Long lived particles in heavy ion collisions

Based on: `arXiv:1810.09400`

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thanks goes to M. Borsato, E. Chapon, A. De Roeck, G. Krintiras, S. Lowette, J. Jowett, J. Prisciandaro

Heavy Ions and Hidden Sectors

Motivation

- So far the LHC has not found any new physics beyond the SM
- Initial focus lies on heavy new physics
- During the high luminosity run the focus will shift towards searches of weakly coupled particles

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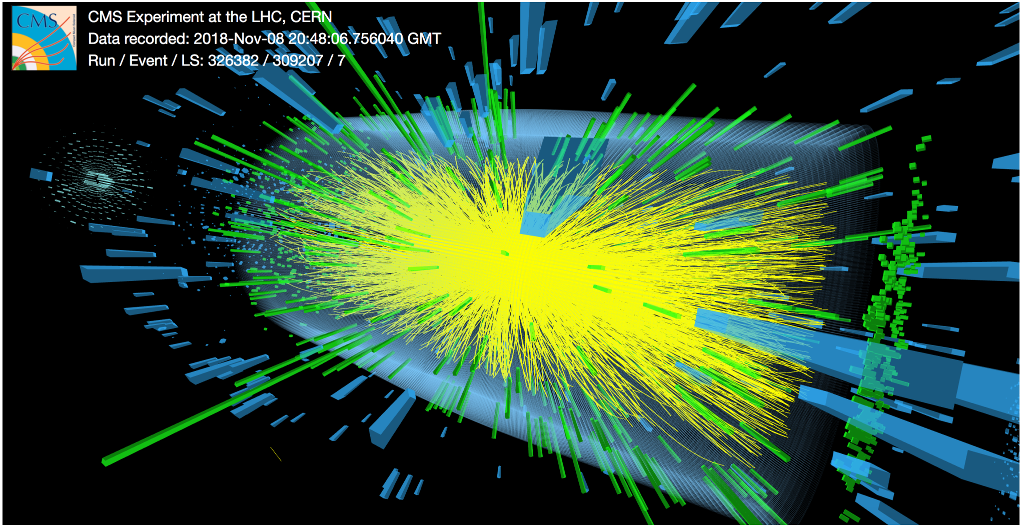
- So far the LHC has not found any new physics beyond the SM
- Initial focus lies on heavy new physics
- During the high luminosity run the focus will shift towards searches of weakly coupled particles
- We propose to utilize also the heavy ion runs for this goal

PbPb Nov 2018

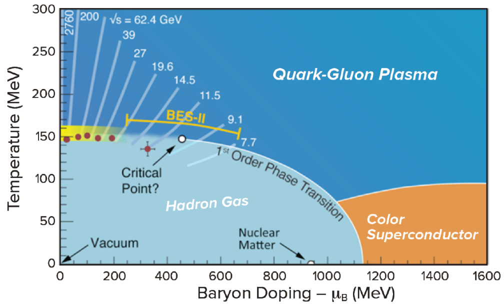


Nuclear matter

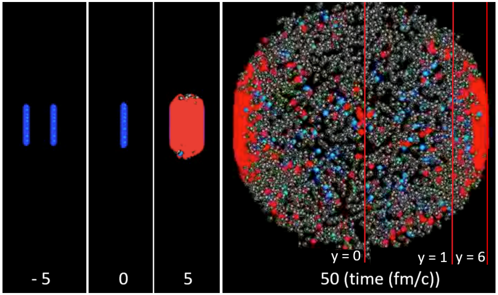
[Busza, Rajagopal, and Schee 2018]

One of the main goals of the heavy ion runs is a better understanding of nuclear matter, especially the quark gluon plasma (QGP)

Phase diagram of nuclear matter

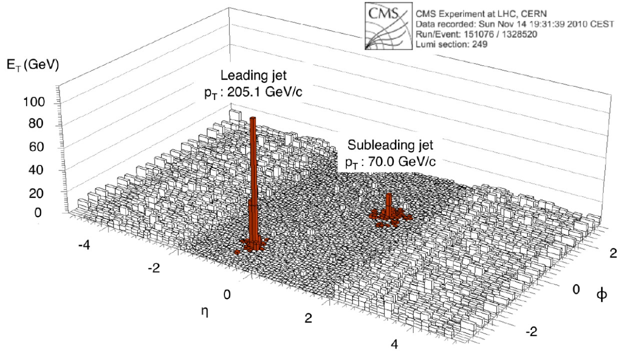


Simulation of a heavy ion event



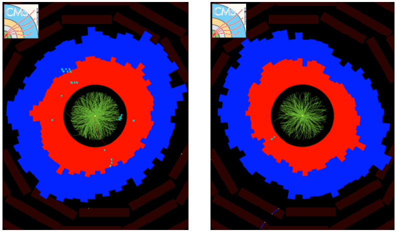
The QGP is indicated in red.

Jet quenching



- two jets of very different energies
- one jet lost more energy as it traversed the droplet of QGP

CMS event display



- azimuthal distribution of charged tracks (green) and energy in the ECAL (red) HCAL (blue)
- large azimuthal anisotropies

"It is remarkable that the strongly coupled character (left) and the liquid nature (right) of the QGP formed in these collisions can be seen so clearly in individual events."

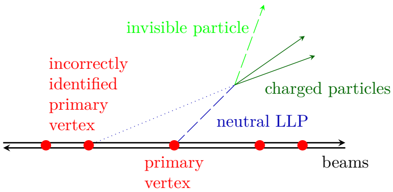
This is in strong contrast to *pp* searches at the LHC.

Properties of the heavy ions runs

Advantage

- no pile-up; single primary vertex
- large nucleon multiplicity
  e.g. $A(\mathrm{Pb}) = 208$, $Z(\mathrm{Pb}) = 82$
- Number of parton level interactions per collision scales with A
  e.g. $\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{pp}} \propto A^2 = 43\,264$

Single primary vertex



Better event reconstruction possible

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 which is problematic for heavy new physics
- The instantaneous luminosity is lower for larger A
- The LHC has allocated much less time to heavy ions runs than to protons runs

The reason for the low luminosities are secondary beams

[Jowett 2018]

For heavy ions there are additional contributions to the crosssection

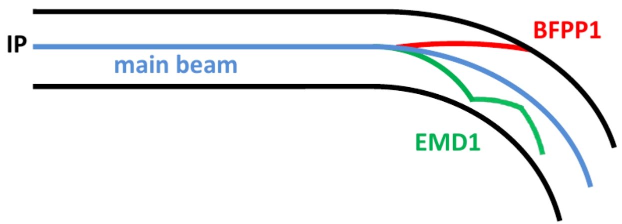
electromagnetic dissociation (EMD): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \rightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n$

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

this leads to

- faster beam decay
- secondary beams consisting of ions with different charge/mass ratio which can accidentally quench the magnets

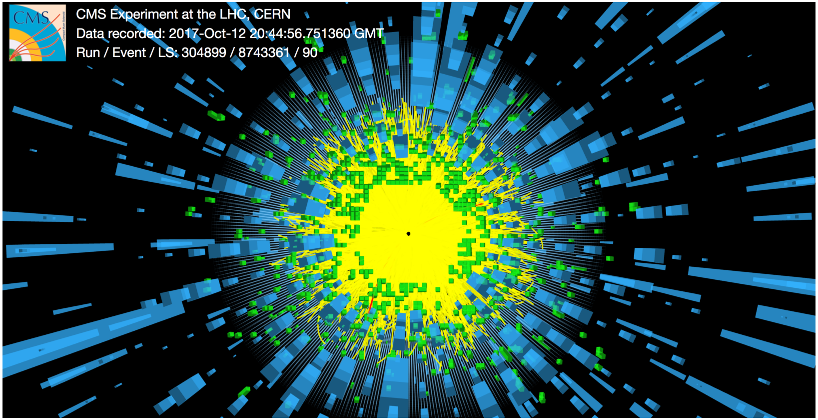
[Schaumann 2015]



Lighter ions

- *pp* and PbPb are only two extreme cases
- remember the runs using *p*Pb 2013, 2016
- there is interest in using intermediate ions
- XeXe has been collided in 2017
- there are ideas to experiment with other intermediate ions

XeXe (2017)



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

	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

$$\sigma_{\text{EMD}} \propto \frac{(A-Z)Z^3}{A^{2/3}}, \qquad \sigma_{\text{BFPP}} \propto Z^7 .$$

[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

$$\sigma_{\text{EMD}} \propto \frac{(A-Z)Z^3}{A^{2/3}}\,, \qquad \sigma_{\text{BFPP}} \propto Z^7\,.$$

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

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

where $p = 1$ is a conservative assumption while $p = 1.9$ is a optimistic assumption. The XeXe run archieved $p = 0.75$ after only few hours of tuning. This allows to be optimistic.

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

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

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

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

The average luminosity using the optimal run time is

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

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

[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]	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 $t_{\text{ta}} = 2.5\,\text{h}$

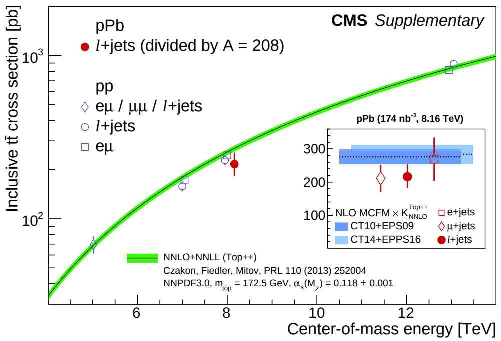
and neglecting operational efficiencies

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

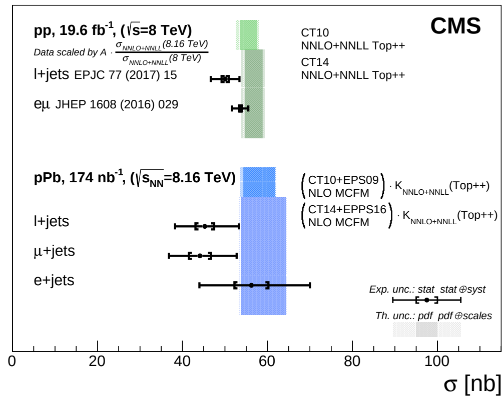
- The gain in crosssection is overcompensated by the loss in luminosity.
- However, low luminosity allows for very low triggers
- Lighter mediators are accessible

Are heavy ion runs interesting for SM processes?

pPb run of Nov. 2016 $\sqrt{s_{NN}} = 8.16\,\mathrm{TeV}$



Comparison at $\sqrt{s} = 8\,\mathrm{TeV}$



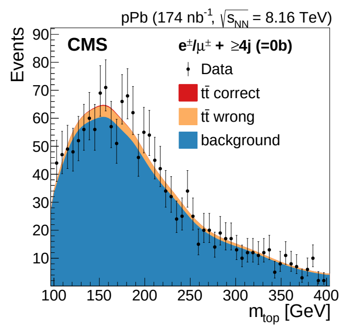
- CMS recorded $\sim 174\,\mathrm{nb}^{-1}$ of good pPb data which seems to be a tiny amount.
- but it corresponds to a *pp* Luminosity of $174\,\mathrm{nb}^{-1} \times A_{\mathrm{Pb}} = 36\,\mathrm{pb}^{-1}$.
- the nucleon multiplicity in A enables this analysis

b-tagging in heavy ion searches

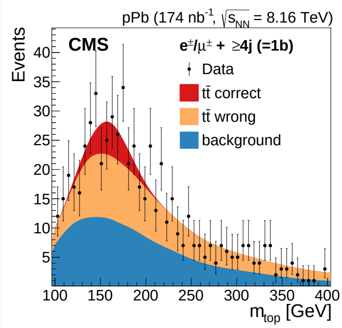
[CMS 2017]

Invariant mass m_{top} distribution of the $t \to jj'b$ candidates

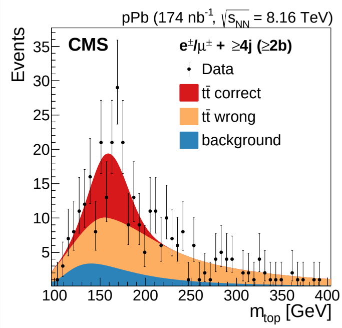
0 b-tagged jets



1 b-tagged jet



2 b-tagged jets



b-tagging

- The b-tagging is a crucial step to reduce the background
- The standard b-tagging algorithms work better in pPb than in pp
- This is not true anymore for PbPb due to track multiplicity

Are there models of new physics testable in heavy ion runs?

ALPs in heavy ion collisions

See previous talk by Simon Knapen and the talks by Jeremi Niedziela and David d'Enterria later today.

Is it possible to search for BSM physics in the very busy collisions of heavy ions?

Heavy Neutral Leptons (HNLs) in the νMSM

[Asaka and Shaposhnikov 2005]

As an example of models with displace vertices we are using HNL.

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

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

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 $\theta = vyM_M^{-1}$
  The mass can be of order of the electroweak scale
- 3 light neutrinos $\nu_i \simeq V^\dagger_\nu(\nu_L - \theta\nu^2_R)_i + \text{c.c.}$ with a mass matrix $m_\nu = -\theta M_M \theta^T$

Phenomenological consquences

- The parameter suffice to explain neutrino oscillation data.
- 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

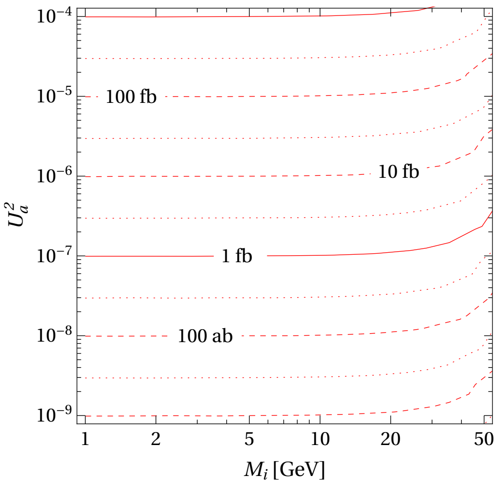
Effectively a single HNL N might be visible at colliders

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

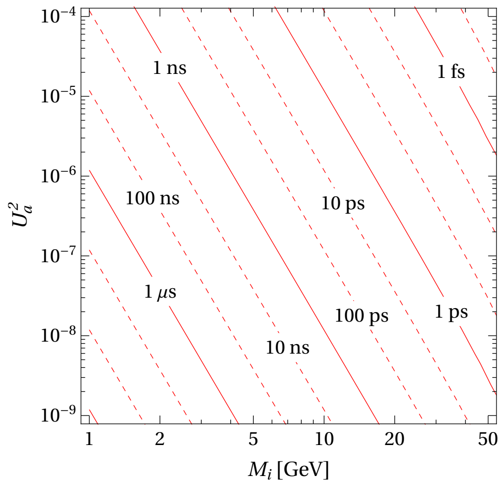
Observables are functions of the mass M_i and the coupling $U_a^2 = |\theta_a|^2$.

Properties of the HNL

Crosssection



Lifetime



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

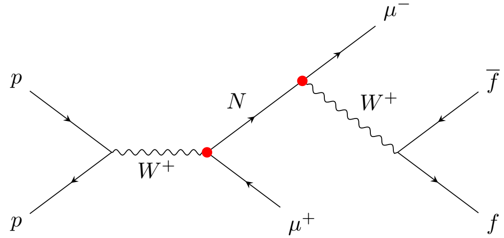
HNL at the LHC

W-boson mediator

- Simulation using `MadGraph5_aMC@-NLO`

  [Alwall et al. 2011; Degrande et al. 2016]
- trigger on first μ with $p_T > 25\,\mathrm{GeV}$
- search for displaced μ with $d > 5\,\mathrm{mm}$
- Usual strategy to search for displaced HNLs in pp collisions

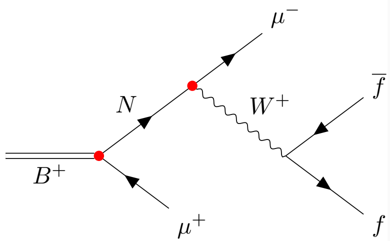
Process



B-meson mediator

- lower trigger possible:

  e.g. $p_T > 3\,\mathrm{GeV}$
- already probed at LHCb
- considered by CMS using parked data.



Analytic estimate

Number of observable events

The decay rate can be estimated to be

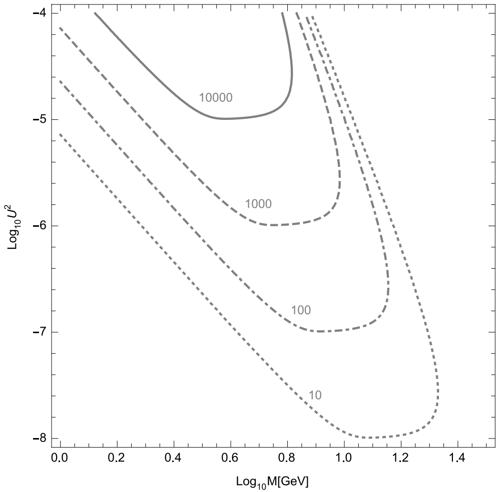
$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U^2 M^5 \ ,$$

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

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

- 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
- $f_{\rm cut}$ all efficiencies

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



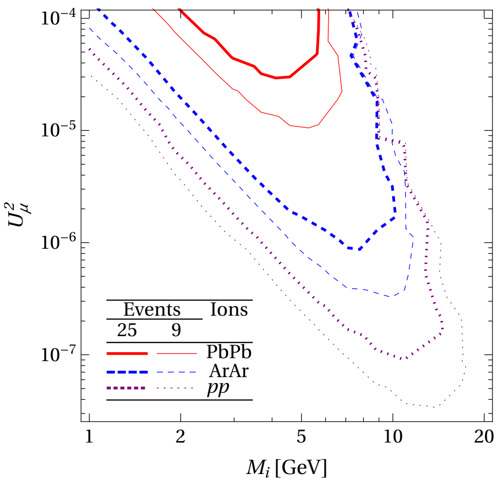
B-mesons

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

Simulation for heavy ions

We have extended `MadGraph5_aMC@NLO` to be able to simulate heavy ion collisions.
All event numbers for equal running time with $L_{\text{int}} = 5.79 \times 10^4$, 7.72 and $10^{-2}\,\text{pb}^{-1}$.

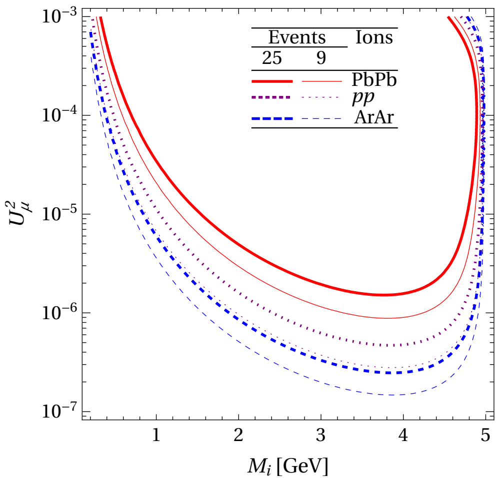
Simulation for W-boson mediator



Con Event rate is not competitive

Pro BSM physics is measurable in a new environment

Estimate for B-meson mediator



- Significantly lowered triggers for heavy ions.
- Intermediate ions have an advantage over *pp* and PbPb

Conclusion

- Heavy ion collisions allow to search for hidden new physics
- Intermediate ions can be very interesting for searches of new physics
- Lower trigger requirements could be the key advantage of heavy ion collisions over proton collisions.
- Searches for displaced new physics circumvent the noisy inner tracker
- HNL are a simple example of this idea, but other models are just as well testable

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