Theory review on Charged Lepton Flavor Violation

Avelino Vicente
IFIC – CSIC / U. Valencia

FPCP 2021
Shanghai

Introduction

Before the LHC started operating we all hoped for great discoveries...

LHC expectations

Microscopic black holes

Extra dimensions

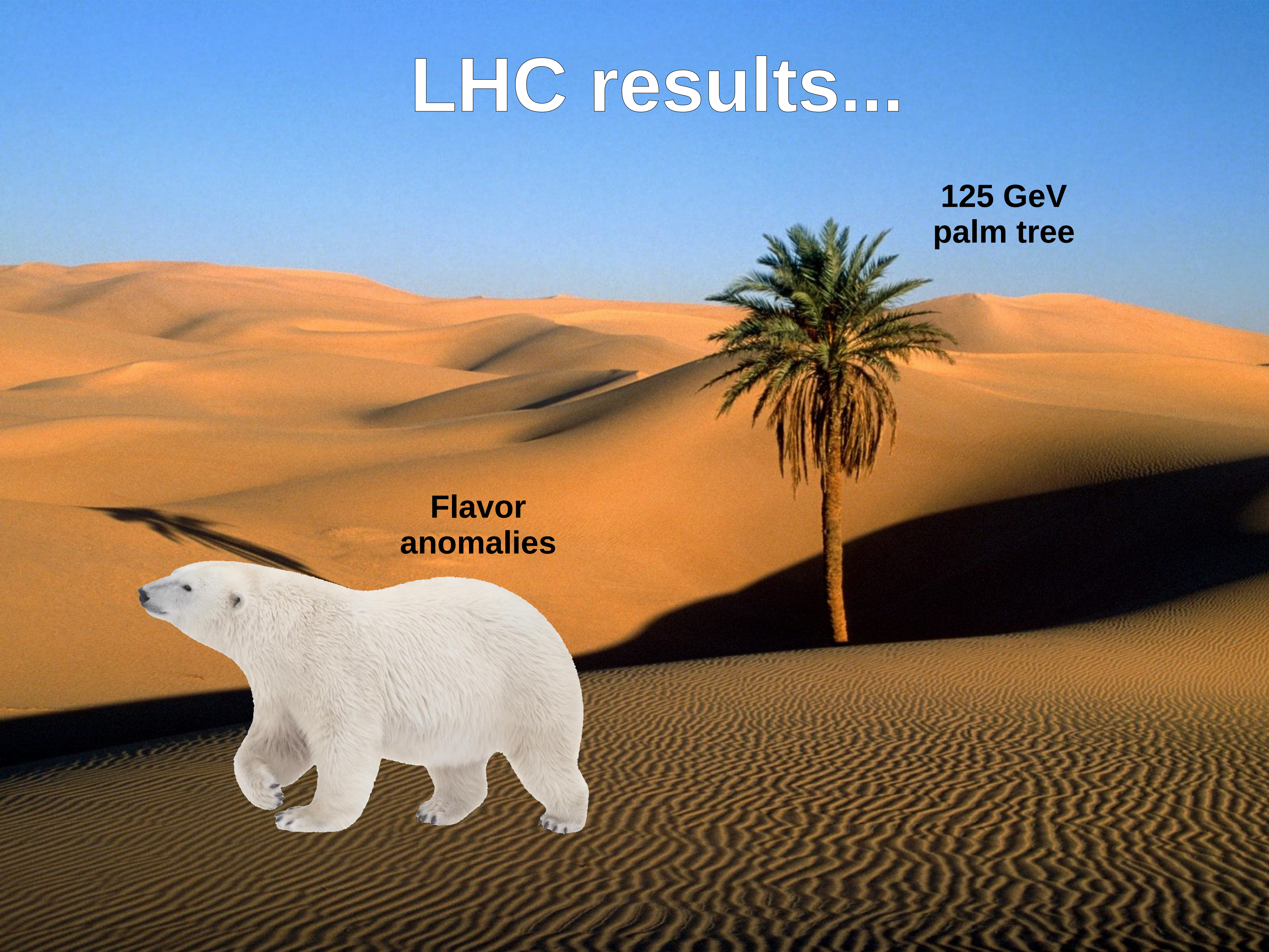
Supersymmetry

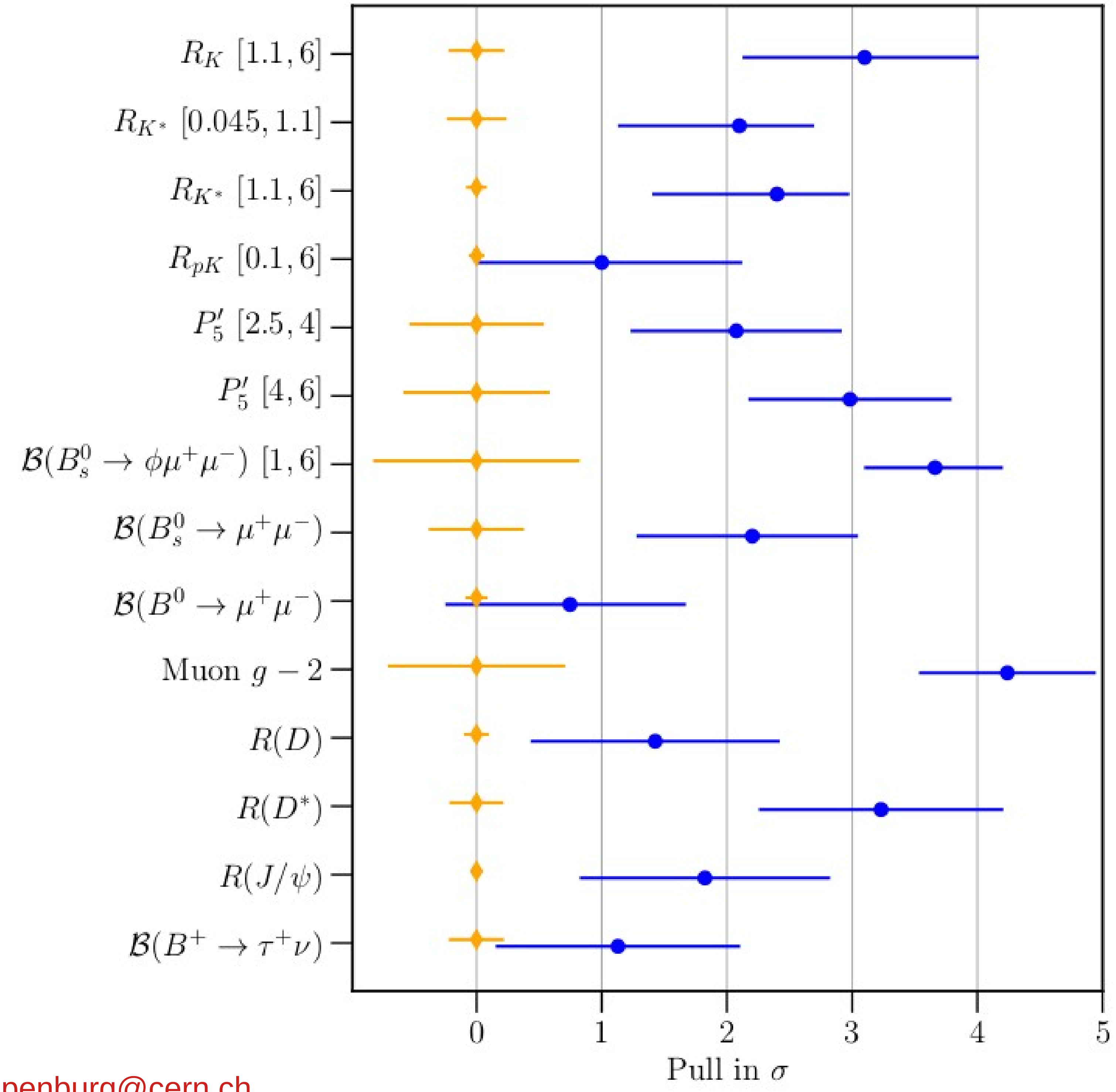
Compositeness

LHC results...

125 GeV
palm tree

LHC results...





patrick.koppenburg@cern.ch

Introduction

Do we have a good reason to go Beyond the Standard Model?

Introduction

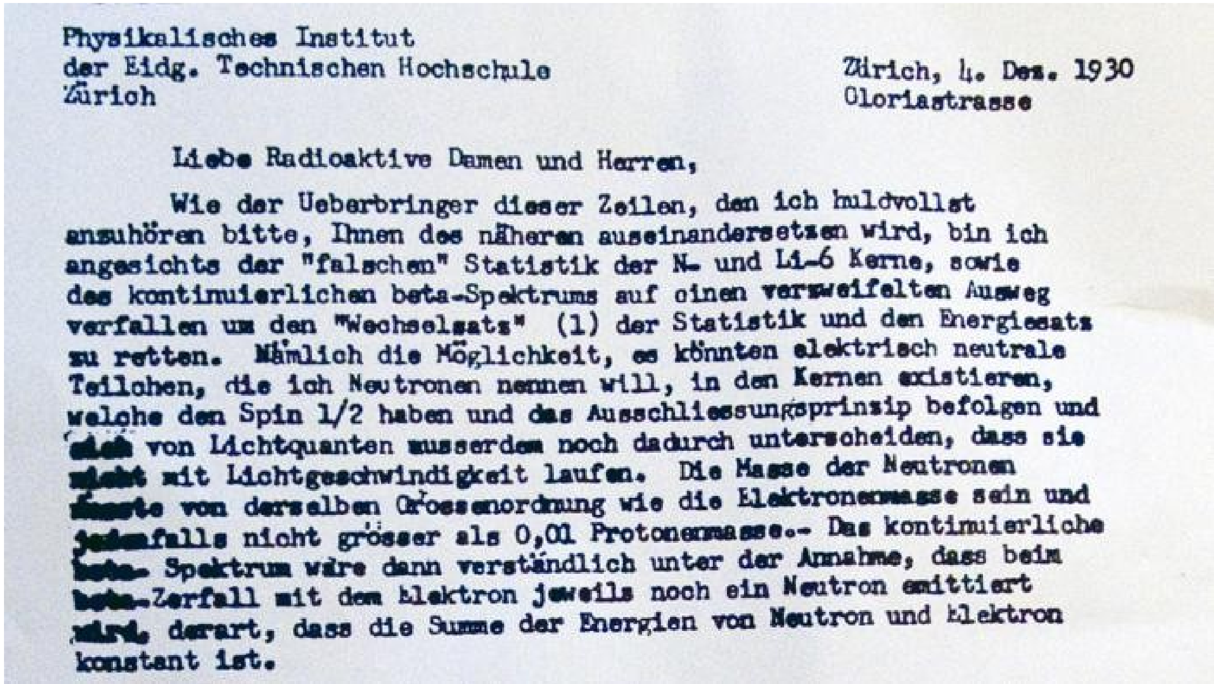
Do we have a good reason to go Beyond the Standard Model?

Neutrinos!

The lepton sector is still
to be understood!

Neutrinos and the lepton sector

Dear radiactive Ladies and Gentlemen...



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

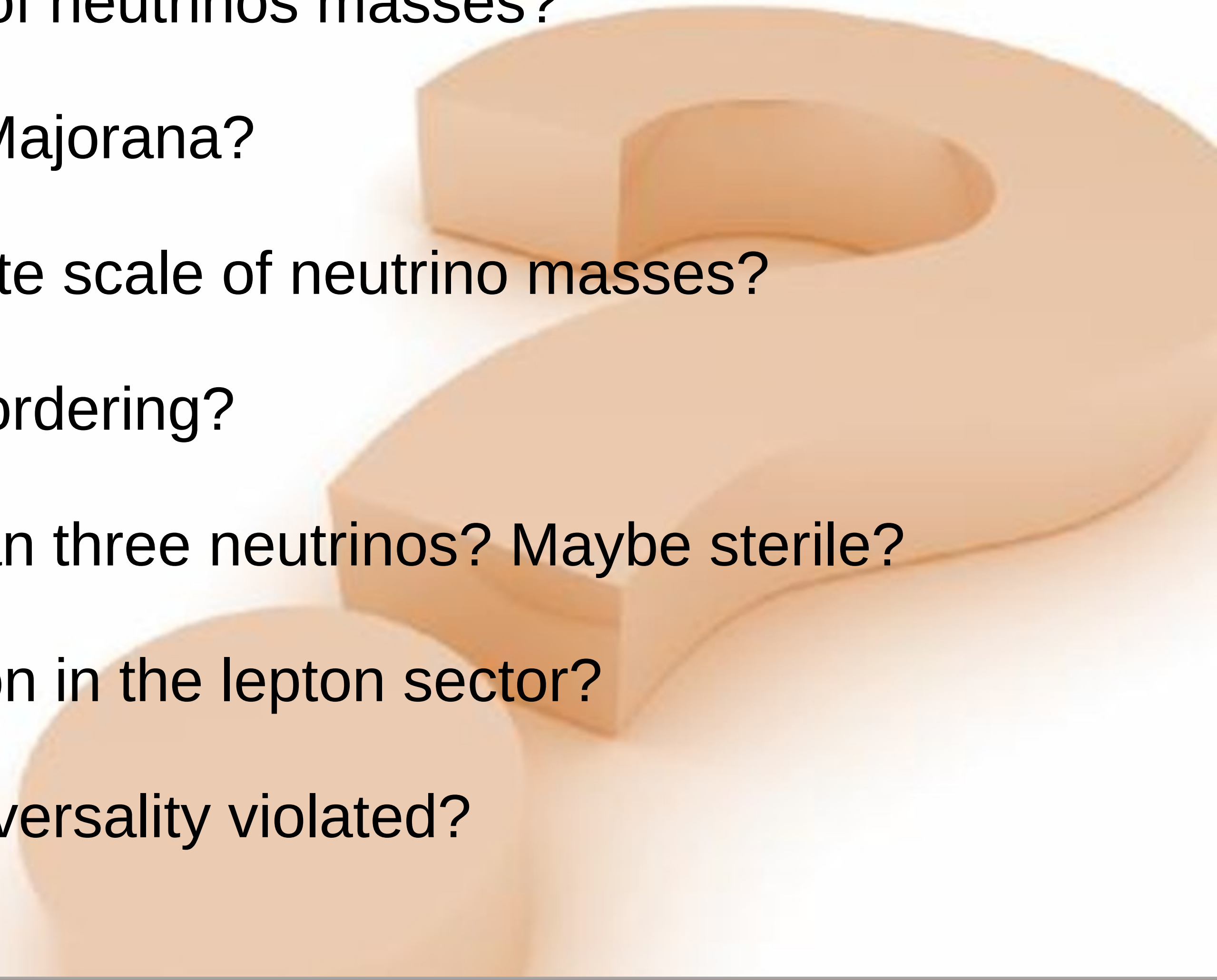
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

December 4th, 1930
Letter to his colleagues in Tübingen

1930
Pauli's neutrino hypothesis

Open questions



What is the origin of neutrinos masses?

Are they Dirac or Majorana?

What is the absolute scale of neutrino masses?

What is the mass ordering?

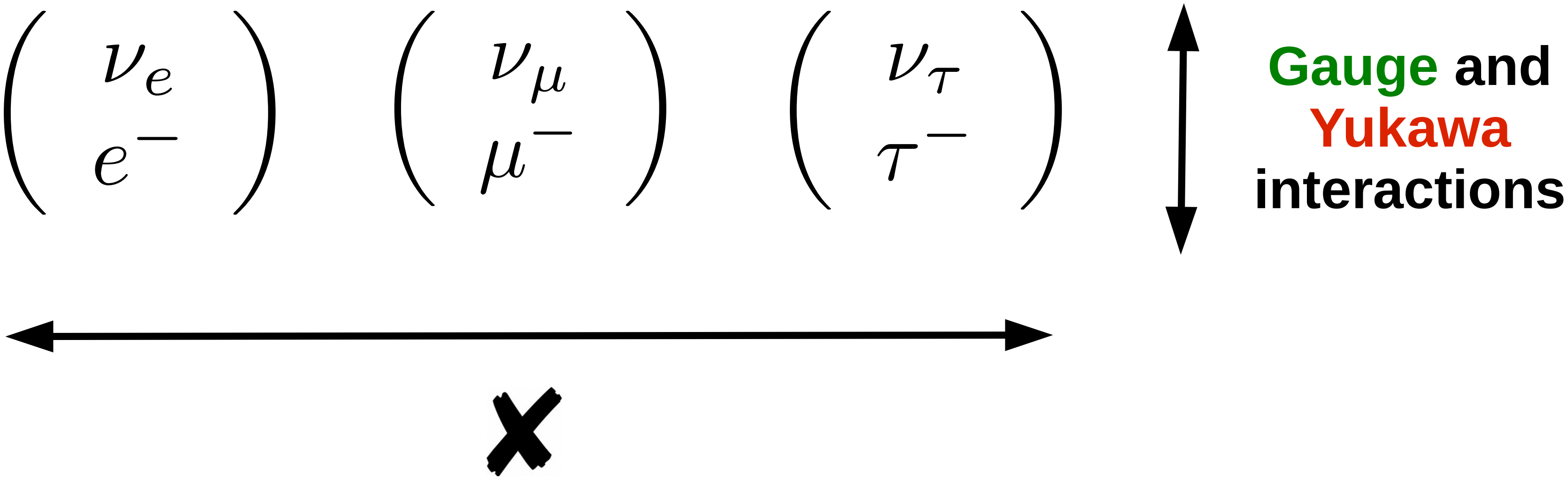
Are there more than three neutrinos? Maybe sterile?

Is there CP violation in the lepton sector?

Is lepton flavor universality violated?

Lepton flavor violation

In the **Standard Model**, three copies of the leptonic SU(2) doublet are introduced



$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Gauge and Yukawa interactions

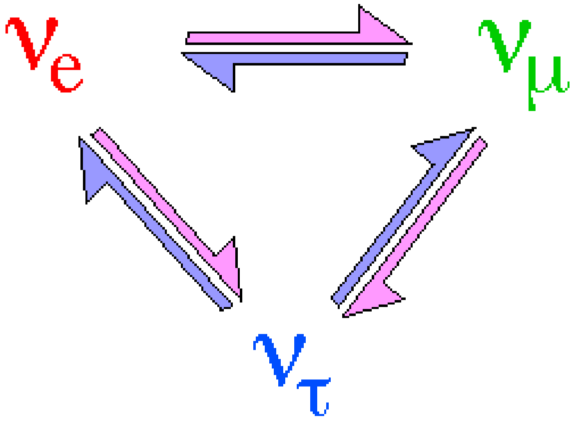
✗

Is lepton flavor a conserved quantity?

Neutrino oscillations: LFV

We already know the answer: NO

Neutrino flavor oscillations: flavor violating process!



Then... is this process a sign of BSM physics?

Yes it is!

What about CLFV?

In conclusion, lepton flavor is **not** conserved: there is **lepton flavor violation (LFV)**

However... what about **charged lepton flavor violation (CLFV)**?

$\mu^- \to e^- \gamma$

$\tau^- \to \mu^- \mu^+ \mu^-$

$K_L^0 \to \pi^0 e^- \mu^+$

$h \to \mu^- \tau^+$

$\pi^0 \to e^- \mu^+$

...

Never observed...

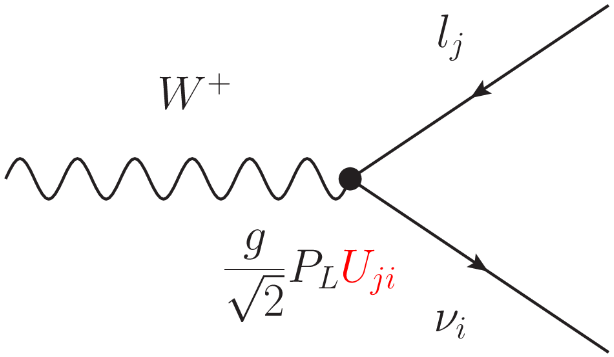
What about CLFV?

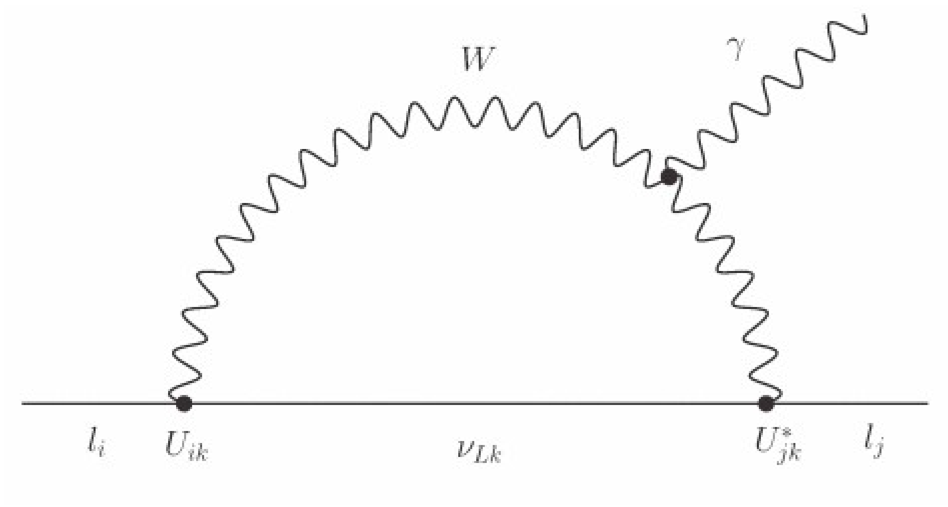
SM + Dirac neutrino masses

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} U_{ji} \bar{l}_j \gamma^\mu P_L \nu_i W_\mu^- + \text{c.c.}$$

U : lepton mixing matrix

[analog of the CKM matrix in the lepton sector]





$$\text{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_k U_{ek} U^*_{\mu k} \frac{m^2_{\nu k}}{m^2_W} \right|^2 \lesssim 10^{-54}$$

[Petcov, 1977]

Since neutrino masses are the only source of LFV, all cLFV amplitudes are strongly suppressed (in fact, GIM suppressed)

Why do we care about LFV?

The observation of CLFV would be a clear signal of (non-trivial) physics beyond the Standard Model

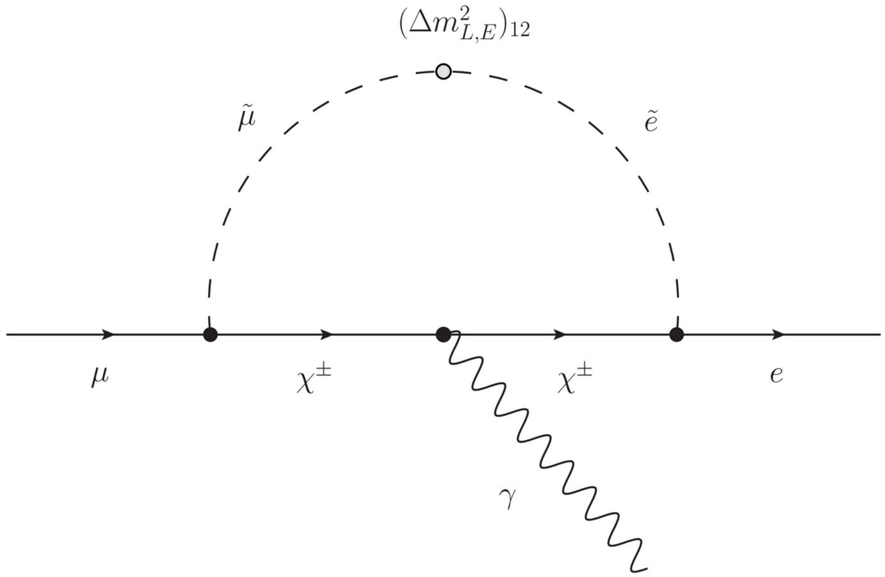
In fact, most BSM models predict large CLFV rates

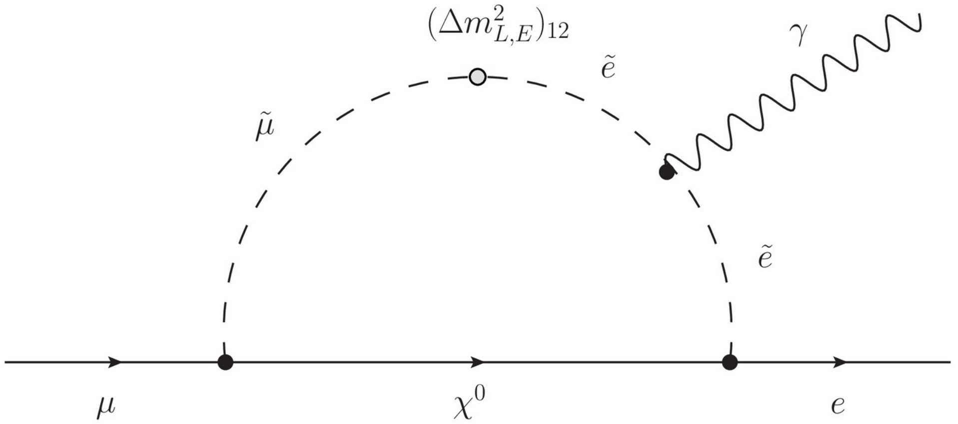
We can probe very high energy scales!

$$\mathcal{O} = \frac{c_{e\mu}}{\Lambda^2}\,\bar{\mu}e\bar{e}e \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{c_{e\mu}}} \gtrsim 100\,\text{TeV}$$

Why do we care about LFV?

Example 1: Supersymmetric models

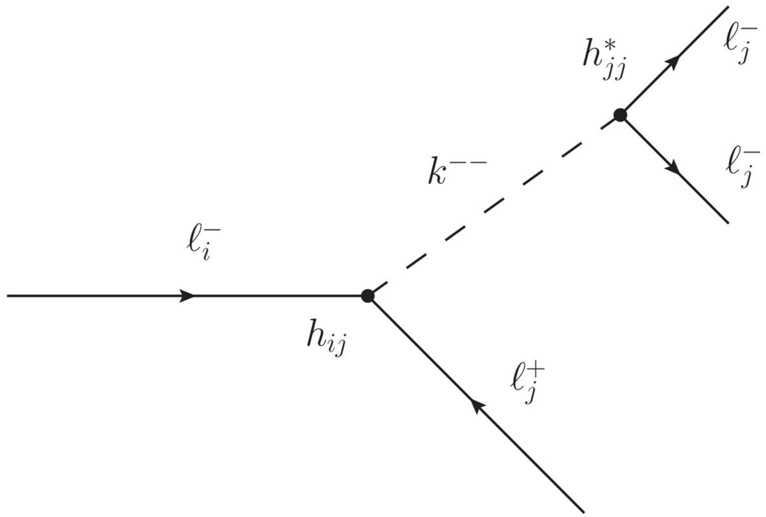




Sleptons: a whole new sector coupled to the SM leptons
Strong constraints on the off-diagonal soft terms

Why do we care about LFV?

Example 2: Babu-Zee model



$$\mathrm{BR} \sim \left| \frac{h_{ij} h_{jj}^*}{m_k^2} \right|^2$$

Small off-diagonal h couplings and/or heavy k's are required

Experimental projects

LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	4.2×10^{-13}	6×10^{-14} (MEG)
$\tau \to e\gamma$	3.3×10^{-8}	$\sim 10^{-8} - 10^{-9}$ (B factories)
$\tau \to \mu\gamma$	4.4×10^{-8}	$\sim 10^{-8} - 10^{-9}$ (B factories)
$\mu \to 3e$	1.0×10^{-12}	$\sim 10^{-16}$ (Mu3e)
$\tau \to 3e$	2.7×10^{-8}	$\sim 10^{-9} - 10^{-10}$ (B factories)
$\tau \to 3\mu$	2.1×10^{-8}	$\sim 10^{-9} - 10^{-10}$ (B factories)
μ^-, Au $\to e^-$, Au	7.0×10^{-13}	—
μ^-, SiC $\to e^-$, SiC	—	2×10^{-14} (DeeMe)
μ^-, Al $\to e^-$, Al	—	$10^{-15} - 10^{-17}$ (COMET) $10^{-17} - 10^{-18}$ (Mu2e)
μ^-, Ti $\to e^-$, Ti	4.3×10^{-12}	$\sim 10^{-18}$ (PRISM/PRIME)

Experimental projects

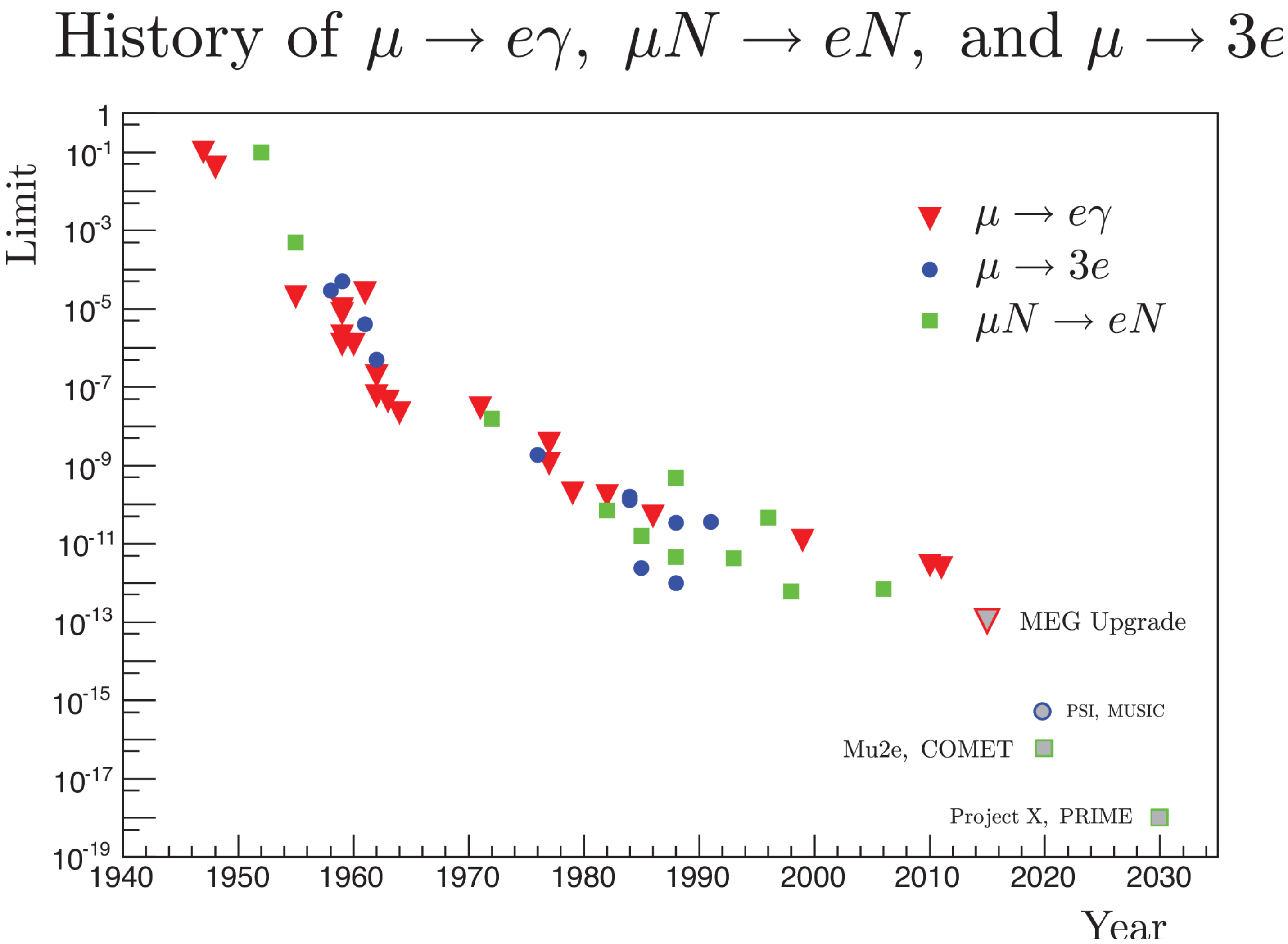
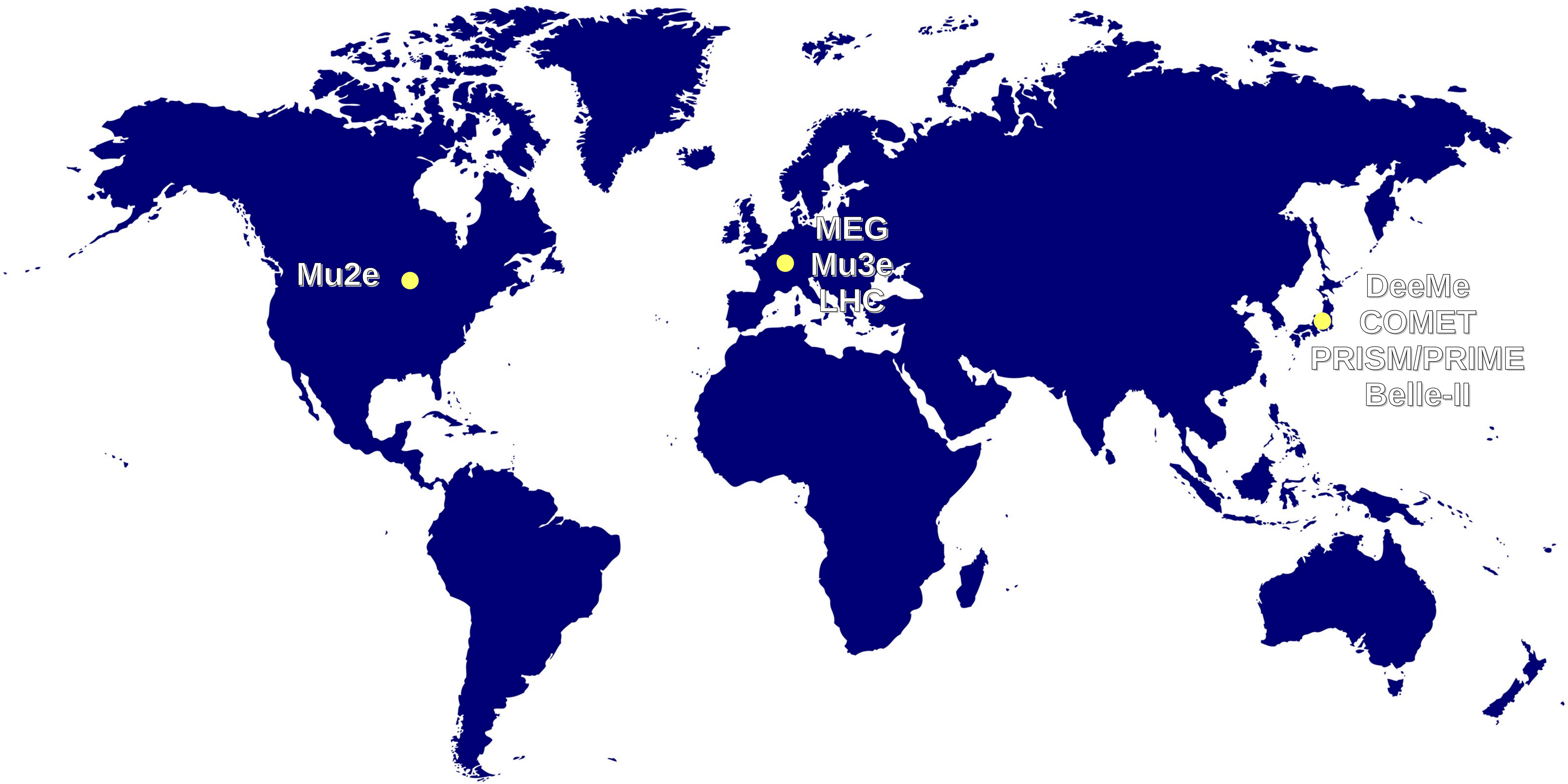


Figure taken from Bernstein & Cooper [arXiv:1307.5787]

Experimental projects



LFV : Where to look for?

$\ell_i \to \ell_j \gamma$

$\ell_i \to 3\,\ell_j$

$\ell_i \to \ell_j \ell_k \ell_k$

$\mu - e$

conversion in nuclei

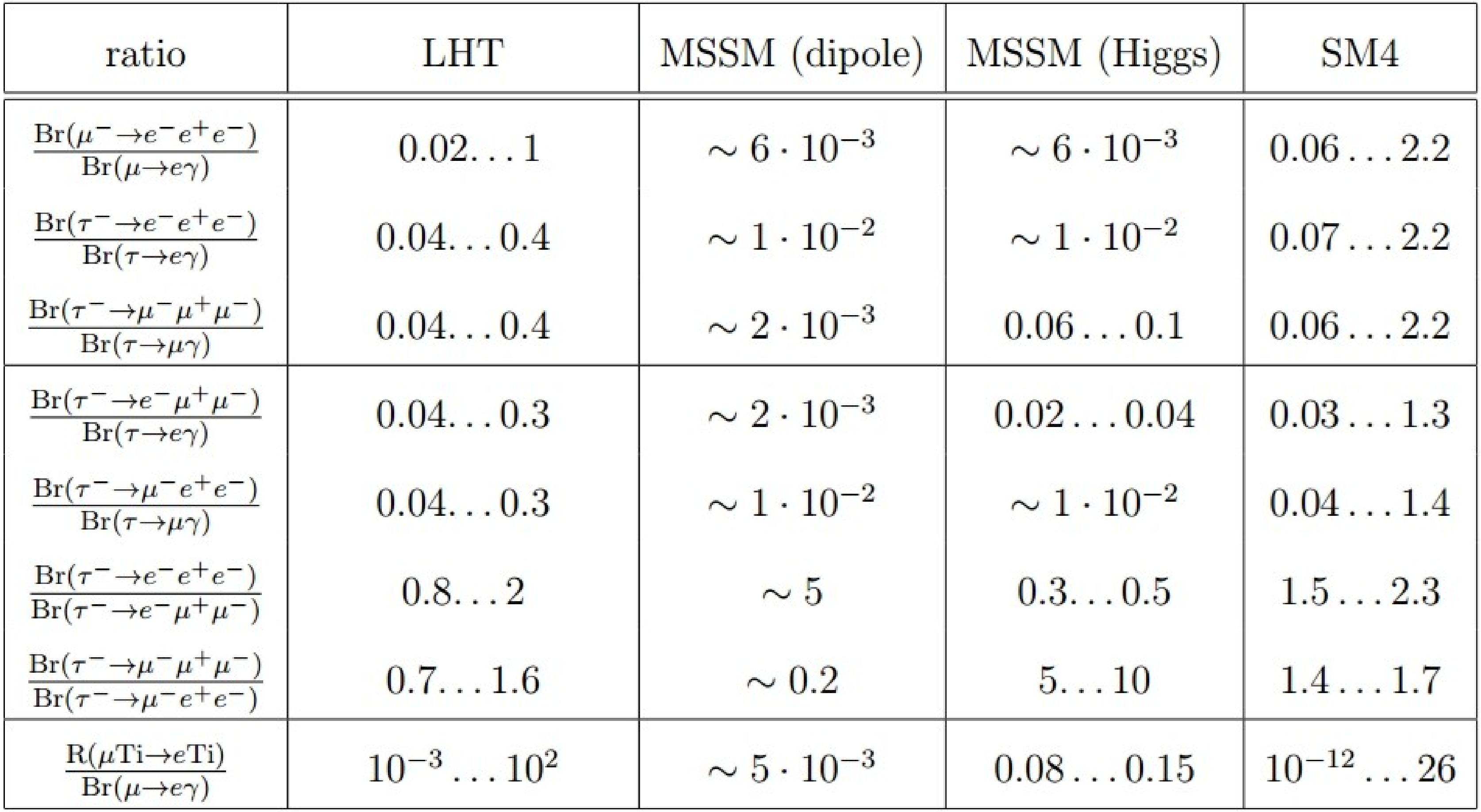
BSM

LFV at colliders

$M \to \ell_i \ell_j$

LFV : Where to look for?

Everywhere!



ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\text{Br}(\mu^-\to e^-e^+e^-)}{\text{Br}(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{\text{Br}(\tau^-\to e^-e^+e^-)}{\text{Br}(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{\text{Br}(\tau^-\to \mu^-\mu^+\mu^-)}{\text{Br}(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$	$0.06\ldots2.2$
$\frac{\text{Br}(\tau^-\to e^-\mu^+\mu^-)}{\text{Br}(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$	$0.03\ldots1.3$
$\frac{\text{Br}(\tau^-\to \mu^-e^+e^-)}{\text{Br}(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{\text{Br}(\tau^-\to e^-e^+e^-)}{\text{Br}(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2$	~ 5	$0.3\ldots0.5$	$1.5\ldots2.3$
$\frac{\text{Br}(\tau^-\to \mu^-\mu^+\mu^-)}{\text{Br}(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$	$1.4\ldots1.7$
$\frac{\text{R}(\mu\text{Ti}\to e\text{Ti})}{\text{Br}(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

Table taken from Buras et al [arXiv:1006.5356]

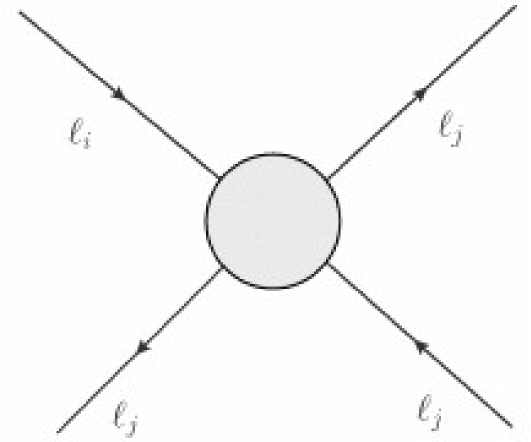
$\ell_i \to 3\,\ell_j$ vs $\ell_i \to \ell_j\gamma$

What contribution dominates $\ell_i \to 3\,\ell_j$?

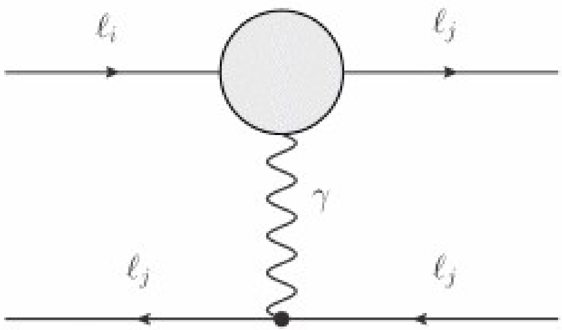
In many models of interest: Photonic dipole contributions

Most popular example: MSSM

[Hisano et al 1996; Arganda, Herrero 2006]



$\simeq$



Dipole dominance

$$\frac{BR(\ell_i \to 3\,\ell_j)}{BR(\ell_i \to \ell_j\gamma)} = \frac{\alpha}{3\pi}\left(\log\frac{m_{\ell_i}^2}{m_{\ell_j}^2} - \frac{11}{4}\right) \Rightarrow \quad BR(\ell_i \to \ell_j\gamma) \gg BR(\ell_i \to 3\,\ell_j)$$

The LFV program

In order to unravel the physics behind LFV (and perhaps neutrino masses!) we must:

- Search for LFV in as many observables as possible: they might have information about different sectors of the theory
- Study the relations among different observables (ratios, correlations, hierarchies...)
- Understand the origin of such relations: what is the underlying physics?

Outline of the talk

- Introduction: Lepton Flavor Violation **FINISHED!**
- Selected topics
  - 3-loop neutrino mass models and CLFV
  - Ultralight scalars and CLFV
- Final remarks

Chuck Norris fact of the day

Chuck Norris counted to infinity. Twice.

3-loop ν mass models and CLFV

With Ricardo Cepedello, Martin Hirsch and Paulina Rocha-Morán

JHEP 08 (2020) 067 [arXiv:2005.00015]

3-loop neutrino mass models

3-loop Majorana neutrino mass models
can actually be very simple

Minimal models

KNT model: Krauss, Nasri & Trodden, 2002

AKS model: Aoki, Kanemura & Seto, 2008

Cocktail model: Gustafsson, No & Rivera, 2012

[Full classification in Cepedello et al, 2018]

3-loop neutrino mass models

3-loop Majorana neutrino mass models
can actually be very simple

Minimal models

KNT model: Krauss, Nasri & Trodden, 2002

AKS model: Aoki, Kanemura & Seto, 2008 ◄—

Cocktail model: Gustafsson, No & Rivera, 2012

Focus on AKS...

... but similar (qualitative) conclusions hold for the other two

[Full classification in Cepedello et al, 2018]

The AKS model

[Aoki, Kanemura, Seto, 2008]

	gen	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
Φ	1	$\mathbf{2}$	$1/2$	$+$
φ	1	$\mathbf{1}$	0	$-$
S	1	$\mathbf{1}$	1	$-$
N	3	$\mathbf{1}$	0	$-$

← 2nd Higgs doublet

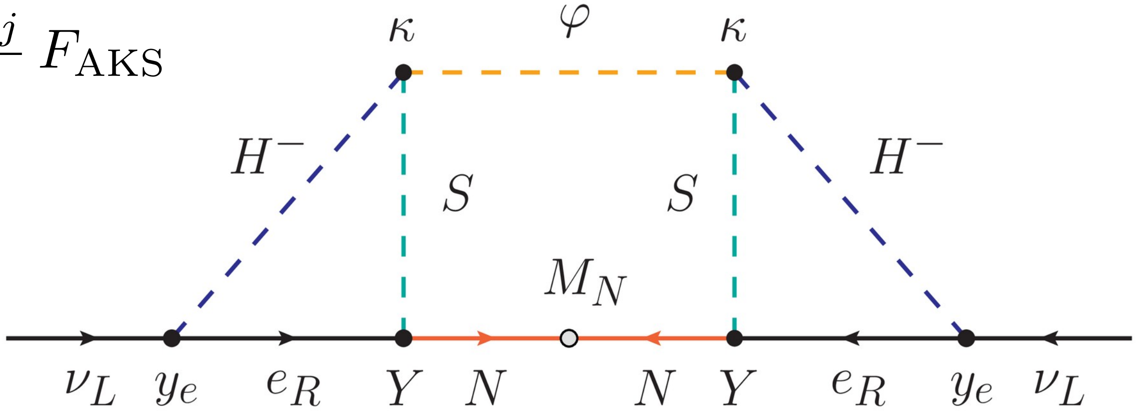
← real

Conserved $\mathbb{Z}_2$ parity

Dark Matter!

$$-\mathcal{L} \supset Y\, \overline{e_R^c}\, N S^* + \frac{1}{2} M_N \overline{N^c} N + \kappa\, \phi\, \Phi S^* \varphi + \text{h.c.}$$

$$(m_\nu)_{ij} = C_{\text{AKS}} \frac{\kappa^2}{(16\pi^2)^3} \frac{m_i\, Y_{i\alpha}\, Y_{j\beta}\, m_j}{(M_N)_{\alpha\beta}} F_{\text{AKS}}$$



(+ diagram with crossed S lines)

Y : parametrized *à la* Casas-Ibarra

Master parametrization

[Cordero-Carrión, Hirsch, AV, 2018, 2019]

Neutrino mass in the AKS model

$$(m_\nu)_{ij} = C_{\rm AKS} \, \frac{\kappa^2}{(16\pi^2)^3} \, \frac{m_i \, Y_{i\alpha} \, Y_{j\beta} \, m_j}{(M_N)_{\alpha\beta}} \, F_{\rm AKS}$$

[Casas, Ibarra, 2001]

$$Y = \frac{i\,(16\pi^2)^{3/2}}{\kappa \, \tan\beta} \, \mathcal{R} \, \sqrt{M_N/F_{\rm AKS}} \, \sqrt{\widehat{\mathcal{M}}_\nu} \, U^\dagger \, \widehat{\mathcal{M}}_e^{-1}$$

Neutrino mass in the AKS model

$$(m_\nu)_{ij} = C_{\text{AKS}} \, \frac{\kappa^2}{(16\pi^2)^3} \, \frac{m_i \, Y_{i\alpha} \, Y_{j\beta} \, m_j}{(M_N)_{\alpha\beta}} \, F_{\text{AKS}}$$

[Casas, Ibarra, 2001]

$$Y = \frac{i \, (16\pi^2)^{3/2}}{\kappa \, \tan\beta} \, \mathcal{R} \, \sqrt{M_N / F_{\text{AKS}}} \, \sqrt{\widehat{\mathcal{M}}_\nu} \, U^\dagger \, \widehat{\mathcal{M}}_e^{-1}$$

Fit to oscillation data

Simple estimate

$$\xrightarrow{\qquad\qquad}$$

$$R = \mathbb{I}$$

$m_\nu \sim 0.1$ eV

$$Y \sim \begin{array}{c} \begin{array}{ccc} 1/m_e & 1/m_\mu & 1/m_\tau \\ \uparrow & \uparrow & \uparrow \end{array} \\ \begin{pmatrix} 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \end{pmatrix} \end{array}$$

Neutrino mass in the AKS model

$$(m_\nu)_{ij} = C_{\text{AKS}} \, \frac{\kappa^2}{(16\pi^2)^3} \, \frac{m_i \, Y_{i\alpha} \, Y_{j\beta} \, m_j}{(M_N)_{\alpha\beta}} \, F_{\text{AKS}}$$

[Casas, Ibarra, 2001]

$$\boxed{Y = \frac{i \, (16\pi^2)^{3/2}}{\kappa \, \tan\beta} \, \mathcal{R} \, \sqrt{M_N / F_{\text{AKS}}} \, \sqrt{\widehat{\mathcal{M}}_\nu} \, U^\dagger \, \widehat{\mathcal{M}}_e^{-1}}$$

Fit to oscillation data

Simple estimate

$$\xrightarrow{\qquad\qquad}$$

$$R = \mathbb{I}$$

$$m_\nu \sim 0.1 \text{ eV}$$

$$Y \sim \begin{array}{c} \begin{array}{ccc} 1/m_e & 1/m_\mu & 1/m_\tau \\ \uparrow & \uparrow & \uparrow \end{array} \\ \begin{pmatrix} 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \\ 100 & 1 & 0.1 \end{pmatrix} \end{array}$$

LFV constraints

Perturbativity

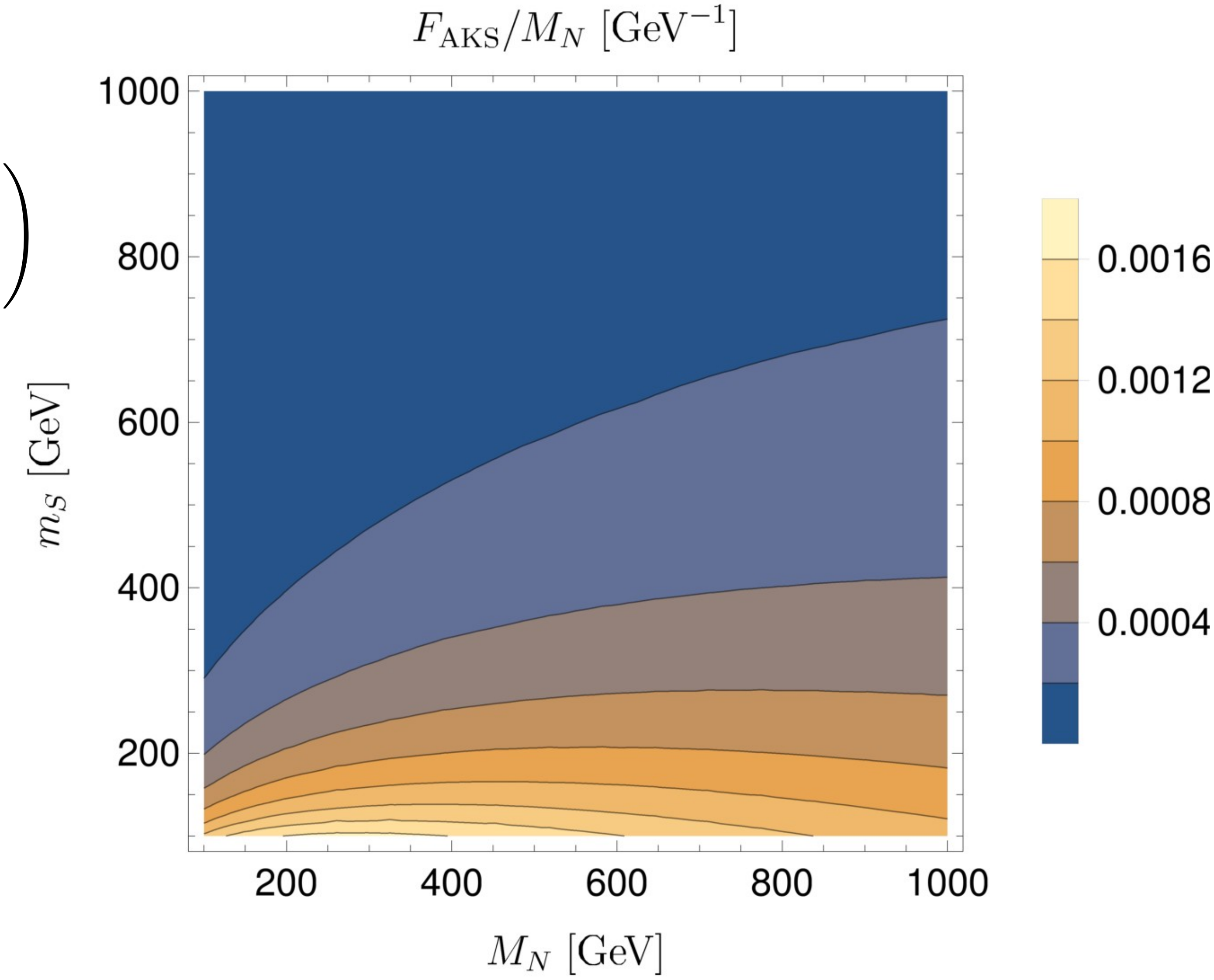
AKS loop function

Loop function

$$F_{\text{AKS}}\left(\frac{M_S^2}{M_N^2},\frac{M_\varphi^2}{M_N^2},\frac{M_{H^\pm}^2}{M_N^2}\right)$$

Common scalar mass

$$M_S = M_\varphi = M_{H^\pm} \equiv m_S$$



AKS loop function

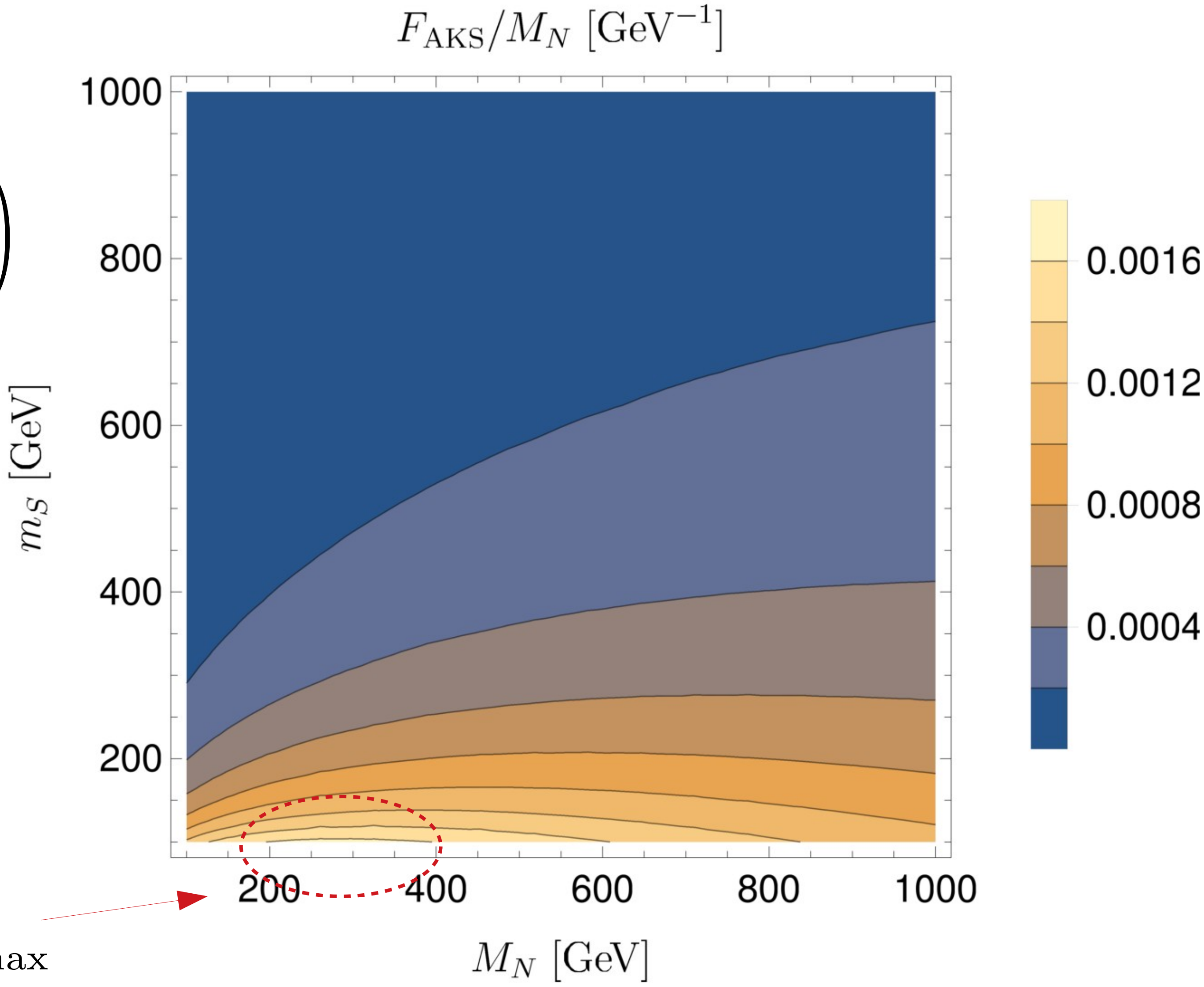
Loop function

$$F_{\mathrm{AKS}}\left(\frac{M_S^2}{M_N^2}, \frac{M_\varphi^2}{M_N^2}, \frac{M_{H^\pm}^2}{M_N^2}\right)$$

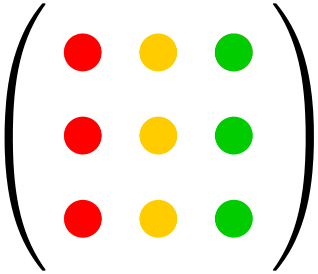
Common scalar mass

$$M_S = M_\varphi = M_{H^\pm} \equiv m_S$$

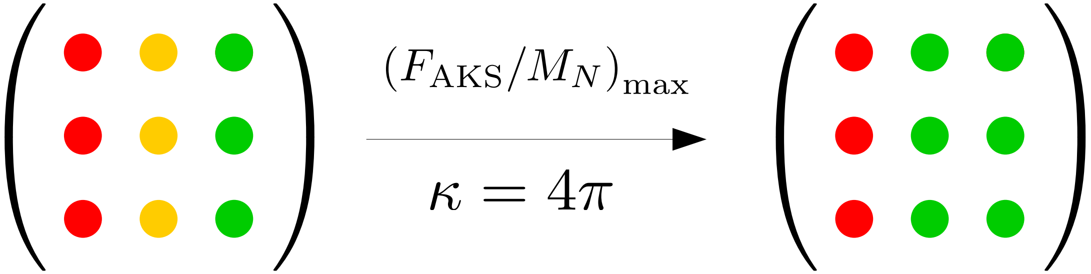
$$(F_{\mathrm{AKS}}/M_N)_{\mathrm{max}}$$



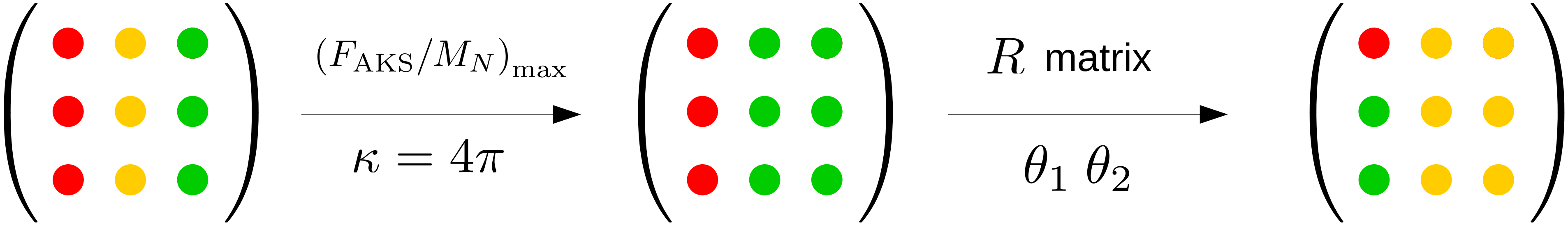
Fine-tuning Y in the AKS model



Fine-tuning Y in the AKS model



Fine-tuning Y in the AKS model



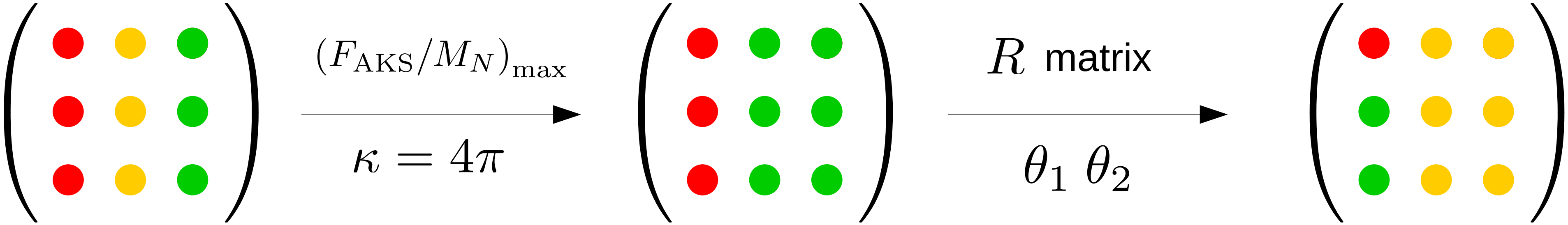
$$Y = \frac{i\,(16\pi^2)^{3/2}}{\kappa\;\tan\beta}\,\mathcal{R}\,\sqrt{M_N/F_{\rm AKS}}\,\sqrt{\widehat{\mathcal{M}}_\nu}\,U^\dagger\,\widehat{\mathcal{M}}_e^{-1}$$

$$R = R(\theta_1, \theta_2, \theta_3)$$

θ_i : complex angles

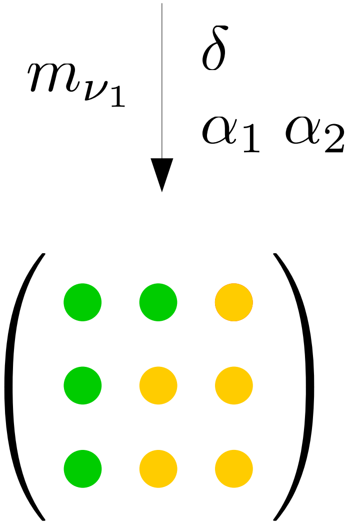
$$\theta_1 \;\; \theta_2 \quad \Rightarrow \quad Y_{21,31} \to 0$$

Fine-tuning Y in the AKS model

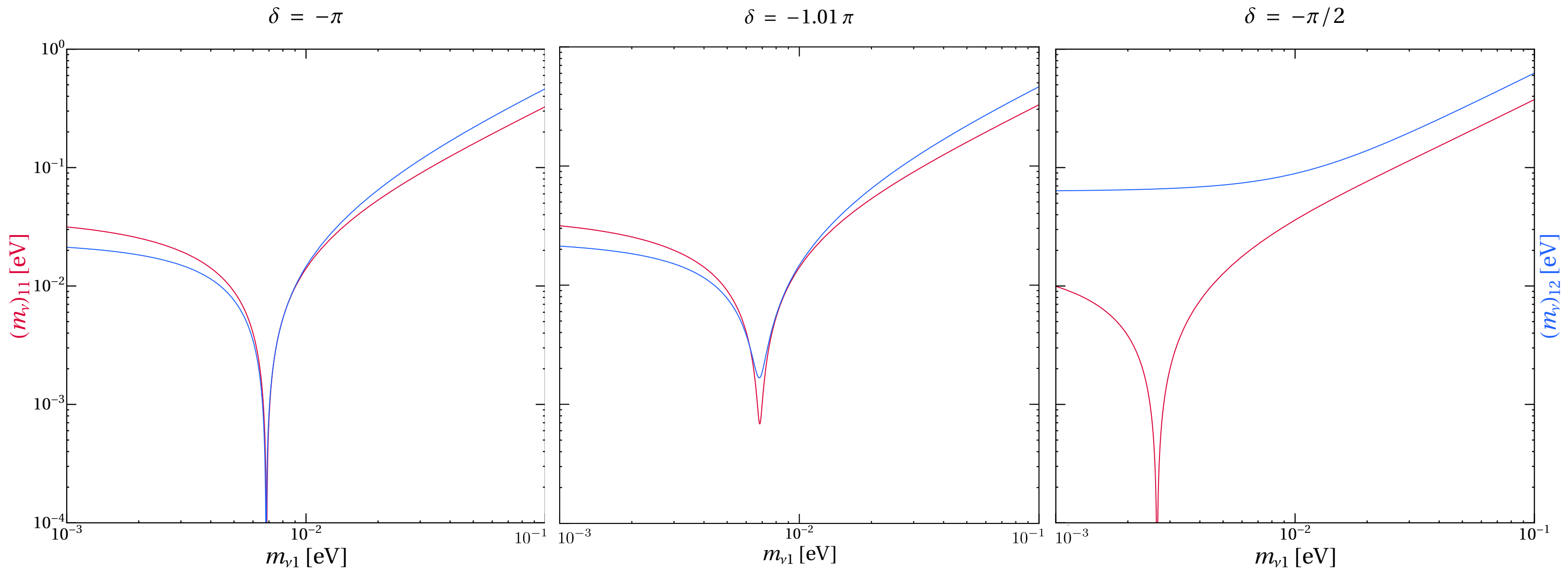


$\xrightarrow[\kappa = 4\pi]{(F_{\text{AKS}}/M_N)_{\text{max}}}$

R matrix $\xrightarrow[\theta_1\ \theta_2]{}$



m_{ν_1} $\downarrow$ δ $\alpha_1\ \alpha_2$



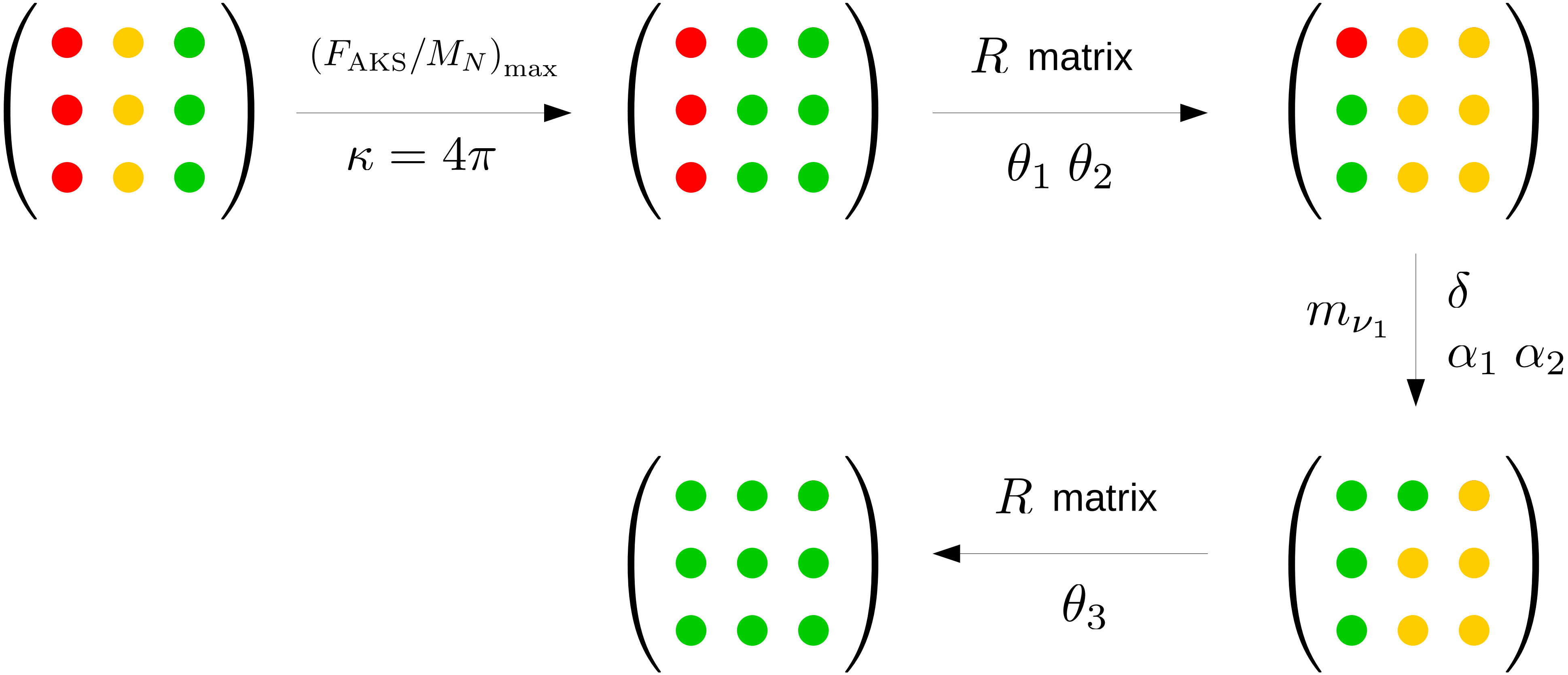
2σ tension with fits

[De Salas et al, 2020]

Fine-tuned

Partially working for $\delta = -\frac{\pi}{2}$

Fine-tuning Y in the AKS model



$(F_{\text{AKS}}/M_N)_{\text{max}}$

$\kappa = 4\pi$

R matrix

$\theta_1 \ \theta_2$

m_{ν_1}

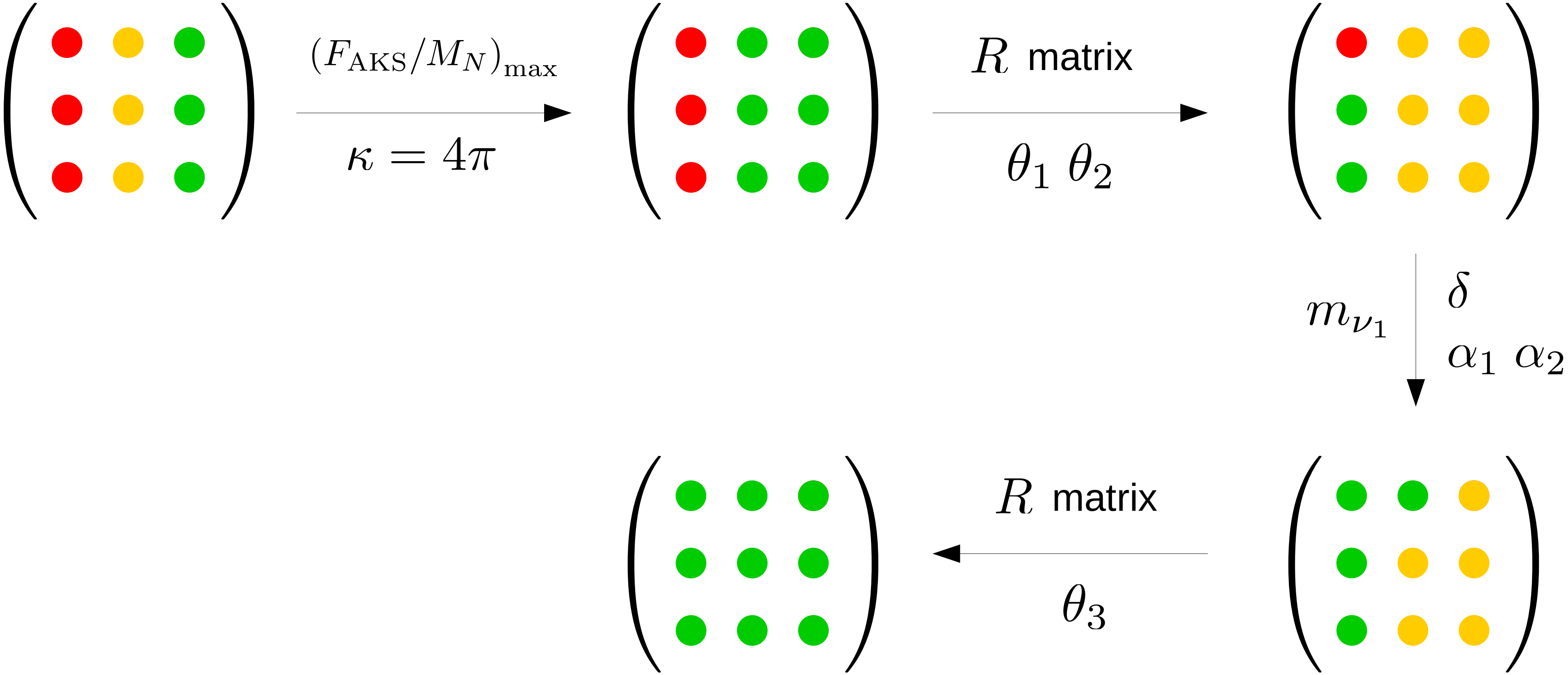
δ

$\alpha_1 \ \alpha_2$

R matrix

θ_3

Fine-tuning Y in the AKS model



$(F_{\text{AKS}}/M_N)_{\text{max}}$

$\kappa = 4\pi$

R matrix

$\theta_1 \; \theta_2$

m_{ν_1}

δ

$\alpha_1 \; \alpha_2$

R matrix

θ_3

Perturbativity + flavor = (fine-tuning)$^{\mathbf{4}}$

\+
largish LFV
effects

Ultralight scalars and CLFV

With Pablo Escribano

JHEP 03 (2021) 240 [arXiv:2008.01099]

Ultralight scalars

ϕ : ultralight scalar that couples to charged leptons

$m_\phi \ll m_e$

($m_\phi = 0$ included)

Motivation: axion, axion-like particles, majoron, familon, Goldstone bosons...

Ultralight scalars

ϕ : ultralight scalar that couples to charged leptons

$$m_\phi \ll m_e$$

($m_\phi = 0$ included)

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\ell\ell\phi} + \mathcal{L}_{\ell\ell\gamma} + \mathcal{L}_{4\ell}$$

Ultralight scalars

ϕ : ultralight scalar that couples to charged leptons

$$m_\phi \ll m_e$$

($m_\phi = 0$ included)

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\ell\ell\phi} + \mathcal{L}_{\ell\ell\gamma} + \mathcal{L}_{4\ell}$$

$$\mathcal{L}_{\ell\ell\phi} = \phi \, \overline{\ell}_\beta \left(S_L^{\beta\alpha} P_L + S_R^{\beta\alpha} P_R \right) \ell_\alpha + \text{h.c.}$$

Ultralight scalars

ϕ : ultralight scalar that couples to charged leptons

$m_\phi \ll m_e$

($m_\phi = 0$ included)

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\ell\ell\phi} + \mathcal{L}_{\ell\ell\gamma} + \mathcal{L}_{4\ell}$$

$$\mathcal{L}_{\ell\ell\phi} = \phi\,\bar{\ell}_\beta \left(S_L^{\beta\alpha} P_L + S_R^{\beta\alpha} P_R \right) \ell_\alpha + \text{h.c.}$$

General dimensionless complex coefficients

Particular cases:

- Real $S_{L,R}$ ⟶ Pure scalar
- Imaginary $S_{L,R}$ ⟶ Pure pseudoscalar ⟶ Axion, ALPs, majoron...

Talk by Robert Ziegler

Ultralight scalars

ϕ : ultralight scalar that couples to charged leptons

$$m_\phi \ll m_e$$

($m_\phi = 0$ included)

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\ell\ell\phi} + \mathcal{L}_{\ell\ell\gamma} + \mathcal{L}_{4\ell}$$

$$\mathcal{L}_{\ell\ell\phi} = \phi\,\bar{\ell}_\beta \left(S_L^{\beta\alpha} P_L + S_R^{\beta\alpha} P_R \right) \ell_\alpha + \text{h.c.}$$

$$\mathcal{L}_{\ell\ell\gamma} = \frac{e\, m_\alpha}{2}\, \bar{\ell}_\beta\, \sigma^{\mu\nu} \left[\left(K_2^L\right)^{\beta\alpha} P_L + \left(K_2^R\right)^{\beta\alpha} P_R \right] \ell_\alpha F_{\mu\nu} + \text{h.c.}$$

$$\mathcal{L}_{4\ell} = \sum_{\substack{I=S,V,T \\ X,Y=L,R}} \left(A_{XY}^I\right)^{\beta\alpha\delta\gamma}\, \bar{\ell}_\beta \Gamma_I P_X \ell_\alpha\, \bar{\ell}_\delta \Gamma_I P_Y \ell_\gamma + \text{h.c.}$$

Leptonic observables

ϕ : ultralight scalar that couples to charged leptons

$$m_\phi \ll m_e$$

($m_\phi = 0$ included)

Produced in the final state

- $\ell_\alpha \to \ell_\beta \, \phi$
- $\ell_\alpha \to \ell_\beta \, \phi \, \gamma$

Virtual particle

- $\ell_\alpha \to \ell_\beta \, \gamma$
- $\ell_\alpha^- \to \ell_\beta^- \, \ell_\beta^- \, \ell_\beta^+$
- $\ell_\alpha^- \to \ell_\beta^- \, \ell_\gamma^- \, \ell_\gamma^+$
- $\ell_\alpha^- \to \ell_\beta^+ \, \ell_\gamma^- \, \ell_\gamma^+$
- Lepton dipole moments (AMMs & EDMs)

[Escribano, AV, 2020]

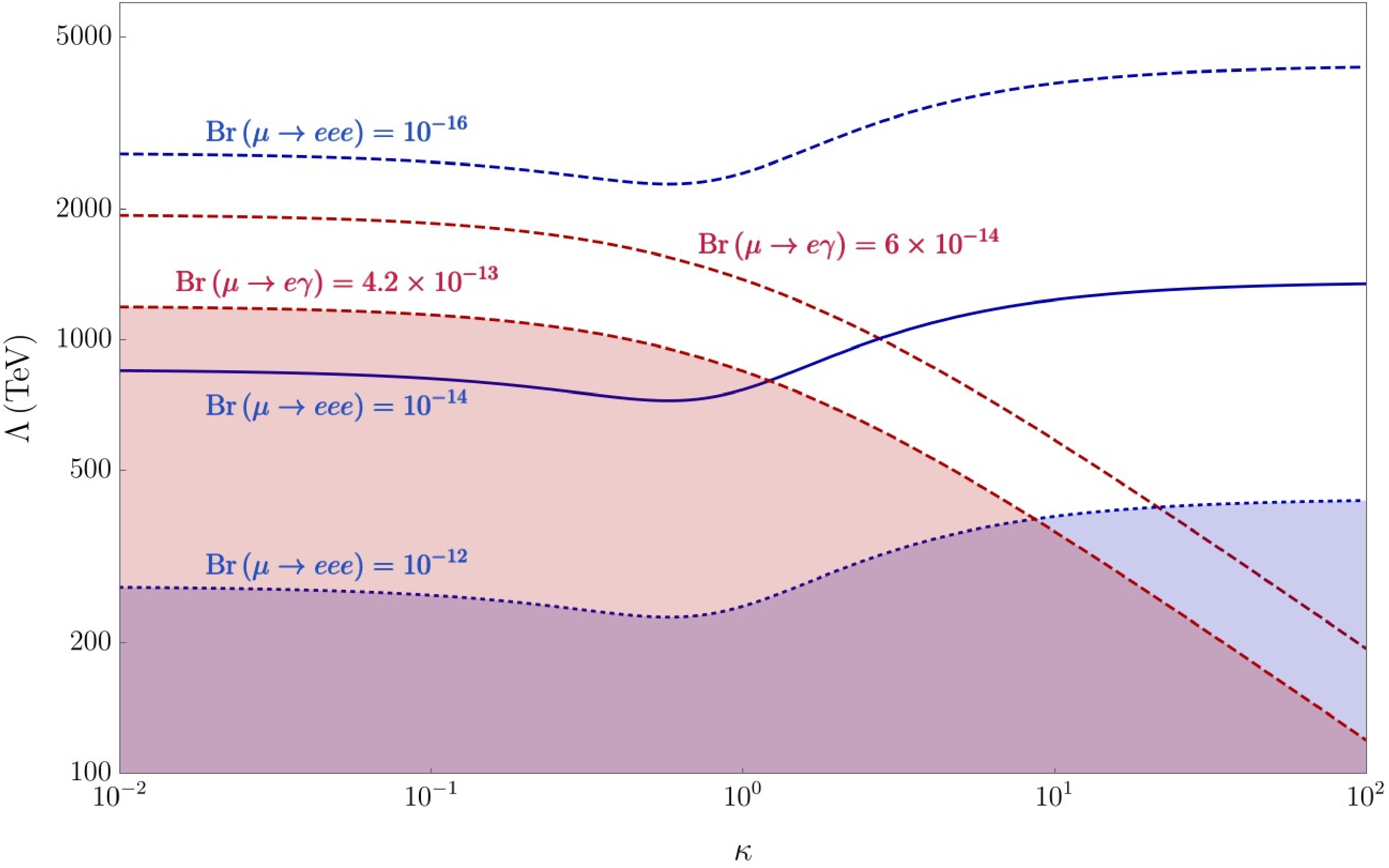
Leptonic observables

NEW!

Infrared divergence

$$
\begin{aligned}
&\Gamma_\phi\left(\ell_\alpha^- \to \ell_\beta^- \ell_\beta^- \ell_\beta^+\right) = \\
&\frac{m_\alpha}{512\pi^3}\Bigg\{\left(\left|S_L^{\beta\alpha}\right|^2 + \left|S_R^{\beta\alpha}\right|^2\right)\left\{\left|S^{\beta\beta}\right|^2\left(4\log\frac{m_\alpha}{m_\beta} - \frac{49}{6}\right) - \frac{2}{6}\left[\left(S^{\beta\beta*}\right)^2 + \left(S^{\beta\beta}\right)^2\right]\right\} \\
&- \frac{m_\alpha^2}{6}\Bigg\{S_L^{\beta\alpha} S^{\beta\beta} A_{LL}^{S*} + 2S_L^{\beta\alpha} S^{\beta\beta*} A_{LR}^{S*} + 2S_R^{\beta\alpha} S^{\beta\beta} A_{RL}^{S*} + S_R^{\beta\alpha} S^{\beta\beta*} A_{RR}^{S*} \\
&- 12\left(S_L^{\beta\alpha} S^{\beta\beta} A_{LL}^{T*} + S_R^{\beta\alpha} S^{\beta\beta*} A_{RR}^{T*}\right) - 4\left(S_R^{\beta\alpha} S^{\beta\beta} A_{RL}^{V*} + S_L^{\beta\alpha} S^{\beta\beta*} A_{LR}^{V*}\right) \\
&+ 6e^2\left[S_R^{\beta\alpha} S^{\beta\beta}\left(K_2^L\right)^{\beta\alpha*} + S_L^{\beta\alpha} S^{\beta\beta*}\left(K_2^R\right)^{\beta\alpha*}\right] + \Bigg\}\Bigg\}
\end{aligned}
$$

$$
S^{\beta\beta} = S_L^{\beta\beta} + S_R^{\beta\beta*}
$$



$$e\,\left(K_2^L\right)^{\beta\alpha} \equiv \frac{1}{(\kappa+1)\,\Lambda^2} \qquad S_L^{\beta\alpha} \equiv m_\alpha\,\frac{\kappa}{(\kappa+1)\,\Lambda}$$

Final remarks

Final remarks

LFV is going to live a golden age

Many LFV observables. Correlations are not only possible, but in fact expected!

We must be ready: understand the LFV anatomy, patterns, correlations, hierarchies...

Thank you!

谢谢！

Backup slides

The KNT model

[Krauss, Nasri, Trodden, 2002]

	gen	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
h	1	$\mathbf{1}$	1	$+$
S	1	$\mathbf{1}$	1	$-$
N	3	$\mathbf{1}$	0	$-$

Singly charged scalars

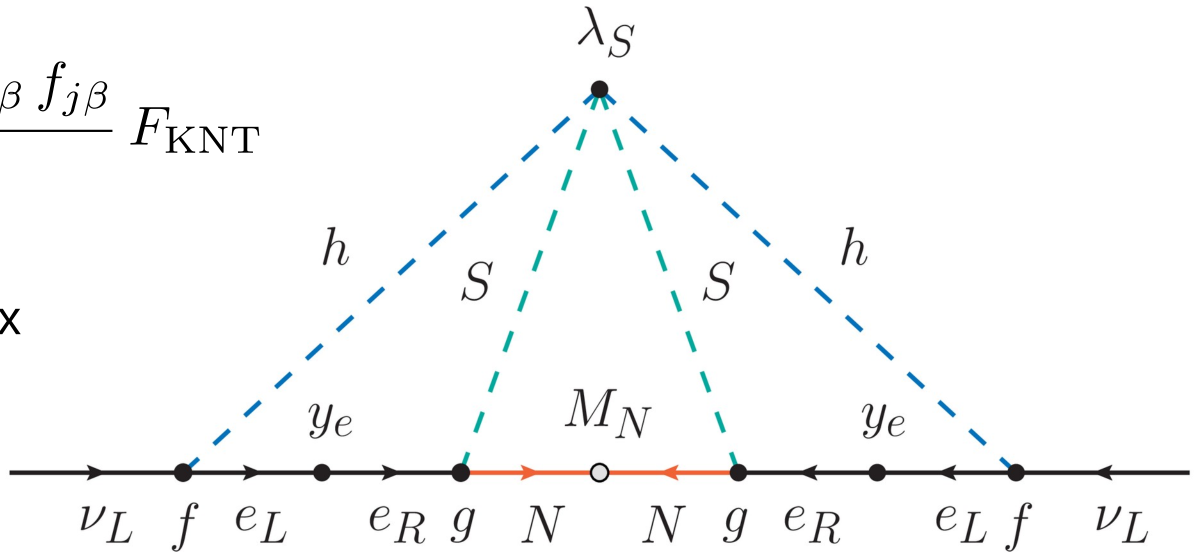
Conserved $\mathbb{Z}_2$ parity

Dark Matter!

$$-\mathcal{L} \supset f\,\overline{\ell^c}\,\ell\,h + g\,\overline{N^c}\,e_R\,S + \frac{1}{2}M_N\overline{N^c}N + \lambda_S\,(hS^*)^2 + \text{h.c.}$$

$$(m_\nu)_{ij} = \frac{\lambda_S}{(16\pi^2)^3}\,\frac{f_{i\alpha}\,m_\alpha\,g^*_\alpha\,g^*_\beta\,m_\beta\,f_{j\beta}}{(M_N)_{\alpha\beta}}\,F_{\text{KNT}}$$

f : antisymmetric Yukawa matrix



The Cocktail model

[Gustafsson, No, Rivera, 2012]

	gen	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathbb{Z}_2$
S	1	$\mathbf{1}$	1	$-$
ρ	1	$\mathbf{1}$	2	$+$
η	1	$\mathbf{2}$	$1/2$	$-$

Inert doublet

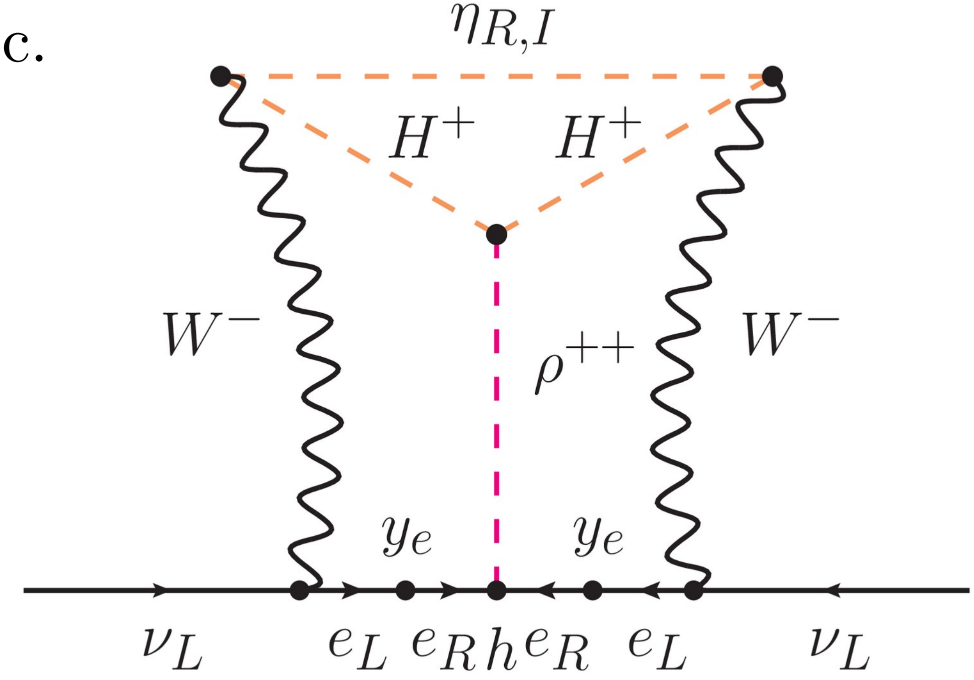
Conserved $\mathbb{Z}_2$ parity

Dark Matter!

$$-\mathcal{L} \supset h\, \overline{e^c_R} e_R\, \rho + \frac{1}{2}\, \lambda_5\, (\phi \eta^*)^2 + \text{h.c.}$$

$$(m_\nu)_{ij} = \frac{\lambda_5}{(16\pi^2)^3} \frac{m_i\, h_{ij}\, m_j}{v}\, F_{\text{Cocktail}}$$

h : symmetric Yukawa matrix
(type-II seesaw-like)



FlavorKit

[Porod, Staub, AV, 2014]

A computer tool that provides automatized analytical and numerical computation of flavor observables. It is based on SARAH, SPheno and FeynArts/FormCalc.

Lepton flavor	**Quark flavor**
$\ell_\alpha \to \ell_\beta \gamma$	$B^0_{s,d} \to \ell^+ \ell^-$
$\ell_\alpha \to 3\,\ell_\beta$	$\bar{B} \to X_s \gamma$
$\mu - e$ conversion in nuclei	$\bar{B} \to X_s \ell^+ \ell^-$
$\tau \to P\,\ell$	$\bar{B} \to X_{d,s} \nu \bar{\nu}$
$h \to \ell_\alpha \ell_\beta$	$B \to K \ell^+ \ell^-$
$Z \to \ell_\alpha \ell_\beta$	$K \to \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	ΔM_K and ε_K
	$P \to \ell \nu$

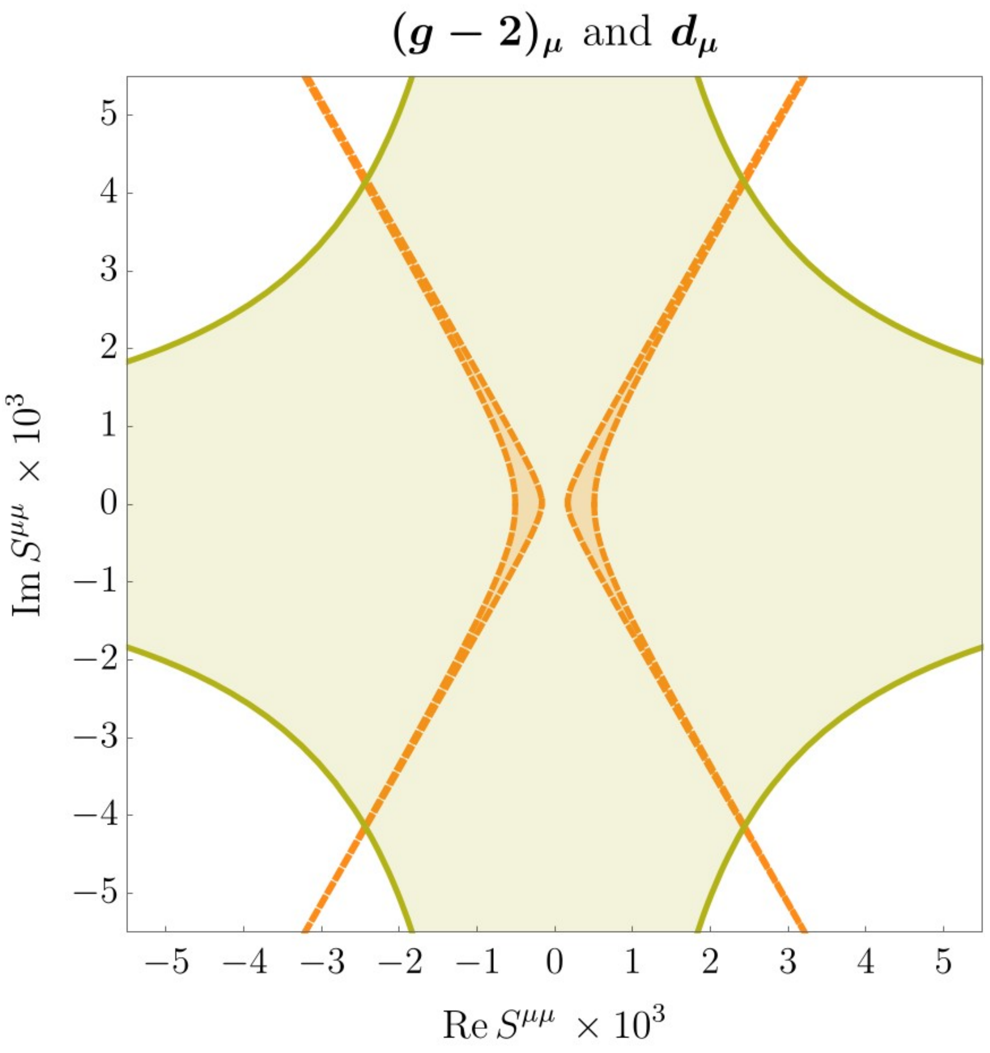
Not limited to a single model: use it for the model of your choice

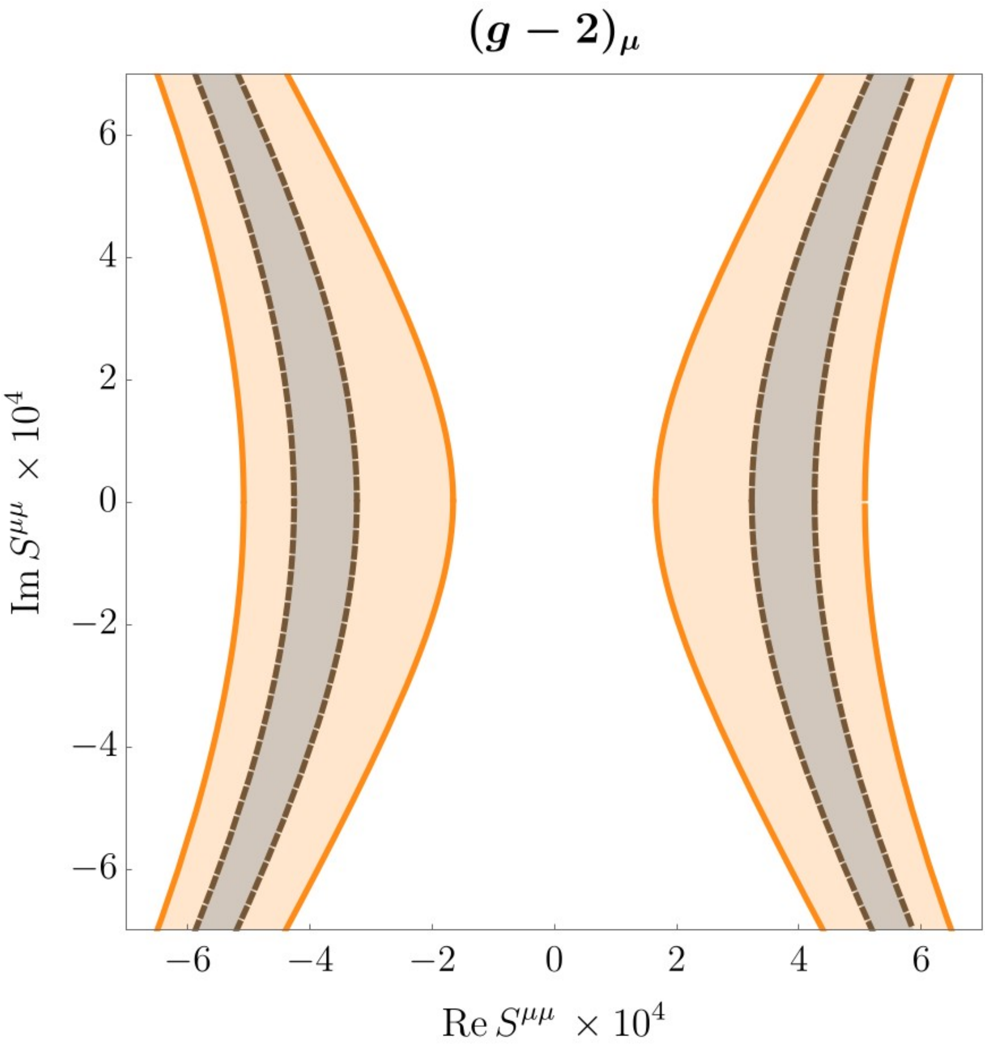
Easily extendable

Many observables ready to be computed in your favourite model!

Manual: arXiv:1405.1434
Website: http://sarah.hepforge.org/FlavorKit.html

Muon g-2





Flavor diagonal scenario

$$\Delta a_\alpha = \frac{1}{16\pi^2}\left[3\,(\mathrm{Re}\, S^{\alpha\alpha})^2 - (\mathrm{Im}\, S^{\alpha\alpha})^2\right]$$

[Escribano, AV, 2020]