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LCWS 2000

PROSPECTS FOR FINDING HEAVY MAJORANA NEUTRINO SIGNALS AT THE L.C. IN THE ABSENCE OF $\beta\beta_{0\nu}$.

1) Motivation for possible existence of heavy Majorana neutrinos, N_M.

2) Using the Linear Collider for an N_M search:
   - parameter range,
   - cross-sections,
   - experimental signals,
   - backgrounds.

3) Compatibility with existing evidence:
   - rare decays of leptons
   - neutrinoless double beta decay

4) Conclusions: We will see them if ...

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SEARCH FOR HEAVY MAJORANA NEUTRINOS WITH THE LINEAR COLLIDER

The neutrino mass problem remains one of the most challenging items on our plate when we consider the Standard Model and its limits:

- SM: neutrinos are massless; they are left-handed only.
- We do not know whether they are properly represented by DIRAC or MAJORANA field operators

THE SM. DOES NOT CARE

Mass terms in the Lagrangean:

connect right-handed / left-handed fields

$$-\mathcal{L}_{Dirac} = m_D \bar{\nu}_L N_R + h.c.$$

$$-\mathcal{L}_{Majorana} = \frac{1}{2} m_M \bar{\nu}_L \nu_R^c + h.c$$

- NEUTRINO MASSES

3 known generations

$\left.\begin{array}{l}\nu_e \\ \nu_\mu \\ \nu_\tau\end{array}\right\}$ masses are small, may vanish.

IF $m(\nu_i) = 0$, NO HELICITY FLIP POSSIBLE

→ LEPTON NUMBER MAY BE A MEANINGLESS CONCEPT

DIRAC EQUATION "ALLOWS" FOR THE PARTICLE/ANTIPARTICLE CONCEPT VIA EL. CHARGE

→ IN THE ABSENCE OF CHARGE, HELICITY CONSERVATION MAY BE THE ONLY REASON WHY ν AND $\bar{\nu}$ LOOK DIFFERENT:

$$CPT\,|\ldots;\lambda\rangle \rightarrow |\ldots;-\lambda\rangle$$

FOR $m(\nu) = 0$, THERE IS NO MEANING TO A DIFFERENCE BETWEEN

$\left.\begin{array}{l}\text{DIRAC} \\ \text{MAJORANA}\end{array}\right\}$ MASSES

BUT...

THIS SCENARIO IS STARTING TO CRUMBLE

SOLAR NEUTRINO ANOMALY?

ATMOSPHERIC NEUTRINO ANOMALY?

OSCILLATIONS? LSND ... KARMEN ... KAMIOKANDE ... ?

Irrespective of the outcome of these searches

m_ν = very small (if not ϕ)

for ν_e, ν_μ, ν_τ

HIGHER SYMMETRY SCHEMES WOULD BE PLACATED BY A

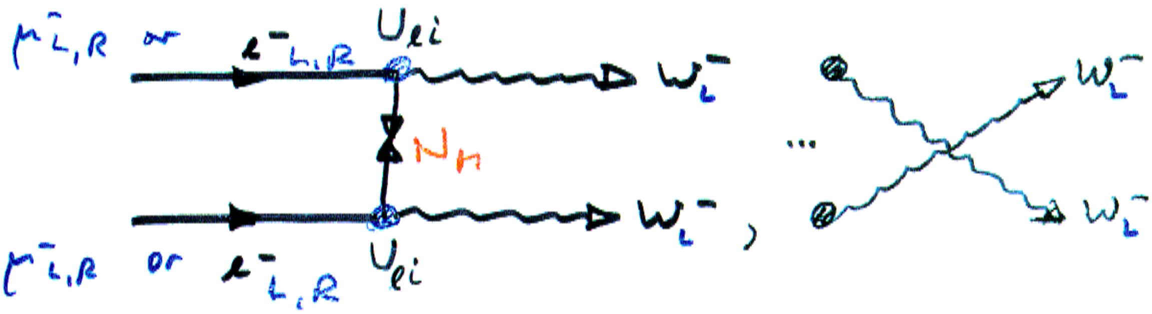
SEE-SAW MECHANISM

$m_\nu \, m_N \approx m_\ell^2$ ← charged lepton mass

↑ O(1 TeV)

A UNIQUE OPPORTUNITY AT LIKE-SIGN MUON & e^-e^- COLLIDERS:

A SIMPLE CONFIGURATION IS ACCESSIBLE



IF CROSS-SECTIONS ARE PROMISING,

THERE ARE SOME UNIQUE ADVANTAGES:

- PLENTIFUL SOURCES AVAILABLE
- EASY BACK-TO-BACK FINAL-STATE KINEMATICS
- POLARIZABILITY OF e^- BEAMS MAKES CHIRAL COUPLINGS ADJUSTABLE !
- ¿ MUON POLARIZATION?

earlier work: Ushio (1982)
Rizzo (1982)
London et al (1987)
Maalampi et al (199[illegible])

work done with
PETER MINKOWSKI

Nuc. Phys. B416, 3 (1994)
Phys Lett. B374, 116 (1996)

WE WORK IN THE KINEMATIC RÉGIME

$$\boxed{2 m_W \ll \sqrt{s} \lesssim M_1}$$

WITH COUPLING/MIXING PARAMETERS (FOR THE ELECTRONS)

$$U_{eA} \qquad\qquad A = 1, 2, (\cdots)$$

THE OVERALL NEUTRINO MASS MATRIX IS THEN

$$\mathcal{M} = \left(\begin{array}{c|ccc|ccc} & & \alpha & & & A & \\ & 1 & 2 & 3 & 1 & 2 & \cdots \\ \hline \alpha \left\{ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} \right. & & 0 & & & \mu^T & \\ \hline A \left\{ \begin{matrix} 1 \\ 2 \\ \vdots \end{matrix} \right. & & \mu & & & M & \end{array} \right)$$

AND

$$\mathcal{M} = U \, m_D \, U^T$$

↳ diagonal matrix

$$m_1, m_2, m_3, M_1, M_2$$

INCLUDING ALL KINEMATIC INTEGRATIONS, WE ARRIVE AT CROSS-SECTIONS

$$\boxed{\sigma(e_i^- e_i^- \xrightarrow{N} W^-_{long} W^-_{long}) \simeq \frac{1}{M^2 [TeV]^2} \left(\frac{s}{M^2} \right)^2 \left(\frac{h_{ei}}{4\pi} \right)^2}$$

mixing parameter (h_{ei})

$$M = \sqrt{M_1 M_2} \gtrsim 1\text{–}10 \ TeV$$

The resulting cross-section estimates are conservative:

they assume ~ equal mixings for μ, e with N_M

↳ which are to be identified with right-handed singlets that occur naturally in the decomposition of $E(6) \to SO(10) \to \cdots \to$ S.M.

They lead to small → respectable event rates for realistic L.C. luminosities

for standard 10^7 sec year:

event rate / y

$\sqrt{s}$	$\mathcal{L}$ \ U_{Ne}	2×10^{-4}	5×10^{-3}
0.5 TeV	$10^{34}\ cm^{-2} sec^{-1}$	0.1	60
1. TeV	10^{34} "	2	1,000
	10^{35} "	20	10,000

- SPECTACULAR FINAL-STATE SIGNALS:

$W^+ \rightarrow$ } back-to-back decays into
$W^- \rightarrow$ }

- reconstructed hadronic jets
- { $\mu^- \mu^-$, $\mu^- e^-$, $\mu^- \tau^-$, $\tau^- e^-$ } with missing $p_\perp$

- All presently discussed L.C. detectors will have a good efficiency for identifying these final states

with good efficiency

IF BACKGROUNDS ARE MANAGEABLE

- Is the principal "generator" of similar signals →

$e^-e^- \to W^-W^- \nu_e \nu_e$

A SERIOUS BACKGROUND TO THE LEPTON-# VIOLATING PROCESS WITH N_M EXCHANGE?

NO!

- $\nu_e \nu_e$ GENERALLY ESCAPE WITH ~ HALF THE C.M. ENERGY

  ⇝ E_{CAL} CUTS WILL DO THE TRICK.

- • ALL BACKGROUND GRAPHS COUPLE A GAUGE BOSON TO e_L

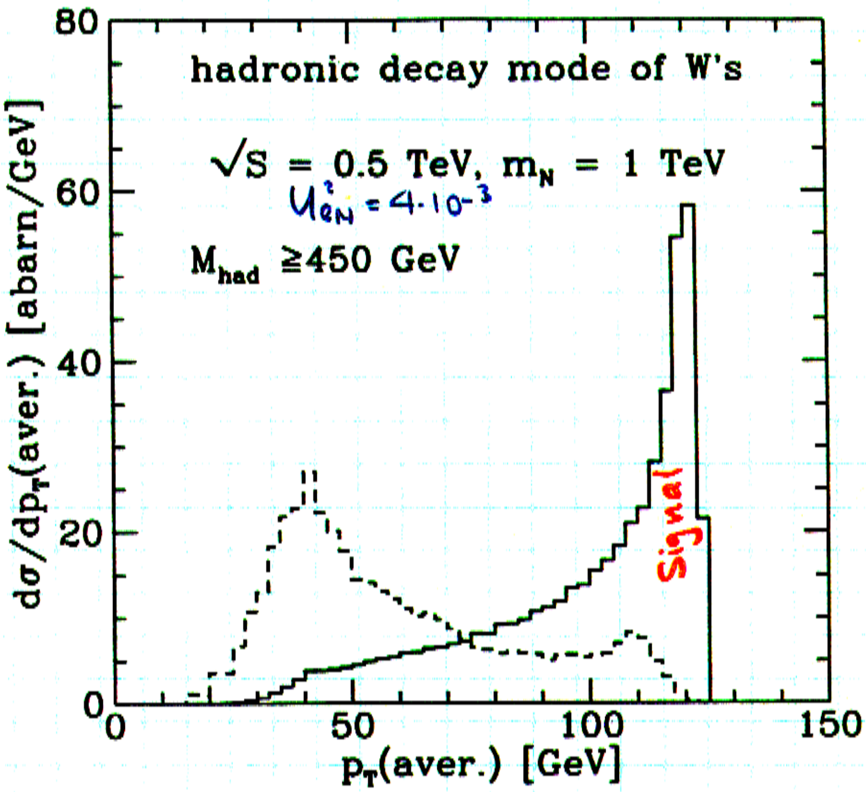
  ⇝ CHANGING THE BEAM POL'N WILL ELIMINATE <u>ALL</u> 9 TOPOLOGIES

  (in the absence of W_R)

bckg: $e^- e^- \to e^- e^- W^+ W^-$

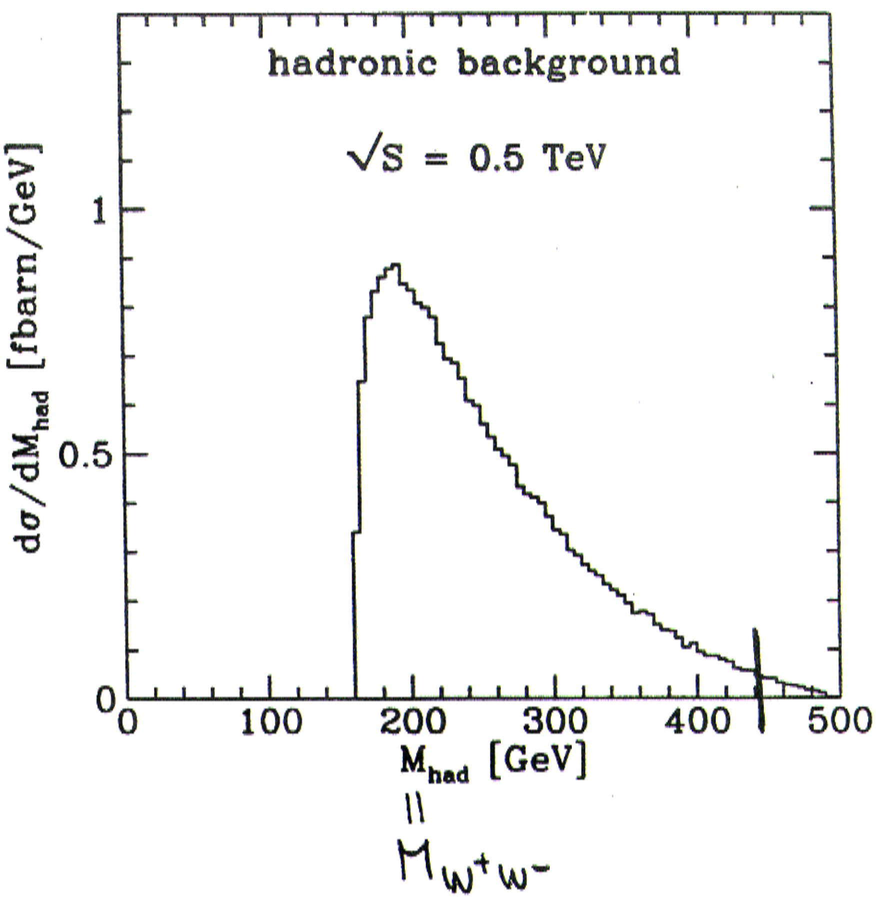
C. Greub

$\sqrt{s} = 500$ GeV



$$p_\perp(\text{aver.}) = \frac{1}{4}\left[|p_\perp|^{\text{jet }1} + \ldots + |p_\perp|^{\text{jet }4}\right]$$

$e_L^- e_L^- \longrightarrow W^+ W^- e^- e^-$
in Weizsäcker Williams approx.



Make a cut somewhere here ⇒ reduces backgr. but not signal

IS THIS COMPATIBLE WITH EVIDENCE ON LEPTON FLAVOR VIOLATION / UNIVERSALITY?

η^N (circled) $\sim U_{ei}$

A COMPARISON OF

- • $\mu^- \to e^- \bar{\nu}_e \overset{(-)}{\nu}_\mu \longleftrightarrow (A,Z) \to (A,Z+1)\, e\, \bar{\nu}_e$
- •• $\pi^\pm \to \mu^\pm \overset{(-)}{\nu}_\mu \longleftrightarrow \pi^\pm \to e^\pm \overset{(-)}{\nu}_e$
- ••• $\mu^- \to e^- \bar{\nu}_e \nu_\mu \longleftrightarrow \tau^- \to \nu_\tau \mu^- \overset{(-)}{\nu}_\mu$

  $\to \nu_\tau e^- \bar{\nu}_e$

PERMIT A CHECK ON **UNIVERSALITY**

$\Rightarrow$ NO SEVERE LIMIT ON $|\eta^{(N)}|$

$|U_{ei}|$

PARAMETRIZATION OF

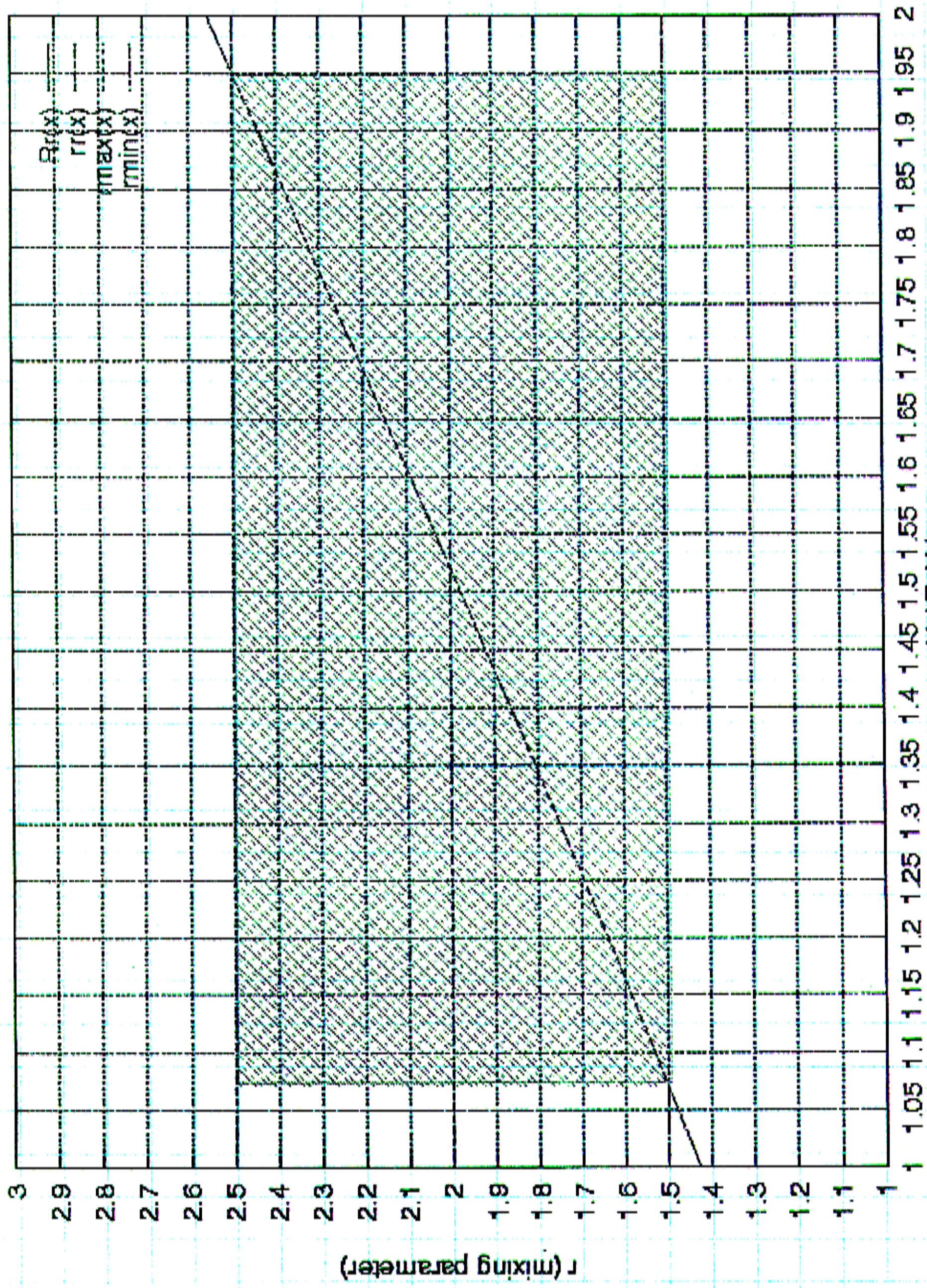
$\mu^\pm \to e^\pm \gamma\,,\ e^\pm e^+ e^-$

$\tau^\pm \to \mu^\pm \gamma\,,\ e^\pm \gamma$

$\mu\,(A,Z) \to e\,(A,Z)$

PERMITS SIMILAR ANALYSIS OF **LEPTON FLAVOR VIOLATION**

$\mu \to e\gamma$, <u>eee</u> IS MOST RESTRICTIVE AND GIVES THE LOWER LIMIT



relative coupling strength $r = |V_{ei}^2| / 2\times10^{-4}$

Discovery limit (> 8 events/year) at $\sqrt{s} = 0.5$ TeV e^-e^- collider

Figure 1: Discovery potential for a heavy neutrino flavor in the coupling and mass parameter space r , M. The range corresponding to $1.5 \le r \le 2.5$ is shown as shaded region.

IS SIMILAR INFORMATION AVAILABLE FROM OTHER SOURCES ?

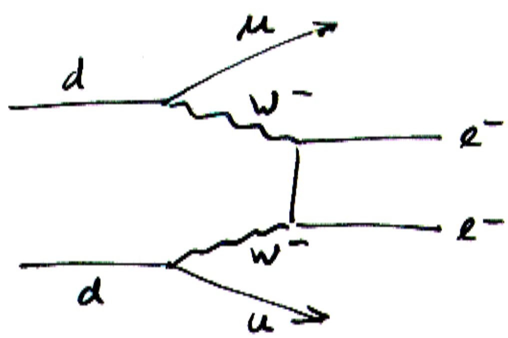
THE CLASSICAL STUDIES OF MAJORANA VS. DIRAC NATURE OF NEUTRINO MASS ARE DONE BY THE SEARCH FOR

NEUTRINO-LESS DOUBLE β DECAY.

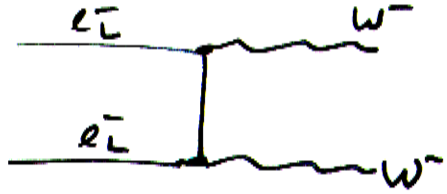
$$ {}^{Z}_{A}N \to {}^{Z+2}_{A}N' + \boxed{2e} $$

line spectrum

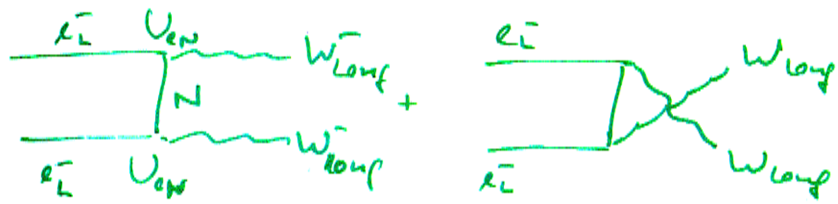
BUT:



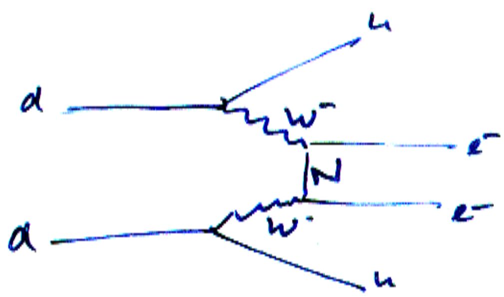
IS **NOT** SIMPLY THE INVERSE OF



Recall we are comparing



with



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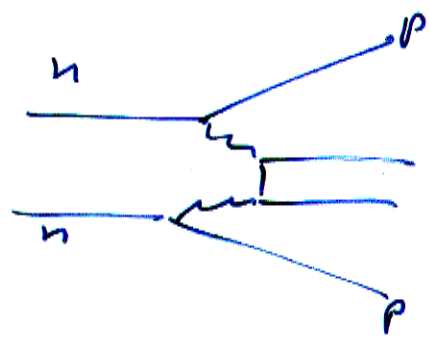

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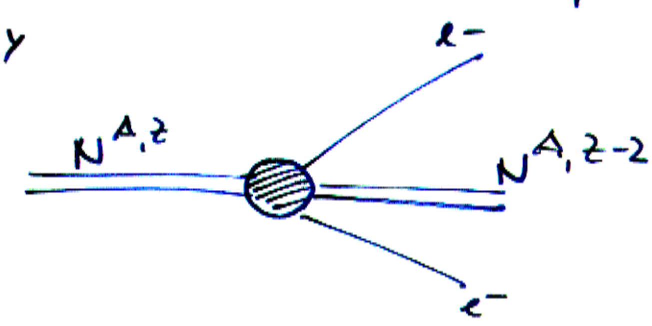
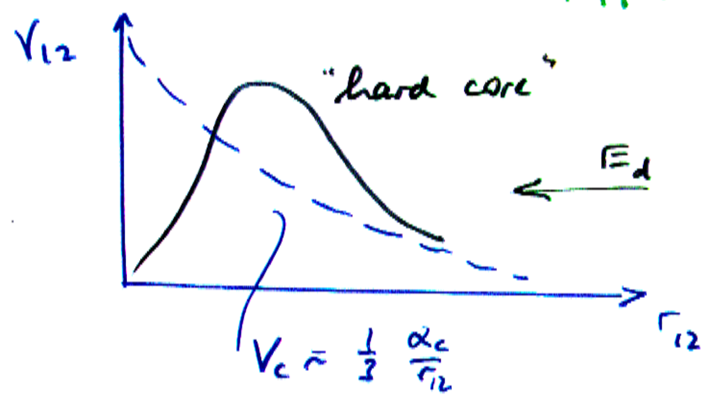


TRUE "INVERSE ββ$_{0\nu}$" WOULD BE ...

$\sim e^- e^- \, {}^{76}Se \to {}^{76}Ge$

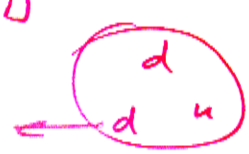
TWO d QUARKS FROM 2 NEUTRONS INSIDE THE NUCLEUS NEED TO APPROACH WITHIN 10^{-16} cm !

THE COLOR COULOMB BARRIER WILL TRY TO FORBID THAT:



2 neutrons (color-saturated ddu groupings) will have to approach such that 2 d's – one from each n – will be within $\sim 10^{-16}$ cm of each other

- COLOR FACTOR OF 3
- COULOMB "HARD CORE" PENETRATION
- BREAKING UP COLOR-SATURATED



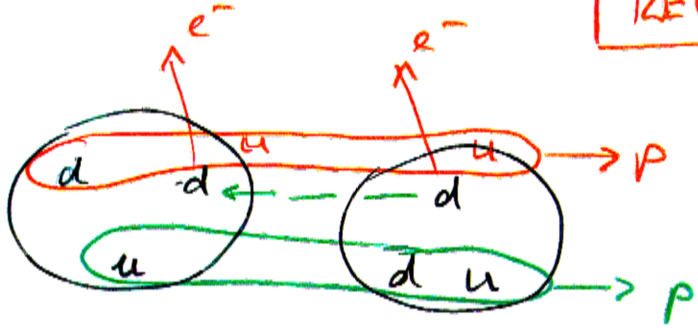
2 possibilities:

- SPIN - SINGLET dd

  → EXCLUSION PRINCIPLE DICTATES

- COLOR $\underset{\sim}{6}$ dd

REPULSIVE

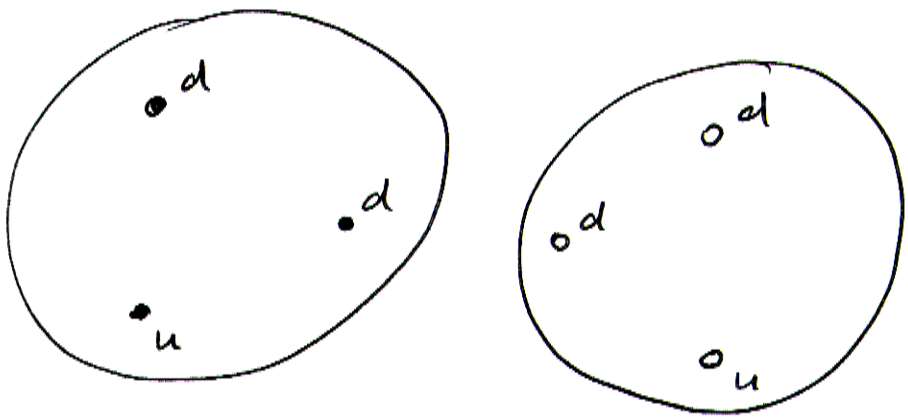


WE ESTIMATE DEPRESSION BY A FACTOR OF > 100!

- SPIN - TRIPLET dd
- COLOR $\underset{\sim}{\bar{3}}$ dd

ATTRACTIVE

BUT: ANOTHER SUPPRESSION FROM SPIN dd $\underset{\sim}{3}$ CONFIGURATION, POSSIBLE ONLY IN Δ (inside nucleus)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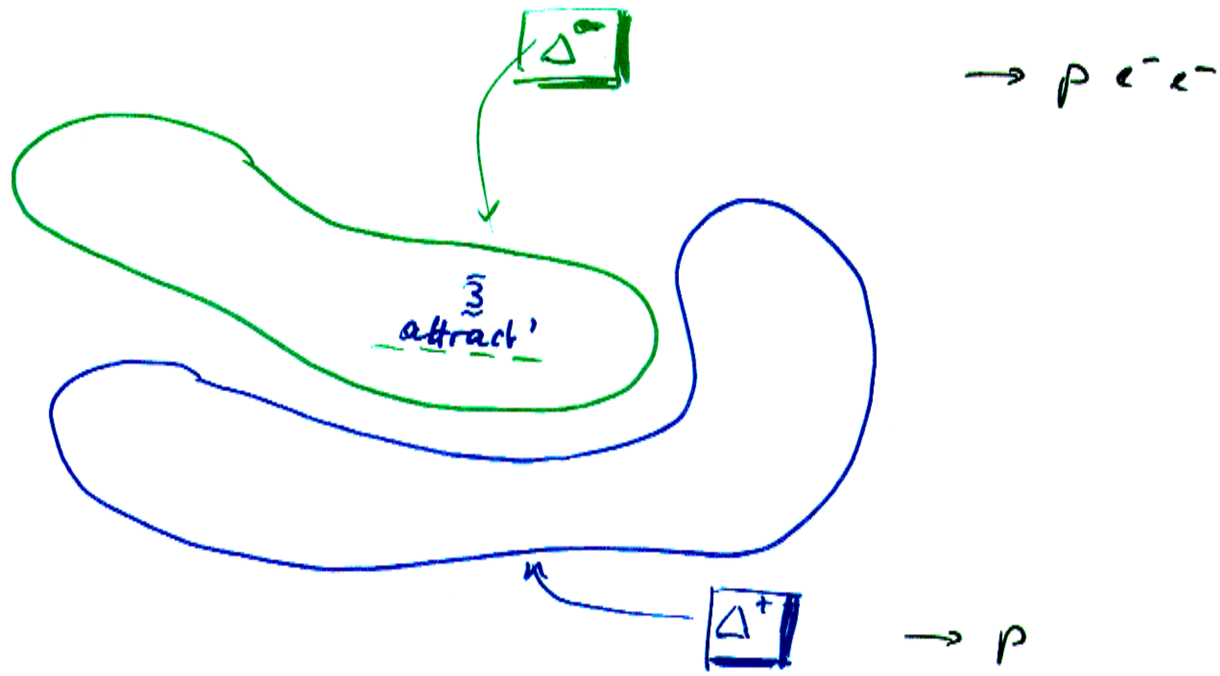
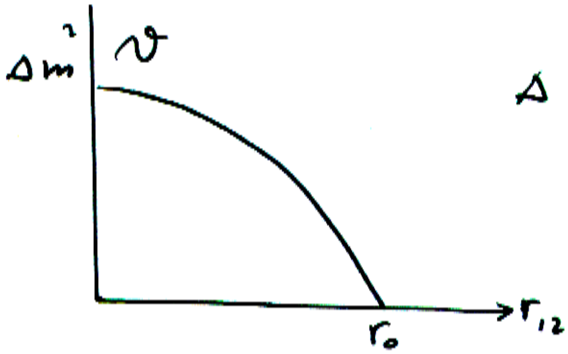


and, of course, the two protons have to find their home in the daughter nucleus

$$N^{A,Z} \longrightarrow N^{A,Z-2}\, e^- e^-$$

Estimate the threshold ("hard core") to penetrate in this case

$$\frac{S_{dd}}{2} \sim \Delta m^2 \rightarrow p^2 + V$$



$$\Delta m = m(\Delta) - m(n) \approx 0.3 \text{ GeV}$$

$$V_2 \sim \Delta m^2 \left(1 - \frac{r^2}{r_0^2}\right)$$

So, altogether we're looking at a factor

for $S \rightarrow nn \rightarrow \Delta^+ \Delta^-$

with $\Delta m^2 = m_\Delta^2 - m_n^2$

$$S \sim \frac{\pi}{4} \sqrt{\Delta m^2} \; r_{12} \, (dd)$$

($\sqrt{\Delta m^2}$ ~ 600 MeV)

choose $r_{12} \sim 1$ fm for triplet case

$$S = \sqrt{\Delta m^2} \int_0^{r_0} dr \sqrt{1 - \frac{r^2}{r_0^2}}$$

⟶ a more refined treatment leads to a suppression factor of 50 – 80, to be multiplied by the color suppression factor 3.

BOTH spin $\underset{\sim}{1}$, color $\underline{6}$ } eventually lead
spin $\underset{\sim}{3}$, color $\underline{\overline{3}}$ }

to strong suppression of N_H exchange in nuclei

PRESENT OR EXPECTED NON-OBSERVATION OF $\beta\beta_{0\nu}$ DOES NOT CONSTRAIN $e^-e^- \xrightarrow[N_H]{} W^-W^-$ SIGNAL

CONCLUSIONS

- THE LINEAR COLLIDER CAN MEASURE W^-W^- PRODUCTION FROM e^-e^- COLLISIONS, MEDIATED BY HEAVY MAJORANA NEUTRINOS.
- SIGNALS ARE UNMISTAKEABLE.
- ENERGIES, LUMINOSITIES OF TESLA, ILC ARE SUFFICIENT.
- EASY POLARIZATION SWITCH FROM $e_L e_L$ TO $e_L e_R$ OR $e_R e_R$ IS VITAL FOR SIGNAL IDENTIFICATION, BACKGROUND SUPPRESSION.
- A SIGNAL FOR N_M OF TeV MASS WILL ALSO ESTABLISH A 10^{-16} cm LOOK AT QUARK-QUARK INTERACTIONS IF N_M IS NOT MEDIATING $\beta\beta_{no\,\nu}$
- A N_M SIGNAL WILL HELP TO RESOLVE TWO UNEXPLAINED ODDITIES OF THE S.M.:

  $m_\nu \approx 0$

  m_D vs. m_M

AND DON'T FORGET:

THE CHARACTERISTIC ENERGY DEPENDENCE OF

$$e^-_L e^-_L \xrightarrow{N_m} W^- W^-$$

GIVES A DIRECT MEASUREMENT OF m_{N_m} AND MIXING PARAMETERS U_{ei}

whereas

a signal from $\beta\beta_{0\nu}$ is interpretable by a multiple array of processes other than ν_m — (SUSY graphs, ...)

gives no decisive evidence.

(→ Oxford proc.)