HEP BSM Searches: Inter-Frontier Connections

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- *T.D. Lee Institute/Shanghai Jiao Tong Univ.*
- *UMass Amherst*
- *Caltech*

About MJRM:

Science

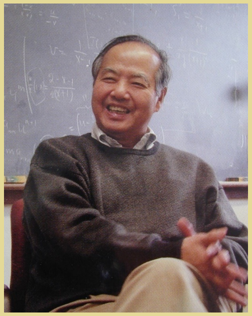
Family

Friends

My pronouns: he/him/his
 # MeToo
https://michaelramseymusolf.com

EW & BSM EIC Workshop
Institute for Nuclear Theory
February 15, 2024

T. D. Lee Institute / Shanghai Jiao Tong U.



A point of convergence of the world's top scientists

A launch pad for the early-career scientists

Director

Founded 2016

A world famous source of original innovation

100+

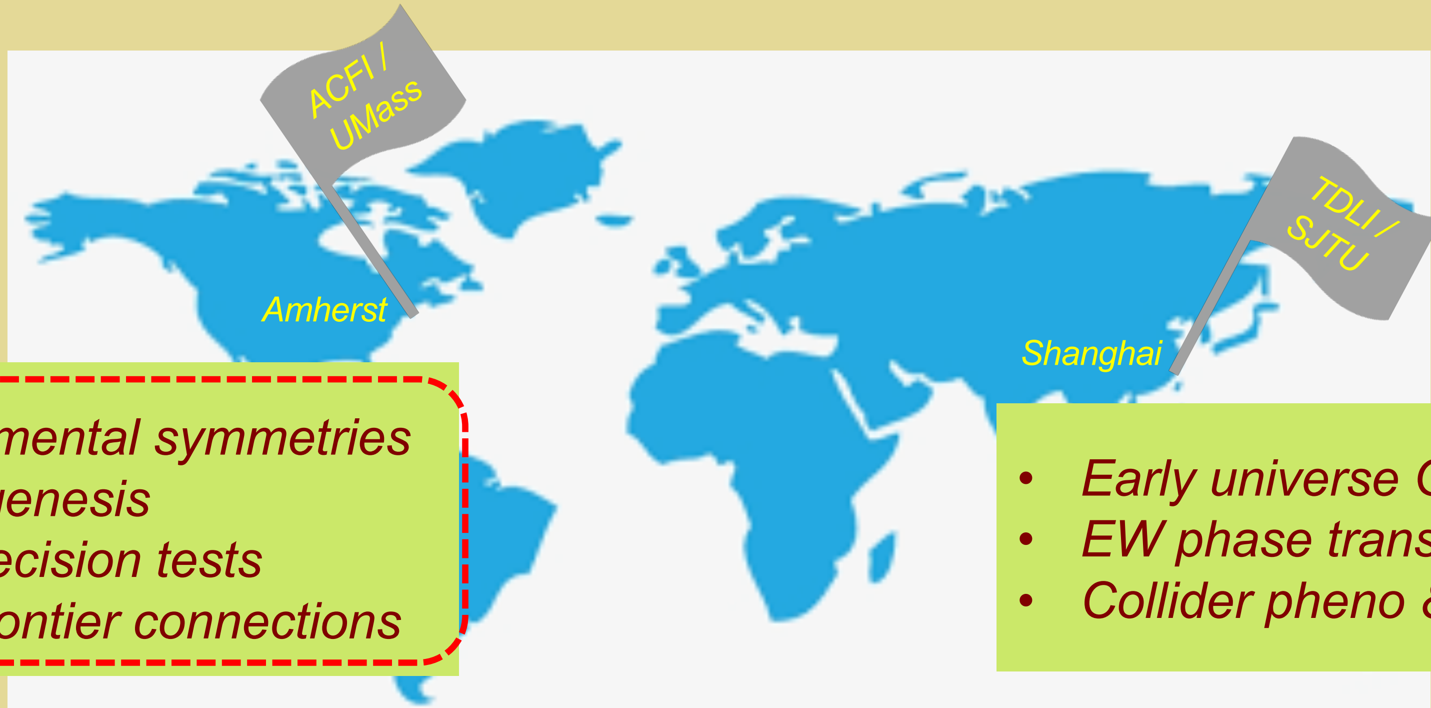
faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

Theory & Experiment

- Particle & Nuclear Physics
- Astronomy & Astrophysics
- Quantum Science
- Dark Matter & Neutrino
- Laboratory Astrophysics
- Topological Quantum Computation

https://tdli.sjtu.edu.cn/EN/

MJRM: Scientist & "Ambassador"

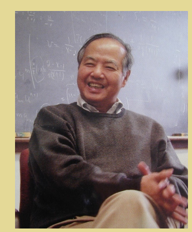


This talk: NP-HEP interfrace

- *Fundamental symmetries*
- *Baryogenesis*
- *EW precision tests*
- *Inter-frontier connections*

- *Early universe QFT*
- *EW phase transition*
- *Collider pheno & Higgs*

- ***Global effort: ~ 20 researchers***
- ***Foster scientific connections***
- ***Science First ! 科学 第一 ！***



Goals for this Talk: What I Won't Do

- *Give a comprehensive survey of BSM searches at the high energy frontier*
- *Chase anomalies: M_W , $(g\text{-}2)_\mu$, …*
- *Make explicit reference to all previous BSM talks in this workshop*

Goals for this Talk: What I'll Try to Do

- ***Contextualize*** ***the EIC electroweak and BSM program with respect to HEP BSM searches***
- ***Illustrate*** ***inter-frontier connections between the HEP and NP programs***
- ***Highlight*** ***developments, opportunities, and challenges in two areas: EW precision tests and searches for BSM lepton number violation***
- ***Invite*** ***discussion, other ideas, and future explorations***

Disclaimer

- *Apologies for omissions of references to other important work*
- *Will not cover charged lepton flavor violation → see excellent talks this workshop*

Outline

I. Questions & Frontiers

II. Electroweak precision tests: what are the possible BSM "footprints" and what is the relevant BSM mass scale ?

III. What is the scale of lepton number violation ?

IV. Outlook

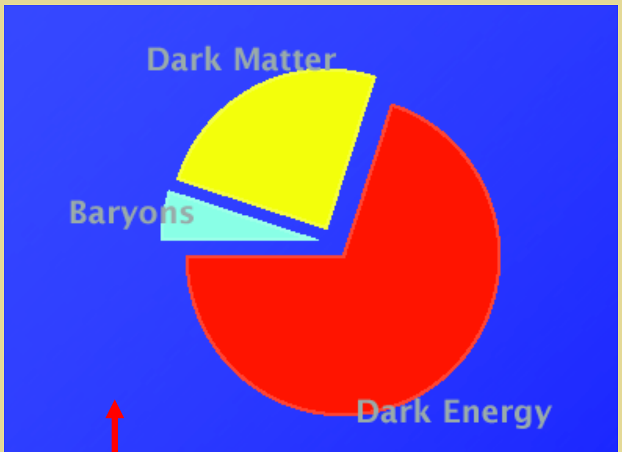
Back up slides for another day…

- Where is the CP-violation needed to explain the matter-antimatter asymmetry ?
- Was there an electroweak phase transition ?

I. Questions & Frontiers

Fundamental Questions

MUST *answer*



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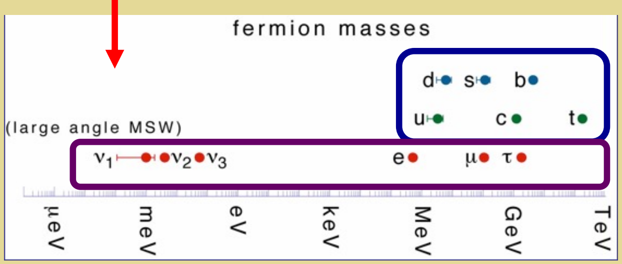
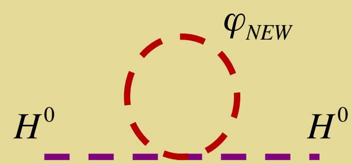


Origin of m_ν

SHOULD *answer*



$\Delta m^2 \sim \lambda \Lambda^2$

?

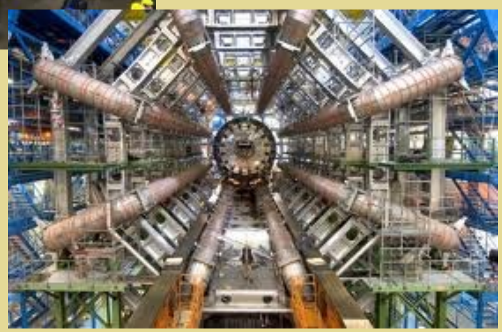
$\Lambda_{\text{Cosmological}}$

Experimental Probes: Energy Frontier

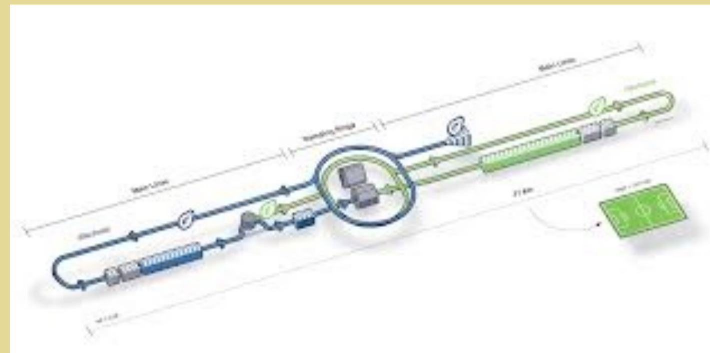
LHC

ATLAS

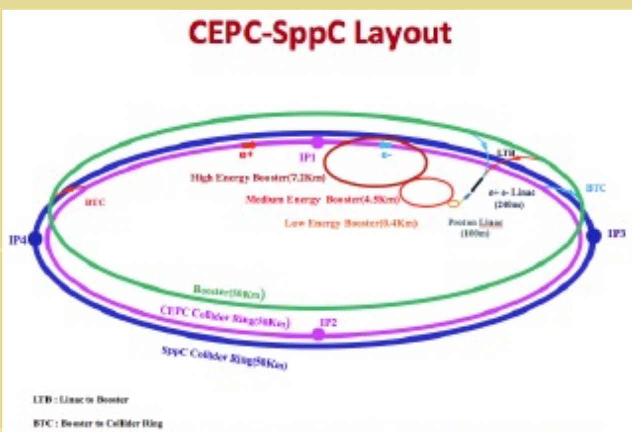
CMS



International Linear Collider



Future Circular e^+e^- & pp



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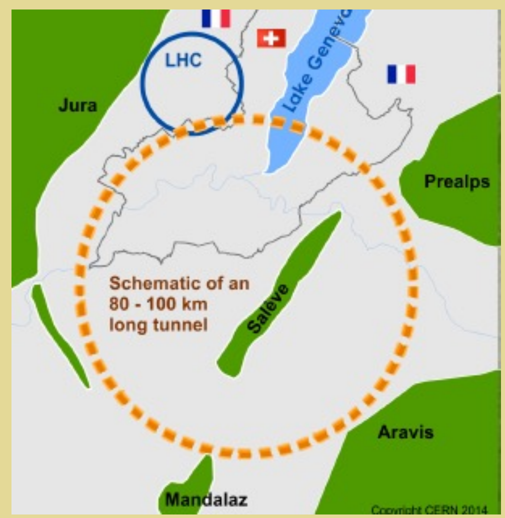
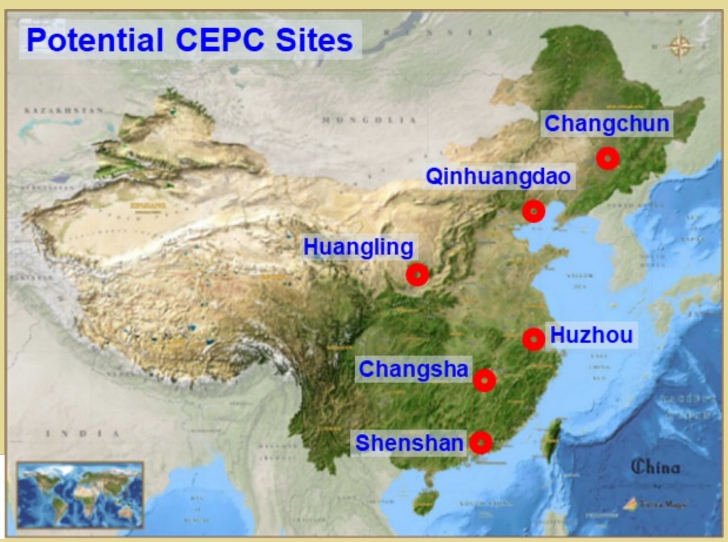
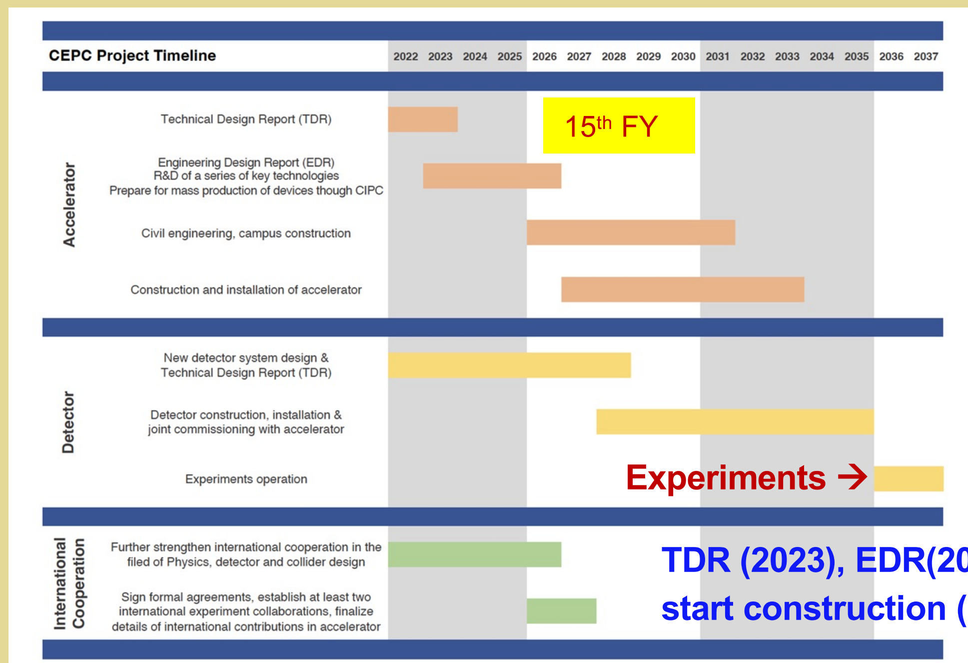


Future Colliders: CEPC

- The idea of CEPC was proposed in Sep. 2012, and quickly gained the momentum in IHEP and in the world.
- The CEPC aims to start operation in 2030's, as a Higgs (Z / W) factory in China.
- To run at $\sqrt{s}$ ~ 240 GeV, above the **ZH** production threshold for ≥1 M Higgs; at the **Z** pole for ~Tera Z;   at the $\mathbf{W^+W^-}$ pair and then $t\bar{t}$ pair production thresholds.
- Higgs, EW, flavor physics & QCD, probes of physics BSM.
- Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the far future.



Yuhui Li, CEPC 2023, Nanjing



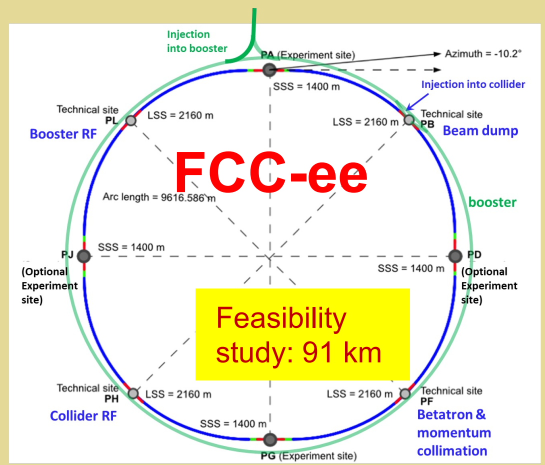
TDR (2023), EDR(2026), start construction (2027-8)

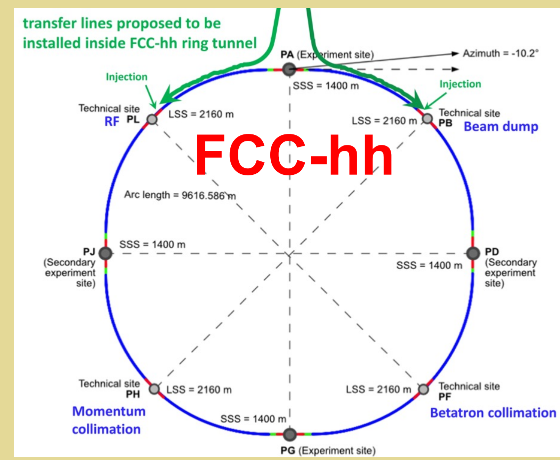
Future Colliders: FCC

comprehensive long-term program maximizing physics opportunities

European Strategy for Particle Physics 2020

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders (e.g. model-independent measurements of the Higgs couplings at FCC-hh thanks to input from FCC-ee; and FCC-hh as "energy upgrade" of FCC-ee)
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC





2020 - 2040 | **2045 - 2063** | **2070 - 2095**

Future Colliders: ILC & CLIC

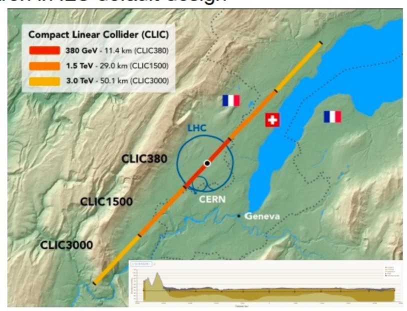
Linear Colliders

ILC & CLIC specs

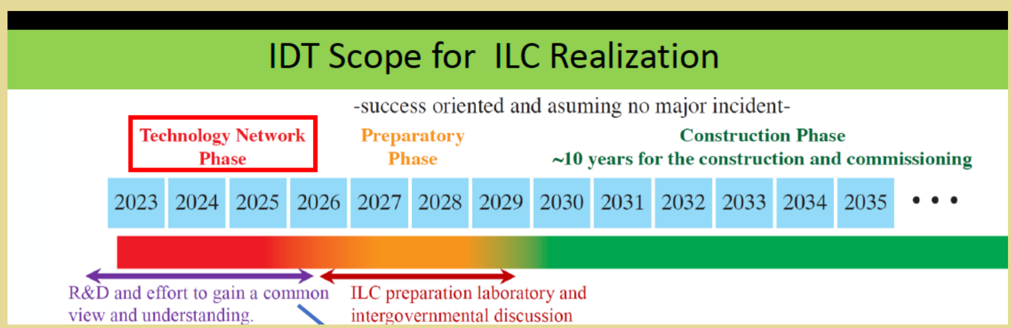
東京大学 THE UNIVERSITY OF TOKYO

- Energy extendability to TeV scale lies in the heart of linear colliders: ILC focuses on √s from 250 GeV to 1 TeV; CLIC 380 GeV to 3 TeV; keeping options to run at Z-pole ("GigaZ")
- Complementary approaches: "Warm" & "Cold" accelerating technologies; 72MeV/m @ CLIC380; 31.5MeV/m @ ILC250
- Polarized beams: both offering 80% for electron; 30% for positron in ILC default design

ILC250 ~ 20km

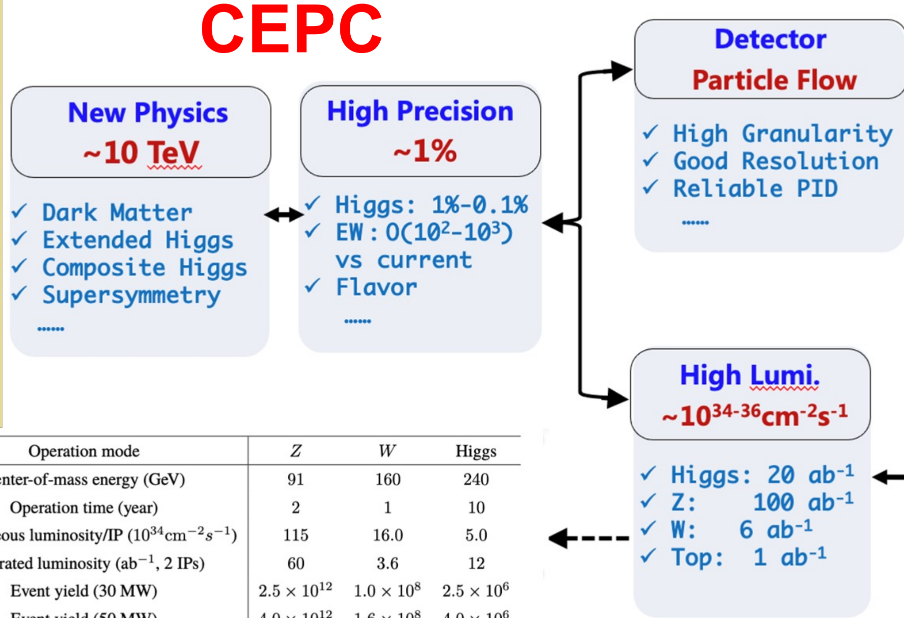


- MEXT (represents Japanese government) didn't approve the original Pre-Lab proposal [newsline]
- Not entirely negative: pointed out what directions to move forward ["hosting is not the problem", S.Asai]
- Support to carry out time-critical R&D that was in the Pre-Lab proposal
- A really encouraging sign from this April: a fact of 2 increase on KEK funding for ILC R&D by MEXT
- ILC Technology Network (ITN) is launched: memorandum between KEK & CERN signed
- Promotion under leadership by International Development Team (IDT), KEK and ILC-Japan



Future Colliders: Specs

CEPC



Operation mode	Z	W	Higgs
Center-of-mass energy (GeV)	91	160	240
Operation time (year)	2	1	10
Instantaneous luminosity/IP (10^{34}cm$^{-2}s^{-1}$)	115	16.0	5.0
Integrated luminosity (ab^{-1}, 2 IPs)	60	3.6	12
Event yield (30 MW)	2.5×10^{12}	1.0×10^{8}	2.5×10^{6}
Event yield (50 MW)	4.0×10^{12}	1.6×10^{8}	4.0×10^{6}

FCC-ee

double ring e^+e^- collider, with full-energy booster

2 or 4 interaction points

efficient $\mathcal{L}$ from Z to $t\bar{t}$

thanks to twin-aperture magnets, high-Q SRF, efficient RF power sources, top-up injection, etc.

>2.5 ab^{-1} / IP with ~0.5x10^{6} H / IP (3y)

>75 ab^{-1} / IP with ~2x10^{12} Z / IP (4y)

LEP: 17 x 10^{6} Z

ILC

	91 GeV	250 GeV	350 GeV	500 GeV	1000 GeV
$\int \mathcal{L}$ (ab^{-1})	0.1	2	0.2	4	8
duration (yr)	1.5	11	0.75	9	10
beam polarization (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(LL, LR, RL, RR) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)
δ_{ISR} (%)	10.8	11.7	12.0	12.4	13.0
δ_{BS} (%)	0.16	2.6	1.9	4.5	10.5

[arXiv:2203.07622]

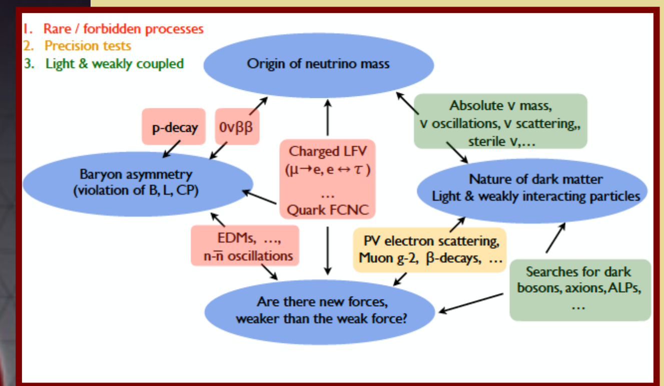
CLIC

	380 GeV	1.5 TeV	3 TeV
∫L (ab^{-1})	1	2.5	5
P(e-,e+;%)	80/0	80/0	80/0
(LR,RL)	(50,50)	(80,20)	(80,20)

[arXiv:2203.07622]

Frontiers

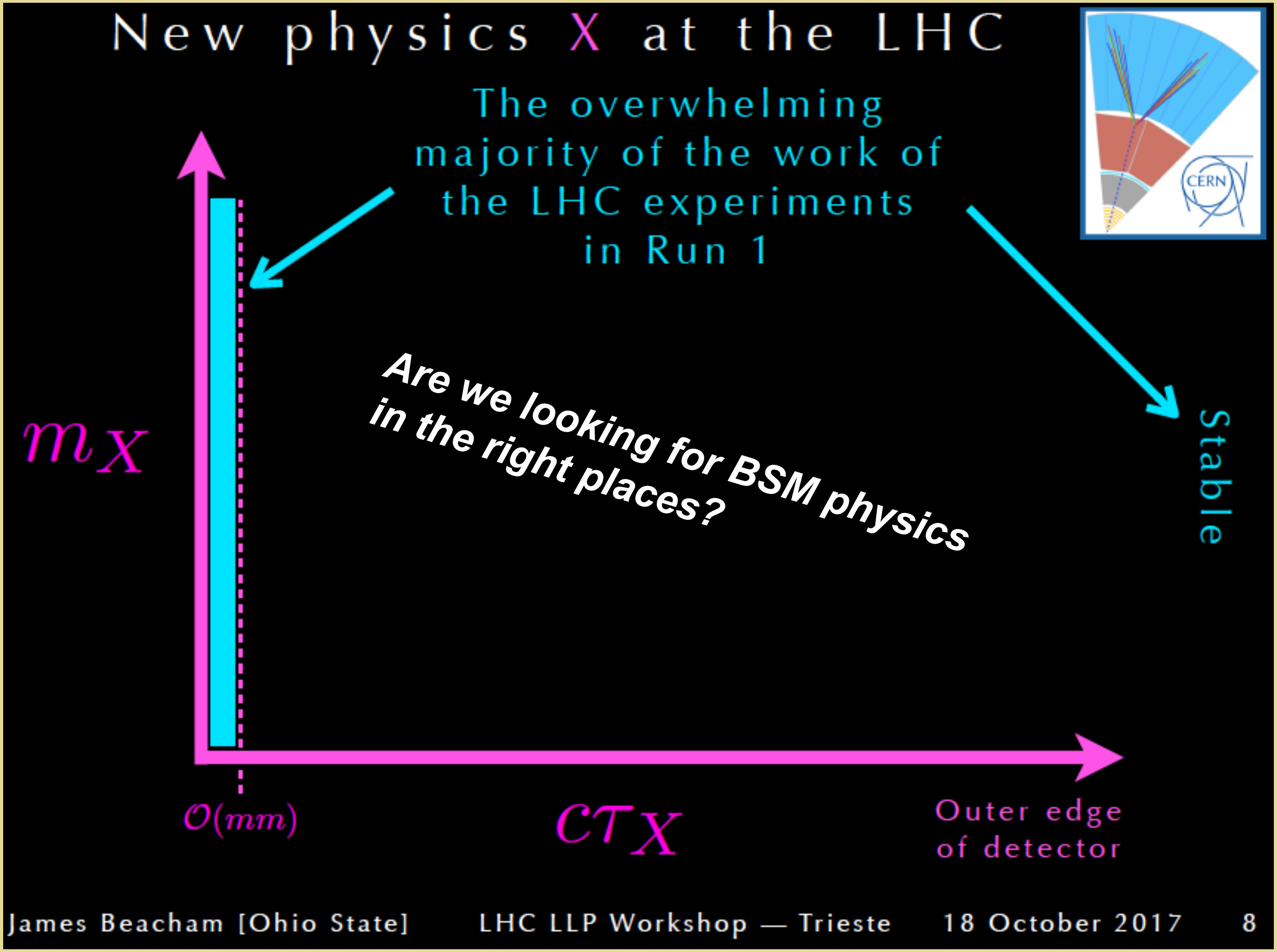
Lifetime Frontier



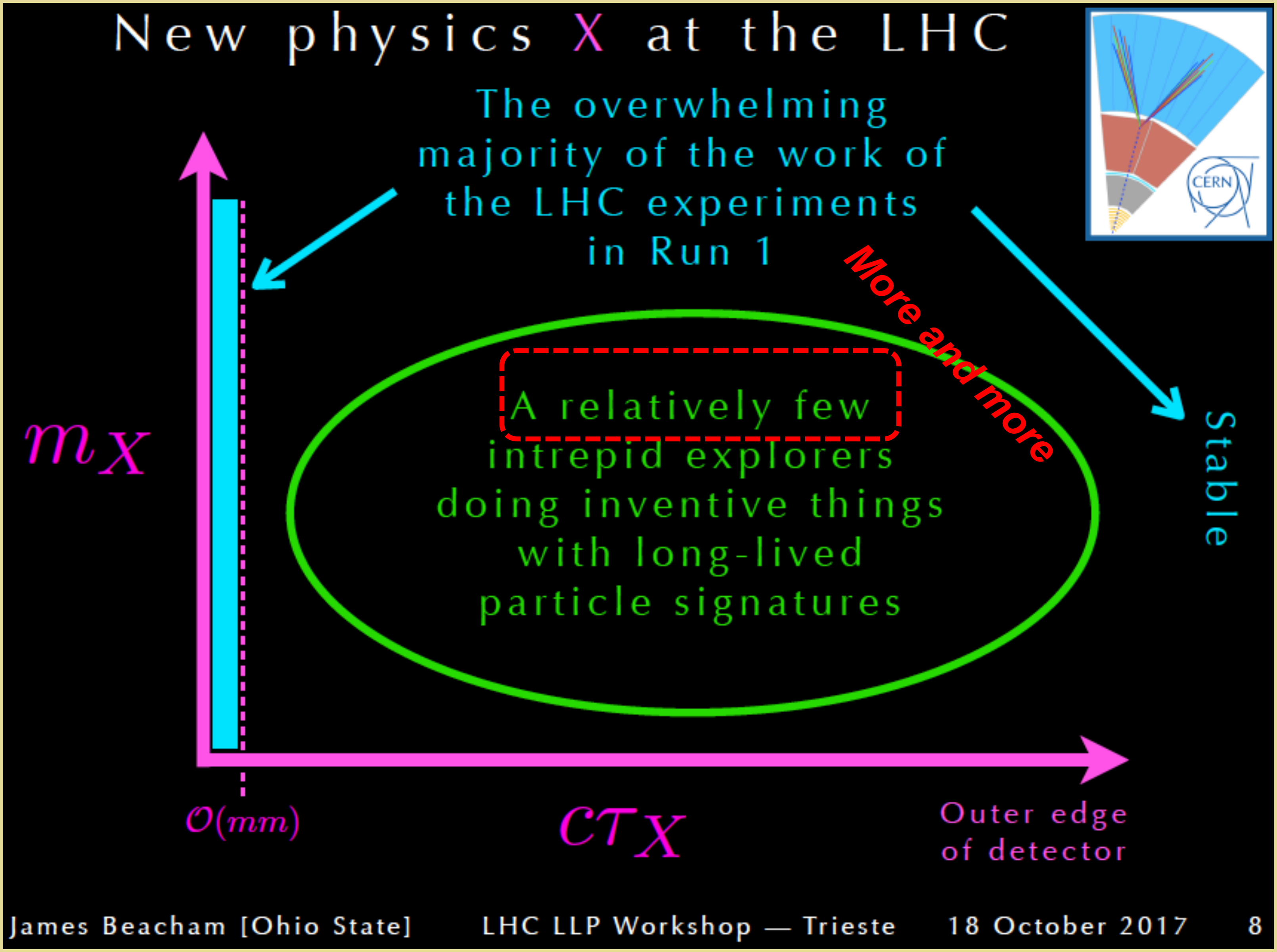
V. Cirigliano, this workshop

Historical artifact: US HEP vision → still useful mnemonic

A New LHC Emphasis: Lifetime Frontier



A New HEP Emphasis: Lifetime Frontier



Why Should BSM LLP's Exist ?

Large scale hierarchies & broken symmetries

$c\tau \longleftrightarrow \left(\frac{M_X}{M_Y}\right) >> 1$

- *Heavy (off shell) mediator: Hidden valley*

$c\tau \longleftrightarrow \left(\frac{M_X}{\Delta M}\right) >> 1$

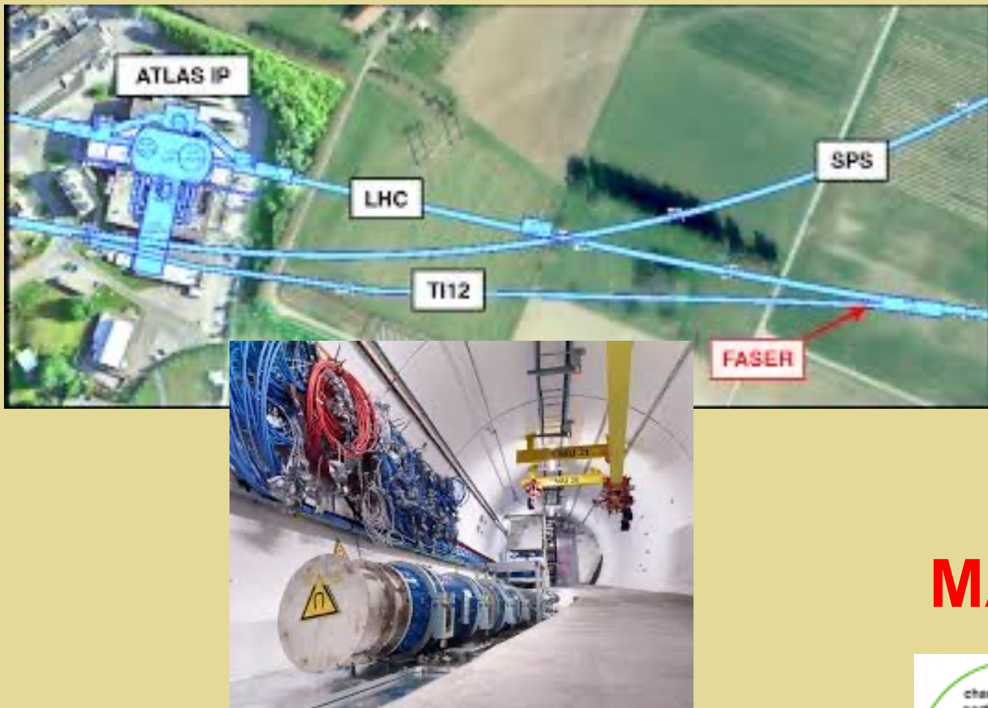
- *Compressed spectrum : Stealth SUSY*

$(c\tau)^{-1} \longleftrightarrow g_X << 1$

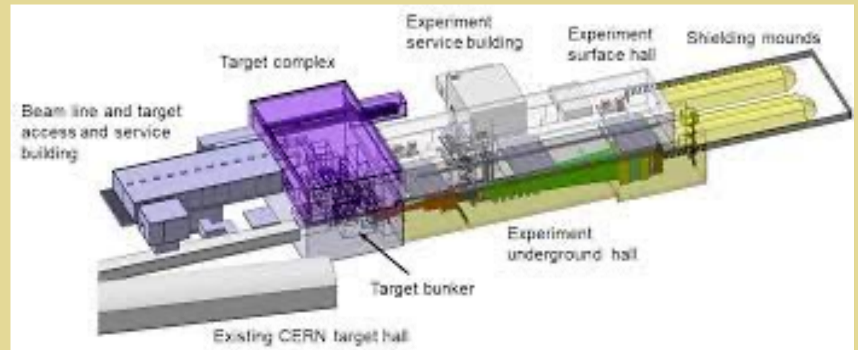
- *Broken symmetry: RPV SUSY*
- *Scale ratio: N_R , Z_D*

A New HEP Emphasis: Lifetime Frontier

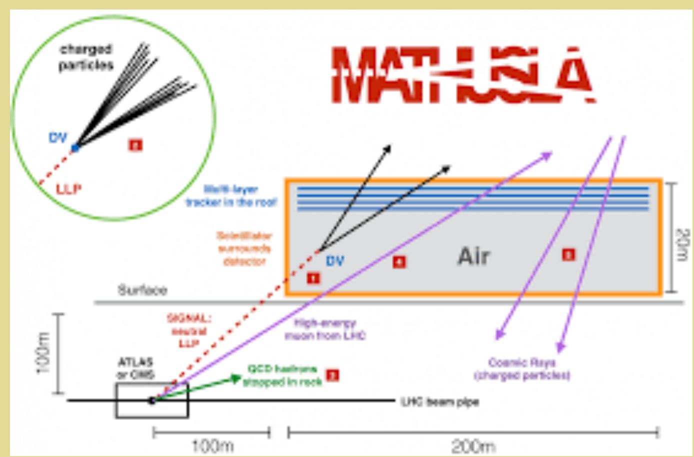
FASER



SHiP (proposed)

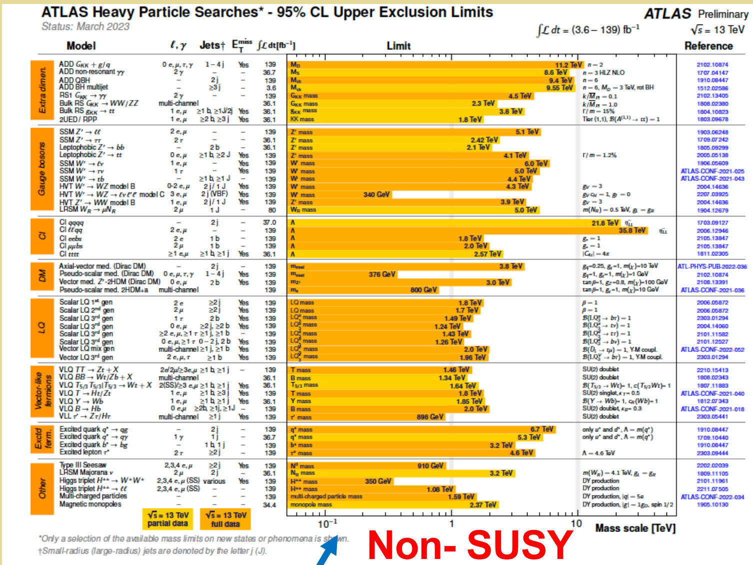


MATHUSLA (proposed)

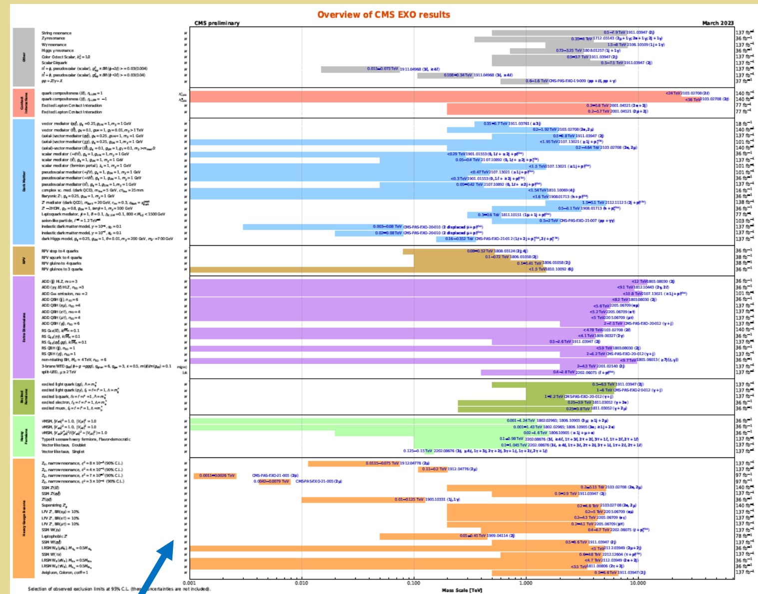


+ ATLAS, CMS, LHCb

Energy Frontier: LHC

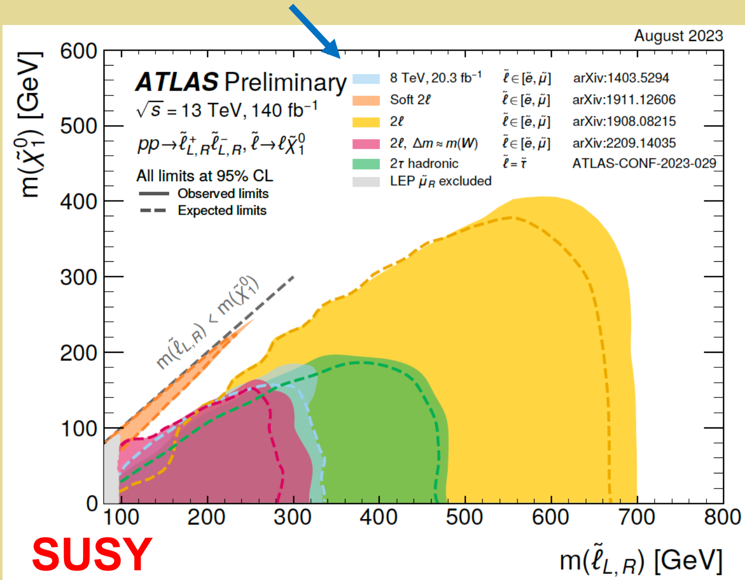


Non- SUSY

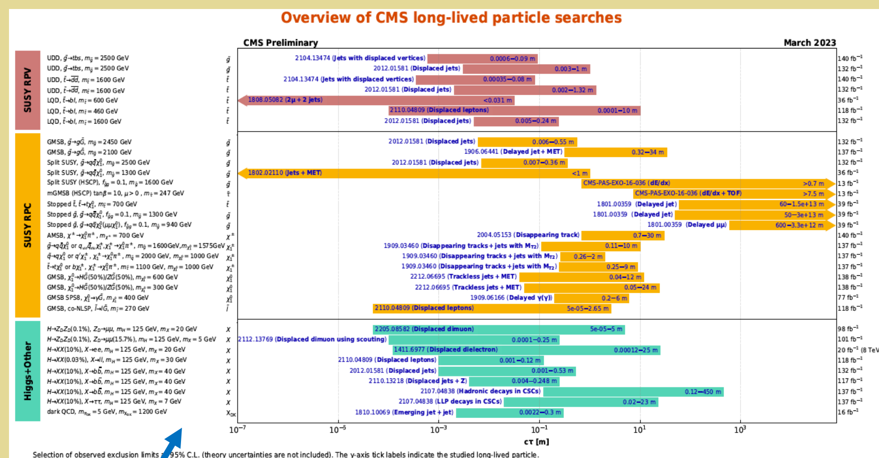


ATLAS: Heavy BSM (prompt)

CMS: Heavy BSM (prompt)

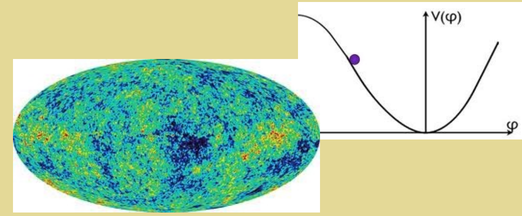


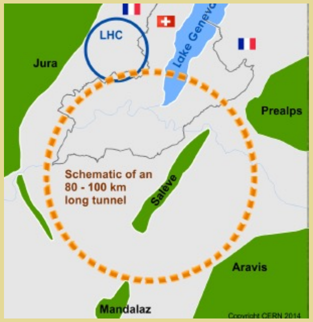
SUSY

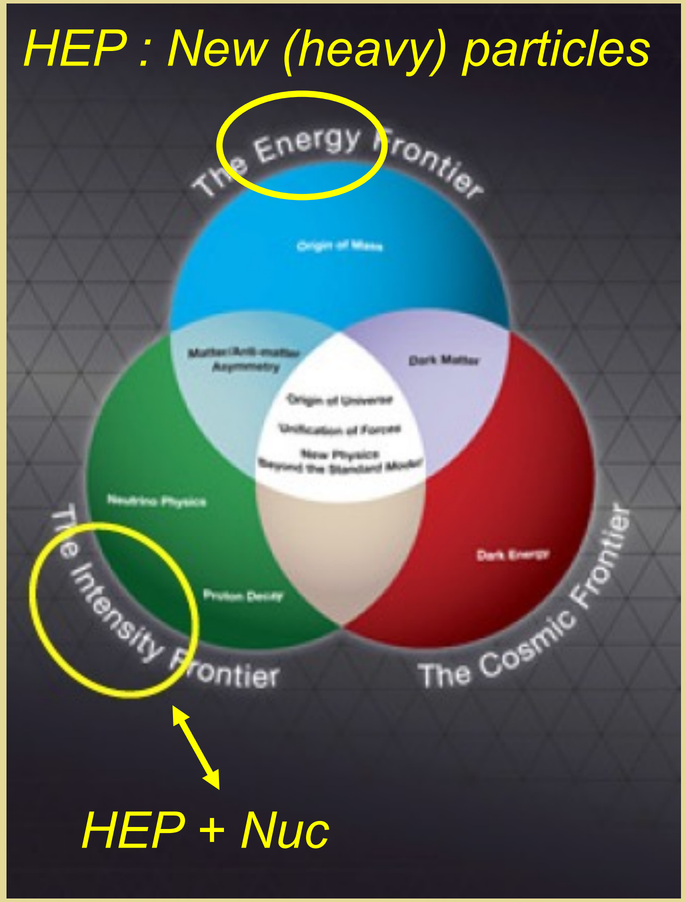


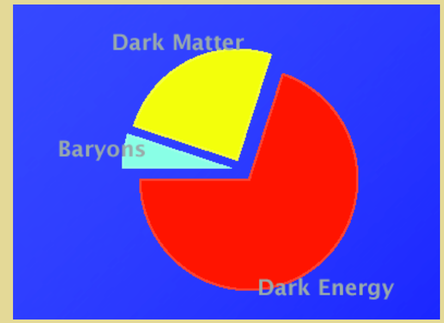
CMS: LLP

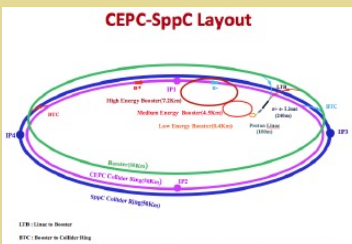
Frontiers

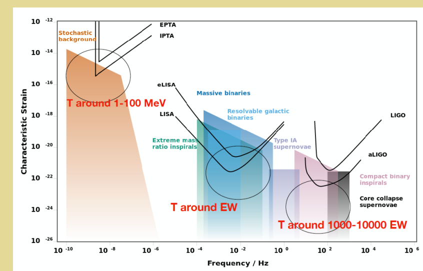








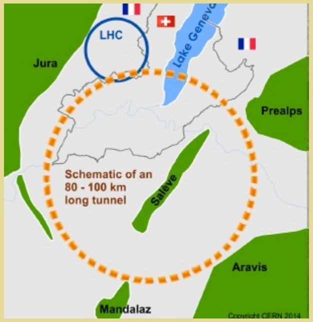


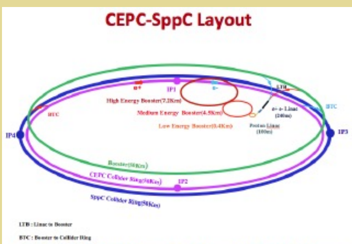


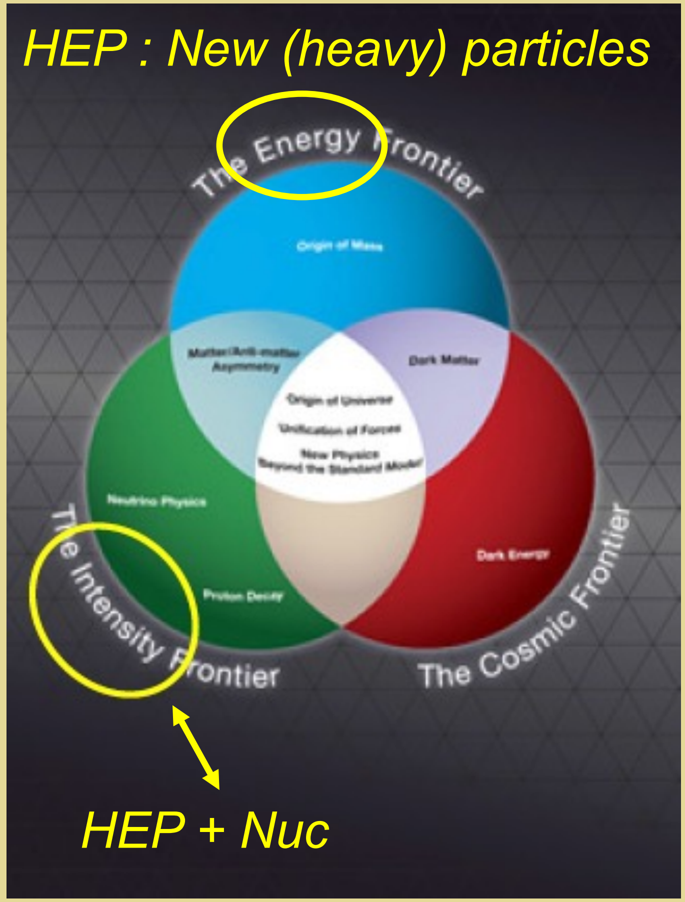
- *Precision tests: muon g-2, PV ee…*
- *Fundamental symmetry tests (CP, Lepton number…)*
- *Neutrino properties*
- *Flavor physics*

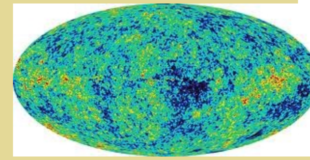
Historical artifact: US HEP vision → still useful mnemonic

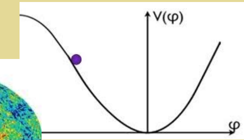
Frontiers

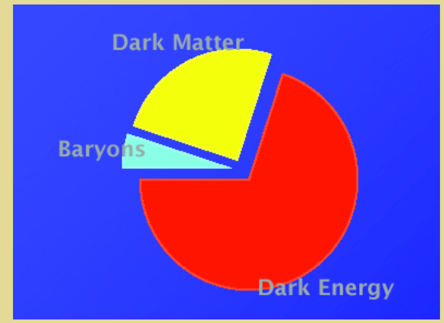


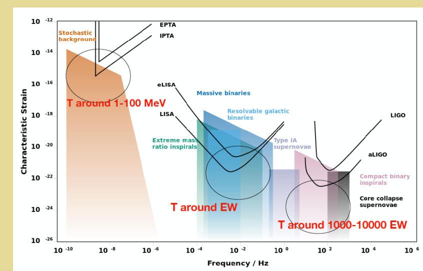












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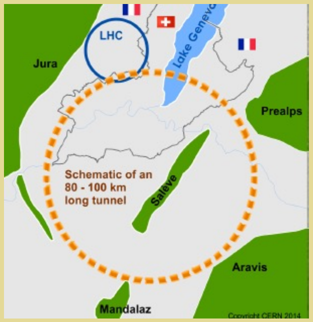
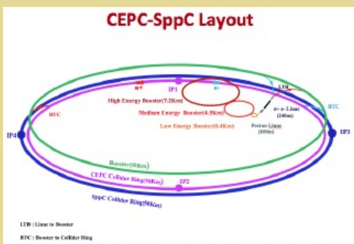
- ***Atomic, Molecular, Optical***
- ***Condensed Matter***

Frontiers





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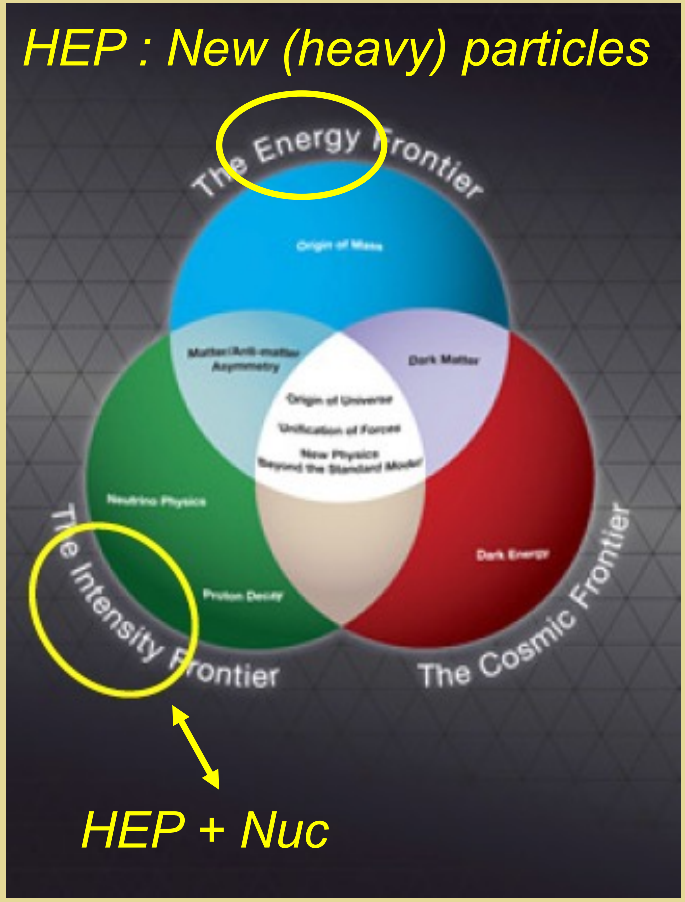

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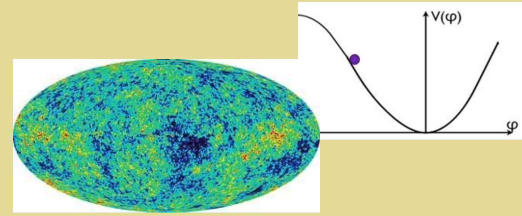
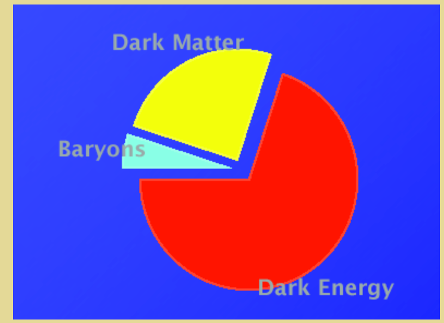
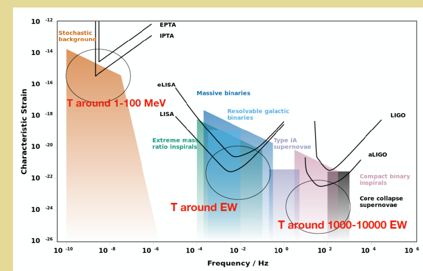




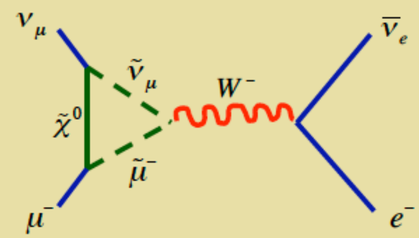


- ***Atomic, Molecular, Optical***
- ***Condensed Matter***

Intensity Frontier: BSM Footprints

New Symmetries

1. *Origin of Matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*



Discovery

Discovery

New particle searches: does the observed BSM "species" fit the footprints ?

Fundamental symmetry & precsion tests: draw inferences about BSM scenarios from a variety of measurements

Precision ~ BSM Mass Scale

Precision ~ Mass Scale

$$\delta_{NEW} = \frac{\Delta O^{NEW}}{O^{SM}} \approx \frac{\alpha}{\pi}\left(\frac{M}{\tilde{M}}\right)^2$$

Loop effect

$M = m_\mu$ $\delta \sim 2 \times 10^{-9}$

$\delta^{exp} \sim 1 \times 10^{-9}$

$M = M_W$ $\delta \sim 10^{-3}$

Interpretability

- *Precise, reliable SM predictions*
- *Comparison of a variety of observables*
- *Special cases: SM-forbidden or suppressed processes*

$\delta_{NEW} \sim C\ (M_W / \Lambda)^2$

$\Lambda < 1$ TeV (loop) *Above example*

$\Lambda \sim 10$ TeV (tree)

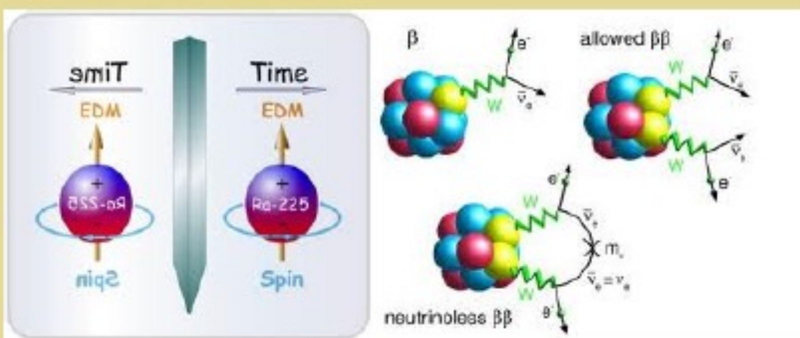
Nuclear Physics Connections

Lepton number

$0\nu\beta\beta$ Decay

EDMs

CP & T



Fundamental symmetries & neutrinos: "Intensity Frontier"

Precision tests

Muon g-2, PV ee, β decay…

More Matter than Antimatter ?

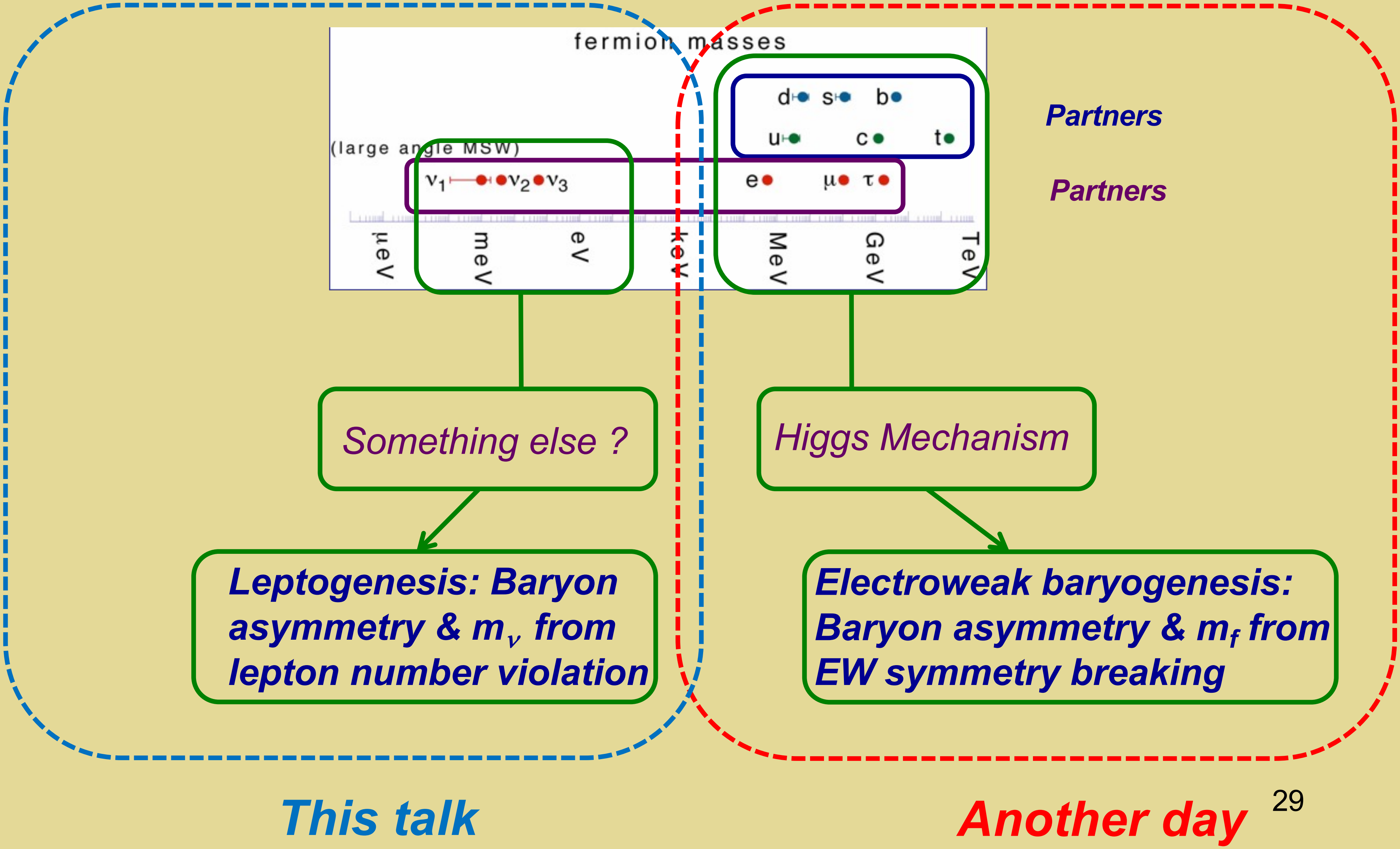
Paradigmatic inter-frontier challenge

Ingredients for Baryogenesis

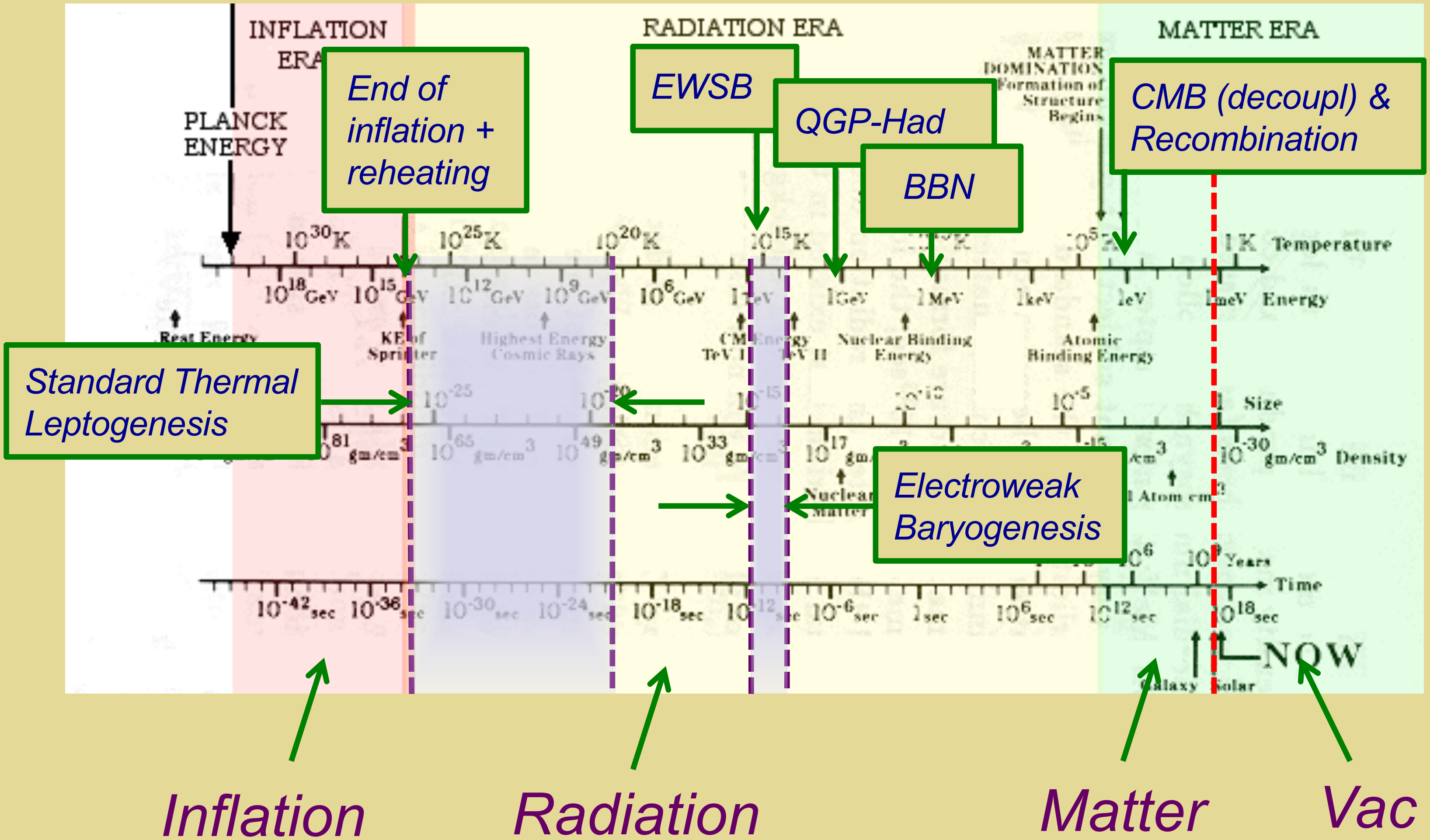
Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	*BSM*
• *B violation (sphalerons)*	✓	✓
• *C & CP violation*	✗	✓
• *Out-of-equilibrium or CPT violation*	✗	✓

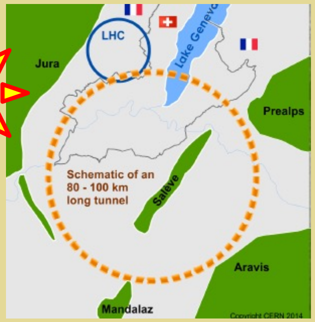
Fermion Masses & Baryon Asymmetry

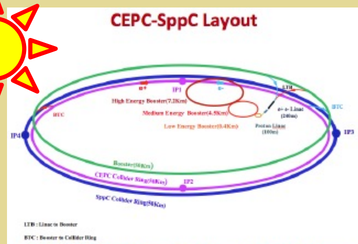


Cosmic History

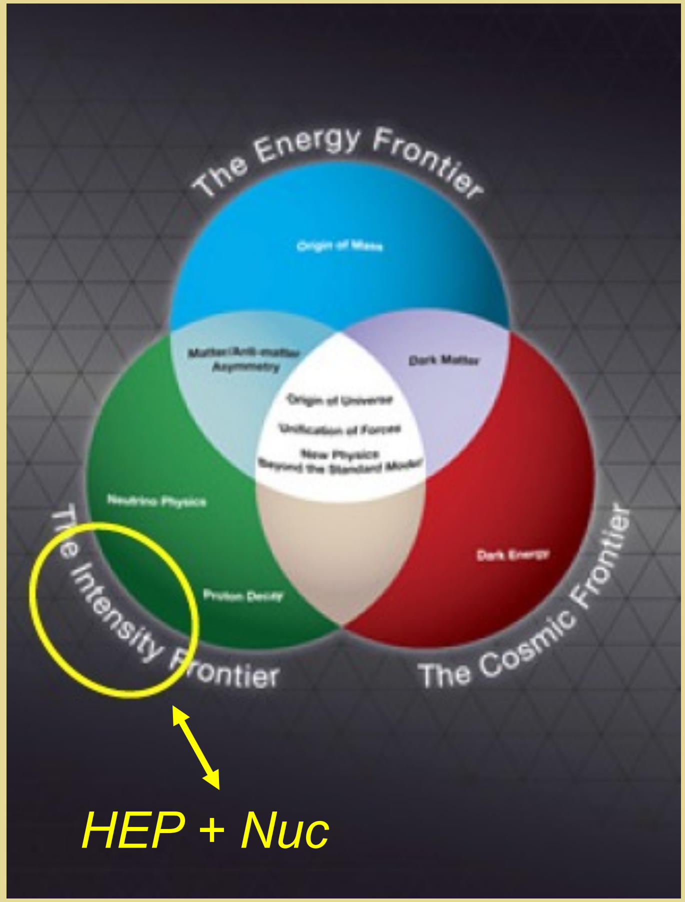


Frontiers

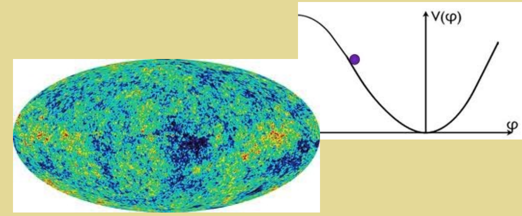


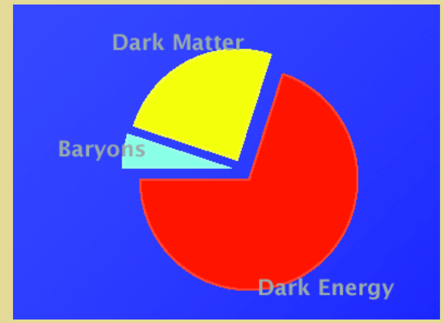


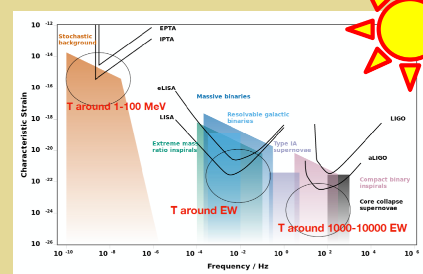
- *Precision tests: muon g-2, PV ee…*
  Fundamental symmetry tests (CP, Lepton number…)
- *Neutrino properties*
- *Flavor physics*



Historical artifact: US HEP vision → still useful mnemonic



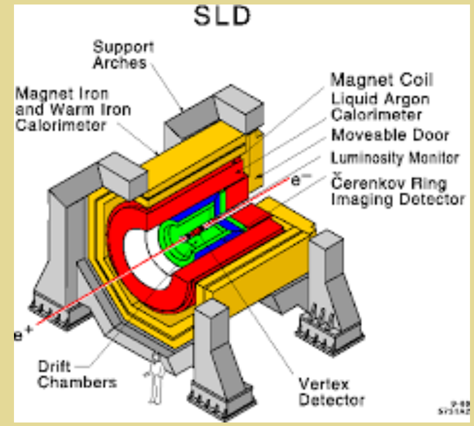


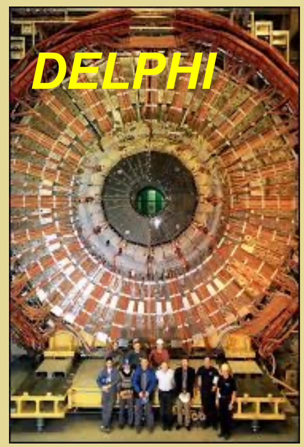


- ***Atomic, Molecular, Optical***
- ***Condensed Matter***

II. Electroweak Precision Tests

High Energy EW Precision



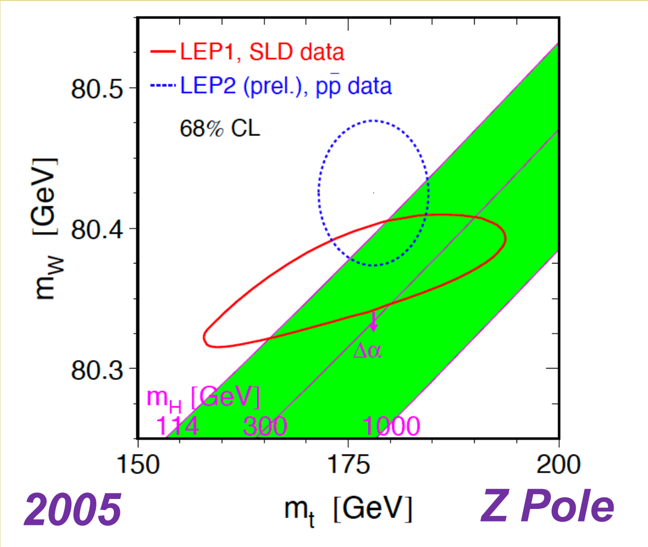


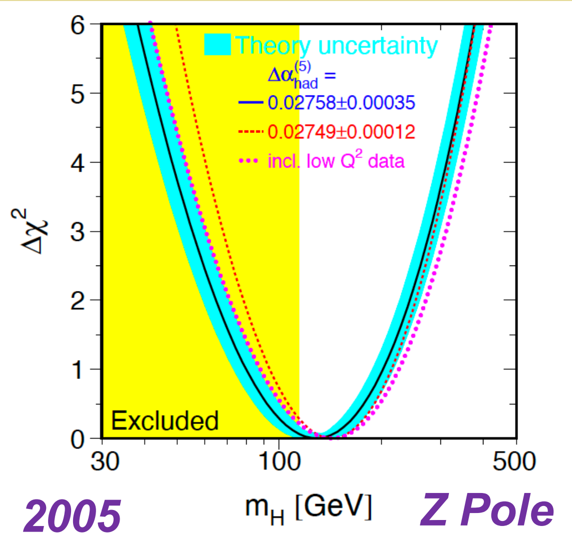
+ polarization

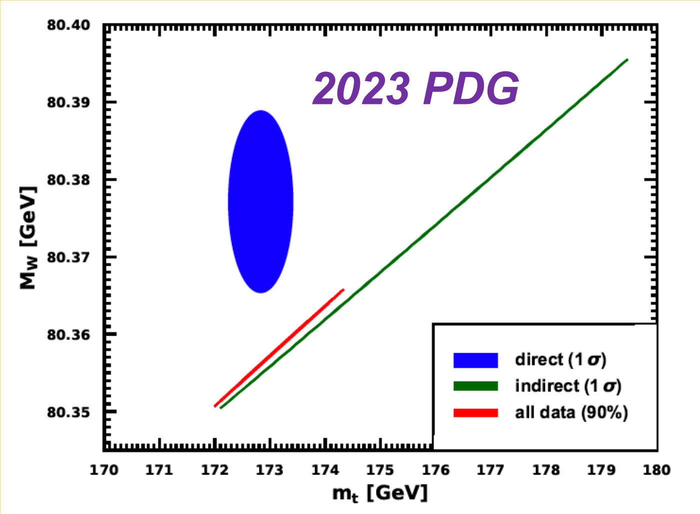
LEP: 17 x 10^6 Z

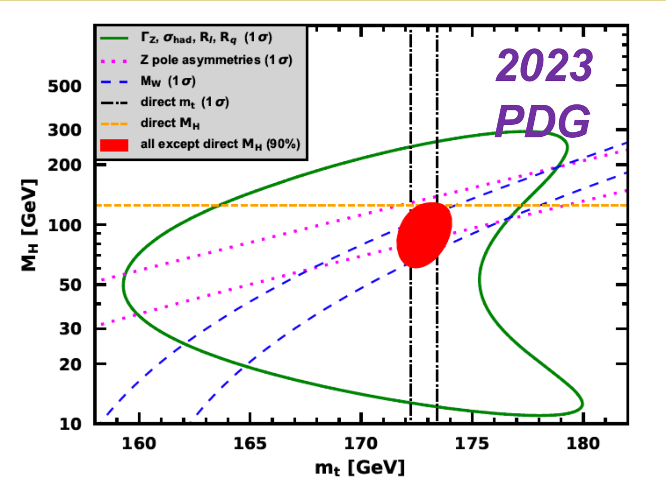
SLC: 0.6 x 10^6 Z

High Energy EW Precision









High Energy EW Precision

2023 PDG

Quantity	Value	Standard Model	Pull
m_t [GeV]	172.83 ± 0.59	173.13 ± 0.56	-0.5
M_H [GeV]	125.30 ± 0.13	125.30 ± 0.13	0.0
Γ_H [MeV]	$3.2^{+2.4}_{-1.7}$	4.12 ± 0.05	-0.4
M_W [GeV]	80.387 ± 0.016	80.360 ± 0.006	1.7
	80.376 ± 0.033		0.5
	80.366 ± 0.017		0.4
Γ_W [GeV]	2.046 ± 0.049	2.089 ± 0.001	-0.9
	2.195 ± 0.083		1.3
$\mathcal{B}(W \to \text{hadrons})$	0.6736 ± 0.0018	0.6751 ± 0.0001	-0.8
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0001	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0002	1.3
$Q_W(p)$	0.0719 ± 0.0045	0.0709 ± 0.0002	0.2
$Q_W(\text{Cs})$	-72.82 ± 0.42	-73.24 ± 0.01	1.0
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.90 ± 0.02	0.1
$\hat{s}_Z^2(\text{eDIS})$	0.2299 ± 0.0043	0.23122 ± 0.00004	-0.3
τ_τ [fs]	290.75 ± 0.36	288.90 ± 2.24	0.8
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4510.88 \pm 0.60) \times 10^{-9}$	$(4508.61 \pm 0.03) \times 10^{-9}$	3.8

High Energy EW Precision

2023 PDG

LEP: 17 x 10^6 Z

Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1882 ± 0.0020	-0.3
Γ_Z [GeV]	2.4955 ± 0.0023	2.4941 ± 0.0009	0.6
σ_{had} [nb]	41.481 ± 0.033	41.482 ± 0.008	0.0
R_e	20.804 ± 0.050	20.736 ± 0.010	1.4
R_μ	20.784 ± 0.034	20.736 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.781 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01617 ± 0.00007	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0996 ± 0.0016	0.1029 ± 0.0002	-2.0
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0002	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1030 ± 0.0002	-0.4
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23155 ± 0.00004	0.7
	0.23148 ± 0.00033		-0.2
	0.23129 ± 0.00033		-0.8
A_e	0.15138 ± 0.00216	0.1468 ± 0.0003	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

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LEP: 17 x 10^6 Z

SMEFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2}\mathcal{O}_{6,i} \qquad \delta \sim c_i \frac{v^2}{M^2}$$

Dimensions six operators			$m_h = 115$ GeV $c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB}$	=	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10
$\mathcal{O}_H$	=	$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6
$\mathcal{O}_{LL}$	=	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1
$\mathcal{O}'_{HL}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	8.4	8.8
$\mathcal{O}'_{HQ}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8
$\mathcal{O}_{HL}$	=	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2
$\mathcal{O}_{HQ}$	=	$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4
$\mathcal{O}_{HE}$	=	$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7
$\mathcal{O}_{HU}$	=	$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3
$\mathcal{O}_{HD}$	=	$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5

M_{MIN} : Barbieri & Strumia '00

→ "Little Hierarchy Problem"

BSM physics @ M ~ 10 TeV ?

High Energy EW Precision

2023 PDG

LEP: 17 x 10^6 Z

Future $e^+ e^-$: few x 10^{12} Z

~ 300 x better stat precision

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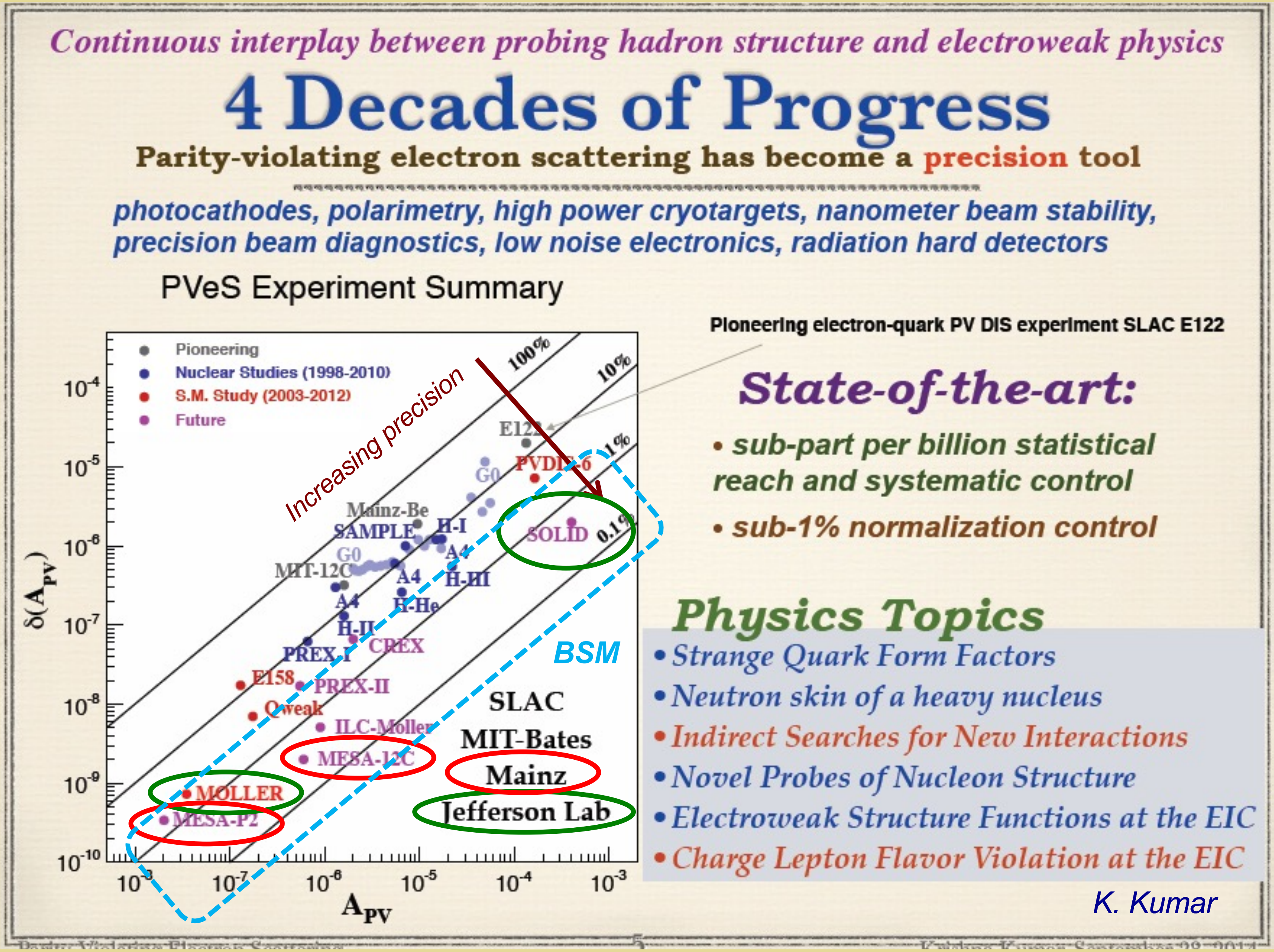
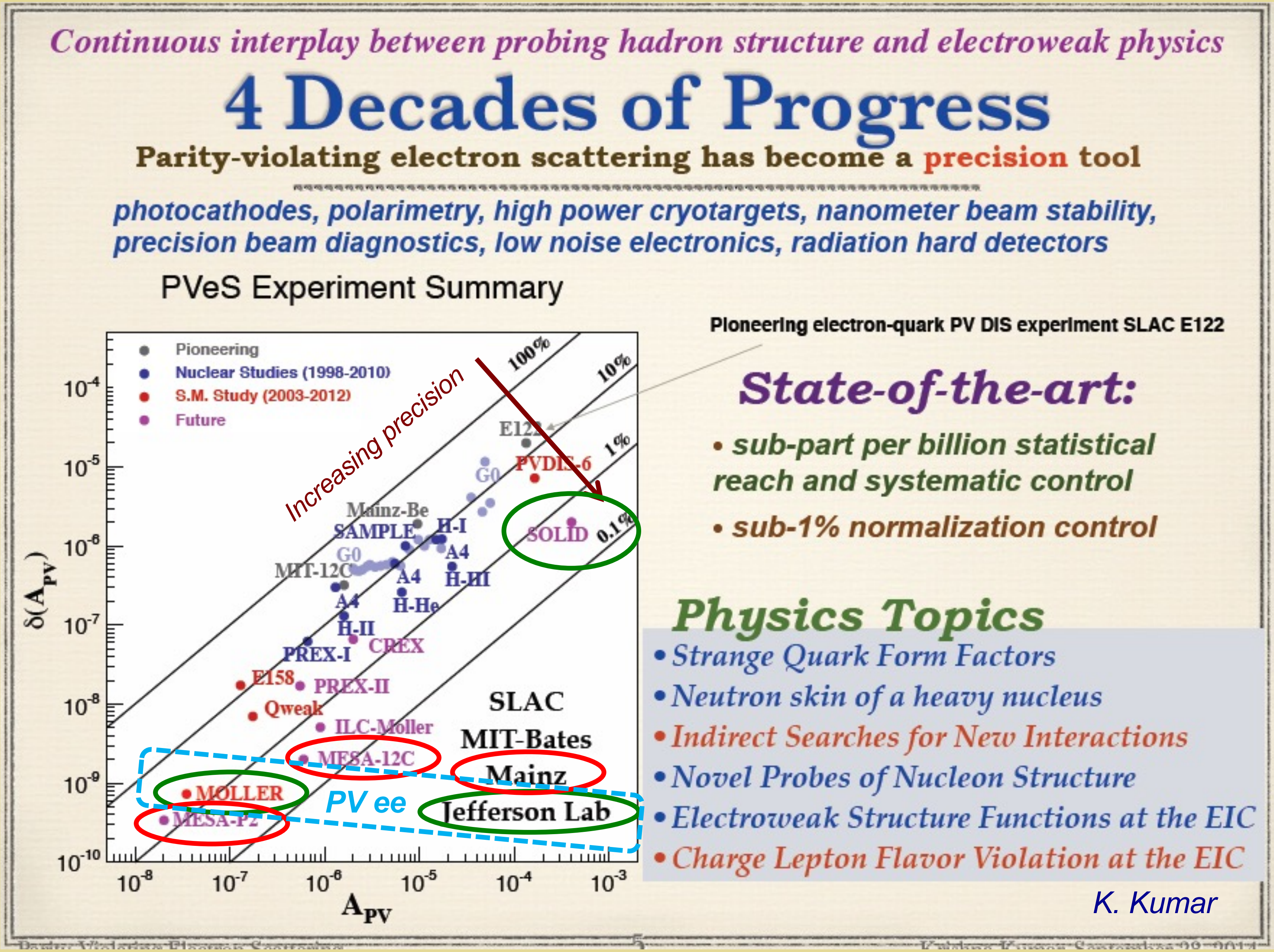
Low Energy: PV Electron Scattering



Low Energy: PV Electron Scattering

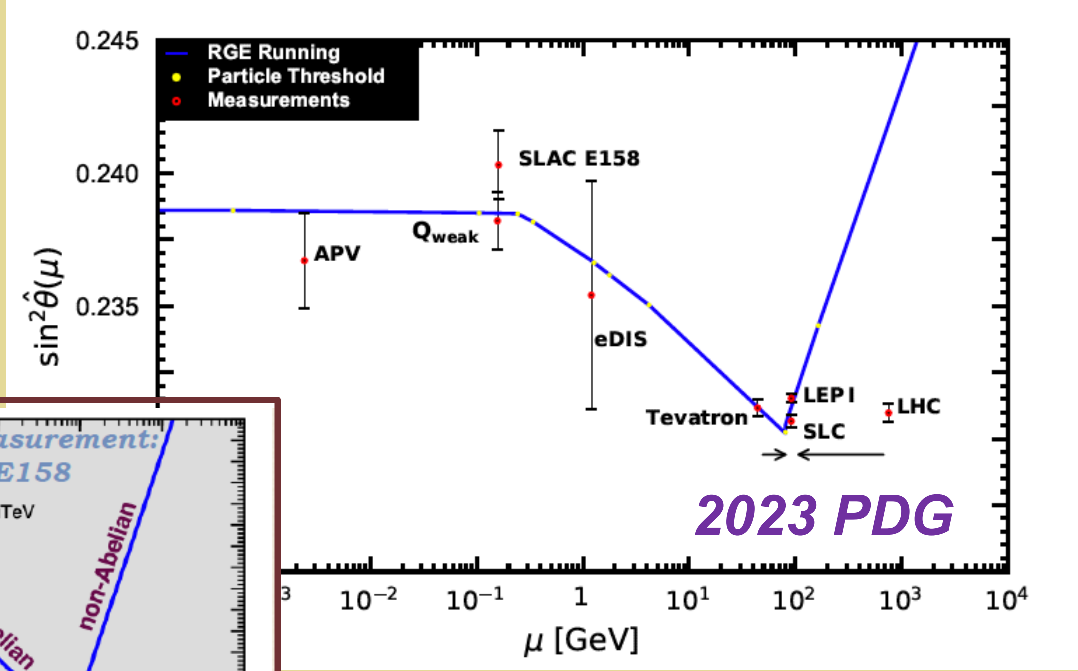


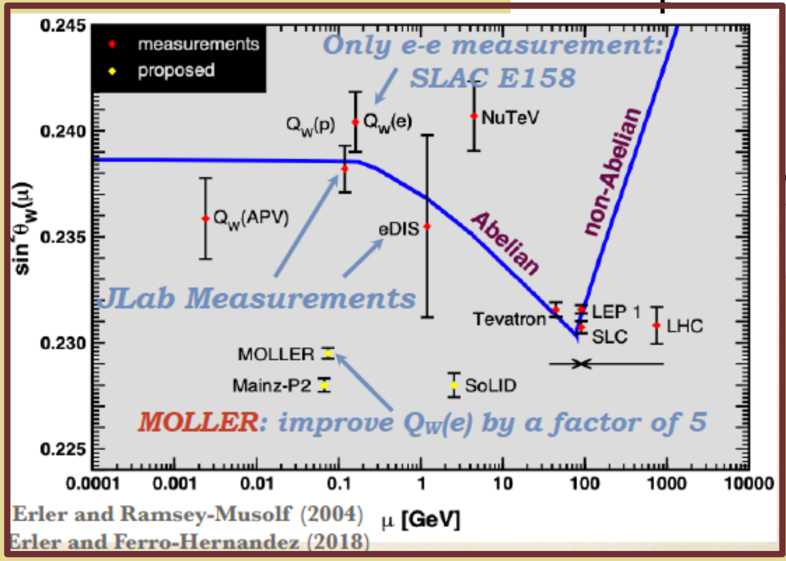
High Energy – Low Energy Interplay

MOLLER Experiment

$\delta(Q^e_W) = \pm\, 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

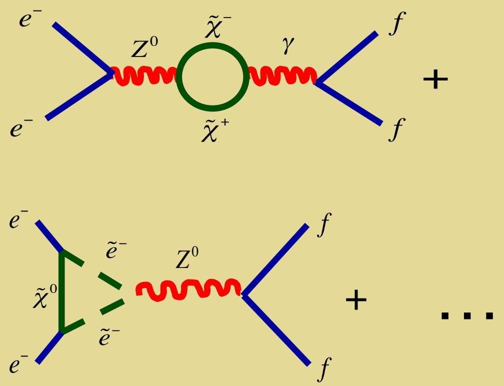
Exp't precision (goal)



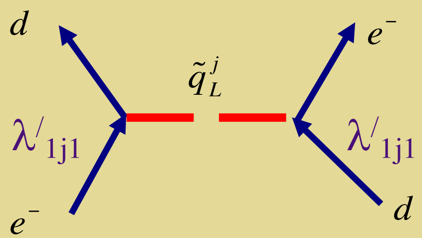


Deviations: BSM "Footprints"

SUSY

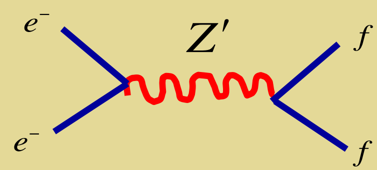


Radiative Corrections



RPV

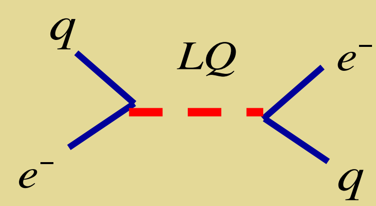
Z' Bosons



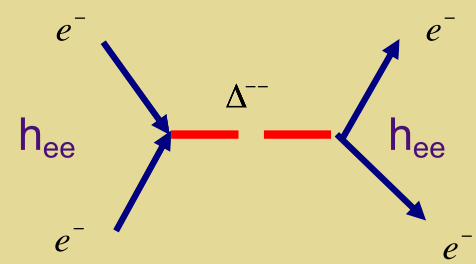
Semi-leptonic only

Moller only

Leptoquarks

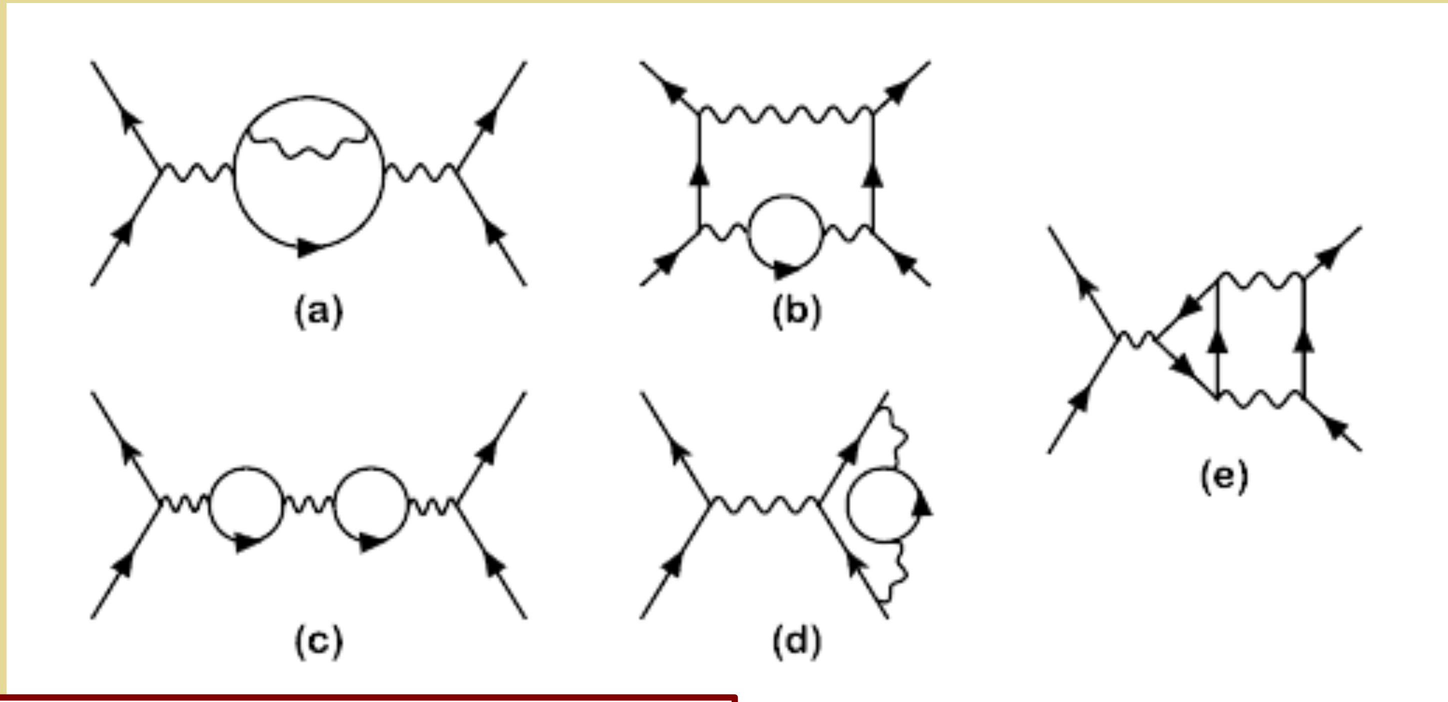


Doubly Charged Scalars



Two-Loop EW Radiative Corrections

Closed fermion loops: gauge invariant



PHYSICAL REVIEW LETTERS **126**, 131801 (2021)

Parity-Violating Møller Scattering at Next-to-Next-to-Leading Order: Closed Fermion Loops

Yong Du,[1,*] Ayres Freitas,[2,†] Hiren H. Patel,[3,‡] and Michael J. Ramsey-Musolf[4,1,5,§]

[1]*Amherst Center for Fundamental Interactions, Physics Department, University of Massachusetts Amherst, Amherst, Massachusetts 01003 USA*
[2]*Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT-PACC), Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[3]*Department of Physics and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, California 95064, USA*
[4]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[5]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125 USA*

(Received 17 January 2020; revised 22 July 2020; accepted 23 February 2021; published 29 March 2021)

Two-Loop EW Radiative Corrections

$\delta(Q^e{}_W) = \pm\, 2.1\ \%\ (\text{stat.}) \pm 1.1\ \%\ (\text{syst.})$ — *Exp't precision (goal)*

BSM probe !

Quantity	Contribution ($\times 10^{-3}$)	% shift *
$1 - 4\sin^2\theta_W$	$+74.4$	
$\Delta Q^e_{W(1,1)}$	-29.0	- 39%
$\Delta Q^e_{W(1,0)}$	$+\ 3.1$	+ 4%
$\Delta Q^e_{W(2,2)}$	$-\ 2.12^{+0.014}_{-0.024}$	- 4.4%
$\Delta Q^e_{W(2,1)}$	$+\ 1.65^{+0.010}_{-0.007}$	+ 3.4%
$\Delta Q^e_{W(2,0)}$	$\pm\ 0.18$ (estimate)	+/- 0.4%

Must ! (−4.4%, +3.4%)

Safe ! (+/- 0.4%)

Loop order

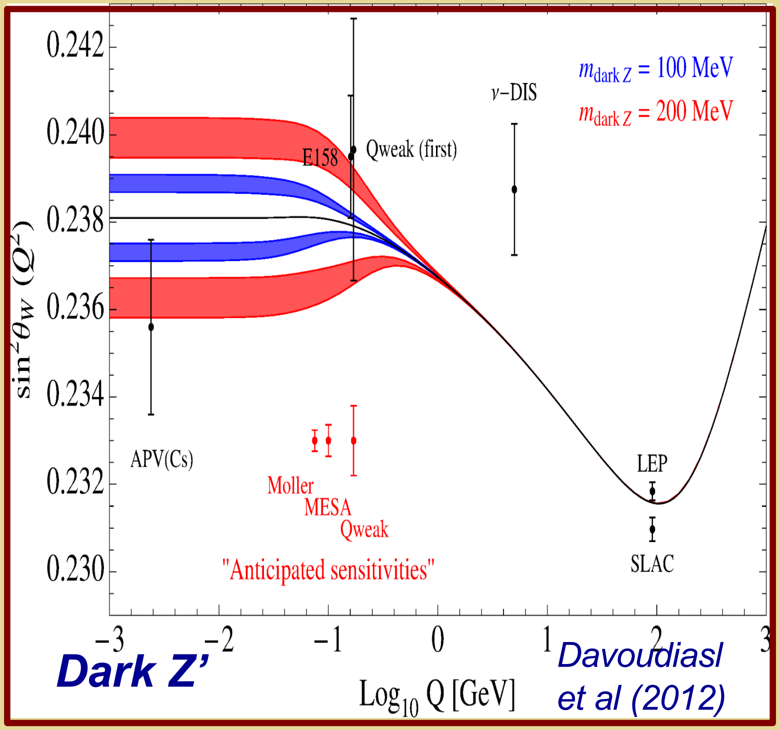
# of closed fermion loops

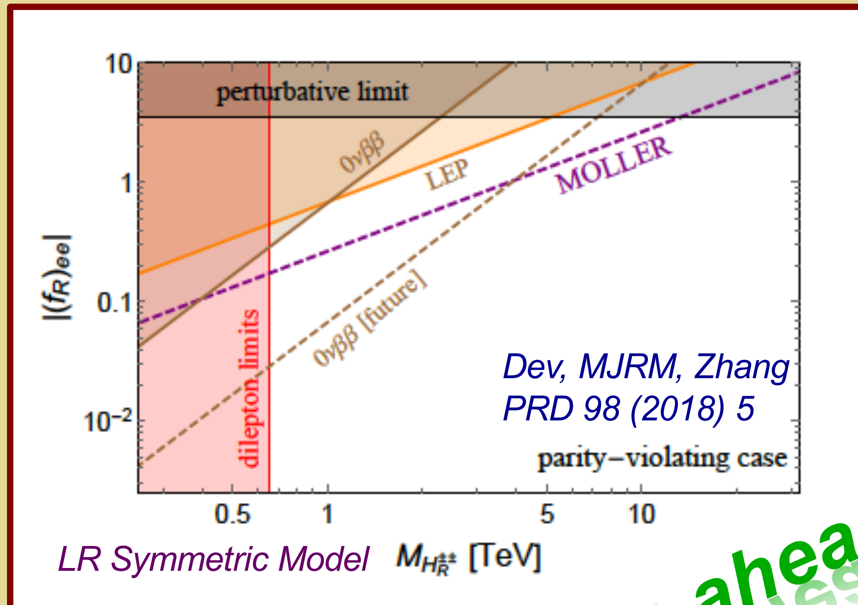
** Relative to preceding order*

Du, Freitas, Patel, MJRM PRL 126 (2021) 131801 [1912.08220]

PV Moller Scattering

Search for additional neutral weak force that is inaccessible to the Large Hadron Collider



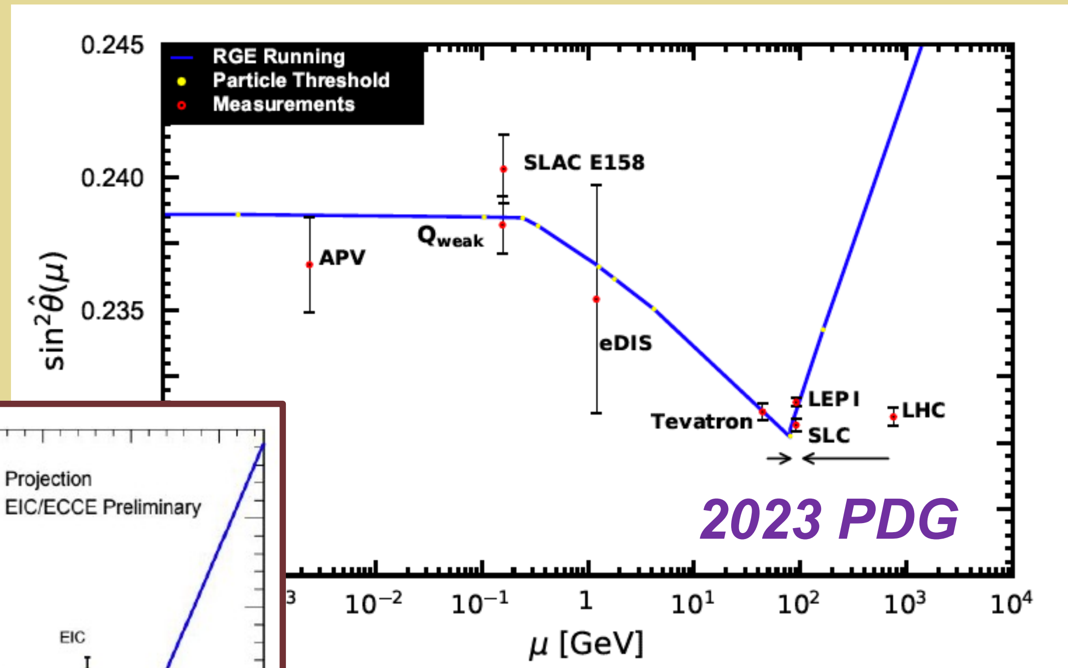


Update ahead

Dark Sector: Z'

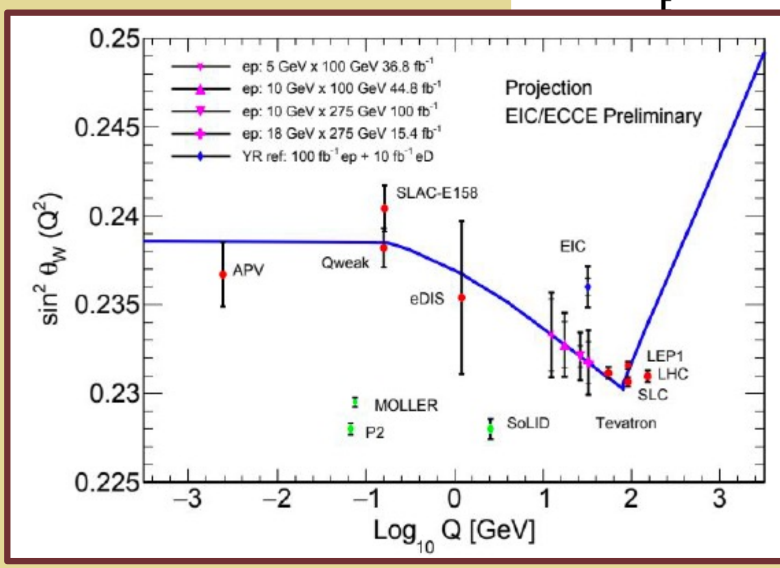
Type II Seesaw: H^{++}

High Energy – Low Energy Interplay



2023 PDG

EIC Prospective



M. Nycz, this meeting

BSM “value added” ?

The Competition : "Short Term"

Ultra-Precise Weak Mixing Angle

- Make a "cut" on measurements with uncertainty ~ 0.0003X or better

Exp.	$\sin^2\theta_{eff}^{lept}$	Ref.	
LEP+SLD: A_{FB}^{B}	0.23221±0.00029		*b-quarks*
SLD: A_i	0.23098±0.00026		*light-quarks*
*Tevatron	0.23148±0.00033	PRD 2016	*light-quarks*
ATLAS 8 TeV 20.2 fb^{-1}	0.23140±0.00036 *ATL–CONF–2018–037*	unpublished	*light-quarks* $\ell^+\ell^-$

- CMS is getting ready to release their 13 TeV data
  - *Expected uncertainty: 0.00024*
  - *This would be an extraordinary achievement!*

Special thanks to Arie Bodek

theory $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.23122(4)$

expt. $\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.23116(13)$

- Ultimate sensitivity at LHC
  - *There are plans to improve on the above by a factor of 2, but only after the HL-LHC upgrade*
- Window for MOLLER and P2 to contribute!
  - *Combined would be 0.00020, but must achieve the final result by 2030…*
  - *Must try to get to design goals!*

K. Kumar, this meeting

The Competition : Longer Term

2023 PDG

LEP: 17 x 10^6 Z

Future $e^+ e^-$:
few x 10^{12} Z

~ 300 x better stat precision

Caveat: SM theory challenge

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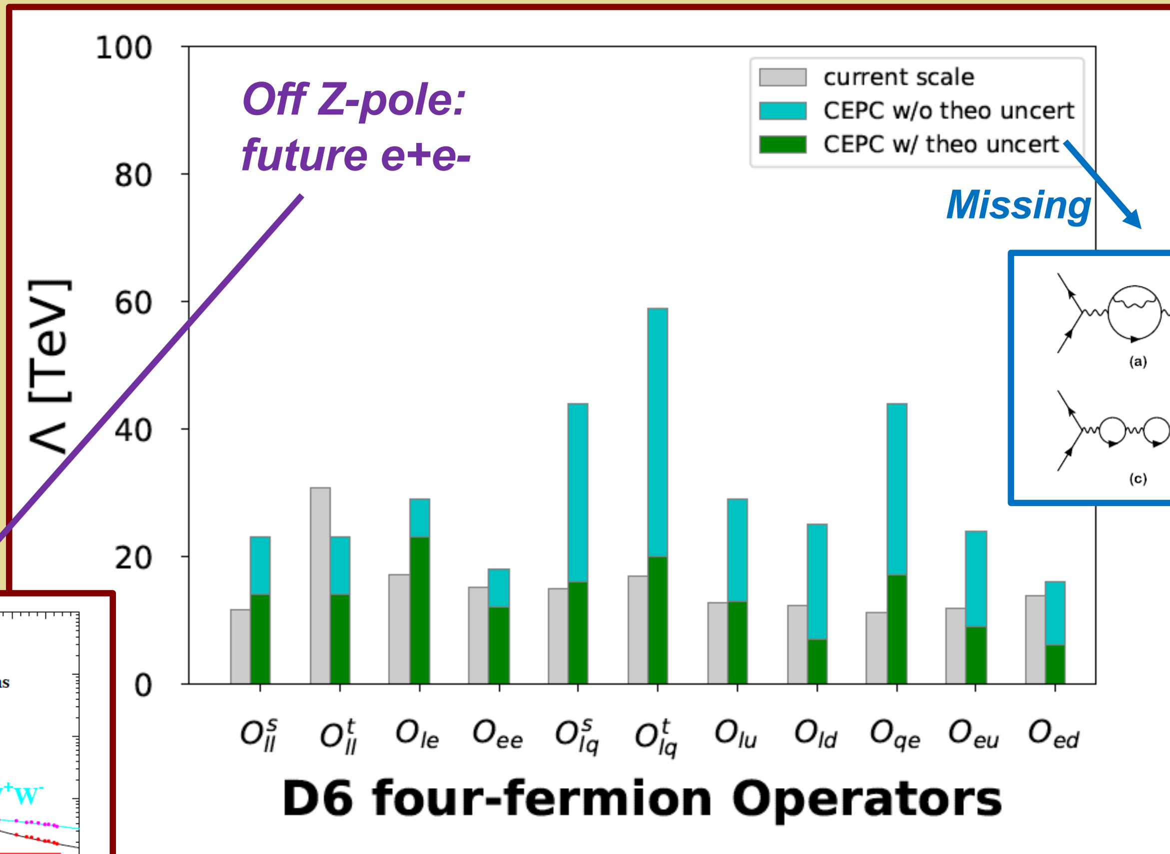
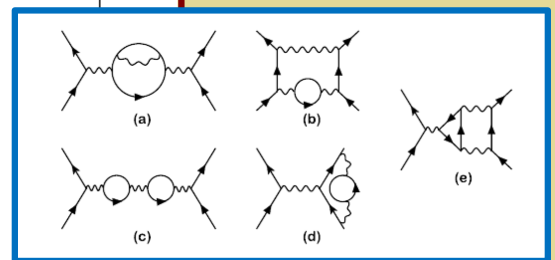
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1030 ± 0.0002	-0.4
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23155 ± 0.00004	0.7
	0.23148 ± 0.00033		-0.2
	0.23129 ± 0.00033		-0.8
A_e	0.15138 ± 0.00216	0.1468 ± 0.0003	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

The Competition : Longer Term





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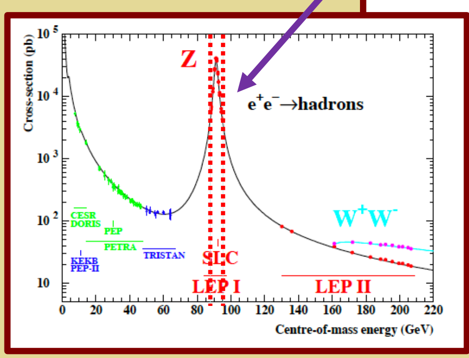


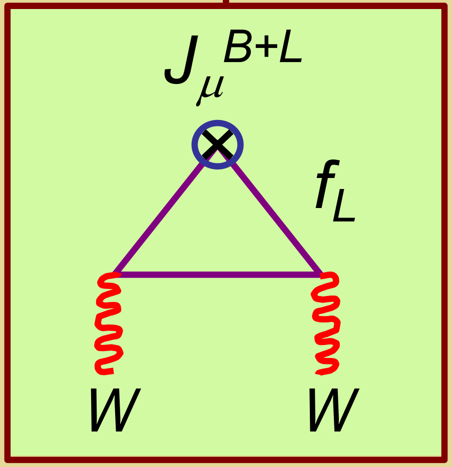
Shao-Feng Ge, MJRM, Zhuo-Ni Qian, Jia Zhou
2024.NNNN [hep-ph]

III. What is the LN Violation Mass Scale ?

SM: B+L Not Conserved

B+L Anomaly

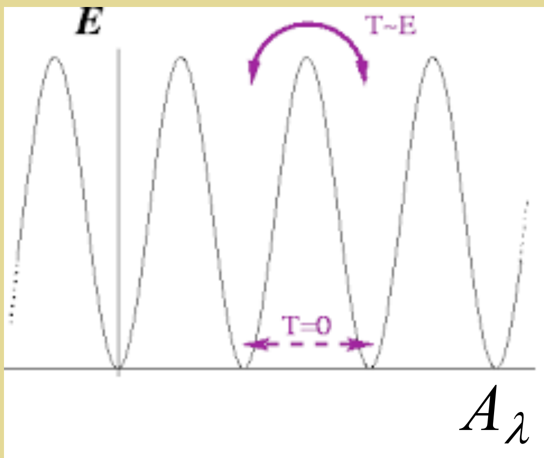
$$\partial^\mu J_\mu^{B+L} = \frac{2N_F}{32\pi^2} \times \left\{ g^2 W^a_{\mu\nu} \widetilde{W}^{\mu\nu\, a} - g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu} \right\}$$

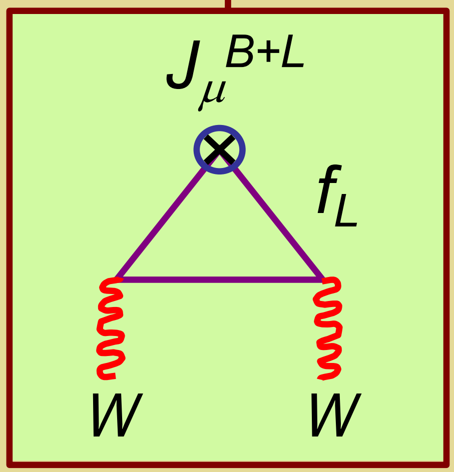


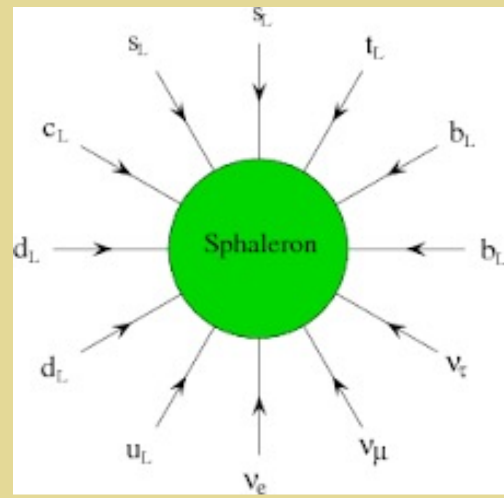
SM B+L Violation & Sphalerons

B+L Anomaly

$$\partial^\mu J_\mu^{B+L} = \frac{2N_F}{32\pi^2} \times \left\{ g^2 W^a_{\mu\nu} \widetilde{W}^{\mu\nu\, a} - g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu} \right\}$$





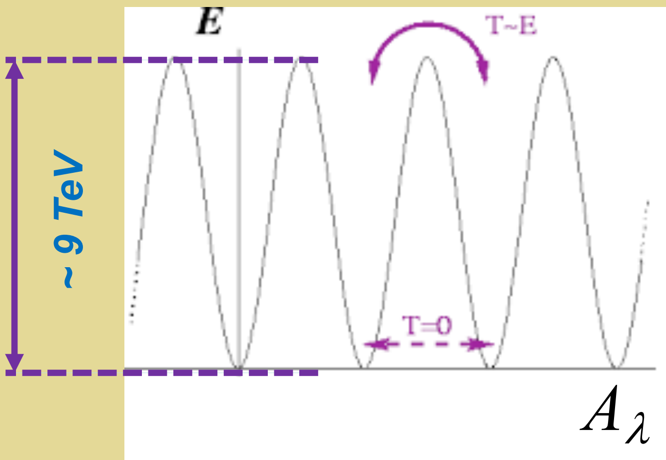


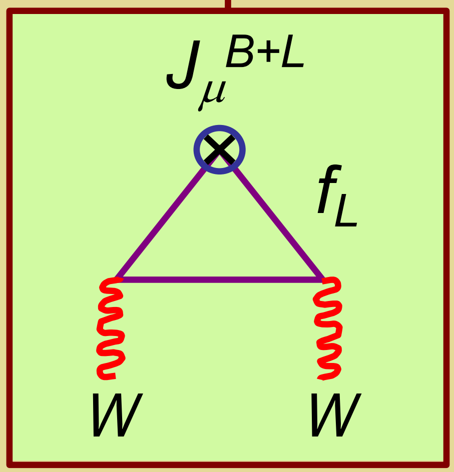
Sphaleron Configuration → *Anomaly* → *Δ (B+L) $\propto N_F$*

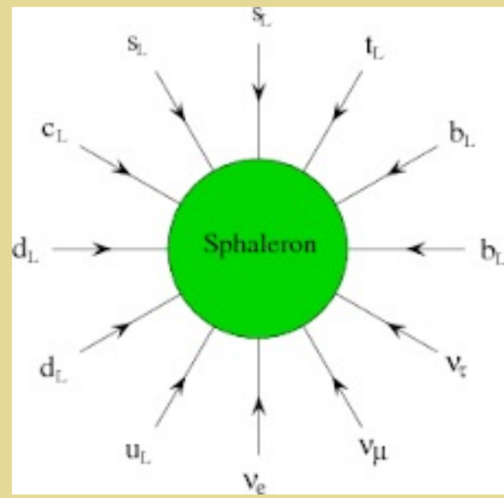
SM B+L Violation & Sphalerons

B+L Anomaly

$$\partial^\mu J_\mu^{B+L} = \frac{2N_F}{32\pi^2} \times \left\{ g^2 W_{\mu\nu}^a \widetilde{W}^{\mu\nu\, a} - g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu} \right\}$$







Sphaleron Configuration → *Anomaly* → *Δ (B+L) $\propto N_F$*

Additional LN Violation: Questions

- *Are there additional sources of LN violation at the classical (Lagrangian) level?*
- *If so, what is the associated LNV mass scale ?*
- *What is the sensitivity of ton-scale $0\nu\beta\beta$-decay searches under various LNV scenarios ?*
- *What are the inter-frontier implications?*

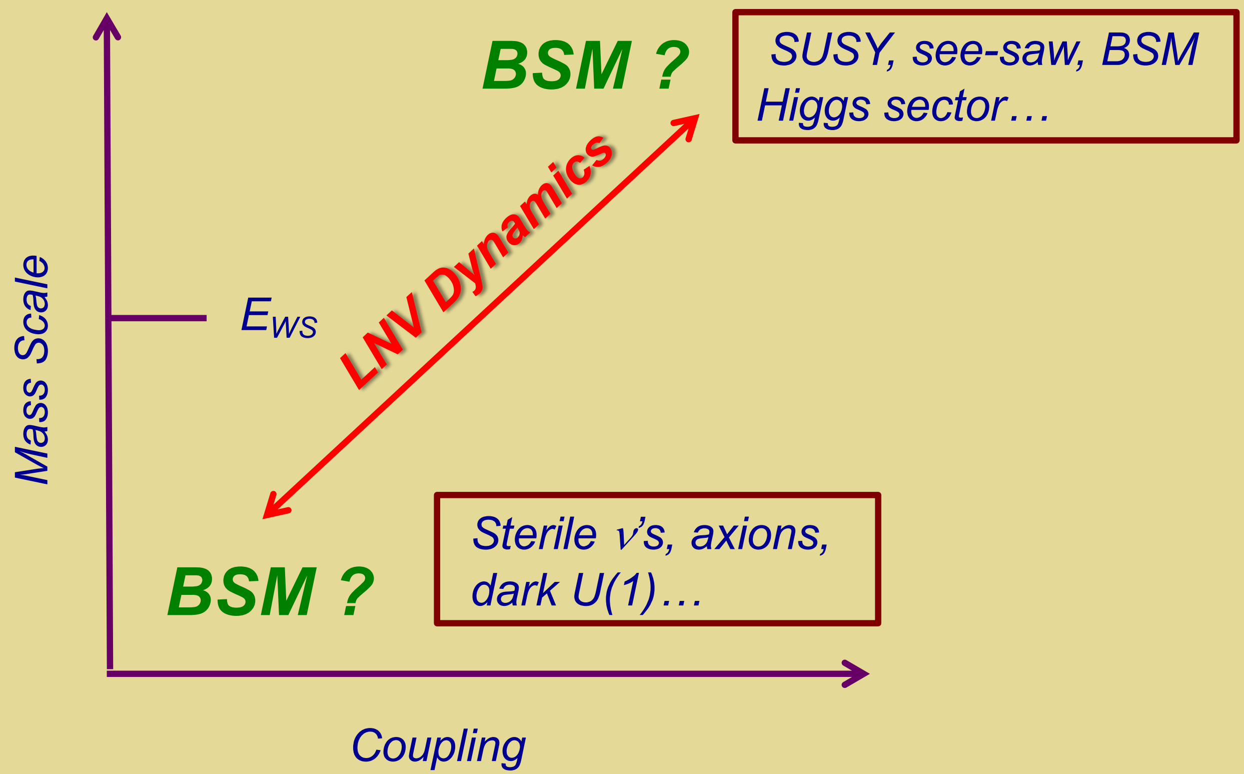
Origin of m_ν

Cosmology:
- **BAU**
- **Σm_ν**

ν Pheno
- **$0\nu\beta\beta$ decay**
- **μ_ν**

Colliders

LNV Physics: Where Does it Live ?



Is the BSM LNV scale (associated with m_ν) far above E_{WS} ? Near E_{WS} ? Well below E_{WS} ?

Lepton Number: ν 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

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

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

Dirac

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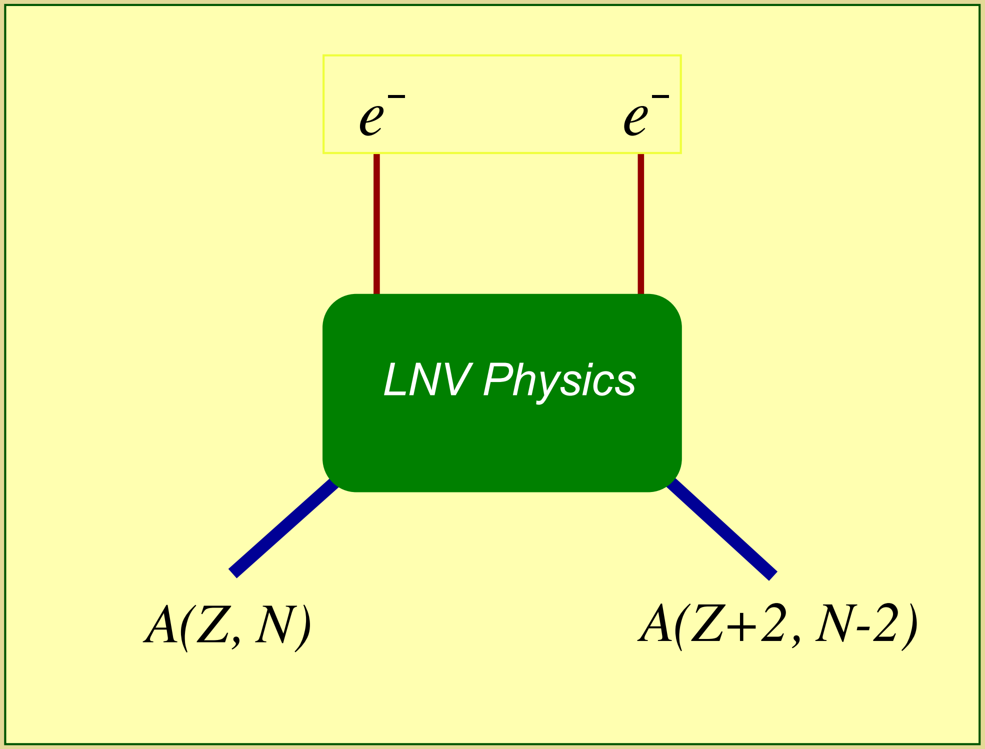

0νββ-Decay: LNV? Mass Term?

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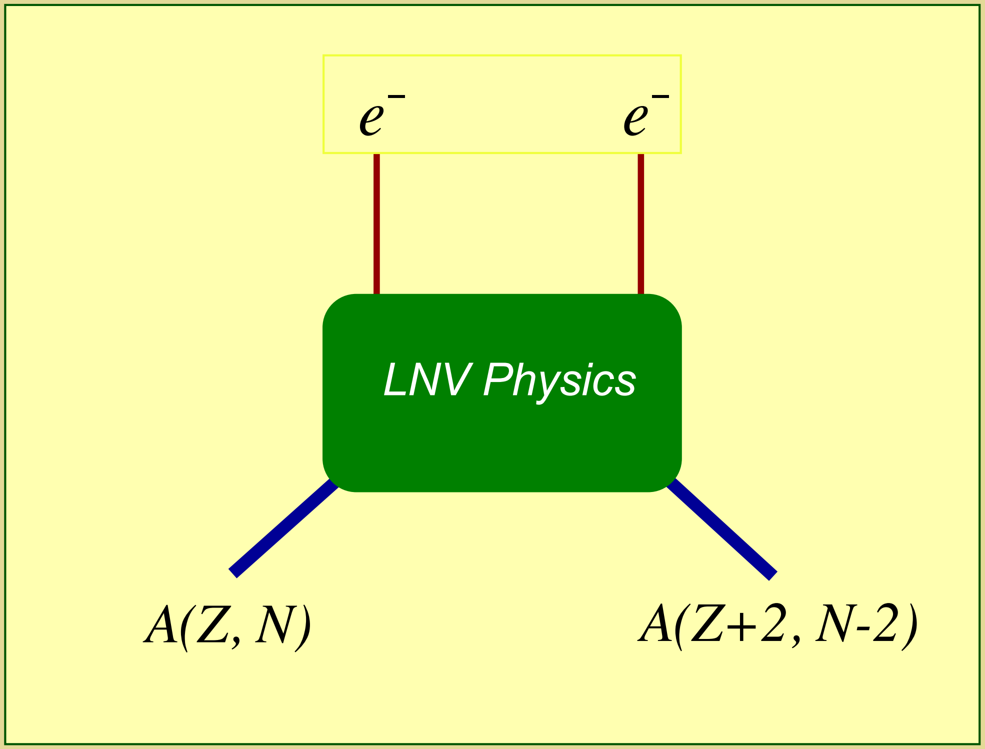
Majorana

Impact of observation

- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*



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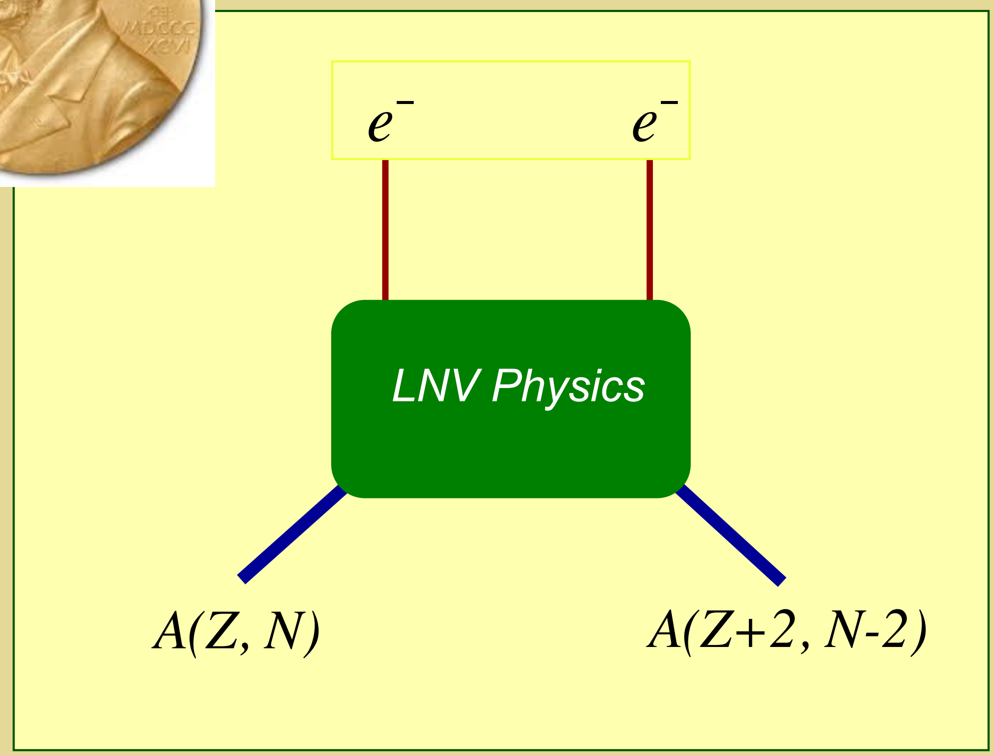
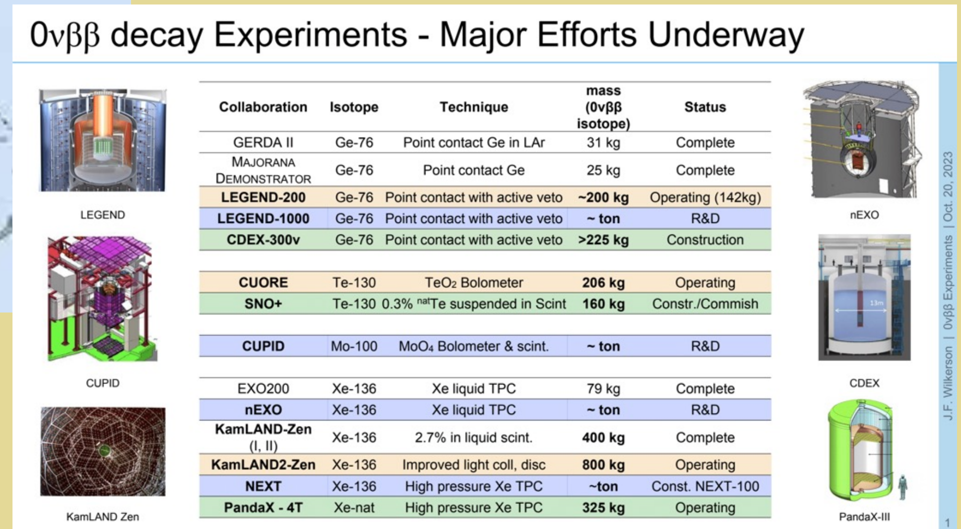


NLDBD Experimental Horizons

Thanks: J. Wilkerson



0νββ decay Experiments - Major Efforts Underway

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
GERDA II	Ge-76	Point contact Ge in LAr	31 kg	Complete
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Complete
LEGEND-200	Ge-76	Point contact with active veto	**~200 kg**	Operating (142kg)
LEGEND-1000	Ge-76	Point contact with active veto	**~ ton**	R&D
CDEX-300ν	Ge-76	Point contact with active veto	**>225 kg**	Construction
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Constr./Commish
CUPID	Mo-100	MoO_4 Bolometer & scint.	**~ ton**	R&D
EXO200	Xe-136	Xe liquid TPC	79 kg	Complete
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**400 kg**	Complete
KamLAND2-Zen	Xe-136	Improved light coll, disc	**800 kg**	Operating
NEXT	Xe-136	High pressure Xe TPC	**~ton**	Const. NEXT-100
PandaX - 4T	Xe-nat	High pressure Xe TPC	**325 kg**	Operating

- ***Global effort to deply "ton scale" expt's → 100 x better lifetime sensitivity***
- ***Top priority for U.S. nuclear science***

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

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

Dirac

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

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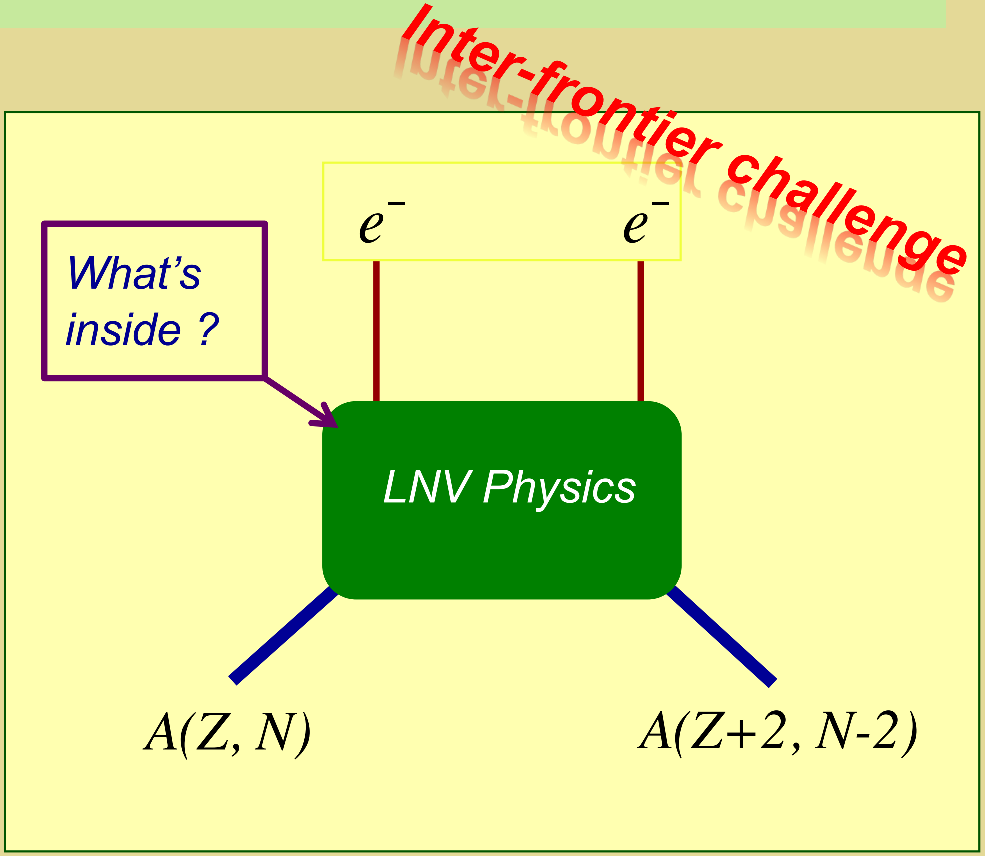

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **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 LNV
- > 3 light neutrinos

How can we determine the underlying LNV physics?

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
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The "Standard Mechanism"

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

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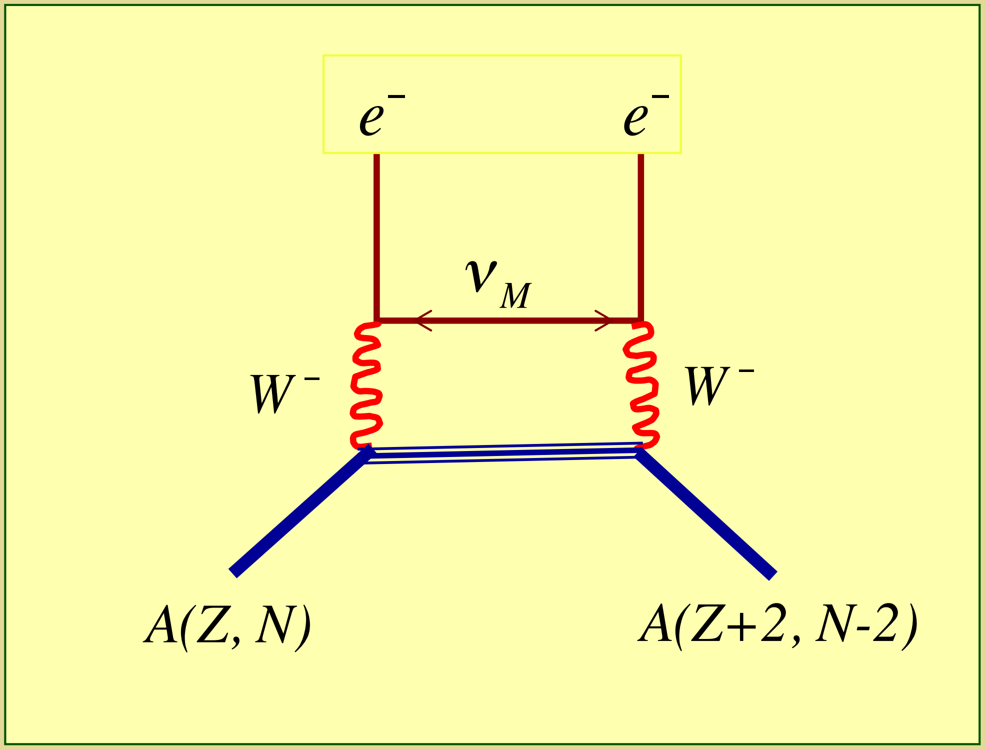
Dirac

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

Majorana

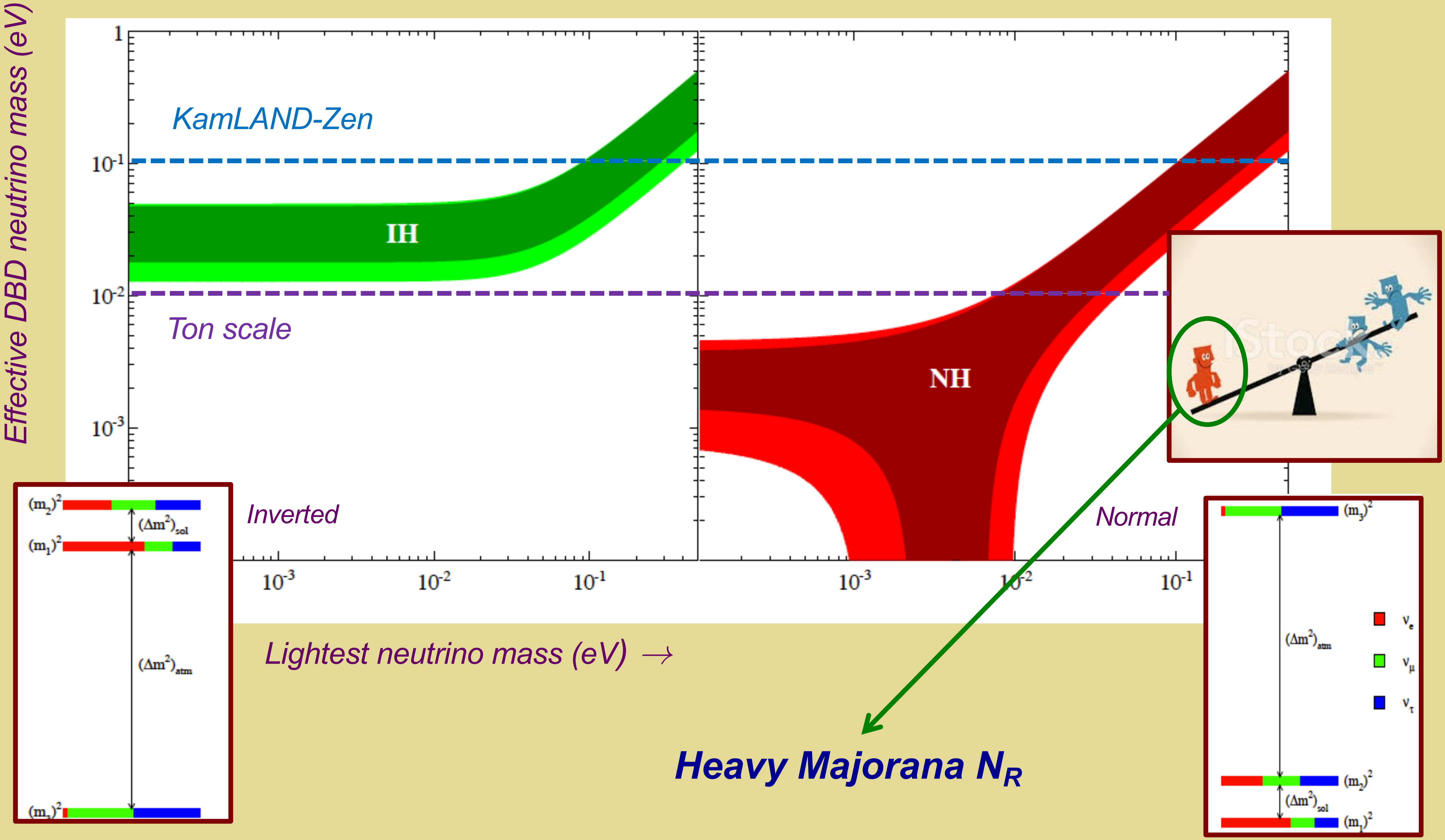
"Standard" Mechanism

- *Light Majorana mass generated at the conventional see-saw scale: $\Lambda \sim 10^{12} - 10^{15}$ GeV*
- *3 light Majorana neutrinos mediate decay process*



$0\nu\beta\beta$-Decay: “Standard” Mechanism

Three active light neutrinos



Neutrinos and the Origin of Matter

- *Heavy neutrinos decay out of equilibrium in early universe*

- *Majorana neutrinos can decay to particles and antiparticles*

- *Rates can be slightly different (CP violation)*

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \bar{\ell} H^*)$$

- *Resulting excess of leptons over anti-leptons partially converted into excess of quarks over anti-quarks by Standard Model sphalerons*

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*
- *3 light neutrinos with TeV scale LNV*
- *> 3 light neutrinos*

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

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

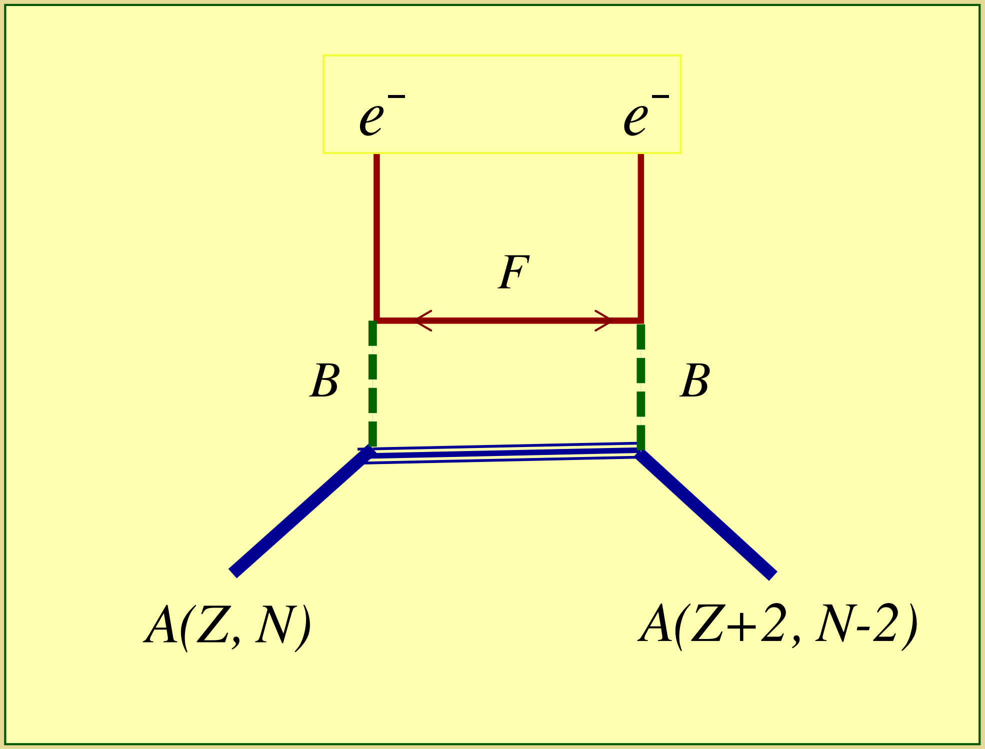
Dirac

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

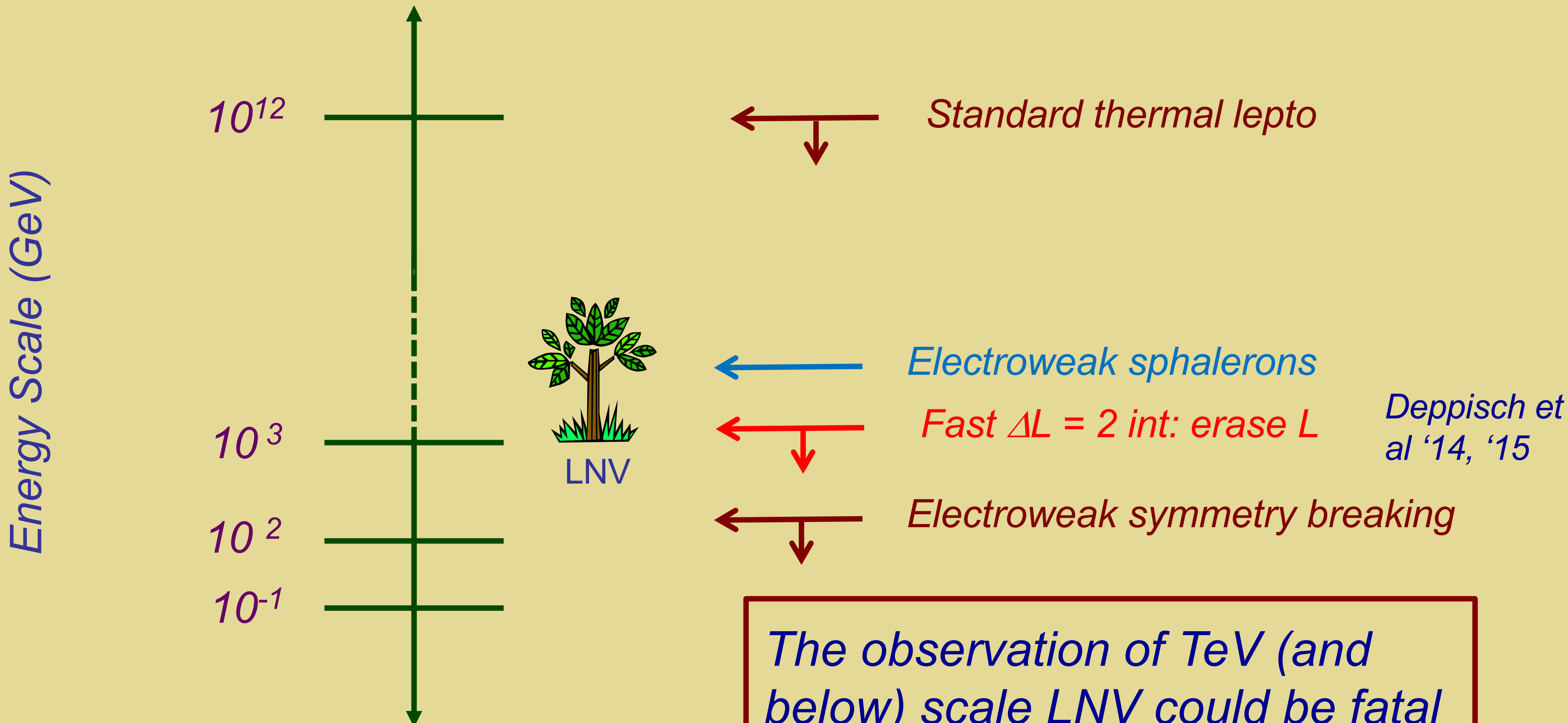
Majorana

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*



Low Scale LNV & Leptogenesis



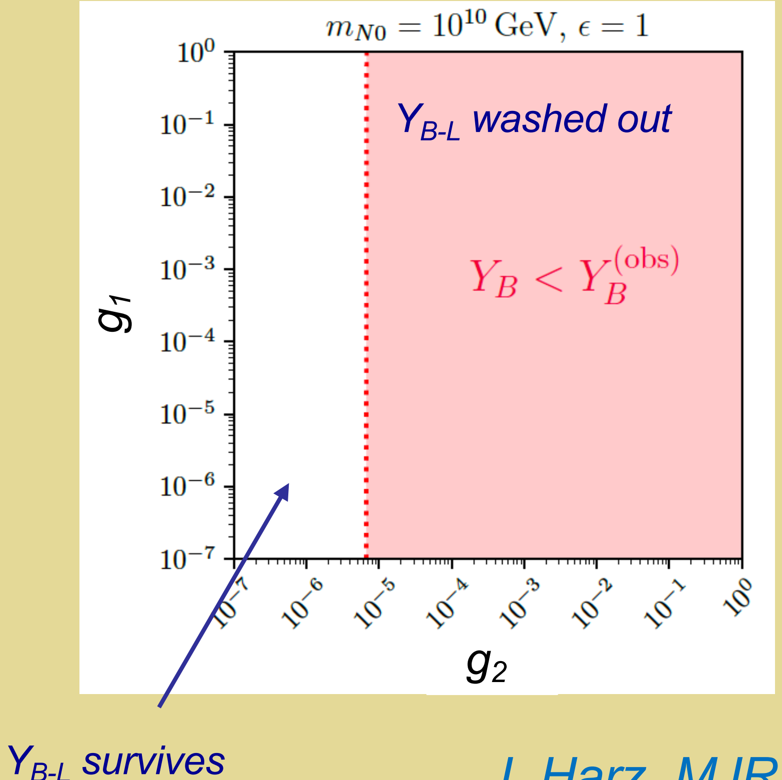
The observation of TeV (and below) scale LNV could be fatal to the leptogenesis paradigm

Leptogenesis & TeV Scale LNV: Example

The "O2 Model": similar ingredients as in scotogenic neutrino mass models (but no Z_2 symmetry)

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

S:	*(1, 2, ½)*	
F:	*(1, 0, 0)*	*Majorana*



J. Harz, MJRM, T. Shen, S. Urrutia-Quiroga '21

Low Scale LNV Probes

- *New scalars (type II see saw)*
- *New LNV interactions (hadron collider)*
- *Heavy neutral leptons (sterile ν…)*

BSM LNV: Questions

- *Are there additional sources of LNV at the classical (Lagrangian) level?*
- *If so, what is the associated LNV mass scale ?*
- *What is the sensitivity of ton-scale $0\nu\beta\beta$-decay searches under various LNV scenarios ?*
- *What are the inter-frontier implications?*

Origin of m_ν

Cosmology:

- **BAU**
- **Σm_ν**
- **Grav waves**

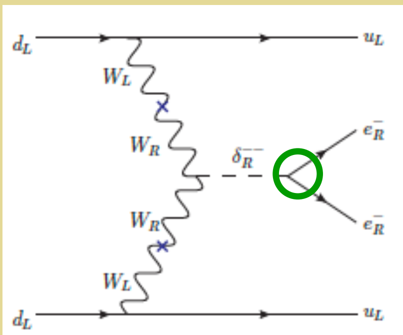
FSNN:

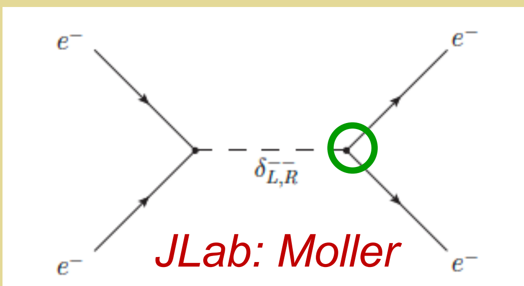
- **$0\nu\beta\beta$ decay**
- **μ_ν**
- **ν osc**
- **PV ee …**

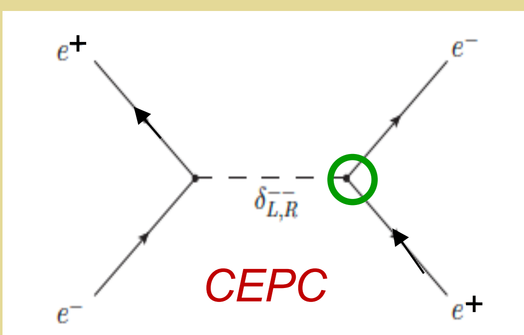
Colliders

LNV: Scalar Fields & m_ν

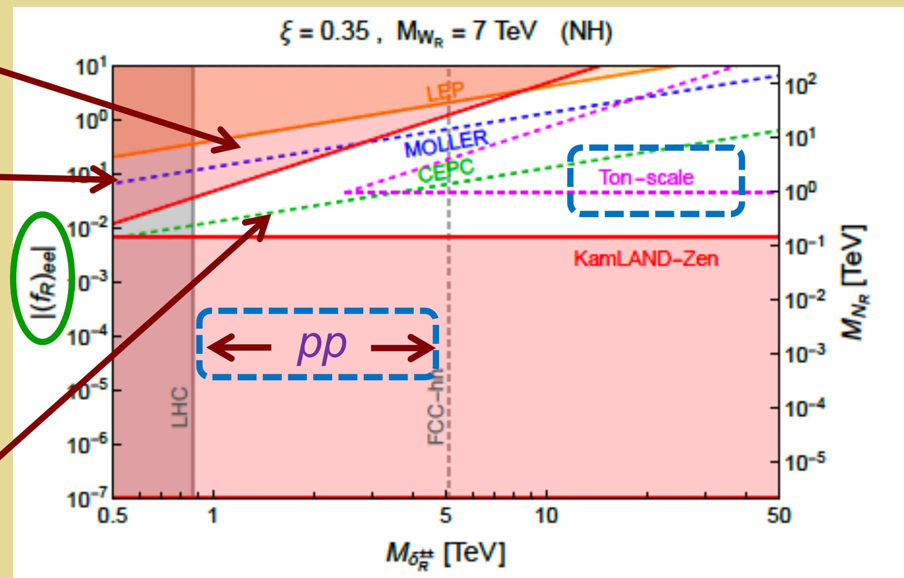
$0\nu\beta\beta$ Decay, PV $e^-e^- \rightarrow e^-e^-$, $e^+e^- \rightarrow e^+e^-$ & pp collisions







mLRSM type II Seesaw: δ^{--}



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BSM LNV: $0\nu\beta\beta$-Decay & pp Colliders

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

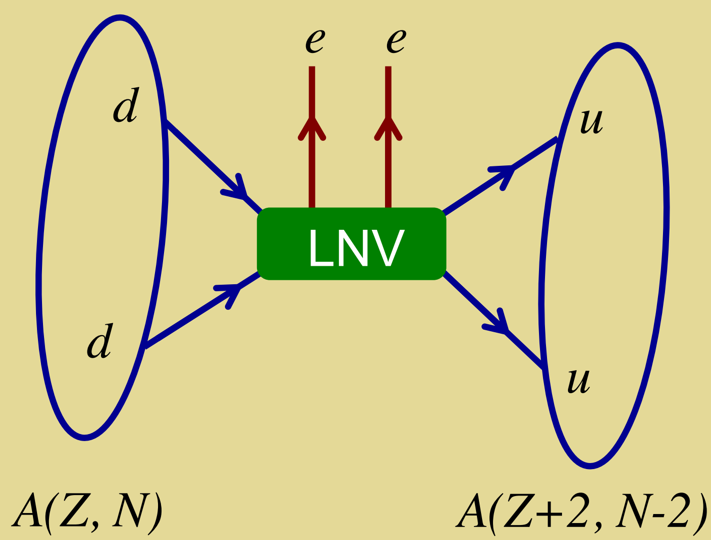
Dirac

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

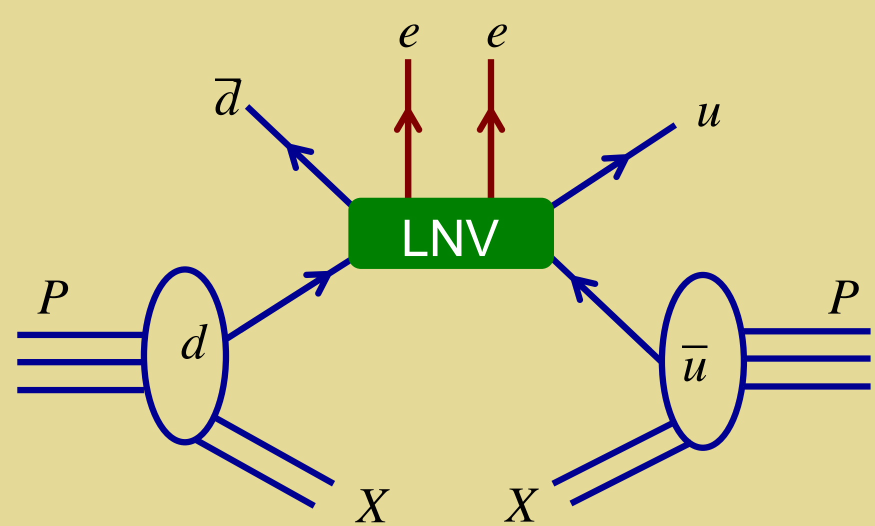
Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



pp Collisions



Numerous studies: another talk…

TeV-Scale LNV: lepto, $0\nu\beta\beta$-Decay & Colliders

The "O2 Model": similar ingredients as in scotogenic neutrino mass models (but no Z_2 symmetry)

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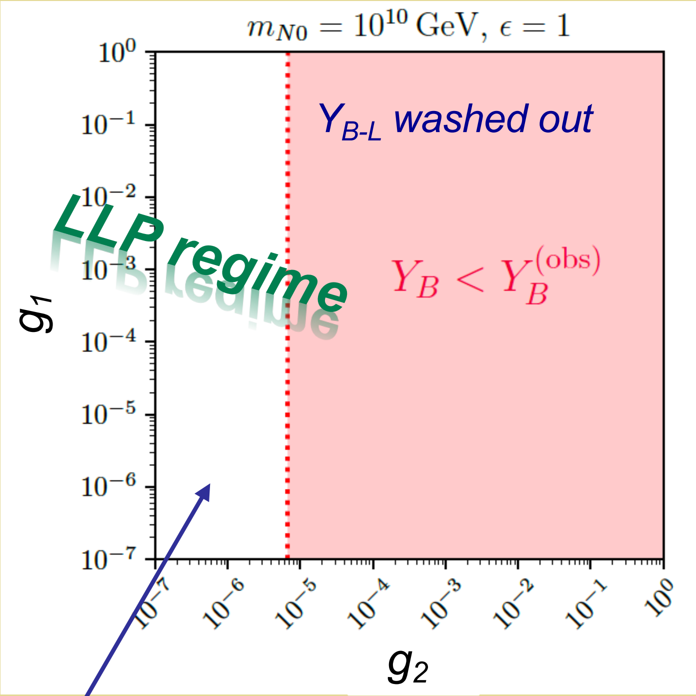
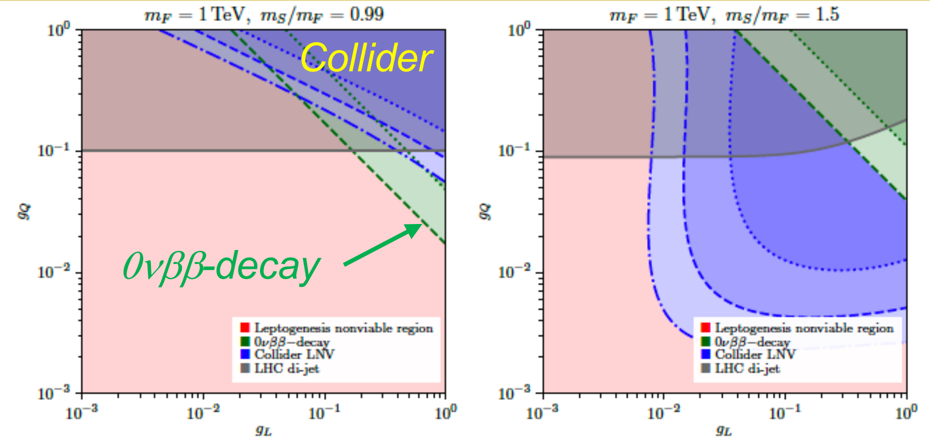


Y_{B-L} survives



Comparing $0\nu\beta\beta$-decay, collider, & cosmo

Collider – $0\nu\beta\beta$ – overlap: < TeV scale LNV "smoking gun"

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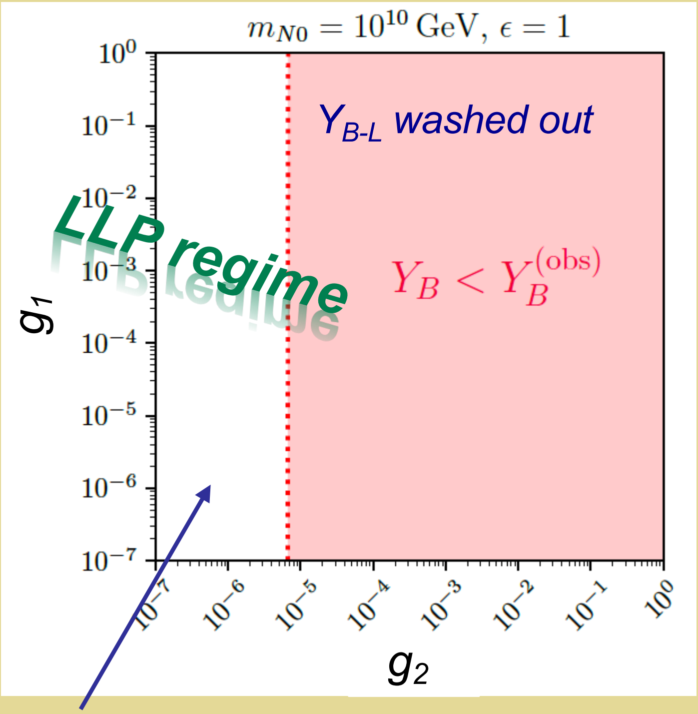
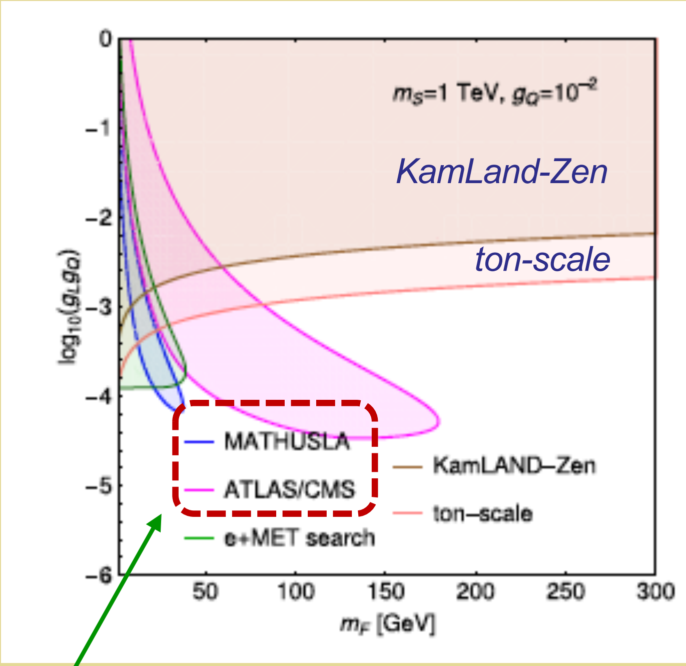
LLP Searches for LNV



Y_{B-L} survives

Simplified Model



LHC long-lived
particle searches

G. Li, MJRM, S. Su,
J.C. Vasquez '22

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- **Grav waves**

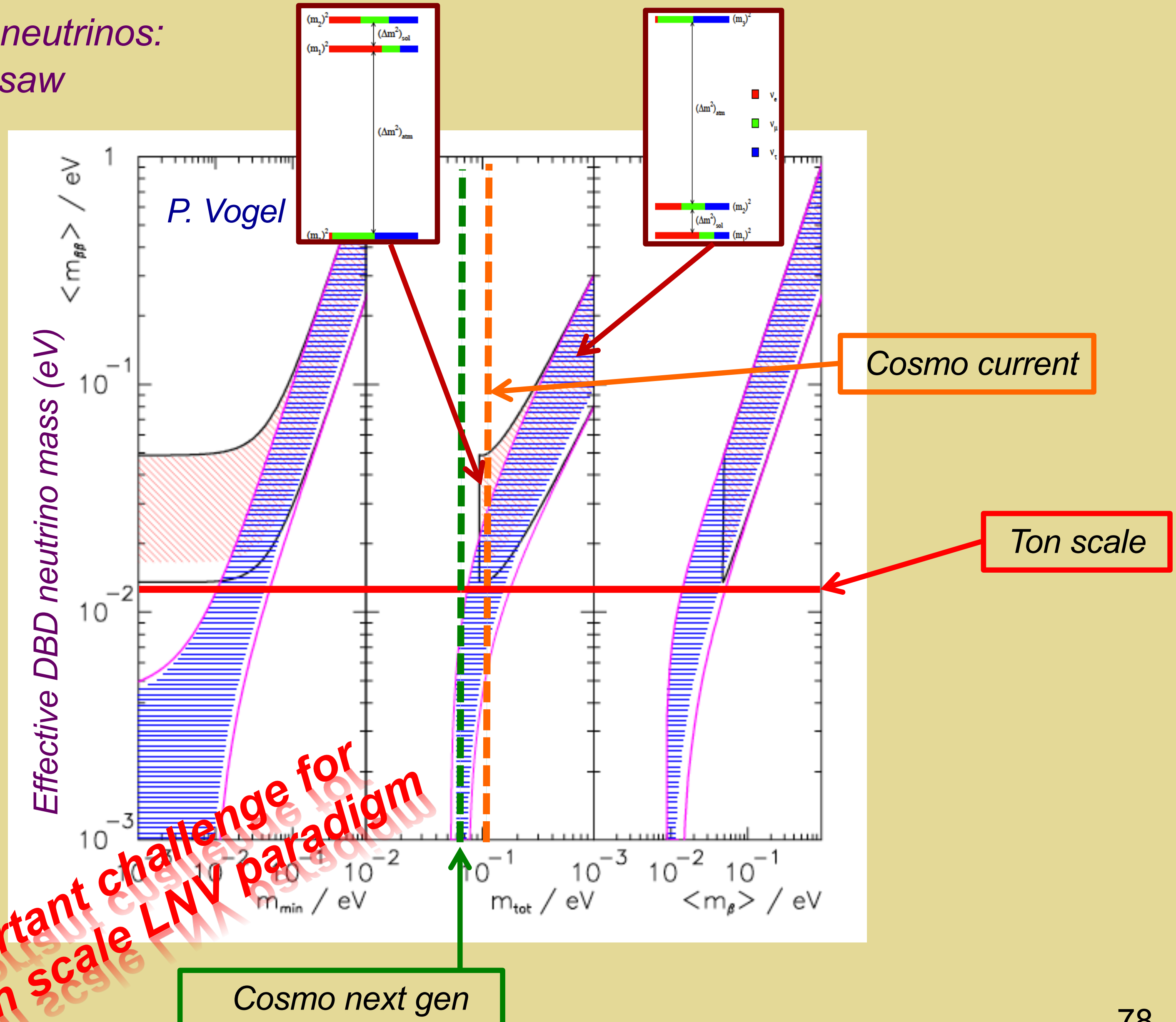
FSNN:

- $0\nu\beta\beta$ **decay**
- μ_ν
- ν **osc**
- **PV ee …**

Colliders

Σm_ν from Cosmo: $0\nu\beta\beta$-Decay Implications

Three active light neutrinos:
conventional see-saw



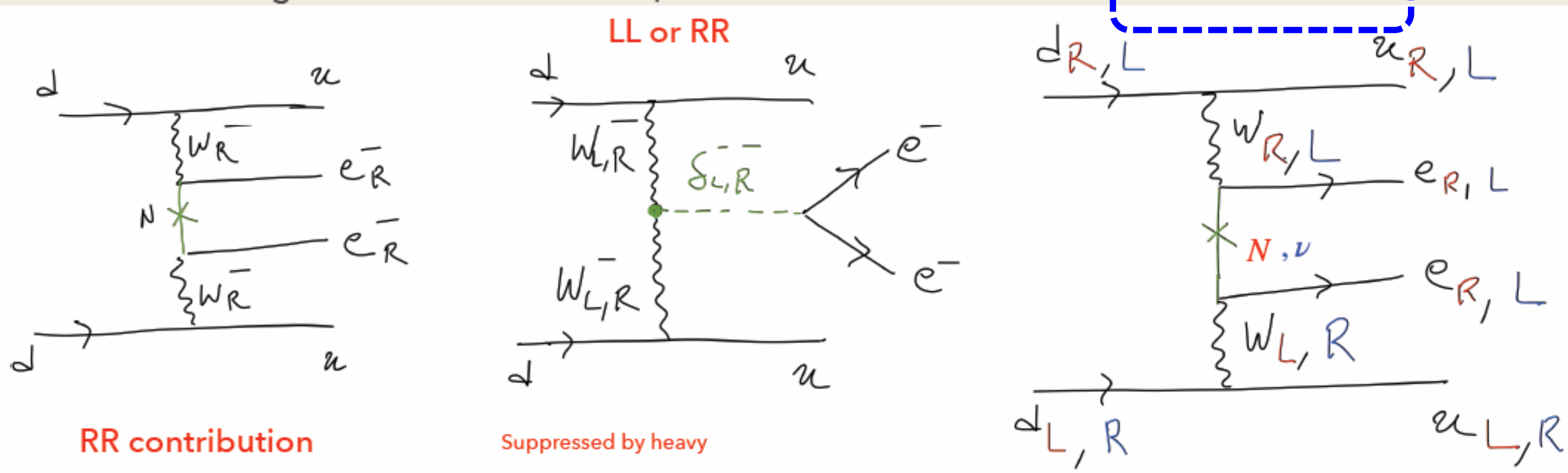
An important challenge for the high scale LNV paradigm

Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay

Long range chiral enhancement

- There are the following contributions (on top of the usual light neutrino contribution)

LR contribution



RR contribution

Suppressed by heavy

δ^{++} masses and LFV constraints (Tello and Senjanovic. ArXiv: 1011.3522)

ATLAS limit ~ 800 GeV) (arXIv: 1710.09748)

The Blue contributions are

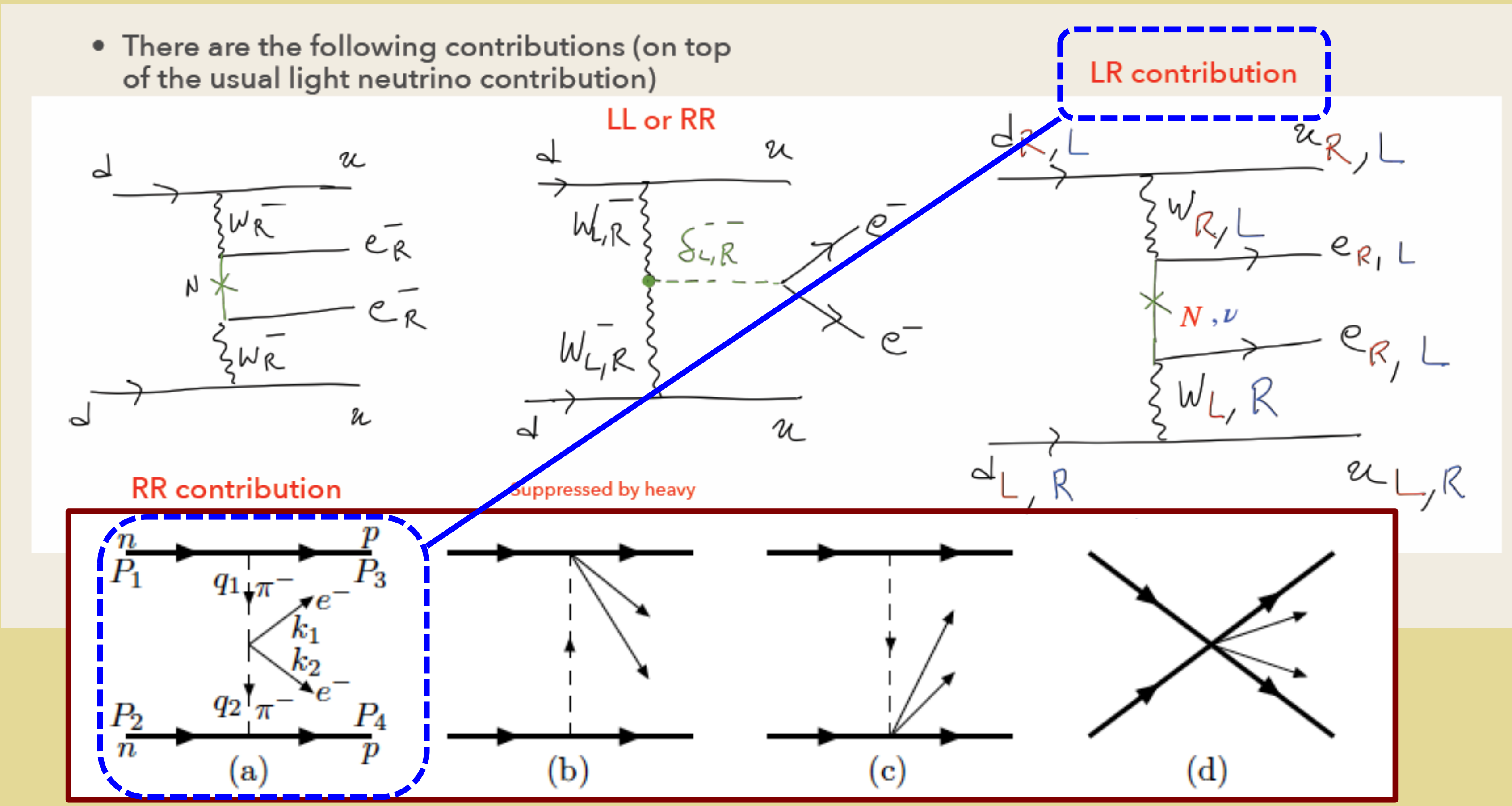
Suppressed by small heavy-light

Neutrino mixing

Thanks! Juan Carlos Vasquez

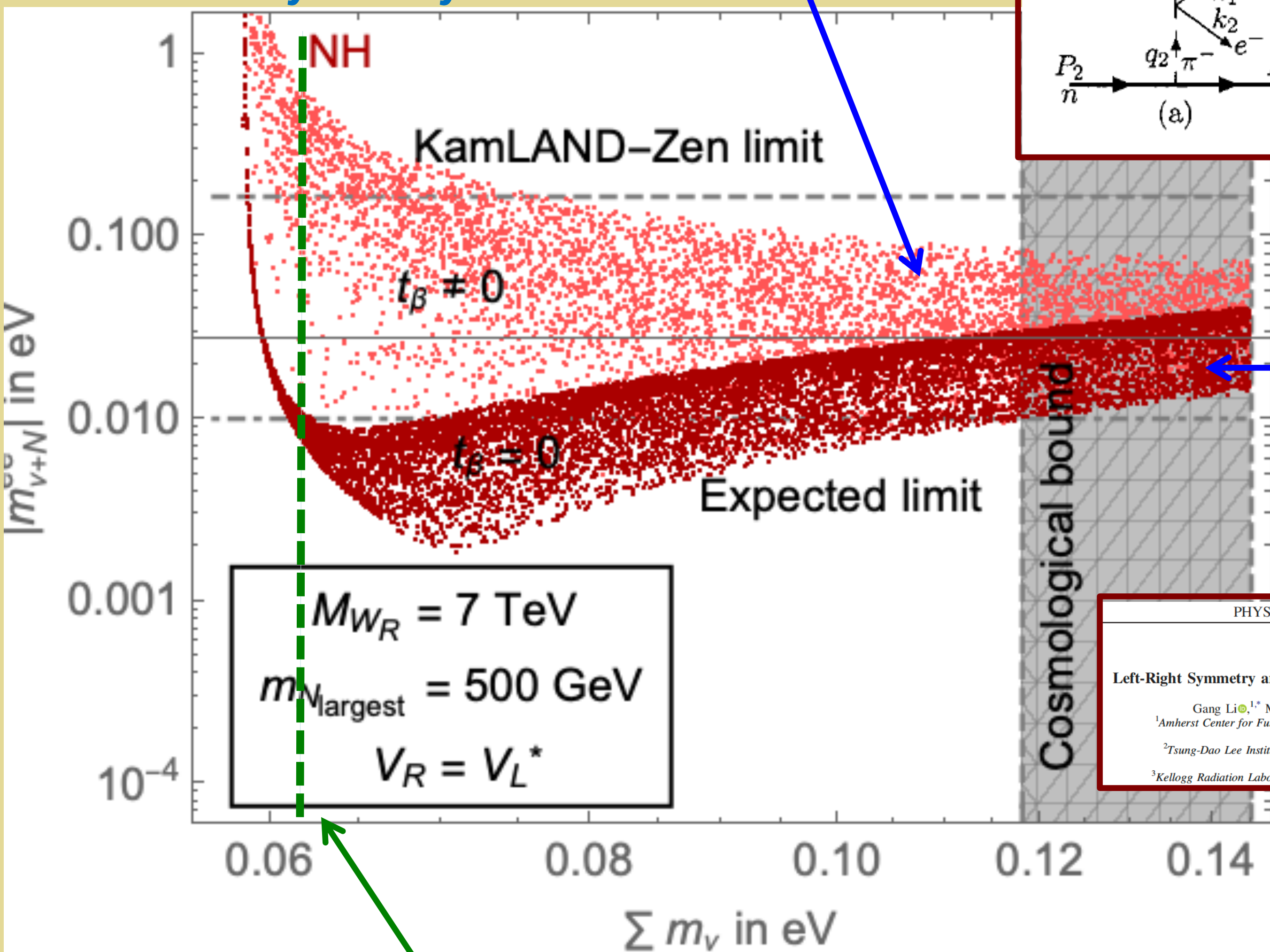
Minimal LR Symmetric Model: $0\nu\beta\beta$-Decay

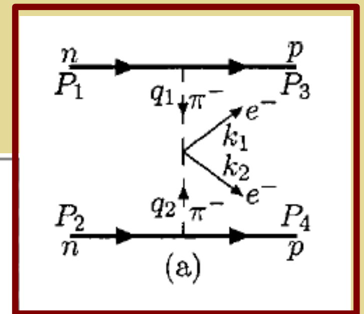
Long range chiral enhancement

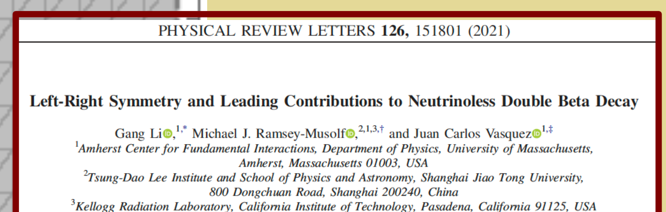


Thanks! Juan Carlos Vasquez

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



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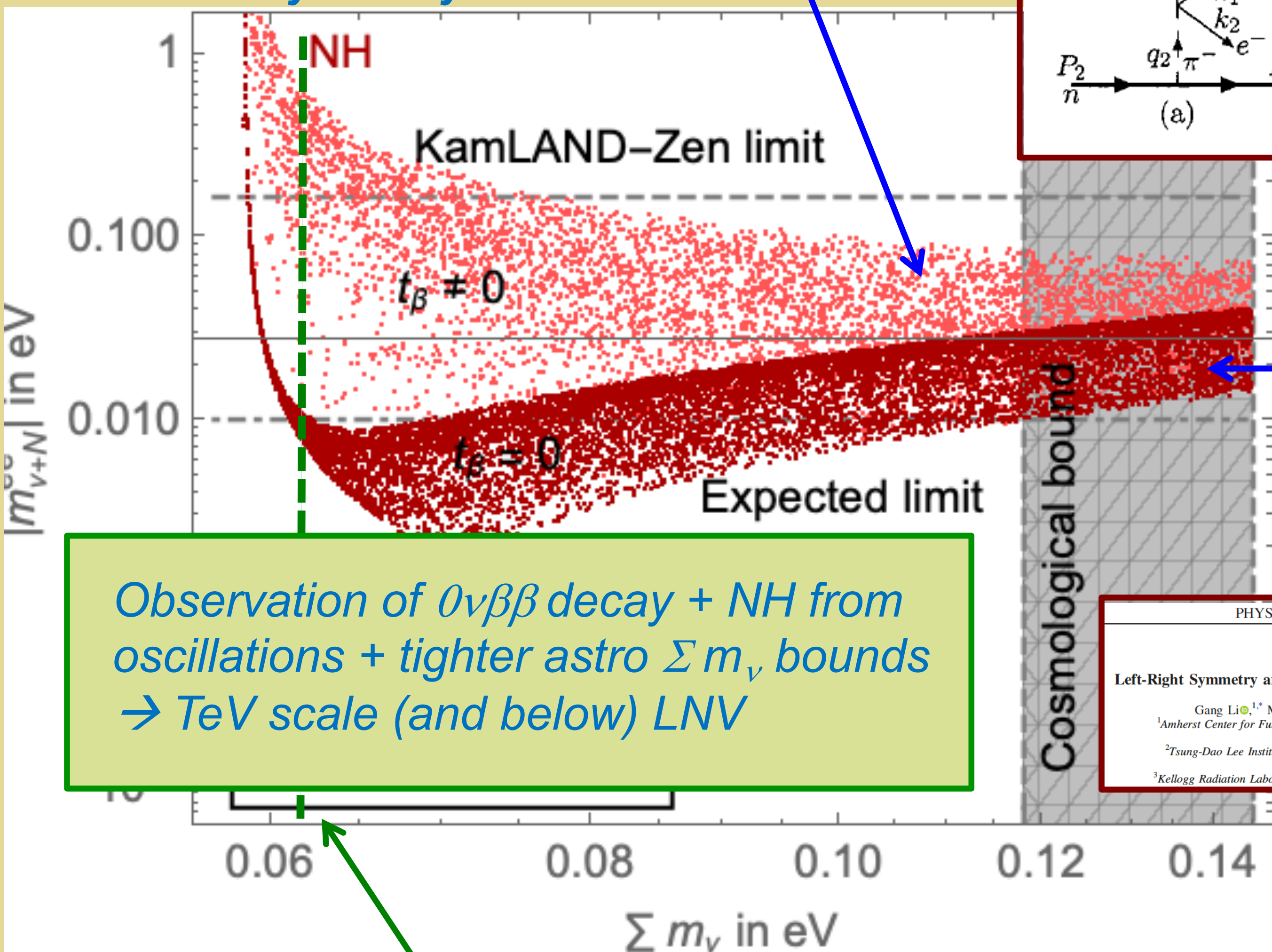
Left-Right Symmetry and Leading Contributions to Neutrinoless Double Beta Decay

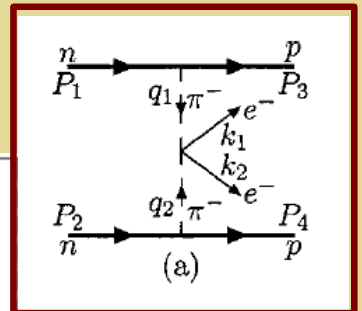
Gang Li,[1,*] Michael J. Ramsey-Musolf,[2,1,3,†] and Juan Carlos Vasquez[1,‡]
[1]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*
[2]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*
[3]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*

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

EFT: Long range

Minimal LR Symmetry





Short range only

Observation of $0\nu\beta\beta$ decay + NH from oscillations + tighter astro $\Sigma\, m_\nu$ bounds
→ TeV scale (and below) LNV

~ Cosmo next gen


PHYSICAL REVIEW LETTERS **126,** 151801 (2021)

Left-Right Symmetry and Leading Contributions to Neutrinoless Double Beta Decay

Gang Li,[1,*] Michael J. Ramsey-Musolf,[2,1,3,†] and Juan Carlos Vasquez[1,‡]

[1]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*

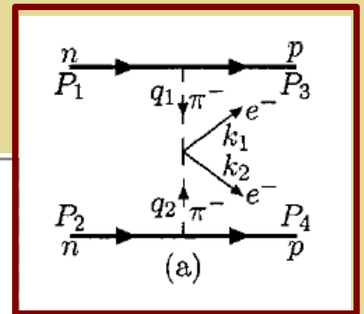
[2]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China*

[3]*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, USA*

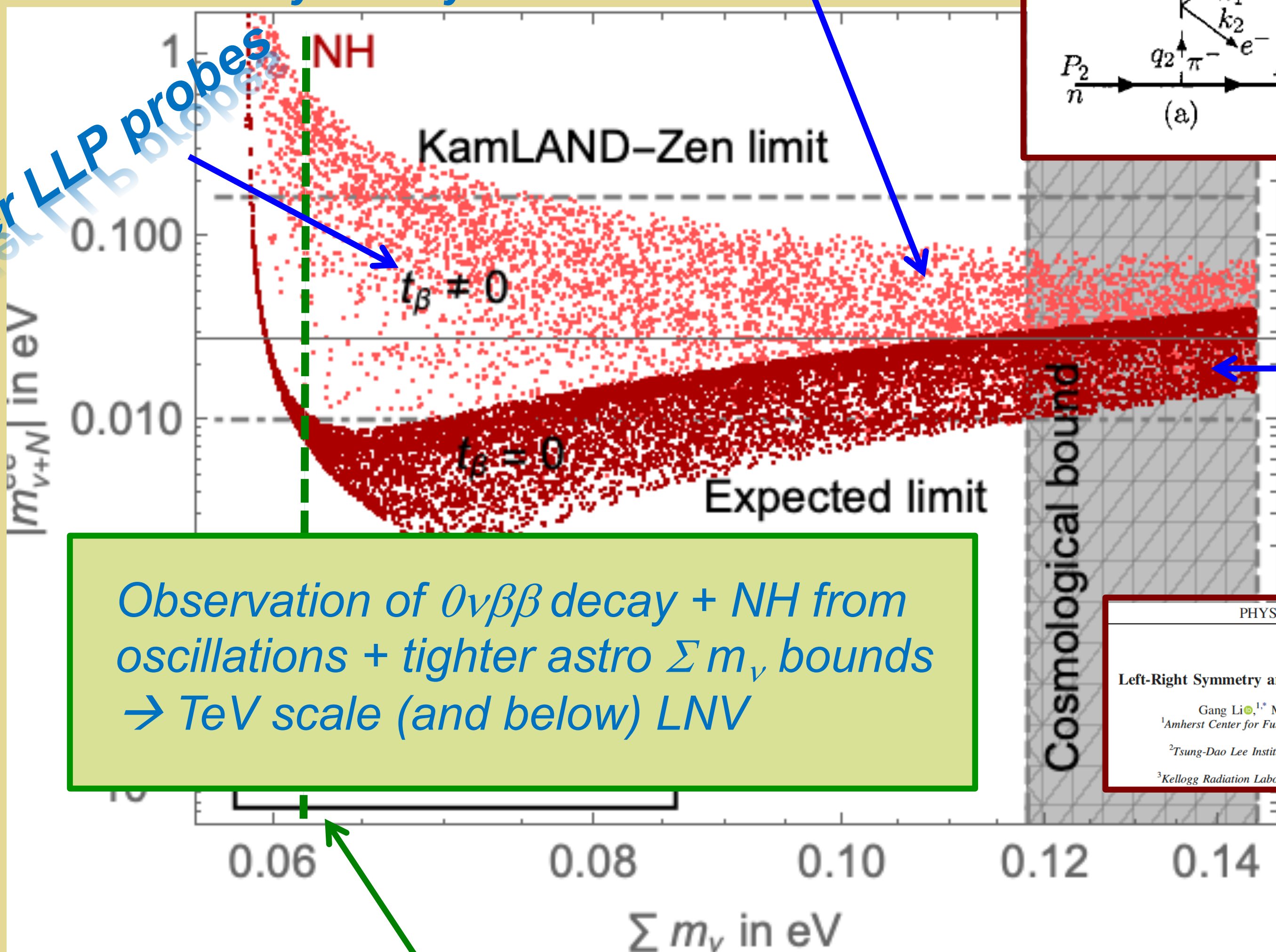
TeV-Scale LNV: $0\nu\beta\beta$-Decay & Σm_ν

Minimal LR Symmetry

EFT: Long range



Collider LLP probes



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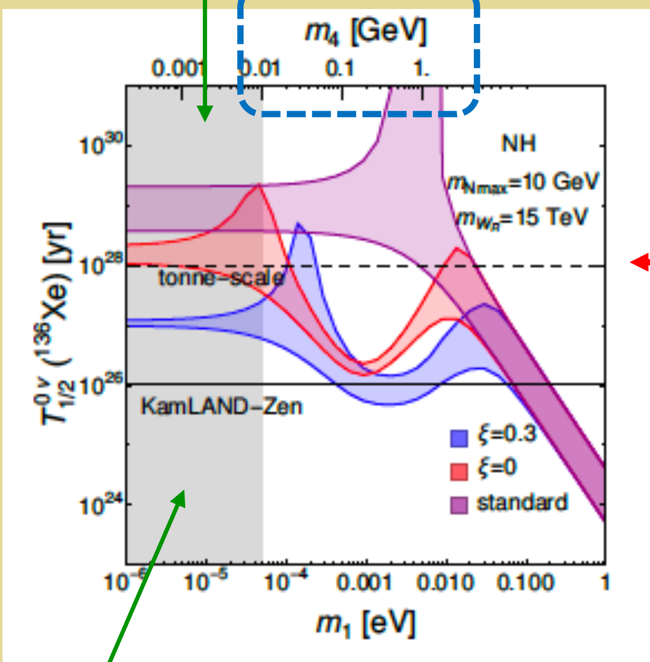
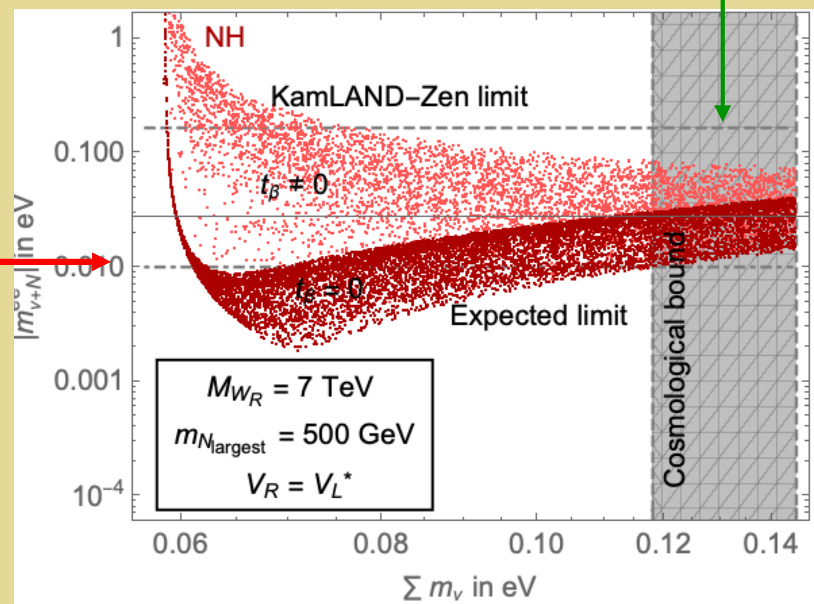
~ Cosmo next gen

More Than 3 Light Neutrinos: MeV-GeV

mLRSM



Simplified Model



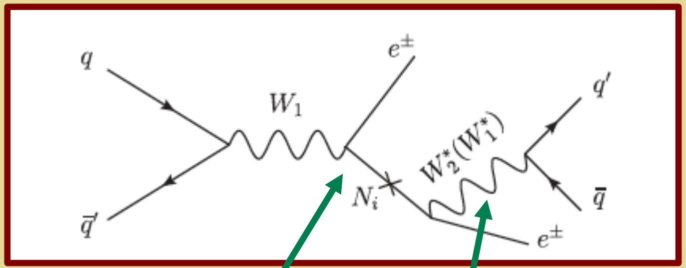
Current Σm_ν exclusion

J. De Vries, G. Li, MJRM, J. C. Vasquez '22

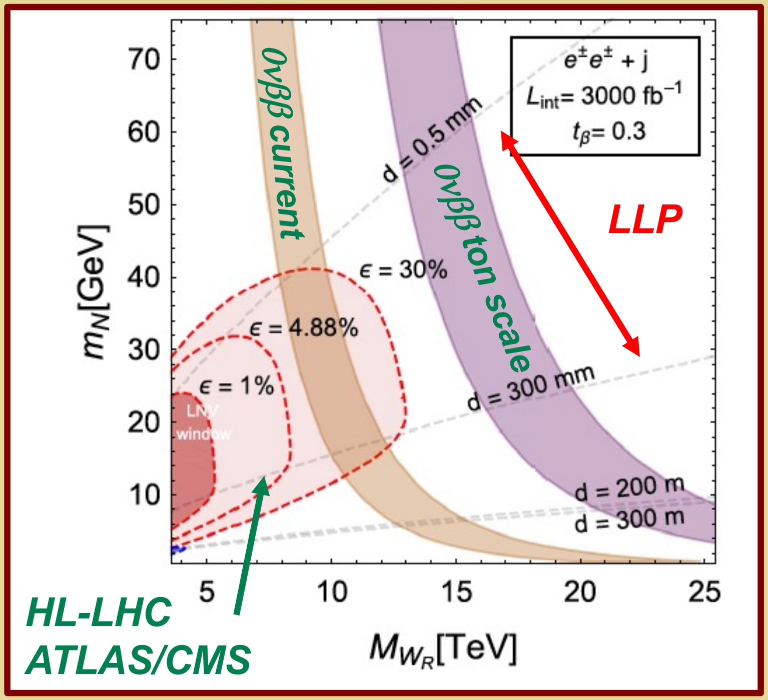
G. Li, MJRM, J. C. Vasquez '21

TeV LNV: LLP & Σm_ν

On-shell W → N e → e e jj



$g_X << 1$ $\left(\frac{M_X}{M_Y}\right) >> 1$



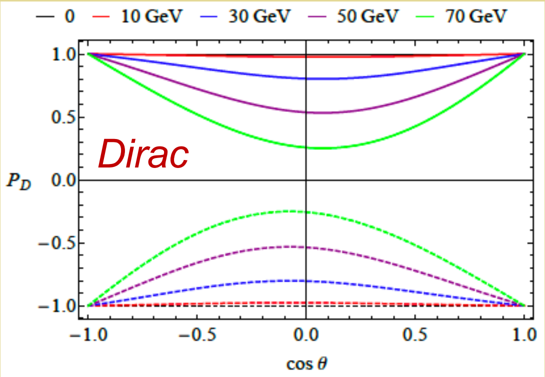
Improvement in efficiency → extend beyond current DBD reach

G. Li, MJRM, J.C. Vasquez, '22

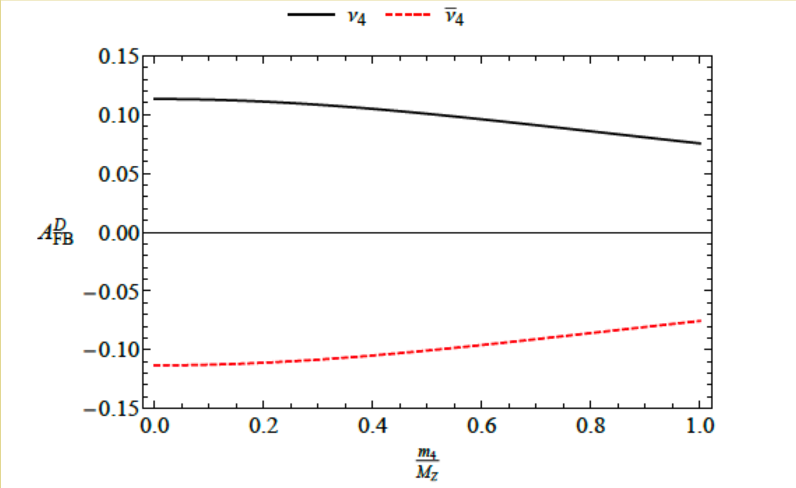
Light ν : Lepton Collider Probes

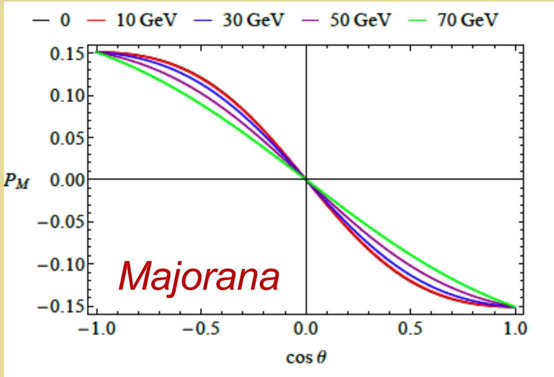
$e^+ e^- \to Z^0 \to N\ N$ vs $e^+ e^- \to Z^0 \to N\ \bar{N}$

N Polarization



Lepton FB Asymmetry





A_{FB} : vanish for Majorana N

M. Drewes 2210.17110 (mini-review)
Blondel, de Gouvea, Kayser 2105.06576

Light ν : Lepton Collider Probes

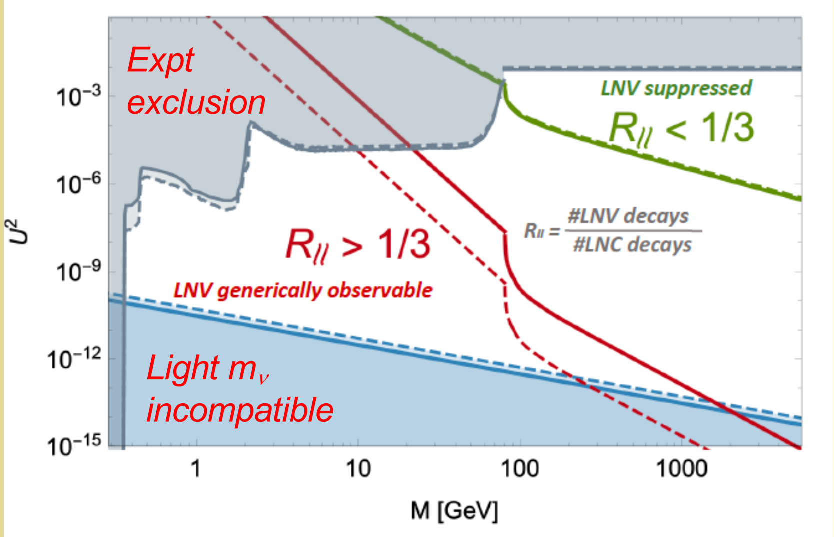
$e^+ e^- \rightarrow Z^0 \rightarrow N\,N$ vs $e^+ e^- \rightarrow Z^0 \rightarrow N\,\bar{N}$

Displaced decays (LLPs)

$$N_{\text{obs}} \simeq \text{u}_\beta^2 N_{\text{HNL}\alpha} \left[\exp(-l_0/\lambda_N) - \exp(-l_1/\lambda_N)\right] \epsilon_{\alpha\beta},$$

$\lambda_N^{Majorana} = 2 \times \lambda_N^{Dirac}$

LLP LNV Observability



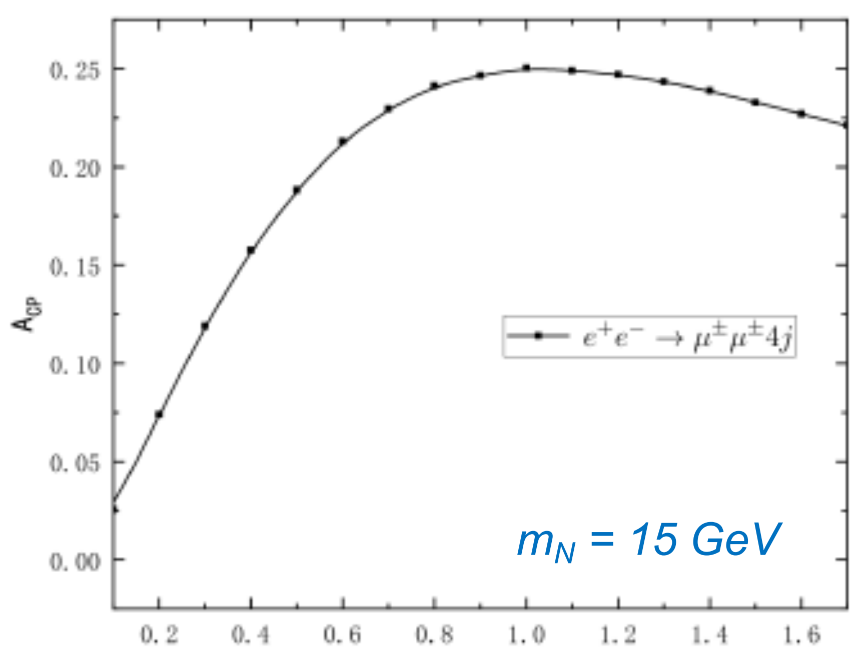
Active-HNL Mixing

M. Drewes 2210.17110 (mini-review)
Blondel, de Gouvea, Kayser 2105.06576

W Pair Production

LNV + CPV

$$\mathcal{A}_{CP} = \frac{Br(\ell^+\ell^- \to \mu^+\mu^+4j) - Br(\ell^+\ell^- \to \mu^-\mu^-4j)}{Br(\ell^+\ell^- \to \mu^+\mu^+4j) + Br(\ell^+\ell^- \to \mu^-\mu^-4j)}$$



$h = \Delta m / \Gamma_{N_a}$

BSM LNV: Questions

- *Are there additional sources of LNV at the classical (Lagrangian) level?*
- *If so, what is the associated LNV mass scale ?*
- *What is the sensitivity of ton-scale $0\nu\beta\beta$-decay searches under various LNV scenarios ?*
- *What are the inter-frontier implications?*

Origin of m_ν

Cosmology:
- **BAU**
- **Σm_ν**
- **Grav waves**

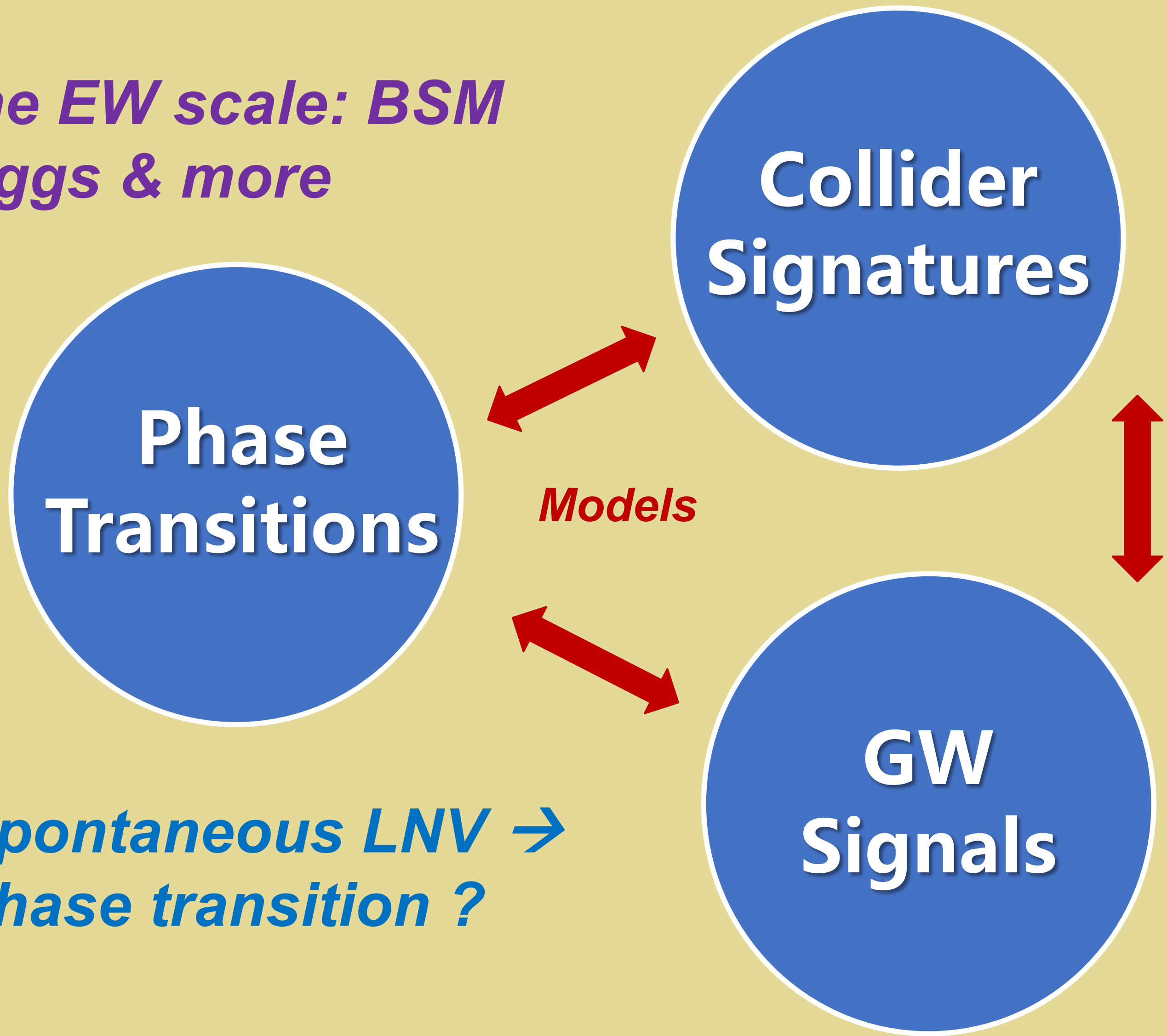
FSNN:
- **$0\nu\beta\beta$ decay**
- **μ_ν**
- **ν osc**
- **PV ee …**

Colliders

Spontaneous LNV: Higgs, GW, Collider

The EW scale: BSM Higgs & more

LHC + Higgs factories

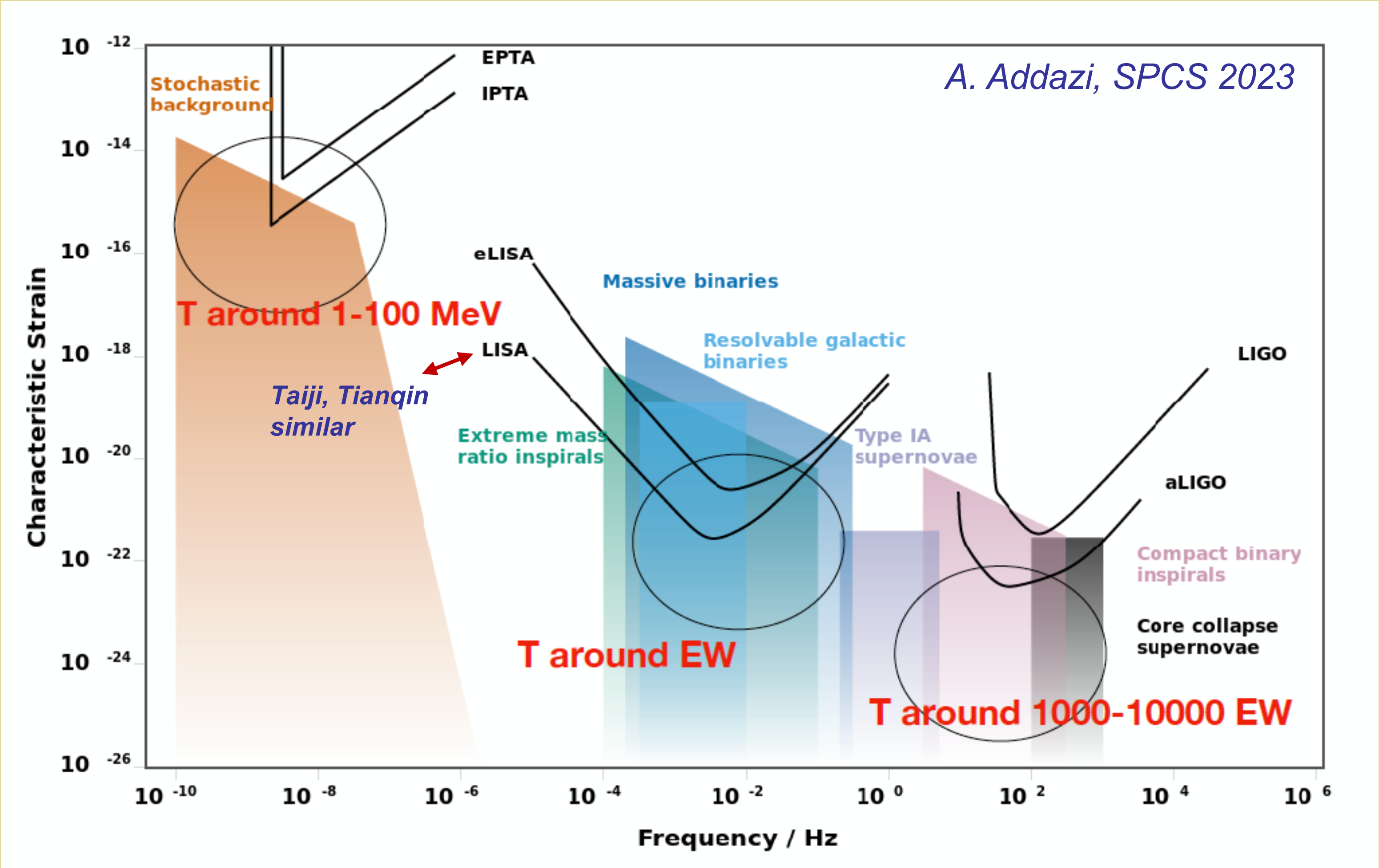


Complementary probes

LISA, Taiji, Tianqin

Spontaneous LNV → phase transition ?

Gravitational Waves

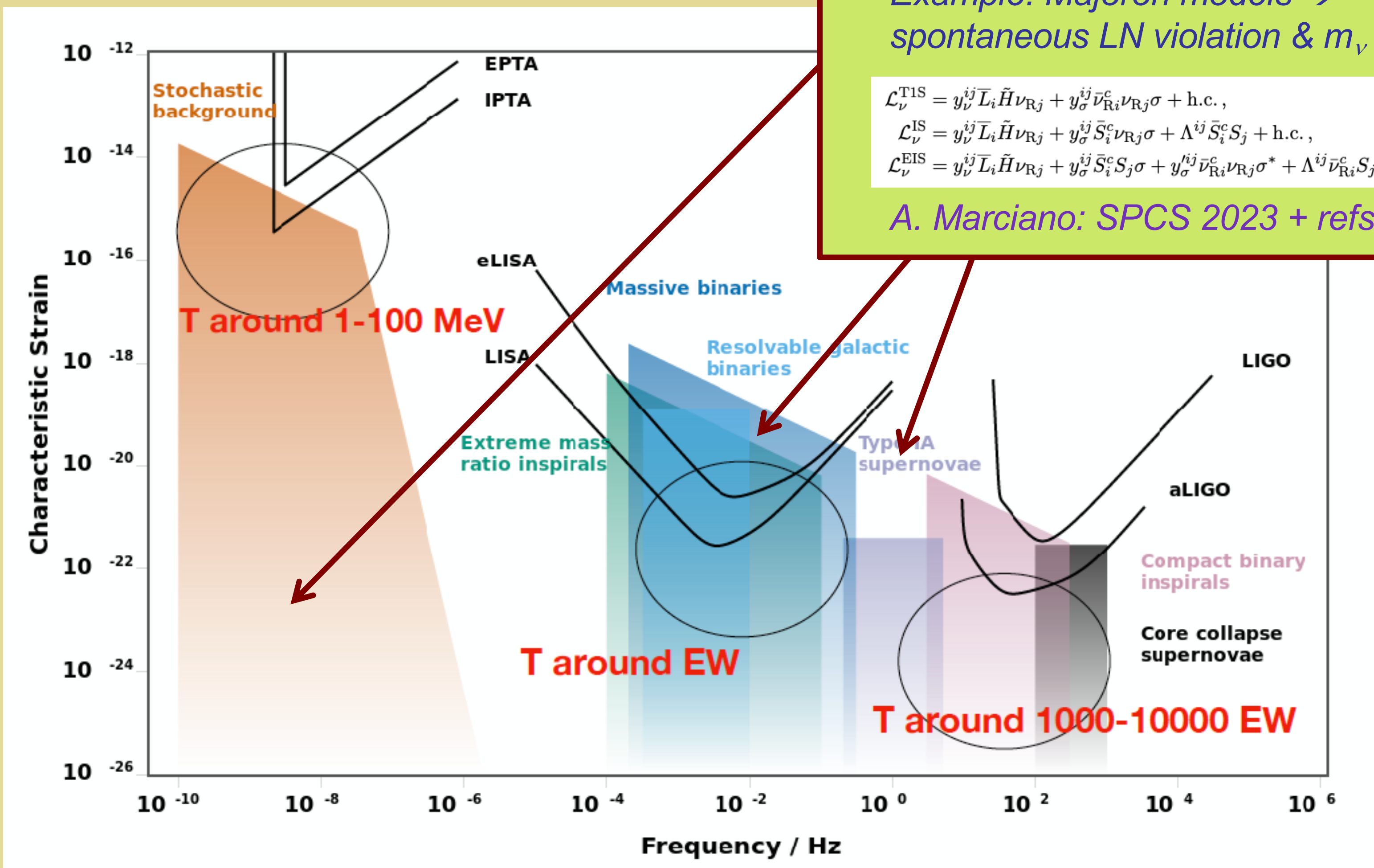


LNV Scalar Field & GW

Example: Majoron models → spontaneous LN violation & m_ν

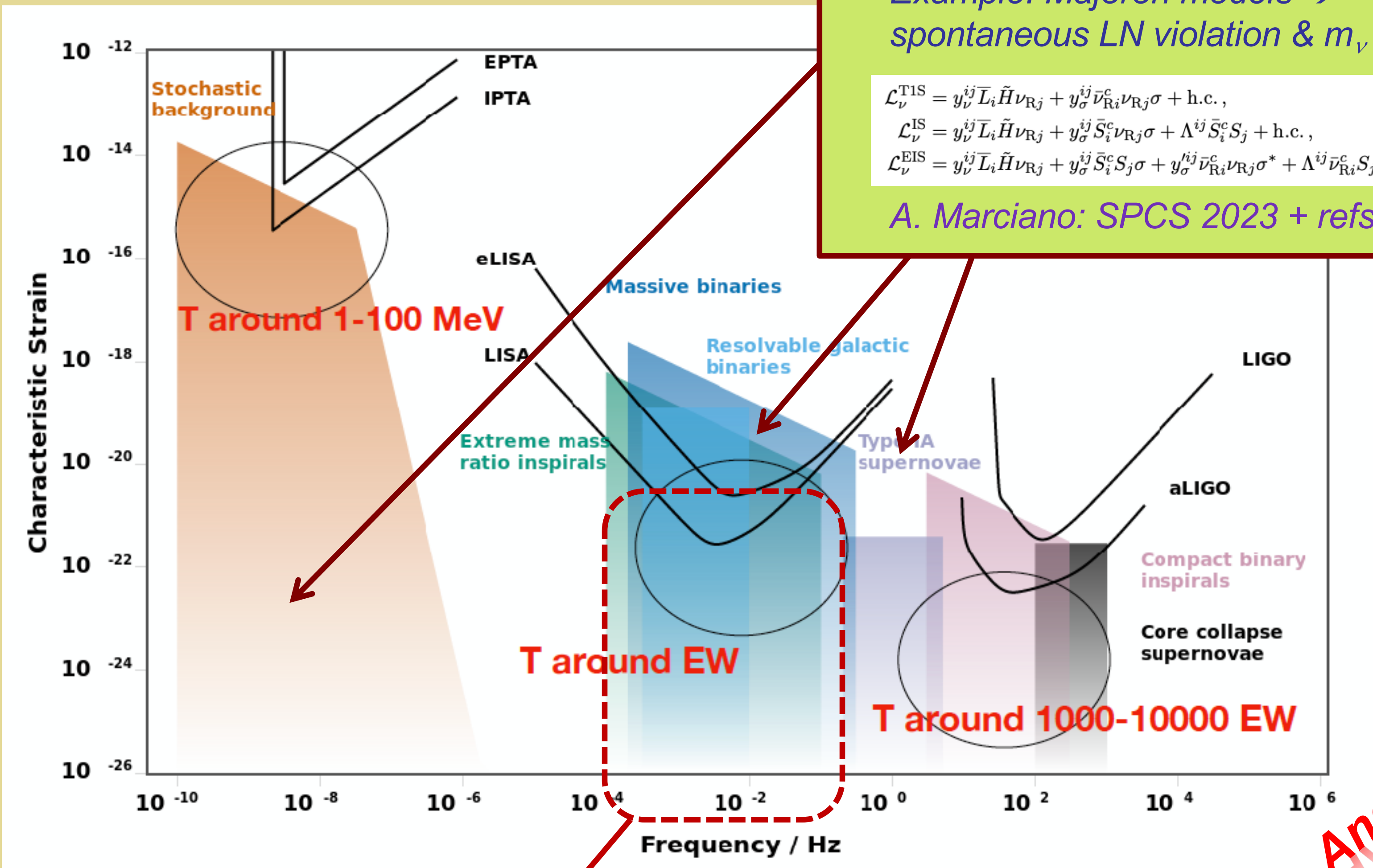
$$\mathcal{L}_\nu^{\rm T1S} = y_\nu^{ij}\overline{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{\nu}_{{\rm R}i}^c\nu_{{\rm R}j}\sigma + {\rm h.c.}\,,$$
$$\mathcal{L}_\nu^{\rm IS} = y_\nu^{ij}\overline{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{S}_i^c\nu_{{\rm R}j}\sigma + \Lambda^{ij}\bar{S}_i^c S_j + {\rm h.c.}\,,$$
$$\mathcal{L}_\nu^{\rm EIS} = y_\nu^{ij}\overline{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{S}_i^c S_j\sigma + y_\sigma^{\prime ij}\bar{\nu}_{{\rm R}i}^c\nu_{{\rm R}j}\sigma^* + \Lambda^{ij}\bar{\nu}_{{\rm R}i}^c S_j + {\rm h.c.}$$

A. Marciano: SPCS 2023 + refs



Phase transition associated with spontaneous LNV → non-astrophysical GW source

LNV Scalar Field & GW



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$$\mathcal{L}_\nu^{\rm EIS} = y_\nu^{ij}\overline{L}_i\tilde{H}\nu_{{\rm R}j} + y_\sigma^{ij}\bar{S}_i^c S_j\sigma + y_\sigma'^{ij}\bar{\nu}_{{\rm R}i}^c\nu_{{\rm R}j}\sigma^* + \Lambda^{ij}\bar{\nu}_{{\rm R}i}^c S_j + {\rm h.c.}$$

A. Marciano: SPCS 2023 + refs

Another day

EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales

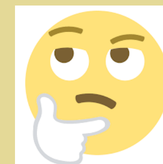
IV. Outlook - A

- *There exists a rich complementarity involving the intensity, high energy, lifetime, and cosmic frontiers*
- *For EW precision BSM probes, it's all about the error bars → challenge for EIC*
- *NP fundamental symmetry tests poised to discover BSM footprints, while BSM searches at the high energy, lifetime, and cosmic frontiers could discover the underlying dynamics (LNV as a "poster child")*

IV. Outlook - B

What are the EIC implications ?

- ***EIC EW precision tests as a BSM probe: may have limited impact***



- ***EIC fundamental symmetry tests: competition for lepton number, baryon number, CP is tough but charged lepton flavor violation is a unique opportunity***

  - *Gonderinger, MJRM, JHEP 11 (2010) 045*
  - *Cirigliano, Fuyuto, Lee, Mereghetti, Yan, JHEP 03 (2021) 256*
  - *Talks in this workshop*