LEPTOGENESI A BASSA SCALA E PROSPETTIVE SPERIMENTALI

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Incontri di Fisica delle Alte Energie 2019

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In collaborazione con:

A. Abada, G. Arcadi, V. Domcke, M. Drewes, A. Giammanco, J. Hajer, J. Klaric and O. Mattelaer

UCLouvain

Observational problems of the SM

Two seemingly unrelated observations cannot be accounted for in the Standard Model

NuFIT 3.2 (2018)

Neutrinos are massive and leptons mix

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler and T. Schwetz, arXiv:1611.01514 [hep-ph]

The Universe has a negligible amount of antimatter

$$\eta_{\Delta B} = (6.13 \pm 0.03) \times 10^{-10}$$

N. Aghanim *et al.* [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO]

The natural (simple) way

Complete the SM field pattern with **right-handed neutrinos**

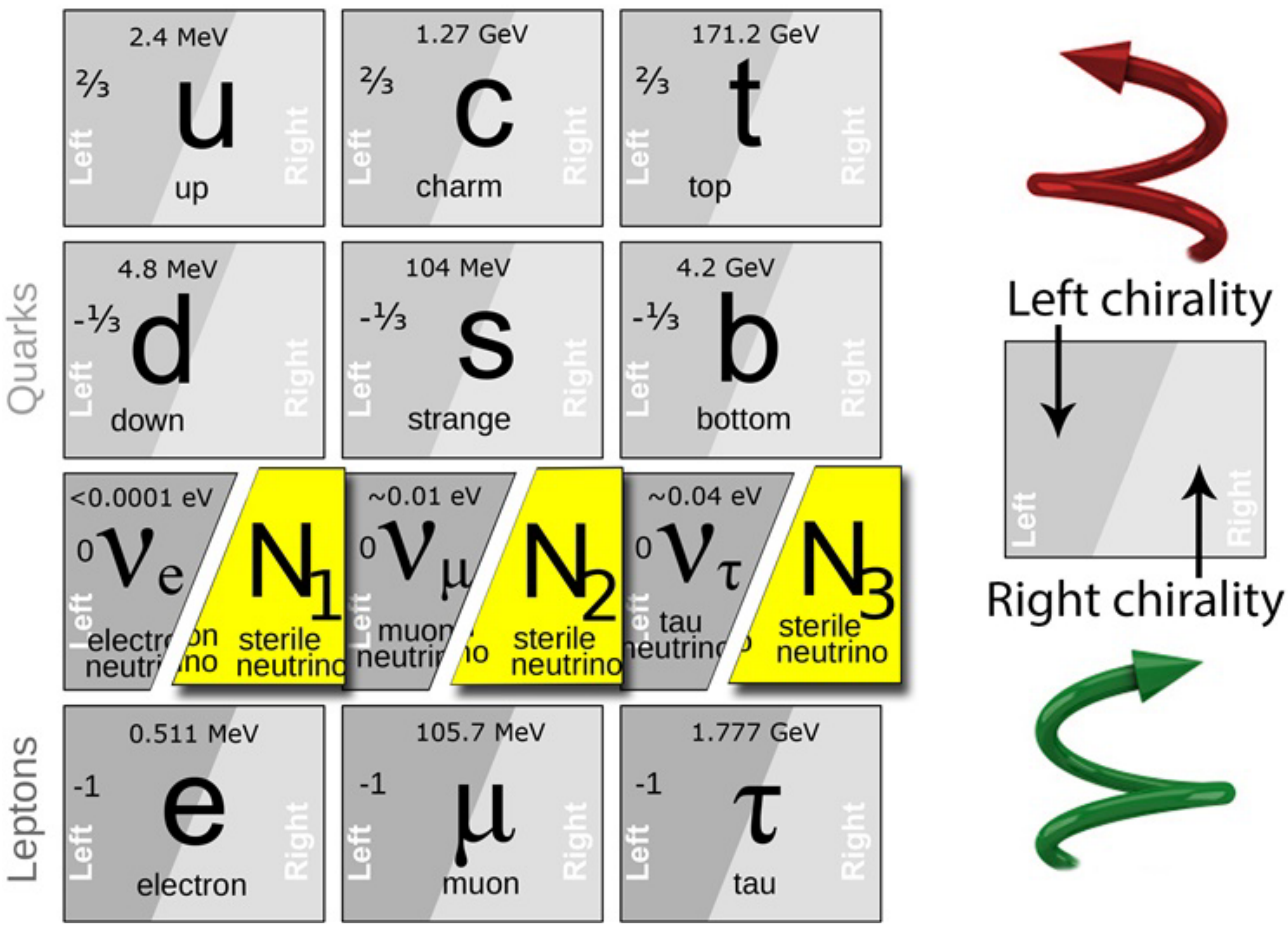

Figure from S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

Neutrino masses and leptogenesis

Type-I seesaw mechanism: SM + gauge singlet fermions N_I

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N_I}\partial\!\!\!/ N_I - \left(F_{\alpha I}\overline{\ell_L^\alpha}\widetilde{\phi}N_I + \frac{M_{IJ}}{2}\overline{N_I^c}N_J + h.c. \right)$$

After electroweak phase transition $< \Phi > = v \simeq 174$ GeV

$$m_\nu = -v^2 F \frac{1}{M} F^T$$

The Lagrangian provides the ingredients for leptogenesis too

Sakharov conditions

- **Complex Yukawa** couplings ***F*** as a source of $\not{CP}$ ✓
- $\not{B}$ from sphaleron transitions until $T_{EW} \simeq 140$ GeV ✓
- sterile neutrinos deviations from thermal equilibrium ✓

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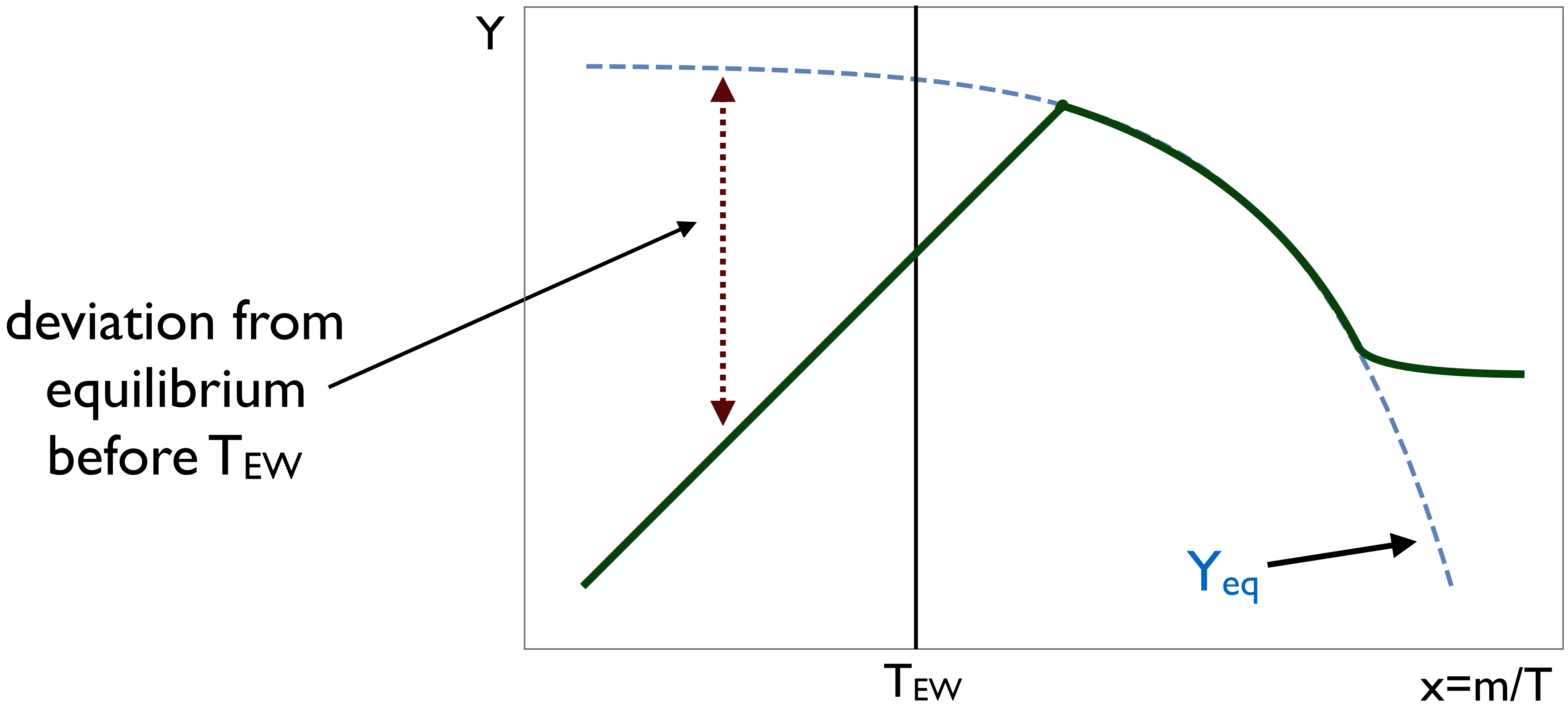
- **Complex Yukawa** couplings ***F*** as a source of ~~**CP**~~ ✓
- ~~B~~ from sphaleron transitions above $T_{EW} \simeq$ 140 GeV ✓
- sterile neutrinos deviations from thermal equilibrium ✓

BAU: ARS mechanism

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255

Sterile neutrinos out of equilibrium at large temperatures



From the seesaw relation

$$m_\nu = -v^2 F \frac{1}{M} F^T \simeq 0.3 \left(\frac{\text{GeV}}{M}\right)\left(\frac{F^2}{10^{-14}}\right) \text{eV}$$

M ~ GeV to reproduce ν masses → **Testable**

ARS leptogenesis

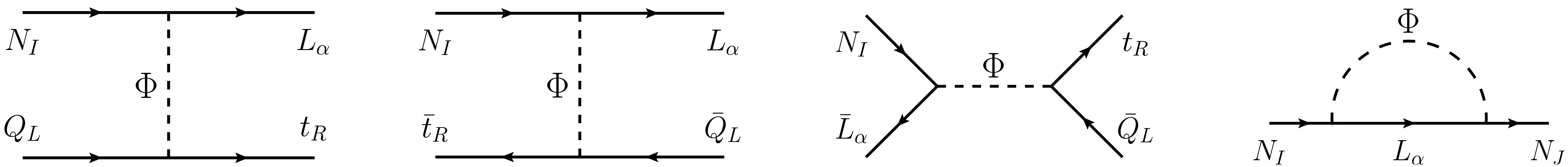
<u>How does the mechanism work?</u>

A. Abada, S. Antusch, E. K. Akhmedov, G. Arcadi, T. Asaka, S. Blanchet, I. Boiarska, K. Bondarenko, A. Boyarsky, L. Canetti, A. Caputo, E. Cazzato, V. Domcke, M. Drewes, S. Eijima, O. Fischer, T. Frossard, B. Garbrecht, J. Ghiglieri, D. Gueter, T. Hambye, P. Hernández, H. Ishida, M. Kekic, J. Klaric, M. Laine, J. López-Pavón, M.L., M. Ovchynnikov, J. Racker, N. Rius, V. A. Rubakov, O. Ruchayskiy, J. Salvado, M. Shaposhnikov, A. Y. Smirnov, D. Teresi, I. Timiryasov…

Two kinds of $\not{CP}$ processes

Lepton number conserving

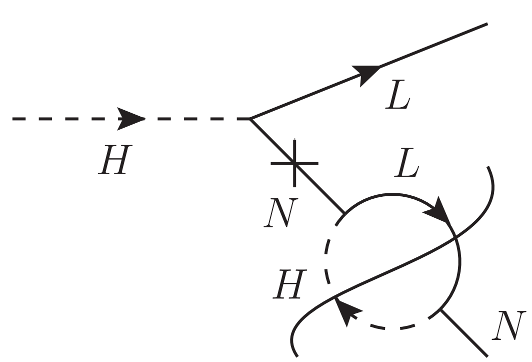
(neutrino generation and oscillations)



Lepton number violating

(thermal Higgs decay)

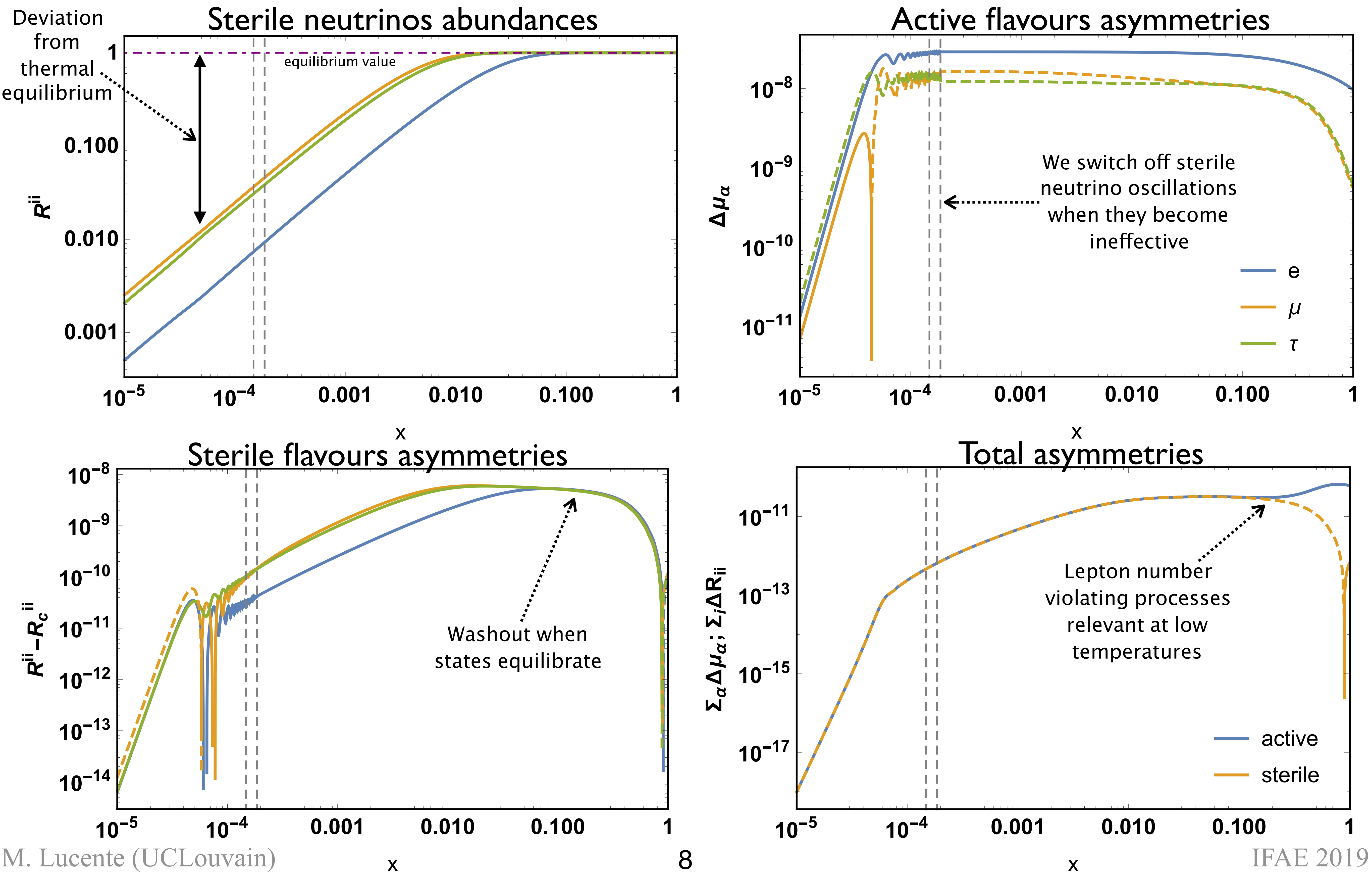
T. Hambye and D. Teresi, arXiv:1606.00017 [hep-ph], arXiv:1705.00016 [hep-ph]



$\propto \dfrac{M^2}{T^2}$ relevant at late times

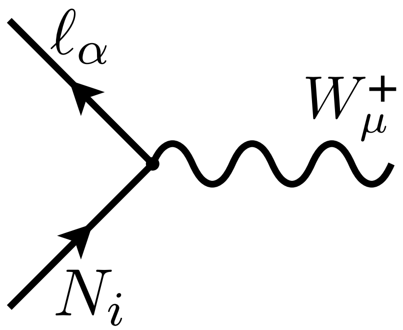
Asymmetry generation example with 3 RHN

$x = \frac{T}{T_{\rm EW}}$ T_{EW} = 140 GeV R :sterile neutrinos density matrix μ_α : active flavours chemical potentials

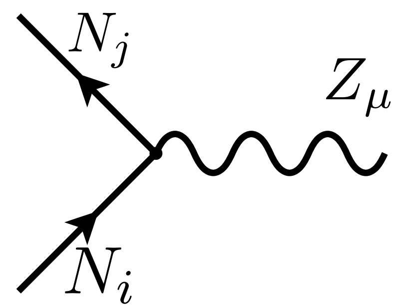


HNL phenomenology

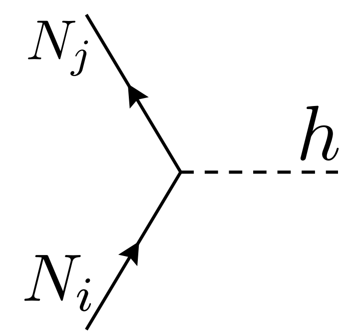
$$C_{ij} \equiv \sum_{\alpha=e,\mu,\tau} \mathcal{U}^*_{\alpha i}\,\mathcal{U}_{\alpha j}$$



$\propto i\,\frac{g}{\sqrt{2}}\mathcal{U}_{\alpha i}$



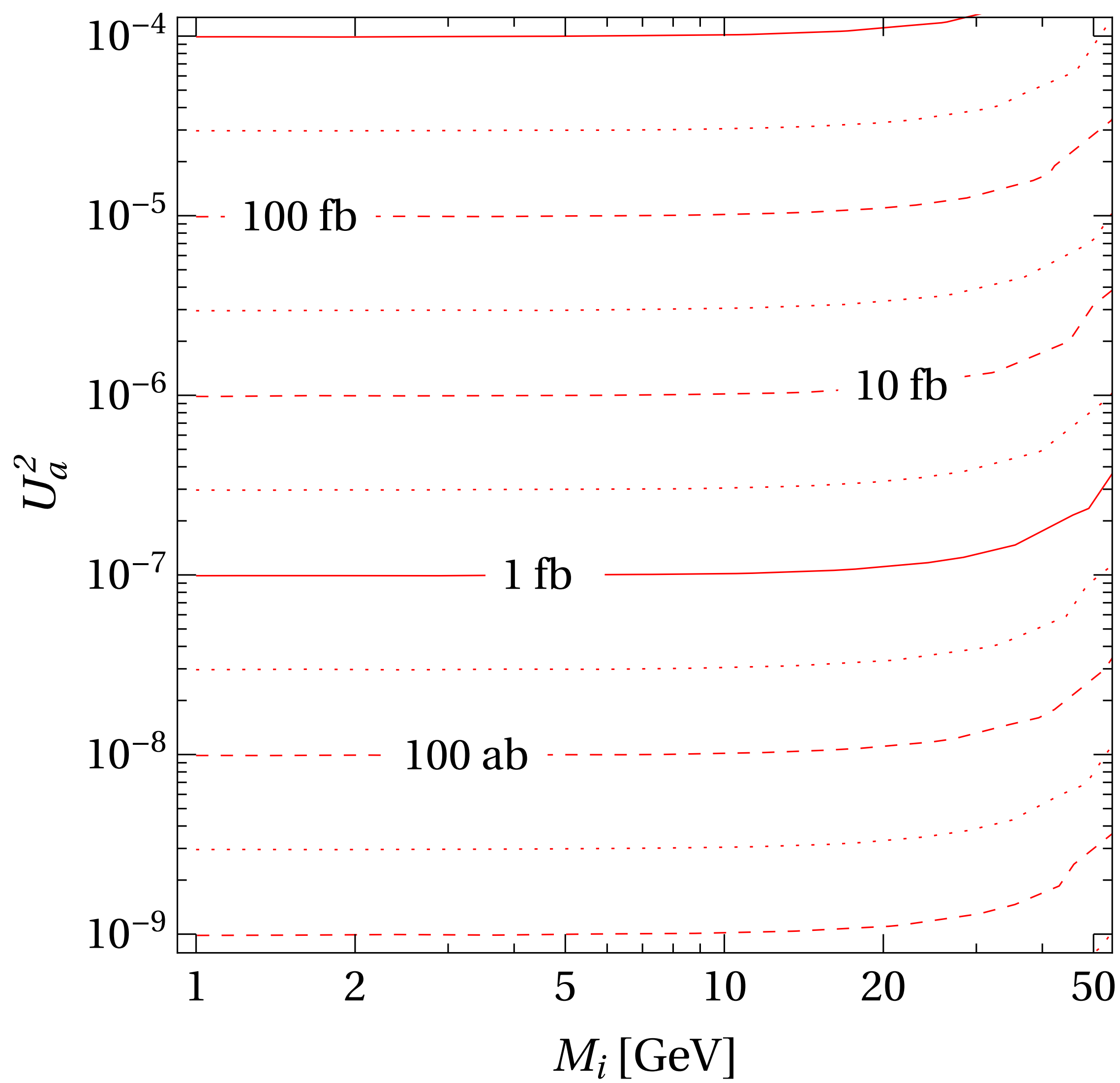
$\propto i\,\frac{g}{4c_w}C_{ji}$



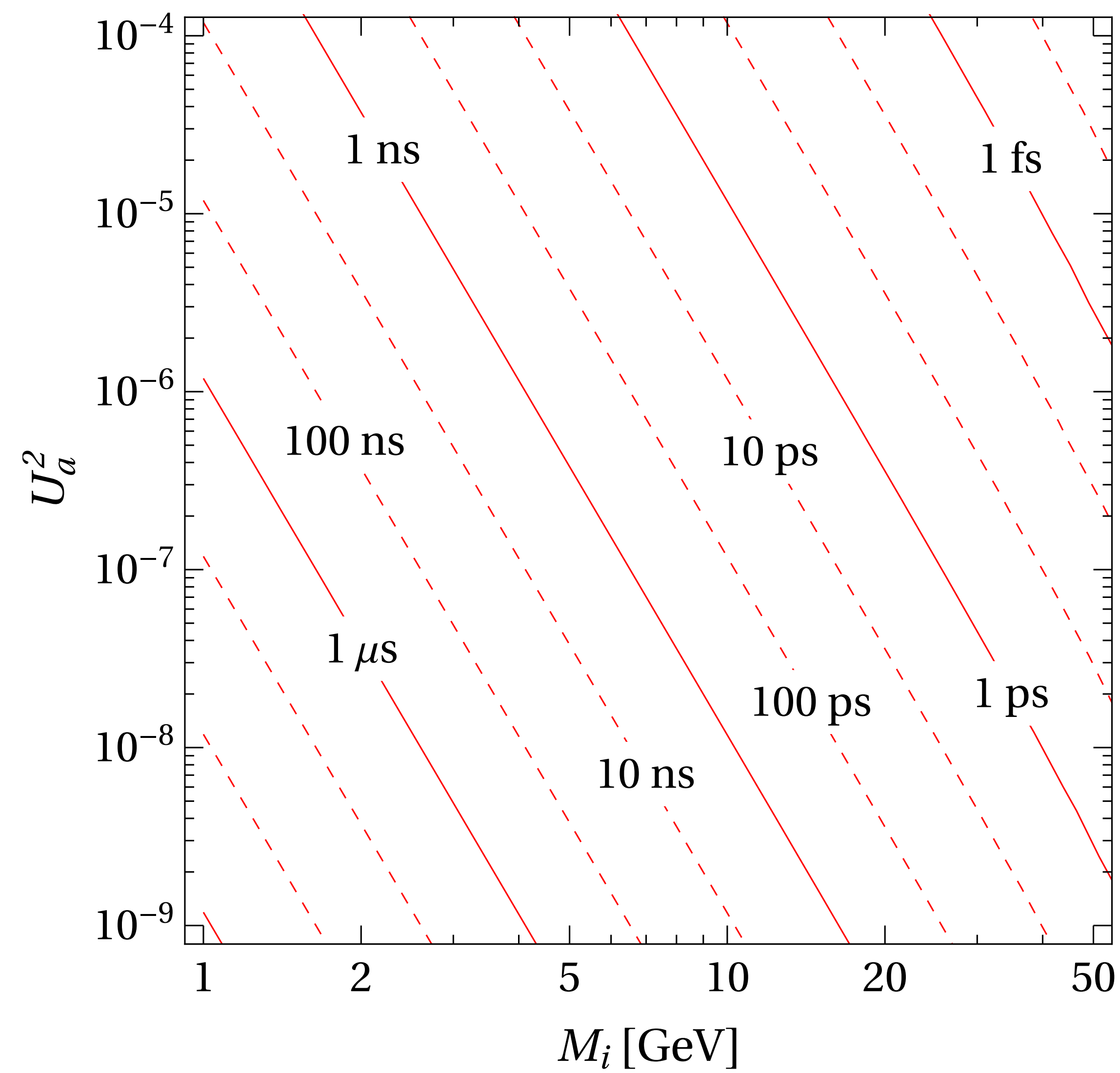
$\propto i\,\frac{g}{4}\frac{m_j}{M_W}C_{ji}$

M. Drewes and J. Hajer, arXiv:1903.06100 [hep-ph]

Production cross section



Lifetime



$\sigma \propto U_a^2$ for $M \lesssim 50$ GeV

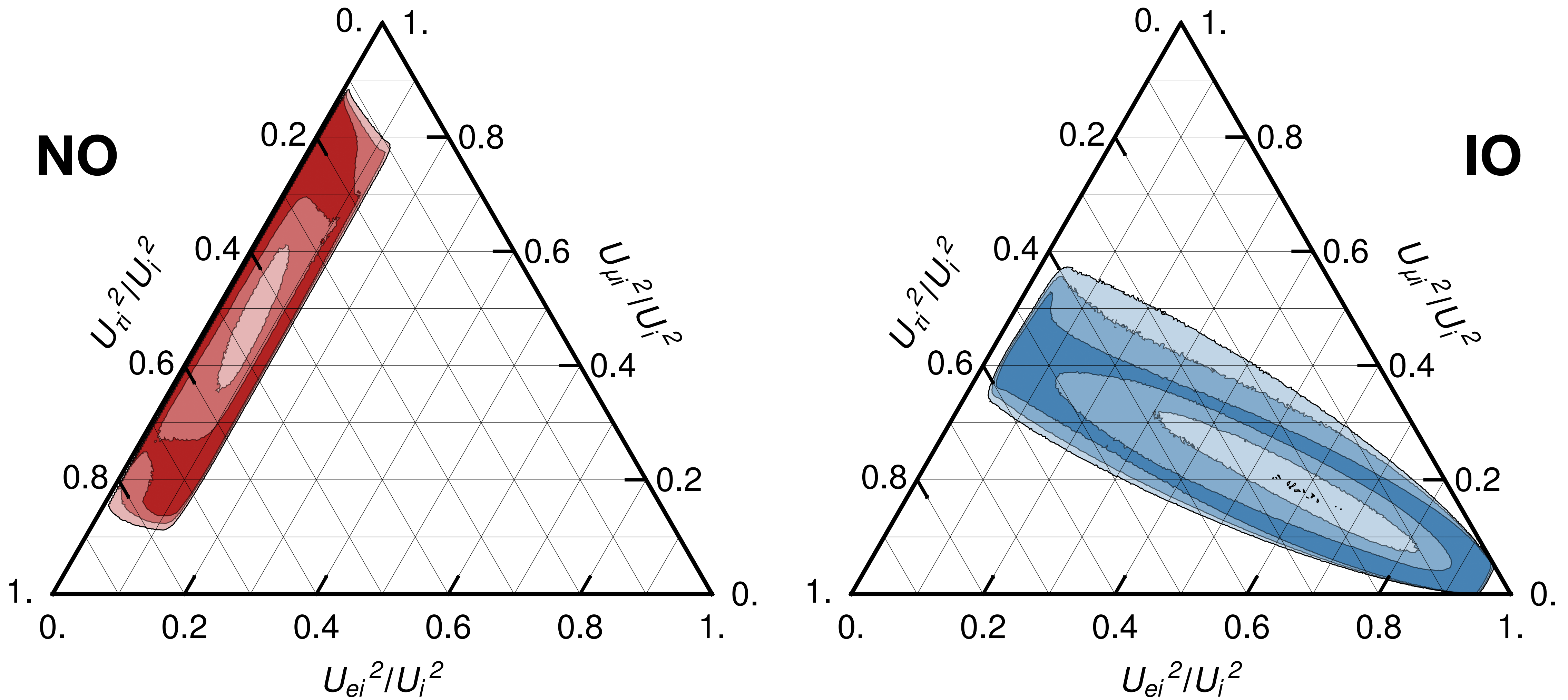
GeV masses result in observable **macroscopic displacement**

The minimal scenario: 2 RH-Neutrinos

Two RH-neutrinos suffice to account for neutrino oscillation data

S. F. King, hep-ph/9912492, hep-ph/0204360
P. H. Frampton, S. L. Glashow and T. Yanagida, hep-ph/0208157
A. Donini, P. Hernandez, J. Lopez-Pavon and M. Maltoni, arXiv:1106.0064 [hep-ph]

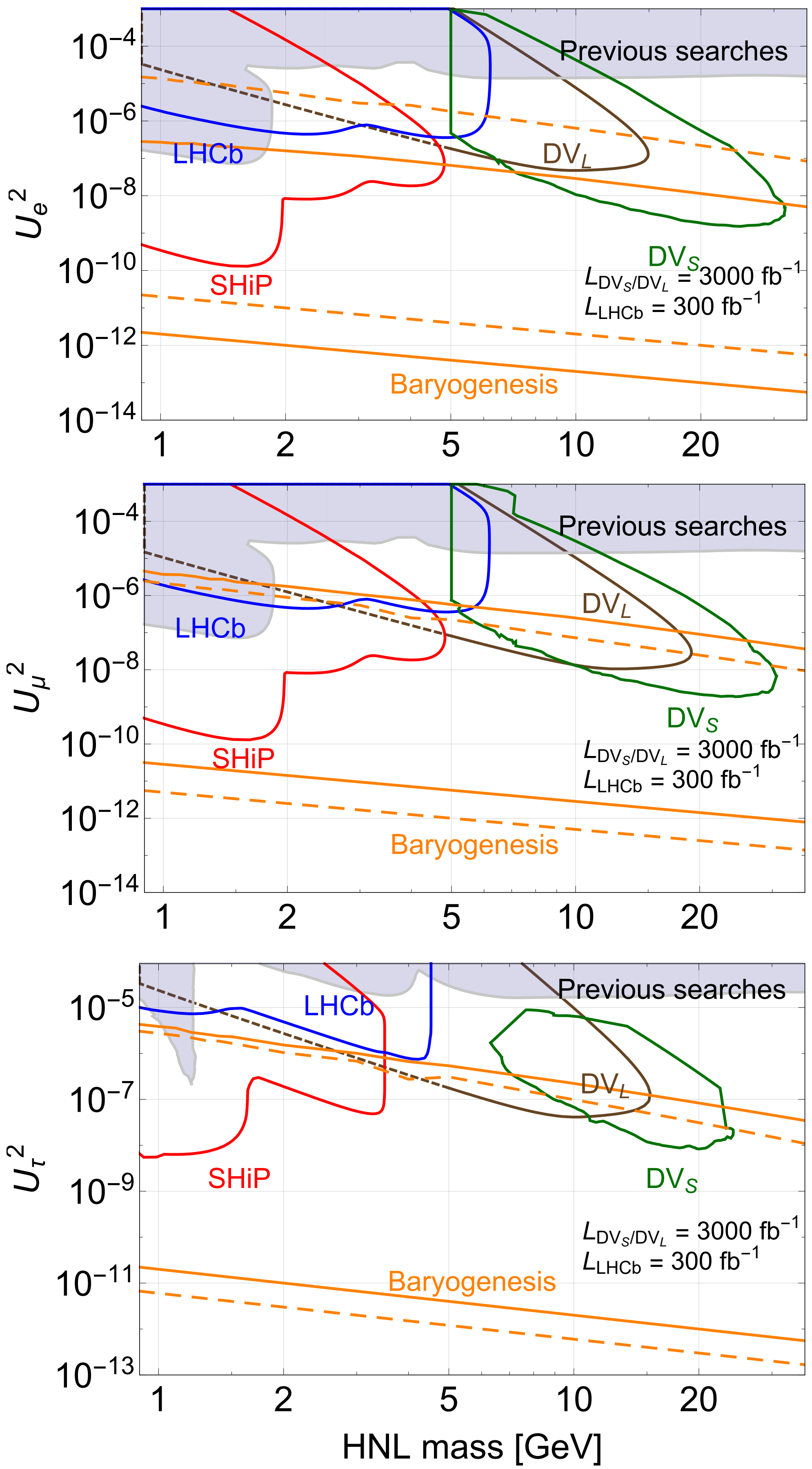
Constrained flavour pattern



M. Drewes, J. Hajer, J. Klaric and G. Lanfranchi, arXiv:1801.04207 [hep-ph]
A. Caputo, P. Hernandez, J. Lopez-Pavon and J. Salvado, arXiv:1704.08721 [hep-ph]

Large hierarchies in the couplings to different SM flavours not allowed

Leptogenesis with 2 RH-neutrinos



Too large active-sterile couplings enable equilibration of HNL and asymmetry washout

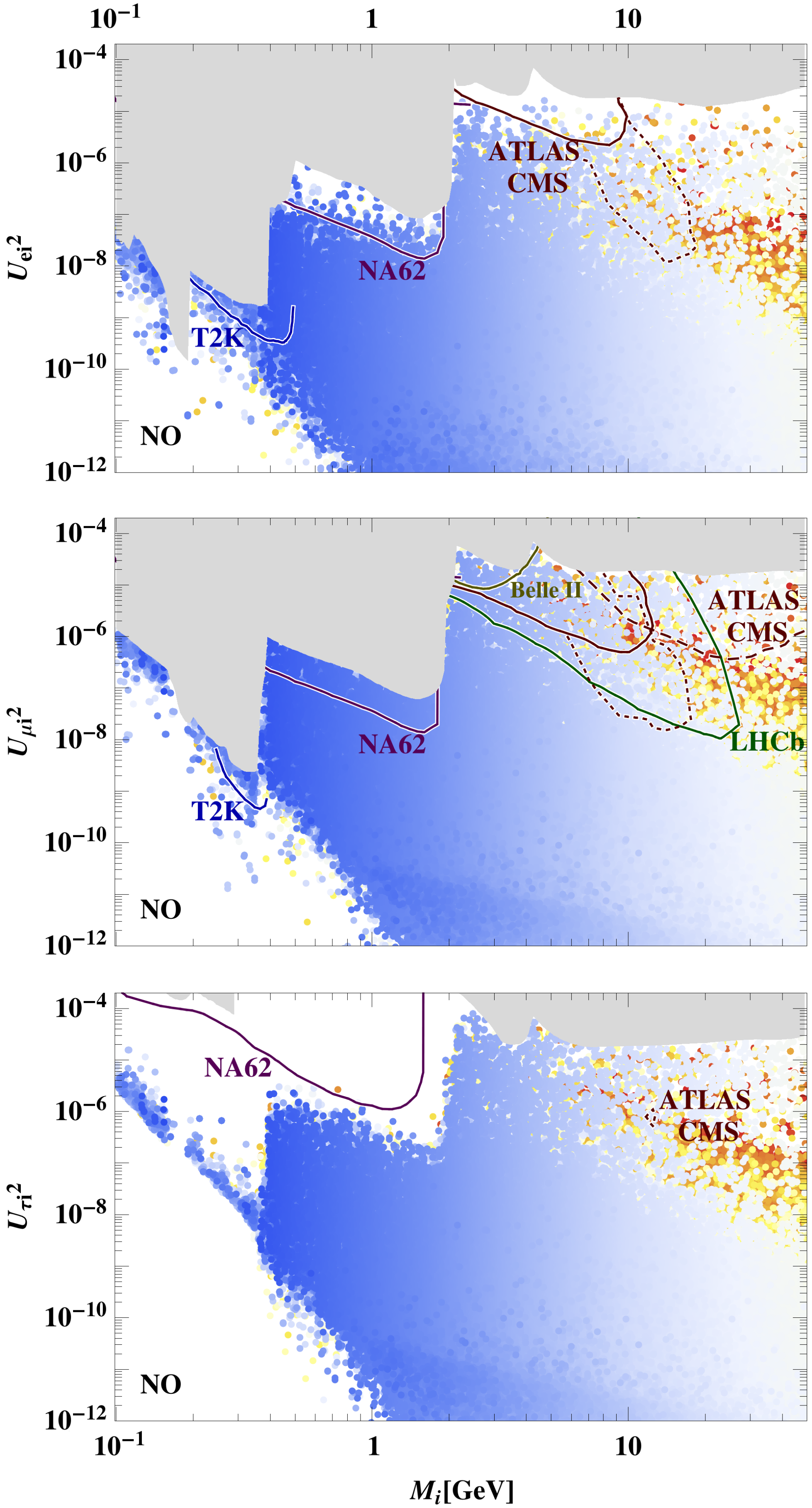
Washout is flavour-dependent, but "democratic" couplings for 2 RHN

Not possible to store the asymmetry in a feebly coupled flavour while the other mixings are large

Figures from I. Boiarska, K. Bondarenko, A. Boyarsky, S. Eijima, M. Ovchynnikov, O. Ruchayskiy and I. Timiryasov, arXiv:1902.04535 [hep-ph]

See also L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]; A. Abada, G. Arcadi, V. Domcke and M.L., arXiv:1507.06215, arXiv:1709.00415 [hep-ph]; P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, arXiv:1508.03676, arXiv:1606.06719 [hep-ph]; S. Eijima, M. Shaposhnikov and I. Timiryasov, arXiv:1808.10833 [hep-ph]

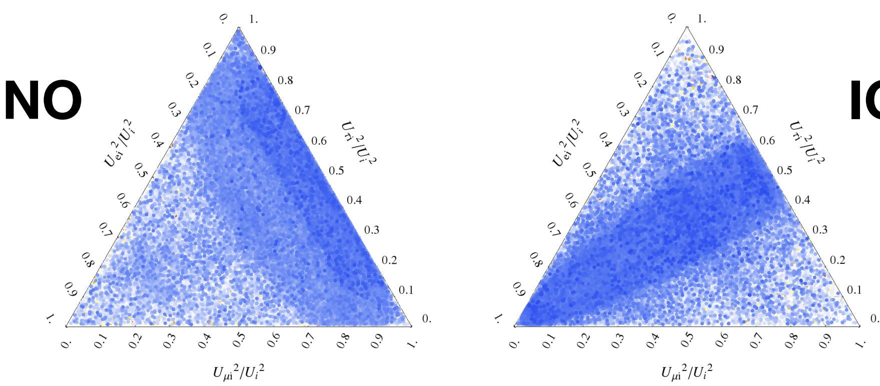
Leptogenesis with 3 RH-neutrinos



New effects peculiar to 3 RHN case

Larger flavour hierarchies are allowed

NO



IO

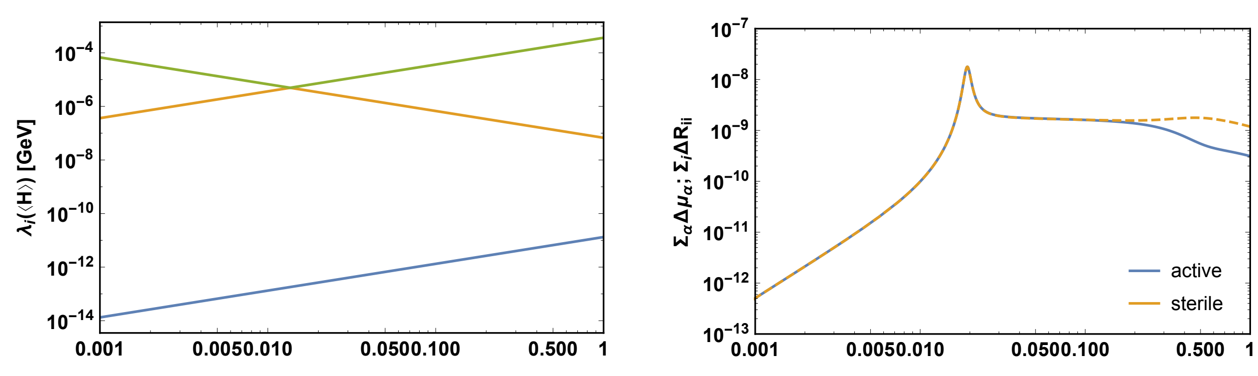
Asymmetry in the heavy neutrino oscillations

2 flavour oscillations are CP-conserving

3 flavour oscillations are CP-violating

→ New source term

Resonantly enhanced asymmetry

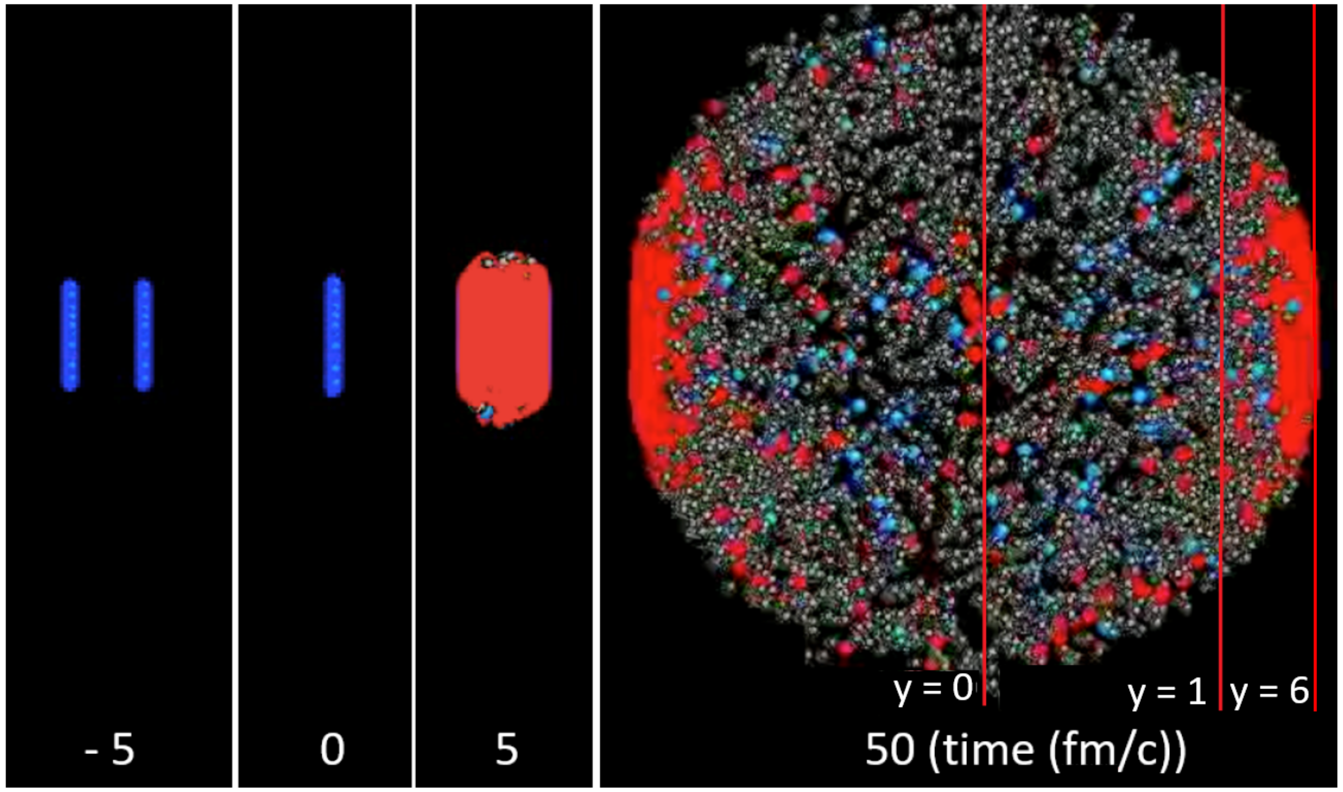


A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M.L., arXiv:1810.12463 [hep-ph]

A Heavy Metal Path to New Physics

Heavy ion collisions

Each nucleus ${}^{A}_{Z}N$ contains A nucleons



In *NN* collisions, number of parton level interactions enhanced by a factor A^2

For instance with ${}^{208}_{82}\mathrm{Pb}$ ▶ $\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{\mathrm{pp}}} \propto A^2 \simeq 4.3 \times 10^4$

See also R. Bruce *et al.*, arXiv:1812.07688 [hep-ph]

Features of Heavy Ions runs

Smaller collision energy

$$\sqrt{s_{\mathrm{PbPb}}} = 5.52 \text{ TeV} \quad \textit{vs} \quad \sqrt{s_{\mathrm{pp}}} = 14 \text{ TeV}$$

Lower instantaneous luminosity

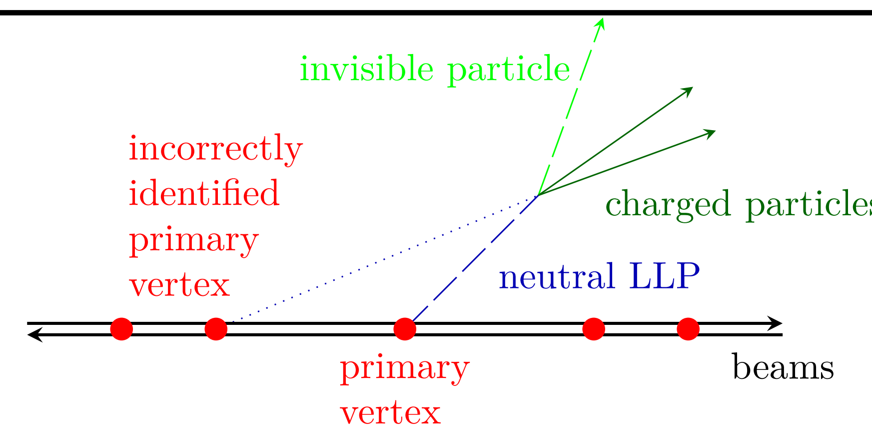
Int. luminosity	expected *pp*	expected PbPb
Run 2	100 fb^{-1}	1 nb^{-1}
HL LHC	3000 fb^{-1}	10 nb^{-1}

Cross section enhancement

$$\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{\mathrm{pp}}} \propto A^2 \simeq 4.3 \times 10^4$$

Lower primary vertex mis-identification

(no pile-up)



Larger track multiplicity

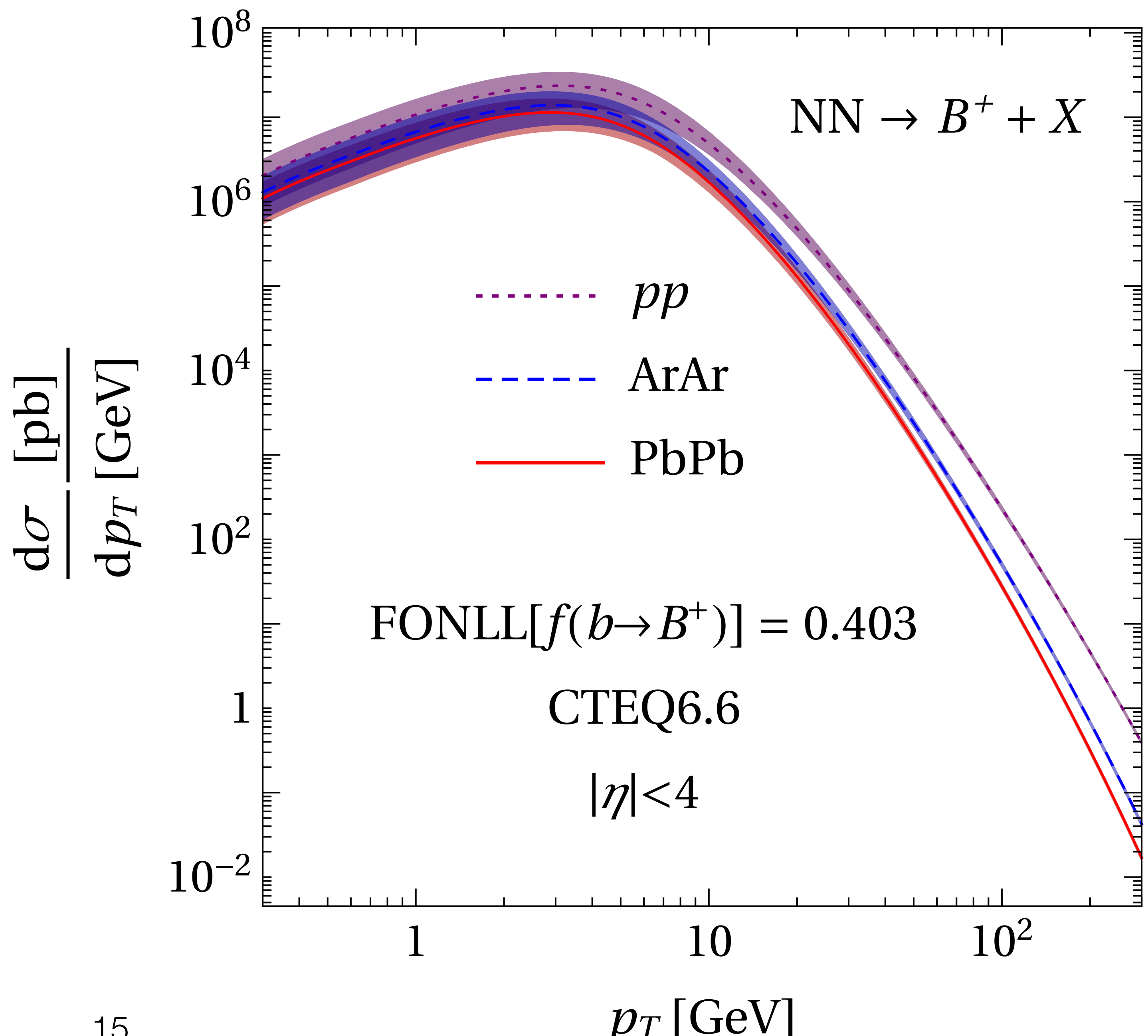
Charged tracks	*pp*	PbPb
Run 3	~ 750	~ 10000
HL LHC	~ 5000	~ 10000

Lower instantaneous luminosity

The lower instantaneous luminosity allows to lower the trigger thresholds

Can test regions of parameter space that are difficult to be tested with protons

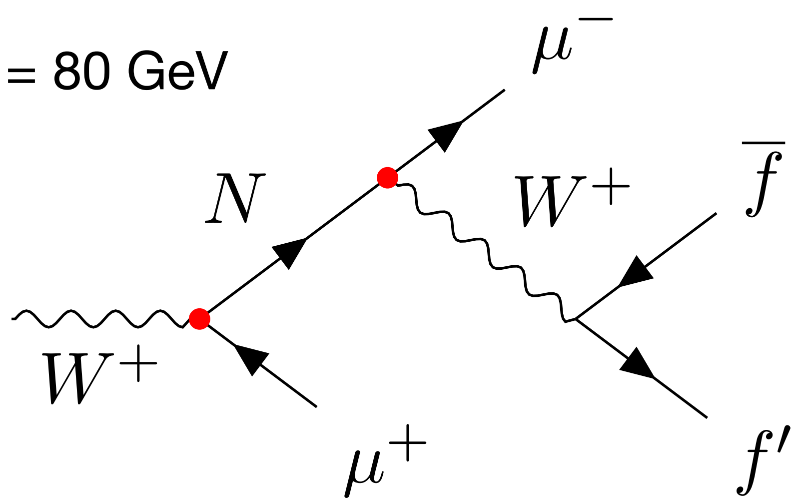
E.g. scenarios involving light mediators result in signatures with low transverse momentum p_T



HNL production/decay

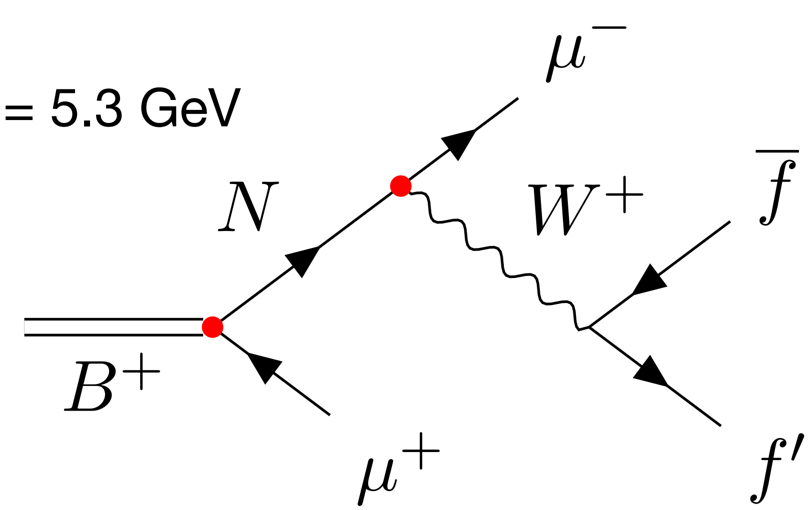
We consider two channels: W and B mediated HNL production

M_W = 80 GeV



- Fully simulated using `MadGraph5_aMC@NLO`
- trigger on first μ with **p_T > 25 GeV**
- search for displaced μ with d > 5 mm

M_B = 5.3 GeV



- Cannot be fully simulated in `MadGraph5_aMC@NLO`
- Use analytic estimate validated against W simulation

$$N_d = \frac{L_{\text{int}}\sigma_B^{[A,Z]}}{9}\left[1-\left(\frac{M_i}{m_B}\right)^2\right]^2 U_\mu^2\left(e^{-l_0\lambda}-e^{-l_1\lambda}\right) f_{\text{cut}}$$

- trigger on first μ with **p_T > 3 GeV for HI collisions**, realistic online trigger for pp collisions
- search for displaced μ with d > 5 mm

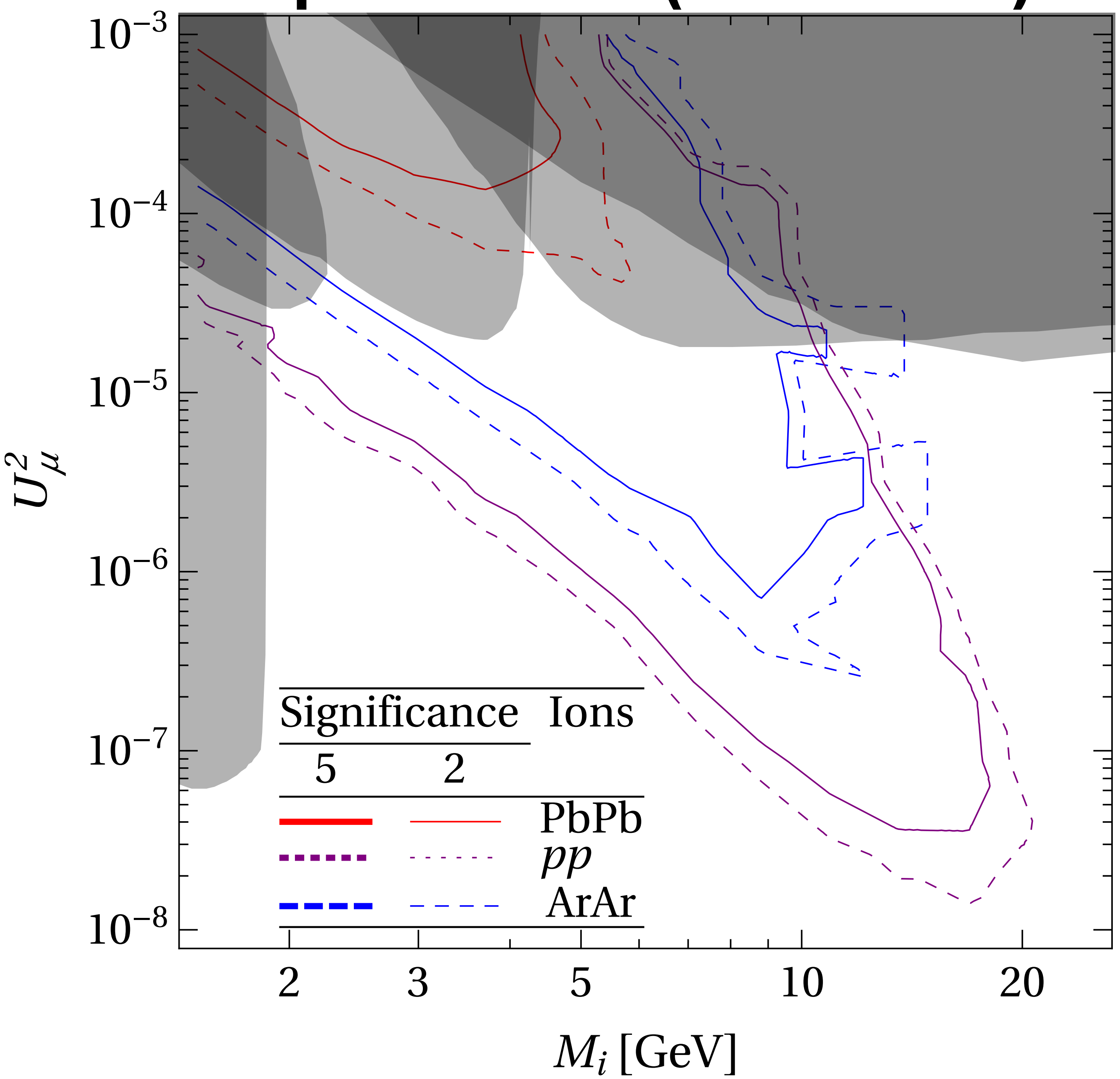
Results

Same running time

$$L_{\text{int}}(pp) = 5.79 \times 10^4 \text{ pb}^{-1}$$
$$L_{\text{int}}(\text{ArAr}) = 7.72 \text{ pb}^{-1}$$
$$L_{\text{int}}(\text{PbPb}) = 10^{-2} \text{ pb}^{-1}$$

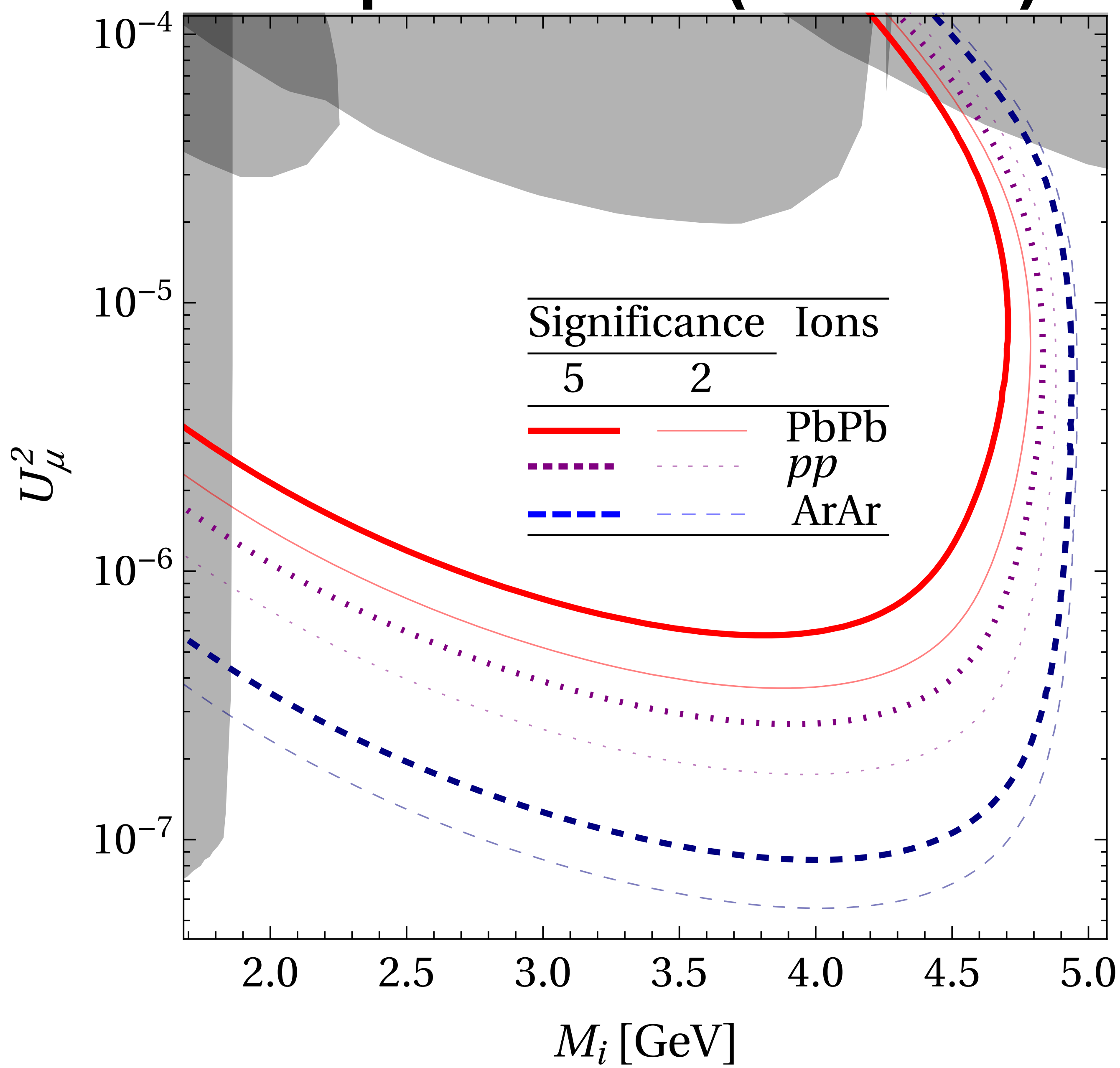
M. Drewes, A. Giammanco, J. Hajer, M.L. and O. Mattelaer, arXiv:1810.09400 [hep-ph]

W-production (simulation)



- Event rate **not competitive**
- **Complementary** test of BSM

B-production (estimate)



- Gain from low p_T **overcompensates** smaller luminosity
- **Intermediate** mass **ions** more competitive than *pp* and PbPb

Conclusion

We performed the **first systematic study** of the **low-scale leptogenesis** scenario in the minimal Standard Model extended with **3 right-handed neutrinos** having masses at the **GeV scale**

Low-scale solutions are **testable** in **current experiments** in the large-mixing region

Heavy ion collisions allow to search for **hidden new physics**

Lower trigger requirements could be the key advantage of heavy ion collisions over proton collisions

HNL are a **simple example** of this idea, but other models are just as well testable

Backup

Kinetic equations for freeze-in leptogenesis

G. Sigl and G. Raffelt, Nucl. Phys. B 406 (1993) 423; E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255; T. Asaka and M. Shaposhnikov, hep-ph/0505013; T. Asaka, S. Eijima and H. Ishida, arXiv:1112.5565 [hep-ph]; L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]; P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, arXiv:1606.06719 [hep-ph]; S. Antusch, E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter and J. Klaric, arXiv:1710.03744 [hep-ph]; A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M.L., arXiv:1810.12463 [hep-ph]

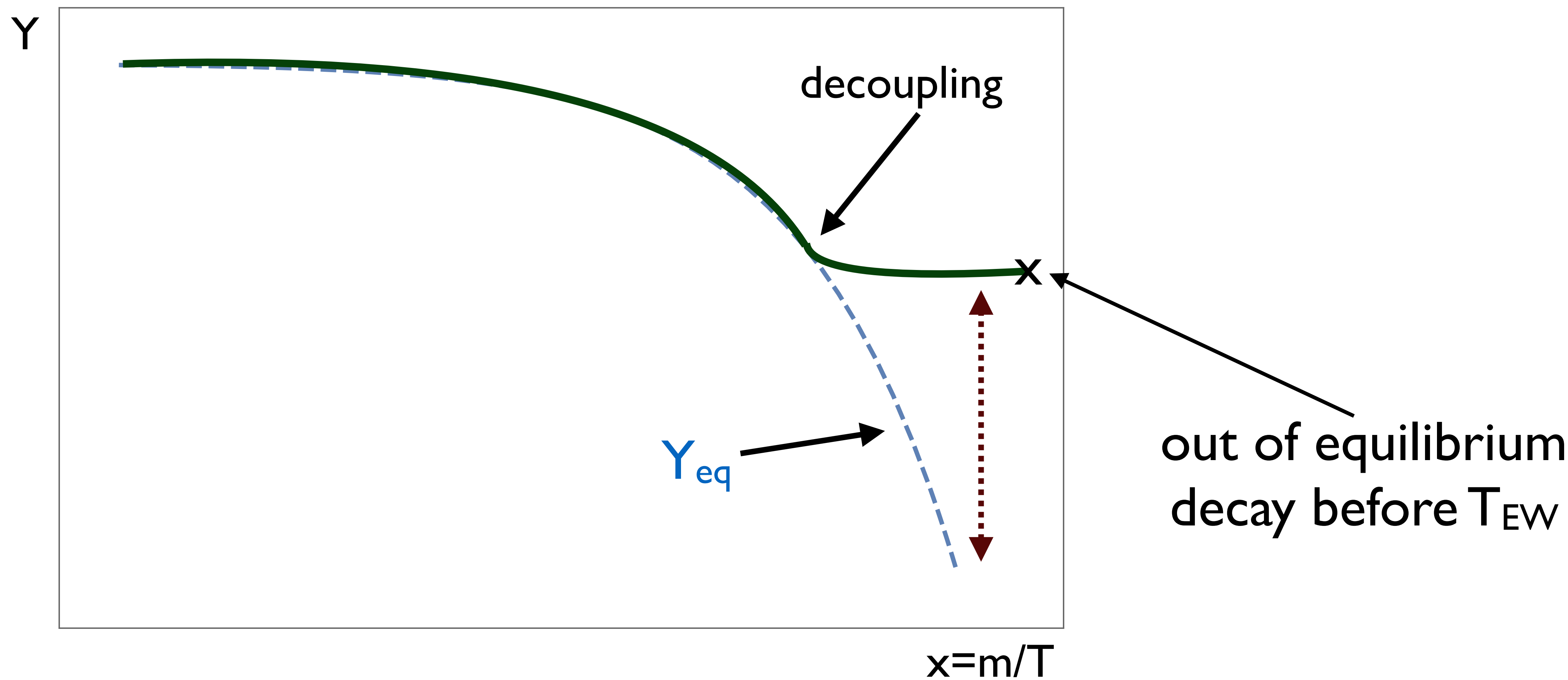
$$\begin{aligned}\frac{dR_N}{dt} =& - i\,[\langle H\rangle, R_N] - \frac{1}{2}\langle\gamma^{(0)}\rangle \left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle \left\{F^\dagger \mu F, R_N\right\} + \langle\gamma^{(1a)}\rangle F^\dagger \mu F + \\ & - \frac{1}{2}\langle\widetilde{\gamma}^{(0)}\rangle \left\{M_M F^T F^* M_M, R_N - I\right\} + \frac{1}{2}\langle\widetilde{\gamma}^{(1b)}\rangle \left\{M_M F^T \mu F^* M_M, R_N\right\} + \\ & - \langle\widetilde{\gamma}^{(1a)}\rangle M_M F^T \mu F^* M_M \,,\end{aligned}$$

$$\begin{aligned}\frac{d\mu_{\Delta_a}}{dt} =& - \frac{9\,\zeta(3)}{2N_D\,\pi^2} \Big\{\langle\gamma^{(0)}\rangle \left(F R_N F^\dagger - F^* R_{\bar N} F^T\right) - 2\langle\gamma^{(1a)}\rangle \mu F F^\dagger + \\ & + \langle\gamma^{(1b)}\rangle \mu \left(F R_N F^\dagger + F^* R_{\bar N} F^T\right) \\ & + \langle\widetilde{\gamma}^{(0)}\rangle \left(F^* M_M R_{\bar N} M_M F^T - F M_M R_N M_M F^\dagger\right) - 2\langle\widetilde{\gamma}^{(1a)}\rangle \mu F^* M_M^2 F^T \\ & + \langle\widetilde{\gamma}^{(1b)}\rangle \mu \left(F^* M_M R_{\bar N} M_M F^T + F M_M R_N M_M F^\dagger\right)\Big\}_{aa} \,,\end{aligned}$$

BAU: Thermal leptogenesis

Sterile neutrinos in thermal equilibrium if $|F| \gtrsim 10^{-7}$

Thermal leptogenesis: sterile neutrinos in equilibrium at large temperatures



<u>Generation of a lepton asymmetry due to the CP-violating decay of the particles</u>

M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45

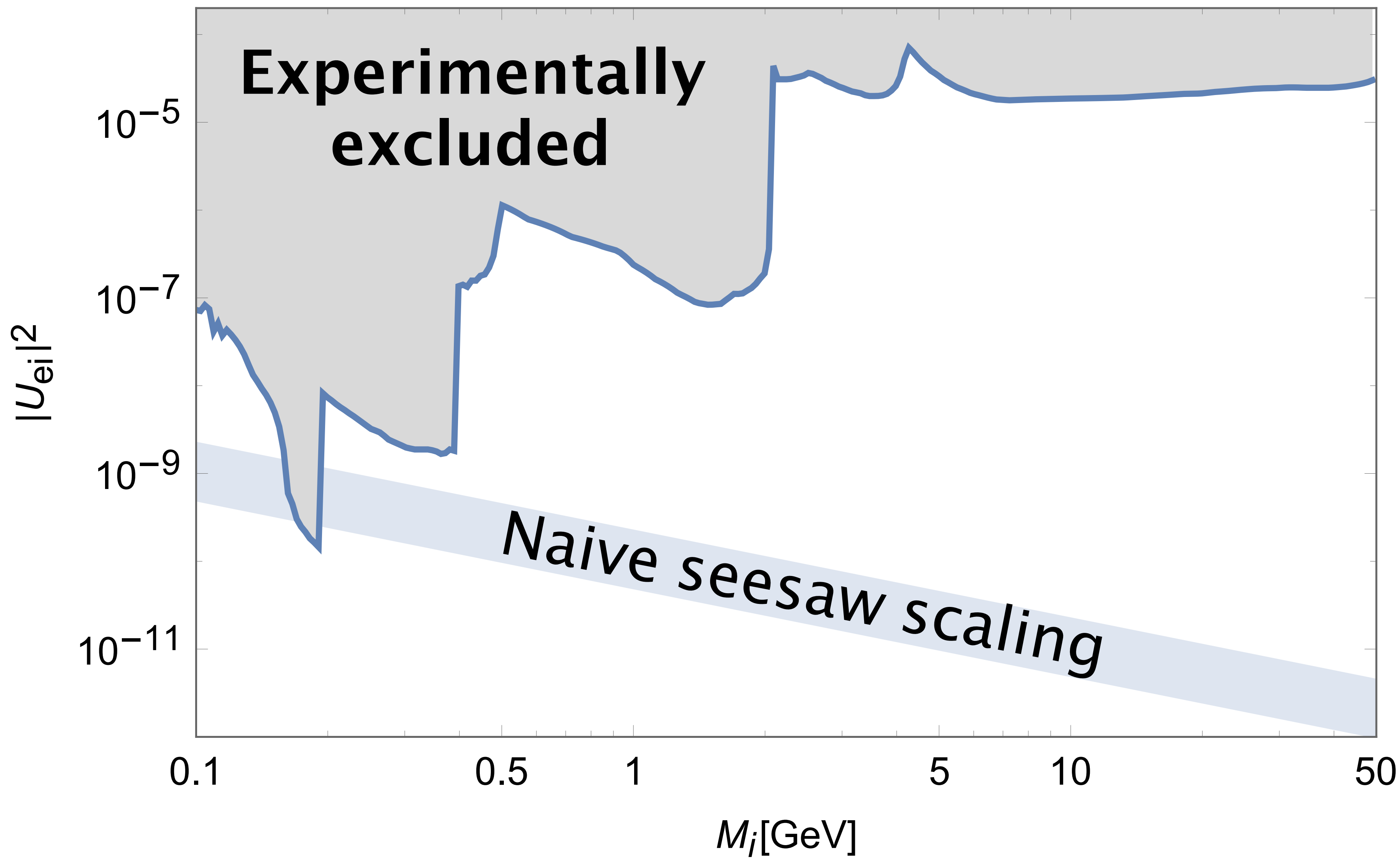
M > 10^6 GeV to reproduce observed BAU (relaxed to M > TeV for degenerate masses) → Difficult to test in laboratory

S. Davidson, E. Nardi and Y. Nir, arXiv:0802.2962 [hep-ph]
A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0605281
A. Pilaftsis and T. E. J. Underwood, hep-ph/0309342
K. Moffat, S. Pascoli, S. T. Petcov, H. Schulz and J. Turner, arXiv:1804.05066 [hep-ph]

Testability?

Seesaw scaling $$m_\nu = -v^2 F \frac{1}{M} F^T$$

In the **absence** of any **structure** in the F and M matrices $$|U_{\alpha i}| \lesssim \sqrt{\frac{m_\nu}{M}} \lesssim 10^{-5}\sqrt{\frac{\text{GeV}}{M}}$$



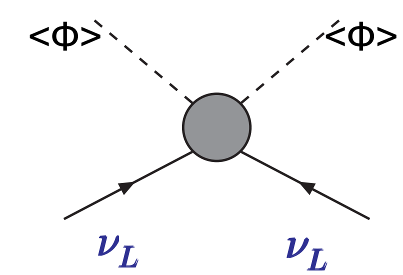
But these are (complex) matrices: cancellations are possible

SM as an effective theory

Relaxing the renormalizability condition there is only one dim=5 gauge invariant operator (Weinberg operator) S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566

ΔL = 2

$$\frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{l^c_{L\alpha}}\widetilde{\Phi}^*\right)\left(\widetilde{\Phi}^\dagger l^\beta_L\right) + h.c. \quad \xrightarrow{\text{EWSB}} \quad \frac{v^2}{2}\frac{c_{\alpha\beta}}{\Lambda}\overline{\nu^c_{L\alpha}}\nu_{L\beta} + h.c.$$



Λ → New physics scale

$$c_{\alpha\beta}\frac{v}{\Lambda}v \lesssim \text{eV} \ll v$$

Why are neutrinos so light?

<u>Suppression mechanisms</u>

- $\frac{v}{\Lambda} \ll 1$ High NP scale
- $c_{\alpha\beta} \ll 1$ Symmetry (Lepton number)
- $c_{\alpha\beta} \ll 1$ Accidental cancellations

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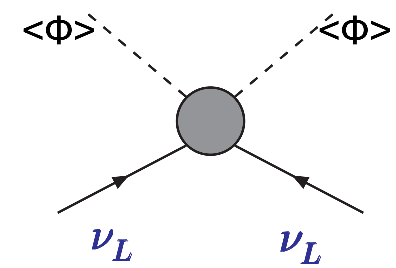

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- $c_{\alpha\beta} \ll 1$ Symmetry (Lepton number)
- $c_{\alpha\beta} \ll 1$ Accidental cancellations

Fine tuning

If a symmetry is present in the Lagrangian, it will be manifest at any order in perturbation theory → The **neutrino mass scale** is **stable** under **radiative corrections**

We compute neutrino masses m_ν at 1-loop, and quantify the level of fine-tuning of a solution as

$$f.t.(m_\nu) = \sqrt{\sum_{i=1}^{3} \left(\frac{m_i^{\text{loop}} - m_i^{\text{tree}}}{m_i^{\text{loop}}} \right)^2}$$

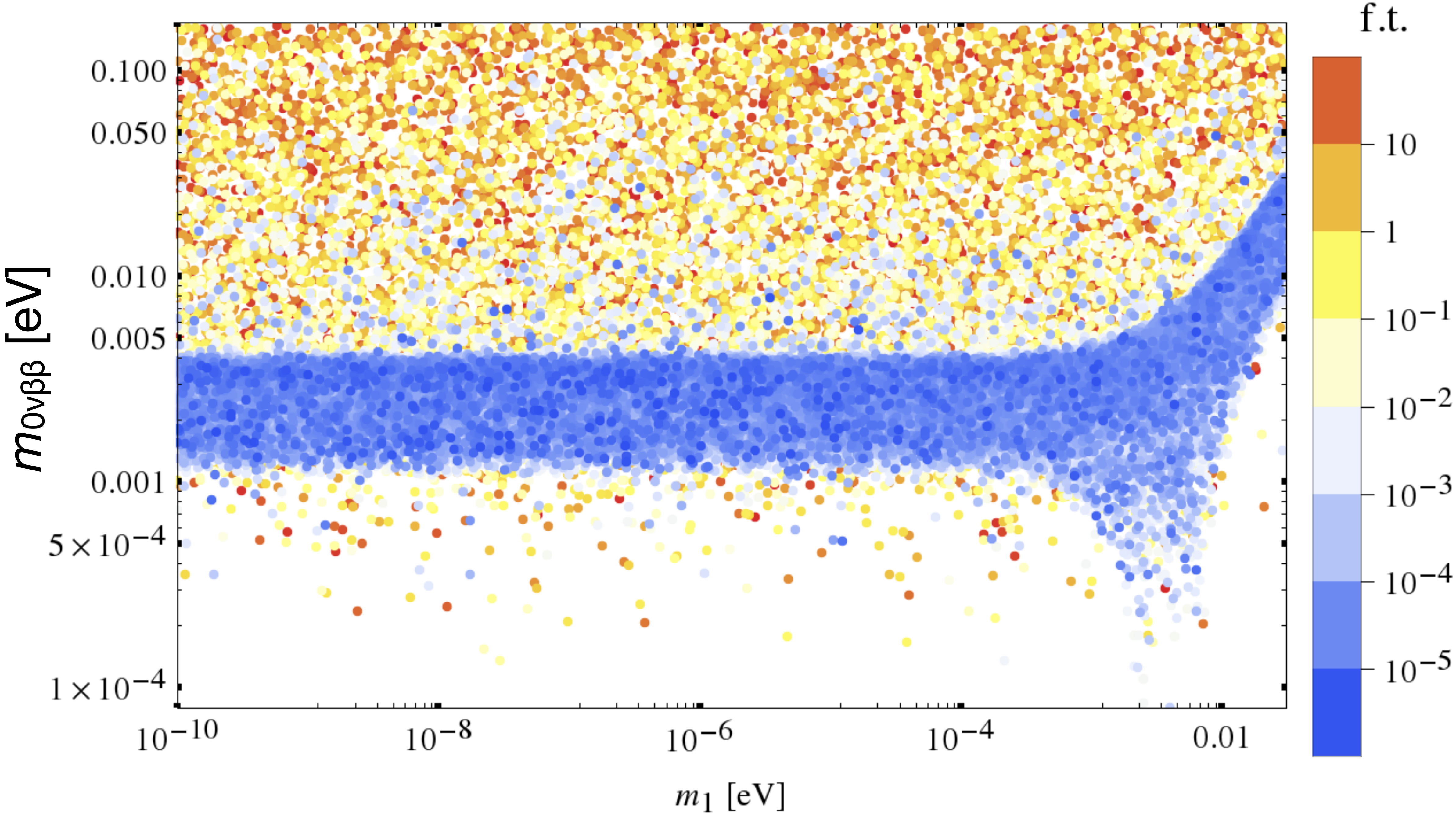
m_i^{loop}
1-loop neutrino mass spectrum

m_i^{tree}
tree-level neutrino mass spectrum

Neutrinoless effective mass

0νββ decay is a lepton number violating process → It violates the B - L symmetry

Normal Ordering



Mass spectrum with 3 right-handed neutrinos and B - L approximate symmetry

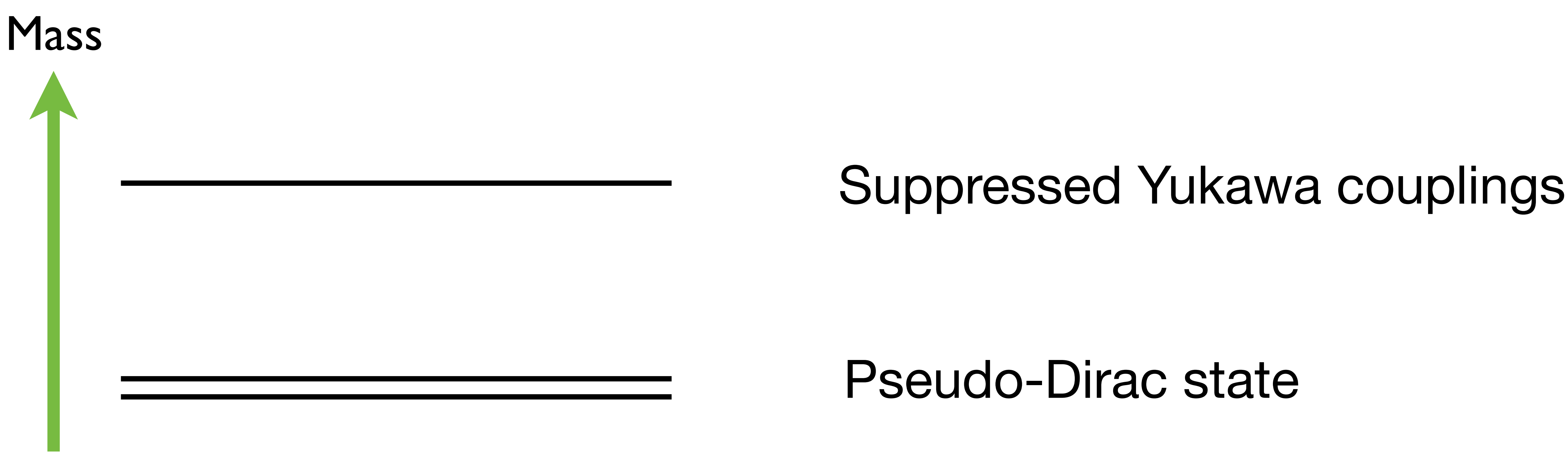
How to preserve lepton number with Majorana states?

→ Pair two states to form a Dirac state (*equal masses, maximal mixing, opposite CP*)

or

→ Decouple a state

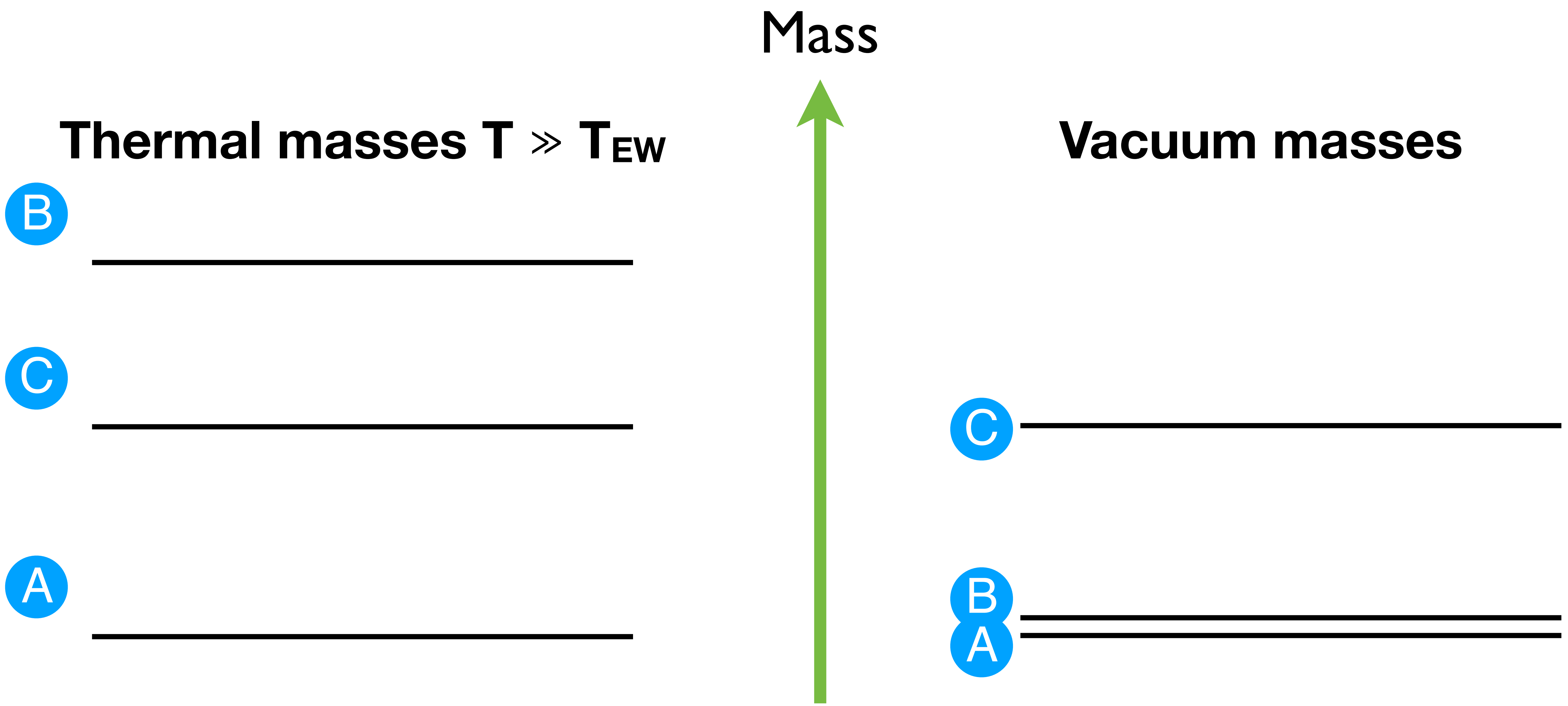
If there is an **odd number** of **right-handed neutrinos** and **B - L** approximate **symmetry**



New mechanism: resonant asymmetry production in the B - L symmetry

$$T_{\text{crossing}} \approx \frac{2\sqrt{2}\bar{M}\sqrt{\mu'^2-1}}{\sqrt{\sum_a |F_a|^2}} = 2.8\times 10^5\ \text{GeV}\left(\frac{\bar{M}}{\text{GeV}}\right)\frac{\sqrt{\mu'^2-1}}{\sqrt{\sum_a |(F_a/10^{-5})|^2}}$$

Mass spectrum with 3 right-handed neutrinos and B - L symmetry

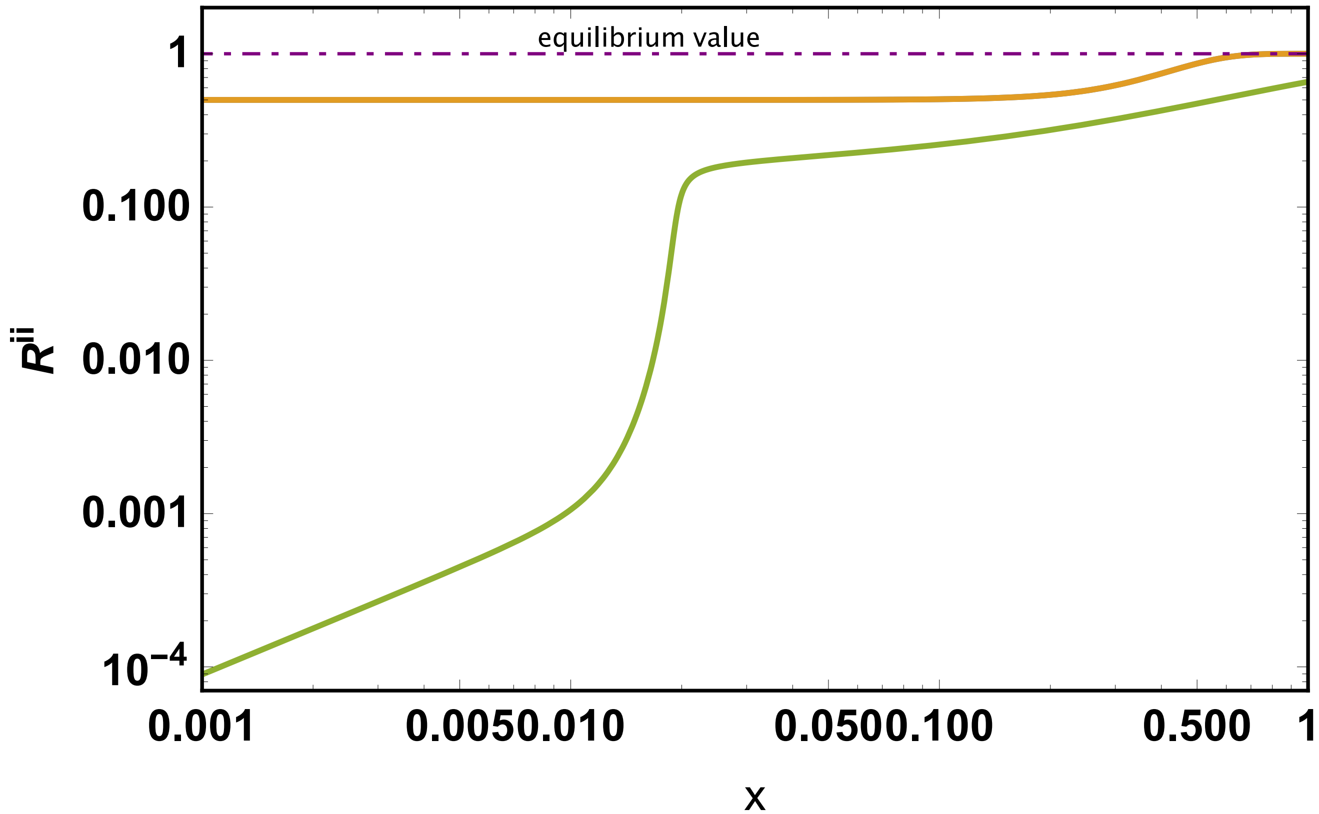


If the vacuum mass of the decoupled state is heavier than the pseudo-Dirac one, there is **necessarily** a level crossing at some finite temperature!

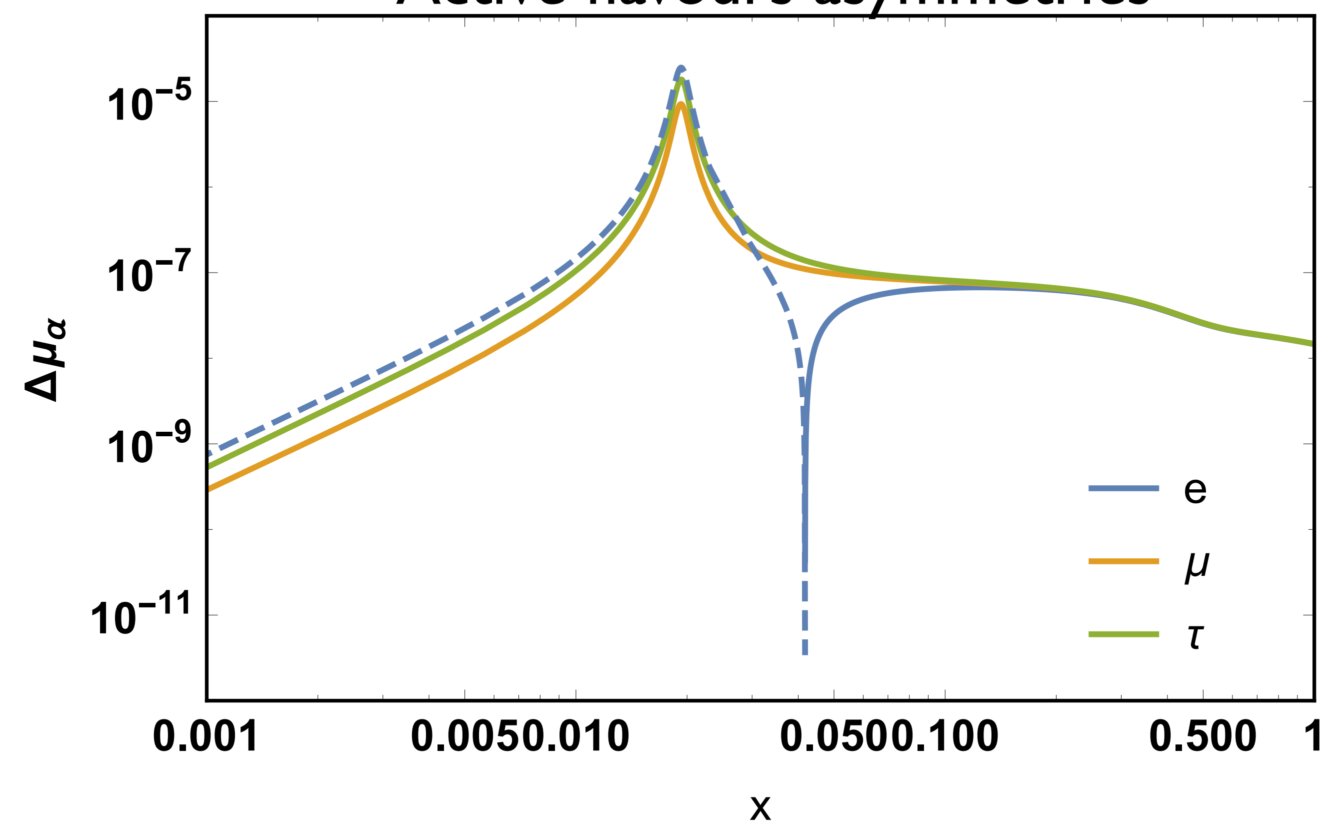
Level crossing: resonant asymmetry production

$x = \frac{T}{T_{\text{EW}}}$ T_{EW} = 140 GeV R :sterile neutrinos density matrix μ_α : active flavours chemical potentials

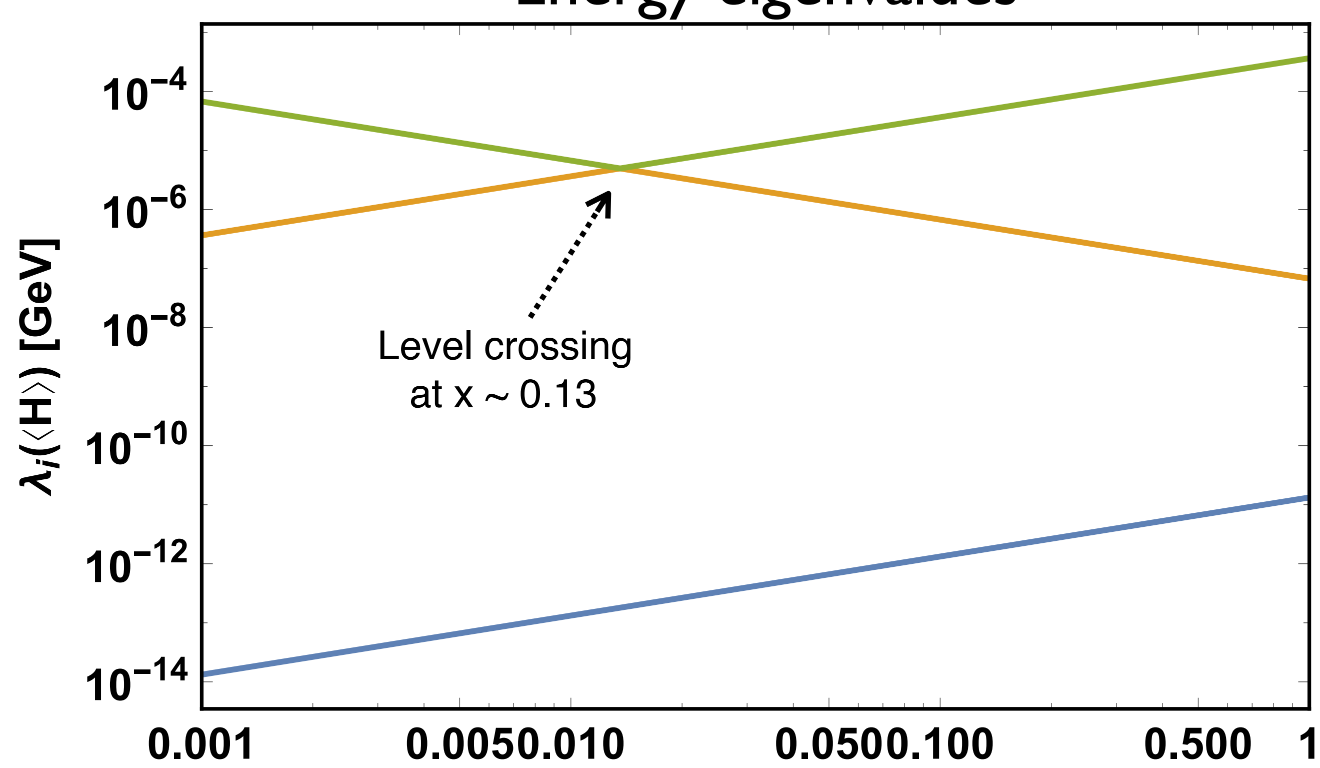
Sterile neutrinos abundances



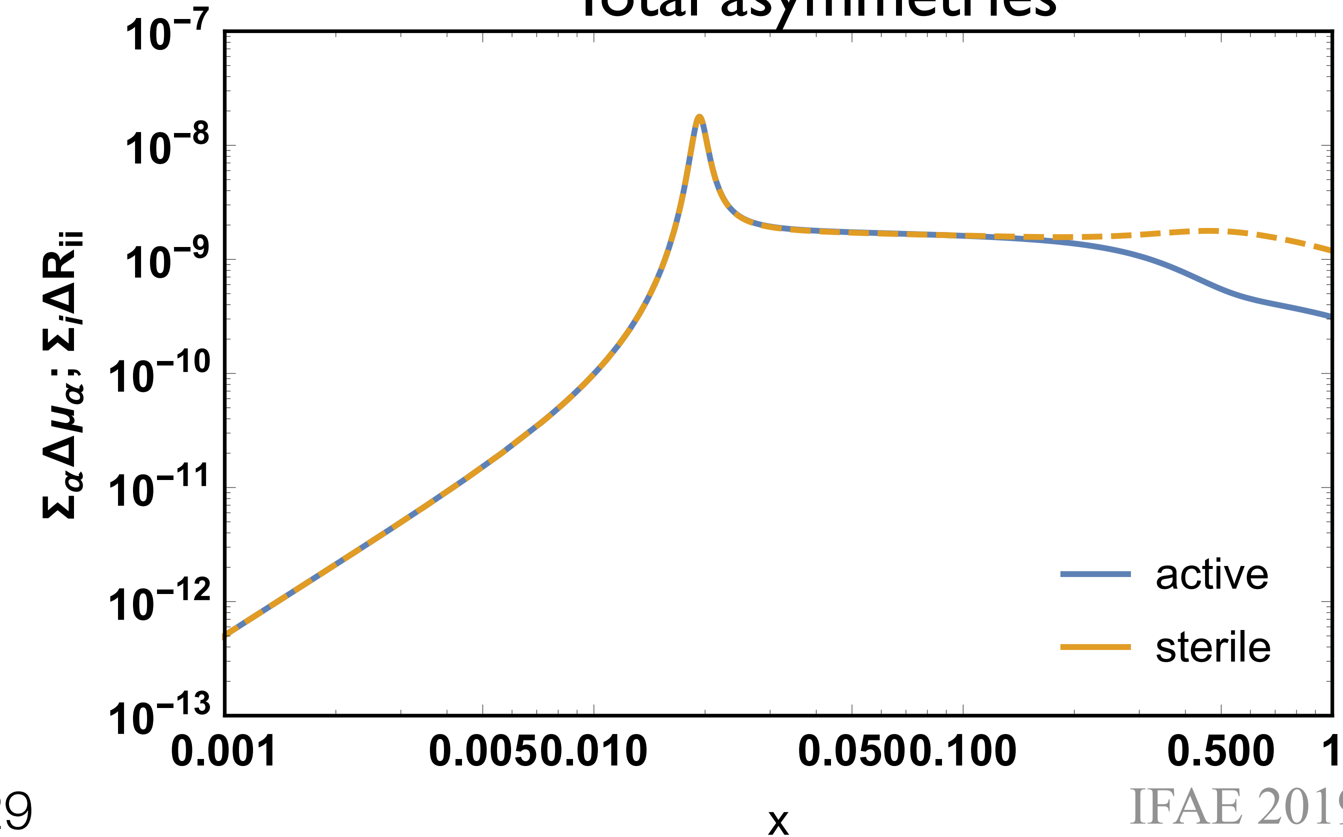
Active flavours asymmetries



Energy eigenvalues



Total asymmetries



HI: Smaller collision energy

The charge to mass ratio is smaller for heavy ions → **Smaller energy collision per nucleon**

$$\sqrt{s_{\mathrm{PbPb}}} = 5.52\ \mathrm{TeV}$$

$$\sqrt{s_{\mathrm{pp}}} = 14\ \mathrm{TeV}$$

Scaling factor

$$\frac{\sigma_{\mathrm{pp}}\,(14\ \mathrm{TeV})}{\sigma_{\mathrm{PbPb}}\,(5.52\ \mathrm{TeV})}$$

- Typically larger for gluon-initiated processes than for quark-antiquark ones
- Grows with the particle masses in the final state

HI: Lower instantaneous luminosity

LHC can only collect a sizeably lower luminosity with heavy ions due to machine limitations

Int. luminosity	expected *pp*	expected PbPb
Run 2	100 fb^{-1}	1 nb^{-1}
HL LHC	3000 fb^{-1}	10 nb^{-1}

This is due to ultraperipheral electromagnetic interactions:

Bound-Free Pair-Production (BFPP): $\sigma_{\mathrm{BFPP}} \propto Z^7$

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + \mathrm{e}^+$$

Electromagnetic Dissociation (EMD): $\sigma_{\mathrm{EMD}} \propto \frac{(A-Z)\,Z^3}{A^{2/3}}$

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \longrightarrow ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + \mathrm{n}$$

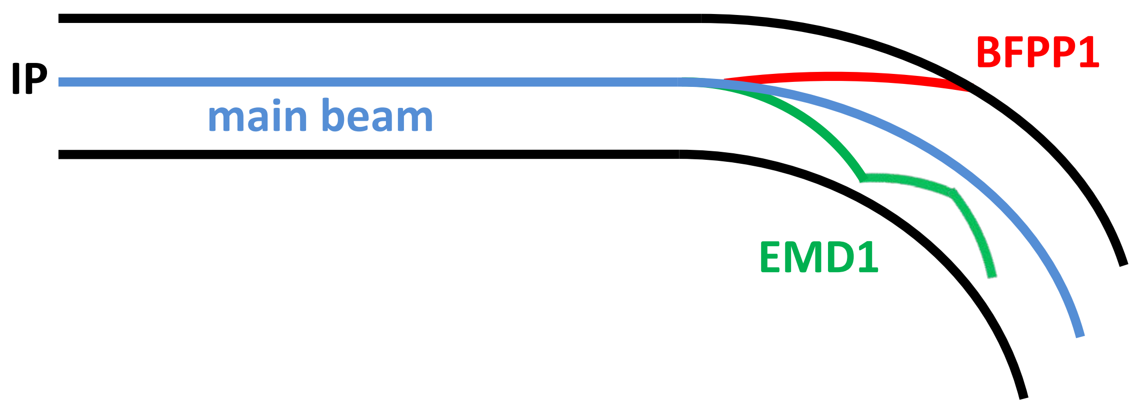
For *PbPb* with E_b=7ZTeV

	BFPP		EMD			Hadronic
Symbole	$\sigma_{\mathrm{c,BFPP1}}$	$\sigma_{\mathrm{c,BFPP2}}$	$\sigma_{\mathrm{c,EMD1}}$	$\sigma_{\mathrm{c,EMD2}}$	$\sum \sigma_{\mathrm{c,EMD}}$	$\sigma_{\mathrm{c,hadron}}$
Cross-section [b]	281	0.006	96	29	226	8

M. Schaumann, CERN-THESIS-2015-195

HI: Impact of electromagnetic processes

Two problems arise



Creation of secondary beams with wrong charge to mass ratio

▼

Risk of quenching magnets!

Machine

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0 \tau_b}$$

$$\tau_b = \frac{n_b}{\sigma_{\text{tot}} n_{\text{IP}}} \frac{N_0}{L_0}$$

- N_b: number of ions per bunch
- N_0: initial value for N_b
- n_b: number of bunches per beam
- n_{IP}: number of interaction points
- L_0: initial value for luminosity

Larger value of σ_{tot}

▼

Faster beam decay

Physics

M. Benedikt, D. Schulte and F. Zimmermann, Phys. Rev. ST Accel. Beams 18 (2015) 101002

HI: Cross section enhancement

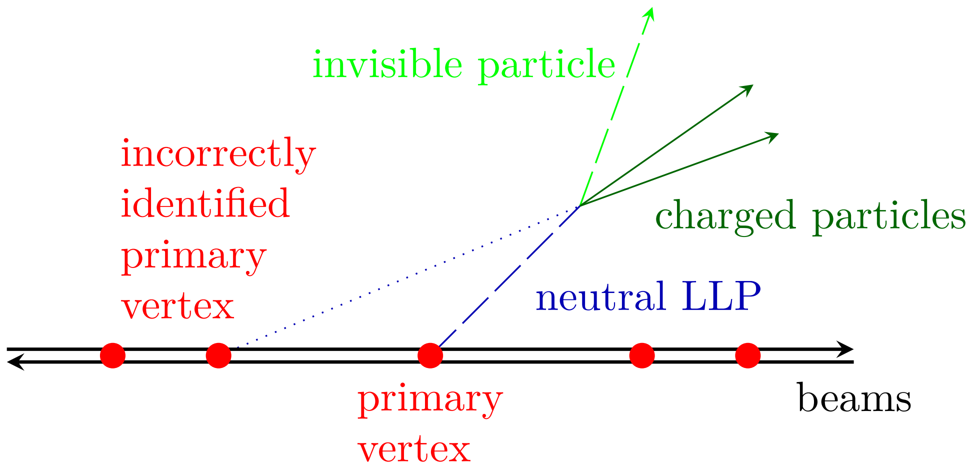
In *NN* collisions, number of parton level interactions enhanced by a factor A^2

↓

This partially compensates the loss in statistics due to a lower luminosity

HI: Lower primary vertex mis-identification

There is no pile-up in heavy ion collisions!

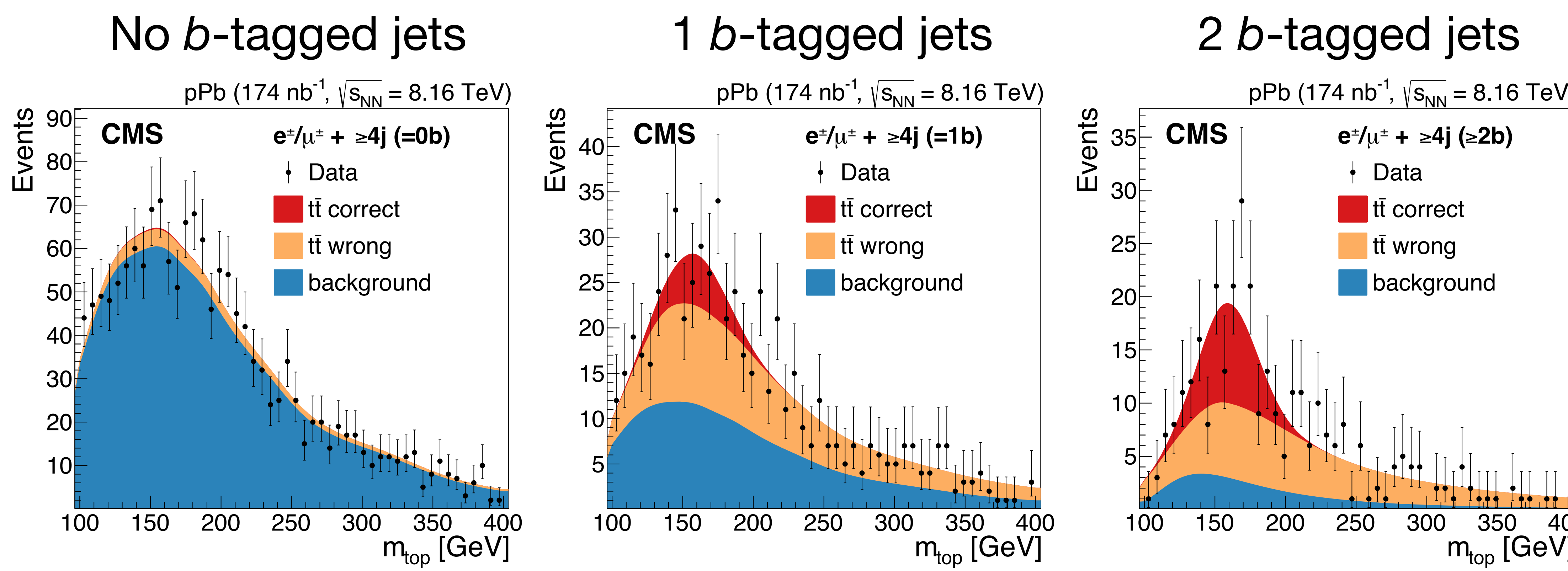


This allows to better identify primary vertices

▼

Background reduction

For instance, misidentification rate of light-jets is **smaller in pPb than in pp** events (0.1 % vs 0.8%)



CMS Collaboration, arXiv:1709.07411 [nucl-ex]

HI: Larger track multiplicity

Huge number of tracks from PbPb events, but same vertex

In ATLAS/CMS tracking acceptance

For central events at $\sqrt{s_{\mathrm{PbPb}}} = 5.52\ \mathrm{TeV}$

ALICE Collaboration, arXiv:1512.06104 [nucl-ex]

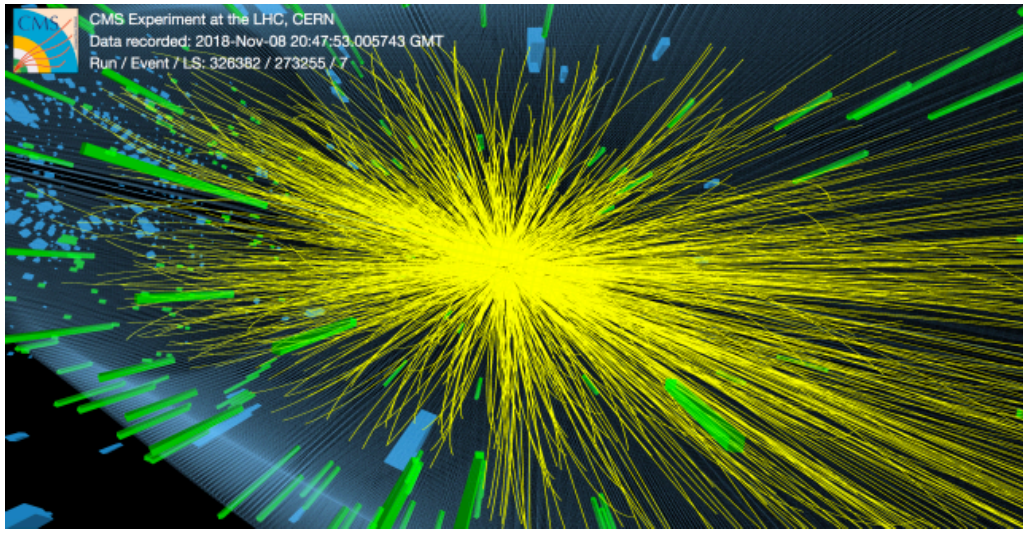
~ 10 000 charged tracks

In *pp* multiplicity mainly due to pile-up

CMS Collaboration, arXiv:1507.05915 [hep-ex]
ATLAS Collaboration, arXiv:1606.01133 [hep-ex]
ALICE Collaboration, arXiv:1509.08734 [nucl-ex]

~ 750 charged tracks for Run 3
~ 5 000 charged tracks at HL-LHC

G. Apollinari, I. Béjar Alonso, O. Brüning, M. Lamont, and L. Rossi, 10.5170/CERN-2015-005
G. Apollinari, O. Brüning, T. Nakamoto and L. Rossi, arXiv:1705.08830 [physics.acc-ph]



Not big difference at HL-LHC, and we expect vertex reconstruction to be affected more from pile-up than from track multiplicity
(cf. b-tagging performance in top searches with *pp* and *p*Pb)

HI: Luminosity estimation

From $\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0 \tau_b}$ ▶ $N_b(t) = \frac{N_0}{1+\theta_t}$ with $\theta_t = \frac{t}{\tau_b}$

The luminosity at one interaction point is $L = k\ N_b^2$

where k is a parameter depending on the other beam properties (revolution frequency, number of bunches, emittance, width)

The integrated luminosity is thus $\Sigma(t) = L_0 \tau_b \frac{\theta_t}{1+\theta_t}$

Turnaround time *t_a: average time between two physics runs*

Average luminosity $L_{\mathrm{ave}}(t) = \frac{\Sigma(t)}{t + t_{\mathrm{ta}}}$ maximised for $t_{\mathrm{opt}} = \tau_b \sqrt{\theta_{\mathrm{ta}}}$

$$L_{\mathrm{ave}}(t_{\mathrm{opt}}) = \frac{L_0}{\left(1+\sqrt{\theta_{\mathrm{ta}}}\right)^2}$$

HI: Initial bunch intensity

The initial number of ions per bunch
***N_b* is a key parameter for luminosity**

Luminosity at one interaction point is proportional to N_b^2

We use the empirical expression

$$N_b\left({}^{A}_{Z}N\right) = N_b\left({}^{208}_{82}\mathrm{Pb}\right)\left(\frac{Z}{82}\right)^{-p}$$

where
$p = 1$ **conservative** assumption
$p = 1.9$ **optimistic** assumption

J. Jowett, Workshop on the physics of HL-LHC, and perspectives at HE-LHC, (2018)

The XeXe run achieved $p = 0.75$ after only few hours of tuning ▶ This allows to be optimistic

HI: Result for different ions

pp and PbPb are two extreme cases
Intermediate ions could be interesting

$p = 1.9$
$t_a = 2.5$ h

			Cross section						Luminosity			
	M [GeV]	$\sqrt{s_{NN}}$ [TeV]	σ_{EMD} [b]	σ_{BFPP} [b]	σ_{had} [b]	σ_{tot} [b]	σ_W [nb]	$A^2\sigma_W$ [μb]	L_0 [$1/\mu\text{b s}$]	τ_b [h]	L_{ave} [$1/\mu\text{b s}$]	N_N/N_p [1]
$^{1}_{1}$H	0.931	14.0	0	0	0.0710	0.07	56.0	0.0560	21.0×10^3	75.0	15.0×10^3	1
$^{16}_{8}$O	14.9	7.00	0.074	24×10^{-6}	1.41	1.48	28.0	7.17	94.3	6.16	35.2	0.30
$^{40}_{18}$Ar	37.3	6.30	1.2	0.0069	2.6	3.81	25.2	40.3	4.33	11.2	2.00	0.0957
$^{40}_{20}$Ca	37.3	7.00	1.6	0.014	2.6	4.21	28.0	44.8	2.90	12.4	1.38	0.0735
$^{78}_{36}$Kr	72.7	6.46	12	0.88	4.06	16.9	25.8	157	0.311	9.40	0.135	0.0253
$^{84}_{36}$Kr	78.2	6.00	13	0.88	4.26	18.1	24.0	169	0.311	8.77	0.132	0.0266
$^{129}_{54}$Xe	120	5.86	52	15	5.67	72.67	23.4	390	0.0665	4.73	0.0223	0.0103
$^{208}_{82}$Pb	194	5.52	220	280	7.8	508	22.1	955	0.0136	1.50	2.59×10^{-3}	0.0029

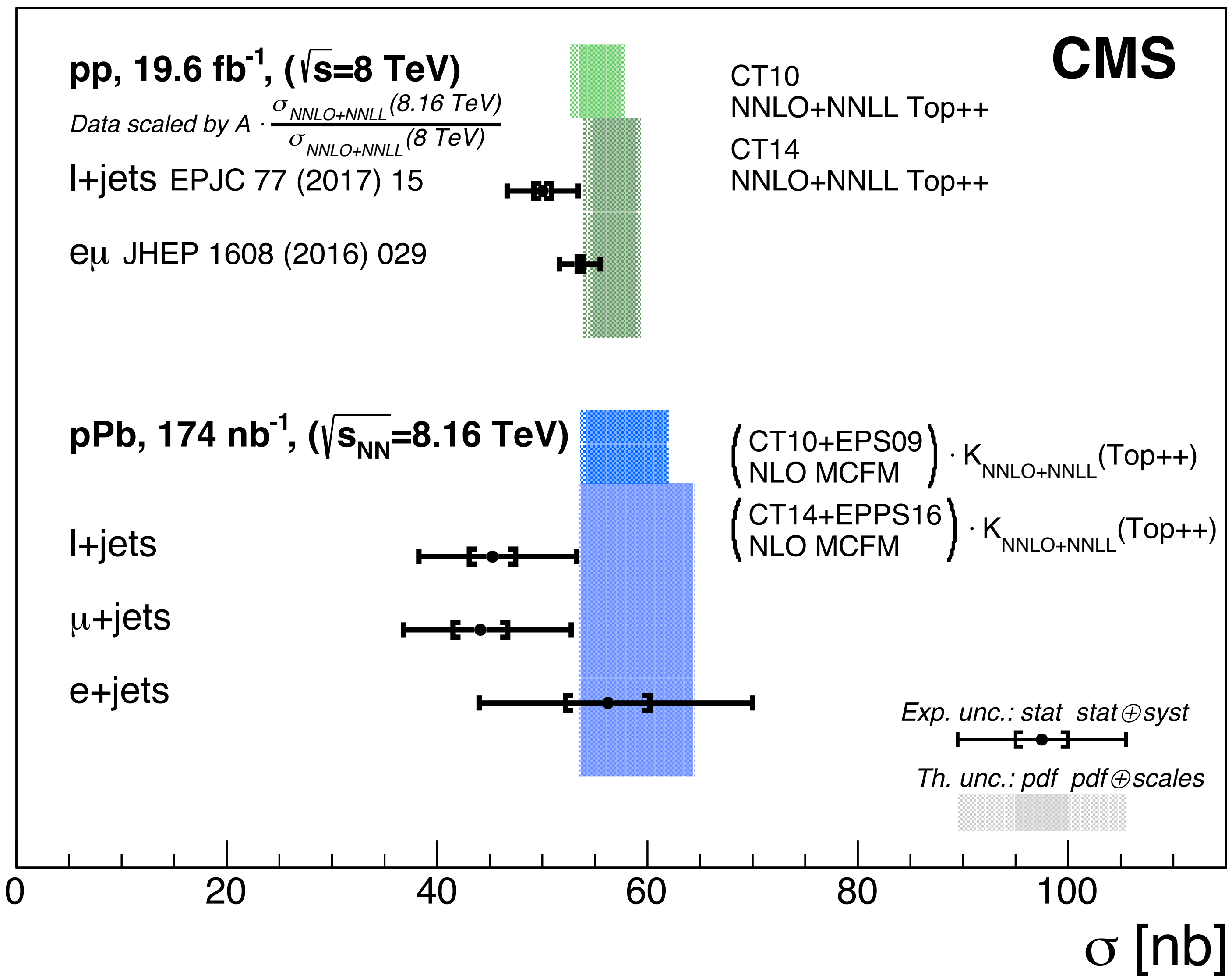
↑ W boson production cross section

↑ # events w.r.t. proton runs

Example: SM tests with Heavy Ions

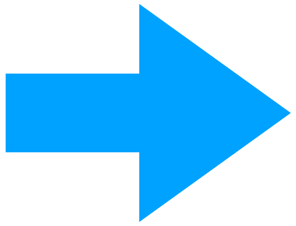
tt̄ cross section measurement in *pp* and *p*Pb collisions

CMS Collaboration, arXiv:1709.07411 [nucl-ex]



$^{208}_{82}\mathrm{Pb}$

174 nb^{-1} collected in *p*Pb collisions



corresponds to 174 x A_{Pb} nb^{-1} ≃ 36 pb^{-1}

Example: BSM tests with Heavy Ions

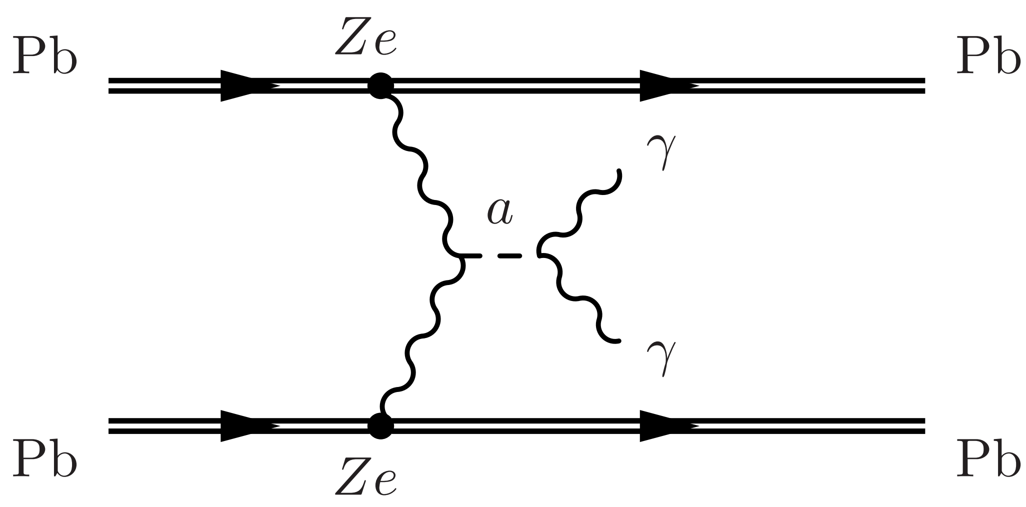
Testing axion-like particles with ultra-peripheral heavy-ion collisions

S. Knapen, T. Lin, H. K. Lou and T. Melia, arXiv:1607.06083 [hep-ph]

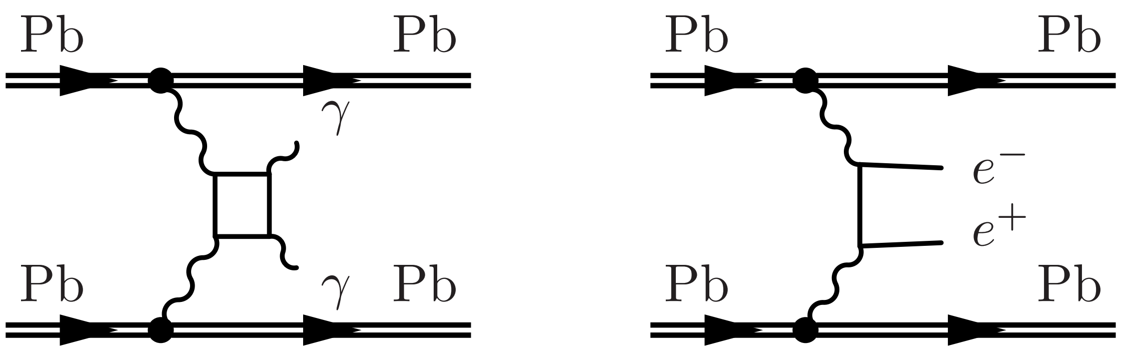
$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\widetilde{F}$$

The photon-photon luminosity is enhanced by Z^4 w.r.t. proton collisions

Signal



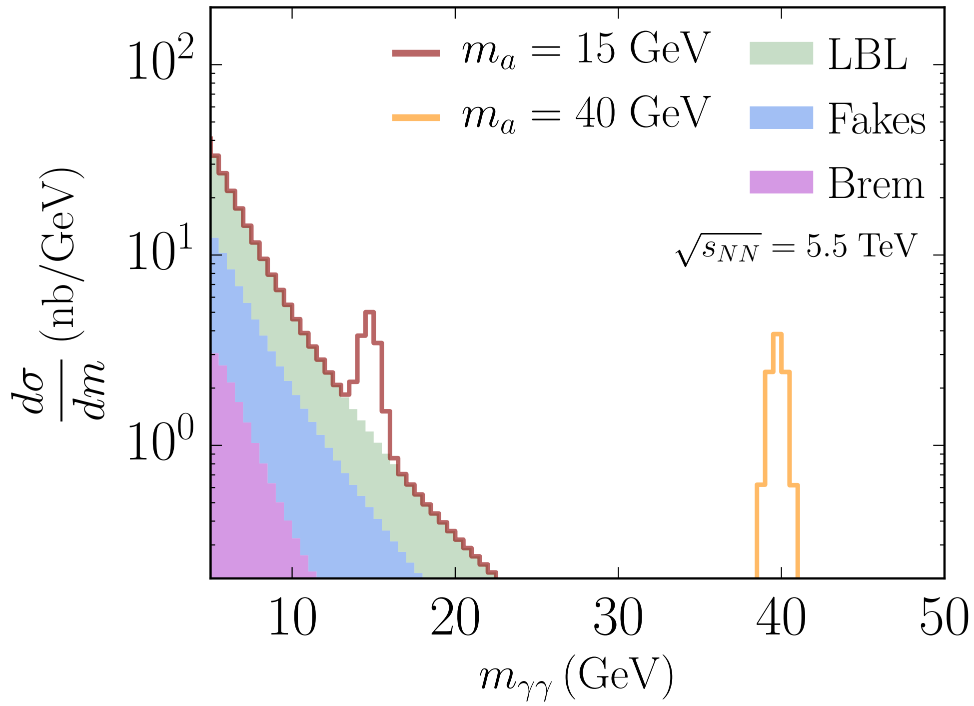
Background



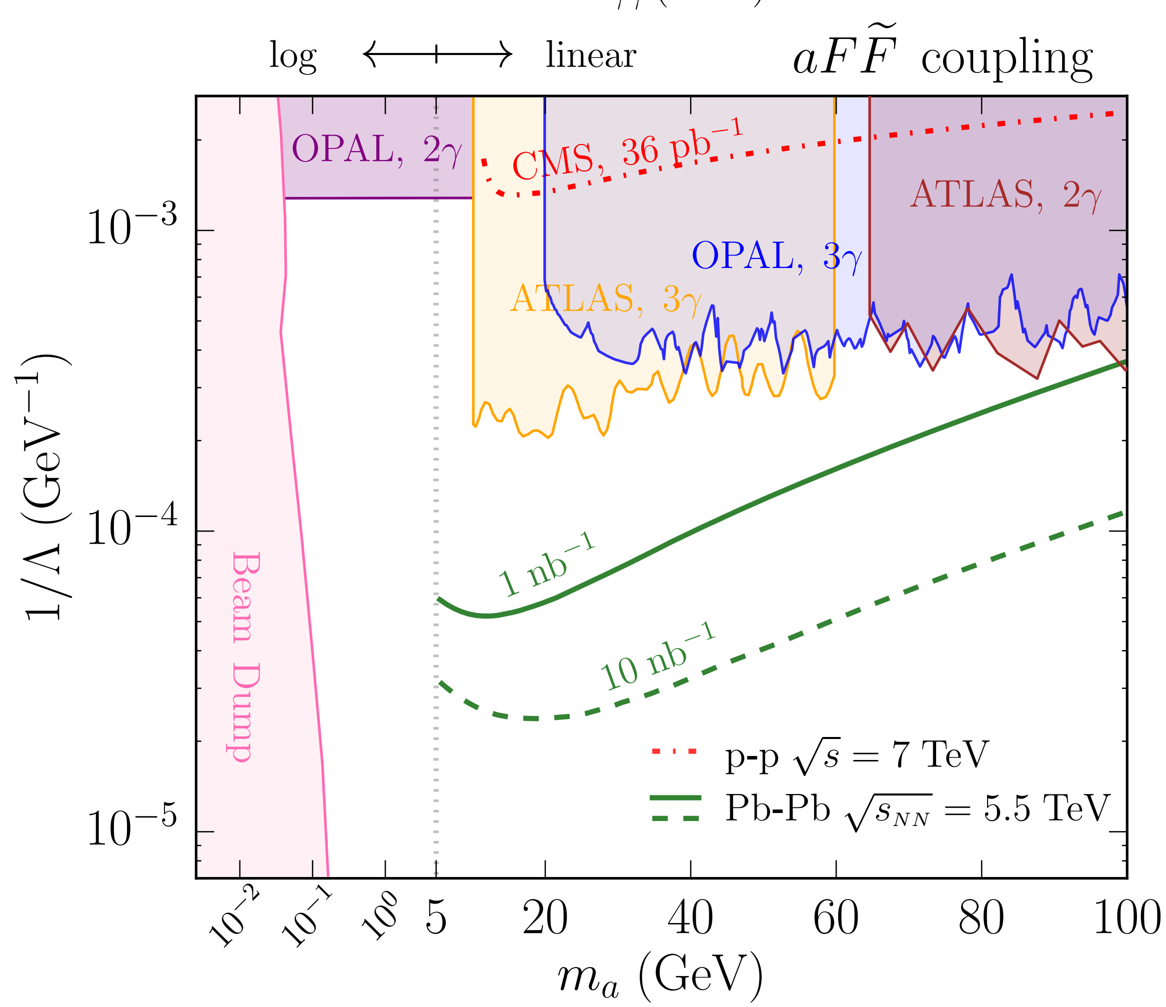
Nuclei do not fragment in the process

Axion-like particles with Heavy Ion collisions

S. Knapen, T. Lin, H. K. Lou and T. Melia, arXiv:1607.06083 [hep-ph]



Signal and background simulation



Expected sensitivity

1 nb^{-1}: current PbPb run

10 nb^{-1}: HL PbPb run

PbPb searches can provide stronger limits w.r.t. *pp* ones