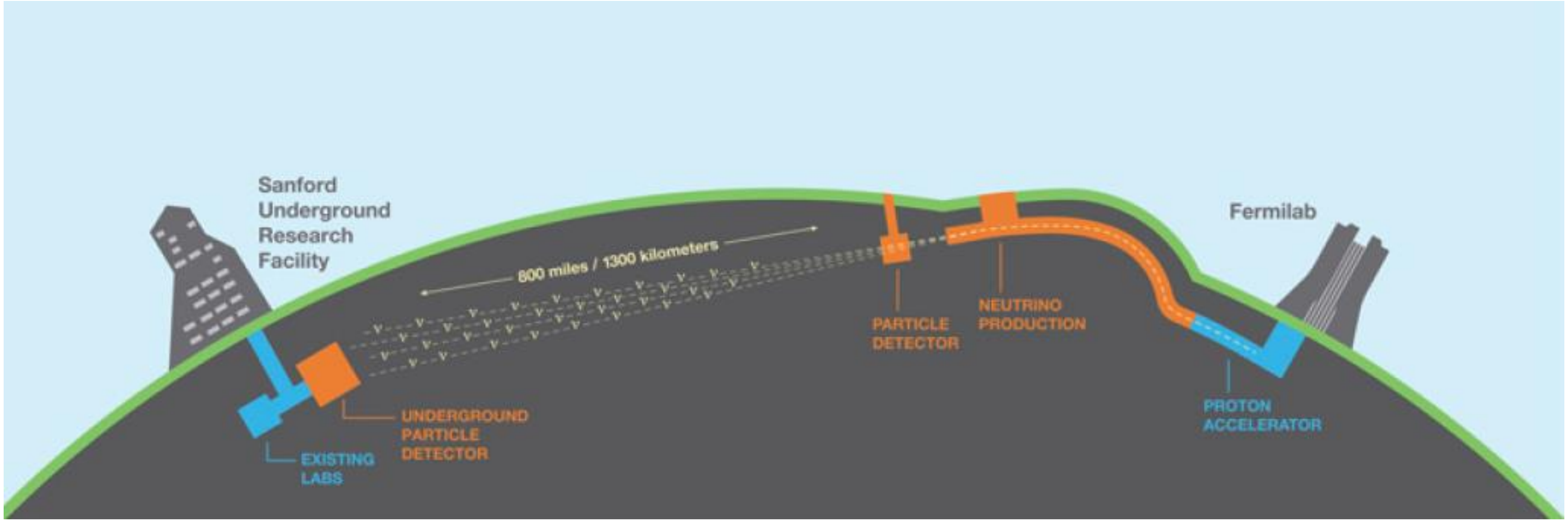
A High Pressure TPC for the DUNE Near Detector



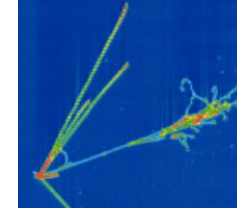
Dec 15 – 17, 2021

D. González-Díaz (IGFAE)
16-12-2021

for the DUNE collaboration

IGFAE
Instituto Galego de Física de Altas Enerxías

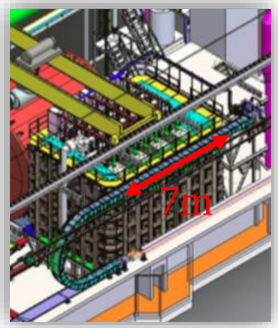
Long-baseline neutrino oscillations (DUNE's core idea)



Fermilab

ν_μ

LAr near detector (ND)

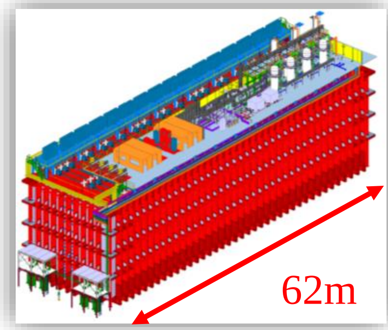


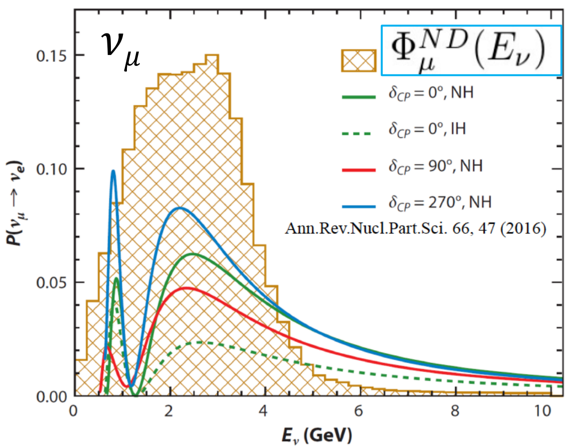
ν_μ

ν_e

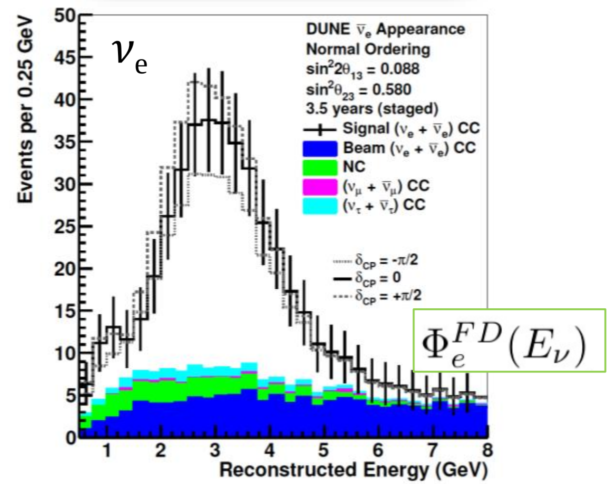
1300km

LAr far detector (FD)





$$P(\nu_\mu \to \nu_e) = \frac{\Phi_e^{FD}(E_\nu)}{\Phi_\mu^{ND}(E_\nu)}$$



$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

mass difference

$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$$

matter effect

$$a = G_F N_e/\sqrt{2}$$

The experimental challenge

$$P(\nu_\mu \to \nu_e) = \frac{\Phi_e^{FD}(E_\nu)}{\Phi_\mu^{ND}(E_\nu)}$$

$$N_e^{FD}(E_\nu) = \Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)$$

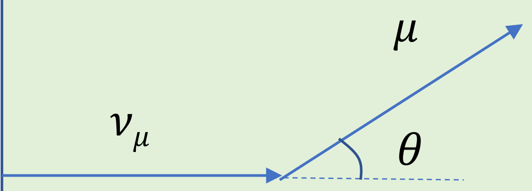
$$\frac{N_e^{FD}(E_{rec})}{N_\mu^{ND}(E_{rec})} = \frac{\int dE_\nu \mathbf{D}^{FD}(E_\nu \to E_{rec}) \Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)}{\int dE_\nu \mathbf{D}^{ND}(E_\nu \to E_{rec}) \Phi_\mu^{ND}(E_\nu) \times \sigma_\mu(E_\nu) \times \epsilon_\mu^{ND}(E_\nu)}$$

energy reconstruction bias

cross section

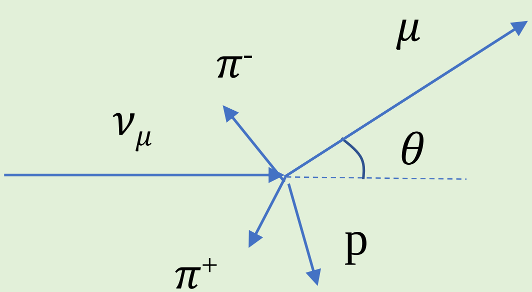
reconstruction efficiency

this is what you see in dense media



$E_\nu(\theta, E_\mu)$

and this is what you don't see!

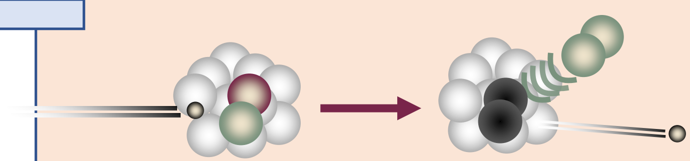


$E_{rec}(\theta, E_\mu)$

a) Fermi motion

b) Final state interaction [FSI] (and related, re-interaction in dense media)

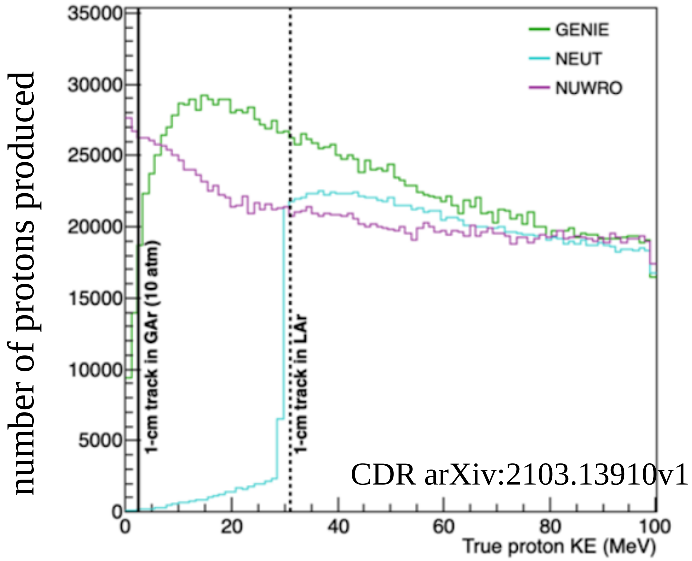
c) 2p2h excitation



The experimental challenge

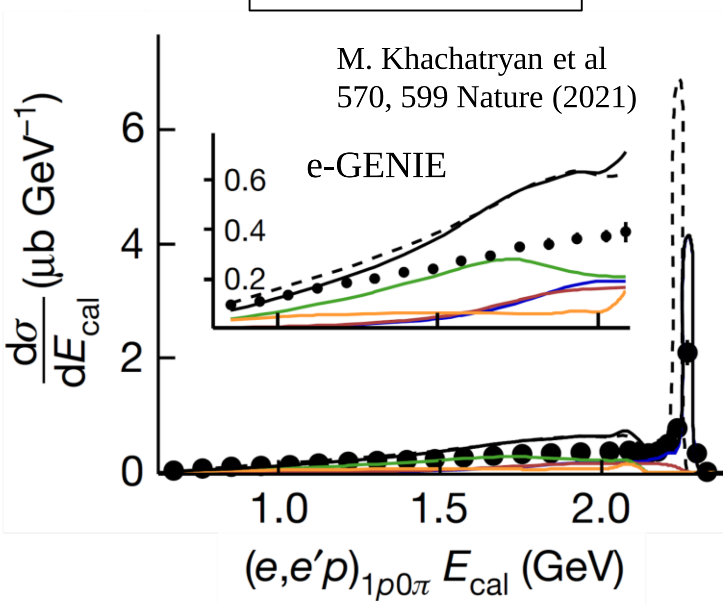
some known biases

from ν interactions



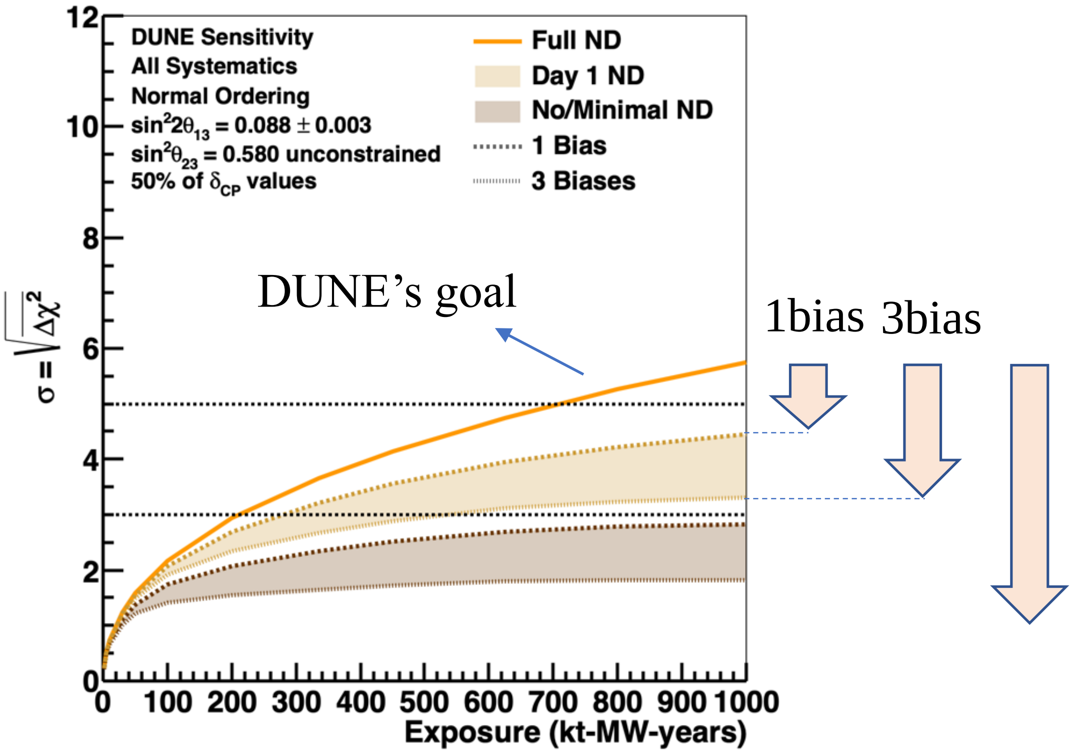
CDR arXiv:2103.13910v1

from e$^-$ interactions



M. Khachatryan et al
570, 599 Nature (2021)

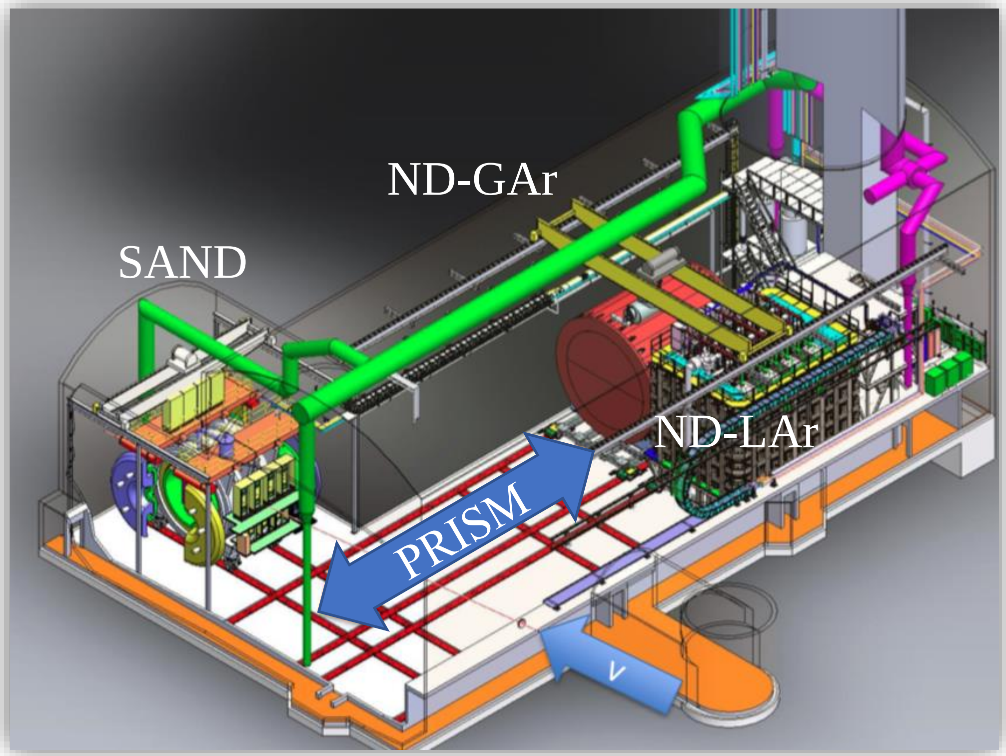
δ_{CP} sensitivity to 50% of the values



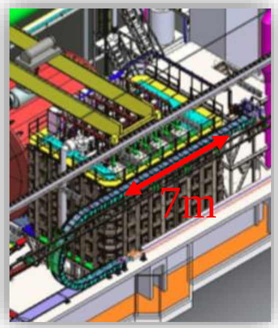
*example of a well-understood bias from reconstruction in dense media (*multi-π production*)

The experimental challenge

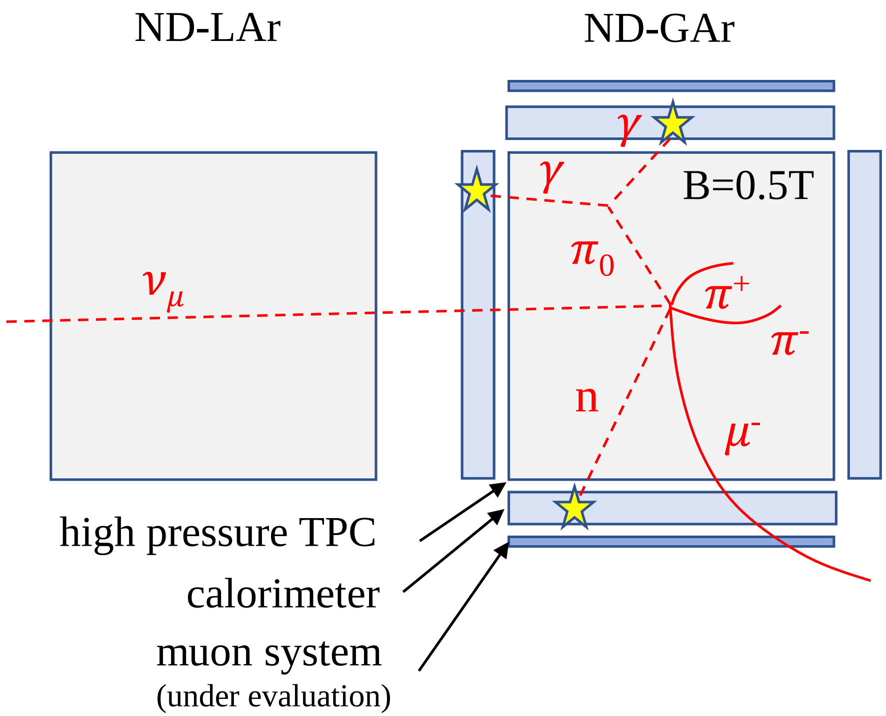
that's the reason why the complete
near detector complex looks like this

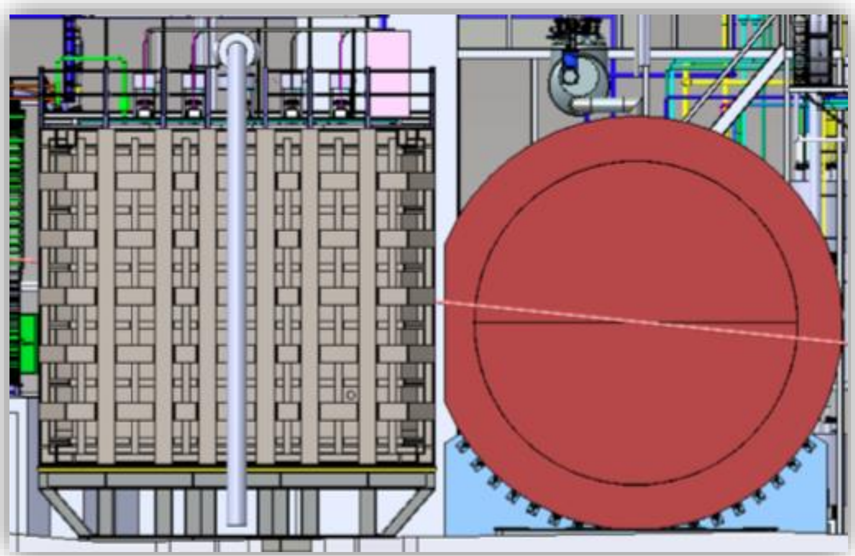


and not like this!



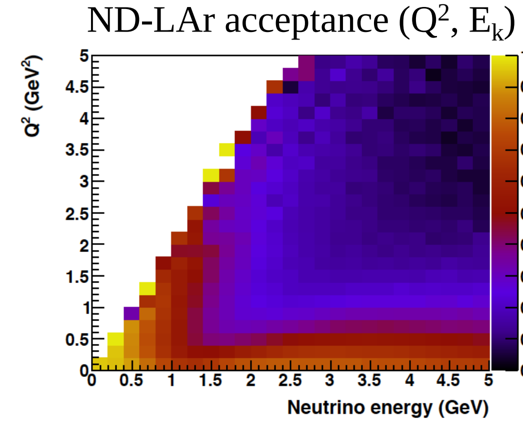
ND-GAr as a 4π & low tracking-threshold device with n, π_0 reconstruction capability

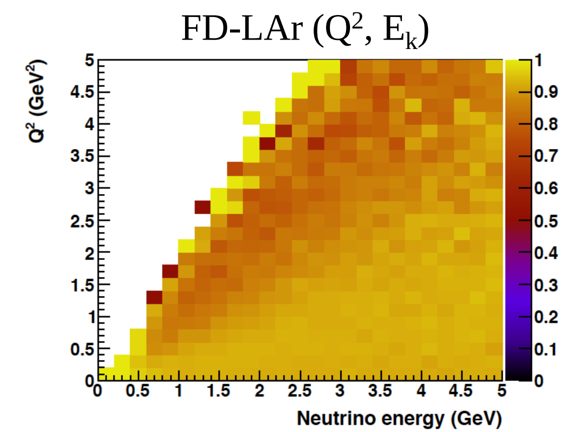


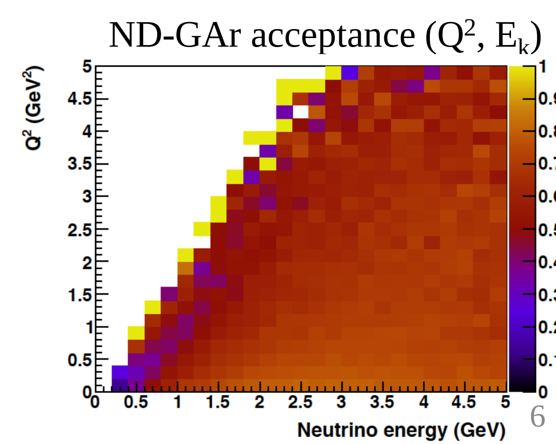


ν_μ-CC:
1.64 x 10^6 evt/ton/yr
ν_μ-NC
5.52 x 10^5 evt/ton/yr

*possible thanks to pressurization, detector size and sheer ν-beam power!





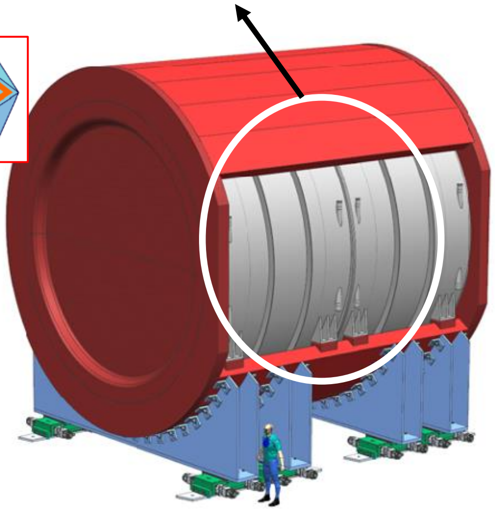


ND-GAr building blocks

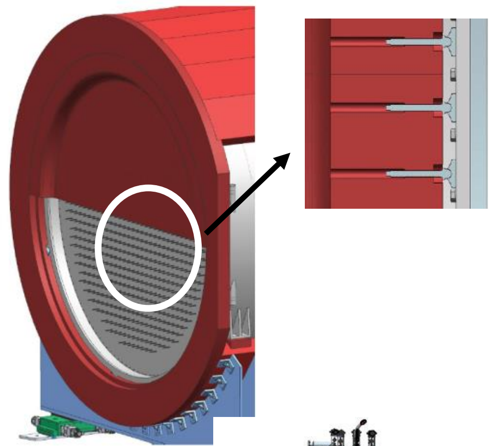
A. Bross et al

ND-GAr building blocks (magnet + vessel)

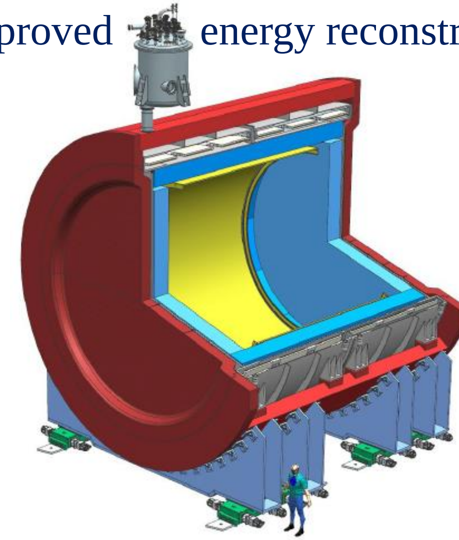
I. Partial yoke ('entrance window for ND-LAr muons')



II. Stayed heads (enables flat end-caps)



III. Calorimeter inside P-vessel! (improved energy reconstruction)

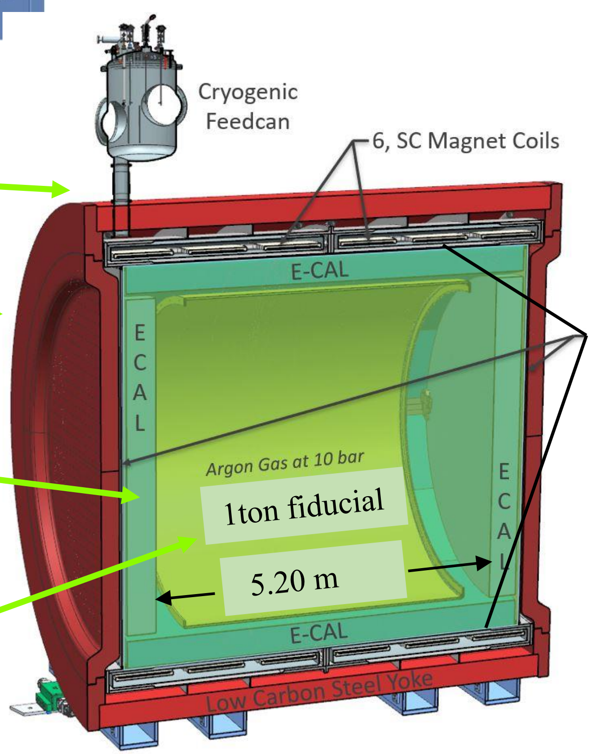


yoke (+ muon tagger)

yoke

calorimeter

Time Projection Chamber

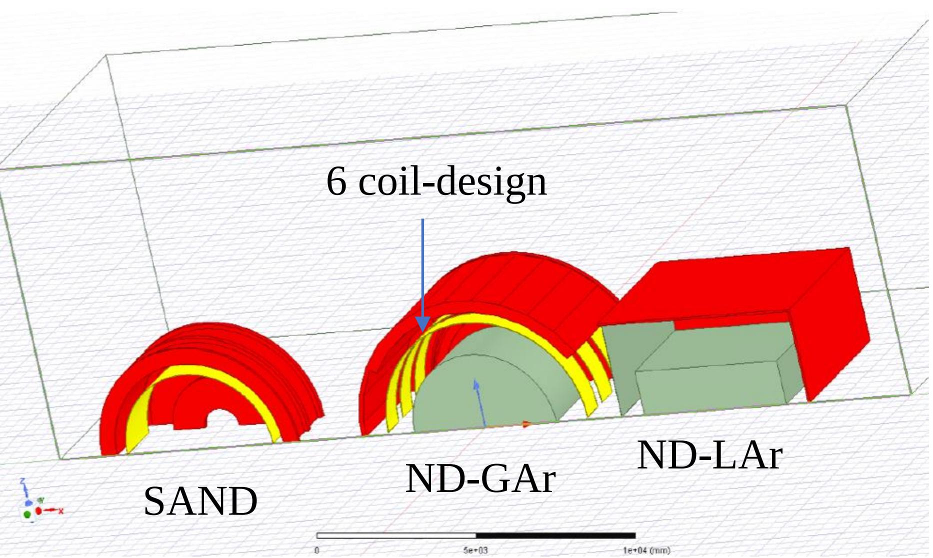


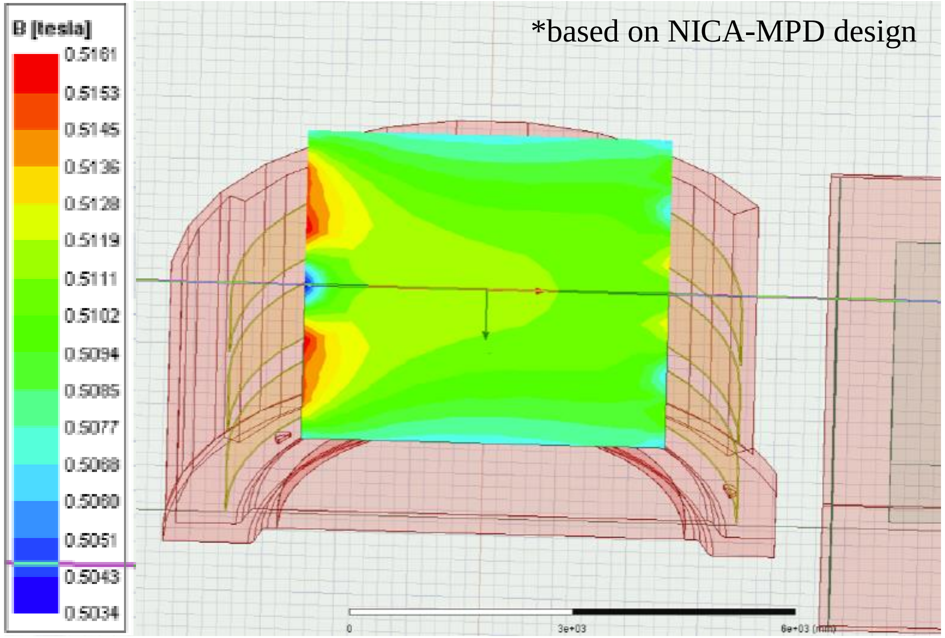
pressure vessel

A. Bersani

ND-GAr building blocks (magnet)

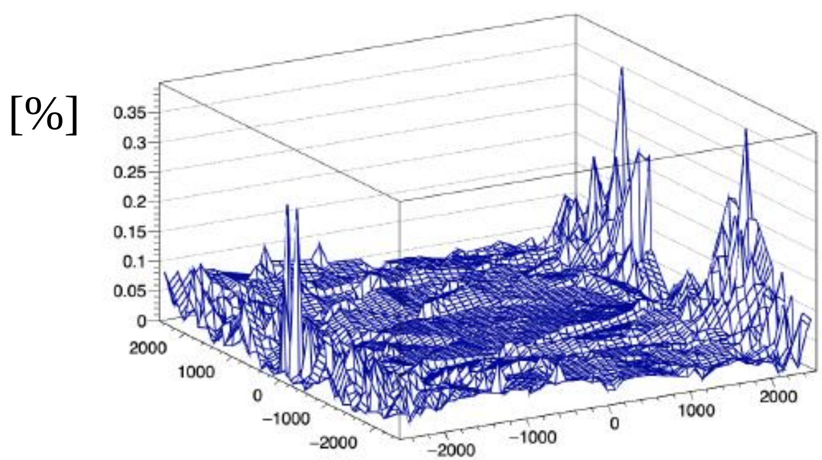
magnetic model





- Operating current: 4665 A
- Minimum field on TPC: 0.5034 T
- Maximum field on TPC: 0.5161 T
- Stored energy: 33.6 MJ
- Inductance: 3.1 H
- Force on SAND yoke: 6 kN
- Force on coils: 160 kN (to SAND)
- Force on ND-LAr structure: 60 kN
- Residual field in SAND: < 0.0005 T

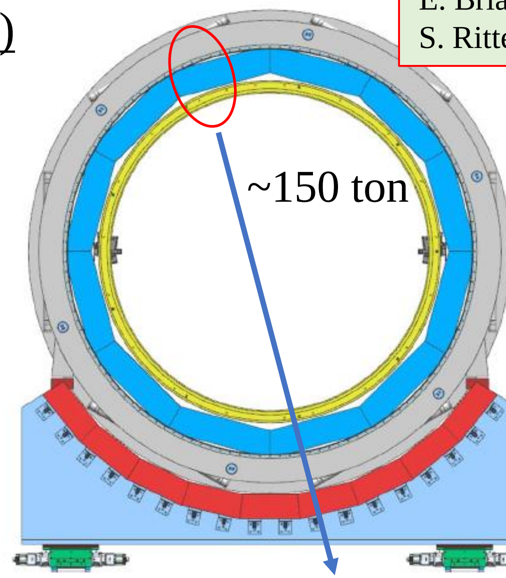
B deviation in the TPC with SAND on



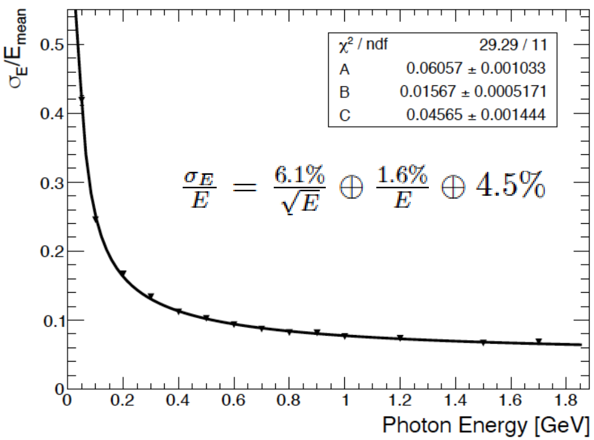
ND-GAr building blocks (calorimeter)

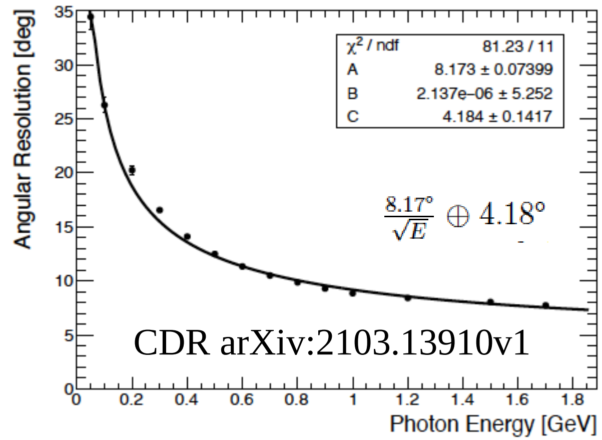
E. Brianne
S. Ritter

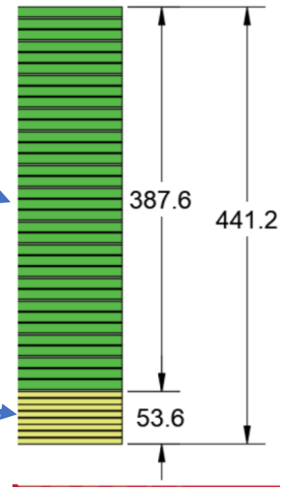
- 12-side design (5modules per side, along TPC drift axis)
- 8 pad-based layers of lead/scintillator (0.7/5 mm) +
  34 strip-based layers of lead/scintillator (1.4/10 mm)
- Space resolution ~2.5 cm x 2.5 cm // time resolution ~1 ns



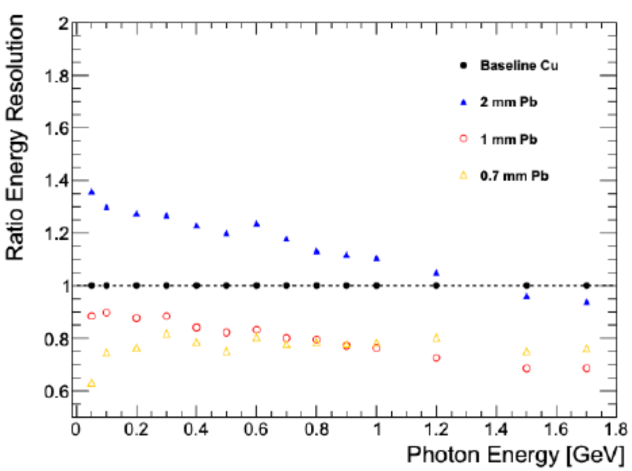
old design (relying on Cu-absorbers)

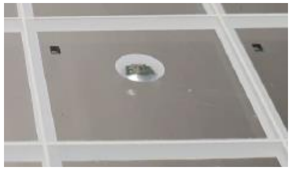


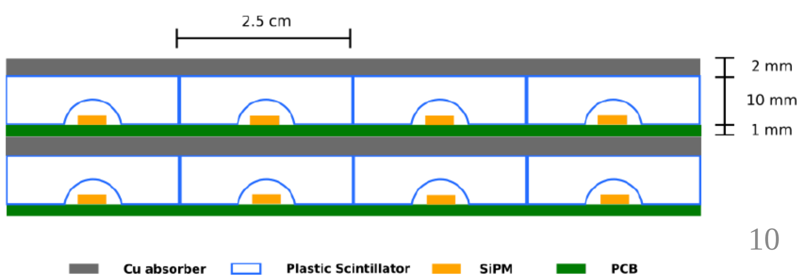




new design (relying on Pb-absorbers)

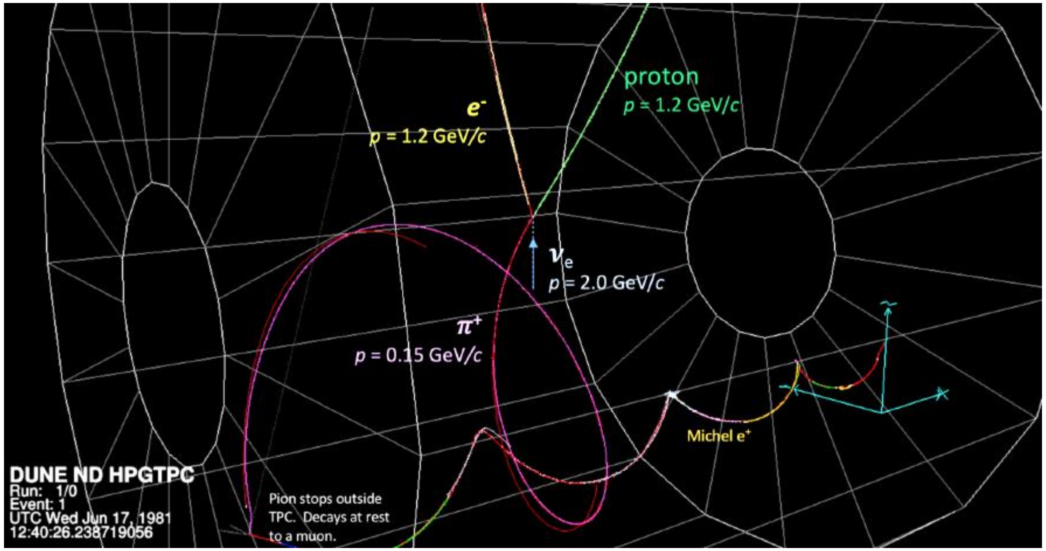






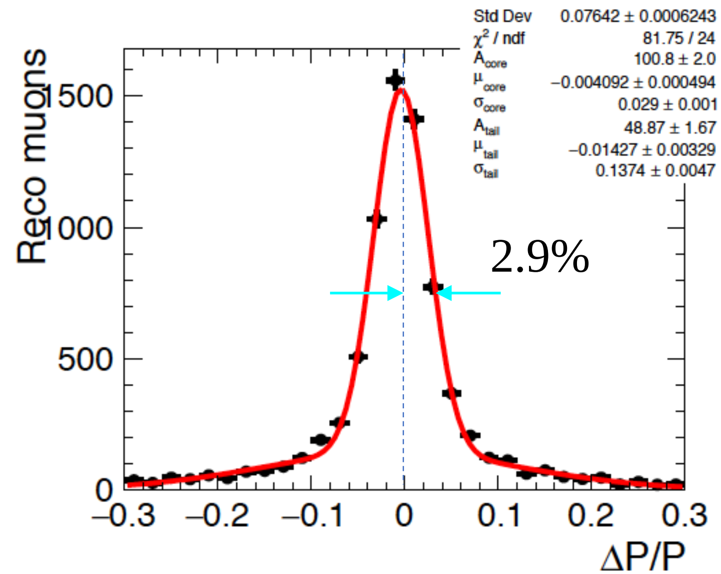
T. Junk et al

ND-GAr (main performances as a magnetic spectrometer)

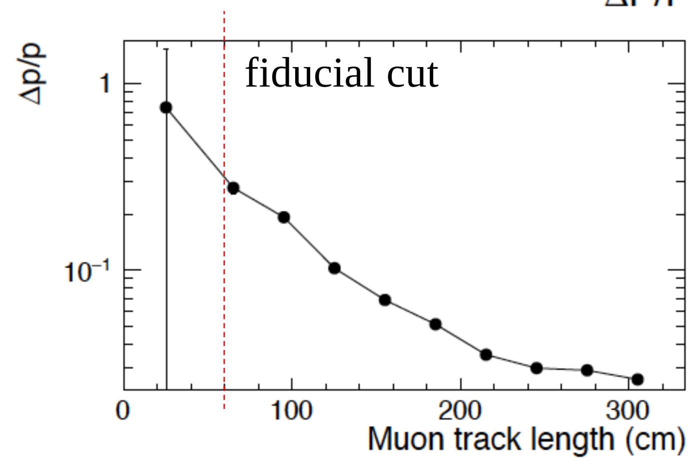


reconstruction with DUNE/Garsoft
*(https://github.com/DUNE/garsoft)

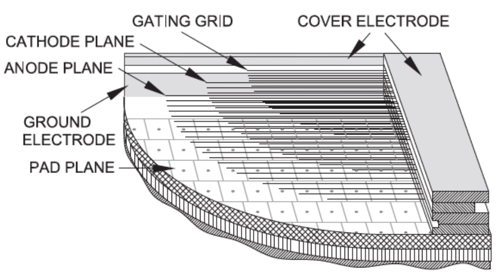
GENIE ν_μ sample over the entire chamber

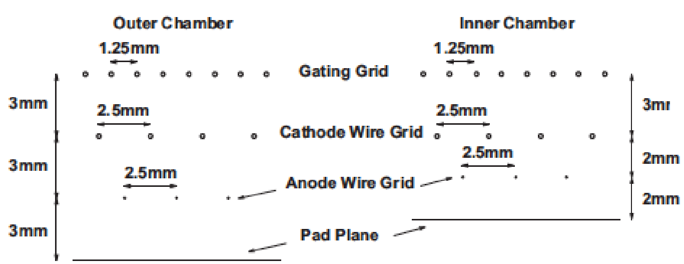


- pad size based on ALICE layout: pads up to to 6x15 mm^2 (good a priory for a ~5 MeV/4 cm tracking threshold).
- Include pad-response function and diffusion (Ar/CH_4).
- Charge induction + Charge threshold + Hit-map formation in the pad plane.
- Track reconstruction.

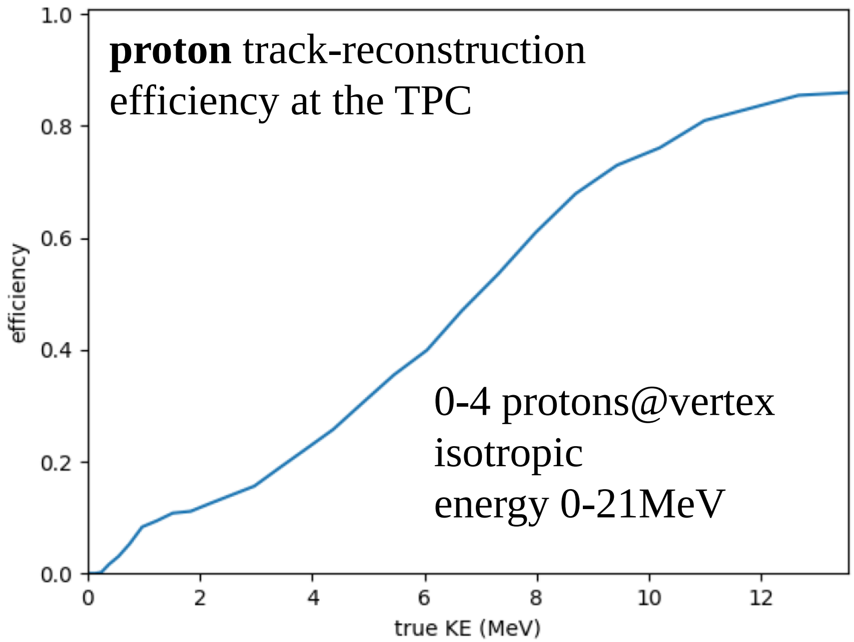


*tracking still under development

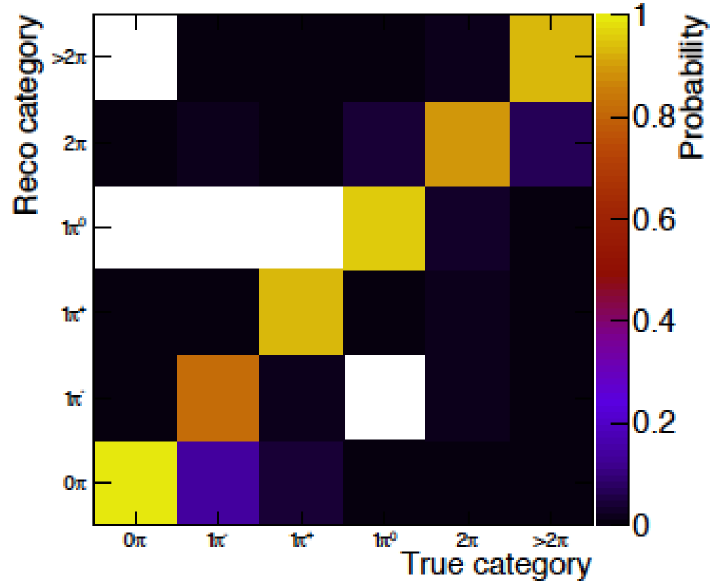


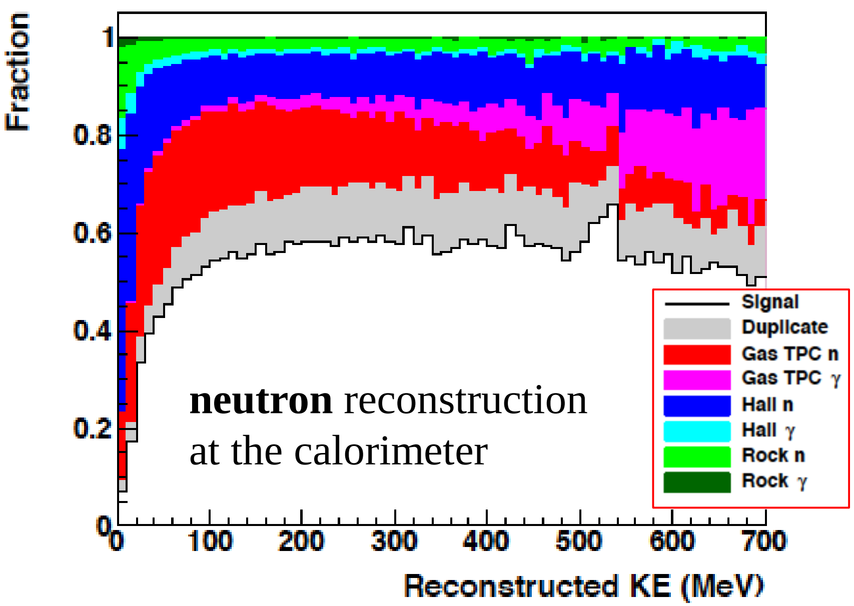


ND-GAr (main performances at reconstructing vertex activity)



pion reconstruction matrix





such a PID performance in a beam-dump configuration is attractive for BSM searches!

- "Hunting for light dark matter with DUNE PRISM" https://inspirehep.net/literature/1792307
- "Probing source and detector nonstandard interaction parameters at the DUNE near detector" https://inspirehep.net/literature/1797242
- "Tau neutrinos at DUNE: New strategies, new opportunities" https://inspirehep.net/literature/1804526
- "Heavy axion opportunities at the DUNE near detector" https://inspirehep.net/literature/1829748
- "Searching for Physics Beyond the Standard Model in an Off-Axis DUNE Near Detector" https://inspirehep.net/literature/1845342
- "Light, long-lived $B-L$ gauge and Higgs bosons at the DUNE near detector" https://inspirehep.net/literature/185888

ongoing R&D towards a **1ton** gaseous TPC for ν physics

P. Hamacher-Baumann

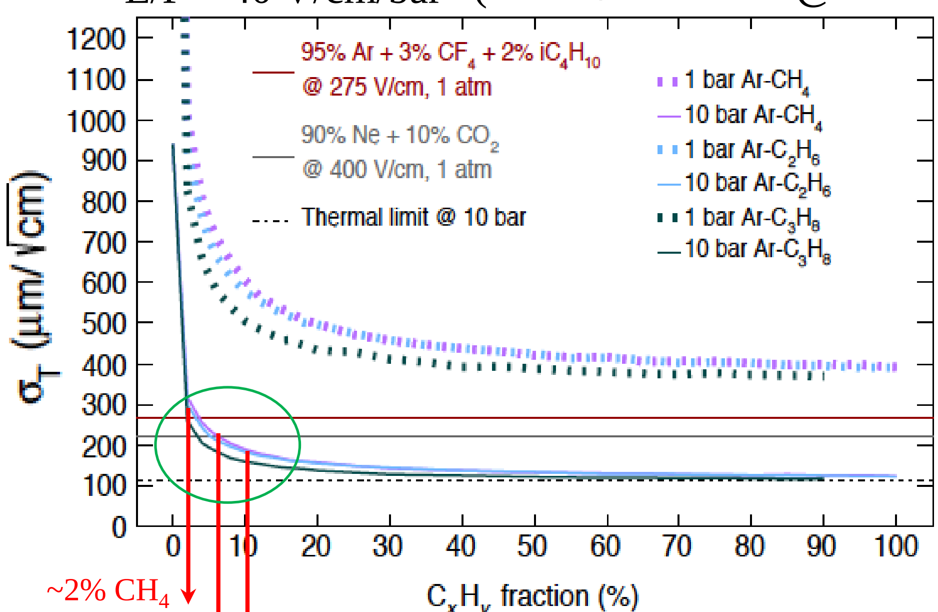
Optimization of gas mixture and operating voltage

- Use hydrocarbons as quenchers (CO_2 has lower Penning effect and dissociative attachment leading to worse energy resolution and it could enhance attachment in the drift region).
- CH_4 at 10% simple (PEP4), but explosive in air.
- CH_4 even at 2% likely to provide enough VUV quenching at 10bar.

DRIFT

DIFFUSION

E/P = 40 V/cm/bar **(200 kV over 5 m @10 bar!)**

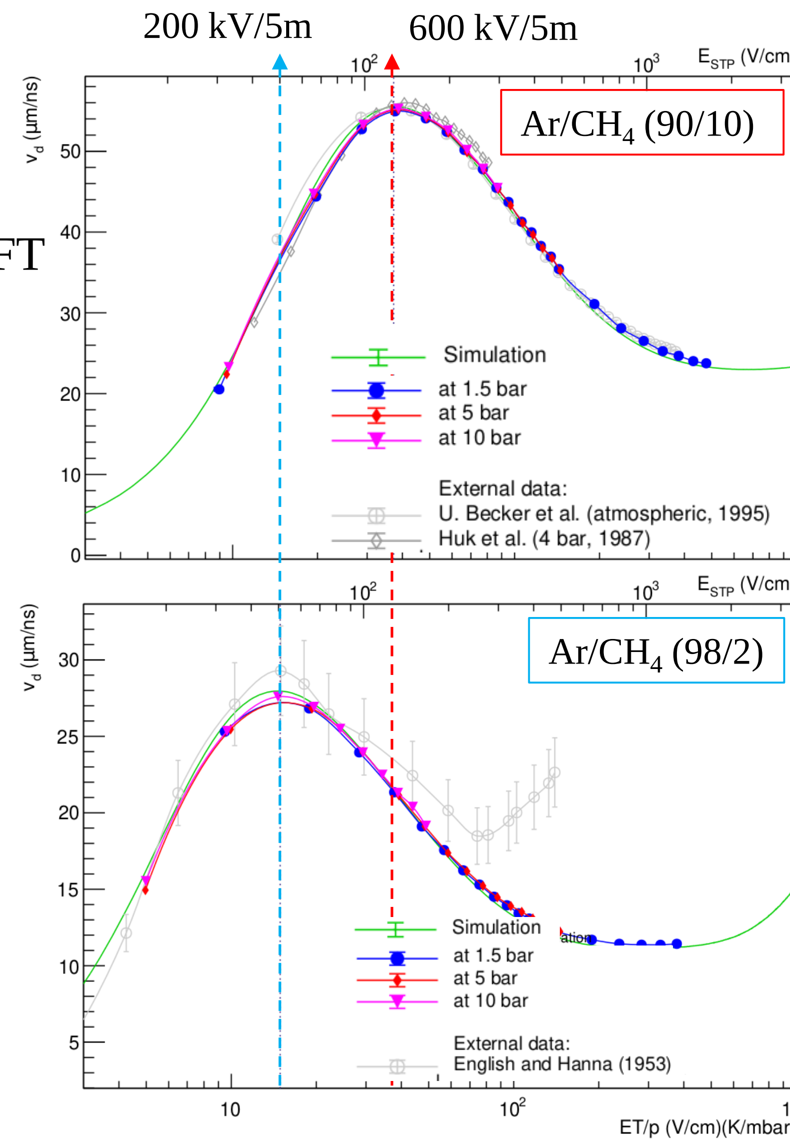


~2% CH_4

~5% CH_4

~10% CH_4 (P10)

P. Hamacher-Baumann et al., Phys. Rev. D 102, 033005 (2020)
B. Al Atoum et al., Com. Phys. Comm. 254, 107357 (2020)

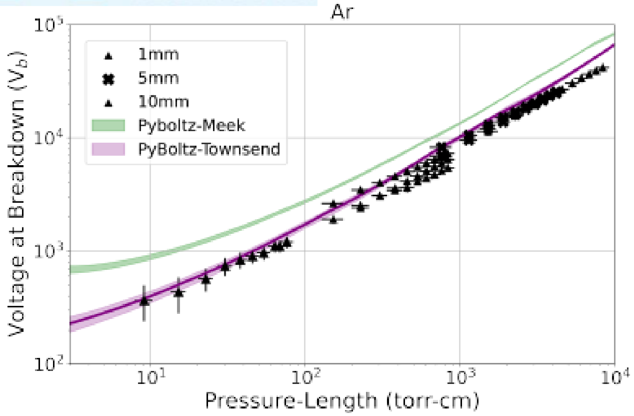


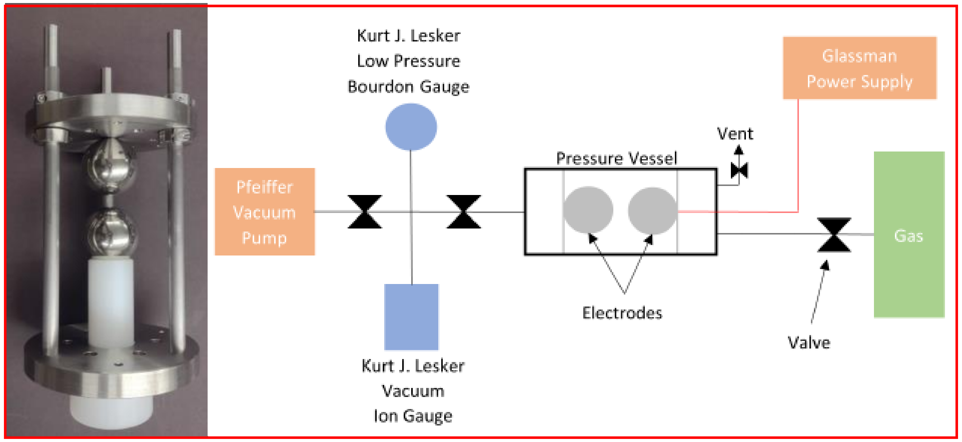
much higher immunity against T-variations!

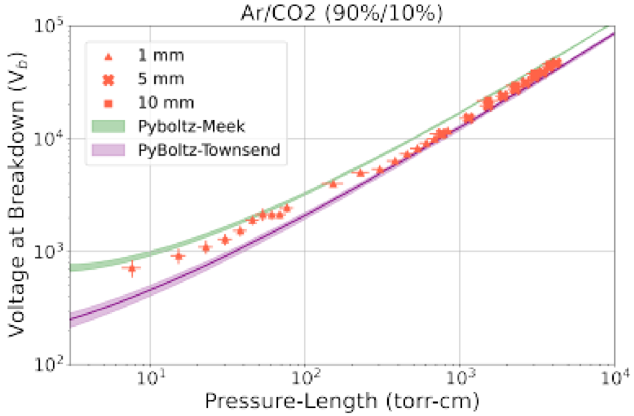
UNIVERSITY OF TEXAS ARLINGTON

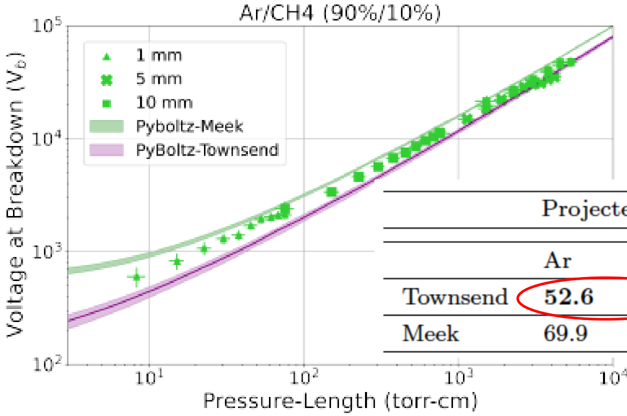
L. Norman
K. Silva
B. Jones

Gas electrical breakdown







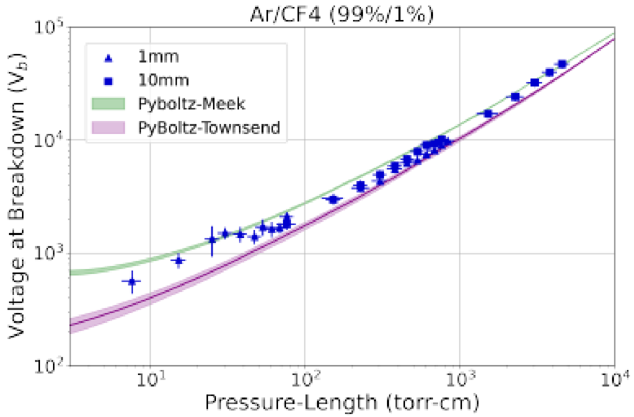


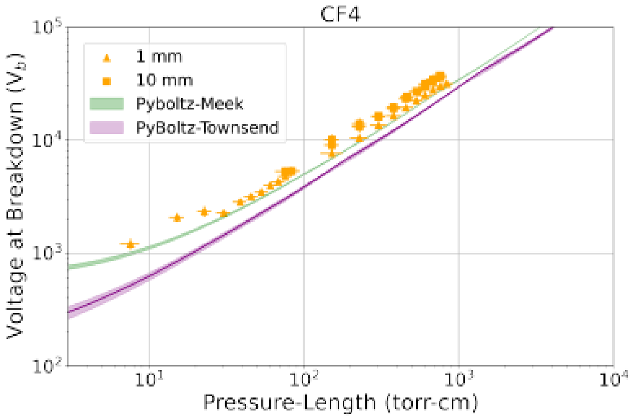
'Dielectric Strength of Noble and Quenched Gases for High Pressure Time Projection Chambers' arXiv:2107.07521v2

Projected Breakdown Voltage at 10 bar, 1 cm (kV)

	Ar	Xe	Ar-CF_4	Ar-CH_4	Ar-CO_2	CO_2	CF_4
Townsend	**52.6**	**75.4**	61.7	63.9	68.6	129.5	179.7
Meek	69.9	98.9	72.1	80.3	87.3	**171.2**	**212.2**

good prospects for insulation up to 200 kV in 10 cm gaps!

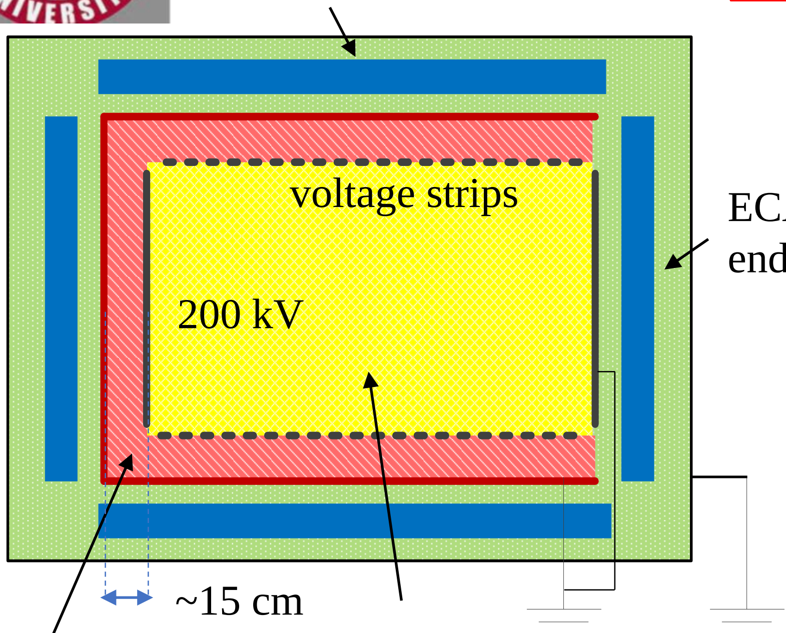


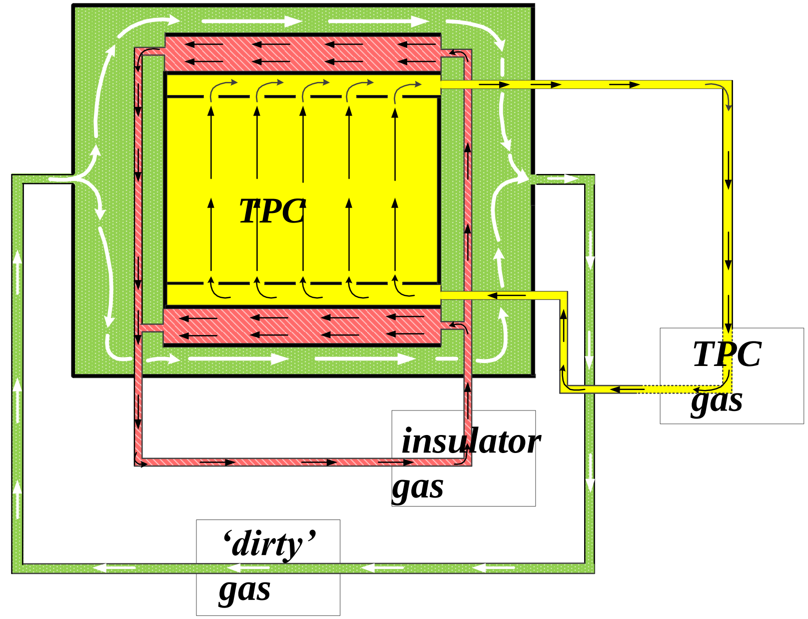


C. Hayes

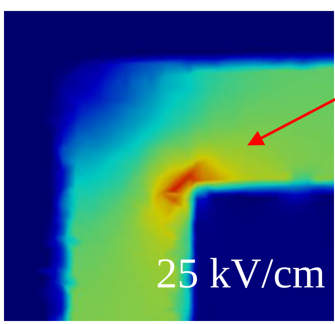
Field cage (under design)

concept borrowed from ALICE (don't rely on solid insulators!)

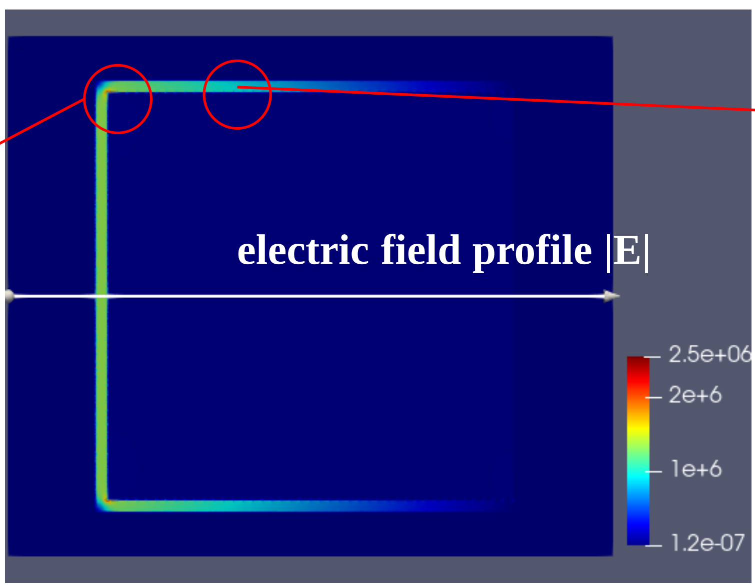


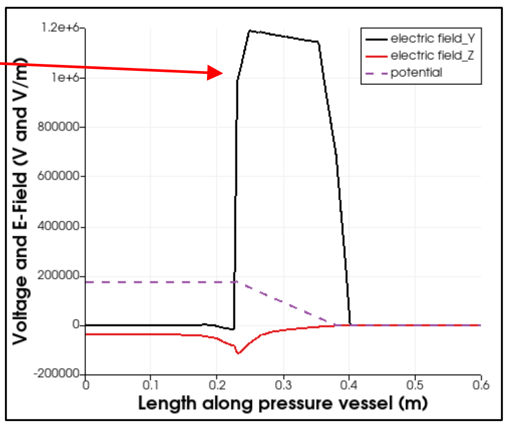


~12 kV/cm



HV-connector region (special design needed)





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D.J. Fernández Posada

Gas distribution (under design)

gas quality will be limited by outgassing (leak rates and gas poisoning small)

$$Q = Q_0 e^{-\eta z} \qquad \eta \cong C_{O2}(E/P) \cdot \frac{1}{v_d}\left(1 + \frac{f_{H2O}}{1000}\right) \cdot P^2 \cdot f_{O2}$$

Huk et al., NIM A 267(1988)107-119

$\eta z < 10\%$ for z =5 m → f_{O2} < 0.3 ppm, f_{H2O} < 100 ppm

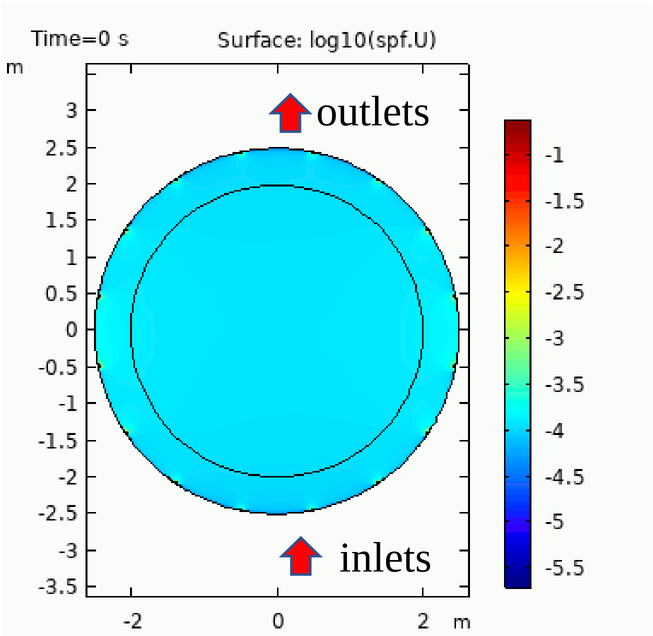
(much lower than any other gaseous TPC!)

*ALICE spec is f_{O2} < 5 ppm

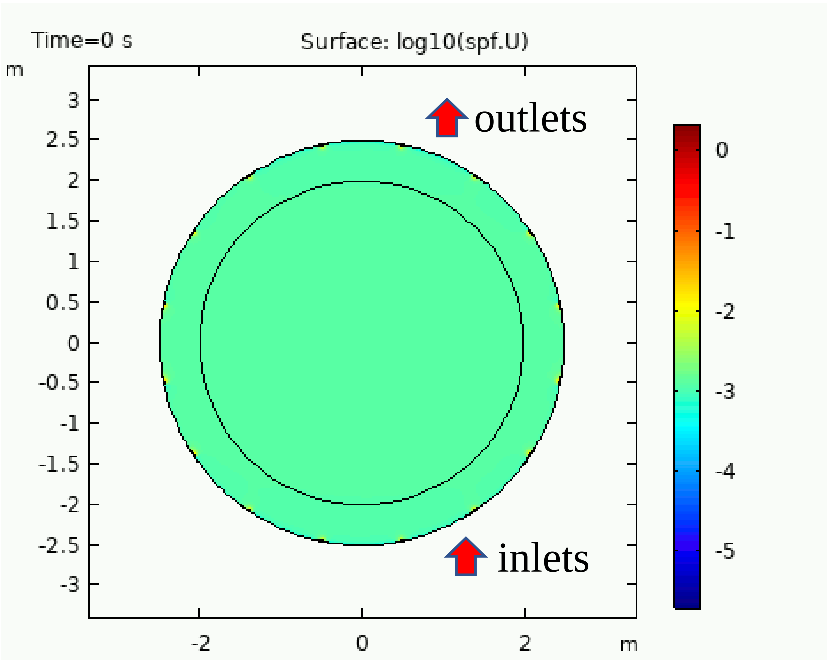
⇨ taking values from outgassing tables, this is achievable in few hours at a flow of ~50 normal m^3/h

⇨ depending on gas flow distribution of course…

(material selection/cleaning essential!)



radial holes

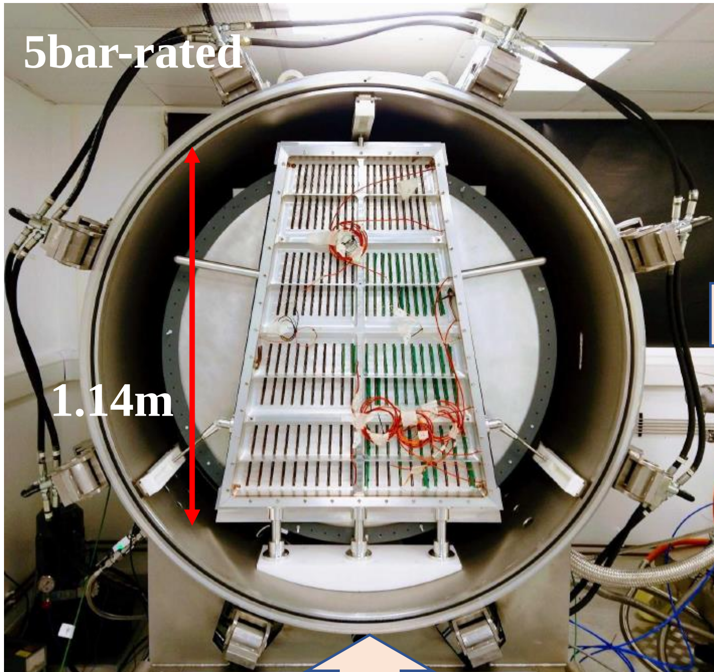


vertical holes

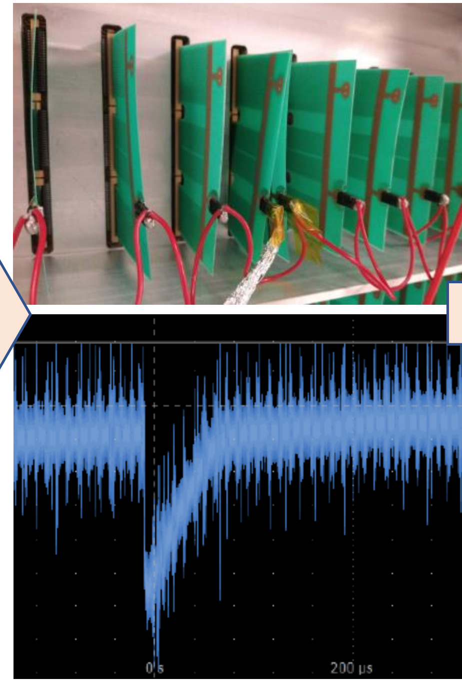
Ash Ritchie-Yates

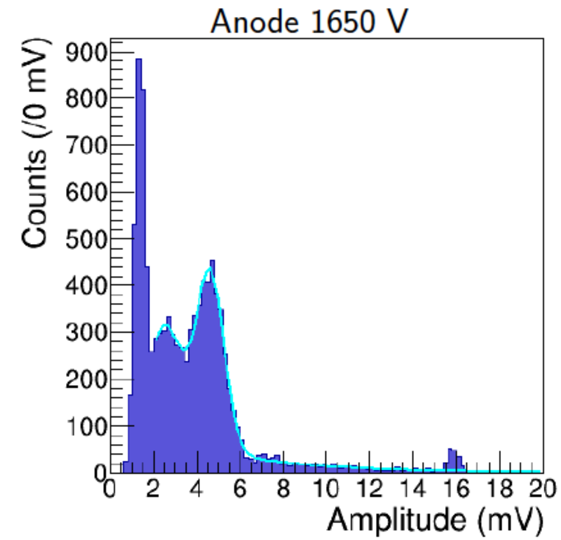
Gain measurements of multiwire-based readout at high pressure

OROC chamber under test at Royal Holloway high pressure chamber

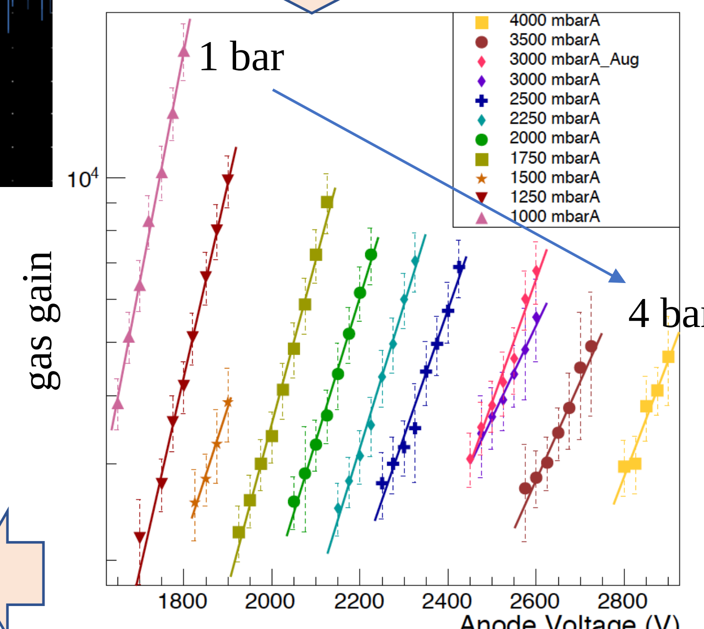


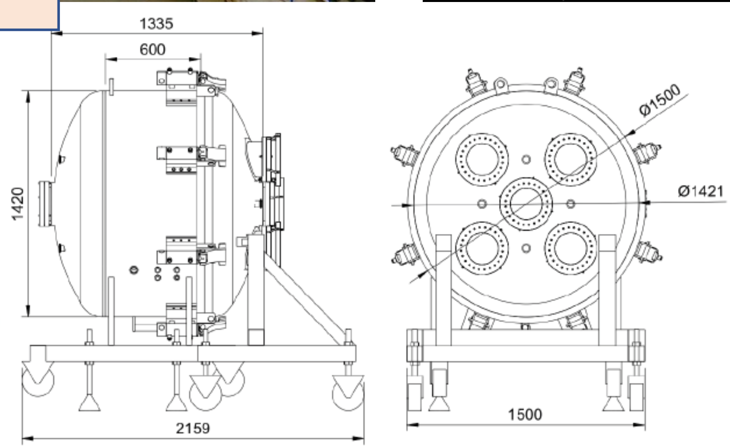
signal from 22 pads recorded with CREMAT CR-111 charge-amplifier!





Ar/CO_2 (90/10)





Queen Mary University of London

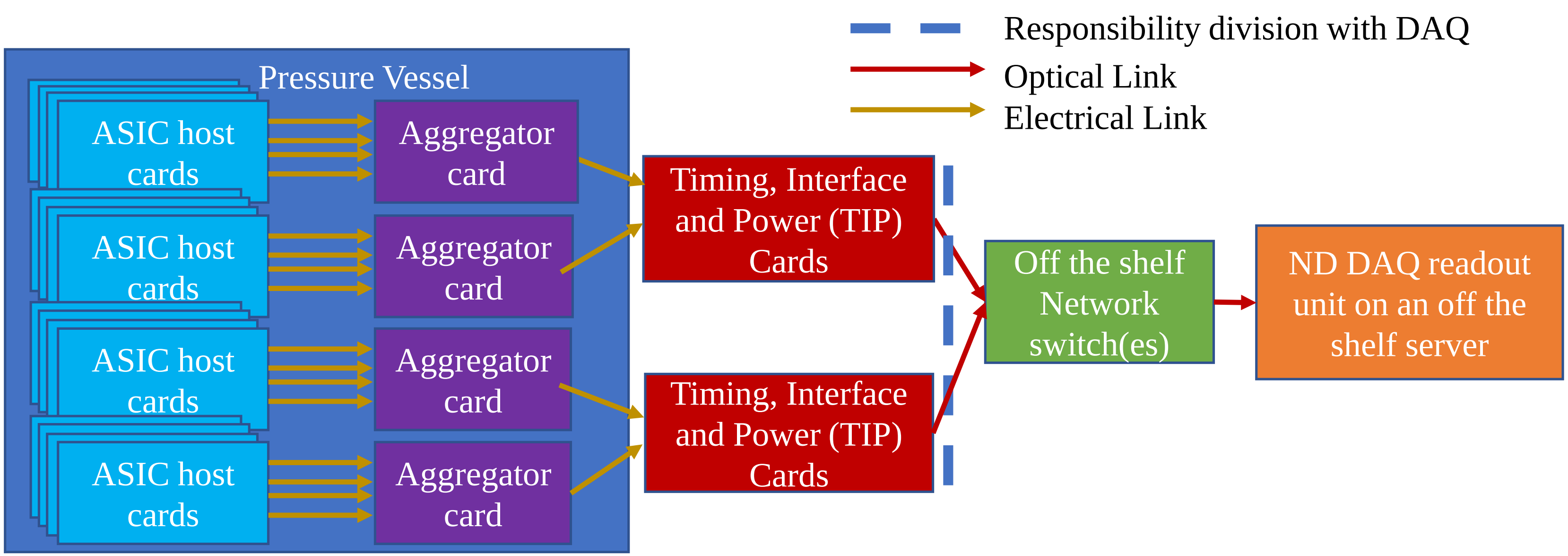
Imperial College London

Royal Holloway University of London

test at FermiLab intended for 2022!

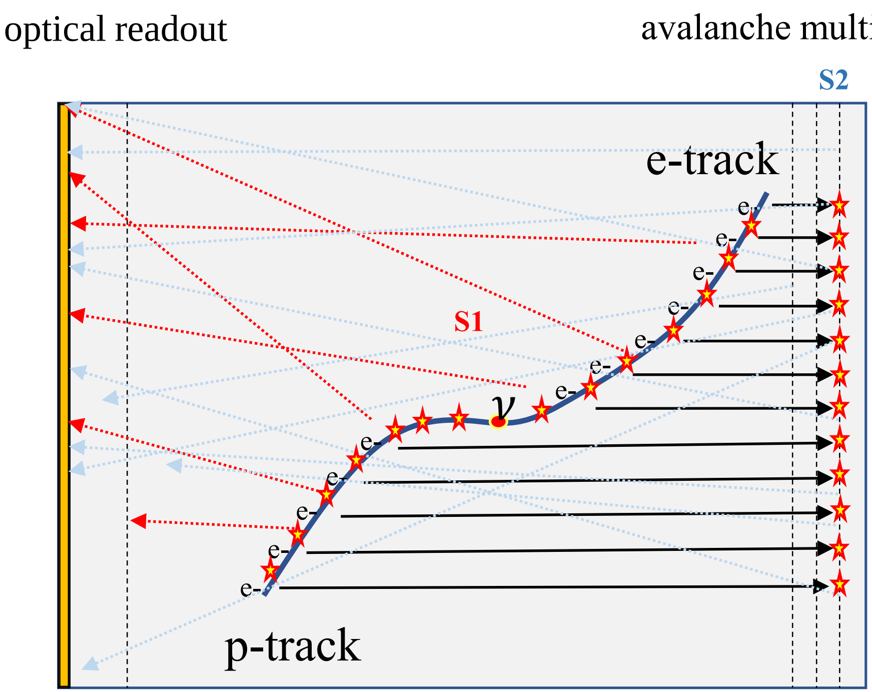
Electronics and DAQ

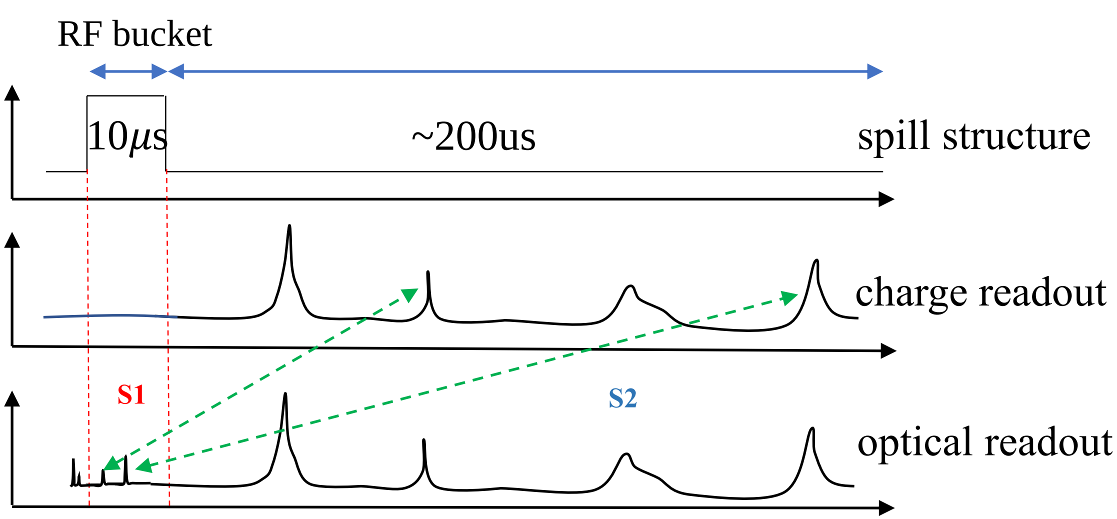
- Electronics will have ~700 k channels and must work at high pressure in ~0.5 T field.
- Imperial (Aggregators and TIPs), FNAL and Pittsburgh (ASIC hosts) are designing the system with all components currently in prototyping.
- Will interface with TCP/IP based DUNE DAQ via off the shelf networking.
- Aiming to use this system for the OROC beam test in the 2022/23 beam time at FNAL test beam facility.



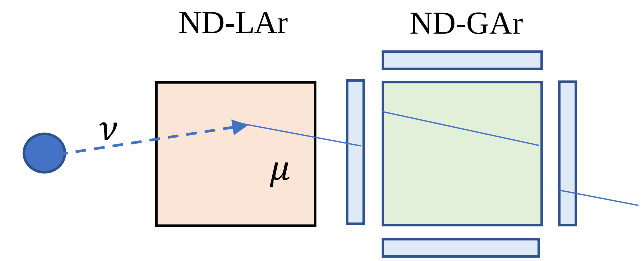
probably based on SAMPA chip

Scintillating gases (concept)

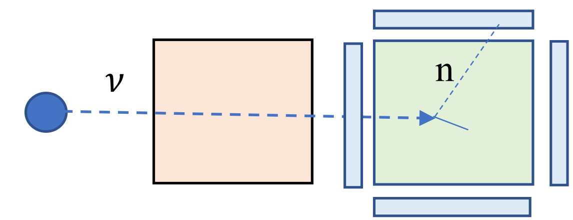




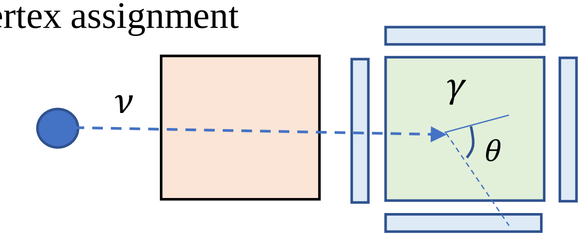
a) Improved track matching with ND-LAr



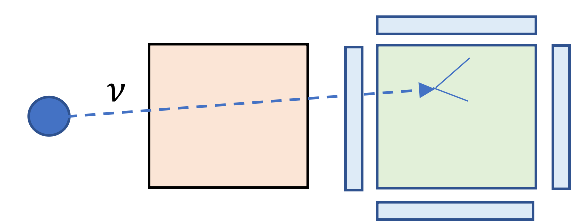
b) (NC) Neutron energy reconstruction via ToF



b') (NC) Improved n, γ angular reconstruction, vertex assignment



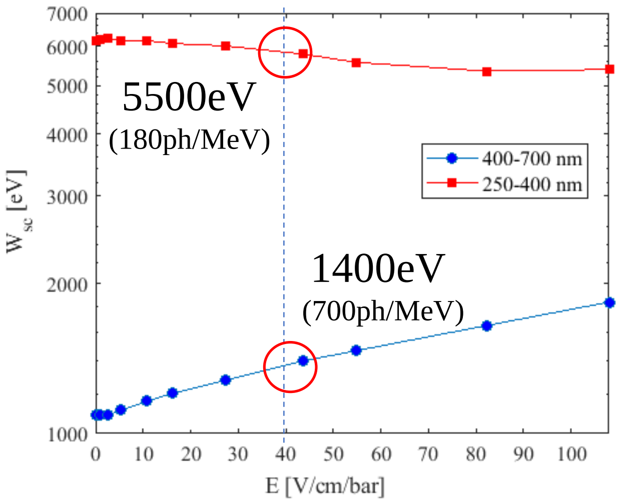
c) Low energy nuclear physics and BSM

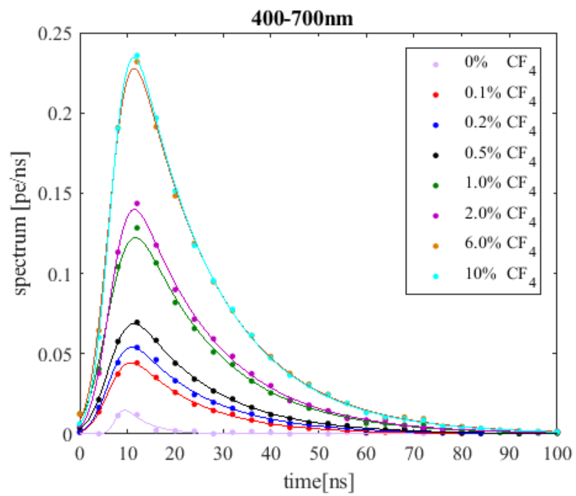


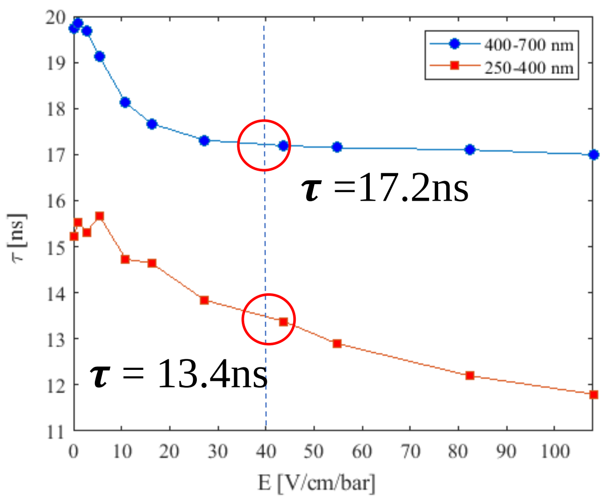
Scintillating gases (proof of principle)

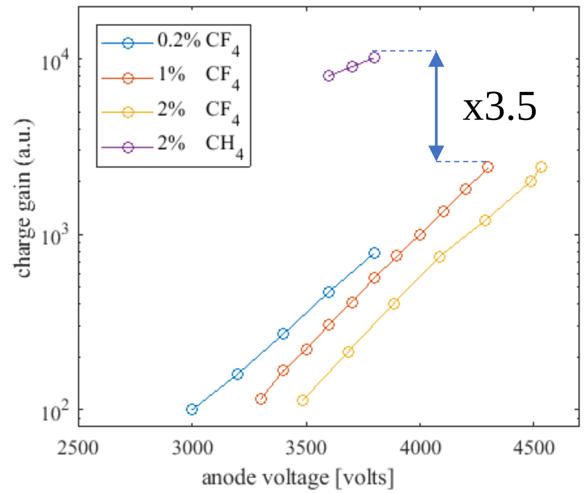
P. Amedo
S. Leardini

Ar/CF_4 (99/1%) @ 10bar









~3.5% of the scintillation in pure Ar

~x3.5 reduced gain compared to Ar/CH_4 (98/2)

other properties of Ar-CF_4 at 1%

- $\boldsymbol{\sigma}_T$ = 1.6 mm in 1 m
  (*better than Ar/CH_4 mixtures*)
- V_d~3.5 cm/us @ 40 V/cm/bar
  (*similar to Ar/CH_4 mixtures*)
- 2.2% fraction by mass
  (*less than Ar/CH_4 at 90/10*)

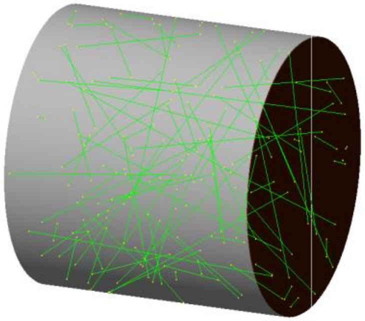
seems to fit the bill…

what else?

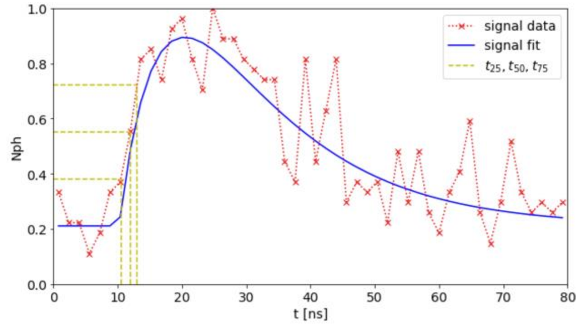
A. Saa

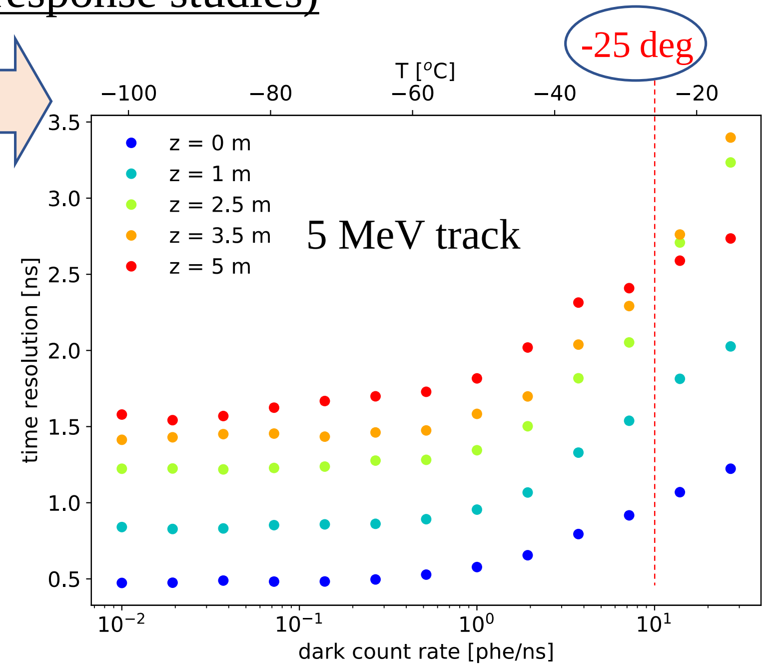
Scintillating gases (optical response studies)

Geant4 simulations

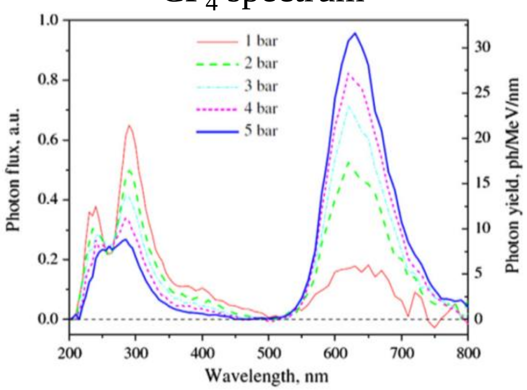


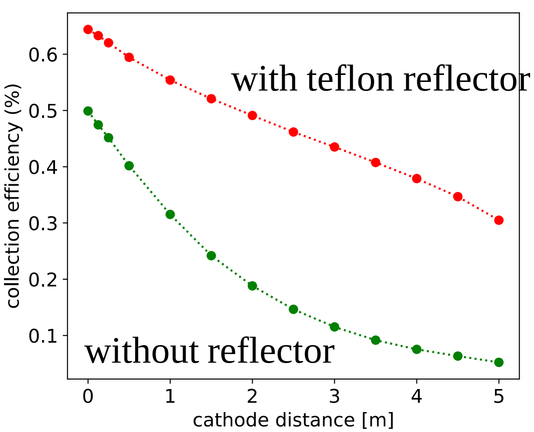
pulse reconstruction at the tracking threshold (5 MeV)

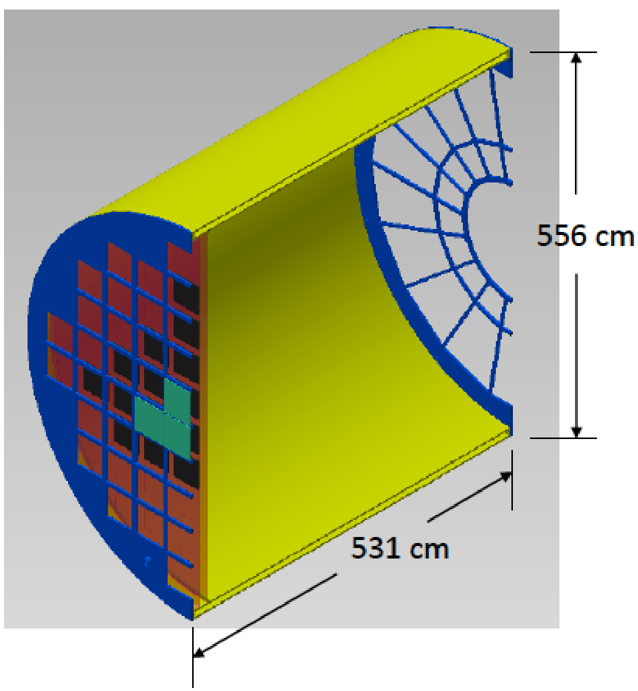




CF_4 spectrum





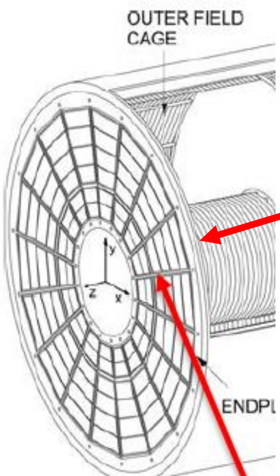


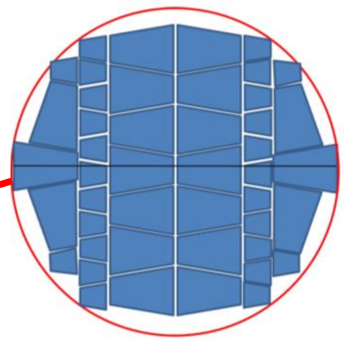
20 m^2	covered area
125-150	modules in cathode plane
256	tiles per module
16	SiPMs (6mm x 6mm) per tile (ganged)
32000	readout channels
-25 deg	operating temperature

mini-module demonstrator currently under construction at IGFAE!

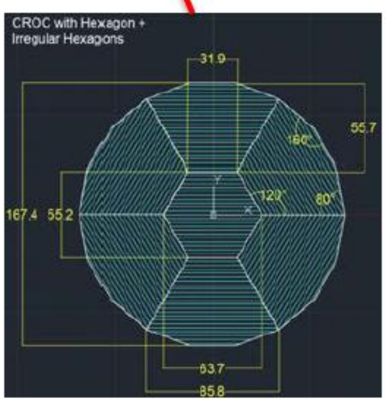
Another important R&D line: optimization of the readout plane (just starting)

I. If readout is based on ALICE chambers…



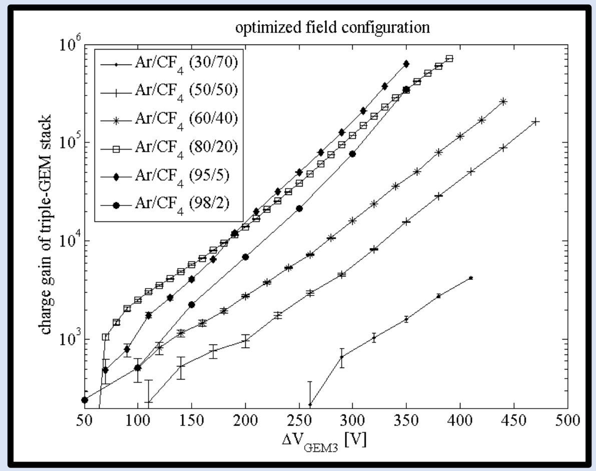


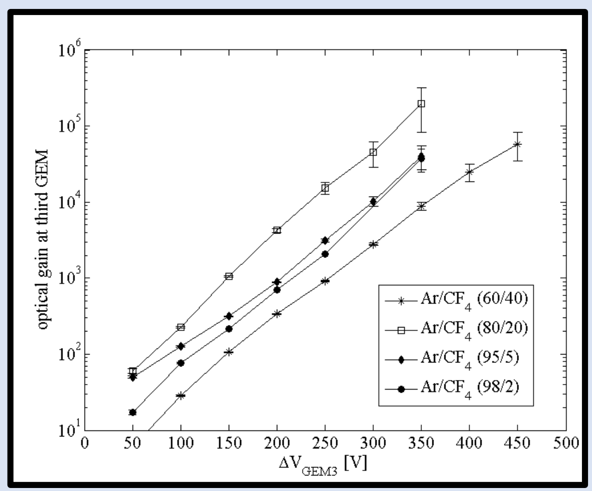
new arrangement?



new chambers for central hole?

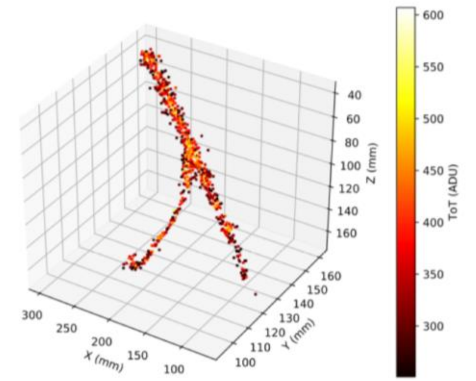
II. Is it possible to guarantee good avalanche gain and shadow secondary scintillation from the photosensor plane?

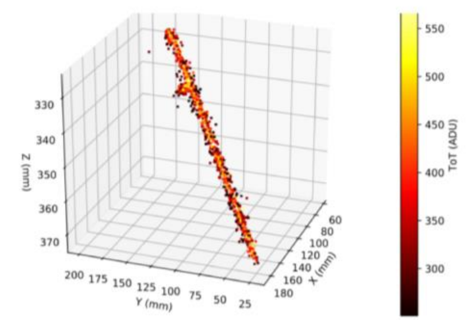




C. Bault et al. ‘GEM-based readouts and mixtures for optical TPCs’ (Vienna 2016)

III. Other ionization readouts that could improve on point-resolution and gain at high pressure down to the target goals?





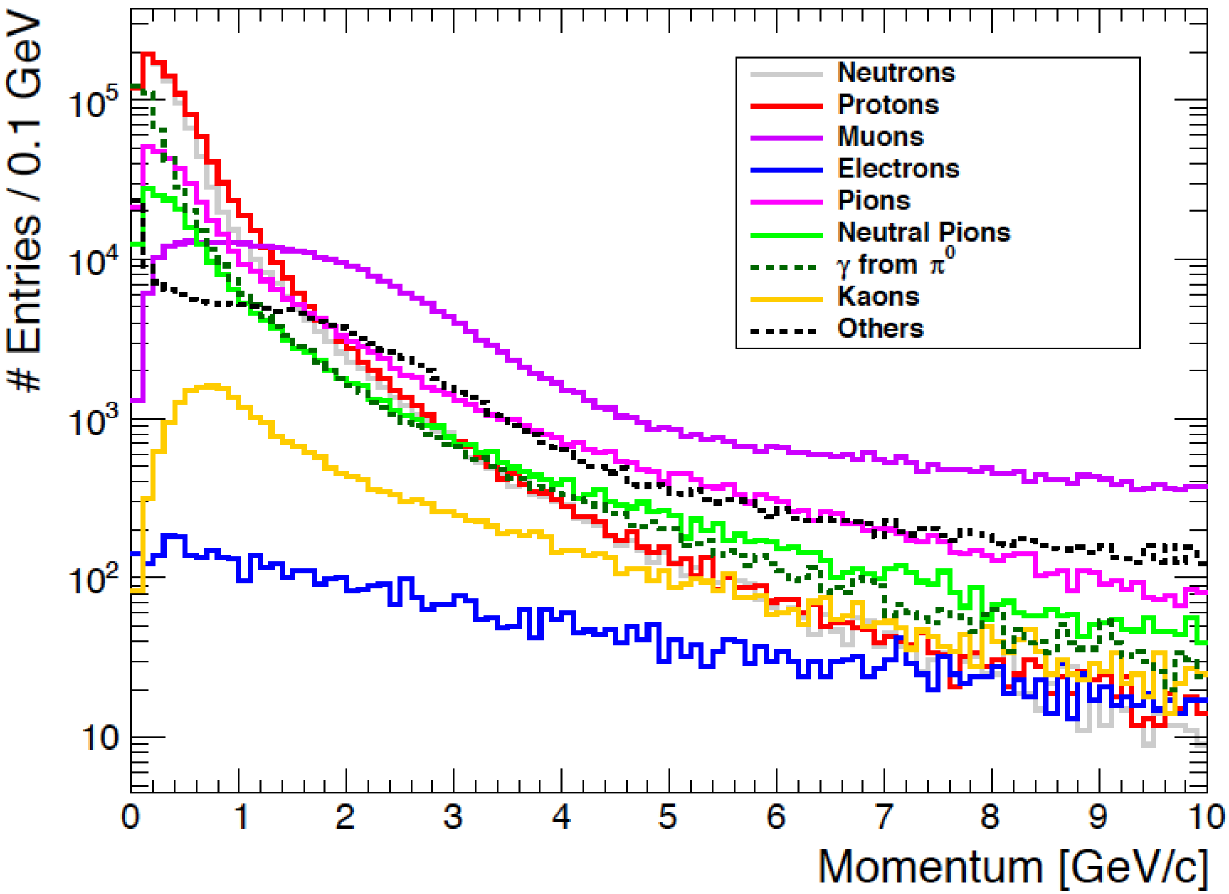
K. Mavrokoridis*, et al ‘ARIADNE: A novel photographic 1-ton dual-phase LAr-TPC’

Conclusions

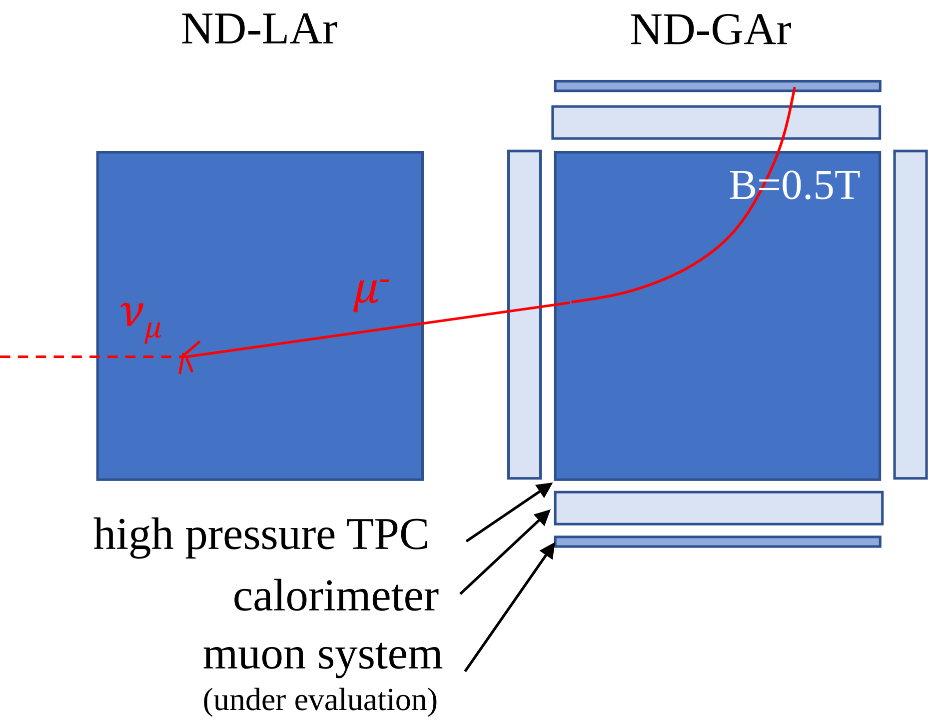
- A solid concept for a 1ton gaseous argon TPC for precision neutrino physics has been put forward over the last years.
- Simulations confirm the possibility of reconstruction and identification of γ, π_0, $\pi^{+/-}$, n, p, e, μ down to about 5 MeV in 4π.
- Good avalanche gain achieved at 4 bar for MWPC (on the way to 10 bar!).
- Ground-breaking results demonstrate a tracking threshold of 5 MeV and time resolution of 1 ns ***in the primary scintillation signal*** with ***just*** 1% CF_4 addition to argon. Instrumenting most of the cathode plane with SiPMs and operation at -25 deg needed!.
- Important R&D areas will need to be covered over the next years: field-cage design, HV feedthroughs, gas distribution, gas mixture optimization, optimization of the optical and charge readout.

appendix

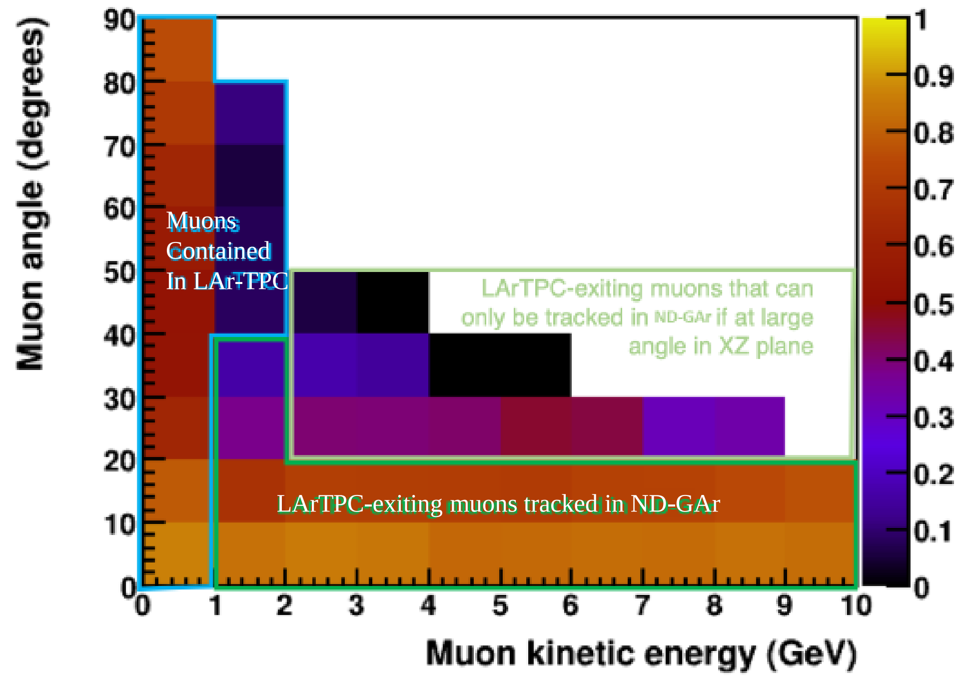
particle distribution at ND-GAr HPTPC

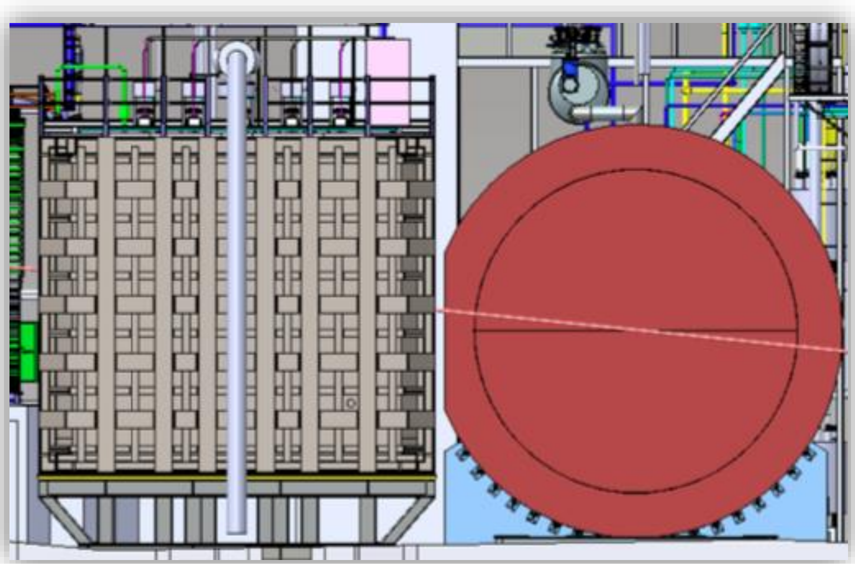


ND-GAr as a forward spectrometer



ND-LAr acceptance (ϑ, E_k)





- cover forward ND-LAr acceptance
- do charge determination to assess wrong-sign ν-beam contamination

L. Emberger

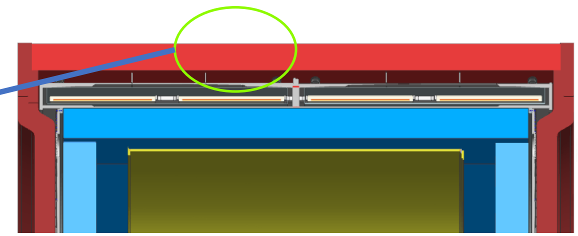
MAX-PLANCK-INSTITUT FÜR PHYSIK

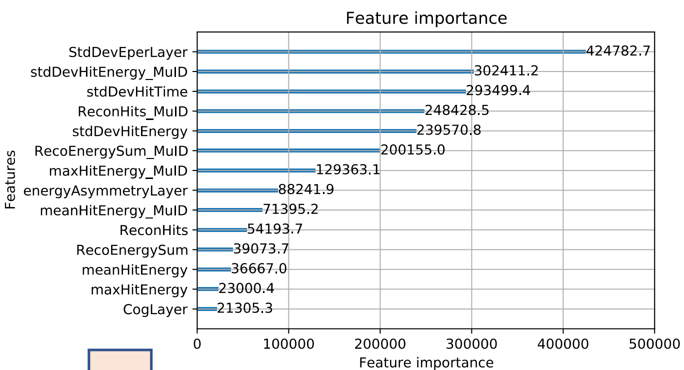
ND-GAr building blocks (muon system)

active medium (could be RPCs or scintillator)

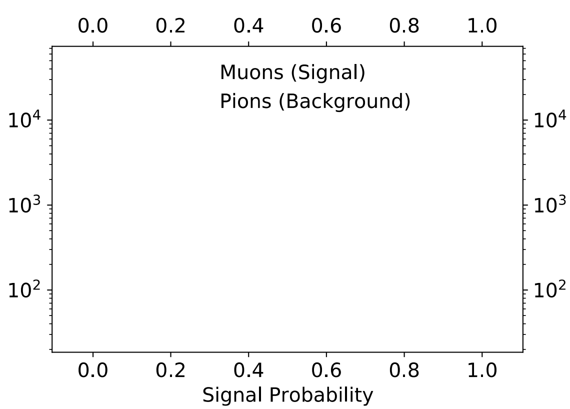
1.67cm

5cm

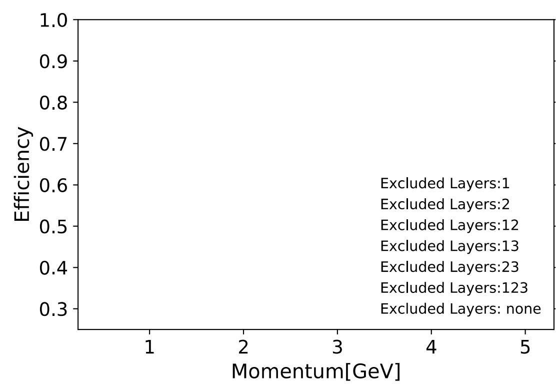




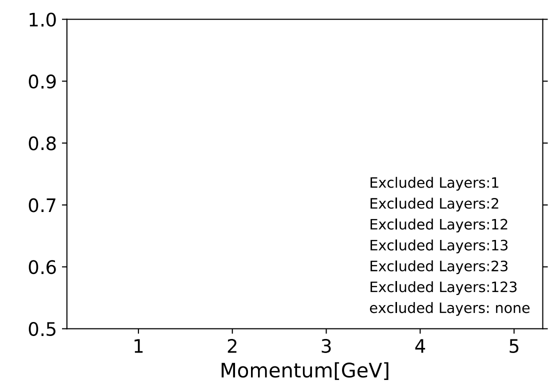
BDT classifier

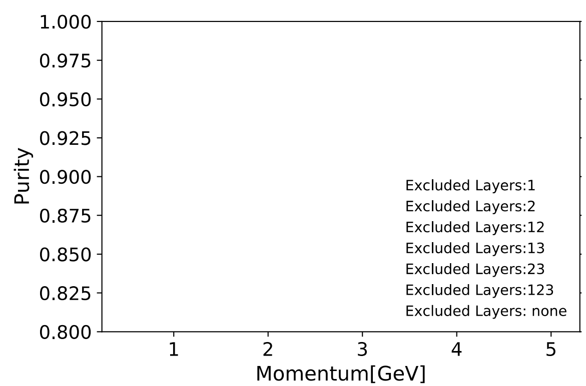


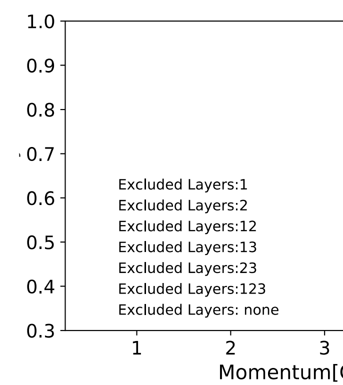
muon identification



pion identification

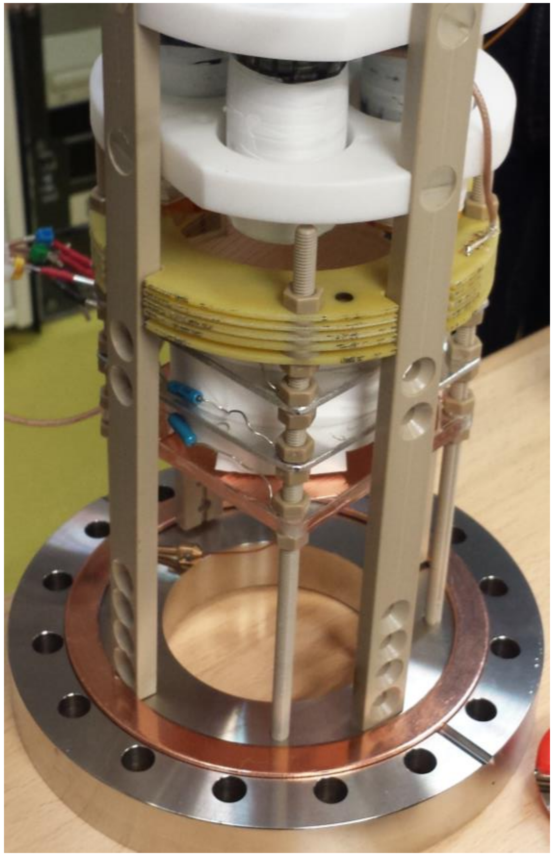


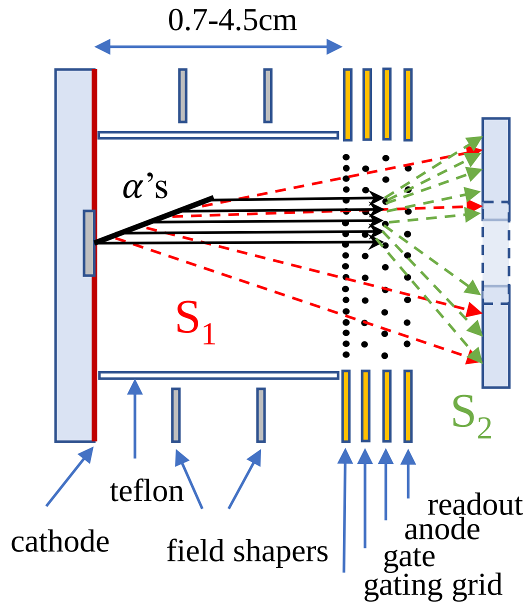




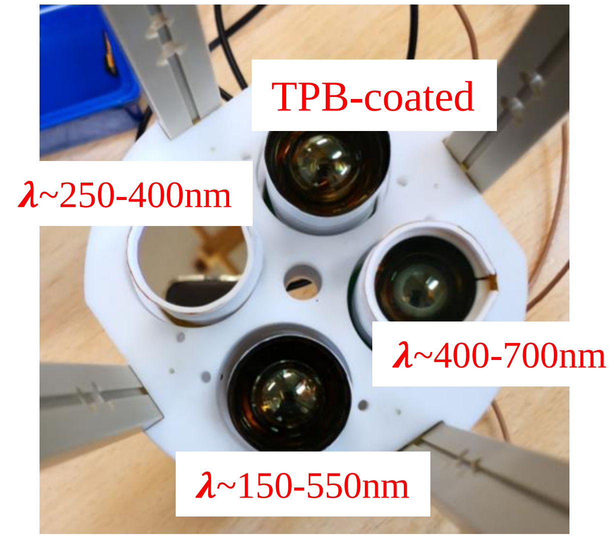
Experimental setup and recent measurements

field cage and PMTs

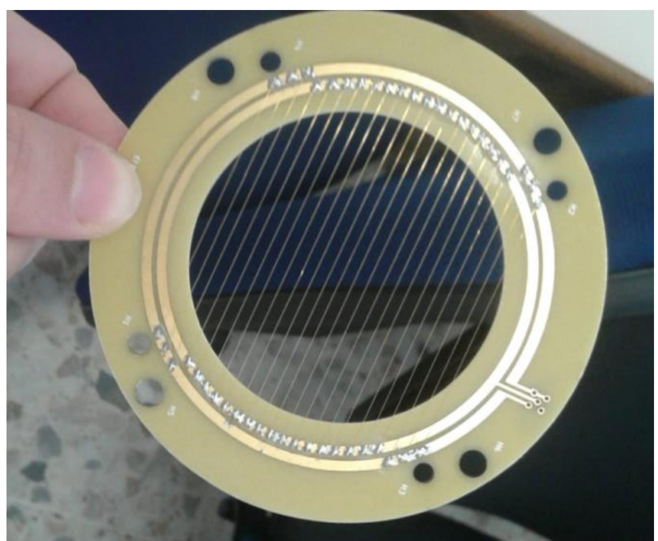




PMT plane



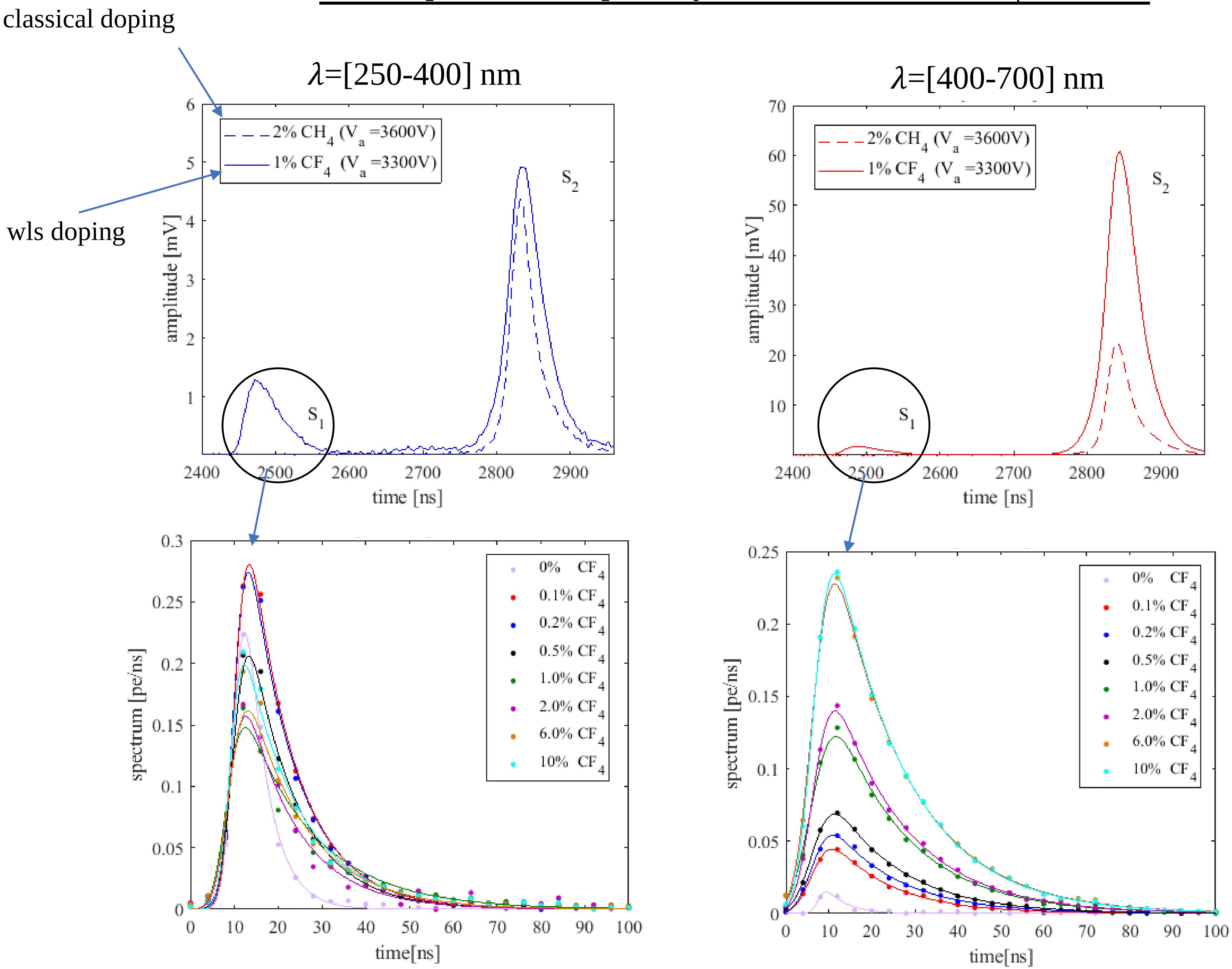
Mini-MWPCs



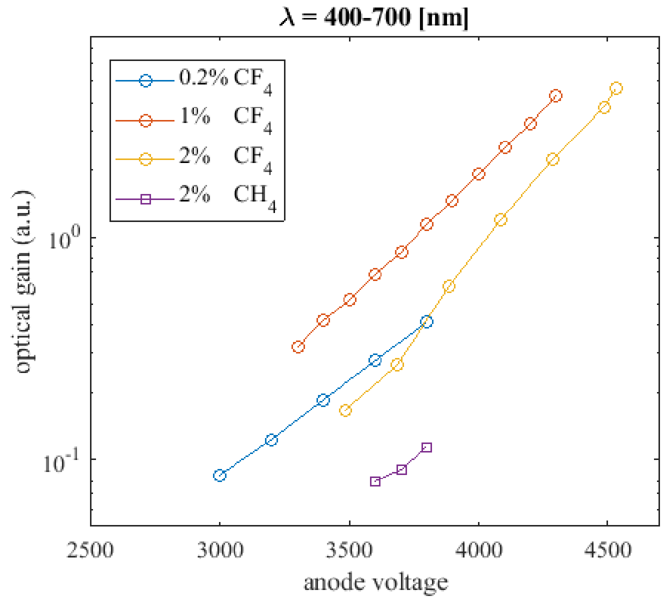
- Commissioned in pure Xe.
- Achieved purity compatible with <100ppms N_2, <1ppm O_2, <1ppm H_2O.
- $W_{sc} = 40 \pm 10$eV.
- τ_3 (triplet) up to 98ns.

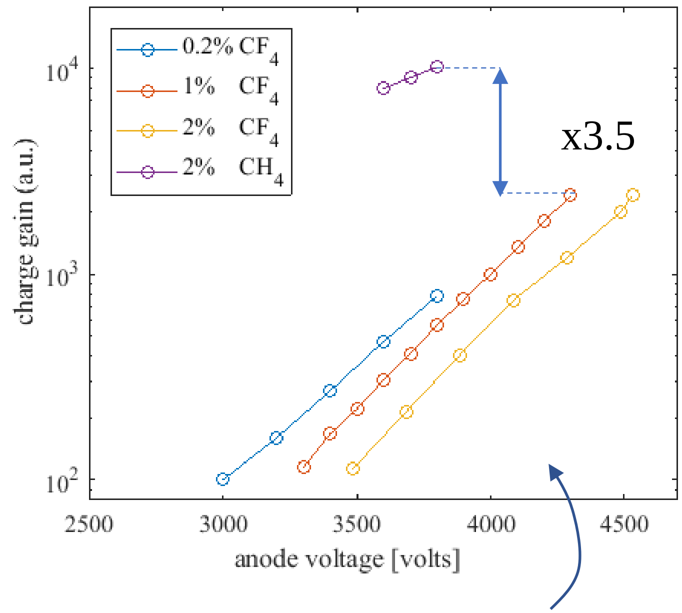
https://arxiv.org/pdf/1907.03292.pdf

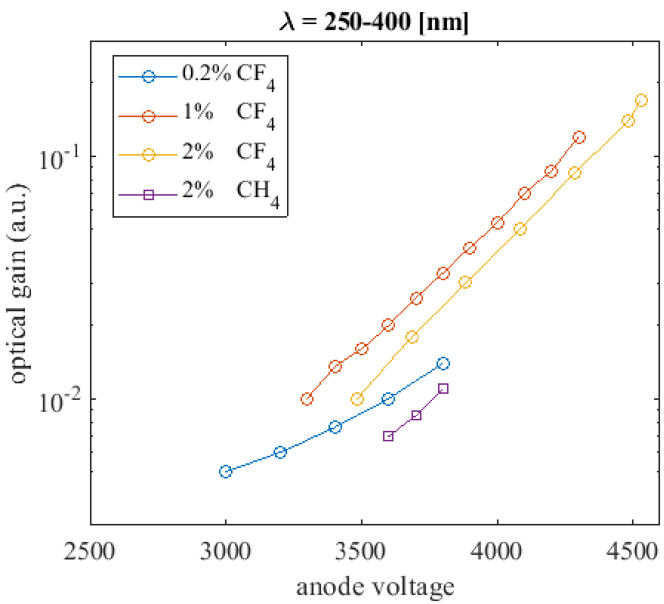
Time dependence of primary scintillation in Ar/CF_4 at 10 bar

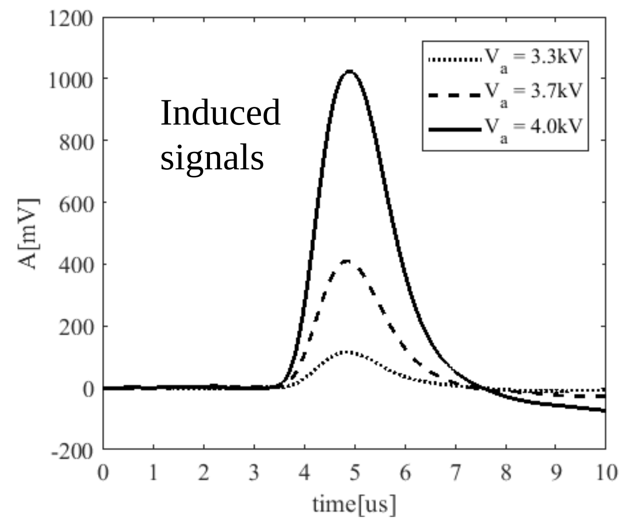


Optical and charge gain in Ar/CF_4 at 10 bar (wire chamber stability)



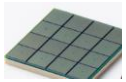




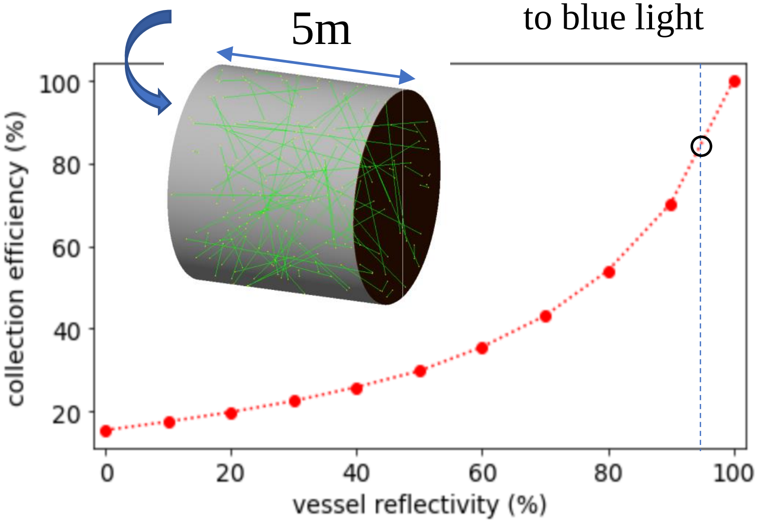


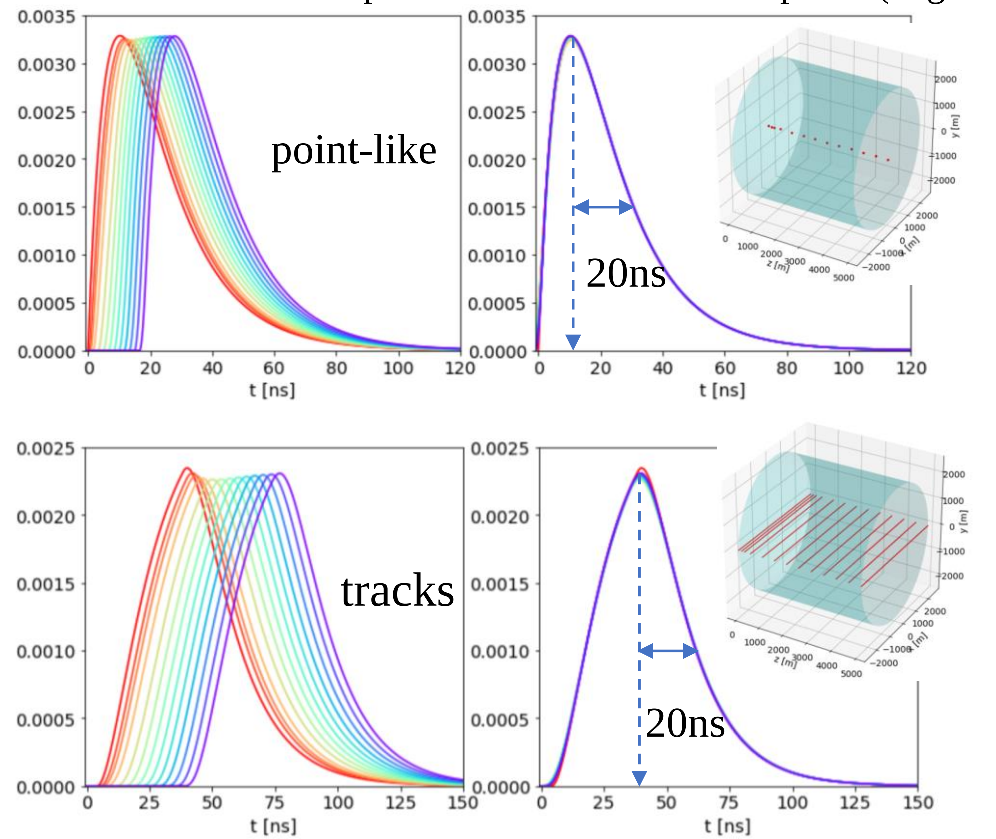
Optical response of ND-GAr from Geant4 simulations

SiPM-based readout plane



Teflon reflectivity to blue light





number of photoelectrons

geometrical efficiency>50%

N_{phe} = Y x GE x QE > 350 phe/5 MeV

scintillation yield: 1/1400eV

quantum efficiency ~20%

signal time spread around 15-20 ns

compatible with sub-ns timing!