LHC and the new Higgs-boson interactions

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“big unanswered questions”

about fundamental particles & their interactions

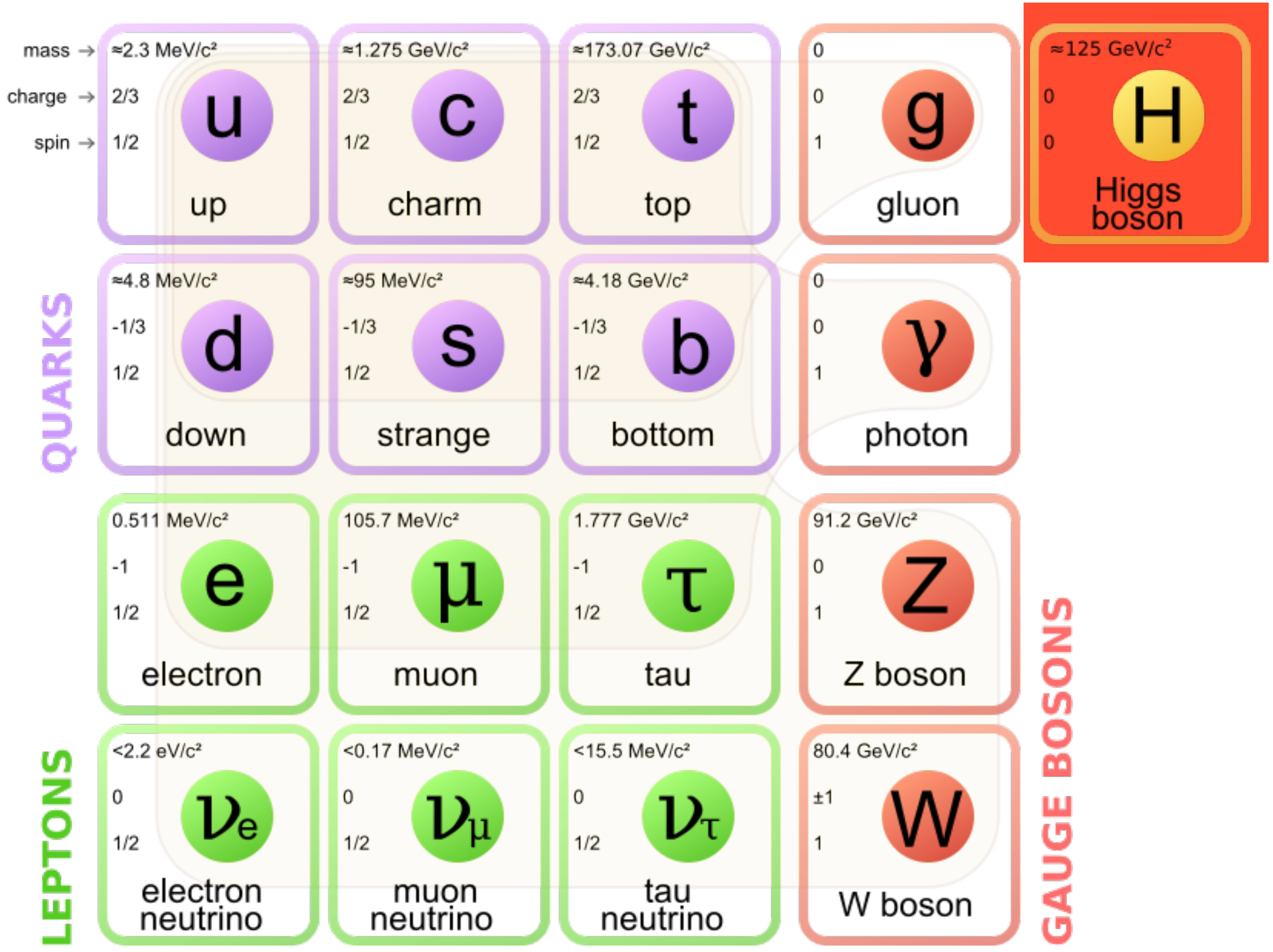
(dark matter, matter-antimatter asymmetry,
nature of dark energy, hierarchy of scales…)

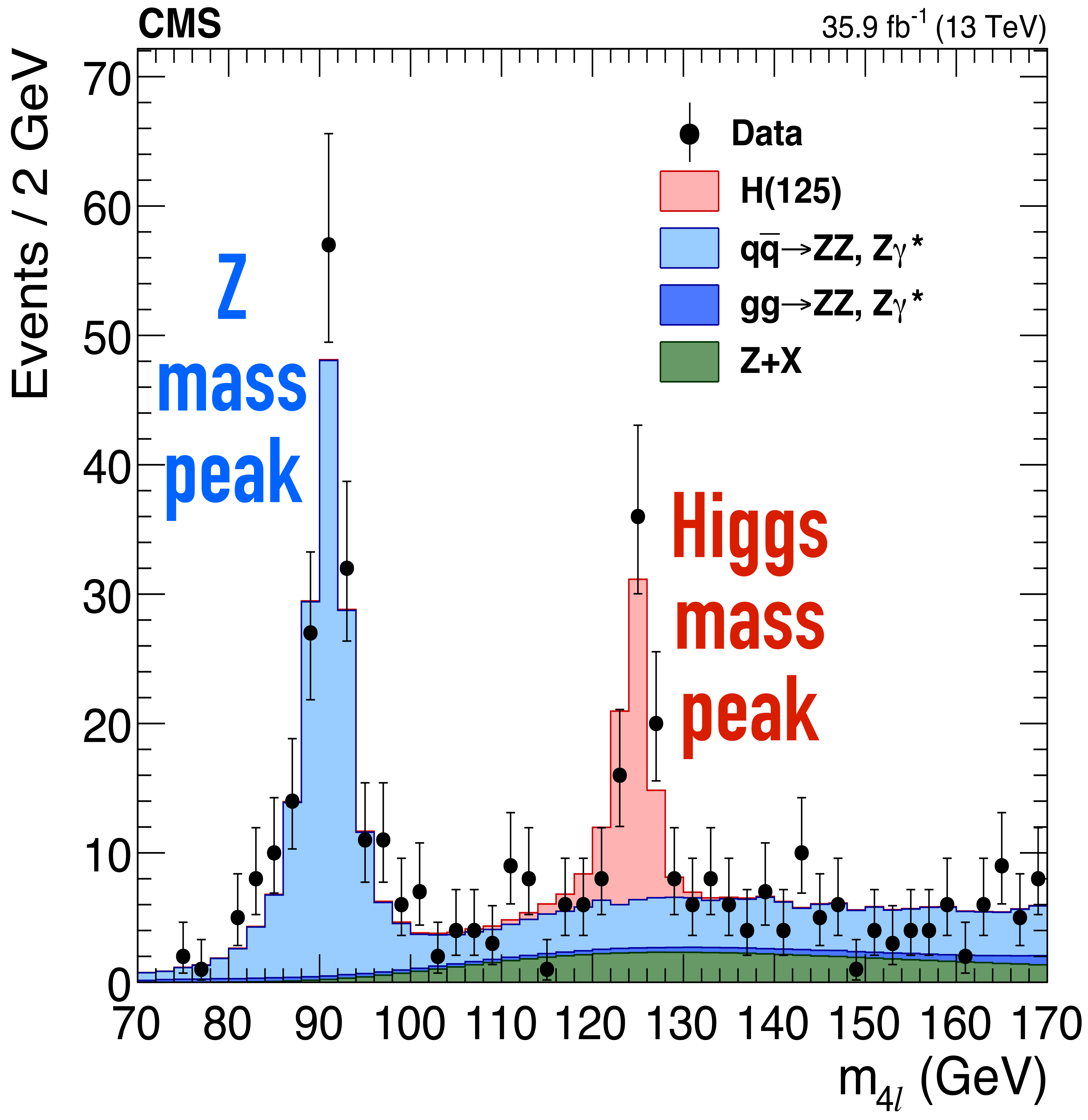
v.

“big answerable questions”

and how we go about answering them

The Higgs boson



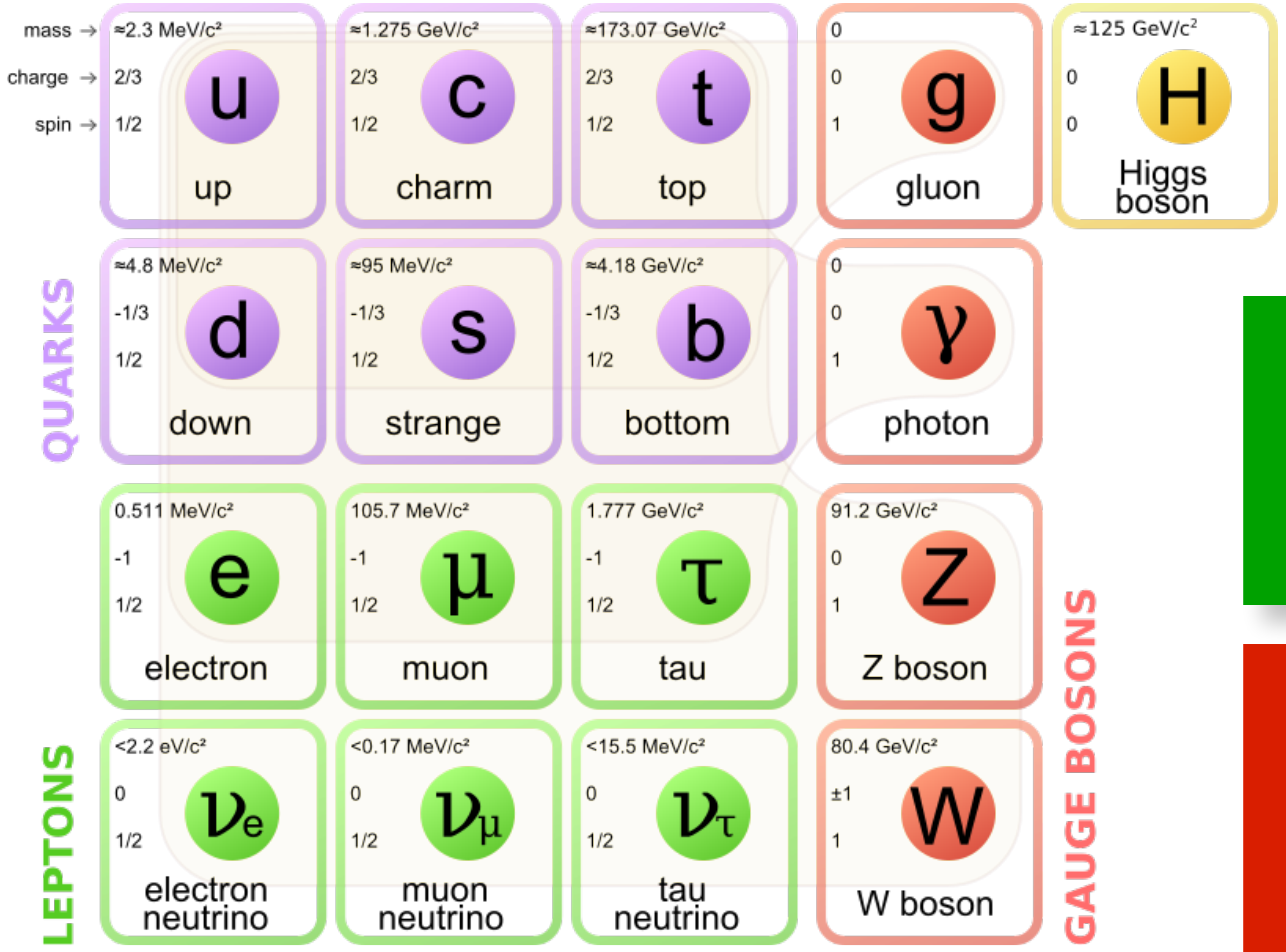


ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

2012 discovery of a Higgs-like boson

plot shows more recent data

The Higgs boson (2012)



Success!

“The Standard Model is complete”

Crisis!

No supersymmetry, no extra dimensions, there’s nothing left for us to do . . .

The New York Times

By DENNIS OVERBYE JUNE 19, 2017

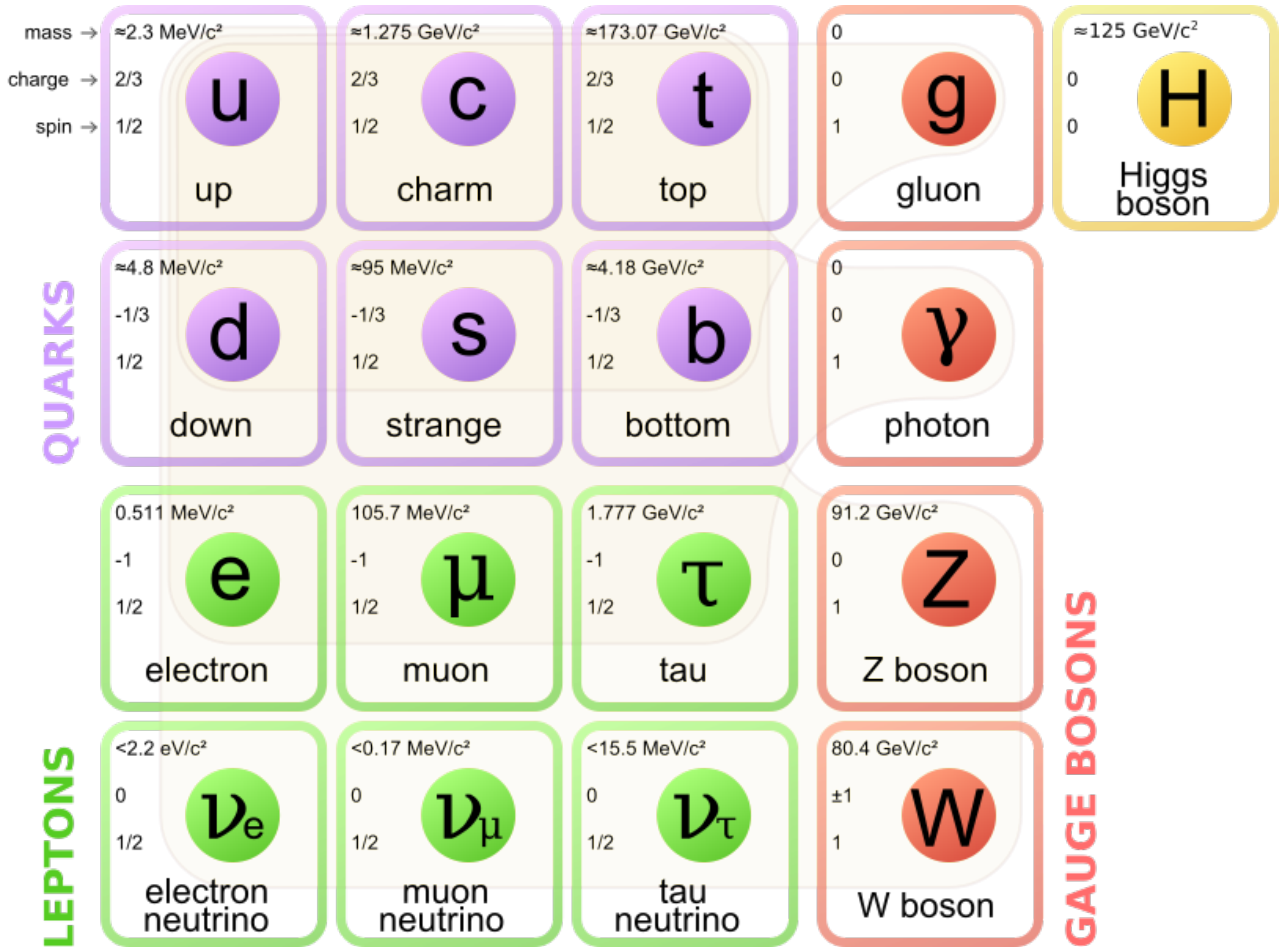
[…]

What if there is nothing new to discover? ***That prospect is now a cloud hanging over the physics community.***

[…]

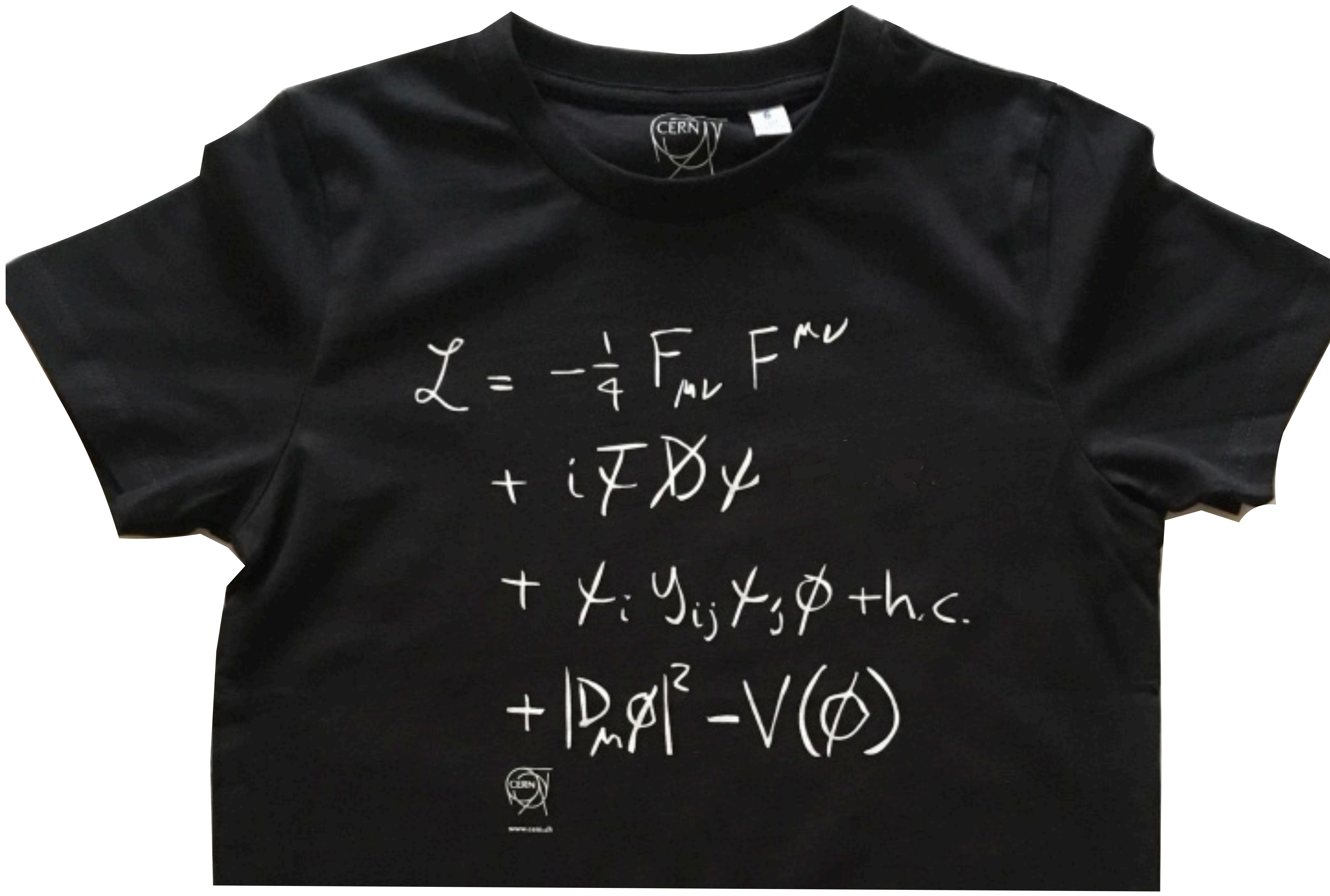
https://www.nytimes.com/2017/06/19/science/cern-large-hadron-collider-higgs-physics.html

what is the Standard Model?



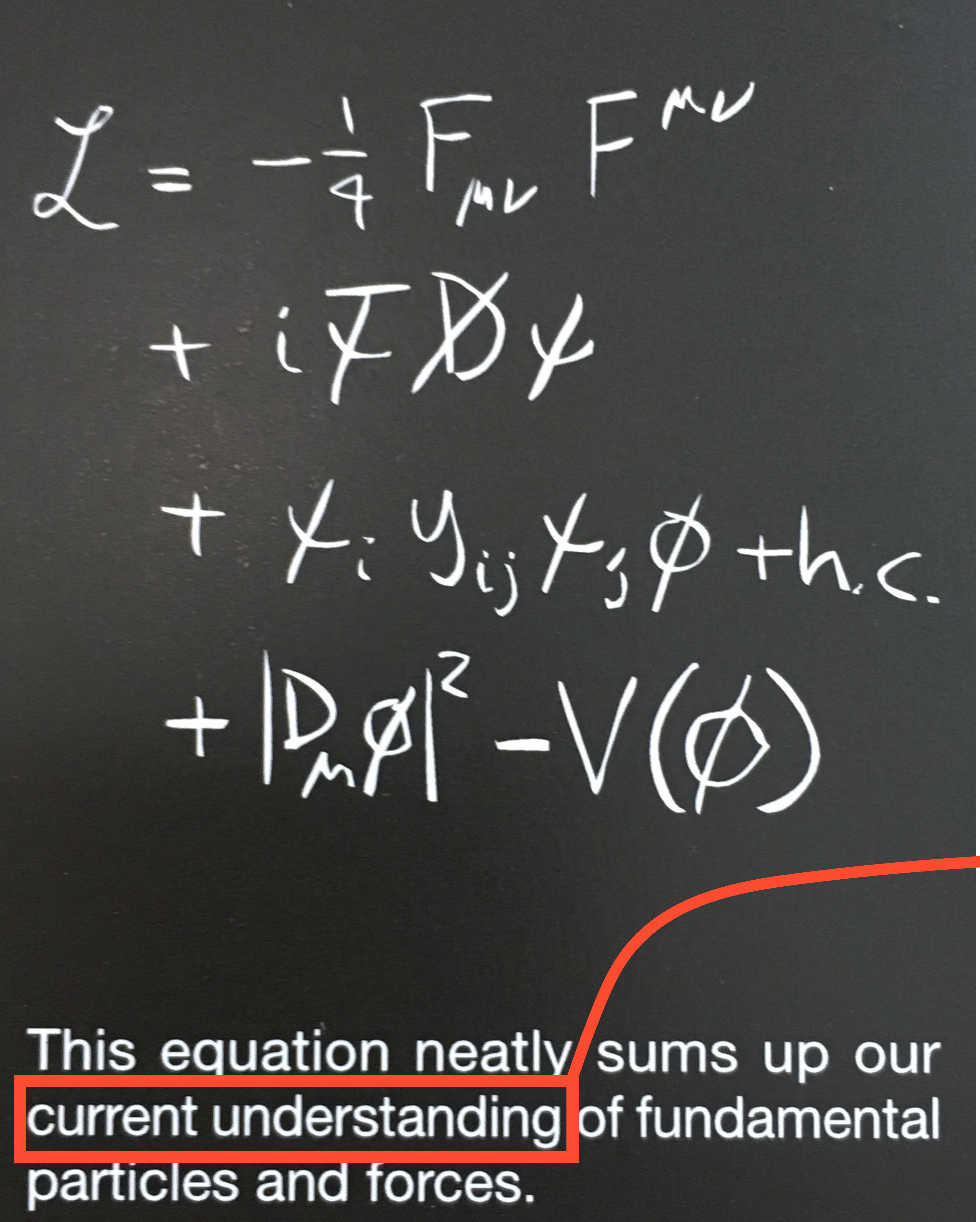
particles

+



interactions

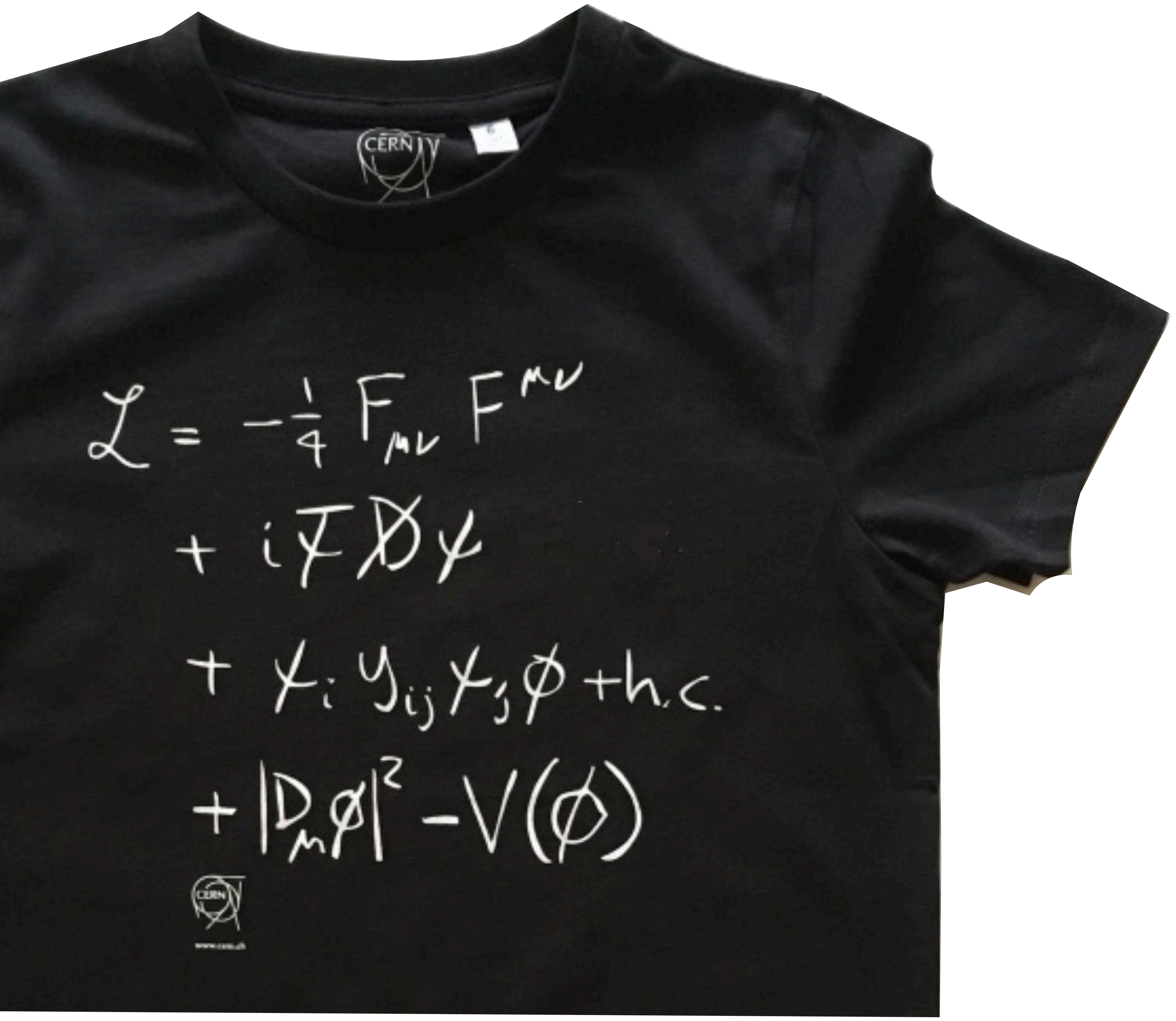
Standard Model — knowable unknowns



This is what you get when you buy one of those famous CERN T-shirts

"understanding" = knowledge ?

"understanding" = assumption ?



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Standard Model Lagrangian (including neutrino mass terms)
From *An Introduction to the Standard Model of Particle Physics, 2nd Edition*,
W. N. Cottingham and D. A. Greenwood, Cambridge University Press, Cambridge, 2007,
Extracted by J.A. Shifflett, updated from Particle Data Group tables at pdg.lbl.gov, 2 Feb 2015.

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)}\\
& +(\bar\nu_L,\bar e_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar e_R\sigma^\mu iD_\mu e_R + \bar\nu_R\sigma^\mu iD_\mu\nu_R + \text{(h.c.)} && \text{(lepton dynamical term)}\\
& -\frac{\sqrt2}{v}\left[(\bar\nu_L,\bar e_L)\,\phi M^e e_R + \bar e_R\bar M^e\bar\phi\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] && \text{(electron, muon, tauon mass term)}\\
& -\frac{\sqrt2}{v}\left[(-\bar e_L,\bar\nu_L)\,\phi^* M^\nu\nu_R + \bar\nu_R\bar M^\nu\phi^T\begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right] && \text{(neutrino mass term)}\\
& +(\bar u_L,\bar d_L)\,\tilde\sigma^\mu iD_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar u_R\sigma^\mu iD_\mu u_R + \bar d_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)}\\
& -\frac{\sqrt2}{v}\left[(\bar u_L,\bar d_L)\,\phi M^d d_R + \bar d_R\bar M^d\bar\phi\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] && \text{(down, strange, bottom mass term)}\\
& -\frac{\sqrt2}{v}\left[(-\bar d_L,\bar u_L)\,\phi^* M^u u_R + \bar u_R\bar M^u\phi^T\begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right] && \text{(up, charmed, top mass term)}\\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar\psi = \text{(h.c.)}\psi = \psi^\dagger = \psi^{*T}$, and the derivative operators are

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \tag{2}$$

$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R, \tag{3}$$

$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \tag{4}$$

ϕ is a 2-component complex Higgs field. Since $\mathcal{L}$ is $SU(2)$ gauge invariant, a gauge can be chosen so ϕ has the form

$$\phi^T = (0, v+h)/\sqrt2, \qquad <\phi>_0^T = \text{(expectation value of } \phi) = (0,v)/\sqrt2, \tag{5}$$

where v is a real constant such that $\mathcal{L}_\phi = \overline{(\partial_\mu\phi)}\partial^\mu\phi - m_h^2[\bar\phi\phi - v^2/2]^2/2v^2$ is minimized, and h is a residual Higgs field. B_μ, $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are the gauge boson vector potentials, and $\mathbf{W}_\mu$ and $\mathbf{G}_\mu$ are composed of 2×2 and 3×3 traceless Hermitian matrices. Their associated field tensors are

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu). \tag{6}$$

The non-matrix $A_\mu, Z_\mu, W_\mu^\pm$ bosons are mixtures of $\mathbf{W}_\mu$ and B_μ components, according to the weak mixing angle θ_w,

$$A_\mu = W_{11\mu}sin\theta_w + B_\mu cos\theta_w, \qquad Z_\mu = W_{11\mu}cos\theta_w - B_\mu sin\theta_w, \qquad W_\mu^+ = W_\mu^{-*} = W_{12\mu}/\sqrt2, \tag{7}$$

$$B_\mu = A_\mu cos\theta_w - Z_\mu sin\theta_w, \quad W_{11\mu} = -W_{22\mu} = A_\mu sin\theta_w + Z_\mu cos\theta_w, \quad W_{12\mu} = W_{21\mu}^* = \sqrt2\,W_\mu^+, \quad sin^2\theta_w = .2315(4). \tag{8}$$

The fermions include the leptons e_R, e_L, ν_R, ν_L and quarks u_R, u_L, d_R, d_L. They all have implicit 3-component generation indices, $e_i = (e,\mu,\tau)$, $\nu_i = (\nu_e,\nu_\mu,\nu_\tau)$, $u_i = (u,c,t)$, $d_i = (d,s,b)$, which contract into the fermion mass matrices $M_{ij}^e, M_{ij}^\nu, M_{ij}^u, M_{ij}^d$, and implicit 2-component indices which contract into the Pauli matrices,

$$\sigma^\mu = \left[\begin{pmatrix}1&0\\0&1\end{pmatrix}, \begin{pmatrix}0&1\\1&0\end{pmatrix}, \begin{pmatrix}0&-i\\i&0\end{pmatrix}, \begin{pmatrix}1&0\\0&-1\end{pmatrix}\right], \quad \tilde\sigma^\mu = [\sigma^0, -\sigma^1, -\sigma^2, -\sigma^3], \quad tr(\sigma^i) = 0, \quad \sigma^{\mu\dagger} = \sigma^\mu, \quad tr(\sigma^\mu\sigma^\nu) = 2\delta^{\mu\nu}. \tag{9}$$

The quarks also have implicit 3-component color indices which contract into $\mathbf{G}_\mu$. So $\mathcal{L}$ really has implicit sums over 3-component generation indices, 2-component Pauli indices, 3-component color indices in the quark terms, and 2-component $SU(2)$ indices in $(\bar\nu_L,\bar e_L)$, $(\bar u_L,\bar d_L)$, $(-\bar e_L,\bar\nu_L)$, $(-\bar d_L,\bar u_L)$, $\bar\phi$, $\mathbf{W}_\mu$, $\binom{\nu_L}{e_L}$, $\binom{u_L}{d_L}$, $\binom{-e_L}{\nu_L}$, $\binom{-d_L}{u_L}$, ϕ.

The electroweak and strong coupling constants, Higgs vacuum expectation value (VEV), and Higgs mass are,

$$g_1 = e/cos\theta_w, \quad g_2 = e/sin\theta_w, \quad g > 6.5e = g(m_\tau^2), \quad v = 246GeV(PDG) \approx \sqrt2\cdot180\,GeV(CG), \quad m_h = 125.02(30)GeV \tag{10}$$

where $e = \sqrt{4\pi\alpha\hbar c} = \sqrt{4\pi/137}$ in natural units. Using (4,5) and rewriting some things gives the mass of $A_\mu, Z_\mu, W_\mu^\pm$,

$$-\frac14 B_{\mu\nu}B^{\mu\nu} - \frac18 tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) = -\frac14 A_{\mu\nu}A^{\mu\nu} - \frac14 Z_{\mu\nu}Z^{\mu\nu} - \frac12\mathcal{W}_{\mu\nu}^-\mathcal{W}^{+\mu\nu} + \begin{pmatrix}\text{higher}\\ \text{order terms}\end{pmatrix}, \tag{11}$$

$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu, \quad \mathcal{W}_{\mu\nu}^\pm = D_\mu W_\nu^\pm - D_\nu W_\mu^\pm, \quad D_\mu W_\nu^\pm = [\partial_\mu \pm ieA_\mu]W_\nu^\pm, \tag{12}$$

$$D_\mu <\phi>_0 = \frac{iv}{\sqrt2}\begin{pmatrix}g_2W_{12\mu}/2\\ g_1B_\mu/2 + g_2W_{22\mu}/2\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix}W_{12\mu}/\sqrt2\\ (B_\mu sin\theta_w/cos\theta_w + W_{22\mu})/\sqrt2\end{pmatrix} = \frac{ig_2v}{2}\begin{pmatrix}W_\mu^+\\ -Z_\mu/\sqrt2\,cos\theta_w\end{pmatrix}, \tag{13}$$

$$\Rightarrow \quad m_A = 0, \qquad m_{W^\pm} = g_2v/2 = 80.425(38)GeV, \qquad m_Z = g_2v/2cos\theta_w = 91.1876(21)GeV. \tag{14}$$

Ordinary 4-component Dirac fermions are composed of the left and right handed 2-component fields,

$$e = \begin{pmatrix}e_{L1}\\ e_{R1}\end{pmatrix}, \ \nu_e = \begin{pmatrix}\nu_{L1}\\ \nu_{R1}\end{pmatrix}, \ u = \begin{pmatrix}u_{L1}\\ u_{R1}\end{pmatrix}, \ d = \begin{pmatrix}d_{L1}\\ d_{R1}\end{pmatrix}, \quad \text{(electron, electron neutrino, up and down quark)} \tag{15}$$

$$\mu = \begin{pmatrix}e_{L2}\\ e_{R2}\end{pmatrix}, \ \nu_\mu = \begin{pmatrix}\nu_{L2}\\ \nu_{R2}\end{pmatrix}, \ c = \begin{pmatrix}u_{L2}\\ u_{R2}\end{pmatrix}, \ s = \begin{pmatrix}d_{L2}\\ d_{R2}\end{pmatrix}, \quad \text{(muon, muon neutrino, charmed and strange quark)} \tag{16}$$

$$\tau = \begin{pmatrix}e_{L3}\\ e_{R3}\end{pmatrix}, \ \nu_\tau = \begin{pmatrix}\nu_{L3}\\ \nu_{R3}\end{pmatrix}, \ t = \begin{pmatrix}u_{L3}\\ u_{R3}\end{pmatrix}, \ b = \begin{pmatrix}d_{L3}\\ d_{R3}\end{pmatrix}, \quad \text{(tauon, tauon neutrino, top and bottom quark)} \tag{17}$$

$$\gamma^\mu = \begin{pmatrix}0 & \sigma^\mu\\ \tilde\sigma^\mu & 0\end{pmatrix} \qquad \text{where} \ \ \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2Ig^{\mu\nu}. \quad \text{(Dirac gamma matrices in chiral representation)} \tag{18}$$

The corresponding antiparticles are related to the particles according to $\psi^c = -i\gamma^2\psi^*$ or $\psi_L^c = -i\sigma^2\psi_R^*$, $\psi_R^c = i\sigma^2\psi_L^*$. The fermion charges are the coefficients of A_μ when (8,10) are substituted into either the left or right handed derivative operators (2-4). The fermion masses are the singular values of the 3×3 fermion mass matrices M^ν, M^e, M^u, M^d,

$$M^e = \mathbf{U}_L^{e\dagger}\begin{pmatrix}m_e&0&0\\0&m_\mu&0\\0&0&m_\tau\end{pmatrix}\mathbf{U}_R^e, \ M^\nu = \mathbf{U}_L^{\nu\dagger}\begin{pmatrix}m_{\nu_e}&0&0\\0&m_{\nu_\mu}&0\\0&0&m_{\nu_\tau}\end{pmatrix}\mathbf{U}_R^\nu, \ M^u = \mathbf{U}_L^{u\dagger}\begin{pmatrix}m_u&0&0\\0&m_c&0\\0&0&m_t\end{pmatrix}\mathbf{U}_R^u, \ M^d = \mathbf{U}_L^{d\dagger}\begin{pmatrix}m_d&0&0\\0&m_s&0\\0&0&m_b\end{pmatrix}\mathbf{U}_R^d, \tag{19}$$

$$m_e = .510998910(13)MeV, \quad m_{\nu_e} \sim .001 - 2eV, \quad m_u = 1.7 - 3.1MeV, \quad m_d = 4.1 - 5.7MeV, \tag{20}$$

$$m_\mu = 105.658367(4)MeV, \quad m_{\nu_\mu} \sim .001 - 2eV, \quad m_c = 1.18 - 1.34GeV, \quad m_s = 80 - 130MeV, \tag{21}$$

$$m_\tau = 1776.84(17)MeV, \quad m_{\nu_\tau} \sim .001 - 2eV, \quad m_t = 171.4 - 174.4GeV, \quad m_b = 4.13 - 4.37GeV, \tag{22}$$

where the $\mathbf{U}$s are 3×3 unitary matrices ($\mathbf{U}^{-1} = \mathbf{U}^\dagger$). Consequently the "true fermions" with definite masses are actually linear combinations of those in $\mathcal{L}$, or conversely the fermions in $\mathcal{L}$ are linear combinations of the true fermions,

$$e_L' = \mathbf{U}_L^e e_L, \quad e_R' = \mathbf{U}_R^e e_R, \quad \nu_L' = \mathbf{U}_L^\nu\nu_L, \quad \nu_R' = \mathbf{U}_R^\nu\nu_R, \quad u_L' = \mathbf{U}_L^u u_L, \quad u_R' = \mathbf{U}_R^u u_R, \quad d_L' = \mathbf{U}_L^d d_L, \quad d_R' = \mathbf{U}_R^d d_R, \tag{23}$$

$$e_L = \mathbf{U}_L^{e\dagger}e_L', \quad e_R = \mathbf{U}_R^{e\dagger}e_R', \quad \nu_L = \mathbf{U}_L^{\nu\dagger}\nu_L', \quad \nu_R = \mathbf{U}_R^{\nu\dagger}\nu_R', \quad u_L = \mathbf{U}_L^{u\dagger}u_L', \quad u_R = \mathbf{U}_R^{u\dagger}u_R', \quad d_L = \mathbf{U}_L^{d\dagger}d_L', \quad d_R = \mathbf{U}_R^{d\dagger}d_R'. \tag{24}$$

When $\mathcal{L}$ is written in terms of the true fermions, the $\mathbf{U}$s fall out except in $\bar u_L'\mathbf{U}_L^u\tilde\sigma^\mu W_\mu^\pm\mathbf{U}_L^{d\dagger}d_L'$ and $\bar\nu_L'\mathbf{U}_L^\nu\tilde\sigma^\mu W_\mu^\pm\mathbf{U}_L^{e\dagger}e_L'$. Because of this, and some absorption of constants into the fermion fields, all the parameters in the $\mathbf{U}$s are contained in only four components of the Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}^q = \mathbf{U}_L^u\mathbf{U}_L^{d\dagger}$ and four components of the Pontecorvo-Maki-Nakagawa-Sakata matrix $\mathbf{V}^l = \mathbf{U}_L^\nu\mathbf{U}_L^{e\dagger}$. The unitary matrices $\mathbf{V}^q$ and $\mathbf{V}^l$ are often parameterized as

$$\mathbf{V} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}e^{-i\delta/2}&0&0\\0&1&0\\0&0&e^{i\delta/2}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}\\0&1&0\\-s_{13}&0&c_{13}\end{pmatrix}\begin{pmatrix}e^{i\delta/2}&0&0\\0&1&0\\0&0&e^{-i\delta/2}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}, \quad c_j = \sqrt{1-s_j^2}, \tag{25}$$

$$\delta^q = 69(4)\,\text{deg}, \quad s_{12}^q = 0.2253(7), \quad s_{23}^q = 0.041(1), \quad s_{13}^q = 0.0035(2), \tag{26}$$

$$\delta^l = ?, \quad s_{12}^l = 0.560(16), \quad s_{23}^l = 0.7(1), \quad s_{13}^l = 0.153(28). \tag{27}$$

$\mathcal{L}$ is invariant under a $U(1)\otimes SU(2)$ gauge transformation with $U^{-1} = U^\dagger$, $detU = 1$, θ real,

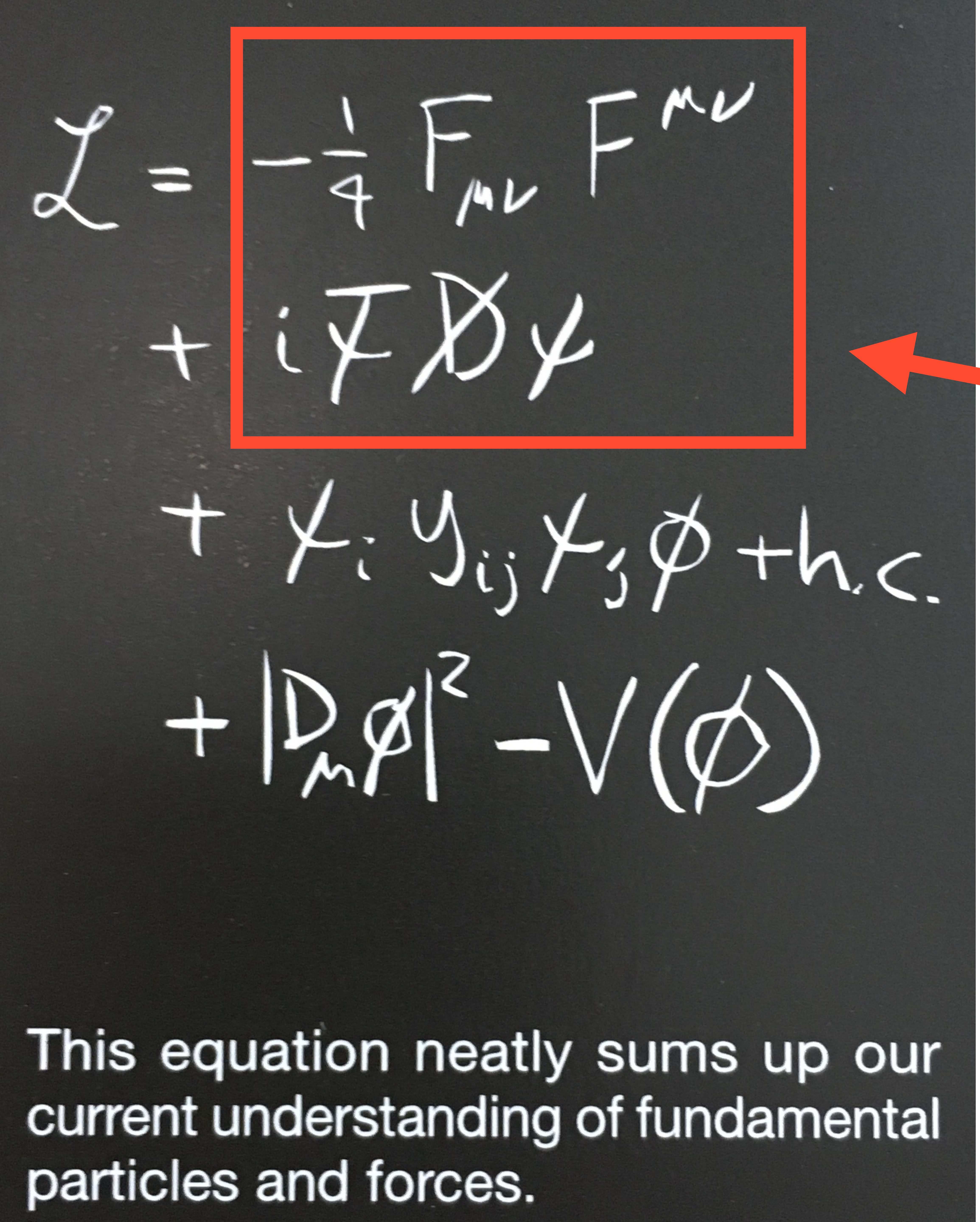
$$\mathbf{W}_\mu \to U\mathbf{W}_\mu U^\dagger - (2i/g_2)U\partial_\mu U^\dagger, \quad \mathbf{W}_{\mu\nu} \to U\mathbf{W}_{\mu\nu}U^\dagger, \quad B_\mu \to B_\mu + (2/g_1)\partial_\mu\theta, \quad B_{\mu\nu} \to B_{\mu\nu}, \quad \phi \to e^{-i\theta}U\phi, \tag{28}$$

$$\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} \to e^{i\theta}U\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad \begin{pmatrix}u_L\\ d_L\end{pmatrix} \to e^{-i\theta/3}U\begin{pmatrix}u_L\\ d_L\end{pmatrix}, \quad \begin{matrix}\nu_R \to \nu_R, & u_R \to e^{-4i\theta/3}u_R,\\ e_R \to e^{2i\theta}e_R, & d_R \to e^{2i\theta/3}d_R,\end{matrix} \tag{29}$$

and under an $SU(3)$ gauge transformation with $V^{-1} = V^\dagger$, $detV = 1$,

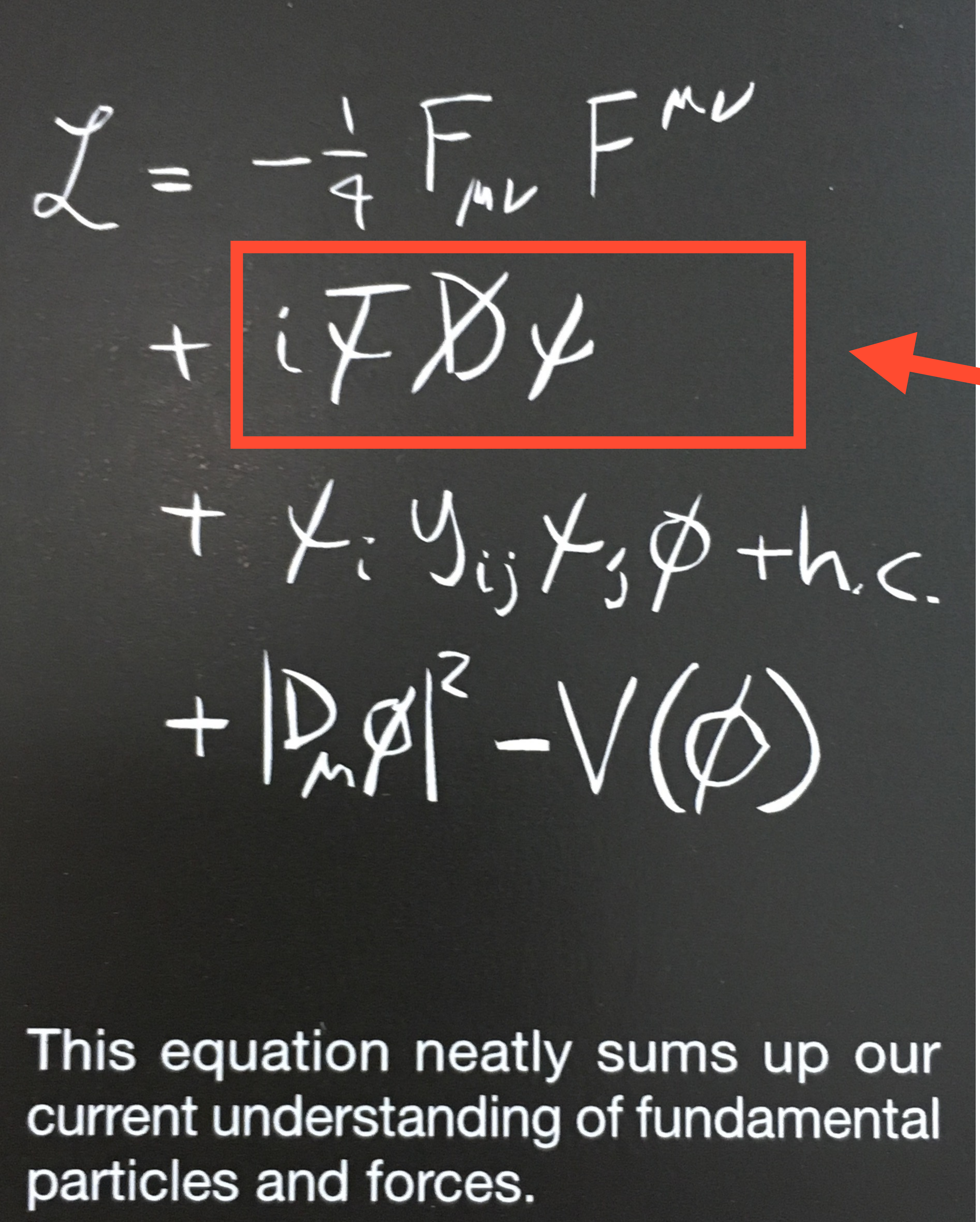
$$\mathbf{G}_\mu \to V\mathbf{G}_\mu V^\dagger - (i/g)V\partial_\mu V^\dagger, \quad \mathbf{G}_{\mu\nu} \to V\mathbf{G}_{\mu\nu}V^\dagger, \quad u_L \to Vu_L, \quad d_L \to Vd_L, \quad u_R \to Vu_R, \quad d_R \to Vd_R. \tag{30}$$

http://einstein-schrodinger.com/Standard_Model.pdf



What does it mean?

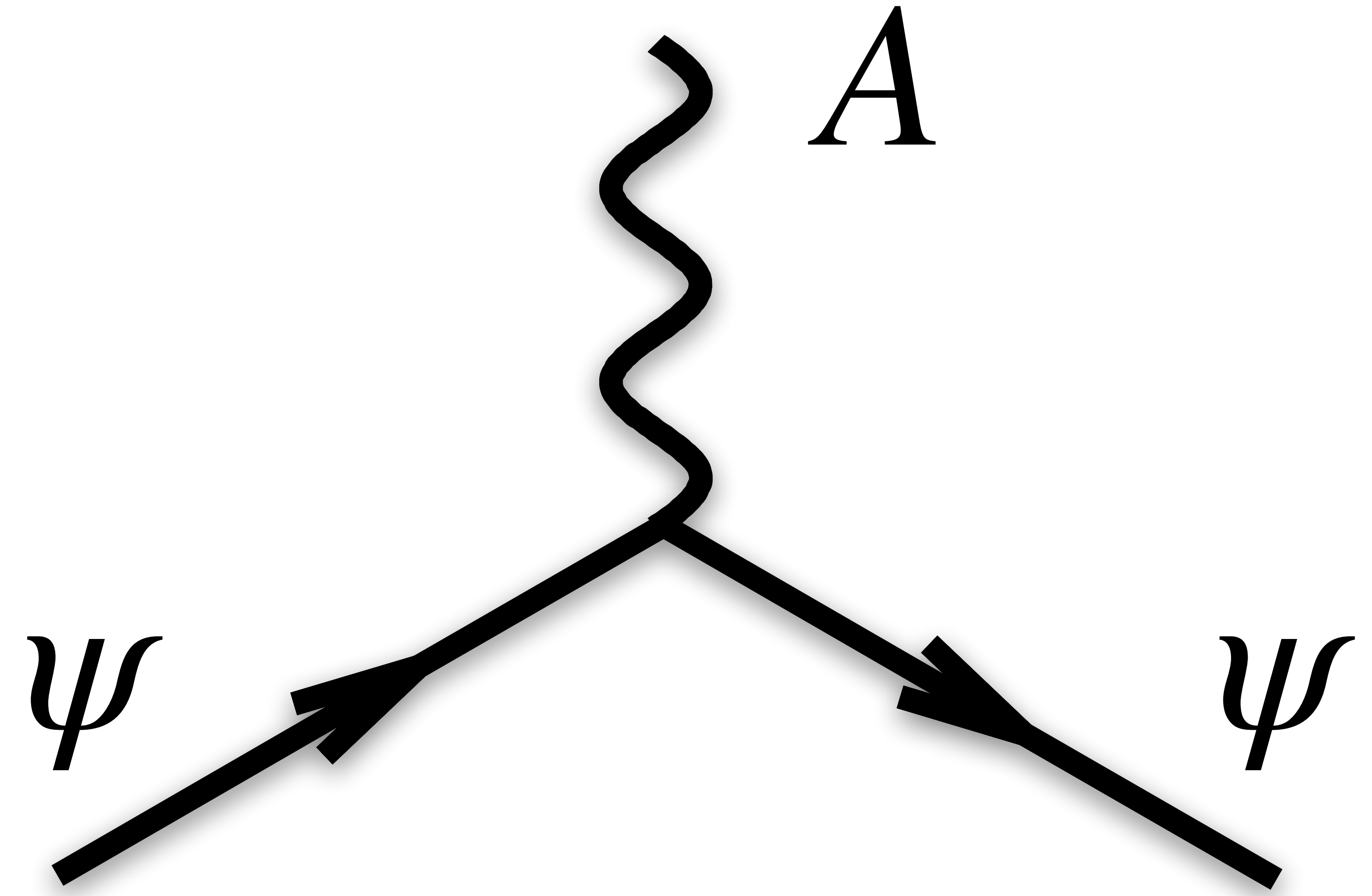
Quantum formulation of Maxwell's equations, (and their analogues for the weak and strong forces).



What does it mean?

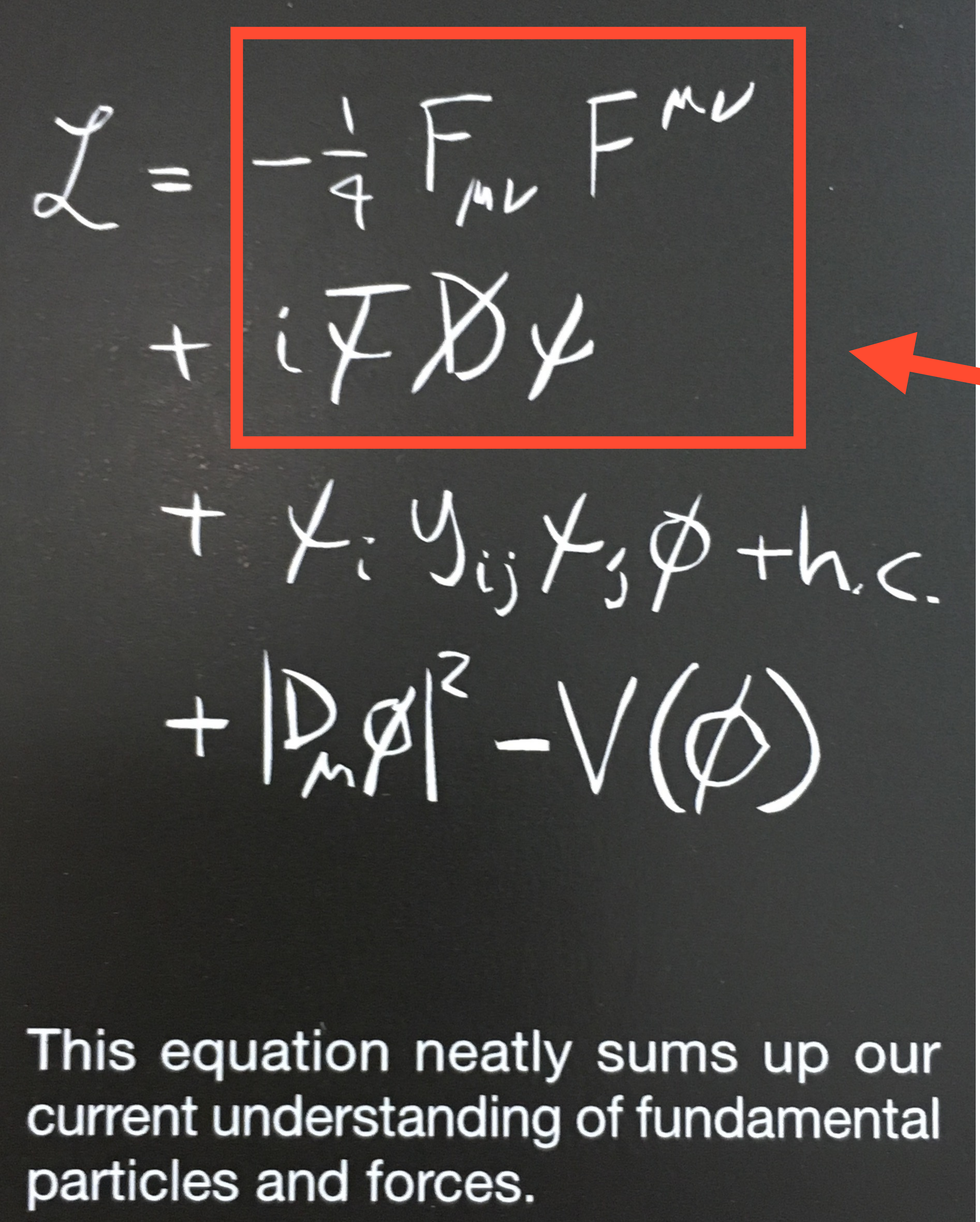
ψ = *fermion (e.g. electron) field*

$D \sim eA$(=*photon field*) $+ \cdots$



tells you there's an

electron-photon interaction vertex



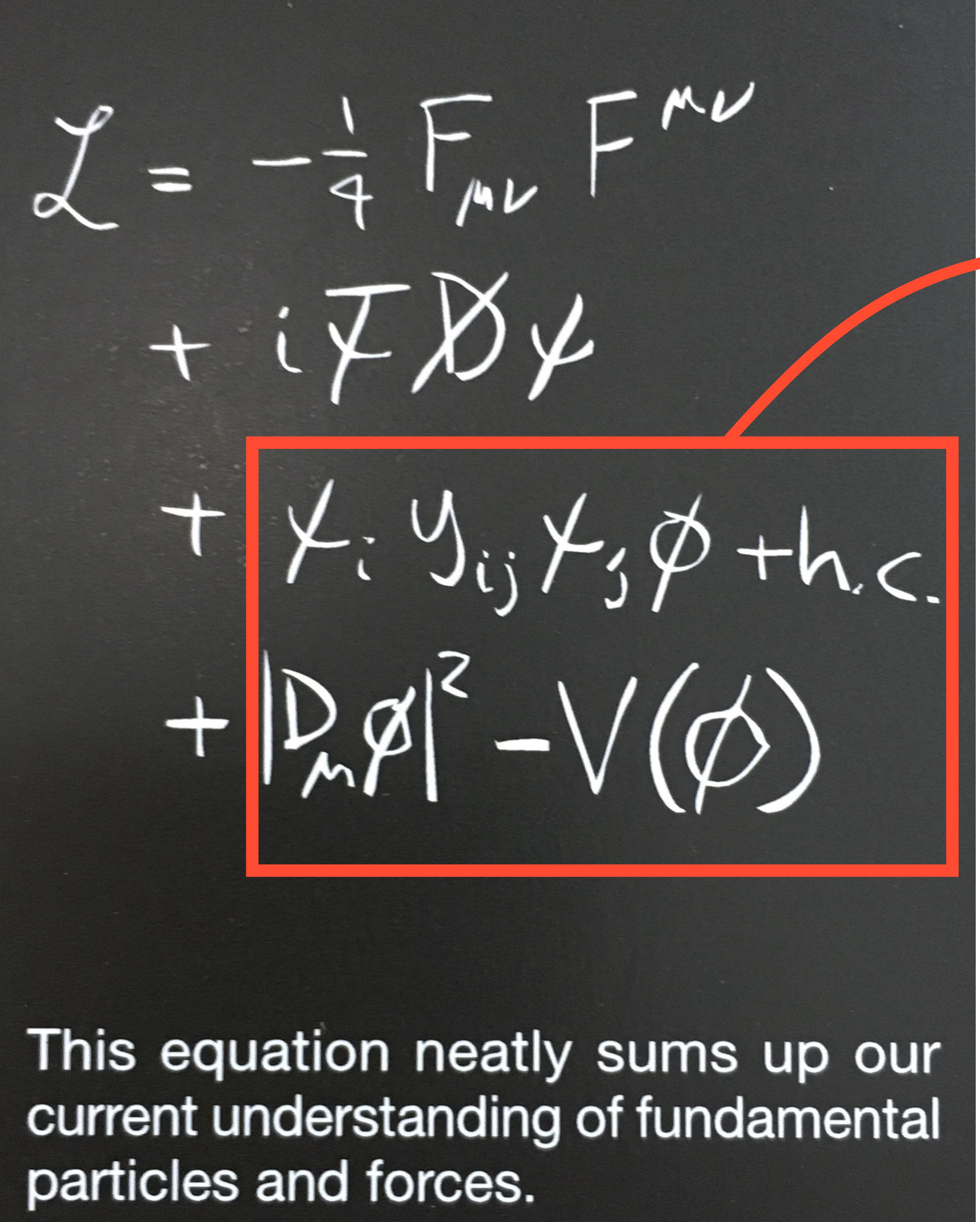
What does it mean?

many experiments have probed these so-called "gauge" interactions (in classical form, they date back to 1860s)

Describe electromagnetism, full electroweak theory & the strong force.

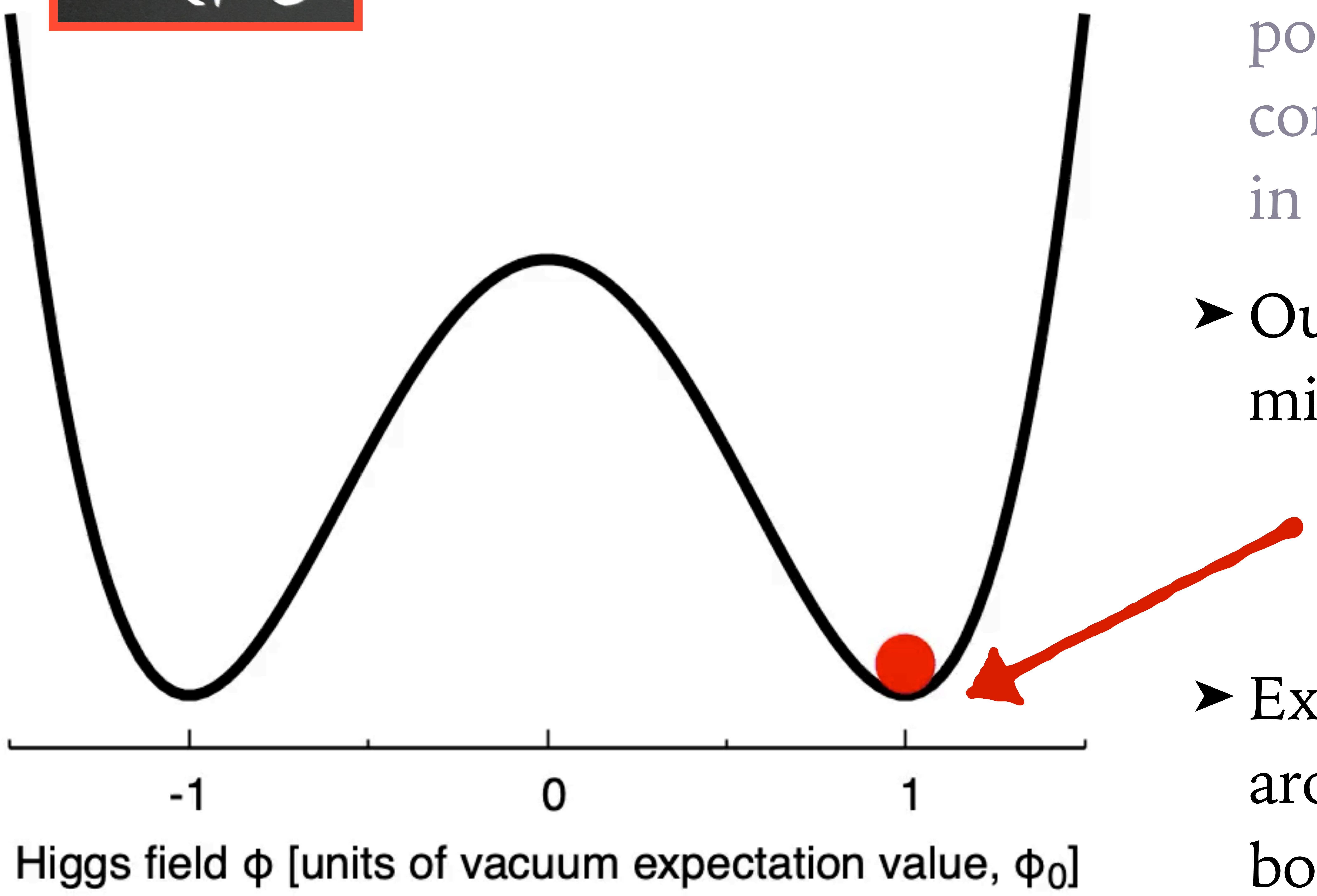
They work to high precision (best tests go up to 1 part in 10^8)

Higgs sector



until 7 years ago none of these terms had ever been directly observed.

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

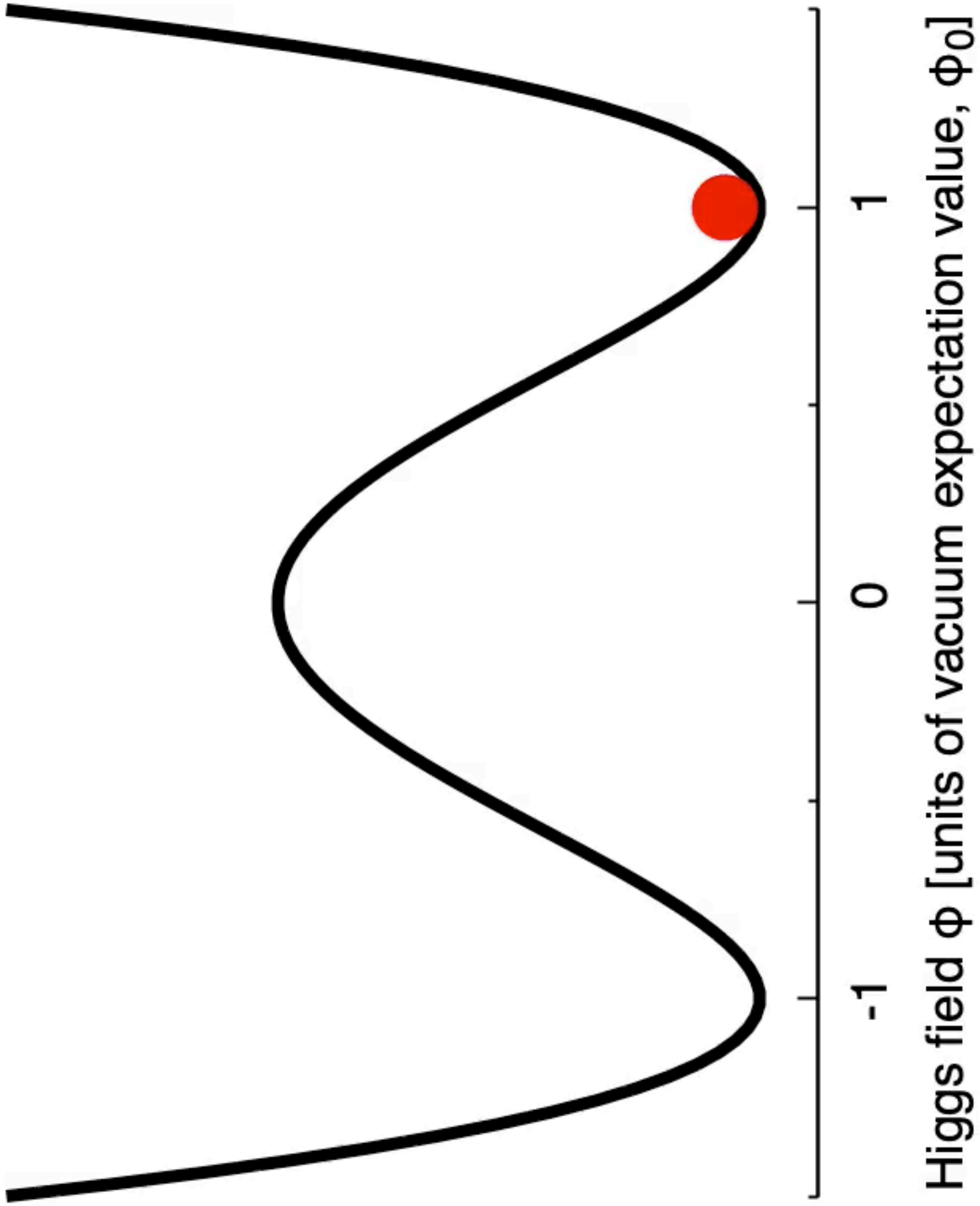


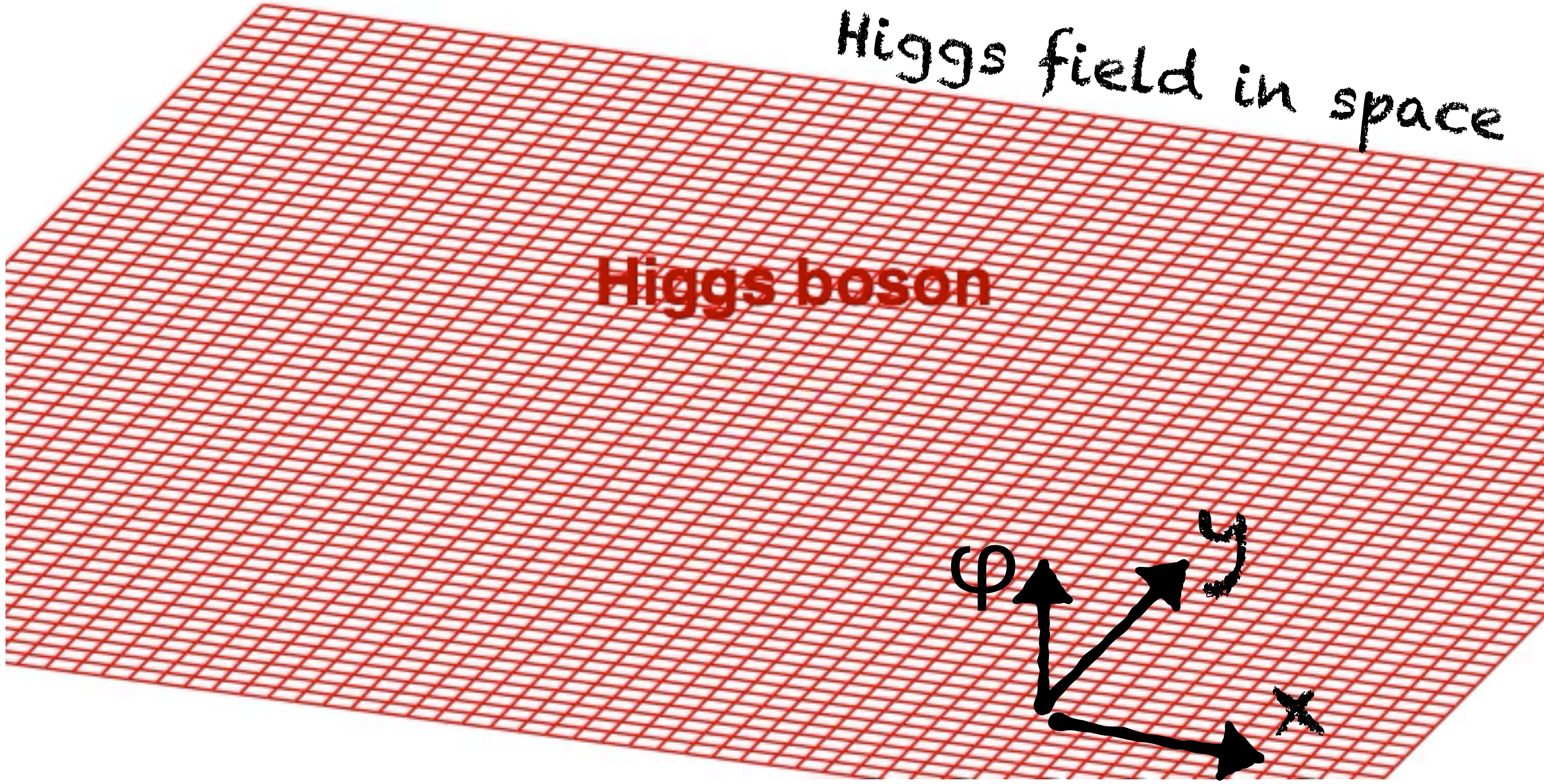
- φ is a field at every point in space (plot shows potential vs. 1 of 4 components, at 1 point in space)
- Our universe sits at minimum of V(φ), at

$$\phi = \phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$

- Excitation of the φ field around φ_0 is a Higgs boson ($\varphi = \varphi_0 + H$)

$$\varphi = \varphi_0 + H$$





Higgs field can be different at each point in space

A Higgs boson at a given point in space is a localised fluctuation of the field

$\varphi = \varphi_0 + H$

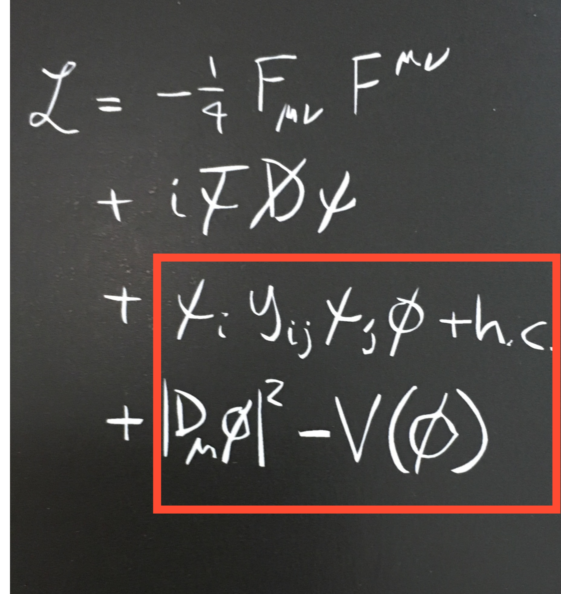
established

(2012 Higgs boson discovery)

$= -\mu^2\phi^2 + \lambda\phi^4$

hypothesis

what terms are there in the Higgs sector?
2. Gauge–Higgs term

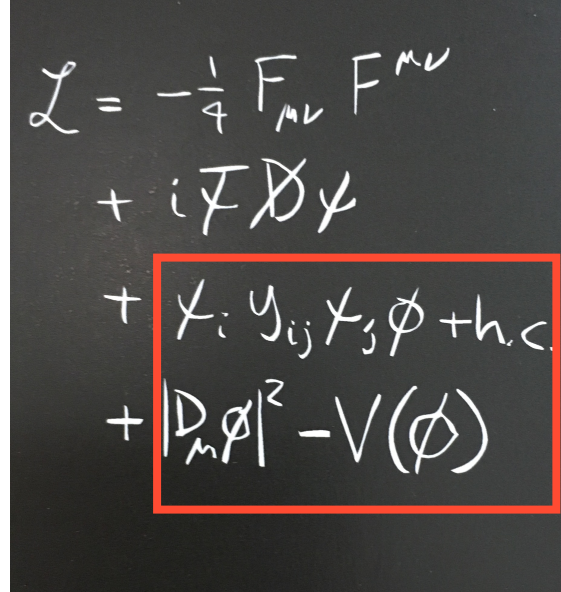


This equation neatly sums up our current understanding of fundamental particles and forces.

$$|D_\mu \phi|^2 \to \underbrace{g^2 \phi_0^2}_{\text{constants}} \underbrace{Z_\mu Z^\mu}_{\text{fields}} + \underbrace{2g^2 \phi_0}_{\text{constants}} \underbrace{H\, Z_\mu Z^\mu}_{\text{fields}} + \dots$$

Z-boson mass term

HZZ interaction term



This equation neatly sums up our current understanding of fundamental particles and forces.

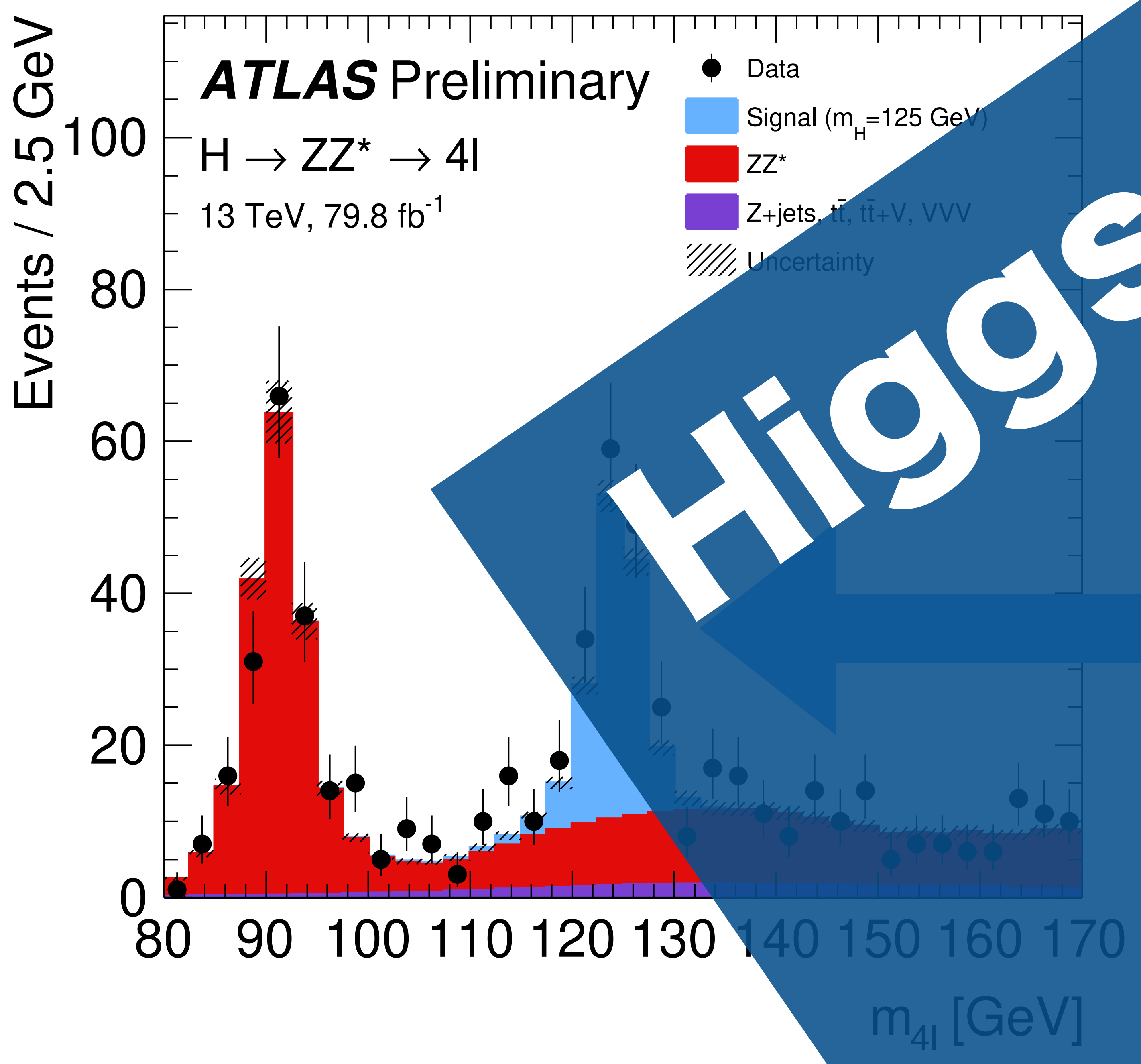
what terms are there in the Higgs sector?

2. Gauge-Higgs term

$$\rightarrow g^2 \phi_0^2 Z_\mu Z^\mu + 2g^2 \phi_0 H Z_\mu Z^\mu + \ldots$$

Z boson mass term *ZZH interaction term*

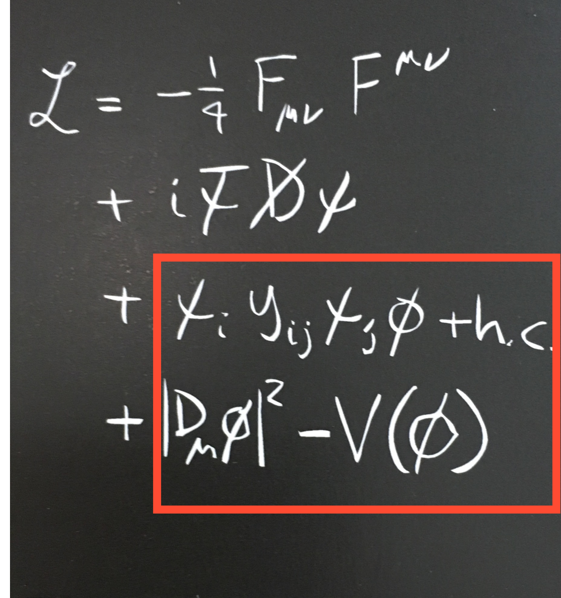
Higgs (BEH) mechanism for vector boson mass = 2013 Nobel prize



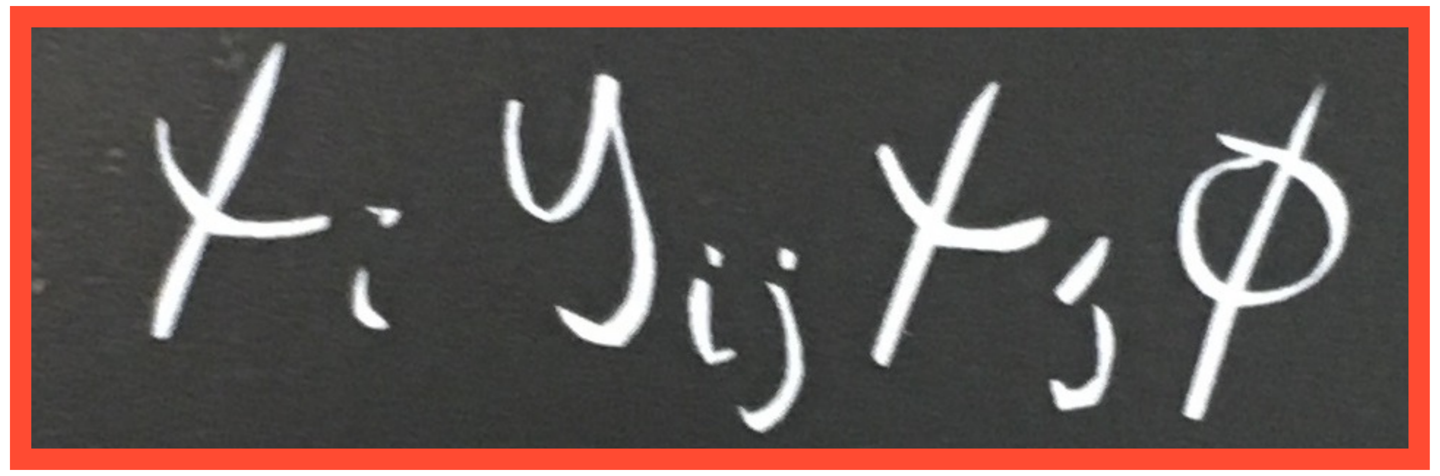
H → ZZ*

Higgs mechanism predicts specific relation between Z-boson mass and HZZ interaction

what terms are there in the Higgs sector?
3. Fermion–Higgs (Yukawa) term



This equation neatly sums up our current understanding of fundamental particles and forces.



$$\rightarrow \quad y_{ij}\,\phi_0\,\psi_i\,\psi_j \; + \; y_{ij}\,H\,\psi_i\,\psi_j$$

fermion mass term

$m_i = y_{ii}\phi_0$

Higgs-fermion-fermion interaction term; coupling $\sim y_{ii}$

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10$[illegible]
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1

ν_e		e	$3 \cdot 10^{-6}$
ν_μ	$\sim 10^{-13}$?	μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10^{-4}$

the subject of the next few slides

$$\phi = \phi_0 + H$$

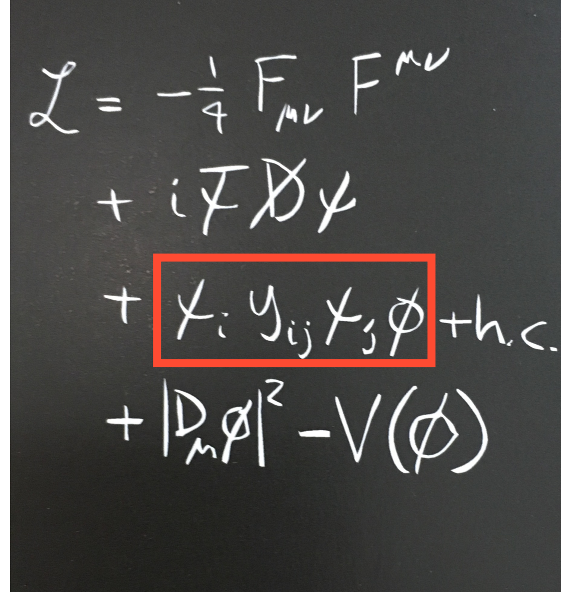
Yukawa interaction hypothesis

Yukawa couplings ~ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength is not quantised

(i.e. no underlying unit of charge across particles)

Why do Yukawa couplings matter?
(1) Because, within SM **conjecture**, they're what give masses to all **quarks**



This equation neatly sums up our current understanding of fundamental particles and forces.

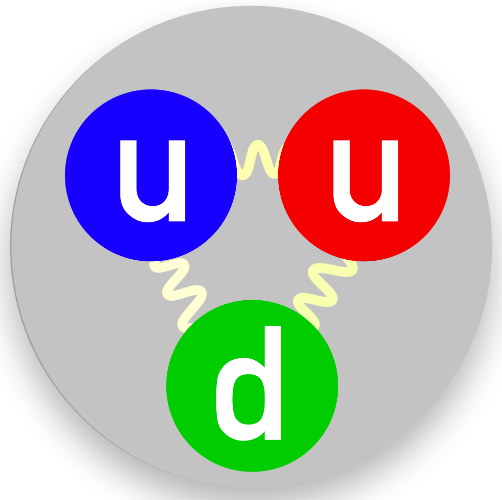
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

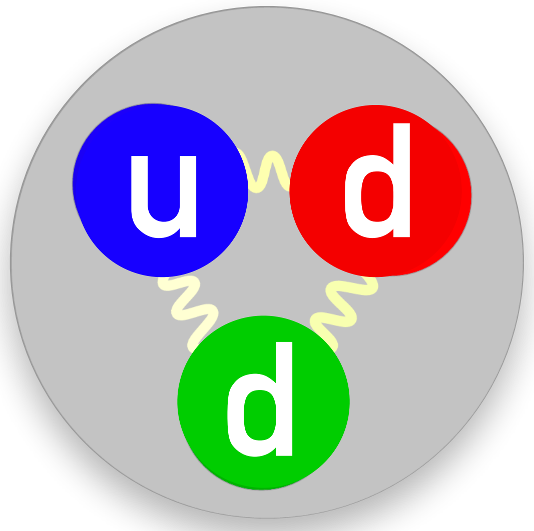
So protons are **lighter** than neutrons,
→ protons are stable.

Which gives us the hydrogen atom,
& chemistry and biology as we know it

proton
mass = 938.3MeV

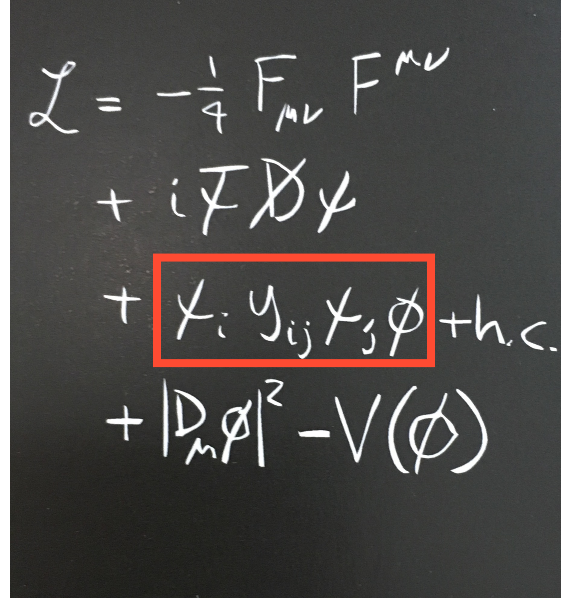


neutron
mass = 939.6MeV



Why do Yukawa couplings matter?

(2) Because, within SM **conjecture**, they're what give masses to all **leptons**



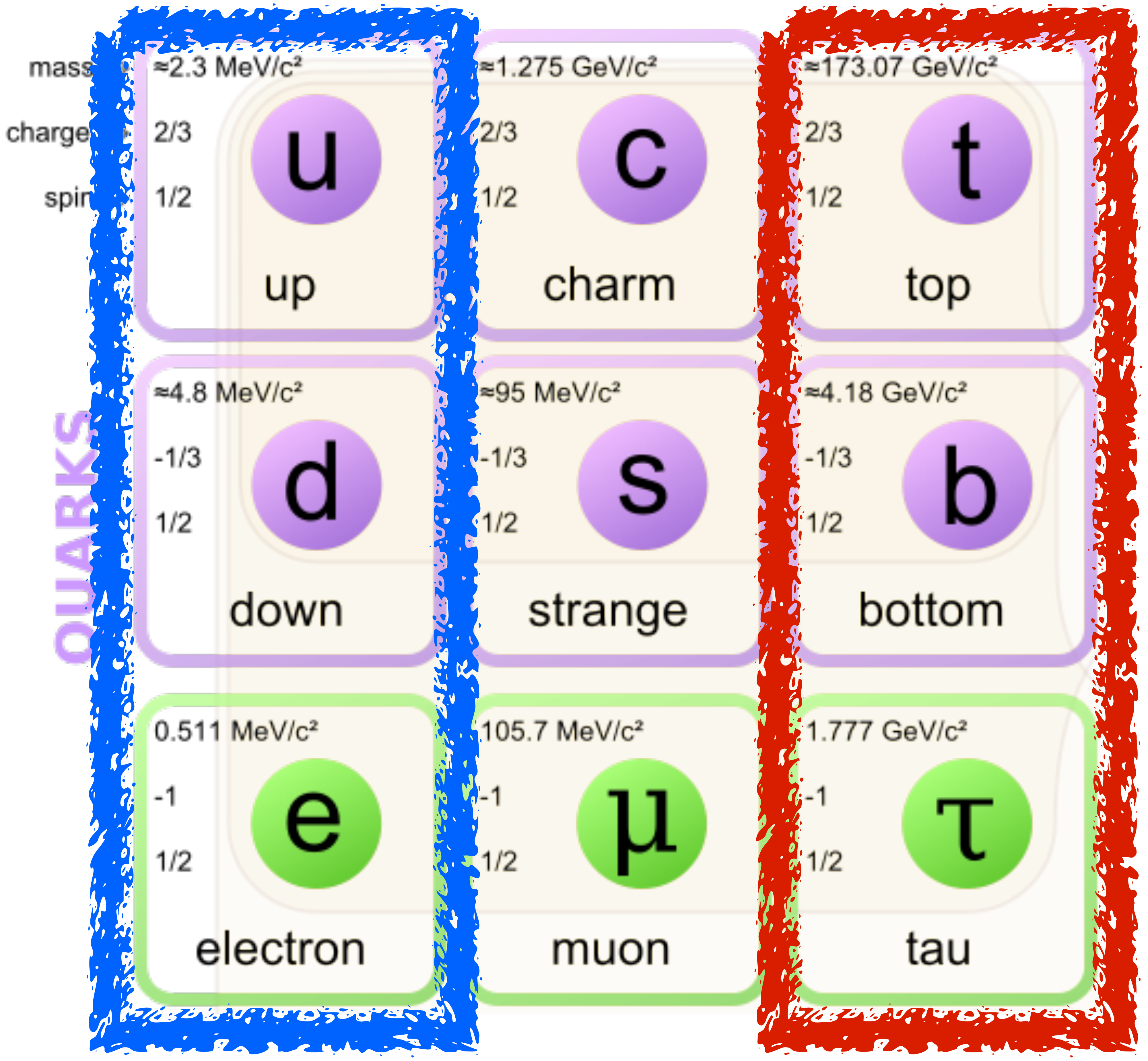
This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c\alpha} \propto \frac{1}{y_e}$$

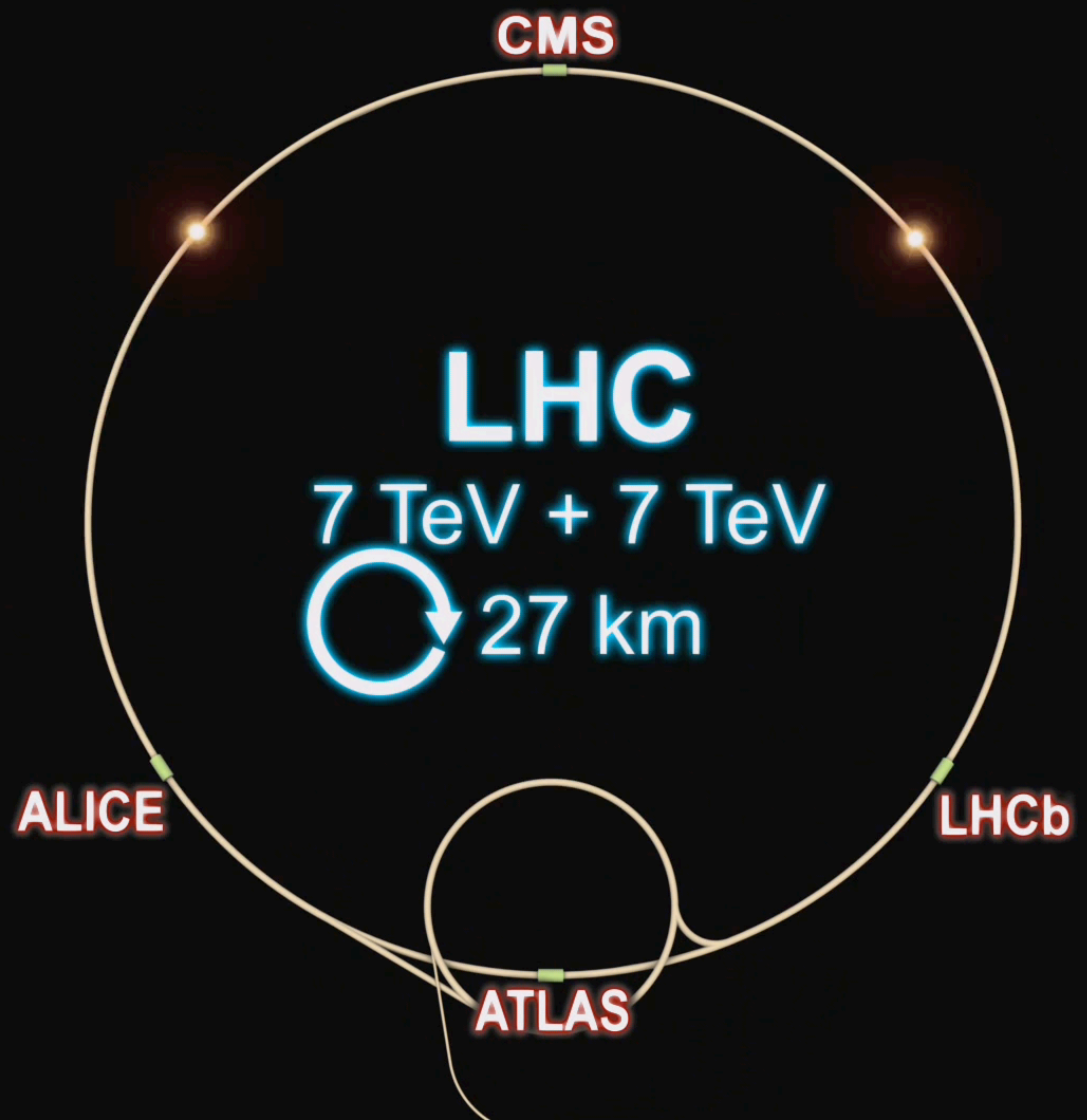
electron mass determines size of all atoms

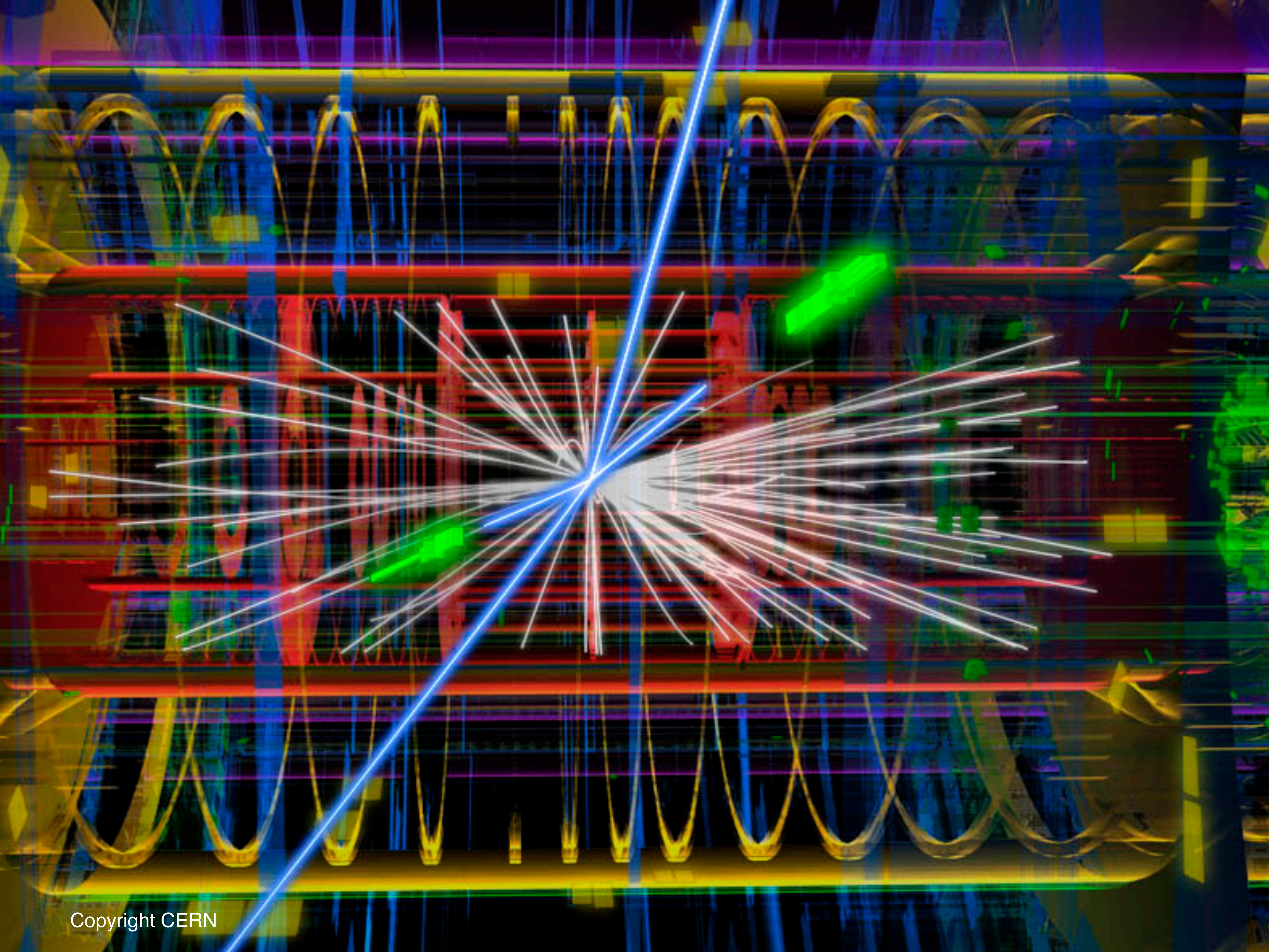
it sets energy levels of all chemical reactions



1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): too weak to test today

3rd generation (us) has high mass because of strong interactions with Higgs field (and so with Higgs bosons): can potentially be tested


CMS
LHC
7 TeV + 7 TeV
27 km
ALICE
LHCb
ATLAS



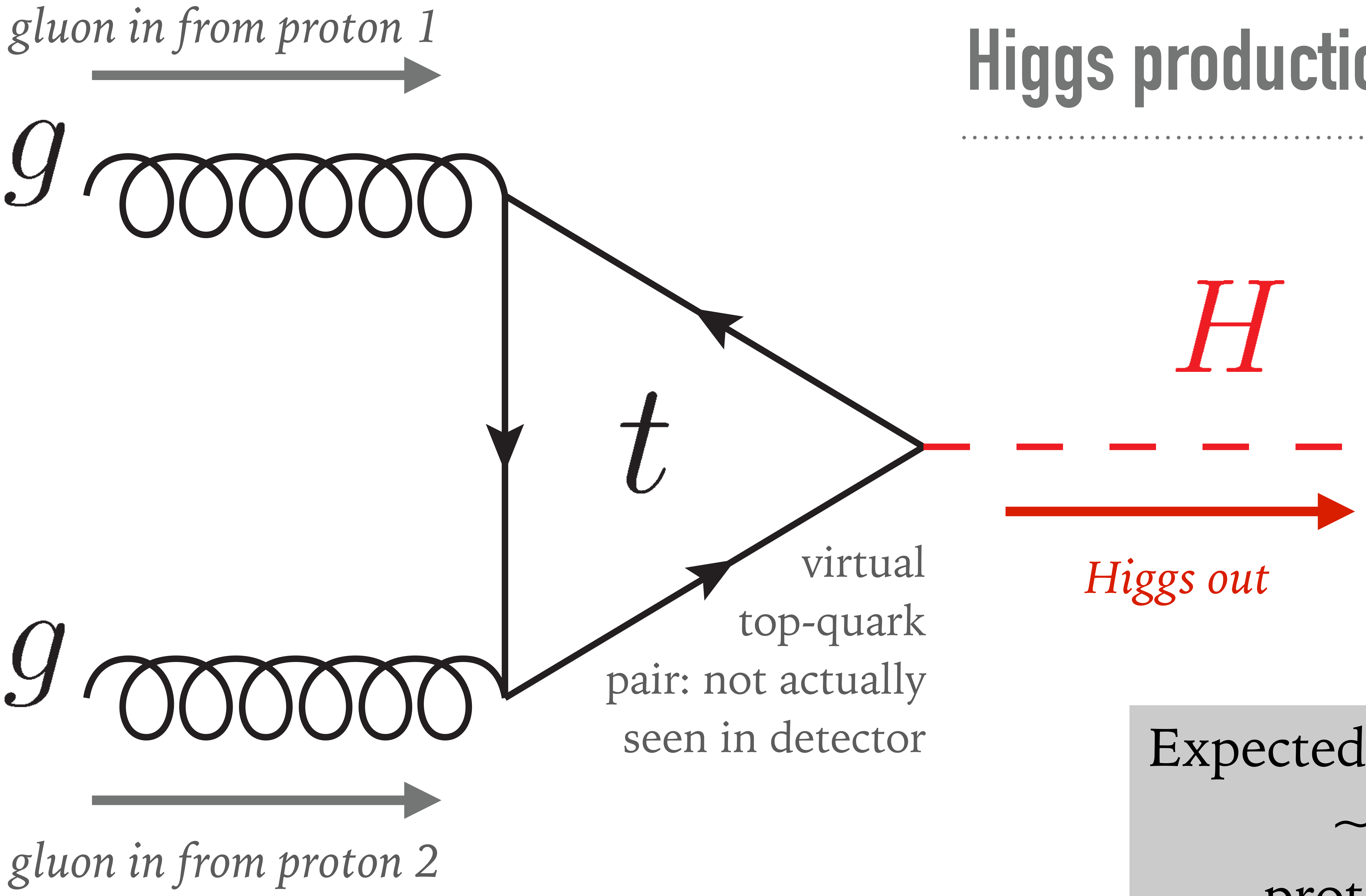
ATLAS & CMS
@LHC

~up to 2 billion collisions/second

(+ lower rates at LHCb and ALICE)

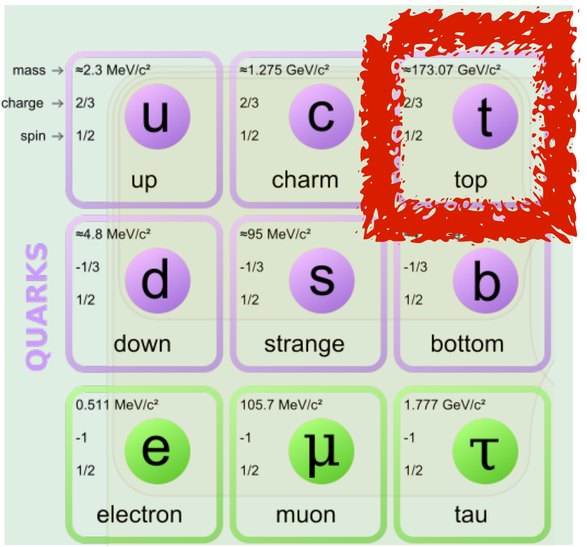
what underlying processes tell us about Yukawa interactions?

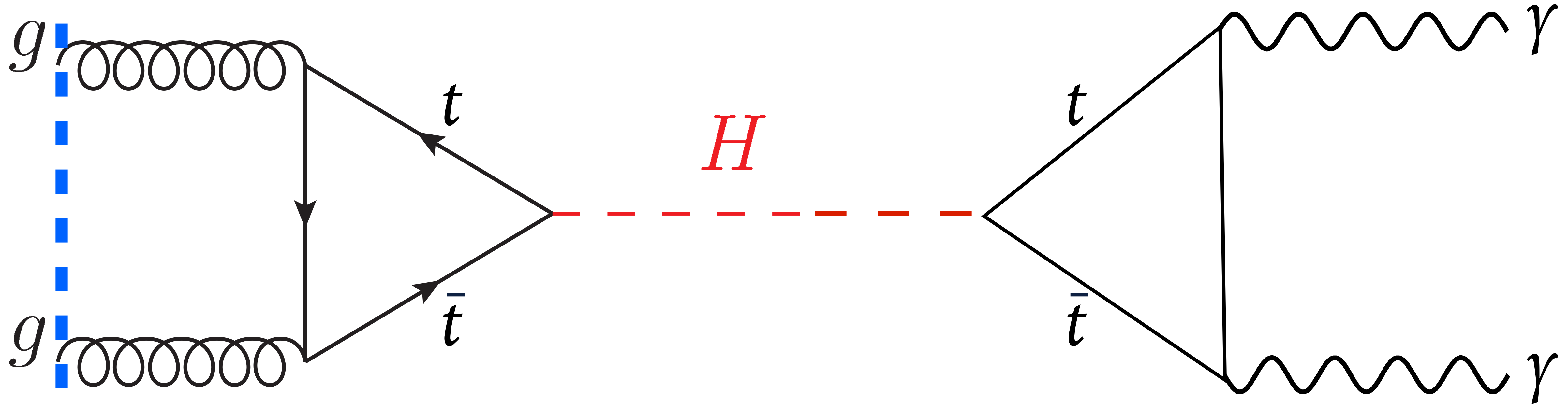
Higgs production: the dominant channel



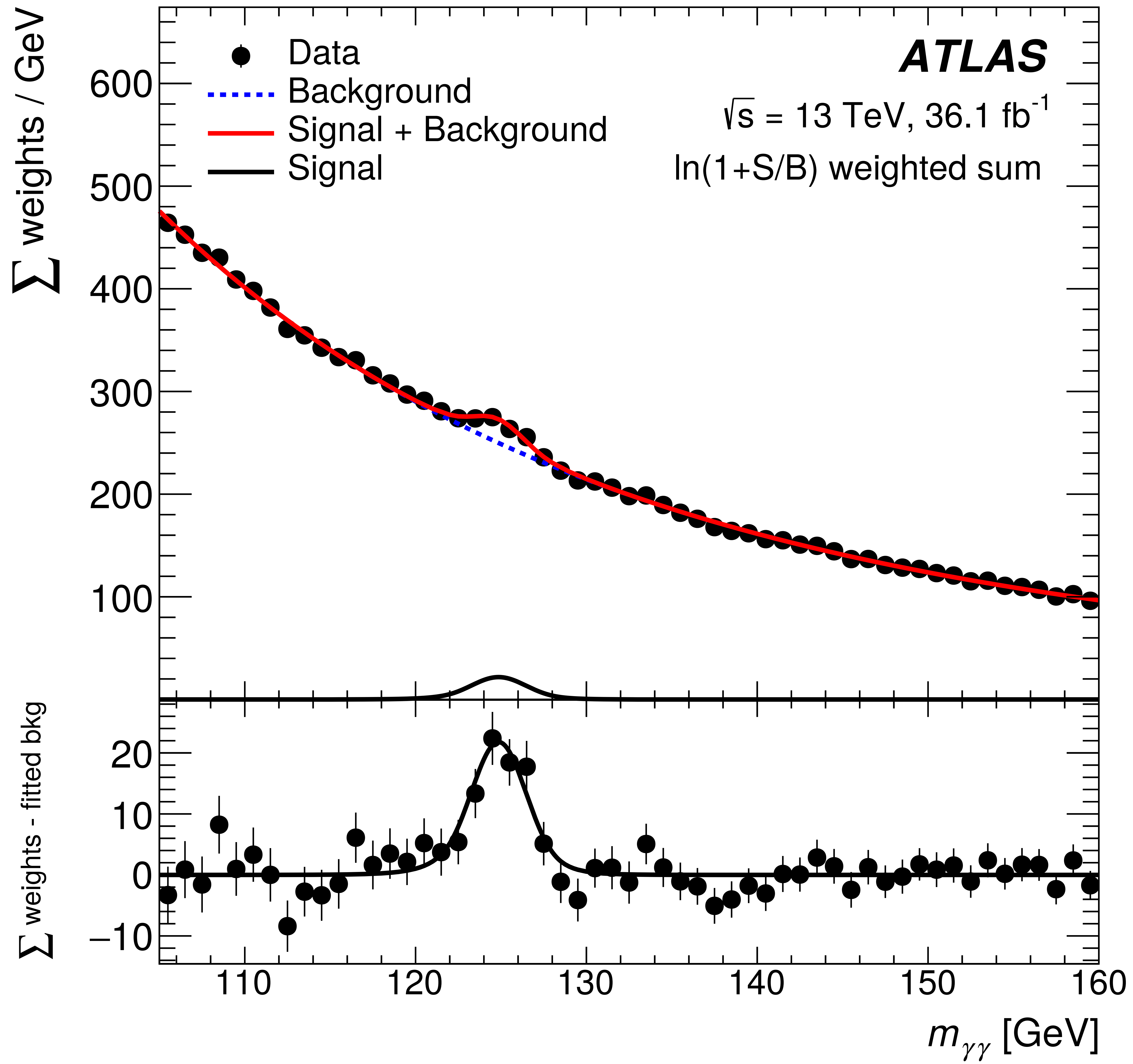
Expected to happen once for every ~2 billion inelastic proton–proton collisions

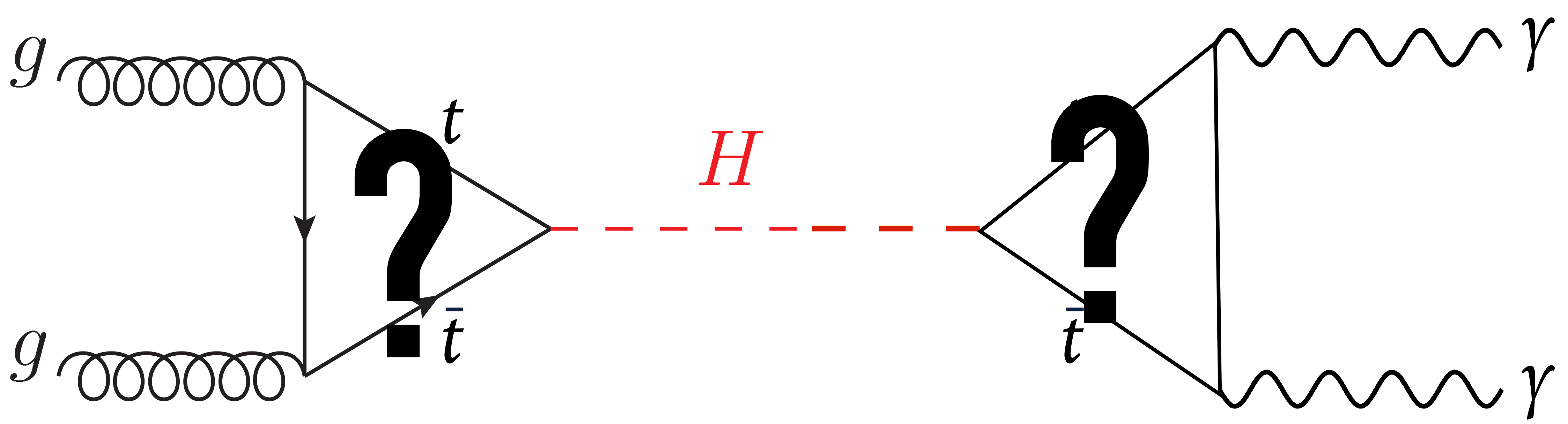
LHC data consistent with that already at discovery in 2012




g
g
t
t̄
H
t
t̄
γ
γ

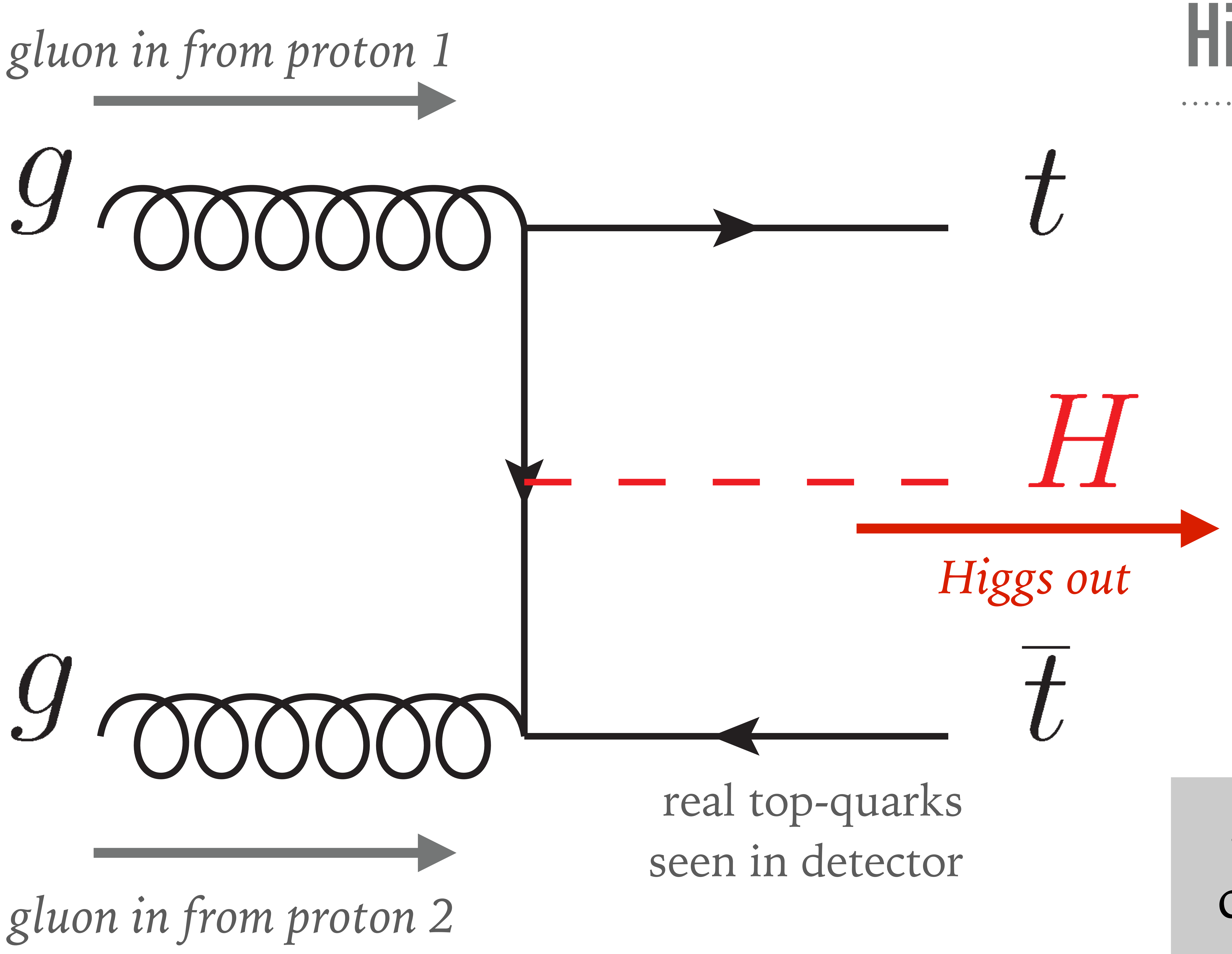

luon
gluo
φ
y
x
Higgs field in space





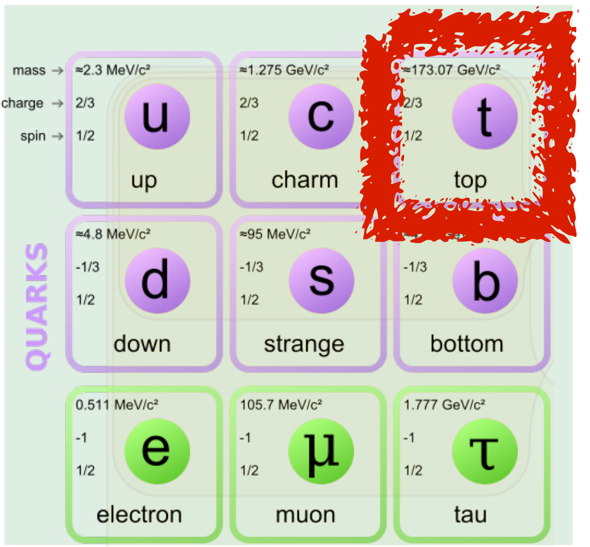
but how can you be sure the Higgs boson is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?

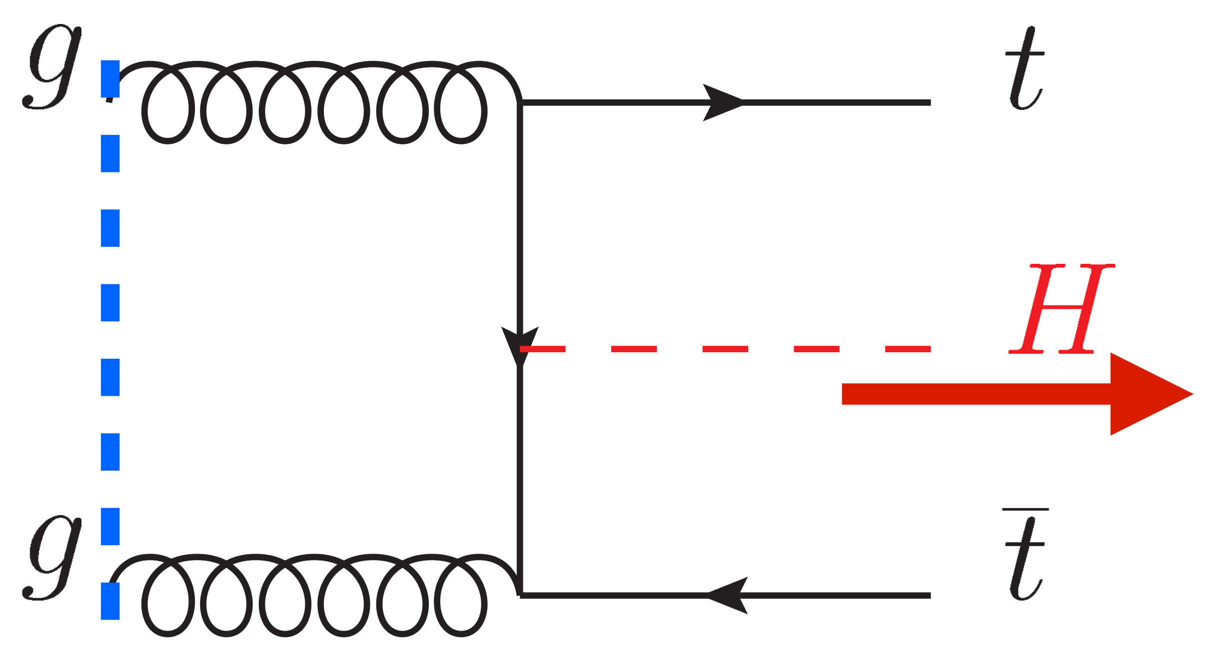
Higgs production: the ttH channel



If SM top-Yukawa hypothesis is correct, expect 1 Higgs for every 1600 top-quark pairs.

(rather than 1 Higgs for every 2 billion pp collisions)



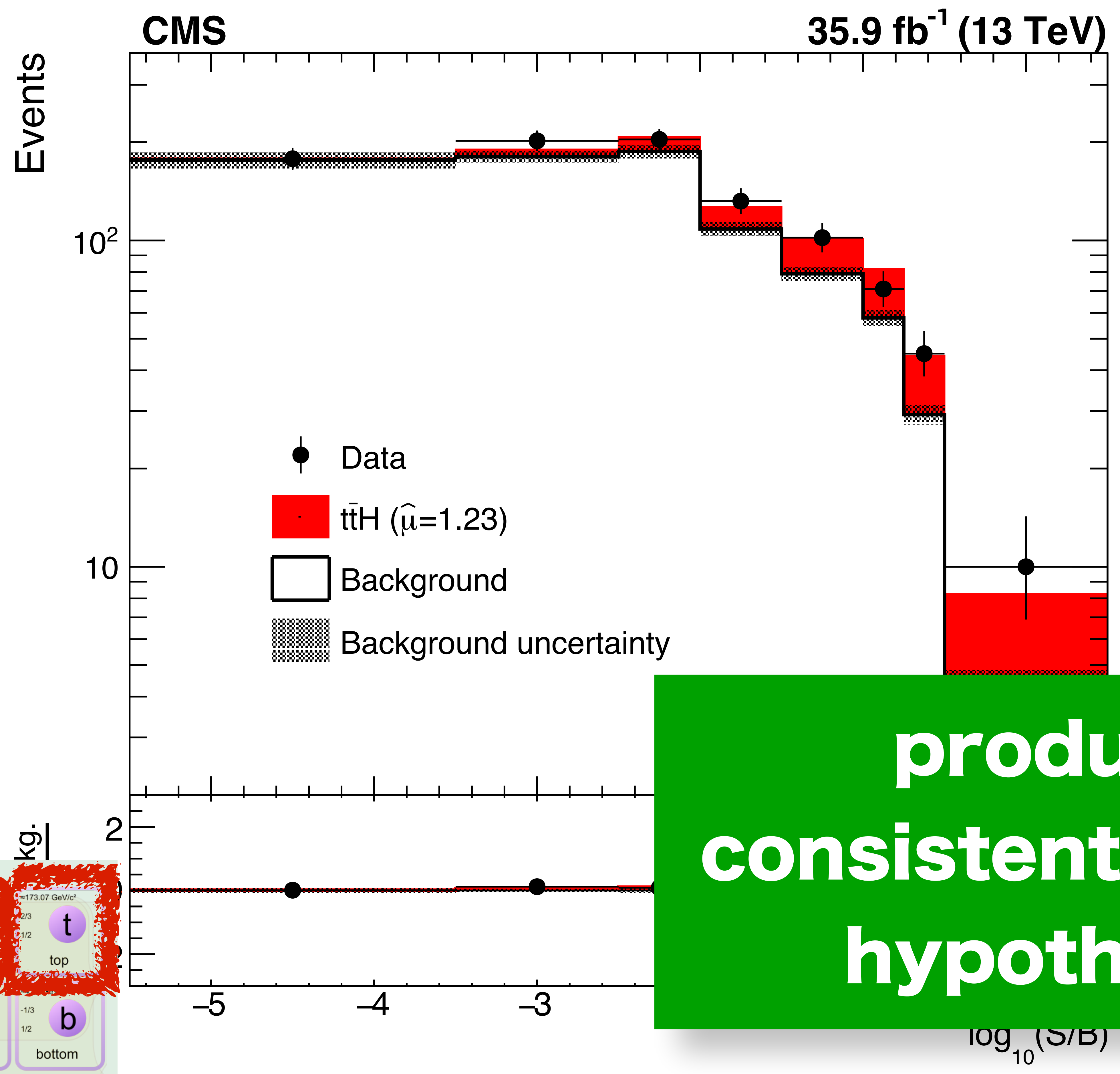

g
t
H
g
$\bar{t}$

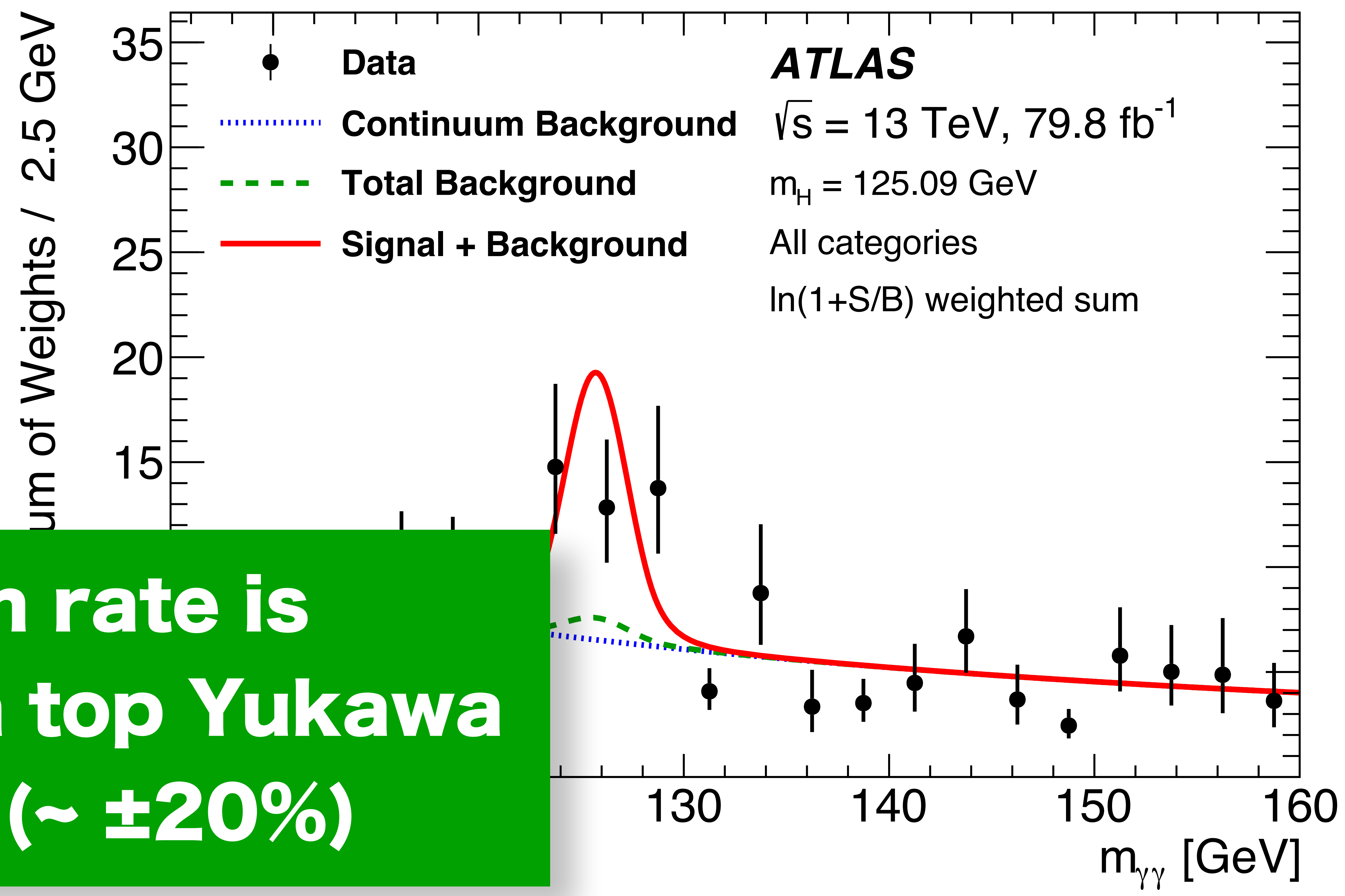

luon
gluo
φ
y
x
Higgs field in space

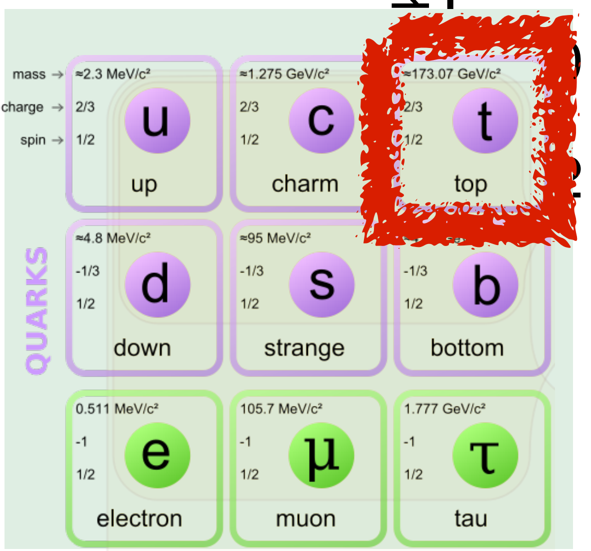
the news of the past year: ATLAS & CMS see events with top-quarks & Higgs simultaneously

CMS > 5-sigma ttH

ATLAS > 5-sigma ttH

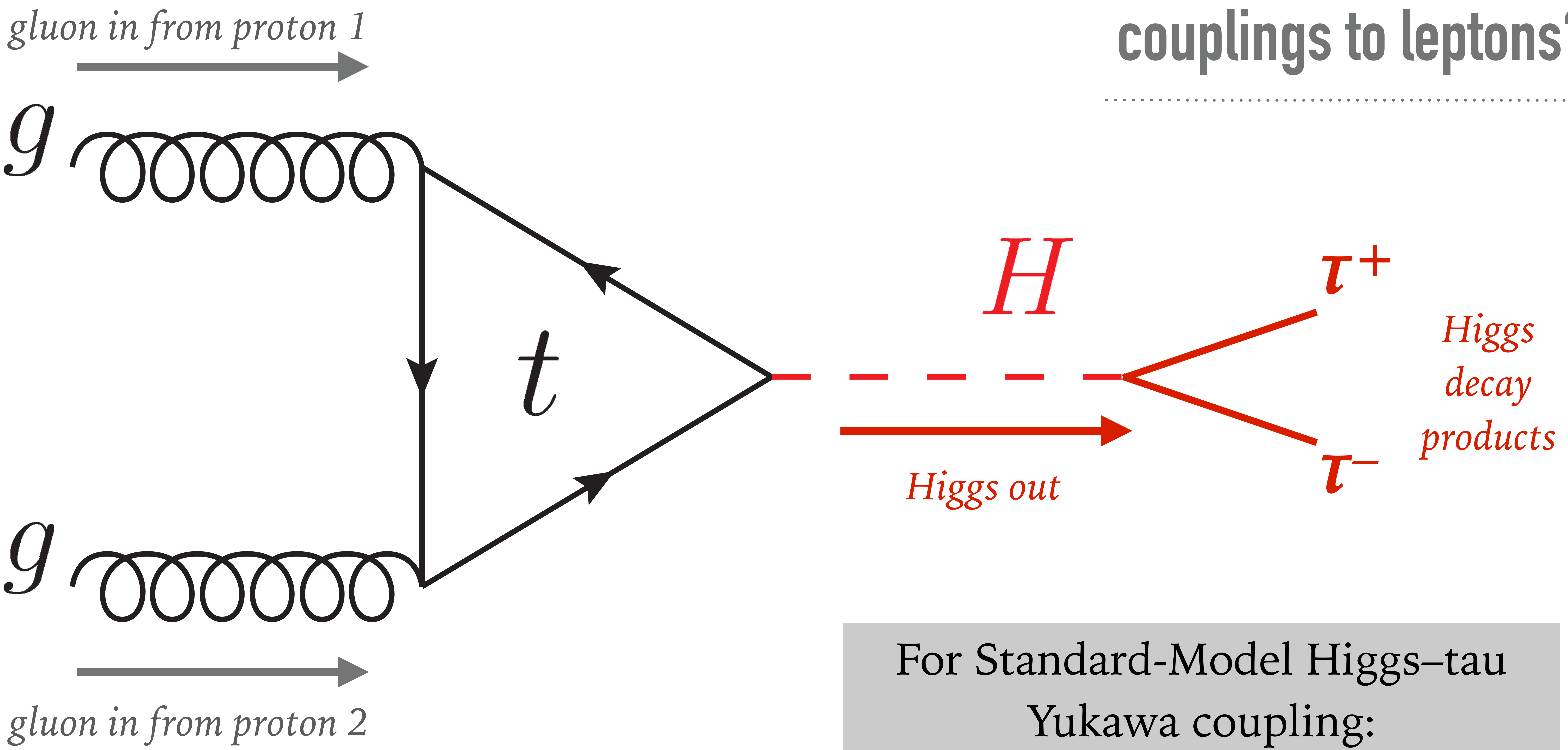






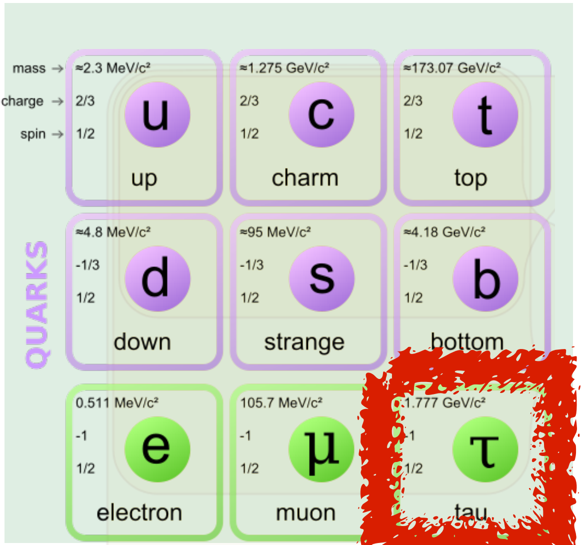
production rate is consistent with top Yukawa hypothesis (~ ±20%)

couplings to leptons?



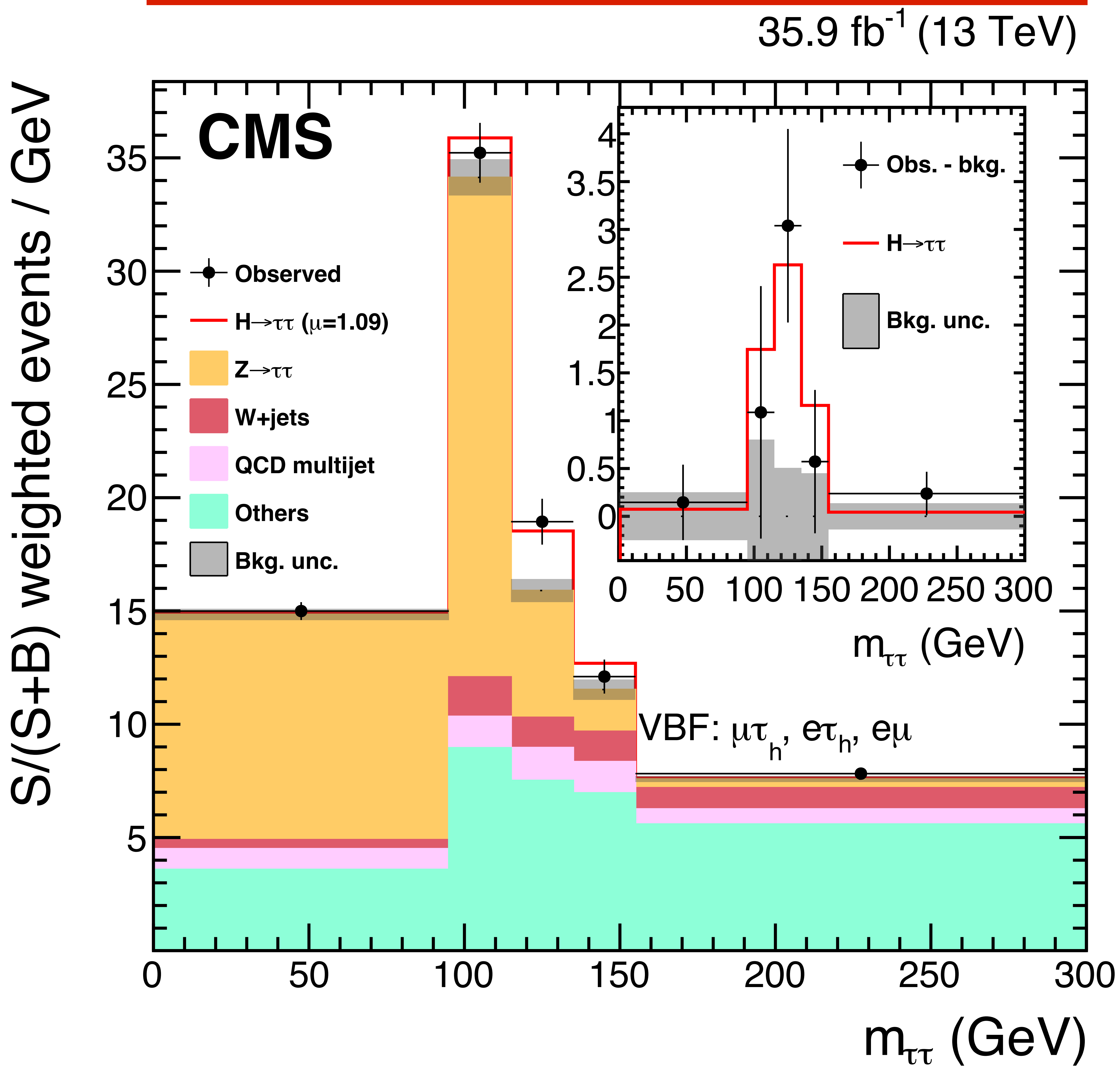
For Standard-Model Higgs–tau Yukawa coupling:

~ 1 in every 16 Higgs bosons decays to $\tau^+\tau^-$

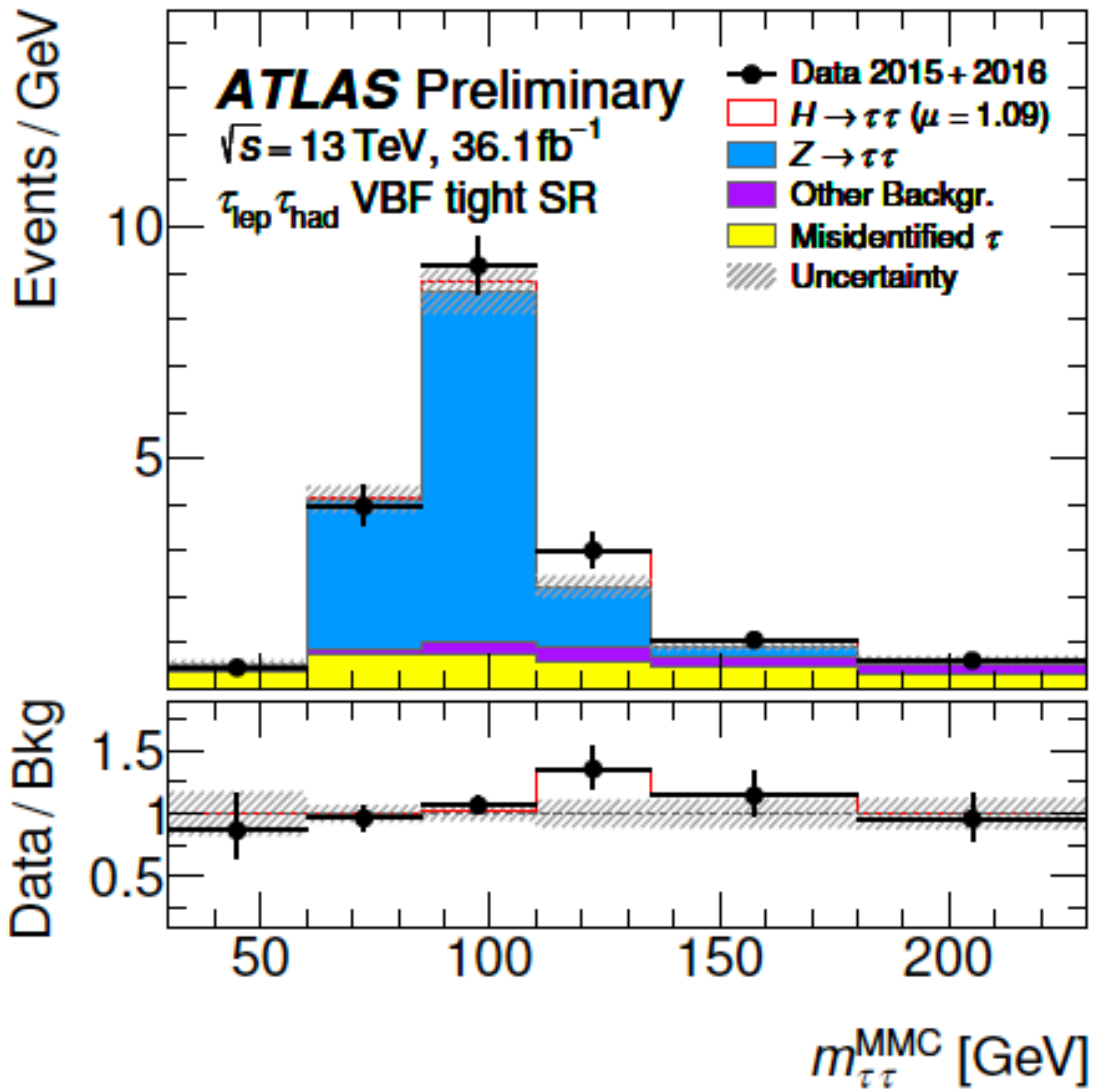


observation of H → ττ

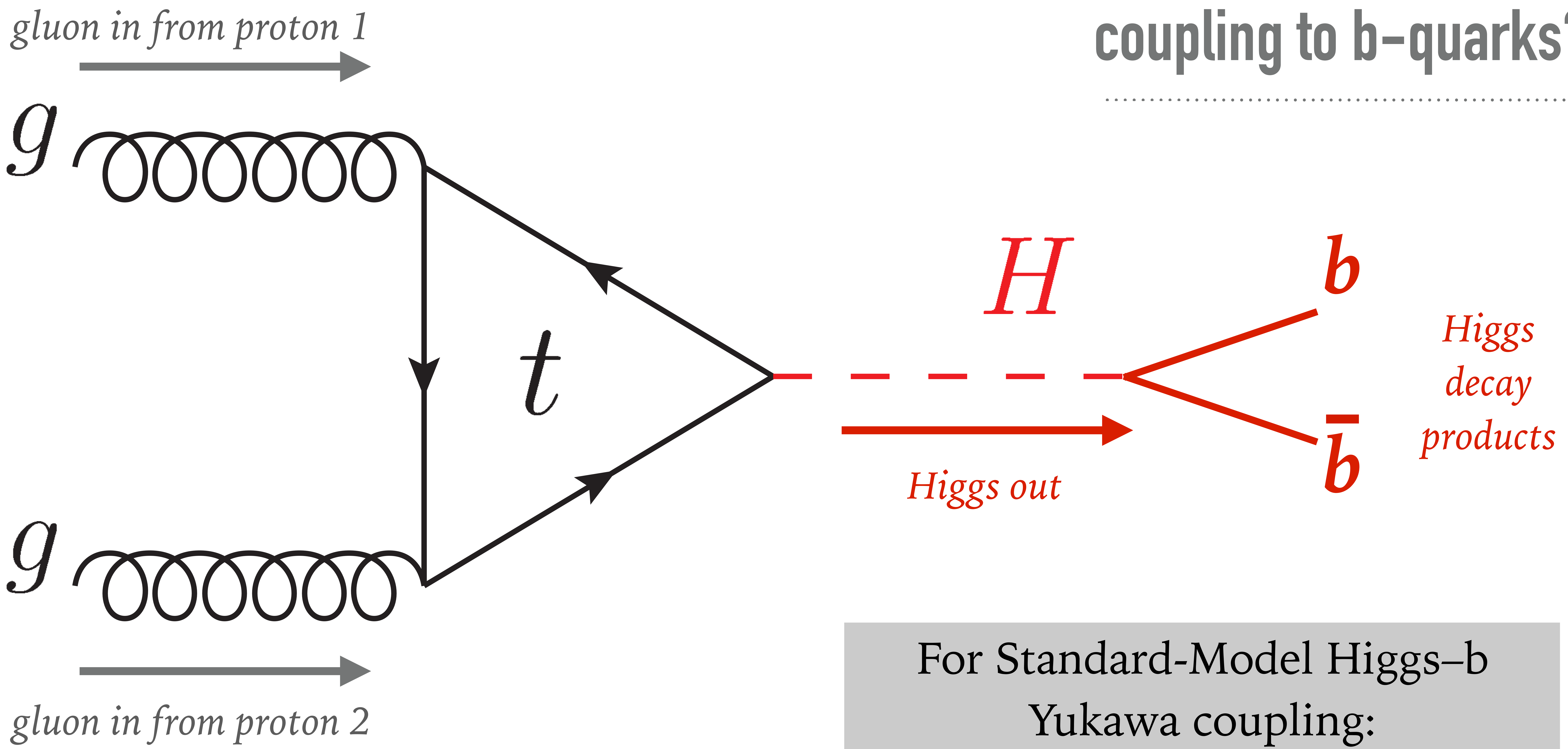
~2 years ago:
CMS >5-sigma H → τ τ



1 year ago:
ATLAS >5-sigma H → τ τ

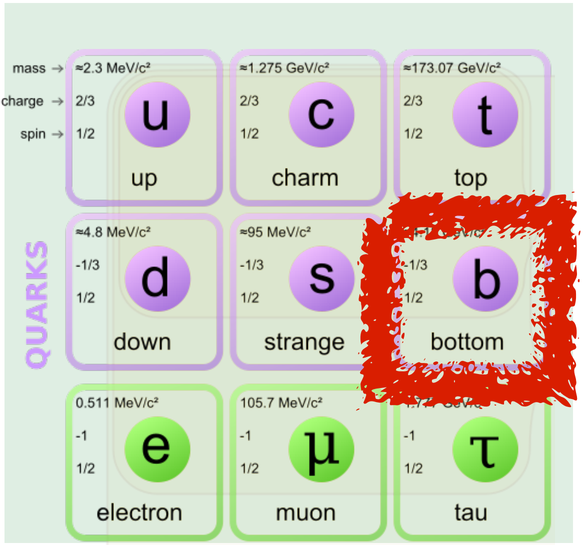


coupling to b-quarks?



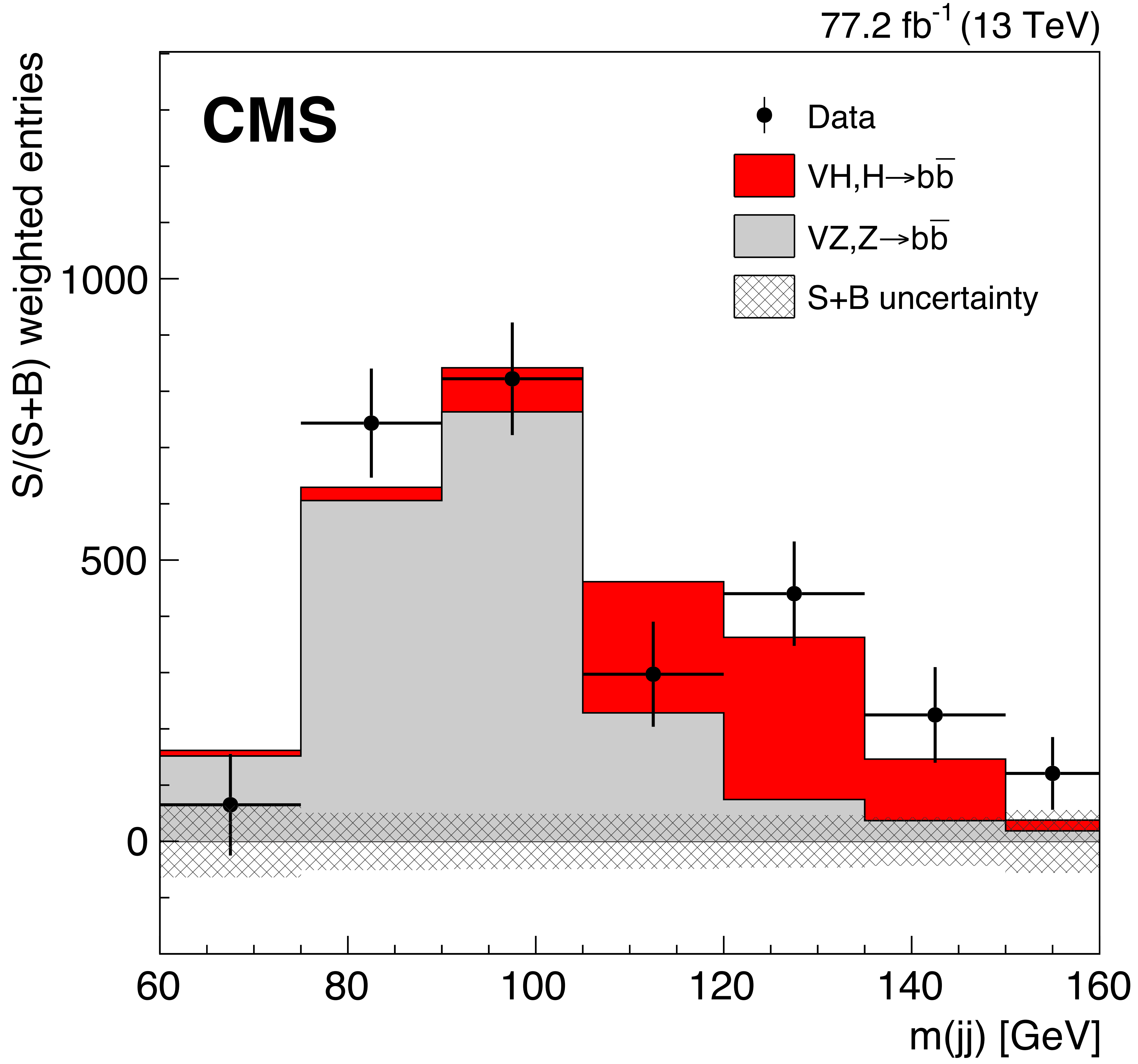
For Standard-Model Higgs–b Yukawa coupling:

~ 58% of Higgs bosons should decay to bb

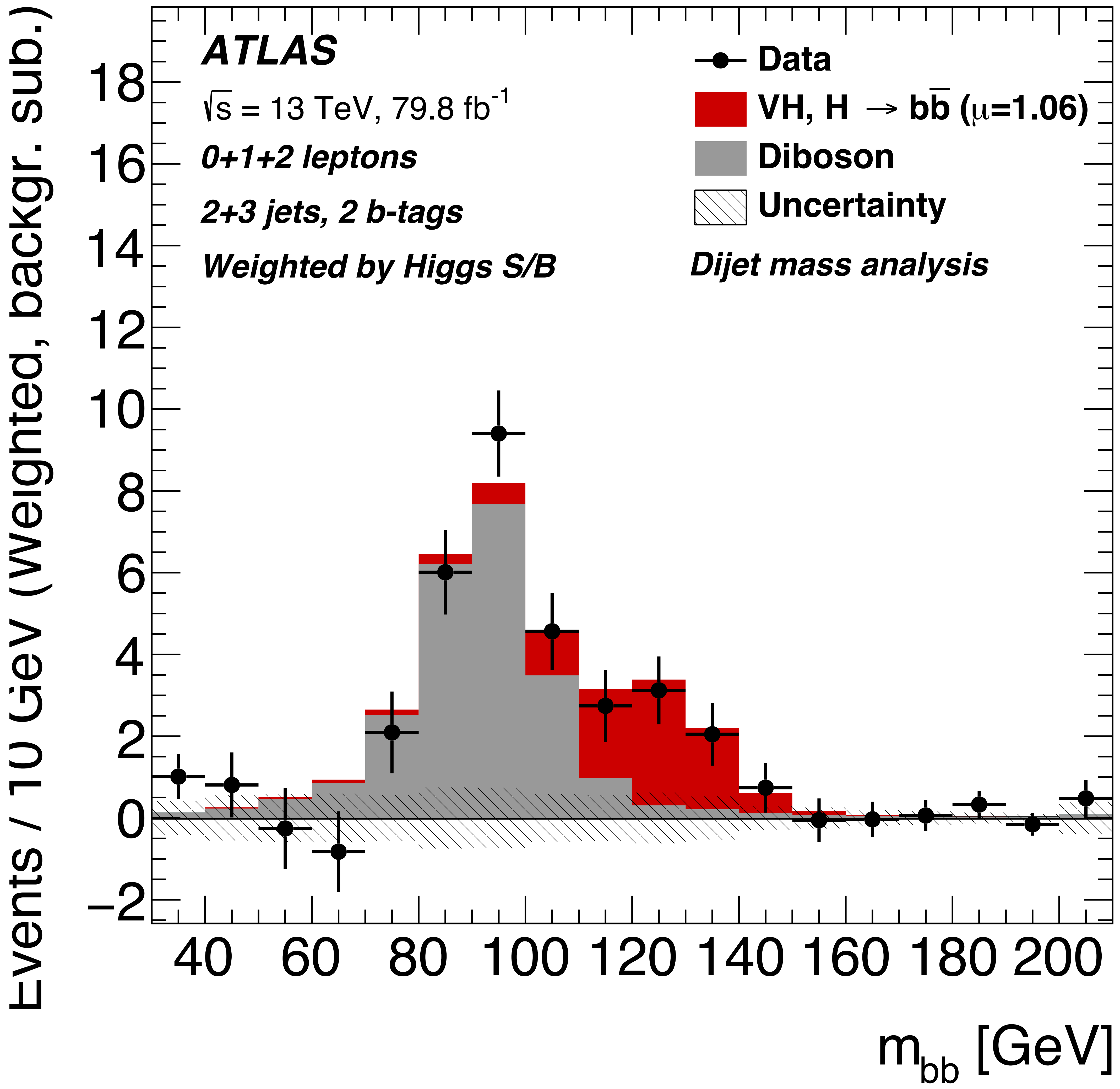


six months ago, observation of H → bb

CMS >5-sigma H → bb



ATLAS > 5-sigma H → bb



Analysis includes key idea from Butterworth, Davison, Rubin, Salam (PRL 100 (2008) 242001)

what's the message?

The >5σ observations of the ttH process and of H → ττ and H→ bb decays, independently by ATLAS and CMS, **firmly establish the existence of a new kind of fundamental interaction**, Yukawa interactions.

Yukawa interactions are important because they are:
(1) **qualitatively unlike any quantum interaction probed before** (effective charge not quantised),
(2) **hypothesized to be responsible for the stability of hydrogen**, and for determining the size of atoms and the energy scales of chemical reactions.

Establishing the pattern of Yukawa couplings across the full remaining set of quarks and charged leptons is one of the major challenges for particle physics today.

Is this any less important than the discovery of the Higgs boson itself?

My opinion: no, because fundamental interactions are as important as fundamental particles

what could one be saying about it?

This is a **fifth force, the "Higgs force"**

(up to you to decide whether you prefer to talk about new interactions or new force)

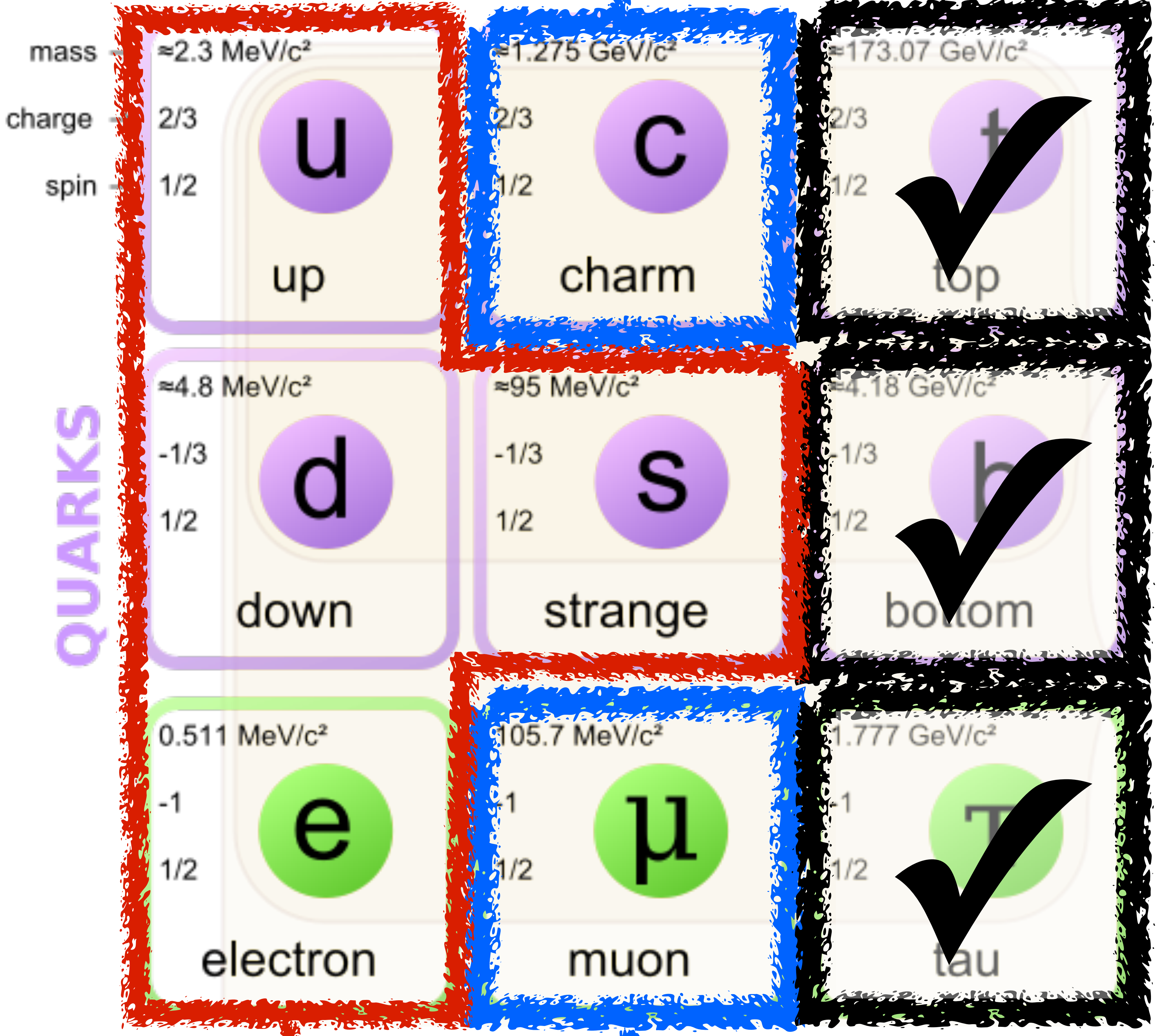
Is this any less important than the discovery of the Higgs boson itself?

My opinion: no, because fundamental interactions are as important as fundamental particles

Yukawas

today: no evidence yet
(1 in 35 decays)
needs an e^+e^-
or ep collider

overall normalisation
(related to Higgs width):
needs an e^+e^- collider



today: no evidence yet
(1 in 4000 decays)
no clear route to
establishing SM
couplings at 5σ

today: no evidence yet
(1 in 4570 decays)
observable at the LHC
within about 10 years.

Bottom-Yukawa coupling

How?

- Look for Higgs decays into t
- Huge background from jet e additional objects to tag: VB
- Complex final states ⟹ mul jets to objects and to disting

Greatest challenges

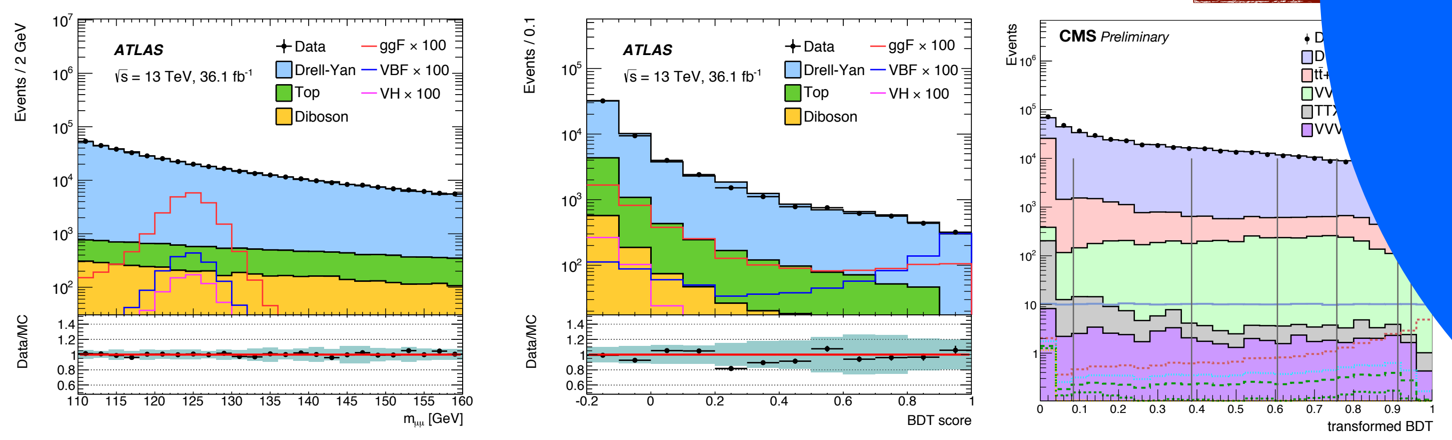
- Good **flavour tagging** perfo
- Large backgrounds from *tt* a

Grefe C. Grefe - Higgs

Search for $H \to \mu\mu$

Phys. Rev. Lett. 119 (20

CMS-PAS-



- Loose event selection **requiring two isolated OS muons** and veto *b*-jets
- Large background from Drell-Yan and smaller background from top quarks
- Signal and background described by analytical functions; fit to di-muon mass distribution in all signal regions

- Use **BDT to select events in 2 VBF** categories (m_{jj}, $p_T^{\mu\mu}$, $|\Delta\eta_{jj}|$, ΔR_{jj}, etc.)

ATLAS

- All other events categorised in 6 *ggF* categories based on $p_T^{\mu\mu}$ and $|\Delta\eta_{\mu}|$

- Separate signal from background using BDT ($p_T^{\mu\mu}$, $\eta_{\mu\mu}$, m_{jj}, $|\Delta\eta_{jj}|$, $N_{b\text{-jets}}$ etc.)

CMS

- De sc

Grefe C. Grefe - Higgs couplings to ferm

so much more to do with the Higgs sector

[LHCP conf. 2018]

EFT approach

Well-defined theoretical approach

Assumes New Physics states are heavy

Write Effective Lagrangian with only light (SM) particles

BSM effects can be incorporated as a momentum expansion

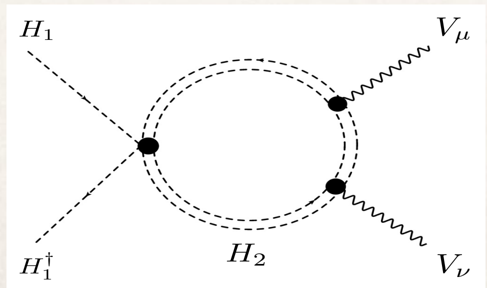
dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\mathcal{O}_i^{d=8} + \ldots$$

BSM effects SM particles

example:

2HDM



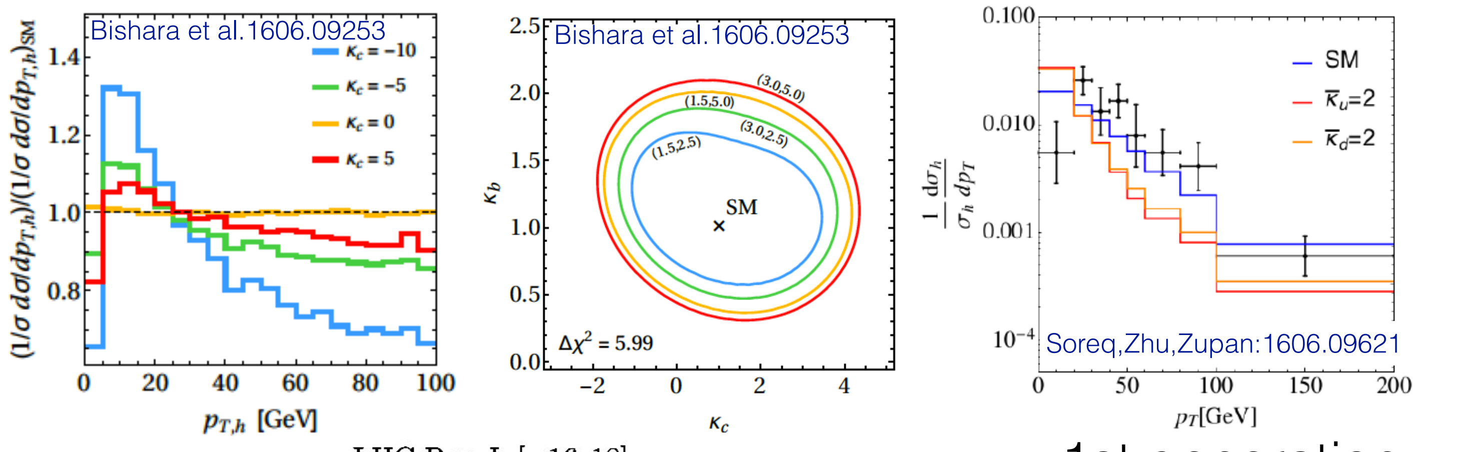
$$\frac{ig}{2m_W^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$

where $\bar{c}_W = \dfrac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$

Sanz

Light quark Yukawas (2)

New idea: Using kinematic distributions i.e. the Higgs pT



κ_c LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$

HL-LHC: $[-0.6, 3.0]$

1st generation

To be fully explored

Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging)

(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)

$ZH(H \to c\bar{c})$ gives a limit of 110 x SM expectation (ATLAS-CONF-2017-078)

Vryonidou LHCP2018 13

The Higgs potential

Higgs potential: $V(H) = \frac{1}{2}M_H^2H^2 + \lambda_{HHH}vH^3 + \frac{1}{4}\lambda_{HHHH}H^4$

Fixed values in the SM: $\lambda_{HHH} = \lambda_{HHHH} = \dfrac{M_H^2}{2v^2}$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

What can measuring λ_{HHH} tell us?

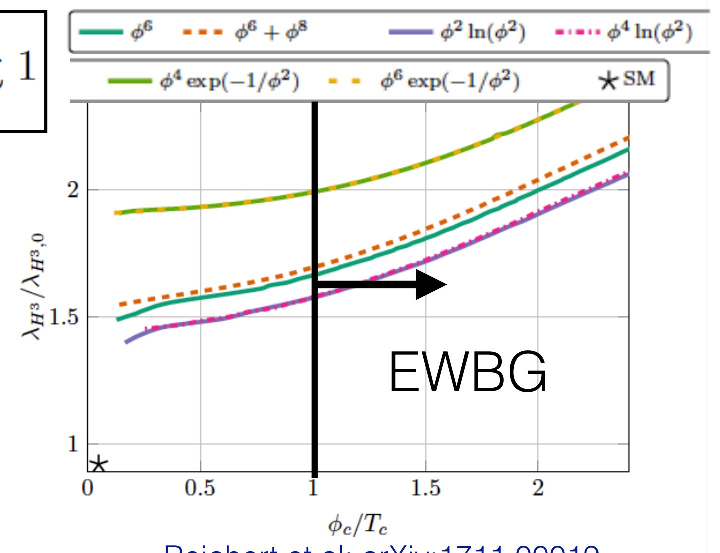
Electroweak baryogenesis requires a first order strong EWPT ➡ $\dfrac{\phi_c}{T_c} \gtrsim 1$

$\lambda_{H^3}/\lambda_{H^3,SM} < 1.5 : \phi_c/T_c < 1$

EW baryogenesis is disfavoured

$\lambda_{H^3}/\lambda_{H^3,SM} > 2 : \phi_c/T_c > 1$

EW baryogenesis is favoured



Reichert et al: arXiv:1711.00019

Vryonidou LHCP2018 20

A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

Phase transitions
Baryogenesis
gravitational waves

Fate of the Universe
Stability

The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales

Exploiting complementarity with cosmo/astro probes

Similar story for Axions and ALPs, scalars are versatile

Sanz

for parts of Higgs sector, we know what to do to get answers.
What about other “big” questions

Nature of dark matter (& dark energy)

Fine-tuning (e.g. supersymmetry and similar)

Matter-antimatter asymmetry of the universe

[…]

“

Finding dark matter and studying it will be the biggest challenge for the Large Hadron Collider's second run

-a large LHC experiment's spokesperson [2015]

https://www.pbs.org/newshour/science/large-hadron-collider-gears-find-dark-matter-new-particles-second-run

dark matter

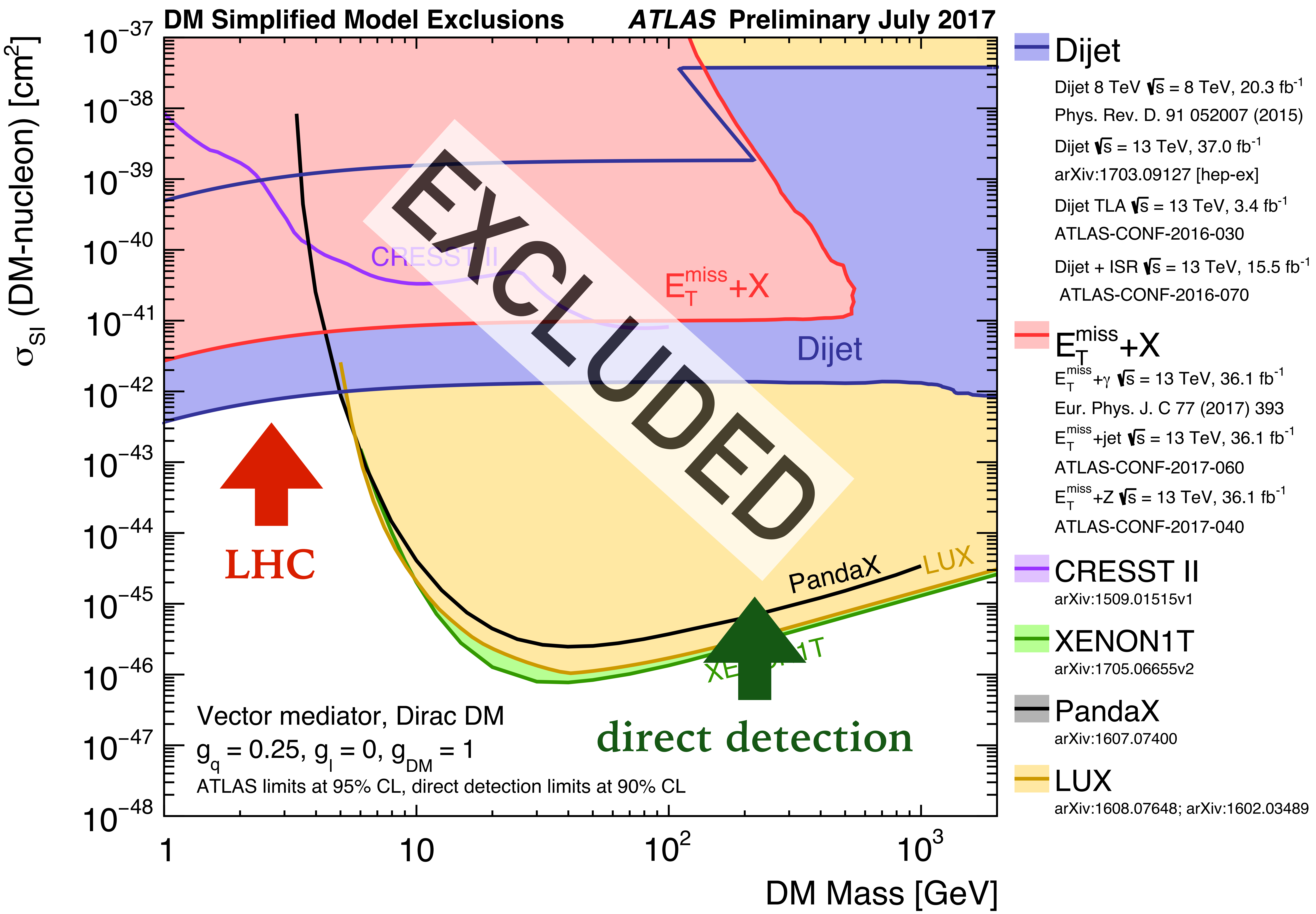
Rotation curve of spiral galaxy Messier 33

Looking beyond the SM: searches for dark matter at LHC & elsewhere

Classic dark-matter candidate: a weakly-interacting massive particle (**WIMP**, e.g. from supersymmetry).

Masses ~ GeV upwards

(search interpretations strongly model dependent)



musn't be (too) disappointed at lack of dark matter signal at LHC

Evidence for dark matter exists since the 1930s.

Today we know that

- **there are many possible models**
- **the range of parameters they span is large**

We must deploy full ingenuity in searching for dark matter, including at LHC.

But must also recognise that it has remained elusive for 80–90 years, and chances of finding it in any given year are small!

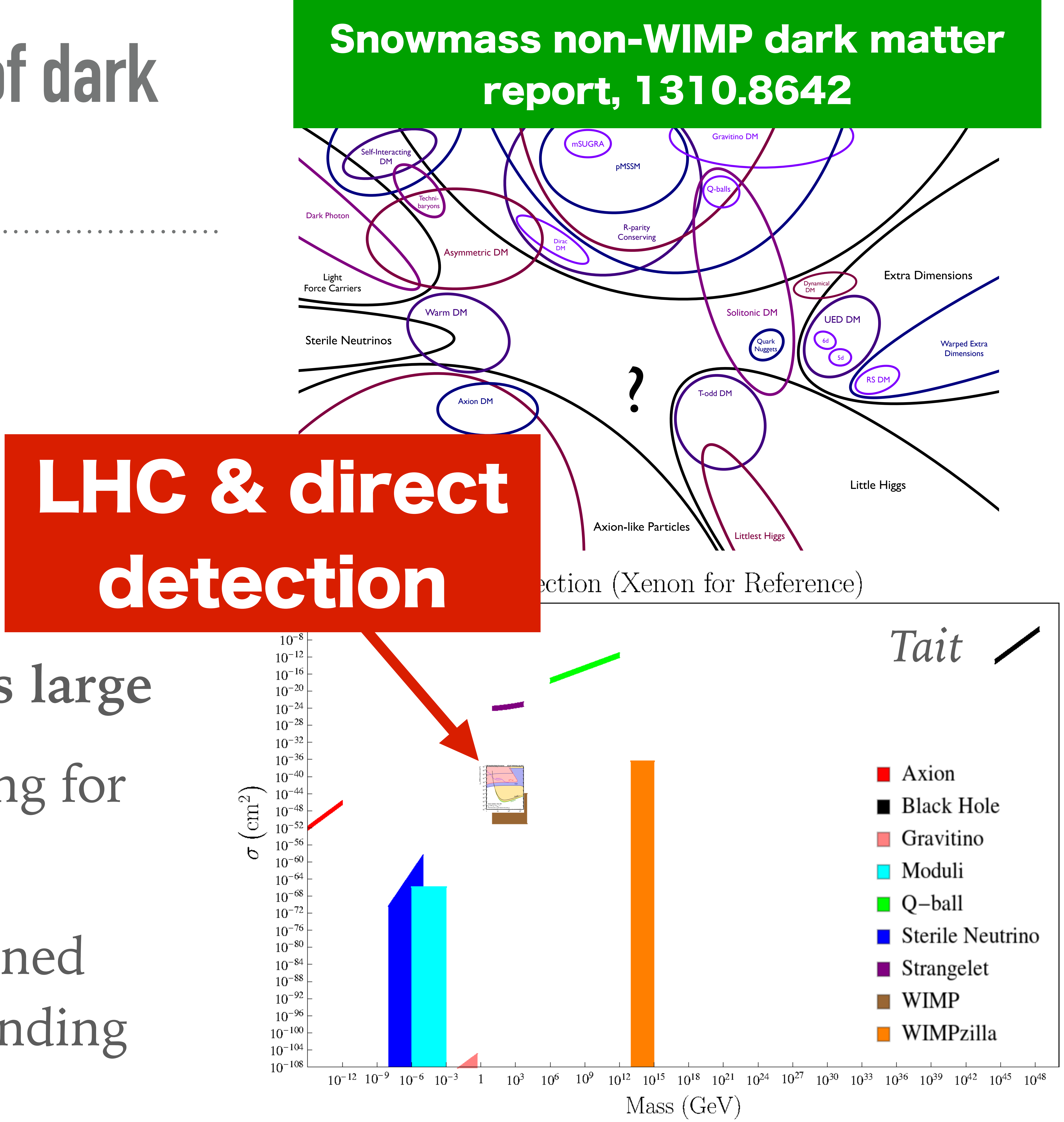


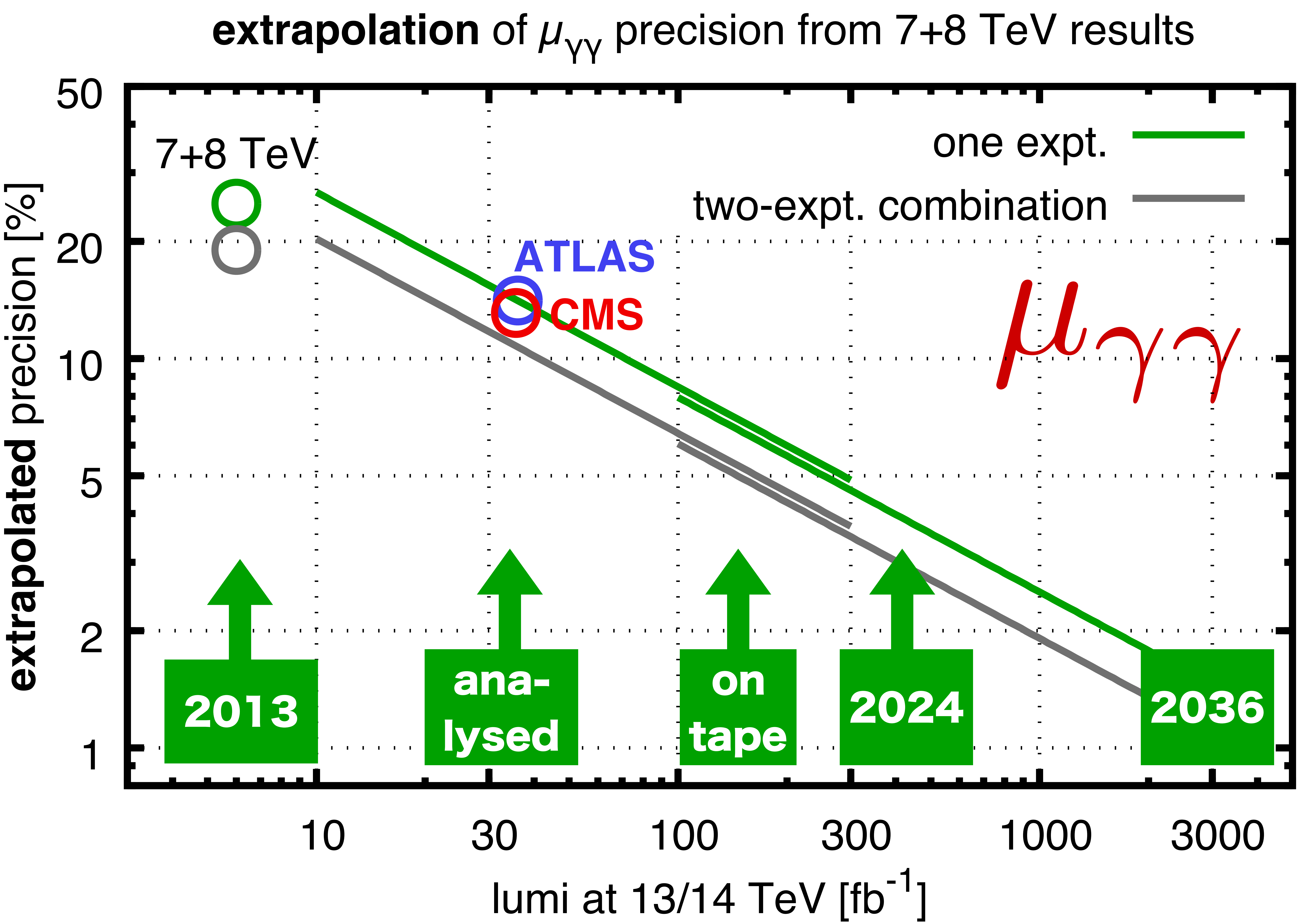
Figure 1. *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of masses and interaction cross sections.*

future progress?

(1) approved plans

LHC will collect ~40–100 times more data than used for the plots shown so far, though at mostly similar energy (13–14 TeV). That programme is called High-Luminosity LHC (HL-LHC)

Higgs precision (H → γγ) : optimistic estimate v. luminosity & time

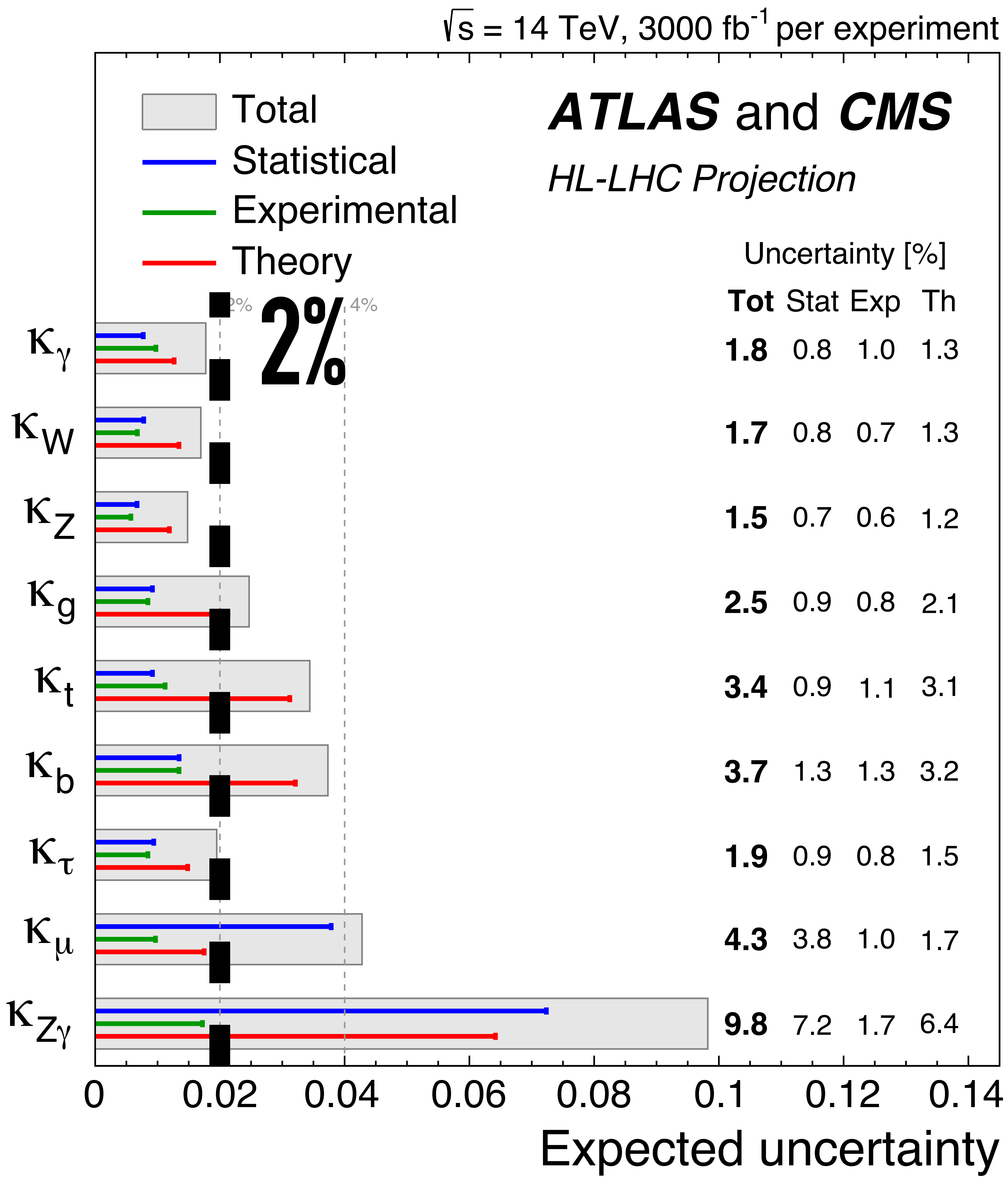


Today, Higgs coupling precisions are in the 10-20% range.

The LHC has the statistical potential to take Higgs physics from "observation" to 1–2% precision

1 fb^{-1} = 10^{14} collisions

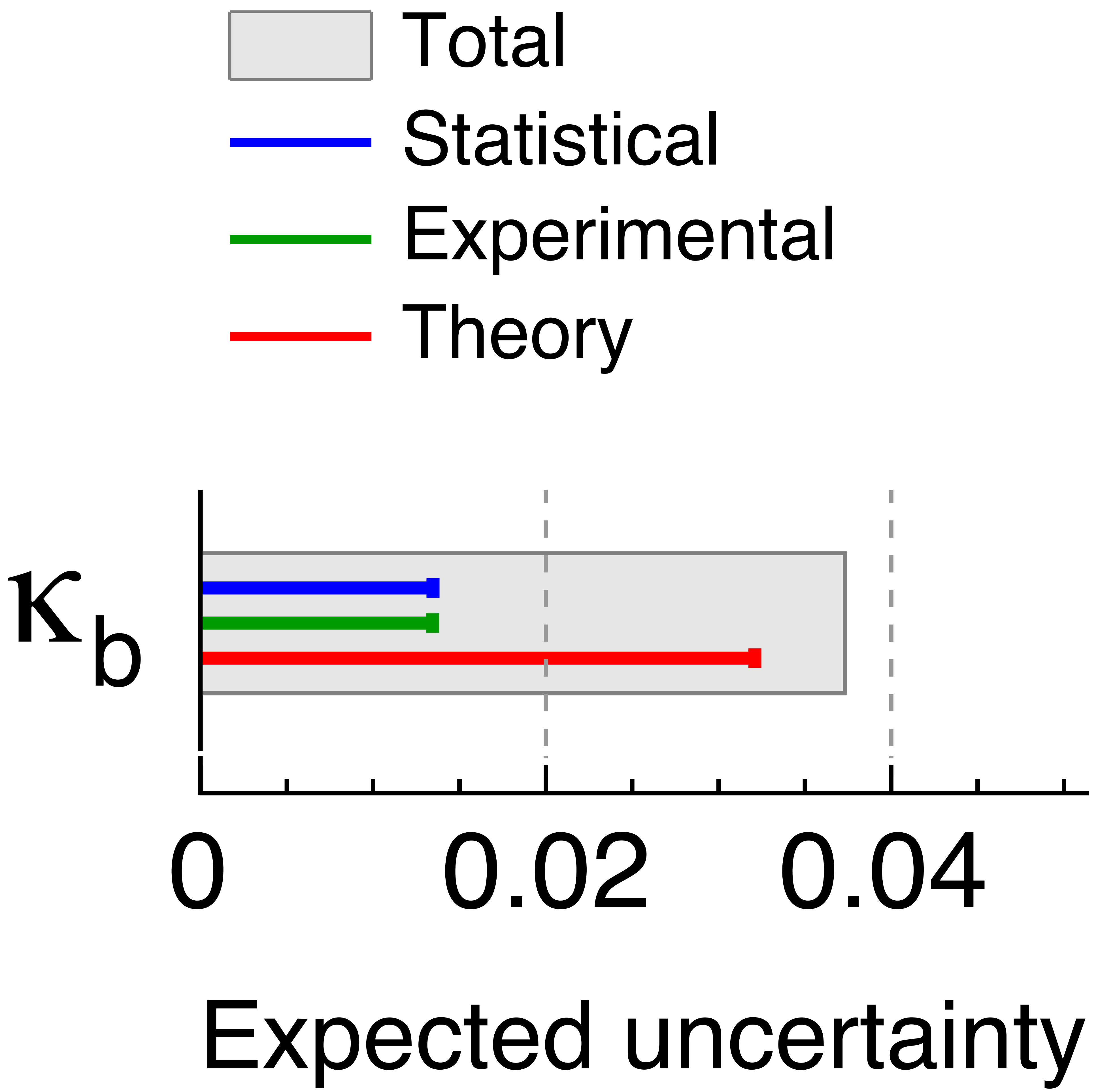
HL-LHC official Higgs coupling projections (by ~2036)



We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings
if theoretical interpretations can be made sufficiently accurate

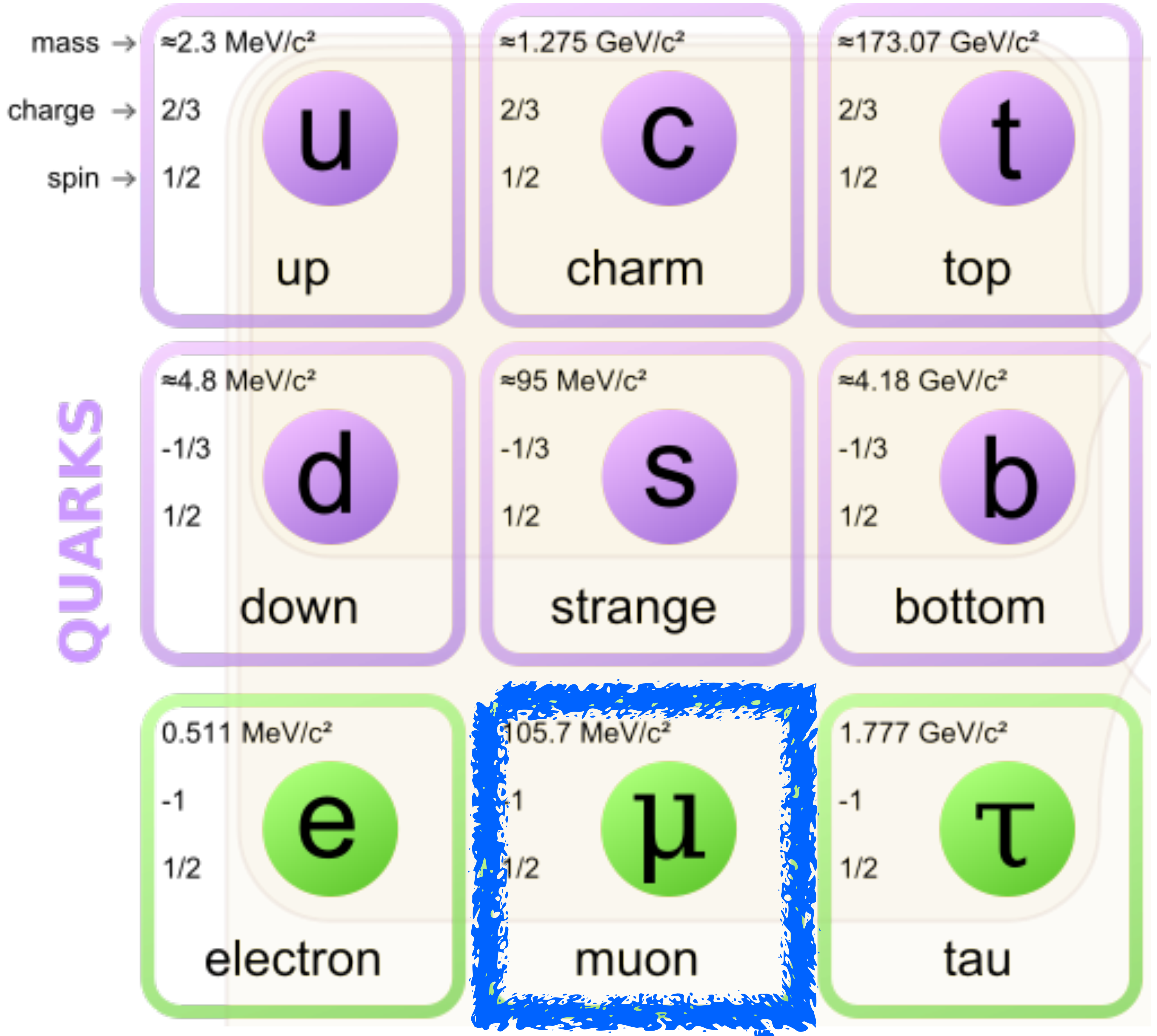
HL-LHC official Higgs coupling projections (by ~2036)



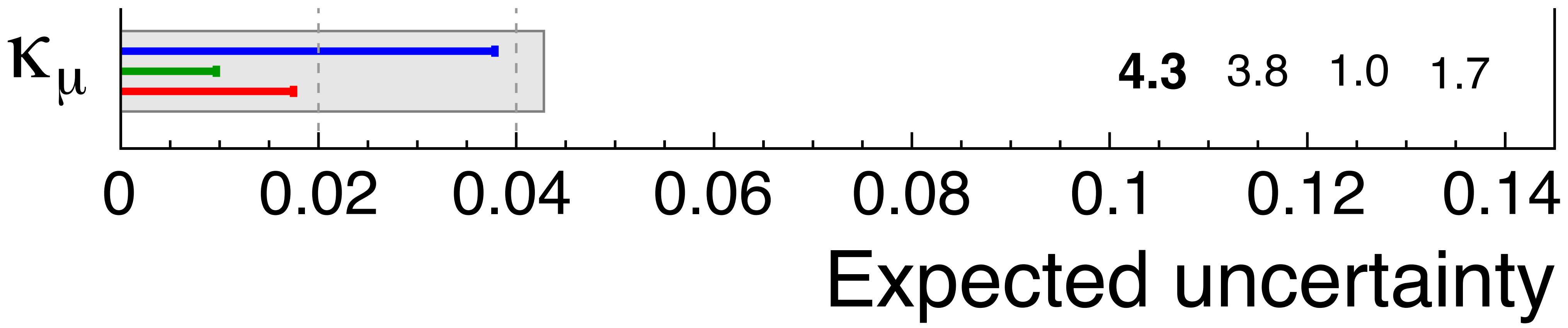
We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings
if theoretical interpretations can be made sufficiently accurate

2nd-generation Yukawas at HL-LHC (H→ μμ)



i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
c	$8 \cdot 10^{-3}$	s	$6 \cdot 10^{-4}$
b	$3 \cdot 10^{-2}$	t	1
ν_e	$\sim 10^{-13}$	e	$3 \cdot 10^{-6}$
ν_μ		μ	$6 \cdot 10^{-4}$
ν_τ		τ	$1 \cdot 10$[illegible]



today: no evidence yet
(1 in 4570 decays)

observable at HL-LHC
(within about 10 years)

future progress?

(2) proposed future colliders

e^+e^-: ILC, CLIC, CepC, FCC-ee, LEP3

pp: CppC, HE-LHC, FCC-hh

ep: LHeC, FCC-eh

e^+e^- & eh colliders: coupling measurements (precision)

Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	FCC-ee			FCC-eh
Luminosity (ab^{-1})	3	2	0.5	5 @ 240 GeV	+1.5 @ 365 GeV	+ HL-LHC	2
Years	25	15	7	3	+4	—	20
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.8	6.3	2.7	**1.3**	1.1	SM
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.3	0.35	0.80	0.2	**0.17**	0.16	0.43
$\delta g_{HWW}/g_{HWW}$ (%)	1.4	1.7	1.3	1.3	**0.43**	0.40	0.26
$\delta g_{Hbb}/g_{Hbb}$ (%)	2.9	1.8	2.8	1.3	**0.61**	0.55	0.74
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	6.8	1.7	**1.21**	1.18	1.35
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.8	2.2	3.8	1.6	**1.01**	0.83	1.17
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.7	1.9	4.2	1.4	**0.74**	0.64	1.10
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.4	13	n.a.	10.1	**9.0**	3.9	n.a.
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.6	6.4	n.a.	4.8	**3.9**	1.1	2.3
$\delta g_{Htt}/g_{Htt}$ (%)	2.5	–	–	–	–	2.4	1.7
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.2	$< $ **1.0**	< 1.0	n.a.

e+e− & eh colliders: Higgs-charm (2nd generation) coupling

today: no evidence yet

(1 in 35 decays)

needs an e+e− or ep collider

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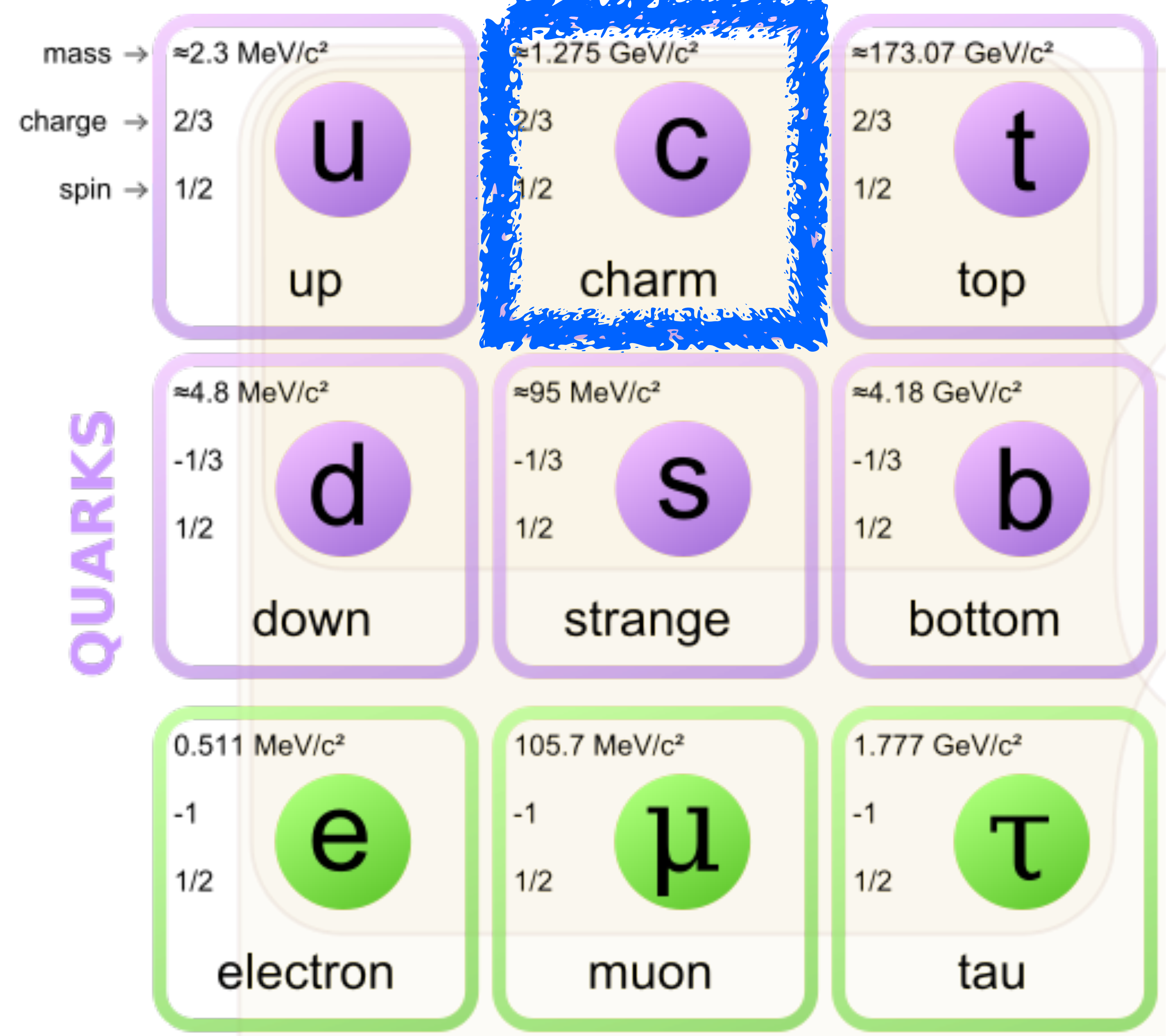
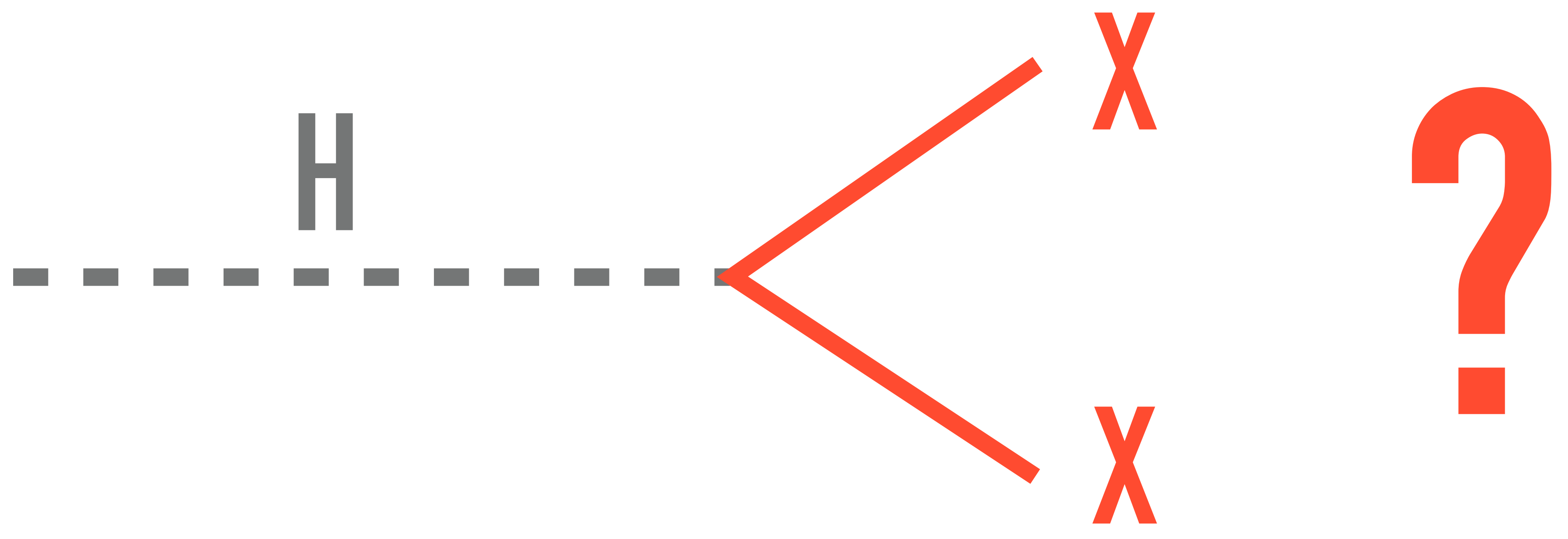


e^+e^- colliders: total Higgs width (≡ lifetime)

All current fits need to make assumptions about the total Higgs width (sum over all decay channels, whether observed or not).

Only e^+e^- colliders can measure this directly.

$$\Gamma_H = \sum_X$$



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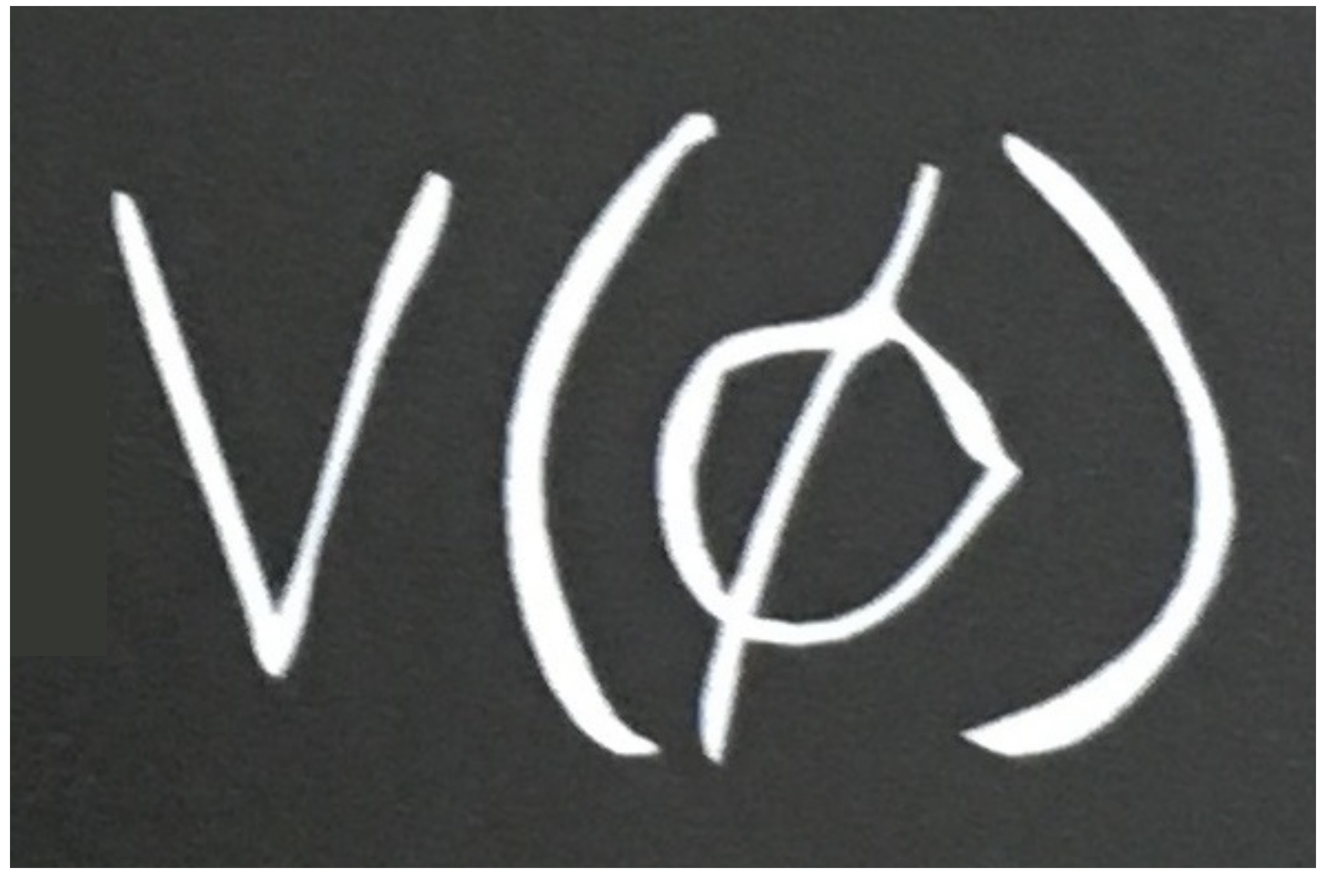
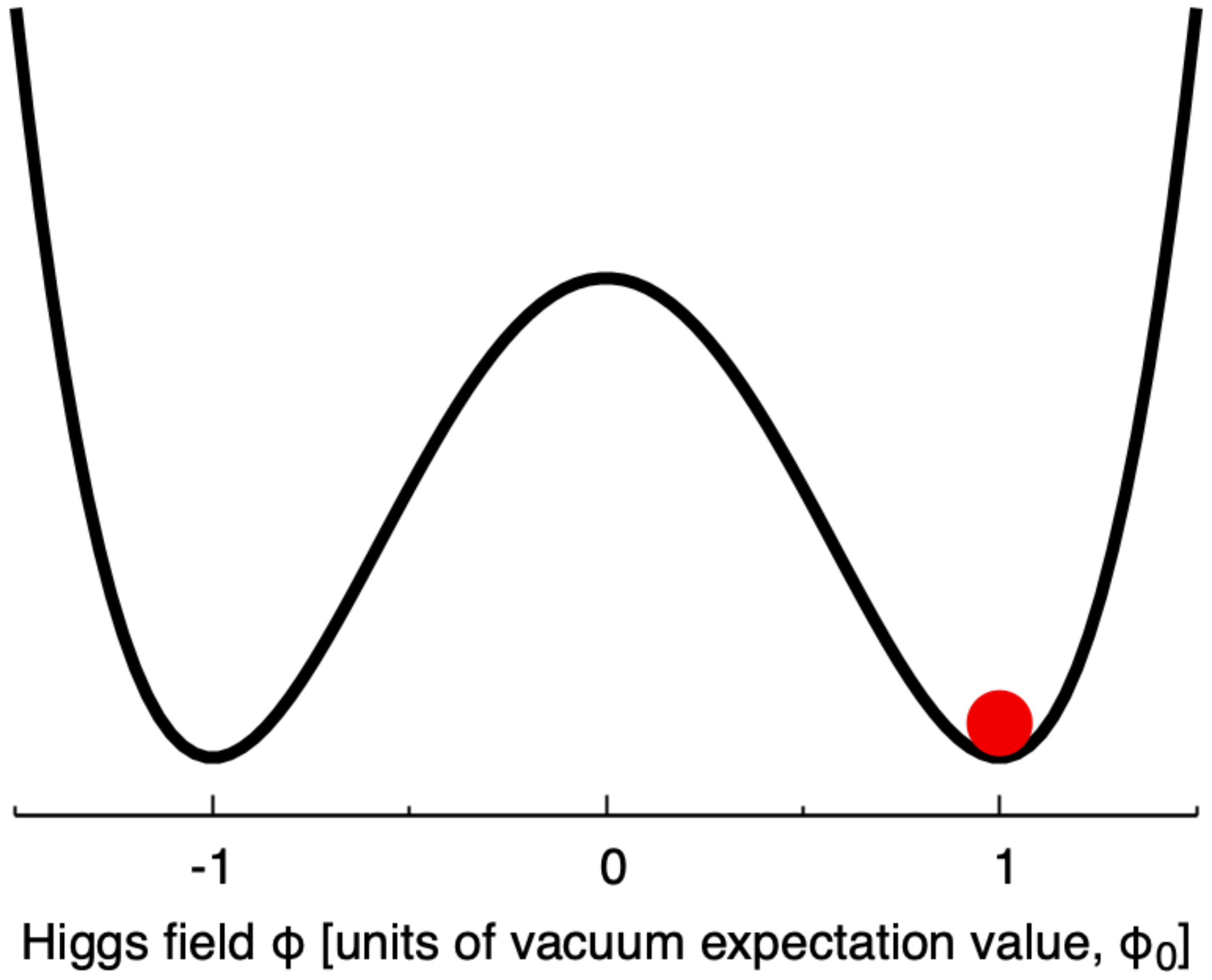
pp colliders (concentrate on FCC-hh)

Figure 2: Higgs production cross sections versus collision energies normalized to the 14 TeV rates.

Higgs production rate increases substantially with collider centre-of-mass energy

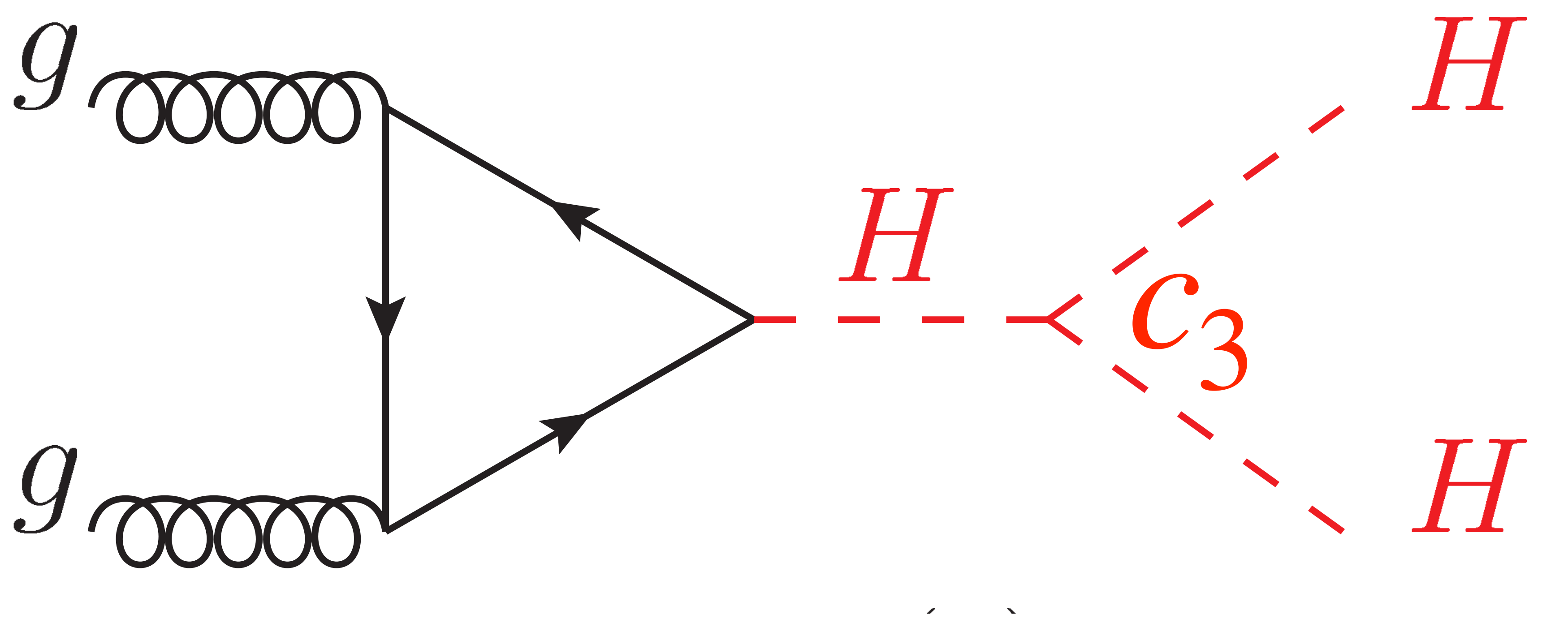
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \quad ?$$





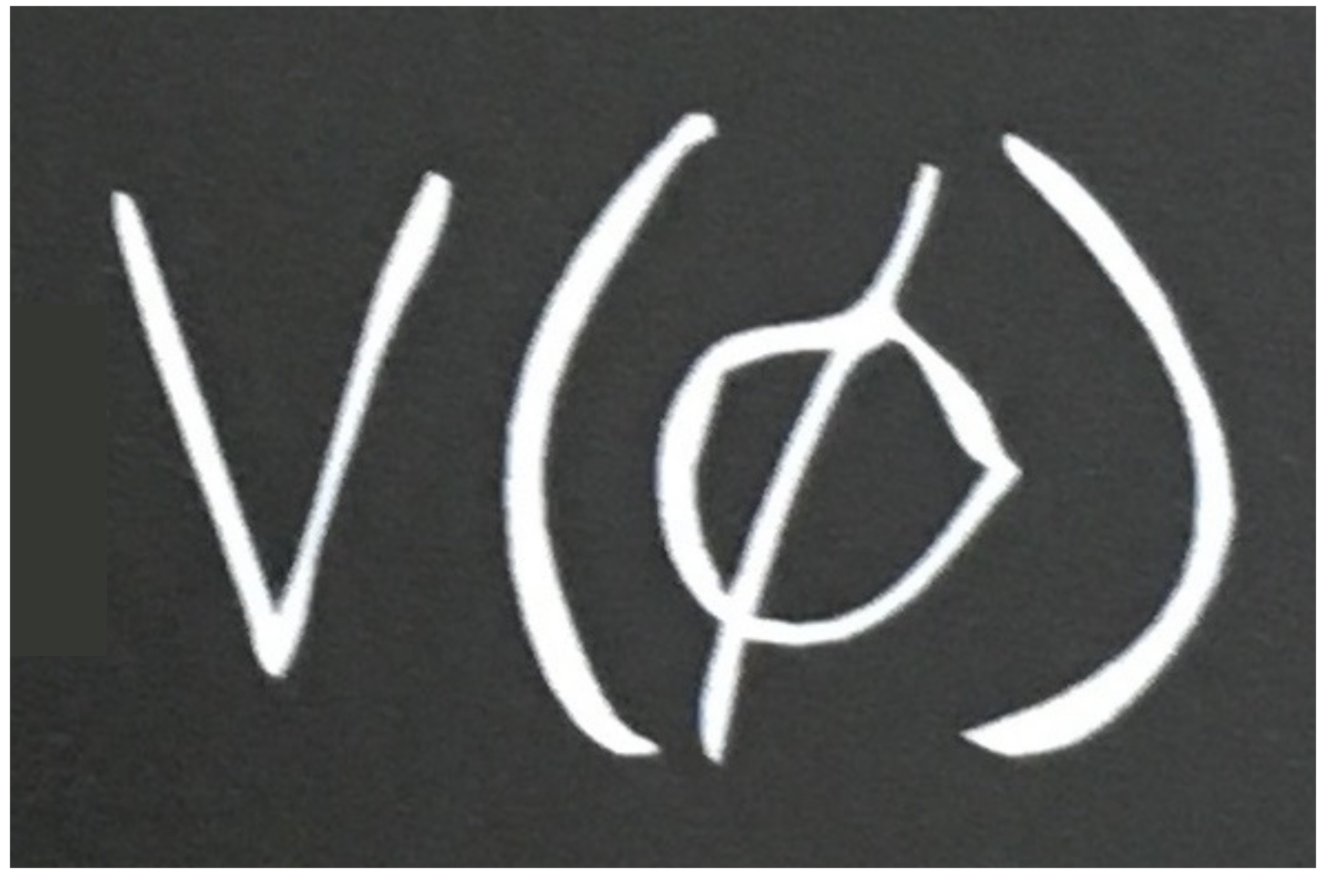
- **The Higgs potential holds together the rest of the standard model (keystone)**
- so far (as a fundamental potential) only ever seen in textbooks!
- $-\varphi^2 + \varphi^4$ implies specific Taylor expansion around $\varphi=\varphi_0$:

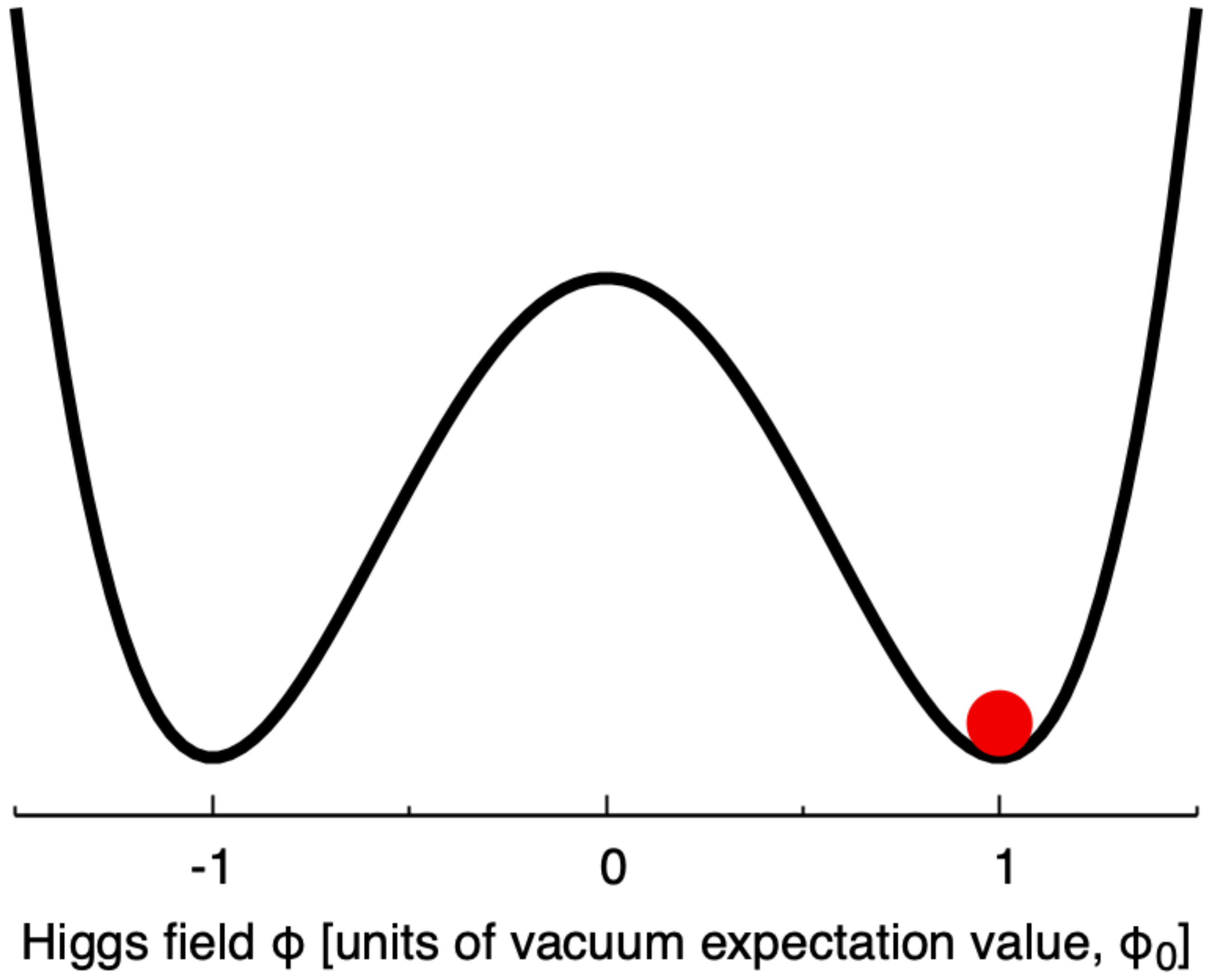
$$V(\phi_0 + H) = V_0 + \frac{1}{2}m_H^2 H^2 + c_3 H^3 + \cdots$$



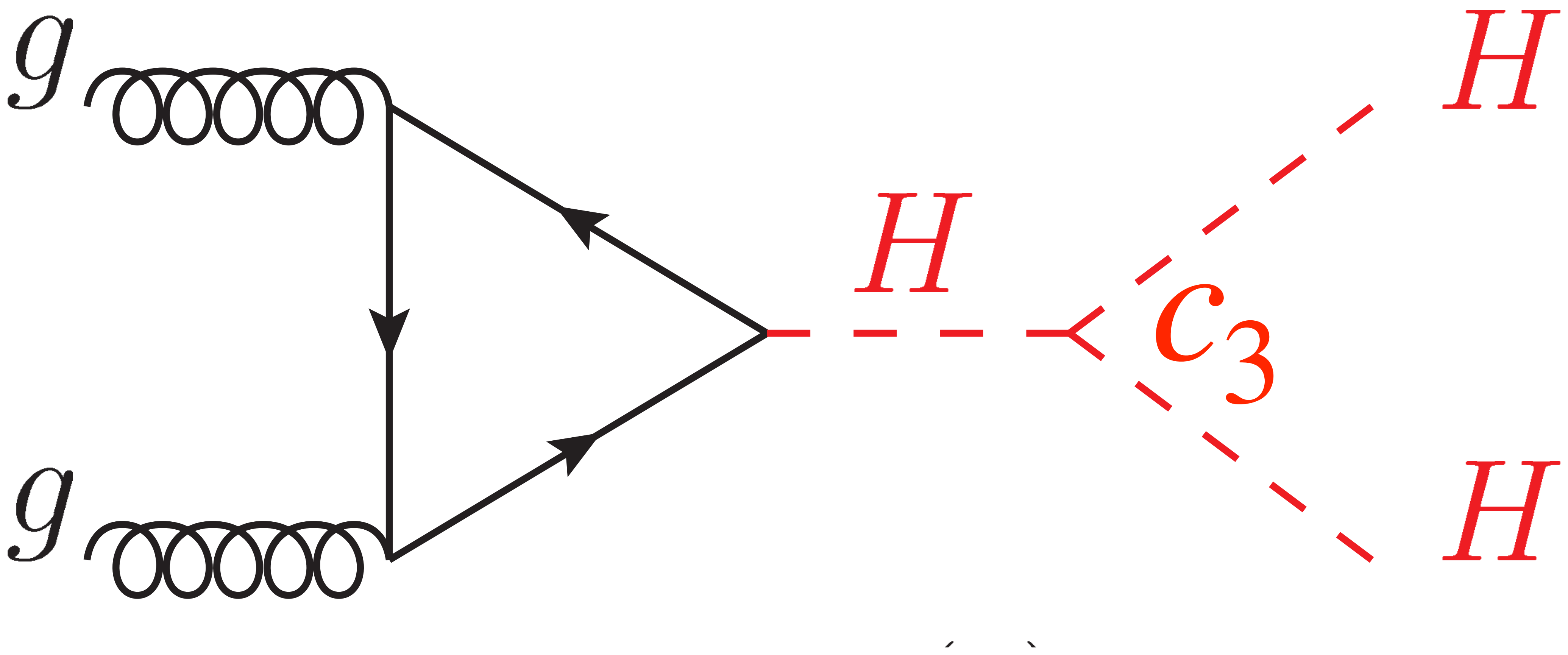

g
g
H
c_3
H
H
luon
gluo
φ
y
x
Higgs field in space

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \quad ?$$





FCC-hh channel	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\rightarrow 4\ell]$
c_3 precision	6.5%	14%



For comparison (HL)-LHC can get $\sim\pm 50\%$ accuracy

European Strategy Update

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

The European Strategy for Particle Physics is the cornerstone of Europe's decision-making process for the long-term future of the field. Mandated by the CERN Council, it is formed through a broad consultation of the grass-roots particle physics community, it actively solicits the opinions of physicists from around the world, and it is developed in close coordination with similar processes in the US and Japan in order to ensure coordination between regions and optimal use of resources globally.

ongoing (2018 - 2020)

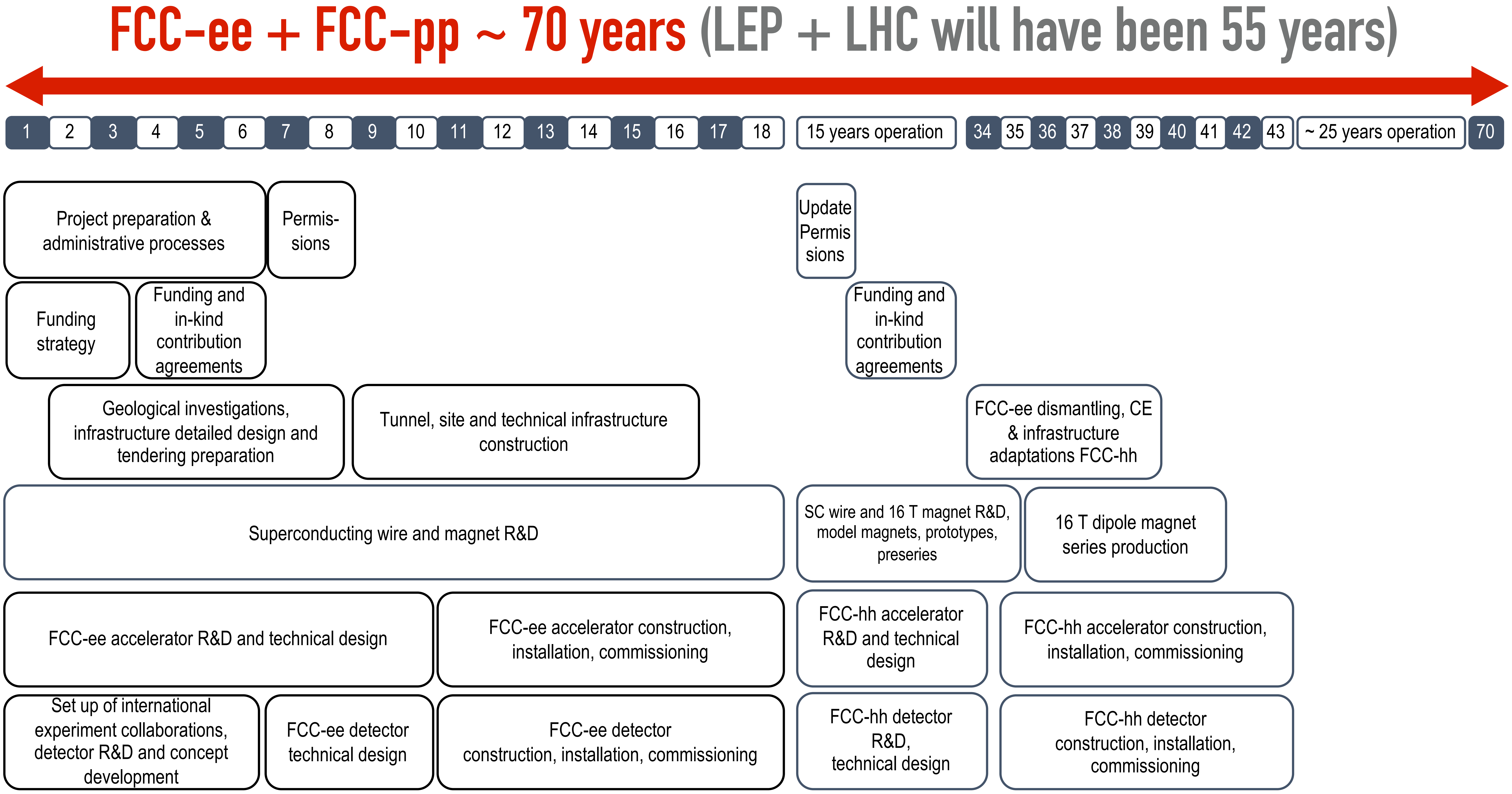


Figure 9: Overview of implementation timeline for the integral FCC program, starting in 2020. Numbers in the top row indicate the year. Physics operation for FCC-ee would start towards the end-2030s; physics operation for FCC-hh would start in the mid-2060s.

closing

the Higgs sector is unlike anything probed before in particle physics, much of it remains to be established & explored

it is remarkably fortunate that so much can be done with the LHC and possible next-generation colliders

e.g. accessing Yukawa couplings beyond the 3rd generation,
the triple-Higgs coupling → Higgs-field potential, SM keystone,
& the pathway from discovery to precision

meanwhile, the search for new physics continues

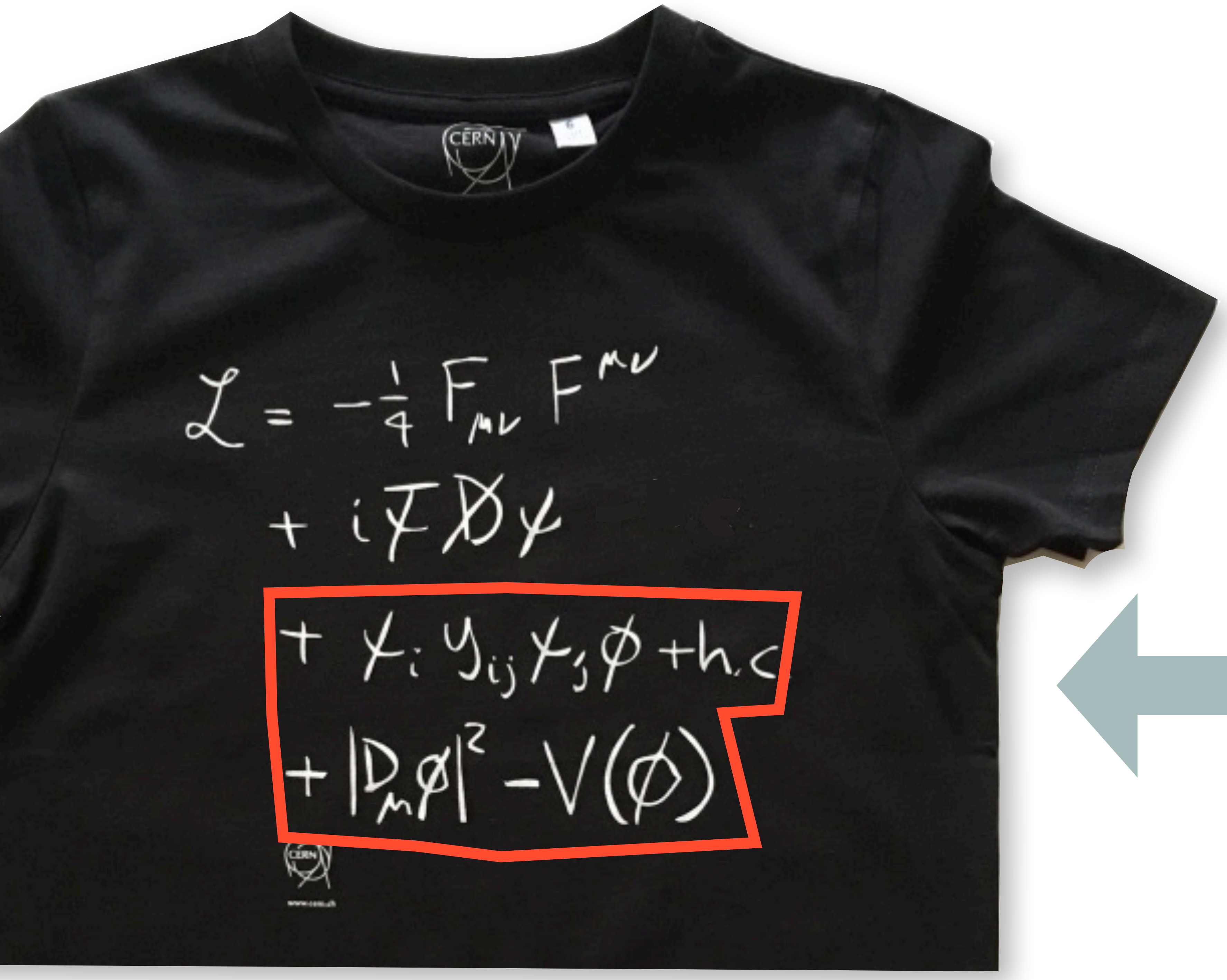
with much scope for inventing ingenious search techniques, and identifying novel models that could be probed

(And finding other things to do with the particles we have)

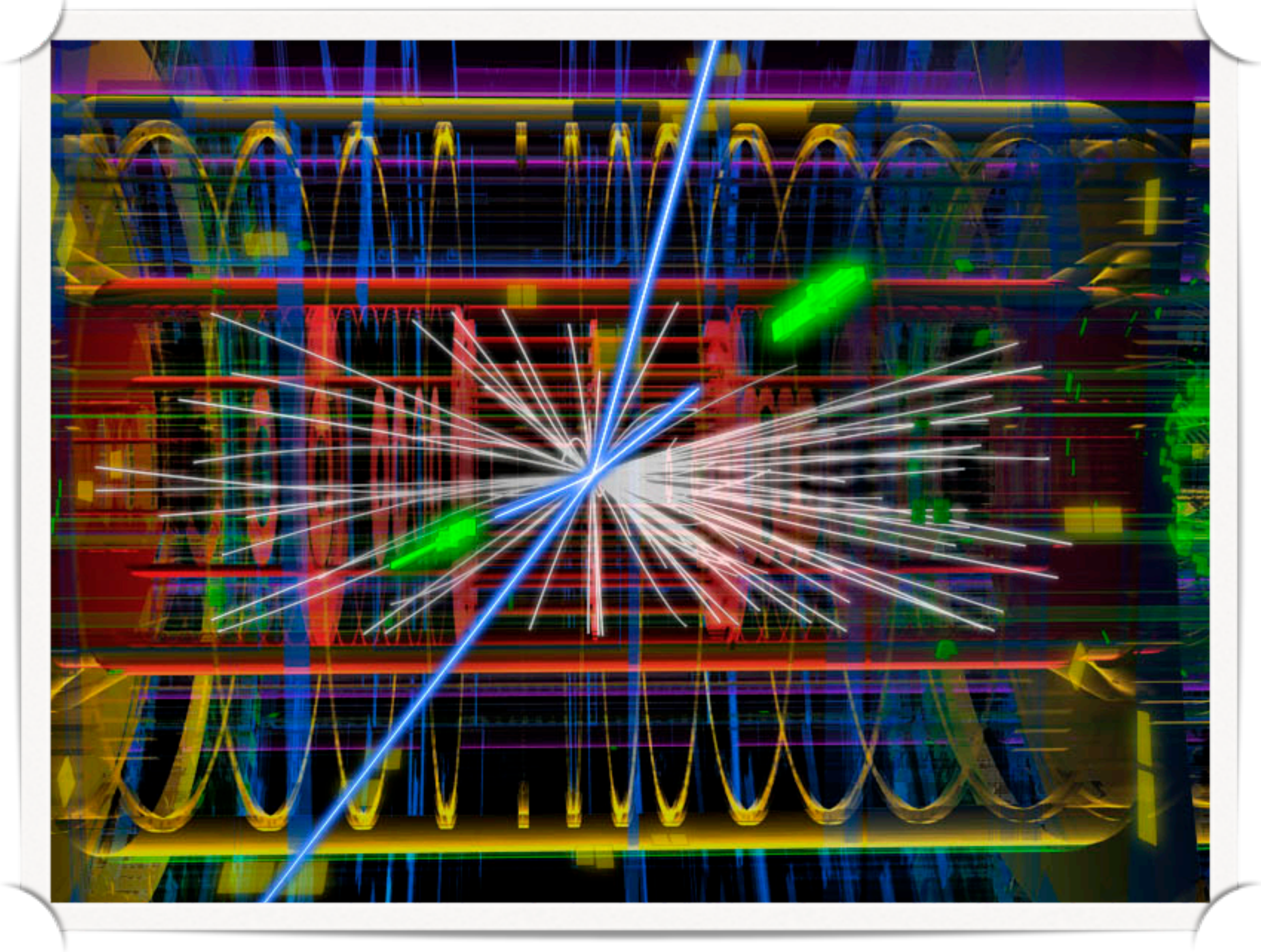
searches, Higgs & other standard-model physics share in common

the need to think about how we relate the underlying laws of particle physics with observations of $\sim 10^{16}$ high-energy proton collisions

UNDERLYING THEORY



EXPERIMENTAL DATA



how do you make a quantitative connection?

The subject of the next two talks