FLASY 2014: Summary Talk

Stefan Antusch

University of Basel
Department of Physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Flasy2014, University of Sussex, UK

June 21, 2014

An ongoing very exciting match ...

Many great players (topics) ...

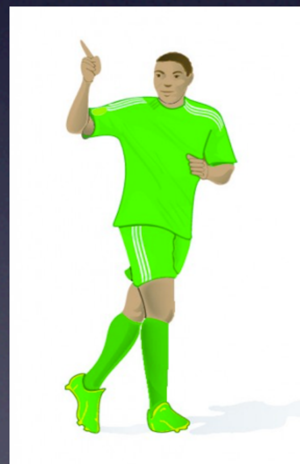
Neutrino Physics

Flavour Phenomenology

GUTs

Dark Matter,
Leptogenesis
Inflation

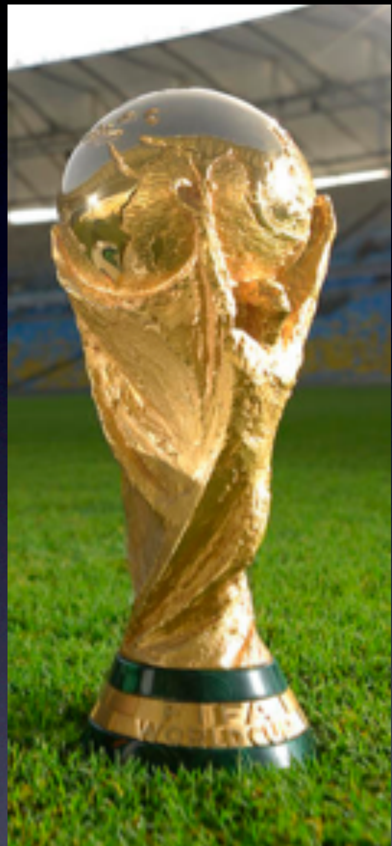
Colliders,
TeV physics



Flavour model building

...

Aim of the “FLASY Championship”



→ Towards a more fundamental theory (& symmetries) beyond the SM

Many interesting talks

Neutrino Physics

Rodejohann, No, Hartnell, Weber, Lindner, Tanimoto, Merle, Emanuel-Costa, Ludl, Fujimoto, Rojas, Moumni

Colliders, TeV physics

Schmidt, Deppisch, Redi, Romao

Flavour Phenomenology

Voena, Khalil, Crivellin, Yamaguchi, Ziegler, Rohrwild, Vincente Montesinos, Martin Camalich, Hiller, Fleischer, Spradlin, Kubo, Schacht, Lenz, Zwicky, van Dyk, Czerwinski, Paradisi, Brod, Stamou, Yamamoto

Models of Flavour

Feruglio, Nardi, Ko, Mondragon, Ivanov, Serodio, Solaguren-Beascoa, Neder, Bonilla, Trautner, de Medeiros Varzielas, Holthausen, Ding, Luhn, Malinsky

Dark Matter, Leptogenesis, Inflation

Morisi, Monroe, Aoki, Watanabe, Peinado, Haba, Schumacher, Takahashi, Sil

GUTs

Shafi, Spinrath, Maurer, Gonzales-Cannales, Muramatsu

My appologies that I will only be able to discuss a selection of aspects ...

Many Thanks to all speakers!

Present status: Fermion masses

$m_u \approx 0.0013$ GeV ± 30%
$m_c \approx 0.63$ GeV ± 3%
$m_t \approx 172.2$ GeV ± 1%

→ hierarchical masses
(even more hierarchical than M_d, M_e)

Up-type quarks

M_u

Down-type quarks

M_d

Running masses at $\mu = M_Z$
(from arXiv:1306.6879)

$m_d \approx 0.0026$ GeV ± 10%
$m_s \approx 0.054$ GeV ± 5%
$m_b \approx 2.86$ GeV ± 1%

→ hierarchical masses

Neutrinos

m_ν

Charged leptons

M_e

from NuFIT Collaboration:

$|m_3^2 - m_1^2| \approx 2.4 \cdot 10^{-3}$ eV^2
$m_2^2 - m_1^2 \approx 7.5 \cdot 10^{-5}$ eV^2
all three m_i below ~ 0.5 eV

→ tiny masses, scheme unknown

$m_e \approx 0.000485$ GeV
$m_\mu \approx 0.103$ GeV
$m_\tau \approx 1.75$ GeV

→ hierarchical masses

Mixing parameters

Conventional (PDG) parameterization for the mixing matrices U_{CKM} and U_{PMNS}:

"Dirac" CP phase δ

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot P_{Maj}$$

(if Majorana masses)

mixing angle θ_{23}

mixing angle θ_{13}

mixing angle θ_{12}

Present status: Mixing parameters

from NuFIT Collaboration:

U_{PMNS}:

$\theta_{12}^{PMNS} \approx 33.5° \pm 0.8°$
$\theta_{23}^{PMNS} \approx 42° \pm 1°$
or $49° \pm 2°$
$\theta_{13}^{PMNS} \approx 8.5° \pm 0.2°$

δ^{PMNS} = 'unknown'
but first hints
($\varphi_{1,2}^{Maj}$ = unknown)

Up-type quarks | Down-type quarks

$M_u \longleftrightarrow M_d$

$U_{CKM} = U^{u\dagger} U^d$

Neutrinos | Charged leptons

$m_\nu \longleftrightarrow M_e$

$U_{PMNS} = U^{e\dagger} U^\nu$

from UTfit Collaboration:

U_{CKM}:

$\theta_{12}^{CKM} \equiv \theta_C \approx 13.0°$
$\theta_{23}^{CKM} \approx 2.4°$
$\theta_{13}^{CKM} \approx 0.2°$

$\delta^{CKM} \approx 69° \pm 3°$

→ two large mixings
→ $\theta_{13}^{PMNS} = O(\theta_C)$
→ unknown phases

→ very small 2-3 and 1-3 mixings
→ only not-so-small mixing is the Cabibbo angle θ_C
→ "large" CP phase δ^{CKM}

Issues in the SM

- Gravity
- Neutrino mass
- Dark matter, Baryon asymmetry of the Universe
- Gauge hierarchy
- Strong CP
- Fermion masses and mixing
- QCD dynamics

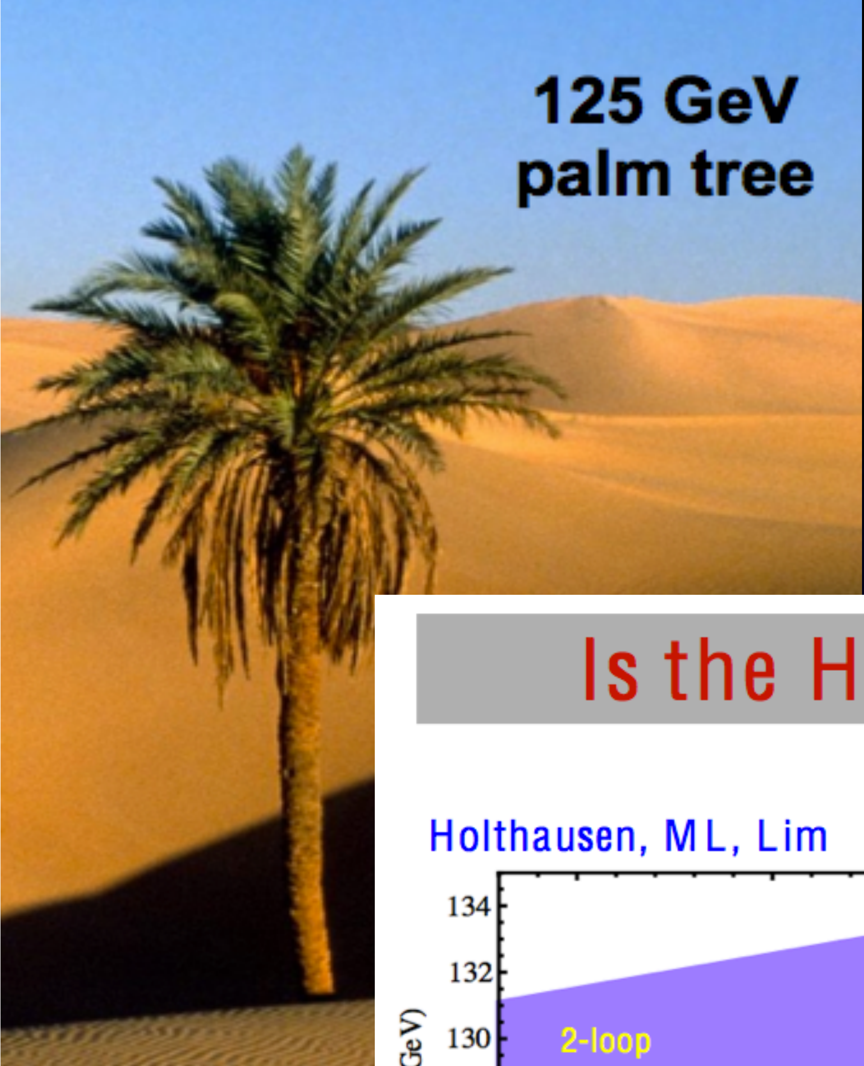
....

→ from talk by A. Watanabe

Colliders, TeV physics

LHC results...


LHC results...
125 GeV
palm tree
→ from talk by
Avelino Vincente



But the ‘plam tree’ is of course a great discovery and a crucial piece of information!

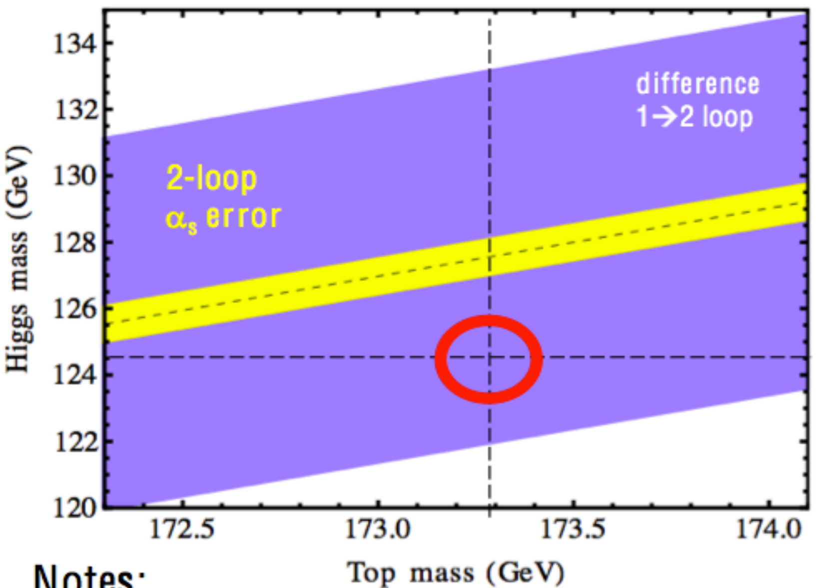
The SM is perturbative at least till the Planck scale.

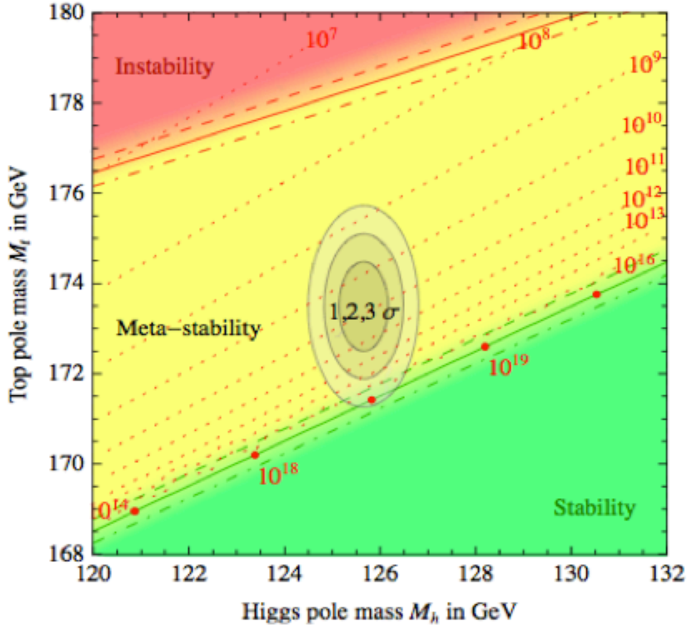
→ talk by J. Kubo

Is the Higgs Potential at M_{Planck} flat?

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

Holthausen, ML, Lim





Notes:

→ talk by M. Lindner

→ from talk by M. Lindner

What about the hierarchy problem?

→ GR is different: Non-renormalizable!

→ requires new concepts beyond QFT/gauge **theories: ...** ?

→ BAD: We have no facts which concepts are realized by nature

Supersymmetry?

→ assumed/discussed in many talks

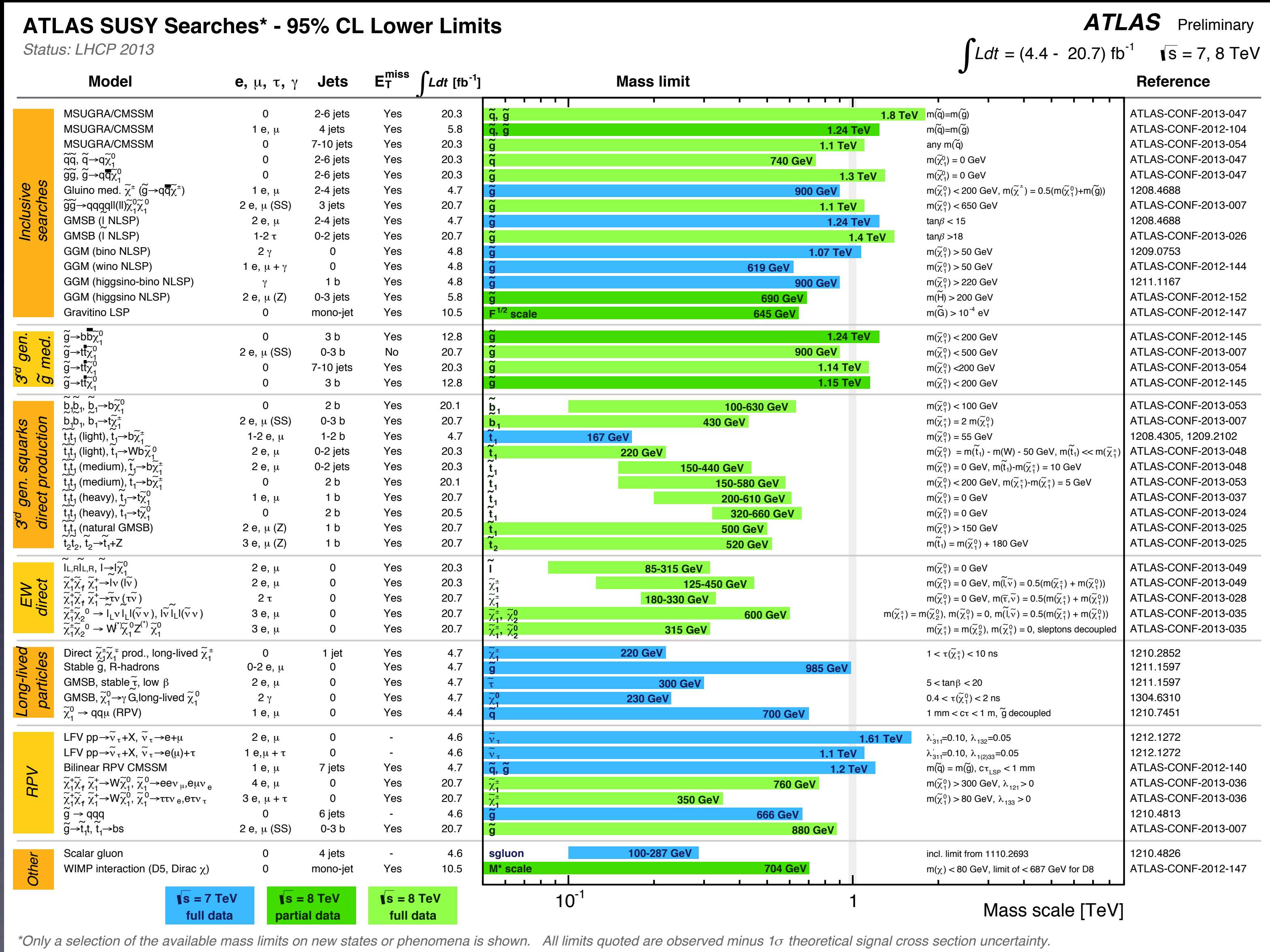
Conformally invariant extension of the SM?

→ talks by Manfred Lindner and Jisuke Kubo

...

LHC: Higgs discovery, SUSY searches, flavour observables, no signals beyond SM

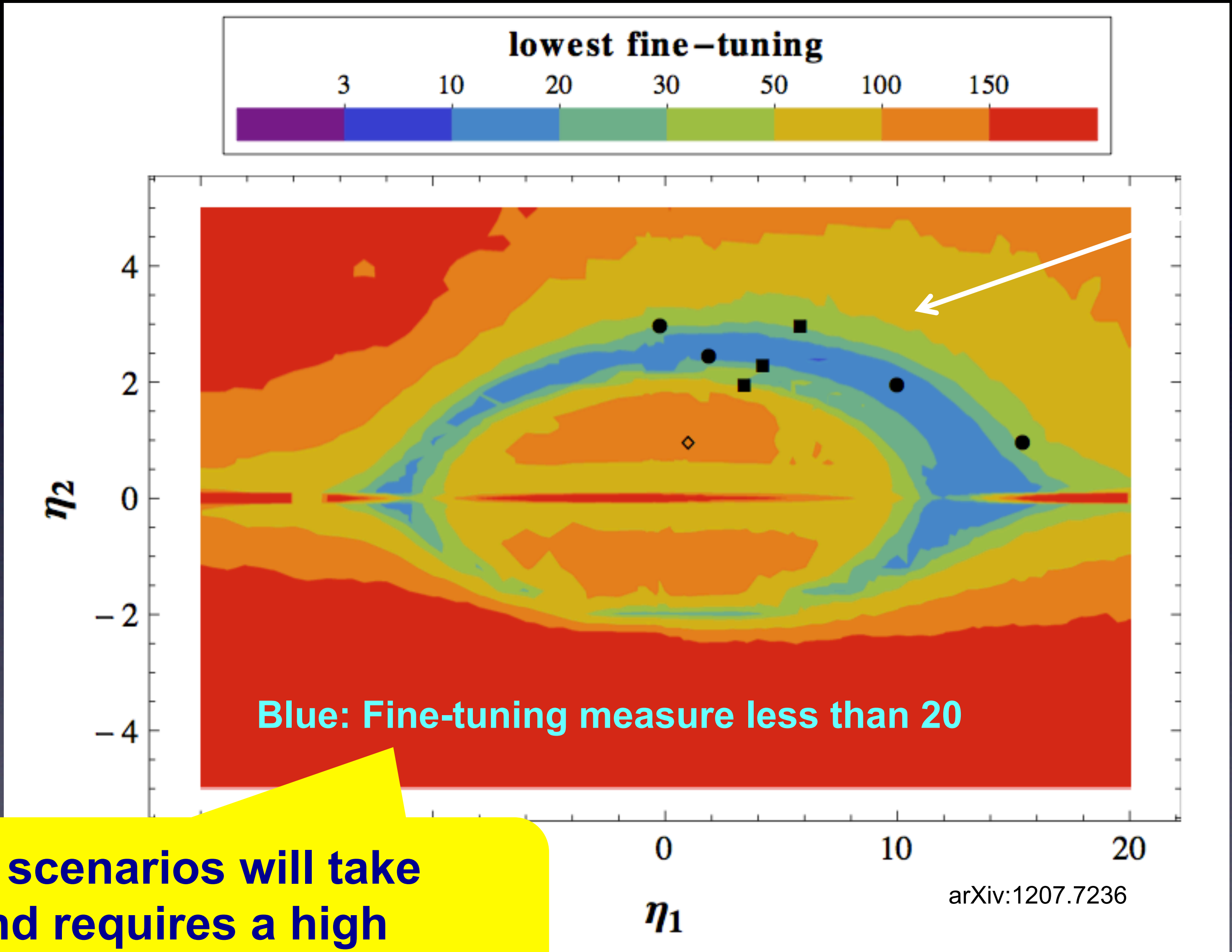
Example (from Atlas)



But there are still various SUSY scenarios with rather low fine-tuning ...

Example: MSSM with non-universal gaugino masses ($\eta_i := M_i/M_3$):

included: $m_h \sim 125$ GeV



Black dots and squares: selection of theory predictions ...

Tesing these scenarios will take some time and requires a high luminosity upgrade of the LHC

But new physics could also show up in precision flavour physics experiments!

Precision flavour experiments, Flavour phenomenology

But also flavour experiments are facing a 'tough defense'

No deviations of the SM observed yet!
→ talk by P. Spradlin
But very sensitive probes of NP possible → talks by R. Fleischer, A. Lenz, D. van Dyk, K. Yamamoto

A lot of discussion on how to interpret the $B \to K^* l\, l$ 'anomaly'? New physics?

For example:

1. The $B \to K^* \ell\ell$ decay is a very rich probe of $b \to s$ FCNCs
2. There is a $\sim$4-σ tension between 1 fb^{-1} data and some SM predictions
   - New physics mechanisms invoquing C_9 can solve the anomaly
3. We adopt the *R*fit philosophy for the treatment of hadronic uncertainties
   - Our **predictions** reasonably agree with the SM
   - Alternative explanation within the SM in terms of power corrections

→ talk by M. Camalich

–Non-resonant decays provide a background to important signal modes $B \to K^*(\to K\pi)\mu\mu$ and $B_s \to \varphi(\to KK)\mu\mu$. We present distributions for low recoil.

→ talk by G. Hiller

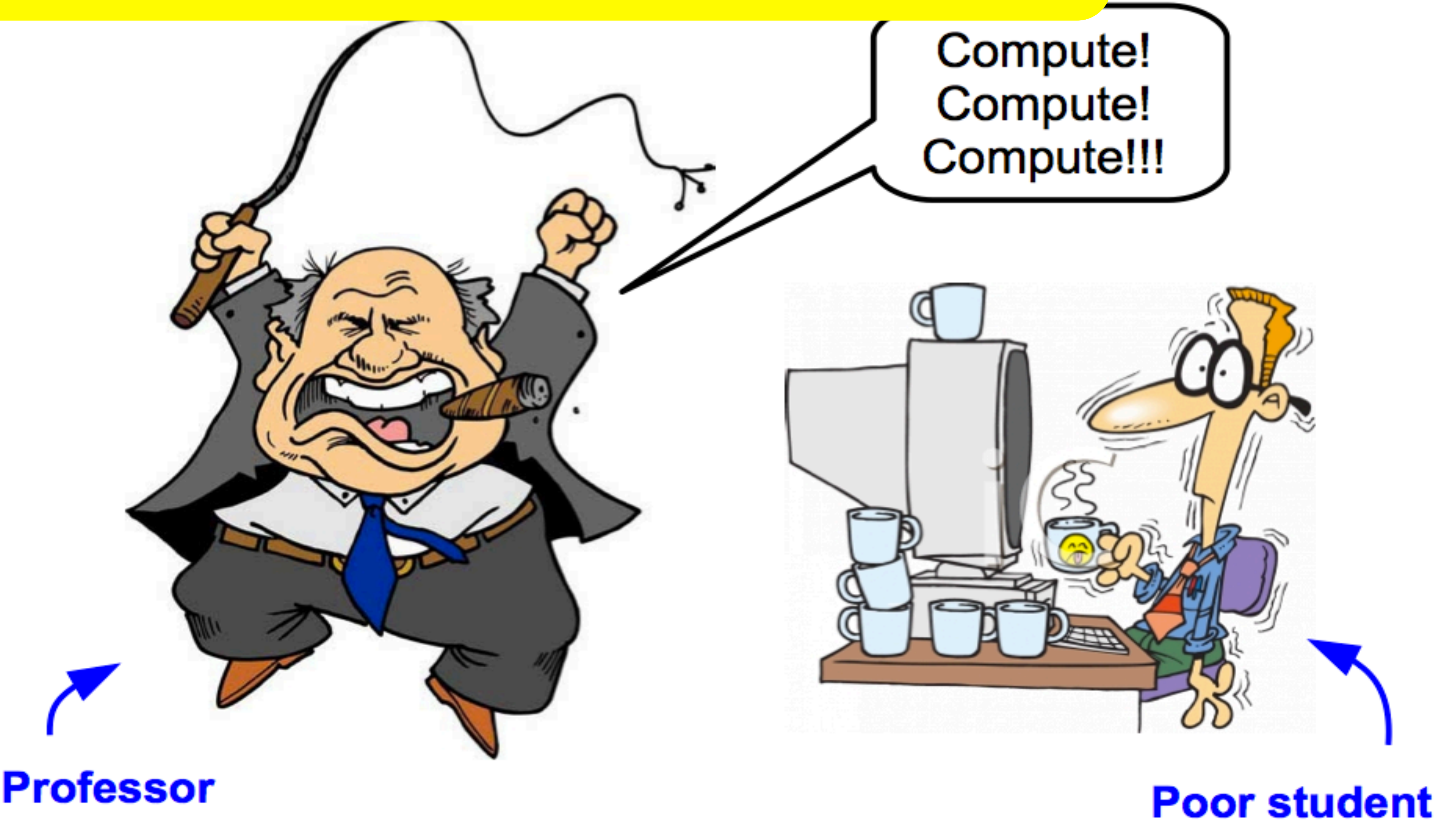
- large effects in broad charm resonances
  factorisation fails 350% (nominal correction 50%)

→ talk by R. Zwicky

Asking the goal-line technology: Is it a goal (= is it new physics)?

But not only the defense is tough ... also the ball is 'difficult to play' → theory calculations

It is great that helpful software tools are made available to the cummunity!



Neutrino Physics

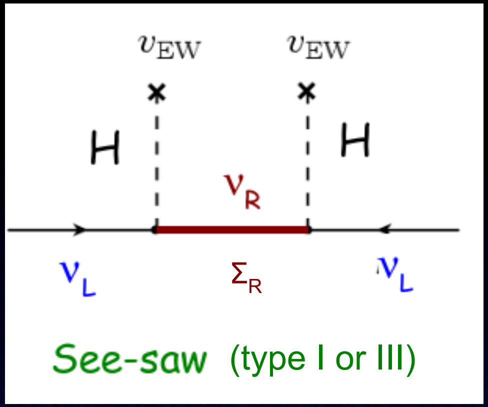
Many unknowns remain …

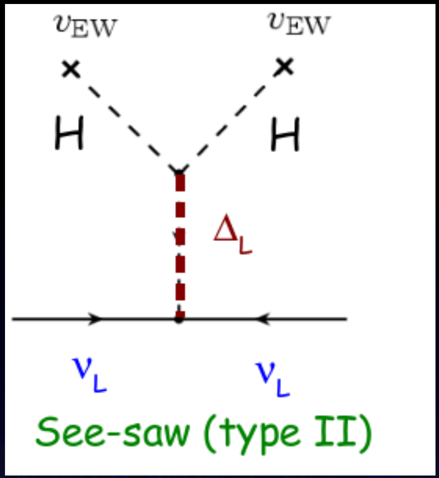
- What are the values of the Dirac CP phase δ^{PMNS}
- Is the mass scheme “normal” or “inverse”, i.e., what is sgn(Δm_{31}^2)?
- What is the deviation of θ_{23}^{PMNS} from maximal (i.e. from 45°)
- What is the absolute neutrino mass scale?
- Are neutrino masses of Dirac- or Majorana-type?
- If they are Majorana-type, what are the values of the Majorana phases?

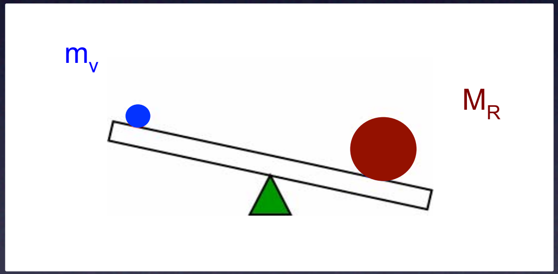
Great also for theorists! It means it is still possible to make predictions!

What is the origin of neutrino masses? How to extend the SM?

... most talks were assuming:







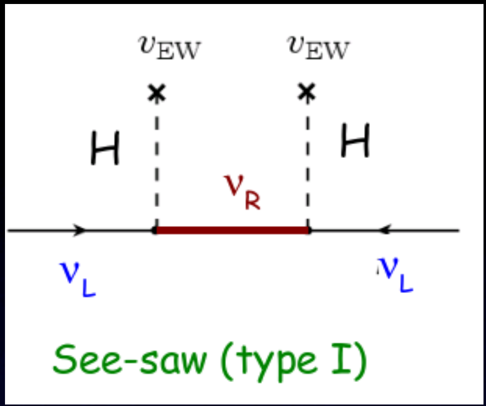
At which scale?

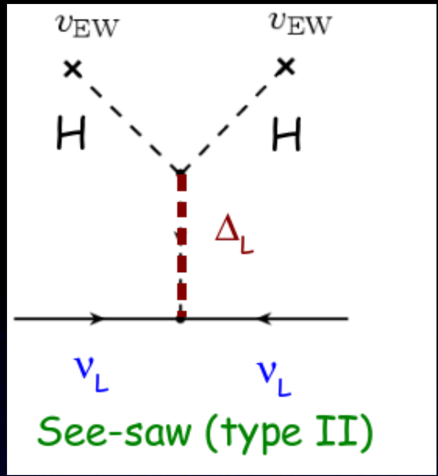
(A) At high scale ($\sim M_{GUT}$)
(B) At TeV scale ($\rightarrow$ colliders, LHC)
(C) At keV scale ($\rightarrow$ warm DM)
(D) At eV energies (light sterile ν's)

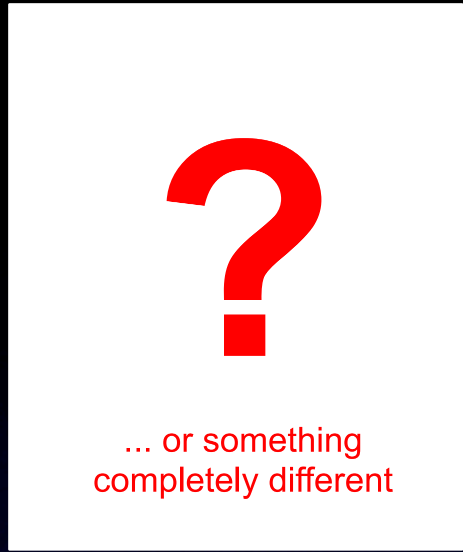
Which mechanism?

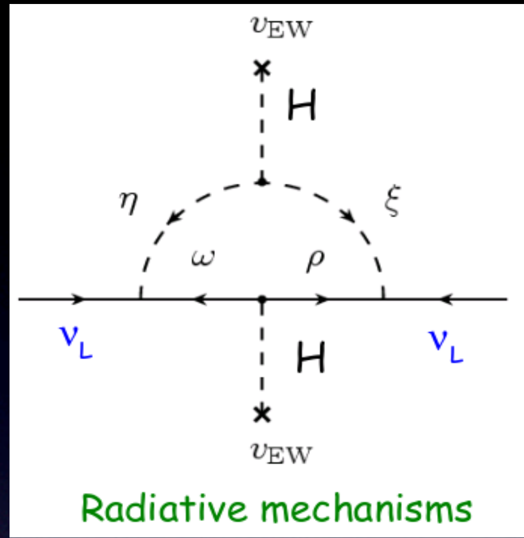
Is it a tree-level "Seesaw" mechanism?

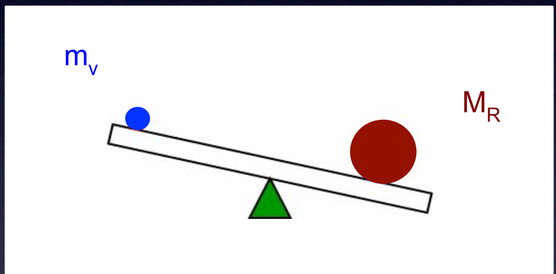
... or something else?

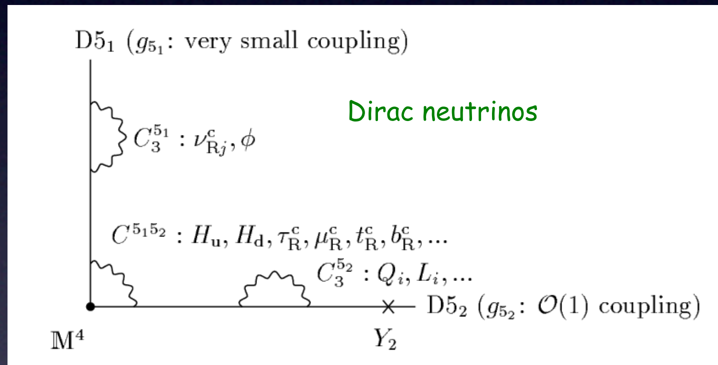


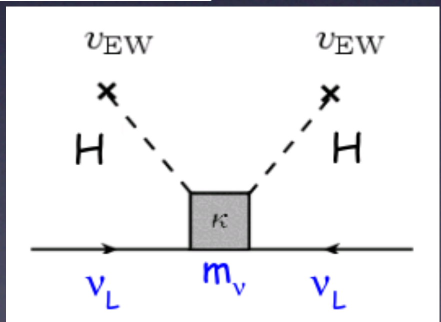


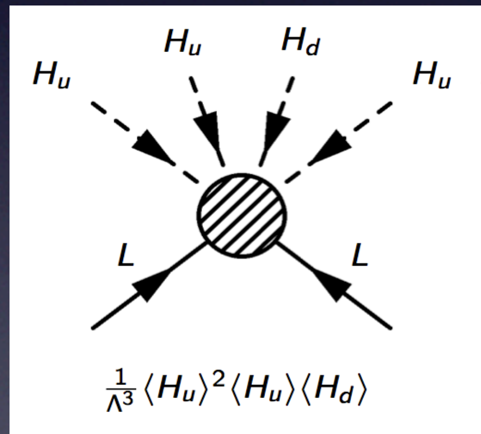


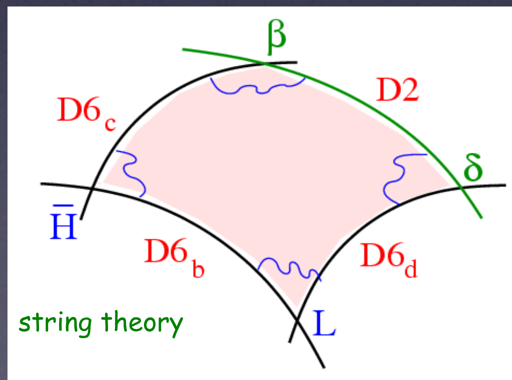






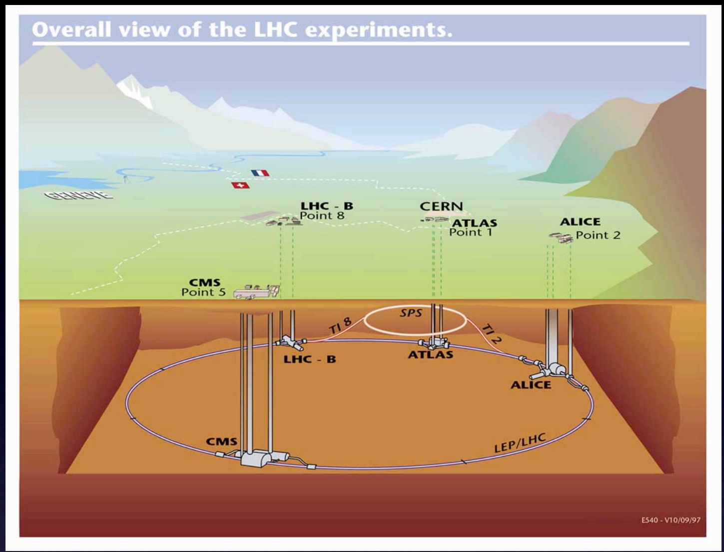




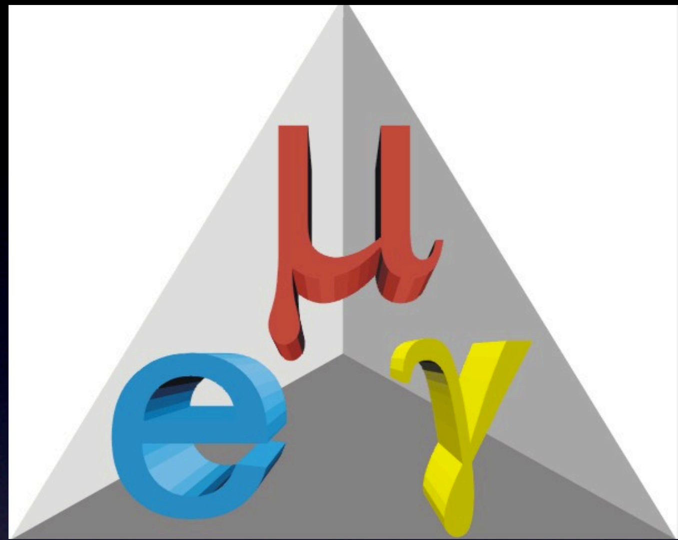


$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta}\, \left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) + h.c.$$

What is the origin and nature of the neutrino masses?
We have to combine all sources of information ...

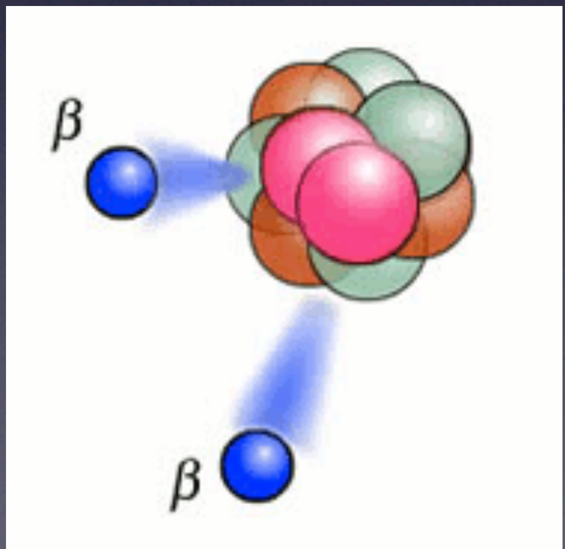


Colliders



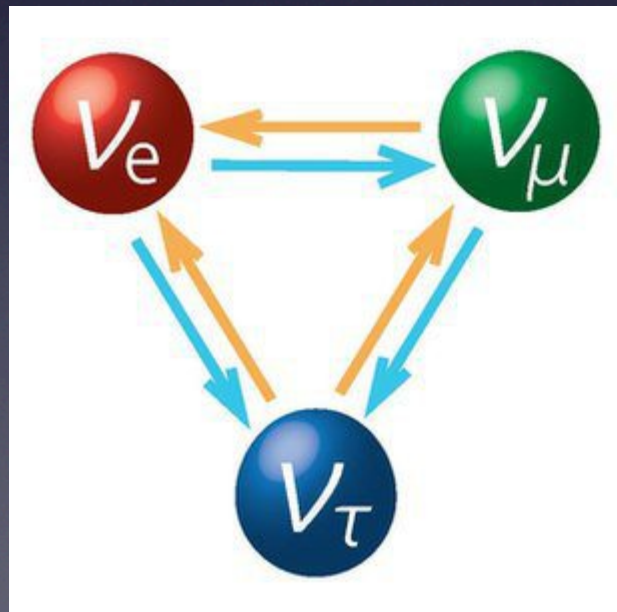
→ talk by C. Voena

indirect tests (e.g. LFV, non-unitarity)



0νββ decay, Tritium β decay, cosmology

→ talk by J. Hartnell



Neutrino oscillations

→ talk by A. Weber

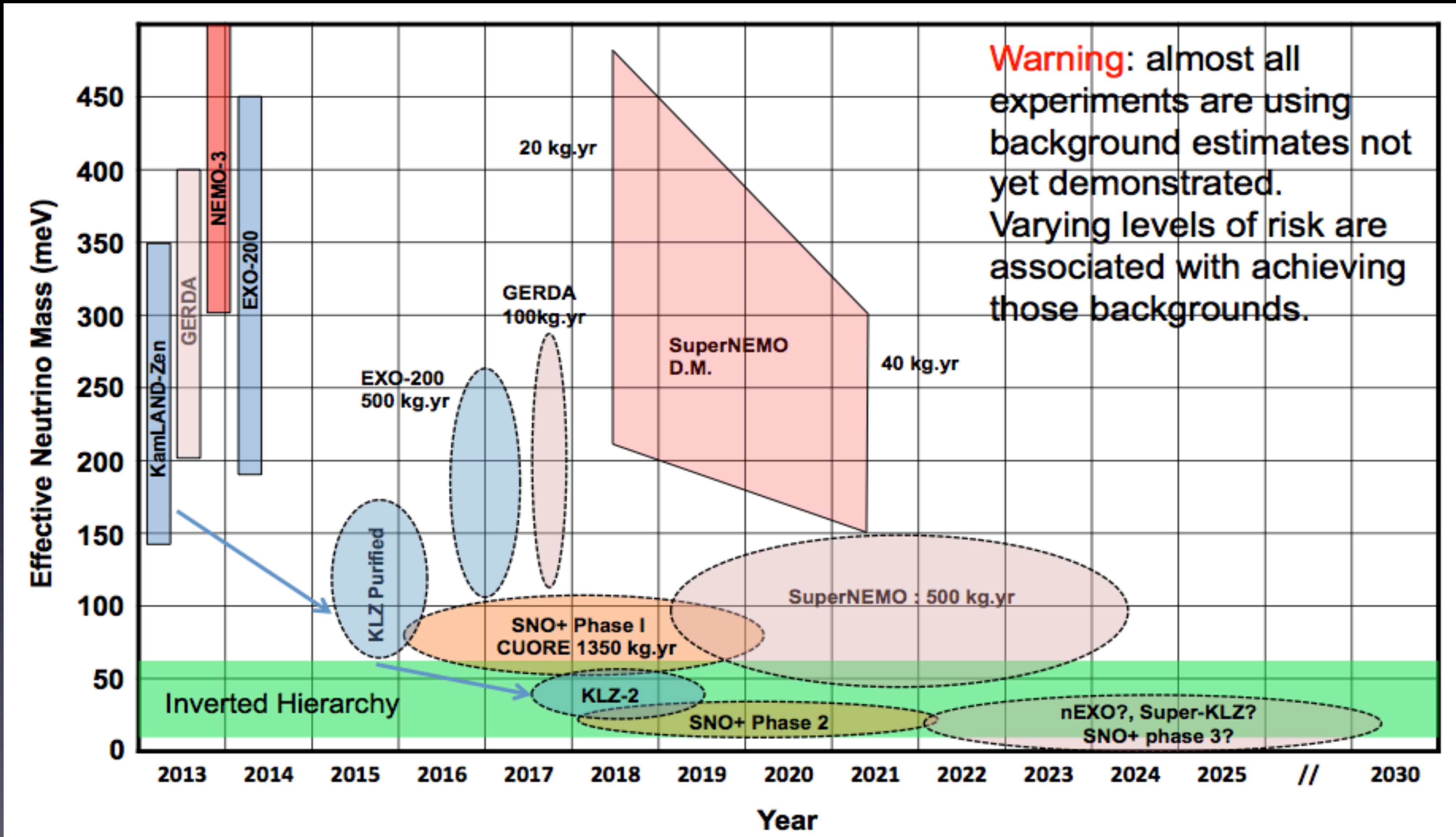
Present and future sensitivities of charged LFV experiments

process	current exp.	future exp.
K^0 mixing	$\epsilon_K = (2.228 \pm 0.011) \times 10^{-3}$	—
D^0 mixing	$A_\Gamma = (-0.02 \pm 0.16)\%$	$\pm 0.007\%$ LHCb $\pm 0.06\%$ Belle II
B_d mixing	$\sin 2\beta = 0.68 \pm 0.02$	± 0.008 LHCb ± 0.012 Belle II
B_s mixing	$\phi_s = 0.01 \pm 0.07$	± 0.008 LHCb
d_{Hg}	$< 3.1 \times 10^{-29}\ e\mathrm{cm}$	–
d_{Ra}	–	$\lesssim 10^{-29}\ e\mathrm{cm}$
d_n	$< 2.9 \times 10^{-26}\ e\mathrm{cm}$	$\lesssim 10^{-28}\ e\mathrm{cm}$
d_p	–	$\lesssim 10^{-29}\ e\mathrm{cm}$
d_e	$< 1.05 \times 10^{-27}\ e\mathrm{cm}$ YbF	$\lesssim 10^{-30}\ e\mathrm{cm}$ YbF, Fr
$\mu \to e\gamma$	$< 5.4 \times 10^{-13}$ MEG	$\lesssim 6 \times 10^{-14}$ MEG upgrade
$\mu \to 3e$	$< 1.0 \times 10^{-12}$ SINDRUM I	$\lesssim 10^{-16}$ Mu3e
$\mu \to e$ in Au	$< 7.0 \times 10^{-13}$ SINDRUM II	–
$\mu \to e$ in Al	–	$\lesssim 6 \times 10^{-17}$ Mu2e

Table: Summary of current and selected future expected experimental limits on CP violation in meson mixing, EDMs and lepton flavor violating processes.

→ from talk by Paride Paradisi

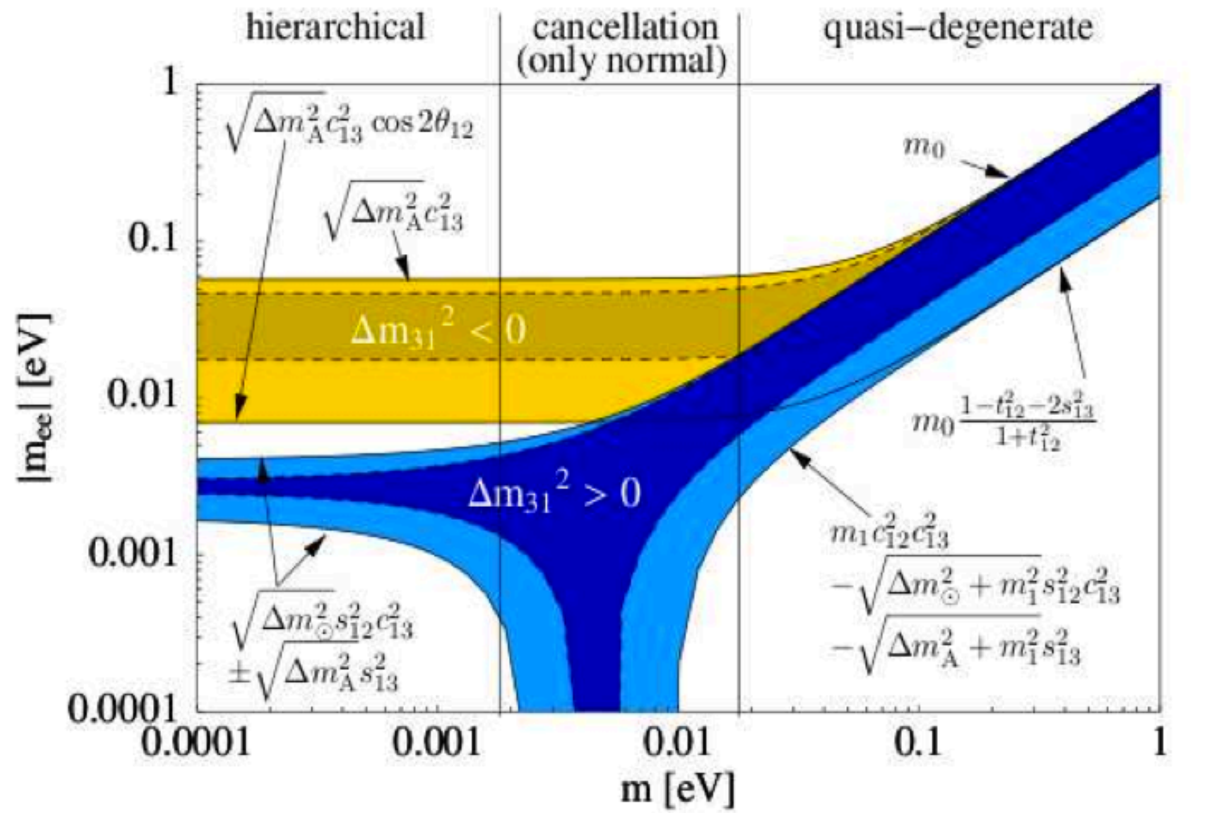
$0\nu\beta\beta$ decay: Future sensitivities



→ talk by Jeff Hartnell

→ talk by W. Rodejohann

The usual plot

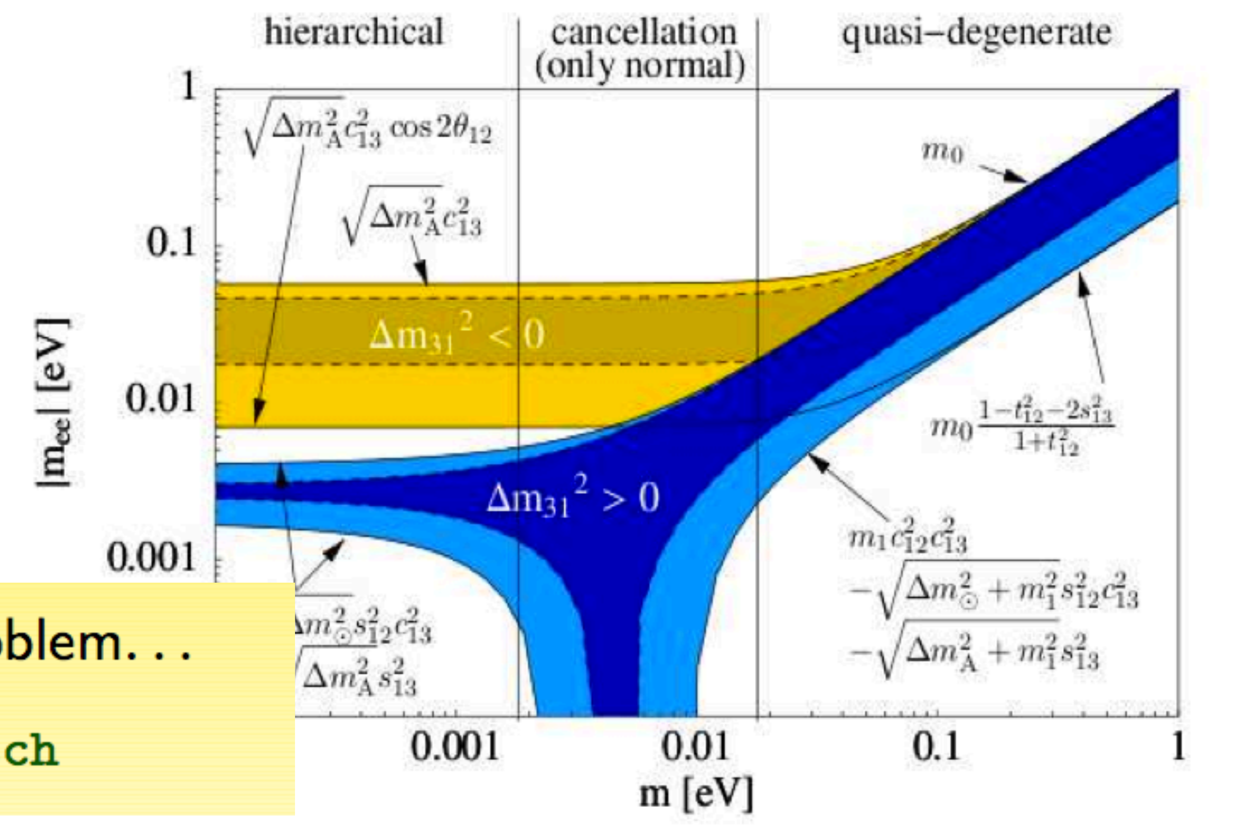


Ruling out Inverted Hierarchy

$$|m_{ee}|^{\rm IH}_{\rm min} = (1-|U_{e3}|^2)\sqrt{|\Delta m_A^2|}\,(1-2\sin^2\theta_{12})$$
$$= (0.011\ldots 0.022)\ \text{eV}$$

→ talks by F. Deppisch, W. Rodejohann

The usual plot



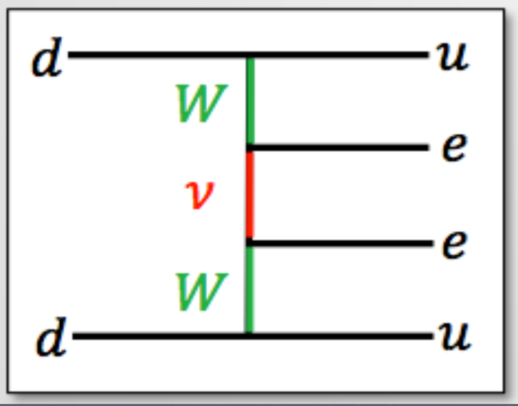
Once we start to observe *0νββ decay:*

⇒ need to solve the inverse problem. . .

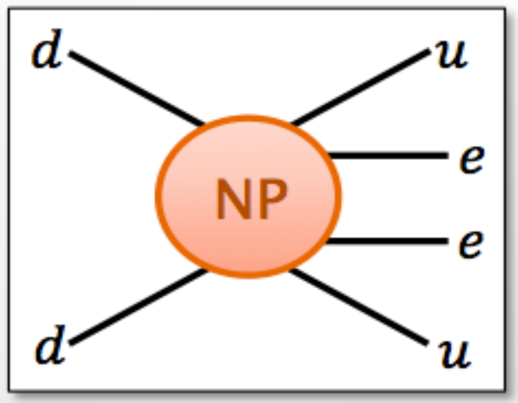
see `talk by Frank Deppisch`

Non-standard contributions to *0νββ decay* possible!

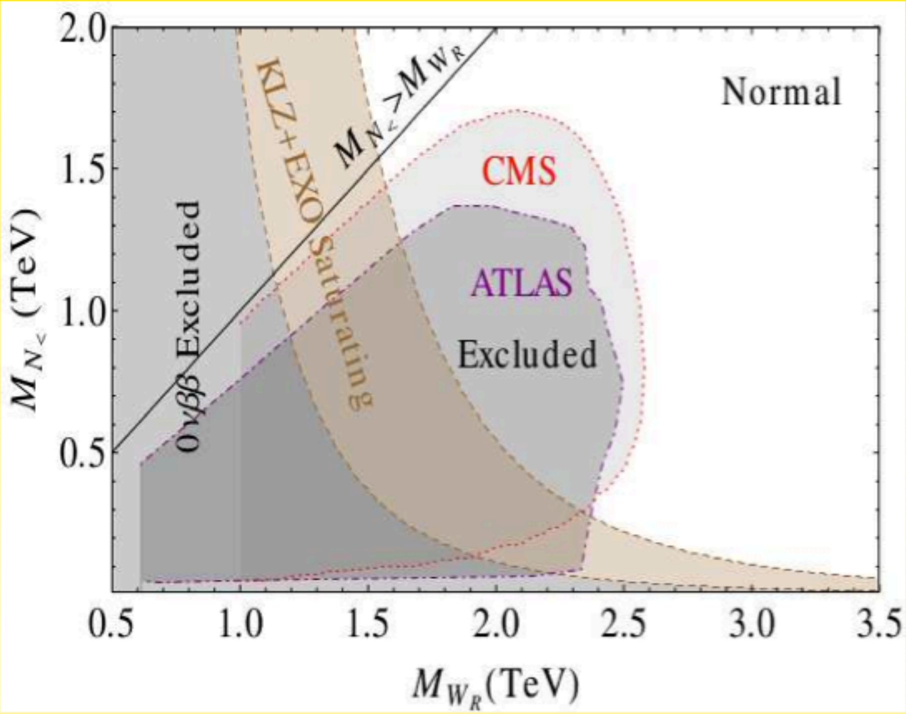
Light Neutrino Exchange



General Effective Operator



LHC can probe non-standard sources of 0νββ decay!



Bhupal Dev, Goswami, Mitra, W.R., Phys. Rev

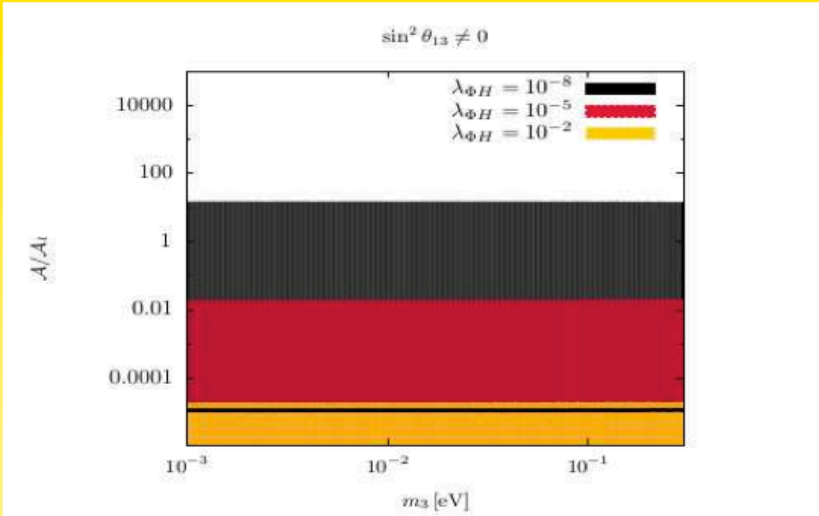
$1\ \mathrm{eV} = 1\ \mathrm{TeV}$

→ from talk by W. Rodejohann

... and we have also seen more or less hidden advertising for the speakers favourite football team ...

3.) New particles generating $0\nu\beta\beta$

new contribution can dominate over standard one:



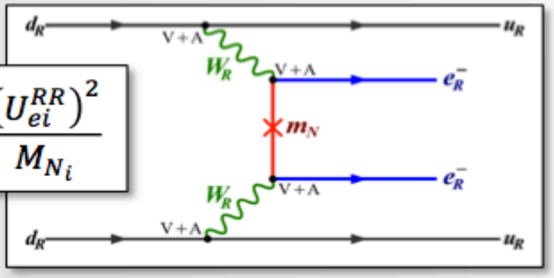
see talk by Jose No for another example

LNV at the LHC

University College London

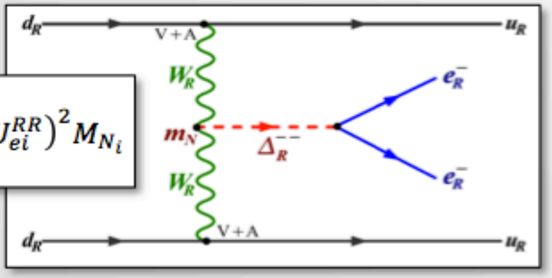
- Contributions to $0\nu\beta\beta$
  - Heavy Neutrinos

$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \sum_i \frac{(U_{ei}^{RR})^2}{M_{N_i}}$$

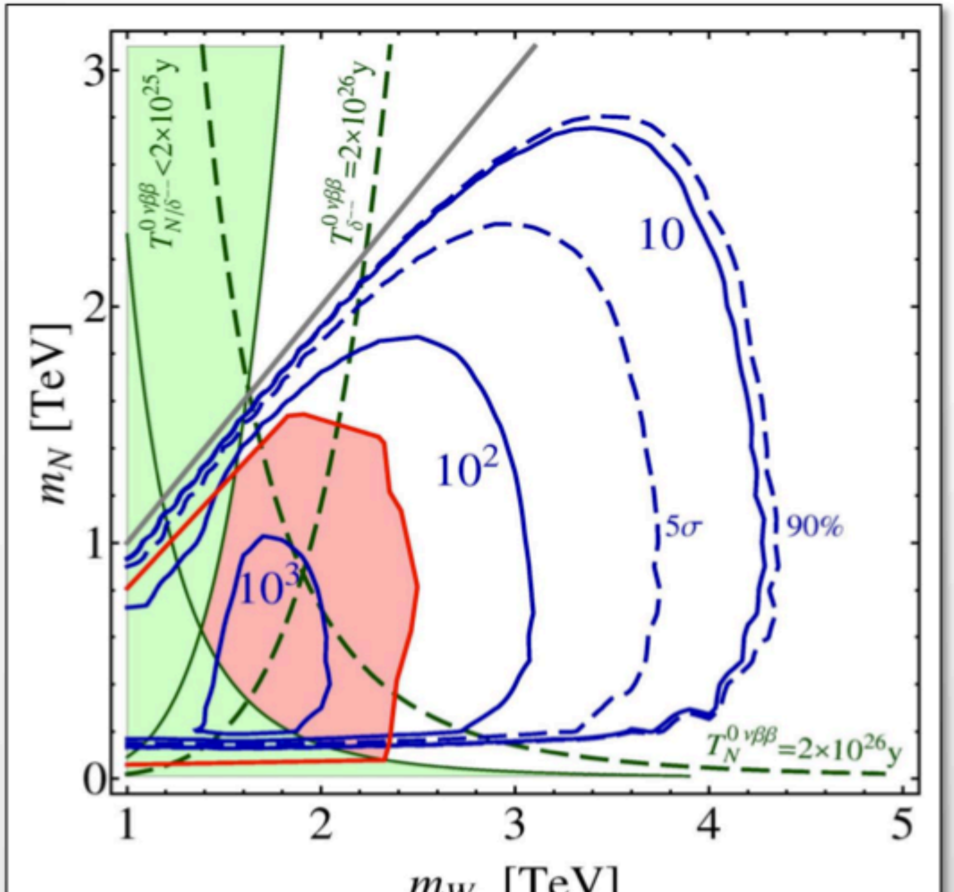


  - Triplet R-Higgs

$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \frac{m_p}{M^2_{\Delta_R^{--}}} \sum_i (U_{ei}^{RR})^2 M_{N_i}$$



  - LR-Mixing neglected



LHC reach @ 14 TeV, 30 fb^{-1}
Same Sign Leptons

→ talk by F. Deppisch

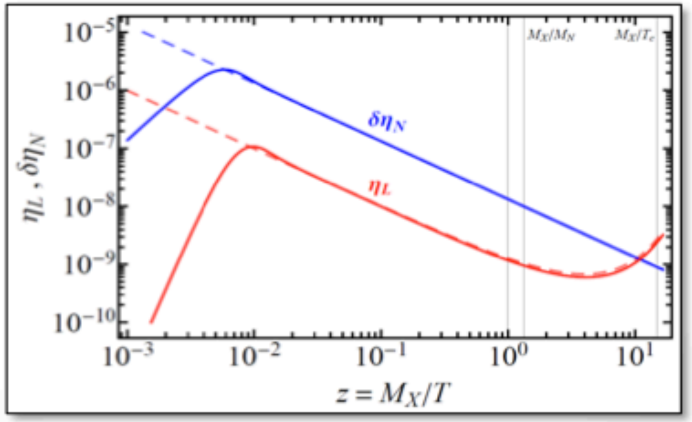
Falsifying Leptogenesis at the LHC (FFD, Harz, Hirsch, Phys. Rev. Lett. 112, 221601)

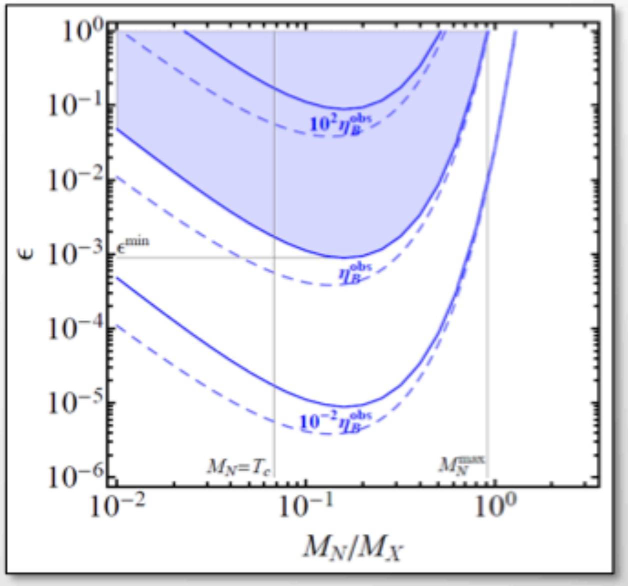
University College London

- Classic Leptogenesis with one heavy neutrino N, neglecting flavour
  - Upper limit on baryon asymmetry

$$\log_{10}\left|\frac{\eta_B}{\eta_B^{\mathrm{obs}}}\right| < 2.4\frac{M_X}{\mathrm{TeV}}\left(1-\frac{4}{3}\frac{M_N}{M_X}\right) + \log_{10}\left[|\epsilon|\left(\frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^{2}\right]$$

  - LNV is observed at LHC
    - → High scale Leptogenesis ($M_N > M_X$) is not viable
    - → Strong limit on CP asymmetry ϵ for low scale Leptogenesis ($M_{EW} < M_N < M_X$)
- Caveat
  - Asymmetry can be present in one lepton generation only
    - Falsification requires observation of LNV in all flavours (or observation of low energy LFV such as $\tau \to e\gamma$)





→ talk by F. Deppisch

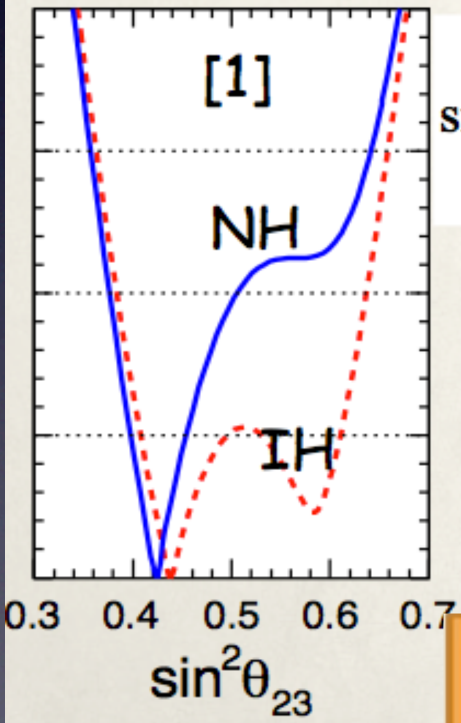
What is the data on neutrino mixing (and CP violation) telling us about flavour symmetries?

→ talk by F. Feruglio

anything special from data, requiring a symmetry?

1. ϑ_{23} maximal ?
2. $\delta_{CP} = -\pi/2$?
3. U_{PMNS} close to TB (BM,...) ?

3 examples from a longer list...



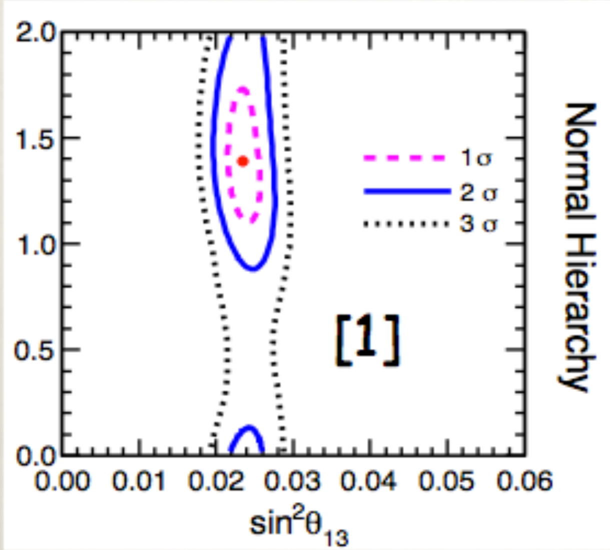
$$\sin^2\vartheta_{23} = \begin{cases} 0.567^{+0.032}_{-0.128} & \text{(NH)} \\ 0.573^{+0.025}_{-0.043} & \text{(IH)} \end{cases}$$

[2]

global fit:
[1] Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo 1312.2878
[2] Forero, Tortola, Valle 1405.7540

T2K has a slight hint for the normal hierarchy with a value of δ_{CP} of $-\pi/2$

$\delta_{CP} = -\pi/2$?



→ talk by Alfons Weber on T2K results

Future results will have interesting implications

- no maximal ϑ_{23} from an exact symmetry

  broken abelian symmetries do not work
  [not a theorem but no counterexamples]

  → we are left with broken non-abelian symmetries

→ talk by F. Feruglio

<u>direct models:</u>

5 include CP in the SB pattern

$$G_{CP} = G_f \rtimes CP$$

[F. F, C. Hagedorn and R. Ziegler 1211.5560, 1303.7178
Ding,King,Luhn,Stuart 1303.6180
Ding, King, Stuart 1307.4212]

$$G_e \qquad G_\nu = Z_2 \times CP$$

mixing angles and CP violating phases

$$(\vartheta_{12}^0, \vartheta_{23}^0, \vartheta_{13}^0, \delta^0, \alpha^0, \beta^0)$$

predicted in terms of a single real parameter $0 \le \vartheta \le \pi$

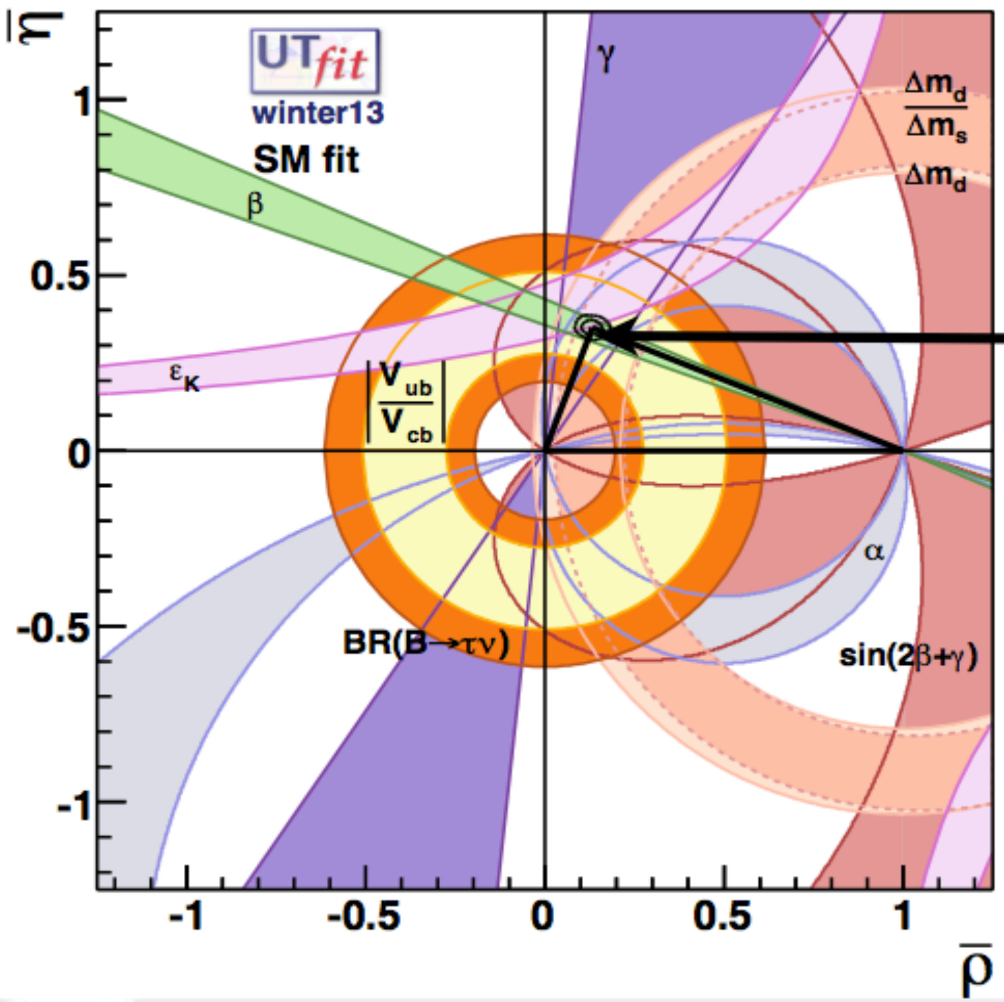
<u>indirect models:</u>

alternative simple ways to predict the CP phases from spontaneous breaking of CP

more on CP & flavour later in the talk ...

If $\delta^{PMNS} \approx -90°$ should get confirmed, how can we understand its origin?

Remark: We are having such a situation already in the quark sector!



$$(V^\dagger_{\mathrm{CKM}} V_{\mathrm{CKM}})_{bd} = 0$$

Fit result:

$$\alpha = (88.7 \pm 3.1)^\circ$$

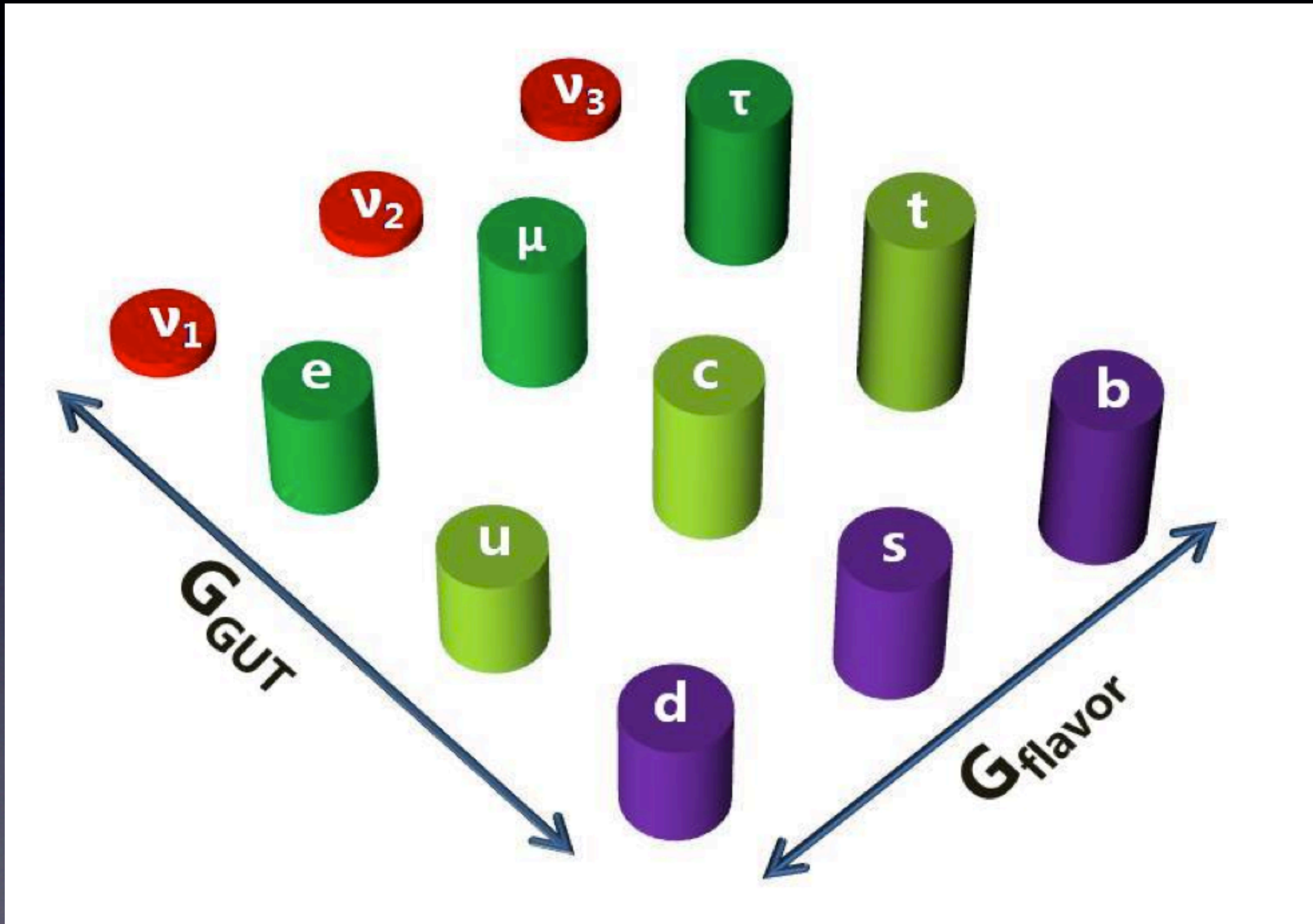
[UTFit Winter '13 SM Fit]

Accident or sign of spontaneous CP violation?

... can be explained by spontaneous CP breaking: arXiv:1103.5930

GUTs

Very predictive framework: (SUSY) Flavour GUTs



→ from talk by Thomas Neder

Advantages of SUSY GUT

two unifications

- gauge interactions
- particles (especially matters)

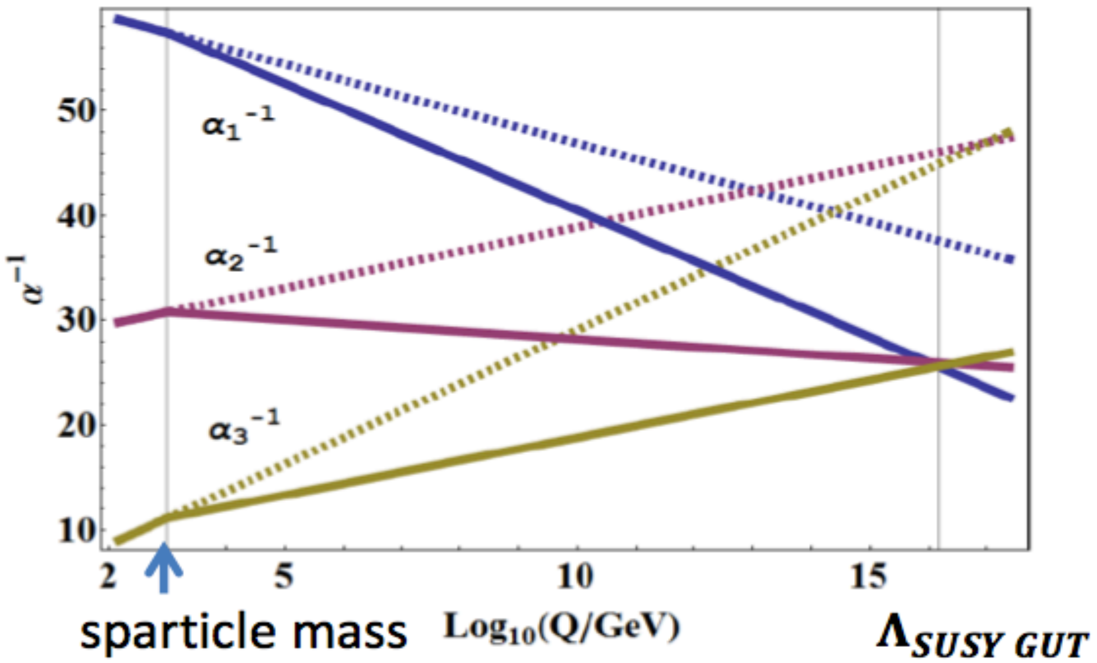
⇔

two supports

- gauge coupling unification
- quark and lepton masses and mixings

● unification of gauge interactions

SM gauge group G_{SM} is unified into grand unification group.



:SM

:MSSM

$\Lambda_{SUSY\ GUT} \sim 2 \times 10^{16}$ Ge

→ from talk by Y. Muramatsu

From unification of particles: Predictions for GUT scale Yukawa coupling ratios

Conventional: 3rd family Yukawa unification, GJ factor of 3

$$F_3 T_3 \langle \overline{H}_5 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} b^c_R \\ b^c_B \\ b^c_G \\ \tau \\ -\nu_\tau \end{pmatrix} \begin{pmatrix} 0 & -t^c_G & t^c_B & -t_R & -b_R \\ t^c_G & 0 & -t^c_R & -t_B & -b_B \\ -t^c_B & t^c_R & 0 & -t_G & -b_G \\ t_R & t_B & t_G & 0 & -\tau^c \\ b_R & b_B & b_G & \tau^c & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v \end{pmatrix}$$

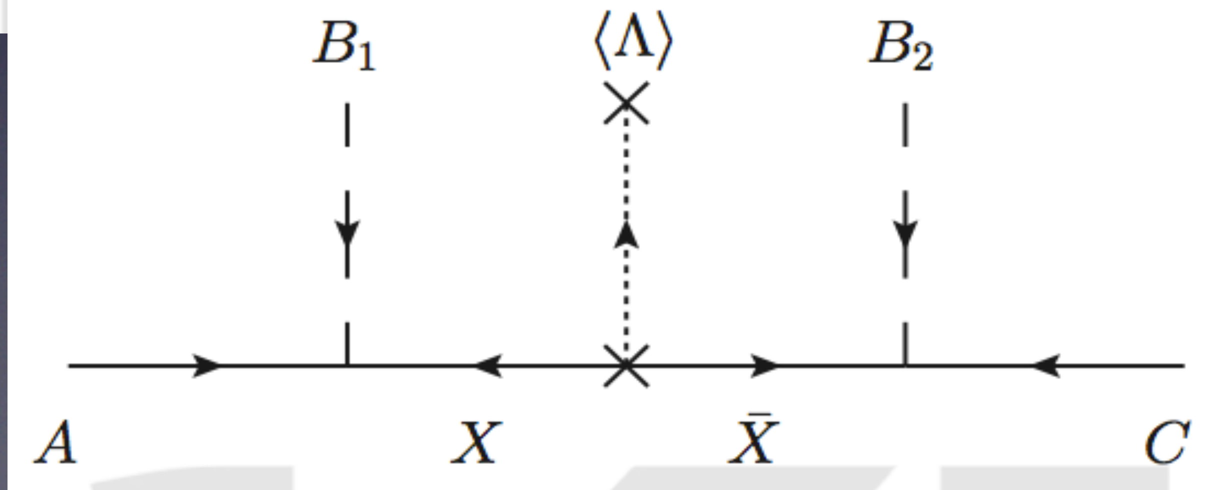
$$\overset{SSB}{\longrightarrow} -\frac{v}{\sqrt{2}} \left(\bar{b} b + \bar{\tau} \tau \right) \longrightarrow y_\tau / y_b = 1$$

[Georgi, Glashow '74, see also talk by Q. Shafi]

Using a 45-dim. Higgs gives a ratio of -3

→ talk by Q. Shafi

Alternative ratios:
from effective operators



→ talk by M. Spinrath

→ talk by M. Spinrath

Alternative Ratios III

[Antusch, MS '09; MS '10; Antusch, King, MS '13;
dim. 6 SU(5) operators Antusch *et al.* '14]

Operator Dimension	$(Y_e)_{ji}/(Y_d)_{ij}$	
4	1	
	-3	
5	1/6	[Antusch, King, MS '13]
	-1/2	[Antusch, MS '09; MS '10]
	-2/3	[Antusch, King, MS '13]
	1	
	±3/2	[Antusch, MS '09; MS '10]
	-3	
	9/2	[Antusch, MS '09; MS '10]
	6	[Antusch, MS '09; MS '10]
	-18	[Antusch, MS '09; MS '10]

Summary of possible predictions from SU(5)

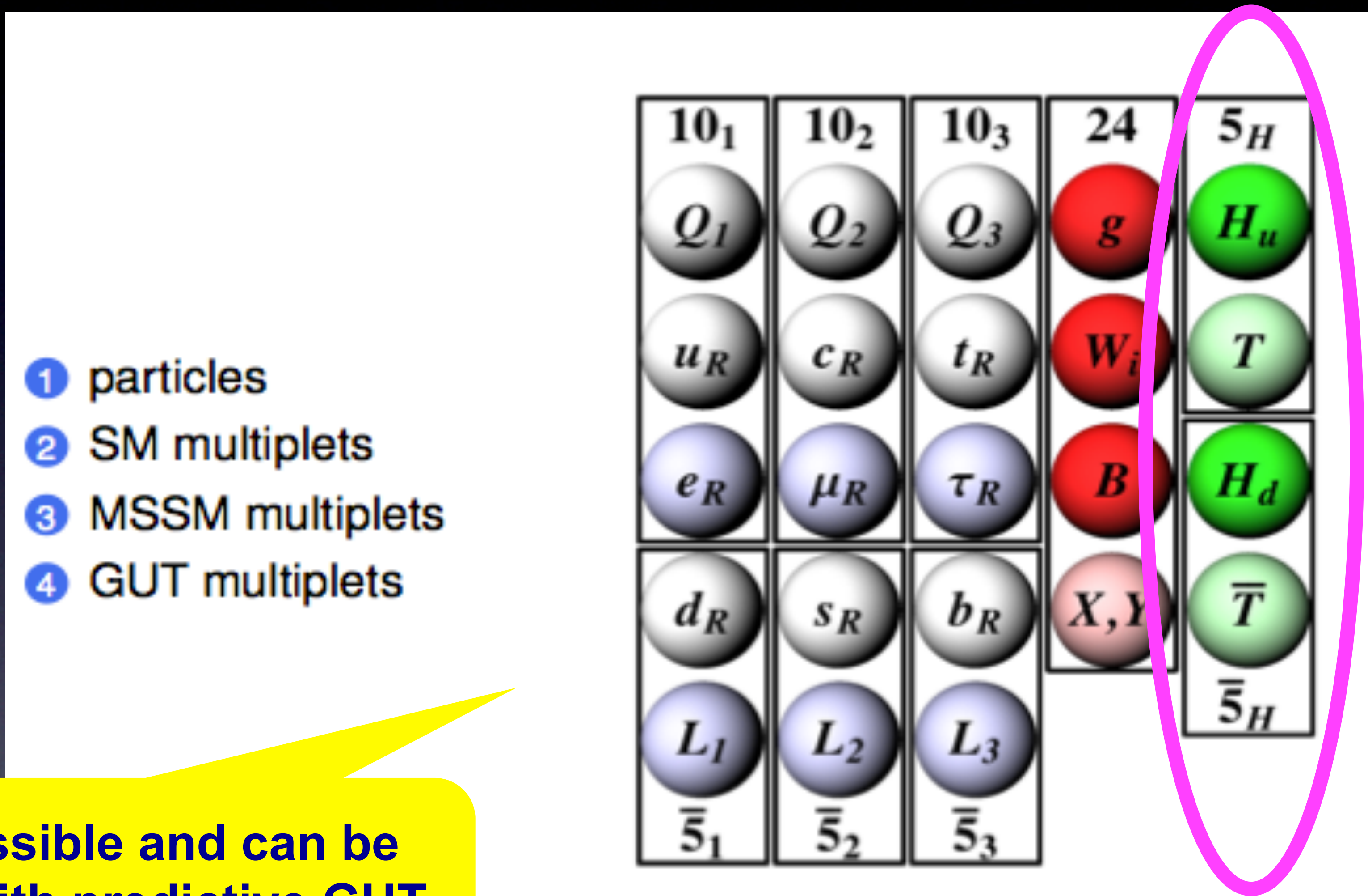
Operator Dimension	$((Y_e)_{ij}/(Y_d)_{ij}, (Y_u)_{ij}/(Y_d)_{ij})$	
4	(1, 1)	
	(-3, 1)	
5	(0, ±1)	[Antusch, King, MS '13]
	(-1/3, ±1)	[Antusch, King, MS '13]
	(1, ±1)	
	(3/2, ±1)	[Antusch, King, MS '13]
	(-3, ±1)	
	(9, ±1)	[Antusch, MS '09; MS '10]

Summary of possible predictions from Pati-Salam

Which ratios are realistic?

→ ratios imply testable constraints on the SUSY spectrum

Challenge for GUTs: Doublet-Triplet splitting (& proton decay)



Solution possible and can be combined with predictive GUT flavour models

→ talk by Vinzenz Maurer

Family symmetries: Can solve SUSY flavour problem!

Explain flavour structure in the SM, e.g.:

$$M_d \sim \begin{pmatrix} 0 & \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} v_{\rm d}$$

Generate flavour stucture of the SUSY particles:

$$\widetilde{M}_{d_R} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m_0 + \begin{pmatrix} \varepsilon_1^2 & \varepsilon_1^2 & \varepsilon_1^2 \\ \varepsilon_1^2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1^2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} m_0$$

Family symmetry!

$$A_d \sim \begin{pmatrix} 0 & \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_2^2 \\ \varepsilon_1\varepsilon_2 & \varepsilon_2^2 & \varepsilon_3^2 \end{pmatrix} A_0$$

SUSY flavour structure related to the one of the SM

sMSSM : (Flavour) Symmetry-based MSSM

K. Babu, I. Gogoladze, S. Rizvi, QS.

- *Motivation*: Realize Supersymmetric Models in which symmetry considerations alone dictate the form of the SUSY breaking Lagrangian.

→ talk by Q. Shafi

(with gravity mediation)

Relating Sflavor and Flavor

Suggestive that sfermion masses controlled by same dynamics that render Yukawas small

Flavor Symmetry

↙ $(\tilde{m}^2_U)_{ij}$ ↘ y^U_{ij}

Realization depends on relation of messenger scales

$\Lambda_S \longleftrightarrow \Lambda_F$

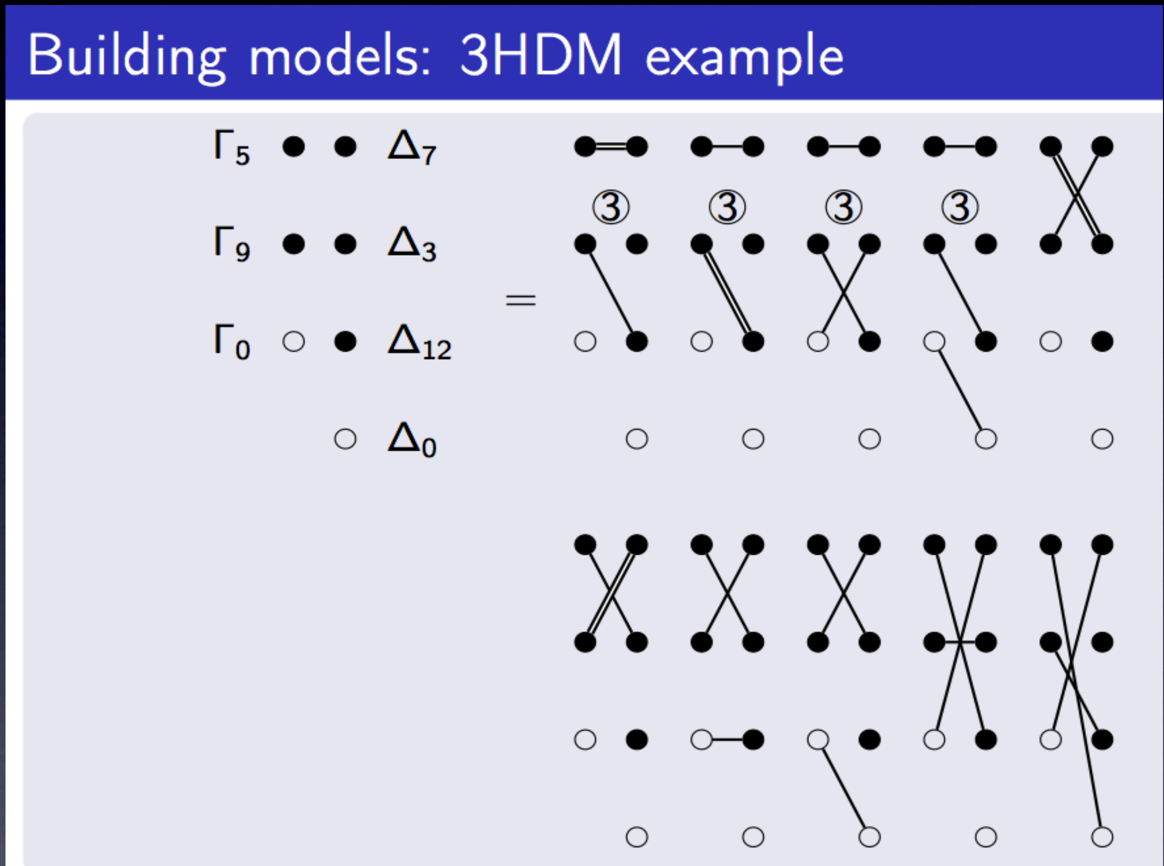
scale SUSY messengers — scale flavor messengers

Flavoured gauge mediation:

→ talk by R. Ziegler

Alternative to GUTs: Multi Higgs Flavour Models ... at TeV energies

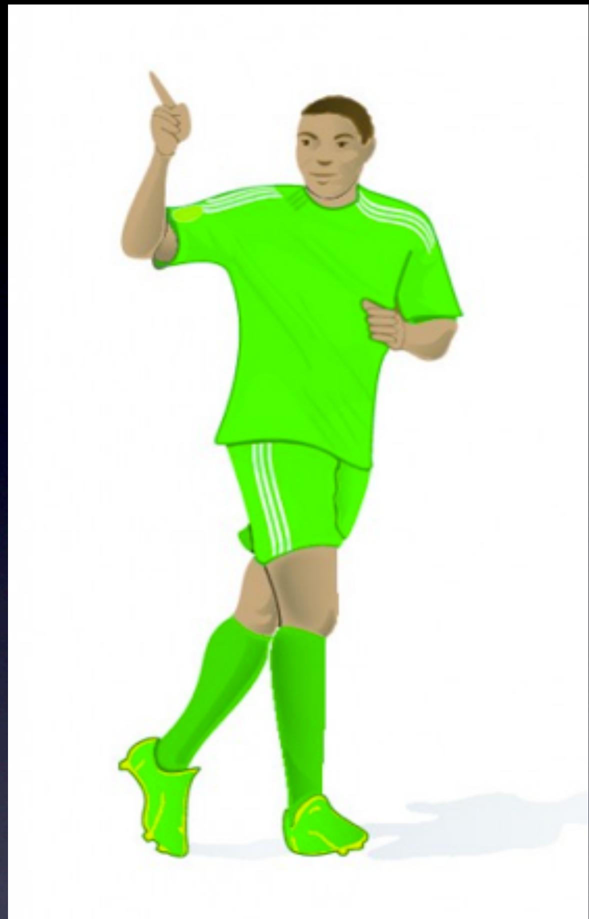
→ talks by M. Mondragon, I. Ivanov, H. Serodio



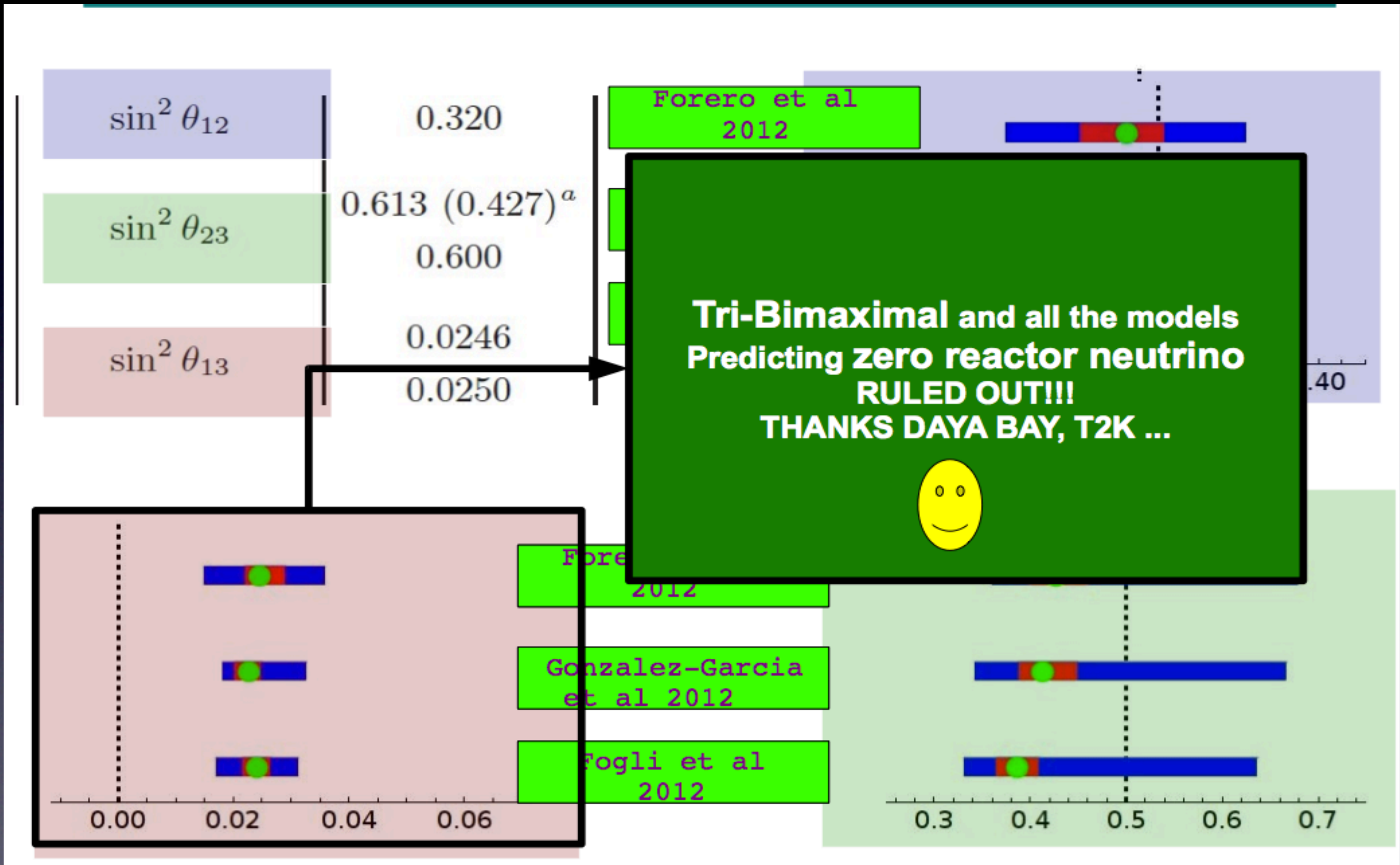
Systematic treatment of all possibilities

How generic is residual symmetry?

→ talk by I. Ivanov

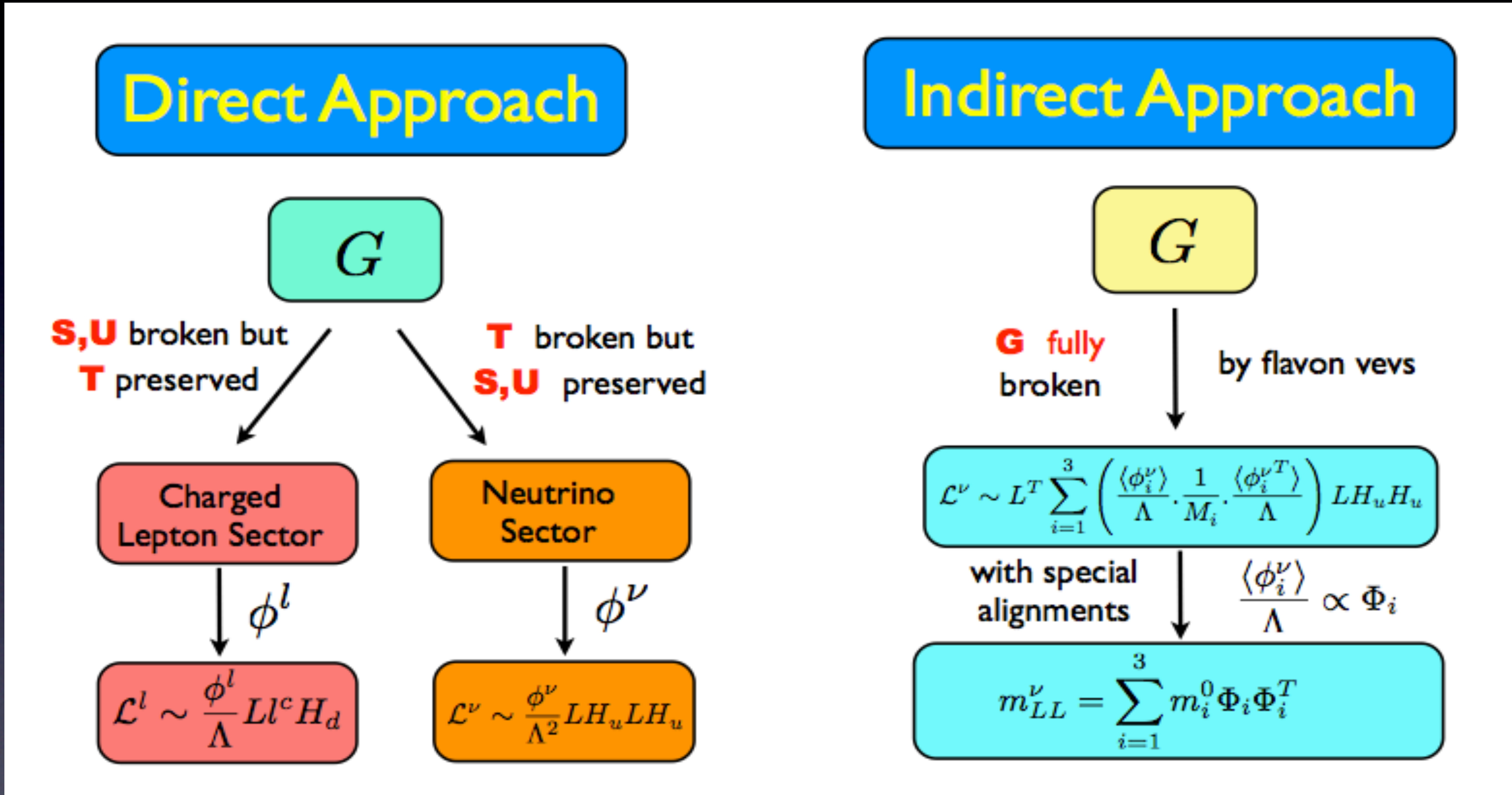


Models of Flavour



→ from talk by Eduardo Peinado

Most models follow one of the two approaches to flavour model building ...



After θ_{13}^{PMNS} discovery:
Consider larger groups (e.g. $\Delta(6n^2)$)

→ talk by Thomas Neder

After θ_{13}^{PMNS} discovery:
(i) alternative flavon vev directions
(ii) charged lepton corrections

→ talk by Alma Rojas

Testing classes of lepton flavour models: sumrules!

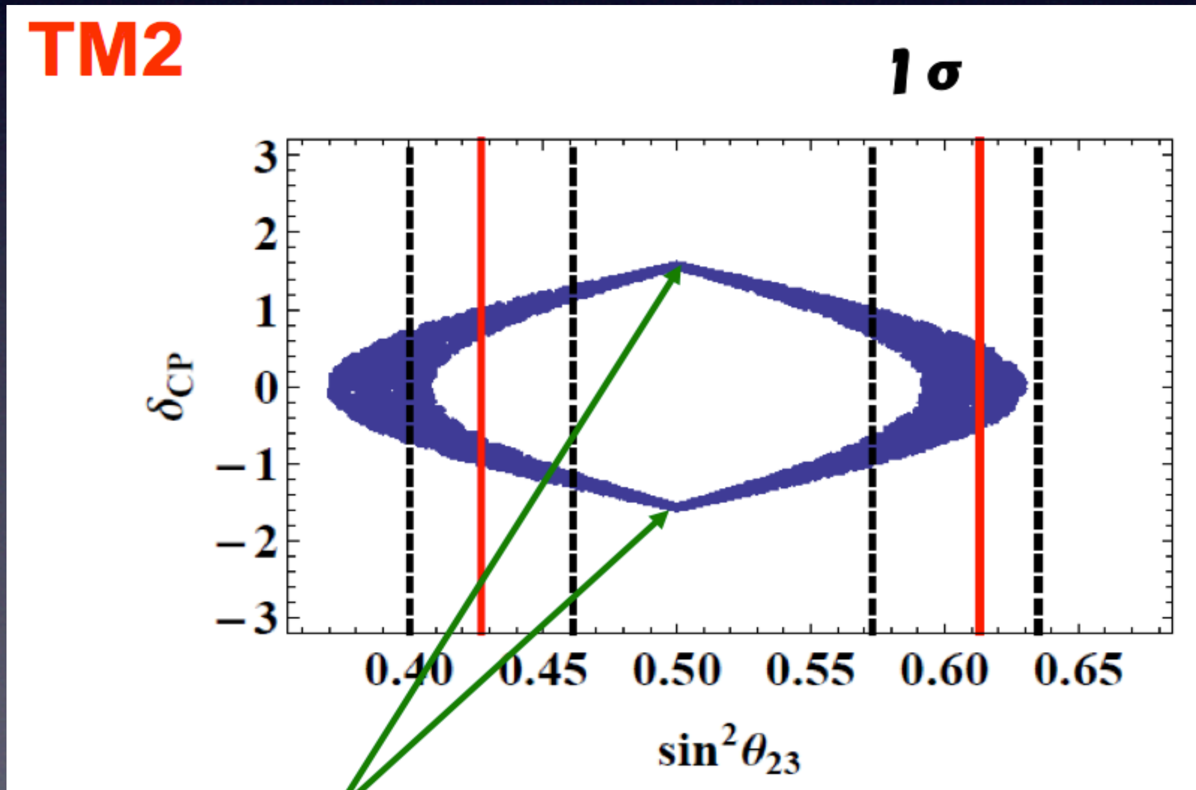
1) mixing sum rules

2) mass sum rules

Examples for mixing sum rules: Tri-maximal mixing 2

TM2: Including CP phase

$$V_\nu = \begin{pmatrix} 2c/\sqrt{6} & 1/\sqrt{3} & 2se^{-i\sigma}/\sqrt{6} \\ -c/\sqrt{6} + se^{i\sigma}/\sqrt{2} & 1/\sqrt{3} & -se^{-i\sigma}/\sqrt{6} - c/\sqrt{2} \\ -c/\sqrt{6} - se^{i\sigma}/\sqrt{2} & 1/\sqrt{3} & -se^{-i\sigma}/\sqrt{6} + c/\sqrt{2} \end{pmatrix}$$

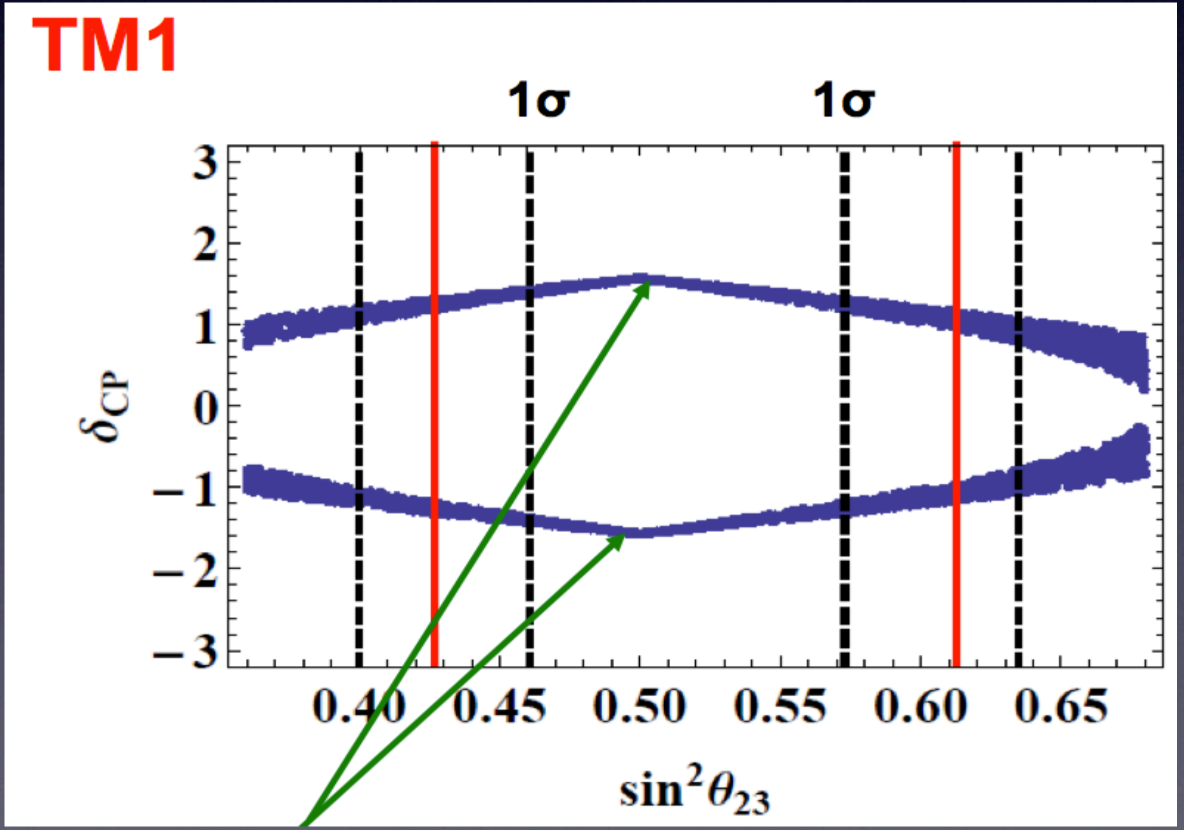


→ talks by M. Tanimoto

Examples for mixing sum rules: Tri-maximal mixing 1

TM1: Including CP phase

$$V_\nu = \begin{pmatrix} 2/\sqrt{6} & c/\sqrt{3} & se^{-i\sigma}/\sqrt{3} \\ -1/\sqrt{6} & c/\sqrt{3} + se^{i\sigma}/\sqrt{2} & se^{-i\sigma}/\sqrt{3} - c/\sqrt{2} \\ -1/\sqrt{6} & c/\sqrt{3} - se^{i\sigma}/\sqrt{2} & se^{-i\sigma}/\sqrt{3} + c/\sqrt{2} \end{pmatrix}$$



→ talks by M. Tanimoto

Example: Mixing sum rule if θ_{13}^{PMNS} generated by charged lepton correction θ_{12}^{e}

Leading order mixing pattern from m_ν, e.g.: $U_\nu = U_{TB}$

Charged lepton mixing contribution dominated by 1-2 mixing θ_{12}^{e}

$m_\nu \longleftrightarrow M_e \rightarrow \theta^e_{12}$

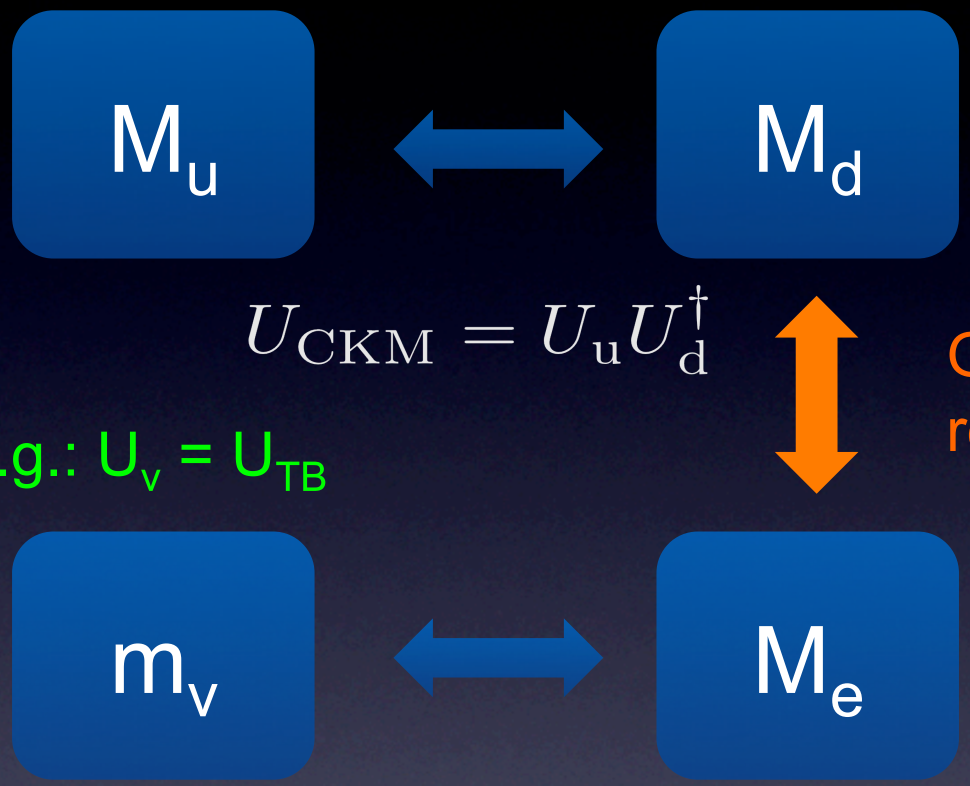
$$U_{\rm MNS} = U_{\rm e} U_\nu^\dagger$$

1) Prediction for θ_{13}^{PMNS}

(for $\theta^\nu_{13}, \theta^e_{13} \ll \theta^e_{12}$)

$$\theta_{13}^{\rm PMNS} = \frac{\theta^{\rm e}_{12}}{\sqrt{2}}$$

Example: Mixing sum rule if θ_{13}^{PMNS} generated by charged lepton correction θ_{12}^{e}



$\rightarrow \theta_{12}^{d} \sim \theta_C$

$U_{\rm CKM} = U_{\rm u} U_{\rm d}^\dagger$

e.g.: $U_\nu = U_{TB}$

$\rightarrow \theta_{12}^{e}$

$U_{\rm MNS} = U_{\rm e} U_\nu^\dagger$

c_{ij}: Clebsch Gordan coefficients

1) Prediction for θ_{13}^{PMNS}

(for $\theta_{13}^{\nu}, \theta_{13}^{e} \ll \theta_{12}^{e}$)

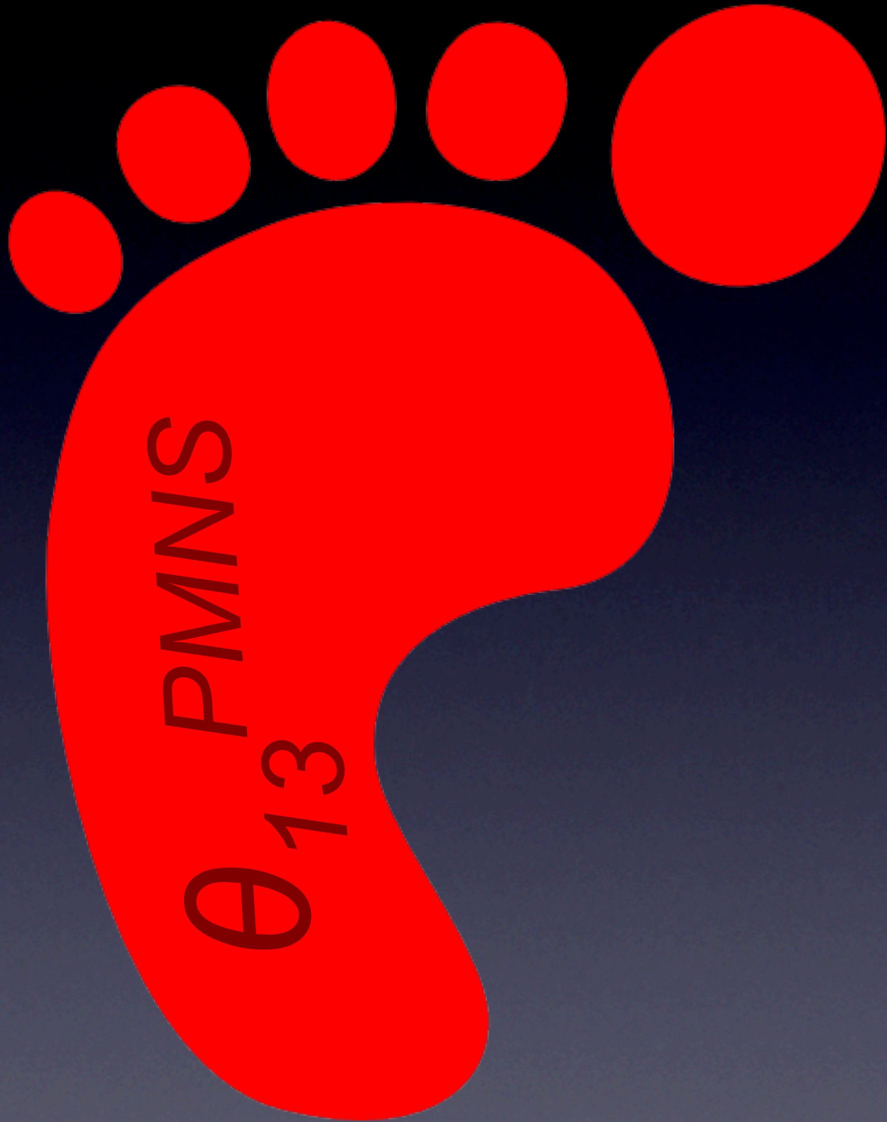
$$\theta_{13}^{\rm PMNS} = \frac{\theta_{12}^{\rm e}}{\sqrt{2}} = \frac{\theta_{\rm C}}{\sqrt{2}} \frac{c_{12}}{c_{22}}$$

See e.g.: arXiv:1107.3728, 1108.0614

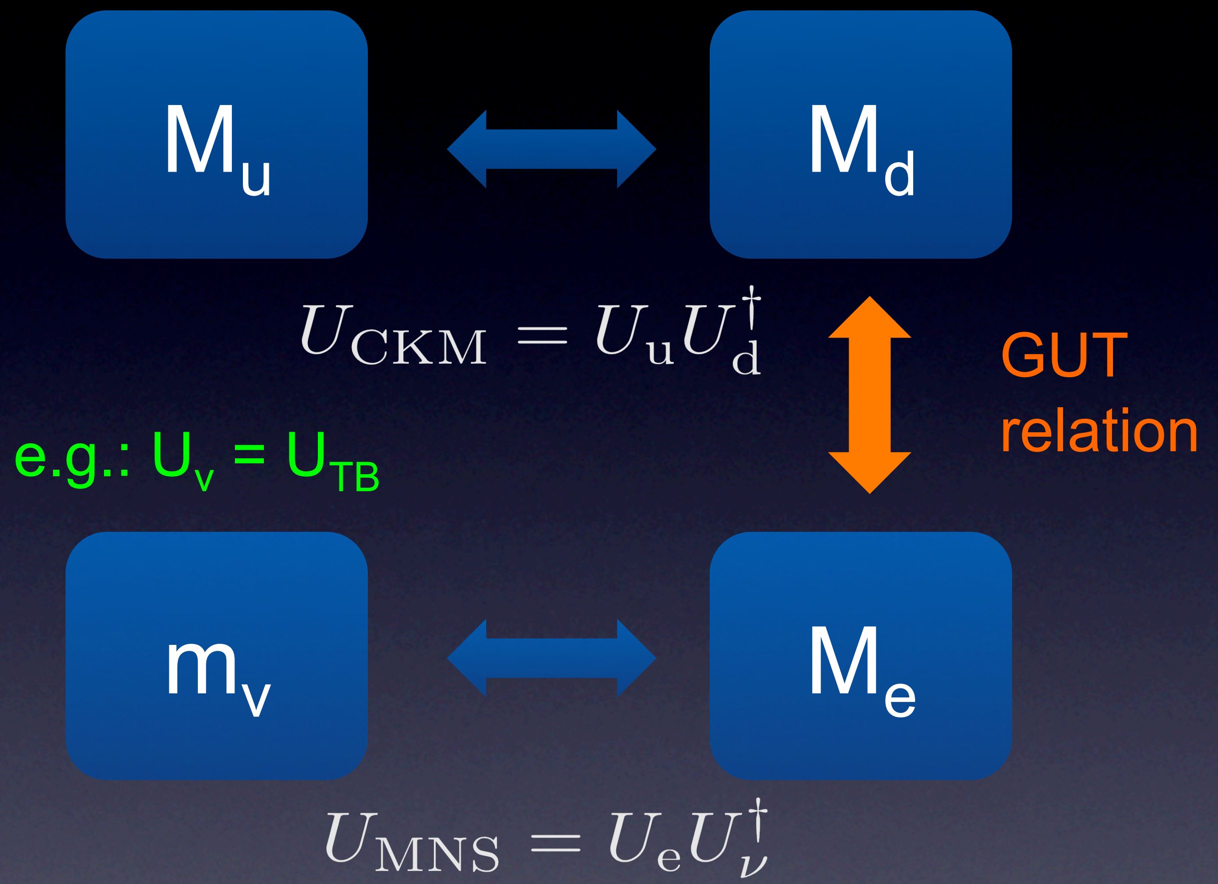
Interesting possibility:

Is $\theta_{13}^{PMNS} \approx \theta_C/\sqrt{2}$

the footprint of a GUT?



Example: Mixing sum rule if $\theta_{13}^{\mathrm{PMNS}}$ generated by charged lepton correction θ_{12}^{e}



2) Lepton mixing sum rule
(for $\theta_{13}^{\nu}, \theta_{13}^{e} \ll \theta_{12}^{e}$)

$$\theta_{12}^{\mathrm{PMNS}} = \theta_{12}^{\nu} + \theta_{13}^{\mathrm{PMNS}} \cos(\delta^{\mathrm{PMNS}})$$

hep-ph/0508044, hep-ph/0506297, hep-ph/0508031

Reconstructing θ_{12}^{ν} using the lepton mixing sum rule

$$\theta_{12}^{\mathrm{PMNS}} = \theta_{12}^{\nu} + \theta_{13}^{\mathrm{PMNS}} \cos(\delta^{\mathrm{PMNS}})$$

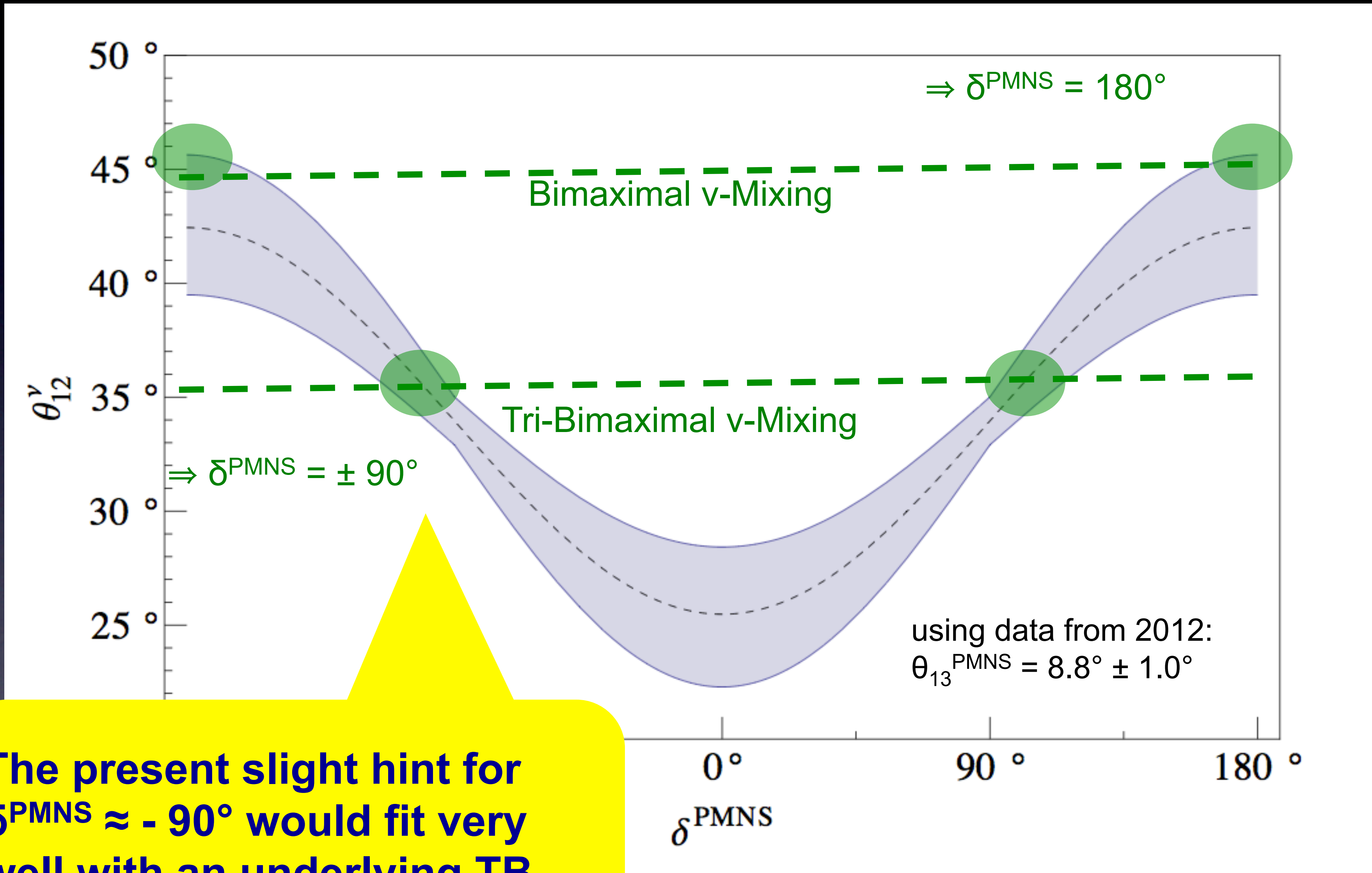


figure from arXiv:1205.1051

The present slight hint for $\delta^{\mathrm{PMNS}} \approx -90°$ would fit very well with an underlying TB mixing in the neutrino sector!

Example: mass sum rules

- initial observation: if M_ν constains two decisive parameters (typically by two flavon couplings), then it yields a mass sum rule

... different flavour groups in direct models can generate a large number of different sum rules, e.g.:

$$\frac{1}{\tilde{m}_3} + \frac{2i(-1)^\eta}{\tilde{m}_2} = \frac{1}{\tilde{m}_1}$$

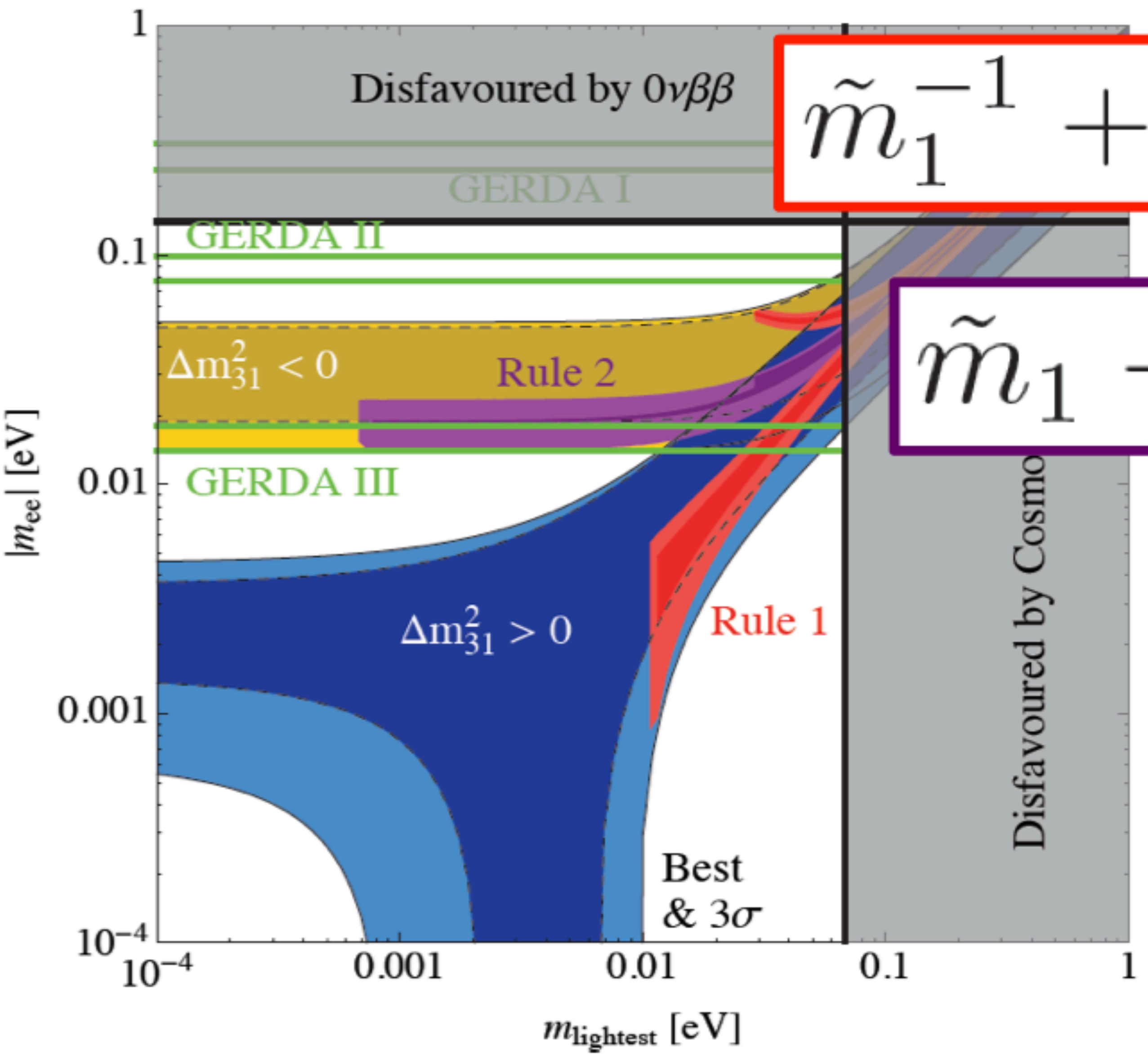
King, Luhn, Stuart: Nucl. Phys. **B867**, 203 (2013)

model: Δ(96) & seesaw type I

→ talks by A. Merle, W. Rodejohann

Example: mass sum rules

- model distinction:



$$\tilde{m}_1^{-1} + \tilde{m}_2^{-1} = \tilde{m}_3^{-1}$$

$$\tilde{m}_1 + \tilde{m}_2 = \tilde{m}_3$$

Distinctive power in spite of nuclear physics uncertainties!!!

→ talks by A. Merle, W. Rodejohann

Combining flavour symmetry and CP symmetry:

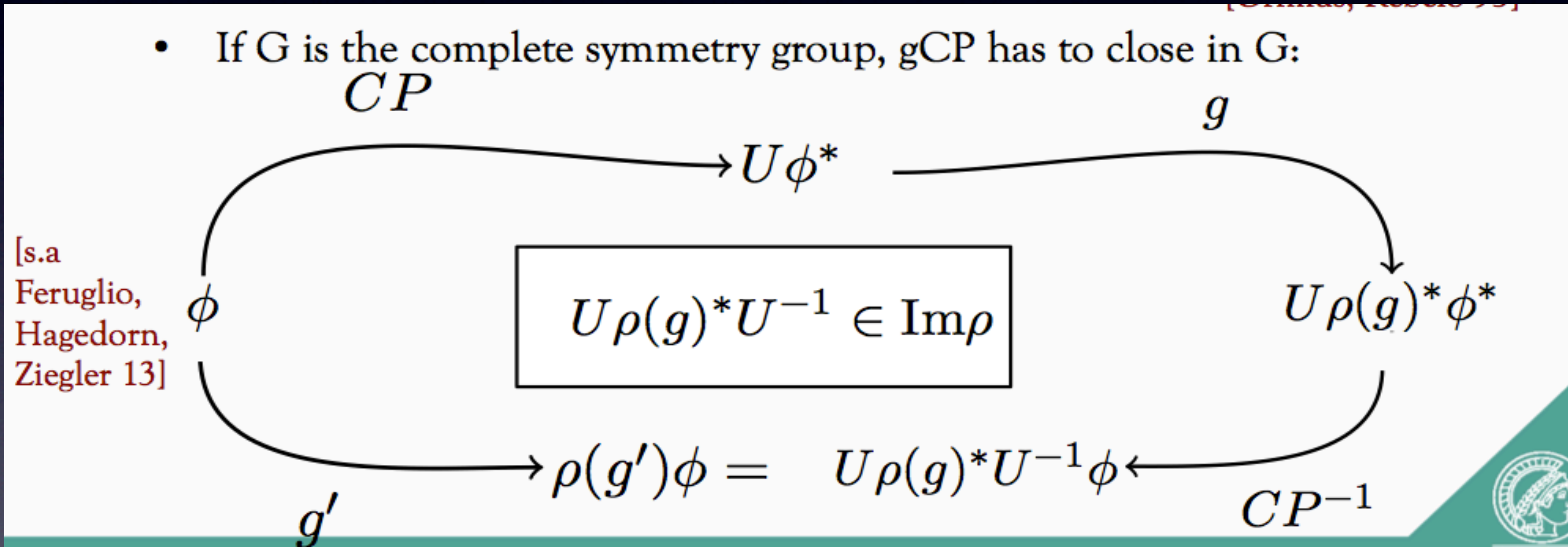
Predicting δ^{PMNS} from spontaneous CP breaking

→ talks by M. Holthausen, I. de Medeiros Varzielas, G.-J. Ding, A. Trautner, T. Neder

Spontaneous CP violation & flavour models

Generalized CP: Outer automorphisms of G_F

M. Holthausen, M. Lindner M. A. JHEP 1304 (2013) 122 [arXiv:1211.6953]



→ talk by Martin Holthausen

Spontaneous CP violation & flavour models

- CP transformations are **outer automorphisms** of G
- *Not* all outer automorphisms are CP transformations
- Two types of discrete groups:
  - Type I: incompatible with CP ✗ Attention: some (model dependent) fine print!
  - Type II: compatible with CP ✓

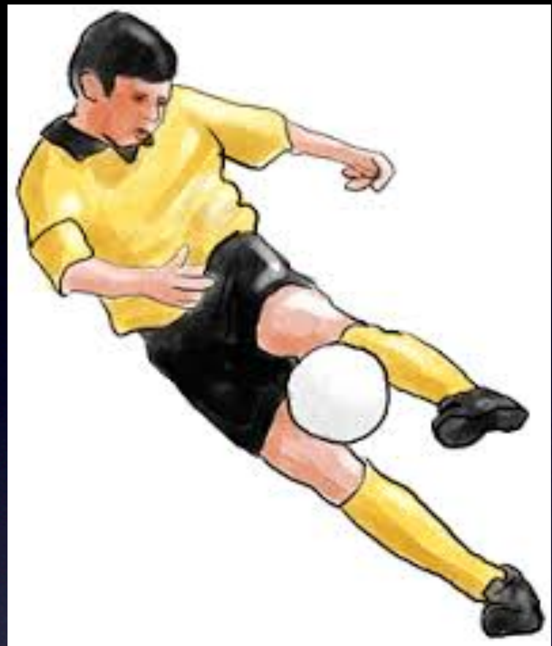
→ talk by Andreas Trautner

Geometrical CP violation with complete fermion sector

Conclusions

- First time GCPV with viable fermions.
- Precision data restricts viable irrep. choices.
- Additional symmetry safeguards potential.
- Same symmetry alleviates mass hierarchies.
- Constructed compatible lepton models.

→ talk by Ivo de Medeiros Varzielas



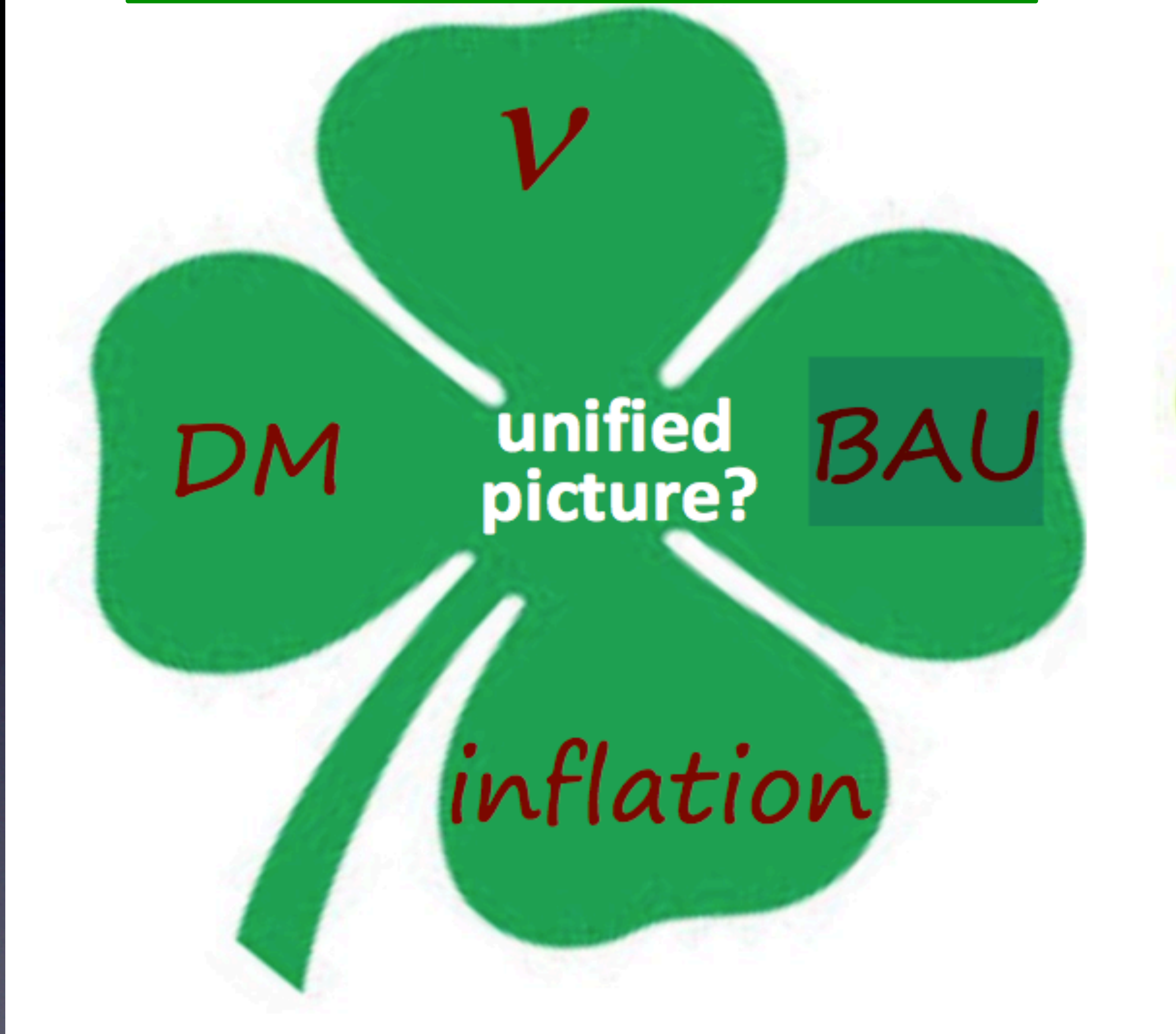
Cosmology:

Dark Matter, Leptogenesis, Inflation

Four-leaf clover

→ from talk
by S. Morisi

→ talks by
S. Morisi,
M. Aoki,
A. Watanabe,
E. Peinado,
N. Haba



→ talk by A. Sil

→ talks by R. Takahashi, S. Morisi

→ talks on flavour - DM connection by S. Morisi, M. Aoki, A. Watanabe, E. Peinado, N. Haba

DM ν fla-sy

Discrete Dark Matter

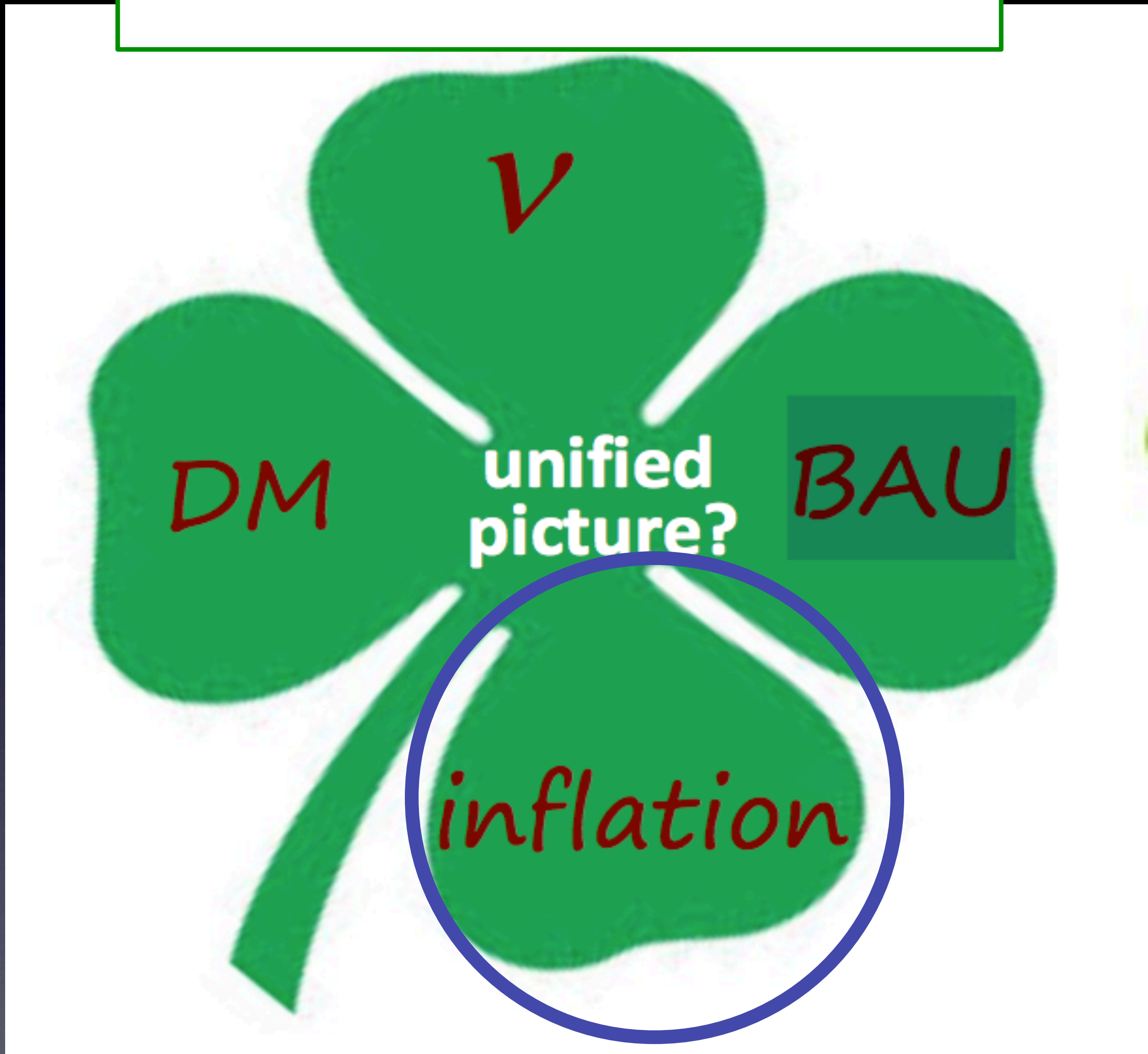
Hirsch, SM, Peinado, Valle PRD 10'
Meloni,SM,Peinado, PLB 11'
Boucenna et al, JHEP 11'
Meloni,SM,Peinado, PLB 11'
Toorop,Bazzocchi,M, NPB 12'
Boucenna et al, PRD 12'

The flavor symmetry stabilizes the DM

G_f → (spontaneously) Z_2 stabilize the DM (typically imposed by hand)

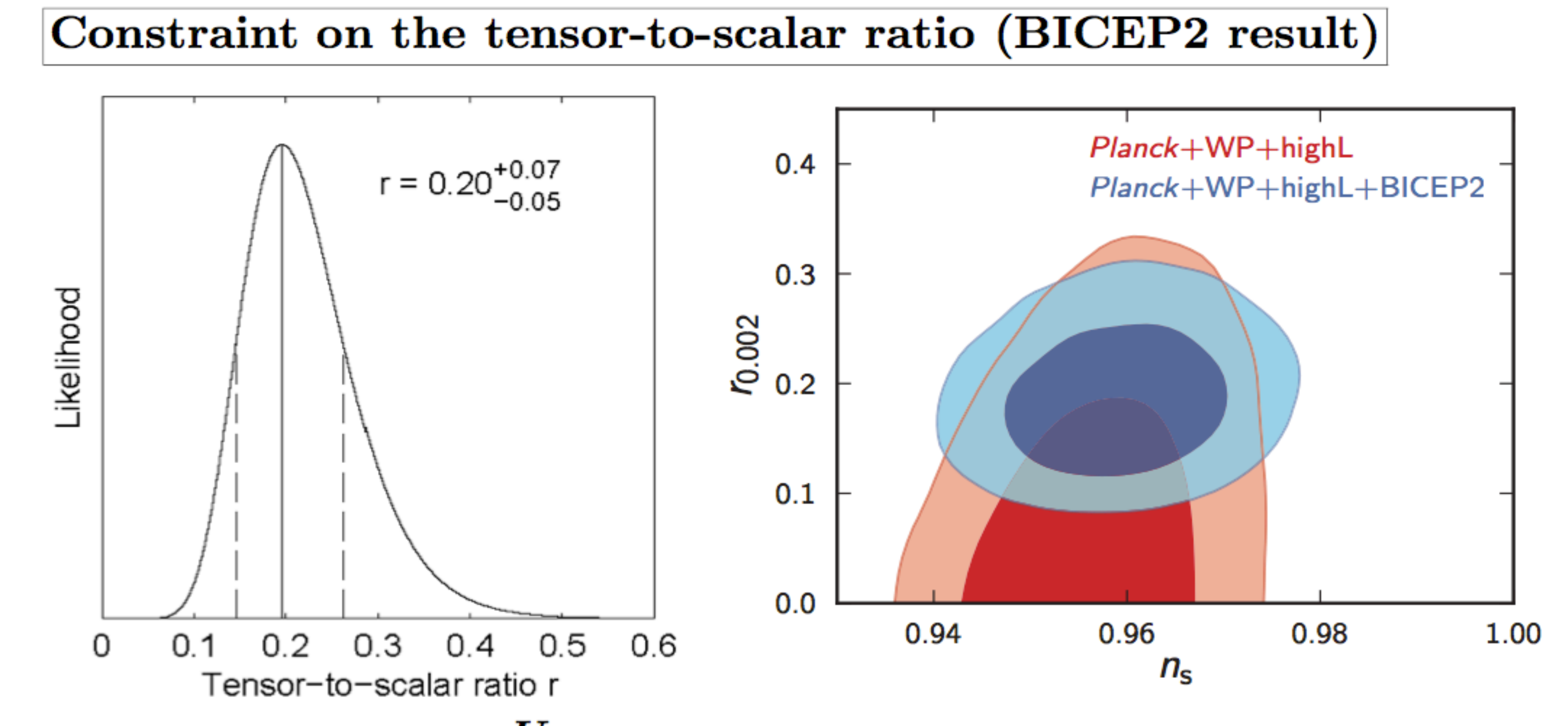
→ talks on DM experiments by J. Monroe

Four-leaf clover



→ from talk by S. Morisi

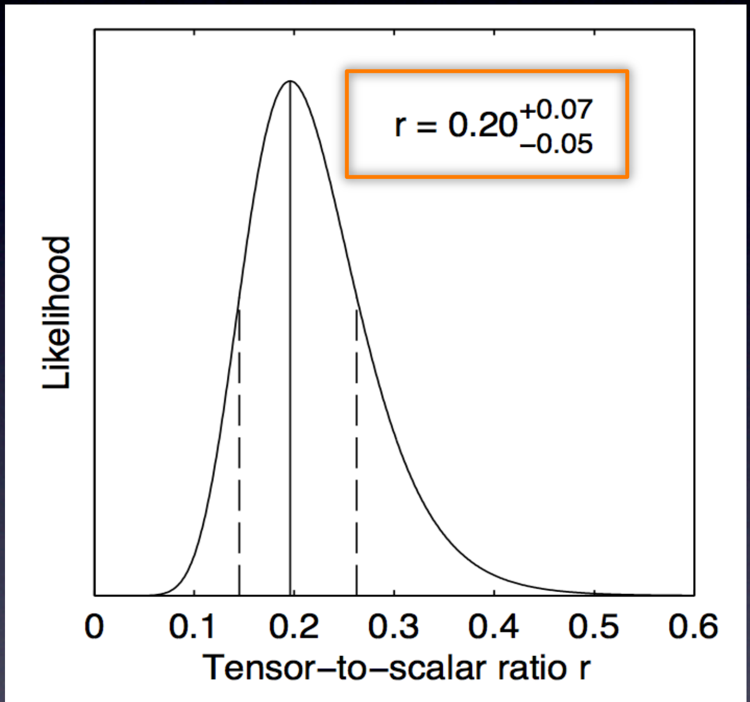
We also discussed a lot about the possible implications of the BICEP2 result ...



→from talk by R. Takahashi

If confirmed …

BICEP2 (2014)

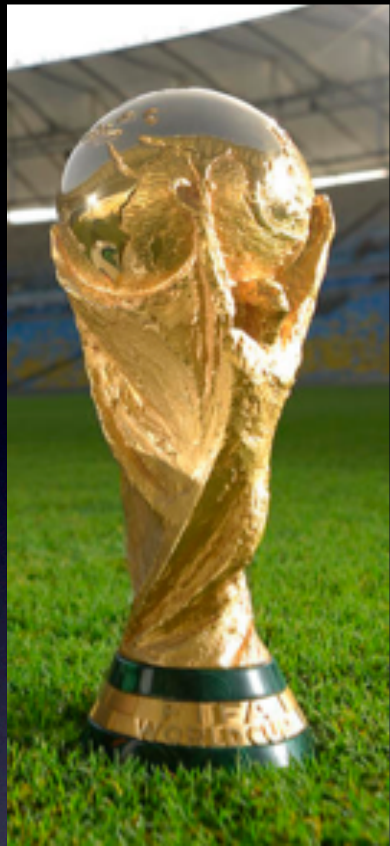


Important implications
(if 'large' r gets confirmed):

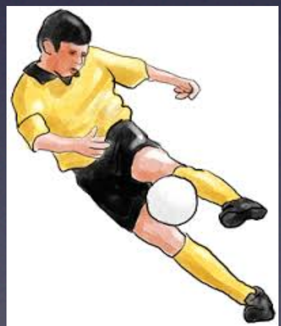
- **Confirmation of "smoking gun of inflation"**
- **$V_0 \sim M_{GUT} = 2 \times 10^{16}$ GeV (looks like pointing at possible connection to particle physics phase transition around M_{GUT})**
- **Slow-roll inflation: Large r implies large $\Delta\Phi > O(m_{Pl})$: For predictive models with so large $\Delta\Phi$, need to go beyond effective field theory …**

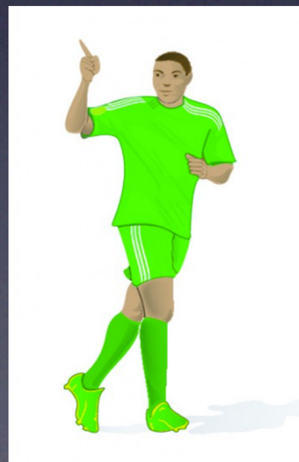
Vacuum energy during inflation can be calculated from r: $V_0^{\frac{1}{4}} \approx 2.2 \times 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.2}\right)^{\frac{1}{4}}$

Lets us all continue to join forces ...



... to win the FLASY Chamionship!





Special Thanks and Applause to the Organisers!

Looking forward to FLASY 2015 !