A Heavy Metal Path to New Physics

Based on: `arXiv:1810.09400`

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thanks goes to M. Borsato, A. De Roeck, G. Krintiras, J. Jowett

Searching for long-lived particles at the LHC – Fourth workshop of the LHC LLP Community

Motivation

- So far the LHC has not found any new physics beyond the SM
- Initial focus on heavy new physics
- During the high luminosity run it will be optimized for searches of weakly coupled particles
- We propose to utilize also the heavy ion runs for this goal

Heavy Ions

Heavy Ion

Reasoning

The number of parton level interactions per collision scales with A^2.

For e.g. Pb with $A = 208$ this results in

$$\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{pp}} \propto 43\,264$$

Drawbacks

- There are a huge number of tracks near the interaction point which makes the search for prompt new physics extremely challenging
- The collision energy per nucleon is smaller. e.g. $\sqrt{s_{NN}} = 5.02\,TeV$ for Pb
- The instantaneous luminosity is lower for larger A
- The LHC has allocated much less time to heavy ions runs than to protons runs
- The experiments might not wish to collect the maximal possible luminosity e.g. LHCb uses about 10 % of the available luminosity for its QGP studies

Secondary beams

For heavy ions there are additional contributions to the crosssection

electromagnetic dissociation (EMD): $^{208}_{82}\mathrm{Pb} + {}^{208}_{82}\mathrm{Pb} \rightarrow {}^{208}_{82}\mathrm{Pb} + {}^{207}_{82}\mathrm{Pb} + n$

bound-free pair production (BFPP): $^{208}_{82}\mathrm{Pb} + {}^{208}_{82}\mathrm{Pb} \rightarrow {}^{208}_{82}\mathrm{Pb} + {}^{208}_{81}\mathrm{Tl} + e^{+}$

this leads to

- Faster beam decay
- Secondary beams consisting of ions with different charge/mass ratio can accidentally quench the magnets

The secondary beams can be disposed by directing them in the space between the magnets

Crosssections

[Jowett 2018]

	M [GeV]	$\sqrt{s_{NN}}$ [TeV]
$^{1}_{1}\mathrm{H}$	0.931	14.0
$^{16}_{8}\mathrm{O}$	14.9	7.00
$^{40}_{18}\mathrm{Ar}$	37.3	6.30
$^{40}_{20}\mathrm{Ca}$	37.3	7.00
$^{78}_{36}\mathrm{Kr}$	72.7	6.46
$^{84}_{36}\mathrm{Kr}$	78.2	6.00
$^{129}_{54}\mathrm{Xe}$	120	5.86
$^{208}_{82}\mathrm{Pb}$	194	5.52

Crosssections

[Jowett 2018]

	M [GeV]	$\sqrt{s_{NN}}$ [TeV]	σ_{EMD} [b]	σ_{BFPP} [b]	σ_{had} [b]	σ_{tot} [b]
${}^{1}_{1}\text{H}$	0.931	14.0	0	0	0.071	0.07
${}^{16}_{8}\text{O}$	14.9	7.00	0.074	2.4×10^{-5}	1.4	1.47
${}^{40}_{18}\text{Ar}$	37.3	6.30	1.2	0.0069	2.6	3.81
${}^{40}_{20}\text{Ca}$	37.3	7.00	1.6	0.014	2.6	4.21
${}^{78}_{36}\text{Kr}$	72.7	6.46	12	0.88	4.1	17.0
${}^{84}_{36}\text{Kr}$	78.2	6.00	13	0.88	4.3	18.2
${}^{129}_{54}\text{Xe}$	120	5.86	52	15	5.7	72.7
${}^{208}_{82}\text{Pb}$	194	5.52	220	280	7.8	508

Crosssections

[Jowett 2018]

	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]
${}^{1}_{1}\text{H}$	0.931	14.0	0	0	0.071	0.07	56.0	0.056
${}^{16}_{8}\text{O}$	14.9	7.00	0.074	2.4×10^{-5}	1.4	1.47	28.0	7.17
${}^{40}_{18}\text{Ar}$	37.3	6.30	1.2	0.0069	2.6	3.81	25.2	40.3
${}^{40}_{20}\text{Ca}$	37.3	7.00	1.6	0.014	2.6	4.21	28.0	44.8
${}^{78}_{36}\text{Kr}$	72.7	6.46	12	0.88	4.1	17.0	25.8	157
${}^{84}_{36}\text{Kr}$	78.2	6.00	13	0.88	4.3	18.2	24.0	169
${}^{129}_{54}\text{Xe}$	120	5.86	52	15	5.7	72.7	23.4	390
${}^{208}_{82}\text{Pb}$	194	5.52	220	280	7.8	508	22.1	955

Instantaneous luminosity

The luminosity at one interaction point (IP) is [Benedikt, Schulte, and Zimmermann 2015]

$$L = \frac{f_{\text{rev}} n_b}{4\pi\beta^*\epsilon} N_b^2$$

- N_b are number of ions per bunch
- n_b is the number of bunches per beam
- $f_{\text{rev}} = {}^{2\pi r}/_{c}$ is the revolution frequency of 11.2 kHz
- ϵ is the horizontal and vertical geometric RMS emittance
- The β function of the beam at the position z is related to the width of the its Gaussian distribution via $\sigma^2(z) = \epsilon\beta(z)$.
- β^* is the value of the $\beta(z)$ function at the IP ($z = 0$).

The initial bunch intensity [Jowett 2018]

for arbitrary ions is fitted to the information of the lead run

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

where $p = 1$ is a conservative assumption while $p = 1.9$ is a optimistic assumption.

Luminosity evolution

[Benedikt, Schulte, and Zimmermann 2015]

The loss of number of ions per bunch N_b over time is given by

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\frac{N_b^2}{N_0 \tau_b}\,, \qquad \tau_b = \frac{n_b}{\sigma_{\text{tot}} n_{\text{IP}}} \frac{N_0}{L_0}\,,$$

where n_{IP} is the number of interaction points.

For a given turnaround time t_{ta} between the physics runs

the integrated luminosity is maximised by

$$t_{\text{opt}} = \tau_b \sqrt{\theta_{\text{ta}}}\,, \qquad \text{with} \qquad \theta_{\text{ta}} = \frac{t_{\text{ta}}}{\tau_b}\,.$$

The average luminosity using the optimal run time is

$$L_{\text{ave}}(t_{\text{opt}}) = \frac{L_0}{(1 + \sqrt{\theta_{\text{ta}}})^2}\,.$$

Crosssection gain vs. luminosity loss

[Jowett 2018]

Under Optimistic assumption of $p = 1.9$ and $t_{\mathrm{ta}} = 2.5\,\mathrm{h}$

and neglecting operational efficiencies

	$A^2\sigma_W$ [μb]
$^{1}_{1}\mathrm{H}$	0.056
$^{16}_{8}\mathrm{O}$	7.17
$^{40}_{18}\mathrm{Ar}$	40.3
$^{40}_{20}\mathrm{Ca}$	44.8
$^{78}_{36}\mathrm{Kr}$	157
$^{84}_{36}\mathrm{Kr}$	169
$^{129}_{54}\mathrm{Xe}$	390
$^{208}_{82}\mathrm{Pb}$	955

Crosssection gain vs. luminosity loss

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and neglecting operational efficiencies

	$A^2\sigma_W$ [μb]	L_0 [$1/\mu\mathrm{b\,s}$]	τ_b [h]	L_{ave} [$1/\mu\mathrm{b\,s}$]
$^{1}_{1}\mathrm{H}$	0.056	21.0×10^3	75.0	15.0×10^3
$^{16}_{8}\mathrm{O}$	7.17	94.3	6.16	35.2
$^{40}_{18}\mathrm{Ar}$	40.3	4.33	11.2	2.00
$^{40}_{20}\mathrm{Ca}$	44.8	2.90	12.4	1.38
$^{78}_{36}\mathrm{Kr}$	157	0.311	9.40	0.135
$^{84}_{36}\mathrm{Kr}$	169	0.311	8.77	0.132
$^{129}_{54}\mathrm{Xe}$	390	0.0665	4.73	0.0223
$^{208}_{82}\mathrm{Pb}$	955	0.0136	1.50	2.59×10^{-3}

Crosssection gain vs. luminosity loss

[Jowett 2018]

Under Optimistic assumption of $p = 1.9$ and $t_{\text{ta}} = 2.5\,\text{h}$

and neglecting operational efficiencies

	$A^2\sigma_W$ $[\mu\text{b}]$	L_0 $[1/\mu\text{b s}]$	τ_b [h]	L_{ave} $[1/\mu\text{b s}]$	$N/N(p)$ [1]
${}^{1}_{1}\text{H}$	0.056	21.0×10^3	75.0	15.0×10^3	1
${}^{16}_{8}\text{O}$	7.17	94.3	6.16	35.2	0.30
${}^{40}_{18}\text{Ar}$	40.3	4.33	11.2	2.00	0.0957
${}^{40}_{20}\text{Ca}$	44.8	2.90	12.4	1.38	0.0735
${}^{78}_{36}\text{Kr}$	157	0.311	9.40	0.135	0.0253
${}^{84}_{36}\text{Kr}$	169	0.311	8.77	0.132	0.0266
${}^{129}_{54}\text{Xe}$	390	0.0665	4.73	0.0223	0.0103
${}^{208}_{82}\text{Pb}$	955	0.0136	1.50	2.59×10^{-3}	0.0029

The gain in crosssection is overcompensated by the loss in luminosity.

Heavy Neutral Leptons

νMSM

[Asaka and Shaposhnikov 2005]

The SM is extended with 3 sterile neutrinos ν_{Ri}

$$\Delta\mathcal{L} = -y_{ai}\bar{\ell}_a \varepsilon \phi^* \nu_{Ri} - y^*_{ai}\overline{\nu_R}_i \phi^T \varepsilon^\dagger \ell_a - \frac{1}{2}\left(\overline{\nu^c_R}_i M_i \nu_R + \overline{\nu_R}_i M_i \nu^c_{Ri}\right)$$

where M_M is the Majorana mass matrix.

After electroweak symmetry breaking the seesaw mechanism leads to

- 3 heavy mass eigenstates $N_i \simeq (\nu_R + \theta^T \nu^c_L)_i + \text{c.c.}$, where $\theta = vyM_M^{-1}$
- 3 light neutrinos $\nu_i \simeq V^\dagger_\nu(\nu_L - \theta\nu^2_R)_i + \text{c.c.}$ with a mass matrix $m_\nu = -\theta M_M \theta^T$

The heavy mass eigenstates can have a mass of order of the electroweak scale.

One of the neutrino decouples and can play the role of dark matter.

Another heavy neutrino can be a long lived state observable at the LHC.

Interactions

Effectively we couple one heavy neutrino N with mass M and mixing angles θ_a to the SM

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\overline{N}\theta_a^*\gamma^\mu e_{La}W_\mu^+ - \frac{g}{\sqrt{2}}\overline{e_{La}}\gamma^\mu\theta_a N W_\mu^- - \frac{g}{2\cos\theta_W}\overline{N}\theta_a^*\gamma^\mu\nu_{La}Z_\mu \\ - \frac{g}{2\cos\theta_W}\overline{\nu_{La}}\gamma^\mu\theta_a N Z_\mu - \frac{g}{\sqrt{2}}\frac{M}{m_W}\theta_a h\overline{\nu_{L\alpha}}N - \frac{g}{\sqrt{2}}\frac{M}{m_W}\theta_a^* h\overline{N}\nu_{La} \ .$$

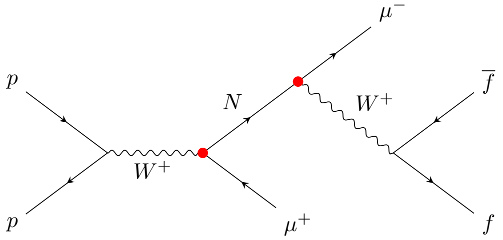
Observables are functions of the mass M_i and the coupling $U_a^2 = |\theta_a|^2$.

HNL at the LHC

Simulation

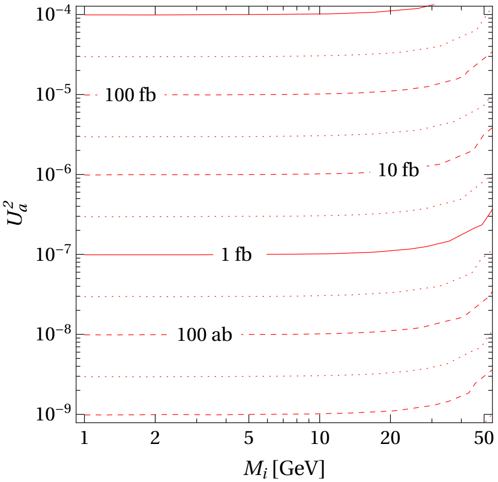
- using `MadGraph5_aMC@NLO` [Alwall et al. 2011; Degrande et al. 2016]
- Production via electroweak bosons
- trigger on first lepton
- search for displaced lepton

Process

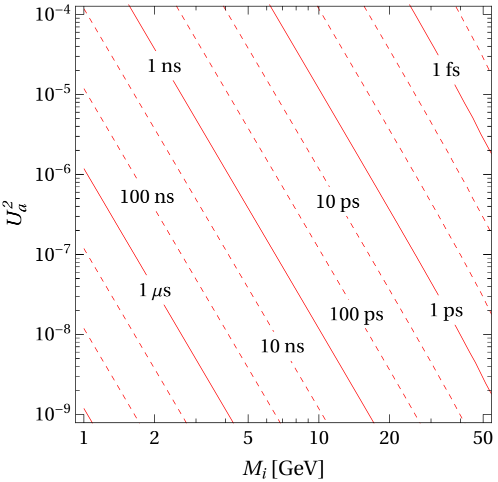


Properties of the HNL

Crosssection



Lifetime



- Masses of a few GeV lead to observable macroscopic displacement.
- In the relevant mass range the crosssection is $\sigma \propto U_a^{-2}$

Analytic estimate

Number of observable events

The decay rate can be estimated to be

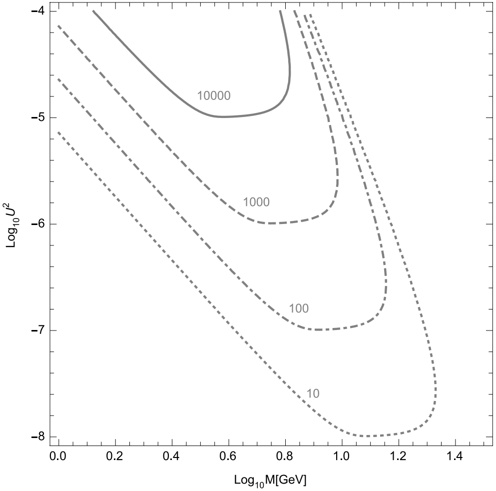
$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U^2 M^5 \ ,$$

The number of events that can be seen in a detector can be estimated as

$$N_d[W \to \ell N \to \ell\bar{\ell} f f'] \sim L_{\text{int}} \sigma_\nu U^2 \left(e^{-l_0/\lambda_N} - e^{-l_1/\lambda_N}\right) f_{\text{cut}} \ ,$$

- l_1 is the length of the effective detector volume
- l_0 the minimal displacement that is required by the trigger
- $\lambda_N = \frac{\beta\gamma}{\Gamma_N}$ decay length of the heavy neutrino
- f_{cut} all efficiencies

N_d for $L = 100\,\text{fb}^{-1}$ of pp

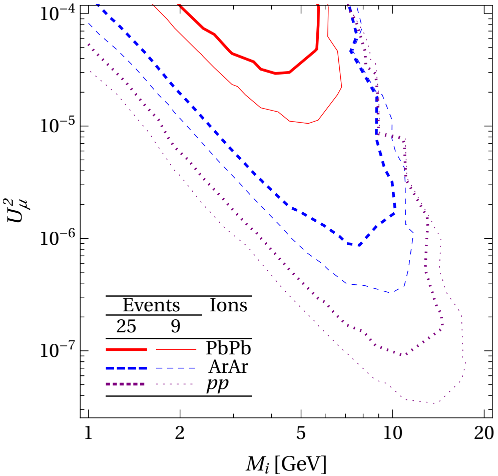


Heavy Neutral Leptons in Heavy Ion Collisions

Simulation for heavy ions

We have extended `MadGraph5_aMC@NLO` to be able to simulate heavy ion collisions.

Significance



Preliminary Conclusion

Con:

- Event rate is not competitive

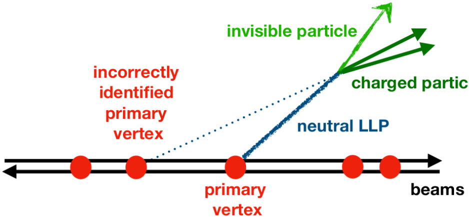
Pro:

- Heavy Neutrinos properties are measurable in a completely different environment

Possible Improvement

No Pile-up

- All track come from the same vertex
- this allows to reconstruct non trivial displaced signatures



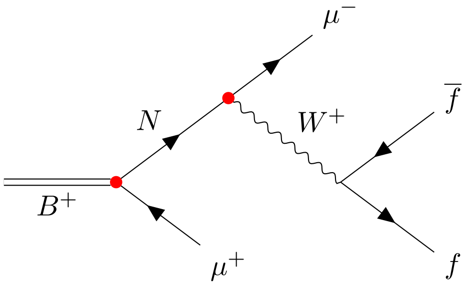
Advantage of low luminosity

- Very low triggers are possible
- Light mediators
- B-meson in the case of HNL

B-meson production

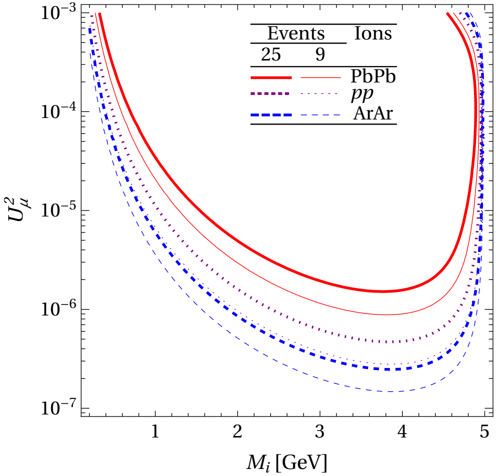
Light mediator

For mediators with low mass very low triggers can lead to a large improvement in heavy ions runs.



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

Analytic estimate



Event numbers for equal running time and significantly lowered triggers for heavy ions.

Conclusion

Summary

- Heavy ion collisions allow to search for hidden new physics
- For searches with low p_T heavy ion collision can even be better than proton collisions.

Further open Questions

- What is the largest possible initial intensity for heavy ions?
- How much can we gain by leveling?
- . . . ?

Announcement

We are organizing a workshop on “Heavy Ions and Hidden Sectors”
at CP3 in UCLouvain from 4th to 5th of December 2018
in order to bring interested parties together:
`https://agenda.irmp.ucl.ac.be/event/3186`

Thank you!

References

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