An up-to-date view of lepton flavour observables

Michele Frigerio
Laboratoire Charles Coulomb, CNRS & UM2, Montpellier

MF & Albert Villanova del Moral, JHEP 1307 (2013) 146
MF, Thomas Hambye & Eduard Massó, *PRX 1, 021026 (2011)*

LPC Clermont-Ferrand - 5 November 2013

Outline

- Lepton physics & the electroweak scale
- Lepton flavour observables: present & future data
- Lepton flavour symmetries: where do we stand
- Minimal flavour structures: a conspiracy for non-maximal 2-3 mixing
- A connection between neutrinos and very light dark matter candidates

- Lepton physics & the electroweak scale
- Lepton flavour observables: present & future data
- Lepton flavour symmetries: where do we stand
- Minimal flavour structures: a conspiracy for non-maximal 2-3 mixing
- A connection between neutrinos and very light dark matter candidates

Beyond the Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{EWSB} + \mathcal{L}_{flavour}$$

4 + 2 + 13 parameters

It works damnably well up to the TeV scale...

Beyond the Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{EWSB} + \mathcal{L}_{flavour}$$

4 + 2 + 13 parameters

It works damnably well up to the TeV scale...

New physics at larger scales can be encoded in higher-dimensional operators:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_{D=5} + \frac{1}{\Lambda^2}\mathcal{L}_{D=6} + \ldots$$

Beyond the Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{EWSB} + \mathcal{L}_{flavour}$$

4 + 2 + 13 parameters

It works damnably well up to the TeV scale...

New physics at larger scales can be encoded in higher-dimensional operators:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_{D=5} + \frac{1}{\Lambda^2}\mathcal{L}_{D=6} + \ldots$$

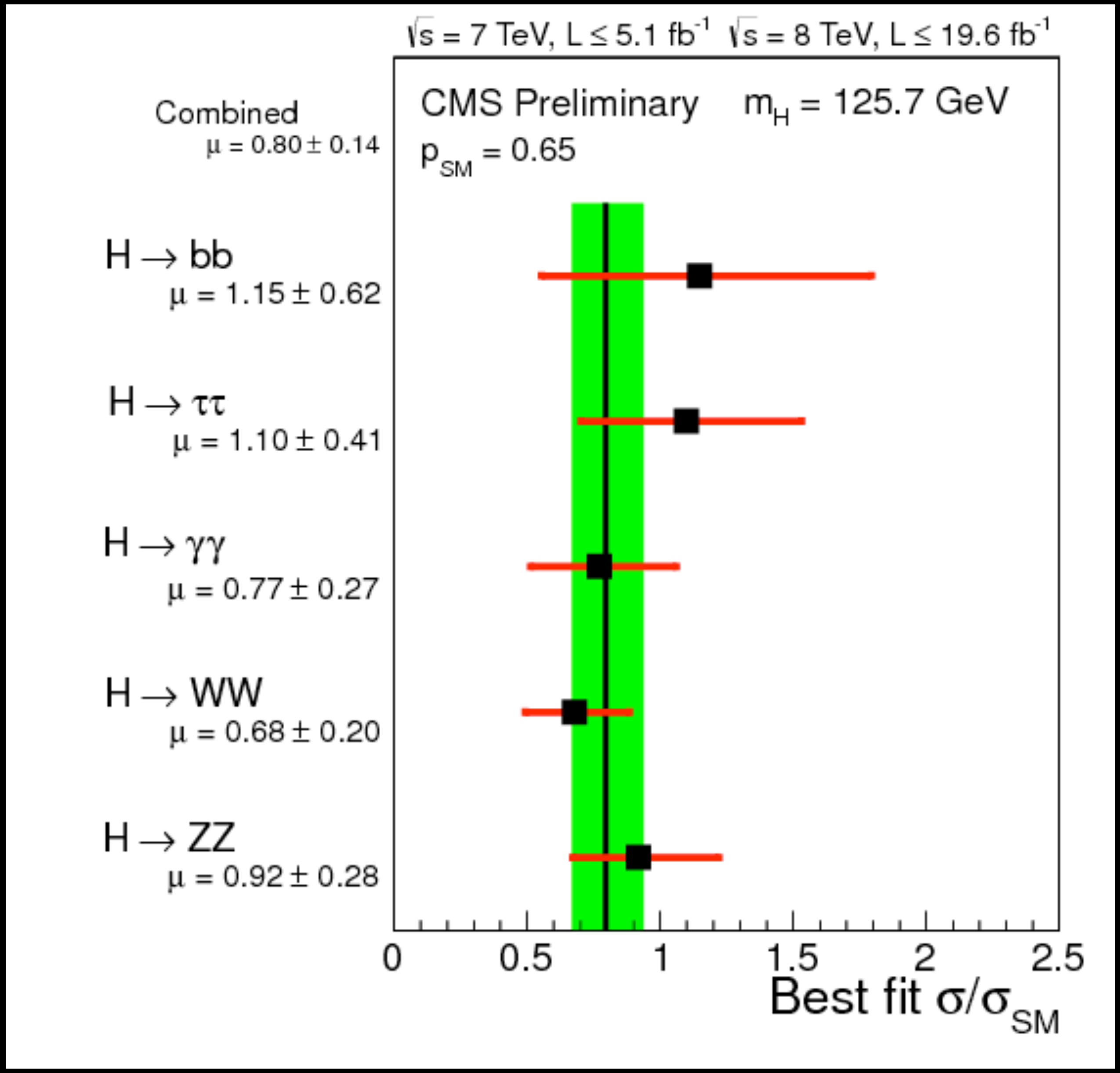
New physics below 100 GeV should be very weakly coupled to the SM: typically gauge singlet states ...

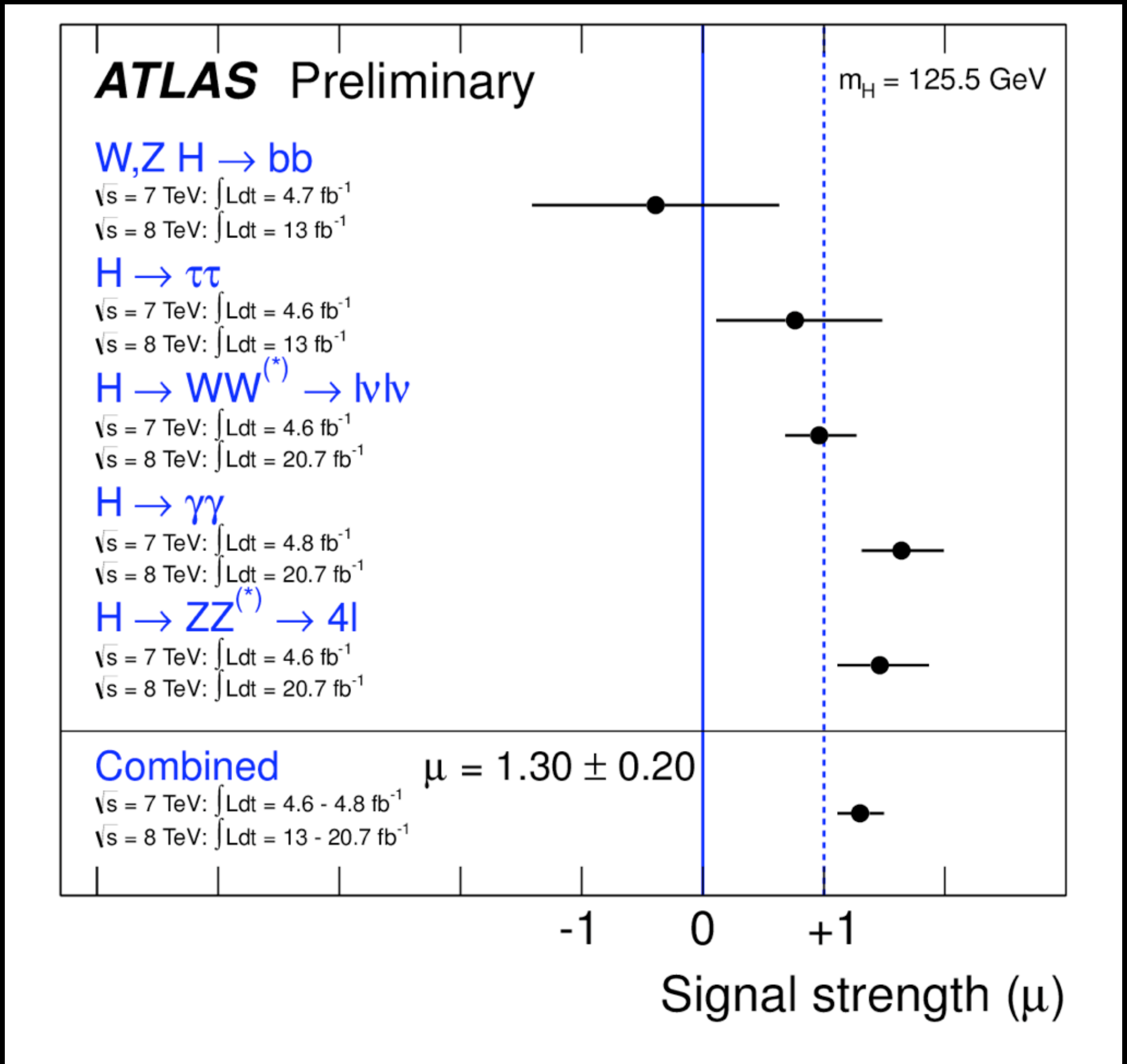
Where should we search?

Definitely, the most motivated new physics signals are expected in the Electroweak Symmetry Breaking Sector... alas, no luck so far

Where should we search?

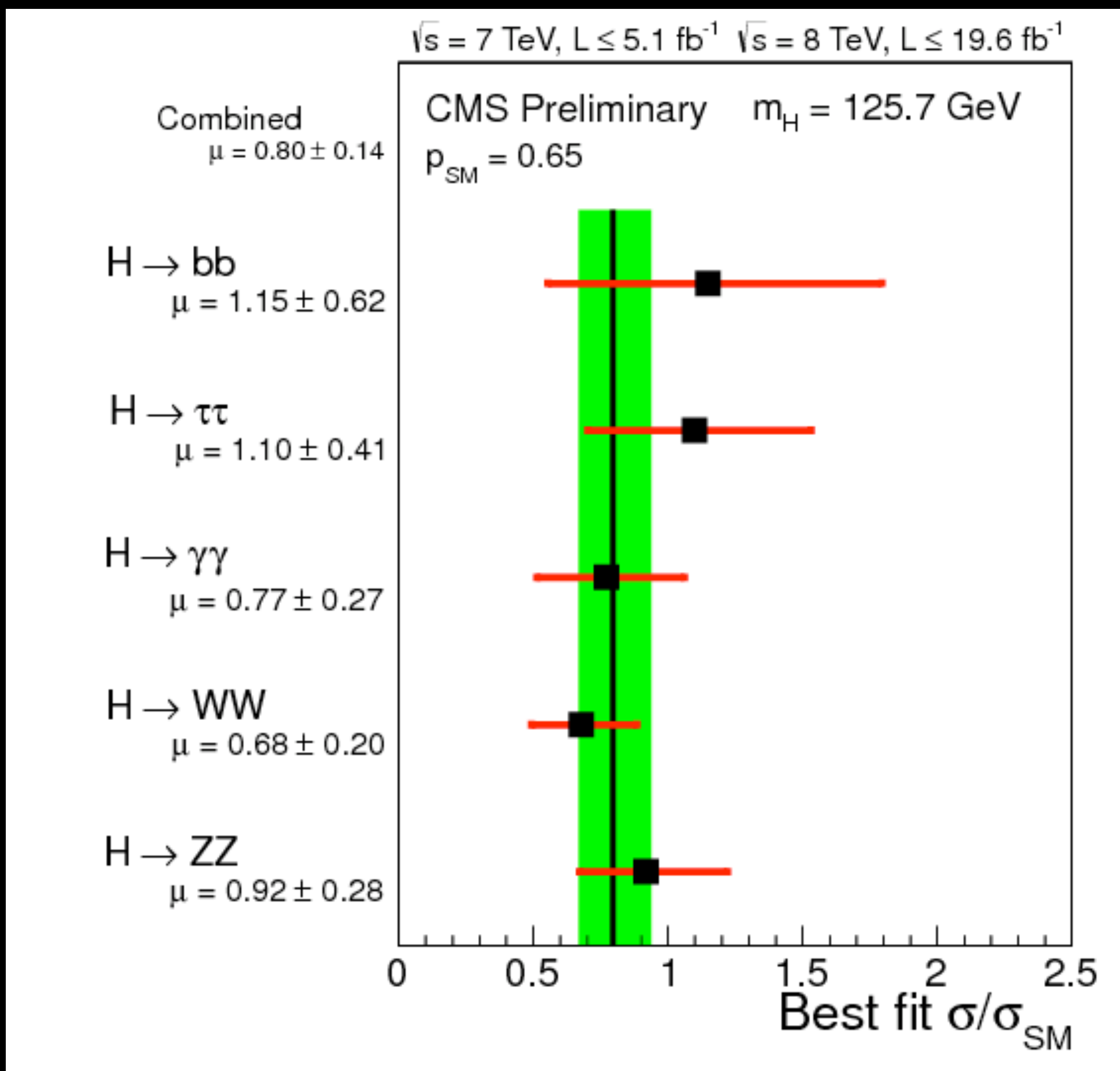
Definitely, the most motivated new physics signals are expected in the Electroweak Symmetry Breaking Sector... alas, no luck so far

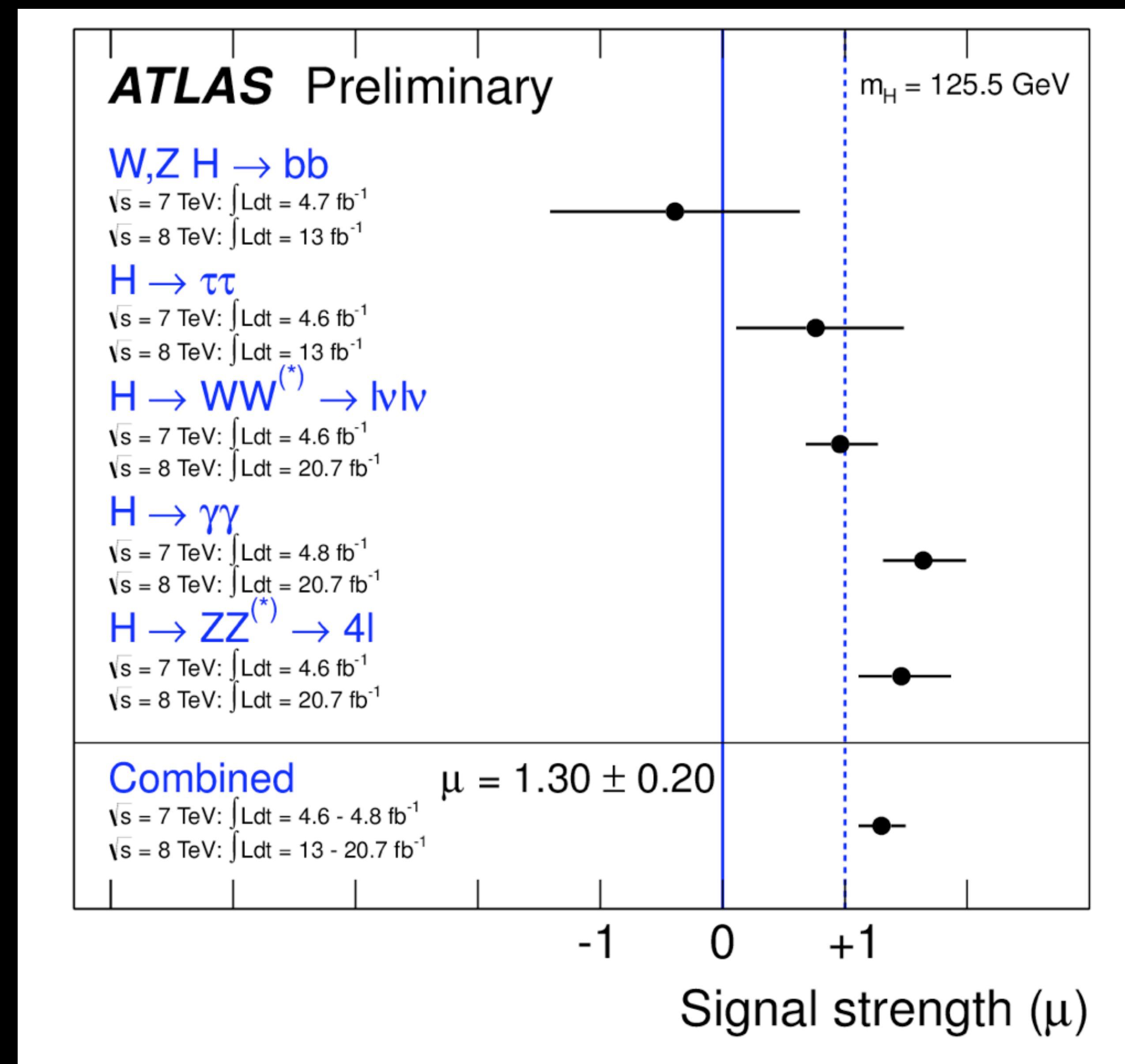




Where should we search?

Definitely, the most motivated new physics signals are expected in the Electroweak Symmetry Breaking Sector… alas, no luck so far





Still room for natural EWSB, especially one should watch for the top sector observables

The importance of being massive

The discovery of neutrino oscillations amounts to

- a new energy scale, $m_\nu \sim 0.1$eV, probably associated to another one, $\Lambda = v^2/m_\nu \sim 10^{14}$GeV
- the breaking of fundamental symmetries, lepton flavour numbers, and probably lepton number too
- 9 basic parameters, that add to the 19 SM parameters to define the ν-SM

The importance of being massive

The discovery of neutrino oscillations amounts to

- a new energy scale, $m_\nu \sim 0.1$eV, probably associated to another one, $\Lambda = v^2/m_\nu \sim 10^{14}$GeV
- the breaking of fundamental symmetries, lepton flavour numbers, and probably lepton number too
- 9 basic parameters, that add to the 19 SM parameters to define the ν-SM

$$\frac{1}{\Lambda}\mathcal{L}_{D=5} = \frac{c_{ij}}{2\Lambda} l_{Li} l_{Lj} \phi\phi + h.c.$$

The smallness of Λ is protected by a symmetry (lepton number): hopefully D=6 operators are less suppressed !

The importance of being massive

The discovery of neutrino oscillations amounts to

- a new energy scale, $m_\nu \sim 0.1$eV, probably associated to another one, $\Lambda = v^2/m_\nu \sim 10^{14}$GeV
- the breaking of fundamental symmetries, lepton flavour numbers, and probably lepton number too
- 9 basic parameters, that add to the 19 SM parameters to define the ν-SM

$$\frac{1}{\Lambda}\mathcal{L}_{D=5} = \frac{c_{ij}}{2\Lambda} l_{Li} l_{Lj} \phi\phi + h.c.$$

The smallness of Λ is protected by a symmetry (lepton number): hopefully D=6 operators are less suppressed !

$$(m_\nu)_{ij} = c_{ij}\frac{v^2}{\Lambda}$$

The scale of flavour symmetry breaking remains unknown, and possibly out of reach

Charged lepton flavour violation

- Charged lepton flavour violation effects from $l_L l_L \Phi\Phi$ are extremely suppressed, by $(m_\nu/m_W)^4$
- However, new physics in the multi-TeV range generically violates flavour, in the quark and in the lepton sector
- Rare lepton processes are indirectly sensitive to new states potentially much heavier than the LHC reach

Charged lepton flavour violation

- Charged lepton flavour violation effects from $l_L l_L \Phi\Phi$ are extremely suppressed, by $(m_\nu/m_W)^4$
- However, new physics in the multi-TeV range generically violates flavour, in the quark and in the lepton sector
- Rare lepton processes are indirectly sensitive to new states potentially much heavier than the LHC reach

$$\frac{1}{\Lambda^2}\overline{l_L}\sigma^{\mu\nu}F_{\mu\nu}\phi e_R$$

$$BR(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13} \ (90\%\mathrm{C.L.})$$

MEG 2009-2011, arXiv:1303.0754

upgrade for (10 x present sensitivity)

Charged lepton flavour violation

- Charged lepton flavour violation effects from $l_L l_L \Phi\Phi$ are extremely suppressed, by $(m_\nu/m_W)^4$
- However, new physics in the multi-TeV range generically violates flavour, in the quark and in the lepton sector
- Rare lepton processes are indirectly sensitive to new states potentially much heavier than the LHC reach

$$\frac{1}{\Lambda^2}\overline{l_L}\sigma^{\mu\nu}F_{\mu\nu}\phi e_R$$

$$BR(\mu^+ \to e^+\gamma) < 5.7 \times 10^{-13} \ (90\%\text{C.L.})$$

MEG 2009-2011, arXiv:1303.0754

upgrade for (10 x present sensitivity)

$$+\frac{1}{\Lambda^2}\overline{l_L}e_R\overline{q_L}u_R$$

$$R(\mu^-\text{Ti} \to e^-\text{Ti}) < 4.3 \times 10^{-12} \ (90\%\text{C.L.})$$

SINDRUM II, PLB 317 (1993) 631

improvement by a factor 10^6 expected with COMET

Extra lepto-philic light states

Extra lepto-philic light states

- Light neutral particles may have escaped detection if sufficiently weakly coupled to the SM

Extra lepto-philic light states

- Light neutral particles may have escaped detection if sufficiently weakly coupled to the SM
- Spin 1: $U(1)_{B-L}$ may be weakly gauged and spontaneously broken at low energies (sub-MeV scale, *Nelson-Walsh '07*)

Extra lepto-philic light states

- Light neutral particles may have escaped detection if sufficiently weakly coupled to the SM
- Spin 1: $U(1)_{B-L}$ may be weakly gauged and spontaneously broken at low energies (sub-MeV scale, *Nelson-Walsh '07*)
- Spin 1/2: they are generically sterile neutrinos, that may be useful to explain oscillations anomalies (eV scale, *Kopp-Machado-Maltoni-Schwetz '13*), or the dark matter relic density (keV scale, *Shaposhnikov '07*), ...

Extra lepto-philic light states

- Light neutral particles may have escaped detection if sufficiently weakly coupled to the SM
- Spin 1: $U(1)_{B-L}$ may be weakly gauged and spontaneously broken at low energies (sub-MeV scale, *Nelson-Walsh '07*)
- Spin 1/2: they are generically sterile neutrinos, that may be useful to explain oscillations anomalies (eV scale, *Kopp-Machado-Maltoni-Schwetz '13*), or the dark matter relic density (keV scale, *Shaposhnikov '07*), ...
- Spin 0: if the lepton number (the lepton flavour group) is broken spontaneously, there must be a light Goldstone boson, the Majoron (several flavoured Goldstone bosons): good dark matter candidates!

Extra lepto-philic light states

- Light neutral particles may have escaped detection if sufficiently weakly coupled to the SM
- Spin 1: $U(1)_{B-L}$ may be weakly gauged and spontaneously broken at low energies (sub-MeV scale, *Nelson-Walsh '07*)
- Spin 1/2: they are generically sterile neutrinos, that may be useful to explain oscillations anomalies (eV scale, *Kopp-Machado-Maltoni-Schwetz '13*), or the dark matter relic density (keV scale, *Shaposhnikov '07*), ...
- Spin 0: if the lepton number (the lepton flavour group) is broken spontaneously, there must be a light Goldstone boson, the Majoron (several flavoured Goldstone bosons): good dark matter candidates!
- Cosmology may give indications for extra light degrees of freedom. Unfortunately there is no compelling evidence at present. E.g. Planck data require $N_{eff} = 3.3 \pm 0.5$ (95% C.L.)

- Lepton physics & the electroweak scale
- Lepton flavour observables: present & future data
- Lepton flavour symmetries: where do we stand
- Minimal flavour structures: a conspiracy for non-maximal 2-3 mixing
- A connection between neutrinos and very light dark matter candidates

Lepton flavour parameters

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \overline{e_{L\alpha}} \gamma^{\mu} W_{\mu}^{+} \nu_{L\alpha} - m_{\alpha} \overline{e_{L\alpha}} e_{R\alpha} - \frac{1}{2} \nu_{L\alpha} (m_{\nu})_{\alpha\beta} \nu_{L\beta} + h.c.$$

3 charged lepton masses m_e, m_μ, m_τ + Majorana mass matrix for ν_e, ν_μ, ν_τ :

$$m_\nu = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

Lepton flavour parameters

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \overline{e_{L\alpha}} \gamma^\mu W_\mu^+ \nu_{L\alpha} - m_\alpha \overline{e_{L\alpha}} e_{R\alpha} - \frac{1}{2} \nu_{L\alpha} (m_\nu)_{\alpha\beta} \nu_{L\beta} + h.c.$$

3 charged lepton masses m_e, m_μ, m_τ + Majorana mass matrix for ν_e, ν_μ, ν_τ :

$$m_\nu = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

a 3x3 complex symmetric matrix contains 9 physical parameters: 6 moduli + 3 CP-violating phases (3 phases absorbed in ν_e, ν_μ, ν_τ)

Lepton flavour parameters

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \overline{e_{L\alpha}} \gamma^\mu W_\mu^+ \nu_{L\alpha} - m_\alpha \overline{e_{L\alpha}} e_{R\alpha} - \frac{1}{2} \nu_{L\alpha} (m_\nu)_{\alpha\beta} \nu_{L\beta} + h.c.$$

3 charged lepton masses m_e, m_μ, m_τ + Majorana mass matrix for ν_e, ν_μ, ν_τ :

$$m_\nu = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

a 3x3 complex symmetric matrix contains 9 physical parameters: 6 moduli + 3 CP-violating phases (3 phases absorbed in ν_e, ν_μ, ν_τ)

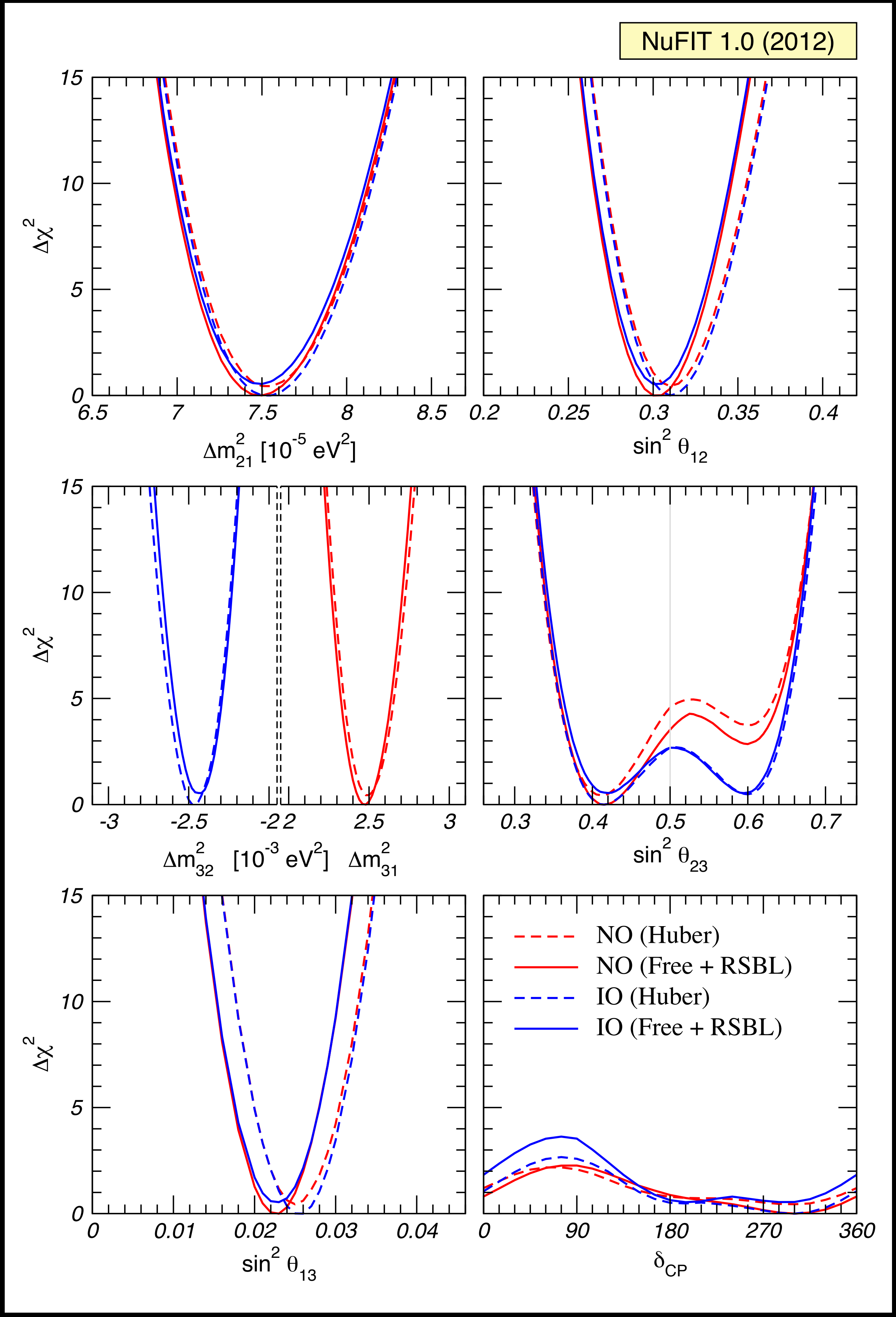
$$m_\nu = U^* \mathrm{diag}(m_1 e^{-2i\rho}, m_2, m_3 e^{-2i\sigma}) U^\dagger$$

$$U = R(\theta_{23}) R(\theta_{13}, \delta) R(\theta_{12})$$

Neutrino oscillation data

sensitivity to 3 mixing angles, 2 mass differences, 1 phase

Gonzalez-Garcia Maltoni Salvado Schwetz

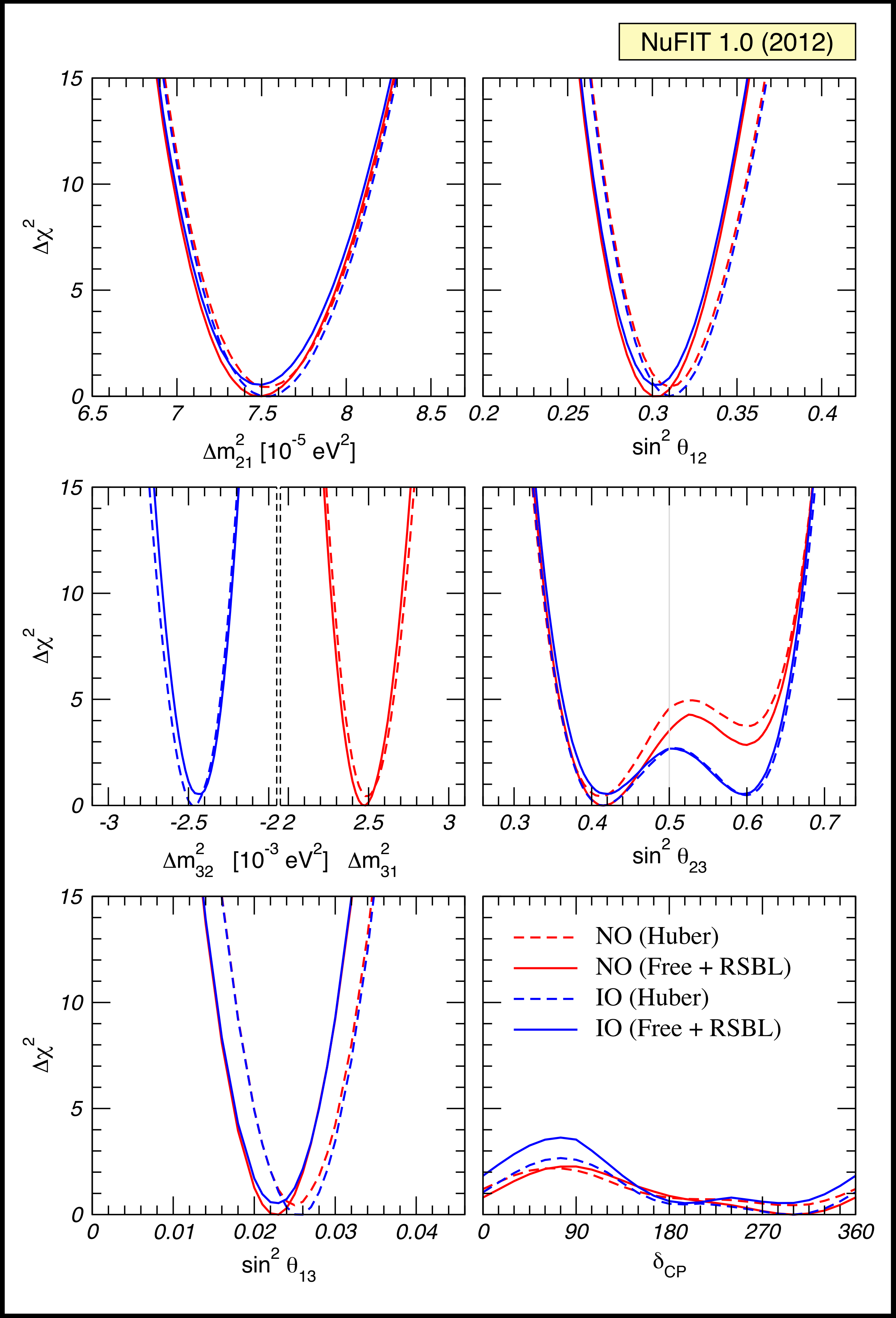


Neutrino oscillation data

sensitivity to 3 mixing angles, 2 mass differences, 1 phase

The mass squared differences are precisely known, up to one sign: $m_3 > m_{1,2}$ (Normal Ordering) or $m_3 < m_{1,2}$ (Inverted Ordering)

Gonzalez-Garcia Maltoni Salvado Schwetz



Neutrino oscillation data

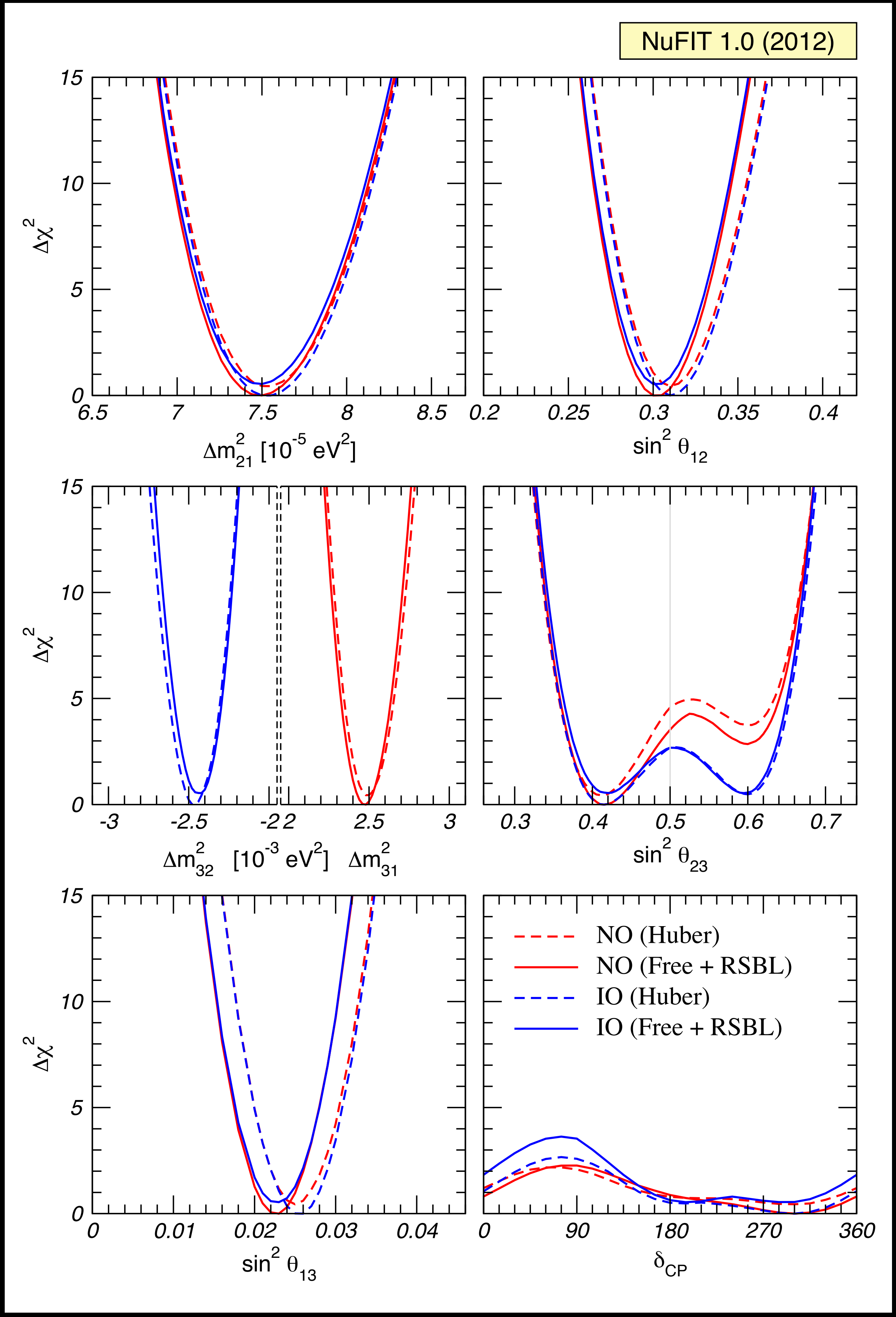
sensitivity to 3 mixing angles, 2 mass differences, 1 phase

The mass squared differences are precisely known, up to one sign: $m_3 > m_{1,2}$ (Normal Ordering) or $m_3 < m_{1,2}$ (Inverted Ordering)

The 2012 revolution: θ_{13} measured (reactor ν's) almost as precisely as θ_{12} (solar ν's).

The mixing angle θ_{23} (atmospheric ν's) is not precisely determined yet.
There is a 2σ preference for a non-maximal value (accelerator ν's).

Gonzalez-Garcia Maltoni Salvado Schwetz



Neutrino oscillation data

sensitivity to 3 mixing angles, 2 mass differences, 1 phase

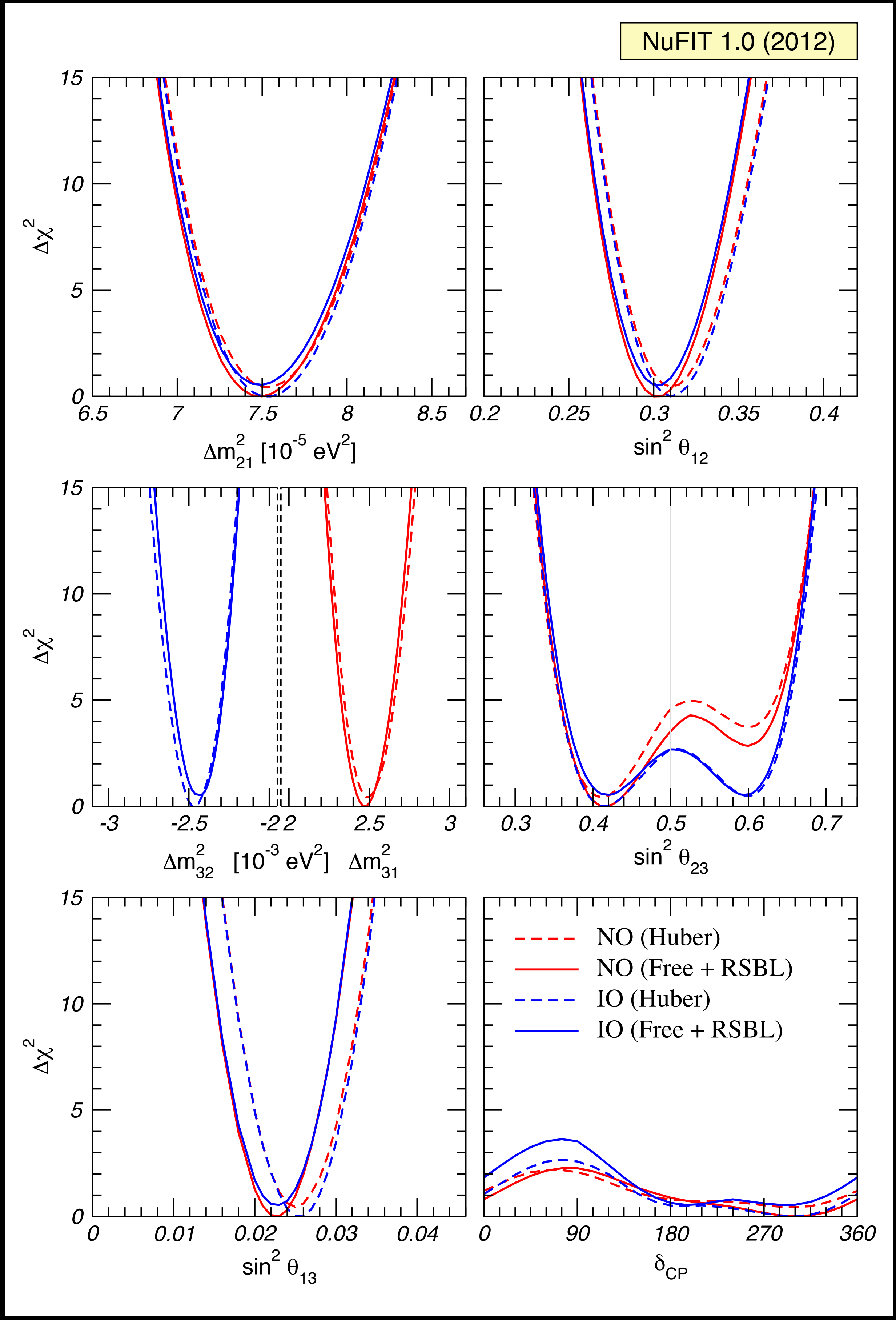
The mass squared differences are precisely known, up to one sign: $m_3 > m_{1,2}$ (Normal Ordering) or $m_3 < m_{1,2}$ (Inverted Ordering)

The 2012 revolution: θ_{13} measured (reactor ν's) almost as precisely as θ_{12} (solar ν's).

The mixing angle θ_{23} (atmospheric ν's) is not precisely determined yet.
There is a 2σ preference for a non-maximal value (accelerator ν's).

Lepton CP-violation is behind the corner ?
Some values of δ already disfavoured at 1σ

Gonzalez-Garcia Maltoni Salvado Schwetz



Neutrino oscillation data

sensitivity to 3 mixing angles, 2 mass differences, 1 phase

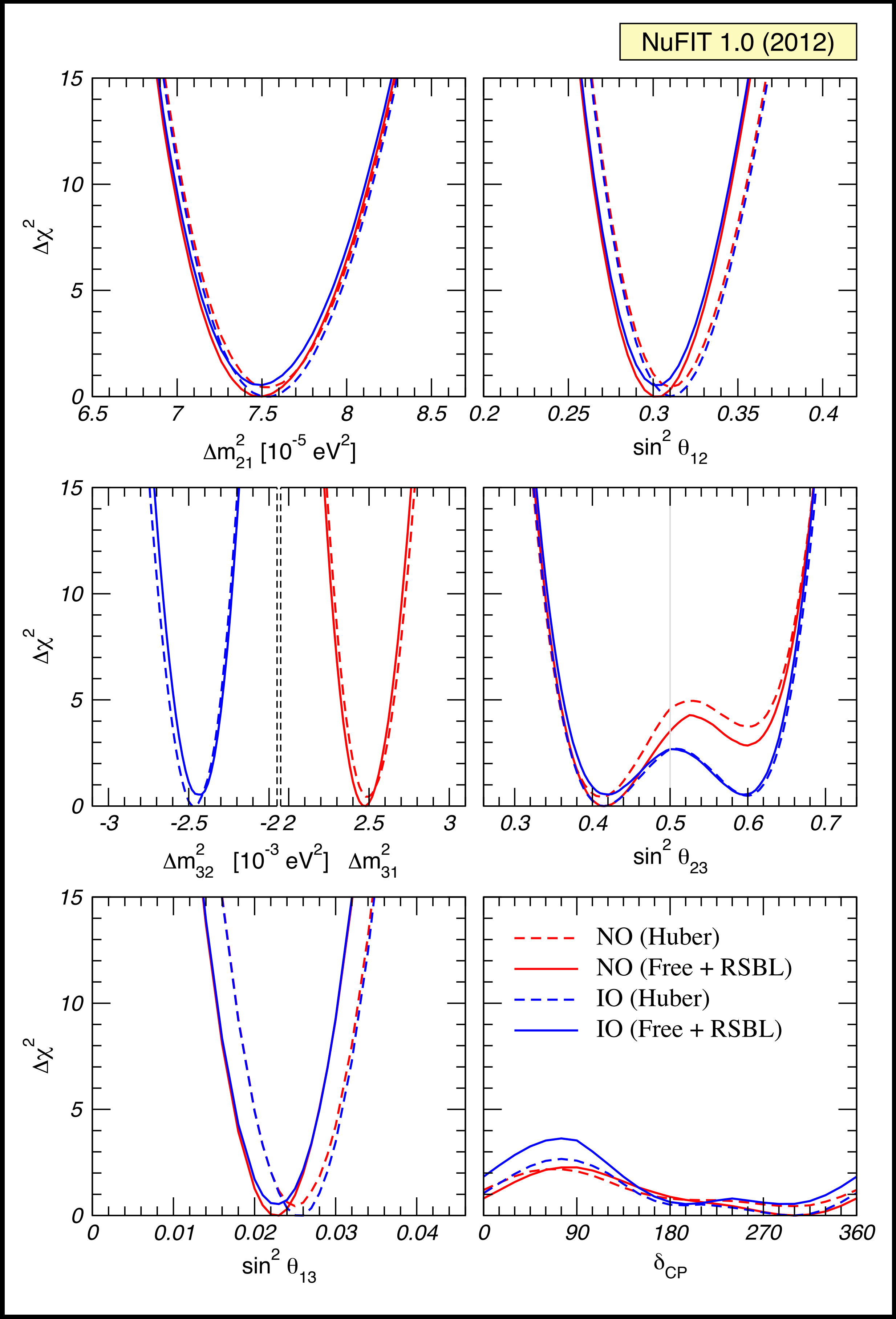
The mass squared differences are precisely known, up to one sign: $m_3 > m_{1,2}$ (Normal Ordering) or $m_3 < m_{1,2}$ (Inverted Ordering)

The 2012 revolution: θ_{13} measured (reactor ν's) almost as precisely as θ_{12} (solar ν's).

The mixing angle θ_{23} (atmospheric ν's) is not precisely determined yet.
There is a 2σ preference for a non-maximal value (accelerator ν's).

Lepton CP-violation is behind the corner ?
Some values of δ already disfavoured at 1σ

Gonzalez-Garcia Maltoni Salvado Schwetz



Neutrino oscillation data

sensitivity to 3 mixing angles, 2 mass differences, 1 phase

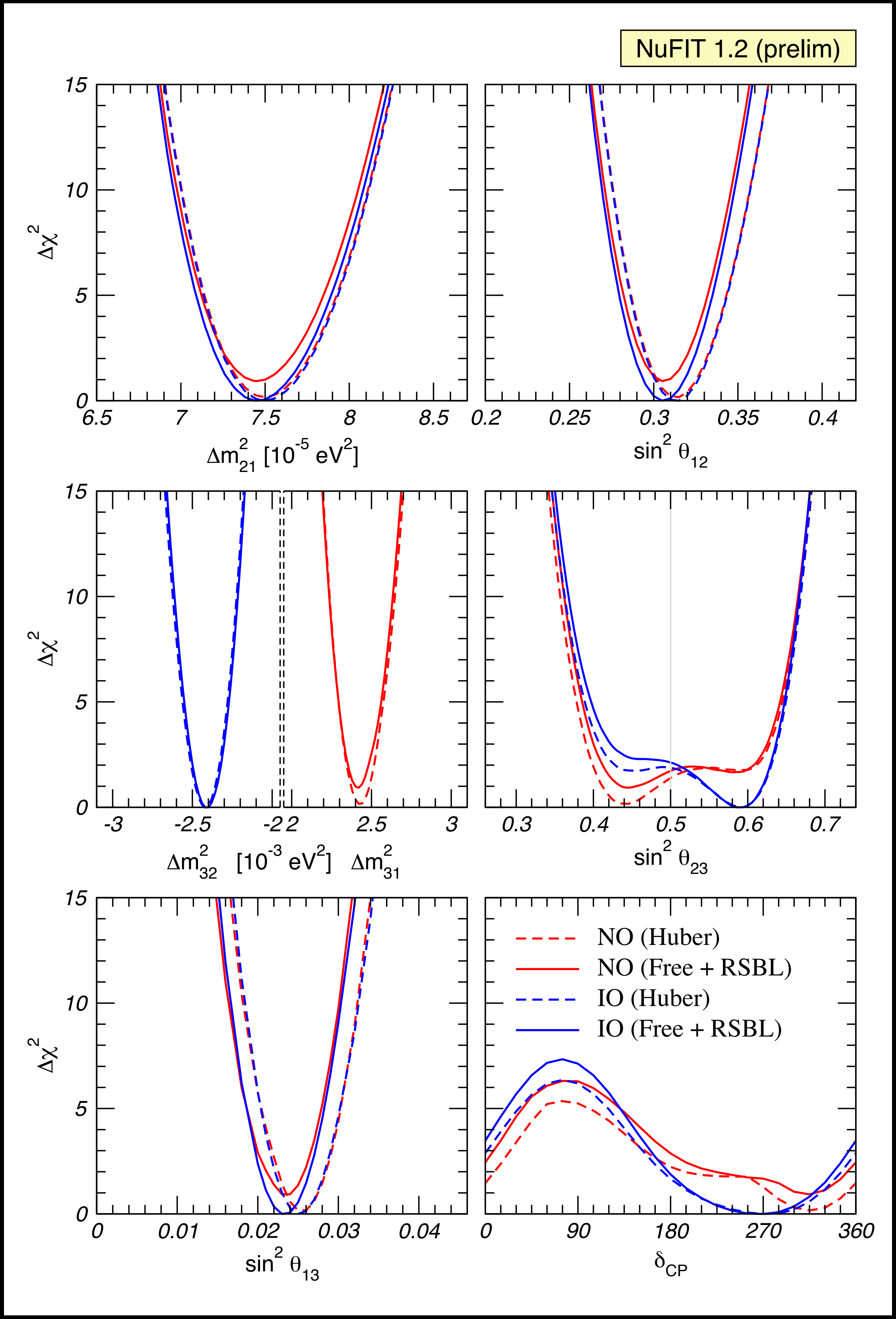
The mass squared differences are precisely known, up to one sign: $m_3 > m_{1,2}$ (Normal Ordering) or $m_3 < m_{1,2}$ (Inverted Ordering)

The 2012 revolution: θ_{13} measured (reactor ν's) almost as precisely as θ_{12} (solar ν's).

The mixing angle θ_{23} (atmospheric ν's) is not precisely determined yet.
There is a 2σ preference for a non-maximal value (accelerator ν's).

Lepton CP-violation is behind the corner ?
Some values of δ already disfavoured at 1σ

Gonzalez-Garcia Maltoni Salvado Schwetz



Future experimental targets

Future experimental targets

- Precision in oscillation experiments means essentially:
  - to close in on $0.34 < \sin^2\theta_{23} < 0.67$ (3σ)
  - to tell the mass ordering, normal or inverted
  - to narrow the window $0 \leq \delta < 2\pi$

Future experimental targets

- Precision in oscillation experiments means essentially:
  - to close in on $0.34 < \sin^2\theta_{23} < 0.67$ (3σ)
  - to tell the mass ordering, normal or inverted
  - to narrow the window $0 \leq \delta < 2\pi$
- The lighest neutrino mass lies in the range:
  $0 < m_{light} < 0.5$ eV (conservative 95% C.L. from cosmological data); direct measurement with KATRIN ?

Future experimental targets

- Precision in oscillation experiments means essentially:
  - to close in on $0.34 < \sin^2\theta_{23} < 0.67$ (3σ)
  - to tell the mass ordering, normal or inverted
  - to narrow the window $0 \leq \delta < 2\pi$
- The lighest neutrino mass lies in the range: $0 < m_{light} < 0.5$ eV (conservative 95% C.L. from cosmological data); direct measurement with KATRIN ?
- Only one realistic observable is sensitive to the two Majorana-type CP-violating phases: the neutrinoless 2β-decay effective mass, $0 < m_{ee} < 0.38$ eV (90% C.L. by EXO-200, KamLAND-Zen pushed down to 0.25 eV; similar bound from a different isotope by GERDA)

- Lepton physics & the electroweak scale
- Lepton flavour observables: present & future data
- Lepton flavour symmetries: where do we stand
- Minimal flavour structures: a conspiracy for non-maximal 2-3 mixing
- A connection between neutrinos and very light dark matter candidates

A theory for lepton flavour ?

A theory for lepton flavour ?

Few years ago, after a seminar on flavour models ...

A theory for lepton flavour ?

Few years ago, after a seminar on flavour models ...

A well-known physicist in the audience commented: “After many decades spent to measure precisely quark masses and the CKM mixing parameters, we did not learn anything on the underlying origin of flavour.”

A theory for lepton flavour ?

Few years ago, after a seminar on flavour models ...

A well-known physicist in the audience commented: "After many decades spent to measure precisely quark masses and the CKM mixing parameters, we did not learn anything on the underlying origin of flavour."

The well-known speaker replied: "It is just you who did not learn anything!"

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

4 poorly constrained observables: $x_i = \theta_{23},\ m_{\rm light},\ \delta,\ m_{ee}$

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

4 poorly constrained observables: $x_i = \theta_{23},\ m_{\rm light},\ \delta,\ m_{ee}$

For any given flavour model, M_ν depends on n parameters

Frigerio & Villanova del Moral, 2013

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

4 poorly constrained observables: $x_i = \theta_{23},\ m_{\rm light},\ \delta,\ m_{ee}$

For any given flavour model, M_ν depends on n parameters

When n ≤ 4: $x_i^{\pm} = x_i^{\pm}(p_a)$

Frigerio & Villanova del Moral, 2013

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

4 poorly constrained observables: $x_i = \theta_{23},\ m_{\text{light}},\ \delta,\ m_{ee}$

For any given flavour model, M_ν depends on n parameters

When n ≤ 4: $x_i^\pm = x_i^\pm(p_a)$

When n = 5: $x_i^\pm = x_i^\pm(x_j, p_a)$

Frigerio & Villanova del Moral, 2013

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

4 poorly constrained observables: $x_i = \theta_{23},\ m_{\text{light}},\ \delta,\ m_{ee}$

For any given flavour model, M_ν depends on n parameters

When n ≤ 4: $x_i^{\pm} = x_i^{\pm}(p_a)$

When n = 5: $x_i^{\pm} = x_i^{\pm}(x_j, p_a)$

When n = 6: $x_i^{\pm} = x_i^{\pm}(x_j, x_k, p_a)$ and so on ...

Frigerio & Villanova del Moral, 2013

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

4 poorly constrained observables: $x_i = \theta_{23},\ m_{\rm light},\ \delta,\ m_{ee}$

For any given flavour model, M_ν depends on n parameters

When n ≤ 4: $x_i^\pm = x_i^\pm(p_a)$

When n = 5: $x_i^\pm = x_i^\pm(x_j, p_a)$

When n = 6: $x_i^\pm = x_i^\pm(x_j, x_k, p_a)$ and so on ...

Frigerio & Villanova del Moral, 2013

One can derive these functions analytically, avoiding scans and/or approxs

From the neutrino mass matrix to the observables

4 precisely known parameters: $p_a = \Delta m^2_{21},\ |\Delta m^2_{31}|,\ \theta_{12},\ \theta_{13}$

4 poorly constrained observables: $x_i = \theta_{23},\ m_{\rm light},\ \delta,\ m_{ee}$

For any given flavour model, M_ν depends on n parameters

When n ≤ 4: $x_i^\pm = x_i^\pm(p_a)$

When n = 5: $x_i^\pm = x_i^\pm(x_j, p_a)$

When n = 6: $x_i^\pm = x_i^\pm(x_j, x_k, p_a)$ and so on ...

Frigerio & Villanova del Moral, 2013

One can derive these functions analytically, avoiding scans and/or approxs

No matter how complicated the model, its predictivity depends on n only

A five-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix}$$

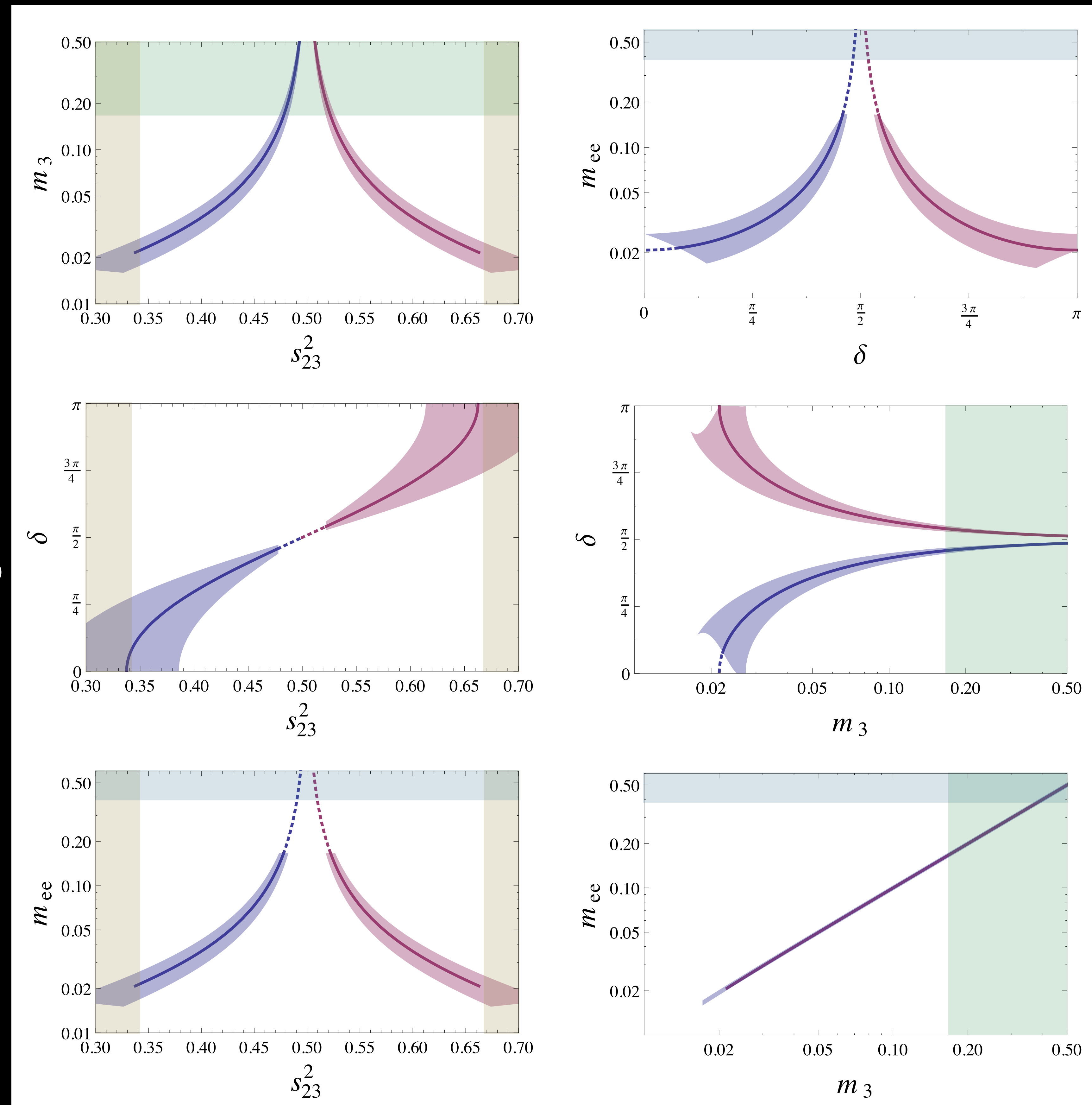
$$x_i(x_j, p_a)$$

A five-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix}$$

$$x_i(x_j, p_a)$$

Inverted Ordering (Normal is disfavoured)



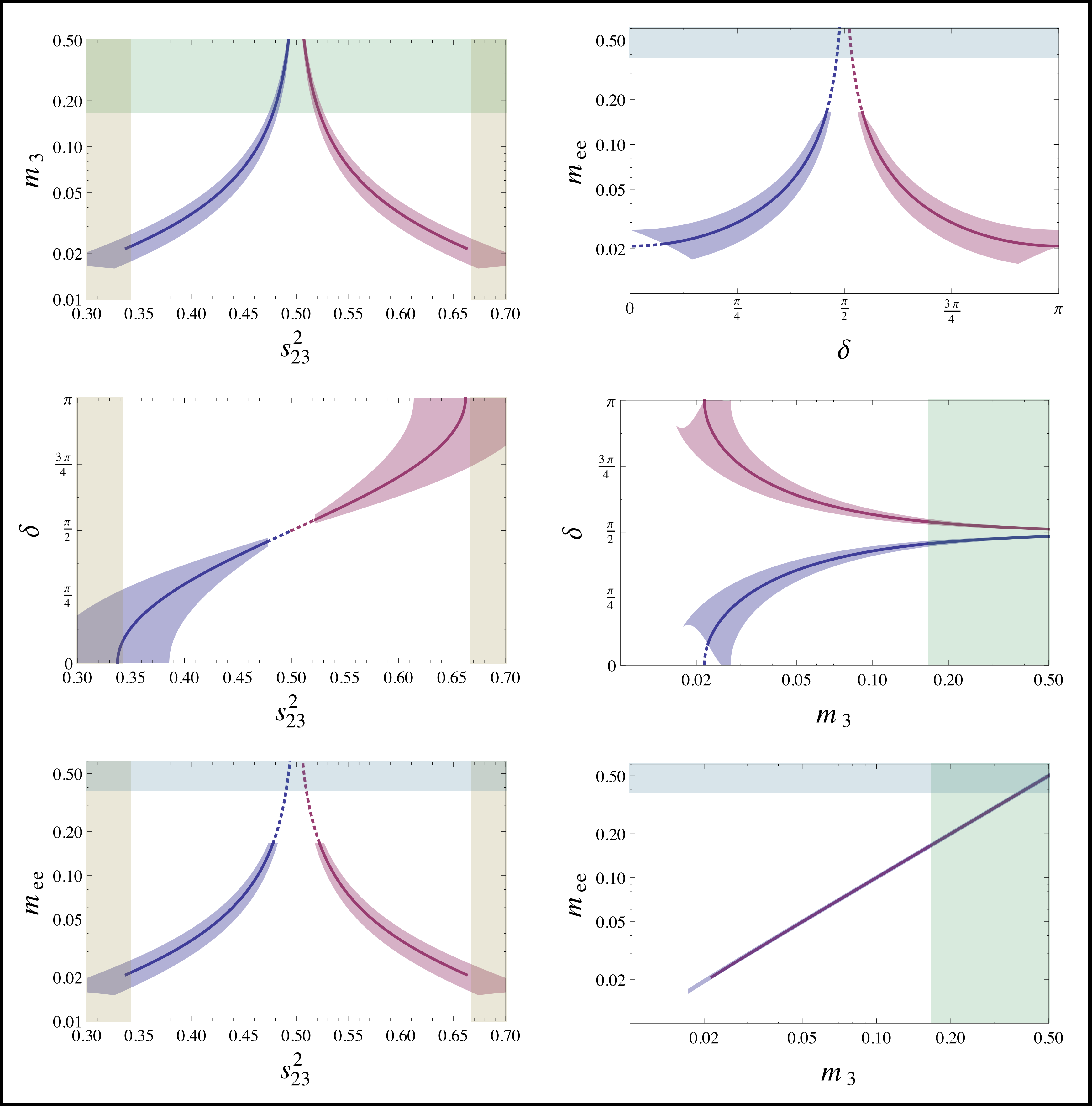
A five-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix}$$

$$x_i(x_j, p_a)$$

Purple lines: best fit values of the input parameters

Inverted Ordering (Normal is disfavoured)



A five-parameter mass matrix

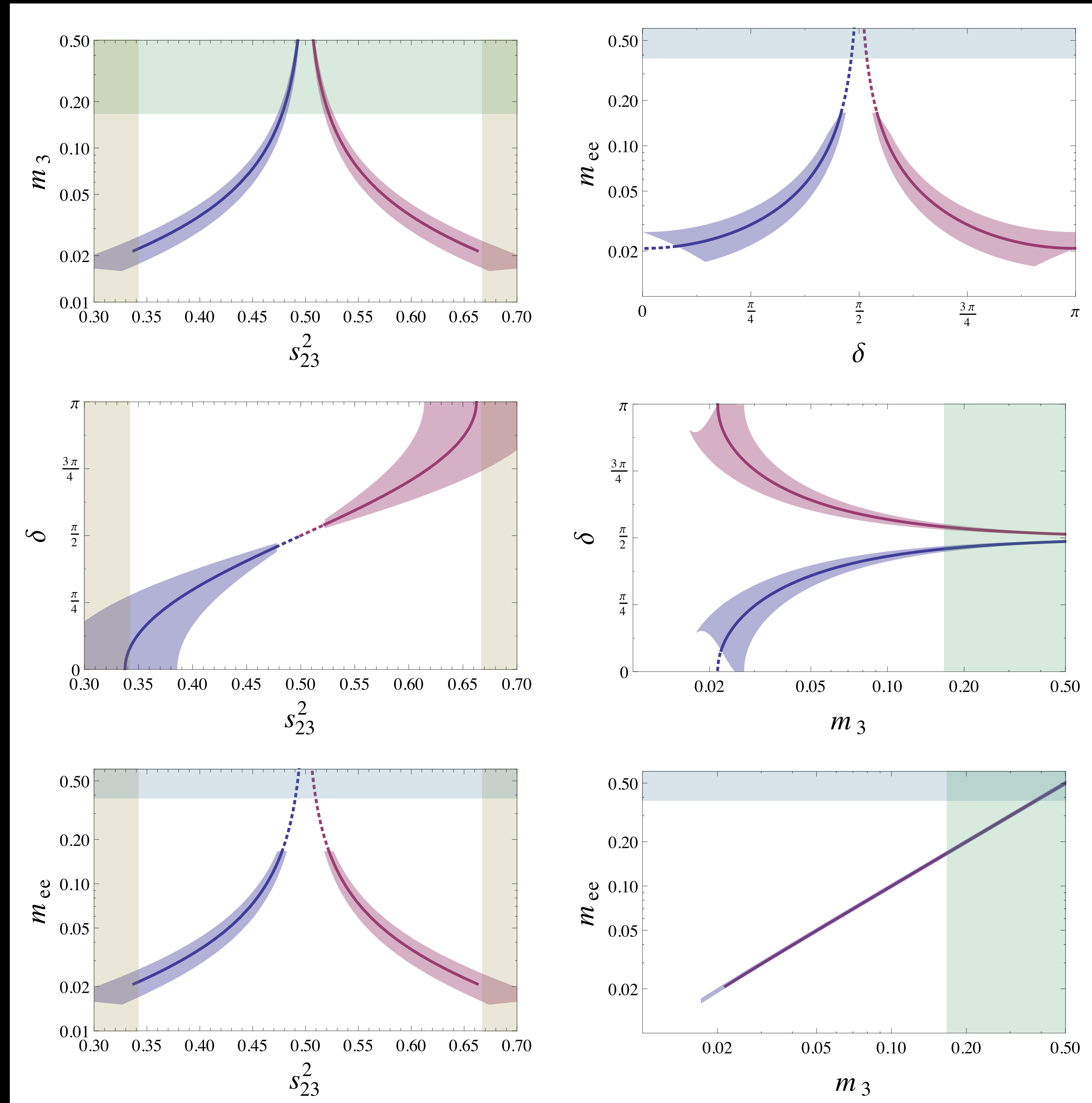
$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix}$$

$$x_i(x_j, p_a)$$

Purple lines: best fit values of the input parameters

Purple regions: 3σ ranges of the input parameters

Inverted Ordering (Normal is disfavoured)

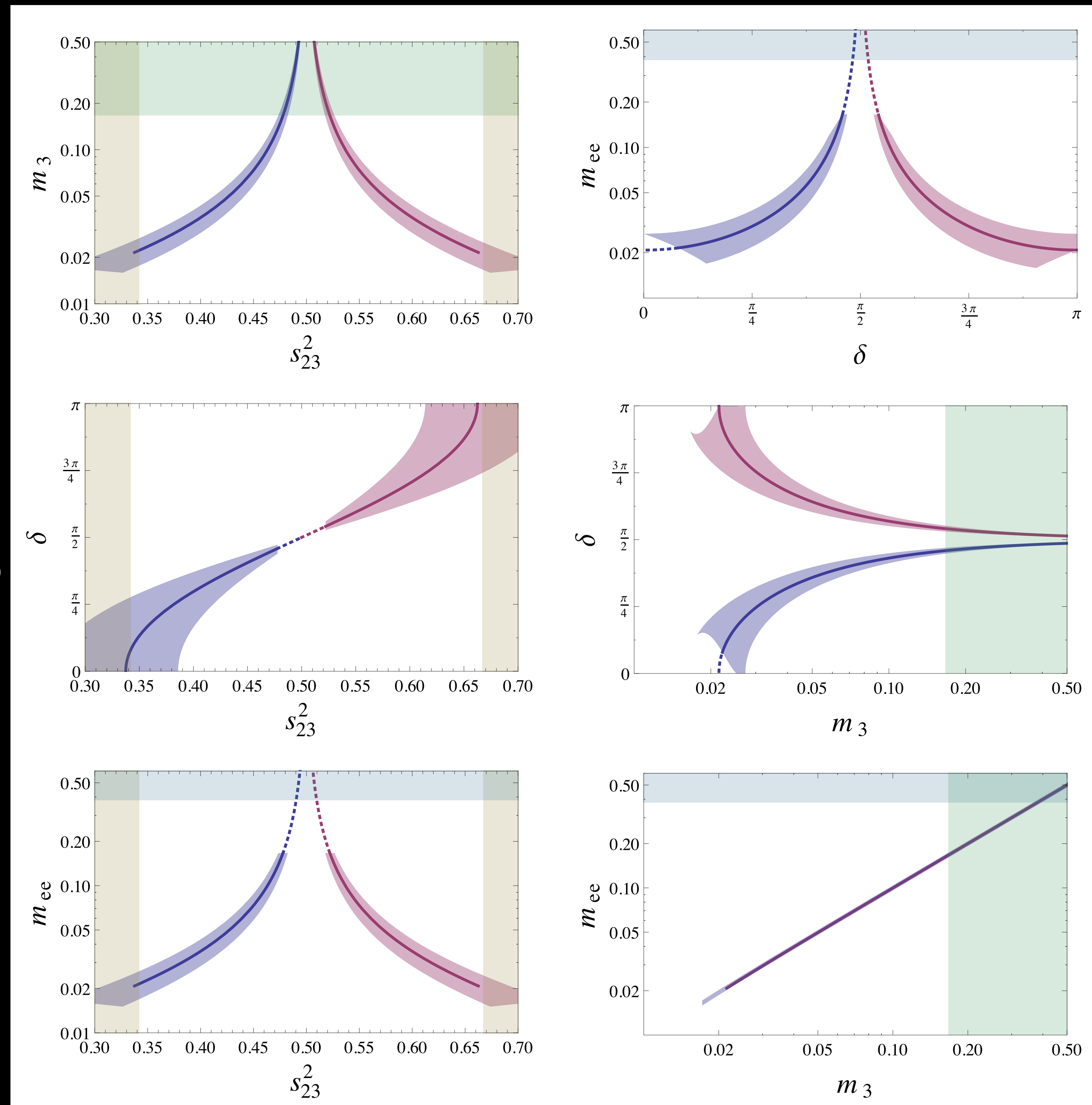


A five-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix}$$

$$x_i(x_j, p_a)$$

Inverted Ordering (Normal is disfavoured)



<u>Purple lines</u>: best fit values of the input parameters

<u>Purple regions</u>: 3σ ranges of the input parameters

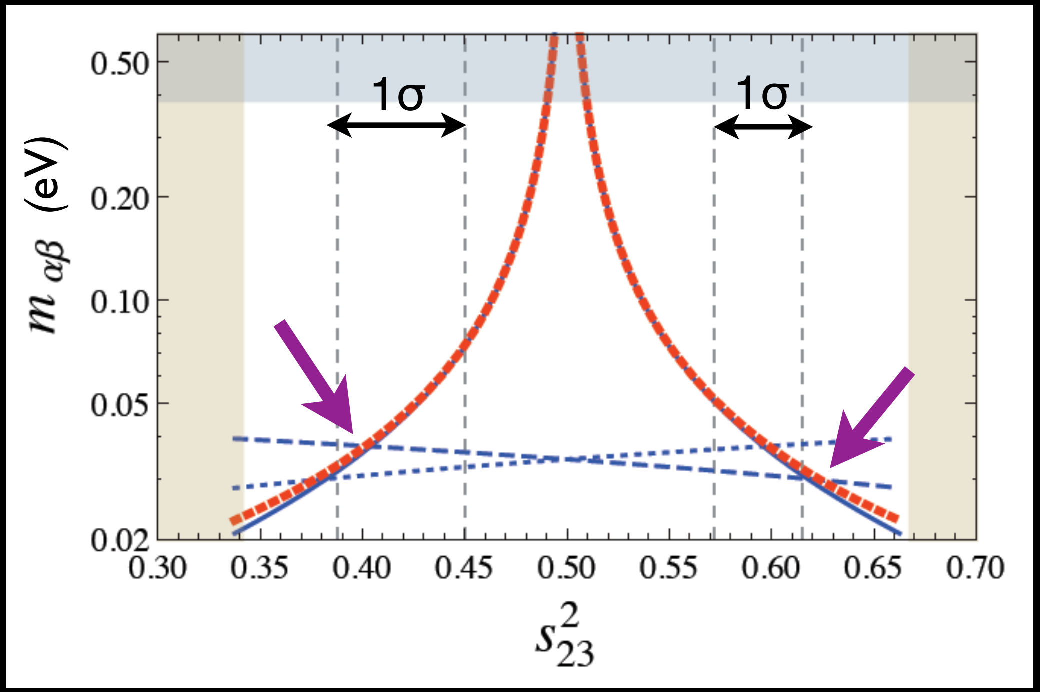
<u>Shaded bands and dashed lines</u>: excluded by bounds on the output parameters

- Lepton physics & the electroweak scale
- Lepton flavour observables: present & future data
- Lepton flavour symmetries: where do we stand
- Minimal flavour structures: a conspiracy for non-maximal 2-3 mixing
- A connection between neutrinos and very light dark matter candidates

A four-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix} \longrightarrow$$

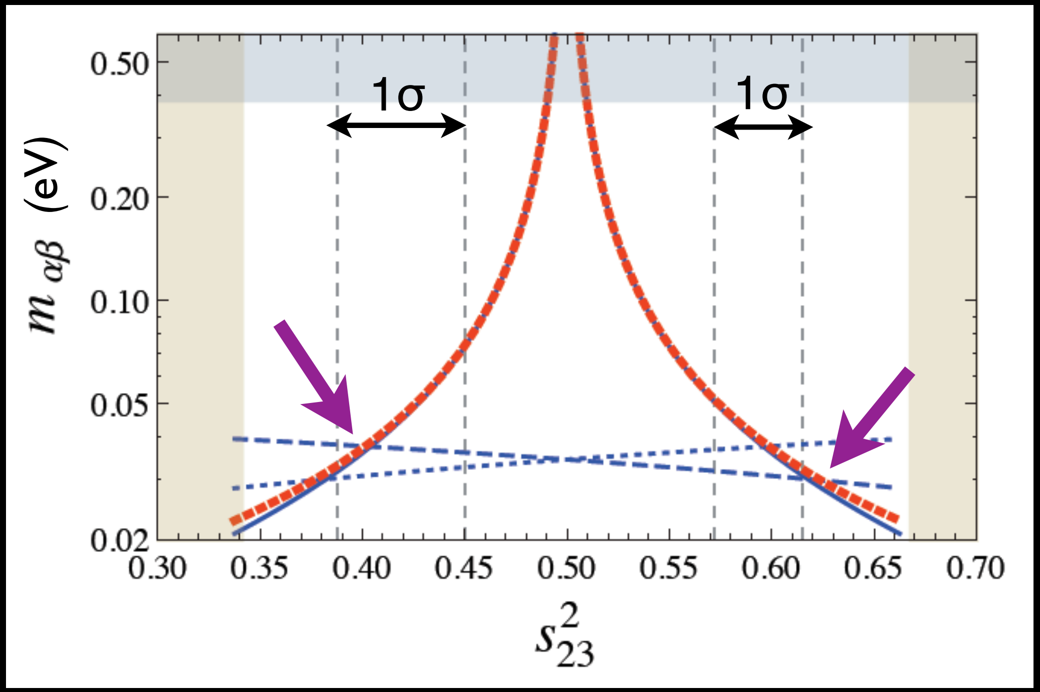
Inverted Ordering



A four-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix} \longrightarrow$$

Inverted Ordering

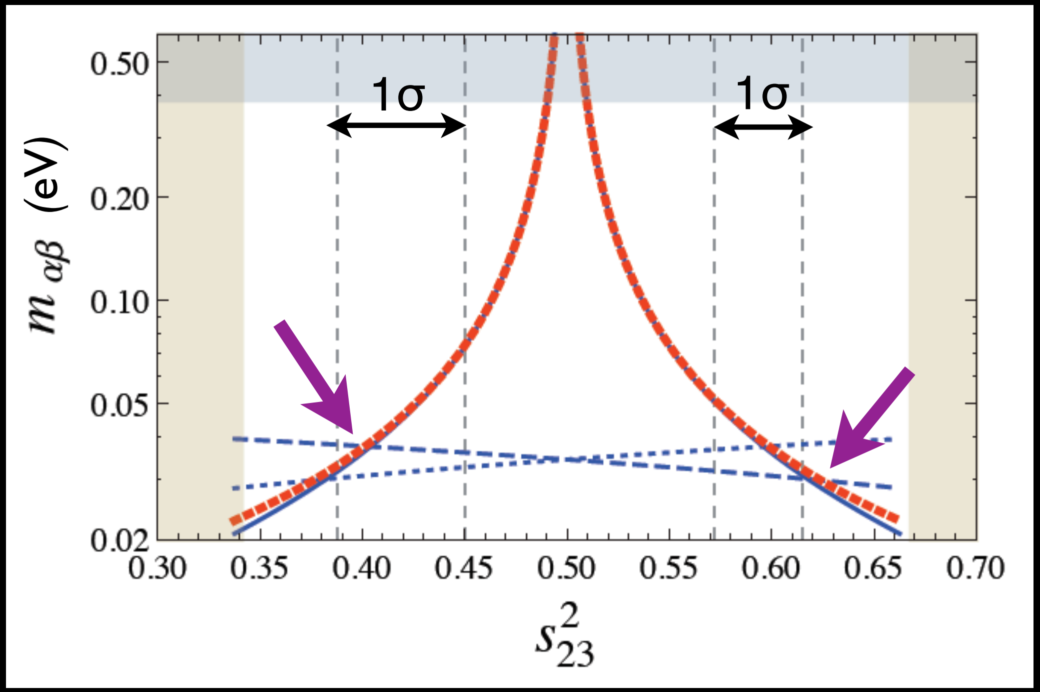


$$\longrightarrow M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

A four-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix} \longrightarrow$$

Inverted Ordering



$$\longrightarrow M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

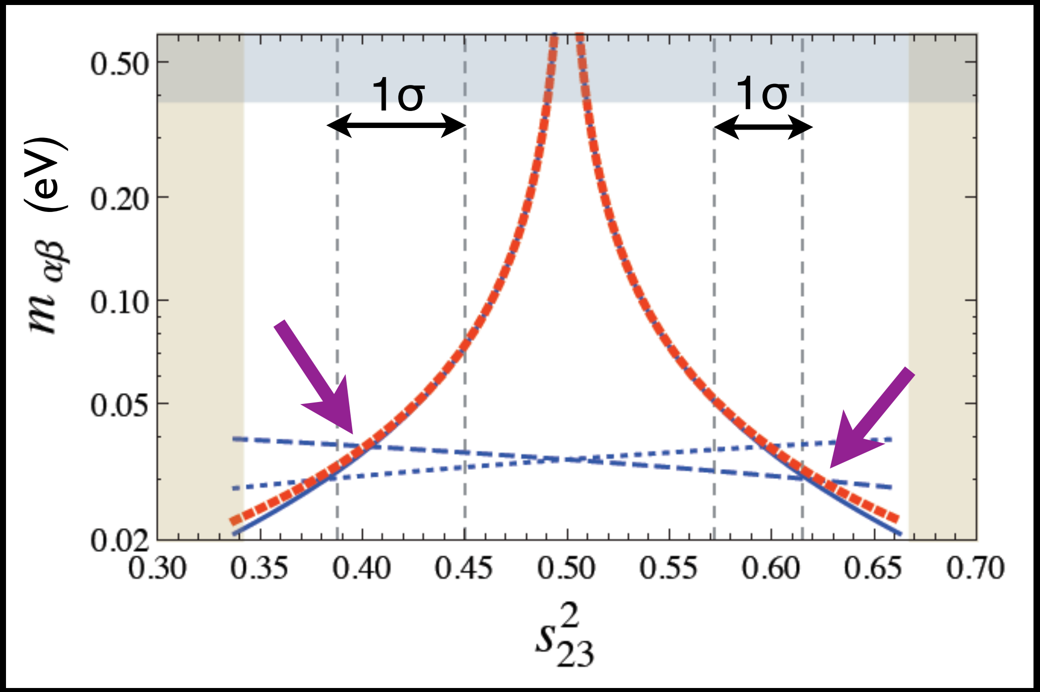
only 4 physical parameters: |a|, |b|, |c| and arg[(ad)/(bc)]

$$x_i(p_a)$$

A four-parameter mass matrix

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & d \\ c & d & 0 \end{pmatrix} \longrightarrow$$

Inverted Ordering



$$\longrightarrow M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

only 4 physical parameters: |a|, |b|, |c| and arg[(ad)/(bc)]

$$x_i(p_a)$$

$$\begin{cases} \sin^2\theta_{23} = 0.40^{+0.02}_{-0.01} \\ \cos\delta = 0.59^{+0.12}_{-0.14} \\ m_{\rm light} = m_3 = 0.037^{+0.001}_{-0.002}\,\text{eV} \\ m_{ee} = 0.036^{+0.002}_{-0.001}\,\text{eV} \end{cases}$$

$$\begin{cases} \sin^2\theta_{23} = 0.62^{+0.03}_{-0.02} \\ \cos\delta = -0.75^{+0.15}_{-0.12} \\ m_{\rm light} = m_3 = 0.0289^{+0.0002}_{-0.0001}\,\text{eV} \\ m_{ee} = 0.0284^{+0.0000}_{-0.0001}\,\text{eV} \end{cases}$$

A bottom-up model

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

Can one justify such a matrix structure by a (spontaneously broken) flavour symmetry ?

A bottom-up model

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

Can one justify such a matrix structure by a (spontaneously broken) flavour symmetry ?

- $M_{e\mu} = M_{\tau\mu}$ implies that (L_e, L_τ) transform in a doublet representation 2_L , coupled to a doublet 2_Φ of scalar fields (flavons) with $\langle\Phi\rangle = b(1,1)$

A bottom-up model

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

Can one justify such a matrix structure by a (spontaneously broken) flavour symmetry ?

- $M_{e\mu} = M_{\tau\mu}$ implies that (L_e, L_τ) transform in a doublet representation 2_L , coupled to a doublet 2_Φ of scalar fields (flavons) with $\langle\Phi\rangle = b(1,1)$
- $M_{ee} \neq M_{\tau\tau} = 0$ implies that $2_L \times 2_L$ couples to a second flavon doublet $2_{\Phi'}$ with $\langle\Phi'\rangle = a(1,0)$, and one needs $2_\Phi \neq 2_{\Phi'}$

A bottom-up model

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

Can one justify such a matrix structure by a (spontaneously broken) flavour symmetry ?

- $M_{e\mu} = M_{\tau\mu}$ implies that (L_e, L_τ) transform in a doublet representation 2_L , coupled to a doublet 2_Φ of scalar fields (flavons) with $\langle\Phi\rangle = b(1,1)$
- $M_{ee} \neq M_{\tau\tau} = 0$ implies that 2_L x 2_L couples to a second flavon doublet $2_{\Phi'}$ with $\langle\Phi'\rangle = a(1,0)$, and one needs $2_\Phi \neq 2_{\Phi'}$
- Since L_μ transforms as a singlet 1_L and $M_{\mu\mu} = 0$, one needs 1_L x $1_L \neq 1$

A bottom-up model

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

Can one justify such a matrix structure by a (spontaneously broken) flavour symmetry ?

- $M_{e\mu} = M_{\tau\mu}$ implies that (L_e, L_τ) transform in a doublet representation 2_L , coupled to a doublet 2_Φ of scalar fields (flavons) with $\langle\Phi\rangle = b(1,1)$
- $M_{ee} \neq M_{\tau\tau} = 0$ implies that 2_L x 2_L couples to a second flavon doublet $2_{\Phi'}$ with $\langle\Phi'\rangle = a(1,0)$, and one needs $2_\Phi \neq 2_{\Phi'}$
- Since L_μ transforms as a singlet 1_L and $M_{\mu\mu} = 0$, one needs 1_L x $1_L \neq 1$
- At the same time the charged lepton mass matrix M_e must be diagonal, requiring a flavour misalignment with respect to M_ν

A bottom-up model

$$M_\nu = \begin{pmatrix} a & b & c \\ b & 0 & b \\ c & b & 0 \end{pmatrix}$$

Can one justify such a matrix structure by a (spontaneously broken) flavour symmetry ?

- $M_{e\mu} = M_{\tau\mu}$ implies that (L_e, L_τ) transform in a doublet representation 2_L , coupled to a doublet 2_Φ of scalar fields (flavons) with $\langle\Phi\rangle = b(1,1)$
- $M_{ee} \neq M_{\tau\tau} = 0$ implies that $2_L \times 2_L$ couples to a second flavon doublet $2_{\Phi'}$ with $\langle\Phi'\rangle = a(1,0)$, and one needs $2_\Phi \neq 2_{\Phi'}$
- Since L_μ transforms as a singlet 1_L and $M_{\mu\mu} = 0$, one needs $1_L \times 1_L \neq 1$
- At the same time the charged lepton mass matrix M_e must be diagonal, requiring a flavour misalignment with respect to M_ν

All this can be realized with the order-12 group $Q_6 \equiv D'_3$ that has representations 2_1, 2_2, 1, 1', 1'', 1'''

A top-down model

A top-down model

- Do not postulate a given form for M_ν and M_e, rather build a flavour model that (i) is minimal according to a few theoretical criteria (ii) is viable

A top-down model

- Do not postulate a given form for M_ν and M_e, rather build a flavour model that (i) is minimal according to a few theoretical criteria (ii) is viable
- Assign the 3 lepton families as $L_i \sim (2\,,\,1)$; non-trivial mixing needs a doublet flavon $\Phi \sim 2$; assume that 2 is the unique representation for the flavons

A top-down model

- Do not postulate a given form for M_ν and M_e, rather build a flavour model that (i) is minimal according to a few theoretical criteria (ii) is viable
- Assign the 3 lepton families as $L_i \sim (2\,,\,1)$; non-trivial mixing needs a doublet flavon $\Phi \sim 2$; assume that 2 is the unique representation for the flavons
- Demand viable mass matrices with the smallest number of free parameters: then the flavour group has to be D_4 (the symmetry of a square), broken by $\langle\Phi_\nu\rangle = (1,0)$ in M_ν and by $\langle\Phi_e\rangle = (1,1)$ in M_e (or vice versa)

A top-down model

- Do not postulate a given form for M_ν and M_e, rather build a flavour model that (i) is minimal according to a few theoretical criteria (ii) is viable
- Assign the 3 lepton families as $L_i \sim (2\,,\,1)$; non-trivial mixing needs a doublet flavon $\Phi \sim 2$; assume that 2 is the unique representation for the flavons
- Demand viable mass matrices with the smallest number of free parameters: then the flavour group has to be D_4 (the symmetry of a square), broken by $\langle\Phi_\nu\rangle = (1,0)$ in M_ν and by $\langle\Phi_e\rangle = (1,1)$ in M_e (or vice versa)
- Definite correlations among the observables follow

A top-down model

- Do not postulate a given form for M_ν and M_e, rather build a flavour model that (i) is minimal according to a few theoretical criteria (ii) is viable

- Assign the 3 lepton families as $L_i \sim (2\ ,\ 1)$; non-trivial mixing needs a doublet flavon $\Phi \sim 2$; assume that 2 is the unique representation for the flavons

- Demand viable mass matrices with the smallest number of free parameters: then the flavour group has to be D_4 (the symmetry of a square), broken by $\langle\Phi_\nu\rangle = (1,0)$ in M_ν and by $\langle\Phi_e\rangle = (1,1)$ in M_e (or vice versa)

- Definite correlations among the observables follow

For more general models of this type, see Hernandez & Smirnov 2012

A top-down model

- Do not postulate a given form for M_ν and M_e, rather build a flavour model that (i) is minimal according to a few theoretical criteria (ii) is viable
- Assign the 3 lepton families as $L_i \sim (2\,,\,1)$; non-trivial mixing needs a doublet flavon $\Phi \sim 2$; assume that 2 is the unique representation for the flavons
- Demand viable mass matrices with the smallest number of free parameters: then the flavour group has to be D_4 (the symmetry of a square), broken by $\langle\Phi_\nu\rangle$ = (1,0) in M_ν and by $\langle\Phi_e\rangle$ = (1,1) in M_e (or vice versa)
- Definite correlations among the observables follow

For more general models of this type, see Hernandez & Smirnov 2012

Mass ordering is normal

$$2s_{12}^2c_{23}^2s_{13}^2 + 4s_{12}c_{12}s_{23}c_{23}s_{13}\cos\delta + 2c_{12}^2s_{23}^2 = 1$$

One finds $m_l \gtrsim 0.036$ eV and $m_{ee} \gtrsim 0.012$ eV (the lower bounds corresponding to no CP violation)

A top-down model

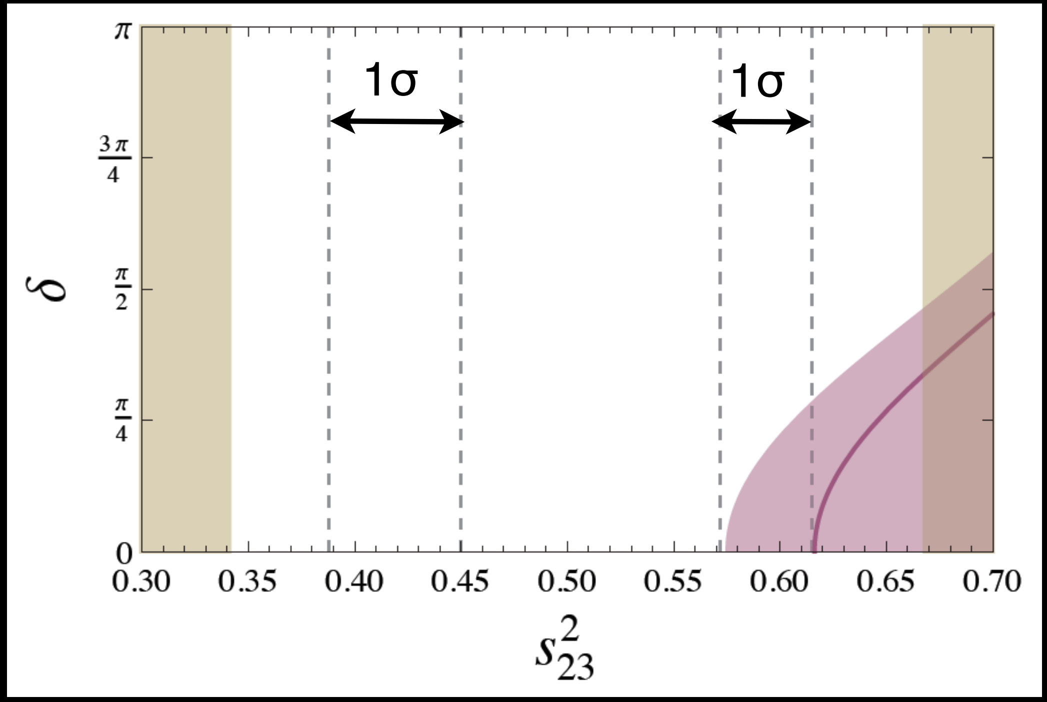
- Do not postulate a given form for M_ν and M_e, rather build a flavour model that (i) is minimal according to a few theoretical criteria (ii) is viable
- Assign the 3 lepton families as $L_i \sim (2\,,\,1)$; non-trivial mixing needs a doublet flavon $\Phi \sim 2$; assume that 2 is the unique representation for the flavons
- Demand viable mass matrices with the smallest number of free parameters: then the flavour group has to be D_4 (the symmetry of a square), broken by $\langle \Phi_\nu \rangle = (1,0)$ in M_ν and by $\langle \Phi_e \rangle = (1,1)$ in M_e (or vice versa)
- Definite correlations among the observables follow

For more general models of this type, see Hernandez & Smirnov 2012

Mass ordering is normal

$$2s_{12}^2c_{23}^2s_{13}^2 + 4s_{12}c_{12}s_{23}c_{23}s_{13}\cos\delta + 2c_{12}^2s_{23}^2 = 1$$

One finds $m_l \gtrsim 0.036$ eV and $m_{ee} \gtrsim 0.012$ eV (the lower bounds corresponding to no CP violation)



A minimal model is predictive !

in spite of non-zero & non-maximal mixing angles

A minimal model is predictive !

in spite of non-zero & non-maximal mixing angles

Is a minimal model convincing ?

let us try to find a pretty one

The 3 families in a triplet

The 3 families in a triplet

- In principle, the most ambitious possibility is that all 3 lepton families transform together under the flavour group

The 3 families in a triplet

- In principle, the most ambitious possibility is that all 3 lepton families transform together under the flavour group
- The smallest group with a dim-3 representation is A_4, the symmetry group of a regular tetrahedron (*Ma-Rajasekaran, ...*), with tensor product $3 \times 3 = 1 + 1' + 1'' + 3_s + 3_a$

The 3 families in a triplet

- In principle, the most ambitious possibility is that all 3 lepton families transform together under the flavour group
- The smallest group with a dim-3 representation is A_4, the symmetry group of a regular tetrahedron (*Ma-Rajasekaran, ...*), with tensor product $3 \times 3 = 1 + 1' + 1'' + 3_s + 3_a$
- With appropriate assignments of the field, breaking A_4 to Z_3 in m_e and to Z_2 in m_ν (*Altarelli-Feruglio, ...*), one can obtain tri-bi-maximal mixing: $\sin^2\theta_{12} = 1/3$, $\sin^2\theta_{23} = 1/2$, $\sin^2\theta_{13} = 0$. Large corrections are needed by now ...

The 3 families in a triplet

- In principle, the most ambitious possibility is that all 3 lepton families transform together under the flavour group
- The smallest group with a dim-3 representation is A_4, the symmetry group of a regular tetrahedron (*Ma-Rajasekaran, ...*), with tensor product $3 \times 3 = 1 + 1' + 1'' + 3_s + 3_a$
- With appropriate assignments of the field, breaking A_4 to Z_3 in m_e and to Z_2 in m_ν (*Altarelli-Feruglio, ...*), one can obtain tri-bi-maximal mixing: $\sin^2\theta_{12} = 1/3$, $\sin^2\theta_{23} = 1/2$, $\sin^2\theta_{13} = 0$. Large corrections are needed by now ...
- To enforce this result a few technicalities are needed. A different, economical implementation of the A_4 symmetry can lead to a better agreement with data

Off-diagonal ν masses

As in the radiative model by Zee (PLB93,389,1980) and Wolfenstein (NPB175,93,1980)

$$M_\nu^{\rm off} = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix}$$

This is perfectly A_4-symmetric, if leptons (l_e, l_μ, l_τ) and flavons ($\varphi_e, \varphi_\mu, \varphi_\tau$) form A_4-triplets:
$y^{\rm off} (\varphi_e l_\mu l_\tau + l_e \varphi_\mu l_\tau + l_e l_\mu \varphi_\tau)$ is invariant

Off-diagonal ν masses

As in the radiative model by Zee (PLB93,389,1980) and Wolfenstein (NPB175,93,1980)

$$M_\nu^{\rm off} = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix}$$

This is perfectly A_4-symmetric, if leptons (l_e, l_μ, l_τ) and flavons ($\varphi_e, \varphi_\mu, \varphi_\tau$) form A_4-triplets: $y^{\rm off}\,(\varphi_e l_\mu l_\tau + l_e \varphi_\mu l_\tau + l_e l_\mu \varphi_\tau)$ is invariant

$$\frac{1}{\tan(2\theta_{12})}\,\frac{1}{\tan(2\theta_{23})}\,\frac{2(1-2\sin^2\theta_{13})}{\sin\theta_{13}(1-3\sin^2\theta_{13})} = \pm 1$$

(and no CP violation: $\delta=0,\pi$)

Off-diagonal ν masses

As in the radiative model by Zee (PLB93,389,1980) and Wolfenstein (NPB175,93,1980)

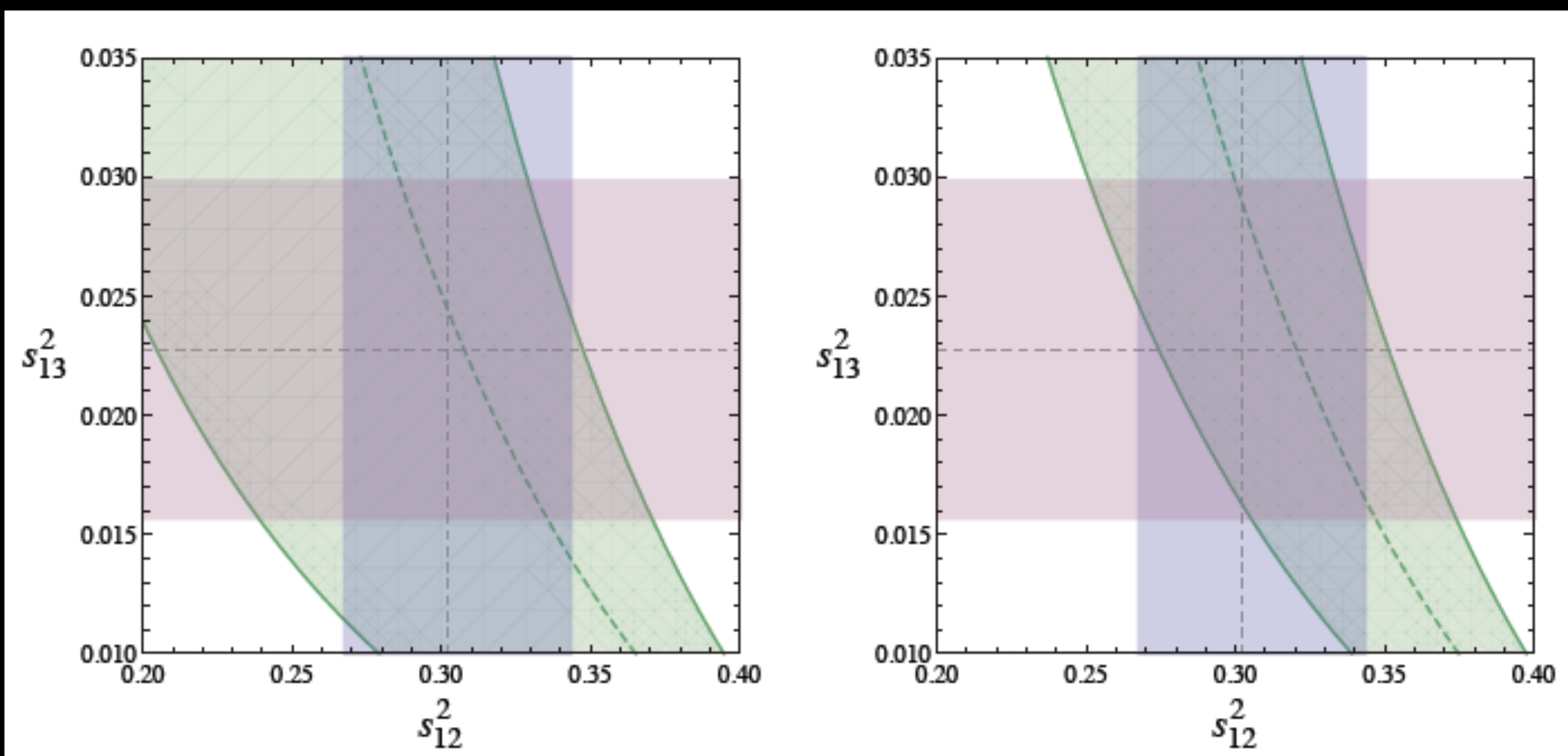
$$M_\nu^{\rm off} = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix}$$

This is perfectly A_4-symmetric, if leptons (l_e, l_μ, l_τ) and flavons ($\varphi_e, \varphi_\mu, \varphi_\tau$) form A_4-triplets: $y^{\rm off}\,(\varphi_e l_\mu l_\tau + l_e \varphi_\mu l_\tau + l_e l_\mu \varphi_\tau)$ is invariant

$$\frac{1}{\tan(2\theta_{12})}\,\frac{1}{\tan(2\theta_{23})}\,\frac{2(1-2\sin^2\theta_{13})}{\sin\theta_{13}(1-3\sin^2\theta_{13})} = \pm 1$$

(and no CP violation: $\delta=0,\pi$)

$\theta_{23} < \pi/4$ $\theta_{23} > \pi/4$



3σ range for θ_{12} and 3σ range for θ_{13} superimpose perfectly with 1σ range for θ_{23}

Off-diagonal + the identity

- Since a decade we know that M_ν^{off} alone cannot accommodate Δm^2_{ij}
- However the A_4-triplet of leptons form
  necessarily another A_4-invariant:
  $y^{univ}(l_e l_e + l_\mu l_\mu + l_\tau l_\tau)$
- This does not affect the prediction for θ_{23} (and for δ)
- M_e can be kept diagonal by breaking A_4 to $Z_2 \times Z_2$
- Now Δm^2_{ij} are reproduced, in addition m_{ee} and m_{light} are correlated

Off-diagonal + the identity

- Since a decade we know that M_ν^{off} alone cannot accommodate Δm^2_{ij}
- However the A_4-triplet of leptons form necessarily another A_4-invariant: $y^{univ}(l_e l_e + l_\mu l_\mu + l_\tau l_\tau)$

$$M_\nu = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix} + d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

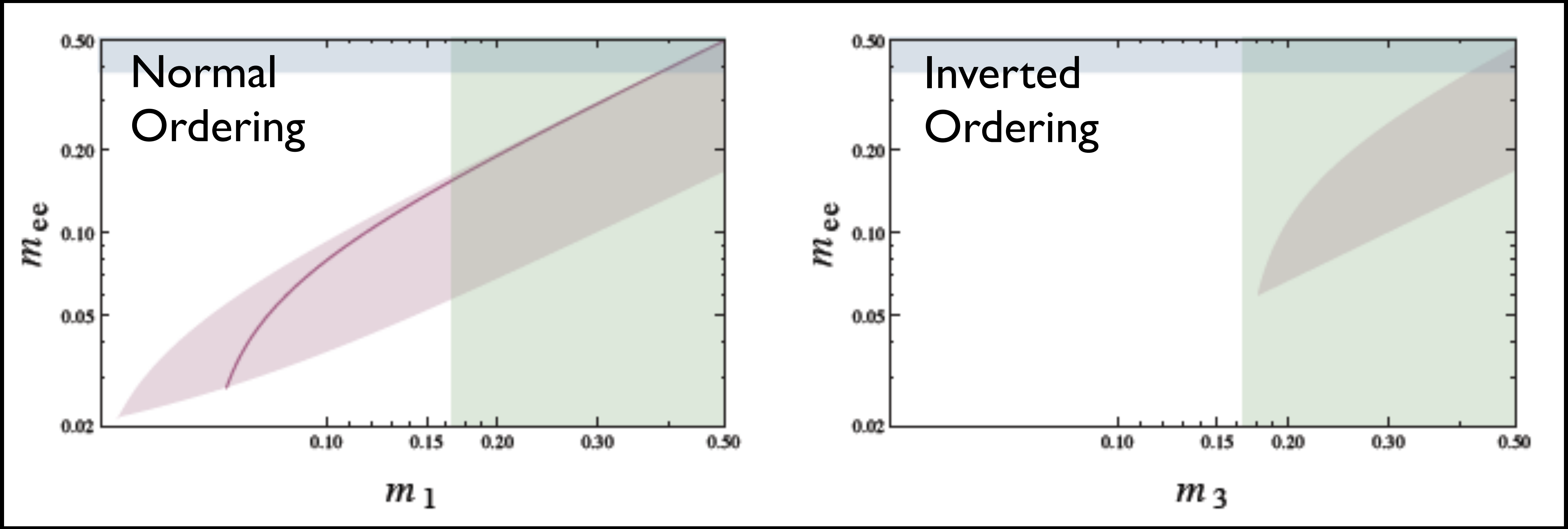
- This does not affect the prediction for θ_{23} (and for δ)
- M_e can be kept diagonal by breaking A_4 to $Z_2 \times Z_2$
- Now Δm^2_{ij} are reproduced, in addition m_{ee} and m_{light} are correlated

Off-diagonal + the identity

- Since a decade we know that M_ν^{off} alone cannot accommodate Δm^2_{ij}
- However the A_4-triplet of leptons form necessarily another A_4-invariant: $y^{univ}(l_e l_e + l_\mu l_\mu + l_\tau l_\tau)$

$$M_\nu = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix} + d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- This does not affect the prediction for θ_{23} (and for δ)
- M_e can be kept diagonal by breaking A_4 to $Z_2 \times Z_2$
- Now Δm^2_{ij} are reproduced, in addition m_{ee} and m_{light} are correlated



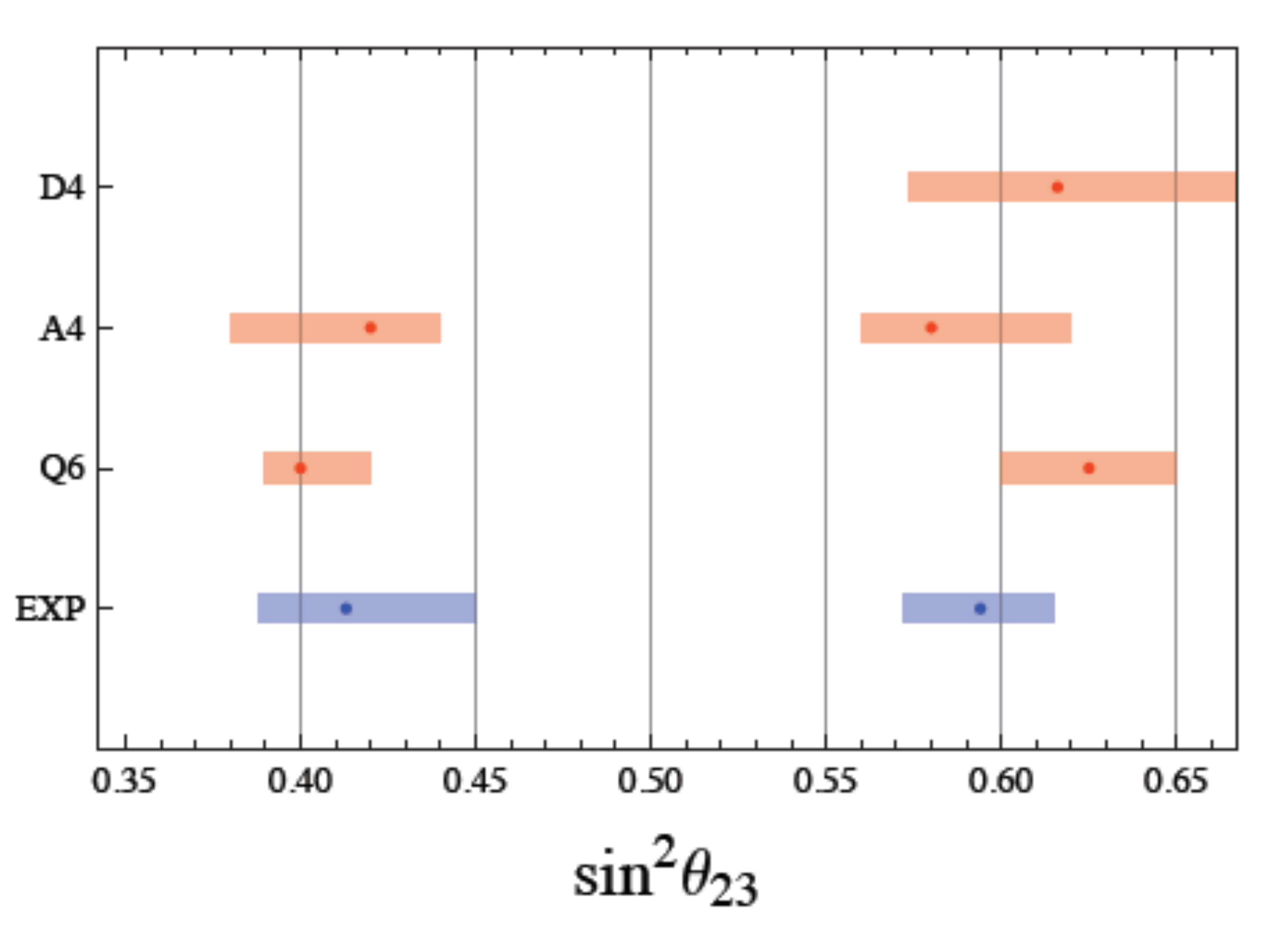
The case for non-maximal θ_{23}

Several minimal flavour structures imply a deviation from maximal 2-3 mixing of the size that is presently suggested by the data

The case for non-maximal θ_{23}

Several minimal flavour structures imply a deviation from maximal 2-3 mixing of the size that is presently suggested by the data

global 3ν fit at 1σ



Frigerio & Villanova del Moral
1303.5284 - summary plot

The case for non-maximal θ_{23}

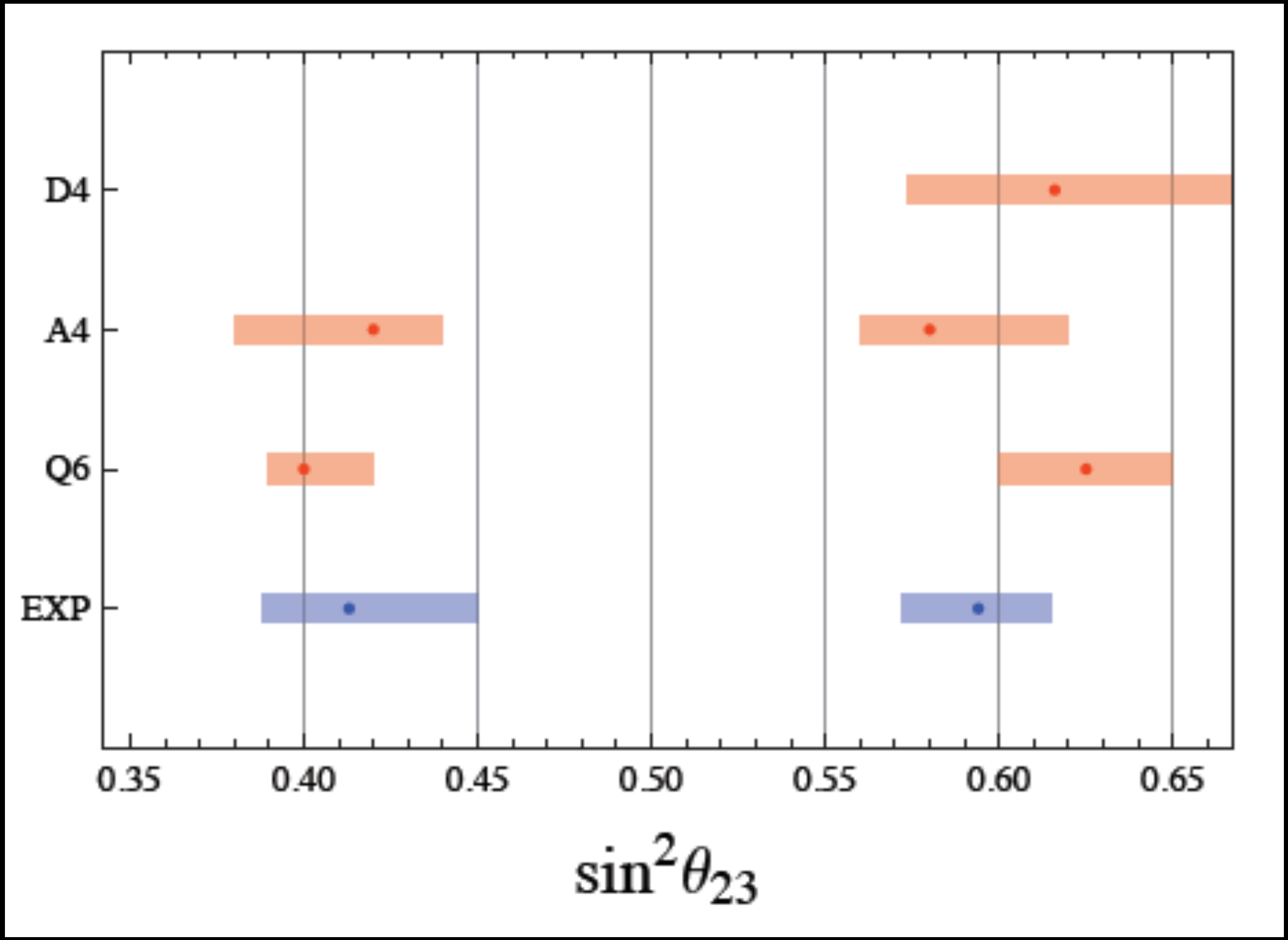
Several minimal flavour structures imply a deviation from maximal 2-3 mixing of the size that is presently suggested by the data

top-down 1+2 model

off-diagonal + identity model

bottom-up 1+2 model

global 3ν fit at 1σ



Frigerio & Villanova del Moral
1303.5284 - summary plot

Room for future improvements

Room for future improvements

- M_ν = off-diagonal + the identity seems a neat, appealing scenario

Room for future improvements

- M_ν = off-diagonal + the identity seems a neat, appealing scenario
- One would like a dynamical reason for $m_e << m_\mu << m_\tau$.
  In the present setting it can be realized, but in a bit clumsy way.

Room for future improvements

- M_ν = off-diagonal + the identity seems a neat, appealing scenario
- One would like a dynamical reason for $m_e << m_\mu << m_\tau$.
  In the present setting it can be realized, but in a bit clumsy way.
- Symmetry would prefer equal off-diagonal entries in M_ν ($A_4 \rightarrow Z_3$).
  The required, small differences may be explained by RGEs.
  In principle such model could be even more predictive...

Room for future improvements

- M_ν = off-diagonal + the identity seems a neat, appealing scenario
- One would like a dynamical reason for $m_e \ll m_\mu \ll m_\tau$.
  In the present setting it can be realized, but in a bit clumsy way.
- Symmetry would prefer equal off-diagonal entries in M_ν ($A_4 \to Z_3$).
  The required, small differences may be explained by RGEs.
  In principle such model could be even more predictive...
- What is the mechanism inducing the off-diagonal & the identity terms? Radiative, seesaw, both? At what energy scale(s)?

Conclusions

Conclusions

- Leptons provide a number of ways to explore new physics beyond the Standard Model

Conclusions

- Leptons provide a number of ways to explore new physics beyond the Standard Model
- So far, just one solid evidence: oscillations between 3 active neutrinos, that unveil the structure of lepton flavour

Conclusions

- Leptons provide a number of ways to explore new physics beyond the Standard Model
- So far, just one solid evidence: oscillations between 3 active neutrinos, that unveil the structure of lepton flavour
- Our attempt to provide a up-to-date theoretical interpretation

Conclusions

- Leptons provide a number of ways to explore new physics beyond the Standard Model
- So far, just one solid evidence: oscillations between 3 active neutrinos, that unveil the structure of lepton flavour
- Our attempt to provide a up-to-date theoretical interpretation
- Simplicity should be searched for in the structure of the lepton mass matrices, not in the value of the observables

Conclusions

- Leptons provide a number of ways to explore new physics beyond the Standard Model
- So far, just one solid evidence: oscillations between 3 active neutrinos, that unveil the structure of lepton flavour
- Our attempt to provide a up-to-date theoretical interpretation
- Simplicity should be searched for in the structure of the lepton mass matrices, not in the value of the observables
- Minimal models can sharply predict future observables

Conclusions

- Leptons provide a number of ways to explore new physics beyond the Standard Model
- So far, just one solid evidence: oscillations between 3 active neutrinos, that unveil the structure of lepton flavour
- Our attempt to provide a up-to-date theoretical interpretation
- Simplicity should be searched for in the structure of the lepton mass matrices, not in the value of the observables
- Minimal models can sharply predict future observables
- With the least possible assumptions, we found a preference for a deviation from maximal θ_{23} of the presently preferred size

Addendum

- Lepton physics & the electroweak scale
- Lepton flavour observables: present & future data
- Lepton flavour symmetries: where do we stand
- Minimal flavour structures: a conspiracy for non-maximal 2-3 mixing
- A connection between neutrinos and very light dark matter candidates

pNGBs: generalities

pNGBs: generalities

- spontaneously symmetry breaking (SB) of a global symmetry: massless spin-0 field with only derivative interactions, an exact Nambu-Goldstone boson (NGB)

pNGBs: generalities

- spontaneously symmetry breaking (SB) of a global symmetry: massless spin-0 field with only derivative interactions, an exact Nambu-Goldstone boson (NGB)
- explicitly SB (by a coupling or an anomaly): the pseudo-NGB acquires a mass and non-derivative interactions

pNGBs: generalities

- spontaneously symmetry breaking (SB) of a global symmetry: massless spin-0 field with only derivative interactions, an exact Nambu-Goldstone boson (NGB)
- explicitly SB (by a coupling or an anomaly): the pseudo-NGB acquires a mass and non-derivative interactions
- approximate symmetry: the scale of spontaneous SB is much larger than the scale of explicit SB

Virtues of pNGBs as dark matter

Virtues of pNGBs as dark matter

- The pNGB mass scale is not chosen ad-hoc: it is induced by a physical scale, e.g. Λ_{QCD} or Λ_{EW}, and it can be radiatively stable

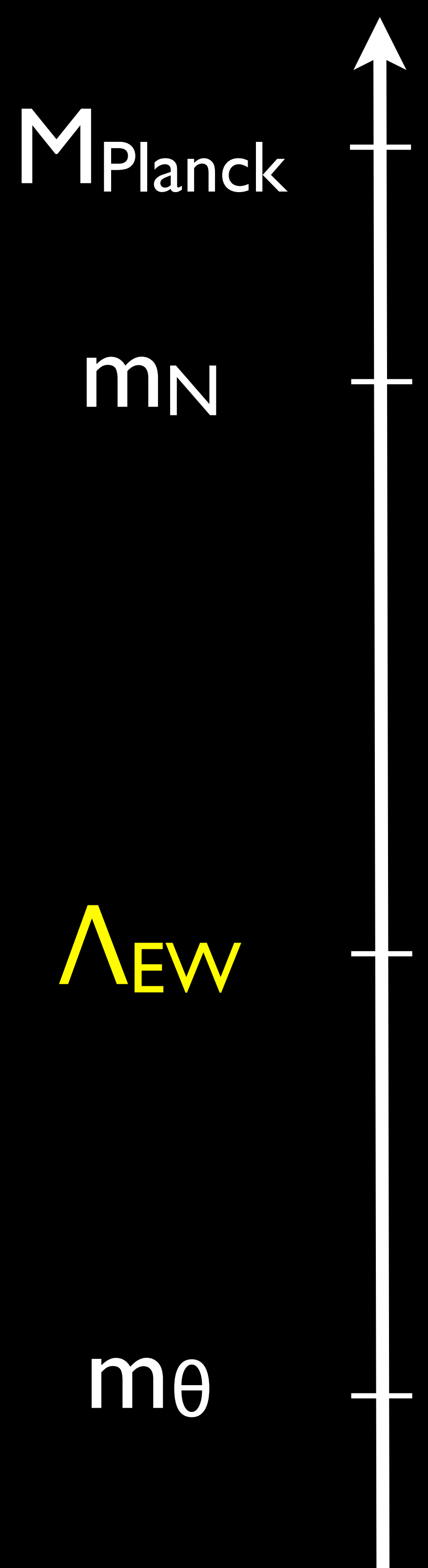
Virtues of pNGBs as dark matter

- The pNGB mass scale is not chosen ad-hoc: it is induced by a physical scale, e.g. Λ_{QCD} or Λ_{EW}, and it can be radiatively stable
- Explicit SB induces both the pNGB mass & its couplings to the SM, that control its relic density: one-to-one correspondence between m_{DM} and Ω_{DM}

Virtues of pNGBs as dark matter

- The pNGB mass scale is not chosen ad-hoc: it is induced by a physical scale, e.g. Λ_{QCD} or Λ_{EW}, and it can be radiatively stable
- Explicit SB induces both the pNGB mass & its couplings to the SM, that control its relic density: one-to-one correspondence between m_{DM} and Ω_{DM}
- If the spontaneous SB scale f is very large, the pNGB is automatically long-lived: its lifetime grows with f^2.
For DM one needs $\tau_{DM} > \tau_0 = 5 \cdot 10^{17}$s [$\tau(DM \to e^+e^-) > 10^{26}$s]

pNGBs from the seesaw scale

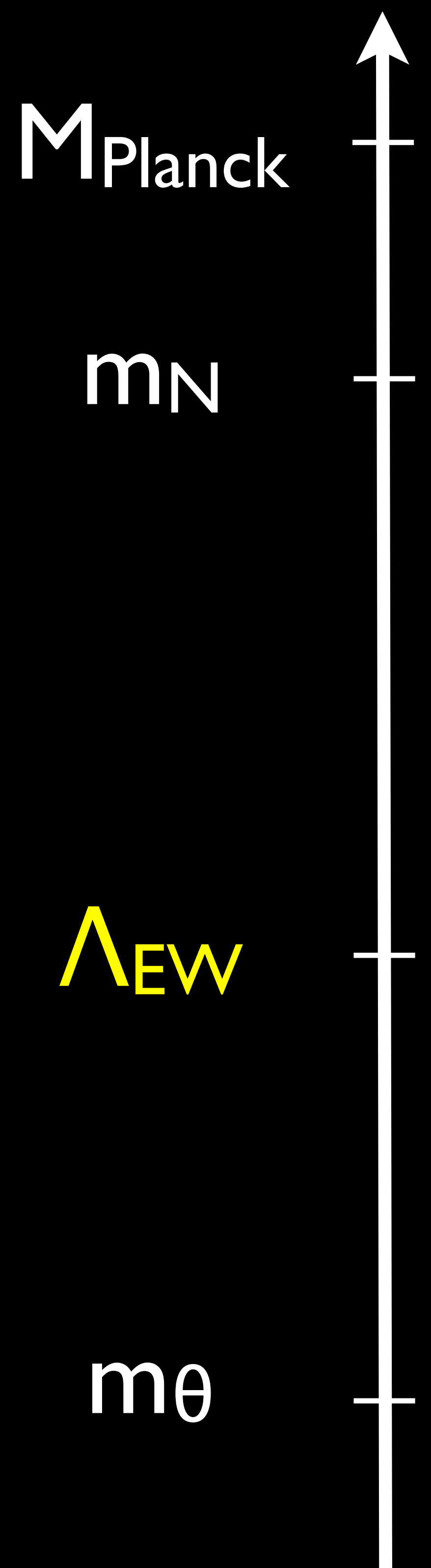


pNGBs from the seesaw scale

n sterile neutrinos can receive their mass from SSB of their SU(n) symmetry: $m_N = g\, f = g < \varphi\, e^{i\theta/f} >$
(generalization of the singlet Majoron model)

Chikashige, Mohapatra, Peccei '81

pNGBs from the seesaw scale



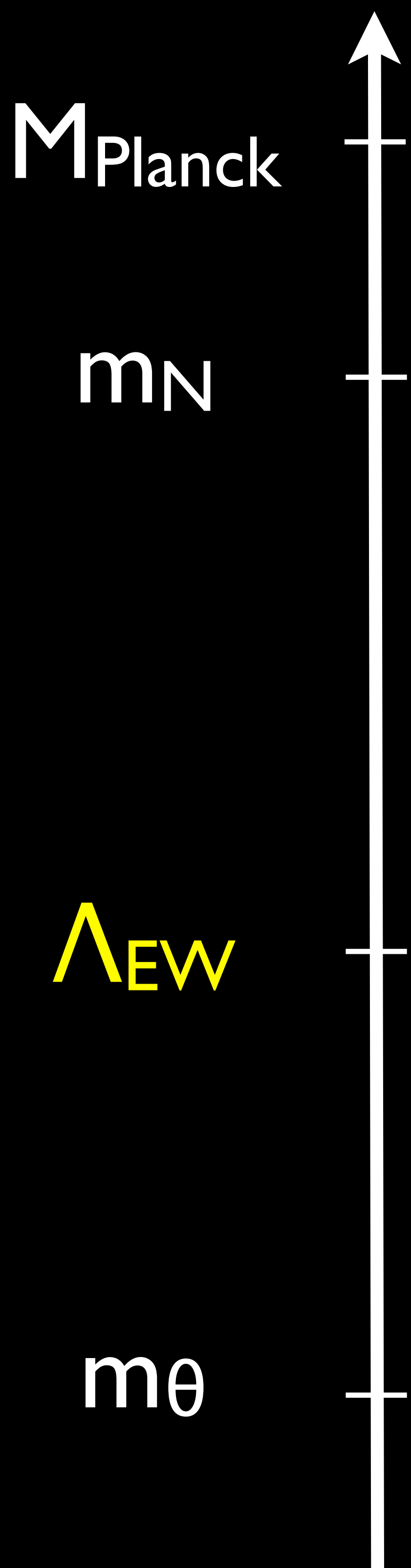
n sterile neutrinos can receive their mass from SSB of their SU(n) symmetry: $m_N = g\, f = g < \varphi\, e^{i\theta/f} >$

(generalization of the singlet Majoron model)

Chikashige, Mohapatra, Peccei '81

The neutrino Yukawa couplings to the Higgs will break explicitly some of these family symmetries

pNGBs from the seesaw scale



n sterile neutrinos can receive their mass from SSB of their SU(n) symmetry: $m_N = g\, f = g < \varphi\, e^{i\theta/f} >$
(generalization of the singlet Majoron model)

Chikashige, Mohapatra, Peccei '81

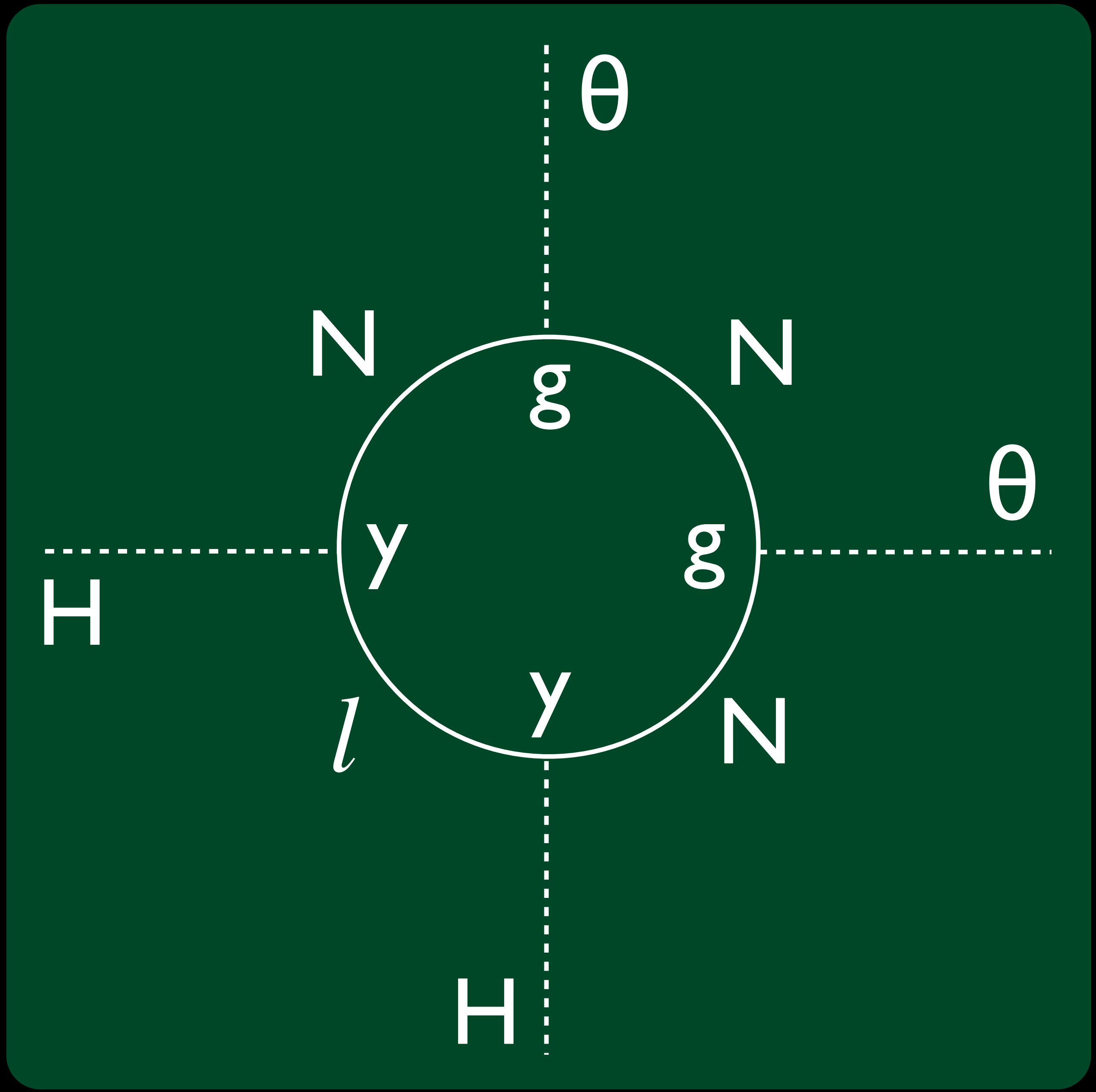
The neutrino Yukawa couplings to the Higgs will break explicitly some of these family symmetries

It turns out that this kind of pNGB θ is long-lived and a good DM candidate for $m_\theta \sim$ MeV

Frigerio, Hambye, Masso '11

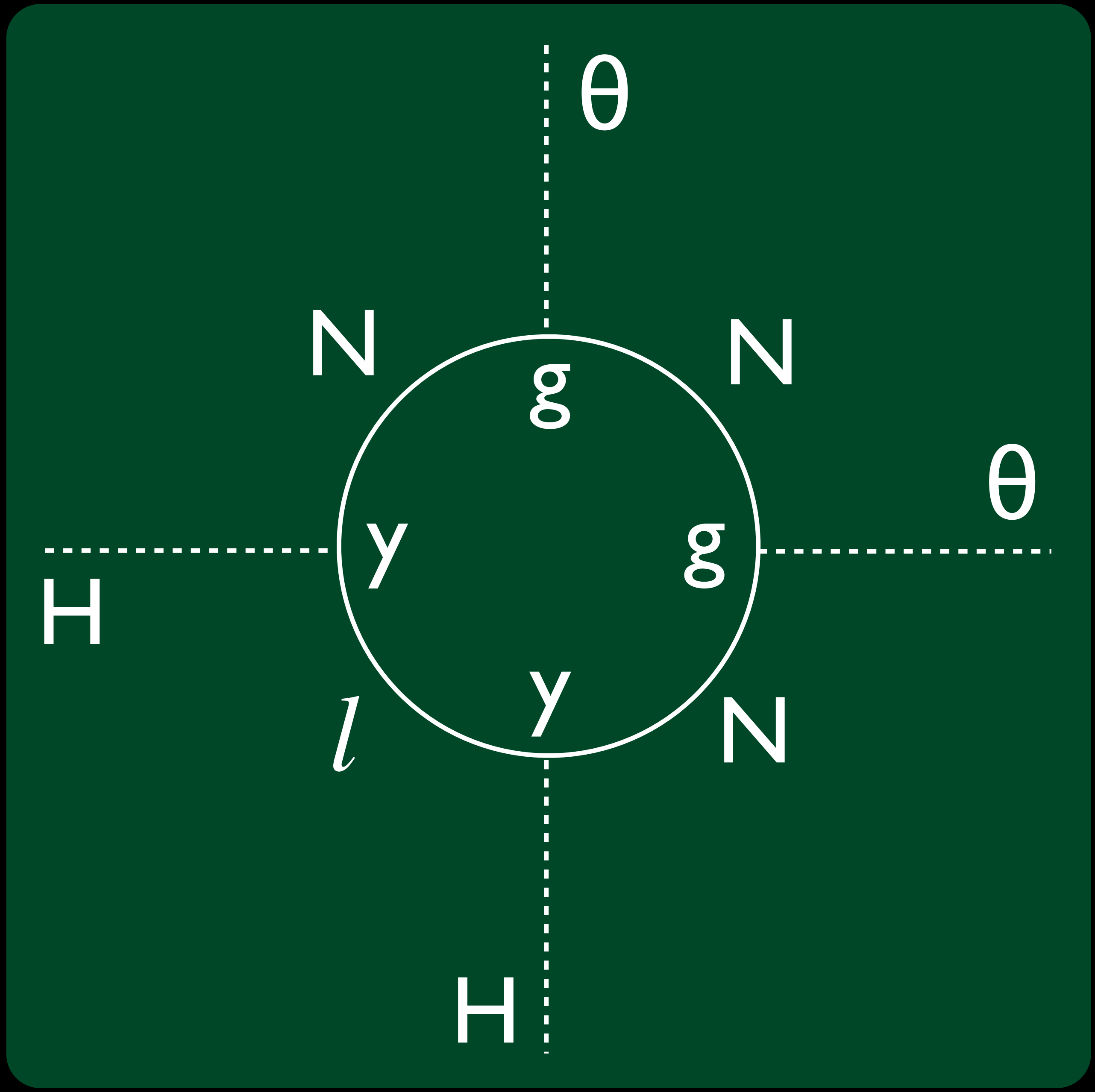
θ-Higgs coupling in a nutshell

$$-\mathcal{L} \supset l_\alpha (y_{\alpha j} v) N_j \left(\frac{H}{v}\right) + \frac{1}{2} N_i (g_{ij} f) N_j \exp\left(i \frac{\theta}{f}\right)$$



θ-Higgs coupling in a nutshell

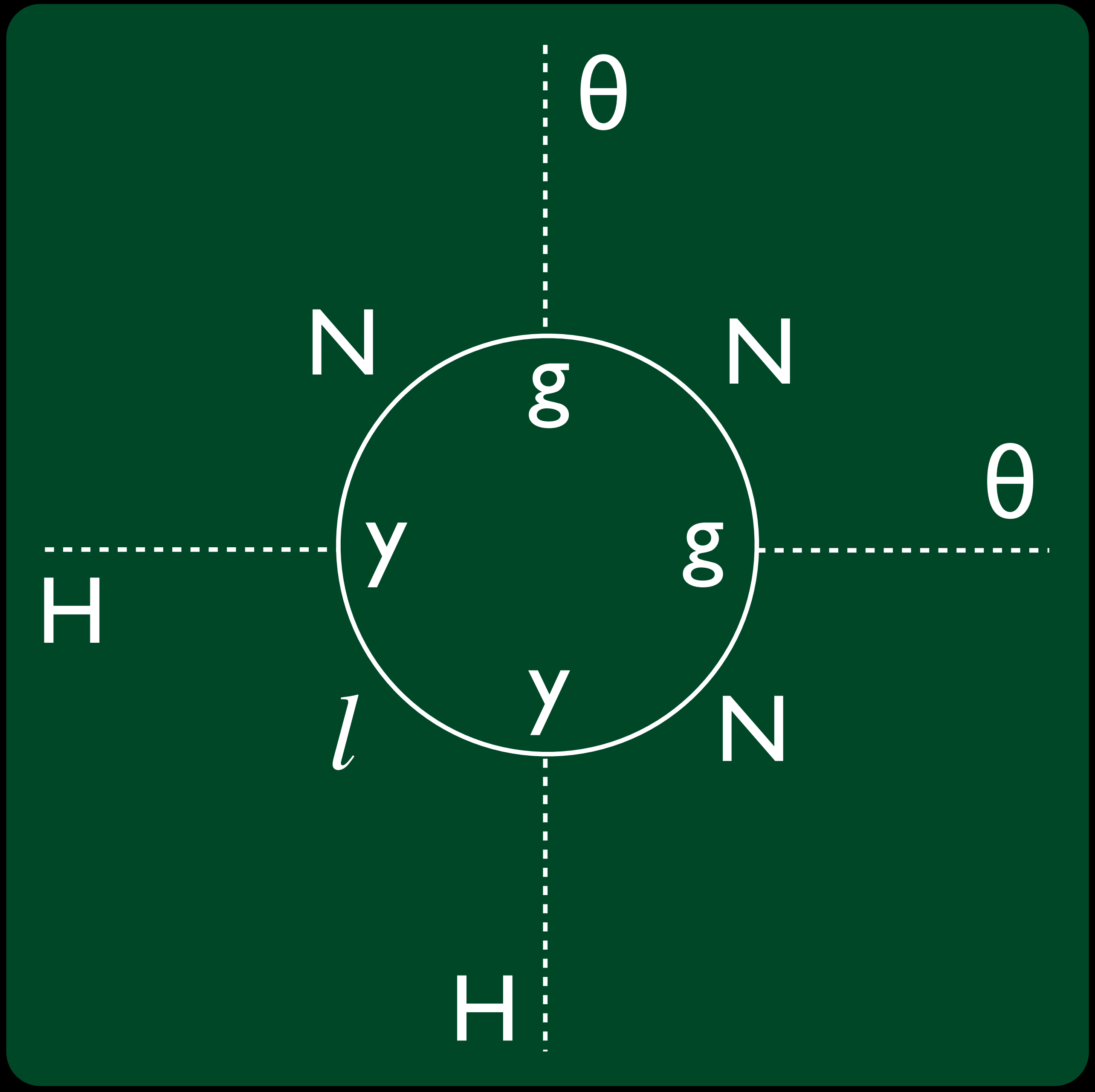
$$-\mathcal{L} \supset l_\alpha (y_{\alpha j} v) N_j \left(\frac{H}{v}\right) + \frac{1}{2} N_i (g_{ij} f) N_j \exp\left(i\frac{\theta}{f}\right)$$



$$-\mathcal{L}_{eff} \supset \lambda \theta^2 H^\dagger H$$

θ-Higgs coupling in a nutshell

$$-\mathcal{L} \supset l_\alpha (y_{\alpha j} v) N_j \left(\frac{H}{v}\right) + \frac{1}{2} N_i (g_{ij} f) N_j \exp\left(i\frac{\theta}{f}\right)$$

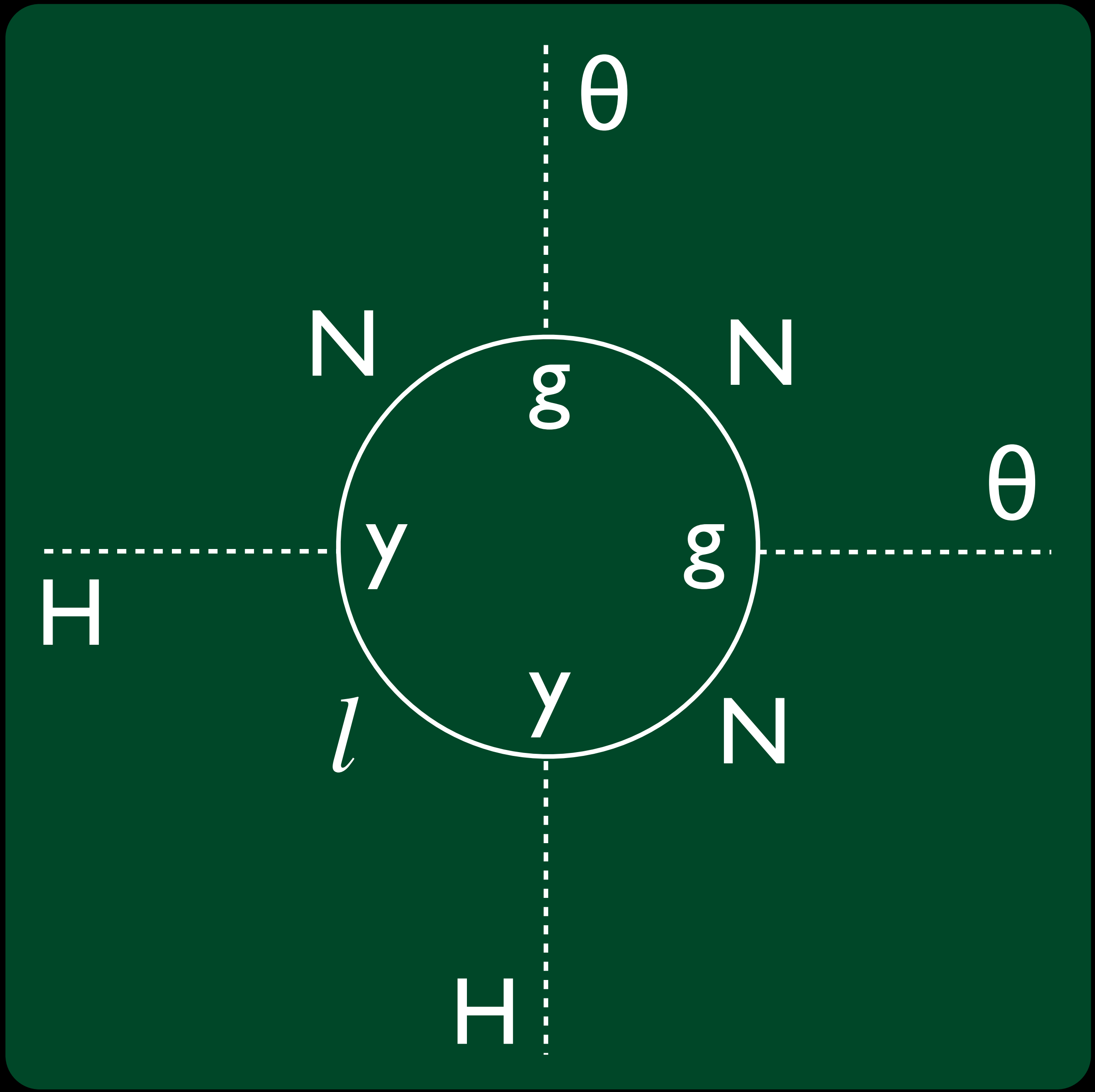


$$-\mathcal{L}_{eff} \supset \lambda \theta^2 H^\dagger H$$

$$\lambda \simeq \frac{1}{16\pi^2} g^2 y^2 \log \frac{\Lambda^2}{f^2}$$

θ-Higgs coupling in a nutshell

$$-\mathcal{L} \supset l_\alpha (y_{\alpha j} v) N_j \left(\frac{H}{v}\right) + \frac{1}{2} N_i (g_{ij} f) N_j \exp\left(i\frac{\theta}{f}\right)$$



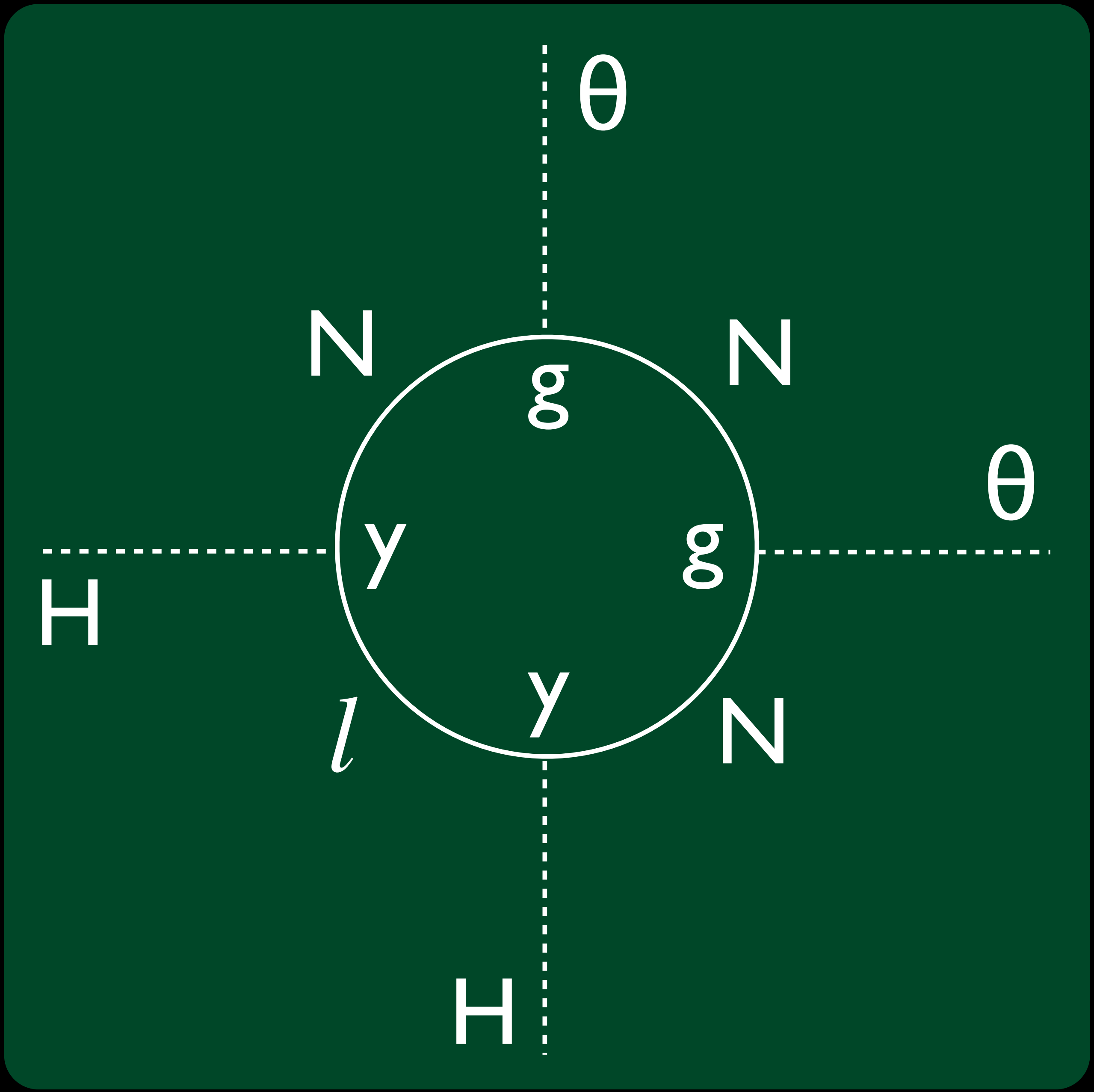
$$-\mathcal{L}_{eff} \supset \lambda \theta^2 H^\dagger H$$

$$\lambda \simeq \frac{1}{16\pi^2} g^2 y^2 \log\frac{\Lambda^2}{f^2}$$

$$m_\theta^2 = \lambda v^2 \ll \Lambda_{EW}^2$$

θ-Higgs coupling in a nutshell

$$-\mathcal{L} \supset l_\alpha (y_{\alpha j} v) N_j \left(\frac{H}{v}\right) + \frac{1}{2} N_i (g_{ij} f) N_j \exp\left(i\frac{\theta}{f}\right)$$



$$-\mathcal{L}_{eff} \supset \lambda \theta^2 H^\dagger H$$

$$\lambda \simeq \frac{1}{16\pi^2} g^2 y^2 \log \frac{\Lambda^2}{f^2}$$

$$m_\theta^2 = \lambda v^2 \ll \Lambda_{EW}^2$$

Many details & subtleties ...

Hill, Ross '88; Little Higgs models; Frigerio, Hambye, Masso '11

Freeze-out or... freeze-in

$$-\mathcal{L}_{eff} \supset \frac{\lambda}{2} H^\dagger H\, \eta\, \eta$$

- Freeze-out: η thermalizes and later decouples, at $T \lesssim m_\eta$.
  To obtain the correct Ω_{DM} one needs $m_\eta \approx 50$ GeV.

  e.g. Farina, Pappadopulo, Strumia, 2010

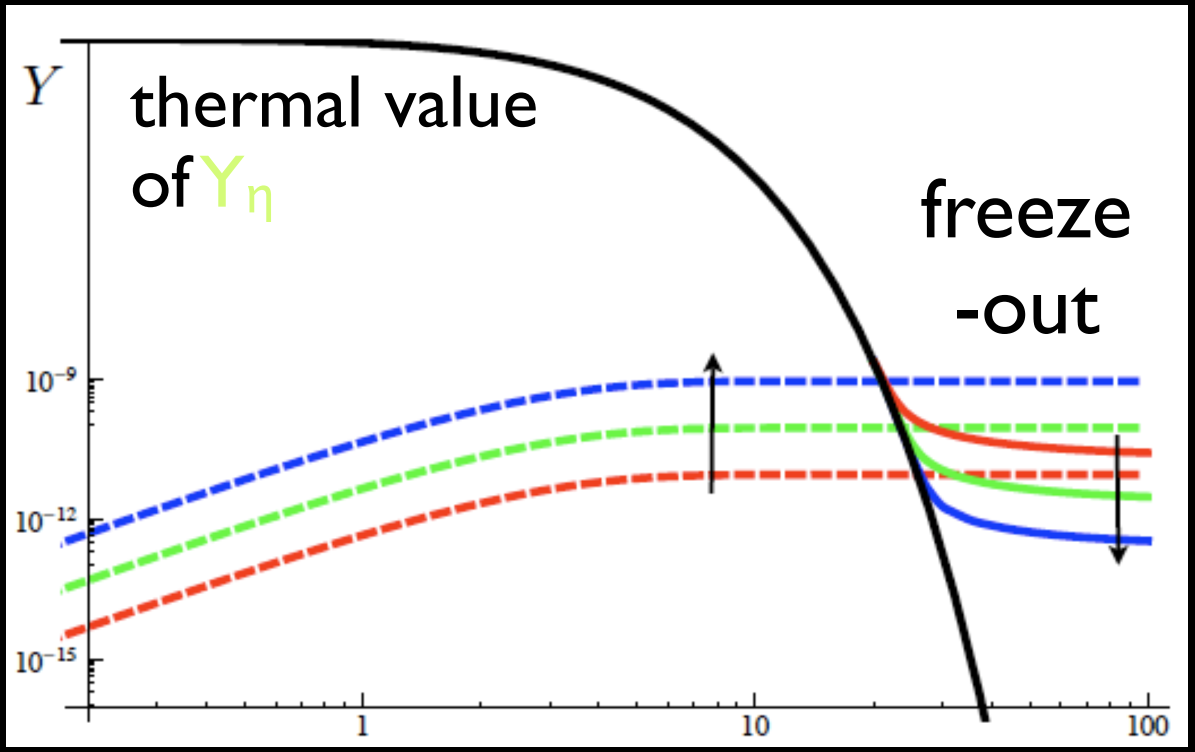
Freeze-out or... freeze-in

$$-\mathcal{L}_{eff} \supset \frac{\lambda}{2} H^\dagger H \, \eta \, \eta$$

- Freeze-out: η thermalizes and later decouples, at T ≤ m_η.
  To obtain the correct Ω_{DM} one needs $m_\eta \approx 50$ GeV.

  e.g. Farina, Pappadopulo, Strumia, 2010

Y = n/s



$z_{f.o.} = m_\eta/T$

arrows indicate increasing values of λ

Freeze-out or... freeze-in

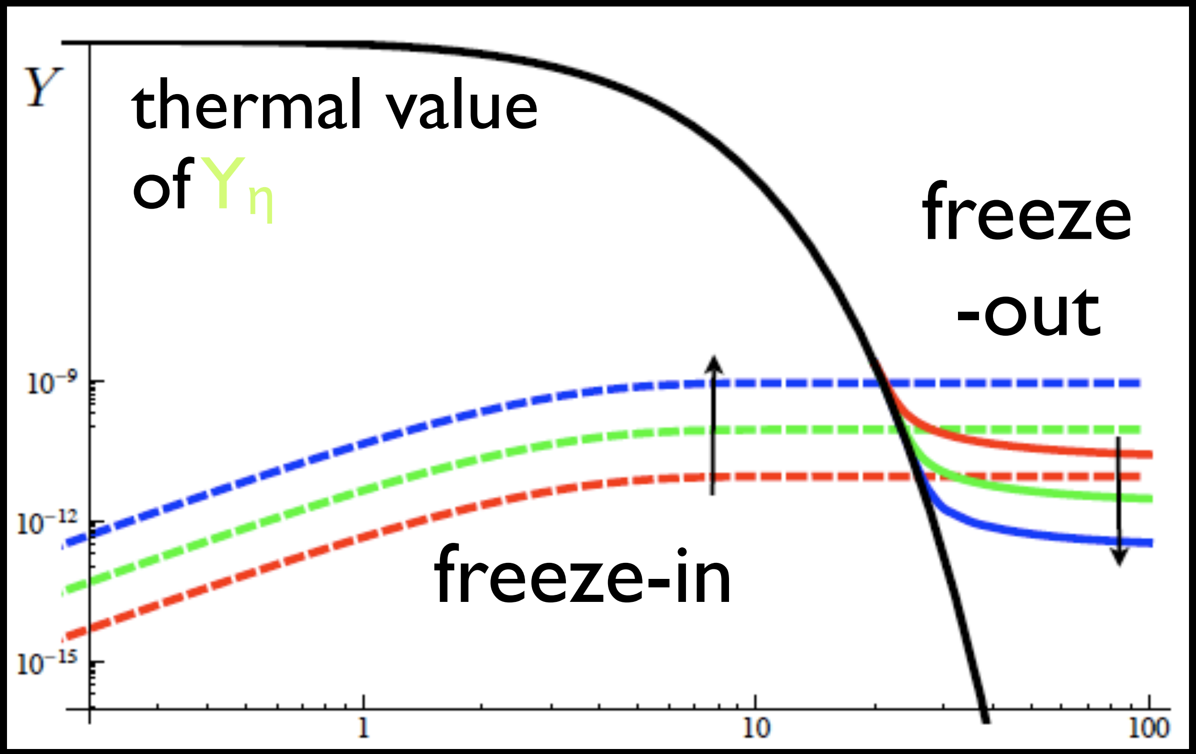
$$-\mathcal{L}_{eff} \supset \frac{\lambda}{2} H^\dagger H\, \eta\, \eta$$

- Freeze-out: η thermalizes and later decouples, at $T \lesssim m_\eta$.
  To obtain the correct Ω_{DM} one needs $m_\eta \approx 50$ GeV.

  e.g. Farina, Pappadopulo, Strumia, 2010

from Hall, Jedamzik, March-Russell, West, 2009

$Y = n/s$



$z_{f.o.} = m_\eta/T$

arrows indicate increasing values of λ

Freeze-out or... freeze-in

$$-\mathcal{L}_{eff} \supset \frac{\lambda}{2} H^\dagger H \,\eta\,\eta$$

- Freeze-out: η thermalizes and later decouples, at T ≤ m_η.
  To obtain the correct Ω_{DM} one needs $m_\eta \approx 50$ GeV.

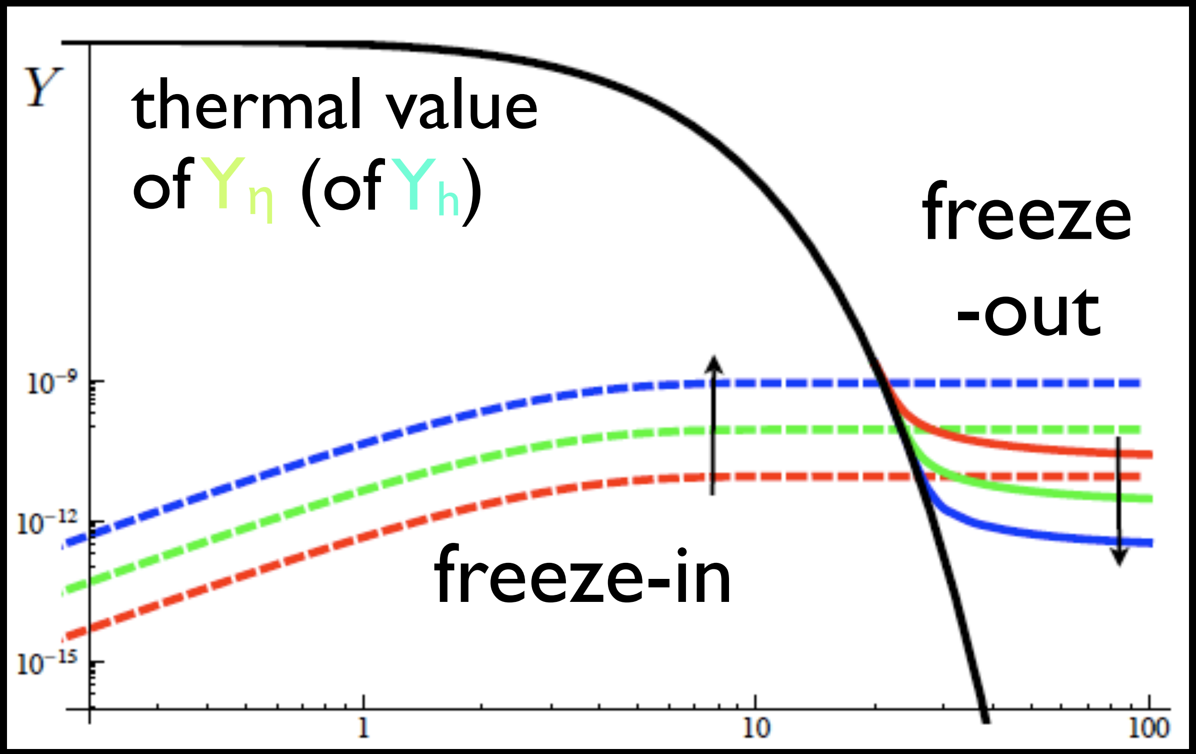
  e.g. Farina, Pappadopulo, Strumia, 2010

- Freeze-in: a less-than-thermal population of η's is produced by the annihilation/decay of heavier particles, X= h, W, Z.
  The η number density reaches a plateau at T ≈ m_X.
  We found that Ω_{DM} is reproduced for $m_\eta \approx 3$ MeV ($\lambda \approx 10^{-10}$).

  Frigerio, Hambye, Masso 2011

from Hall, Jedamzik, March-Russell, West, 2009

Y = n/s



$z_{f.o.} = m_\eta/T$
$z_{f.i.} = m_h/T$

arrows indicate increasing values of λ

θ-couplings to SM fermions

Since θ has the coupling $g\theta NN$, and since N mixes with ν,
θ decays into light neutrinos at tree-level

$$\Gamma(\theta \to \nu\nu) = \frac{1}{16\pi} g^2_{\theta\nu\nu} m_\theta$$

$$g_{\theta\nu\nu} \simeq 10^{-21} \left(\frac{\text{MeV}}{m_\theta}\right)^2 \left(\frac{g}{10^{-3}}\right)^3 \left(\frac{m_\nu}{\text{eV}}\right)^2$$

θ-couplings to SM fermions

Since θ has the coupling gθNN , and since N mixes with ν,
θ decays into light neutrinos at tree-level

$$\Gamma(\theta \to \nu\nu) = \frac{1}{16\pi} g^2_{\theta\nu\nu} m_\theta$$

$$g_{\theta\nu\nu} \simeq 10^{-21} \left(\frac{\text{MeV}}{m_\theta}\right)^2 \left(\frac{g}{10^{-3}}\right)^3 \left(\frac{m_\nu}{\text{eV}}\right)^2$$

Since ν couples to Z and W, at one-loop θ couples also to charged fermions, both leptons and quarks

$$\Gamma(\theta \to f\bar{f}) = \frac{1}{8\pi} g^2_{\theta f\bar{f}} m_\theta$$

$$g_{\theta f\bar{f}} \simeq 10^{-22} \left(\frac{10^7 \text{GeV}^2 G_F}{16\pi^2}\right) \left(\frac{g}{10^{-3}}\right) \left(\frac{m_f}{\text{MeV}}\right) \left(\frac{m_\nu}{\text{eV}}\right)$$

Allowed regions for θ dark matter