The Problem of Proton Decay

Neutrino oscillations @Venezia, 8 Feb. 2006

..an invitation to discuss about the future

Luciano Maiani
Universita' di Roma "La Sapienza"
INFN, Roma, Italy

A simple gauge group: why?

- Standard Model Gauge Group: G_{SM}= SU(3)xSU(2) xU(1):
  - not simple: 3 couplings,
  - not even semi-simple: charges not necessarily in rational ratios

BUT in Nature:

- charge is quantized: 3Q=integers;
- charge MUST be quantized for anomalies to cancel (Bouchiat, Ilipoulos and Meyer):
  - anomaly proportional to $A = \Sigma_{doublets}\, Q$
  - For one family: Q(e)+Q(ν)+ 3Q(u)+3Q(d)=-1+3(2/3)-3(1/3) = 0
  - quarks and leptons must appear in "correlated groups".

A simple Gauge Group...

- Implies the existence of Super Heavy masses & particles:
  - $g_1, g_2, g_3 \rightarrow g_{GUT}$
  - couplings run logarithmically, hence it takes a long time to get to Unification: $M_{GUT} \sim 10^{14}$ -10^{16} GeV >> M_Z (Georgi, Quinn, Weinberg)
- proton decay is induced by new (broken) gauge particle exchange;
- we can relate super heavy M_{GUT} to the remarkable stability of the proton
- experimentally $\tau_p > 10^{32}$-10^{33} years (see later)

A family of purely left-handed fields

- Replace the field e_R with the L-positron field L, $(e^C)_L$
- same for the right-handed fields, u_R, d_R

NOTE:

- $(e^C)_L$ *destroys a L-handed positron and creates a R-handed electron*;
- $[(e^C)_L]^+$ *creates a L-handed positron and destryos a R-handed electron*, like e_R.
- In fact, in the Majorana representation, $e^C=e^+$.

- In conclusion: drop the subscript L and write the fields of the first family according to ($Q=T_3+1/2Y$):

$$l=\begin{pmatrix}\nu\\ e\end{pmatrix}_{\substack{Y=-1\\ color=1}};(e^c)_{\substack{Y=2\\ color=1}}$$

$$q=\begin{pmatrix}u\\ d\end{pmatrix}_{\substack{Y=1/3\\ color=3}};(u^c)_{\substack{Y=-4/3\\ color=\bar{3}}};(d^c)_{\substack{Y=2/3\\ color=\bar{3}}}$$

SU(5) (Georgi & Glashow)

- SU(5) ⊃SU(3)⊗SU(2)⊗U(1). Use the decomposition:

$$T_{SU(5)} = \begin{pmatrix} T_{SU(3)} - 2/3 & X \\ Y & T_{SU(2)} + 1 \end{pmatrix}$$

  - T are n^2 -1 hermitian, traceless, n x n matrices that generate SU(n), (n=2, 3, 5),
  - Y=weak hypercharge: $Q=T_3+1/2Y$ (Tr Y=0)
  - Electric charges are given according to $Q=T_3+1/2Y$. In the fundamental, 5, rep :

$$"5" = \begin{pmatrix} \begin{pmatrix} -1/3 \\ -1/3 \\ -1/3 \end{pmatrix} \\ \begin{pmatrix} +1 \\ 0 \end{pmatrix} \end{pmatrix} = (3,0)_{-2/3} + (1,1/2)_{+1}$$

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- "10" the antisymmetric combination of two "5"s.

- 10+5-bar contain all the fields of a family:

$$"\bar{5}" = (\bar{3},0)_{+2/3} + (1,1/2)_{-1} = \qquad "10" = (\bar{3},0)_{-4/3} + (3,1/2)_{1/3} + (1,0)_{+2}$$

$$= d^c \oplus l \qquad = u^c \oplus q \oplus e^c$$

The left-right symmetric solution: O(10)

- Add an SU(2) singlet, corresponding to a right-handed neutrino:

$$l = \begin{pmatrix} \nu \\ e \end{pmatrix}_{\substack{Y=-1 \\ color=1}} ;(e^c)_{\substack{Y=2 \\ color=1}} \; (\nu')_{\substack{Y=0 \\ color=1}}$$

$$q = \begin{pmatrix} u \\ d \end{pmatrix}_{\substack{Y=1/3 \\ color=3}} ;(u^c)_{\substack{Y=-4/3 \\ color=\bar{3}}} ;(d^c)_{\substack{Y=2/3 \\ color=\bar{3}}}$$

- $SU(2)_L$ singlets can be arranged in doublets of a new weak isospin, $SU(2)_R$:

$$SU(2)_R :$$

$$l'^c = \begin{pmatrix} e^c \\ \nu' \end{pmatrix}_{\substack{Y'=+1 \\ color=1}} ;q'^c = \begin{pmatrix} d^c \\ u^c \end{pmatrix}_{\substack{Y'=-1/3 \\ color=1}}$$

- The gauge group becomes $SU(3)\otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$
- the old weak hypercharge has been replaced by a new one, Y', according to:

$$Q = T_{3L} + T_{3R} + \frac{1}{2}Y'$$

-
-
- It turns out that: $Y' = B - L$

The Pati - Salam way (bottom-up)

- Start from the low energy L-R symmetric group: $SU(3)\otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$
- the two SU(2) gauge couplings are related by Parity, we have 3 gauge couplings as before
- A first unification is in the Pati - Salam group, which identifies the lepton number as the 4th color:

$$SU(3)\otimes U(1)_{B-L} \subset SU(4);$$
$$ovvero:$$
$$SU(3)\otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \subset SU(4)\otimes SU(2)_L \otimes SU(2)_R$$

- It is known that:

$$SU(4) = O(6);$$
$$SU(2)\otimes SU(2) = O(4)$$

- so that we arrive to O(10) (H. Friztsch and P. Minkowski, H. Georgi) along the ***Pati-Salam way***:

$$SU(3)\otimes SU(2)_L \otimes U(1)_Y \subset SU(3)\otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \subset$$
$$\subset SU(4)\otimes SU(2)_L \otimes SU(2) = O(6)\otimes O(4) \subset O(10)$$

- The spinorial representation of O(10) is 16 dimensional, and it contains exactly the fields of one family, 10+5bar + one R-handed neutrino.

O(10) and the neutrino mass

- The currents of O(10) are in fact vector currents (since they conserve parity): thus O(10) is anomaly-free.
- O(10) reduces to SU(5) according to: O(10)$\supset$ U(5)=SU(5)$\otimes$U(1)$_{B-L}$
- The spinorial rep 16 of O(10) reduces in SU(5) according to:

$$(16)_{O(10)} = (\bar{5} \oplus 10 \oplus 1)_{SU(5)}$$

The formula "explains" the misterious anomaly cancellation between 5-bar and 10

- $(\nu')^c = \nu_R$. A Majorana mass for ν_R , M_R, is SU(5) invariant, and is naturally of order M_{GUT}
- The system ν_R- ν_L gives a ***Majorana neutrino*** ν_L with a ***very small mass*** (see-saw):

$$m_{\nu_L} = \frac{m_D^2}{M_R}$$

- for the third generation neutrino: $m_\nu \approx 5\ 10^{-2}$ eV from the oscillations of atmospheric neutrinos, assuming m_D=Dirac mass $\approx m_{top}$ we find $M_R \approx 10^{15}$ GeV $\approx M_{GUT}$

STRIKINGLY, A SUPERHEAVY MASS APPEARS AGAIN FROM A COMPLETELY INDEPENDENT PHYSICS

Proton Decay in GUTs

Non-diagonal gauge bosons in SU(5), associated to the generators X and Z =X$^+$, induce baryon number violating transitions :

$$u \to e^+ + X^{-1/3}; \qquad X^{-1/3} + d \to u^c$$

$$(u+d) + u = p \to (u^c + e^+) + u = e^+ + \pi^0$$

B-L is conserved

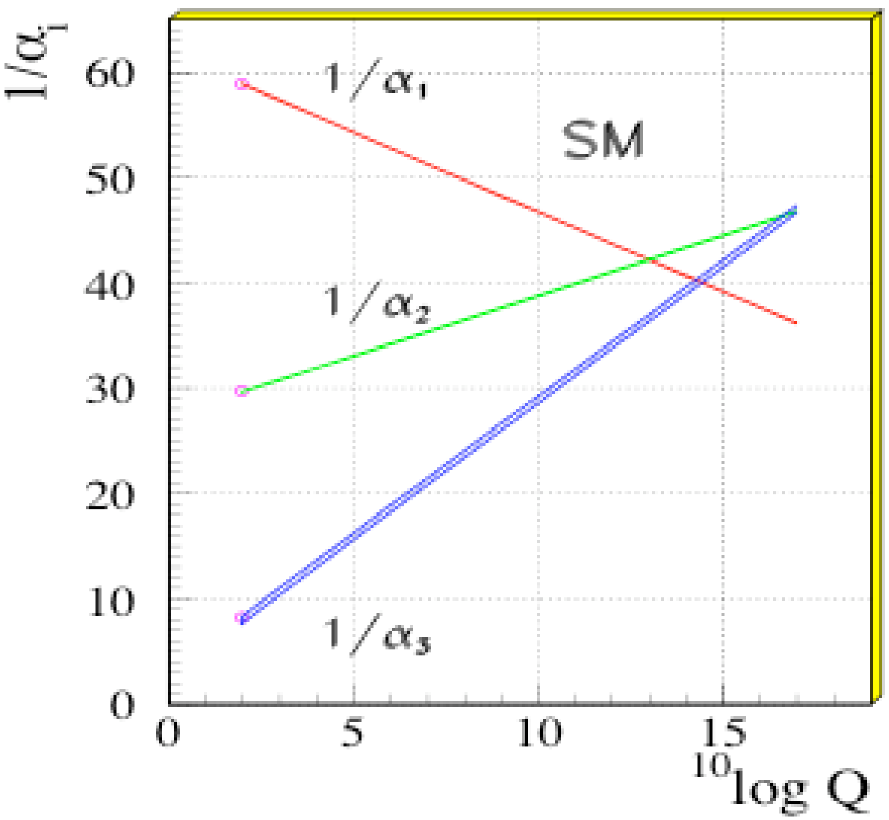
B-violating transitions are also induced by the Triplet component of the Higgs field (a 5):

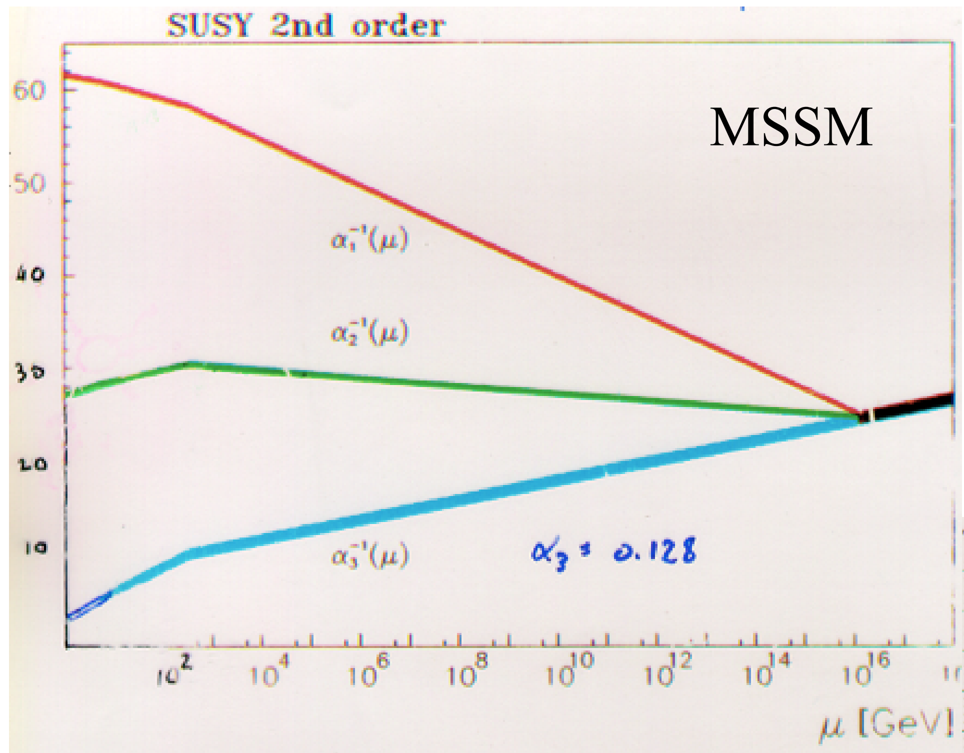
$$H_5 = \begin{pmatrix} H_3 \\ \phi \end{pmatrix};\ H_3 = \begin{pmatrix} -1/3 \\ -1/3 \\ -1/3 \end{pmatrix};H_2 = \begin{pmatrix} +1 \\ 0 \end{pmatrix}$$

making H_3 superheavy requires very unnatural fine-tuning. A split matter multiplet is also a source of trouble in SUSY GUTs .

Do couplings meet in SU5???

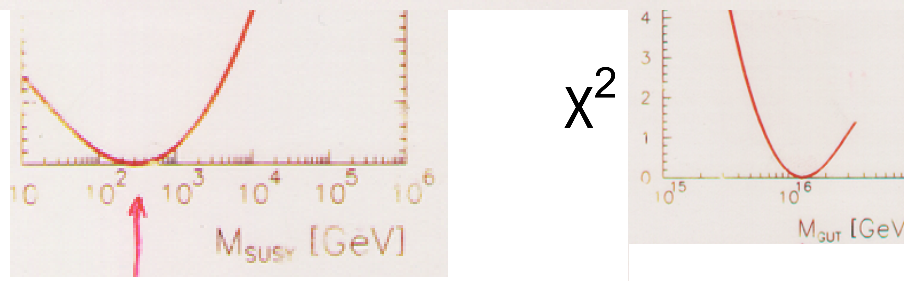
Extrapolation to very high energy of the ST running couplings with the couplings determined at LEP (100 GeV) and three families;





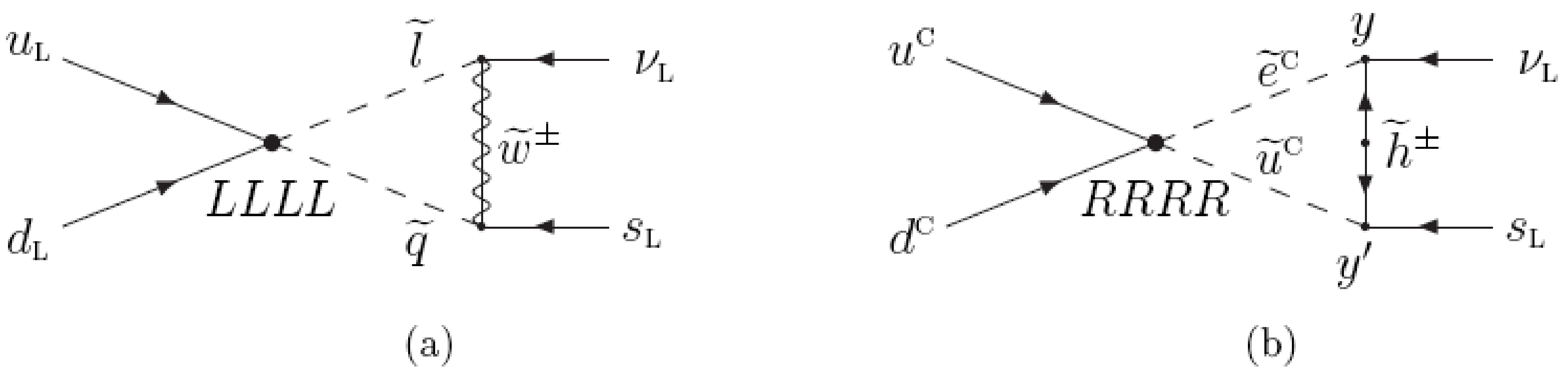
$$M_{GUT} = 10^{16.1 \pm 0.3}\ GeV$$

$$M_{SUSY} = 10^{2.5 \pm 1.0}\ GeV$$



SUSY introduces new elements in proton decay

- The amplitudes mediated by GUT bosons (dimension 6 operators) become very small
- there is a risk of "weak-like" proton decay (dimension 4 operators), but it can be exorcised with appropriate symmetries (R-symmetry)
- processes mediated by the ***triplet higgsino*** emerge (dimension 5 operators)



Proton Decay via dimension five operators: They result from exchange of the lepto-quarks (SUSY partner of H_3) followed by gaugino or higgsino dressing.

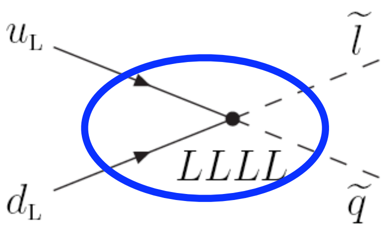
$$Amp \simeq \frac{\lambda_u \lambda_d}{M_{H_3}} \cdot \frac{1}{M_{SUSY}} \cdot \frac{\alpha_S}{2\pi}$$

Proton Decay in a Consistent Supersymmetric SU(5) GUT Model

D. Emmanuel-Costa and S. Wiesenfeldt

hep-ph/0302272

Nucl. Phys. B 661 (2003) 62-82.



- In terms of superfields: $O_{LLLL} = \Phi\Phi\Phi L$ is antisymmetric in color, hence antisymmetric in flavour, so channel with 2nd generation particles dominate:

Dimopoulos, Raby and Wilczek

-
- $$p \rightarrow K^+ \bar{\nu} \; or, \; K^0 \mu^+$$
- the smallness of the Yukawa couplings wins the day, the dimension 5 contribution is not dissimilar from usual GUT estimates, but more uncertain

D. Emmanuel-Costa and S. Wiesenfeldt

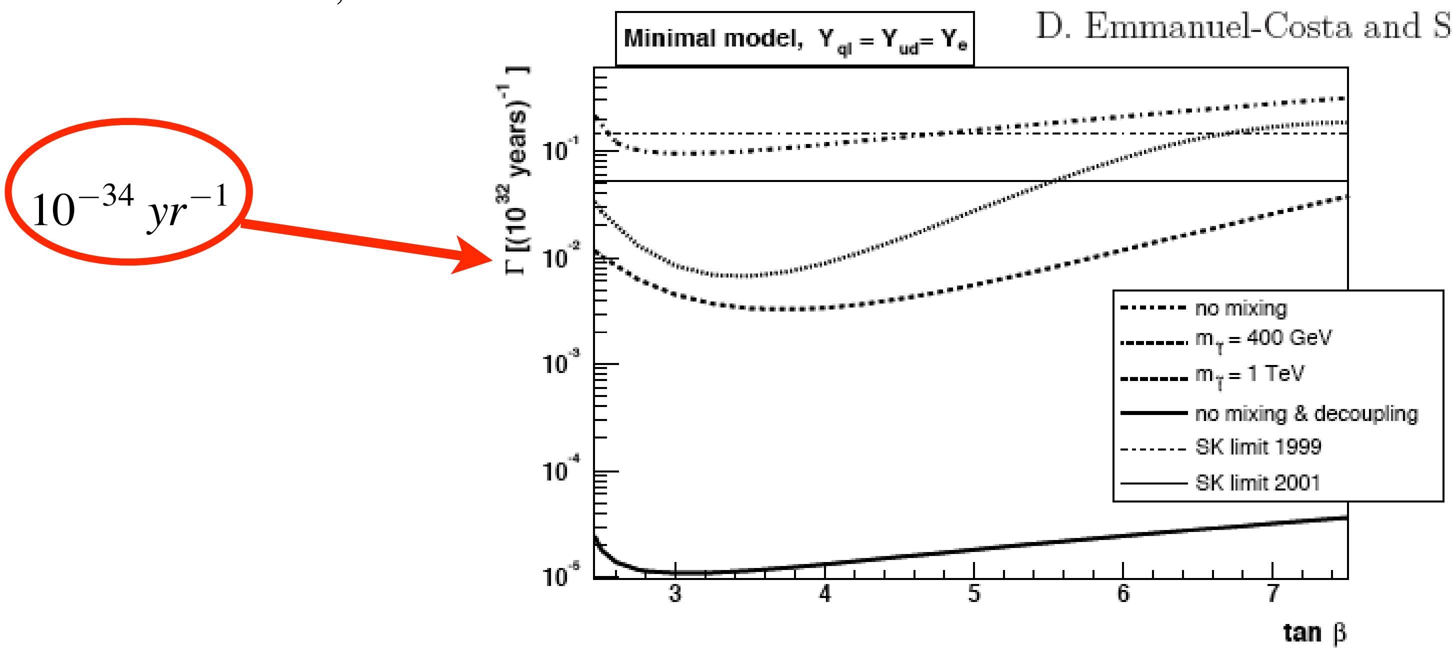


Figure 3: Decay rate $\Gamma(p \to K^+\bar{\nu})$ as a function of $\tan\beta$ with $Y_{ql} = Y_{ud} = Y_e$. The mixing matrix $\mathcal{M}$ is taken arbitrary or $\mathcal{M} = \mathbb{1}$.

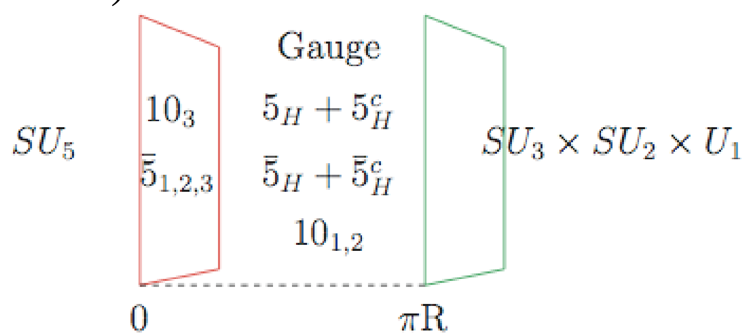
Extra Dimensions @ GUT scale?

Triplet-Doublet Splitting, Proton Stability and an Extra Dimension

Yoshiharu KAWAMURA*)
Department of Physics, Shinshu University, Matsumoto 390-8621, Japan

(Received December 11, 2000)

- Assumption: some fields satisfy odd boundary conditions in the extra dimension
- n=0 mode forbidden: seen from 4D these particles have a (large) mass, M≈1/R
- applies to H_3 as well as to the GUT bosons
- a new way to generate symmetry breaking (by the way..this is how O. Klein gave a mass to the W!)
- of course ***non-renormalizable***: makes sense only if SUSY GUT is a part of a consistent theory including gravity, Superstring and the like
- SUSY GUT in 5D can have a lot of freedom (see e.g. S. Raby, SUSY02, DESY)



and suppress or enhance proton decay...see e.g.

Proton Lifetime from SU(5) Unification in Extra Dimensions

Maria Laura Alciati [1] Ferruccio Feruglio [2]
Dipartimento di Fisica 'G. Galilei', Università di Padova
INFN, Sezione di Padova, Via Marzolo 8, I-35131 Padua, Italy
Yin Lin [3] and Alvise Varagnolo [4]
Scuola Normale Superiore, Pisa
INFN, Sezione di Pisa, I-56126 Pisa, Italy

The Super-Kamiokande Collaboration
arXiv:hep-ex/0502026 v1 15 Feb 2005

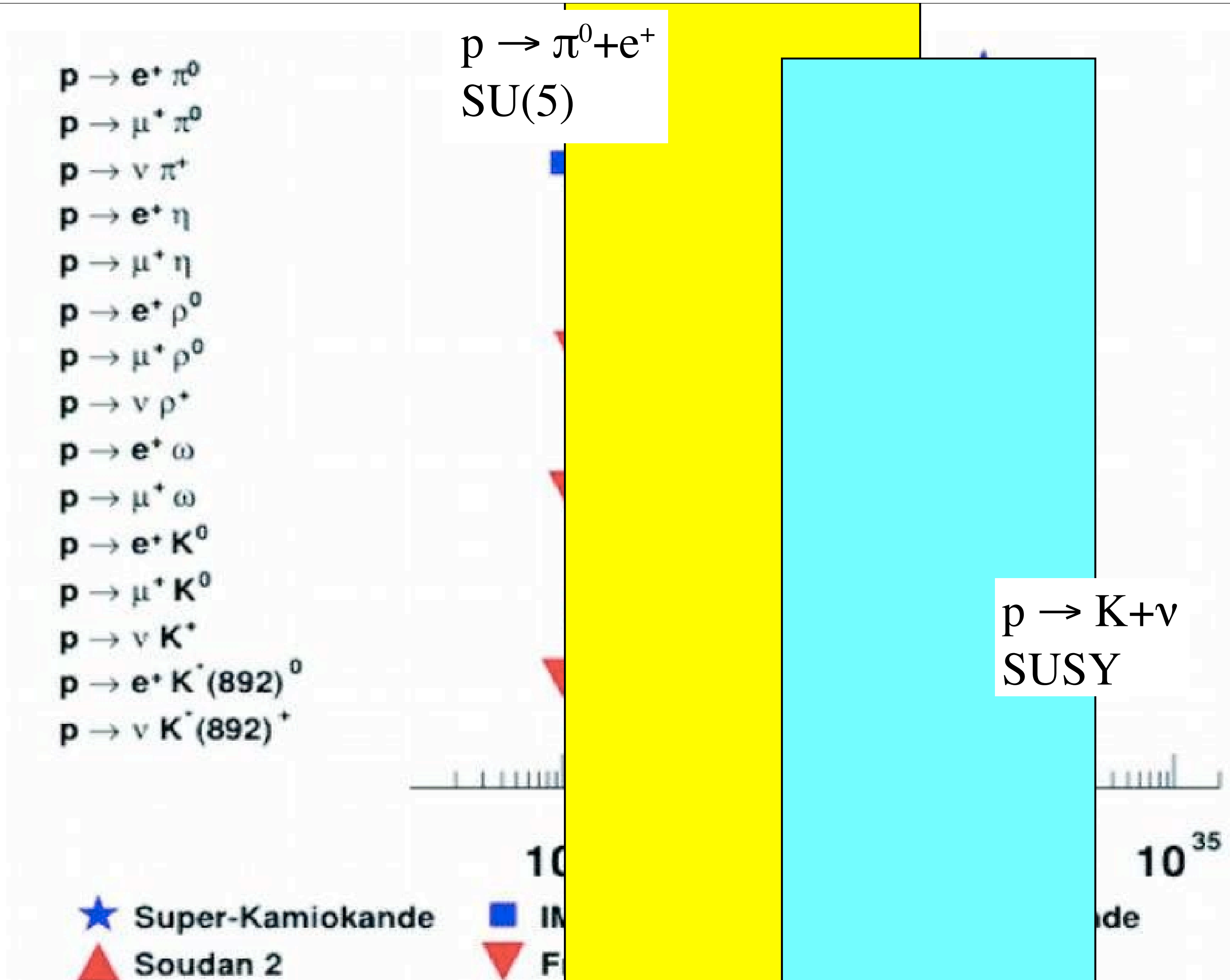
APS/123-QED

Search for nucleon decay via modes favored by supersymmetric grand unification models in Super-Kamiokande-I

Summary of nucleon decay search. The numbers in the parentheses are the systematic uncertainties (%).

mode	method	efficiency (%)	background	candidate	lower limit ($\times 10^{32}$years)
$p \to \bar{\nu} K^+$	total				23
	prompt gamma-ray search	8.6 (20.)	0.7 (59.)	0	10.
	mono-energetic muon search	35.6 (2.5)	—	—	6.4
	$K^+ \to \pi^+\pi^0$ search	6.0 (8.8)	0.6 (74.)	0	7.8
$n \to \bar{\nu} K^0$	total				1.3
	$K_S^0 \to \pi^0\pi^0$	6.9 (16.)	19. (44.)	14	1.3
	$K_S^0 \to \pi^+\pi^-$	5.5 (14.)	11. (41.)	20	0.69
$p \to \mu^+ K^0$	total				13
	$K_S^0 \to \pi^0\pi^0$	5.4 (11.)	0.4 (78.)	0	7.0
	$K_S^0 \to \pi^+\pi^-$ Method 1	7.0 (9.5)	3.2 (41.)	3	4.4
	$K_S^0 \to \pi^+\pi^-$ Method 2	2.8 (12.)	0.3 (76.)	0	3.6
$p \to e^+ K^0$	total				10
	$K_S^0 \to \pi^0\pi^0$	9.2 (5.8)	1.1 (62.)	1	8.4
	$K_S^0 \to \pi^+\pi^-$ Method 1	7.9 (12.)	3.6 (50.)	5	3.5
	$K_S^0 \to \pi^+\pi^-$ Method 2	1.3 (19.)	0.04 (146.)	0	1.6

NOTE: K^+ does not emit Cerenkov light. It is searched via
- gamma signal from excited nucleus
- $K^+ \to \pi^+\pi^0$ or $\mu^+\nu$



Ver ... for proton decay

Getting above 10^{34}y

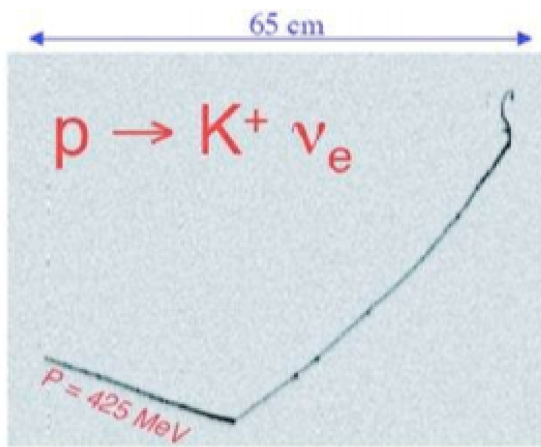
- Massive water Cerenkov detectors in the megaton range: Hyper Kamiokande
- Liquid Argon detectors in the 100 kton range (evolution of ICARUS in the “Dewar” concept)

The liquid Argon TPC: a powerful detector for future neutrino experiments and proton decay searches

A. Ereditato[a] and A. Rubbia[b]

[a]Istituto Nazionale di Fisica Nucleare, INF

[b]Institut für Teilchenphysik, ETHZ, CH-80



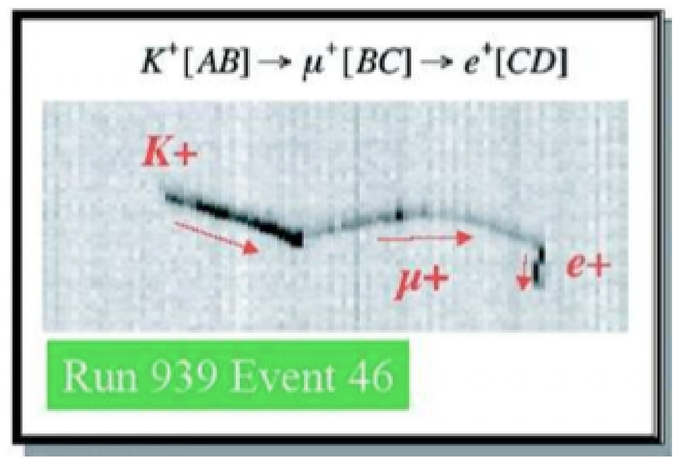
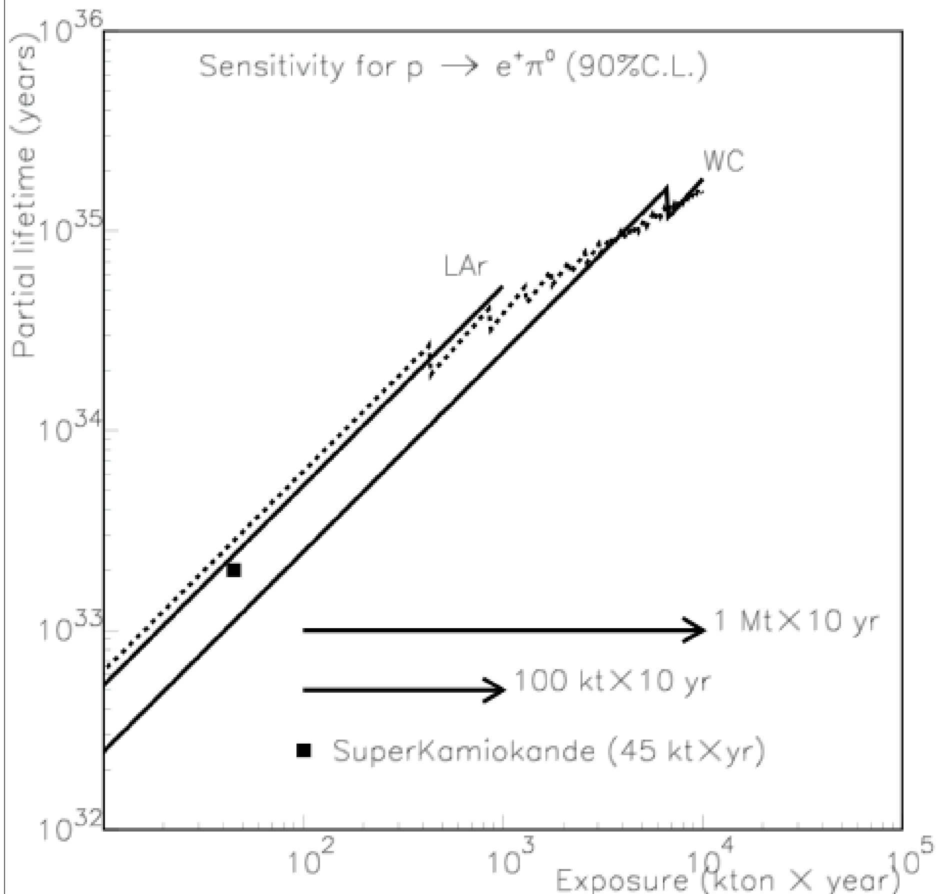


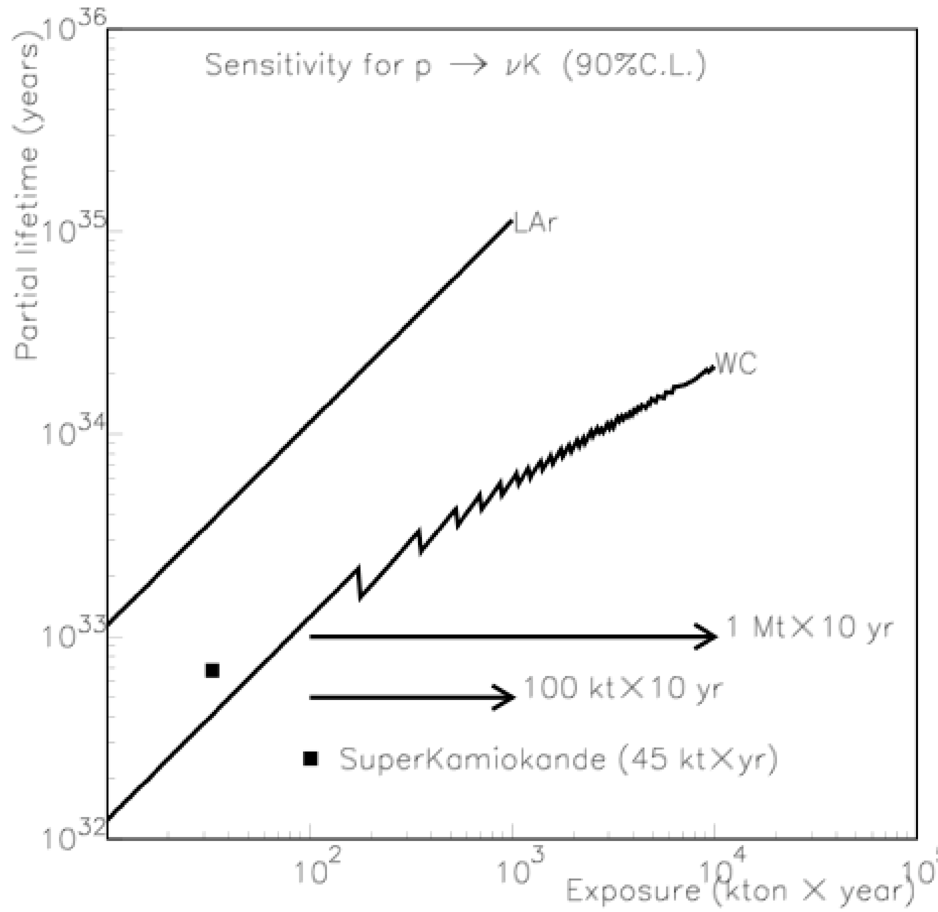
Figure 6: (left) MC event of $p \to K^+\nu$ in a liquid Argon TPC. (right) Real event collected in ICARUS T600 cosmic run performed on surface with a stopping kaon topology

Discovery potential of Water Cerenkov and Liquid Argon technologies

Very massive underground detectors for proton decay searches[1]

A. Rubbia

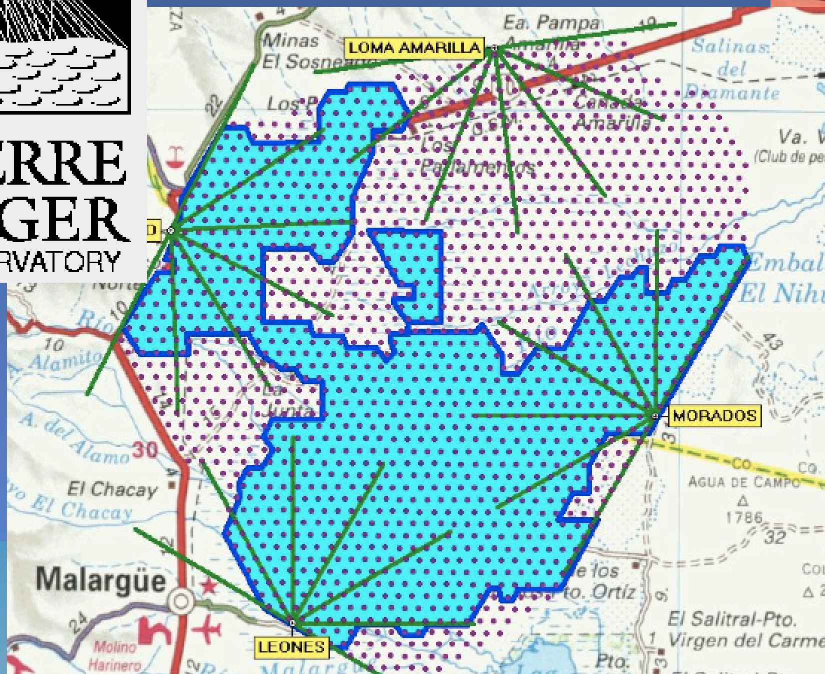


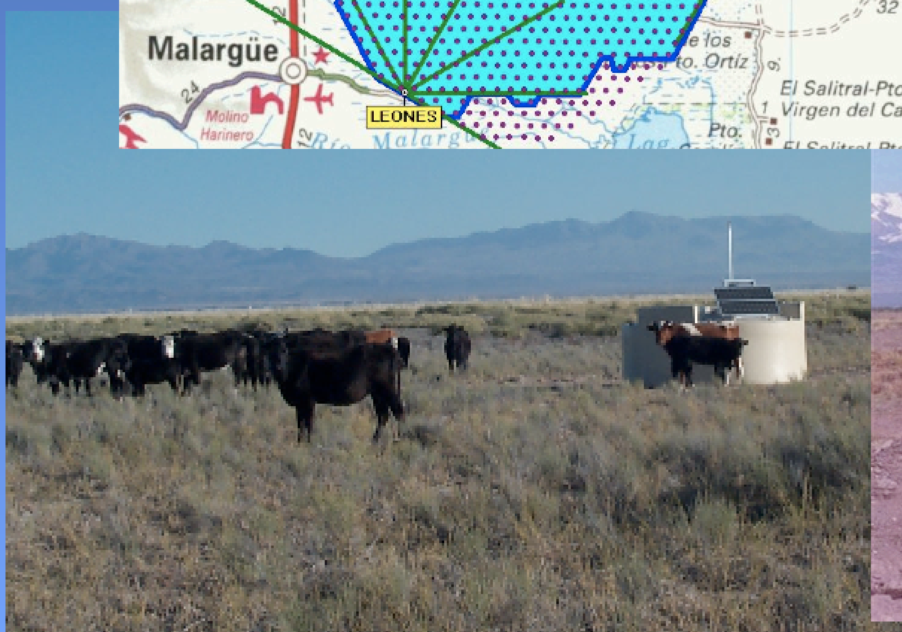


Can we ever observe superheavy particles???

- Yes...if they are among the relics of the Big Bang...and long lived!
- In this case, their decay products appear as Ultra High Energy Cosmic Rays, above the GKZ cutoff at about 10^{20} eV;
- A new installation: the Pierre Auger Observatory in Mendoza (Argentina) started in 2005 the observation of extended air showers from UHECR in the austral hemisphere;
- The PA Observatory is operated by a large international collaboration (many groups from CERN Member States!)
- a second site, in Colorado, was decided last year, to observe the northern sky;
- a few slides for Auger, courtesy of prof. Arnulfo Zepeda.

Montaje del Detector de Superficie





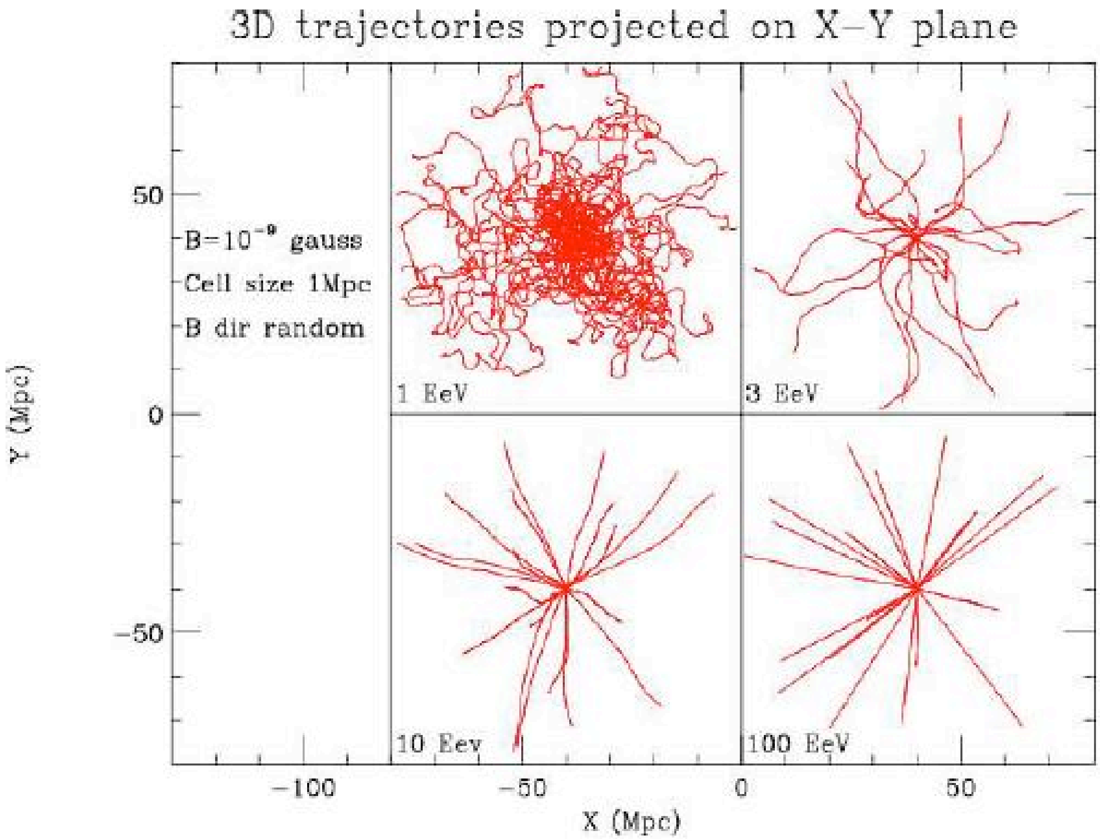
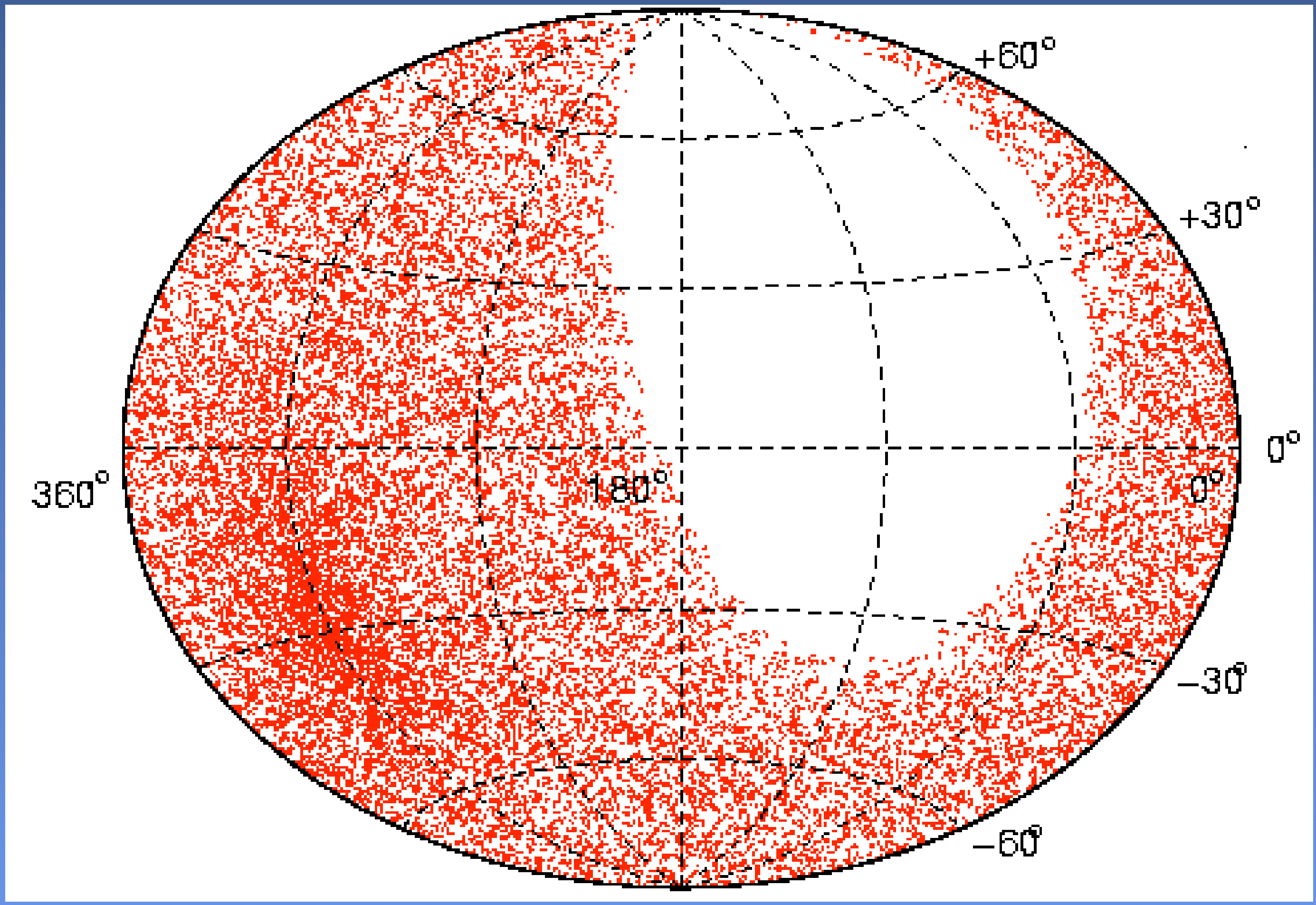


Figure 7: Projected view of 20 trajectories of proton primaries emanating from a point source for several energies. Trajectories are plotted until they reach a physical distance from the source of 40Mpc. See text for details.

Sky Map of Data set

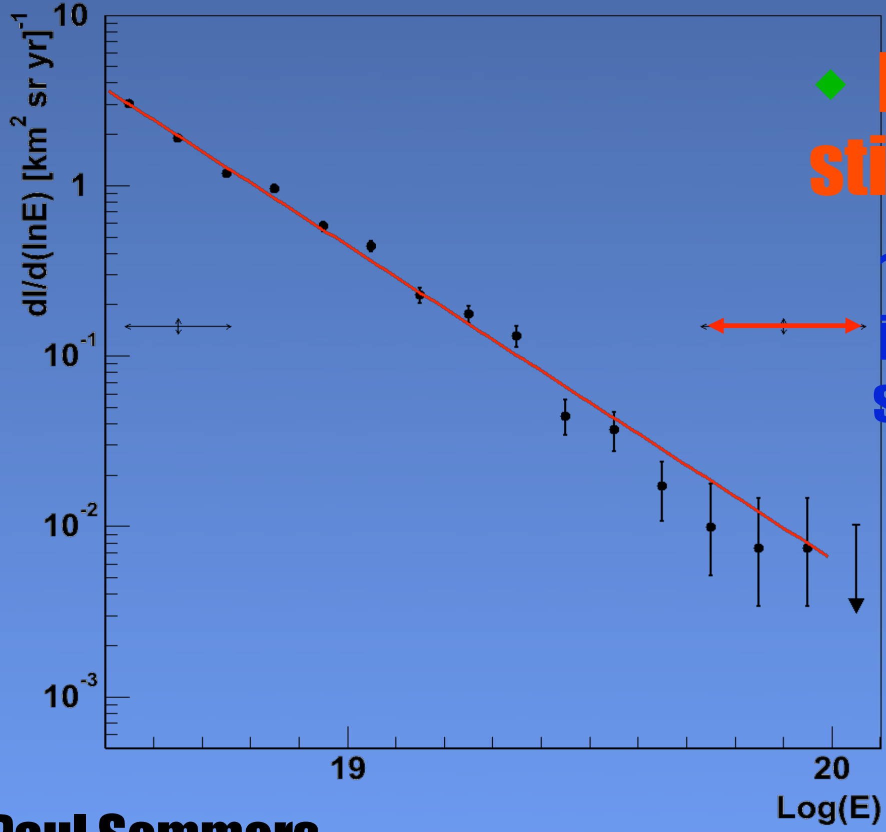


Galactic Coordinates

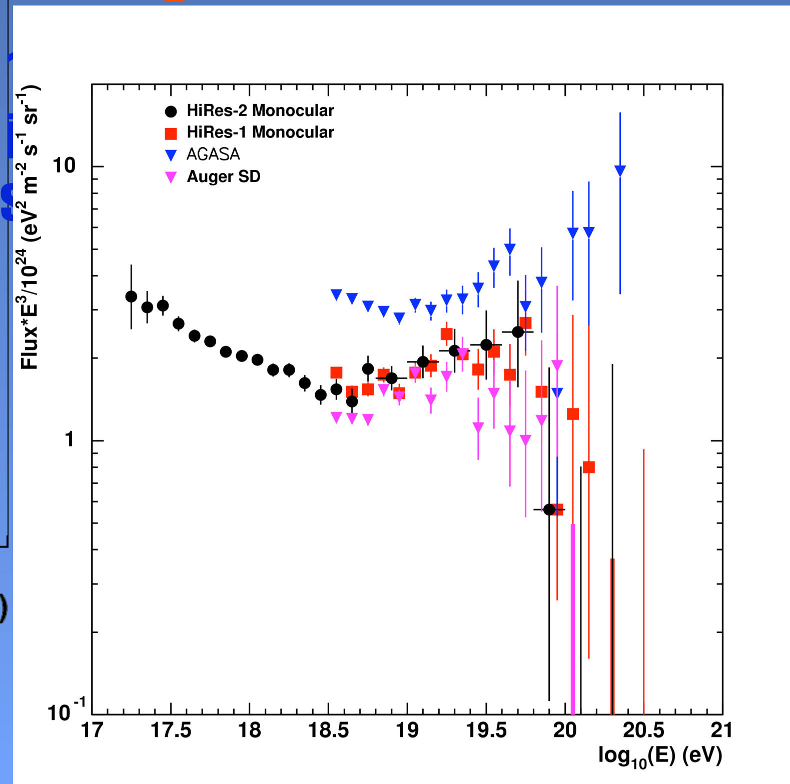
29th ICRC Pune

PIERRE AUGER OBSERVATORY

Auger SD spectrum



- Energy scale uncer. still large



Paul Sommers

Conclusions

- Charge quantization and Anomaly cancellation call for a unified structure for quarks and leptons
- In turn, this requires a SuperHeavy mass level and a finite lifetime for the proton
- The existence of a superheavy mass level is supported by the observed neutrino mass
- Supersymmetry at 1 TeV makes Grand Unification more coherent and calls for $p \to K^+ \nu$ and partial lifetimes in excess of 10^{33} yrs
- The GUT mass may be the level at which new, Kaluza Klein dimensions show up, solving the Higgs triplet mass puzzle: GUT bosons may be n=1 excited KK particles!

Conclusions (cont'd)

- New technologies for water and LAr detectors may allow exploration of the predicted range of lifetimes;

- Decays of superheavy particle may be the source of Ultra High Energy cosmic rays, above the GKZ cutoff at 10^{20} eV;
- if so, superheavy particles can be studied directly with AUGER and its evolutions like EUSO

- if observed, proton decay offers a wealth of different modes, which should reveal the structure of the B-violating interactions.