Nordita Colloquium, Stockholm, Febr. 15, 2007

The Fate of Lepton Number in the LHC Era.

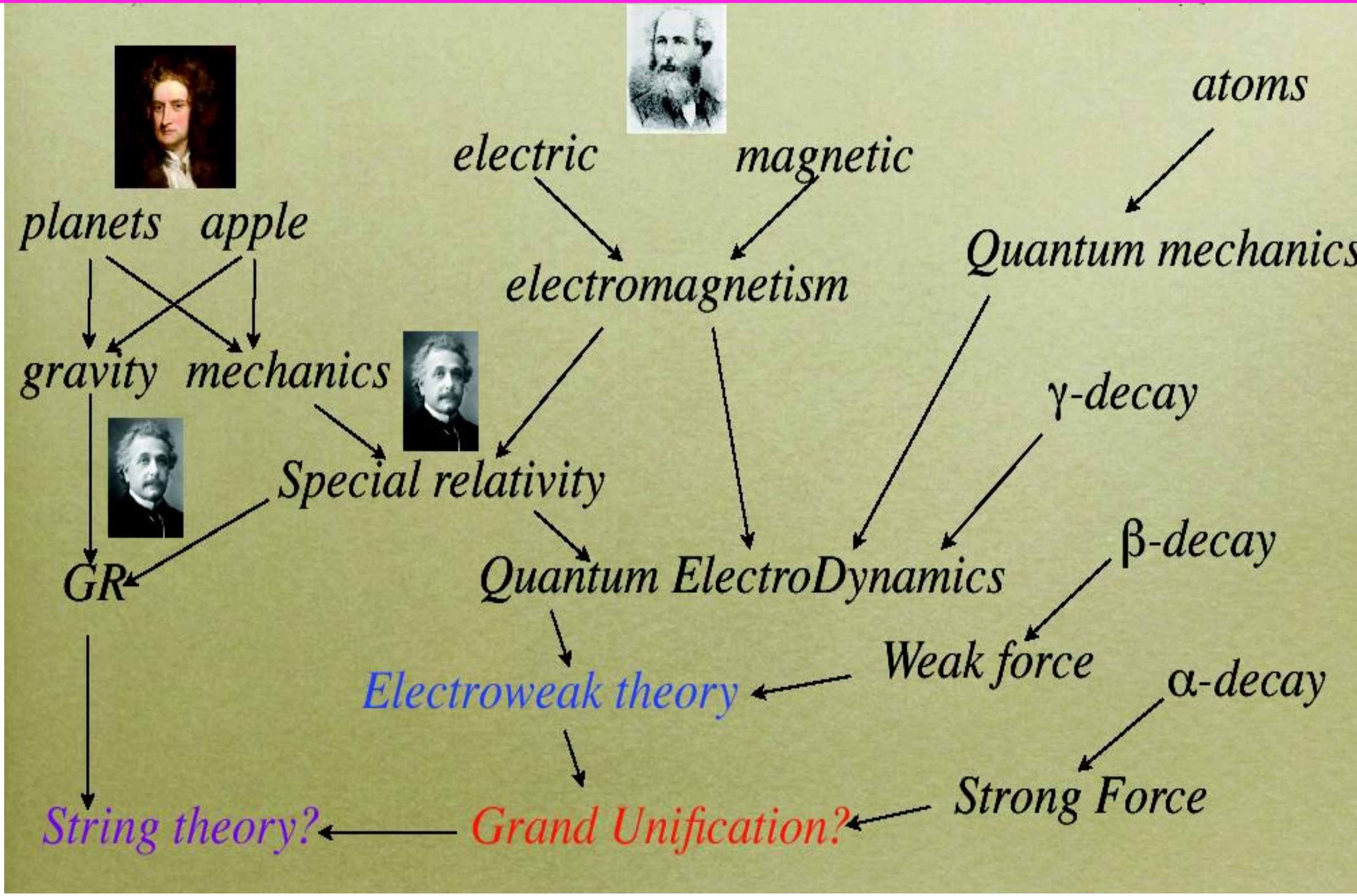
Antonio Masiero

Univ. of Padova

and

INFN, Padova

UNIFICATION of FUNDAMENTAL INTERACTIONS



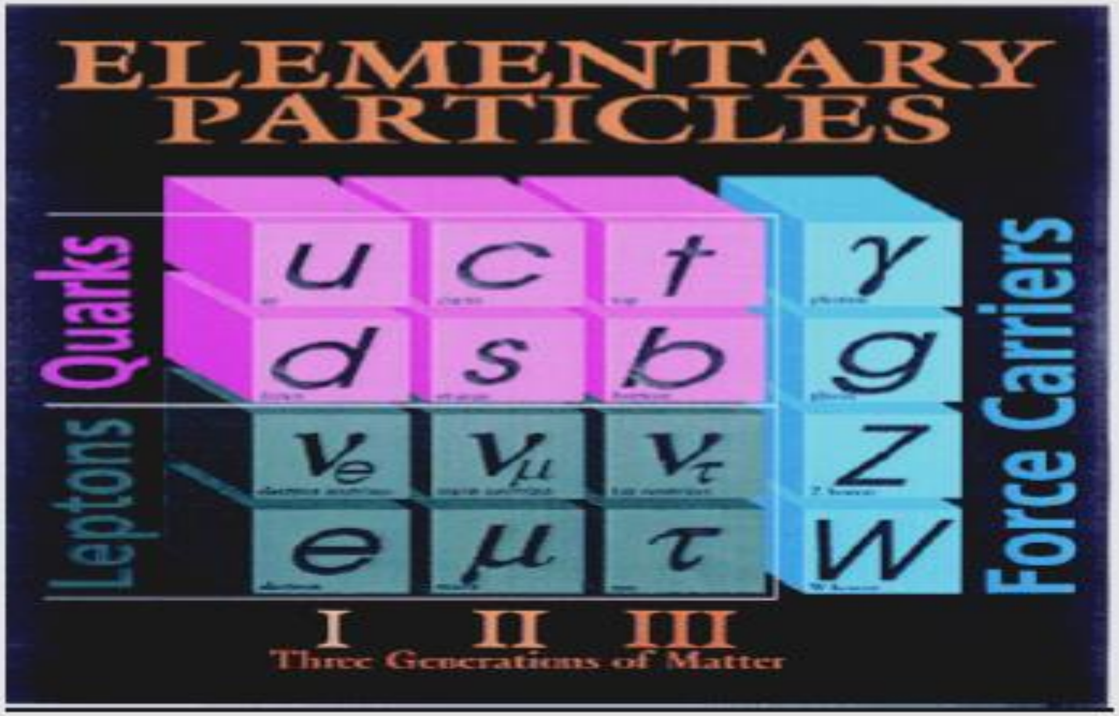
Courtesy of H. Murayama

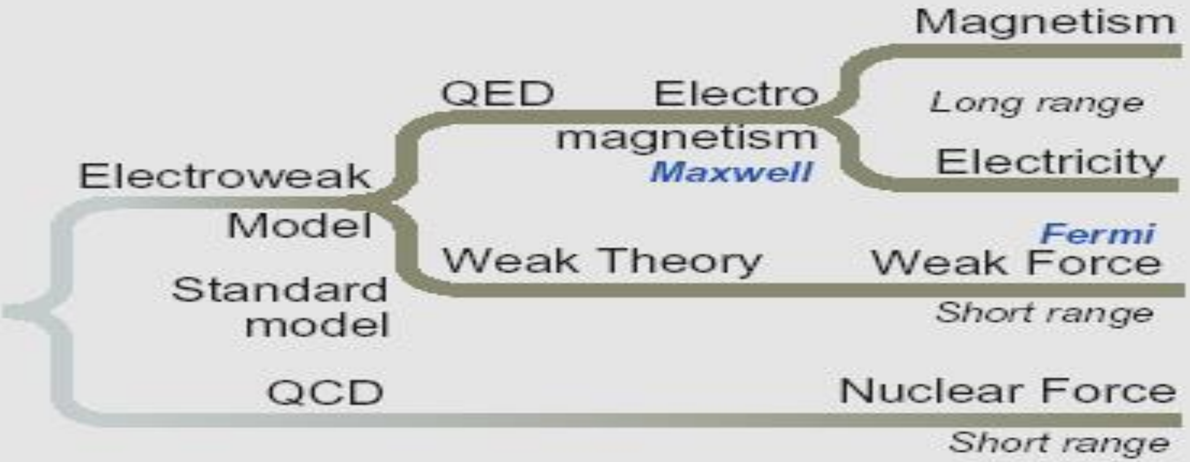
Going up in Energy

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

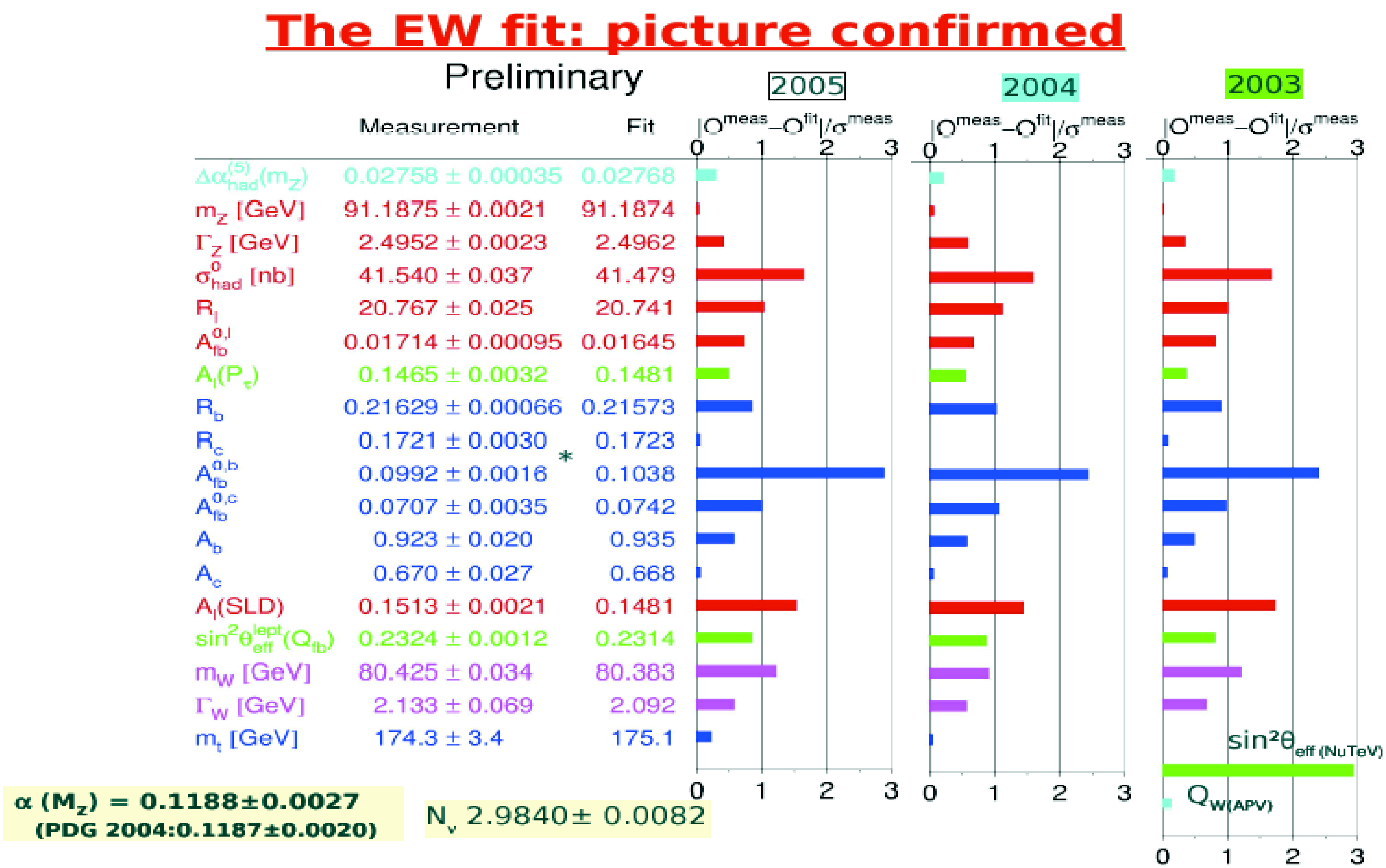
LHC: THE DISCOVERY MACHINE FOR THE NEW PHYSICS AT THE TEV SCALE

THE G-W-S STANDARD MODEL





Particle Physics SM: (amazingly) good description of fundamental interactions down to distances of O (10^{-18} m.)



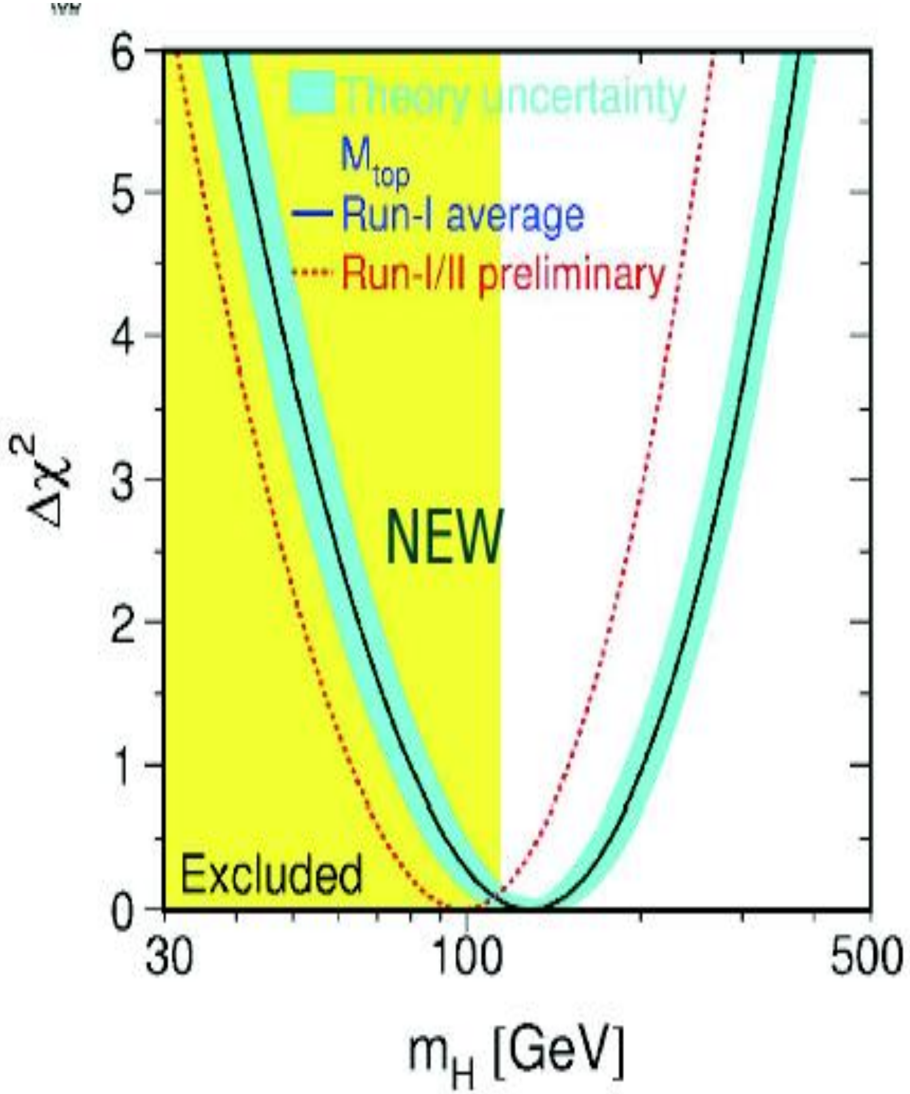
Where all masses come from:

the HIGGS particle

$M_{Higgs} = 98^{+52}_{-26}$ GeV

$M_{higgs} < 208$ GeV @95% C.L.

The Higgs has already "shown up" as a VIRTUAL particle in electroweak radiative effects



STRATEGIES TO SEARCH FOR NEW PHYSICS

HIGH ENERGY : have enough energy to produce new particles and observe them

HIGH INTENSITY : have enough luminosity to copiously produce known particles and observe rare processes involving them (Rare Decays, Oscillations, CP violation) → NEW PHYSICS in the VIRTUAL PARTICLES RUNNING IN THE LOOPS. Probe new particles at the electroweak scale through their VIRTUAL EFFECTS → observe deviations from the SM expectations for such rare processes

VIRTUAL EFFECTS for REAL NEW PHYSICS

THE HEISENBERG'S UNCERTAINTY PRINCIPLE ENSURES THAT MEASUREMENTS OF PROCESSES INVOLVING LOOPS (I.E., WITH THE PRESENCE OF VIRTUAL PARTICLES) CAN GIVE ACCESS TO HIGH MASS SCALE PHYSICS BEFORE ACCELERATORS ARE ABLE TO DIRECTLY PROBE THOSE SCALES

EX. : the suppression of $K_L \longrightarrow \mu^+ \mu^-$ hint for the existence of the CHARM quark. Calculation of its mass from the observed rate of $K - \bar{K}$ oscillations.

Heaviness of the TOP quark from observed largeness of $B - \bar{B}$ oscillations.

Flavor Physics: the Triumph of the CKM flavor structure of the SM

Quark Sector

- *1964 Fitch and Cronin discover CP violation (indirect CP in neutral K)*
- *1999 CPLEAR establishes T violation in K mixing*
- *2000 KTeV/NA48 establish direct CP violation in ε'/ε*
- *2002 BABAR/Belle establish indirect CP violation in B_d meson, confirming Kobayashi-Maskawa theory*

By now we have achieved a “redundant” determination of the CKM mixing elements entering the quark mixing in the SM, i.e. we are probing the validity of the CKM ansatz predicted by the SM

The CKM flavor structure of the SM is the DOMINANT SOURCE of the hadronic flavor mixing (with new physics sources of flavor confined to be not larger than 20% of the CKM source)

WHY TO GO BEYOND THE SM

"OBSERVATIONAL" REASONS

- •HIGH ENERGY PHYSICS

NO (but $A_{FB}^{Z \to bb}$……)

- •FCNC, CP≠

NO (but $b \to s\bar{q}q$ penguin …)

- •HIGH PRECISION LOW-EN.

NO (but $(g-2)_\mu$ …)

- •NEUTRINO PHYSICS

YES $m_\nu \neq 0$, $\theta_\nu \neq 0$

- •COSMO - PARTICLE PHYSICS

YES (DM, ΔB_{cosm}, INFLAT., DE)

THEORETICAL REASONS

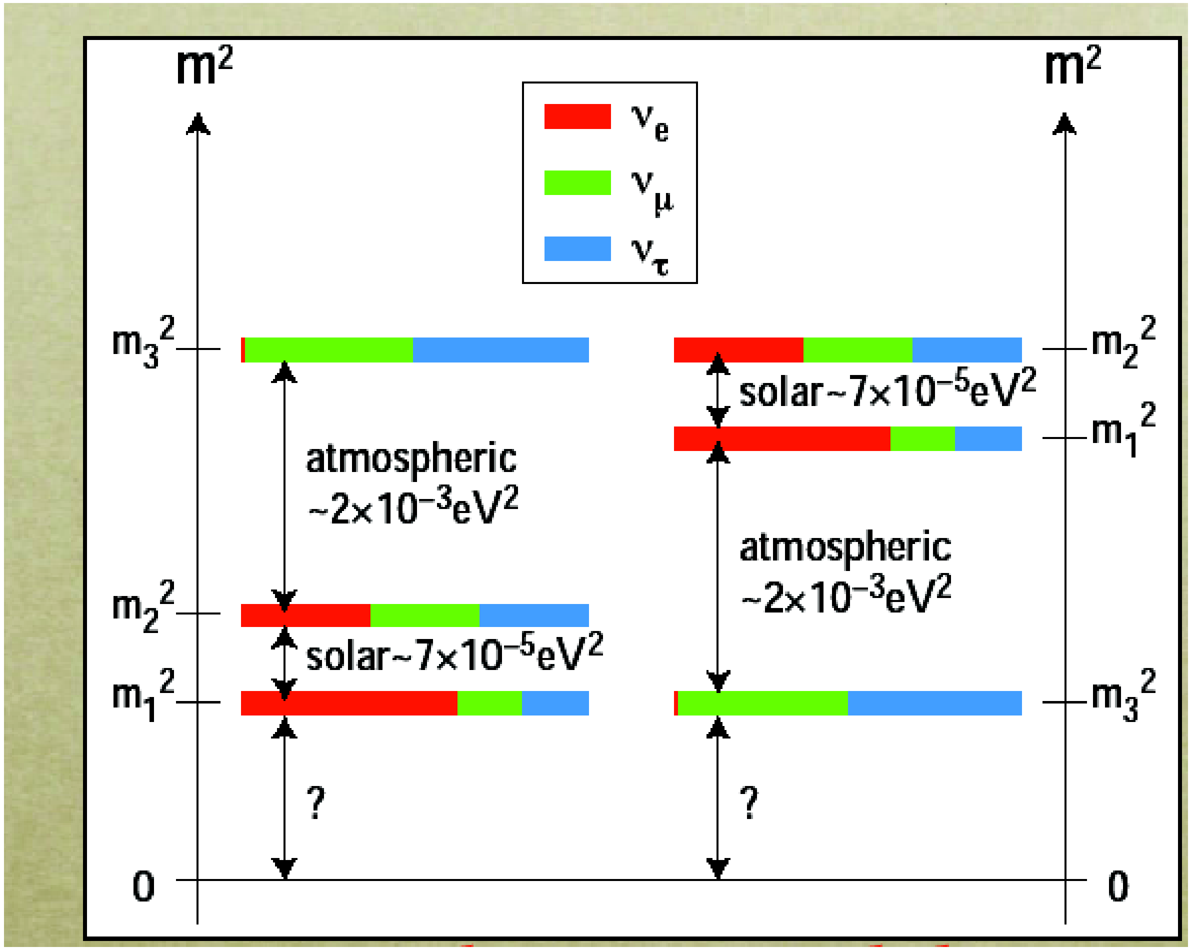
- •INTRINSIC INCONSISTENCY OF SM AS QFT

NO (spont. broken gauge theory without anomalies)

- •NO ANSWER TO QUESTIONS THAT "WE" CONSIDER "FUNDAMENTAL" QUESTIONS TO BE ANSWERED BY "FUNDAMENTAL" THEORY

YES (hierarchy, unification, flavor)

Neutrinos are MASSIVE:
New Physics IS there!



THE FATE OF LEPTON NUMBER

L VIOLATED → υ Majorana ferm.

L CONSERVED → υ Dirac ferm. (dull option)

$h\,\bar{\upsilon}_L H\,\upsilon_R \longrightarrow m_\upsilon = h\,\langle H\rangle$ $M_\upsilon < 5$ eV $\rightarrow h < 10^{-11}$

EXTRA-DIM. ν_R in the bulk: small overlap?

SMALLNESS of m_υ

↓

PRESENCE OF A NEW PHYSICAL MASS SCALE

NEW HIGH SCALE   NEW LOW SCALE

SEE - SAW MECHAN.

Minkowski; Gell-Mann, Ramond, SlansKy, Vanagida

↓

ν_R ENLARGEMENT OF THE FERMIONIC SPECTRUM

$M\upsilon_R\,\upsilon_R + h\,\bar{\upsilon}_L\,\phi\,\upsilon_R$

	υ_L	υ_R
υ_L	~O	$h\,\langle\phi\rangle$
υ_R	$h\,\langle\phi\rangle$	M

LR Models?

MAJORON MODELS

Gelmini, Roncadelli

↓

Δ ENLARGEMENT OF THE HIGGS SCALAR SECTOR

$h\,\upsilon_L\,\upsilon_L\,\Delta$

$m_\upsilon = h\,\langle\Delta\rangle$

N.B.: EXCLUDED BY LEP!

“MASS PROTECTION”

For FERMIONS, VECTOR (GAUGE) and SCALAR BOSONS

SIMMETRY PROTECTION

- -FERMIONS → chiral symmetry

  $f_L f_R$ not invariant under SU(2)x U(1)

- -VECTOR BOSONS → gauge symmetry

→ FERMIONS and W,Z VECTOR BOSONS can get a mass only when the elw. symmetry is broken m_f, $m_W \leq$ <H>

NO SYMMETRY PROTECTION FOR SCALAR MASSES

↓

“INDUCED MASS PROTECTION”

→ Create a symmetry (SUPERSIMMETRY)

Such that FERMIONS ⟷ BONUS

So that the fermion mass “protection” acts also on bosons as long as SUSY is exact

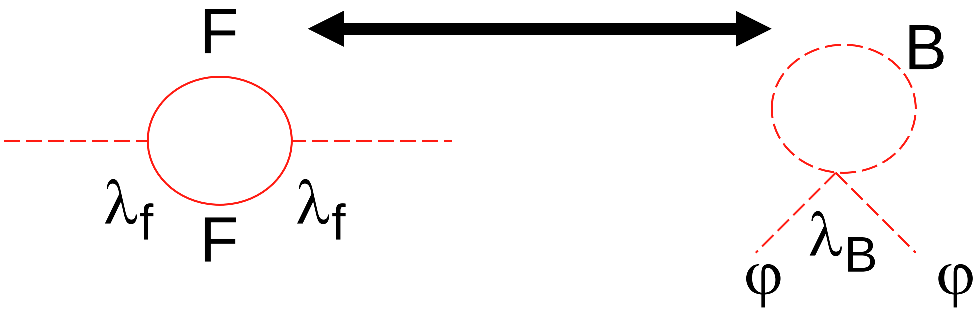
⇨ SUSY BRAKING ~ SCALE OF 0 (10^2-10^3 Gev)

→ LOW ENERGY SUSY

HIERARCHY PROBLEM: THE SUSY WAY

SUSY HAS TO BE BROKEN AT A SCALE CLOSE TO 1TeV $\longrightarrow$ LOW ENERGY SUSY

$m_\varphi^2 \propto \Lambda^2$ $\longrightarrow$ Scale of susy breaking



$$\delta m^2_\varphi \sim \frac{(\lambda_B - \lambda^2_f)}{16\,\pi^2}\,\Lambda^2$$

$\longrightarrow [m^2_B - m^2_F]^{1/2} \sim 1/\sqrt{G_F}$

$\begin{pmatrix} B \\ F \end{pmatrix}$ In SUSY multiplet

SPLITTING IN MASS BETWEEN B and F of O (ELW. SCALE)

LFV and NEW PHYSICS

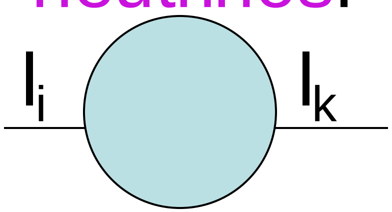
- Flavor in the HADRONIC SECTOR:

  CKM paradigm

- Flavor in the LEPTONIC SECTOR:

  - Neutrino masses and (large) mixings

  - Extreme smallness of LFV in the charged lepton sector of the SM with massive neutrinos:

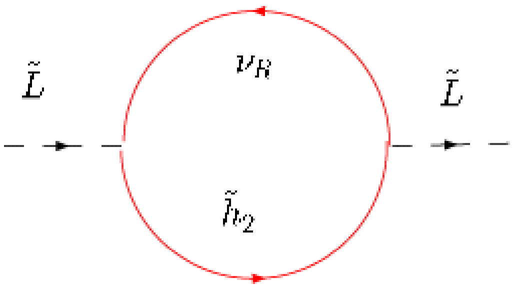


suppressed by $(m_{\nu_i}^2 - m_{\nu_k}^2) / M_W^2$

SUSY SEESAW: Flavor universal SUSY breaking and yet large lepton flavor violation!

Borzumati, A. M. 1986

$$L = f_l \, \bar{e}_R L h_1 + f_\nu \, \bar{\nu}_R L h_2 + M \, \nu_R \nu_R$$



$$\left(m^2_{\tilde{L}}\right)_{ij} \sim \frac{1}{8\pi^2}(3m_0^2 + A_0^2)\left(f_\nu^\dagger f_\nu\right)_{ij} \log\frac{M}{M_G}$$

Non-diagonality of the slepton mass matrix in the basis of diagonal lepton mass matrix depends on the unitary matrix U which diagonalizes $(f_\nu^+ f_\nu)$

LFV in SUSYGUTs with SEESAW

Scale of appearance of the SUSY soft breaking terms resulting from the spontaneous breaking of supergravity

Low-energy SUSY has "memory" of all the multi-step RG occurring from such superlarge scale down to M_W

→ potentially large LFV

Barbieri, Hall; Barbieri, Hall, Strumia; Hisano, Nomura, Yanagida; Hisano, Moroi, Tobe Yamaguchi; Moroi;A.M.,, Vempati, Vives; Carvalho, Ellis, Gomez, Lola; Calibbi, Faccia, A.M, Vempati

LFV in MSSMseesaw: $\mu \rightarrow e\gamma$ Borzumati, A.M.

$\tau \rightarrow \mu\gamma$ Blazek, King;

General analysis: Casas Ibarra; Lavignac, Masina,Savoy; Hisano, Moroi, Tobe, Yamaguchi; Ellis, Hisano, Raidal, Shimizu; Fukuyama, Kikuchi, Okada; Petcov, Rodejohann, Shindou, Takanishi; Arganda, Herrero; Deppish, Pas, Redelbach, Rueckl; Petcov, Shindou

Bright prospects for the experimental sensitivity to LFV

Experiments:

Running: **BaBar**, **Belle**

Upcoming: **MEG** (2007)

Future: **SuperKEKB** (2011)

PRISM/PRIME (next decade)

Super Flavour factory (?)

TABLE I: Present bounds and expected experimental sensitivities on LFV processes

Process	Present bound	Future sensitivity
$BR(\mu \to e\,\gamma)$	1.2×10^{-11}	$\mathcal{O}(10^{-13} - 10^{-14})$
$BR(\mu \to e\,e\,e\,)$	1.1×10^{-12}	$\mathcal{O}(10^{-13} - 10^{-14})$
$CR(\mu \to e \text{ in Ti})$	4.3×10^{-12}	$\mathcal{O}(10^{-18})^a$
$BR(\tau \to e\,\gamma)$	3.1×10^{-7}	$\mathcal{O}(10^{-8})$
$BR(\tau \to e\,e\,e)$	2.7×10^{-7}	$\mathcal{O}(10^{-8})$
$BR(\tau \to \mu\,\gamma)$	6.8×10^{-8}	$\mathcal{O}(10^{-8}) - \mathcal{O}(10^{-9})^a$
$BR(\tau \to \mu\,\mu\,\mu)$	2×10^{-7}	$\mathcal{O}(10^{-8})$

[a]Planned or discussed experiment, not yet under construction

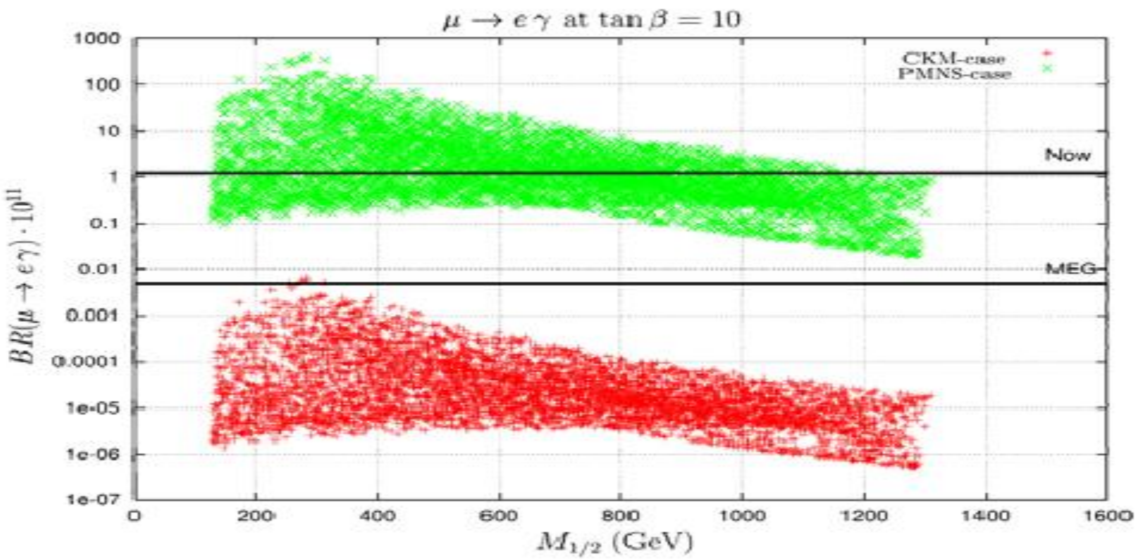
μ ⟶ e+γ in SUSYGUT: past and future

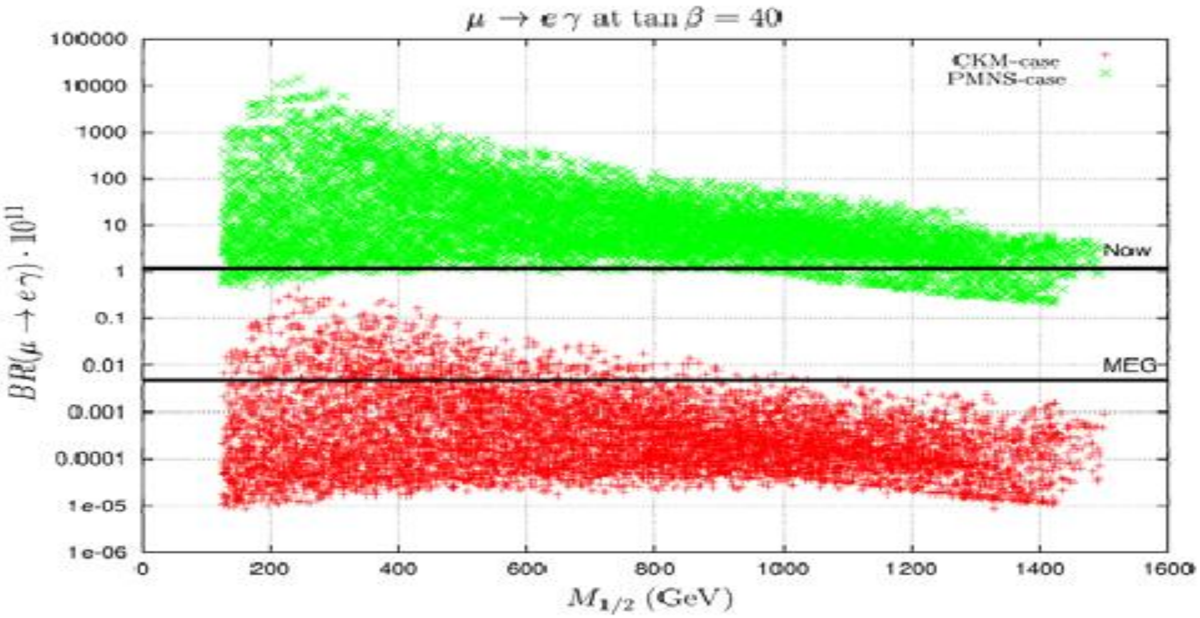
CALIBBI,

FACCIA,

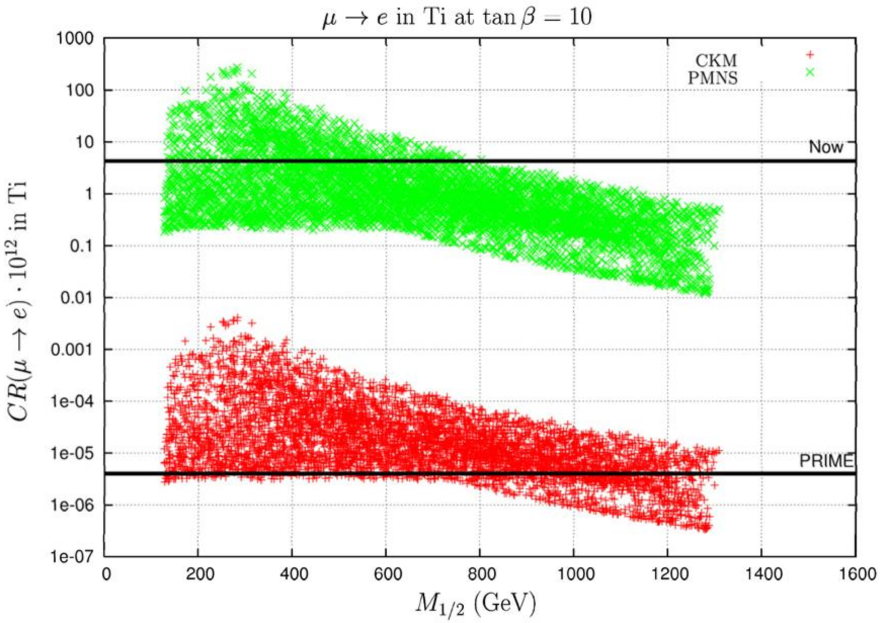
A.M.,

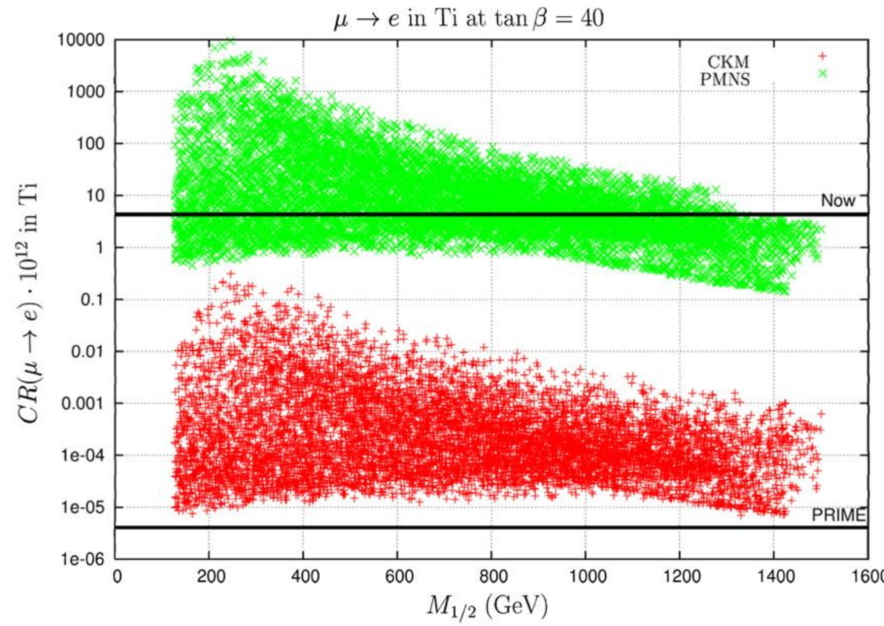
VEMPATI

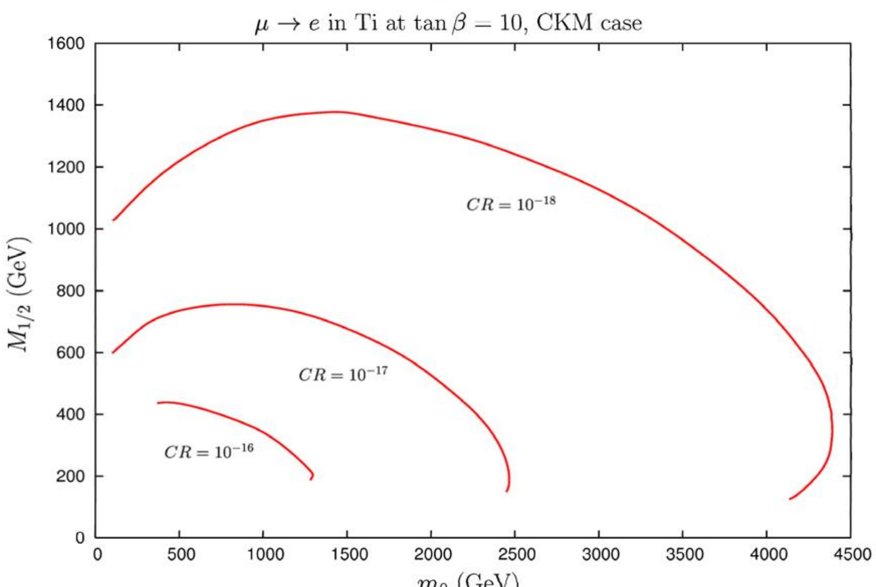


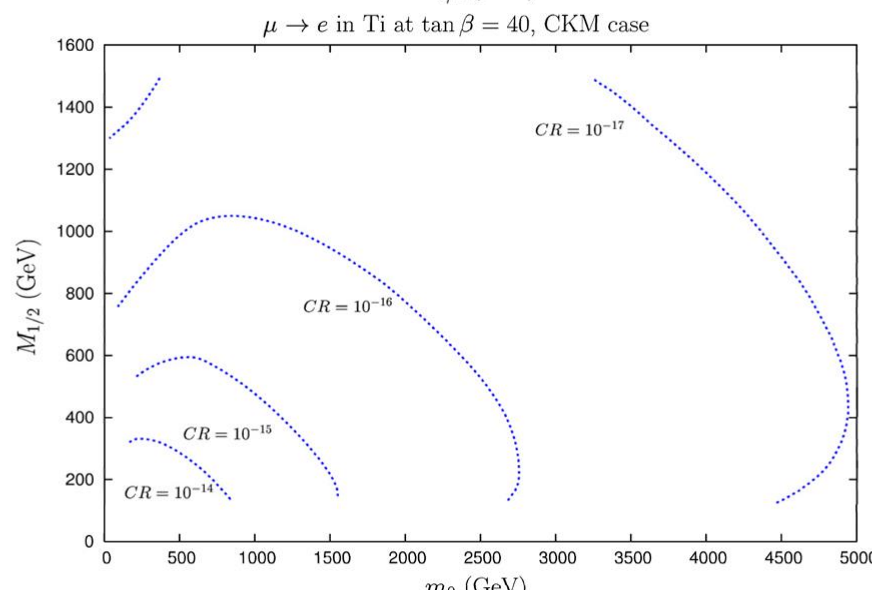


$\mu \to e$ in Ti and **PRISM/PRIME** conversion experiment









LFV ⟷ LHC SENSITIVITIES IN PROBING THE SUSY PARAM. SPACE

TABLE IX: Reach in $(m_0, m_{\tilde{g}})$ of the present and planned experiment from their $\tau \to \mu\gamma$ sensitivity.

	PMNS		CKM	
Exp.	$t_\beta = 40$	$t_\beta = 10$	$t_\beta = 40$	$t_\beta = 10$
BaBar, Belle	1.2 TeV	no	no	no
SuperKEKB	2 TeV	0.9 TeV	no	no
Super Flavour [a]	2.8 TeV	1.5 TeV	0.9 TeV	no

[a] Post–LHC era proposed/discussed experiment

CALIBBI, FACCIA, A.M., VEMPATI

Large ν mixing $\leftrightarrow$ large b-s transitions in SUSY GUTs

In SU(5) $d_R \longleftrightarrow l_L$ connection in the 5-plet
Large $(\Delta^l_{23})_{LL}$ induced by large f_ν of $O(f_{top})$
is accompanied by large $(\Delta^d_{23})_{RR}$

In SU(5) assume large f_ν (Moroi)
In SO(10) f_ν large because of an underlying Pati-Salam symmetry
(Darwin Chang, A.M., Murayama)

See also: Akama, Kiyo, Komine, Moroi; Hisano, Moroi, Tobe, Yamaguchi, Yanagida; Hisano, Nomura; Kitano,Koike, Komine, Okada

FCNC HADRON-LEPTON CONNECTION IN SUSYGUT

If

soft SUSY breaking terms arise
at a scale > M_{GUT}, they have to respect
the underlying quark-lepton GU symmetry

constraints on δ^{quark} from LFV and
constraints on δ^{lepton} from hadronic FCNC

Ciuchini, A.M., Silvestrini, Vempati, Vives PRL

general analysis Ciuchini, A.M., Paradisi, Silvestrini, Vempati, Vives hep-ph/0702144

DEVIATION from μ - e UNIVERSALITY

A.M., Paradisi, Petronzio

- Denoting by $\Delta r_{NP}^{e-\mu}$ the deviation from $\mu - e$ universality in $R_{K,\pi}$ due to new physics, i.e.:

$$R_{K,\pi} = R_{K,\pi}^{SM} \left(1 + \Delta r_{K,\pi\, NP}^{e-\mu}\right),$$

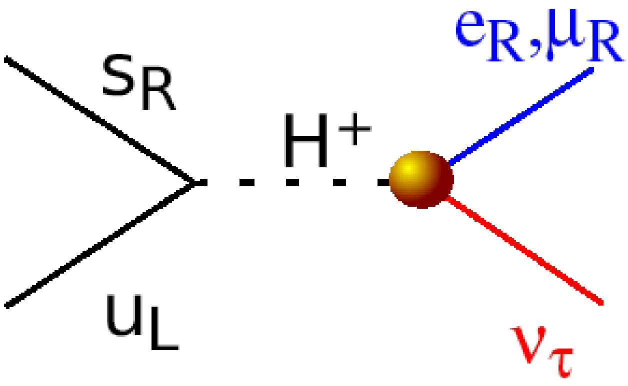
- we get at the 2σ level:

$$-0.063 \leq \Delta r_{K\, NP}^{e-\mu} \leq 0.017 \quad \text{NA48/2}$$

$$-0.0107 \leq \Delta r_{\pi\, NP}^{e-\mu} \leq 0.0022 \quad \text{PDG}$$

H mediated LFV SUSY contributions to R_K

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)} \ , \quad i = e, \mu, \tau$$



$$eH^{\pm}\nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \ \ t_\beta = 40 \ \ M_{H^\pm} = 500 \mathrm{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\ SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right) \left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

Extension to B → lν deviation from universality
Isidori, Paradisi

THE COSMIC MATTER-ANTIMATTER ASYMMETRY PUZZLE:
-why only baryons
-why $N_{baryons}/N_{photon} \sim 10^{-10}$

- NO EVIDENCE OF ANTIMATTER WITHIN THE SOLAR SYSTEM
- ANTIPROTONS IN COSMIC RAYS: IN AGREEMENT WITH PRODUCTION AS SECONDARIES IN COLLISIONS
- IF IN CLUSTER OF GALAXIES WE HAD AN ADMIXTURE OF GALAXIES MADE OF MATTER AND ANTIMATTER ⟶ THE PHOTON FLUX PRODUCED BY MATTER-ANTIMATTER ANNIHILATION IN THE CLUSTER WOULD EXCEED THE OBSERVED GAMMA FLUX
- IF $N_{ba.} = N_{antibar}$ AND NO SEPARATION WELL BEFORE THEY DECOUPLE . WE WOULD BE LEFT WITH $N_{bar.}/N_{photon} << 10^{-10}$
- IF BARYONS-ANTIBARYONS ARE SEPARATED EARLIER ⟶ DOMAINS OF BARYONS AND ANTIBARYONS ARE TOO SMALL SMALL TODAY TO EXPLAIN SEPARATIONS LARGER THAN THE SUPERCLUSTER SIZE

⬇

- ONLY MATTER IS PRESENT
- HOW TO DYNAMICALLY PRODUCE A BARYON-ANTIBARYON ASYMMETRY STARTING FROM A SYMMETRIC SITUATION

SM FAILS TO GIVE RISE TO A SUITABLE COSMIC MATTER-ANTIMATTER ASYMMETRY

- SM DOES NOT SATISFY AT LEAST TWO OF THE THREE SACHAROV'S NECESSARY CONDITIONS FOR A DYNAMICAL BARYOGENESIS:

- NOT ENOUGH CP VIOLATION IN THE SM → NEED FOR NEW SOURCES OF CPV IN ADDITION TO THE PHASE PRESENT IN THE CKM MIXING MATRIX
- FOR $M_{HIGGS} > 80$ GeV THE ELW. PHASE TRANSITION OF THE SM IS A SMOOTH CROSSOVER

→ NEED NEW PHYSICS BEYOND SM. IN PARTICULAR, FASCINATING POSSIBILITY: THE ENTIRE MATTER IN THE UNIVERSE ORIGINATES FROM THE SAME MECHANISM RESPONSIBLE FOR THE EXTREME SMALLNESS OF NEUTRINO MASSES

MATTER-ANTIMATTER ASYMMETRY ⟷ NEUTRINO MASSES CONNECTION: BARYOGENESIS THROUGH LEPTOGENESIS

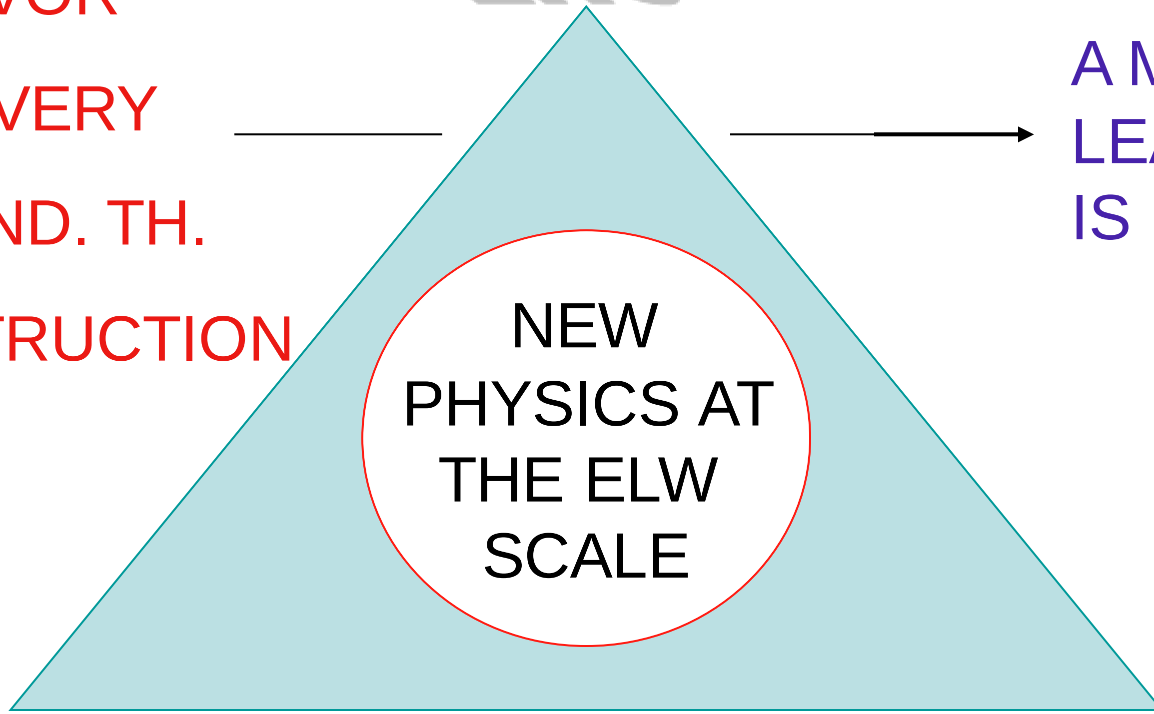
- Key-ingredient of the SEE-SAW mechanism for neutrino masses: large Majorana mass for RIGHT-HANDED neutrino
- In the early Universe the heavy RH neutrino decays with Lepton Number violatiion; if these decays are accompanied by a new source of CP violation in the leptonic sector, then

→ it is possible to create a lepton-antilepton asymmetry at the moment RH neutrinos decay. Since SM interactions preserve Baryon and Lepton numbers at all orders in perturbation theory, but violate them at the quantum level, such LEPTON ASYMMETRY can be converted by these purely quantum effects into a BARYON-ANTIBARYON ASYMMETRY (Fukugita-Yanagida mechanism for leptogenesis)

LHC

DM - FLAVOR
for DISCOVERY
and/or FUND. TH.
RECONSTRUCTION

A MAJOR
LEAP AHEAD
IS NEEDED



DARK MATTER

$m_\chi\ n_\chi\ \sigma_\chi \ldots$

LINKED TO COSMOLOGICAL EVOLUTION

→ Possible interplay with dynamical DE

"LOW ENERGY" PRECISION PHYSICS

FCNC, CP ≠, (g-2), $(\beta\beta)_{0\nu\nu}$