LLP Searches in Heavy Ion Collisions at the LHC

Heavy Ions and New Physics ECT* Workshop 2021

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What is this talk about?

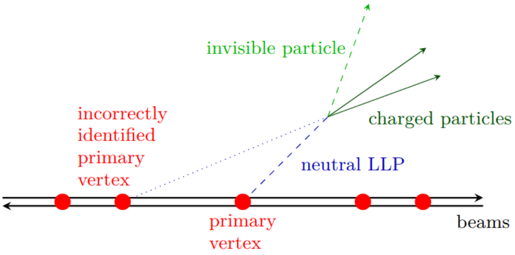
- Motivate long lived particles (LLP) searches in heavy ion (HI) collisions
- Review a previous study by my collaborators on the search of LLP in HI collisons [Phys. Rev. Lett. 124 (2020) 8 and Phys. Rev. D 101 (2020) 5]
- Touch on our current project as a continuation of the previous one **[PRELIMINARY]**
  Ongoing work [M. Drewes, HF, A. Giammanco, J. Hajer]

Why HI searches at the LHC?

- New physics might not be necessarily heavy but might be feebly coupled to the SM
- Feeble coupling to the SM can lead to the production of long lived particles (LLP)
- For LLP, the benefits of HI searches can be an **almost ideal primary vertexing** compared to pp collisions
- If new physics is also of low masses, **minimal triggers** in HI can help accessing low mass signals with soft final states
- HI collisions can offer entirely **new production mechanisms,** e.g. photon initiated production of BSM states with QED coupling

The “pileup problem"

- In proton-proton mode, overlapping collisions per bunch translate into pileup **which leads to:**
  - Higher thresholds compared to what can be used in HI runs
  - Complication in the reconstruction of final states from displaced vertices



- In HI collisions, **one true primary interaction** is expected

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Adding heavy neutrinos to the SM

The SM is minimally extended with with right handed neutrinos,

$$\mathcal{L}_{\nu_R} = \frac{i}{2}\overline{\nu_R}\partial\!\!\!/\nu_R - F_a\overline{l_{La}}\epsilon\phi^*\nu_R - \frac{1}{2}\overline{\nu_R^c}M\nu_R + h.c. \quad . \tag{1}$$

The mixing angle describing heavy neutrino interaction with the SM,

$$\theta_a = \langle\phi\rangle\frac{F_a}{M}, \qquad U_a^2 \equiv |\theta_a|^2. \tag{2}$$

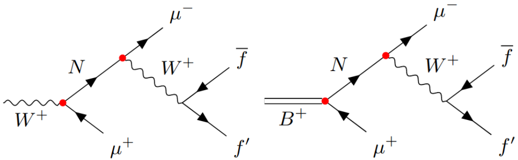
U_a^2 is interpreted in relation to the production cross section of N.
After EWSB, the Lagrangian reads,

$$\mathcal{L} \supset \frac{-m_W}{v}\overline{N}\theta_a^*\gamma^\mu e_{La}W_\mu^+ - \frac{M}{v}\theta_a h\overline{\nu_{L\alpha}}N + h.c. \tag{3}$$

where N is the heavy neutrino mass eigenstate, $N \simeq \nu_R + \theta_a\nu_{La}^c$.

Search for the heavy neutrinos

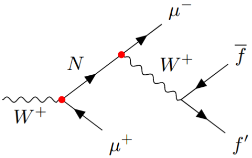
- Heavy neutrino masses below the weak gauge bosons masses **can lead to displaced vertex signals at the LHC**
- **Two production modes to be considered:**
  - for $M > 5GeV \rightarrow$ production in decay of Z/W is dominant
  - for $M < 5GeV \rightarrow$ production in b−flavoured hadron decay is dominant

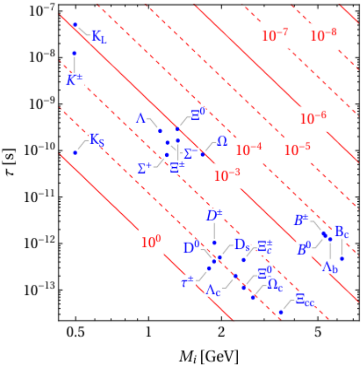


In the following slides, I will discuss the study of heavy neutrinos in both production modes.

Search for the heavy neutrinos continued

in W boson decays



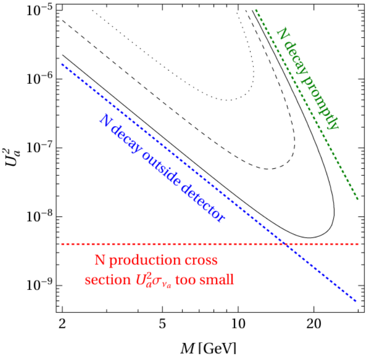


- Simulation is via MG5_aMC@NLO
- Search is in event samples triggered by a single or a pair of muons. Single muon trigger $p_T = 25 GeV$
- Background from long lived SM hadrons is suppressed by **minimum displacement requirement** of the secondary vertex to be $5mm$
- Two displaced tracks are required to have **invariant mass greater than** $5GeV$ to suppress B-mesons background

Simplified detector model

The number of displaced vertex events are estimated using:

$$N_d \simeq L_{int}\sigma_v\left(\frac{U_a^2 U_b^2}{U^2}\right)(e^{-l_0/\lambda_N} - e^{-l_1/\lambda_N})f_{cut} \quad (4)$$



- l_0 is the minimal displacement required by the trigger
- l_1 is the effective length of the detector
- λ_N is the particle's decay length

Search for the heavy neutrinos continued

in B meson decays

- The simulation of heavy neutrinos in B-meson decays is technically challenging
- The simplified detector model is modified to estimate the sensitivity in heavy ion runs,

$$N_{obs} = L_{int}\frac{\sigma_b}{9}\left(1-\frac{M^2}{m_B^2}\right)U_\mu^2\left(e^{-l_0/\lambda_N}-e^{-l_1/\lambda_N}\right)f_{cut}. \quad (5)$$

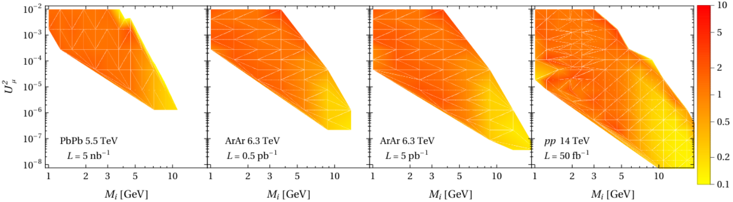
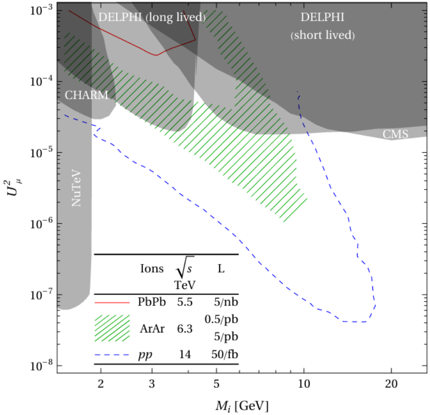


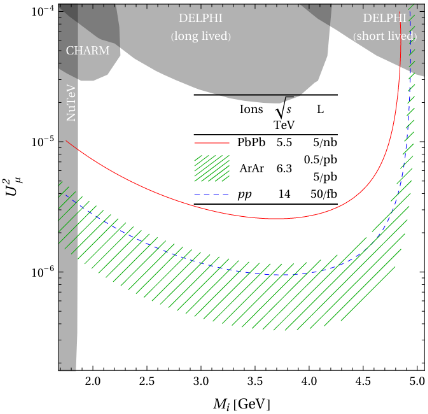
Figure shows the performance of the detector model (in the W-boson case) compared to an actual simulation

Results: 5σ sensitivity in the CMS detector

W boson case



B meson case



- HI **doesn't compete** with pp in the the W boson case
- **Improvement** for B-mesons with low *pT* trigger
- The absence of pileup is not exploited

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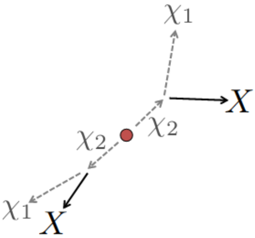
The Idea

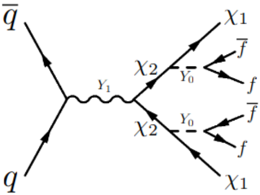
- Exploit the low thresholds as in the B-meson case
- Exploit the absence of pileup in HI collisions

We look for dimuon soft signatures; soft and displaced muon tracks
[see the talk by Susanne Westhoff]

Long lived signatures at the LHC

- A simplified model [arXiv1704.06515] for Dark Matter is used
- The model predicts some new dark matter states: **displaced** χ_2 decaying into χ_1 and some SM object X





- **SM object** $X \equiv \bar{f}f$ are two fermions decaying via the light mediator Y_0
- Y_0 is a **resonance** at $m(Y_0) = 5GeV$

HI signal simulation via MG5_aMC@NLO

- The signal is simulated via MG5_aMC@NLO
- **MG5 are modified:**
  - **Beam energies:**
    - `set ebeam1 2750*208`
    - `set ebeam2 2750*208`
  - PDF **dedicated to $^{208}_{82}$Pb ions:**
    - `set pdlabel lhapdf`
    - `set lhaid 901300`
- Cross sections from the signal simulation:
  - **pp** $\rightarrow \sigma_{pp}^{sig} = 5.096 pb$
  - **HI** $\rightarrow \sigma_{HI}^{sig} = 1958 pb$

Cross section is an order of $\sim 10^4$ larger as expected

HI background simulation via Pythia8

- $b\bar{b} \to \mu^+\mu^-$ is the background process
- **Pythia switches for simulating b physics are used for both pp and HI modes:**
  - `HardQCD:gg2bbbar`
  - `HardQCD:qqbar2bbbar`
- **Pythia is modified for $^{208}_{82}$Pb runs:**
  - `Beams:idA = 1000822080`
  - `Beams:idB = 1000822080`
  - `Beams:eCM = 5520.0`
  - `HeavyIon:mode = 1`
- **Cross sections from the background simulation:**
  - **pp** $\to \sigma_{pp}^{bkg} = 3.50x10^5 pb$
  - **HI** $\to \sigma_{HI}^{bkg} = 4.16x10^{10} pb$

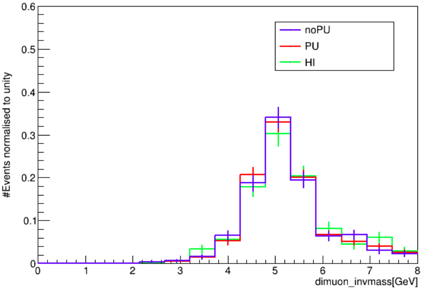
The same order of $\sim 10^4$ enhancement as in the signal simulation

The analysis

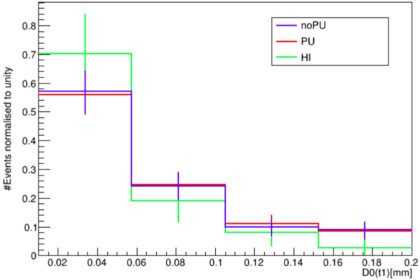
- **The analysis runs through DELPHES for detector simulation**
  - MinBias events are generated for the pileup simulation
  - The simulation superimposes several pp collisions
  - Distribution in time and space (Z-direction) is modified
- A maximum displacement strategy is followed, i.e. per event, only select the muon pair for which one track has the largest transverse impact parameter, $D0$
- **The analysis has two free parameters:**
  - **Secondary vertex radius:** distance between the origin of two tracks
  - **Minimal D0**: minimal tracks displacement required

A first look

$m(Y0)$ **in SIG**



$D0(t1)$ **in BKG**



Our study is ongoing, but we see preliminary indications that a displacement cut can potentially enhance the sensitivity in HI compared to pp

Summary

- HI might have a better handle over pp in some corners of the parameter space where the signal is soft and displaced
- The study of heavy neutrinos in displaced vertices showed an improvement for HI over pp at reduced trigger thresholds, i.e. when accessing low pT physics
- For the DM LLP search, progress has been made on the simulation front
- .. and are currently studying the signal and the background distributions in pp and in HI to test our initial hypothesis