Lecture V: Energy Frontier Connections

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U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

ACFI NLDBD School
10/31-11/3 2017

Lecture V Goals

- *Provide some background on present & prospective opportunities for neutrino physics probes at high energy colliders*
- *Alert you to the prospects for LNV searches at the high energy frontier*
- *Illustrate the complementarity with $0\nu\beta\beta$-decay*
- *Invite questions !*

Lecture V Outline

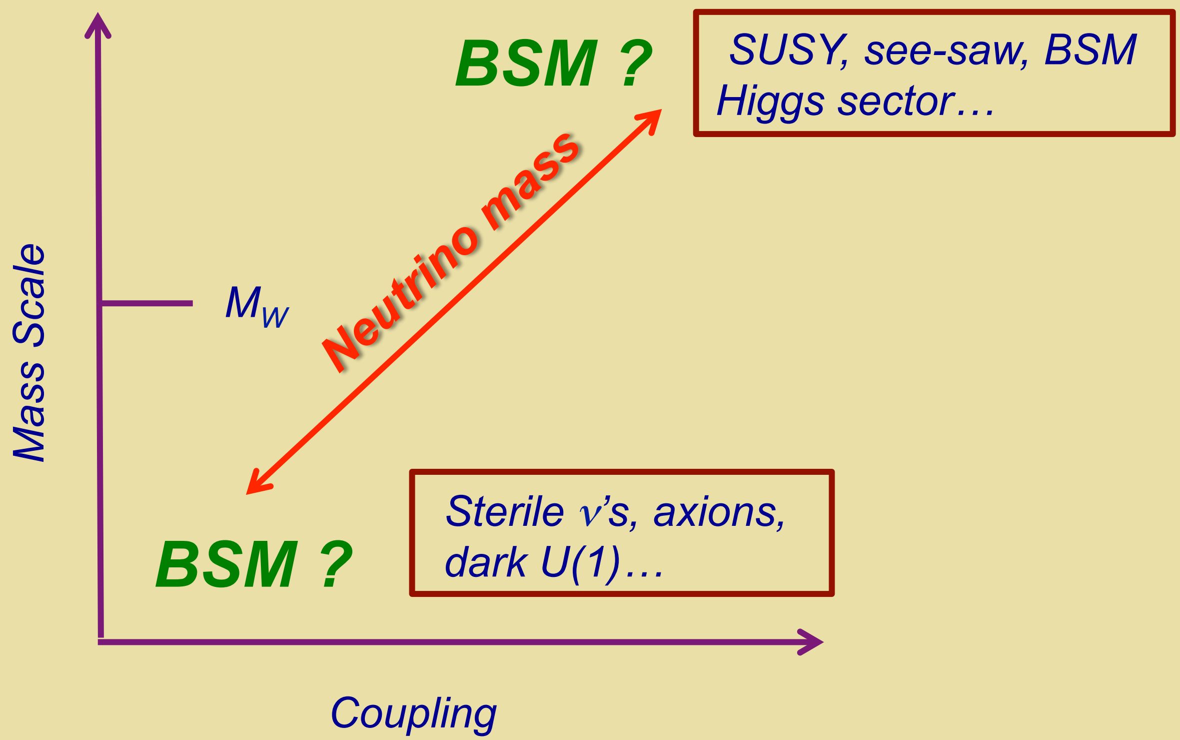
I. Context

II. TeV Scale (and below) LNV

III. Sterile neutrinos

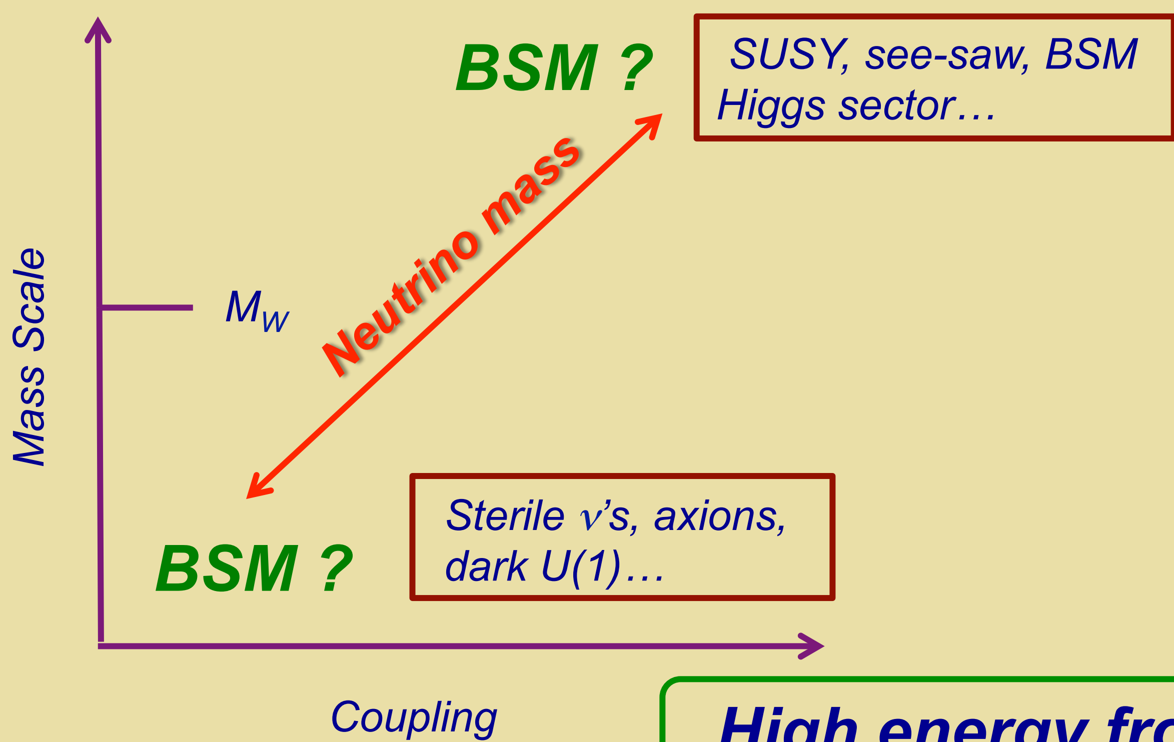
I. Context

BSM Physics: Where Does it Live ?



Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

BSM Physics: Where Does it Live ?



High energy frontier

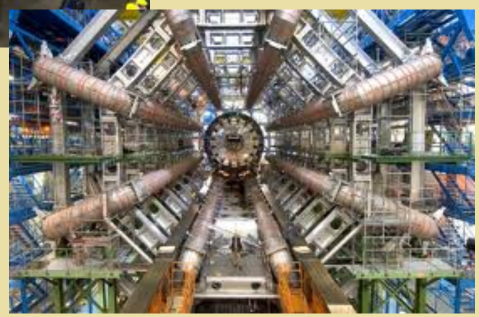
Is the mass scale associated with m_ν far above M_W ? Near M_W ? Well below M_W ?

Energy Frontier

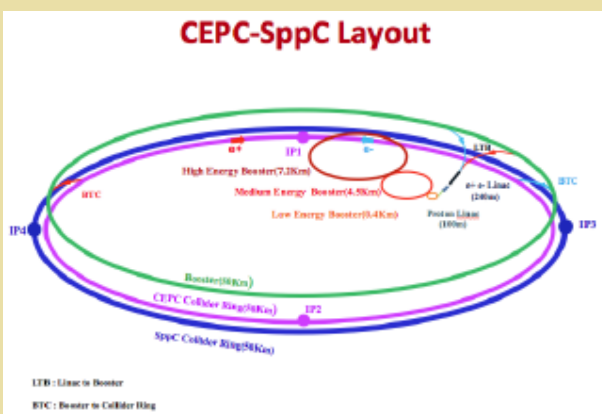
LHC

CMS

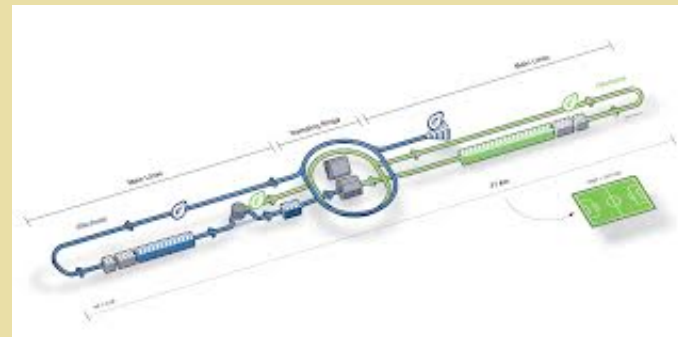
ATLAS



Future Circular e^+e^- & pp



International Linear Collider



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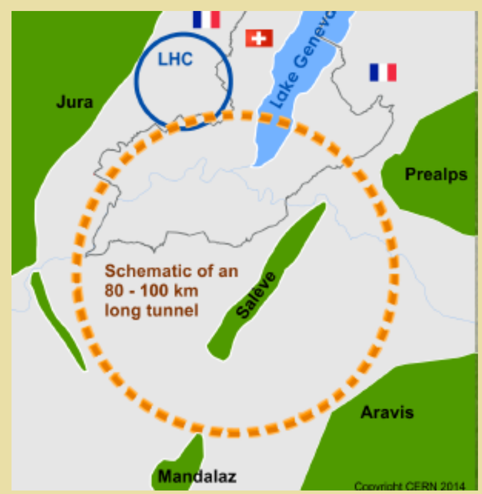
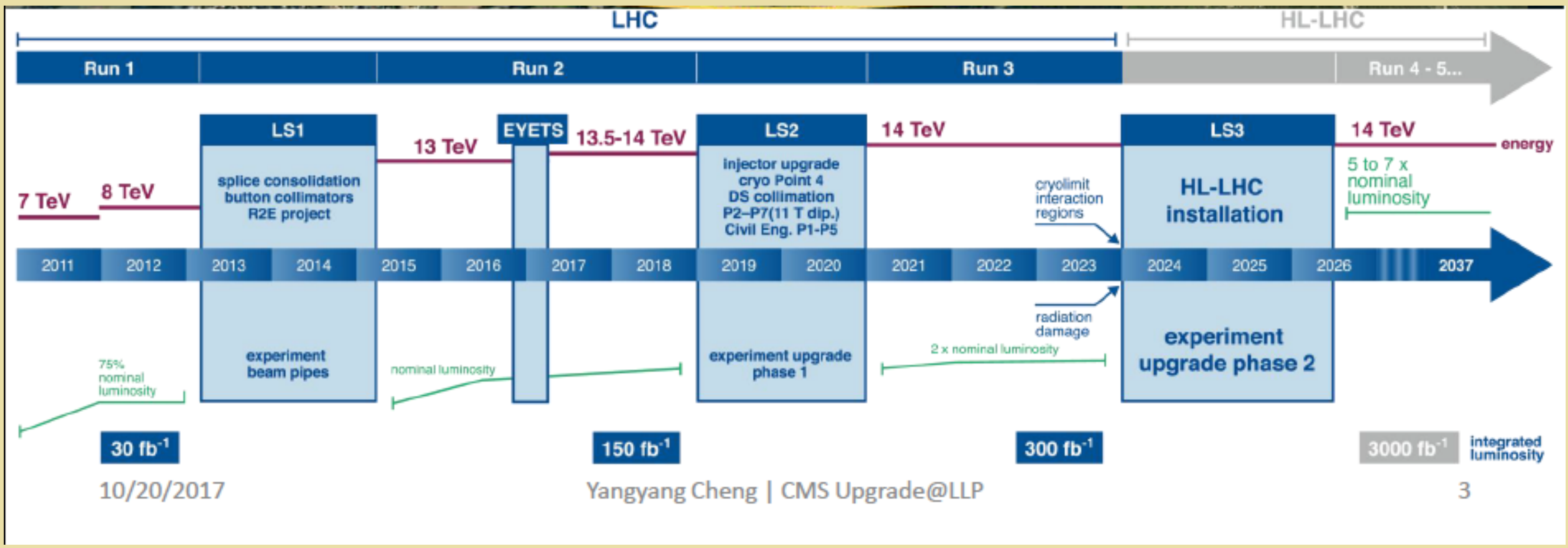
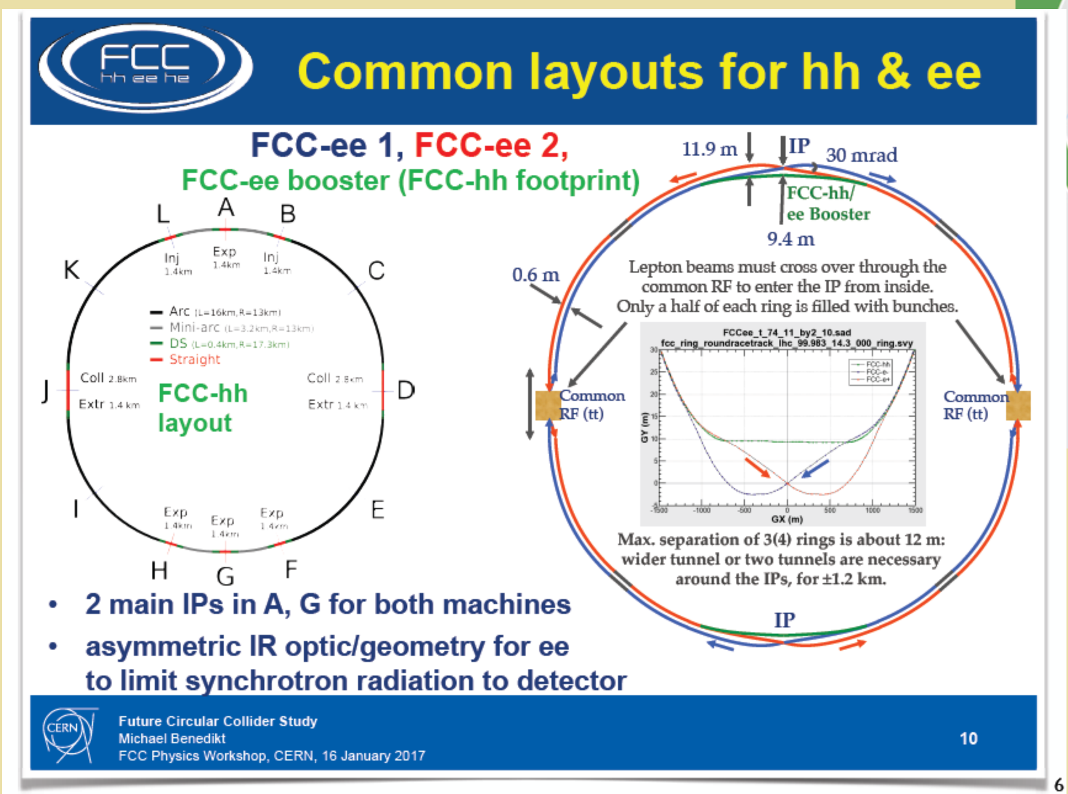


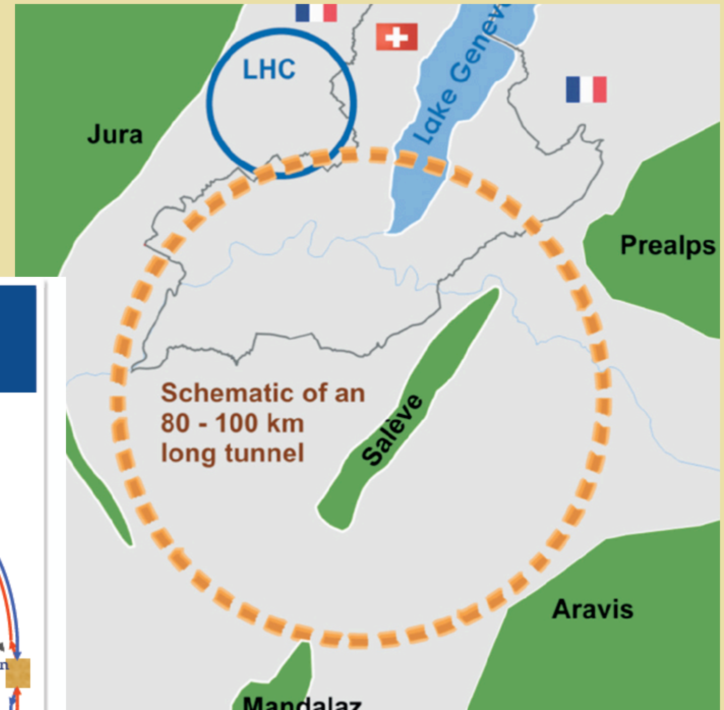
Energy Frontier

LHC / HL-LHC



Future Circular Colliders





Future Circular Colliders

lepton collider parameters

parameter	FCC-ee (400 MHz)					LEP2
Physics working point	Z		WW	ZH	tt_{bar}	
energy/beam [GeV]	45.6		80	120	175	105
bunches/beam	30180	91500	5260	780	81	4
bunch spacing [ns]	7.5	2.5	50	400	4000	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
beam current [mA]	1450	1450	152	30	6.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.34
synchrotron power [MW]	100					22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5

identical FCC-ee baseline optics for all energies

FCC-ee: 2 separate rings, LEP: single beam pipe

FCC-he & HE-LHC-ep parameters

parameter	FCC-he	ep at HE-LHC	ep at HL-LHC	LHeC
E_p [TeV]	50	12.5	7	7
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	3.5	1.7	1.3	1.3
bunch spacing [ns]	25	25	25	25
protons / bunch [10^{11}]	1	2.5	2.2	1.7
$\gamma\varepsilon_p$ [μm]	2.2	2.5	2.0	3.75
electrons / bunch [10^9]	2.3	2.3	2.3	1.0
electron current [mA]	15	15	15	6.4
IP beta function β_p* [m]	15	10	7	10
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
proton-ring filling factor	0.8	0.8	0.8	0.8
luminosity [10^{33} $cm^{-2}s^{-1}$]	11	9	8	1.3

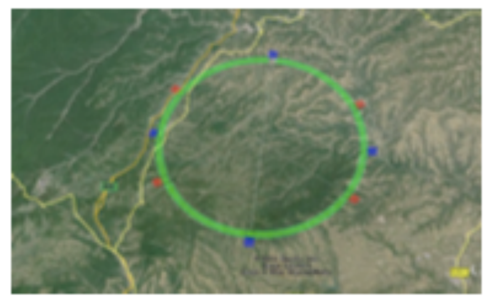
Hadron collider parameters

parameter	FCC-hh		HE-LHC* (*tentative)	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		3.6	(0.35) 0.18

Future Circular Colliders

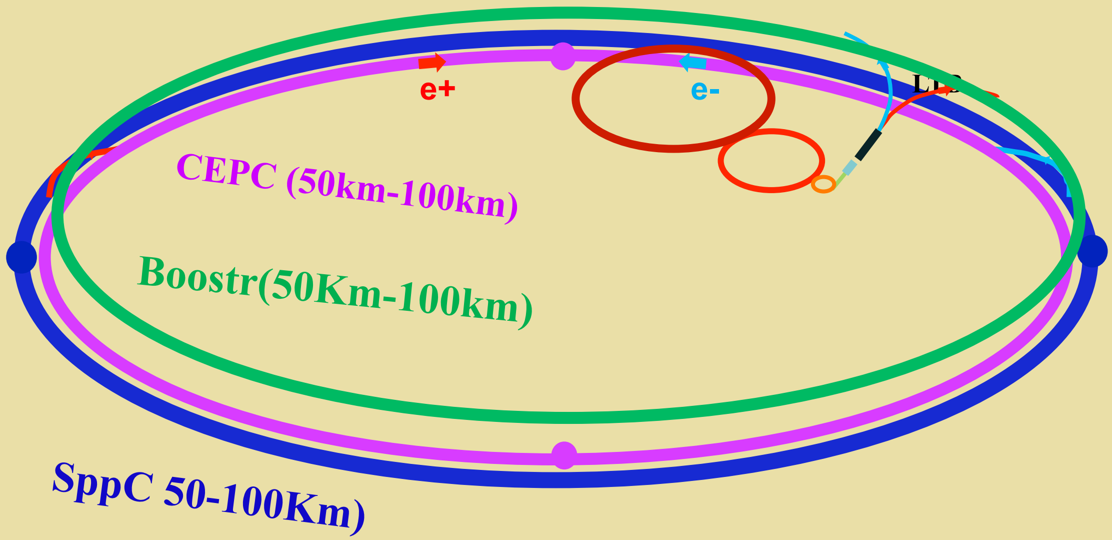
Possible site of CEPC-SppC

Q. Qin, PANIC 2017, Beijing



1. QingHuangDao, Hebei（completed preCDR）
2. Huangling, Shaanxi（2017.1 signed contract to exp.）
3. ShenShan, Guangdong, （completed in August, 2016）
4. …

CEPC / SppC



Q. Qin, PANIC 2017, Beijing

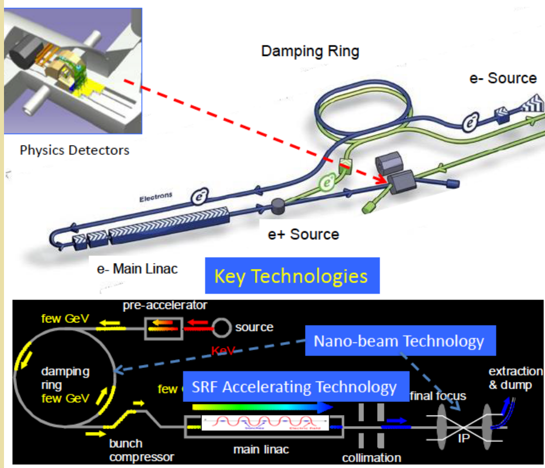
Parameter	Design Goal
Particles	e+, e-
Center of mass energy	2 x 120 GeV
Peak Luminosity	>2 x $10^{34}/cm^2/s$
No. of IP	2

SppC

Parameter	Unit	Value		
		PreCDR	CDR	Ultimate
Circumference	km	54.4	100	100
C.M. energy	TeV	70.6	75	125-150
Dipole field	T	20	12	20-24
Injection energy	TeV	2.1	2.1	4.2
Number of IPs		2	2	2
Nominal luminosity per IP	$cm^{-2}s^{-1}$	$1.2x10^{35}$	$1.0x10^{35}$	-
Beta function at collision	m	0.75	0.75	-
Circulating beam current	A	1.0	0.7	-
Bunch separation	ns	25	25	-
Bunch population		$2.0x10^{11}$	$1.5x10^{11}$	-
SR power per beam	MW	2.1	1.1	-
SR heat load per aperture @arc	W/m	45	13	-

ILC

ILC Acc. Design Overview (in TDR)

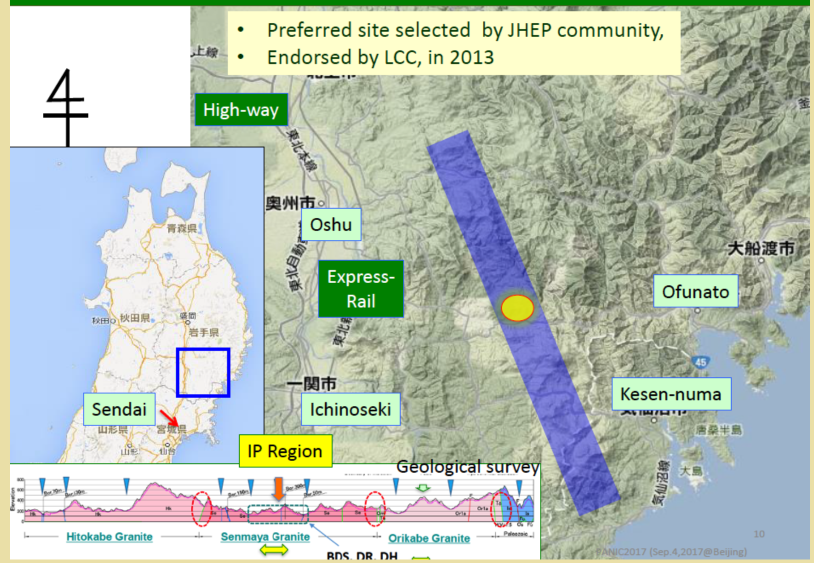


Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8×10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m $Q_0 = 1 \times 10^{10}$

PANIC2017 (Sep.4,2017@Beijing)

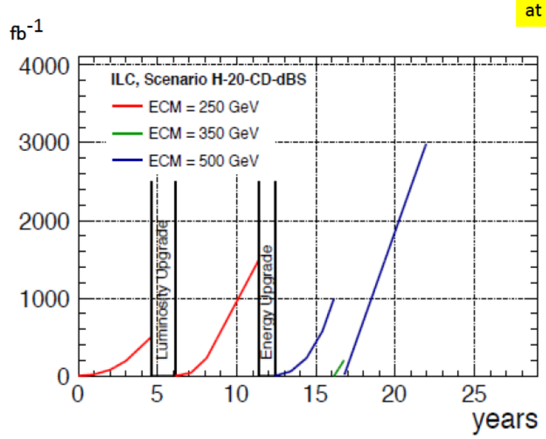
ILC Site Candidate Location in Japan: Kitakami

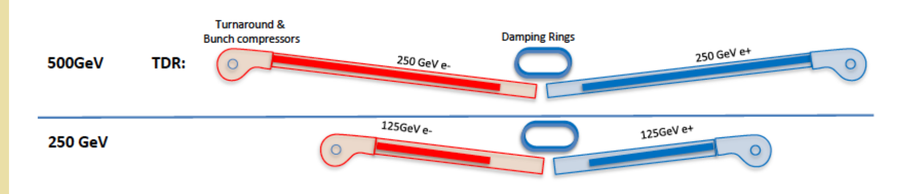
- Preferred site selected by JHEP community,
- Endorsed by LCC, in 2013



Example of luminosity and energy evolution

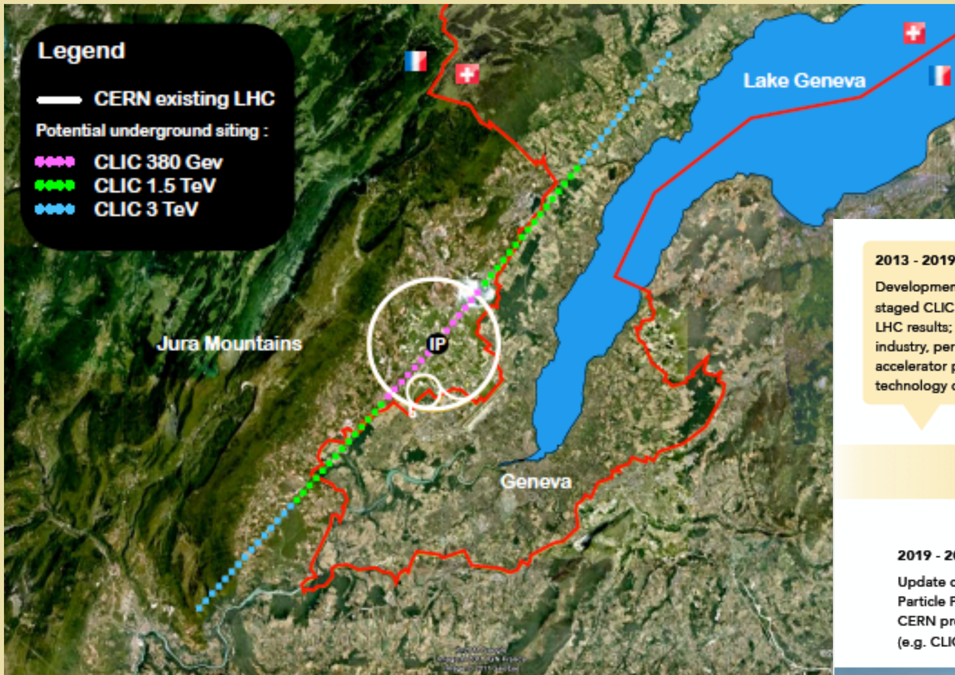
Junpin Tian (U.Tokyo) at AWLC17

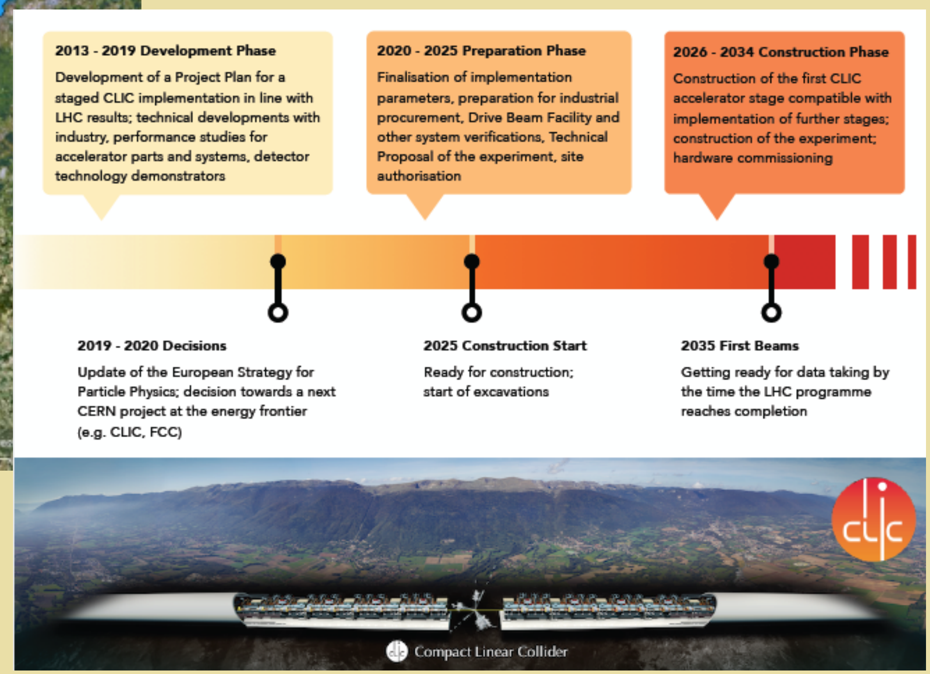




Shin Michizono, PANIC 2017, Beijing

Compact Linear Collier (CLIC)





ACFI Workshop: July 2017

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

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Neutrinos at the High Energy Frontier

Date: Tuesday, July 18, 2017 - 9:00am to Thursday, July 20, 2017 - 5:00pm

Location: LGRT 419B

Given that neutrino mass is so far the only laboratory evidence for physics beyond the Standard Model, understanding its origin could provide a key to unlock the secrets of the new physics. In the LHC era and in anticipation of exciting developments of future colliders, it is timely to discuss how effectively the neutrino mass physics could be probed at the high energy frontier. The workshop will bring together theorists and experimentalists to develop a roadmap for neutrino physics at the high energy frontier. Attention will be given to possibilities for new searches at the LHC, opportunities with prospective future e+e-, pp, and ep colliders, and their complementarity. The complementarity with the low-energy experiments at the intensity frontier, as well as the implications for other outstanding puzzles such as the matter-antimatter asymmetry and dark matter, will also be touched upon. We anticipate these discussions will lead to a white paper for energy frontier neutrino physics.

Co-organizers:

Alain Blondel, CERN

Bhupal Dev, Washington University

Julia Harz, Paris LPTHE

Pilar Hernandez, Valencia University and CERN

Miha Nemevsek, Stefan Institute

Michael Ramsey-Musolf, UMass Amherst

Upcoming Seminars

ACFI Seminar

Dirac Attack! Searching for Light Dark Matter with Dirac Materials

Tue, Oct 31, 2017 - 2:30pm

Yonatan Kahn

LGRT 1033

ACFI Seminar

TBA

Tue, Nov 7, 2017 - 2:30pm

Graham White

LGRT 419B

ACFI Seminar

Gravitational Wave Memory effect in all dimensions

Thu, Nov 9, 2017 - 10:45am

Gautam Satishchandran

LGRT 419B

All upcoming ACFI seminars

II. TeV Scale (and below) LNV

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ Underlying Physics $\rightarrow A(Z+2, N-2) + e^- e^-$

- 3 light neutrinos only: source of neutrino mass at the very high see-saw scale
- 3 light neutrinos with TeV scale source of neutrino mass
- > 3 light neutrinos

LNV Mass Scale & $0\nu\beta\beta$-Decay

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- 3 light neutrinos with TeV scale source of neutrino mass
- > 3 light neutrinos

Two parameters: Effective coupling & effective heavy particle mass

$0\nu\beta\beta$-Decay: LNV? Mass Term?

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

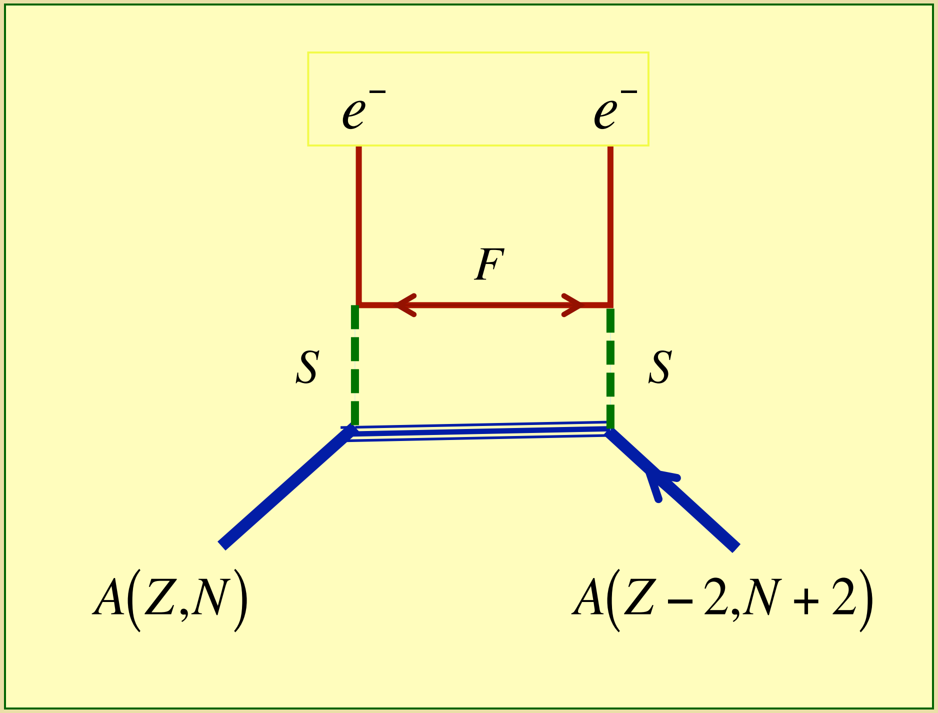
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



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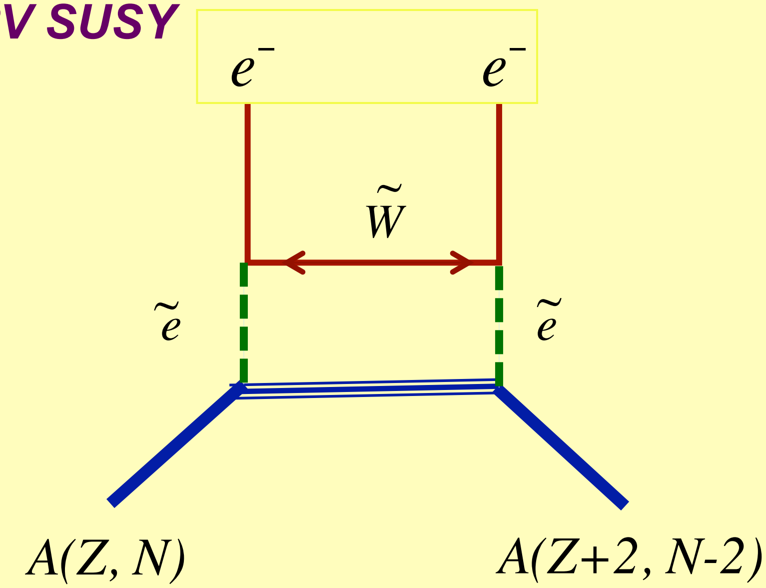
RPV SUSY



$0\nu\beta\beta$-Decay: LNV? Mass Term?

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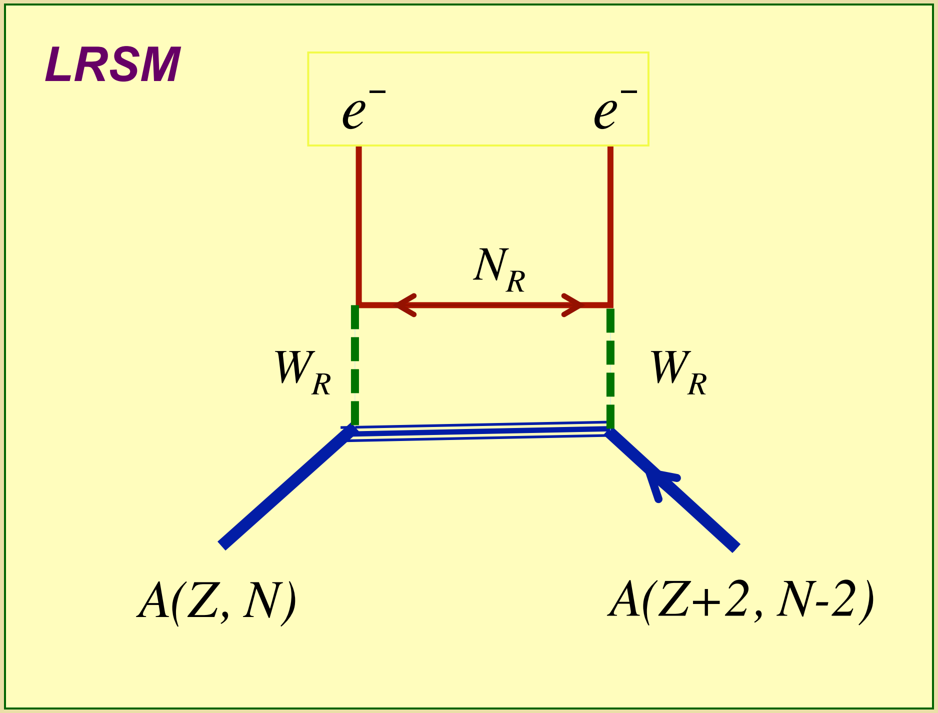

$0\nu\beta\beta$-Decay: TeV Scale LNV

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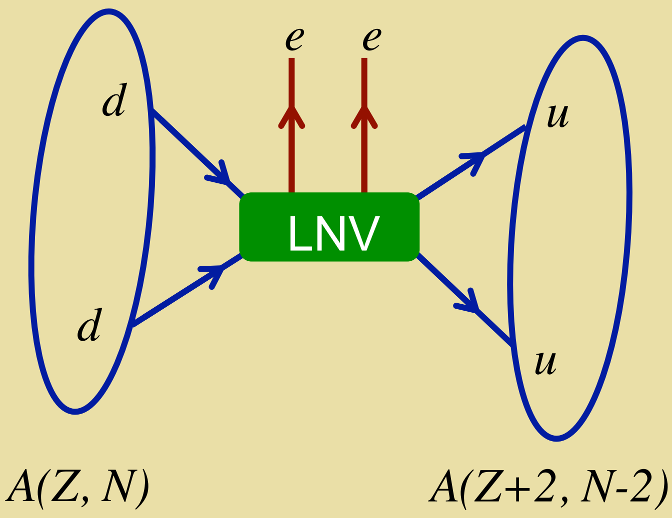
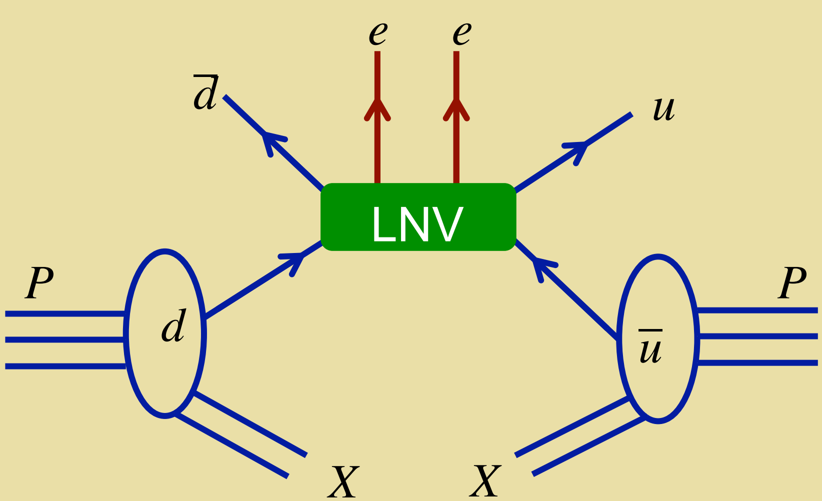
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

$0\nu\beta\beta$-Decay



pp Collisions



0νββ-Decay: TeV Scale LNV

$$\mathcal{L}_{\mathrm{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \mathrm{h.c.}$$

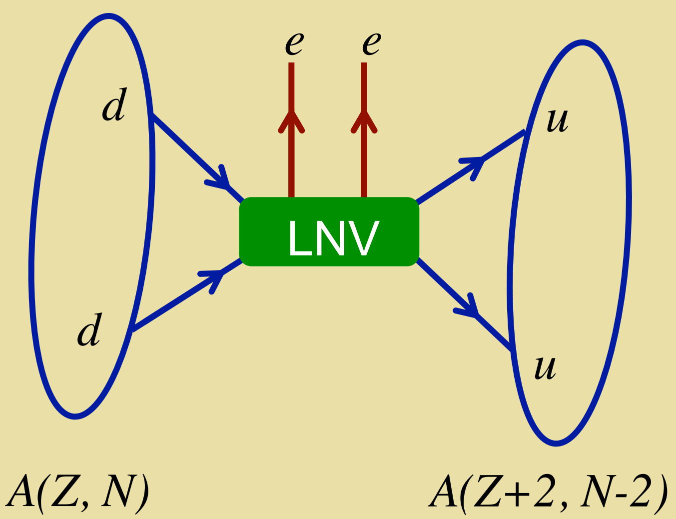
Dirac

$$\mathcal{L}_{\mathrm{mass}} = \frac{y}{\Lambda}\bar{L}^{c}HH^{T}L \; + \; \mathrm{h.c.}$$

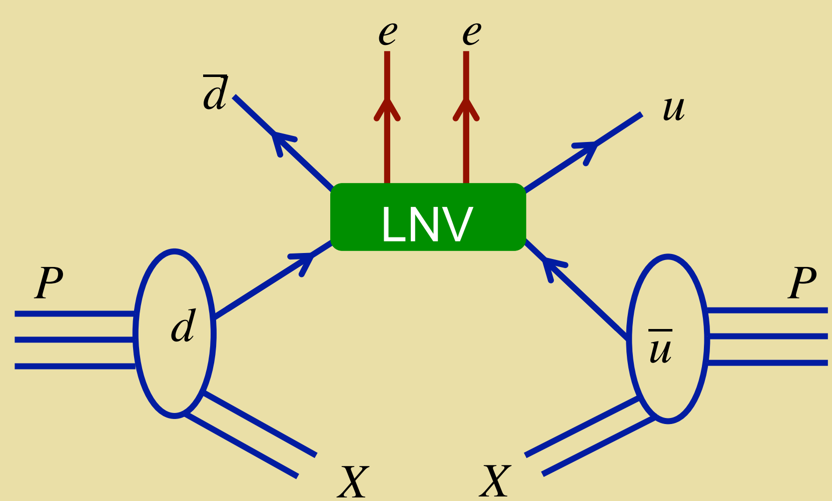
Majorana

LHC: SS Dilepton + Dijet

0νββ-Decay



pp Collisions



$0\nu\beta\beta$-Decay: TeV Scale LNV

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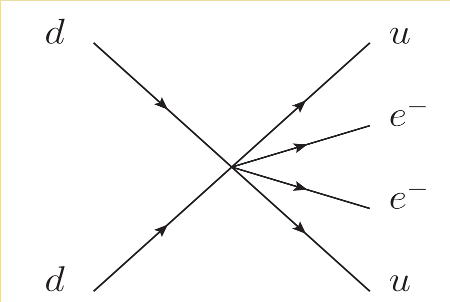
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

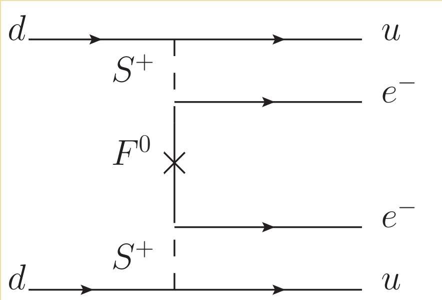
TeV Scale LNV

$0\nu\beta\beta$ - decay



*Can it be discovered with combination of **$0\nu\beta\beta$** & LHC searches ?*

LHC: pp $\rightarrow$ jj e^-e^-



Simplified models

Simplified Models: Illustrative Case

$$\mathcal{L}_{\text{INT}} = g_1 \bar{Q}_i^a d^a S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \text{H.c.}$$

S: *(1, 2, ½)*

F: *(1, 0, 0)* *Majorana*

$0\nu\beta\beta$-Decay: TeV Scale LNV

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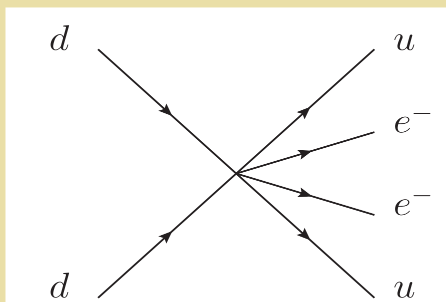
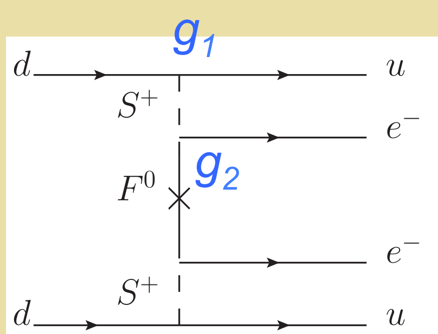
TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: $pp \rightarrow$ $jj\, e^- e^-$



Effective operators:

$$\mathcal{L}^{\text{eff}}_{\text{LNV}} = \frac{C_1}{\Lambda^5}\mathcal{O}_1 + \text{h.c.}$$

$$\mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C$$

$$C_1 = g_1^2 \, g_2^2$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

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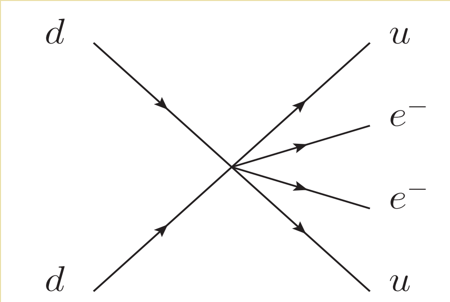
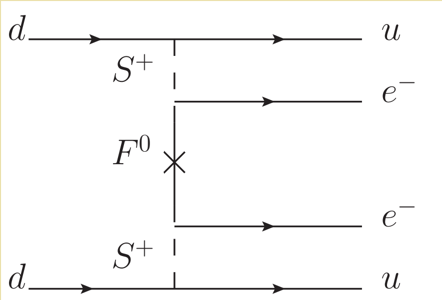
TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: pp $\rightarrow$ jj e⁻e⁻



Effective operators:

$$\mathcal{L}^{\rm eff}_{\rm LNV} = \frac{C_1}{\Lambda^5}\mathcal{O}_1 + {\rm h.c.}$$

$$\mathcal{O}_1 = \bar{Q}\tau^+ d\bar{Q}\tau^+ d\bar{L}L^C$$

$$g_{\rm eff} \ = C_1(\Lambda)^{1/4}$$

$0\nu\beta\beta$-Decay: TeV Scale LNV

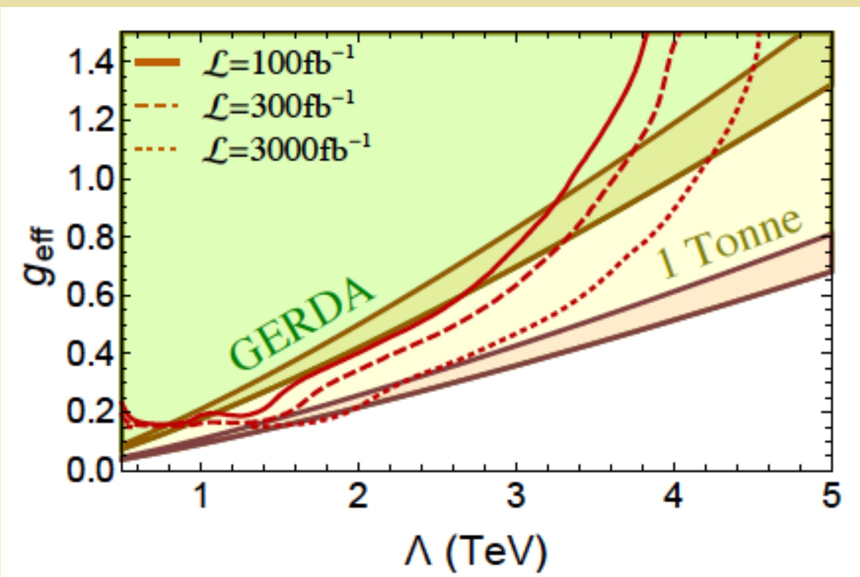
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

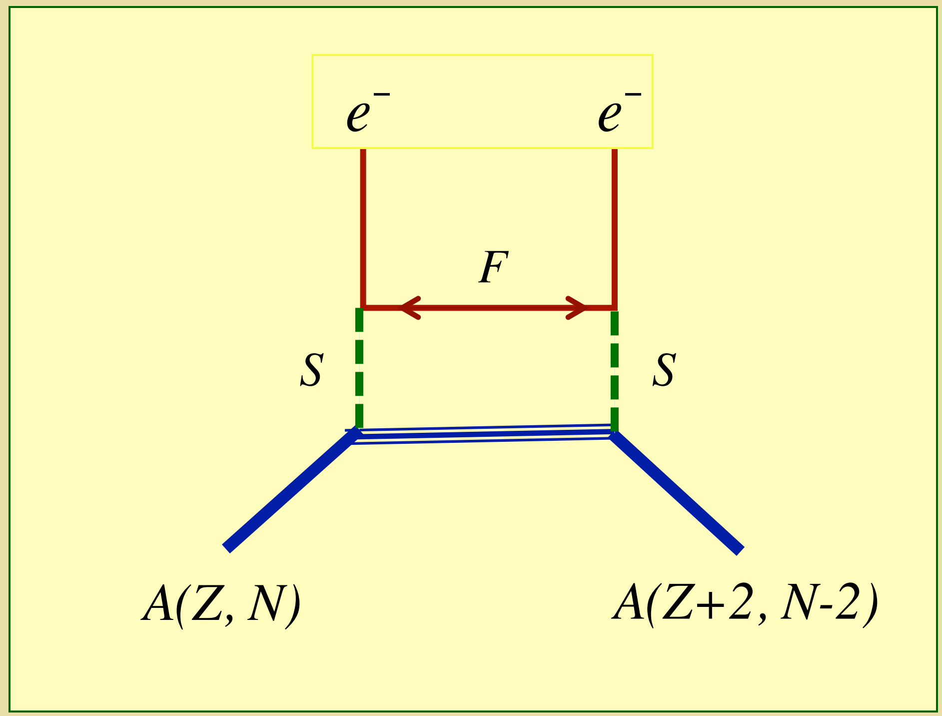
$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444



$0\nu\beta\beta$-Decay: TeV Scale LNV

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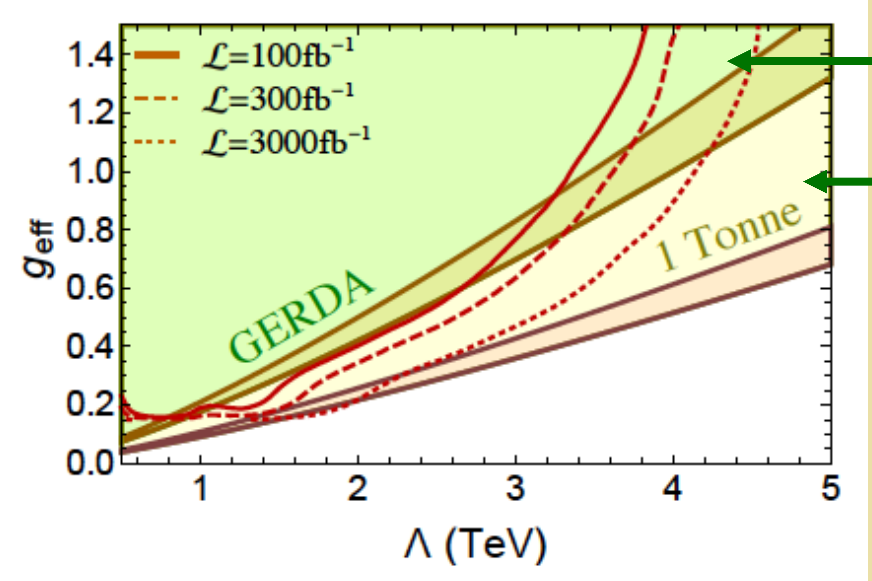

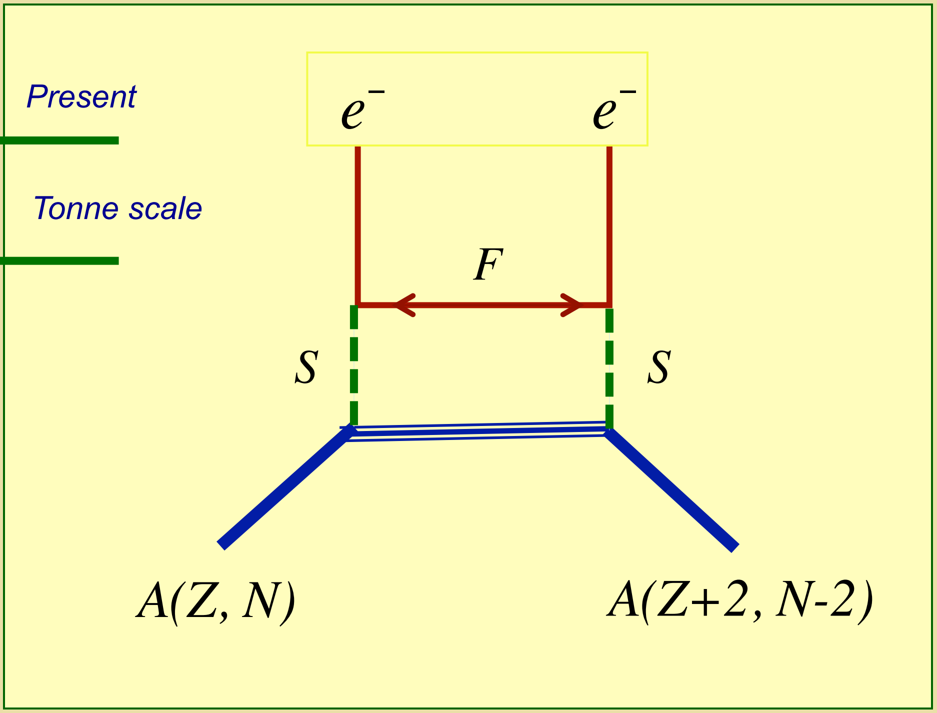

T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV

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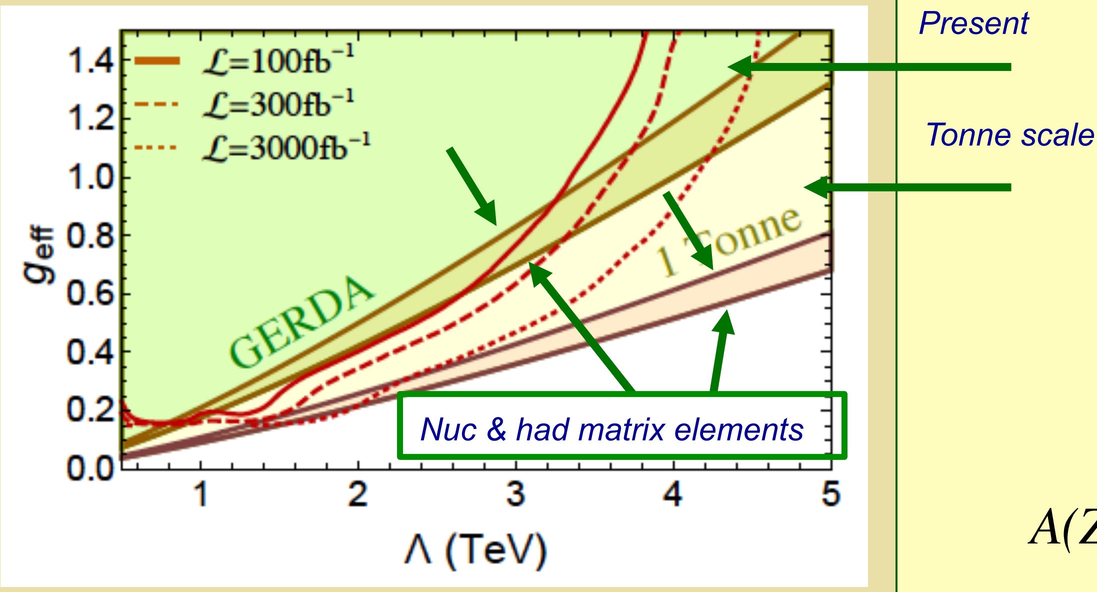
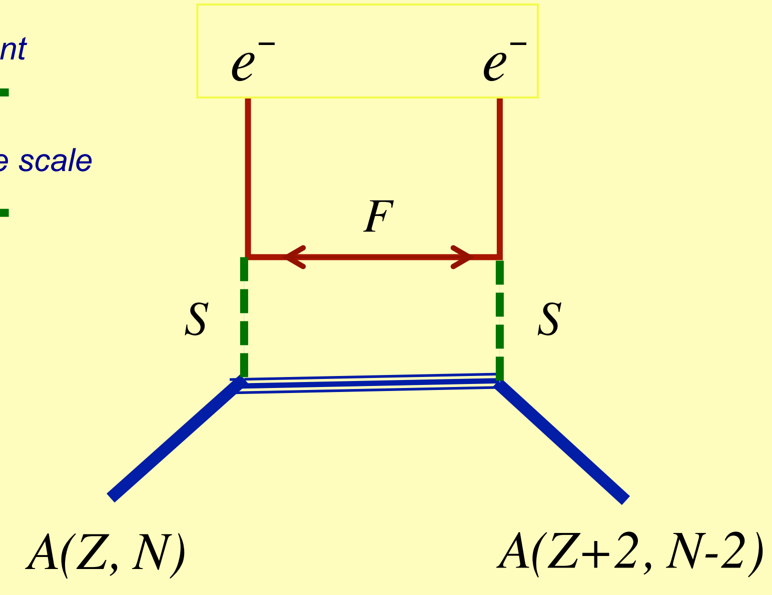
$$\mathcal{L}_{\mathrm{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \mathrm{h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV

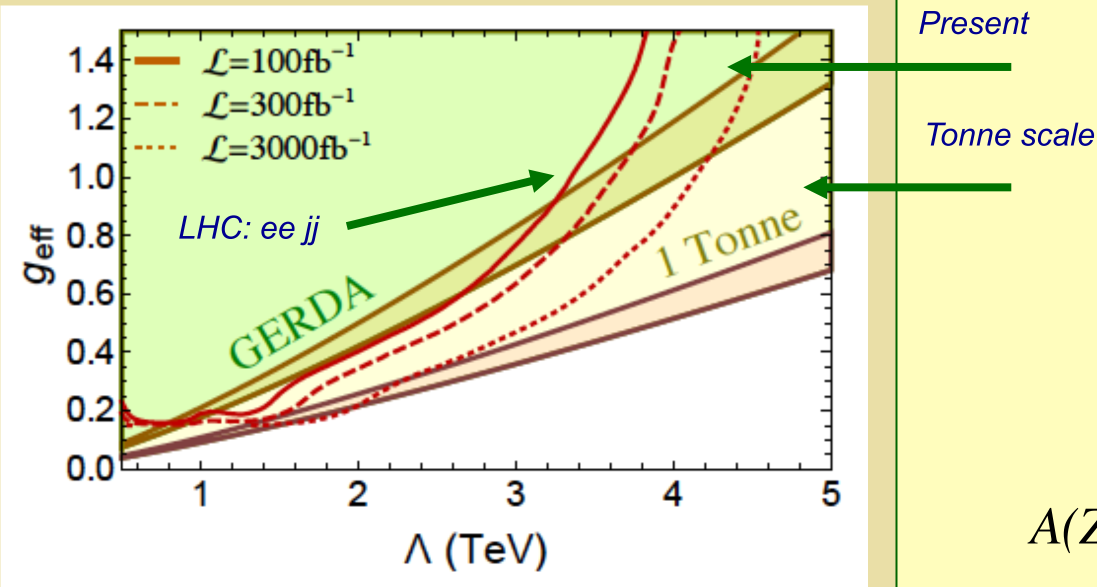
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

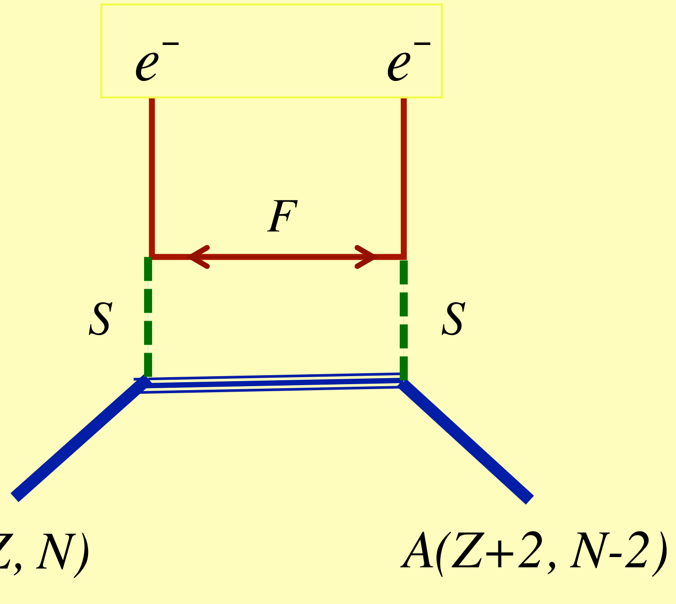
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

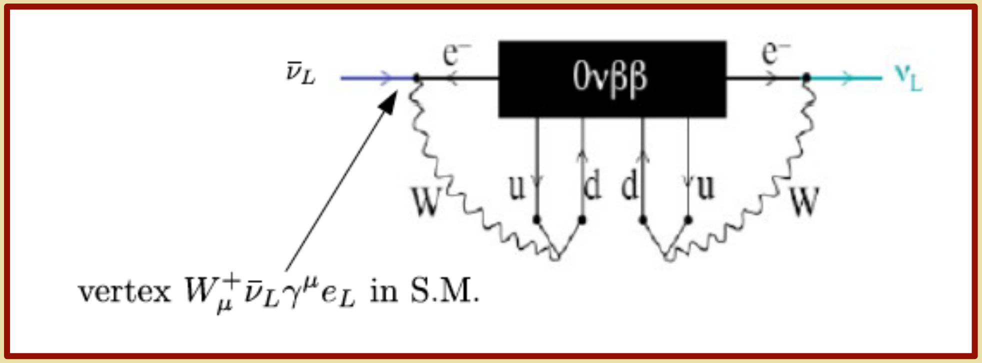
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

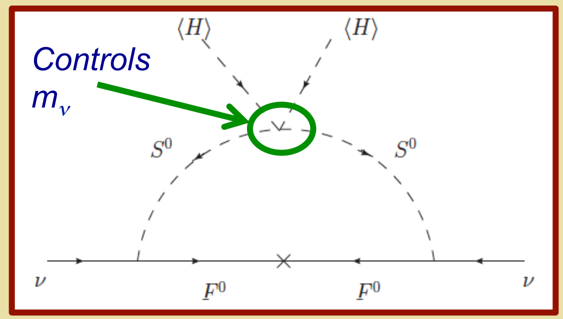
Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Implications for m_ν:





Schecter-Valle: non-vanishing Majorana mass at (multi) loop level

Simplified model: possible (larger) one loop Majorana mass

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

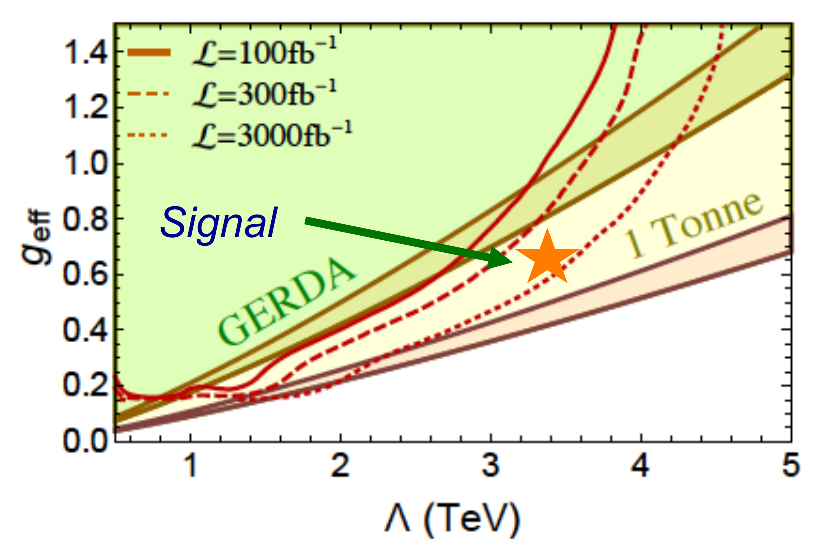
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

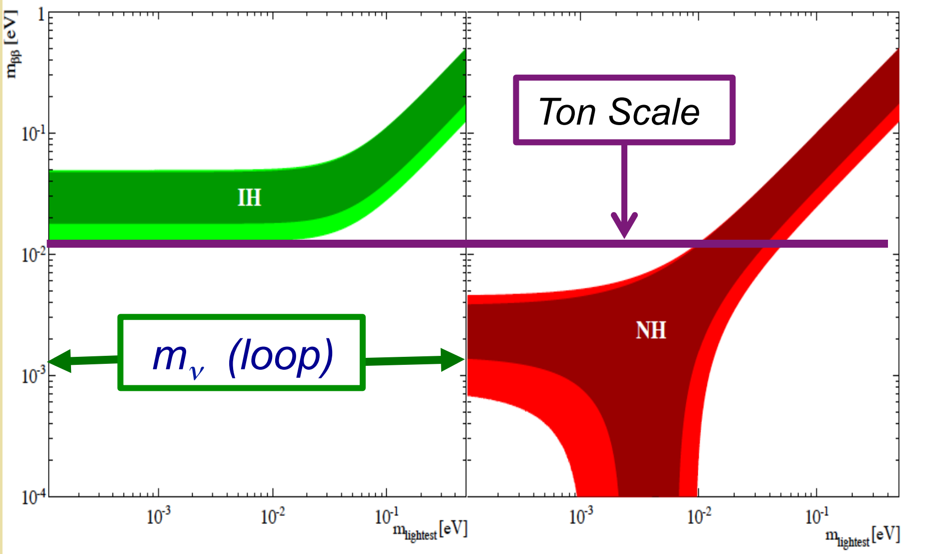
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Implications for m_ν:





A hypothetical scenario

$0\nu\beta\beta$ / LHC Interplay: Matrix Elements

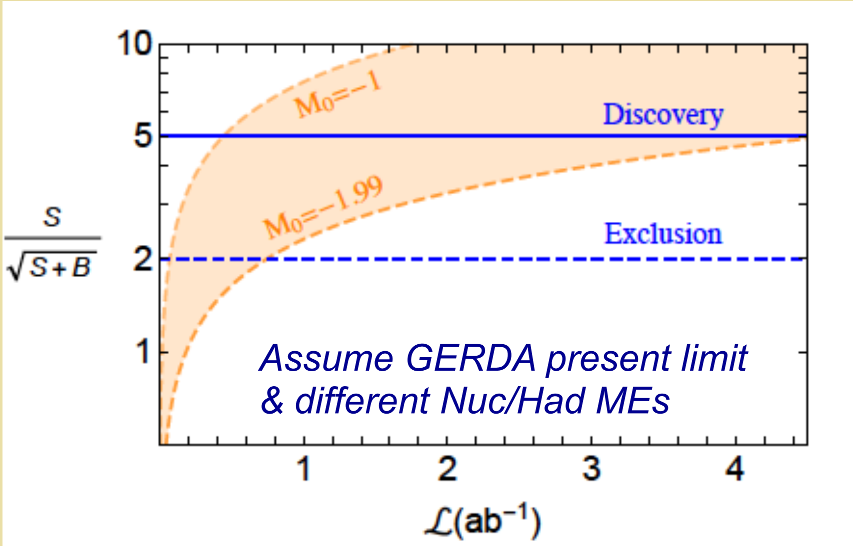
$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R + \text{h.c.}$$

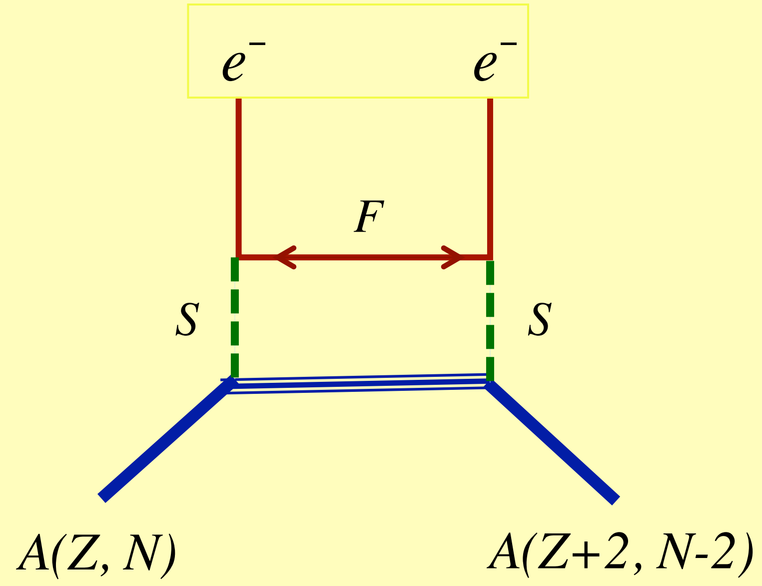
Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L + \text{h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV





T. Peng, MRM, P. Winslow 1508.04444

$0\nu\beta\beta$ / LHC Interplay: Matrix Elements

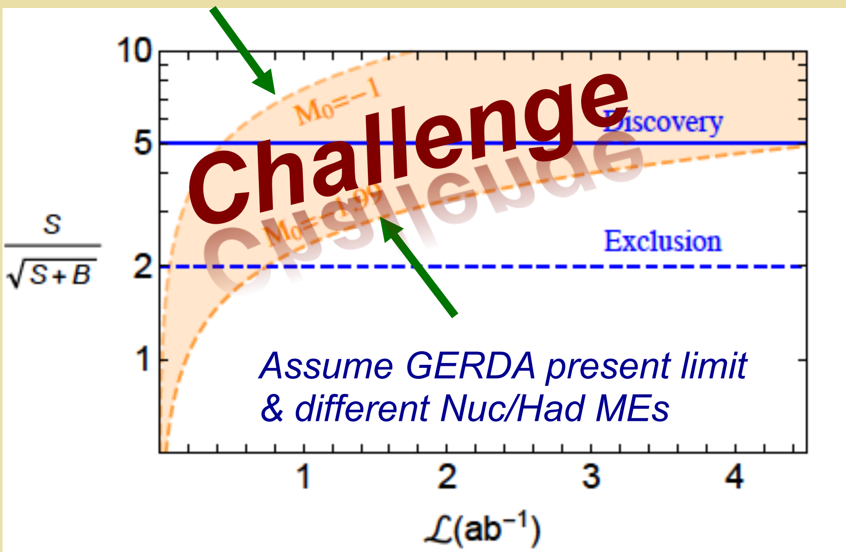
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; {\rm h.c.}$$

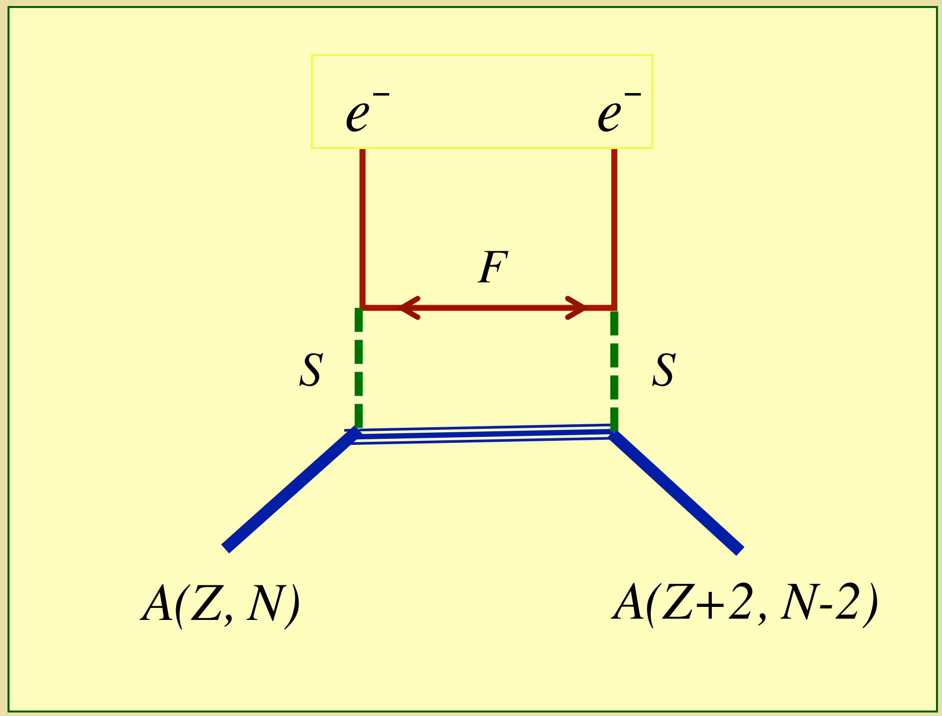
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; {\rm h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV





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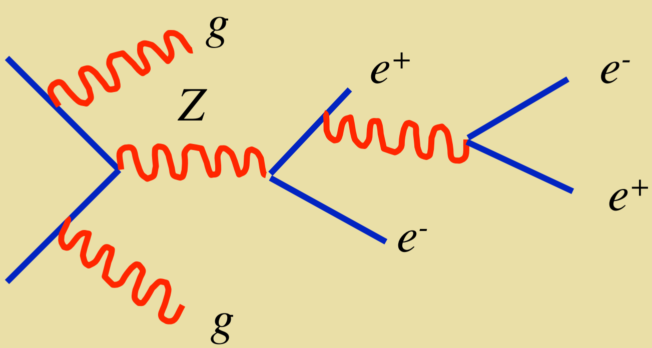
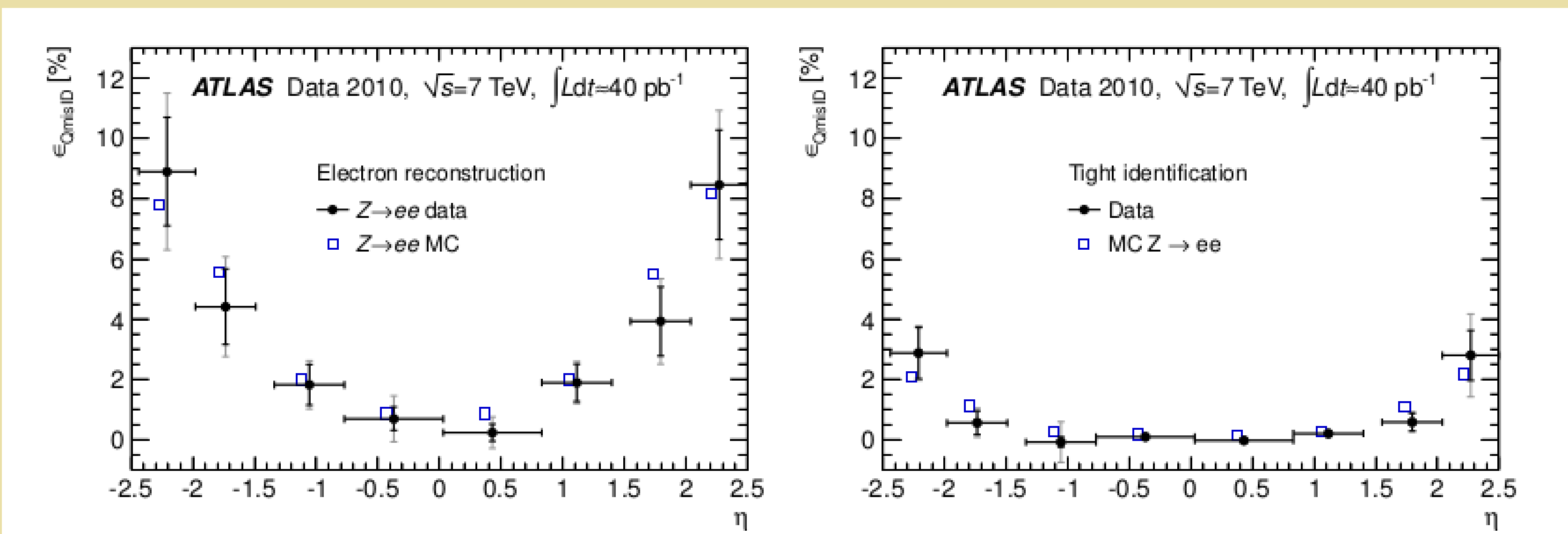
$0\nu\beta\beta$-Decay / LHC Comparison: Details

- *LHC: Backgrounds*
- *LHC energy scale $\rightarrow$ $0\nu\beta\beta$-decay scale: running*
- *$0\nu\beta\beta$-decay: hadronic & nuclear matrix elements*

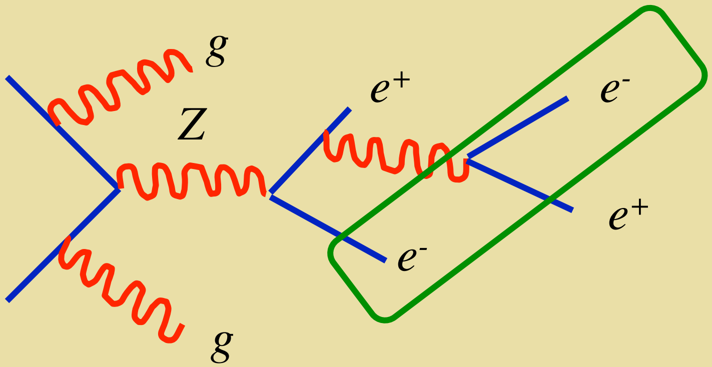
LHC Backgrounds: Charge Flip



e^+ transfers most of p_T to conversion e^- ;
Z / γ^* + jets $\rightarrow$ apparent $e^- e^-$ jj event

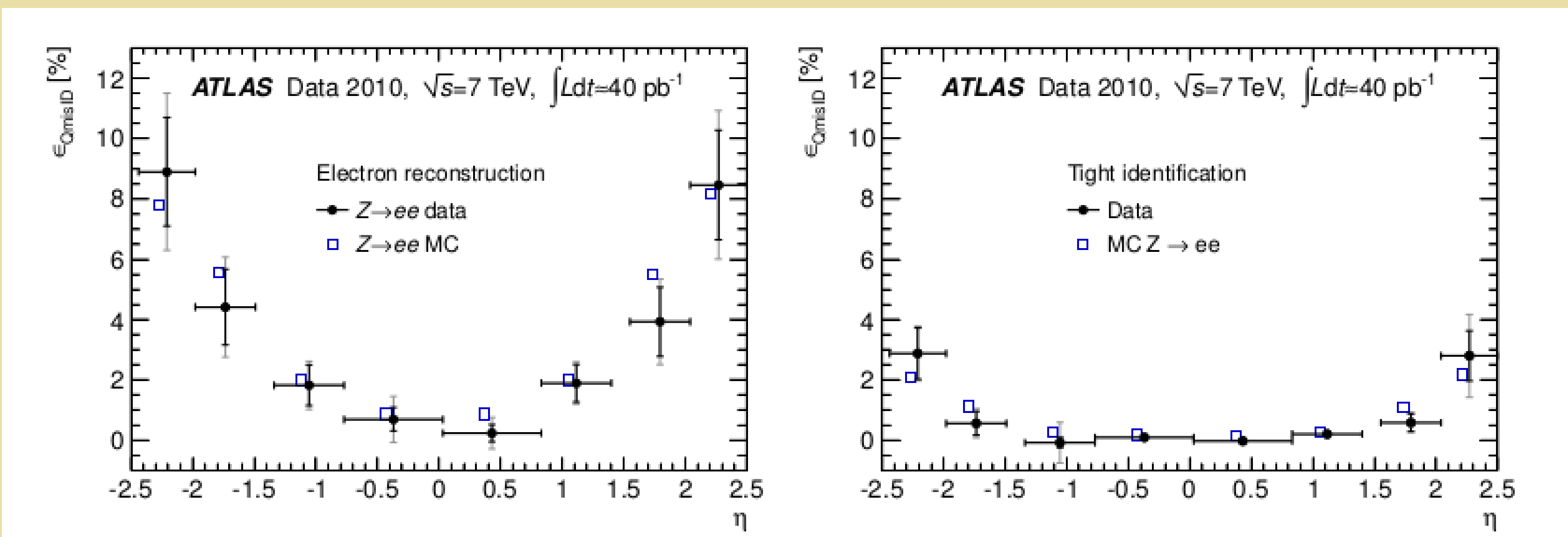


LHC Backgrounds: Charge Flip



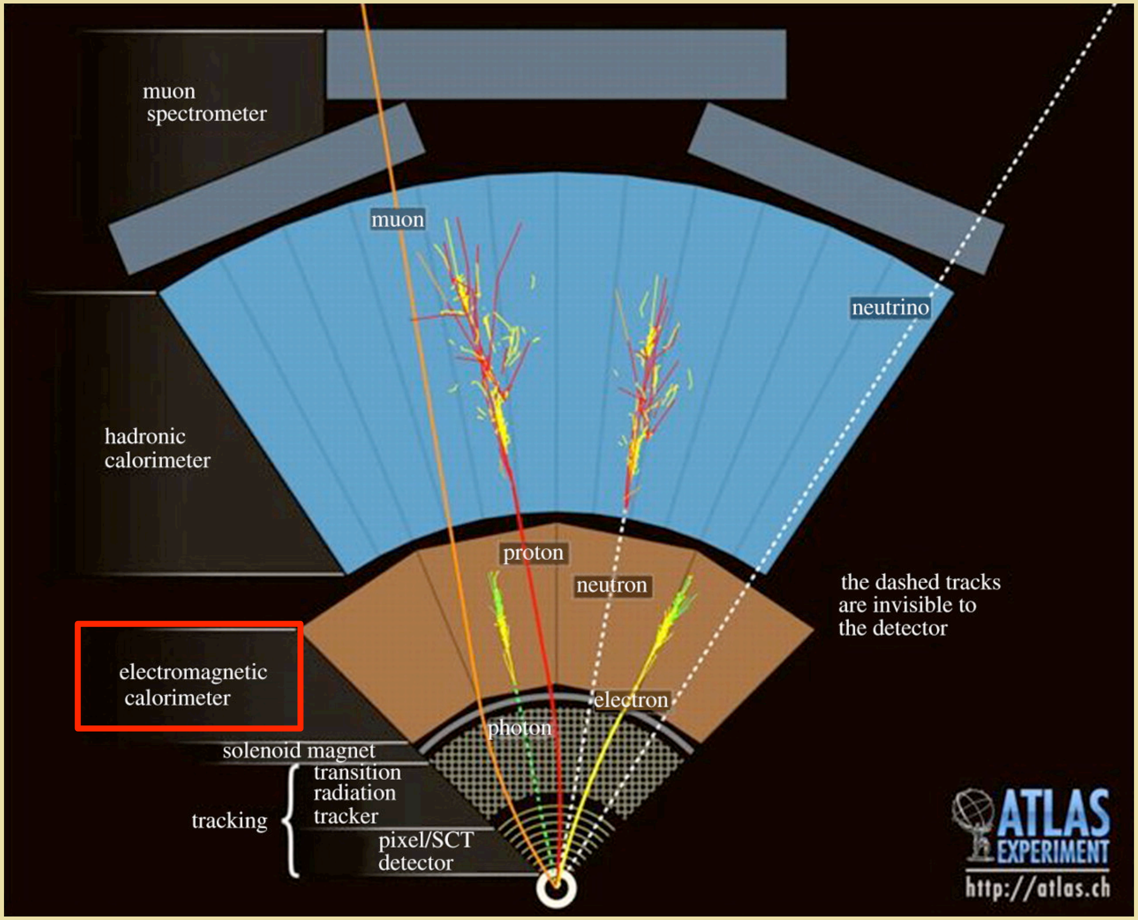
Looks like SS dilepton

e^+ transfers most of p_T to conversion e^- ;
Z / γ^* + jets $\rightarrow$ apparent e^- e^- jj event

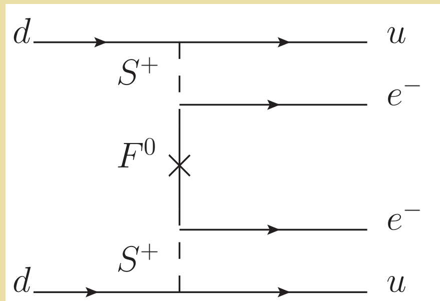


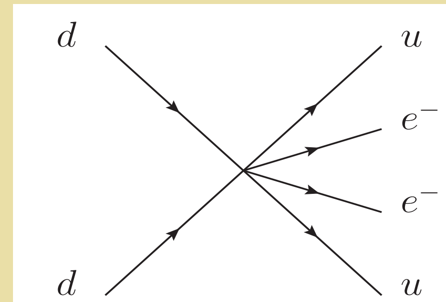
LHC Backgrounds: Jet Fakes

Jet depositing energy in EM calorimeter



Energy Scale Evolution

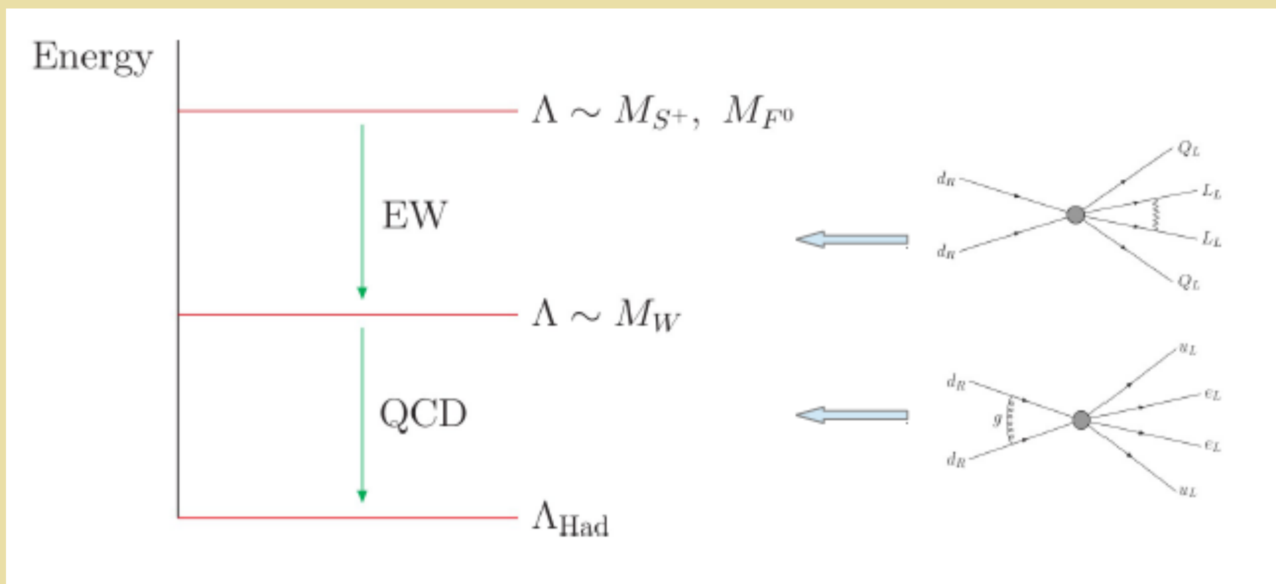




LHC: pp → jj e⁻e⁻

$0\nu\beta\beta$ - decay

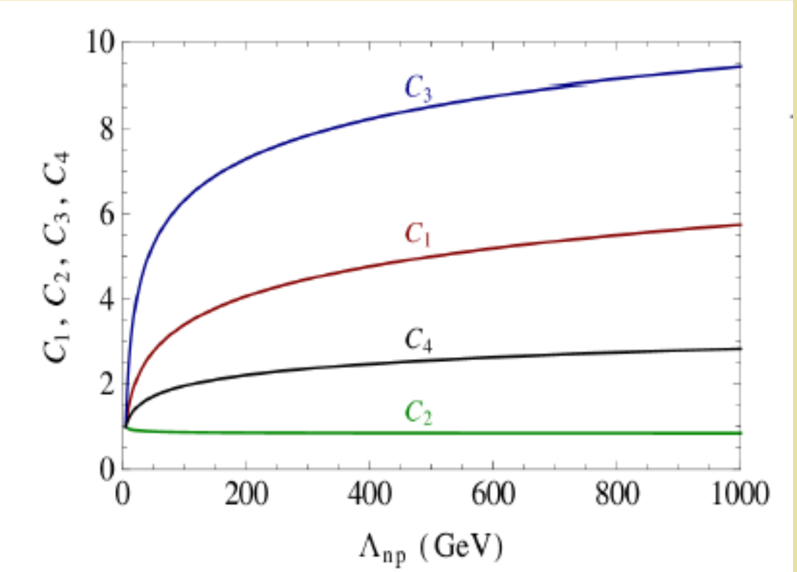
Running



Energy Scale Evolution

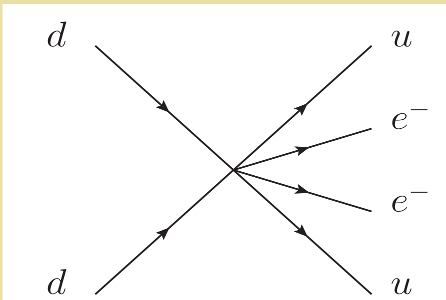
Low energy: *QCD Running*

$$\mathcal{O}_1 = (\bar{u}_L d_R)(\bar{u}_L d_R)(\bar{e}_L e^c_R),$$
$$\mathcal{O}_2 = (\bar{u}_L \sigma^{\mu\nu} d_R)(\bar{u}_L \sigma_{\mu\nu} d_R)(\bar{e}_L e^c_R),$$
$$\mathcal{O}_3 = (\bar{u}_L t^a d_R)(\bar{u}_L t^a d_R)(\bar{e}_L e^c_R),$$
$$\mathcal{O}_4 = (\bar{u}_L t^a \sigma^{\mu\nu} d_R)(\bar{u}_L t^a \sigma_{\mu\nu} d_R)(\bar{e}_L e^c_R).$$

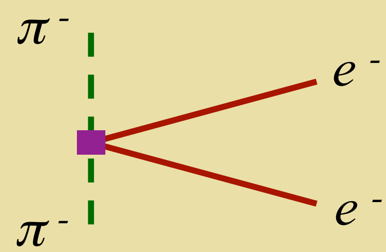


Assuming C_k = 1 at μ = 5 GeV $\rightarrow$ Effective DBD amplitude for $\mathcal{O}_1$ substantially weaker for given LHC constraints

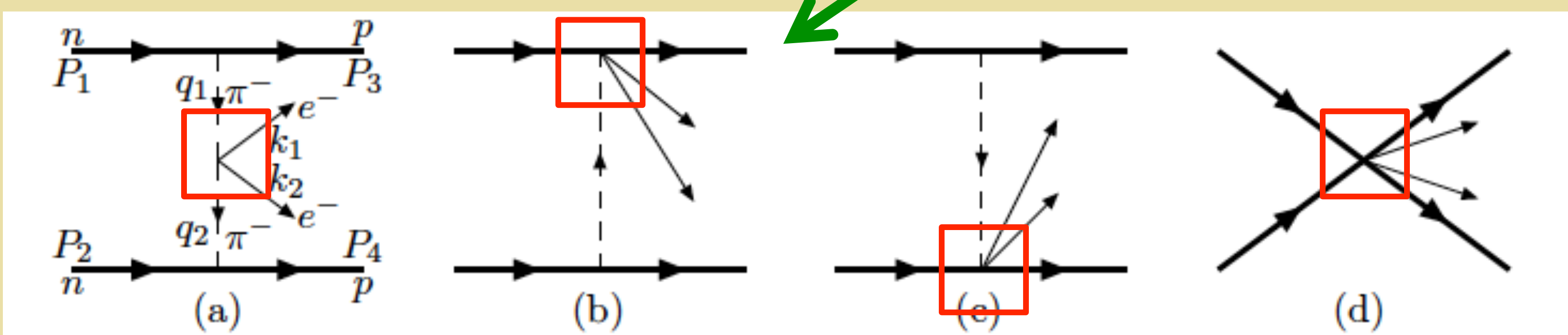
Hadronic & Nuclear Matrix Elements



Quarks & leptons



Hadrons & leptons



Nuclei

$0\nu\beta\beta$-Decay: TeV Scale LNV

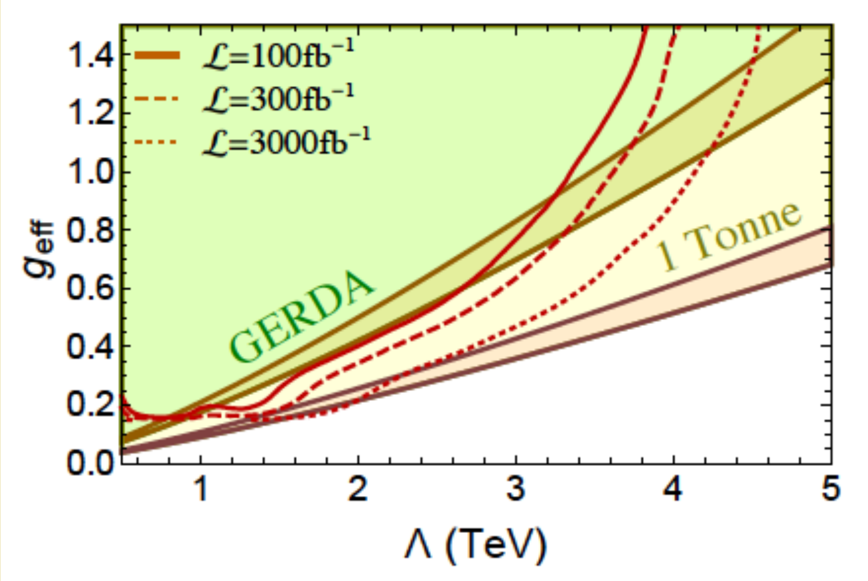
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Benchmark Sensitivity: TeV LNV



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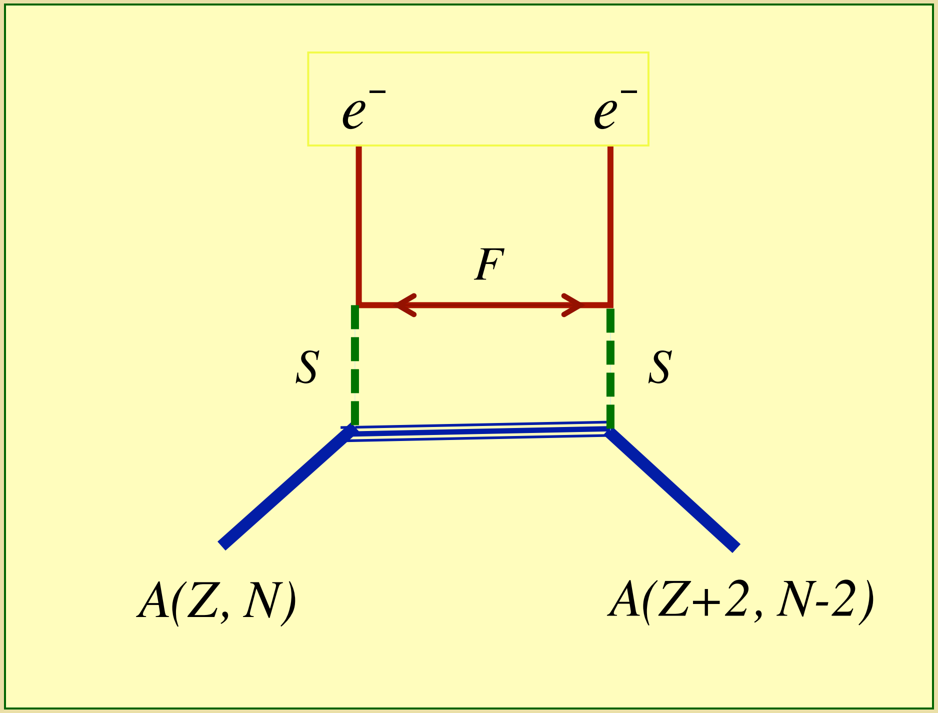


$0\nu\beta\beta$-Decay: LNV? Mass Term?

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

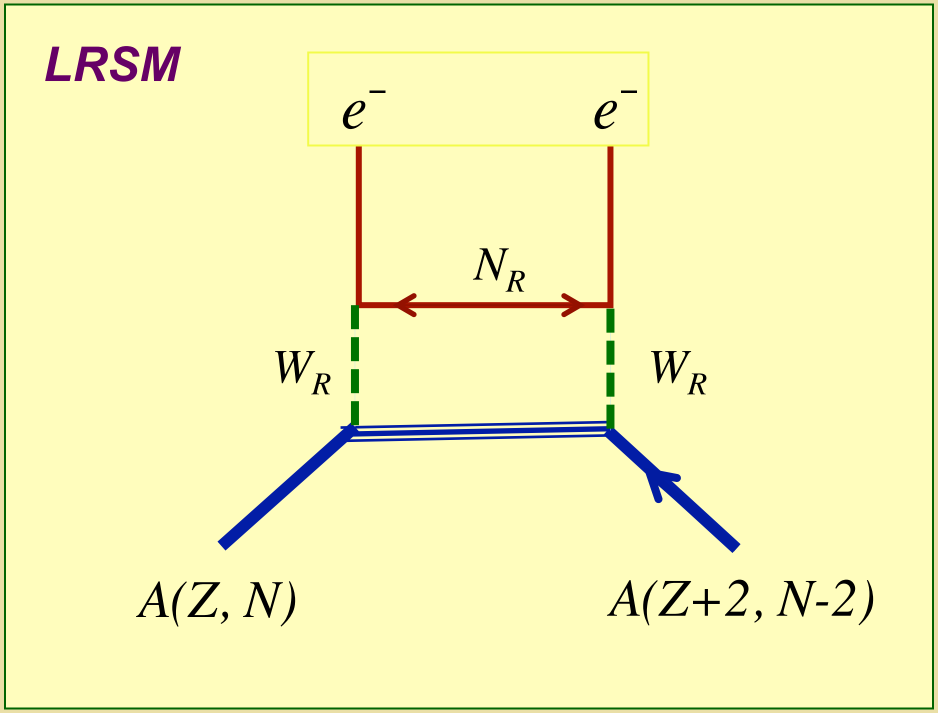
Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

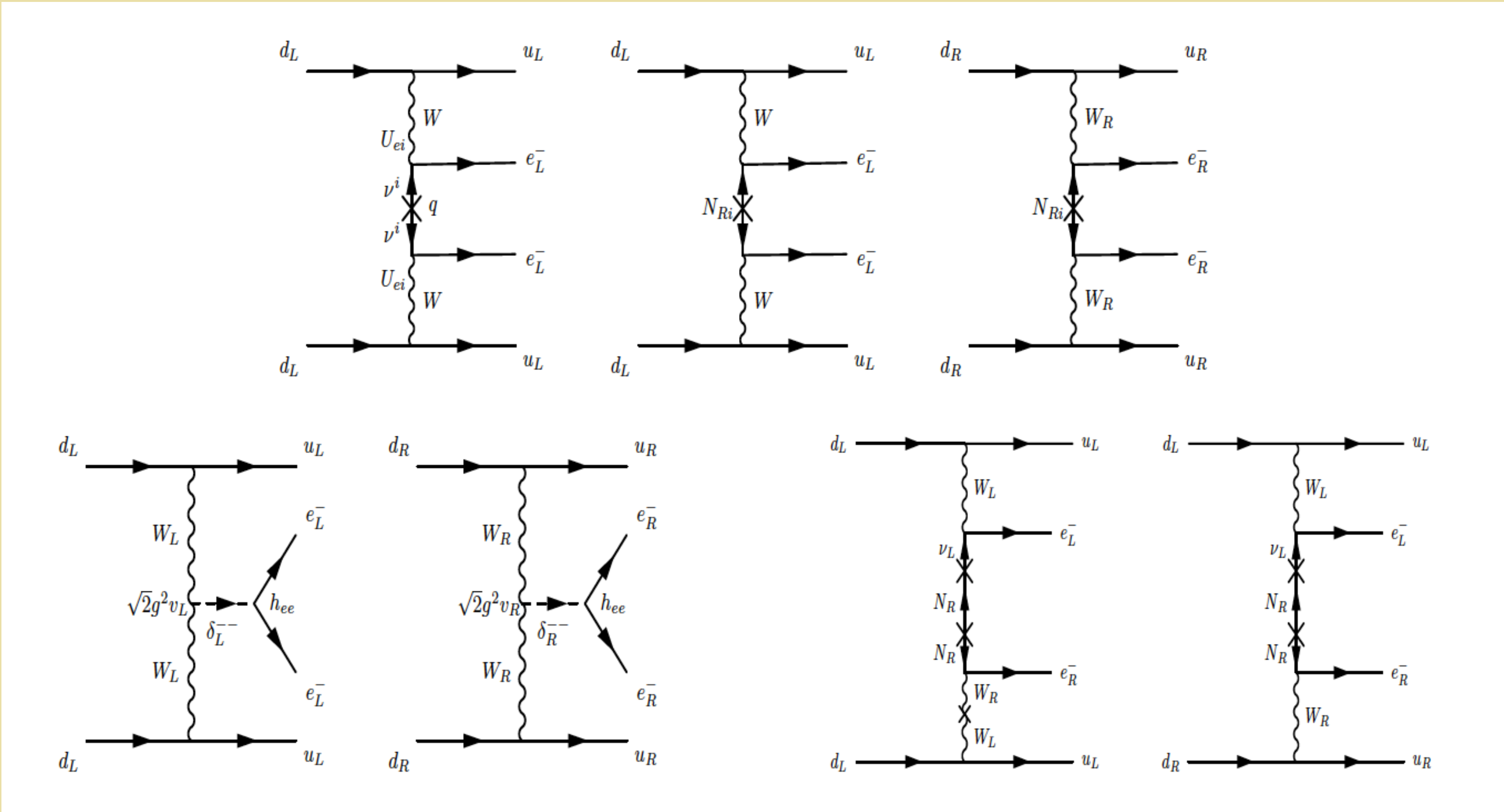
Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



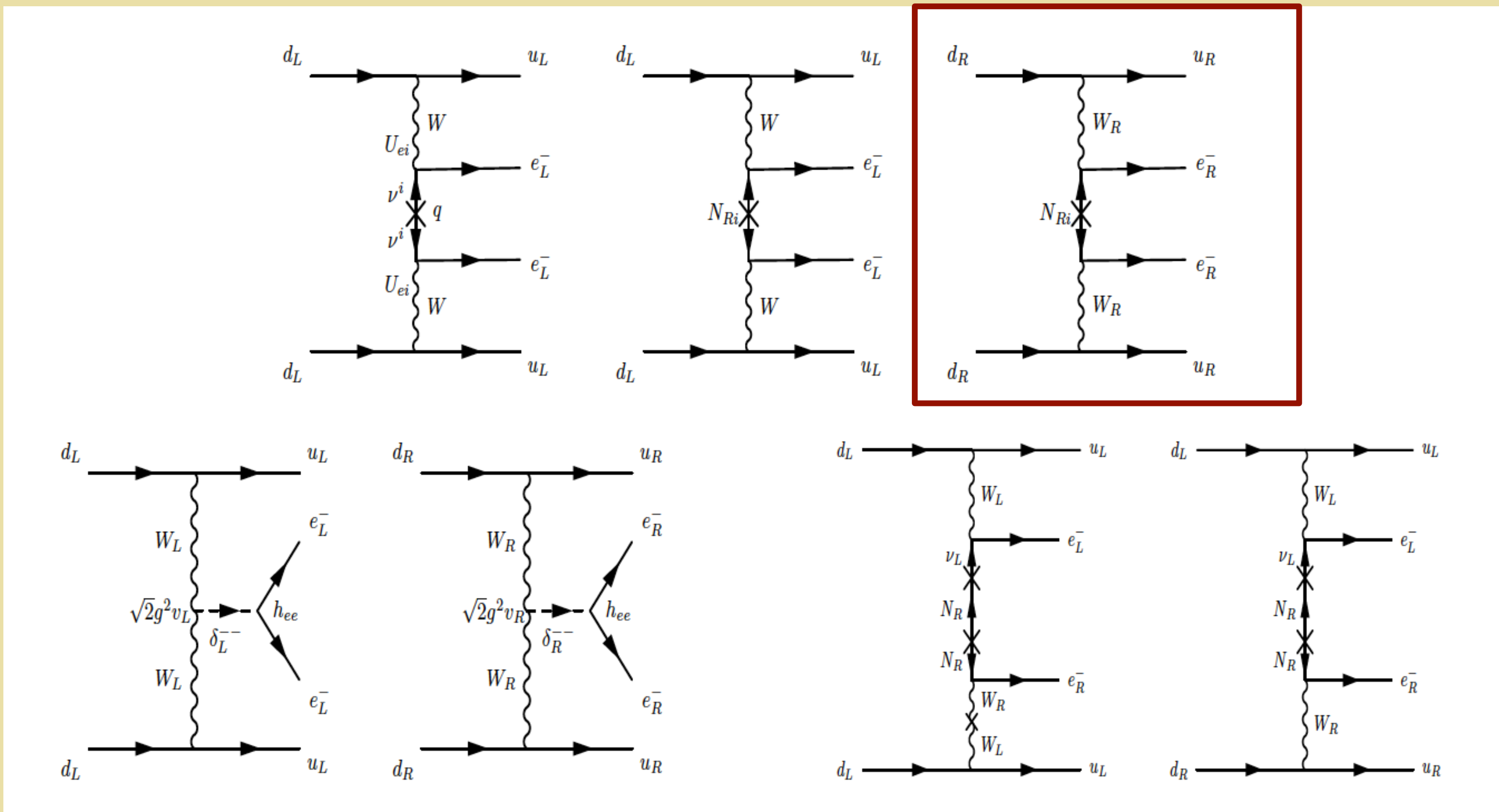
LRSM



W. Rodejohann, INT '17

LRSM

W_R - N_R



d_L u_L W U_{ei} e_L^- ν^i q ν^i e_L^- U_{ei} W d_L u_L
d_L u_L W e_L^- N_{Ri} e_L^- W d_L u_L
d_R u_R W_R e_R^- N_{Ri} e_R^- W_R d_R u_R
d_L u_L W_L e_L^- $\sqrt{2}g^2 v_L$ h_{ee} δ_L^{--} W_L e_L^- d_L u_L
d_R u_R W_R e_R^- $\sqrt{2}g^2 v_R$ h_{ee} δ_R^{--} W_R e_R^- d_R u_R
d_L u_L W_L e_L^- ν_L N_R N_R e_R^- W_R W_L d_L u_L
d_L u_L W_L e_L^- ν_L N_R N_R e_R^- W_R d_R u_R

$0\nu\beta\beta$-Decay: TeV Scale LNV

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

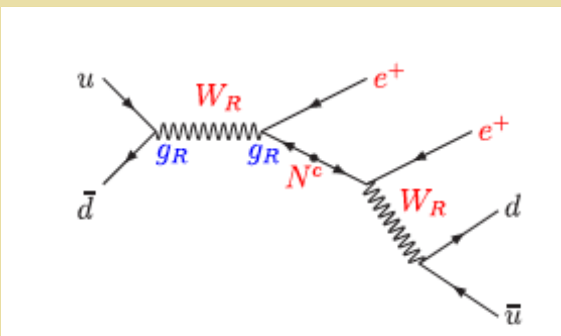
Dirac

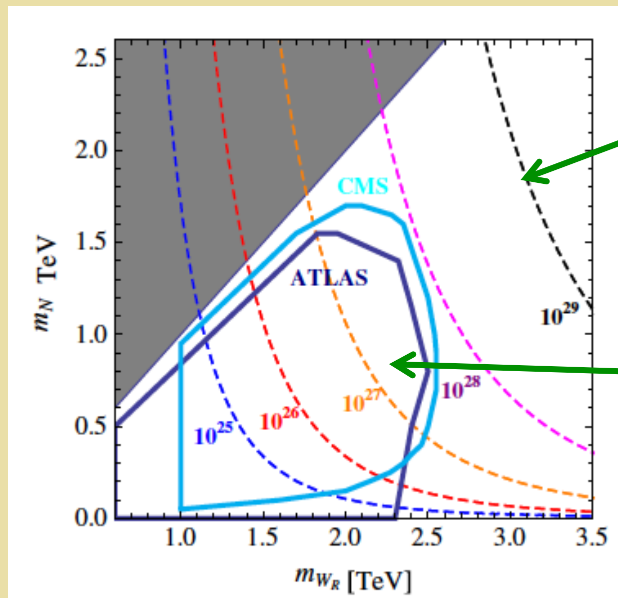
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

LHC: SS Dilepton + Dijet

LHC Production & $0\nu\beta\beta$-Decay



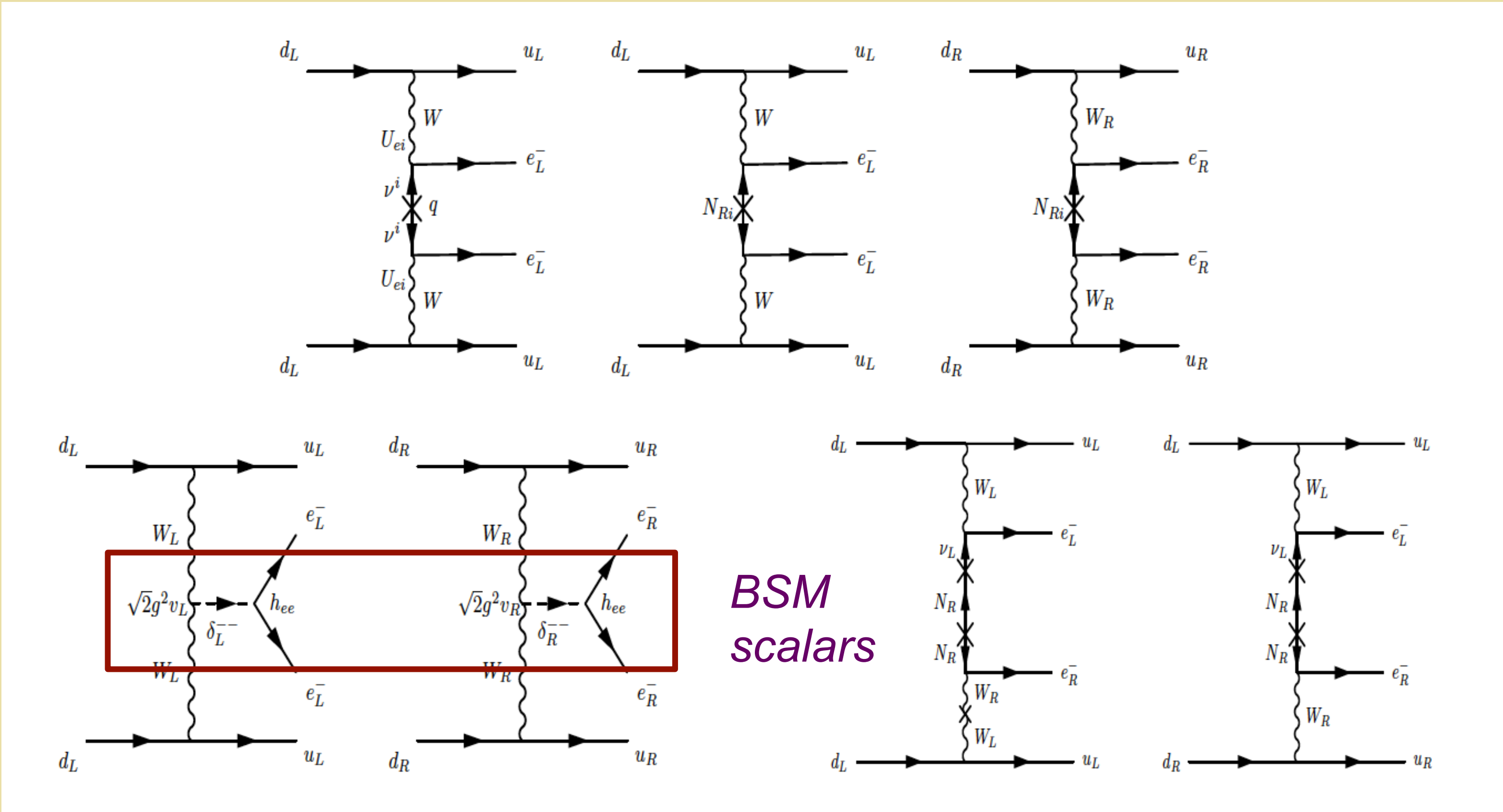


^{76}Ge τ (0ν)

LHC exclusion

Helo et al, PRD 88.011901, 88.073011

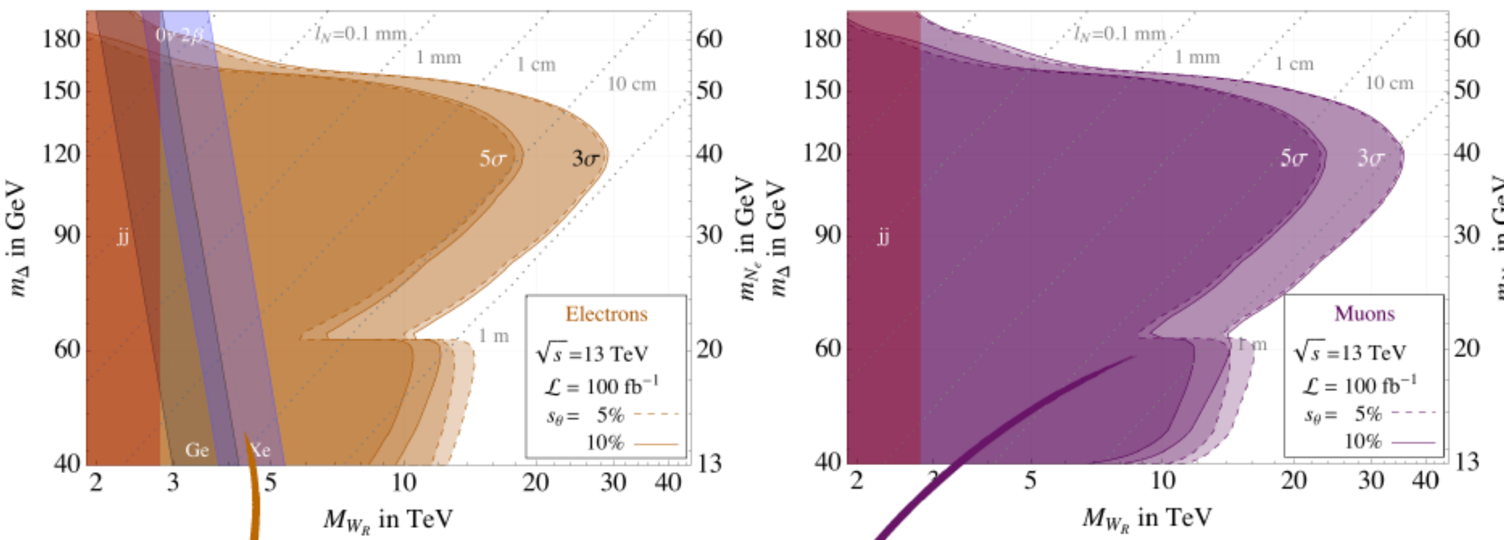
LRSM



LRSM

$$c\tau_N^0 \simeq 0.1\ \mathrm{mm}\left(\frac{40\ \mathrm{GeV}}{m_N}\right)^5\left(\frac{M_{W_R}}{5\ \mathrm{TeV}}\right)^4$$

Combined $h \to NN \quad \Delta \to NN \quad \Delta\Delta \to NNNN$



connection to $0\nu2\beta$

GERDA, Neutrino '16

KamLAND-Zen '16

$h \to \Delta\Delta \to NNNN$

displaced 0.01 mm - >1m

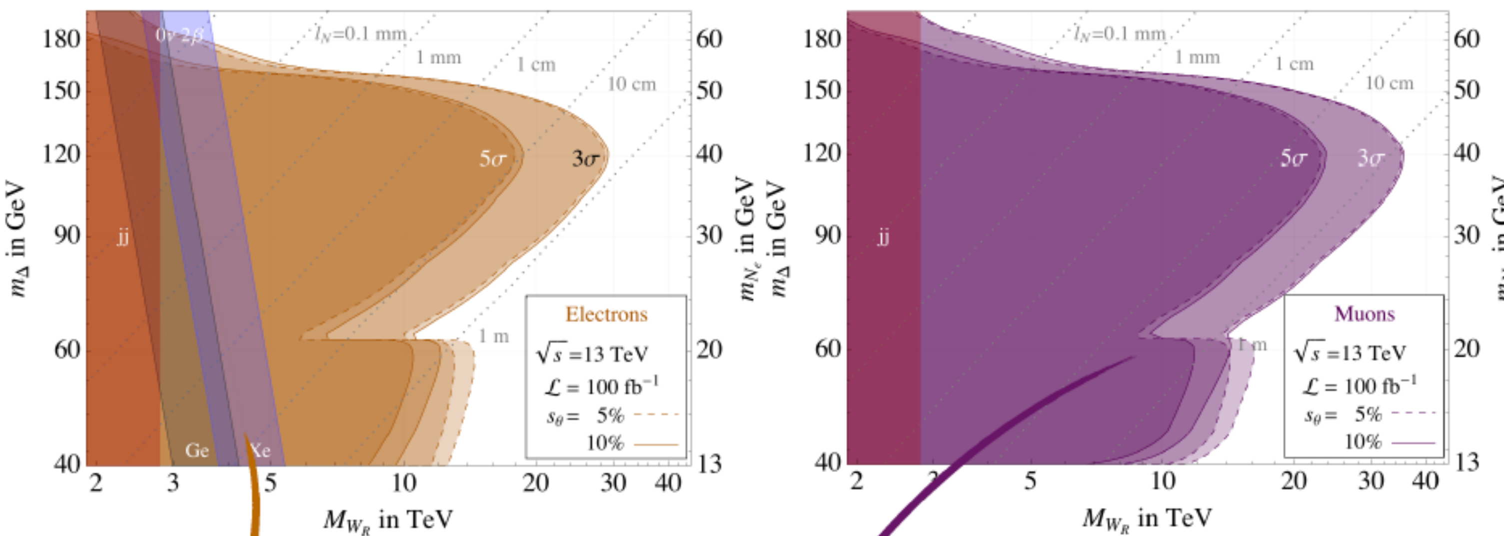
discovery reach beyond direct searches

M. Nemevsek ACFI '17

LRSM

$$c\tau_N^0 \simeq 0.1\ \text{mm} \left(\frac{40\ \text{GeV}}{m_N}\right)^5 \left(\frac{M_{W_R}}{5\ \text{TeV}}\right)^4$$

Combined $h \to NN \quad \Delta \to NN \quad \Delta\Delta \to NNNN$



connection to $0\nu2\beta$

GERDA, Neutrino '16

KamLAND-Zen '16

$h \to \Delta\Delta \to NNNN$

displaced 0.01 mm - >1m

discovery reach beyond direct searches

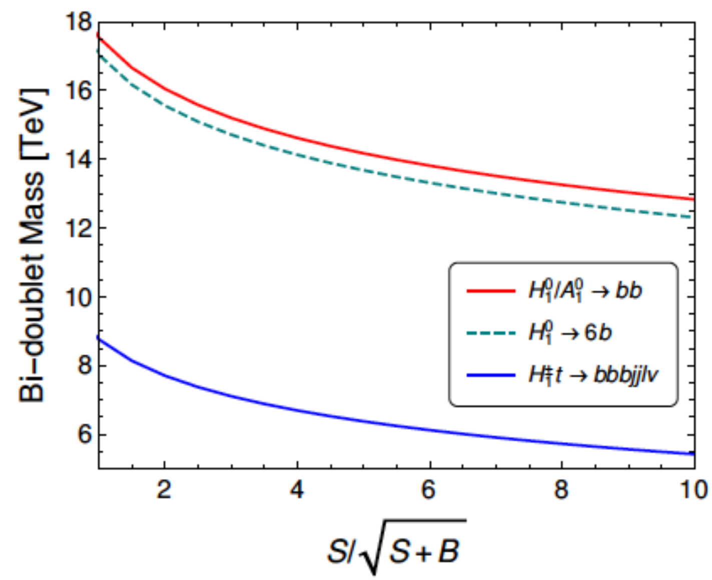
M. Nemevsek ACFI '17

Note: flavor handle at colliders !

LRSM Scalars: Future Colliders

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$
$$\Big\Downarrow \Delta_R\,(\mathbf{1},\mathbf{3},2) \qquad \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3^0,\, H_2^{\pm\pm}$$
$$SU(2)_L \times U(1)_Y$$
$$\Big\Downarrow \Phi\,(\mathbf{2},\mathbf{2},0) \qquad \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow h,\, \boxed{H_1^0,\, A_1^0,\, H_1^\pm}$$
$$U(1)_{\rm EM}$$

$\sqrt{s} = 100$ TeV, $\mathcal{L} = 30$ ab^{-1}



3σ sensitivities: $\{15.2\,\mathrm{TeV},\ 14.7\,\mathrm{TeV},\ 7.1\,\mathrm{TeV}\}$

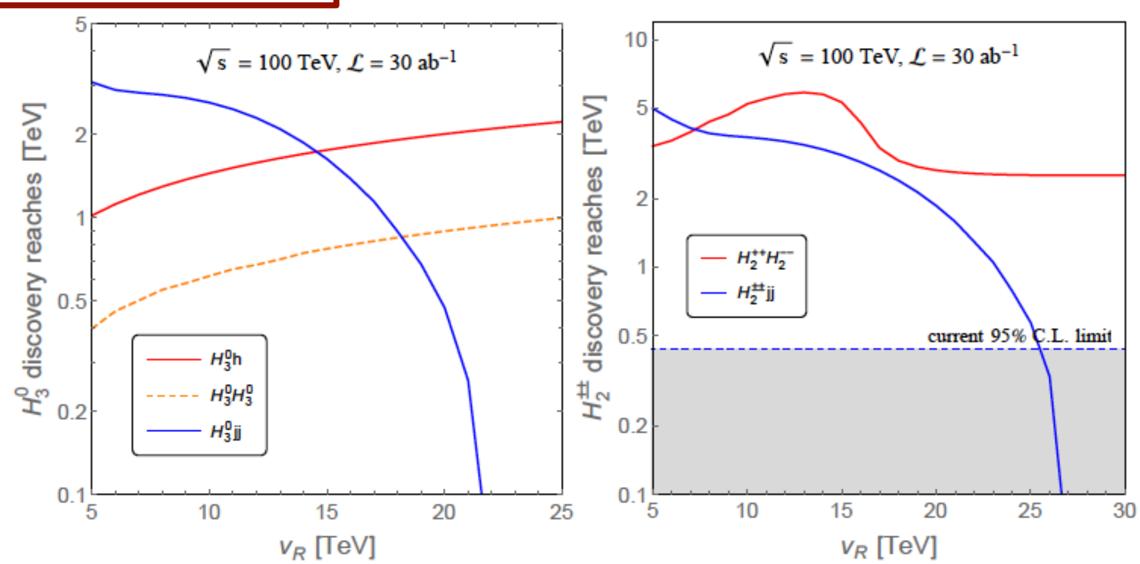
LRSM Scalars: Future Colliders

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \;\Big\Downarrow\; \Delta_R\,(\mathbf{1},\mathbf{3},2) \qquad \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3^0,\, H_2^{\pm\pm}$$

$$SU(2)_L \times U(1)_Y \;\Big\Downarrow\; \Phi\,(\mathbf{2},\mathbf{2},0) \qquad \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow h,\, H_1^0,\, A_1^0,\, H_1^\pm$$

$$U(1)_{\rm EM}$$

← *Majorana mass*



- Probable at the few-TeV scale, depending on the RH scale v_R.
- The SM Higgs portal production of H_3^0 depends also on the quartic couplings.
- Bump structure in the right panel: $\Rightarrow Z_R$ resonance.

III. RH Neutrinos

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **Underlying Physics** $\rightarrow A(Z+2, N-2) + e^- e^-$

- 3 light neutrinos only: source of neutrino mass at the very high see-saw scale
- 3 light neutrinos with TeV scale source of neutrino mass
- > 3 light neutrinos

RH Sterile Neutrinos

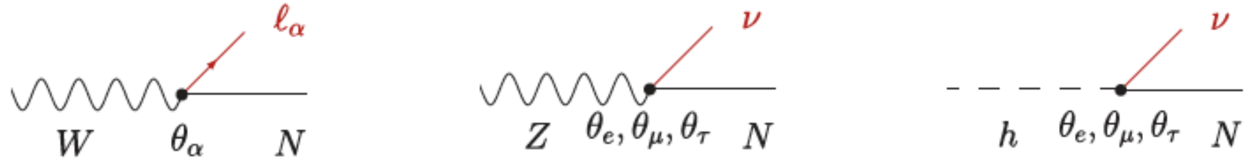
- The leptonic mixing matrix to leading order in θ_α

Mixing matrix of the light ν $\equiv U_{\text{PMNS}}$

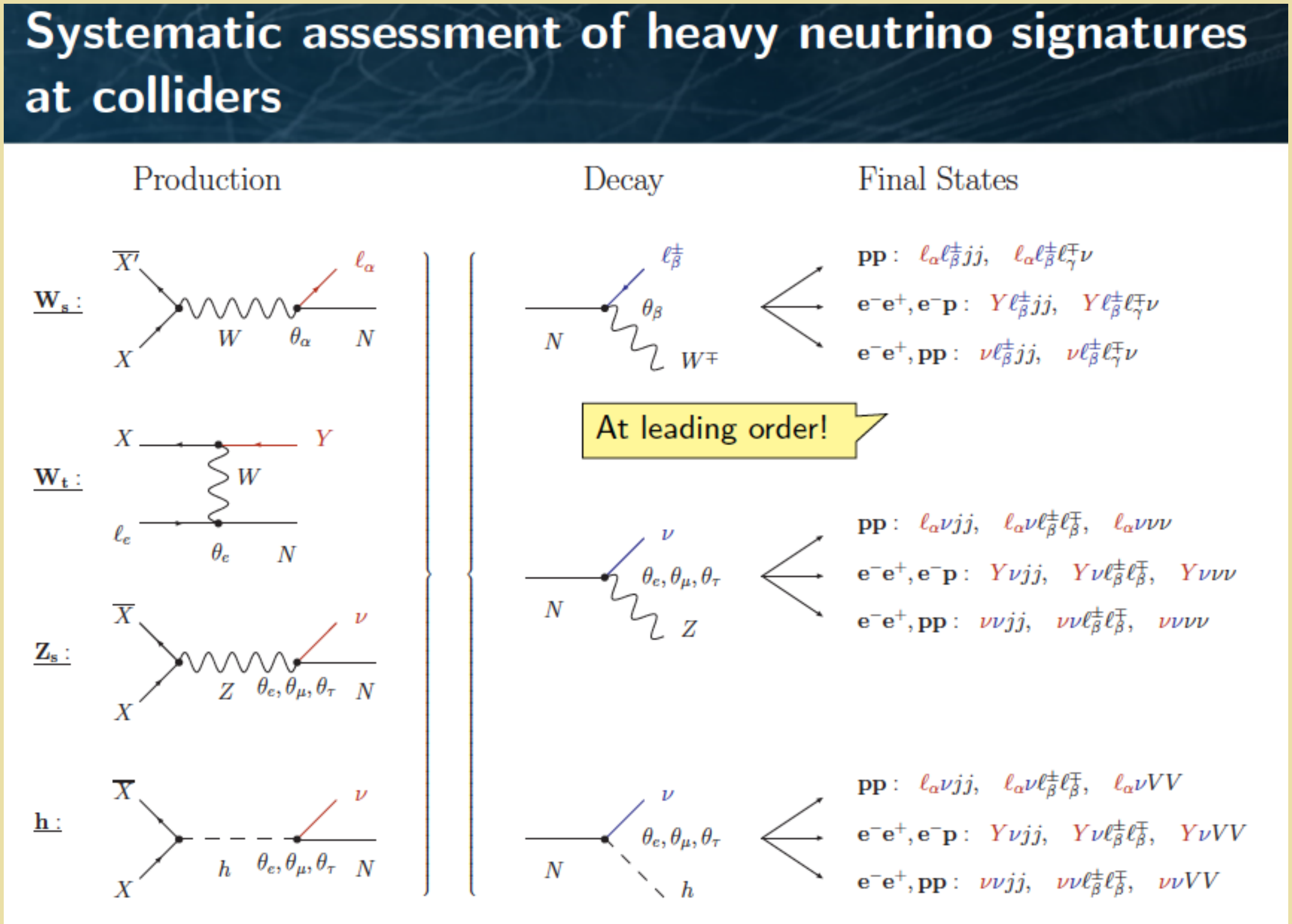
$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{i}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu1} & \mathcal{N}_{\mu2} & \mathcal{N}_{\mu3} & -\frac{i}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau1} & \mathcal{N}_{\tau2} & \mathcal{N}_{\tau3} & -\frac{i}{\sqrt{2}}\theta_\tau & \frac{1}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{i}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

Sterile ν mix with active ones

$\Rightarrow$ Heavy ν (mass eigenstates) participate in weak interaction processes:

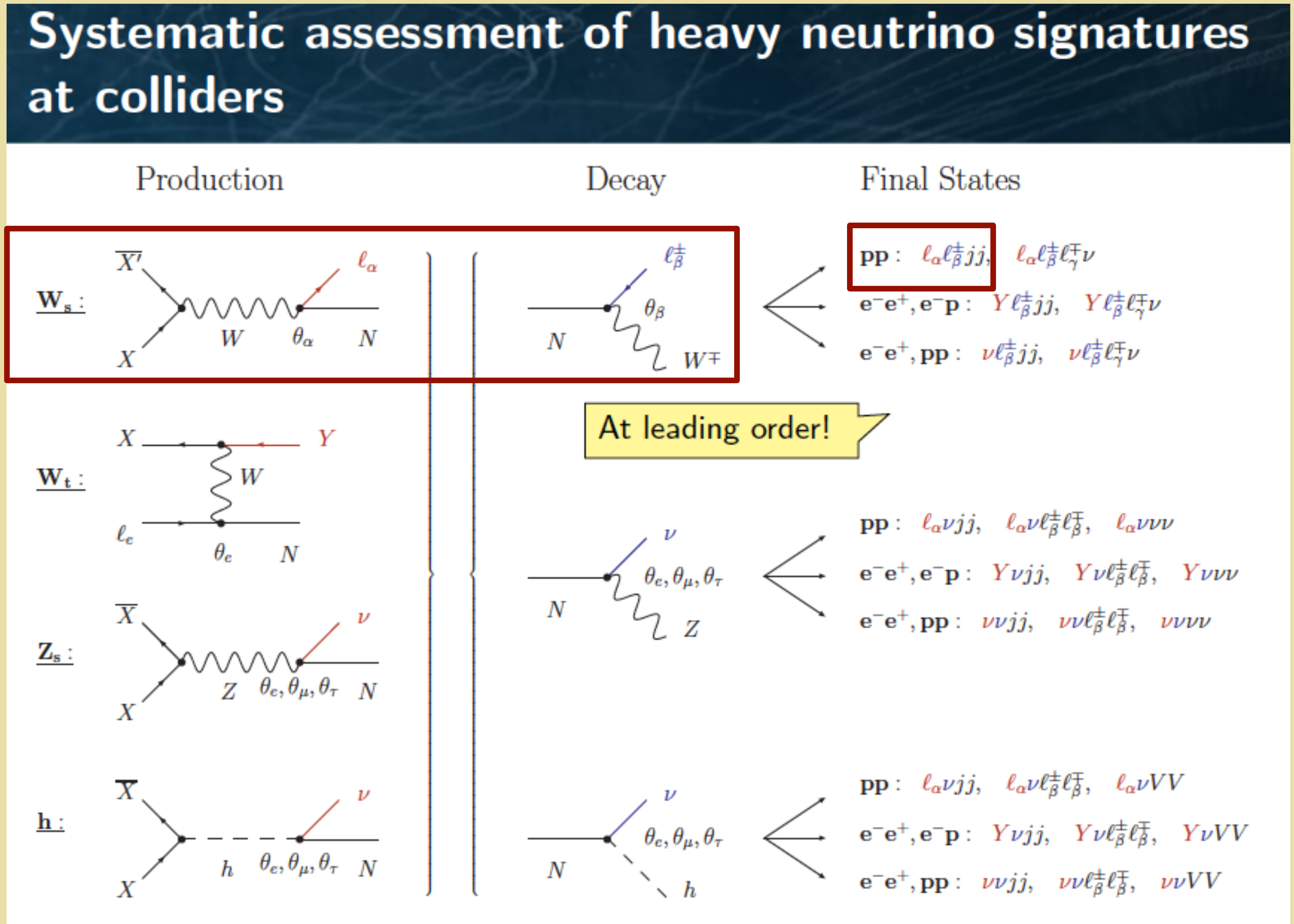


RH Sterile Neutrinos



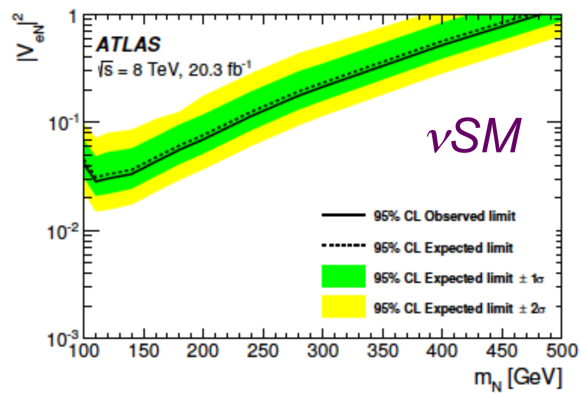
E. Cazzato

RH Sterile Neutrinos: LHC Prompt

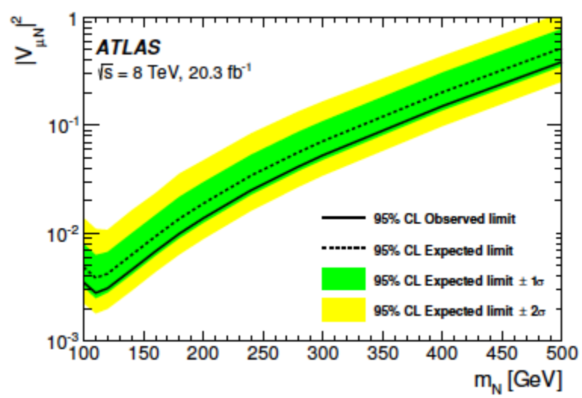


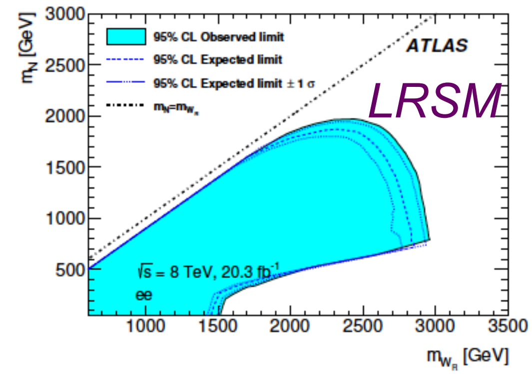
E. Cazzato

RH Sterile Neutrinos: LHC Prompt

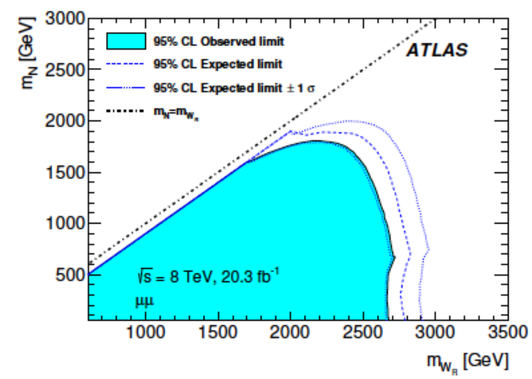


(b)





(a)

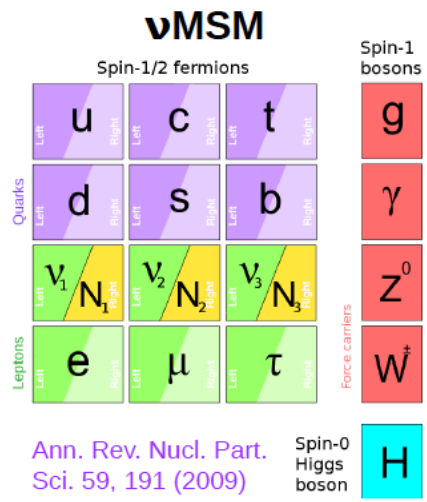


(c)

ATLAS: 1506.06020

$pp \to \ell\ell jj$

Long Lived RH Neutrinos

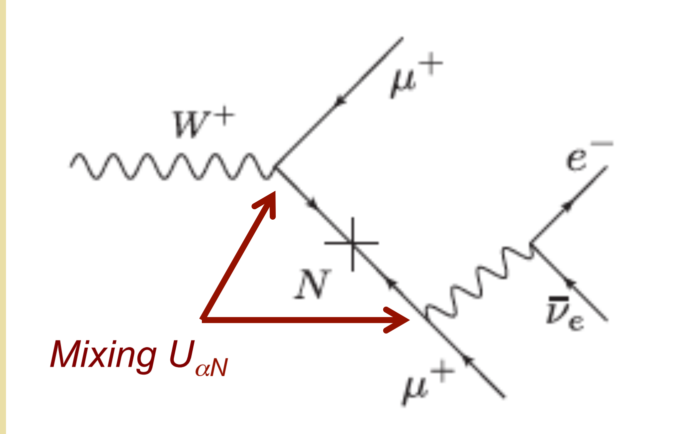


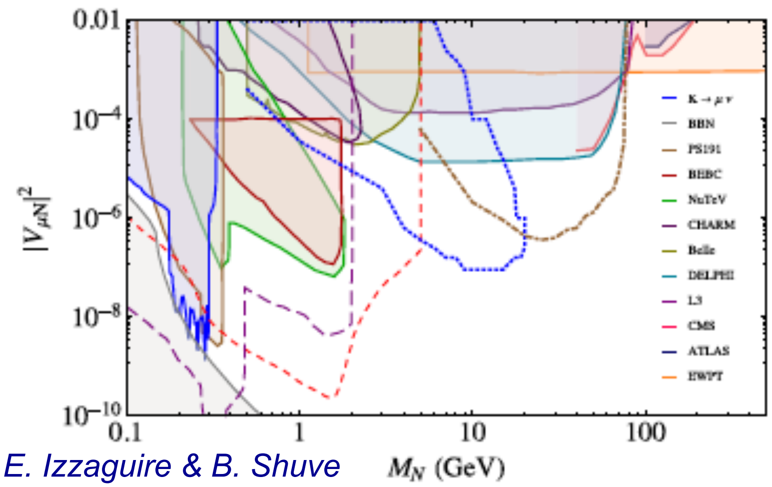
Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

P. Mermod

N_1 mass ~keV
→ **dark matter**

$N_{2,3}$ mass ~GeV
→ **seesaw**
→ **leptogenesis**





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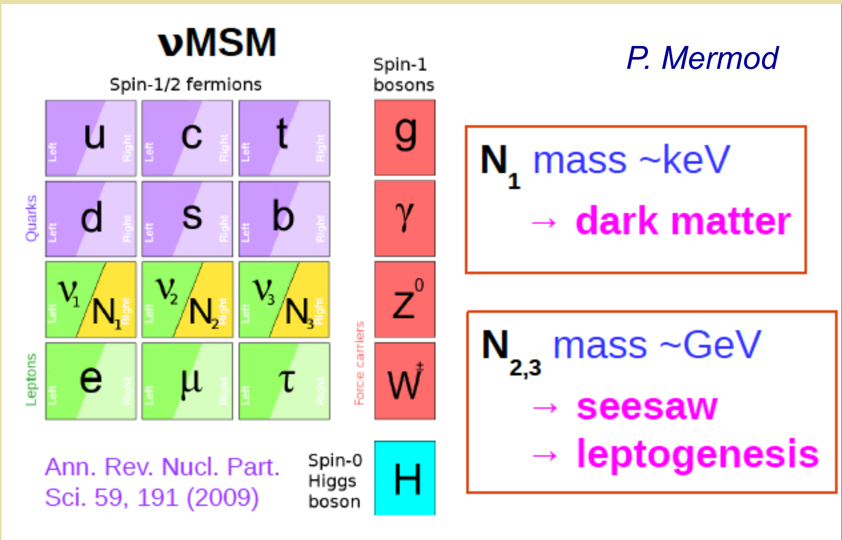
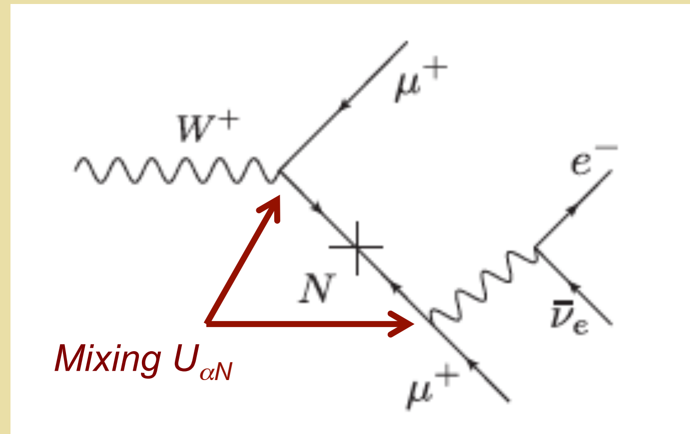
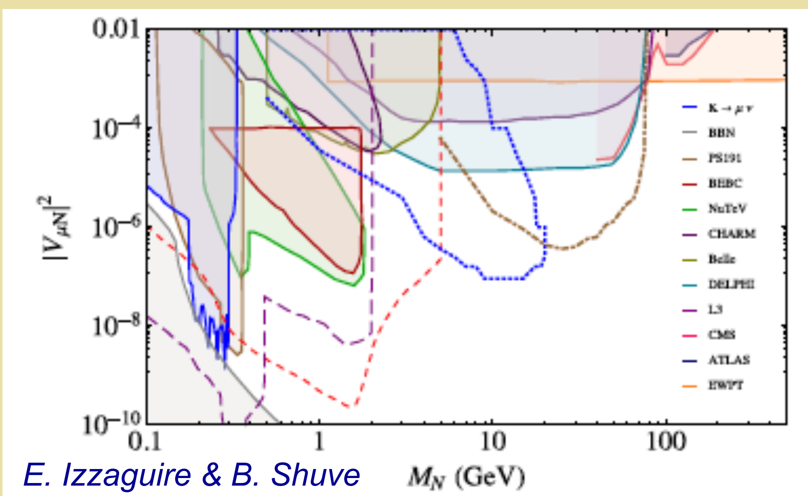
Long Lived RH Neutrinos







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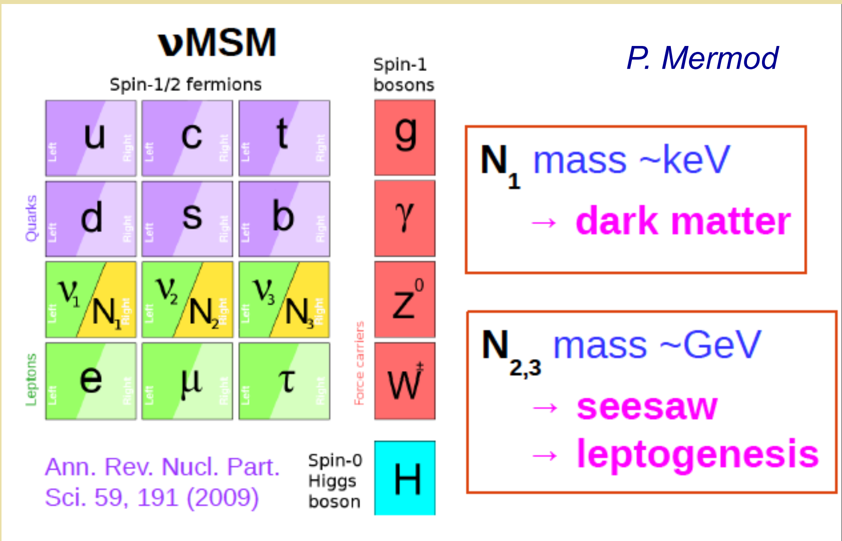
Type I see-saw: νSM

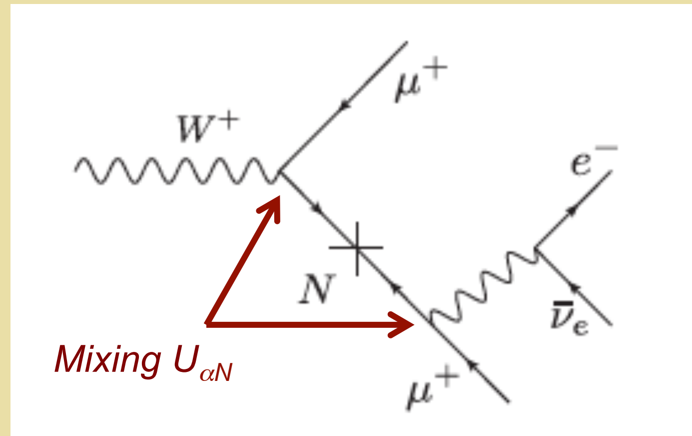
$$U_{\alpha N} \sim \frac{m_D}{M_N}$$

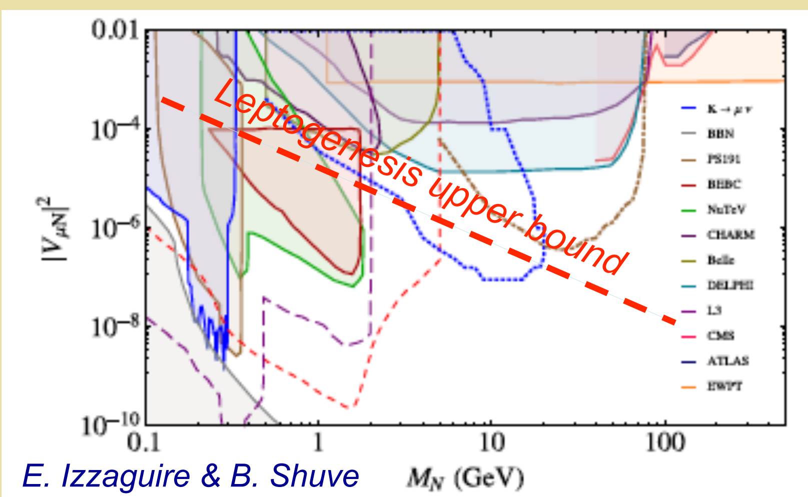
Type I & II see-saw: LRSM

$$U_{\alpha N} \sim \sqrt{\frac{v_L}{v_R} - \frac{m_\nu}{M_N}}$$

Long Lived RH Neutrinos



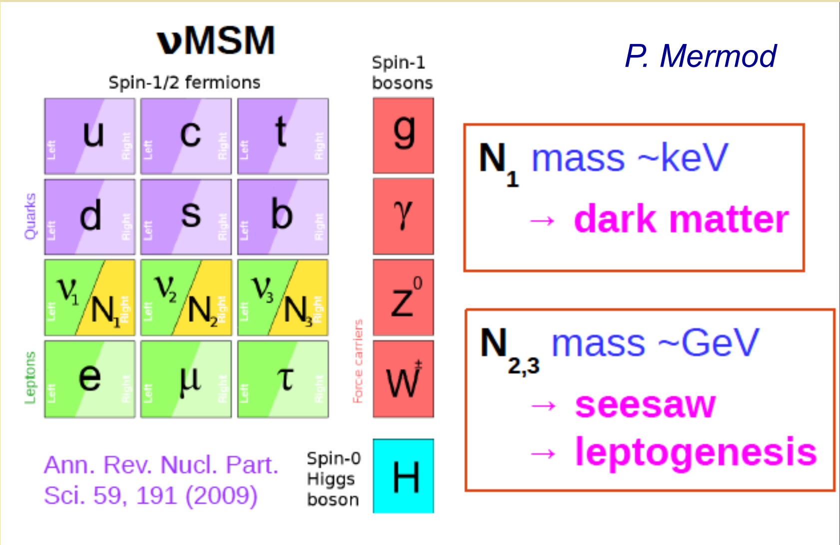


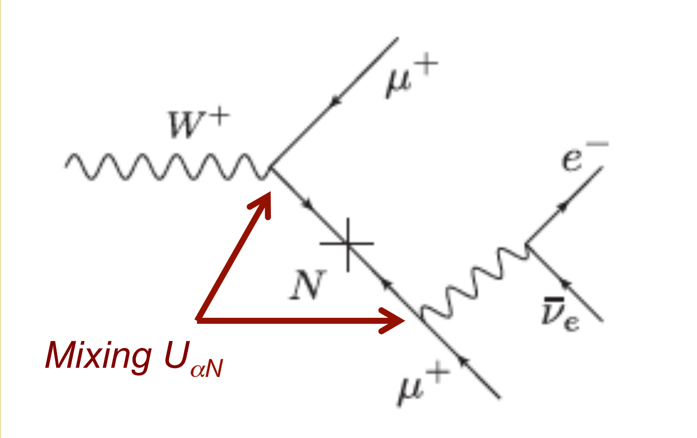


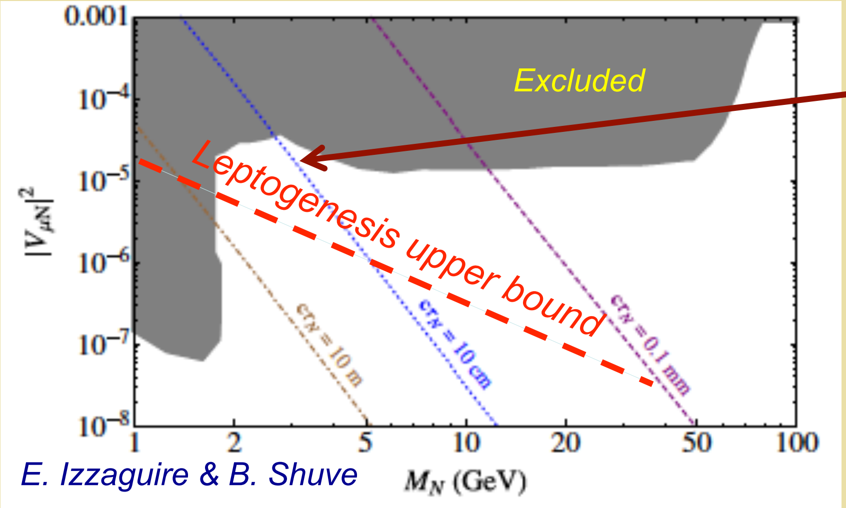
BAU from Leptogenesis

- *Drewes et al '16*
- *Lower bound < 10^{-10}*

Long Lived RH Neutrinos



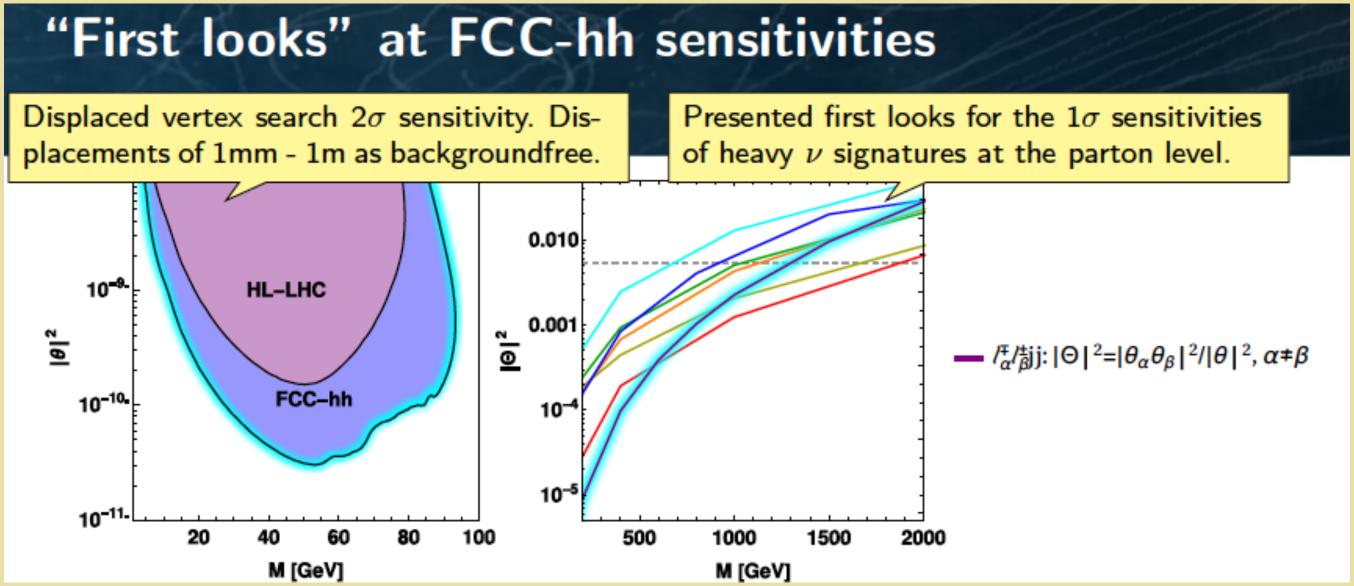


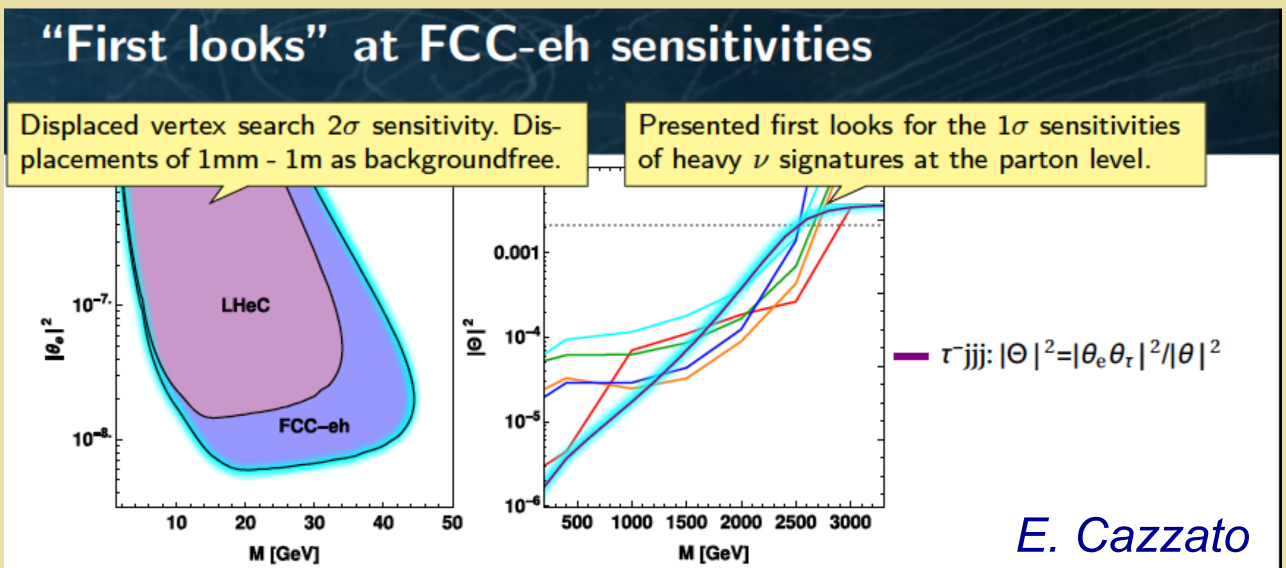


$$\Gamma(N \to \ell_\alpha^- \ell_\beta^+ \nu_\beta) = \frac{G_F^2 M_N^5 |V_{\alpha N}|^2}{192\pi^3}$$

See also: Helo, Kovalenko & Hirsch

RH Sterile Neutrinos: Future Colliders



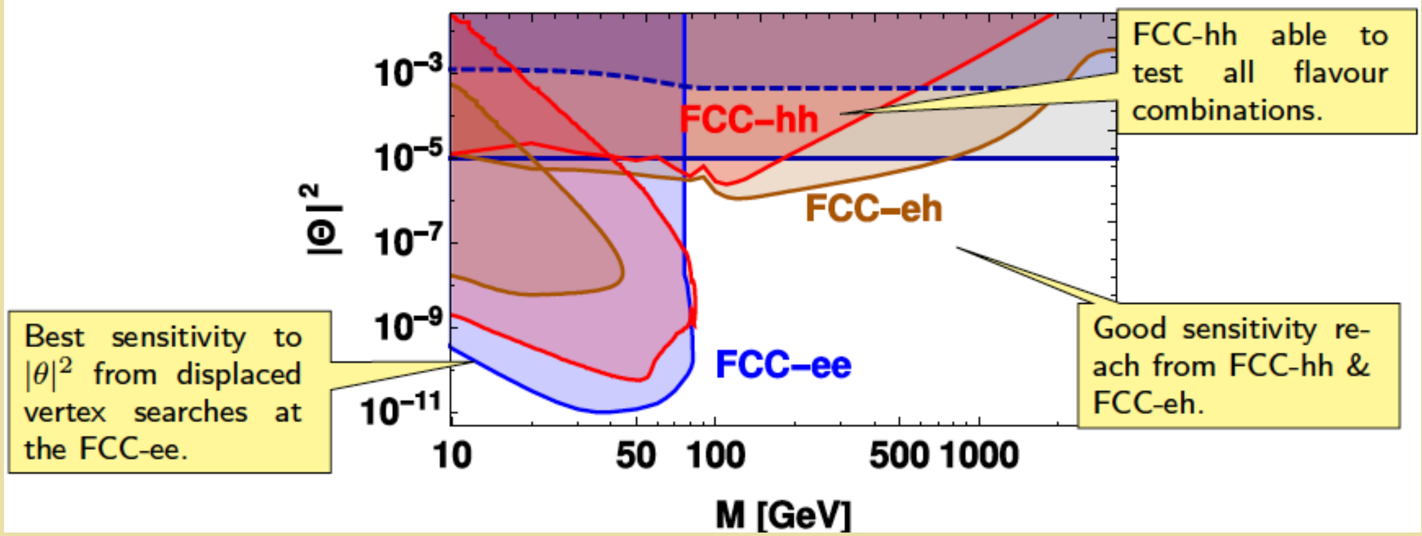


E. Cazzato

RH Sterile Neutrinos: Future Colliders

Summary

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search



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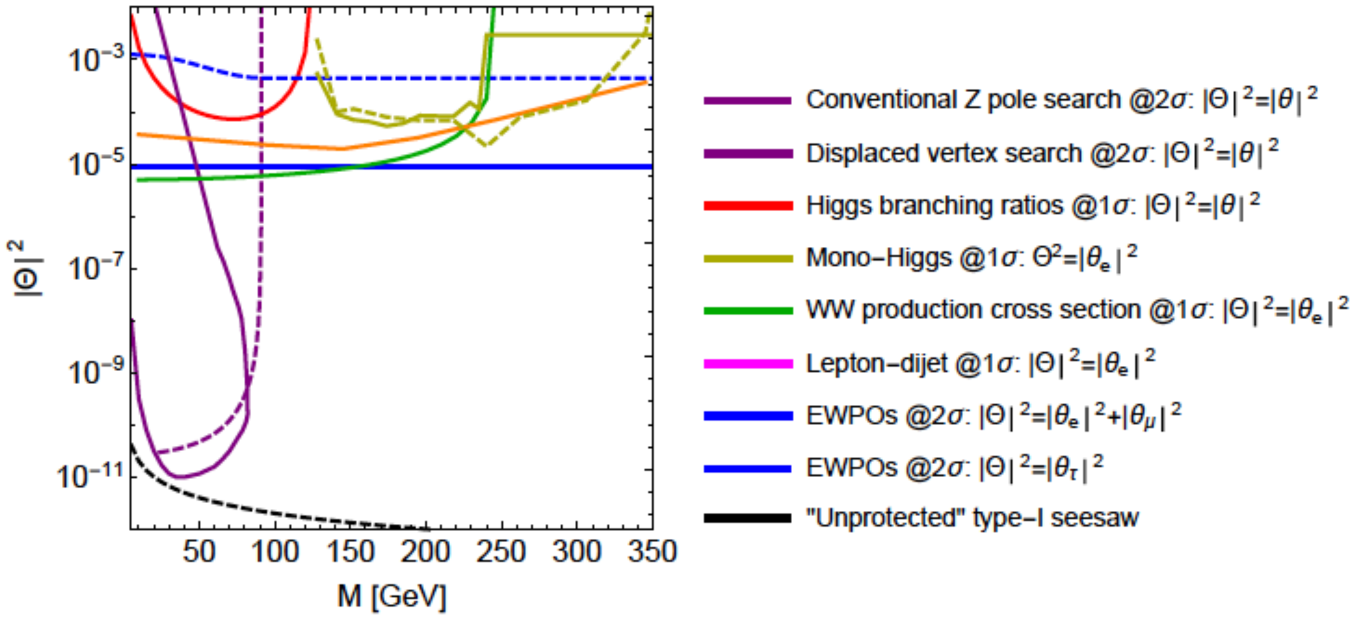
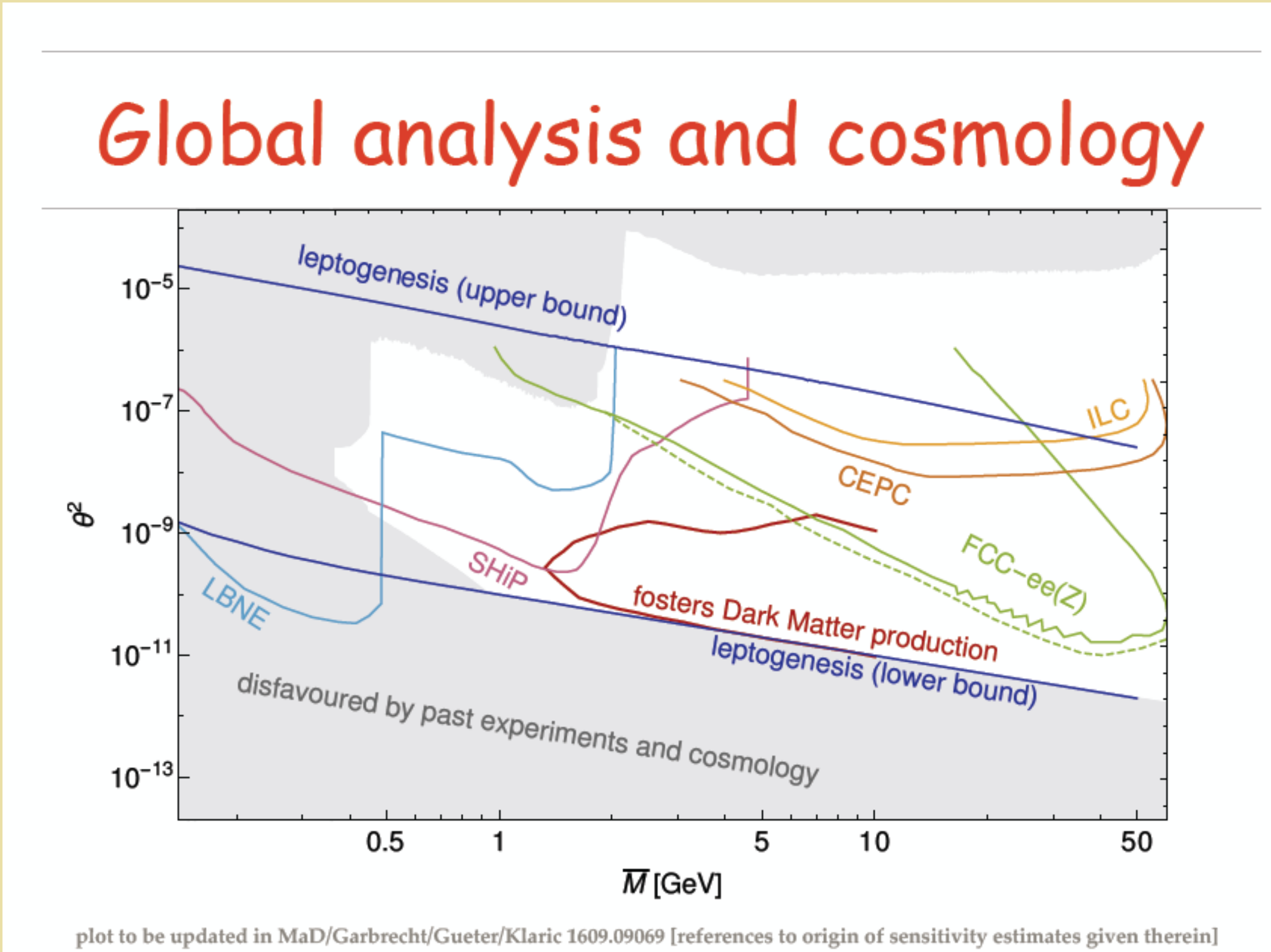
RH Sterile Neutrinos

Summary: FCC-ee sensitivities



- Displaced vertex searches test $|\theta|^2 \sim 10^{-11}$ for $M \leq m_W$.
- EWPOs test $|\theta|^2 \sim 10^{-5}$ up to $M \sim 60$ TeV with $\mathcal{O}(1)$ Yukawa couplings.

RH Sterile Neutrinos



Lecture V Summary

- *High energy colliders provide a powerful means of probing dynamics of neutrino mass generation if it is associated with physics at or below the TeV scale*
- *The LHC along with future e^+e^- and pp colliders provide LNV probes that are complementary to $0\nu\beta\beta$-decay*
- *The observation of LNV in both $0\nu\beta\beta$-decay and high energy collider searches would indicate the energy scale for neutrino mass generation lies at or below the TeV scale*
- *The collider discovery of other ingredients in neutrino mass models would help unravel one of the key open problems in fundamental interaction physics*