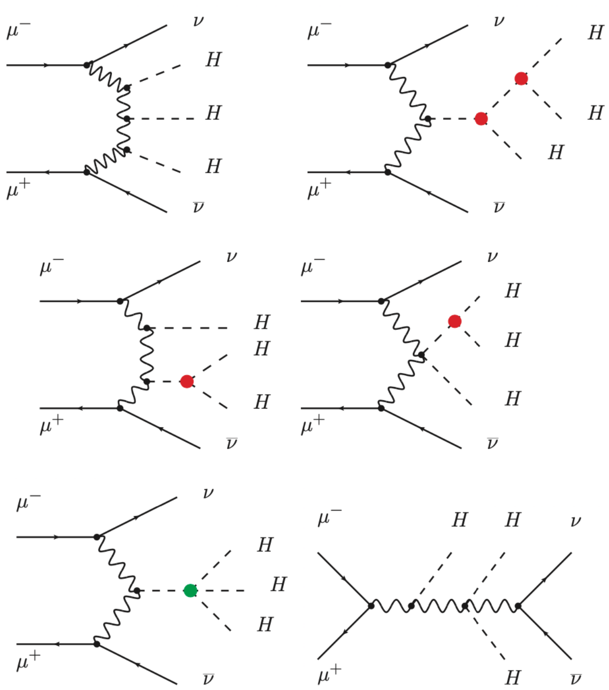


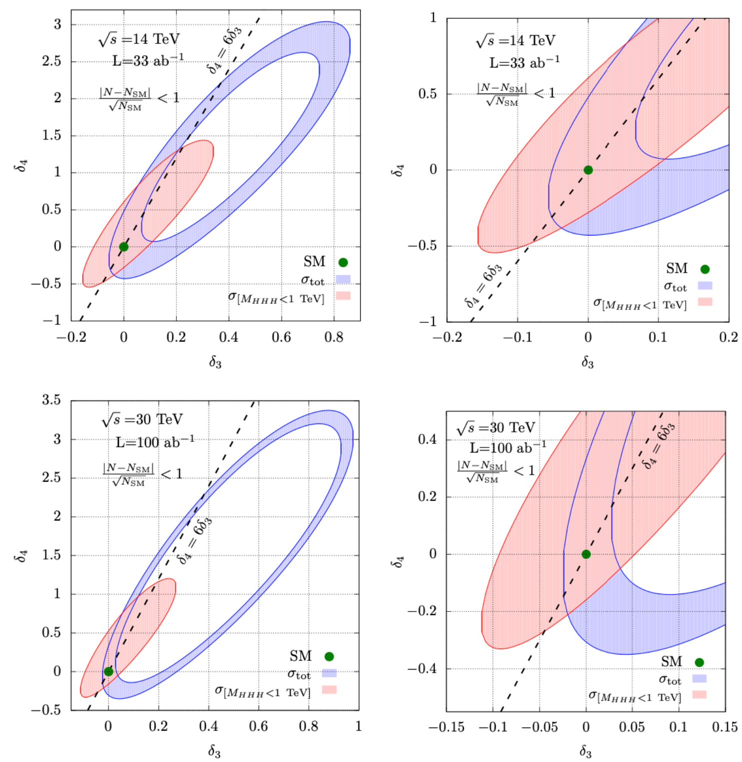
As we go to very high energies, need to do the same for the Higgs!

- HHH and HHHH final states have not been searched for experimentally. **What are the SM predictions??**

This is a new frontier waiting to be explored further. There's a study on HHH final state at the Muon collider:

Chiesa et al: 2003.13628

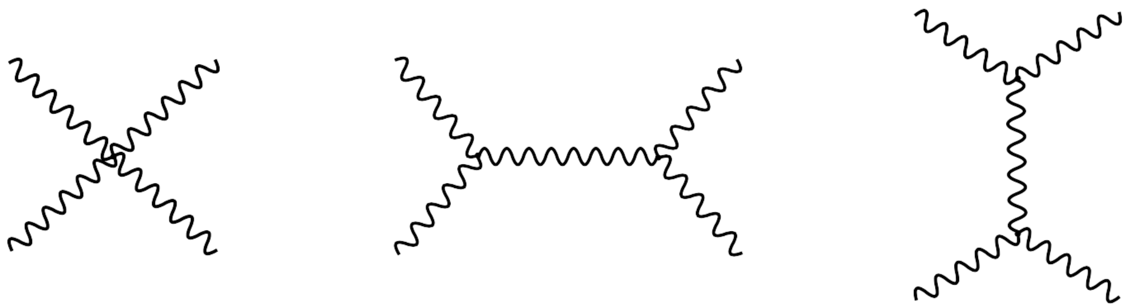




See also: IL, N. Shah, X. Wang: 2012.00773; Egana-Ugrinovic, Homiller, Meade: 2101.04119
C.-W. Chiang, T.-K. Kuo, IL: 2202.02954

- Would like to single out one very important prediction of SM Higgs to be tested precisely:

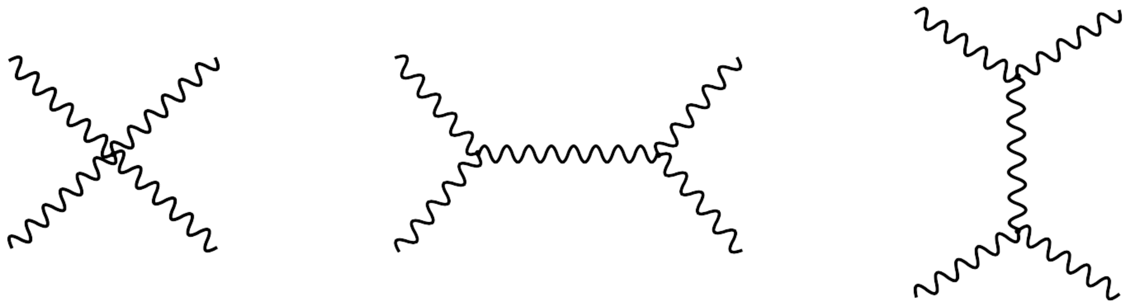
  Without the Higgs, WW scattering amplitude violates unitarity:

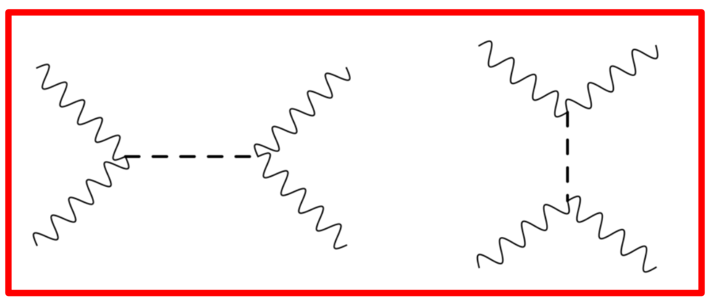


$$\mathcal{A}(W_L^+W_L^- \to W_L^+W_L^-) \simeq \frac{g^2}{4m_W^2}(s+t) \ .$$

- Would like to single out one very important prediction of SM Higgs to be tested precisely:

  Including the Higgs contribution allows the growth to be cancelled completely,





provided the HWW coupling have precisely the form in the SM!

This is an extremely simple and economical solution, except…

Nature has never chosen this simple solution before…

(Recall we have NOT observed a fundamental scalar previously!)

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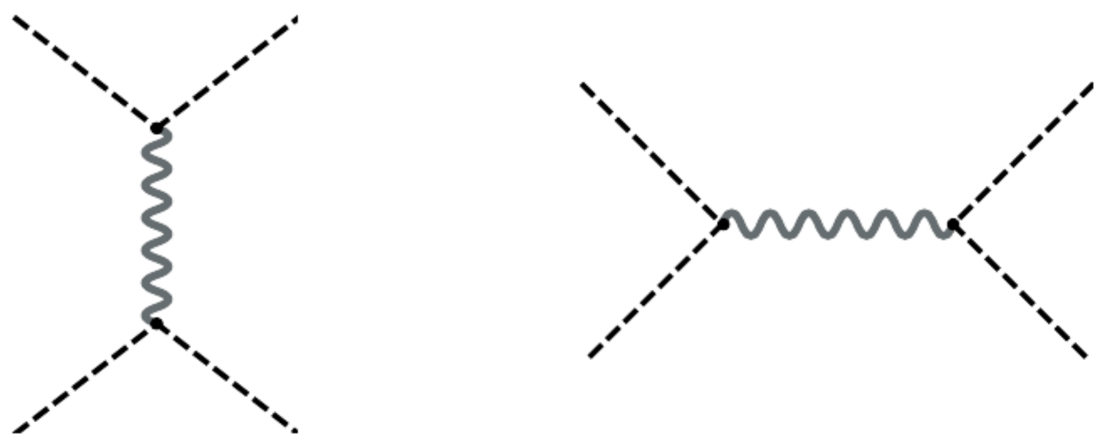
(Recall we have NOT observed a fundamental scalar previously!)

For example, pi-pi scattering in low-energy QCD is unitarized by a series of heavy resonances, including the spin-1 rho meson:



Each resonance only partially unitarizes the pi-pi scattering.

If the 125 GeV Higgs only partially unitarize the VV scattering

→ the HVV coupling will deviate from the SM expectation!!

Unitarization in VV scattering is only tested with O(10%) uncertainty.

→ Clearly not sufficient!

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→ Clearly not sufficient!

To test this prediction we need

- More precise measurements of HVV couplings.
- Direct measurements of VV scatterings.

How precise is precise enough?

By accident, generic deviations from SM are quadratic in $1/M_{\text{new}}$:

$$\mathcal{O}\left(\frac{v^2}{M_{\text{new}}^2}\right) \sim 5\% \times \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2$$

To establish credible deviations we need percent level precision!

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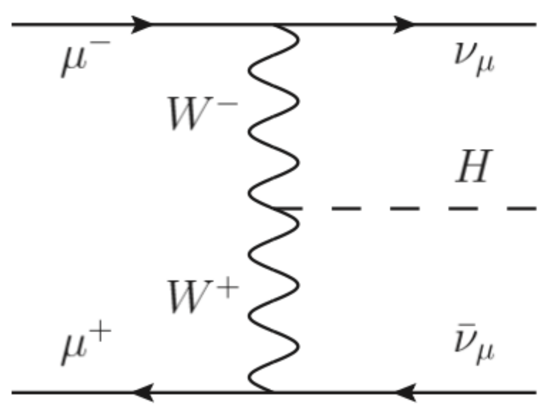
At a high energy muon collider, single Higgs production goes through the VBF topology. Moreover, both WW and ZZ fusion need to be considered:

$$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu\ H \qquad (WW\ \text{fusion}),$$
$$\mu^+\mu^- \to \mu^+\mu^-\ H \qquad (ZZ\ \text{fusion}).$$



However, in the ZZ fusion channel, the outgoing muons are very forward and may escape detections:

T. Han, D. Liu, IL, X. Wang: 2008.12204

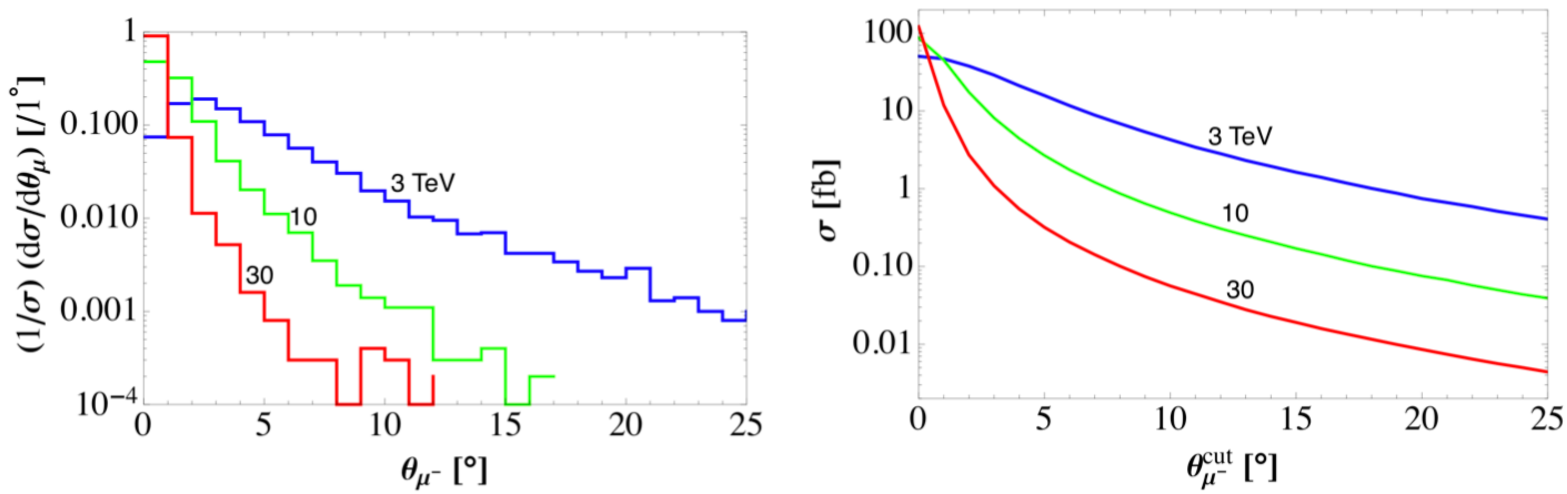


Figure 3: $\mu^+\mu^- \to \mu^+\mu^- H$ via ZZ fusion with $\sqrt{s} = 3, 10$ and 30 TeV for (a) angular distribution θ_{μ^-}, and (b) total cross section versus an angular cut $\theta^{\rm cut}_{\mu^-}$.

This led to the notion of a "inclusive process,"

- Inclusive channel: events from WW fusion and from ZZ fusion without detecting muons;

similar to that at a hadron collider!

A preliminary study using the "kappa" formalism at the muon collider:

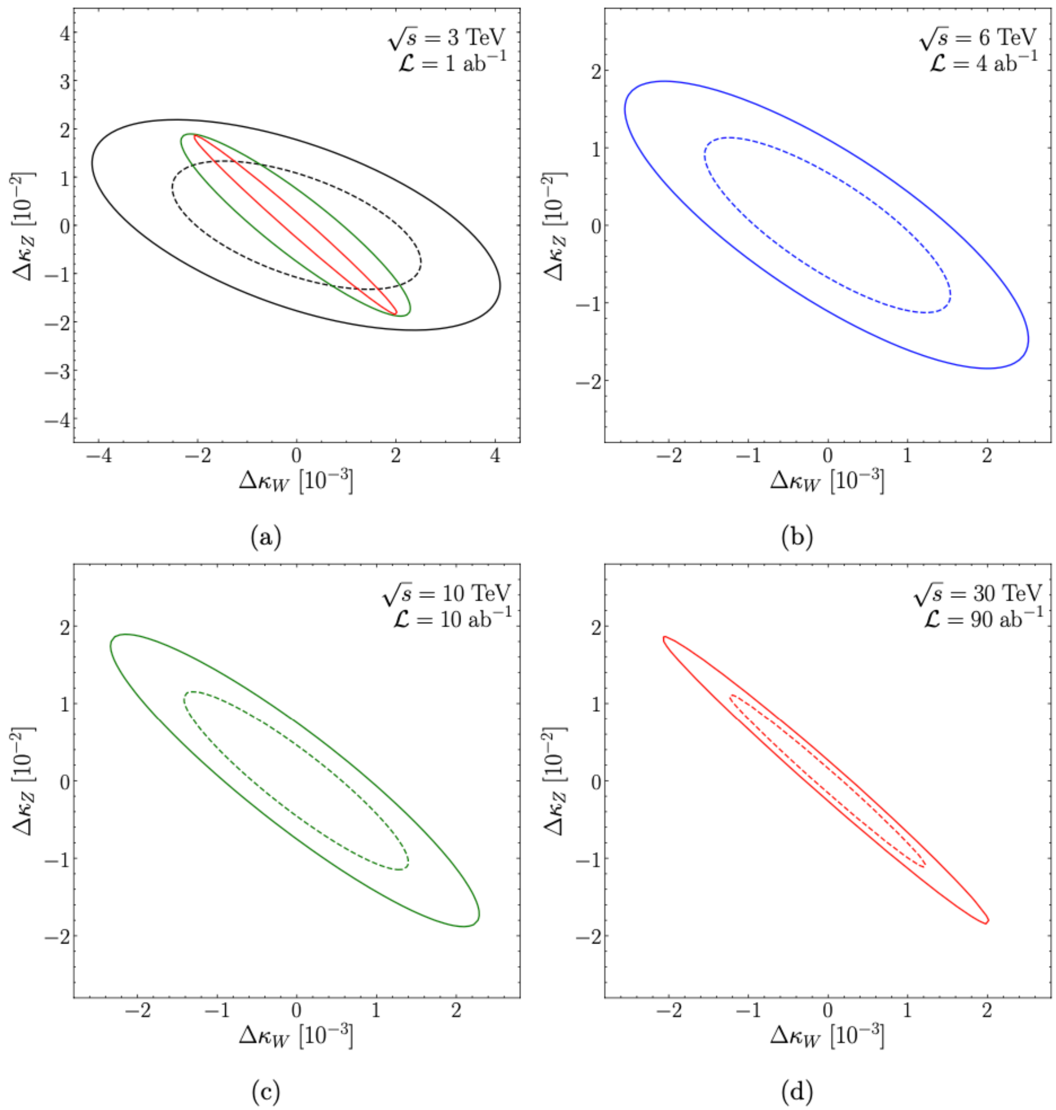
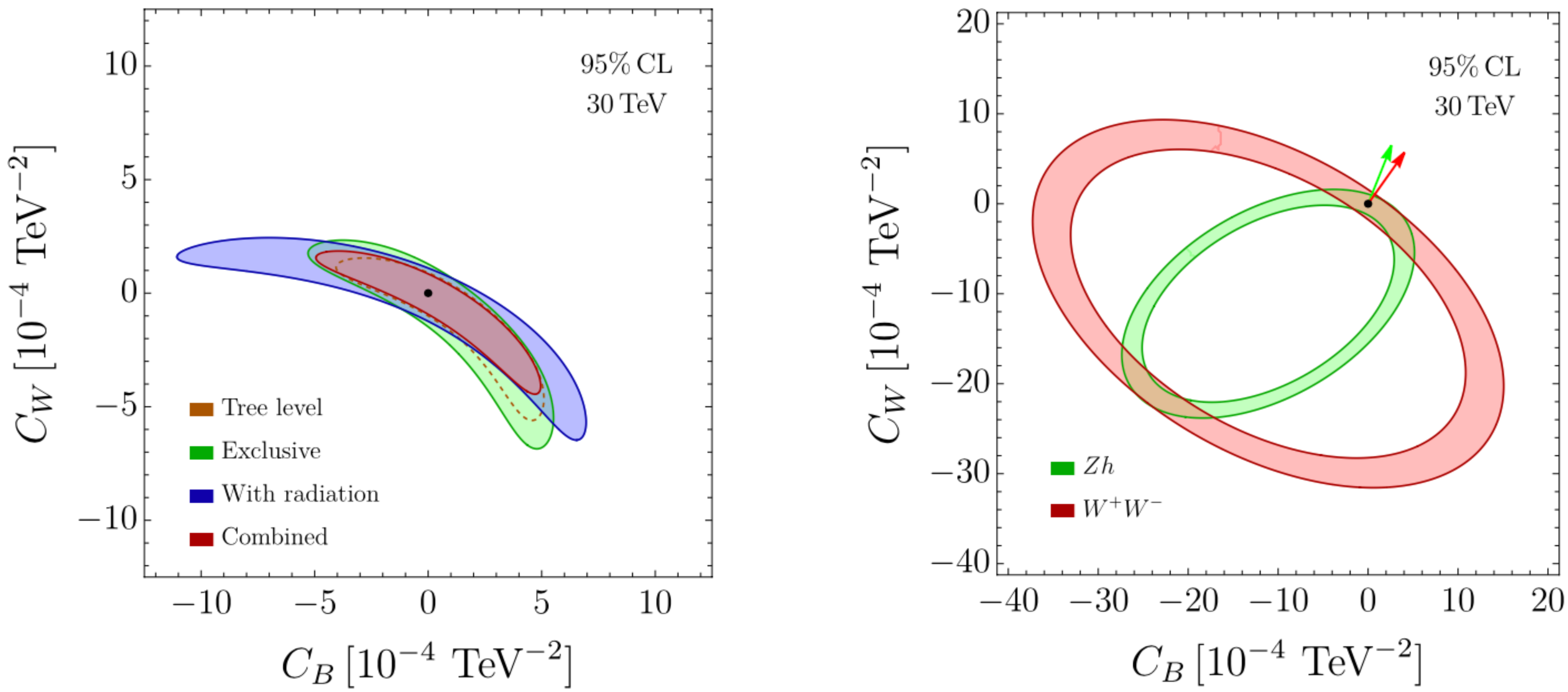


Figure 6: Correlated bounds with 95% C.L. (solid) and 68% C.L. (dashed) in the $\Delta\kappa_W$-$\Delta\kappa_Z$ plane for $\sqrt{s} = 3, 6, 10, 30$ TeV, respectively. In (a), inner ellipses (solid) include the 95% C.L. results for 10 TeV and 30 TeV for comparison.

VV scattering (and diboson final states) have received some attention at the Muon collider:

Di-boson	$O_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$ $O_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$



D. Buttazzo, R. Franceschini, A. Wulzer: 2012.11555
A. Wulzer et. al.: 2202.10509

A New Regime of QFT

At 10 TeV, the SM enters into a new regime of QFT which has never been studied/observed previously:

$$E \gg m_W \qquad\qquad (\text{Casimir}) \times \frac{\alpha_2}{\pi} \log^2 \frac{E}{m_W} \sim \mathcal{O}(1)$$

We will observe enhanced electroweak radiations in a *nearly* massless non-abelian gauge theory!

This is not dissimilar to QCD and QED in the high energy regime (E>> Λ_{QCD} and E >>μ_{IR}), with one crucial difference:

At 10 TeV, the SM enters into a new regime of QFT which has never been studied/observed previously:

$$E \gg m_W \qquad\qquad (\text{Casimir}) \times \frac{\alpha_2}{\pi} \log^2 \frac{E}{m_W} \sim \mathcal{O}(1)$$

We will observe enhanced electroweak radiations in a *nearly* massless non-abelian gauge theory!

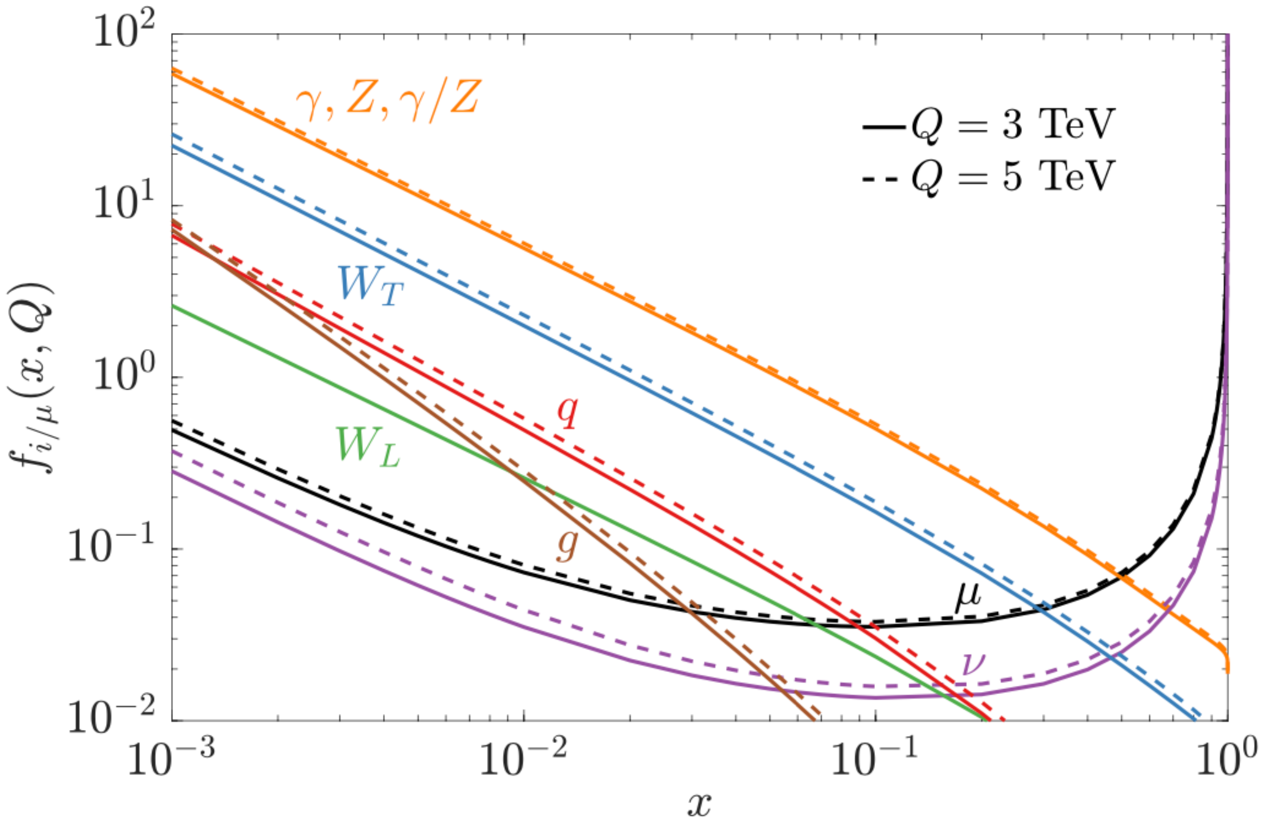
This is not dissimilar to QCD and QED in the high energy regime (E>> Λ_{QCD} and E >>μ_{IR}), with one crucial difference:

Electroweak symmetry is broken and electroweak ”color” is observable!

This is a new phase of non-abelian gauge theory we would not be able to study/observe at lower energies or elsewhere!

There are several novel features in this regime of broken gauge theory:

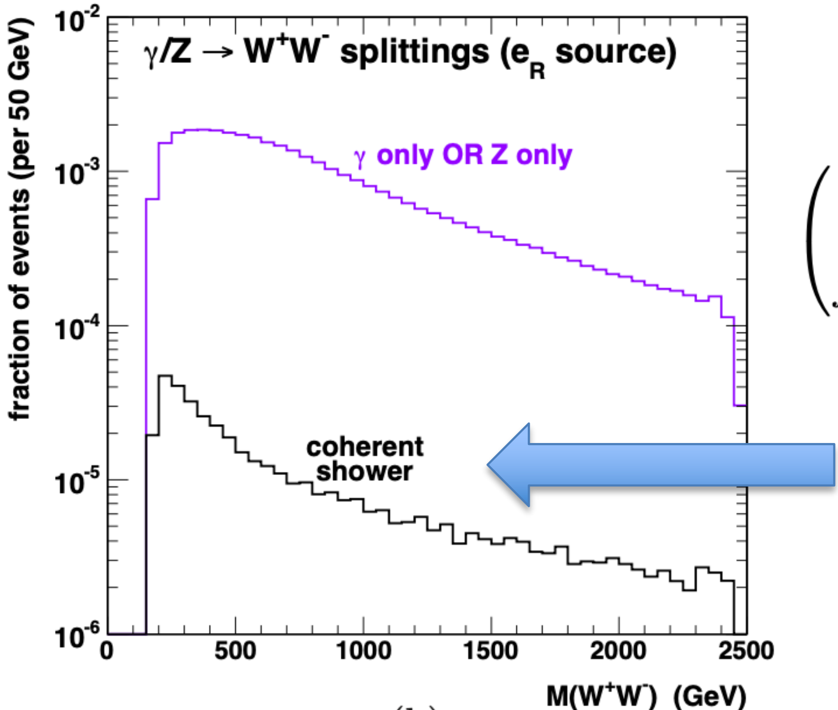
- The muon effectively becomes a composite particle and the collision is described by electroweak parton distribution functions:



T. Han, Y. Ma, K. Xie: 2007.14300; 2103.09844

(See also A. Constantini et. al.: 2005.10289; S. Chen et. al.: 2202.10509.)

More importantly, at energies far above the EW scale, the PDFs evolve according to **unbroken** SU(2)xU(1) gauge theory, meaning it's crucial to take into account B-W^3 mixing and interference effects:



(b)

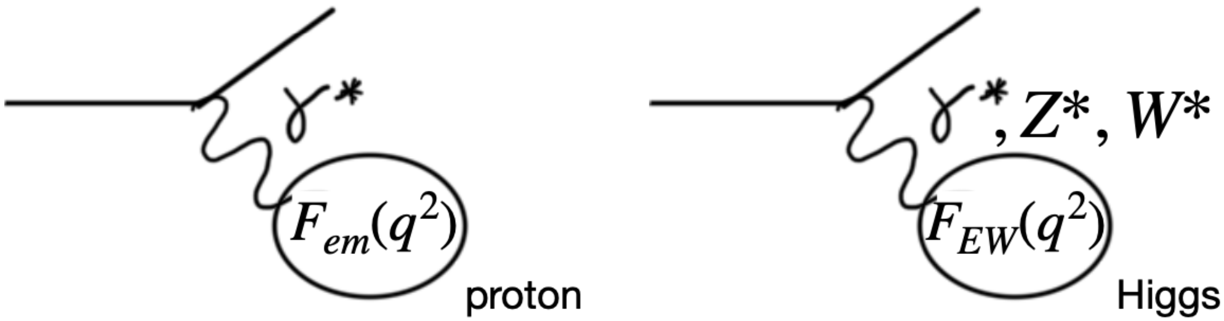
J. Chen, T. Han, B. Tweedie: 1611.00788

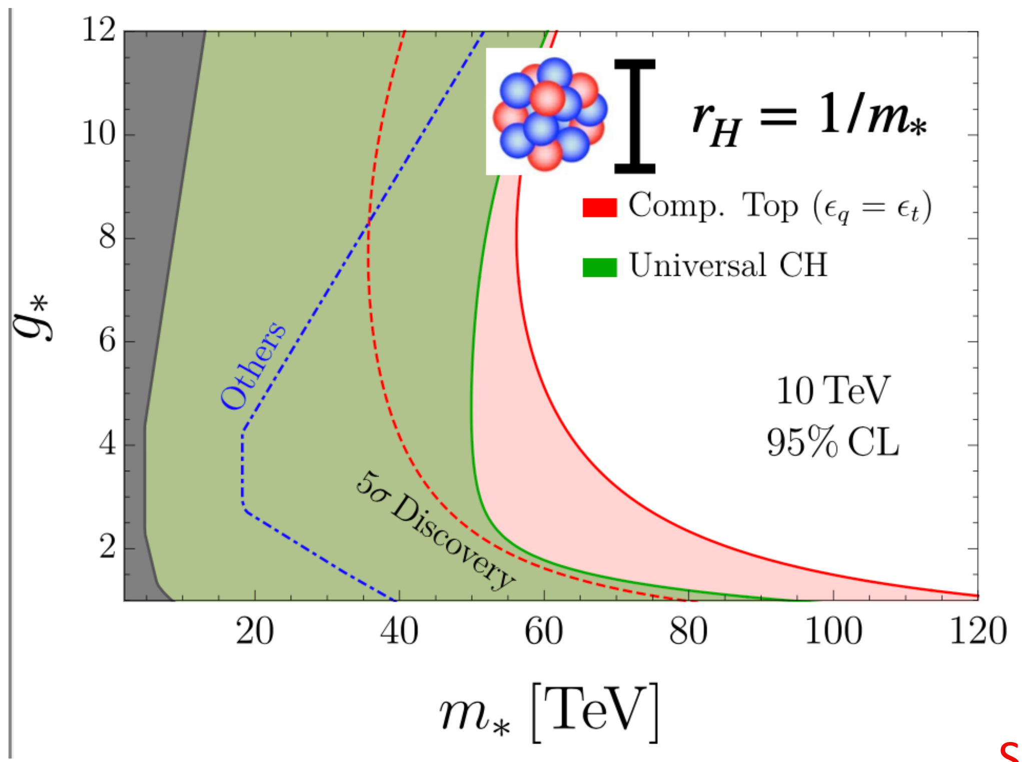
$$\begin{pmatrix} f_B \\ f_{W^3} \\ f_{BW^3} \end{pmatrix} = \begin{pmatrix} c_W^2 & s_W^2 & -c_W s_W \\ s_W^2 & c_W^2 & c_W s_W \\ 2c_W s_W & -2c_W s_W & c_W^2 - s_W^2 \end{pmatrix} \begin{pmatrix} f_\gamma \\ f_Z \\ f_{\gamma Z} \end{pmatrix}$$

Retaining B-W^3 interference!

This is an important prediction of SM, which need to be further refined and tested at a high energy lepton collider!

- There is a process that is an analogy of Deep Inelastic Scattering, which probes the "compositeness" of the Higgs:

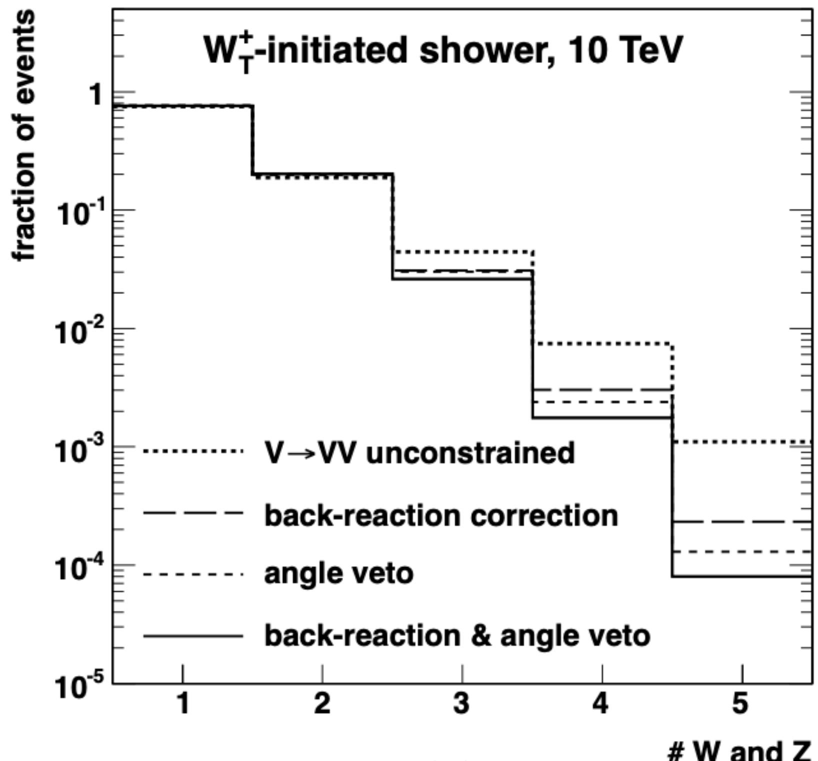




Slides from A. Wulzer

The need to consider electroweak “parton showering” gives rise to the concept of ”weak jets.”

One example is multiple collimated EW bosons initiated from transverse gauge bosons:

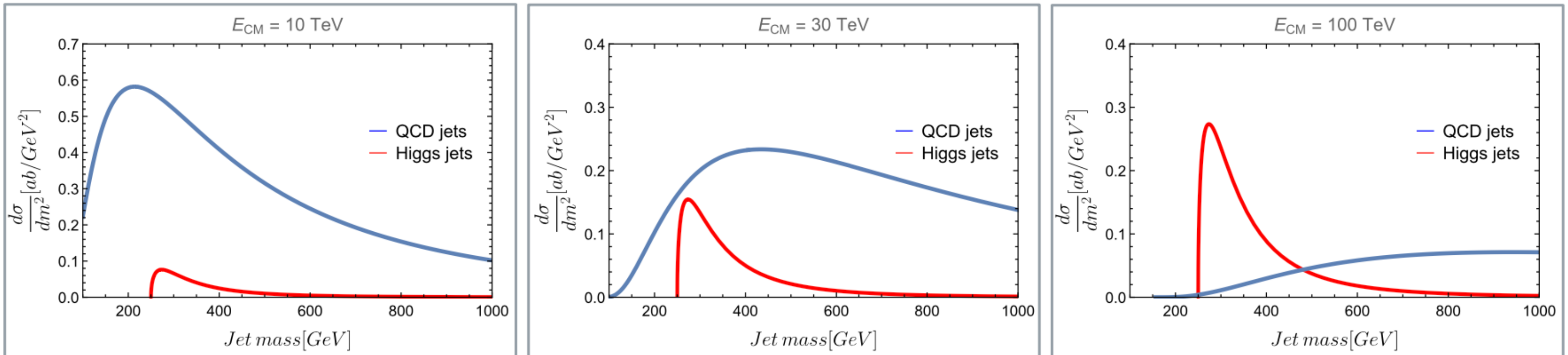


(b)

J. Chen, T. Han, B. Tweedie: 1611.00788

One could also have "Higgs jet," which have distinct features due to the presence of "super-renormalizable" trilinear coupling:

COMPARISON PLOTS



$C_{EW}^{(1)}\ (10\ TeV) = -1.178$ $\quad$ $C_{EW}^{(1)}\ (30\ TeV) = -1.984$ $\quad$ $C_{EW}^{(1)}\ (100\ TeV) = -3.108$

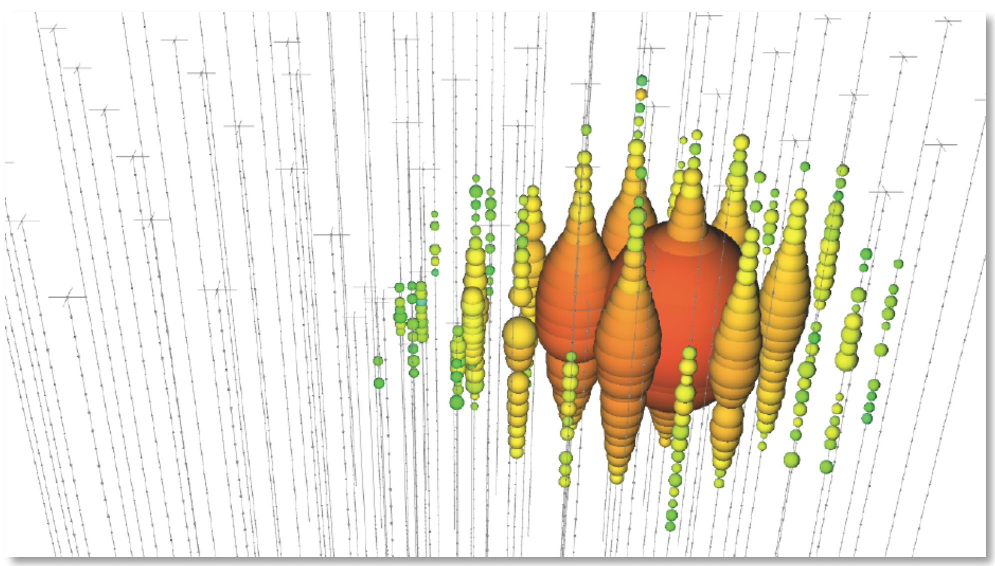
Preliminary work by J. Desai and G. Sterman

Strong Synergies with the Neutrino Frontier

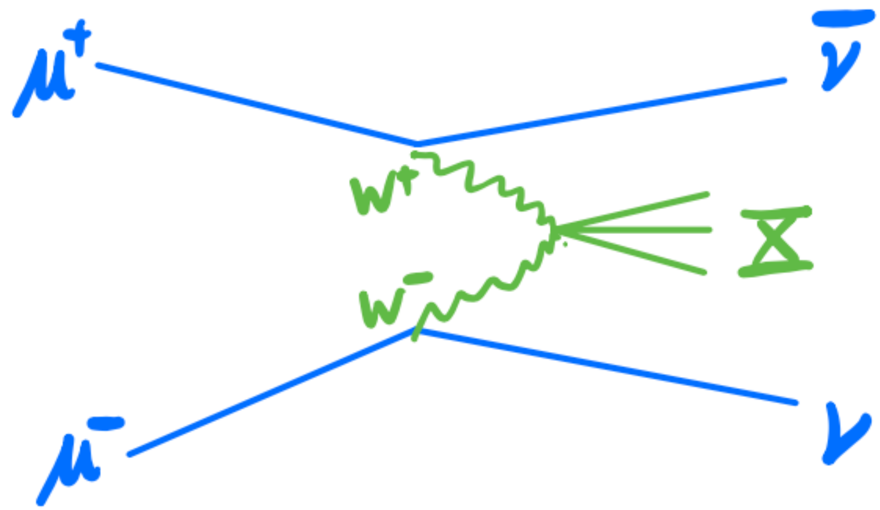
One of the most interesting questions (benchmarks) is the electroweak parton showering of a high energy neutrino:

- Can a very energetic neutrino be "seen" via the final state radiation?
  (A ν-jet ?)

- What about through its interactions with detector materials ??
  (A ν-calorimeter?)

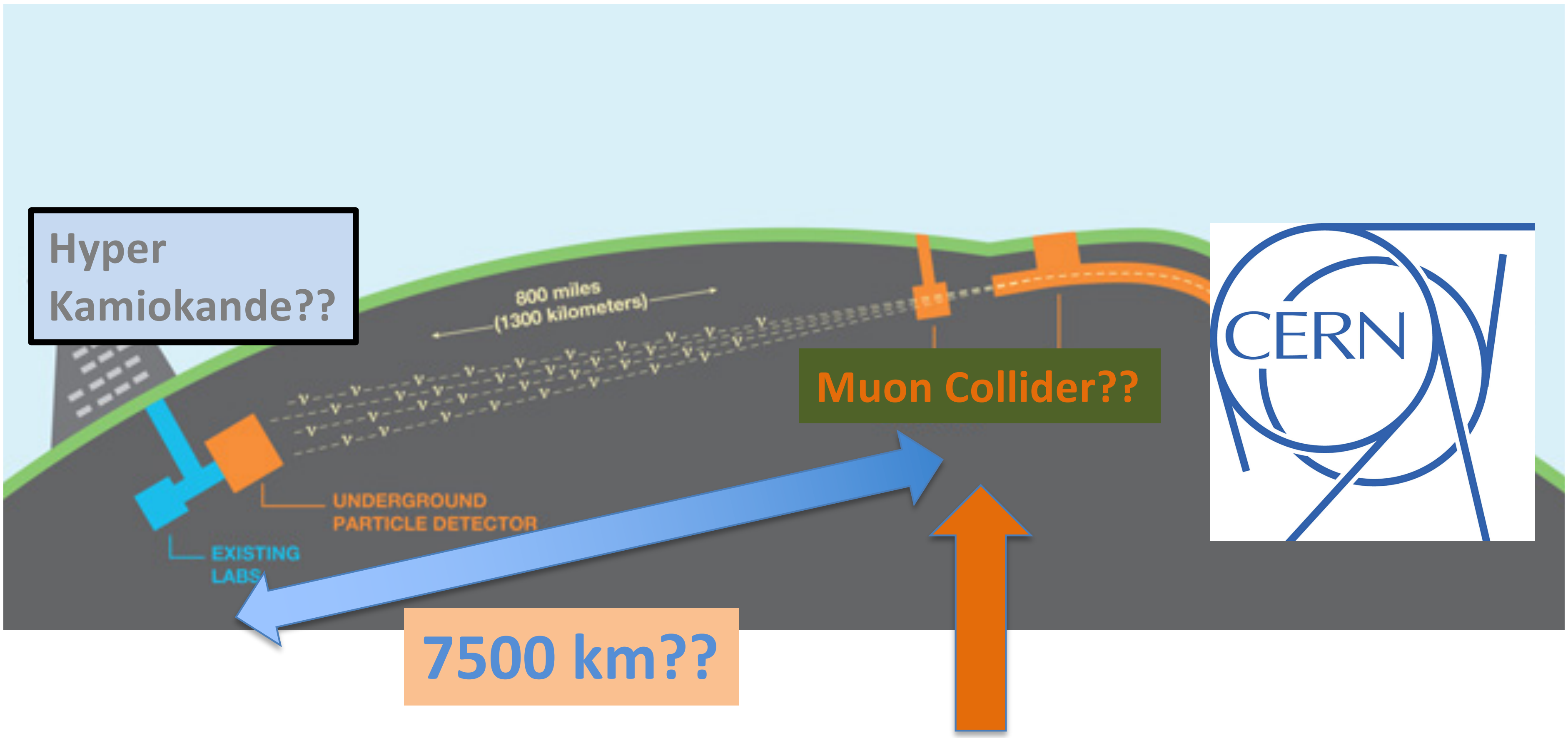


- A high energy muon beam is also a high energy neutrino beam:



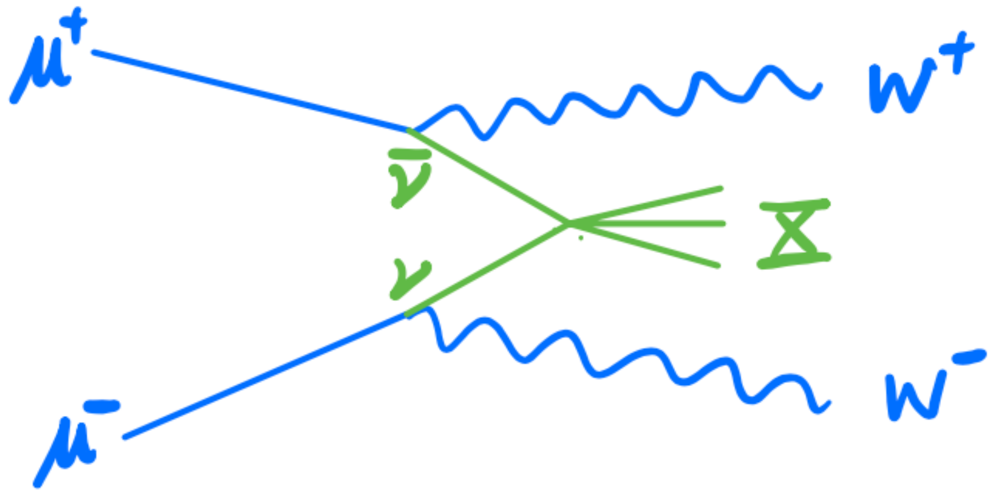
Can we direct the neutrino beam somewhere and do some neutrino physics?

A suggestion by R. Kitano, a colleague at KEK:



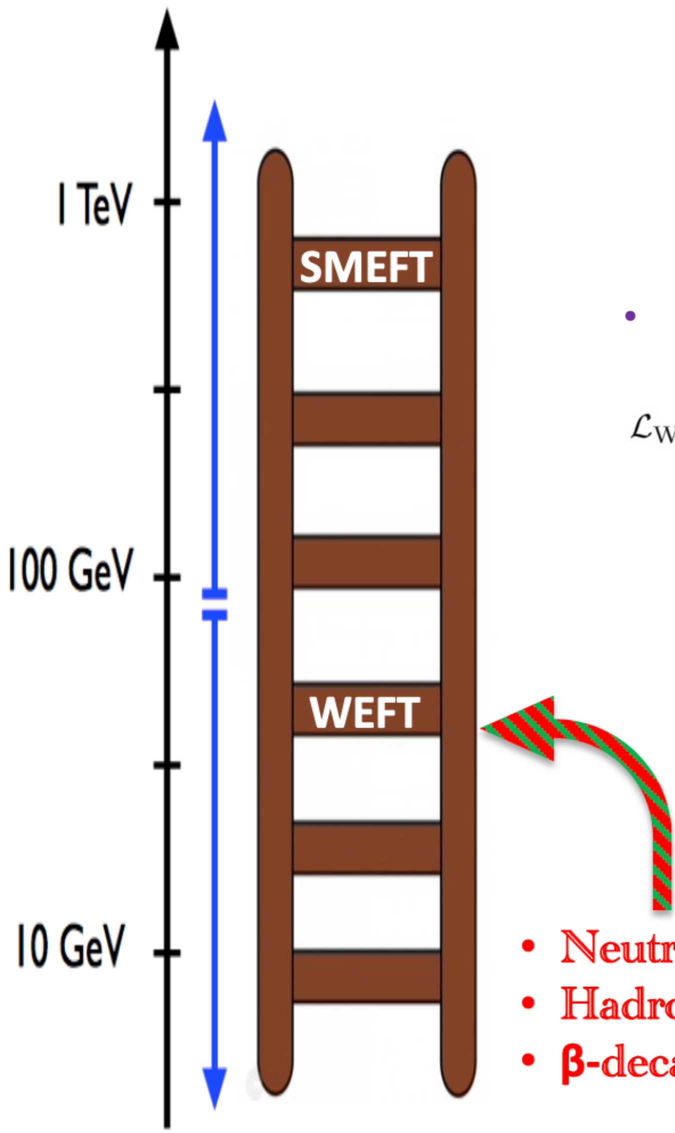
Much higher energy neutrino beam.
Matter effects are more important!

- A high energy muon collider is also a high energy neutrino collider:



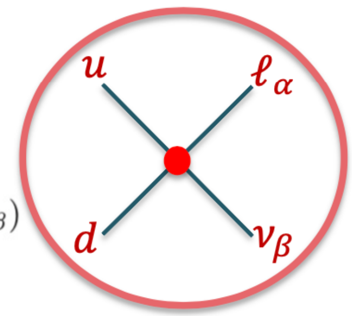
Could provide constraints to Non-standard Interactions that are complementary to low-energy probes!

EFT ladder



- CC: New left/right handed, (pseudo)scalar and tensor interactions

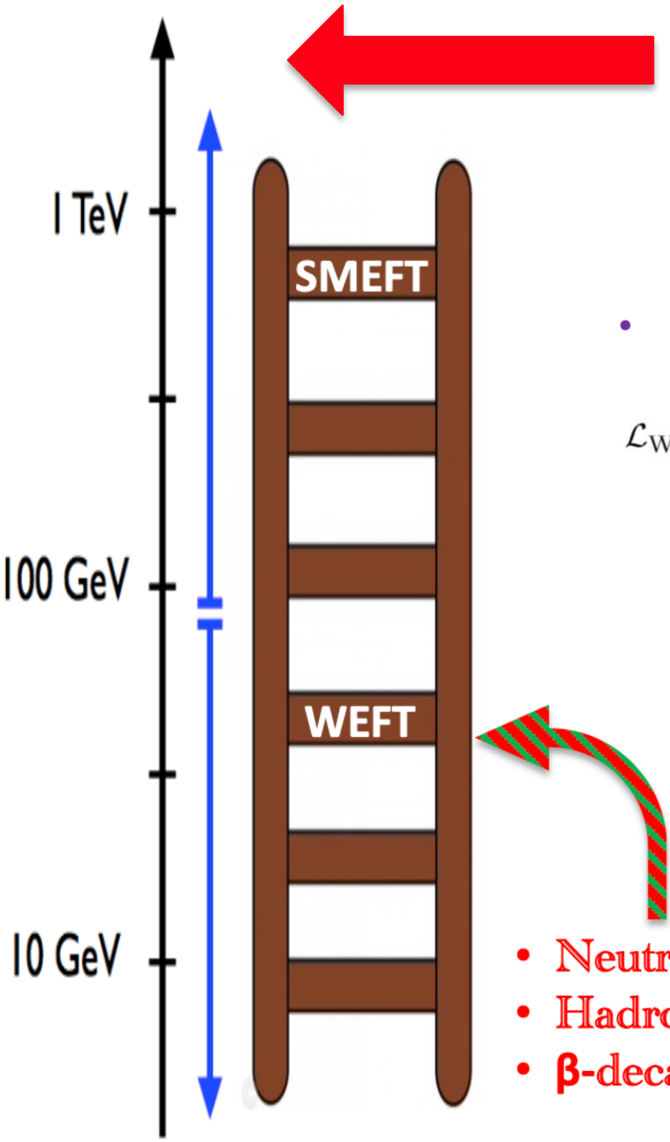
$$
\begin{aligned}
\mathcal{L}_{\rm WEFT} \supset\; & -\frac{2V_{ud}}{v^2}\Big\{ [\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\
& + [\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\
& + \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L \nu_\beta) \\
& + \frac{1}{4}[\hat{\epsilon}_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu} P_L d)(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta) + \text{h.c.}\Big\}
\end{aligned}
$$



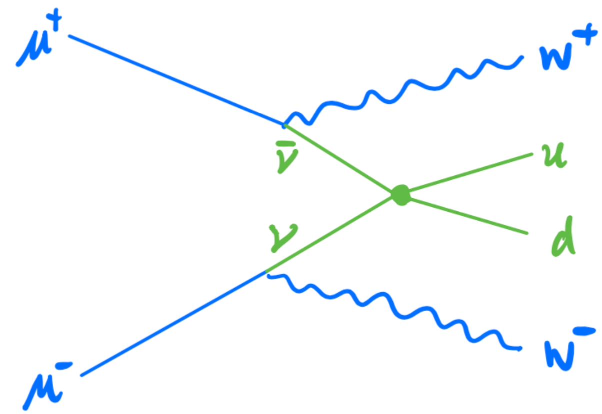
- Neutrino experiments
- Hadron Decays
- **β-decays**

Art work by Z. Tabrizi

EFT ladder



10 TeV MuC:



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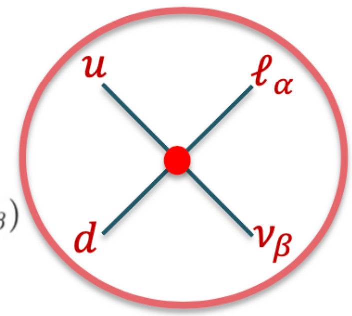
$$\mathcal{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{ [\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L\nu_\beta) + \frac{1}{4}[\hat{\epsilon}_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}$$



- Neutrino experiments
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Art work by Z. Tabrizi

A 10 TeV Muon Collider could:

- Study the microscopic nature of the Higgs boson as the most exotic state of matter in Nature.
- Testing unverified predictions of the SM.
- Explore the last vestiges of WIMP dark matter.
- Observe a new regime of quantum field theories.
- Strong synergies with the neutrino frontier.

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Any BSM discovery will be icing on the cake!!