Higgs Mechanism & Ultraviolet/Infrared Mixing

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P&i Faculté
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Université de Strasbourg

master
PSA
Physique Subatomique
Astroparticules

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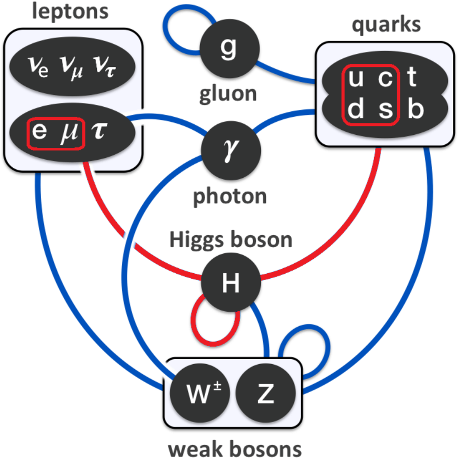
LES 2 INFINIS
LYON

cnrs
NUCLÉAIRE
& PARTICULES

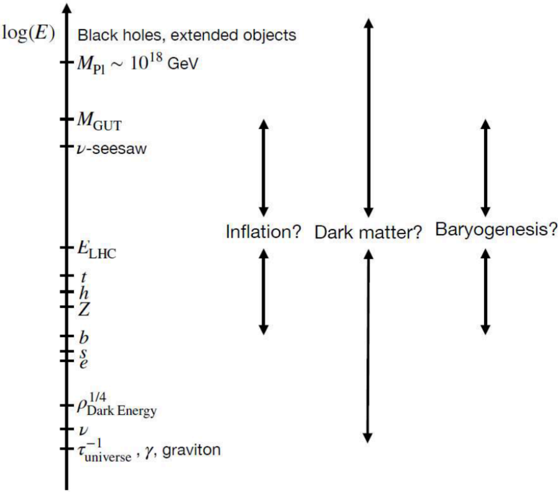
The Standard Model



- Central role of the Higgs
- Not all couplings observed yet
- SM-like Higgs 10 %

  ⇒ Need **precision** for the Higgs

New Physics



- Standard Model = effective field theory

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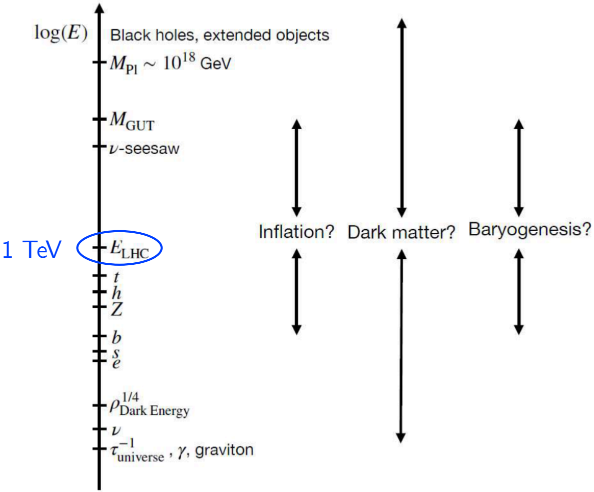

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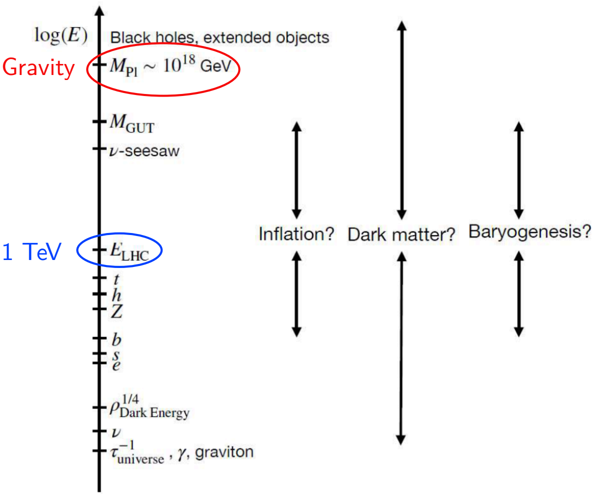
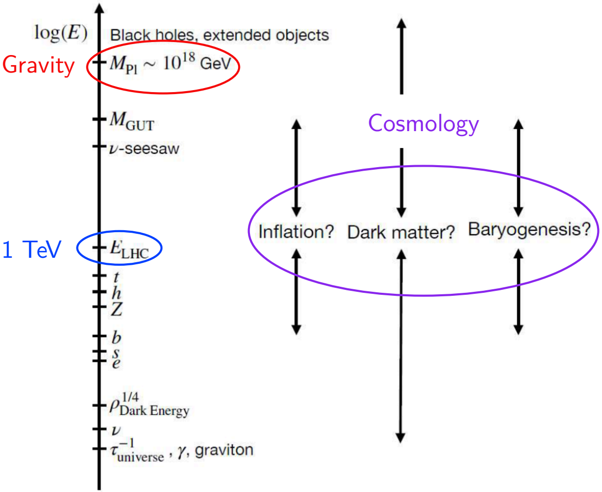


- Standard Model = effective field theory
- Planck scale ≡ ultimate cut-off

New Physics



- Standard Model $=$ effective field theory
- Planck scale $\equiv$ ultimate cut-off
- Standard Model $=$ incomplete

Hierarchy Problem

Key motivation for new physics for over 40 years!

$$(m_H^{\textbf{exp}})^2 \qquad = \qquad (m_H^{\mathrm{R}})^2 \qquad + \qquad \delta_{\mathrm{SM}}(m_H^2)$$

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Higgs mass
measured at LHC
$\simeq 125$ GeV

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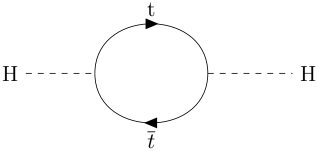
Contributions from radiative corrections to Higgs mass
$E < \Lambda_{\mathrm{SM}}$



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Higgs mass measured at LHC
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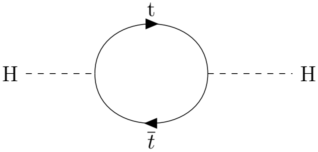
Renormalized mass: contains contributions
$E > \Lambda_{\mathrm{SM}}$

Contributions from radiative corrections to Higgs mass
$E < \Lambda_{\mathrm{SM}}$



Hierarchy Problem

$$\frac{\delta_{\mathrm{SM}}(m_H^2)}{(m_H^{\mathrm{exp}})^2} \simeq \left(\frac{\Lambda_{\mathrm{SM}}}{500\ \mathrm{GeV}}\right)^2$$

$\Rightarrow$ **New physics $\lesssim 1$ TeV** to screen UV contributions to $(m_H^R)^2$
ex: supersymmetric particles, target of LHC ! → not observed ...

$\longrightarrow$ Little hierarchy: $\Lambda_{\mathrm{SM}} \gg m_H \Rightarrow$ **unnatural fine-tuning!**
ex: $\sim 1\%$ *in supersymmetry*

New Approach: UV/IR Mixing

Inspired by gravity:

Quantum mechanics: $E \sim \frac{\hbar}{\Delta L}$

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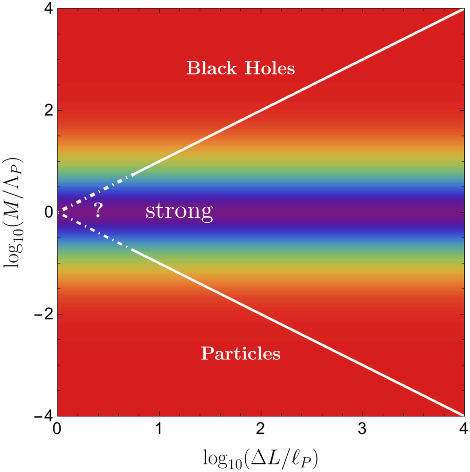

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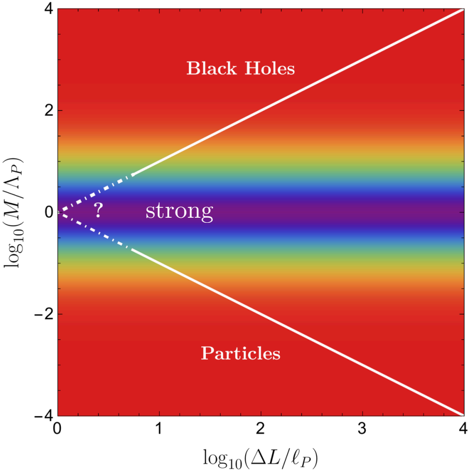

Gravity: $\Delta L \sim G_N E$

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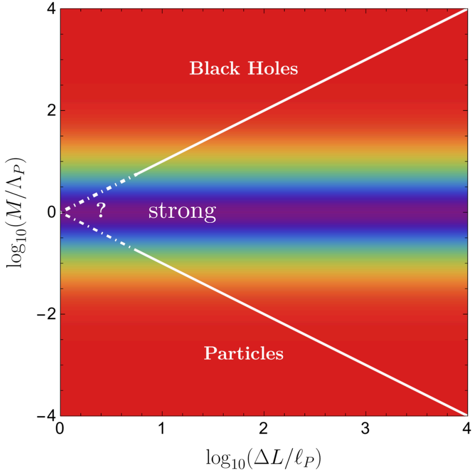

Gravity: $\Delta L \sim G_N E$

UV/IR connexion

Quantum mechanics: $E \sim \dfrac{\hbar}{\Delta L}$

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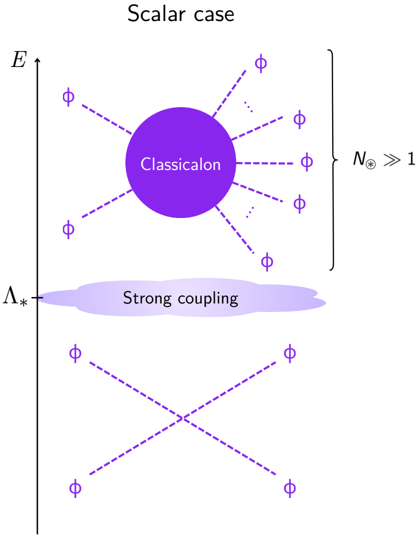


G. Dvali et al., JHEP 08 (2011) 108, arXiv:1010.1415

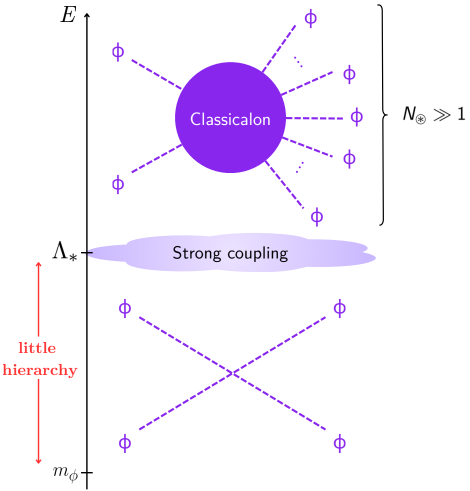
$\longrightarrow$ applications in modified gravity / cosmology

F. Nortier, JHEP 03 (2026) 230, arXiv:2511.01739

$\longrightarrow$ need for a little hierarchy: $\Lambda_* \gg m_\phi$

New Approach: UV/IR Mixing

Scalar case



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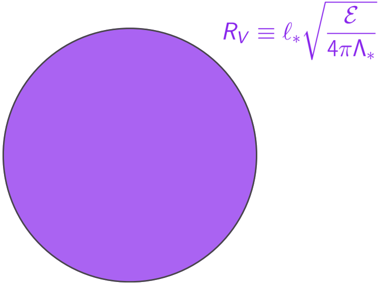
Classicalization via Vainshtein Screening

$$\mathcal{L}_X = \partial_\mu \phi \, \partial^\mu \phi + \underbrace{\frac{c_2}{\Lambda_*^4} \left(\partial_\mu \phi \, \partial^\mu \phi \right)^2}_{\text{classicalization trigger}}$$



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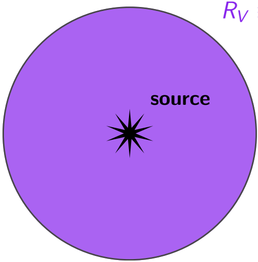
$$R_V \equiv \ell_*\sqrt{\frac{\mathcal{E}}{4\pi\Lambda_*}}$$



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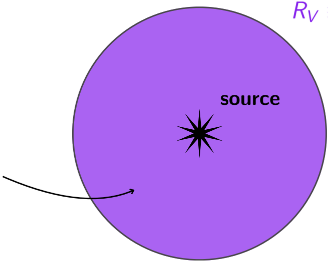
- Euler-Lagrange equation:

$$\phi' - \frac{c_2}{\Lambda_*^4}\phi'^3 = \frac{1}{4\pi r^2}\frac{\mathcal{E}}{\Lambda_*}$$

$$R_V \equiv \ell_*\sqrt{\frac{\mathcal{E}}{4\pi\Lambda_*}}$$



Non-linear regime

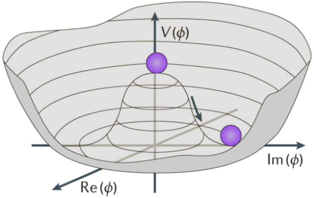
$$\frac{\overline{\phi}'}{\Lambda_*^2} \sim \left(\frac{R_V}{r}\right)^{2/3} \gg 1$$

Linear regime

$$\frac{\overline{\phi}'}{\Lambda_*^2} \sim \left(\frac{R_V}{r}\right)^{2} \ll 1$$

The Abelian Higgs Mechanism

$$\mathcal{L}_{\text{Higgs}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^*(D^\mu\phi) - V(\phi)$$



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

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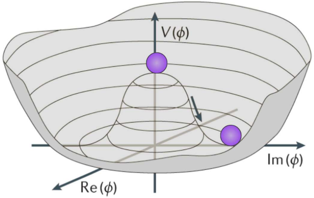

$$V(\phi) = \underbrace{\mu^2}_{<0}\phi^*\phi + \underbrace{\lambda}_{>0}(\phi^*\phi)^2$$

$$\rightarrow \text{minimun: } \langle\phi\rangle = \pm v = \pm\sqrt{\frac{-\mu^2}{\lambda}}$$

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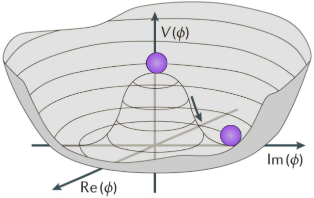

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- Polar parametrization: $\phi(x) = \frac{1}{\sqrt{2}}\rho(x)e^{i\theta(x)} \longrightarrow$ unitary gauge: $\phi(x) = \frac{1}{\sqrt{2}}\rho(x)$

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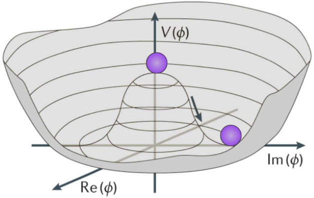

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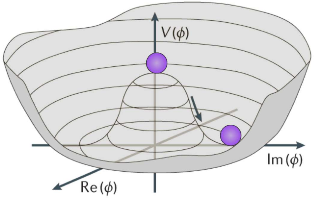

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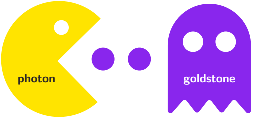
$\Rightarrow \mathcal{L}_{\text{Higgs}} \supset \underbrace{\tfrac{1}{2}e^2v^2}_{=m_A^2}A_\mu A^\mu$: photon acquires a mass !



Prototype Model of a Higgs Classicalizer

Goal: embed Higgs mechanism in a classicalization framework

$$\mathcal{L}_X = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_J + \left(\partial_\mu\phi\right)^* \left(\partial^\mu\phi\right) + \frac{c_2}{\Lambda_*^4}\left[\left(\partial_\mu\phi\right)^* \left(\partial^\mu\phi\right)\right]^2$$

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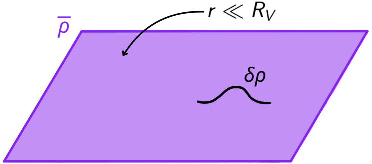
where $D_\mu = \partial_\mu + ieA_\mu$

- Polar parametrization: $\phi(x) = \frac{1}{\sqrt{2}}\rho(x)e^{i\theta(x)}$ $\longrightarrow$ unitary gauge: $\phi(x) = \frac{1}{\sqrt{2}}\rho(x)$
- Quantum fluctuations: $\rho(x) = \overline{\rho}(x) + \delta\rho$

$\rightarrow$ we treat the photon perturbatively: $\begin{cases} e \ll 1, \\ A_\mu = \delta A_\mu \end{cases}$



Higgs Classicalizer: Kinetic Terms

$$\mathcal{L}_{kin} = \frac{Z(x)}{2}\left[(\partial_t \delta\rho)^2 - (\partial_\Omega \delta\rho)^2 - B(x)\cdot(\partial_r \delta\rho)^2\right]$$

with $(\partial_\Omega \delta\rho)^2 \equiv \frac{1}{r^2}(\partial_\theta \delta\rho)^2 + \frac{1}{r^2 \sin^2\theta}(\partial_\varphi \delta\rho)^2$

Inside Vainshtein core ($r \ll R_V$):

$$\mathcal{L}_{kin} \sim \frac{1}{2}\left[(\partial_t \delta\rho_Z)^2 - (\partial_\Omega \delta\rho_Z)^2 - 2(\partial_r \delta\rho_Z)^2\right]$$

where $\delta\rho_Z(x) \equiv \sqrt{Z}\,\delta\rho(x)$ (field-strength renormalization)

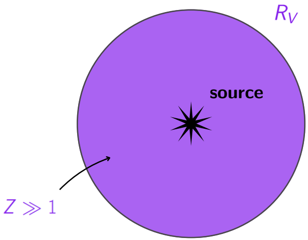
Higgs Classicalizer: Interaction Terms

$$\mathcal{L}_{\text{int}}^{(0)} = -\frac{1}{\Lambda_*^4}(\partial_\mu \delta\rho\, \partial^\mu \delta\rho)(\partial_\nu \overline{\rho}\, \partial^\nu \delta\rho) - \frac{1}{4\Lambda_*^4}(\partial_\mu \delta\rho\, \partial^\mu \delta\rho)^2$$

Inside Vainshtein core ($r \ll R_V$):

$$\mathcal{L}_{\text{int}}^{(0)} \sim \frac{\partial_r \delta\rho_Z (\partial_\mu \delta\rho_Z\, \partial^\mu \delta\rho_Z)}{\Lambda_B{}^2} - \frac{(\partial^\mu \delta\rho_Z\, \partial_\mu \delta\rho_Z)^2}{4\Lambda_B{}^4}$$

where $\Lambda_B \equiv \sqrt{Z}\Lambda_* \gg \Lambda_*$



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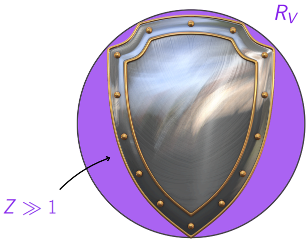
where $\Lambda_B \equiv \sqrt{Z}\Lambda_* \gg \Lambda_*$

$\Rightarrow$ **Blueshift !!!**



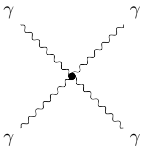
Higgs Classicalizer: Interaction Terms

Inside Vainshtein core ($r \ll R_V$):

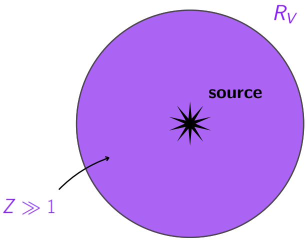
- photon effective mass:

$$m_A^{eff} \sim eZ\left(3\frac{r}{\ell_*}\right)\Lambda_*$$

- 4 photons coupling:



$$\propto e^4\frac{Z^2}{4}\left(3\frac{r}{\ell_*}\right)^4$$



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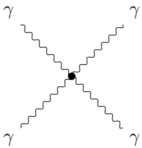

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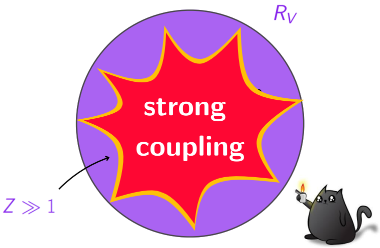

$\Rightarrow$ Not possible to define Λ_B...

Chameleon Mechanism

Idea: modifying the coupling constant $e \to e_{\text{eff}} \ll 1$ for $r \ll R_V$

$$\to \mathcal{L}_{gauge} = -\frac{1}{4} e^{a(\zeta)} F_{\mu\nu} F^{\mu\nu}, \quad \zeta \equiv \frac{\phi^* \phi}{\Lambda_*^2}$$

$$A_\mu \to \tilde{A}_\mu = e^{a(\zeta)/2} A_\mu \quad \Rightarrow \quad e \to e_{\text{eff}} = e^{-a(\zeta)/2} e$$

Constraints on $a(\zeta)$:

- Entire function of ζ
- Linear regime: $a(\zeta) \xrightarrow[\zeta \to 0]{} 0$
- Non-linear regime: $a(\zeta) \xrightarrow[\zeta \gg 1]{} +\infty$

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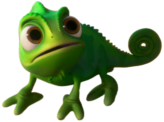
But new terms pop up...



Conclusion & Outlooks

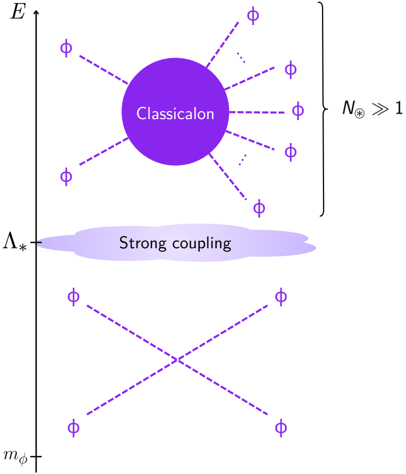
- What is left to do:
  - Study the coupling of quantum fluctuations with chameleon mechanism
  - Study of linear parametrization and gauge fixing
- Main problem come from covariant derivatives

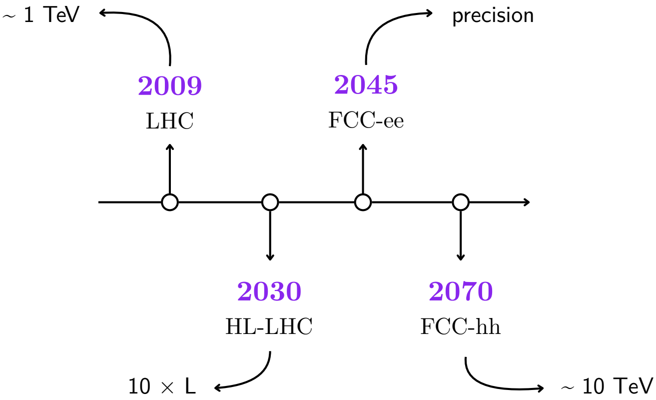
$\Rightarrow$ New model:

$$\frac{(\partial_\mu \Phi \, \partial^\mu \Phi)^2}{\Lambda_*^8}, \quad \text{with } \Phi = H^\dagger H$$

Thanks for your attention!

Colliders & Classicalization





$\sim$ 1 TeV

2009
LHC

2045
FCC-ee

precision

2030
HL-LHC

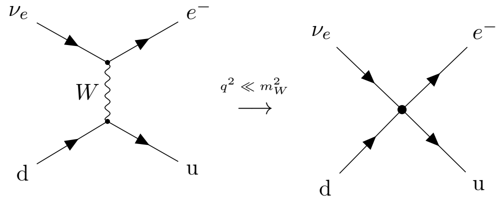
10 × L

2070
FCC-hh

$\sim$ 10 TeV

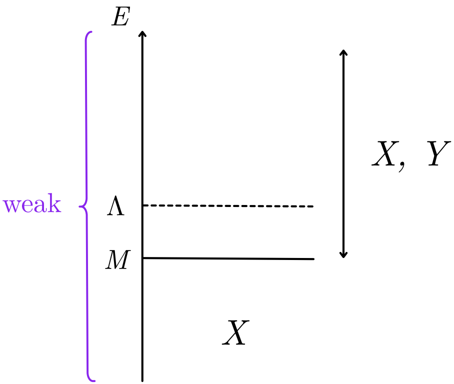
Effective Field Theory

EFT: Framework to describe physics at a given energy scale E, independently of unknown high/low energy dynamics, *e.g. Fermi theory of weak interactions*

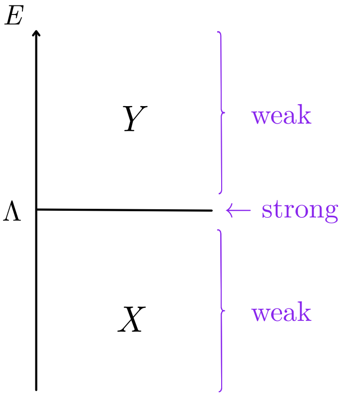


$$\frac{-i(g_{\mu\nu} - q_\mu q_\nu / m_W^2)}{q^2 - m_W^2} \xrightarrow[q^2 \ll m_W^2]{} \frac{1}{q^2 - m_W^2} = -\frac{1}{m_W^2}\left(1 + \frac{q^2}{m_W^2} + \frac{q^4}{m_W^4} + \cdots\right)$$

Wilsonian UV-completions



e.g. Fermi theory of weak interactions



e.g; QCD; $X =$*quarks, gluons and* $Y =$ *baryons, mesons,...*

Classicalon Solution with a Complex Scalar Field

$$\mathcal{L}_X = (\partial_\mu\phi)^*(\partial^\mu\phi) + \frac{c_2}{\Lambda_*^4}\left[(\partial_\mu\phi)^*(\partial^\mu\phi)\right]^2 + \underbrace{\frac{1}{\Lambda_*}\left(\phi^* J + \phi J^*\right),}_{\mathcal{L}_J} \qquad \text{where } J = -\frac{1}{\sqrt{2}}(\mathcal{E}_1 + i\mathcal{E}_2)\,\delta^{(3)}(\mathrm{r})$$

→ linear parametrization: $\phi(x) = \frac{1}{\sqrt{2}}[\phi_1(x) + i\phi_2(x)]$

Euler-Lagrange equations:

$$\phi_i' - \frac{c_2}{\Lambda_*^4}\left(\frac{\mathcal{E}}{\mathcal{E}_i}\right)^2 \phi_i'^3 = \frac{\mathcal{E}_i}{r^2\Omega\Lambda_*}$$

Background solution:

$$\frac{\overline{\phi}_i'}{\Lambda_*^2} = \begin{cases} \left(\frac{\mathcal{E}_i}{\mathcal{E}}\right)\left(\frac{R_V}{r}\right)^2 \ll 1 & \text{for } r \gg R_V \text{ (linear regime)}, \\ \mathcal{O}(1) & \text{for } r \sim R_V \text{ (transition regime)}, \\ (-c_2)^{-1/3}\left(\frac{\mathcal{E}_i}{\mathcal{E}}\right)\left(\frac{R_V}{r}\right)^{2/3} \gg 1 & \text{for } r \ll R_V \text{ (non-linear regime)}, \end{cases}$$

An Analogy with Black Holes

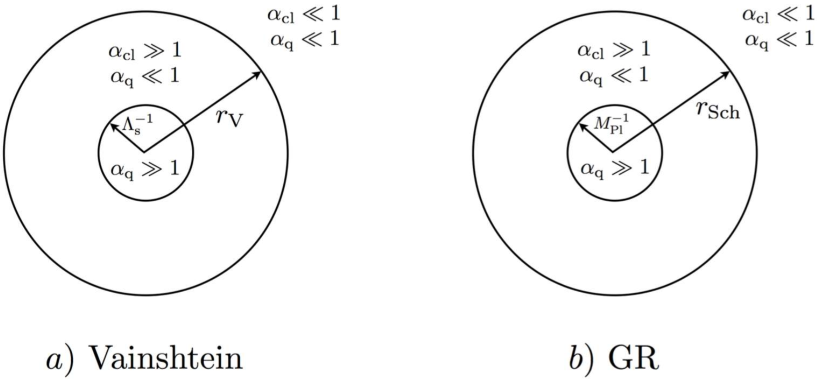


Illustration from arXiv:1312.2006