Title: Standard Model-15

Date: Jan 23, 2015 09:00 AM

URL: http://pirsa.org/15010018

Abstract:

Neutrino Oscilations

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - \sum_{i<j} 4\,\mathrm{Re}\left(J_{ij}^{\beta\alpha}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) - \sum_{i<j} 2\,\mathrm{Im}\left(J_{ij}^{\beta\alpha}\right) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

$J_{ij}^{\beta\alpha} = V^*_{\alpha i} V_{\beta i} V^*_{\beta j} V_{\alpha j}$ $\quad V$ = PMNS Matrix

V = unitary 3×3 matrix $\quad$ 3 angles + 6 phases

if neutrinos are Dirac: absorb 5 phases (analogous CKM)

if neutrinos are Majorana: absorb 3 phases

$U M U$

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$$J_{ij}^{\beta\alpha} = V_{\alpha i}^{*} V_{\beta i} V_{\beta j}^{*} V_{\alpha j}$$

V = PMNS Matrix

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if neutrinos are

if neutrinos a

$\nu M \nu$

standard parametrization

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_1} & 0 \\ 0 & 0 & e^{i\delta_2} \end{pmatrix}$$

Dirac phase

Majorana phases

$s_{ij} = \sin\theta_{ij}$; $c_{ij} = \cos\theta_{ij}$

neutrino oscilations do not depend on δ_1, δ_2

$$\sum_{i<j} 4\,\mathrm{Re}\left(J_{ij}^{\beta\alpha}\right)\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) - \sum_{i<j} 2\,\mathrm{Im}\left(J_{ij}^{\beta\alpha}\right)\sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

U = PMNS Matrix

angles + 6 phases

if neutrinos are Dirac : absorb 5 phases (analogous CKM)

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$U M U$

neutrino sources

* sun ν_e
* cosmic rays hitting atmosphere

$$\pi^+ \to \mu^+ \nu_\mu \qquad \pi^- \to \mu^- \bar{\nu}_\mu$$

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \qquad \mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$$\frac{N(\nu_\mu)}{N(\nu_e)} = 2$$

* nuclear reactors $\bar{\nu}_e$
* neutrino beams ν_μ, $\bar{\nu}_\mu$

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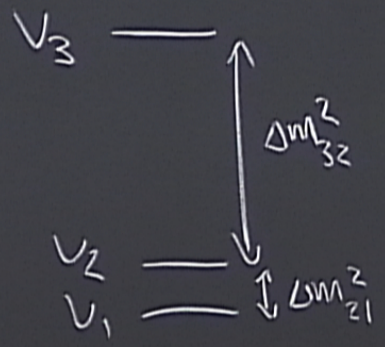
we know θ_{12}, θ_{23}, θ_{13} at % level
Δm^2_{21}, Δm^2_{32}

we don't know 1) CP violating phase δ_{CP}

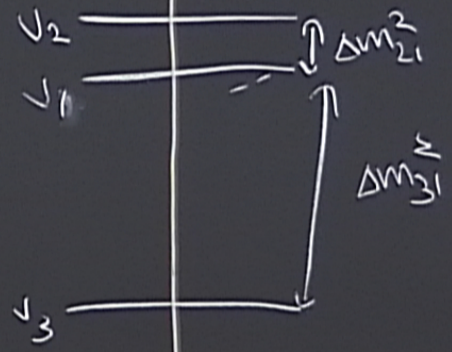
at % level

ating phase δ_{CP}

2) neutrino mass hierarchy



Normal hierarchy



Inverted hierarchy

3) absolute scale of neutrino masses

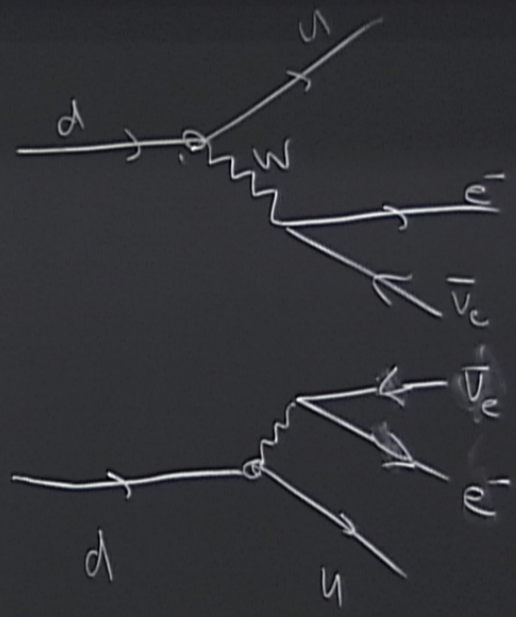
$\overline{M(\nu_e)} = ?$

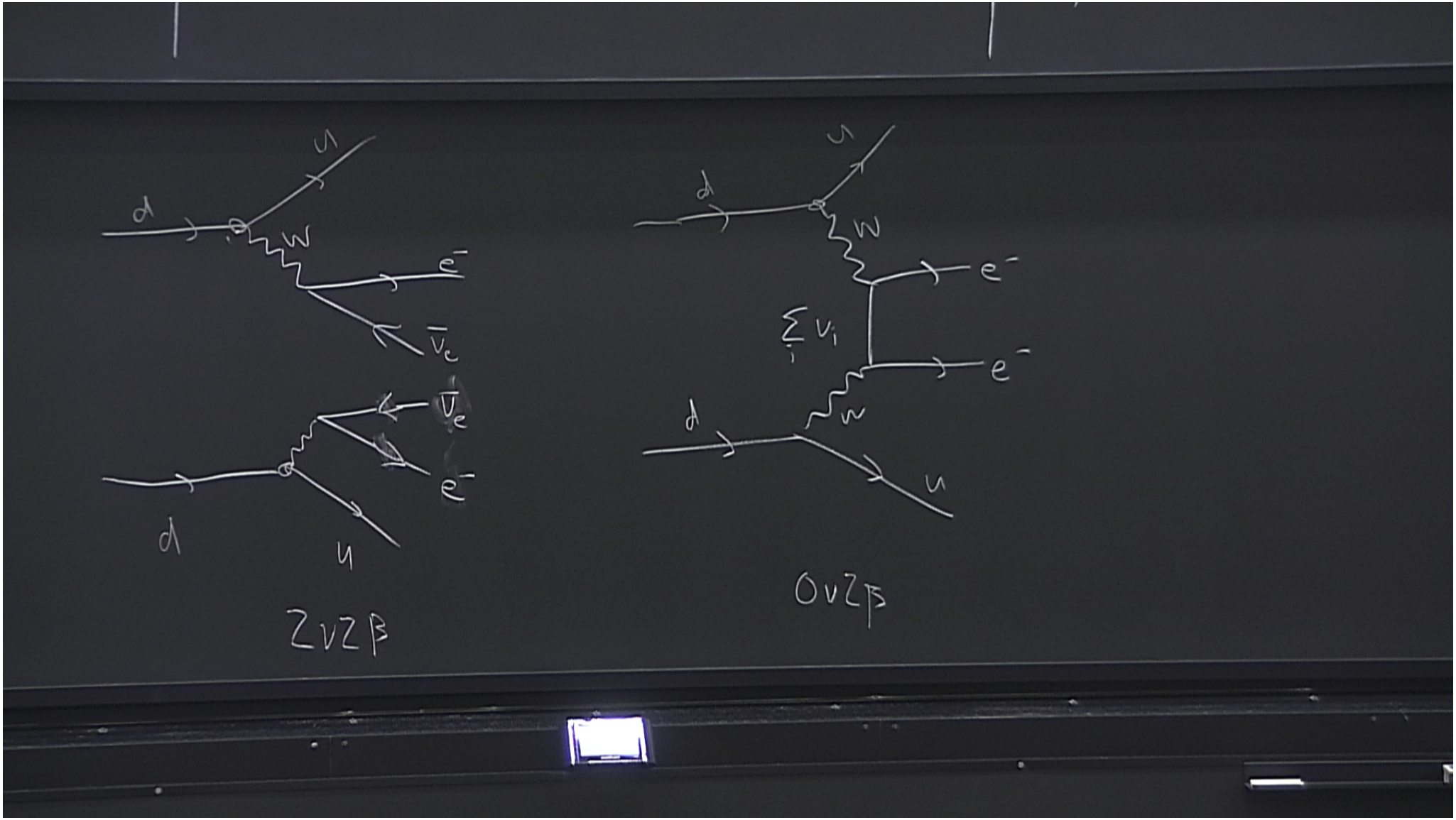
4) case ν's Dirac or Majorana

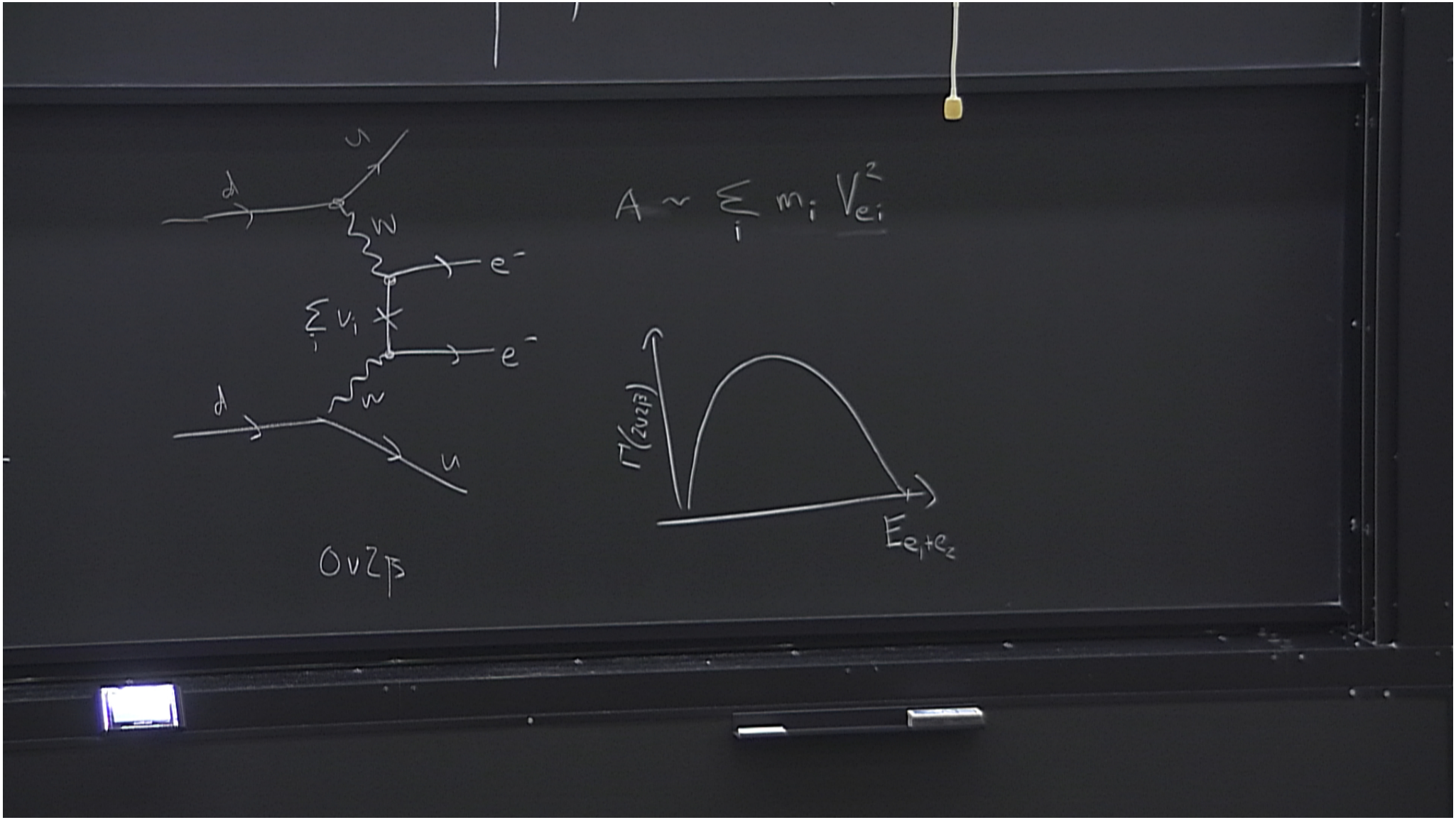
neutrinoless double β-decay ($0\nu\beta\beta$)

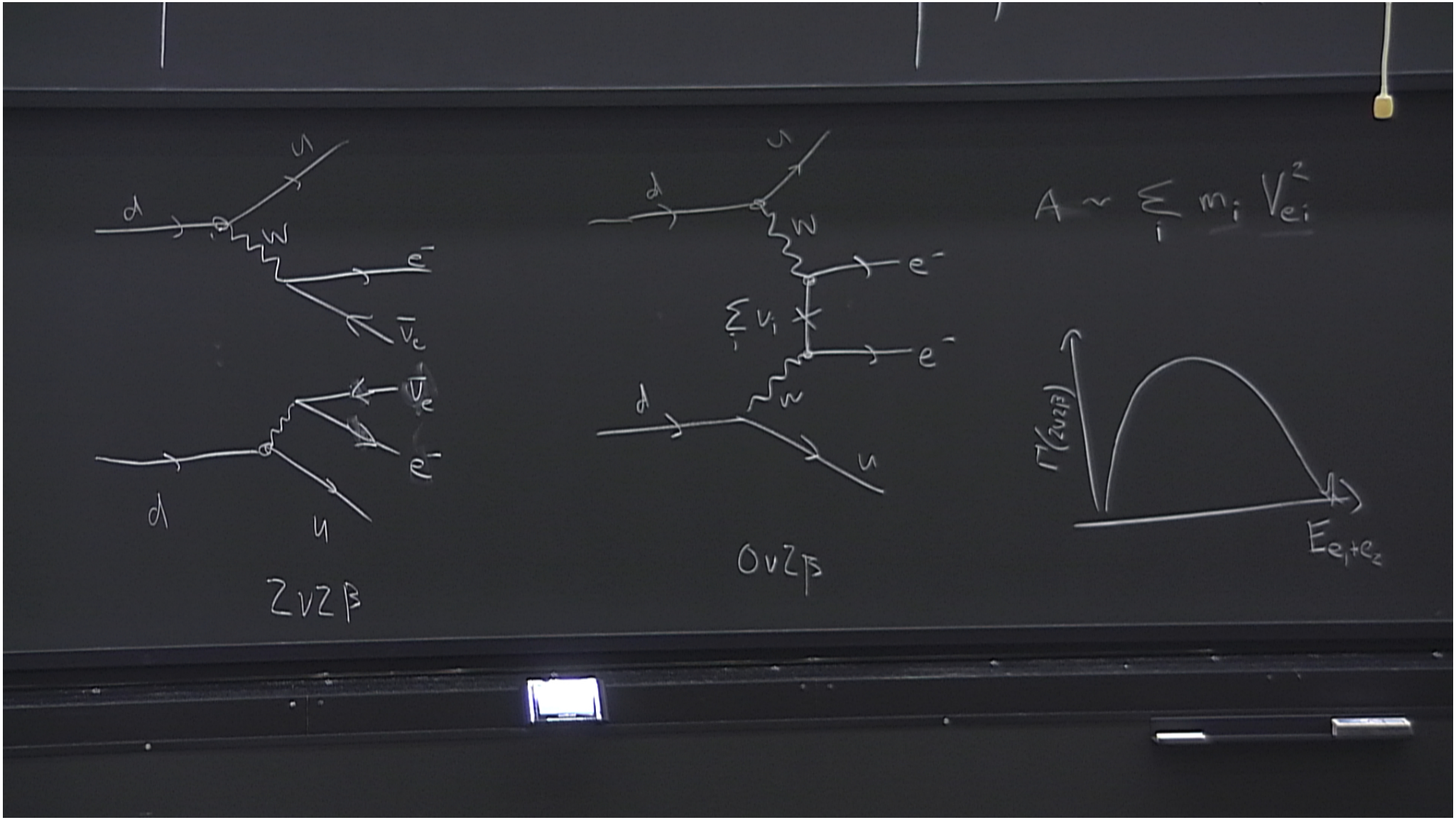
$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^- + 2\bar{\nu}_e$$

^{76}Ge, ^{136}Xe




d
u
W
e⁻
ν̄e
ν̄e
e⁻
d
u
2νββ
d
u
W
e⁻
Σ νi
e⁻
d
W
u
0νββ


d
u
W
e⁻
e⁻
$\sum_i \nu_i$
d
u
$A \sim \sum_i m_i V_{ei}^2$
$\Gamma(2\nu\beta\beta)$
$E_{e_1+e_2}$
$0\nu2\beta$

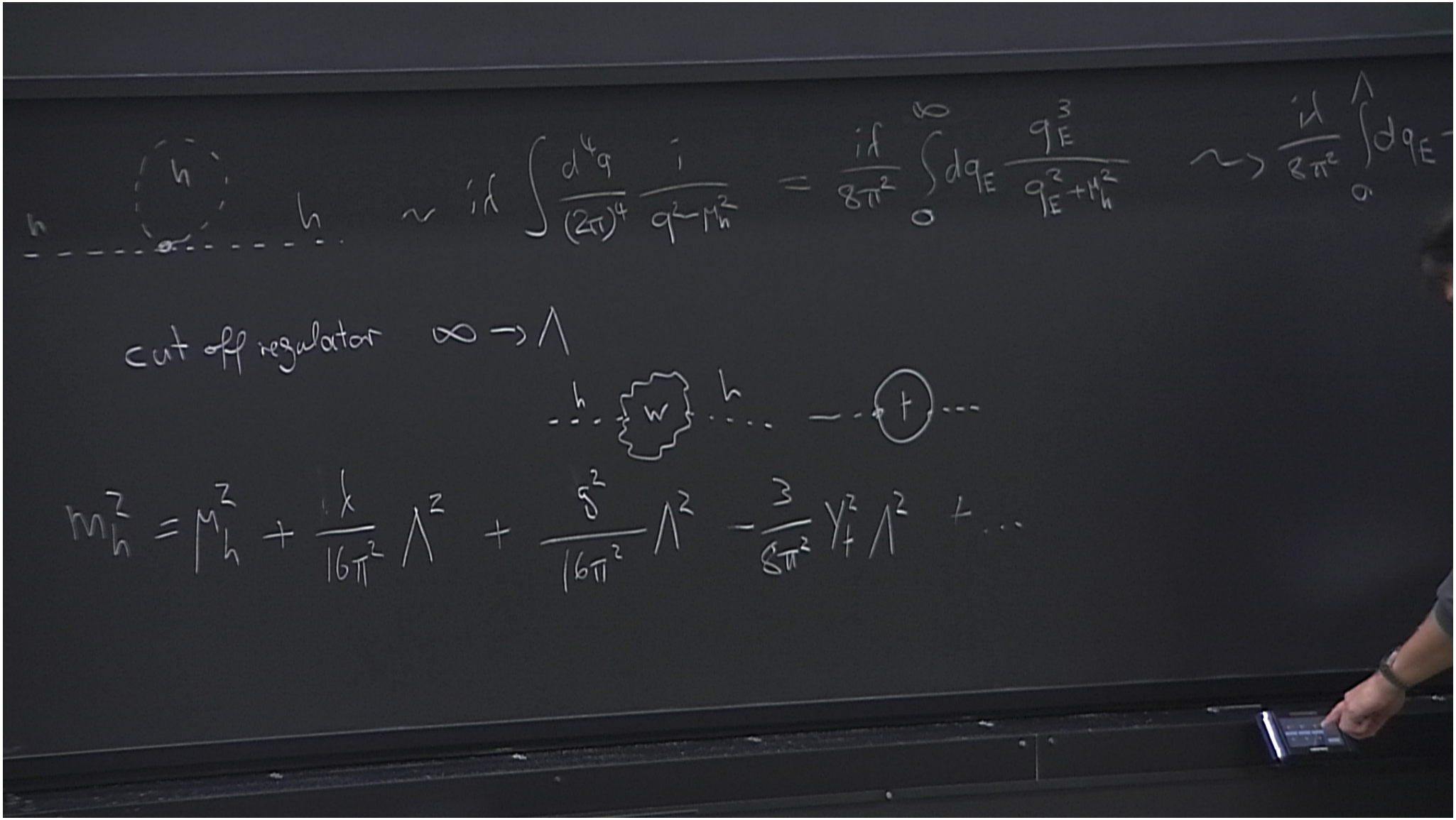

d
u
W
e⁻
ν̄e
ν̄e
e⁻
d
u
2ν2β
d
u
W
e⁻
Σ νi
e⁻
W
d
u
0ν2β
A ~ Σi mi Vei²
Γ(2ν2β)
Ee1+e2

The Higgs and the hierarchy problem

$$V(H) = -\frac{\mu_h^2}{2}(H^\dagger H) + \lambda (H^\dagger H)^2 \qquad m_h = \mu_h \simeq 125\,\text{GeV}$$

$$M_{Pl} = \sqrt{\frac{1}{G_N}} \simeq 10^{19}\,\text{GeV}$$

hierarchy is not stable against Quantum corrections


h
h
h
$\sim i\lambda \int \frac{d^4q}{(2\pi)^4} \frac{i}{q^2-M_h^2} = \frac{i\lambda}{8\pi^2} \int_0^\infty dq_E \frac{q_E^3}{q_E^2+M_h^2} \sim \frac{i\lambda}{8\pi^2} \int_0^\Lambda dq_E$
cut off regulator $\infty \to \Lambda$
h
W
h
t
$m_h^2 = M_h^2 + \frac{\lambda}{16\pi^2}\Lambda^2 + \frac{g^2}{16\pi^2}\Lambda^2 - \frac{3}{8\pi^2} Y_t^2 \Lambda^2 + \dots$

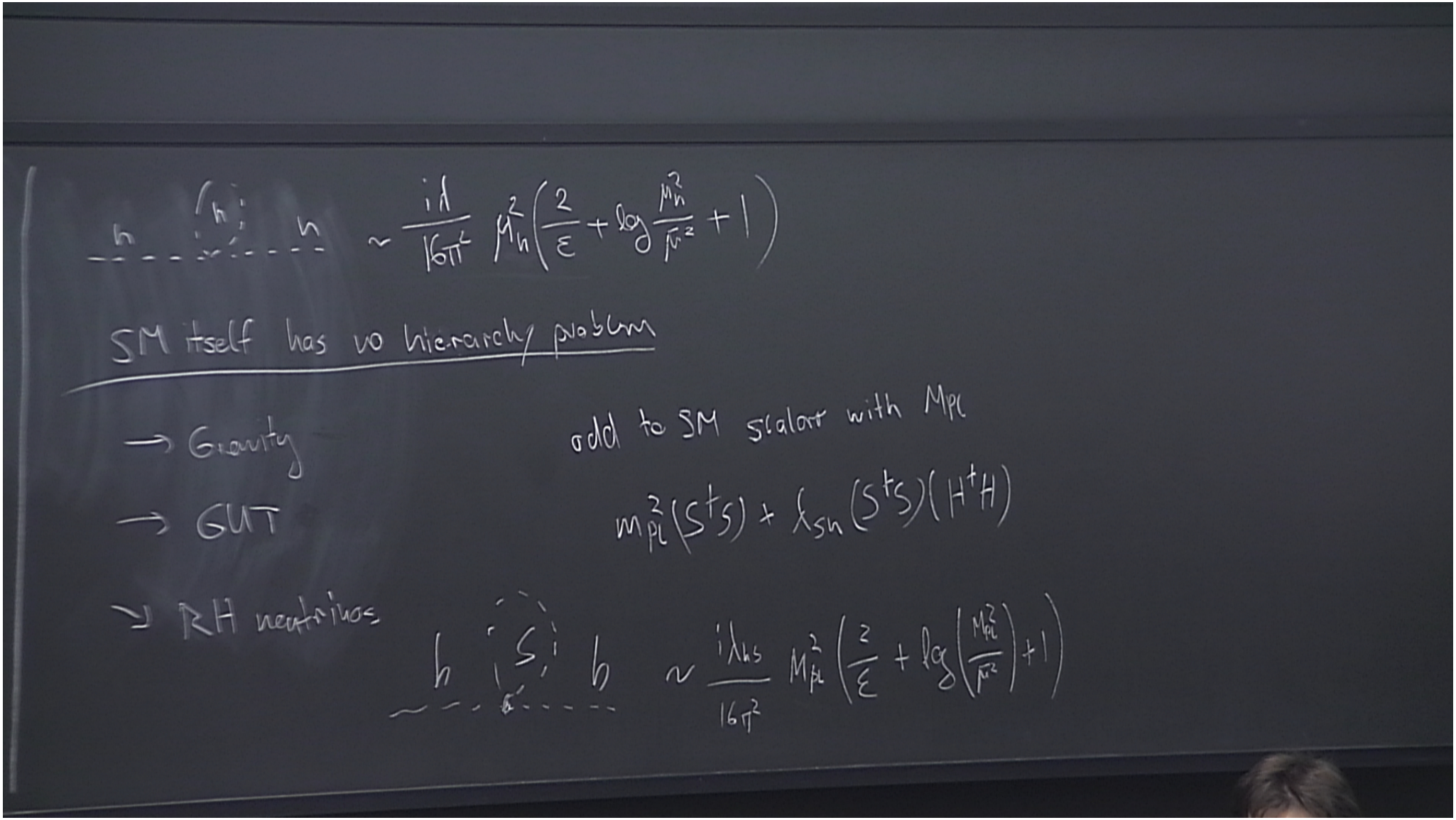
$$\int dq_E \frac{q_E^3}{q_E^2+M_h^2} \rightsquigarrow \frac{i\mathcal{A}}{8\pi^2}\int_0^{\Lambda} dq_E \frac{q_E^3}{q_E^2+M_h^2} = \frac{i\mathcal{A}}{16\pi^2}\left[\Lambda^2 + M_h^2 \log\frac{M_h^2}{\Lambda^2} + \ldots O\left(\frac{M_h^4}{\Lambda^2}\right)\right]$$

physical interpretation of Λ ?

Λ scale until SM is valid

$\Lambda \leq M_{Pl}$ $\qquad M_h^2 + \frac{1}{16\pi^2}\Lambda^2 \simeq (125\,\mathrm{GeV})^2$

$\Lambda >> M_h$ $\rightarrow$ fine tuning hierarchy problem


h
h
h
$\sim \frac{id}{16\pi^2} M_h^2 \left(\frac{2}{\epsilon} + \log\frac{M_h^2}{\mu^2} + 1\right)$
SM itself has no hierarchy problem
→ Gravity
→ GUT
↘ RH neutrinos
odd to SM scalar with M_{Pl}
$m_{Pl}^2 (S^\dagger S) + f_{sh} (S^\dagger S)(H^\dagger H)$
h
S
h
$\sim \frac{i\lambda_{hs}}{16\pi^2} M_{Pl}^2 \left(\frac{2}{\epsilon} + \log\left(\frac{M_{Pl}^2}{\mu^2}\right) + 1\right)$