

A Heavy Metal Path to New Physics

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We show that heavy ion collisions at the LHC provide a promising environment to search for signatures with displaced vertices in well-motivated New Physics scenarios. The lower instantaneous luminosity in heavy ion collisions allows to operate the LHC experiments with very loose triggers. For scenarios in which long-lived particles are produced in the decay of light particles, this can increase the number of observable events by several orders of magnitude. If ions lighter than Pb are used, as it is currently discussed in the heavy ion community for unrelated reasons, this can lead to a higher sensitivity per time of running than in pp collisions. We illustrate that explicitly for heavy neutrinos in the Neutrino Minimal Standard Model. Another advantage of heavy ion collisions is the fact that there is no pile up, i.e., the average number of simultaneous interactions per bunch crossing is well below unity. This entirely removes the problem of mis-identifying the location of the primary vertex, which may be the key to trespass the systematics wall due to background uncertainties in the cases where background contamination mostly comes from SM particles that originate from different parts of the interaction region. This provides strong motivation to further explore the possibility to search for New Physics in heavy ion collisions.

Introduction. The Large Hadron Collider (LHC) at CERN is currently the world's most powerful particle collider. It was built for three main reasons, *i*) to unveil the origin of the electroweak symmetry breaking (EWSB), *ii*) to search for New Physics beyond the Standard Model (SM) and *iii*) to study the properties of the quark-gluon plasma (QGP). The first goal has been achieved with the discovery of a scalar boson [1, 2], commonly referred to as “Higgs boson”, which (given the properties that have been measured so far) strongly suggests that the Brout-Englert-Higgs mechanism [3–5] is responsible for the spontaneous EWSB in the SM. Heavy ion collisions at the LHC have considerably helped to understand the quark-gluon plasma at high collision energies [6]. However, contrary to expectations based on naturalness arguments, no new elementary particle other than the Higgs boson has been found to date, neither any other deviation from the SM. In this Letter, we point out that the heavy ion collisions, which are originally motivated to create a QGP, can also be exploited to extend the search for new particles to parameter regions that are inaccessible with proton collisions.

The motivations for the existence of new elementary particles are manifold. Apart from theoretical questions such as the *hierarchy problem* and the *flavour puzzle* in the SM, there are a number of unexplained observational facts. These include the *origin of neutrino masses*, the observed *Dark Matter* (DM) and the *baryon asymmetry of the universe* (BAU). These problems clearly indicate the existence of New Physics beyond the SM, and many theories that aim to explain them predict the existence

of new particles with masses near the electroweak scale. From an experimental viewpoint, there could be two explanations why no new particles have been found to date: Either they are too heavy to be produced in collisions at the LHC at all, or they are too feebly coupled to be produced in significant numbers. While the former possibility unavoidably necessitates the construction of more powerful colliders (“energy frontier”), the latter option provides a strong incentive to increase the number of collisions (“intensity frontier”) and/or reduce the backgrounds in experiments. In this Letter we focus on the second possibility, which in many cases gives rise to comparably *long-lived particles* (LLPs). An overview of well-motivated New Physics scenarios of this kind can e.g. be found in [7].

Long-lived Particles. Particles that exist for long enough to travel macroscopic (measurable) distances in the LHC experiments appear in many models of physics beyond the SM. This leads to striking *displaced vertex* or *displaced track* signatures. LLPs usually owe their longevity to feeble interactions with SM particles, often in combination with a comparably low mass. This is particularly well-motivated in theories with dark or hidden sectors that communicate with the SM only via so-called “portal” interactions. These sectors may include one or several DM candidates, as well as the ingredients to explain the generation of neutrino masses and/or the BAU.

Recently several proposals have been made to improve the sensitivity of the LHC to very large displacements, including the addition of extra detectors along the beamline or at the surface [7–11]. In this work we pursue another direction and explore the idea that the discovery potential of the existing detectors can be improved by searches with heavy ion collisions. The displacement makes it comparably easy to distinguish the signal from the dirty environment that is created in a heavy ion collision because all tracks from SM interactions must originate from within the microscopic volume of the two colliding nuclei.

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Heavy ion collisions at the LHC. With respect to protons, a larger number of parton level interactions per collision can be achieved for heavy ions, as each nucleus contains A nucleons, providing an enhancement of up to four orders of magnitude ($\approx A^2$, with $A = 208$ for the lead isotope accelerated in LHC beams, $^{208}_{82}\text{Pb}$) in hard-scattering cross sections with respect to pp collisions at the same centre-of-mass energy per nucleon. There are, however, several drawbacks.

- 1) The collision energy per nucleon is smaller (e.g. $\sqrt{s_{\text{NN}}} = 5.52$ TeV for Pb beams), therefore paying a price with respect to pp collisions at 14 TeV. The scaling factor $\sigma_{pp}(14 \text{ TeV})/\sigma_{\text{NN}}(5.52 \text{ TeV})$ is typically larger for gluon-initiated processes than for quark-antiquark collisions, and it depends strongly (grows with) the particle masses in the final state of the hard process under consideration. This effect is comparably weak for masses at the EW scale [12]; for instance, it only reduces the W -boson production cross section per nucleon by a factor of order one, c.f. Table I.
- 2) Heavy ion collisions are known to produce a huge number of tracks near the interaction point. While this makes it very difficult to search for prompt signatures, feebly interacting LLPs can leave the luminous region before decaying. Their decay can produce displaced tracks at macroscopic distances from the interaction point that can easily be distinguished from the tracks that originate from the fireball created in the collision itself. Moreover, due to the high pile-up during Run 4 in pp collisions, the track multiplicity in ion collisions is expected to be comparable for pp and PbPb¹ and even smaller for lighter ion beams [19].
- 3) The instantaneous luminosity in heavy ion runs is considerably lower than in pp collisions, cf. Table I. The current expectation for the next PbPb Run, planned in late 2018, is to accumulate 1 nb^{-1} of collisions, while 10 nb^{-1} are expected to be accumulated during the high-luminosity phase of the

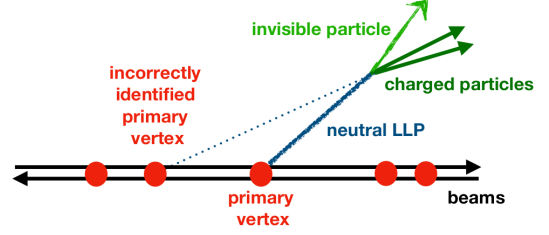


Figure 1: Example of a signature that is difficult to search for in high pile-up pp collisions. Heavy ion collisions can provide a cleaner environment.

accelerator (HL-LHC) [20]. Even considering the enhancement due to nucleon-nucleon combinatorics, this cannot compete with the statistics available in pp data. This poses the strongest limitation to displaced vertex searches. We discuss it in some detail in the following section.

- 4) Heavy ion Runs at the LHC are relatively short (not more than one month is allocated in the yearly schedule). This is obviously not a fundamental restriction. To remain independent of possible changes in the planning, in the following we compare the sensitivity per running time, given a realistic instantaneous luminosity.

On the other hand, there are key advantages in heavy ion collisions.

- I) The number of parton level interactions per collision is larger.
- II) The probability of mis-identifying the primary vertex is practically negligible for heavy ion collisions.² This is in contrast to the pile up that one has to face when colliding high intensity proton beams, which leads to tracks that originate from different points in the same bunch crossing and creates a considerable background for displaced signatures. Hence, heavy ion collisions provide a much cleaner environment to search for signatures stemming from the decay of LLPs that are heavy enough that the decay products' momenta are not colinear, cf. Figure 1.

¹ In PbPb collisions, hard-scattering signals are more likely to originate in the most central events, where up to around 2000 charged particles are produced per unit of rapidity at $\sqrt{s_{\text{NN}}} = 5.52$ TeV [13], meaning that around 10000 tracks can be found in the tracking acceptance of the multi-purpose experiments ATLAS and CMS. In contrast, pp collisions during standard Runs in 2017 were typically overlaid by about 30 pile-up events, each adding about 25 charged particles on average within the tracking acceptance of the multi-purpose detectors [14–16], meaning that ≈ 750 charged particles per event are coming from pileup. This is not expected to increase by a large factor until the end of Run 3. The HL-LHC will bring a big jump: current projections assume that, in order to accumulate 3000 fb^{-1} as planned, each bunch crossing will be accompanied by about 200 pile-up events [17, 18], meaning 5000 additional charged particles per hard-scattering event. In conclusion, in the HL-LHC era the difference in track multiplicity between PbPb and pp collisions will reduce to a mere factor of two.

² Although a very large track multiplicity is expected to degrade the reconstruction and identification of displaced vertices, the adverse effect of pile up on vertex-finding performance is coming more from the presence of additional primary-interaction vertices than from the sheer number of tracks. This is demonstrated for example from the comparison of b -tagging performance in pp and $p\text{Pb}$ collisions in $t\bar{t}$ studies [22]: using the same algorithm as the standard pp analysis, and an equal efficiency of correctly tagging b -quark-initiated jets, the misidentification rate of light jets is smaller in $p\text{Pb}$ events (0.1 % vs. 0.8 %) in spite of the larger track multiplicity. Although those algorithms will have to be retuned to recover a comparable efficiency in the more extreme conditions of high-centrality PbPb collisions, we take it as an indication that at first order pile up affects displaced-particle performance more than track multiplicity.

	M [GeV]	$\sqrt{s_{NN}}$ [TeV]	Cross section						Luminosity			N_N/N_p [1]
			σ_{EMD} [b]	σ_{BFPP} [b]	σ_{had} [b]	σ_{tot} [b]	σ_W [nb]	$A^2\sigma_W$ [μb]	L_0 [1/μb s]	τ_b [h]	L_{ave} [1/μb s]	
^1_1H 0.931	14.0	14.0	0	0	0.0710	0.07	56.0	0.0560	21.0×10^3	75.0	15.0×10^3	1
$^{16}_8\text{O}$ 14.9	7.00	7.00	0.074	24×10^{-6}	1.41	1.48	28.0	7.17	94.3	6.16	35.2	0.30
$^{40}_{18}\text{Ar}$ 37.3	6.30	6.30	1.2	0.0069	2.6	3.81	25.2	40.3	4.33	11.2	2.00	0.0957
$^{40}_{20}\text{Ca}$ 37.3	7.00	7.00	1.6	0.014	2.6	4.21	28.0	44.8	2.90	12.4	1.38	0.0735
$^{78}_{36}\text{Kr}$ 72.7	6.46	6.46	12	0.88	4.06	16.9	25.8	157	0.311	9.40	0.135	0.0253
$^{84}_{36}\text{Kr}$ 78.2	6.00	6.00	13	0.88	4.26	18.1	24.0	169	0.311	8.77	0.132	0.0266
$^{129}_{54}\text{Xe}$ 120	5.86	5.86	52	15	5.67	72.67	23.4	390	0.0665	4.73	0.0223	0.0103
$^{208}_{82}\text{Pb}$ 194	5.52	5.52	220	280	7.8	508	22.1	955	0.0136	1.50	2.59×10^{-3}	0.0029

Table I: Cross sections and luminosities for different heavy ions based on [21]. The luminosities are calculated under the optimistic assumption of $p = 1.9$ and $t_{\text{ta}} = 2.5$ h and neglecting operational efficiencies. The cross sections are related via $\sigma_{\text{tot}} = \sigma_{\text{EMD}} + \sigma_{\text{BFPP}} + \sigma_{\text{had}}$. The last column contains the ratio between the number of produced W -bosons in NN- and pp -production.

III) The lower instantaneous luminosity can enable ATLAS and CMS to significantly lower their trigger thresholds, in particular for clean analysis objects such as muons. This, e.g., allows to search for signatures with comparably low transverse momentum p_T , which is particularly interesting in scenarios involving light mediators.

The effect of point II) is model dependent and requires a detailed quantitative analysis. This goes beyond the scope of the present Letter, whose main purpose is to point out the potential of heavy ion collisions. We will therefore in the following entirely focus on aspect III) for illustrative purposes.

Average instantaneous luminosity. The instantaneous luminosity in heavy ion collisions is limited by several factors. First, there are technical limitations on the performance of the injectors. Second, the cross section per nucleon in the interaction points is larger than for pp collisions. This leads to a more rapid decline in the beam intensity. Most of the interactions are unwanted electromagnetic interactions in the stronger Coulomb fields and soft hadronic processes, i.e., electromagnetic dissociation (EMD) and bound-free pair production (BFPP), cf. e.g. references [23–25] and references therein for details. In addition to the loss in beam intensity, these processes tend to produce secondary beams that can potentially quench the LHC magnets. The latter problem was only recently solved for ATLAS and CMS by directing the secondary beams between the magnets, while a special new collimator is required for ALICE [26, 27]. Finally, a maximal number of events is not necessarily ideal for experiments that primarily study the QGP. For instance, the ALICE experiment is limited in the amount of data that it can acquire by the repetition time of its time projection chamber [28], thus instantaneous luminosity is levelled at their interaction point by adjusting the horizontal separation between the bunches. Similarly also the LHCb experiment only uses about 10 % of the available beam intensity [29].

The upper limit on the achievable instantaneous luminosity depends on the mass number A and charge Z of the concerned nuclei in a complicated manner and is currently under investigation. For the purpose of the present Letter we use the numbers presented in Table I, which are computed based on estimates presented at a recent HL-LHC workshop [21]. In the following we briefly summarise how we used these data. The luminosity at an interaction point behaves as $L \propto n_b N_b^2$ [30], where n_b is the number of bunches per beam and N_b is the number of nucleons per bunch. The average luminosity for the optimal run time is [30, 31]

$$L_{\text{ave}} = L_0 \left(1 + \sqrt{t_{\text{ta}}/\tau_b}\right)^{-2}, \quad (1)$$

where L_0 is the initial luminosity, τ_b is the (initial) beam lifetime and t_{ta} the turnaround time between two fillings. The initial bunch intensity roughly follows $N_b \left(\frac{A}{Z}\right) = N_b \left(\frac{208}{82}\text{Pb}\right) \left(\frac{Z}{82}\right)^{-p}$ where the exponent characterises the number of nucleids per bunch. For a given isotope, it is limited by the heavy-ion injector chain, the bunch charges and intra-beam scatterings. Simple estimates based on fixed target studies with Ar beams suggest that $p < 1.9$ is realistic [21].

An example: Heavy Neutrinos. Right handed neutrinos ν_R appear in many extensions of the SM and could, depending on their mass M , explain several open puzzles in cosmology and particle physics, cf. e.g. [32]. The SM Lagrangian is augmented by the extension

$$\frac{i}{2} \bar{\nu}_R \not{\partial} \nu_R - F_a \bar{\ell}_{La} \varepsilon \phi^* \nu_R - \frac{1}{2} \bar{\nu}_R^c M \nu_R + \text{h.c.}, \quad (2)$$

which is well-known from the type-I seesaw mechanism [33–38]. Here ℓ_{La} are the SM lepton doublets, ε is the antisymmetric SU(2) tensor and ϕ the SM scalar doublet. For M below the electroweak scale, the Lagrangian (2) effectively describes the Neutrino Minimal Standard Model (νMSM) [39, 40], a minimal extension of the SM that

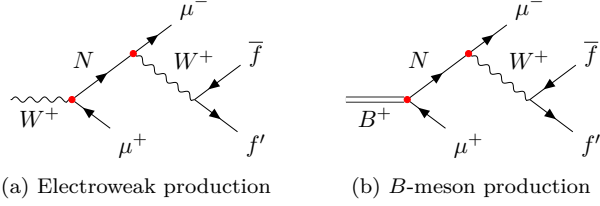


Figure 2: Production and decay of heavy neutrino mass eigenstates N . The tiny couplings inducing the displaced signature are indicated by red vertices.

can simultaneously explain the light neutrino masses, the BAU and the DM [41, 42], cf. [43] for a review. The heavy neutrinos interactions with the SM can be described by the mixing angles $\theta_a = \langle \phi \rangle F_a M^{-1}$, which characterise the relative suppression of their weak interactions compared to those of the light neutrinos. If the heavy neutrinos approximately respect a generalised $B - L$ symmetry [44], then the $U_a^2 \equiv |\theta_a|^2$ can be large enough [45] to allow for detection in displaced vertex searches at the LHC [46–52] or at future collider [53–56] while in agreement with all experimental constraints, cf. e.g. [57–59] and references therein.

For M below the weak gauge boson masses, the heavy neutrinos can be long-lived enough to produce displaced vertex signals. The dominant production channel for $M > 5$ GeV is the decay of real Z (W) bosons, in which the heavy neutrinos are produced along with a neutrino ν_a (charged lepton ℓ_a), while for $M < 5$ GeV the production in b hadron decays dominates, cf. Figure 2. The number of heavy neutrinos that are produced along with a lepton of flavour a can be estimated as $\sim U_a^2 \sigma_\nu^{[A,Z]}$, where σ_ν is the production cross section for light neutrinos. It is given by $\sigma_\nu = \sigma_W^{[A,Z]}/3$ in W -decays and $\sigma_\nu = \sigma_B^{[A,Z]}/9$ in B -decays, where $\sigma_W^{[A,Z]}$ and $\sigma_B^{[A,Z]}$ are the W and B production cross sections in collisions of the ion species with $[A, Z]$. They then decay (semi-)leptonically [42, 57, 60, 61].

The number of displaced vertex events with lepton flavour a from the first vertex and b from the second vertex that can be seen in a detector can then be estimated as

$$N_d \simeq L_{\text{int}} \sigma_\nu \frac{U_a^2 U_b^2}{U^2} \left(e^{-l_0/\lambda} - e^{-l_1/\lambda} \right) f_{\text{cut}}, \quad (3)$$

where l_1 is the length of the effective detector volume, l_0 the minimal displacement that is required by the trigger, $\lambda = \beta\gamma/\Gamma_0$ is the particle decay length, with Γ_0 the heavy neutrino decay rate, β the heavy neutrino velocity, $\beta\gamma = |\mathbf{p}|/M$ are Lorentz factors, $U^2 = \sum_a U_a^2$ and $f_{\text{cut}} \in [0, 1]$ is an overall efficiency factor related to cuts due to triggers, detector geometry and efficiency. Since l_1 is largest for muons, in the following we concentrate on the case $b = \mu$. Moreover, we employ the simplified assumption $U^2 = U_\mu^2$, in which case the estimate (3) reduces to $N_d \simeq L_{\text{int}} \sigma_\nu U_\mu^2 (e^{-l_0/\lambda} - e^{-l_1/\lambda})$.

We first focus on the production in W decays and calculate the Feynman rules of the heavy neutrinos coupled to

the SM with **FeynRules** 2.3 [62] using the implementation described in references [57, 63, 64]. Subsequently we generate events with **MadGraph5_aMC@NLO** 2.6.2 [65] which we have extended in order to also be able to simulate heavy ion collisions. We calculate the total decay width of the heavy neutrinos with **MadWidth** [66] and simulate their decays into leptons with **MadSpin** [67, 68]. The remaining decays, showering and hadronisation of colored particles is done by **Pythia** 8.2 [69]. Subsequently, we perform a fast simulation of the HL-CMS detector response. We trigger on a charged muon with $p_T > 25$ GeV and $|\eta| < 2.5$ and require a second lepton with $p_T > 5$ GeV and $l_0 > 5$ mm. We assume that leptons can be tagged with a constant efficiency if their remaining path within the tagger is longer than 1 m, for shorter distances we assume an exponential decrease in the tagging efficiency. For sufficiently large displacement the background, dominated by cosmic rays and beam-halo muons [70], can be neglected for the purpose of this Letter. We also ignore the scattering of ordinary neutrinos that come from the collision point, based on the low cross section of charged-current interaction in the detector material.

The results displayed in Figure 3a show that, for the channels considered here the suppression of the number of events due to the limited instantaneous luminosity of heavy ion runs overcompensates the A^2 enhancement per collision. However, for lighter nuclei such as Ar, the difference in the expected number of events per unit of running time is only slightly more than an order of magnitude. Removing the triggers, i.e. point III), only marginally improves the sensitivity because most $\mu^\pm$ from the W -decay in the primary vertex have $p_T > 25$ GeV due to the mass of the W boson.

The situation is very different for the production in B meson decays: because of the much smaller B meson mass, the heavy neutrinos generally have p_T well below the trigger level, and removing the triggers can lead to a much larger number of observable events. The production of heavy neutrinos in B meson decays cannot be simulated in the same way as described above, we therefore resort to the approximation (3) to estimate the number of events. To ensure its validity, we first test it against our simulation, using $\sigma_\nu = \sigma_W/3$, $l_0 = 1.5$ cm, $l = 1.5$ m, $|\mathbf{p}| = 60$ GeV and $\Gamma_0 \simeq 11.9 \times G_F^2/96\pi^3 U^2 M^5$ [42, 60]. This simple estimate allows to reproduce the correct number of events from W decays in pp , ArAr and PbPb collisions up to a factor of order one in most of the parameter space. We then apply the formula to estimate the number of events from B decays in heavy ion collisions without trigger and compare it to what can be achieved in pp collisions with realistic kinematic requirements for the online triggers. For this purpose, we use the B meson production cross sections per nucleon σ_B^{pp} and σ_B^{PbPb} measured in [71], respectively. For lighter ion collisions, such as ArAr, σ_B^{PbPb} is a conservative estimate; we expect $\sigma_B^{\text{ArAr}} > \sigma_B^{\text{PbPb}}$ due to the larger nuclear modification factor, simply because the mesons have a higher chance to escape the

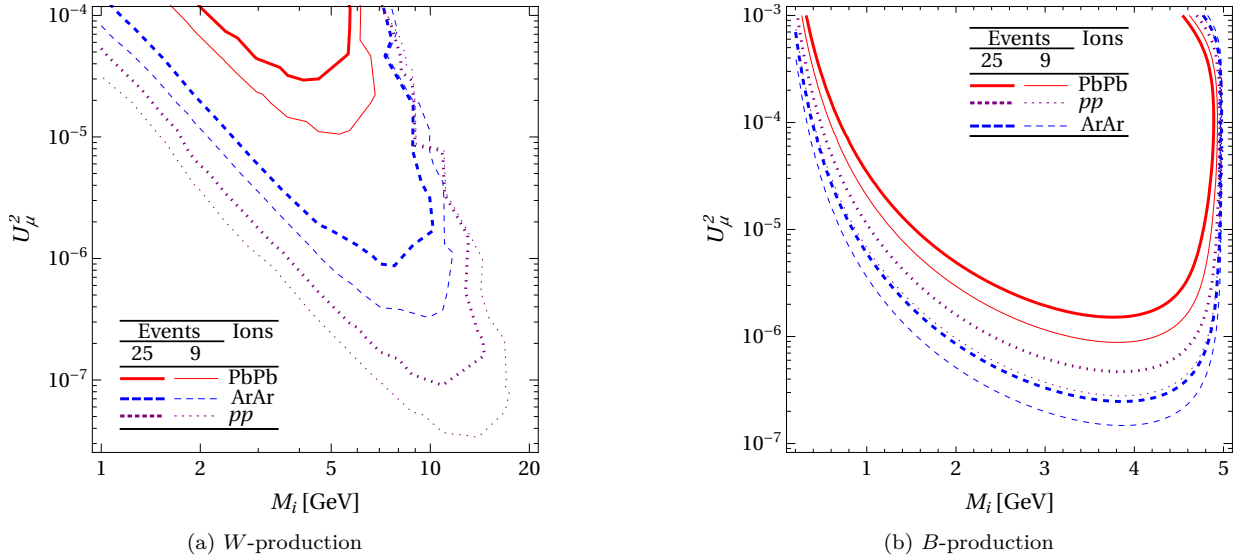


Figure 3: CMS reach for pp (dotted purple), ArAr (dashed blue), and PbPb (solid red) with equal running time corresponding to a luminosity per nucleon of $L_{\text{int}} = 5.79 \times 10^4$, 7.72 and 10^{-2} pb^{-1} , respectively (cf. Table I). The thin and thick curves correspond to 9 and 25 signal events, respectively. The result in Panel (a) is based on a simulation of W induced processes using **MadGraph** while the one in Panel (b) is an estimate on processes based on B -meson decays. In Panel (b) we assume the usage of optimised triggers for pp collisions and very loose triggers for heavy ion collisions.

(smaller) fireball unharmed. We can then estimate the number of events as

$$\frac{L_{\text{int}} \sigma_B^{[A,Z]}}{9} \left[1 - \left(\frac{M_i}{m_B} \right)^2 \right]^2 \frac{U_a^2 U_b^2}{U^2} \left(e^{-t_0/\lambda} - e^{-t_1/\lambda} \right) f_{\text{cut}}. \quad (4)$$

For a comparison between pp and heavy ion collisions we can ignore the effects of detector geometry and efficiencies on f_{cut} because they are very similar. We use $\Gamma_0 \simeq 4 \times G_F^2/96\pi^3 U^2 M^5$ [60], $|\mathbf{p}| = 10 \text{ GeV}$ and employ a cut of $p_T > 25 \text{ GeV}$ in pp collisions and of $p_T > 3 \text{ GeV}$ in heavy ion collisions, the latter being the minimum transverse momentum that allows a charged particle to cross the muon chambers of the CMS experiment. Using the p_T distributions for the B mesons from [71] as a proxy for those of the charged leptons from the primary vertex³ we obtain $f_{\text{cut}}^{pp}/f_{\text{cut}}^{\text{ion}} \simeq 10^{-2}$. Figure 3b shows that the gain in sensitivity from low p_T events overcompensates the effect of the smaller instantaneous luminosity.

Discussion and conclusions. We studied the potential to search for LLPs via displaced vertex searches in heavy ion collisions, using the specific case of heavy neutrinos as an illustrative example. We find that, if the same cuts are applied as in pp collisions, the limitations on the

instantaneous luminosity for Pb suppress the observable number of events per unit of run time by 2–3 orders of magnitude. The suppression comprises only roughly one order of magnitude for lighter nuclei, such as Ar, the use of which is currently explored by the heavy ion community for other reasons [21]. A positive aspect of the lower instantaneous luminosity is, however, that key triggers can be operated with low or even no kinematic thresholds. This in particular allows to search for events with $p_T \ll 25 \text{ GeV}$, which can make up the vast majority of events in scenarios where the LLPs are produced in decays of light particles. As a result, the number of observable events per time of running in heavy ion collisions can be larger than in pp collisions, leading to a higher sensitivity. We illustrate this for the specific case of heavy neutrinos produced in B -meson decays. Another advantage of heavy ion collisions, which we have not explored quantitatively in this work, is that all tracks originate from a small (fm sized) region, i.e., there is no pile up. This entirely removes the problem of identifying the location of the primary vertex, which may be the key to trespass the “systematics wall” due to background uncertainties in cases where background contamination mostly comes from real SM particles (as opposed to misidentified or fake ones). In summary we find that LLP searches in heavy ion collisions do not only provide a probe of New Physics in a different environment, but can actually be more sensitive than similar searches in pp collisions. Together with a number of previous proposals [72, 73], these results provide strong motivation to explore the potential to use heavy ion collisions at the LHC to search for New Physics, either in a parasitic mode or in dedicated Runs.

³ This is conservative because, due to the declining spectrum $d\sigma_B^{\text{PbPb}}/dp_T \sim p_T^{-4}$, the kinematics of the decays $B^\pm \rightarrow \mu^\pm N$ and $N \rightarrow \mu^\pm f \bar{f}$ tend to increase the p_T of the final state particles compared to that of the B meson. This effect is more pronounced at the lower cut 3 GeV than at 25 GeV . Hence, using the p_T distribution of the B as a proxy overestimates $f_{\text{cut}}^{pp}/f_{\text{cut}}^{\text{ion}}$.

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