A heavy metal path to new physics: long-lived particle searches in future heavy ion runs

Based on: `arXiv:1810.09400`

Jan Hajer

Centre for Cosmology, Particle Physics and Phenomenology — Université catholique de Louvain

in collaboration with M. Drewes, A. Giammanco, M. Lucente, O. Mattelaer
thanks goes to
M. Borsato, E. Chapon, A. De Roeck, G. Krintiras, S. Lowette, J. Jowett, J. Prisciandaro

GDR QCD 2018

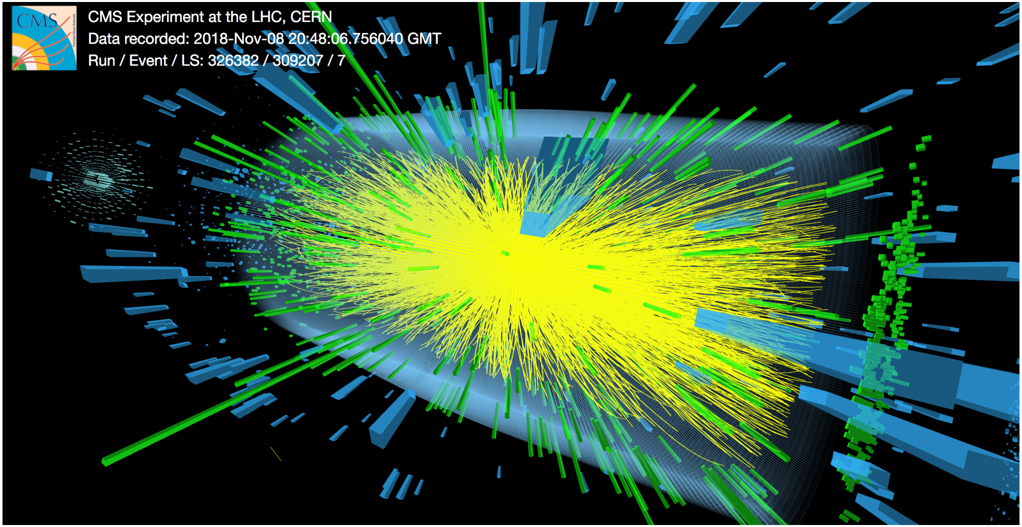
Motivation

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

Motivation

- So far the LHC has not found any new physics beyond the SM
- Initial focus of the proton runs 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



Properties of the heavy ions runs

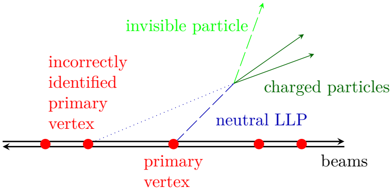
Advantage

- 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

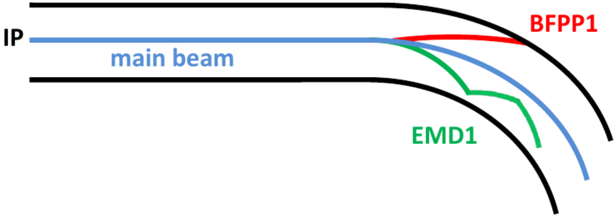
electromagnetic dissociation (EMD): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \rightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{207}\mathrm{Pb}^{82+} + n$

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

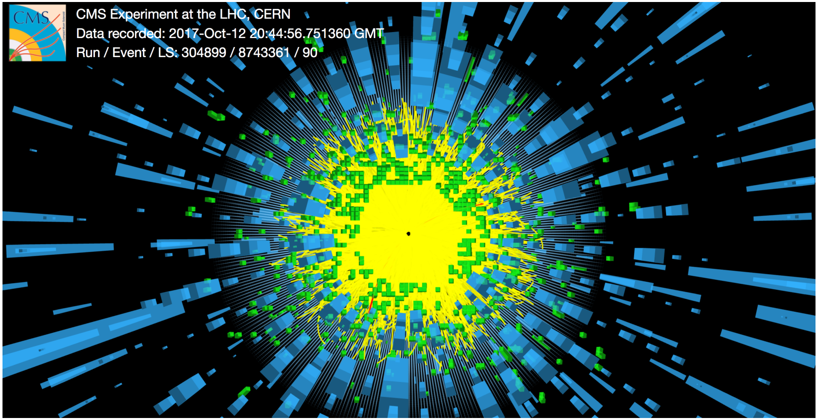
[Schaumann 2015]



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

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

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

Crosssections

	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]

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

- N_b are number of ions per bunch
- n_b is the number of bunches per beam
- $f_{\mathrm{rev}} = {}^{2\pi r}/_{c}$ 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.

Luminosity evolution

[Benedikt, Schulte, and Zimmermann 2015]

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

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

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

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

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]
$^{1}_{1}$H	0.056
$^{16}_{8}$O	7.17
$^{40}_{18}$Ar	40.3
$^{40}_{20}$Ca	44.8
$^{78}_{36}$Kr	157
$^{84}_{36}$Kr	169
$^{129}_{54}$Xe	390
$^{208}_{82}$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} [$1/\mu\mathrm{b\,s}$]
$^{1}_{1}$H	0.056	21.0×10^3	75.0	15.0×10^3
$^{16}_{8}$O	7.17	94.3	6.16	35.2
$^{40}_{18}$Ar	40.3	4.33	11.2	2.00
$^{40}_{20}$Ca	44.8	2.90	12.4	1.38
$^{78}_{36}$Kr	157	0.311	9.40	0.135
$^{84}_{36}$Kr	169	0.311	8.77	0.132
$^{129}_{54}$Xe	390	0.0665	4.73	0.0223
$^{208}_{82}$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 $t_{\mathrm{ta}} = 2.5\,\mathrm{h}$

and neglecting operational efficiencies

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

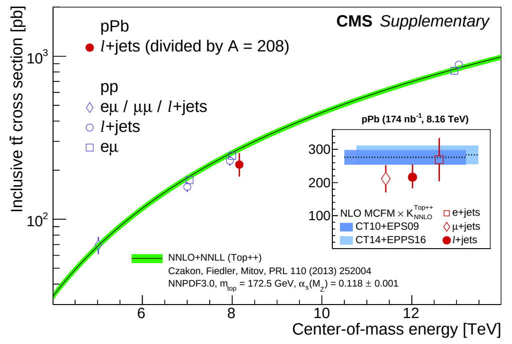
- The gain in crosssection is overcompensated by the loss in luminosity.
- However, low luminosity allows for very low triggers
- Lighter mediators are accessible

Are heavy ion runs interesting for SM processes?

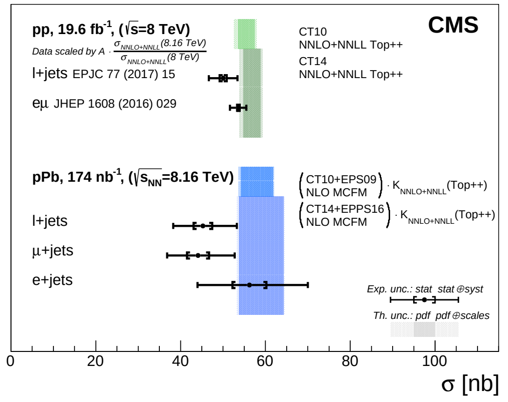
$\bar{t}t$ crosssection in pPb

[CMS 2017]

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



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



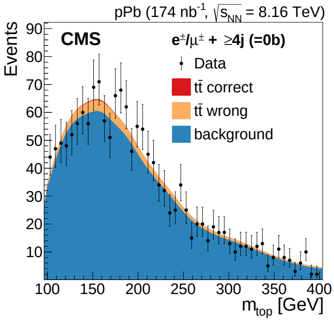
- CMS recorded $\sim 174\,\text{nb}^{-1}$ of good pPb data which seems to be a tiny amount.
- but it corresponds to a *pp* Luminosity of $174\,\text{nb}^{-1} \times A_{\text{Pb}} = 36\,\text{pb}^{-1}$.
- the nucleon multiplicity in A enables this analysis

b-tagging in heavy ion searches

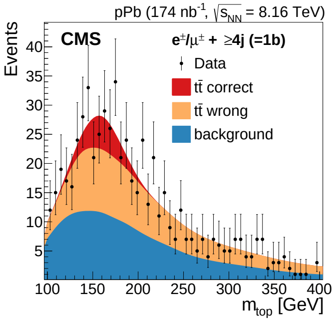
[CMS 2017]

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

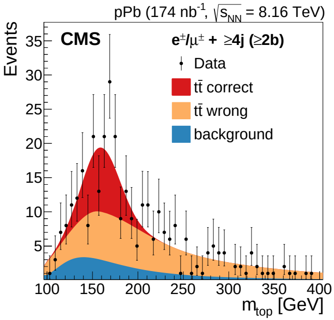
0 *b*-tagged jets



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 *p*Pb 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?

BSM physics in heavy ion collisions

[Knapen et al. 2017]

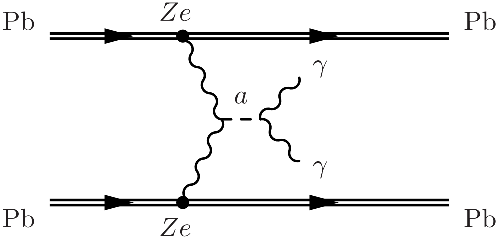
An example: Axion like particles (ALP)

A light pseudoscalar a couples to photons

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

Detection strategy

Ultraperipherical collisions



This idea exploits only the small subset of events with almost empty detector.

Charge multiplicity

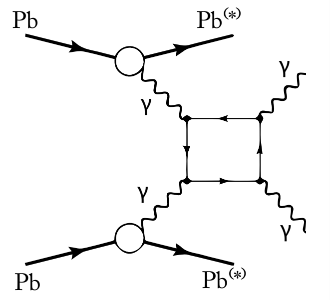
- Each proton can couple to a photon
- The signal scales with Z^4

ALPs in PbPb

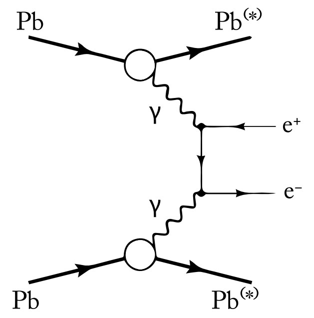
[CMS 2018]

The main backgrounds are

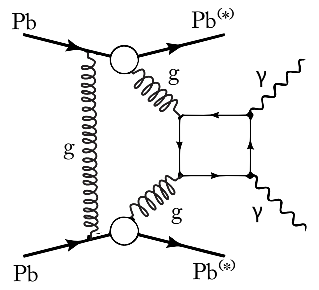
ligh-by-light scattering



fake signals



central exclusive di-photon production

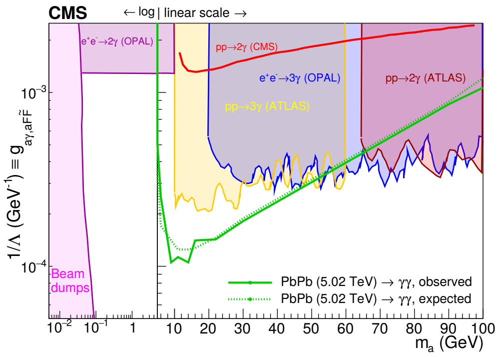


- Thresholds for photons and electrons are lowered to 1 GeV.
- Exactly two photons with $E_T > 2\,\text{GeV}$ and $|\eta| < 2.4$.
- Diphoton Invariant mass larger than 5 GeV.
- The rest of the event is empty
- Photon candidates must only be incompatible with stochastic noise in the ECAL

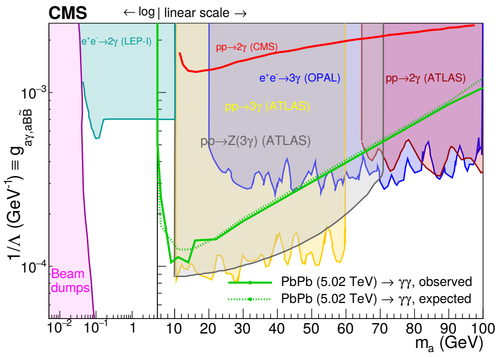
Exclusion limits in ALP coupling and mass

[CMS 2018]

ALP-photon only



ALP-neutral gauge boson



In comparison to beam dump, e^+e^- collisions at LEP and *pp* collisions at the LHC.

- PbPb data at 5.02 TeV (2015) is competitive with *pp* Run-1 data at 7 and 8 TeV up to large m_a.
- The analysis covers a blind spot at low m_a due to low trigger requirements

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

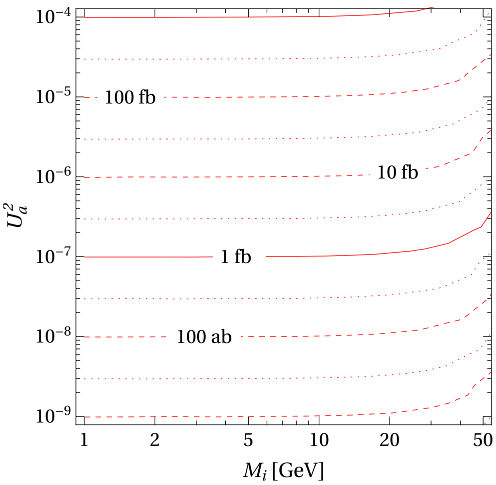
Effectively a single HNL N might be visible at colliders

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

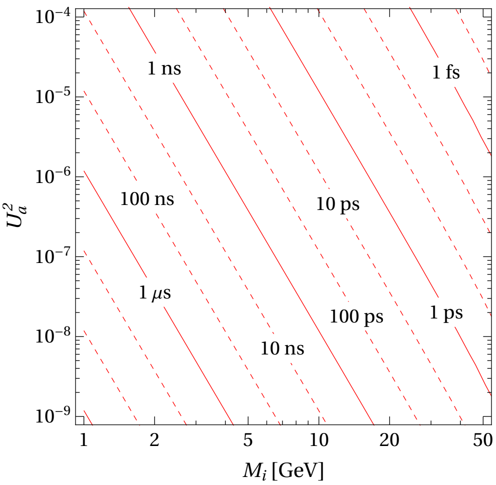
Observables are functions of the mass M_i and the coupling $U_a^2 = |\theta_a|^2$.

Properties of the HNL

Crosssection



Lifetime



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

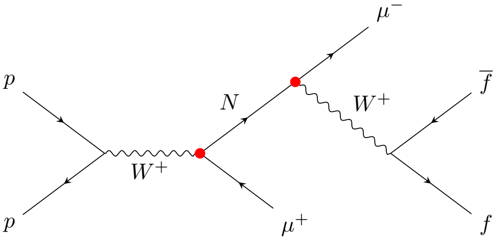
HNL at the LHC

W-boson mediator

- Simulation using `MadGraph5_aMC@-NLO`

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

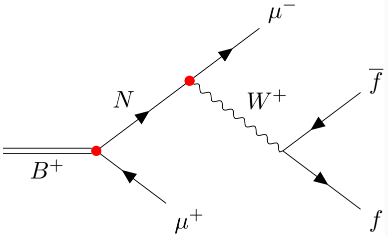
Process



B-meson mediator

- lower trigger possible:

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



Analytic estimate

Number of observable events

The decay rate can be estimated to be

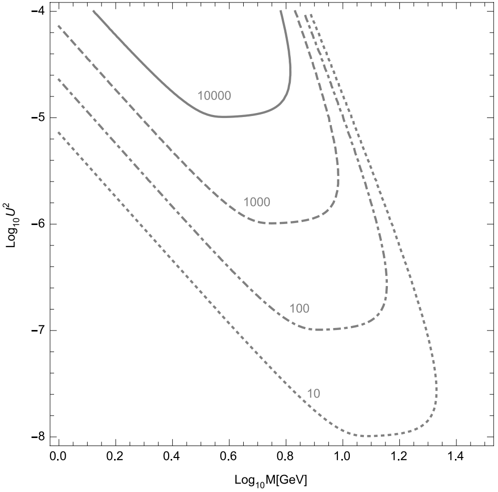
$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U^2 M^5 \ ,$$

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

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

- 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



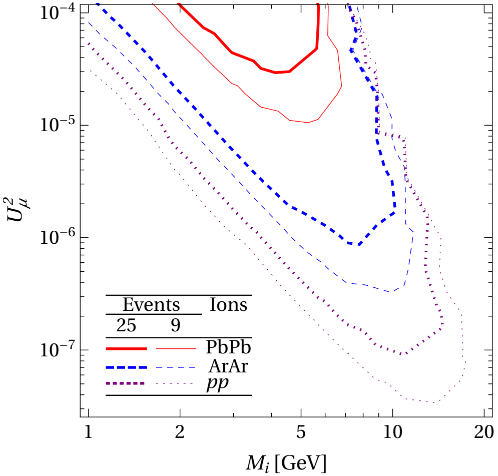
B-mesons

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

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 $10^{-2}\,\text{pb}^{-1}$.

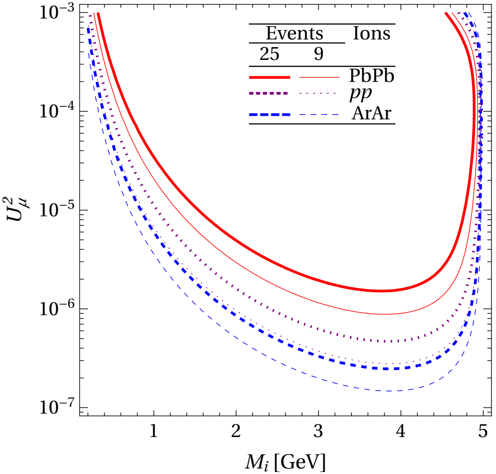
Simulation for *W*-boson mediator



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

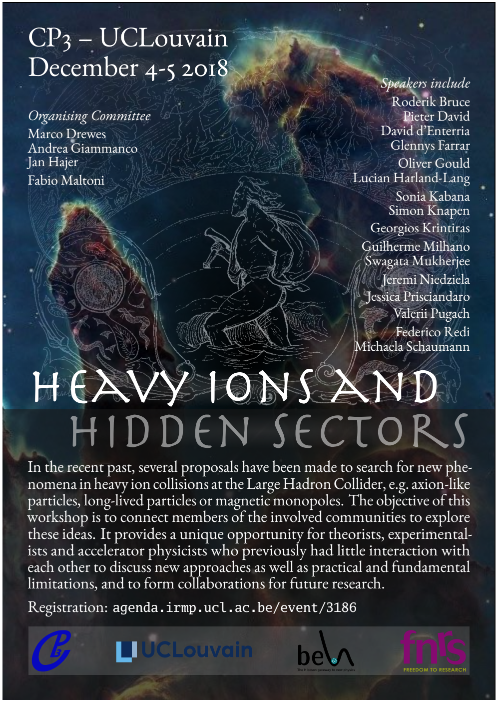
- Heavy ion collisions allow to search for hidden new physics
- Intermediate ions can be very interesting for searches of new physics
- Lower trigger requirements could be the key advantage of heavy ion collisions over proton collisions.
- Searches for displaced new physics circumvent the noisy inner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

Thank you

Further open Questions

- Are there other kinds of new physics that would be interesting to search for in heavy ion collisions?
- What is the largest possible initial intensity for heavy ions?
- How much can we gain by leveling?
- . . . ?

We are organizing a Workshop addressing this questions:



CP3 – UCLouvain
December 4-5 2018

Organising Committee
Marco Drewes
Andrea Giammanco
Jan Hajer
Fabio Maltoni

Speakers include
Roderik Bruce
Pieter David
David d'Enterria
Glennys Farrar
Oliver Gould
Lucian Harland-Lang
Sonia Kabana
Simon Knapen
Georgios Krintiras
Guilherme Milhano
Swagata Mukherjee
Jeremi Niedziela
Jessica Prisciandaro
Valerii Pugach
Federico Redi
Michaela Schaumann

HEAVY IONS AND HIDDEN SECTORS

In the recent past, several proposals have been made to search for new phenomena in heavy ion collisions at the Large Hadron Collider, e.g. axion-like particles, long-lived particles or magnetic monopoles. The objective of this workshop is to connect members of the involved communities to explore these ideas. It provides a unique opportunity for theorists, experimentalists and accelerator physicists who previously had little interaction with each other to discuss new approaches as well as practical and fundamental limitations, and to form collaborations for future research.

Registration: `agenda.irmp.ucl.ac.be/event/3186`

References

M. Drewes, A. Giammanco, J. Hajer, M. Lucente, and O. Mattelaer. “A Heavy Metal Path to New Physics”. arXiv: `1810.09400 [hep-ph]`. CP3-18-60.

M. Schaumann. “Heavy-ion performance of the LHC and future colliders”. PhD thesis. Aachen, Germany: RWTH Aachen U. CERN-THESIS-2015-195, URN:NBN:DE:HBZ:82-RWTH-2015-050284.

J. Jowett. “HL-LHC performance: Update for HE-LHC and light ions”. URL: `https://indico.cern.ch/event/686494/timetable`.

M. Benedikt, D. Schulte, and F. Zimmermann. “Optimizing integrated luminosity of future hadron colliders”. *Phys. Rev. ST Accel. Beams* 18, p. 101002. DOI: `10.1103/PhysRevSTAB.18.101002`.

CMS Collaboration. “Observation of top quark production in proton-nucleus collisions”. *Phys. Rev. Lett.* 119.24, p. 242001. DOI: `10.1103/PhysRevLett.119.242001`. arXiv: `1709.07411 [nucl-ex]`. CMS-HIN-17-002, CERN-EP-2017-239.

S. Knapen, T. Lin, H. K. Lou, and T. Melia. “Searching for Axionlike Particles with Ultraperipheral Heavy-Ion Collisions”. *Phys. Rev. Lett.* 118.17, p. 171801. DOI: `10.1103/PhysRevLett.118.171801`. arXiv: `1607.06083 [hep-ph]`.

References

CMS Collaboration. "Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\mathrm{TeV}$". arXiv: 1810.04602 [hep-ex]. CMS-FSQ-16-012, CERN-EP-2018-271.

T. Asaka and M. Shaposhnikov. "The νMSM, dark matter and baryon asymmetry of the universe". *Phys. Lett.* B620, pp. 17–26. DOI: 10.1016/j.physletb.2005.06.020. arXiv: hep-ph/0505013 [hep-ph].

J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer. "MadGraph 5: Going Beyond". *JHEP* 06, p. 128. DOI: 10.1007/JHEP06(2011)128. arXiv: 1106.0522 [hep-ph]. FERMILAB-PUB-11-448-T.

C. Degrande, O. Mattelaer, R. Ruiz, and J. Turner. "Fully-Automated Precision Predictions for Heavy Neutrino Production Mechanisms at Hadron Colliders". *Phys. Rev.* D94.5, p. 053002. DOI: 10.1103/PhysRevD.94.053002. arXiv: 1602.06957 [hep-ph]. IPPP-16-13, MCNET-16-05.