Title: Standard Model

Speakers: Brian Shuve

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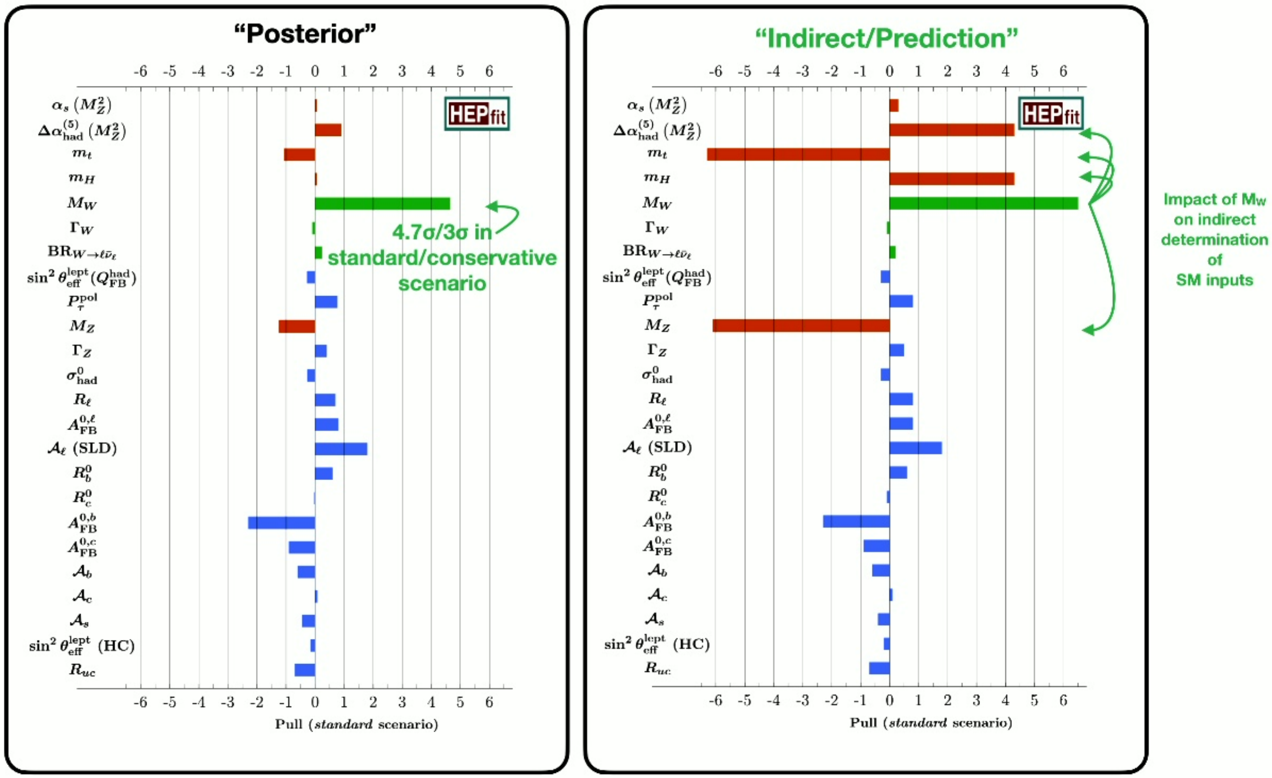
URL: https://pirsa.org/23060056

Updated EW Fits



de Blas *et al.*, arXiv:2204.04204

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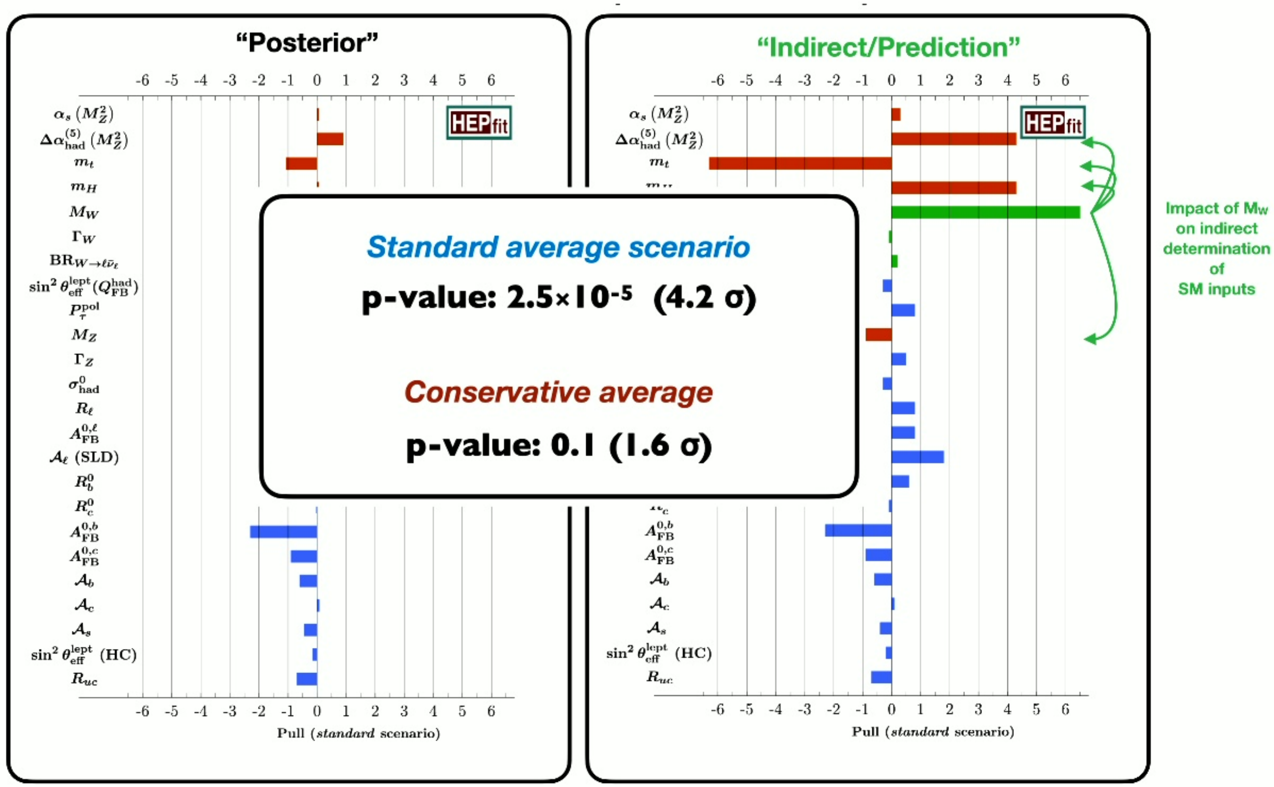


de Blas *et al.*, arXiv:2204.04204

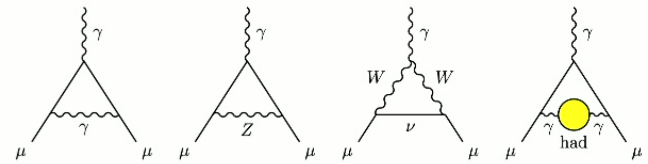
Including New Physics

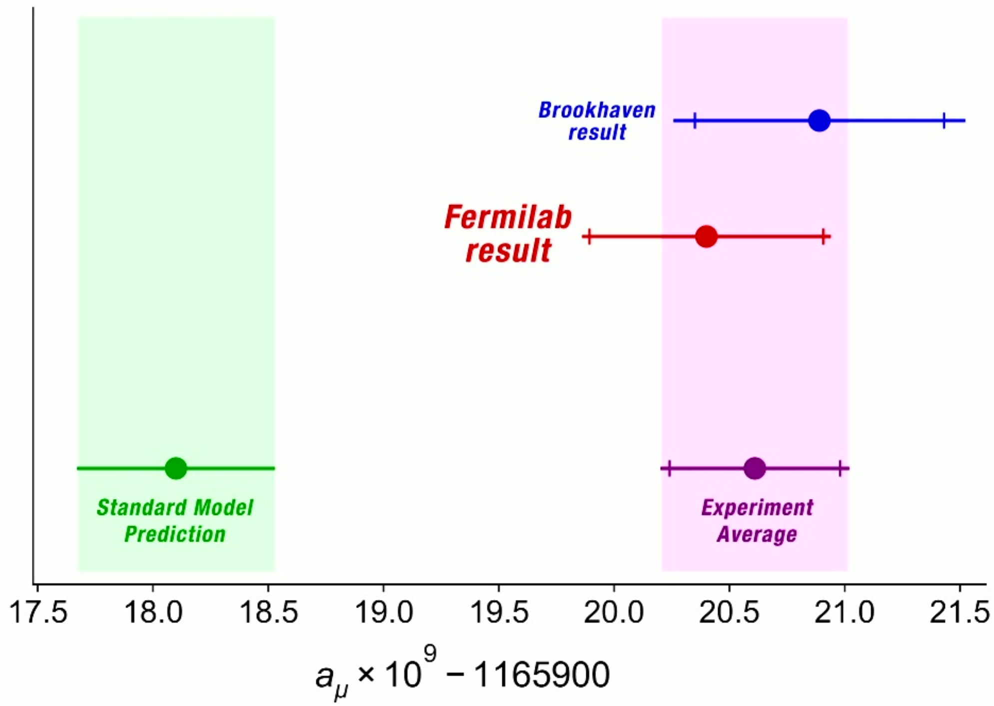
	Measurement	ST	STU	SMEFT
M_W [GeV]	80.4133 ± 0.0080	80.4100 ± 0.0077	80.4133 ± 0.0080	80.4133 ± 0.0080
Γ_W [GeV]	2.085 ± 0.042	2.09214 ± 0.00072	2.09251 ± 0.00075	2.0778 ± 0.0070
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23142 ± 0.00013	0.23147 ± 0.00014	–
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.1478 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0014
Γ_Z [GeV]	2.4955 ± 0.0023	2.49812 ± 0.00099	2.4951 ± 0.0022	2.4955 ± 0.0023
σ_h^0 [nb]	41.480 ± 0.033	41.4910 ± 0.0077	41.4905 ± 0.0077	41.481 ± 0.032
R_ℓ^0	20.767 ± 0.025	20.7506 ± 0.0084	20.7510 ± 0.0084	20.769 ± 0.024
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01638 ± 0.00023	0.01630 ± 0.00024	0.01659 ± 0.00032
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1478 ± 0.0011	0.1474 ± 0.0011	0.1488 ± 0.0014
R_b^0	0.21629 ± 0.00066	0.21591 ± 0.00010	0.21591 ± 0.00010	0.21632 ± 0.00065
R_c^0	0.1721 ± 0.0030	0.172198 ± 0.000054	0.172200 ± 0.000054	0.17159 ± 0.00099
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10362 ± 0.00075	0.10336 ± 0.00077	0.1008 ± 0.0014
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07407 ± 0.00058	0.07387 ± 0.00059	0.0734 ± 0.0022
$\mathcal{A}_b$	0.923 ± 0.020	0.934812 ± 0.000097	0.934779 ± 0.000099	0.903 ± 0.013
$\mathcal{A}_c$	0.670 ± 0.027	0.66815 ± 0.00052	0.66796 ± 0.00053	0.658 ± 0.020
$\mathcal{A}_s$	0.895 ± 0.091	0.935710 ± 0.000096	0.935676 ± 0.000097	0.905 ± 0.012
${\rm BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108386 ± 0.000022	0.108380 ± 0.000022	0.10900 ± 0.00038
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.23142 ± 0.00013	0.23147 ± 0.00014	–
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000032	0.172222 ± 0.000032	0.17161 ± 0.00098

de Blas *et al.*, arXiv:2204.04204

Other Oddities: muon g-2

- Result from April 2021





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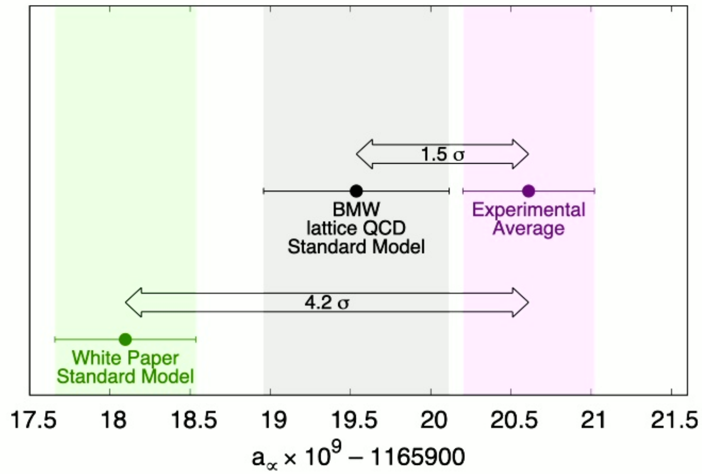

[Muon g-2 Theory Initiative, Phys.Rept. 887 (2020) 1-166]

[Budapest–Marseille–Wuppertal-coll., Nature 593 (2021) 7857]

[Muon g-2 coll., Phys. Rev. Lett. 126, 141801 (2021)]

- Increase to hadronic cross section disfavored > 1 GeV
  Keshavarsi *et al.*, arXiv:2006.12666
- Low-mass modifications to hadronic cross section also appear ruled out
  di Luzio *et al.*, arXiv:2112.08312

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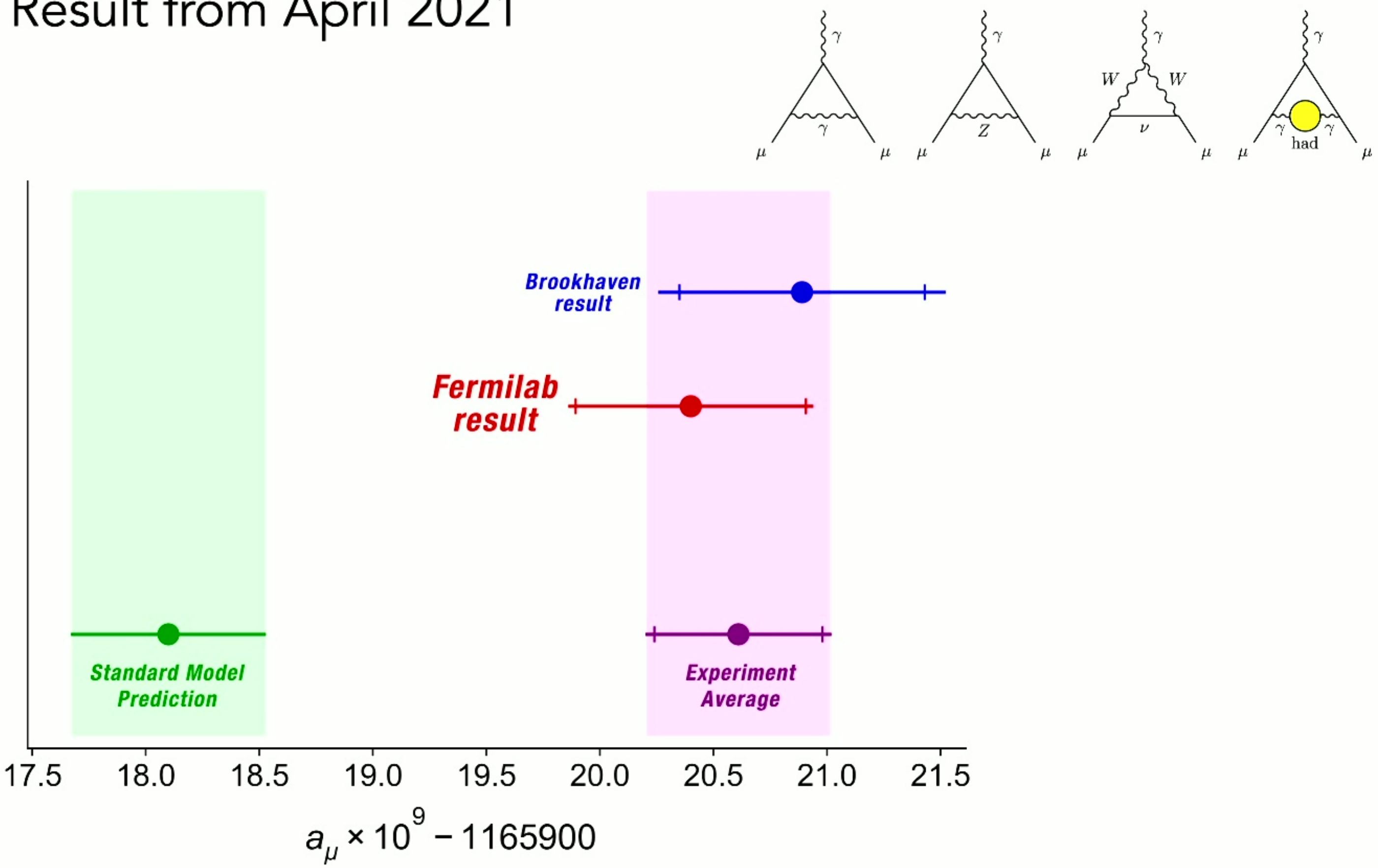

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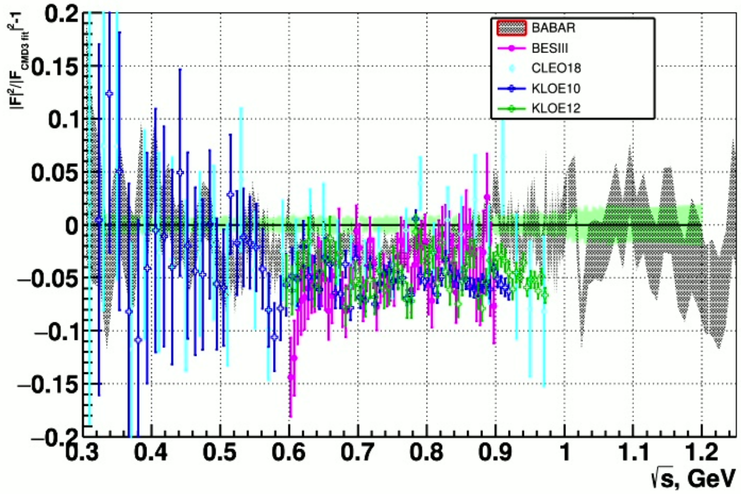
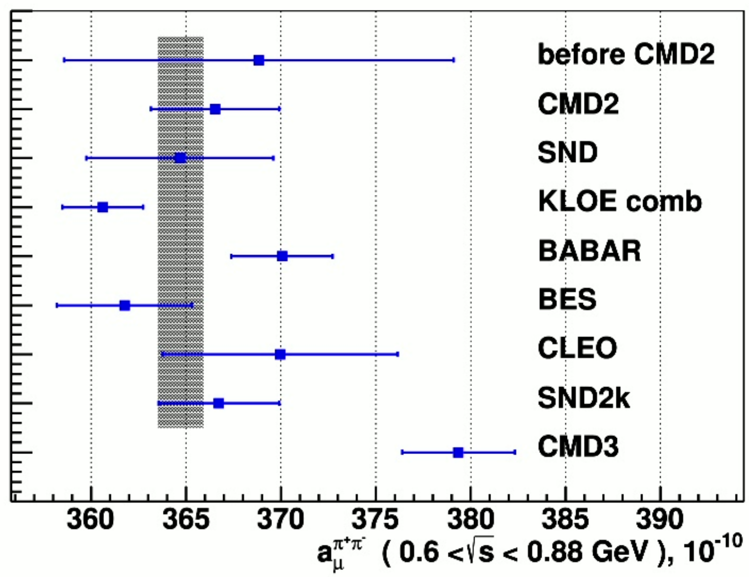
CMD3, arXiv:2302.08834





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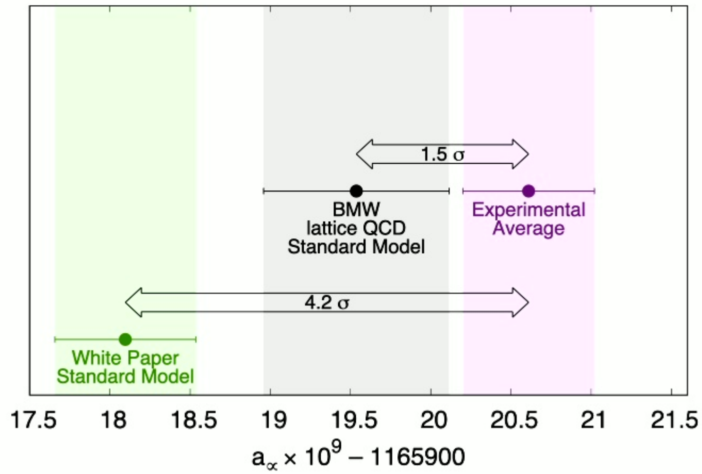

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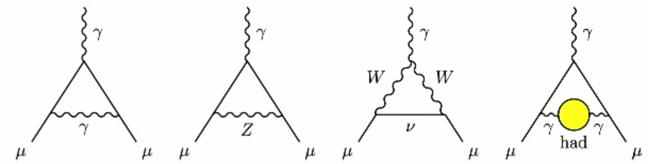
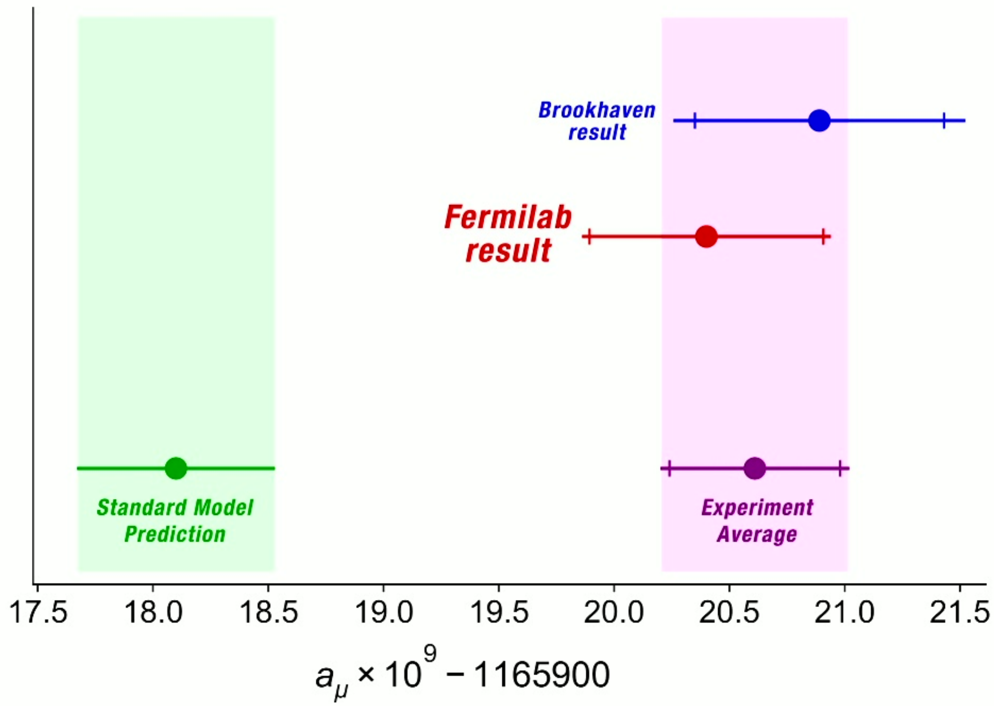
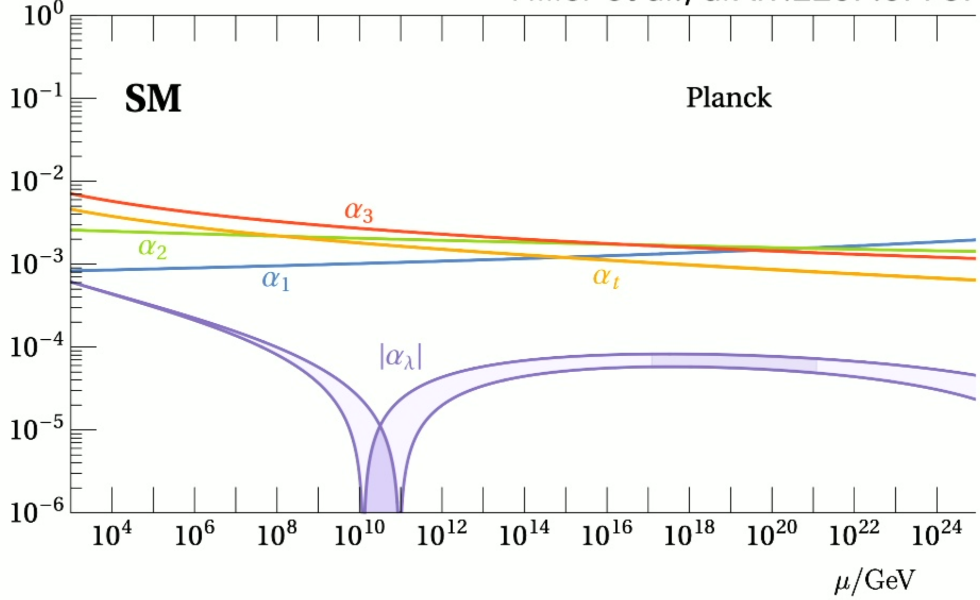




Other Oddities

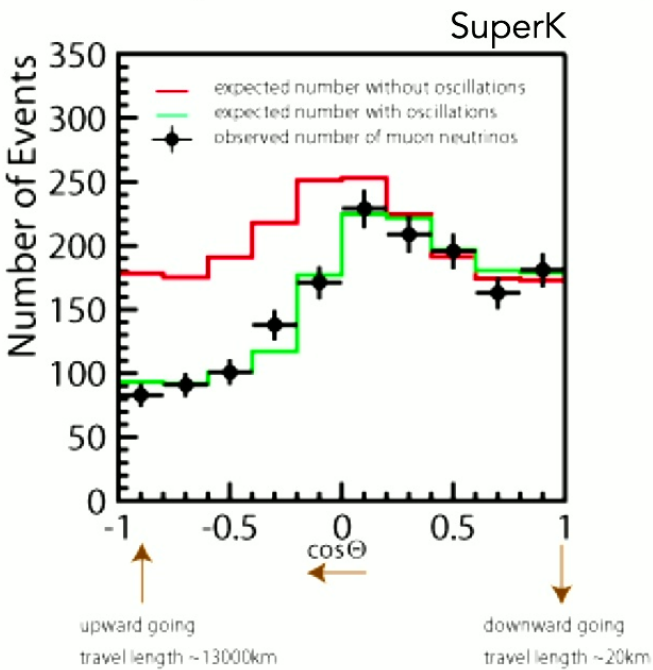
- Renormalization group evolution might drive Higgs quartic coupling negative! This would lead to an unstable vacuum

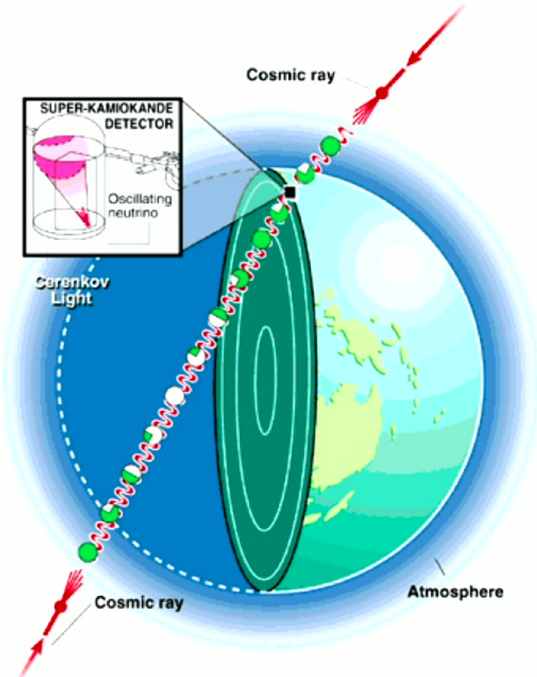
Hiller *et al.*, arXiv:2207.07737



Last topic: Neutrino & Flavour

- Neutrinos are found to oscillate
- In atmosphere: $\pi^+ \to \mu^+ \nu_\mu$

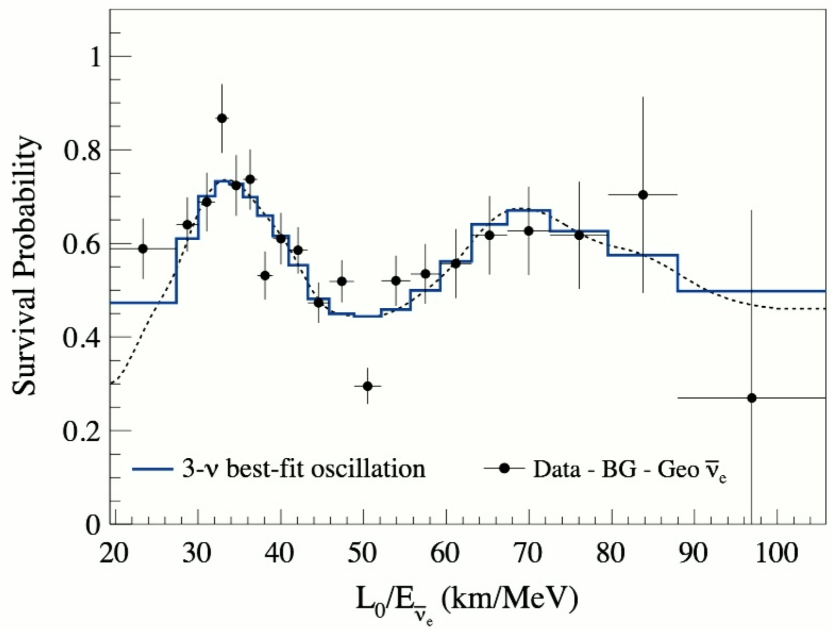




Last topic: Neutrino & Flavour

- Neutrinos are found to oscillate
- Electron antineutrinos from nuclear reactors:

KamLAND, arXiv:1303.4667



Lecture 4: Neutrinos & Flavour

Mass Lagrangian

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$\mathcal{L} = - y^e_{ij} H^* e^\dagger_{Ri} L_j + h.c.$$

$$\longrightarrow - \boxed{\frac{y^e_{ij} v}{\sqrt{2}}} e^\dagger_{Ri} L_j + h.c.$$

$$M^e_{ij} = \frac{y^e_{ij} v}{\sqrt{2}}$$

Lecture 4: Neutrinos & Flavour

Mass Lagrangian

$$\mathcal{L} = - y^e_{ij} H^* e^\dagger_{Ri} L_j + h.c. \qquad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$\longrightarrow - \boxed{\frac{y^e_{ij} v}{\sqrt{2}}} e^\dagger_{Ri} L_j + h.c. \qquad \bar{e} P_L e$$

$$i,j = 1,2,3$$

$$M^e_{ij} = \frac{y^e_{ij} v}{\sqrt{2}}$$

singular value decomposition

$$M^e = U^\dagger M^e_D V \qquad U, V \text{ unitary}$$

$$e_R \to U e_R$$

$$L \to V L.$$

$$\mathcal{L} = -M^e_{D\,ij}\, e^\dagger_{Ri}\, e_{Lj} + h.c. \qquad \text{nice!} \qquad i = e, \mu, \tau$$

singular value decomposition

$$M^e = U^\dagger M^e_D V \qquad U, V \text{ unitary}$$

diagonal

$$e_R \to U e_R$$

$$L \to V L.$$

$$M^e_{D\,ij} = m_{ei}\,\delta_{ij}$$

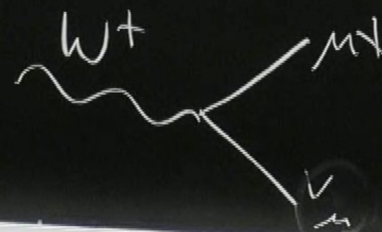
$$\mathcal{L} = -M^e_{D\,ij}\, e^\dagger_{Ri}\, e_{Lj} + h.c. \qquad \text{nice!} \qquad i = e, \mu, \tau$$

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

charged current interactions stay same:

$$\bar{\nu}_L \gamma^\mu W_\mu^+ e_L^- \longrightarrow \bar{\nu}_L \gamma^\mu W_\mu^+ e_L^-$$

* flavour states are mass eigenstates

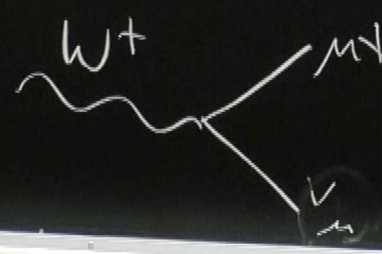


$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

charged current interactions stay same:

$$\bar{\nu}_L \gamma^\mu W_\mu^+ e_L^- \longrightarrow \bar{\nu}_L \gamma^\mu W_\mu^+ e_L^-$$

* flavour states are mass eigenstates $\longrightarrow$ ν are stationary states



$\longrightarrow$ contradiction w/ ν osc.

what we want :

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

ν_1, ν_2, ν_3 are mass eigenstates

ν_1 has the "most overlap" with ν_e

ν_3 " " least

$$|\psi(0)\rangle = |\nu_e\rangle$$

$$|\psi(t)\rangle = U_{e1} e^{-iE_1 t}|\nu_1\rangle + U_{e2} e^{-iE_2 t}|\nu_2\rangle + \dots$$

$$\text{OSC} \longleftrightarrow E_1 \neq E_2$$

what we want:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

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ν_3 " " least " "

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$$|\psi(t)\rangle = U_{e1} e^{-iE_1 t}|\nu_1\rangle + U_{e2} e^{-iE_2 t}|\nu_2\rangle + \dots$$

osc $\Longleftrightarrow$ $E_1 \neq E_2$, not in minimal SM

Non-zero ν mass

Add a RH neutrino N_R

$$\mathcal{L}_\nu = -F(\epsilon H) N_R^\dagger L + h.c.$$

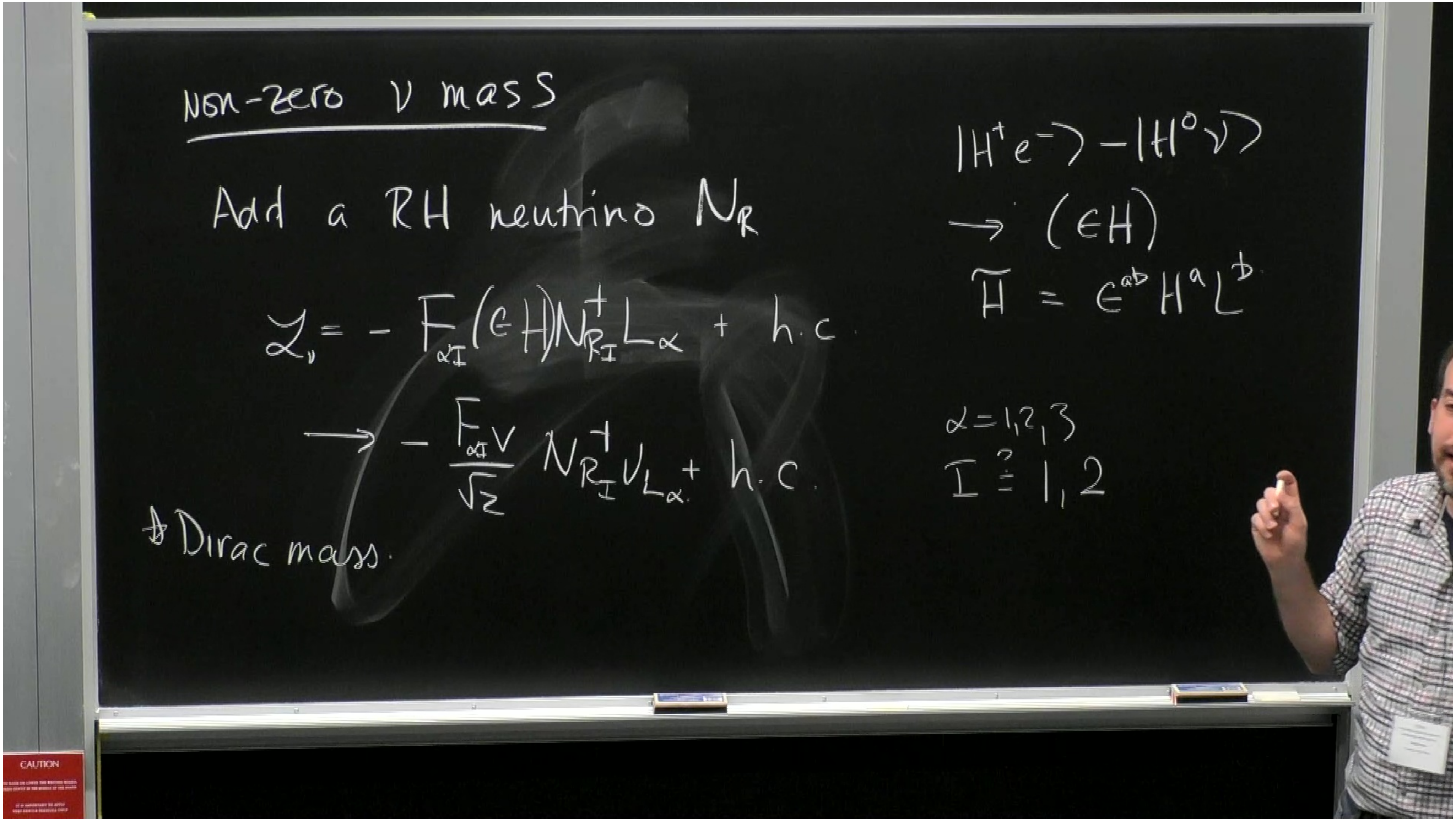
$$\longrightarrow -\frac{Fv}{\sqrt{2}} N_R^\dagger \nu_L + h.c.$$

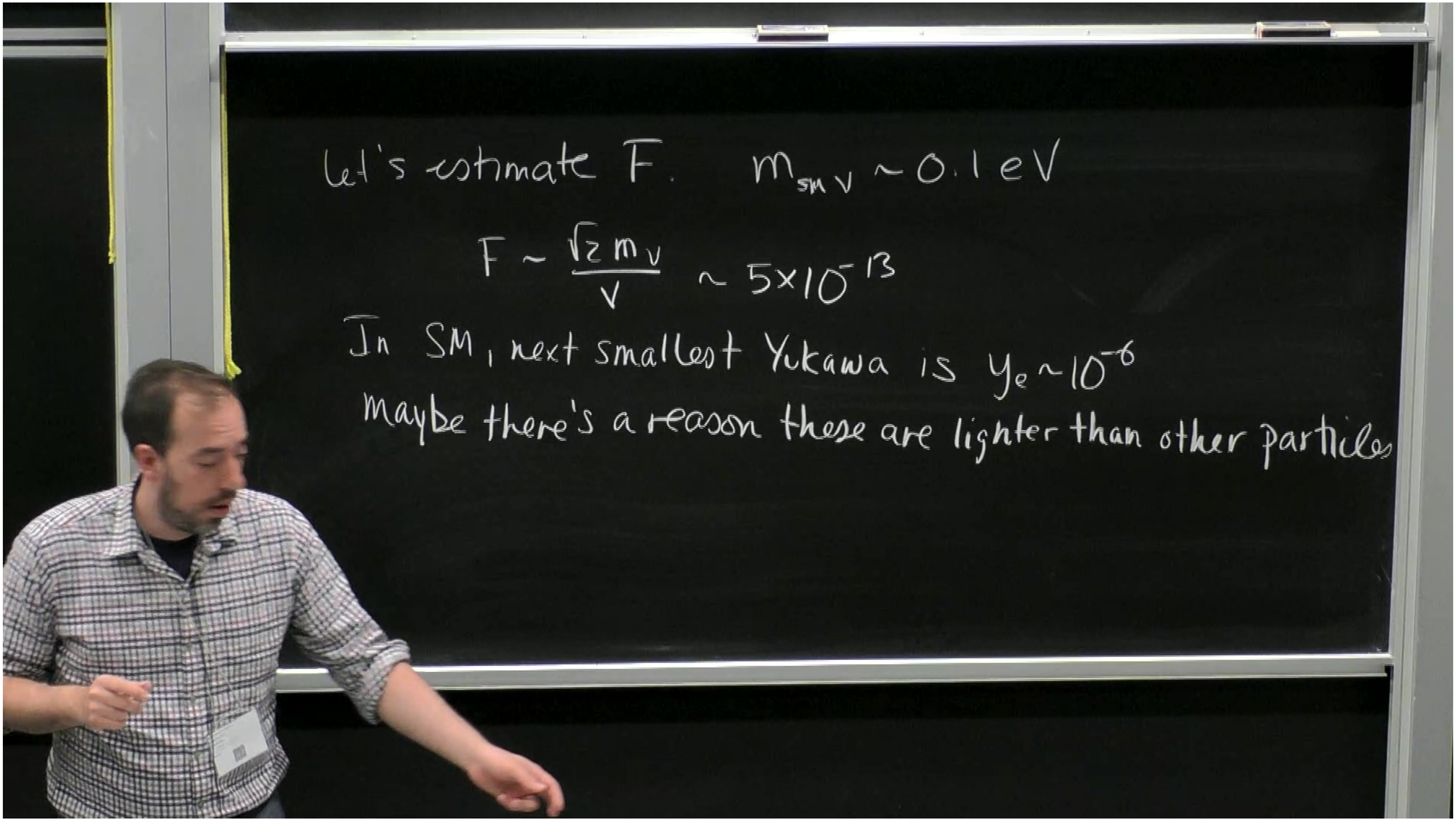
$\Rightarrow$ Dirac mass.

$$|H^+ e^-\rangle - |H^0 \nu\rangle$$

$$\to (\epsilon H)$$

$$\tilde{H} = \epsilon^{ab} H^a L^b$$


Non-zero ν mass
Add a RH neutrino N_R
$\mathcal{L}_\nu = - F_{\alpha I} (\epsilon H) N^{\dagger}_{R_I} L_\alpha + h.c.$
$\longrightarrow - \frac{F_{\alpha I} v}{\sqrt{2}} N^{\dagger}_{R_I} \nu_{L_\alpha} + h.c.$
$\Rightarrow$ Dirac mass.
$|H^+ e^-\rangle - |H^0 \nu\rangle$
$\rightarrow (\epsilon H)$
$\tilde{H} = \epsilon^{ab} H^a L^b$
$\alpha = 1, 2, 3$
$I \overset{?}{=} 1, 2$


Let's estimate F. $m_{SM\,\nu} \sim 0.1\,\mathrm{eV}$
$F \sim \frac{\sqrt{2}\, m_\nu}{v} \sim 5\times10^{-13}$
In SM, next smallest Yukawa is $y_e \sim 10^{-6}$
maybe there's a reason these are lighter than other particles

Now, need to diagonlize

$$M_D = \frac{FV}{\sqrt{2}}$$

↑ Dirac ν mass matrix

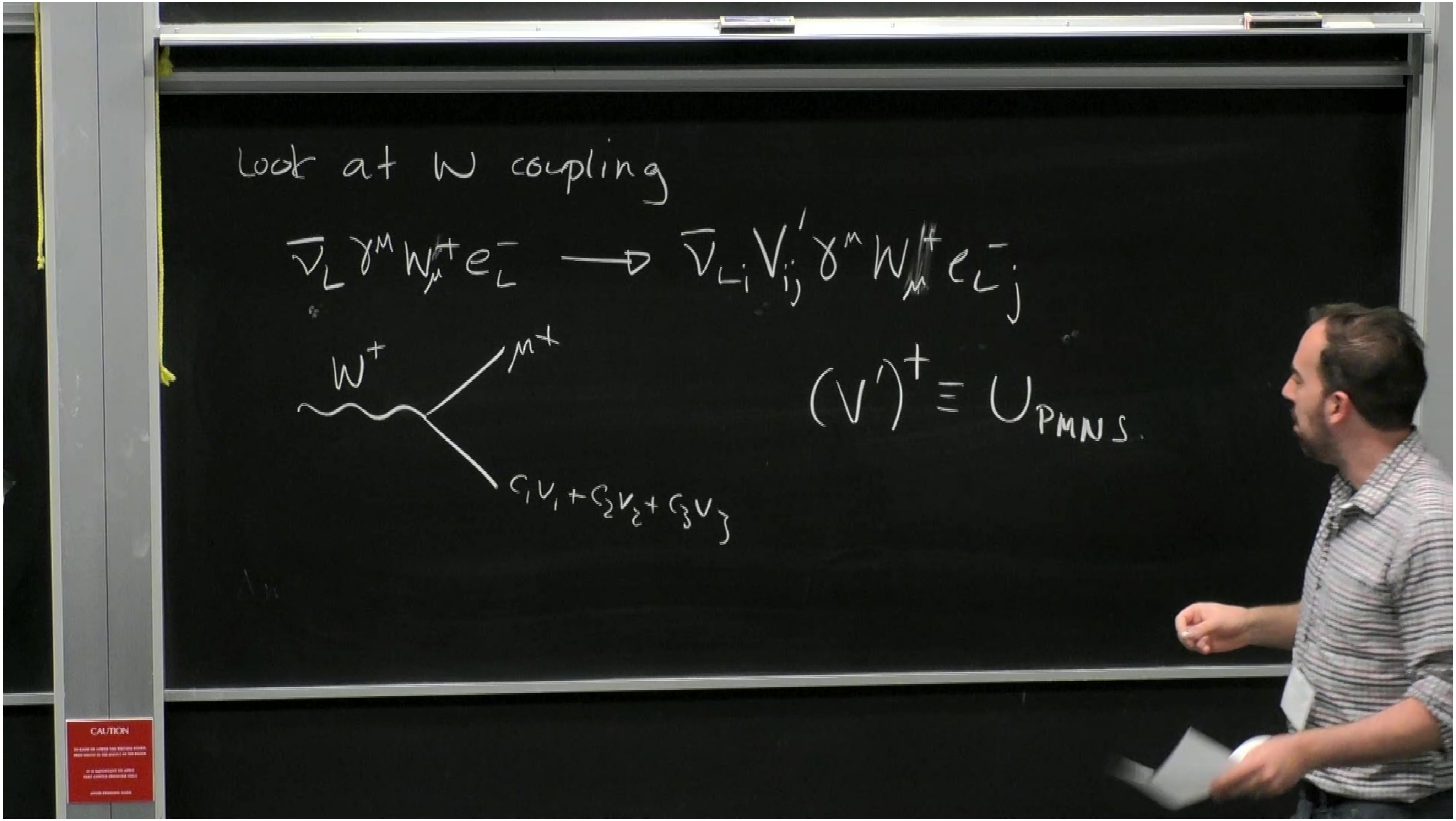
→ do SVD again

$N_R \to U' N_R$

↑ unitary assoc ν mass SVD

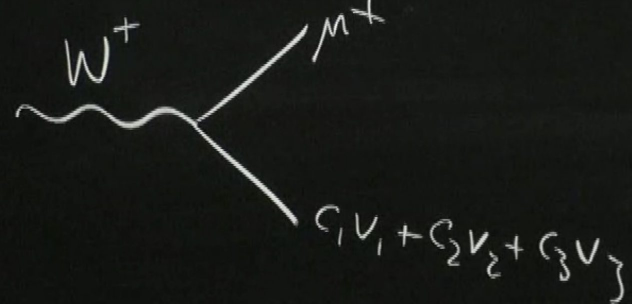
$\nu_L \to V' \nu_L$.

This diagonalizes M_D for ν.


Look at W coupling
$\bar{\nu}_L \gamma^\mu W_\mu^+ e_L^- \longrightarrow \bar{\nu}_{L_i} V'_{ij} \gamma^\mu W_\mu^+ e_{L_j}^-$
W^+
μ^+
$c_1 \nu_1 + c_2 \nu_2 + c_3 \nu_3$
$(V')^\dagger \equiv U_{PMNS}$
CAUTION

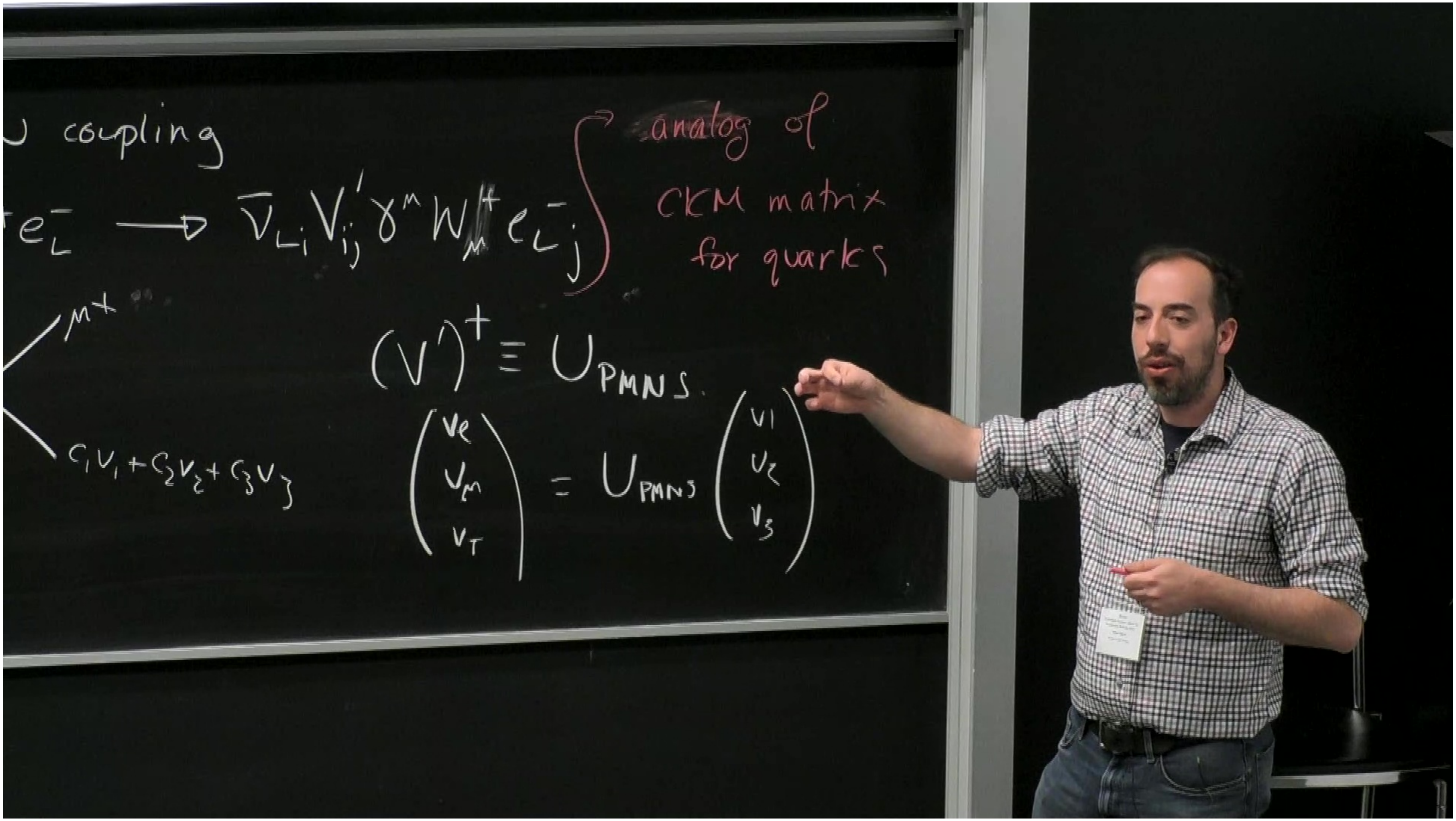
Look at W coupling

$$\bar{\nu}_L \gamma^\mu W_\mu^+ e_L^- \longrightarrow \bar{\nu}_{L_i} V'_{ij} \gamma^\mu W_\mu^+ e_{L_j}^-$$



$$(V')^\dagger \equiv U_{PMNS}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$


coupling
analog of
CKM matrix
for quarks
$(V')^{\dagger} \equiv U_{PMNS}$
$c_1 \nu_1 + c_2 \nu_2 + c_3 \nu_3$

Lecture 4: Neutrinos & Flavour

If I do same thing for Z coupling.

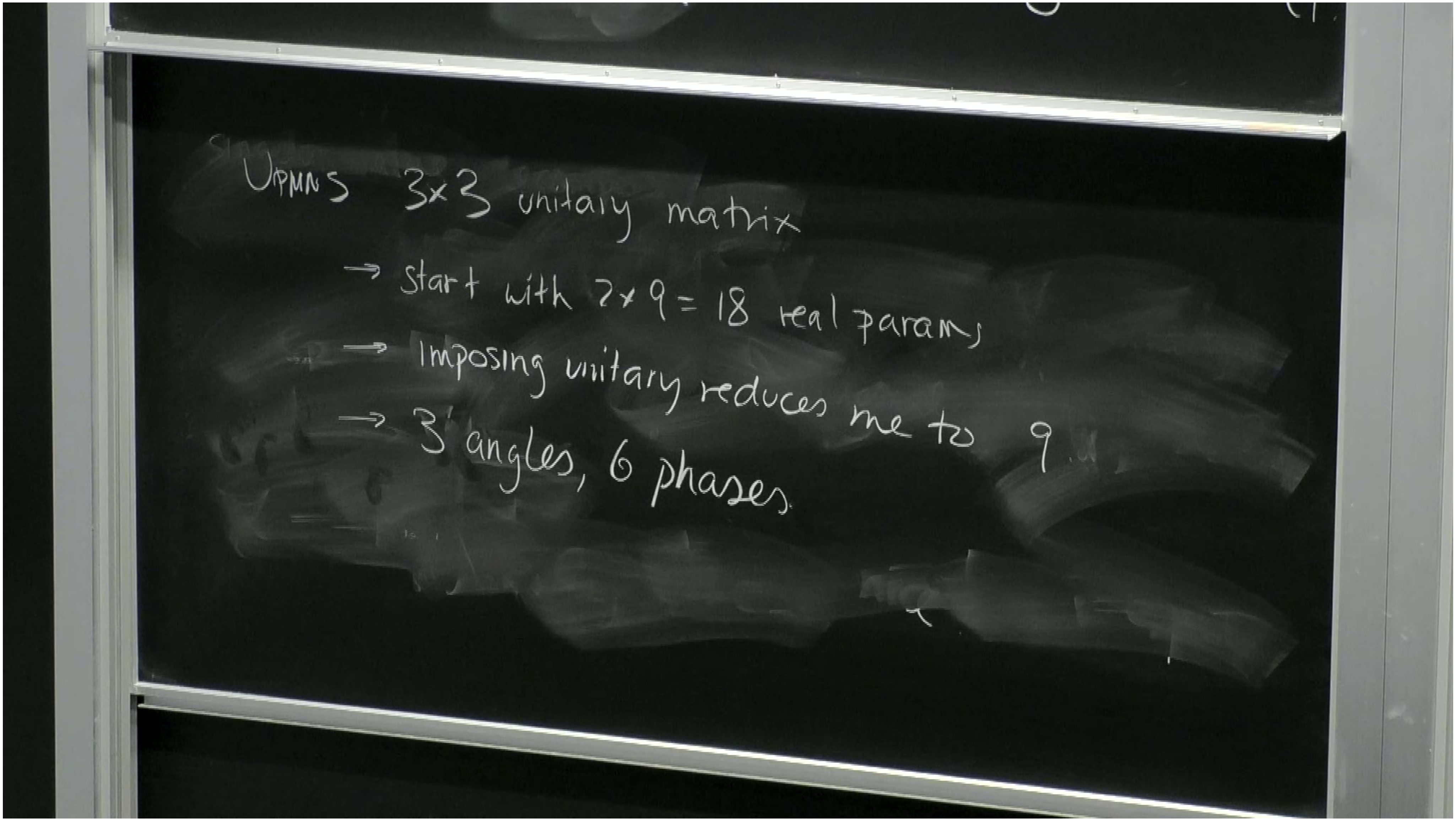
$$\bar{\nu}_L \gamma^\mu Z_\mu \nu_L \longrightarrow \bar{\nu}_L \gamma^\mu Z_\mu \nu_L .$$

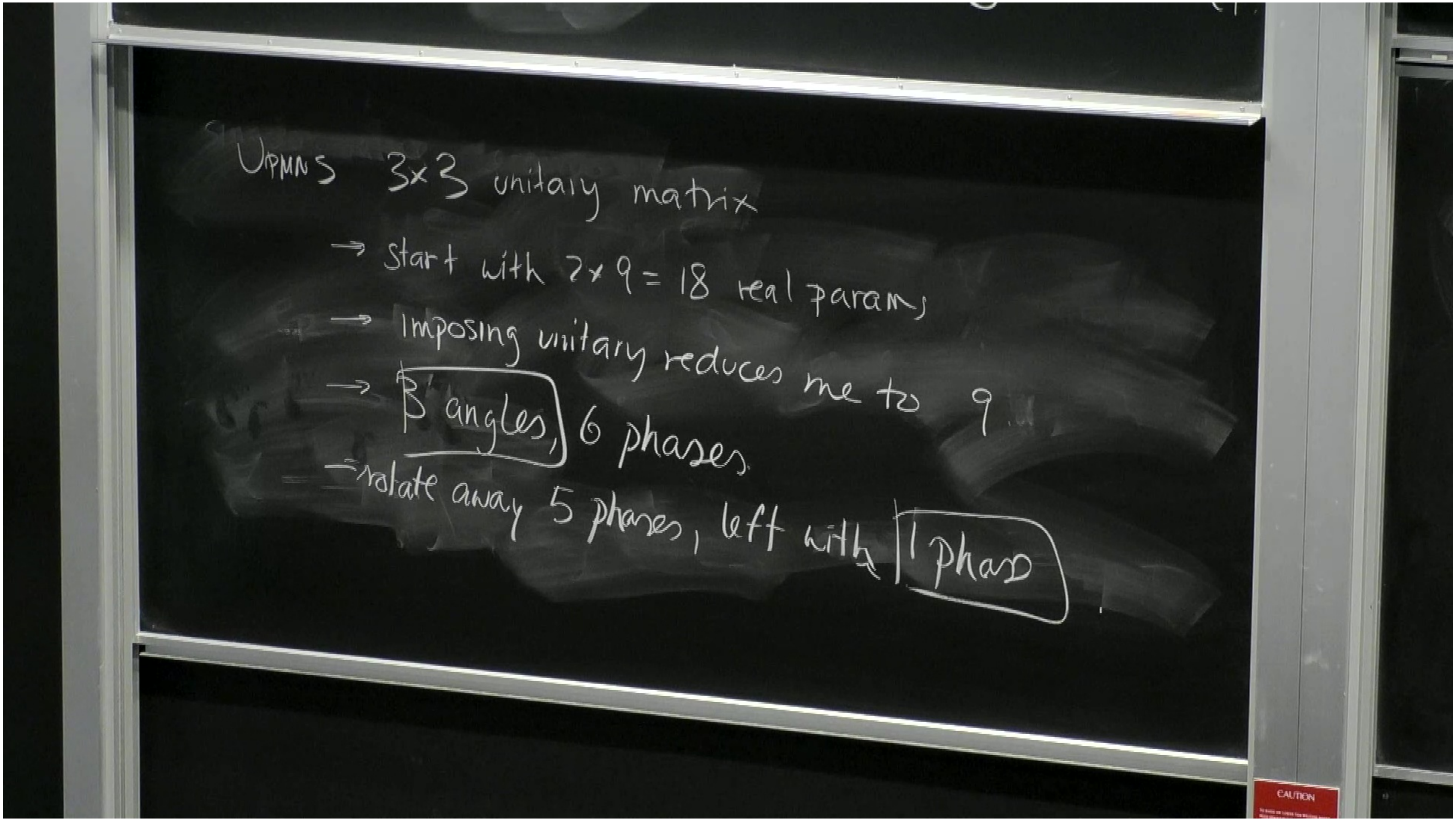
☆ flavour conserved in <u>neutral</u> interactions at tree level

SM forbids: $\mu^- \to e^- \gamma$.

$t \to c Z$.

$$\left.\begin{array}{l} h \to e\mu \\ h \to \bar{b} s \end{array}\right] \text{all not at tree level!}$$


U_PMNS 3×3 unitary matrix
→ start with 2×9 = 18 real params
→ Imposing unitary reduces me to 9
→ 3 angles, 6 phases


U PMNS 3x3 unitary matrix
→ start with 2x9 = 18 real params
→ imposing unitary reduces me to 9
→ 3 angles, 6 phases.
→ rotate away 5 phases, left with 1 phase

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{23} \rightarrow \cos\theta_{23}$

$\theta_{12} \sim 34^\circ$

$\theta_{23} \sim 45^\circ$

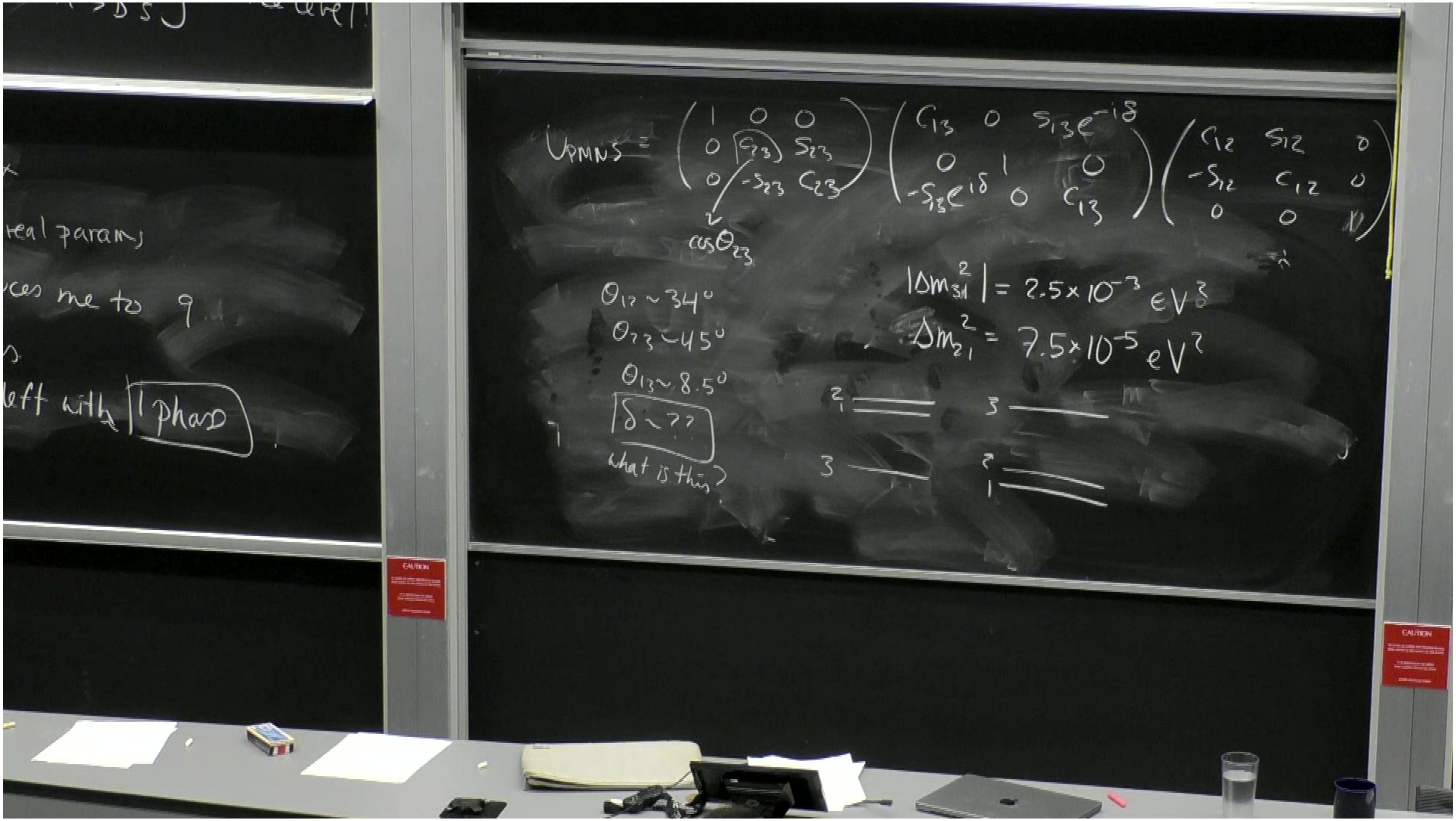
$\theta_{13} \sim 8.5^\circ$

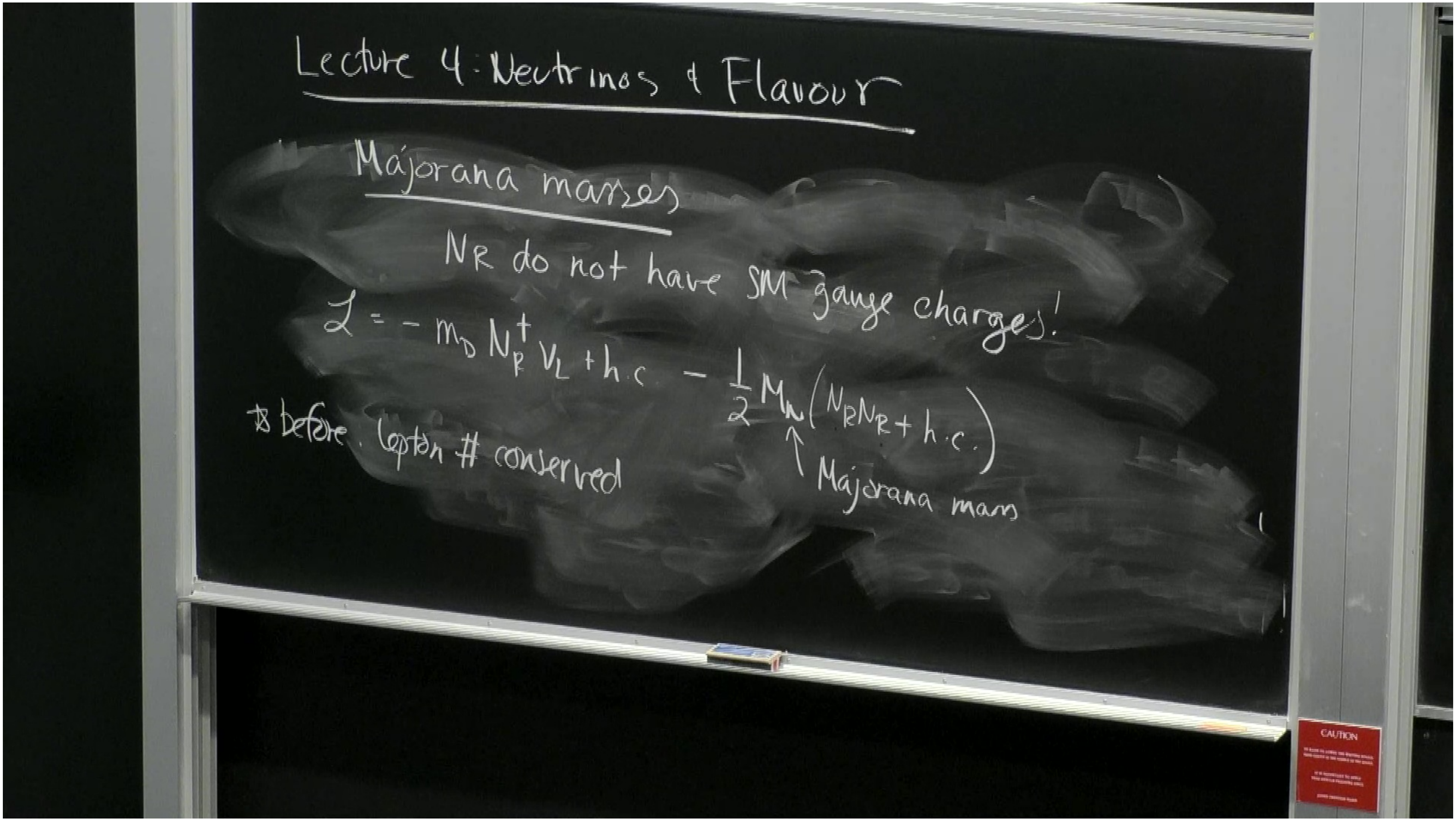
$\boxed{\delta \sim ??}$

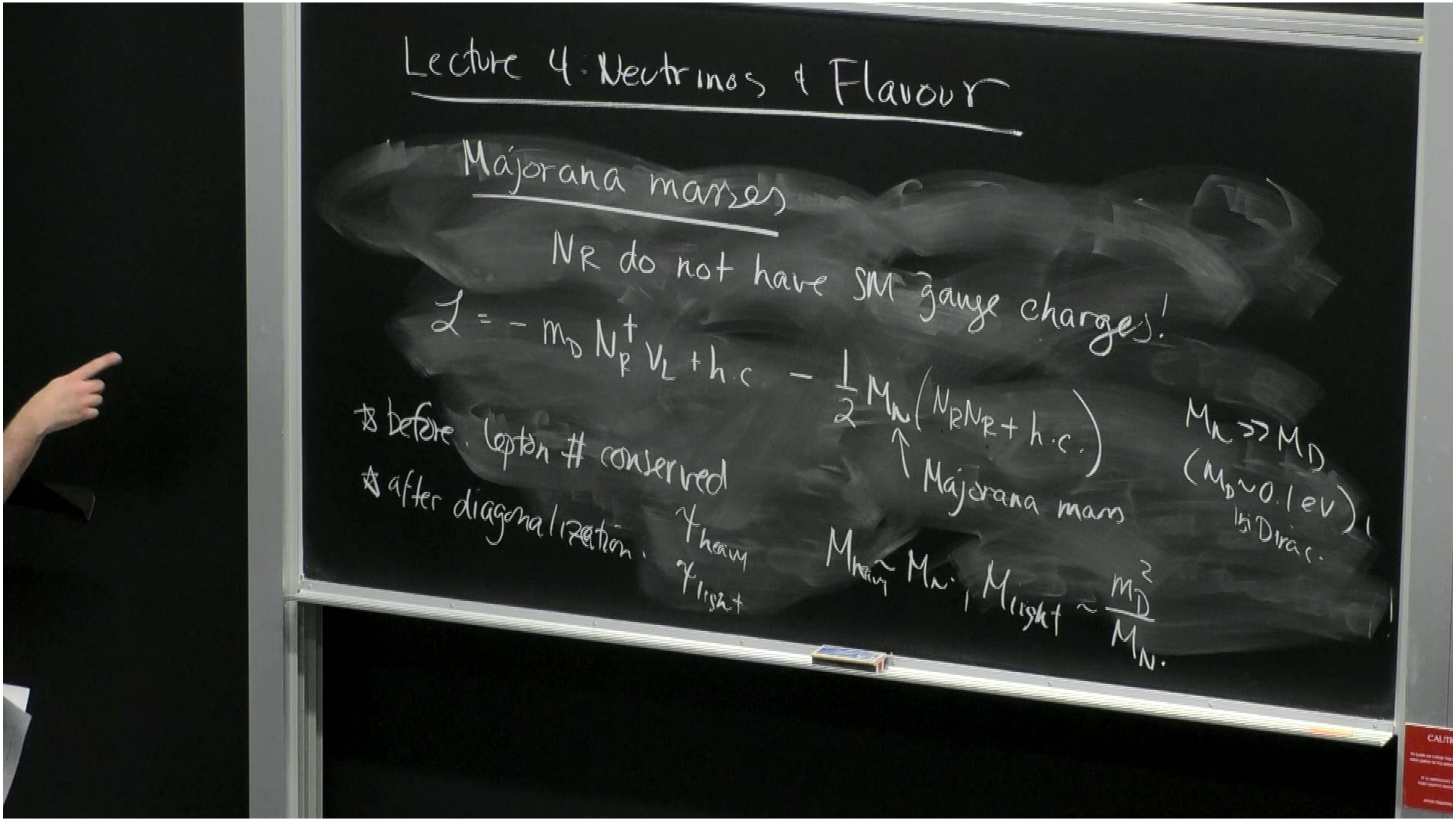
what is this?

$|\Delta m^2_{31}| = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{21} = 7.5 \times 10^{-5}\ \mathrm{eV}^2$


U_PMNS = (1 0 0; 0 c23 s23; 0 -s23 c23)(c13 0 s13 e^-iδ; 0 1 0; -s13 e^iδ 0 c13)(c12 s12 0; -s12 c12 0; 0 0 1)
cos θ23
real params
ces me to 9
left with 1 phase
θ12 ~ 34°
θ23 ~ 45°
θ13 ~ 8.5°
δ ~ ??
what is this?
|Δm²31| = 2.5 × 10⁻³ eV²
Δm²21 = 7.5 × 10⁻⁵ eV²
2
1
3
3
2
1
CAUTION


Lecture 4: Neutrinos & Flavour
Majorana masses
N_R do not have SM gauge charges!
$\mathcal{L} = - m_D N_R^\dagger \nu_L + h.c. - \frac{1}{2} M_N (N_R N_R + h.c.)$
Majorana mass
* before: lepton # conserved
CAUTION


Lecture 4: Neutrinos & Flavour
Majorana masses
N_R do not have SM gauge charges!
$\mathcal{L} = - m_D N_R^\dagger \nu_L + h.c. - \frac{1}{2} M_N (N_R N_R + h.c.)$
Majorana mass
$M_N \gg M_D$
$(M_D \sim 0.1\,eV)$
Dirac
* before: lepton # conserved
* after diagonalization: ν_{heavy} ν_{light}
$M_{heavy} \sim M_N$, $M_{light} \sim \frac{m_D^2}{M_N}$.

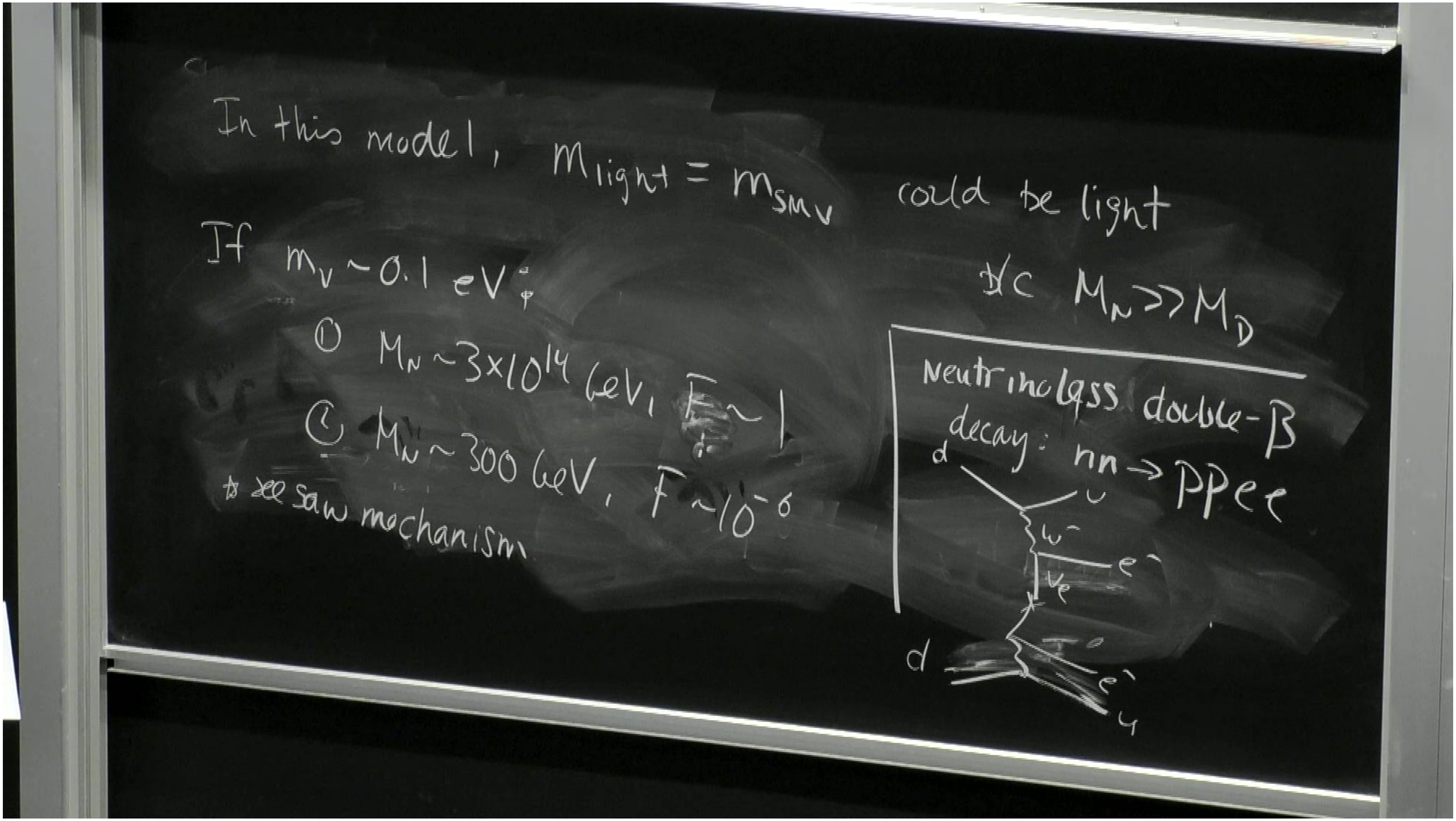
In this model, $m_{light} = m_{SM\nu}$ could be light

If $m_\nu \sim 0.1$ eV: b/c $M_N \gg M_D$

① $M_N \sim 3 \times 10^{14}$ GeV, $F \sim 1$

② $M_N \sim 300$ GeV, $F \sim 10^{-6}$

⇒ see saw mechanism


In this model, $m_{light} = m_{SM\nu}$ could be light
If $m_\nu \sim 0.1$ eV:
b/c $M_N \gg M_D$
① $M_N \sim 3\times10^{14}$ GeV, $F \sim 1$
② $M_N \sim 300$ GeV, $F \sim 10^{-6}$
* see saw mechanism
Neutrinoless double-β decay: $nn \to ppee$
d
u
W^-
e^-
ν_e
d
e^-
u