Alcune questioni nella fenomenologia della fisica oltre il modello standard

Andrea Romanino

SISSA

- The hierarchy problem
  - Supersymmetry
  - Extra-dimensions
  - Split SUSY
- Flavour physics
  - Models and their tests
  - Unitarity triangle
  - New physics in B's, K's
- Neutrino physics
  - Phenomenology
  - Model building
  - Astrophysics

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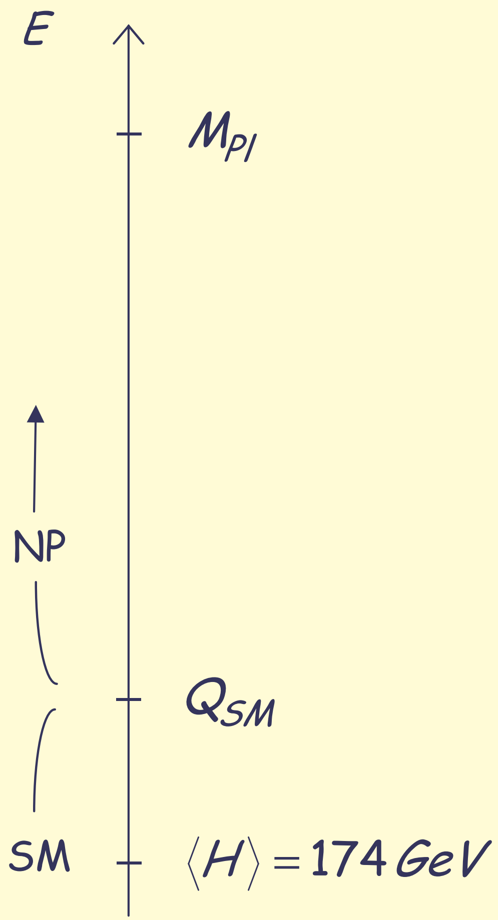
The hierarchy problem as a guideline for NP



The SM is an effective theory valid below Q_{SM}

- Where is Q_{SM} ?
- What type of physics above Q_{SM} ?

Where is Q_{SM} ?

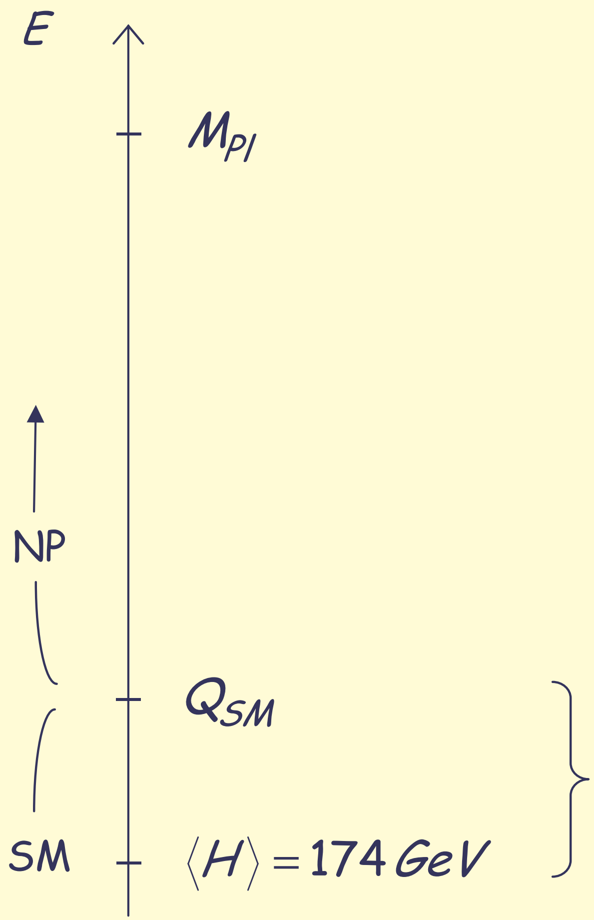
The main upper limit follows from solving the hierarchy problem

$$m_h^2 = m_h^2(Q_{SM}) + \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2 - 2M_W^2 - M_Z^2 - m_h^2)Q_{SM}^2$$

$$= \begin{cases} m_h^2(Q_{SM}) + m_h^2\left(\frac{Q_{SM}}{0.5\,\text{TeV}}\right)^2 & \text{if } m_h = 115\,\text{GeV} \\ m_h^2(Q_{SM}) + m_h^2\left(\frac{Q_{SM}}{2\,\text{TeV}}\right)^2 & \text{if } m_h = 250\,\text{GeV} \end{cases}$$

- Q_{SM} is the scale of the degrees of freedom cutting off the Higgs mass quadratic divergence
- $Q_{SM} \lesssim \text{TeV}$ barring accidental cancellations

Some solutions

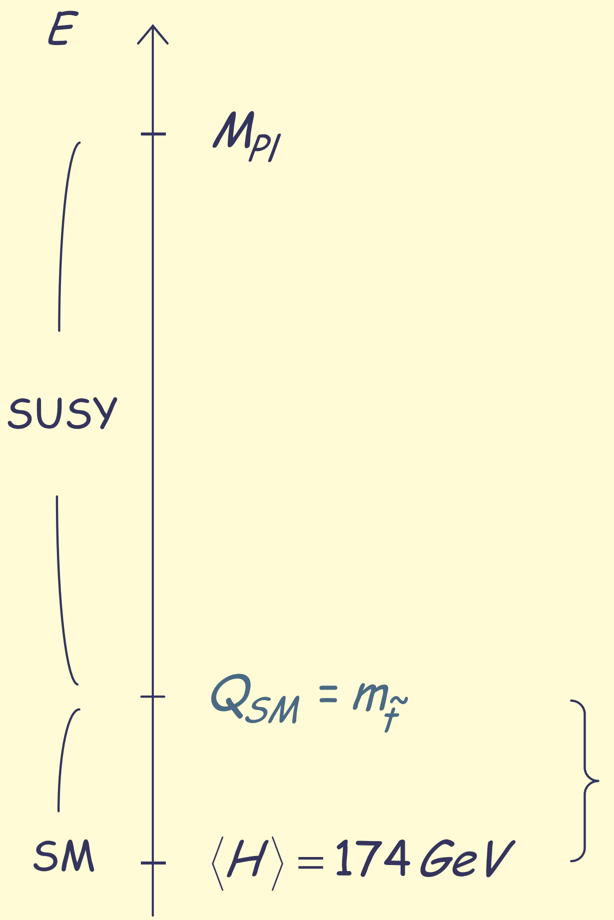


- Technicolor
- Little Higgs
- Extra-dimensions
- Warped compactification

EWPT: lower limit on Q_{SM}

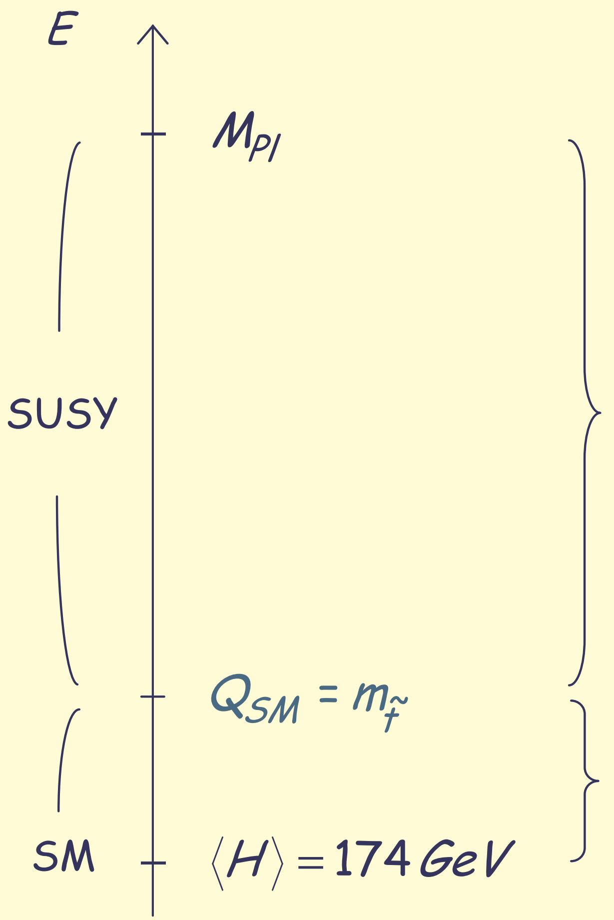
$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{SM}^2$$

MSSM



$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \, Q_{SM}^2$$

MSSM



$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{SM}^2 \log \frac{M_{Pl}^2}{Q_{SM}^2}$$

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{SM}^2$$

Ignoring the hierarchy problem

- Abandon the hierarchy problem as a guideline for NP

- Use gauge coupling unification and DM as guidelines instead. A more general version of the MSSM with light fermions and $\langle H \rangle < \tilde{m} < M_{Pl}$ still emerges as the most simple and coherent possibility
  - $\tilde{m} \sim \langle H \rangle$: MSSM
  - $\tilde{m} \gg \langle H \rangle$: Split SUSY (SpS)

- SpS vs MSSM
  - Exacerbates the FT problem
  - \+ Cleans up the MSSM while preserving the successes
  - \+ Well defined and predictive, with 4 (not 100's) additional parameters
  - \+ Different (new) phenomenology and experimental signatures
  - \+ New model building options, insights

Cleaning up the MSSM

- Successes of the MSSM
  - Gauge coupling unification
  - Natural dark matter candidate (with R-parity)

- Nuisances
  - Potentially > 100 parameters (CMSSM)
  - FCNCs and CP-violation in particular EDMs (SUSY breaking mechanism, symmetries)
  - Proton decay from dimension 5 operators (non minimal models)
  - Gravitino and moduli problem (low reheating T)
  - Fine-tuning (NMSSM)

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  } scalars

- SpS: fermions ~ TeV, scalars (but 1 Higgs) » TeV
  (retains the successes, nuisances evaporate – except FT)

The structure of Split Supersymmetry

- Sfermion masses: $\langle H \rangle \ll \tilde{m} < 10^{13}\,\mathrm{GeV}$

  $Q > \tilde{m}:$ MSSM

  $Q < \tilde{m}:$ SM $+ \tilde{H}_u, \tilde{H}_d, \tilde{G}, \tilde{W}, \tilde{B}$

- Relevant new terms in the low energy theory (R-parity)

  $$\sqrt{2} H^{\dagger} (g_u \tilde{W} + g'_u \tilde{B}) \tilde{H}_u + \sqrt{2} H^{T} (g_d \tilde{W} + g'_d \tilde{B}) \tilde{H}_d$$

  $$\frac{M_3}{2} \tilde{G}\tilde{G} + \frac{M_2}{2} \tilde{W}\tilde{W} + \frac{M_1}{2} \tilde{B}\tilde{B} + \mu \tilde{H}_u \tilde{H}_d$$

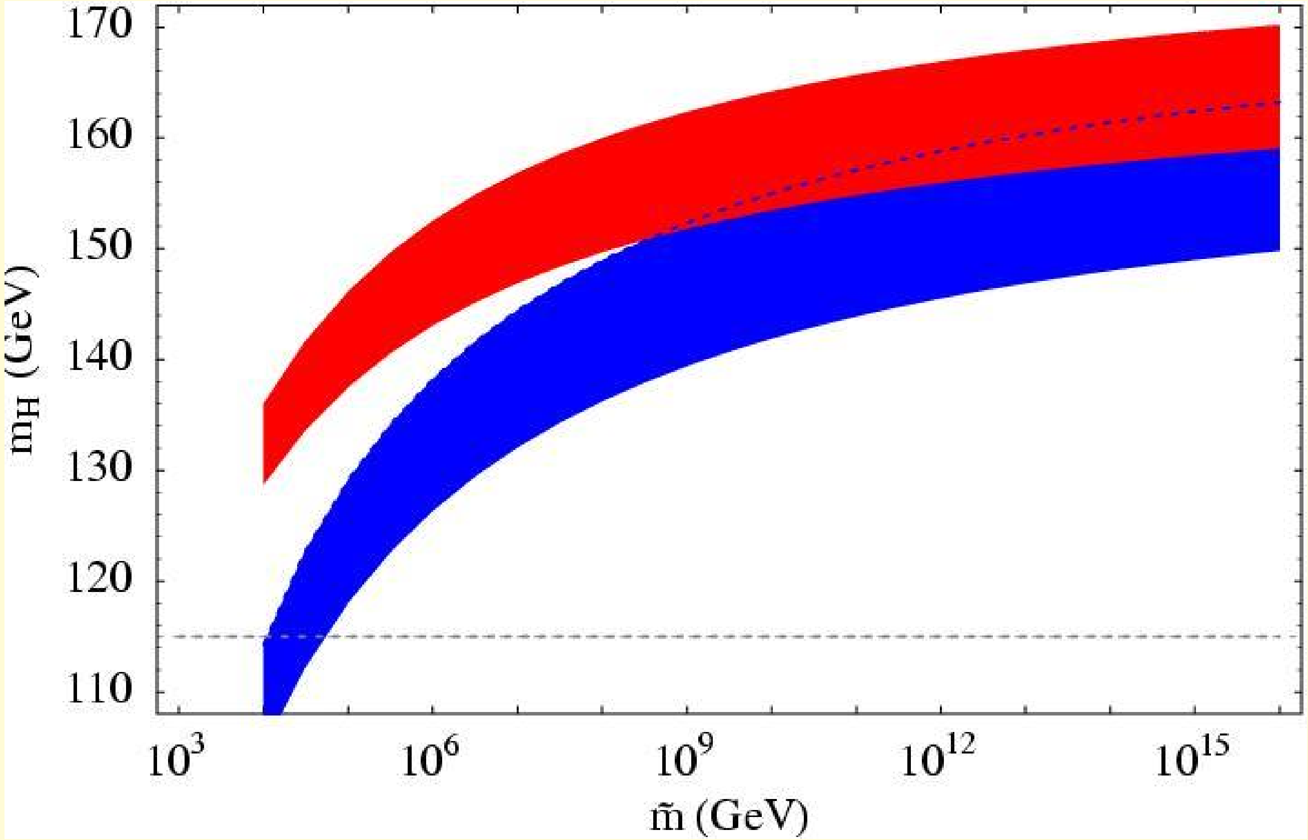
- New parameters (using matching conditions, gaugino mass relation)

  $M_2, \mu, \tilde{m}, \tan\beta$ (-the Higgs coupling)

Phenomenology and signatures

- Unification
- Dark matter
- Higgs mass
- Quasi-stable gluino
- Sfermion spectrum
- SUSY couplings
- EDMs
- Proton decay
- R-parity

Higgs mass

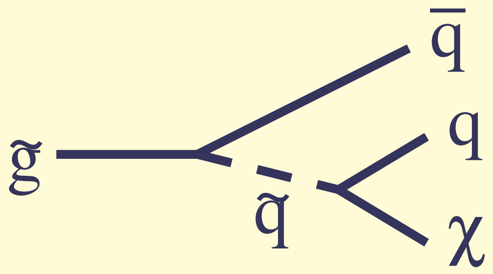


[*Arvanitaki Davis Graham Wacker, Giudice AR*]

The radiative corrections to the Higgs mass are enhanced by a large logarithm

(essentially no lower limit on tanβ from Higgs searches)

Upper bound on the SUSY-breaking scale



$$\tau_{\tilde g} \approx \left(\frac{\text{TeV}}{M_{\tilde g}}\right)^5 \left(\frac{\tilde m}{10^{13}\,\text{GeV}}\right)^4 0.4\ \text{Gyr}$$

Searches for heavy isotopes : $\tau_{\tilde g} < 10^{16}$ sec $\Rightarrow \tilde m <$ few 10^{13} GeV

(if $M_{\tilde g} = 1$ TeV) [Smith et al, Smith, Hemmick et al, Starkman Gould Esmailzadeh Dimopoulos]

Caveats:

- Gluino mass heavier than 10 TeV
- Relic abundance not reflected in the local abundance of heavy isotopes
- Gluino not produced after reheating

Collider signatures

- The gluino is likely to be stable on detector time-scales
- It hadronizes in R-hadrons (-mesons, -baryons, -gluons)
- If charged: slow, highly ionizing track
- If neutral: missing energy, mild hadronic activity, triggered by single jet (gluon emission)
- Energy, charge, Baryon-number exchange
- Sensitivities:
  - Run II: ~200 GeV; LHC: 1 TeV (model independent)
  - Run II: ~400 GeV; LHC: 2.5 TeV (if charged)

  [Baer Cheung Gunion, Raby Tobe, Mafi Raby; recent studies: Kraan, Kilian Plehn Richardson Schmidt, Hewett Lillie Masip Rizzo]
- Also: gluinonium [Cheung, Keung]; gluinos from cosmic rays (if seen give a lower limit on the SUSY-breaking scale)
  [Albuquerque Farrar Kolb; recent studies: Anchordoqui Goldberg Nunez, Hewett Lillie Masip Rizzo]

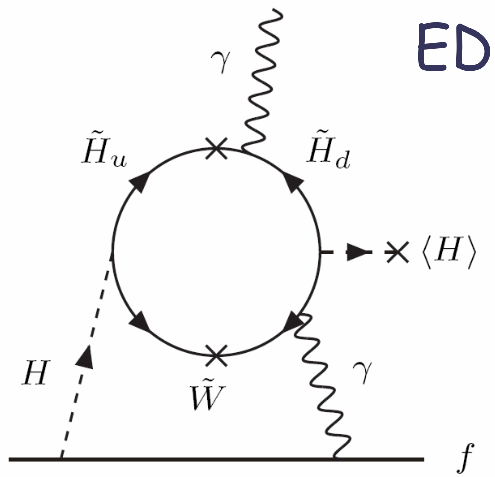
Heavy sfermions suppress flavour & CP violation

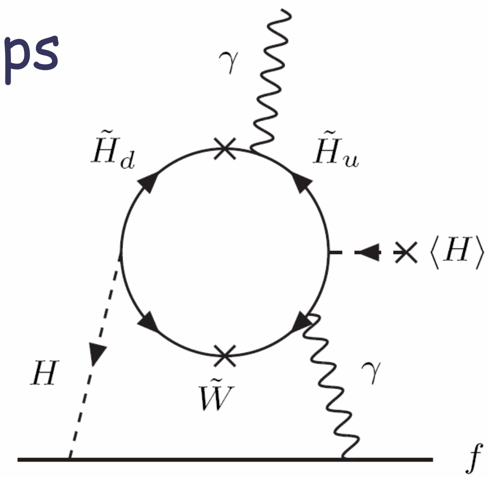
New source of flavour-diagonal CP violation remains:

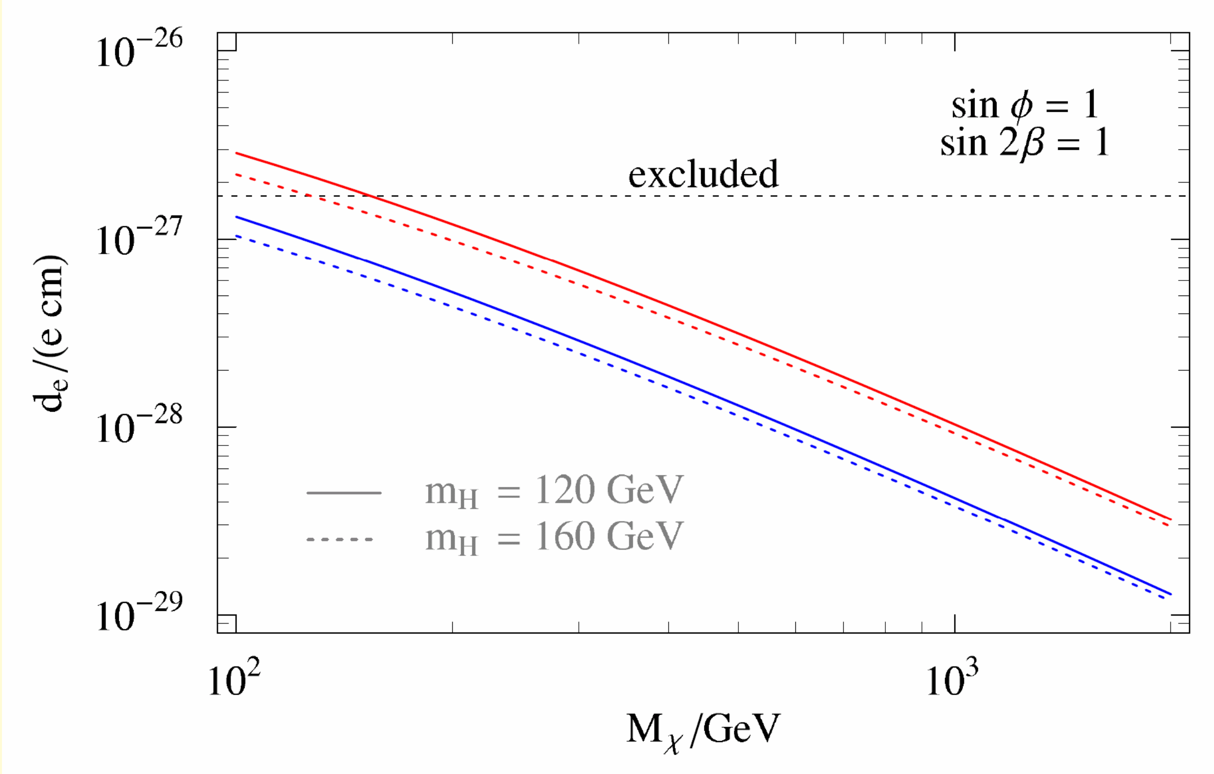
$$\mathcal{L} = \frac{M}{2}\tilde{W}\tilde{W} + \mu H_u H_d + \frac{g_u}{\sqrt{2}} H^* \tilde{W}\tilde{H}_u + \frac{g_d}{\sqrt{2}} H \tilde{W}\tilde{H}_d + \text{h.c.}$$

CP violating invariant: $\text{Im}\left(g_u^* g_d^* M \mu\right)$

EDM at 2-loops







Present limit: $d_e < 1.7 \times 10^{-27}$ *ecm* at 95% CL (DeMille et al.)

Future: DeMille et al. (Yale) 10^{-29} *ecm* in 3 years and 10^{-31} *ecm* in 5 years.

Lamoreaux et al. (Los Alamos): 10^{-31} *ecm* and eventually 10^{-35} *ecm*.

Results from Hinds et al. (Sussex) and Semertzidis et al. (Brookhaven) plans to improve by 10^5 sensitivity on muon EDM

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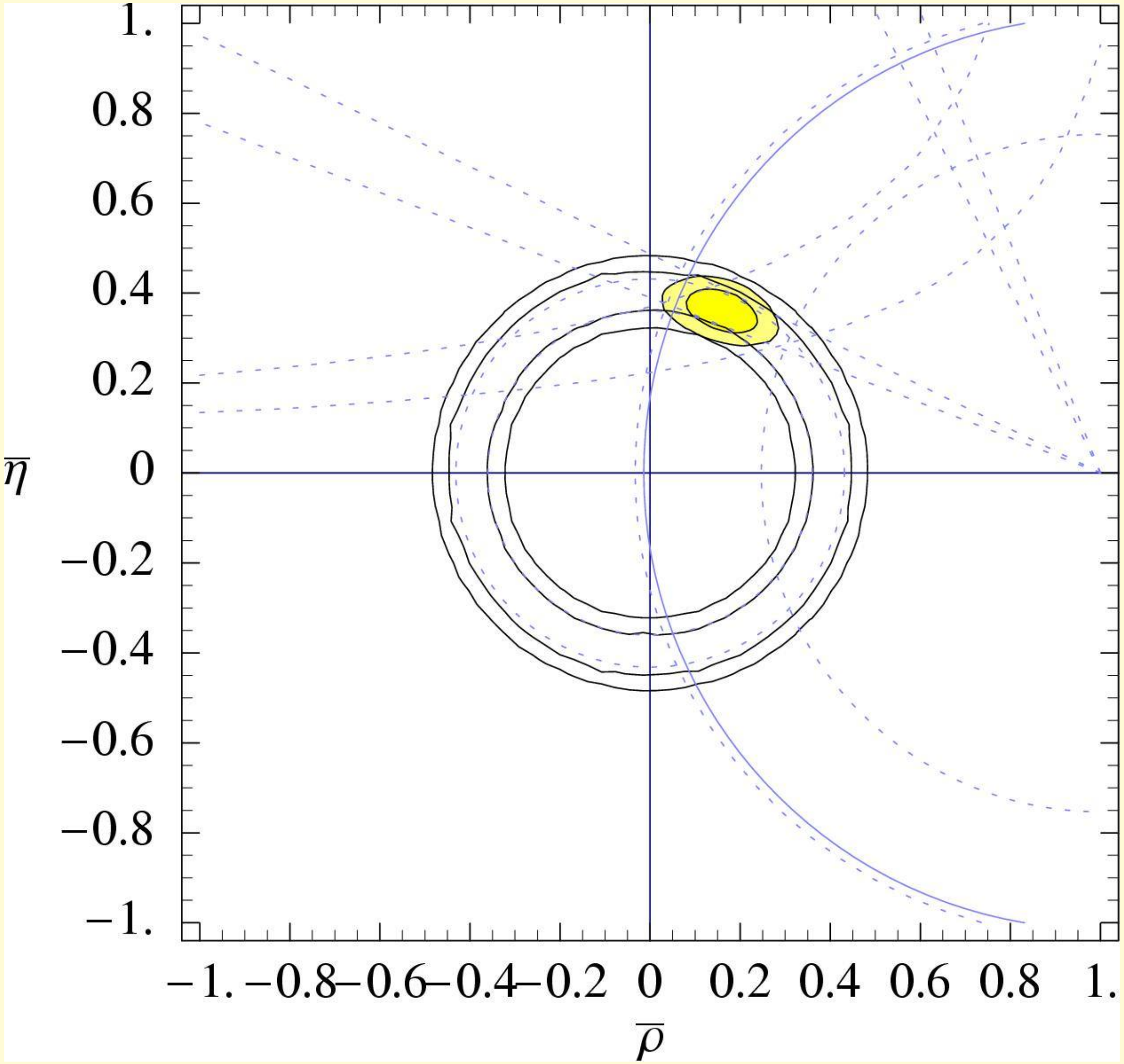
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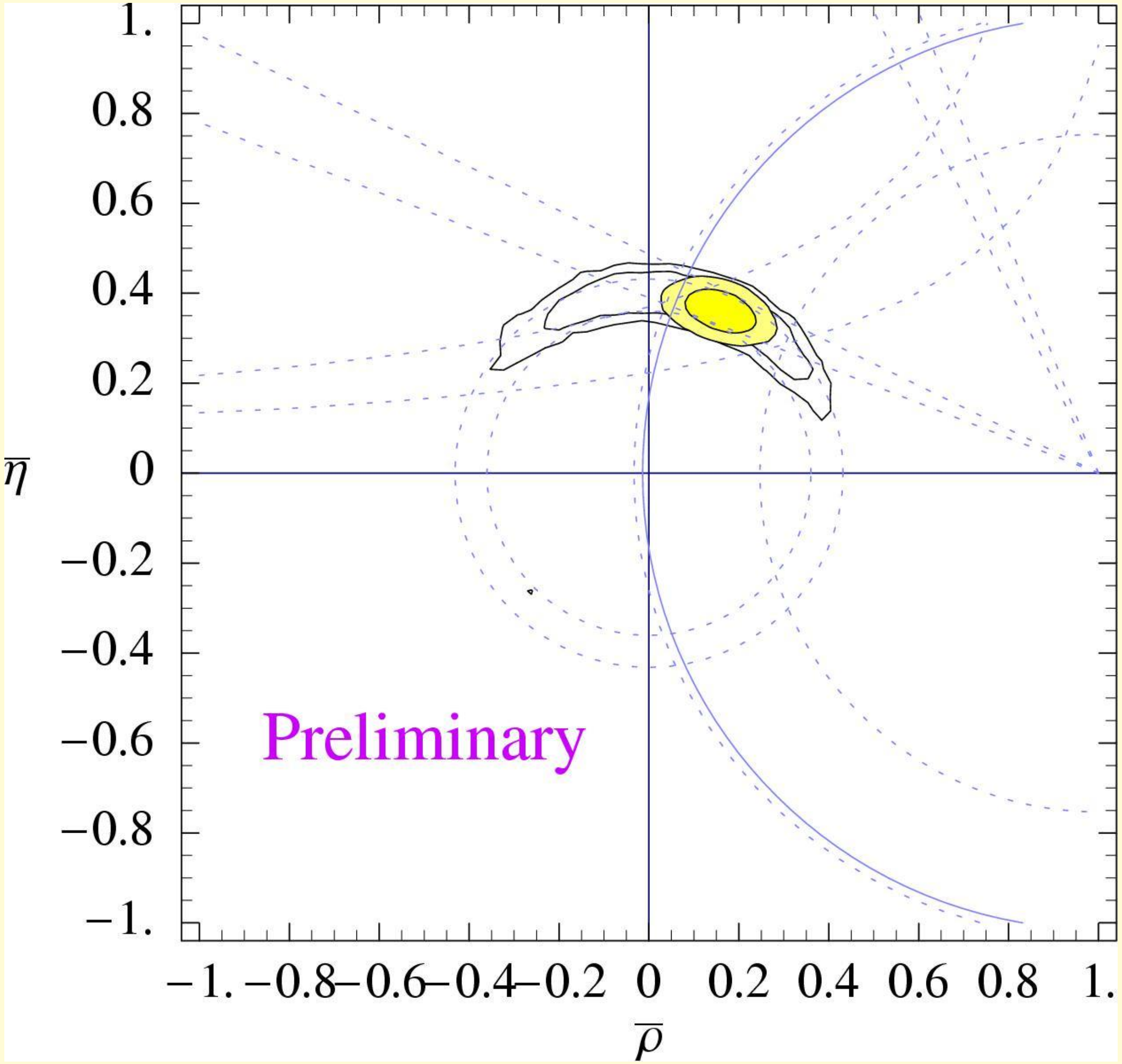
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Physical observables in the leptonic sector

$$m_e, m_\mu, m_\tau, m_1, m_2, m_3, \theta_{23}, \theta_{12}, \theta_{13}, \delta, \alpha, \beta$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

$$(0 \le \theta_{12}, \theta_{23}, \theta_{13} \le \pi/2, \quad 0 \le \delta \le 2\pi)$$

$$L \supset -m_{e_i} e_i^c e_i - \frac{g}{\sqrt{2}} U_{ij} \bar{e}_i \hat{W} P_L \nu_j - \frac{1}{2} m_i \nu_i \nu_i$$

CP-violation

- Is there CP-violation in the lepton sector?
- Is it at the origin of the Baryon asymmetry in the universe?
- Can we observe it in neutrino experiments?
  - Dirac (CKM-like) CP-violation
  - Majorana CP-violation

CKM-like CP-violation

$$P(\nu_{e_i} \to \nu_{e_j}) = P(\bar{\nu}_{e_j} \to \bar{\nu}_{e_i}) = P_{CP} + P_{\not{CP}}$$
$$P(\bar{\nu}_{e_i} \to \bar{\nu}_{e_j}) = P(\nu_{e_j} \to \nu_{e_i}) = P_{CP} - P_{\not{CP}}$$

At accelerators, due to the smallness of $\Delta m^2_{SUN} / \Delta m^2_{ATM}$ and of θ_{13} :

$$\left.\begin{aligned} P_{CP}(\nu_\mu \leftrightarrow \nu_\tau) &\sim \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{ATM} L}{4E} \\ P_{CP}(\nu_e \leftrightarrow \nu_\mu) &\sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ATM} L}{4E} \\ P_{CP}(\nu_e \leftrightarrow \nu_\tau) &\sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ATM} L}{4E} \end{aligned}\right\} + \Delta m^2_{SUN} \text{ corrections}$$

CKM-like CP-violation

Large angles (unlike in quark sector) enhance CP-violation

O(1)

?

LBL

$$P_{\not{CP}} = \pm\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\sin\delta\; S_{SUN} S^2_{ATM}$$

A small θ_{13} enhances the $\nu_e \leftrightarrow \nu_{\mu,\tau}$ CP - asymmetry

$$a = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} \propto \frac{1}{\sin 2\theta_{13} + \text{corr.}}$$

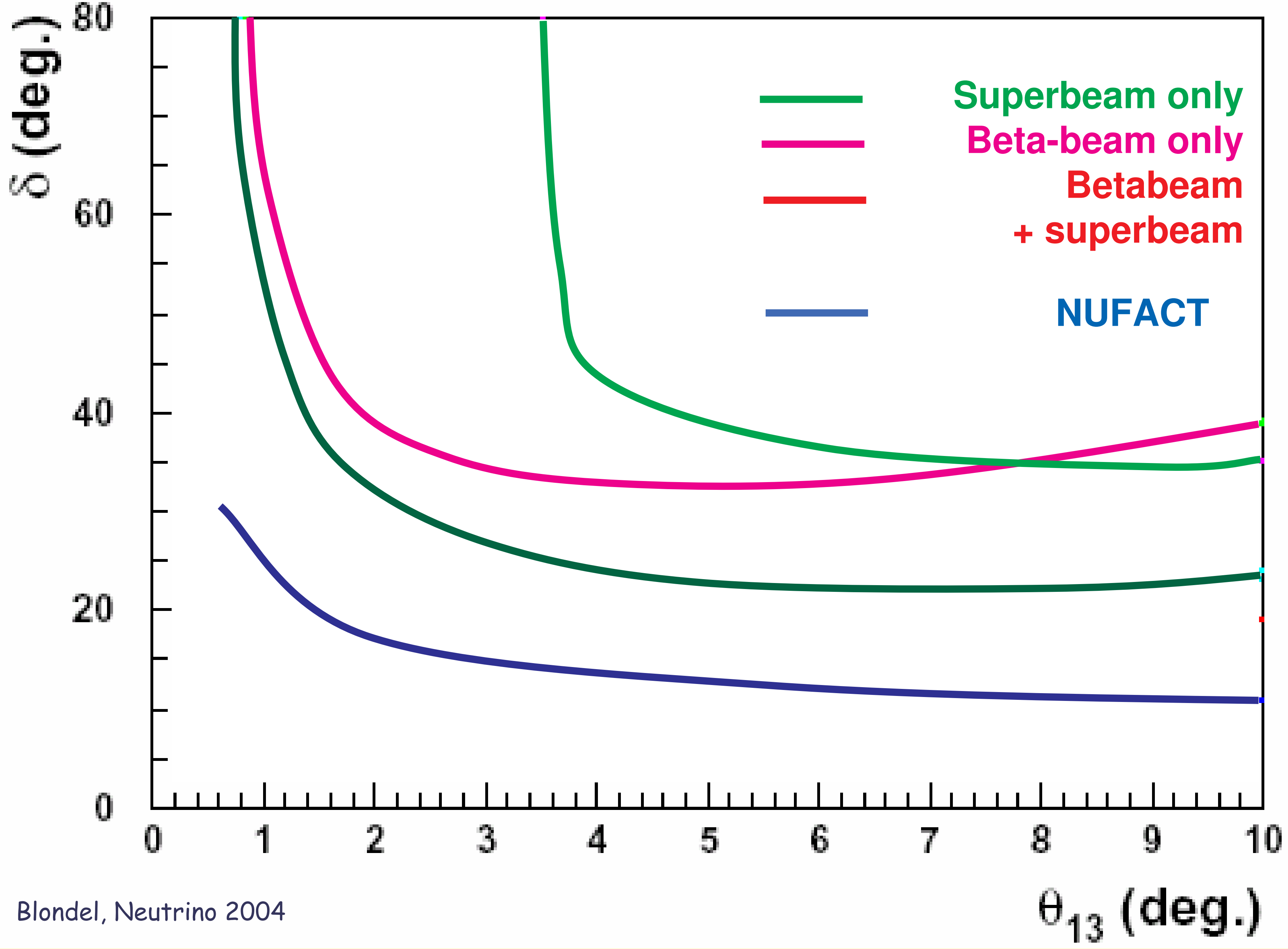
[Dick, Freund, Lindner, AR]

The statistical sensitivity is independent of θ_{13} (on a wide range)

$$\delta a \sim \frac{1}{\sqrt{N}} \propto \frac{1}{\sin 2\theta_{13}} \Rightarrow \text{stat. error} \sim \delta a / a \sim \text{constant with } \theta_{13}$$

[AR]

3 sigma sensitivity of various options



Blondel, Neutrino 2004

Importance of θ_{13}

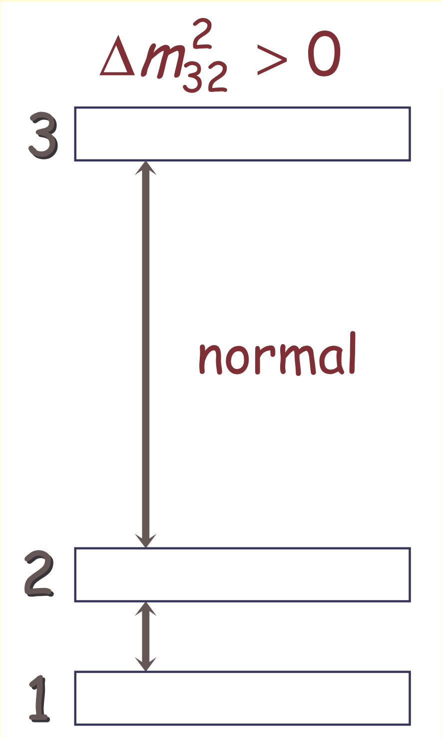
- Origin of masses and mixing
  - Discriminate models
  - Origin of atmospheric angle
  - Origin of solar angle
  - Neutrino mass pattern
- Phenomenology
  - Access leptonic CP-violation
  - Supernova signals
  - Subleading effects
- Experiments
  - Rich experimental program available
- $P(\nu_e \leftrightarrow \nu_\mu) \sim \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{23} L}{4E}$

Standard labeling of eigenstates

$0 < \Delta m^2_{21} < |\Delta m^2_{32}|$ uniquely defines the labeling

$\Delta m^2_{21} > 0$ by definition, Δm^2_{32} can have both signs:

$$\begin{pmatrix} \Delta m^2_{21} \equiv \Delta m^2_{SUN} \\ |\Delta m^2_{32}| \equiv \Delta m^2_{ATM} \end{pmatrix}$$



e.g.:

$m_1 < m_2 \ll m_3$

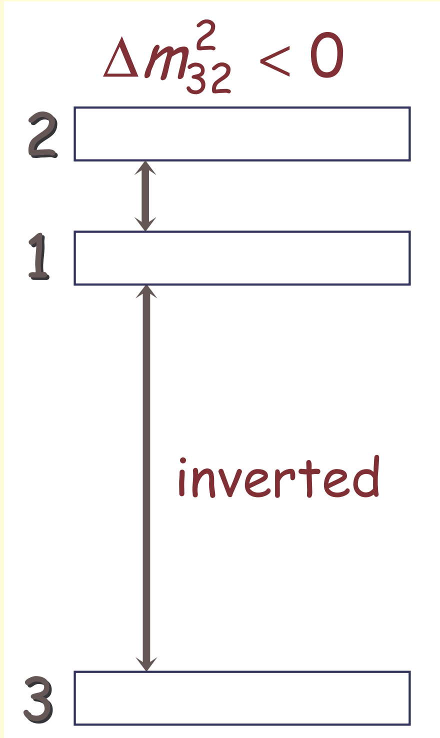
(hierarchical)

$m_1 \approx m_2 \approx m_3$

(degenerate)

$m_1 \approx m_2 < m_3$

(neither)



e.g.:

$m_1 \approx m_2 > m_3$

(inverse hierarchical)

$m_1 \approx m_2 \approx m_3$

(degenerate)

Origin of "neutrino" mixing

$$m_U = U_{u_c}^T m_U^{diag} U_u \qquad V = U_u U_d^\dagger$$
$$m_D = U_{d_c}^T m_D^{diag} U_d$$

$$m_\nu = U_\nu^T m_\nu^{diag} U_\nu \qquad U = U_e U_\nu^\dagger$$
$$m_E = U_{e_c}^T m_E^{diag} U_e$$

The neutrino angles can in principle originate from either m_ν or m_e

(the distinction is physical in terms of the physics giving rise to the masses)

Expectations for θ_{13}

- Inverse Hierarchy: barring tunings or cancellations, θ_{13} must be close to the experimental limit

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In fact:

- an inverse hierarchy requires, barring tunings, a correction to θ_{12} from m_E
- a correction to θ_{12} from m_E contributes to θ_{13}

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$$U = \dots \begin{pmatrix} c_{12}^e & s_{12}^e & \\ -s_{12}^e & c_{12}^e & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & \\ -1/\sqrt{2} & 1/\sqrt{2} & \\ & & 1 \end{pmatrix} \dots$$

$$\theta_{12}^e \sim \frac{45^\circ - \theta_{12}}{\sqrt{2}} \Rightarrow s_{13} \supset s_{12}^e s_{23} \sim \frac{45^\circ - \theta_{12}}{2} \sim \text{exp limit}$$

- In all cases, θ_{12}^e contributes to θ_{13}

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θ_{12}^e is also model-dependent, but involves the charged fermions

$$m_D = \ldots \begin{pmatrix} 0 & \varepsilon' & \\ \varepsilon' & \varepsilon & \\ & & 1 \end{pmatrix} \quad \text{is successful:} \quad \theta_c \approx \sqrt{\frac{m_d}{m_s}} \quad \text{(precise)}$$

[Gatto Sartori]

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[Gatto Sartori]

Implementing the same pattern in m_E (e.g. SU(5))

$$\theta_{12}^e \approx \sqrt{\frac{m_e}{m_\mu}} = \frac{1}{3}\sqrt{\frac{m_d}{m_s}} \approx \frac{\theta_c}{3}$$

$$\theta_{13} \supset s_{23}\sqrt{\frac{m_e}{m_\mu}} \sim \frac{1}{3} \times \text{exp limit} \sim 3^o$$

Central value observable with suberbeams (but > O(1) uncertainty)

Minimal models

- Use the minimal number of "effective" parameters needed to account for the data: 4+1

- Produce 2 relations among
  $\theta_{23} \quad \theta_{12} \quad \theta_{13} \quad \delta \quad \Delta m^2_{32} \quad \Delta m^2_{21} \quad m_{ee}$

  i.e. a prediction for θ_{13}, m_{ee}

Reducing the number of parameters

- Simplest possibility: assume the presence of (2) zeros in the neutrino mass matrix written in the flavor basis, $(m_\nu)_{e_i e_j}$

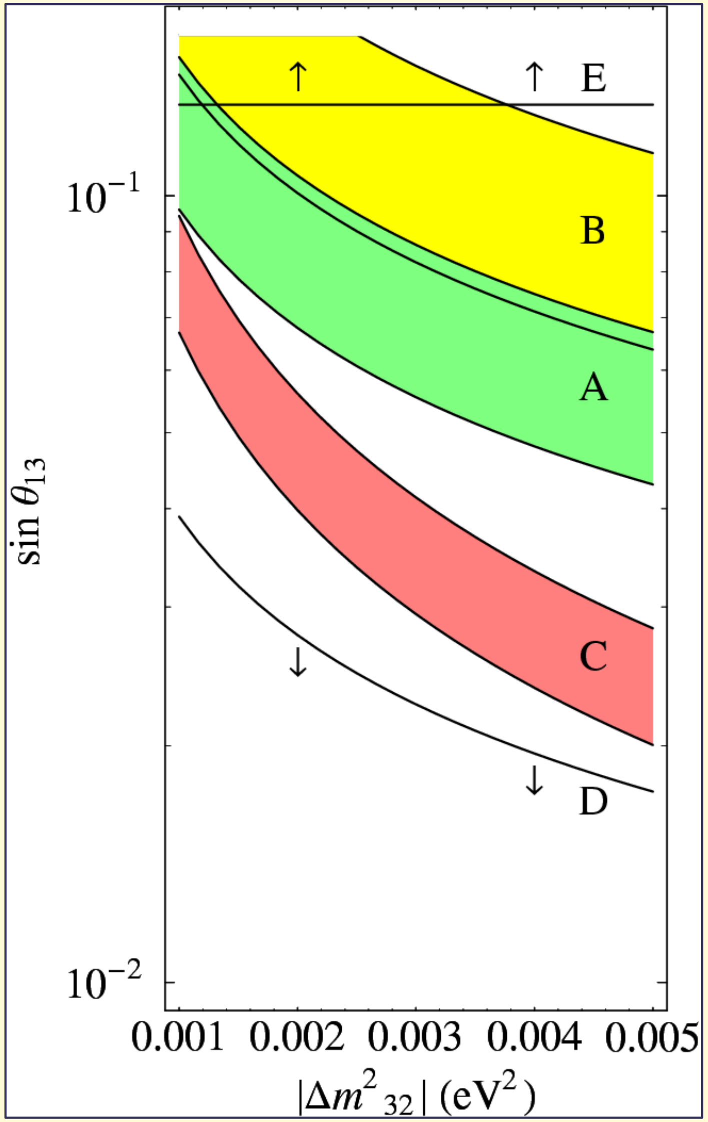
  [Frampton, Glashow, Marfatia]

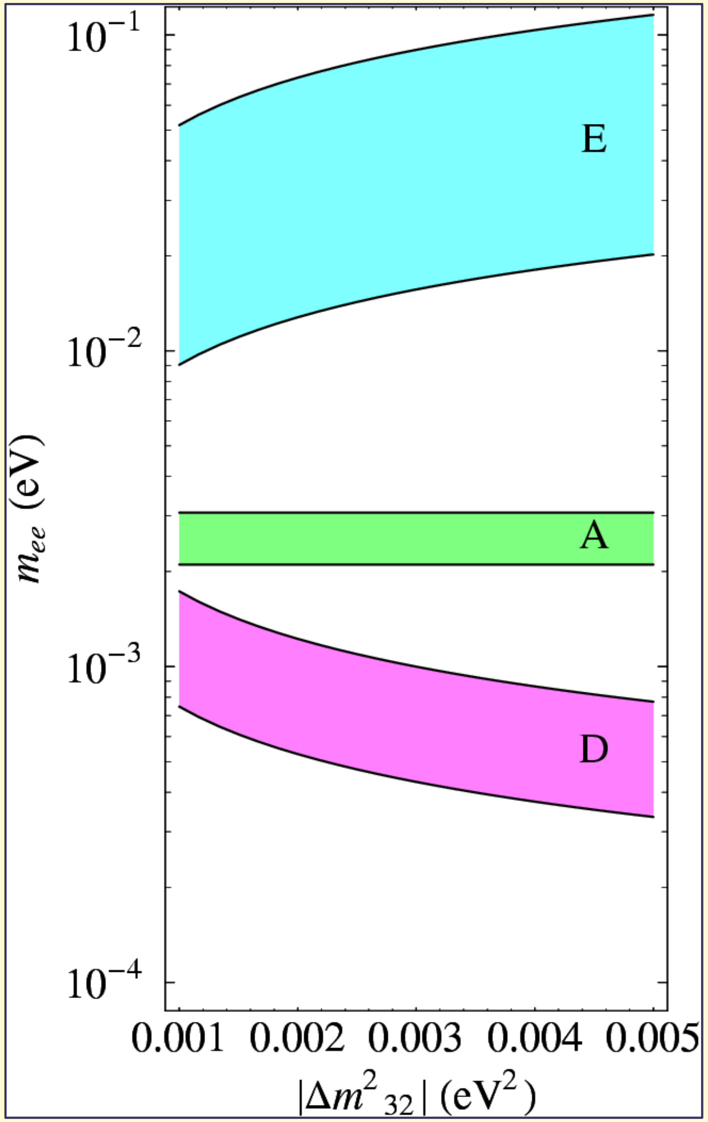
- However, the parameters in $(m_\nu)_{e_i e_j}$ are only combinations of the parameters in the basic lagrangian

- Our approach: [Barbieri, Hambye, AR]
  - assume the relative smallness (vanishing) of some parameters in the basic lagrangian (m_E, μ, M)
  - assume there are no correlations among those parameters (non-abelian symmetries could give rise to further possibilities) [e.g. Ibarra, Ross]

- We find only 5 possible predictions

Predictions for θ_{13}, m_{ee}





Barbieri, Hambye, AR