LHC AND THE ORIGIN OF NEUTRINO MASS

Goran Senjanović

ICTP

B. Bajc, G. S., 06

B.Bajc, M. Nemevšek, G. S., 07

In progress with A. Arhrib, B. Bajc, D. Ghosh, T. Han, G.-Y. Huang, I. Puljak, neutrinos massive but light

$m_\nu \lesssim 1eV$ from beta decay

$$\Delta m_A^2 \sim 10^{-3} eV^2 \qquad \Delta m_{sun}^2 \sim 10^{-5} eV^2$$

how come they are so different from charged fermions?

With the degrees of freedom of the SM

ν masses parametrized by

Weinberg $d = 5$ effective operator

$$\mathcal{L} = Y_{ij} \frac{L_i H H L_j}{M}$$

L - left-handed leptonic doublet

H - Higgs doublet (with a vev v)

$$\frac{v^2}{M} Y = U_{PMNS} \; m_\nu^{diag} \; U_{PMNS}^T$$

neutrino mass - Majorana

M signals the appearence of new physics majorana neutrinos

Violation of lepton number: $\Delta L = 2$

- neutrino-less double beta decay $\nu 0\beta\beta$

  a text-book fact

- same sign charged lepton pairs in colliders

Keung, G.S., 83

charged fermions cannot be majorana

- If M is huge, no hope of direct observation of new physics
- $M = 10^{13} GeV - 10^{14} GeV$ corresponds to Y of order one
- However, small Yukawas are natural in a sense of being protected by symmetries

  and most of the SM Yukawas are small
- Keep M free and look for theoretical predictions (grand unification)

Only 3 ways of producing the Weinberg operator

By exchange of heavy

- fermion singlet $(1_C, 1_W, Y = 0)$ TYPE I SEESAW

  right-handed neutrino

  Minkowski, 77

  Mohapatra, Senjanović, 79

  Gell-Mann et al, 79

  Glashow, 79

  Yanagida, 79

- boson weak triplet $(1_C, 3_W, Y = 2)$ TYPE II SEESAW

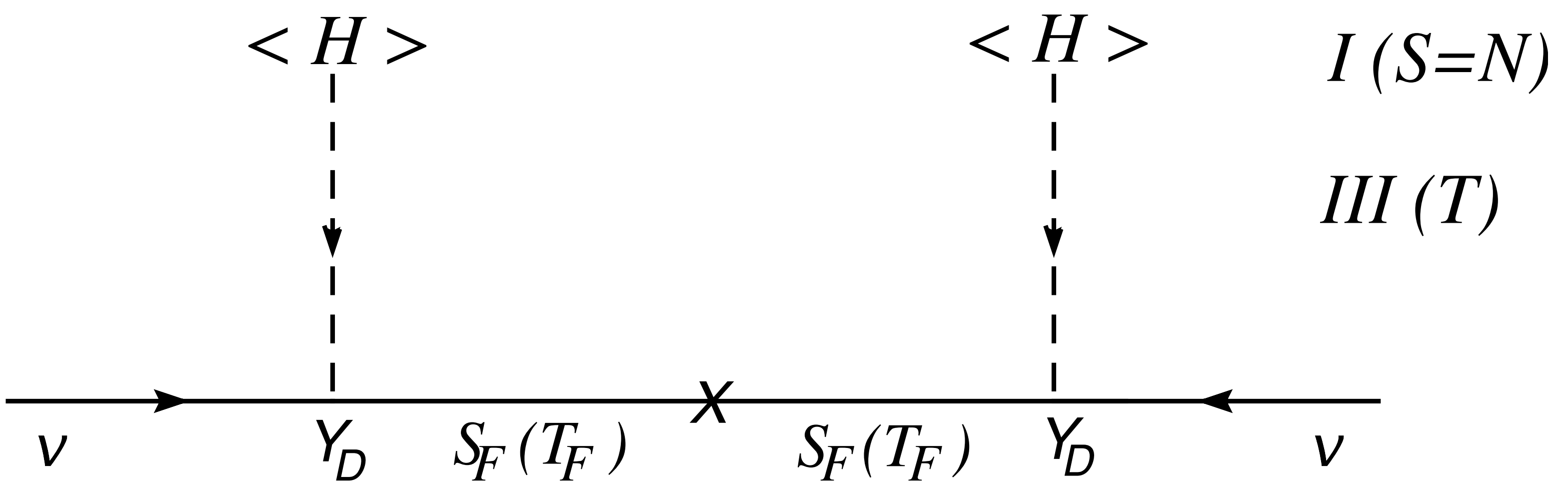
  Lazarides et al, 80

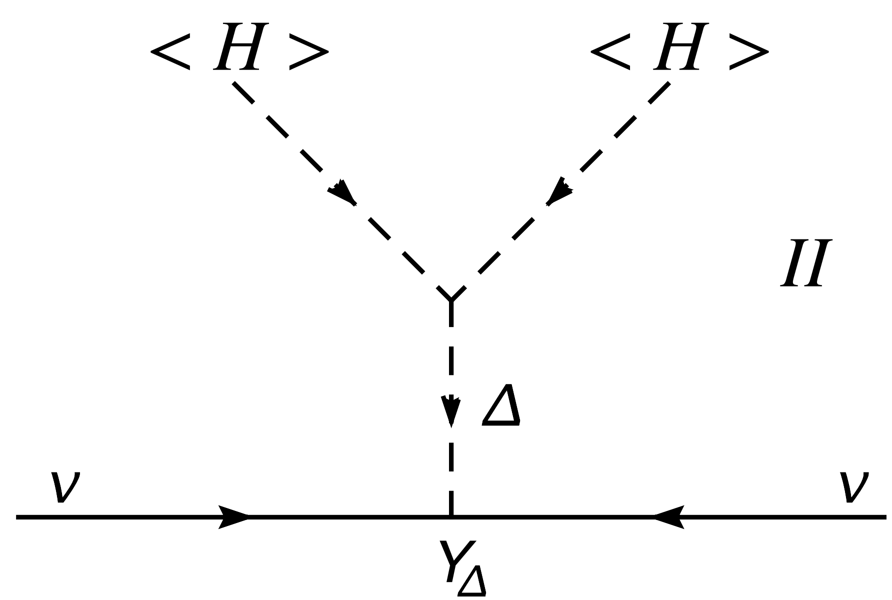
  Mohapatra, Senjanović, 80

- fermion weak triplet $(1_C, 3_W, Y = 0)$ TYPE III SEESAW

Foot et al, 86

I and II very well studied, III almost ignored in the past


< H >
< H >
I (S=N)
III (T)
ν
Y_D
S_F (T_F)
X
S_F (T_F)
Y_D
ν



< H >
< H >
II
Δ
ν
ν
Y_Δ

the three types of seesaw - the same d=5 operator

by itself not more useful than just Weinberg operator

unless

- we can reach the scale M
- we have a theory of these singlets, triplets (GUT for example)

This reminiscent of the Fermi theory of low energy weak interactions:

saying that the four fermion interactions can be described by the exchange of a W boson

useful

- when you can reach the new scale (M_W)
- you have a theory of this new particle: $SU(2)_L \times U(1)$ SM

correlates different processes at low energies $E << M_W$

ν mass window to new physics - if Majorana

- Dirac case complete - new physics not necessary.

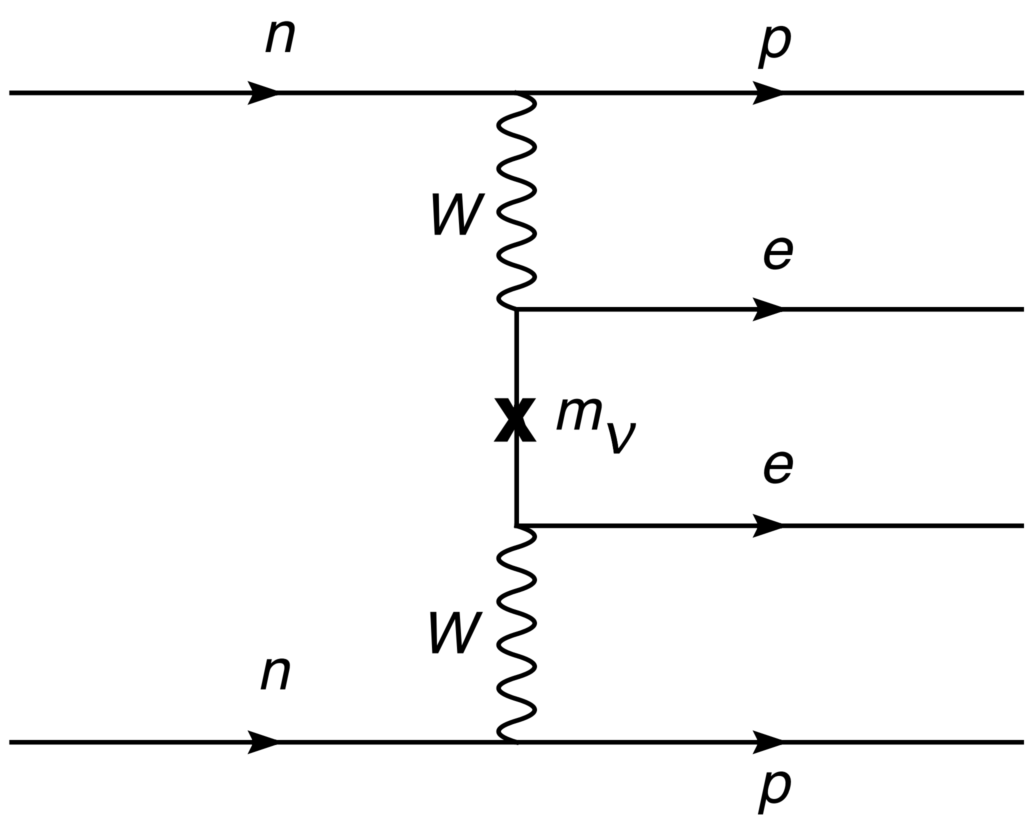
  only neutrino oscillations. the rest, such as LFV suppressed by small neutrino masses ($m_\nu \lesssim 1 eV$ from beta decay)

- SM with Majorana neutrino not complete

  BSM theory a must

- Majorana case connects m_ν to different new phenomena like

  desperately searched for $\nu 0\beta\beta$ decay

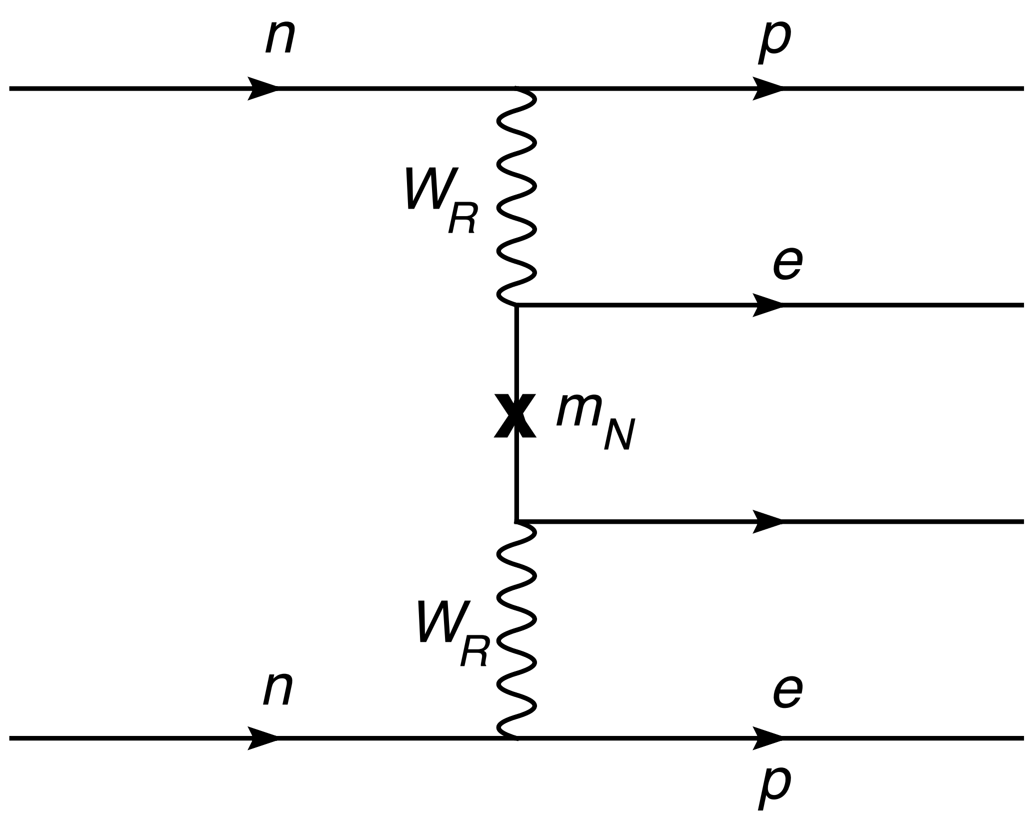

n
p
W
e
m
ν
e
W
n
p

probes m_ν in the region: 0.1 - 1 eV

However, in general m_ν not directly connected to $\nu 0\beta\beta$ decay:
depends on the completion of SM

Example:

LR symmetry with low W_R, ν_R masses has a nonzero $\nu 0\beta\beta$ decay even with y_D, $m_\nu \to 0$


n
p
W_R
e
m_N
W_R
n
e
p

easily dominates for M_R in the TeV region, and M_N in the 100 - 1000 GeV

This is why it is important for the see-saw to be traced in colliders:

measure $\Delta L = 2$ operators not only in $\nu 0\beta\beta$ decays, but also in colliders

Keung, Senjanović, 83

L-R symmetric theories:

$$SU(2_L)\times SU(2)_R\times \mathrm{U}(1)$$

Pati, Salam, Mohapatra, G.S.

- W_L implies W_R

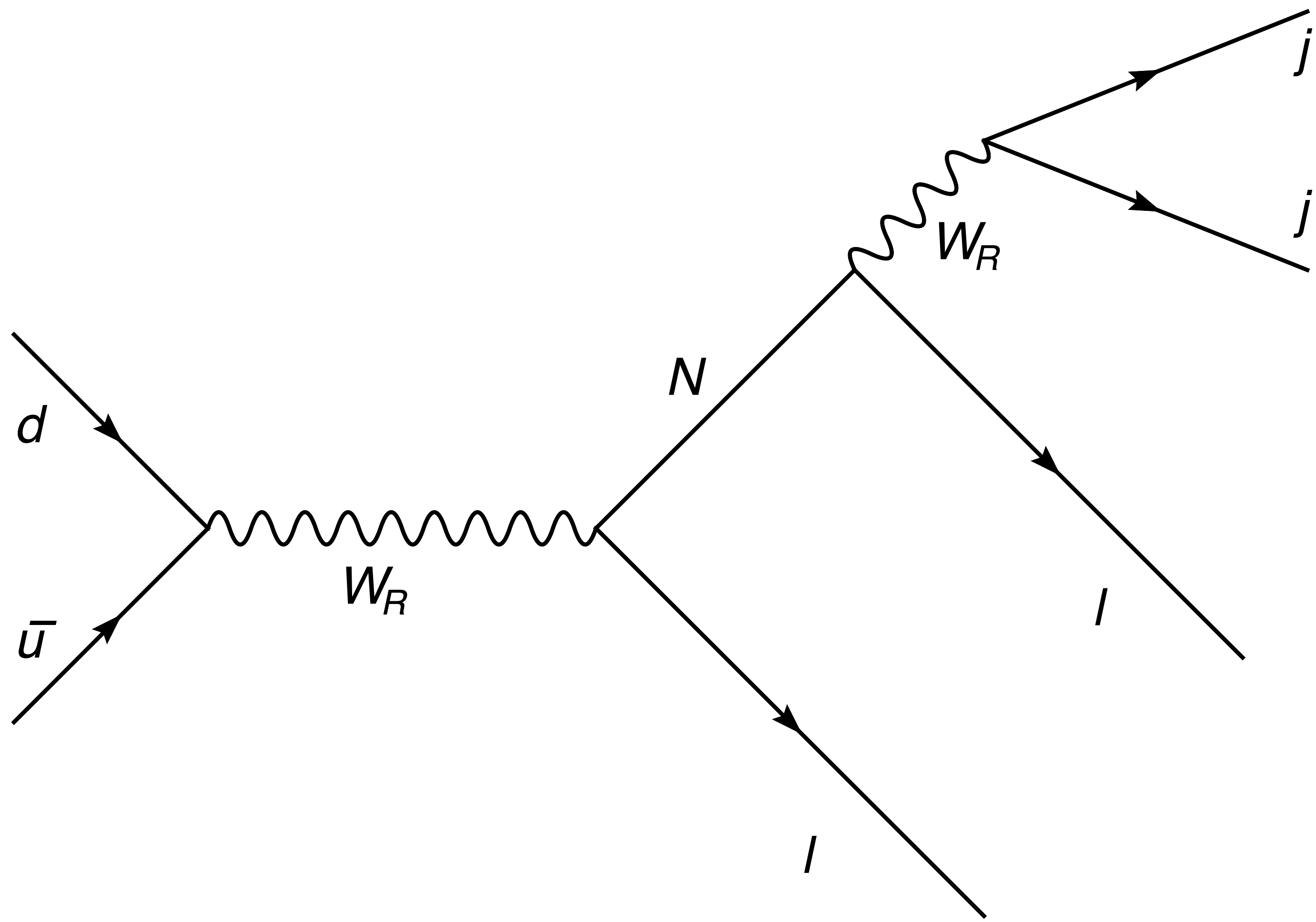
  $M_R \gtrsim 1.6\ TeV$ from $K_L - K_S$ mixing (theoretical limit in the minimal model)

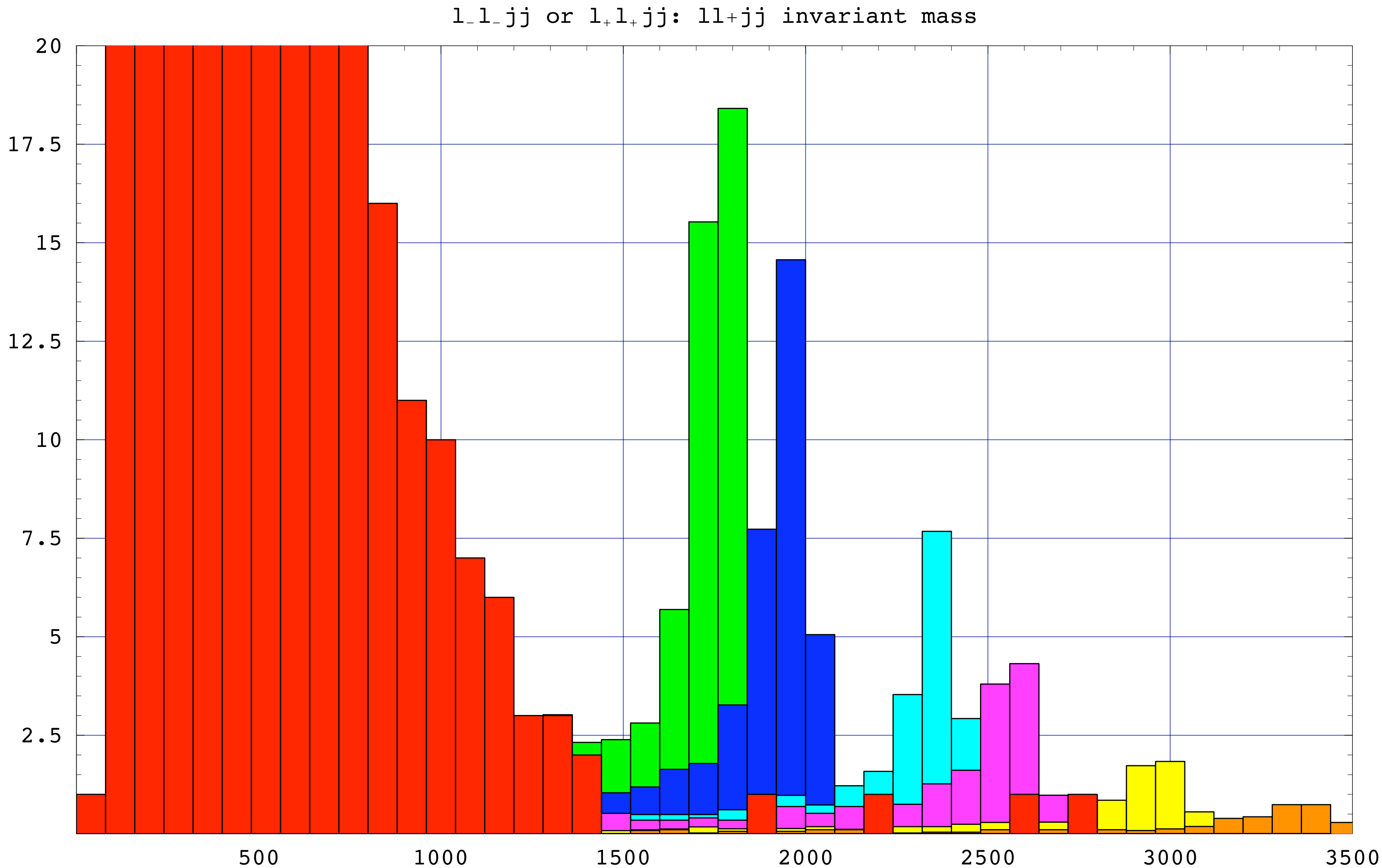
- ν_L implies ν_R

  m_{ν_R} of order M_R

- Type I seesaw: connects neutrino mass to scale of parity restoration

- colliders: produce W_R through Drell-Yan


j
j
W_R
N
d
l
$\bar{u}$
W_R
l



number of events for $L = 8fb^{-1}$ (courtesy of F. Nesti)

$M_R(TeV) = 1.8 \quad 2 \quad 2.4 \quad 2.6 \quad 3 \quad 3.4$

- direct test of parity restoration: discovery of W_R just as W_L at SPS 25 years ago
- direct test of lepton number violation
- determination of W_R and N masses

Ferrari et al, 99

Gninenko et al, 07

CMS study, in preparation

LHC easily probes W_R up to 3.5 TeV and ν_R in 100 - 1000 GeV

for integrated luminosity of 30 fb^{-1}

needs study of flavor dependence - connection with flavor violation:

$$\mu \to e\gamma,\ \mu \to ee\bar{e}$$

Nesti, Tello, GS, work in progress

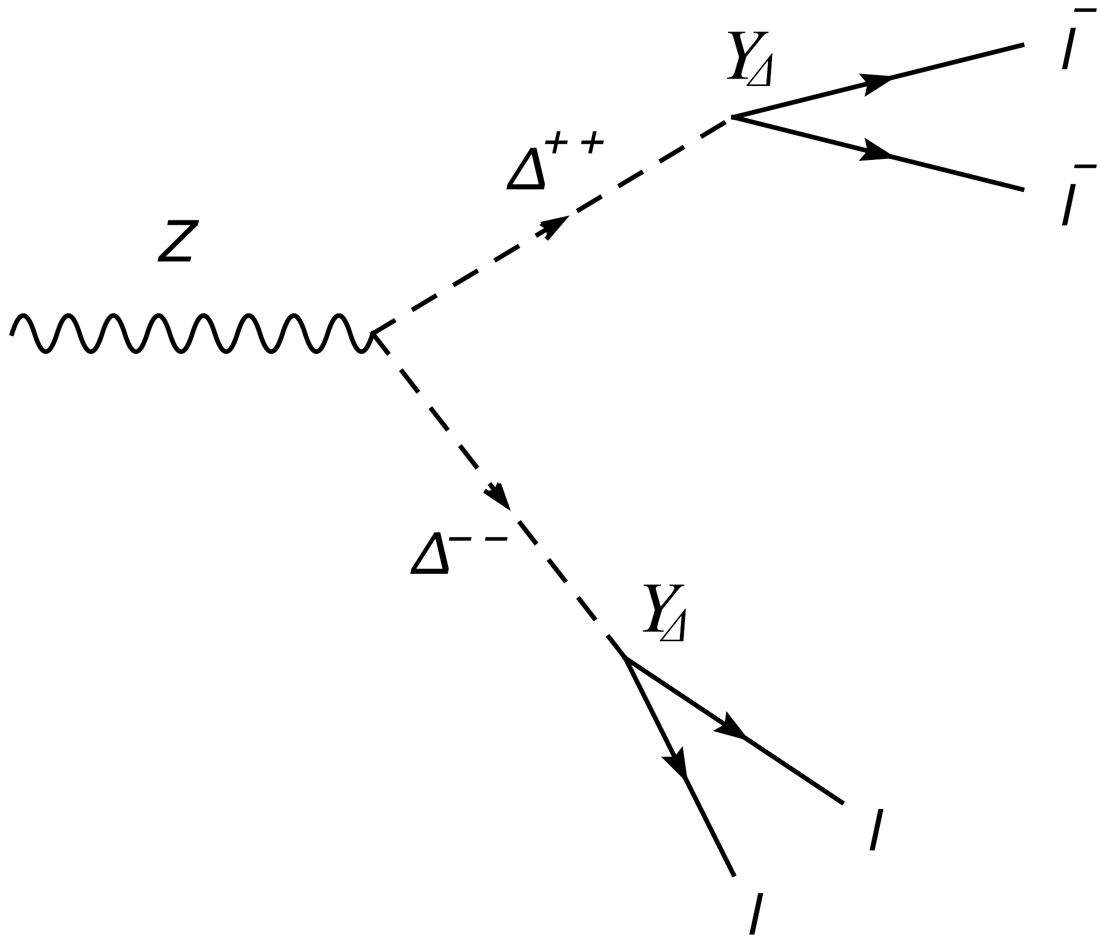
L-R theory: also type II

Type II: pair production of doubly charged Higgses which decay into same sign lepton (anti lepton) pairs

$$M_\nu = Y_\Delta v_\Delta$$

probe directly M_ν if no type I

Kadastik, Raidal, Rebane,07 and references therein



Z
Δ++
Δ− −
Y_Δ
Y_Δ
l̄
l̄
l
l

Datta, Guchait, Pilaftsis, 93

Datta, Guchait, Roy, 93

Ferrari et al, 99

Han, Zhang, 06

Gninenko et al, 07

del Aguila, Aguilar-Saveedra, Pittau, 07

del Aguila, Aguilar-Saveedra, 07

Han et al, 07

Akeroyd, Aoki, Sugiyama, 07

Fileviez Perez et al, 07

Kadastik, Raidal, Rebane,07

Kersten and Smirnov, 07

Chao et al, 08

Franceschini, Hambye, Strumia, 08

Fileviez Perez et al, 08

many more in type I and also type II

seesaw scale: grand unification

Simple predictive GUT with seesaw at LHC?

MINIMAL (non supersymmetric) SU(5)

The minimal Georgi-Glashow model ruled out because

Minimal: $24_H + 5_H + 3(10_F + \overline{5}_F)$

1. gauge couplings do not unify

   - 2 and 3 meet at 10^{16} GeV (as in susy),

   - but 1 meets 2 too early at $\approx 10^{13}$ GeV

2. neutrinos massless (as in the SM)

   possible higher dimensional operator not enough: neutrino mass too small ($\lesssim 10^{-4} eV$)

Weinberg $d = 5$ effective operator

$$\mathcal{L} = Y_{ij} \frac{L_i H H L_j}{M}$$

where now $H = 5_H$, $L = \overline{5}_F$

and

$M \gtrsim 10 \times \mathrm{M_{GUT}} \gtrsim 10^{17}$ GeV (needed for perturbativity)

gives

$$m^{\nu} \approx Y \frac{v^2}{M} \lesssim 10^{-4}\,\mathrm{eV}$$

Add just one extra fermionic 24_F

Under $SU(3)_C \times SU(2)_W \times U(1)_Y$ decomposition

$$24_F = (1,1)_0 + (1,3)_0 + (8,1)_0 + (3,2)_{5/6} + (\bar{3},2)_{-5/6}$$

Bajc, Nemevsek, G.S.

singlet $S = (1, 1)_0$
triplet $T = (1, 3)_0$

$$\mathcal{L}_{Y\nu} = L_i \left(y_T^i T + y_S^i S \right) H + h.c.$$

Mixed Type I and Type III seesaw:

$$(M_\nu)^{ij} = v^2 \left(\frac{y_T^i y_T^j}{m_T} + \frac{y_S^i y_S^j}{m_S} \right)$$

one massless neutrino

hierarchical spectrum

either normal or inverse hierarchy

1-loop result:

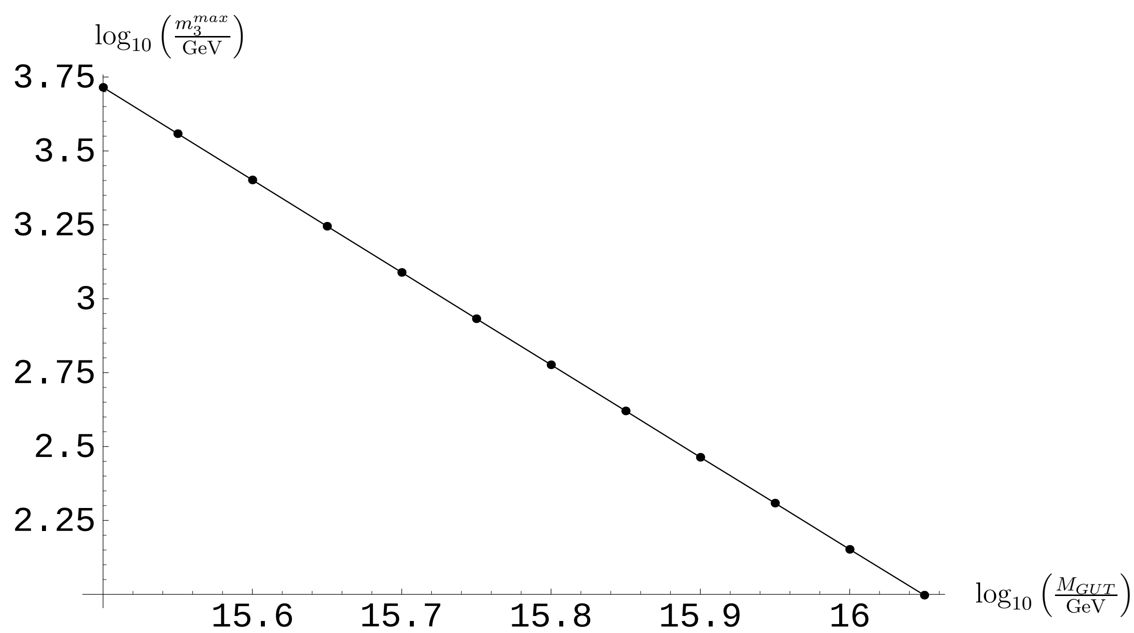
$$M_{GUT} \gtrsim 10^{15.5}\ \mathrm{GeV}\ (\tau_p \gtrsim 10^{33} yr)$$

$$\rightarrow m_3 \lesssim 1\mathrm{TeV}$$

triplet (like wino in MSSM) slows down $U(1)$ coupling

effectively: light wino, gluino heavy ($10^7 GeV$), no higgsino, no sfermions (irrelevant for unification - split susy)

$m_3^{max} - M_{GUT}$ at two loops

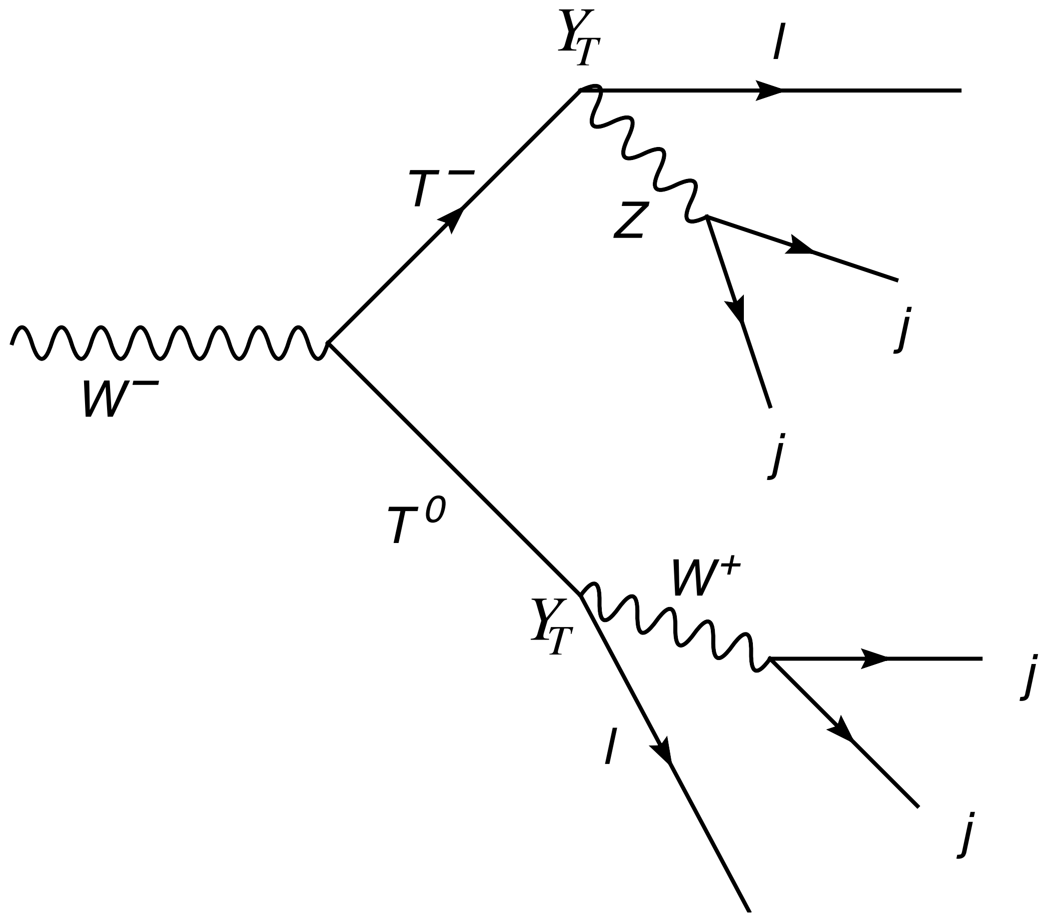


T at LHC ?

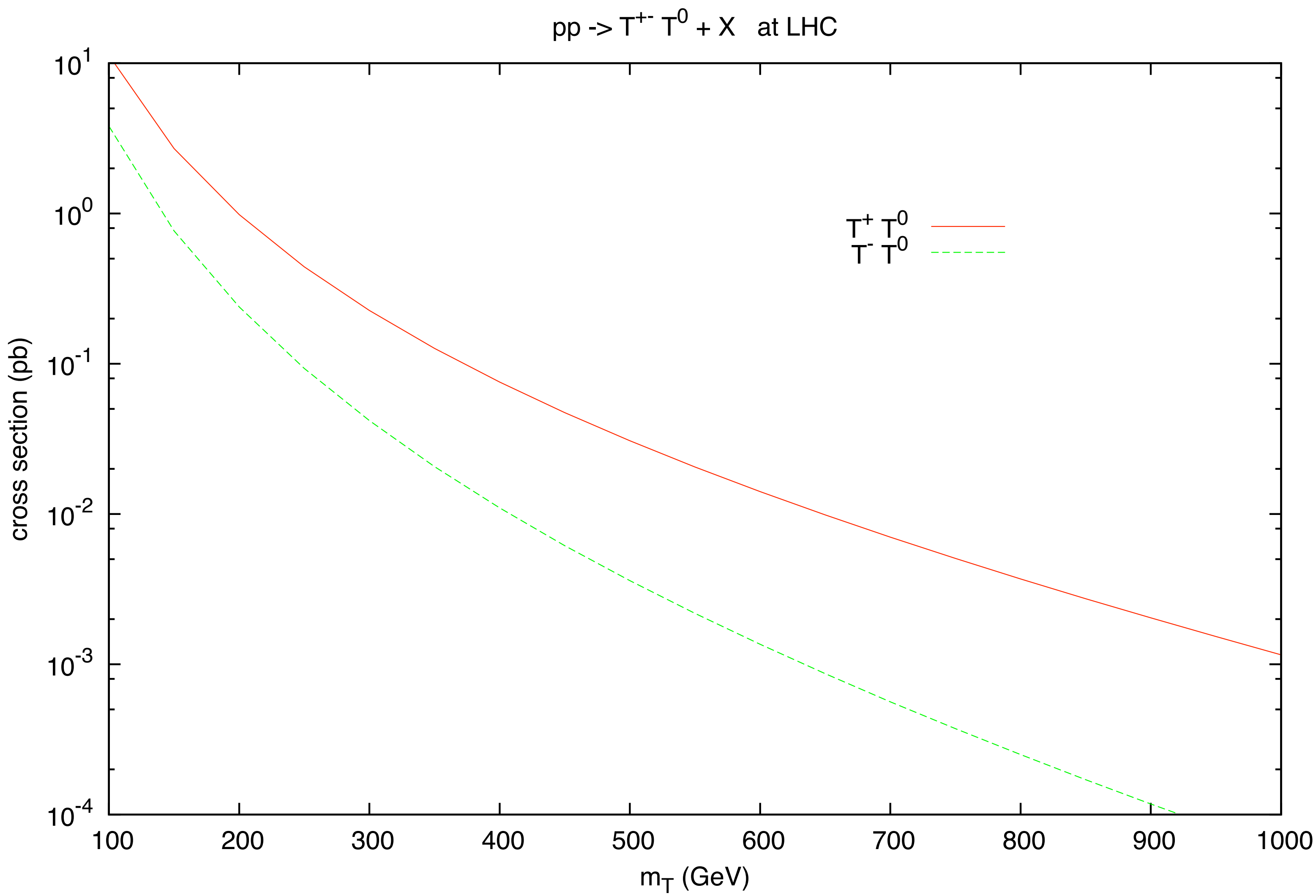
$T^{0,\pm}$ weak triplet

$\longrightarrow$ produced through gauge interactions (Drell-Yan)

$$pp \to W^{\pm} + X \to T^{\pm}T^{0} + X$$
$$pp \to (Z \,\mathrm{or}\, \gamma) + X \to T^{+}T^{-} + X$$



Y_T
l
T^-
Z
j
W^-
j
T^0
W^+
Y_T
j
l
j


pp -> T+- T0 + X at LHC
cross section (pb)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
100
200
300
400
500
600
700
800
900
1000
mT (GeV)
T+ T0
T- T0

$$\Gamma_T \approx m_T |y_T|^2$$

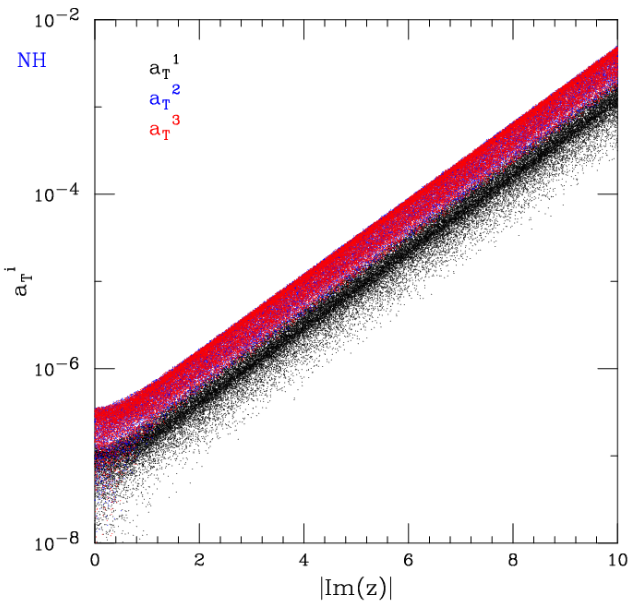
The best channel is like-sign dileptons + jets

$$BR(T^\pm T^0 \to l_i^\pm l_j^\pm + 4 \text{ jets}) \approx \frac{1}{20} \times \frac{|y_T^i|^2 |y_T^j|^2}{(\sum_k |y_T^k|^2)^2}$$

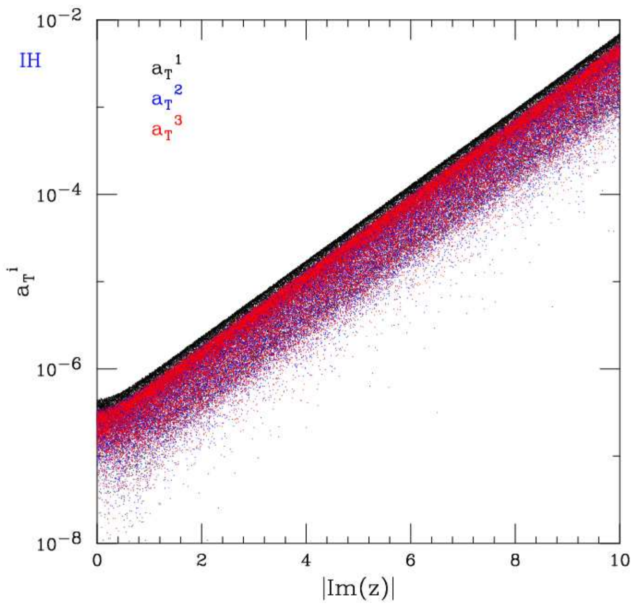
Same couplings y_T^i contribute to

- ν mass matrix
- T decays

Scanning over whole parameter space

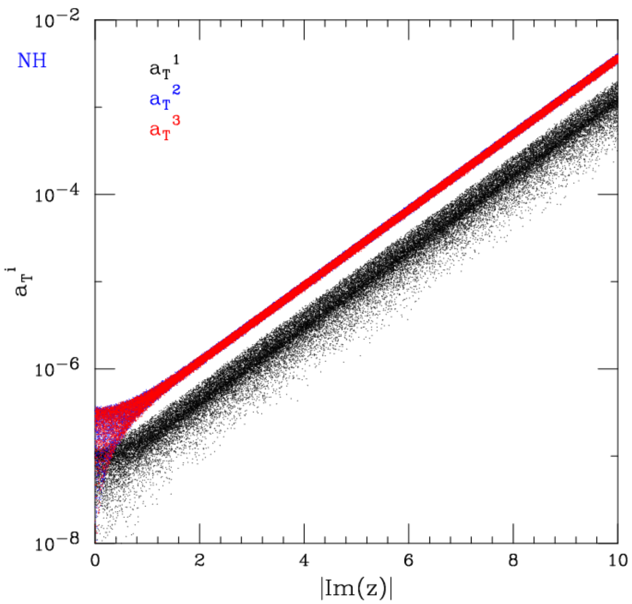


normal hierarchy

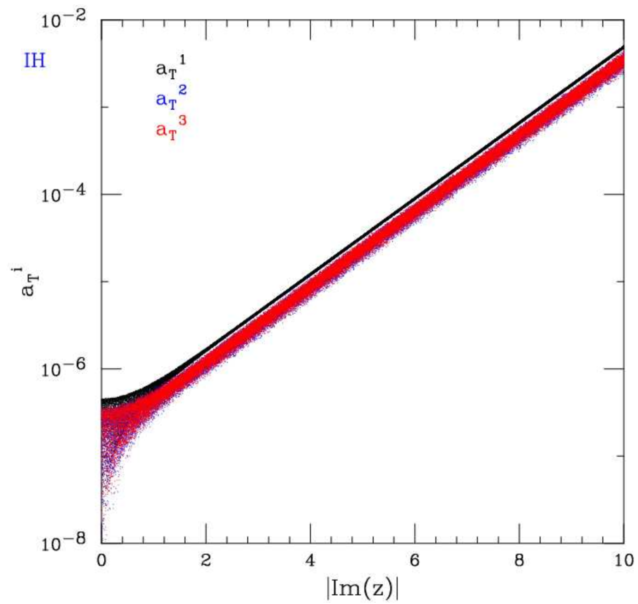


inverse hierarchy

Assuming Majorana phase $\Phi = 0$



normal hierarchy



inverse hierarchy

Incremental increase of cuts on the signal ($M_T = 200$ GeV):

$\sigma_{signal} = 119$ fb without any cuts

Cuts $\Downarrow$	$\sigma_{\text{sig.}}$(fb)
$p_T(\ell) > 15$(GeV)	115
$p_T(jets) > 20$ (GeV)	64
$\mid \eta(\ell) \mid < 2.5$	50
$\mid \eta(jets) \mid < 3$	48
$\Delta R_{\ell\ell} > 0.3$	45
$\Delta R_{\ell j} > 0.5$	37
$\Delta R_{jj} > 0.5$	32
$\not{p}_T < 25\,\text{GeV}$	22

Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović, to appear

SM backgrounds appear under control:

$\sigma_{background} \lesssim 1 fb$ with cuts

Franceschini, Hambye, Strumia, 08

Conclusions

- experimental probe of (Majorana) neutrino mass origin: lepton number violation at LHC (same sign dileptons), a high energy analogue of neutrino-less double beta decay

- L-R theory: possible discovery of W_R and ν_R through parity restoration and lepton number violation

  spectacular, but the low scale relevant for LHC not predicted

- an explicit example of predictive GUT theory: ordinary minimal SU(5) with extra fermionic adjoint

- weak fermionic triplet predicted in the TeV range (type III)

  its decay connected with neutrino mass

R measures separations

$$R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2}$$

where $\Delta\phi$ and $\Delta\eta$ are the azimuthal angular separation and (pseudo) rapidity difference between two particles