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Shatalov[96], K. Shaw[165a,165b], C.Y. Shehu[150], P. Sherwood[77], L. Shi[152,v], S. Shimizu[66], C.O. Shimmin[164], M. Shimojima[101], M. Shiyakova[64], A. Shmeleva[95], M.J. Shochet[31], D. Short[119], S. Shrestha[63], E. Shulga[97], M.A. Shupe[7], S. Shushkevich[42], P. Sicho[126], O. Sidiropoulou[155], D. Sidorov[113], A. Sidoti[133a], F. Siegert[44], Dj. Sijacki[13a], J. Silva[125a,125d], Y. Silver[154], D. Silverstein[144], S.B. Silverstein[147a], V. Simak[127], O. Simard[5], Lj. Simic[13a], S. Simion[116], E. Simioni[82], B. Simmons[77], D. Simon[34], R. Simoniello[90a,90b], P. Sinervo[159], N.B. Sinev[115], V. Sipica[142], G. Siragusa[175], A. Sircar[78], A.N. Sisakyan[64,*], S.Yu. Sivoklokov[98], J. Sjölin[147a,147b], T.B. Sjursen[14], H.P. Skottowe[57], K.Yu. Skovpen[108], P. Skubic[112], M. Slater[18], T. Slavicek[127], K. Smajek[87], B.H. Smart[46], L. Smestad[14], S.Yu. Smirnov[97], Y. Smirnov[97], L.N. Smirnova[98,w], O. Smirnova[80], K.M. Smith[53], M. Smizanska[71], K. Smolek[127], A.A. Snesarev[95], G. Snidero[75], S. Snyder[25], R. Sobie[170,k], F. Socher[44], A. Soffer[154], D.A. Soh[152,v], C.A. Solans[30], M. Solar[127], J. Solc[127], E.Yu. Soldatov[97], U. Soldevila[168], A.A. Solodkov[129], A. Soloshenko[64], O.V. Solovyanov[129], V. Solovyev[122], P. Sommer[48], H.Y. Song[33b], N. Soni[1], A. Sood[15], A. Sopczak[127], B. Sopko[127], V. Sopko[127], V. Sorin[12], M. Sosebee[8], R. Soualah[165a,165c], P. Soueid[94], A.M. Soukharev[108,c], D. South[42], S. Spagnolo[72a,72b], F. Spanò[76], W.R. Spearman[57], F. Spettel[100], R. Spighi[20a], G. Spigo[30], L.A. Spiller[87], M. Spousta[128], T. Spreitzer[159], R.D. St. Denis[53], S. Staerz[44], J. Stahlman[121], R. Stamen[58a], S. Stamm[16], E. Stanecka[39], R.W. Stanek[6], C. Stanescu[135a], M. Stanescu-Bellu[42], M.M. Stanitzki[42], S. Stapnes[118], E.A. Starchenko[129], J. Stark[55], P. Staroba[126], P. Starovoitov[42], R. Staszewski[39], P. Stavina[145a,*], G. Steele[53], P. Steinberg[25], I. Stekl[127], B. Stelzer[143], H.J. Stelzer[30], O. Stelzer-Chilton[160a], H. Stenzel[52], S. Stern[100], G.A. Stewart[53], J.A. Stillings[21], M.C. Stockton[86], M. Stoebe[86], G. Stoicea[26a], P. Stolte[54], S. Stonjek[100], A.R. Stradling[8], A. Straessner[44], M.E. Stramaglia[17], J. Strandberg[148]

Chip

Brock

University Extinguished Professor,
Physics & Astronomy, MSU

MICHIGAN STATE | MSU Global
UNIVERSITY
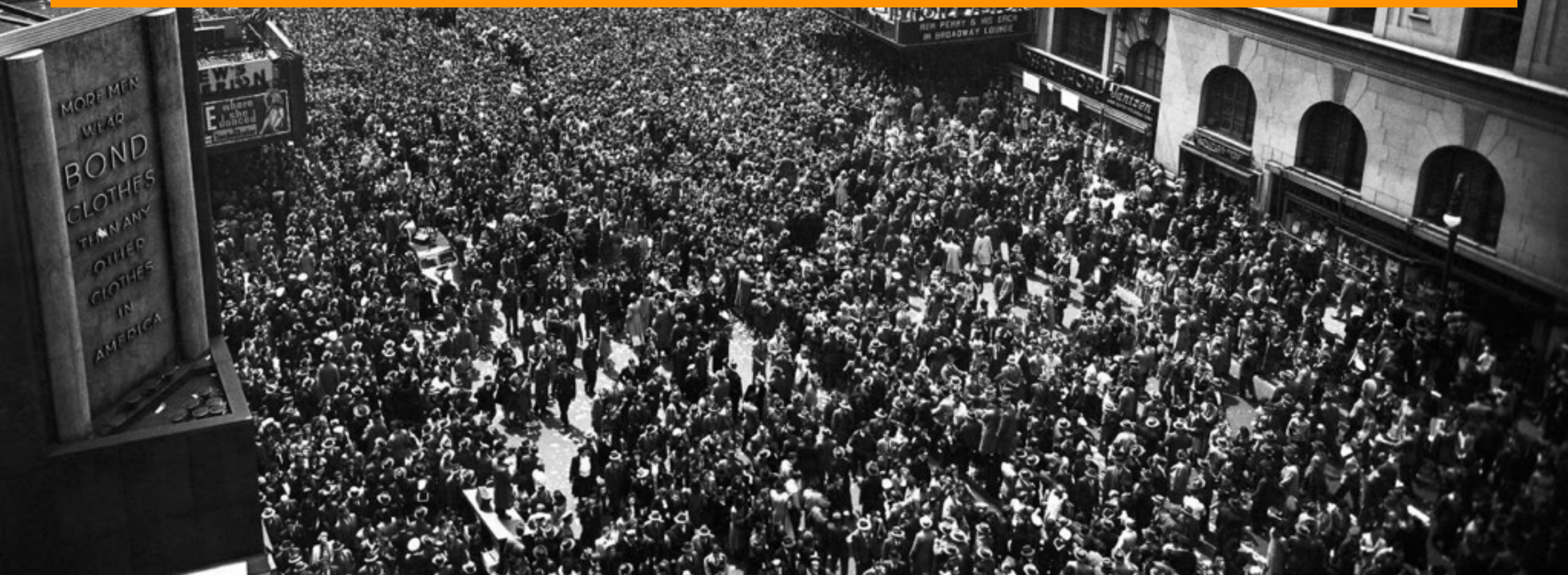
when I'm done:

- whole-field planning in particle physics

- the untenable nature of the "Standard Model"

- how the Higgs Boson informs the next steps in collider physics

it takes a village to plan in HEP

Two vehicles:

■ **"Snowmass"**

organized by DPF

two comprehensive studies in 2001 and 2013 and...now, two more. different.

■ **"P5"**

Particle Physics Project Prioritization Panel

sub-panel of HEPAP

Two vehicles:

■ **"Snowmass"**

organized by DPF

two comprehensive studies in 2001 and 2013 and…now, two more. different.

■ **"P5"**

Particle Physics Project Prioritization Panel

sub-panel of HEPAP

not a great history

apologies to Pearls Before Swine by Stephan Pastis
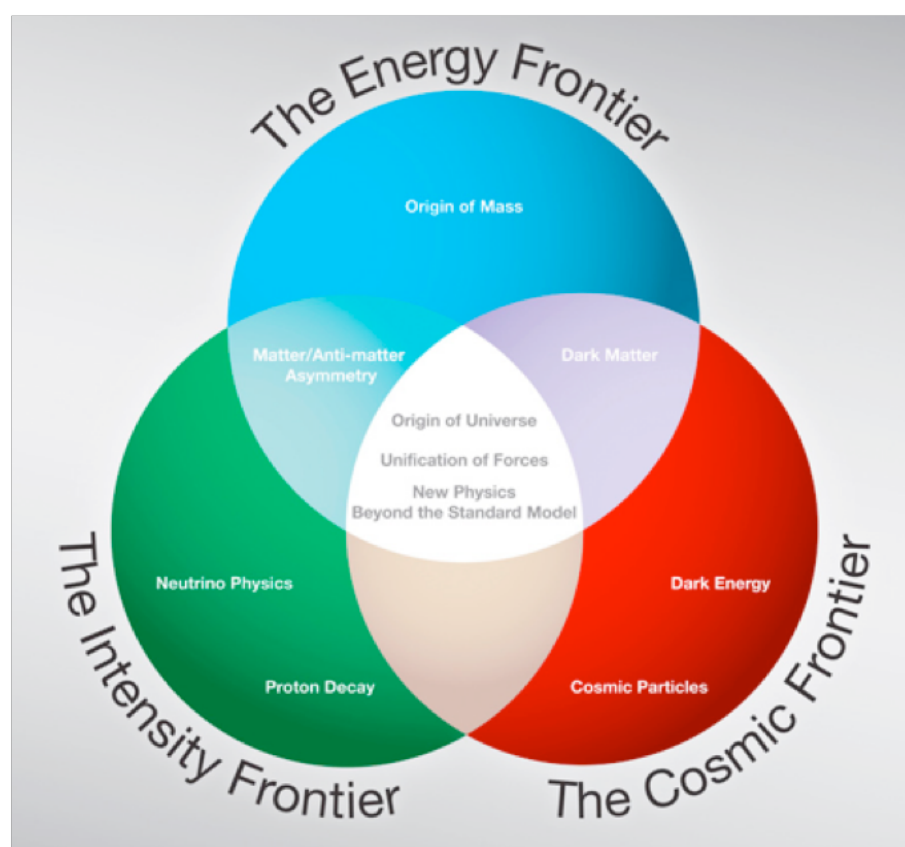
- The 2008 P5 recommendations – Three **Frontiers...**"the circles"

- In the US we bickered and didn't own the process and hence, the results

By 2011 it was time for another P5.
It had to be different.

...more like Nuclear Physics.

Snowmass → P5 after LHC's first run

Our primary theme.

energy

intensity   cosmic
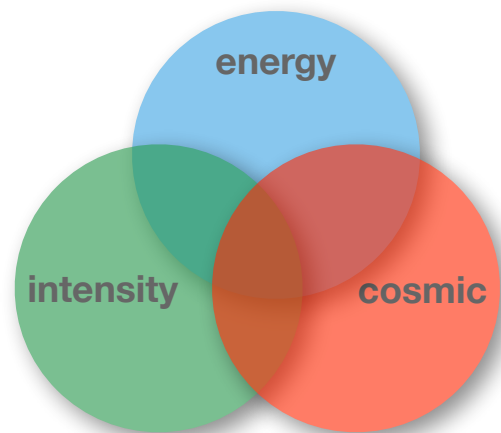
■ DPF started organizing

in 2011

Our primary themes.

energy

intensity   cosmic
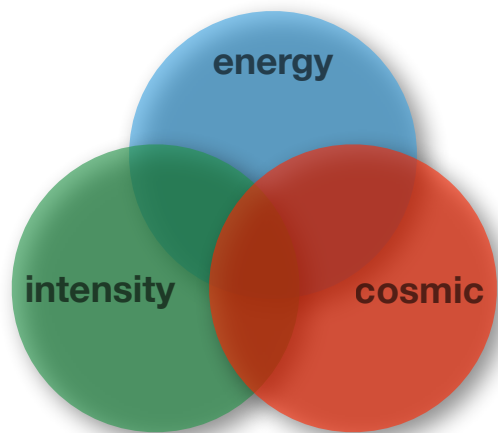
This was the Snowmass organizational reality:

energy
Frontier

cosmic
Frontier

intensity
Frontier

computing
Frontier

outreach
Frontier

"capabilities"

facilities
Frontier

instr.
Frontier

My job:

energy Frontier

intensity

cosmic
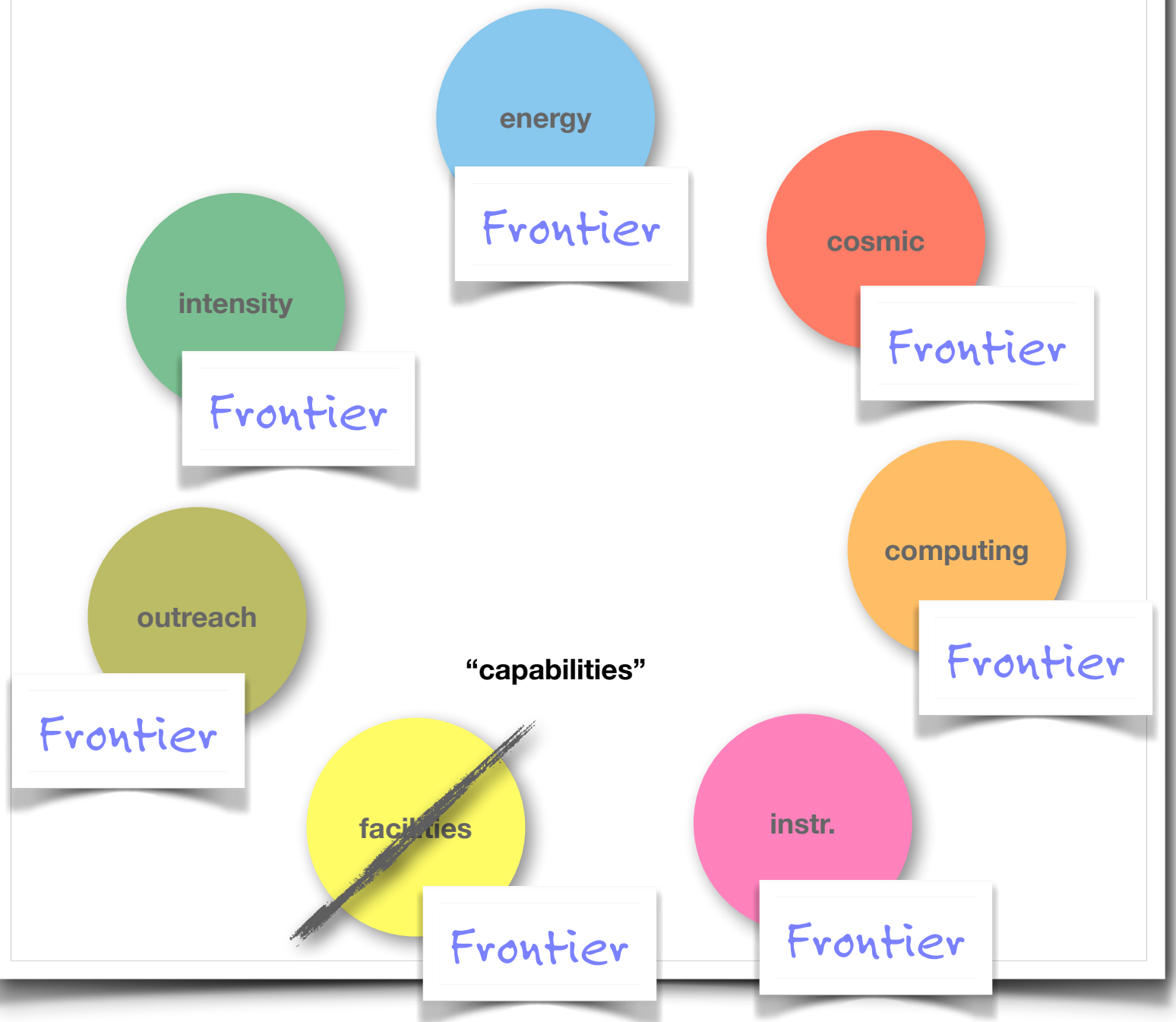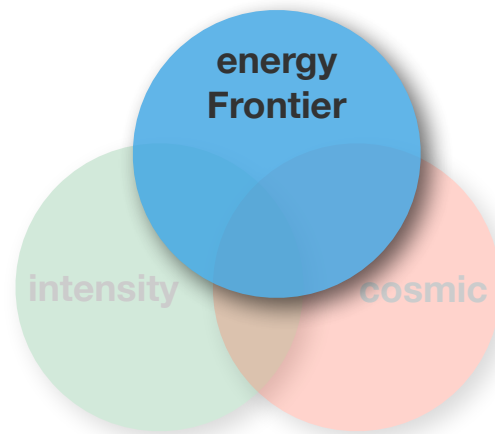
We worked together & apart:

"Snowmass"*: **2013**

P5: October **2014**
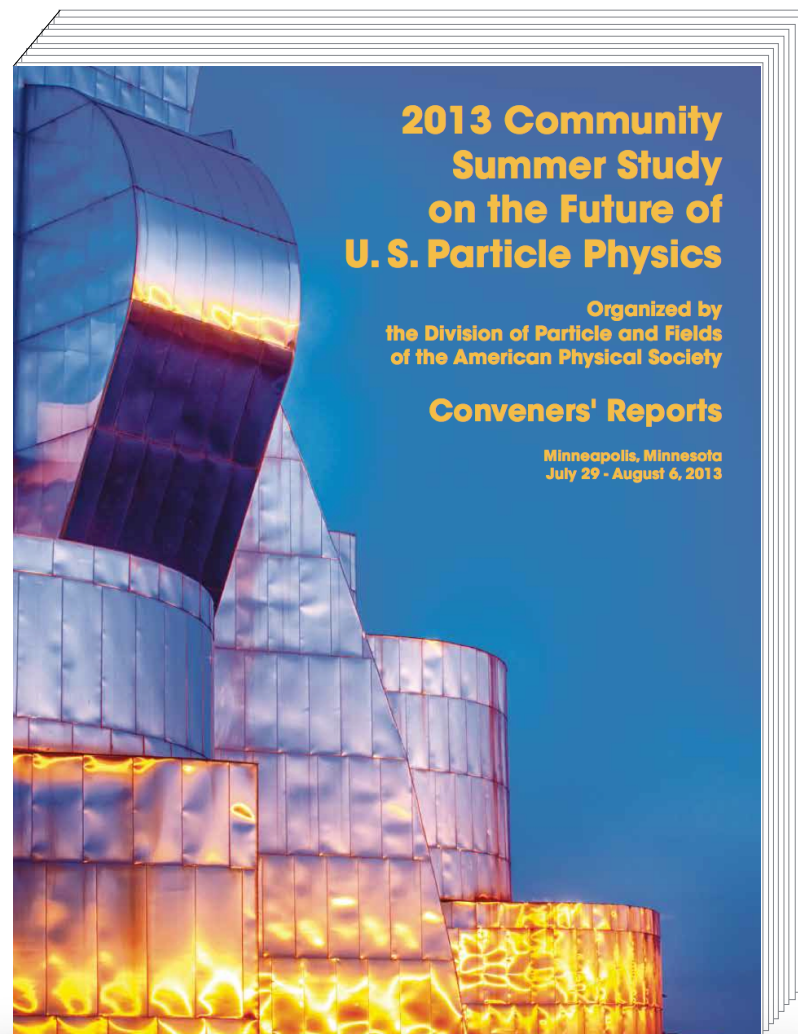
2013 Community Summer Study on the Future of U. S. Particle Physics

Organized by the Division of Particle and Fields of the American Physical Society

Conveners' Reports

Minneapolis, Minnesota
July 29 - August 6, 2013

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)   May 2014

* There's a story there.
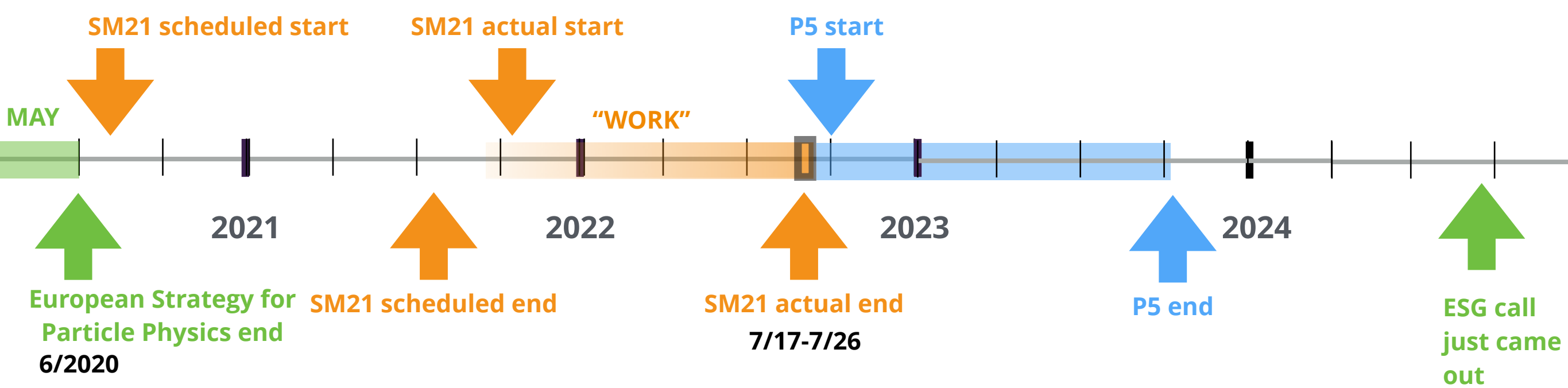
■ The LHC running is just beginning

Higgs discovery

"phase 0 upgrades"

"phase 1 upgrades"

we are here

| 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |

Snowmass13 & P5

Snowmass21 & P5

Run I
8 TeV
$0.75\ 10^{34}\ cm^{-2}s^{-1}$

Run II
13 TeV
$1.5\ 10^{34}\ cm^{-2}s^{-1}$

Run III
13.6 TeV
$1.7\text{-}2.2\ 10^{34}\ cm^{-2}s^{-1}$

20 fb^{-1}

~190 fb^{-1}

goal: 450 fb^{-1}

currently peak luminosity >2 x design
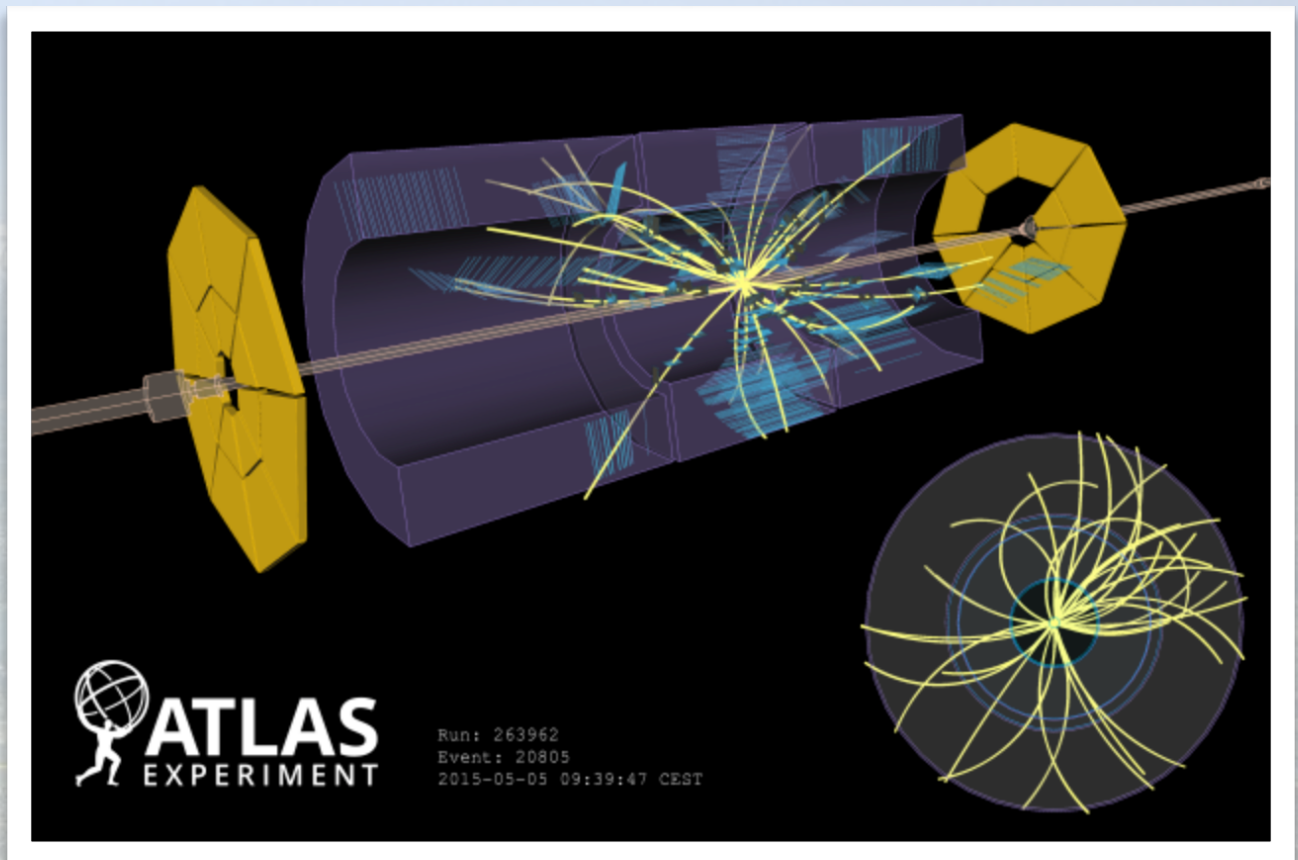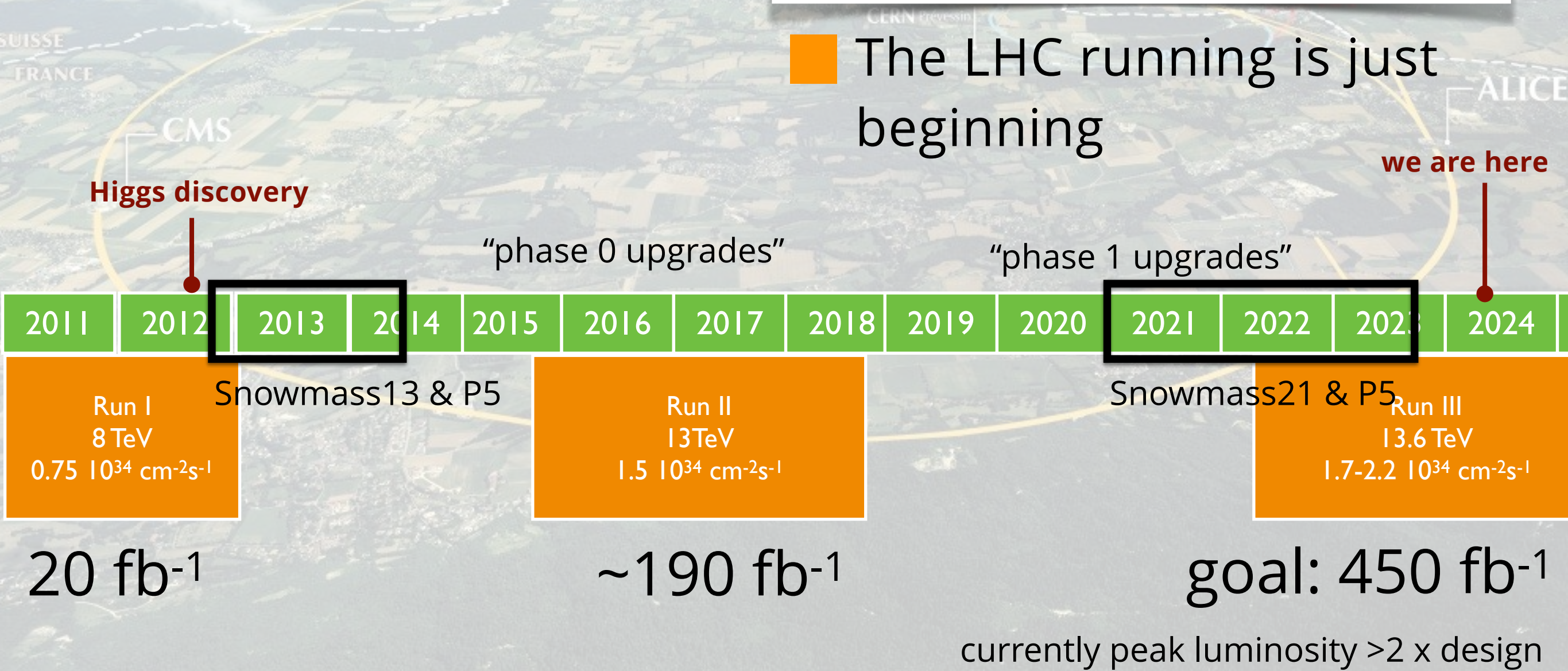
We worked together & apart…and again:
"Snowmass" 2021
P5: December 1, 2023

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

A strategic plan for the High Energy Physics Advisory Panel

2023 "Science Drivers":

- Elucidate the Mysteries of **Neutrinos**
- Reveal the Secrets of the **Higgs Boson**
- Determine the Nature of **Dark Matter**
- Understand What Drives **Cosmic Evolution**
- Search for Direct Evidence of **New Particles**
- Pursue Quantum Imprints of **New Phenomena**

particle physics

Why the Standard Model victory laps?

between **1967 - 2012**

■ history was made

1967

👑👑👑

2012

👑👑👑

between **1967 - 2012**
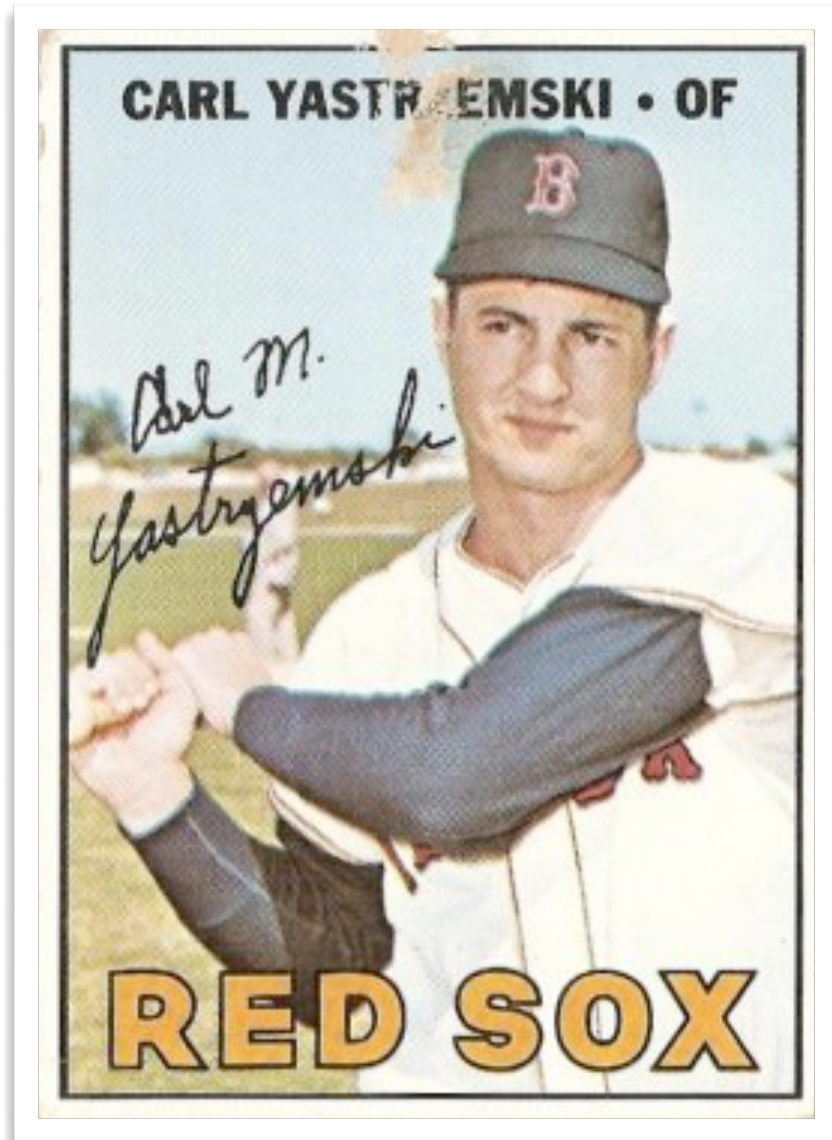
1967
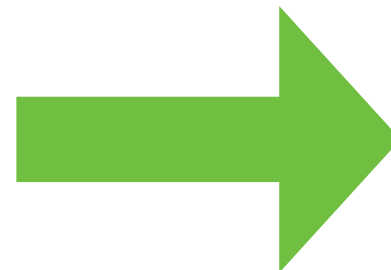
2012

30,000 ft View of the Standard Model

Key: modern colliders

Fermilab
Tevatron, 1983-2011
CDF & DO
p - $\bar{p}$

CERN
LHC, 2010-present
ATLAS, CMS, LHCb
p - p

CERN
SPS, 1981-1990
UA1 & UA2
p - $\bar{p}$

SLAC
SLC, 1989-1998
SLD
e - $\bar{e}$

DESY
HERA, 1992-2007
ZEUS & H1
e - p

CERN
LEP, 1989-2000
ALEPH, DELPHI, L3, OPAL
e - $\bar{e}$

A theme? hadron collider...followed by precision lepton collider **?**
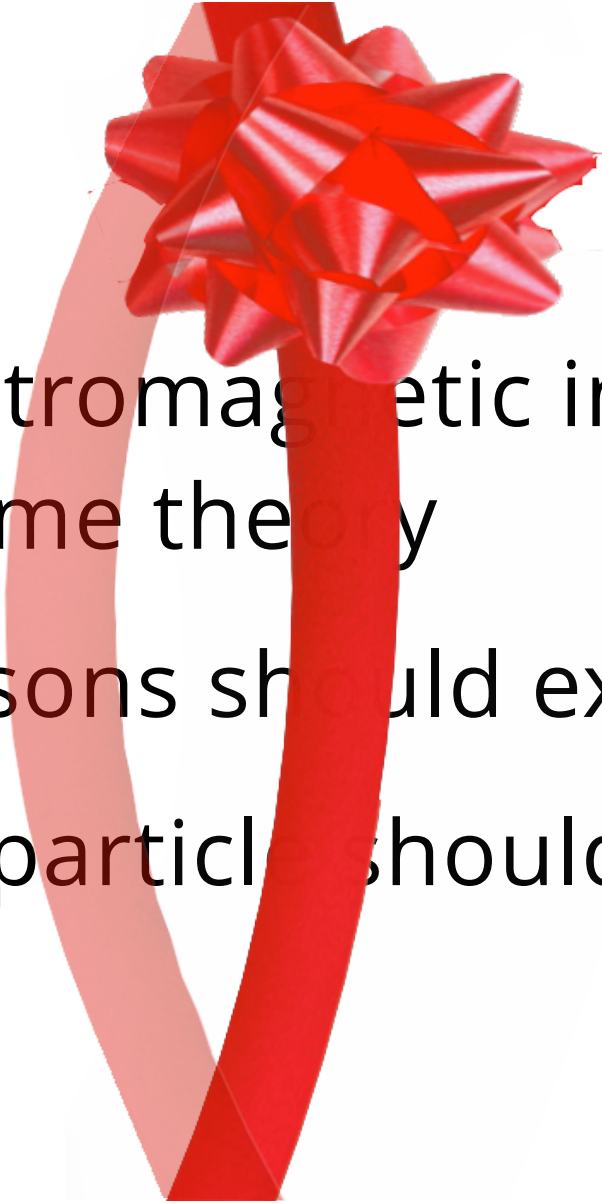
guided research
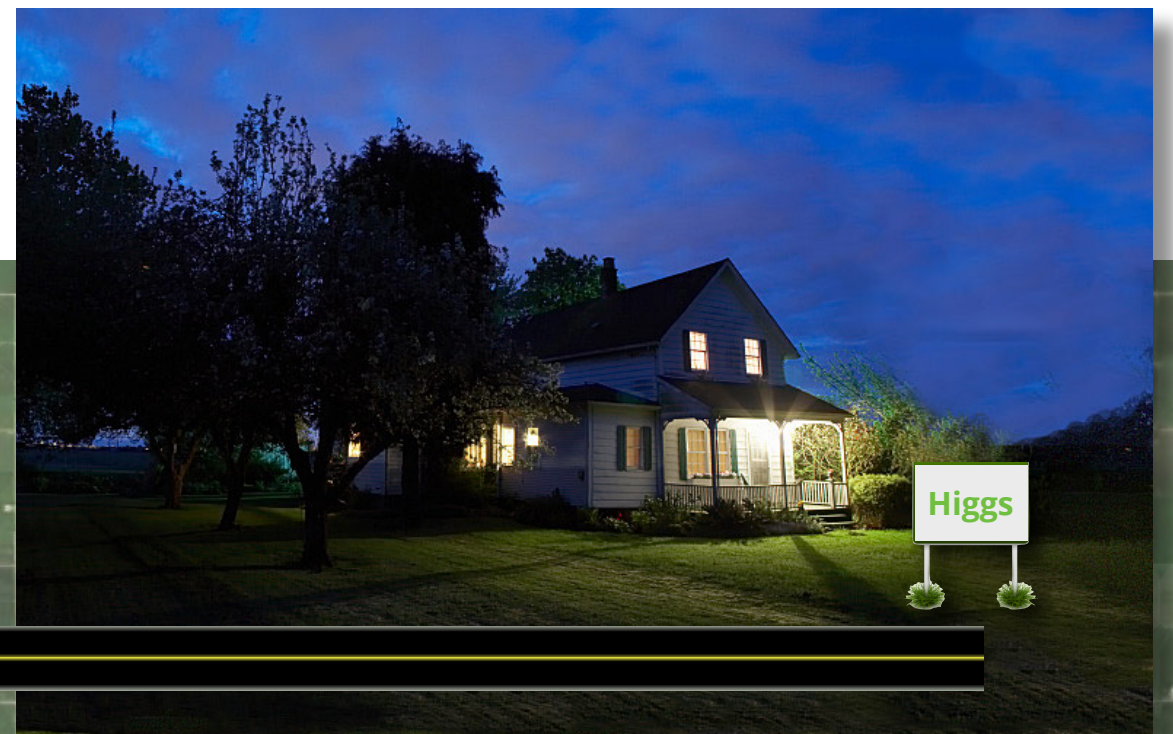
Because: 3 SM predictions

- The weak and electromagnetic interactions originate in the same theory

- 3 spin 1 vector bosons should exist: γ, $W^{\pm}$, Z^0

- A spin-0 field and particle should exist

- The weak and electromagnetic interactions originate in the same theory
- 3 spin 1 vector bosons should exist: γ, $W^{\pm}$, Z^0
- A spin-0 field and particle should exist

1/3 SM predictions

■ The weak and electromagnetic interactions originate in the same theory
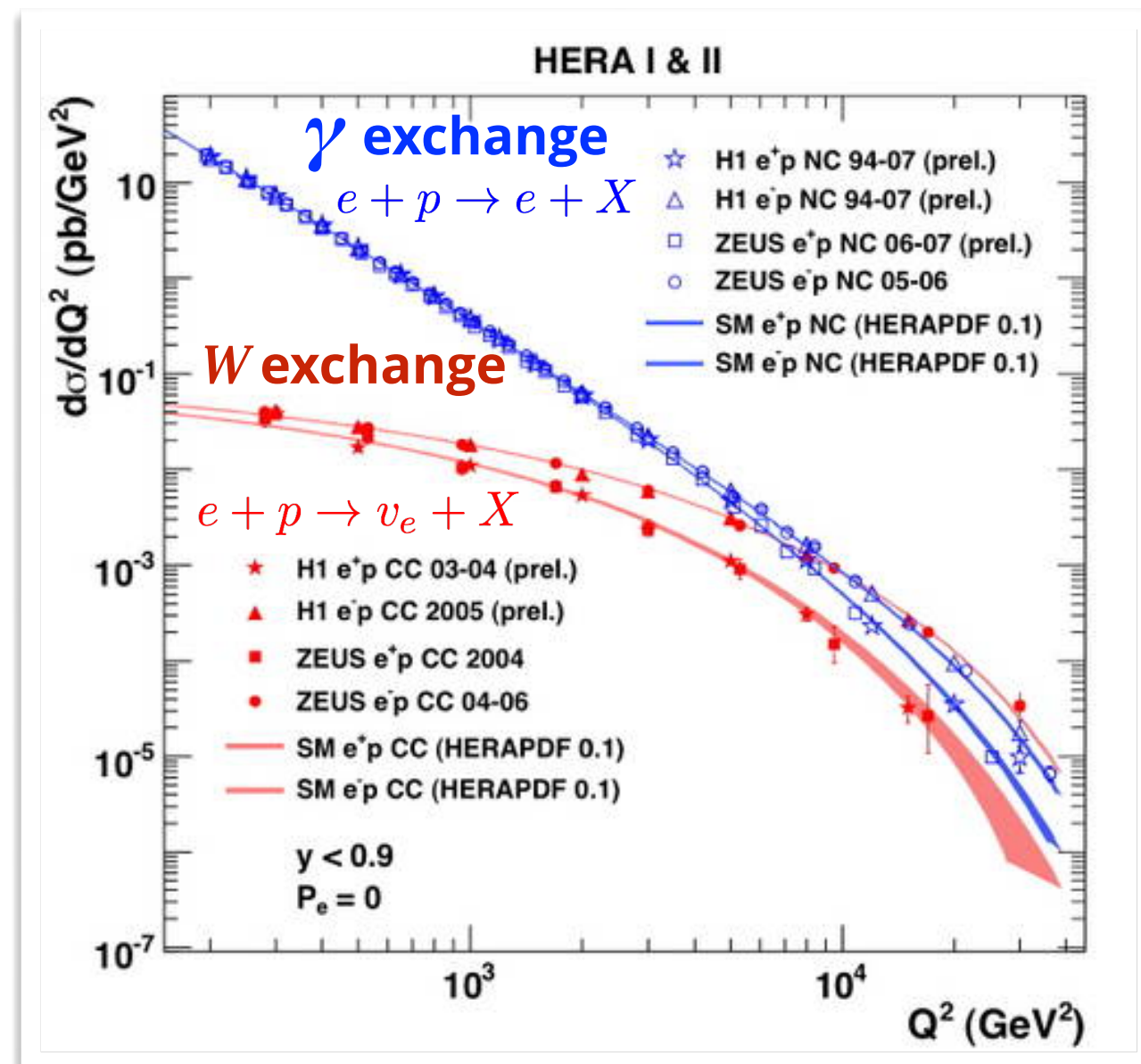
2/3 SM predictions

Z mass = 91.1876 ± 0.0021 GeV/c²

1/2 W mass of 80.385 ± 0.015 GeV/c²

■ 3 spin 1 vector bosons should exist: γ, $W^{\pm}$, Z^0
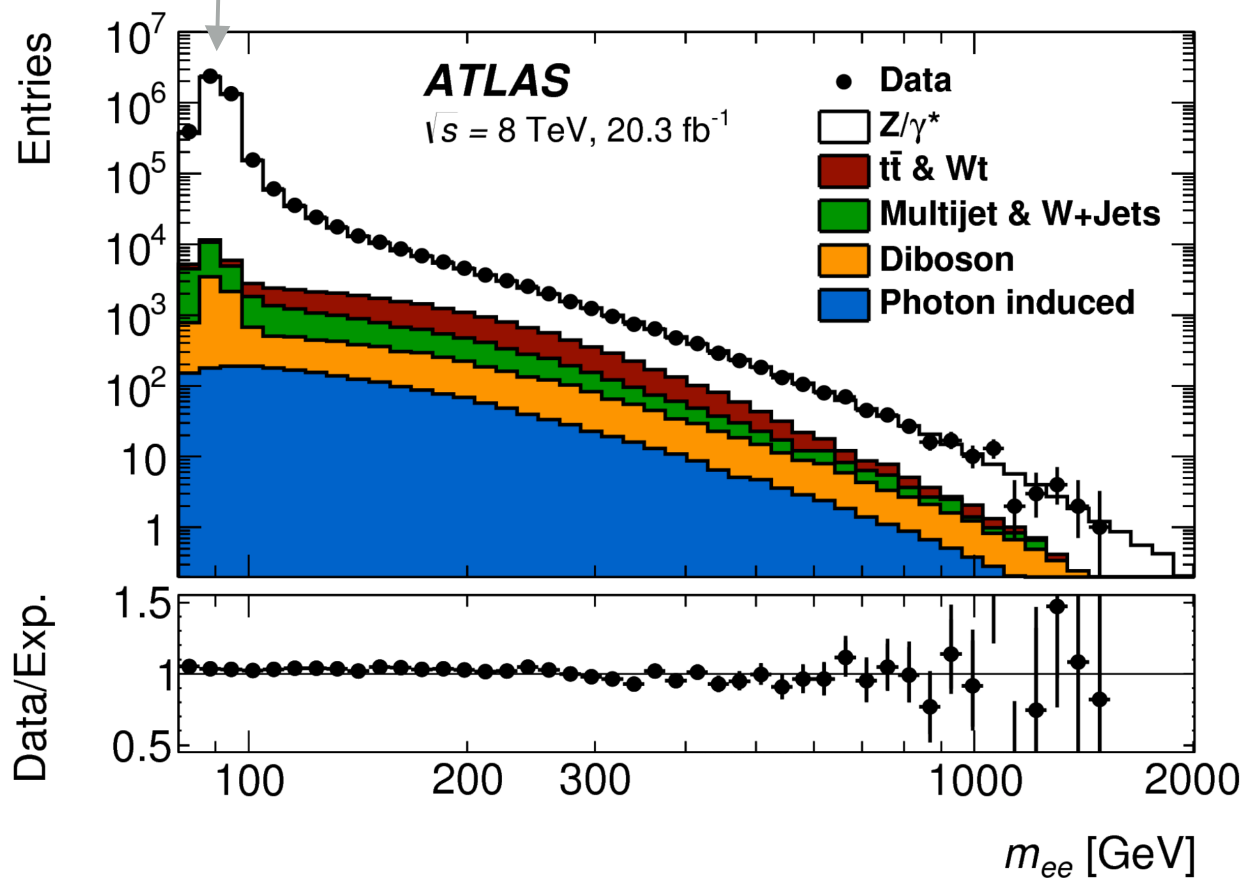
$$Z^0 \rightarrow e^+ + e^-$$
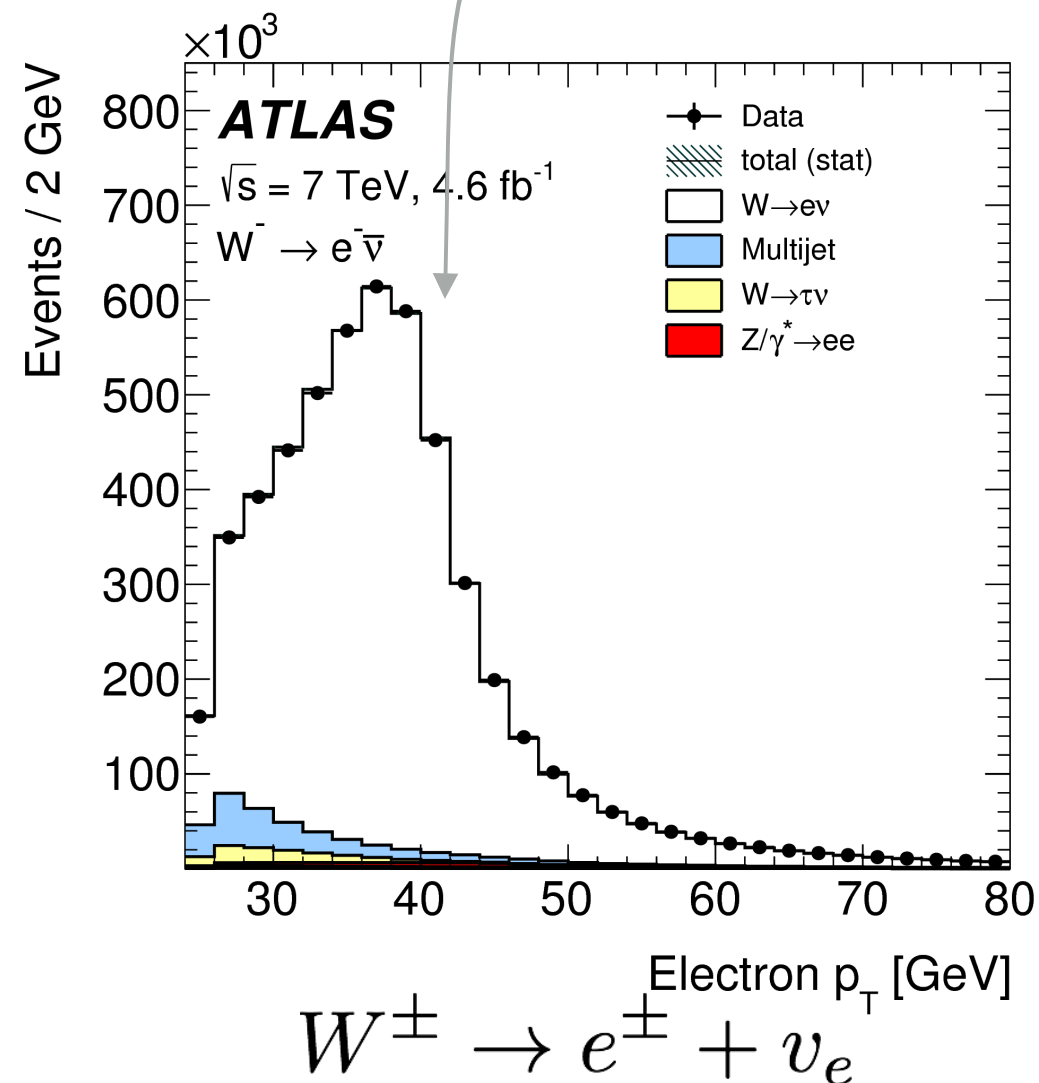
$$W^{\pm} \rightarrow e^{\pm} + v_e$$

3/3 SM predictions

◼️ A spin-0 field and particle should exist

and so began a story

1929-2024
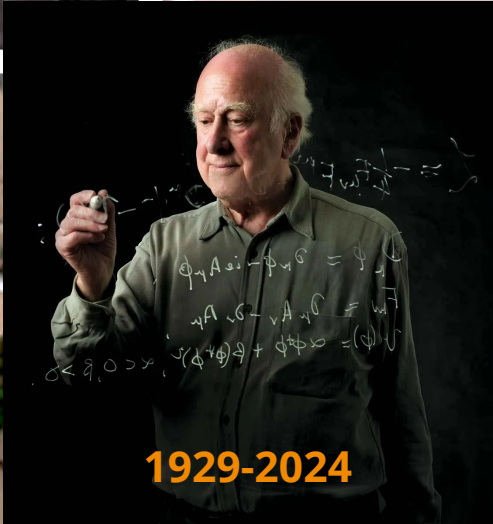
4th of July, 2012

the 2012 discovery

■ completed the story

unrelenting 40 year effort.
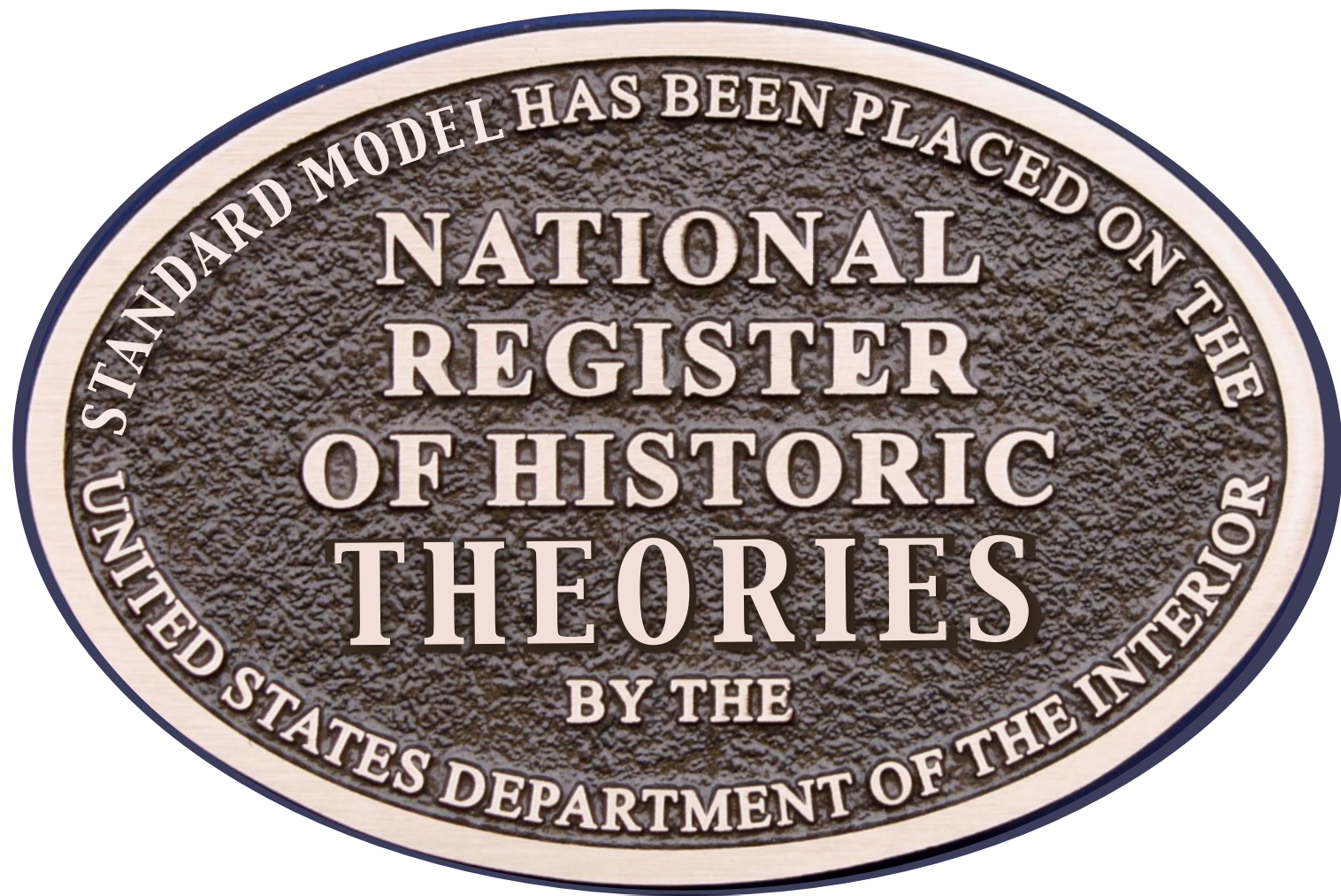
STANDARD MODEL HAS BEEN PLACED ON THE

NATIONAL
REGISTER
OF HISTORIC
THEORIES

BY THE

UNITED STATES DEPARTMENT OF THE INTERIOR

We're schizophrenic about the Standard Model

Like the nursery rhyme

THERE was a little girl who had a little curl
Right in the middle of her forehead;
When she was good, she was very, very good,
And when she was bad she was horrid.

◼ when the SM is good,

it's very good

◼ when it's bad

it's very...confusing

1860   1880   1900   1920   1940

2 decades pass

2 more decades pass

yet 2 more decades pass

power, motors, telegraph, radio, Planck, Einstein

electron discovered

Hertzian waves

Maxwell's Theory

Zeeman & Lorentz
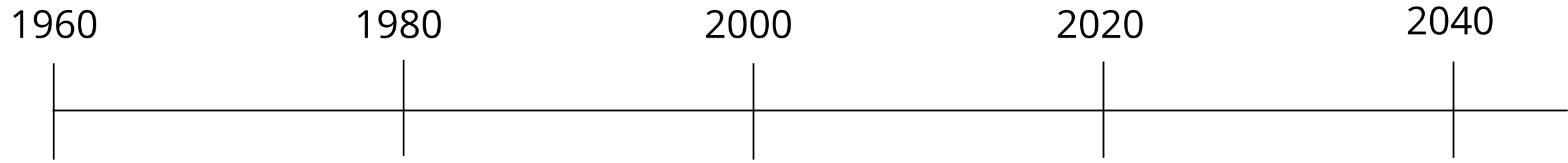
Abraham-Lorentz self-energy crisis
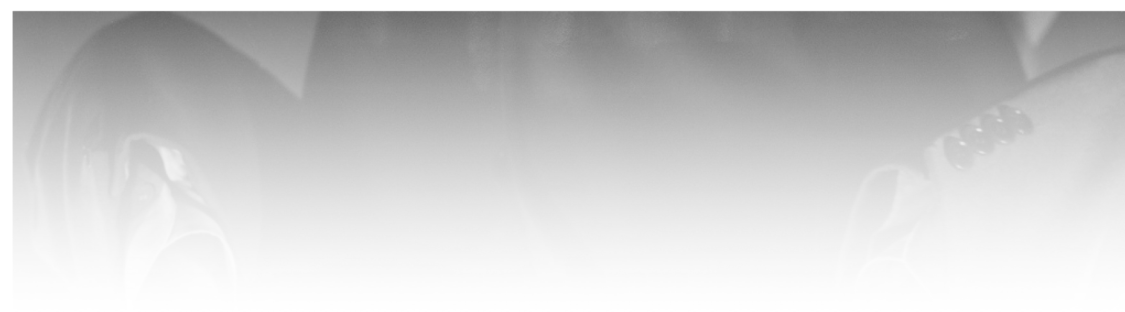
1.5 decades pass

2.5 more decades pass

1960   1980   2000   2020   2040

SM amazing

Higgs Boson Discovery

W/Z

Anderson

Brout, Englert, Guralnik, Hagen, Higgs, Kibble

Weinberg/ Salam

Higgs Boson phenomenology
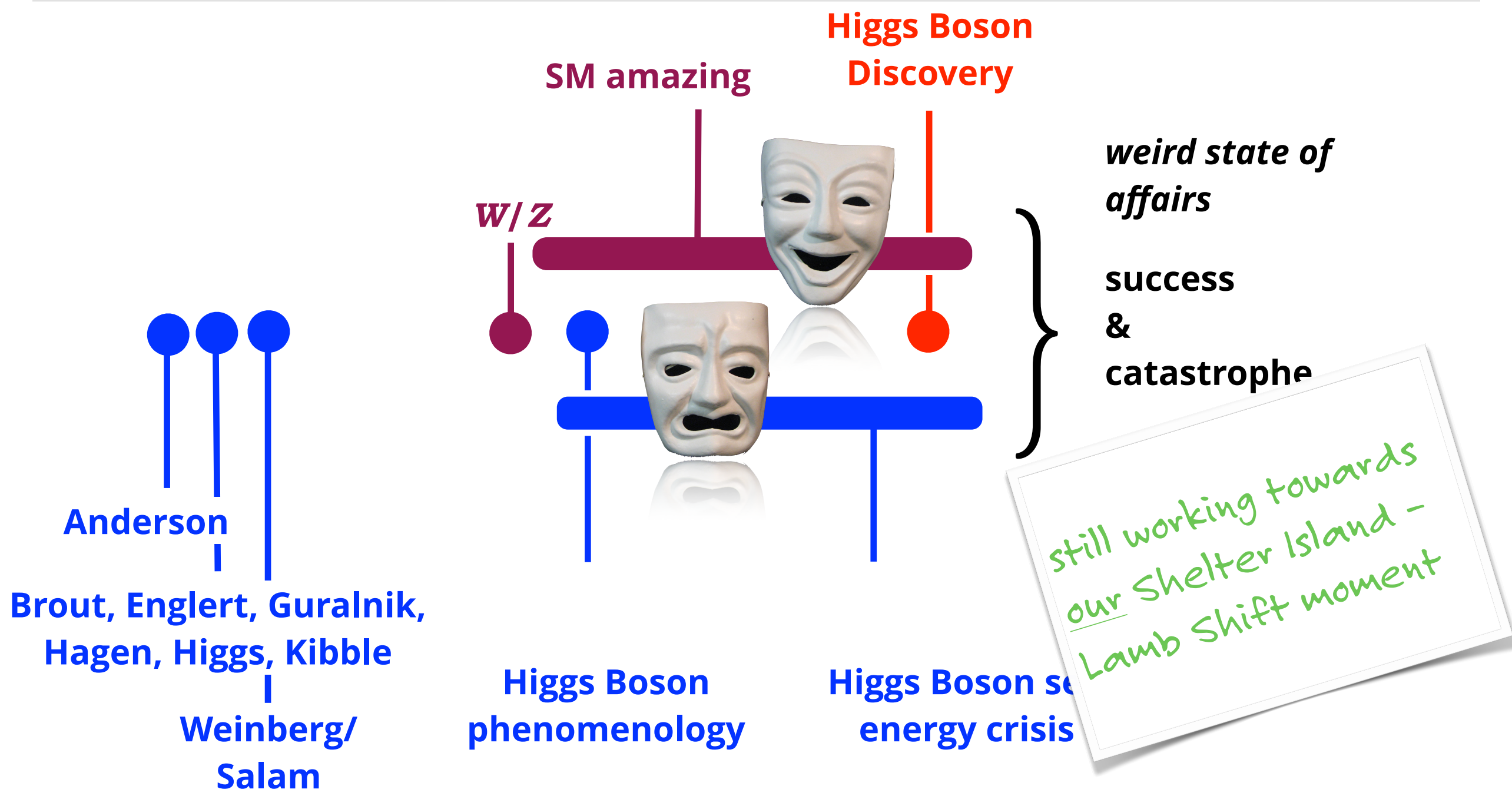
The Standard Model ingredients:

■ The Gauge Principle

circa 1918, 1954

demand of a symmetry

■ Spontaneous Symmetry Breaking

circa 1950, 1964

effective theory of phase transitions

particle physics
periodic table?

particle stamp collecting

& their interactions

spin 1/2

🟧 the players:

quarks

$$\frac{2}{3}e$$

$$\frac{1}{3}e$$

leptons

$$0e$$

$$-e$$

spin 1

🟧 the messenger fields

Z		
Z boson	γ	g
W	*gamma*	*gluon*
W boson		

weak   E&M   strong

H
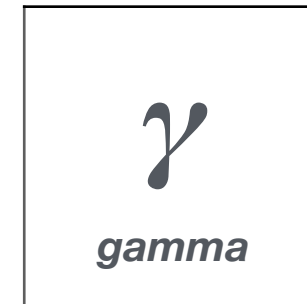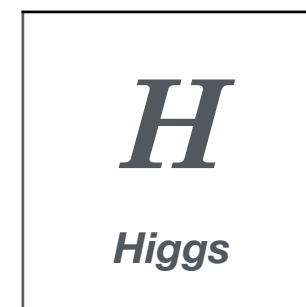
Higgs

um…the Higgs Force?
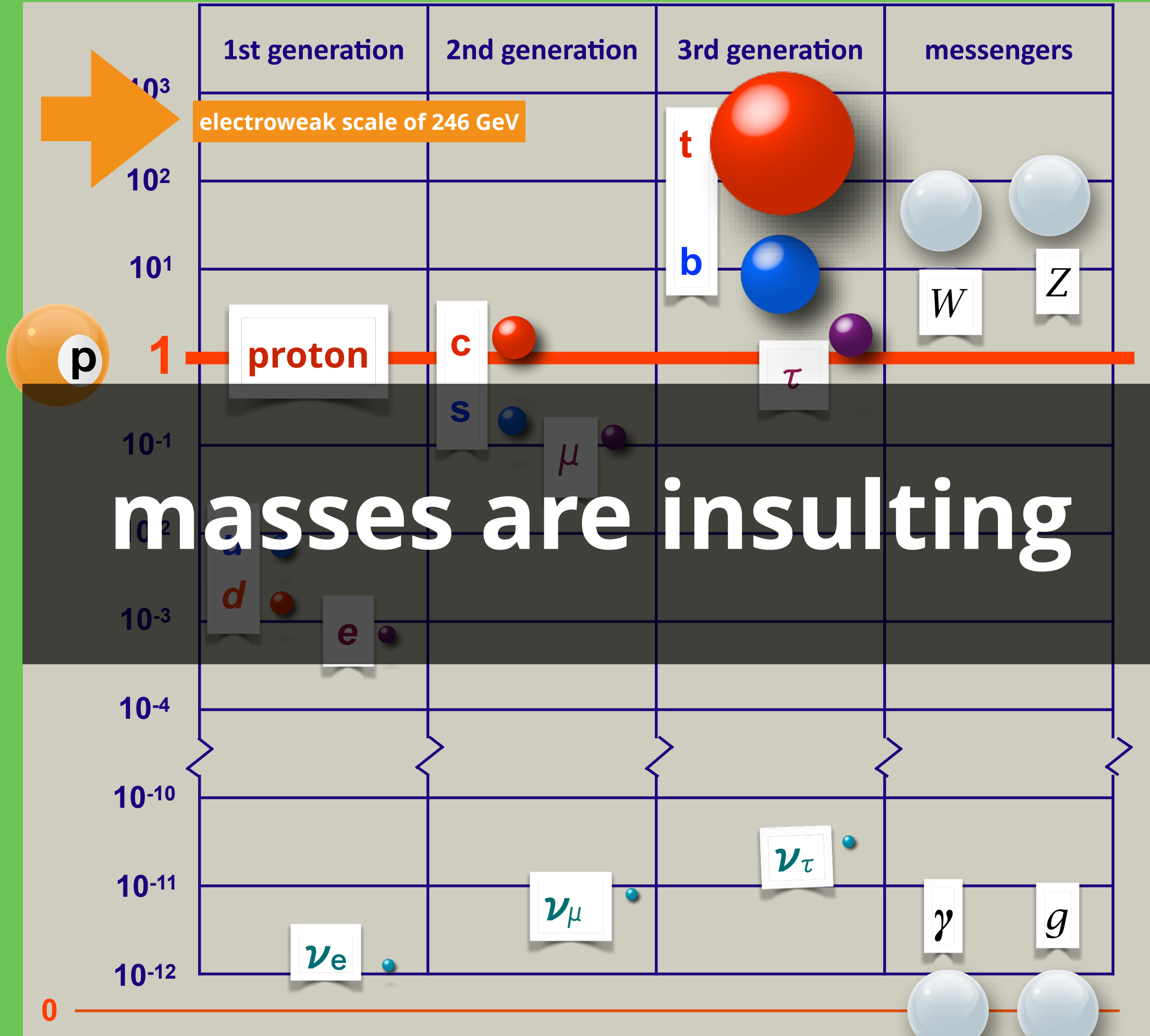
what's great

about the Standard Model?

1. the Gauge Principle
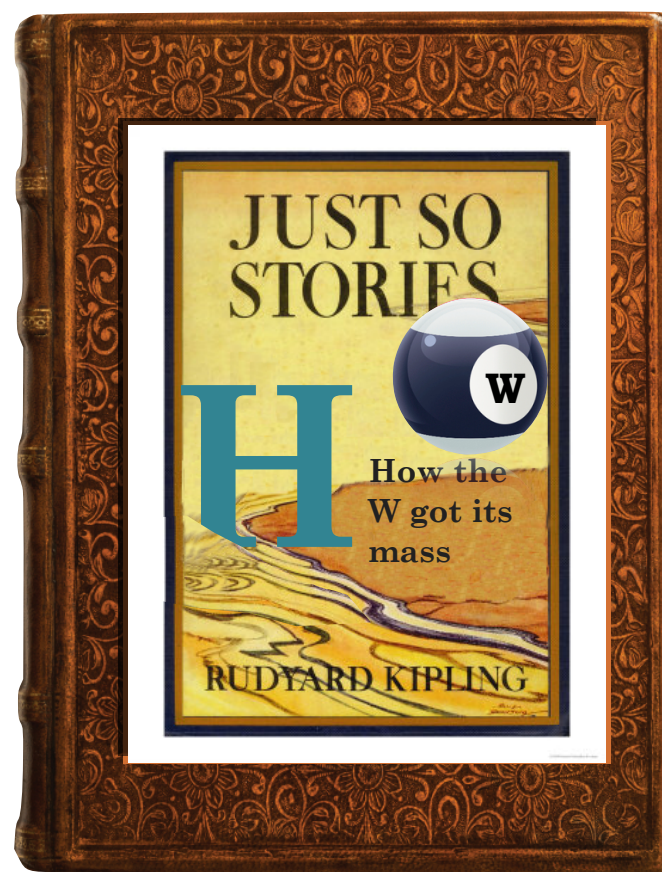
Gauge Principle

Extremely powerful and pretty.

- Q: generator of a group, with "charge" q

- θ a parameter

$$\left.\begin{array}{c} \\ \\ \end{array}\right\} \; U(Q) = e^{iQ\theta}$$

Demand Invariance…

$$\psi(x) \rightarrow e^{iQ\theta}\psi(x)$$

Global

it's a kind of magic*

Invariance of the **Local** sort demands

- the existence of a massless spin-1 field, $A_\mu(x)$

- and prescribes coupling: $\psi(x) : qA_\mu(x)\bar{\psi}(x)\gamma^\mu\psi(x)$
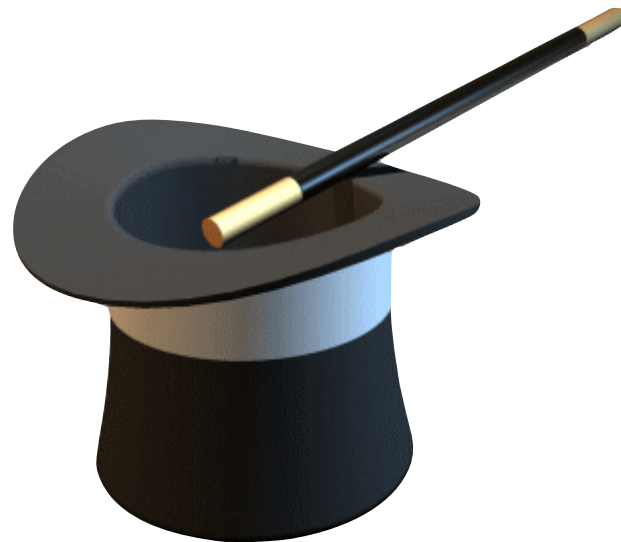
- **The demand of a symmetry forces the photon to exist!**

* Ask me afterwards for my tried-and-true baseball analogy for the Gauge Principle

Gauge Principle piece:

■ "Unfolds" rather neatly

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$W^{\pm}, Z^0, \gamma$

$W^{\pm}, Z^0, \gamma$

$W^{\pm}, Z^0, \gamma$

$W^{\pm}, Z^0, \gamma$

$$+ i\bar{\psi} \slashed{D} \psi$$

$W^{\pm}, Z^0, \gamma$

$e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau,$
u, d, c, s, t, b

that's really great

this Standard Model

the Gauge Principle:

Standard
Model

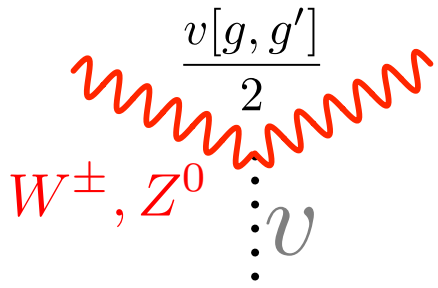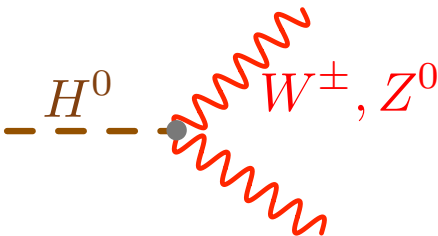| Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	-0.4	-0.2
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
σ_{had} [nb]	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_μ	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_τ	20.764 ± 0.04	20.789 ± 0.011	-0.6	-0.5
R_b	0.21629 ± 0.000	21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.003	17227 ± 0.00004	-0.1	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	1633 ± 0.00021	-0.7	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$		± 0.0007	-2.6	
$A_{FB}^{(0,c)}$				
$A_{FB}^{(0,s)}$				
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$				
A_e				
A_μ			-0.4	-0.3
A_τ	0.136 ± 0.015		-0.8	-0.7
	0.1439 ± 0.0043		-0.8	-0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	-0.6	-0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4	-0.4

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	-0.1	-0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		-0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\text{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

The most accurate and precise scientific model in history

"Standard Model"

standard |ˈstandərd|
noun

1 a level of quality or attainment

model |ˈmädl|
noun

2 ...a simplified description, esp. a mathematical one, of a system or process, to assist calculations and predictions

what's embarrassing

about the Standard Model?

it's not a dynamical theory

SM as an effective theory

A Dynamic Walking Model

trunk velocity

swing pendulum

stance-leg inverted pendulum

push-off

collision

body-weight support

B Dynamic Walking Human

COM velocity

push-off

collision

body-weight support

I can draw free-body diagrams and make a SM of walking
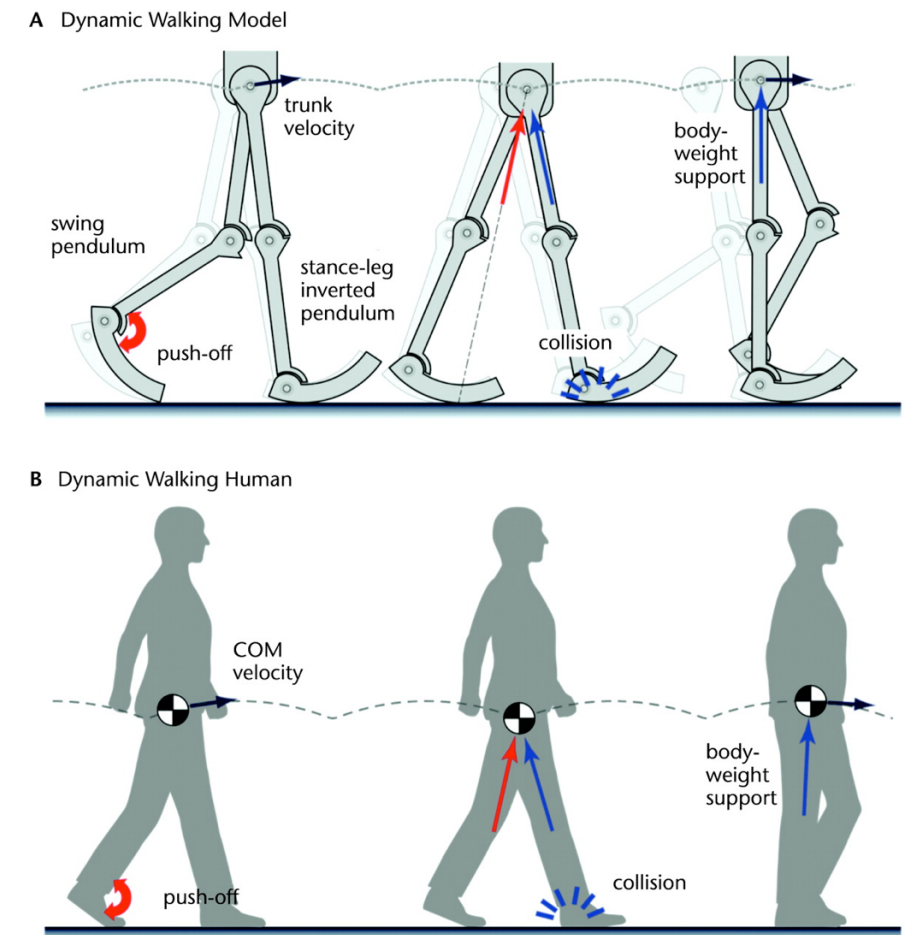
I can draw free-body diagrams and make a SM of walking

A Dynamic Walking Model

trunk velocity

body-weight support

swing pendulum

stance-leg inverted pendulum

push-off

collision

B Dynamic Walking Human

COM velocity

body-
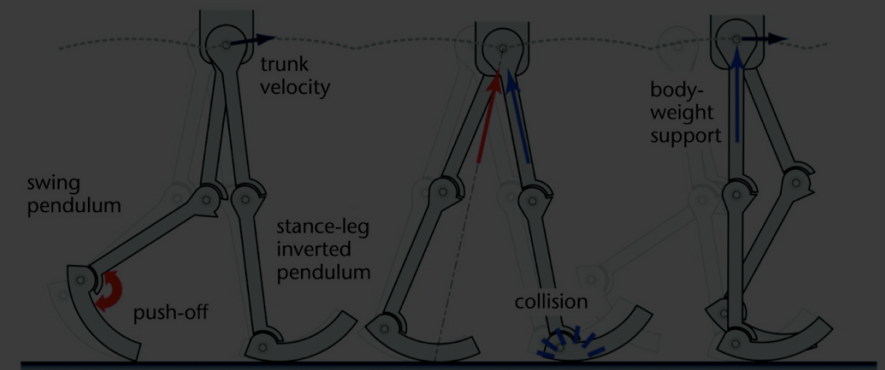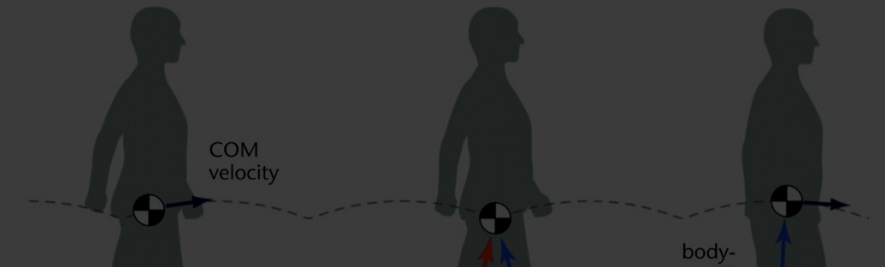
SM is an effective theory

But it's not the actual physiology of walking!

Ulnar nerve

Common peroneal nerve

Deep peroneal nerve

Superficial peroneal nerve

Sciatic nerve

Muscular branches of femoral nerve

Saphenous nerve

Tibial nerve

Torsion

Extension/Contraction

Flexion

Compression
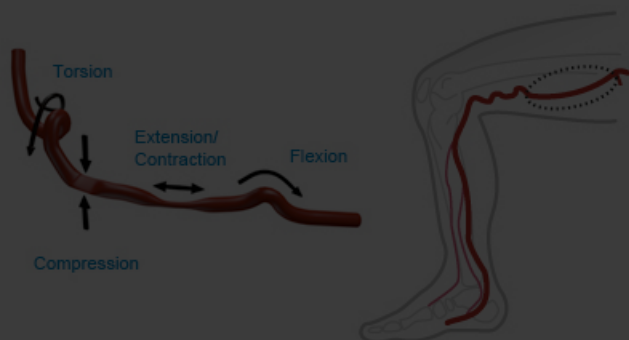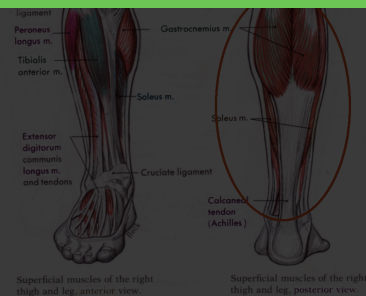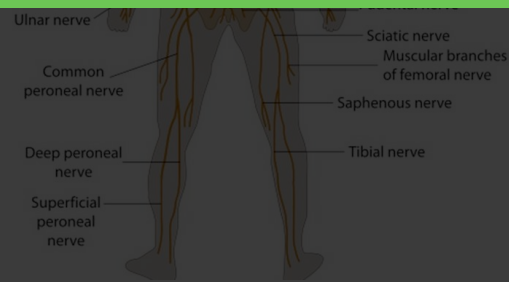
what's confusing

about the Standard Model?

2. Spontaneous Symmetry Breaking

◼ SSB is the story of the Higgs Boson

How?

■ a meaningless operation?

$$\mathcal{L} = \text{ blah blah blah } + \mu^2 \text{ blah } + \text{ blah blah blah}$$

$$\mathcal{L} = \text{ blah blah blah } - \mu^2 \text{ blah } + \text{ blah blah blah}$$

SSB is like a magnet

$$\mathcal{L} = \text{blah blah blah} + \boxed{(T - T_C)} \times \text{blah} + \text{blah blah blah}$$

$T > T_C$

$T < T_C$

F

M
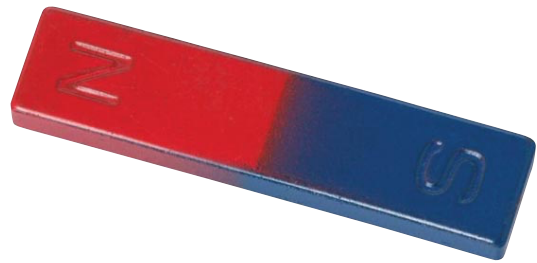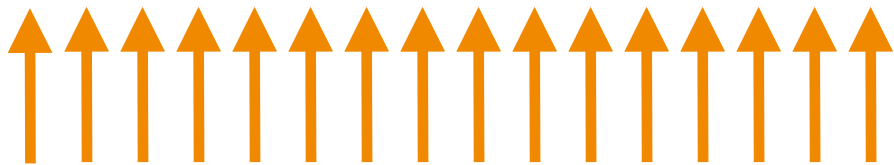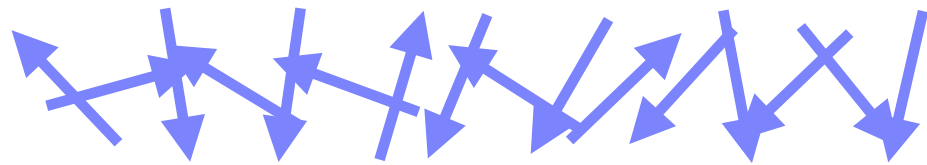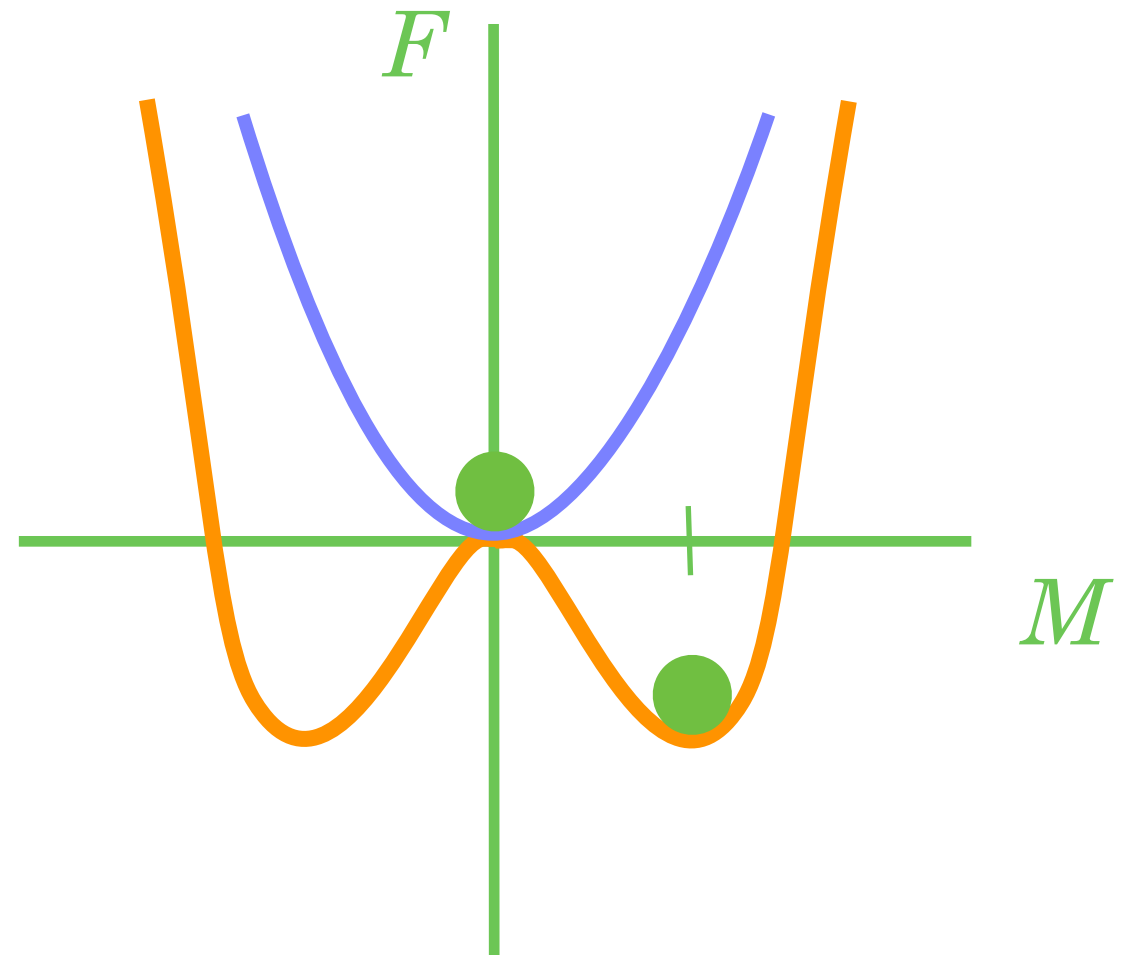
the Ginsburg-Landau

effective theory

originally of superconductivity
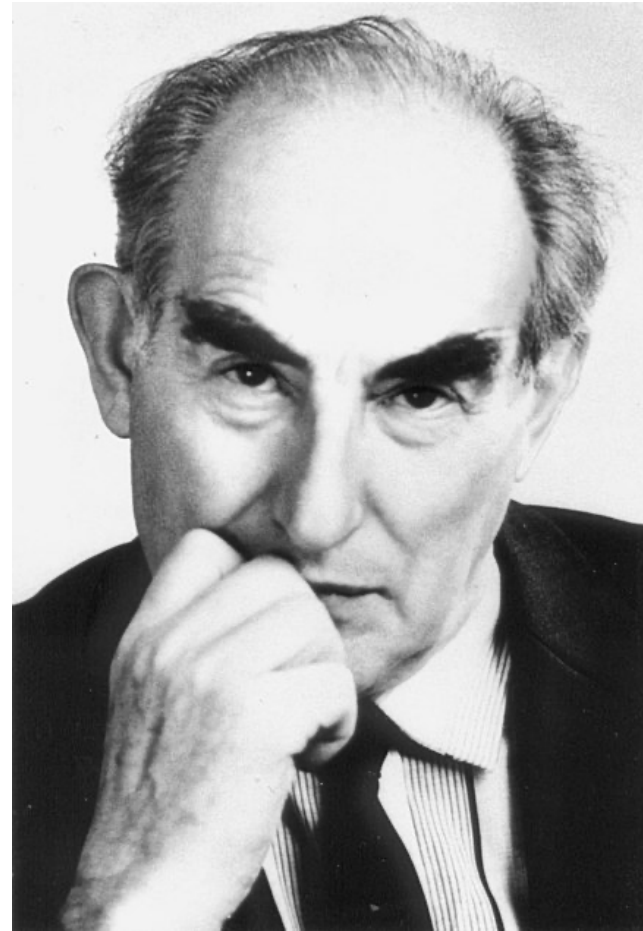
Vitaly Ginzburg 1916 - 2009   **Lev Landau 1908 - 1968**
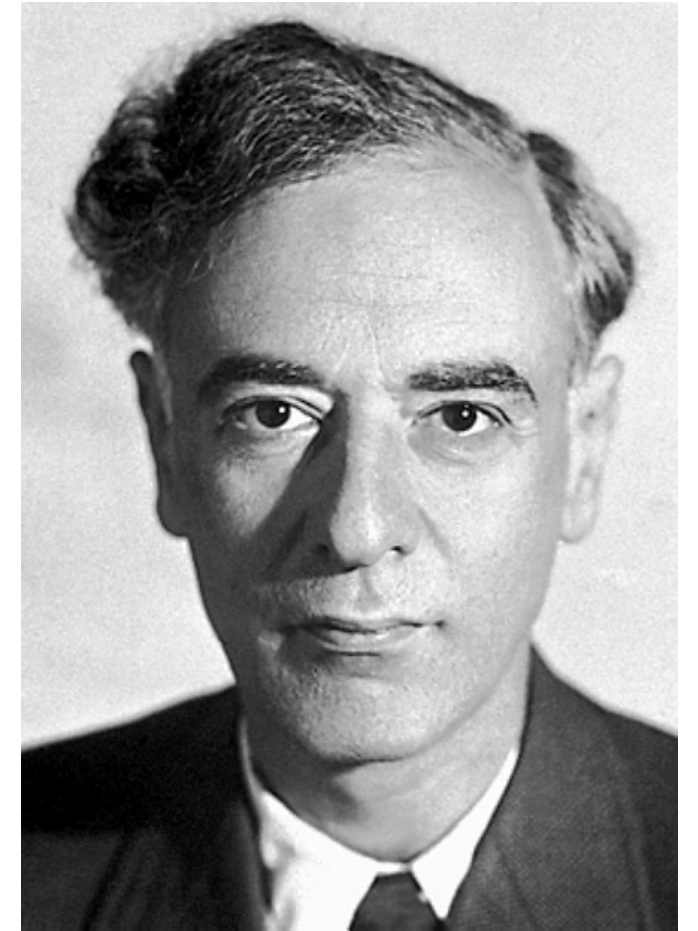
in the SM

We live in the broken symmetry world

& trying to discover how
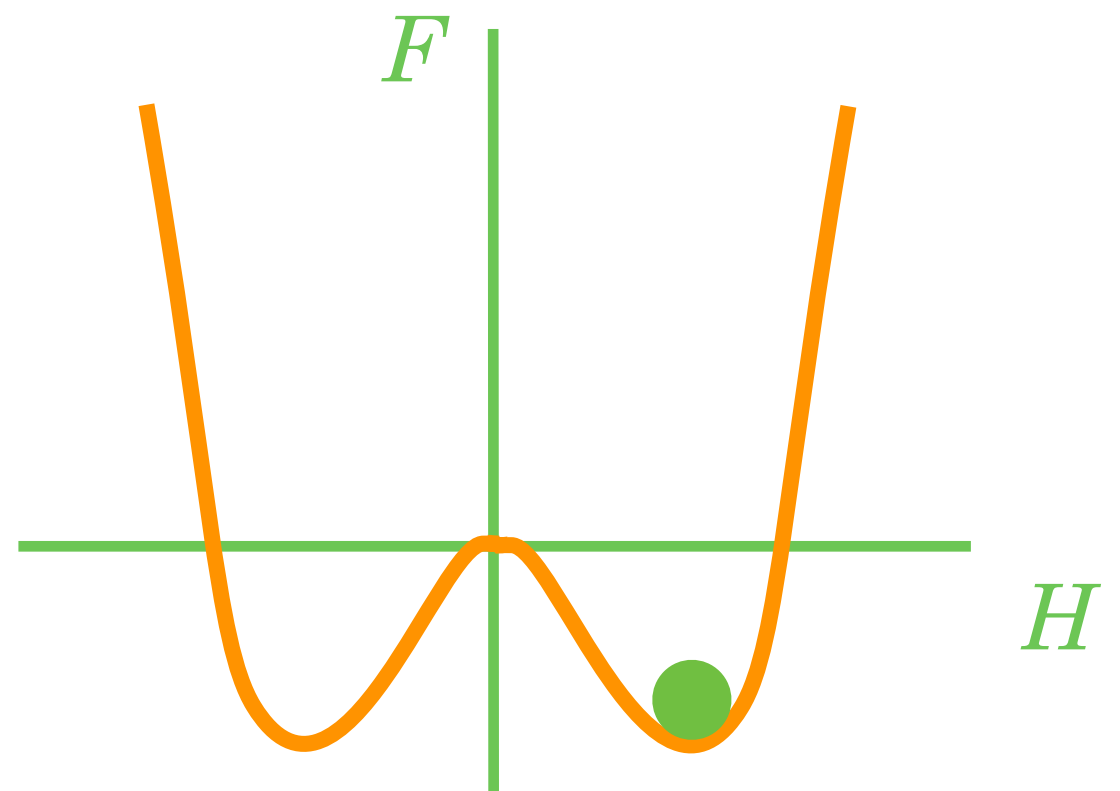
a Universal phase transition?

■ @ picosecond after the BB
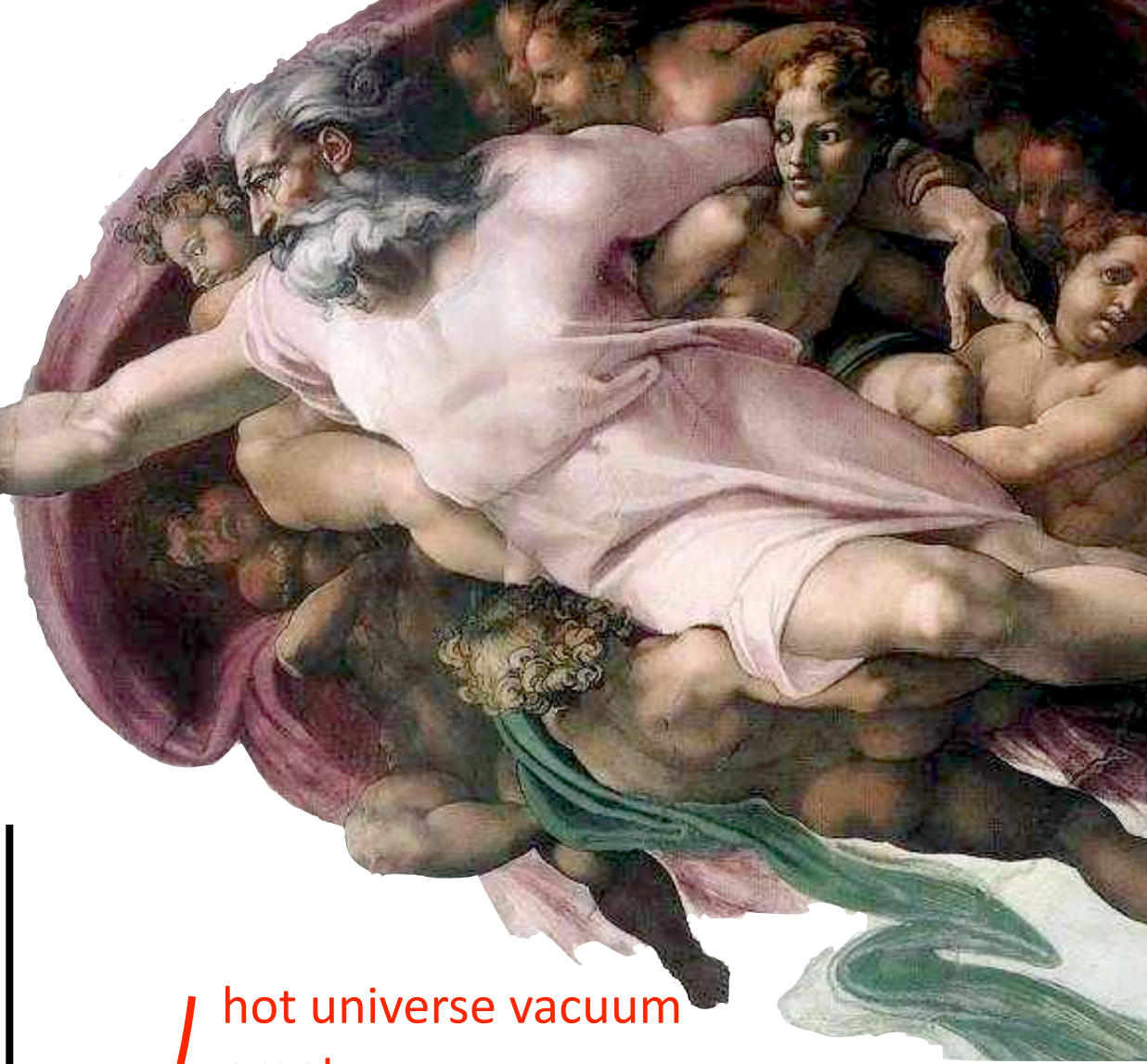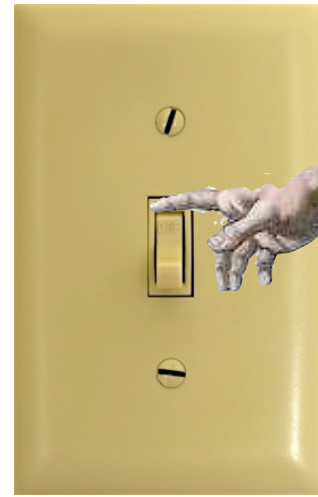
$$V = \frac{1}{2}\mu^2(\text{higgs field})^2 + \lambda(\text{higgs field})^4$$

$\mu^2 > 0, \lambda > 0$

$\mu^2 < 0, \lambda > 0$

pay attention to this parameter

E (entire universe)

hot universe vacuum empty

v

higgs field

cold universe vacuum full of the Higgs Field
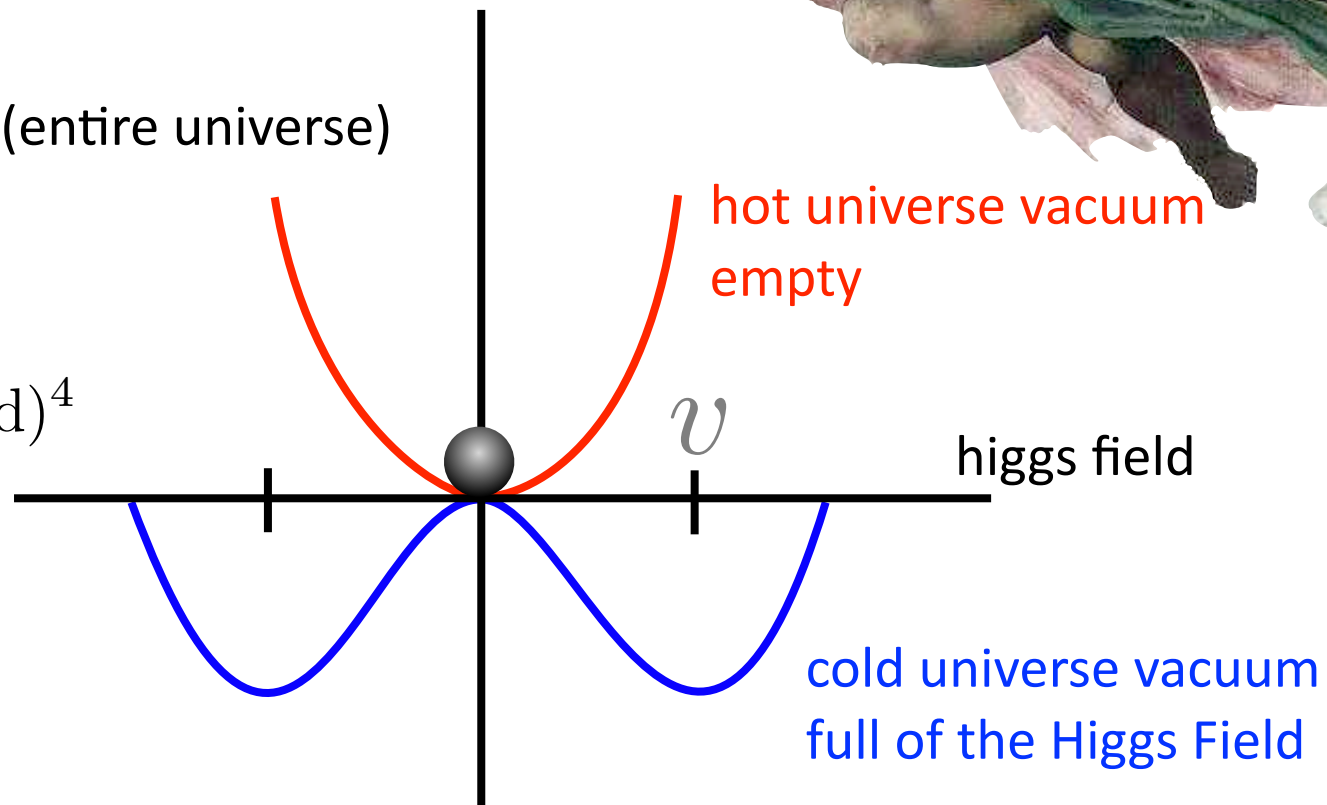
$v = 246\ \text{GeV}...\text{it's \underline{on}.}$

$$V = \frac{1}{2}\mu^2(\text{higgs field})^2 + \lambda(\text{higgs field})^4$$

$\mu^2 < 0, \lambda > 0$

E (entire universe)

v

higgs field
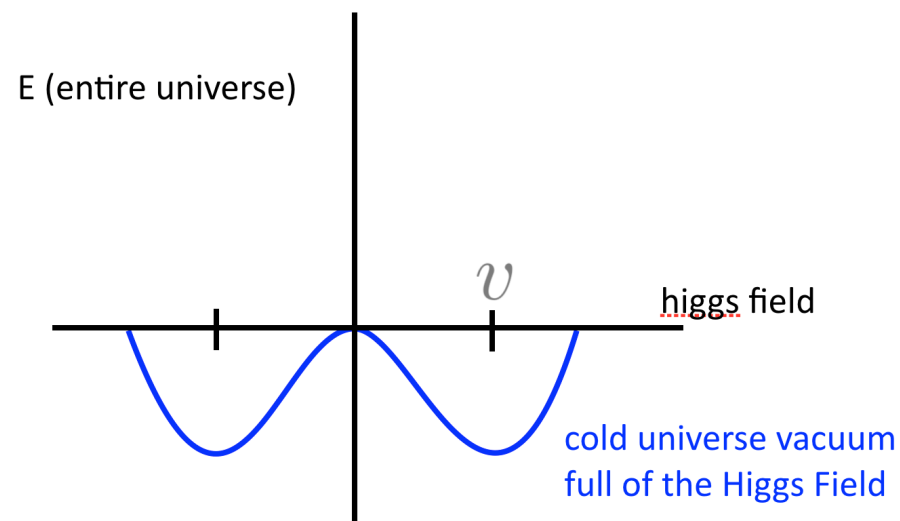
cold universe vacuum
full of the Higgs Field

$|-\mu^2| \cong 88.4(\ \text{GeV})^2$

$\lambda \cong 0.129$

$v \cong 246\ \text{GeV}$

a^0 $_0$〜〜〜〜〜

B^0 $_0$〜〜〜〜〜〜

B^+ $_+$〜〜〜〜〜〜

B^- $_-$〜〜〜〜〜〜

$\phi \begin{pmatrix} ^+ \text{-----} \\ _0 \text{-----} \end{pmatrix}$

$\phi^* \begin{pmatrix} ^- \text{-----} \\ _0 \text{-----} \end{pmatrix}$

γ

Z

$W^\pm$

H^0

t = the beginning 0 s   t = 10^{-12} s   t = 10^{+18}s

The Standard Model ingredients:
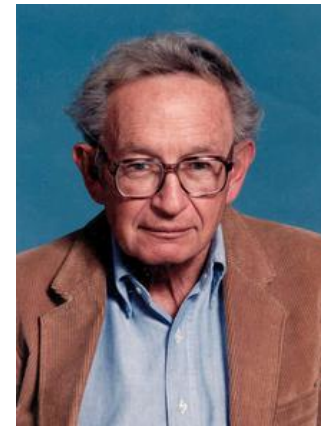
Anderson

Higgs   Kibble   Guralnik   Hagen   Englert   Brout
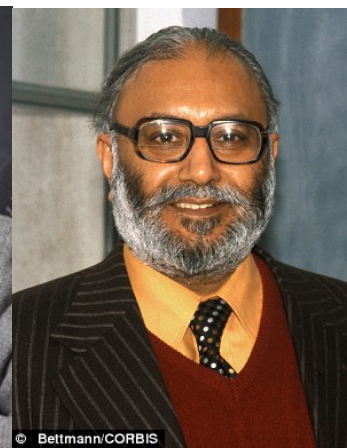
Weinberg   Salam   Glashow

what's exciting

about the Standard Model?

its historical significance & Higgs Field
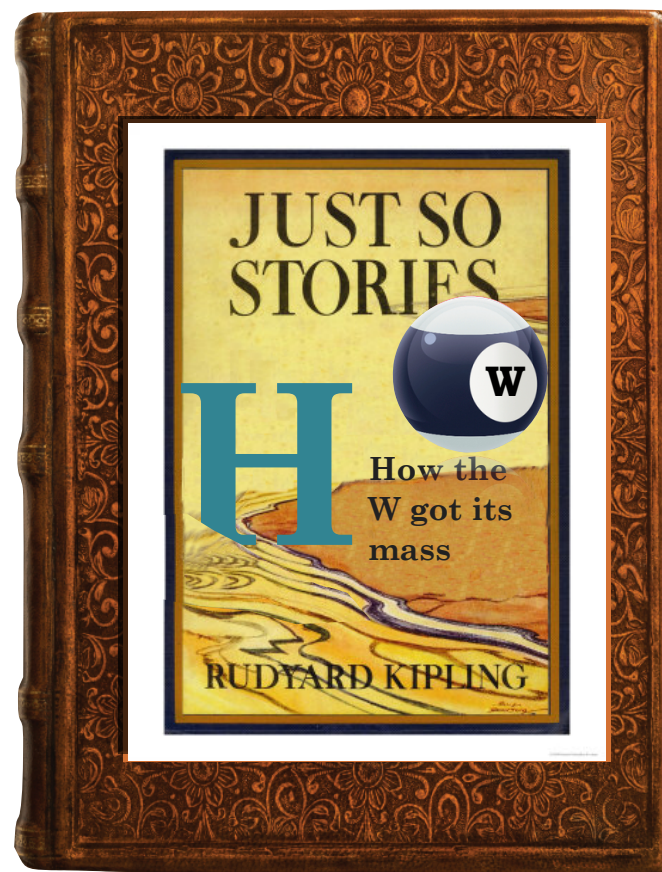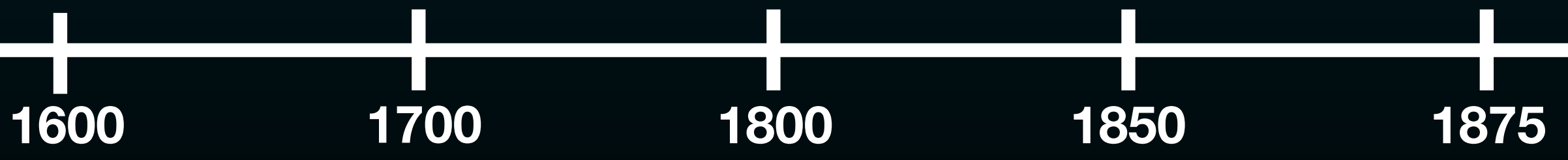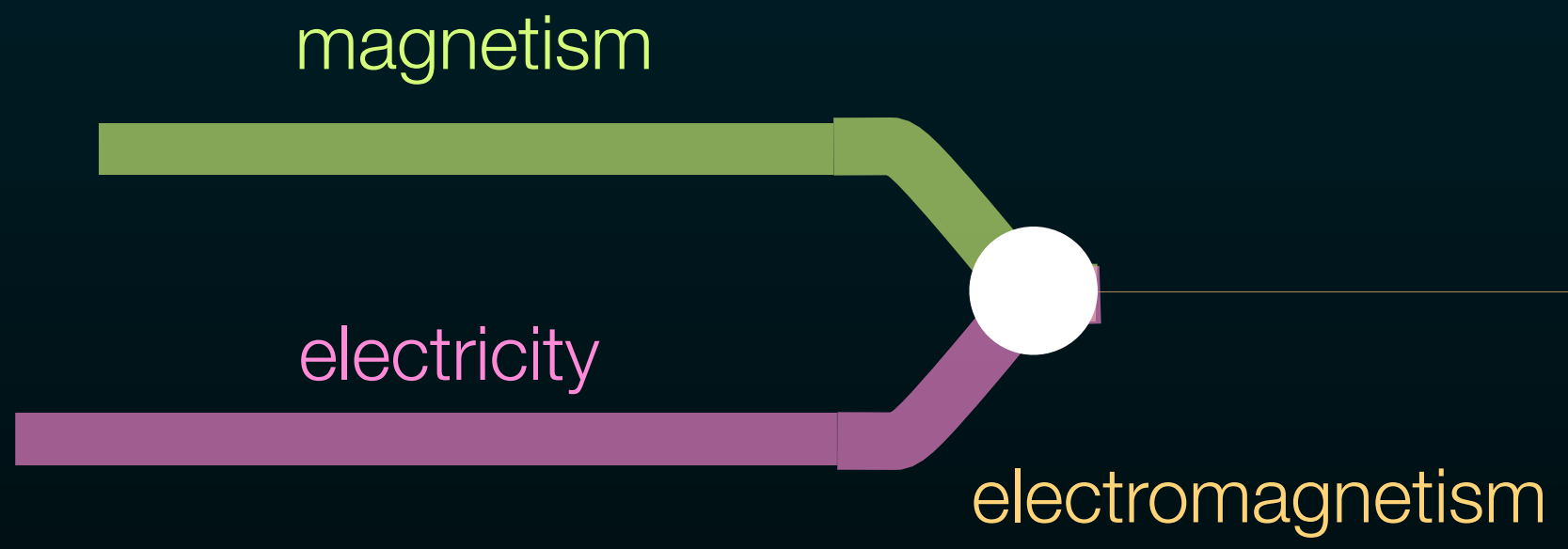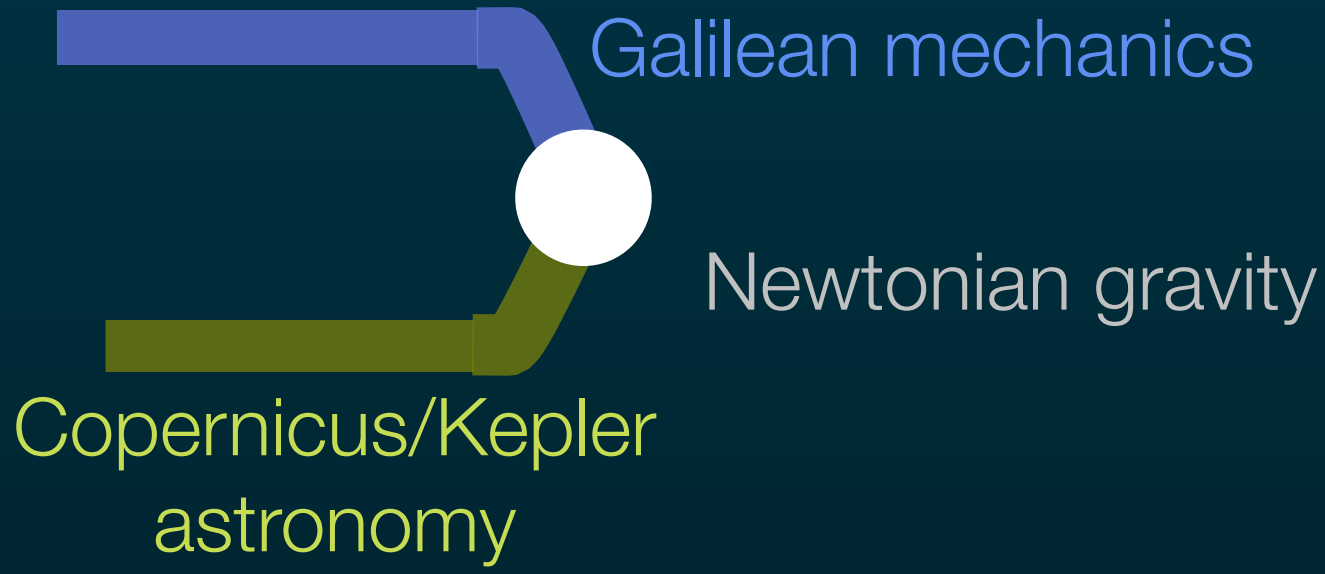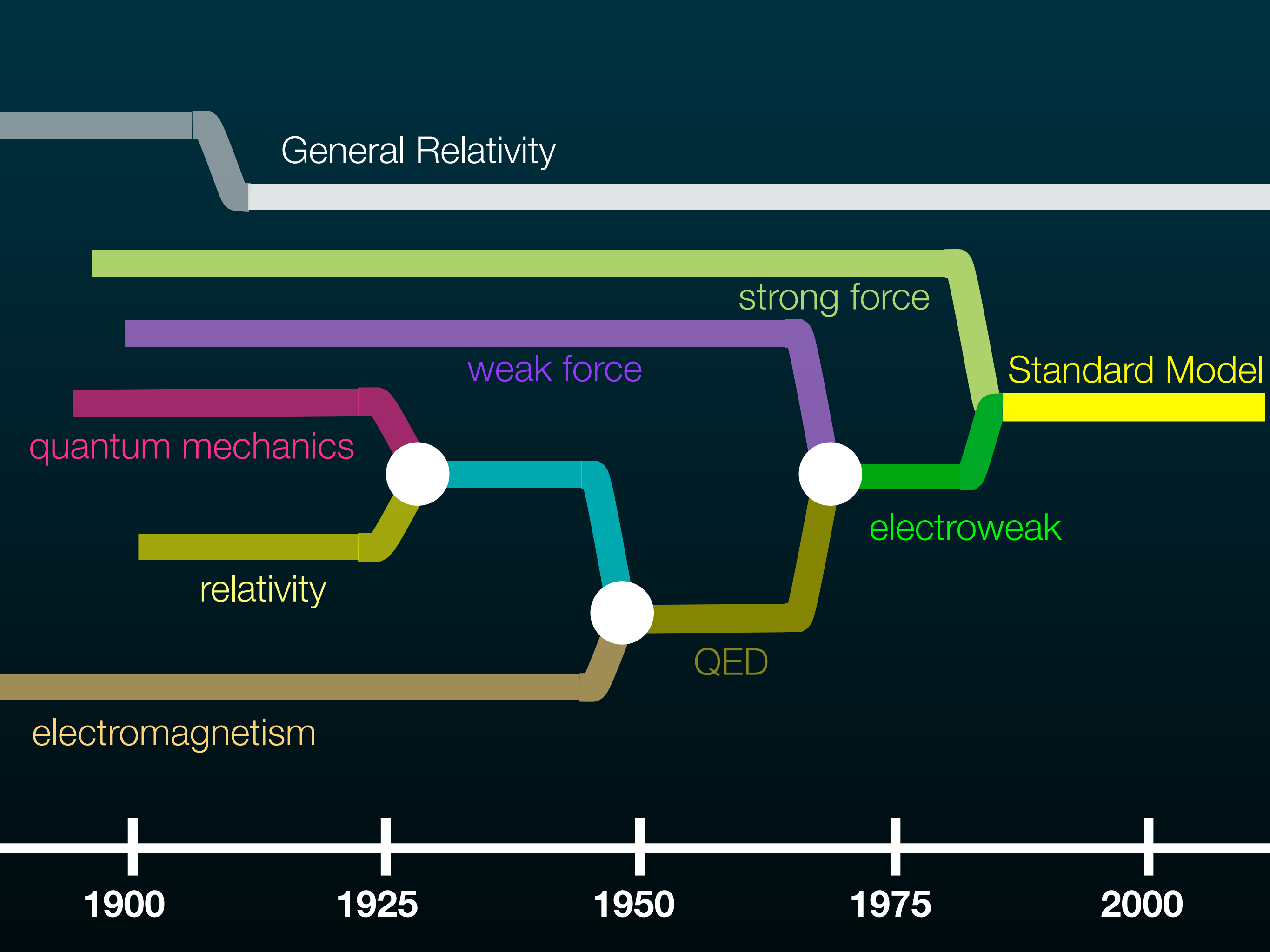
The job of the Higgs **Field** is special.
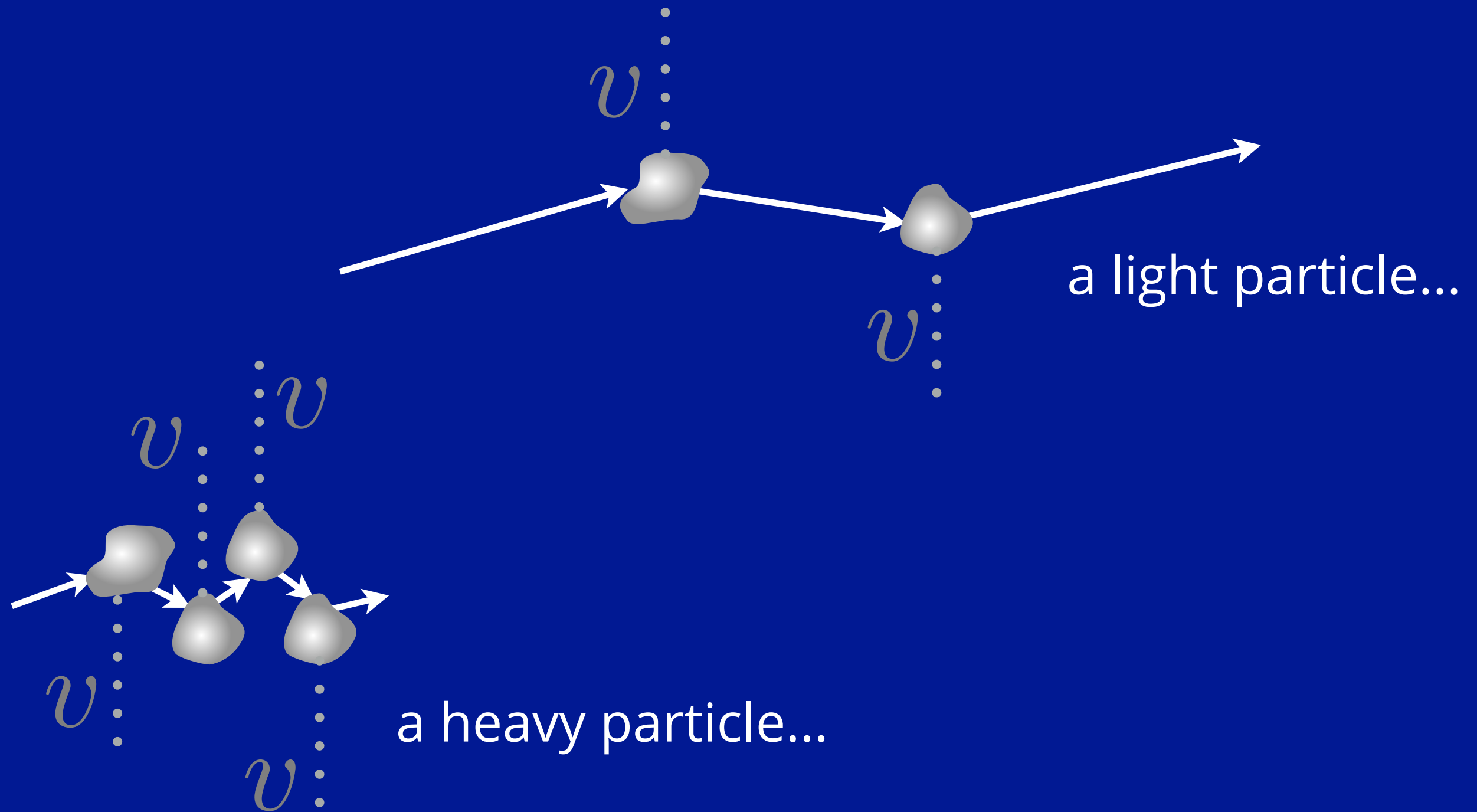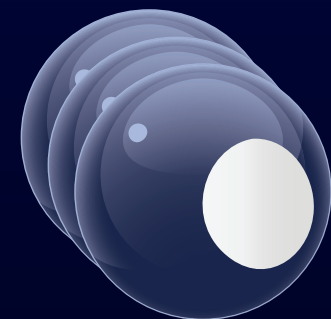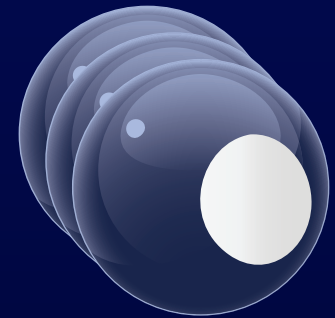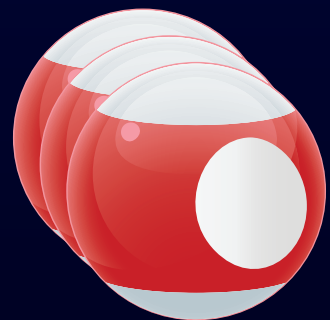
mass*

was born

in the Higgs Field

*charged fermions and W/Z!

what's challenging

about the Standard Model?

all things Higgs
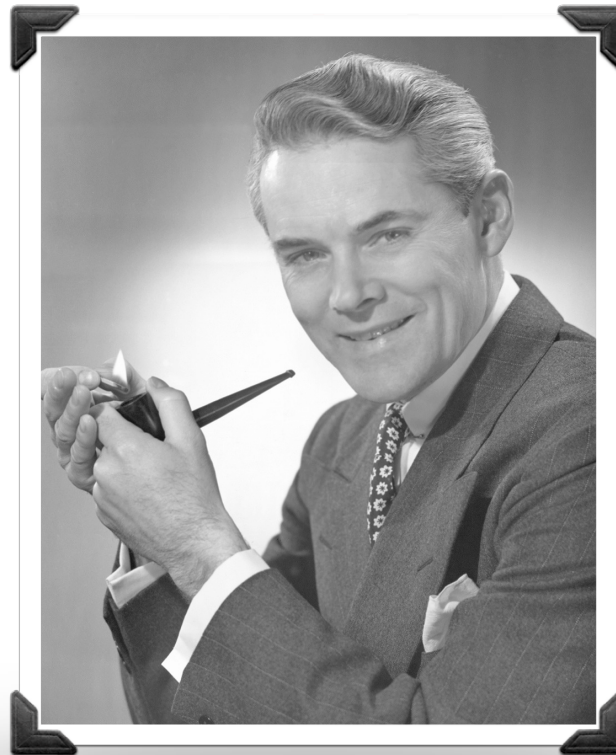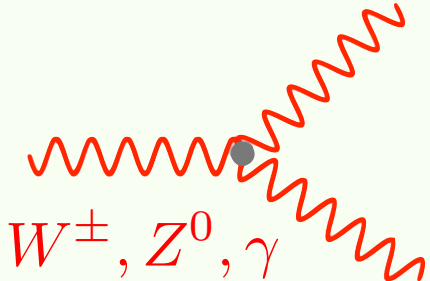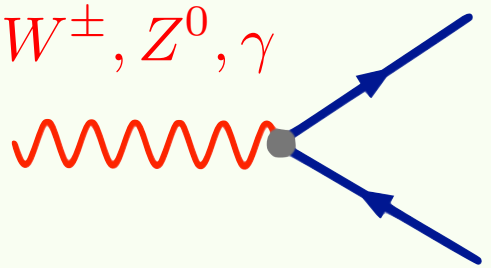
0+ Higgs Boson is not your father's particle!

Higgs Field piece:

■ "Unfolds" rather neatly
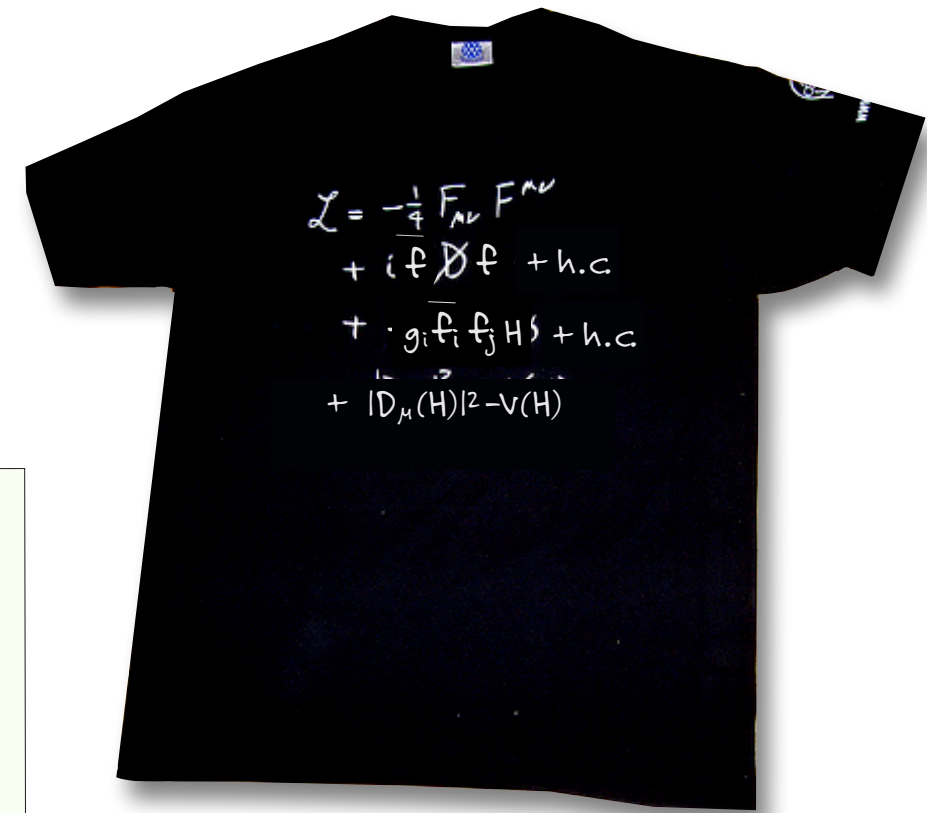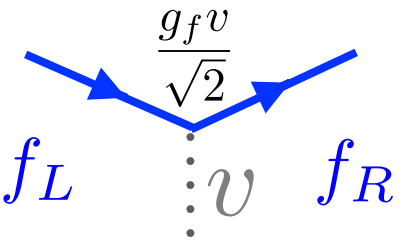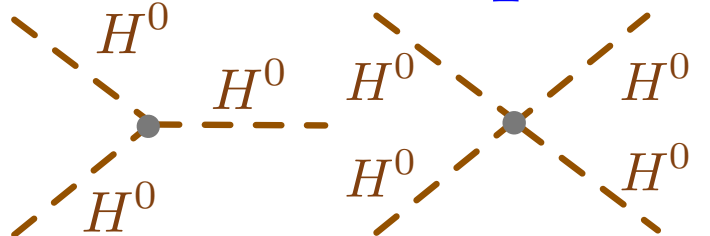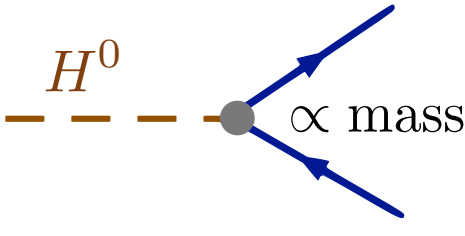
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$W^\pm, Z^0, \gamma$

$W^\pm, Z^0, \gamma$

$W^\pm, Z^0, \gamma$

$W^\pm, Z^0, \gamma$

$$+ i\bar{\psi} \slashed{D} \psi$$

$W^\pm, Z^0, \gamma$

$\left.\begin{array}{l} e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau, \\ u, d, c, s, t, b \end{array}\right\}$

$\frac{v[g, g']}{2}$

$W^\pm, Z^0$ $\quad v$

$H^0 \quad v \quad H^0$

$\frac{g_f v}{\sqrt{2}}$

$f_L \quad v \quad f_R$

$$+ |D_\mu H|^2 - \lambda v^2 H^2 + \lambda v H^3 - \frac{\lambda}{4} H^4 + g_i \bar{f}_{Li} f_{Ri} H + \frac{g v}{\sqrt{2}} \bar{f} f$$

$H^0 \quad W^\pm, Z^0$

$H^0 \quad H^0 \quad H^0 \quad H^0$

$H^0 \quad H^0 \quad H^0 \quad H^0$

$H^0 \quad \propto \text{mass}$

$\left.\begin{array}{l} e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau, \\ u, d, c, s, t, b \end{array}\right\}$

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i f \slashed{D} f \quad + h.c$
$+ \cdot g_i \bar{f}_i f_j H \, \flat + h.c$
$+ |D_\mu(H)|^2 - V(H)$

Let's talk about the Higgs Boson.

What happened in July, 2012?

the Object Itself?
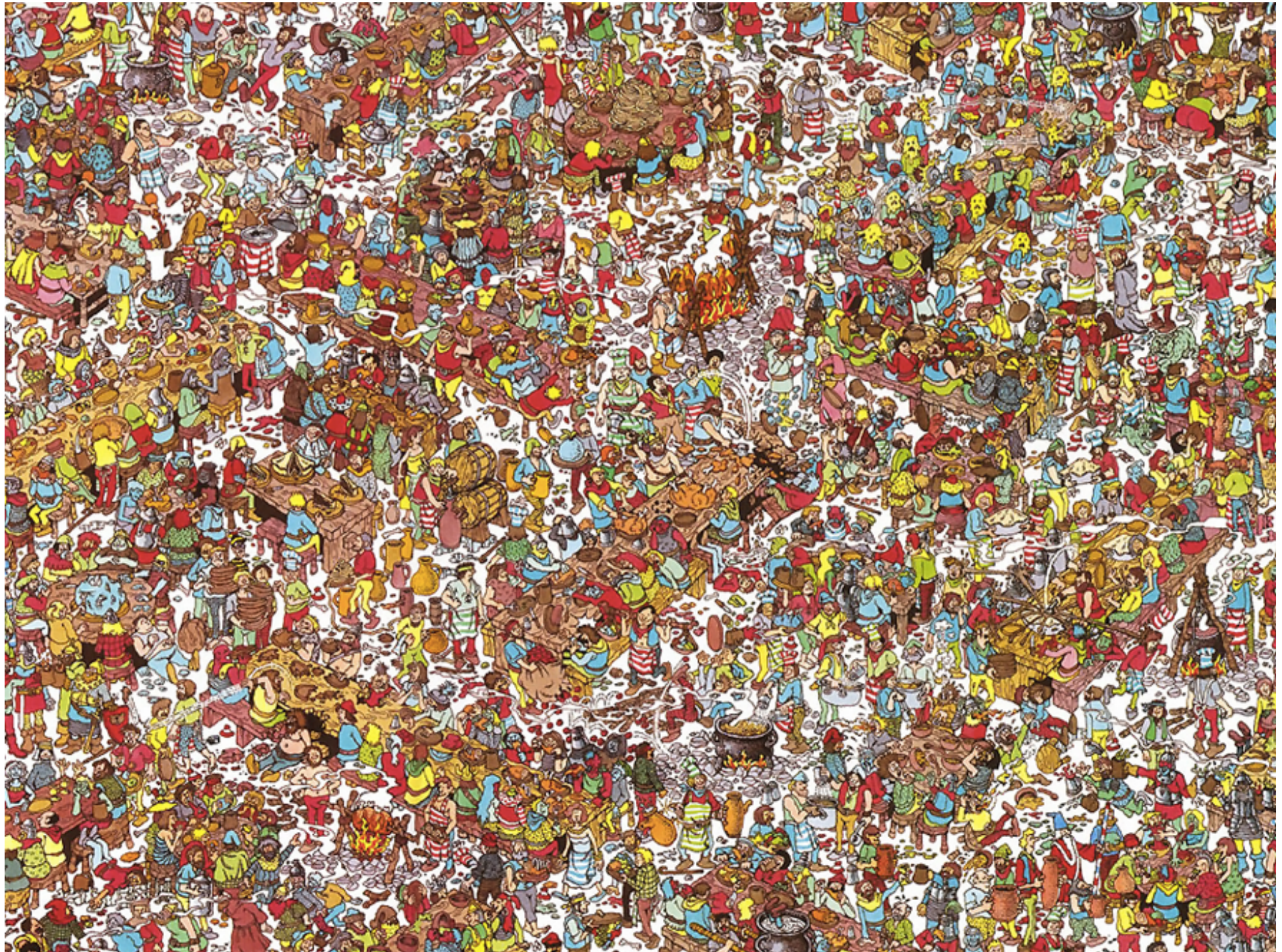
the Object Itself? is...

hazy

Higgs particle ▮ strange.

quantum numbers of the vacuum
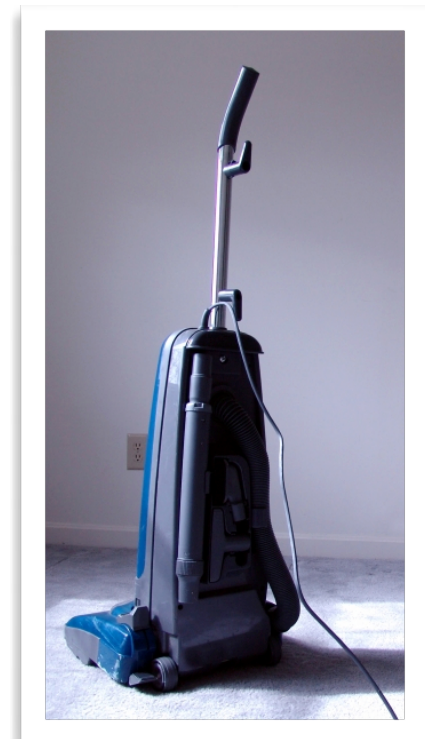
How many things are only one thing?

FAMILIES

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

$$W^\pm, Z^0, \gamma, g$$

■ **an elementary *singlet***

■ or part of a **doublet**

$$\phi \begin{pmatrix} + \text{---------} \\ 0 \text{---------} \end{pmatrix}$$

$$\phi^* \begin{pmatrix} - \text{---------} \\ 0 \text{---------} \end{pmatrix}$$

an elementary *singleton*?
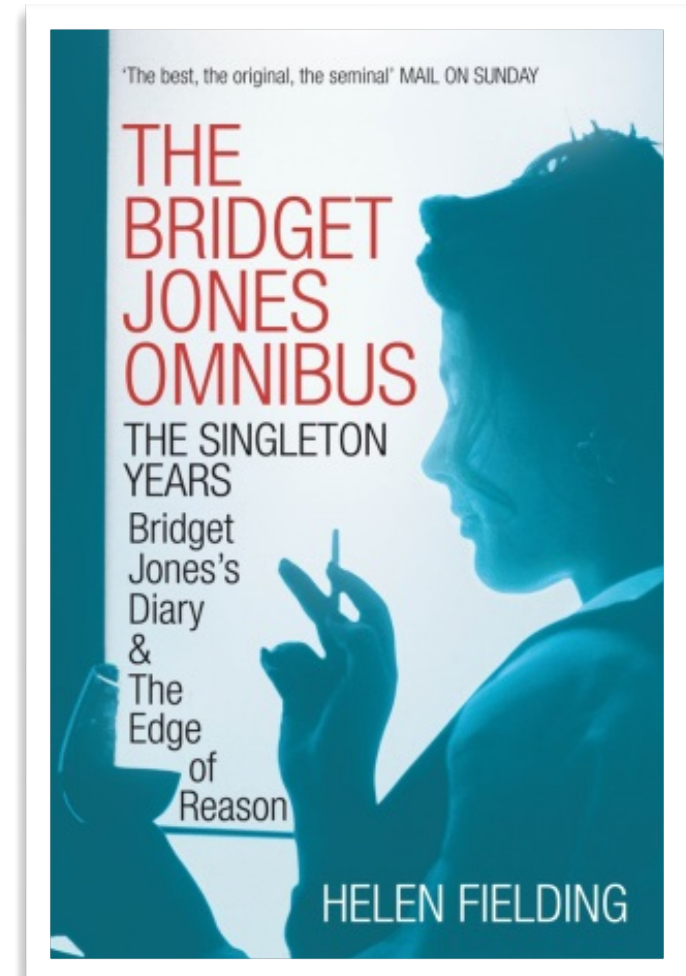
Much confusion centers on

■ the "Higgs" Potential.

Our future mission: to unpack it.

$$V = V_0 - |D_\mu H|^2 + \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 - g_i \bar{f}_{Li} f_{Ri} H$$

vacuum energy

Higgs mass

Higgs potential shape

fermion couplings

loops

in relativistic quantum field theory

🟩 the Feynman rules:
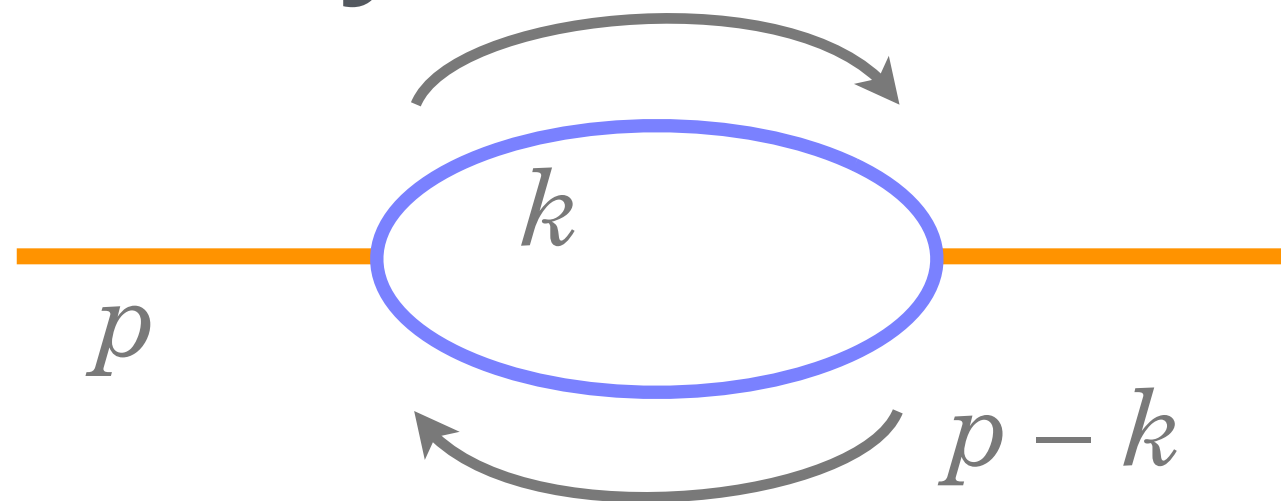
$$\int_0^\Lambda dk \, (\text{all known particles}) + \int_0^\Lambda dk \, (\text{all } \textit{un}\text{-known particles})$$

not mysticism

■ Quantum "Loops" are at the core of our language

traditionally highly predictive
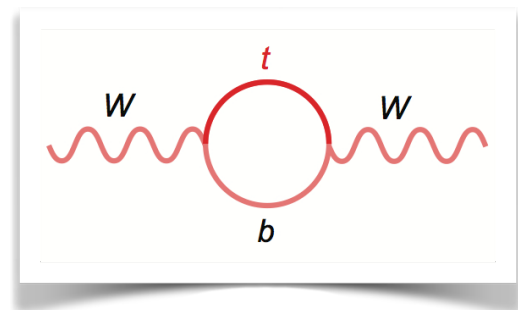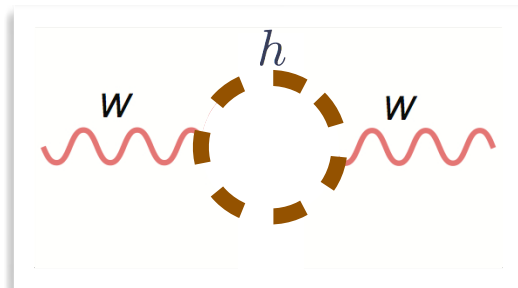
highly accurate

not mysticism

■ Quantum "Loops" are at the core of our language

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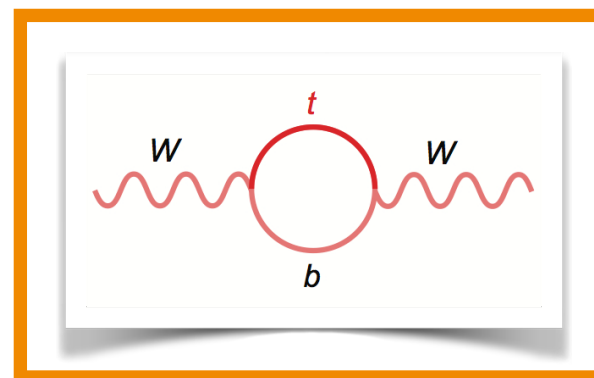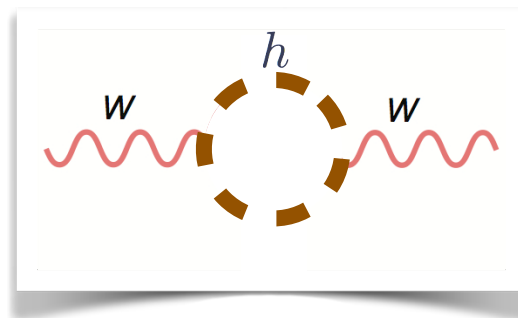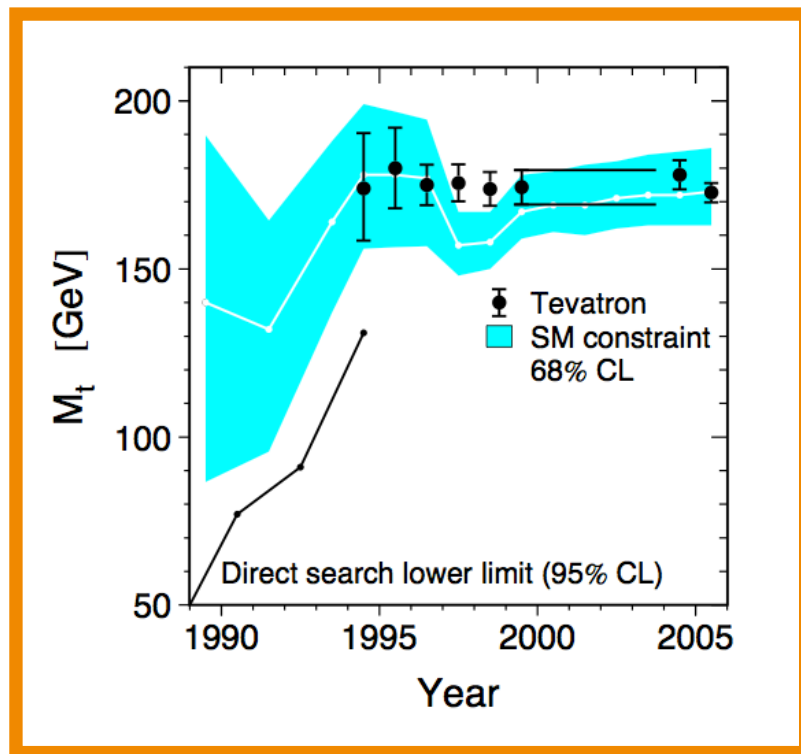
highly accurate

EW fits: top quark

not mysticism

■ Quantum "Loops" are at the core of our language

traditionally highly predictive

highly accurate
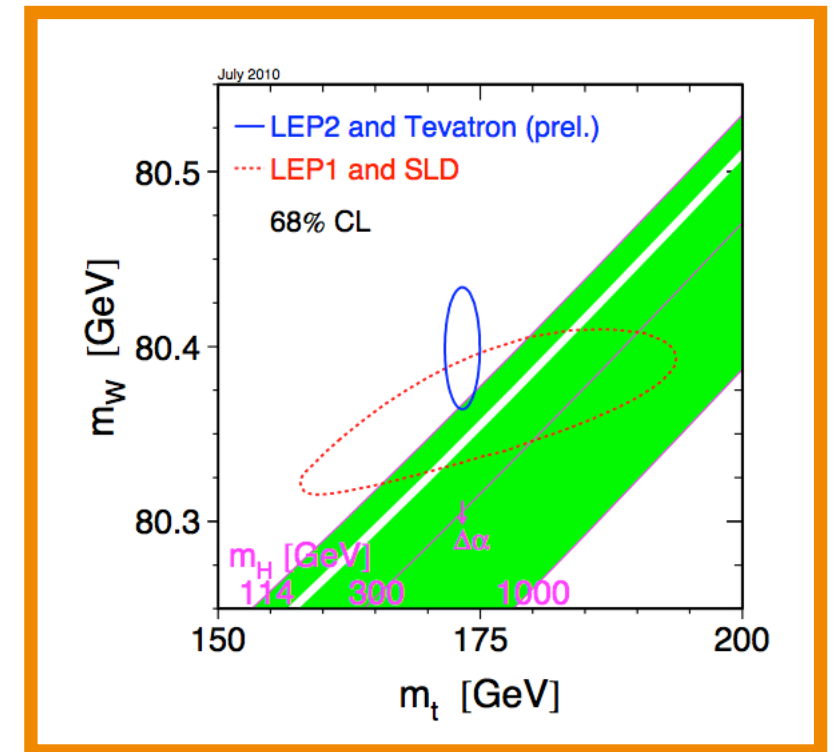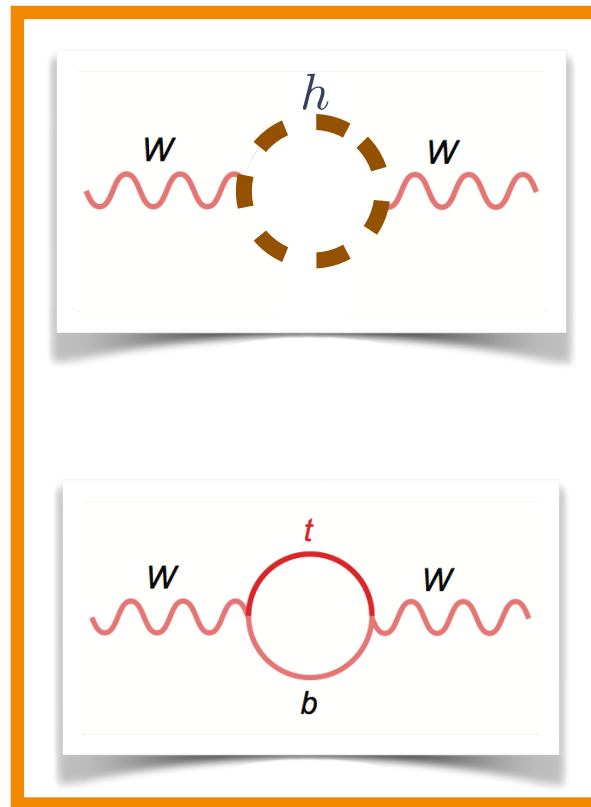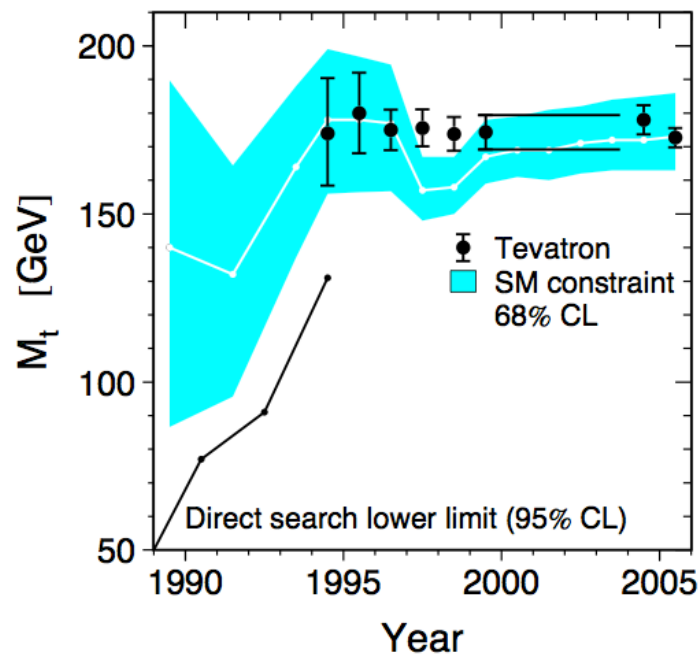
EW fits: top quark

EW fits: Higgs boson

How about ▇ a spin 0, elementary particle?

First-ever spin 0 elementary particle.

$$V = \boxed{\lambda v^2 H^2}$$

$$M_H^2 = M_{\text{tree}}^2 + \delta M^2$$

$$\delta M^2 \propto \frac{c}{16\pi^2} g^2 \Lambda^2$$

3 kinds of loops

$$V = \boxed{\lambda v^2 H^2}$$

$$M_H^2 = M_{\text{tree}}^2 + \left(\vphantom{\frac{H}{H}} \right) + \left(\vphantom{\frac{t}{t}} \right) + \left(\vphantom{\frac{W,Z}{H}} \right)$$

M_{physical}^2

$M_H \sim 125 \text{ GeV/c}^2$

0
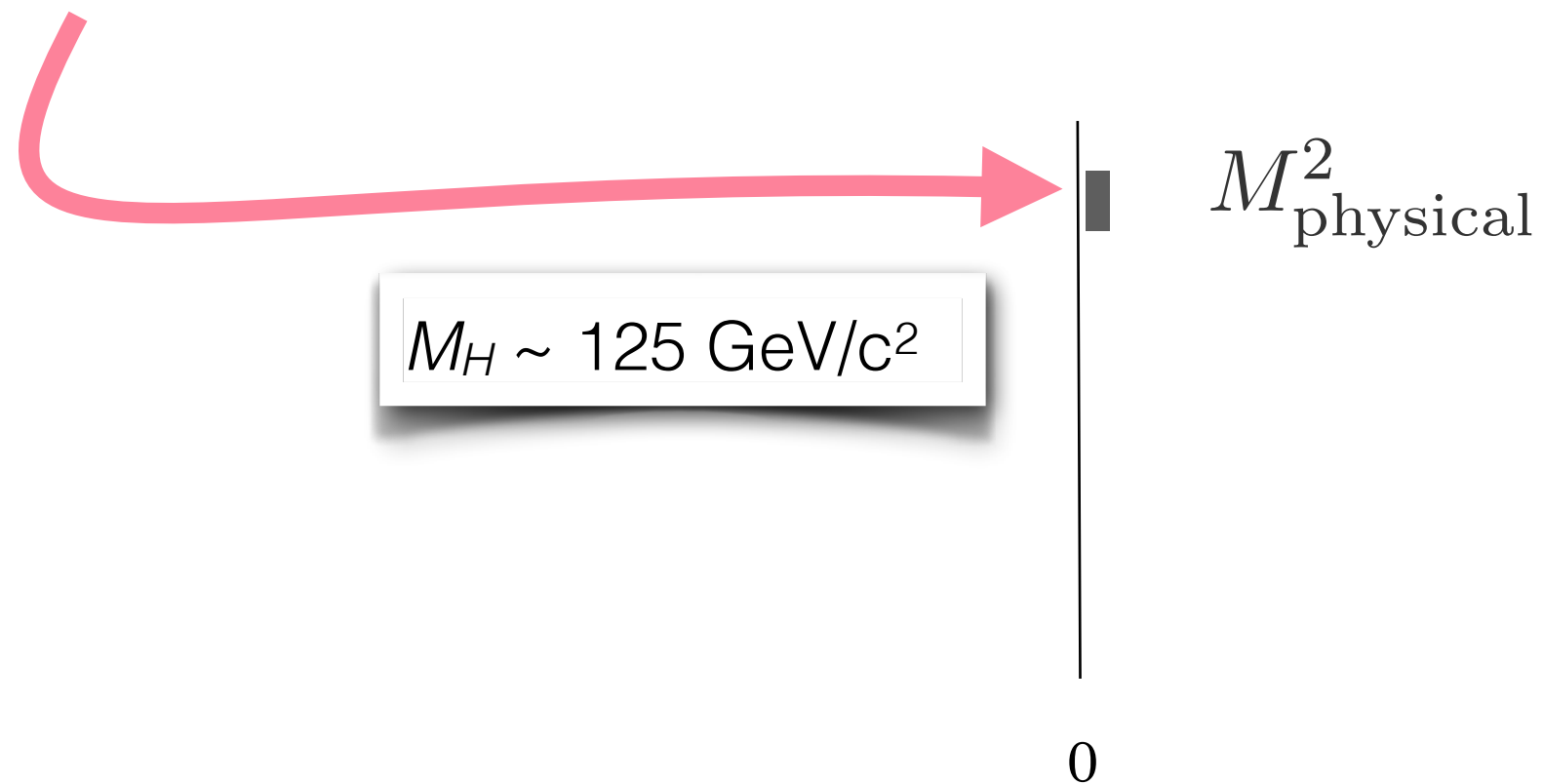
Top loop is big and negative

$$V = \boxed{\lambda v^2 H^2}$$

$$M_H^2 = M_{\text{tree}}^2 + \left(\right) + \left(\right) + \left(\right)$$

$M_H \sim 125 \text{ GeV/c}^2$

M_{physical}^2

M_H^2

m_t^2

$M_{W,Z}^2$

0
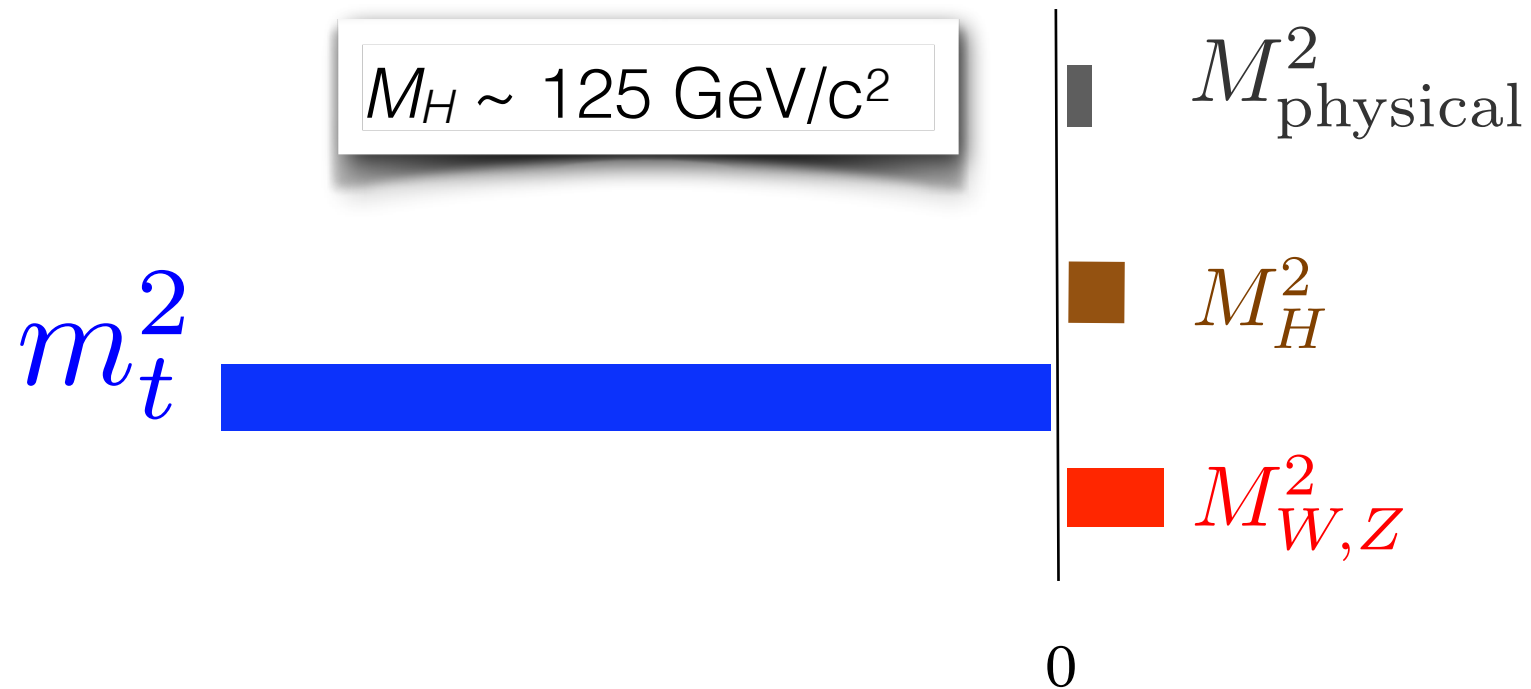
Requiring a large, opposing tree value

$$V = \boxed{\lambda v^2 H^2}$$

$$M_H^2 = M_{\text{tree}}^2 + \left(\underset{H \quad H}{\overset{H}{\bigcirc}} \right) + \left(\underset{H}{\overset{t}{\underset{t}{\bigcirc}}} \right) + \left(\underset{H \quad H}{\overset{W,Z}{\bigcirc}} \right)$$

$M_H \sim 125$ GeV/c²

M_{physical}^2

M_{tree}^2

M_H^2

m_t^2

$M_{W,Z}^2$

0
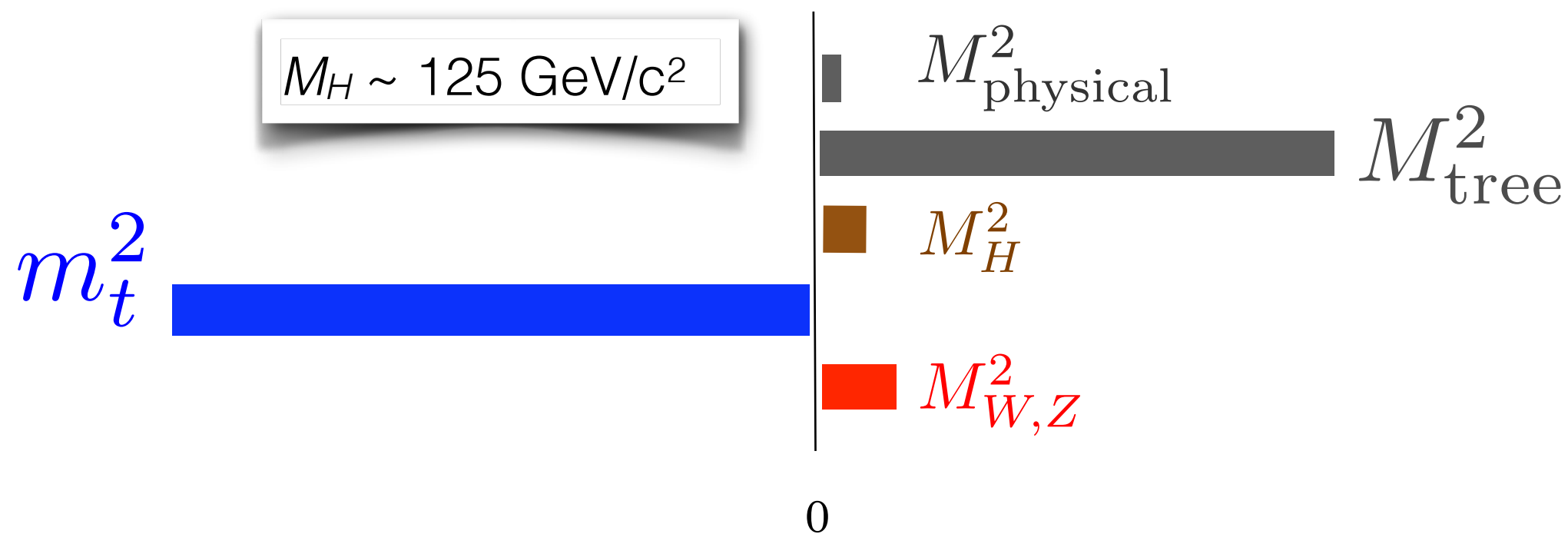
An enormous fine-tuning

$$V = \boxed{\lambda v^2 H^2}$$

$$M_H^2 = M_{\text{tree}}^2 + \left(\begin{array}{c} H \\ \bigcirc \\ H \quad H \end{array} \right) + \left(\begin{array}{c} t \\ H \quad \bigcirc \quad H \\ t \end{array} \right) + \left(\begin{array}{c} W,Z \\ \text{\Large\char`\}} \\ H \quad H \end{array} \right)$$

m_t^2

$M_H \sim 125 \text{ GeV/c}^2$

M_{physical}^2

M_{tree}^2 } un-fine tuning?

M_H^2

$M_{W,Z}^2$

"hierarchy problem"

0
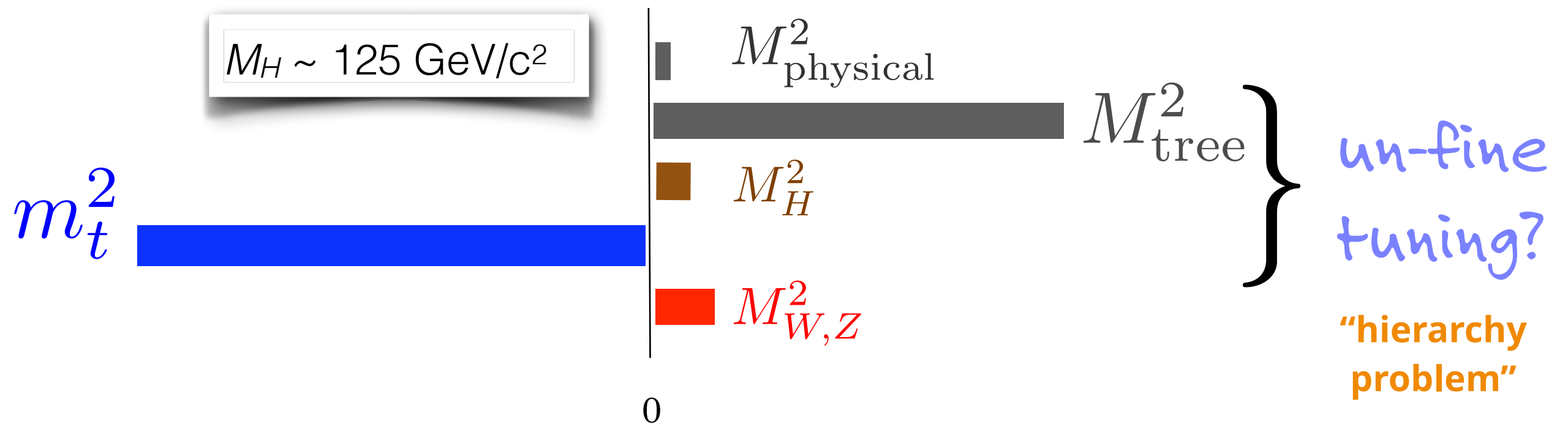
if next scale is ■ the Planck Scale?

$$M_H^2 = \text{(nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n60,000)}$$
$$- \text{(nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n44,375)}$$

$$M_H^2 = 125^2$$

"coincidence"?

There's no coincidence in science.

Perhaps a huge hint?
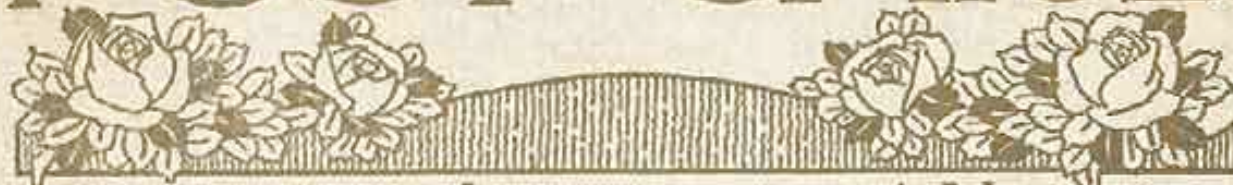
of something "BSM"?

no shortage of ideas

$$M_H^2 = M_{\text{tree}}^2 + \left(\begin{array}{c} H \\ \bigcirc \\ H \quad H \end{array} \right) + \left(\begin{array}{c} t \\ \bigcirc \\ H \quad \overline{t} \quad H \end{array} \right) + \left(\begin{array}{c} W,Z \\ \text{(vvv)} \\ H \quad H \end{array} \right) + \left(- - \text{BSM} - - \right)$$

m_t^2

$M_H \sim 125$ GeV/c²

M_{physical}^2

M_{tree}^2

M_H^2

$M_{W,Z}^2$

0

Perhaps a huge hint?

of something "BSM"?

no shortage of ideas

$$M_H^2 = M_{\text{tree}}^2 + \left(\right) + \left(\right) + \left(\right) + \left(\text{BSM} \right)$$

$M_H \sim 125$ GeV/c²

M_{physical}^2

M_{tree}^2

m_t^2

M_H^2

new stuff

$M_{W,Z}^2$

0
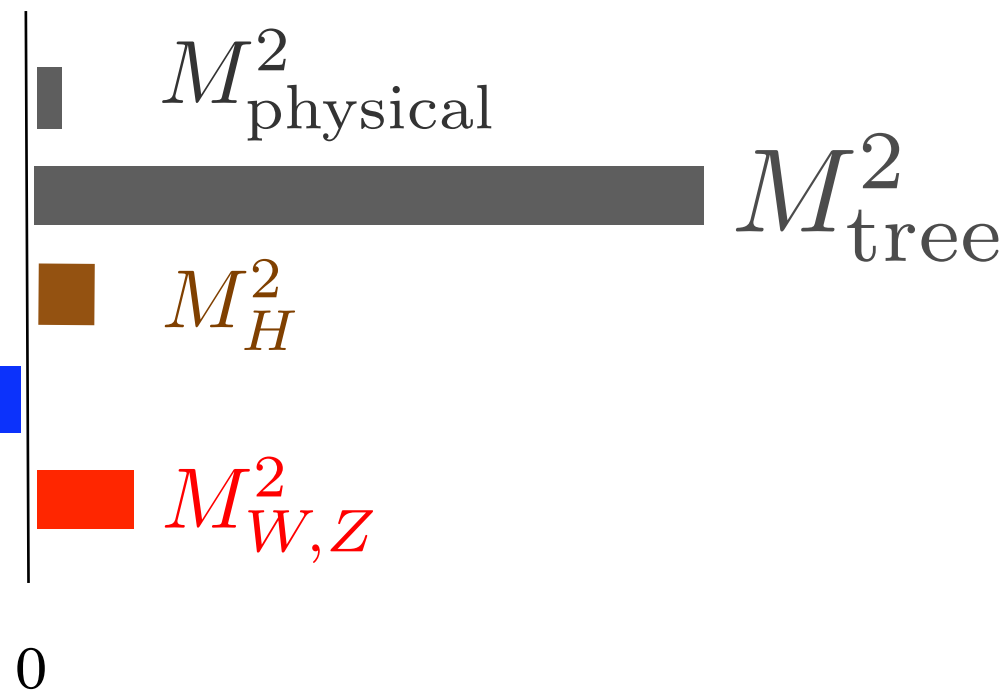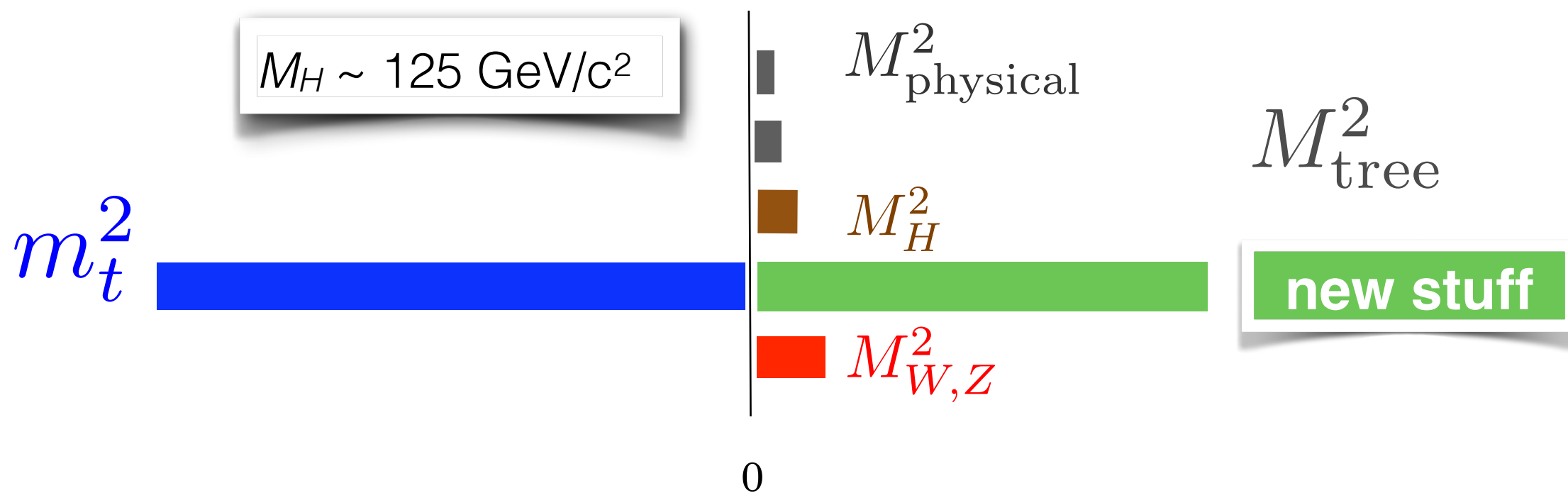
looking for new physics at the ~1 TeV scale

"natural"

new stuff

Broadly speaking, categories of new stuff:

Supersymmetric theories –   a Bose-like stop

Little Higgs-like theories –   a Vector-top

Composite Higgs –   a Cooper Pair-like H

Extra dimensional theories

new stuff

Broadly speaking, categories of new stuff:

Supersymmetric theories –   a Bose-like stop

Little Higgs-like theories –   a Vector-like top

Composite Higgs –   a Cooper Pair-like H

Extra dimensional theories

■ **or we tend to default to ideas like:**

the multiverse or...

anthropomorphism

This article is from the In-Depth Report The Higgs Boson at Last?

How the Higgs Boson Might Spell Doom for the Universe

Under the simplest assumptions, the measured mass of the Higgs could mean the universe is unstable and destined to fall apart. But don't worry—it won't happen for billions of eons

March 26, 2013 | By Saswato R. Das

Physicists recently confirmed that the Large Hadron Collider (LHC) at CERN, the particle physics laboratory in Geneva, had indeed found a Higgs boson last July, marking a culmination of one of the longest and most expensive searches in science. The
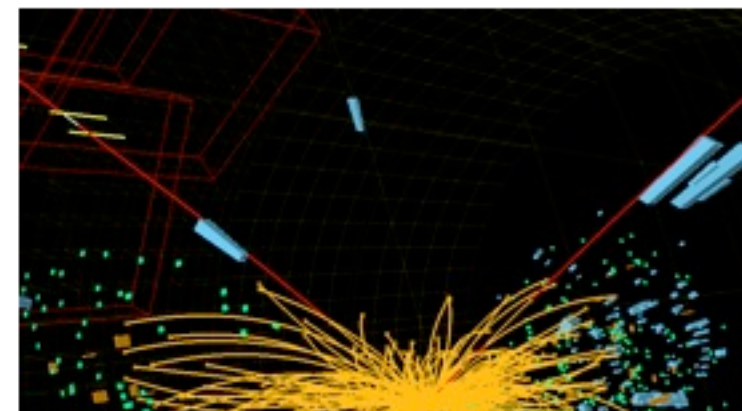
doom?

$$V = \lambda v H^3 + \frac{\lambda}{4} H^4$$

Another consequence of a spin 0 fundamental particle.

The shape of the vacuum potential could change...and the bottom could fall out.

POST CARD

Correspondence   Address

Hints?
Top and Higgs making trouble

To: 2024

From:

Nature

3σ bands in
$M_t = 173.3 \pm 0.8$ GeV (gray)
$\alpha_3(M_Z) = 0.1184 \pm 0.0007$ (red)
$M_h = 125.1 \pm 0.2$ GeV (blue)

Higgs quartic coupling λ

$M_t = 171.1$ GeV
$\alpha_s(M_Z) = 0.1205$
$\alpha_s(M_Z) = 0.1163$
$M_t = 175.6$ GeV

RGE scale μ in GeV
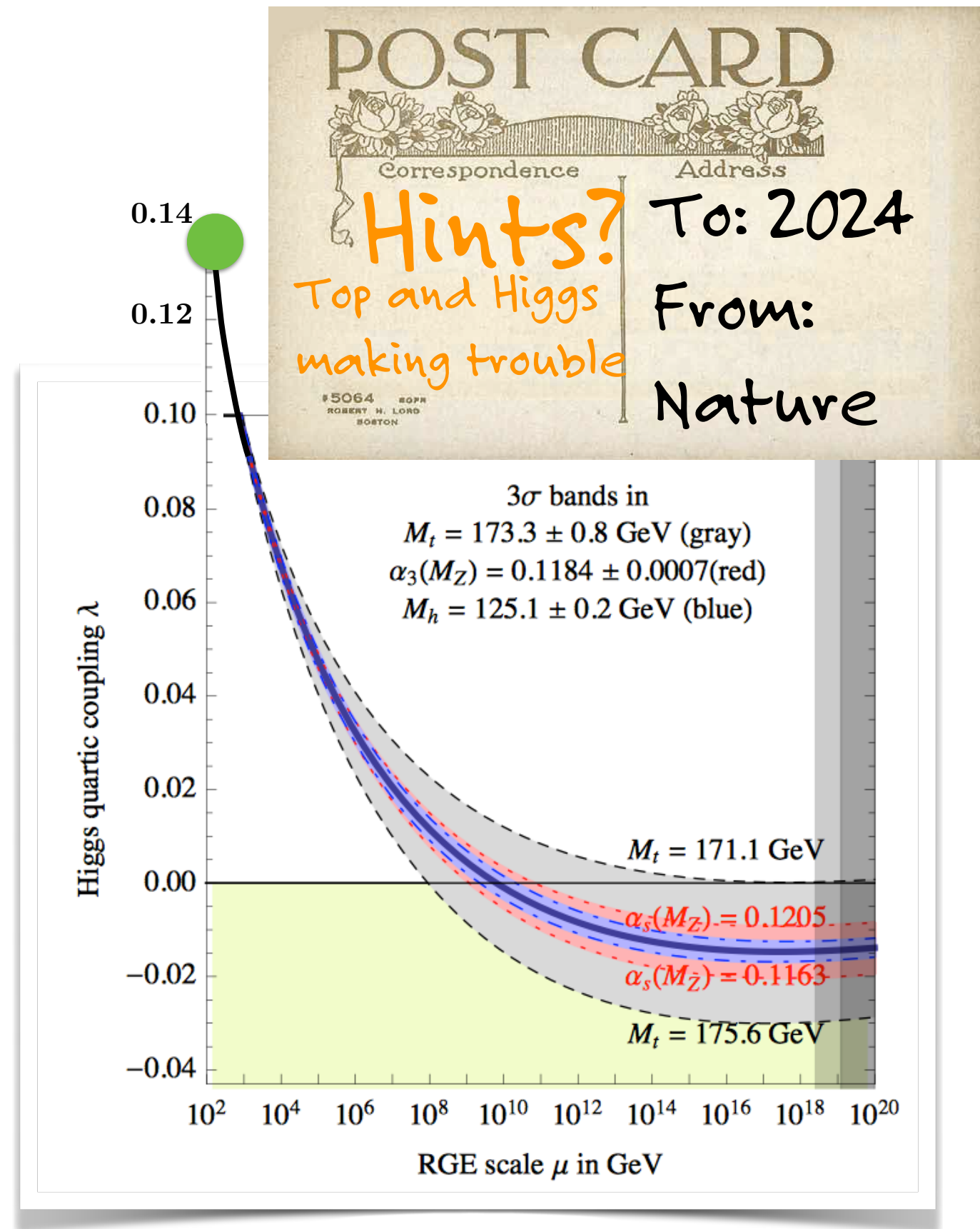
arXiv:1307.3536

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

The Standard Model is just weird.

These are: the best of times

- and the best of times!

the 2021 Snowmass "Energy Frontier"

Meenakshi Narain* **Laura Reina** **Alessandro Tricoli**
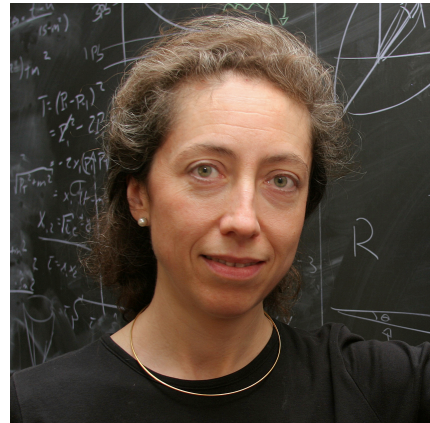
*** (RIP)**

2021 EF working groups

EF01: The Higgs Boson

🟩 *Sally Dawson (BNL), Caterina Vernieri (SLAC)*

EF02: EW Physics: Higgs Boson as a portal to new physics

🟩 *Patrick Meade (Stony Brook), Isobel Ojalvo (Princeton)*

EF03: EW Physics: Heavy flavor and top quark physics

🟩 *Reinhard Schwienhorst (MSU), Doreen Wackeroth (Buffalo)*

EF04: EW Physics: EW Precision Physics and constraining new physics

🟩 *Alberto Belloni (Maryland), Ayres Freitas (Pittsburgh) Junping Tian (Tokyo)*

EF05: QCD and strong interactions:Precision QCD

🟩 *Michael Begel (BNL), Stefan Hoeche (FNAL), Michael Schmitt (Northwestern)*

EF06: QCD and strong interactions:Hadronic structure and forward QCD

🟩 *Huey-Wen Lin (MSU), Pavel Nadolsky (SMU), Christophe Royon (Kansas)*

EF07: QCD and strong interactions: Heavy Ions

🟩 *Yen-Jie Lee (MIT), Swagato Mukherjee (BNL)*

EF08: BSM: Model specific explorations

🟩 *Jim Hirschauer (FNAL), Elliot Lipeles (UPenn), Nausheen Shah (Wayne State)*

EF09: BSM: More general explorations

🟩 *Tulika Bose (U Wisconsin-Madison), Zhen Liu (Maryland), Simone Griso (LBL)*

EF10: BSM: Dark Matter at colliders

🟩 *Caterina Doglioni (Lund), LianTao Wang (Chicago), Antonio Boveia (Ohio State)*

FOCUS ON LHC RUN 3
+ "HIGH-LUMINOSITY-LHC" HL-LHC

A three-pronged research program still relevant:

Mass, CP, and especially couplings

Measure properties of the Higgs boson.

Measure properties of the: t, W, and Z

Search for TeV-scale particles

A three-pronged research program still relevant:

They talk to the Higgs Field

■ Measure properties of the Higgs boson.

■ Measure properties of the: t, W, and Z

■ Search for TeV-scale particles

A three-pronged research program:

Inspired by the hierarchy problem

M^2_{physical}

M^2_H

m^2_t

$M^2_{W,Z}$

0
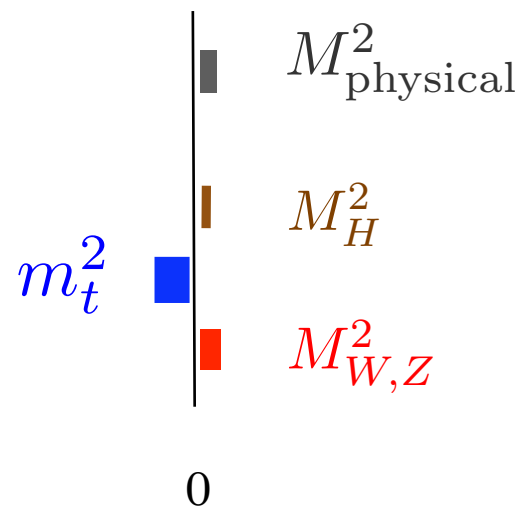
■ Measure properties of the Higgs boson.

■ Measure properties of the: t, W, and Z

■ Search for multi-TeV-scale particles

let's [image: milk carton] the future:

The Higgs Boson

is it alone?

is it alone?

a part of a family?

different in tiny details?
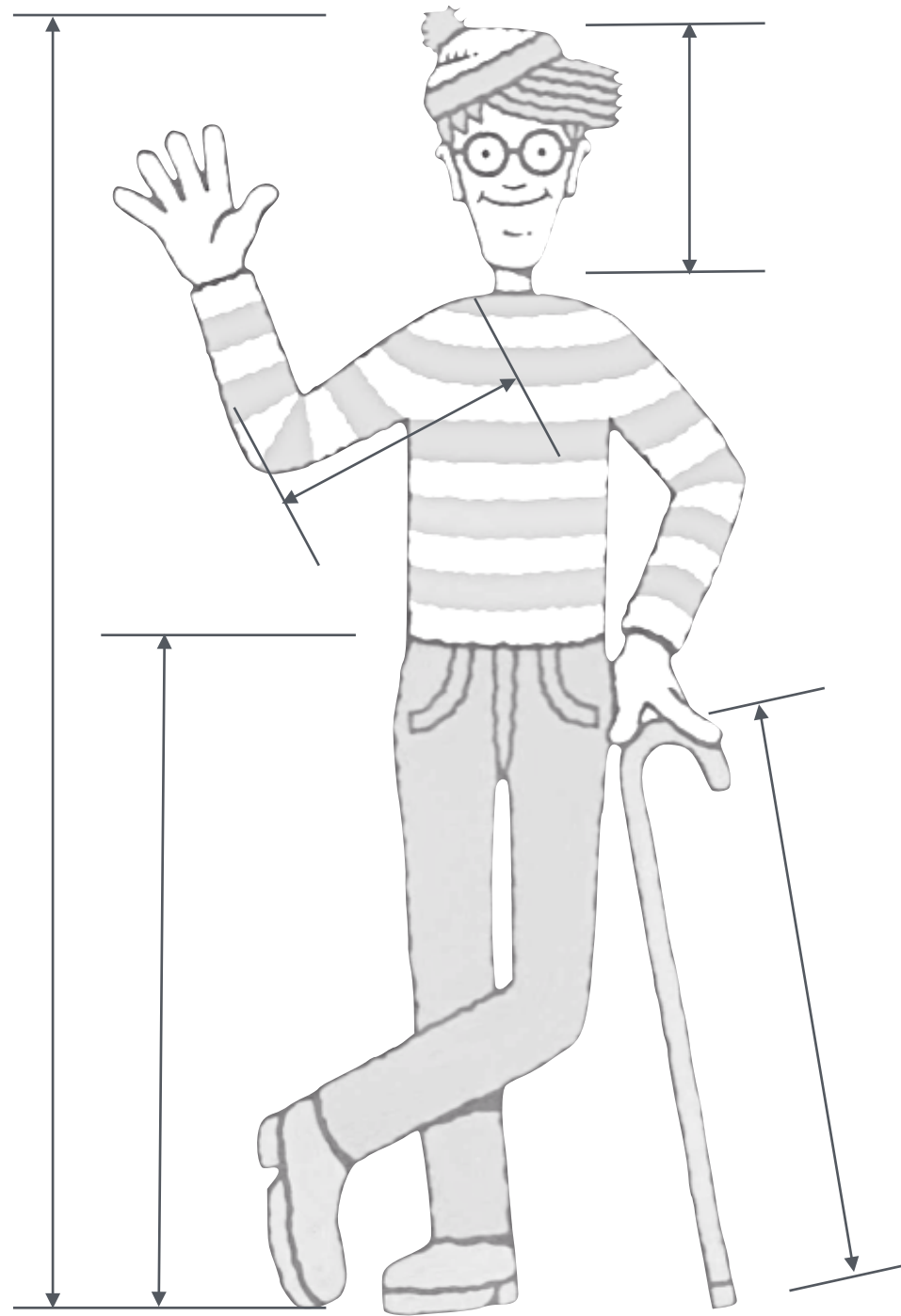
ATLAS
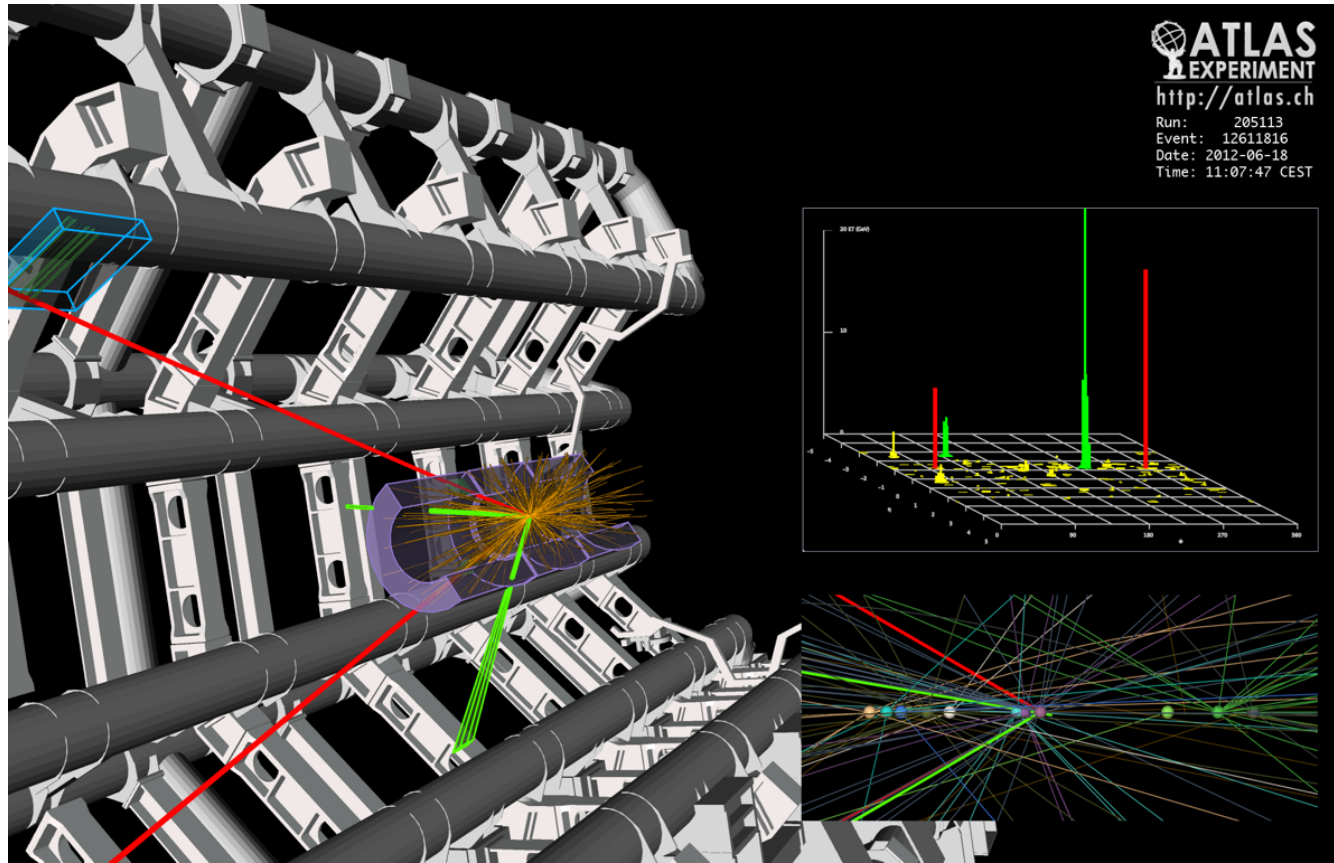
Golden Channel
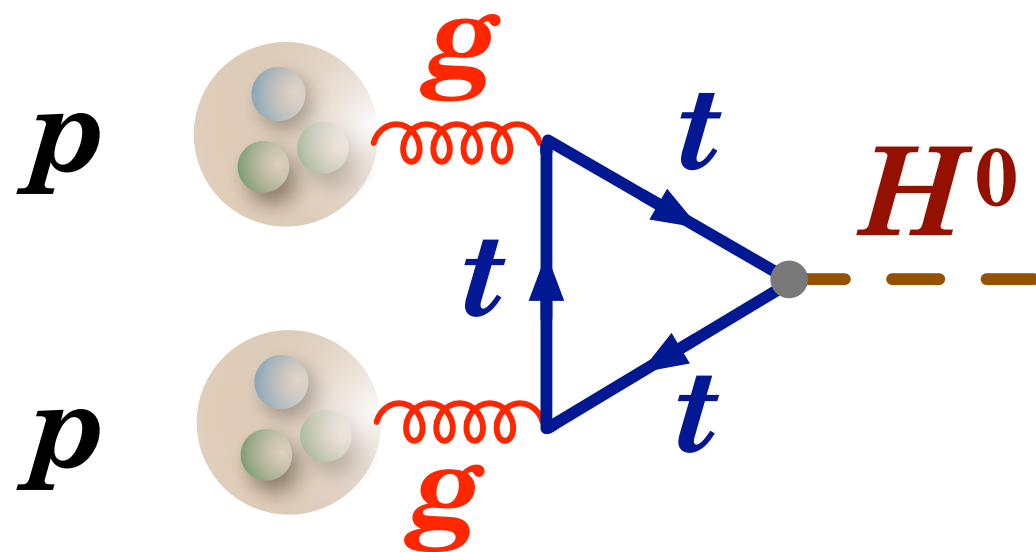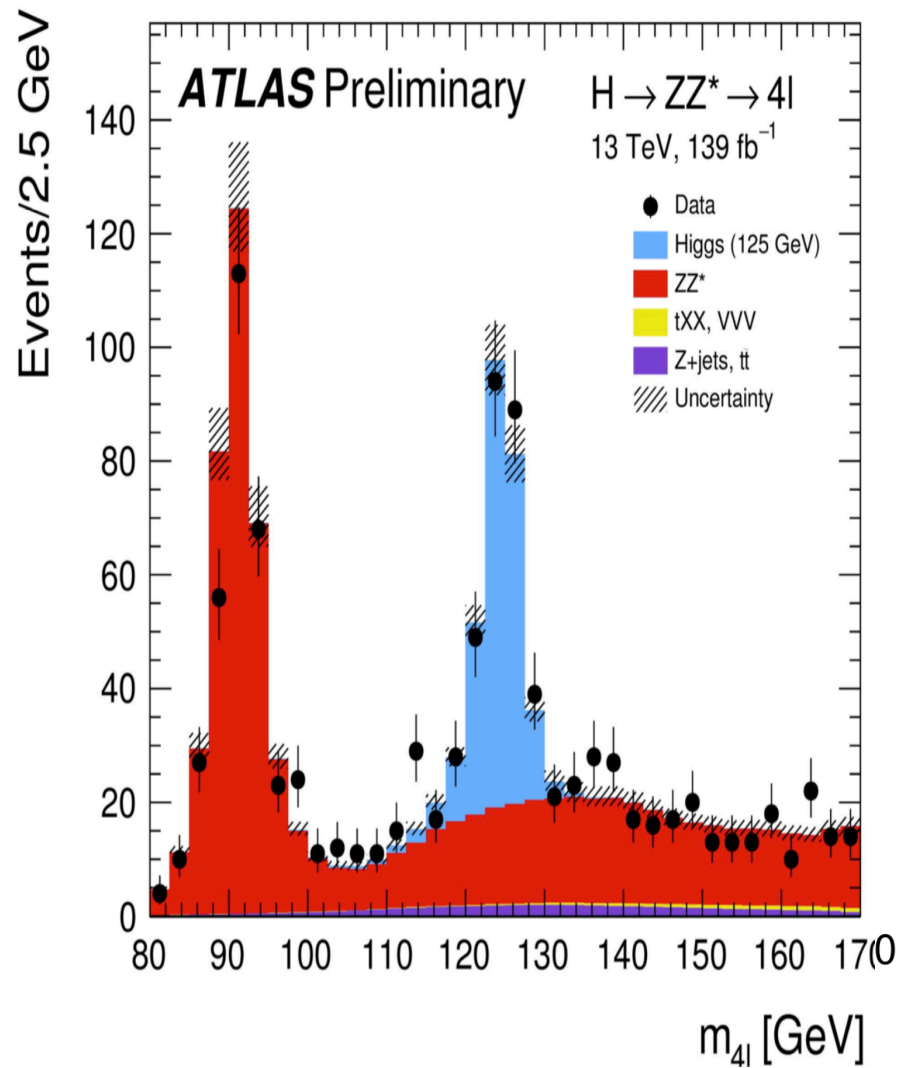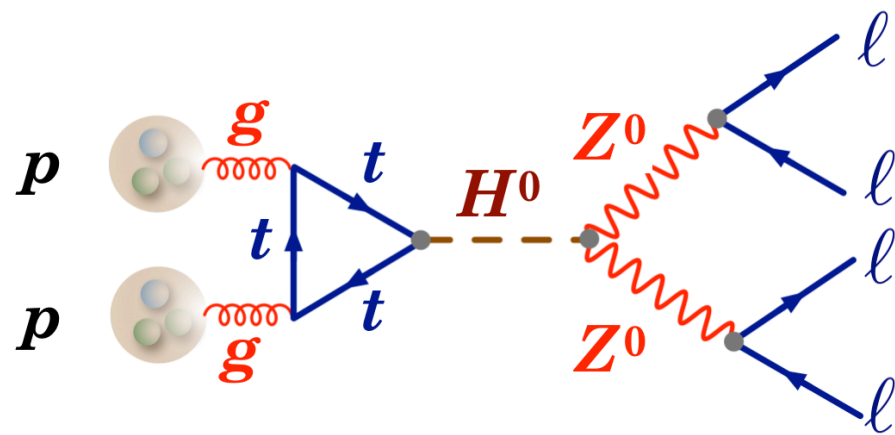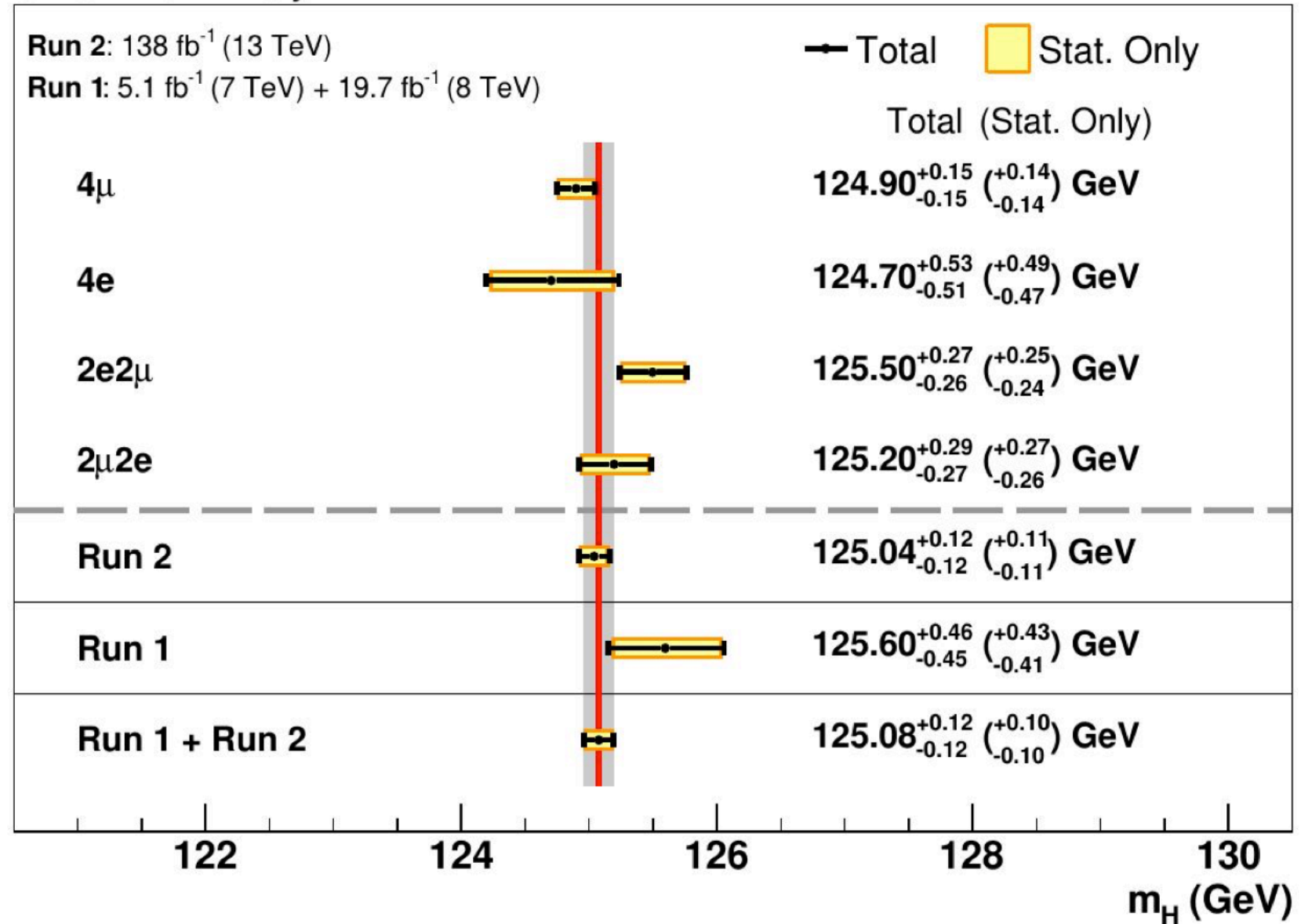
$$m_{\mathrm{H}}(\mathrm{CMS}) = 125.08 \pm 0.10(\mathrm{stat}) \pm 0.05(\mathrm{syst}) \ \mathrm{GeV} \qquad ZZ \to 4\ell$$

$$m_{\mathrm{H}}(\mathrm{ATLAS}) = 125.11 \pm 0.09(\mathrm{stat}) \pm 0.06(\mathrm{syst}) \ \mathrm{GeV} \qquad ZZ \to 4\ell + 2\gamma$$
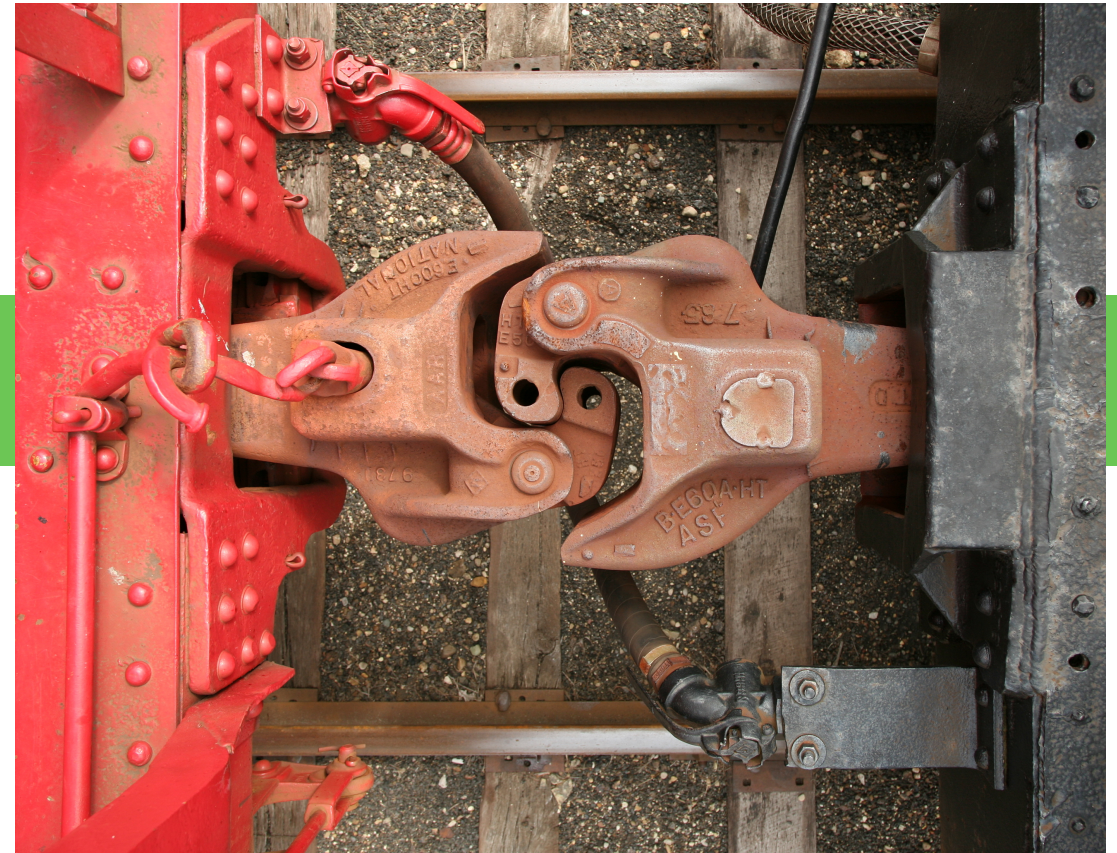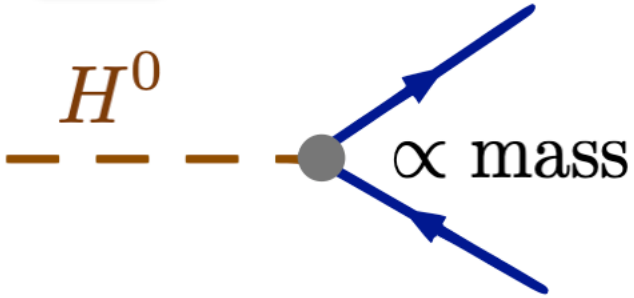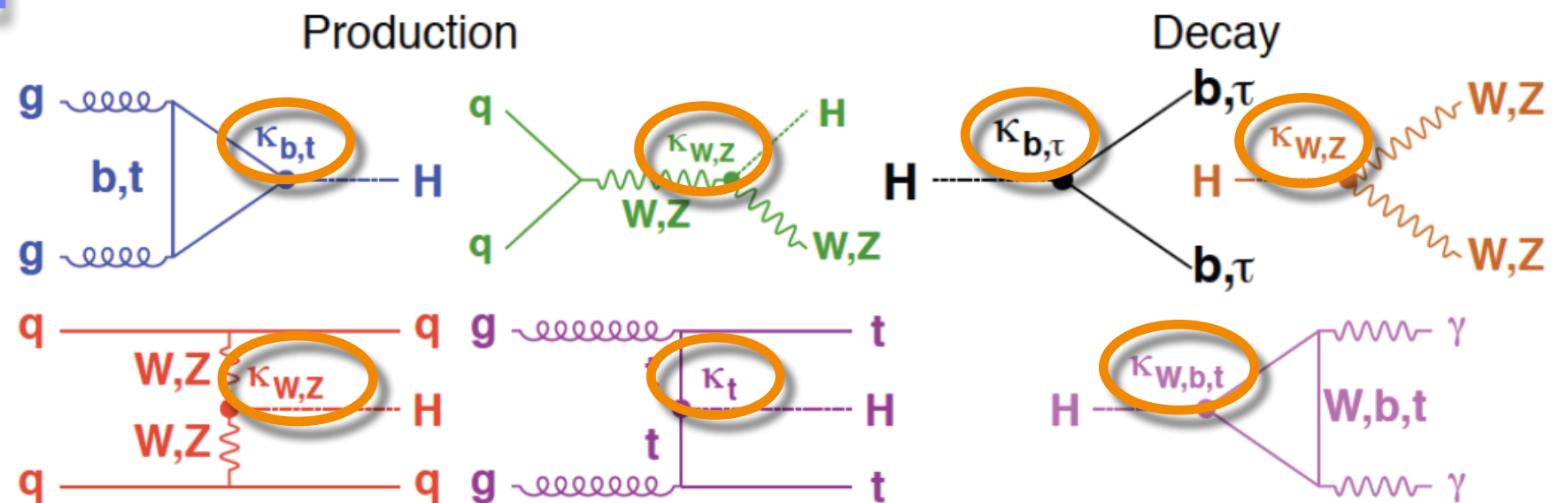
couplings

couplings

$$V(\text{fermions}) = \boxed{g_i} \bar{f}_{Li} f_{Ri} H$$

Higgs discovery spawned an industry
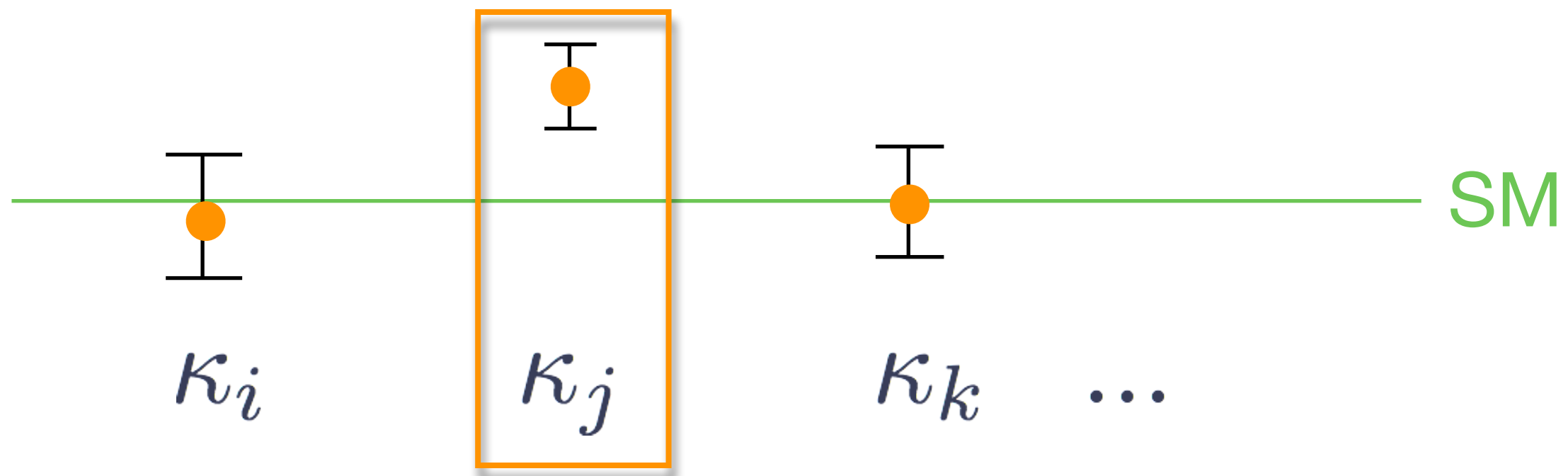
precision fitting

$$+ \boxed{g_i} \bar{f}_{Li} f_{Ri} H$$

$$H^0 \quad \propto \text{mass}$$

$$\mathcal{L} \propto \sum_i^{\text{fermions}_i} \boxed{(\kappa_i)} g_i f_i f_i H$$

Production   Decay

a campaign

Measure the couplings of Higgs... to **everything**

how well?

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Benchmark for discovery is few % to sub-%

κ_i κ_j κ_k ...

SM
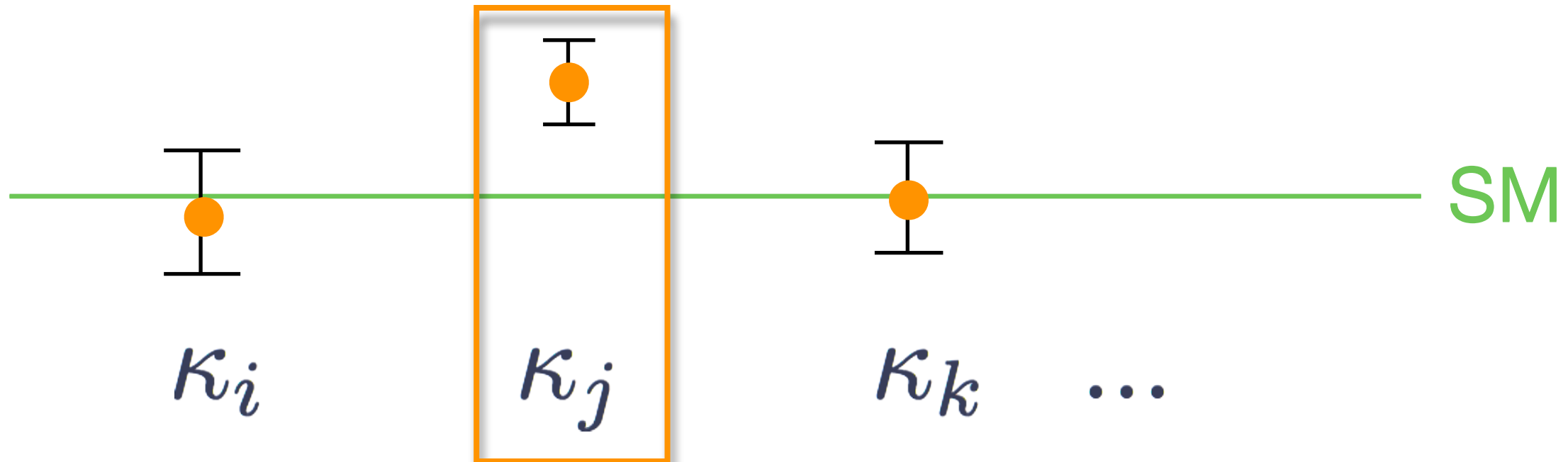
The couplings:

κ_{fermions}

$\kappa_{W,Z,\gamma}$
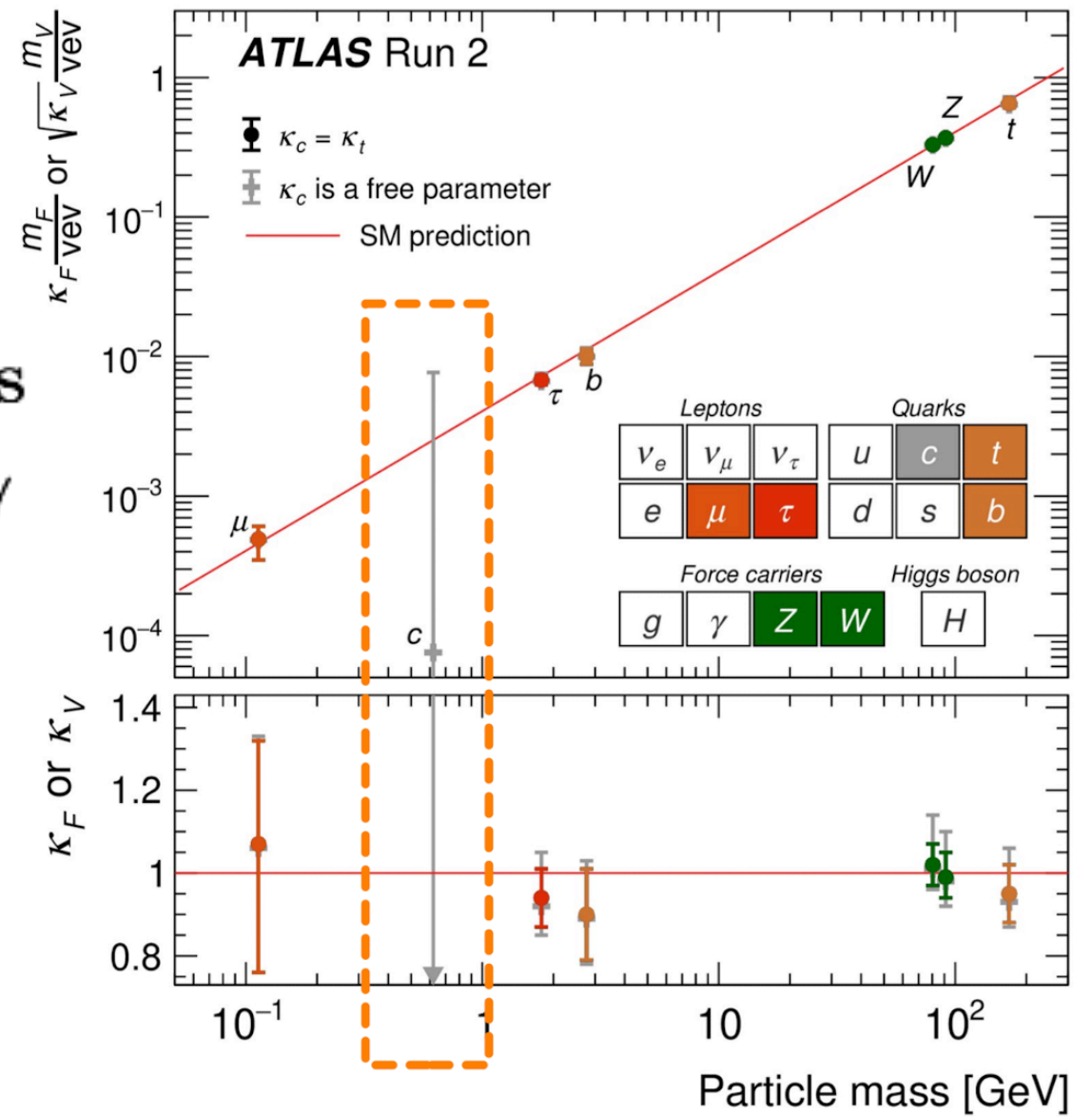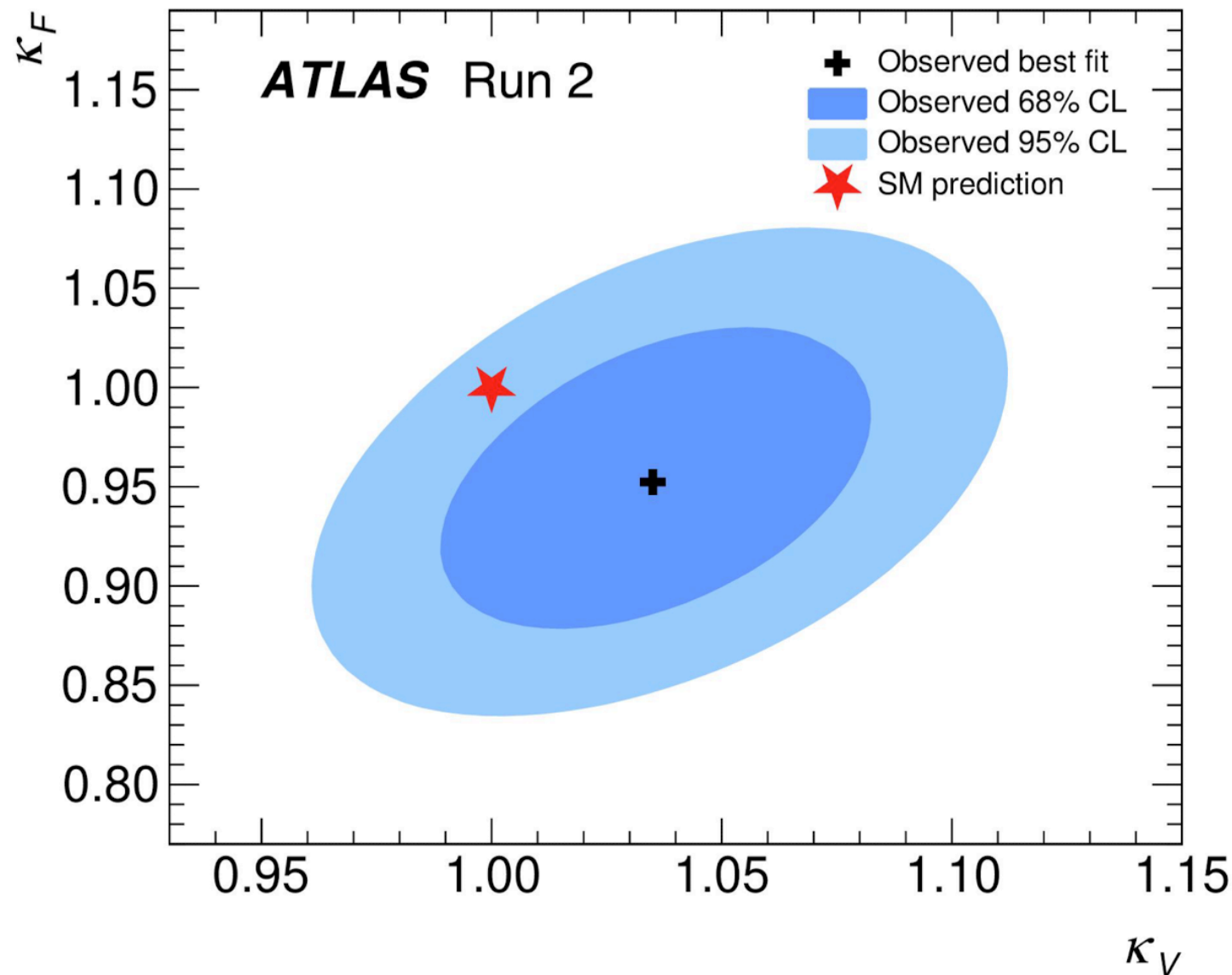
sort of 5%

Extrapolating to future machines

Snowmass 13 versus ESG 19 versus Snowmass 21

by facility

κ_W — LHC-8TeV, LHC300, HL-LHC, ILC500, ILC500-up, ILC1000, ILC1000-up, TLEP, CLIC1400, CLIC3000 (snowmass 21 / ESG prediction - 2019)
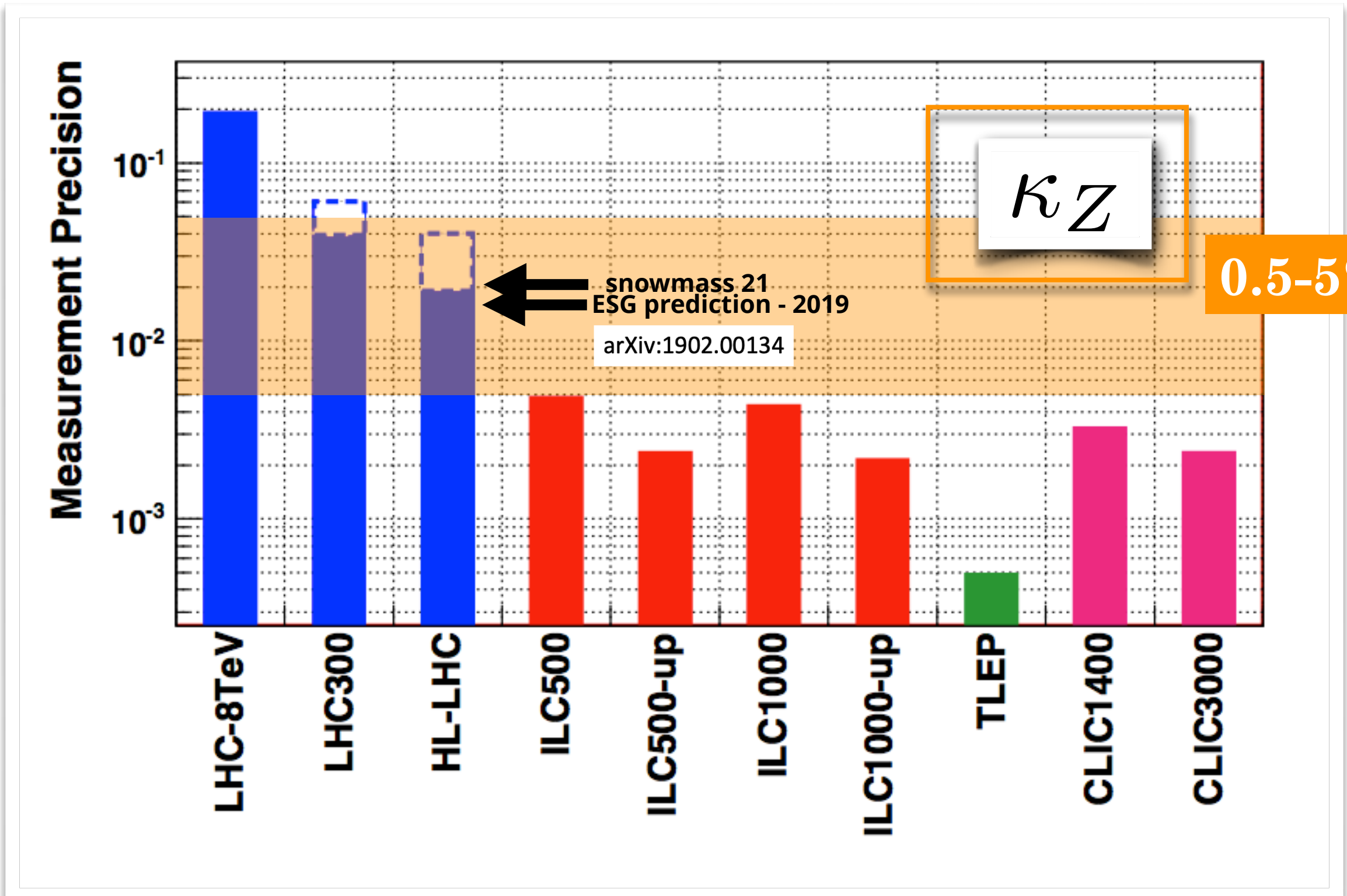
κ_b — LHC-8TeV, LHC300, HL-LHC, ILC500, ILC500-up, ILC1000, ILC1000-up, TLEP, CLIC1400, CLIC3000 (snowmass 21 / ESG prediction - 2019) — 0.5-5%

κ_γ — LHC-8TeV, LHC300, HL-LHC, ILC500, ILC500-up, ILC1000, ILC1000-up, TLEP, CLIC1400, CLIC3000 (snowmass 21 / ESG prediction - 2019)

κ_t — LHC-8TeV, LHC300, HL-LHC, ILC500, ILC500-up, ILC1000, ILC1000-up, TLEP, CLIC1400, CLIC3000 (ESG prediction - 2019 / snowmass 21) — 0.5-5%

Measurement Precision

Precision Study of Electroweak Physics

Electroweak Precision Observables

■ Correlating the Spin 1 messengers, leptons, quarks, and the Higgs boson

then this happened:

Electroweak Precision Observables

■ Correlating the Spin 1 messengers, leptons, quarks, and the Higgs boson
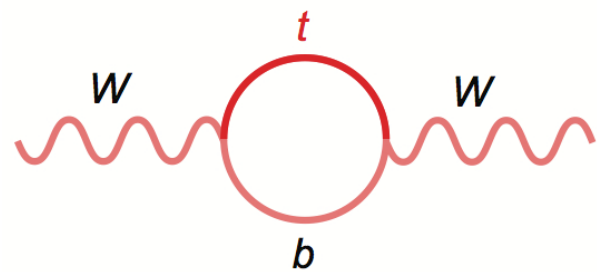
Systematics goal of $M_W = \pm\, 5\ \mathrm{MeV}/c^2$
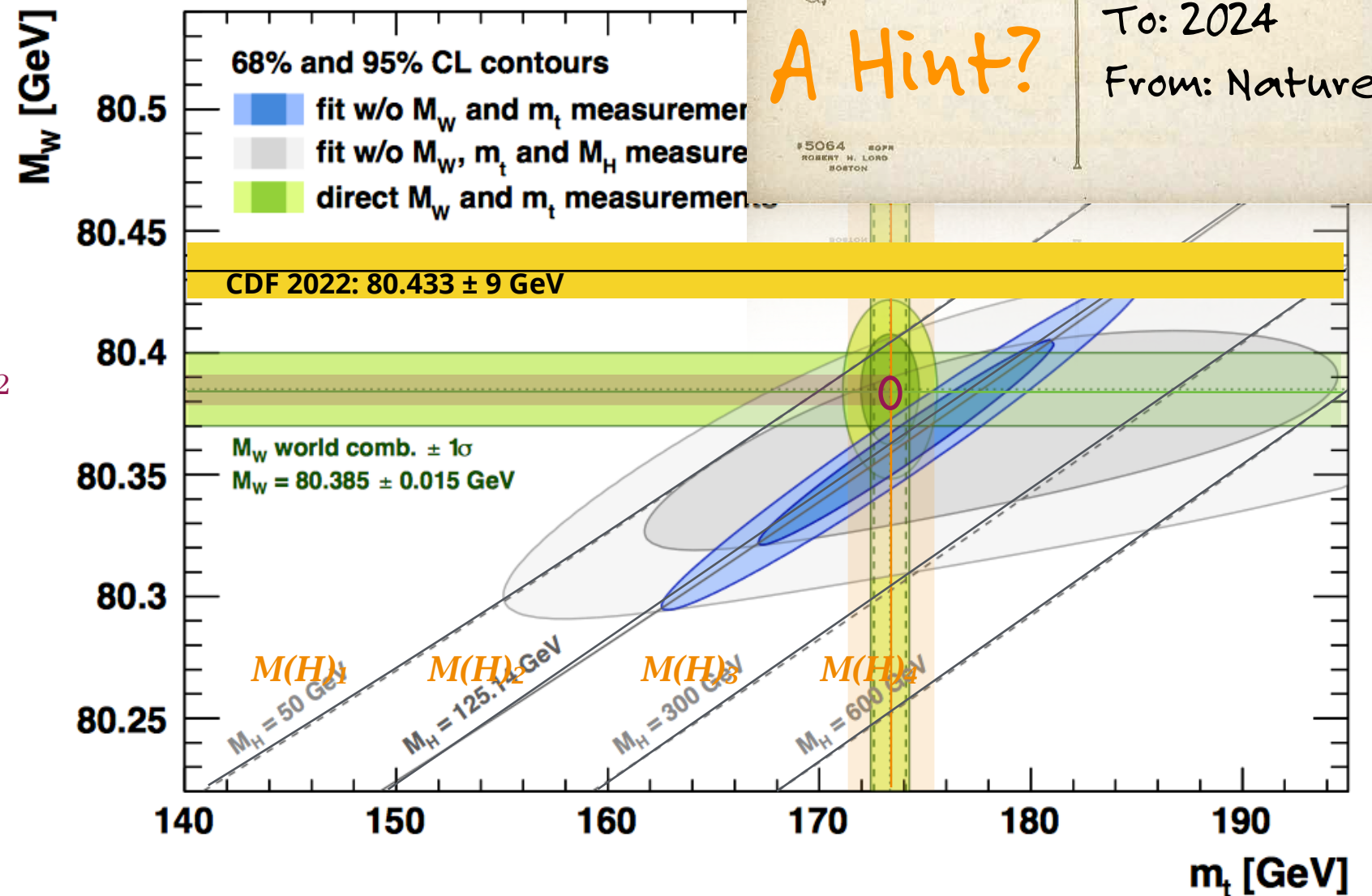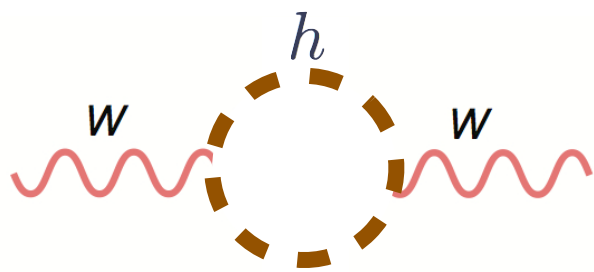
Fully Understanding the Top Quark
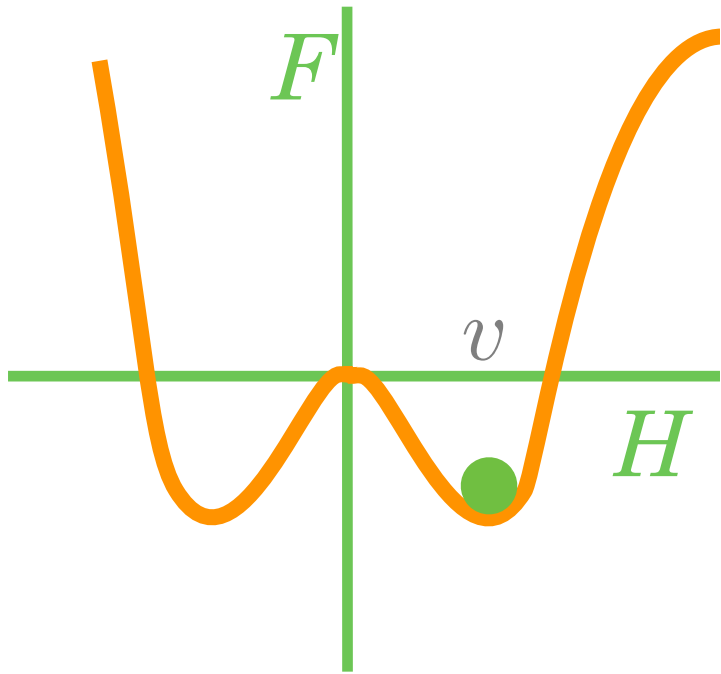
- **Remember this?**

- **and this?**

quantum corrections can lead to a new vacuum

POST CARD

Correspondence   Address

Hints?

To: 2024

Top and Higgs
making trouble

From: Nature
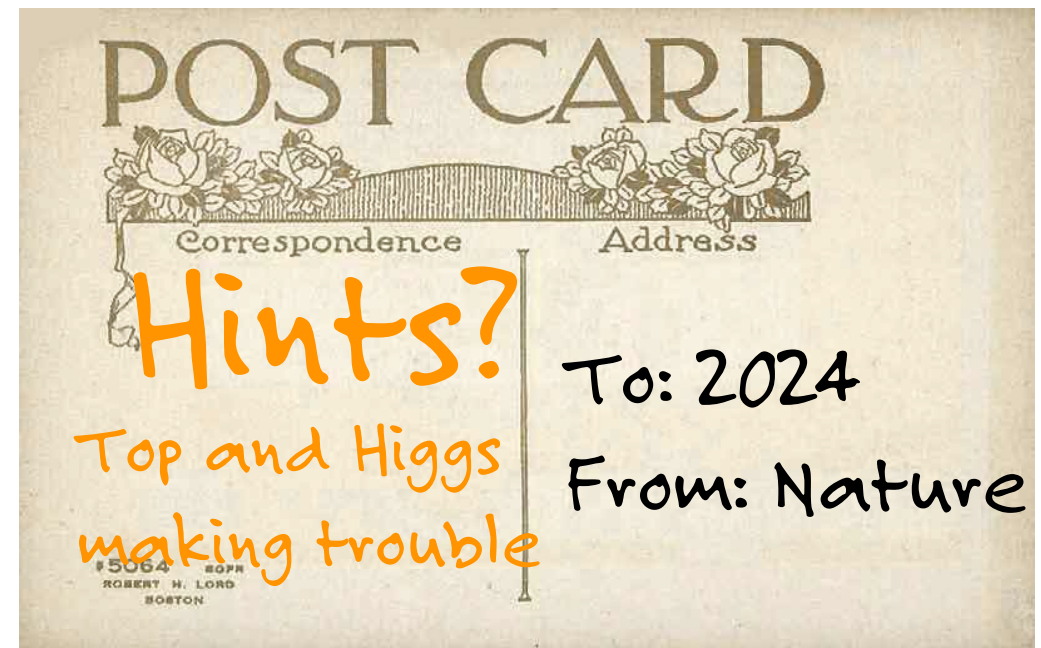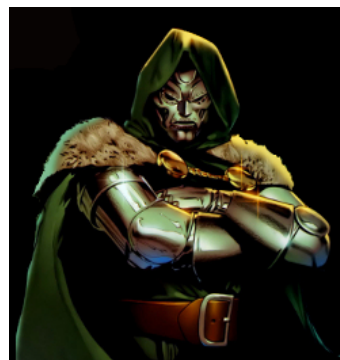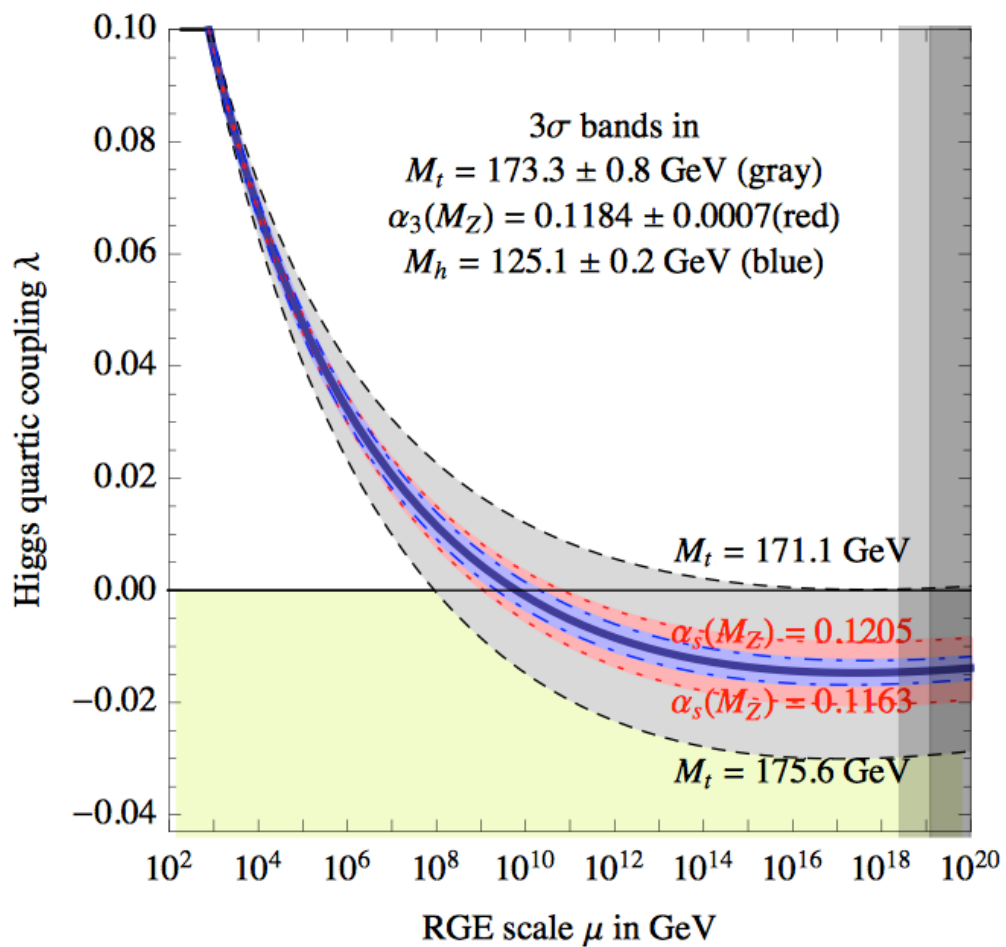
why measure m_t precisely?

$$V = \lambda v H^3 + \frac{\lambda}{4} H^4$$

Our vacuum metastable?

Top mass M_t in GeV — Instability, Meta-stability, Stability, Non-perturbability

unstable, metastable, absolutely stable

m_t / GeV vs m_h / GeV

2406.05180

■ E... s

k... on

■ fu...

la...

POST CARD
Correspondence   Address

Hints?
Top and Higgs making trouble

To: 2024
From: Nature
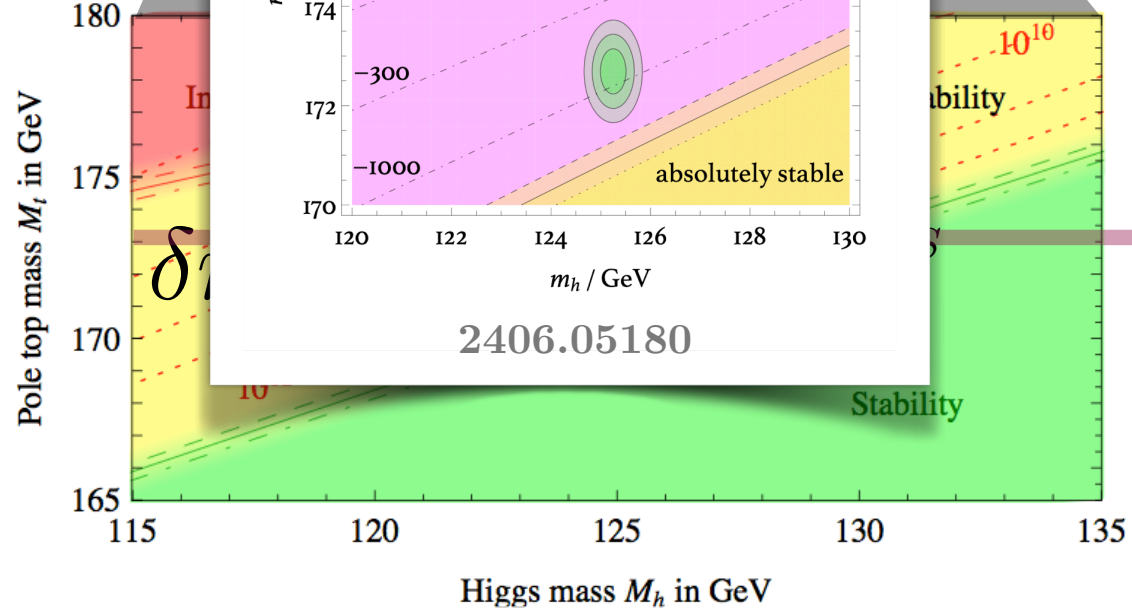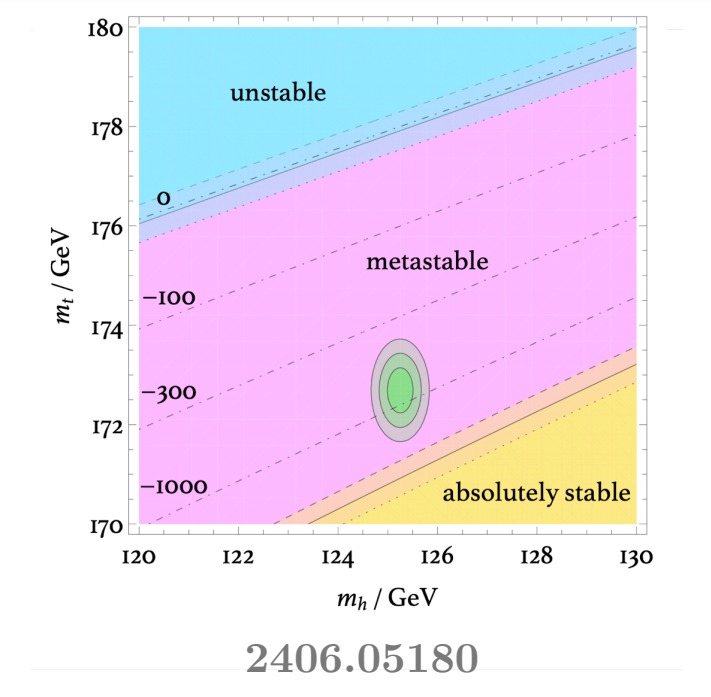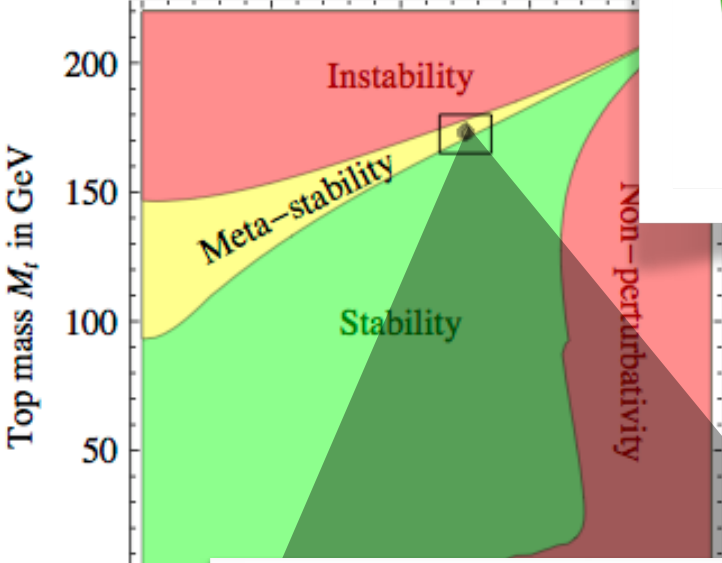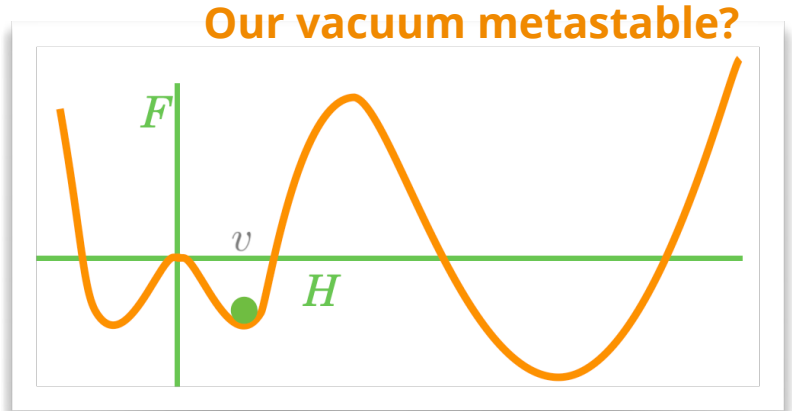
Systematics goal of $m_{top} = \pm 500$ MeV/c^2

Pole top mass M_t in GeV vs Higgs mass M_h in GeV

■ But it's a part of the potential problem

Ytterbium in a single package
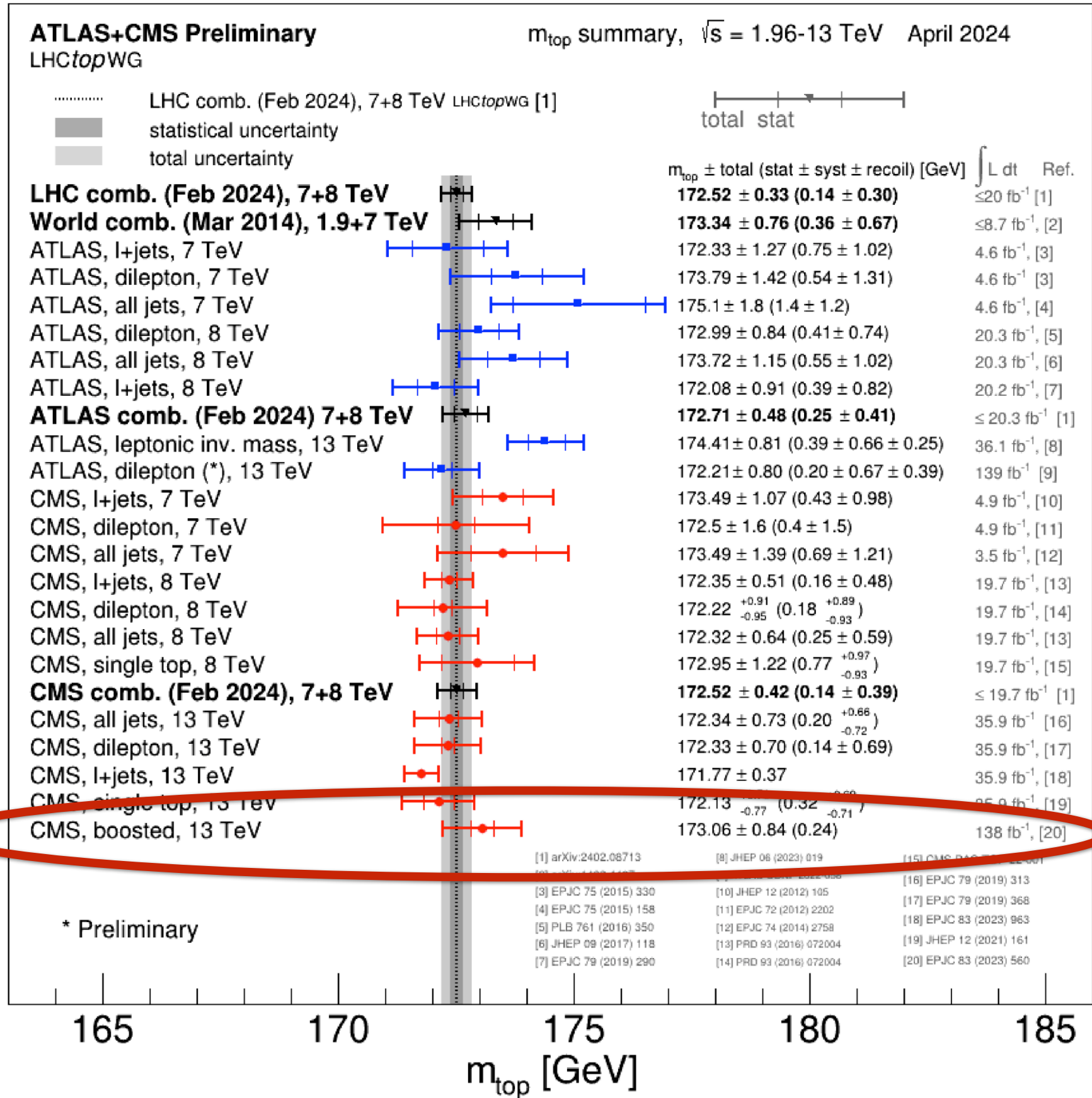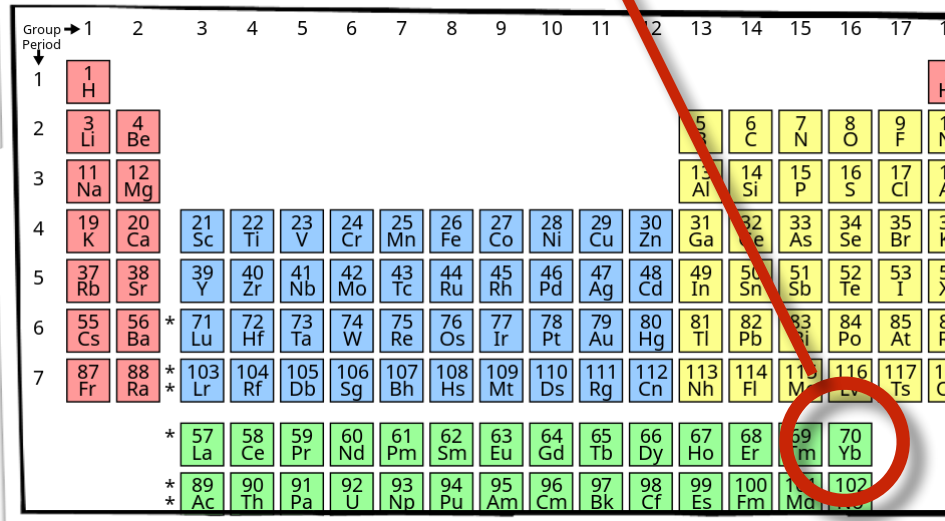
OBTW…that potential shape?

from higgs-higgs self-coupling λ

modified HIggs structure

Landau-Ginzburg Higgs   Nambu-Goldstone Higgs   Coleman-Weinberg Higgs   Tadpole-Induced Higgs

vacuum strability

3σ bands in
$M_t = 173.3 \pm 0.8$ GeV (gray)
$\alpha_3(M_Z) = 0.1184 \pm 0.0007$ (red)
$M_h = 125.1 \pm 0.2$ GeV (blue)

$M_t = 171.1$ GeV

$\alpha_s(M_Z) = 0.1205$

$\alpha_s(M_Z) = 0.1163$

$M_t = 175.6$ GeV

Higgs quartic coupling λ

RGE scale μ in GeV

chasing $\kappa_\lambda = \lambda/\lambda_{\rm SM}$

$H^0 \to bb, WW, \tau\tau, ZZ, \gamma\gamma$

$H^0 \to bb, WW, \tau\tau, ZZ, \gamma\gamma$

$\to bb, WW, \tau\tau, ZZ, \gamma\gamma$

$\to bb, WW, \tau\tau, ZZ, \gamma\gamma$

$H^0 \to bb, WW, \tau\tau, ZZ, \gamma\gamma$

$H^0 \to bb, WW, \tau\tau, ZZ, \gamma\gamma$
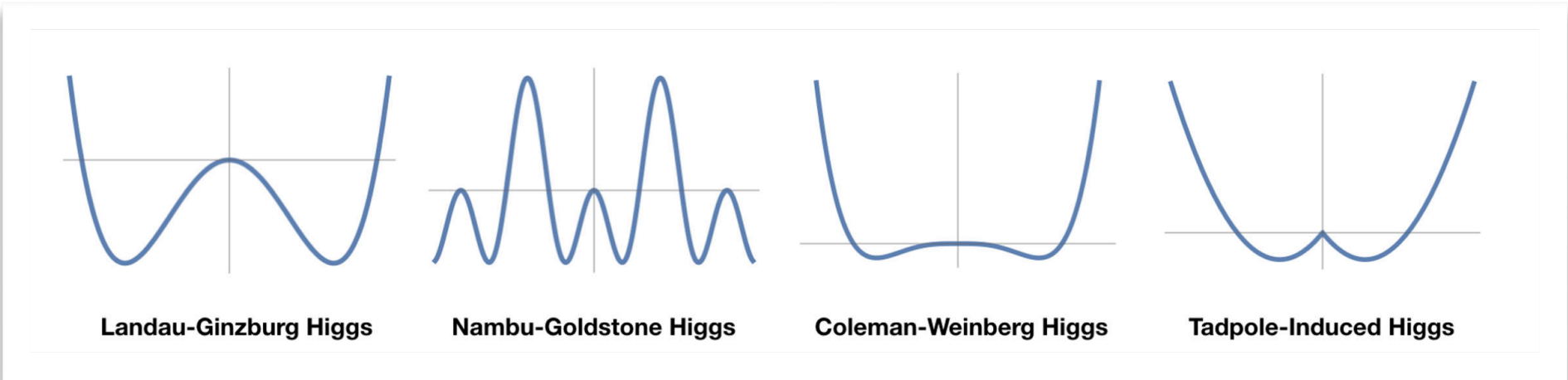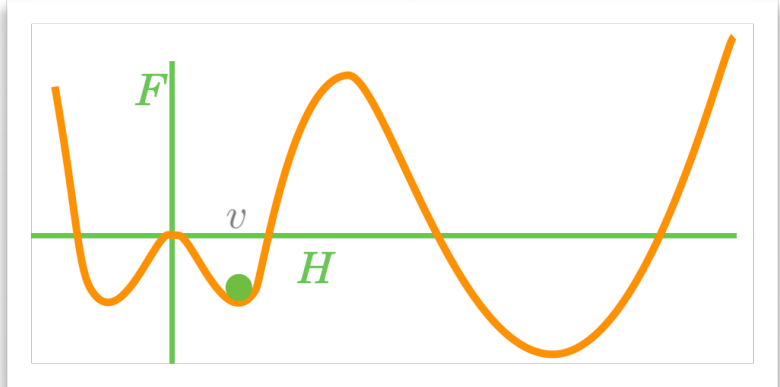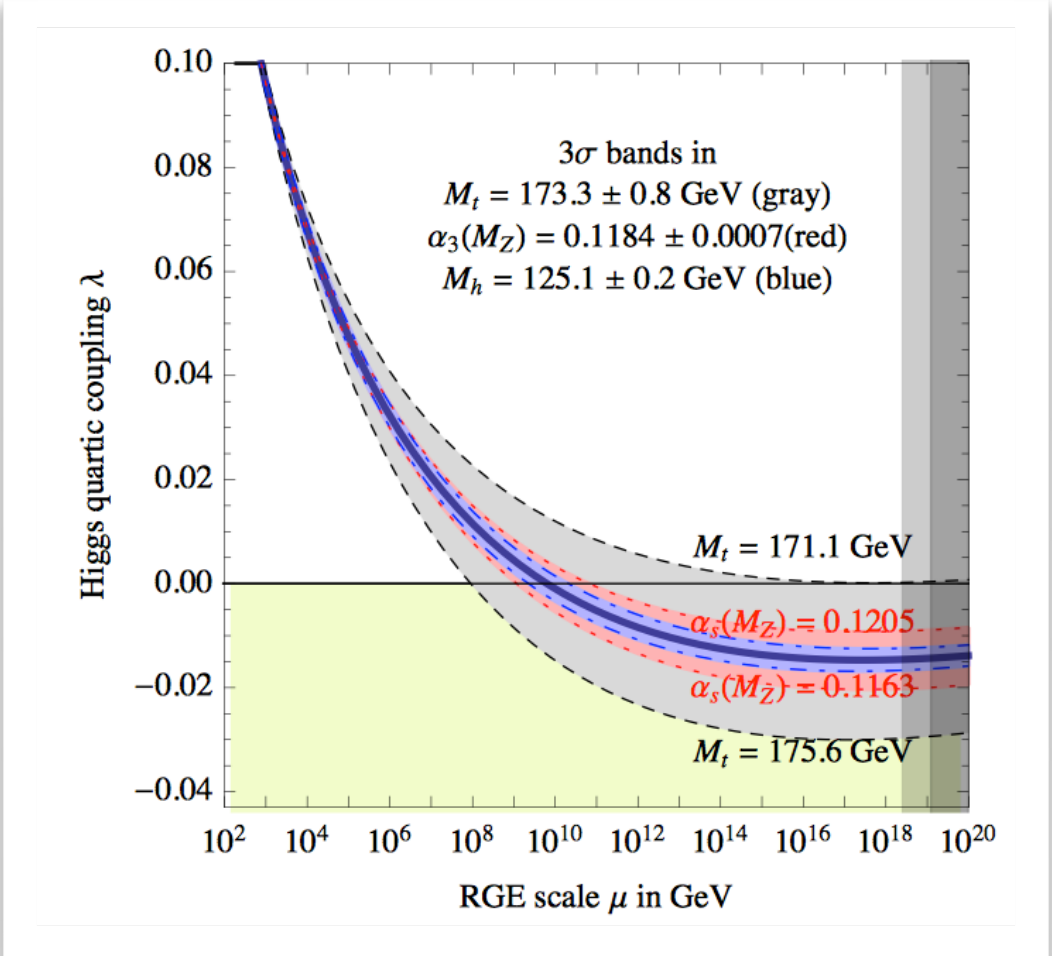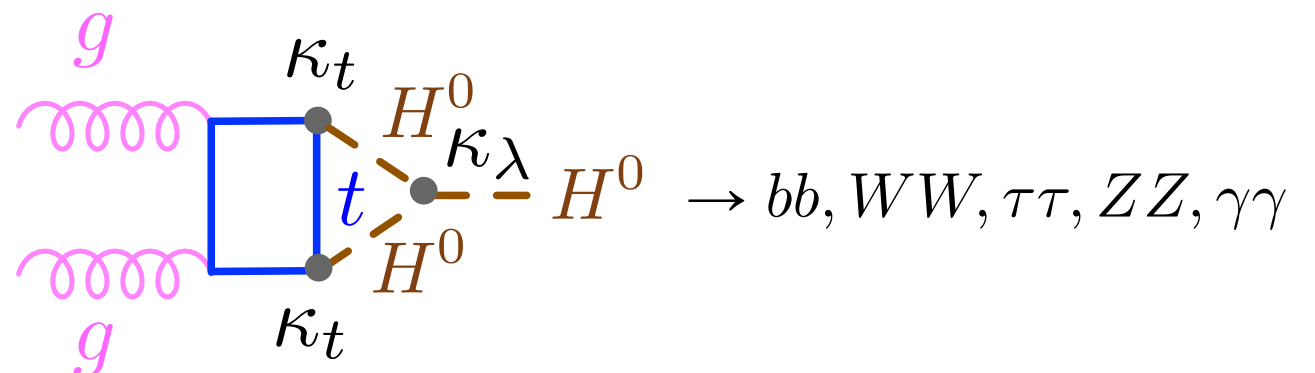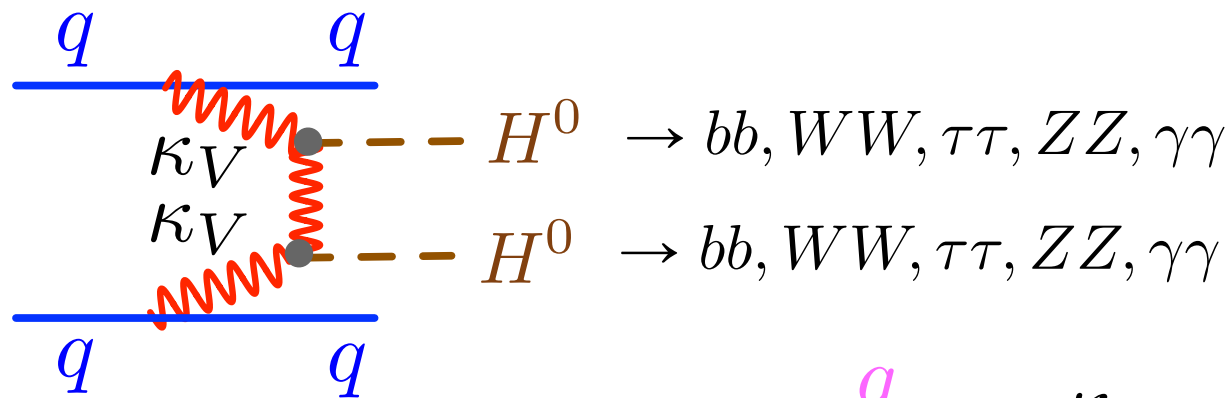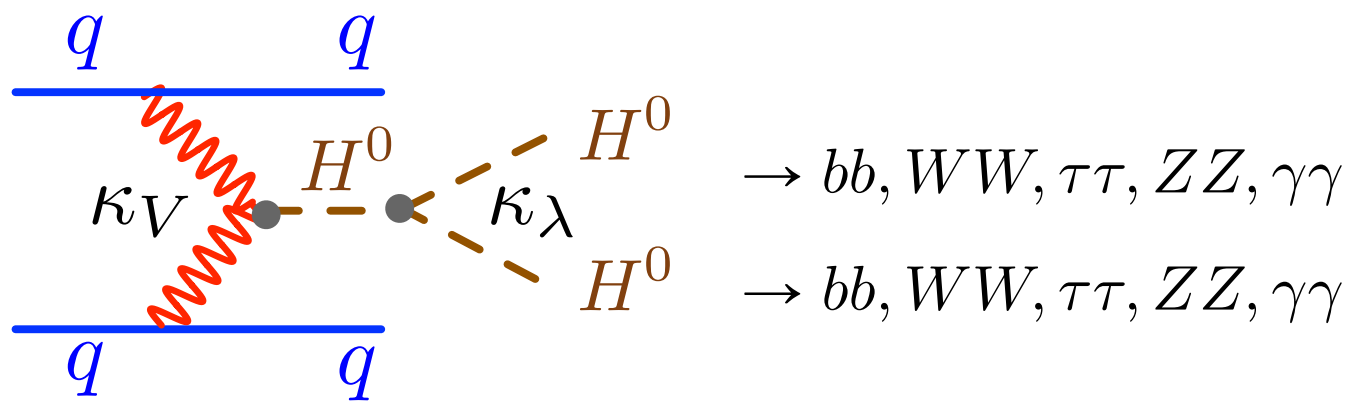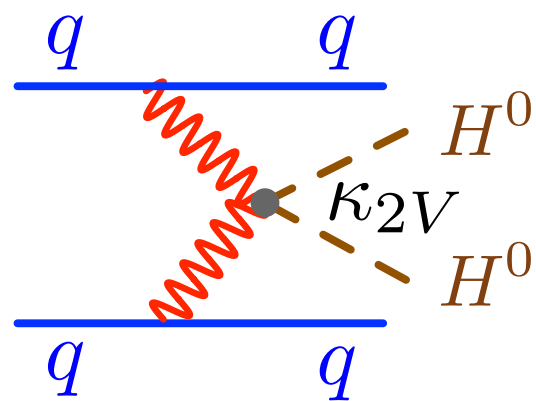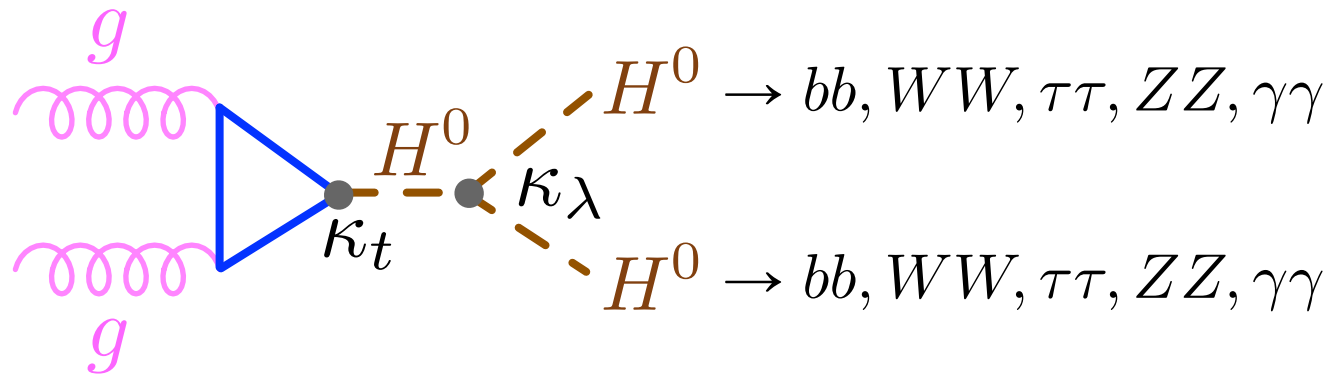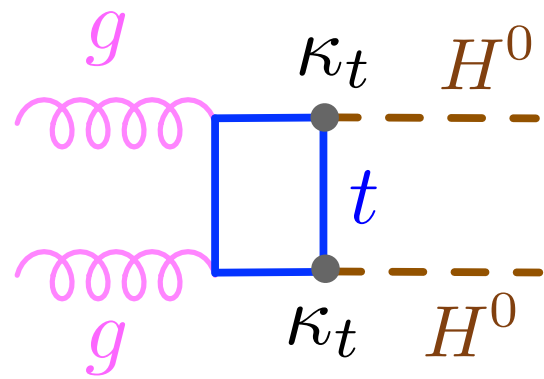
$bbbb$
$+$
$bb\tau\tau$
$+$
$bb\gamma\gamma$

Plus 4 1-loop single-Higgs production channels...like:

$H^0 \to bb, WW, \tau\tau, ZZ, \gamma\gamma$

hard to predict cleverness

$$bbbb + bb\tau\tau + bb\gamma\gamma$$

ATLAS

$\sqrt{s}$ = 13 TeV, 126—139 fb^{-1}
All other κ fixed to SM
Observed

— 68% CL $HH + H$
--- 95% CL $HH + H$
— 68% CL H
--- 95% CL H
— 68% CL HH
--- 95% CL HH
☆ SM prediction
✚ Best fit $HH + H$
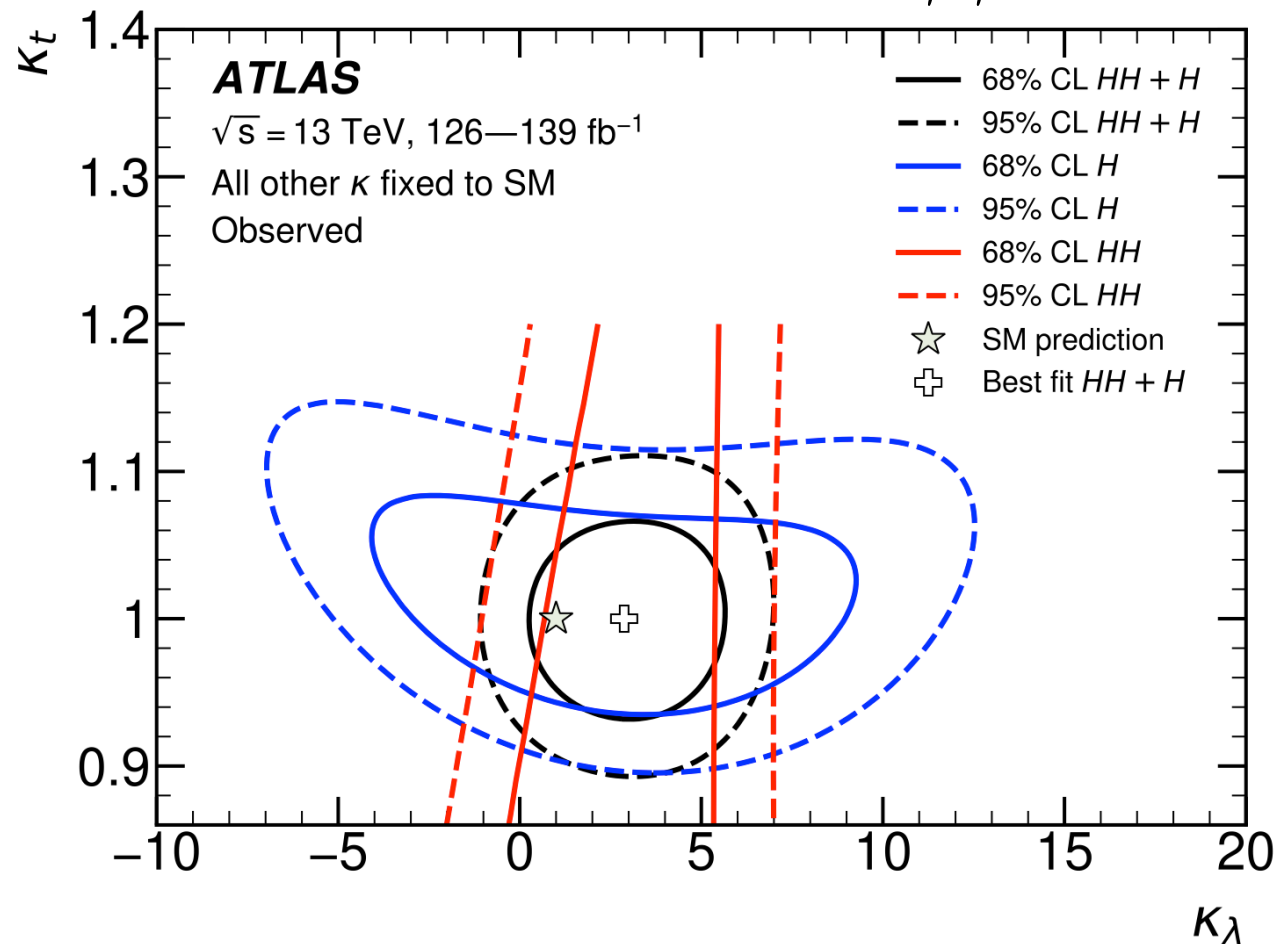
2015 extrapolation to 3000 fb^{-1}:

"...we can project an exclusion at 95% Confidence Level of BSM HH production with $\lambda_{HHH}/\lambda_{SM} \leq -4$ and $\lambda_{HHH}/\lambda_{SM} \geq 12$"

ATL-PHYS-PUB-2015-046

SM for all other couplings, @95% CL:

$$-0.4 < \kappa_\lambda < 6.3$$

relaxing other couplings, @95% CL:

$$-1.4 < \kappa_\lambda < 6.1$$

ATLAS-CONF-2021-052

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
HH → $b\bar{b}\tau^+\tau^-$

— Observed limit (95% CL)
--- Expected limit (95% CL)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
☆ SM prediction

Observed: $\kappa_\lambda \in [-2.4, 9.2]$
Expected: $\kappa_\lambda \in [-2.0, 9.0]$

Observed: $\kappa_\lambda \in [-2.4, 9.2]$
Expected: $\kappa_\lambda \in [-2.0, 9.0]$

Katharine Leney pointed this out
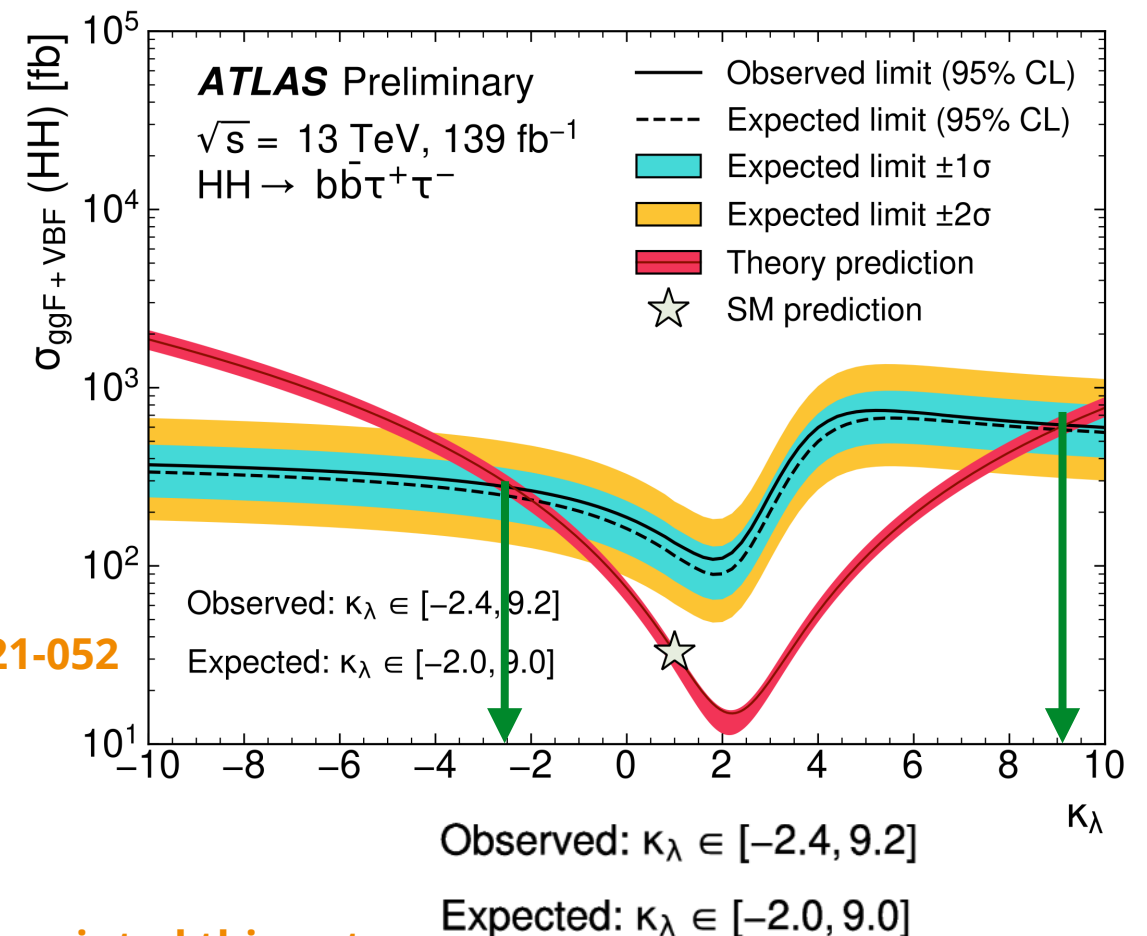
data make you smarter
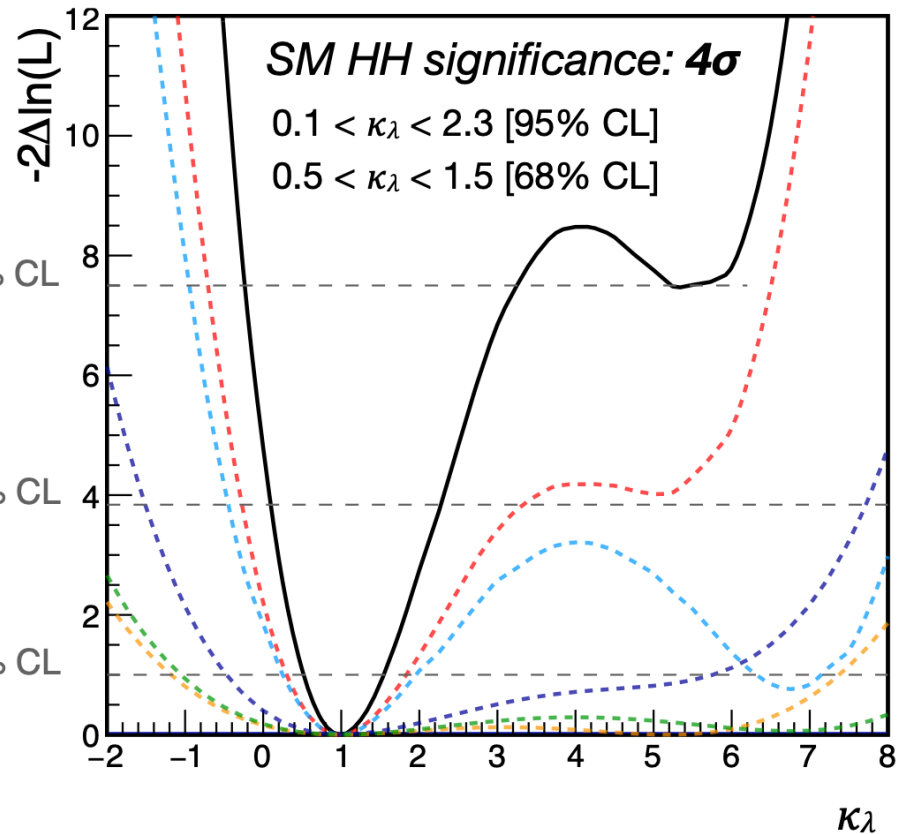
European Strategy (2018) CERN-2019-007
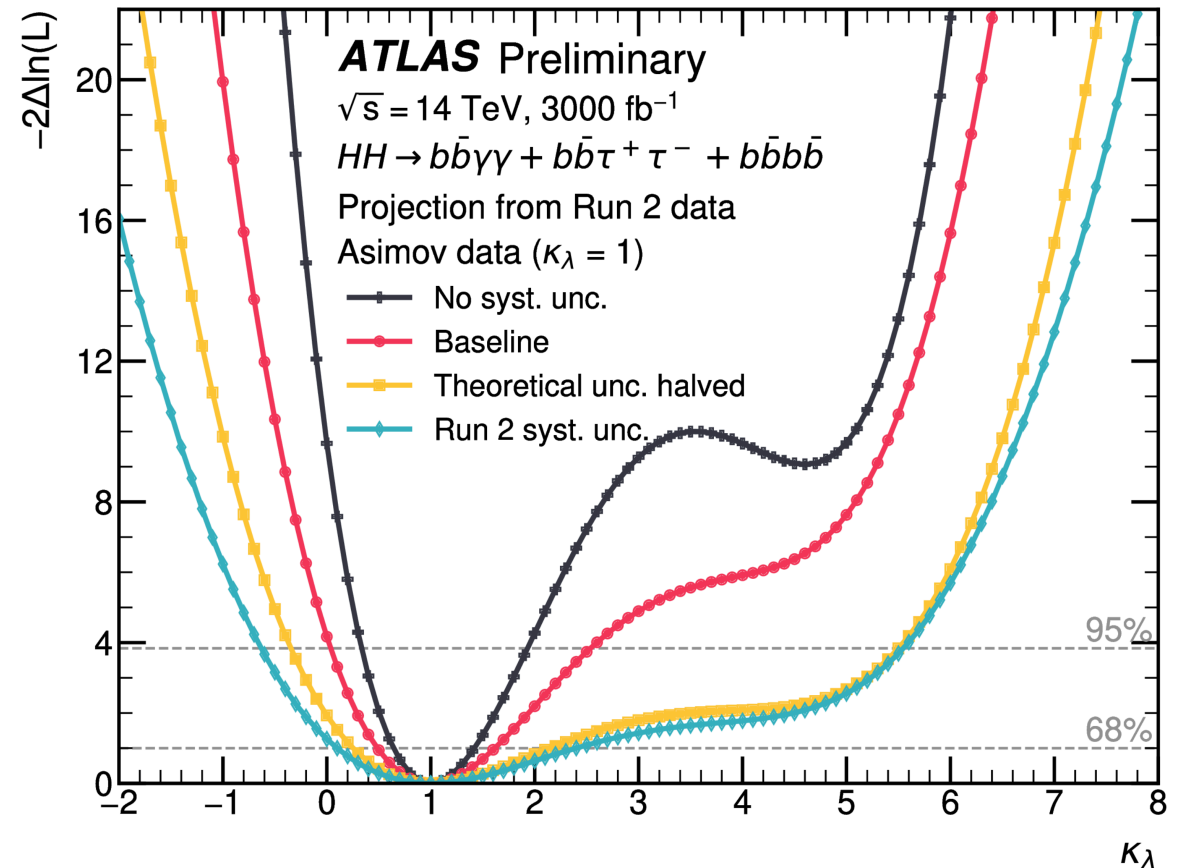
Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]

Now ATL-PHYS-PUB-2022-053

we have been saying ±50%...maybe better?
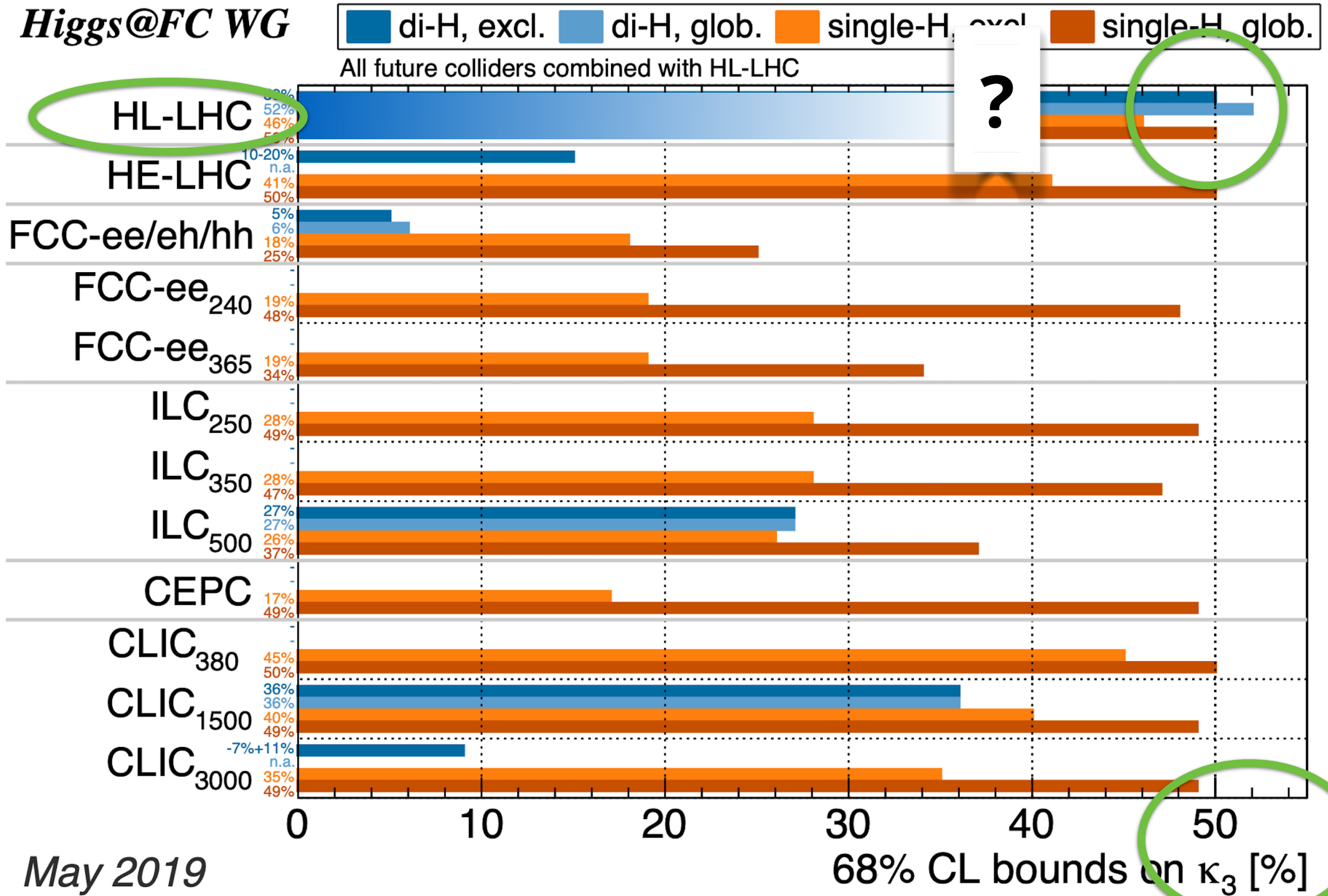
The precision Higgs Boson program is in full swing.

The Path Beyond the Standard Model

history suggests

new families

Expansion of the gauge groups

Compositeness

Beyond the Standard Model:

motivation from:
non-zero neutrino mass,
the hierarchy problem,
the EW parameter hints,
passing the TeV scale,
the antimatter problem, &
the dark matter problem

We're digging deep now

Searching with exquisite precision for:

new particle LHC searches...TeV in hand

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 13$ TeV

I TeV scale

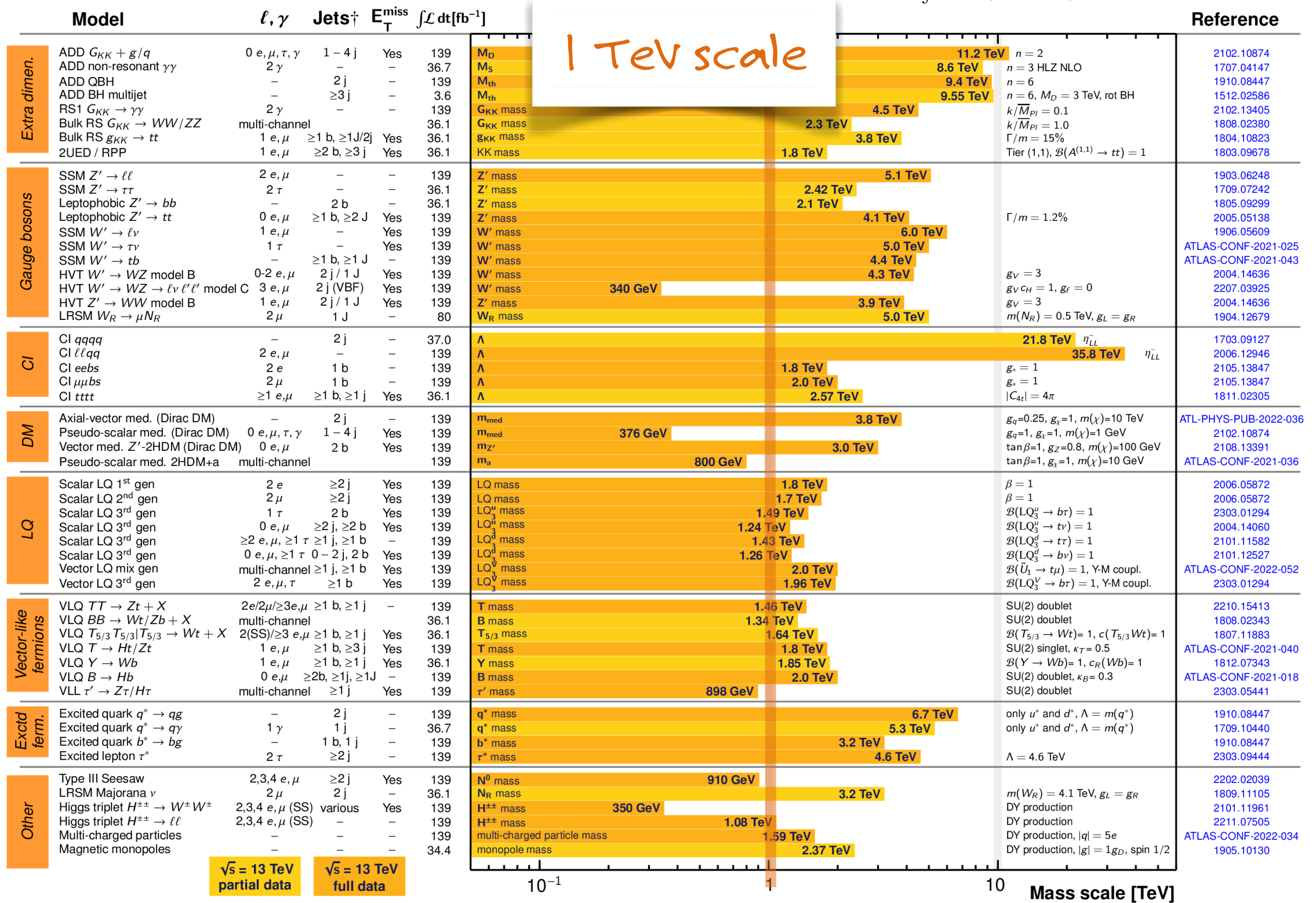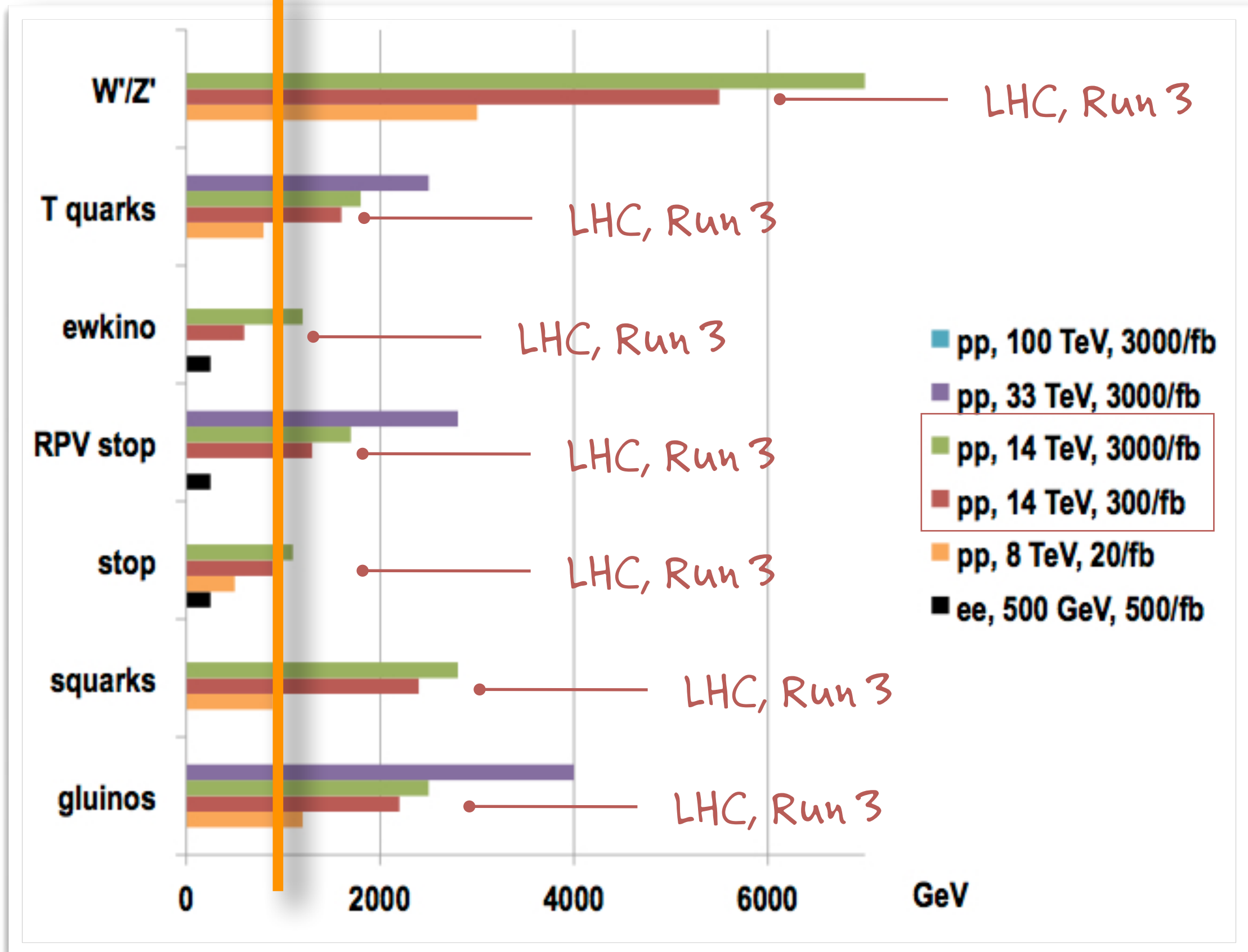| Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$		Limit		Reference
Extra dimen.								
ADD $G_{KK} + g/q$	$0\ e,\mu,\tau,\gamma$	$1-4$ j	Yes	139	M_D	11.2 TeV	$n=2$	2102.10874
ADD non-resonant $\gamma\gamma$	2γ	–	–	36.7	M_S	8.6 TeV	$n=3$ HLZ NLO	1707.04147
ADD QBH	–	2 j	–	139	M_{th}	9.4 TeV	$n=6$	1910.08447
ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
RS1 $G_{KK} \to \gamma\gamma$	2γ	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl}=0.1$	2102.13405
Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl}=1.0$	1808.02380
Bulk RS $g_{KK} \to tt$	$1\ e,\mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m=15\%$	1804.10823
2UED / RPP	$1\ e,\mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt)=1$	1803.09678
Gauge bosons								
SSM $Z' \to \ell\ell$	$2\ e,\mu$	–	–	139	Z' mass	5.1 TeV		1903.06248
SSM $Z' \to \tau\tau$	2τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
Leptophobic $Z' \to tt$	$0\ e,\mu$	≥ 1 b, ≥ 2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m=1.2\%$	2005.05138
SSM $W' \to \ell\nu$	$1\ e,\mu$	–	Yes	139	W' mass	6.0 TeV		1906.05609
SSM $W' \to \tau\nu$	1τ	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
SSM $W' \to tb$	–	≥ 1 b, ≥ 1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
HVT $W' \to WZ$ model B	0-2 e,μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V=3$	2004.14636
HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	3 e,μ	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H=1$, $g_f=0$	2207.03925
HVT $Z' \to WW$ model B	$1\ e,\mu$	2 j / 1 J	Yes	139	Z' mass	3.9 TeV	$g_V=3$	2004.14636
LRSM $W_R \to \mu N_R$	2μ	1 J		80	W_R mass	5.0 TeV	$m(N_R)=0.5$ TeV, $g_L=g_R$	1904.12679
CI								
CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}	1703.09127
CI $\ell\ell qq$	2 e,μ	–	–	139	Λ	35.8 TeV	η_{LL}^-	2006.12946
CI $eebs$	2 e	1 b	–	139	Λ	1.8 TeV	$g_*=1$	2105.13847
CI $\mu\mu bs$	2μ	1 b	–	139	Λ	2.0 TeV	$g_*=1$	2105.13847
CI $tttt$	$\geq 1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ	2.57 TeV	$|C_{4t}|=4\pi$	1811.02305
DM								
Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med}	3.8 TeV	$g_q=0.25$, $g_\chi=1$, $m(\chi)=10$ TeV	ATL-PHYS-PUB-2022-036
Pseudo-scalar med. (Dirac DM)	$0\ e,\mu,\tau,\gamma$	$1-4$ j	Yes	139	m_{med}	376 GeV	$g_q=1$, $g_\chi=1$, $m(\chi)=1$ GeV	2102.10874
Vector med. Z'-2HDM (Dirac DM)	$0\ e,\mu$	2 b	Yes	139	$m_{Z'}$	3.0 TeV	$\tan\beta=1$, $g_Z=0.8$, $m(\chi)=100$ GeV	2108.13391
Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a	800 GeV	$\tan\beta=1$, $g_\chi=1$, $m(\chi)=10$ GeV	ATLAS-CONF-2021-036
LQ								
Scalar LQ 1st gen	2 e	≥ 2 j	Yes	139	LQ mass	1.8 TeV	$\beta=1$	2006.05872
Scalar LQ 2nd gen	2μ	≥ 2 j	Yes	139	LQ mass	1.7 TeV	$\beta=1$	2006.05872
Scalar LQ 3rd gen	1τ	2 b	Yes	139	LQ_3^u mass	1.49 TeV	$\mathcal{B}(LQ_3^u \to b\tau)=1$	2303.01294
Scalar LQ 3rd gen	$0\ e,\mu$	≥ 2 j, ≥ 2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu)=1$	2004.14060
Scalar LQ 3rd gen	$\geq 2\ e,\mu, \geq 1\tau$	≥ 1 j, ≥ 1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau)=1$	2101.11582
Scalar LQ 3rd gen	$0\ e,\mu, \geq 1\tau$	0-2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu)=1$	2101.12527
Vector LQ mix gen	multi-channel ≥ 1 j, ≥ 1 b		Yes	139	LQ^V mass	2.0 TeV	$\mathcal{B}(\tilde{U}_1 \to t\mu)=1$, Y-M coupl.	ATLAS-CONF-2022-052
Vector LQ 3rd gen	$2\ e,\mu,\tau$	≥ 1 b	Yes	139	LQ_3^V mass	1.96 TeV	$\mathcal{B}(LQ_3^V \to b\tau)=1$, Y-M coupl.	2303.01294
Vector-like fermions								
VLQ $TT \to Zt + X$	$2e/2\mu/\geq 3e,\mu$ ≥ 1 b, ≥ 1 j		–	139	T mass	1.46 TeV	SU(2) doublet	2210.15413
VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
VLQ $T_{5/3}T_{5/3}|T_{5/3} \to Wt + X$	2(SS)/$\geq 3\ e,\mu$ ≥ 1 b, ≥ 1 j		Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)=1$, $c(T_{5/3}Wt)=1$	1807.11883
VLQ $T \to Ht/Zt$	$1\ e,\mu$	≥ 1 b, ≥ 3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, $\kappa_T=0.5$	ATLAS-CONF-2021-040
VLQ $Y \to Wb$	$1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)=1$, $c_R(Wb)=1$	1812.07343
VLQ $B \to Hb$	$0\ e,\mu$	≥ 2b, ≥ 1j, ≥ 1J	–	139	B mass	2.0 TeV	SU(2) doublet, $\kappa_B=0.3$	ATLAS-CONF-2021-018
VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥ 1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	2303.05441
Exctd. ferm.								
Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1910.08447
Excited quark $q^* \to q\gamma$	1γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass	3.2 TeV		1910.08447
Excited lepton τ^*	2τ	≥ 2 j	–	139	τ^* mass	4.6 TeV	$\Lambda=4.6$ TeV	2303.09444
Other								
Type III Seesaw	2,3,4 e,μ	≥ 2 j	Yes	139	N^0 mass	910 GeV		2202.02039
LRSM Majorana ν	2μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R)=4.1$ TeV, $g_L=g_R$	1809.11105
Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e,μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e,μ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	2211.07505
Multi-charged particles	–	–	–	139	multi-charged particle mass	1.59 TeV	DY production, $|q|=5e$	ATLAS-CONF-2022-034
Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $|g|=1g_D$, spin 1/2	1905.10130

$\sqrt{s}=13$ TeV **partial data** $\sqrt{s}=13$ TeV **full data**

Mass scale [TeV]

10^{-1} 1   10

*Only a selection of the available mass limits on new states or phenomena is shown.
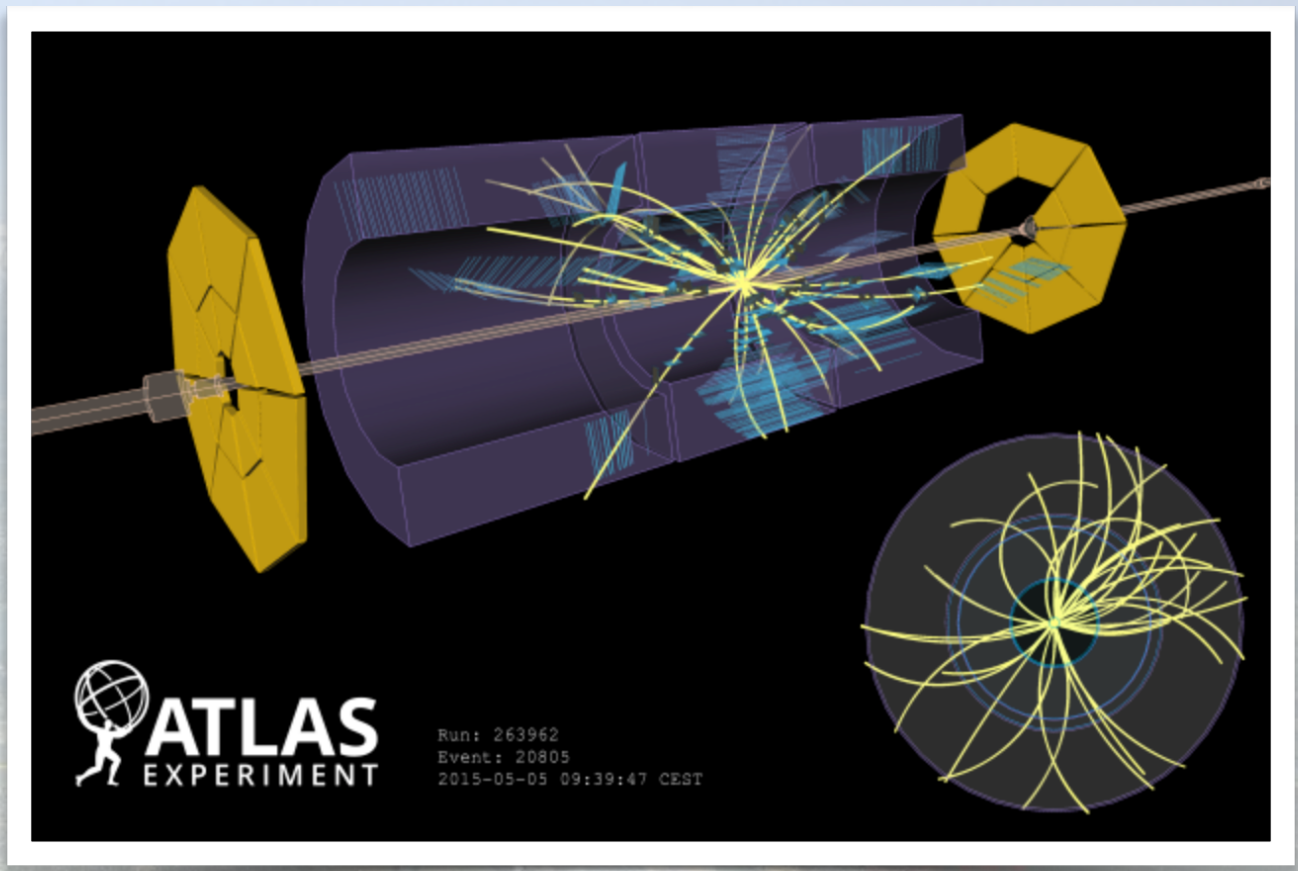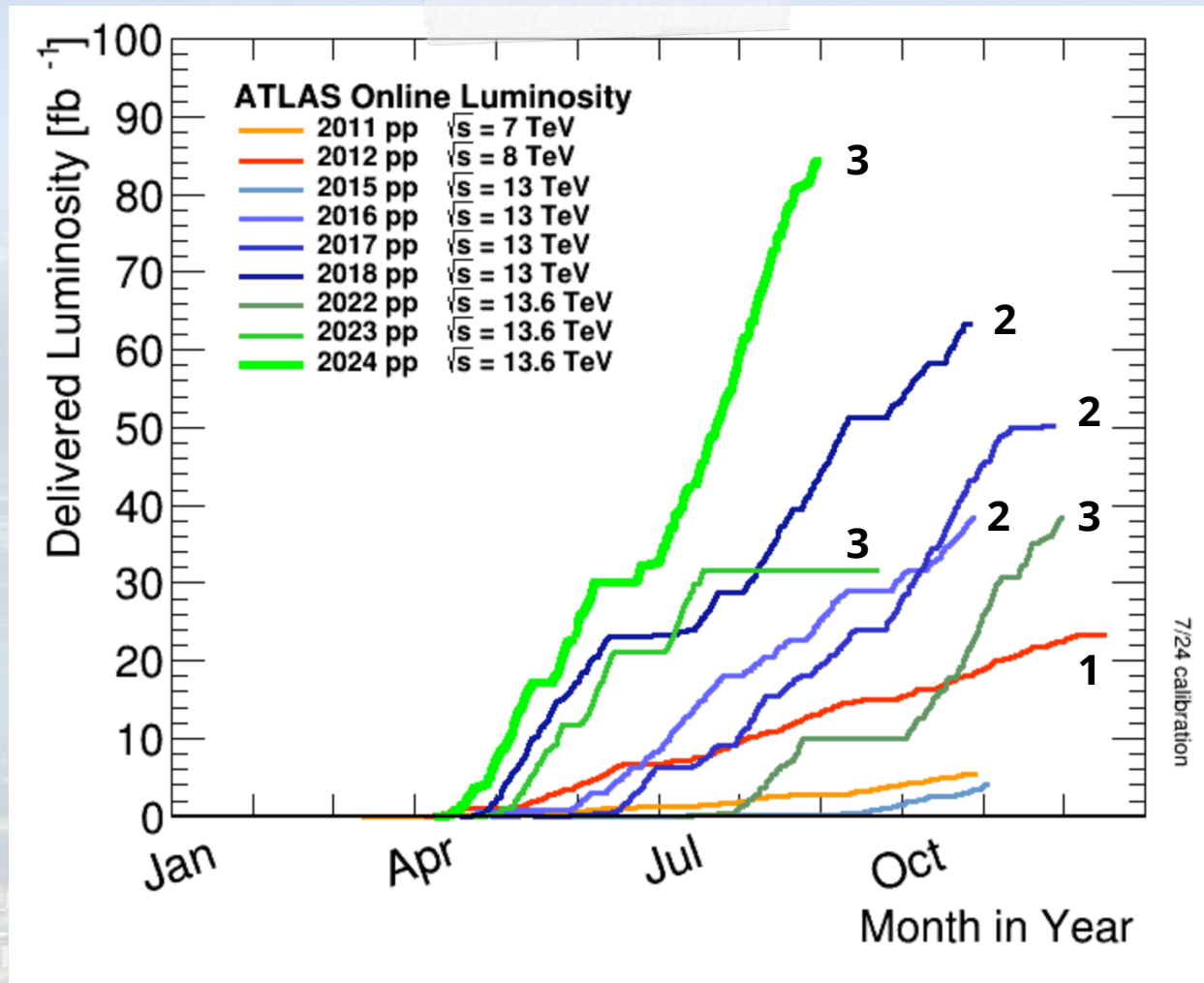
†Small-radius (large-radius) jets are denoted by the letter j (J).
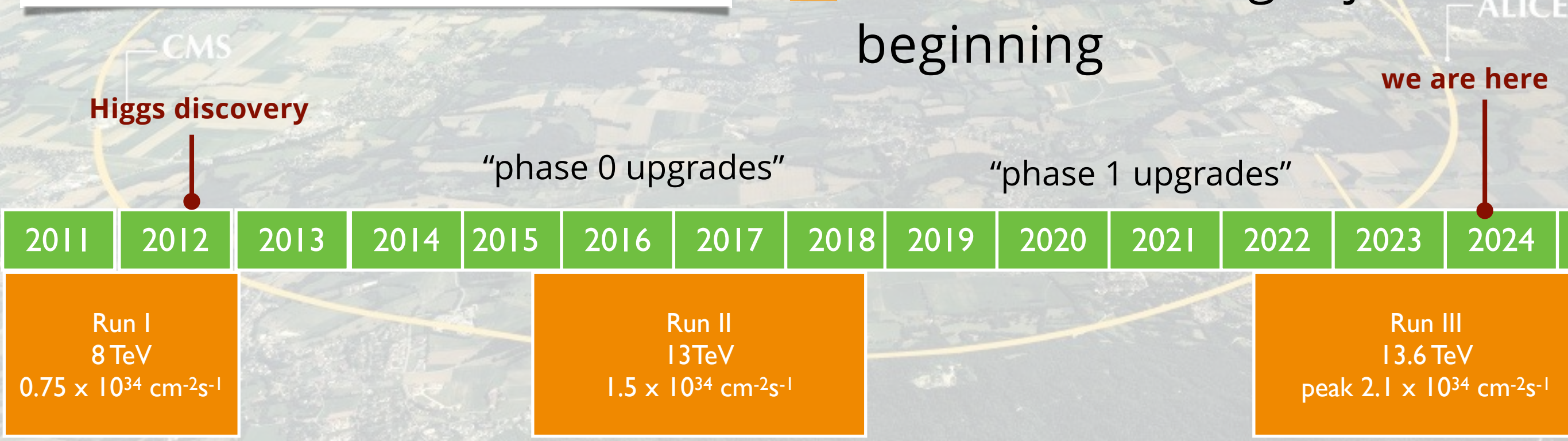
The TeV scale is almost history

the future

12%

The LHC running is just beginning

Higgs discovery

we are here

"phase 0 upgrades"

"phase 1 upgrades"

| 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |

Run I
8 TeV
0.75×10^{34} cm^{-2}s^{-1}

Run II
13 TeV
1.5×10^{34} cm^{-2}s^{-1}

Run III
13.6 TeV
peak 2.1×10^{34} cm^{-2}s^{-1}

20 fb^{-1} ~190 fb^{-1} integrated goal: 450 fb^{-1}

currently peak luminosity >2 x design

Literally right now a 1 year delay is being discussed

I'll be an old man rocking

"HL-LHC upgrades"

2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	

^{2}s^{-1}

Run IV
14 TeV
5×10^{34} cm^{-2}s^{-1}

≥ 3000 fb^{-1}

2 things and then conclusions

thing 1: mass.

Let's be clear.

We collider types say we know about Mass.

As long as we know nothing

about the mass of the neutral

Understanding Mass is still

Really? "all hands on deck"

A Hint?

To: 2024

From: Nature

about 85% of the gravitating

– EF, NF, RPF, and CF

universe

We don't know the Mass story.

thing 2: the circles.

The Bumper Sticker Frontier

they're pithy
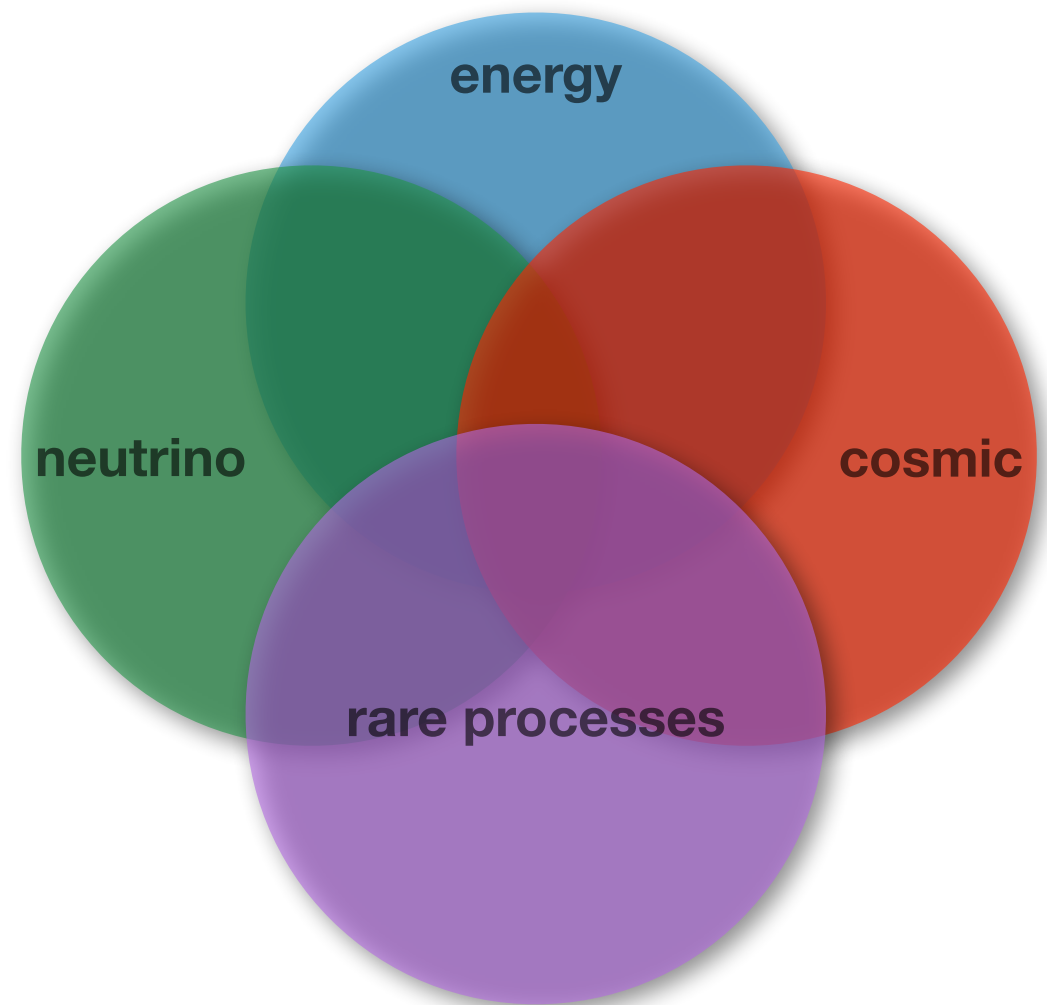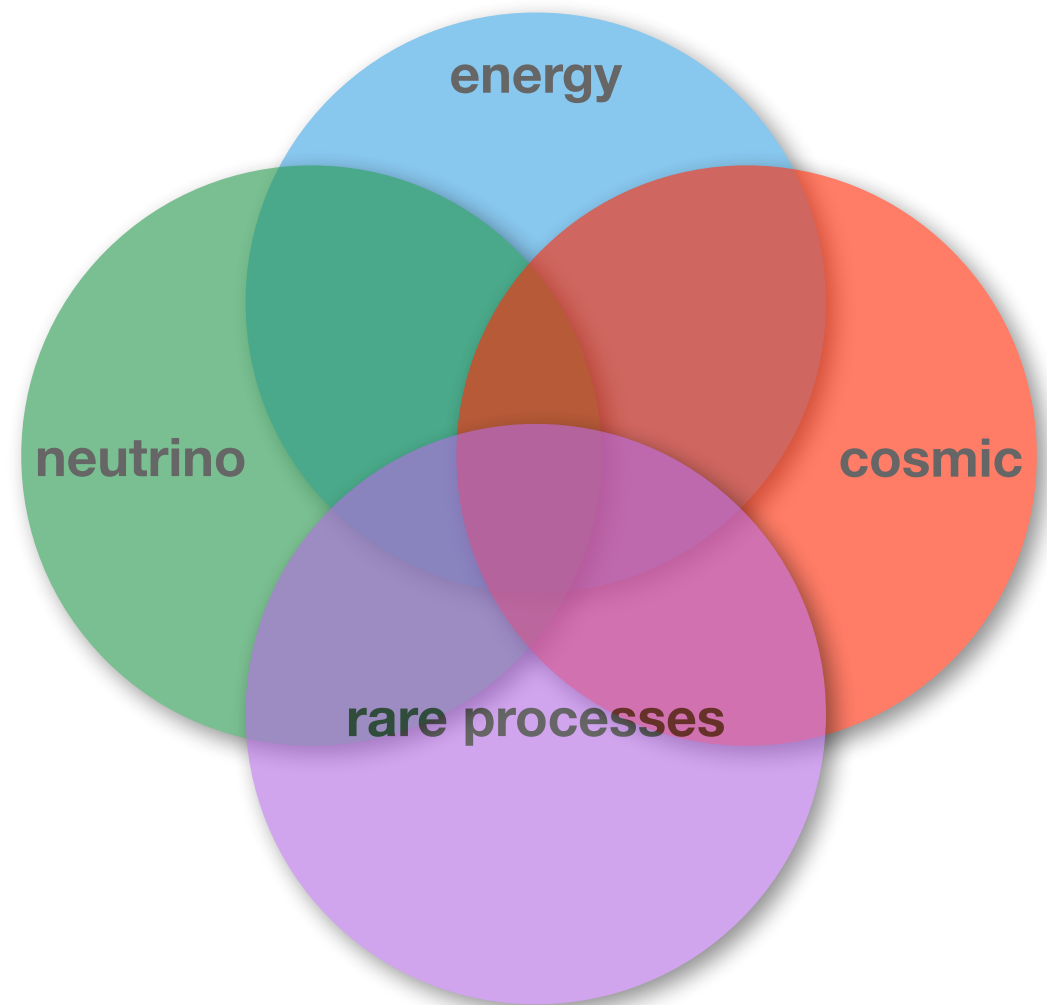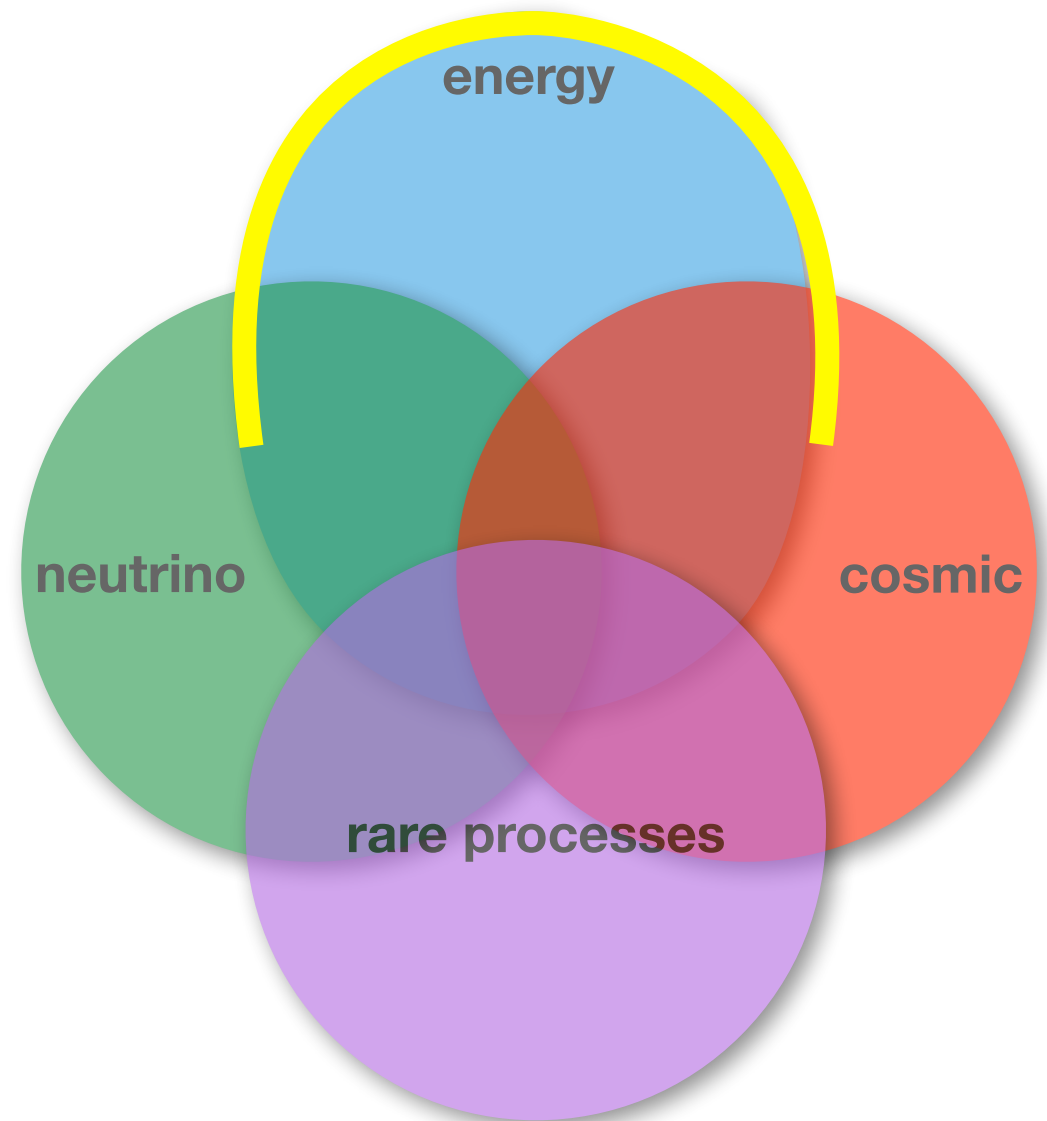
but probably everywhere

a shared "Frontier"
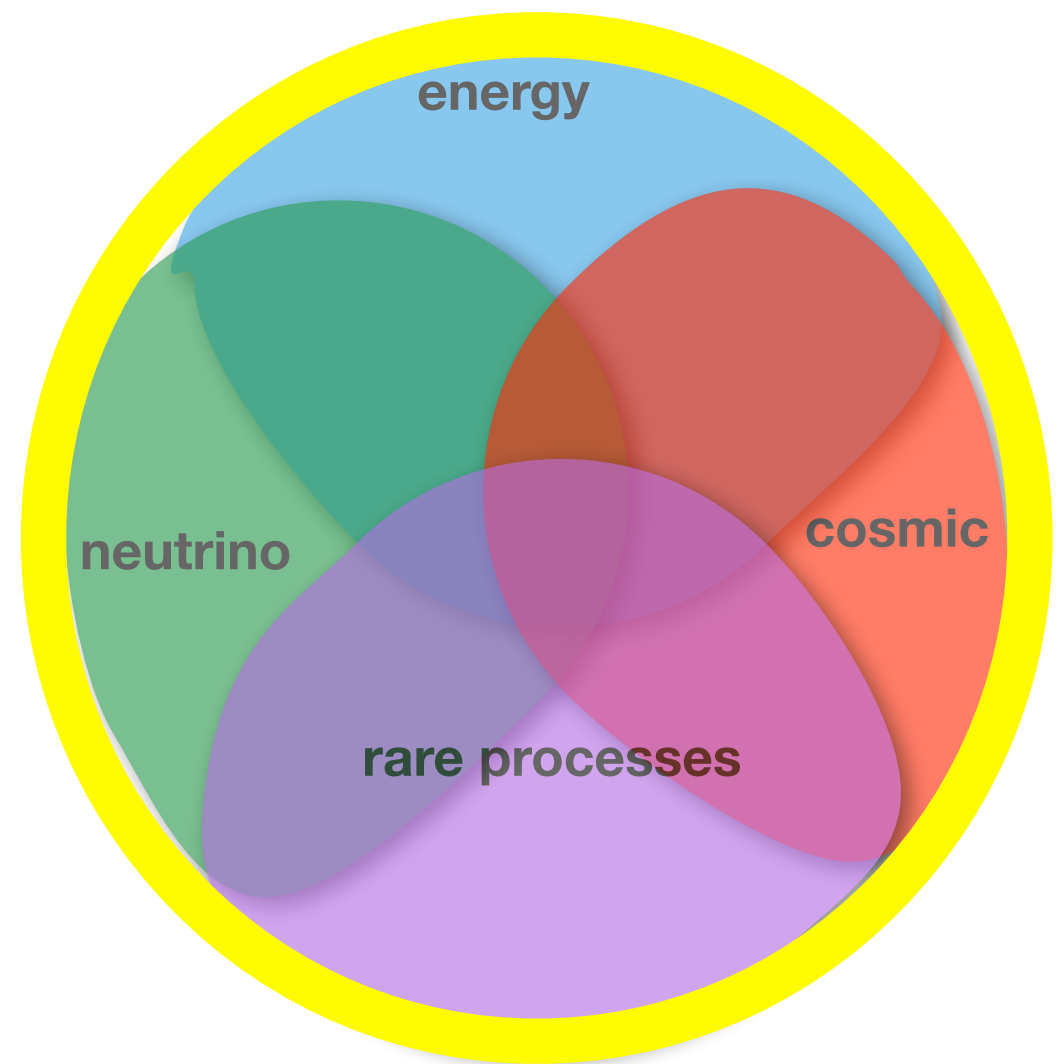
The Higgs particle changed everything.

SM guided research

un-guided research?

over-guided research?

We're exploring.

"Frontier"