Theory of neutrino mass & mixing

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Theory:

conjectures
approaches
scenarios
schemes
models
mechanisms

scans of
- symmetries
- parameters
- field contents

new physics ranges	from	to
mass scale	eV scale	Planck mass $\sim 10^{-9} - 10^{19}$ GeV
mixing	symmetry and hierarchy	anarchy
approaches	minimalistic scenario of nuMSM	sophisticated structures at several new scales
tools	simple minded manipulations with mass and mixing matrices	consideration of geometric and string origins of the observed patterns

At the crossroads

Some of models and approaches may indeed reflect (correspond to) reality

And still some key elements can be missed

Recent developments:

No new physics at LHC, MEG, searches for FCNC, Higgs properties are in agreement with SM

This forces us to take more seriously scenarios with nothing or almost nothing below Planck scale

Content:

To assess possible implications of future measurements

1. Across the scales and patterns
2. Mixing: Symmetry or no symmetry
3. Behind Mass Hierarchy, CP-phase and steriles
4. Theoretical relevance and urgency

Across
the scales
& patterns

Scales and frameworks

GUT - Planck mass

High scale seesaw
Quark- lepton
symmetry /analogy
GUT

Electroweak - LHC

Low scale seesaw,
Radiative
mechanisms,
High dimensional
operators

eV- sub-eV

Scale of neutrino
masses themselves
- Relation to dark
  Energy, MAVAN?

ExtraDimensions

High scale seesaw, unification

$$m_\nu = - m_D{}^T \frac{1}{M_R} m_D$$

similarity: $m_D \sim m_q \sim m_l$

$M_R = M_{GUT} \sim 10^{16}$ GeV

For the heaviest in the presence of mixing

$M_R \sim 10^8 - 10^{14}$ GeV

$$\frac{M_{GUT}{}^2}{M_{Pl}}$$

double seesaw

$M_R \sim 10^{16} - 10^{17}$ GeV

many heavy singlets (RH neutrinos) $N \sim 10^2$
...string theory

GUT

Neutrino mass as an evidence of Grand Unification ?

Gauge coupling unification
BICEP-II ?

Leptogenesis: the CP-violating out of equilibrium decay

High scale seesaw, unification

Natural, minimalistic, in principles

Realizes relations:

Neutrality,
zero charges

Majorana
Nature

Smallness of mass
- high mass scale

Large
mixing

"Neutrinoful Universe"

T. Higaki et al,
arViv:1405.0013

Seesaw sector is responsible for inflation (scalar which breaks B-L and gives masses of RH neutrinos), dark matter, leptogenesis

Fine tuning

Testable?

- Proton decay
- Majorana masses

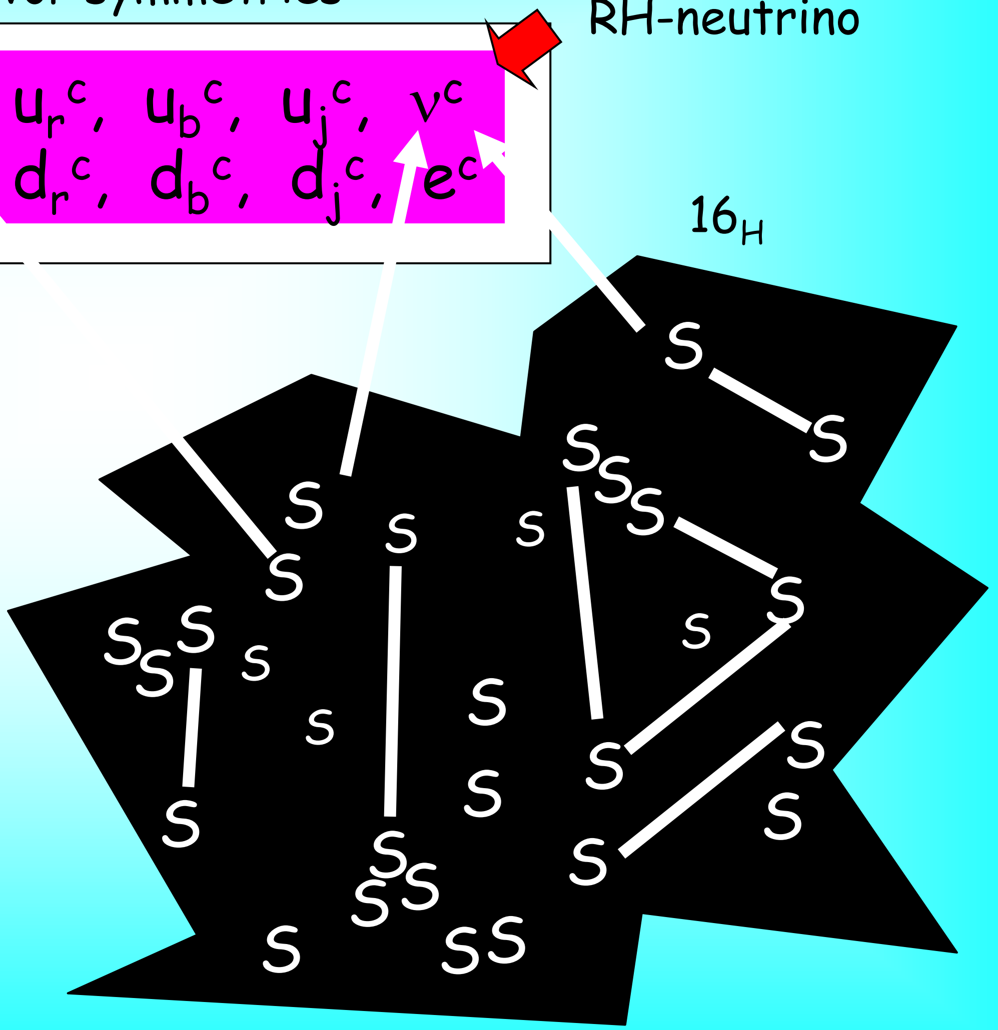
A GUT scenario

SO(10) GUT + hidden sector + flavor symmetries

16

$u_r\ ,\ u_b\ ,\ u_j\ ,\ \nu$ $\quad$ $u_r^c,\ u_b^c,\ u_j^c,\ \nu^c$

$d_r\ ,\ d_b\ ,\ d_j\ ,\ e$ $\quad$ $d_r^c,\ d_b^c,\ d_j^c,\ e^c$



with Hidden sector
at GUT - Planck scales

Double (cascade) seesaw →
explains smallness of neutrino
mass and difference
of q- and l- mixings

Flavor symmetries at very
high scales, above GUT
Symmetries in S- sector?

Randomness (if needed)

but

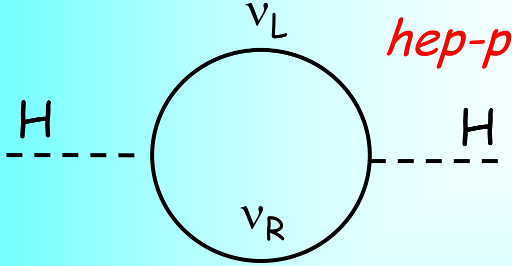
The problem

Natural scale $M_R \sim m_D^2 / m_\nu \sim 10^{14}$ GeV

ν_R introduces new mass scale << M_{Pl}

(Another indication: unification of gauge couplings)

F. Vissani
hep-ph/9709409



$$\delta m_H^2 \sim \frac{y^2}{(2\pi)^2} M_R^2 \log(q/M_R)$$

$$\sim \frac{M_R^3 m_\nu}{(2\pi v)^2} \log(q/M_R)$$

⇨ New physics below Planck scale

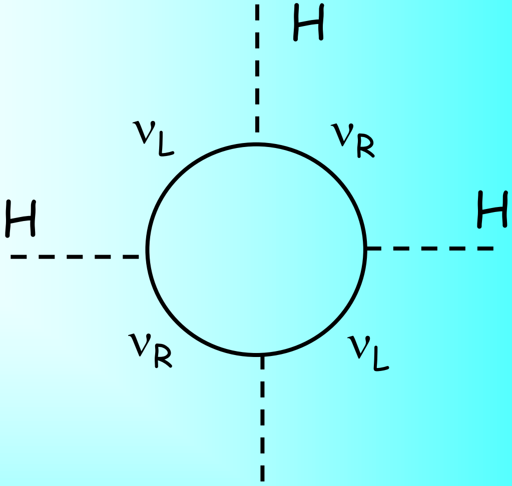
$M_R < 10^7$ GeV

SUSY ?

Hierarchy problem

J Elias-Miro et al,
1112.3022 [hep-ph]

Renormalization of quartic Higgs coupling λ (making it more negative)



Affects stability and lifetime of the EW vacuum

reheating T

$M_R < 10^{13} - 10^{14}$ GeV

EW - LHC scale

- No hierarchy problem (even without SUSY)
- testable at LHC, new particles at 0.1 – few TeV scale
- LNV decays

Low scale seesaw

νMSM

Low scale

L-R

$\cancel{R}_p$-SUSY

Neutralino as RH neutrino

Radiative

One loop

Two loops

Three loops

Small VEV

Higgs Triplet

New Higgs doublets

Inverse seesaw

High dimensional operators

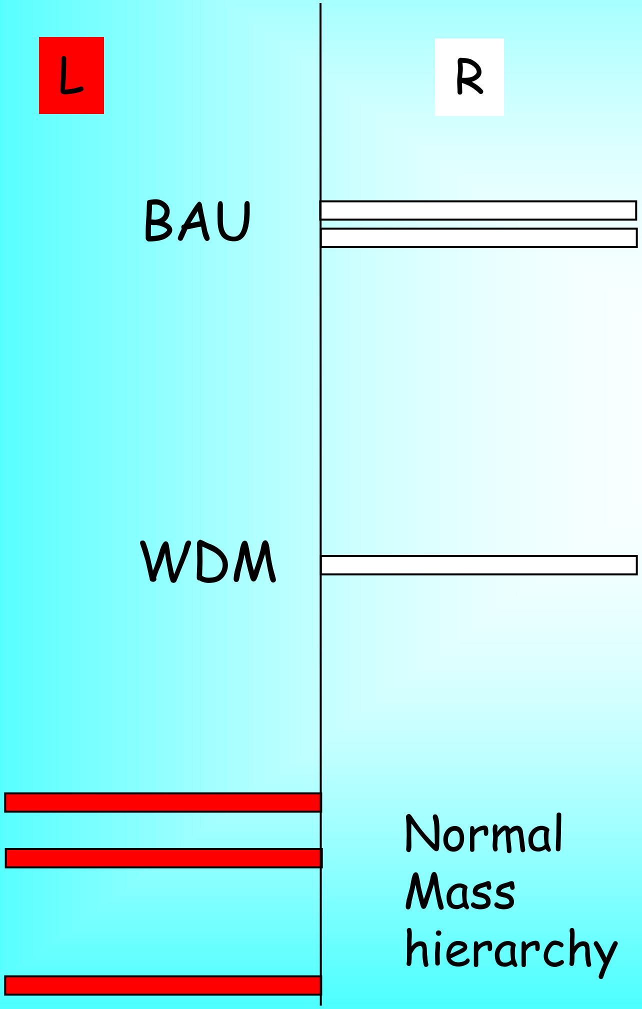
Radiative seesaw

Connection to Dark Matter

ν MSM

M. Shaposhnikov et al

Everything below EW scale
→ small Yukawa couplings



Few 100 MeV – GeV

split ~ eV

- generate light mass of neutrinos
- generate via oscillations lepton asymmetry in the Universe
- can be produced in B-decays (BR ~ 10^{-10})

3- 10 kev

- warm dark matter
- radiative decays → X-rays

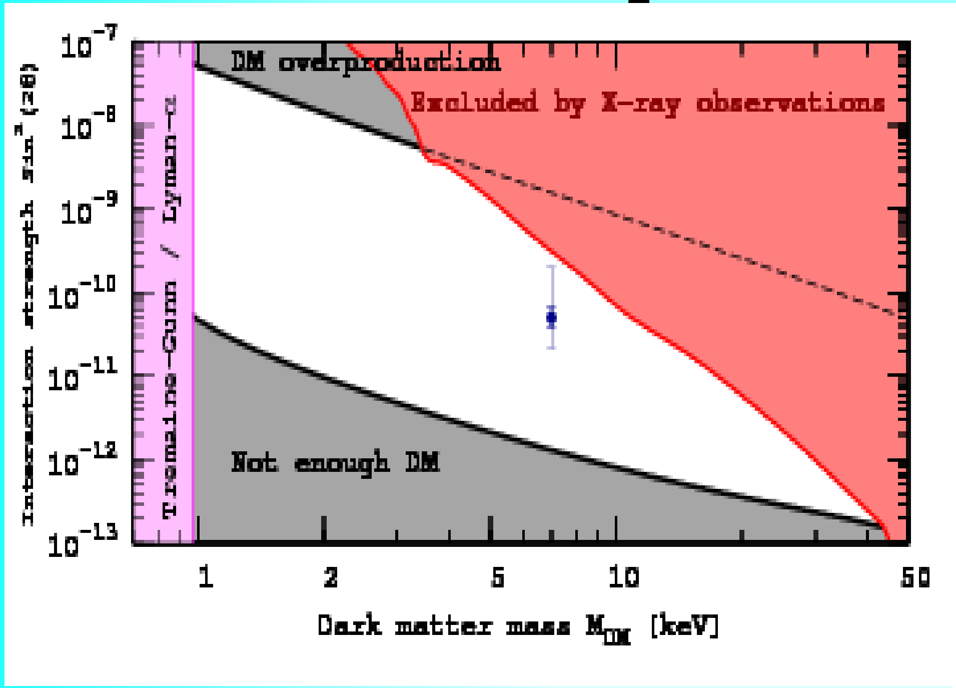
Normal
Mass
hierarchy

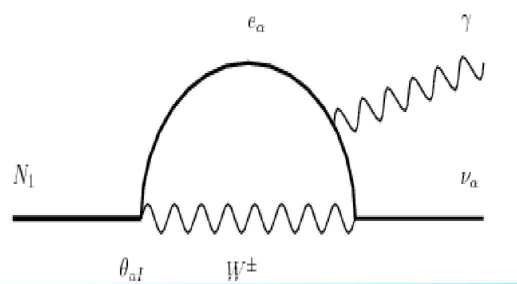
EW seesaw

Higgs inflation

Nothing new below Planck scale

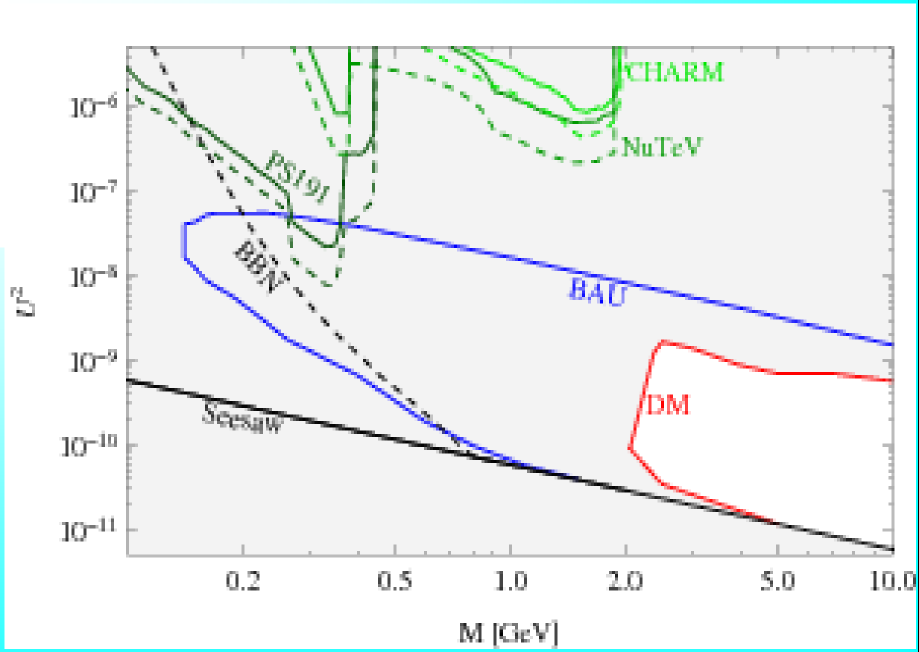
Bounds on parameters of nuMSM





A Boyarsky et al, 1402.4119

The blue point: the best-fit value from M31 (Andromeda galaxy). Thick error bars are ±1σ limits on the flux. Thin error bars correspond to the uncertainty in the DM distribution in the center of M31.



Inverse Seesaw

R.N. Mohapatra
J. Valle

Three additional singlets S which couple with RH neutrinos

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$\mu << M_D$

μ - scale of L violation

⇒ $m_\nu = m_D^T M_D^{-1T} \mu M_D^{-1} m_D$

- pseudo-Dirac neutrino with mass M_D formed by ν^c and S
- one light Majorana neutrino per generation

If $m_D \sim 100$ GeV, $M_D \sim$ few TeV ⇒ $\mu \sim$ keV

Physics of light neutrinos here

- Violation of universality, unitarity in the light sector $\sim 10^{-2}$
- pseudoDirac neurinos at LHC

eV - sub eV scale physics

Very light sector
which may include

- new scalar bosons, majorons, axions,
- new fermions (sterile neutrinos, baryonic nu) ,
- new gauge bosons (e.g. Dark photons)

M. Pospelov

Maybe related to Dark energy, MAVAN

Generate finite neutrino masses, usual Dirac masses can be suppressed by seesaw with $M_R = M_{Pl}$

eV scale Seesaw with RH neutrinos
for sterile anomalies LSND/ MiniBooNE ....

A. De Gouvea

Tests:

5th force searches experiments

Modification of dynamics of neutrino oscillations

Checks of standard oscillation formulas, searches for deviations

Mixing: symmetry or no symmetry?

Tri-bimaximal mixing

P. F. Harrison
D. H. Perkins
W. G. Scott

L. Wolfenstein

$U_{tbm} = U_{23}(\pi/4)\ U_{12}$

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

0.16

0.62

0.78

$\sin^2\theta_{12} = 1/3$

ν_3 is bi-maximally mixed

ν_2 is tri-maximally mixed

Difficult if possible connect to masses
Mixing decouples from masses

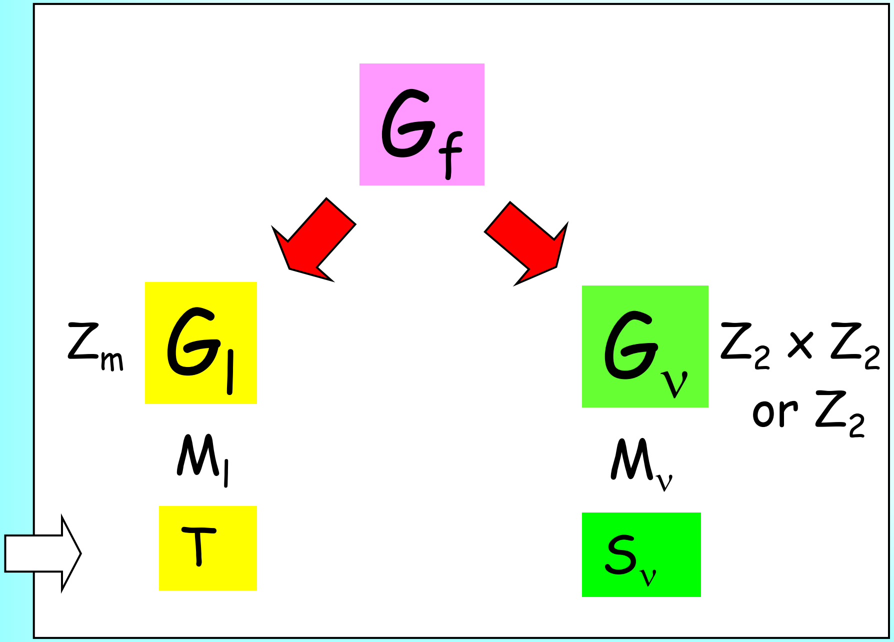
$$\theta_C \sim \sqrt{\frac{m_d}{m_s}}$$

Residual symmetries approach

Acccidental?

Residual symmetries approach

Mixing appears as a result of different ways of the flavor symmetry breaking in the neutrino and charged lepton (Yukawa) sectors.



G_f

Z_m G_l

G_ν $Z_2 \times Z_2$ or Z_2

M_l

M_ν

T

S_ν

Symmetry transformations in mass bases

A_4 S_4 T_7 T'

Flavons

Residual symmetries of the mass matrices

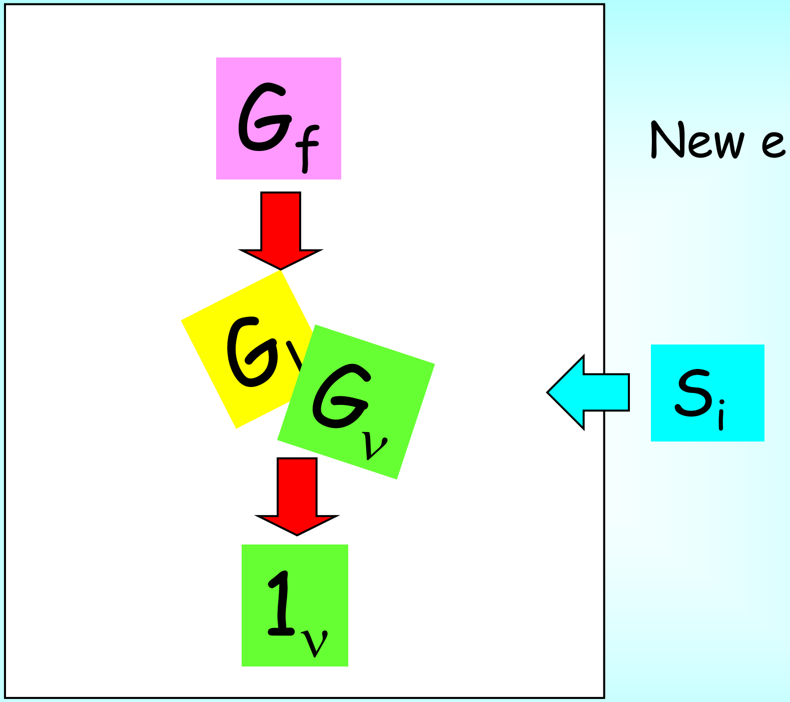
Generic symmetries which do not depend on values of masses to get TBM

$$S_\nu M_\nu S_\nu^T = M_\nu$$

Maximal control over mixing as implied by TBM

Now: broken TBM symmetry

Another realizations of symmetries



New elements

Can mix with
neutrinos only

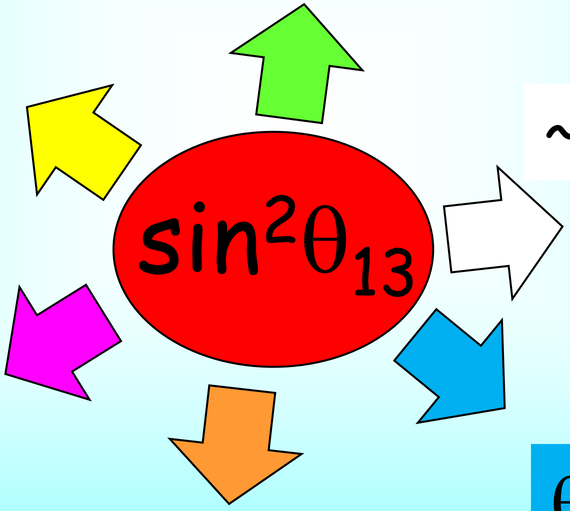
Have Majorana
mass terms

Less symmetry
control over mixing

Mixing originates from
- different nature of the mass terms of the charged leptons (Dirac) and neutrinos (Majorana)
- Mixing from new degrees of freedom (e.g. singlets of SM)

“Degeneracy” of implications

The same 1-3 mixing with completely different implications



$\sin^2\theta_{13}$

``Naturalness''
Absence of
fine tuning of
mass matri

$O(1)\frac{\Delta m_{21}^2}{\Delta m_{32}^2}$

$\theta_{13} = 2^{1/2}(\pi/4 - \theta_{23})$

$\sim \frac{1}{2}\cos^2 2\theta_{23}$

Eby, Frampton, Matsuzaki

universal
$\nu_\mu - \nu_\tau$ -
symmetry
violation

$\sim \frac{1}{4}\sin^2\theta_{12}\sin^2\theta_{23}$

Analogy with
quark mixing
relation

$\sim \frac{1}{2}\sin^2\theta_C$

Quark- Lepton
Complementarity
GUT, family
symmetry

> 0.025

Mixing
anarchy

$\theta_{13} + \theta_{12} = \theta_{23}$

Self-complementarity

$1/3 - |U_{e2}|^2 \sim \sin^2\theta_{13}$

QLC prediction

Quark-Lepton Complementarity

Pheno. level

C. Giunti
M. Tanimoto

$$U_{PMNS} = V_{CKM}^{+} U_{X}$$

H. Minakata, A Y S

From charged leptons or Dirac matrices of charged leptons and neutrinos

Related to mechamism of neutrino mass generation

$U_X = U_{BM},\ U_{TBM}$

General: permutation - to reduce the lepton mixing matrix to the standard form .

$U_{12}(\theta_c)\, U_{23}(\pi/2)$

$\theta_{13} \sim \sqrt{\frac{1}{2}}\ \theta_c$

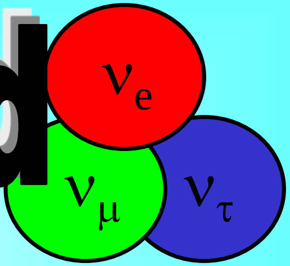
$\sin^2\theta_{13} \sim \frac{1}{2}\sin^2\theta_C$

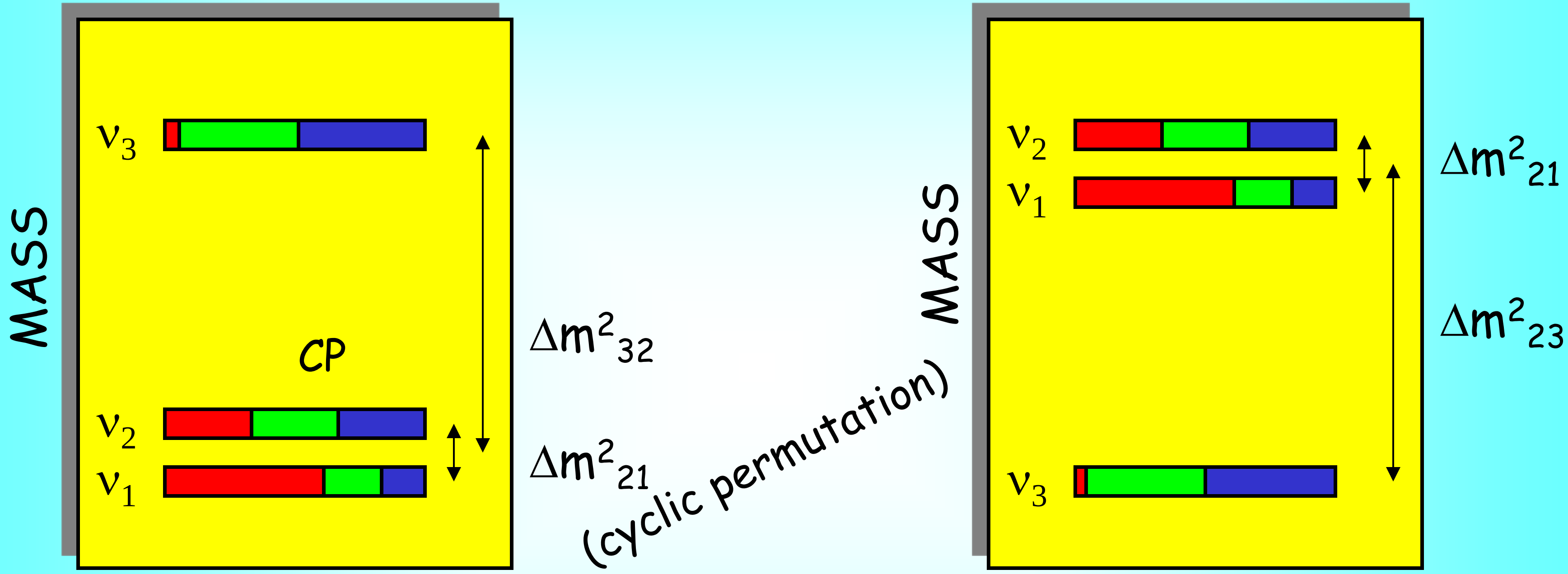
Implies quark –lepton symmetry, unification, GUT?

Should we take this seriously?

Mass hierarchy

Normal vs. inverted





Light flavor (ν_e) in the light states

Weaker mass hierarchy

Light flavor (ν_e) in the heavy states

Mass hierarchy

Further advance

Step to discover CP

important by itself

Theoretical implications

Phenomenology

Supernova neutrinos

Atmospheric neutrinos

bb0n decay

LBL

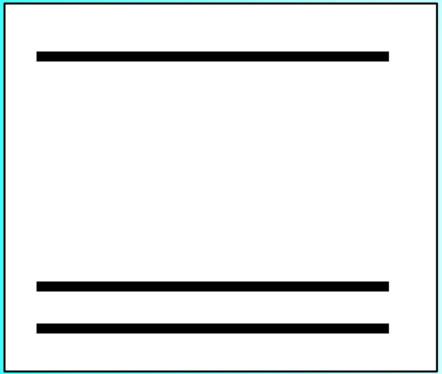
Solar neutrinos

Cosmology

Theoretical implications

generically

Quasi-degenerate
→ symmetry



Normal vs. special

$$\frac{m_2}{m_3} \sim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} = 0.18$$

$$\theta \sim \sqrt{\frac{m_2}{m_3}}$$

Similar to quark spectrum

rescaling

See-saw

Quark-lepton symmetry

Unification

$$\frac{\Delta m}{m} \sim \frac{\Delta m_{21}^2}{2\,\Delta m_{32}^2} = 1.6\ 10^{-2}$$

but 1-2 mixing strongly deviates from maximal

Pseudo-dirac + 1 Majorana

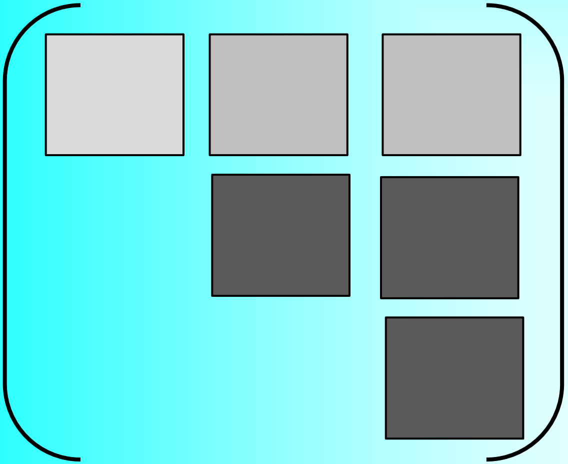
Flavor symmetries

Broken $L_e - L_\mu - L_\tau$ symmetry

Pattern of mass matrices

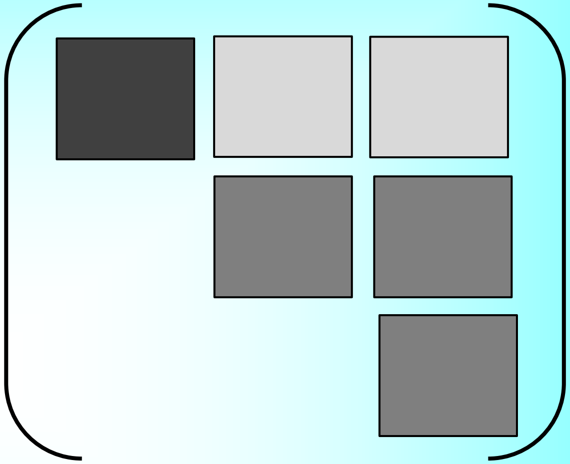
For Majorana
neutrinos

Normal hierarchy

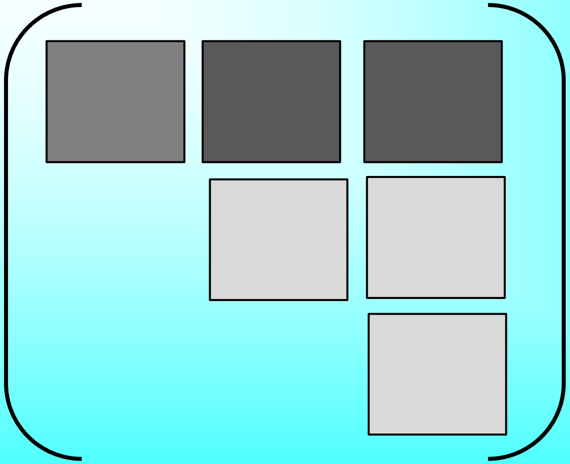


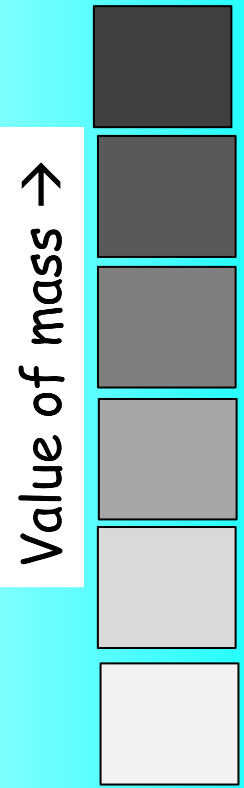
Inverted hierarchy

α = 0



α = π





- different patterns
- different possible
  symmetries

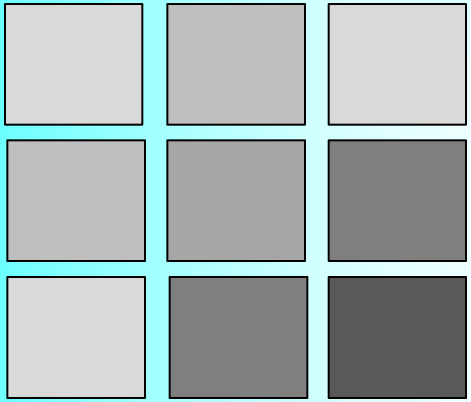
Notice strong dependence
of structure of mass matrix on
the Majorana phases

For two different
Majorana phases

For NH

Flavor alignment

Values of elements gradually decrease from $m_{\tau\tau}$ to m_{ee}



corrections wash out sharp difference of elements of the dominant $\mu\tau$-block and the subdominant e-line

This can originate from power dependence of elements on large expansion parameter $\lambda \sim 0.7 - 0.8$.
Another complementarity: $\lambda = 1 - \theta_C$

Froggatt-Nielsen?

Predicting mass hierarchy

In models with residual (discrete) flavor symmetries mixing does not depend on mass at least in the symmetry limit.
The same mixing pattern can be obtained for NH and IH

The type of hierarchy is fixed by field content (scalar sector), auxiliary symmetries, etc.

Radiative mechanisms have different preferences
those which are related to charged leptons prefer NH

broken $(L_e - L_\mu - L_\tau)$ symmetry

Seesaw type I with quark-lepton analogy (symmetry) leads to NH

Establishing NH would favor the line with similarity with quark sector, high scale seesaw, etc.

If so, one would expect the first quadrant, no eV scale steriles

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

CP-phase

Leptonic CP-phase

phenomenology

Long Baseline Neutrino beams

Atmospheric neutrinos

Cosmic neutrinos

Theoretical Implications
Probe of the underlying Physics,
enters various test equalities

insensitive to CPV in standard 3nu scenario

Solar neutrinos

Supernova neutrinos

0nbb- decay

Cosmology

Leptogenesis

Predicting CP-phase

Special properties of mass matrices
of neutrinos and charged leptons

Textures, symmetries
of mass matrices →
particular values of $\delta_{\ddagger}$

ν_μ - ν_τ reflection
symmetry

Maximal CPV

Explicit models

with discrete symmetries
of Lagrangian

with radiative ν mass
generation

GUT's

Relations with mixing angles as
consequence of symmetries

There is no convincing model/explanation
of the value of phase in quark sector

Can we predict the phase in lepton sector where situation is more complicated
due to additional elements producing smallness of neutrino mass?

Relating to mixing

In the residual symmetry approach

For column of the mixing matrix:

$$|U_{\beta i}|^2 = |U_{\gamma i}|^2$$

$$|U_{\alpha i}|^2 = \frac{1 + a}{4 \sin^2 (\pi k/m)}$$

$k_\alpha = 0$

k, m, p integers which determine symmetry group

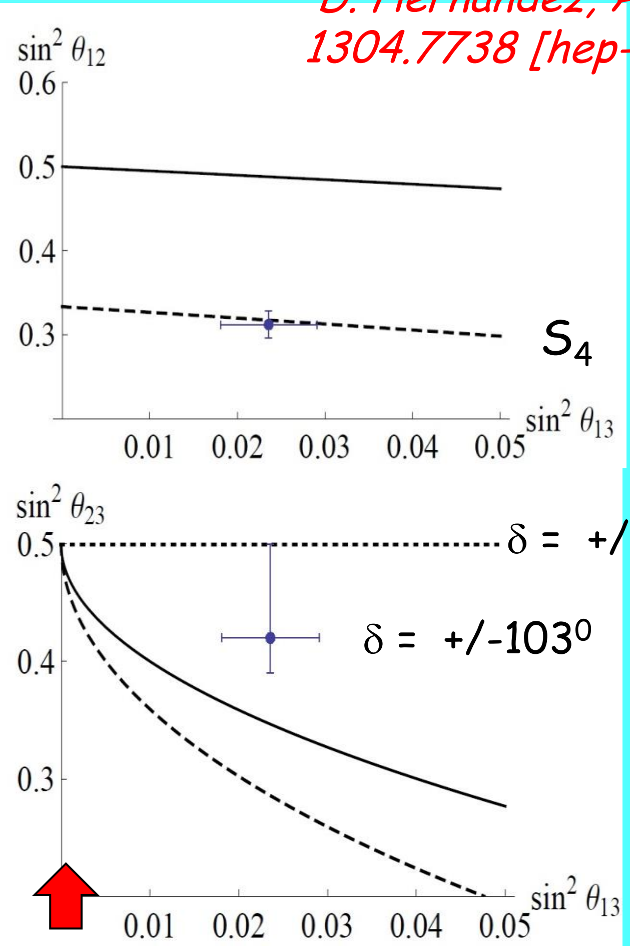
From ν_μ - ν_τ^c reflection symmetry of the mass matrix

$\sin \theta_{13} \cos \delta = 0$

⇒ δ = +/- 90^0

W. Grimus , L. Lavoura,
Y. Farzan, A.S.

D. Hernandez, A Y S.
1304.7738 [hep-ph]



S_4

δ = +/- 90^0

δ = +/-103^0

TBM

Relating to mass degeneracy

Symmetry which left mass matrices invariant for specific mass spectra:

Partially degenerate spectrum $m_1 = m_2\ ,\ m_3$

D. Hernandez, A.S.

Transformation matrix $S_\nu = O_2$ $G_\nu = SO(2) \times Z_2$

Relation: $$\boxed{\sin^2 2\theta_{23} = +/- \sin\delta = \cos\kappa = \frac{m_1}{m_2} = 1}$$

maximal

$+/- \pi/2$

Majorana phase

1-2 mixing is undefined

Small corrections to mass matrix lead to 1-2 mass splitting and 1-2 mixing

Comparing the phases

If δ_l is known we can at least compare it with δ_q

The closest quark-lepton connection

GUT or/and common flavor symmetry
Seesaw type-I
Similarity of the Dirac mass matrices $m_D^{\nu} \sim m_D^{q}$

B. Dasgupta, A.S.

In general

$$U_{PMNS} = U_L U_X$$

$U_L \sim V_{CKM}^*$

Has similar hierarchical structure determined (as in Wolfenstein parametrization) by powers of

$\lambda = \sin \theta_C$

As in QLC

Related to (any) mechanism that explains smallness of neutrino mass

Should be fixed to reproduce correct Lepton mixing angles

$V_{CKM} \sim I \Rightarrow U_X \sim U_{TBM}$

Leptonic CP from CKM

If $U_L \sim V_{CKM}^* \, (\delta_q)$ is the only source of CP violation --

as in the quark sector, U_X is real

$$s_{13} \sin \delta_{CP} = (-c_{23}) \, s_{13}^q \, \sin \delta_q$$

$$\sin \delta_{CP} \sim \lambda^3 / s_{13} \sim \lambda^2$$

$$\sin \delta_{CP} \sim 0.046$$

$\delta_q = 1.2$ +/- 0.08 rad

$\delta_{CP} \sim - \delta$ or $\delta_{CP} \sim \pi + \delta$ where $\delta = (s_{13}^q / s_{13}) \, c_{23} \sin \delta_q$

If other value of phase is observed
→ contributions beyond CKM
(e.g. from the RH sector) or another framework

In general

neglecting terms of the order ~ λ^3

$\sin \delta_{CP} = s_{13}^{-1} [\sin(\alpha_\mu + \delta_X) V_{ud} |X_{e3}| - \sin \alpha_e \, |V_{cd}| X_{\mu 3}]$

here α_μ , δ_X and α_e are parameters of the RH sector

Some special values of δ_{CP} can be obtained under certain assumptions

if $X_{e3} = 0$ $\sin \delta_{CP} \sim - \sin \alpha_e$

and if $\alpha_e = \pi/2$ $\delta_{CP} \sim 3\pi/2$

One can find structure of the RH sector which lead to these conditions

In the Seesaw type I

B Dasgupta A.S

U_x is the matrix diagonalizes

$$M_X = - m_D^{diag} U_R^+ (M_R)^{-1} U_R^* m_D^{diag}$$

Here $m_D = U_L (m_D^{diag}) U_R^+$

In contrast to quarks (Dirac fermions) for Majorana neutrinos the RH rotation that diagonalizes m_D becomes relevant and contributes to PMNS

CPV from U_R

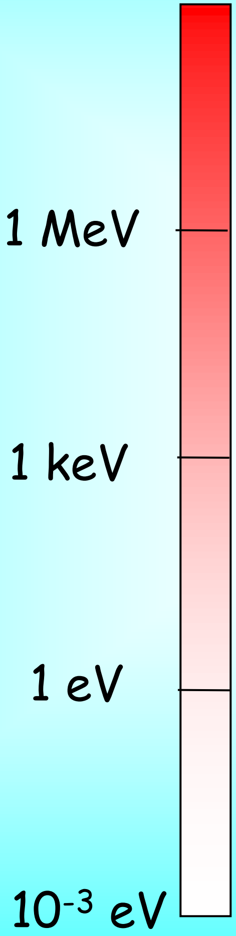
Minimal extension is the L- R symmetry:

$U_R = U_L \sim V_{CKM}^*$ and no CPV in M_R

Seesaw can enhance this small CPV effect so that resulting phase in PMNS is large

Sterile neutrinos

New neutrino states ν_S



	mixing θ_{aS}^2	$\delta m \sim \theta_{aS}^2\ m_S$
■ 5 - 10 keV	$2\ 10^{-11}$	$(1 - 2)\ 10^{-8}$ eV
■ 0.5 - 2 eV	0.02	0.02 eV
■ $(2 - 4)\ 10^{-3}$ eV	10^{-3}	10^{-6} eV

- Warm Dark matter
- Pulsar kick

- LSND, MB
- Reactor Ga anomalies
- Extra radiation

- Solar neutrinos
- Extra radiation in the Universe

Compare with large elements of the mass matrix 0.02 eV

Effect of sterile neutrinos

on the 3ν structure

$$m_\nu = m_a + \delta m$$

Original active mass matrix e.g. from see-saw

$m_a = 0.025$ eV

Induced mass matrix due to mixing with nu sterile

For keV $\delta m \ll m_a$

Decouples from generation of the light neutrino masses argument that this is not RH neutrino but has some other origin

For eV $\delta m \sim m_a$

Not a small perturbation

δm can change structure (symmetries) of the original mass matrix completely

be origin of difference of U_{PMNS} and V_{CKM}

For meV $\delta m \ll m_a$

can be be considered as very small perturbation of the 3ν system

Towards the underlying physics

Theoretical relevance and urgency

Sterile Neutrinos

LSND 1 eV steriles , controversial, not favored… still if exist change theory substantially – not a small perturbation, 3 Dirac CP phases etc

Bound on mixing should be $\theta_{aS}^2 < 10^{-3}$

urgent

Other steriles (7 kev , meV) - small/negligible perturbation of the 3ν theory from other sectors

urgent

Mass Hierarchy

Crucial for SN neutrinos and $\beta\beta\, 0\nu$ decay, important for cosmology and atmospheric neutrinos

Knowledge of H facilitates determination of δ

Will exclude some specific models, will favor certain approach to understand neutrino mass:

NH: q-l similarity, unification, high scale seesaw,
But also some radiative mechanisms

IH: unusual, low (EW TeV) scale mechanisms,
also – radiative, implies symmetry

Theoretical relevance and urgency

CP violation

δ_{CP} enters various test equalities, sum rules, etc., which are probes of underlying physics in certain frameworks and under certain assumptions

Specific values like 0, π , $\pi/2$ may have more straightforward implications (still not unique)

+/- $\pi/2$ can be related (by symmetry) with maximal 2-3 mixing, quasi-degeneracy of mass states ...

Comparison with quark phase will be interesting
Even in unification approach they can be very different.
Substantial deviation of δ_{CP} from 0, π ,
will testify for new sources of CP in lepton sector

Majorana vs. Dirac

Majorana – favored, seesaw , unification line

Theoretical relevance and urgency

2-3 Quadrant

θ_{23} = 45° is special. More important in first place – value of deviation from 45° - that may be
Even more substantial probe of the underlying physics.

For NH: θ_{23} < 45° would be in favor of similarity and unification, otherwise strange

For IH both θ_{23} < 45° and θ_{23} > 45° are possible

Absolute mass scale

Exclude (discover) completely degenerate spectrum

urgent

Progress in understanding the underlying physics may come from Non-neutrino experiments

LHC,
Dark matter

Backup slides

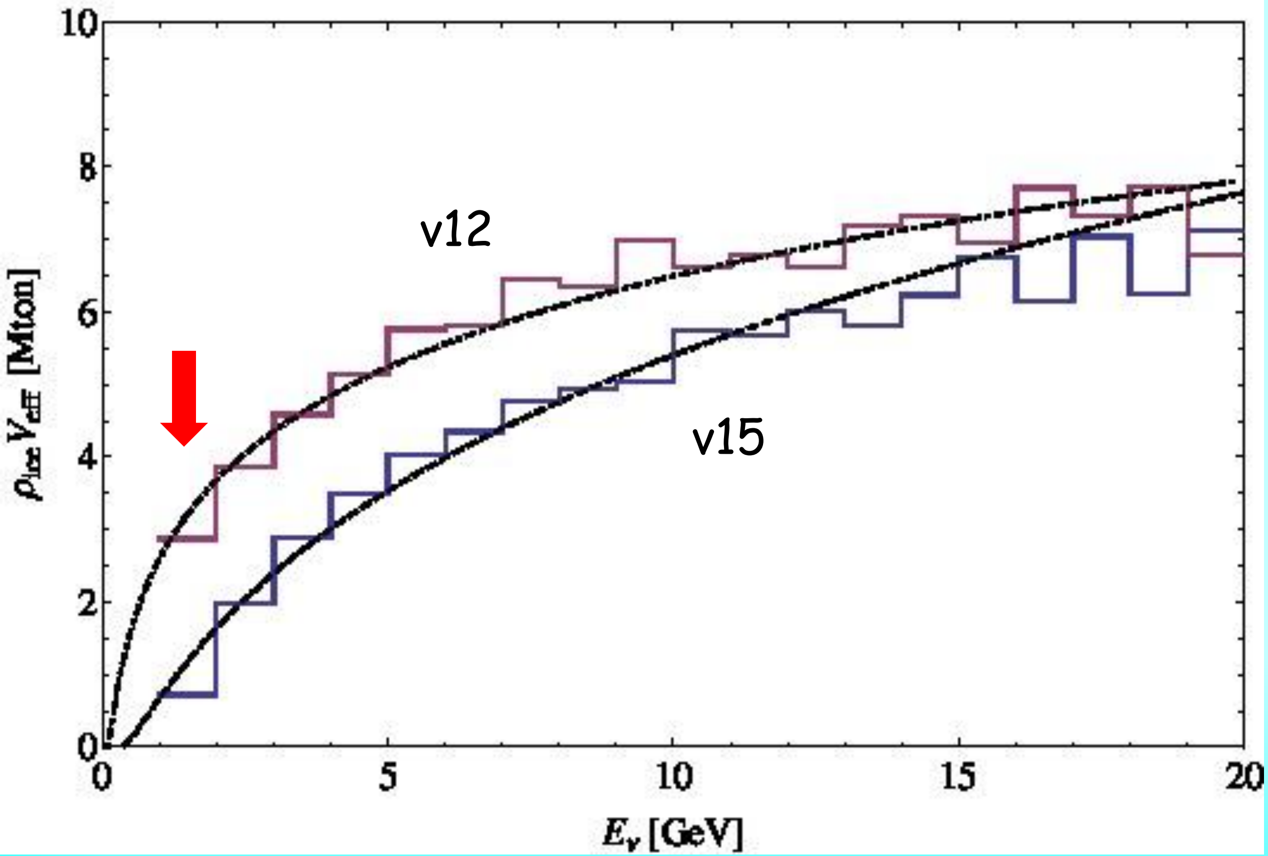
Super-PINGU CP phase with atmospheric neutrinos

S. Razzaque, A.Y.S.
arXiv: 1406.1407 hep-ph

Super-PINGU

S. Razzaque A Y S

Effective volume



Str. DOM's

v15: 40, 60

v12: 126, 60

MICA: 60, 120

MICA: 220, 140

64 3" PMT
per module

Lagre volume at small energies

Distinguishability and CP-difference

Quick estimator (metric) of discovery potential

E. Kh. Akhmedov,
S. Razzaque, A. Y. S.
arXiv: 1205.7071

For each ij- bin
relative CP-difference

$$S_{ij} = \frac{N_{ij}^{\delta} - N_{ij}^{\delta = 0}}{\sqrt{N_{ij}^{\delta = 0}}}$$

no fluctuations

If is true value → N_{ij}^{δ} corresponds to ``true" value of events
→ $N_{ij}^{\delta = 0}$ ``measured" number of events

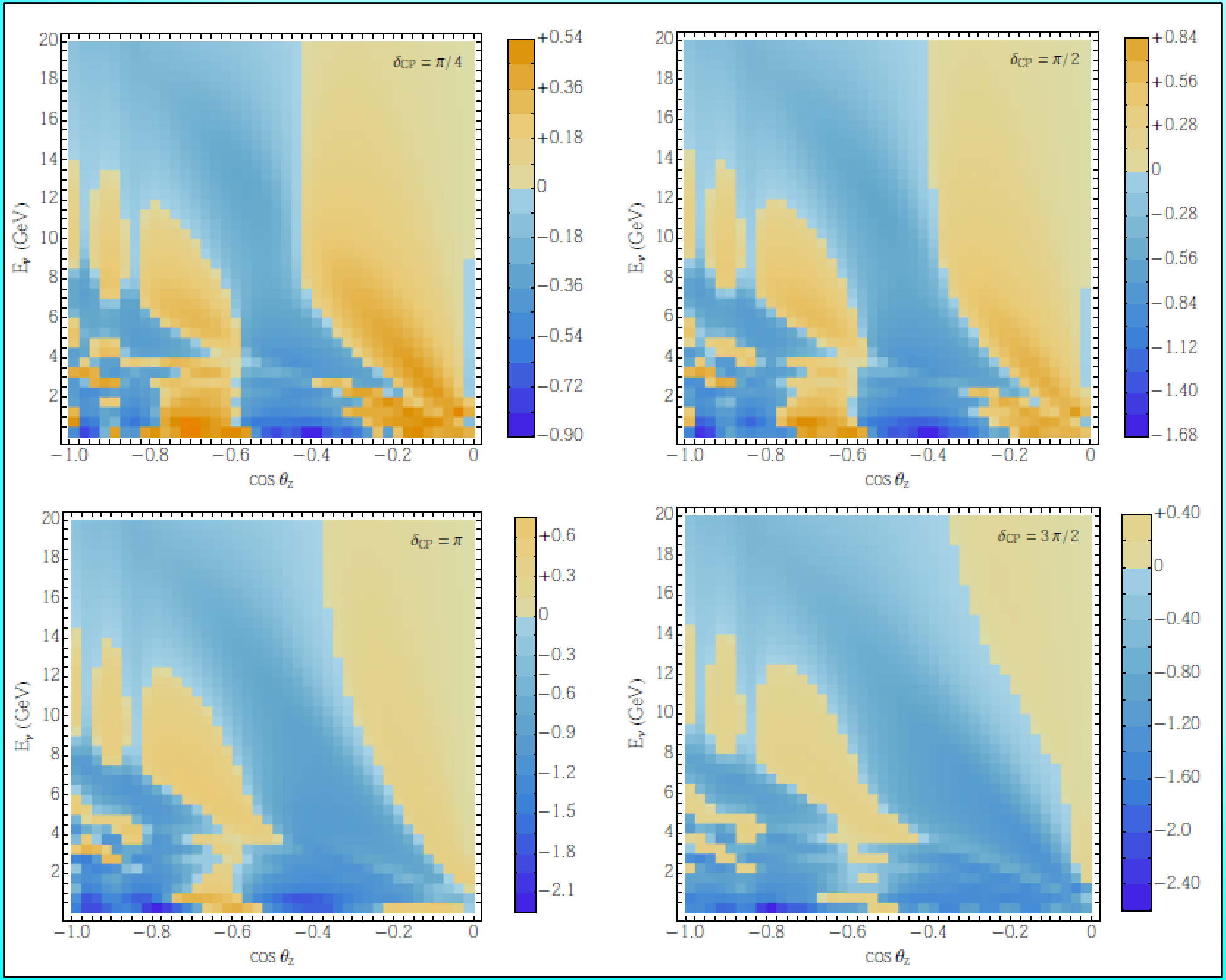
$|S_{ij}|$ - distinguishability of different values of CP-phase

Total distinguishability

$$S^{tot} = [\Sigma_{ij} S_{ij}^{2}]^{1/2}$$

Relative CP differences

tracks

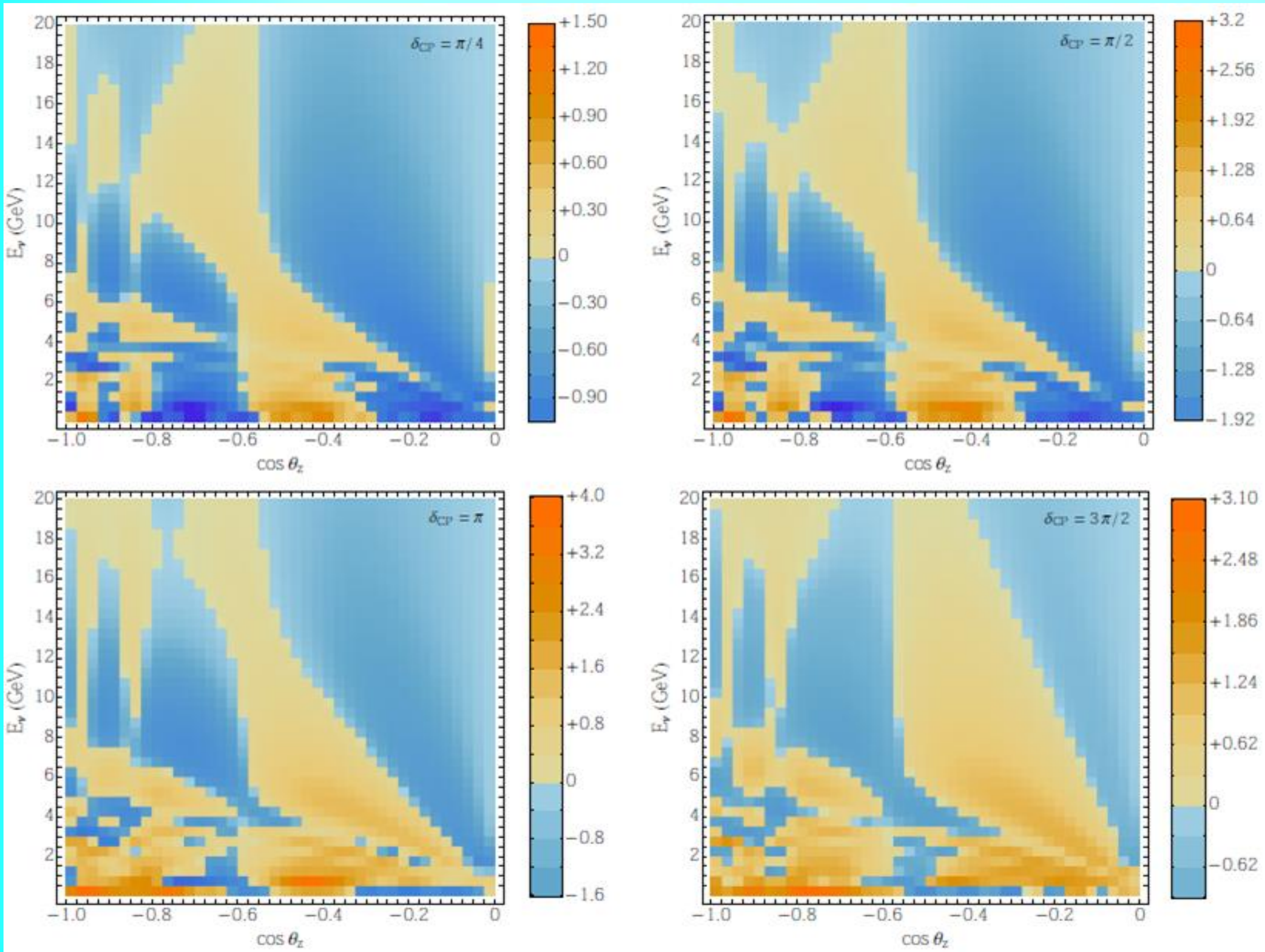


S-distributions for different values of δ

Normal mass hierarchy

Relative CP differences

cascades

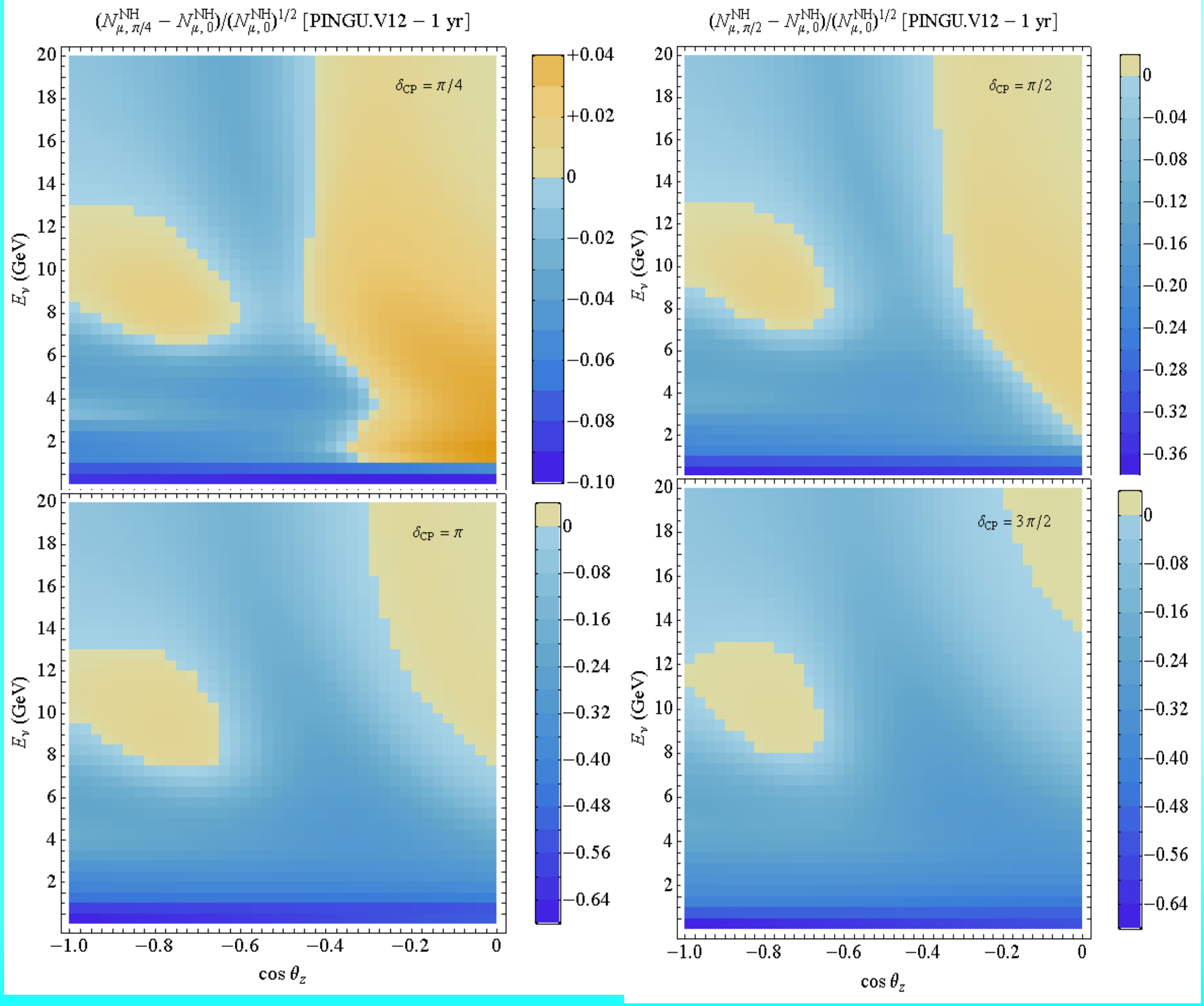


S-distributions for different values of δ

Smearing over E and direction

tracks

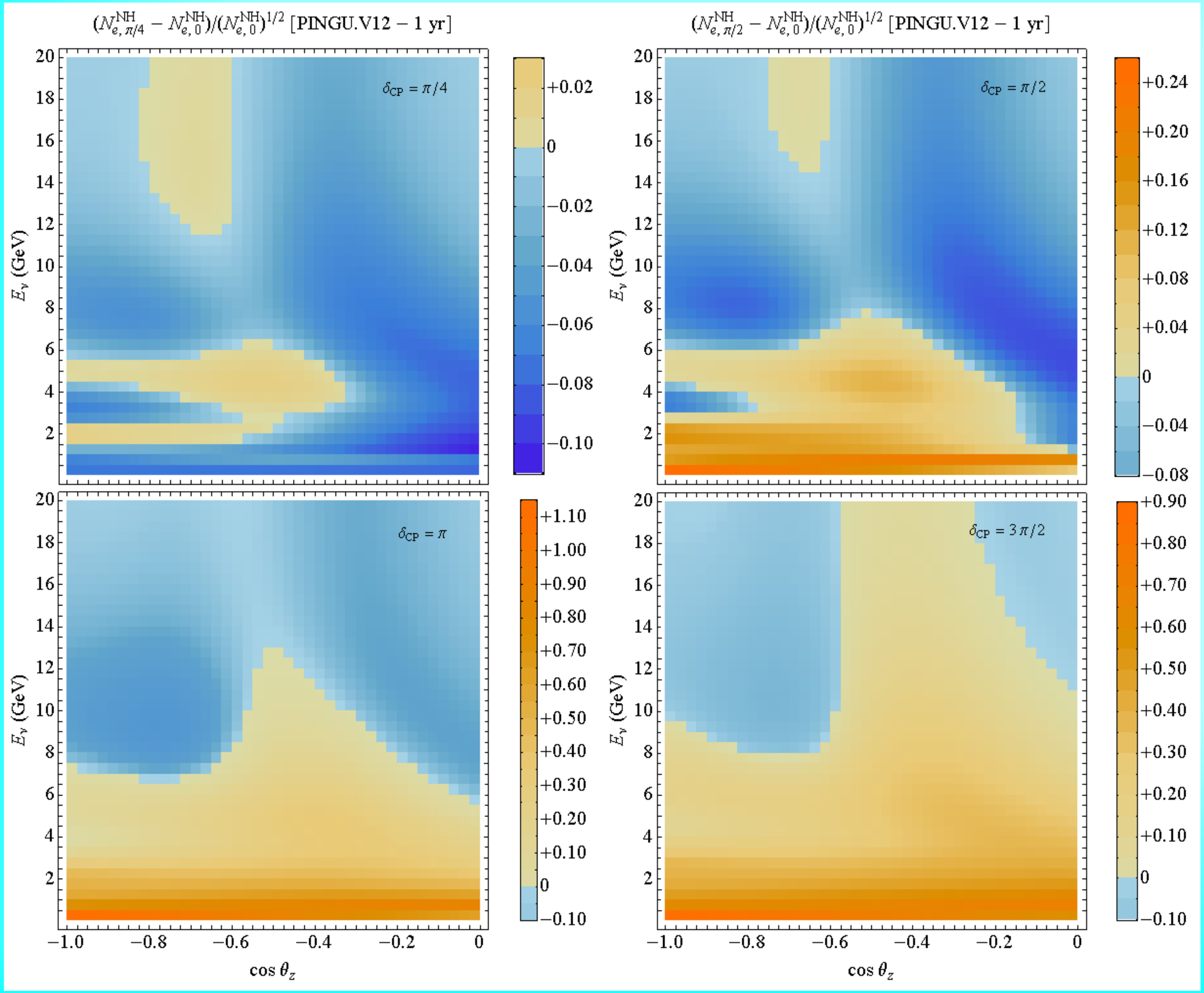
Super PINGU 1 year



Smearing over E and direction

cascades

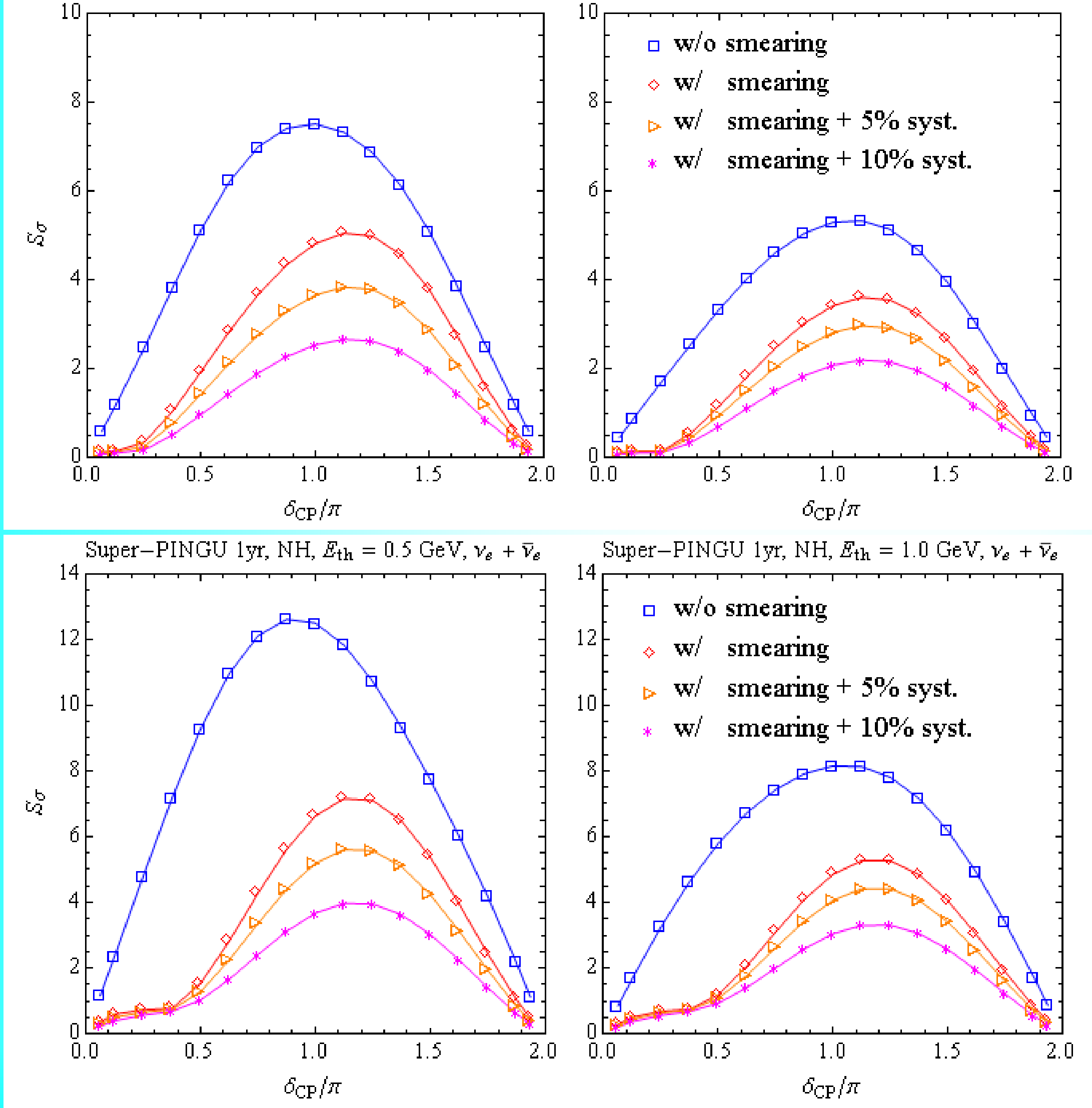
Super PINGU 1 year



Normal mass hierarchy

Solar magic line and interference phase lines determine structure

Total distinguishability



δ from 0

Results and further improvements

Super-PINGU with 0.5 GeV threshold

After 4 years of operation with 5% uncorrelated error

Distinguishability

$\pi/2$ from 0 $S_{tot} = 4 - 5$ (depending on contribution of cascades)

π from 0 $S_{tot} = 6 - 7$

Lowering threshold 1.0 → 0.5 GeV 50 % improvement

Further improvements:

Lowering threshold 0.5 → 0.2 GeV 20 – 30 % improvement

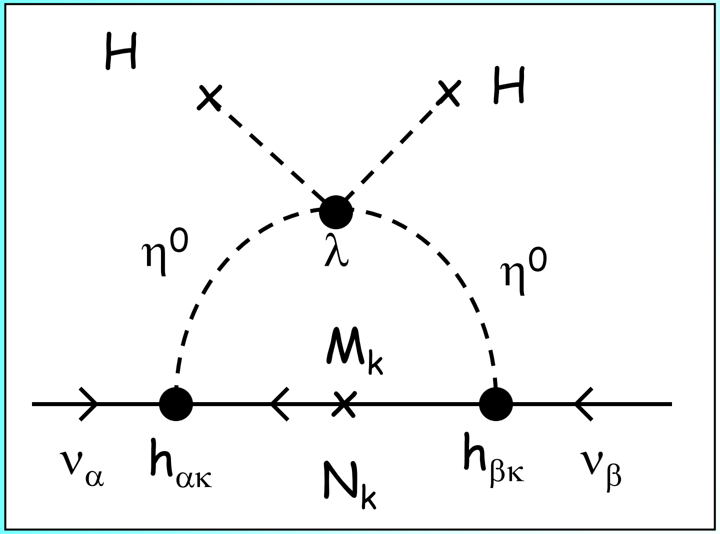
Partial separation of the neutrino and antineutrino events

Larger effective volume at ~ 1 GeV denser DOMs array

Better flavor identification

Increase of exposure time

One loop mechanism



E. Ma, hep-ph 0601225

No RH neutrinos
new higgs doblet (η^+ , η^0)
and fermionic singlets N_k

odd under discrete symmetry Z_2

SM particles are Z_2 even

η^0 has zero VEV

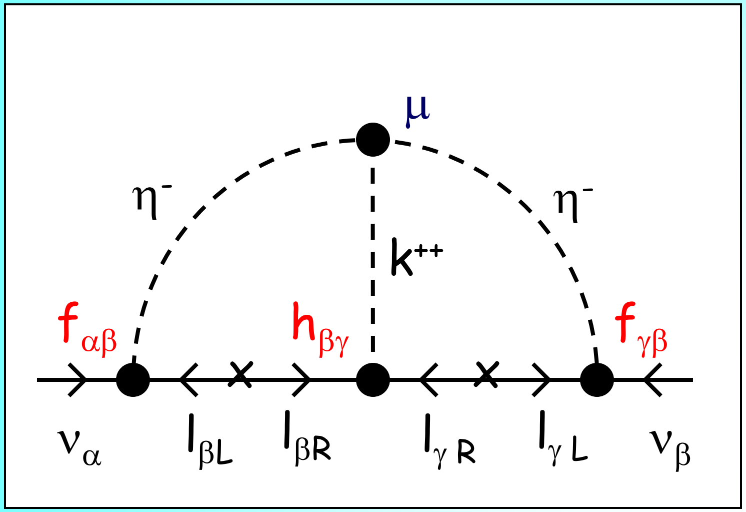
If H gives mass to
charged leptons leptons

If η^0 or is exact
η^0 or lightest N_k are stable and
can be Dark Matter particles

Neutrino mass – DM connection

Zee-Babu mechanism

x



K.S. Babu,
C. Macesanu

No RH neutrinos
new scalar singlets η^- and k^{++}

$$m_\nu \sim 8\, \mu\, f\, m_l\, h\, m_l\, f\, I$$

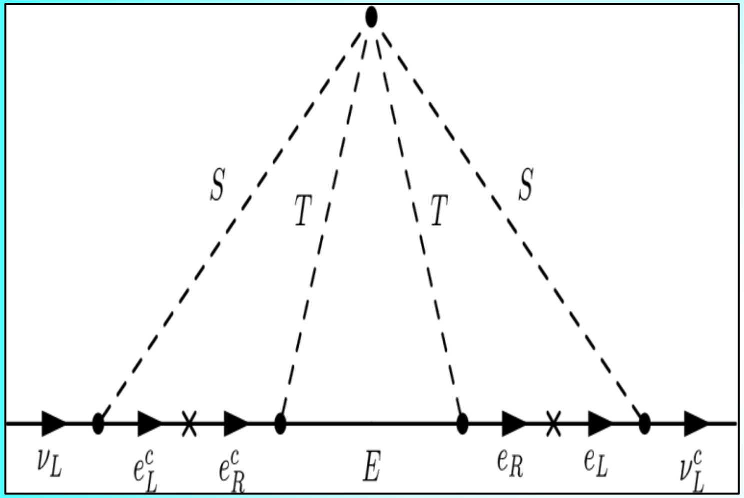
$m_l = \text{diag}\,(m_e, m_\mu, m_\tau)$

f and h are matrices of the couplings in the flavor basis

Features:
- the lightest neutrino mass is zero
- neutrino data require inverted hierarchy of couplings h
- f, h ~ 0.1

Testable:
- new charged bosons
- decays $\mu \to \gamma\, e$, $\tau \to 3\mu$ within reach of the forthcoming experiments

Three loops



A. Ahriche et al,
1404.2696 hep-ph

Z_2 symmetry

S~(1,1,2) and *T*~(1,3,2) are scalars
E~(1,3,0) is a fermionic triplet.
There are three distinct diagrams with the sets
$\{T+, E^0, T-\}$, $\{T^+, (E+)c, T0\}$ and $\{T0, E+, T--\}$
propagating in the inner loop.

Low scale L-R symmetry

$SU(2)_L \times SU(2)_R \times U(1)$

low scale restoration of the L-R symmetry

$M(W_R) \sim$ few TeV

$M(N_R) \sim$ 0.5 - few TeV

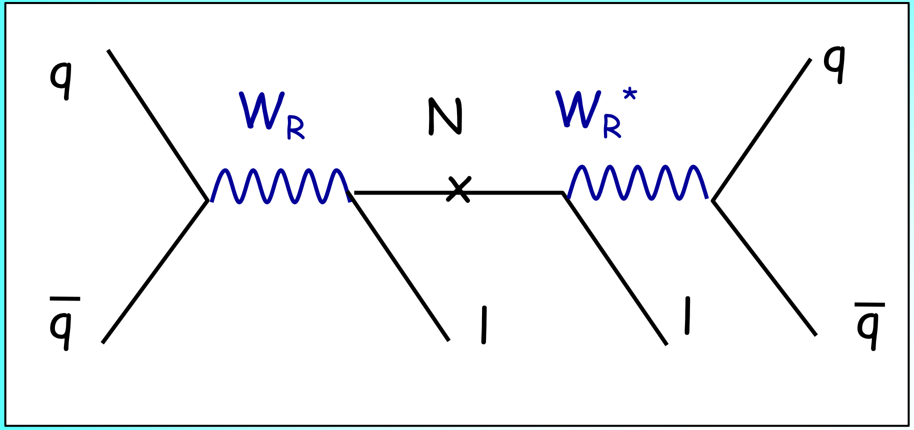
Several contributions to light neutrino mass

See-saw type I with small Yukawa couplings

Higgs Triplet mechanism

Low scale LR symmetry

Senjanovic
Keung



$\beta\beta0\nu$

Type-I

$l\,l\,j\,j$

bi-leptons with the same-sign

No missing energy

Peaks at

$$s\,(jj\,l) = m_N^2$$

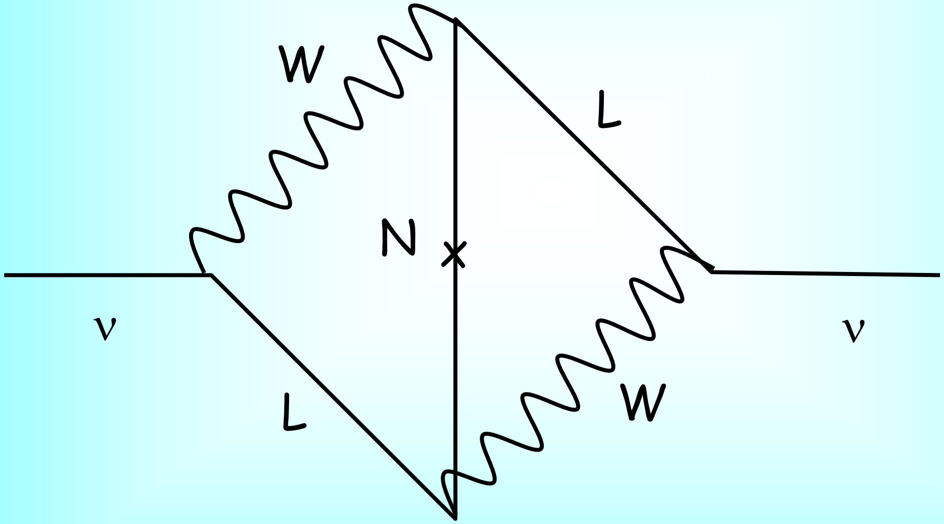
$$s\,(jj\,ll) = m_W^2$$

Also opposite sign leptons

$M\,(W_R) > M\,(N_R)$ -
resonance production of W_R

Two loop mechanism

K S Babu, E Ma



If usual neutrinos mix with heavy Majorana lepton N

4th generation of fermions → main contribution

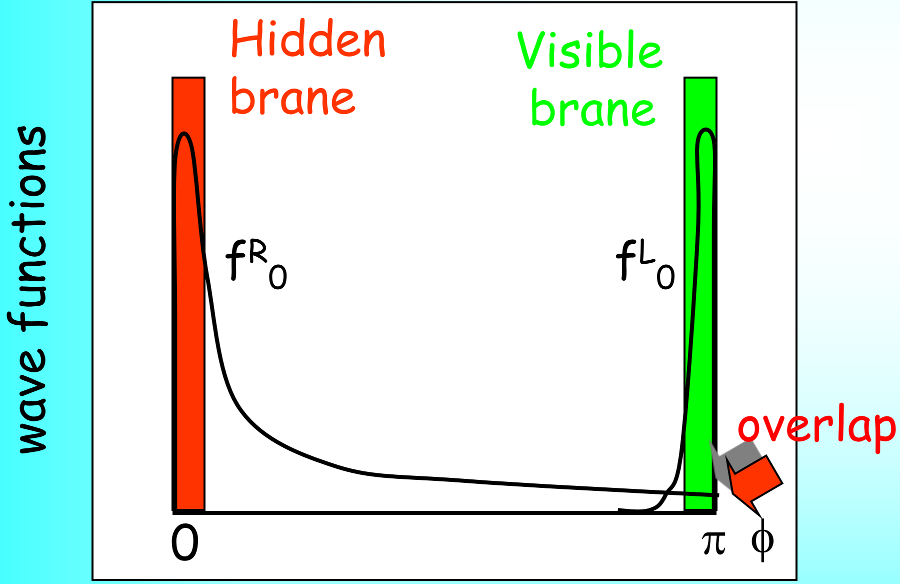
Overlap in extra dimensions

Right handed components are localized differently in extra dimensions

small Dirac masses due to overlap suppression:

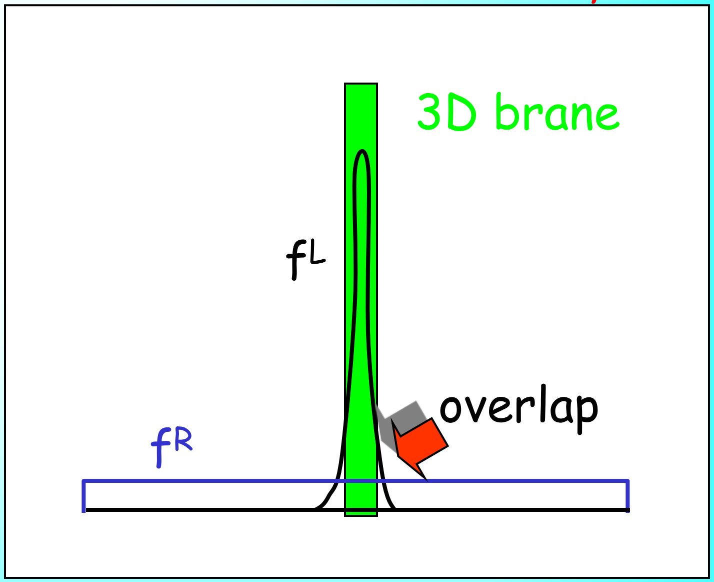
Warped extra D

Grossman
Neubert



Flat extra D

Arkani-Hamed,
Dvali, Dimopoulos

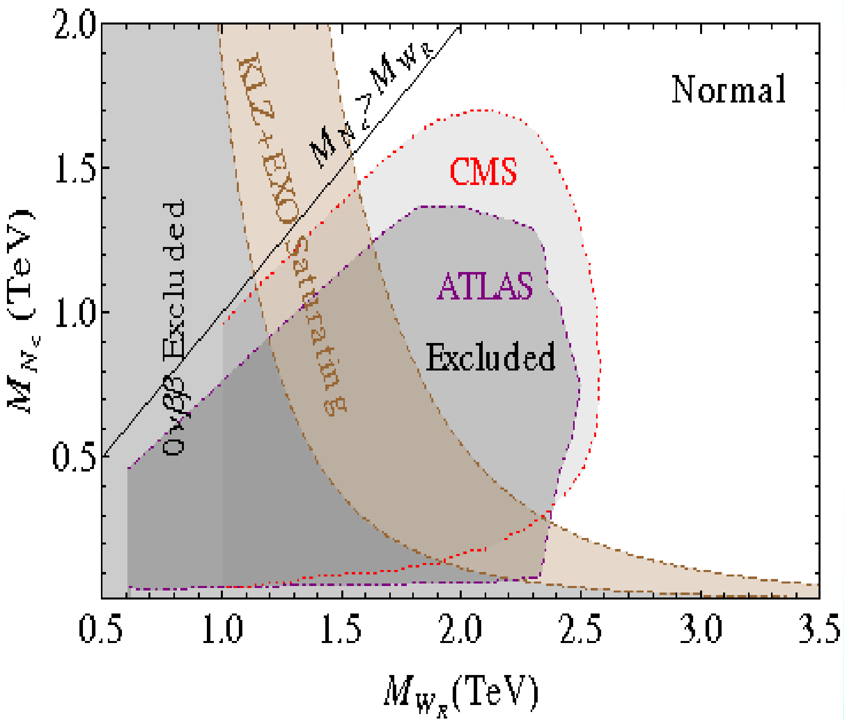


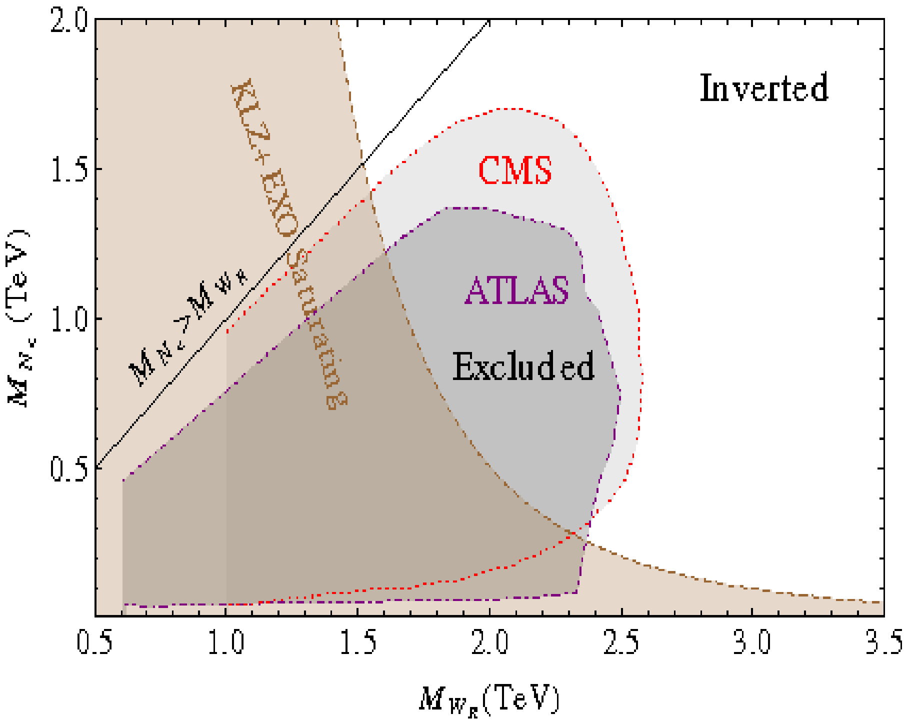
$$m\, \varepsilon\, \overline{f^L}\, f^R \;+\; h.\,c.$$

🡅 amount of overlap in extra D

Bounds on L-R model

P.S Bhupal Dev, et al,
1305.0056 [hep-ph]





Many RH neutrinos

B. Feldstein, W. Klemm
arXiv: 1111.6690

Origins: KK states of extra dimensions

Statistical distribution of Yukawa couplings y

$$\boxed{\rho(y) \sim \frac{1}{y^{1+\delta}}}$$

Y = 10^{-6} - 1

reasonable fit
for charged leptons

M = 10^{14} - 10^{16} GeV

Linear scale

Seesaw type I

Random simulations, random phases

Anarchical spectrum

Bi-maximal mixing

As zero order structure

$U_{bm} = U_{23}^m U_{12}^m$

Two maximal rotations

F. Vissani

V. Barger et al

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

- maximal 2-3 mixing
- zero 1-3 mixing
- maximal 1-2 mixing
- no CP-violation

Scenario:

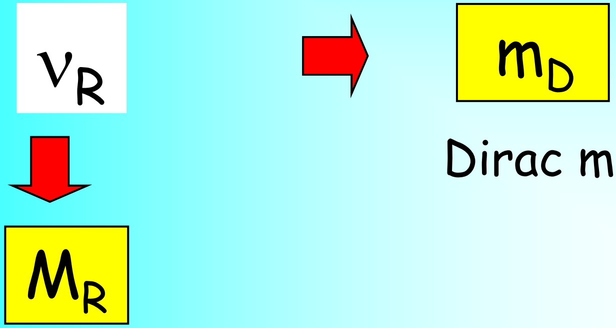
In the lowest approximation:

$V_{quarks} = I, \; U_{leptons} = V_{bm}$
$m_1 = m_2 = 0$

Corrections generate:

- mass splitting
- CKM and
- deviation from bi-maximal

RH neutrinos and see-saw



ν_R → m_D

Dirac mass

↓

M_R

Majorana mass

- Small Yukawa coupling
- New Higgs with small VEV
- New fermions, Multi singlet mechanism + symmetry

Realize see-saw

$$m_\nu = - m_D^T M_R^{-1} m_D$$

Suppression of the Dirac mass

Generation of small finite mass

No new symmetry is needed

Seesaw – only suppression, e.g. if the RH masses are at Planck scale.
The dominant contribution - from another mechanism

Can we really predict the phase?

There is no convincing model/explanation of the value of phase in quark sector

Can we predict the phase in lepton sector where situation is more complicated due to additional elements producing smallness of neutrino mass?

At least compare with the phase in quark sector

- Can the phases be equal? $\sin \delta_l \sim \sin \delta_q$
- Connected in some way?
- Can phases be unrelated to masses or even mixing?
- Take special value like $\pi/2$?

Recall Global fit: $\delta \sim 1.39\,\pi$

Parametrization

and notations

$U_{PMNS}^{std} = U_{23} I_{\delta} U_{13} I_{-\delta} U_{12}$

In general

$U_{PMNS} = D(\phi)\, U_{PMNS}^{std}\, D(\beta)$

$D(\beta) = \mathrm{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$

Majorana phases

D - diagonal matrices with phase factors

Parametrizing U_L and U_X in similar way we have

$U_{PMNS}^{std} = D(\gamma)\, U_L^{std}(\delta_q)\, D(\alpha)\, U_X^{std}(\delta_x)\, D(\eta)$

$D(\alpha) = \mathrm{diag}(e^{i\alpha_e}, e^{i\alpha_\mu}, e^{i\alpha_\tau})$ phases from the RH sector

γ and η should be fixed by standard parametrization conditions

$\mathrm{Arg}\,\{U_{e1}\} = \mathrm{Arg}\,\{U_{e2}\} = \mathrm{Arg}\,\{U_{\mu 3}\} = \mathrm{Arg}\,\{U_{\tau 3}\} = 0$

$|U_{e1}|\, \mathrm{Im}\, U_{\mu 2} = |U_{e2}|\, \mathrm{Im}\, U_{\mu 1}$

Symmetry group relation

Transformations should be taken in the basis where CC are diagonal

$(S_{iU}\ T)^{p} = I$ $\qquad$ $(S_{iU}\ T)^{p} = (W_{iU})^{p} = I$

D. Hernandez, A.S.
1204.0445

In flavor basis

Explicitly

$$(U_{PMNS}\, S_i\, U_{PMNS}^{+}\, T)^{p} = I$$

The main relation: connects the mixing matrix and generating elements of the group in the mass basis

Equivalent to

$$Tr\,(U_{PMNS}\, S_i\, U_{PMNS}^{+}\, T) = a$$

$$a = \Sigma_j \lambda_j$$

$$\lambda_j^{p} = 1 \qquad j = 1,2,3$$

$Tr\,(W_{iU}) = a$

λ_j - three eigenvalues of W_{iU}

Quark-lepton universality?

$V_{ub} = \frac{1}{2} V_{us} V_{cb}$

$\sin\theta_{13} \sim \frac{1}{2} \sin\theta_{12} \sin\theta_{23}$

The same coupling strength between generations

Similar Ansatz for structure of mass matrices

Fritzsch Anzatz similar
to quark sector, RH neutrinos
with equal masses

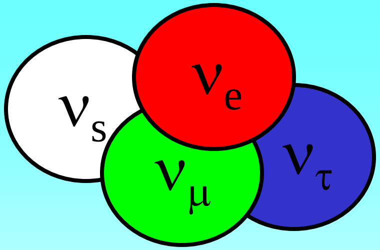
→

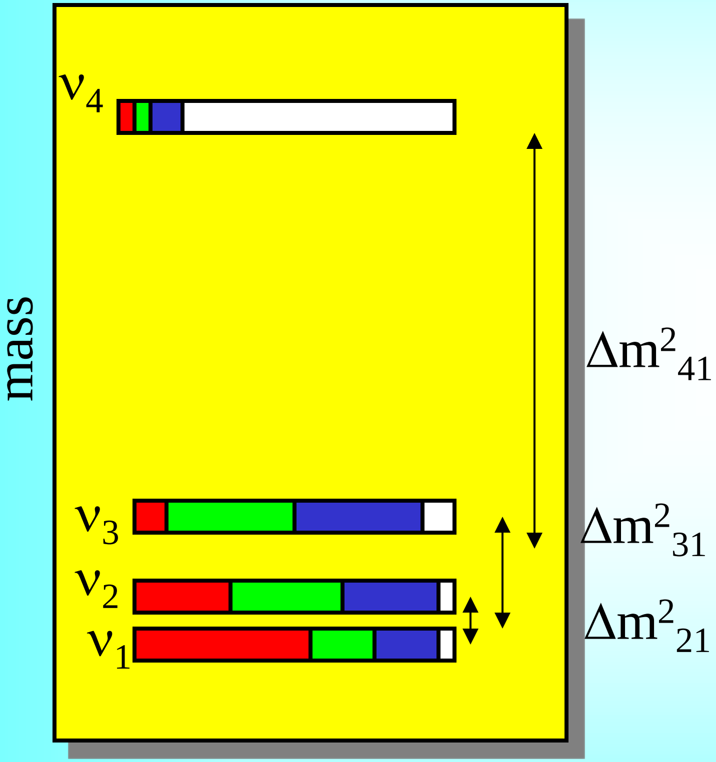
Normal mass hierarhy,
Right value of 13 mixing

Relations between masses and mixing

Flavor ordering in mass matrix

(3 + 1) scheme





LSND/MiniBooNE: vacuum oscillations

$P \sim 4|U_{e4}|^2|U_{\mu 4}|^2$

restricted by short baseline exp.
BUGEY, CHOOZ, CDHS, NOMAD

For reactor and source experiments

$P \sim 4|U_{e4}|^2(1 - |U_{e4}|^2)$

With new reactor data:

$\Delta m_{41}^2 = 1.78\ \mathrm{eV}^2$ ($0.89\ \mathrm{eV}^2$)

$U_{e4} = 0.15$ $U_{\mu 4} = 0.23$

- additional radiation in the universe
- bound from LSS?

Neutrinos & Dark Sector

of the Universe

indirect
connection

Mechanism of
neutrino mass
generation

Z_2

Light active
neutrinos

HDM

Direct
connection

new particles

right handed
neutrinos

play the role of DM

Mixing pattern

New
neutrino
states

Flavor symmetries

ensure stability
of DM particles

Neutrinos
and gravitino
as DM

Warm DM

Dark
Energy

W. Buchmueller

Everything from one

SM and Weinberg operator

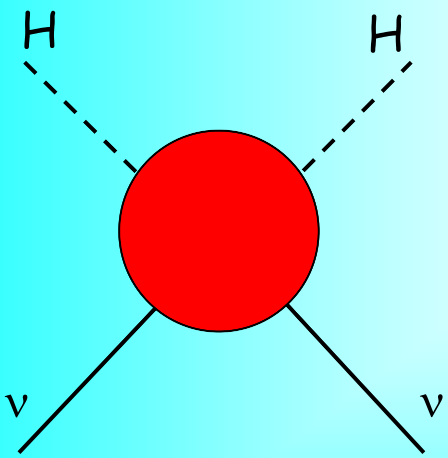
If no new particles at the EW scale, after decoupling of heavy degrees of freedom → set of non-renormalizable operators

S. Weinberg

$$\boxed{\frac{1}{\Lambda} L\,L\,H\,H}$$

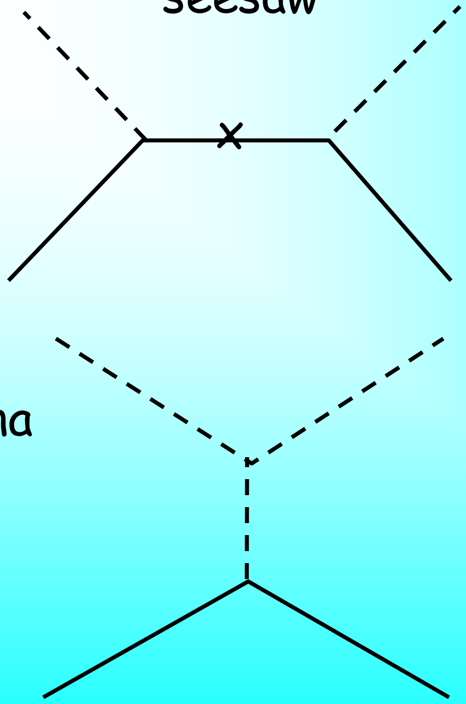
scale of new physics

non – universality,
non- unitarity of
the mixing matrix



Generate Majorana
neutrino

seesaw

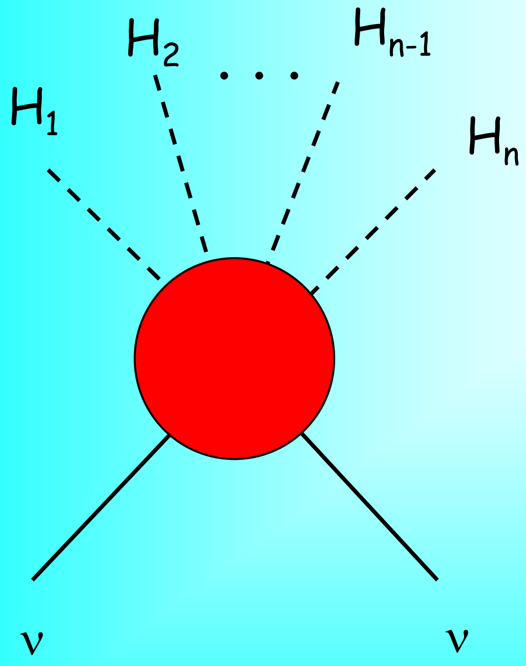


The end of theory ?
Can we say more?

Higher dimension operator

D=5 operator can be suppressed by symmetry

$$H \rightarrow i H$$



$$\frac{1}{\Lambda^{n-1}} \; L\, L\, H^{n}$$

allows to reduce the scale of new physics responsible for neutrino mass generation

$$m_\nu = \frac{\langle H\rangle^{n}}{\Lambda^{n-1}}$$

$$m_\nu = \frac{1}{\Lambda^{n-1}} \Pi_{i\,=\,1\ldots n} \langle H_i\rangle$$

Leptonic CP from CKM

Assume $U_L \sim V_{CKM}^{*}\ (\delta_q)$ is the only source of CP violation --

as in the quark sector, the LH rotation that diagonalizes the Dirac mass matrix

U_X is real

$$\sin\delta_{CP} = -\sin\delta_q \frac{s_{13}^{q}}{s_{13}} c_{23}\left[1 + 2 s_{13} \tan\theta_{23} \cot 2\theta_{12}\right] + O(\lambda^4, \lambda^3 s_{13})$$

⇒ $\sin\delta_{CP} \sim \lambda^3 / s_{13} \sim \lambda^2$

In the lowest order:

$$s_{13} \sin\delta_{CP} = (-c_{23})\, s_{13}^{q}\ \sin\delta_q$$

$\delta_q = 1.2 \pm 0.08$ rad

$\sin\delta_{CP} \sim 0.046$

$\delta_{CP} \sim -\delta$ or $\delta_{CP} \sim \pi + \delta$

where $\delta = (s_{13}^{q} / s_{13})\, c_{23} \sin\delta_q$

If other value of phase is observed
→ contributions beyond CKM (e.g. from the RH sector) or another framework

Effective field theory approach