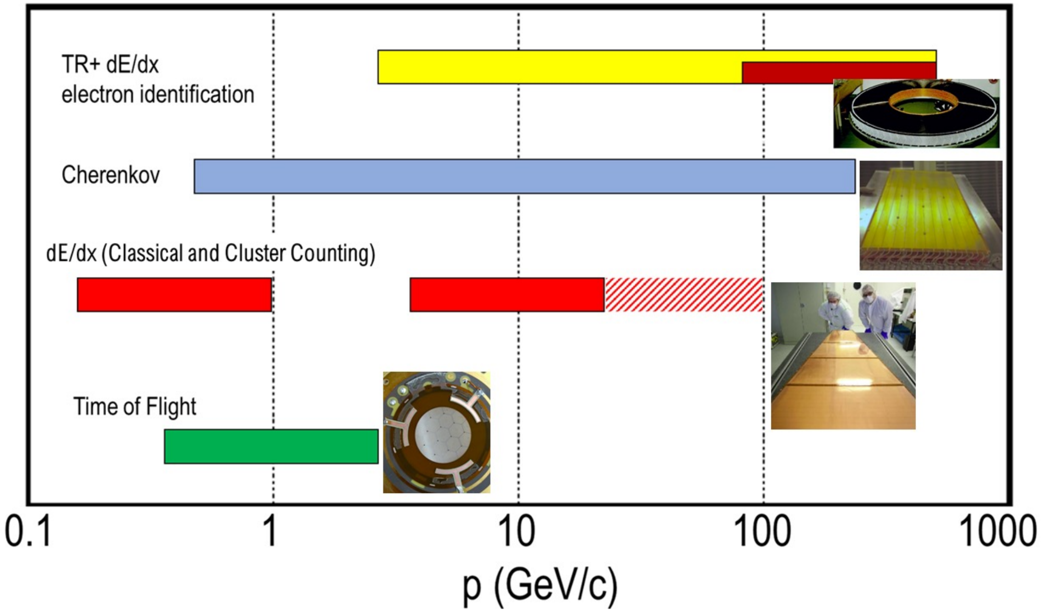
!MPGD
gaseous detectors

E. Radicioni – INFN

MPGD2022 – Dec 11-16, Weizmann Institute of Science

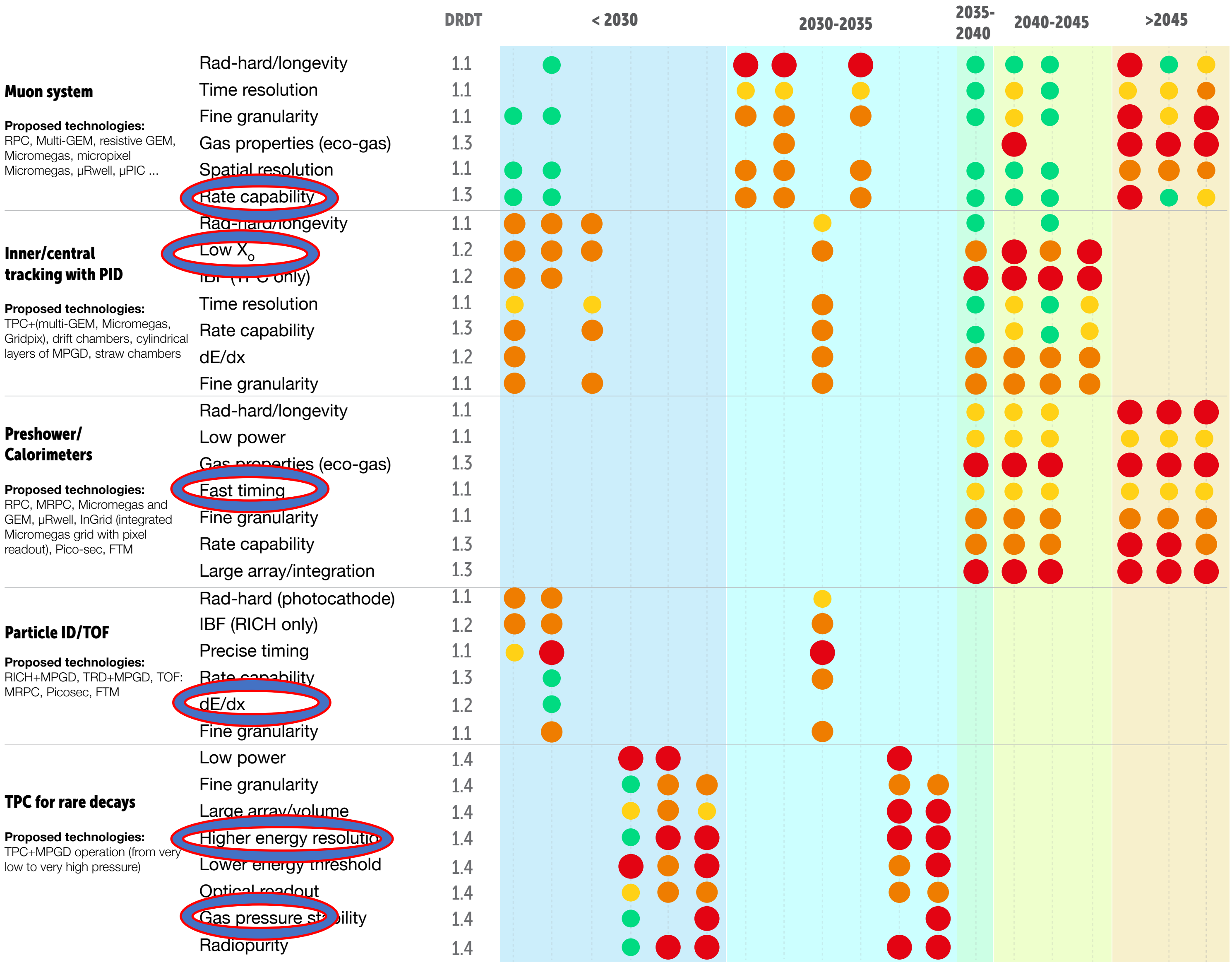
disclaimer

- A wide range of detectors, usage patterns, physics cases and techniques
- Attempting completness is vane
  - Some arbitrary choices were necessary
  - I take responsibility (and apologize) for what is missing



From the home page of the workshop “RD51 Workshop on Gaseous Detector Contributions to PID”

- Rate
- Timing
- Pressure
- dE/dx
- Lightness



		DRDT	< 2030	2030-2035	2035-2040	2040-2045	>2045
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...	Rad-hard/longevity	1.1	🟢	🔴🔴🔴	🟢	🟢🟢	🔴🟢🟡
	Time resolution	1.1		🟡🟡🟡	🟢	🟡🟢	🟡🟡🟠
	Fine granularity	1.1	🟢🟢	🟠🟠🟠	🟢	🟡🟢	🔴🟡🔴
	Gas properties (eco-gas)	1.3		🟠		🔴	🔴🔴🔴
	Spatial resolution	1.1	🟢🟢	🟠🟠🟠	🟢	🟢🟢	🟠🟠🟠
	Rate capability	1.3	🟢🟢	🟠🟠🟠	🟢	🟢🟢	🔴🟢🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠🟠🟠	🟡	🟢	🟢	
	Low X_o	1.2	🟠🟠🟠	🟠	🟠	🔴🟠🔴	
	IBF (TPC only)	1.2	🟠🟠		🔴	🔴🔴🔴	
	Time resolution	1.1	🟡🟡	🟠	🟢	🟡🟢🟡	
	Rate capability	1.3	🟠🟠	🟠	🟢	🟡🟢🟡	
	dE/dx	1.2	🟠	🟠	🟠	🟠🟠🟠	
	Fine granularity	1.1	🟠🟠	🟠	🟠	🟠🟠🟠	
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1			🟡	🟡🟡	🔴🔴🔴
	Low power	1.1			🟡	🟡🟡	🟡🟡🟡
	Gas properties (eco-gas)	1.3			🔴	🔴🔴	🔴🔴🔴
	Fast timing	1.1			🟡	🟡🟡	🟡🟡🟡
	Fine granularity	1.1			🟠	🟠🟠	🟠🟠🟠
	Rate capability	1.3			🟠	🟠🟠	🔴🔴🟠
	Large array/integration	1.3			🔴	🔴🔴	🔴🔴🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠🟠	🟡			
	IBF (RICH only)	1.2	🟠🟠	🟠			
	Precise timing	1.1	🟡🔴	🔴			
	Rate capability	1.3	🟢	🟠			
	dE/dx	1.2	🟢				
	Fine granularity	1.1	🟠	🟠			
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4	🔴🔴	🔴			
	Fine granularity	1.4	🟢🟠🟠	🟠🟠			
	Large array/volume	1.4	🟡🟠🟡	🔴🔴			
	Higher energy resolutio	1.4	🟢🔴🔴	🔴🔴			
	Lower energy threshold	1.4	🔴🟠🔴	🟠🔴			
	Optical readout	1.4	🟡🟠🟠	🟠🟠			
	Gas pressure stability	1.4	🟢🔴	🔴			
	Radiopurity	1.4	🟢🔴🔴	🔴🔴			

RPCs: state of the art and challenge

RPC vs mRPC

	RPC	mRPC
# of gaps	1	4 to 10s
$\rho[\Omega\ \mathrm{cm}]$	$5\mathrm{x}10^{10}$	$5\mathrm{x}10^{12}$
module size	$2\mathrm{m}^2$	$0.1\mathrm{m}^2$
$\mathrm{Hz/cm}^2$	10^4	$5\mathrm{x}10^2$
σ_t [ps]	500	50

RPC and MRPC Common features

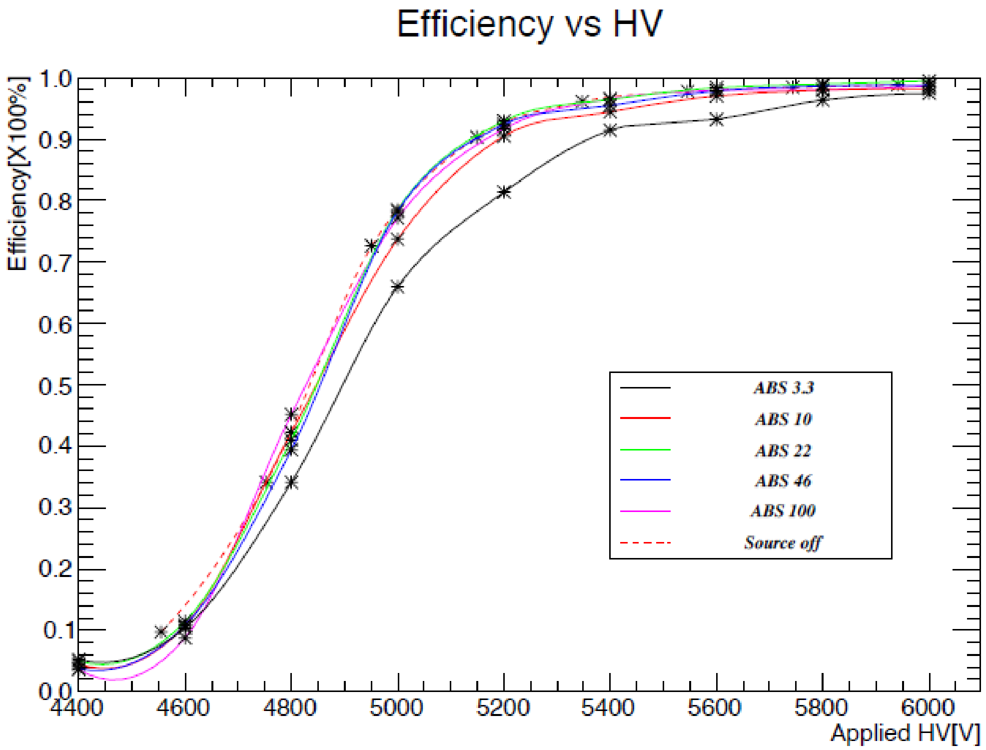
- Target and amplification coincide
- uniform field -> prompt signal
- Target and amplification coincide
- high R electrodes -> Spark less
- Uniform electrode -> simple
- Working at atm pressure -> simple
- Min 1 mm of target for full eff.
- Thin 0.1 mm 2D localization
- Very quenching and electronegative gasses

RPCs: increasing the rate

- rate capability saturates because of the voltage drop:

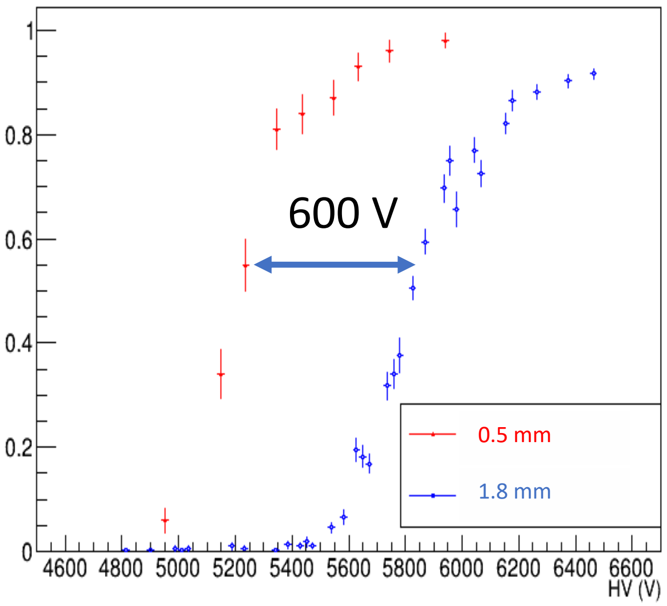
$\Delta V = \langle Q \rangle \cdot \text{freq} \cdot R$

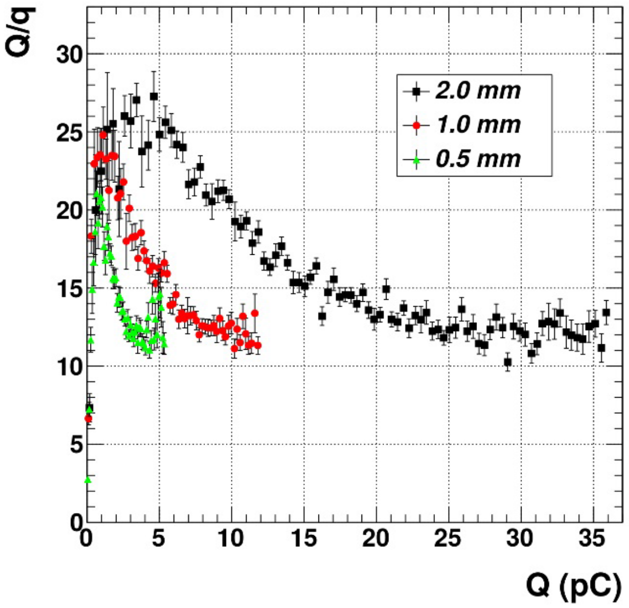
- Reduce R
  - But below a certain value the RPC becomes unstable
- Or reduce <Q>
  - By better S/N of the electronics

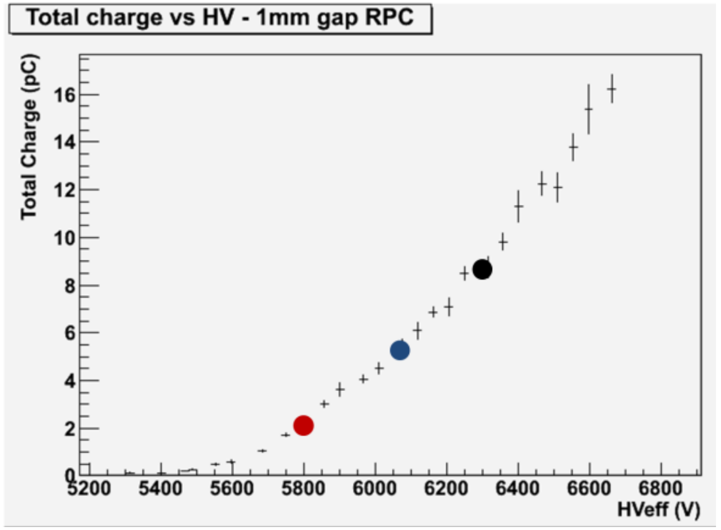


1mm gap ATLAS upgrade
Resistivity → $5*10^{10}$
Noise → 4000 e-
ABS3.3 at GIF++ → ~10 kHz/cm^2

Going further







HV reduction by thinning electrodes

Thinner gap → better Q/q

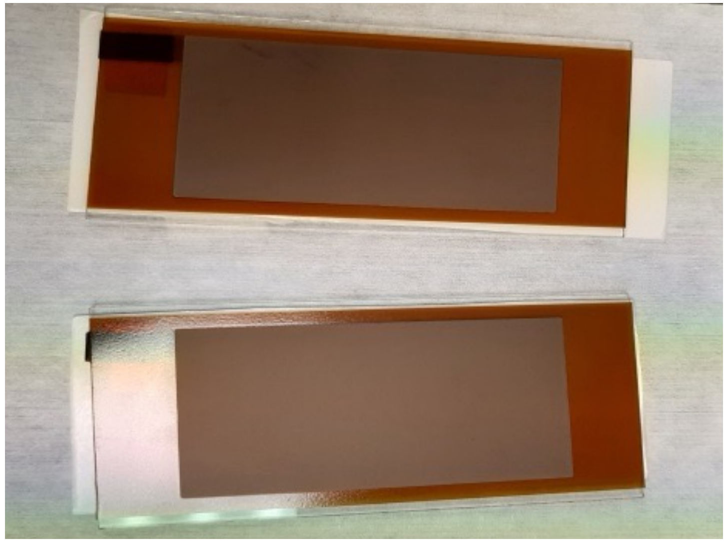
Reducing Q

- Better electronics
- Precision mechanics

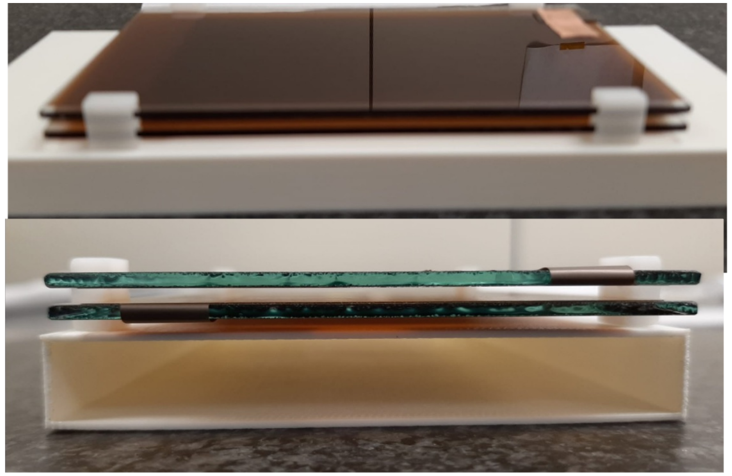
Cross-contamination with ... MPGDs

Mechanical simplicity: sRPC (surface RPC)

- Traditional resistive electrodes replaced by DLC coating
- Technology ported from resistive MPGDs (1)
- Current is evacuated through the surface which might limit the rate
- May achieve up to 10 kHz/cm2 by implementing higher segmentation of the grounding network (as for the MPGDs)



→ Matteo's talk on Wednesday

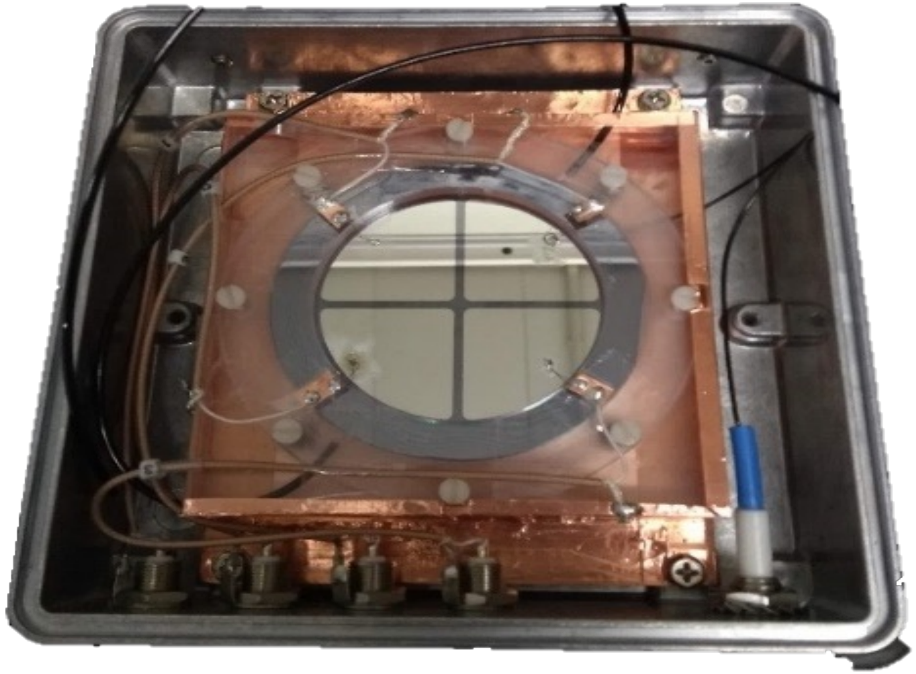


Brevetto in Italia N. 102020000002359 (submitted to INFN 10 Sept 2019 - deposited to Ufficio Brevetti 6 Feb 2020)
INFN – "ELETTRODO PIANO A RESISTIVITÀ SUPERFICIALE MODULABILE E RIVELATORI BASATI SU DI ESSO."

Cross-contamination with ... SS devices

- A new device: single gap semi-conductor RPC
  - electronic carriers behave in a completely different way than in standard resistive plates
- Counting rate > 40 kHz/cm^2
  - 0.6 mm GaAs electrodes
  - Resistivity 1.4×10^8 Ωcm
- 1 MHz/cm^2 seems possible
- Active area 6.25 cm^2

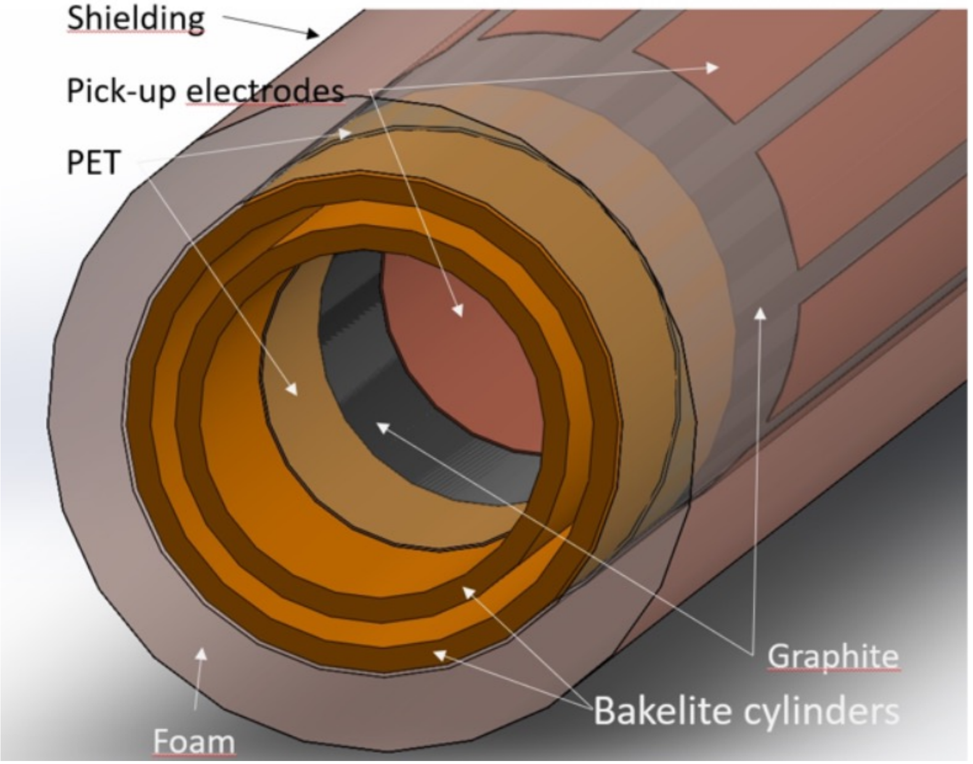
Single-gap semi-conductor RPC



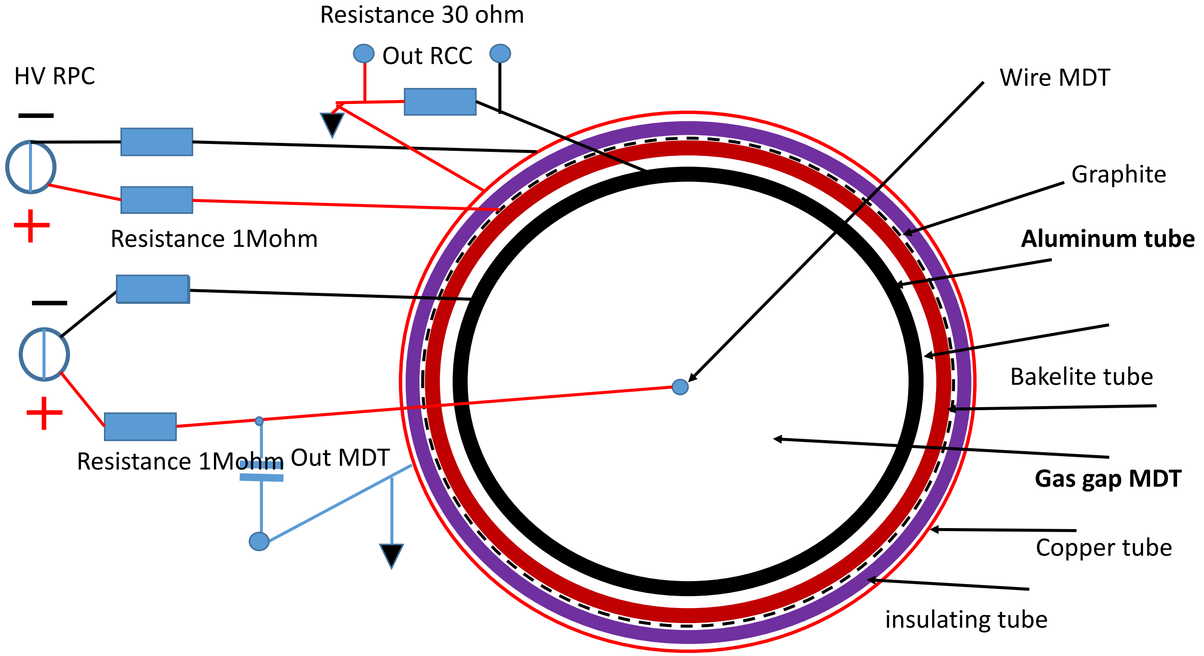
Pressurized operation

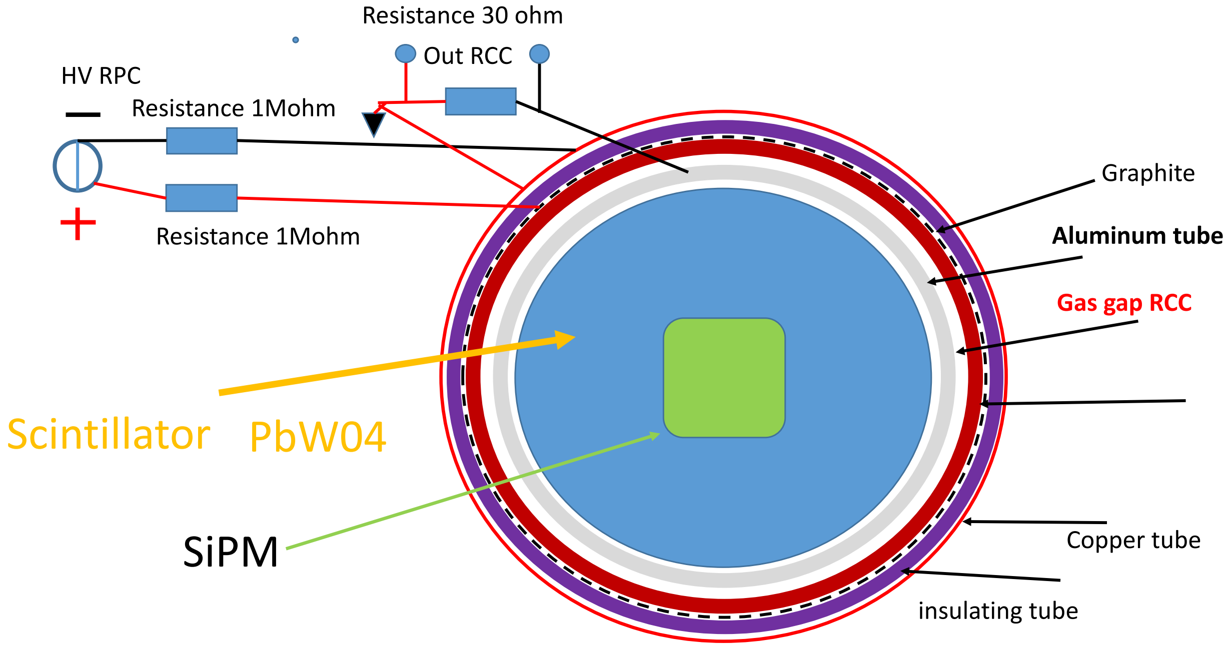
RCC (Resistice Cylindrical Chamber

- Increase the gas target density --> better efficiency even with thin gaps
- Geometrical quenching playing with radii and polarization
  - Eco-friendly mixtures
- Can be integrated with a drift tube for combined precise position/timing measurement



A RCC can be integrated with a tracker or calorimeter





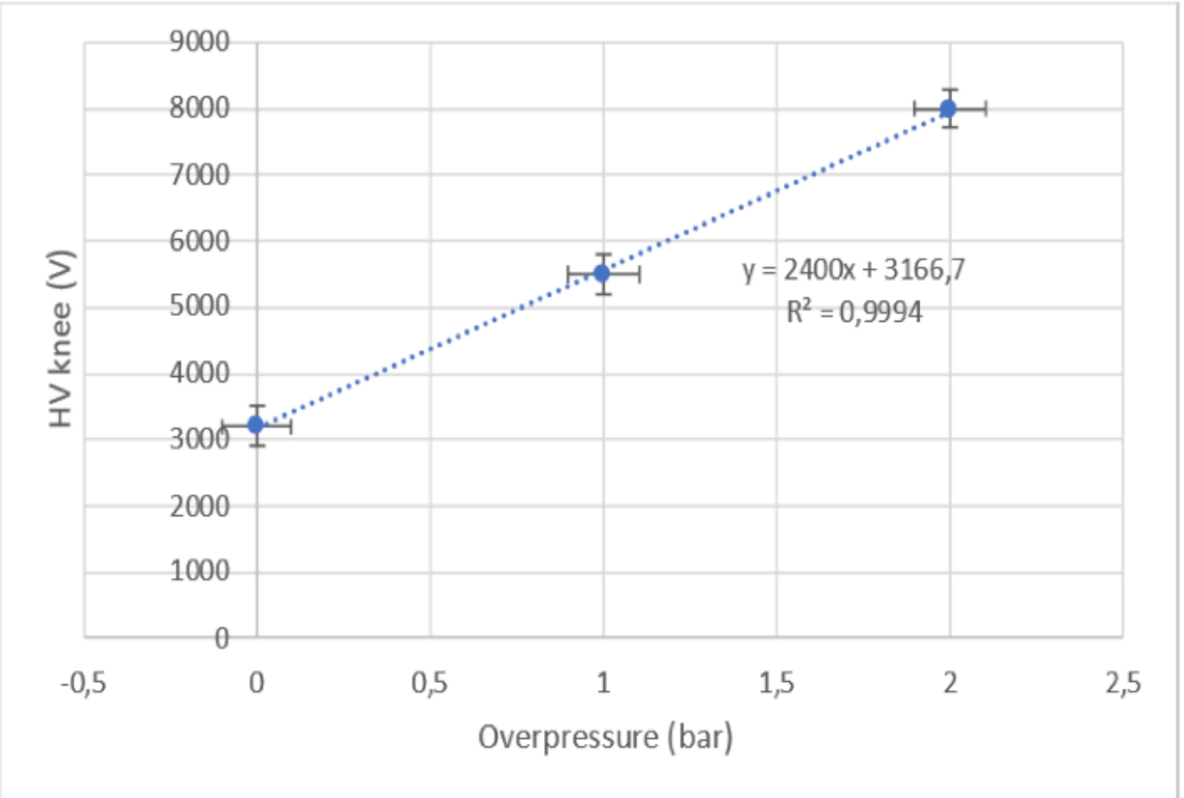
→ This is not to disregard sampling calorimetry with RPCs

→ It is well known that the signal amplitude is proportional to the number of simultaneous tracks up to very high density

  → consequences for analog calorimetry

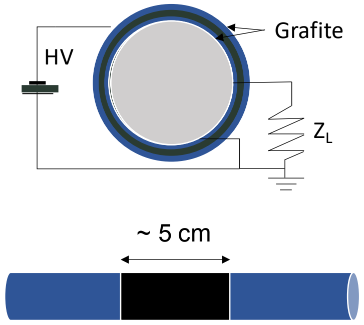
Gaps down to 0.2 mm

Knee VS V



E field

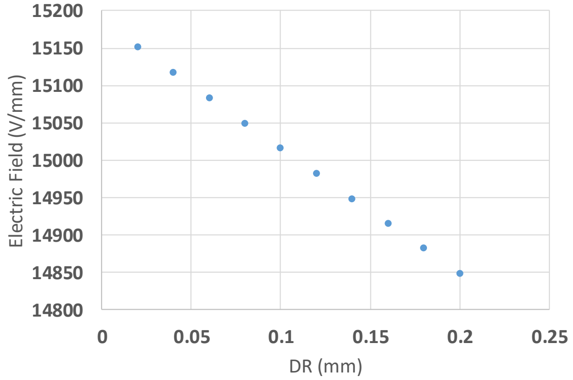
RCC 0.2 mm gap R1=17,6 mm R2=18 mm(prototype design)



D_1 = 17,6 mm
D_2 = 18 mm
Gap = 0,2 mm

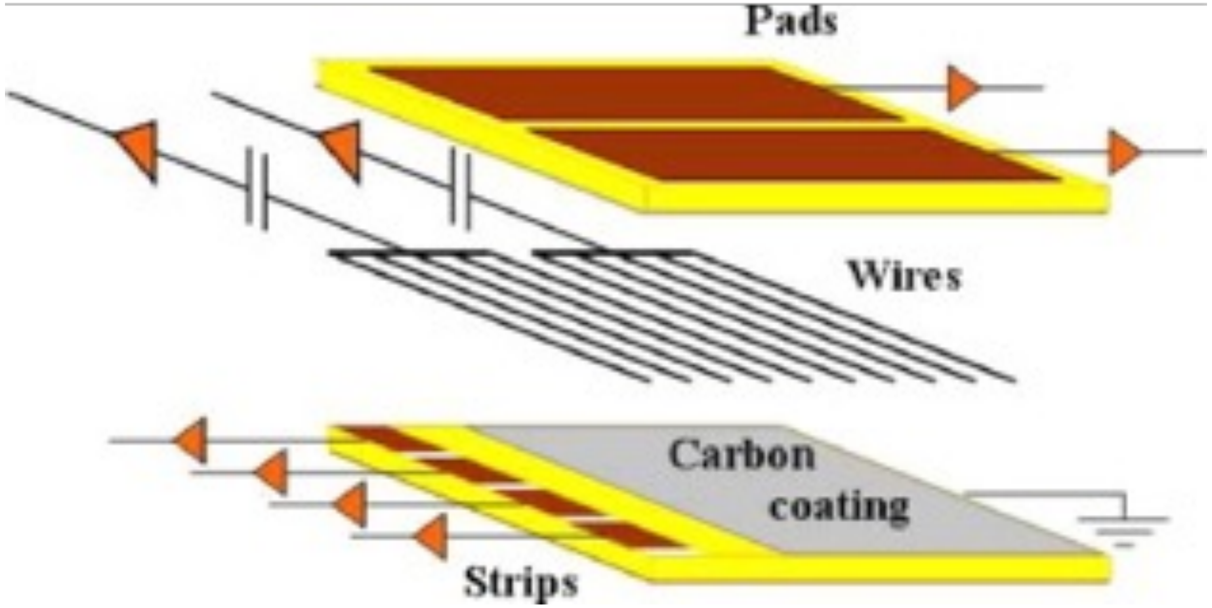
Electric field inside the gas gap with ΔV=+3000 V

$$E(r) = -\frac{V}{r \log \frac{R_1}{R_2}}$$



“Thin Gap”

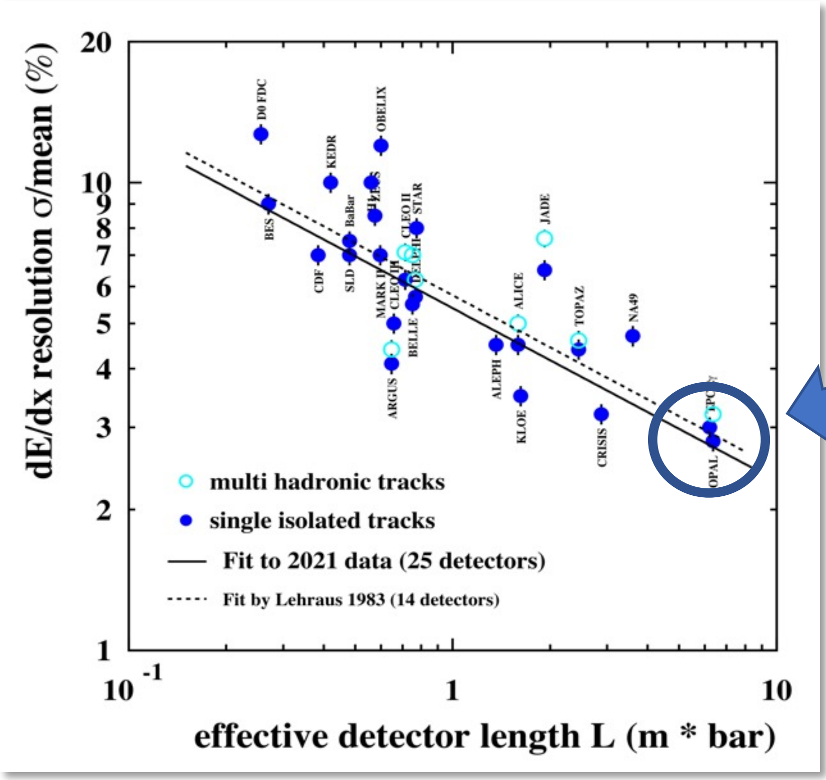
- When we hear “NSW” we usually think “resistive MicroMegas”
- This is not considering the Thin Gap Chambers, in their “small strip” flavour
  - 1.4 mm wire-cathode gap
  - Resistive cathodes
  - optimized for rate in the NSW
- operation in a high gain mode: large saturated signals relatively insensitive to mechanical variations
- narrow timing spread of signals (time jitter) because of a small gap and a small spacing between adjacent wires
- Initially thought for calorimetry, they are a staple in muon triggering @ATLAS in the foreseeable future



Speaking about pressure …

dE/dx and dN_{cl}/dx, take 1

- **dE/dx** resolution around 5% are routinely reached, in excellent conditions and with accurate calibration. It relies on truncated mean techniques, or max likelihood.
- The dependency on P has not been exploited much since the first TPC



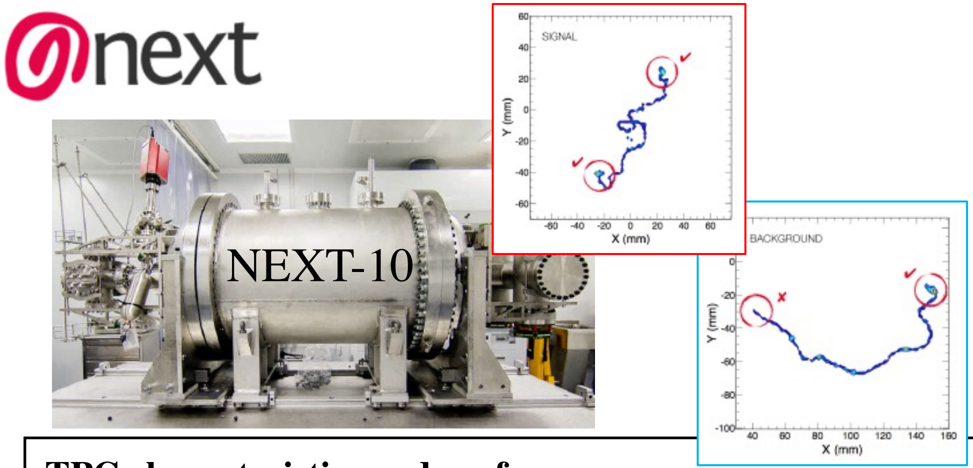
$$\sigma \sim n^{-0.46}(xP)^{-0.32}$$

Lehraus plot: 5.4% typical dE/dx resolution for 1m·bar track length. No significant change since 1983, i.e. since the first TPC

- interest in the P term is renewed where excellent PId is needed together with a large mass of gas **(TPC-as-a-target)**

Possibly in combination with optical readout, two issues require a fresh look

- suitable (modern) gas mixtures for high-P operation
- light pressure-containment vessels



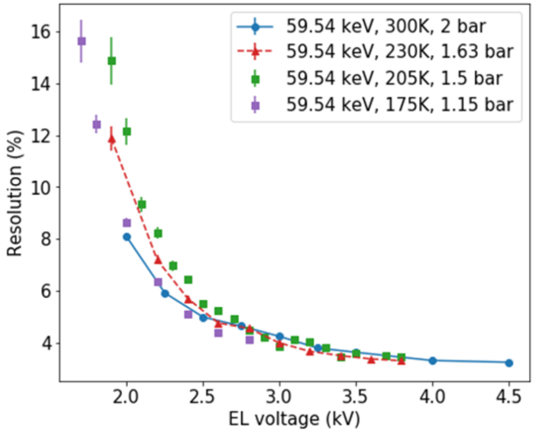
TPC characteristics and performance:

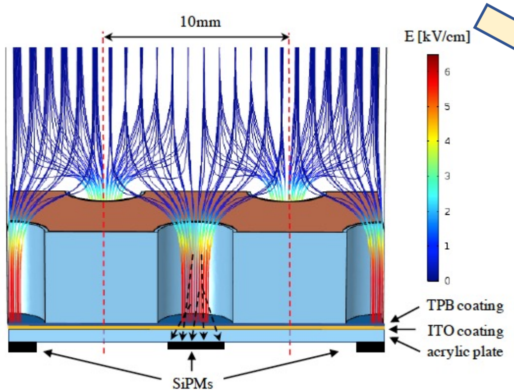
- 3D-reconstruction of tracks through SiPM plane.
- Strong $\beta\beta0\nu$ topological signature (demonstrated).
- <1% energy resolution (demonstrated).
- Technology frozen, NEXT-100 under construction.

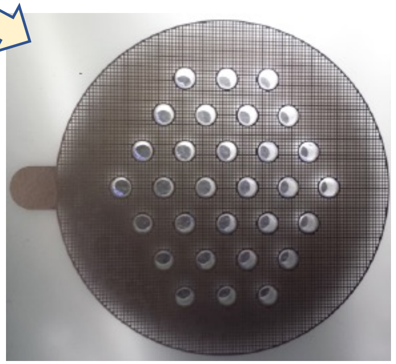
R&D towards NEXT-1Ton (fully explore inverted hierarchy)

- Develop a scheme for Ba-tagging.
- Consider low-diffusion mixtures (Xe/He, Xe/CH_4).
- Study detector cool down (allows replacing PMs by SiPMs, enables higher gas mass for the same pressure, lower outgassing).
- New EL-structures for better scalability, stability and yield.

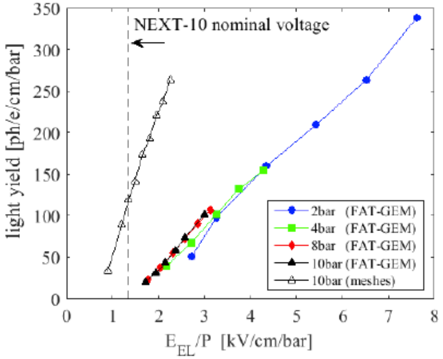
cold xenon



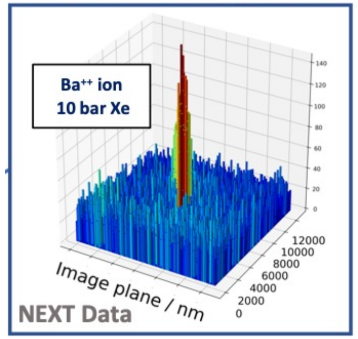




arXiv:1907.03292

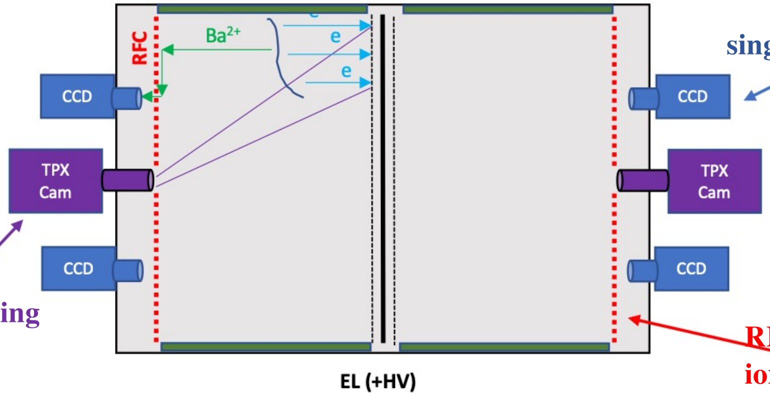


Barium tagging (find 1atom in 1ton of atoms!)



JINST 11 (2016) no.12, P12011
Phys. Rev. Lett 120, 132504 (2018)
Phys.Rev.A 97 (2018) 6, 062509
Nature Sci Rep 9, 15097 (2019)
Nature 583, 48–54 (2020)
JINST 15 (2020) 04, P04022
ACS Sens. 6, 1, 192–202 (2021)

CRAB concept

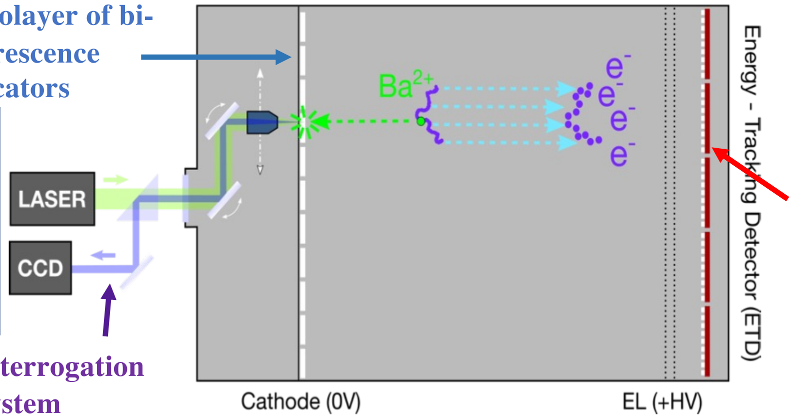


single Ba^{2+} ion tagging

direct UV camera imaging

RF carpet ion transport in xe gas

BOLD concept*(ERC-funded)



monolayer of bi-fluorescence indicators

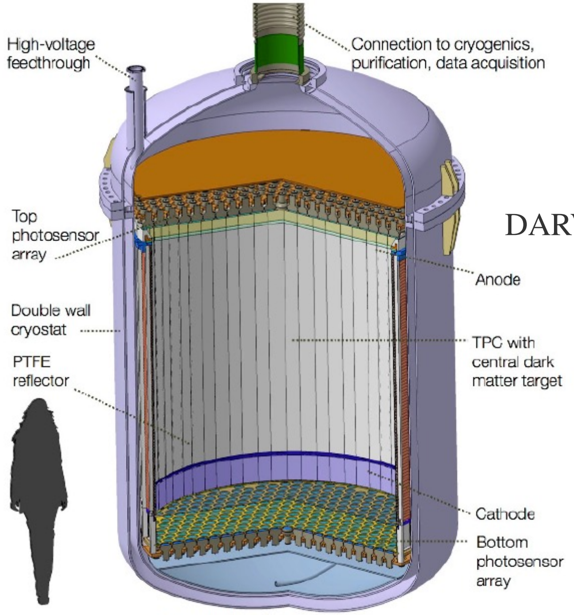
interrogation system

SiPM plane for imaging and to reconstruct energy

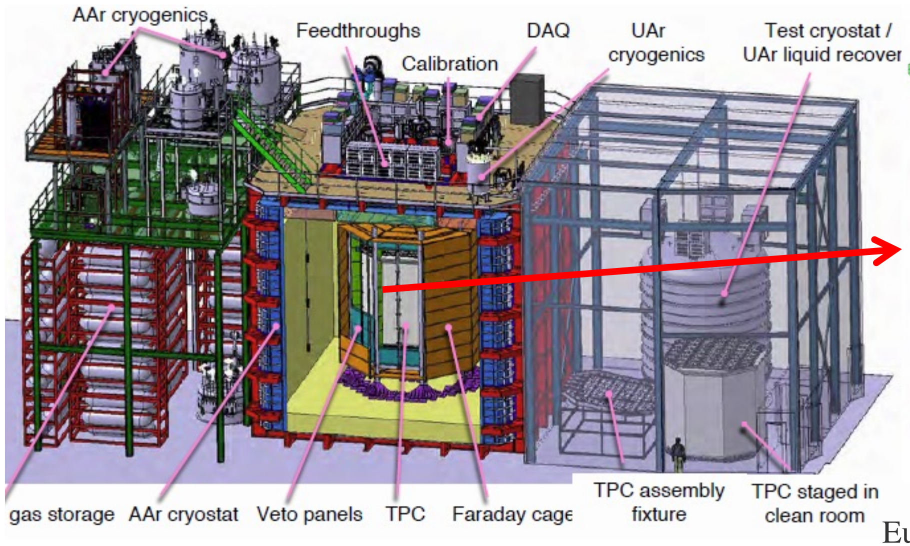
electroluminescent

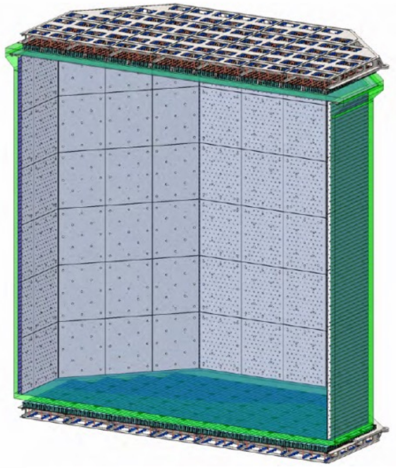
DARWIN ⟺ the ultimate dual-phase noble-element detectors? ⟺ DarkSide20 and ARGO

many more details in L. Baudis
https://indico.cern.ch/event/994687/



DARWIN, JCAP 1611(2016)017





Eur. Phys. J. Plus, 133(2018)131

Goal:

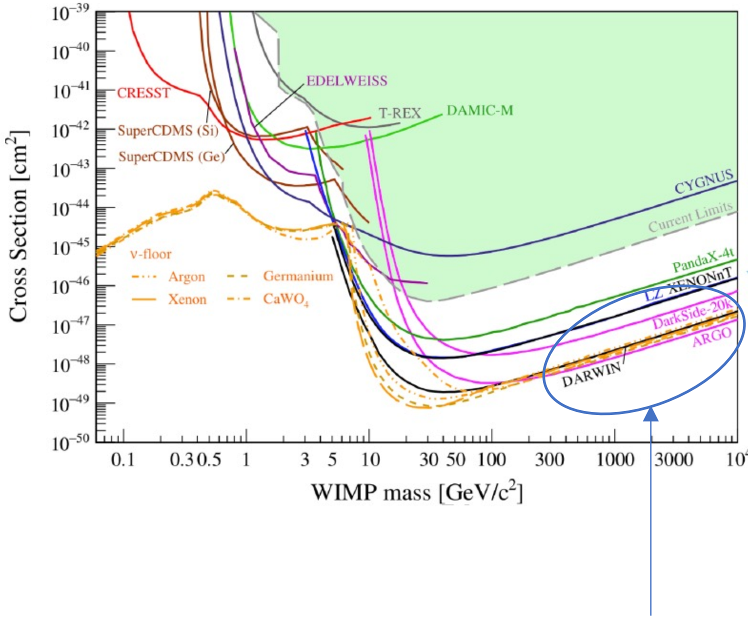
- ➢ Reach sensitivities down to the neutrino floor.

TPC characteristics:

- ➢ Particle discrimination by S1/S2.
- ➢ Drift/diameter: 2.6 m / 2.6 m.
- ➢ Mass: 40 t.

R&D:

- ➢ Learning from large experience with XENON detectors and up-scale solutions. Use PMs.
- ➢ Robust electrode design (up to 50kV).
- ➢ Reduce backgrounds (Rn, n's, γ's).
- ➢ Achieve good liquid purity.



Goal:

- ➢ Reach sensitivities down to the neutrino floor.

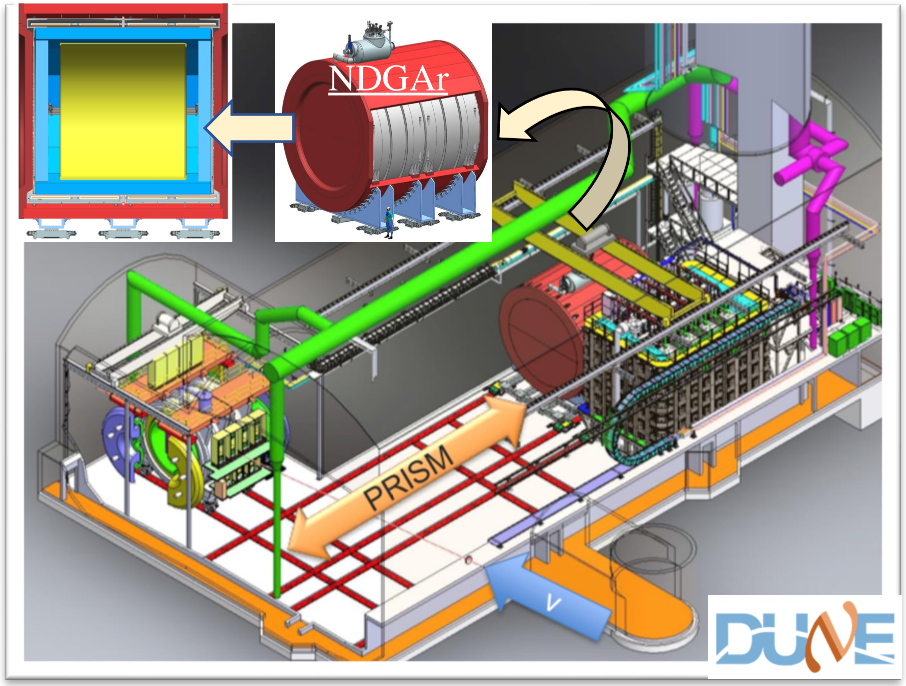
TPC characteristics:

- ➢ Particle discrimination by S1/S2 and pulse shape.
- ➢ Drift/diameter: 3.5 m / 3.5 m.
- ➢ Mass: 51.7 t.

R&D:

- ➢ Instrumented with SiPMs, in assemblies called photodetector modules (PDMs), similar to a 3'' PMT.
- ➢ Possible thanks to the discovery of low radioactivity argon in underground CO_2 wells (UAr) with an activity 1400 (or more) times lower than atmospheric.

electroluminescent



Near Detector Suite has a magnetized high pressure TPC (NDGAr)

Role:

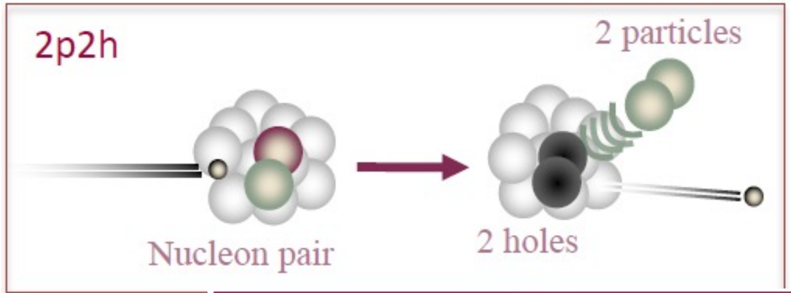
- Tracker for forward-going muons escaping ND-LAr.
- Target: 4π-reconstruction of CC and NC interactions (~1.5M CC evts/yr).

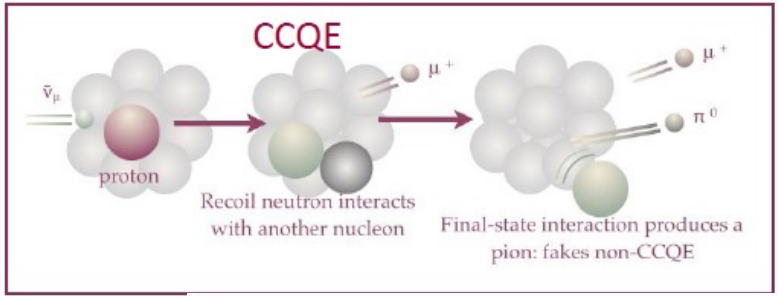
TPC characteristics:

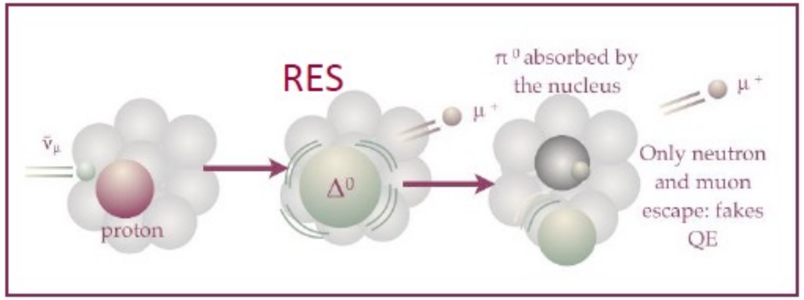
- Nominal pressure 10bar, E_d ~40V/cm/bar. Read out with wires.
- Tracking threshold 5MeV for protons (improvements ongoing).
- Momentum resolution 2.7% for a typical muon sample.
- *Possibility of using primary scintillation under investigation* (never done for a charge-read TPC in a particle physics application)

Nuclear effects in neutrino-nucleus interactions include

- Fermi motion
- FSI (Final State Interaction) breaking up nucleus
- 2p2h

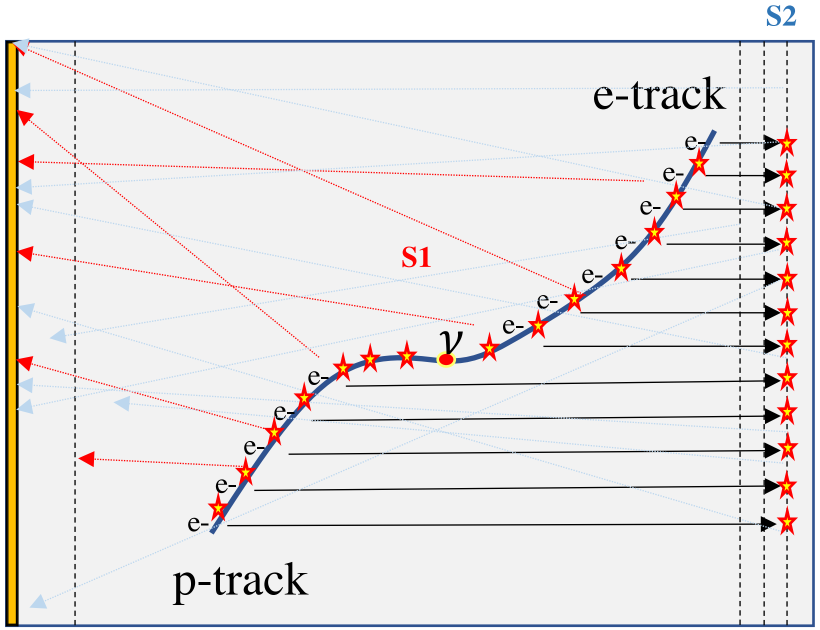


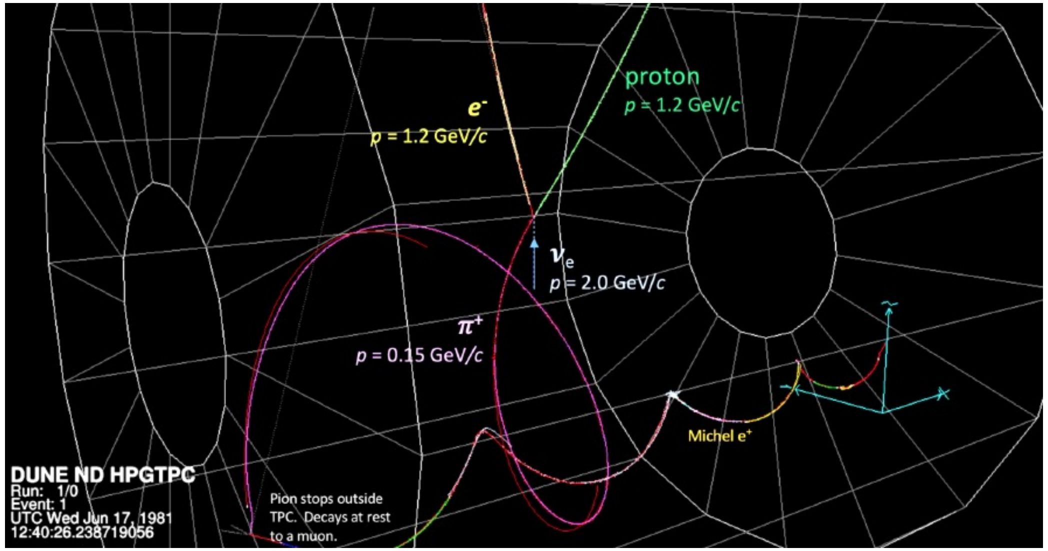




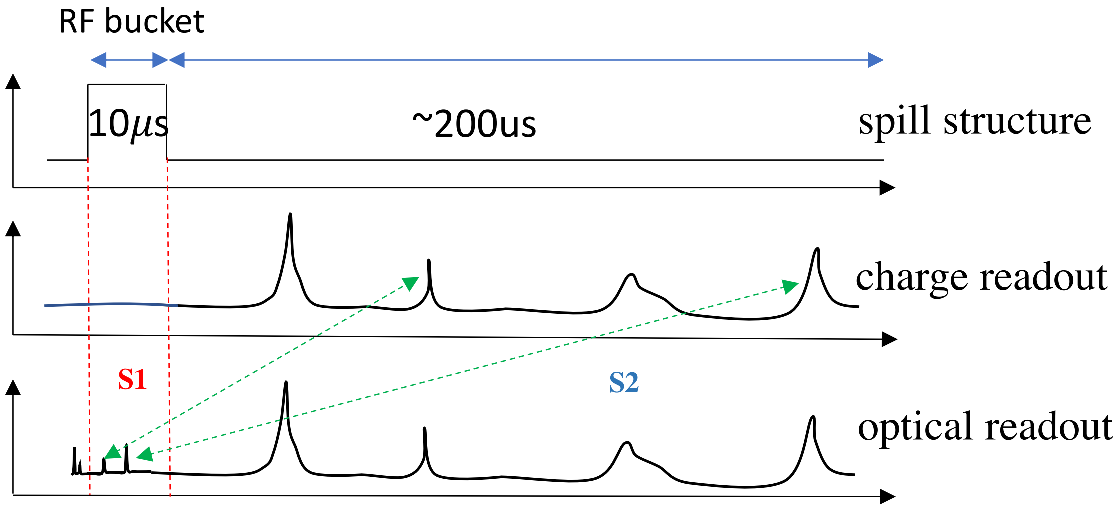
TPC as a target: DUNE close detector

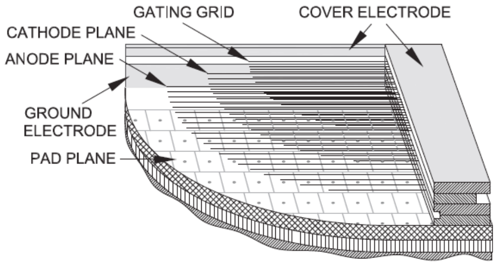
- possibility of reconstruction and identification of γ, π^0, $\pi^{+/-}$, n, p, e, μ down to about 5 MeV in 4π.
- Ground-breaking results demonstrate a tracking threshold of 5 MeV and time resolution of 1 ns in the primary scintillation signal with just 1% CF^4 addition to argon.
  Instrumenting most of the cathode plane with SiPMs

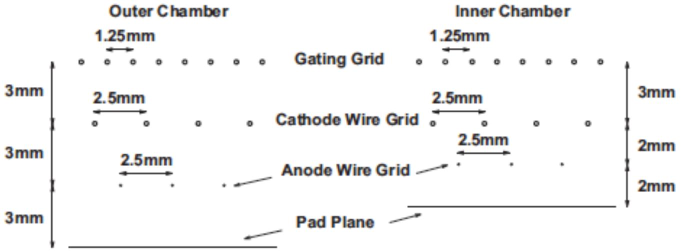




Pion stops outside TPC. Decays at rest to a muon.

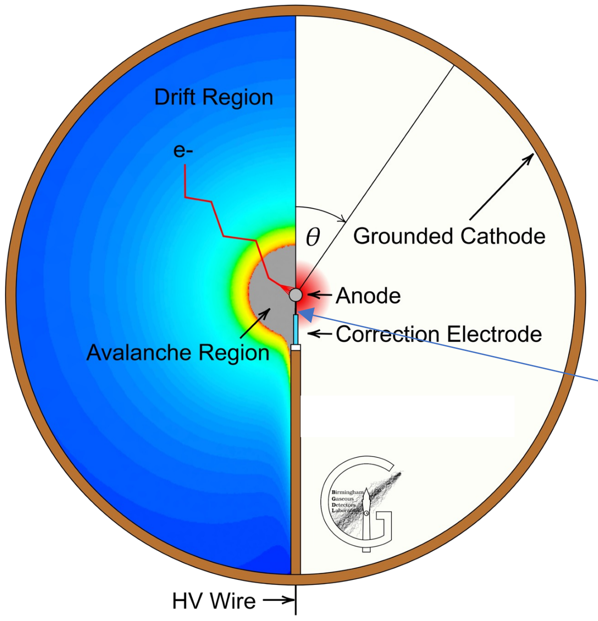






(notice the steady raise of the SiPM as a gaseous detectore readout)

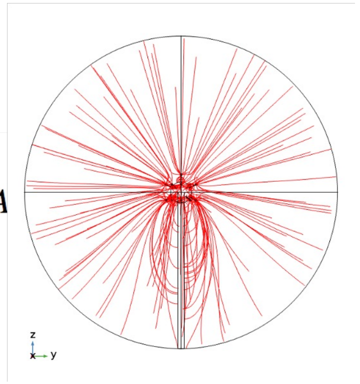
Spherical Proportional Detector



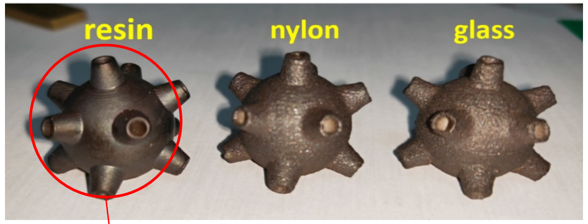
$$E(r) = \frac{V_0}{r^2}\frac{r_A r_C}{r_C - r_A} \approx \frac{V_0}{r^2} r_A$$

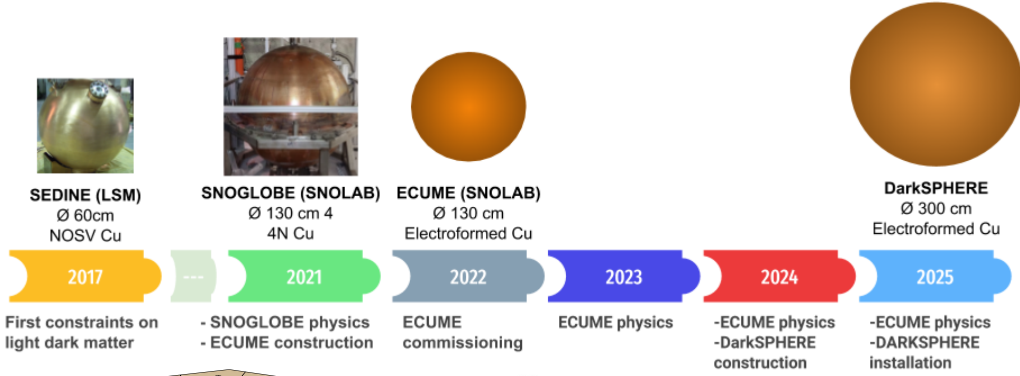
r_A = *anode ball radius*
r_C = *cathode radius*

C≈ r_a= 1 mm < 1pF



central electrode is key
(years of evolution!)





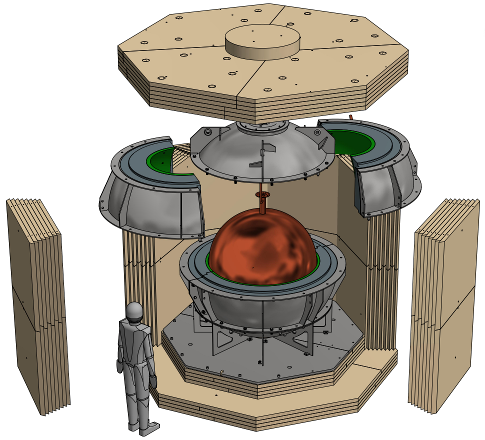
SEDINE (LSM)
Ø 60cm
NOSV Cu

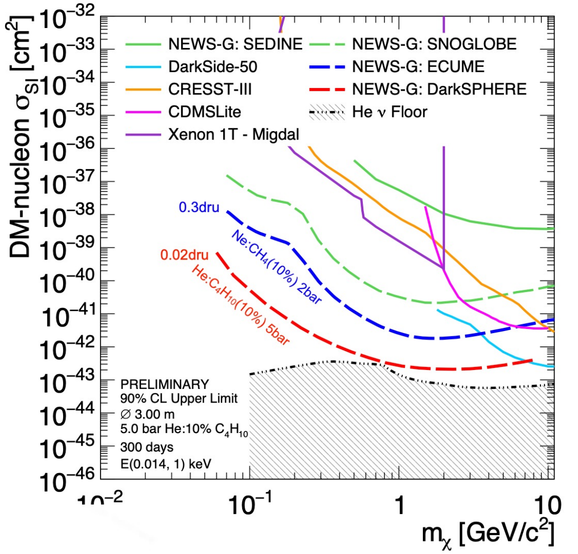
SNOGLOBE (SNOLAB)
Ø 130 cm 4
4N Cu

ECUME (SNOLAB)
Ø 130 cm
Electroformed Cu

DarkSPHERE
Ø 300 cm
Electroformed Cu

2017	---	2021	2022	2023	2024	2025
First constraints on light dark matter		- SNOGLOBE physics - ECUME construction	ECUME commissioning	ECUME physics	-ECUME physics -DarkSPHERE construction	-ECUME physics -DARKSPHERE installation



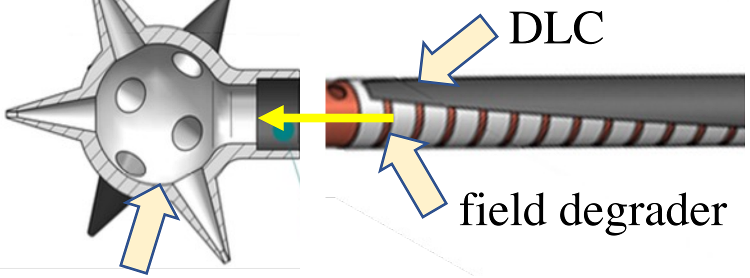


main characteristics (in the inventor's words!):

- Simple and cheap.
- Large volume (i.e., compatible with pressurization).
- Single channel read-out.
- Robustness.
- Good energy resolution.
- Low energy threshold.
- Efficient fiducial cut.
- Low background capability.

→ Very suitable for rare-event searches!!

ACHINOS (v.1)



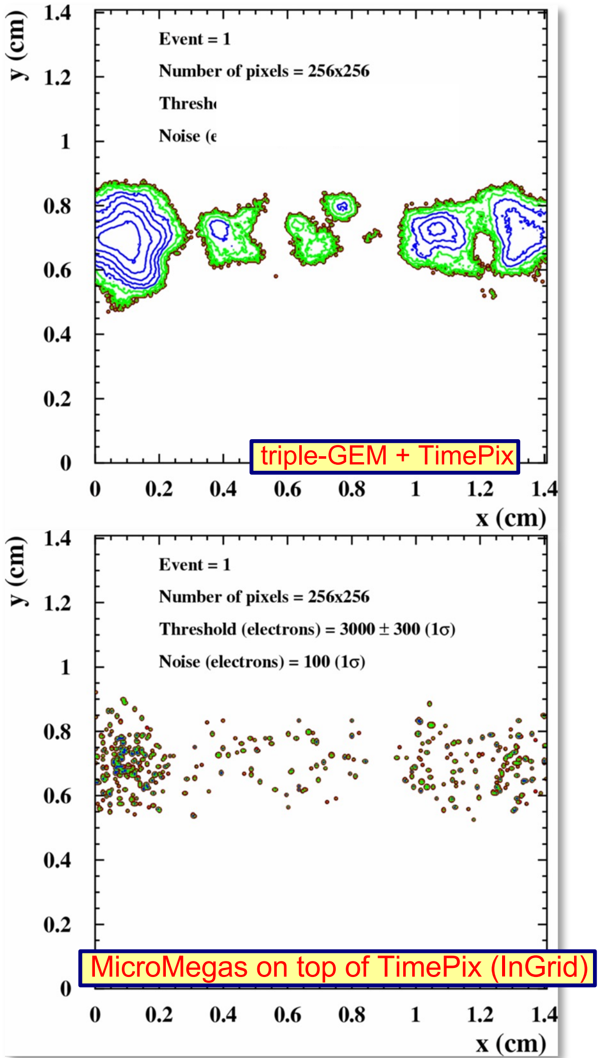
adaptative field (high enough field both close and far from the anode)

ACHINOS (new version)

JINST 3 (2008) P09007
JINST 15 (2020) P11023

dE/dx and dN$_{cl}$/dx, take 2

dN$_{cl}$/dx resolution is potentially better than dE/dx. Cluster counting requires fast electronics and sophisticated counting algorithms, or alternative readout methods. It has the potential of being less dependent on other parameters – however certain gasses (He, Ne) are better suited than others (Ar) due to their primary ionization characteristics



ILD-TPC simulated 100 GeV muon, 100 cm drift
identical events: same generated primary clusters/electrons

$$\sigma \sim (\delta \cdot L)^{-0.5} = \sqrt{N_{cl}}$$

- In cluster-counting mode there is a clear statistical advantage, even taking into account a cluster identification efficiency. There is the potential of better resolution by at least a factor 2 (theoretically)

TPCs may hit intrinsic limitations, and not all TPCs may take advantage

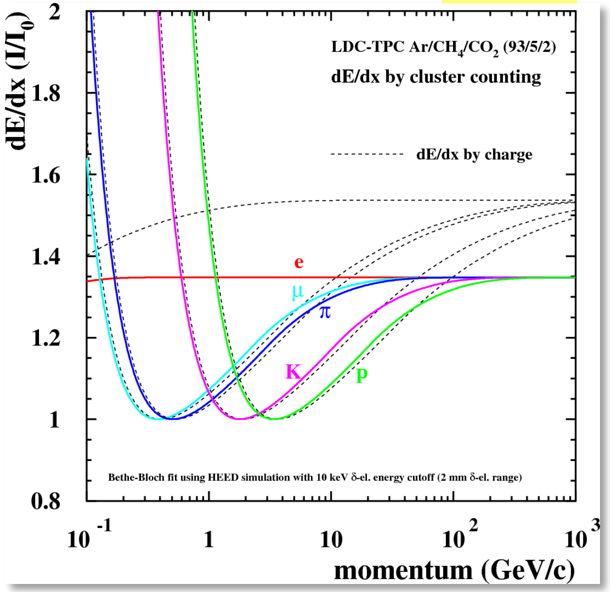
- the relativistic rise is flattened out by a strict primary cluster count → a hybrid approach (dE/dx + dN/dx) may be better suited
- long drift lengths (long. diffusion + attachment) tend to de-cluster the primary ionization. Potential source of systematics.
- optimize the gas for longitudinal diffusion too!

However, DCs may be in a better position

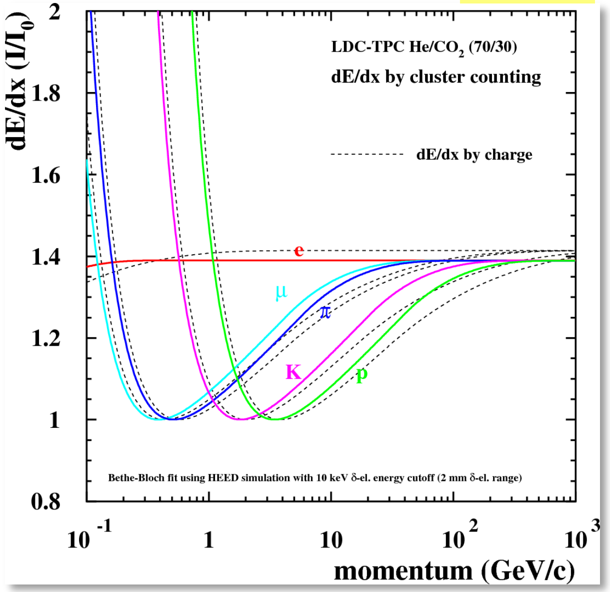
Bethe-Bloch with Cluster Counting – i.e. what matters is separation

- Different Bethe-Bloch functions for dE/dx (by charge) and dN/dx (by cluster counting)
  - relativistic rise differs (important for particle separation)
    - charge measurement is highly sensitive to secondary electrons
    - more secondary electrons (deltas) at higher momenta → larger tails in Landau distribution
    - (perfect) cluster counting ignores them → relativistic rise “truncated”
  - Differences depending on the gas mix: Ar vs He (fewer secondary electrons in Helium)

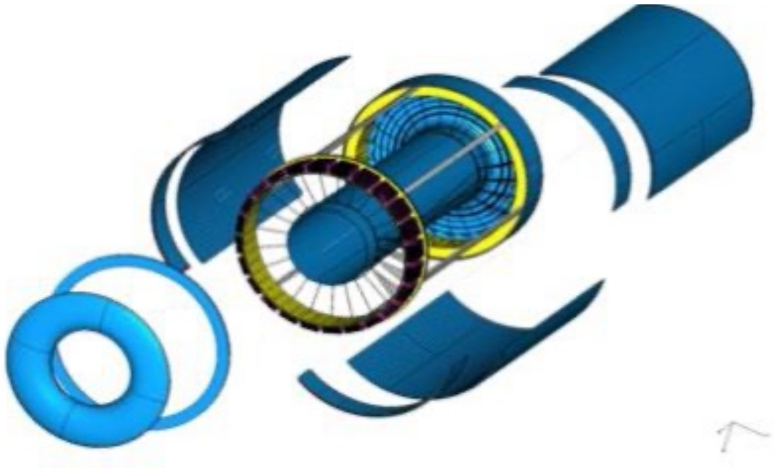
Ar



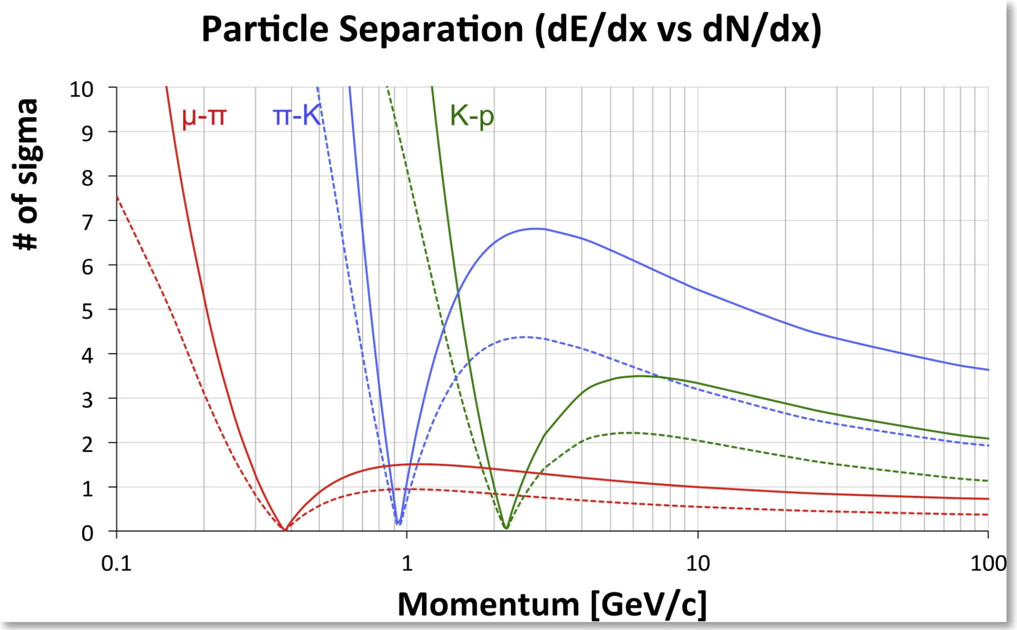
He

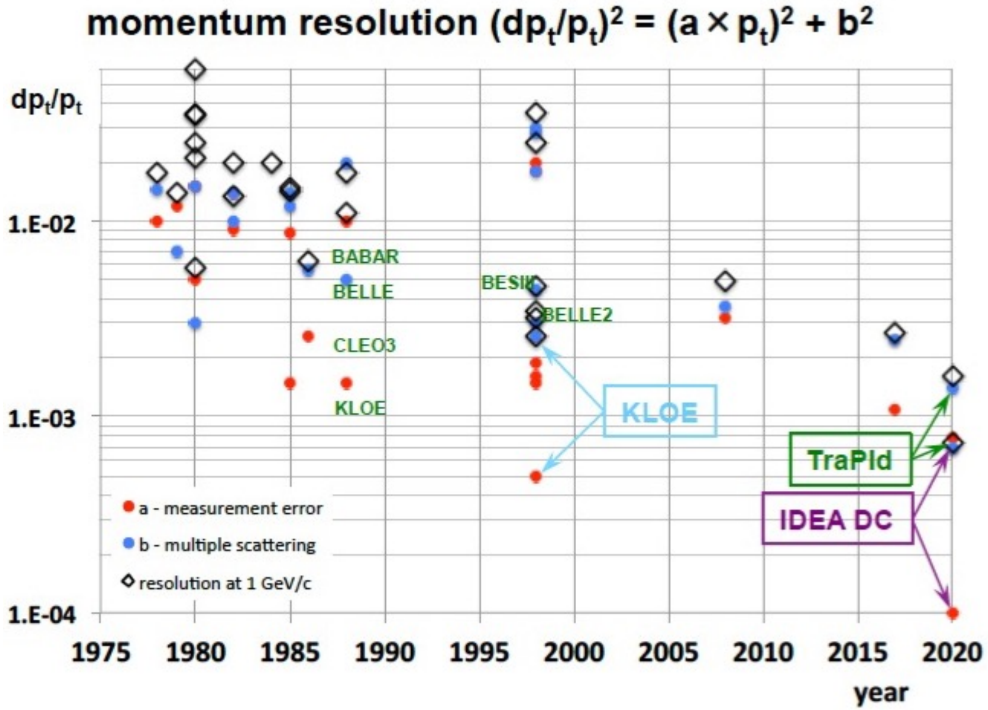


IDEA DC



- Highlights: lightness and dN/dx
- Gas envelope and wire supporting structure separated
- Hope of better PID resolution using cluster counting:
  - Standard truncated mean dE/dx : σ ≃ 4.2%
  - Cluster counting goal: σ ≃ 2.5%
- → mandatory development of suitable FEE for IDEA (one of the AIDAinnova Tasks: low noise, low power,BW > 1 GHz)

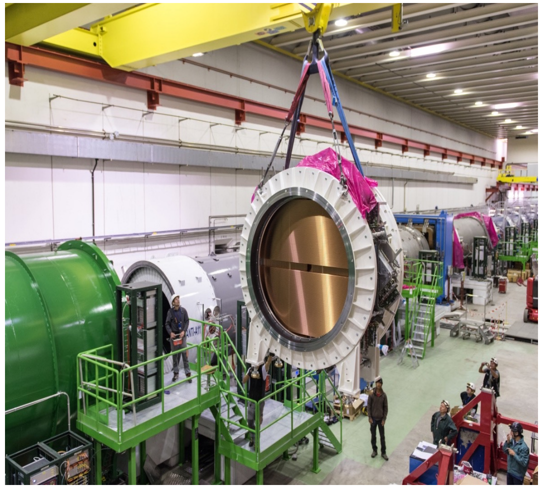




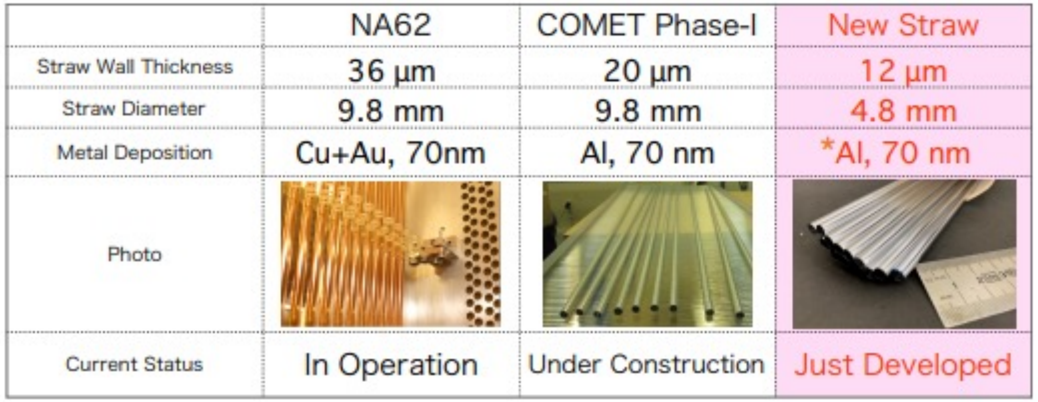
More light tracking: straws

- Ever thinner walls to reduce nX_0
  - Thinner tube films: 30μm -> 20μm -> ~10μm
- Smaller diameters for better timing / occupancy
  - 10mm standard, non critical w.r.t. central wire sag
  - 5mm -> centering and stiffness critical
- Frameless / light frame
  - Glueing together
  - Overpressure to rigidify the tubes
- Charge readout for dE/dx information

NA62 straw tube stations

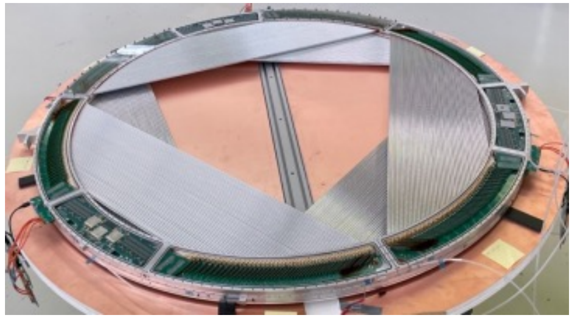


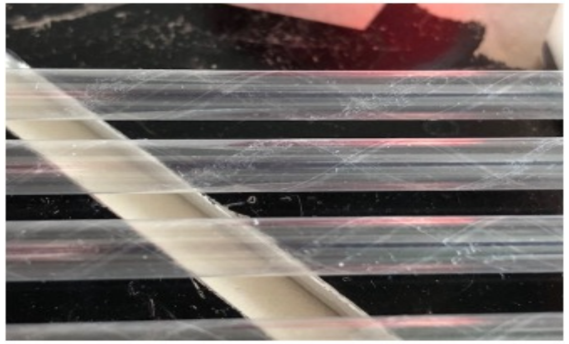
COMET tracker



	NA62	COMET Phase-I	New Straw
Straw Wall Thickness	36 μm	20 μm	12 μm
Straw Diameter	9.8 mm	9.8 mm	4.8 mm
Metal Deposition	Cu+Au, 70nm	Al, 70 nm	*Al, 70 nm
Photo			
Current Status	In Operation	Under Construction	Just Developed

Mu2e experiment

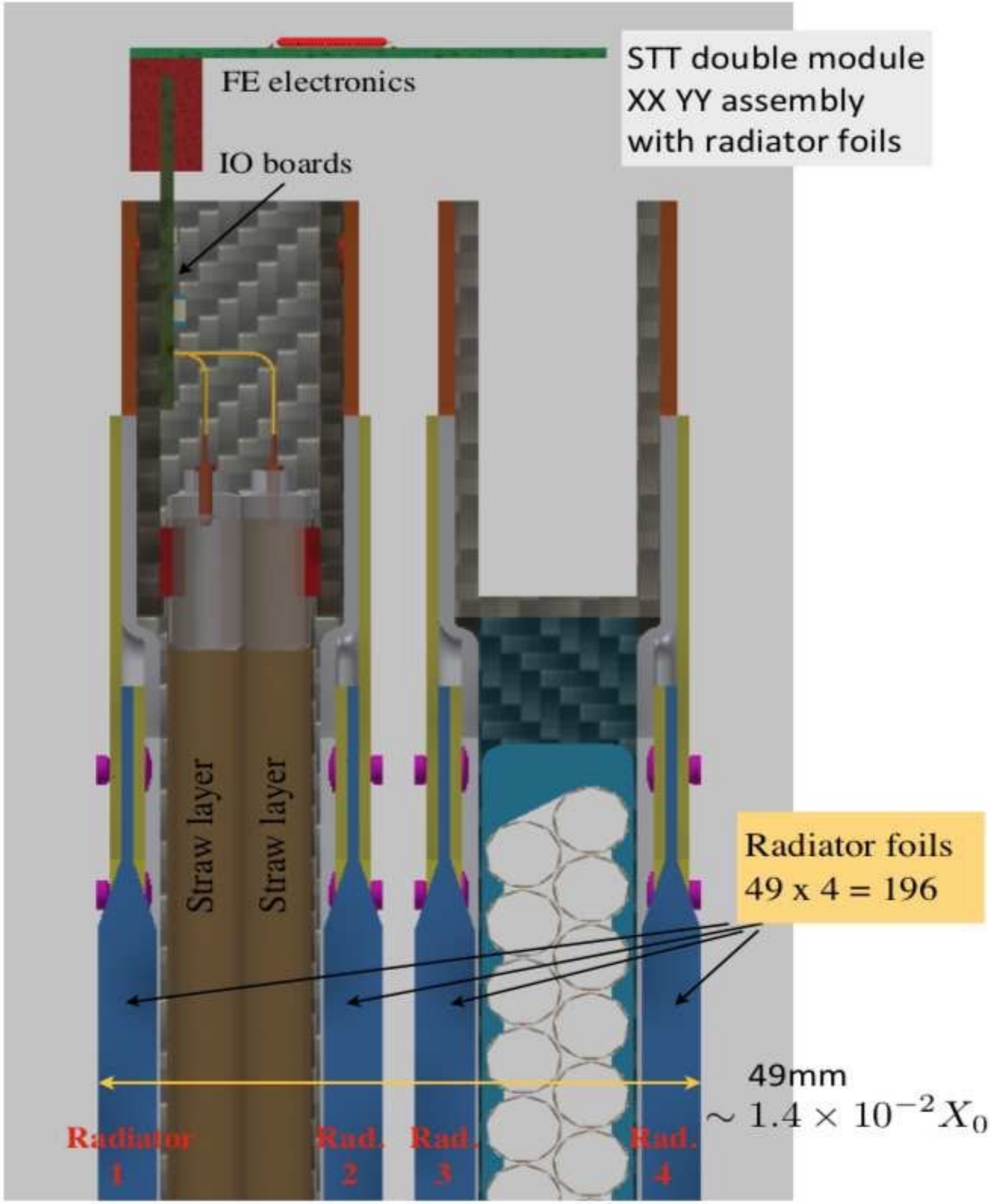




Pressurized 8 μm Mylar Straws

Straws where you do not expect them: DUNE near detector

- An old concept re-booted: NOMAD, i.e. light tracking chambers with embedded target, filling a magnetized volume → grossly approximating a uniform active target
- H-rich target (polypropilene “radiators”)
- Tracking & dE/dx in the straws
- Possible insertion of additional target layers for ν cross-section A-dependence
- The concept here is: to help localize the vertex (and reduce systematic errors on cross-sections), tracking devices must represent a few % of the target mass



Conclusions (if any)

Trends towards

- Thinner gaps (better rate and timing), down to MPGD-like sizes
- Pressurized operations (dE/dx and target-mass driven)
- Attempt at exploiting dN/dx (mostly in drift chambers, again PId driven)
- SiPMs to be seen more and more inside gaseous detectors

a few references and readings

- ECFA TF1 symposium (https://indico.cern.ch/event/999799/) and in particular
  - Giulio Aielli on RPCs (https://indico.cern.ch/event/999799/contributions/4204006/attachments/2235619/3790575/Aielli_ECFA_2021.pdf)
  - Peter Wintz and Piotr Gasik con drift chambers and straw tubes (https://indico.cern.ch/event/999799/contributions/4204009/attachments/2235573/3789004/PW-TF1WireChambers.pdf, https://indico.cern.ch/event/999799/contributions/4204084/attachments/2235667/3789776/gasik_ECFA_21_nobkp.pdf)
  - Diego on TPCs for rare events (TPCs for rare events (https://indico.cern.ch/event/999799/contributions/4204018/attachments/2235884/3789630/DGD_TALK.pdf)
- The recent 2022 RPC workshop at CERN (https://indico.cern.ch/event/1123140/)
- Workshop on gaseous detectors contributions to PID (https://indico.cern.ch/event/996326/) and
  - Michael Hauschild on dN/dx (https://indico.cern.ch/event/996326/contributions/4200962/attachments/2191650/3704305/dEdx.pdf)
- Diego's talk on the DUNE high-pressure gas Ar TPC (https://indico.cern.ch/event/852331/contributions/4611418/attachments/2366772/4041658/Diego_Talk_At_TPC_Conf_LAST.pdf)
- [... and references in the presentations]