ORIGIN

OF

NEURINO MASS

ORIGIN OF NEURINO MASS

SEE-SAW

@

LHC

Goran Senjanović

Bajc, G. S. hep-ph/0612029

Bajc, Nemevšek, G.S.,
[redacted]
hep-ph/0703080

- NEUTRINOS HAVE MASS

$\Uparrow$

NEUTRINO OSCILLATIONS

SUN : $\Delta m^2_{\odot} \simeq 10^{-5} eV^2$ $\theta_{\odot} \simeq 30^{\circ}$

ATMOSPHERE : $\Delta m^2_A \simeq 10^{-3} eV^2$ $\theta_A \simeq 45^{\circ}$

(at least two massive)

- $m_\nu \leq 1 eV$

β decay
cosmology

$m_\nu \gtrsim 1/30$ eV (at least one)

- charged fermions:

m_f : MeV — 200 GeV

PROBLEM ?

NOT REALLY

- **SM**

$$l = \begin{pmatrix}\nu\\ e\end{pmatrix}_L \qquad \Phi = \begin{pmatrix}\varphi^+\\ \varphi^0\end{pmatrix}$$

$$e^c_L \ (\equiv C\bar{e}_R^{\,T}) \qquad \cancel{\nu^c_L}$$

m_e : $Y_e\ l\ \Phi\ e^c$ Weinberg '67

$$m_e = Y_e \langle \Phi \rangle \simeq Y_e M_W$$

$\uparrow$

controlled by Y_e

electron light $\Longleftrightarrow$ $Y_e \ll 1$ $(\sim 10^{-5})$

$Y_f \ll 1$ except $Y_t = 1$

m_ν :

$$Y_{eff}\ \nu_L^T C\, \nu_L\ \frac{\varphi_0\ \varphi_0}{M} \leftarrow \text{new physics}$$

Weinberg '79

- $M \gtrsim M_W \Rightarrow Y_{eff} \ll 1$
- $M \gg M_W \Rightarrow Y_{eff} \simeq O(1)$ More "natural"? NO

WEINBERG

$$\nu C \nu \frac{\varphi_0^2}{M}$$

↑ New heavy particles at M ⇒ integrate out

(see - saw)

Minkowski '77

Gell-Mann et al; Glashow

Mohapatra, G.S; Yanagida '79

(How) many possibilities?

↑

ONLY THREE

$$\ell C \ell \frac{\Phi \Phi}{M}$$

- $\ell^T C \sigma_2 \ell = 0$ SU(2)$_L$ singlet

  $C^T = - C, \quad \sigma_2^T = - \sigma_2$

- $\ell^T C \sigma_2 \vec{\sigma} \ell$ SU(2) triplet

II) $$\underbrace{(\ell^T \sigma_2 \vec{\sigma} \ell)}_{} \; \frac{\Phi^T \sigma_2 \vec{\sigma} \Phi}{M}$$

scalar triplet, $Y = -2$

I) $$\frac{\underbrace{(\ell^T \sigma_2 \Phi)}_{} (\Phi^T \sigma_2 \ell)}{M}$$

↓

fermion singlet, $Y = 0$

III) $$\frac{\underbrace{(\ell^T \sigma_2 \vec{\sigma} \Phi)}_{} (\Phi^T \sigma_2 \vec{\sigma} \ell)}{M}$$

↓

fermion triplet, $Y = 0$

(maximum three : Fierzing)

SM

original see-saw

① add ν^c (right-handed neutrino)

$\geqslant 2$ - at least 2 m_ν

$$\mathcal{L}_Y = Y_D \, \ell \, \sigma_2 \, \Phi \, \nu^c + M \, \nu^c \nu^c$$

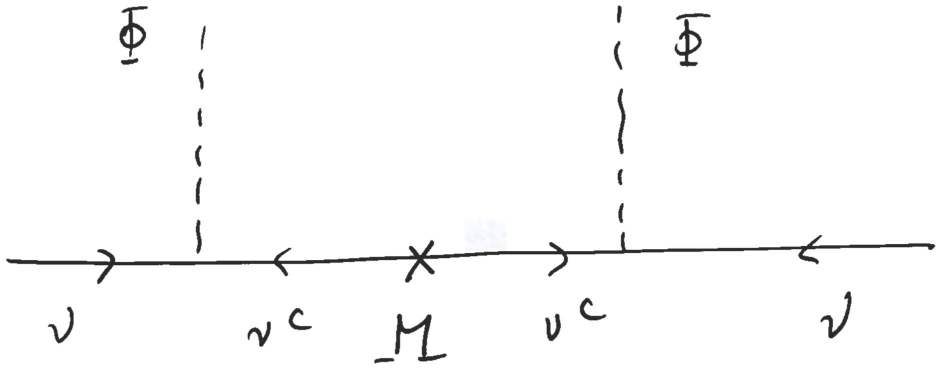
$(M > M_W)$

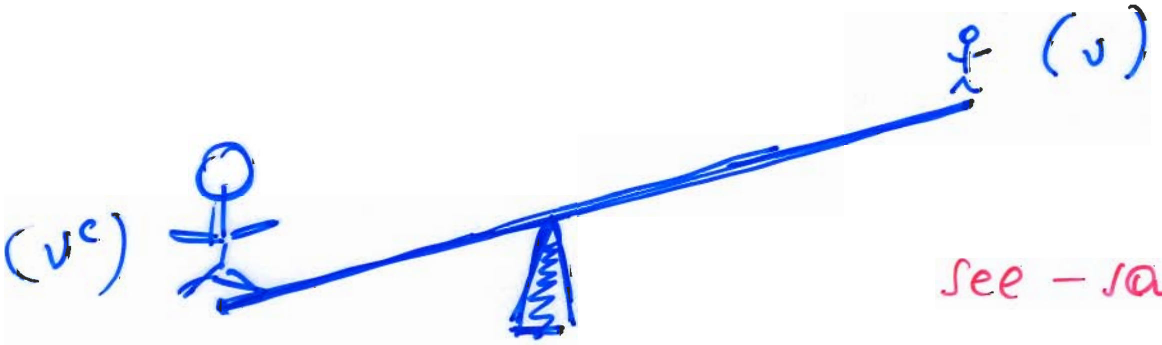
$$\frac{\partial \mathcal{L}}{\partial \nu^c} = 0 \Rightarrow Y_D^2 \frac{(\ell \Phi)(\ell \Phi)}{M}$$

$Y_D \simeq Y_e$ if $M \simeq \cancel{10} M_W$

$Y_e \simeq 10^{-5}$

$$\Rightarrow m_\nu \simeq 10^{-10} \frac{\langle \phi \rangle^2}{M} \simeq 10^{-10} M_W \simeq eV$$





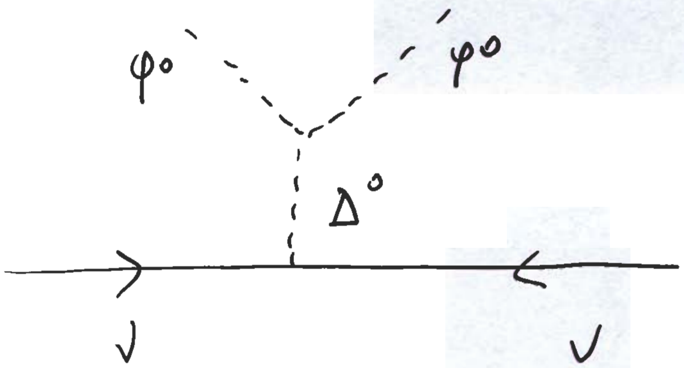
see - saw

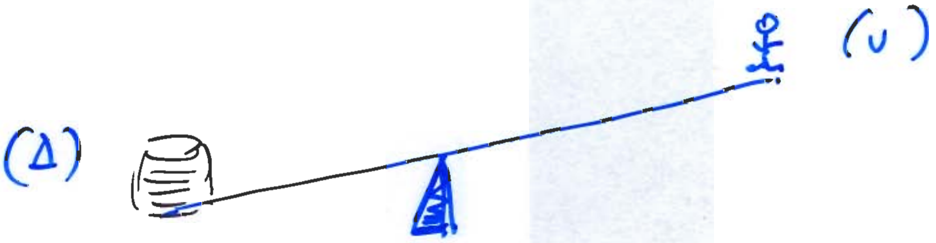
Lazarides, Shafi, Wetterich
Mohapatra, G. S. '80

II

$$\mathcal{L}_y = y_\nu \ell \, \sigma_2 \vec{\sigma} \, \ell \cdot \vec{\Delta} + M_\Delta^2 \vec{\Delta} \cdot \vec{\Delta}^* + \vec{\Delta}^* H^T \sigma_2 \vec{\sigma} H$$

$$\frac{\partial \mathcal{L}}{\partial \Delta} = 0 \Rightarrow \text{Weinberg}$$



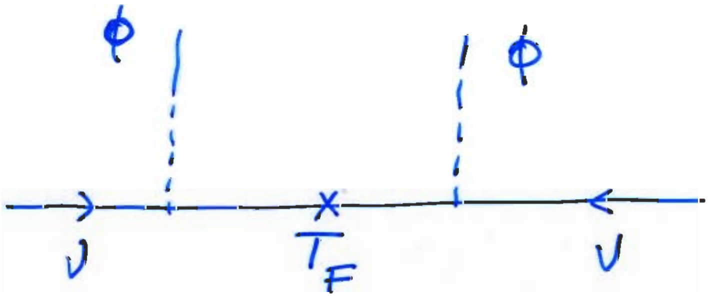


III

Foot et al
(Ma)

$$y_T \, \ell \, \sigma_2 \vec{\sigma} \, \Phi \cdot \vec{T}_F + M_T \vec{T}_F \cdot \vec{T}_F$$

$$\nu^c \longrightarrow \vec{T}_F$$



language only

add new heavy particle

+ new couplings

⇓ integrate out

Weinberg

↑ better language, more appropriate at low energies

$$Y_{eff} \frac{\ell \ell \phi \phi}{M}$$

↑ couplings among known particles

probe them through

$m_\nu, \theta_\nu, \delta_\nu$

- $Y_{eff}^T = Y_{eff}$ 6 complex = 12 real

phases of l_i $(i=1,2,3)$ arbitrary

$12 - 3 = 9$ real parameters

physical parameters:

m_ν (3)

Θ_ℓ (3) — analogue of Θ_C

δ_ℓ (1+ 2) → new Majorana

↑

analogue of δ_{CKM}

9 physical parameters — hard to ~~[illegible]~~ measure

today: 2 m_ν

2 Θ_ℓ

Analogy : ● Fermi theory of weak int.

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \bar{\mu}_L \gamma^\mu \nu_{\mu L} \bar{\nu}_{eL} \gamma^\mu e_L$$

- $\mathcal{L}_{int} = g/\sqrt{2} \; \bar{e}_L \gamma^\mu \nu_L W_\mu^- + h.c.$

small energy : $E \ll M_W$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}$$

↖ tells you nothing ;
instead of coupling between e, ν ⇒
couplings with unknown,
unreachable W^-

- if $E \simeq M_W$ ⇒ useful ([illegible])

- or if a theory of W exists
  e.g. $SM = SU(2)_L \times U(1)_Y$

  ⇓

  neutral current – correlated with charged

see-saw useful if one has
a theory of Y_D, M_R

connect m_ν, θ_ν with new
physical phenomena

- L-R theory   Pati, Mohapatra,
G.S. '74

$$G = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\begin{pmatrix}\nu \\ e\end{pmatrix}_L \longleftrightarrow \begin{pmatrix}\nu \\ e\end{pmatrix}_R$$

I + II typically present

$M_R = ?$

GRAND UNIFICATION

PS → SO(10): L-R important role for

m_ν, θ_ℓ : θ_{13}; m_i/m_j

10^{10} GeV < M_R < 10^{14} GeV

GRAND UNIFICATION

- quantization of charge : monopoles
- gauge coupling unif. : proton decay

(the) MINIMAL THEORY ??

analogue of SM construction

Clue: fermion masses and mixings

⇓

NEUTRINOS

Assumption :

3 + 1 space-time ; not warped

NO supersymmetry

NO ad-hoc discrete sym. (or global)

cont.

MINIMAL SU(5) Grand Unified Theory

F : 10_F, $\bar{5}_F$ (SM family ; NO ν_R)

H : 5_H ($\supseteq$ light doublet) $\langle 5_H \rangle = M_W$

24_H $\langle 24_H \rangle = M_{GUT}$ diag $(2,2,2,-3,-3)$

$\boxed{\text{FAILS}}$

- $m_\nu = 0$ (S.M. $\leq$ SU(5))
- NO UNIFICATION

WAYS OUT:

I) add $1_F = \nu_R$ - NO UNIFICATION

II) add $15_H \supseteq \Delta_H \Rightarrow$ OK, but no predictions for LHC

↙ pdecay fast

Doršner, Filevez-Perez '06

III) $24_F \supseteq T_F$ (need two?)

Ma
Hambye et al

↳ $24_F = 1_F + 3_F + 8^c_F + (2,3_c)_F$

$$\begin{tikzcd} 1_F \arrow[d] & 3_F \arrow[d] \\ I & III \end{tikzcd}$$

sufficient

Bajc, G.S. '06

Bajc, Nemevšek, G.S. '07

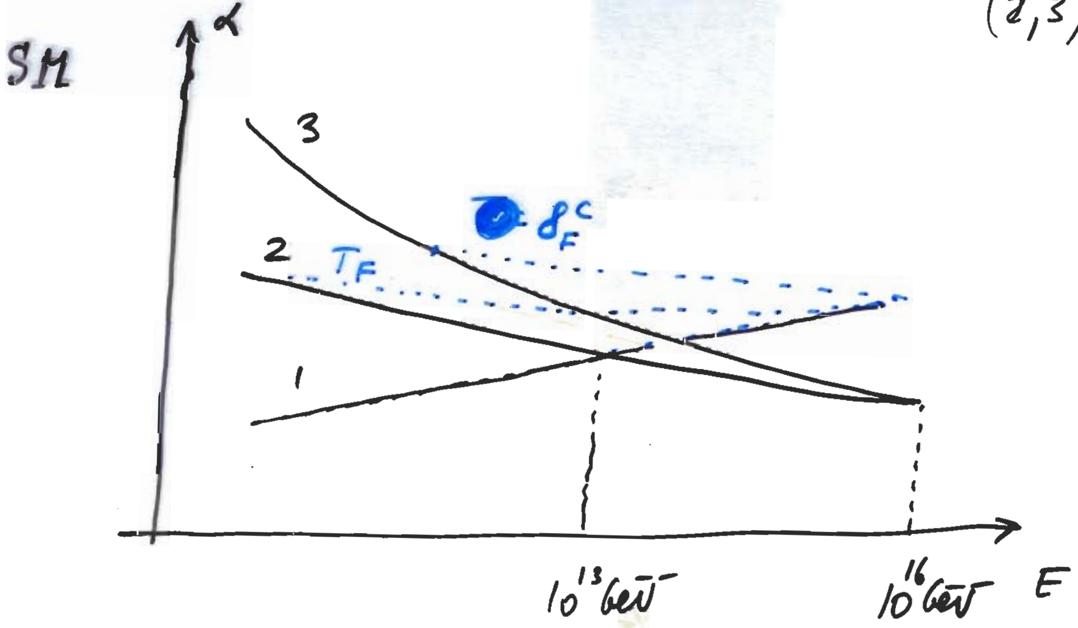
[redacted]

Doršner, Fileviez-Perez '06

prediction: $m_1 = 0$

(one neutrino massless)

● UNIFICATION



$(2,3)_F$: $Y/2 = \frac{5}{6}$

new states: raise α, unless $Y = 0$

T_F $(Y=0)$ ideal ⇒ $m_T \leq$ TeV

$m_8 \simeq 10^7 - 10^9$ GeV

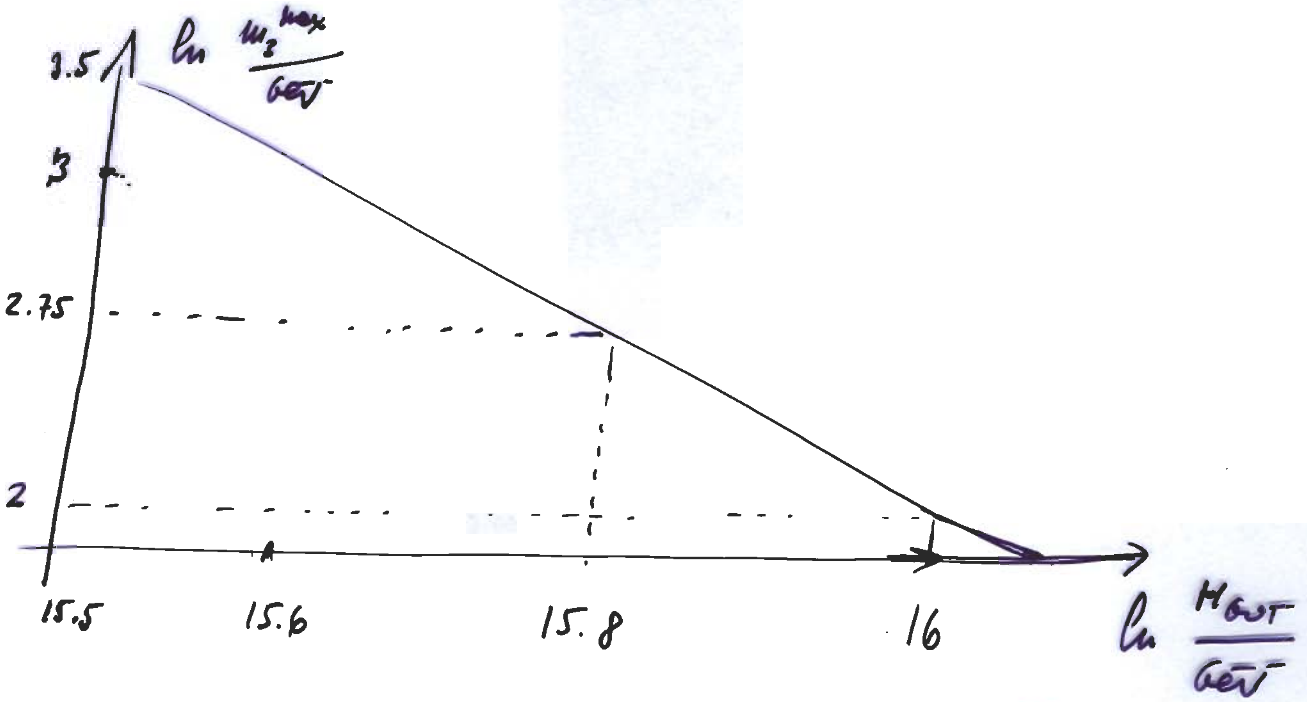
(2-loop)

- $m_{\text{color triplet}} > 10^{12}$ GeV (proton decay) ($\subseteq$ [illegible] 5_H)
- $M_{GUT} > 10^{15.5}$ GeV (proton decay)
- $m^F_{(3,2)} \simeq \frac{M_{GUT}}{100}$ $\left(M_{GUT}^2 / \Lambda \right)$

$\Downarrow$

$M_{GUT} \lesssim 10^{16}$ GeV (hard prediction)

$\tau_p < 10^{36}$ yr observable?



$$\boxed{M_{GUT} \simeq 10^{16}\,\text{GeV} \qquad m_F \simeq 200\,\text{GeV}}$$

$m_F^8 \simeq 10^7 - 10^8$ GeV

- LIMITS

direct: $m_T \gtrsim 100$ GeV

high precision:

- $\Delta m_T \simeq \frac{\alpha}{\pi} M_W \simeq 100$ MeV $\ll M_T$

degenerate limit:

$$S = T = Y \simeq 0$$

$$W = \frac{\alpha}{15\pi} \frac{M_W^2}{M_T^2} \lesssim 10^{-3}$$

just like light (degenerate) wino

NO BETTER THAN DIRECT

TYPICAL OF DEGENERATE MULTIPLETS

Light triplets

LHC : $m_T < 500$ GeV (~ winos)

- weakly produced, ~ winos
- decays $T^- \to W^- + \nu$ $\qquad T^0 \to Z + \nu$

$$Z + \ell \qquad \boxed{\begin{array}{l} \to W^+ + \ell \\ \to W^- + \bar{\ell} \end{array}}$$

directly through Yukawa

$$\mathcal{L}_Y = y_T^k \, T \, \Phi \, l_k + y_S^k \, S \, \Phi \, l_k + m_T \, T T + m_S \, S S$$

$k = 1, 2, 3$

$(3+6=9)$

$$\Gamma(T^- \to Z \, l_k^-) = \frac{m_T}{32\pi} |y_T^k|^2 \left(1 - \frac{m_Z^2}{m_T^2}\right)\left(1 + 2\frac{m_Z^2}{m_T^2}\right)$$

$$\sum_k \Gamma(T^- \to W^- \nu_k) = \frac{m_T}{16\pi} \left(\Sigma |y_T^k|^2\right) \qquad -''-$$

and similar for T_0

- $m_T \simeq 300$ GeV : $|Y_T^{max}| \gtrsim 5 \times 10^{-7} \Rightarrow$

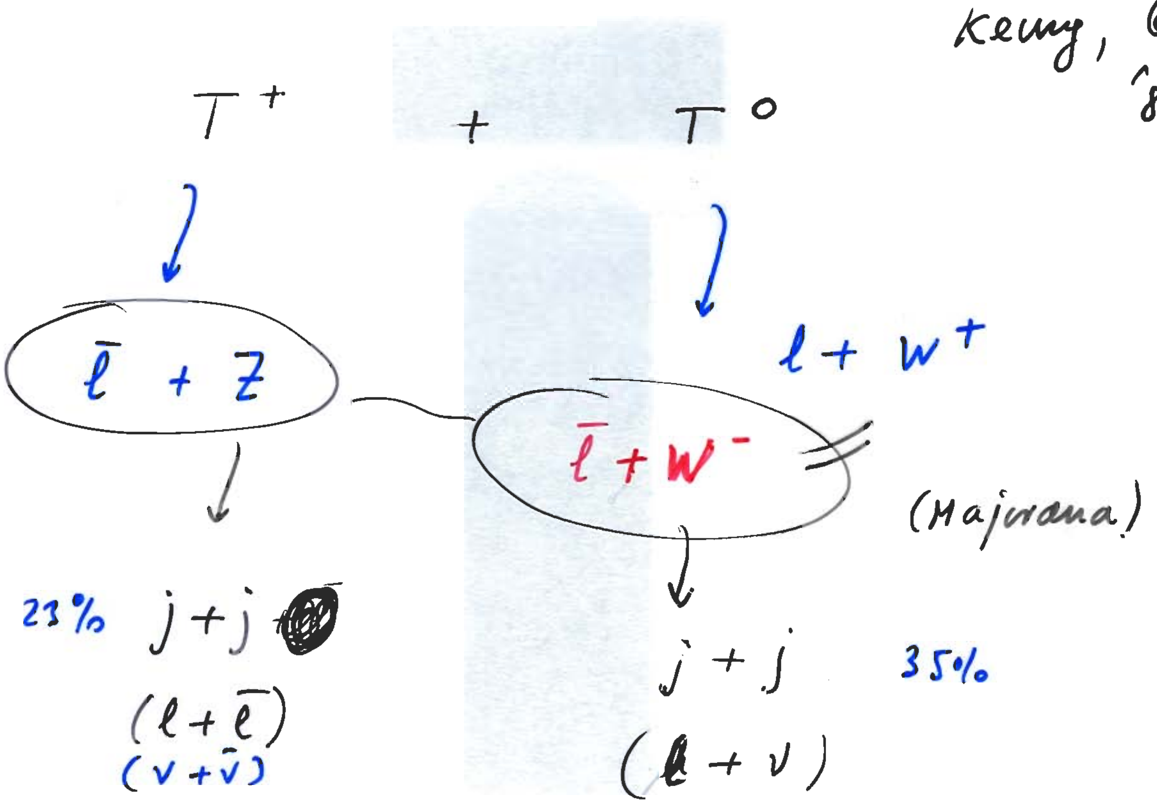
$$(10^{-11} \text{mm} \lesssim) \; \tau_T \lesssim 10^{-1} \text{mm}$$

- **SIGNATURES**

$\bar{\ell} + \bar{\ell}$ + 4 jets

Drell - Yan :

Keung, G.S. '83



BACKGROUND ??! *

PRODUCTION ! wino - like

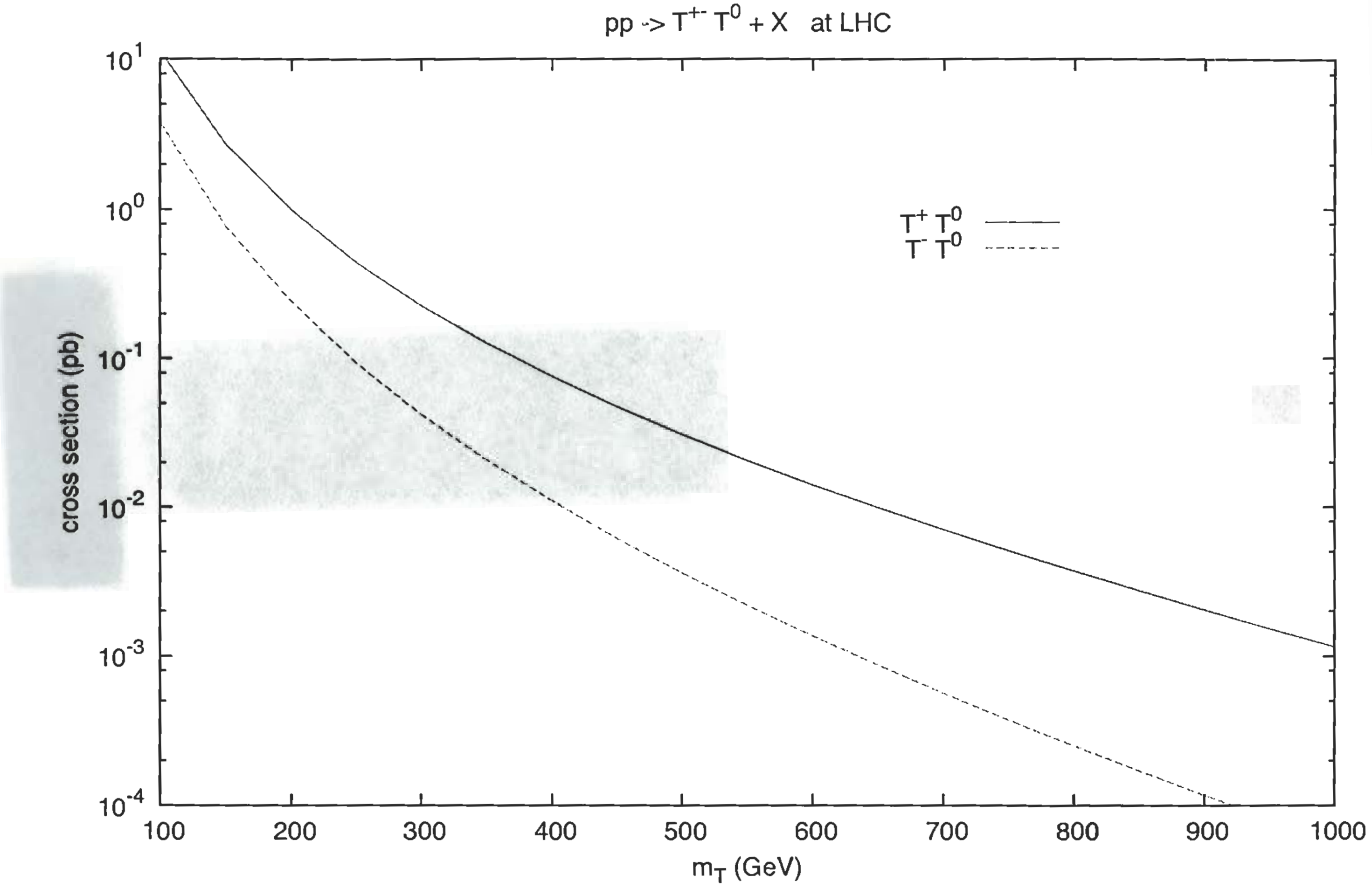
Arhrib, Bajc, G.S.

* Puljak (Split, CMS)

+ Gosh

Tao Han + ...

[redacted]


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

For $\int L dt = 100 \text{ fb}^{-1}$

and m_T =100 (500) GeV

LHC will produce

$1.5 \times 10^6 \; (4 \times 10^3) \; T^{\pm} T^0$ pairs, i.e.

$$10^5 (200) \times \left[\frac{|y_T^i|^2 |y_T^j|^2}{(\sum_k |y_T^k|^2)^2} \right] \; \left(l_i^{\pm} l_j^{\pm} + 4 \text{ jets} \right) \text{ events}$$

SM background

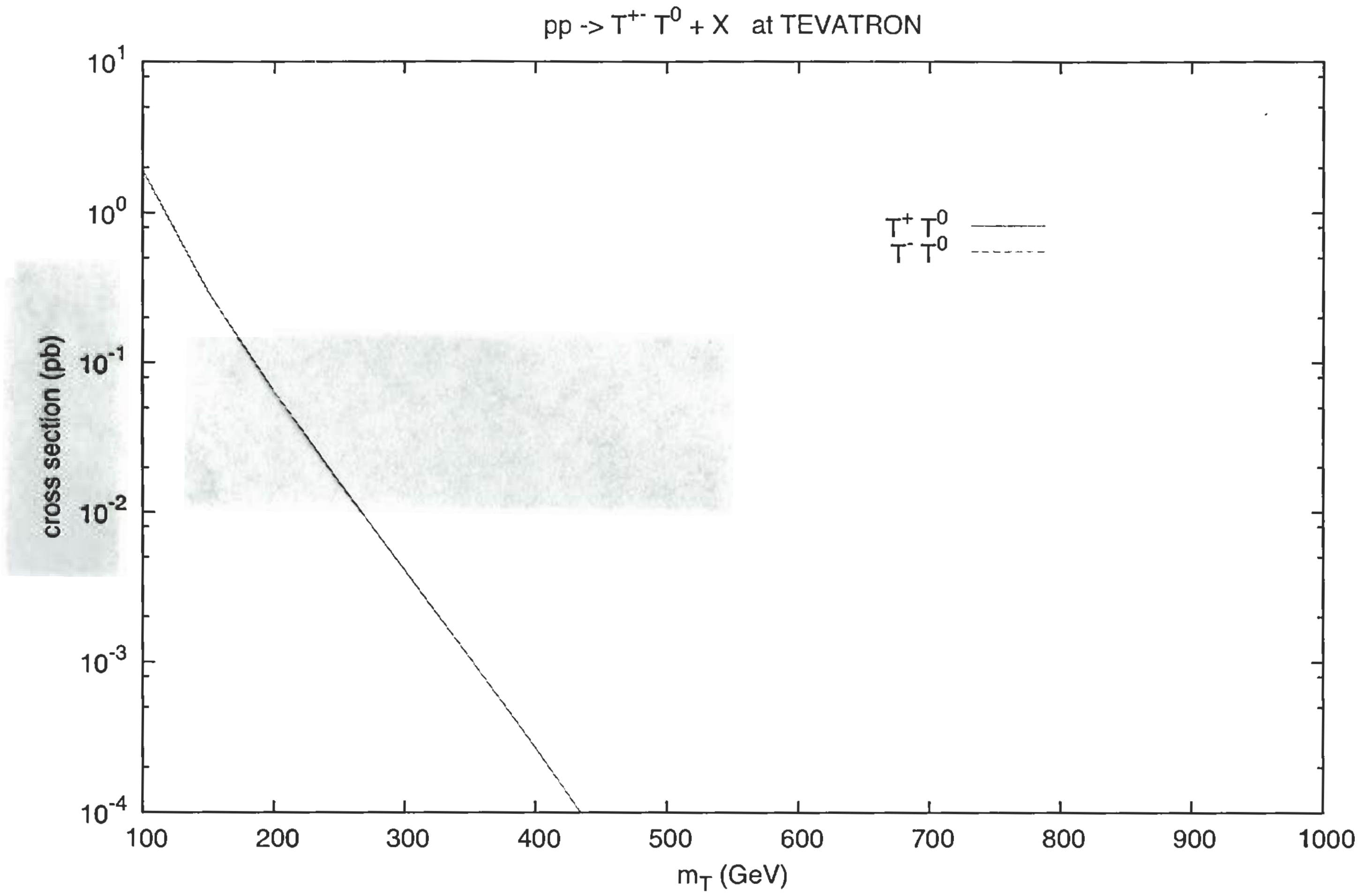
$$pp \to (W^\pm Z\,,\, W^\pm W^\pm\,,\, \bar{t}t)\ + \text{jets}$$

estimate: $\mathcal{O}(10^3)$ like-sign dimuon events for $\int Ldt = 100 fb^{-1}$

Del Aguila, Aguilar-Saavedra, 07

Should be possible to use proper cuts

(common belief that $m_{\tilde{w}} \lesssim 500$ GeV could be found at LHC)


pp -> T+- T0 + X at TEVATRON
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

For $\int Ldt = 1\ \mathrm{fb}^{-1}$

and m_T =100 (200) GeV

TEVATRON would have produced so far

4×10^3 (130) $T^{\pm}T^0$ pairs, i.e.

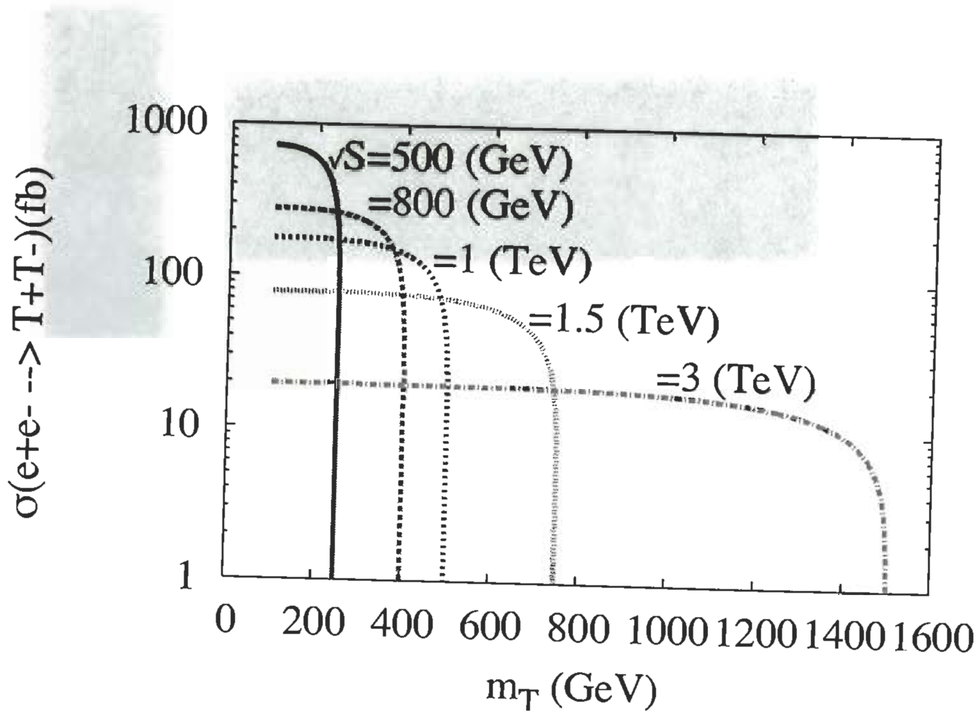
$$200(7) \times \left[\frac{|y_T^i|^2|y_T^j|^2}{(\sum_k |y_T^k|^2)^2}\right] \left(l_i^{\pm}l_j^{\pm} + 4 \text{ jets}\right) \text{ events}$$

Further uncertainties to take into account

- acceptance (geometrical, jet reconstruction, etc) - 30% ?
- reduction of signal events due to cuts (cut acceptance)
- Yukawas (only some leptons can be measured, mainly muons at CMS for example)

What about linear colliders ?

- s-channel process, suppressed at high E
- Z coupling for triplets vectorial → flat angular distribution
- again similar to $\tilde{w}^+\tilde{w}^-$ production in light wino MSSM



- COSMOLOGICAL IMPLICATIONS

  - LEPTOGENESIS

$$\varepsilon_{max} \simeq \frac{1}{16\pi} \frac{m_T (m_3^\nu - m_2^\nu)}{v^2} \qquad m_T \ll m_S$$

$\uparrow$ rigorous — no assumptions as in the three ν_R case

(Davidson, Ibarra)
Raidal, Strumia,
Turzynski '04

$m_T \simeq$ TeV

$\Downarrow$

$$\boxed{\varepsilon_{max} \leq 10^{-12} \text{ - far too small}}$$

$\Downarrow$

Only resonant leptogenesis: $m_T \simeq m_S$

S hard to produce:
$|Y_S| \lesssim 1/10$

unitarity of PMNS $\Leftrightarrow$ LFV

Biggio et al '06

- NO DARK MATTER CANDIDATE

e.g. T_F (unlike wino) decays through Y_T

- $$\mathcal{L}_Y = y\, \underbrace{24_F}_{T_F,\ S_F}\, \underbrace{\bar{5}_F}_{l}\, \underbrace{5_H^*}_{\Phi^*} + \underbrace{24_F\, \bar{5}_F\, 5_H^*\, 24_H/\Lambda}_{\text{necessary}}$$

would not split y_T, y_s

$$\Downarrow$$

$$\mathcal{L}_Y(eff) = y_T^i\, T_F\, \Phi^*\, l_i + y_s^i\, S_F\, \Phi^*\, l_i$$

$$+ m_T\, T_F T_F + m_s\, S_F S_F \qquad i = 1, 2, 3$$

3 + 3 complex Yukawas

↳ make real by phase convention

$$\Downarrow$$

3 + 6 = 9 real couplings

→ 2 masses ($m_1 = 0$)

3 mixings

1 + 1 = 2 phases (only one Majorana phase)

- one massless neutrino

e.g. normal hierarchy $m_1^\nu = 0$

$$\frac{v_w y_T^{i*}}{i\sqrt{2}\, m_T} = U_{i2}\sqrt{m_2^\nu}\cos z \pm U_{i3}\sqrt{m_3^\nu}\sin z$$

$$\frac{i\, v_w y_S^{i*}}{\sqrt{2}\, m_S} = U_{i2}\sqrt{m_2^\nu}\sin z \mp U_{i3}\sqrt{m_3^\nu}\cos z$$

$z \in \mathbb{C}$, U = PMNS (1 + 1 phase only)
↑ Majorana

- Im(z) ≫ 1 (large Yukawa's) ⟶ LFV

$$\theta_{13} = 5^\circ : \left\{ \begin{array}{l} .25 \leq \dfrac{\Gamma(\mu)}{\Gamma(\tau)} \leq 4.3 \\ \\ .02 \leq \dfrac{\Gamma(e)}{\Gamma(\mu,\tau)} \lesssim .5 \end{array} \right\}$$

$$\theta_{13} = 0^\circ \left\{ \Gamma(e) \simeq \Gamma(\mu) \simeq \Gamma(\tau) \right\}$$

- - - - - - - - - - - - - - - - - -

inverse hierarchy: $\Gamma(\mu) = \Gamma(\tau)$

$$.07 \leq \frac{\Gamma(e)}{\Gamma(\mu)} \leq 50$$

no θ_{13} dependence!

OUTLOOK

Minimal SU(5) (type III seesaw)

$\oplus \ 24_F$

T_F (SU(2) triplet ~ wino) $\therefore \boxed{m_T \lesssim \text{TeV}}$

$M_{GUT} \lesssim 10^{16}\,\text{GeV} \Rightarrow \boxed{\tau_p \lesssim 10^{36}\,\text{yr}}$

LHC - proton decay connection

$\downarrow$ measure directly see-saw

- comparison with supersymmetry

$\sim$: light wino ($\leq$ TeV)

heavy gluino ($10^7 - 10^9$ GeV)

decoupled Higgsino ($m_{\tilde{h}} > M_{GUT}$)

Bajc

$\Rightarrow$ consistent with unification :

gluino $M_W - 10^9$ GeV

higgsino $M_W - M_{Pl}$

split (more) supersymmetry

- NATURALNESS

⇓

MSSM : $m_{\tilde{f}} \leq$ TeV

Minimal supersymmetric SU(5)

(ν mass: R-parity violation ?
$\nu_R = L_F$?)

TRESHOLD EFFECTS:

m_3, m_8 ($3_W, 8_c \subseteq 24$)

⇛ NO prediction for M_{GUT}, m_T Bachas, Yosopida

$\downarrow$

10^{11} GeV

[redacted]

⇒ ORDINARY SU(5) - PREDICTIVE,
(much more than the susy SU(5))

MOTIVATION: purely physical, well-defined