Higgs (soon) turns ten

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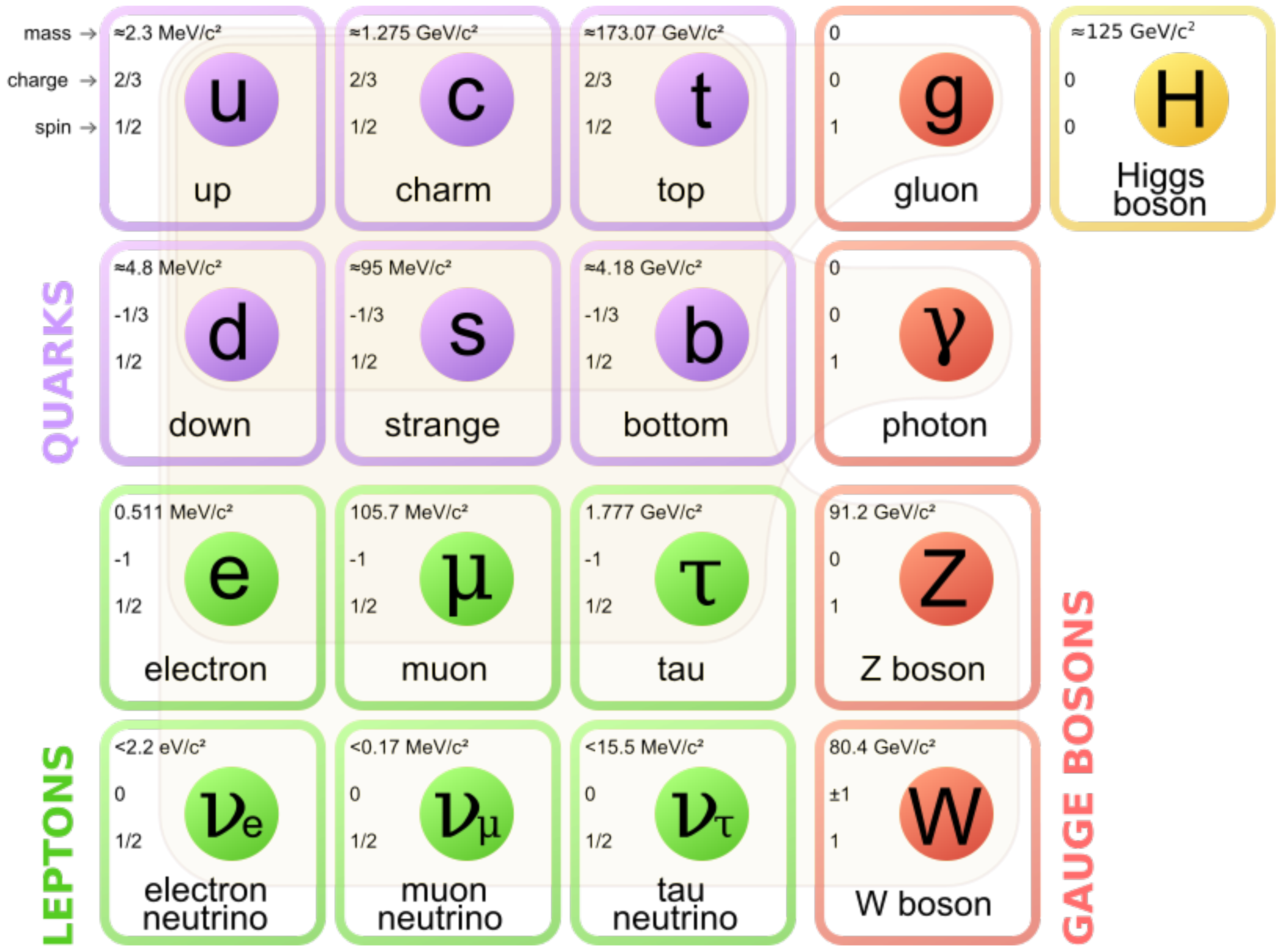
The Higgs boson



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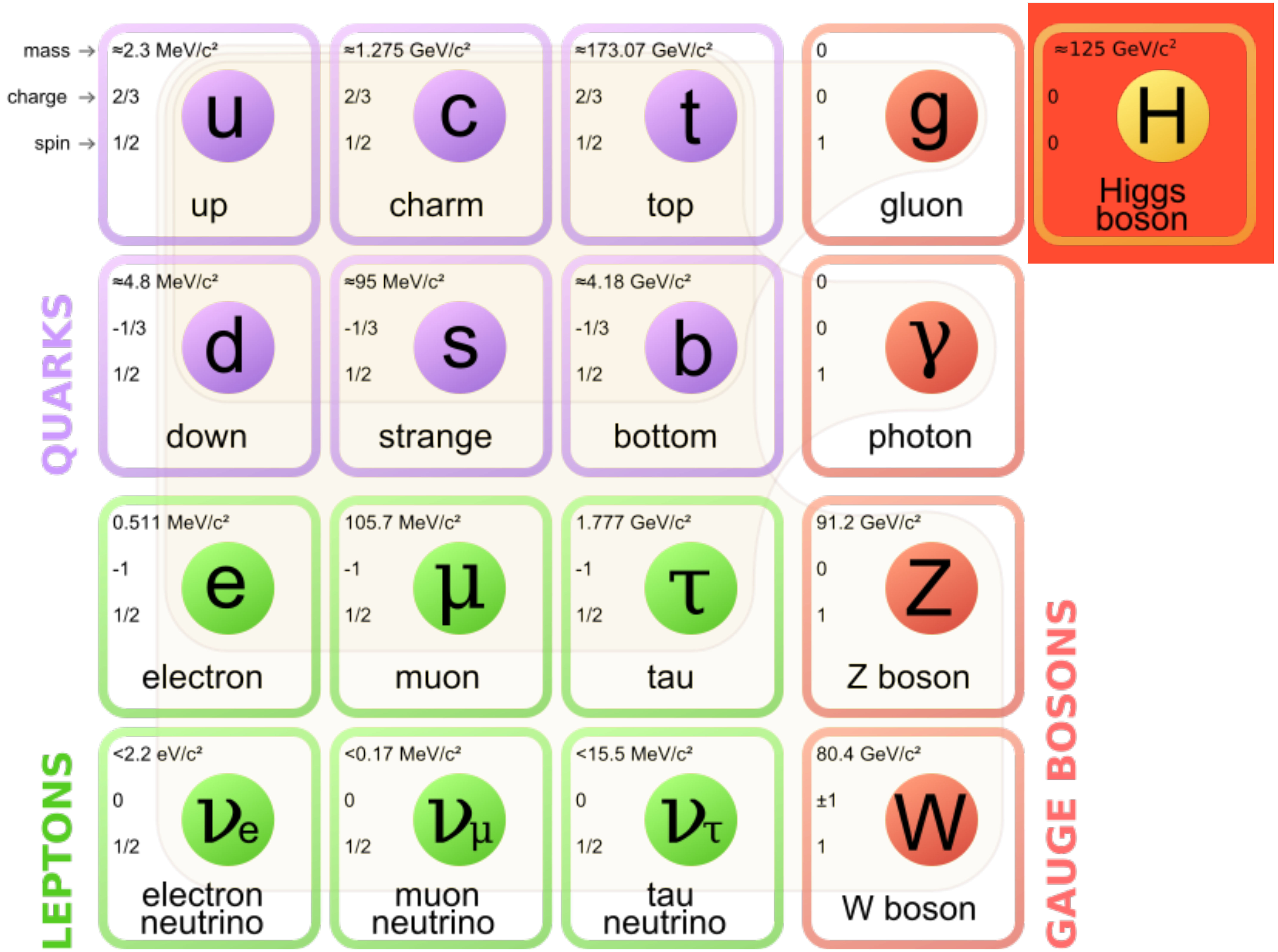
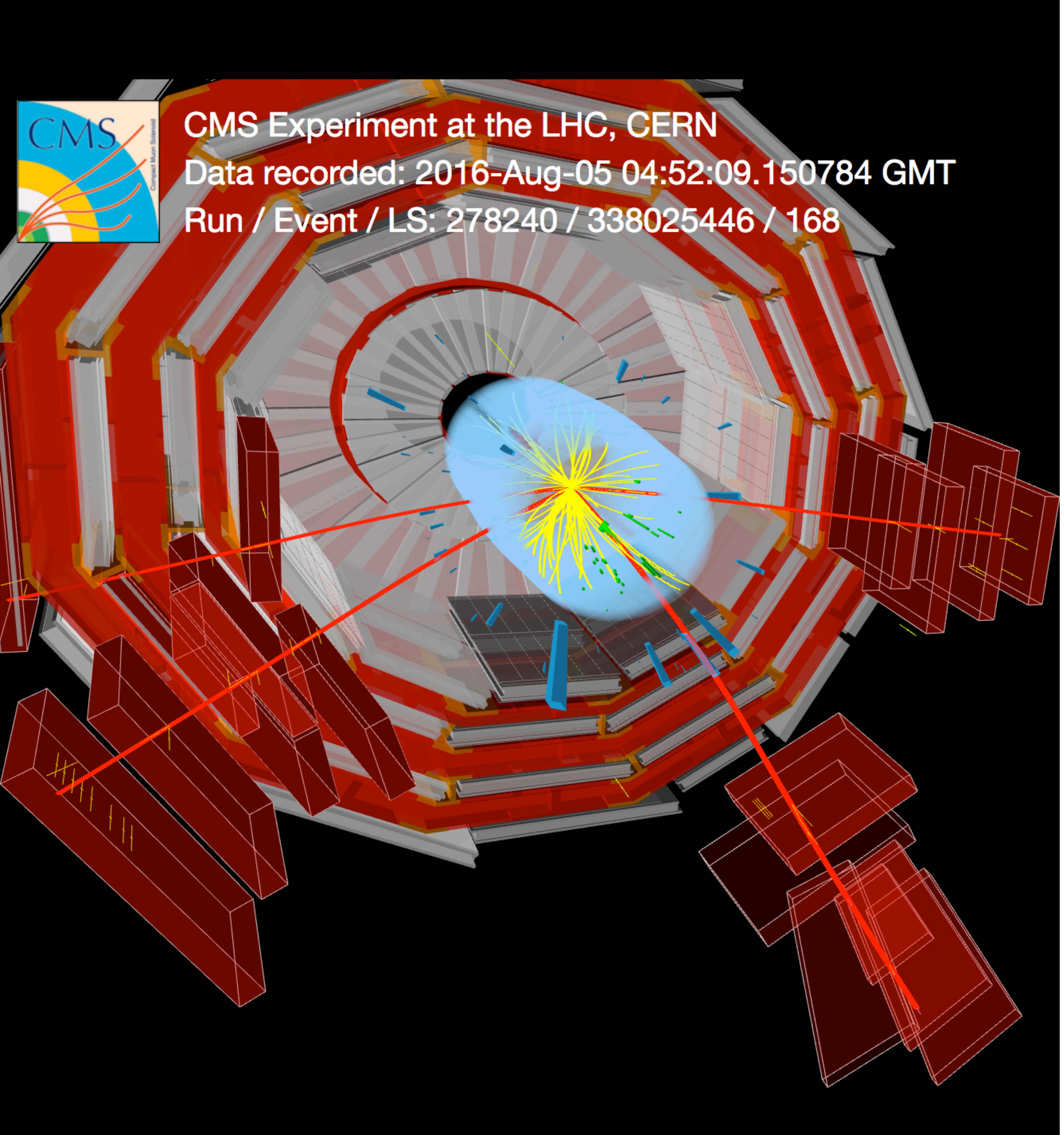




ATLAS and CMS collaborations at CERN's Large Hadron Collider (LHC):

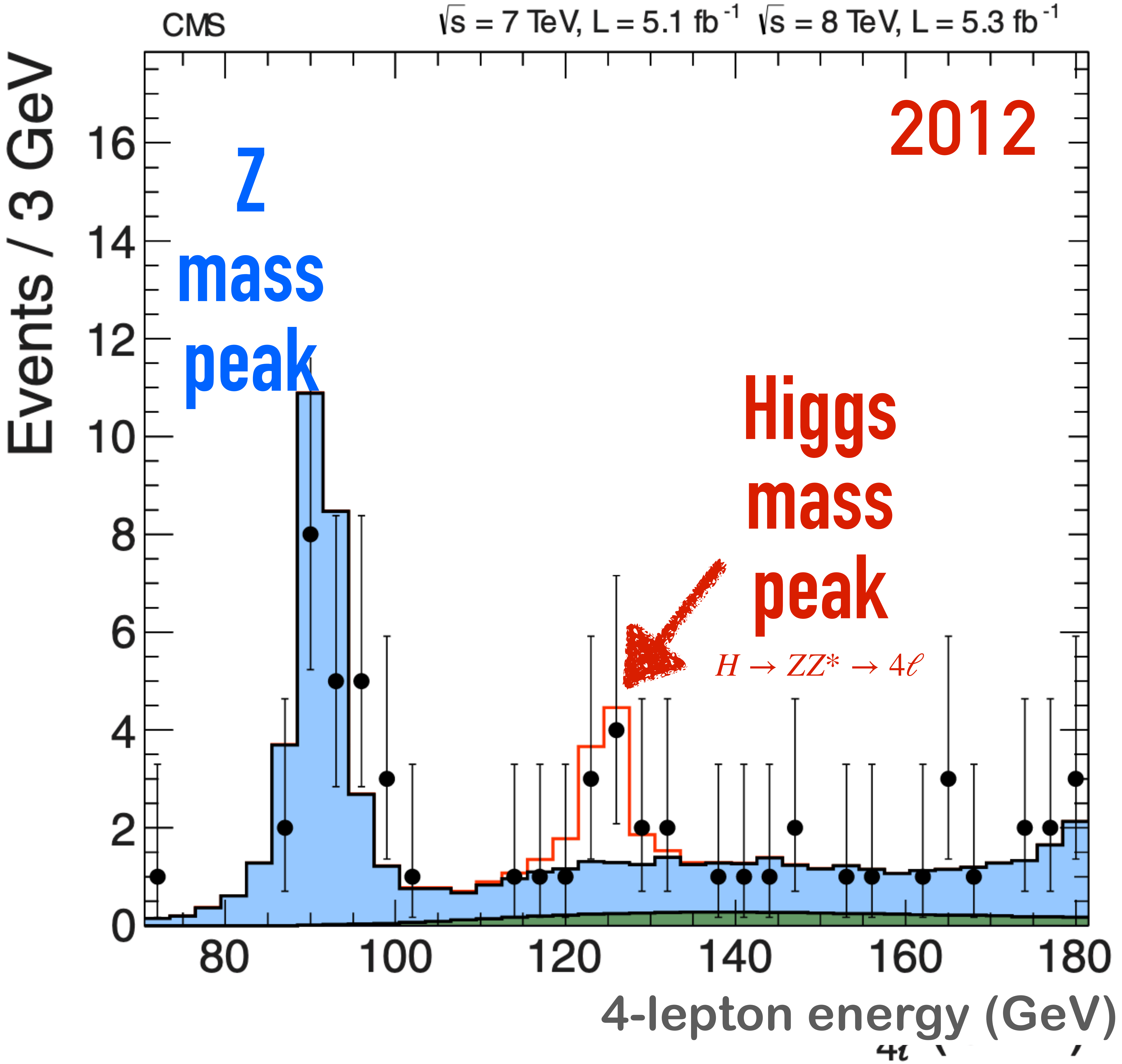
2012 discovery of a Higgs-like boson

Collide protons with protons

Select collision events with four electrons or muons ("leptons")

Add up their energies (in their overall centre-of-mass frame)

Plot distribution of that energy



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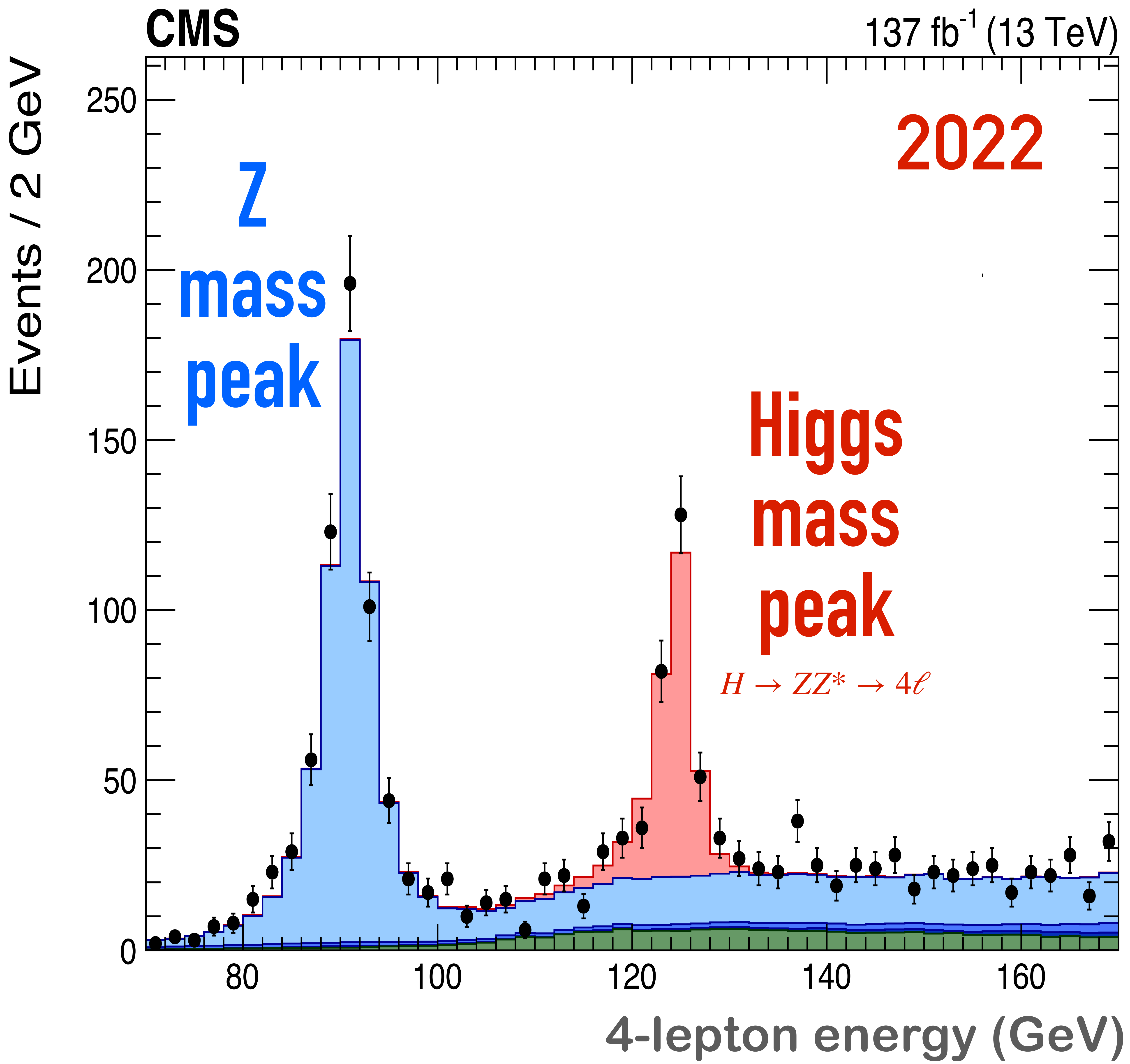

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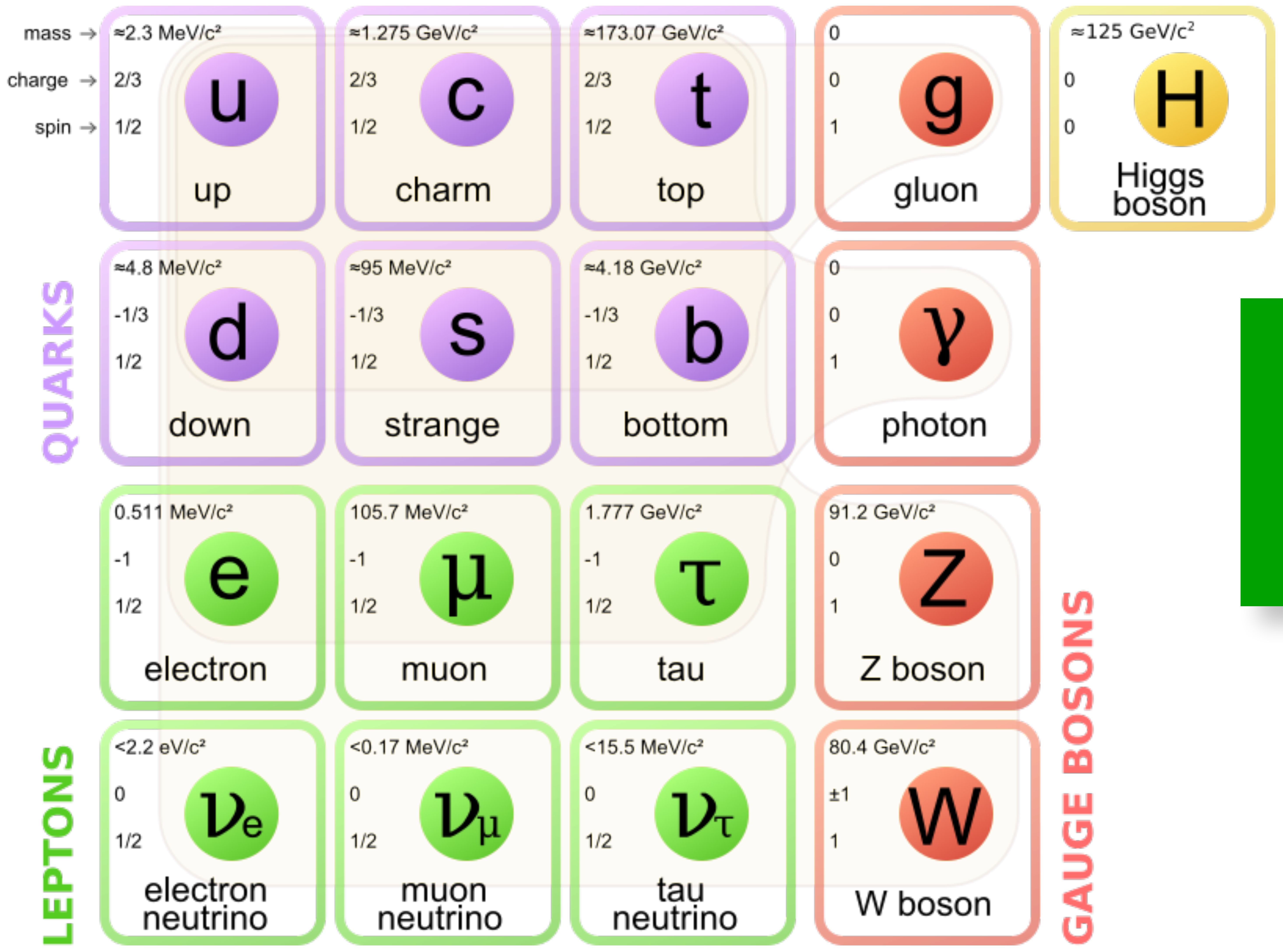
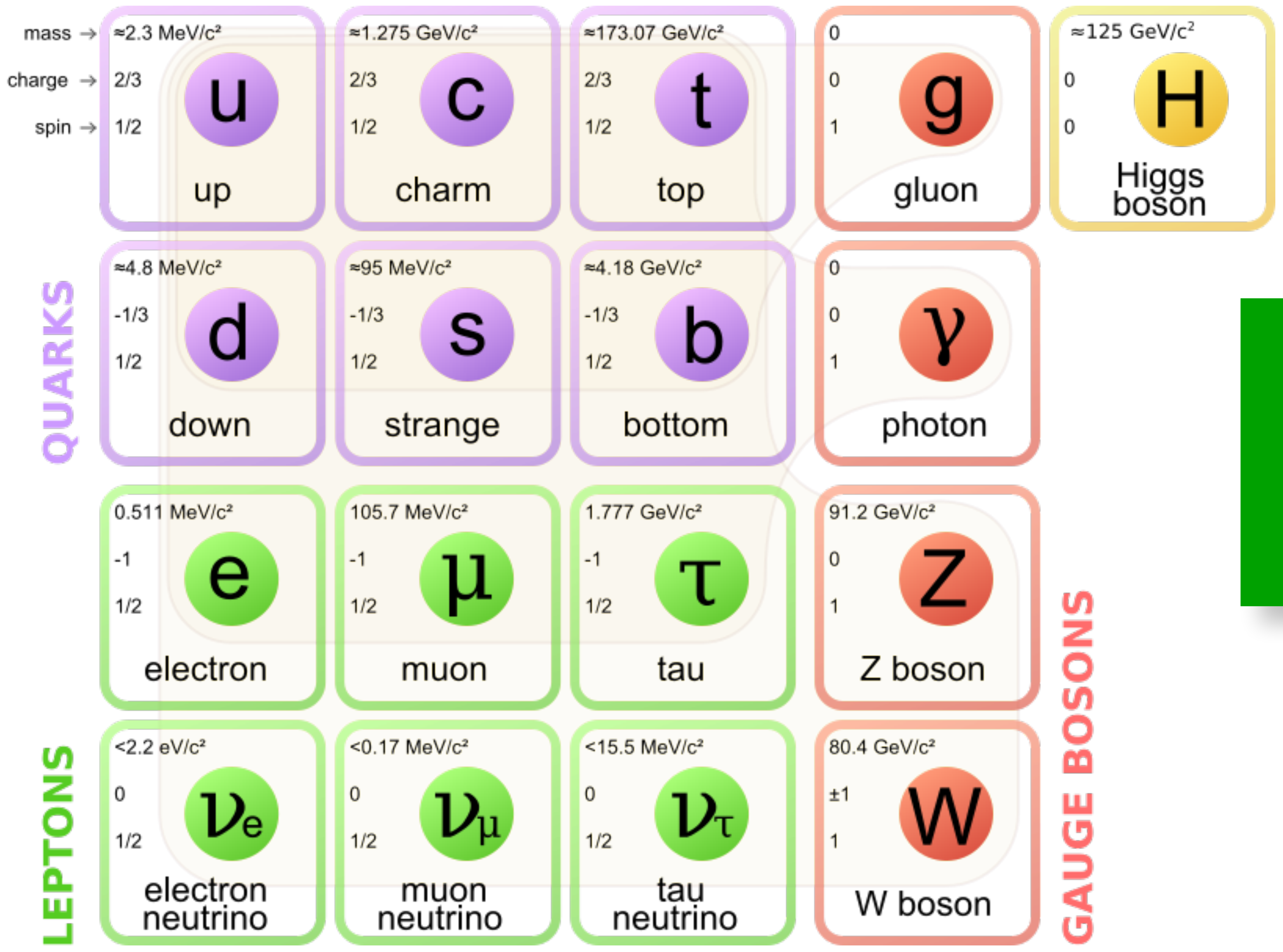


Success!

“The Standard Model is complete”

The Higgs boson (2012)



Success!

"The Standard Model particle set is complete"

particles

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particles

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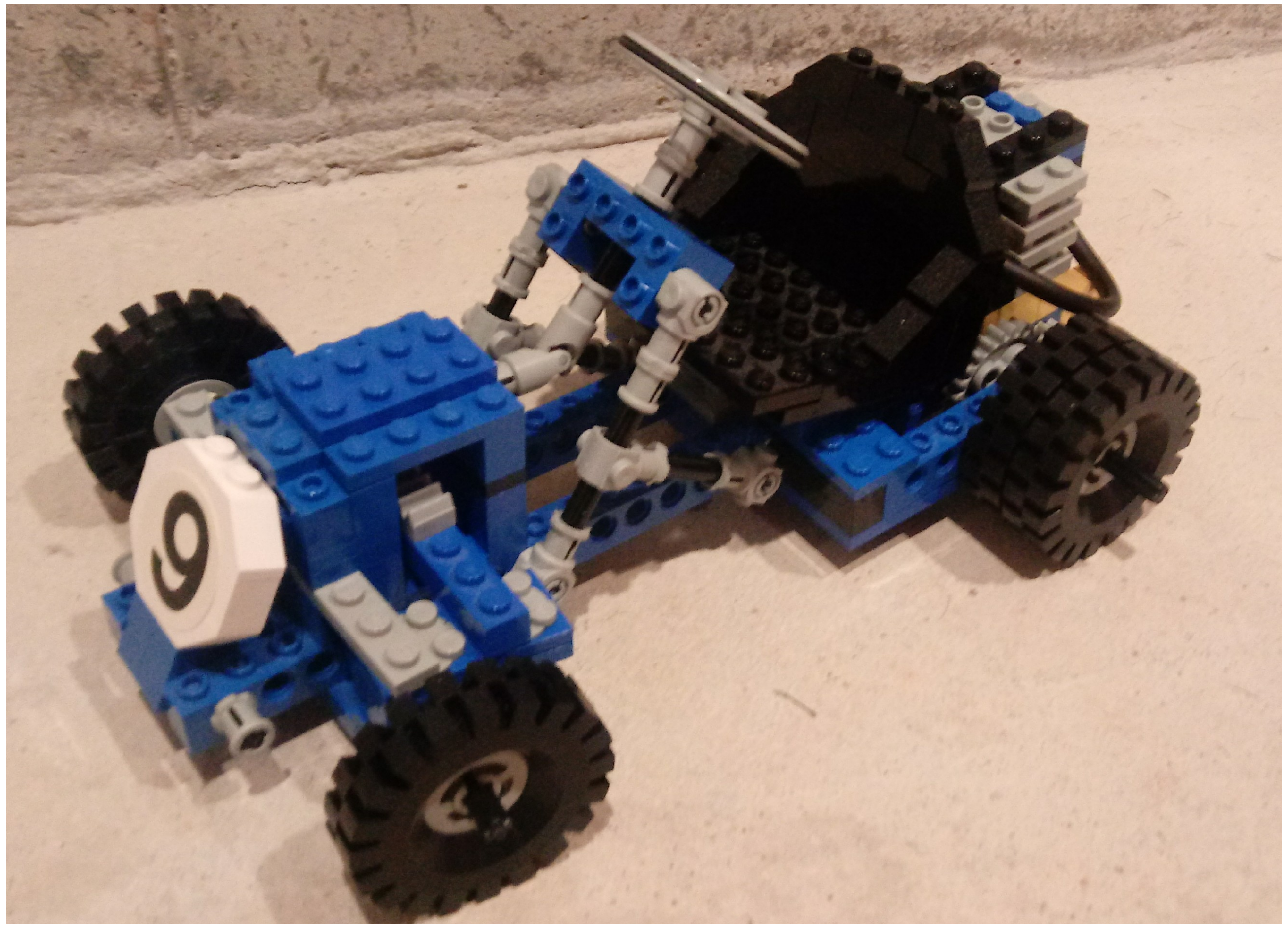
particles + interactions



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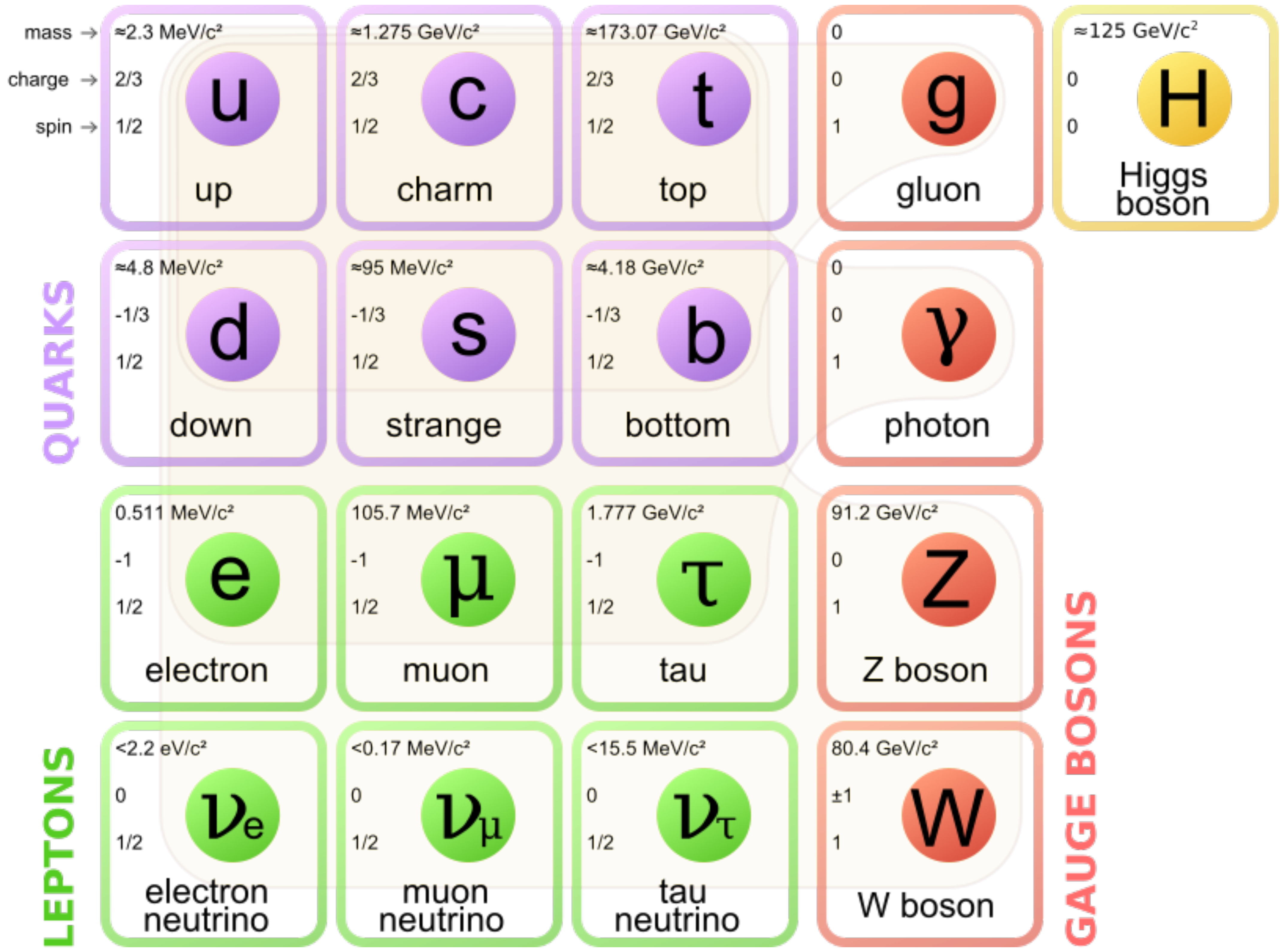
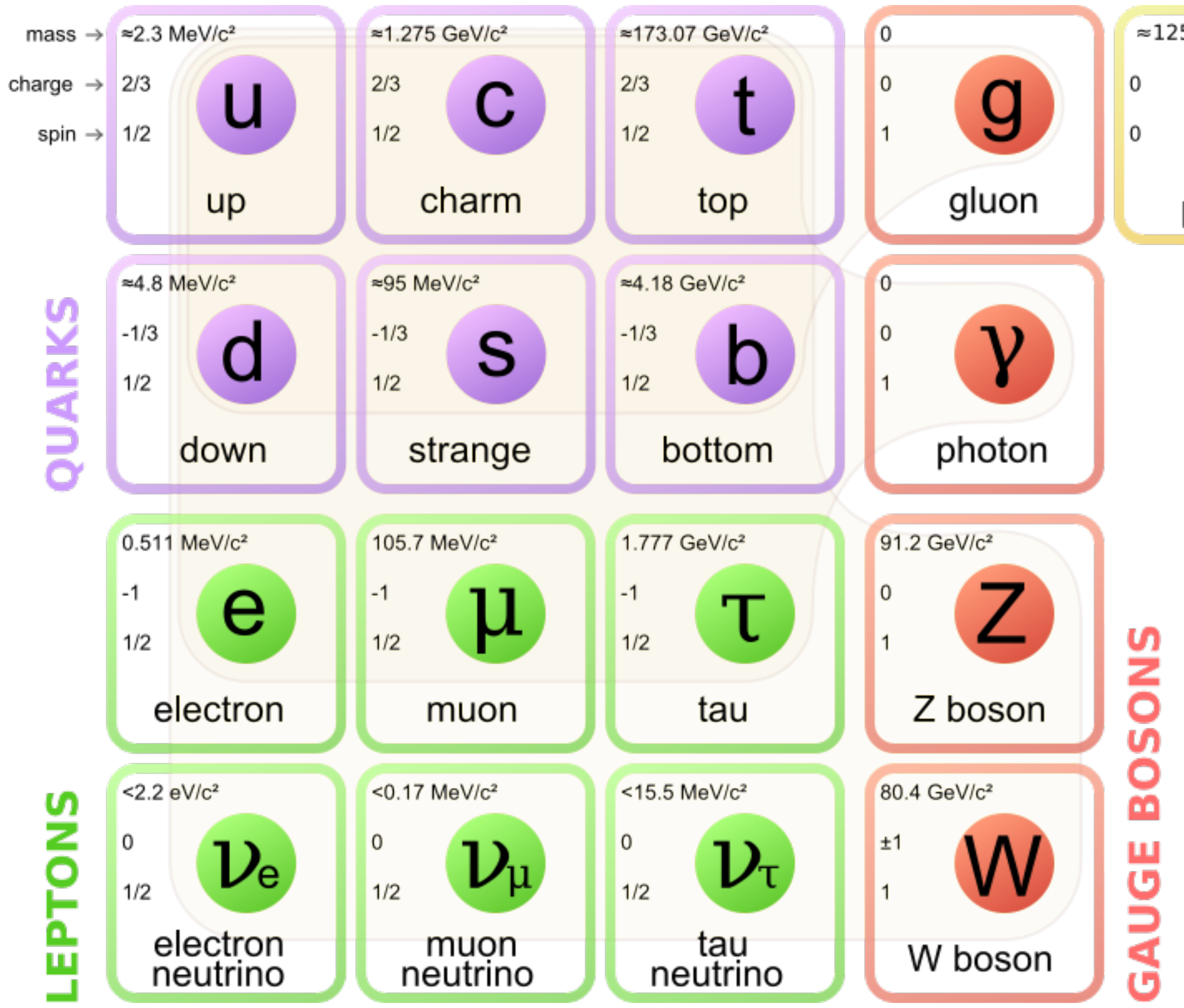
what is the Standard Model?

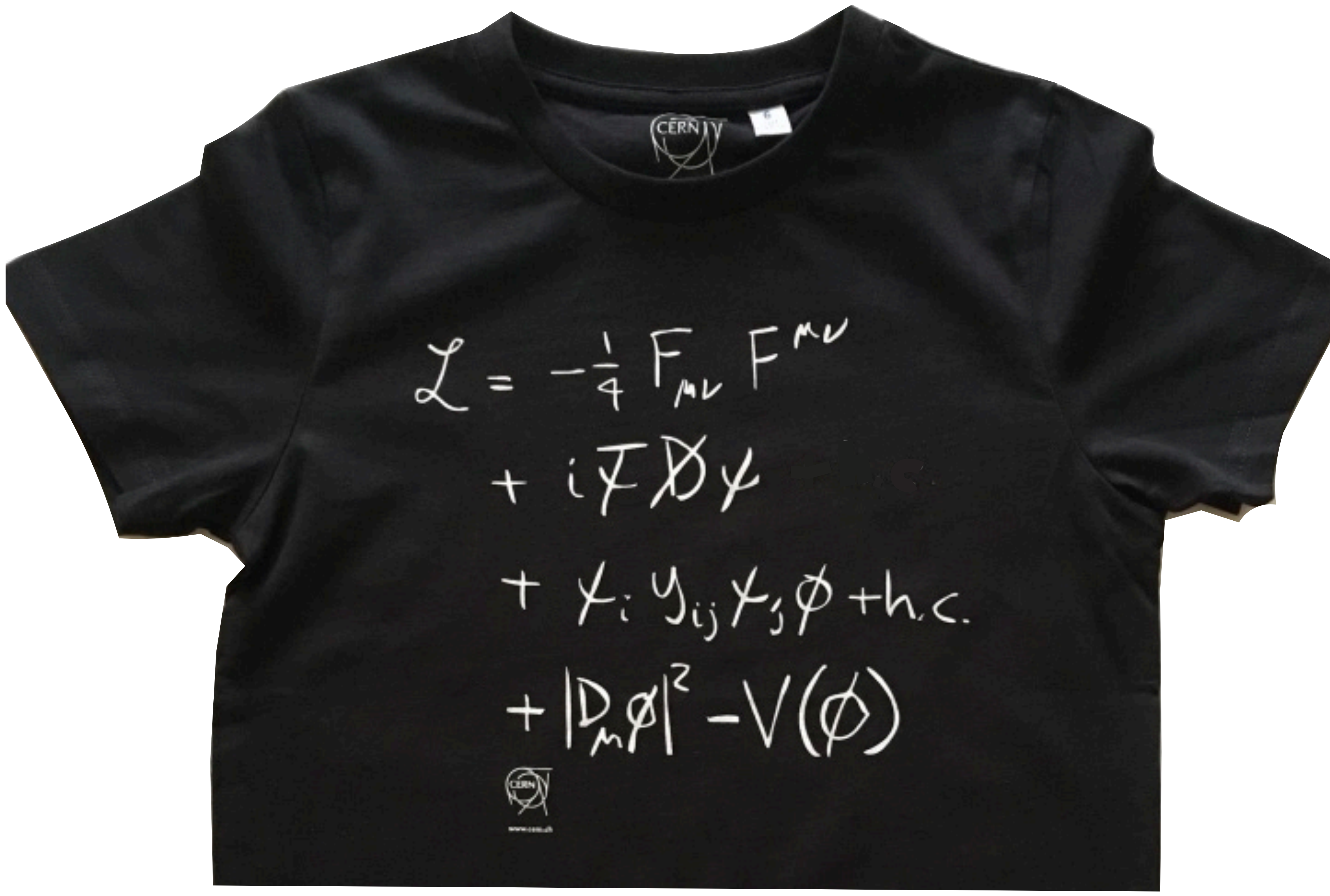


particles

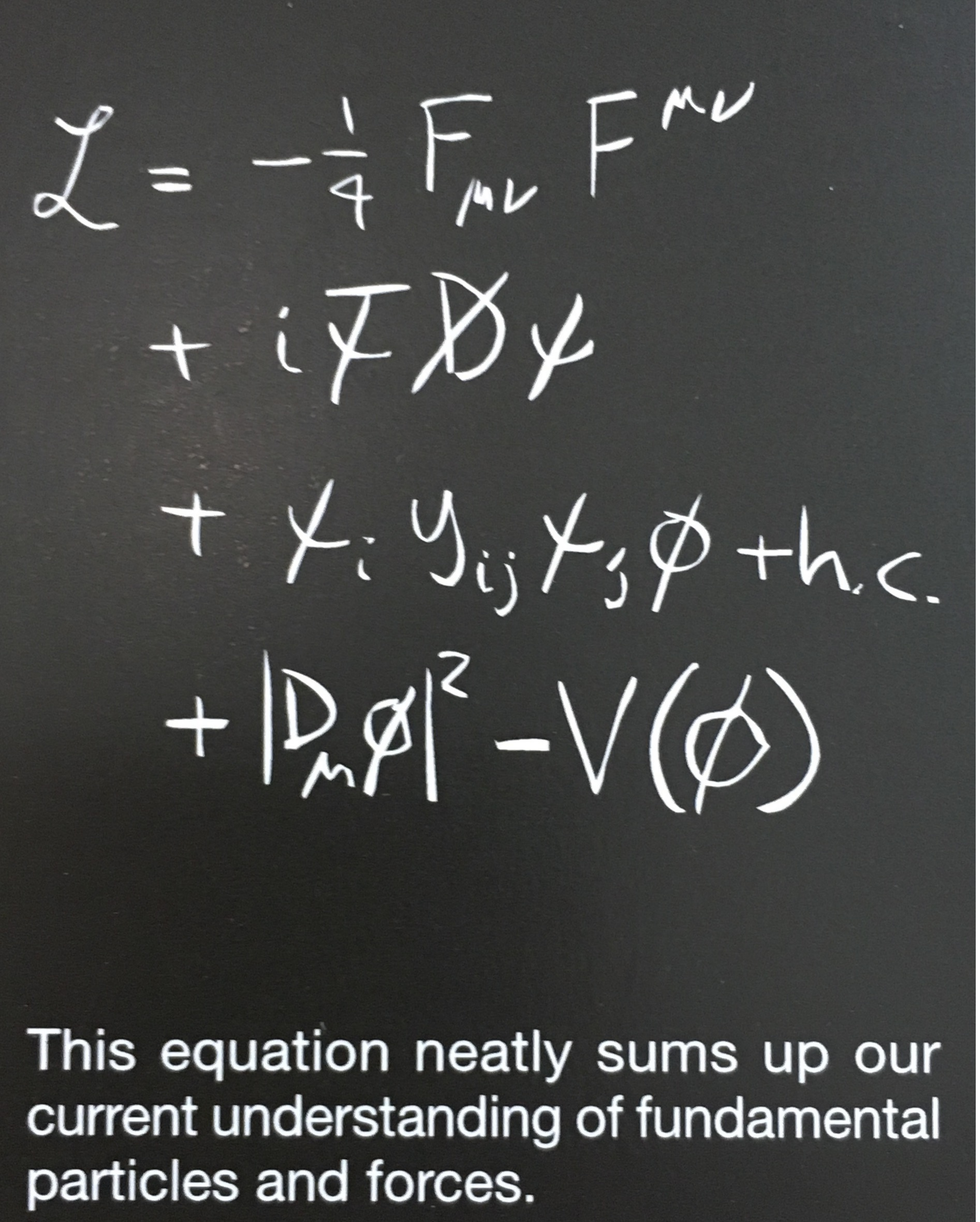
what is the Standard Model?



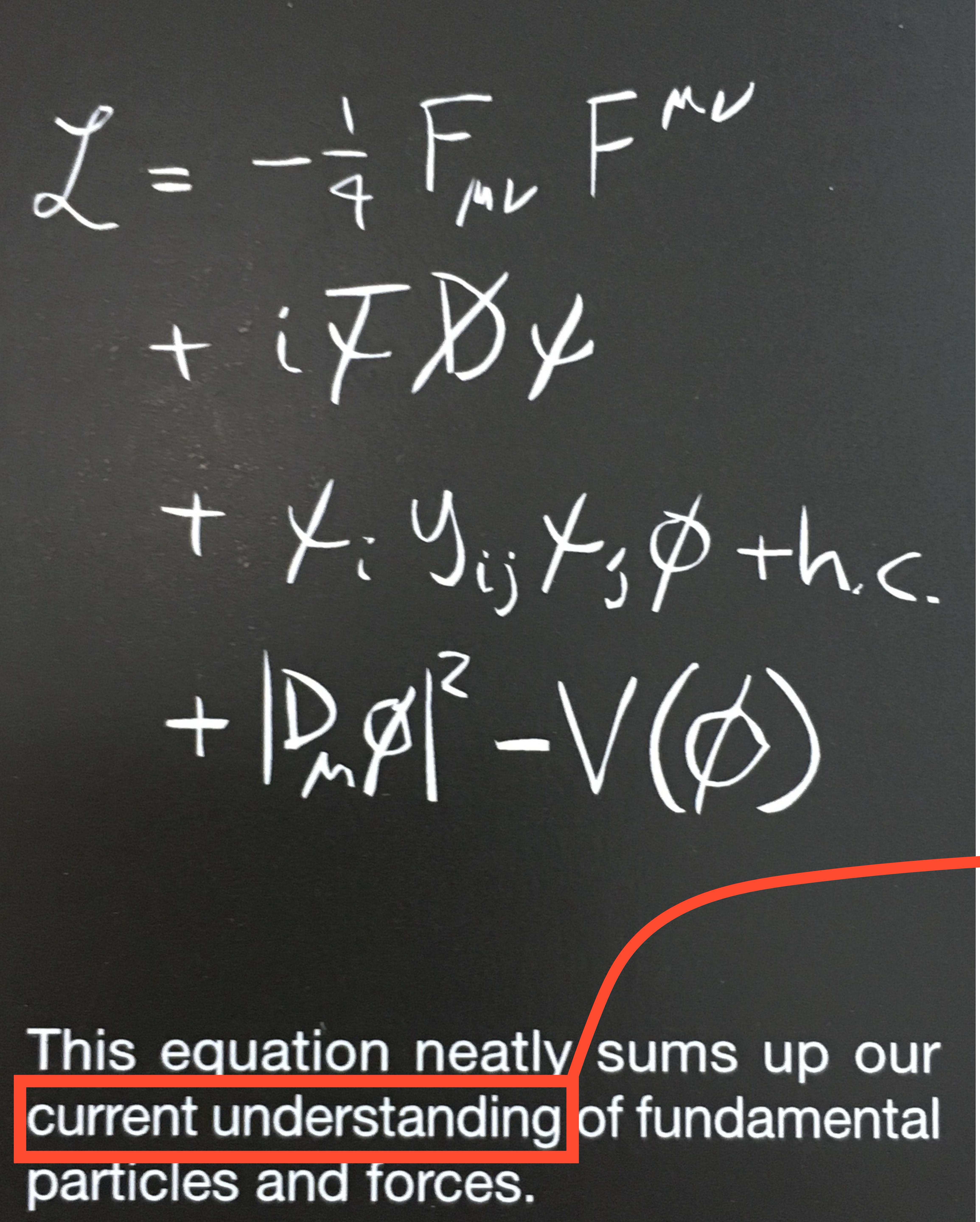
particles



interactions



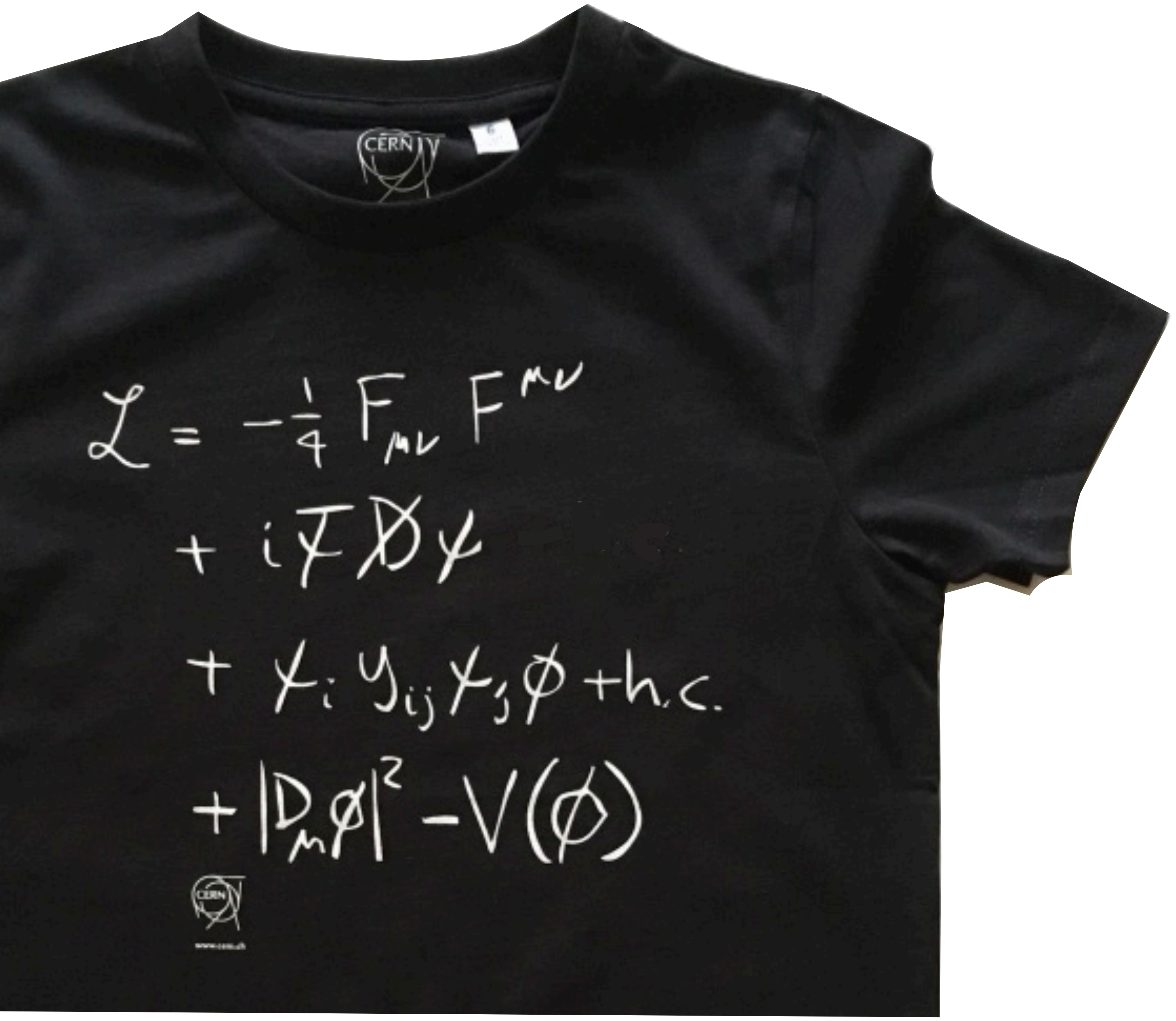
These T-shirts come with a little explanation



These T-shirts come with a little explanation

"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 $(\bar\nu_L, \bar e_L), (\bar u_L, \bar d_L), (-\bar e_L, \bar\nu_L), (-\bar d_L, \bar u_L), \bar\phi$, $\mathbf{W}_\mu$, $\binom{\nu_L}{e_L}, \binom{u_L}{d_L}, \binom{-e_L}{\nu_L}, \binom{-d_L}{u_L}, \phi$.

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 $A_\mu, Z_\mu, W_\mu^\pm$,

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}\mathcal{W}_{\mu\nu}^-\mathcal{W}^{+\mu\nu} + \begin{pmatrix}\text{higher}\\ \text{order terms}\end{pmatrix}, \tag{11}$$

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

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

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

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,

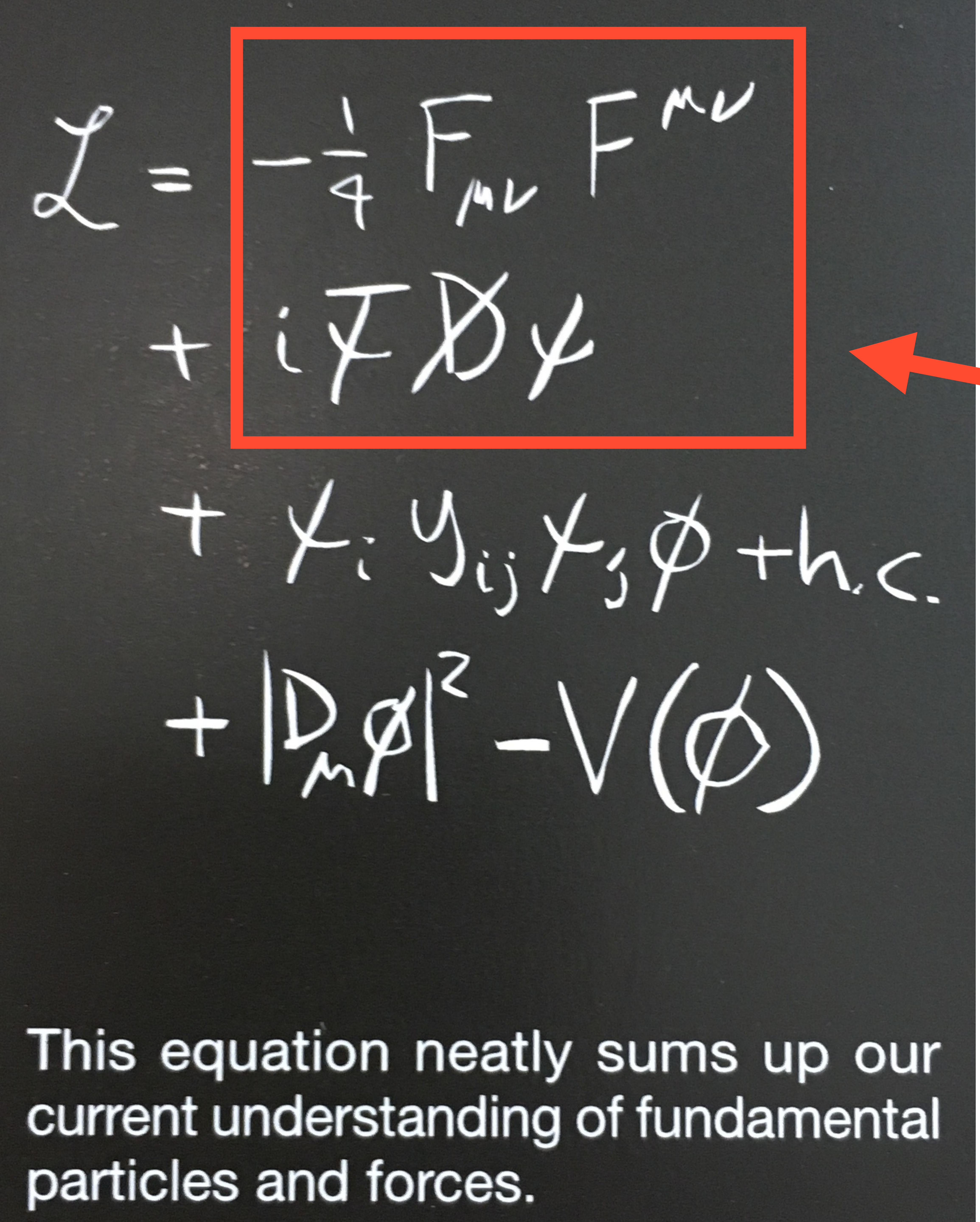
$$\mathbf{W}_\mu \to U\mathbf{W}_\mu U^\dagger - (2i/g_2)U\partial_\mu U^\dagger, \quad \mathbf{W}_{\mu\nu} \to U\mathbf{W}_{\mu\nu}U^\dagger, \quad B_\mu \to B_\mu + (2/g_1)\partial_\mu\theta, \quad B_{\mu\nu} \to B_{\mu\nu}, \quad \phi \to e^{-i\theta}U\phi, \tag{28}$$

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

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

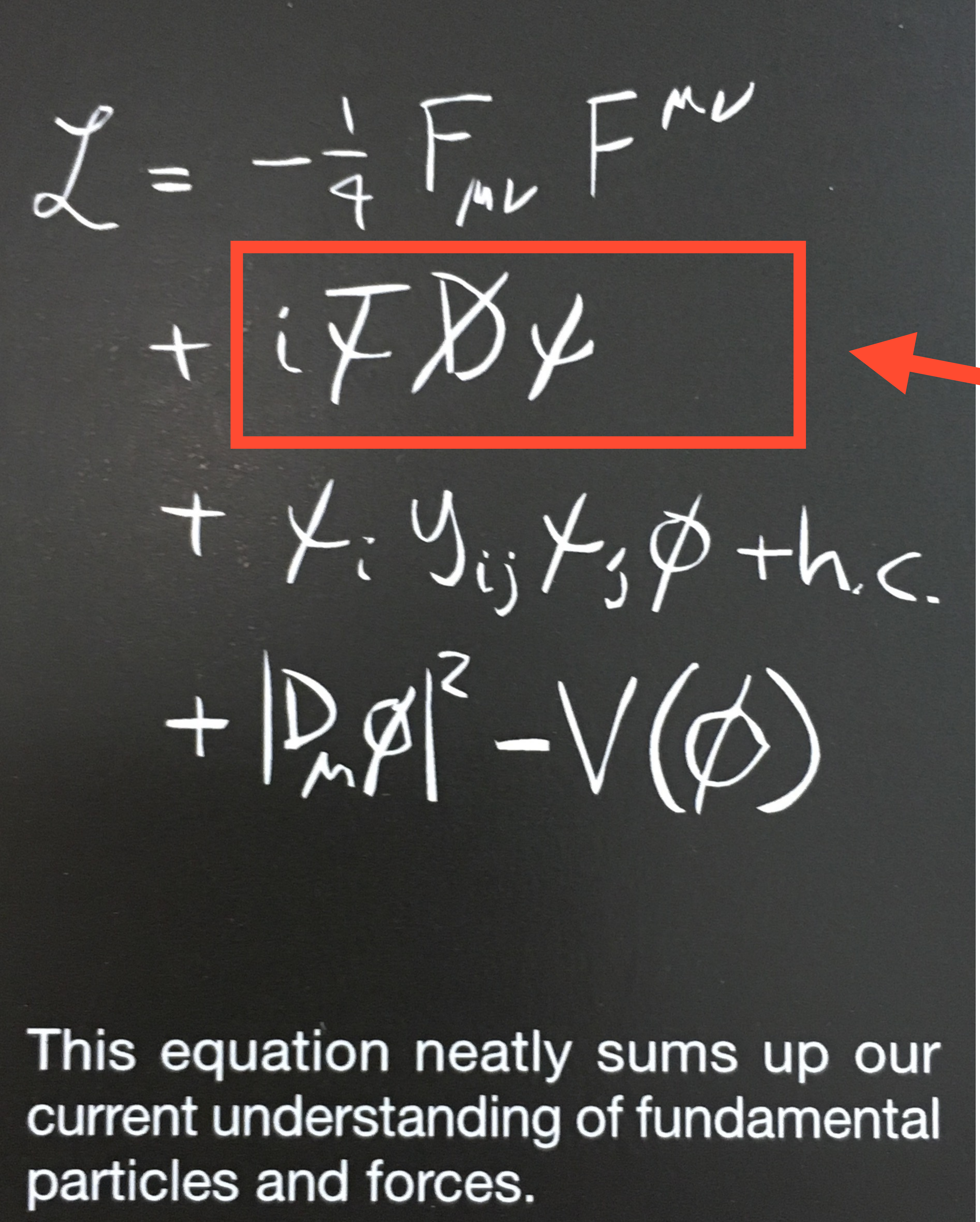
$$\mathbf{G}_\mu \to V\mathbf{G}_\mu V^\dagger - (i/g)V\partial_\mu V^\dagger, \quad \mathbf{G}_{\mu\nu} \to V\mathbf{G}_{\mu\nu}V^\dagger, \quad u_L \to Vu_L, \quad d_L \to Vd_L, \quad u_R \to Vu_R, \quad d_R \to Vd_R. \tag{30}$$

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



What does it mean?

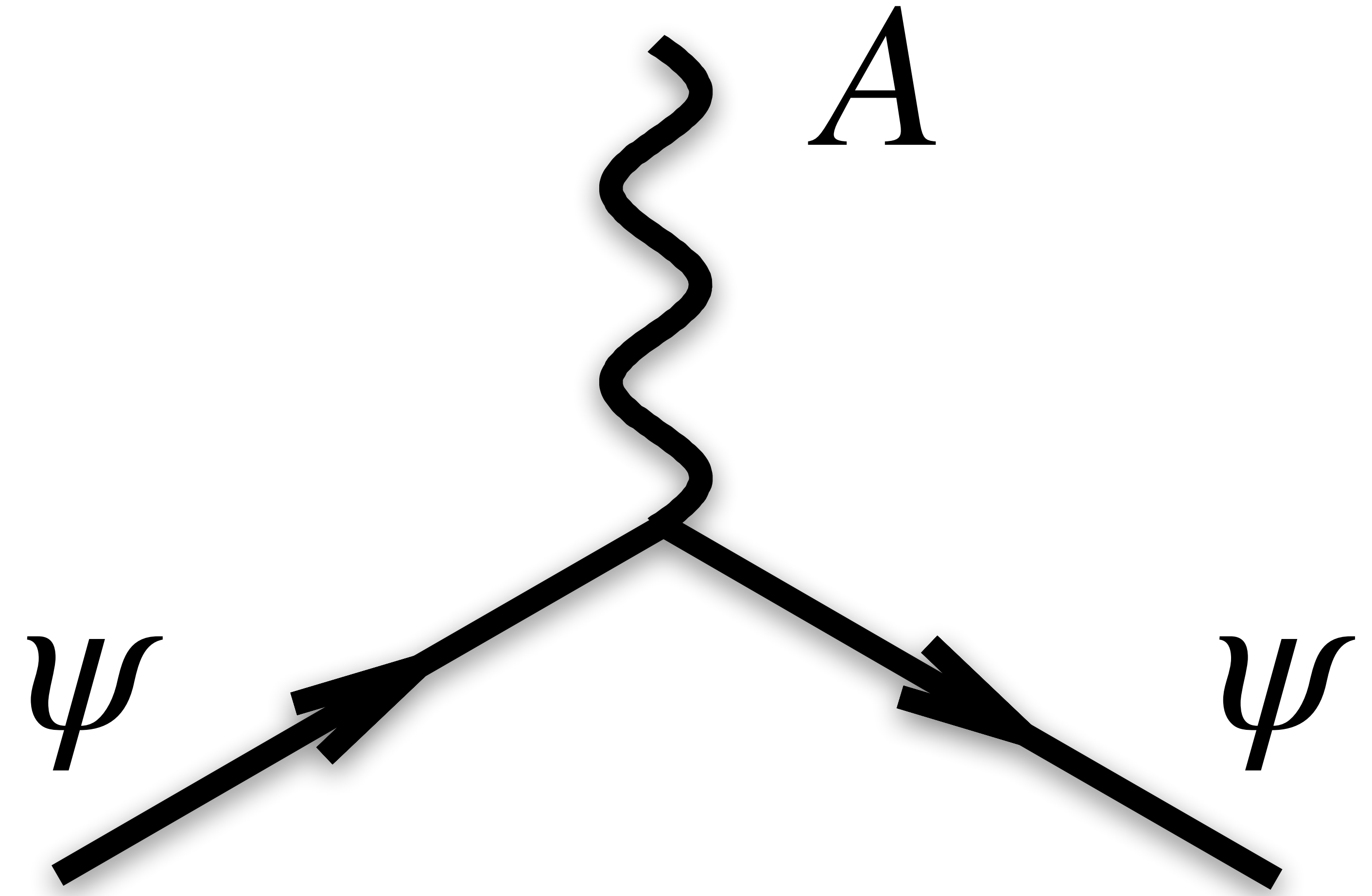
Quantum formulation of Maxwell's equations, (and their analogues for the weak and strong forces).



What does it mean?

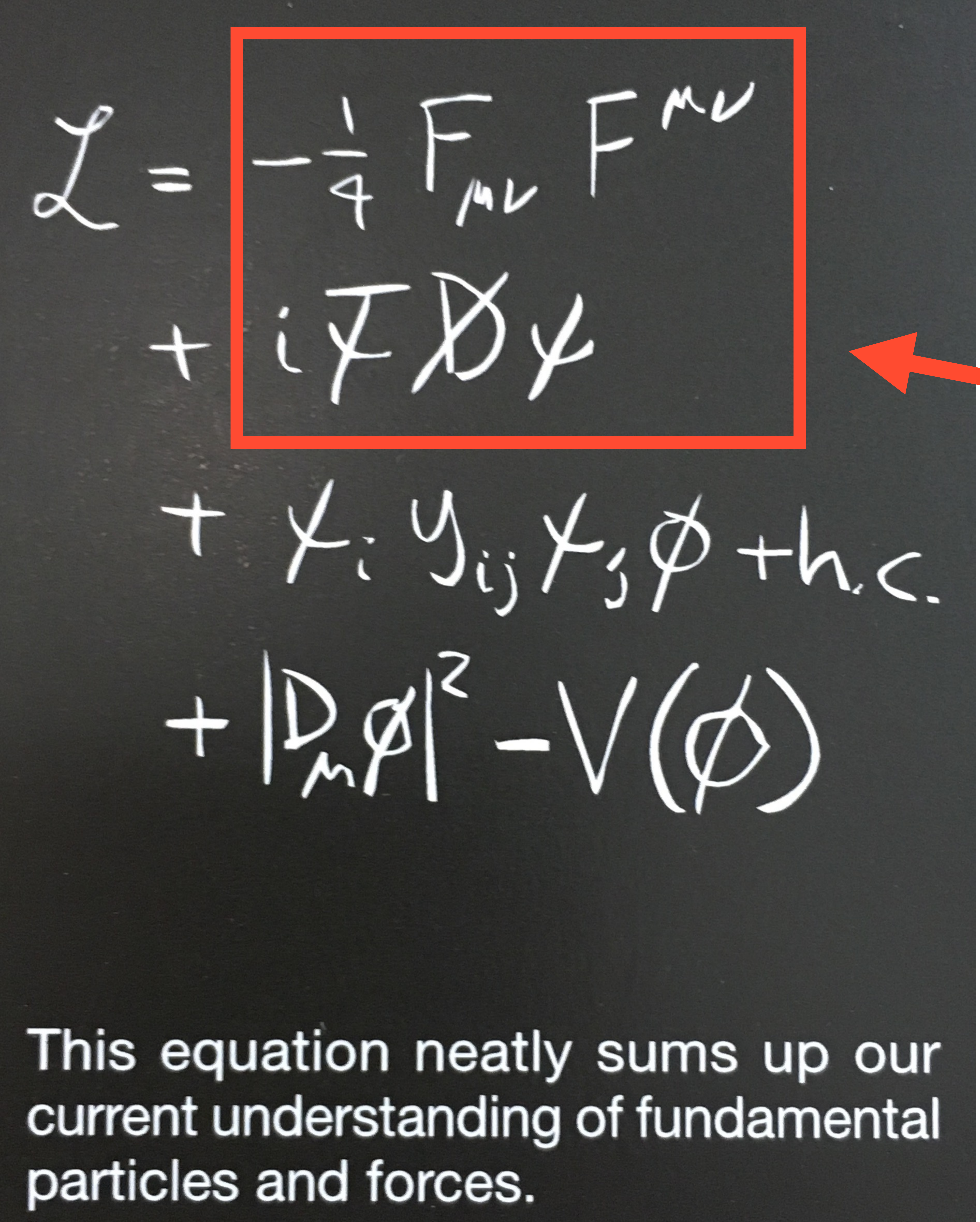
ψ = *fermion (e.g. electron) field*

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



tells you there's an

electron-photon interaction vertex

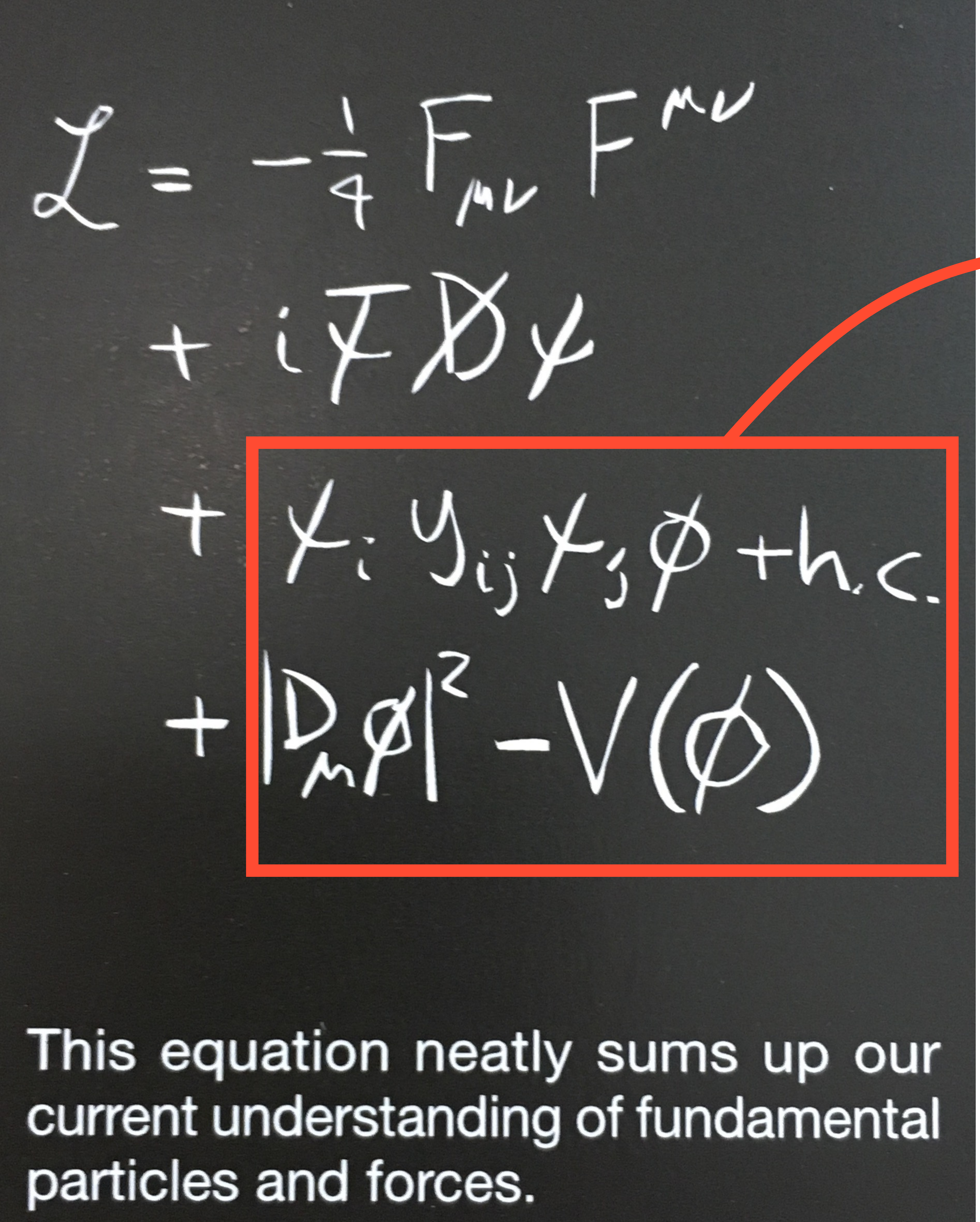


What does it mean?

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.

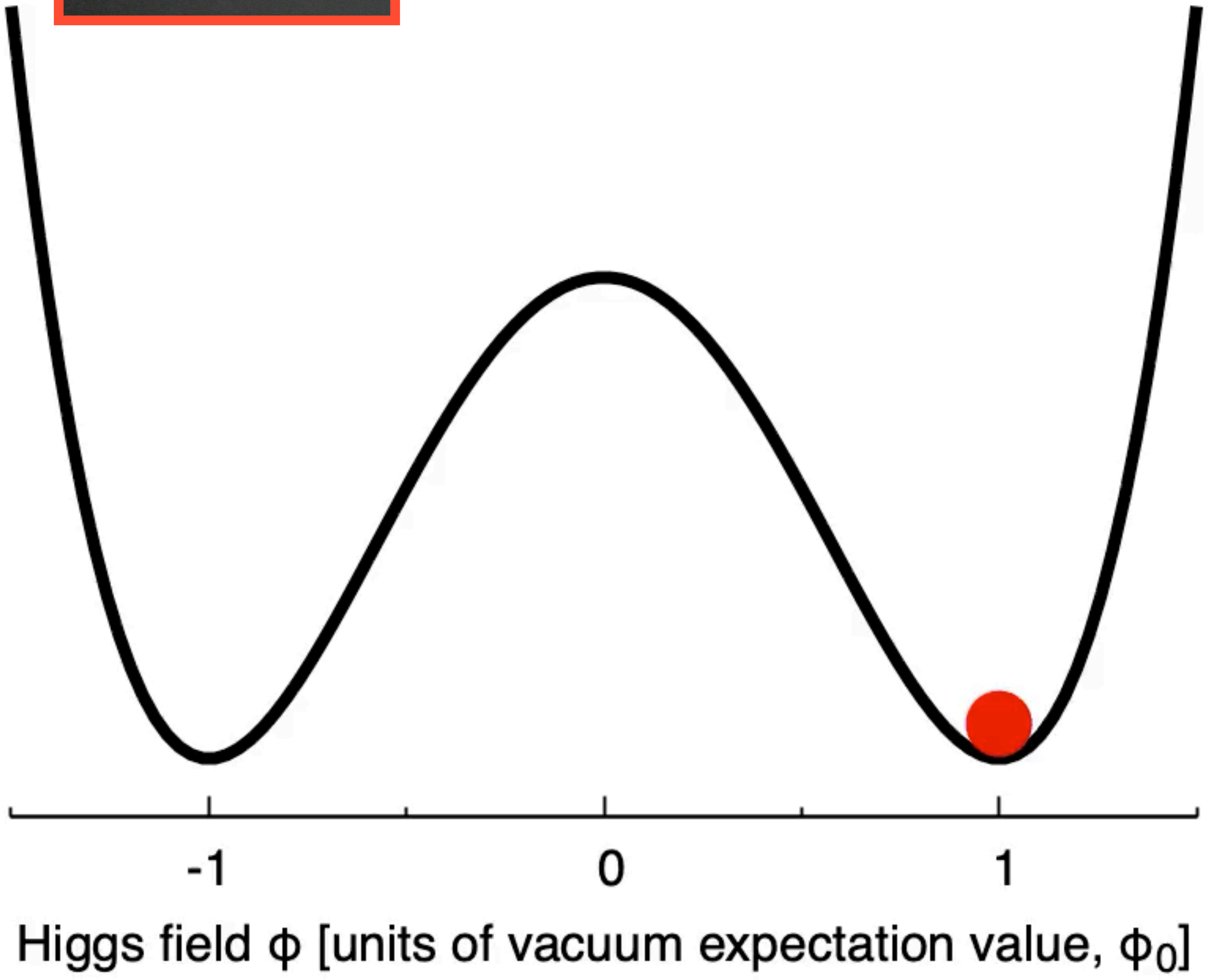
They work to high precision (best tests go up to 1 part in 10^8)



Higgs sector

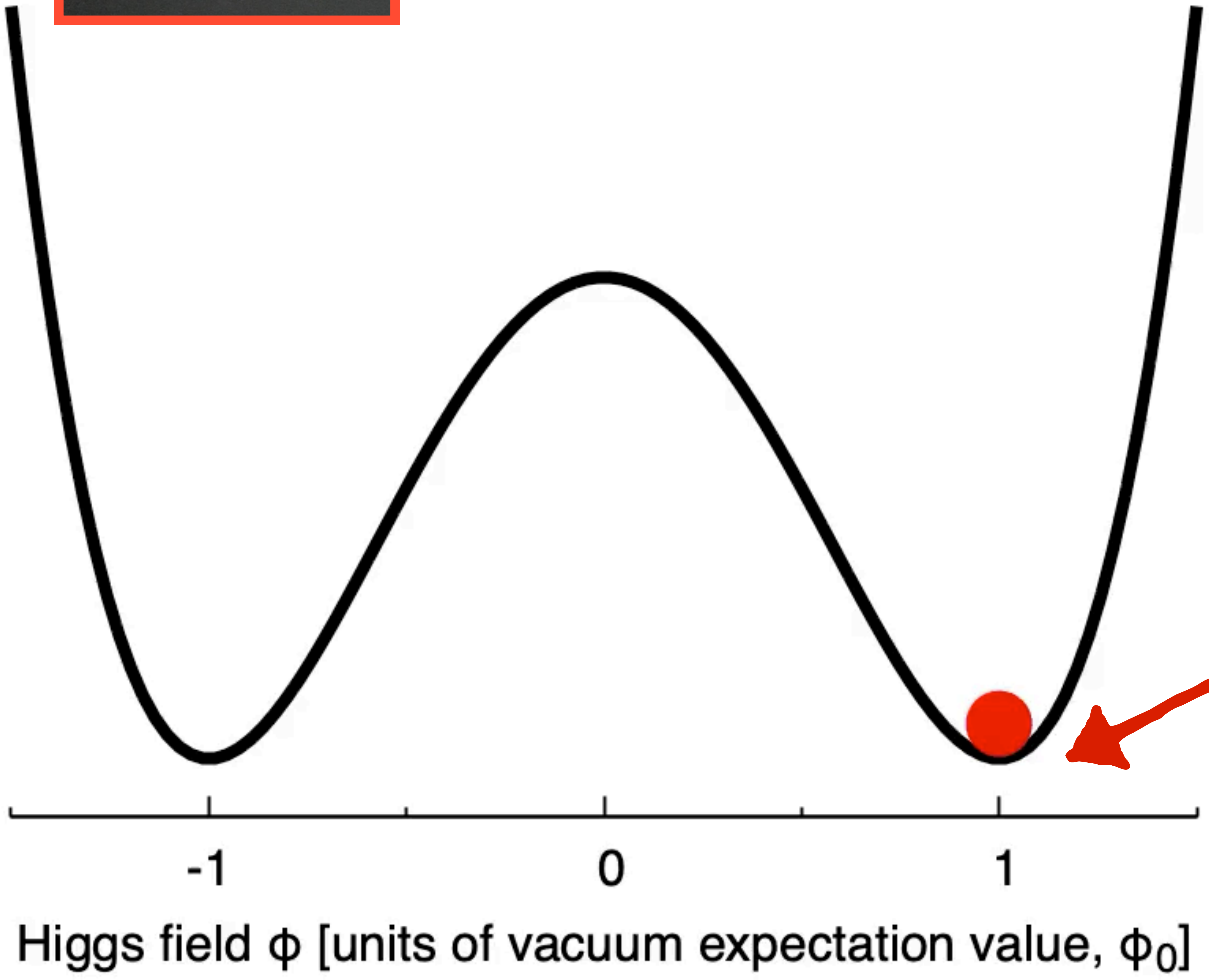
until 10 years ago none of these terms had ever been directly observed.

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



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

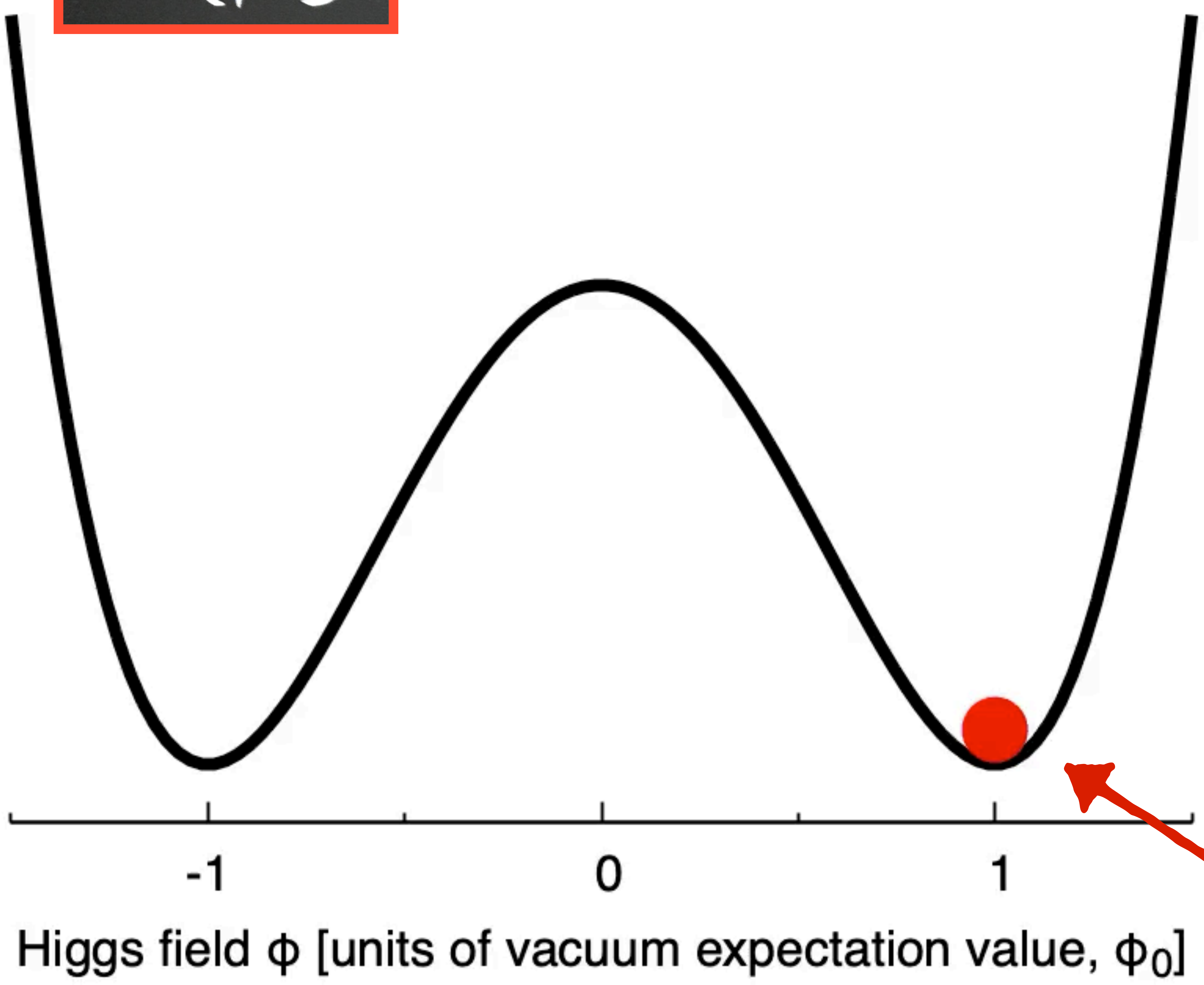
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



- 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

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

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



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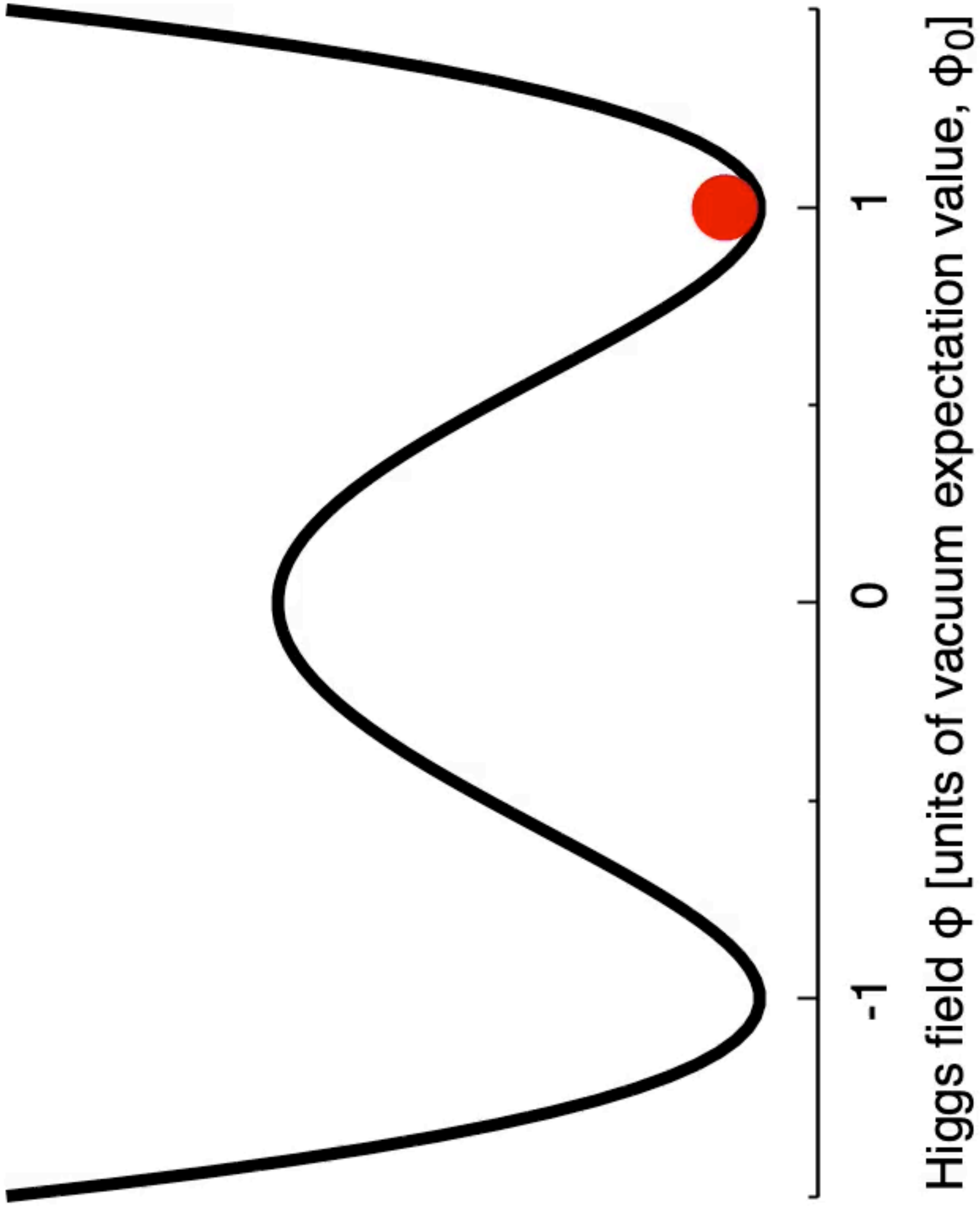
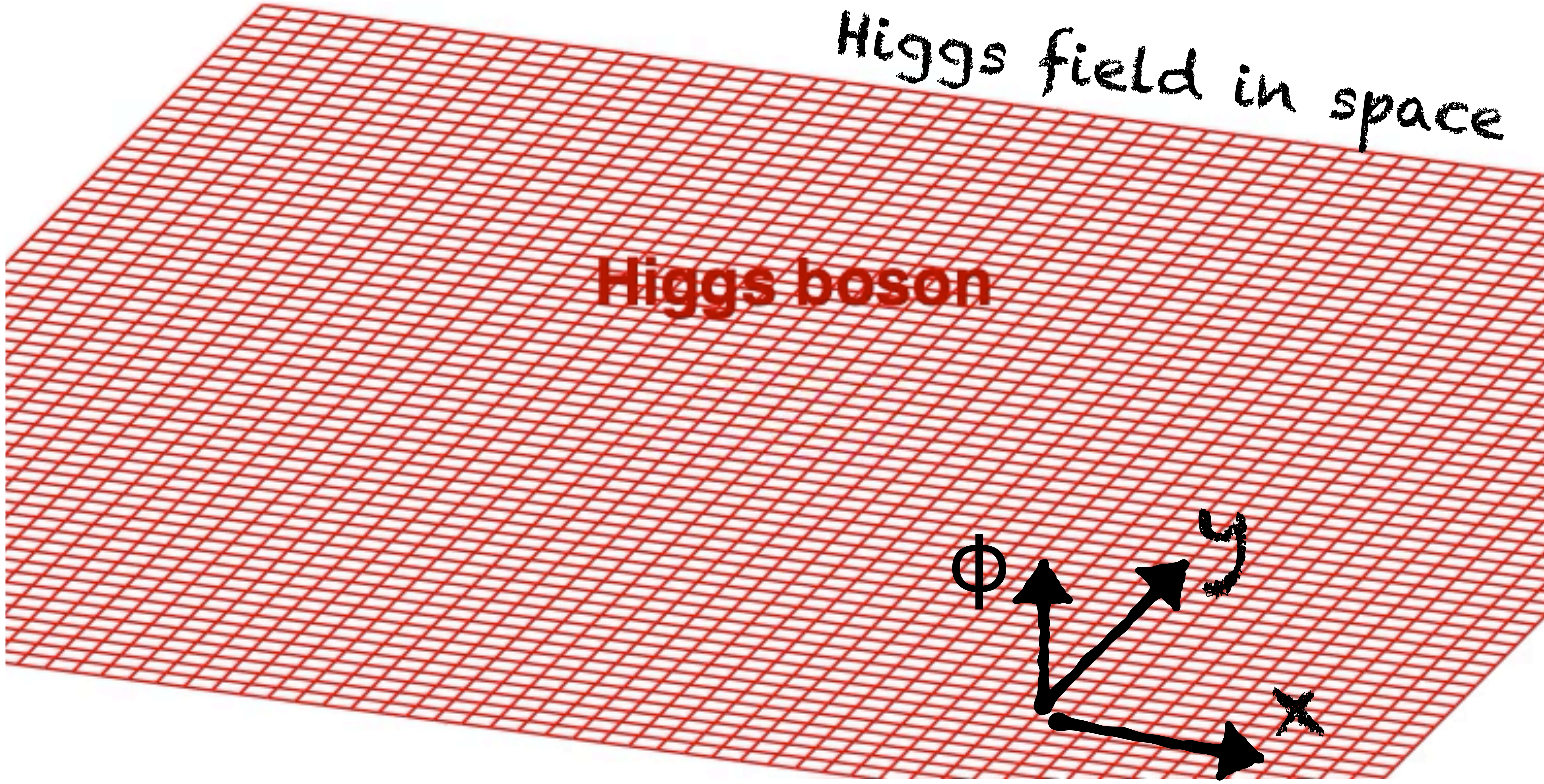
- Our universe sits at minimum of V(φ), at

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

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

$$\varphi = \varphi_0 + H$$

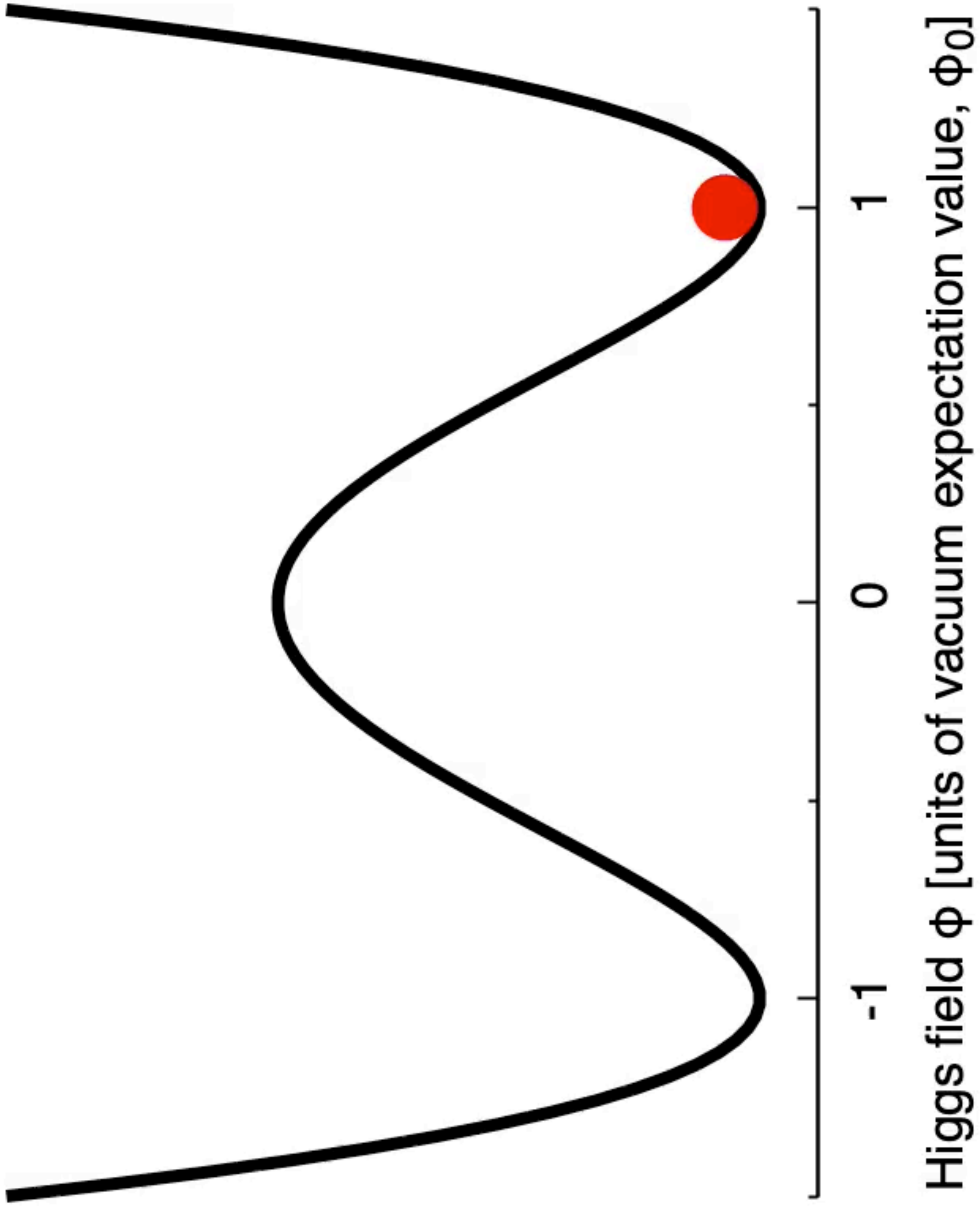


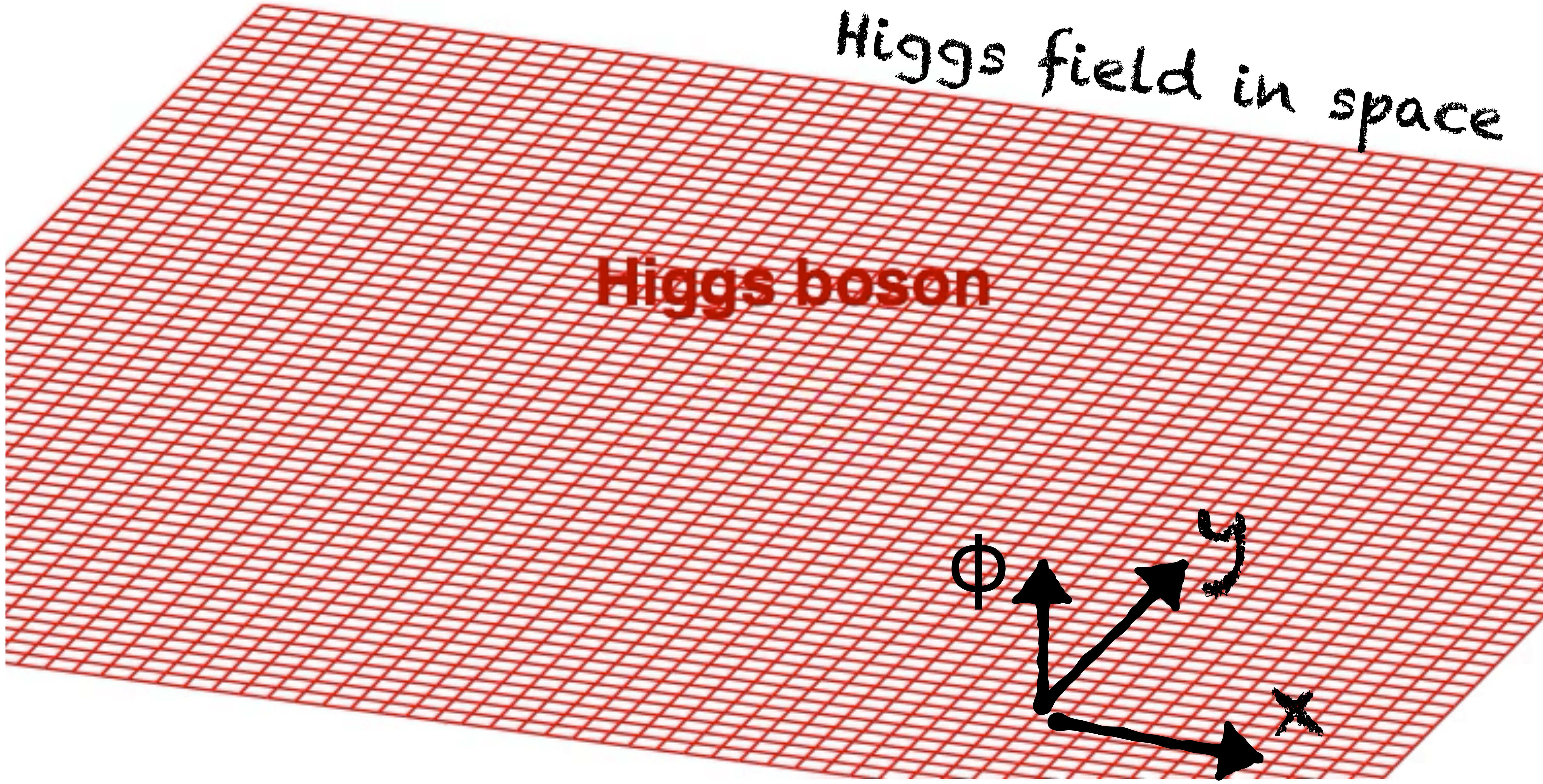


Higgs field can be different at each point in space

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

$$\varphi = \varphi_0 + H$$





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)

$$\varphi = \varphi_0 + H$$

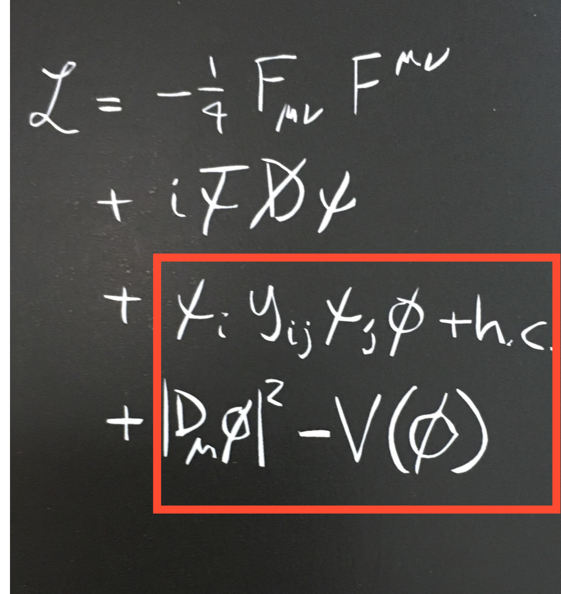
established

(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.

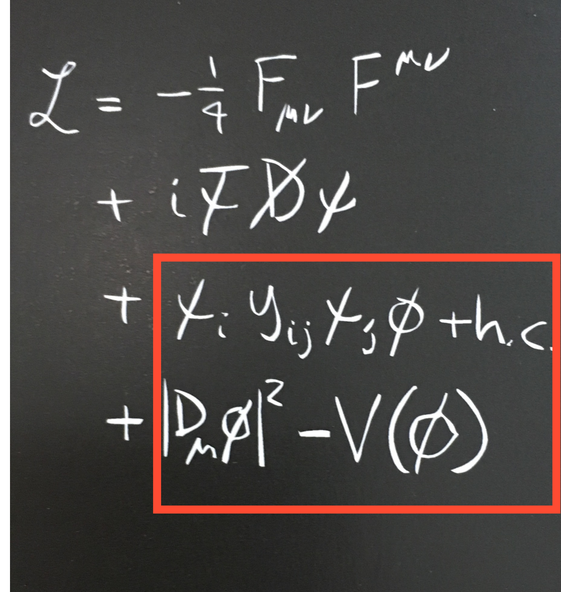
$$\rightarrow \underbrace{g^2 \phi_0^2}_{\text{constants}} \underbrace{Z_\mu Z^\mu}_{\text{fields}} + \underbrace{2g^2 \phi_0}_{\text{constants}} \underbrace{H\, Z_\mu Z^\mu}_{\text{fields}} + \ldots$$

Z-boson mass term

HZZ interaction term

$D_\mu = (\partial_\mu + Z_\mu + \ldots)$ $\quad [\phi^2 = (\phi_0 + H)^2 = \phi_0^2 + 2\phi_0 H + \ldots]$

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



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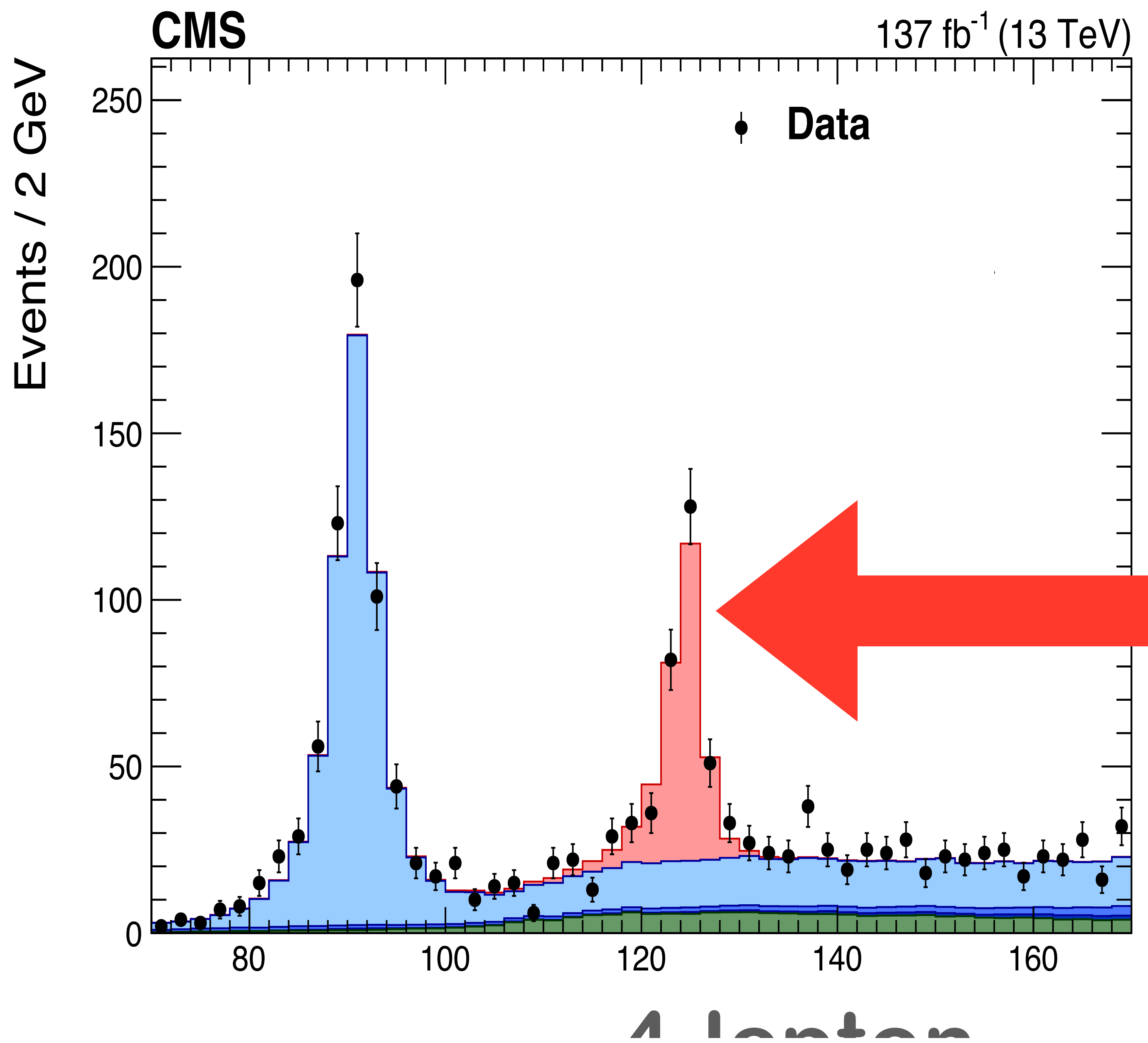
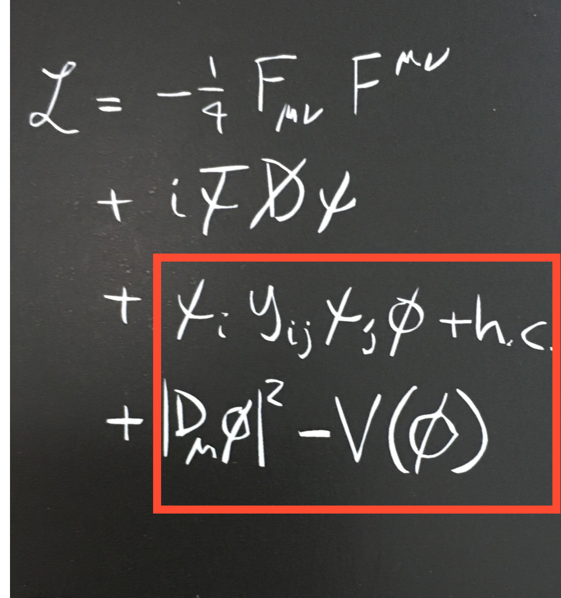


H → ZZ*

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

what terms are there in the Higgs sector?

2. Gauge-Higgs term



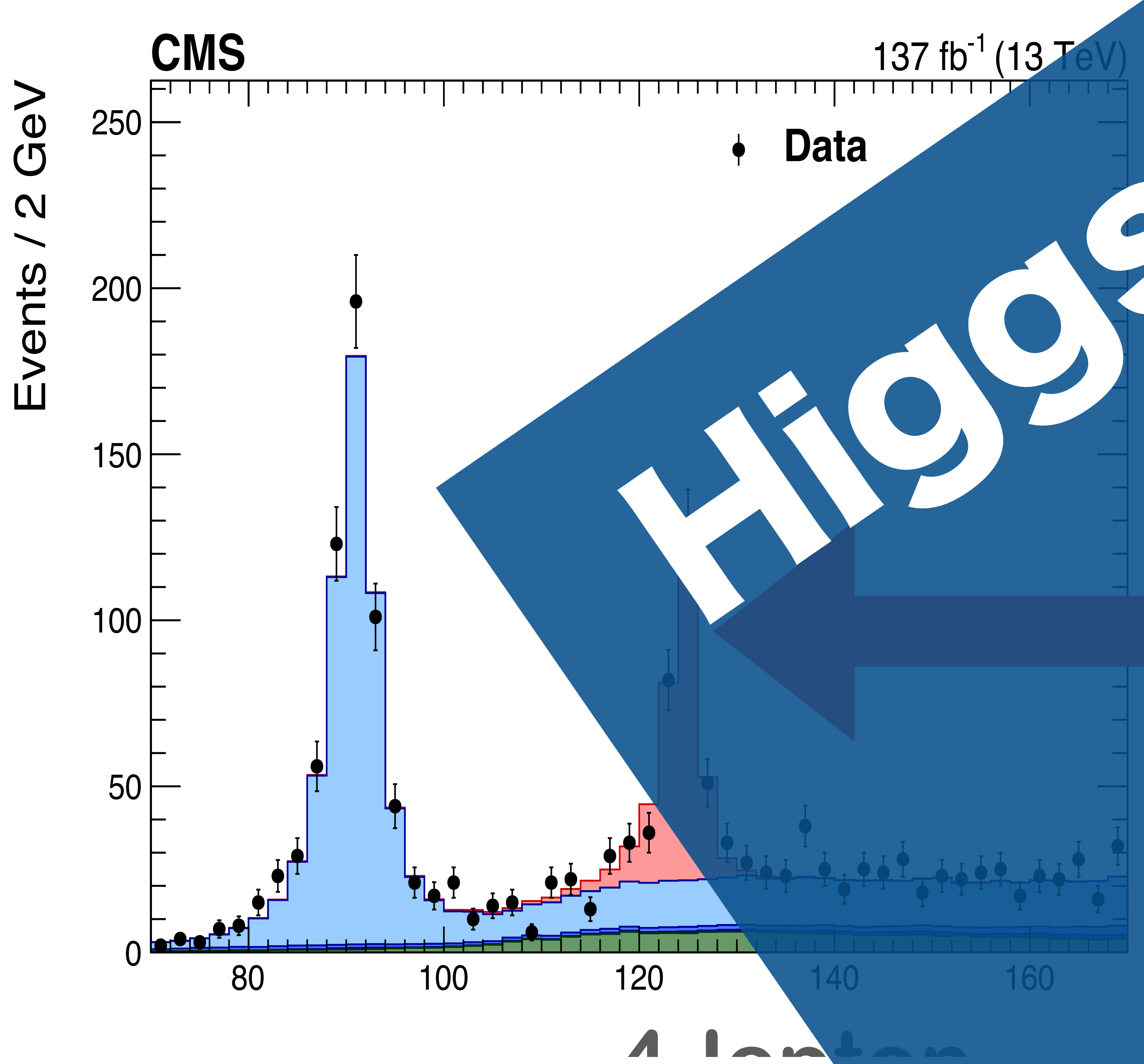
This equation neatly sums up our current understanding of fundamental particles and forces.

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

Z boson mass term

ZZH interaction term

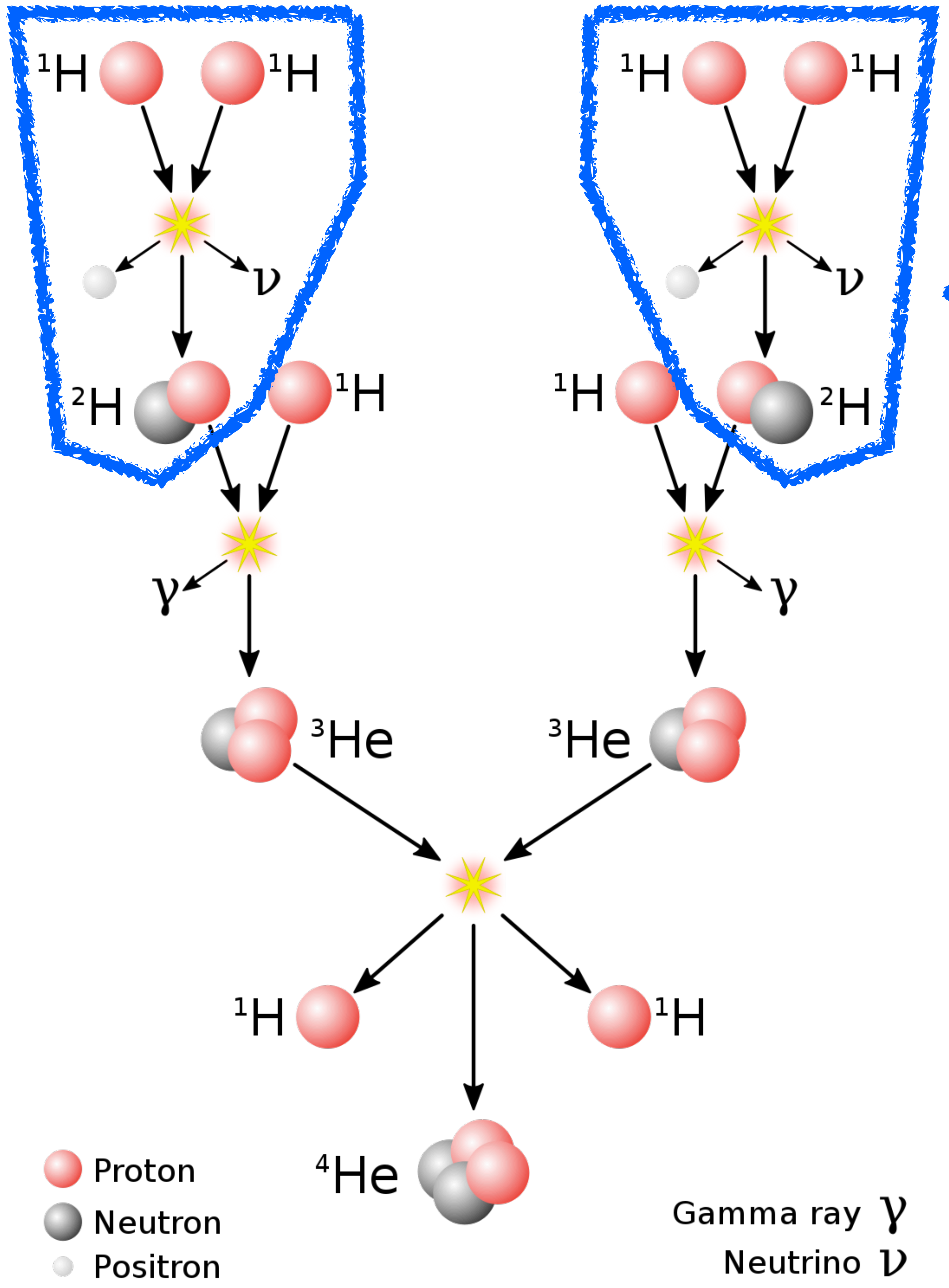
Higgs (BEH) mechanism for vector boson mass = 2013 Nobel prize



H→ZZ*

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

Higgs also generates W-boson mass, which affects lifetime of stars like our sun



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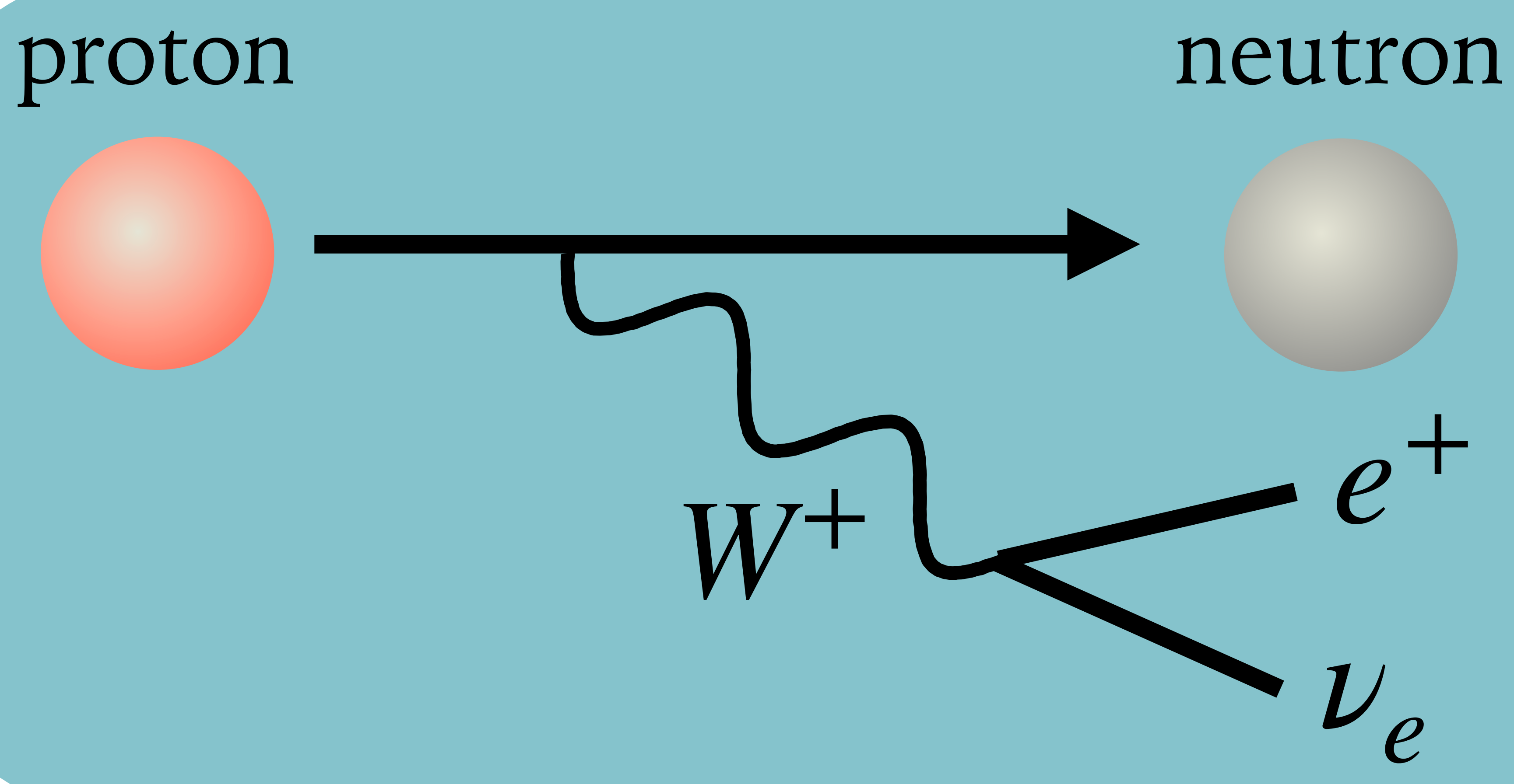
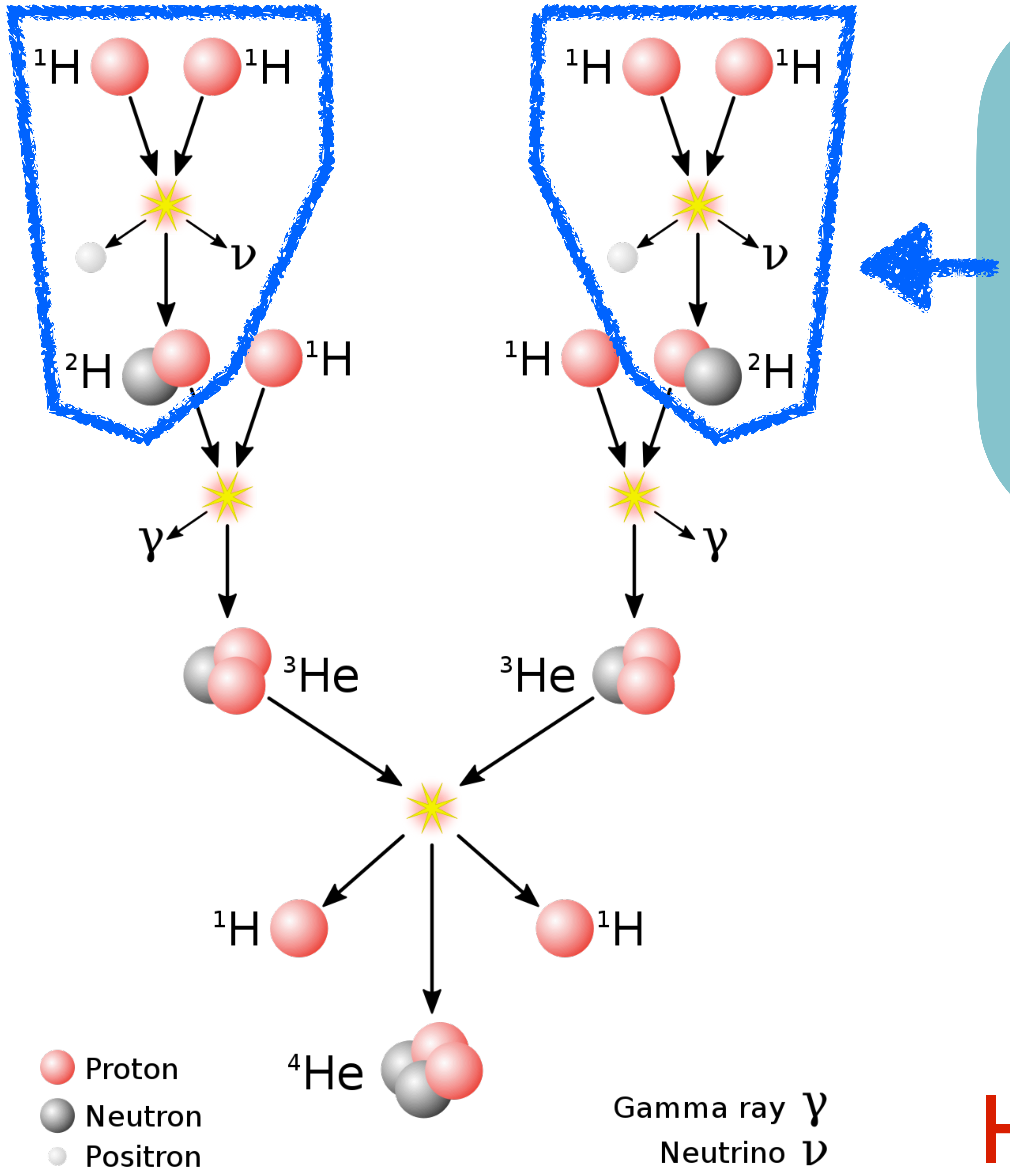
https://commons.wikimedia.org/w/index.php?curid=51118538



$$\text{rate} \sim \frac{1}{m_W^4}$$

Higgs also generates W-boson mass, which affects lifetime of stars like our sun



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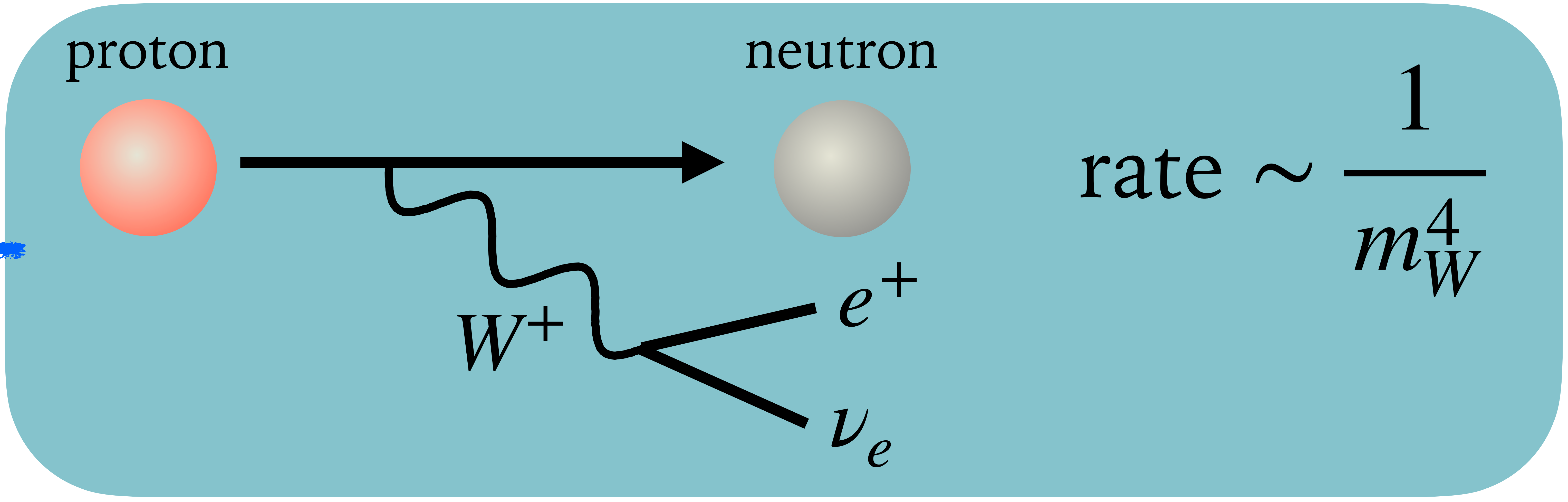
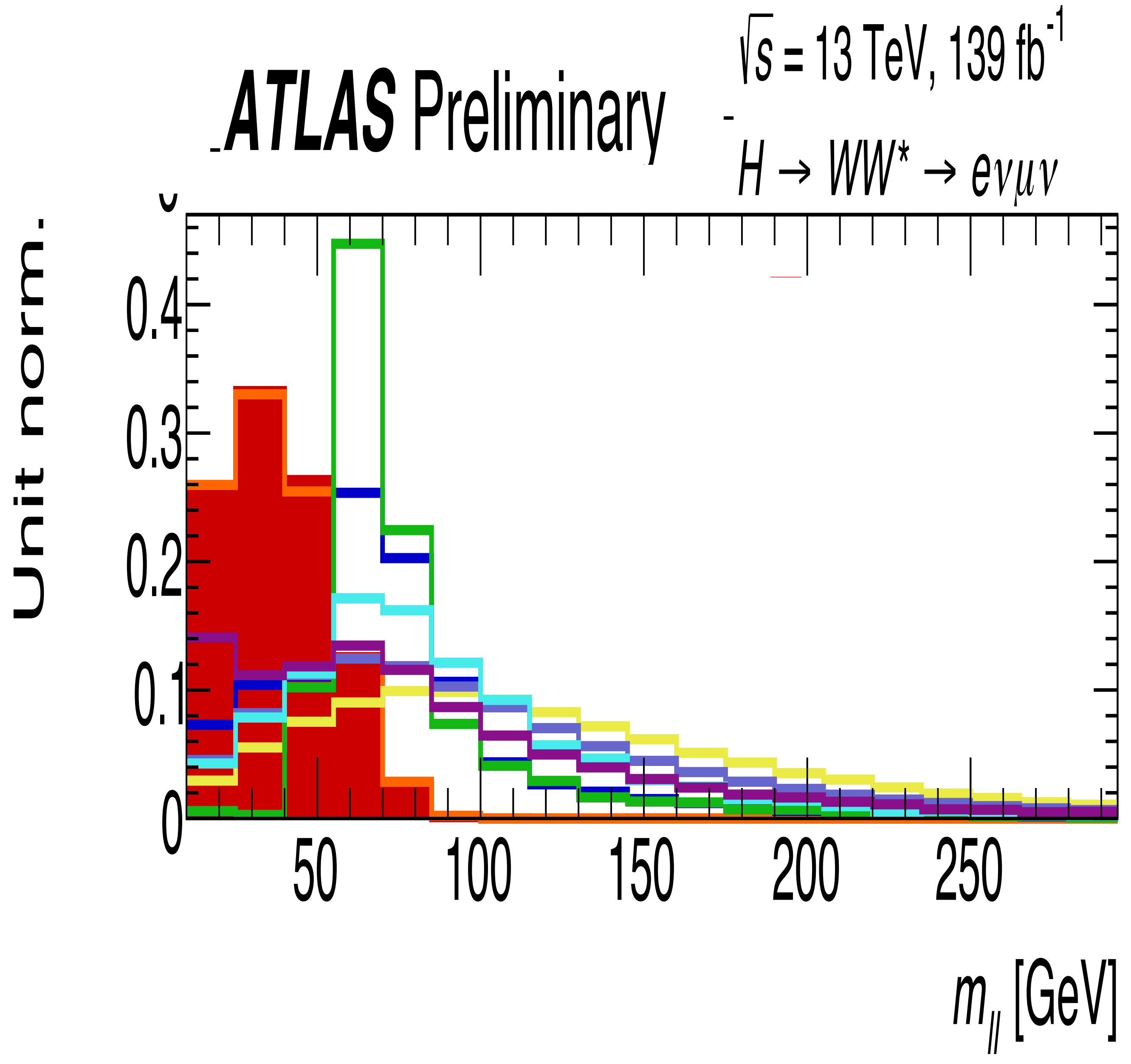
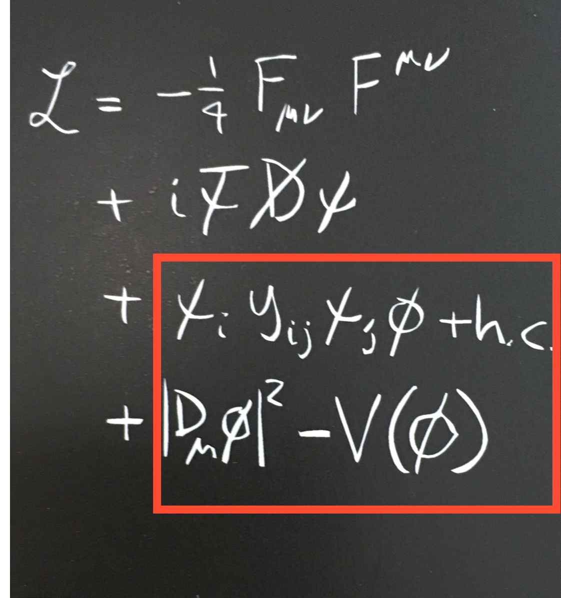


$$\text{rate} \sim \frac{1}{m_W^4}$$

H → WW*



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



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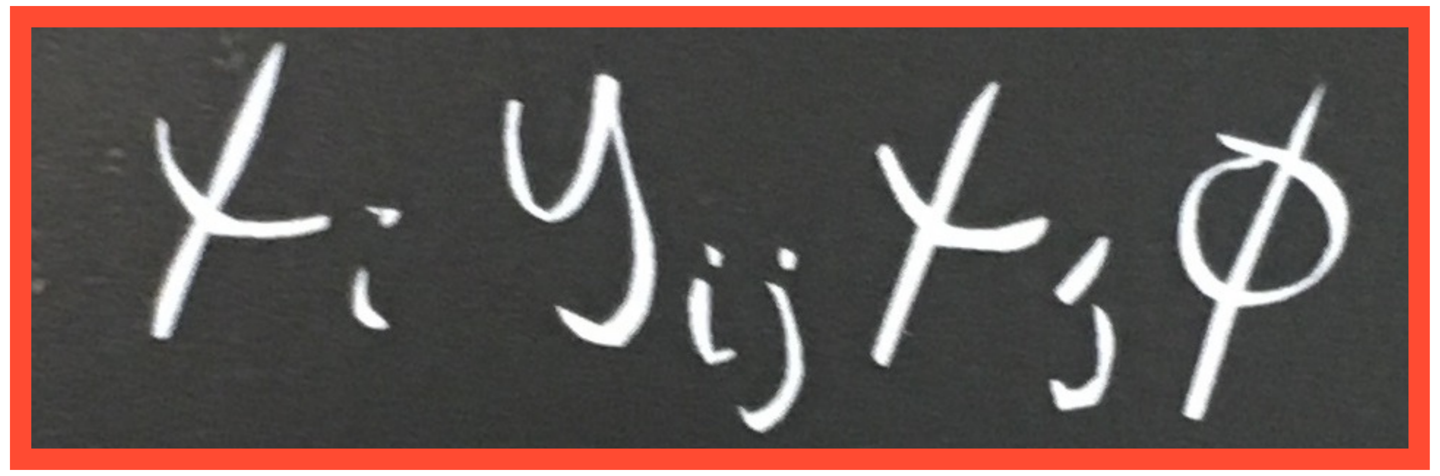


$$\rightarrow \; y_{ij}\,\phi_0\,\psi_i\,\psi_j \; + \; y_{ij}\,H\,\psi_i\,\psi_j$$

fermion mass term

$$m_i = y_{ii}\phi_0$$

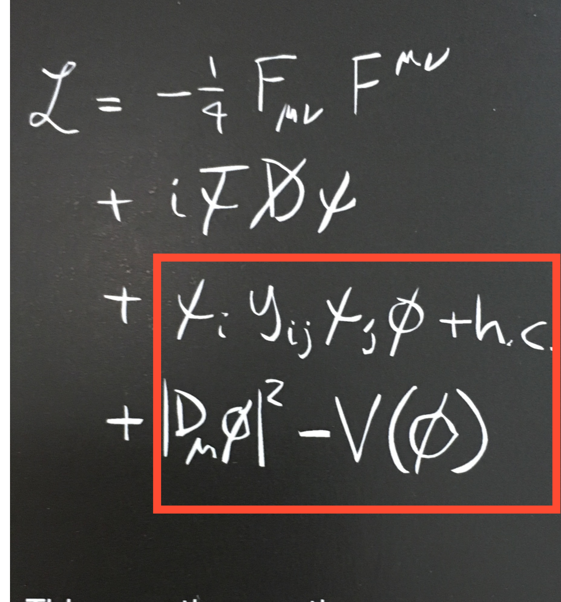
Higgs-fermion-fermion interaction term;

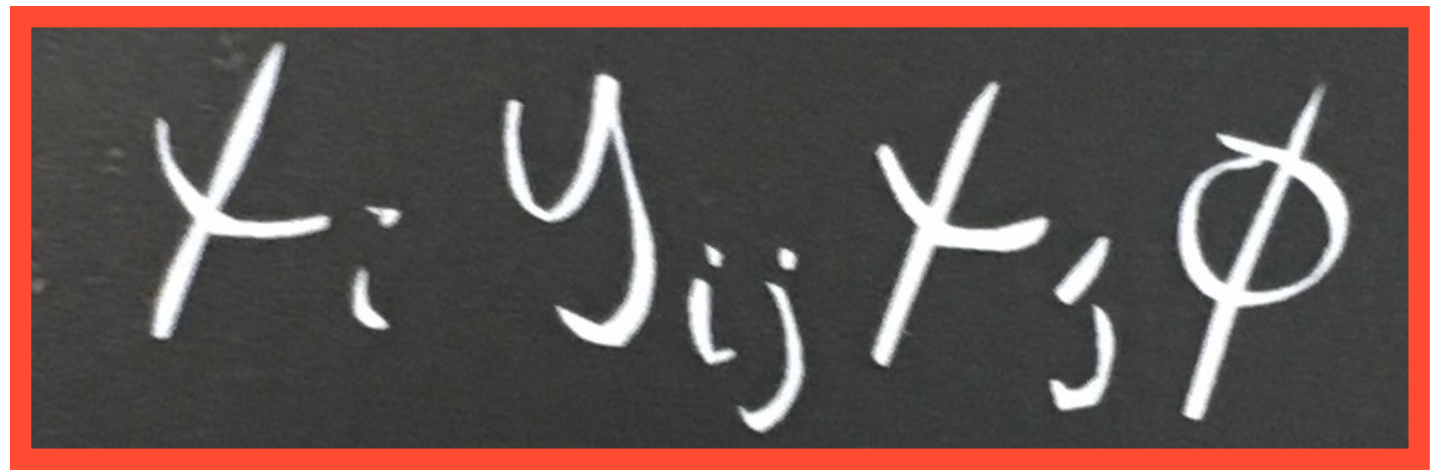
coupling $\sim y_{ii}$

i	y_i	i	y_i
u	$2 \cdot 10^{-5}$	d	$3 \cdot 10^{-5}$
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	$1 \cdot 10^{-4}$

$$\phi = \phi_0 + H$$

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





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

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

the subject of the next few slides

$$\phi = \phi_0 + H$$

Yukawa interaction hypothesis

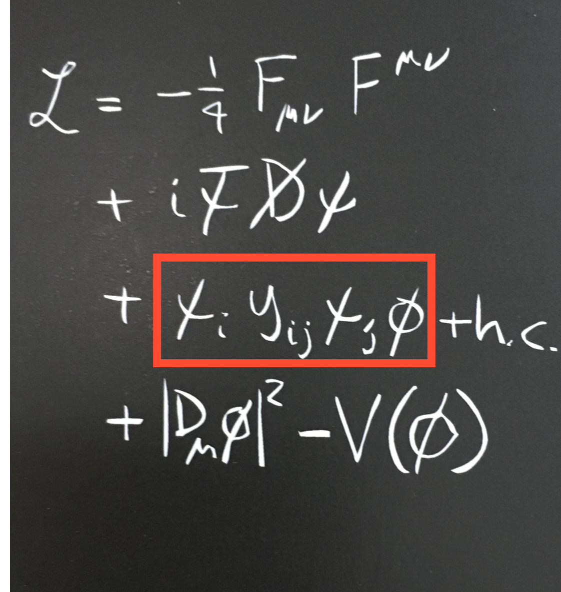
Yukawa couplings ~ fermion mass

first fundamental interaction that we probe at the quantum level where interaction strength (y_{ij}) not quantised

(i.e. no underlying unit of conserved 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.

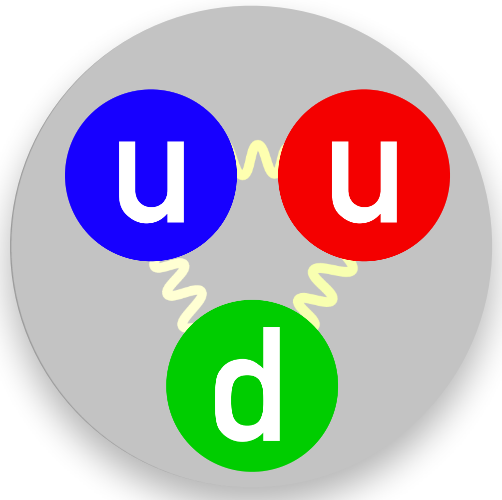
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

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

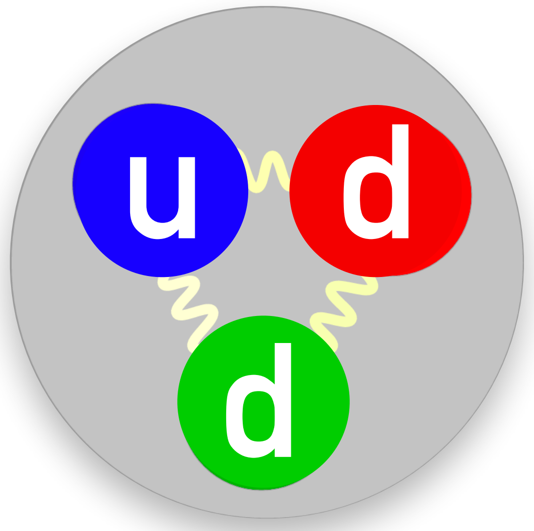
So protons are **lighter** than neutrons,
→ protons are stable.

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

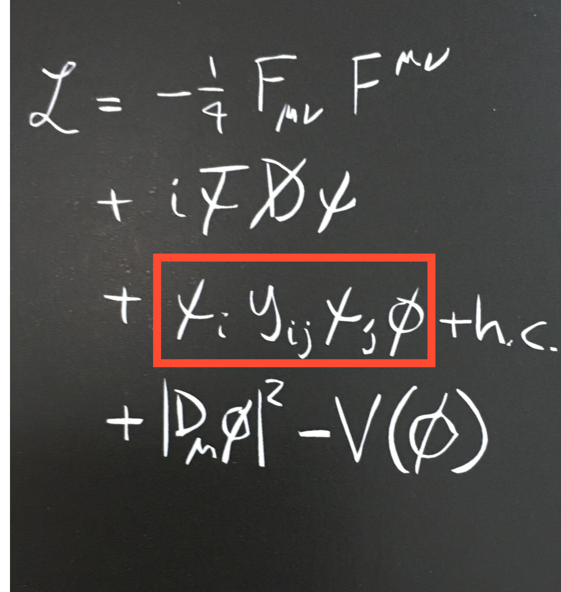
proton
mass = 938.3MeV



neutron
mass = 939.6MeV



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



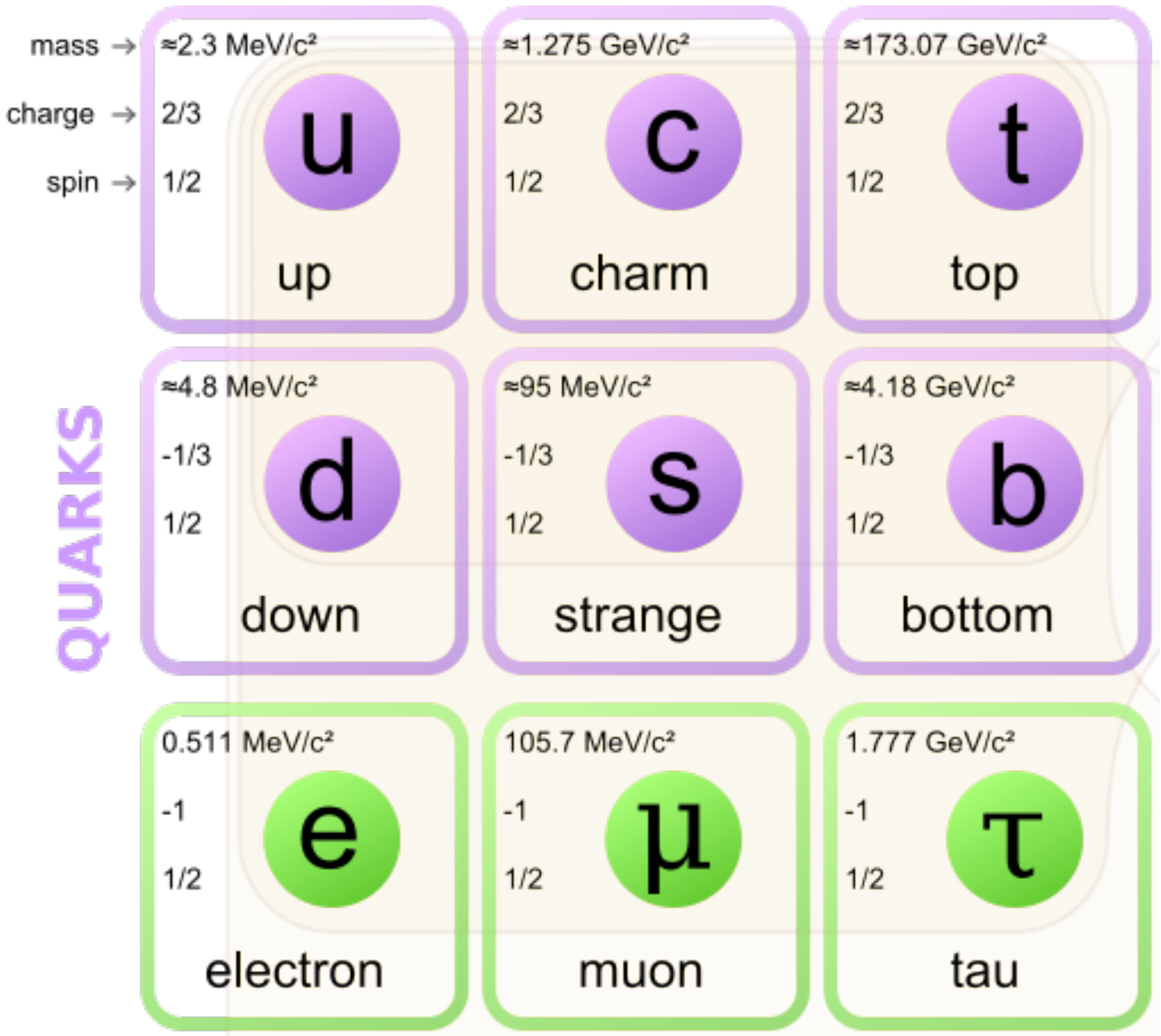
This equation neatly sums up our current understanding of fundamental particles and forces.

Bohr radius

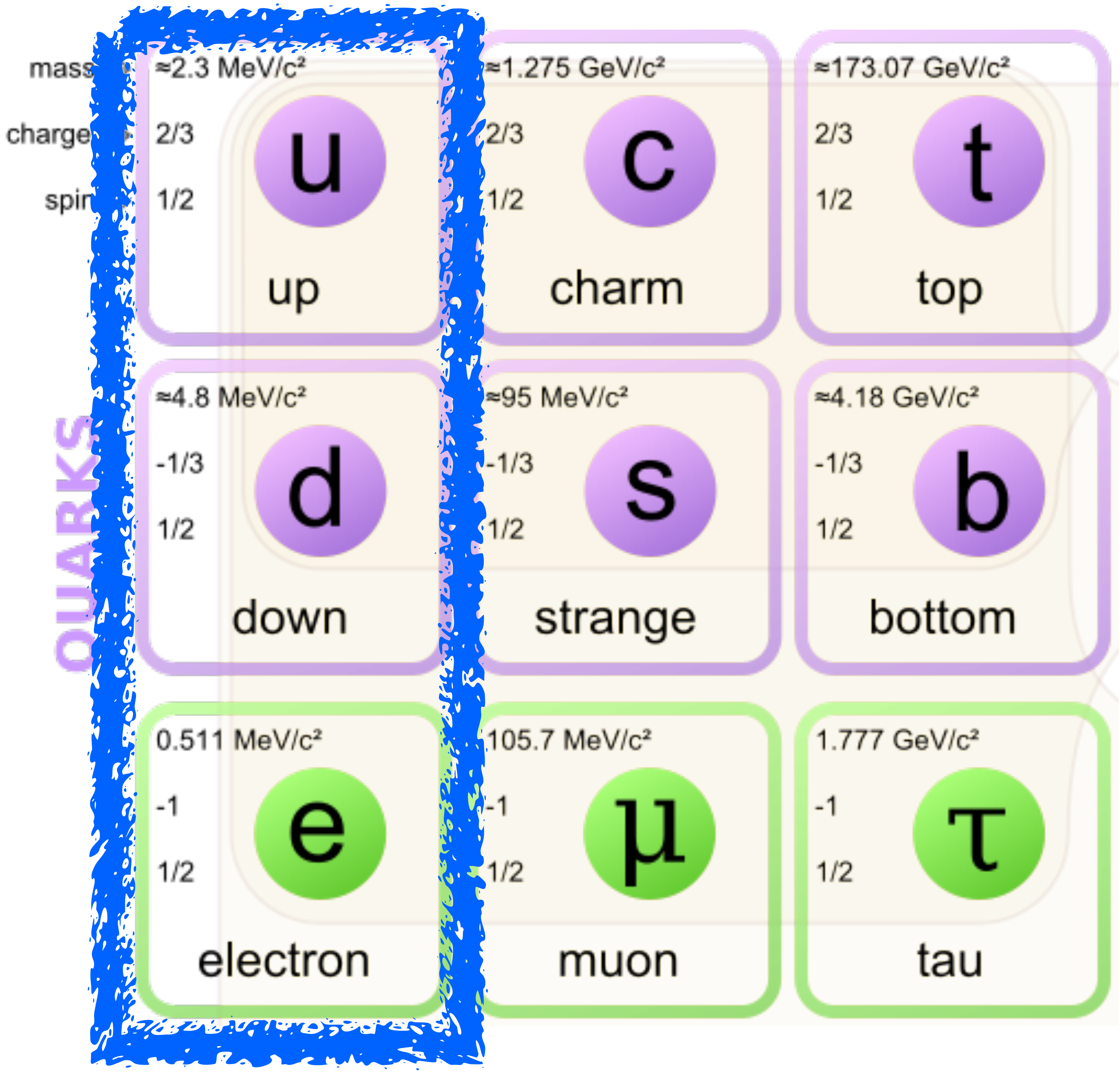
$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \propto \frac{1}{y_e}$$

electron mass determines size of all atoms

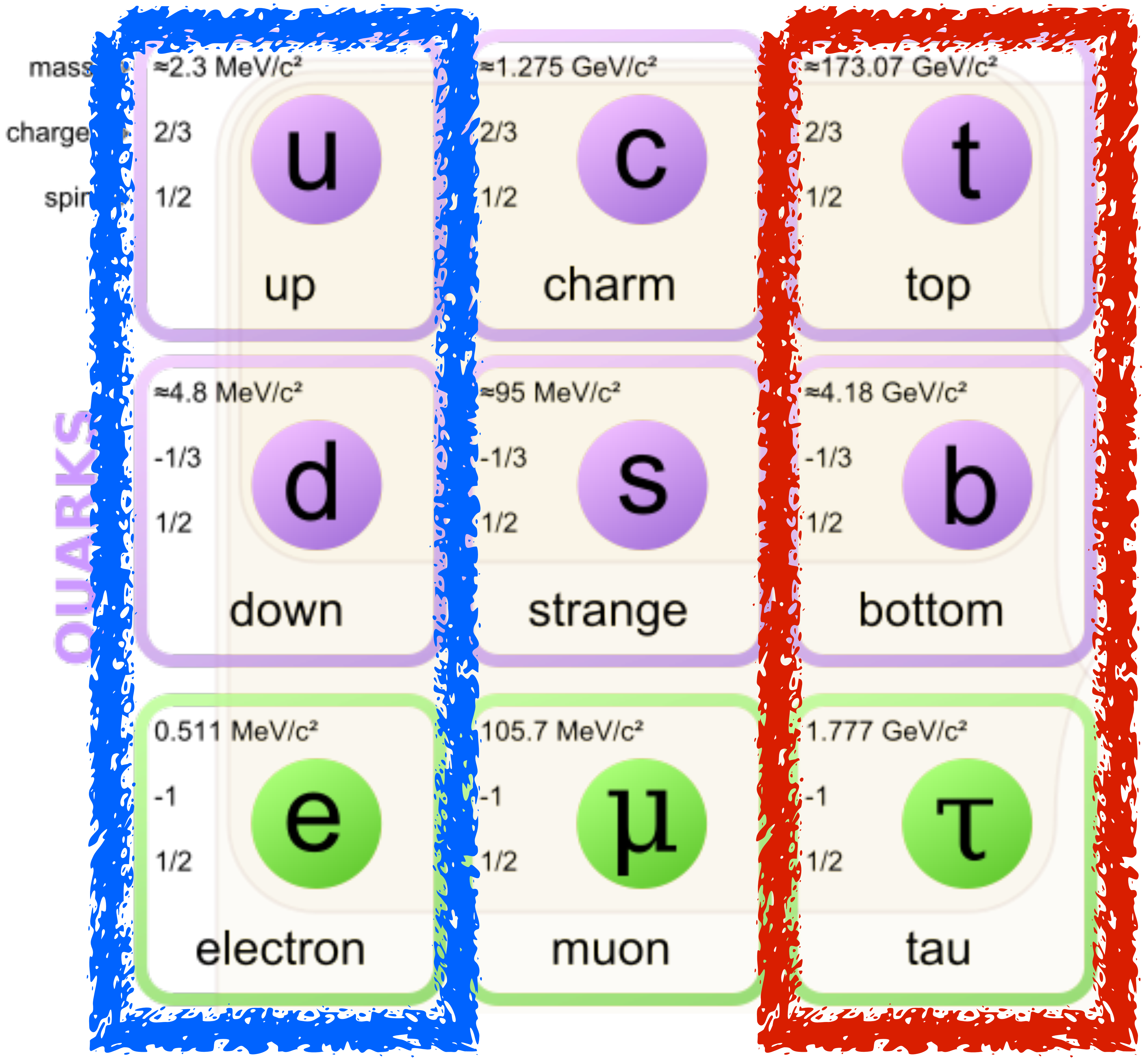
it sets energy levels of all chemical reactions



mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau



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

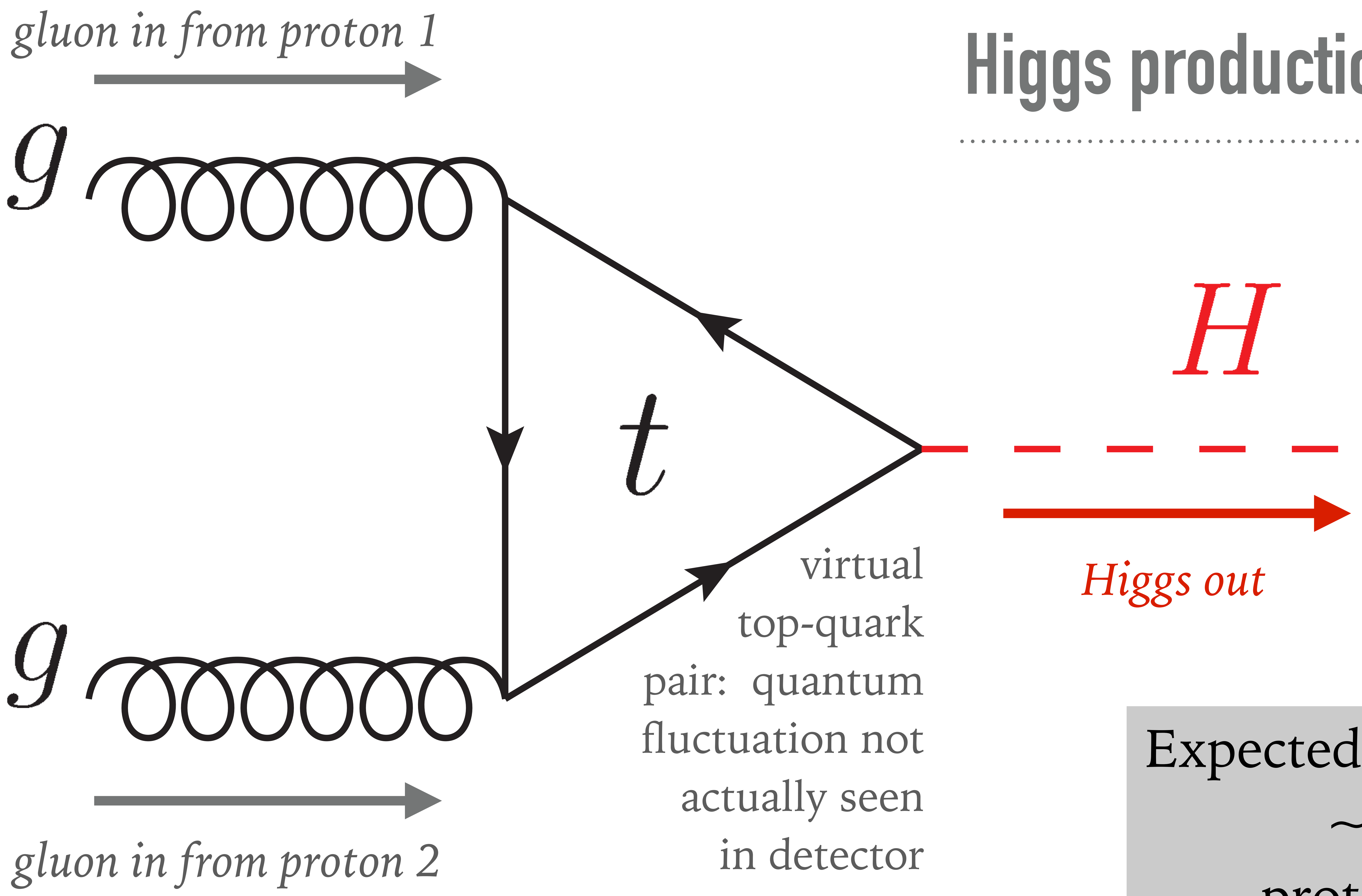


1st generation (us) has low mass because of weak interactions with Higgs field (and so with Higgs bosons): **too weak to test today**

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

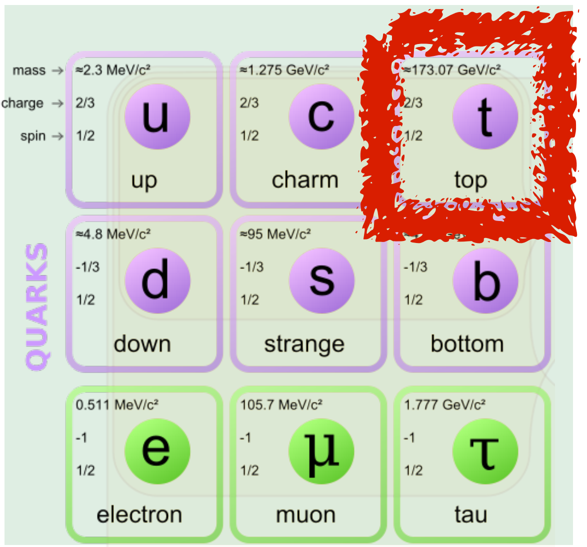
what underlying processes tell us about Yukawa interactions?

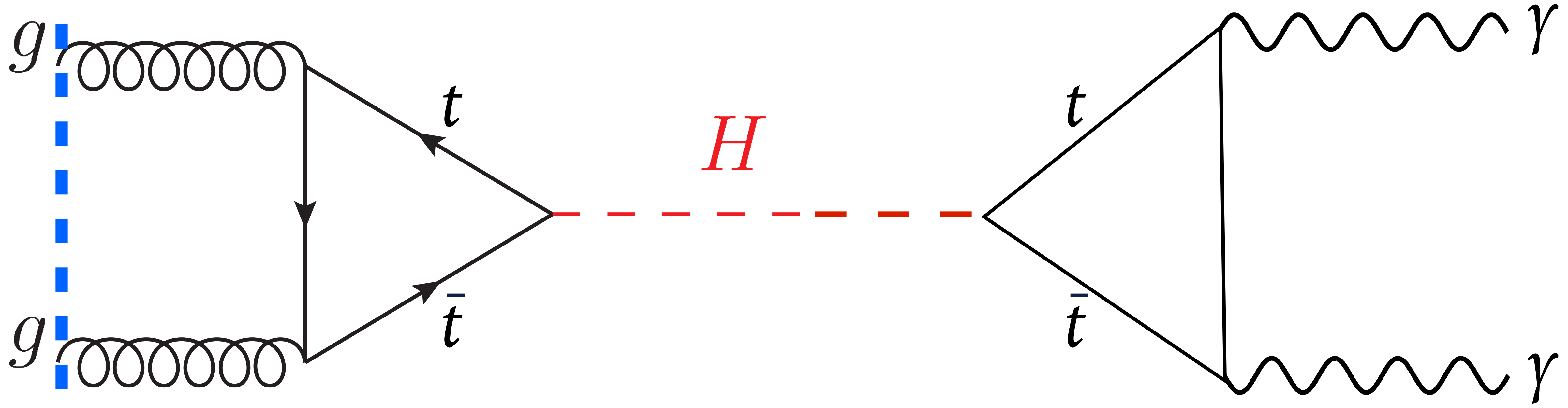
Higgs production: the dominant channel



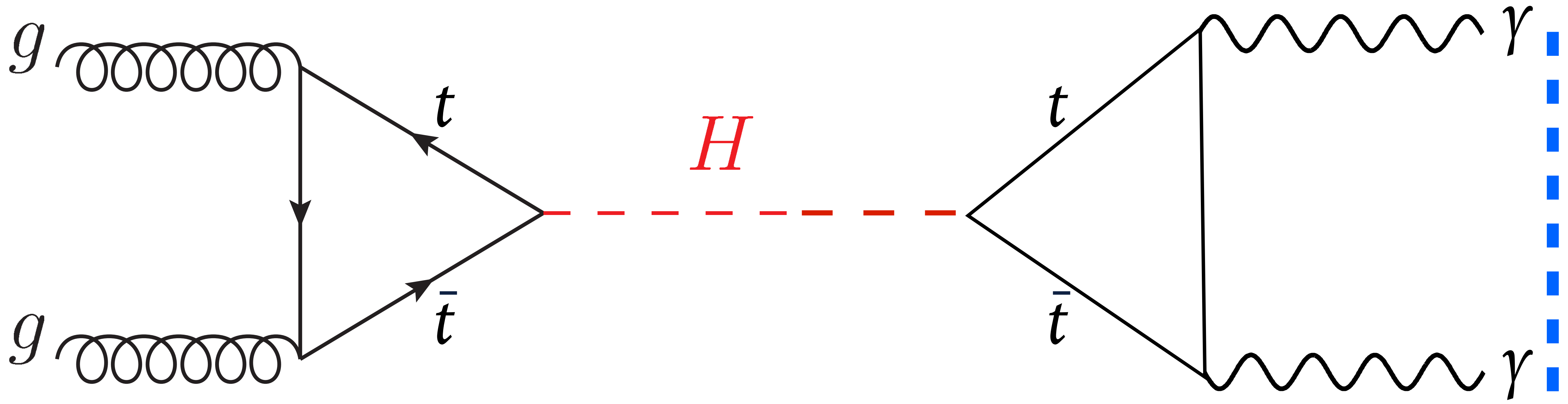
Expected to happen once for every ~2 billion inelastic proton–proton collisions

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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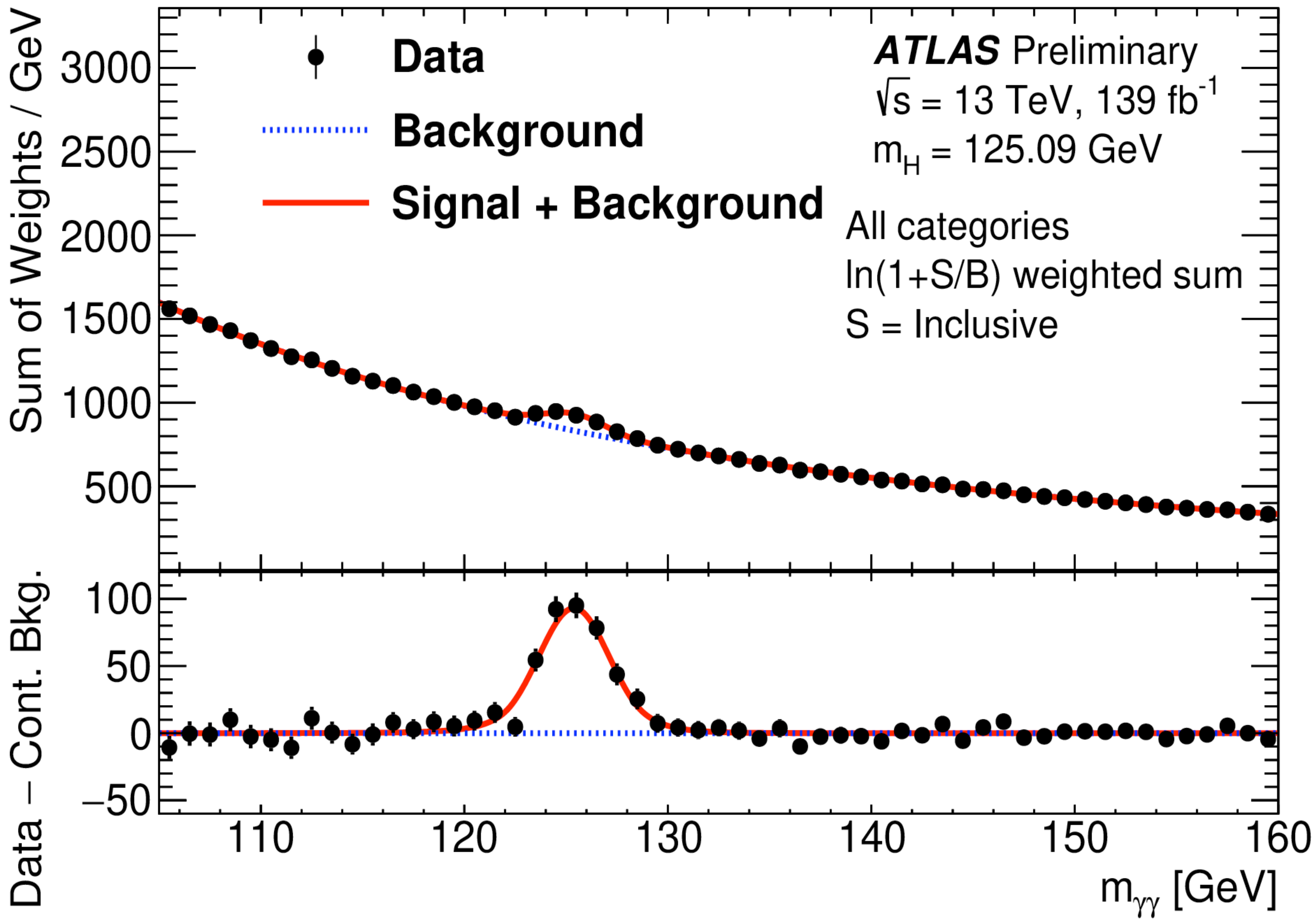
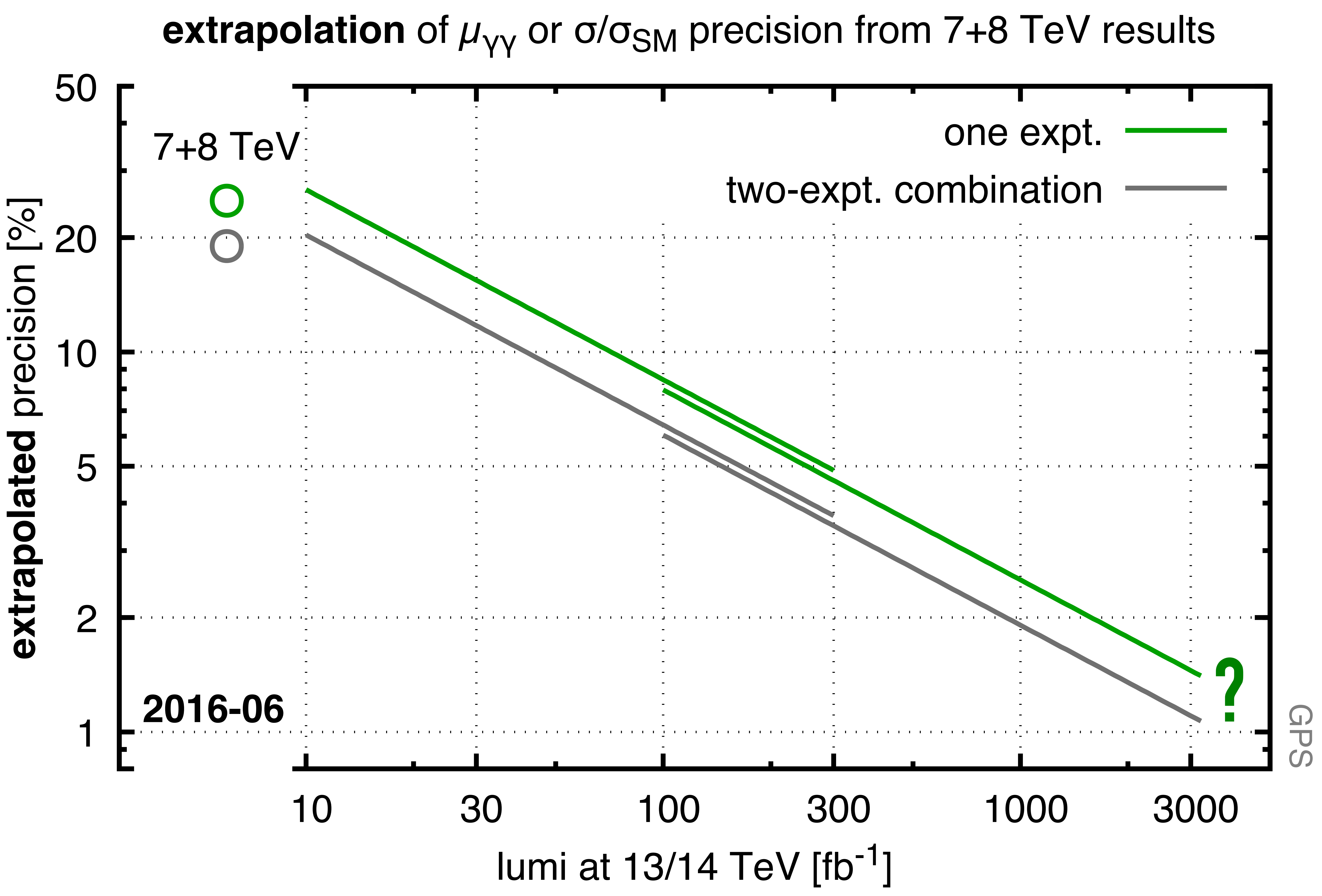
Higgs field in space

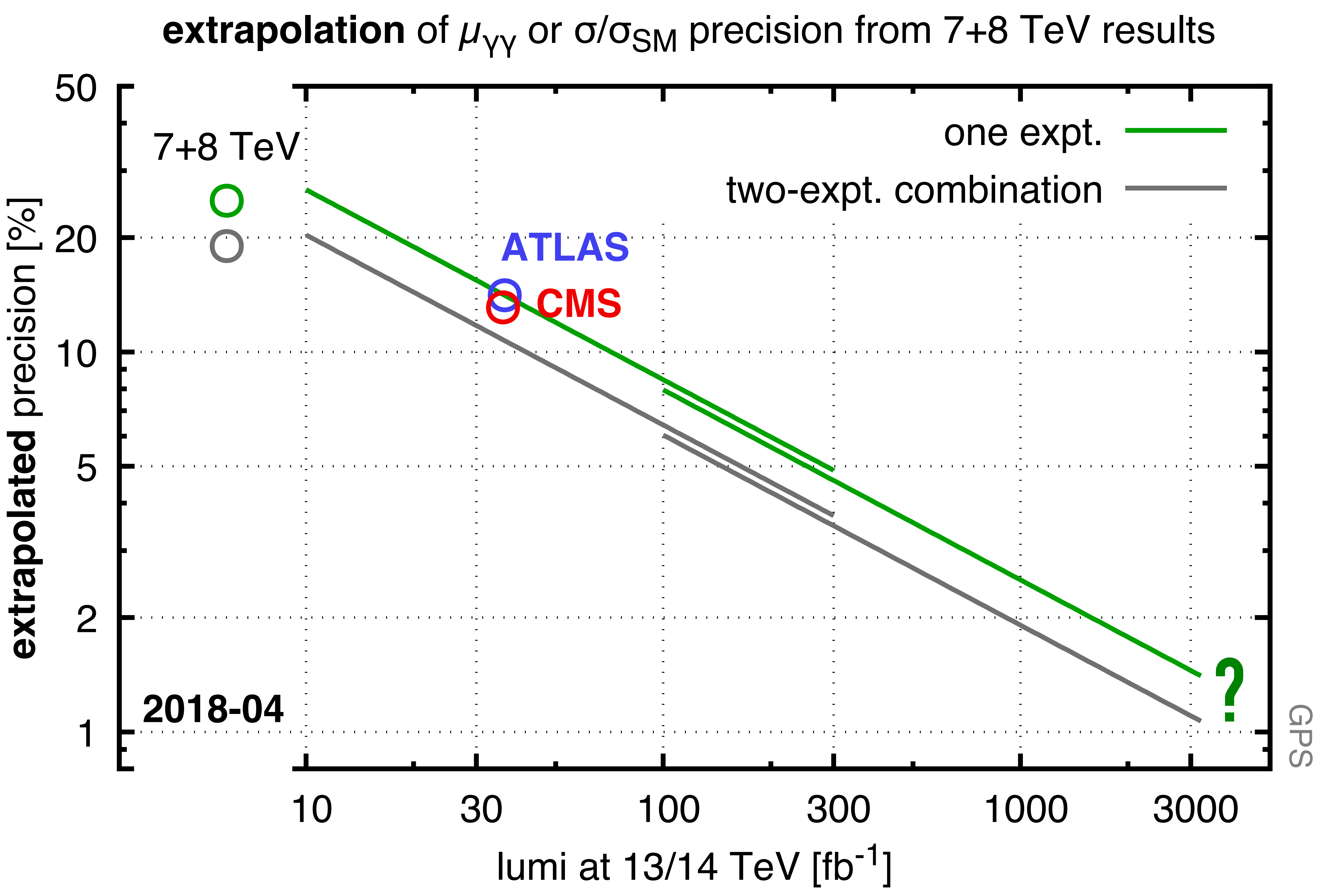


$H \to \gamma\gamma$

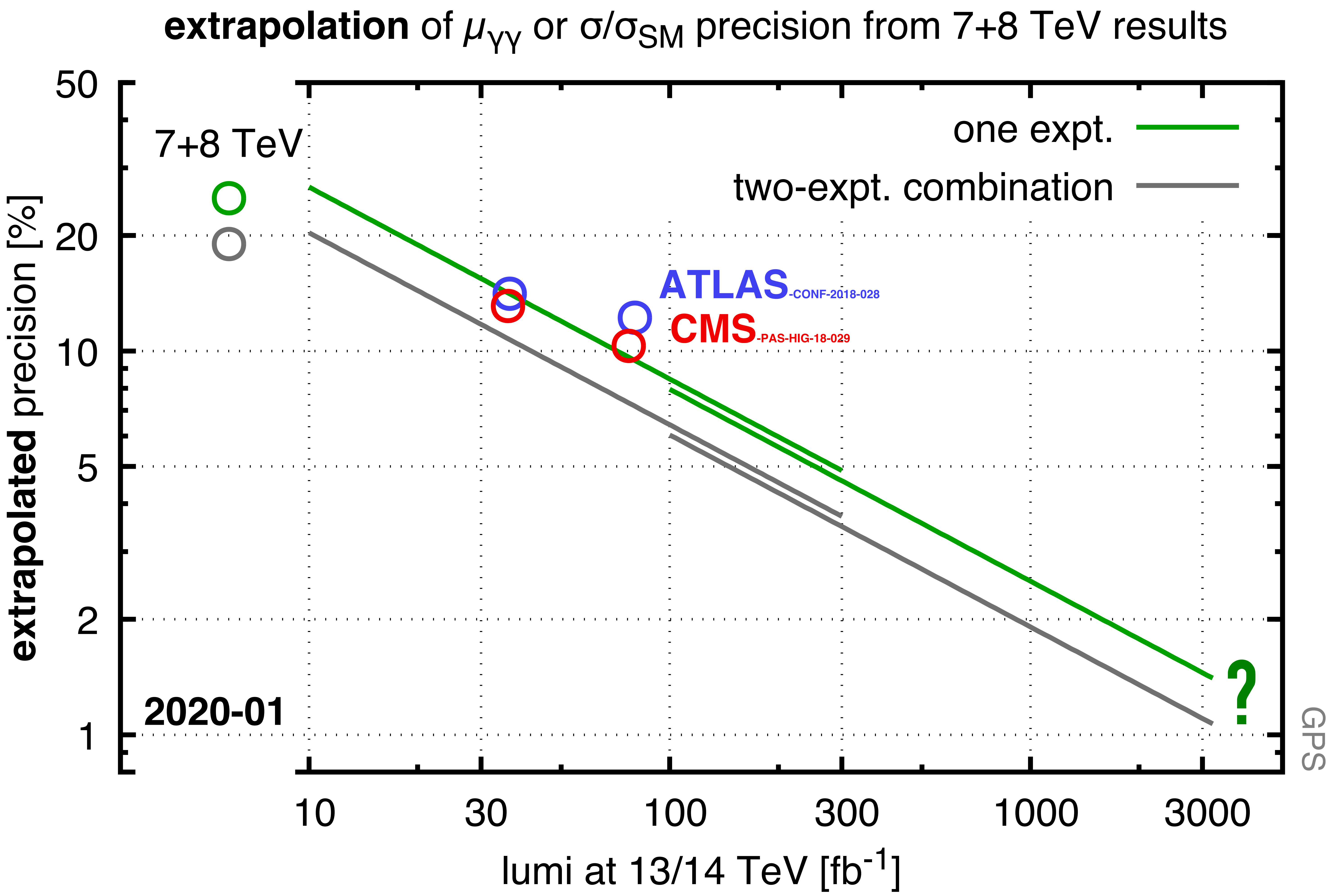
H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings



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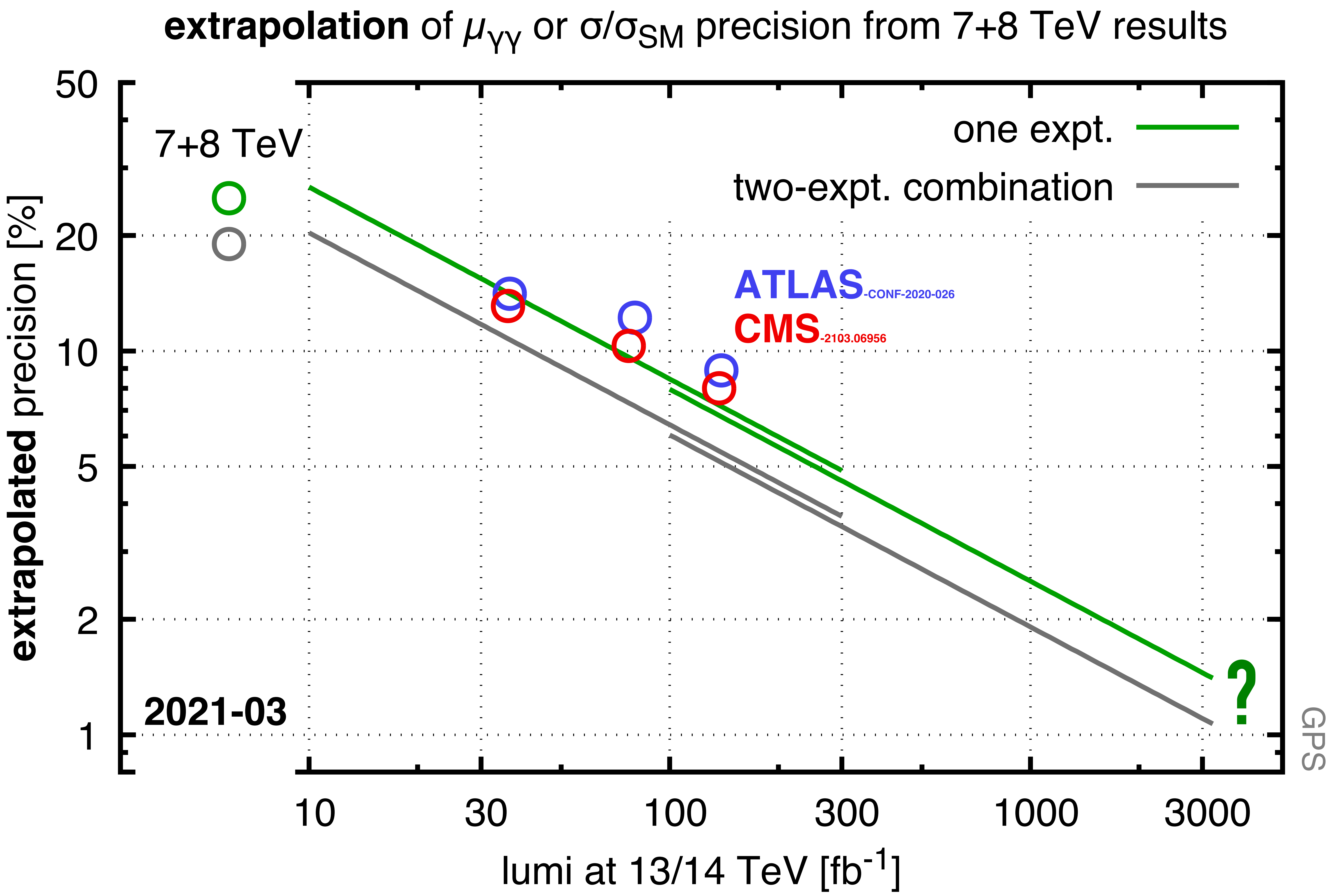
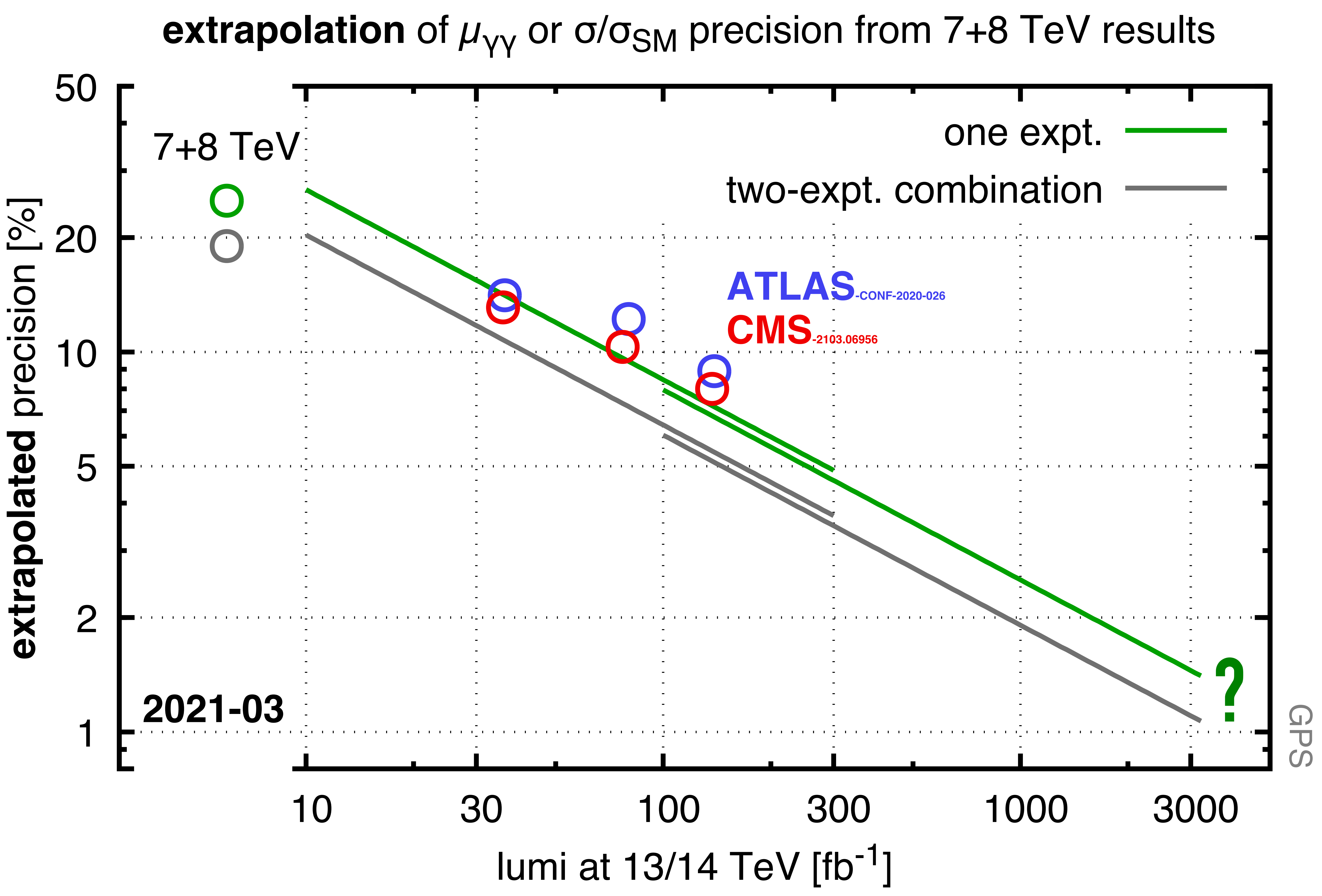
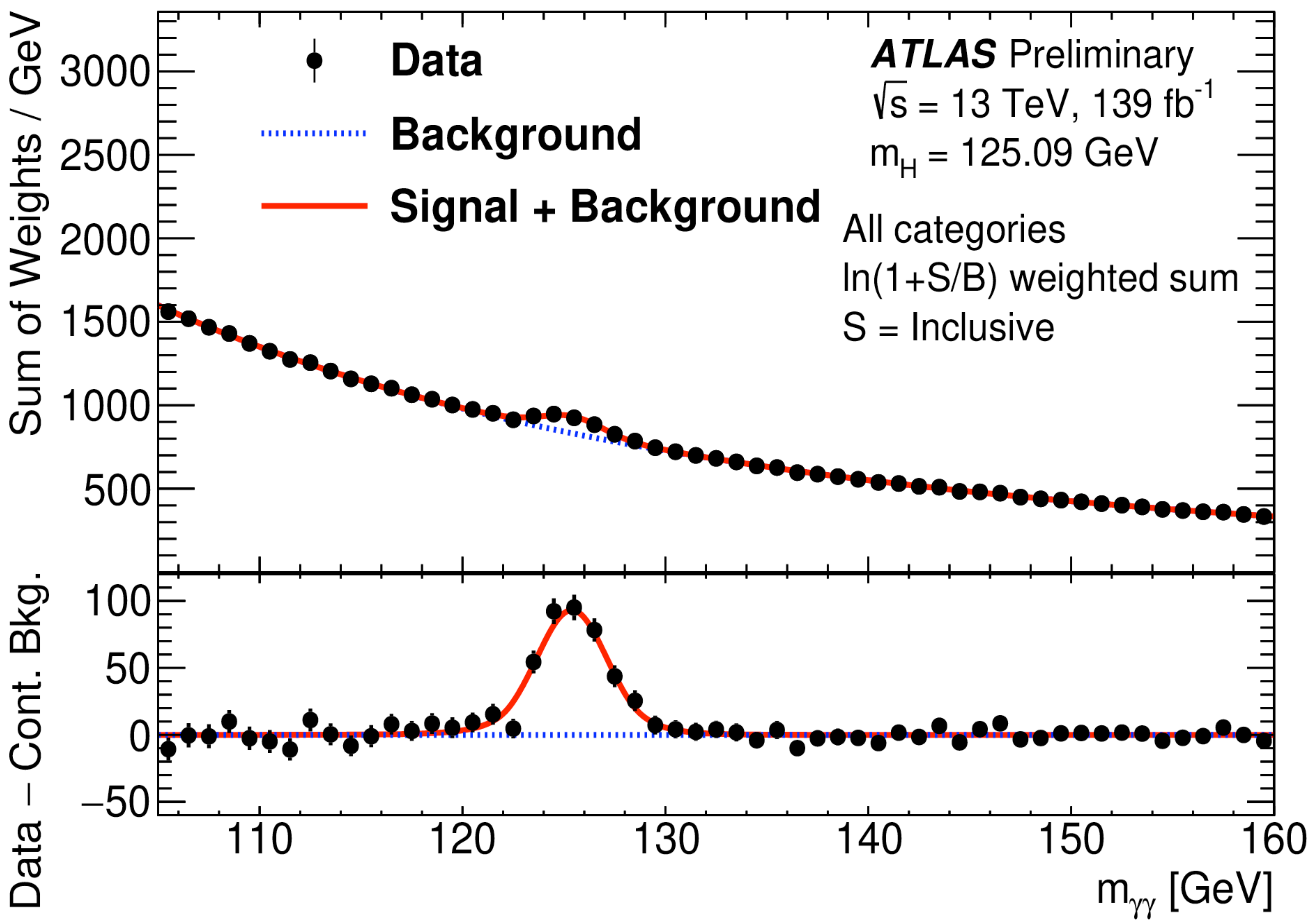


H → γγ, an indirect probe of the top Yukawa, HWW and contact ggH couplings

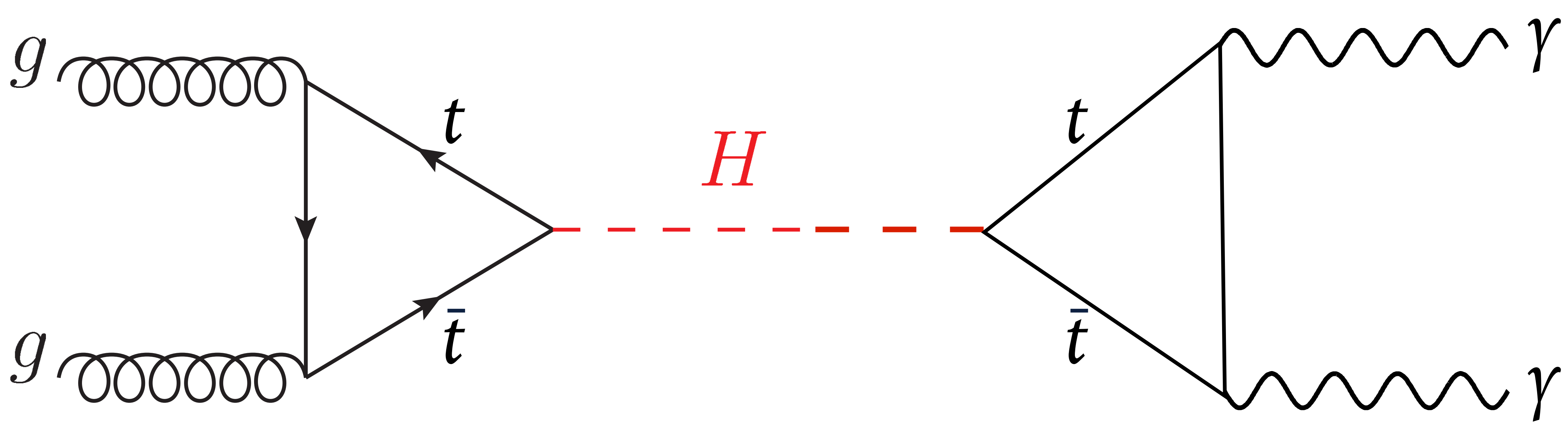


today's ATLAS and CMS total uncertainties (ratio to SM) are at the 8-9% level

5-7% stat.
3-7% syst.
~5% theo.



Data
Background
Signal + Background
ATLAS Preliminary
√s = 13 TeV, 139 fb-1
mH = 125.09 GeV
All categories
ln(1+S/B) weighted sum
S = Inclusive
Sum of Weights / GeV
Data − Cont. Bkg.
mγγ [GeV]



g
g
t
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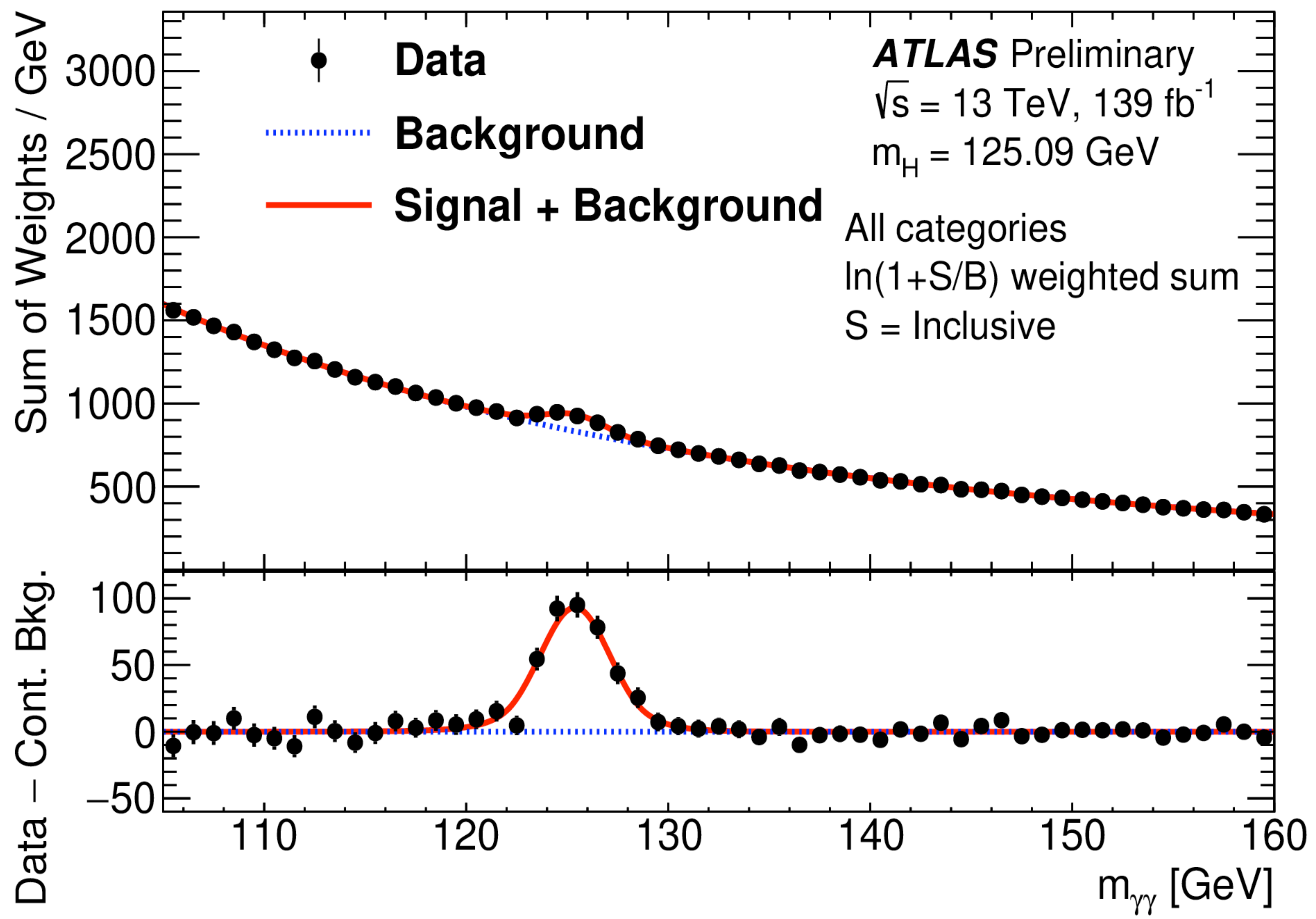
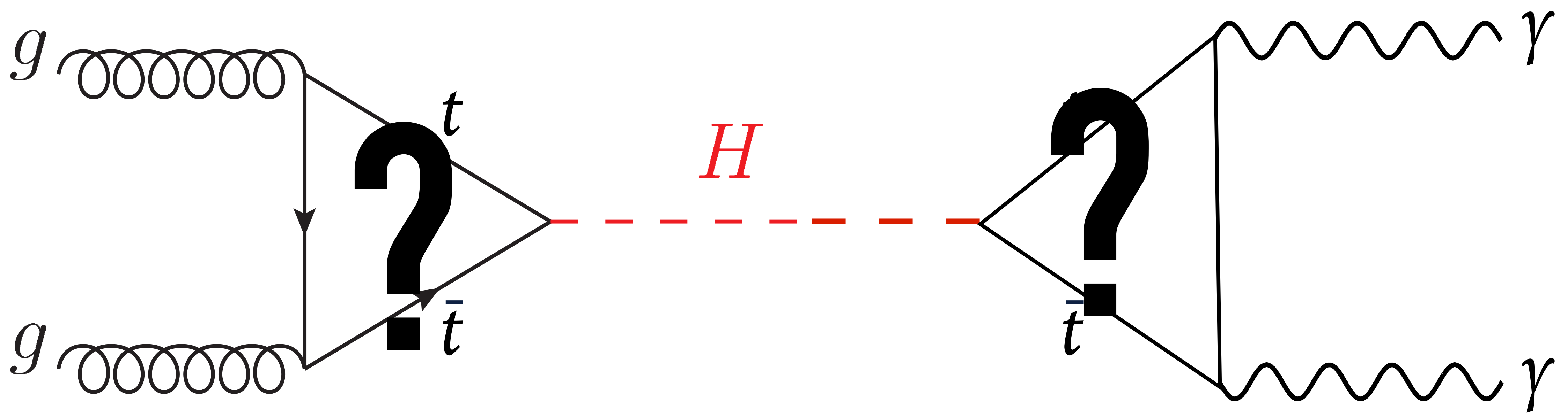
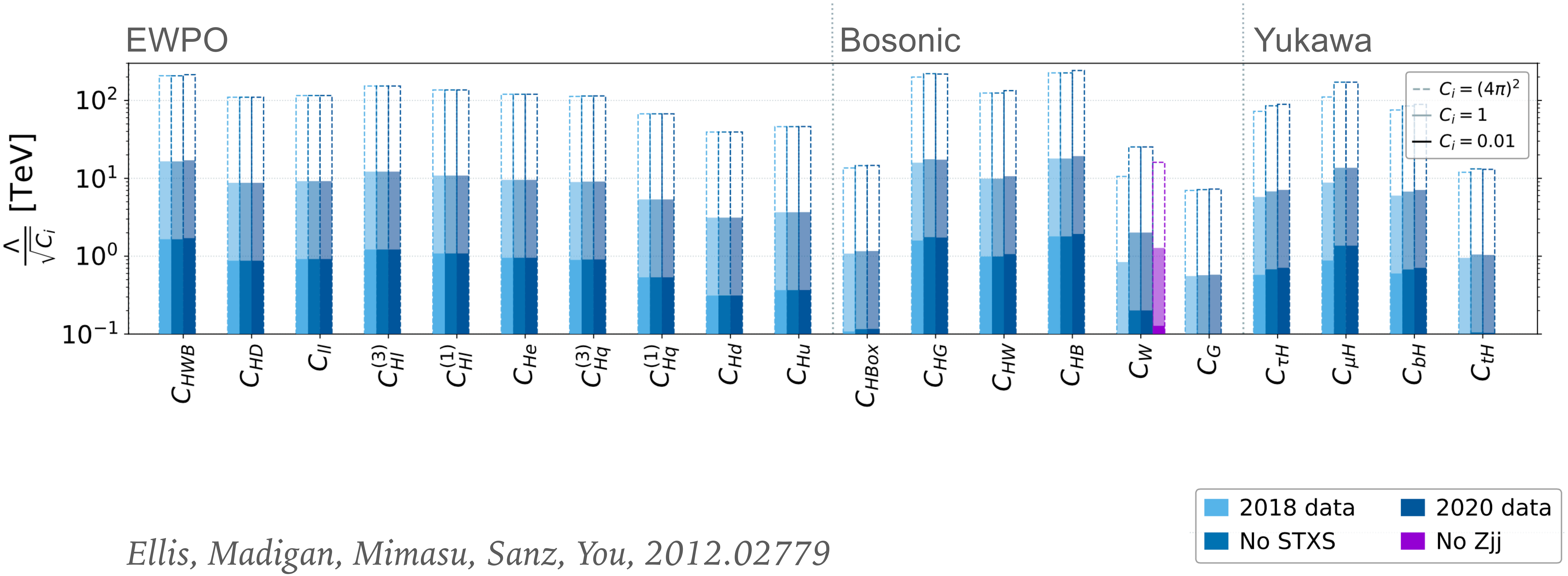
H
t
t̄
γ
γ





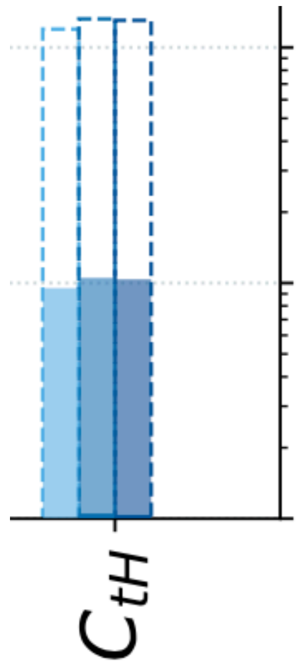
but how can you be sure the Higgs boson is really being radiated off a top-quark, i.e. that you're actually seeing a Yukawa coupling?

We are (indirectly) searching for new physics



Ellis, Madigan, Mimasu, Sanz, You, 2012.02779

We are (indirectly) searching for new physics



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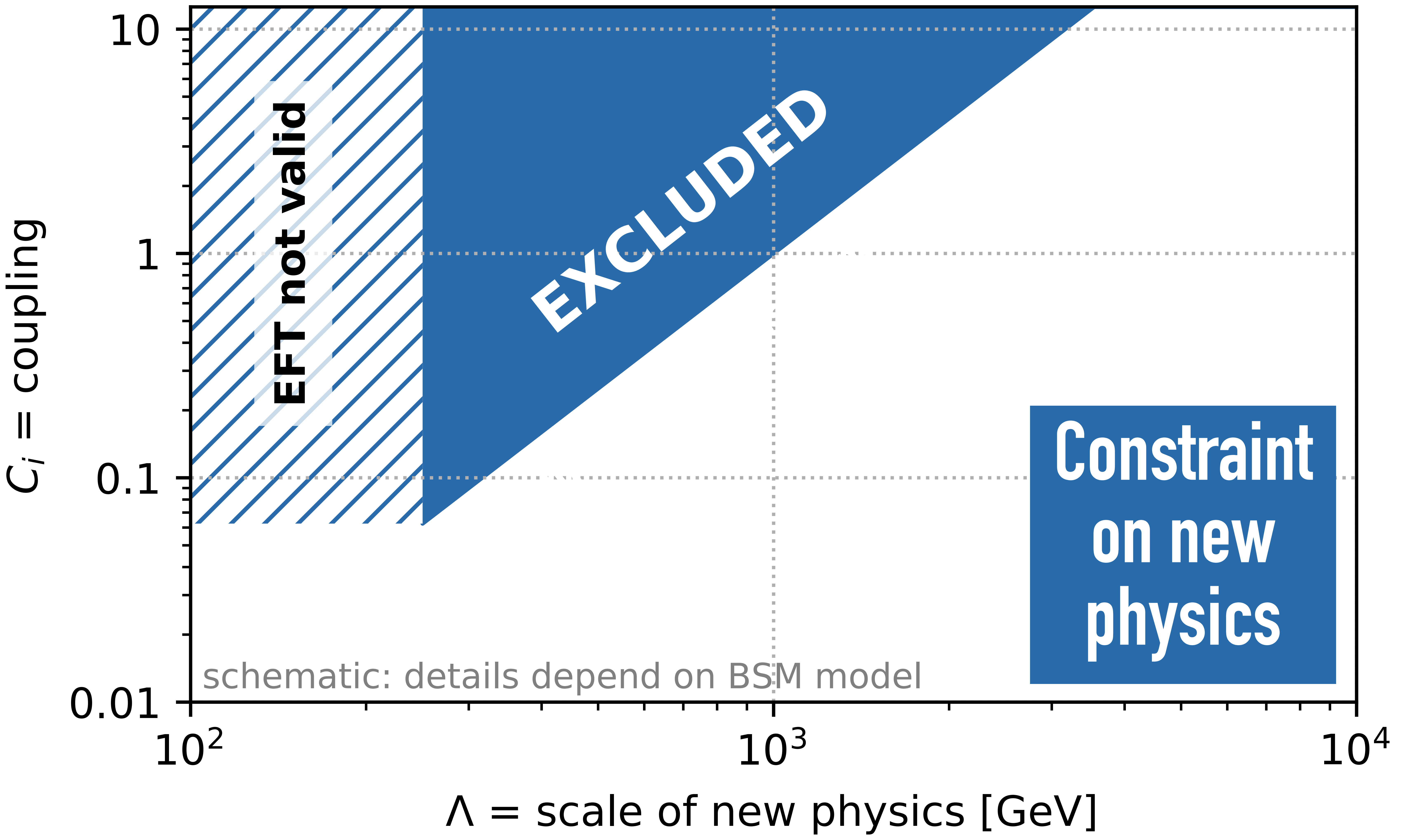

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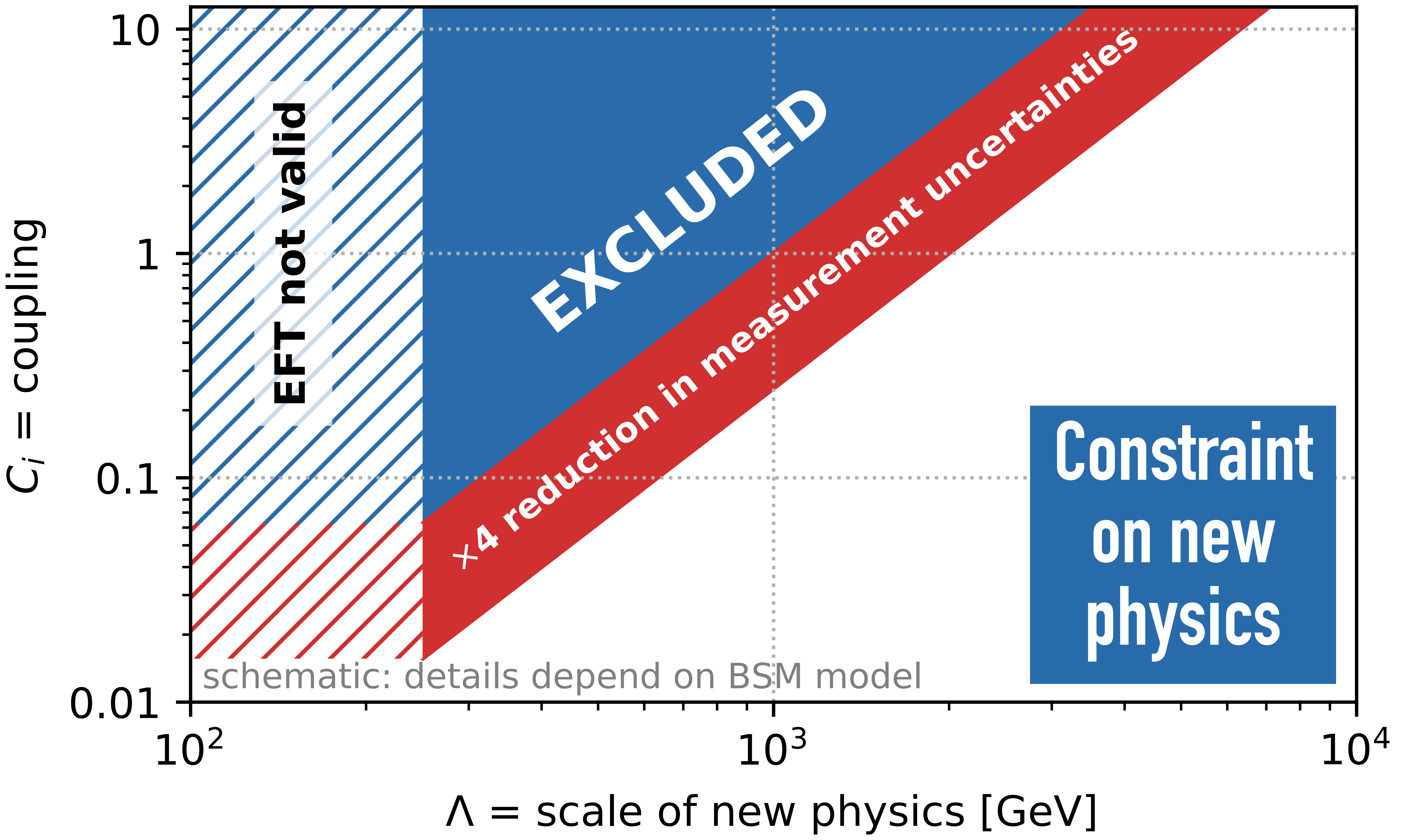

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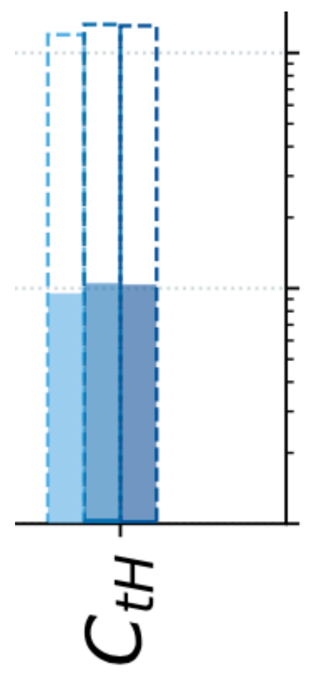
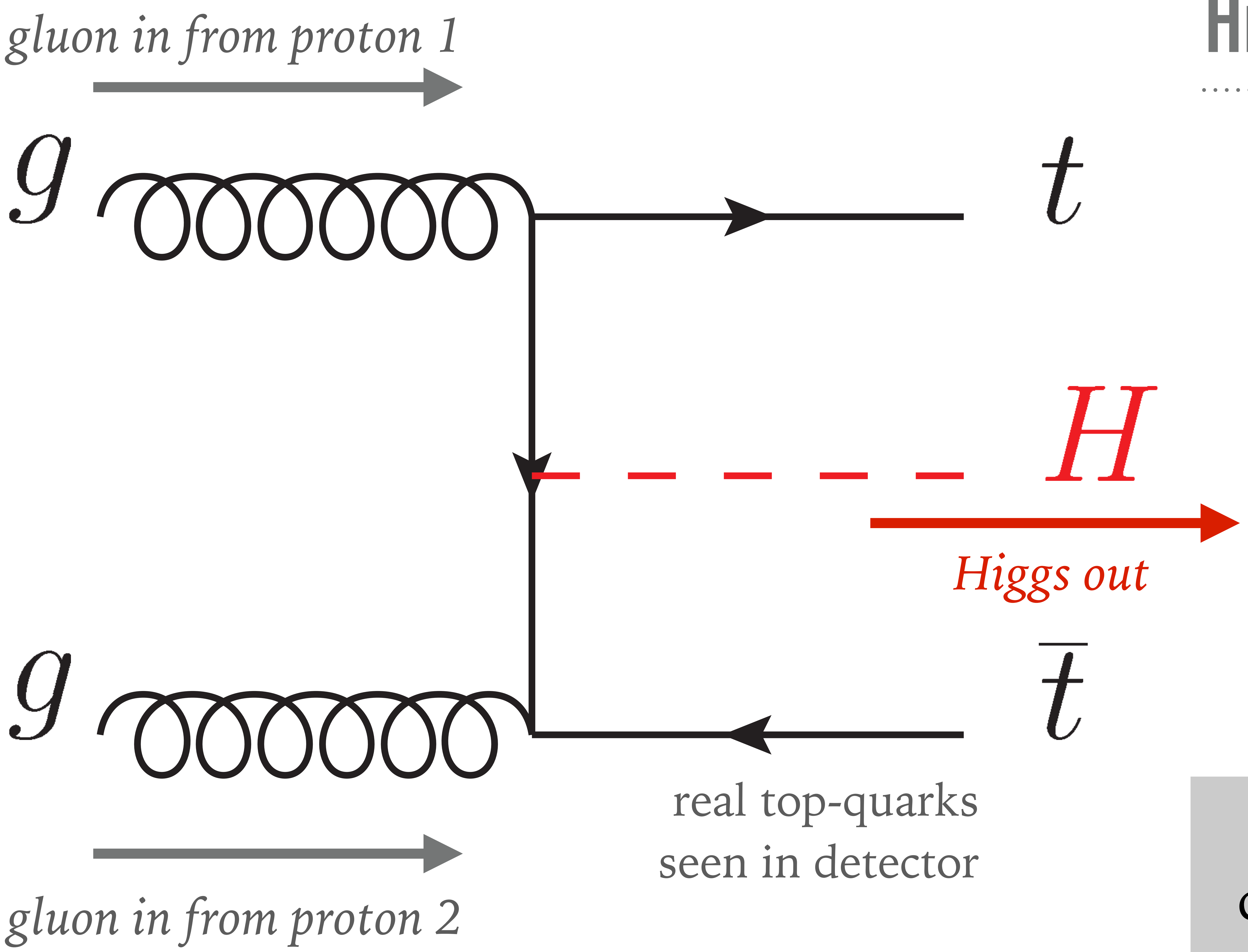
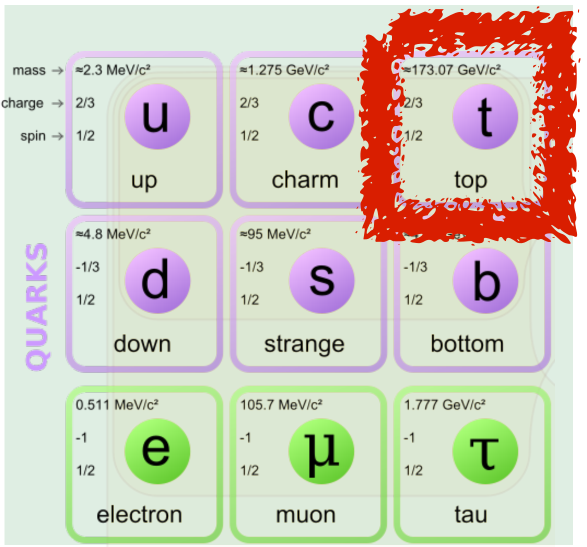


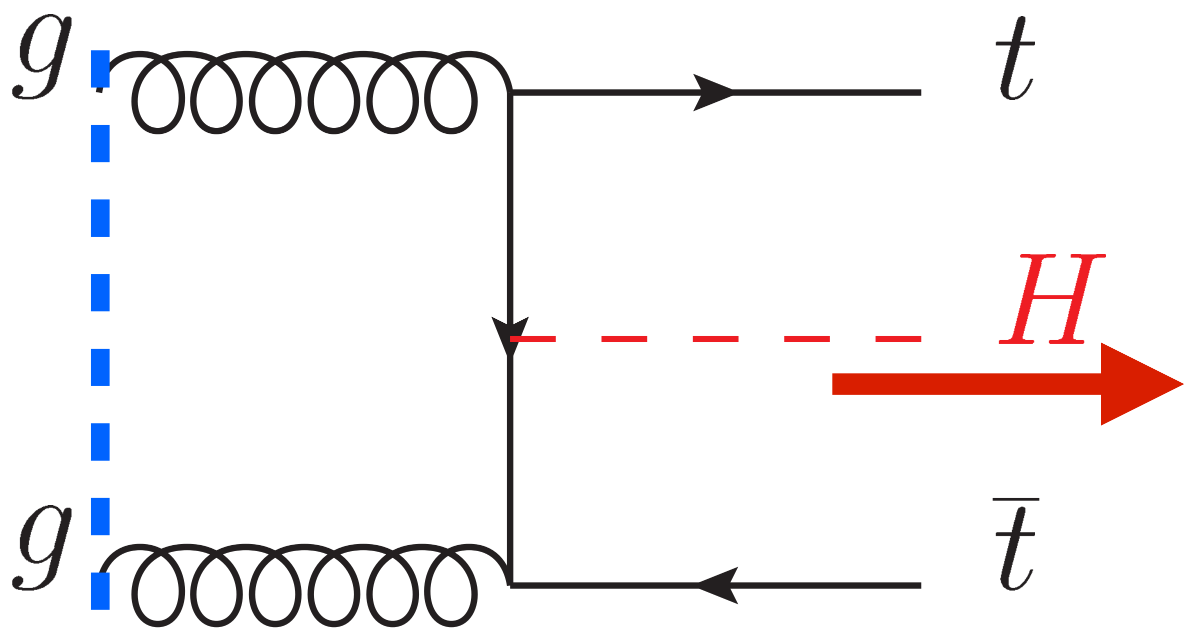
Higgs production: the ttH channel



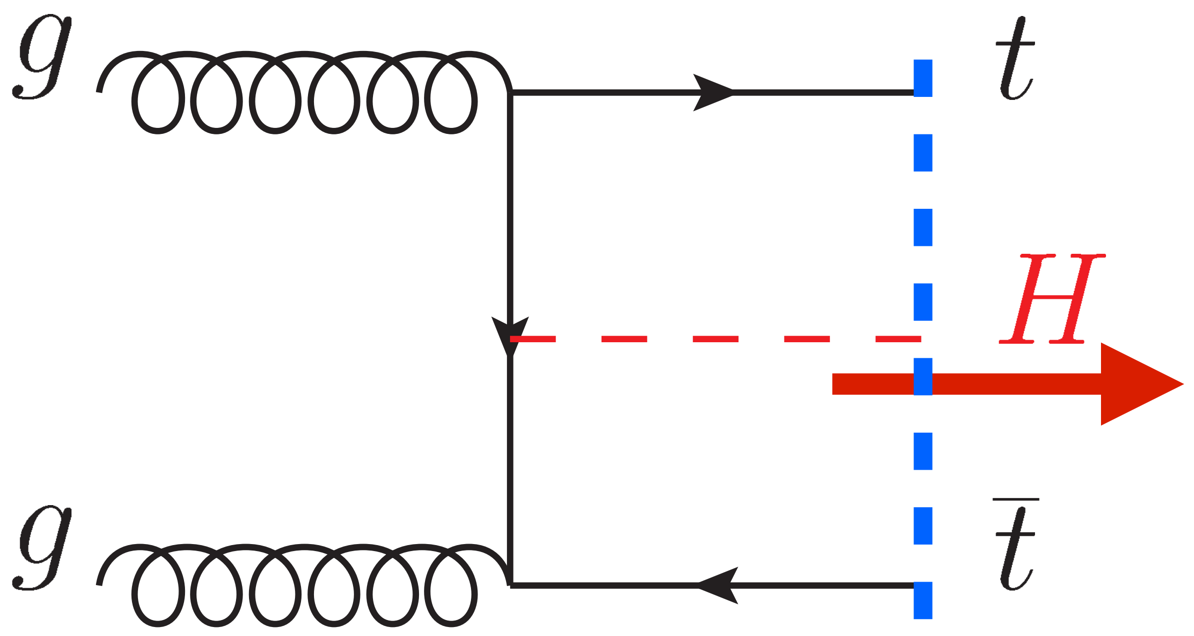
If SM top-Yukawa hypothesis is correct, expect 1 Higgs for every 1600 top-quark pairs.

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

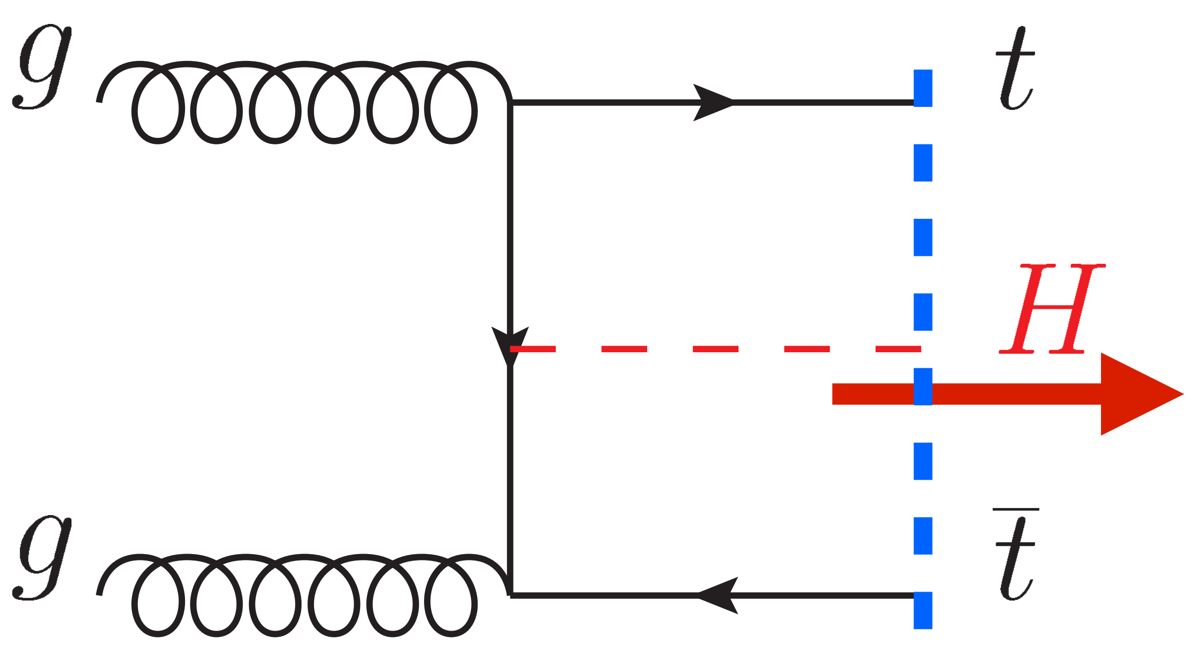



g
t
H
g
$\bar{t}$


luon
gluo
φ
y
x
Higgs field in space


g
t
H
g
$\bar{t}$

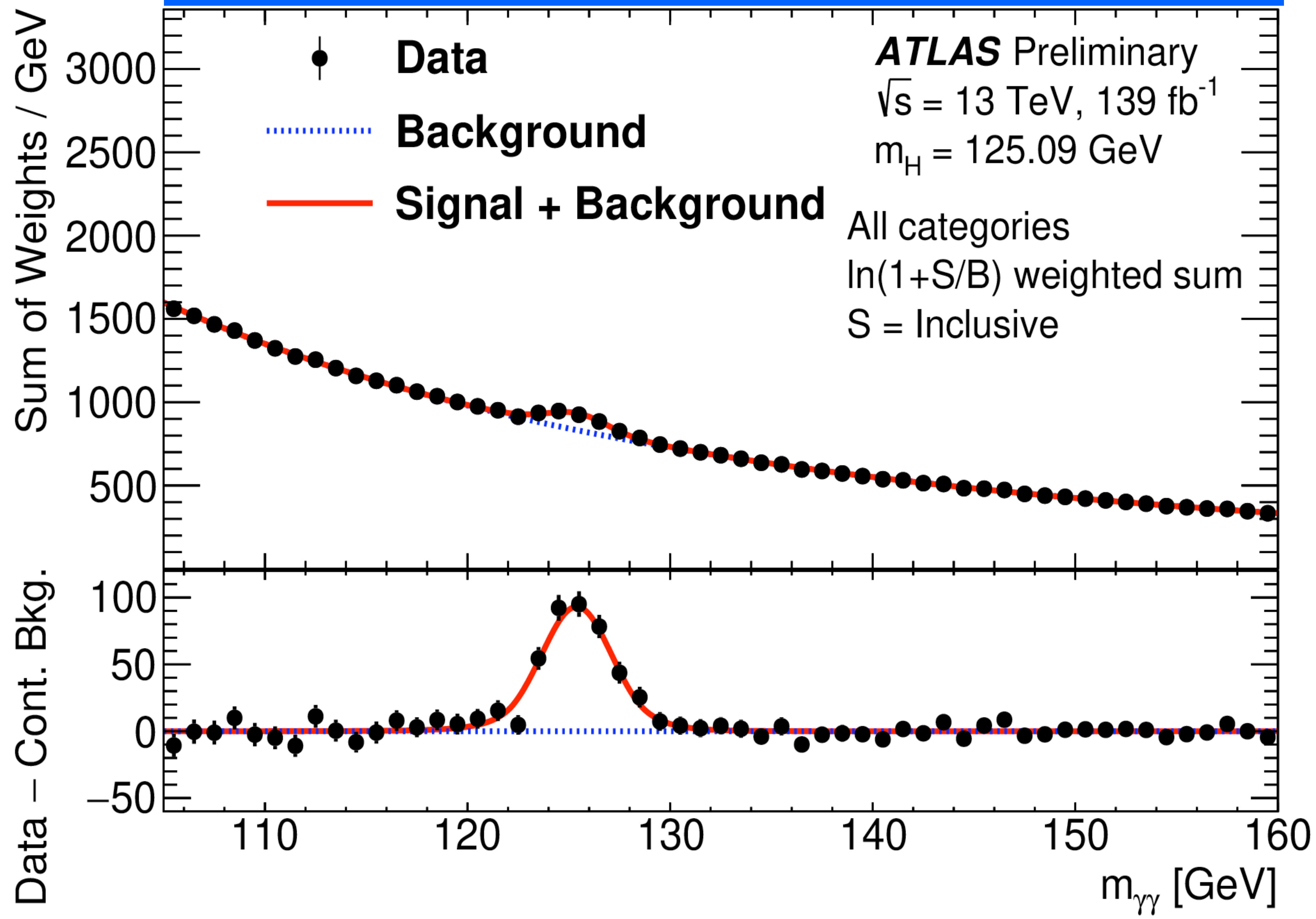

luon
gluo
ϕ
y
x
Higgs field in space


g
t
H
g
$\bar{t}$

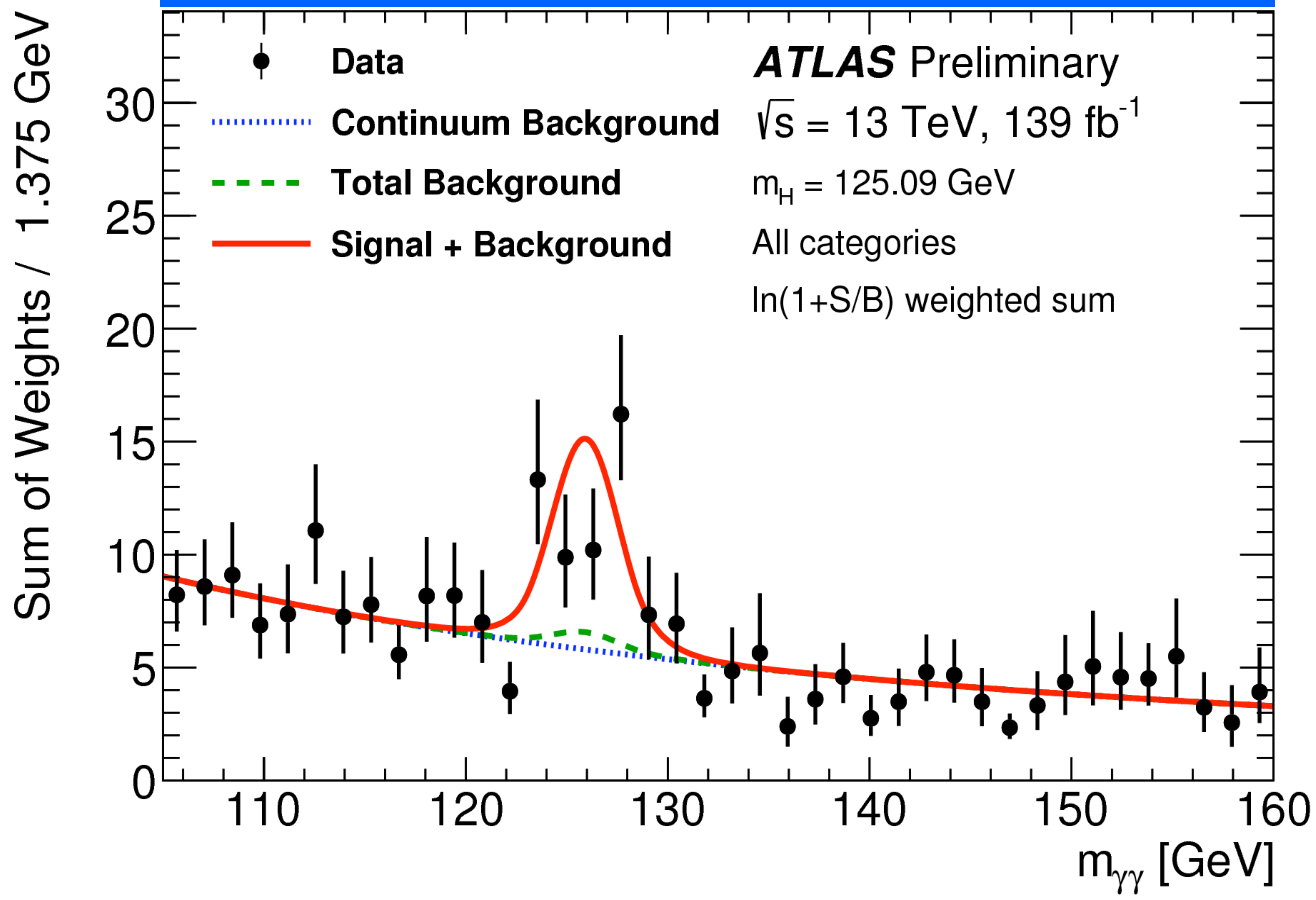

luon
gluo
ϕ
y
x
Higgs field in space

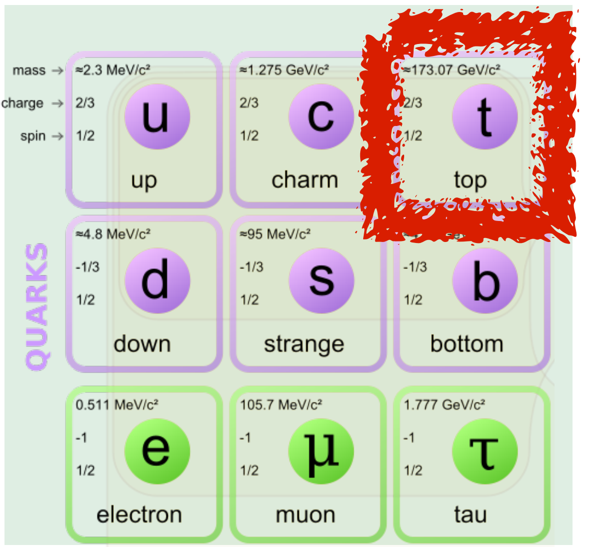
since 2018: ATLAS & CMS see events with top-quarks & Higgs simultaneously

across all events



in events with top quarks



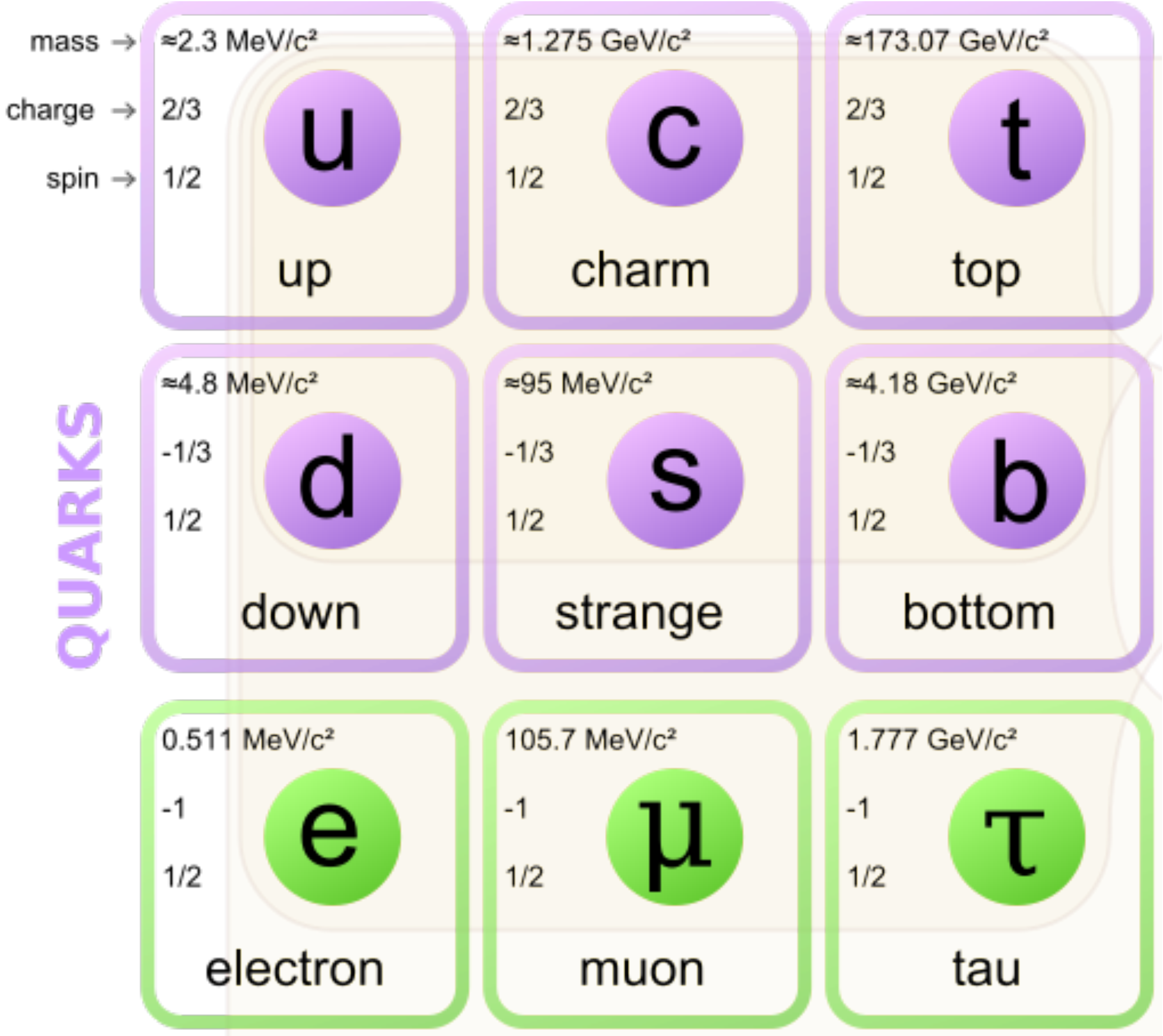


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

(consistent with SM to c. ±25%)

Discovery of 3rd generation Yukawa interactions by ATLAS & CMS



Discovery $\equiv 5\sigma \simeq \pm 20\,\%$

†in part with approach from Butterworth, Davison, Rubin & GPS '08

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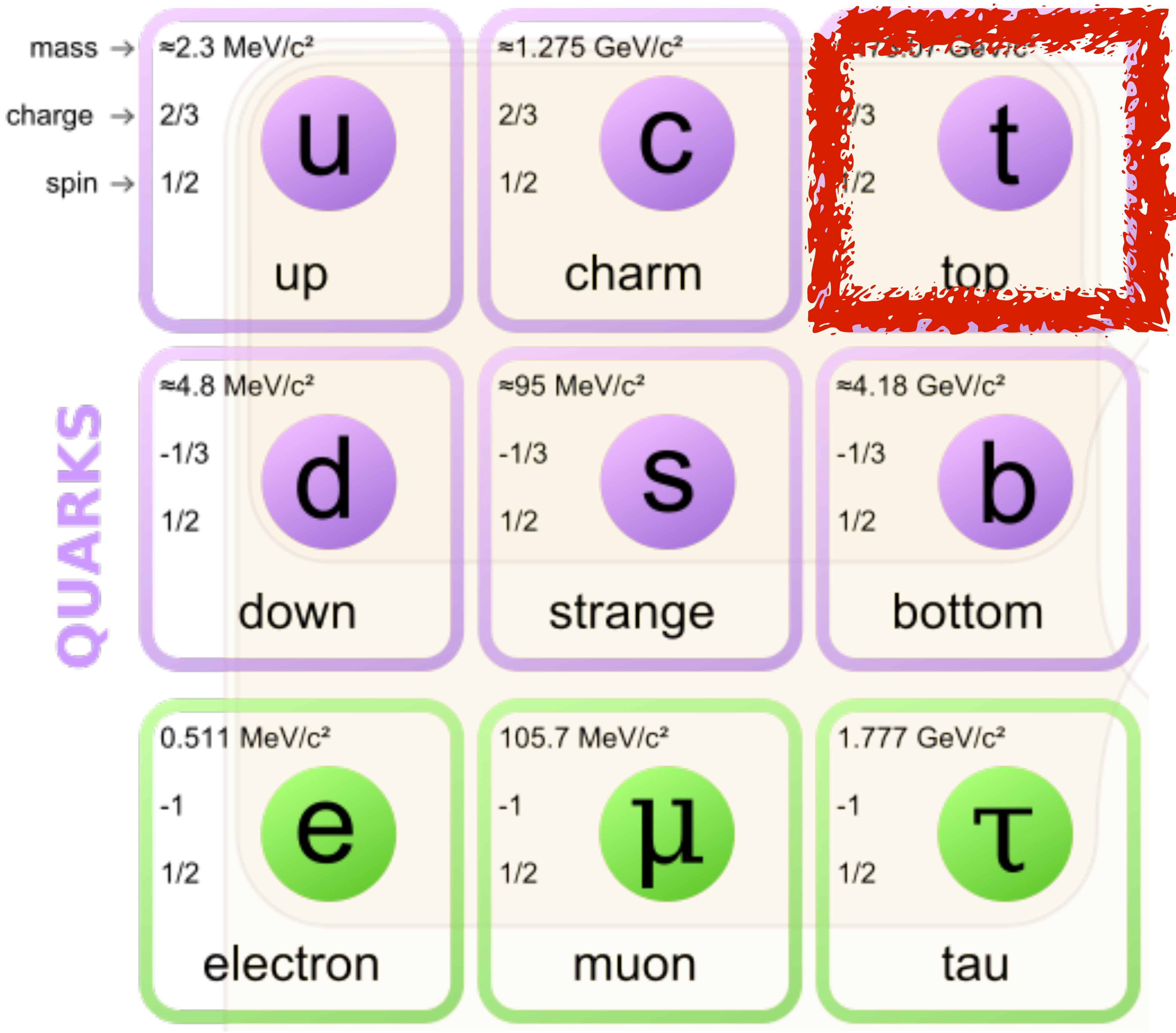

by observing H in association with top quarks

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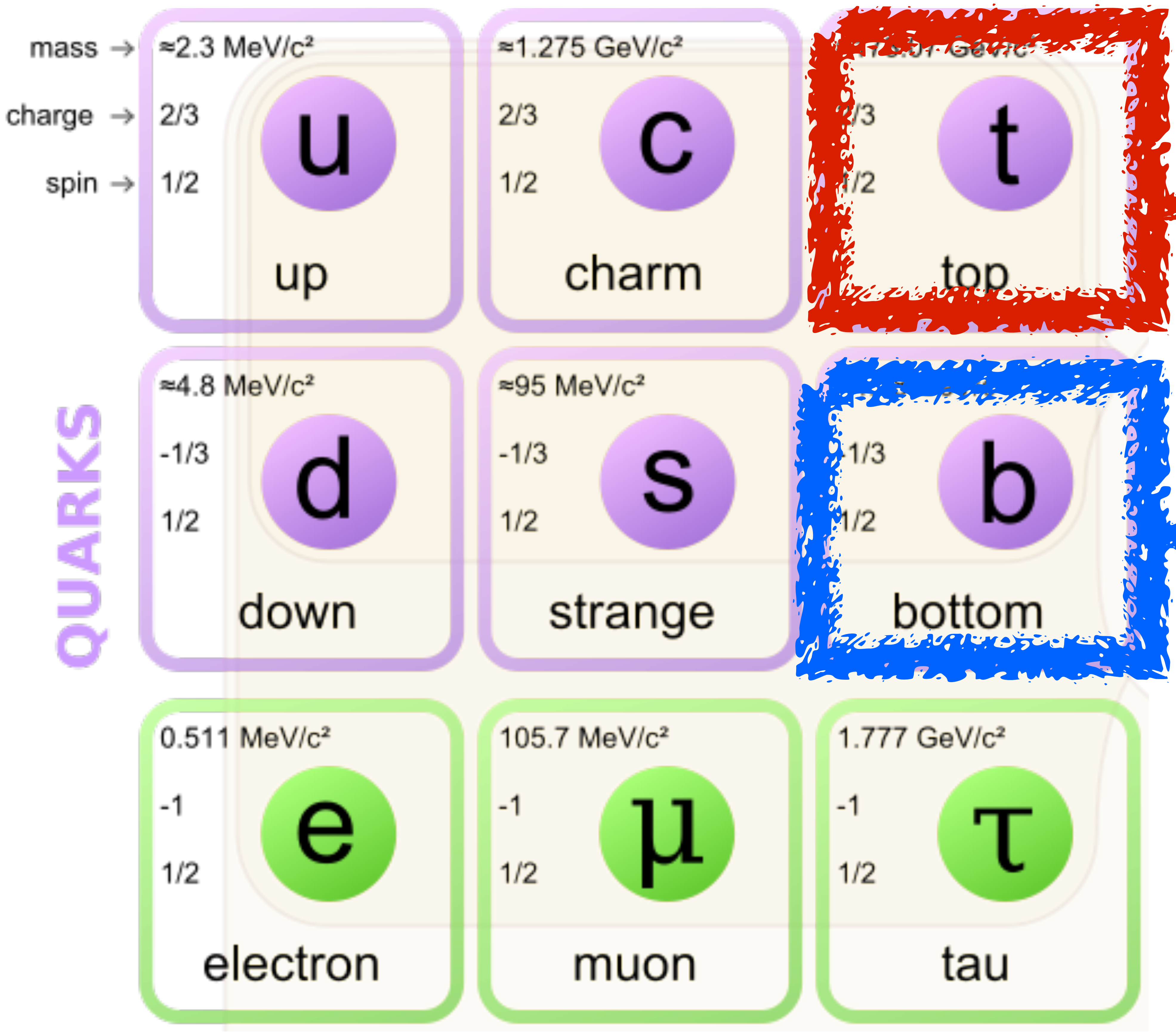

by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays†

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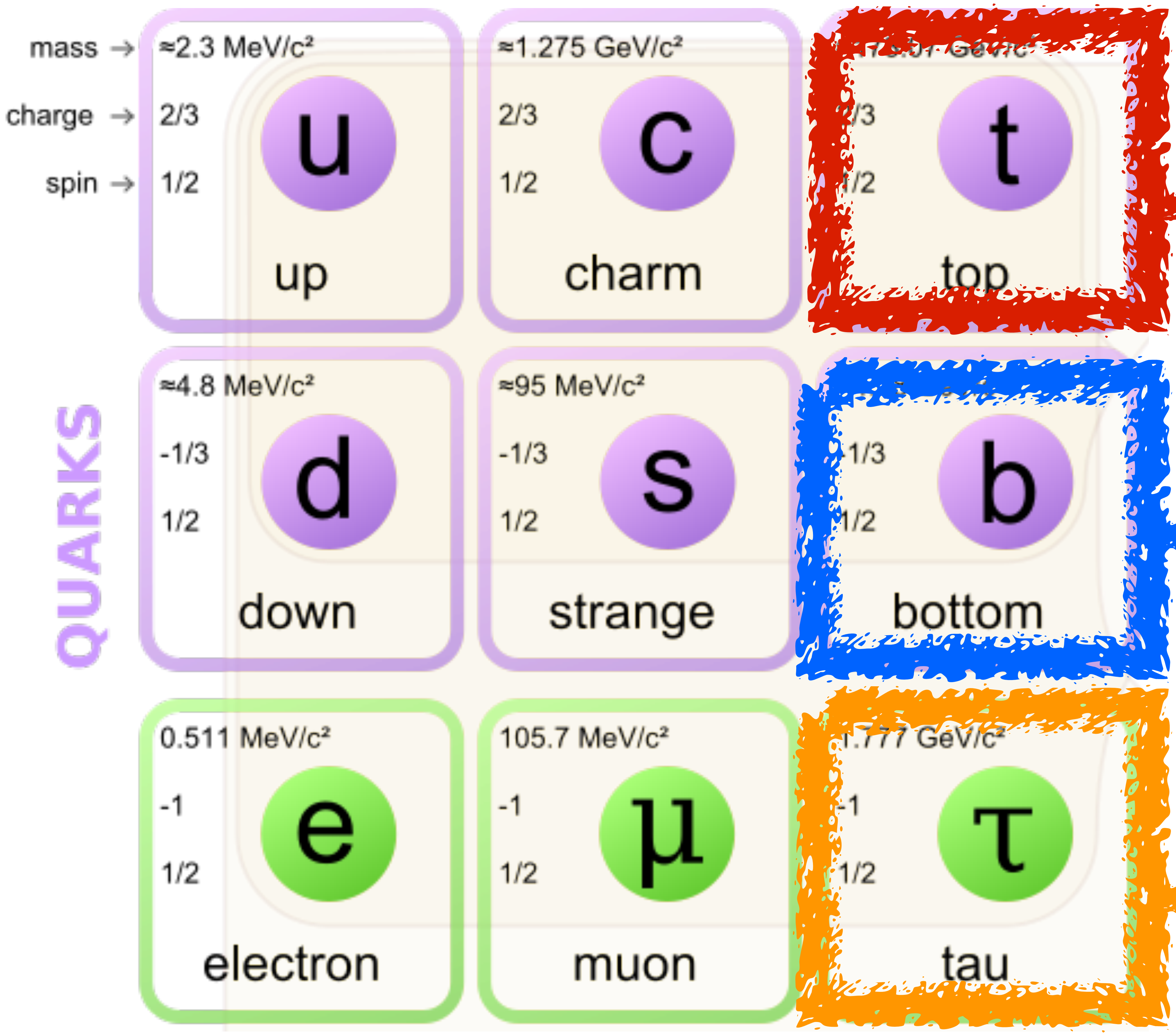
Discovery of 3rd generation Yukawa interactions by ATLAS & CMS



by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays†

by observing $H \to \tau^+\tau^-$ decays

Discovery $\equiv 5\sigma \simeq \pm 20\,\%$

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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.

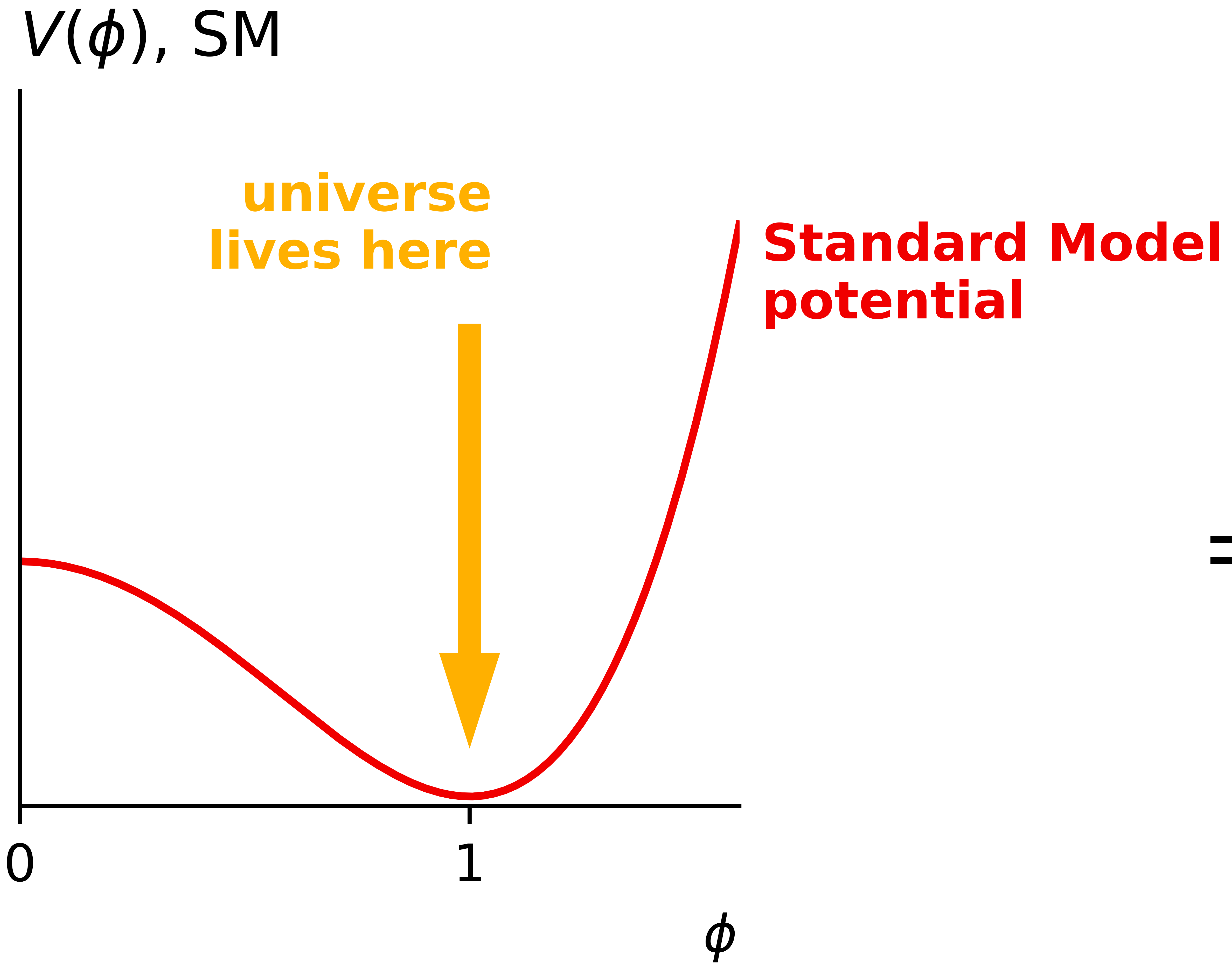
Yukawa interactions are important because they are:

(1) **qualitatively unlike any quantum interaction probed before**
(effective charge not quantised, not conserved)

(2) hypothesized to be responsible for the **stability of hydrogen,** and for determining the **size of atoms** and the energy scales of chemical reactions.

Equivalently this is a **fifth force, the "Higgs force"**

Higgs potential, keystone of the SM — what can we observe experimentally?

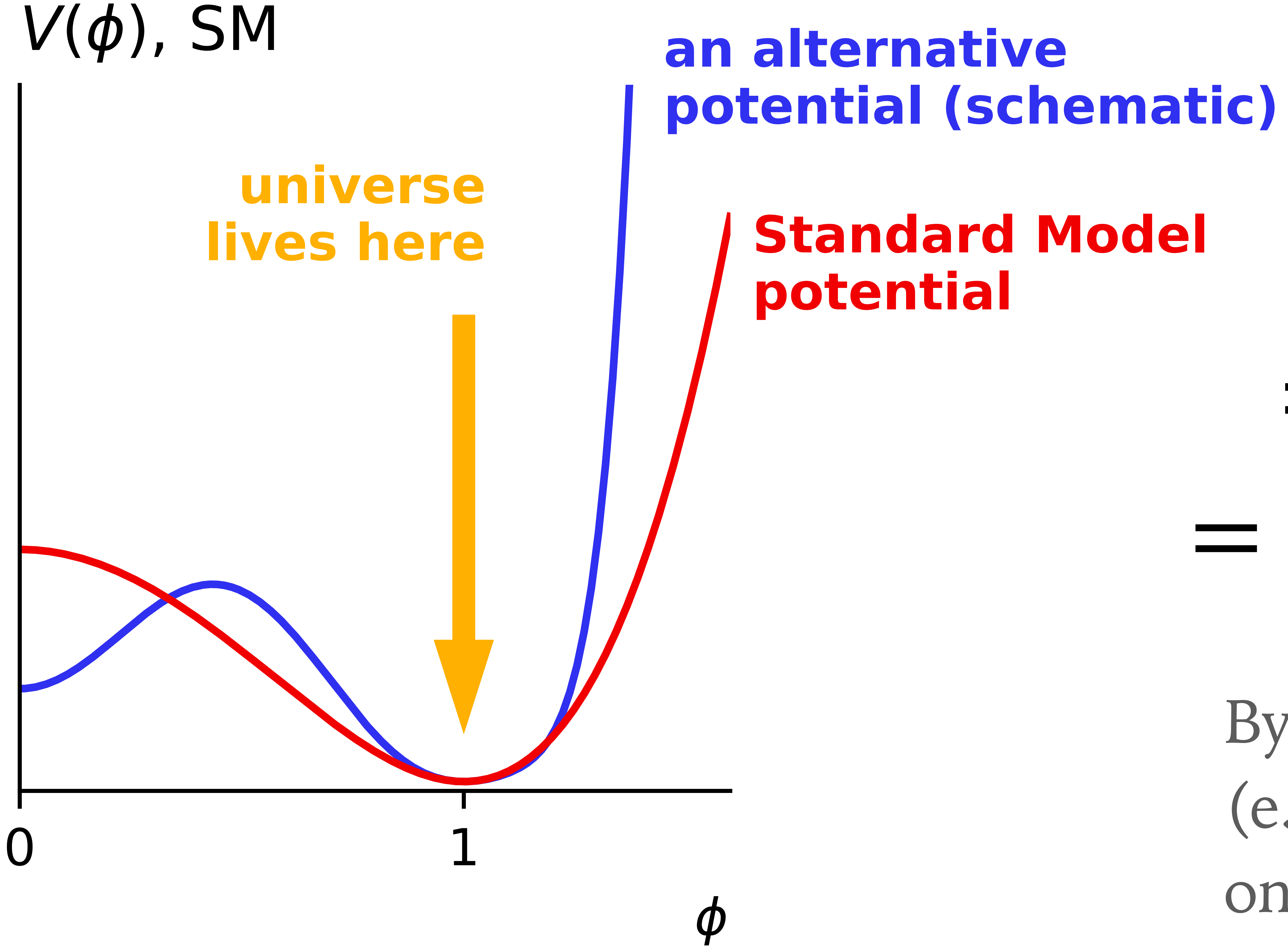


$$= -\mu^2\phi^2 + \lambda\phi^4$$
$$= V(\phi_0) + m^2H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

By trying to observe triple-Higgs interaction (e.g. H → HH) it's possible to get a handle on the third derivative of the potential

NB: realistic alternative models tend to involve additional Higgs-like fields; plot adapted from forthcoming review with Wang & Zanderighi

Higgs potential, keystone of the SM — what can we observe experimentally?



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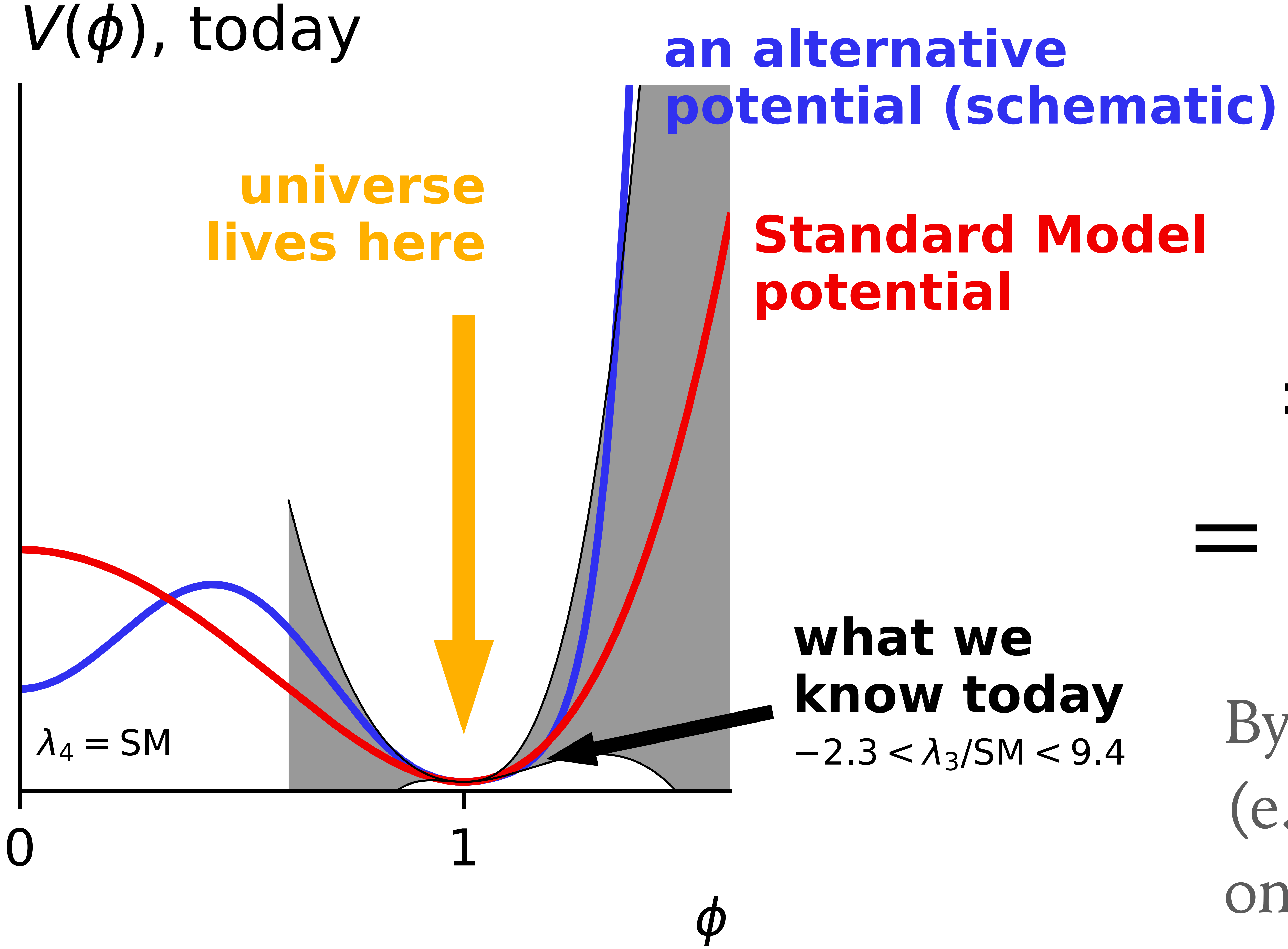

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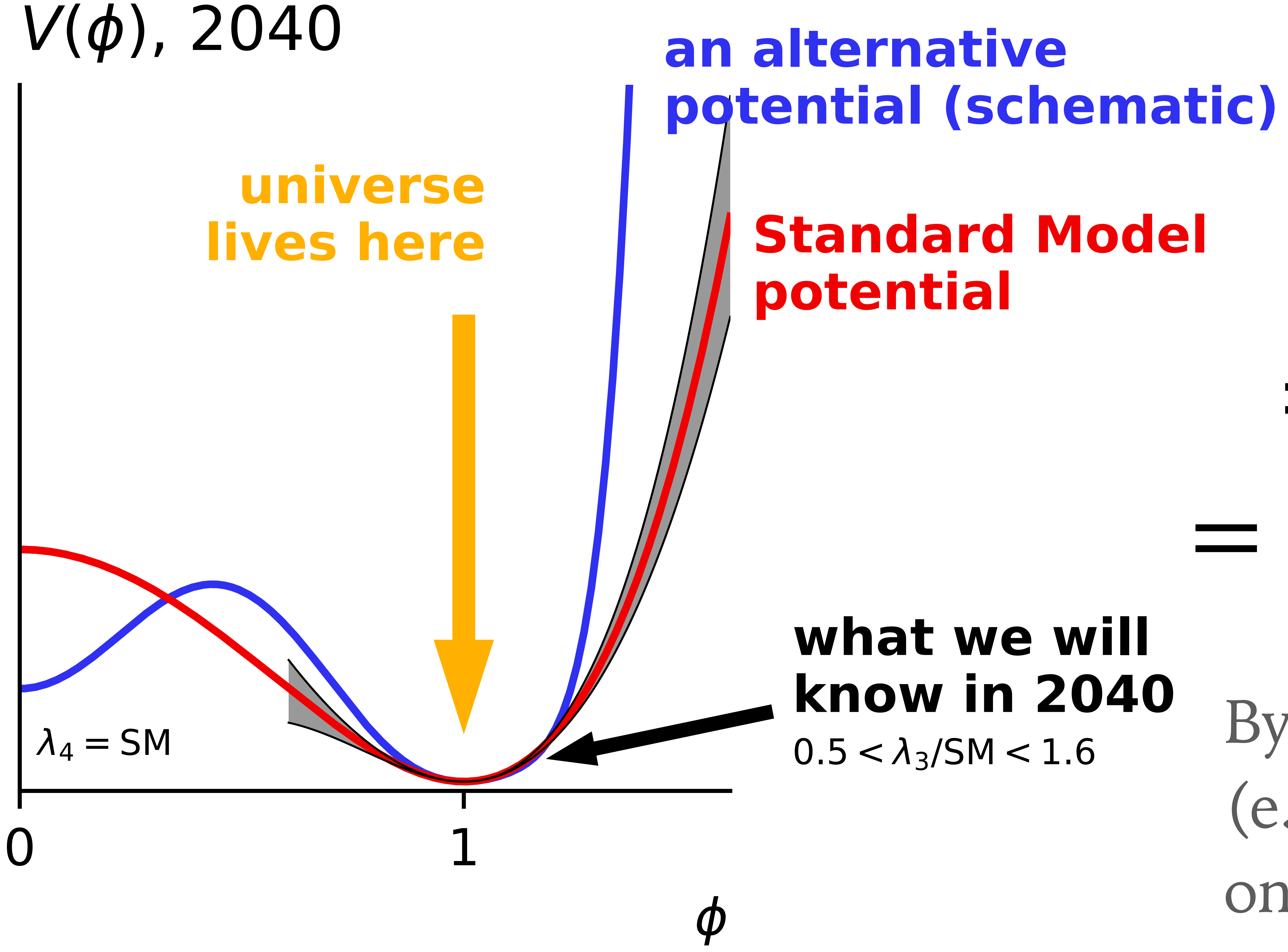

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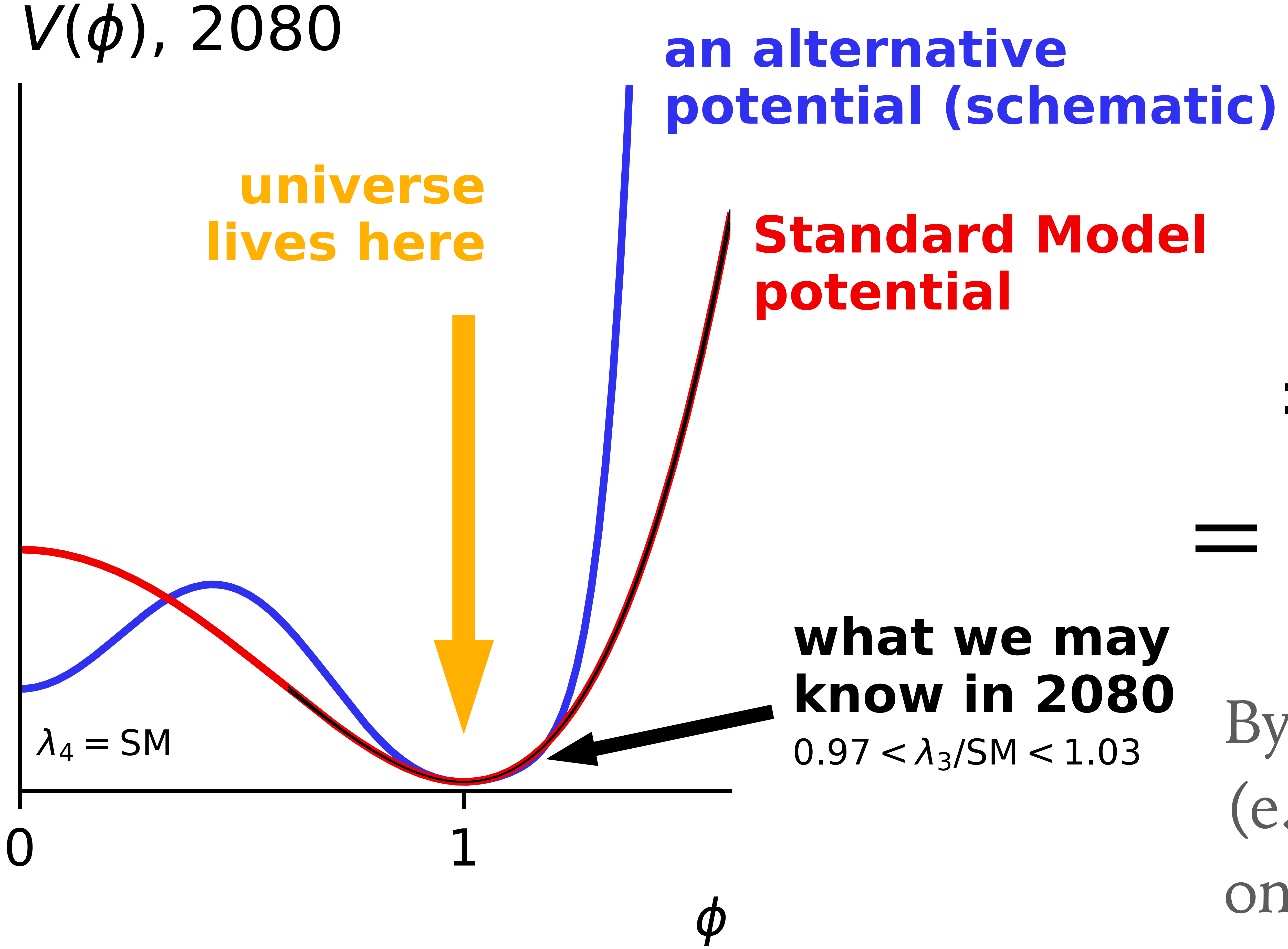

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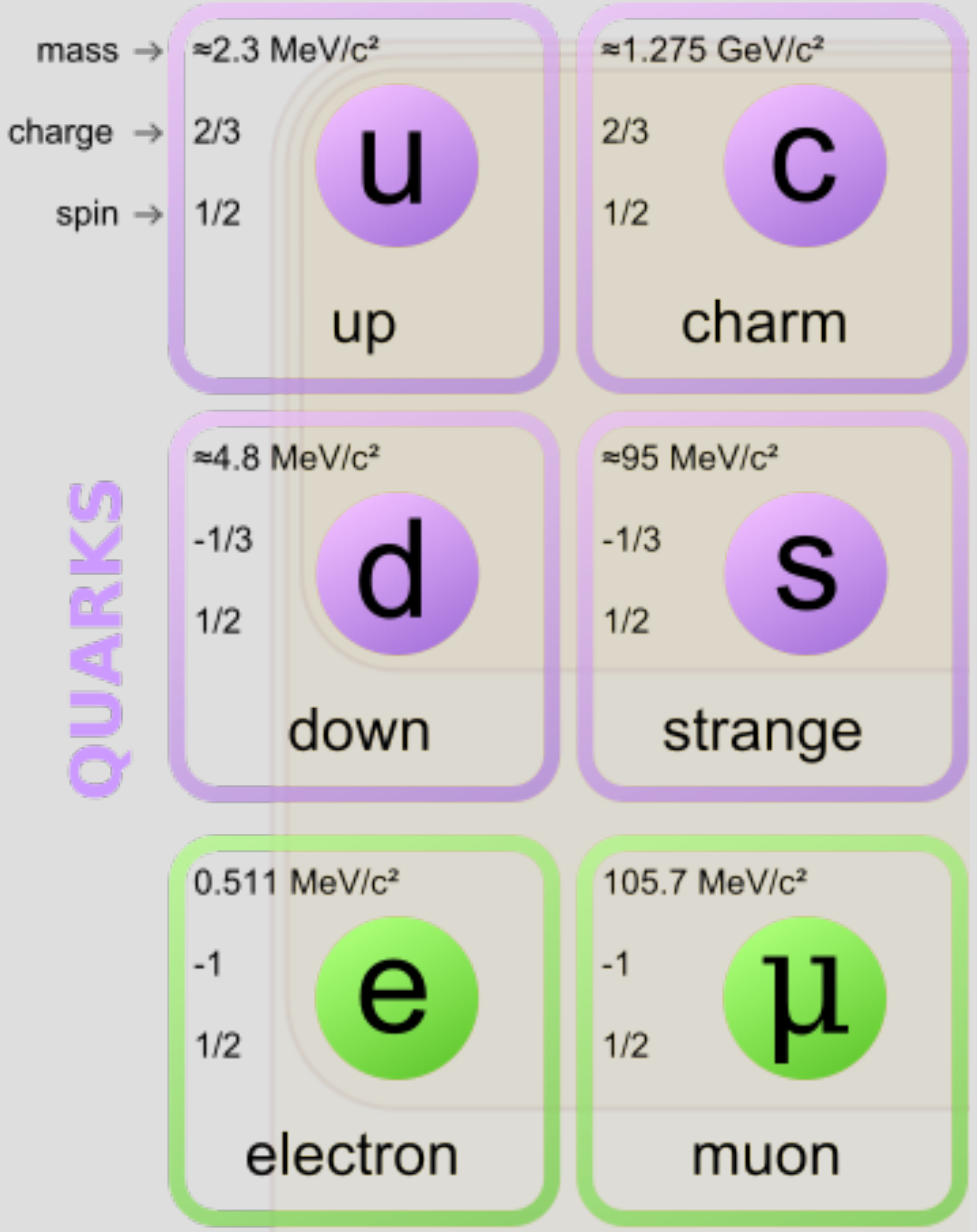
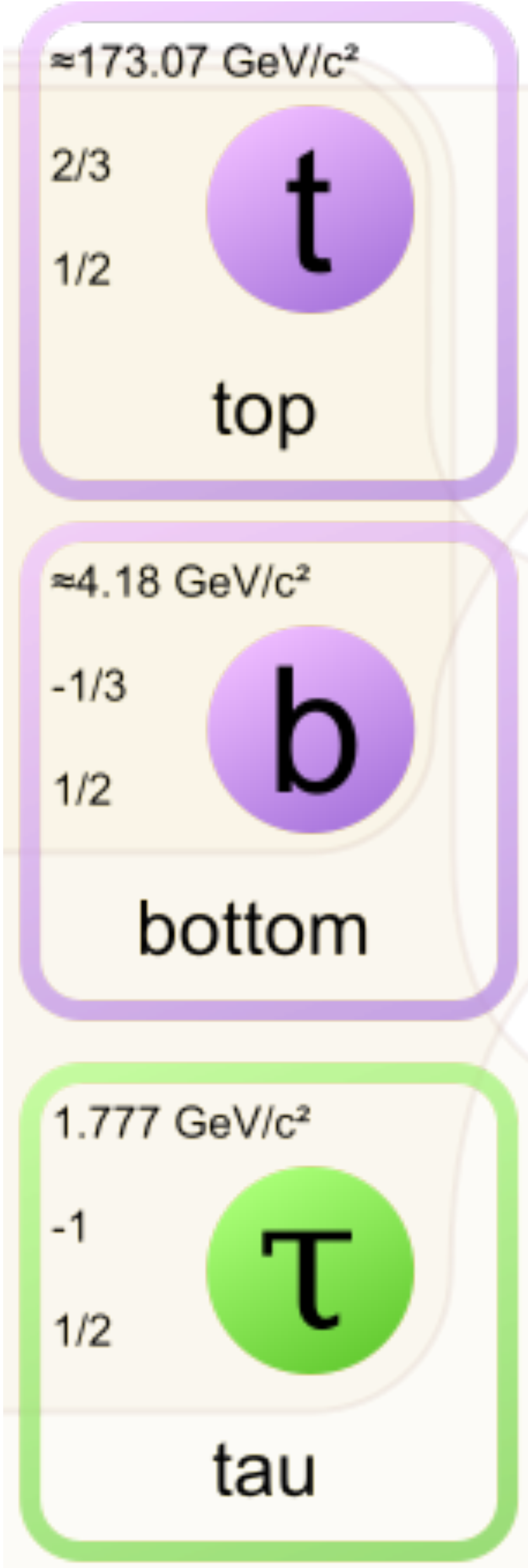
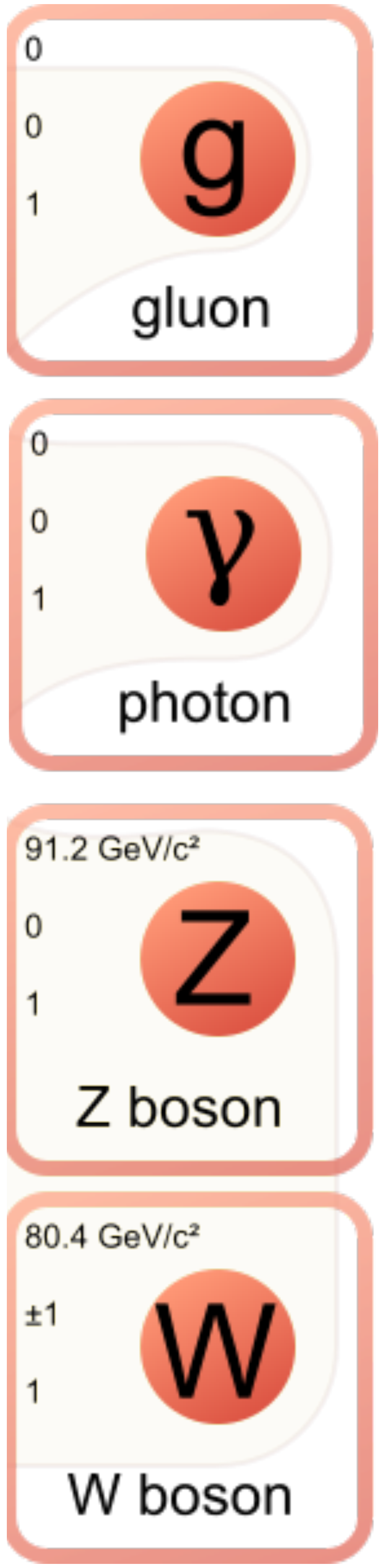
H interaction not yet seen



Are Yukawa interactions responsible for all fermion masses?

H interaction seen





Do these interactions follow the Standard Model to better than current 10% accuracy?

Higgs potential not yet "seen"

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

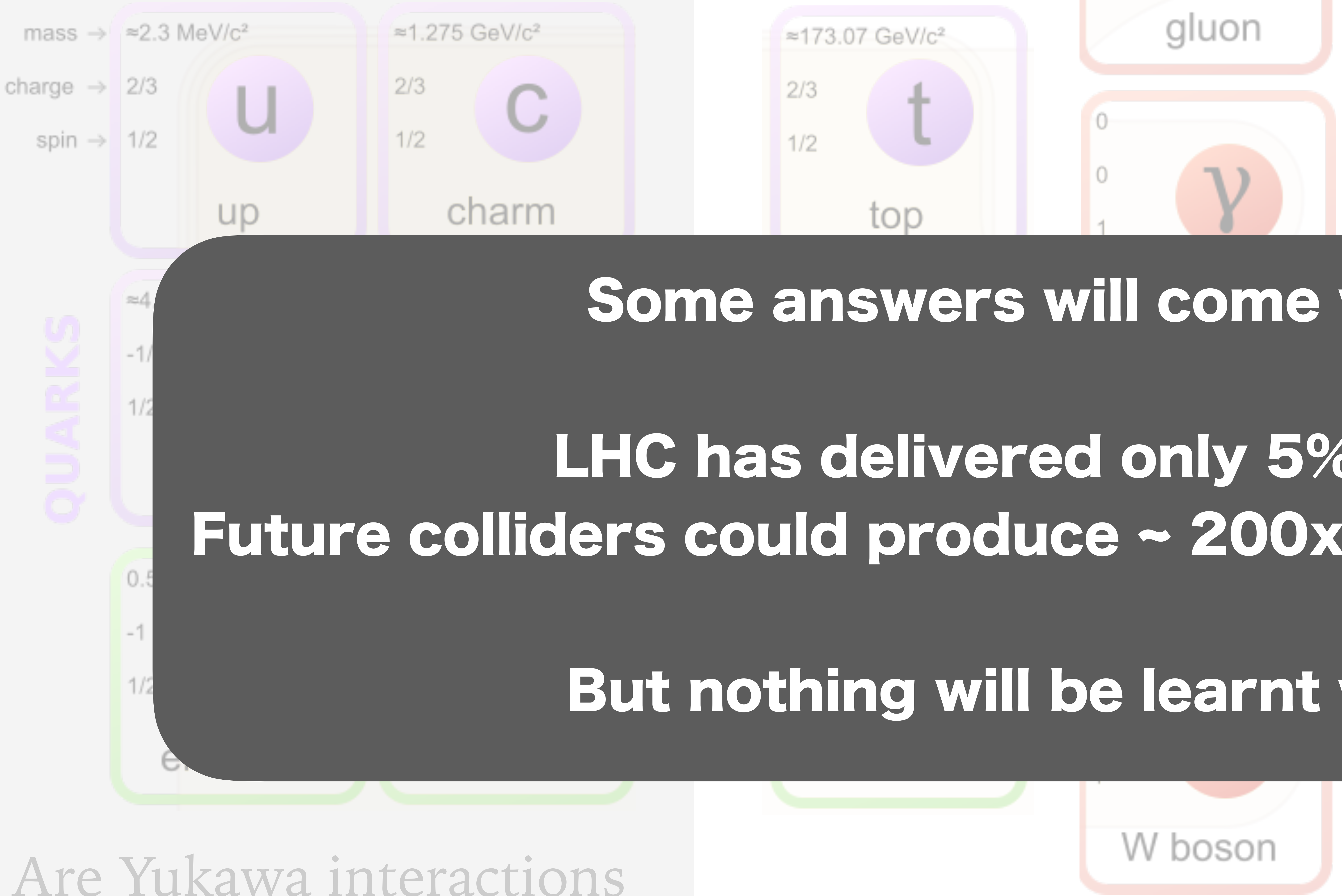
Is this "toy-model" potential Nature's choice?

Does the Higgs behave as a pointlike (fundamental) particle?

H interaction not yet seen

H interaction seen

Higgs potential not yet "seen"



Some answers will come with more data

LHC has delivered only 5% of its collisions
Future colliders could produce ~ 200x more Higgses than the LHC

But nothing will be learnt without QCD . . .

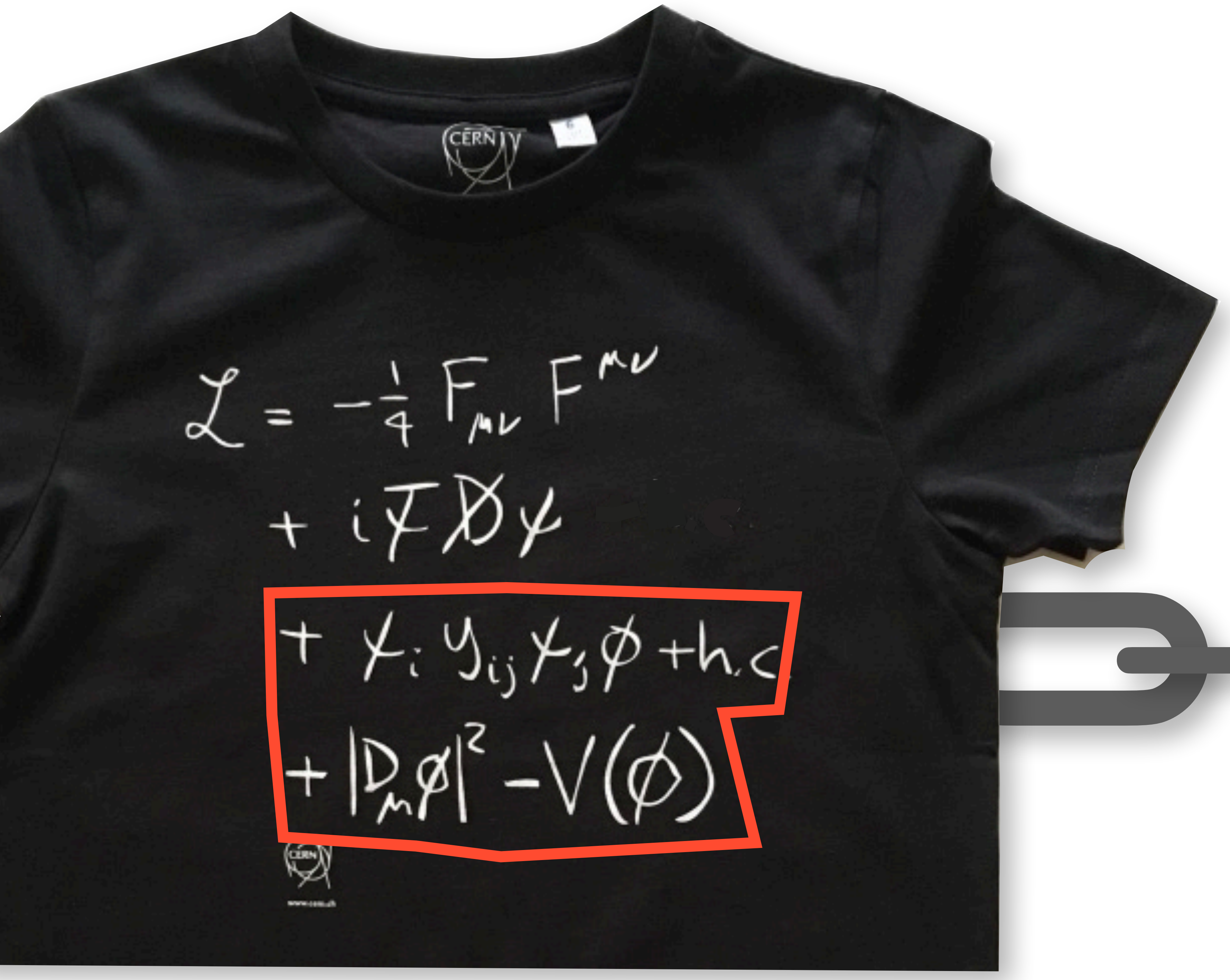
Are Yukawa interactions responsible for all fermion masses?

Do these interactions follow the Standard Model to better than current 10% accuracy?

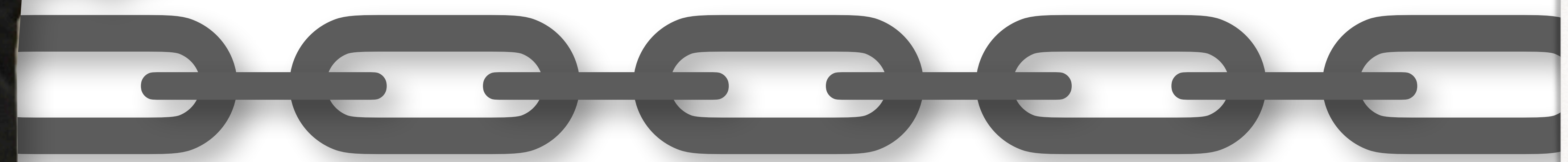
...ntlike (fundamental) particle?

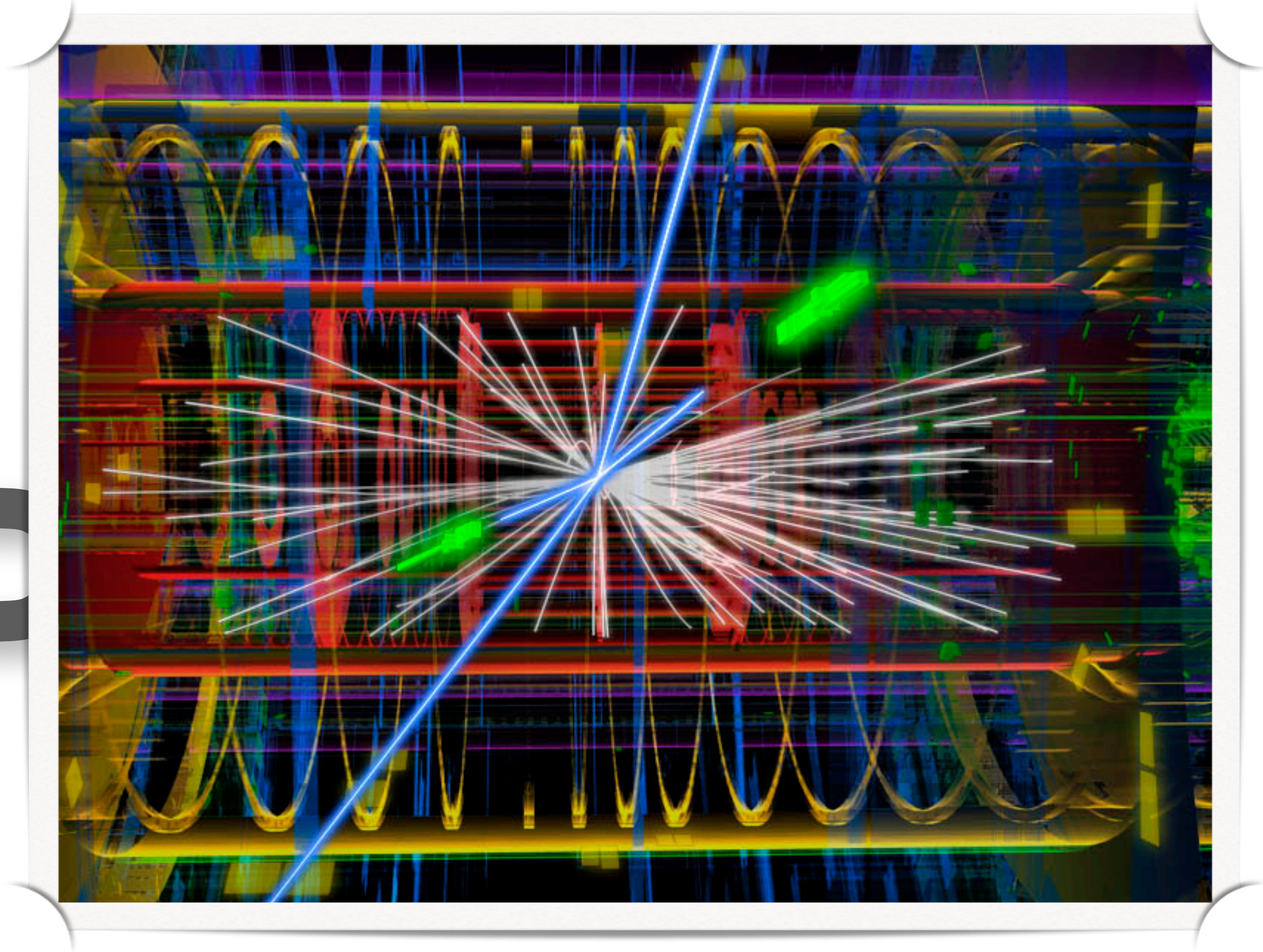
UNDERLYING THEORY

EXPERIMENTAL DATA

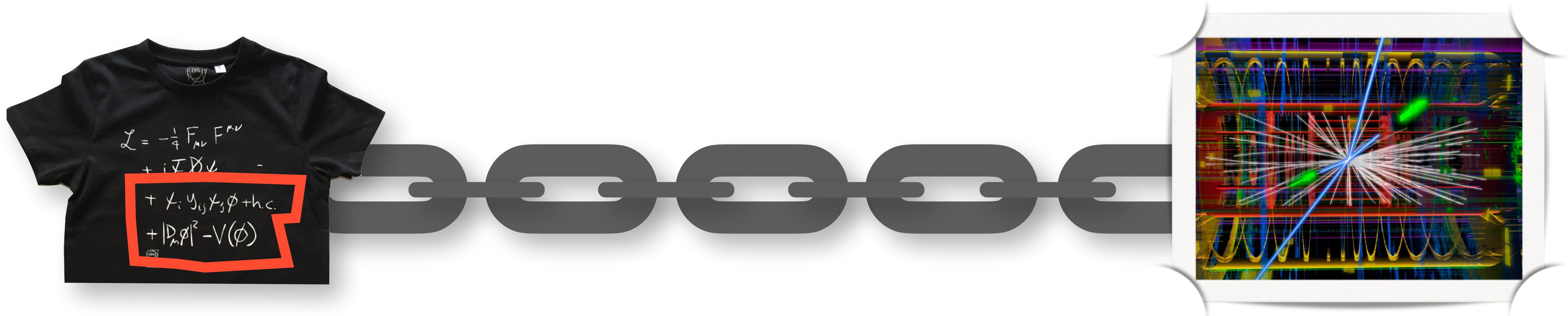


how do you make quantitative connection?





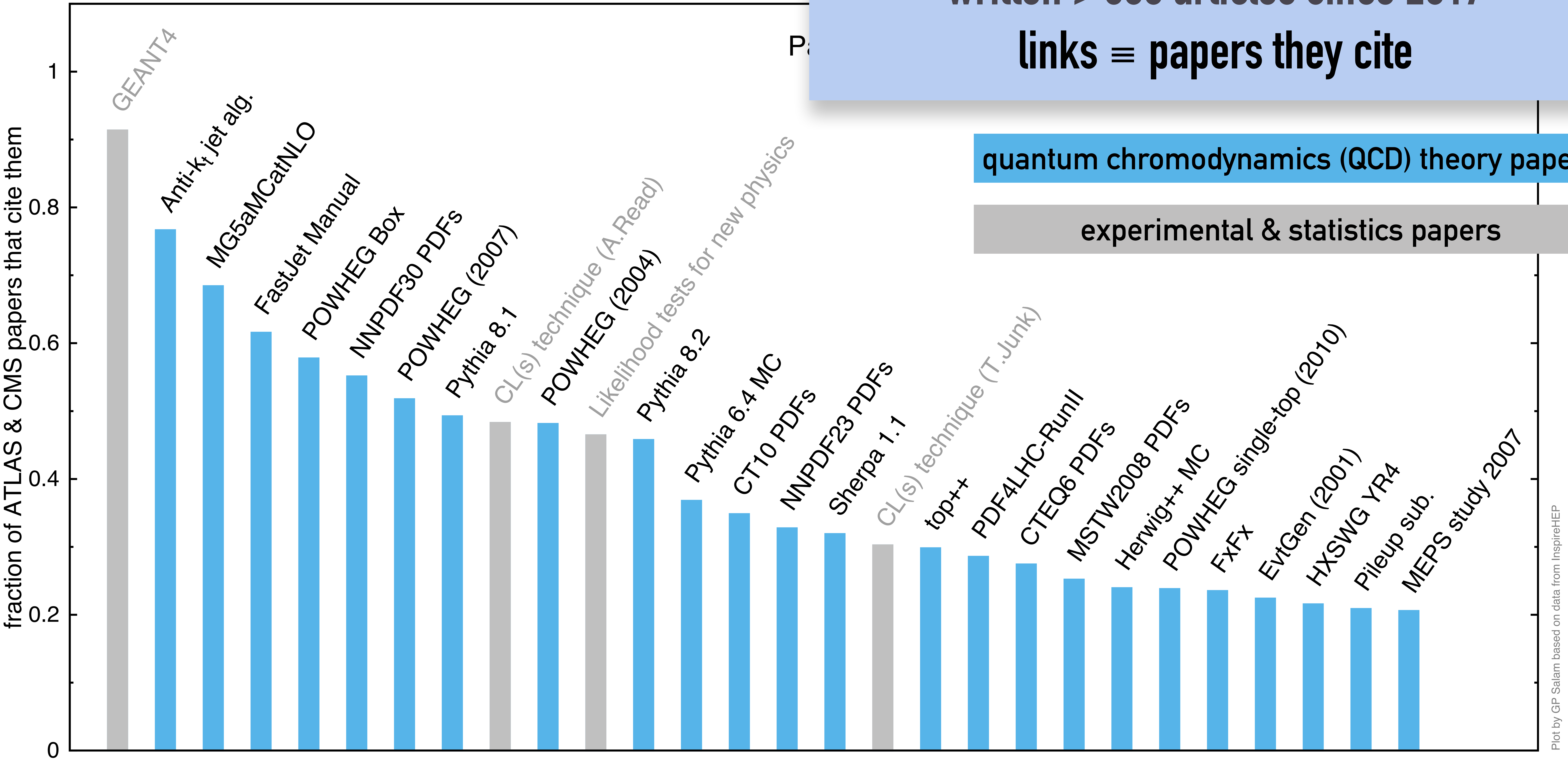
through a chain of experimental and theoretical links



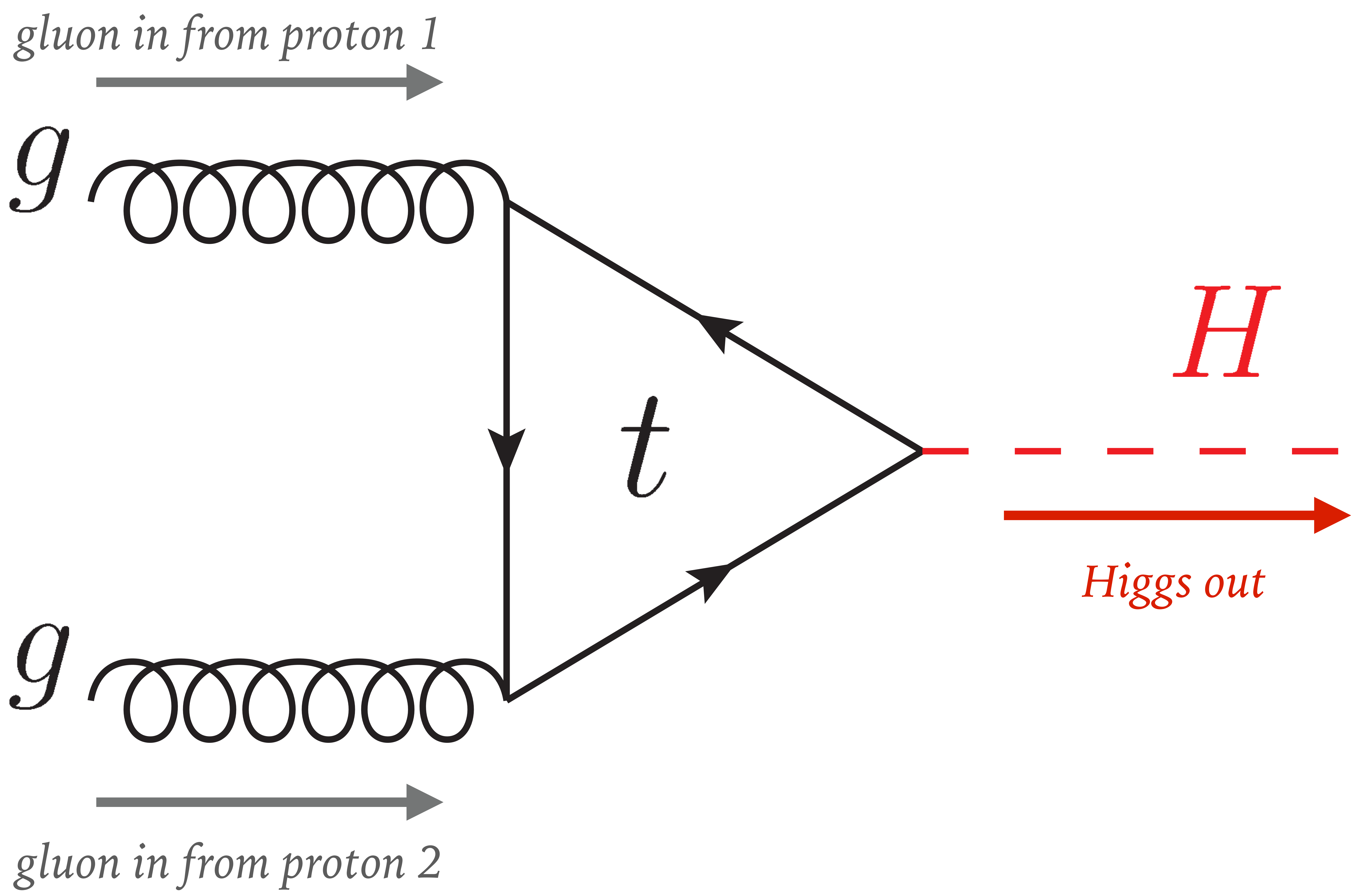
What are the links?

ATLAS and CMS (big LHC expts.) have written >650 articles since 2017

links ≡ papers they cite

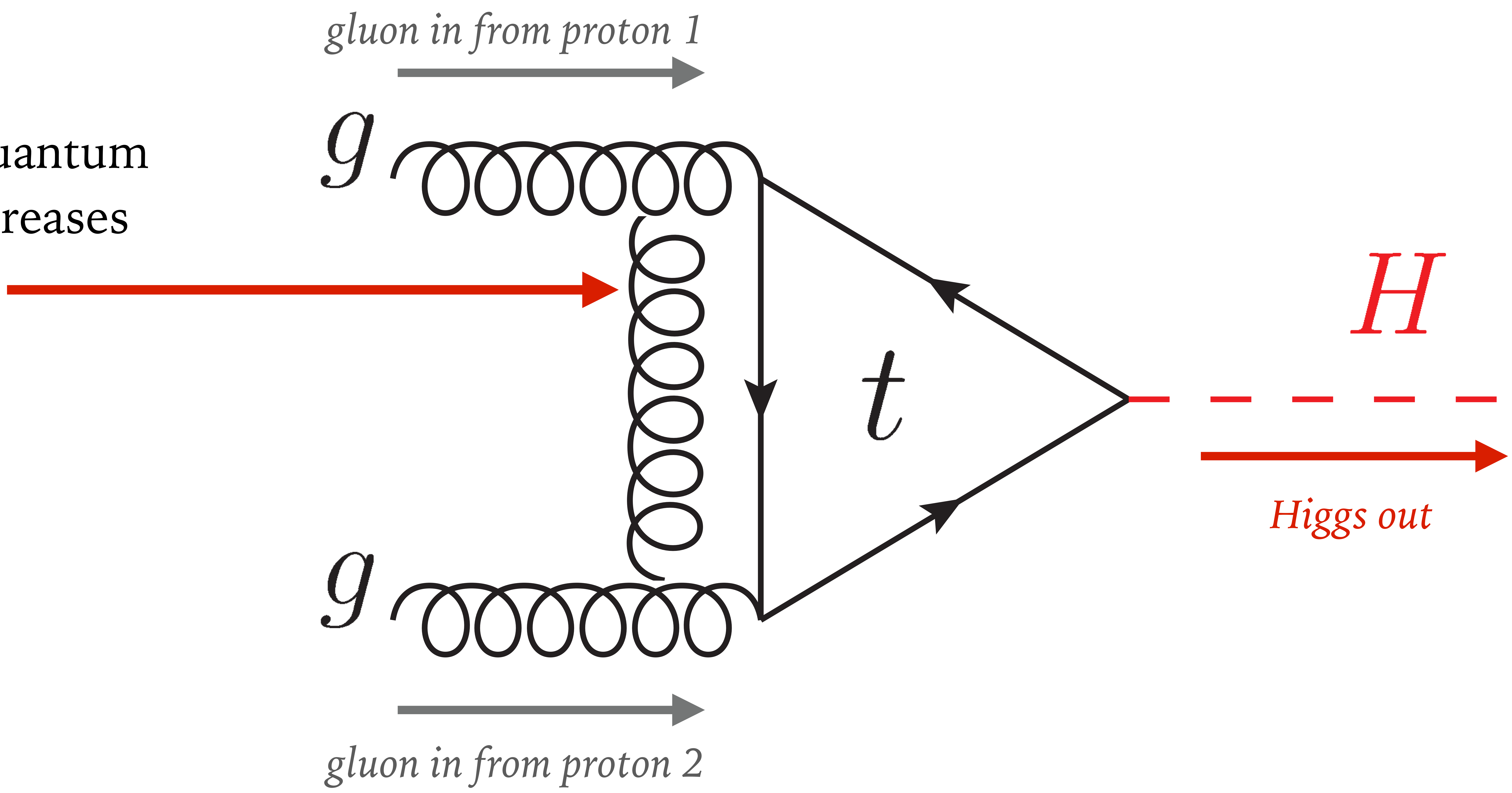


Quantitative Higgs studies need profound understanding of quantum fluctuations



Quantitative Higgs studies need profound understanding of quantum fluctuations

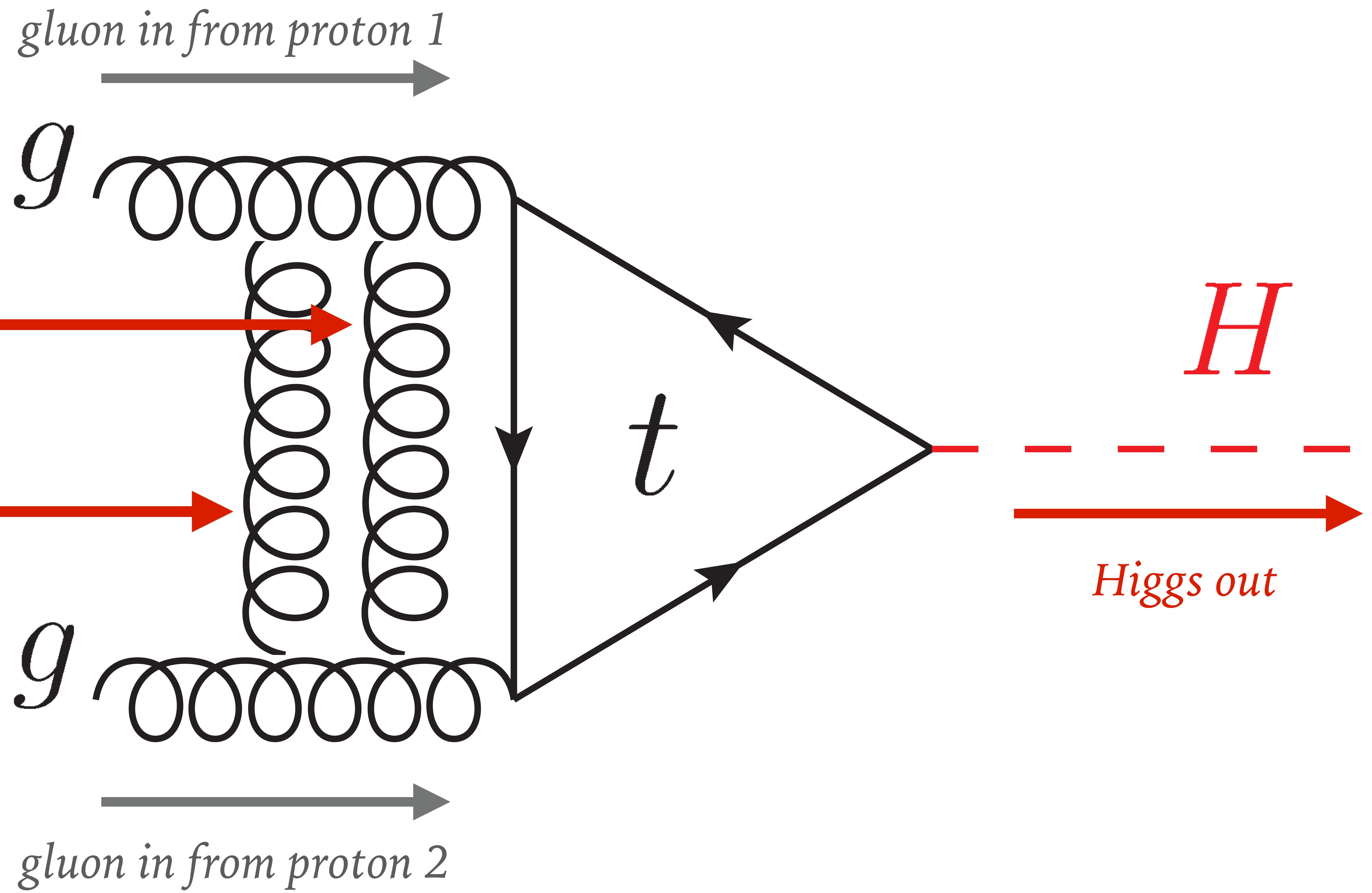
1 additional quantum fluctuation increases rate by × 2.3



Quantitative Higgs studies need profound understanding of quantum fluctuations

1 additional quantum fluctuation increases rate by × 2.3

2nd quantum fluctuation by × 1.26

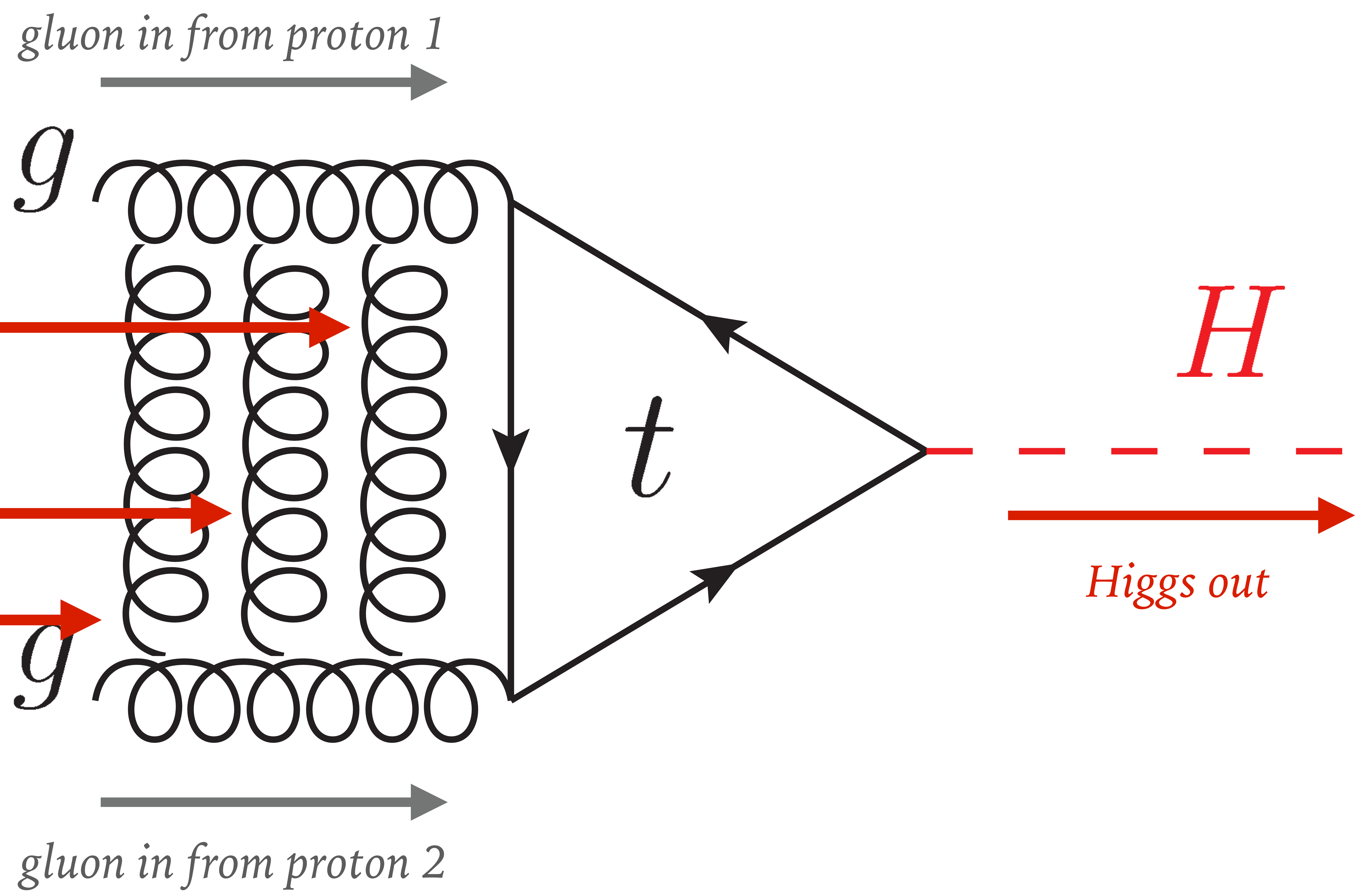


Quantitative Higgs studies need profound understanding of quantum fluctuations

1 additional quantum fluctuation increases rate by $\times 2.3$

2nd quantum fluctuation by $\times 1.26$

3rd by $\times 1.03$



ETH & UZH theorists are [the!] world leaders in understanding these fluctuations

Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC

Giuseppe Bozzi (LPSC, Grenoble), Stefano Catani (INFN, Florence and Florence U.), Daniel de Florian (Buenos Aires U.), Massimiliano Grazzini (INFN, Florence and Florence U.) (Aug, 2005)

Published in: *Nucl.Phys.B* 737 (2006) 73-120 • e-Print: hep-ph/0508068 [hep-ph]

Higgs Boson Gluon-Fusion Production in QCD at Three Loops

Charalampos Anastasiou (Zurich, ETH), Claude Duhr (CERN and Louvain U., CP3), Falko Dulat (Zurich, ETH), Franz Herzog (NIKHEF, Amsterdam), Bernhard Mistlberger (Zurich, ETH) (Mar 20, 2015)

Published in: *Phys.Rev.Lett.* 114 (2015) 212001 • e-Print: 1503.06056 [hep-ph]

Fiducial distributions in Higgs and Drell-Yan production at N^3LL+NNLO #

Wojciech Bizoń (Oxford U., Theor. Phys.), Xuan Chen (Zurich U.), Aude Gehrmann-De Ridder (Zurich U. and Zurich, ETH), Thomas Gehrmann (Zurich U.), Nigel Glover (Durham U., IPPP) et al. (May 15, 2018)

Published in: *JHEP* 12 (2018) 132 • e-Print: 1805.05916 [hep-ph]

outlook

Outlook

- Higgs discovery has opened a new chapter in particle physics
- **Qualitatively new kind of interaction — Yukawa interactions (“fifth force”)**
  - critical to the world as we know it
  - so far probed only to 10–20%, for a subset of the fermions
  - and in only a corner of phase space
- **Huge experimental progress still to come, from (HL)LHC and possible future colliders (e.g. CERN’s Future Circular Collider project)**
  - We may find clues to some of the big mysteries of particles physics and cosmology (dark matter, hierarchy problem, early-universe phase transitions)
  - or we may confirm the SM in its remarkable minimality