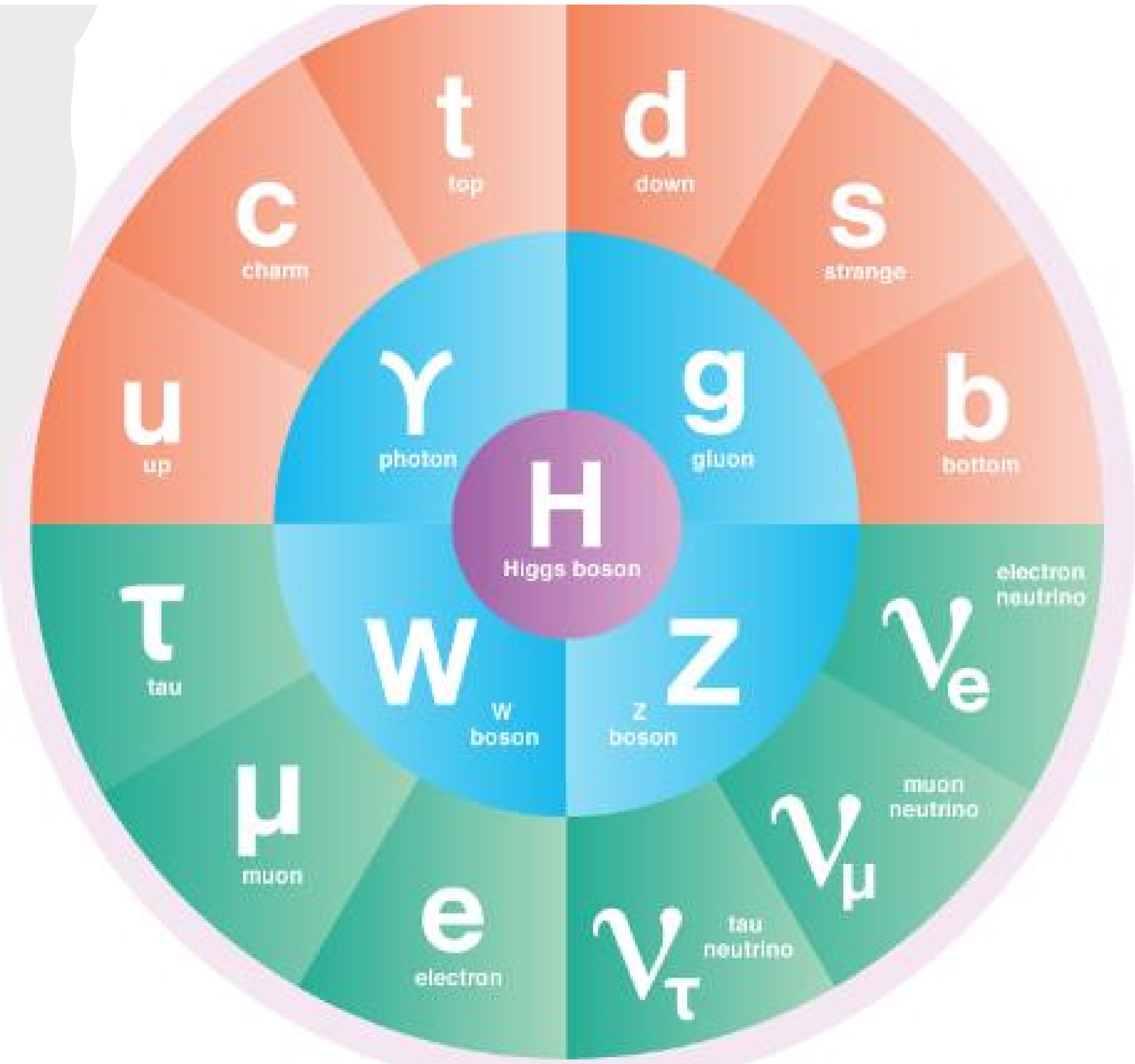
A Particle Physics Guide towards Quantum Gravity



The Standard Model as an Effective Field Theory

Juan Rojo, VU Amsterdam & Theory group, Nikhef

How the standard model EFT can be tested in collider experiments

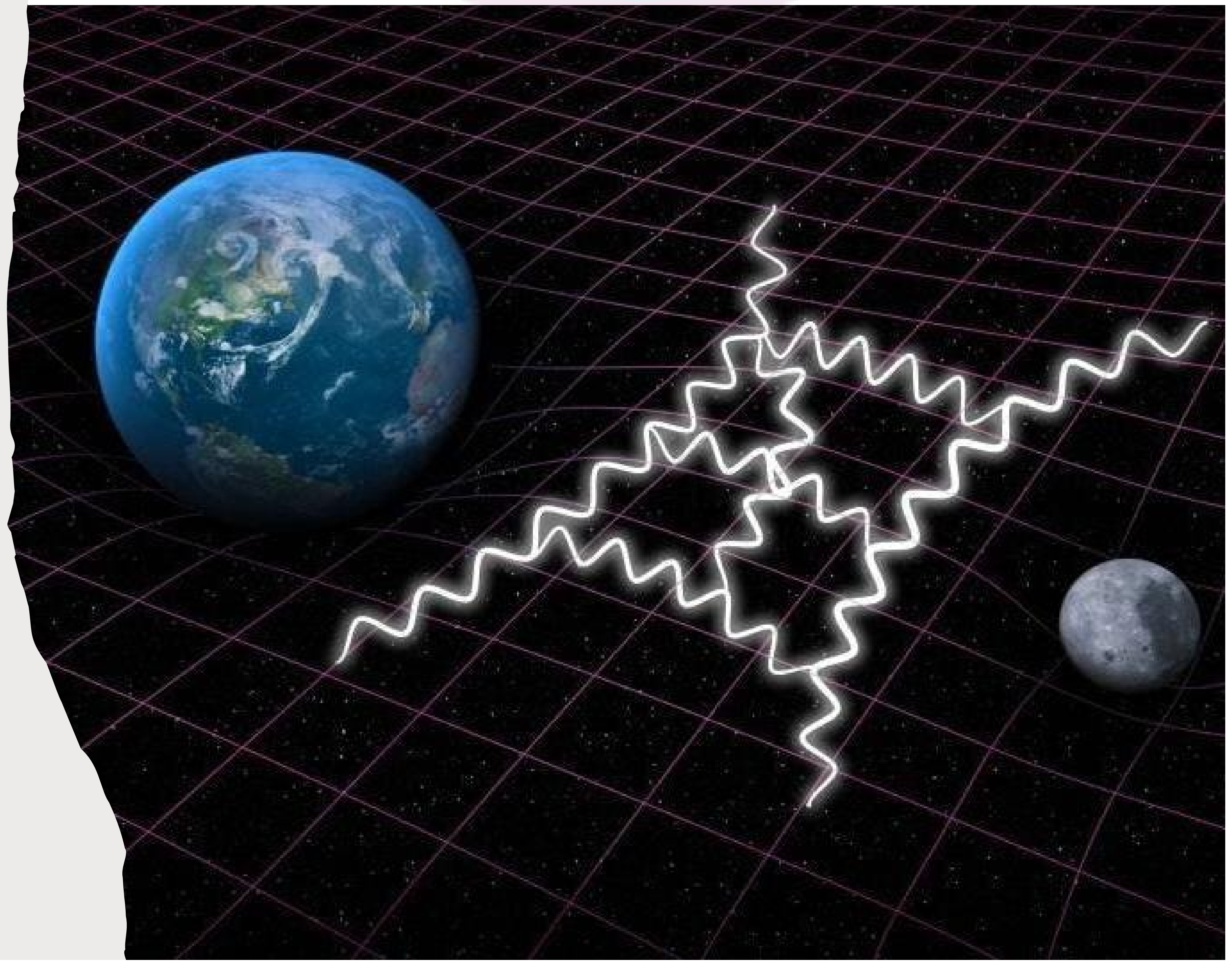
Lydia Brenner, Nikhef & Atlas collaboration

Navigating Across Scales: Functional Renomalization and Asymptotic Safety

Antonio D. Pereira, Fluminense Federal University and RU

Testing Gravity at all Scales

Astrid Eichhorn, University of Southern Denmark



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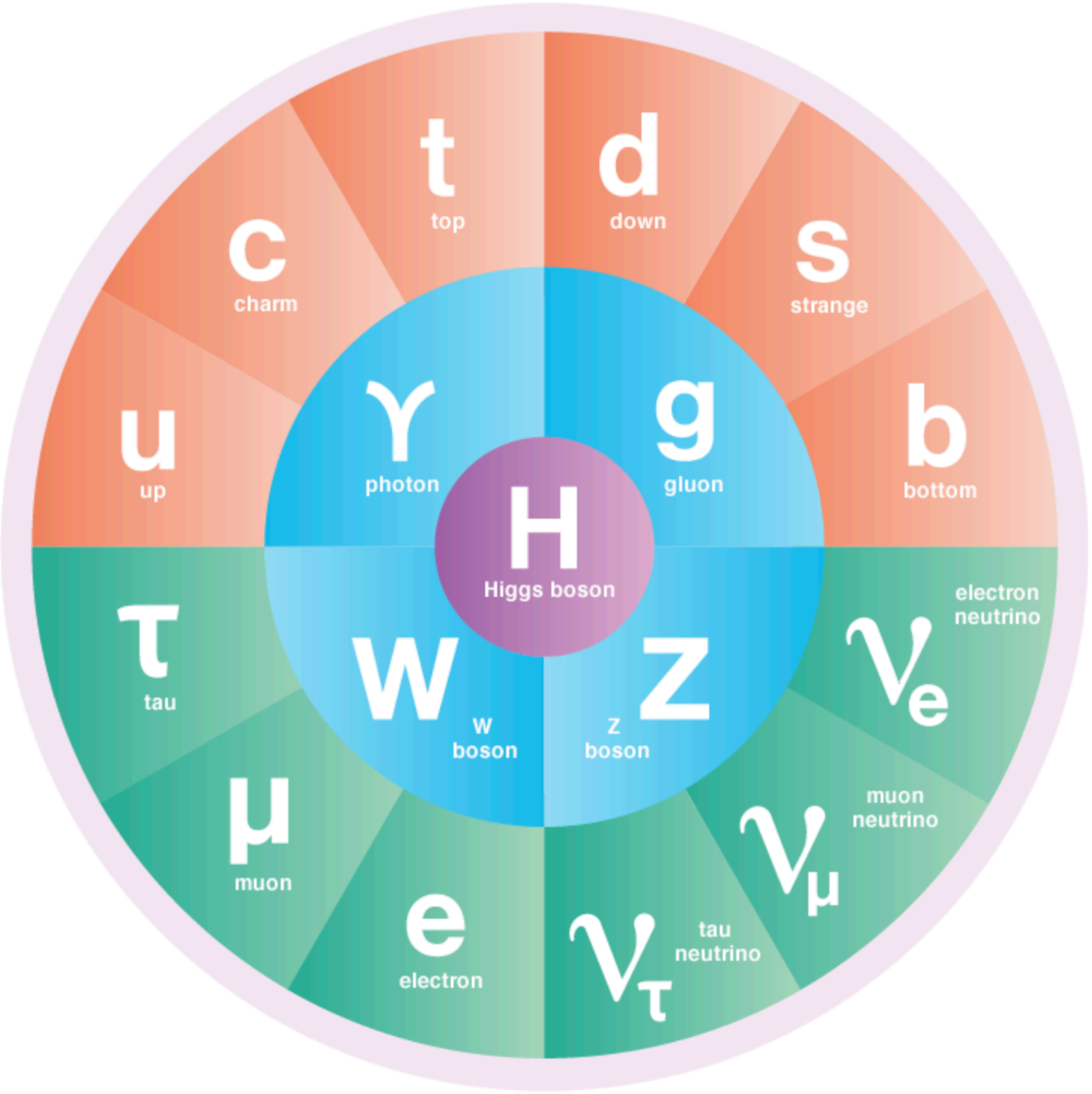
Focus Session:

A Particle Physics Guide Towards Quantum Gravity

NWO Physics 2024, Veldhoven 23/01/2024

A New Standard Model from the Bottom Up

The Standard Model: a Success Story



- **Robust** and **predictive** mathematical framework describing **all known elementary particles** and their (non-gravitational) interactions
- **Matter particles**: three families of quarks and leptons
- **Force mediators**: photon (QED), gluon (strong interaction), W & Z bosons (electroweak force)
- The **Higgs field** and its excitation, the **Higgs boson**: a **completely new fundamental particle & interaction!**

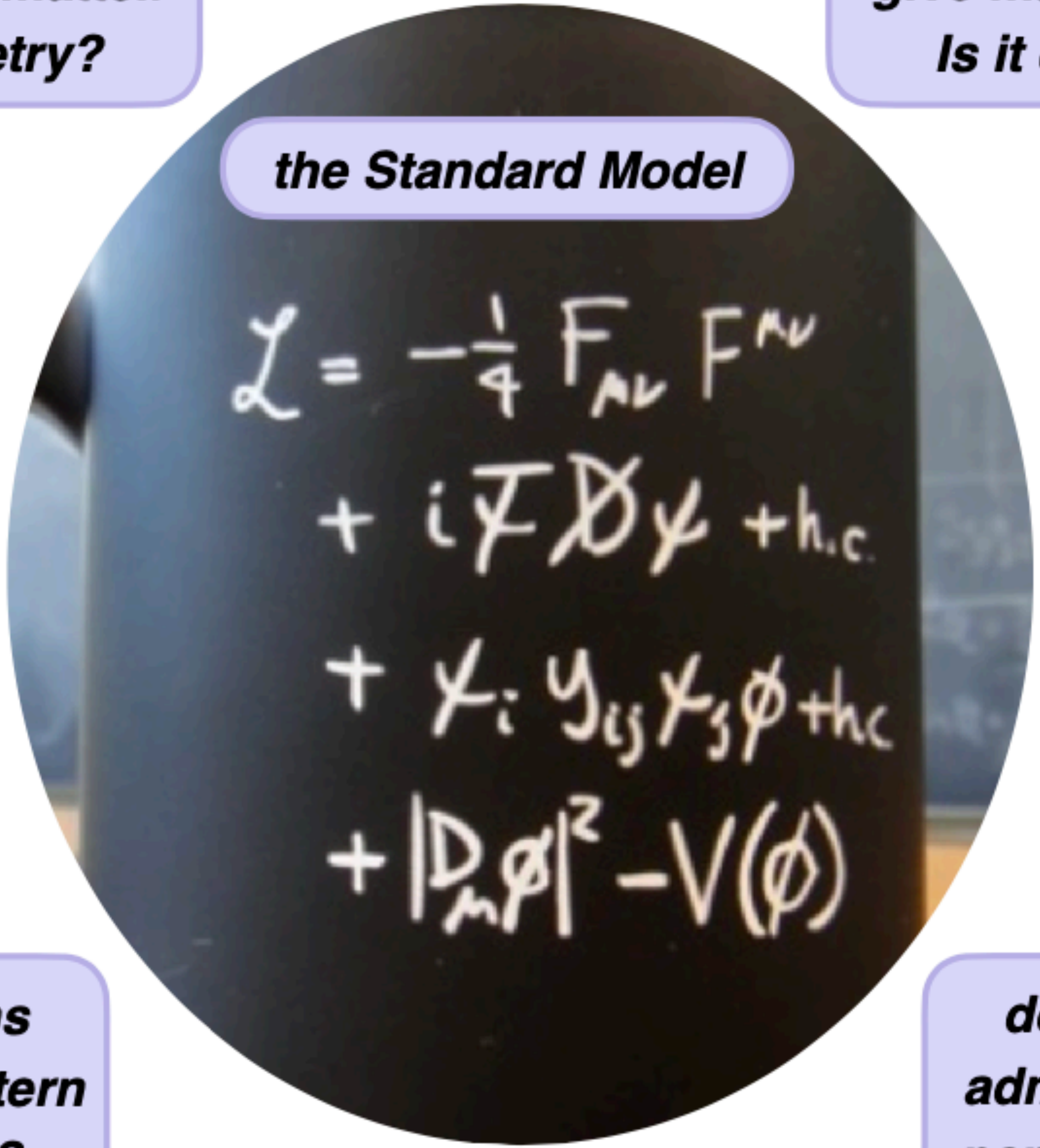
Discovered in 2012, now under intense scrutiny at the Large Hadron Collider at CERN

The Standard Model describes an incredibly wealth of measurements with astonishing precision: a major triumph of modern science

The Standard Model: not the Full Story!

why does our Universe exhibit such a strong matter/ antimatter asymmetry?

why does the Higgs mechanism give mass to elementary particles? Is it effective or fundamental?



what is the correct quantum mechanical description of gravity?

what sets the scale of neutrino masses? Do sterile neutrinos exist?

why do quarks and leptons exhibit such a disparate pattern of masses and couplings?

does Dark Matter admit an elementary particle description?

Innumerable extensions of the SM have been proposed. **None of them has been validated**

The Standard Model from the Bottom-Up

The Standard Model is **fully determined** by the following ingredients

- The **particle (matter) content**: three generations of quarks and leptons
- The **gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly realised $SU(2)_L$ **electroweak symmetry breaking**

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- Requiring **renormalizability**: predictions need to be valid up to **arbitrarily high scales**

$$[F_{\mu\nu}] = 2\,, [\psi] = 3/2\,, [y] = 0\,, [\phi] = 1\ldots$$

$$\mathscr{L}_{\rm SM} = \sum_i c_i \mathcal{O}_i^{(d=4)}$$

dimensionless couplings

All possible operators of **mass-dimension <=4** consistent with above requirements

$$\begin{aligned}\mathcal{L} = &-\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i\bar{\psi} \not{D} \psi + h.c. \\ &+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

extremely predictive and constrained framework

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how essential is this condition?

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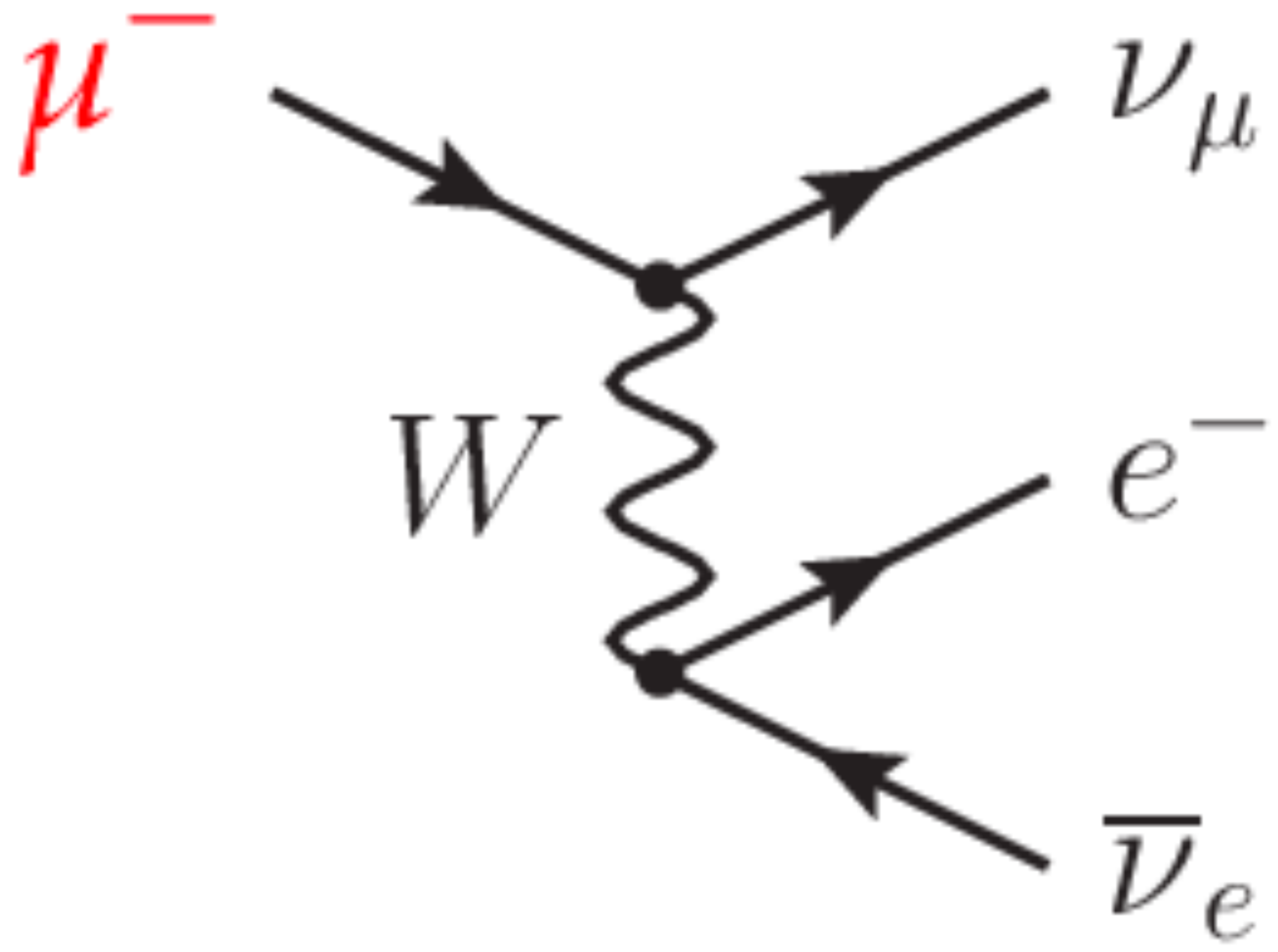
Effective vs Fundamental QFTs

For a sensible QFT, must its predictions be valid to **arbitrarily high scales? No!**



Muon decay in the SM

Mediated by ``heavy" W-boson, m_W = 80 GeV

Involves **dimension-4** interactions with **dimensionless couplings**

$$\mathscr{L}_{\mathrm{SM}} \supset g\bar{\psi}_\ell \gamma^\mu W_\mu \psi_\nu$$

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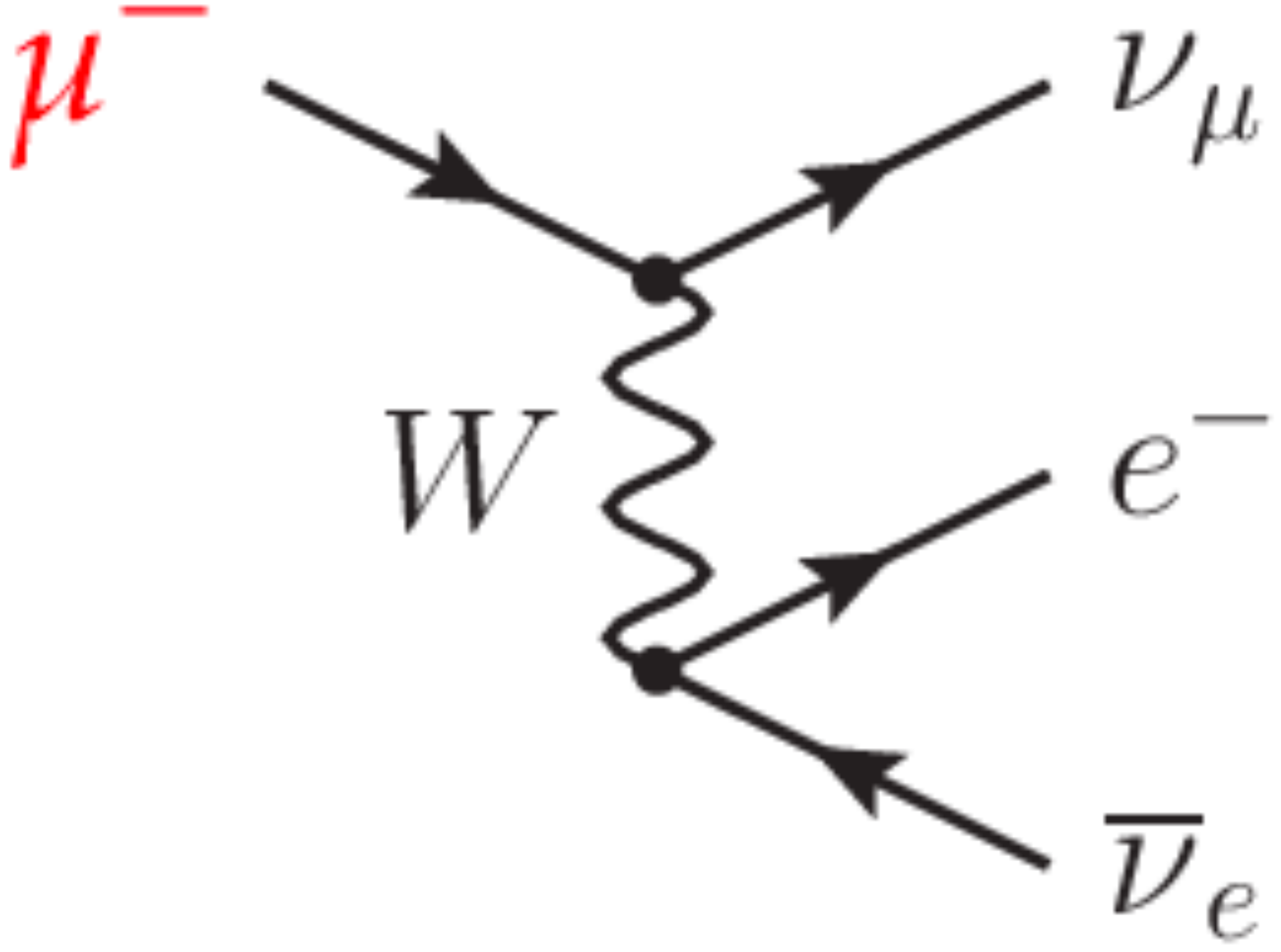

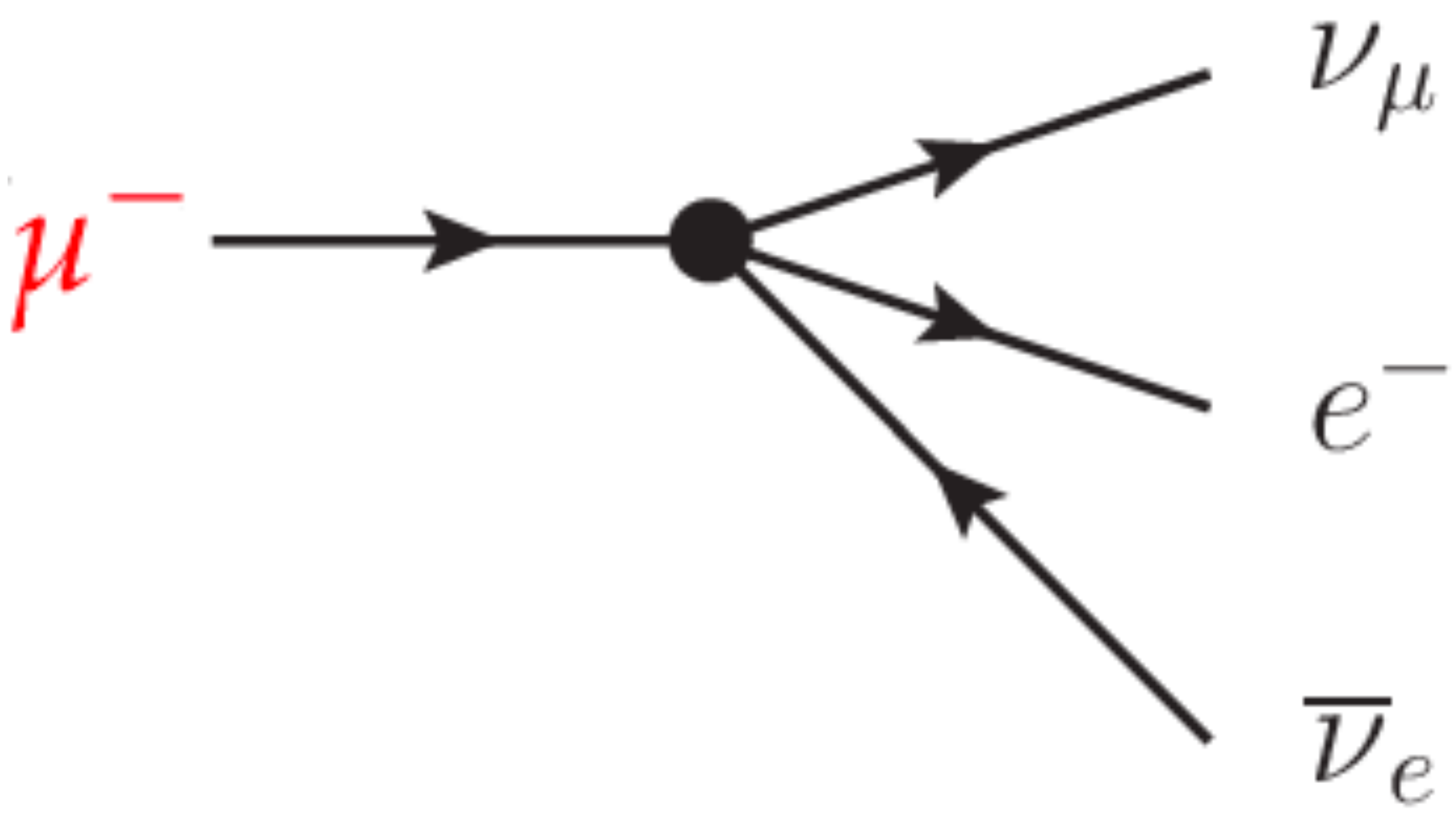

Muon decay in the SM

Muon decay in Fermi Theory $m_\mu \ll m_W$

Mediated by ``heavy" W-boson, m_W = 80 GeV

No explicit force mediator

Involves **dimension-4** interactions with **dimensionless couplings**

dimension-6 interactions with **dimensionfull couplings**

$$\mathscr{L}_{\mathrm{SM}} \supset g\bar{\psi}_\ell \gamma^\mu W_\mu \psi_\nu$$

$$\mathscr{L}_{\mathrm{EFT}} \supset G_F \bar{\psi}_\ell \psi_\nu \bar{\psi}_{\ell'} \psi_{\nu'}$$

$$G_F = 1.2 \times 10^{-5}\,\mathrm{GeV}^{-2}$$

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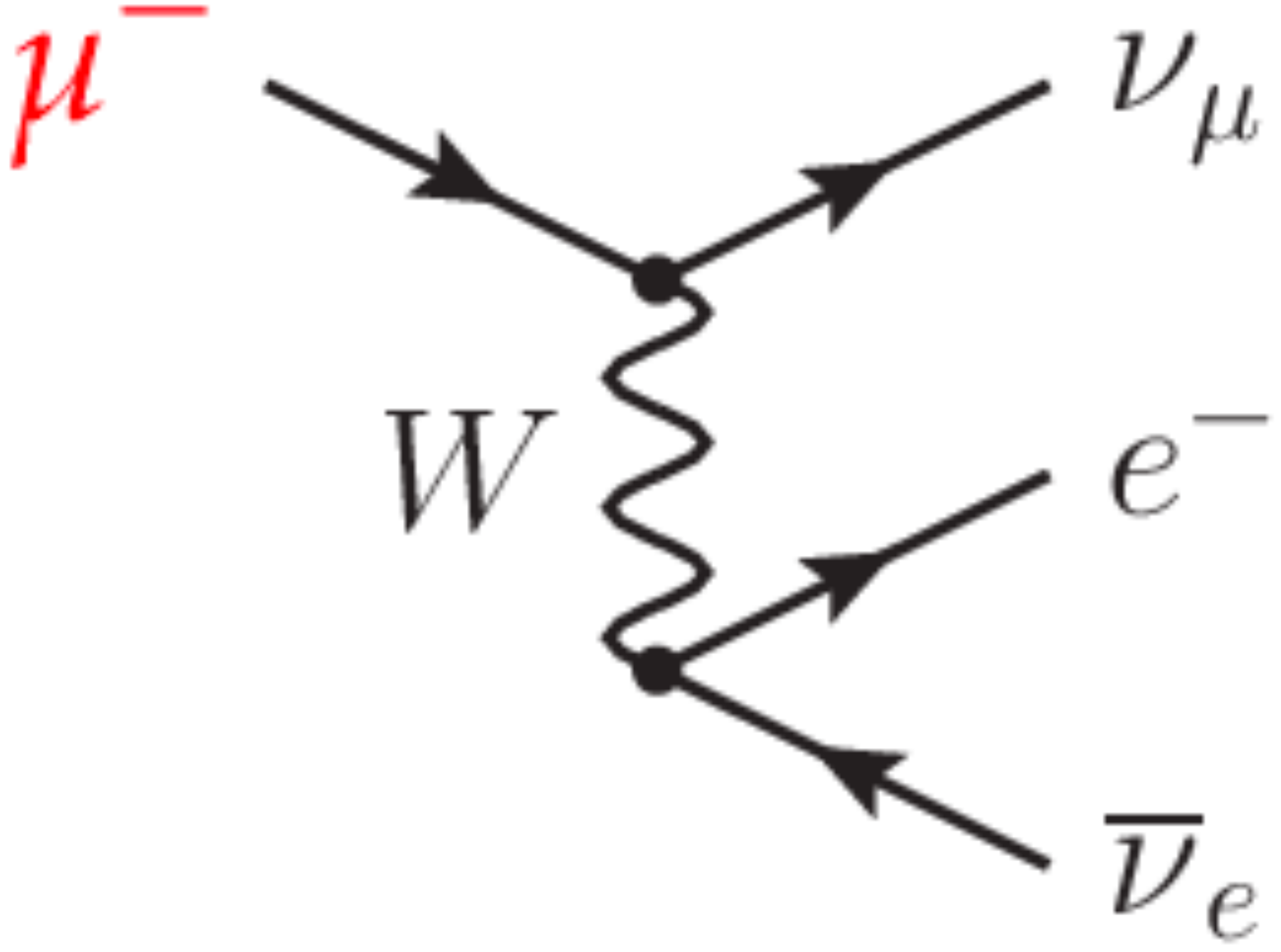

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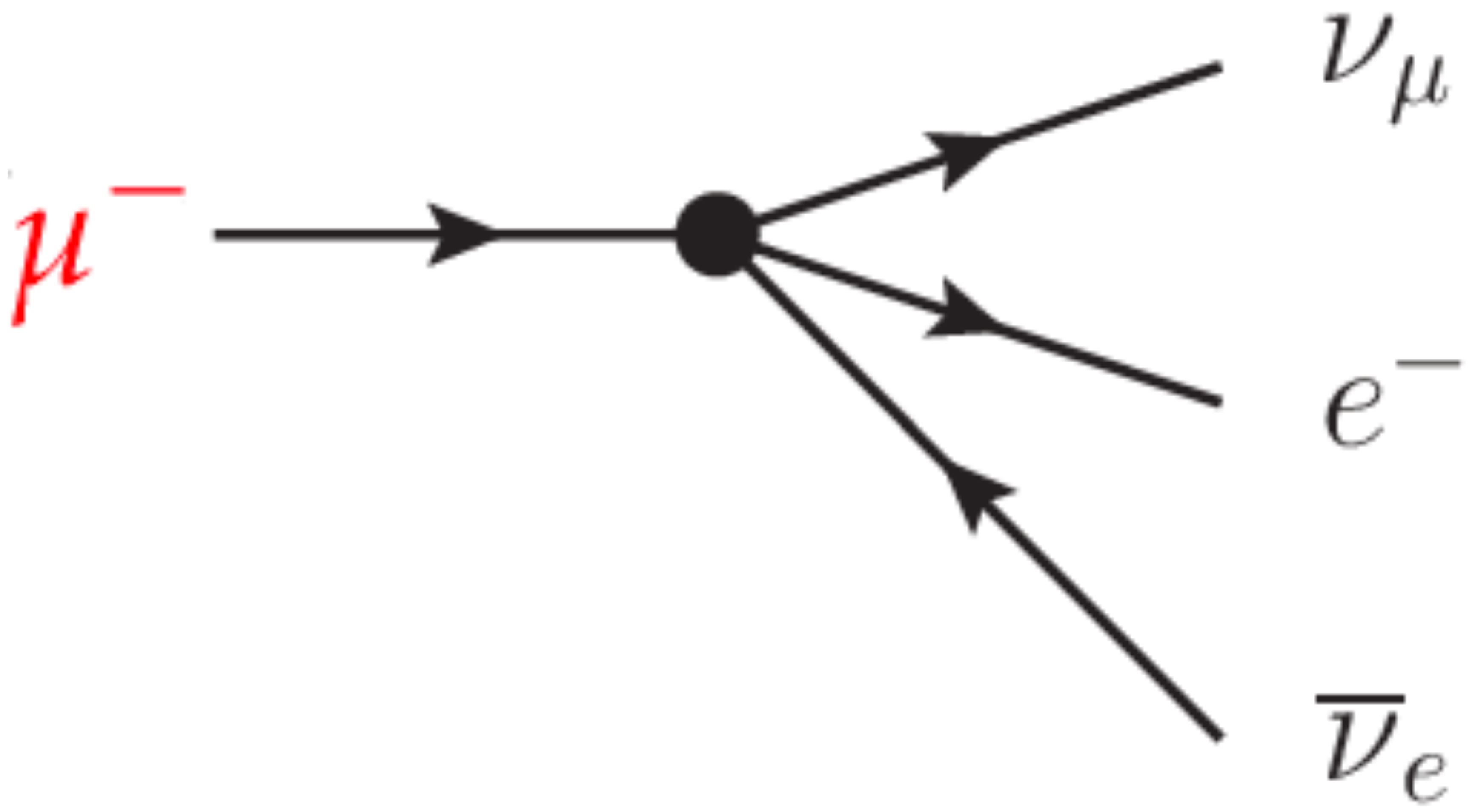

Muon decay in Fermi Theory

$$\mathscr{L}_{\rm EFT} \supset G_F \bar{\psi}_\ell \psi_\nu \bar{\psi}_{\ell'} \psi_{\nu'}$$

The SM and its low-energy EFT result in identical predictions for energies well below the W mass

knowledge of SM Lagrangian irrelevant to precisely compute muon lifetime

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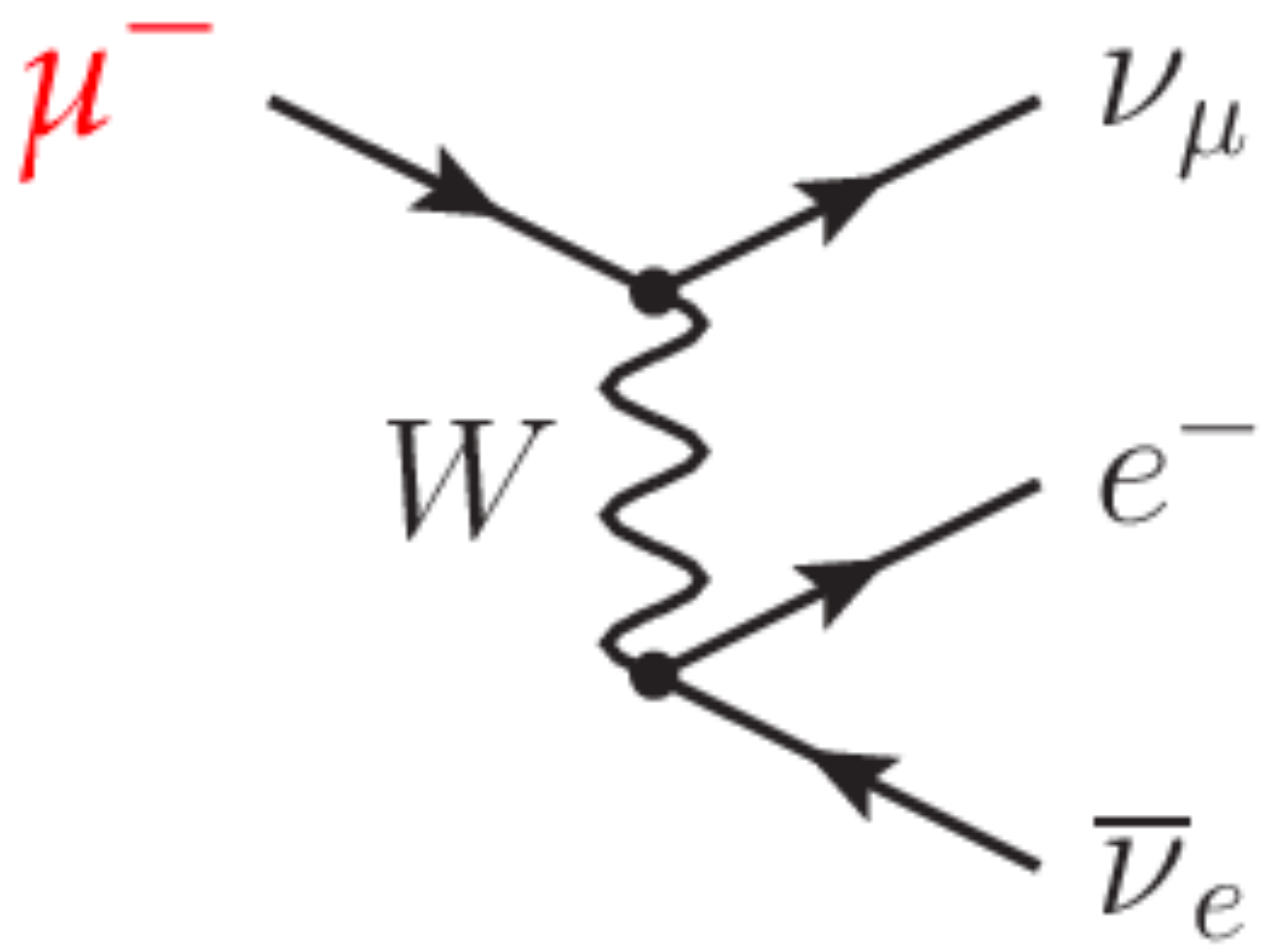

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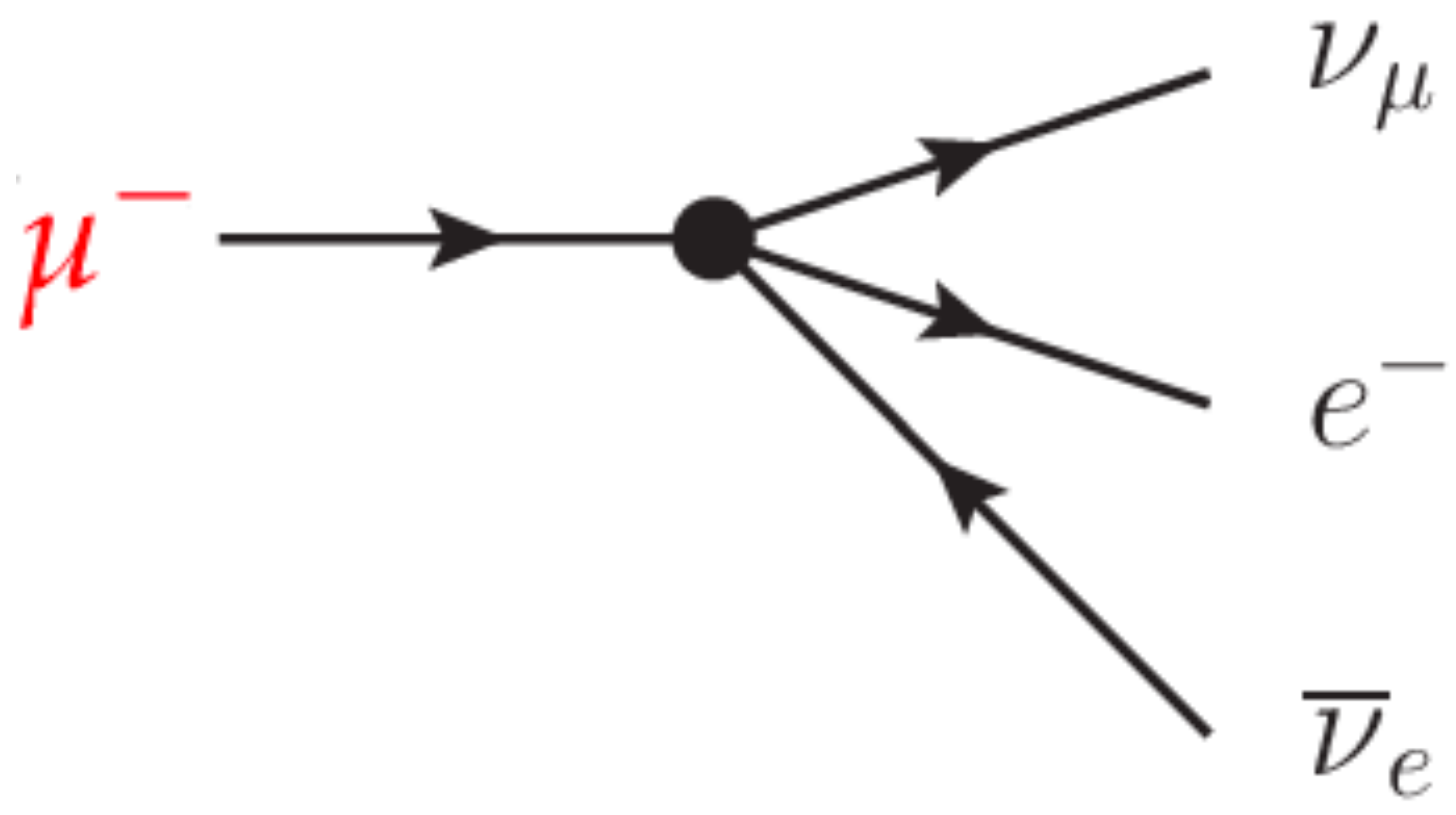

Muon decay in Fermi Theory

$$\mathscr{L}_{\text{EFT}} \supset G_F \bar{\psi}_\ell \psi_\nu \bar{\psi}_{\ell'} \psi_{\nu'}$$

$$G_F \sim \frac{1}{\Lambda^2} \quad \rightarrow \quad \Lambda \sim 300 \text{ GeV}$$

The non-zero value of Fermi's constant predicts the breakdown of the EFT at O(100 GeV): needs to be replaced by a (more) fundamental theory

The EFT loses predictivity above cutoff scale

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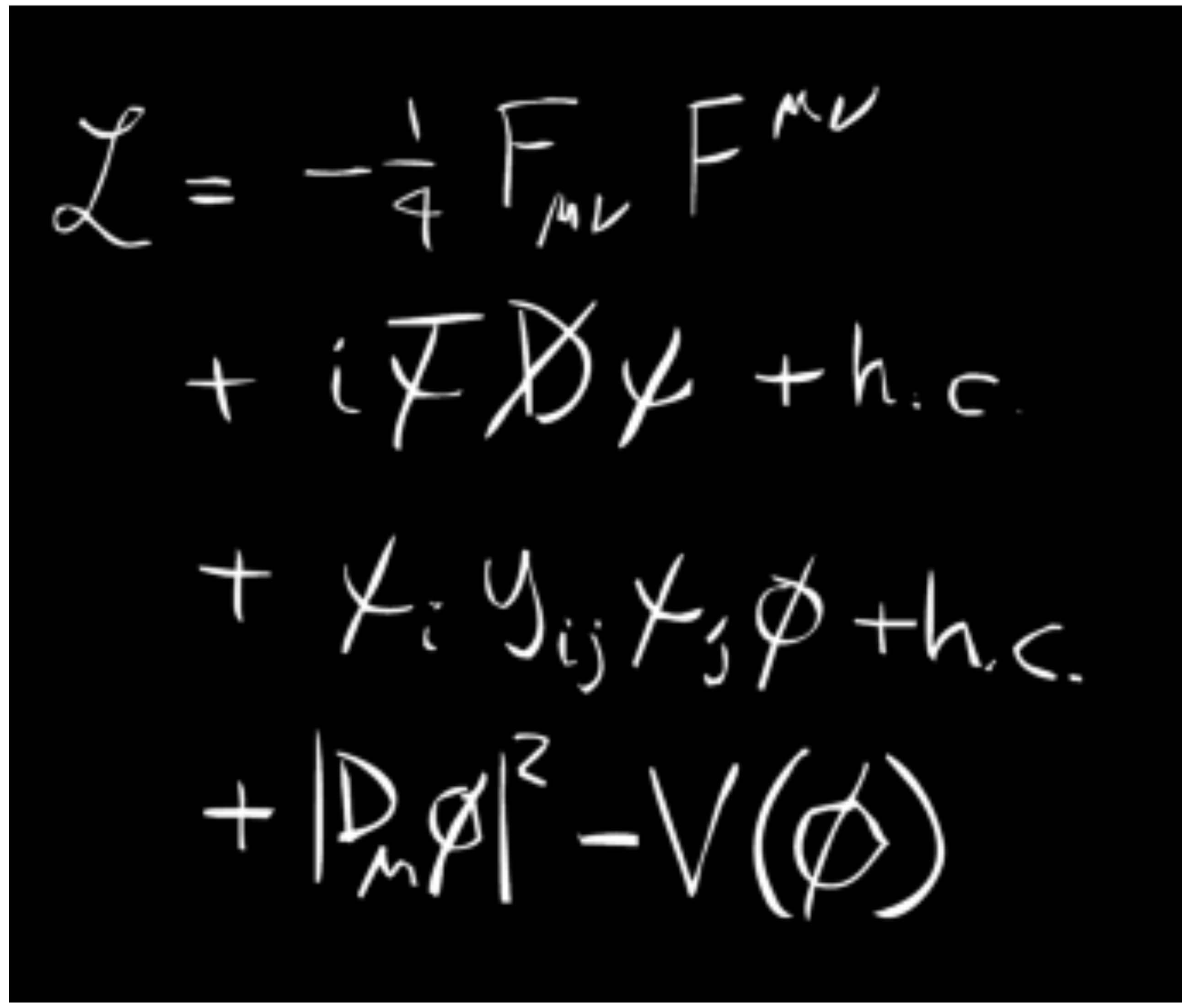

extremely predictive and constrained framework

The (New) Standard Model from the Bottom-Up

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- Predictions **valid only up to a cutoff scale Λ**, above which a new fundamental UV-completion takes over

Requiring the SM to be prediction up the Plank scale is not a necessary condition to describe physics at the scales accessible by experiments!

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Wilson coefficients

higher-dimensional operators built upon SM fields & satisfying all its symmetries

$$\mathscr{L}_{\rm SM} \to \mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{d=5}^{\infty} \sum_{i=1}^{N_d} c_i^{(d)} \frac{\mathcal{O}_i^{(d)}}{\Lambda^{d-4}}$$

well-defined power counting

cutoff scale

when cutoff >> accessible energy scales: recover SM

The (New) Standard Model from the Bottom-Up

- ☑ **Low-energy limit** of generic UV-complete theories that reduce to the SM
- ☑ **Same field content** as in the SM, with **its symmetries built in** (except accidental ones)
- ☑ **Complete basis** at any given mass-dimension: systematic parametrisation of BSM effects
- ☑ **Fully renormalizable**, full-fledged QFT: evaluate higher orders in QCD and EW

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Transparent power counting

when cutoff >> accessible energy scales: recover SM

cutoff scale

Matching to UV-complete theories

- Let us extend the Standard Model with an **additional heavy scalar**: a **second Higgs-like particle**

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + |D_\mu \phi|^2 - m_\phi^2 \phi^\dagger \phi - \Big((y_\phi^e)_{ij}\, \phi^\dagger \bar{e}_R^i \ell_L^j + (y_\phi^d)_{ij}\, \phi^\dagger \bar{d}_R^i q_L^j$$
$$+ (y_\phi^u)_{ij}\, \phi^\dagger i\sigma_2 \bar{q}_L^{T,i} u_R^j + \lambda_\phi\, \phi^\dagger \varphi |\varphi|^2 + \text{h.c.} \Big) - \text{scalar potential}\,,$$

$$\varphi \to \text{SM Higgs} \qquad \phi \to \text{BSM scalar (Higgs like)}$$

- All operators are **d=4** and hence the theory can extrapolate up to arbitrary large energies

$$[\phi, \varphi] = 1\,, \quad [e, \ell, d, q] = 3/2\,, \quad [y] = 0$$

- When heavy scalar mass is above the reach of current experiments, it can be **integrated out**: it will not appear as **explicit degree of freedom,** yet we will still be sensitive to it via **quantum effects** at low energies

$$\mathscr{L}_{\rm UV} \to \mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \text{effective interactions}$$

involving only SM (matter & force) fields, with UV physics parameters entering via Wilson coefficients

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- The corresponding **``low-energy" Lagrangian (SMEFT)** will be given by

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \frac{(c_{u\varphi})_{33}}{\Lambda^2} \mathcal{O}_{u\varphi}^{(33)} + \text{other dimension 6 operators}$$

$$\mathcal{O}_{u\varphi}^{(33)} = \left(\varphi^\dagger \varphi\right) \bar{Q} t \widetilde{\varphi} + {\rm h.c.}$$

built upon SM fields only

Higgs

3rd gen quark doublet

3rd gen quark singlet

If UV theory known: low-energy EFT uniquely specified in terms of UV physics

Matching relations

Wilson coefficient

$$\frac{(c_{u\varphi})_{33}}{\Lambda^2} = -\frac{\lambda_\phi \left(y_\phi^u\right)_{33}}{m_\phi^2}$$

cutoff scale

UV parameters: masses and couplings

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cutoff scale

UV parameters: masses and couplings

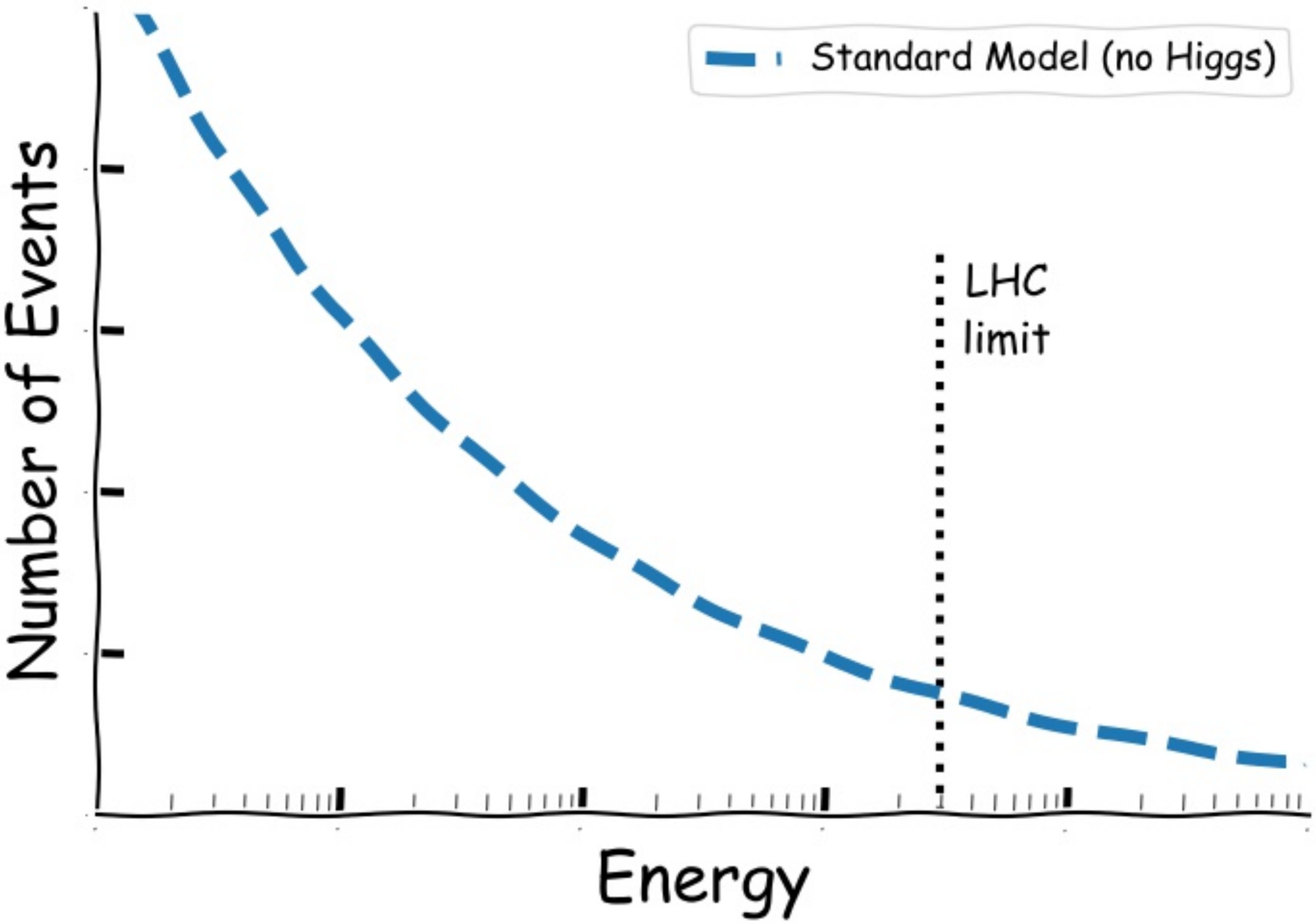
In the absence of top-down UV-model: constrain SMEFT parameters bottom up from data

The SMEFT in the LHC Precision Era

See also Lydia Brenner’s talk

Hunting for New Physics

Hunting for New (Effective) Interactions



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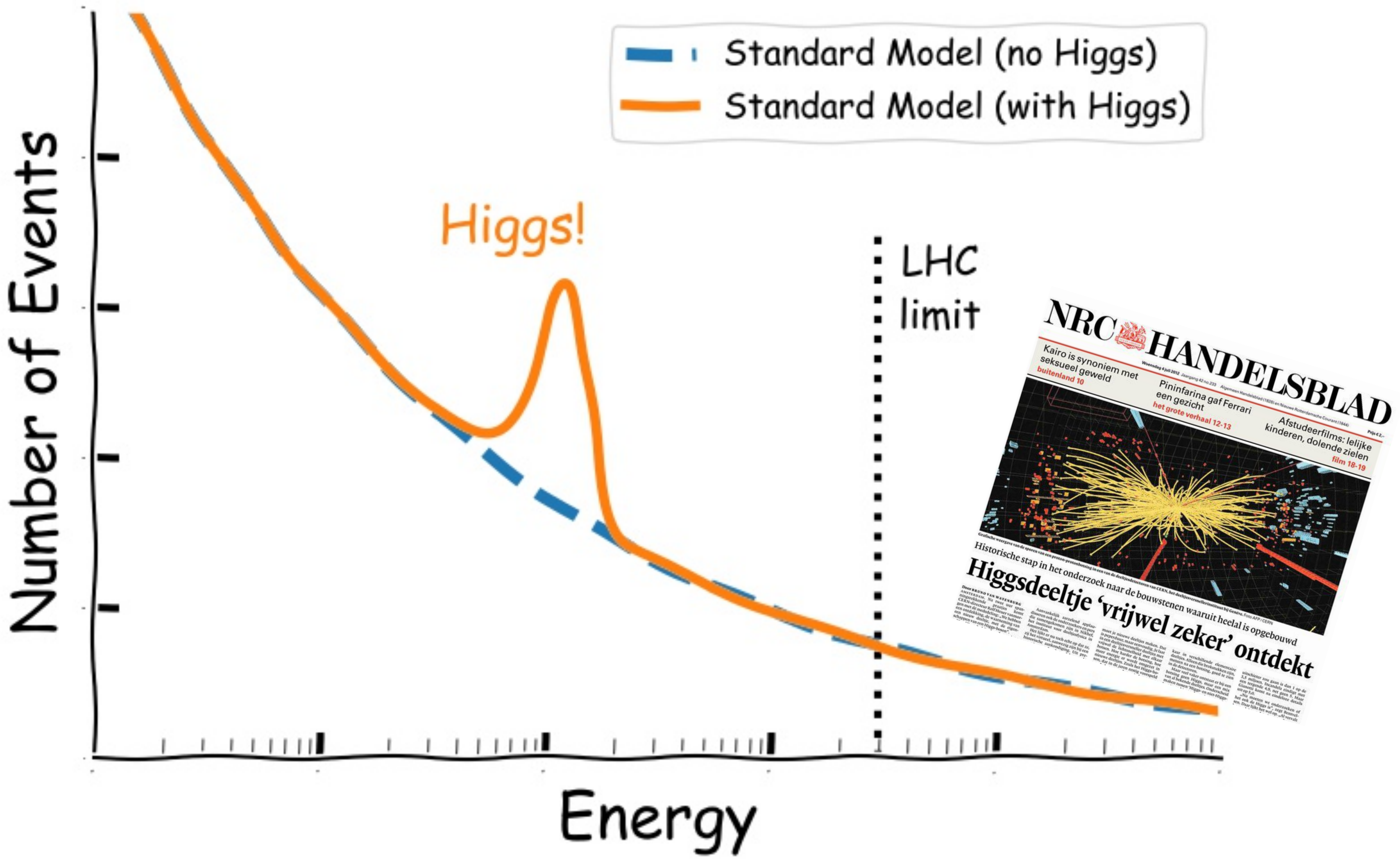

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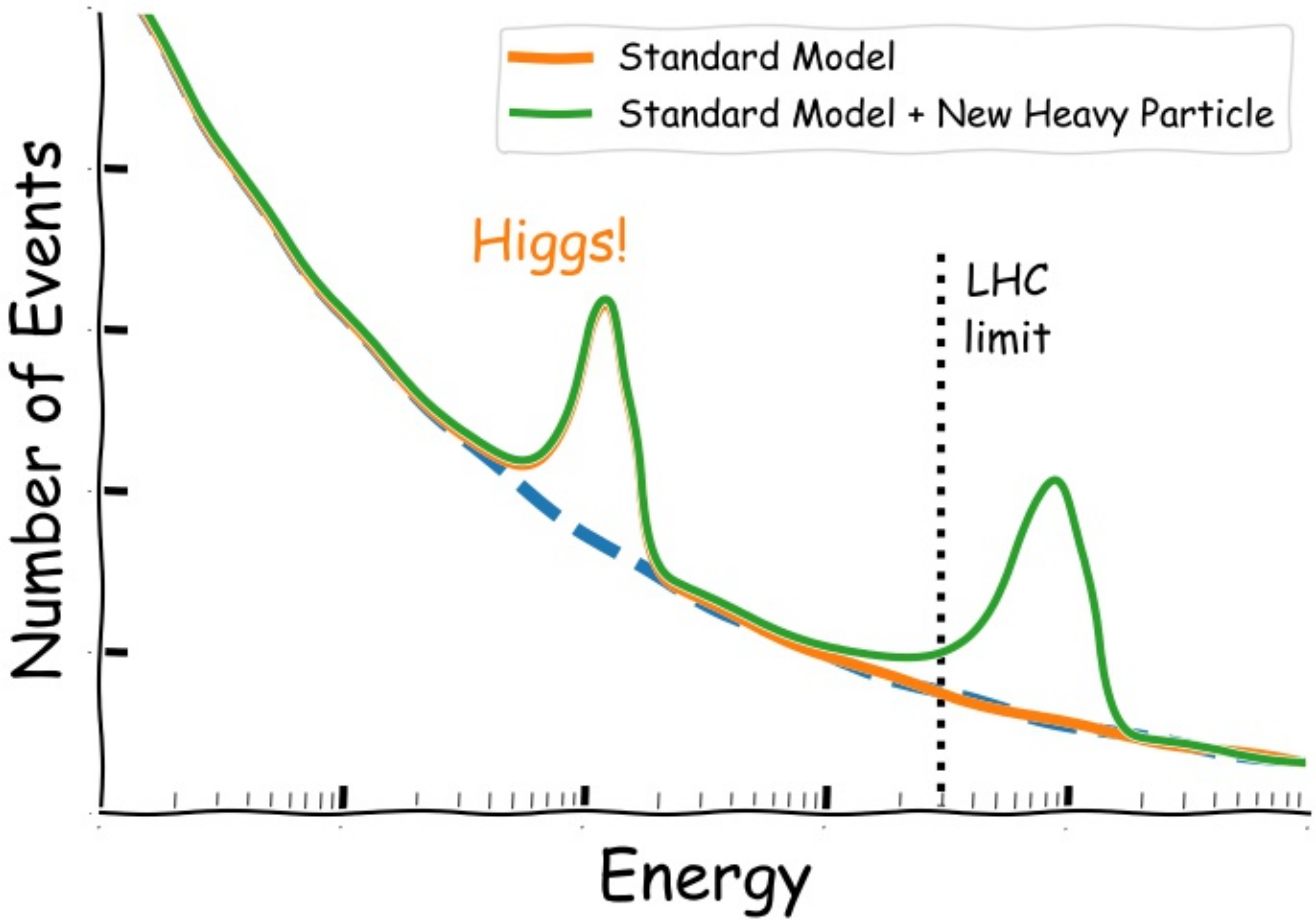

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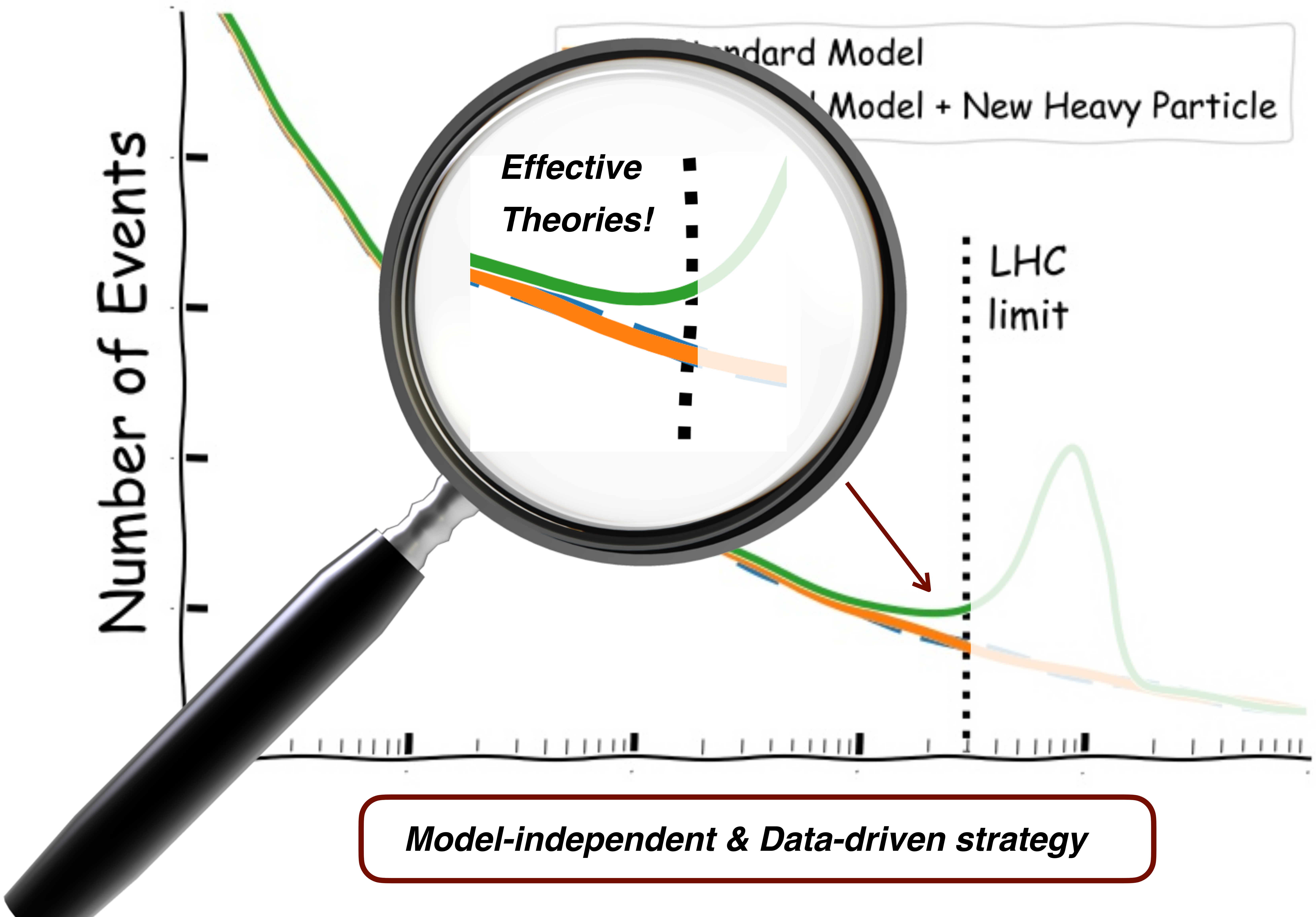

Model-independent & Data-driven strategy

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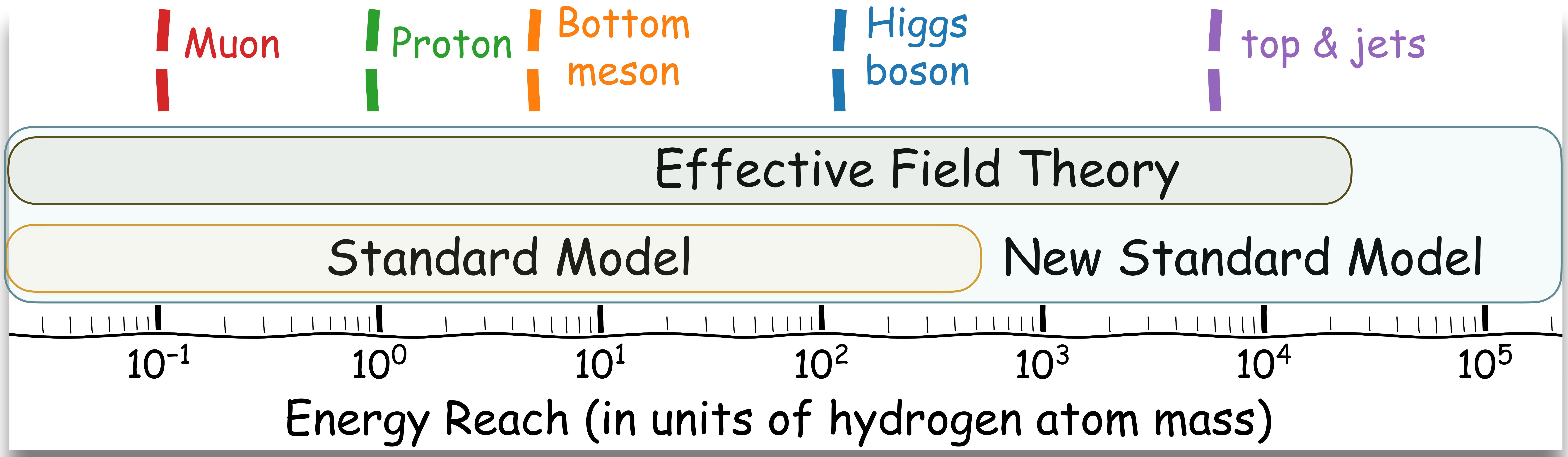


New paradigm: search for new physics as deviations in the properties of the SM particles driven by the new SMEFT interactions

goal: identify higher-dimensional EFT interactions from data

SMEFT @ LHC

- EFT operators may induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

$$\sigma(E) = \sigma_{\rm SM} \times (E)\left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, v^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right) \right)$$

from inclusive cross-sections

from high-energy differential measurements

e.g. an LHC measurement of a **high-energy tail at 4 TeV with 50% precision** may have comparable impact on the SMEFT coefficients as a **LEP measurement with 0.1% precision**

- Differential measurements also provide handles to **disentangle contributions from different EFT operators** since kinematics are different in each bin

flat directions when considering inclusive measurements may go away if the measurement is made differential

Data-driven SMEFT analyses

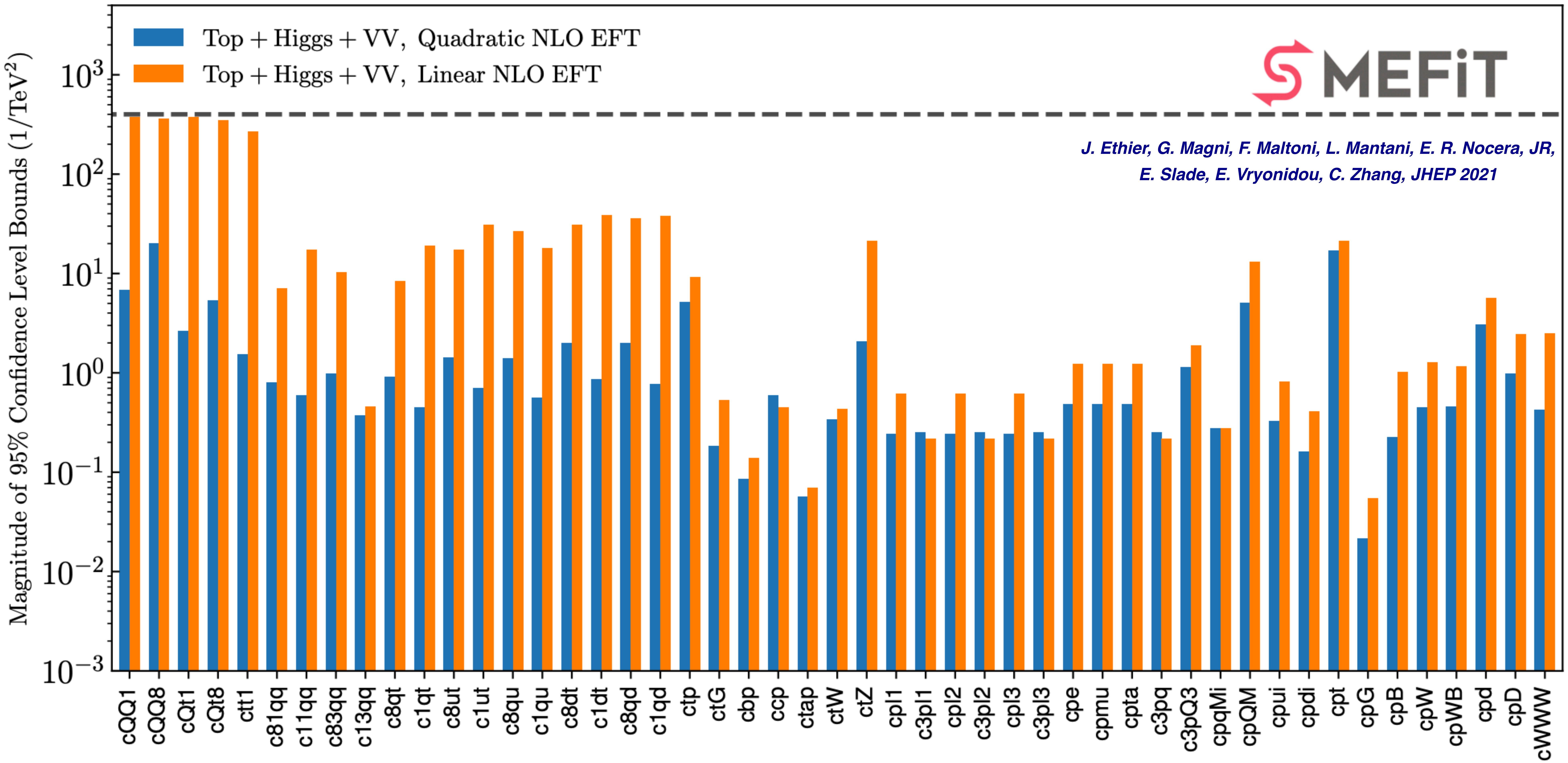
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

A **large number of d=6 SMEFT operators** need to be considered

Without further guidance for theory, **global fit of a broad dataset** only option to move forwards

Global SMEFT analyses: state-of-the-art



Global EFT fits include data on **top quark, Higgs, and gauge boson production**, both inclusive and differential measurements & the constraints from LEP EWPOs

some groups also include LHCb flavour data, but fully ``global LHC EFT fit" still missing ….

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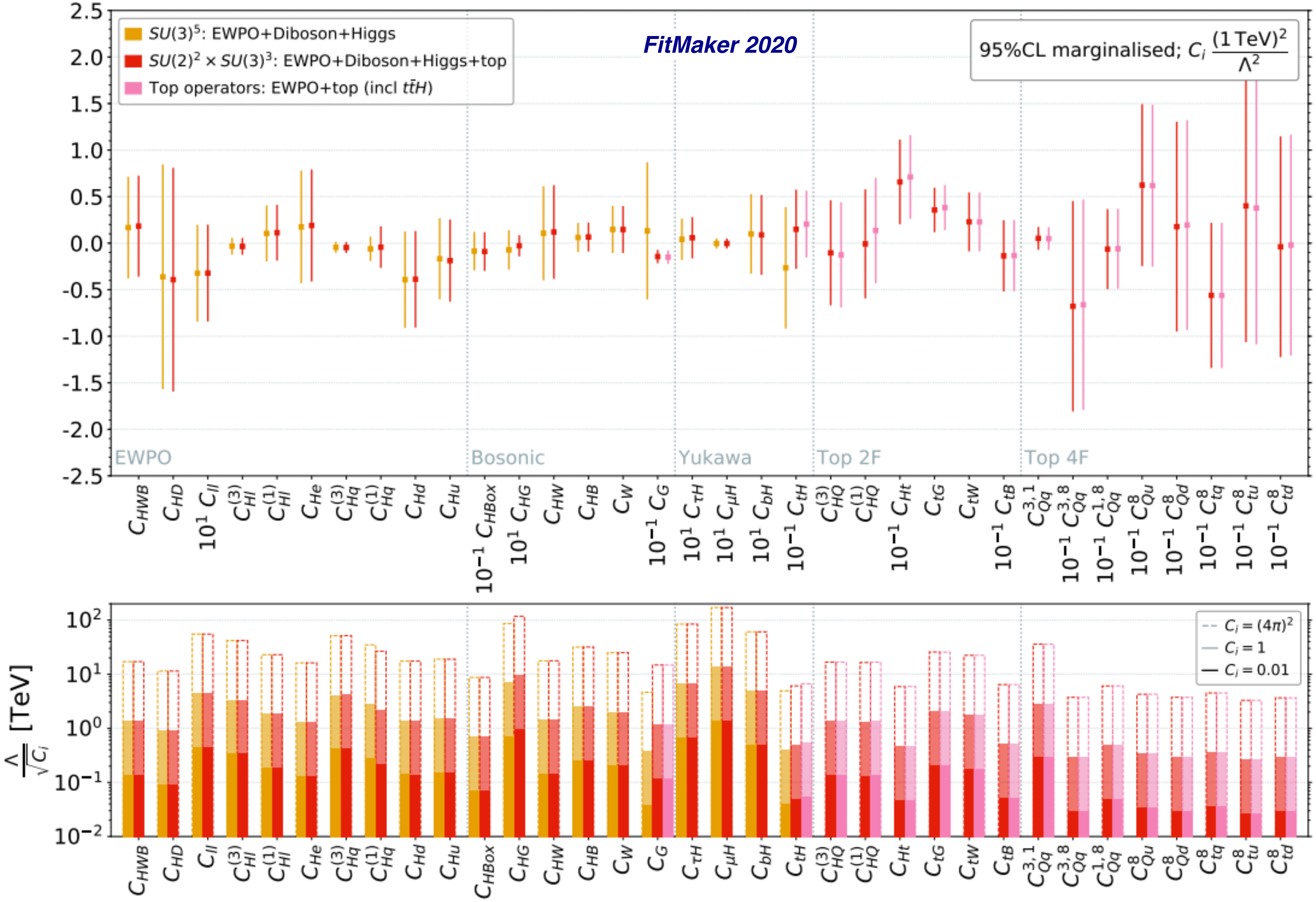
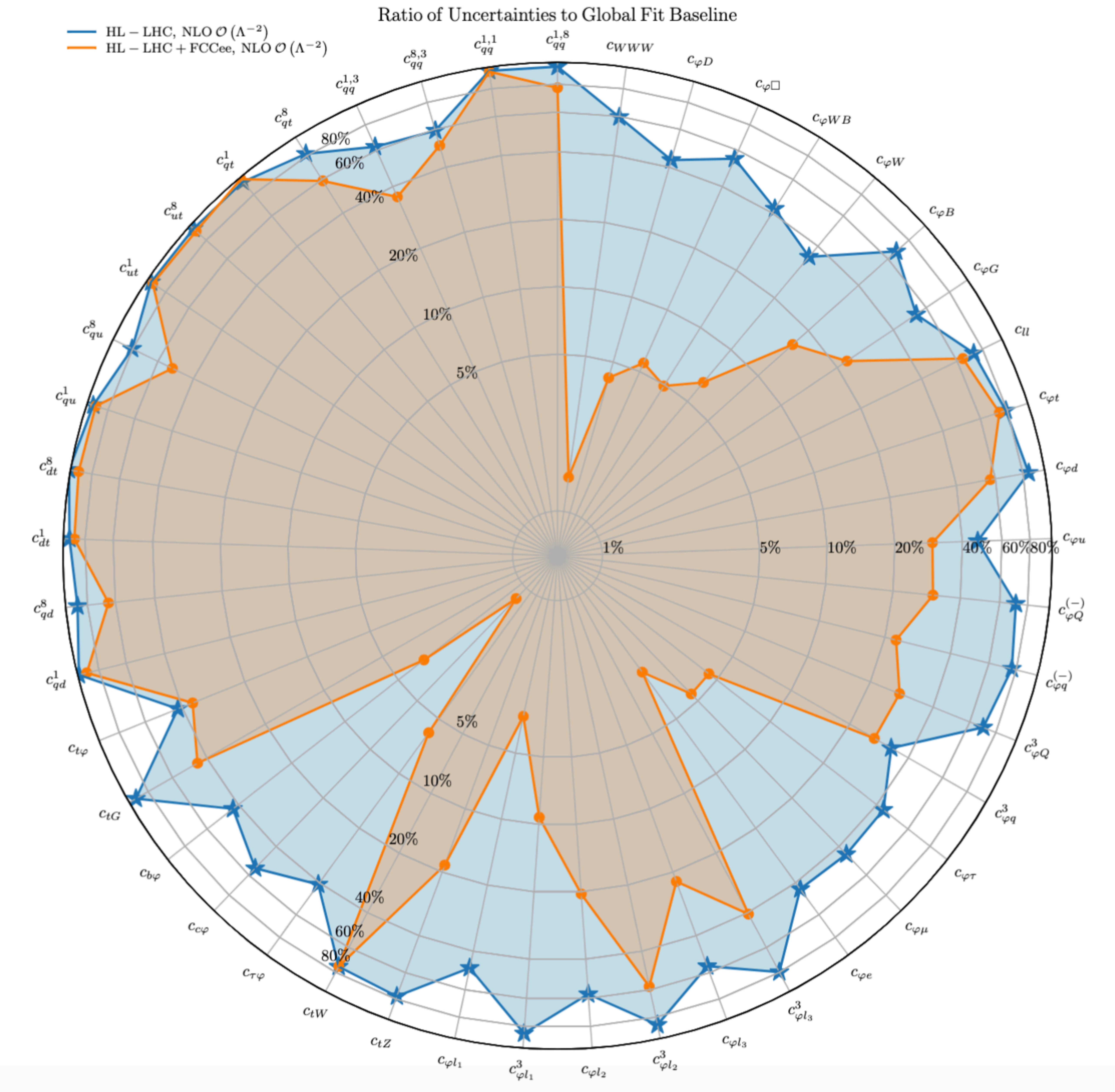


Note sensitivity to energy scales >> direct LHC reach

The Future of SMEFT



- Future particle physics experiments will keep **exploring the EFT parameter space**
- Beyond the improvements at HL-LHC, **huge impact of a future Higgs** and **Tera-Z factory** (FCC-ee)
- Further constraints to arise from **theory considerations** (positivity, families of UV models, flavour, gravity, symmetries, …)

Summary and outlook

- The SMEFT framework provides a robust strategy to **interpret particle physics data in terms of new BSM** phenomena while reducing model assumptions

- A global SMEFT analysis constrains a **plethora of UV-complete scenarios** (matched to the SMEFT) at once: **bridge between data and BSM models**

- Impressive progress in the **theory and phenomenology of the SMEFT** in the recent years

- A main challenge in bottom-up SMEFT analysis is the **large dimensionality of the parameter space** in the absence of further theory guidance

- Any **constraints from UV physics** have a large impact in SMEFT analyses of particle physics, **channeling the experimental information** to the relevant directions in parameter space

Can Quantum Gravity provide such guidance? Stay tuned for the next talks!