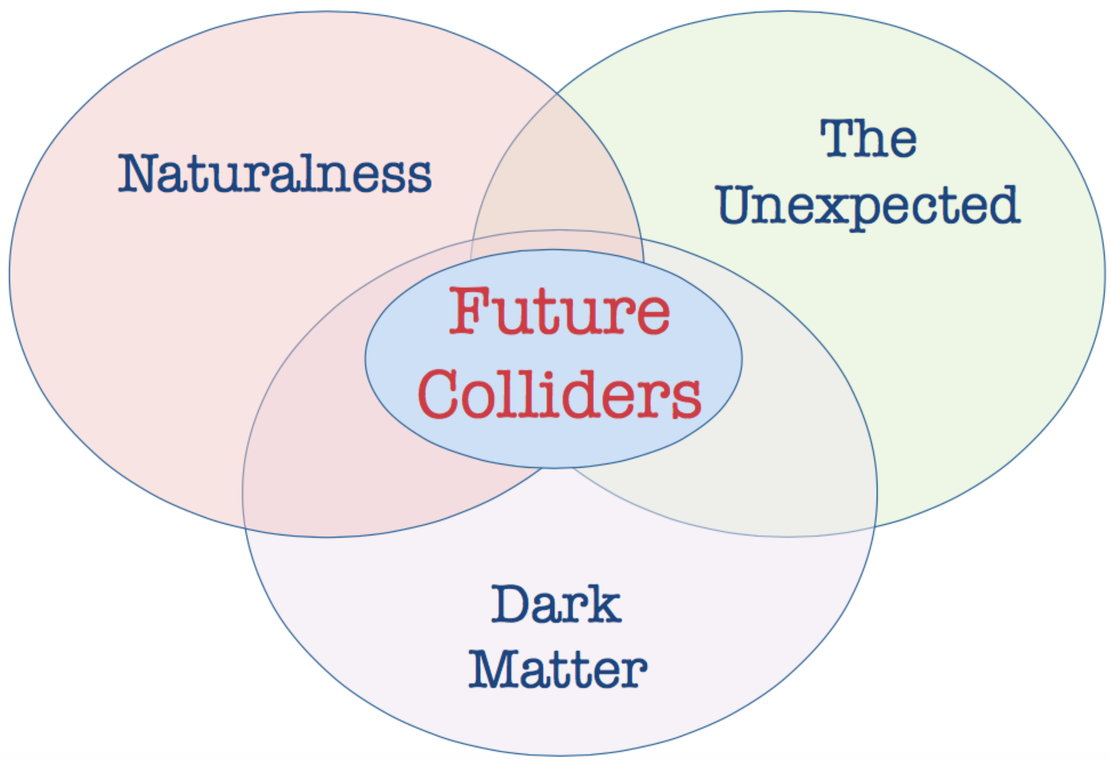
The Standard Model of Particle Physics
What we know and what we do not know

Ashutosh Kotwal
Duke University

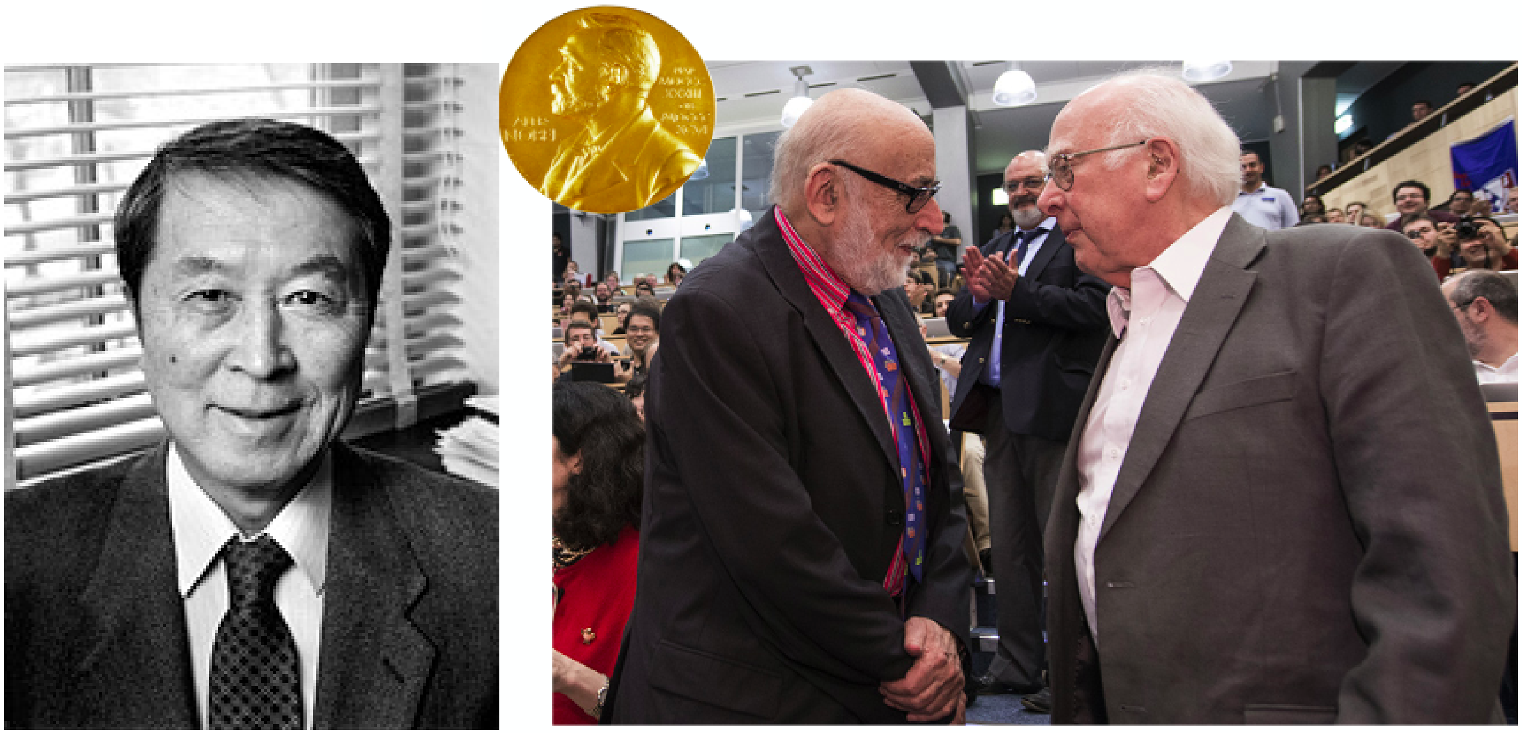


Tata Institute of Fundamental Research
September xxx, 2023

Dawn of a New Age

- 2008 Nobel Prize in Physics

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"



- 2013 Nobel Prize in Physics

  "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"

Old and New Questions

- How to think of the vacuum as a "condensate carrying weak nuclear charge" ?
- How are the mysteries associated with the Higgs field to be solved?
- What is the origin and nature of Dark Matter?
- What is the origin of the matter-antimatter asymmetry in the Universe?
- What is the secret of neutrino masses and mixing?
- Why is Dark Energy so small but non-zero?
- How does SM connect with Gravity?

A Century of Particle Physics

- Success # 1: discovery of 6 quarks and 6 leptons
- 12 fundamental fermions: matter particles (and their antimatter counterparts) derived by combining quantum mechanics and special relativity and group theory

Quarks

$$\mathrm{u} < 1\ \mathrm{GeV} \quad \mathrm{c} \sim 1.5\ \mathrm{GeV} \quad \mathrm{t} \sim 175\ \mathrm{GeV}$$
$$\mathrm{d} < 1\ \mathrm{GeV} \quad \mathrm{s} < 1\ \mathrm{GeV} \quad \mathrm{b} \sim 4.5\ \mathrm{GeV}$$

But the intriguing pattern of mass values is not explained

Leptons

Why 3 generations?

$$\nu_e < 1\ \mathrm{eV} \quad \nu_\mu < 0.17\ \mathrm{MeV} \quad \nu_\tau < 24\ \mathrm{MeV}$$
$$\mathrm{e}\ 0.5\ \mathrm{MeV} \quad \mu\ 106\ \mathrm{MeV} \quad \tau\ 1.8\ \mathrm{GeV}$$

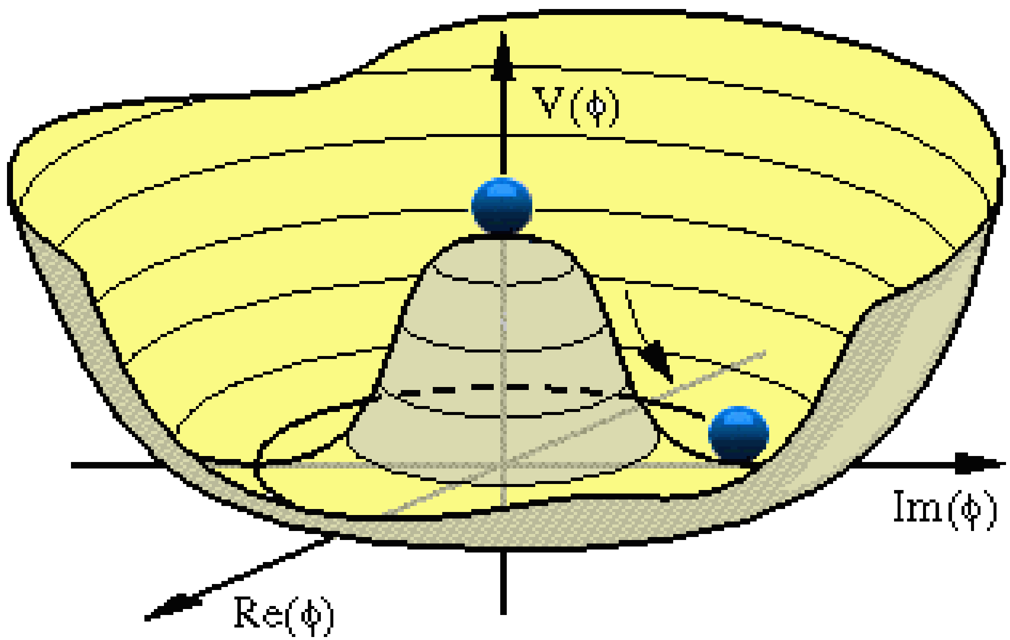
A Century of Particle Physics

- Success # 2: principle of gauge invariance for *predicting* the nature of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - The equations of motion predict terms that describe particle interactions with force fields

Gauge sector $$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

Higgs Condensate Breaks Gauge Symmetry

- Gauge Symmetry predicts all particles should be massless
- Solution: scalar Higgs field develops a condensate that violates the gauge symmetry and generates particle masses via Higgs interactions



- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

Higgs Boson Puzzles

Fundamental *vs* Parametric Physics

- Fundamental principles lead to
  - Chiral fermions from irreducible representations of Lorentz group
    - fermions as spin ½ representations of Lorentz group
    - Fermi-Dirac statistics → Pauli Exclusion Principle
    - why matter occupies volume
  - Massless force mediators (gauge bosons) from gauge invariance
  - Massive gauge bosons and fermions from spontaneous breaking of gauge symmetry

- In comparison, the breaking of gauge symmetry by the Higgs condensate is parametrically induced
  - No dynamic or underlying principle behind it in the Standard Model

Why is Higgs Puzzling

Gauge sector $L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$

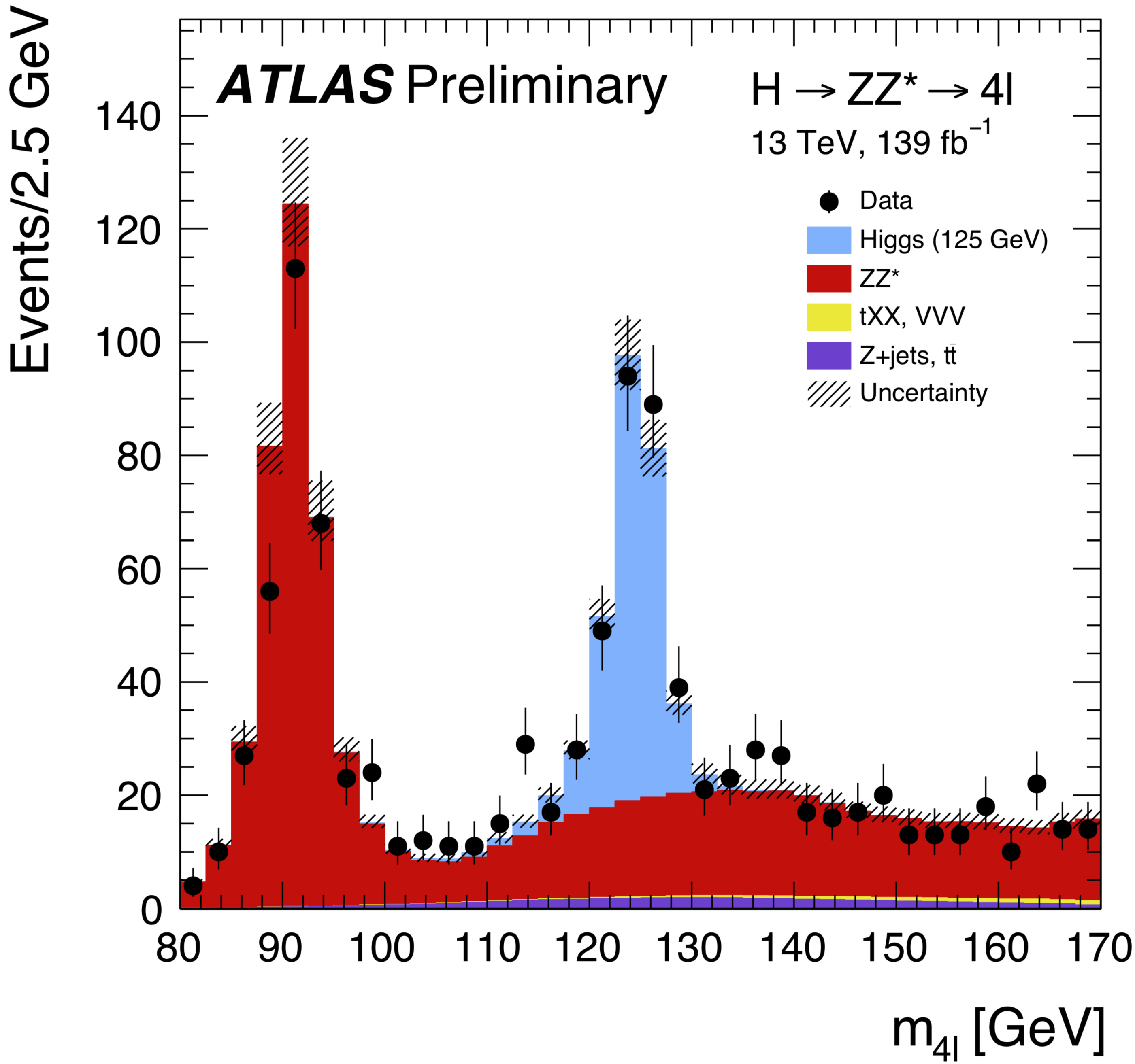
particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

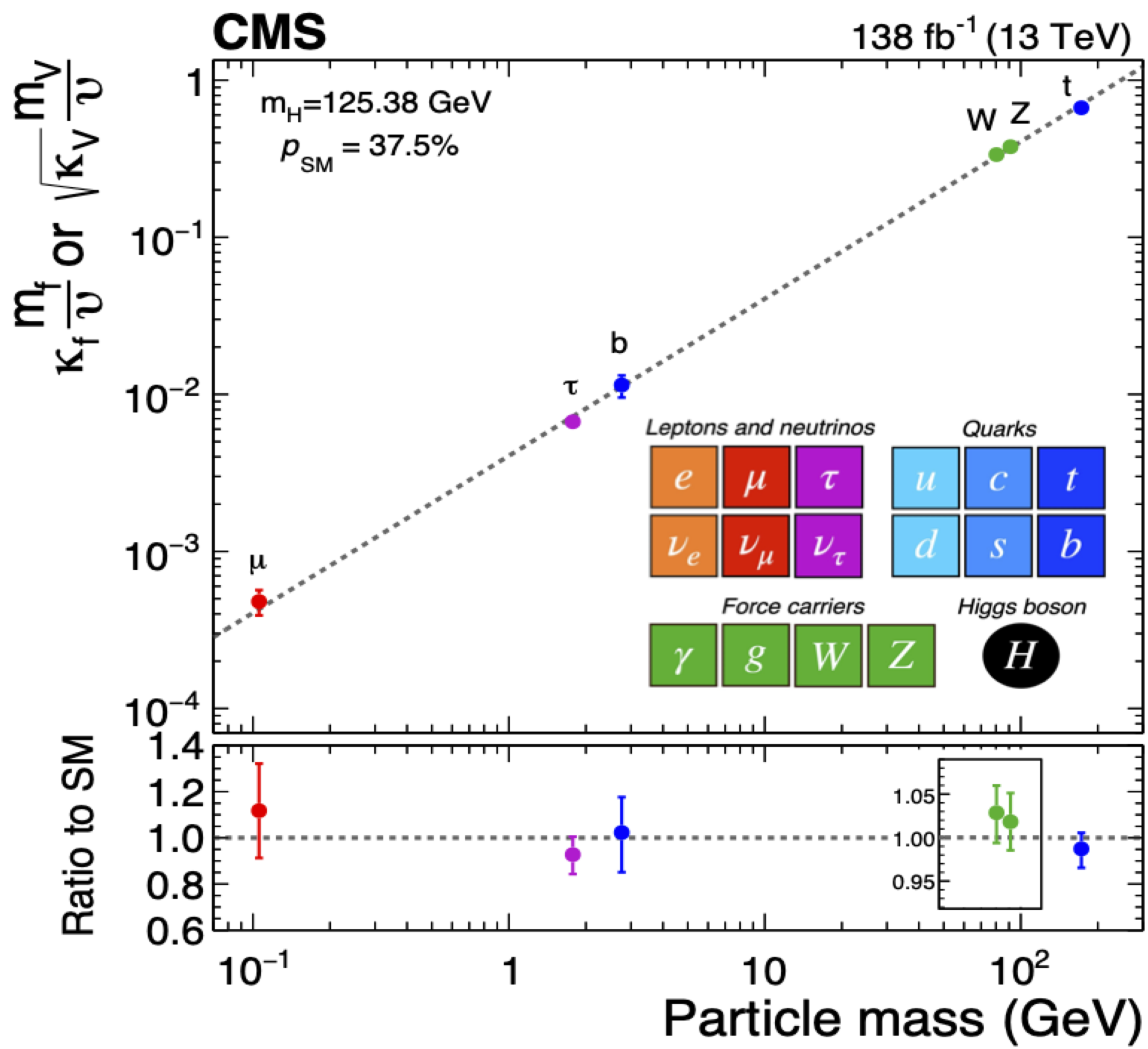
Higgs sector

$$L = \left(h_{ij}\bar{\psi}_i\psi_j H + \mathrm{h.c.}\right) - \lambda|H|^4 + \mu^2|H|^2 - \Lambda_{CC}^4$$

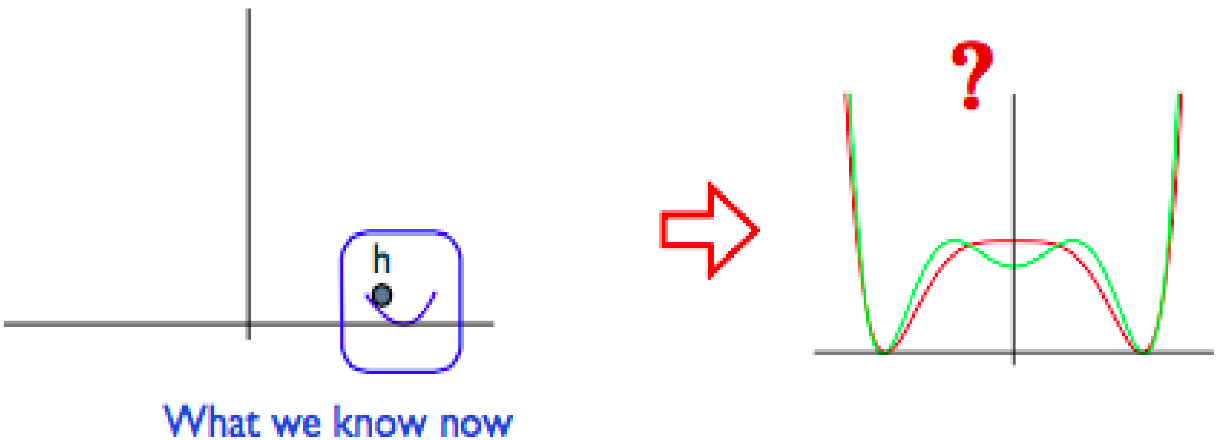
Higgs Signals



Higgs Signals



Why is Higgs Puzzling



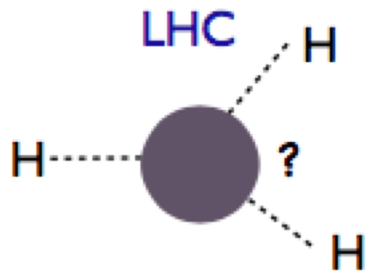
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Ad-hoc potential, similar to and motivated by Landau-Ginzburg theory of superconductivity

Standard Model Higgs potential can be extrapolated to the high-energy of quantum gravity without additional parameters

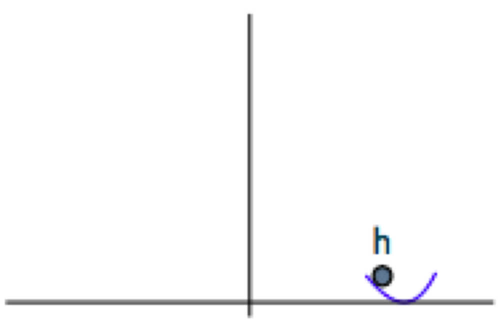
but no a-priori reason for a parameterization to respect this condition

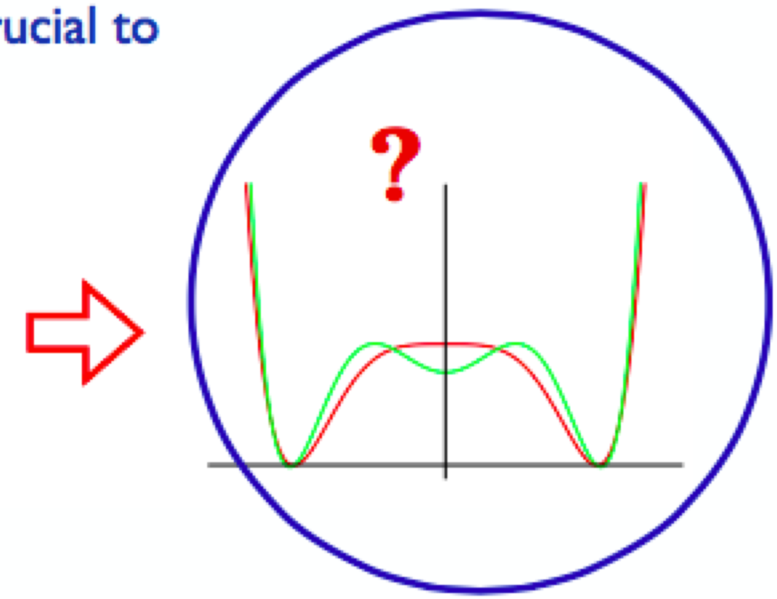
Higgs Self-Coupling



Unique type of coupling for spin-0 scalars
Not seen before in nature!

Measuring it well is crucial to answer this question.





Expect $O(1)$ deviations from SM in self-coupling coefficient

Measuring the Higgs Self-Coupling

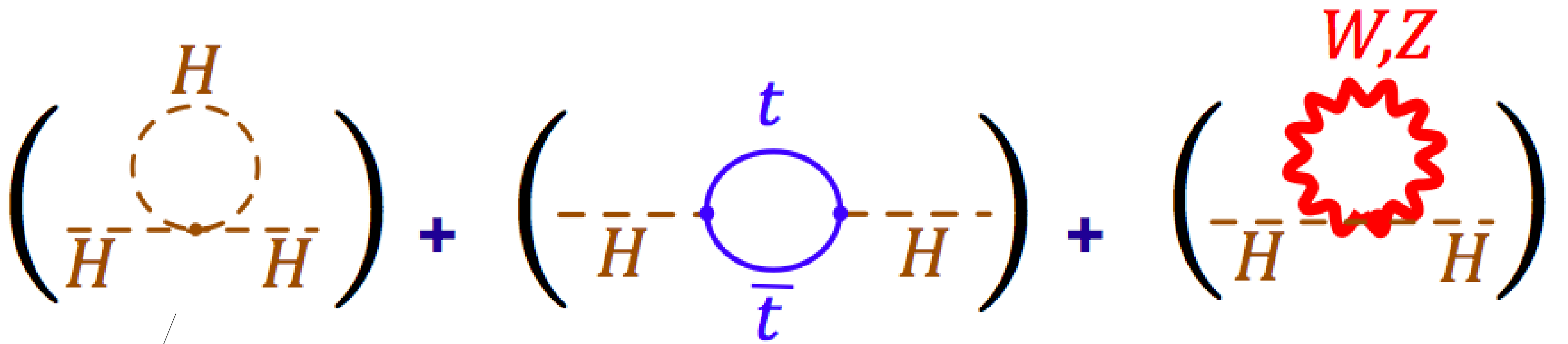
- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

$HH \to b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren Yao arXiv:1506.03302
$\text{FCC}_{@100\text{TeV}}$ 3/ab	30~40%	30%	15%
$\text{FCC}_{@100\text{TeV}}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics o $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach o No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /W_{had} veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included o No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

Work in progress to compare studies, harmonize performance assumptions, optimize, etc
⇒ ideal benchmarking framework

Why is the Higgs Boson so Light?

$$m_H^2 - m_{\text{bare}}^2 =$$



$$\lambda \int^{\Lambda} \mathrm{d}^4k\,(k^2 - m_H^{\,2})^{-1} \sim \Lambda^2 \lambda$$

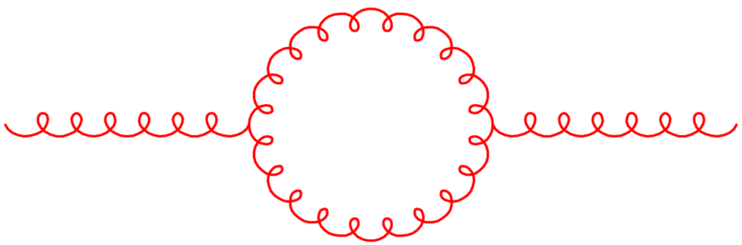
For the first time, we have additive corrections to parameters which are quadratically divergent

The Higgs boson ought to be a very heavy particle, naturally

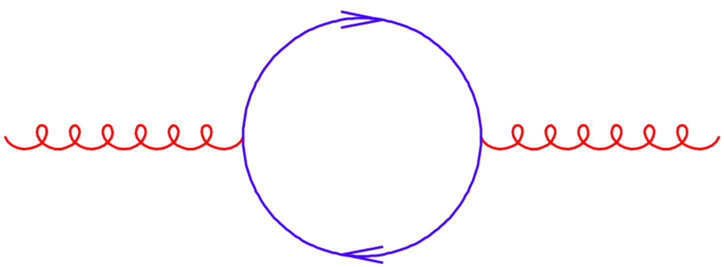
However, observed $m_H << \Lambda$

Well-behaved Quantum Correction - Asymptotic Freedom in QCD

QCD Lagrangian with no dimensioned parameters is scale-invariant classically
BUT quantum loops induce a distance (or momentum) scale dependence !



Color-charge *anti-screening* due to quark loops



Color-charge screening due to quark loops

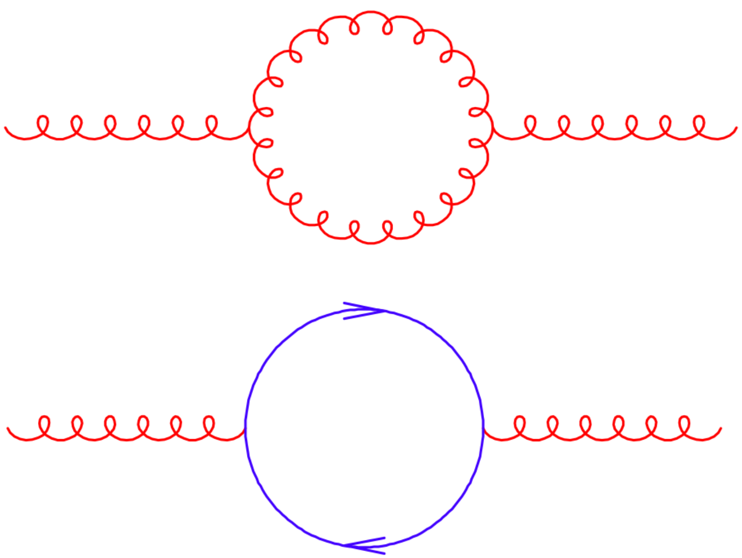
Running of coupling constant induces an energy scale $\Lambda \sim 0.2$ GeV where coupling becomes large

$$\alpha_s = \frac{6\pi}{(33 - 2N_f)\ln(\mu/\Lambda)}$$

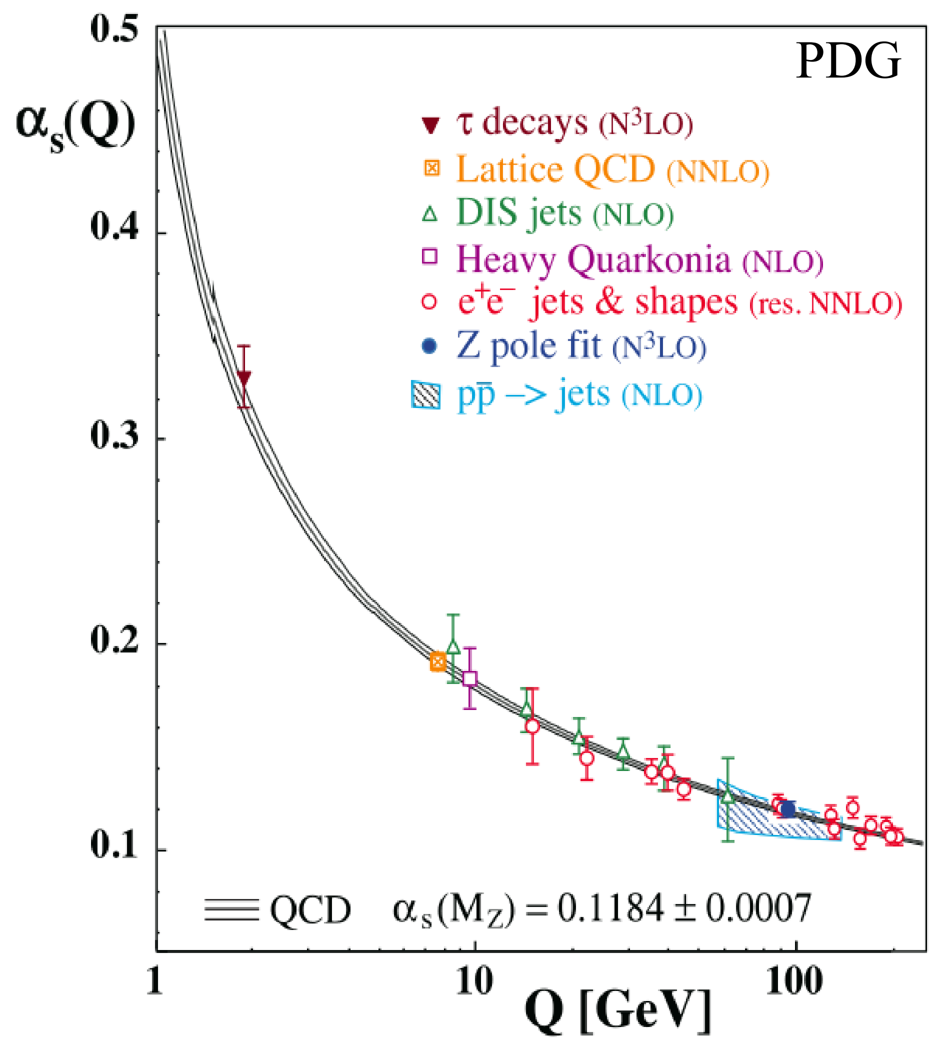
$\alpha_s \to 0$ as $\mu \to \infty$: asymptotic freedom
(2004 Nobel Prize for Gross, Wilczek, Politzer)

N_f = Number of quark flavors

Test of QCD Quantum Loops at High Energy



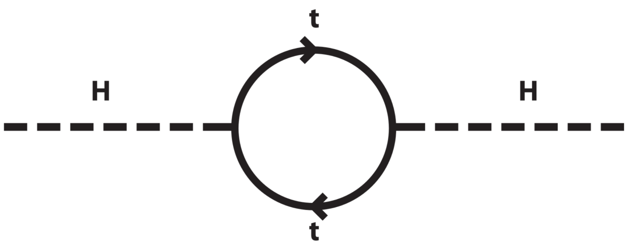
Running of strong coupling has been confirmed experimentally



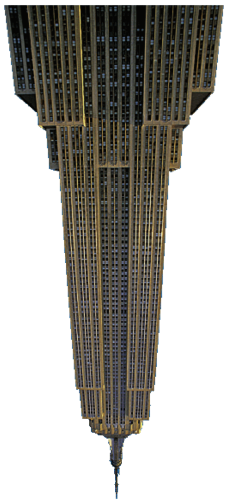
Fine-tuning Problem of Higgs Boson Mass

- The large quantum corrections must be regulated by some very high-energy physics such as energy associated with quantum gravity, $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop



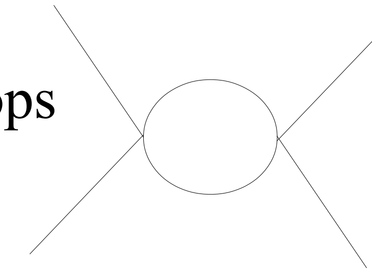
- physical Higgs boson mass ~ 125 GeV

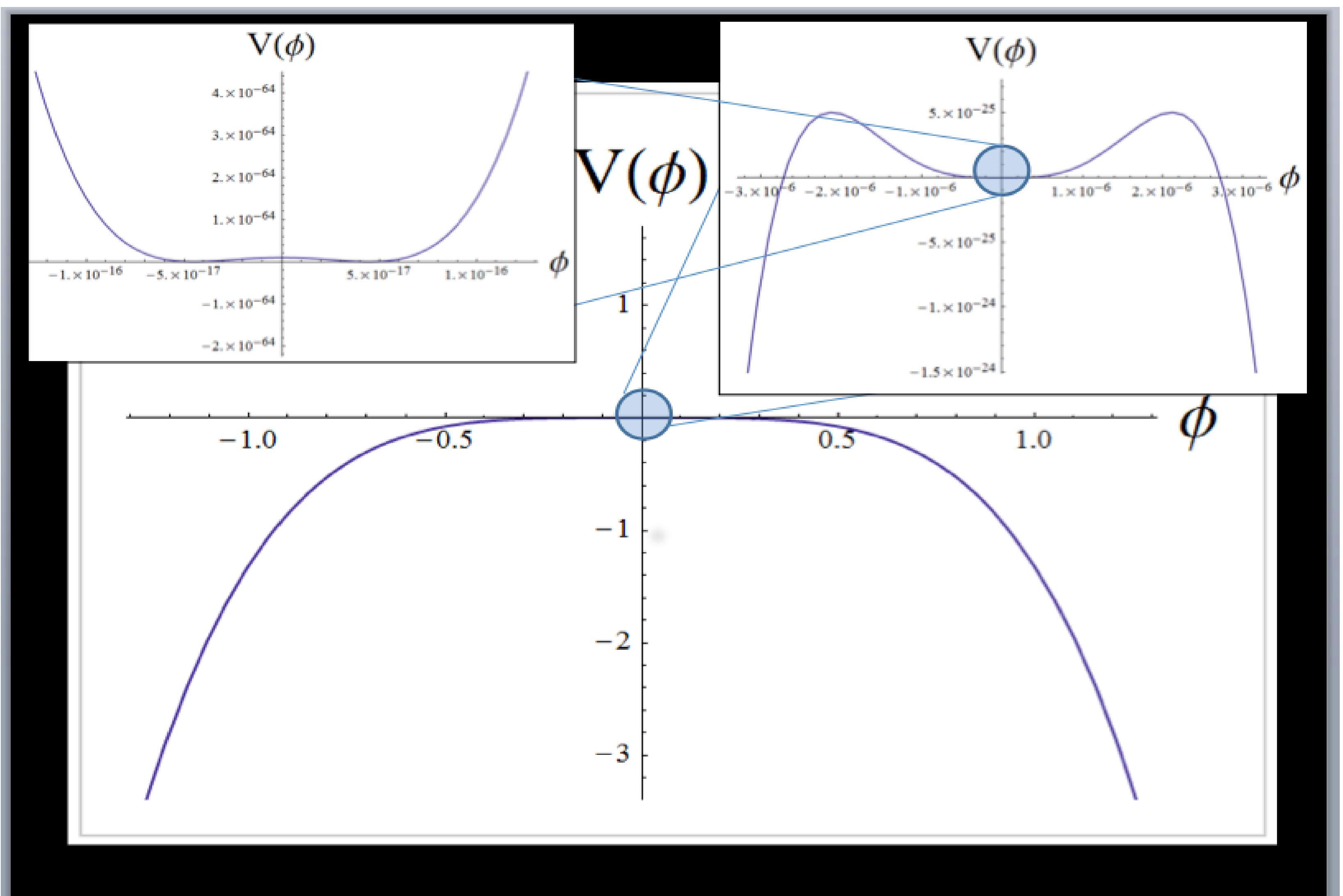


- Therefore need extreme "fine-tuning" of theoretical parameters at high energy
  - Conceptual weakness of Higgs theory as a quantum theory

Quantum Corrections to Higgs Self-Coupling

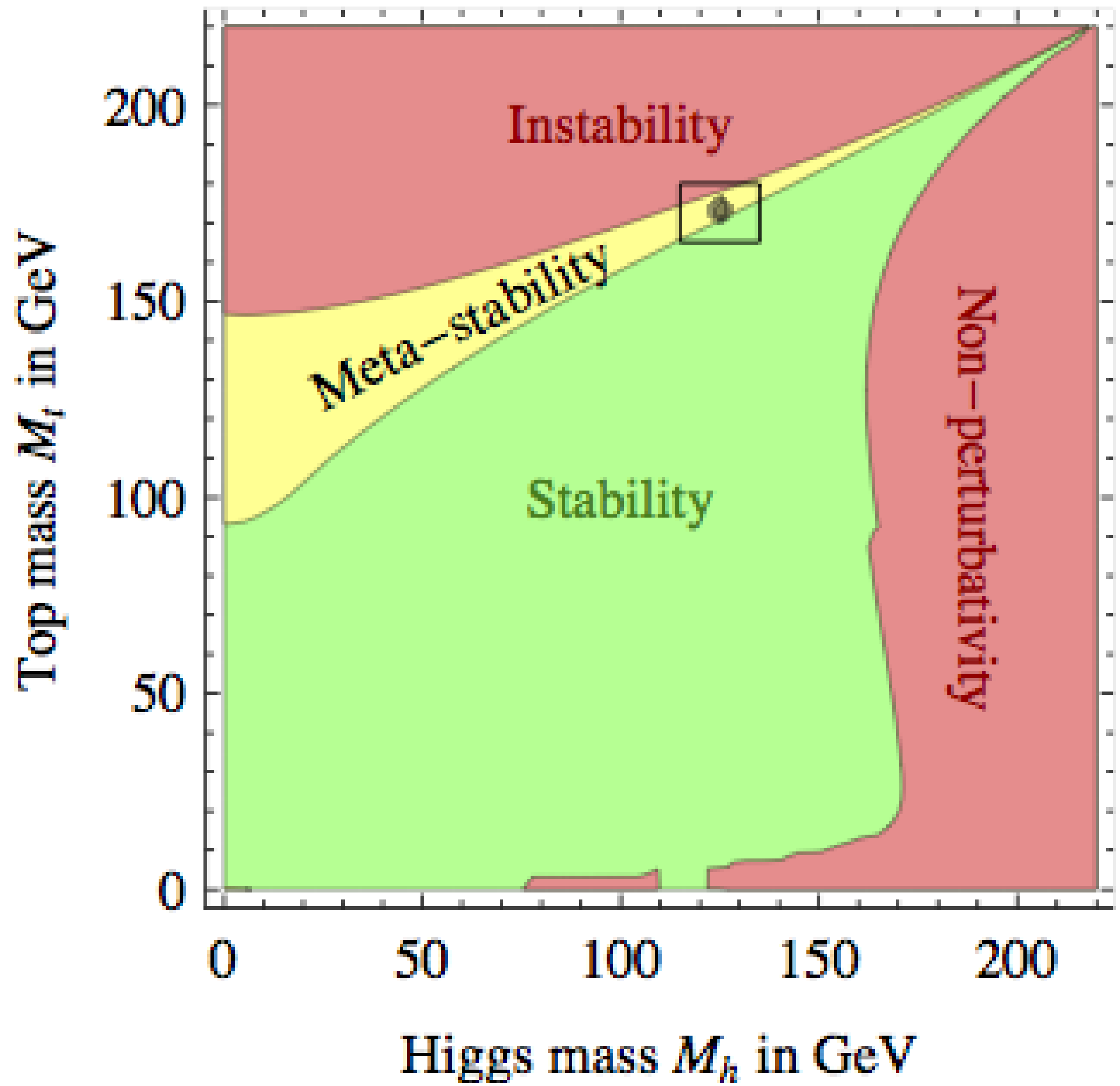
- $\lambda|\phi|^4$ receives quantum corrections from Higgs and top-quark loops





(from Paul Steinhardt)

Stability of Vacuum Ground State

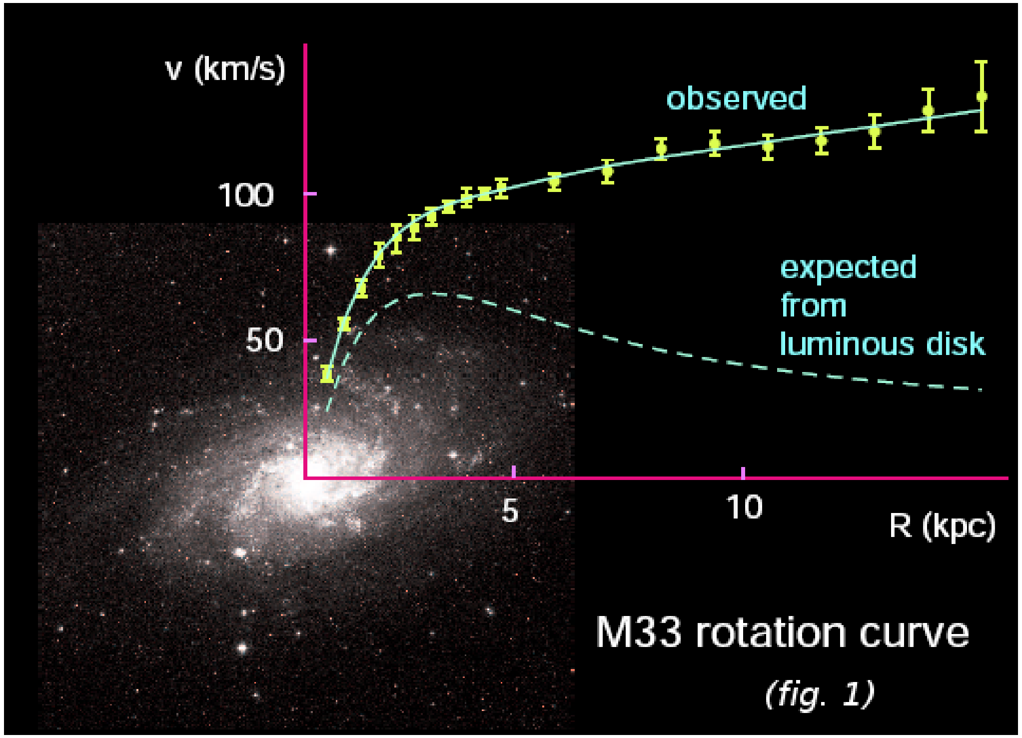


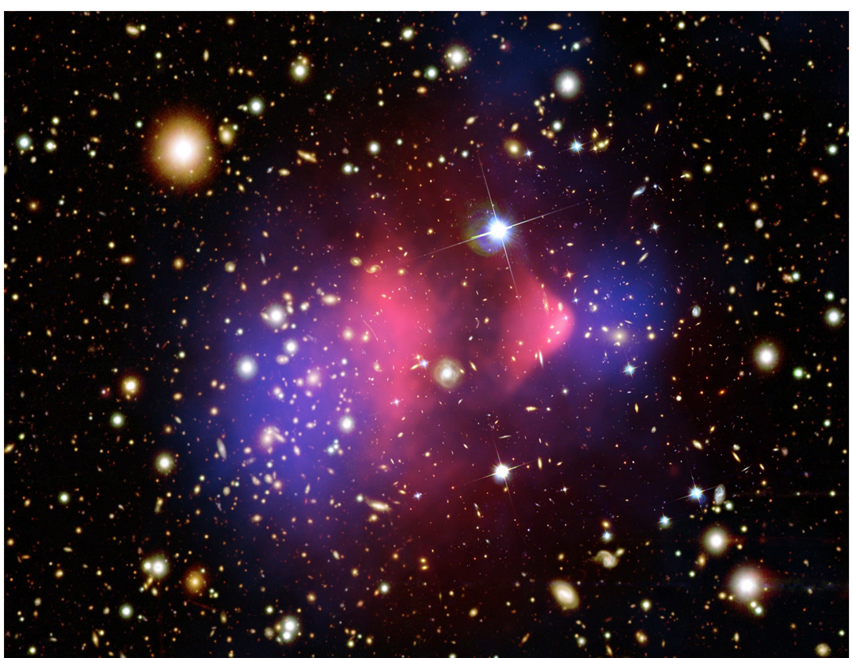
Higgs boson puzzles

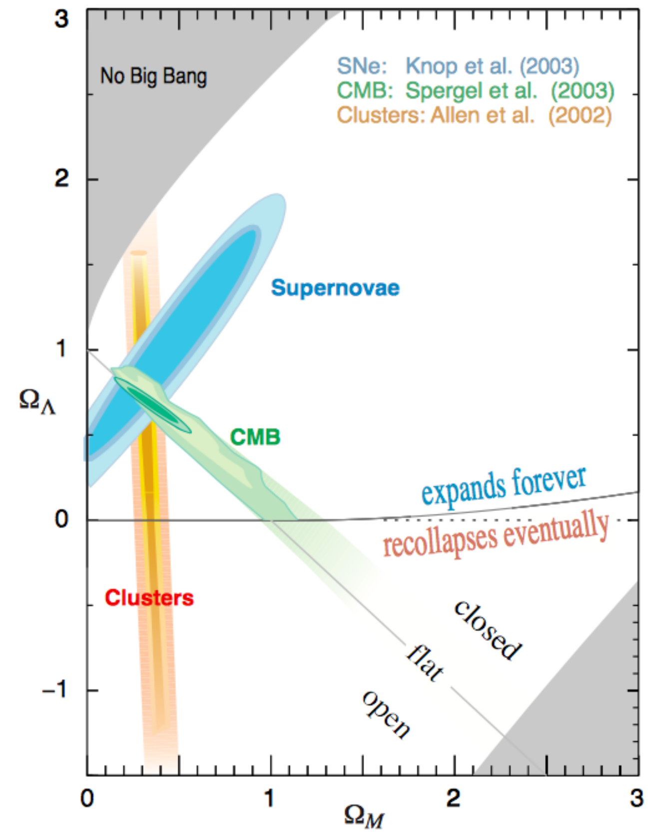
- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a charged condensate
  - But condensate is induced parametrically by ad-hoc Higgs potential, no dynamics in SM
- Parameters of Higgs potential are not stable under quantum corrections
  - First time that the quantum correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions
  - No additional symmetry in SM to protect the Higgs boson mass
- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery

Dark Matter

Dark Matter Particles

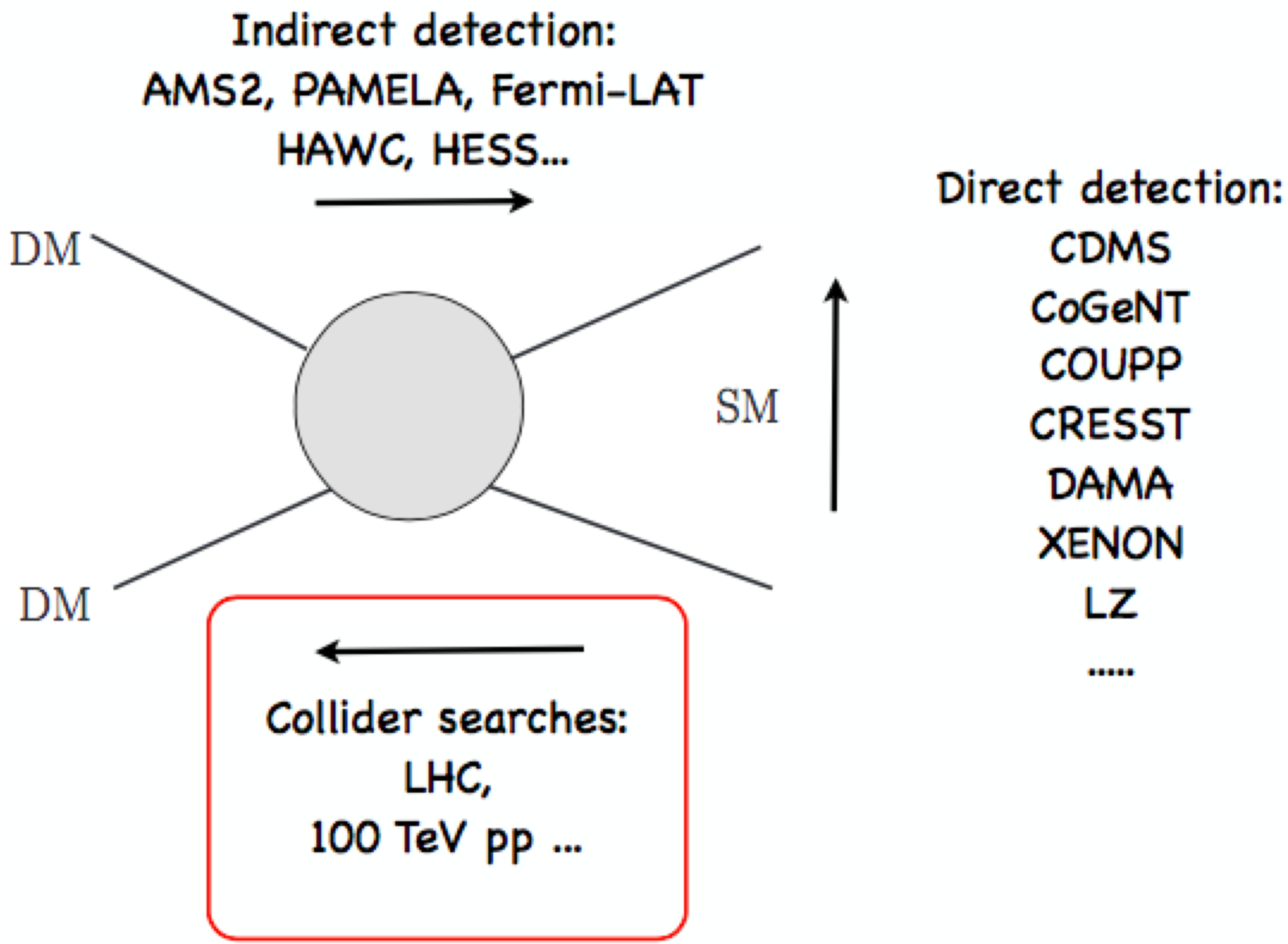




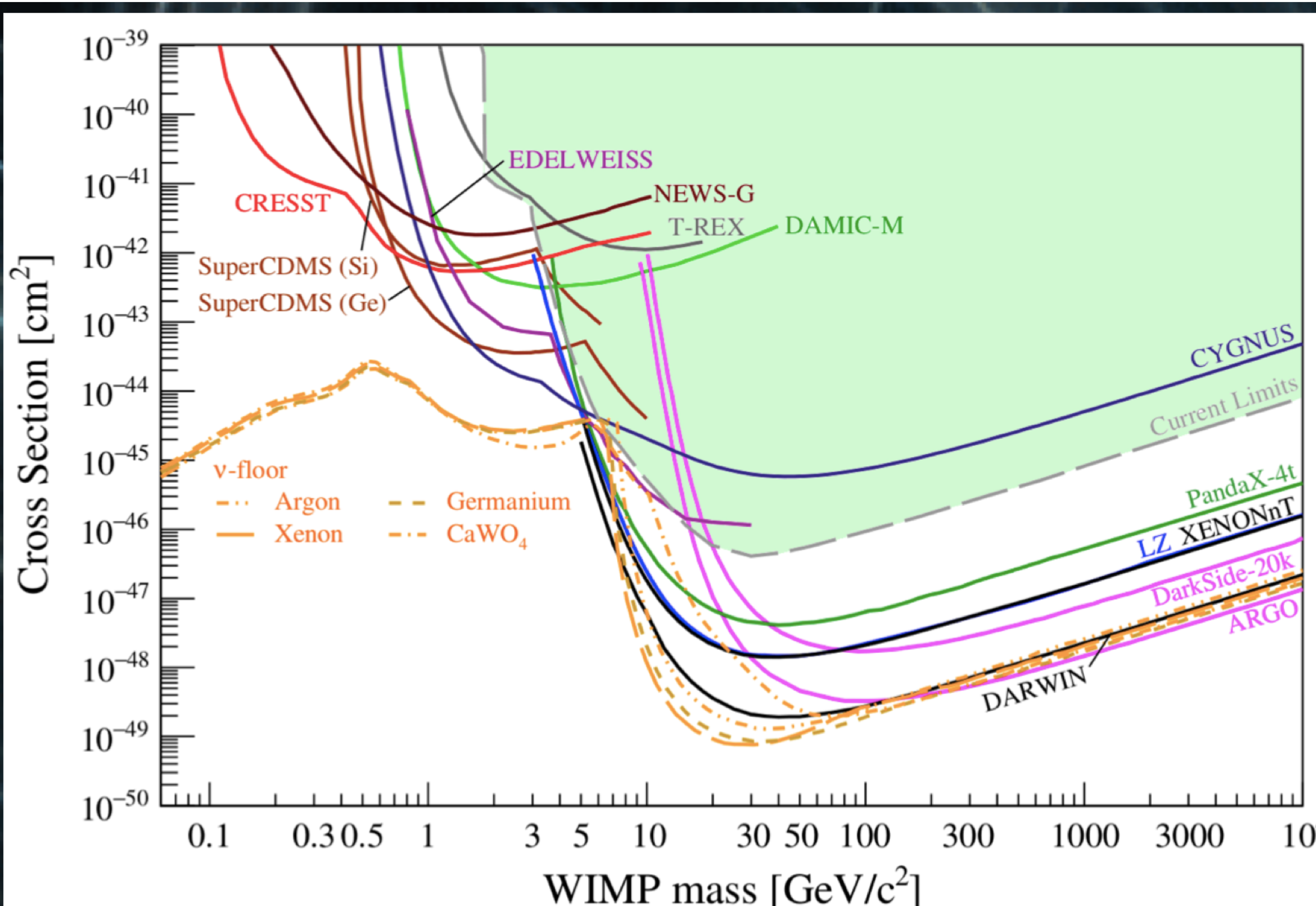


A consistent hypothesis is the existence of new, non-relativistic particles beyond the Standard Model

Searching for WIMP Dark Matter

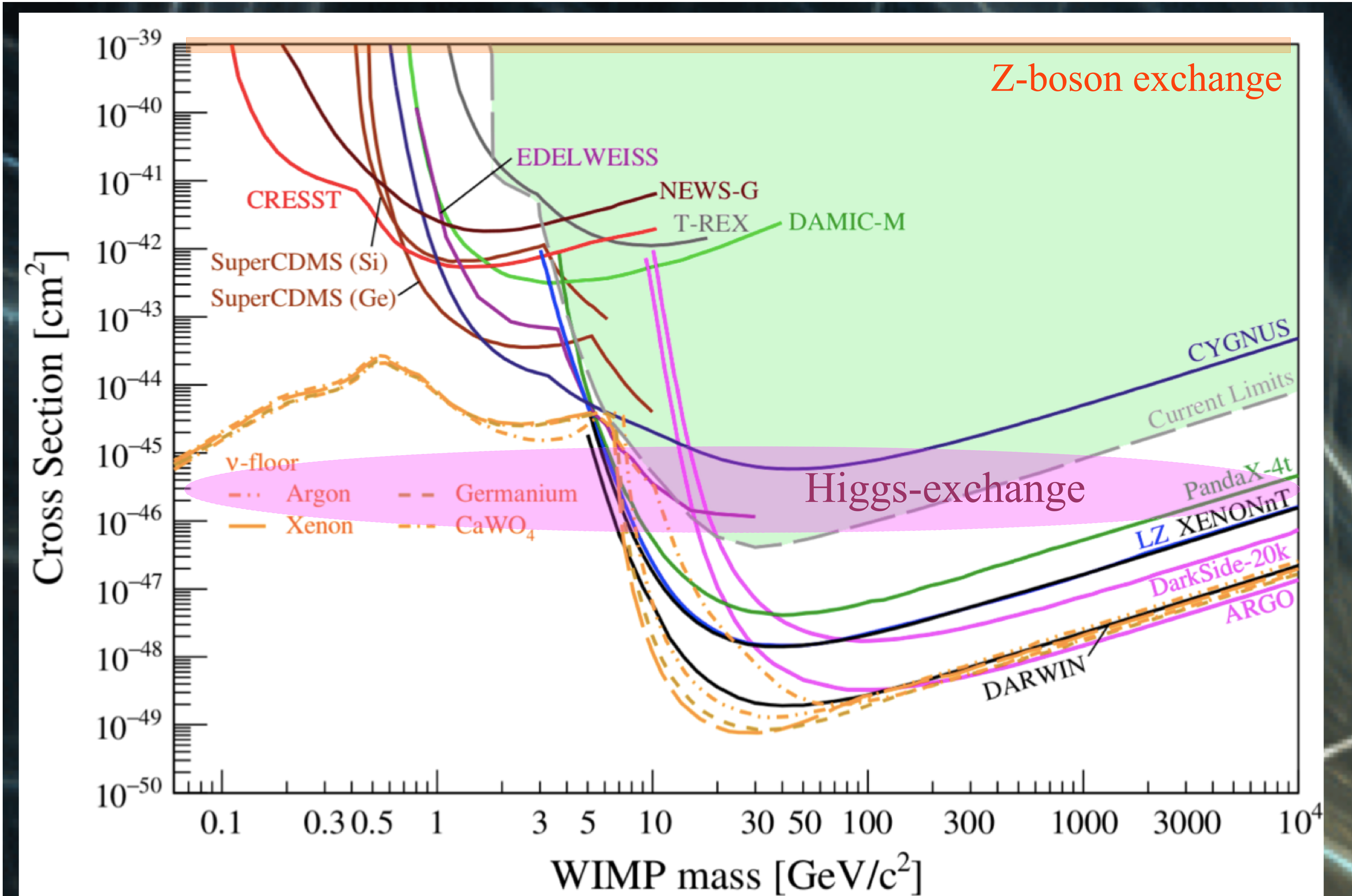


Dark Matter Particles – Direct Detection



Sensitivity projections from the APPEC report, J. Billard et al., (2021) arXiv:2104.07634

Dark Matter Particles – Direct Detection



Sensitivity projections from the APPEC report, J. Billard et al., (2021) arXiv:2104.07634

Collider vs Direct Detection Complementarity

Common ground (almost)

- Axial-Vector mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

- Scalar mediator

  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

Exclusive domains (almost)

- Vector mediator

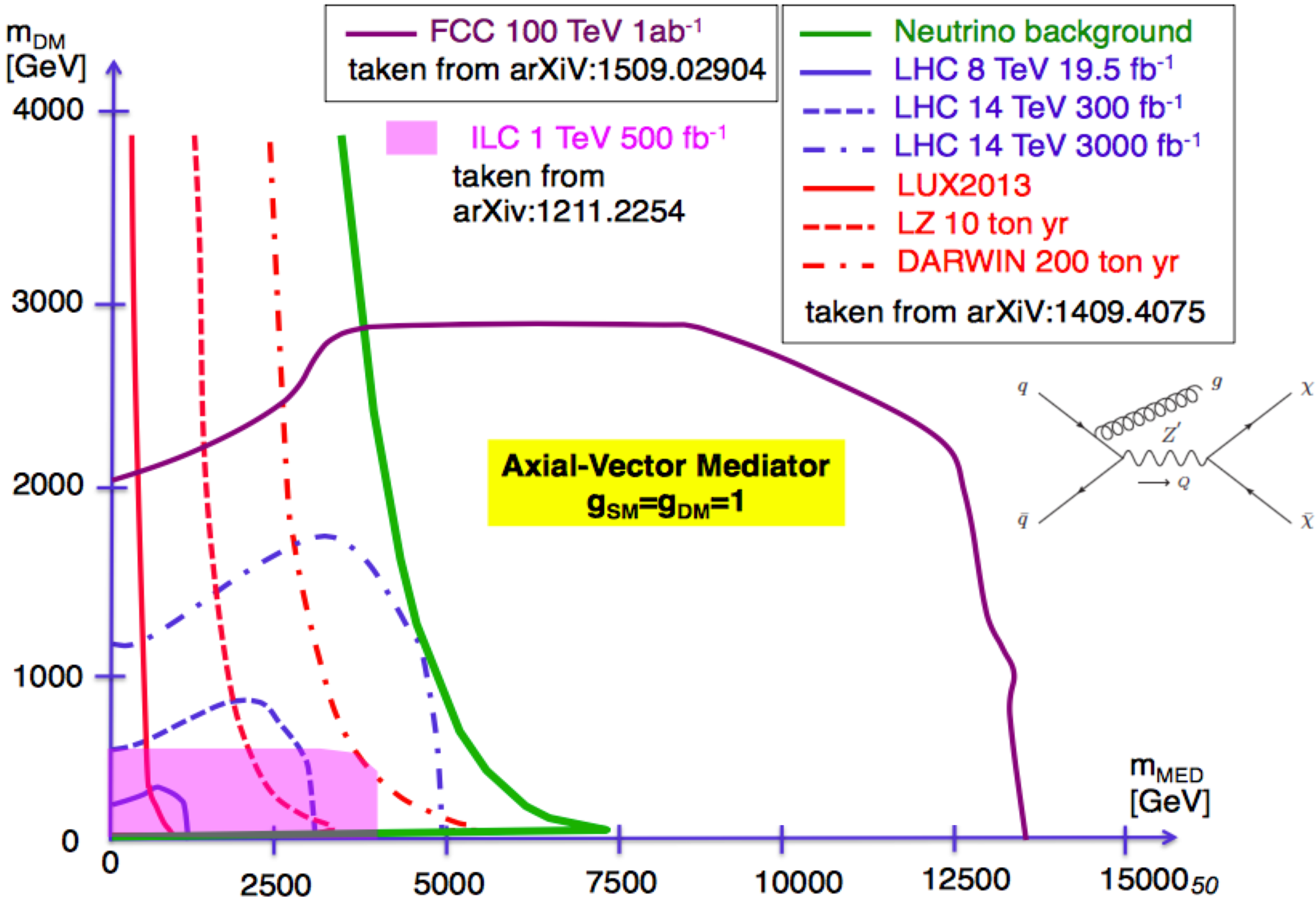
  Besides very low DM masses DD wins clearly over collider

- Pseudo-Scalar mediator

  No competitive limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits

(from O. Buchmuller)

Collider Searches – Large Mediator Mass



Origin of Matter-Antimatter Asymmetry

Origin of Matter-Antimatter Asymmetry

POSSIBLE EXPLANATIONS...

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9} \text{ (from BBN)}$$

⇨ **Baryogenesis at EW Scale** → **TESTABLE!**

⇨ ...

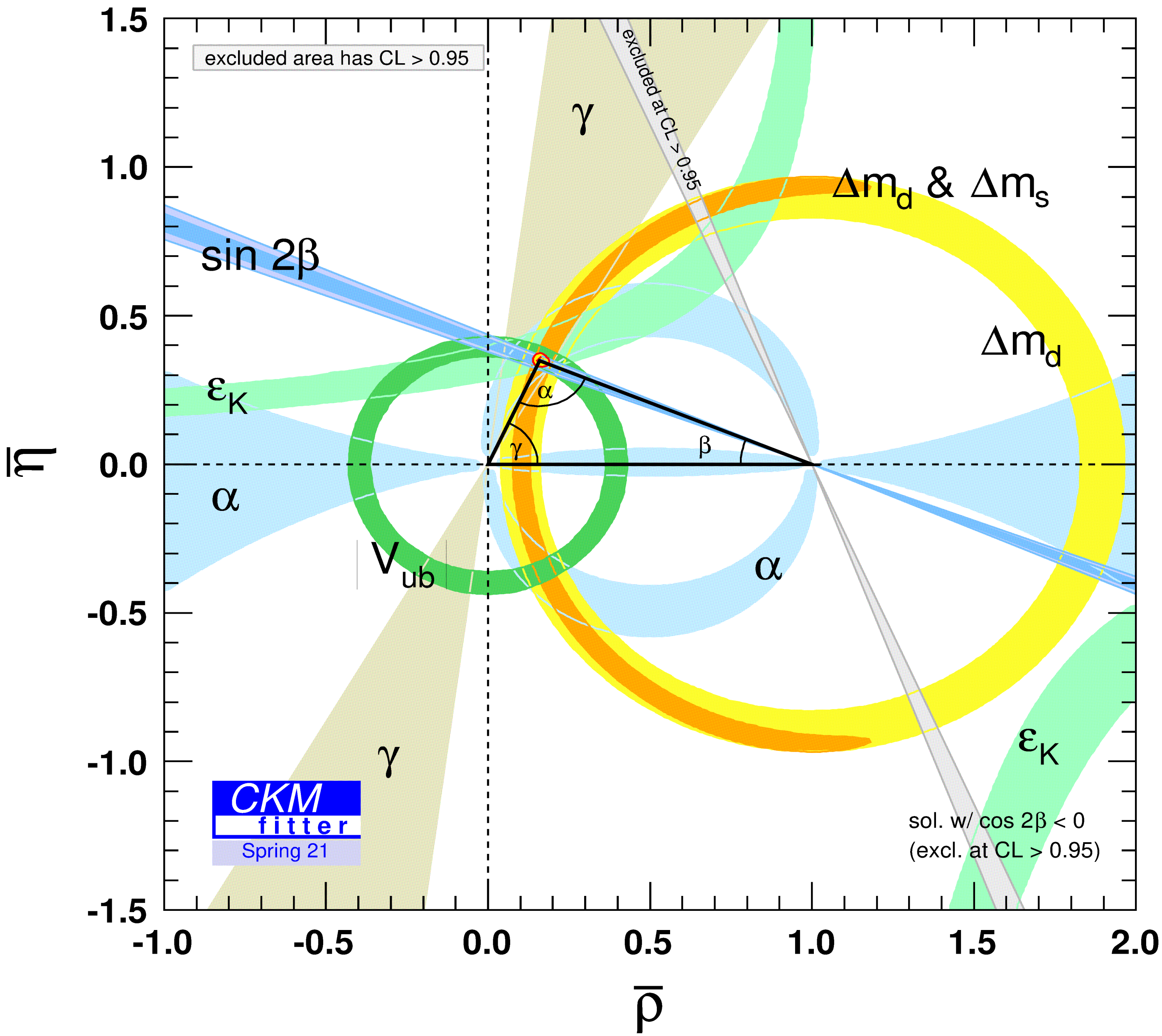
<u>SAKHAROV CONDITIONS</u> *(for dynamical generation of baryon asymmetry)*

B Violation ✓ *Sphalerons*
*V. A. Kuzmin, V. A. Rubakov, M. Shaposhnikov, Phys. Lett. B**155** (1985) 36*

C/CP Violation ✗ *not enough*

Departure from Thermal Equilibrium ✗ *not enough*

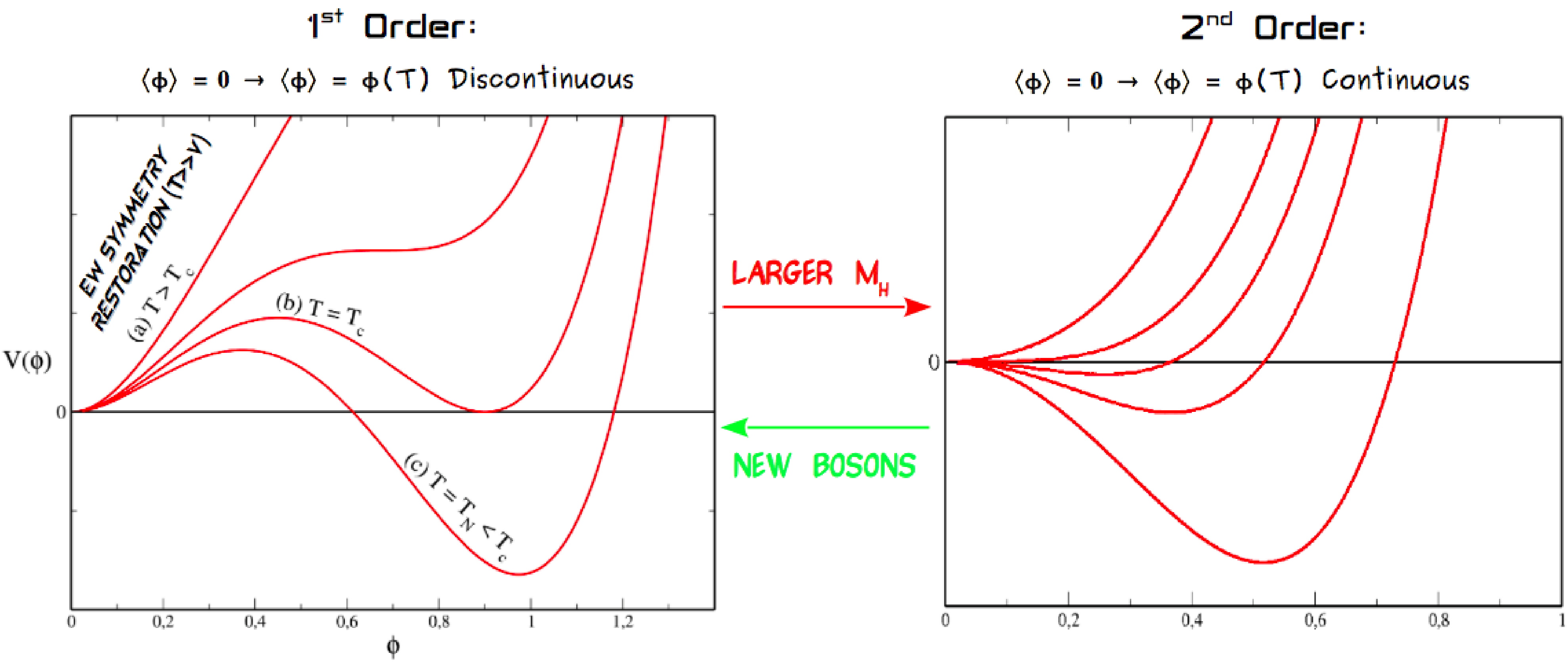
Status of CP Violation in CKM Unitarity Triangle



Higher precision at Belle II and LHCb experiments

Baryon Asymmetry and Higgs Phase Transition

(Ashutosh V. Kotwal, Michael J. Ramsey-Musolf, Jose Miguel No, Peter Winslow
Phys. Rev. D 94 (2016) 3, 035022; arXiv:1605.06123)



In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver
K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. ***77*** *(1996) 2887*

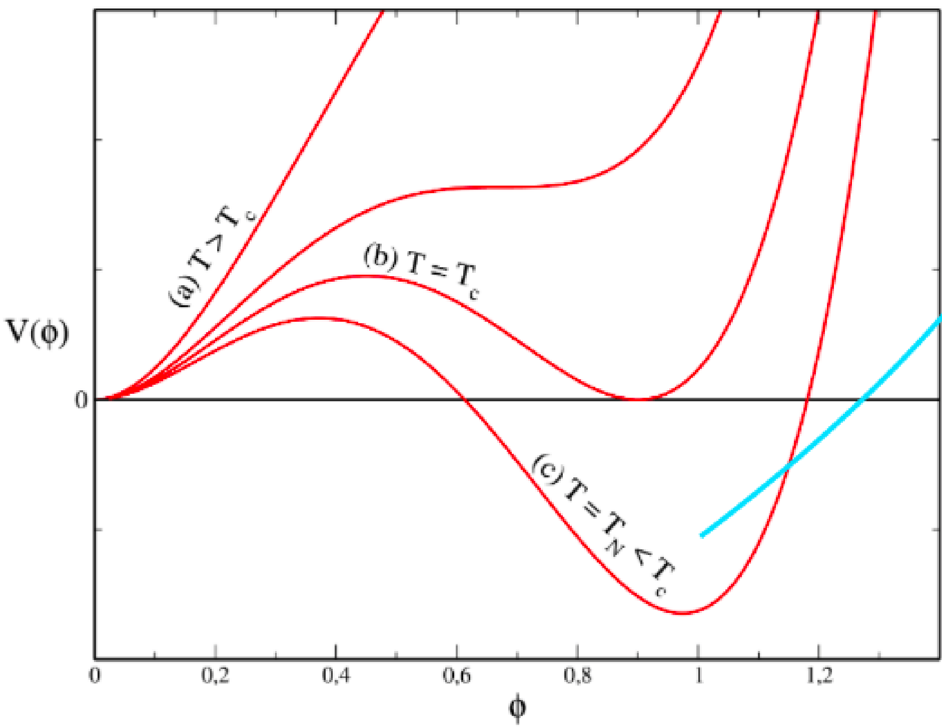
Beyond Standard Model
needed to create matter excess

Standard Model
cannot create matter excess

Baryon Asymmetry and Electroweak Phase Transition

1^{st} Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous

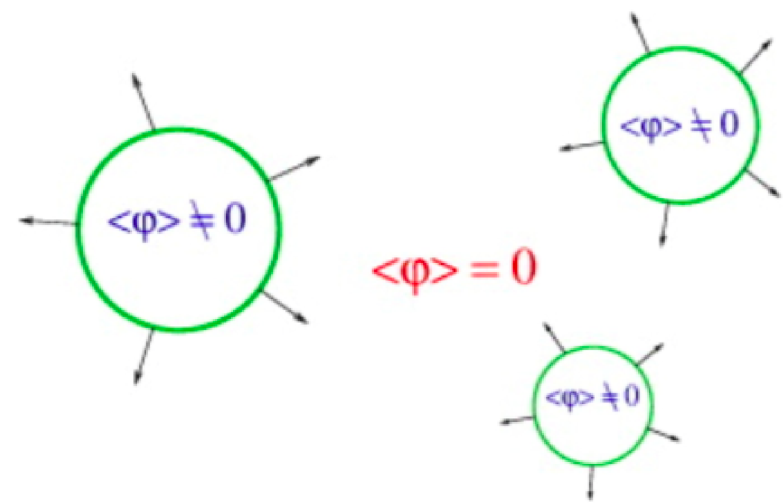


Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)

J. S. Langer, Ann. Phys. ***54*** *(1969) 258*

S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*

A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*

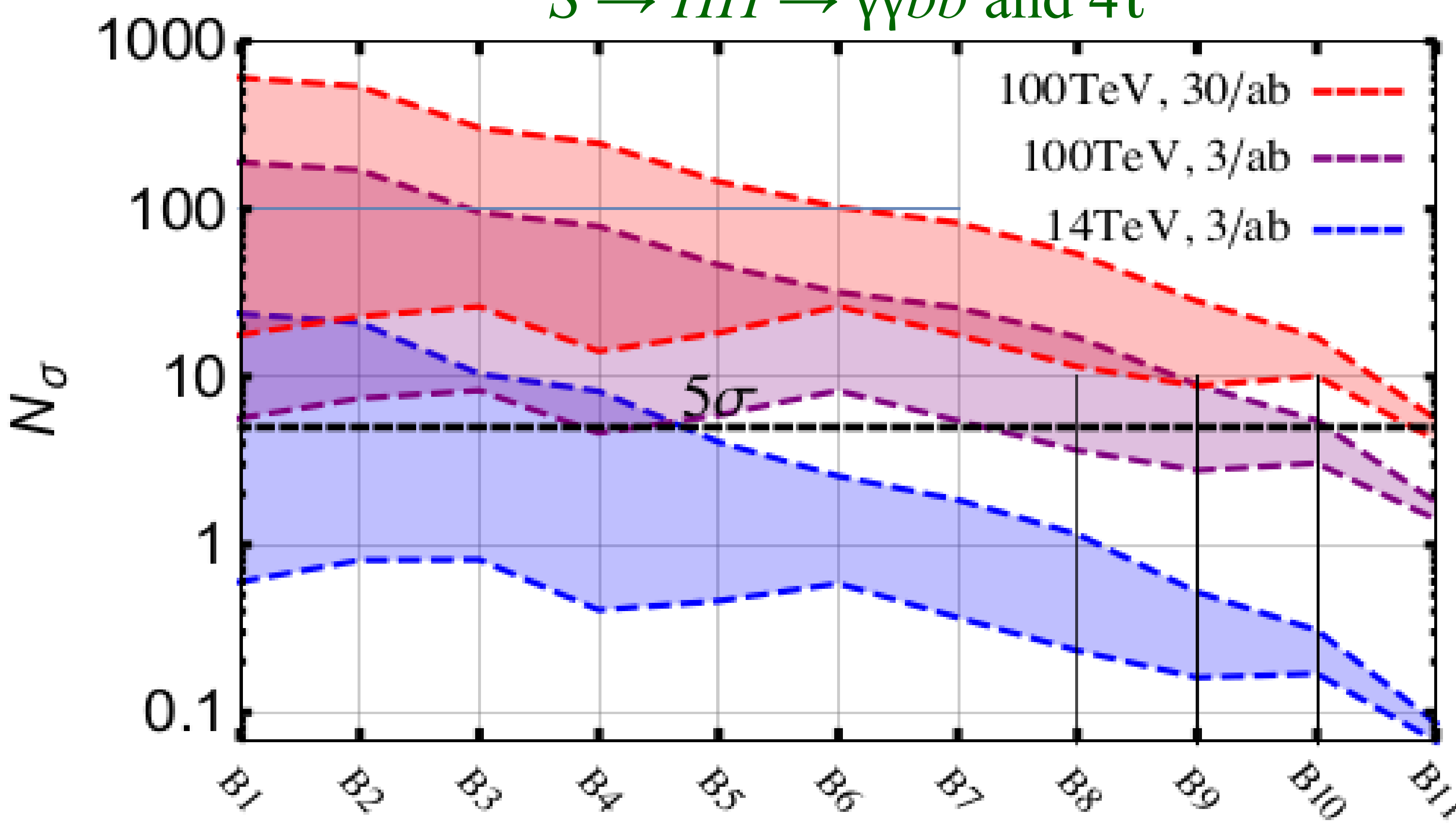


SUDDEN CHANGE IN HIGGS VEV

Inducing First-Order Electroweak Phase Transition

$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

$S \rightarrow HH \rightarrow \gamma\gamma bb$ and 4τ



300 GeV ← benchmark m_S → 900 GeV

(A.V.Kotwal, P. Winslow, J.M. No, M.J.Ramsey-Musolf)

Discovery potential across entire parameter space

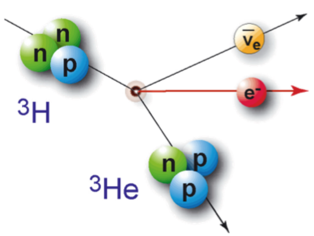
Neutrino Puzzles

Neutrino Puzzles

Neutrino masses << other fermion masses, why?

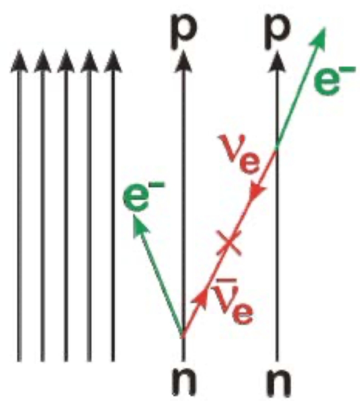
Indication of higher-dimension operator inducing neutrino masses? Seesaw mechanism?

ν experiments provide key insight into the nature of neutrinos and physics beyond the SM



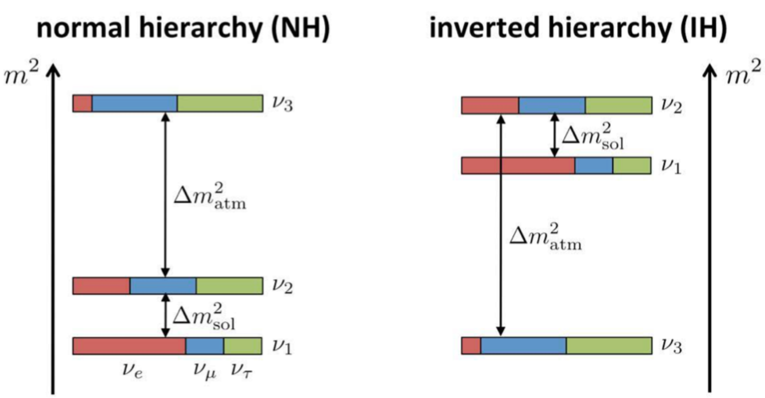
Beta decay allow direct neutrino mass measurements

Aim to reach $m_\nu < 0.04$ eV



Neutrinoless double beta (0νββ) powerful probe of lepton number violation (ΔL=2).

Would establish lepton number violation and demonstrate that neutrinos are Majorana.



Reactor and accelerator experiments will determine mass ordering and probe CP violation.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}}_{U_{\rm PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Precision oscillation measurements will test the 3 flavor paradigm.

Exciting years lie ahead!

(from Karsten Heeger)

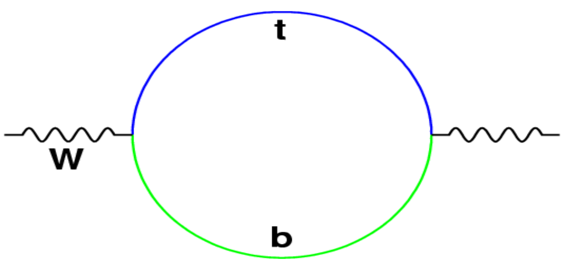
Motivation for Precision Measurements

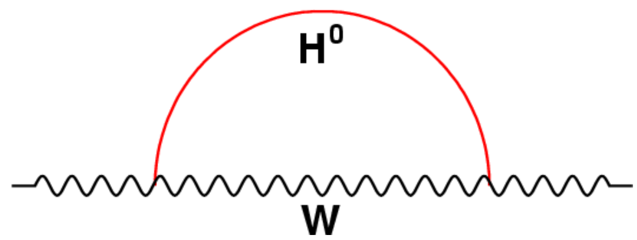
- The electroweak gauge sector of the standard model is constrained by precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \mathrm{GeV}^{-2}$
  - $M_Z = 91.1876\ (21)$ GeV
  - $m_{top} = 172.89\ (59)$ GeV
  - $M_H = 125.25\ (17)$ GeV
- Before quantum corrections, these parameters related to M_W
  - $M_W^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$
    - Where ϑ_W is the Weinberg mixing angle, defined by

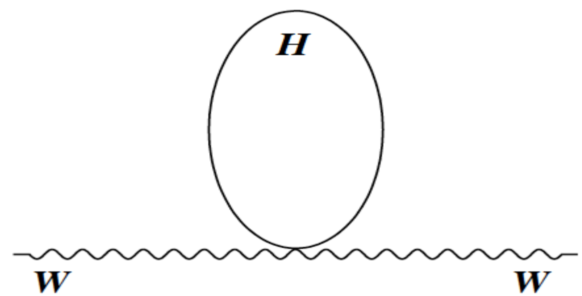
$$\cos\vartheta_W = M_W/M_Z$$

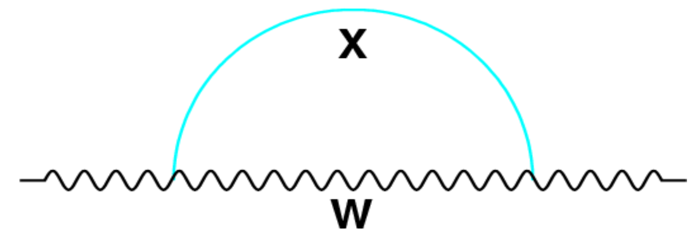
Motivation for Precision Measurements

- Quantum fluctuations due to heavy quark and Higgs loops and (potentially) undiscovered particles









Standard Model calculation : $M_W^2 = \rho\,[M_W(\text{tree})]^2$ where

$\Delta\rho = (\rho\text{-}1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

- Since we know top quark and Higgs boson masses, comparing measured and calculated values of W boson mass tells us about new particles “X” beyond the Standard Model

Motivation for Precision Measurements

- The mass of the W boson is tightly constrained by the symmetries of the standard model, in conjunction with M_{top} and M_{Higgs}
  - The Higgs boson was the last missing component of the model
  - Following the observation of the Higgs boson, a measurement of the W-boson mass provides a stringent test of the model
- The W boson mass is presently constrained by SM global fits to a relative precision of 0.01%
  - provides a strong motivation to test the SM by measuring the mass to the same level of precision
  - SM expectation $M_W = 80{,}357 \pm 4_{inputs} \pm 4_{theory}$ MeV
  - Inputs include Z- and Higgs boson and top-quark masses, EM coupling and muon lifetime measurements

Beyond-SM Modifications to Expected M_W

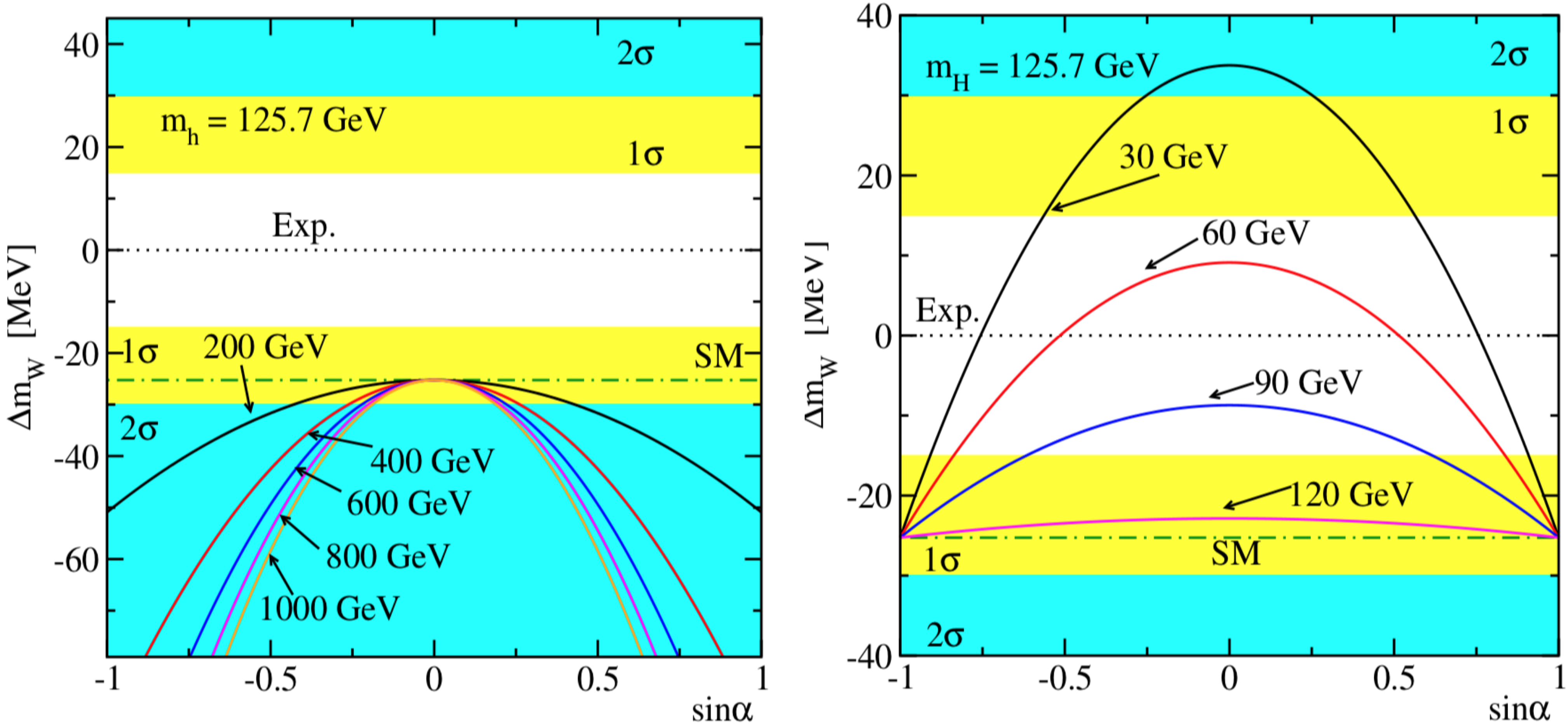
- Hypotheses to provide a deeper explanation of the Higgs field, its potential and the Higgs boson, include
  - Supersymmetry
  - Compositeness
  - New strong interactions
  - Extended Higgs sector

- Hypothetical sources of particulate dark matter

- Additional fundamental forces

Single Scalar Extension of Higgs Sector

Inclusion of an additional scalar particle with no SM charges, which mixes with the Higgs boson

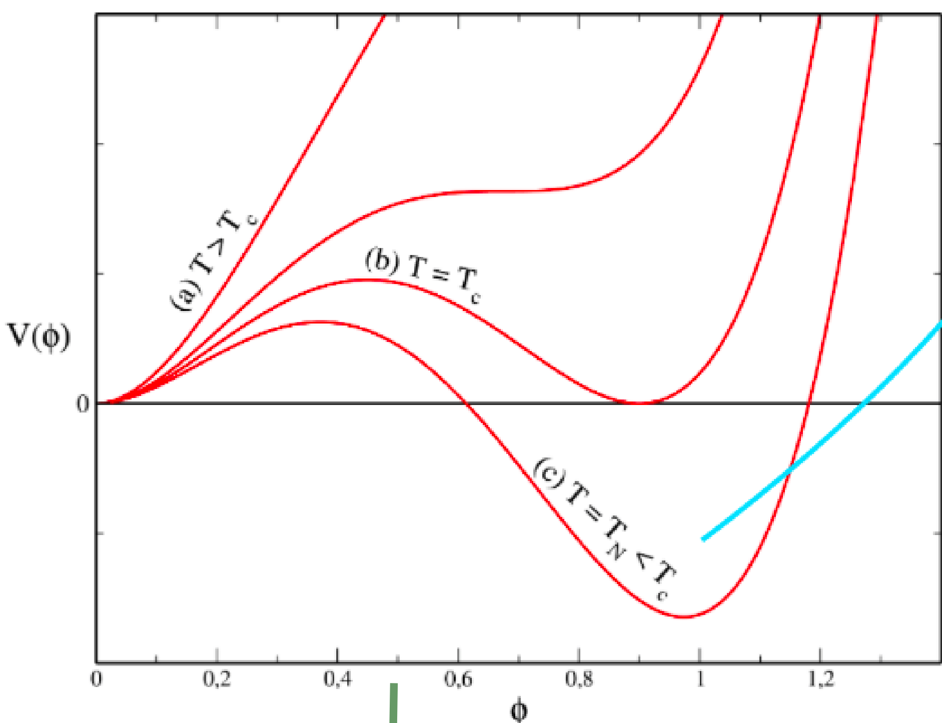


D. López-Val and T. Robens, Phys. Rev. D 90, 114018 (2014)

1^{st} Order Electroweak Phase Transition Induced by Additional Higgs-like Particle

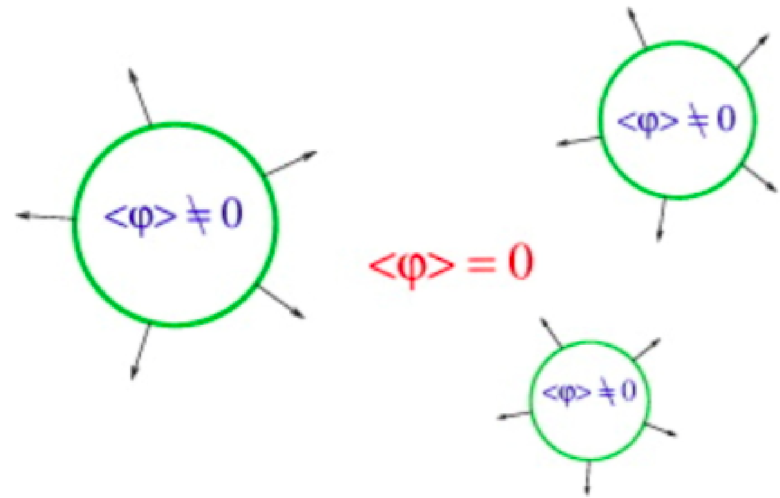
1st Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous



Nucleation of True Vacuum Bubbles (in False Vacuum Sea)

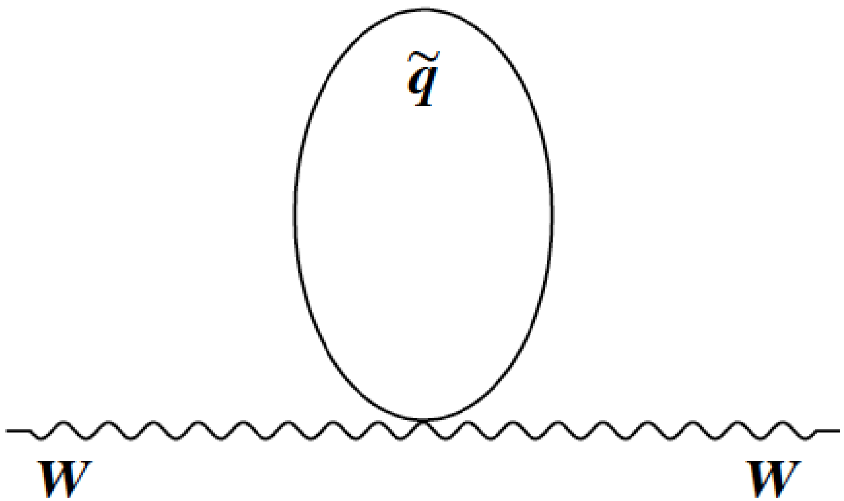
J. S. Langer, Ann. Phys. ***54*** *(1969) 258*
S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*
A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*

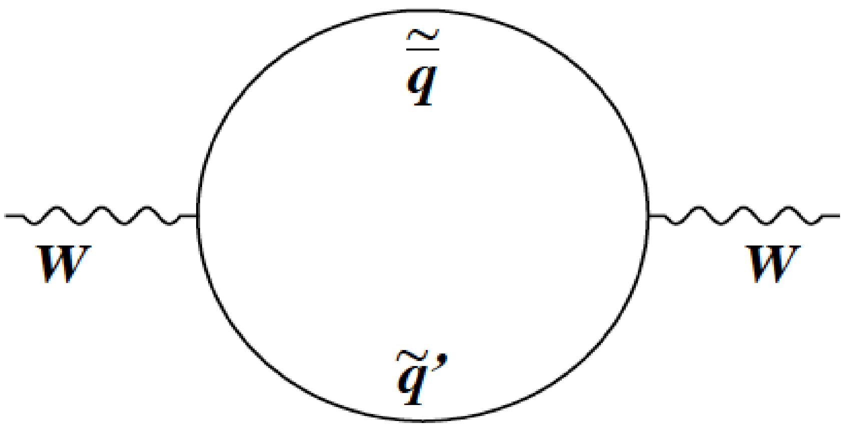


SUDDEN CHANGE IN HIGGS VEV

Satisfies crucial Sakharov condition for creating excess matter in the Universe

Contributions from Supersymmetric Particles

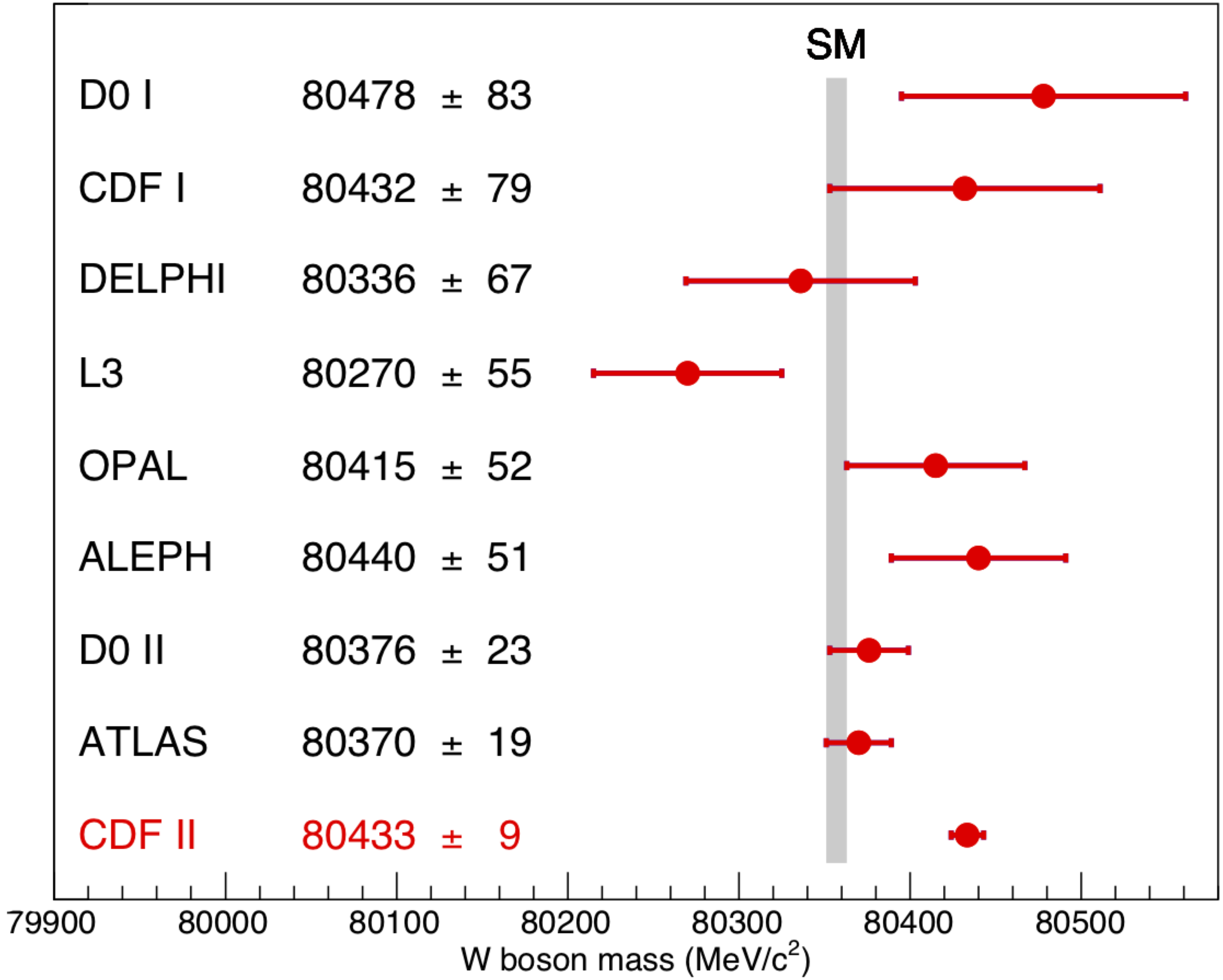




- Quantum correction to W boson mass depends on mass splitting (Δm^2) between supersymmetric quarks

- SUSY loops can contribute tens of MeV to M_W
  - Even with significant exclusions from Large Hadron Collider
  - Supersymmetric particle could constitute dark matter

W Boson Mass Measurements from Different Experiments



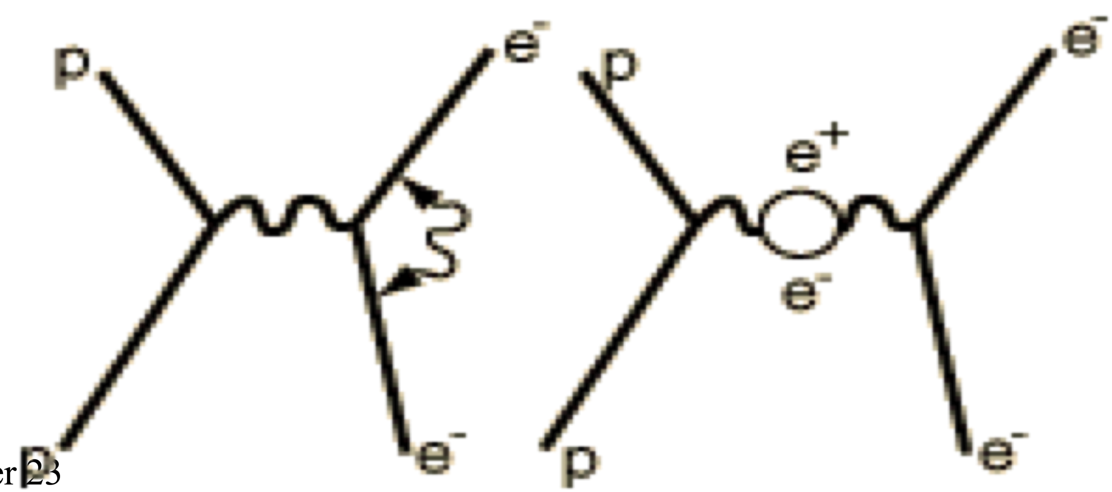
SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ [*JHEP* **2022,** 36 (2022)]

CDFII citation: *Science* **376**, 170 (April 7, 2022); DOI: 10.1126/science.abk1781

Detecting New Physics through Precision Measurements

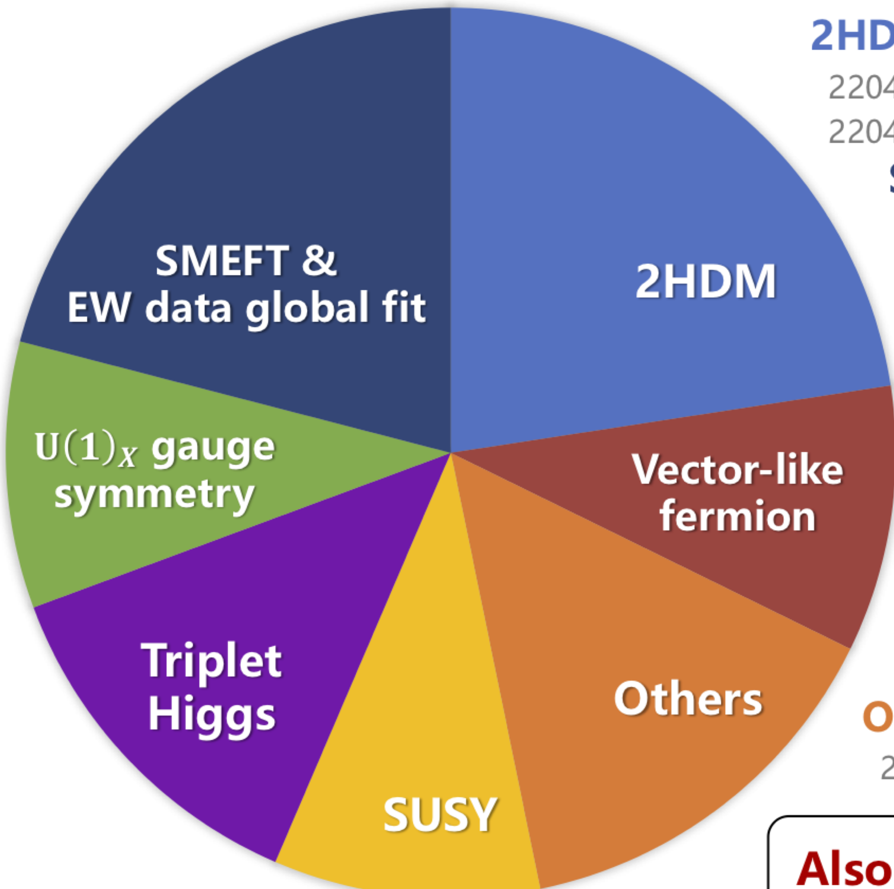
- Willis Lamb (Nobel Prize 1955) measured the difference between energies of $^2S_{½}$ and $^2P_{½}$ states of hydrogen atom
  - 4 micro electron volts difference compared to few electron volts binding energy
  - States should be degenerate in energy according to tree-level calculation
- Harbinger of vacuum fluctuations to be calculated by Feynman diagrams containing quantum fluctuations
  - Modern quantum field theory of electrodynamics followed (Nobel Prize 1965 for Schwinger, Feynman, Tomonaga)



Epilogue

Citations in 7 weeks since publication (April 8, 2022): 126

CDF W mass



Total number: 62*

2HDM: 14
2204.03693/03767/04834/04688/06485/05085/05269/05303
2204.05975/09001/05728/08406/08390/10338

SMEFT & EW data global fit: 13
2204.04805/05260/05284/05267/05992/05965/05965/08546
2204.08440/10130/04191/05283/04204

Triplet Higgs: 8
2204.05031/05760/07144/07511/07844/08266/10274/10315

SUSY: 6
2204.04286/04356/04202/05285/06541/07138

$U(1)_X$ gauge symmetry: 6
2204.07100/08067/09487/09024/09585/10156

Vector-like fermion: 6
2204.07022/07411/08568/09477/09671/05024

Others: 9 (Non-unitarity, leptoquark, singlet scalar, ...)
2204.04559/04672/04770/04514/05302/06327/03996/05942/09031

* Preprints as of April 25th are counted.

Also related to
dark matter, neutrino masses/seesaw, flavor violation, muon g-2, flavor anomalies, gravitational waves, ...

Summary

- The SM is an amazingly successful theory, built on deep principles and has huge experimental confirmation – but many open questions point to a bigger theory that will subsume the SM

- A big hint for beyond SM physics: new CDF result measurement of W boson mass is twice as precise as previous measurements:

  - $M_W = 80433.5 \pm 6.4_{stat} \pm 6.9_{syst}$ MeV
    $= 80433.5 \pm 9.4$ MeV

- Difference from SM expectation of $M_W = 80{,}357 \pm 6$ MeV

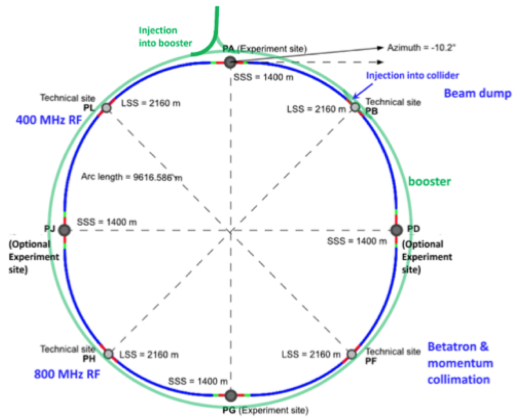
    - significance of 7.0σ
    - suggests the possibility of extensions to the SM

Next Steps for Electroweak Measurements

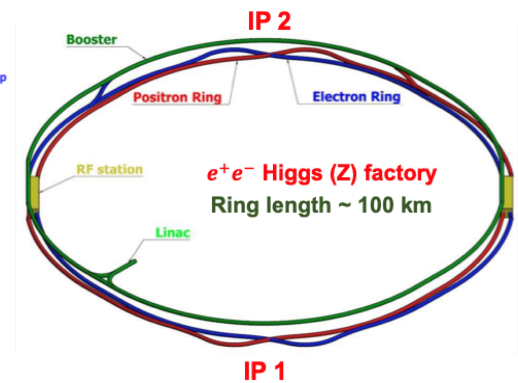
- Electroweak observables access all the mechanisms that can stabilize / explain the light Higgs mass
  - Is it stabilized by a symmetry such as SuperSymmetry ?
  - Is the Higgs boson a pseudo Nambu-Goldstone Boson?
  - Is there new strong dynamics ?
  - Do extra-dimensional models bring the Planck scale close to Electroweak scale?
- Motivation for a W/Z/Higgs factory (electron-positron collider)

Higgs factories (e^+e^-)

Circular



FCC-ee

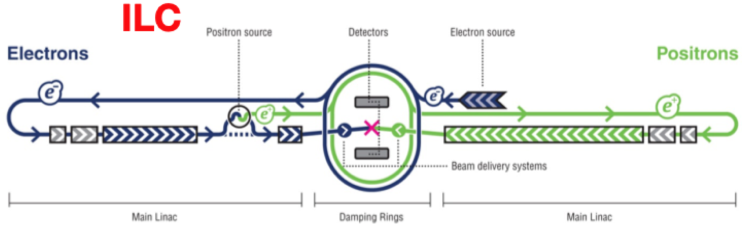


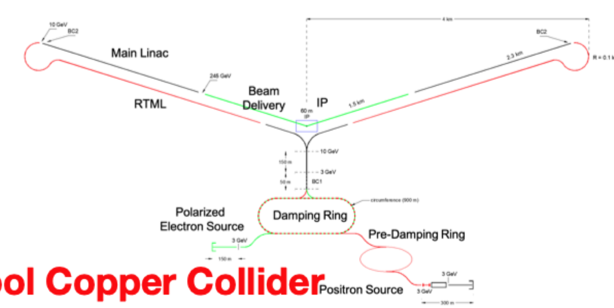
CEPC

+...

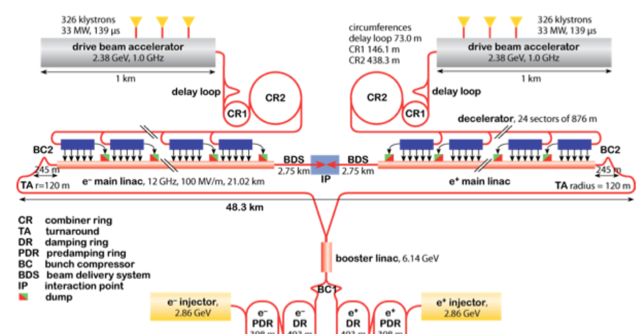
Linear

ILC



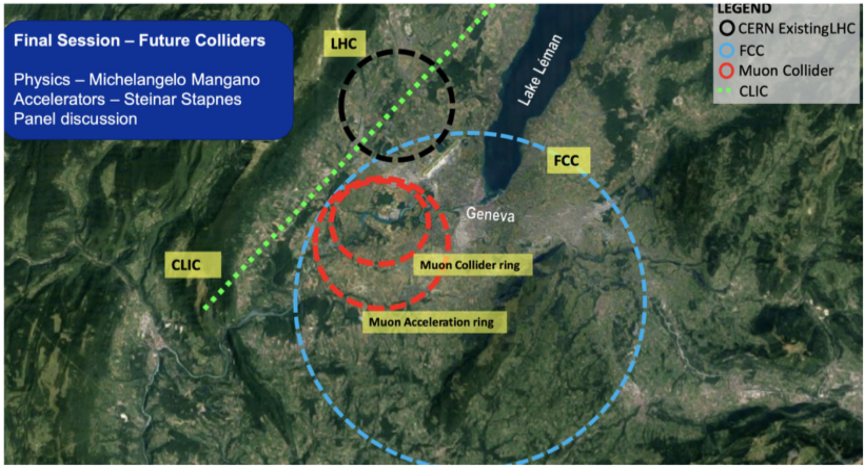


C^3 Cool Copper Collider

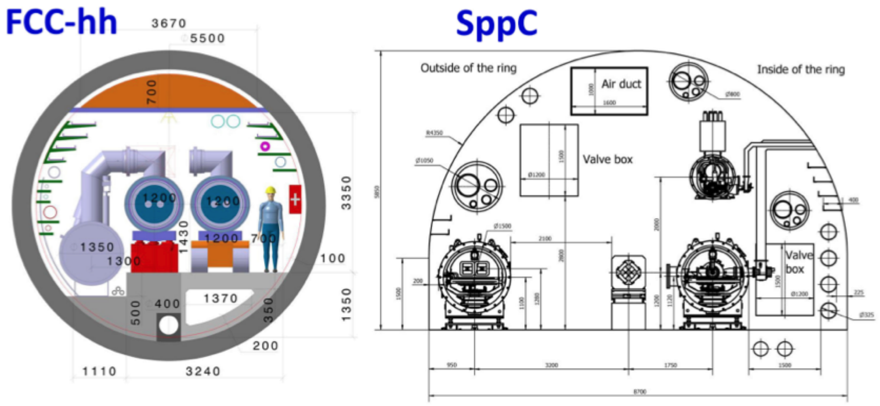


CLIC

Hadron collider



Better for colored new physics.
Noisier collision environment.

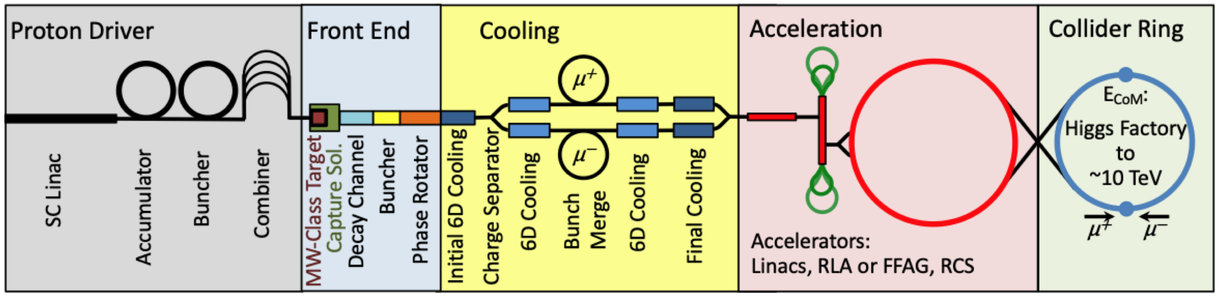


Have a lot of experience with pp.
Need a big ring, and new magnets.

Muon collider

Cleaner (at least for high energy states).
More focus on electroweak processes

Don't know for sure we can make it yet.



Conclusions

- Electron-position colliders (at very high luminosity) and proton / muon colliders (at very high energy) provide unprecedented discovery potential

- New territory explored with precision measurements and direct searches is strongly motivated for
  - Solving the mysteries associated with the Higgs boson
  - Discovering WIMP Dark Matter
  - Understanding the electroweak phase transition and discovering the conditions for electroweak bryogenesis

- Potential for big surprises and discovery of unexpected new principles of nature

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

http://cepc.ihep.ac.cn/preCDR/volume.html

http://tlep.web.cern.ch

http://lhec.web.cern.ch

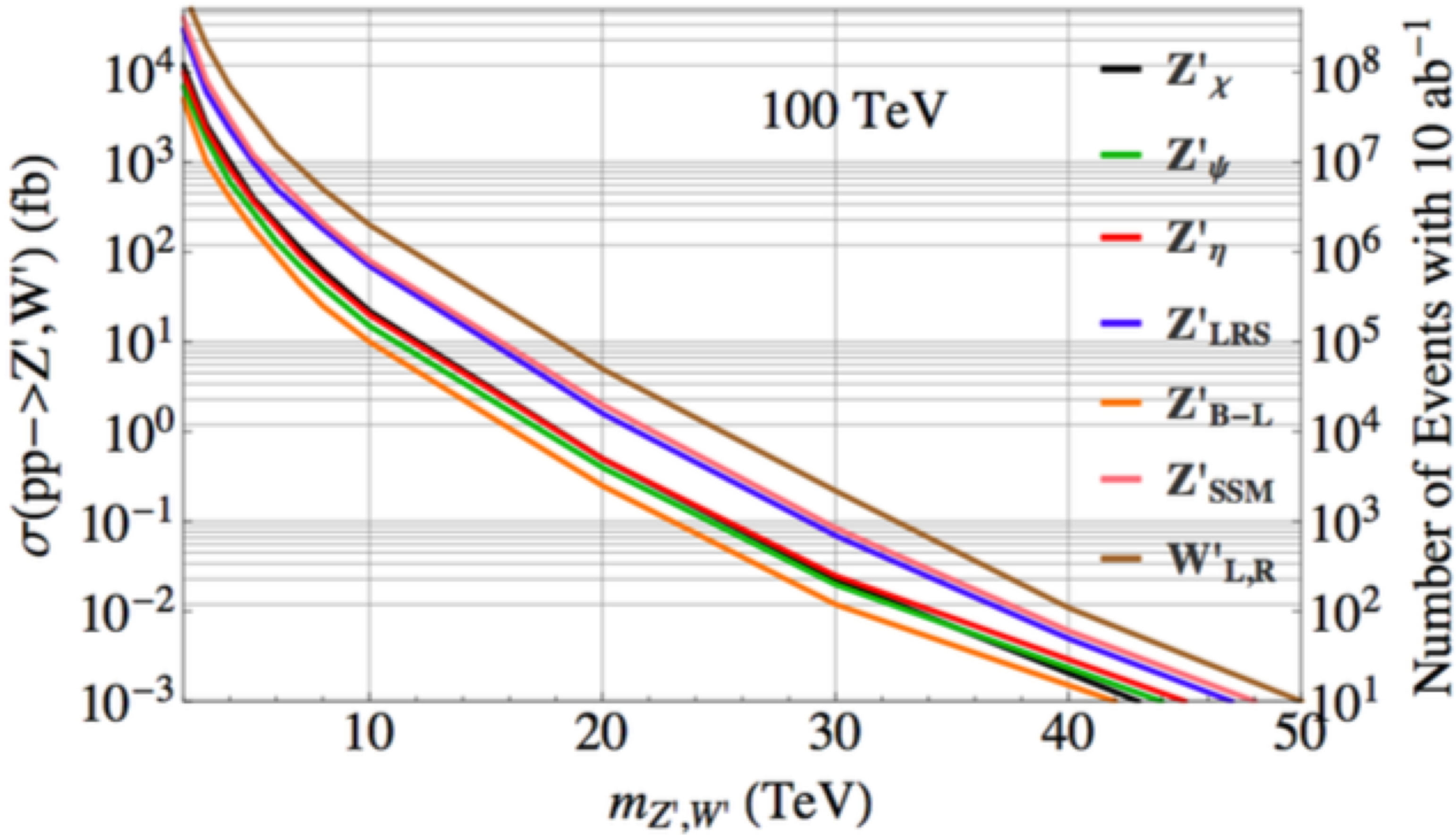
Circular *pp* Collider

Some Experimental Goals

- Testable reasons why the Standard Model must be incomplete
  - Dark Matter could be
    - Weakly-interacting particles
    - Particles interacting through Higgs portal
    - Interacting with SM particles through gravity
  - Electroweak Baryogenesis
    - Can the electroweak phase transition (formation of Higgs VeV) provide the out-of-equilibrium condition needed for matter-antimatter asymmetry observed?
    - Can the parameter space of new physics be a bounded parameter space?
    - Can it be fully covered with a 100-TeV scale *pp* collider?

    YES and YES
- Naturalness – the need to explain the lightness of the Higgs mass – testing Naturalness at 10^{-4}

Exploring New Territory - New Weak Gauge Interactions



Discovery reach

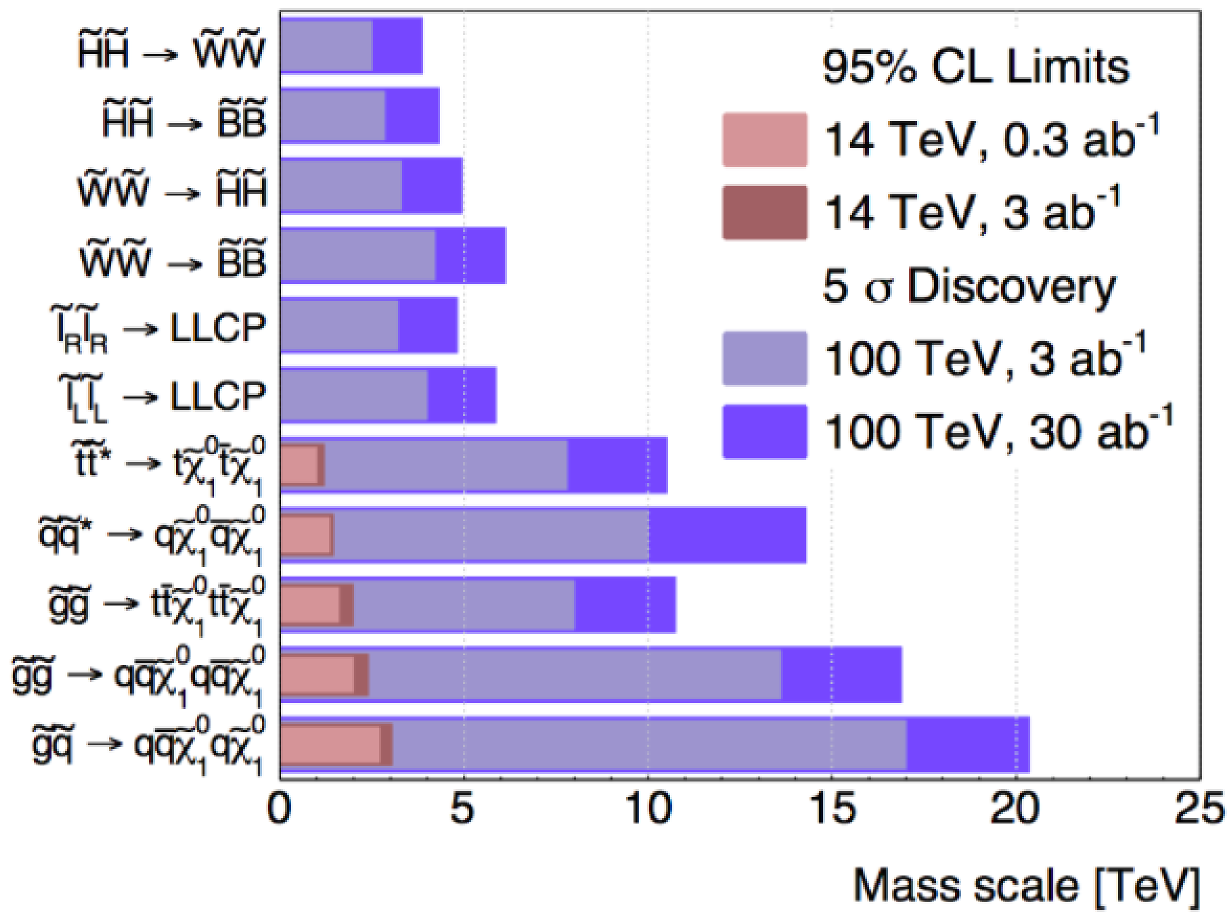
T.Rizzo, arXiv:1403.5465

Model	1 ab^{-1}	10 ab^{-1}	100 ab^{-1}
SSM	23.8	33.3	41.3
LRM	22.6	31.5	39.5
ψ	20.1	29.1	37.2
χ	22.7	30.6	38.2
η	20.3	29.8	38.0
I	22.4	29.2	36.2

10-fold increase in luminosity
→ ~7 TeV increase in mass reach

Exploring New Territory – Squarks and Gluinos

Summary from FCC Report:



Squark & gluino discovery potential up to 10-20 TeV

Full exploration of "low-scale" SUSY