A heavy metal path to new physics

Based on: `CP3-18-60`

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

Winter solstice meeting of the EOS project “be.h”

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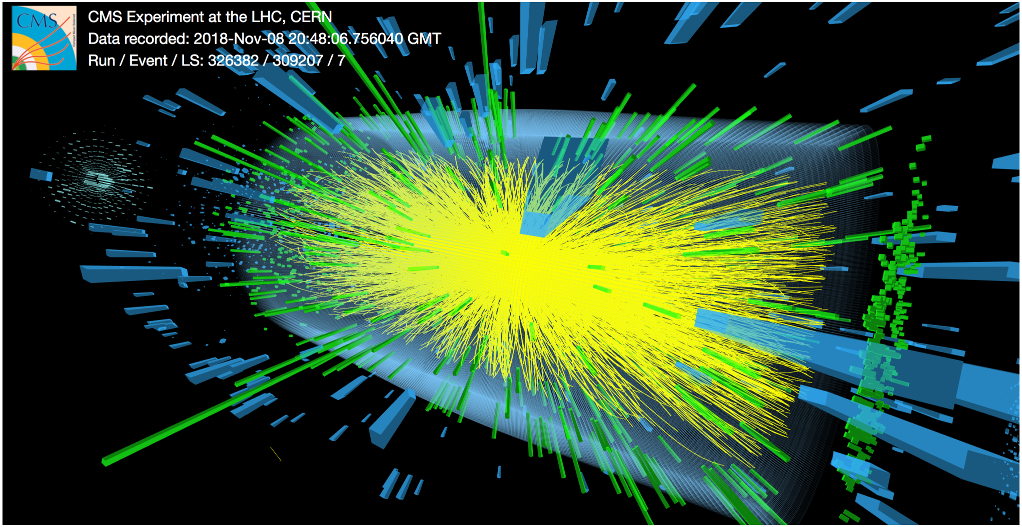
- So far the LHC has not found any new physics beyond the SM
- Initial focus lies on heavy new physics
- During the high luminosity run the focus will shift towards searches of weakly coupled particles
- We propose to utilize also the heavy ion runs for this goal

PbPb Nov 2018



Properties of the heavy ions runs

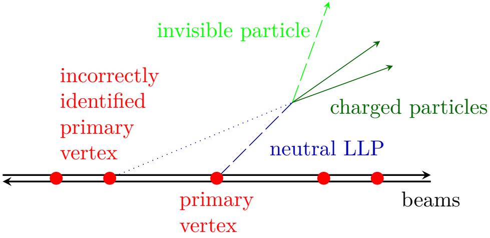
Advantage

- 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. $\frac{\sigma_{\mathrm{PbPb}}}{\sigma_{pp}} \propto A^2 = 43\dot{1}0^3$

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]

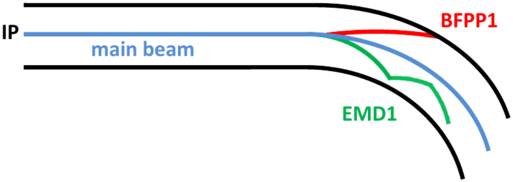
For heavy ions there are additional contributions to the crosssection

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): $^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \rightarrow {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^{+}$

Leads to [Schaumann 2015]

- Larger cross section results in faster beam decay
- Secondary beams consisting of ions with different charge/mass ratio which can accidentally quench the magnets

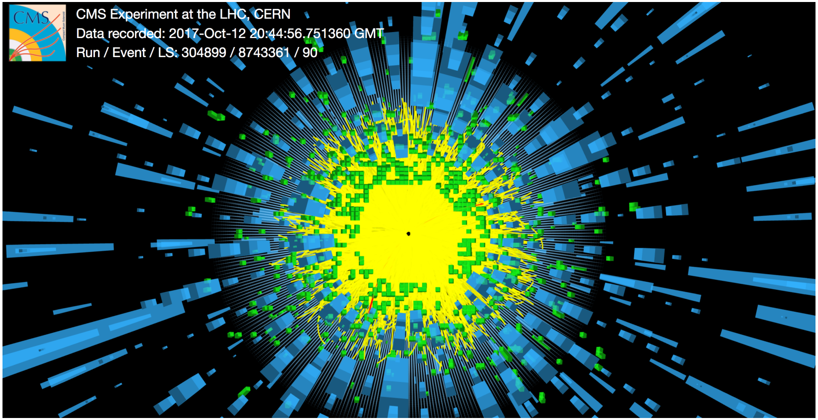


The secondary beams can be disposed by directing them in the space between the magnets.

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

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

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

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

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

Luminosity

[Benedikt, Schulte, and Zimmermann 2015]

The luminosity at one interaction point (IP) is

$L \propto N_b^2$ where N_b are number of ions per bunch

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 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]
$^{1}_{1}$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 $t_{\text{ta}} = 2.5\,\text{h}$

and neglecting operational efficiencies

	$A^2\sigma_W$ [μb]	L_0 [$^1/_{\mu\text{b s}}$]	τ_b [h]	L_{ave} [$^1/_{\mu\text{b s}}$]	$N/N(p)$ [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

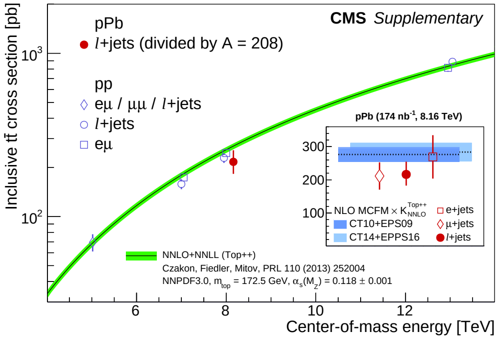
- The gain in crosssection is overcompensated by the loss in luminosity.
- However, low luminosity allows for very low triggers
- Lighter mediators are accessible

Are heavy ion runs interesting for SM processes?

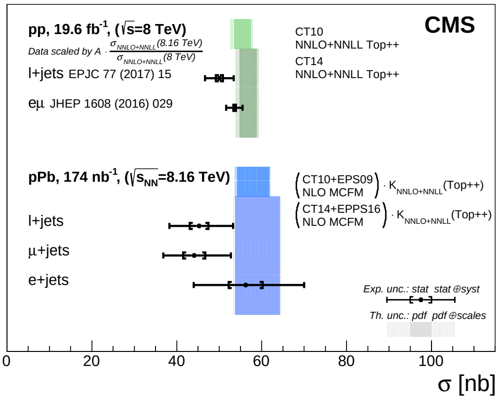
$t\bar{t}$ crosssection in pPb

[CMS 2017]

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



Comparison



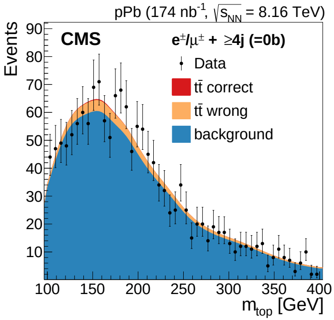
- CMS recorded $\sim 174\,\text{nb}^{-1}$ of good pPb data which seems to be a tiny amount
- But this corresponds to a *pp* Luminosity of $174\,\text{nb}^{-1} \times A_{\text{Pb}} = 36\,\text{pb}^{-1}$
- The nucleon multiplicity in A enables this analysis

b-tagging in heavy ion searches

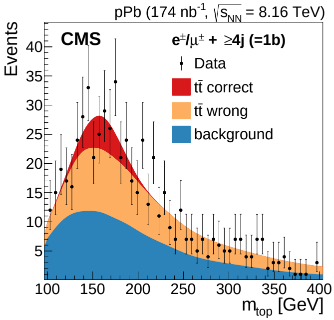
[CMS 2017]

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

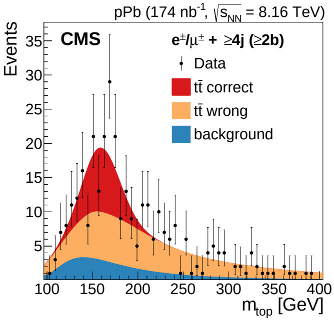
0 *b*-tagged jets



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]

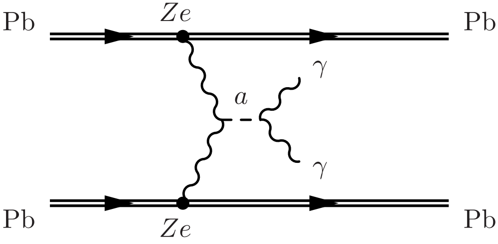
An example: Axion like particles (ALP)

A light pseudoscalar a couples to photons

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

Detection strategy

Ultraperipherical collisions



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

Charge multiplicity

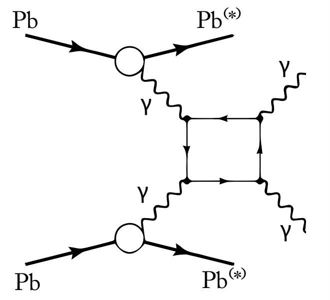
- Each proton can couple to a photon
- The signal scales with Z^4

ALPs in PbPb

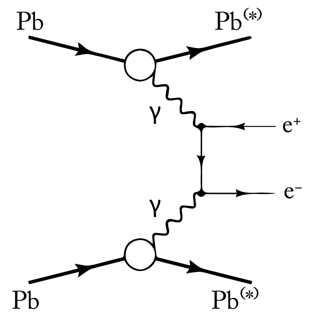
[CMS 2018]

The main backgrounds are

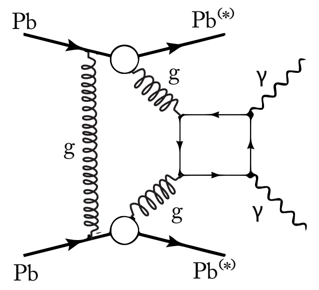
ligh-by-light scattering



fake signals



central exclusive di-photon production

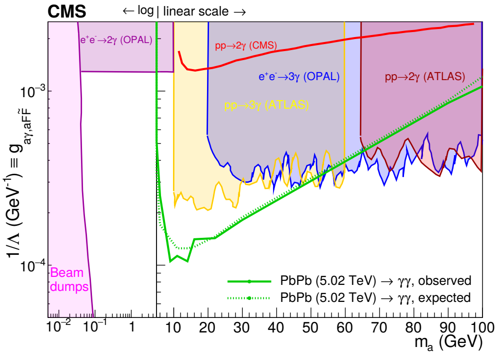


- Thresholds for photons and electrons are lowered to 1 GeV.
- Require exactly two photons with $E_T > 2\,\text{GeV}$ and $|\eta| < 2.4$.
- Diphoton Invariant mass larger than 5 GeV.
- The rest of the event is empty
- Photon candidates must only be incompatible with stochastic noise in the ECAL

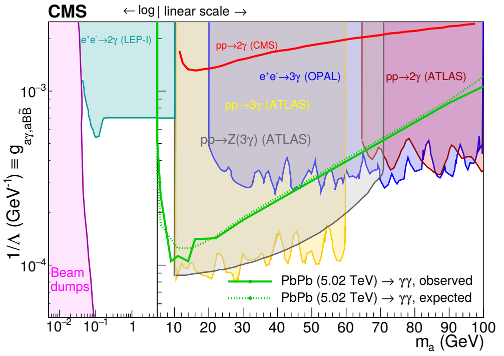
Exclusion limits in ALP coupling and mass

[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}

$$\Delta\mathcal{L} = -y_{ai}\overline{\ell}_a \varepsilon \phi^* \nu_{Ri} - \frac{1}{2}\overline{\nu^c_{R}}_i M_i \nu_R + \text{h.c.}$$

where M_M is the Majorana mass matrix.

After electroweak symmetry breaking the seesaw mechanism leads to

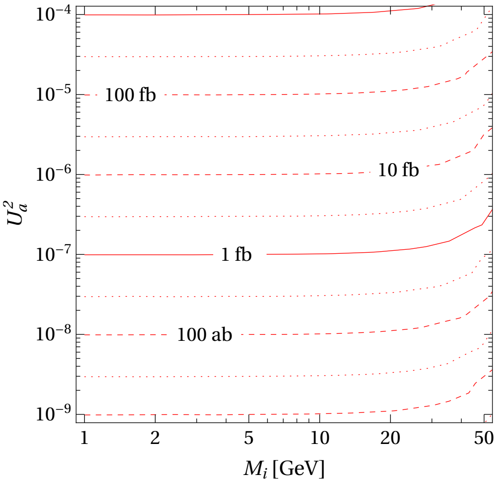
- 3 heavy mass eigenstates $N_i \simeq (\nu_R + \theta^T \nu_L^c)_i + \text{c.c.}$, where $\theta = vyM_M^{-1}$
  The mass can be of order of the electroweak scale
- 3 light neutrinos $\nu_i \simeq V_\nu^\dagger(\nu_L - \theta\nu_R^2)_i + \text{c.c.}$ with a mass matrix $m_\nu = -\theta M_M \theta^T$

Phenomenological consquences

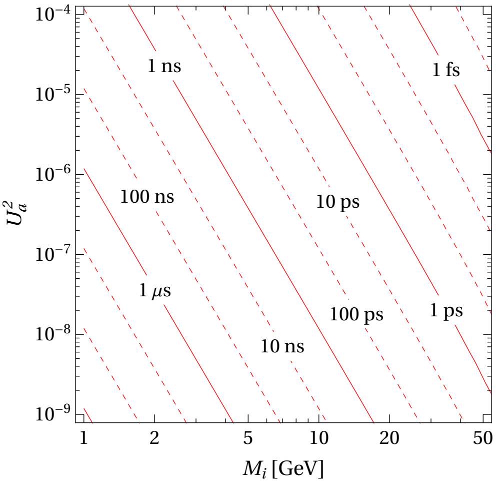
- The parameter suffice to explain neutrino oscillation data.
- One of the neutrino decouples and can play the role of dark matter.
- Another heavy neutrino can be a long lived state observable at the LHC.

Properties of the HNL

Crosssection



Lifetime



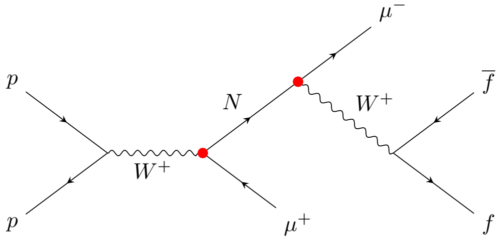
- Masses of a few GeV lead to observable macroscopic displacement.
- In the relevant mass range the crosssection is $\sigma \propto U_a^{-2}$

HNL at the LHC

W-boson mediator

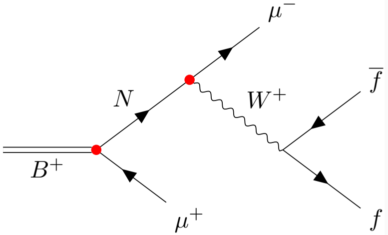
- Simulation using `MadGraph5_aMC@-NLO`
  [Alwall et al. 2011; Degrande et al. 2016]
- Trigger on first μ with $p_T > 25\,\mathrm{GeV}$
- Search for displaced μ with $d > 5\,\mathrm{mm}$
- Usual strategy to search for displaced HNLs in pp collisions

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

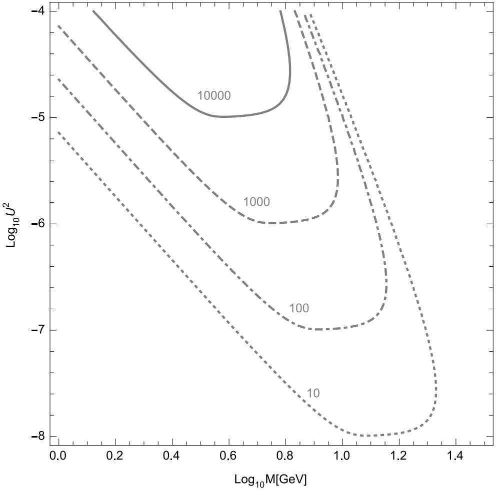
$$\Gamma_N \simeq 11.9 \times \frac{G_F^2}{96\pi^3} U^2 M^5 \ ,$$

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

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

- 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



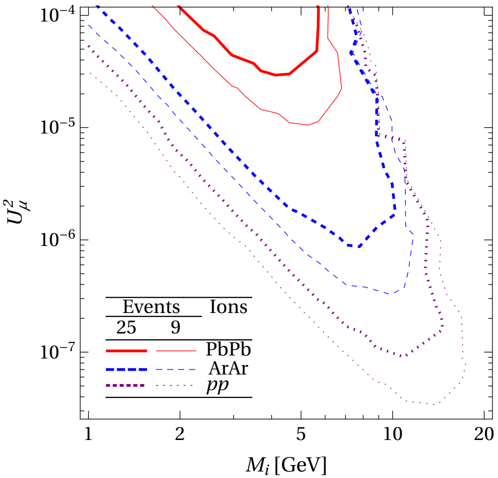
B-mesons

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

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

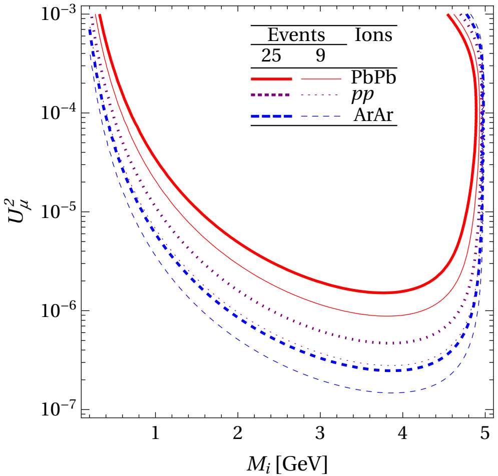
Simulation for *W*-boson mediator



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

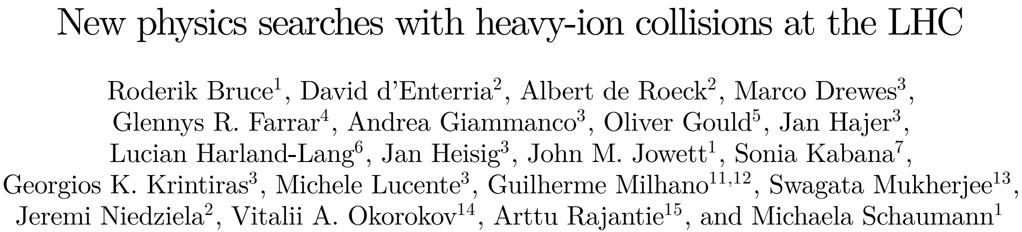
Summary

- 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

Today on arXiv

[Bruce et al. 2018]

Our input to the update of the European Particle Physics Strategy (EPPS)



New physics searches with heavy-ion collisions at the LHC

Roderik Bruce[1], David d'Enterria[2], Albert de Roeck[2], Marco Drewes[3],
Glennys R. Farrar[4], Andrea Giammanco[3], Oliver Gould[5], Jan Hajer[3],
Lucian Harland-Lang[6], Jan Heisig[3], John M. Jowett[1], Sonia Kabana[7],
Georgios K. Krintiras[3], Michele Lucente[3], Guilherme Milhano[11,12], Swagata Mukherjee[13],
Jeremi Niedziela[2], Vitalii A. Okorokov[14], Arttu Rajantie[15], and Michaela Schaumann[1]

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