MPGD applications to fundamental research beyond HEP

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Preamble: Constraints, Limitations, and Assumptions

During preparation

After slides has been completed

Goal

Reality

Warning: the task has a massive scope!

- ➔ Constrain: Time Boundary!
- ➔ Limitation: Personal (limited) experience is the basis for the materials here presented!
- ➔ Assumption: I most probably miss something important!

“Speculative & Ambitious” Program Outline

- General intro MPGD applied to other field than HEP
  - Example of requirements HEP vs LENP / Rare Event search / etc.
- Application to HENP/LENP
  - R&D project with MPGD for EIC
  - Active Target TPC, inverse kinematic nuclear reactions study
    - -) physics, technology, challenges, ...(Operation pure elemental gas)
    - -) Examples of Active Target TPC project
  - Fission Fragment imaging system
- Rare Event Search Applications & Neutrino Physics
  - Exotic decays with MPGD-TPC (Dark Decay, X17 boson, etc..)
  - Cryogenic detector: mostly exotic ideas
  - T2K and DUNE with MPGDs

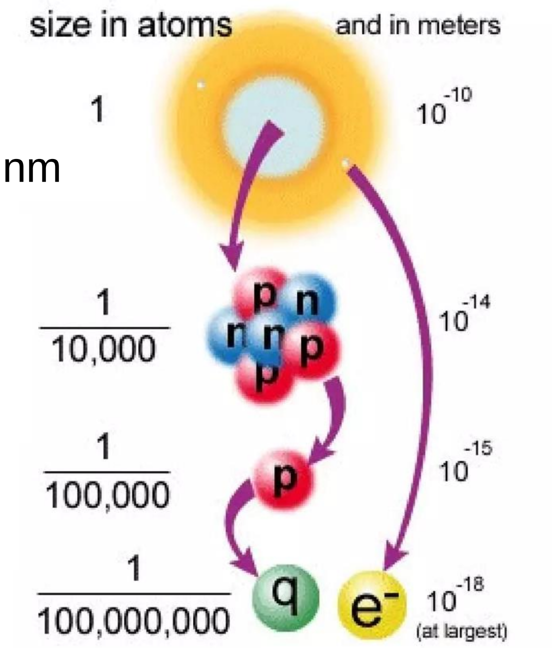
Studying smaller and smaller things…

21 century nuclear science ➔ probe the nuclear matter in all its forms and explore their potential for applications

Build powerful microscope using particle accelerators

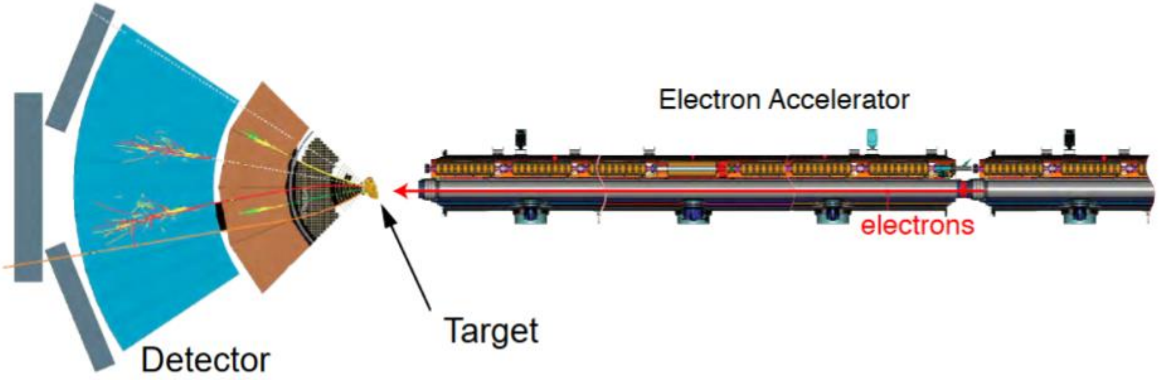
$$\text{Resolution} \sim \lambda = \frac{h}{2\pi}\frac{1}{p}$$

Optical microscope ➔ $\lambda_{photons}$ ~ 380-740 nm
Resolution > 200 nm



Electron microscope ➔ $\lambda_{electron}$ = 2.5 pm (200 keV)
Resolution > 0.1 nm (limited by objective lens system)

Fixed Target Particle
Accelerator experiment ➔ $\lambda_{electron}$ ≈ 0.062 fm (20 GeV)
Resolution ≈ 0.1 fm

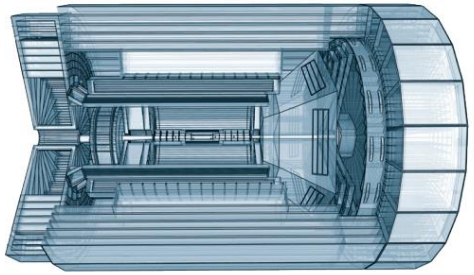


Example: In the 1960s Experiments at SLAC established the quark model and our modern view of particle physics "the Standard Model"

Electron Ion Collider (EIC)

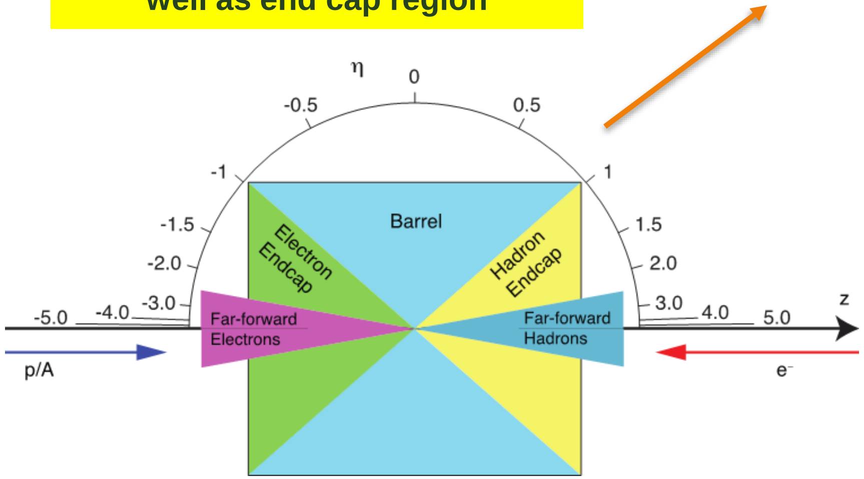
EIC science program:
-) Precision 3D imaging of protons and nuclei
-) Solving the proton spin puzzle
-) Search for saturation
-) Quark and gluon confinement
-) Quarks and gluons in nuclei

At least one large-acceptance detector that can capture most of the particles scattering from the collisions in all directions and at wide range of energies.

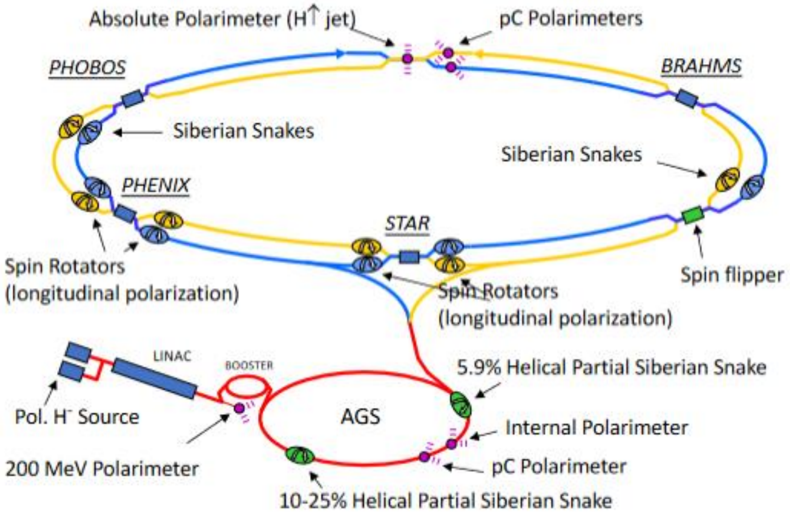


- High-precision tracking systems for reconstructing the trajectories of charged particles
- High-resolution systems for measuring the energies of particles
- Components for precision particle identification
- Efficient data acquisition systems incorporating machine learning and artificial intelligence
- Advances in software and computing for analyzing data

Many baseline EIC detector designs involved various gaseous detectors technologies for tracking in the central as well as end cap region

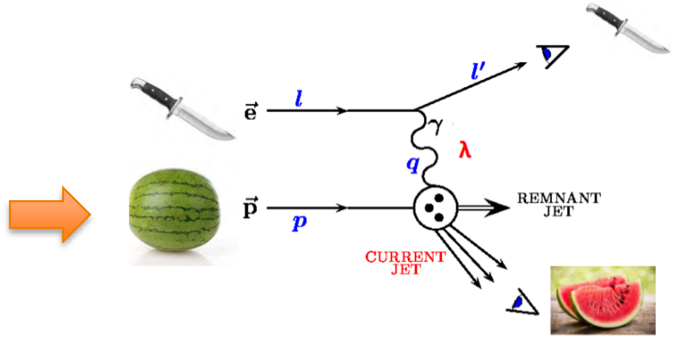


Polarized electron-proton/light ion & electron-Nucleus collider



Study of internal structure of a watermelon:

Deep Inelastic Scattering



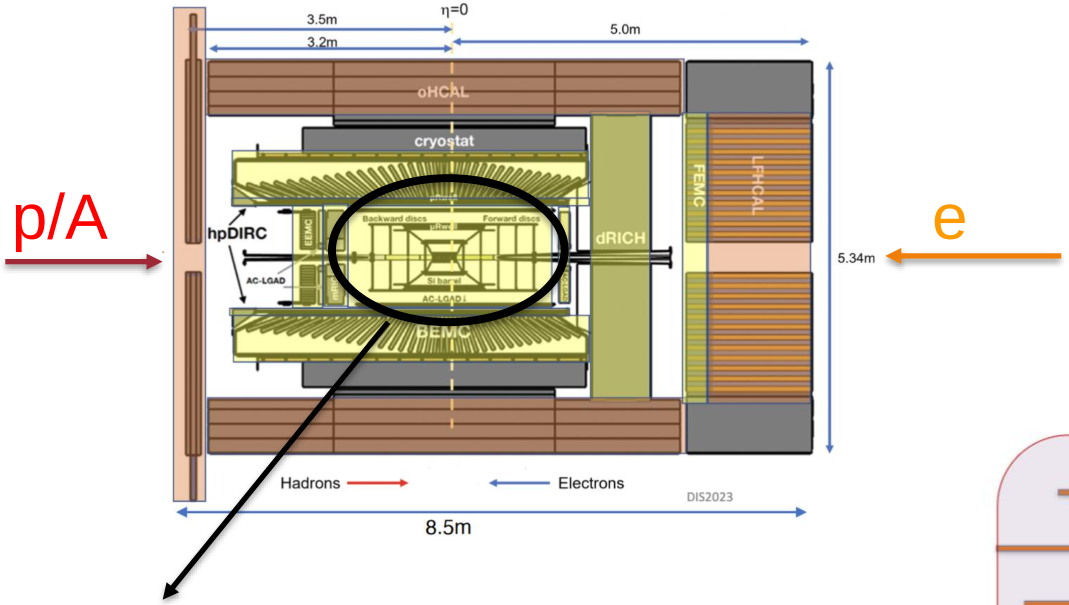
q = h/λ

h = constant
λ = wavelength
q = momentum transferred

Deep Inelastic: (λ << Proton Size)

NNPSS at U. of Tennessee, Lecture on Electron Ion Collider, Abhay Deshpand

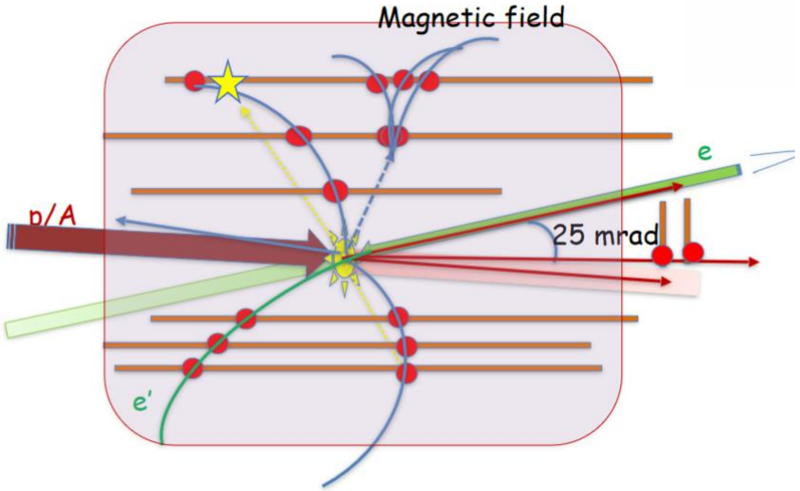
EIC detector and tracking requirements



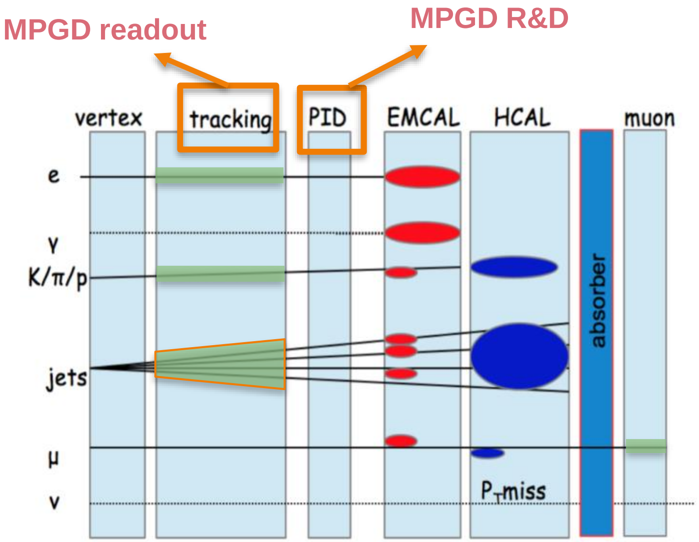
Tracking detectors provide:

- ➢ Space point coordinates and trajectory of charged particles → Vertex
- ➢ Momentum measurements in magnetic (B) field
- ➢ Angle measurements
- ➢ Measurements of primary and secondary vertices
- ➢ Multitrack separation
- ➢ Particle identification (if possible)
- ➢ Low material budget to minimize scattering and secondary interactions.

Selected tracking detector technologies:
Hybrid tracking detector design: Monolithic Active Pixel Sensor (MAPS, ITS3) based silicon vertex/tracking subsystem, the **MPGD tracking subsystem** and the AC-LGAD outer tracker, which also serves as the ToF detector.



Electron – photon separation: charged particles leave a track while the photon interact at most once

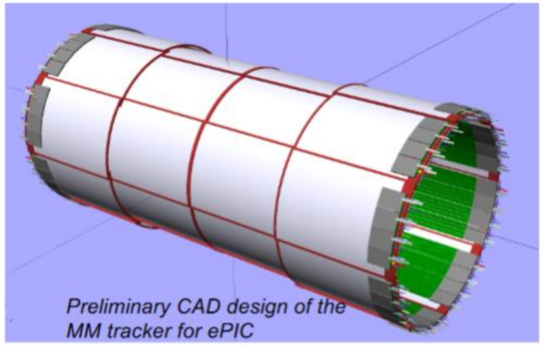


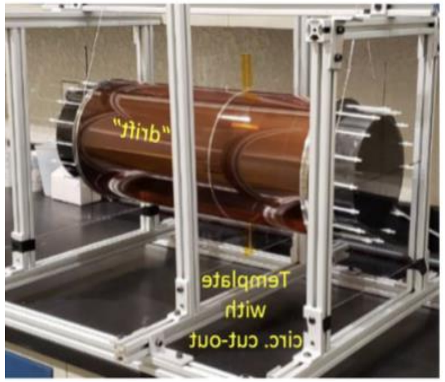
Central Detector Layout

MPGD for tracking/Vertex

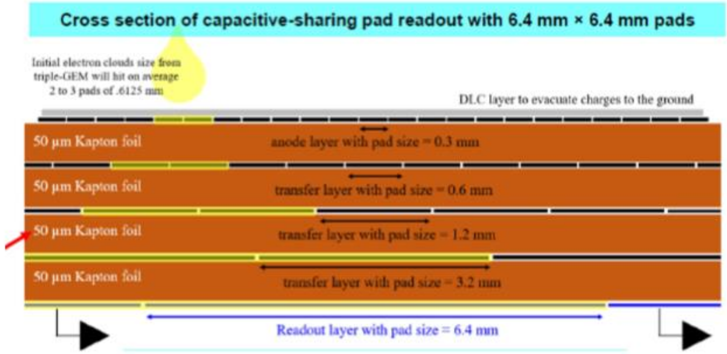
Barrel Main Tracker

- ❑ Hermetic coverage, close to 4π acceptance
  - ⇨ pseudorapidity range up to +/-1
  - ⇨ Large area detectors
- ❑ Low material budget on the level of 3-5% of X/X_0 for the central tracker region
  - ⇨ Gaseous detectors
- ❑ Spatial resolution below 100 μm

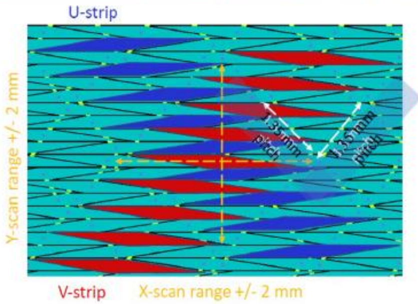




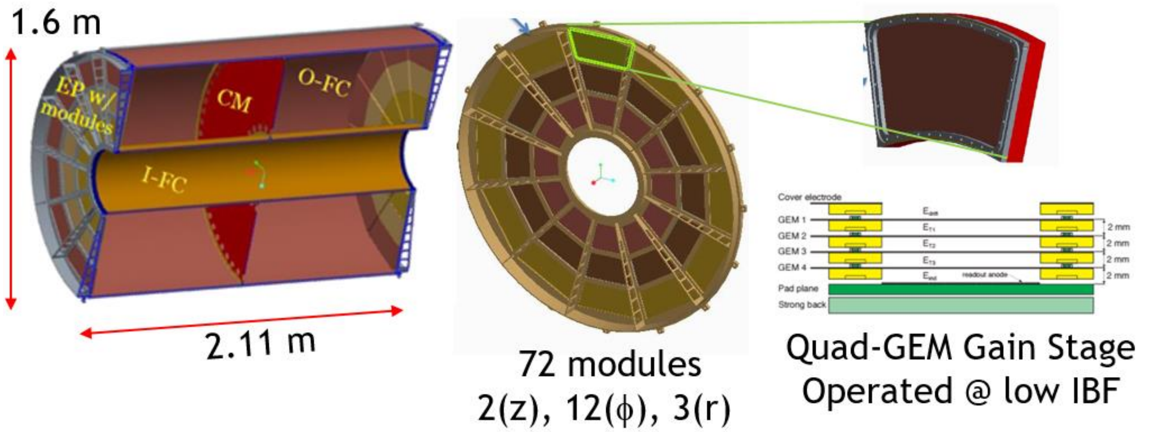
Readout based on μRWELL and capacitive coupling

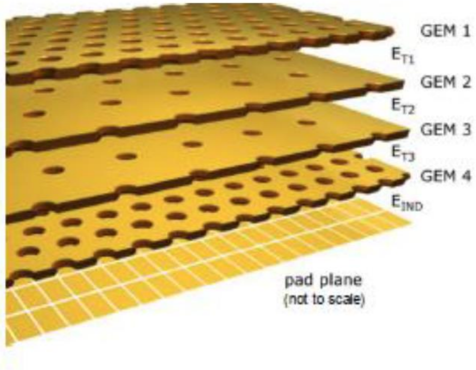


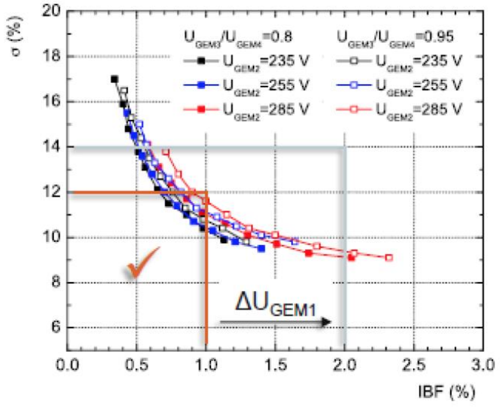
Ref: K. Gnanvo et al., NIM A, 1047 (2023) 167782



Example of proposed concept: GEM for gas amplification





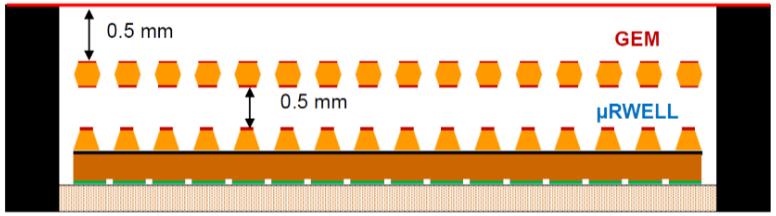


Minimization of ion back flow with quad-GEM (ALICE TPC)

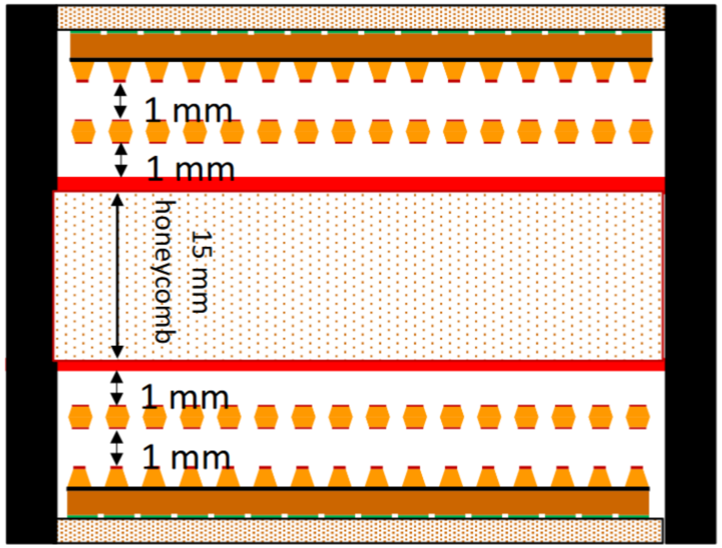
EIC Focused R&D projects

- Large area and low mass MPGD trackers (GEMs, MMs, and uRWells)
  - Cylindrical and planar
- High resolution and low channel count readouts
  - Resistive and capacitive sharing
  - 2 and 3 coordinate readout structures
- Modeling and simulation of resistive elements

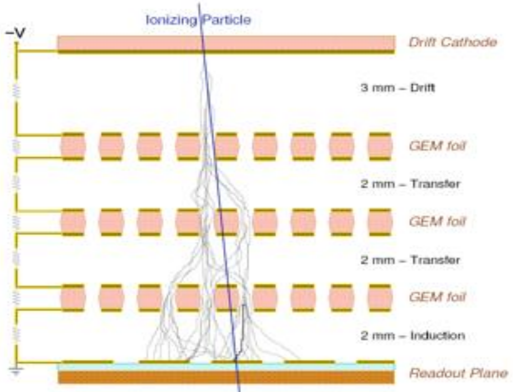
hybrid amplification GEM-µRWELL with 0.5 mm drift gap



Double sided Thin Gap MPGD tracker

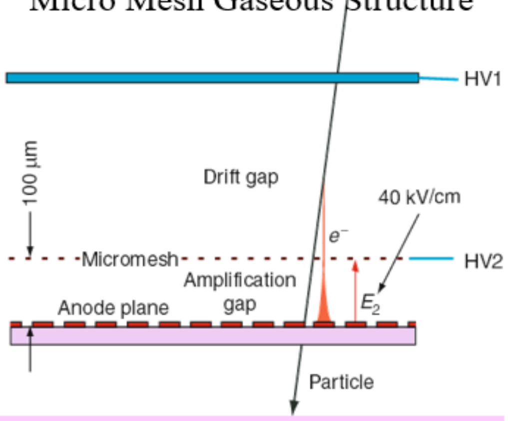


GEM: Gas Electron Multipliers



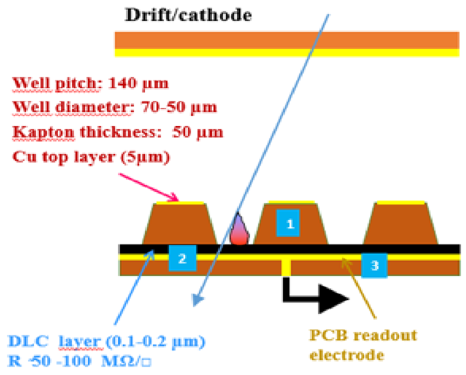
F. Sauli, Nucl. Instr. and Meth. A386 (1997) 531

Micromegas:
Micro Mesh Gaseous Structure



Giomataris, Nucl. Instr. and Meth. A419 (1998) 239

µRWELL:
Resistive micro-WELL Detector

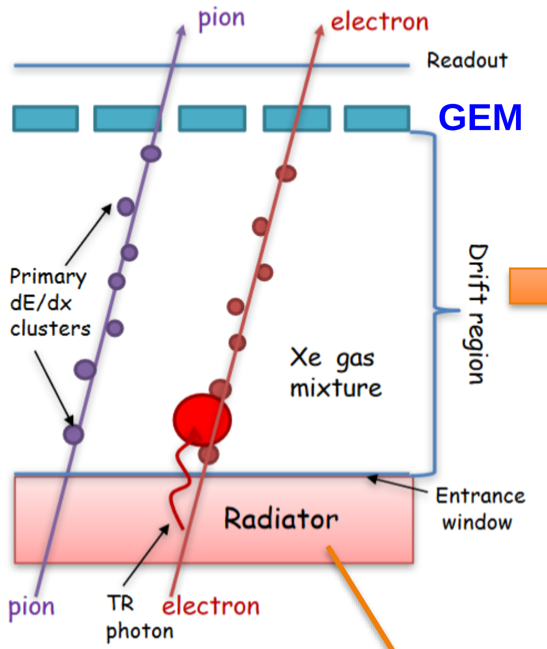


G. Bencivenni et al., 2015_JINST_10_P02008

Sourav Tarafdar, MPGD as tracker for EIC. CPAD workshop Stanford 2023

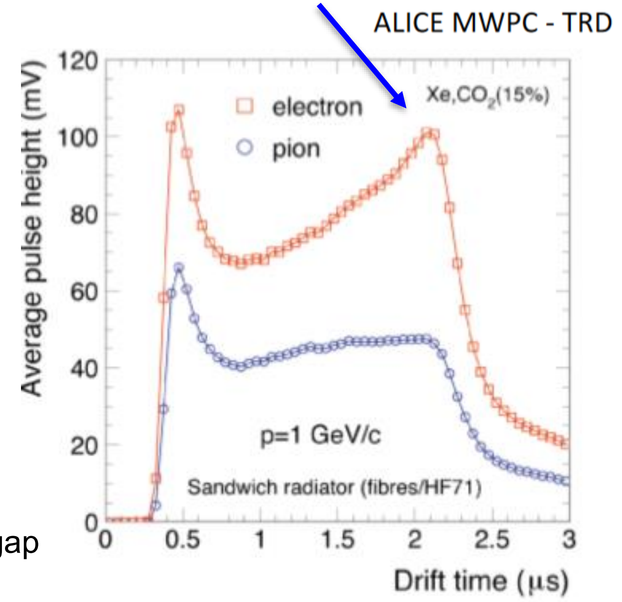
R&D GEM based Transition Radiation Detector/tracker for EIC

- Problem: High multiplicity heavy Ion collisions, large number of pions and Kaons in forward region
  → need to improve e-identification for leptonic/semi-leptonic decays
- Goal: Tracker combined with TRD/PID function: which could provide additional e/hadron rejection 10-100 and will cover energy range 1-100 GeV => GEM based transition radiation detector/tracker GEM-TRD/T

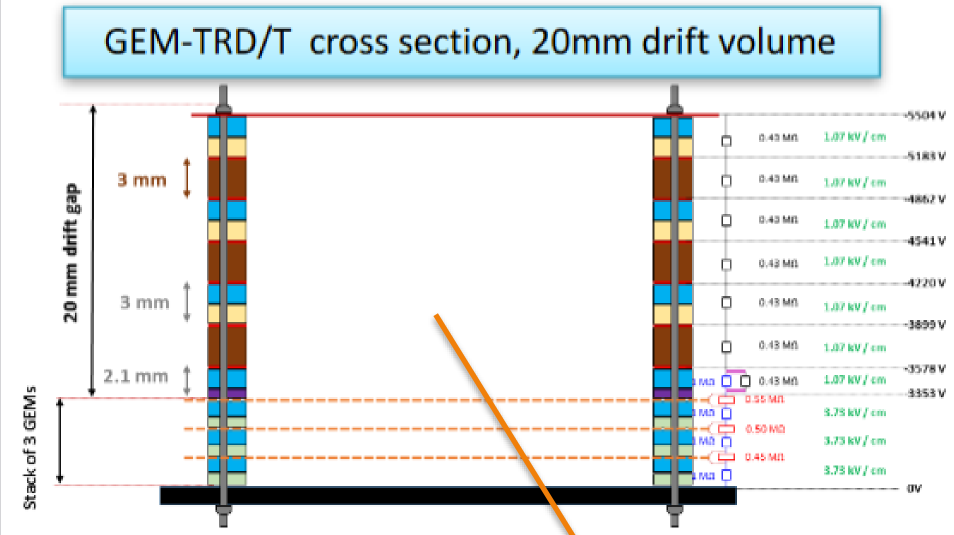


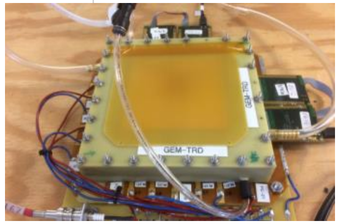
Conventional: 20-30μ Mylar foils & 200-300μ air gap
Propose EIC: multi-layer graphene radiator

For electron: significant increase in the average pulse height at later drift times, due to the absorption of the transition radiation near the entrance of the drift chamber.



UVA prototype (G. Kondo)



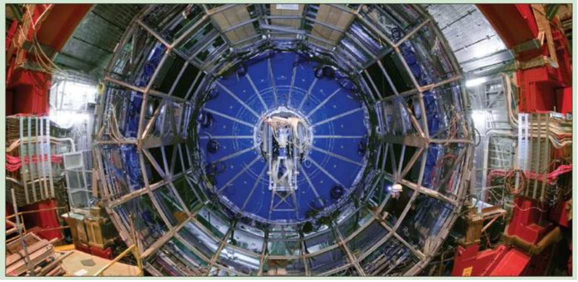


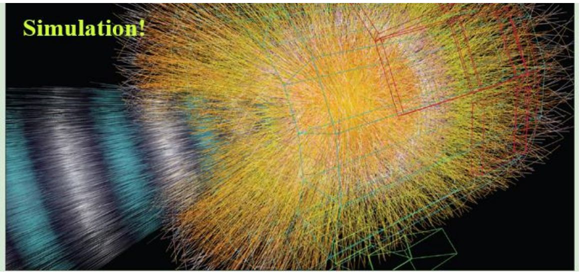
Xe-based mixture (high Z) to absorbed the TRD emissions

Experimental requirements: HEP vs LENP with RIBs

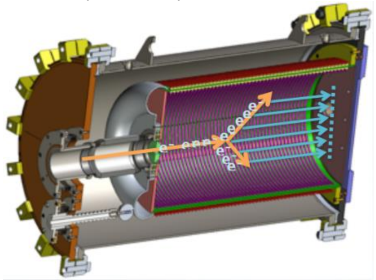
High-E Particle Physics

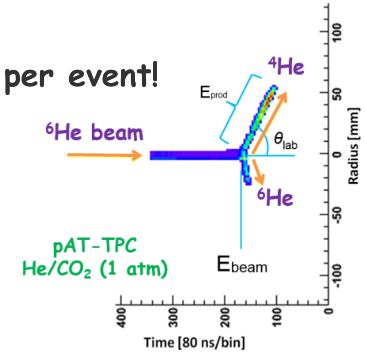
-) High gain (MIPs, Photons, etc.)
-) High Multiplicity
-) Specificity
-) High rate
-) Large & complex
-) IBF → mostly from the gas avalanche readout
-) …





pAT-TPC (NSCL) ➔ few tracks per event!





Low-E Nuclear Physics

-) Modest gain (heavy charged particles)
-) Low Multiplicity
-) Versatility (one setup many experiments)
→ large dynamic range (different pressure)
→ active target mode (pure elemental gas)
-) Low/moderate rate
-) Small setup, simple
-) IBF → mostly from the beam particles
-) …

- Most common MPGD Applications and R&D Projects in LENP
  - Fast beams Tracking (position, angle): FP Drift Chamber readout in high rigidity spectrometer for Bρ measurement
  - Study of Inverse-Kinematic Nuclear Reaction:
    ➔ position-sensitive TPC readout in active target mode, optical (scintillation-based) TPC readout, Exotic decay TPC
  - Fission Fragment imaging
  - Large-area Gaseous PhotoMultiplier

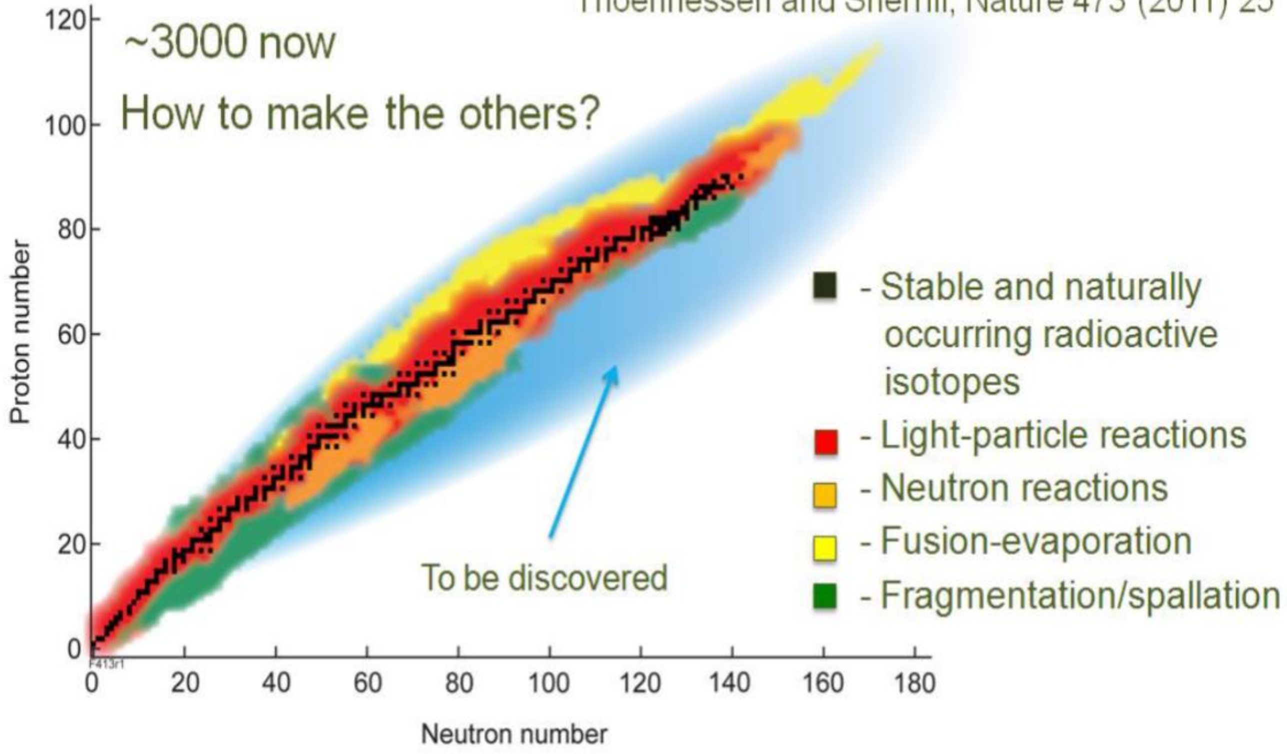
Low-Energy Nuclear Physics with RIBs

Science Program:

- **Properties of atomic nuclei**
  Study of predictive model of nuclei & their interactions, Many-body problem & physics of complex system
- **Astrophysics: Nuclear Processes in the Cosmos**
  Origin of the elements, energy generation in stars, stellar evolution & the resulting compact objects
- **Use atomic nuclei to tests of laws of nature**
  Effects of symmetry violations are amplified in certain nuclei
- **Societal applications and benefits**
  Medicine, energy, material sciences, national security, etc. etc.

Main MPGD applications:
-) Active Target TPC with fast & slow beam
-) Tracking of exotic decay with stopped beams
-) Fission Fragment tracking (fission reactions)
-) Focal-plane tracking for fast beam in spectrometers

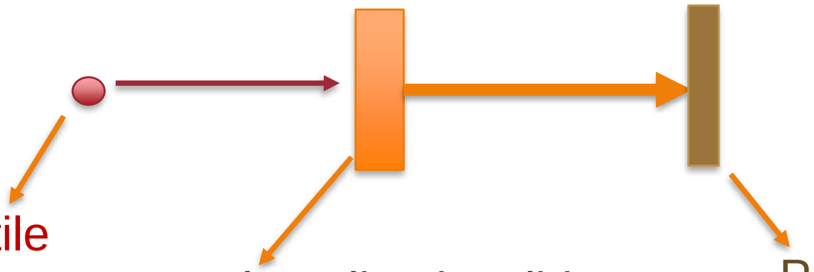
Thoennessen and Sherrill, Nature 473 (2011) 25



Inverse Kinematic with gaseous detector targets

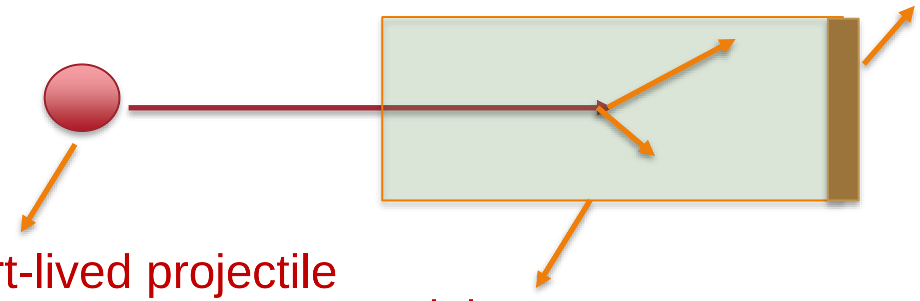
Goal: Study of inverse-kinematic nuclear reactions with resolutions equal to the one achieved in direct kinematics with high-resolution spectrometers + higher efficiency & thicker targets

Direct Kinematic



-) Thin Targets (low luminosity, low straggling, good ΔE/E)
-) Thick Targets (high luminosity, high straggling, poor ΔE/E)
-) Small acceptance angle
-) low energy event trapped in the target

Inverse Kinematic (AT-TPC) → ***gas is simultaneously the target and the tracking medium***

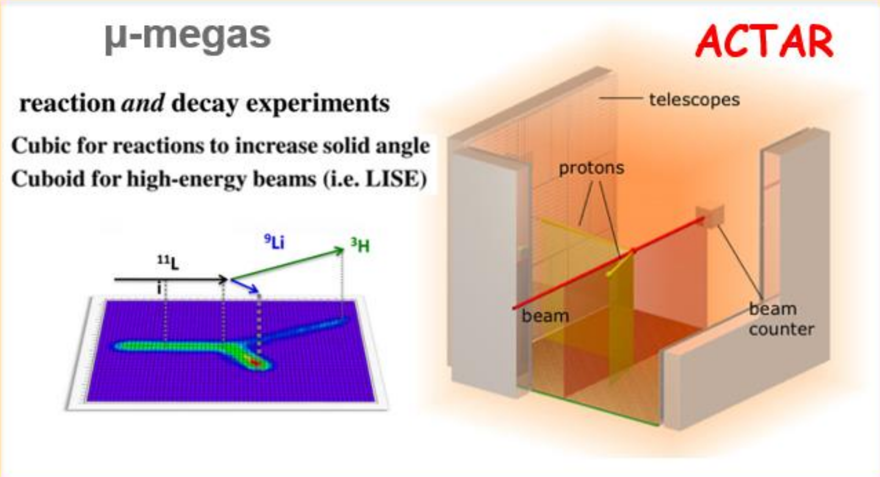


-) 4π acceptance of reaction products
-) Energy loss like thin target = excellent ΔE/E
-) Very high effective thickness ➔ high luminosity
-) Detection efficiency ~100% (+ low energy events)
-) Event-by-event reconstruction in 3 dimensions
-) Different target pressure ➔ Large dynamic range

TPC operated in active target mode → MPGDs

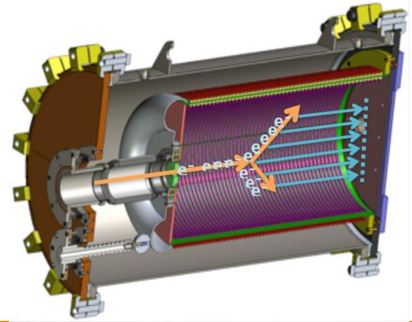
Science program with AT-TPCs

Measurement	Physics	Beam Examples	Beam Energy (A MeV)
Transfer & Resonant Reactions	Nuclear Structure	^{32}Mg(d,p)^{33}Mg ^{26}Ne(p,p)^{26}Ne $^{66,...,70}$Ni(p,p)	3
Astrophysical Reactions	Nucleosynthesis	^{25}Al(^{3}He,d)^{26}Si	3
Fusion and Breakup	Nuclear Structure	^{8}B+^{40}Ar	3
Transfer	Pairing	^{56}Ni+^{3}He	5-19
Fission Barriers	Nuclear Structure	^{199}Tl, ^{192}Pt	20 - 60
Giant Resonances	Nuclear EOS, Nuclear Astro.	^{54}Ni- ^{70}Ni, ^{106}Sn- ^{127}Sn	50 - 200
Heavy Ion Reactions	Nuclear EOS	^{106}Sn - ^{126}Sn, ^{37}Ca - ^{49}Ca	50 - 200



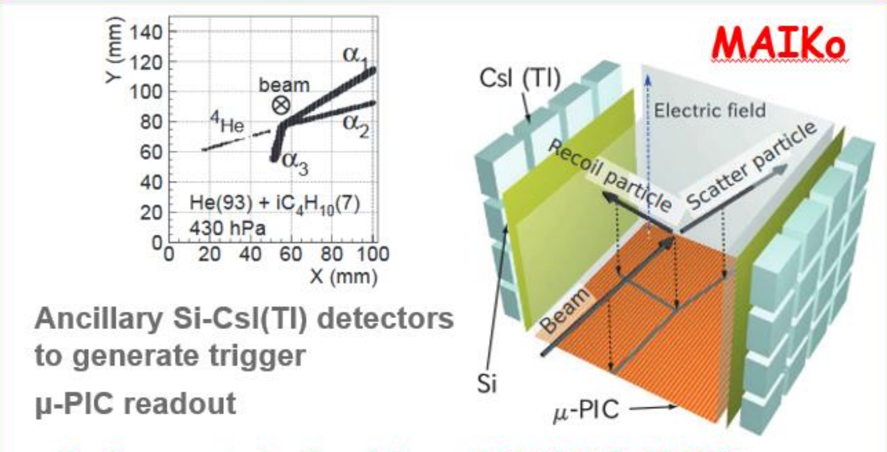
Same goal, different paths:
- -) geometry:
  - → Cylindrical vs cubicle
- -) Gas avalanche readout:
  - → Micromegas
  - → Hole-Types (GEM, …)
  - → μ-PIC
  - → Hybrid …..
- -) Coupled to Ancillary detector
  - → Isomer tagging
  - → Triggering
  - → Particle identification
  - → Neutron detection
- -) With/Without magnetic field

Suzuki et al., NIM A, 691 39 (2012)



Micromegas + M-THGEM

Cylindrical geometry
Readout > 10k pads



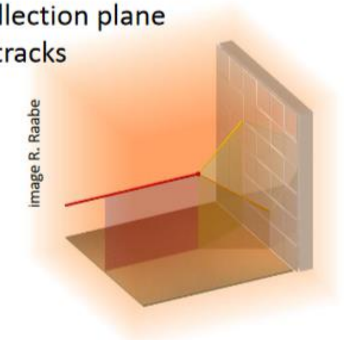
T. Furuno et al., J. of Phys. 569 (2014) 012042

and many more ….

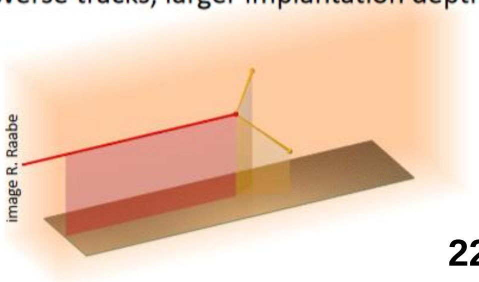
ACtive TARget and Time Projection Chamber (ACTAR TPC)

Two operational modes:

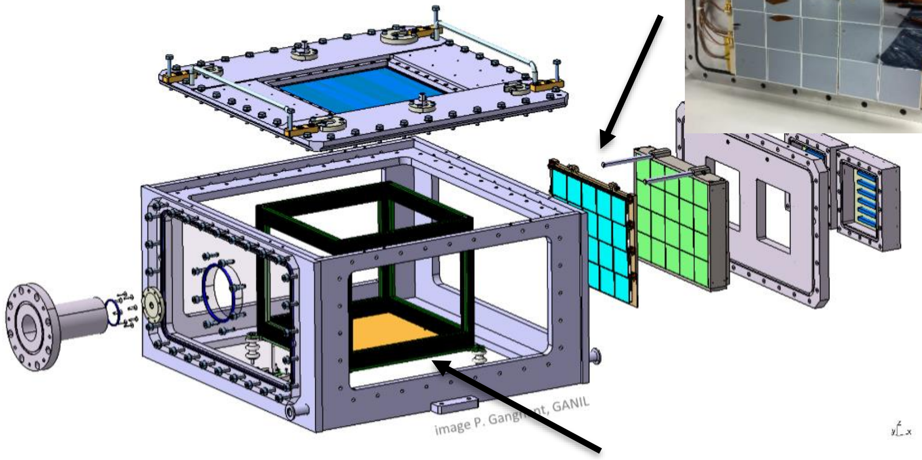
"reaction" chamber
128x128 pads collection plane
large transverse tracks

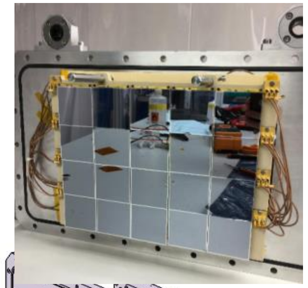


"decay" chamber
256x64 pads collection plane
short transverse tracks, larger implantation depth



ACTAR mechanical design





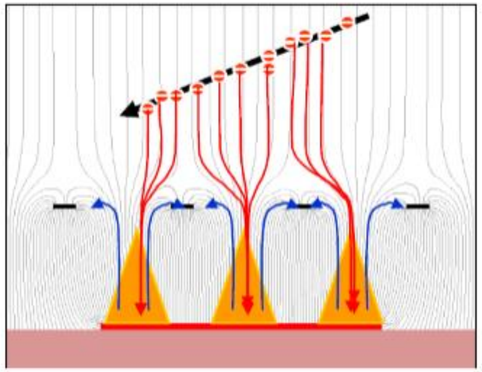
TPC designed to include additional detectors (e.g. Si-PIN):
- tracking of particles escaping the drift region
  → reaction studies and active target mode
- additional position and energy information
  →used also for commissioning

Commissioning of the **128x128 pads full detector**

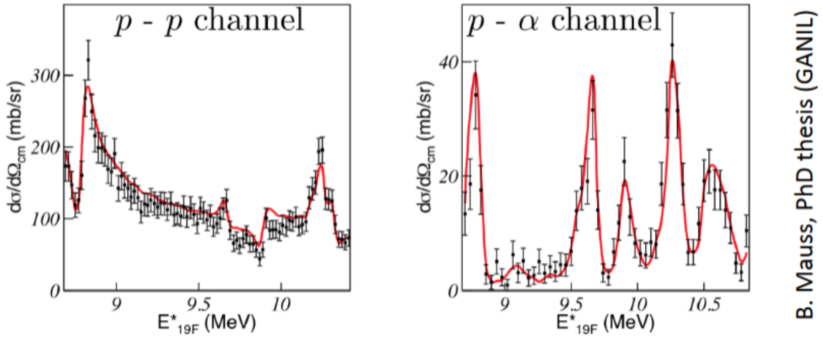
tests @ GANIL (11/2017 & 04/2018)

$^{18}O(p,p)$ and $^{18}O(p,\alpha)$ excitation functions
→ reaction kinematics
part. tracks & energy
→ absolute cross section

Bulk micromegas
220 um avalanche gap
(also possibility to use GEM)



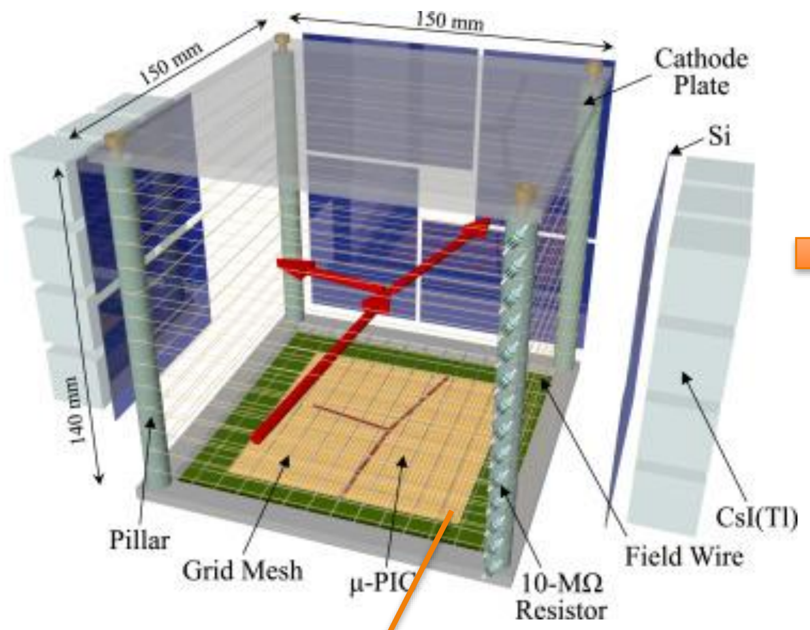
(iC_4H_{10}) gas at 100 mbar

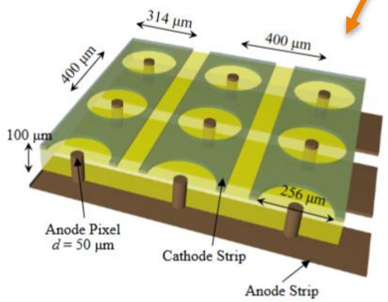


B. Mauss et al., NIM A 940 (2019), 498-504.

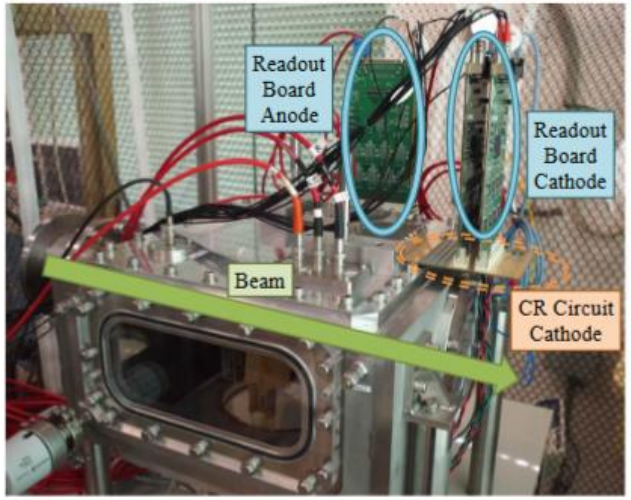
Mu(μ)-PIC based Active target for Inverse Kinematics (MAIKo)

T. Furuno et al., NIM A 908 (2018), 215-224.





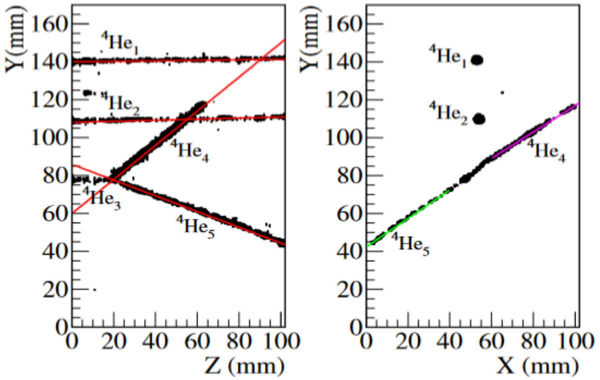
Ancillary Si-CsI(Tl) detectors used to generate trigger
And measure Energy of particle escaping the volume



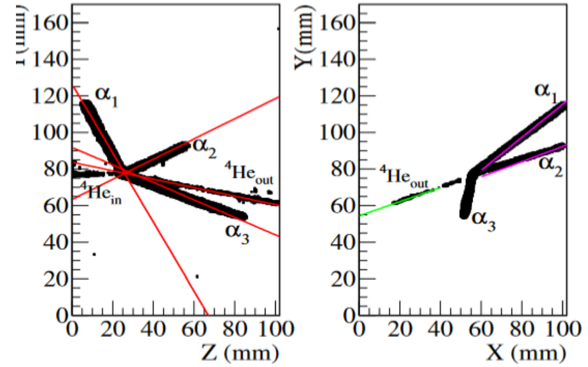
- Detection gas (He) = target gas → Detectable low-energy particles!
- Gas: He + CO_2(7%) @0.5 – 2.0 atm
- Introduce μ-PIC + GEM.
  - μ-PIC (gain~1000): 2-dimensional strip readout (400 μm pitch).
    256A+256C = 512 ch.
  - GEM (gain~30): 140 μm pitch, d=70 μm, t=100 μm (thick GEM)
- TPC track → θ_α , range in the gas / Si+CsI → E_α

✓ beam: ^{4}He @50 MeV
✓ gas: He(93%) + iC_4H_{10}(7%) @430 hPa

^{4}He + ^{4}He elastic



3α decay from $^{12}C^*$



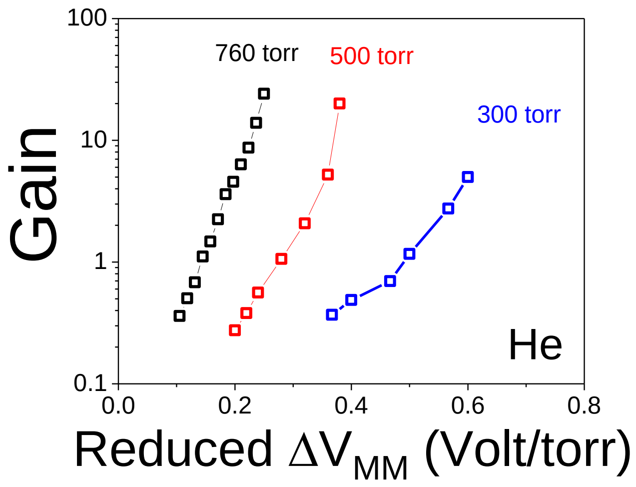
Stability issues in pure elemental gas

- **H_2 as proton target**
  - 1 neutron pickup (p,d)
  - 2 neutron pickup (p,t)
  - p-scattering
- **D_2 as deuteron target**
  - 1 neutron transfer (d,p)
  - 1 proton pickup (d,^{3}He)
  - Inelastic scattering (d,d')
- **^{3}He**
  - 1 proton transfer (^{3}He,d)
- **^{4}He as alpha-particle target**
  - Inelastic scattering (^{4}He, ^{4}He‘),
  - Isoscalar Giant Resonances excitations …
  - Alpha-induced reactions for astrophysical p-process
- **Etc. . .**

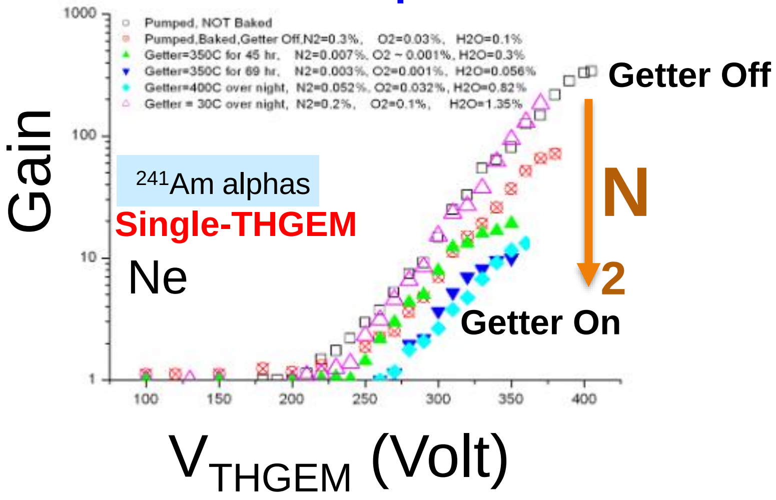
-) Purity (no quencher) → High Reaction Yield
-) Low-Pressure Operation → Large Dynamic Range

Endcap Detector Performance:
Gas Gain, Energy Resolution, Spatial Resolution, Counting Rate Capability, Stability etc…

Micromegas in pure He

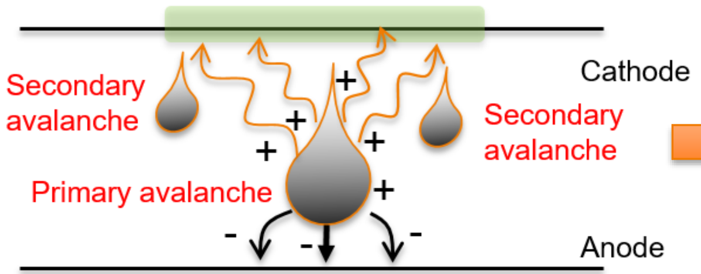


THGEM in pure Ne



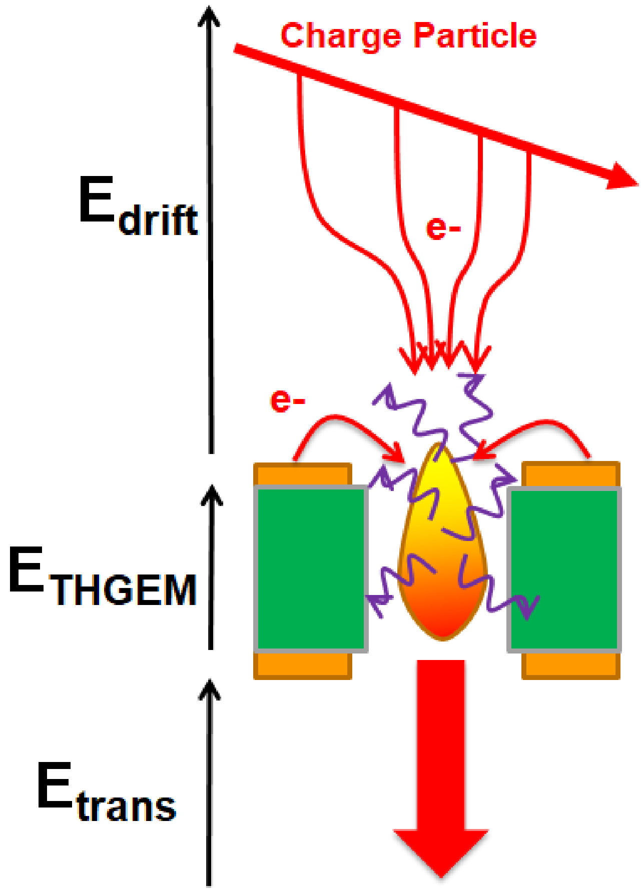
Miyamoto et al. 2010 JINST 5 P05008

Photon-feedback



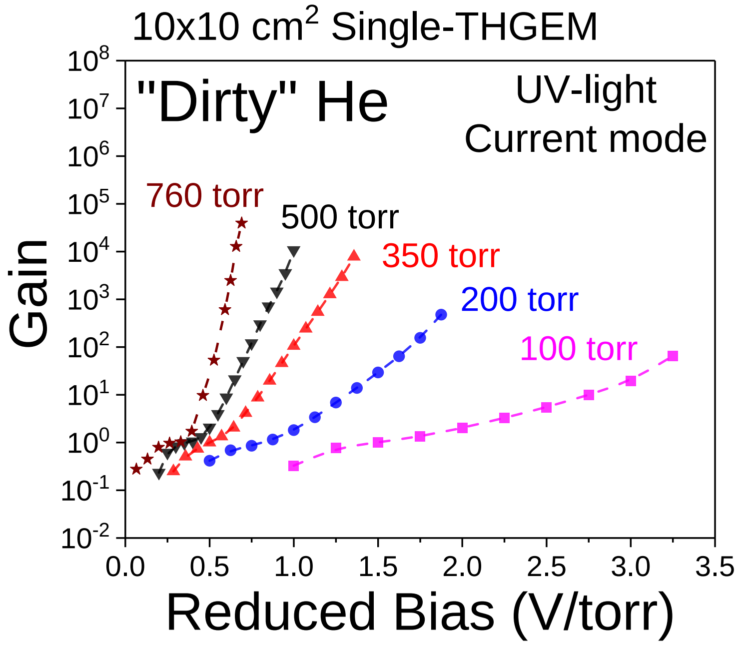
Problem:
Photo-mediated secondary effects induce a transition from the proportional mode to streamer (sparks) in poor quenched gas mixtures!

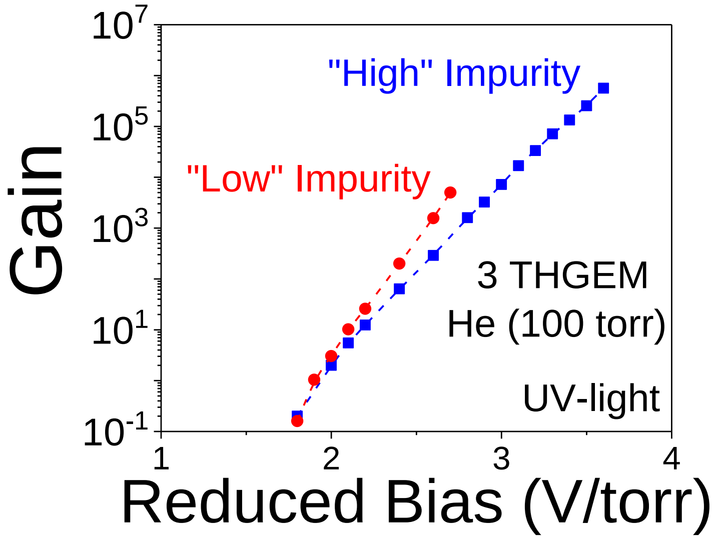
Stability issue for hole-type multipliers in pure elemental gas



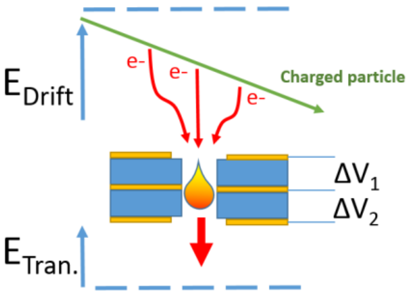
The Problem:

Drop of GEM-like max. achievable gain in pure elemental gas
➔ loss of electron avalanche confinement (within the holes) that results in photo-mediated secondary effects
➔ transition from proportional mode to streamer

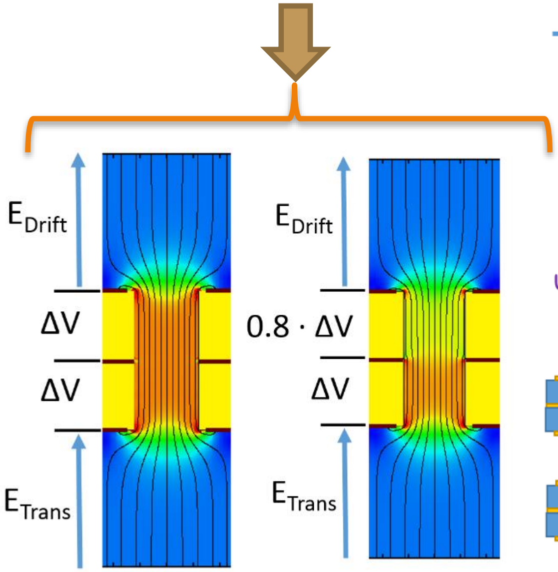




Slow breakdown mitigation using M-THGEM structure

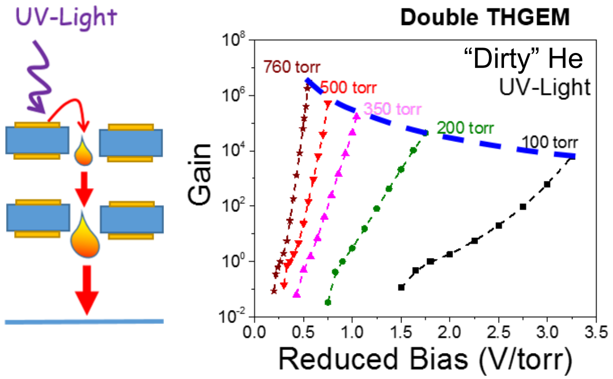


2-Layer M-THGEM

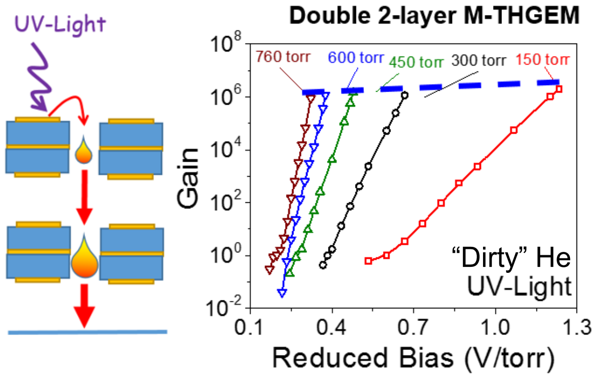


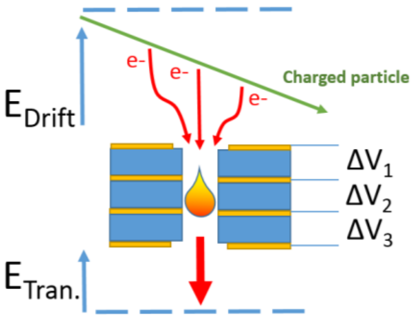
Low pressure

10x10cm² THGEM
(thickness = 0.6 mm, hole = 0.5 mm, pitch = 1 mm)

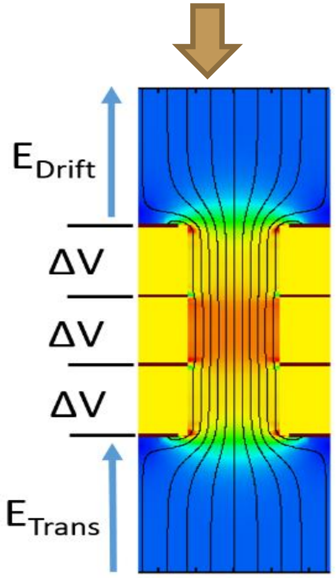


10x10cm² M-THGEM
(thickness = 1.2 mm, hole = 0.5 mm, pitch = 1 mm)





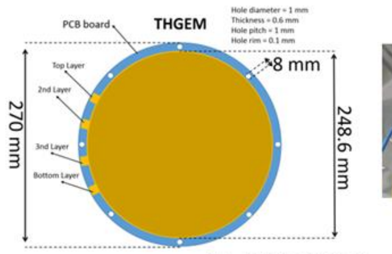
3-Layer M-THGEM

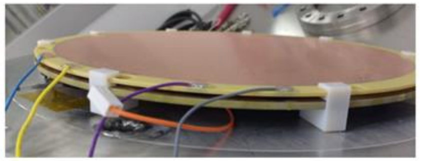


AT-TPC & pure gases

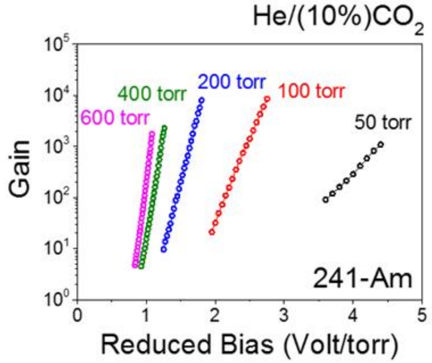
- -) No loss of charge ➔ high gain @ low voltage
- -) Robust avalanche confinement
  ➔ lower secondary effects
- -) Long avalanche region
  ➔ high gain @ low pressure
- -) Field geometry stabilized by inner electrodes
  ➔ reduced charging-up

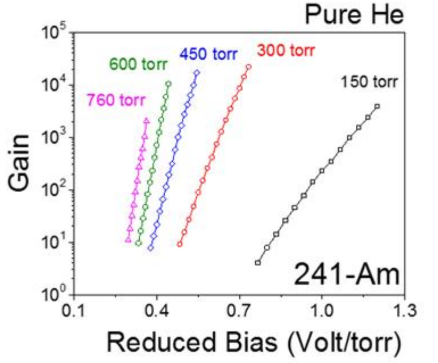
Cortesi et al., Rev. Sci. Ins. 88, 013303 (2017)





Single 3-layer M-THGEM





Active-Target TPC @ Facility for Rare Isotope Beams (FRIB)

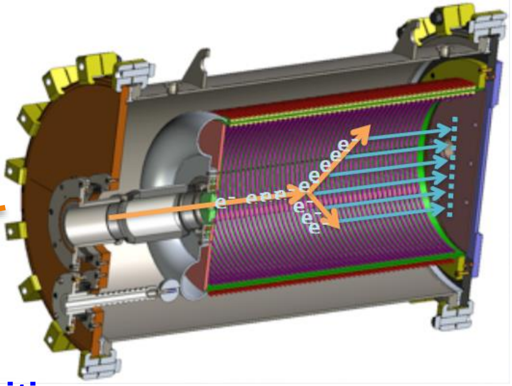
<u>Cylindrical configuration:</u>
Use with solenoid
→ Magnetic field for PID

Problem:
Need to suppressed beam!
→ Smart-ZAP

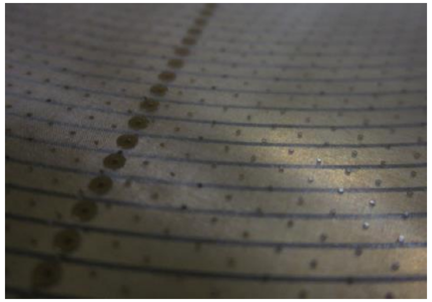

Field Cage

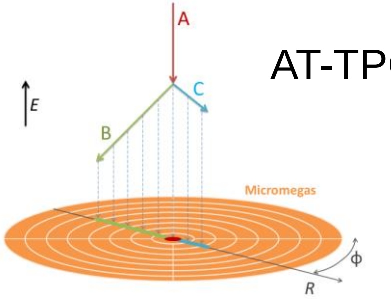
pAT-TPC

- Active volume 25 liters (L = 50 cm, Ø = 25 cm)
- Cylindrical pad plane (1,000 pads)



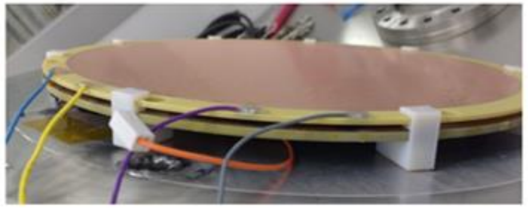
Position-sensitive micromegas pad



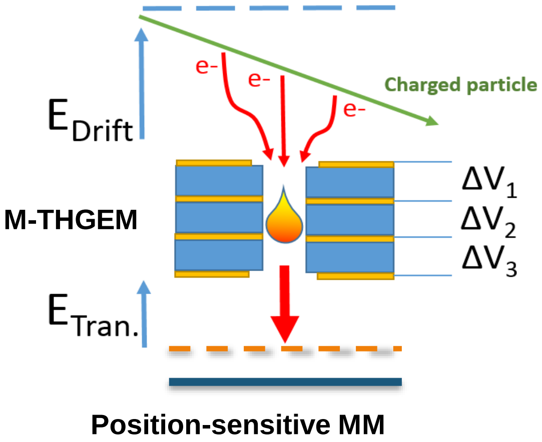


Full scale AT-TPC

- Active volume 200 liters (L = 100 cm, Ø = 50 cm)
- 10,240 triangular pads
- Placed inside 4 Tesla solenoid



AT-TPC Readout pad → GET electronics



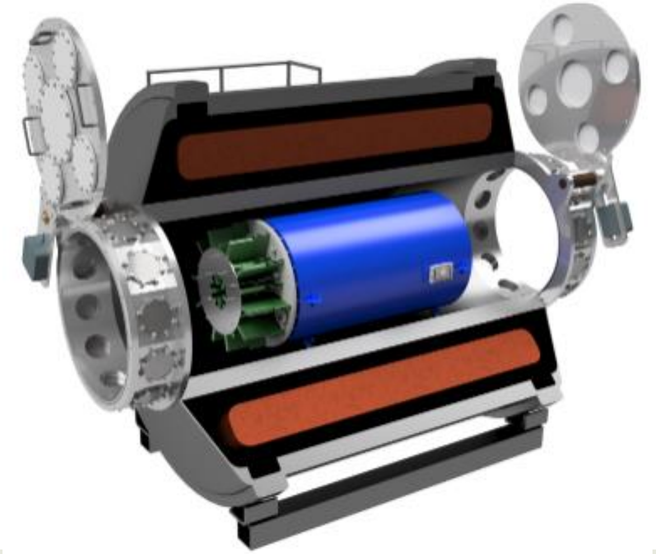
Gain Provided mainly by M-THGEM
Position-sensitive MM for track encoding

Cortesi *et. al.* EPJ Web of Conferences 174, 01007 (2018)

Ayyad et al. Eur. Phys. J. A (2018) 54: 181

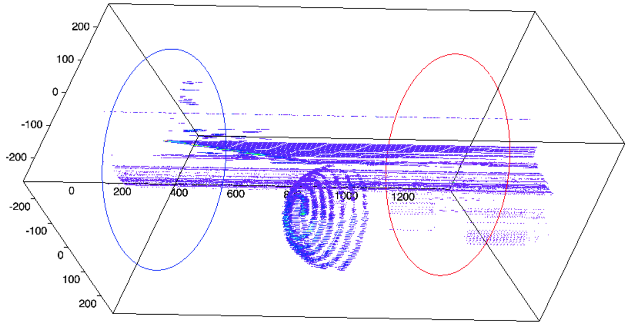
AT-TPC project @ FRIB: the Multi-layer THGEM

SOLARIS (up to 4 Tesla)



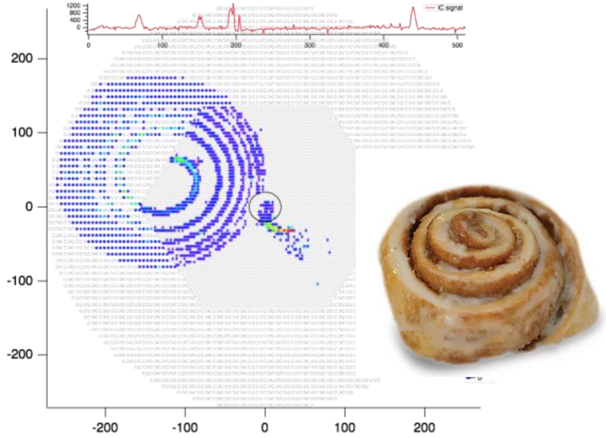
E20009 → pure D_2 (760 Torr)

$^{10}Be(d,p)^{11}Be$



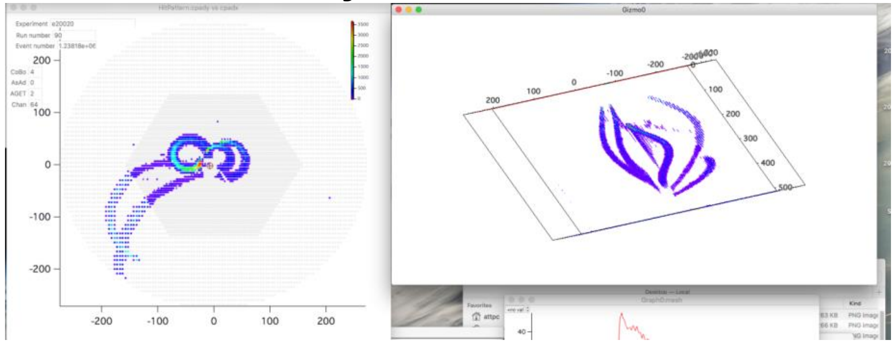
The cinnamon roll: 8 MeV p (5 m range)

Spokesperson: Daniel Bazin



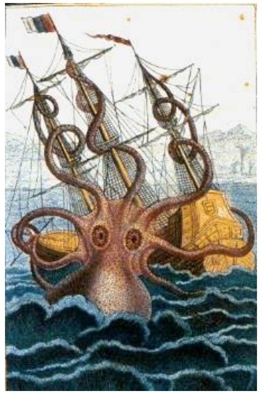
E20020 → pure He (700 Torr)

4 α decay of ^{16}O



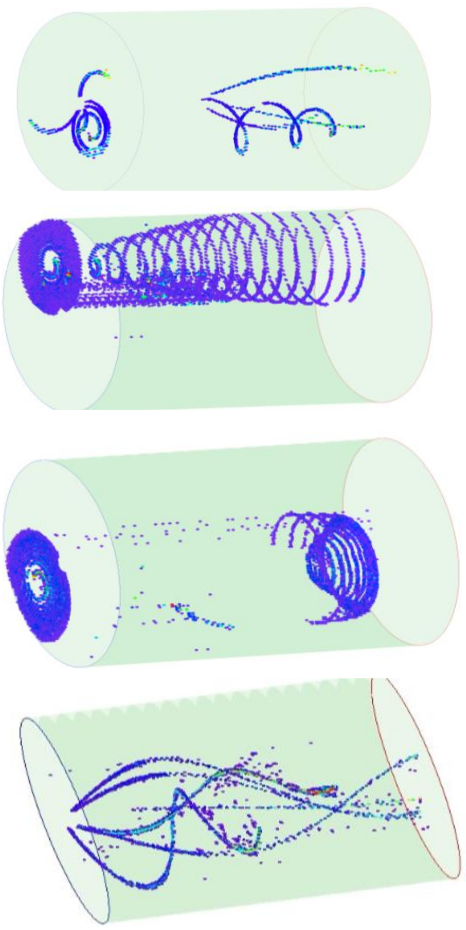
The big Kraken: 5 α-particle tracks

Spokesperson: Clementine Santamaria



More Tracks

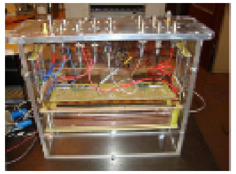
D. Bazin Courtesy

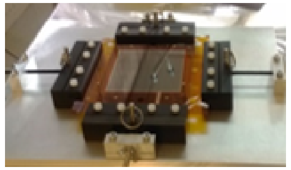
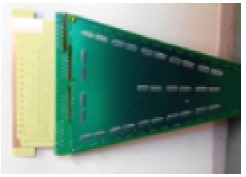
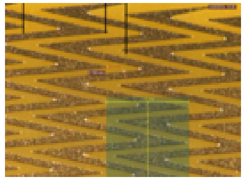
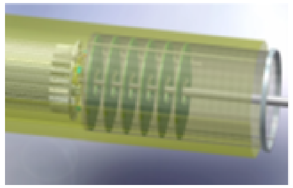
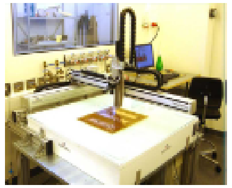


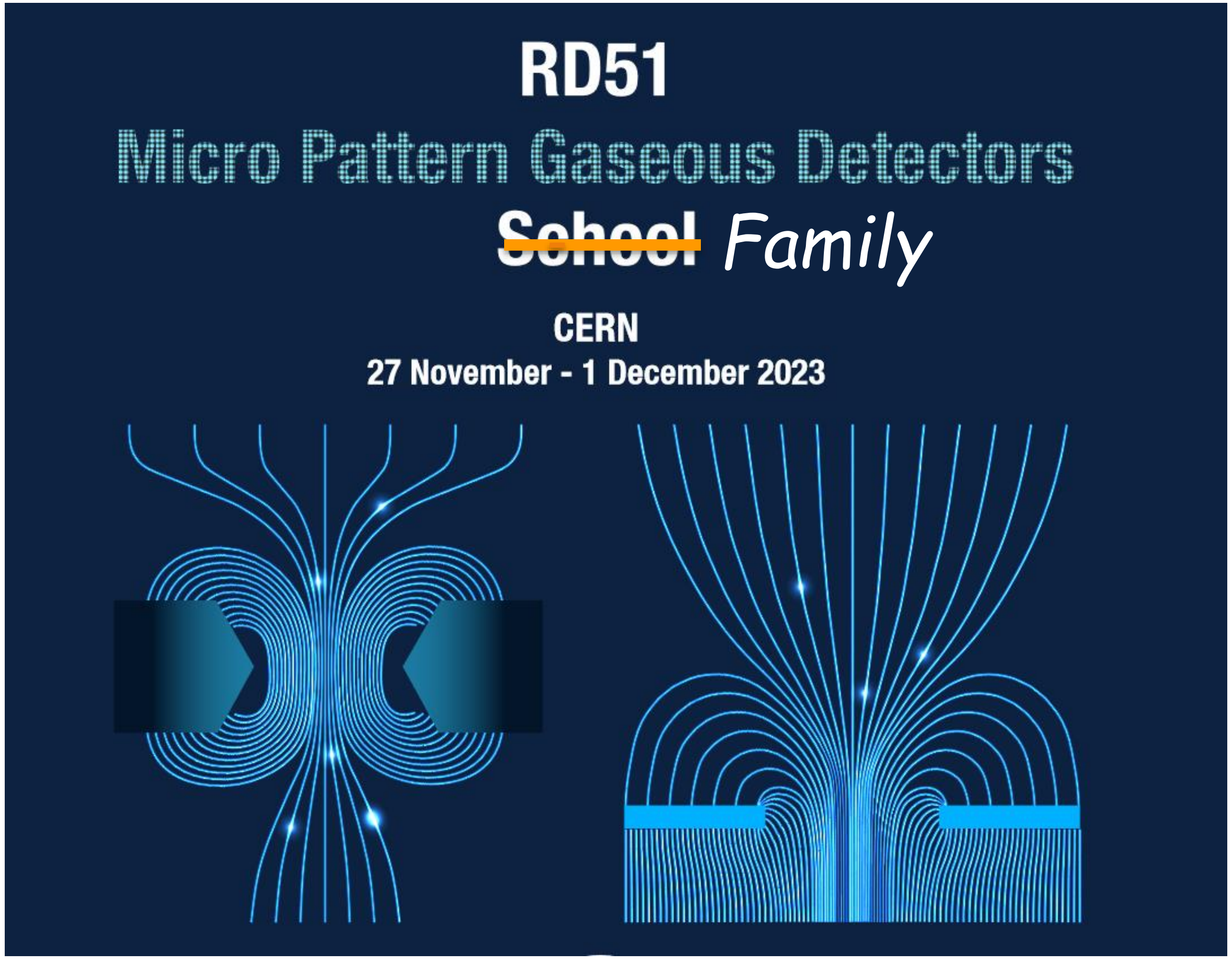
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

MPGD: Tracking for Heavy-Ion/Nuclear Physics

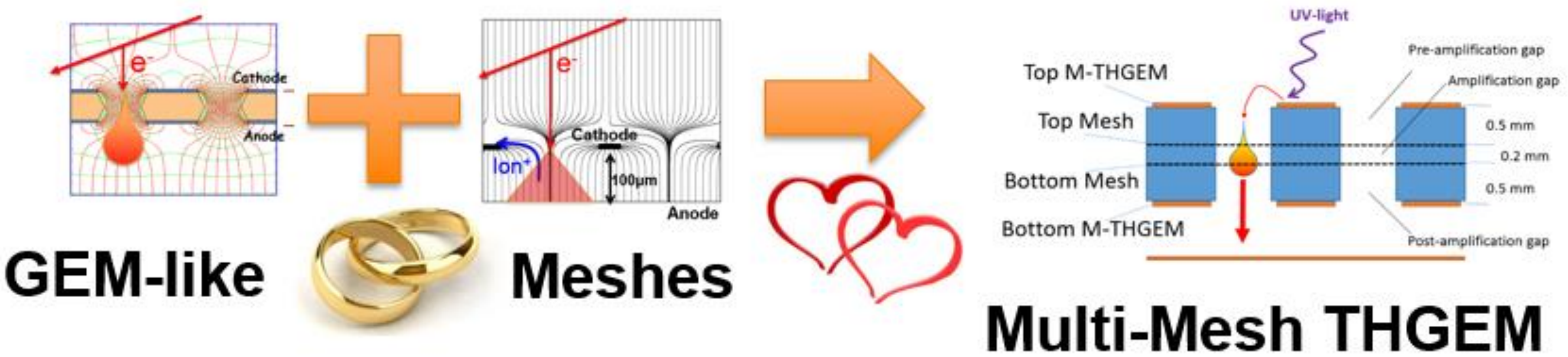
Name (Lab)	MPGD Technology	Volume Area	Pressure (atm)	Operation Performance	Status
ACTAR (GANIL)	μ-megas	8000 cm^3	0.01-3	Counting rate < 10^4 nuclei but higher if some beam masks are used	Under Construction
MAIKo (RNCP)	μ-PIC	2750 cm^3	0.4-1	FADC electronics 2*256 channles	Test
PANDA (FAIR)	μ-megas/GEM	22500 cm^2	1	Continuous-wave operation: 10^{11} interaction/s	Under Construction
CAT (CNS)	GEM	2000 cm^3	0.2-1	FADC electronics 400 channels	Test
pAT-ATP (NSCL)	μ-megas (+THGEM)	2000 cm^3	0.01-1	GET electronics 256 channels	Operational
AT-TPC (NSCL)	μ-megas (+THGEMs)	8000 cm^3	0.01-1	GET electronics >10'000 channels	Operational
TACTIC (CNS)	GEM	8000 cm^3	0.25-1	Low beam energy (<2 MeV/u)	Test
MINOS (CNS)	μ-megas	6000 cm^3	1	# of Channel= 600	Operational
SuperFRS (FAIR)	GEM	Few m^2	1	High dynamic range Particle detection from p to Uranium	Under Construction Run: 2018-2022
…	…	…	…	…	…




RD51
Micro Pattern Gaseous Detectors
~~School~~ Family
CERN
27 November - 1 December 2023

The Battle for the Throne



Example of “Hybrid”-MPGD configurations

S. Kane et al. NIM515 (2003) 261–265

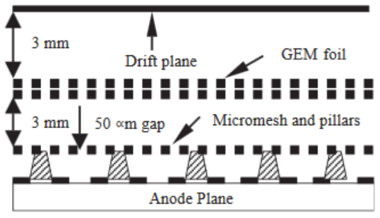
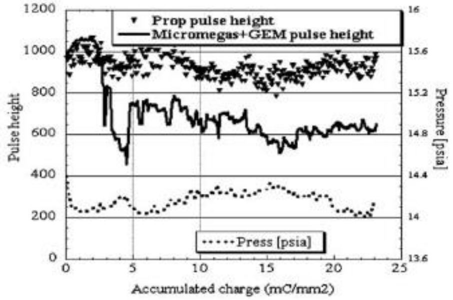
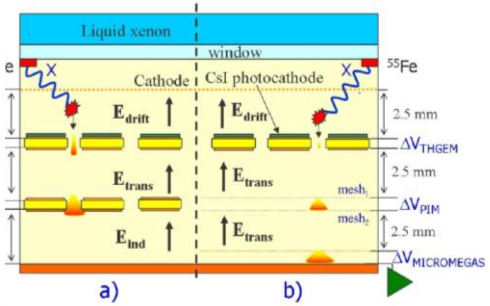


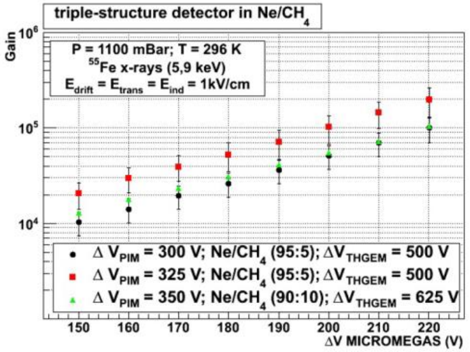
Fig. 2. MICROMEGAS+GEM detector.



Increase Micromegas stability at high gain

S. Duval et al. 2011 JINST 6 P04007

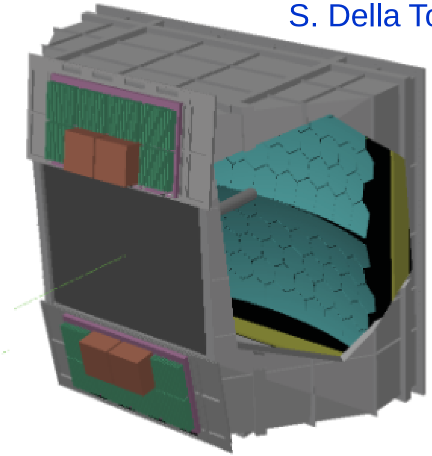


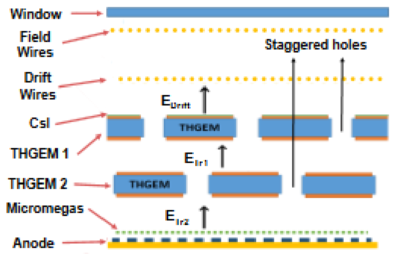


Low IBF & high gain

The MPGD-Based GPM for the upgrade of COMPASS RICH-1

S. Della Torre, MPGD2019, La Rochelle 2019



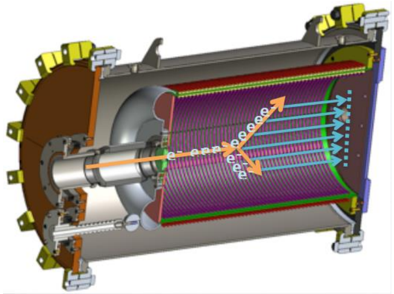


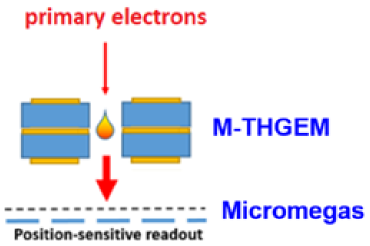
Technological achievement - for the FIRST TIME:

- single photon detection is accomplished by MPGDs
- THGEMs used in an experiment
- First resistive MM used in an experiment
- For the first time MPGD gain > 10k in an experiment

AT-TPC for low-E nuclear physics/astrophysics experiments

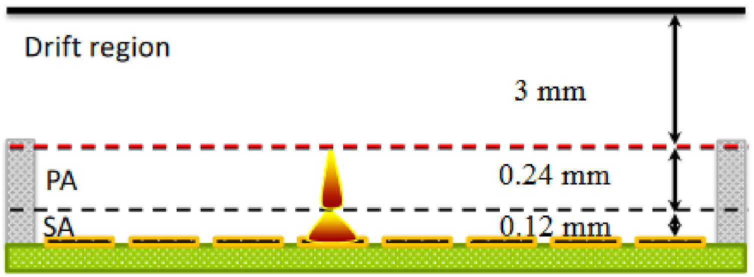
M. Cortesi, MPGD2019, La Rochelle 2019

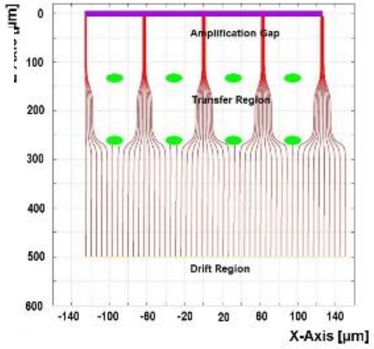




First MPGD operated in “pure” elemental gas & used in several NP experiments in different irradiation conditions

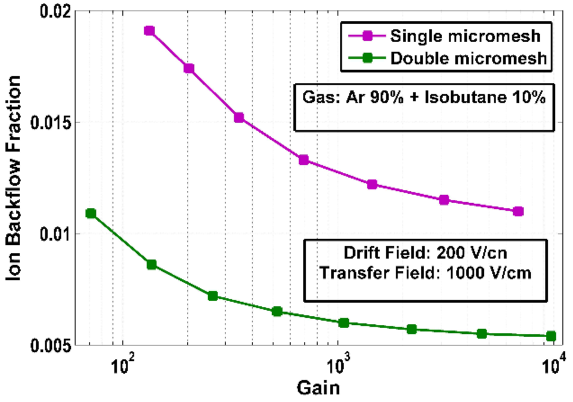
The idea: M-THGEM as support for the Double-MicroMegas

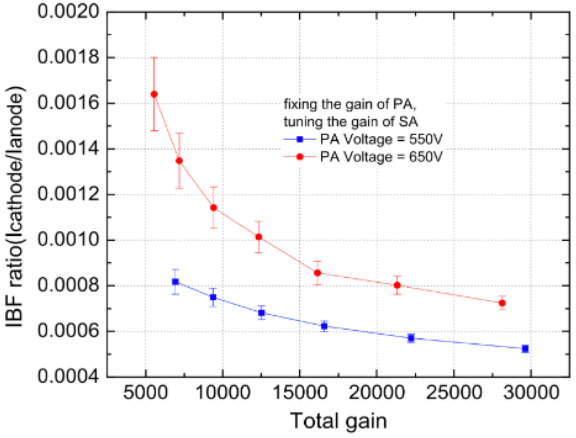




Problem: mechanical stability of DMM over large area

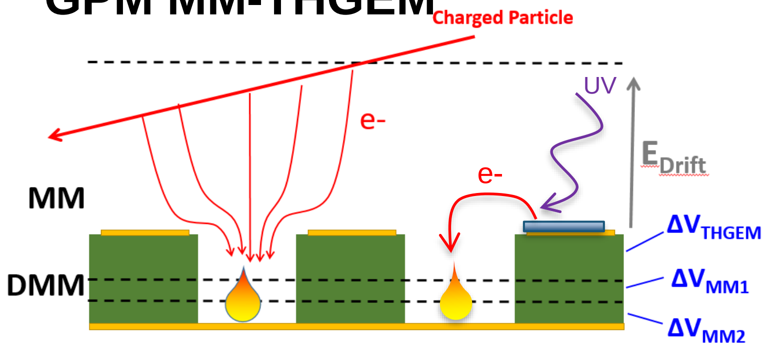
P. Bhattacharya et al 2015 JINST10 P09017

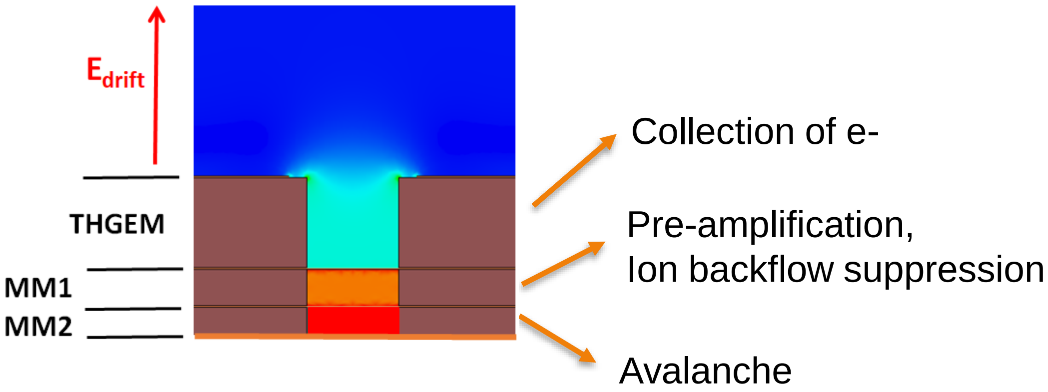




More recent results ➔ IBF ~10^{-4} (B. Qi t al. NIMA 976 (2020) 164282)

GPM MM-THGEM





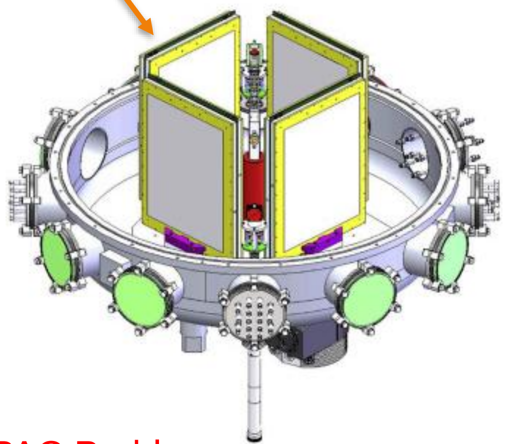
Features:

-) M-THGEM as mechanical support for the meshes
-) Reduced ion backflow
-) Uniform field ➔ Good energy resolution
-) Photocathode on the THGEM top surface for GPM

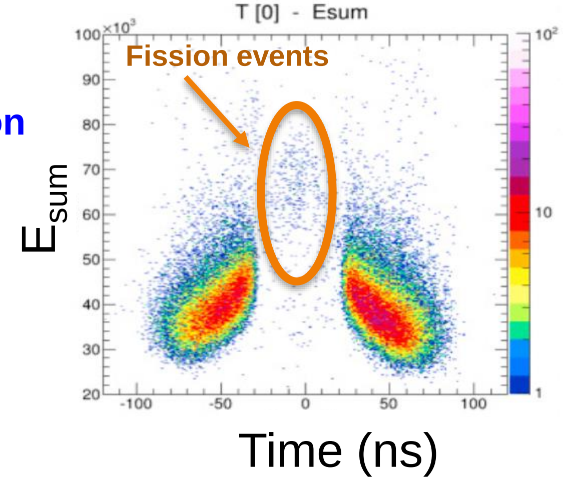
MM-THGEM for Fission Fragment experiment

- Goal: Understand Fusion-Fission and quasi-Fission reaction mechanisms → production of super-heavy elements

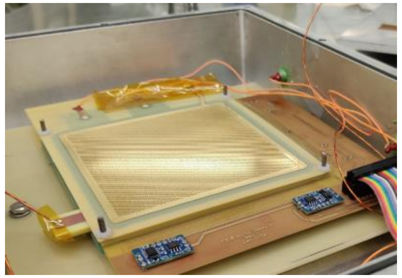
CFFD (NSCL)
Heavy-ion Imaging system:
Velocity vector
→ Mass/Angle distribution

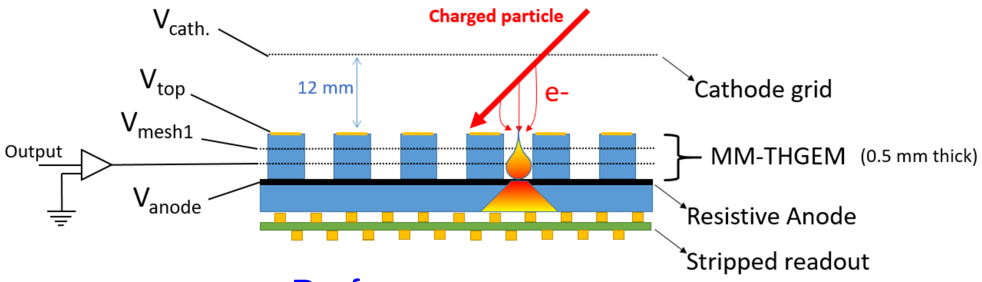


PPAC-based tracking system



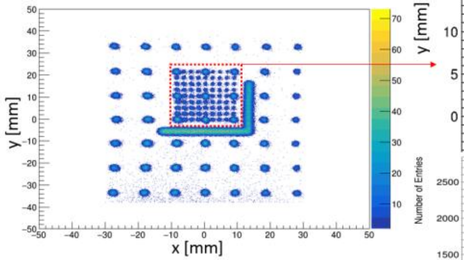
MM-THGEM imaging detector prototype (10x10 cm^2)



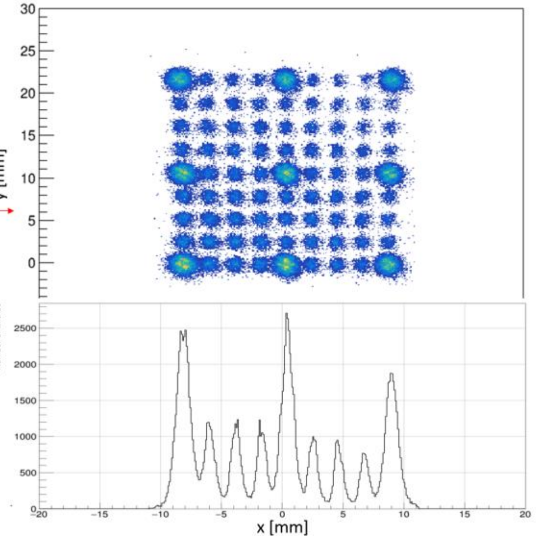


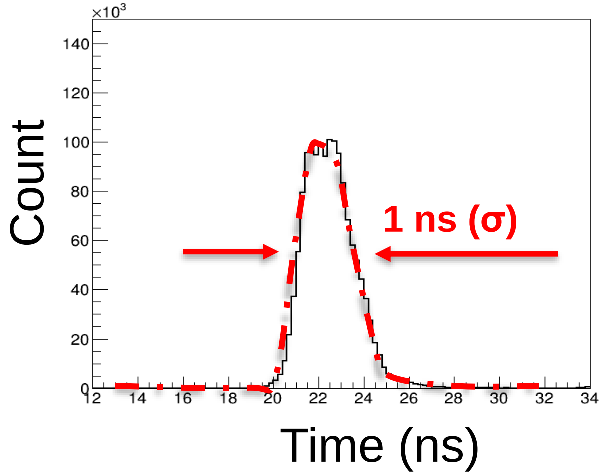
Performance:
-) Spatial Resolution < 0.5 mm (σ)
-) Time resolution ~ 1 ns (σ)

10x10 cm^2



Isobutane (7 Torr)



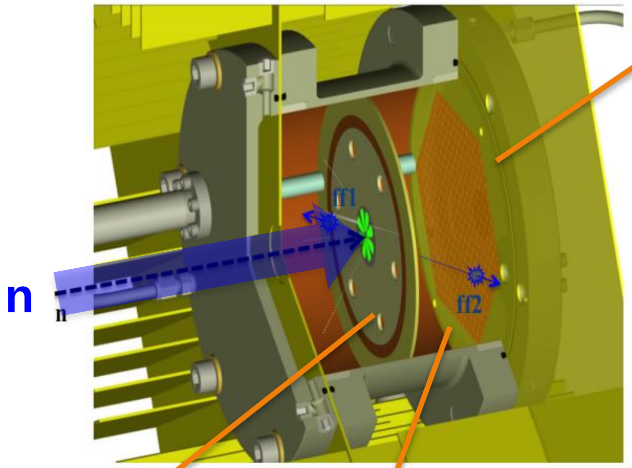


PPAC Problems
-) Large area → Fragile, difficult to maintain
-) Poor spatial resolution ~ 4 mm (FWHM)
-) Modest rates (up to a few kHz)

➔ Test new technology to improve resolution

Neutron Induced Fission Fragment Tracking Experiment

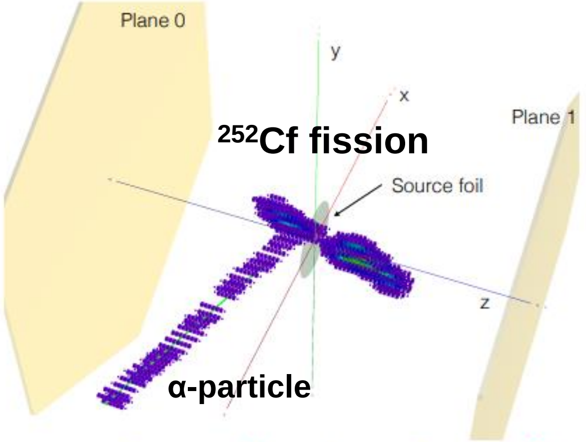
Motivation: Study and improve cross section ratio systematics
NIFFTE: two-chamber MICROMEGAS TPC ➔ precision cross section measurements of neutron-induced fission

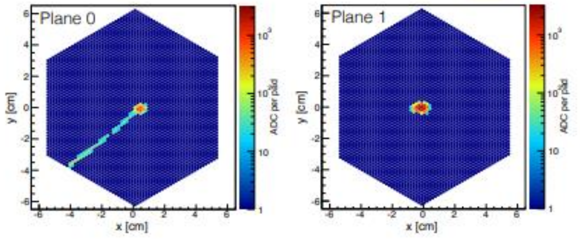


Position-sensitive MM board with 2976 pad (2 mm wide)

Fixed target

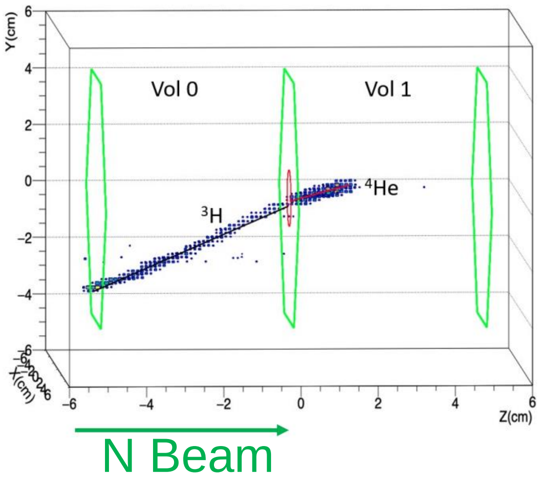
Gas: 95% argon, 5% isobutane

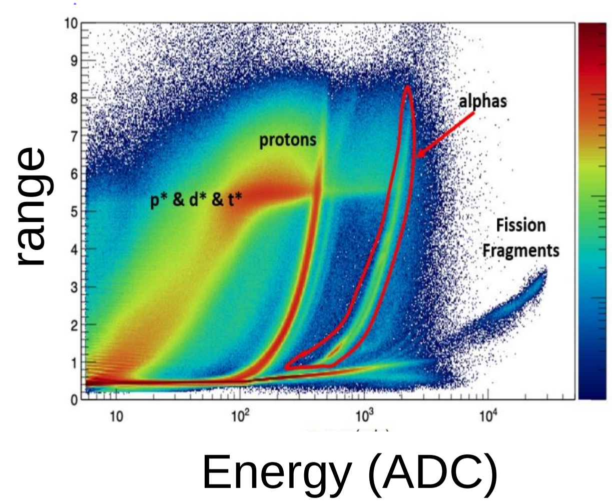




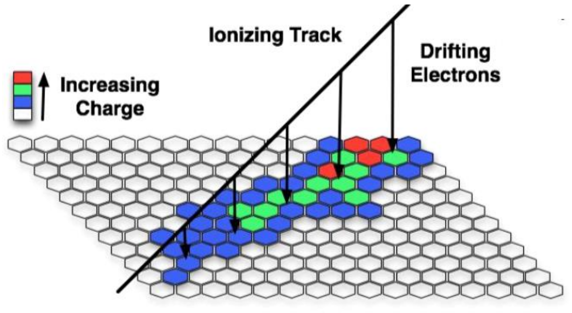
Extensive details can be found in:
NIM A 759 (2014) 50-64

^{6}Li(n,t)α Reaction Event Identification



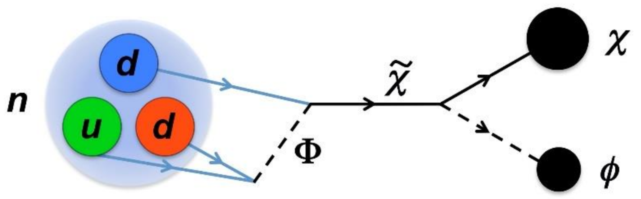


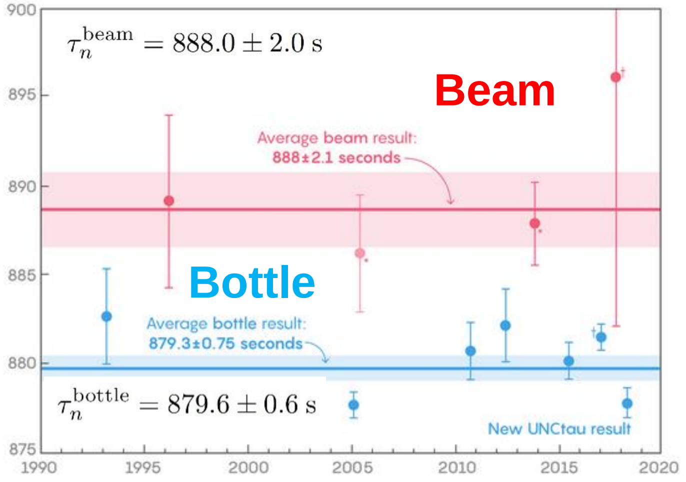
- Neutron time-of-flight measured
- 3D ionization profile for individual tracks provides:
  - Track length
  - Total energy
  - Track direction
  - Bragg Peak
  - Interaction vertex



Applications to exotic decays: Neutron lifetime puzzle & Dark decay

Motivation: Free neutron lifetime measured in beam and in bottle are ~4σ away!
Different observables measuring different decay modes?





Possible explanation (Fornal and Grisntein):
-) the neutron decay to a dark matter particle
➔ 3 different decay mechanisms could be possible
-) A branching ratio of ~1% would explain the n lifetime puzzle

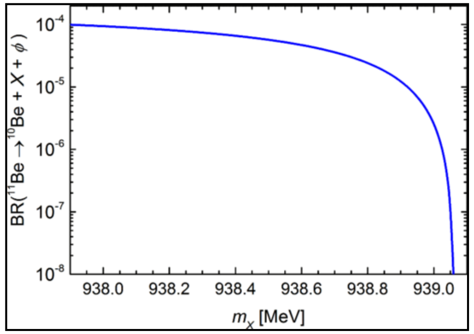
<u>Suggestion:</u> **Dark decay also possible in halo nuclei (weakly bound n) ➔ S_n<1.572 MeV**

Possible candidates: ^{6}He, ^{11}Li, **^{11}Be**, ^{15}C, and ^{17}C

➔ branching ratio upper limit of 10^{-4} depending on the dark particle mass.

^{11}Be → ^{10}Be (β-delay proton emission + dark decay)

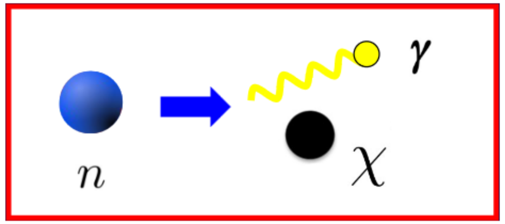
➔ measured using AMS with a branching ratio of 8.3(9) ·10^{-6}



Pfutzner, PRC 97, 042501 (2018)

Dark decay Scenarios

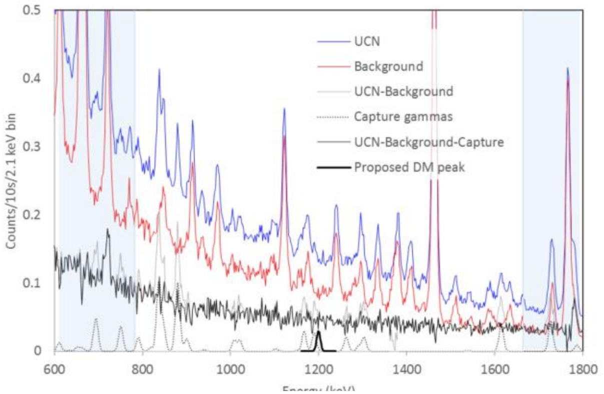
Scenario 1



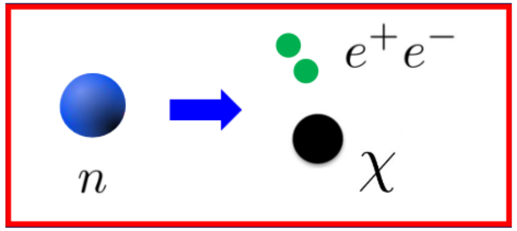
X

Tang et al., *Phys Rev Lett* **121** (2018), 022505

$$0.782 \text{ MeV} < E_\gamma < 1.664 \text{ MeV}$$



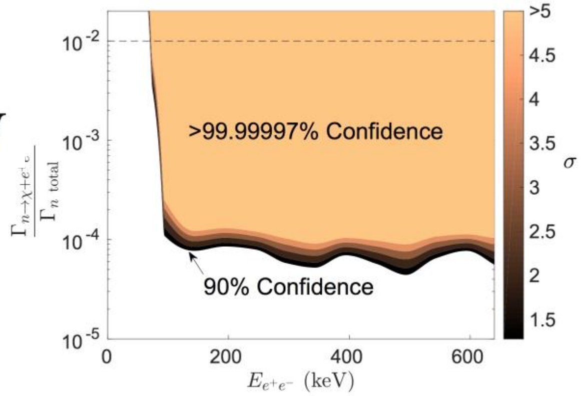
Scenario 2



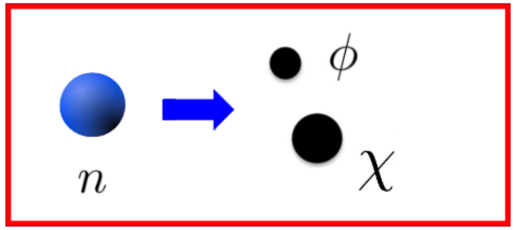
X

Sun et al., *Phys. Rev. C* **97** (2018), 052501

$$2\,m_e + 100 \text{ keV} \leq E_{e^+e^-} < 1.665 \text{ MeV}$$



Scenario 3

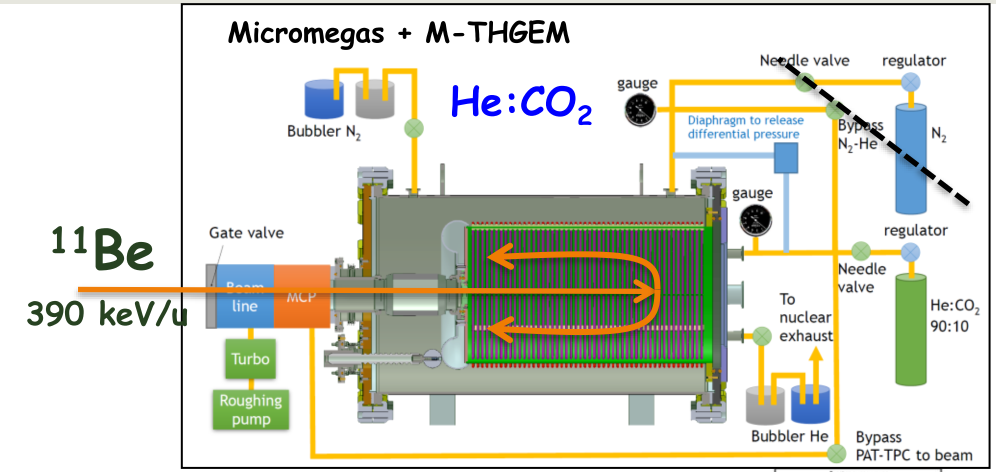


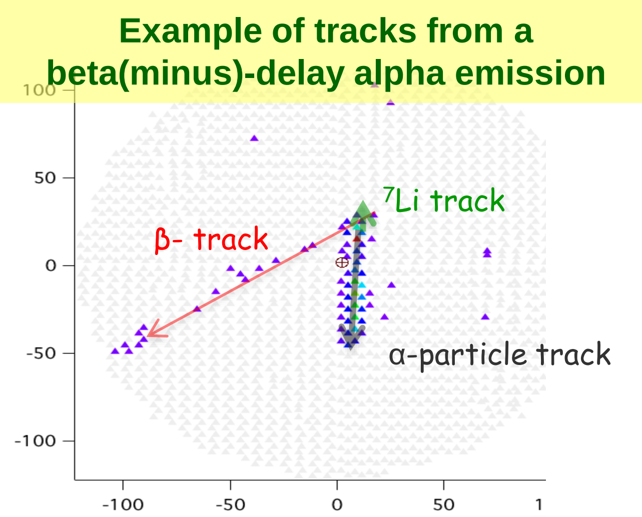
(?)

Fornal and Grisntein, PRL 120, 191801(2018)

MPGD-based TPC readout for dark decay search

First observation of a β^- delay proton emission!



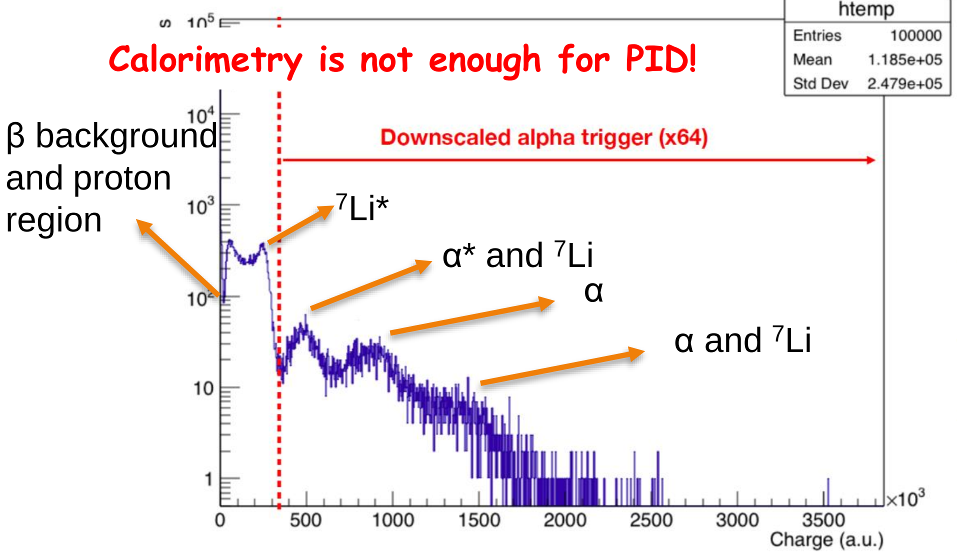


Y. Ayyad (NSCL) et al., Phys. Rev. Lett. 123, 082501

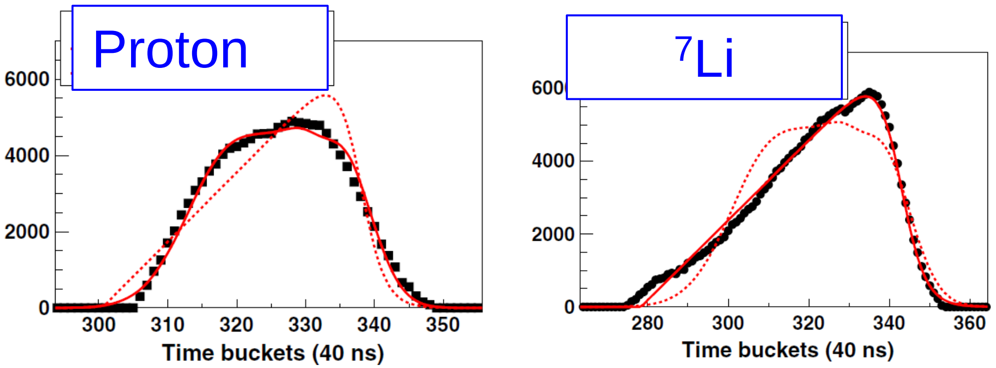
pAT-TPC → tracking of particles with two order of magnitude difference in specific ionization density

Beta-delayed proton decay of 11Be explained by an exotic near-threshold resonance that favors proton decay
➔ No room for dark decay!

E. Lopez-Saavedra et al., PRL 129 (2022), 012502



PID based on analysis of dE



(^{11}Be → ^{10}Be + p) branching ratio results (10^{-5}- 10^{-6}) compatible with AMS ^{11}Be → ^{10}Be value ($8.3\cdot10^{-6}$).

Applications to exotic decays: The X17 Boson

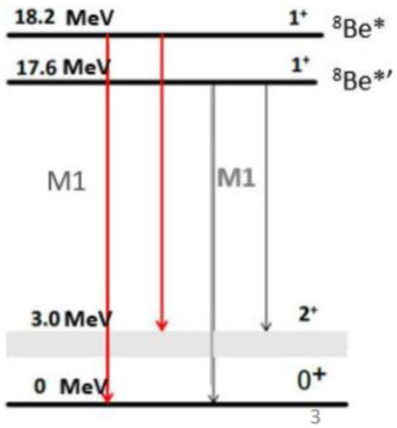
PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

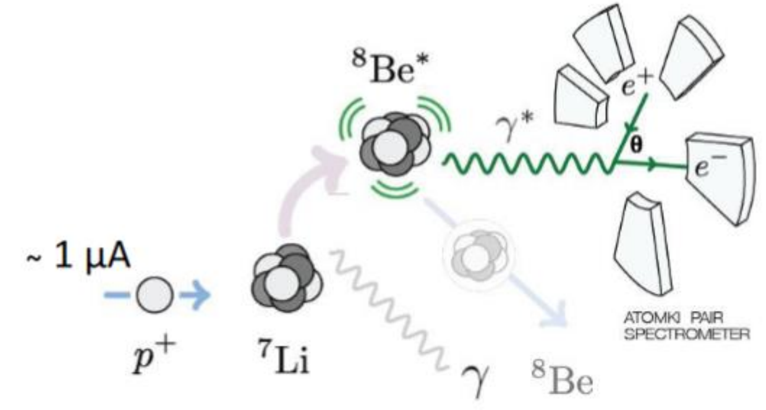
Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

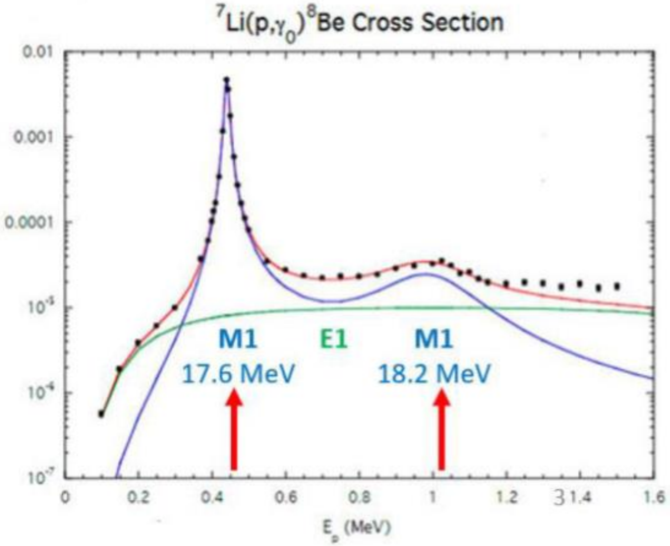
A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

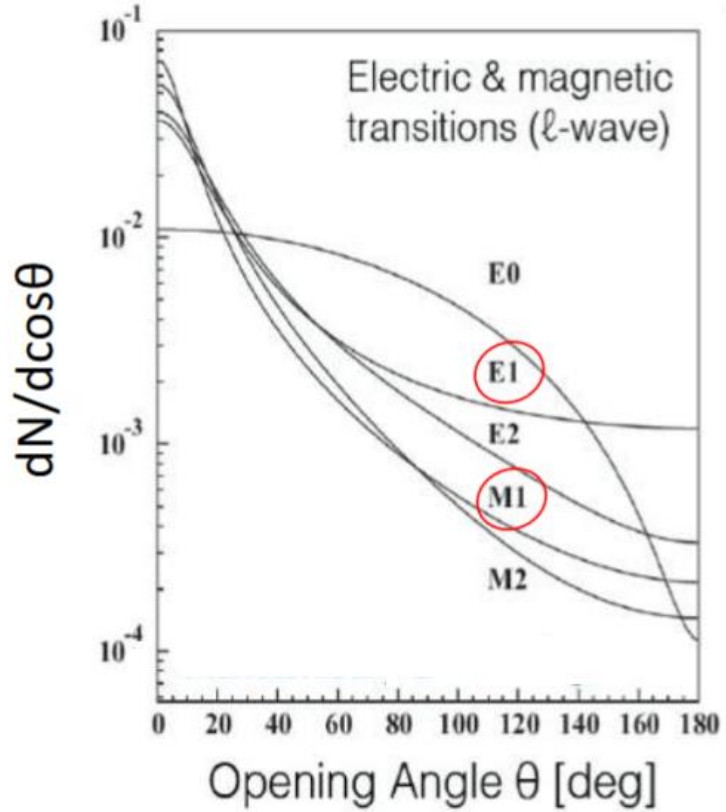
A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(Received 7 April 2015; published 26 January 2016)







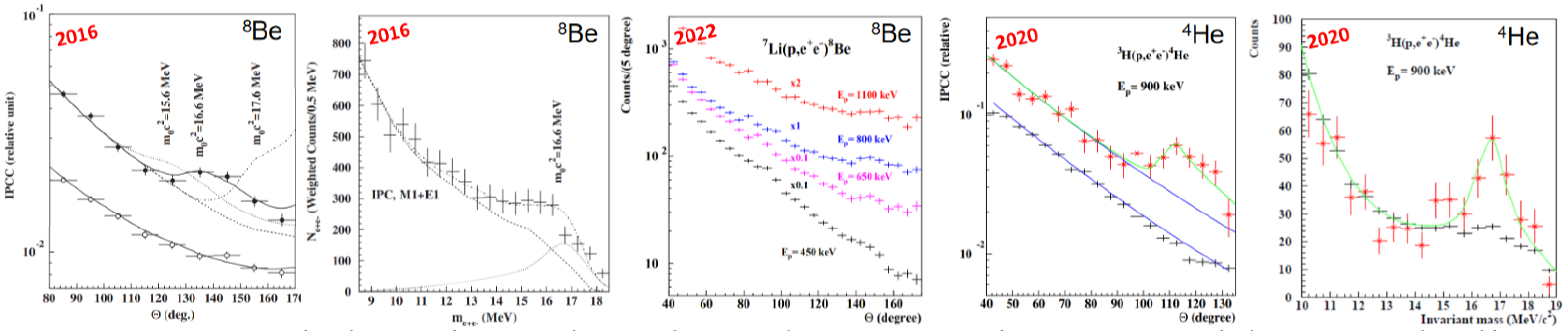
P. Schlüter et al, Physics Reports 75 (1981), pp 327-392.

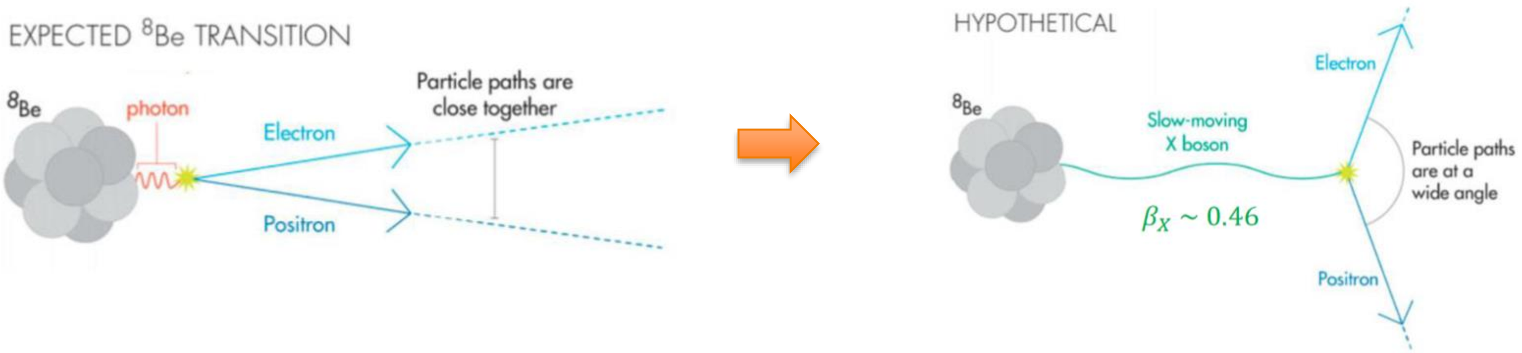


-) Photo-production in ^{8}Be* via p+^{7}Li
-) Fraction of the photons converted into e+e- by IPC
-) Measure angular distribution of the e+e- pair

Decay and Internal Pair Creation (IPC): ATOMKI's Anomaly

A.J. Krasznahorkay et al., Phys. Rev. Lett. 116 (2016) 042501
A.J. Krasznahorkay et al, J. Phys.: Conf. Ser. 1643 (2020) 012001

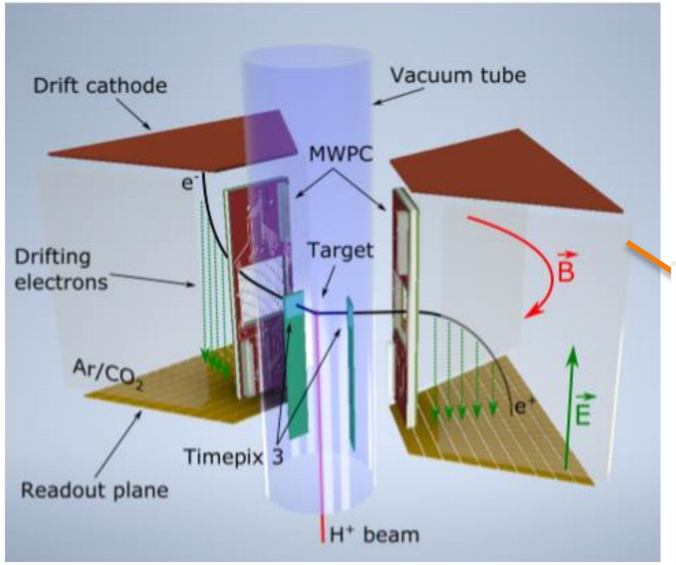




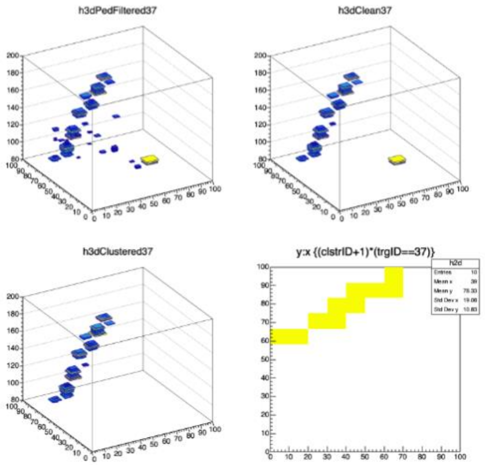
Example of X17 search with MPGD tracking

X17 spectrometer at CTU

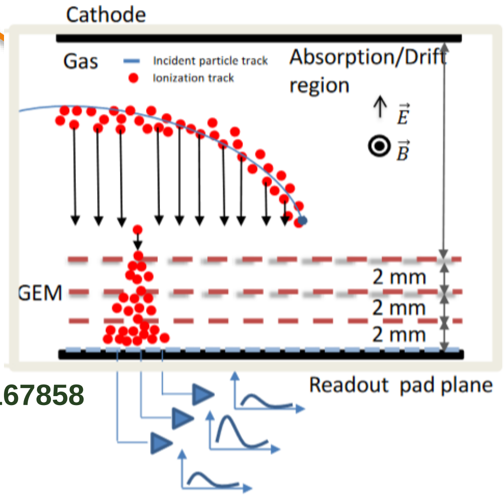
Proposed Detector concept ➔ Three detectors:
1) Timepix3 → angle measurement
2) MWPC → angle and scattering measurement
3) MPGD-TPC → energy measurement and PID



A.F.V. Cortez *et al.*, NIMA 1047, February 2023, 167858

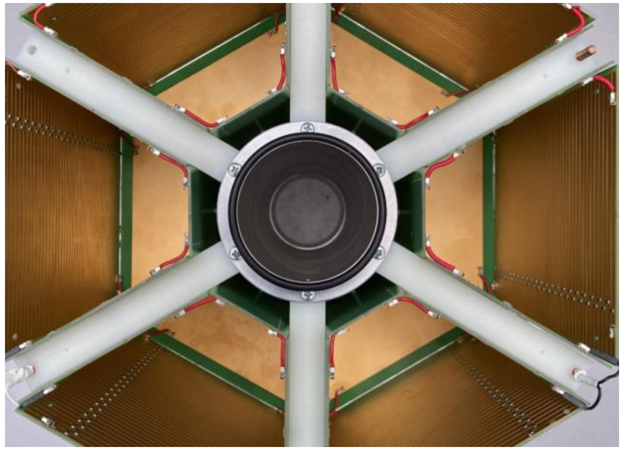


TPC readout based on 3 GEM foils



- XY position given by the readout plane;
- Z coordinate given by the charge drift time;
- 3D tracking (event topology);
- Particle ID;
- Background rejection.

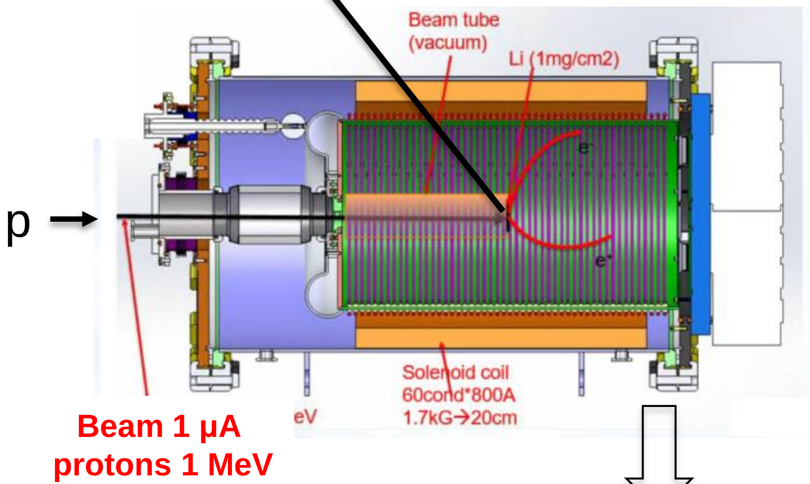
Track recognition with machine learning techniques
1) Unusual **E** × **B** configuration:
➔ Physics reconstruction under development from simulated tracks



- Voltage divider's SMD resistors in foils
- Readout with SAMPA chip (developed by USP for ALICE).

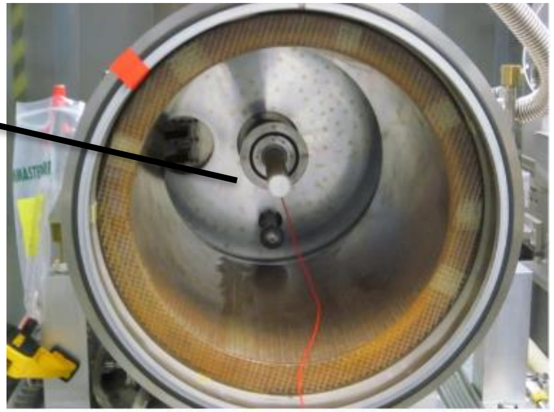
TPC with solid target for X17 boson search

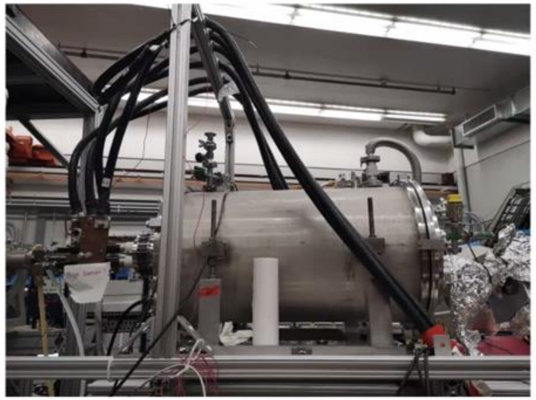
Target:
-) 400 μg/cm Lithium Hydroxide (LiOH)
-) 10 μg/cm Lithium Fluoride (LiF)



M-THGEM+Micromegas

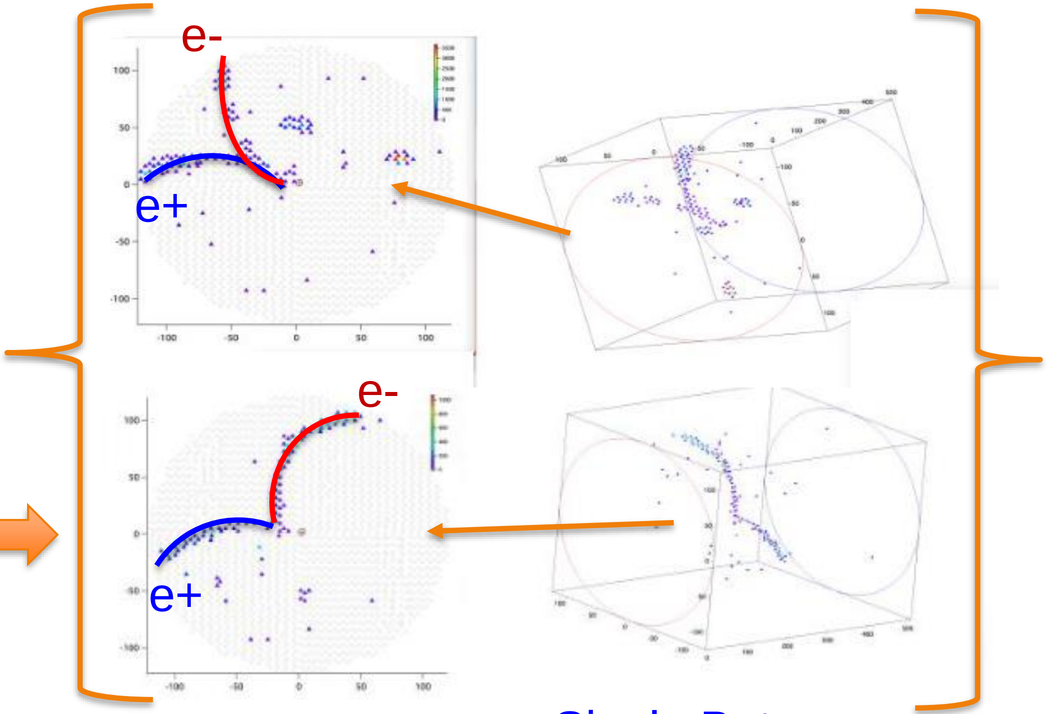
Gas filling: P10 @ 1 atm

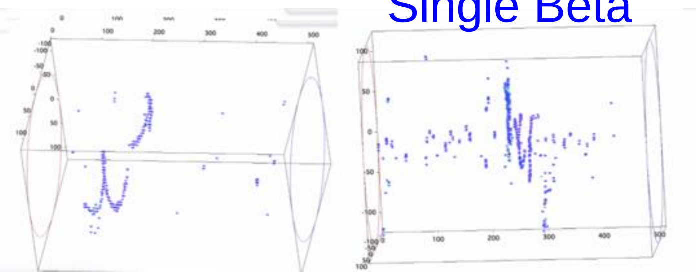




TwinSol – Notre Dame University (Indiana)

Courtesy Y. Ayyad (AT-TPC collaboration)

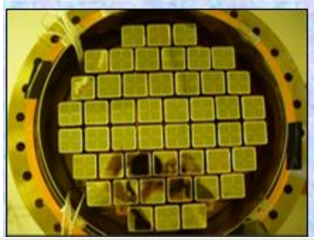


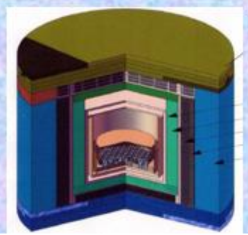


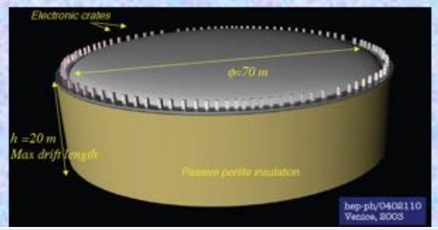
MPGD: Rare event search

from M. Titov MPGD2017

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
DARWIN (multi-ton dual-phase LXe TPC) Start: >2020s	Dark Matter Detection	THGEM-based GPMT	Total area: ~30m^2 Single unit detect. ~20 x20 cm^2	**Max.rate:** 100 Hz/cm^2 **Spatial res.:** ~ 1cm **Time res.:** ~ few ns **Rad. Hard.:** no	Operation at ~180K, radiopure materials, dark count rate ~1 Hz/cm^2
PANDAX III @ China Start: > 2017	Astroparticle physics Neutrinoless double beta decay	TPC w/ Micromegas μbulk	Total area: 1.5 m^2	**Energy Res.:** ~ 1-3% @ 2 MeV **Spatial res.:** ~ 1 mm	High radiopurity High-pressure (10b Xe)
NEWAGE@ Kamioka Run: 2004-now	Dark Matter Detection	TPC w/ GEM+μPIC	Single unit det. ~ 30x30x41(cm^3)	Angular resolution: 40˚ @ 50keV	
CAST @ CERN: Run: 2002-now	AstroParticle Physics: Axions, Dark Energy/ Matter, Chameleons detection	Micromegas μbulk and InGrid (coupled to X-ray focusing device)	Total area: 3 MM μbulks of 7x 7cm^2 Total area: 1 InGrid of 2cm^2	**Spatial res.:** ~100μm **Energy Res:** 14% (FWHM) @ 6keV **Low bkg. levels (2-7 keV):** μMM: 10-6 cts s-1keV-1cm-2 InGrid: 10-5 cts s-1keV-1cm-2	High radiopurity, good separation of tracklike bkg. from X-rays
IAXO Start: > 2023 ?	AstroParticle Physics: Axions, Dark Energy/ Matter, Chameleons detection	Micromegas μbulk, CCD, InGrid (+ X-ray focusing device)	Total area: 8 μbulks of 7 x 7cm2	Energy Res: 12% (FWHM) @ 6keV **Low bkg. Levels (1-7 keV):** μbulk: 10-7cts s-1keV-1cm-2	High radiopurity, good separation of tracklike bkg. from X-rays





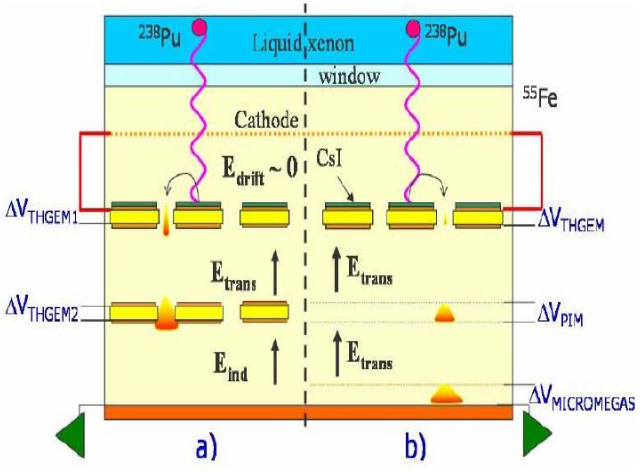


The Cryogenic Frontier for Rare Event Search

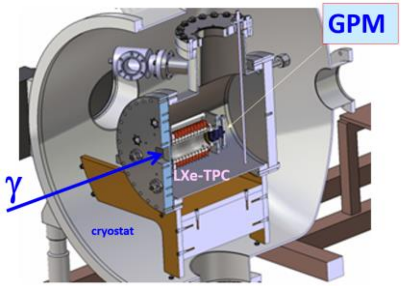
Read-out elements of cryogenic noble liquid detectors → Rear event detectors (n, DM) & Medical Physics (PET)

- Detecting the scintillation light produced in the noble liquids
- Options of scintillator light and ionization charge detection by a same detector!

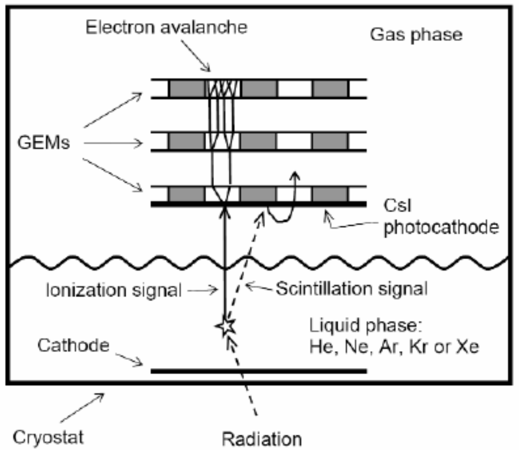
with windows



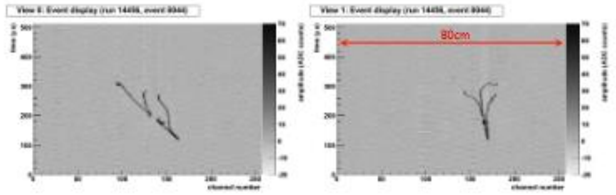
S.Duval et al., JINST 6 (2011) P04007



Windowless (2-phases)

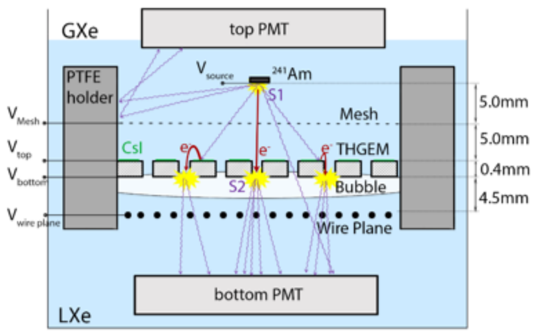


A. Bondar et al., NIMA 556 (2006) 273
B. & Rubbia group ETHz - LArTPC

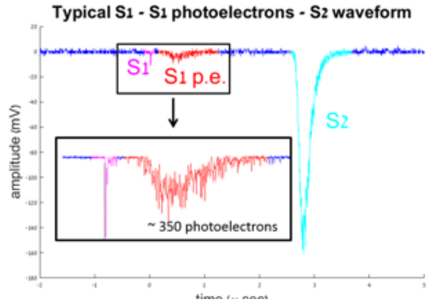


Operated in Cryogenic Liquid

Bubble-assisted Liquid Hole-Multipliers

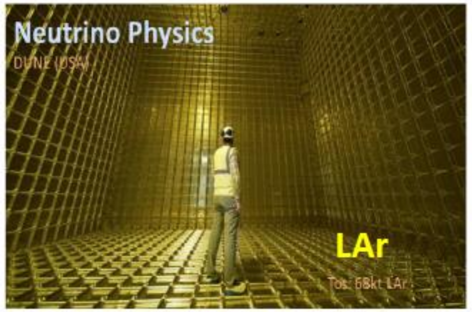


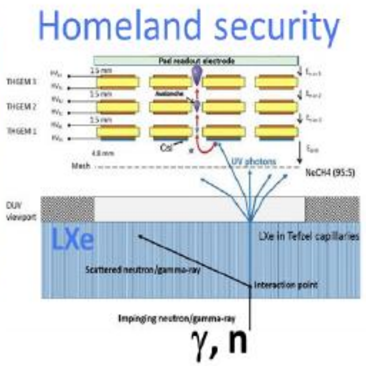
Erdal et al. arXiv:1509.02354

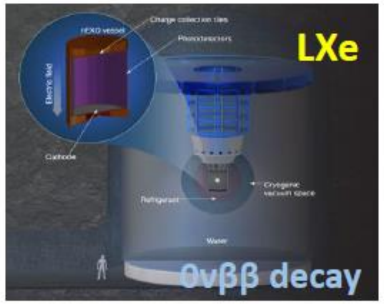


Noble liquid detectors

- ***Why noble-liquid detectors?***
  - High density ➔ higher interaction probability (gamma, n, rare events);
  - High scintillation and ionization yields ➔ VUV photons & Ionization-electrons
  - Scalability (**Xe** cost >>> **Ar**)
- ***What are the challenges ?***
  - Rare events ➔ large volumes, high radiopurity & background discrimination, very high sensitivity
- ***How?***
  - **Charge readout** (with/without multiplication)
  - **Light readout** (primary scintillation & electroluminescence) with PMTs, SiPMs etc.

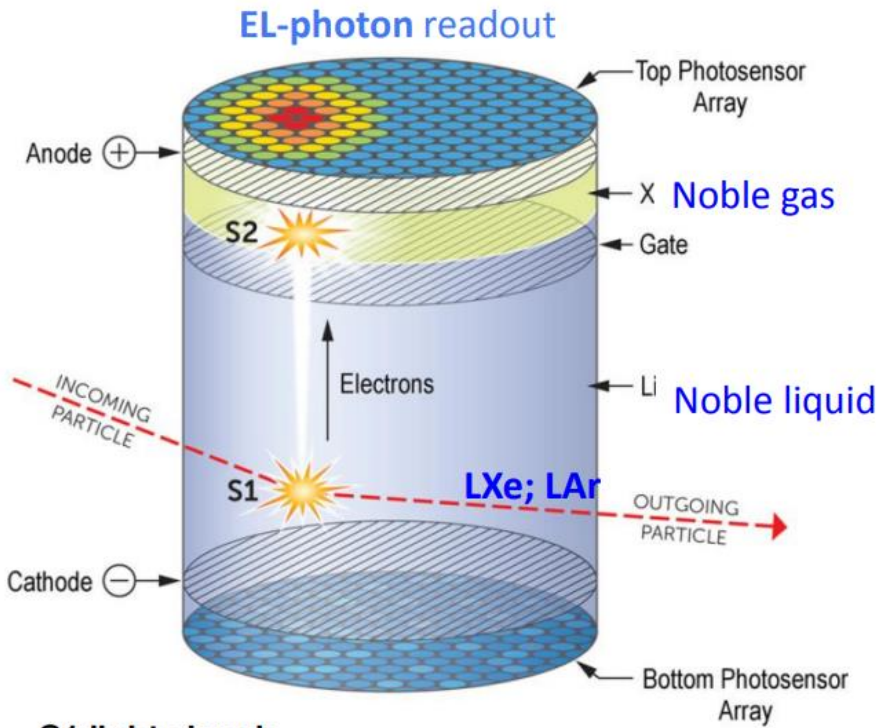






A. Breskin, FRIB seminar 2023

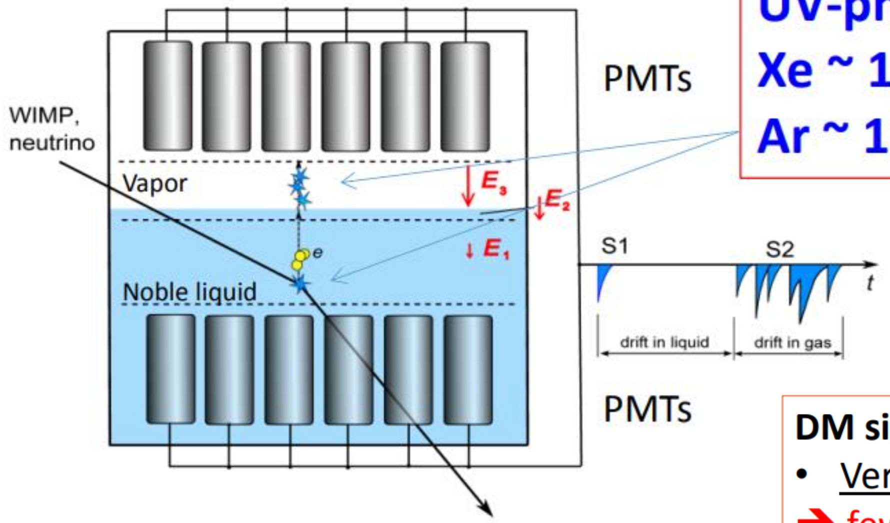
Dual-phase liquid noble-gas TPC



S1 light signal:
- prompt scintillation photons

S2 charge signal:
- secondary scintillation photons from electroluminescence in GXe due to drifted electrons

3D event position reconstruction:
- X,Y: S2 hit pattern
- Z: drift time S2-S1



UV-photons:
Xe ~ 175nm
Ar ~ 128nm

The **EL-photon** readout can be substituted by **charge** readout: electron avalanche multiplication. e.g. in: **LEM (THGEM).**
Proto-DUNE: **too low gain.**

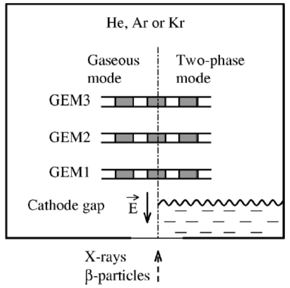
DM signals:
- Very small: low-E recoils eV-KeV
➔ few-to-tens electrons in noble-liquid
- Very rare:

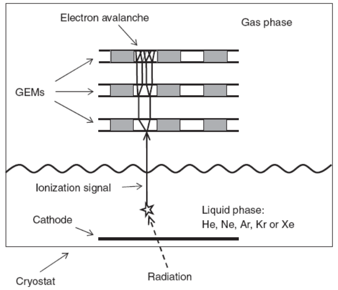
1 event/Kg Y @ low mass
1 event/t Y @ high mass in LXe
- Buried in huge background:

> 10^6-fold higher rates
➔ Underground
➔ Low-radioactivity materials/gas
➔ cosmics VETO

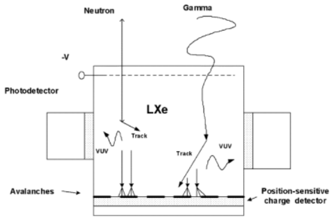
A. Breskin, FRIB seminar 2023

MPGD: cryogenic R&D (Concept Gallery)

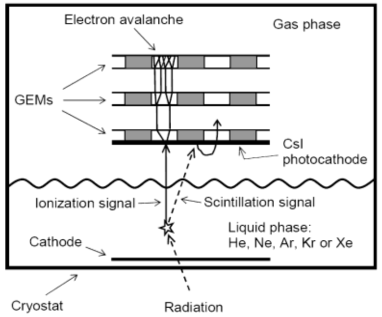




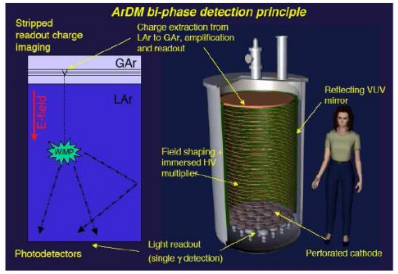
A.Buzulutskov et al, IEEE TNS 50 (2003) 2491;
A.Bondar et al, NIMA 524 (2004) 130



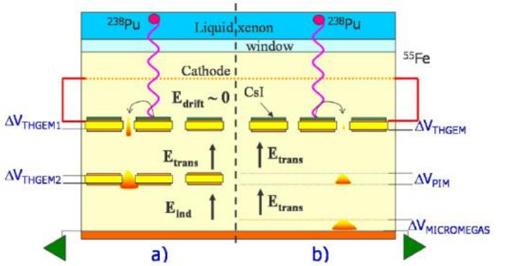
Periale et al, IEEE TNS 52 (2005) 927



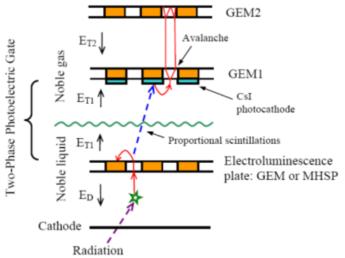
A.Bondar et al, NIMA 556 (2006) 273



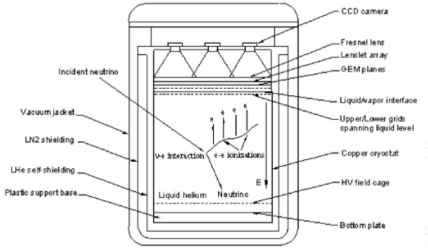
A.Rubbia, J. Phys. Conf. Ser. 39 (2006) 129



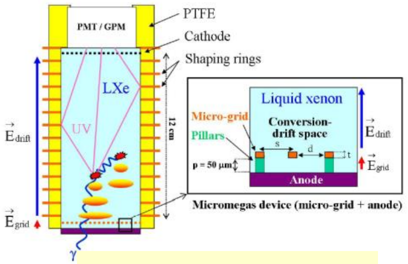
S. Duval et al, JINST 6 (2011) P04007



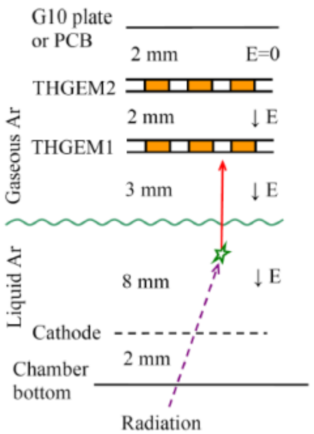
A.Buzulutskov, A.Bondar, JINST 1 (2006) P08006



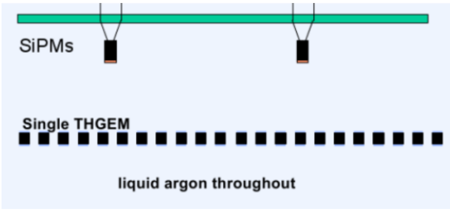
Y.L.Ju et al, Cryogenics 47 (2007) 81



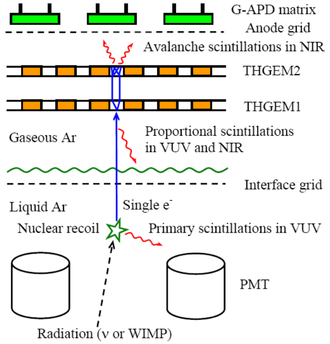
S. Duval et al, JINST 4 (2009) P12008



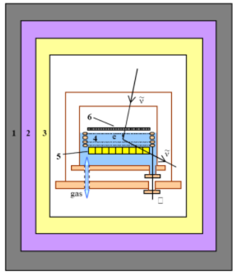
A.Bondar et al, JINST 3 (2008) P07001



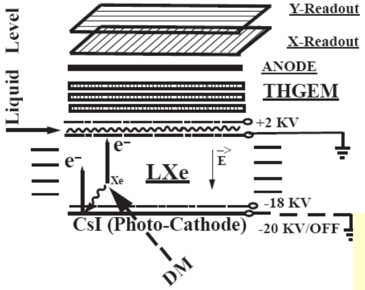
Lightfoot et al, JINST 4 (2009) P04002



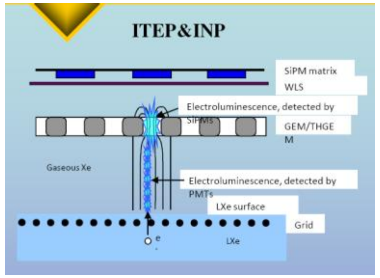
A. Bondar et al, JINST 5 (2010) P08002
A.Buzulutskov et al, EPL 94 (2011) 52001



D.Akimov et al, JINST 4 (2009) P06010



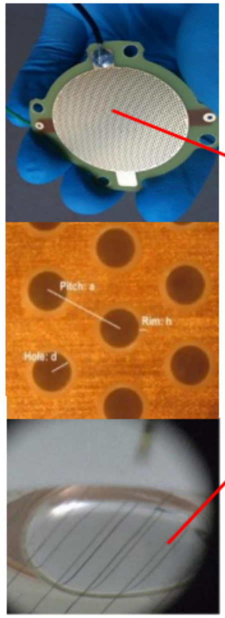
M.Gai et al, Eprint arxiv:0706.1106 (2007)

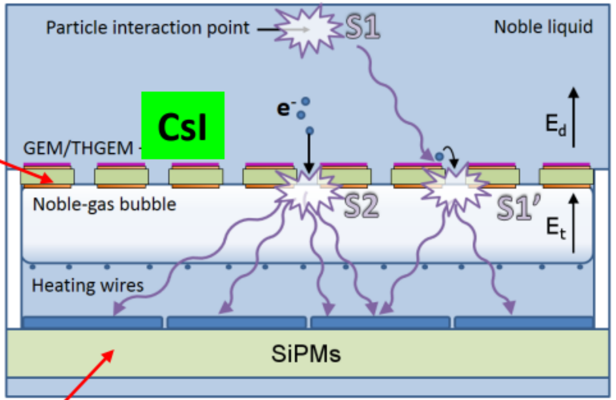


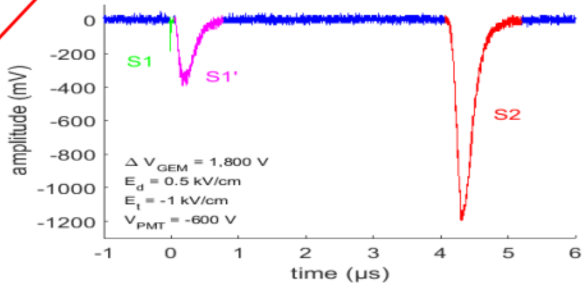
D.Akimov, NIMA 628 (2011) 50

Bubble-assisted Liquid Hole Multiplier LHM

Principle: Radiation-induced electroluminescence from a bubble trapped in noble liquid







- Creating a local "vapor bubble" underneath a perforated electrode, immersed within a large noble-liquid volume.
- The electrode is coated by **CsI UV-photocathode.**
- **BOTH: S2** Electrons and **S1**-induced **S1'** photoelectrons drift from the liquid into the bubble.
- ELECTROLUMINESCENCE within the bubble ➔ **Energy, 2D localization.**
- **Demonstrated in both LXe & LAr.**

Photo-yield: ~**400 photons /e-/4π**

Arazi et al., 2015_JINST 10 P08015
Arazi et al., NIM A 845 (2017) 218
Erdal et al., 2019 JINST 14, P01028
Erdal et al., 2018 JINST 13 P12008
Erdal et al., 2019 JINST 14 P11021

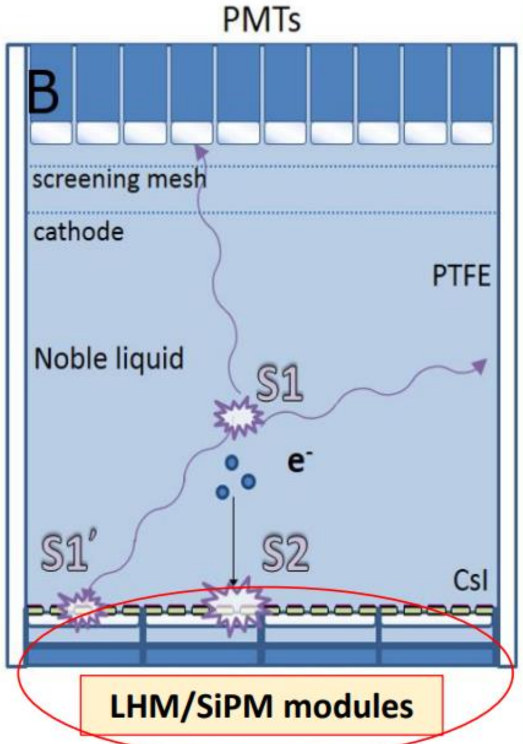
Bubble LHM LXe.mp4

Precise control of the liquid-gas interface, expected:
➔ better S2 resolution
➔ potentially better S2/S1-based background discrimination

A predecessor of single phase!

http://dx.doi.org/10.1088/1475-7516/2016/11/017

Potential DARWIN LHM-TPC



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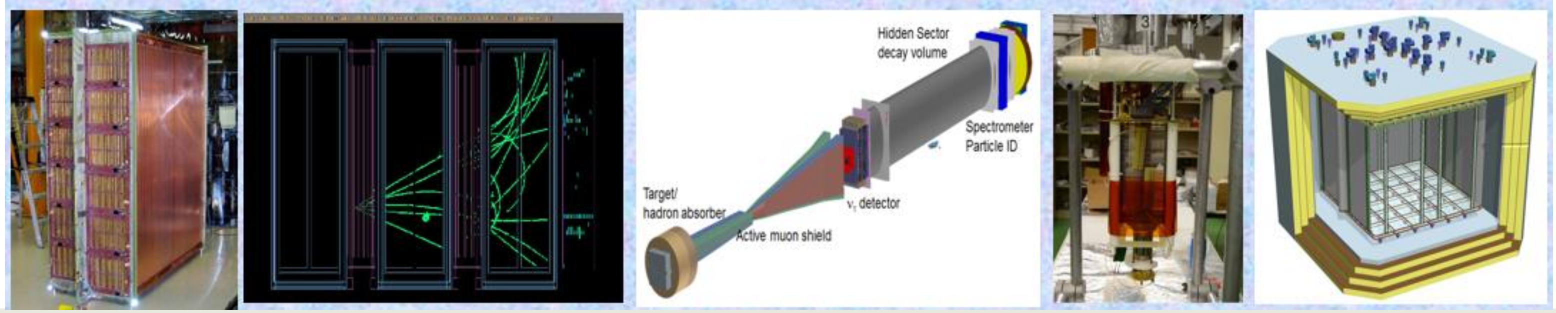
A. Breskin, FRIB seminar 2023

MPGD: application to Neutrino physics

from M. Titov MPGD2017

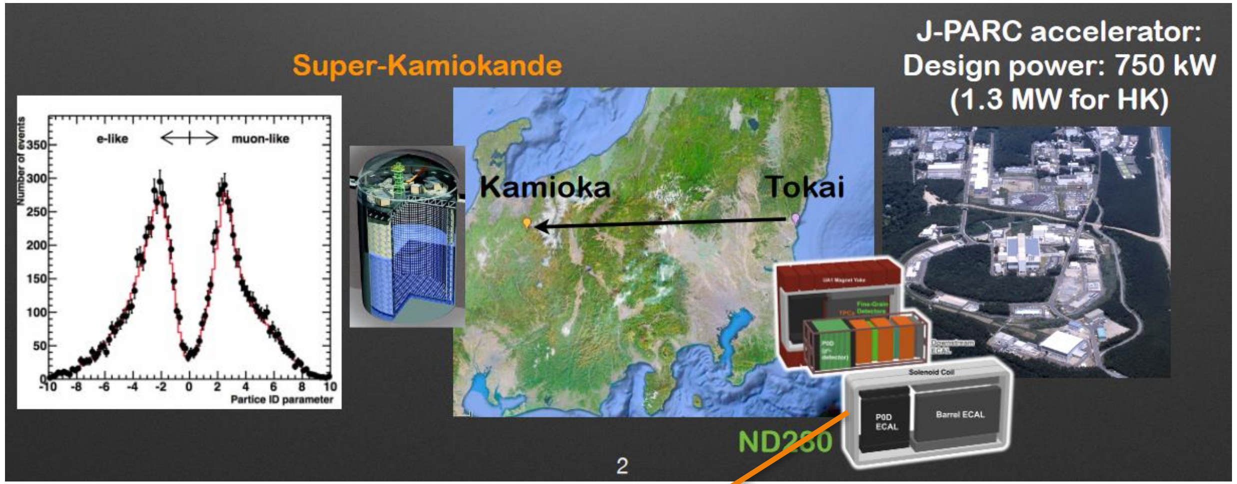
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
T2K @ Japan Start: 2009 - now	Neutrino physics (Tracking)	TPC w/ Micromegas	Total area: ~ 9 m^2 Single unit detect: 0.36x0.34m^2~0.1m^2	**Spatial res.:** 0.6 mm **dE/dx:** 7.8% (MIP) **Rad. Hard.:** no Moment. res.:9% at 1 GeV	The first large TPC using MPGD
SHiP @ CERN Start: 2025-2035	Tau Neutrino Physics (Tracking)	Micromegas, GEM, mRWELL	Total area: ~ 26 m^2 Single unit detect: 2 x 1 m^2 ~ 2m^2	**Max. rate:** < low **Spatial res.:** < 150 µm **Rad. Hard.:** no	Provide time stamp of the neutrino interaction in brick"
LBNO-DEMO (WA105 @ CERN): Start: > 2016	Neutrino physics (Tracking+ Calorimetry)	LAr TPC w/ THGEM double phase readout	Total area: 3 m^2 (WA105-3x1x1) 36 m^2 (WA105-6x6x6) Single unit detect. (0.5x0.5 m2) ~0.25 m^2	WA105 3x1x1 and 6x6x6: **Max. rate:** 150 Hz/m^2 **Spatial res.:** 1 mm **Time res.:** ~ 10 ns **Rad. Hard.:** no	Detector is above ground (max. rate is determined by muon flux for calibration)
DUNE Dual Phase Far Detector Start: > 2023?		LAr TPC w/ THGEM double phase readout	Total area: 720 m^2 Single unit detect. (0.5x0.5 m2) ~ 0.25 m^2	**Max. rate:** 4*10^{-7} Hz/m^2 **Spatial res.:** 1 mm **Rad. Hard.:** no	Detector is underground (rate is neutrino flux)



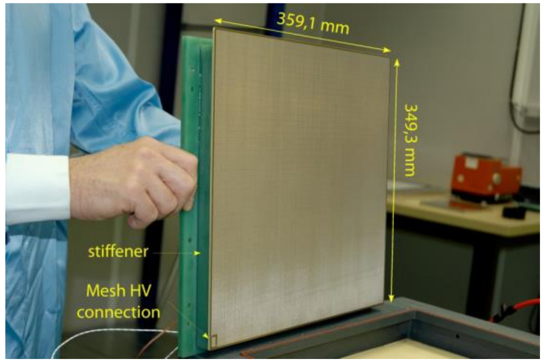
T2K - Tokai to Kamioka

T2K Neutrino Oscillations: **FIRST** and the **LARGEST** TPCs equipped with MM

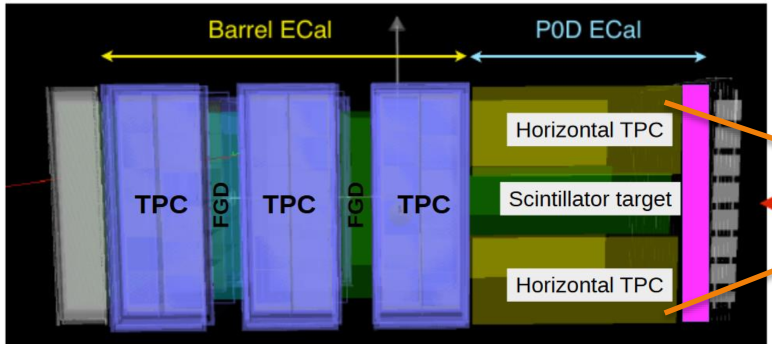
~9 m^2 with 72 bulk MM (120k ch.) operated since 2009



ND280 GOAL: Measure beam spectrum & flavor composition before the oscillations

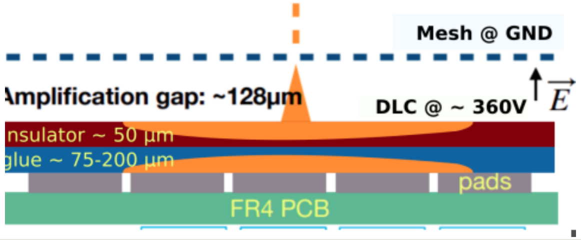


3 Time Projection Chambers: reconstruct momentum & charge of particles, PID based on measurement of ionization



Two new HA-TPC (from 2022)
➔ reconstruction of high angle leptons

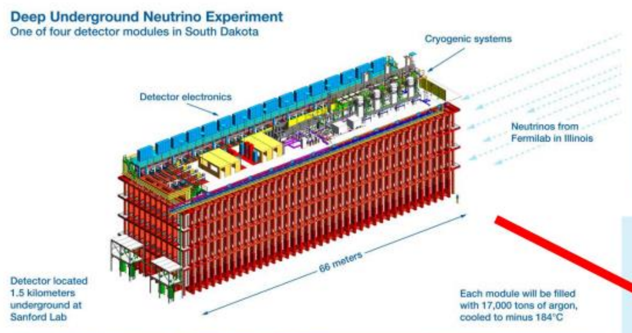
Resistive Micromegas



Deep Underground Neutrino Experiment

DUNE is the US-based next generation of Long Baseline Experiment

- 1300 km between FERMILAB (*beam, near detectors*) and SURF (*far detector*)



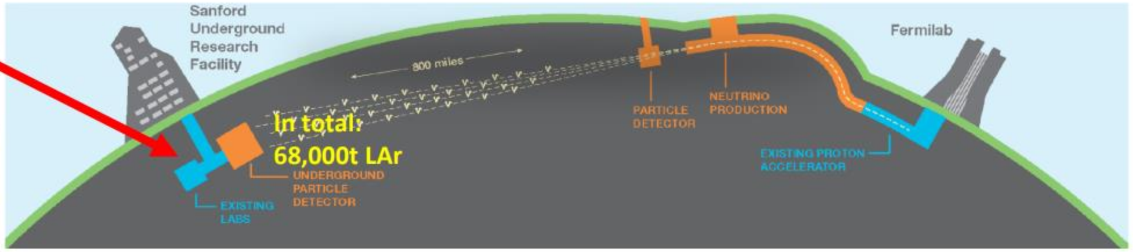
*Inside a **single** proto-DUNE module…*

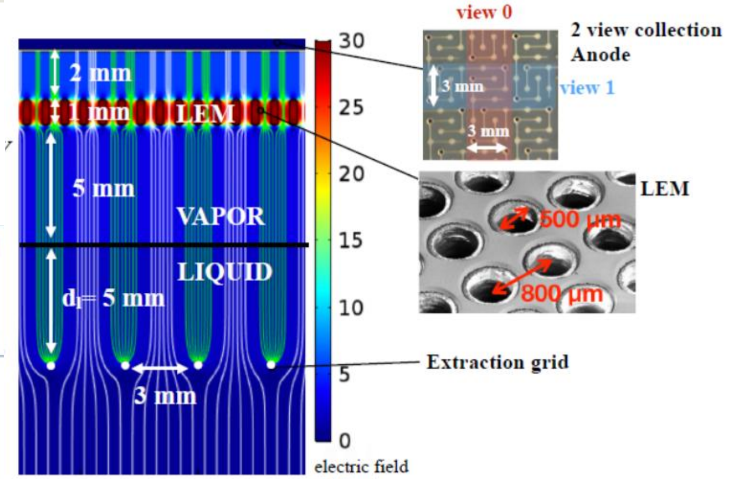
Far Detector
LAr-TPC
Measurement of Oscillated neutrino beam

Neutrino Travel through the Earth 1300 km

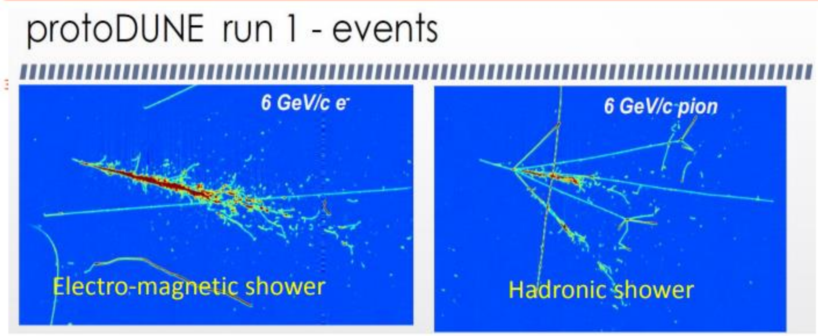
Near Detector
Monitoring unoscillated neutrino energy spectra & composition

Muon neutrino beam
LBNF Neutrino Beam
1.2 MW beam power
→ Upgradeable to 2.4 MW





- Homogeneous drift field thanks to cathode and field cage
- Extraction field between grid and LEM bottom electrode
- Amplification in LEMs holes
- Readout in two directions by induction on the anode by field between LEM top electrode and anode



The Far Detector is made of 4 giant LArTPC modules

- Each module has ~17 kt of LAr
- About 60 m × 12 m × 12 m of active volume
- FD cavern is 1.5 km underground
- Four module -> Four possible designs:
  - Module-1 : Horizontal Drift design
  - Module-2 : Vertical Drift design
  - Module 3-4 : Under discussions

"Speculative & Ambitious" Program Outline

- General intro MPGD applied to other field than HEP
  - Example of requirements HEP vs LENP / Rare Event search / etc.
- Application to HENP/LENP
  - R&D project with MPGD for EIC
  - Active Target TPC, inverse kinematic nuclear reactions study
    - -) physics, technology, challenges, ...(Operation pure elemental gas)
    - -) Examples of Active Target TPC project
  - Fission Fragment imaging system
- Rare Event Search Applications & Neutrino Physics
  - Exotic decays with MPGD-TPC (Dark Decay, X17 boson, etc..)
  - Cryogenic detector: mostly exotic ideas
  - Directional DM (Negative-ion TPC, high pressure TPC, etc.)
  - T2K and DUNE with MPGDs