New directions in BSM searches at FASER and beyond

Sebastian Trojanowski
(strojanowski@camk.edu.pl)
AstroCeNT, Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences

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F. Kling, ST, 2006.10630 (PRD)
K. Jodłowski, ST, 2011.04751
B. Batell, J.L. Feng, ST (to appear)

ASTROCENT

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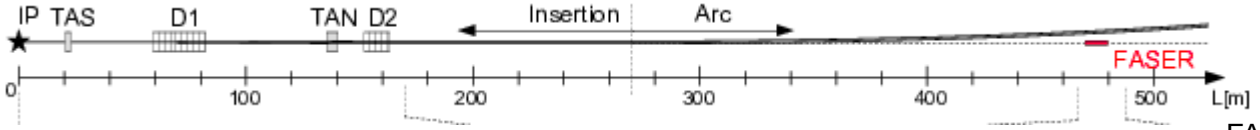
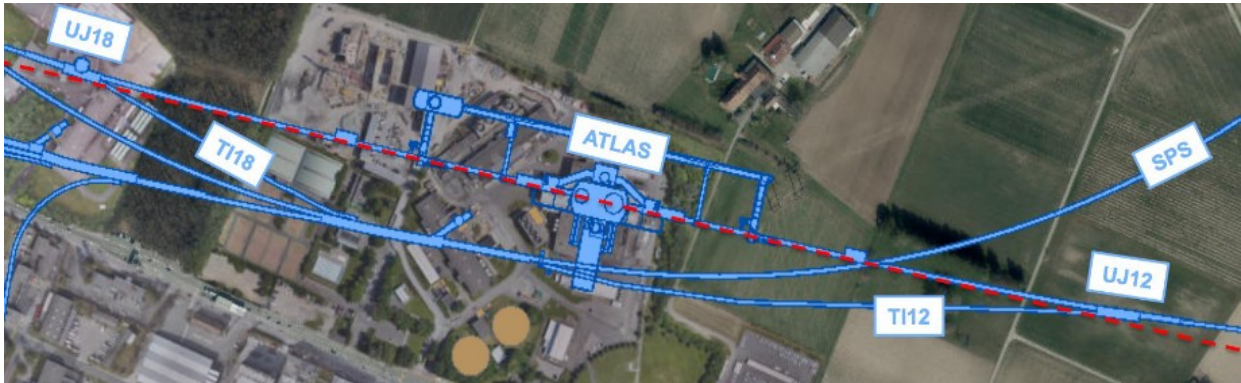
Far-forward searches at the LHC



FASER Collaboration,1908.02310

- Run 3 – FASER / FASERv experiments (approved), SND@LHC (proposed)
  ➡ talks: Susanne Kuehn, Antonia Di Crescenzo
- HL-LHC – (possible upgrade) FASER 2 / FASERv2
- Proposal for HL-LHC: Forward Physics Facility (**FPF**)
  ➡ talk Felix Kling
- Distant (~0.5km) detectors with a small angular coverage – focus on light particles collimated around the beam collision axis
- Multi-purpose experimental facility
  (various signatures of new physics, SM measurements)
- In the TI12/TI18 tunnels:
  Standard Model backgrounds highly suppressed besides neutrino- and muon-induced ones;
  low radiation levels



Experimental signatures

- Displaced LLP decays into two high-energy oppositely charged tracks (main FASER)

THIS TALK

- Neutrino-nuclei scattering events (FASERv, SND@LHC)

- **LLP decays to high-energy photons (FASER [preshower detector])**

- **HL-LHC: scattering of electrons to search DM & study neutrinos**
  (SND@LHC, potential future neutrino detectors based on LAr or emulsion technology)
  ⇨ see also *A. Ariga, T. Ariga, O. Sato etal Snowmass input*
  & B. Batell talk at the recent FPF kickoff meeting

- Search for milli-charged particles, forward MilliQan-type detector FORMOSA
  ⇨ talk Yu-Dai Tsai

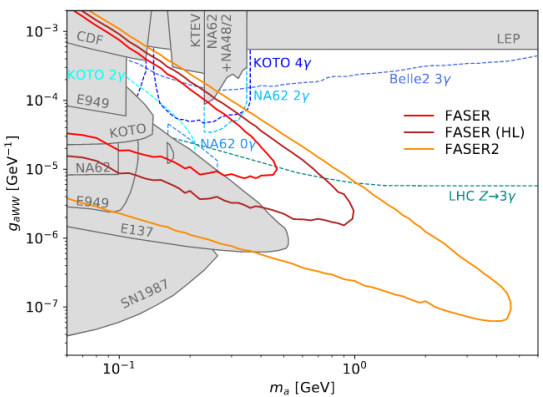
- Muon physics BSM and SM studies
  ⇨ ST talk at the recent FPF kickoff meeting, with F. Kling & others

Search for LLP → γγ in FASER

- High-energy photons (>100GeV) at the FASER location are mostly muon-induced
- They can be rejected based on the detection of time-coincident muon
- Additional handles over neutrino-induced BG come from using the preshower detector
- Two time-concident & high-energy photons are even more difficult to be mimicked by the SM
- Example sensitivity reach for ALPs with the di-photon or $SU(2)_W$ couplings

J.L. Feng, I. Galon, F. Kling, ST, 1806.02348
F. Kling, ST, 2006.10630,

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{g_{aWW}}{4} a W^a_{\mu\nu} \widetilde{W}^a_{\mu\nu}.$$

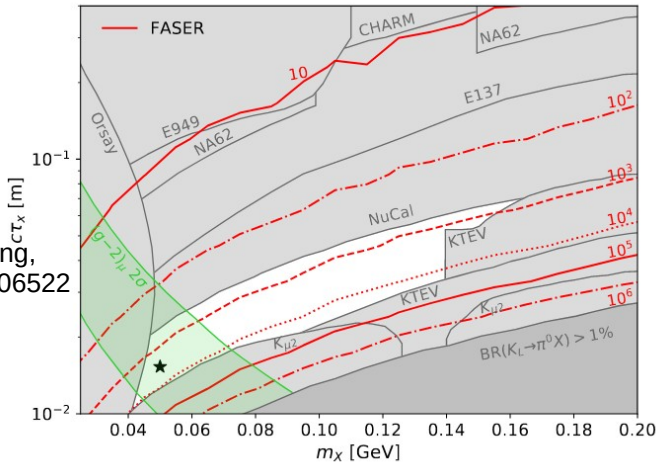


- Dark Higgs with non-universal couplings

$$\mathcal{L} \supset -m_X^2 X^2 + \sum \epsilon_q \frac{m_q}{v} X\bar{q}q + \sum \epsilon_\ell \frac{m_\ell}{v} X\bar{\ell}\ell + \epsilon_W \frac{m_W^2}{v} X W_\mu^+ W^{\mu-},$$

J. Liu, N. McGinnis, C. E. Wagner, X.-P. Wang, 2001.06522

- Inspired by the KOTO anomaly
- decays into e^+e^- and γγ (~10%)
- up to 10^4 events in Run 3

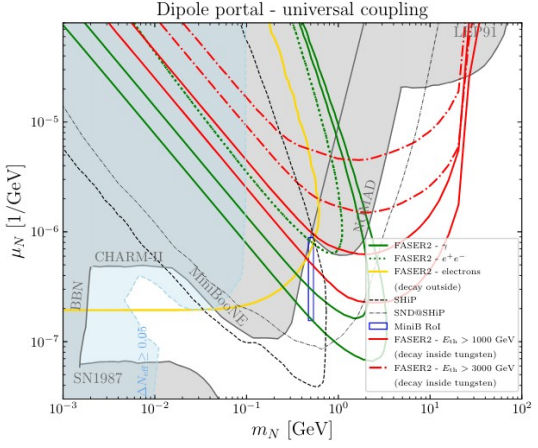


Search for LLP → γ in FASER and emulsion

- Single high-energy photon signature in the decay vessel (>100 GeV):
  - requires very good rejection of muon-induced BG
  - could suffer from residue BG from neutrino interactions in the preshower

- In the emulsion detector (FASERν2):
  - focus on very high-energy photons (>1TeV or even >3TeV) to suppress muon-induced BG
  - if the EM shower leaks to the electronic detector, time info helps to reject BG

K. Jodłowski, ST, 2011.04751



- Dipole portal to HNLs

$$\mathcal{L} \supset \mu_N \, \bar{\nu}_L \sigma_{\mu\nu} N_R F^{\mu\nu} + \text{h.c.},$$

G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, 1803.03262;

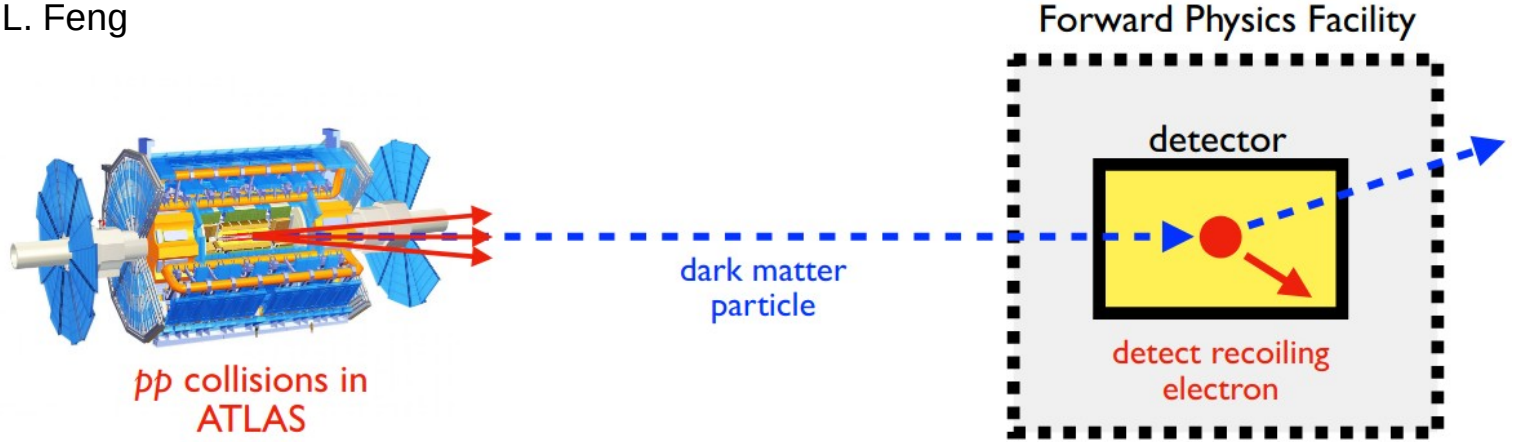
- ν Z → N Z coherent upscat. to HNL off nuclei (suppressed momentum exchange, no other activity at vertex)

- subsequent N → ν γ decay (3-body decays to e+e- have BR<1%)

- up to ~10^3 high-energy photons with >3TeV in HL-LHC

Dark matter search (& neutrino studies)

with B. Batell, J.L. Feng



Detector technology:

- LAr TPC
- emulsion

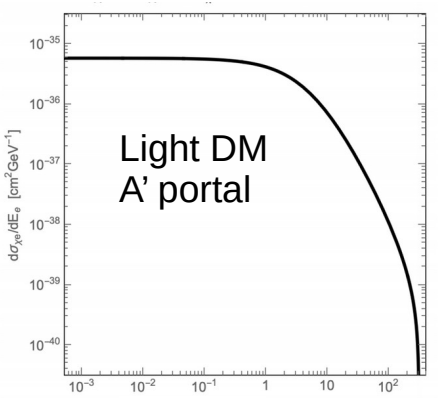
- Search for dark matter scattering off electrons in the electron

- Signature: single-electron-induced EM shower with no hadronic activity

- BSM – light mediators favor low-energy electron recoils
  SM neutrino-induced BG – heavy mediators => more “democratic” recoils

- Similar ideas discussed in the literature: emulsion (SND@SHiP, SND@LHC)
  LAr (MiniBooNE-DM)

credit: Brian Batell



See also: B. Batell, M. Pospelov, A. Ritz, 0906.5614; P. deNiverville, M. Pospelov, A. Ritz, 1107.4580

SM backgrounds (1) – neutrinos

- ν-electron scatterings (both electron and muon neutrinos contribute)
  - favor larger energy transfer to electron "x=Ee/Eν" & lower recoil angles $E_e\,\theta_e^2 \simeq 2m_T(1-x)$

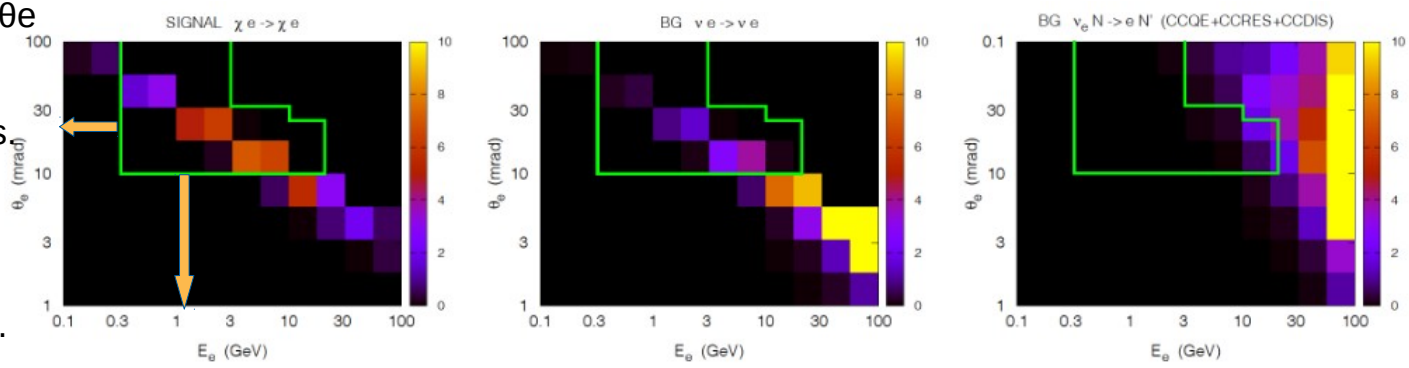
ν-e BG reduced to ~30 events in HL-LHC for 100-tonne LAr TPC detector (3mx3mx10m)
~10 events for 10-tonne tunsgsten/emulsion det. (0.5mx0.5mx2m)

- ν-nuclei scatterings: CCQE, CCRES, CCDIS
  - cuts based on electron recoil energy and angle
    + cuts on additional tracks emerging from the vertex

ν-N BG reduced to ~1 event

Example signal region in Ee, θe

- emulsion:
  - excellent spatial & ang. Res.
  - (a priori) no time info
- LAr TPC:
  - lower energy thresholds
  - probably worse angular res.
  - time info



SM backgrounds (2) – muons

- Large flux of through-going muons

- some of them could be swept away
but high-energy ones (especially >TeV) will probably go through the detector
- $O(10^4)$ Hz

- Muon-induced photons can imitate DM-induced EM showers

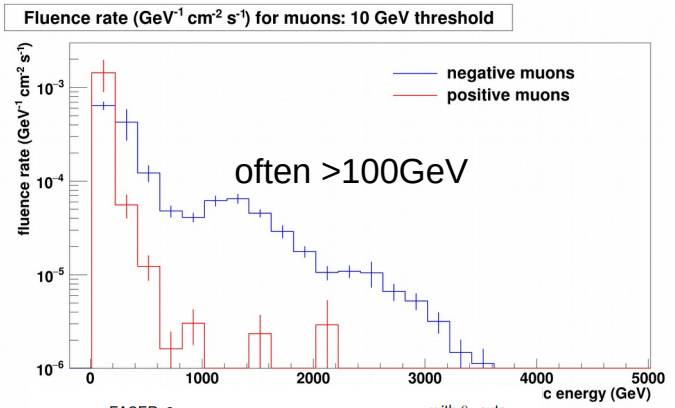
- they are displaced from the parent muon track,
- very challenging to reject them without active muon veto

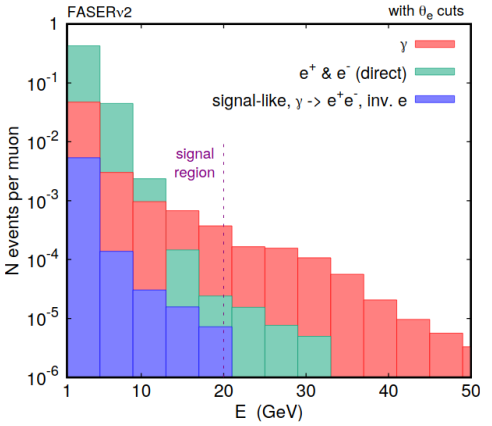
Illustration: emulsion FASER-ν-like detector
$\mu \rightarrow \gamma \rightarrow e^+e^-$ with one of e^+ or e^- below the detectability threshold
while other e^+ or e^- satisfying Ee and θe cuts

- Information about time crucial to search for signal events

- in emulsion: additional tracker layers needed; challenges:
  - cost and operation e.g. alignment
  - event pile-up in emulsion – matching and vertex identification
- in LAr: dynamical time info much easier; challenges and outcome:
  - limitations due to finite drift-time
  - combination of time & spatial info to reject muon-induced BG

FASER Collaboration, 1812.09139, FLUKA simulations, CERN STI Group
M. Sabate-Gilarte, F. Cerutti, and A. Tsinganis



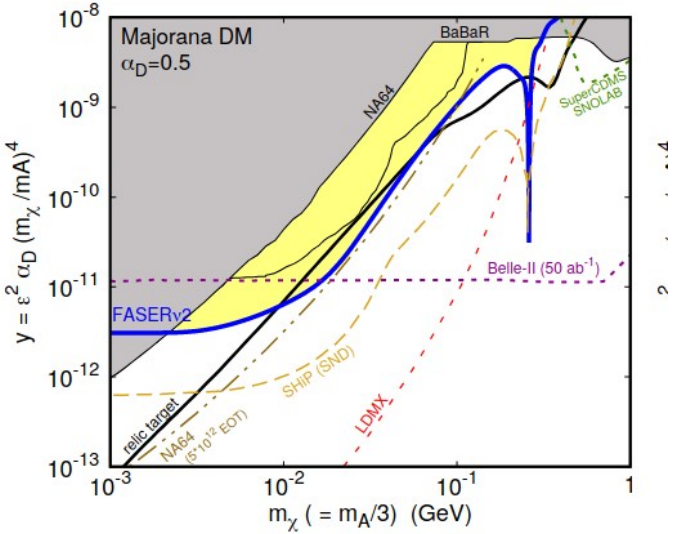


Some results for DM search

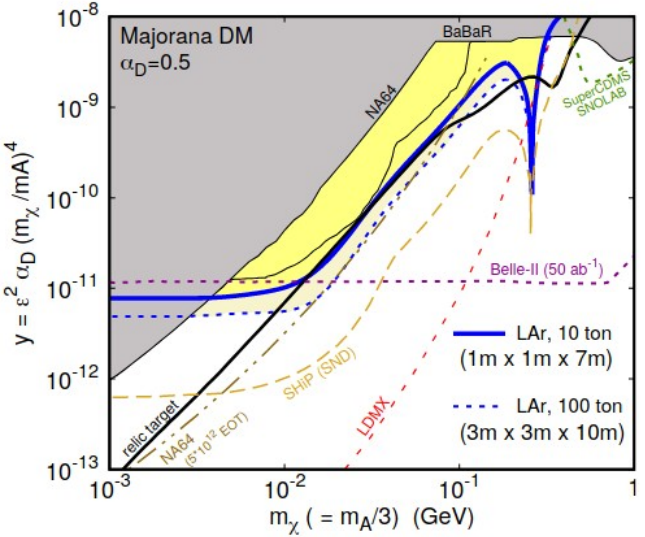
Light Majorana DM with the dark photon mediator

B. Batell, J.L. Feng, ST, to appear

Emulsion: 0.5m x 0.5m x 2m, HL-LHC



LAr TPC: 10- and 100-tonne, HL-LHC

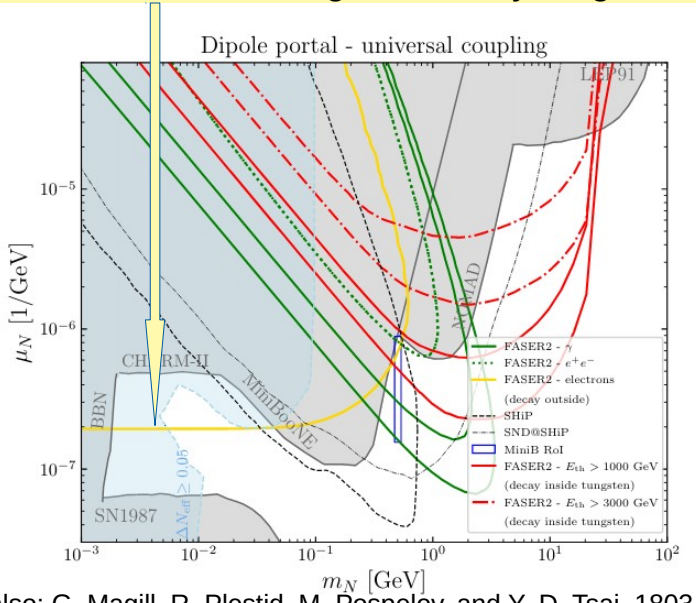


- complementary to missing energy and momentum searches (allows for direct detection)
- artificially boosted DM at the LHC – important if non-relativistic scat. rates suppressed
- further opportunities: neutrino physics (SM and BSM);

with LHC it's "now or never"

Probing BSM neutrino physics with scatterings off electrons

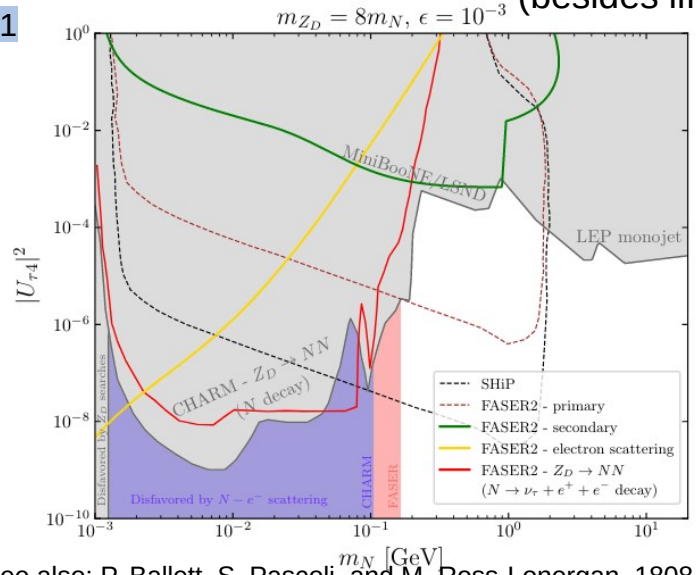
BSM neutrino scatterings:
- dipole portal to HNLs
- large far-forward neutrino flux
- ν e → HNL e upscatterings
- extends the reach to light and very long-lived HNLs



See also: G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, 1803.03262;

K. Jodłowski, ST, 2011.04751

HNL scatterings:
- model with light Z' mediator
- Z' → HNL HNL production
- HNL e → HNL e scatterings
- practically independent of the mixing angle (besides lifetime)



See also: P. Ballett, S. Pascoli, and M. Ross-Lonergan, 1808.02915;
Y. Jho, J. Kim, P. Ko, and S. C. Park, 2008.12598

Bi-modal e^+e^- spectrum due to secondary production of LLPs

More about secondary production: ➡ next talk by K. Jodłowski

- Scenario with light HNLs and Z' mediator – originally proposed to solve the MiniBoonE anomaly

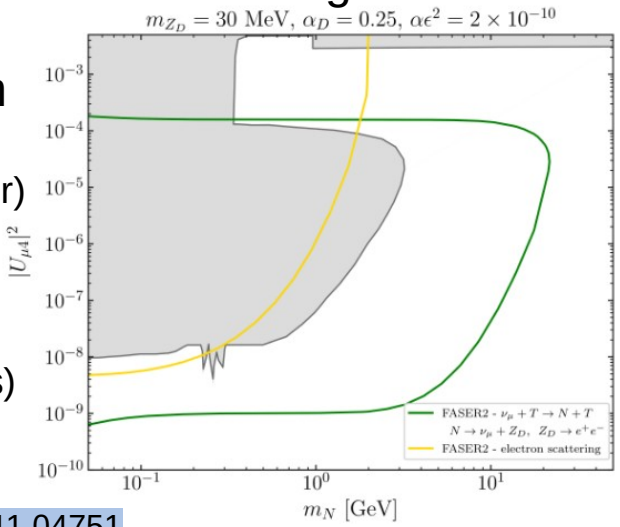
  E. Bertuzzo, S. Jana, P. A. Machado, and R. Zukanovich Funchal, 1807.09877

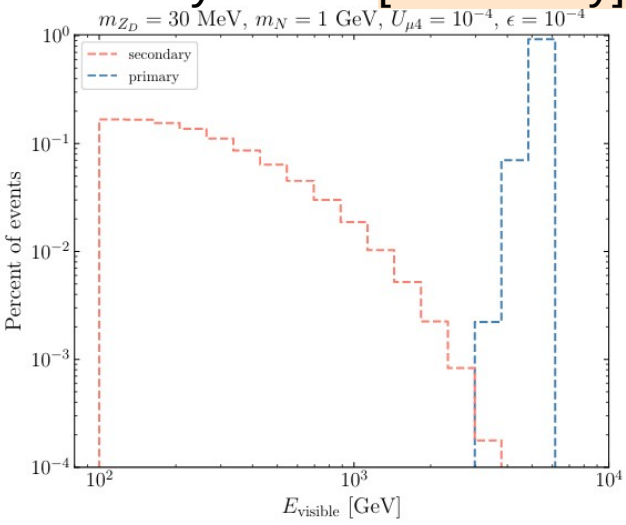
- Z' can be produced directly at the ATLAS IP (e.g. in rare pion decays…) [primary]

- Z' can also be produced in neutrino scatterings in front of the FASER decay vessel [secondary]

- Primary Z's → hard spectrum
  (only highly-boosted LLPs survive until the detector)

- Secondary Z's can be softer
  (production right in front of the detector favored for long-lived LLPs)





K. Jodłowski, ST, 2011.04751

Concluding remarks

- FASER has pointed out a new direction in the LHC searches

- It will offer amazing opportunities already during Run 3
(SM neutrinos, dark photons, ALPs, ...)

- Much more could be achieved during HL-LHC with the FASER and FASERν succesors and other experiments (SND@LHC, FORMOSA, LAr TPC detector,...)

- We have illustrated this for the search for light DM and neutrino-induced new physics, as well as for new-physics models employing high-energy photon signatures

THANK YOU !!!