

Searching for BSM in the DUNE ND

21 October 2019

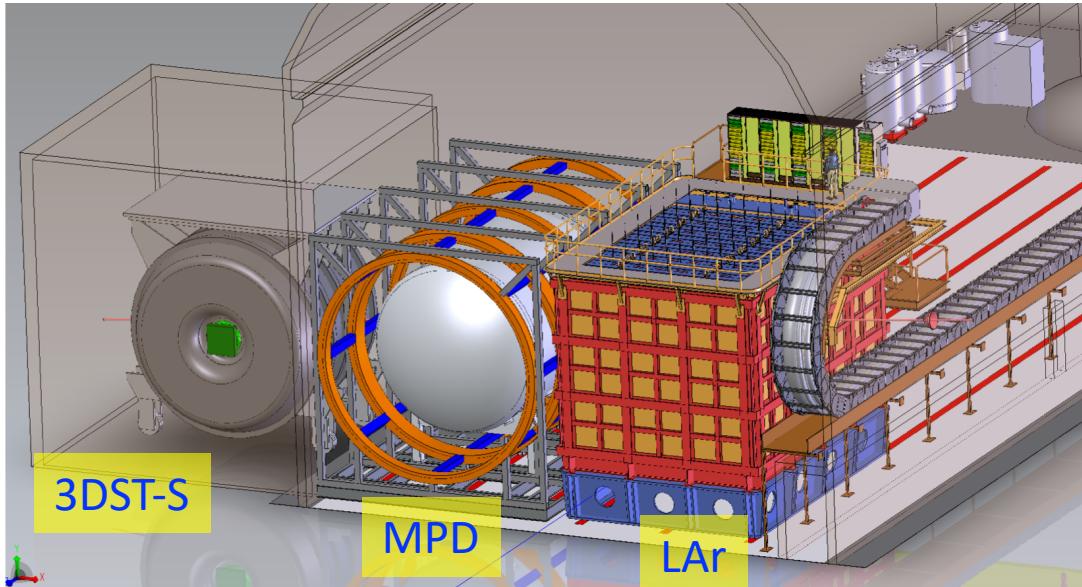
**DUNE-ND Coll. meeting
DESY**

Silvia Pascoli
IPPP, Durham University



In my talk I will refer to the design presented by A. Weber at the Sep 2019 Collaboration meeting:

Reference Design



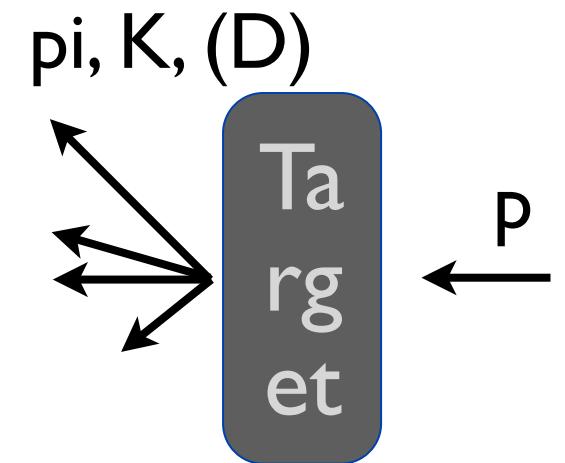
- 3 components
 - LAr TPC with pixelated readout (**50t**)
 - Multi-Purpose Detector (MPD)
 - HPgTPC (**1t**) + ECAL + magnet
 - Three-Dimensional Scintillator Tracker-Spectrometer: 3DST-S
 - 3DST (**8t**) + Trackers + ECAL + magnet
- In addition, the LAr and MPD will be able to move off-axis in order to implement the PRISM concept

■ Target mass

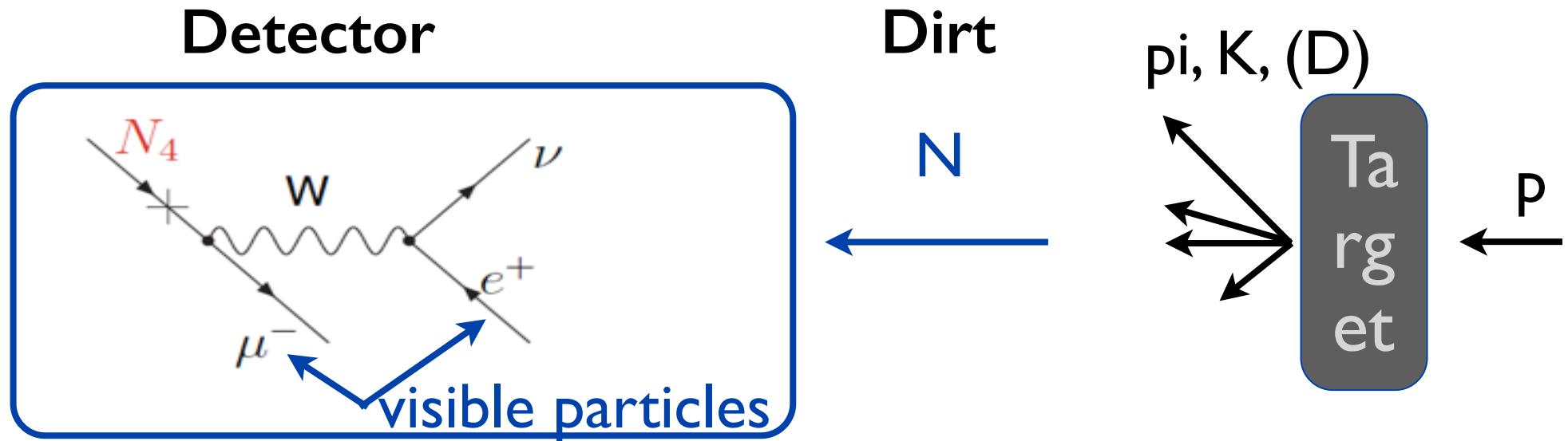
To search directly for BSM in the DUNE ND, we can employ two main exp strategies:

1. **a-la beam dump experiments.**
2. **production (e.g. via NC) and detection in the same detector due to neutrino or other particle beam.**

“A la beam dump” experiment



“A la beam dump” experiment

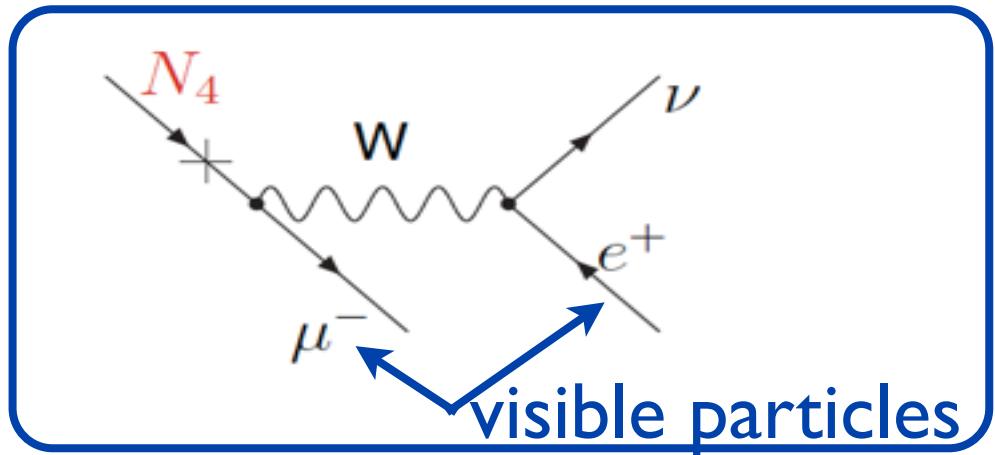


A part from the exp in the 90', in particular PSI91, neutrino accelerator experiments and NA62 can search in this mode.

The typical candidate is a **heavy neutral lepton** or sterile neutrino with ~ 100 MeV mass.

“A la beam dump” experiment

Detector



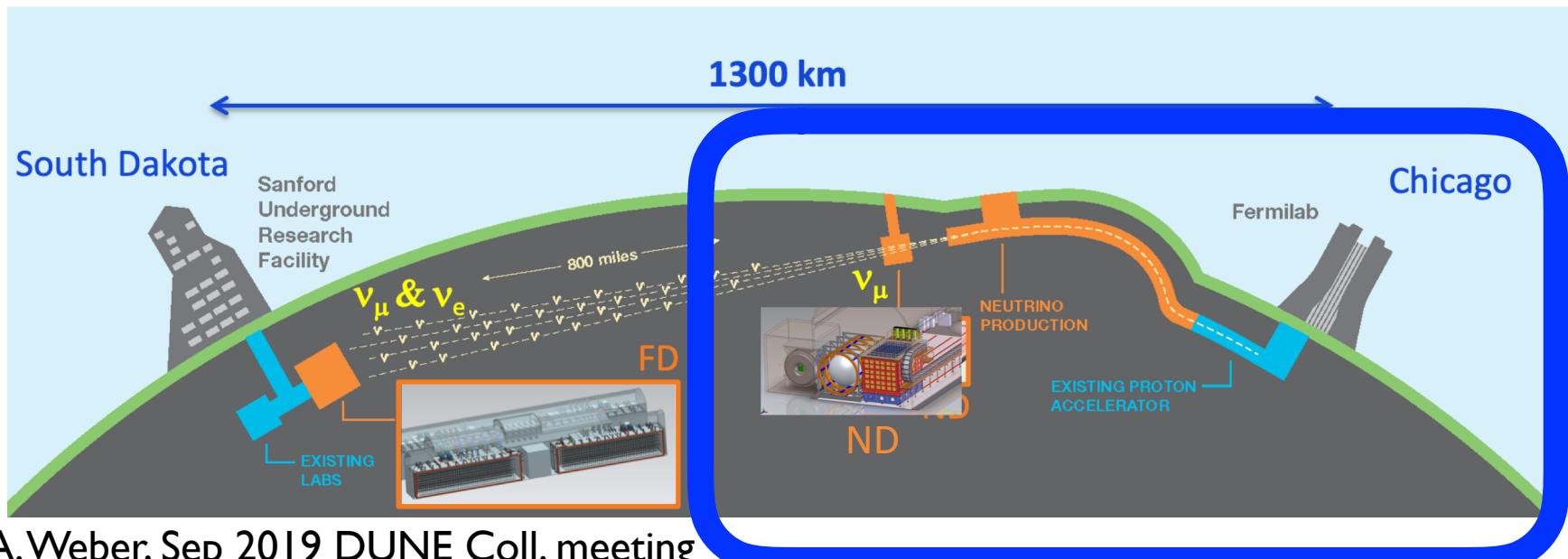
Dirt

N

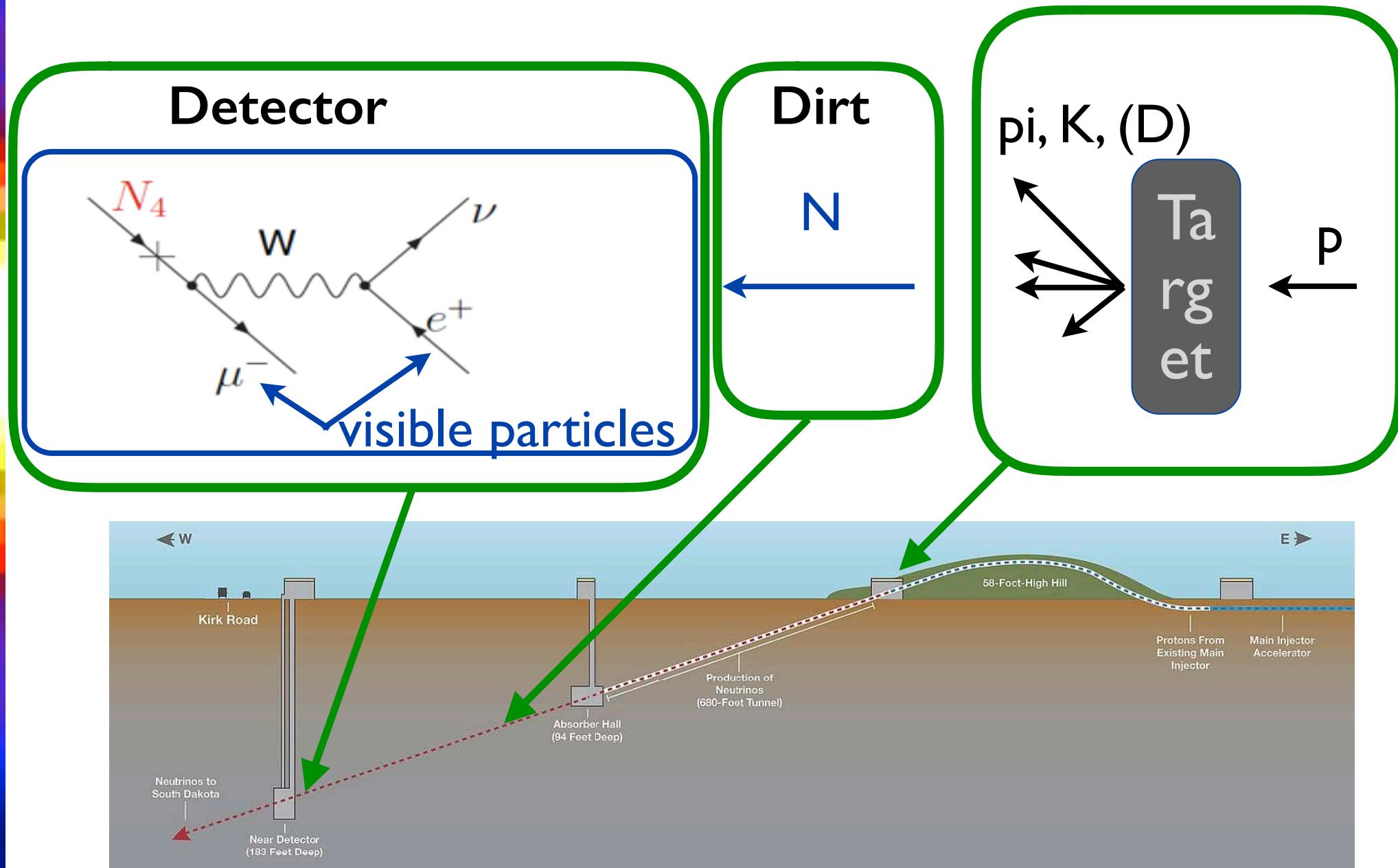
$\pi, K, (D)$

Target

P

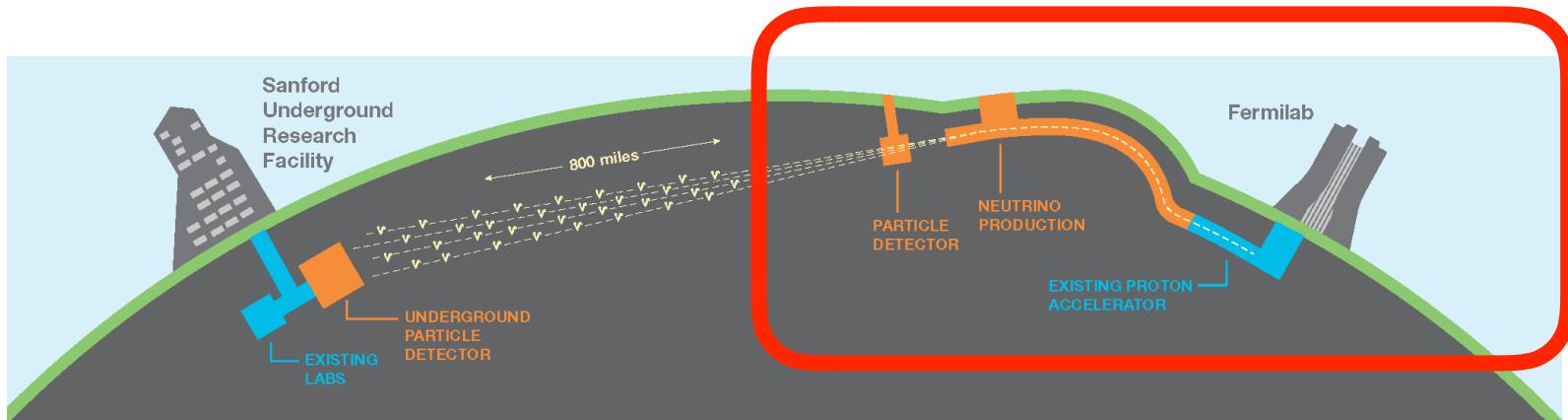


“A la beam dump” experiment



The key characteristic:

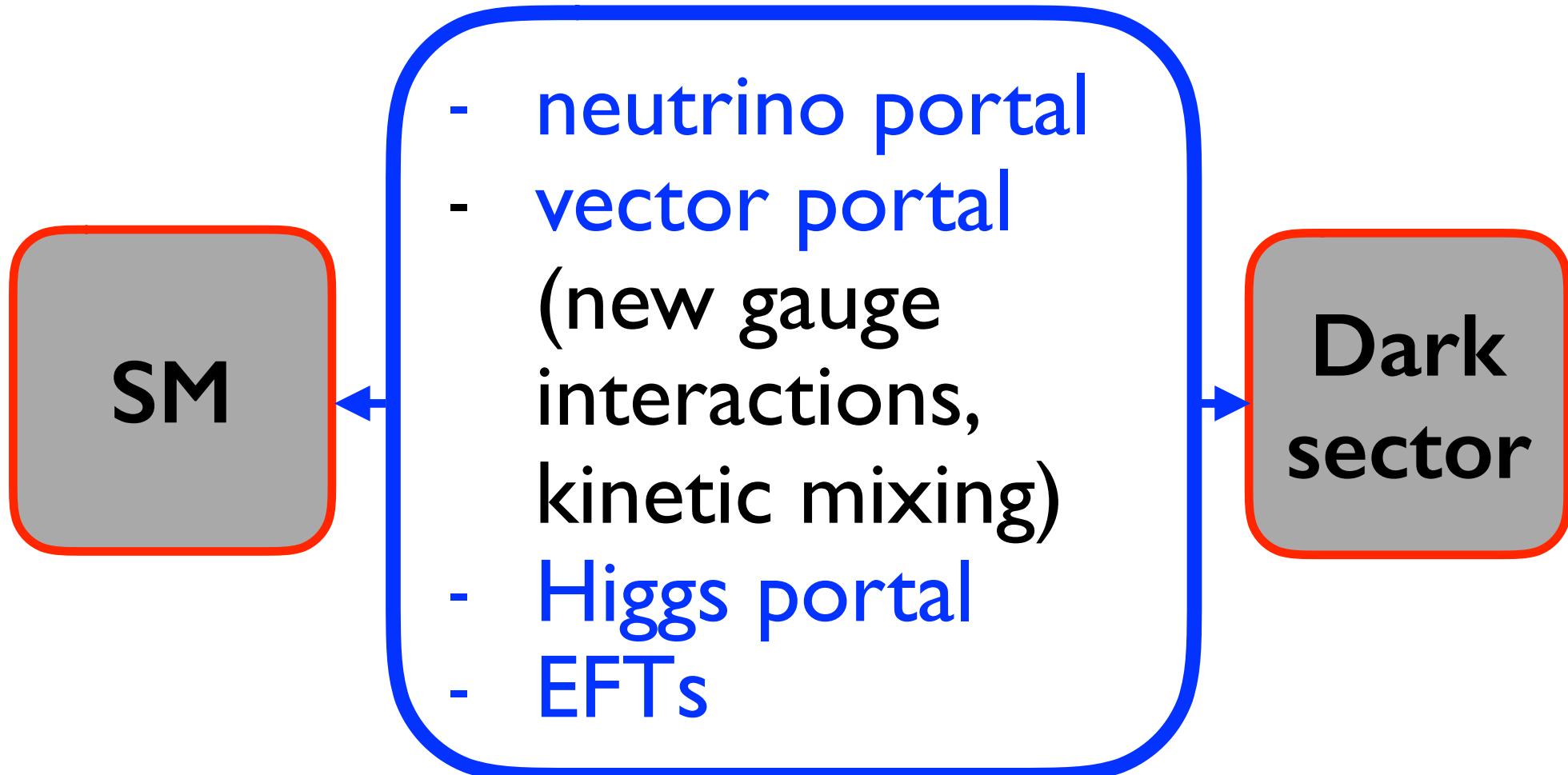
- high proton intensity;
- large volume (not necessarily large mass);
- (distance from target).



| | PS191 | DUNE ND | SBND | NA62 | SHiP |
|----------|-----------------------|-----------------------|----------------------|--------------------|--------------------|
| Baseline | 128 m | 574 m | 110 m | 220 m | 60 m |
| Volume | 216 m^3 | 150 m^3 | 80 m^3 | 750 m^3 | 590 m^3 |
| Energy | 19.2 GeV | 80 GeV | 8 GeV | 400 GeV | 400 GeV |
| POT | 0.86×10^{19} | 1.32×10^{22} | 6.6×10^{20} | 3×10^{18} | 2×10^{20} |
| Exposure | 1.0 | 220.9 | 16.4 | 8.5 | 5820 |

DUNE ND has an exposure $200 \times$ PS191!

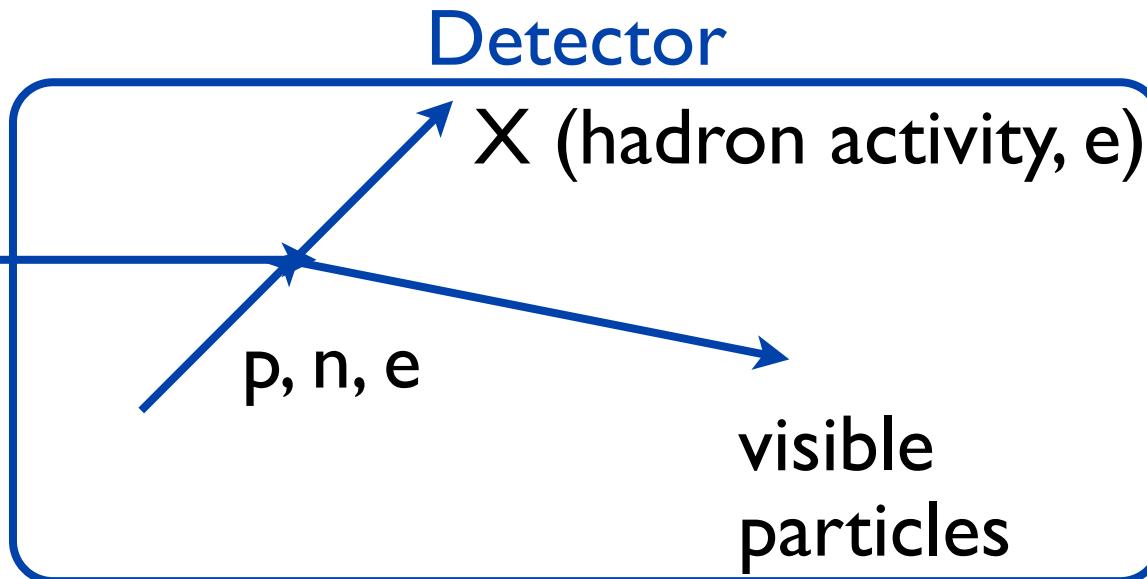
Dark Sectors



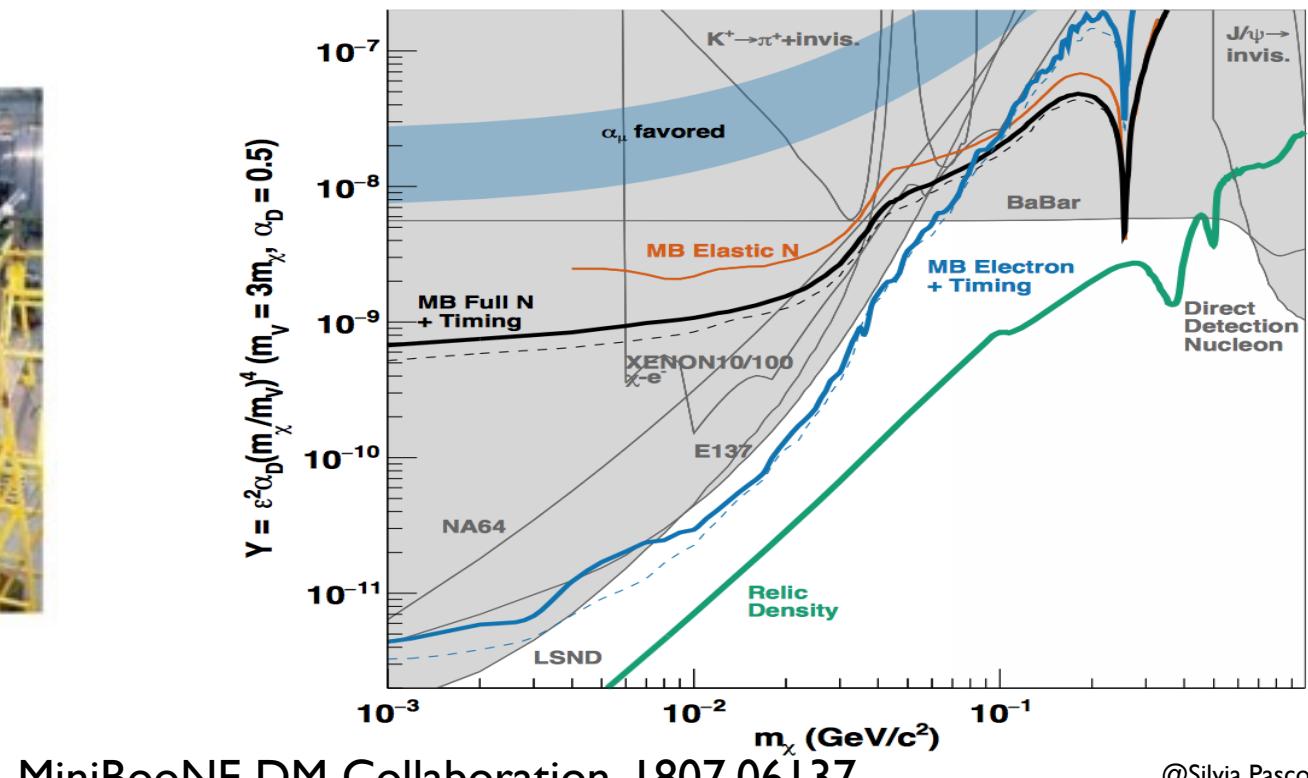
Mediators are produced by p interactions and then decay into SM particles (typically with long lifetimes).

Neutrino or dark sector scattering

neutrino,
DM,
~~XXX,~~
beam



CHARM II

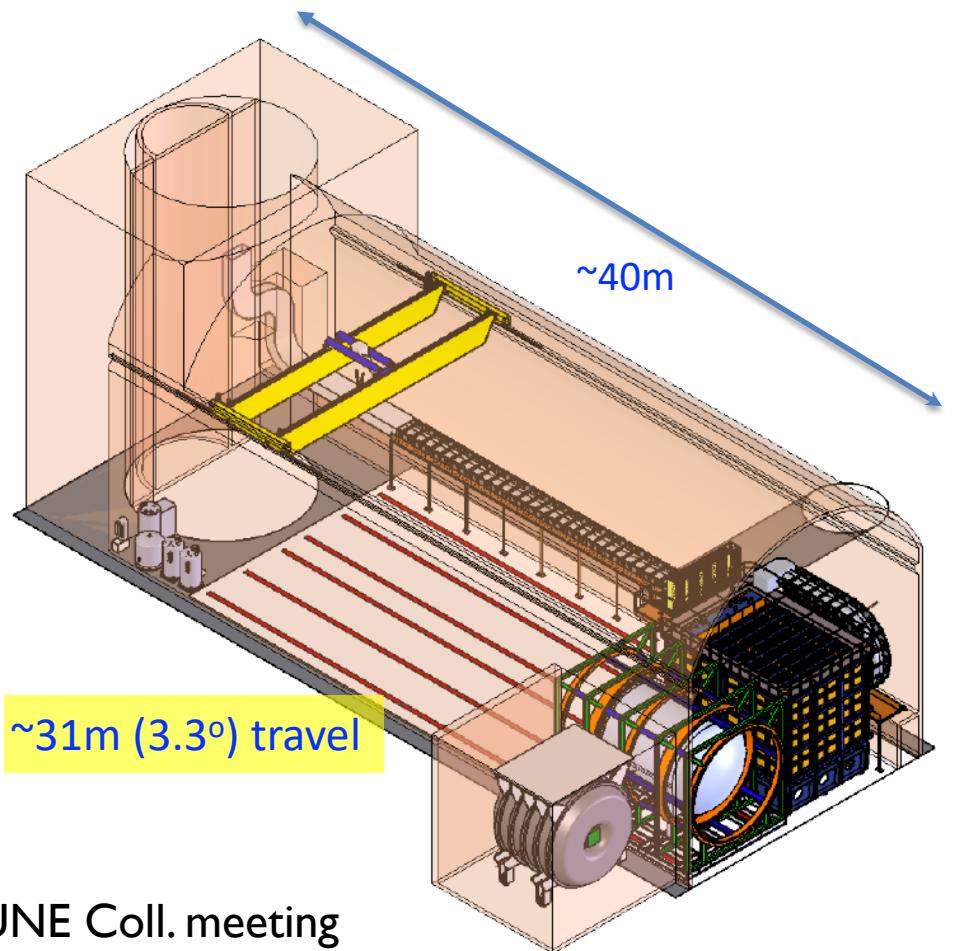


Key characteristics:

- **proton intensity**
- **detector mass**
- **position on/off-axis (for background reduction).**

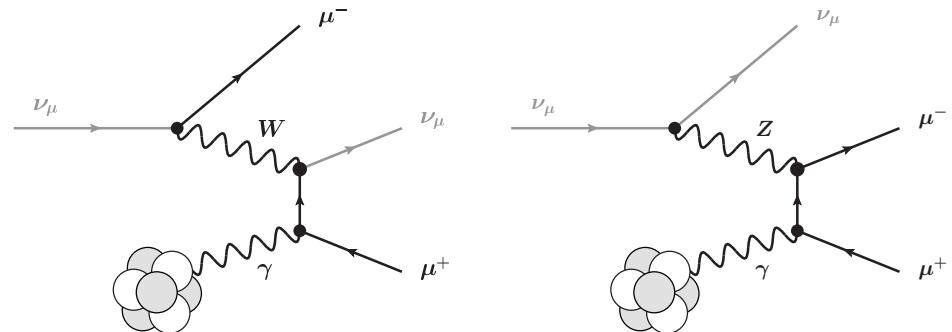
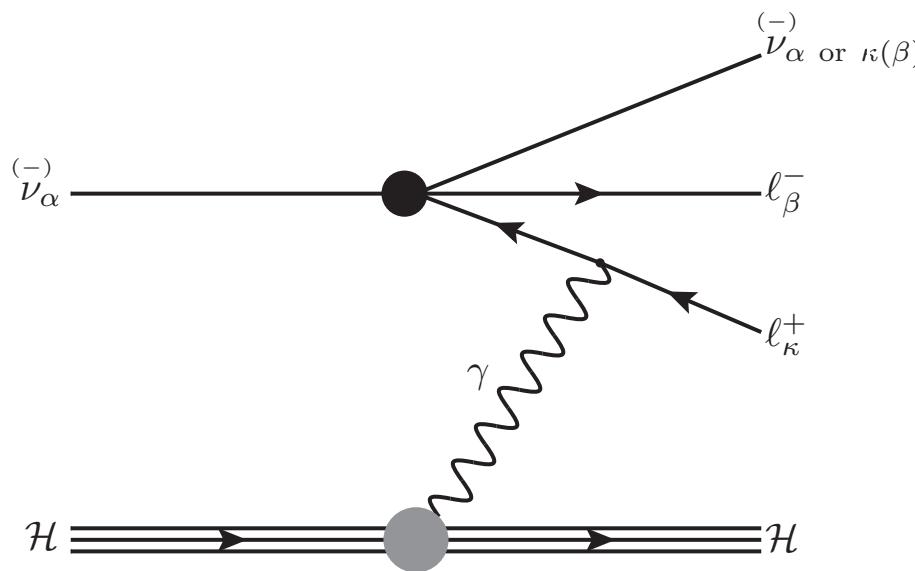
**Most intense
proton beam
available**

| Detector | Target (Fid. mass t) |
|----------|-------------------------|
| LAr | Ar (50) |
| HPgTPC | Ar (1) |
| 3DST-S | CH (8) |



A.Weber, Sep 2019 DUNE Coll. meeting

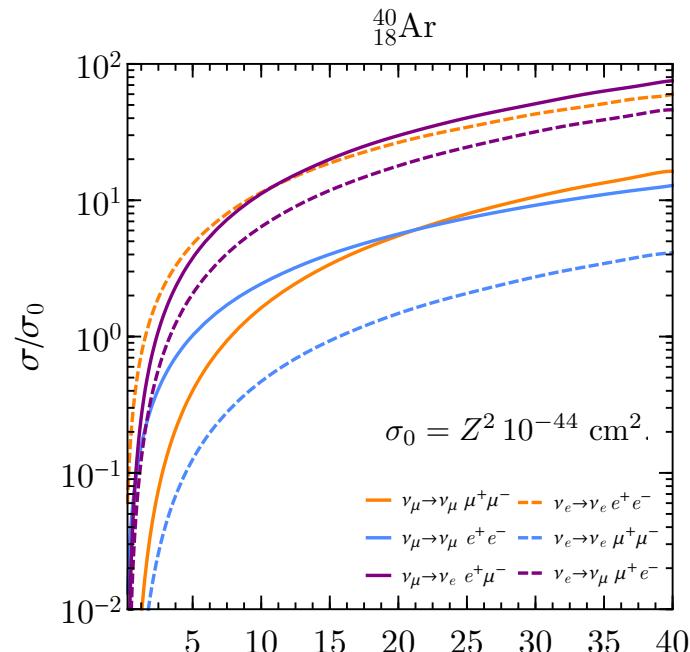
Trident



Altmannshofer et al., 1902.06765

Trident processes are expected in the SM but are very suppressed.

$$\frac{\sigma(\nu_\mu \rightarrow \nu_\mu \mu^+ \mu^-)_{\text{exp}}}{\sigma(\nu_\mu \rightarrow \nu_\mu \mu^+ \mu^-)_{\text{SM}}} = \begin{cases} 1.58 \pm 0.64 & (\text{CHARM-II}) \\ 0.82 \pm 0.28 & (\text{CCFR}) \\ 0.72^{+1.73}_{-0.72} & (\text{NuTeV}) \end{cases}$$

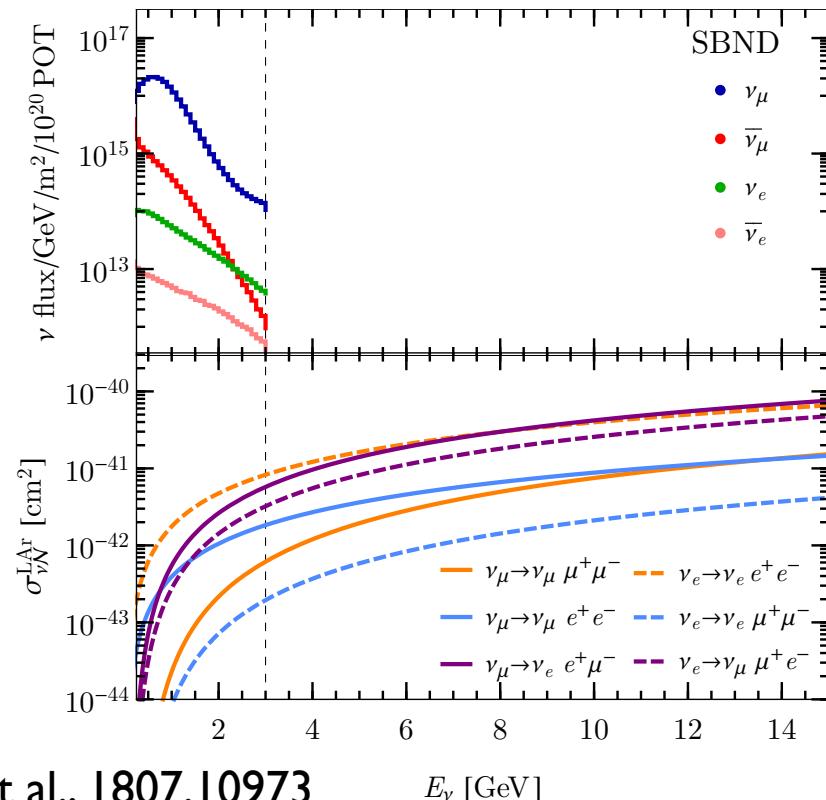
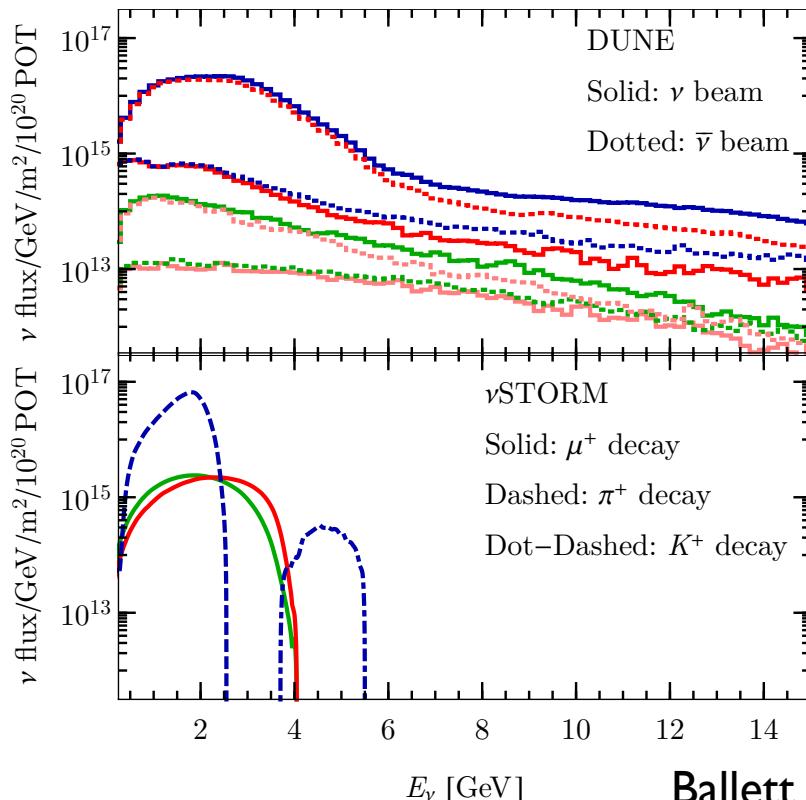


Ballett et al., 1807.10973

E_ν [GeV]

Neutrino accelerator experiments offer new opportunities to discover them.

| Experiment | Baseline (m) | Total Exposure (POT) | Fiducial Mass (t) | E_ν (GeV) |
|-------------|--------------|--------------------------------|-------------------|---------------|
| SBND | 110 | 6.6×10^{20} | 112 | 0 – 3 |
| μ BooNE | 470 | 1.32×10^{21} | 89 | 0 – 3 |
| ICARUS | 600 | 6.6×10^{20} | 476 | 0 – 3 |
| DUNE | 574 | $12.81 (12.81) \times 10^{21}$ | 50 | 0 – 40 |
| ν STORM | 50 | 10^{21} | 100 | 0 – 6 |

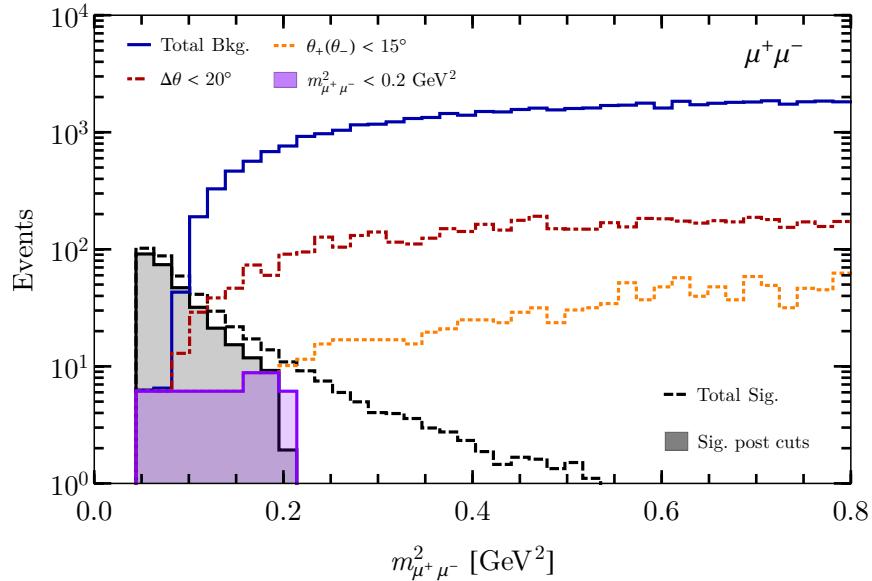


It is a very
rare process
with a cross
section which
increases with
energy.

DUNE is well
suited for this
search.

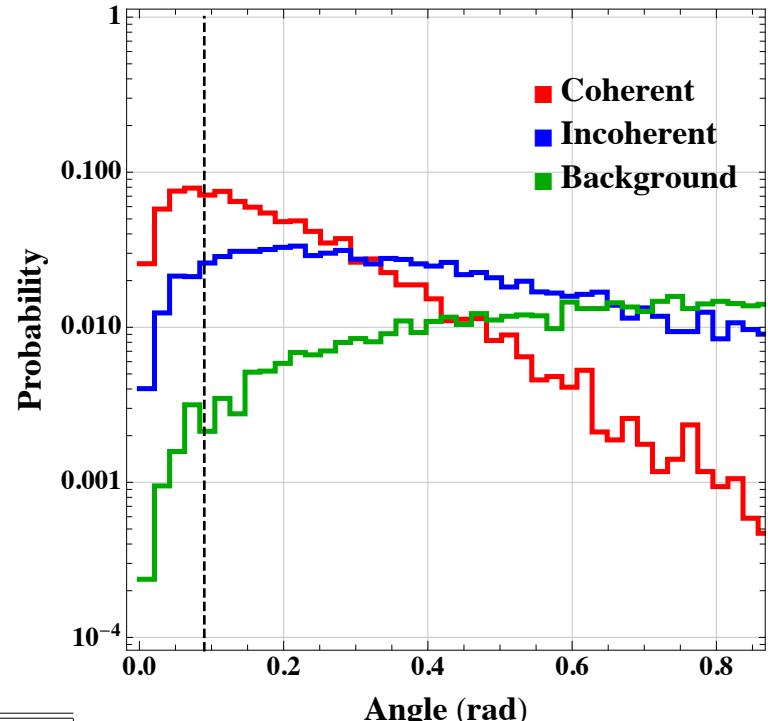
Ballett et al.,
1807.10973

| Channel | SBND | μ BooNE | ICARUS | DUNE ND | ν STORM ND |
|---|------------------|------------------|------------------|--------------------------|----------------|
| $\nu_\mu \rightarrow \nu_e e^+ \mu^-$ | 10 2 | 0.7 0.1 | 1 0.2 | 2844 (235) 654 (56) | 159 35 |
| $\bar{\nu}_\mu \rightarrow \bar{\nu}_e e^- \mu^+$ | 0.4 0.08 | 0.02 0.005 | 0.04 0.008 | 122 (2051) 29 (468) | 23 5 |
| $\nu_e \rightarrow \nu_\mu e^- \mu^+$ | 0.05 0.01 | 0.003 0.0008 | 0.004 0.001 | 22 (7) 7 (2) | 9 3 |
| $\bar{\nu}_e \rightarrow \bar{\nu}_\mu e^+ \mu^-$ | 0.005 0.001 | 0.0003 0.0001 | 0.0005 0.0001 | 5 (14) 2 (4) | — — |
| Total $e^\pm \mu^\mp$ | 10 2 | 0.7 0.1 | 1 0.2 | 2993 (2307) 692 (530) | 191 41 |
| $\nu_\mu \rightarrow \nu_\mu e^+ e^-$ | 6 0.7 | 0.4 0.04 | 0.7 0.07 | 913 (58) 128 (9) | 73 9 |
| $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu e^- e^+$ | 0.2 0.03 | 0.01 0.001 | 0.02 0.002 | 34 (695) 5 (95) | 9 1 |
| $\nu_e \rightarrow \nu_e e^- e^+$ | 0.2 0.02 | 0.01 0.001 | 0.02 0.002 | 50 (13) 8 (2) | 32 4 |
| $\bar{\nu}_e \rightarrow \bar{\nu}_e e^+ e^-$ | 0.02 0.003 | 0.001 0.0001 | 0.002 0.0002 | 10 (34) 2 (5) | — — |
| Total $e^+ e^-$ | 6 0.7 | 0.4 0.0 | 0.7 0.1 | 1007 (800) 143 (111) | 114 14 |
| $\nu_\mu \rightarrow \nu_\mu \mu^+ \mu^-$ | 0.4 0.4 | 0.03 0.03 | 0.04 0.04 | 271 (32) 186 (19) | 9 8 |
| $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \mu^- \mu^+$ | 0.01 0.01 | 0.001 0.0009 | 0.001 0.001 | 14 (177) 9 (127) | 2 1 |
| $\nu_e \rightarrow \nu_e \mu^+ \mu^-$ | 0.002 0.001 | 0.0001 0.0001 | 0.0001 0.0001 | 1 (0.5) 0.7 (0.2) | 0.4 0.3 |
| $\bar{\nu}_e \rightarrow \bar{\nu}_e \mu^+ \mu^-$ | 0.0002 0.0001 | 0.0000 0.0000 | 0.0000 0.0000 | 0.3 (0.9) 0.2 (0.5) | — — |
| Total $\mu^+ \mu^-$ | 0.4 0.4 | 0.0 0.0 | 0.0 0.0 | 286 (210) 196 (147) | 11 9 |

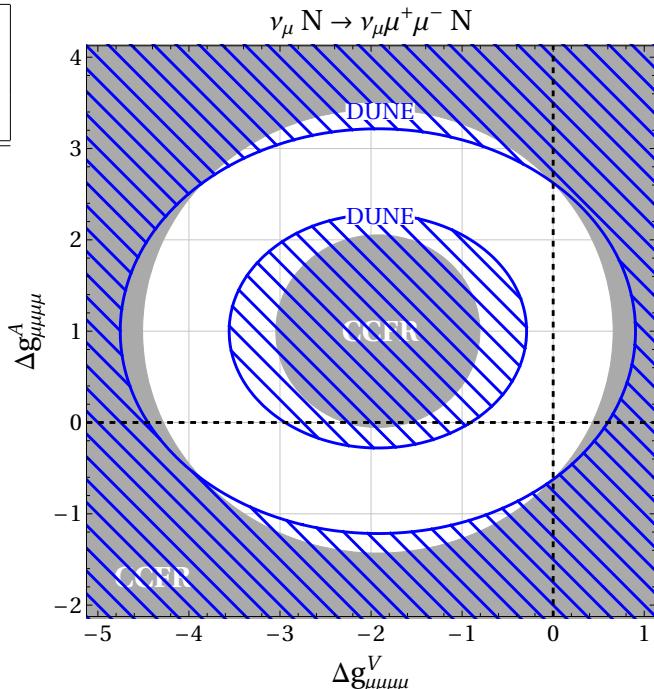


Altmannshofer et al., 1902.06765

| Channel | $N_B^{\text{misID}}/N_{\text{CC}}$ | $N_B^{\text{had}}/N_{\text{CC}}$ | $N_B^{\text{kin}}/N_{\text{CC}}$ | $\epsilon_{\text{sig}}^{\text{coh}}$ | $\epsilon_{\text{sig}}^{\text{dif}}$ 9 |
|-----------------|------------------------------------|----------------------------------|----------------------------------|--------------------------------------|--|
| $e^\pm \mu^\mp$ | $1.67 (1.62) \times 10^{-4}$ | $2.68 (4.31) \times 10^{-5}$ | $4.40 (3.17) \times 10^{-7}$ | 0.61 (0.61) | 0.39 (0.39) |
| $e^+ e^-$ | $2.83 (4.19) \times 10^{-4}$ | $1.30 (2.41) \times 10^{-4}$ | $6.54 (14.1) \times 10^{-6}$ | 0.48 (0.47) | 0.21 (0.21) |
| $\mu^+ \mu^-$ | $2.66 (2.73) \times 10^{-3}$ | $10.4 (9.75) \times 10^{-4}$ | $3.36 (3.10) \times 10^{-8}$ | 0.66 (0.67) | 0.17 (0.16) |

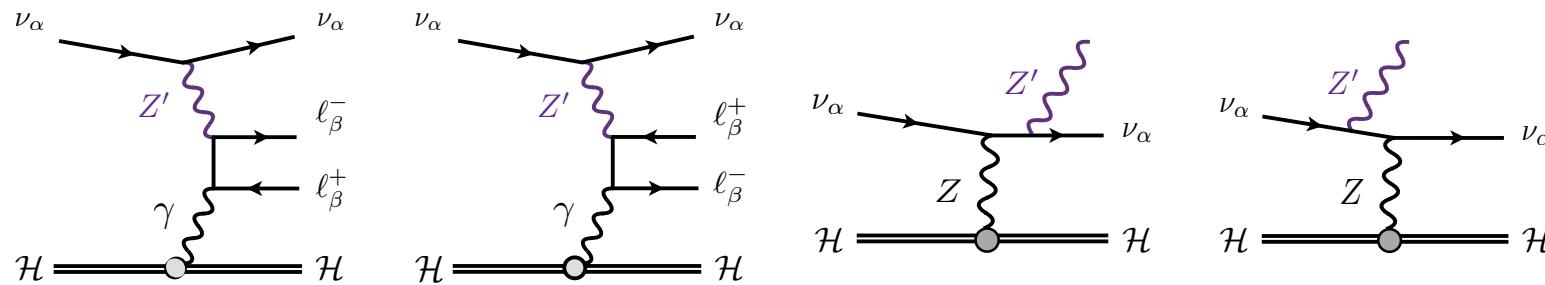


Backgrounds are important but angular distributions and other correlations can be used to significantly reduce them.

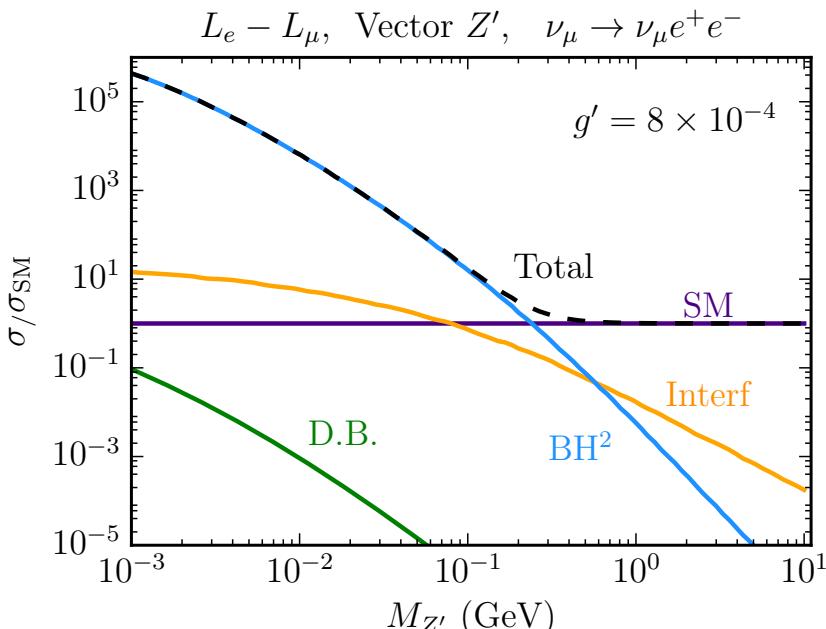


Z' Trident and Scattering

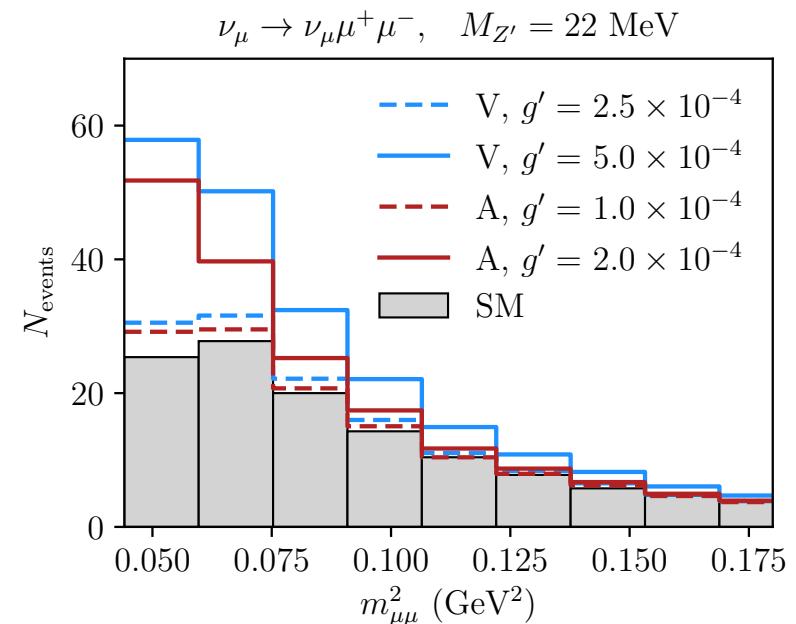
Trident events can be used to search for light vector boson mediators (Z').



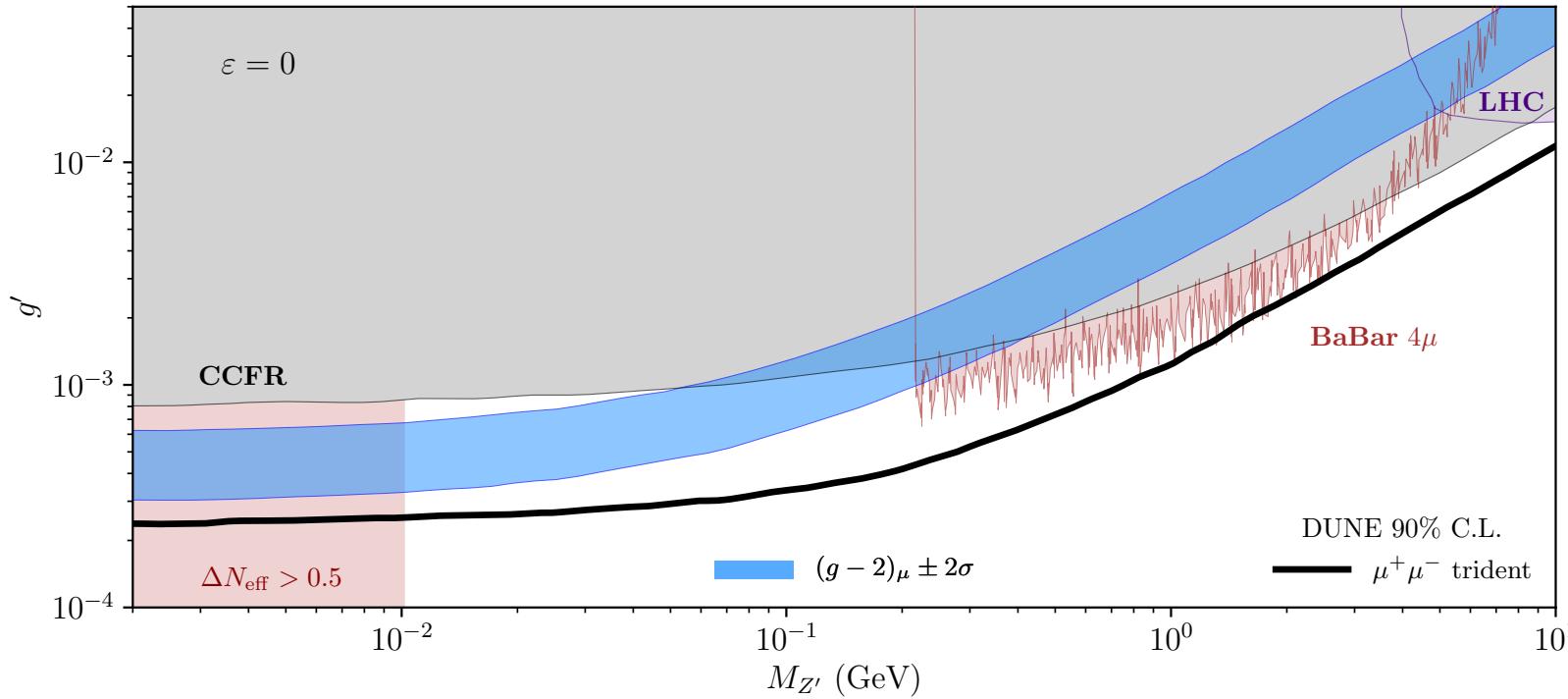
Bethe-Heitler



Dark-Bremsstrahlung



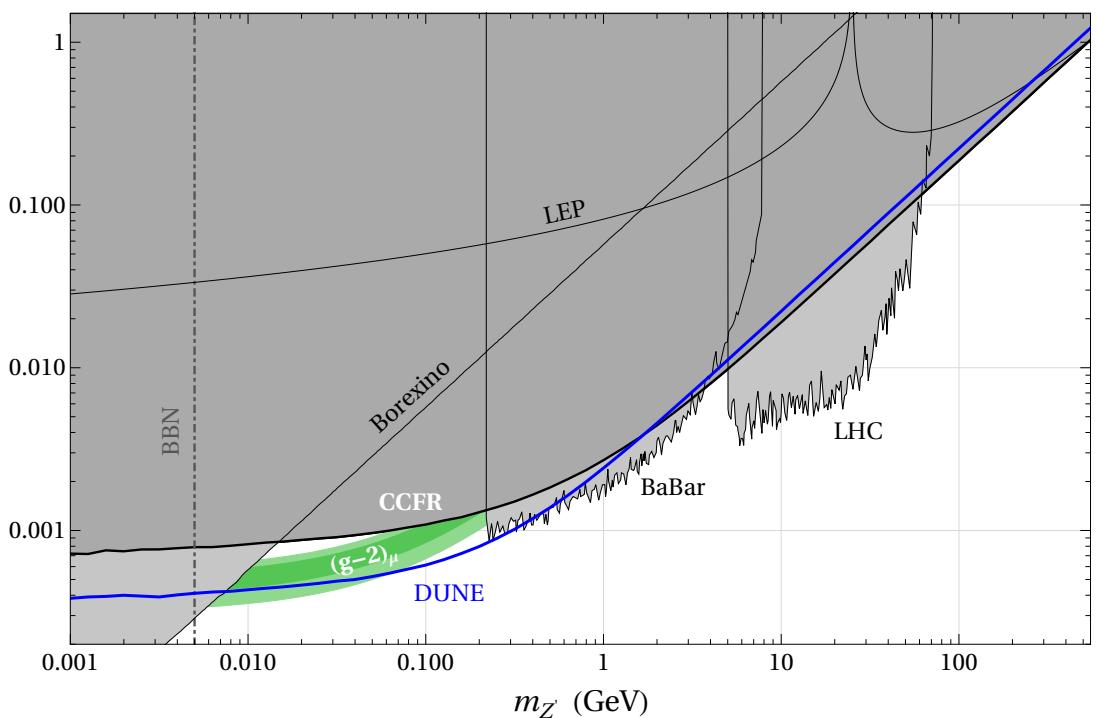
$L_\mu - L_\tau$, DUNE ND, 75 tonnes, 5 y ν -mode + 5 y $\bar{\nu}$ -mode, 120 GeV p^+ , $\sigma_{\text{norm}} = 5\%$



Ballett et al.,
1902.08579

Altmannshofer
et al.,
1902.06765

DUNE-ND would set the most stringent bounds for light gauge bosons for $L_\mu - L_\tau$ models.

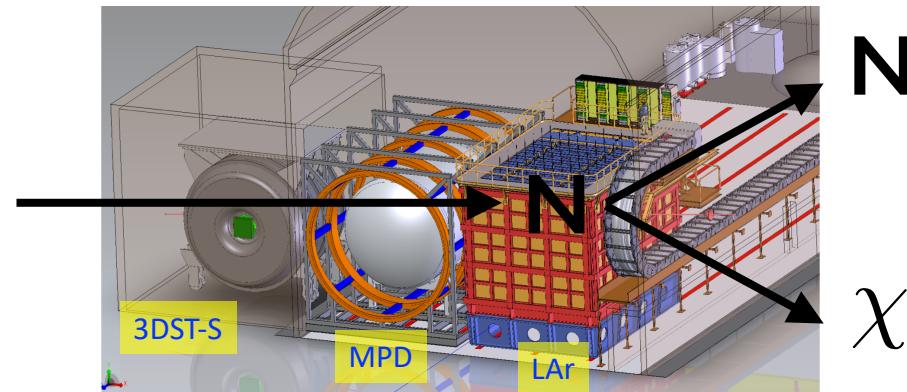


Light DM

With the lack of detection of WIMP, there is growing interest on other mass ranges, in particular below GeV **Light Dark Matter (LDM)**.

Generically, LDM interacts with light mediators (e.g. dark photon) which weakly couple to the SM.

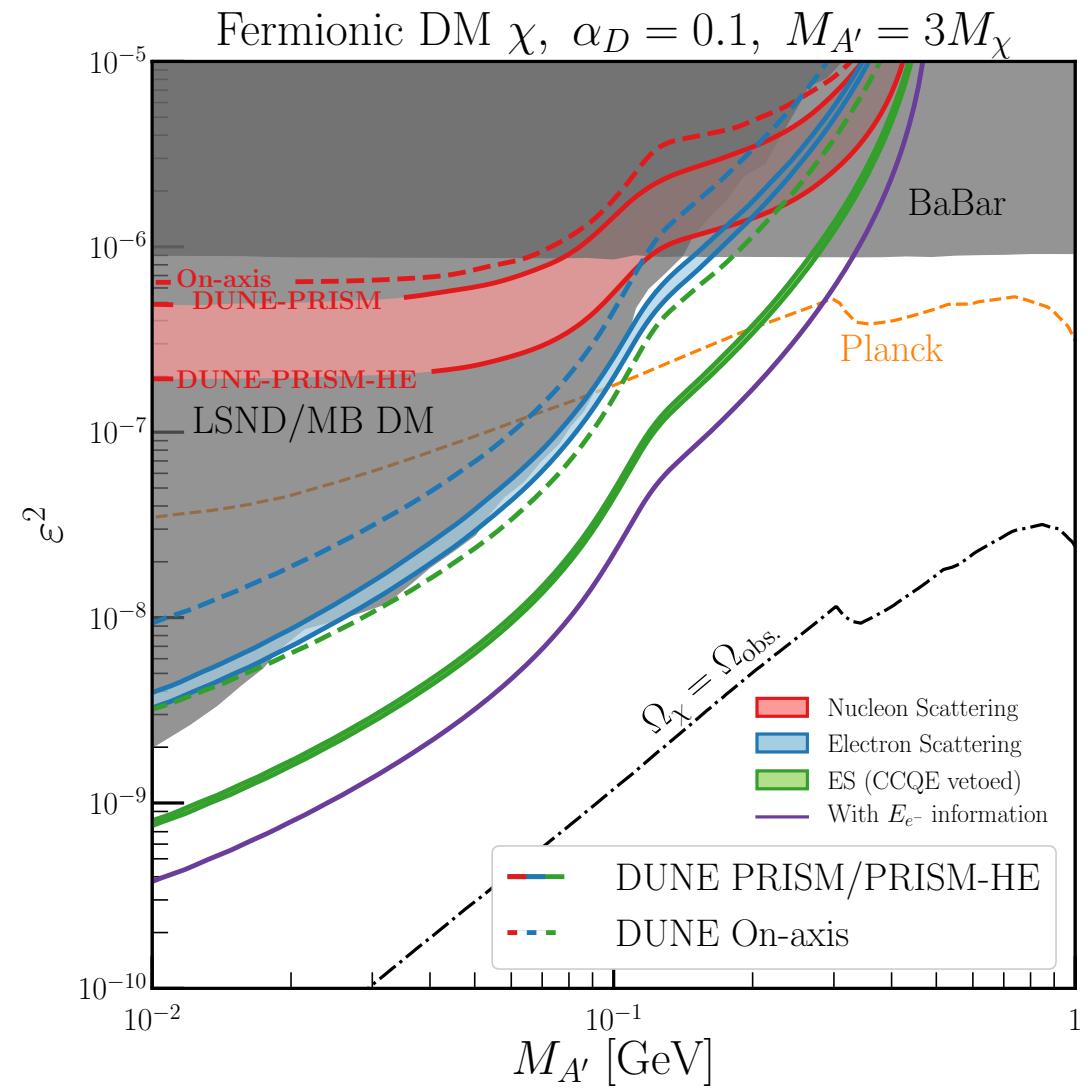
$$\pi_0, \eta \rightarrow \gamma A' \\ A' \rightarrow \bar{\chi} \chi$$



The two key signatures are scattering off nucleons (-> a single proton track) and off electrons (-> very forward single electrons) for light DM.

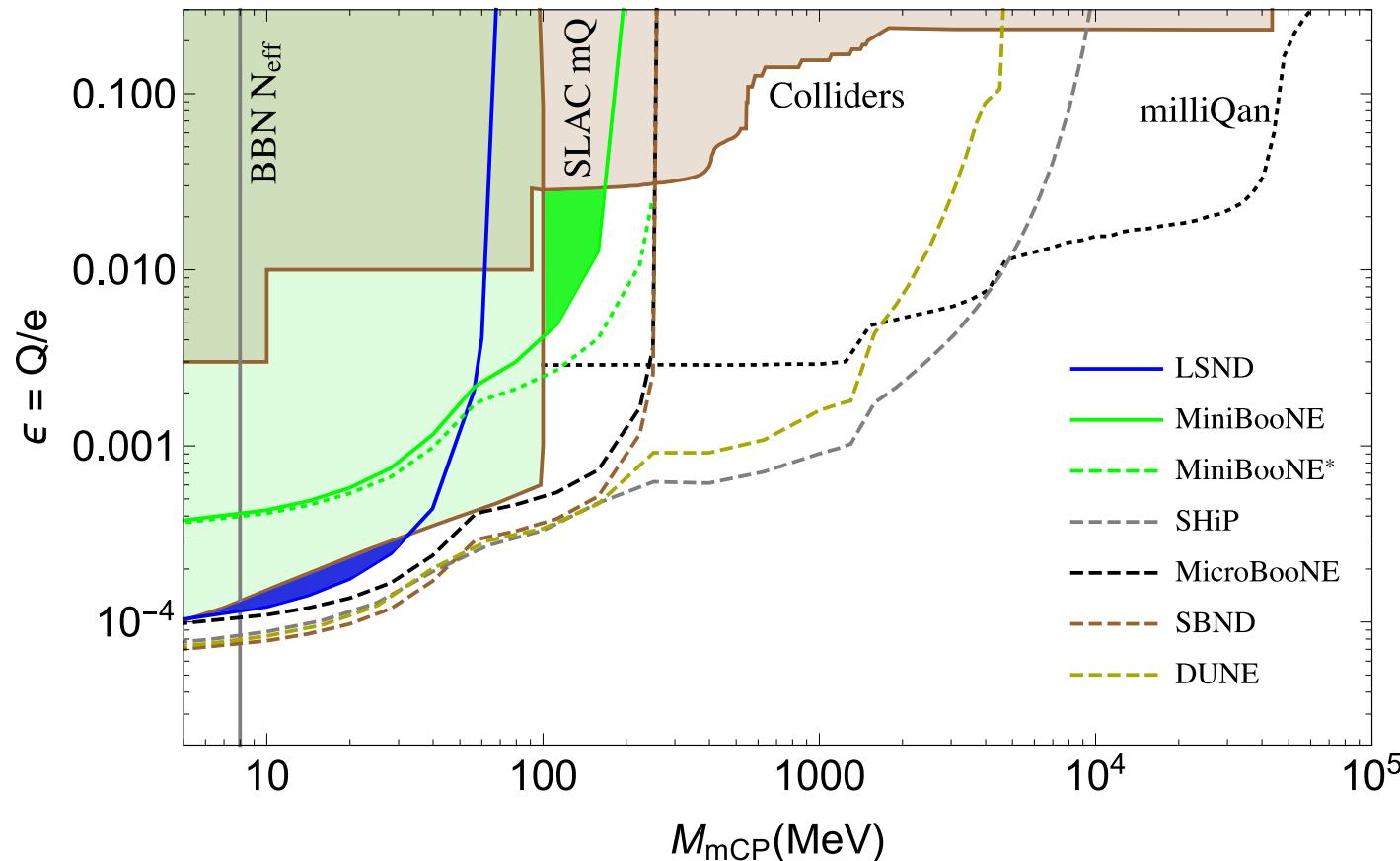
Dominant background is typically due to neutrino interactions (e.g. QE NC events, neutrino scattering off electrons and QE CC electron scattering events).

By going off-axis (DUNE-PRISM) these backgrounds can be reduced.



De Romeri et al., 1903.10505. See also, G. Brown's Master thesis

Milli-Charged Particles



Milli-charged particles emerge in theories with dark sectors. They are produced in neutral meson decays and subsequently scatter off electrons with low energy recoils.

Weak Mixing Angle

$$\sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2}$$

The weak mixing angle is a key parameter in the SM. It can be measured in electron scattering.

Agarwalla, Huber, 1005.1254

Sterile neutrinos

Sterile neutrinos with eV masses could be searched for at the DUNE ND with a different L/E dependence w.r.t. SBN.

Non-unitarity and 0-distance NSIs

Non-unitarity effects or NSIs could lead to specific appearance and disappearance signatures.

Heavy neutral leptons at DUNE ND

Sterile neutrinos: neutral fermionic singlets of the Standard Model. Here, I will assume that they have a Majorana mass > eV. Generically they mix with the light neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{4 \times 4} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Flavour state **Massive state**
Nearly-sterile neutrino,
commonly called sterile neutrino

The diagram illustrates the mixing of four light neutrinos ($\nu_e, \nu_\mu, \nu_\tau, \nu_s$) with four massive neutrinos ($\nu_1, \nu_2, \nu_3, \nu_4$). The light neutrinos are represented by a column vector, and the massive neutrinos are also represented by a column vector. A unitary matrix $U_{4 \times 4}$ relates the two states. The fourth light neutrino, ν_s , is highlighted with a red circle and labeled "Flavour state". The fourth massive neutrino, ν_4 , is highlighted with a red circle and labeled "Massive state" and "Nearly-sterile neutrino, commonly called sterile neutrino".

$$\mathcal{L} = \dots + \bar{\ell}_L U_{\ell 4} \gamma_\mu \nu_{4,L} W^\mu + \text{NC} + \text{h.c.}$$

Adding sterile neutrinos to the Standard Model is the simplest possible extension BSM.

- Theory remains anomaly free.
- Can give origin to neutrino masses and explain their smallness (at least in some cases).
- GUT theories embedding L-R symmetries, e.g. SU(4), SO(10),... predict their existence.
- Apart from GUT theories, there is no strong motivation for choosing one mass scale instead of another (except for a naturalness principle: setting their mass to zero restores lepton number).

What are sterile neutrinos good for?

Neutrino masses

In See-saw models, neutrinos acquire Majorana masses via the interactions with the N.

Baryon asymmetry

In Leptogenesis, the N decays are responsible for the BAU.

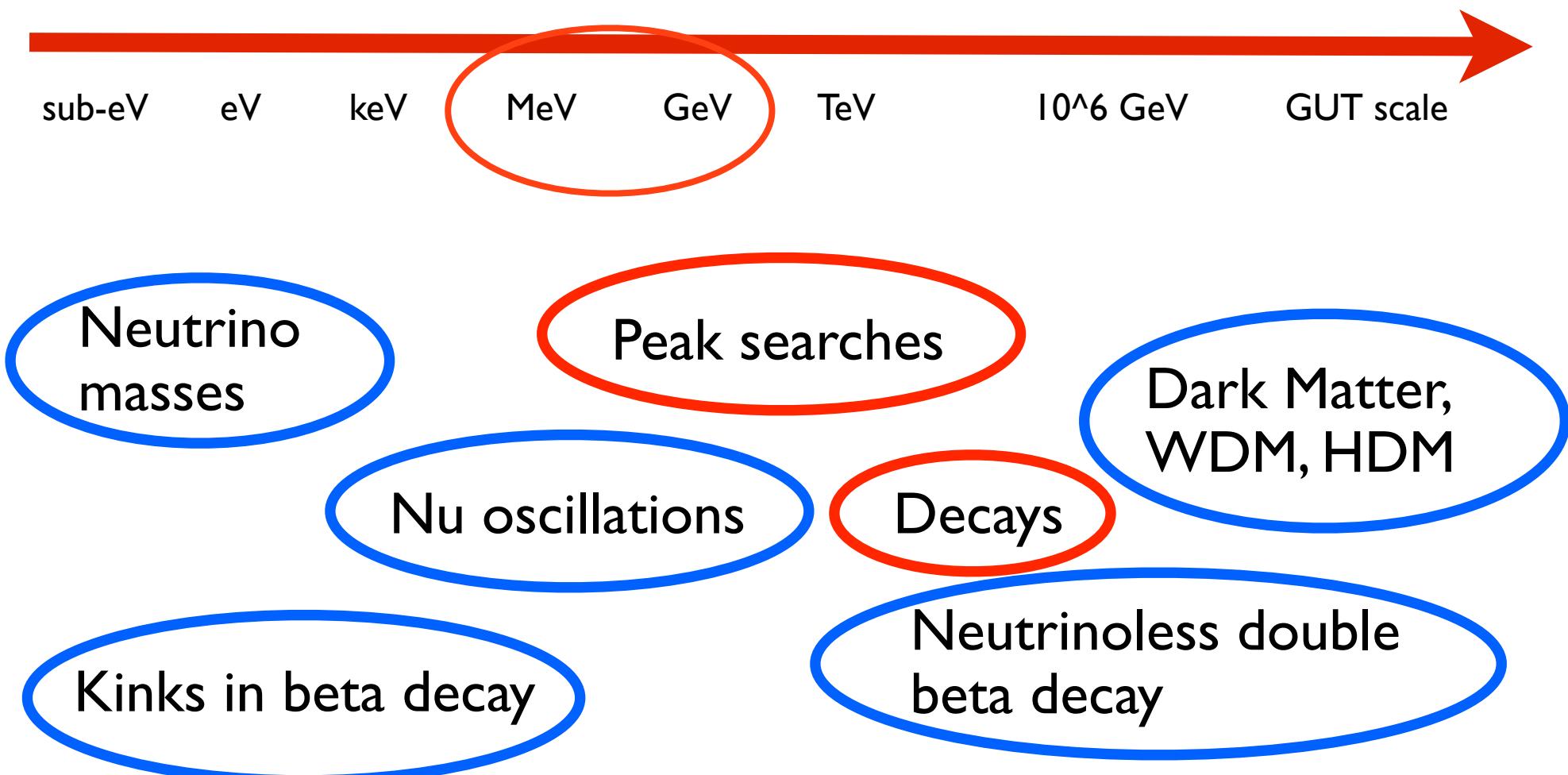
Dark matter

Sterile neutrinos with KeV masses are a favorite Warm DM candidate.

“Vanilla” HNLs

Signatures

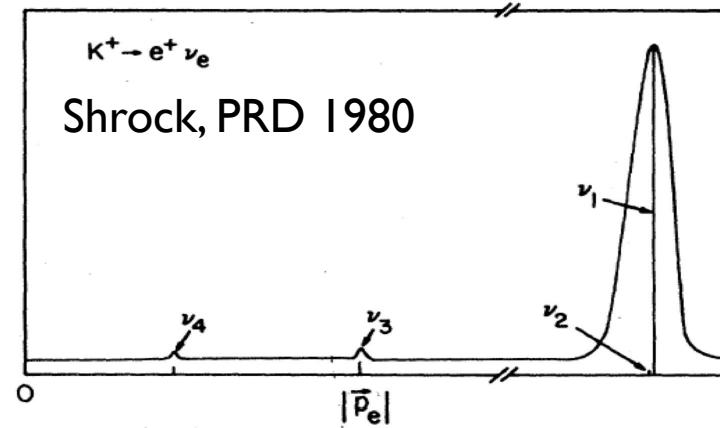
They critically depend on the masses of the sterile neutrinos. Direct searches cannot go beyond TeV masses.



Peak searches

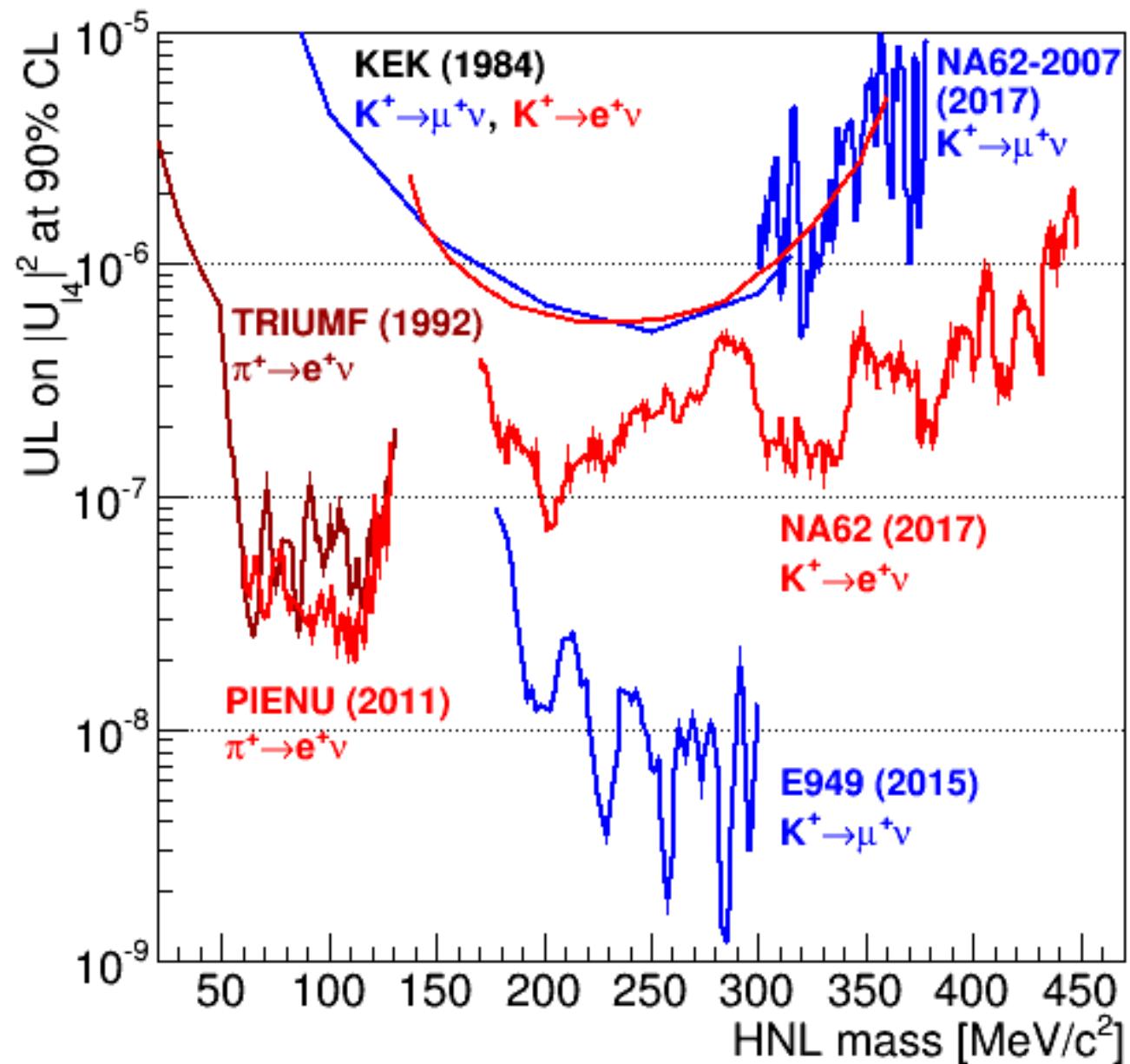
sub-eV eV keV MeV GeV TeV GUT scale

If produced in pion and kaon decays, they would modify the electron and muon spectrum with a peak at lower E.



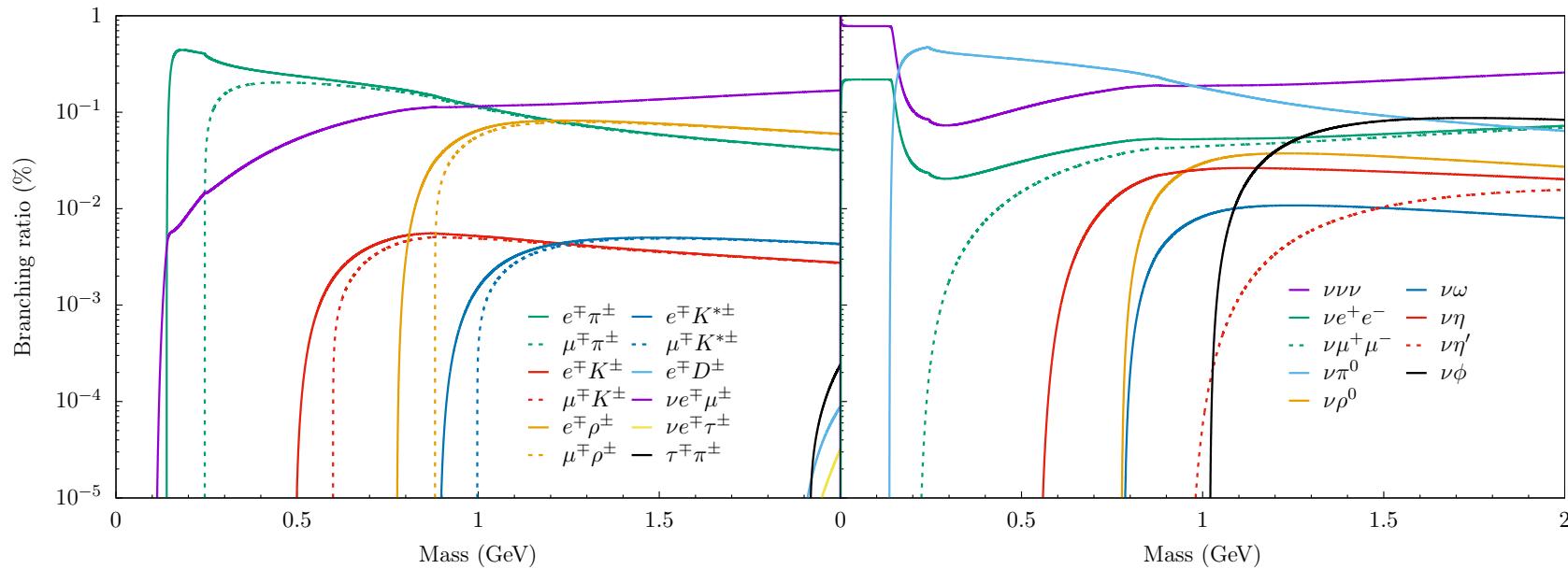
After searches in the 80'-90', NA62 can again perform a search of this kind. The signature is a single positively charged track.

Caveat (thanks to M. Hostert): if the HNL decays very rapidly into charged particles, these limits might need to be reconsidered.



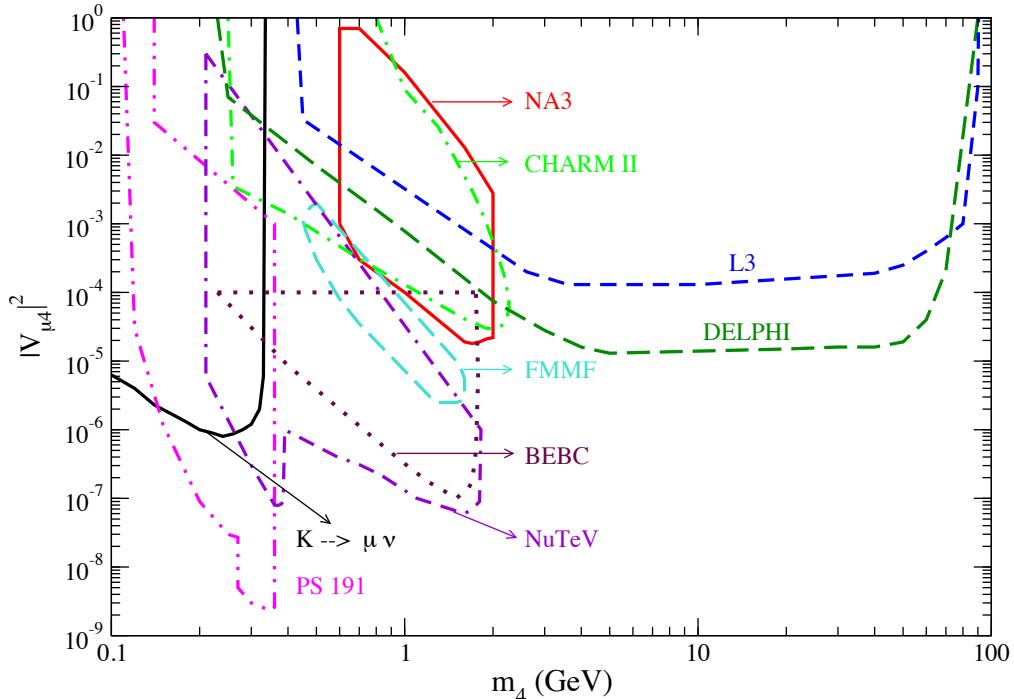
Decay searches

Via mixing, HNLs can be produced in pion and kaon (and other heavy meson) decays, subsequently decaying into visible particles.



Ballett, Boschi, SP, I905.00284

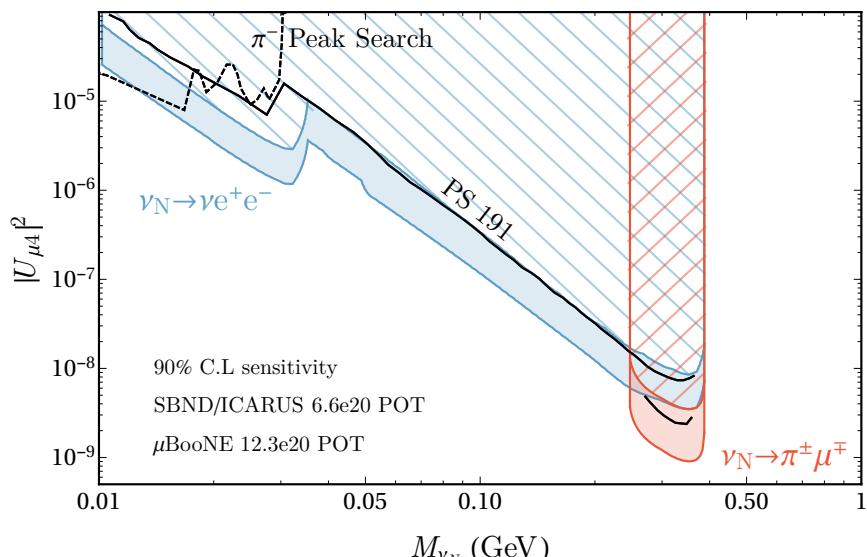
For CC only the ones with the charged lepton associated with the mixing angle are possible.
Searching for different channels would allow to test the “vanilla” HNL hypothesis.



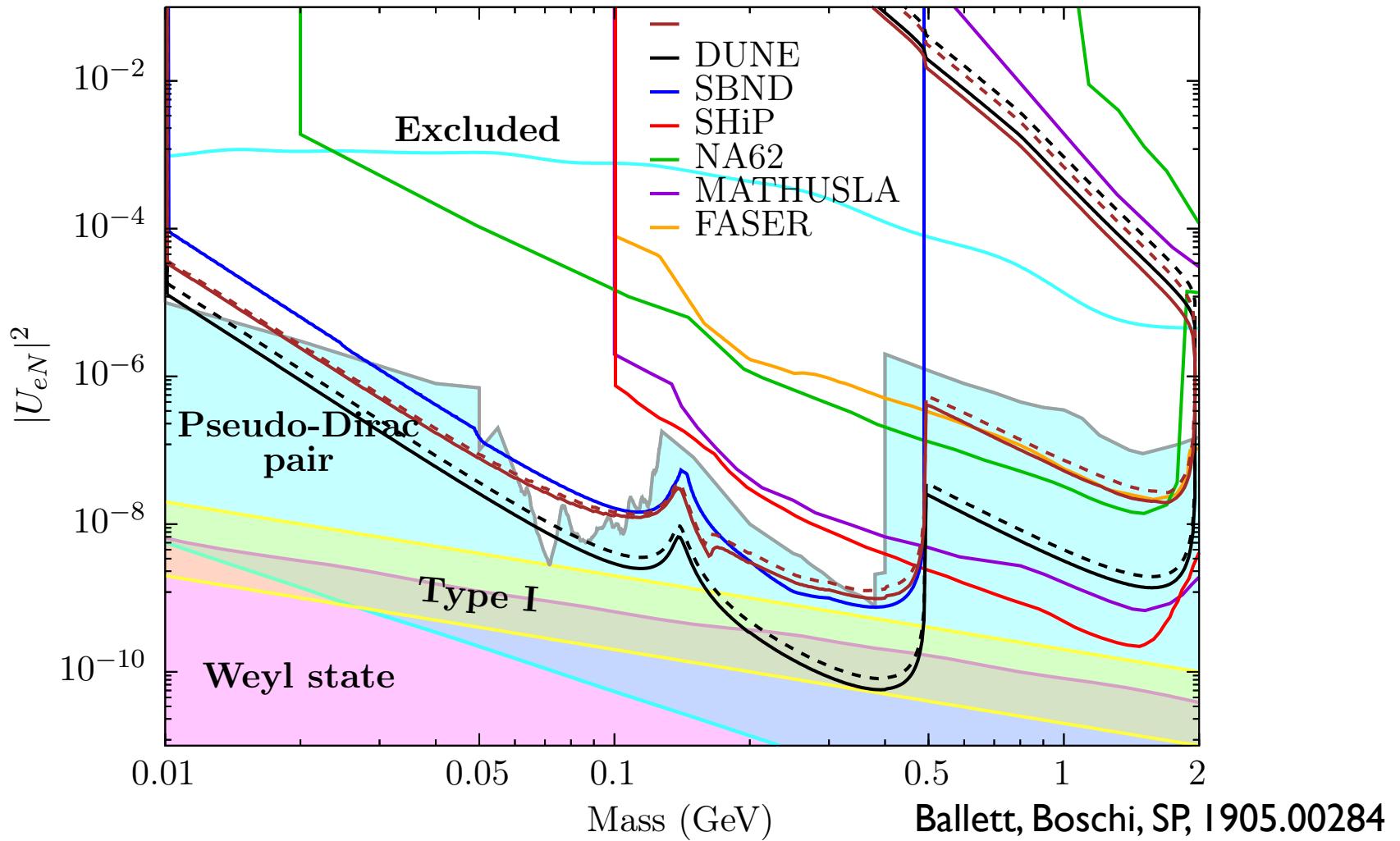
Atre et al., JHEP 0905 (2009)

SHiP is specifically designed to access larger masses, thanks to the higher proton energy and low-Z detector.

The bounds which can be obtained at SBN are stronger than previous searches, mainly thanks to the SBN detector. Precise information about arrival times would provide a smoking gun signature.

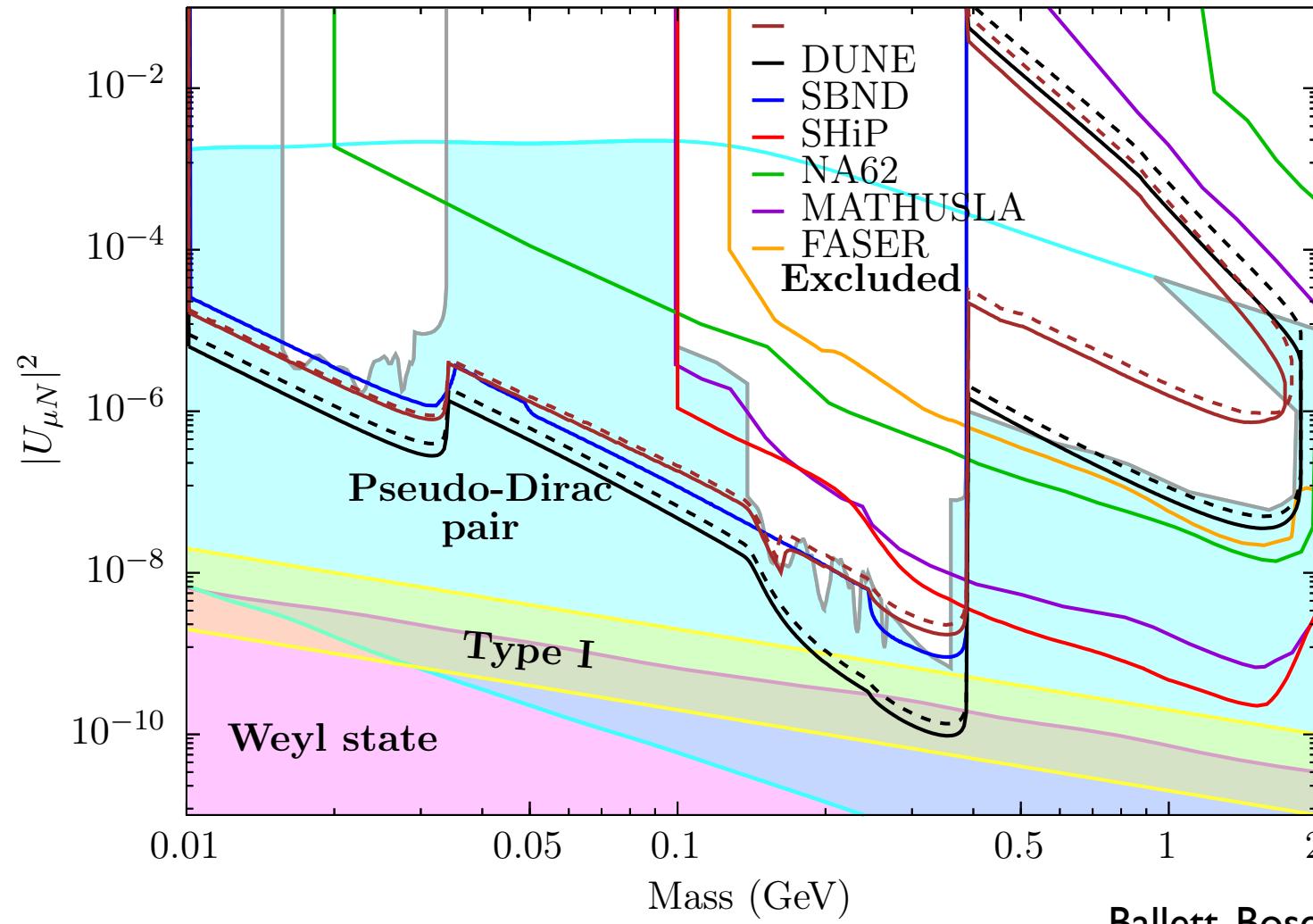


Summary of bounds



DUNE is excellently suited for this type of search and has access to GeV mass and even mixing with the taus.

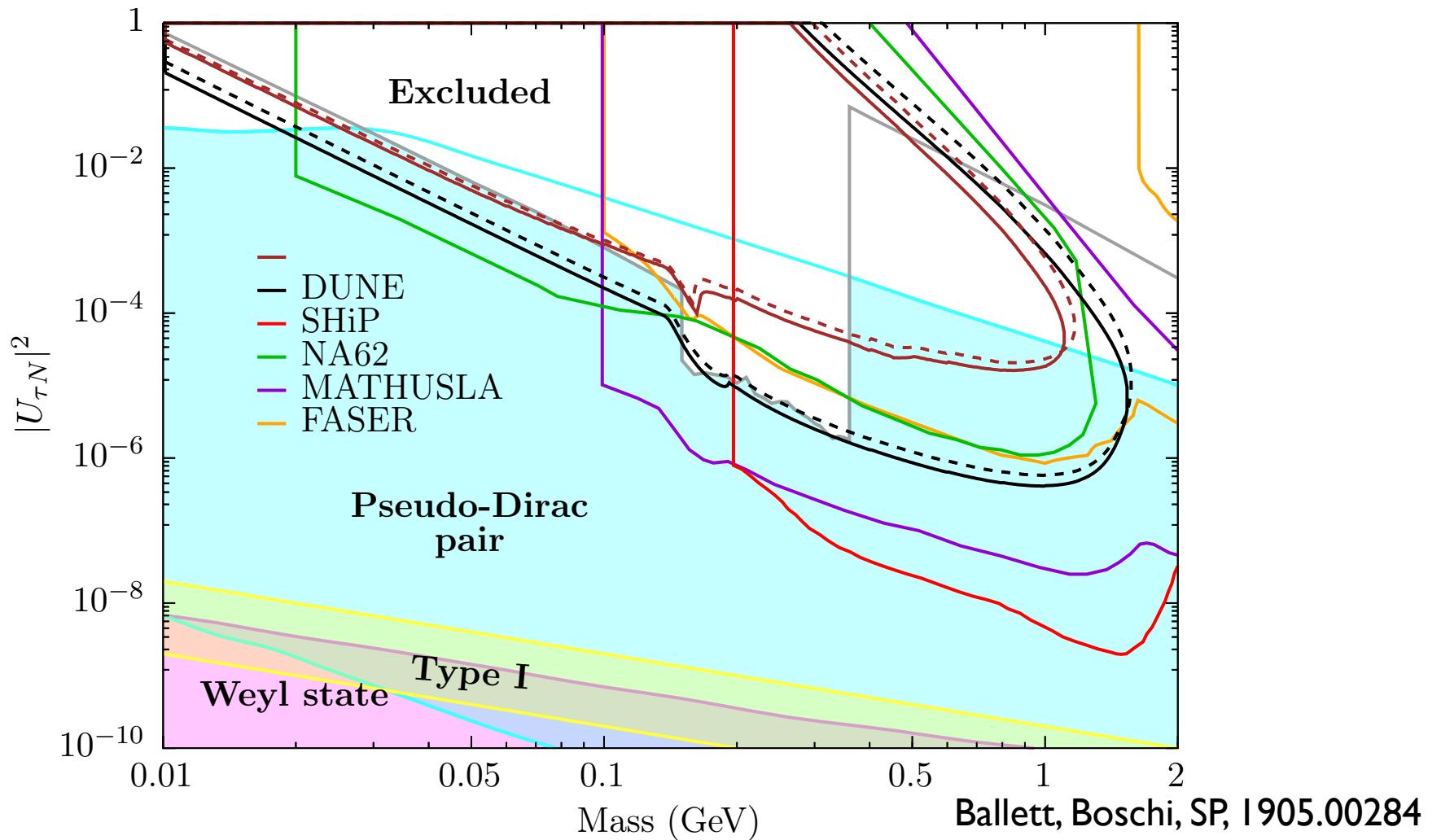
Summary of bounds



Ballett, Boschi, SP, 1905.00284

For muon and electron mixing, the bounds are close to the see-saw band and in any case they are in an interesting region from a theory point of view.

Summary of bounds



Thanks to the Ds production, DUNE ND will have also sensitivity to the mixing with tau neutrinos.

HNLs and a dark sector

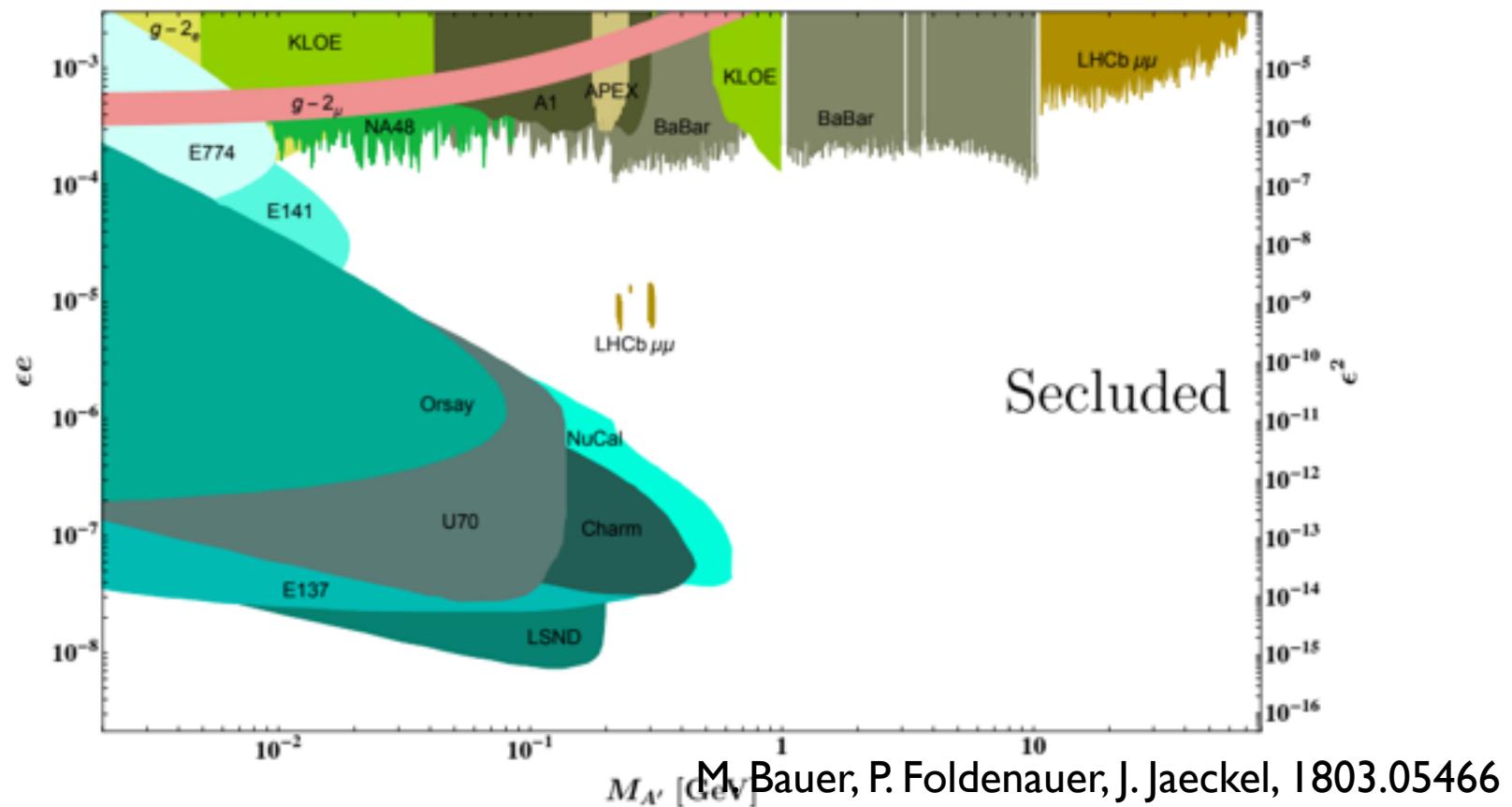
HNLs could be part of a new low energy sectors which contain several new states (neutral fermions, gauge bosons, scalars, DM.)...

How does it “talk” to the SM?

- mixing/Yukawa couplings
- new gauge interactions
- kinetic mixing
- new scalars via the Higgs portal
- EFTs

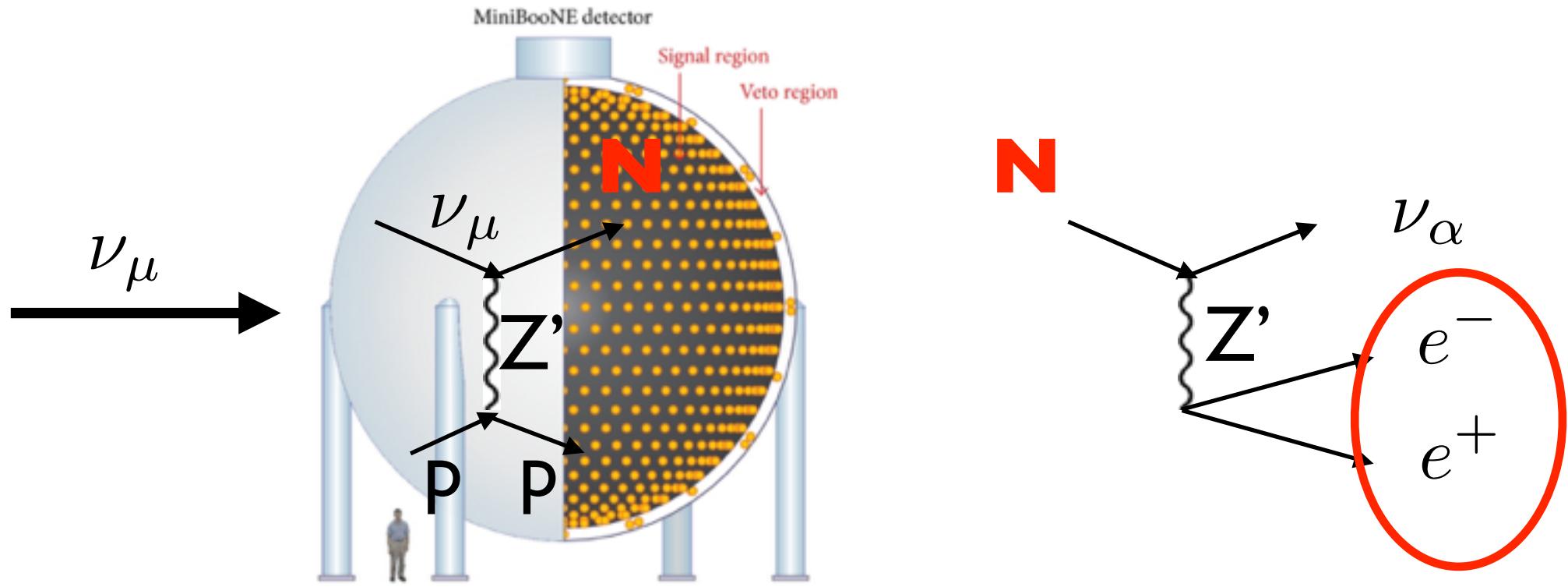
Dark photons/Z'

It is also possible to extend the gauge sector via new $U(1)$ and an associated Z' with light mass and very weak interactions with the SM: mu-tau symmetry, kinetic mixing.



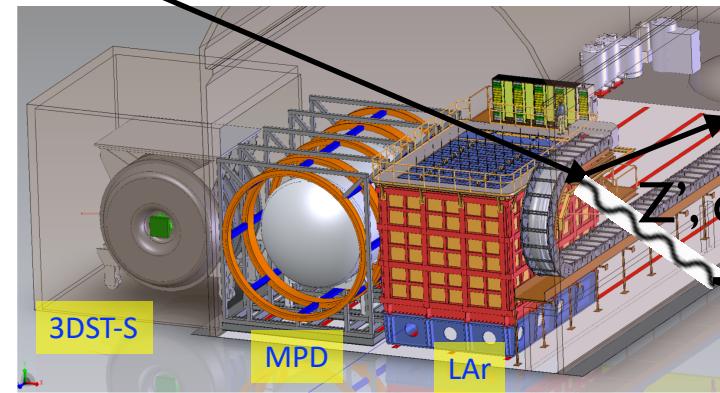
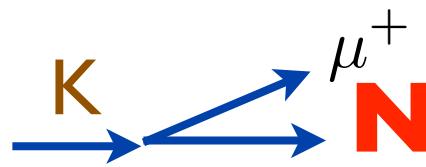
A MiniBooNE low- E excess explanation

A viable explanation of the MiniBooNE low- E excess is provided by introducing a **sterile neutrino**, charged under a new $U(1)$ which mixes with the standard model neutrinos, and a **light gauge boson Z'** .



A unique signature

Typically one can expect the HNLs to decay dominantly via new NC interactions into pairs of leptons, ...



ν_α

Z' , dark photon, dark scalar

$e^-_+ \mu^-_+ \mu^-_+$

One can expect **displaced vertices**, reducing significantly the SM background. DUNE-ND would have excellent sensitivity to search for these HNLs.

Conclusions

BSM models with light sectors (eg. heavy neutral fermions or sterile neutrinos, dark photons, light DM...) are interesting extension of the SM. They can explain neutrino masses and can be connected to the other compelling observational evidences of BSM (DM and the baryon asymmetry).

DUNE-ND has unique opportunities to search for them thanks to high pot, detector complex (and DUNE-PRISM):

- a-la beam dump experiment;
- scattering searches.