Neutrino Paradigm and LHC

Goran Senjanović
ICTP, Trieste

Prepared for CERN, August 1, 2011

New Physics:

these days we all say LHC

and yet...

no hard prediction

most tied to naturalness - soft

try phenomenological (experimental) motivation?

still soft

Neutrino Mass

- the only new established physics beyond SM

if Majorana

window to new physics

serious chance at LHC ?

Talk:

Talk:

- not a review

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- not a review

- a case for LHC as a neutrino machine

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- a case for LHC as a neutrino machine
- case study of a (the?) theory

Talk:

- not a review
- a case for LHC as a neutrino machine
- case study of a (the?) theory
- seesaw at LHC

Dirac '31

Dirac equation '28

Skobeltsyn '23

Chao '29

anti particles

Anderson '32

Segre', Chamberlain '55

particle $\Longrightarrow$ different antiparticle

for every fermion

neutrino = anti neutrino ?

Majorana '37

neutron

Lepton Number Violation:

`creation of electrons'

- neutrino less double beta decay

Racah'37 Furry '38

- colliders - LHC

Keung, GS '83

Parity violation in weak interaction

Lee, Yang '56

not well known:
they argue it is a hidden symmetry *

* mirror fermions

Martinez, Melfo, Nesti, GS '11

Melfo, Nemevsek, Nesti, GS, Zhang '11

Majorana Program: neutrino mass

$$\nu_M = \nu_L + \nu_L^* \quad \Leftrightarrow \quad m_\nu^M (\nu_L \nu_L + h.c.)$$

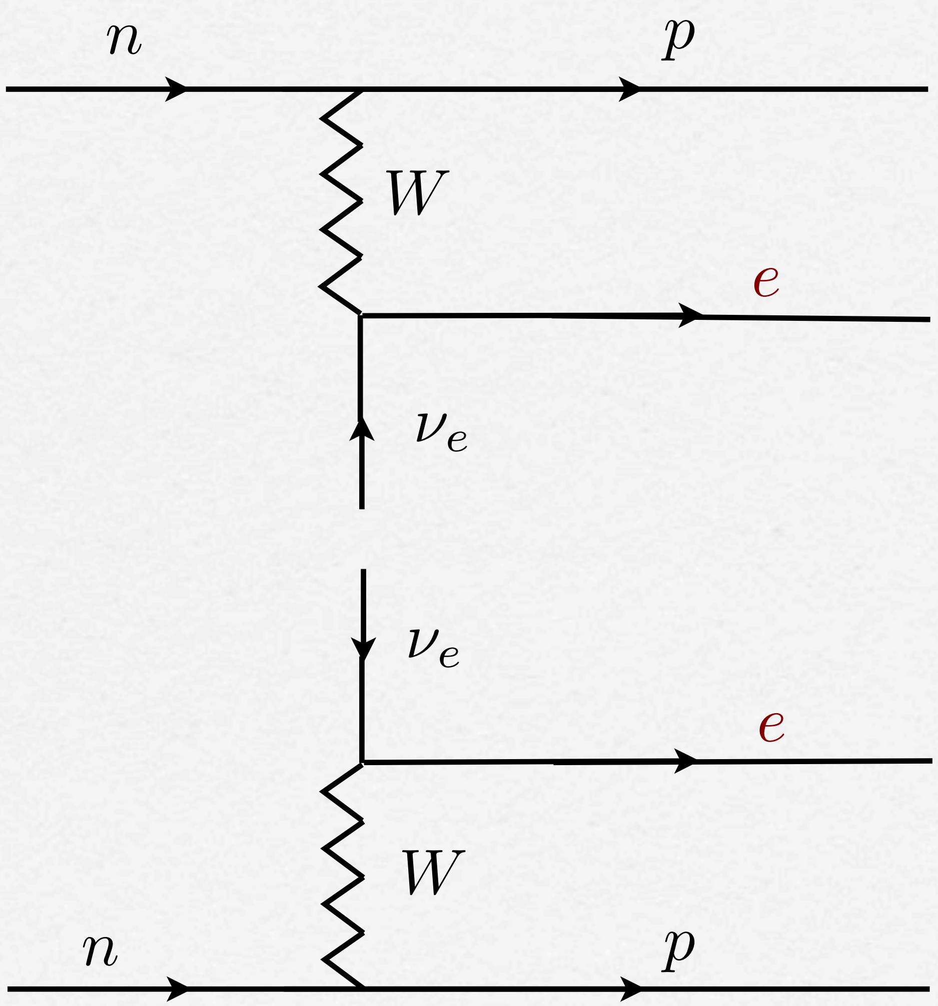
$$\Delta L = 2$$ lepton number violation

forbidden by SM symmetry → window to new physics

Double-beta decay

Goepert-Mayer '35

$$^{76}_{32}Ge \not\to ^{76}_{33} As + e + \bar{\nu} \quad \Rightarrow \quad ^{76}_{32}Ge \to ^{76}_{34} Se + e + e + \bar{\nu} + \bar{\nu}$$



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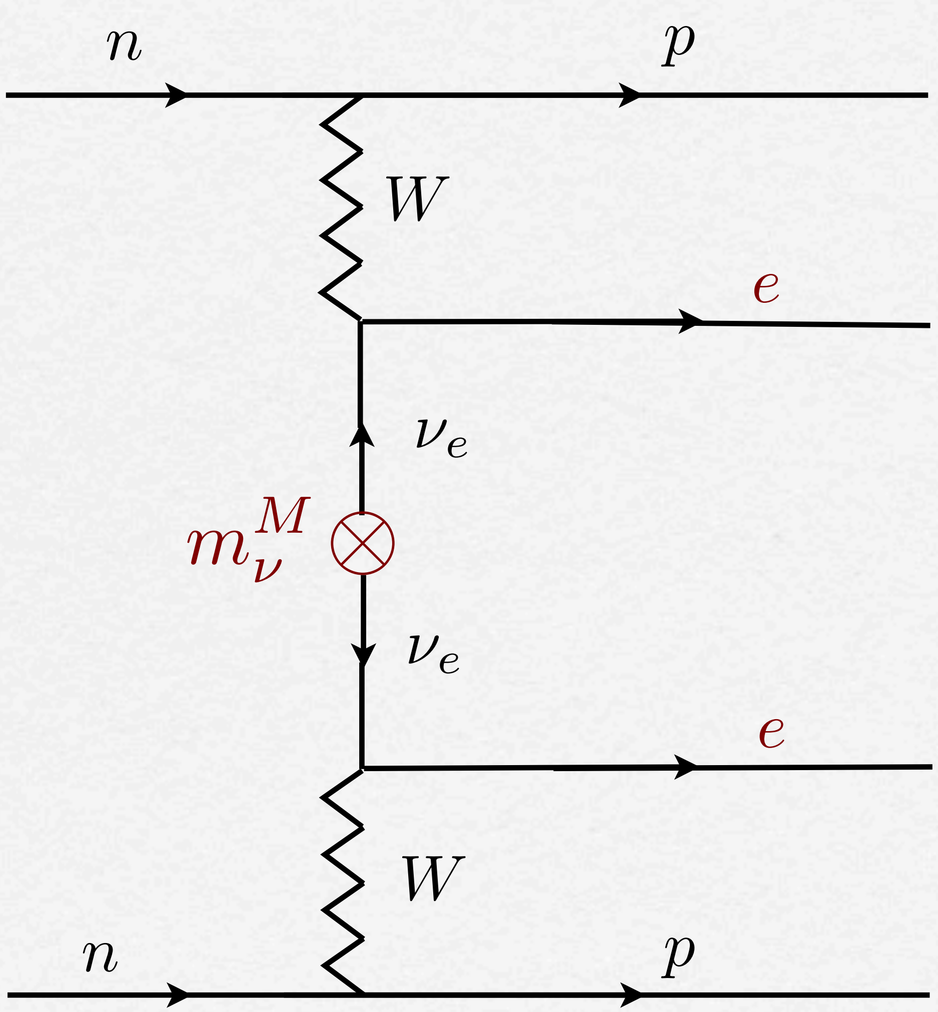

Neutrinoless Double-beta decay

Goepert-Mayer '35

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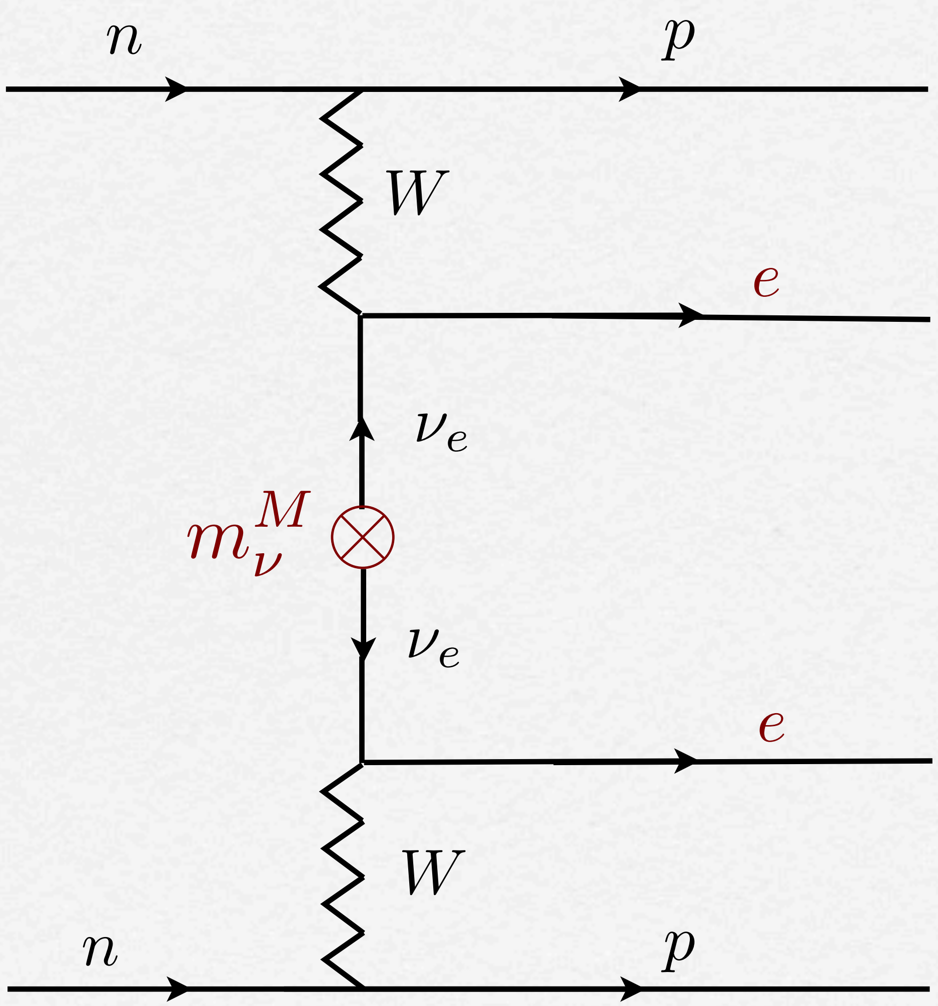
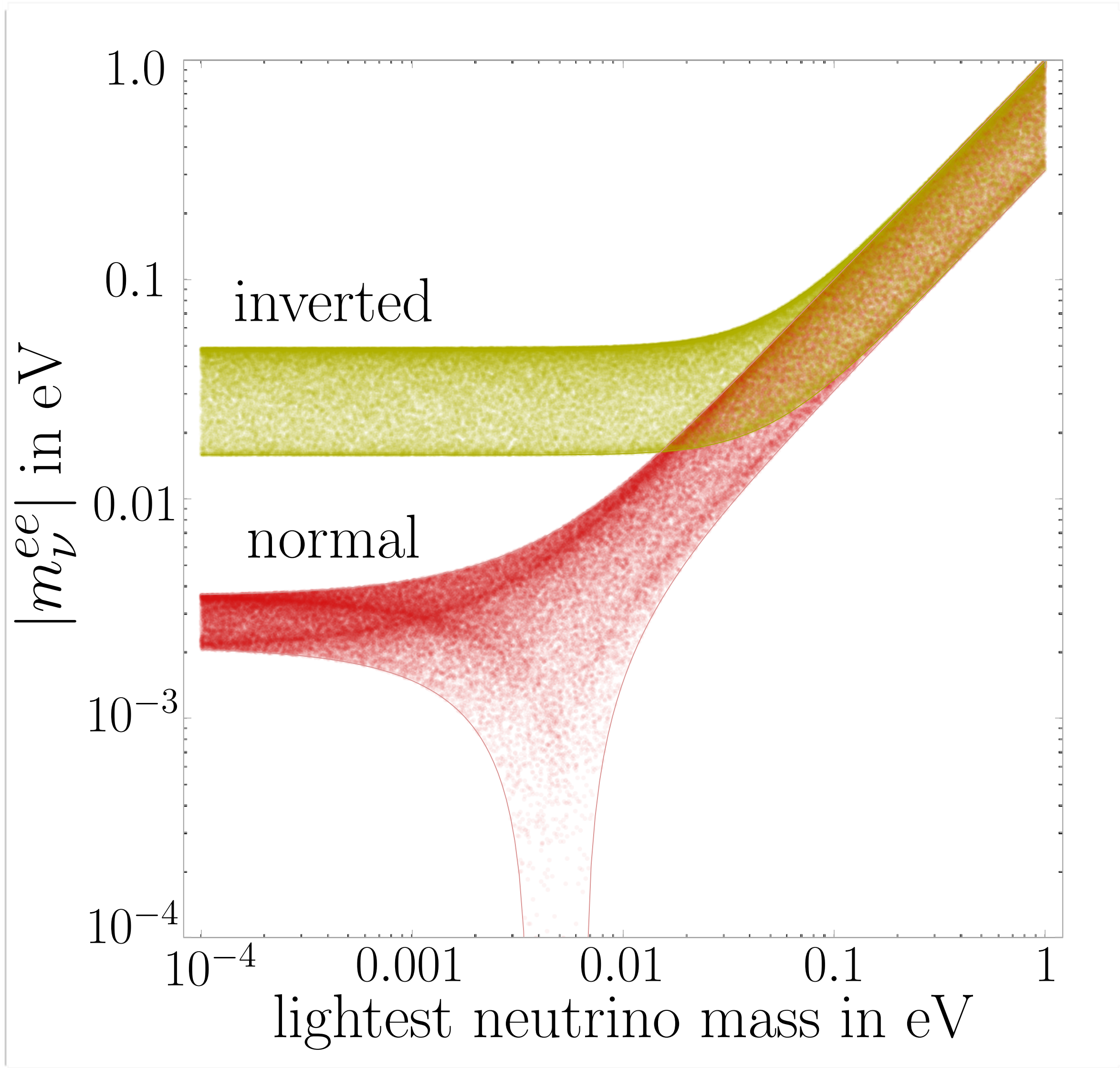


$${}^{76}_{32}Ge \to {}^{76}_{34}Se + e + e$$

proportional to neutrino mass

$$t_{1/2} \geq 10^{24}\, yr \quad \Longrightarrow \quad m_\nu^M \lesssim 1\, eV$$

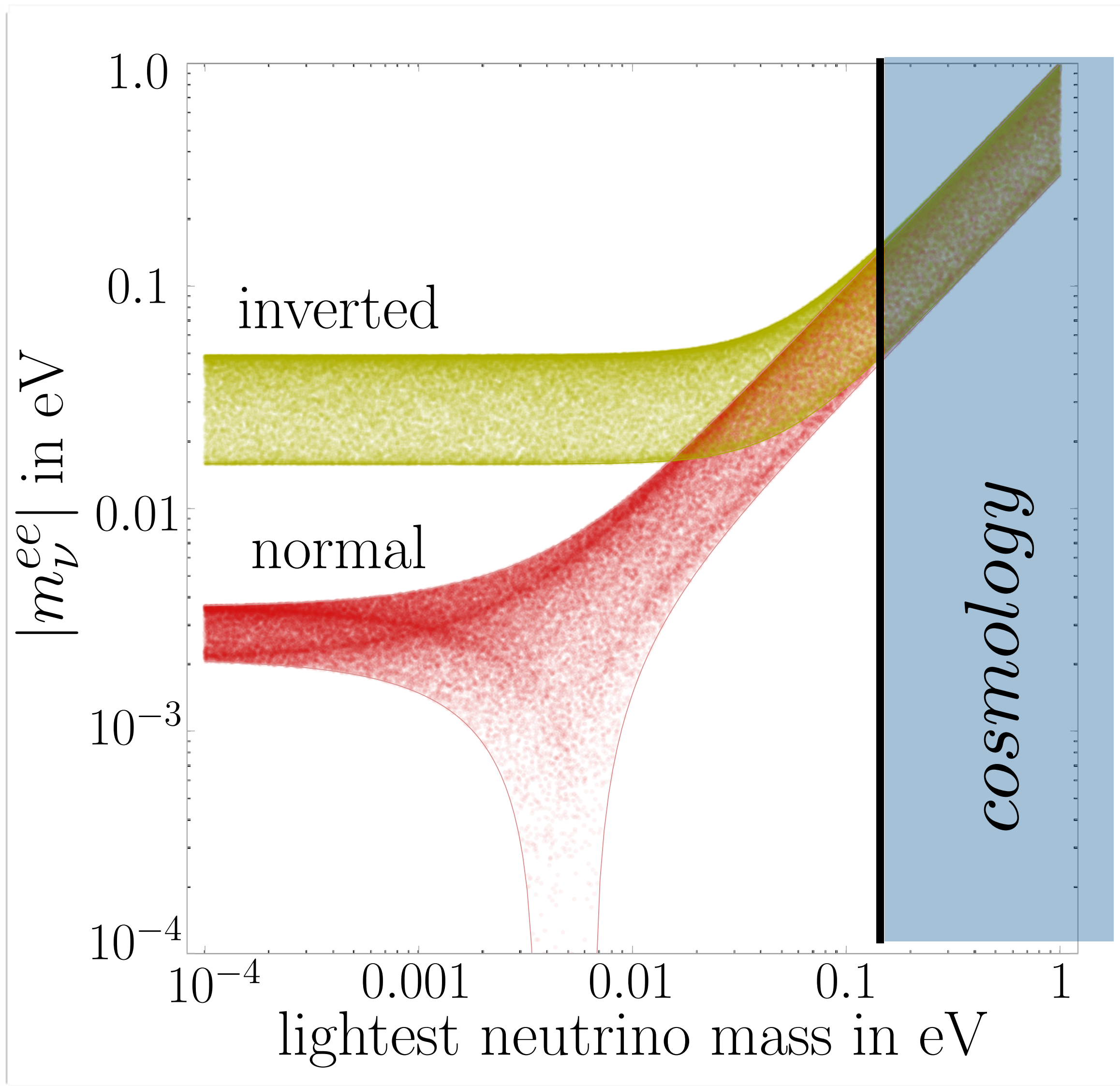
Neutrino mass contribution



	central value
Δm^2_{12}	$= (7.58 \pm 0.21)\ 10^{-5}\ \text{eV}^2$
$\lvert\Delta m^2_{23}\rvert$	$= (2.40 \pm 0.15)\ 10^{-3}\ \text{eV}^2$
$\tan^2\theta_{12}$	$= 0.484 \pm 0.048$
$\sin^2 2\theta_{23}$	$= 1.02 \pm 0.04$
$\sin^2 2\theta_{13}$	$= 0.07 \pm 0.04$

Vissani '02

Neutrino mass contribution



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Seljak, Slosar, Mcdonald '06

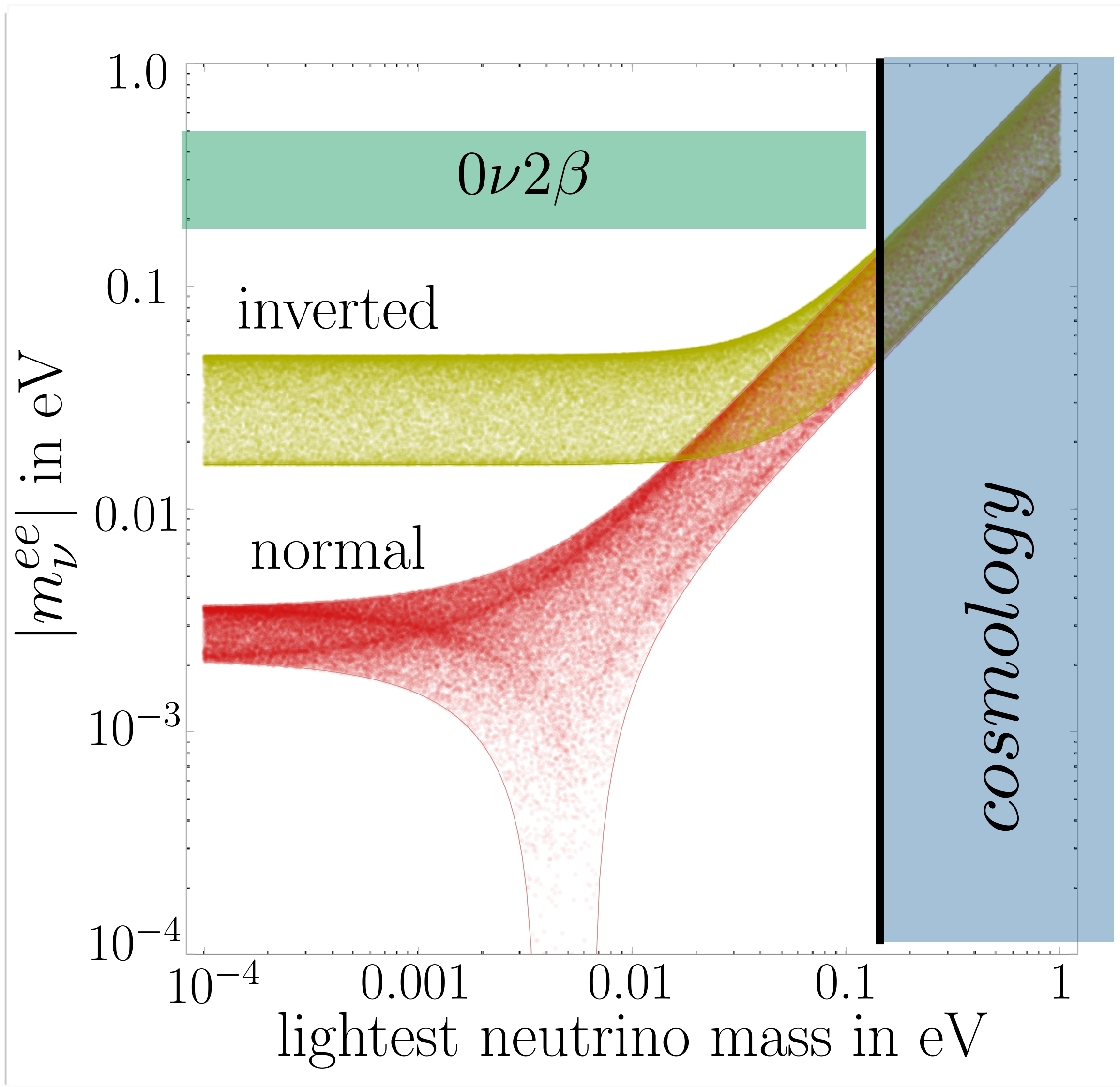
Hannestad et al '10

Vissani '02

Neutrino mass contribution

Klapdor '01-10

HM experiment



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Seljak, Slosar, Mcdonald '06

Hannestad et al '10

Vissani '02

Experiments !

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Sensitivity $\langle m_\nu \rangle$, meV	Status	Start
GERDA	^{76}Ge	18	3×10^{25}	$\sim$ 200	running!	2011
		40	2×10^{26}	$\sim$ 70	in progress	$\sim$ 2012
		1000	6×10^{27}	10-40	R&D	$\sim$ 2015
CUORE	^{130}Te	200	$(6.5 \div 2.1) \times 10^{26}$	20-90	in progress	$\sim$ 2013
MAJORANA	^{76}Ge	30-60	$(1 \div 2) \times 10^{26}$	70-200	in progress	$\sim$ 2013
		1000	6×10^{27}	10-40	R&D	$\sim$ 2015
EXO	^{136}Xe	200	6.4×10^{25}	100-200	in progress	$\sim$ 2011
		1000	8×10^{26}	30-60	R&D	$\sim$ 2015
SuperNEMO	^{82}Se	100-200	$(1 - 2) \times 10^{26}$	40-100	R&D	$\sim$ 2013-2015
KamLAND-Zen	^{136}Xe	400	4×10^{26}	40-80	in progress	$\sim$ 2011
		1000	10^{27}	25-50	R&D	$\sim$ 2013-2015
SNO+	^{150}Nd	56	4.5×10^{24}	100-300	in progress	$\sim$ 2012
		500	3×10^{25}	40-120	R&D	$\sim$ 2015

Rodejohann'11

GERDA@LNGS started

if claim confirmed

expect: a few years

new physics necessary?

$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2}$$

$(p \simeq 100\, MeV)$

Feinberg, Goldhaber '59

Pontecorvo '64

$$\mathcal{A}_{\mathcal{NP}} \propto \frac{G_F^2 M_W^4}{\Lambda^5}$$

$\Lambda \sim TeV$ **LHC**

Neutrino mass: theory

Standard Model: neutrino massless

only ν_L - and $\nu_L \nu_L$ forbidden

Why parity : L $\leftrightarrow$ R broken ?

God may be left-handed, but not an invalid

L-R symmetry

Lee, Yang dream

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R \qquad \begin{matrix} u_R \\ d_R \end{matrix}$$

$$W_L$$

L-R symmetry

Lee, Yang dream

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

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$$W_L \qquad W_R$$

L-R symmetry

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W_L $\qquad$ W_R

$$m_{W_R} \gg m_{W_L}$$

Pati, Salam '74

Mohapatra, GS '75

$E \gg m_{W_R}$ parity restored?

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

$$Q = T_L^3 + T_R^3 + \frac{B-L}{2}$$

- hypercharge Y:

traded for

anomaly free global B-L of SM

- right-handed neutrinos:

LR symmetry & cancel gauge B-L anomaly

Curse: neutrino mass

- neutrino massive -

just like the electron

- naive expectation:

$$m_\nu \simeq m_e$$ (if Dirac particles)

tried hard to avoid it, not convincing

Branco, GS '77

Blessing: neutrino mass

seesaw $\quad M_{\nu_R} \propto M_{W_R}$

$$\begin{matrix} \nu_L \\ \nu_R \end{matrix} \begin{pmatrix} 0 & m_D \\ m_D & M_{\nu_R} \end{pmatrix}$$

$$m_\nu = m_D^T \frac{1}{M_{\nu_R}} m_D$$

Minkowski '77

Mohapatra, GS '79

Maiezza, Nemevsek, Nesti, GS '10

Minimal model:

theoretical limit

$$M_{W_R} \gtrsim 2.5\,\mathrm{TeV}$$

Beall, Bander, Soni '81

Mohapatra, GS, Tran '83

Ecker, Grimus '85

.....

Zhang, An, Ji, Mohapatra '07

rare processes:

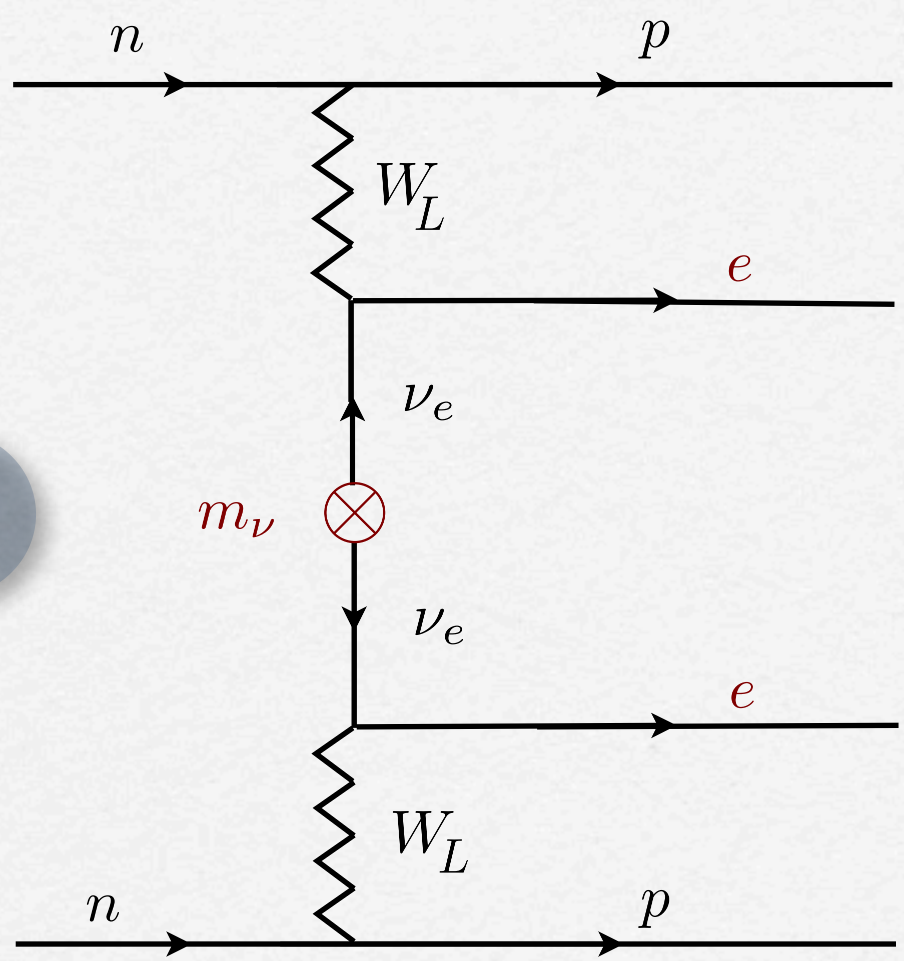
$K_L - K_S$ mass difference...

experiment is catching up !

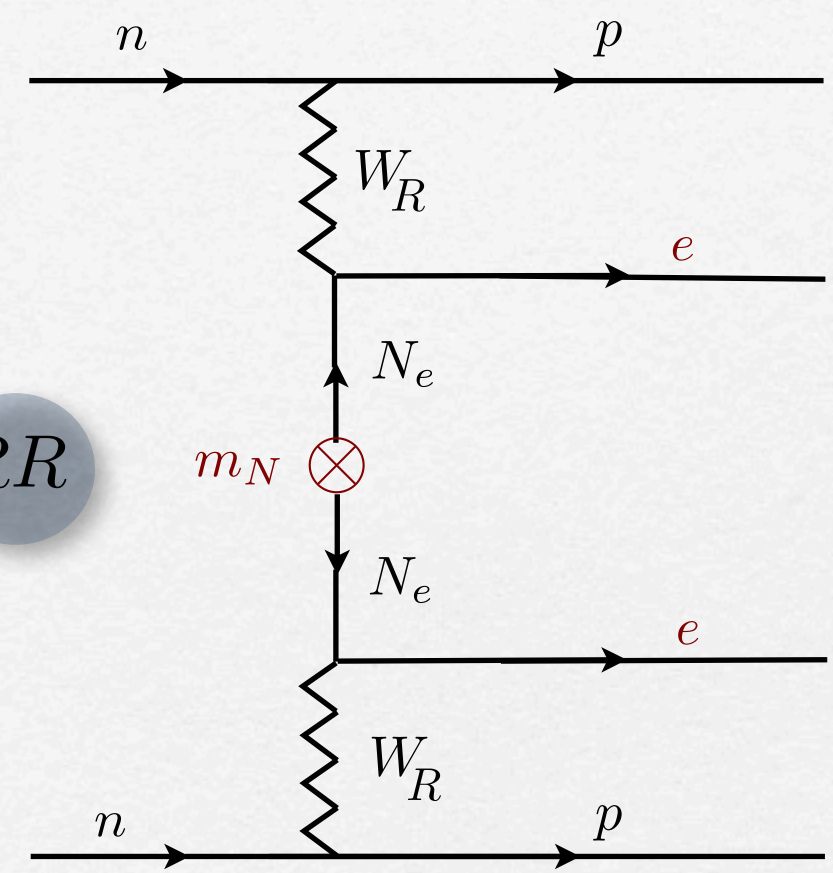
New source for $0\nu 2\beta$

Mohapatra, GS '81

LL



RR



$$LL \propto \frac{1}{M_{W_L}^4} \frac{m_\nu}{p^2}$$

$p \simeq 100 MeV$

$m_\nu \simeq 1\, eV$

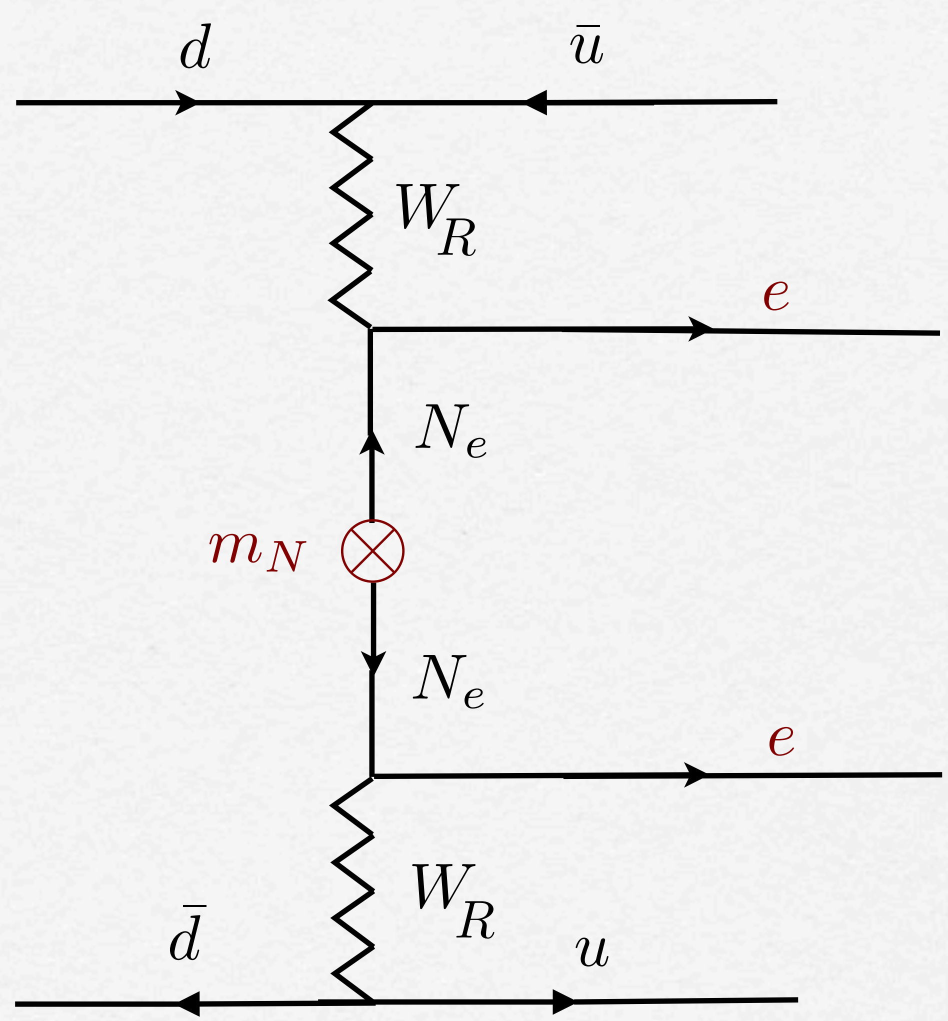
N = right-handed neutrino

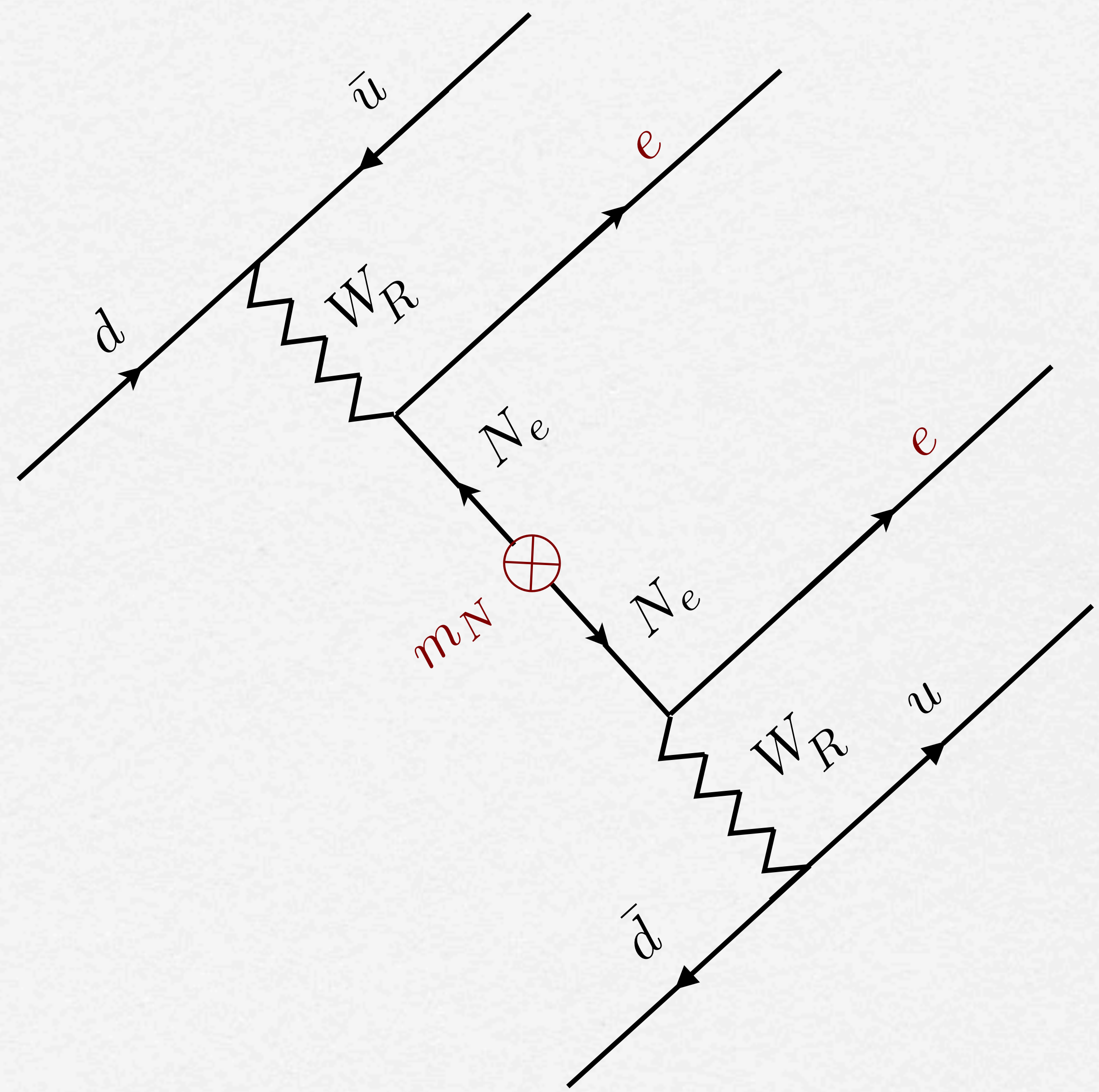
$$RR \propto \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

$M_{W_R} \simeq m_N \simeq 10 M_{W_L}$ ~TeV

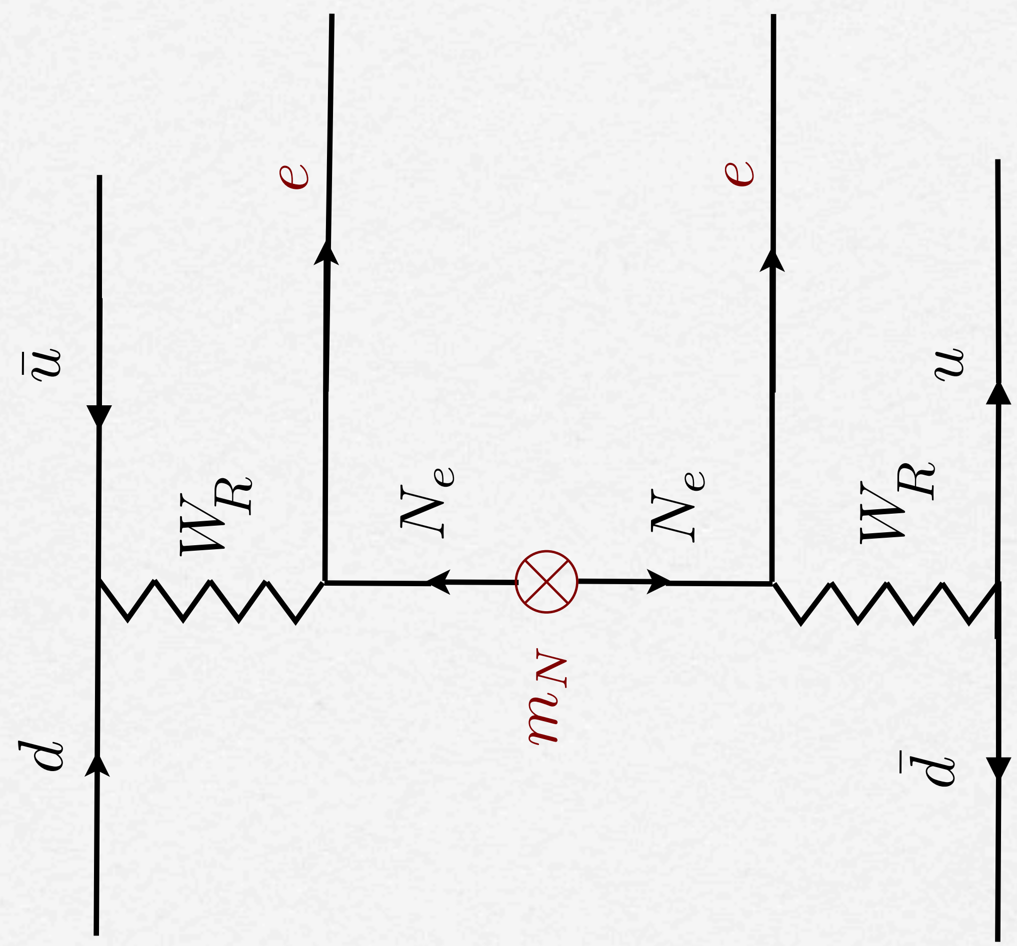
LHC connection?

rotation in a plane





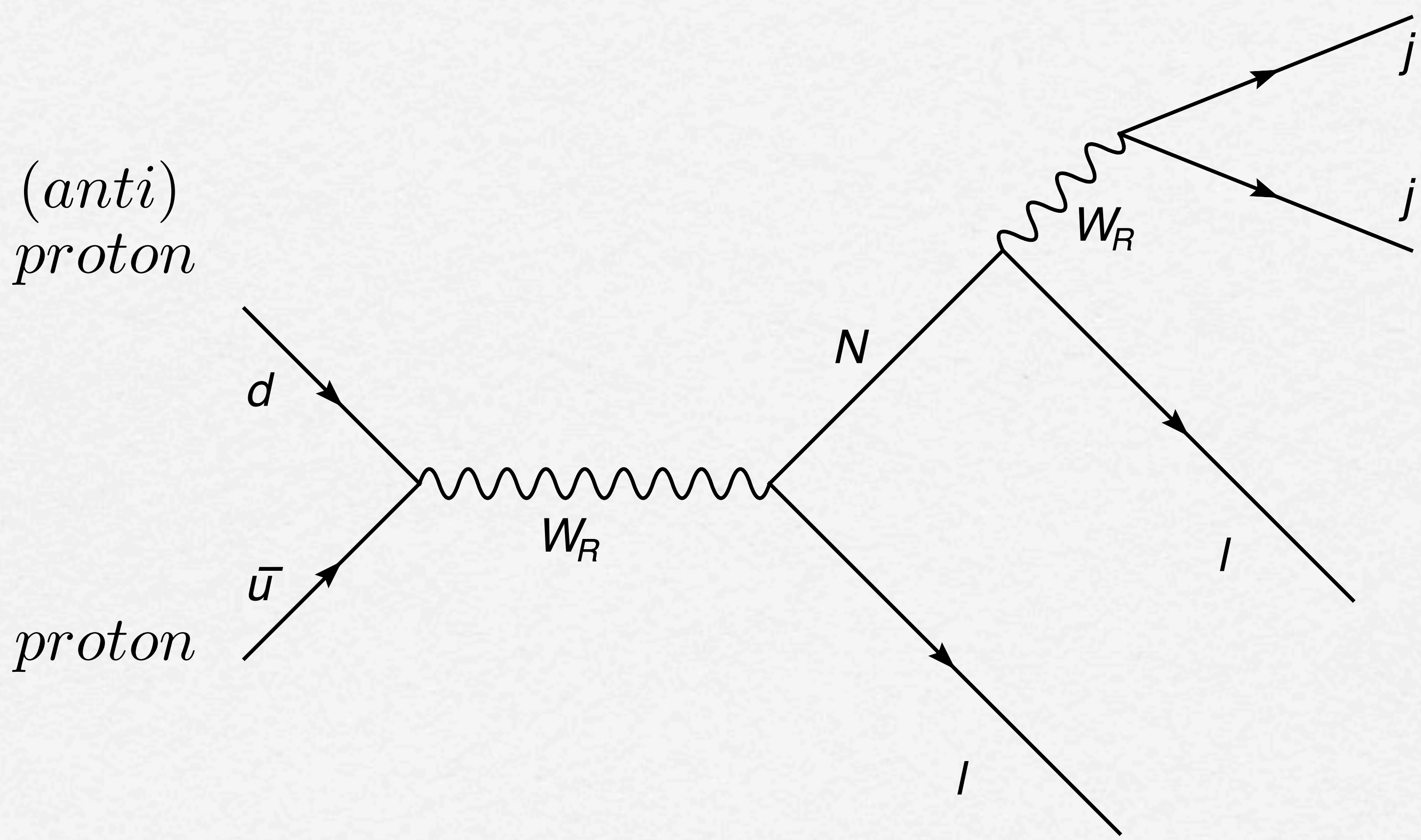
$\bar{u}$
e
d
W_R
N_e
e
m_N
N_e
u
W_R
$\bar{d}$



$\bar{u}$
d
W_R
e
N_e
m_N
N_e
e
W_R
u
$\bar{d}$

W_R production @ colliders

- direct probe of Majorana nature

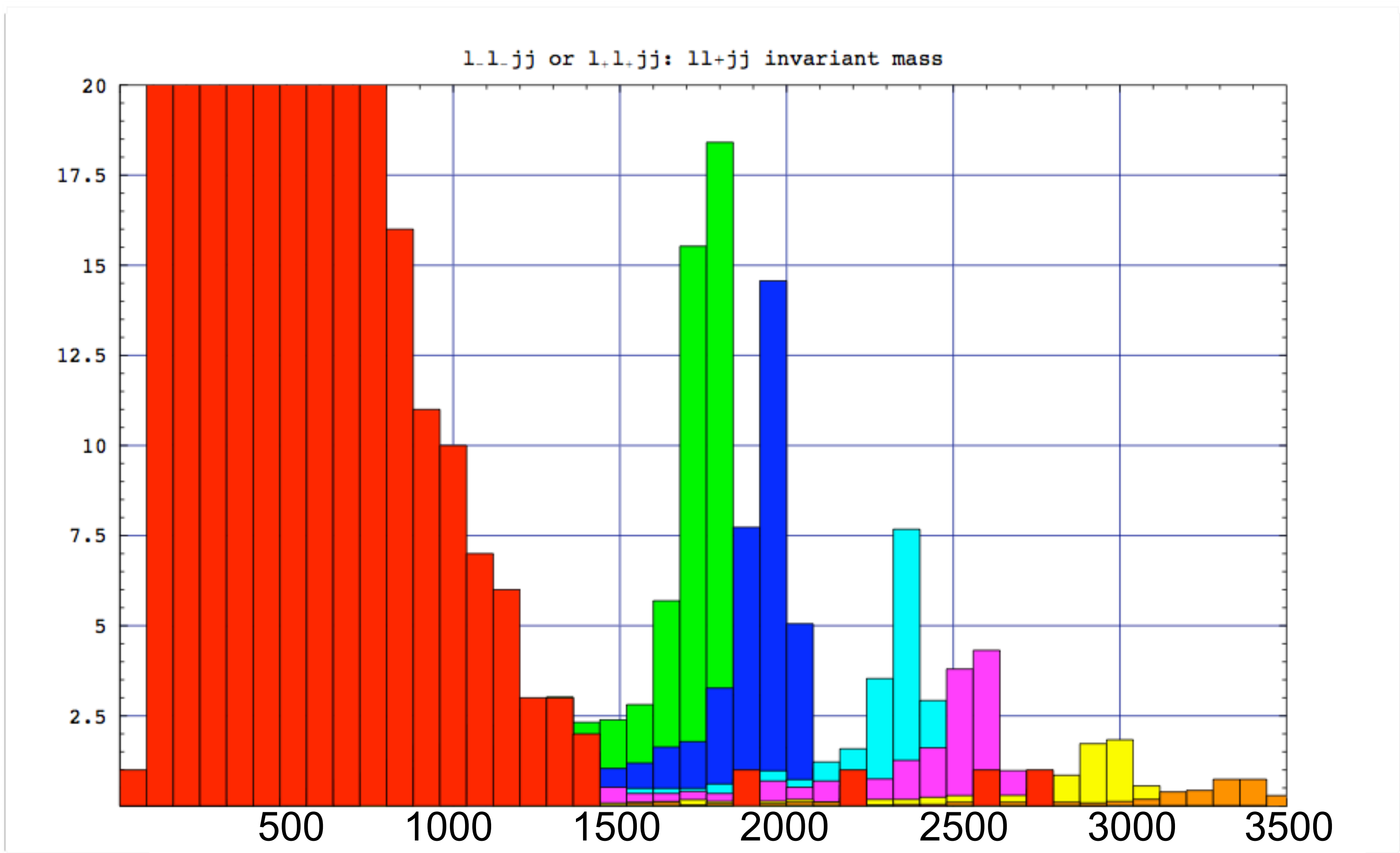


Keung, G.S. '83

- Parity restoration
- Lepton Number Violation: electrons (+ jets)
- Lepton Flavor Violation: flavor structure

14 TeV LHC   L=10/fb

Nesti



red = background

peaks = mass of W_R (GeV)

Gift of LNV:
no background
above 1.5 TeV

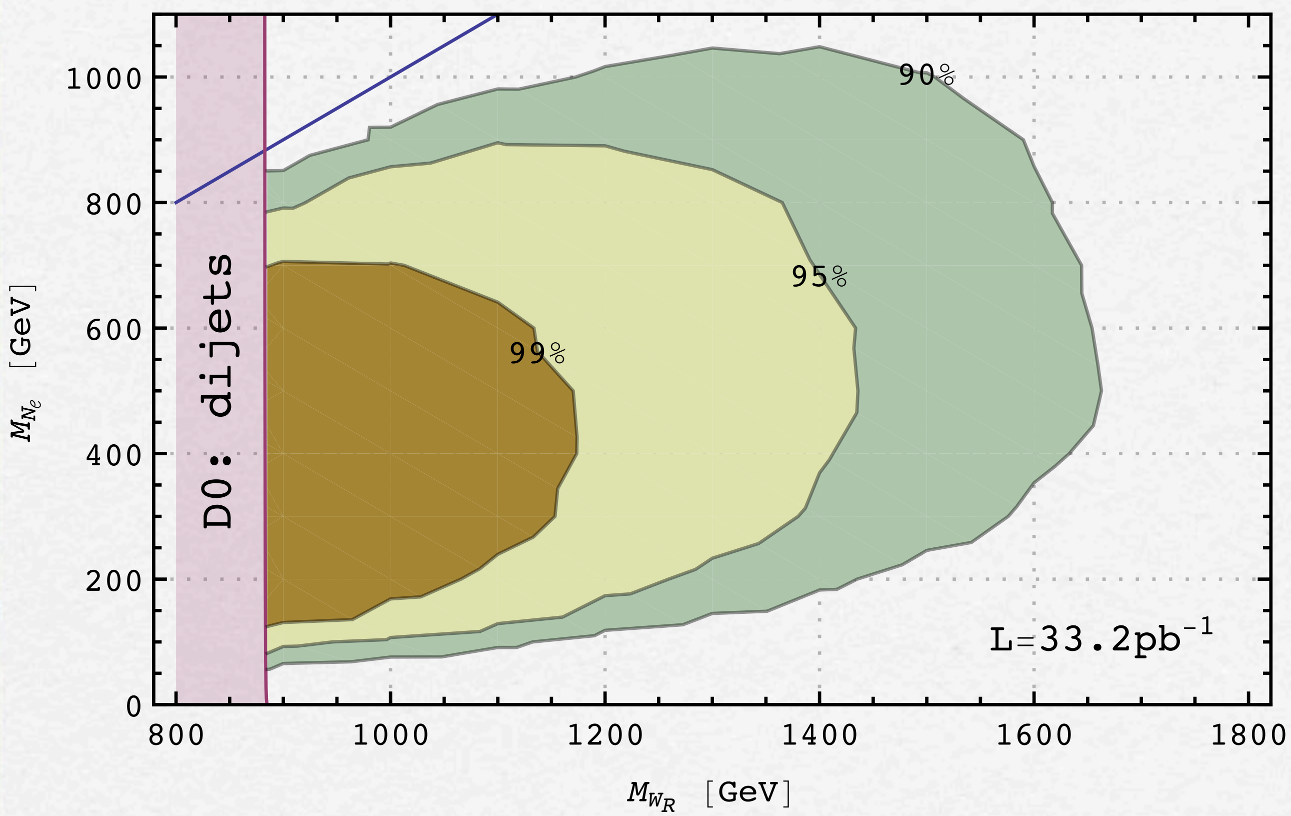
- up to 4 TeV @ L= 30/fb   Gninenko et al '06   CMS
- up to ~ 6 TeV @ L= 300/fb   Ferrari et al, '00   ATLAS

LHC @ E = 7 TeV

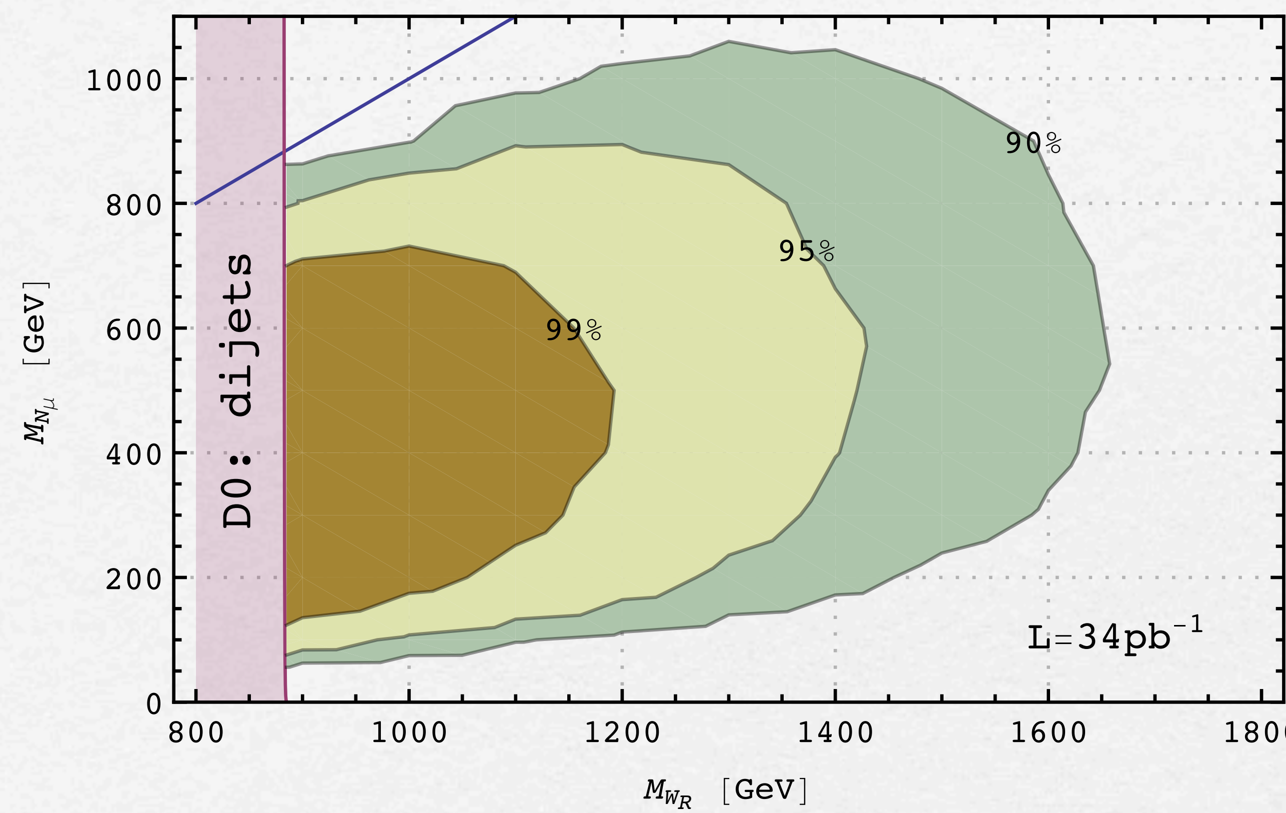
l l j j

Nemevsek, Nesti, GS, Zhang, '11

January



$e\,e$



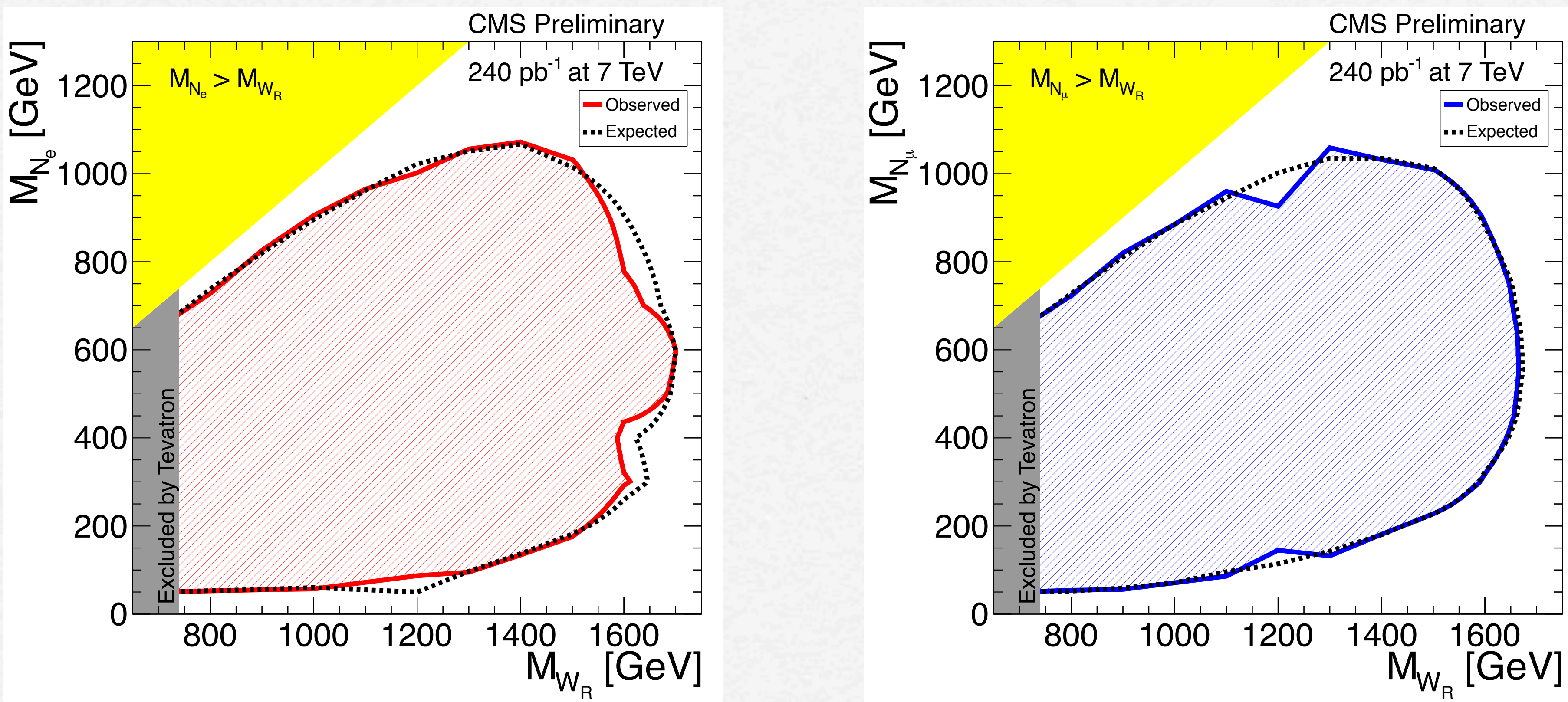
$\mu\,\mu$

early data: L=33-34/pb $M_{W_R} \gtrsim 1.4\,TeV$

estimate: L = 1/fb $M_{W_R} \gtrsim 2.2\,TeV$

LHC @ E = 7 TeV latest: $M_{W_R} \gtrsim 1700\, GeV$ July

$L = 240\,/pb$



(a) Electron channel (b) Muon channel

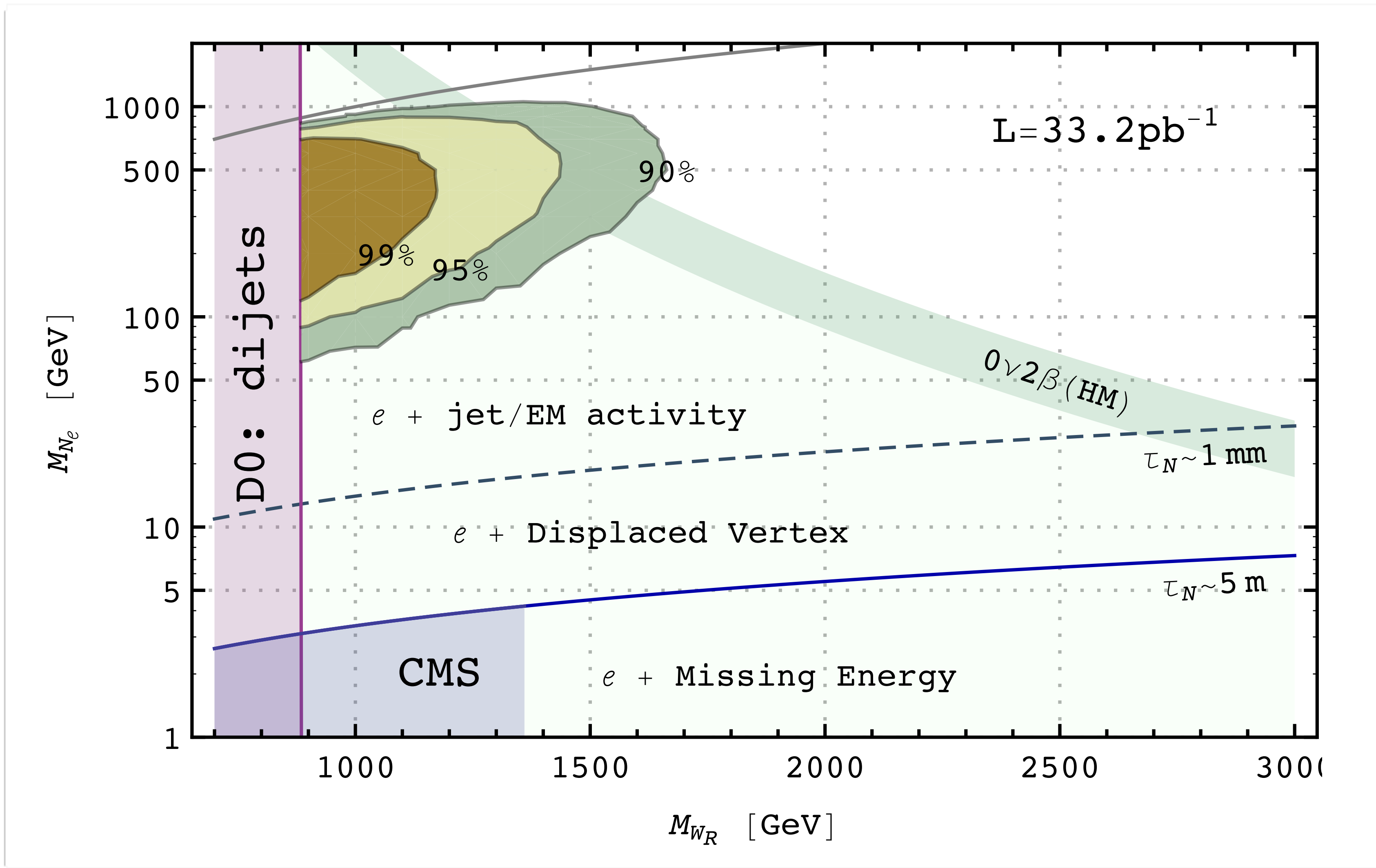
Figure 4: The 95% confidence level excluded (M_{W_R}, M_{N_ℓ}) region for the electron (left) and muon (right) channels.

CMS public note: CMS PAS EXO-11-002

Leonidopoulos, talk @ IECHEP, Grenoble, July

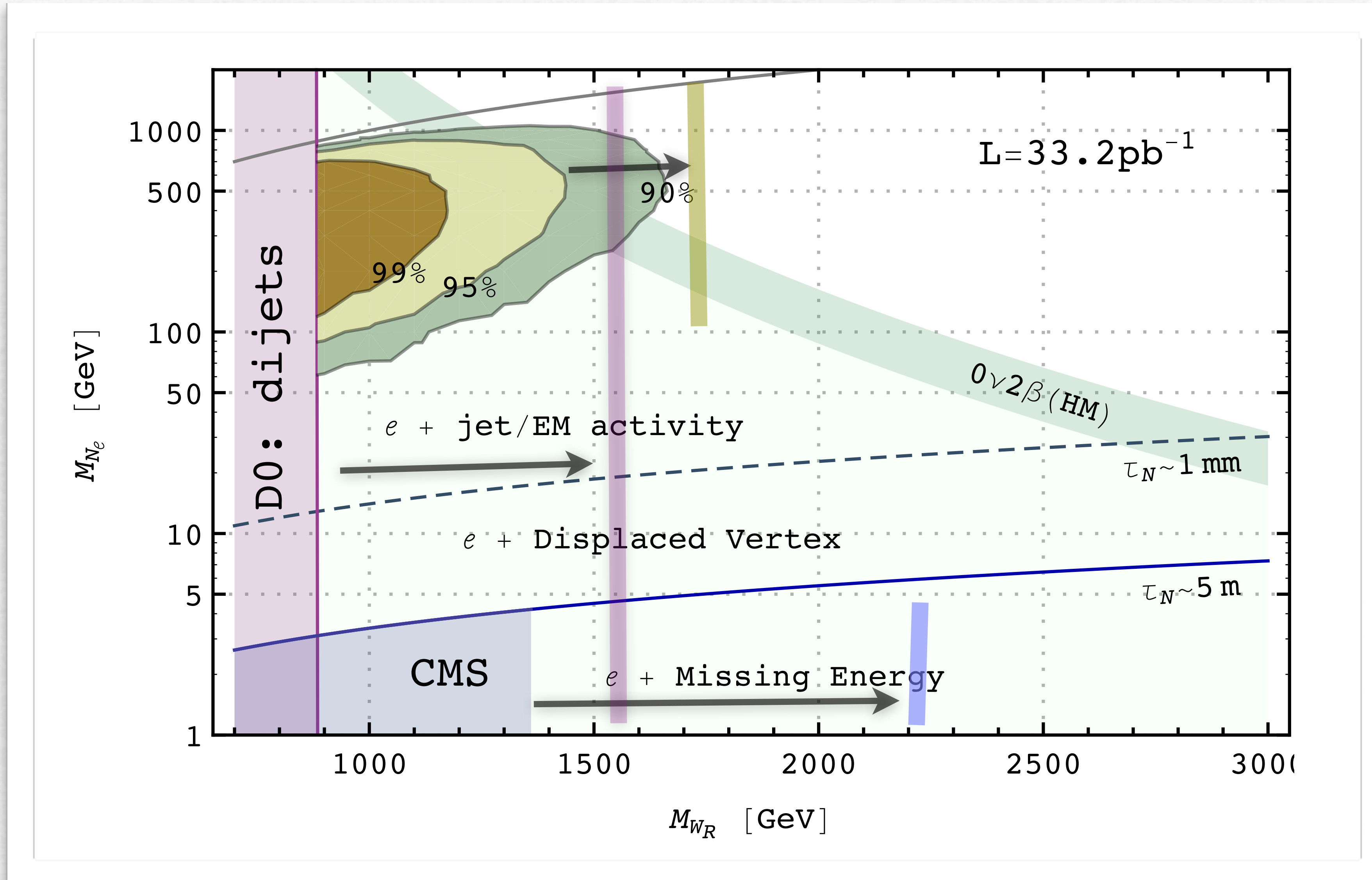
January '11

Nemevsek, Nesti, GS, Zhang, '11



January '11

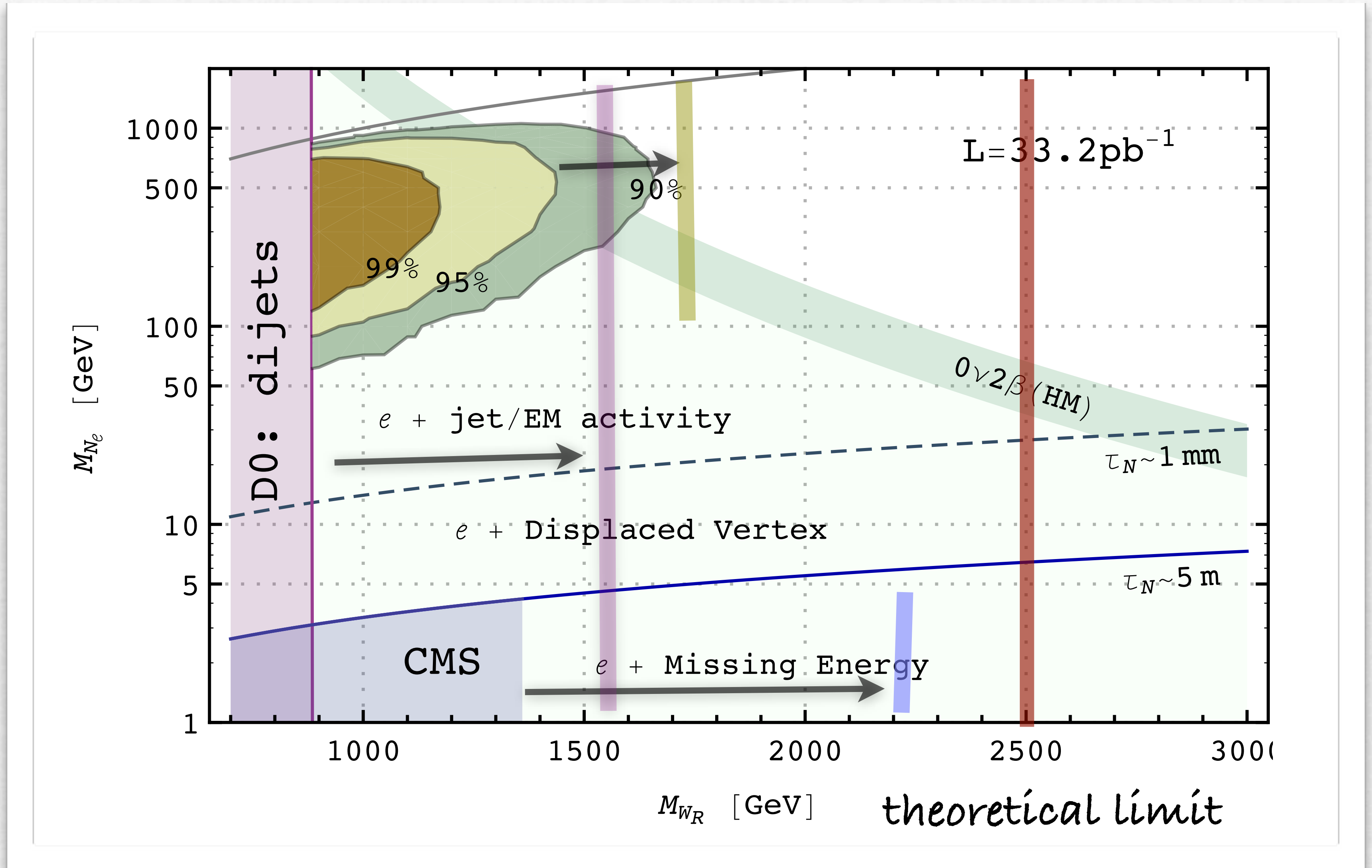
Nemevsek, Nesti, GS, Zhang, '11



July '11

January '11

Nemevsek, Nesti, GS, Zhang, '11



July '11

Model content

Mohapatra, GS '75, '81

Model content

Mohapatra, GS '75, '81

R - triplet

$$\langle \Delta_R \rangle = \begin{pmatrix} & \\ v_R & \end{pmatrix}$$

- mass of N (majorana)
- mass of W_R and Z_R

Mohapatra, GS '75, '81

Model content

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- mass of N (majorana)
- mass of W_R and Z_R

bi-doublet

$$\phi \sim (h_{\mathrm{SM}}, H_{\mathrm{heavy}})$$

$$\langle \phi \rangle = \begin{pmatrix} v & \\ & \sim v \end{pmatrix}$$

- EW symmetry breaking

Model content

Mohapatra, GS '75, '81

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L - triplet

$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

- mass of ν (majorana)

$$v_R \gg v \gg v_L$$

Model content

Mohapatra, GS '75, '81

R - triplet

bi-doublet

L - triplet

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$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

- mass of ν (majorana)

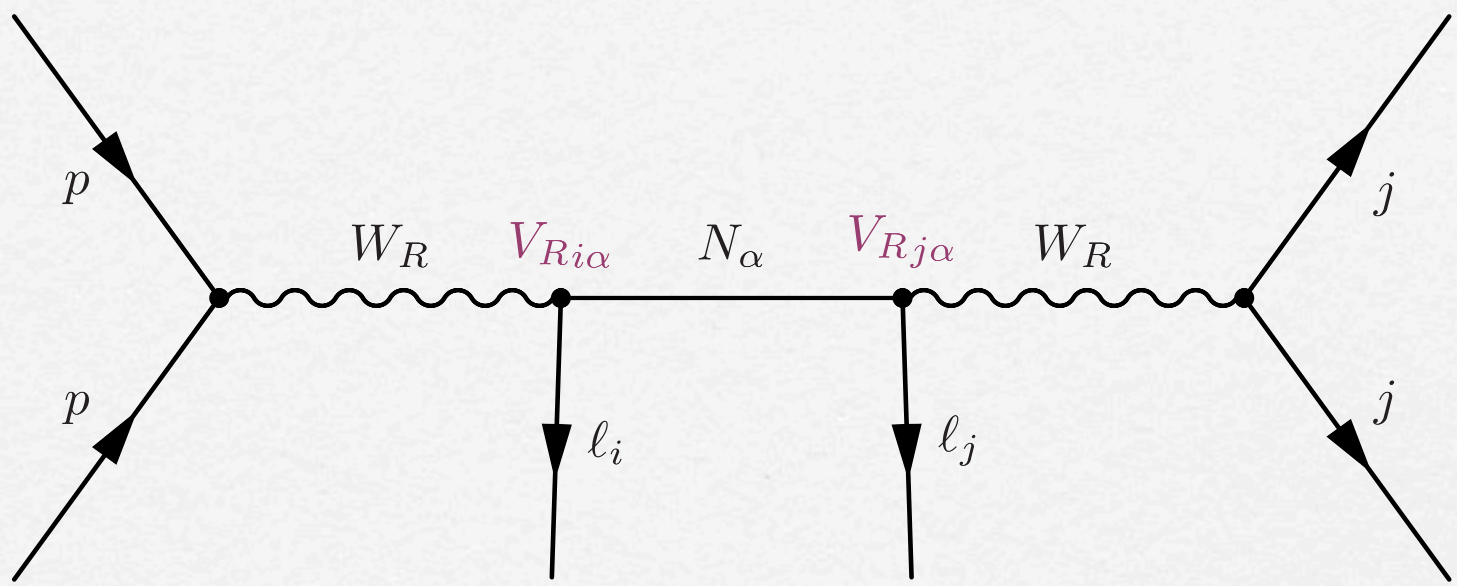
$$v_R \gg v \gg v_L$$

small Yukawa Dirac

$\Longrightarrow$ Type II

LHC: measure m_N and V_R

Keung, G.S. '83



in order to illustrate: type II seesaw

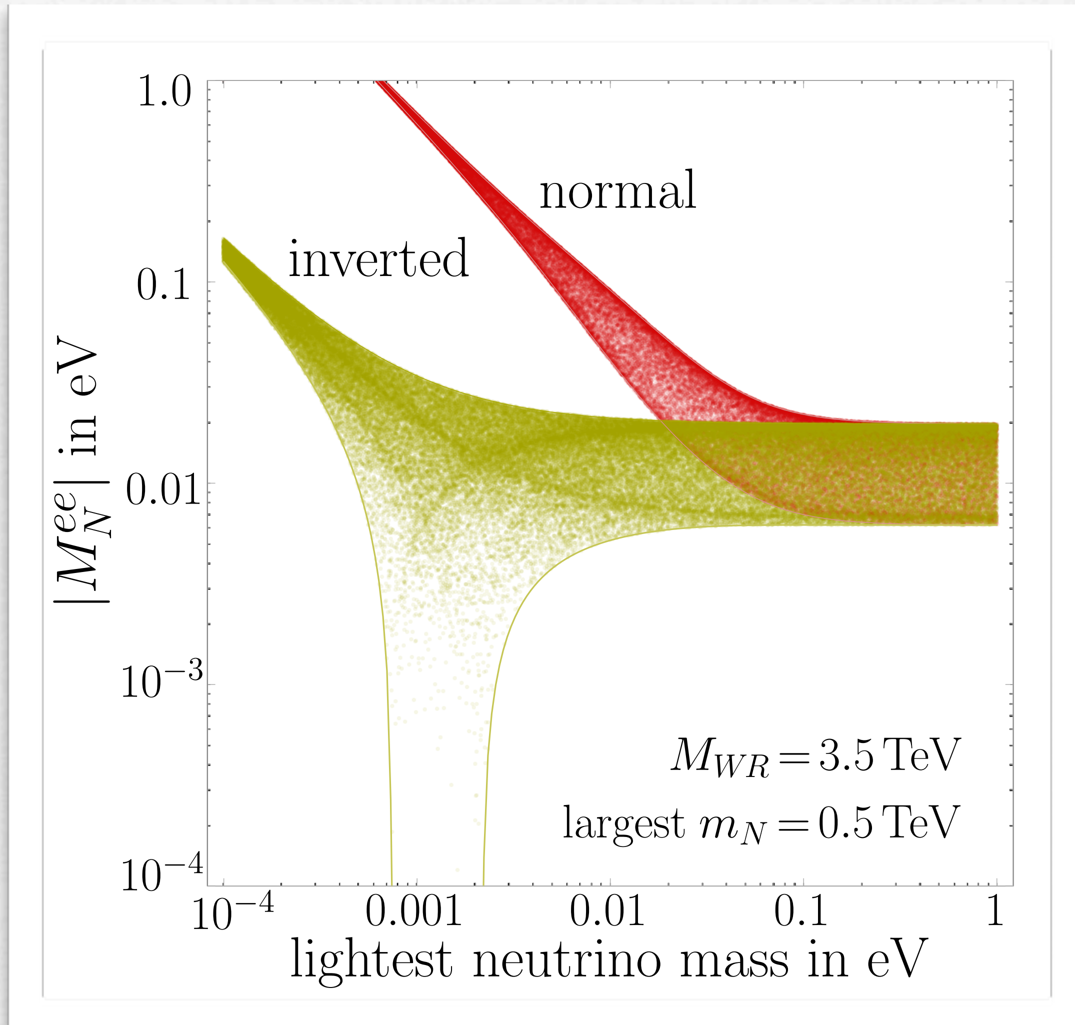
$$V_R = V_L^* \qquad m_N/m_\nu = const$$

Tello, Nemevsek, Nesti, GS, Vissani, PRL'11

Back to neutrinoless double beta decay

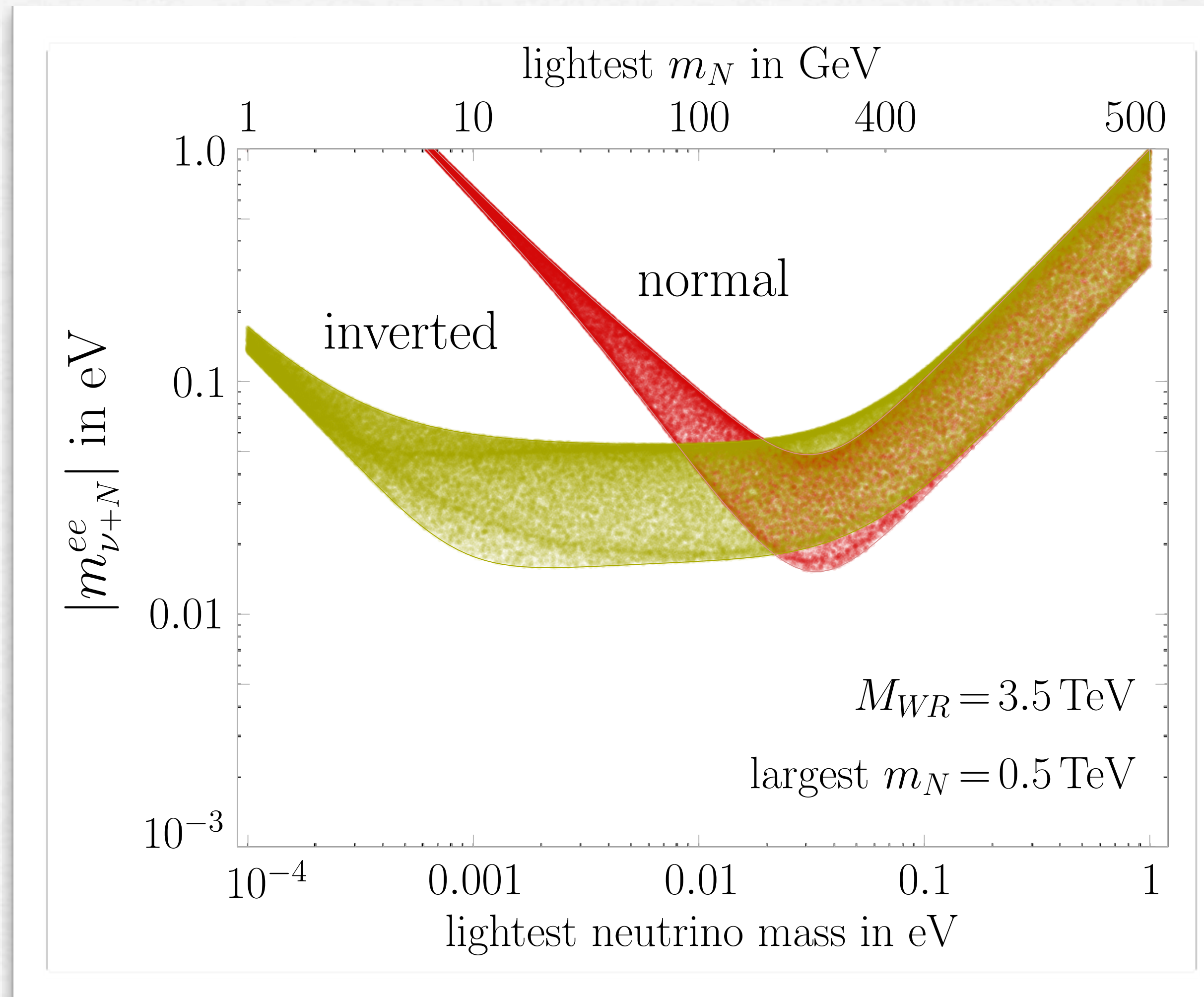
Tello et al '11

Right only



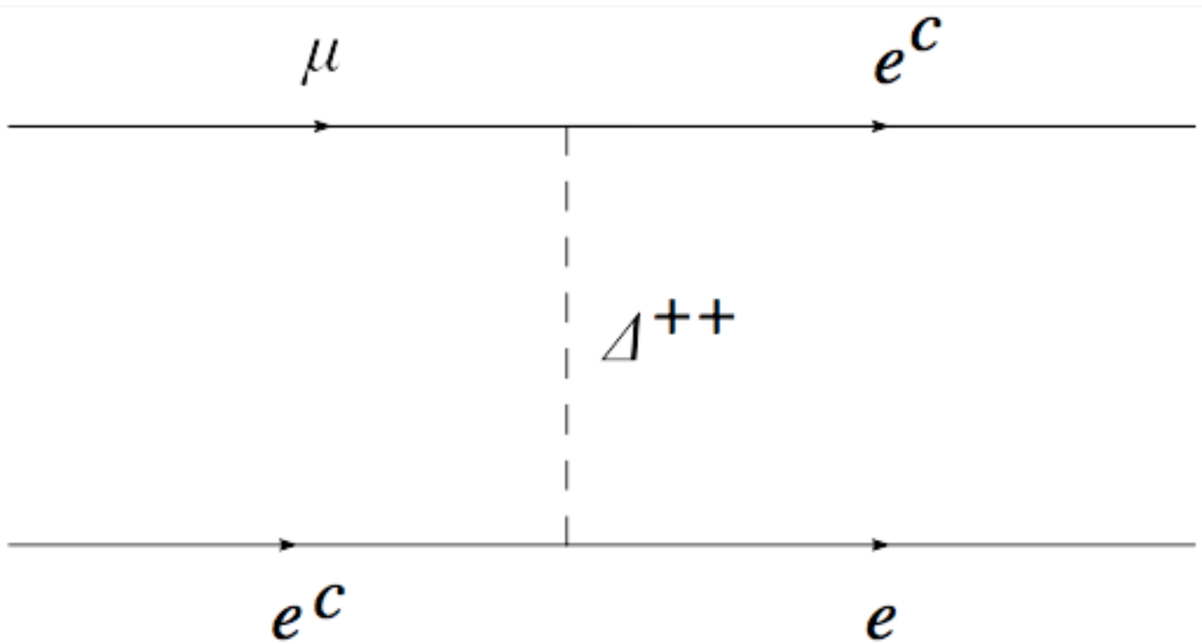
opposite from m_ν

Left + Right



non-vanishing

Lepton Flavor Violation



$$B(\mu \to 3e) = \frac{|Y_{e\mu} Y^*_{ee}|^2}{4G_F^2} \left(\frac{1}{M^4_{\Delta_L}} + \frac{1}{M^4_{\Delta_R}} \right)$$

$$Y_\Delta = \frac{g_R}{M_{W_R}} V_R^T M_N V_R$$

$\mu \to e\, e^c e$

$\Rightarrow m_N \lesssim M_\Delta$

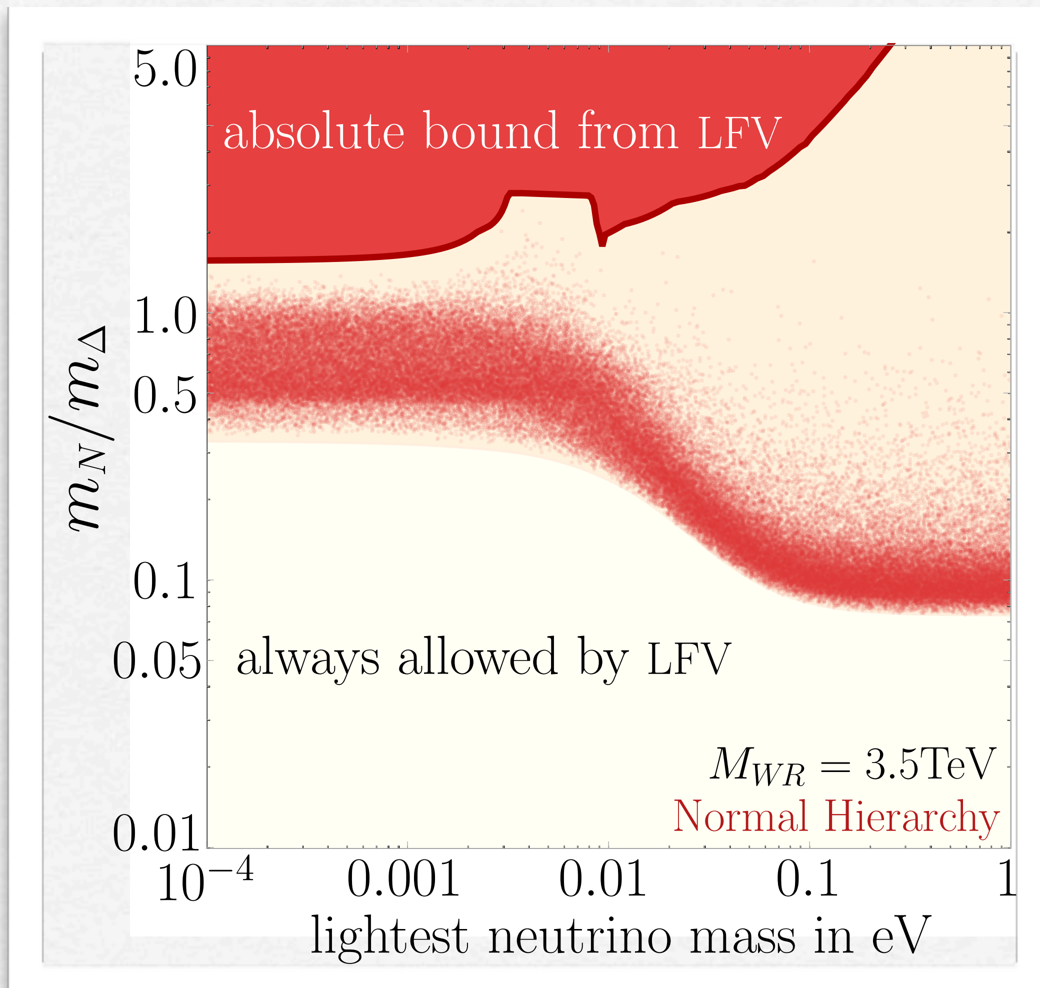
Cirigliano et al '04

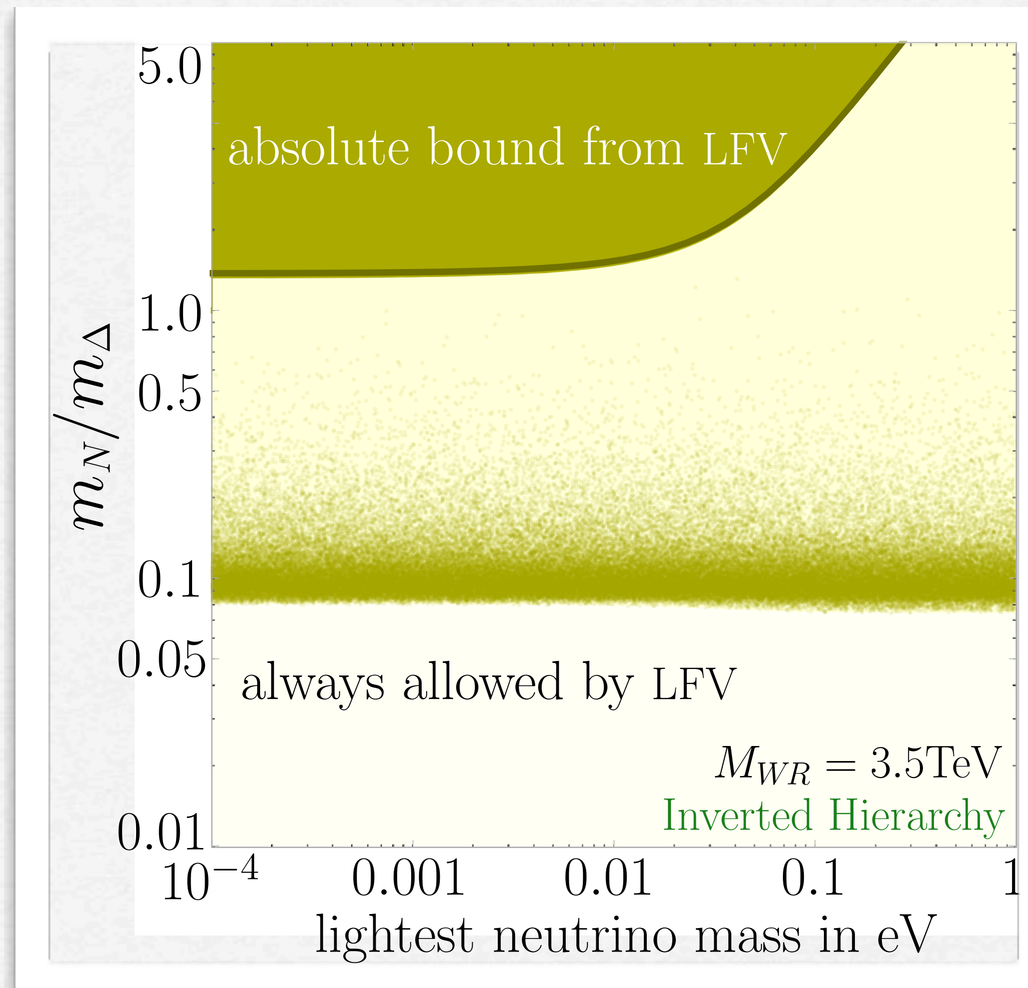
Tello '08

(Loop: $\mu \to e\gamma$ $\mu \to e$ conversion in nuclei)

Lepton Flavor Violation

talk by Nemevsek, NuFact11 - saturday





Tello, Nemevsek, Nesti, GS, Vissani, PRL'11

Neutrino mass: back to basics

Fundamental issues?

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- neutrino much lighter than electron

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  technically natural:

  chiral or lepton number symmetry

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  q-l symmetry badly broken

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neutrino masses/mixings ⟷ new physics

Effective operators and New Physics

SM degrees of freedom

two operators stand out

$$\mathcal{L}_\nu = Y^\nu_{eff} \frac{\ell\ell H H}{\Lambda_\nu}$$

$$\mathcal{L}_p = Y^p_{eff} \frac{qqq\ell}{\Lambda_p^2}$$

Weinberg '79

$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad q = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

H - Higgs doublet

$$Y_{eff} \simeq 1 \quad \Rightarrow \quad \Lambda_\nu \lesssim 10^{14}\, GeV \qquad \Lambda_p \gtrsim 10^{15}\, GeV$$

Grand Unification?

suggestive:

$$\Lambda_\nu \lesssim \Lambda_p \simeq M_{GUT}$$

SO(10) tailor made

minimal supersymmetric version:

$$\theta_{\rm atm} \simeq 45^o \Leftrightarrow \theta_{ub} \simeq 0$$

Bajc, GS, Vissani '02

$$\theta_{13} \simeq 10^o$$

Goh, Mohapatra, Ng '03

$\Downarrow$ T2K

....

GS: review '11

Aulakh '11

No LHC

Fermi theory

$$G_F = \frac{1}{\Lambda^2}$$

$$\Lambda \simeq 300\, GeV$$

$$G_F = \frac{g^2}{8M_W^2} \quad g \simeq 0.6$$

$$M_W \simeq 80\, GeV$$

True scale can be (much) smaller

Gravity

$$G_N = \frac{1}{M_P^2}$$

$$M_P \simeq 10^{19}\, GeV$$

$$G_N = \frac{g^2}{\Lambda_F^2} \quad g \ll 1$$

$$\Lambda_F \simeq TeV$$

$$\Uparrow \; g = (\Lambda_F R)^{-n/2}$$

ADD '98

large extra dimensions

Weinberg's d= 5 operator: UV completion = seesaw

$$(\ell^T \epsilon H) C (H^T \epsilon \ell) \; = \; (\ell^T \epsilon C \vec{\sigma} \ell)(H^T \epsilon \vec{\sigma} H) = (\ell^T \epsilon \vec{\sigma} H) C (H^T \epsilon \vec{\sigma} \ell)$$

singlet fermion
(sterile)
Type I LR

triplet scalar Y=2
Type II LR

triplet fermion
Y=0
Type III SU(5)

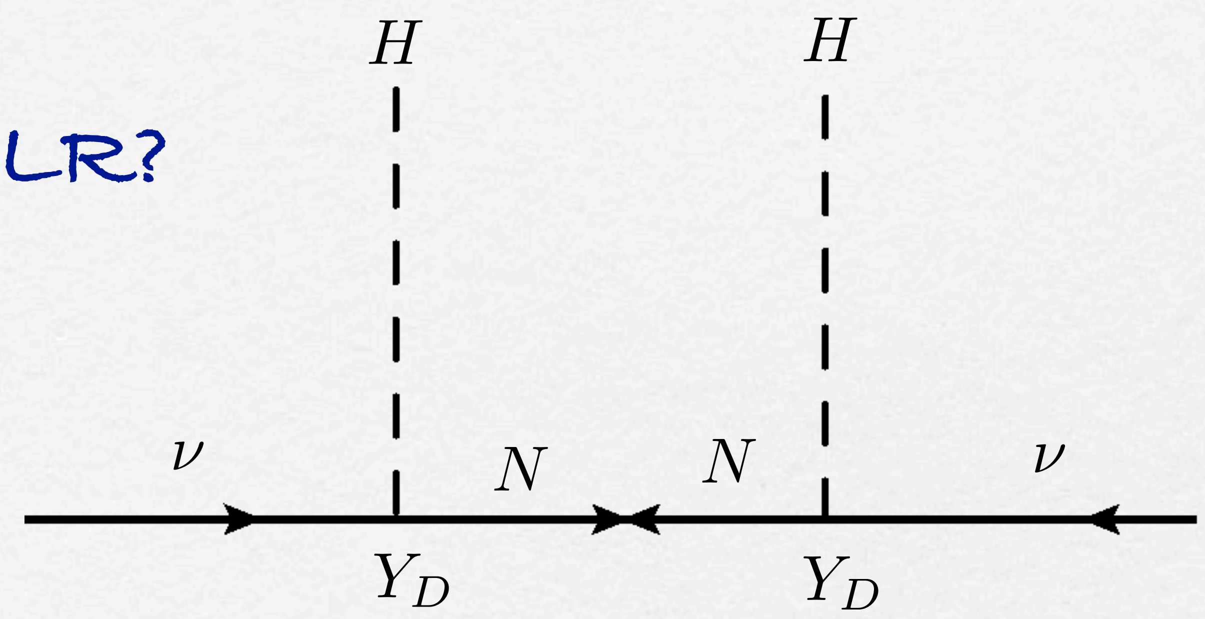
Probing seesaw @ LHC

Type I seesaw

Minkowski '77
Mohapatra, GS '79
Gell-Mann, et al '79
Yanagida '79

integrated out - phantom particle?

sterile neutrino - remnant of LR?



N - hard, if not impossible,
to produce at colliders

crying for W_R

Kersten, Smirnov '07
Datta, Guchait, Pilaftsis '93
Datta, Guchait, Roy '93
Han, Zhang '06
del Aguila, Aguilar-Saavedra, Pittau '07'
del Aguila, Aguilar-Saavedra '08

L-R theory

- understanding P violation
- gauge structure: new currents
- LNV@colliders
- see-saw: ν_R

L-R theory

$$\nu_R$$

GUT

- unification of forces
- charge quantization: monopoles
- fermion mass relations
- proton decay: X boson

GUT

X boson

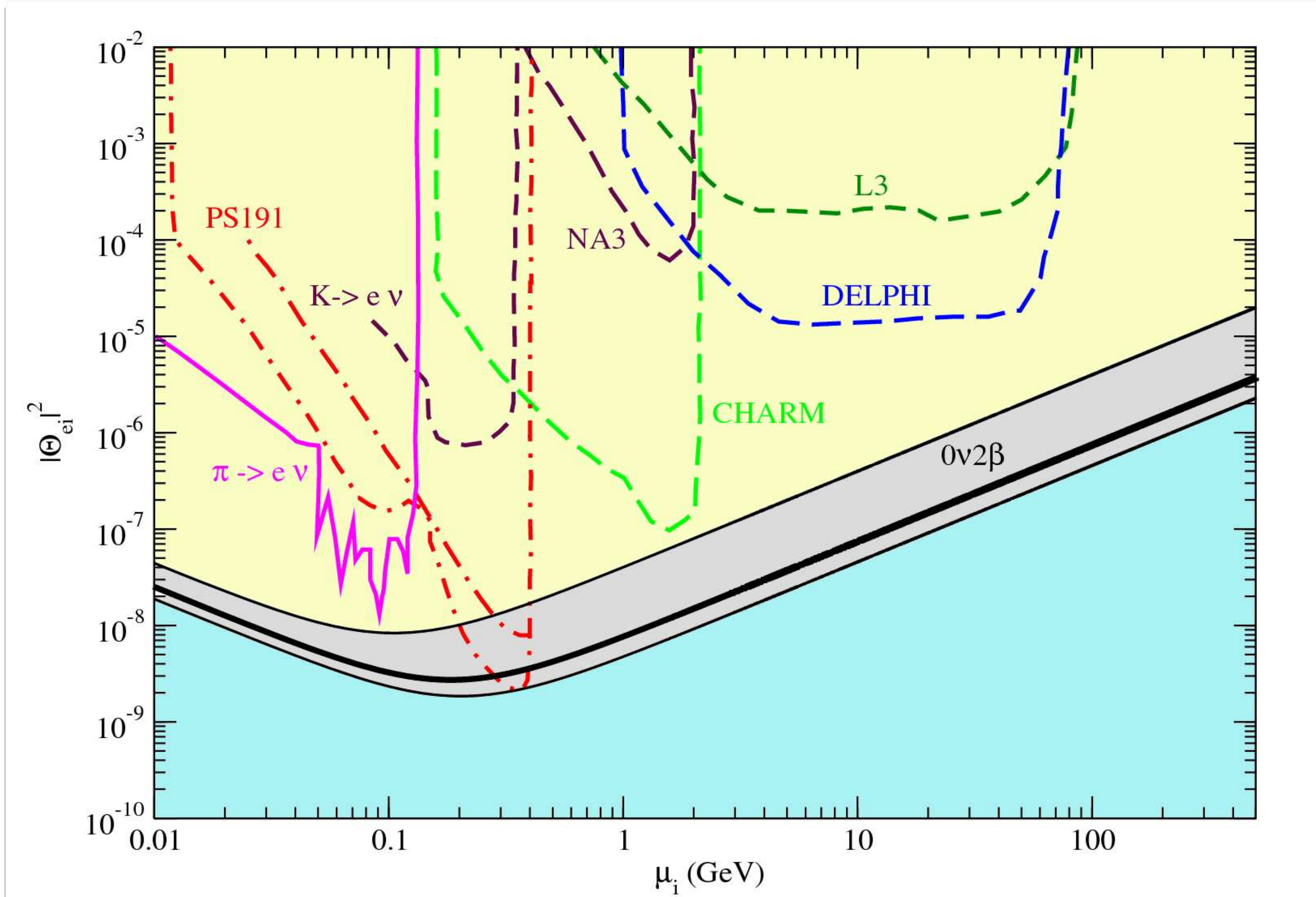
Standard Model

- Electroweak unification
- gauge structure
- W-Z mass ratio
- neutral currents: Z boson

Standard Model

Z boson

Bounds on the e- N mixing



$\mu = m_N$

N can be as light as you wish

light N: NuSM - neutrino mass, baryogenesis, DM

Asaka, Blanchet, Shaposhnikov '05, ...

Atre, Han, Pascoli, Zhang '09

Mitra, GS, Vissani '11

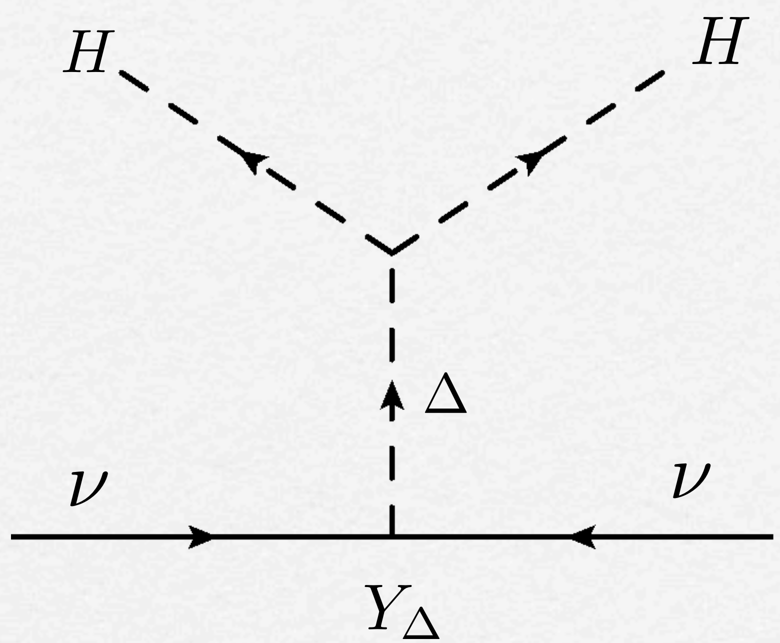
talk by Ibarra

Type II seesaw

Magg, Wetterich '80

Lazarides, Shafi, Wetterich '81

Mohapatra, GS '81



$$\mathcal{L} = Y_\Delta \ell^T \epsilon C \Delta \ell + \mu H^T \epsilon \Delta^\dagger H + m_\Delta^2 \Delta^\dagger \Delta$$

$+ \ldots$

$$v_\Delta \simeq \mu \frac{M_W^2}{m_\Delta^2} \lesssim GeV$$ (ρ parameter)

in components $\begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

remnant of LR theory ?

R - triplet

$$\langle \Delta_R \rangle = \begin{pmatrix} & \\ v_R & \end{pmatrix}$$

bi-doublet

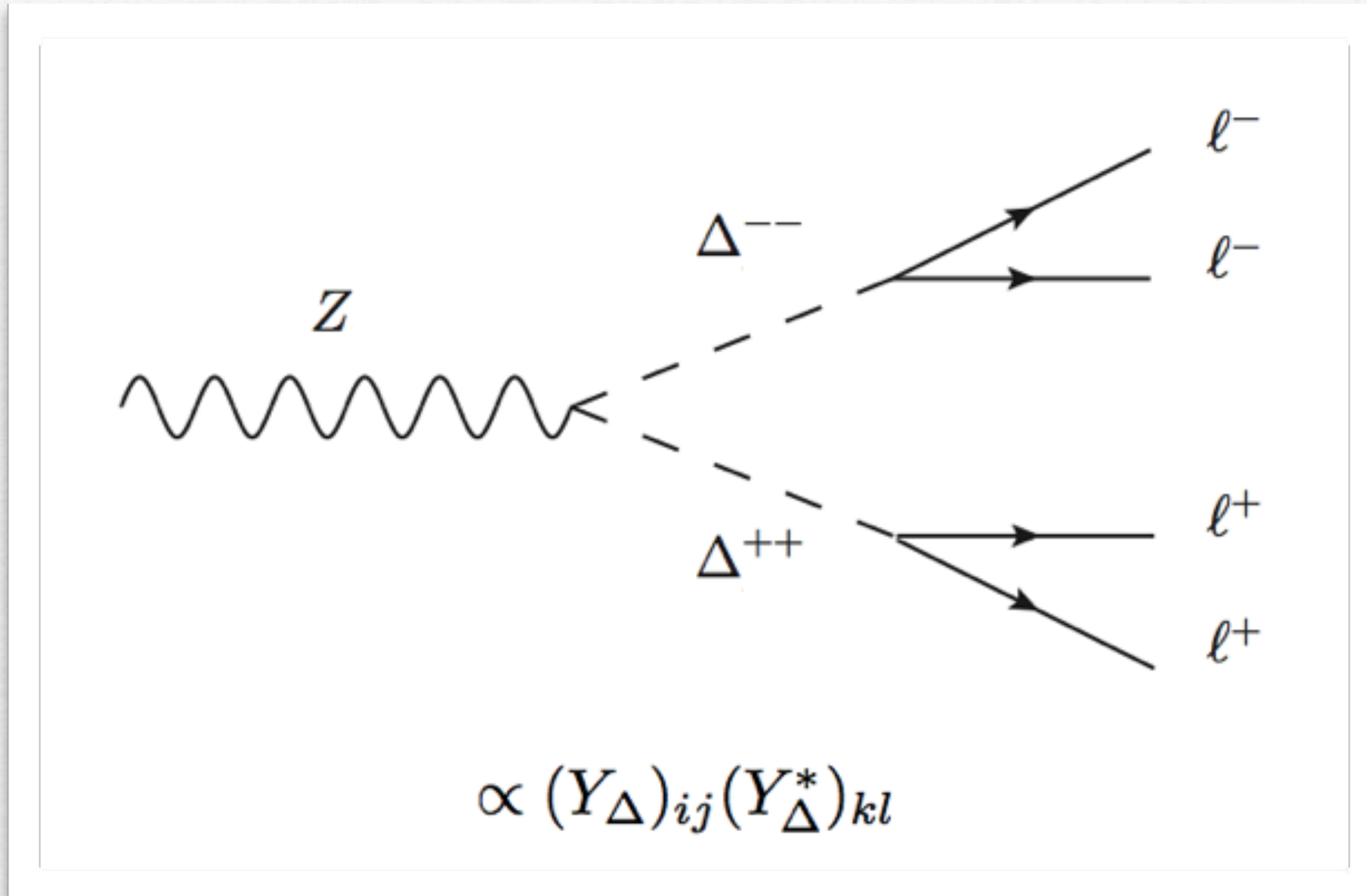
$$\phi \sim (h_{\text{light}}, H_{\text{heavy}})$$

$$\langle \phi \rangle = \begin{pmatrix} v & \\ & v' \end{pmatrix}$$

L - triplet

$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

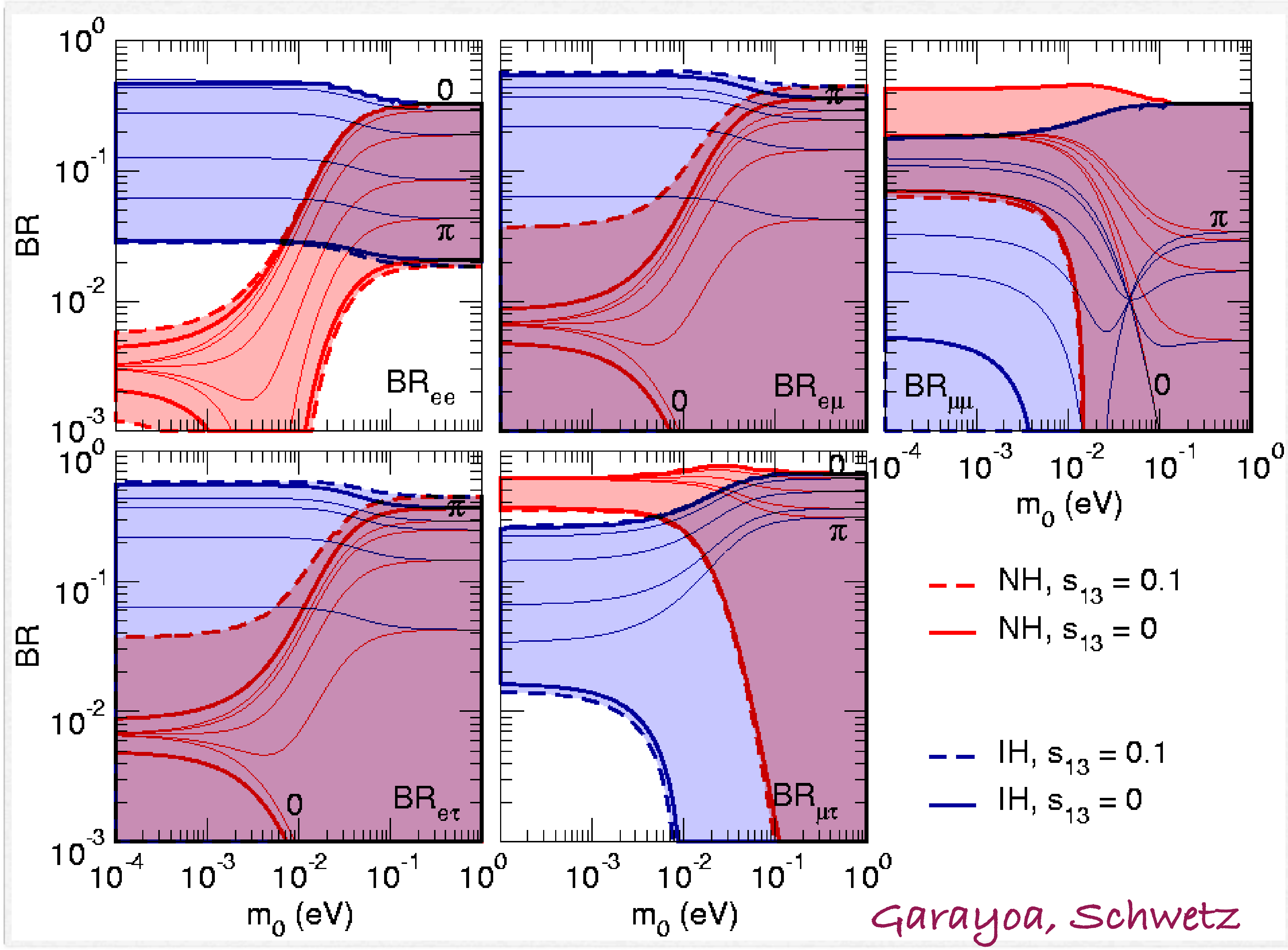
$$v_L \ll v' < v \ll v_R$$



$$M_\nu = U_\ell^T m_\nu U_\ell = Y_\Delta v_\Delta$$

Akeroyd, Aoki, Sugiyama '07
Fileviez-Perez, Han, Huang, Li, Wang '08
del Aguila, Aguilar-Saaverda '08

probe neutrino masses and mixings



probe of:

- hierarchy
- 1-3 mixing

Chun, Lee, Park '03

Garayoa, Schwetz '07

Kafastik, Raidal, Rebane '07

Fileviez Perez, Han, Li, Wang '08

Why only the triplet?

Principle: all "Yukawa" Higgs allowed by the SM symmetries

vevs: color and charge singlets

$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad e_R$$

→

H: Y=1 doublet

Δ: Y=2 triplet

Δ^{--} limits

D0 arXiv:1106.4250

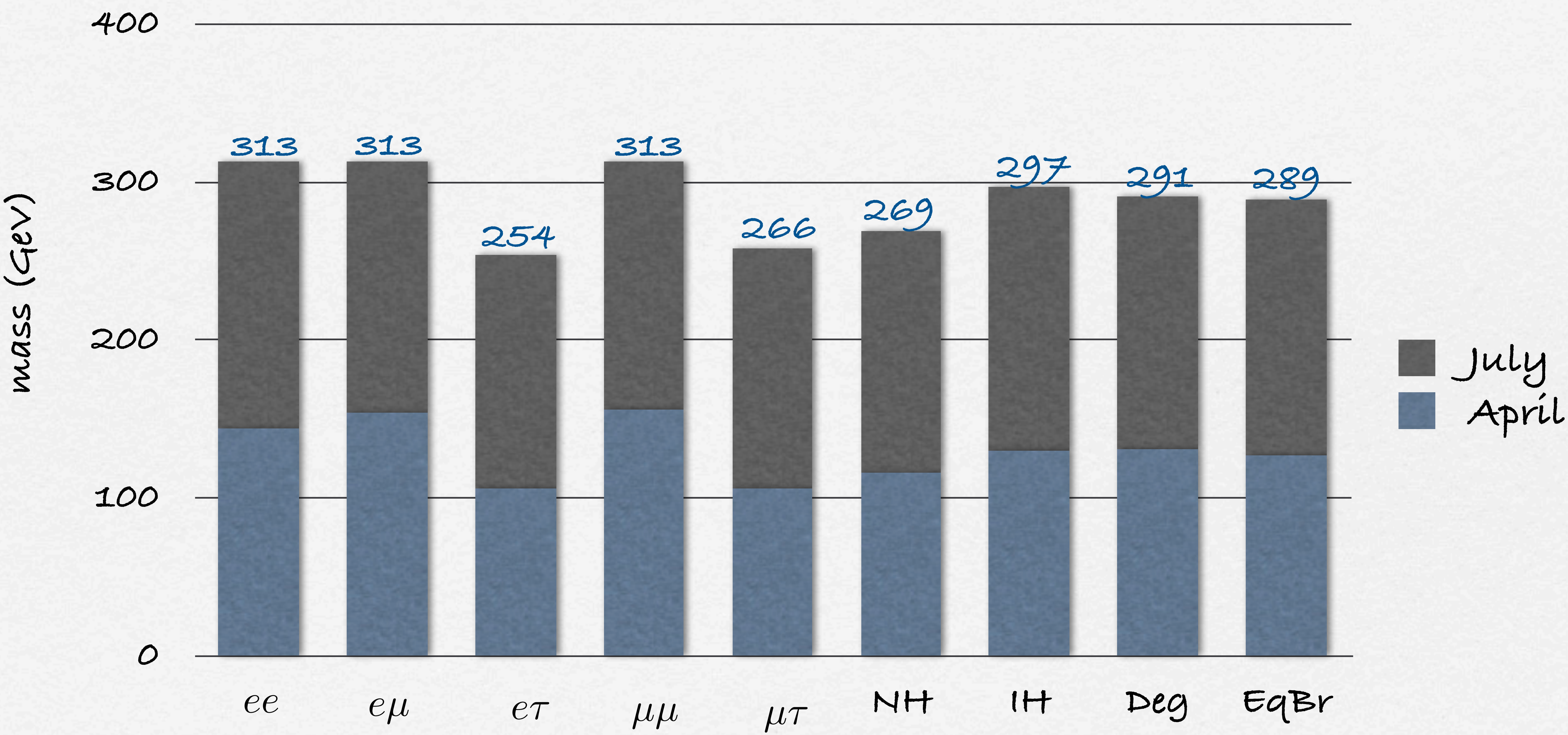
June

Decay	$H_L^{\pm\pm}$		$H_R^{\pm\pm}$	
	expected	observed	expected	observed
$\mathcal{B}(H^{\pm\pm} \to \tau^\pm\tau^\pm) = 1$	116	128		
$\mathcal{B}(H^{\pm\pm} \to \mu^\pm\tau^\pm) = 1$	149	144	119	113
Equal $\mathcal{B}$ into $\tau^\pm\tau^\pm, \mu^\pm\mu^\pm, \tau^\pm\mu^\pm$	130	138		
$\mathcal{B}(H^{\pm\pm} \to \mu^\pm\mu^\pm) = 1$	180	168	154	145

Δ^{--} limits

CMS PAS HIG-11-001

April

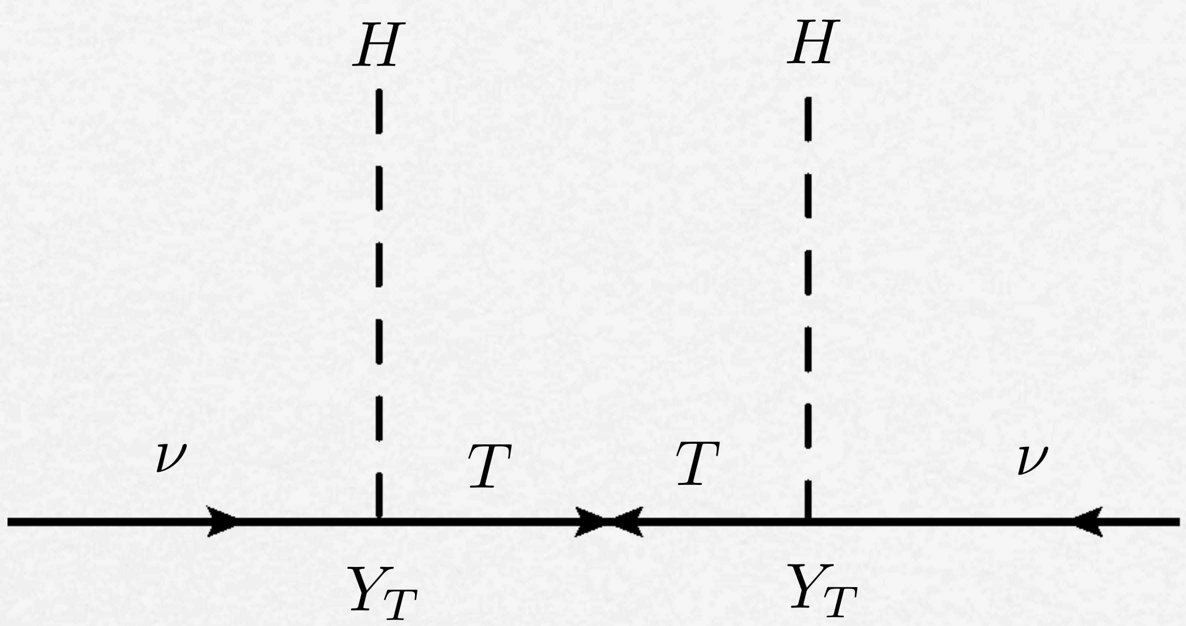


https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11007TWiki

July

Type III seesaw: triplet fermions

Foot, Lew, He, Joshi '89



origin: GUT ?

MINIMAL SU(5)

Georgi-Glashow

- asymmetric matter
  $3\times(10_F + \bar{5}_F)$
- fine-tuning

- no unification
- neutrino massless

one extra fermionic 24_F

Bajc, G.S. '06
Bajc, Nemevsek, G.S. '07

maintains nicely the ugliness of the minimal model :

- asymmetric matter
- even more fine-tuning

but also its predictivity

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

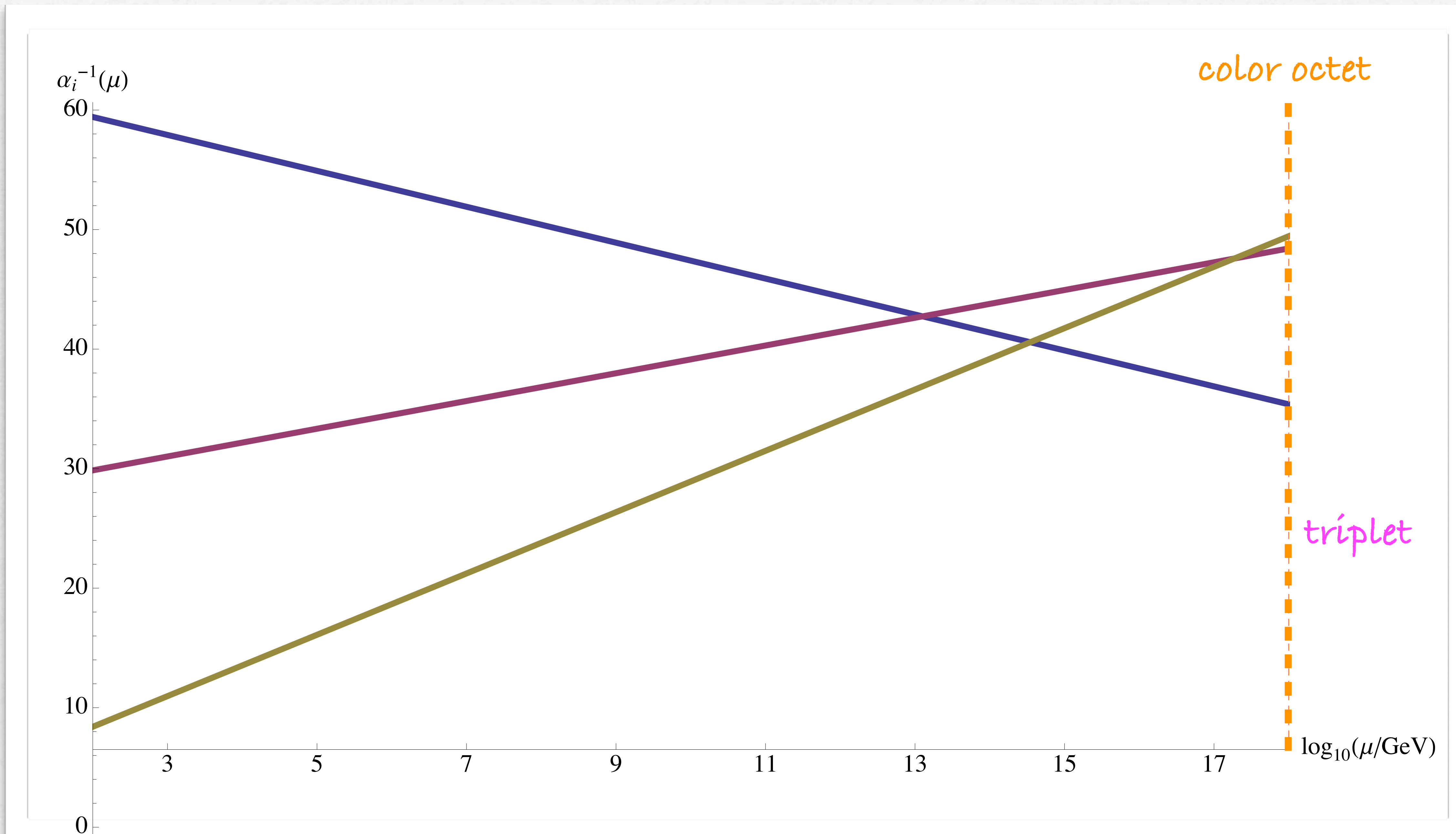
singlet S

triplet T

hybrid: type I + III

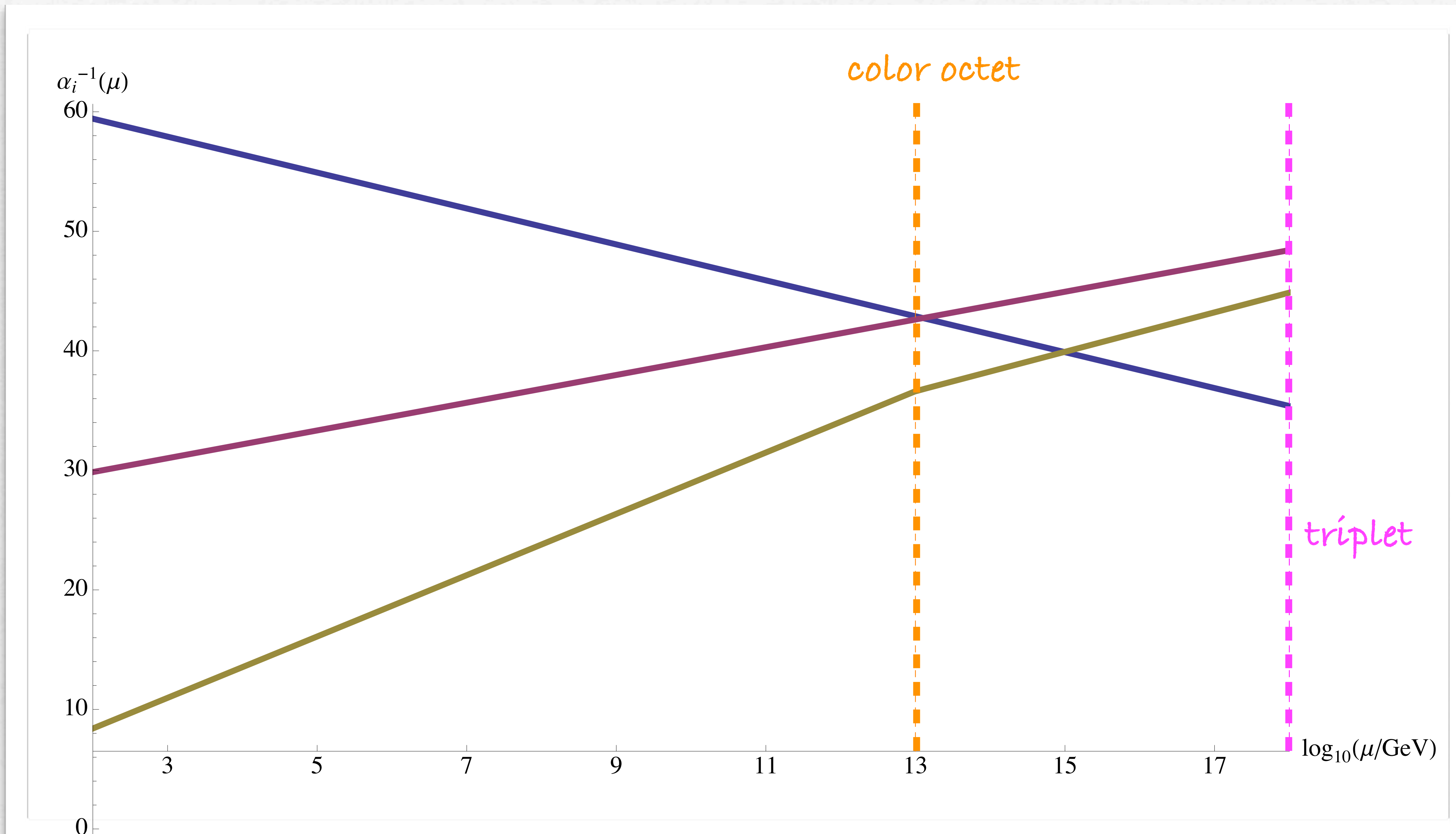
- one massless neutrino
- unification

Bajc, Nemevsek, G.S. '07



- one massless neutrino
- unification

Bajc, Nemevsek, G.S. '07



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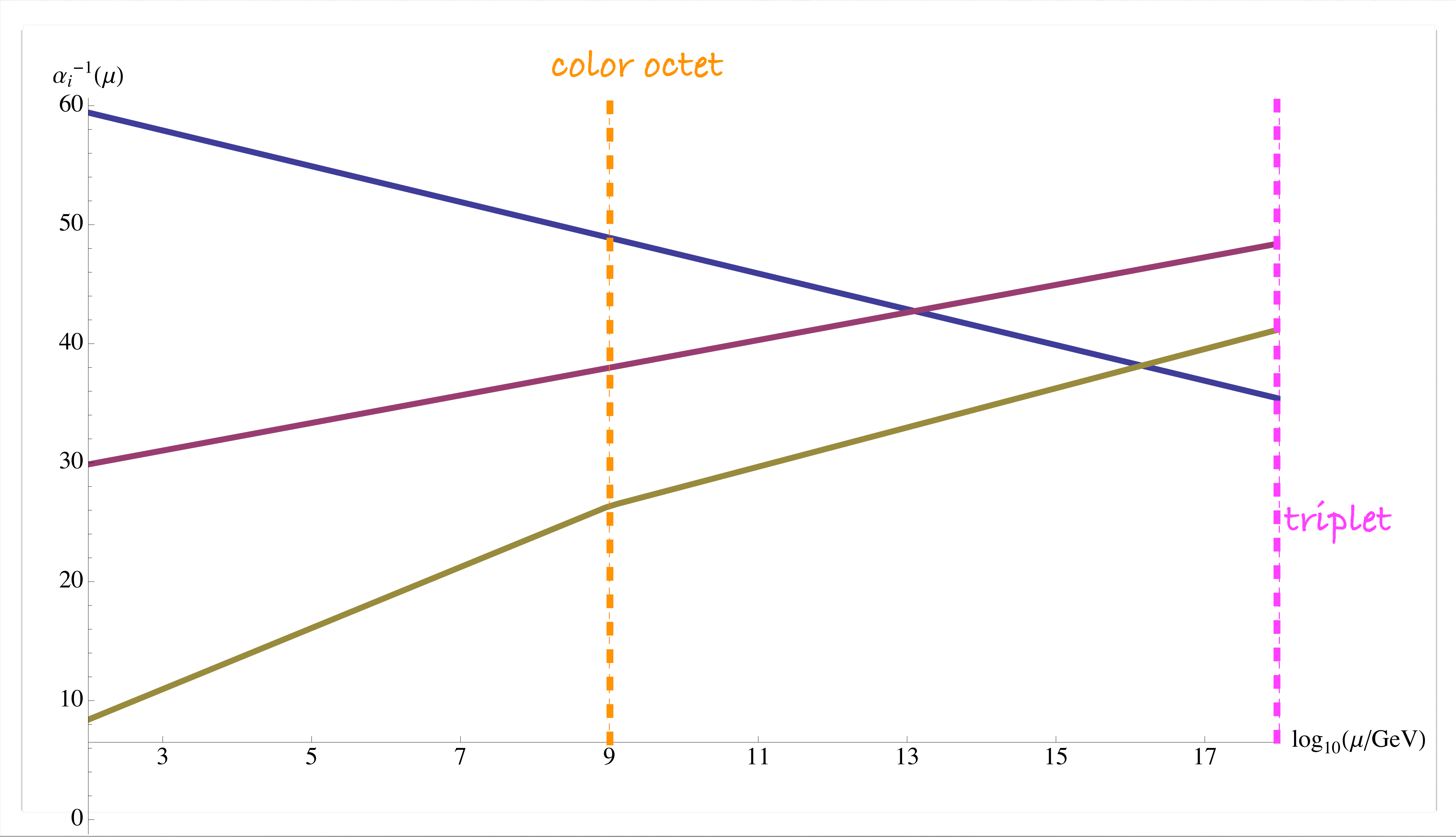
Bajc, Nemevsek, G.S. '07



- one massless neutrino
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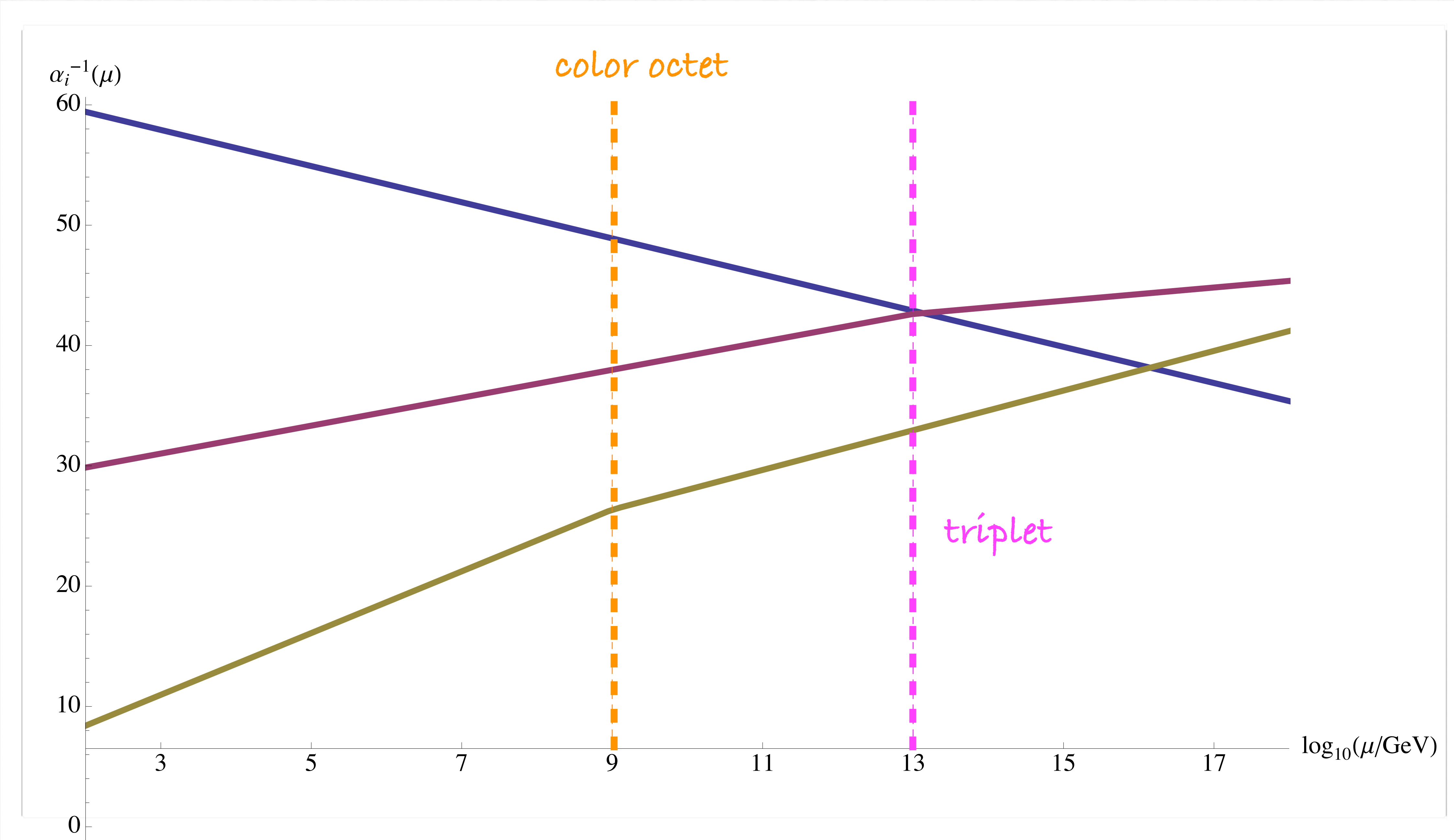
Bajc, Nemevsek, G.S. '07



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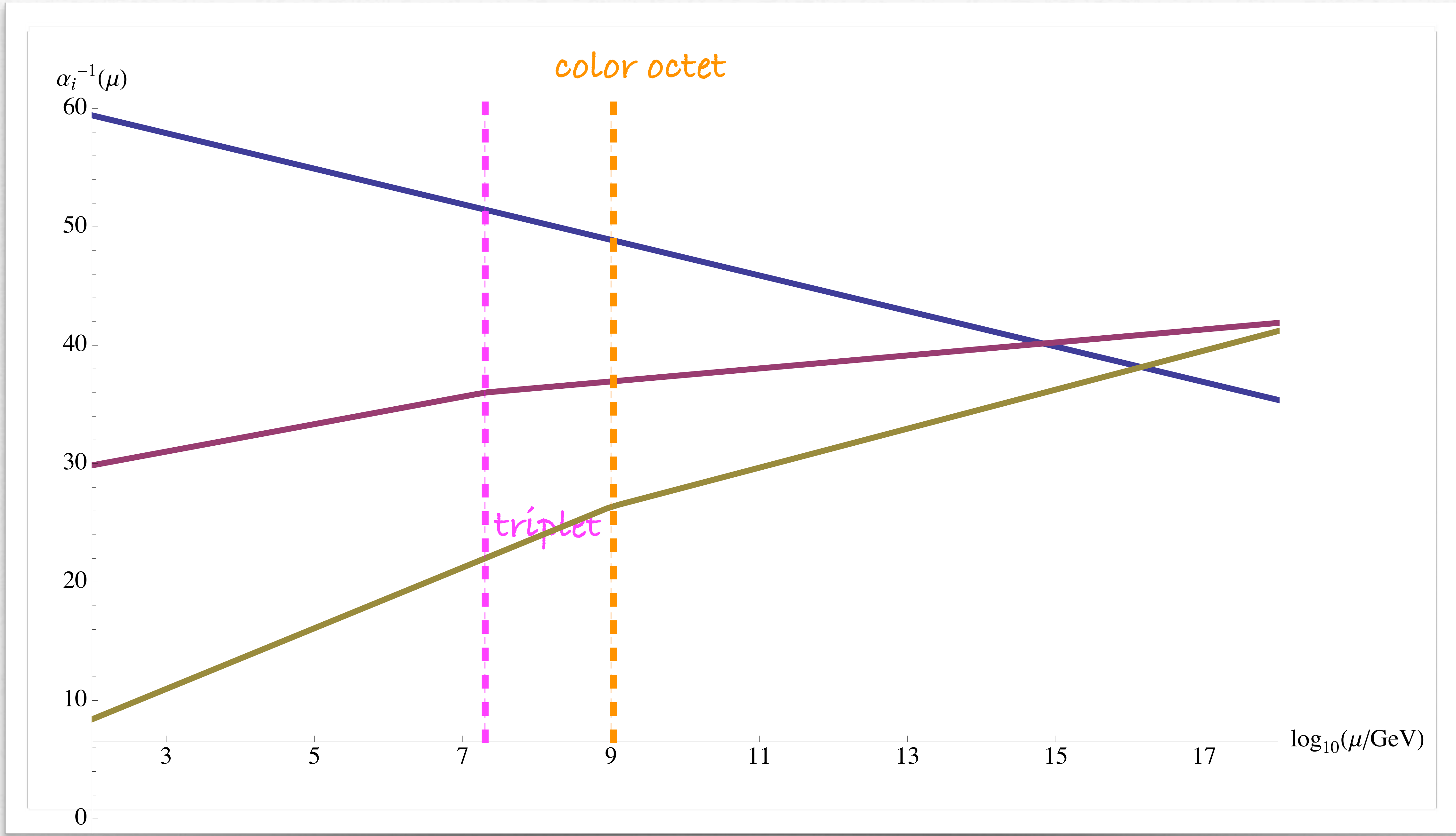
Bajc, Nemevsek, G.S. '07



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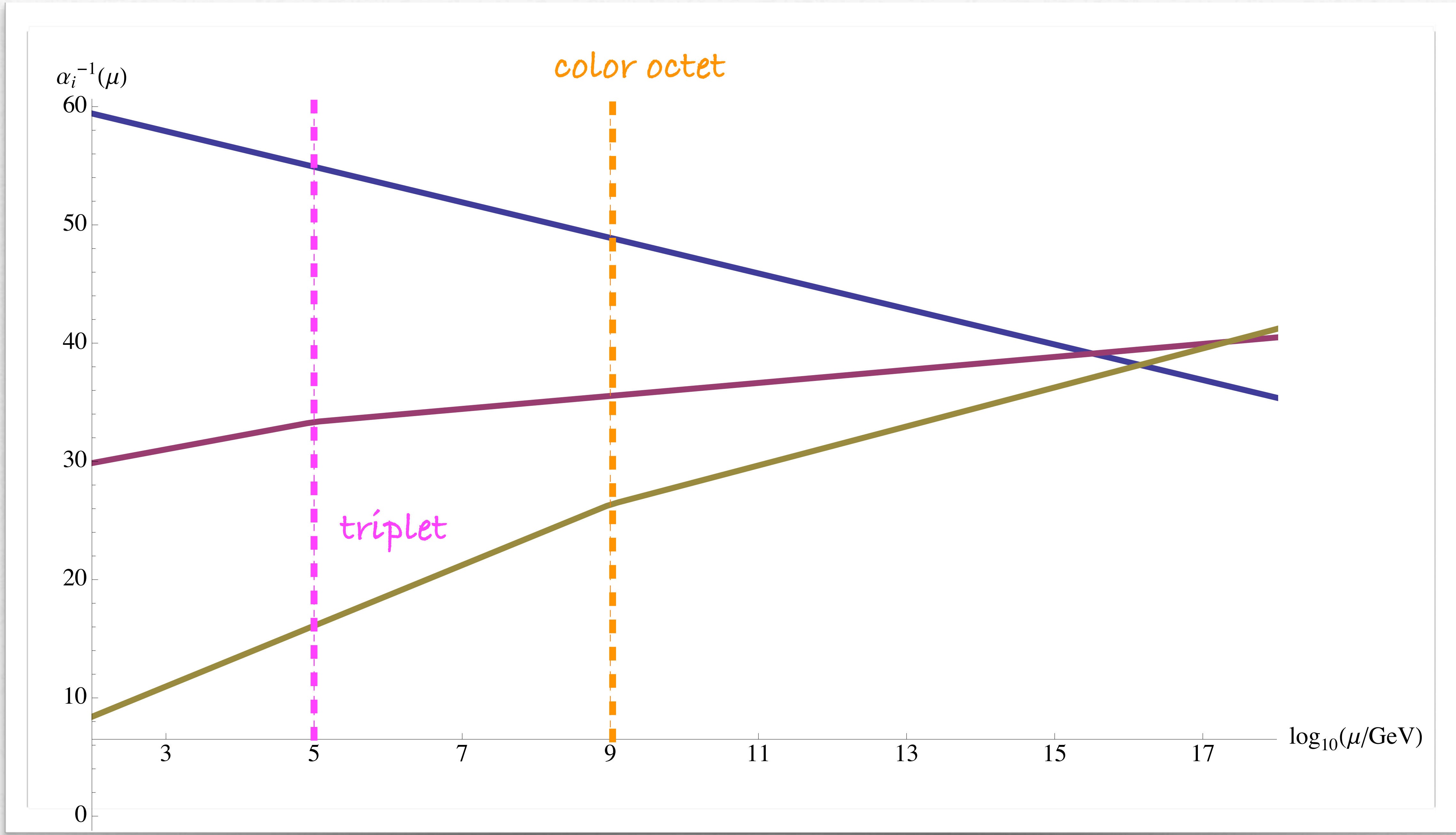
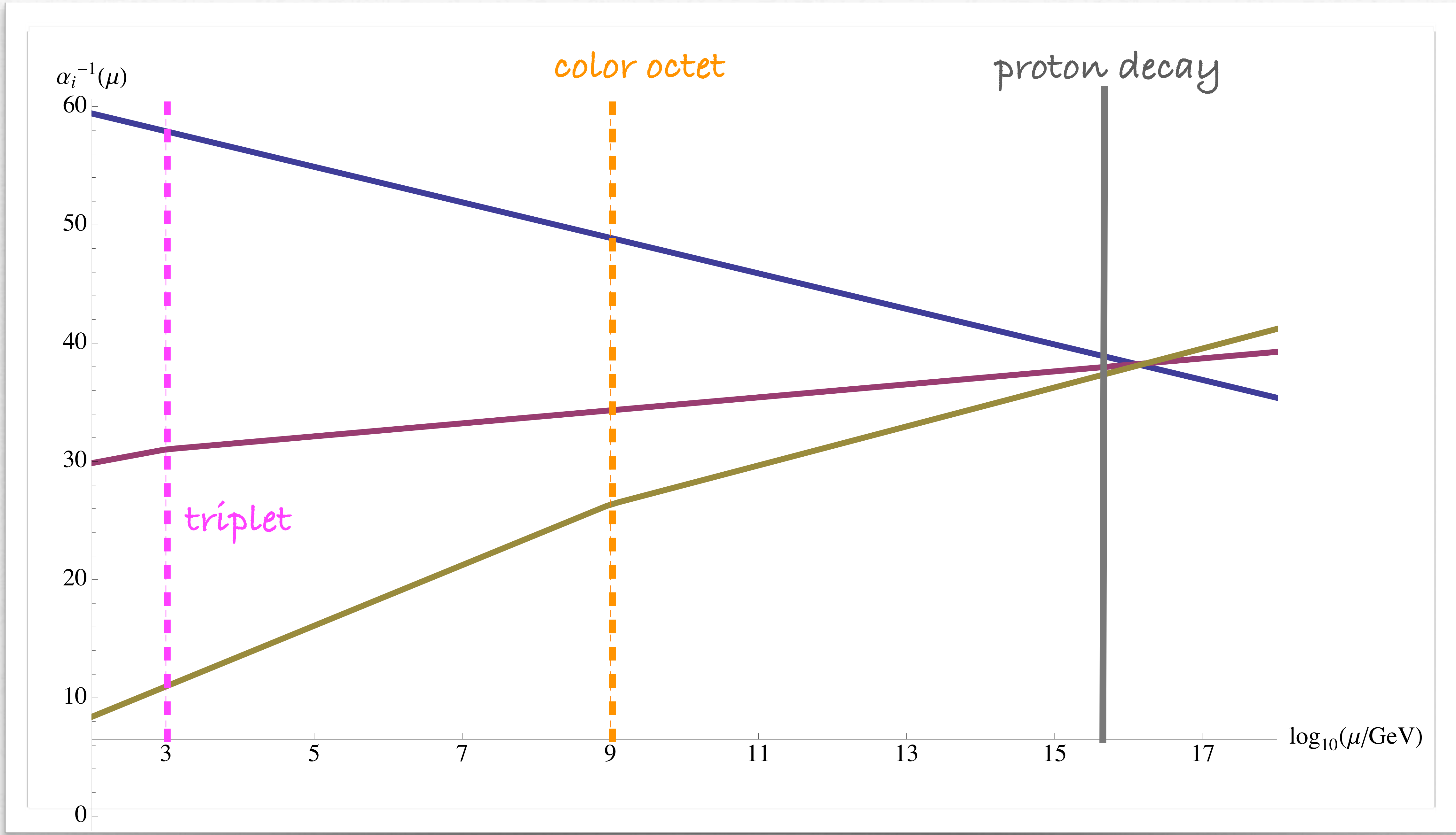
Bajc, Nemevsek, G.S. '07



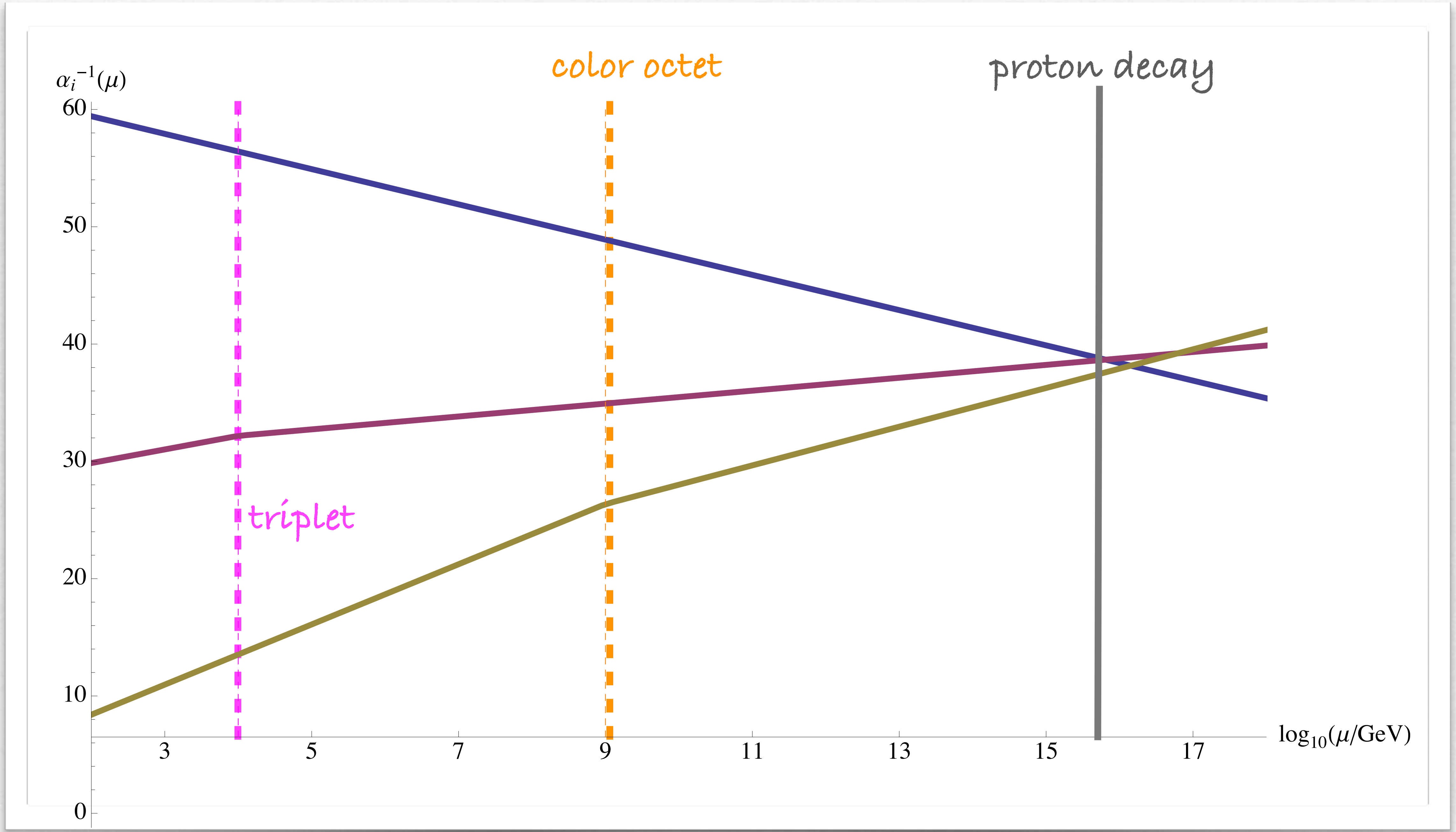
- one massless neutrino
- unification

Bajc, Nemevsek, G.S. '07



- one massless neutrino
- unification

Bajc, Nemevsek, G.S. '07



- one massless neutrino
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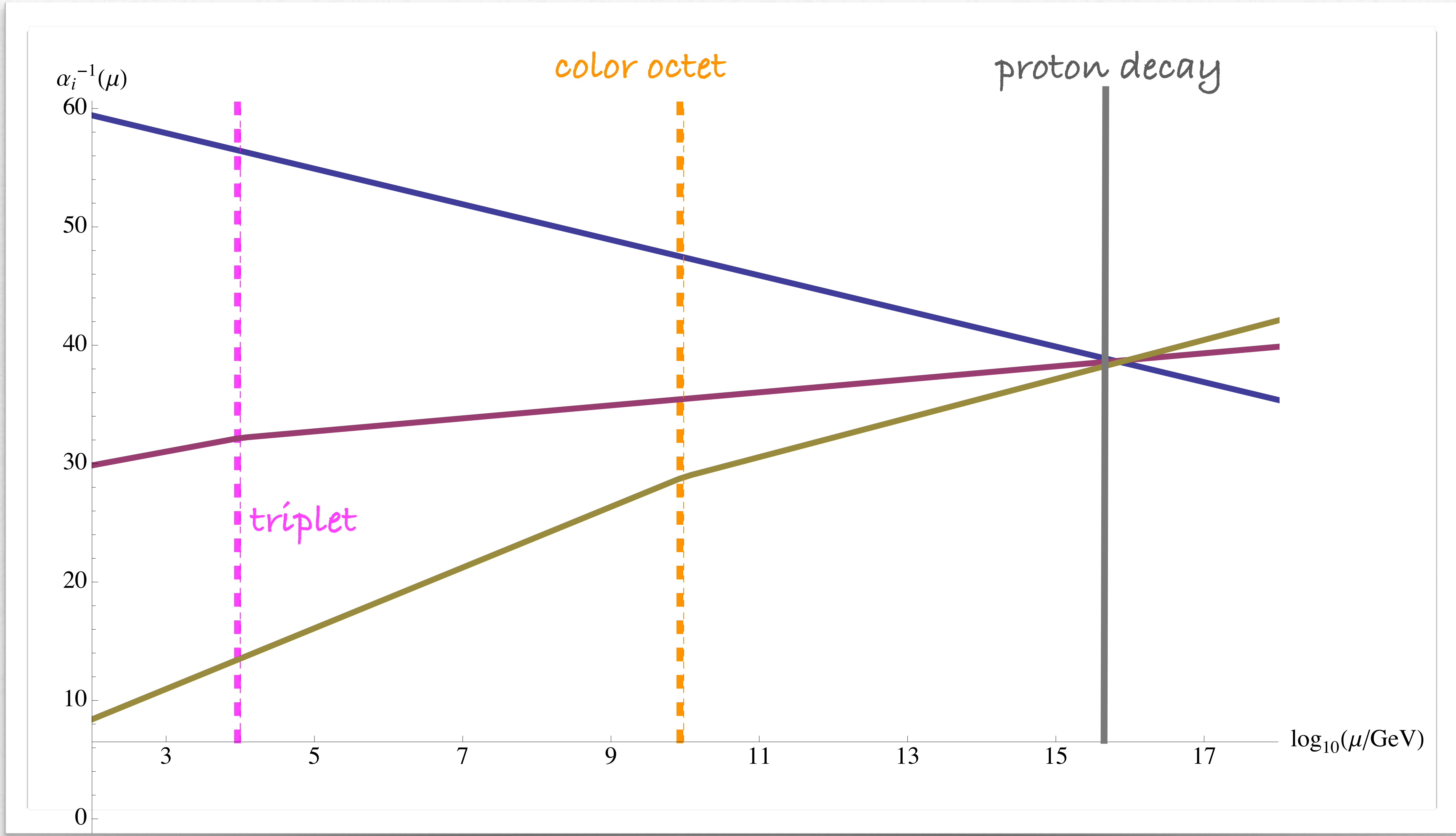
Bajc, Nemevsek, G.S. '07



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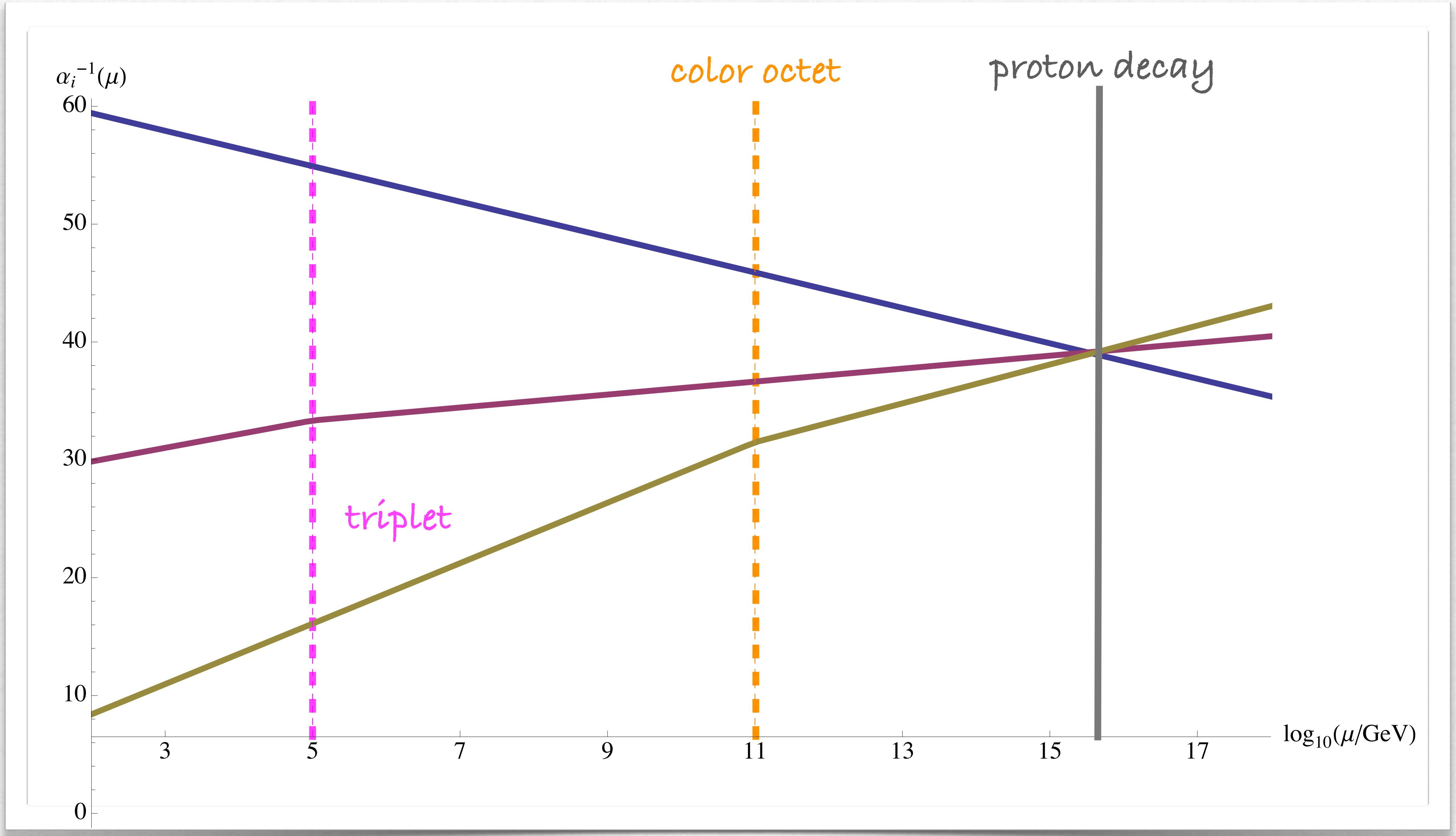
- unification

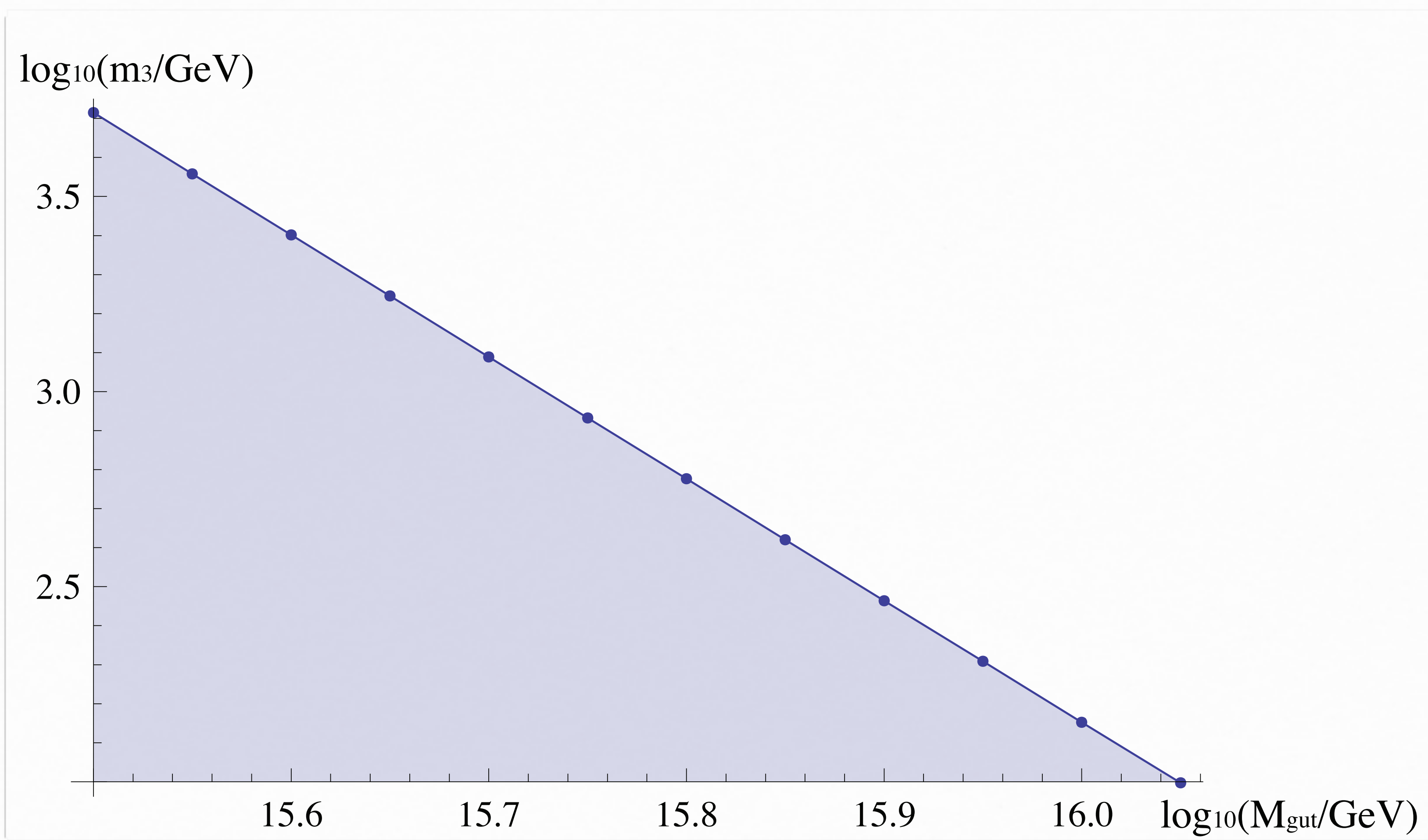
Bajc, Nemevsek, G.S. '07



- one massless neutrino

- unification

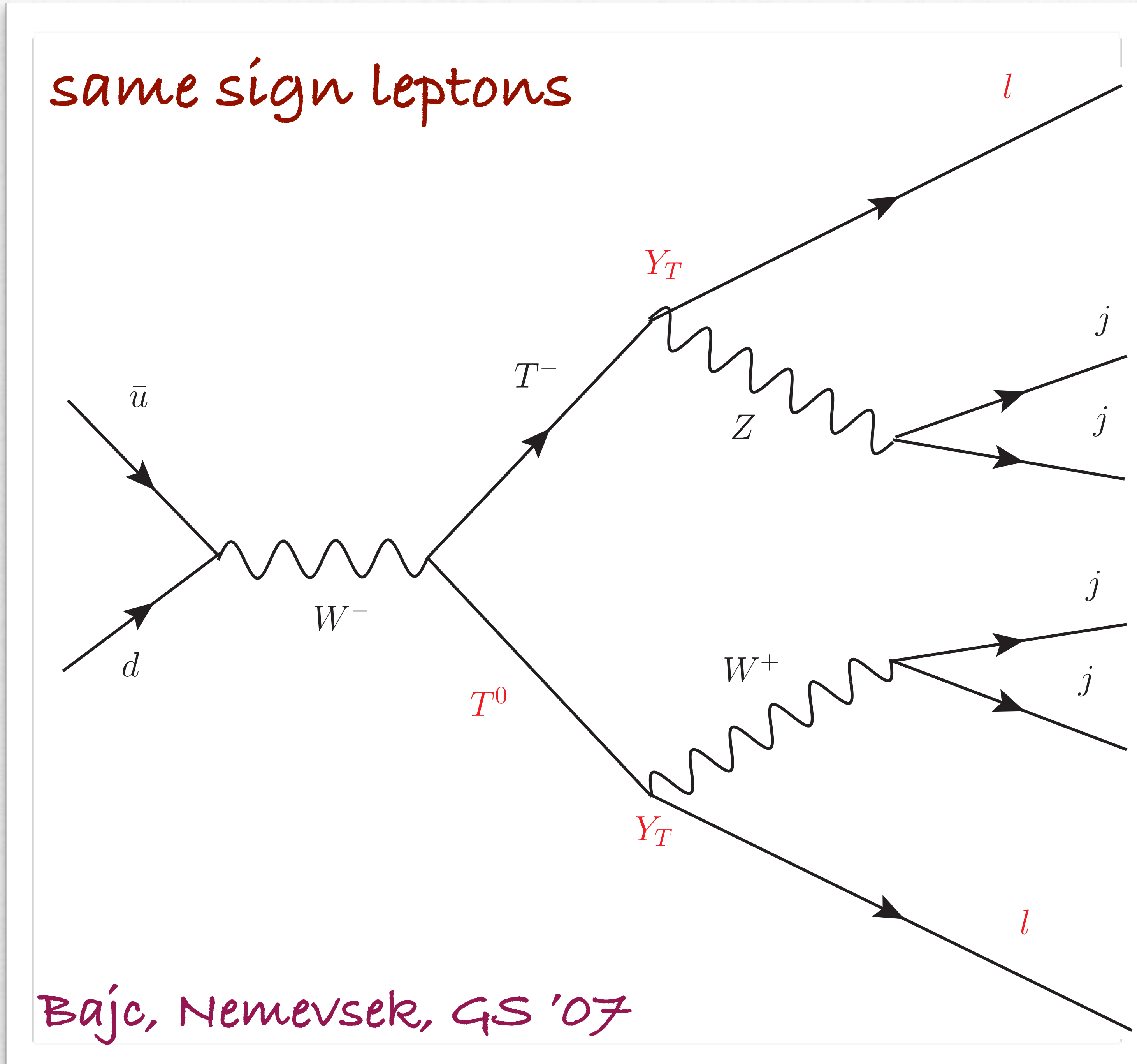
m_T vs M_{GUT}@ two loops



Bajc, Nemevsek, G.S. '07

LHC:

$$\Delta L = 2$$



Franceschini, Hambye, Strumia '08

del Aguila, Aguilar-Saavedra '08

Arhrib, Bajc, Ghosh, Han, Huang, Puljak, GS '09

Probing neutrino parameters

Same couplings y_T^i contribute to:

- neutrino mass matrix
- triplet decays

LHC:

$$m_T \quad \Rightarrow \quad 450\,(700)\,GeV\,@\,L = 10\,(100)\,fb^{-1}$$

Arhrib, Bajc, Ghosh, Han, Huang, Puljak, GS '09

$$vy_T^{i*} = \begin{cases} i\sqrt{M_T}\left(U_{i2}\sqrt{m_2^\nu}\cos z + U_{i3}\sqrt{m_3^\nu}\sin z\right), & \text{NH} \quad (m_1^\nu = 0), \\ i\sqrt{M_T}\left(U_{i1}\sqrt{m_1^\nu}\cos z + U_{i2}\sqrt{m_2^\nu}\sin z\right), & \text{IH} \quad (m_3^\nu = 0), \end{cases}$$

Ibarra, Ross '04

z = complex

Supersymmetry?

- can mimic many of the phenomena
- Type III - wino with R_P violation

$$\mathcal{W}_{\not R_p} = \lambda \ell\ell e^c + \lambda' q\ell d^c + \lambda'' u^c d^c d^c + \mu\, \ell H$$

- too many parameters

→ assumptions about sparticle masses

- supersymmetric seesaw?

subject in itself

LHC:

LHC:

- can probe the origin of neutrino mass

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- can probe the origin of neutrino mass
- can resolve the mystery of parity violation

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Last but not least: measure masses and mixings and provide link with low energy experiments

Thank you