Neutrino and dark matter searches with the far-forward liquid argon detector

Sebastian Trojanowski
AstroCeNT, Nicolaus Copernicus Astronomical Center Polish Academy of Sciences
& National Center for Nuclear Research in Poland

2nd Forward Physics Facility Meeting
May 27, 2021

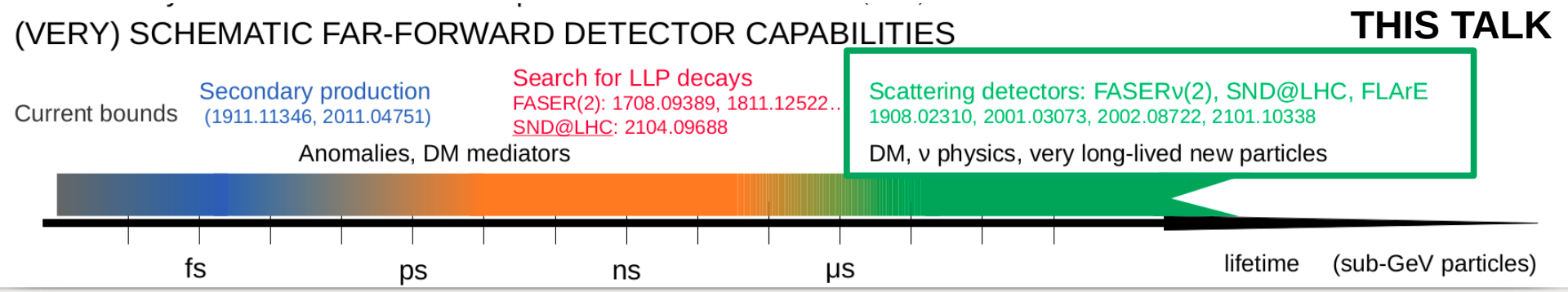
B. Batell, J.L. Feng, A. Ismail, F. Kling, R.M. Abraham, ...

Republic of Poland

Foundation for Polish Science

European Union
European Regional Development Fund

FAR-FORWARD SCATTERING EXPERIMENT



- Search for highly-displaced decays of light new particles

Talk: Adam Ritz
Parallel session: BSM

- Scattering detectors:
especially important if decays not possible (**stable species like ν and DM**)
can also open new detection channels for very long-lived particles

Further talks: Vishvas Pandey
Maria V. Garzelli
Parallel session: QCD and neutrinos

EXTREMELY COLLIMATED FORWARD FLUX

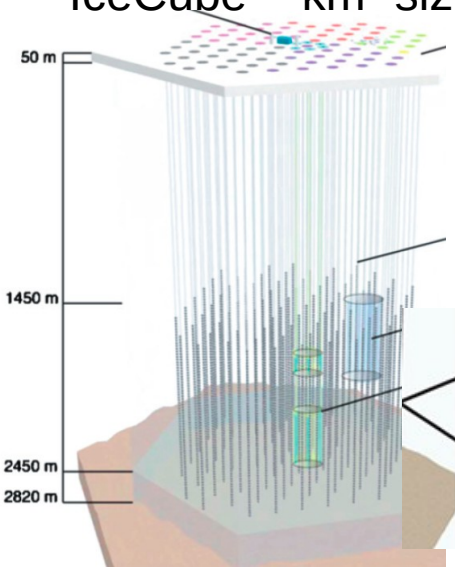
- Example: >10^{18} pions in the HL-LHC

- Above 10 GeV energy, >20% of them go towards a 1m-size far-forward detector placed >0.5km away
  angular size: ~10^{-4} % of forward hemisphere

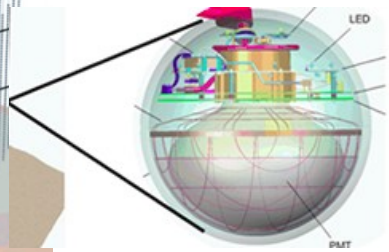
➡ Large flux of neutrinos and potentially BSM particles

- Even small detectors can perform great measurements

IceCube ~ km^3 size detector



Digital Optical Module
total: few x 10^3
33cm diameter



First LHC neutrino candidate events
FASER Collaboration 2105.06197

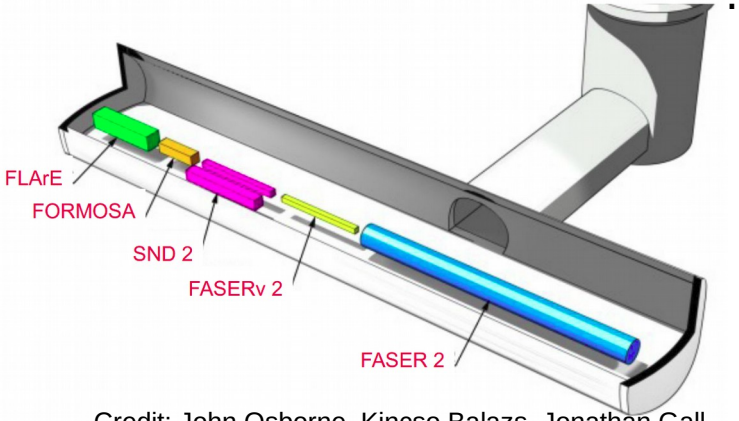
Talk: Tomoko Ariga

IDEA: **F**orward **L**IQUID **AR**GON **E**XPERiMENT (**FLArE**)

B. Batell, J.L. Feng, ST 2101.10338
Snowmass: FASERv2: A Forward Neutrino Experiment at the HL LHC

- Liquid-Argon time projection chamber (TPC) + PMTs to collect scintillation light (a la MicroBooNE,…)
- Dynamical information about the event time, sensitivity to even low-energy signals
- Possible complementarity with other FPF experim
- Focus of the talk is on 10-tonne detector placed in FPF (620m away from the ATLAS IP)

FLArE-10: 1m x 1m x 7m



Credit: John Osborne, Kincso Balazs, Jonathan Gall

- For reference, we also show some results for

FLArE-100: 1.6m x 1.6m x 30m

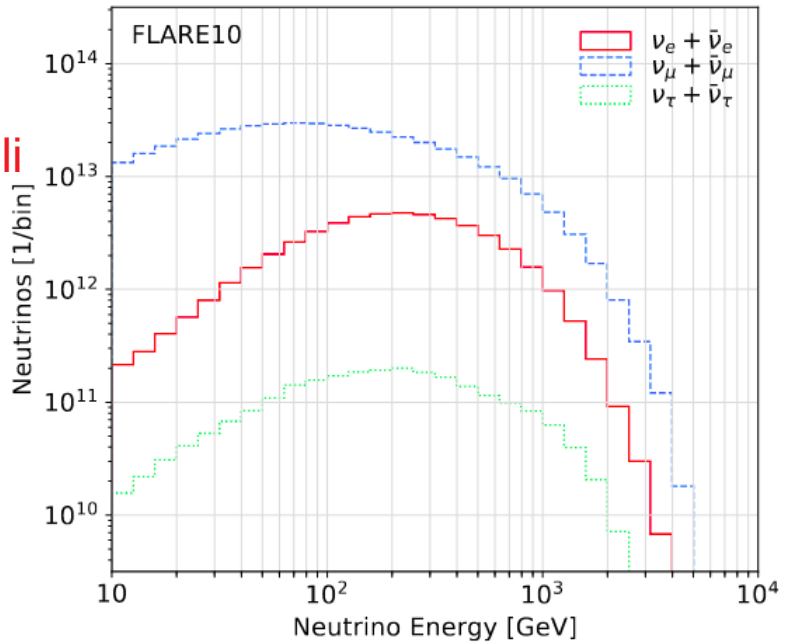
Talks: Milind V. Diwan
Filippo Resnati

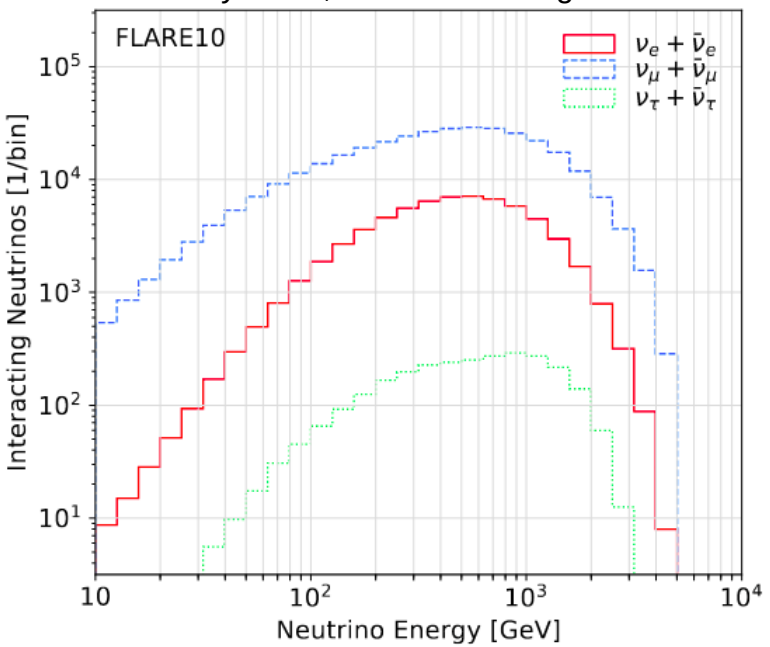
NEUTRINO FLUX

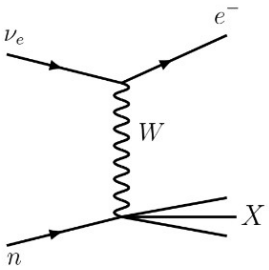
- a few x 10^{14} neutrino going through FLArE-10 during the entire HL-LHC era
- >10^5 expected CC interactions of ν_μ (a few x 10^4 for ν_e, ~2000 ν_τ), and a similar number of NC events
- Typical energy ~ a few hundred GeV, ...
- ...but the visible signal can be either high or low energy depending on the channel

Sibyll 2.3d, see also F. Kling 2105.08270

Further talks:
Maria V. Garzelli
Anna Stasto





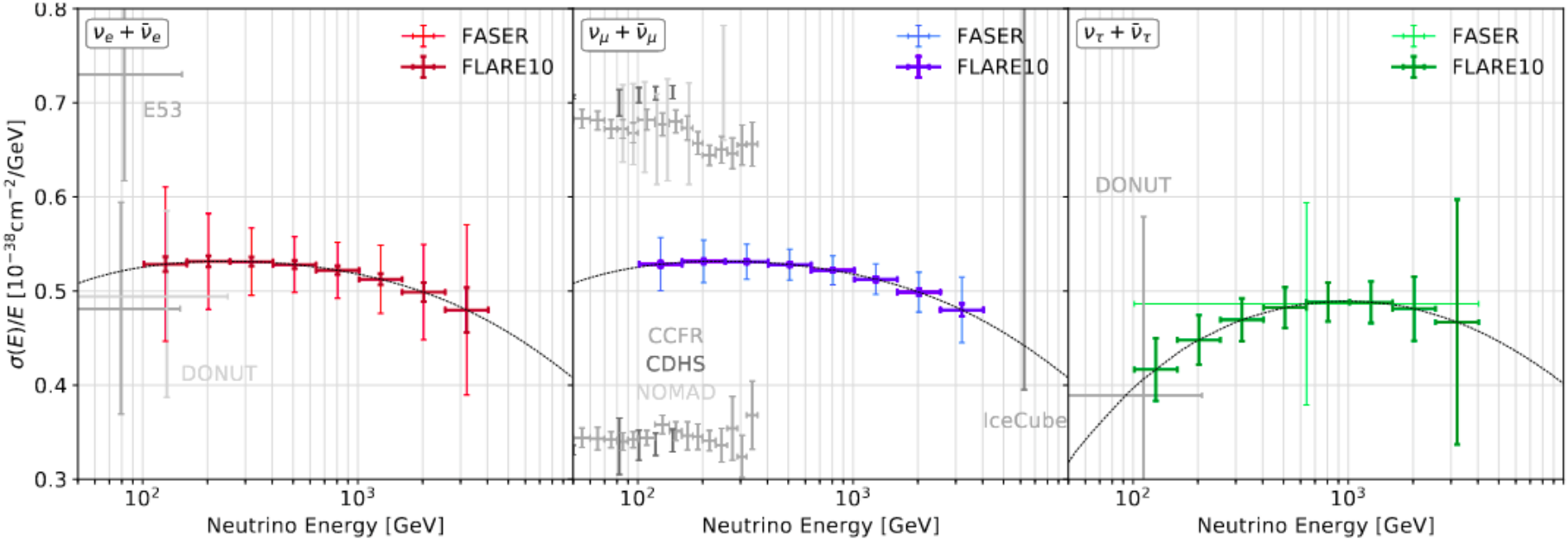


INCLUSIVE NEUTRINO CROSS SECTION

- Dominated by DIS given high energies of incident neutrinos
- Fills in important gap between current measurements (low-energy exps., atmospheric νs)
- Larger statistics ⚑ further improvement wrt expected FASERν and SND@LHC results
- Magnetized detector components could be used to identify the lepton charge (ν vs. ν)

Snowmass 2021: Magnetizing the Liquid Argon TPC

CC scattering cross sections



TAU NEUTRINOS

- Only handful of ν_τ events detected events so far,

  a few tens more will be observed during Run 3 (FASERν, SND@LHC)

- The smallest incident rate ➡ they contribute subdominantly to the total even rate

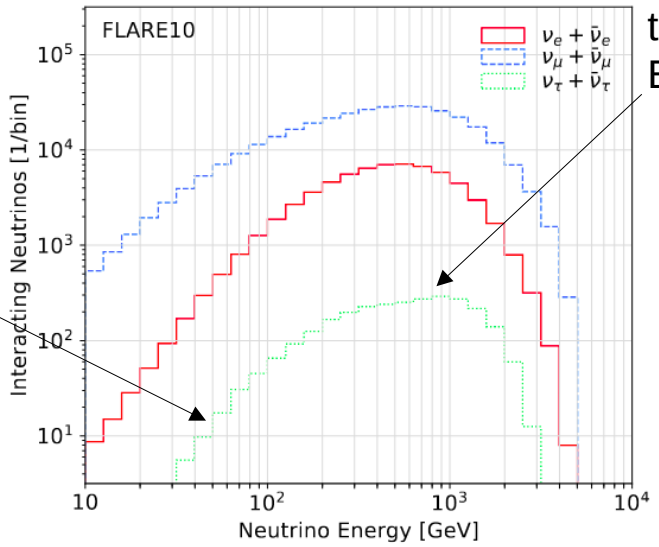
- Can be detected in CC scatterings with outgoing tau leptons

  jet clustering algorithms to study ν_τ in DUNE, P. Machado, H. Schulz, J. Turner 2007.00015

- τ ID at high energies to be studied

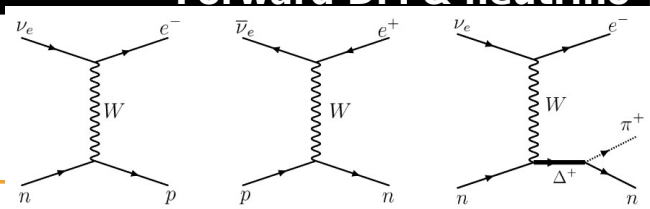
- Cross section measurements, test of lepton universality, ...

tens of events
at E_ν < 50 GeV



thousands of events at
E_ν ~ few hundred GeV

NON-DIS INTERACTIONS



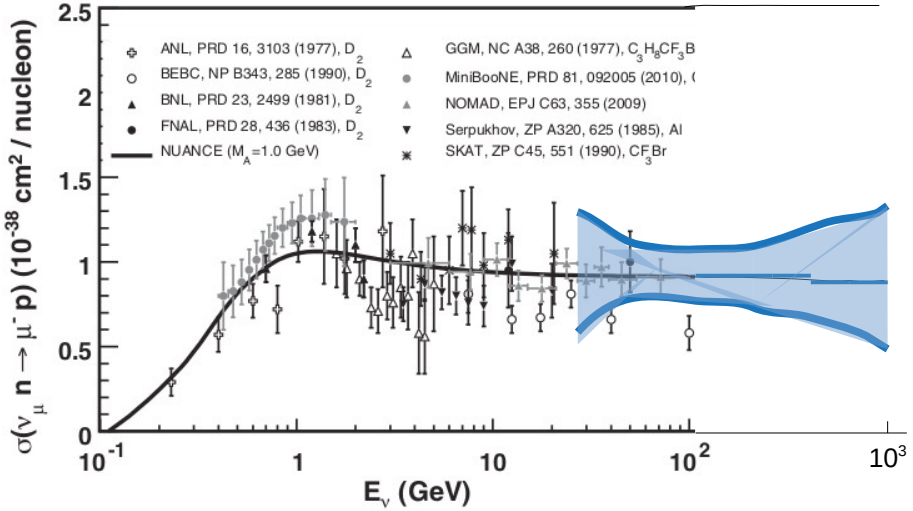
- >10^3 expected quasi-elastic and resonant events (estimated with GENIE)

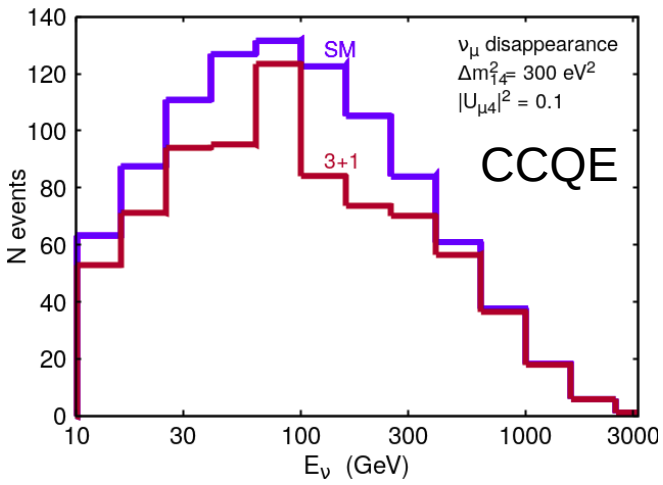
	CCQE				CCRES				NCEL	NCRES
	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	all	all
Event Rate	58	590	47	366	167	1673	184	1219	175	1206

- Typically low momentum exchange, Q^2 ~< GeV^2
- For high-energy neutrinos, typically >95% of E_ν goes into the outgoing lepton
- Consistency check of the neutrino spectrum & cross section measurements

Important input to all studies based on probing neutrino spectrum (QCD, CR physics...)

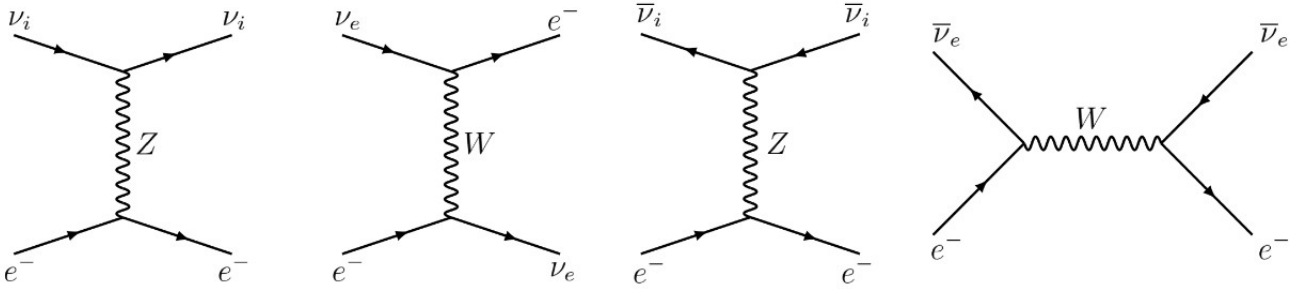
1305.7513





SCATTERINGS OFF ELECTRONS

- High-energy incident neutrinos ➡ scatterings off electrons detectable



	$\nu_\mu e^- \to \nu_\mu e^-$	$\nu_e e^- \to \nu_e e^-$	$\nu_\mu e^- \to \nu_e \mu^-$	$\bar{\nu}_e e^- \to \nu_\mu \mu^-$	$\nu_\tau e^- \to \nu_e \tau^-$
Event rate	28	29	211	11	$< 10^{-4}$

- Could be BG, but can be disentangled from CCQE and CCRES based on the lepton recoil angle, e.g., for E_ν>10 GeV recoil angle <10mrad and the presence of other tracks

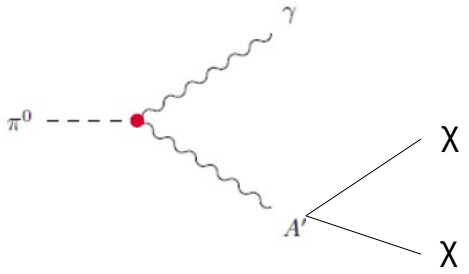
- Independent total ν_μ flux measurement (no ν_μ contribution, small ν_e component) from such scatterings leading to the (collimated) outgoing muon

- Total flux: further contribution to the neutrino oscillation analysis

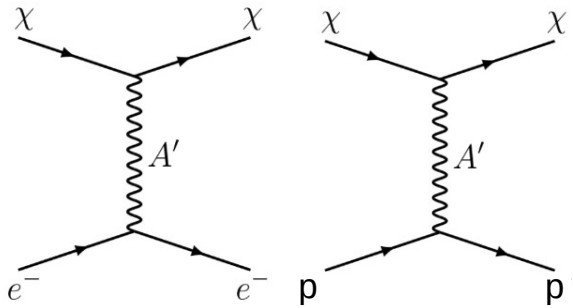
B. Batell, J.L. Feng, ST 2101.10338
B. Batell, J.L. Feng, A. Ismail, F. Kling, ST In preparation

DIRECT DARK MATTER SEARCH

- Light dark matter (LDM) can also be efficiently produced in the far-forward region of the LHC (meson decays, bremsstrahlung, …)



- Detection channels: scatterings off electrons or nuclei (elastic, resonant, DIS)



- Probe of relativistic DM interactions (complementary to traditional DM direct detection)
- Sensitive to also very small fractions of DM or even unstable particles

HNLs with light Z' mediator, K. Jodlowski, ST, 2011.04751

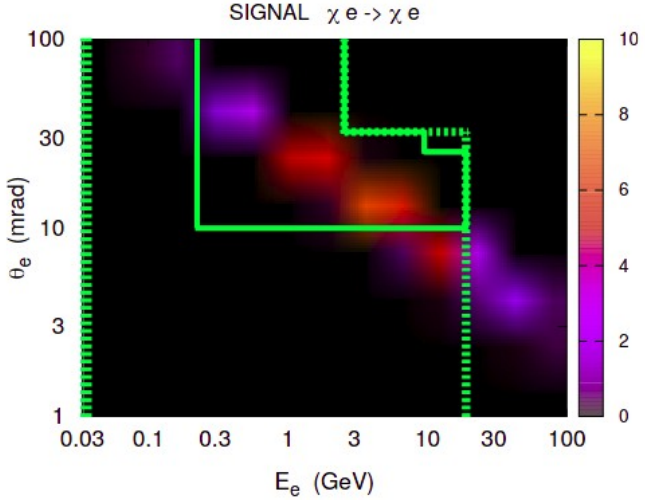
- Benchmark scenarios: dark vector mediator + Majorana or (inelastic) complex scalar DM

$$\mathcal{L} \supset A'_\mu(\epsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_D) \qquad \mathcal{L} \supset \begin{cases} |\partial_\mu \chi|^2 - m_\chi^2 |\chi|^2 & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi} i\gamma^\mu \partial_\mu \chi - \frac{1}{2} m_\chi \overline{\chi}\chi & \text{(Majorana fermion} \end{cases} \qquad J^\mu_D = \begin{cases} i\chi^* \overleftrightarrow{\partial_\mu} \chi & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{(Majorana fermion DM)} \end{cases}.$$

LOW ENERGY DM-INDUCED SIGNAL

- Light mediators favor low energy recoils

- Cuts on the recoil energy and angle help to discriminate signal and ν-induced BG

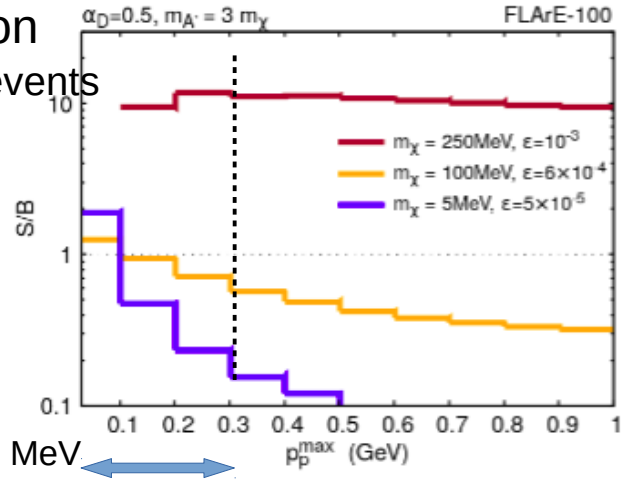


DM-electron

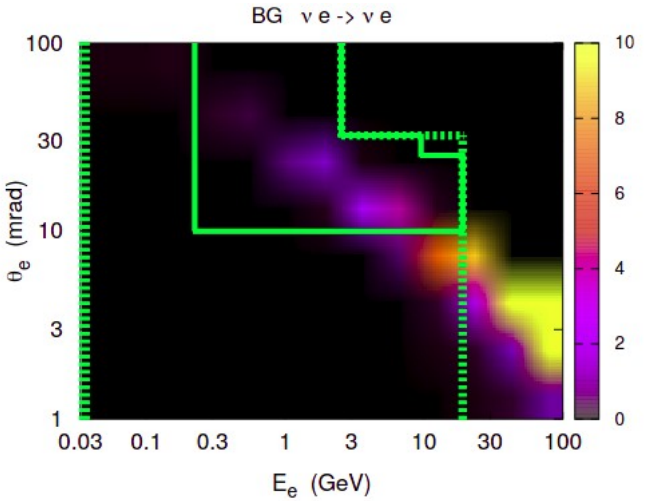
~10 BG events

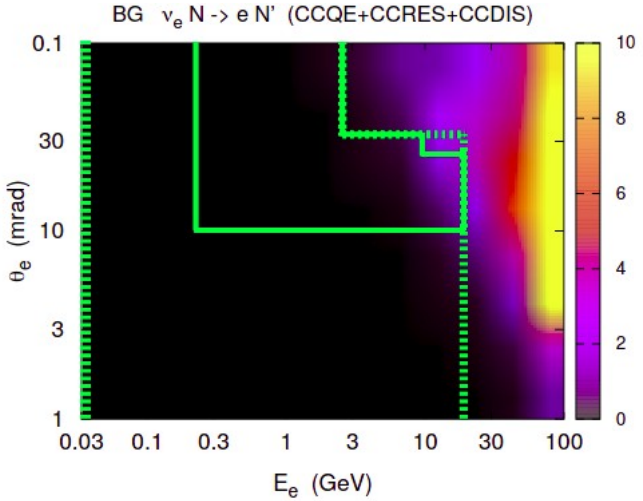
DM-proton

few tens BG events



30 MeV





Muon-induced backgrounds

• LHC is also a muon factory

• Most of muons are deflected by the LHC magnets so that they never reach far-forward detectors...

• ...but the remaining number of expected through-going muons is huge

$N_\mu \sim 10^{11}$ for HL-LHC and the far-forward detector with radius~1m (on axis)

• they can be further deflected by dedicated sweeping magnets

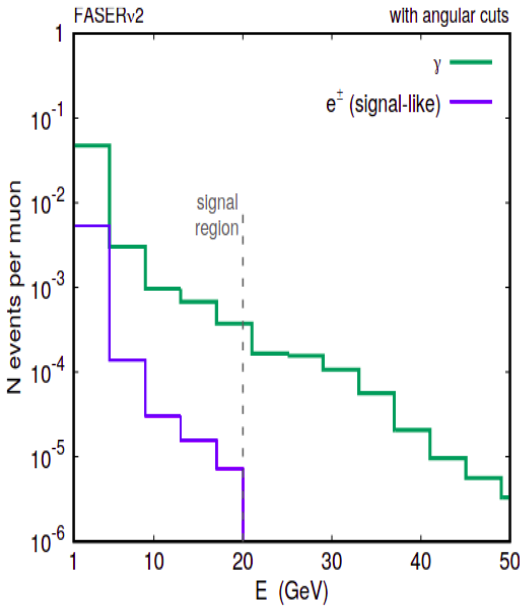
$$h_B \approx \frac{ecd}{E_\mu} B\ell = 60\ \text{cm} \left[\frac{100\ \text{GeV}}{E_\mu}\right] \left[\frac{d}{200\ \text{m}}\right] \left[\frac{B\cdot\ell}{\text{T}\cdot\text{m}}\right]$$

• the most energetic muons can avoid deflection and be source of backgrounds

$\mu N \rightarrow \mu N \gamma$ (photon brem.) + $\gamma N \rightarrow e^+e^- N$ (pair prod.)

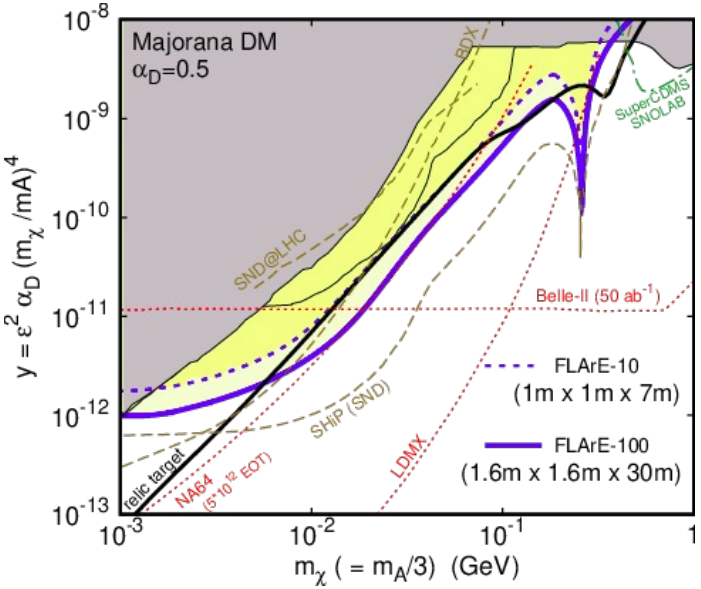
& e^+e^- can be misreconstructed as e^-

• event time information crucial to reject this background

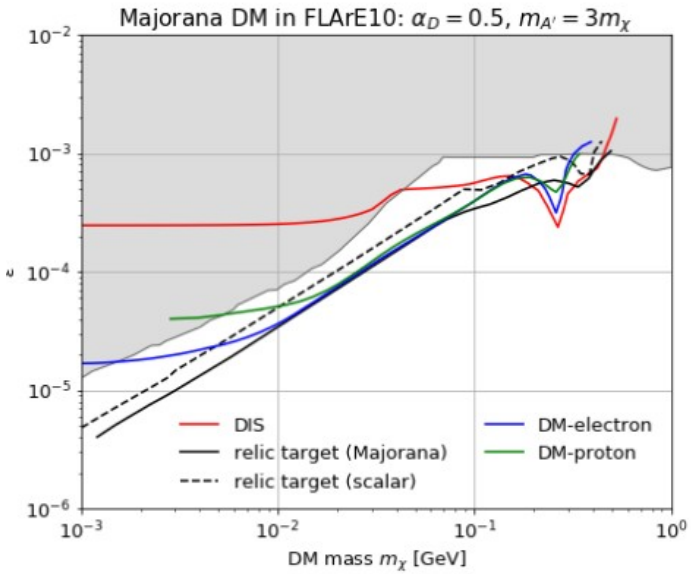


REACH PLOTS (HL-LHC, FLArE)

DM-electron scattering



Combined analyses



- Thermal relic target can be probed in direct searches
- Complementary searches based on leptonic and hadronic interactions
- Additional constraint in the high-mass tail from the search for DIS interactions

CONCLUSIONS

- Scattering detector(s) are very important in the research agenda of the FPF
- They allow to study stable SM (neutrinos) and BSM (dark matter) species...
- ...can also contribute to studies of very long-lived BSM particles (via scattering or decay)
- **FLArE**: **F**orward **L**iquid **Ar**gon **E**xperiment – far-forward LAr TPC detector
- Can detect $>10^5$ neutrino events, including $>10^3$ tau neutrinos
- Rich neutrino program: inclusive scat. cross sections, specific channels, BSM...

K. Jodlowski etal 2011.04751
A. Ismail etal 2012.10500
A. Falkowski etal 2105.12136

- ...detailed far-forward neutrino spectrum measurements (QCD, cosmic rays, oscillations,...)
- DM direct detection experiment at high energies and with collider-produced DM

Feedback highly welcome, everybody is also invited to join these efforts !