THE PROBLEM OF THE MASS IN SM AND BEYOND

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Kavli Institute for the Physics and Mathematics of the Universe, April 27, 2016

UNIVERSIDAD AUTONOMA DE MADRID

invisibles neutrinos, dark matter & dark energy physics

elusives neutrinos, dark matter & dark energy physics

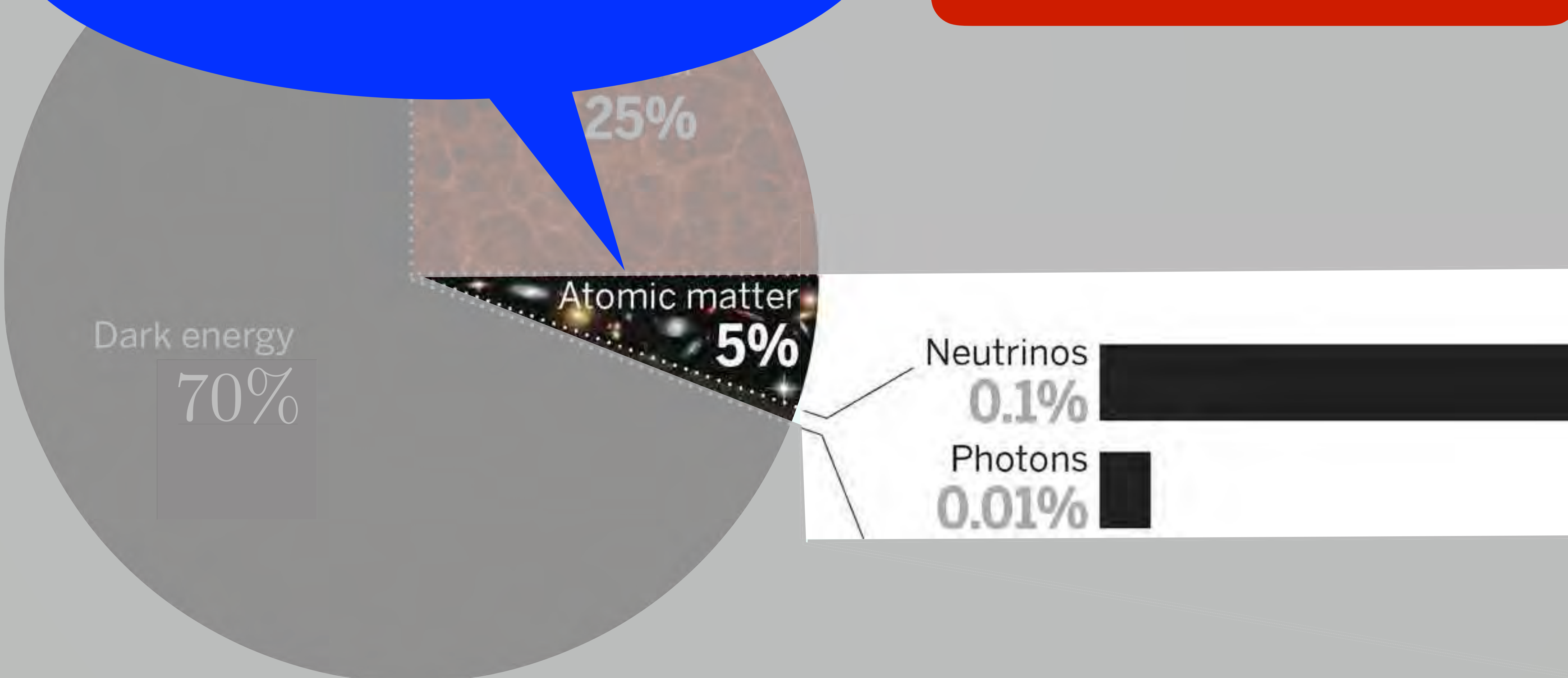
ift Instituto de Física Teórica UAM-CSIC

CSIC

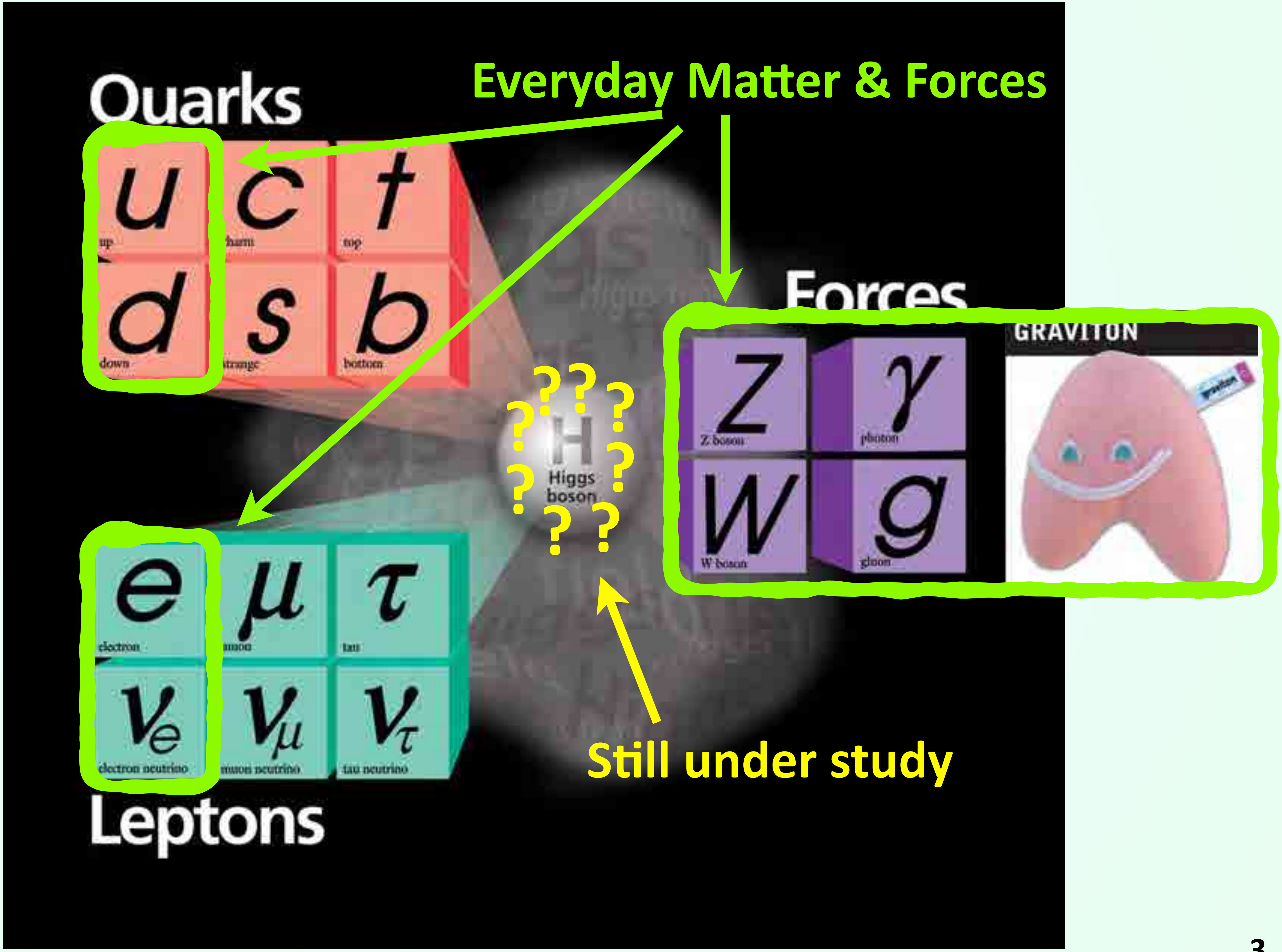
Our universe today

Start from what we know (±)
to infer what we don't know

Focus on
masses & mixings
and on their origins

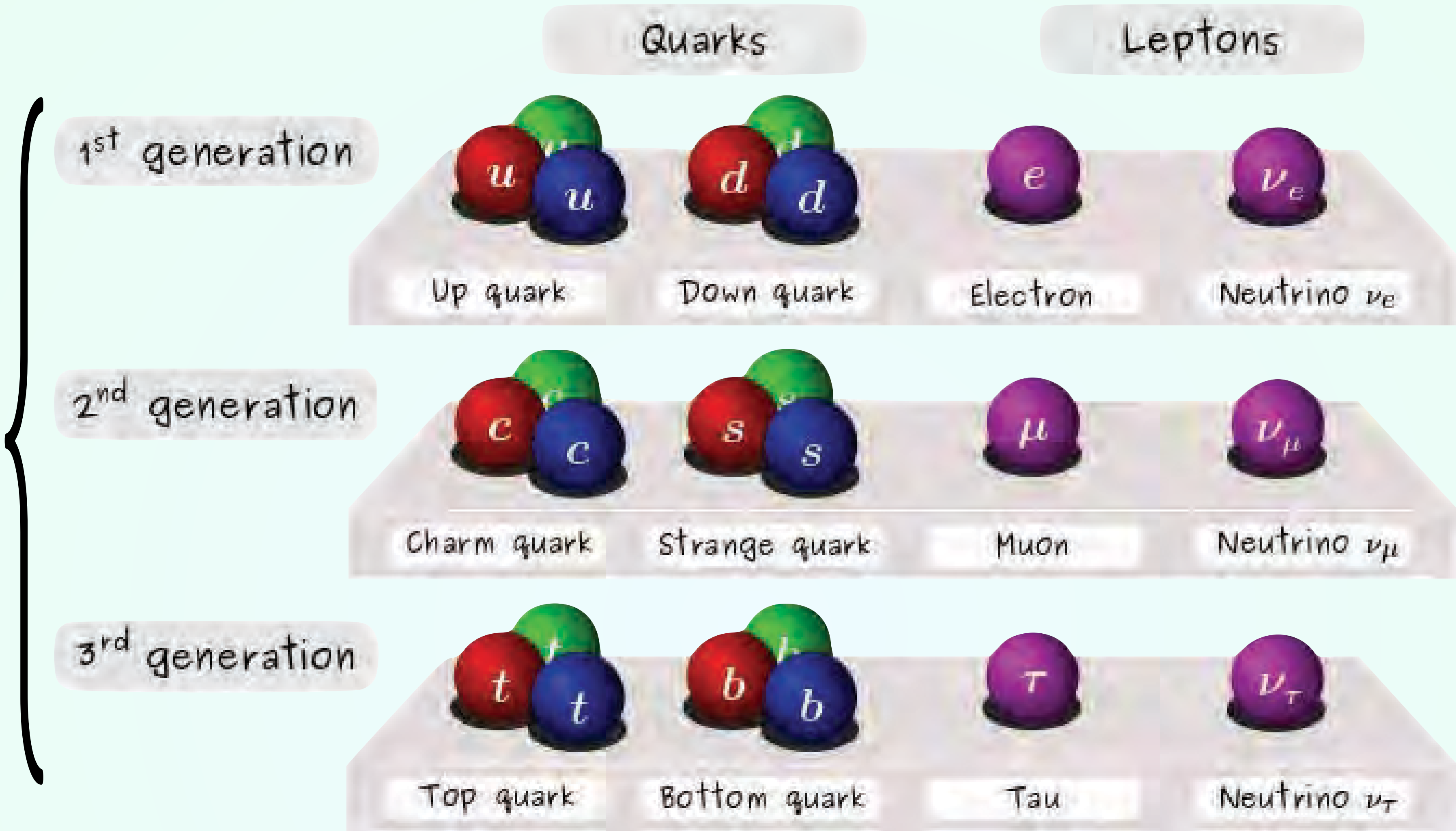


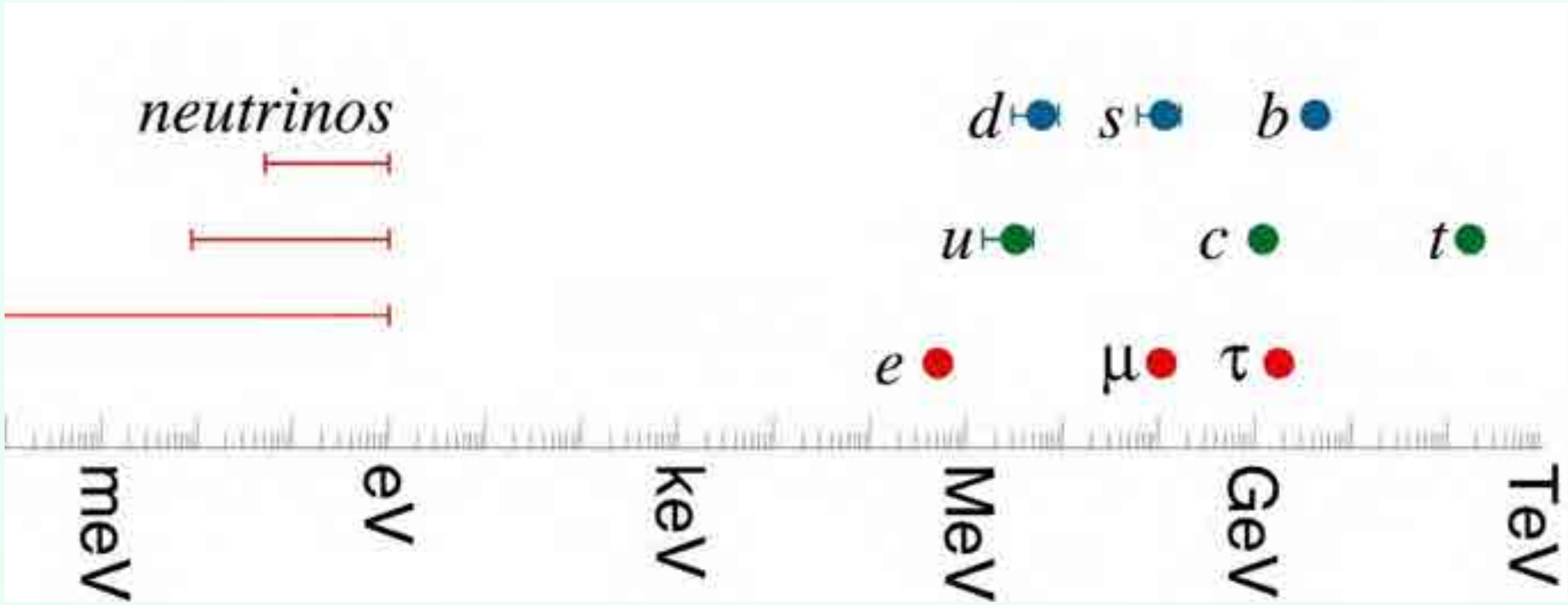
Normal matter



The fermion generations

Why 3?

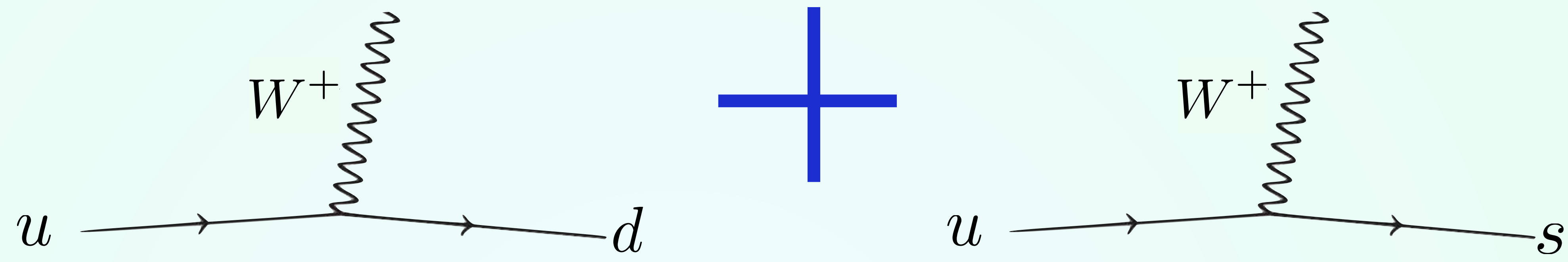




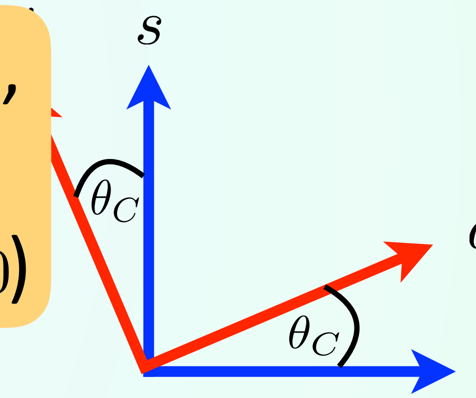
Why so different?

Mixing among generations: quarks

to explain $K^+ \to n e^+ \nu_e$

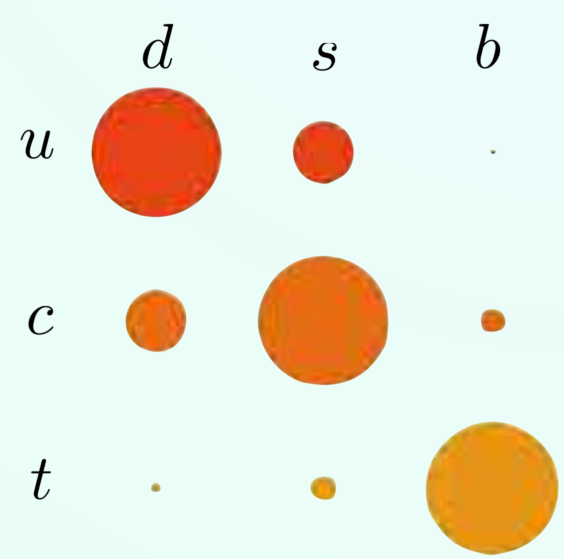


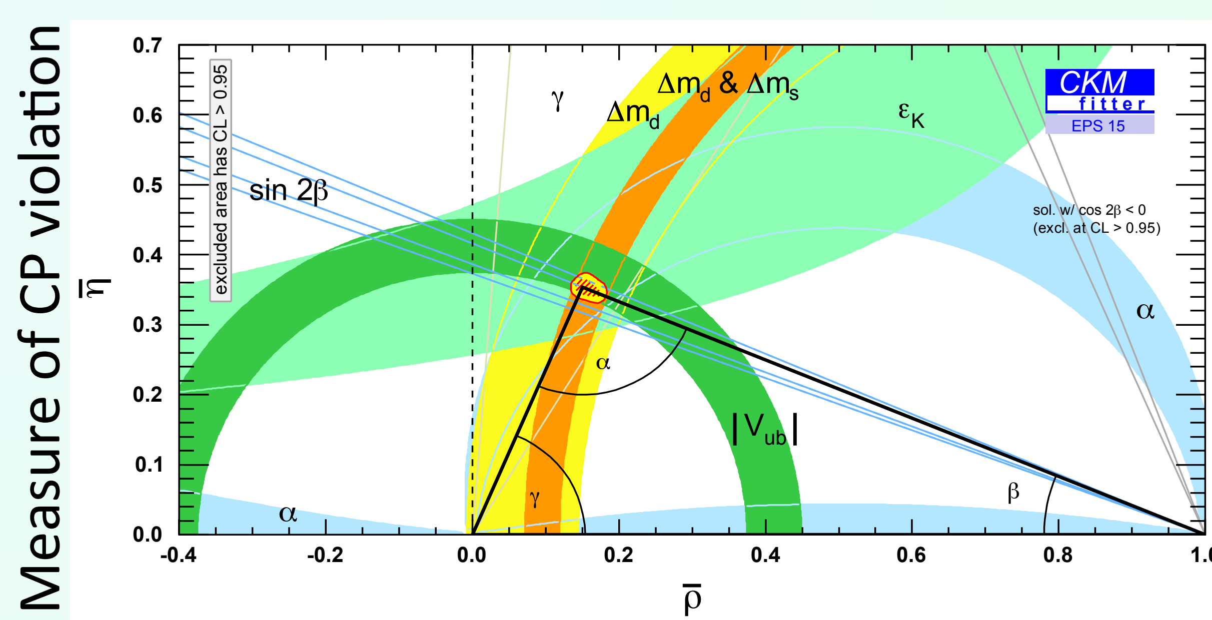
mass eigenstates ≠ interaction eigenstates



Why Nature gives CP violation,
but not enough to explain
Baryon Asymmetry $(B - \bar{B} > 0)$

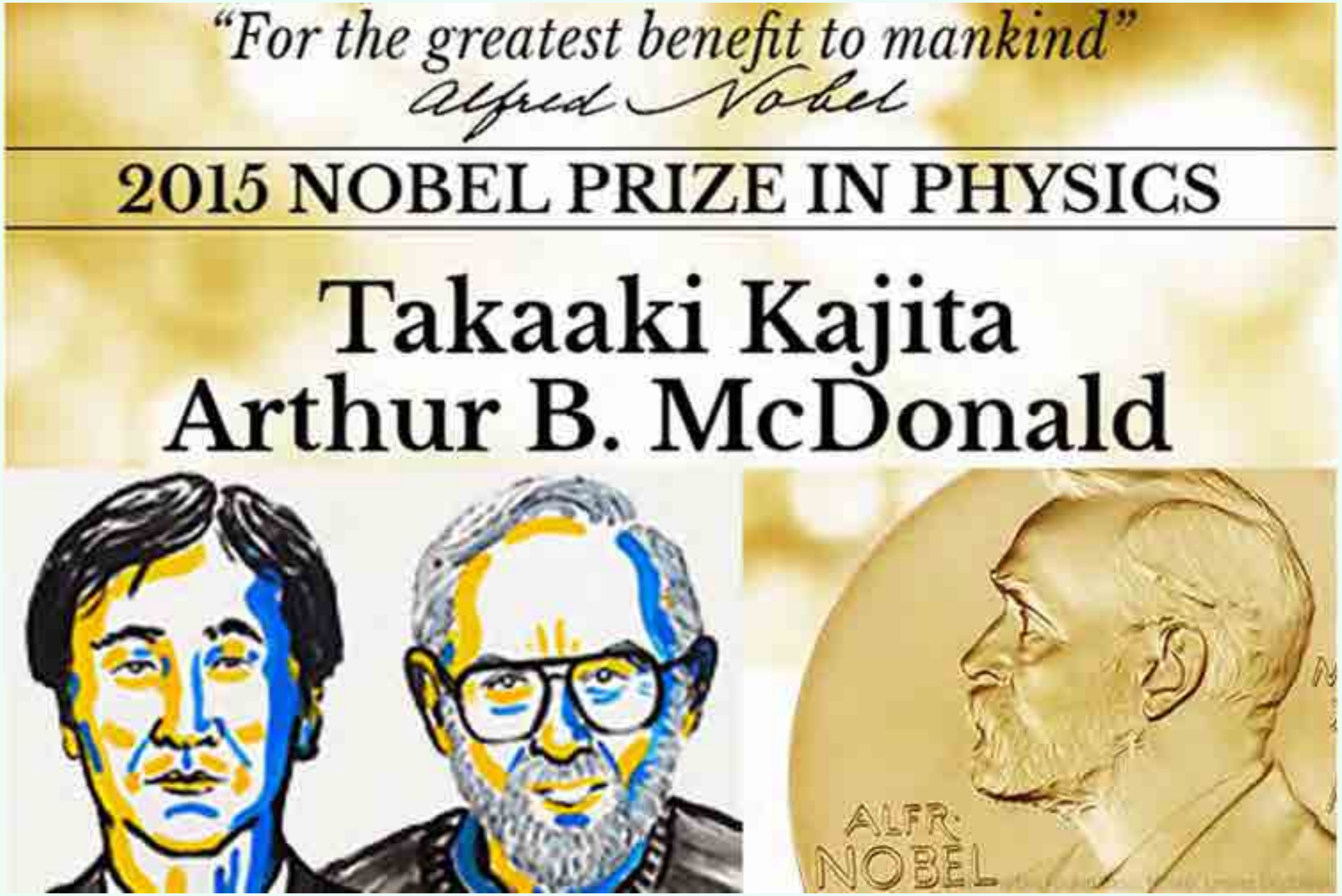
The mixing is among all the three families!





Mixing among generations: leptons

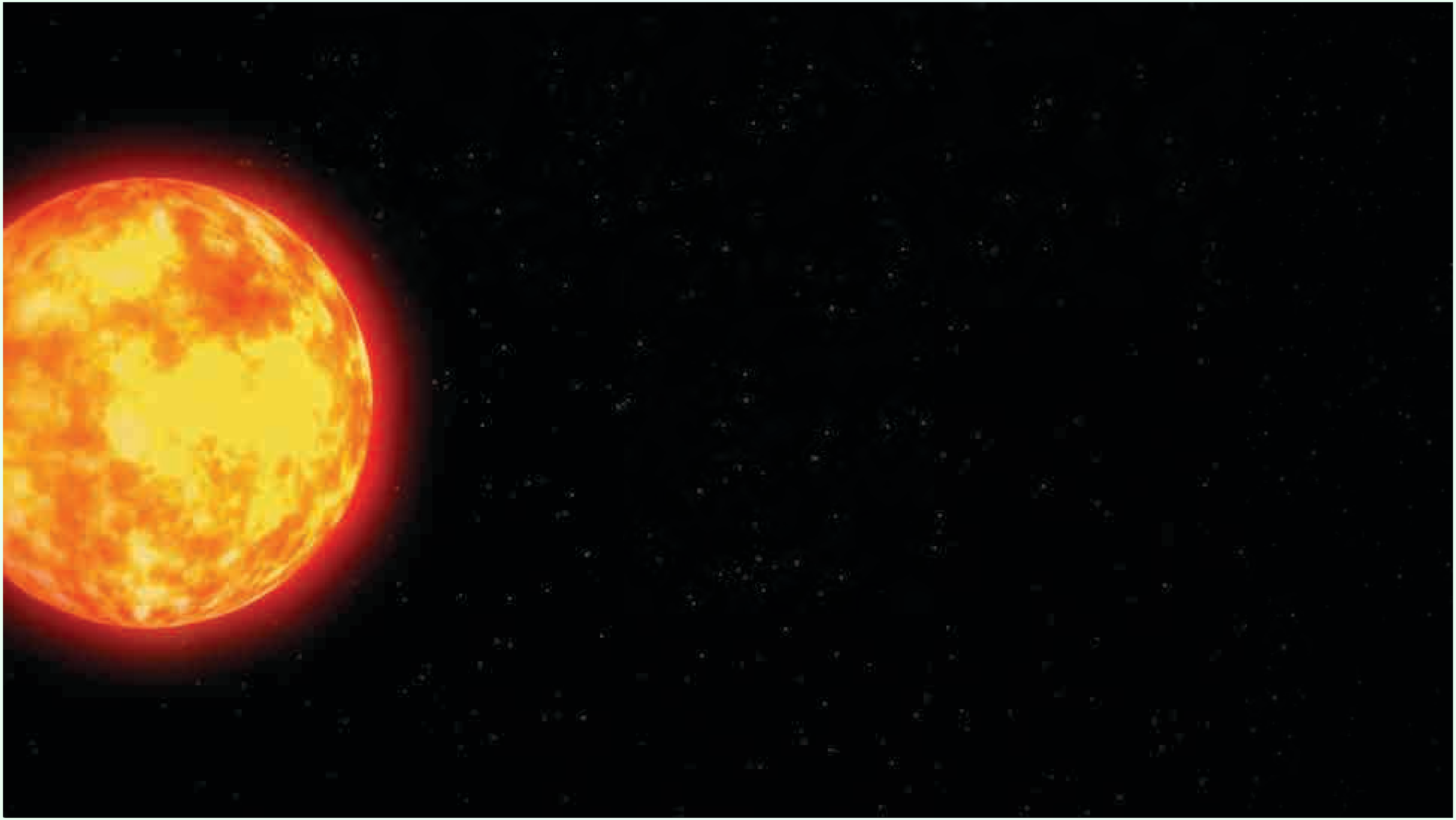
Neutrinos Oscillate!!!



Mixing among generations: leptons

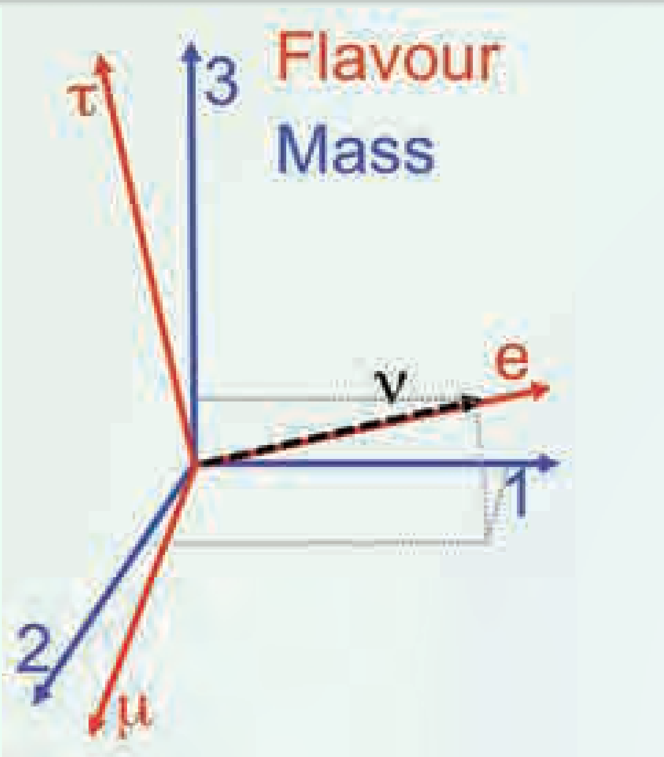
Neutrinos Oscillate!!!

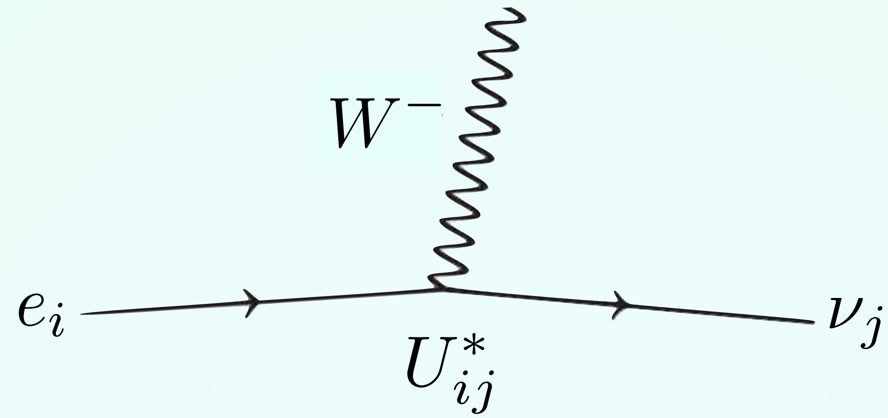
Example: the Sun emits electron neutrinos; we detect ν_e , ν_μ, ν_τ (ν_2)



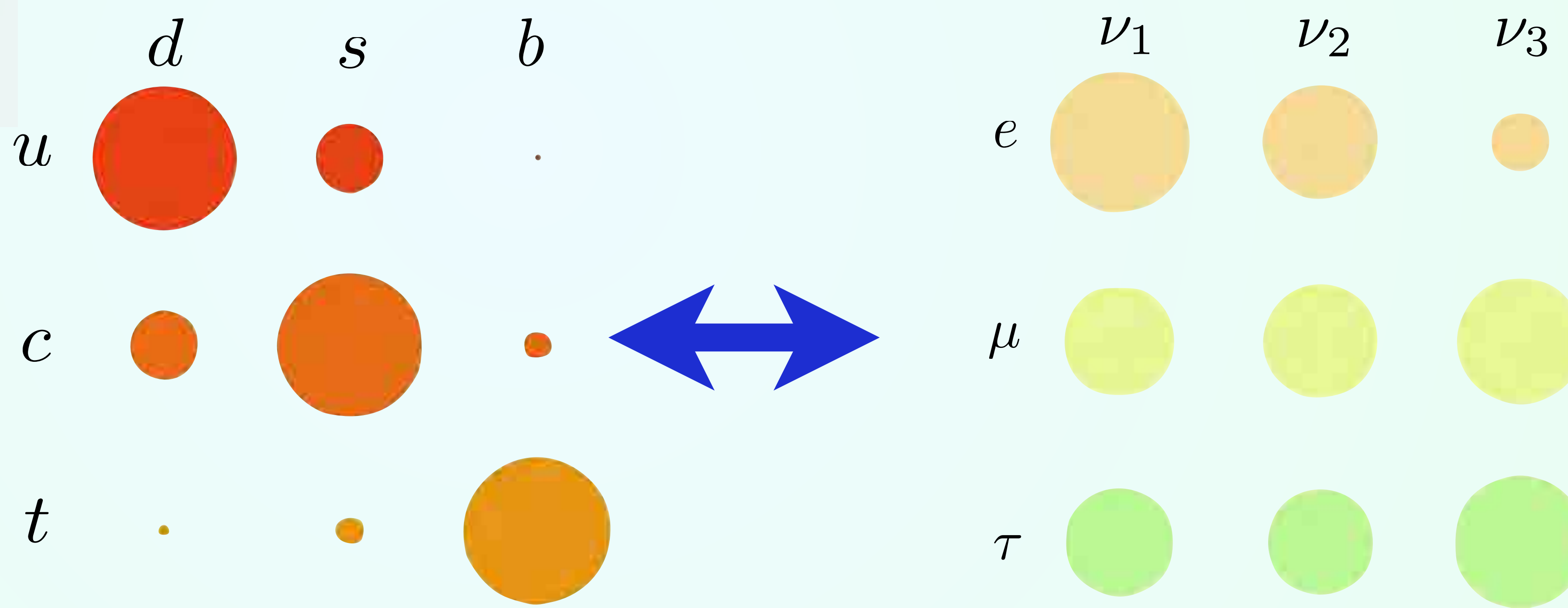
Free adaptation from " ¿Qué son las Oscilaciones de Neutrinos? " by José Luis Crespo Cepeda (student at IFT-UAM)

Mixing among generations: leptons



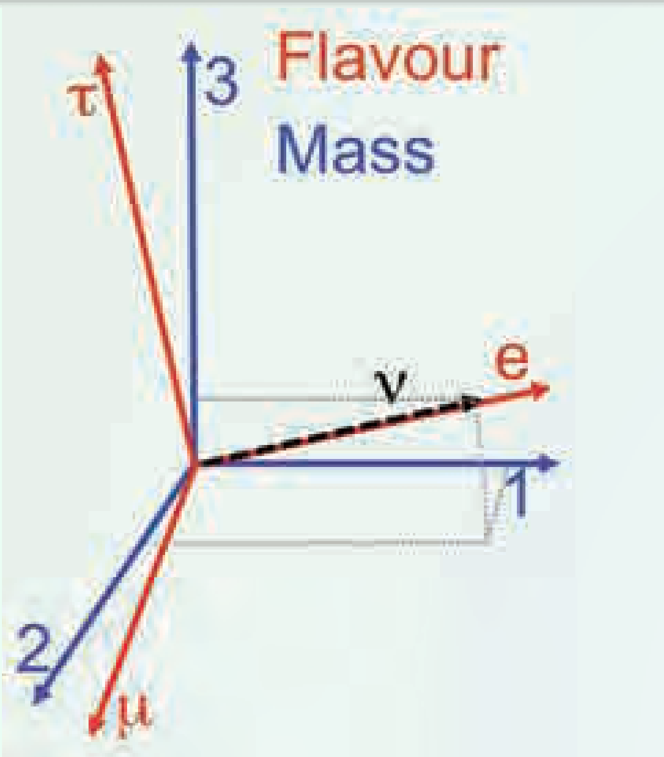


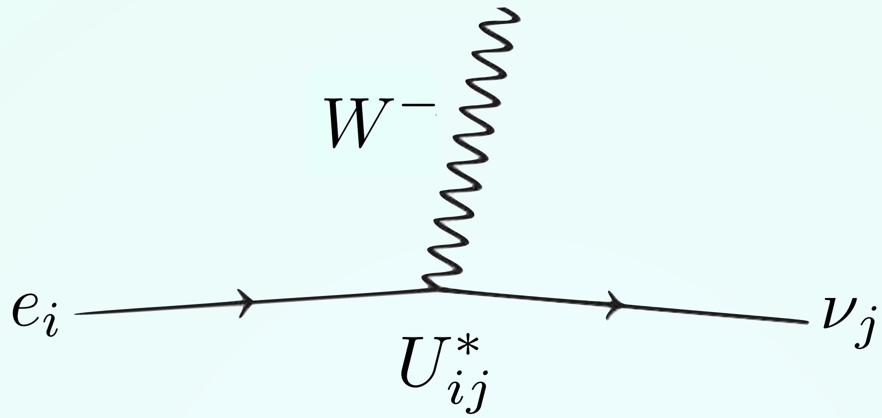
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



Why so different?

Mixing among generations: leptons





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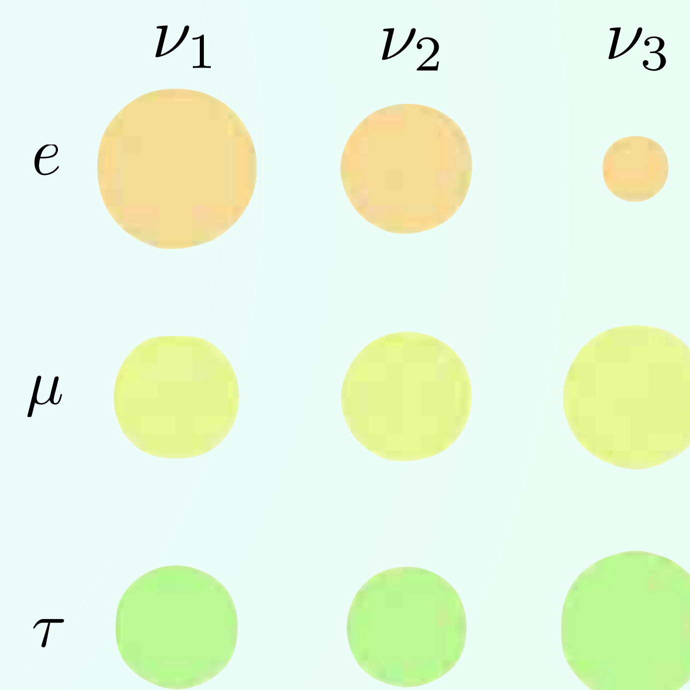
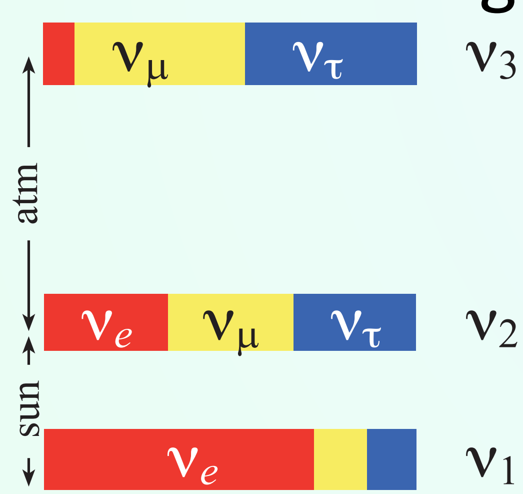
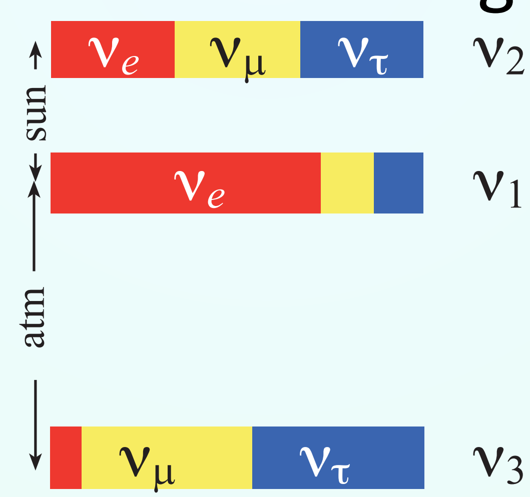


Normal Ordering



Inverse Ordering

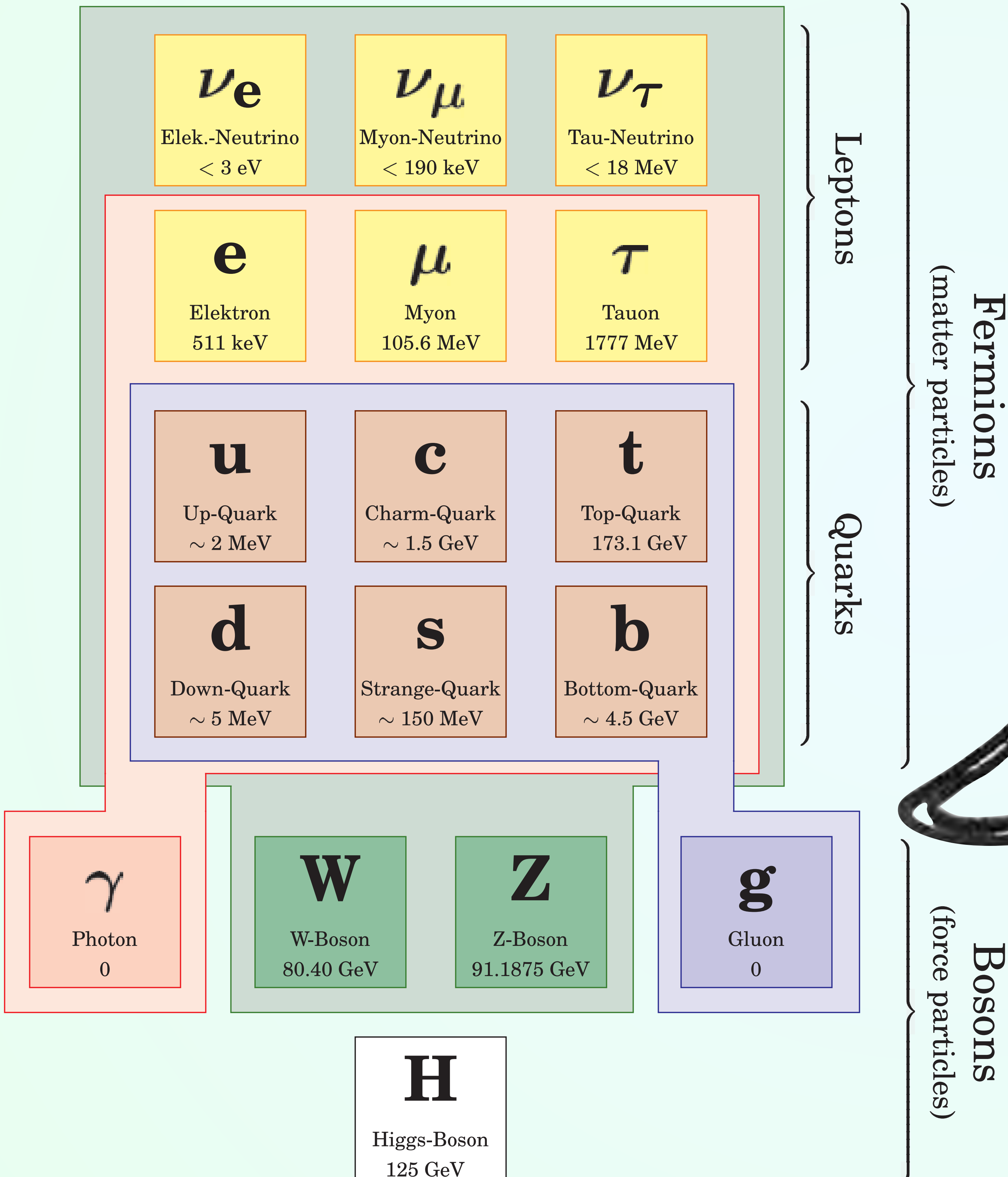


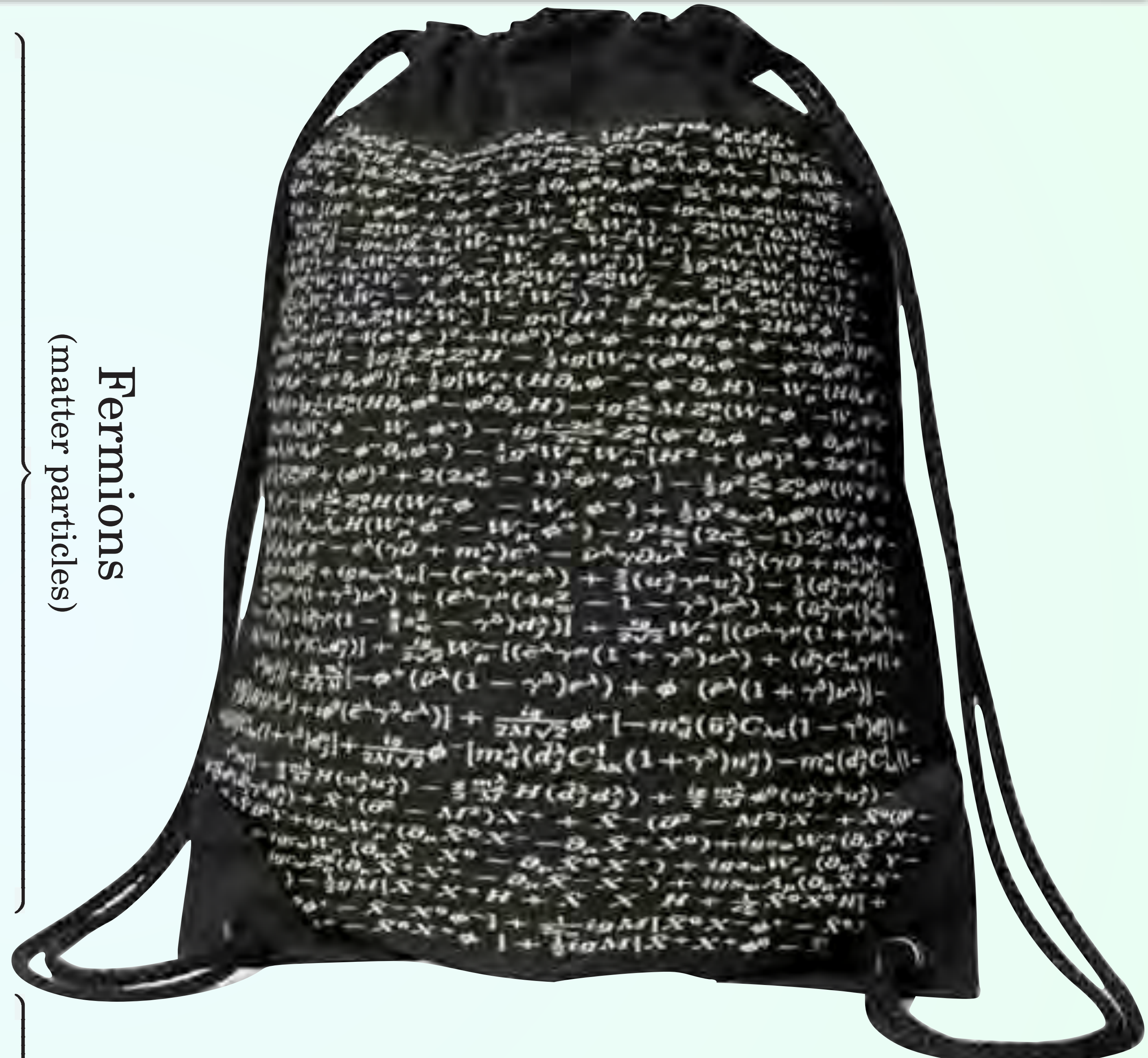
Which is the mass ordering?

Which is the lightest neutrino mass?

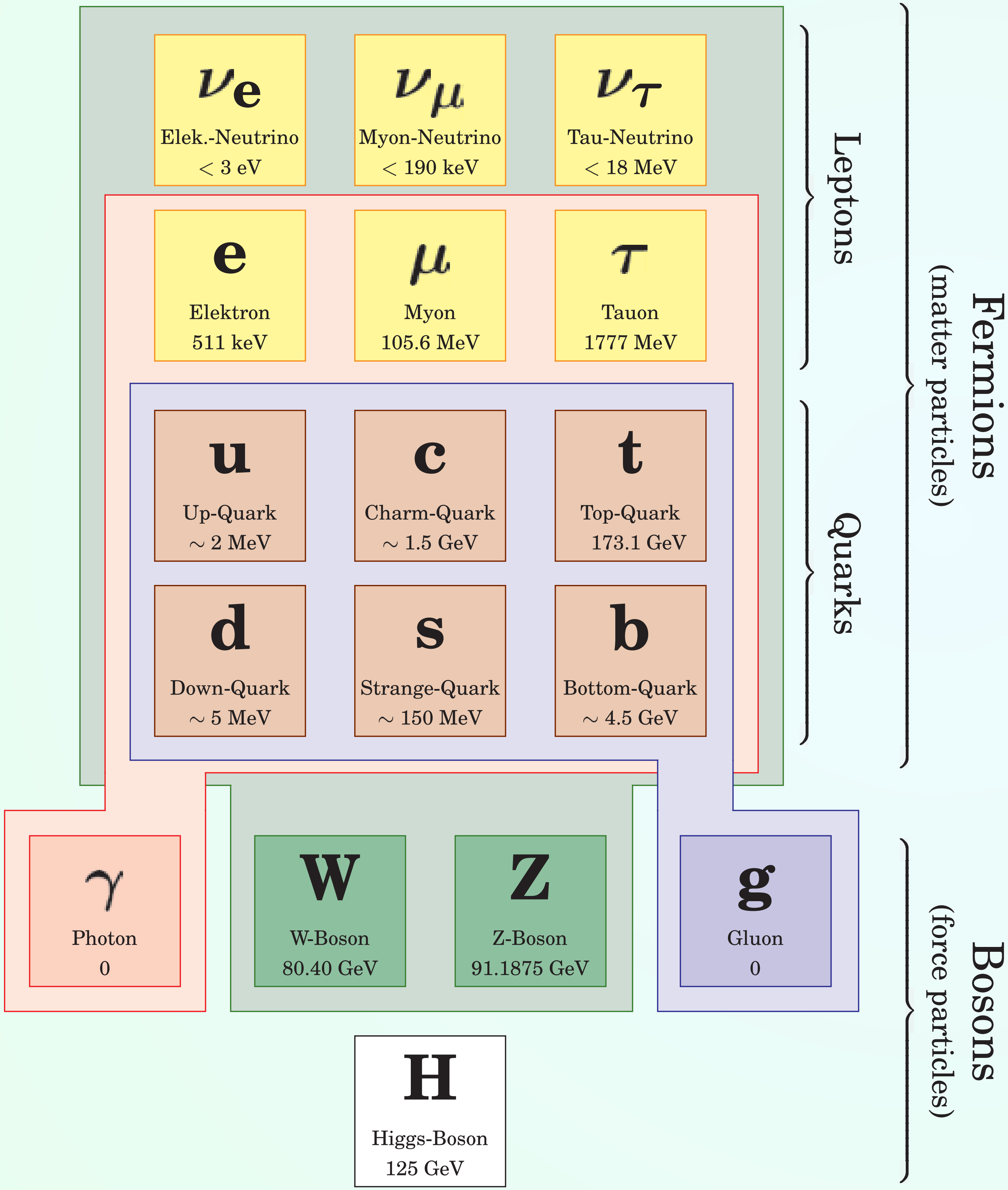
Why so different?

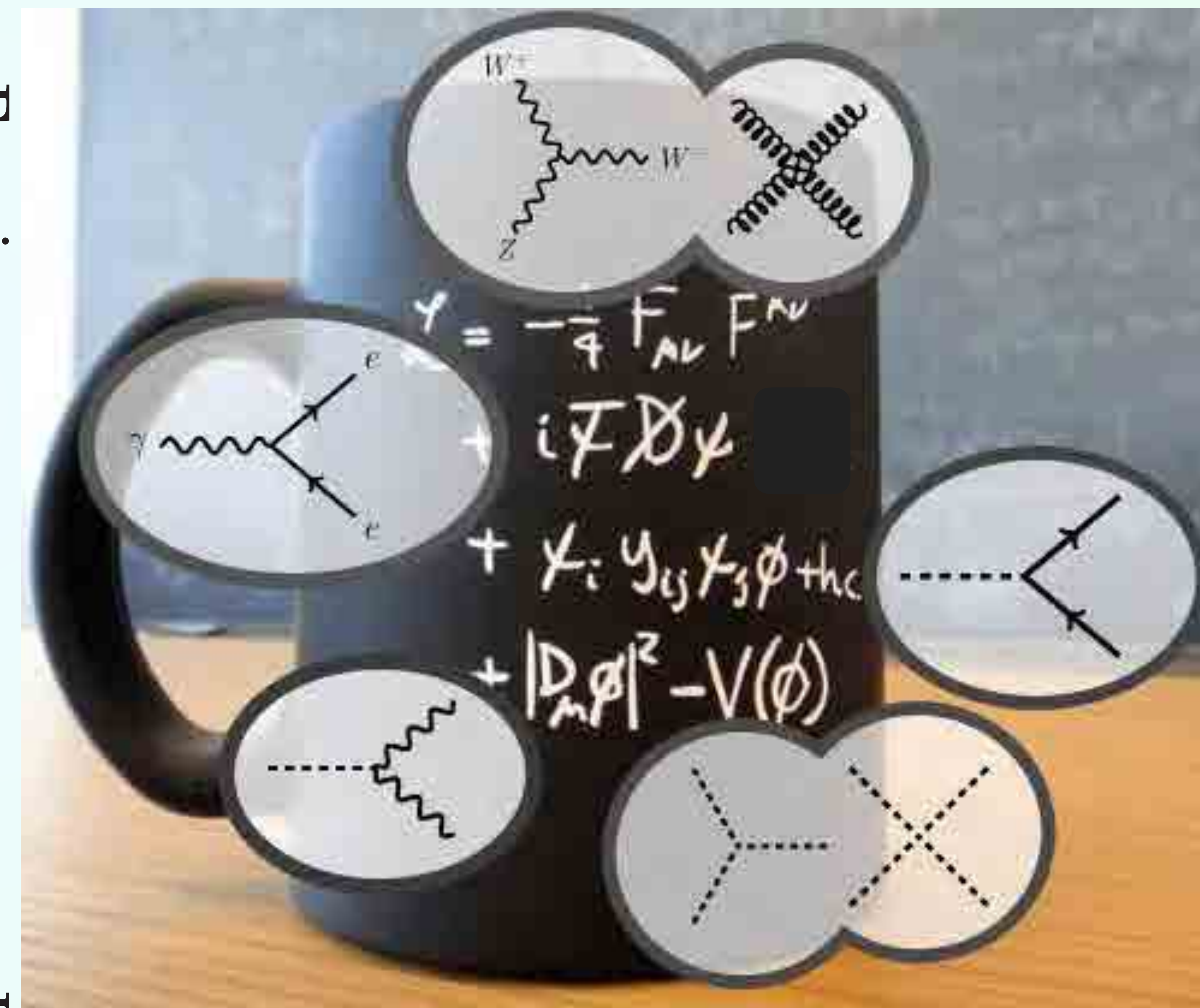
What the Standard Model says!!





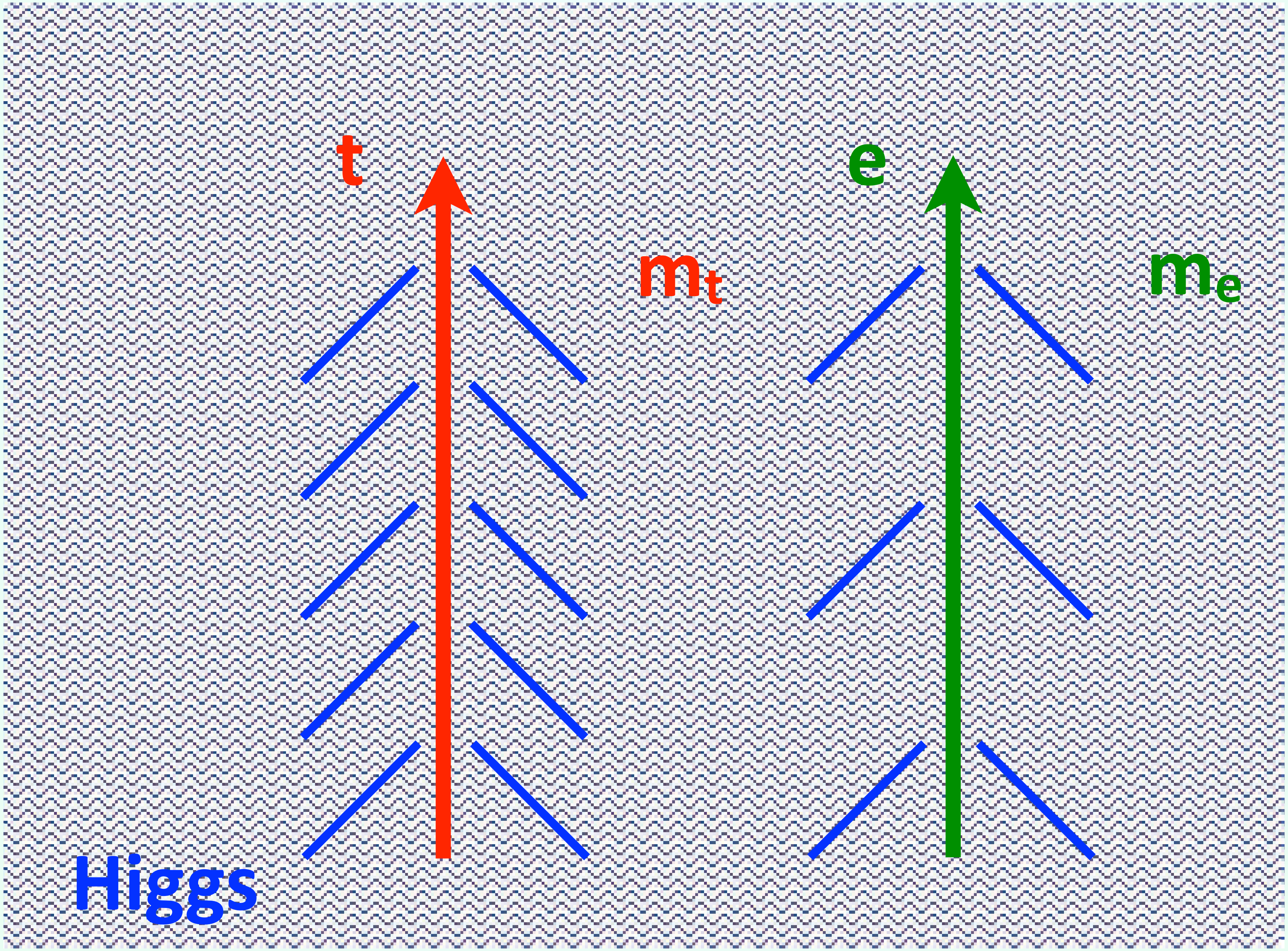
What the Standard Model says!!





Higgs Mechanism

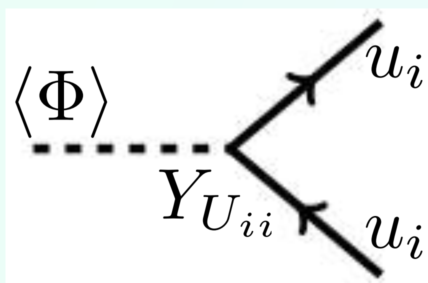
Masses come from the interaction with the Higgs that permeates the vacuum

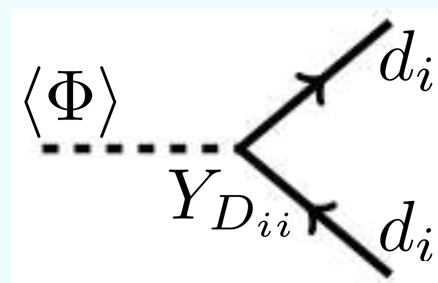


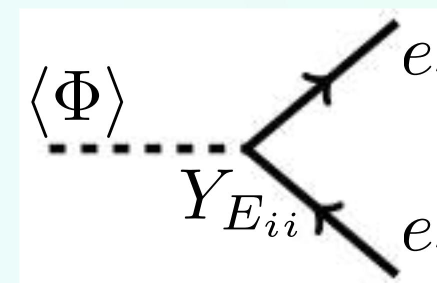
Yukawa Interactions

$$\mathcal{L}_Y = -\left(\bar{Q}_L \Phi \mathcal{Y}_D D_R + \text{h.c.}\right) - \left(\bar{Q}_L \widetilde{\Phi} \mathcal{Y}_U U_R + \text{h.c.}\right) - \left(\bar{L}_L \Phi \mathcal{Y}_E E_R + \text{h.c.}\right)$$

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix} \qquad L_L = \begin{pmatrix} \nu_L \\ E_L \end{pmatrix} \qquad \langle \Phi \rangle = \begin{pmatrix} 0 \\ \dfrac{v+h}{\sqrt{2}} \end{pmatrix} \qquad \langle \widetilde{\Phi} \rangle = \begin{pmatrix} \dfrac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$$







All the quarks and the charges leptons acquire masses!

The Yukawas are just numbers!

Why are so different?

Neutrinos remain massless!!!

How do neutrinos acquire mass?

Many questions!

Experimental Evidences

- Neutrino Masses
- Baryon Asymmetry
- Dark matter
- Gravity

Theoretical Problems

- Why 3 generations?
- Why so different masses & mixings?
- Dark Energy (Cosmological Constant $\Lambda_0 \sim 10^{-123} M_{\text{Planck}}$)
- Strong CP Problem $\theta \widetilde{G}_{\mu\nu} G^{\mu\nu}$ with $\theta < 10^{-10}$
- NP Flavour Problem (no FCNC in BSM)
- Hierarchy Problem (in the presence of NP)

Flavour Puzzle

1

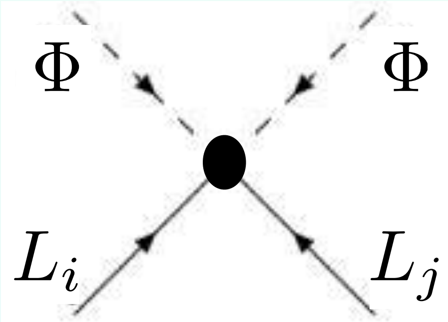
2

NEW PHYSICS

Neutrino Masses: See-Saw

Weinberg Op.: $\mathcal{O}_5 = \frac{1}{\Lambda_{LN}} (\bar{L}_L \widetilde{\Phi}) \mathcal{C}_\nu (\widetilde{\Phi}^T L_L^c)$

Weinberg 1980



$\longrightarrow \quad m_\nu = \frac{v^2}{2} \frac{\mathcal{C}_\nu}{\Lambda_{LN}}$

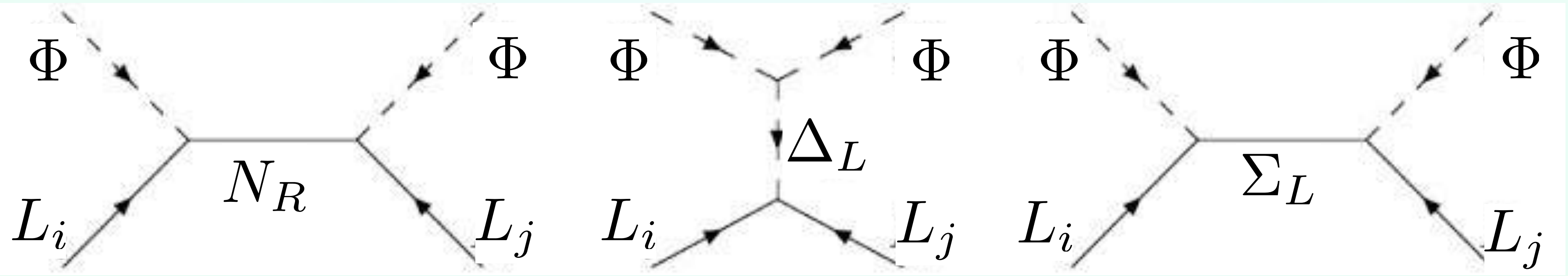
An effective operator is a low-energy description of interactions that could be originated from many different ultraviolet theories.

Why are EFTs useful??

- Only relevant contributions
- Calculations are easier
- Model independent: low-energy spectrum and syms
- Gauge Invariance

Tree level UV theories: $2 \times 2 = 1 + 3$ under $SU(2)_L$

Type I Type II Type III



Yanagida 1979

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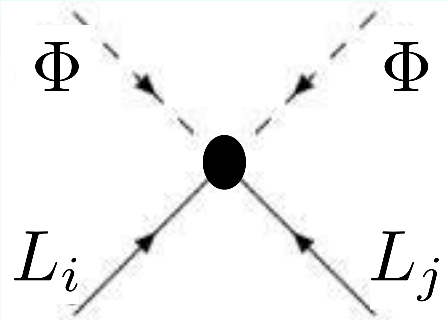

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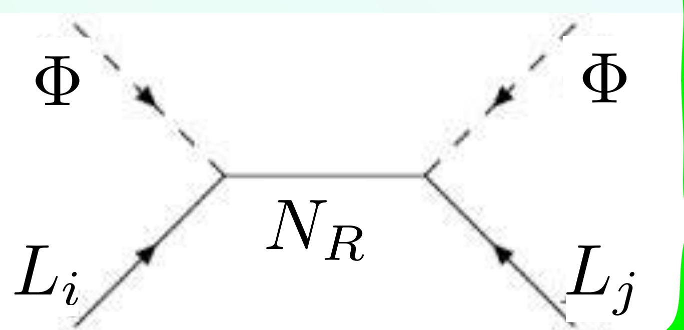

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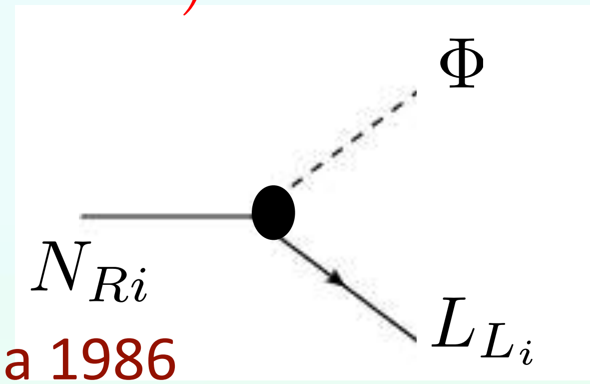
$\longrightarrow$ Leptogenesis



Hukugita&Yanagida 1986

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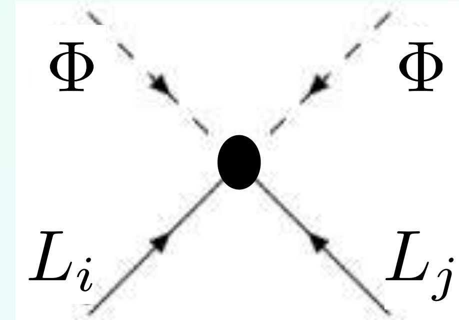


$\longrightarrow \quad m_\nu = \frac{v^2}{2} \frac{\mathcal{C}_\nu}{\Lambda_{LN}}$

An effective operator is a low-energy description of interactions that could be originated from many different ultraviolet theories.

Why are EFTs useful??

- Only relevant contributions
- …um and syms

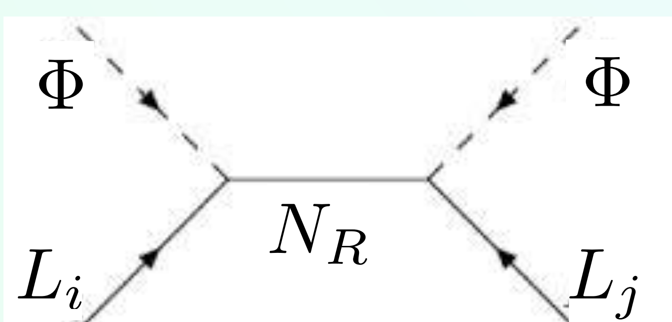
Smallness ok, but…

Why is this only for neutrinos?

How to explain the mixings?

Tree level UV theories: $2 \times 2 = 1 + 3$ under $SU(2)_L$

Type I



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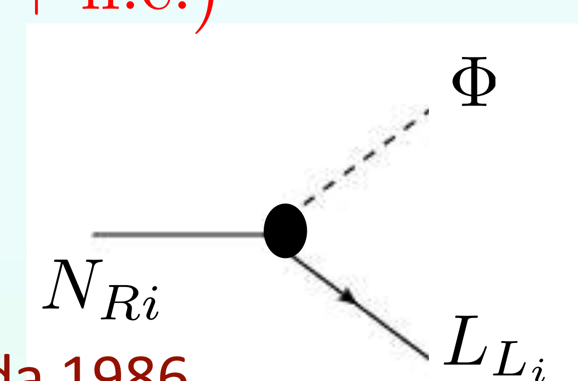
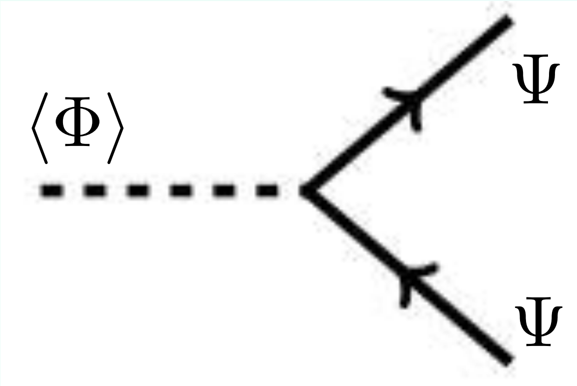
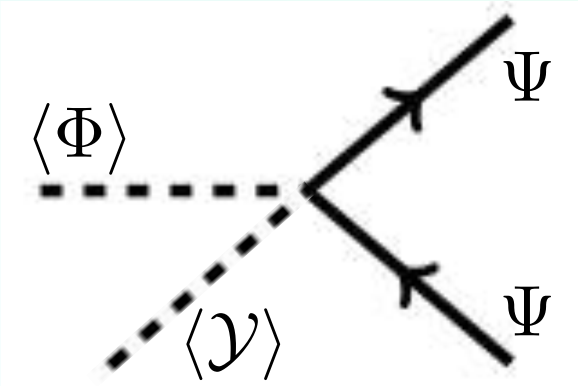


Hukugita&Yanagida 1986

Symmetry to explain Flavour

Idea: Yukawa coupling from the vev of some field





To explain hierarchies and mixing: different flavour informations!

Flavour Symmetries

Which one?

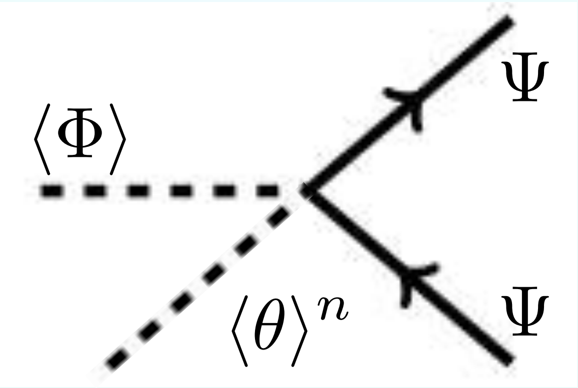
Symmetry to explain Flavour

Top-down approach:

Local	Abelian	Continuous
$\Updownarrow$	$\Updownarrow$	$\Updownarrow$
Global	non-Abelian	Discrete

Froggatt-Nielsen U(1) models

- New scalar field θ, called flavon, which develops a VEV ($\sim$ Higgs mechanism)



- the corresponding non-renormalisable Yukawas read:

$$\frac{\theta^n}{\Lambda_f^n}\bar{L}_{Li}\Phi y_{E_{ij}} E_{Rj} \longrightarrow M_{E_{ij}} = \frac{v}{\sqrt{2}} y_{E_{ij}} \frac{\langle\theta\rangle^n}{\Lambda^n}$$

- Similarly for quarks $\Rightarrow$ Good description of quark masses and mixing and of charged lepton masses!

Symmetry to explain Flavour

Top-down approach:

Local	Abelian	Continuous
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<u>Froggatt-Nielsen U(1) models</u>

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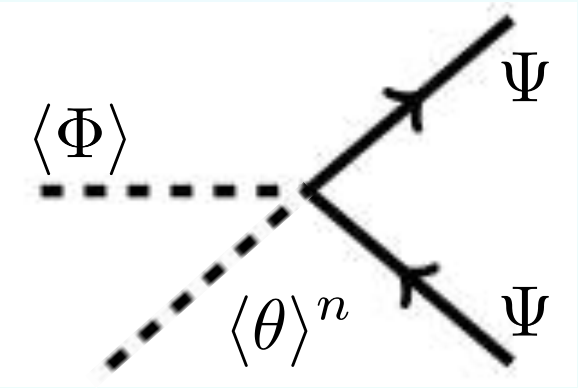

- Many possibilities for neutrinos:

Hall, Murayama & Weiner 2000
de Gouvea & Murayama 2003

  - symmetry at high energy and then no symmetry at low-energy: <u>Anarchy</u>
  - symmetry still present at low-energy: <u>Hierarchy</u>

Symmetry to explain Flavour

Top-down approach:

Local $\Updownarrow$ Globa

Abelian $\Updownarrow$

Continuous $\Updownarrow$ Discrete

- New scalar f ... s mechanism)

- Many possil ... yama & Weiner 2000
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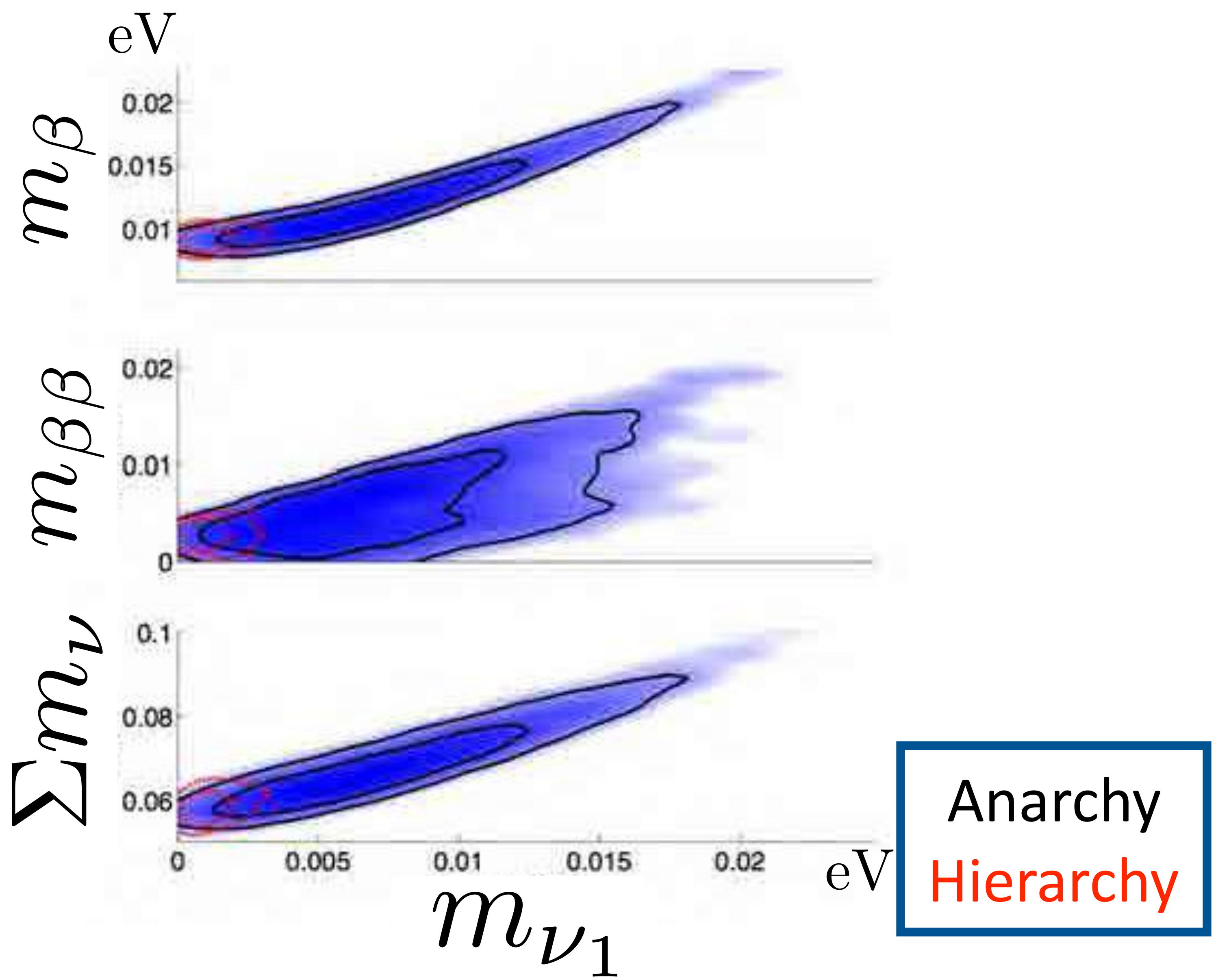
  - symme



Altarelli, Feruglio, Masina & LM, JHEP**1211**(2012)
Bergstrom, Meloni & LM, PR**D89**(2014)

Symmetry to explain Flavour

Top-down approach:

Local ⇕ Globa

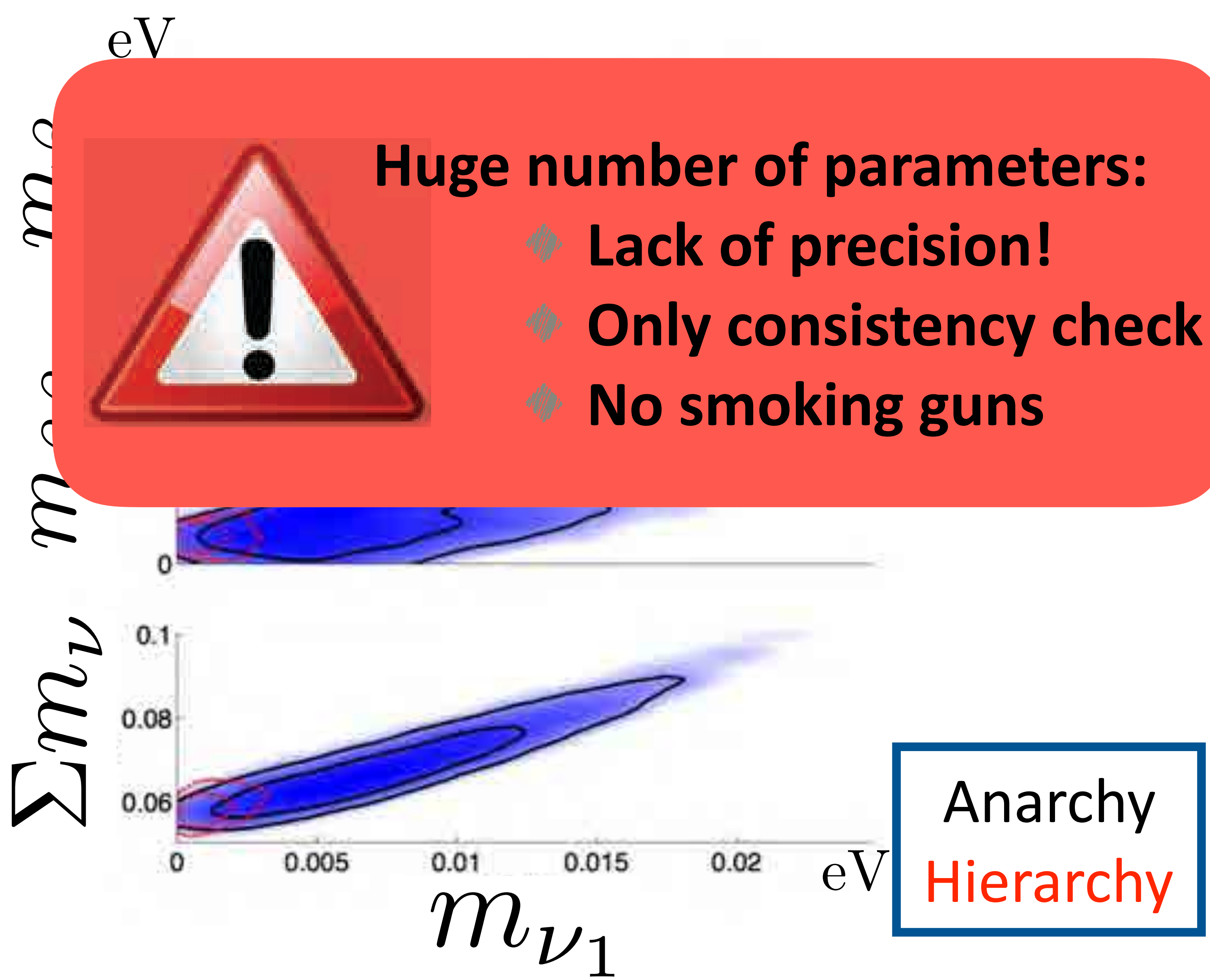
Abelian ⇕

Continuous ⇕ Discrete

- New scalar f ... s mechanism)

Huge number of parameters:

- **Lack of precision!**
- **Only consistency check**
- **No smoking guns**



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Symmetry to explain Flavour

Top-down approach:

Local ⇕ Global

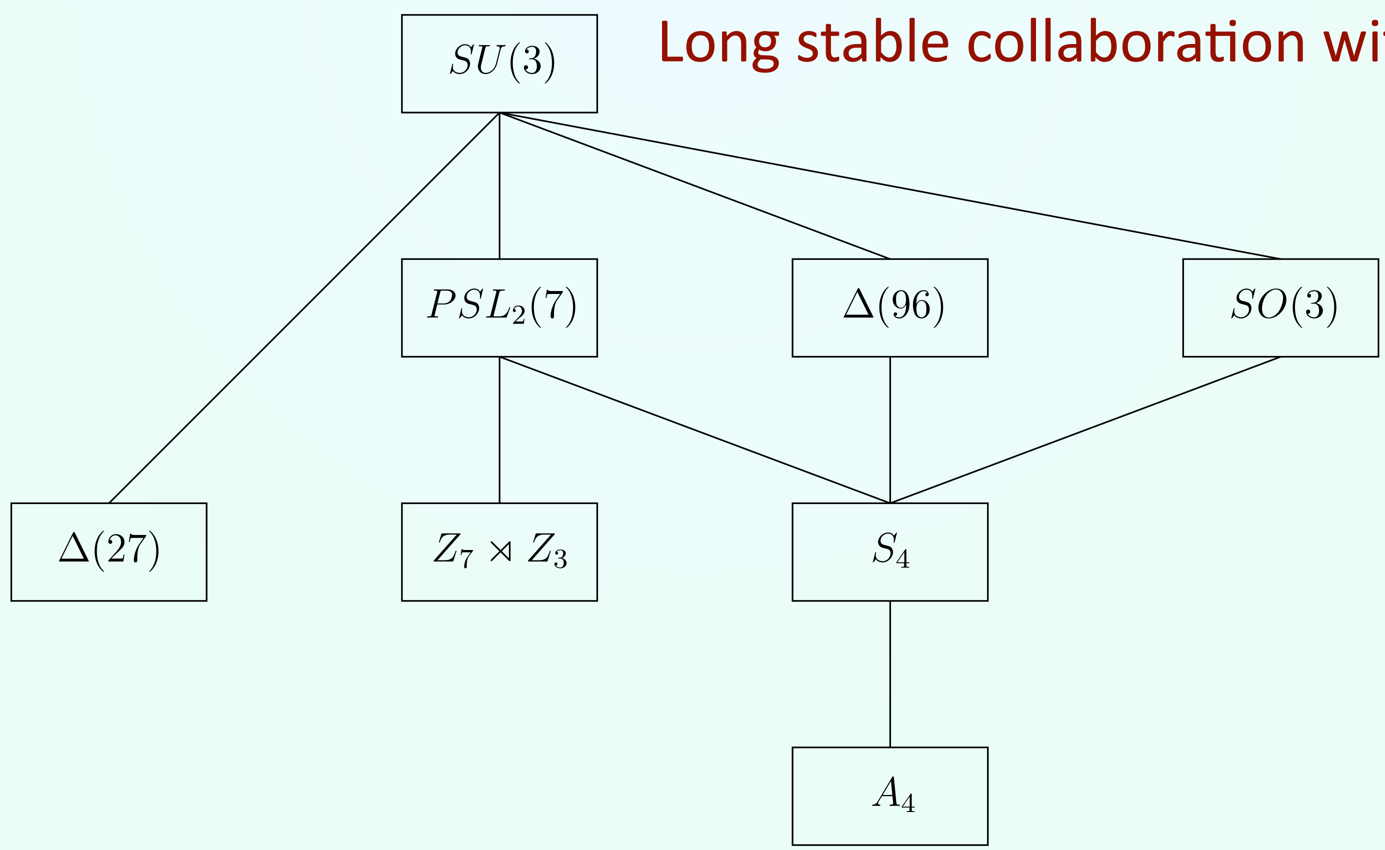
Abelian ⇕ non-Abelian

Continuous ⇕ Discrete

<u>“Discrete” models</u>

The best candidates to reproduce the leptonic flavour structures before 2011

Long stable collaboration with G. Altarelli & F.Feruglio



Symmetry to explain Flavour

Top-down approach:

$$\begin{array}{ccc} \text{Local} & \text{Abelian} & \text{Continuous} \\ \Updownarrow & \Updownarrow & \Updownarrow \\ \text{Global} & \text{non-Abelian} & \text{Discrete} \end{array}$$

<u>"Discrete" models</u>

The best candidates to reproduce the leptonic flavour structures before 2011

Long stable collaboration with G. Altarelli & F.Feruglio

- Great Predictivity
- LO mixing angles determined by GEOMETRY
- Precise mass and angles sum rules

TRI-BIMAXIMAL

Harrison, Perkins & Scott 2002;
Xing 2002

$$U^{TB} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & +1/\sqrt{2} \end{pmatrix}$$

Symmetry to explain Flavour

Top-down approach:

Local ⇕ Global

Abelian ⇕

Continuous ⇕ Discrete

Disfavoured after the discovery of a so large reactor angle!!

The best candi... before 2011

...n with G. Altarelli & F.Feruglio

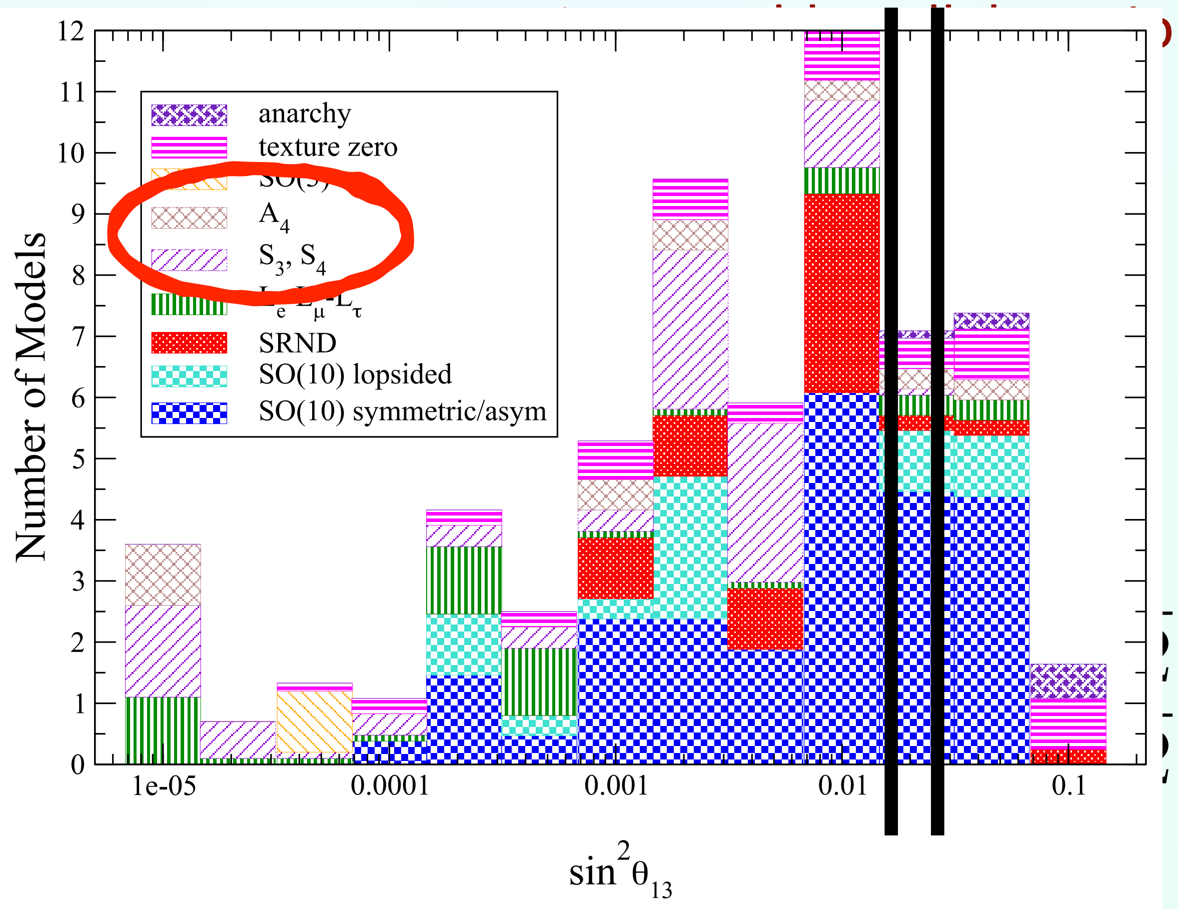
- Great Predictivit...
- LO mixing angles...
- Precise mass and...

TRI-BIMAXIMAL

Harrison, Perkins & Sco...

Xing 2002

U...



Symmetry to explain Flavour

Top-down approach:

Local	Abelian	Continuous
$\Updownarrow$	$\Updownarrow$	$\Updownarrow$
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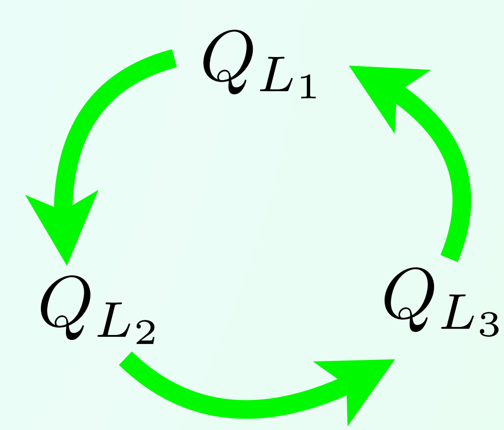
Which symmetry or combinations of syms?

Bottom-up approach may help: flavour symmetry in the SM?

$\longrightarrow$ flavour symmetry of the kinetic terms:

$$\bar{Q}_{L_i}\,\not{D}\,Q_{L_i} \longrightarrow U(3)_{Q_L}$$



SM:
- Quarks $U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$
- Leptons $U(3)_{L_L} \times U(3)_{E_R}$

Type I See-Saw: $U(3)_{L_L} \times U(3)_{E_R} \times U(3)_{N_R}$

Minimal Flavour Violation

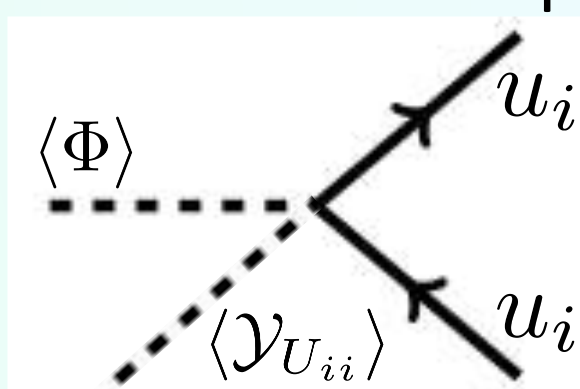
Chivukula & Georgi 1987; D'Ambrosio *et al.* 2002

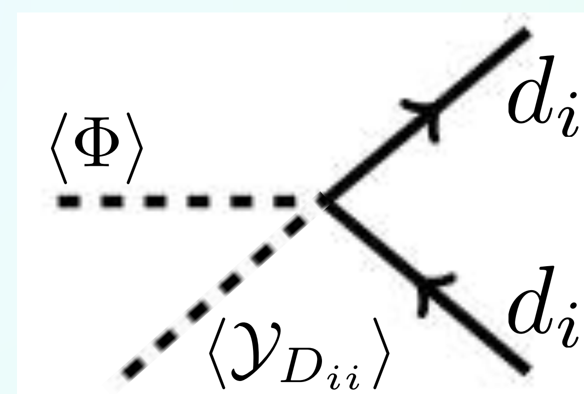
GLOBAL $U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$ has been the key ingredient of the Minimal Flavour Violation (MFV), which solves the NP Flavour Problem:

- $\mathcal{L}_Y = -\left(\bar{Q}_L \Phi \mathcal{Y}_D D_R + \text{h.c.}\right) - \left(\bar{Q}_L \widetilde{\Phi} \mathcal{Y}_U U_R + \text{h.c.}\right)$ made invariant by

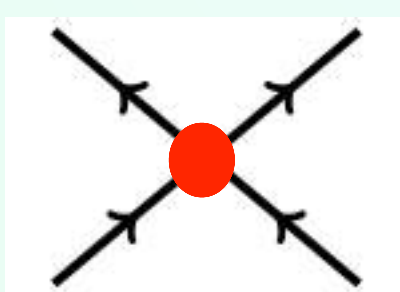
$$\mathcal{Y}_D \longrightarrow \mathcal{Y}_D \sim (3, \bar{3}, 1) \qquad\qquad \mathcal{Y}_U \longrightarrow \mathcal{Y}_U \sim (3, 1, \bar{3})$$

- The Yukawa FIELDS develop values, which are the SM Yukawa couplings:





- Flavour and CP Violation in SM and beyond controlled by the Yukawas



$$\frac{c^{\alpha\beta\gamma\delta}}{\Lambda_f^2}\left(\overline{Q}_\alpha \gamma_\mu Q_\beta\right)\left(\overline{Q}_\gamma \gamma^\mu Q_\delta\right) \quad \text{with} \quad c^{\alpha\beta\gamma\delta}(\mathcal{Y}) \leq 10^{-4}$$

$\Longrightarrow$ Any FCNC process under control with a NP at few TeV

Minimal Flavour Violation

Chivukula & Georgi 1987; D'Ambrosio *et al.* 2002

GLOBAL $U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$ has been the key ingredient of the Minimal Flavour Violation (MFV), which solves the NP Flavour Problem:

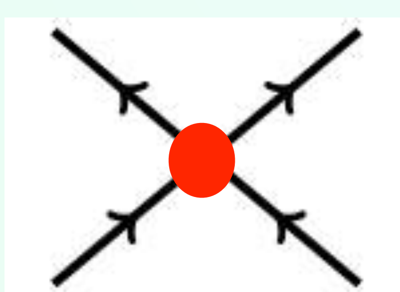
- $\mathcal{L}_Y = -\left(\bar{Q}_L \Phi \mathcal{Y}_D D_R + \text{h.c.}\right) - \left(\bar{Q}_L \tilde{\Phi} \mathcal{Y}_U U_R + \text{h.c.}\right)$ made invariant by

$$\mathcal{Y}_D \longrightarrow \mathcal{Y}_D \sim (3, \bar{3}, 1) \qquad \mathcal{Y}_U \longrightarrow \mathcal{Y}_U \sim (3, 1, \bar{3})$$

- The Yukawa FIELDS develop values, which are the SM Yukawa couplings:

Be aware of the Golstone Bosons

- Flavour and CP Violation in SM and beyond controlled by the Yukawas



$$\frac{c^{\alpha\beta\gamma\delta}}{\Lambda_f^2}\left(\overline{Q}_\alpha \gamma_\mu Q_\beta\right)\left(\overline{Q}_\gamma \gamma^\mu Q_\delta\right) \quad \text{with} \quad c^{\alpha\beta\gamma\delta}(\mathcal{Y}) \leq 10^{-4}$$

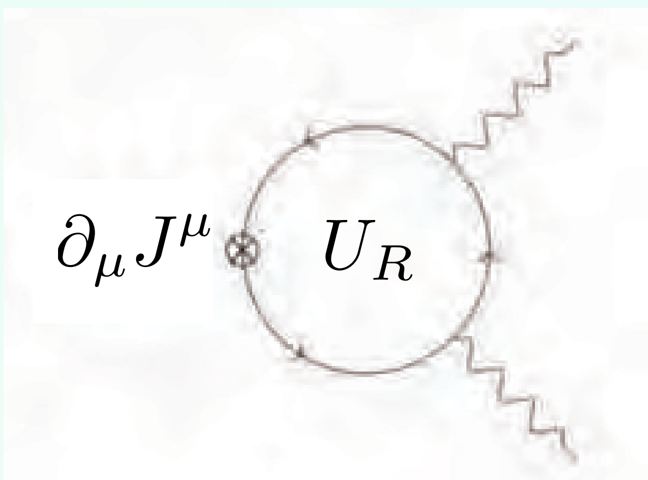
➡ Any FCNC process under control with a NP at few TeV

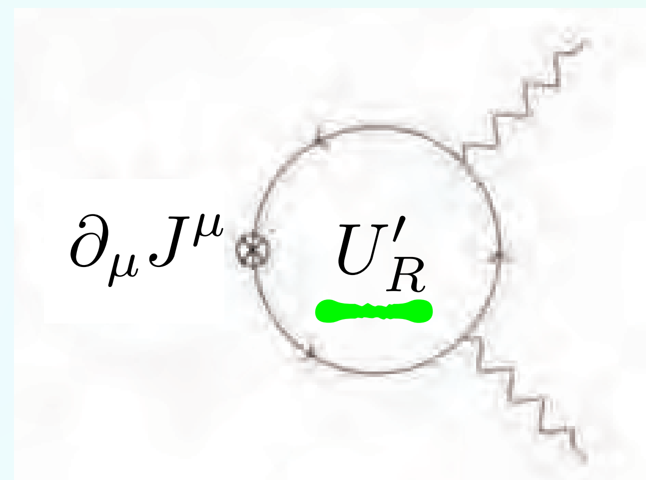
Gauging Minimal Flavour Violation

Grinstein, Redi & Villadoro 2010
Buras, LM & Stamou 2011
Buras, Carlucci, LM & Stamou 2011

GAUGED $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

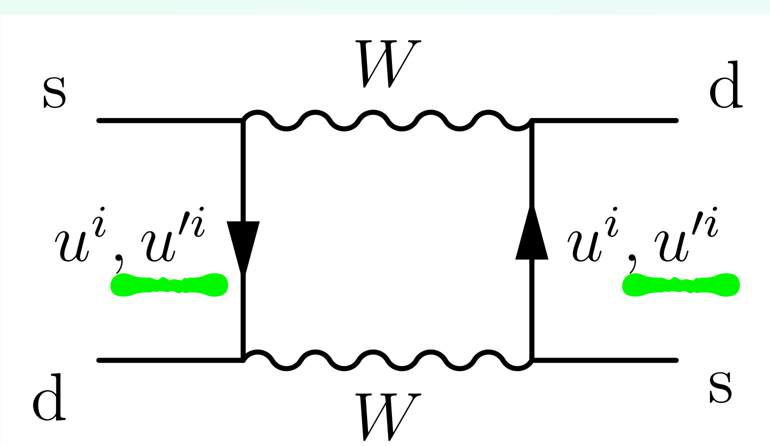
- The theory is renormalisable without GBs!!
- Effects due to new fermions needed for anomaly cancellations





See-Saw-like for ALL the fermions (NOT ONLY neutrinos)

example: Meson oscillation



$m_\psi \propto 1/m_{\psi'}$

$\widetilde{V} = V(1 + \delta V)$

non-unitarity effects

Gauging Minimal Flavour Violation

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Buras, LM & Stamou 2011
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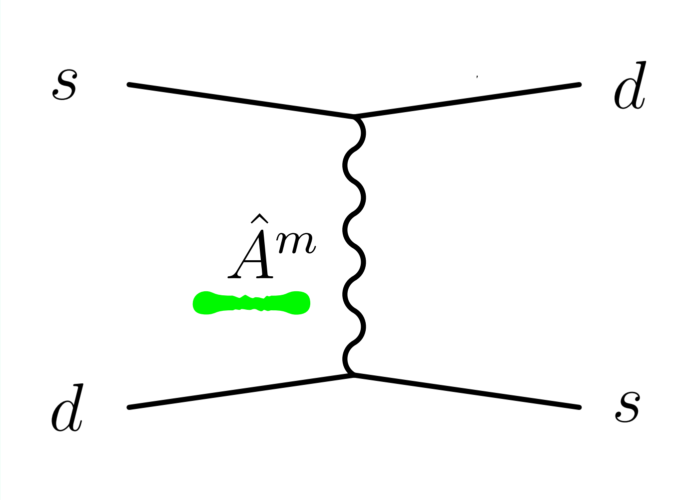
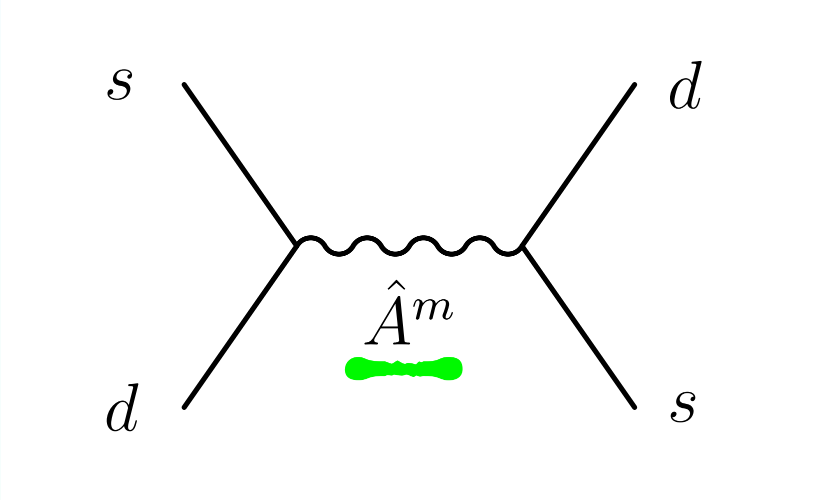
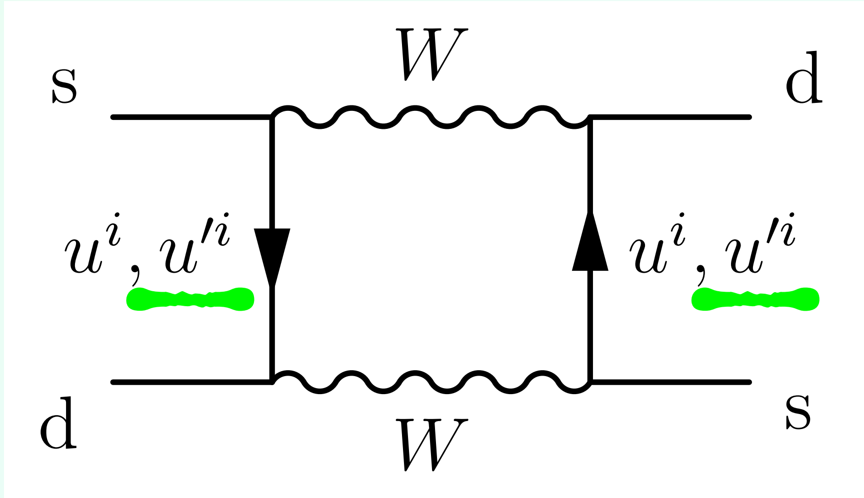
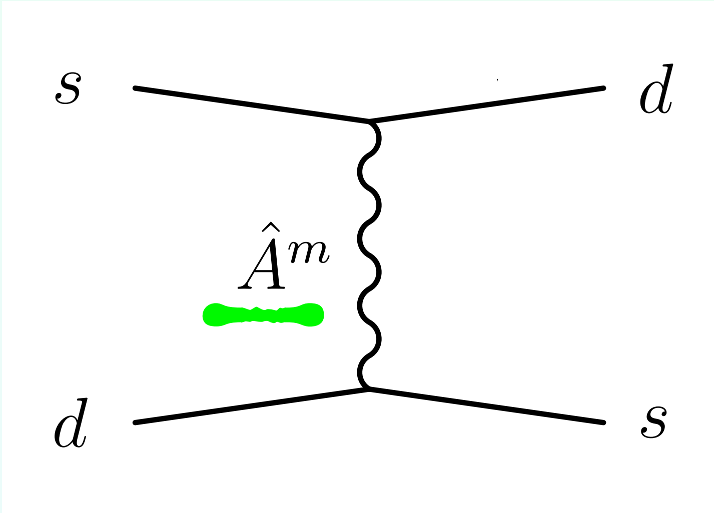
- The theory is renormalisable without GBs!!
- Effects due to new fermions needed for anomaly cancellations
- Effects due to new flavour gauge bosons

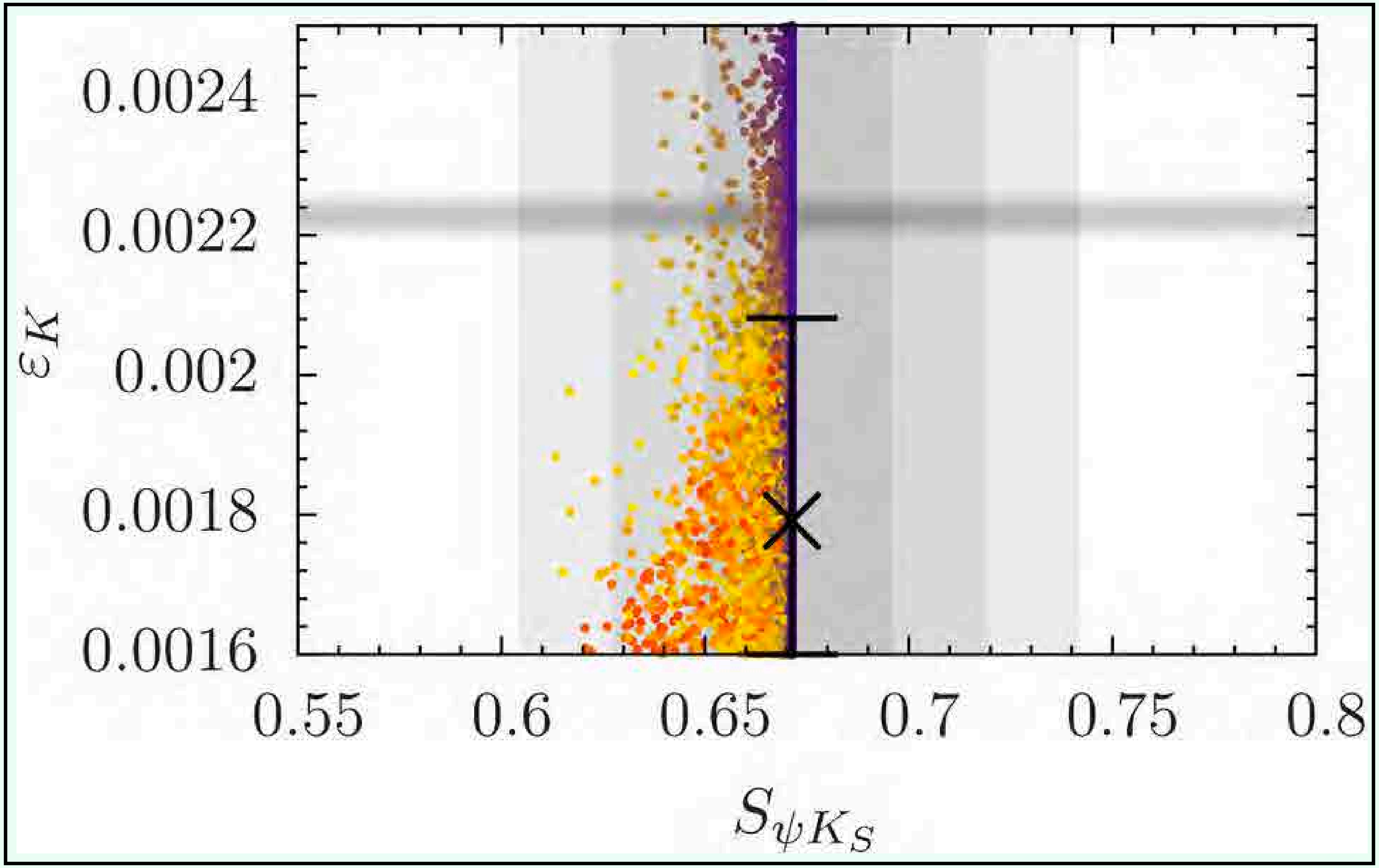
example: Meson oscillation



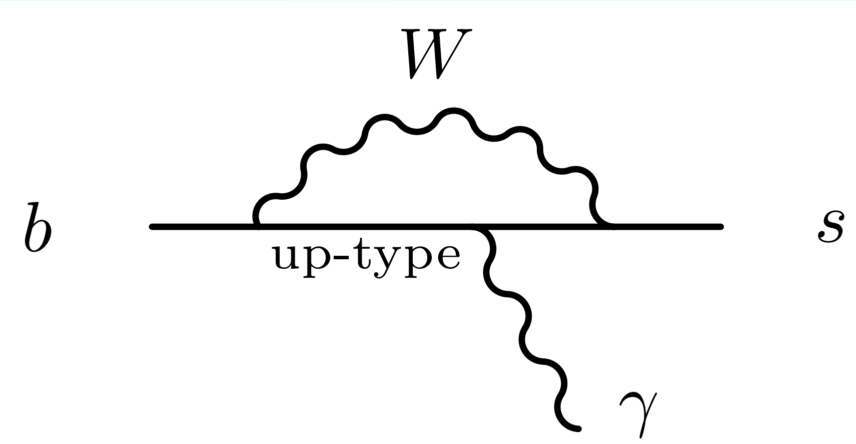


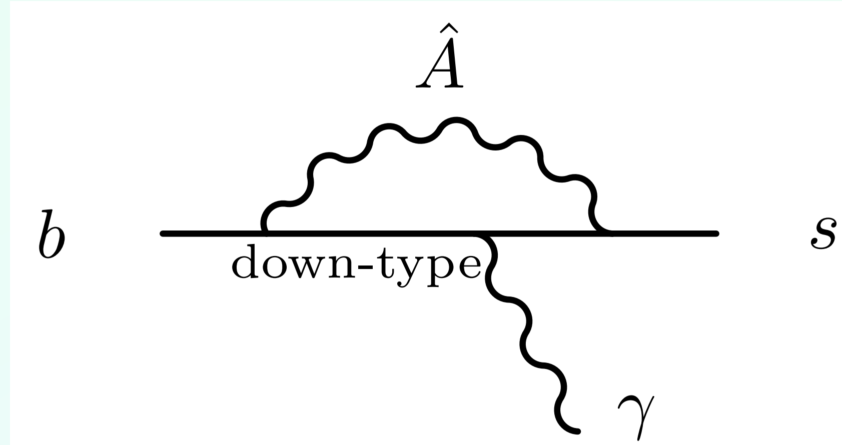


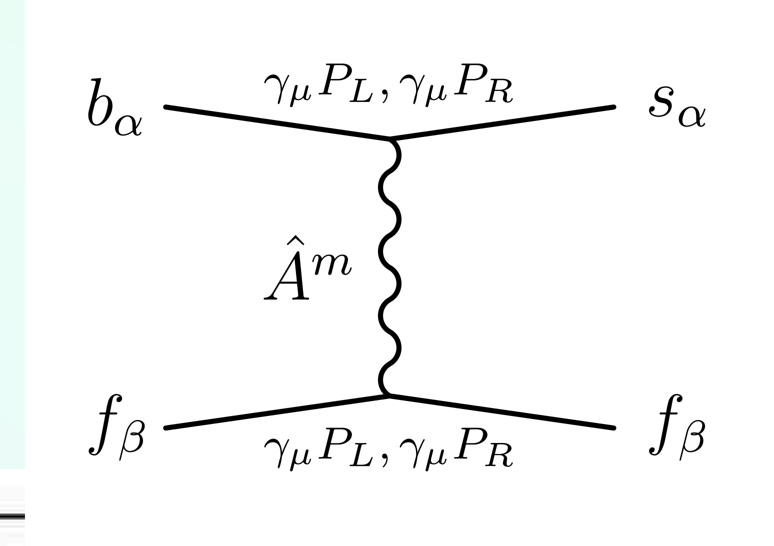


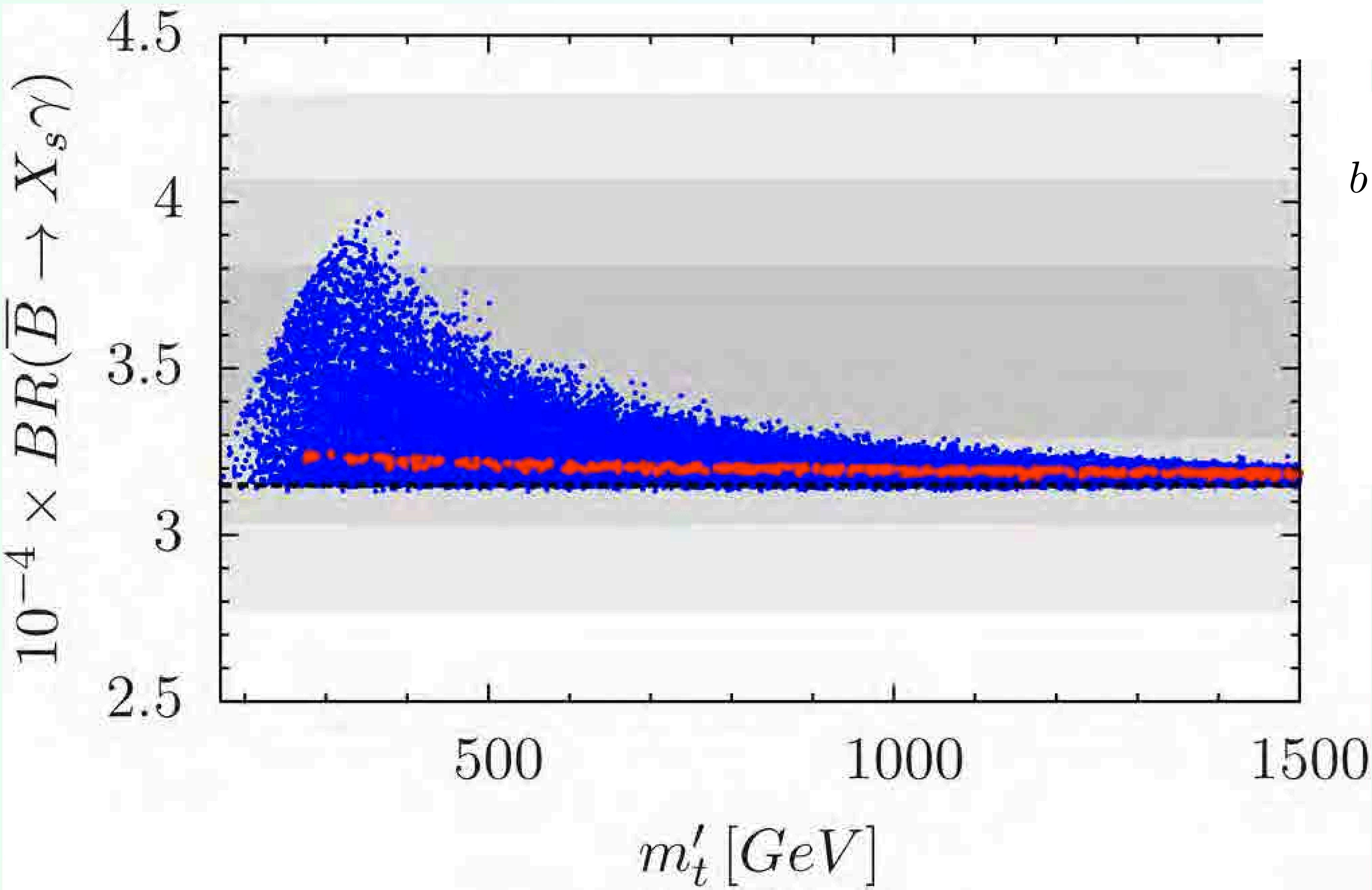


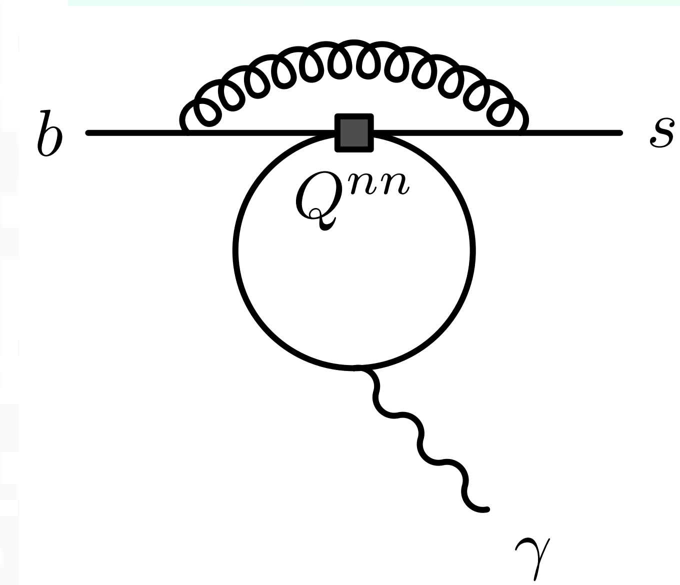
Similar to the Global MFV case











Different to the Global MFV (from universal extra dimension), as it allows only negative contributions

Gauged MLFV

GAUGED $SU(3)_{L_L} \times SU(3)_{E_R} \times SO(3)_{N_R}$

Cirigliano,Grinstein,Isidori&Wise 2005
Alonso,Isidori,LM,Munoz&Nardi 2011
Alonso, Fernandez-Martinez, Gavela, Grinstein, LM & Quilez, to appear

- Similar to the quark case, but…
- Many more possibilities due to the lack of knowledge of neutrino scale

$\mathcal{Y}_\nu \gg \mathcal{Y}_E$

Lepton Universality Violation

Z universality
$M_{\hat{\tau}} > 100.8$ GeV

Muon g-2
$M_A > 253\, g_E$ GeV

Different to the Global MLFV, as it predicts also Flavour Violation

Yukawa Flavon Potential

Does the minimum of the scalar potential justify the observed masses and mixing?

- Quarks: $U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$

Alonso, Gavela, LM & Rigolin, JHEP **1107** (2011)

- $V(\mathcal{Y}_U, \mathcal{Y}_D) \equiv V(\mathcal{I}(\mathcal{Y}_U, \mathcal{Y}_D))$

5 renormalisable Invariants $\mathcal{I}$ ($\mathcal{Y}_i^\dagger \mathcal{Y}_i$) for 10 parameters

- Minimisation of the scalar potential

$$\delta V = 0 \longrightarrow \sum_j \frac{\partial \mathcal{I}_j}{\partial p_i} \frac{\partial V}{\partial \mathcal{I}_j} = 0$$

masses, angles, phase

- Results: $U(3)^3 \to U(2)^3 \times U(1)$

$$\langle \mathcal{Y}_U \rangle \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \langle \mathcal{Y}_D \rangle \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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5 renormalisable Invariants $\mathcal{I}$ ($\mathcal{Y}_i^\dagger \mathcal{Y}_i$) for 10 parameters

Hierarchy:
good first approx.

scal

-No Mixing
-Ligher families
with non renorm?

masses, angles, phase

- Results: $U(3)^3 \to U(2)^3 \times U(1)$

$$\langle \mathcal{Y}_U \rangle \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \langle \mathcal{Y}_D \rangle \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Yukawa Flavon Potential

- Leptons: $SU(3)_{L_L} \times SU(3)_{E_R} \times SO(3)_{N_R}$

Alonso, Gavela, Hernandez & LM, PL**B715** (2012)
Alonso, Gavela, Hernandez, LM & Rigolin, JHEP**1308** (2013)
Alonso, Gavela, Isidori, Maiani, JHEP**1311** (2013)

  - 6 Invariants at renorm. order for 12 parameters.
    One more wrt quarks, due to the $SO(3)_{N_R}$: $\mathcal{Y}_\nu^T \mathcal{Y}_\nu^*$

  - Results:

$$\frac{v^2}{M}\begin{pmatrix} y_{\nu_1}^2 & 0 & 0 \\ 0 & 0 & y_{\nu_2}y_{\nu_3} \\ 0 & y_{\nu_2}y_{\nu_3} & 0 \end{pmatrix} = U_{PMNS}\begin{pmatrix} m_{\nu_1} & 0 & 0 \\ 0 & m_{\nu_2} & 0 \\ 0 & 0 & m_{\nu_2} \end{pmatrix} U_{PMNS}^T$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} \end{pmatrix}$$

Maximal mixing & Majorana phase

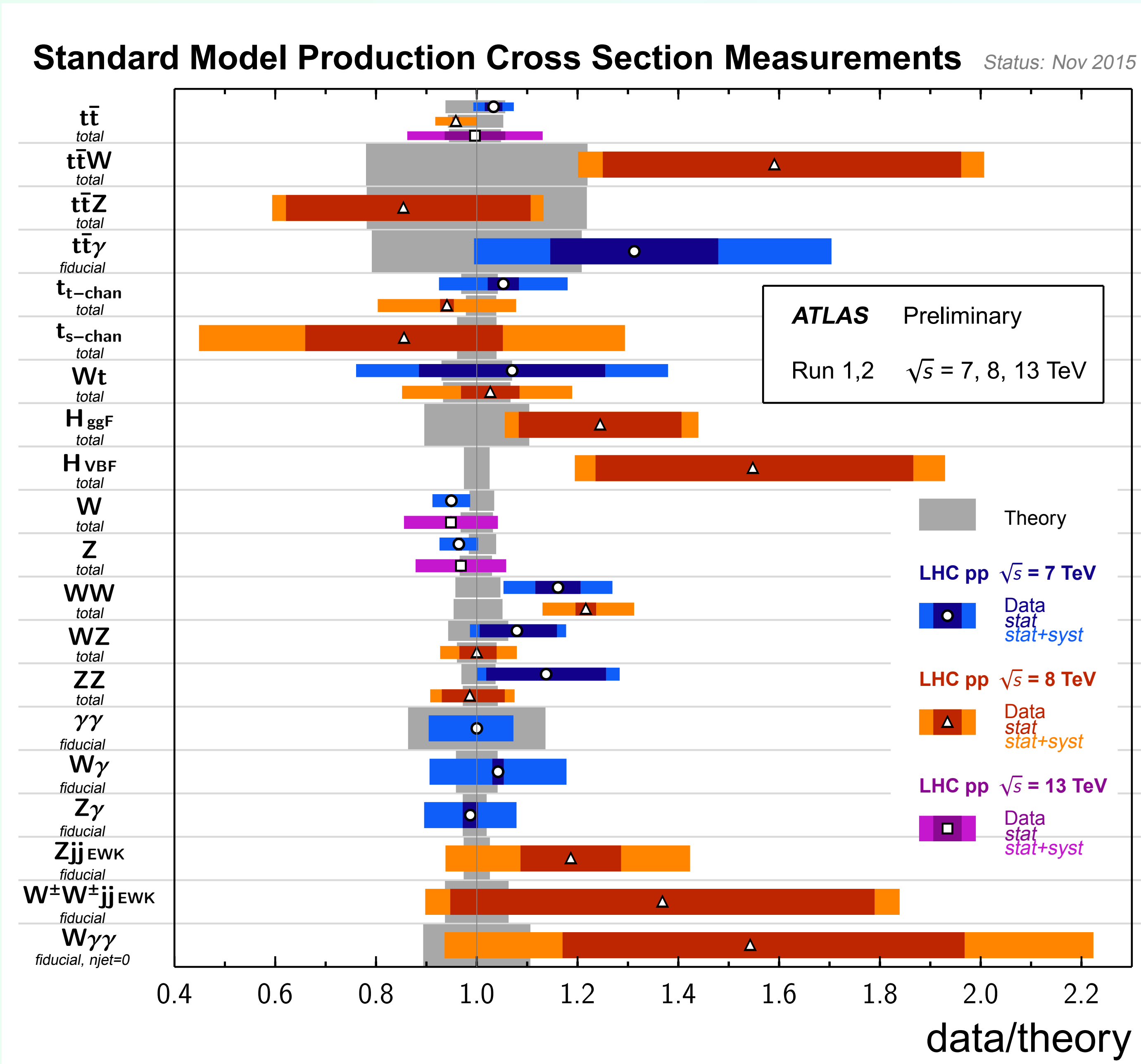
$m_{\nu_2} = m_{\nu_3}$

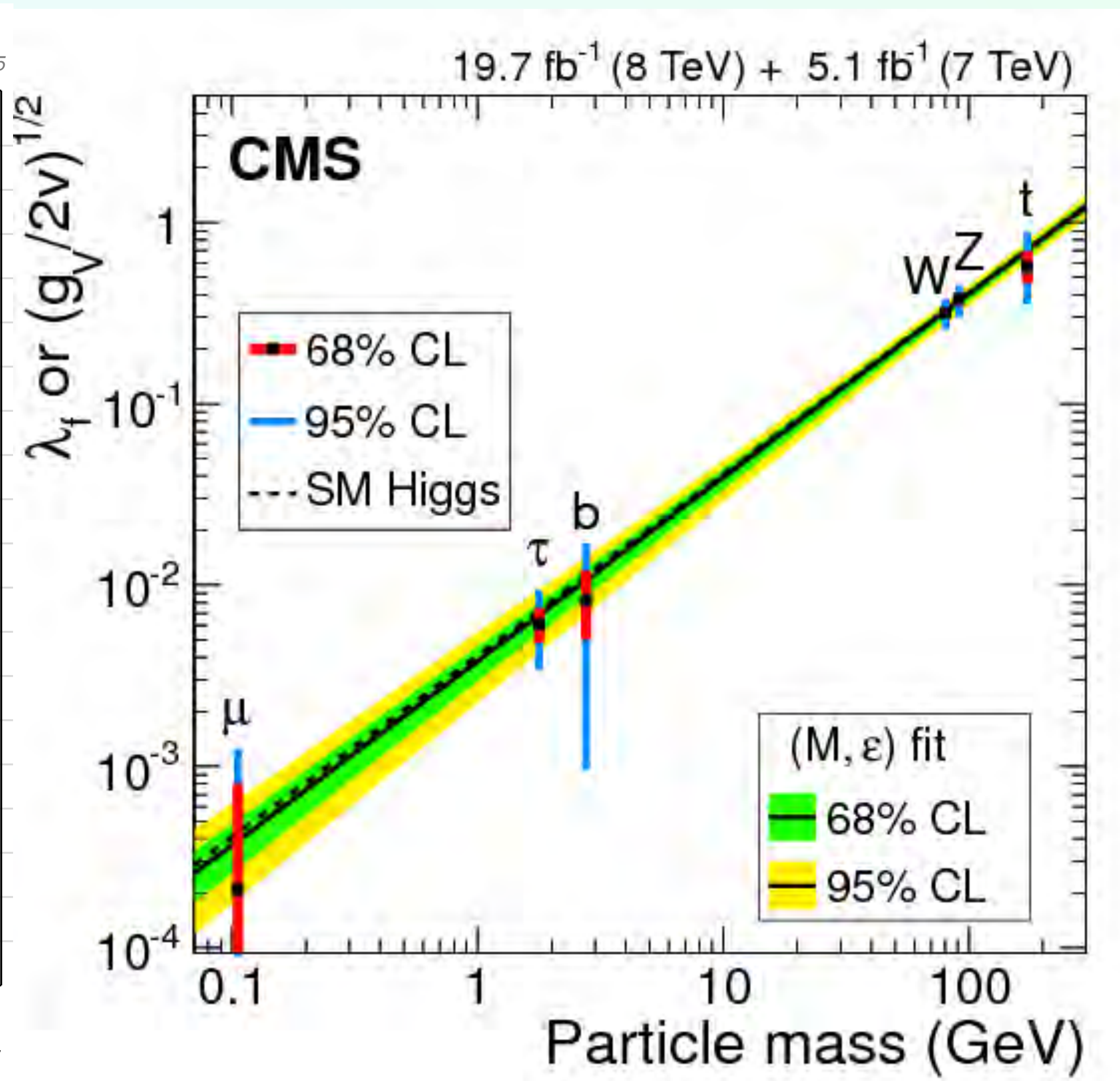
Degenerate masses

wrong sector

Higgs or not Higgs: that is the question

Everything I said if with SM Higgs. Is this sure?

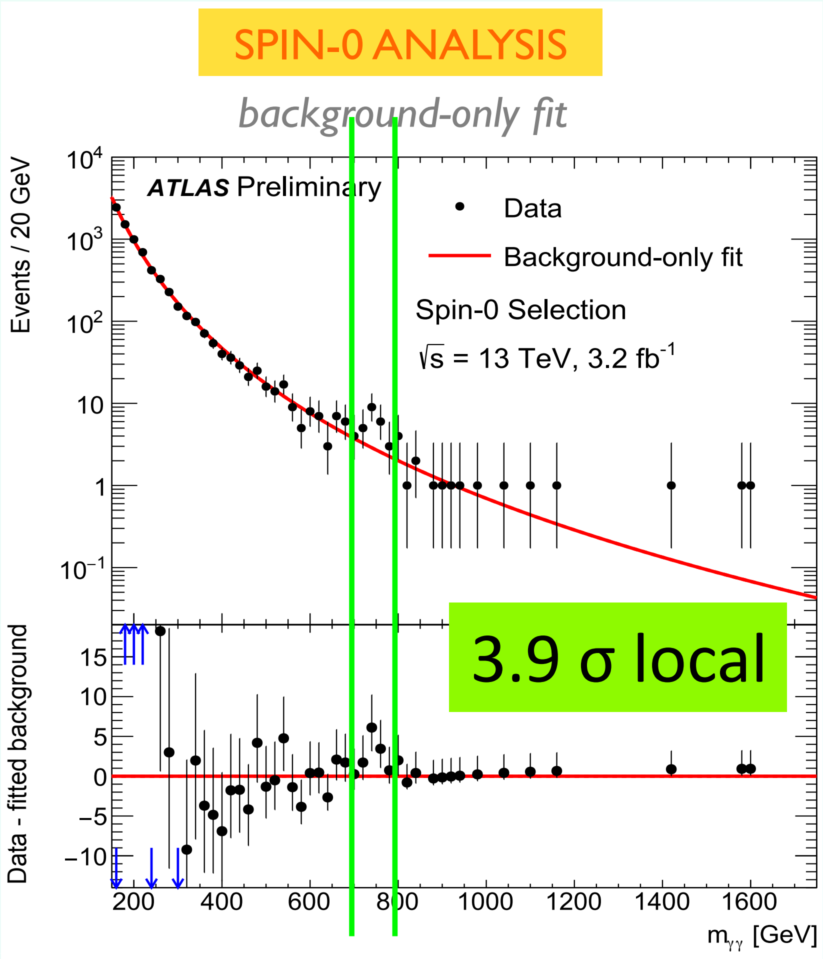


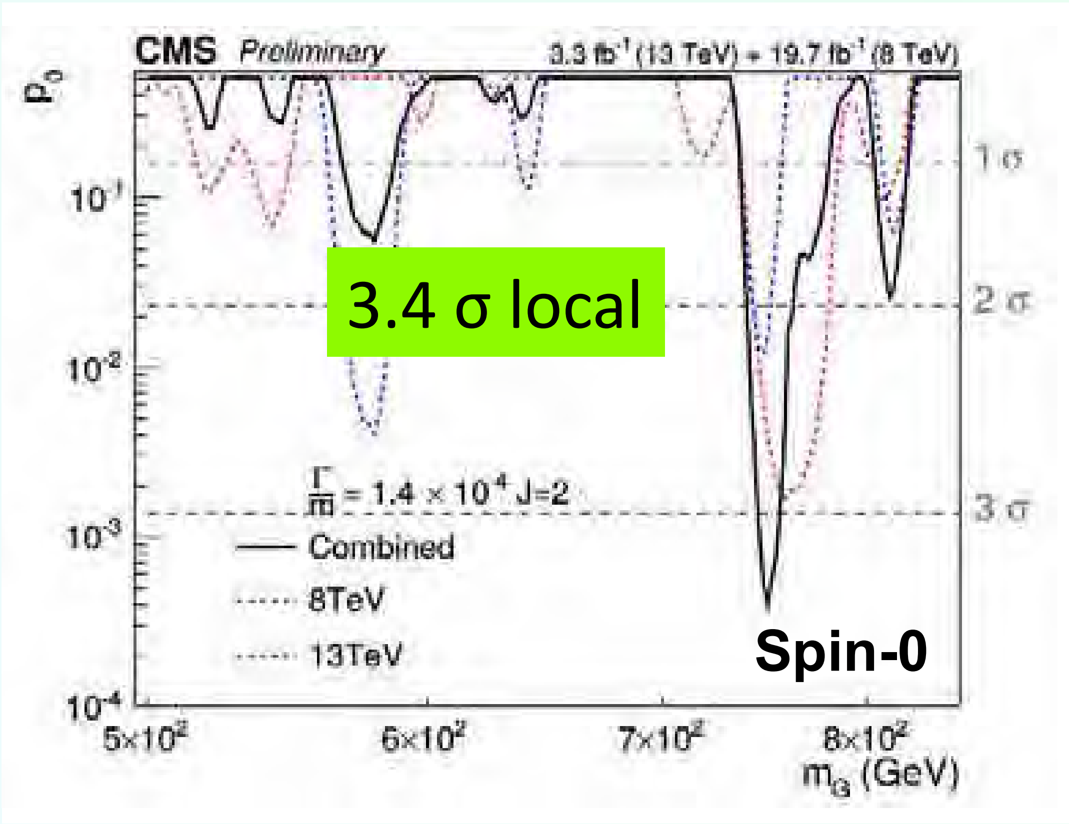


If it is not the SM Higgs, it is very similar!!

Whisperings of BSM

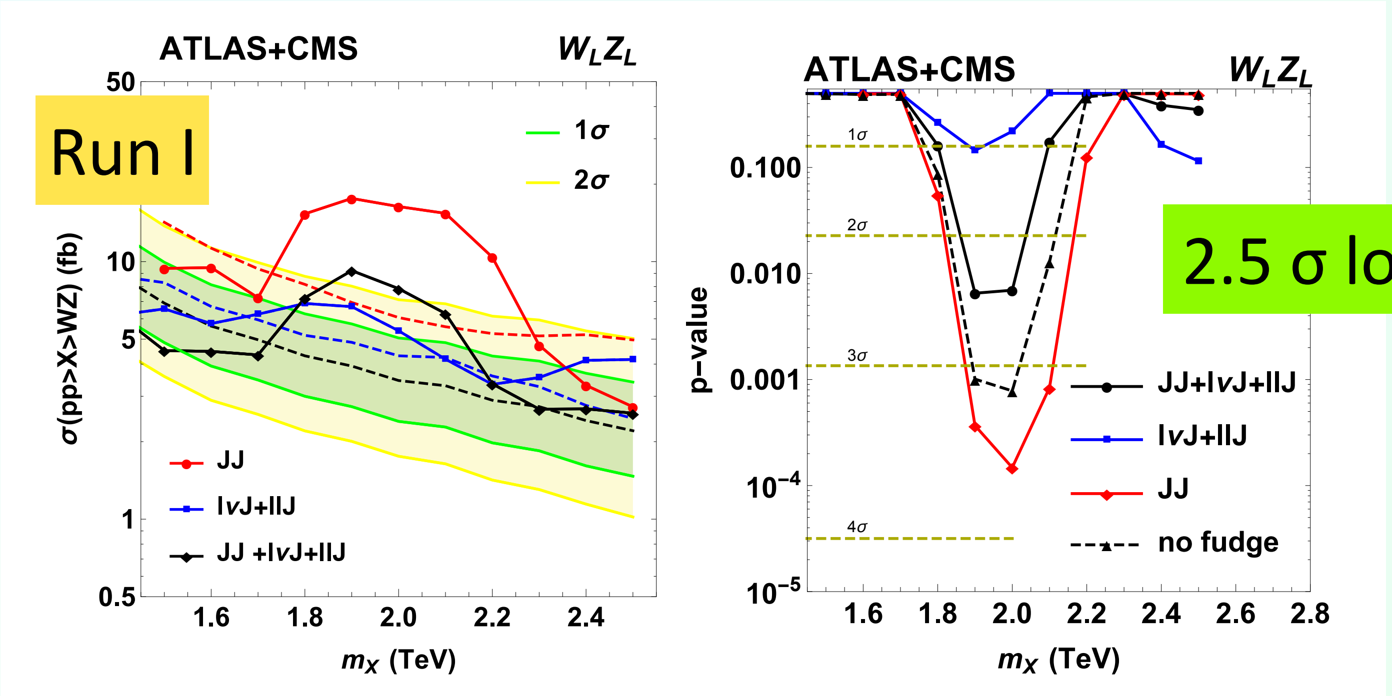
Diphoton Resonance @ 750 GeV





Dijet Diboson Excess @ 2 TeV

Run II: not enough luminosity to exclude or confirm



Indirect Searches by EFTs

EXACT EW DOUBLET

SM

Hierarchy Problem (neutrino masses & DM & Baryon Asym)

(**SUSY**

two $SU(2)_L$ doublets (Solution for HP))

NOT NECESSARILY DOUBLET

Composite Higgs Models

Not exactly an EW doublet, but almost (Solution for HP)

Dilaton or Exotic

EW singlet

Linear Effective Lagrangian SMEFT

$SU(2)_L \times U(1)_Y$ gauge sym

SM spectrum, and in particular exact EW Higgs doublet Φ

Non-Linear Effective Lagrangian HEFT

$SU(2)_L \times U(1)_Y$ gauge sym

SM spectrum, but non-exact EW Higgs doublet h

The SMEFT Lagrangian

In 4 traditional space-time dimensions:

Buchmüller & Wyler, NPB 268 (1986)
Grzadkowski, Iskrzynski, Misiak & Rosiek, JHEP 1010 (2010)

$$\mathcal{L}_{\text{linear}} = \boxed{\mathcal{L}_{SM}} + \boxed{\sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i} + \text{higher orders}$$

with Λ (≥ few TeV) the NP scale

$$\begin{aligned}\mathcal{L}_{SM} = & -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - V(h) \\ & + (D_\mu\Phi)^\dagger(D^\mu\Phi) + i\bar{Q}\not{D}Q + i\bar{L}\not{D}L \\ & - (\bar{Q}_L\Phi\mathcal{Y}_D D_R + \text{h.c.}) - \left(\bar{Q}_L\tilde{\Phi}\mathcal{Y}_U U_R + \text{h.c.}\right) \\ & - (\bar{L}_L\Phi\mathcal{Y}_L L_R + \text{h.c.})\end{aligned}$$

59 (no flavour) d=6 operators preserving SM, lepton, baryon syms

Higgs Physics in SMEFT

Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRD87 (2013)

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi \; G^a_{\mu\nu}G^{a\mu\nu}$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{u\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_{L_3}\Phi u_{R_3})$$

$$\mathcal{O}_{d\Phi,33} = (\Phi^\dagger\Phi)(\bar{Q}_{L_3}\Phi d_{R_3})$$

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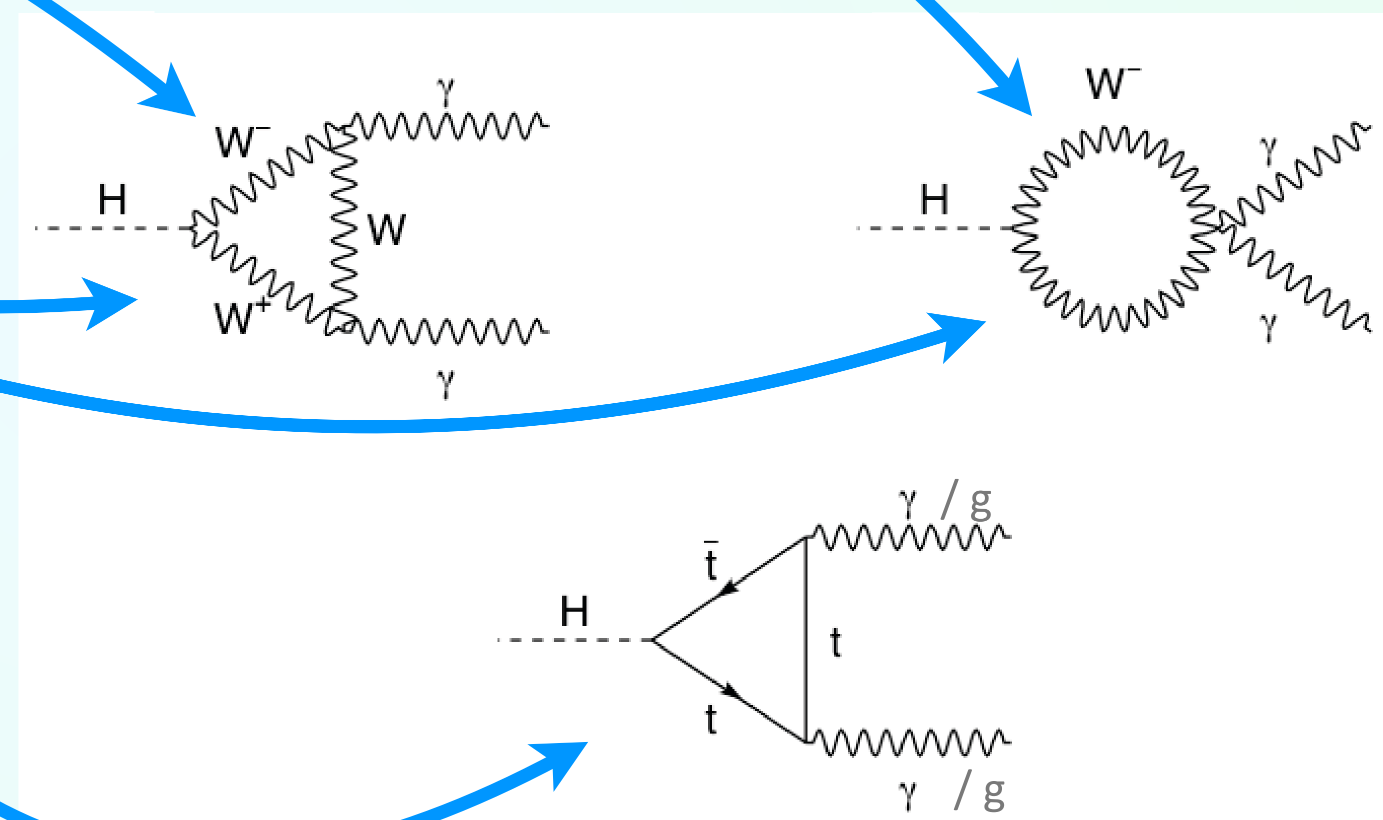
$$\mathcal{O}_{e\Phi,33} = (\Phi^\dagger \Phi)(\bar{L}_{L_3} \Phi e_{R_3})$$

NOT REALLY IMPORTANT

- Contribute to:

HVV VVV VVVV



- Gauge Invariance implies correlations between TGC and HVV

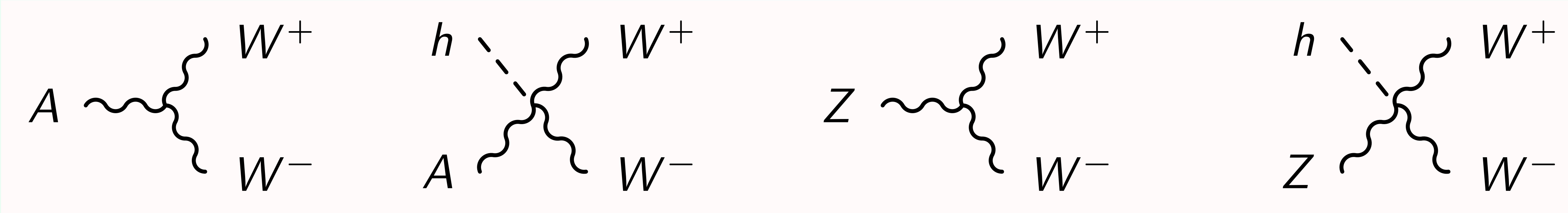
Interplay HVV and TGV

- Correlation between HVV and TGV: Example

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

In unitary gauge can be rewritten as:

$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$
$$- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)$$

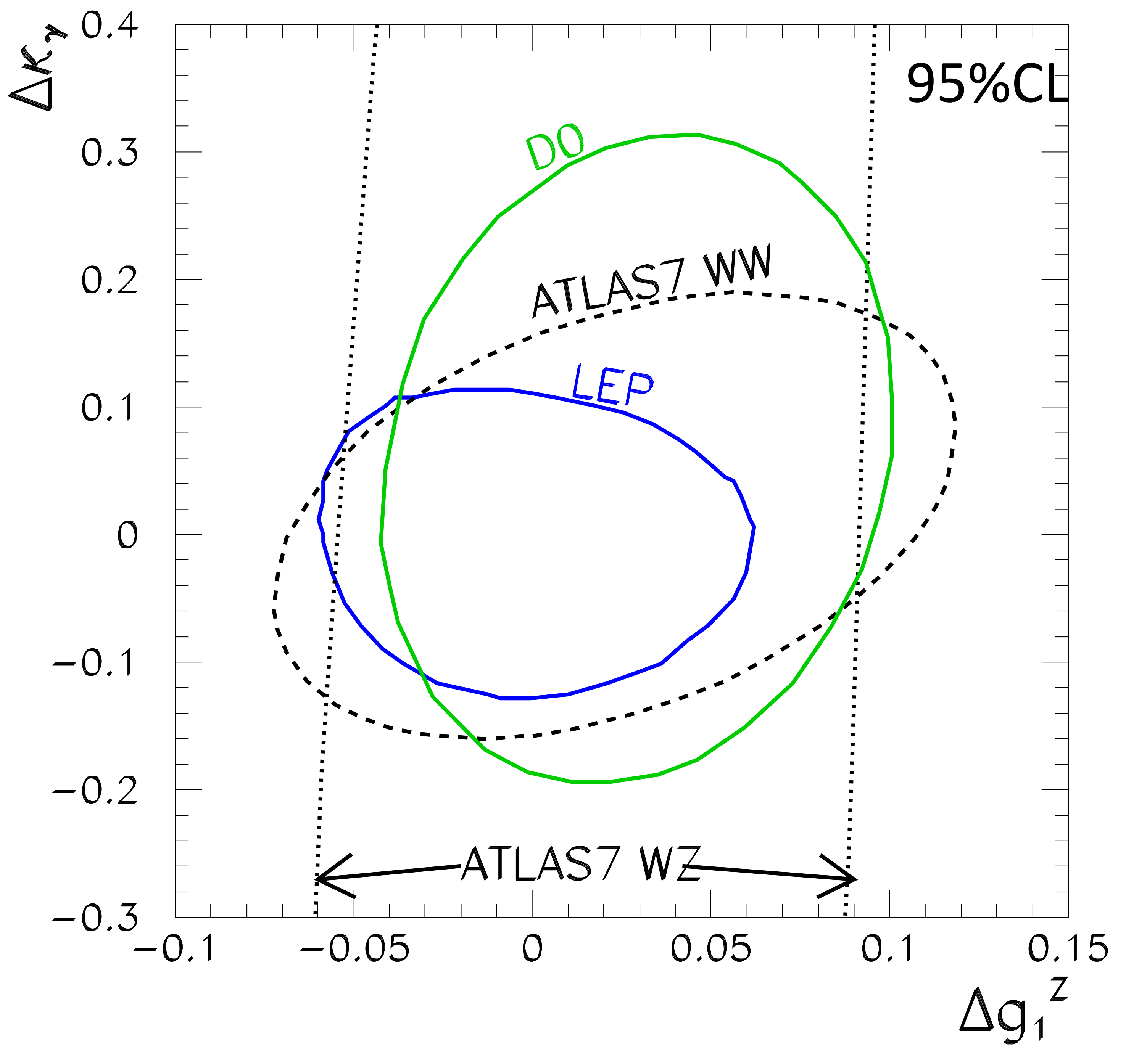


All these couplings are correlated!!

Interplay HVV and TGV

Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRL 111 (2013)

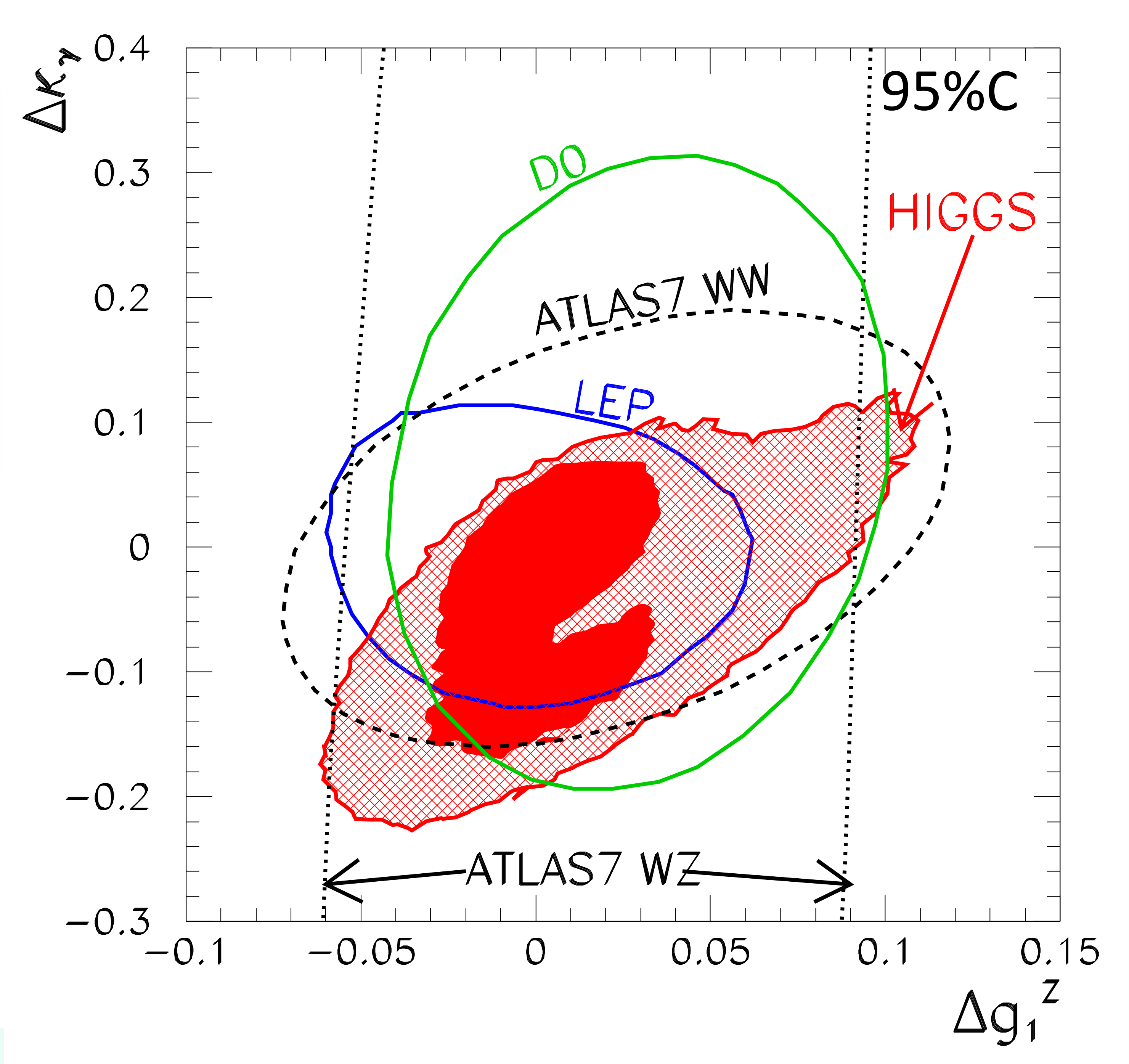
$$\mathcal{L}_{WWV} = -ig_{WWV}\left\{g_1^V\left(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}\right\}$$



Interplay HVV and TGV

Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRL 111 (2013)

$$\mathcal{L}_{WWV} = -\,i g_{WWV}\left\{ g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} \right\}$$



Higgs data bounds (7+8 TeV data used, including kinematics)

HEFT

SMEFT: constructed with

$$\boxed{\Phi(x) = \frac{v+h}{\sqrt{2}} e^{i\sigma_a \pi^a(x)/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}} \longleftrightarrow \textbf{HEFT}$$

Higgs: h **Singlet**

GBs: $\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$

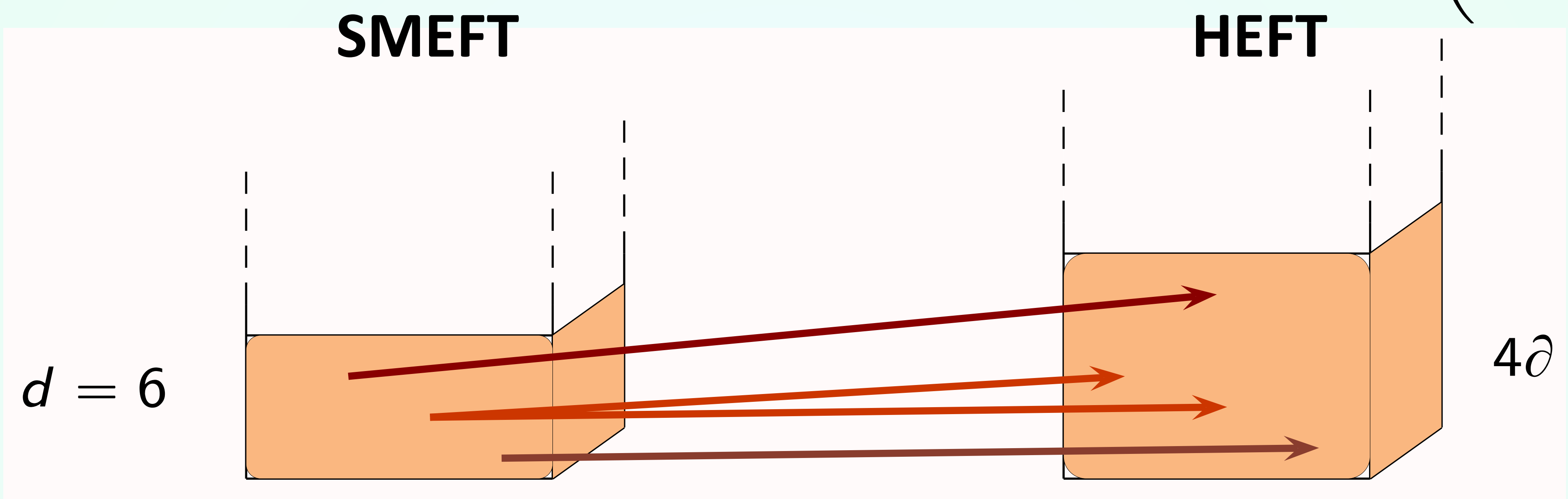
$\mathbf{U}(x) \to L\,\mathbf{U}(x) R^\dagger$

Independent!!

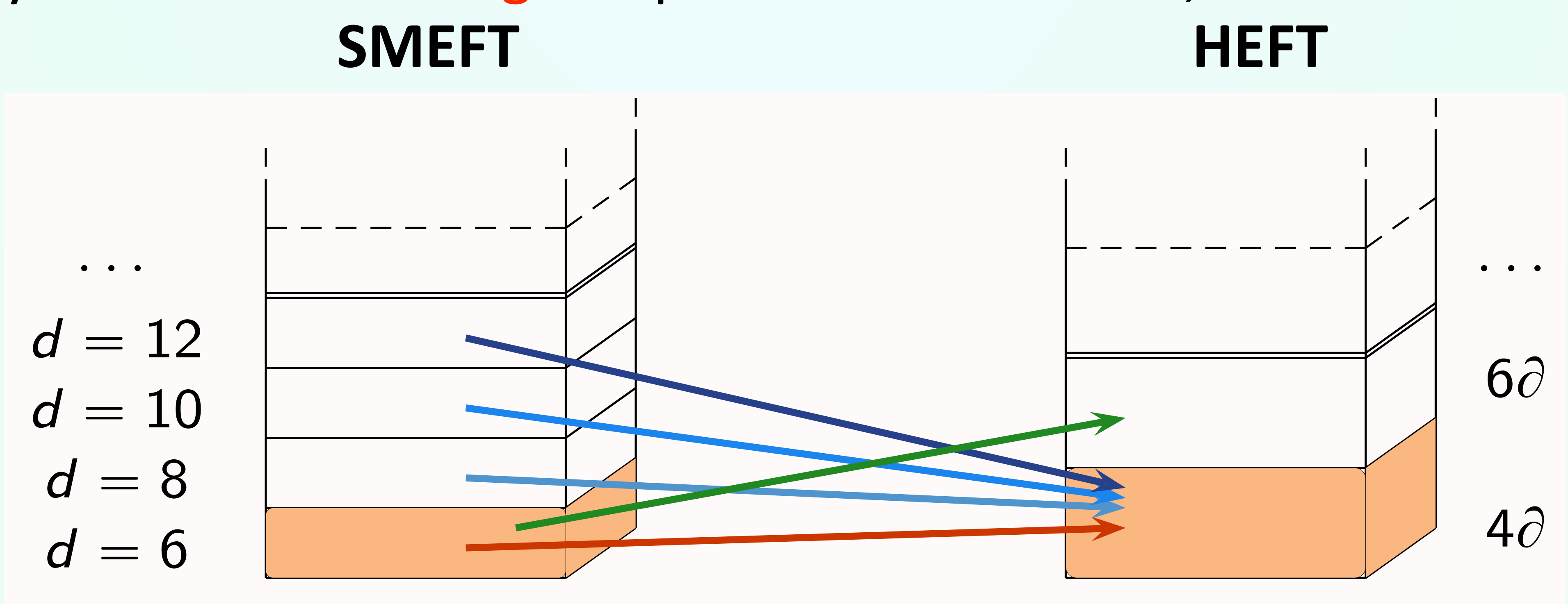
- Being h a singlet: generic functions of h $\boxed{\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots}$
- Being $\boxed{\mathbf{U}(x) \textbf{ vs. } h}$ independent, many more operators can be constructed

Decorrelations & New Signals

- Investigate on the signals of decorrelations: due to the nature of the chiral expansion vs. the linear one, and due to $\mathcal{F}_i(h) \neq \left(1+\frac{h}{v}\right)^2$



- Study the anomalous signals present in the chiral, but absent in the linear



Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)

What is HEFT?

The Higgs Effective Field Theory (HEFT) is a fusion of SMEFT and ChiPT

HEFT

SMEFT

$i\bar{\psi}\not{D}\psi$

$X_{\mu\nu}X^{\mu\nu}$

$\partial_\mu h \partial^\mu h$

+

ChiPT

$\mathbf{U} \equiv e^{2i\mathbf{\Pi}/f}$

$D_\mu \mathbf{U}^\dagger D^\mu \mathbf{U}$

3 GBs SM

HEFT describes an extended class of "Higgs" models:

$$\left.\begin{array}{l}\text{Standard Model}\\ \text{SMEFT}\\ \text{Technicolor-like ansatz}\\ \text{Dilator-Like models}\\ \text{Composite Higgs models}\end{array}\right\}$$

special limits and fixing the parameters

Alonso,Brivio,Gavela,LM&Rigolin, JHEP **12** (2014) 034

Hierro,LM&Rigolin, arXiv:1510.07899

What is HEFT?

The Higgs Effective Field Theory (HEFT) is a fusion of SMEFT and ChiPT

HEFT

SMEFT

$i\bar{\psi}\not{D}\psi$

$X_{\mu\nu}X^{\mu\nu}$

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+

ChiPT

$\mathbf{U} \equiv e^{2i\mathbf{\Pi}/f}$

$D_\mu \mathbf{U}^\dagger D^\mu \mathbf{U}$

3 GBs SM

Building blocks:

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U})\, \mathbf{U}^\dagger \qquad \mathbf{V} \to L\, \mathbf{V}\, L^\dagger$$

$$\mathbf{T} \equiv \mathbf{U}\sigma_3\mathbf{U}^\dagger \qquad \mathbf{T} \to L\, \mathbf{T}\, L^\dagger$$

$$L \in SU(2)_L$$

$\psi_{L,R}$

$A_\mu \qquad X_{\mu\nu}$

h singlet of SM syms: arbitrary $\mathcal{F}(h) = \sum_{i=0} a_i \left(\frac{h}{f}\right)^i$

The HEFT Lagrangian

Azatov, Contino & Galloway JHEP 1204 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, JHEP 1206 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, PLB 722 (2013)
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)
Buchalla, Cata & Krause, NPB 880 (2014)
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM, Rigolin & Yepes, JHEP 1410 (2014)
Brivio, Gonzalez-Fraile, Gonzalez-Garcia & LM, 1604.06801 YESTERDAY

$$\mathcal{L}_{HEFT} = \boxed{\mathcal{L}_0} + \Delta\mathcal{L}$$

$$\begin{aligned}
\mathcal{L}_0 = & -\frac{1}{4}G^{\alpha}_{\mu\nu}\mathcal{G}^{\alpha\,\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \\
D_\mu\Phi^\dagger D^\mu\Phi \rightarrow & \boxed{+\frac{1}{2}\partial_\mu h\partial^\mu h - \frac{v^2}{4}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\mathcal{F}_C(h)} - V(h) + \\
& + i\bar{Q}_L \not{D} Q_L + i\bar{Q}_R \not{D} Q_R + i\bar{L}_L \not{D} L_L + i\bar{L}_R \not{D} L_R + \\
& - \frac{v}{\sqrt{2}}\left(\bar{Q}_L\mathbf{U}\mathcal{Y}_Q(h)Q_R + \mathrm{h.c.}\right) - \frac{v}{\sqrt{2}}\left(\bar{L}_L\mathbf{U}\mathcal{Y}_L(h)L_R + \mathrm{h.c.}\right)
\end{aligned}$$

The HEFT Lagrangian

Alonso, Gavela, LM, Rigolin & Yepes, PLB 722 (2013)
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM, Rigolin & Yepes, JHEP 1410 (2014)
Gavela, Kanshin, Machado & Saa, JHEP 1503 (2015)
Brivio, Gonzalez-Fraile, Gonzalez-Garcia & LM, 1604.06801

$$\mathcal{L}_{HEFT} = \mathcal{L}_0 \boxed{+ \Delta\mathcal{L}}$$

- 148 (no flavour) operators preserving SM, lepton, baryon syms, up to NLO in the renormalisation procedure (4 derivatives & d=6)
- Higgs analysis similar to SMEFT: 10 parameters wrt 9 of SMEFT

Decorrelations

- More important effects when comparing TGV and HVV: for example

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

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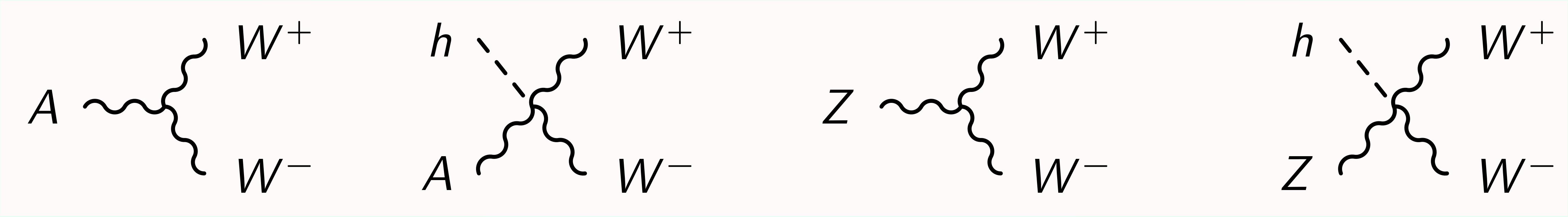
$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$
$$- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^{\mu} \partial^{\nu} h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^{\mu} \partial^{\nu} h (v+h)$$

$$\mathcal{O}_B = \frac{v^2}{16}\mathcal{P}_2(h) + \frac{v^2}{8}\mathcal{P}_4(h)$$ **with** $$\mathcal{F}_i(h) = \left(1 + \frac{h}{v}\right)^2$$

$$\mathcal{P}_2(h) = i B_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\left[\mathbf{V}^{\mu}, \mathbf{V}^{\nu}\right]\right) \mathcal{F}_2(h)$$
$$\mathcal{P}_4(h) = i B_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^{\mu}\right) \partial^{\nu} \mathcal{F}_4(h)$$



Decorrelations

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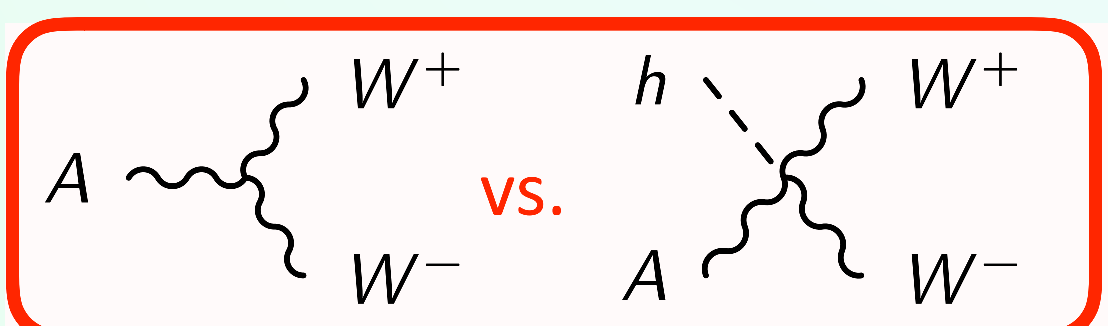
$$\Rightarrow \quad \mathcal{O}_B = \frac{v^2}{16} \mathcal{P}_2(h) + \frac{v^2}{8} \mathcal{P}_4(h) \quad \text{with} \quad \mathcal{F}_i(h) = \left(1 + \frac{h}{v}\right)^2$$

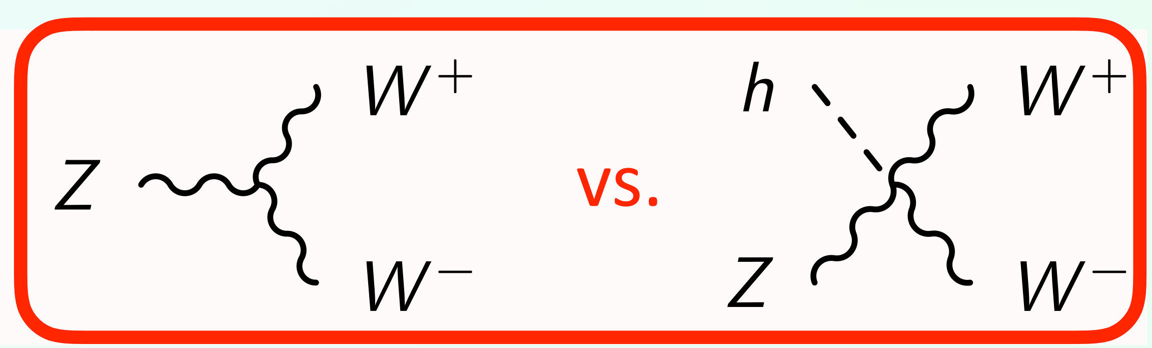
$$\mathcal{P}_2(h) = 2ieg^2 A_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) - 2\frac{ie^2 g}{\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h)$$

$$\mathcal{P}_4(h) = -\frac{eg}{\cos\theta_W} A_{\mu\nu} Z^{\mu} \partial^{\nu} \mathcal{F}_4(h) + \frac{e^2}{\cos^2\theta_W} Z_{\mu\nu} Z^{\mu} \partial^{\nu} \mathcal{F}_4(h)$$

due to the decorrelation in the $\mathcal{F}_i(h)$ functions: i.e.

[see also Isidori&Trott, 1307.4051]





Decorrelations

- More important effects when comparing TGV and HVV: for example

$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$
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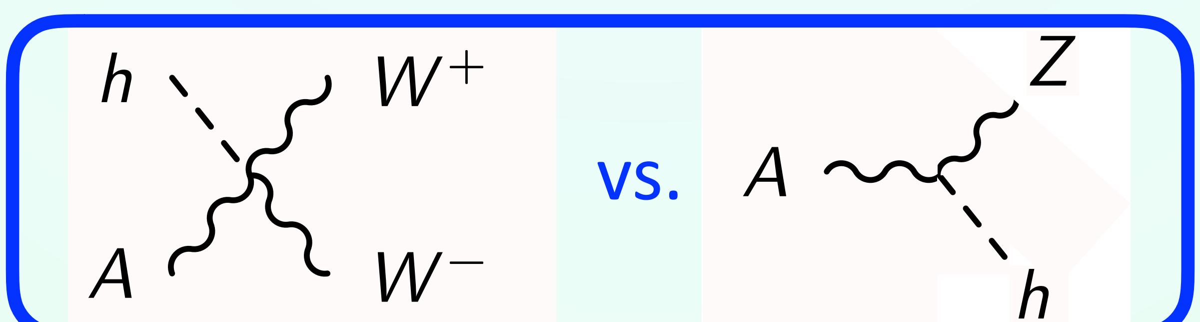
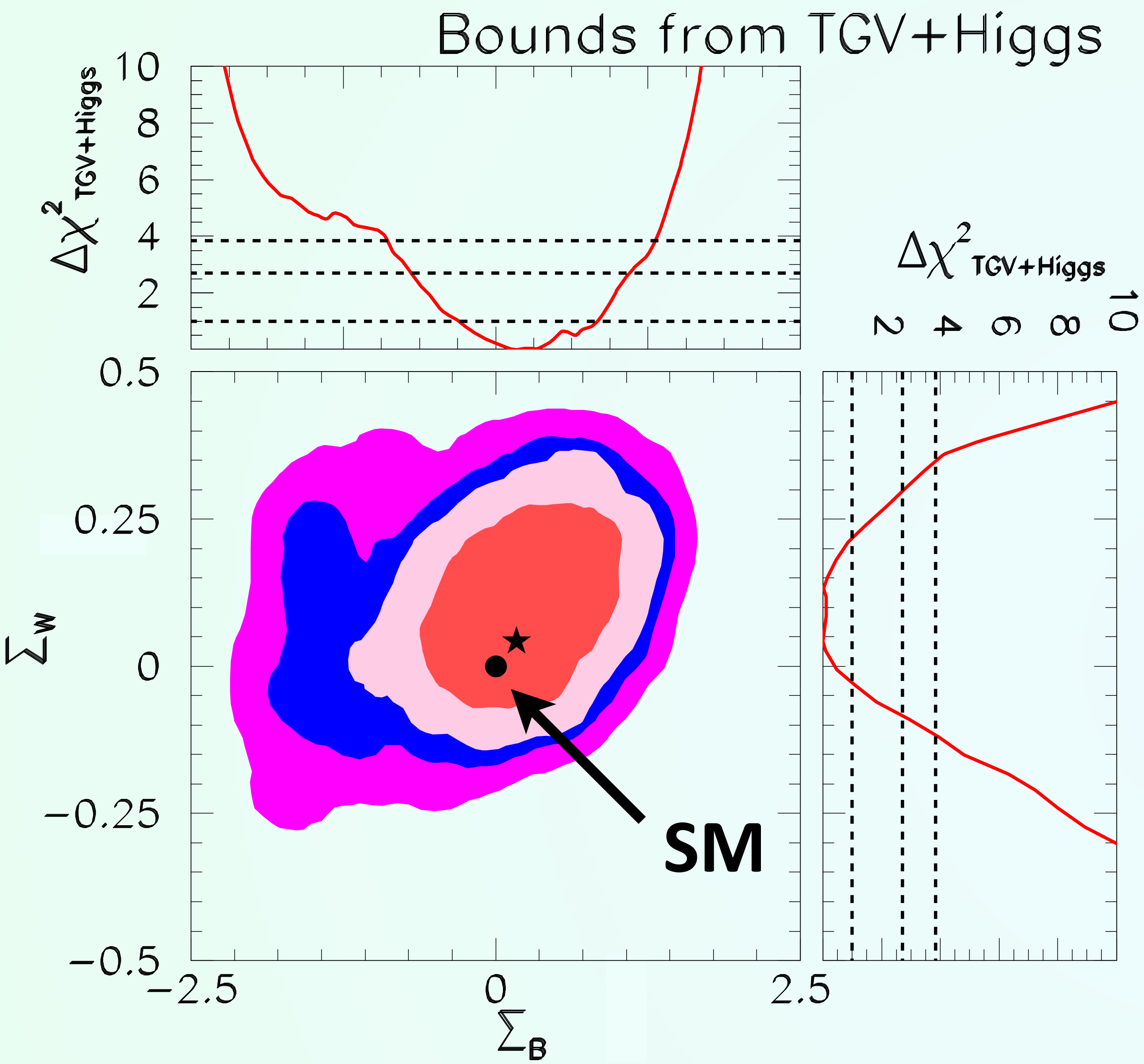
due to the nature of the chiral operators (different c_i coefficients): i.e.

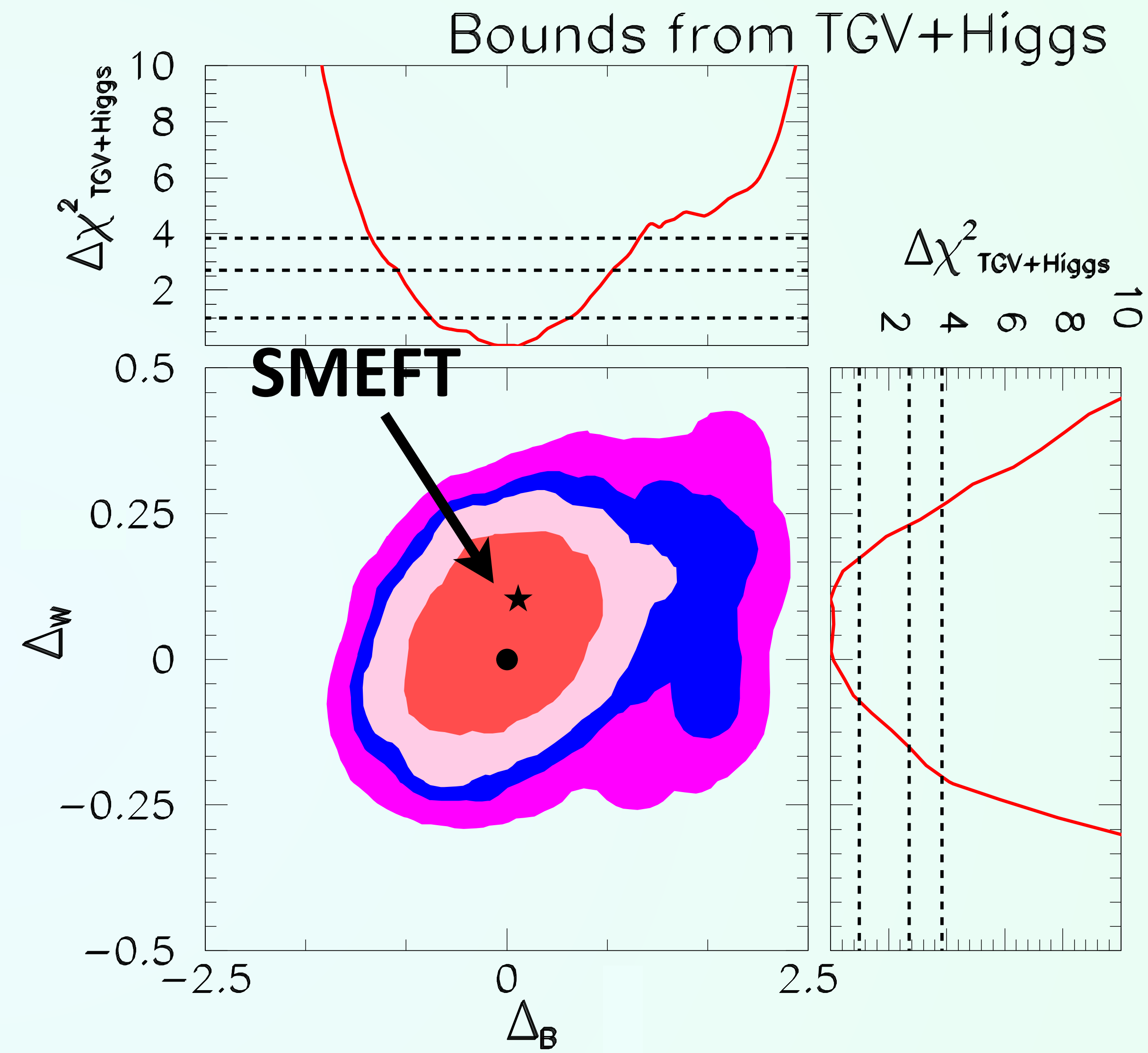


Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)
Brivio, Gonzalez-Fraile, Gonzalez-Garcia & LM, 1604.06801

SM vs. BSM



SMEFT vs. HEFT



$$\Sigma_B = 4(2c_2 + a_4) \to f_B$$

$$\Delta_B = 4(2c_2 - a_4) \to 0$$

$$\Sigma_W = 2(2c_3 - a_5) \to f_W$$

$$\Delta_W = 2(2c_3 + a_5) \to 0$$

Data: Tevatron D0 and CDF Collaborations and LHC, CMS, and ATLAS Collaborations at 7 TeV and 8 TeV for final states $\gamma\gamma$, W^+W^-, ZZ, $Z\gamma$, $b\bar{b}$, and $\tau\bar{\tau}$

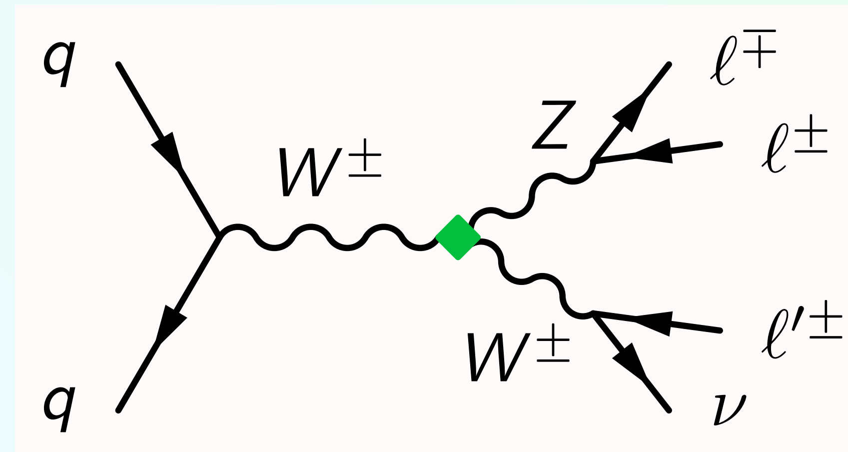
New Signals

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)

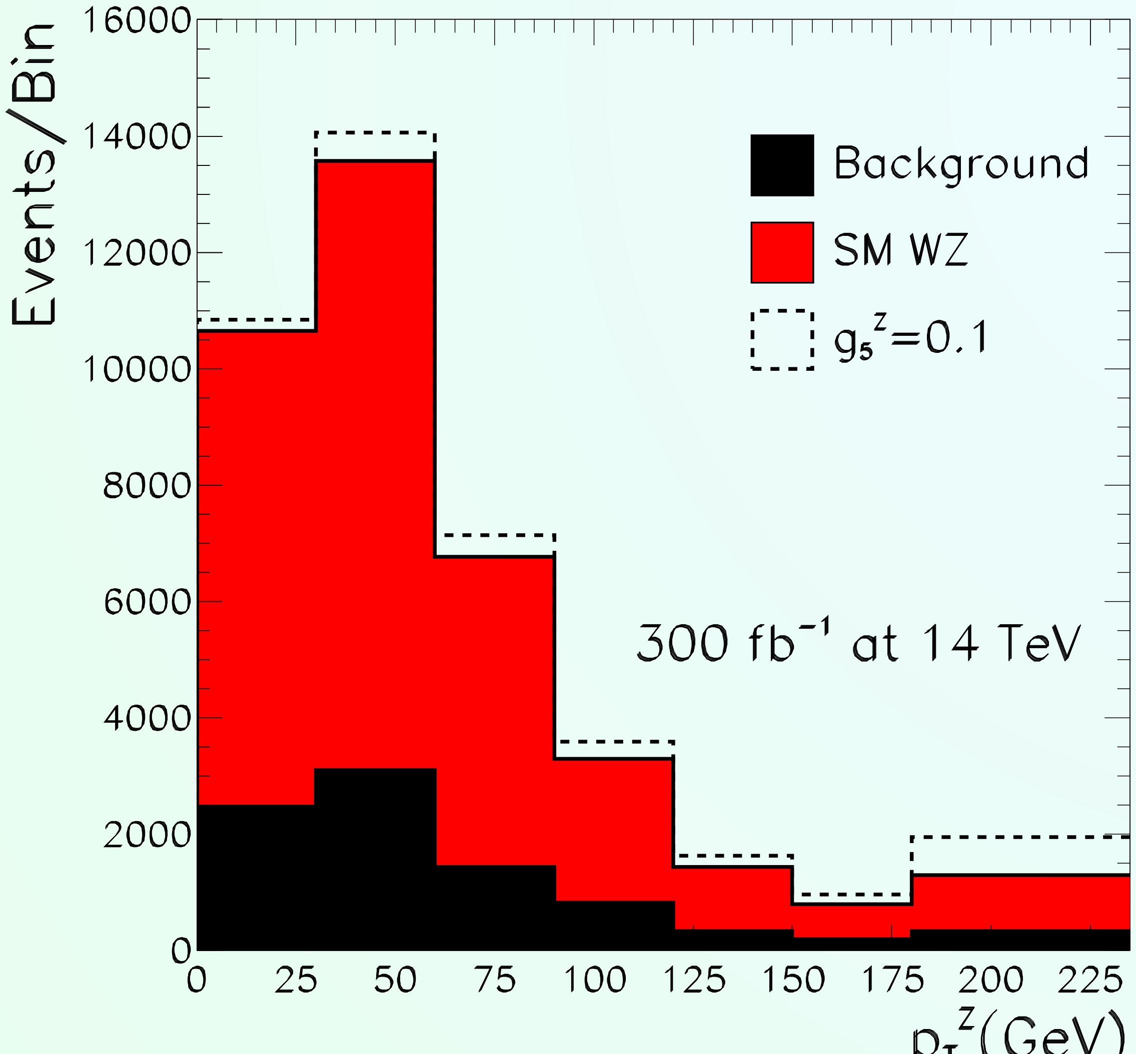
Signals expected in the chiral basis, but not in the linear one (d=8)

$$\mathcal{P}_{14}(h) = \varepsilon^{\mu\nu\rho\lambda}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}(h)$$

$$g_5^Z\,\varepsilon^{\mu\nu\rho\lambda}\partial_\mu W_\nu^+ W_\rho^- Z_\lambda \mathcal{F}_{14}(h)$$



number of expected events (WZ production) with respect to the Z p_T



@95% CL:

present $g_5^Z \in [-0.08, 0.04]$

LHC(7+8+14) $g_5^Z \in [-0.033, 0.028]$

Message to Experimental Collaborations: please, do this dedicate analysis!

Conclusions and future directions

Alonso, Gavela, LM, Rigolin & Yepes 2012

Interplays

MFV Flavour symmetries

Safe FCNC & LFV

Quarks - Leptons Majorana nature

Find a final solution for the scalar potential

Exploit other strategies: multi-Yukawa fields?

SM Higgs or not?

Disentangling Effects

New Signals

What with 750 GeV?

Full flavour analysis

Interplays

Dark Matter

Is DM another flavour?
Lopez-Honores & LM 2013

How it speaks with SM?
Brivio,Gavela,LM,Mimasu,No,Rey,Sanz 2015

Interplays