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Activities with Micromegas at high pressure at UNIZAR

Outline

- Why high pressures
- How do we work at HP? Activities at Zaragoza
  - Components of the system: vessel, readout, gas system
  - Gas choice
  - Operating at HP and some results
    - Small TPC
    - NEXT-MM

- Summary and Conclusions

Why high pressure

The usual reasons why one would like to go to High Pressures:

- Increase efficiency

$$l = (n\sigma)^{-1}$$

mean free path

$$-\frac{dE}{dx} \sim \rho \frac{Z}{A} \frac{z^2}{\beta^2}$$

stopping power

$$\mu = \sigma \frac{N_a \rho}{A}$$

absorption coefficient

- Increase target mass: rare-event searches

$$R \approx n\sigma_{W,N} \langle \upsilon \rangle \frac{M_{det}}{m_N}$$

detected recoil rate

$$\mathrm{R} \approx \ln 2 \, N_A \frac{M\, f}{W} \frac{\varepsilon\, t}{T_{1/2}^{0\nu}}$$

detected 0νββ events

- Restrict volume/dimensions

n: number density, σ: cross section, ρ: density, Z: atomic number of absorber, A: atomic weight of absorber, z: charge in units of e, β: υ/c of incident particle, N_A: Avogadro's number, $\sigma_{W,N}$: cross section of WIMP interaction with target N, $\langle \upsilon \rangle$: mean WIMP velocity, m_N: mass of nucleus N, W : molecular weight of ββ isotope, f : isotopic abundance, ε: detector efficiency, $T^{0\nu}_{1/2}$: 0νββ mean life time

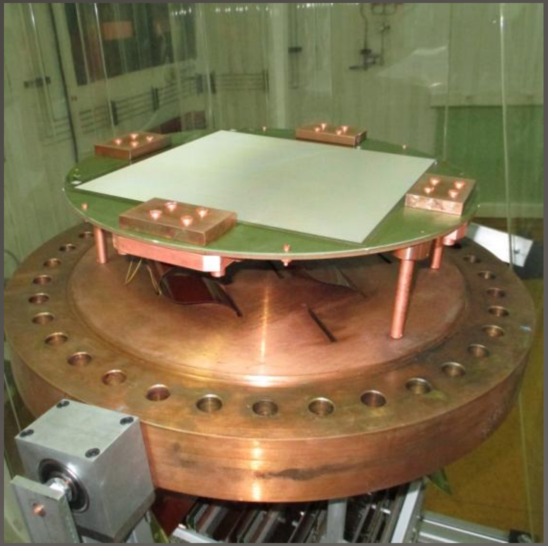
Activities at UNIZAR with MM

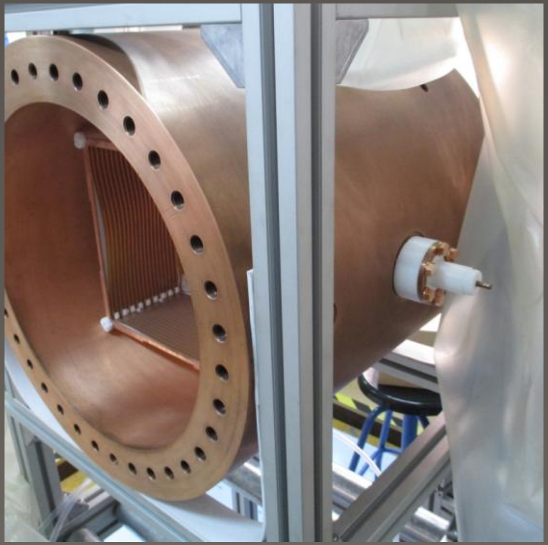
The T-REX Project: in Rare-Event searches, topology can be the key: (ERC ST-G)
merge MPGDs (Micromegas) with low-background techniques in TPCs

- Axions
  - CAST, IAXO ~1.5bar
- Double beta decay
  - NEXT ~10 bar
- Dark Matter
  - TREX-DM ~10 bar
- Simulation and analysis tools
  - RESTSoft
- General MPGD R&D

TREX-DM

- A Micromegas TPC for low-mass WIMPS
  - Ar-based mixture, open loop, up to 10 bar
  - Bulk micromegas to begin with, otherwise microbulks
    - looking into producing a "clean" bulk mM
- Aim: proof of operation and background assessment



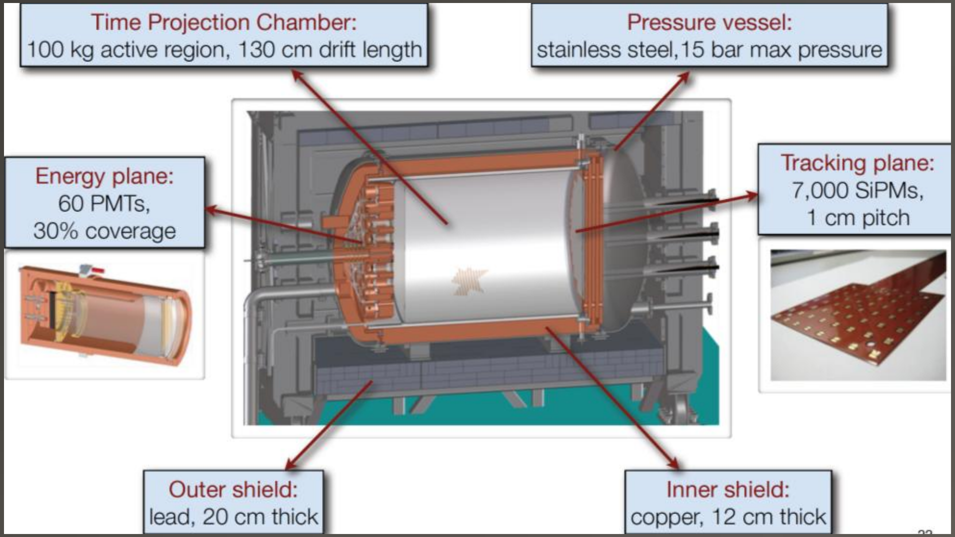


Hopefully soon more to tell on this…

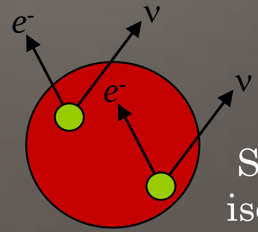
0ν double beta decay

NEXT-100: *a TPC with a SiPM/PMT readout based on electroluminescence to search for the 0νββ of ^{136}Xe*

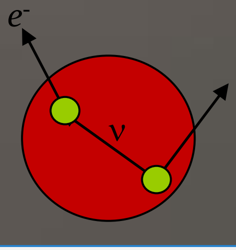
V. Alvarez et al., 2012 JINST 7 T06001



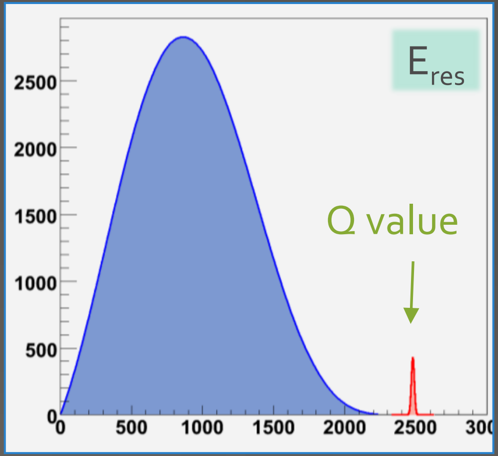
2014-2016
NEXT-NEW ~10kg
2016 on
NEXT-100



2νββ: Standard, 10 isotopes so far

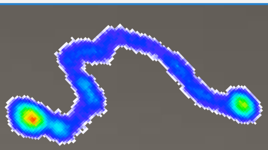


0νββ: Yet to be seen



E_{res} of <0.8% FWHM @$Q_{\beta\beta}$ shown

V. Alvarez et al., 2013 JINST 8 P09011



a signal event:
two blobs

In parallel, we have been working on the feasibility of a TPC with a Xe-based mixture, equipped with a MM readout

High Pressure TPC: Vessel

Spectroscopy: increased thickness of walls makes them suitable mainly for gammas
Rare events: the target is inside… (radio)purity is important.

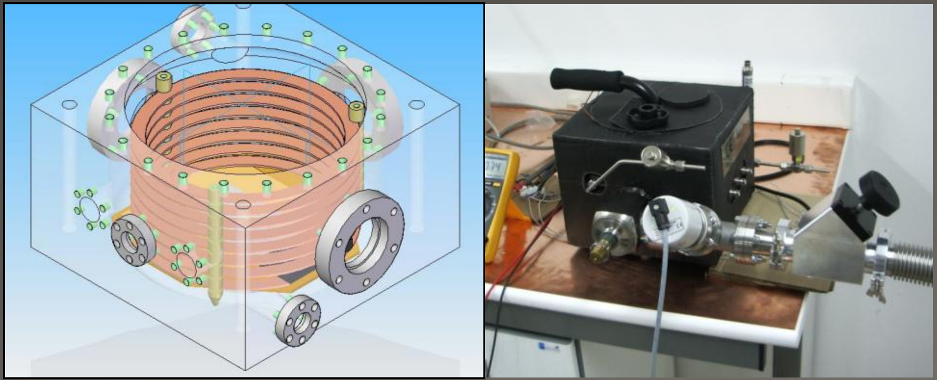
“contradiction”: High vacuum and High pressure vessels!
Vacuum: leak tightness, low outgassing, bake-out cycles
High Pressure: max pressure of operation x factor of safety

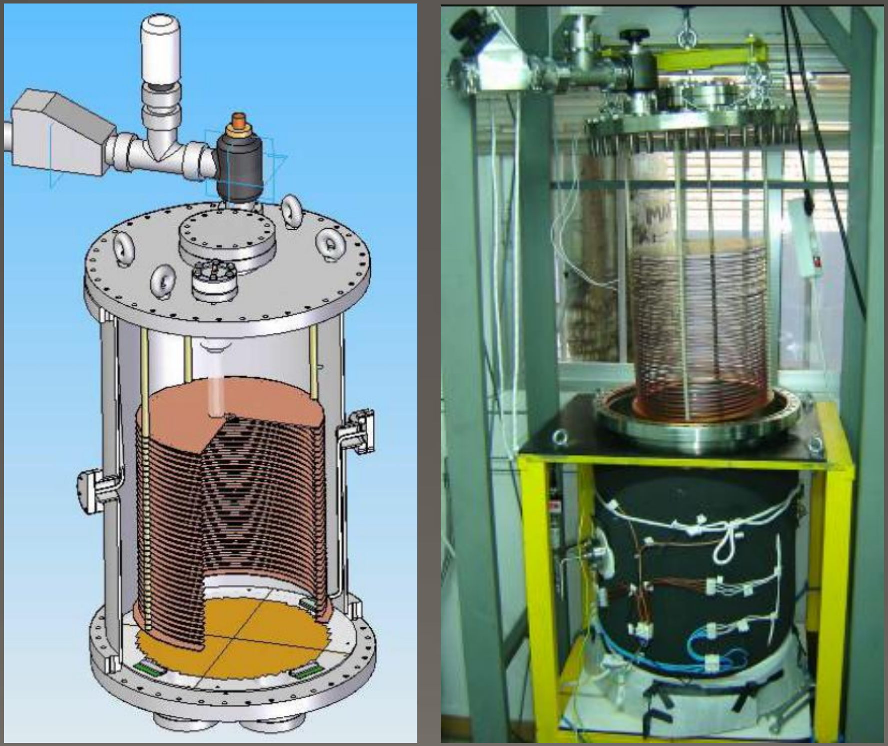
Small TPC

2L
6cm drift
14cm diametre

NEXT-MM

73L
39cm drift
30cm diametre





To test radiopure solutions although detector not radiopure

High Pressure TPC: Micromegas

- Experience from CAST:
  - microbulk Micromegas show excellent performance regarding gain, spatial resolution, energy resolution and radiopurity
- Need to scan pressure ranges of 1-10 bar
- Possible gain optimization

$$M = \exp(APd\, e^{-BPd/V})$$

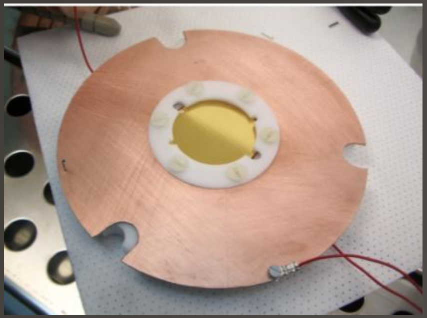
was not taken into account for gap (range, availability etc)

but points towards small gaps, ongoing studies in Saclay

S. Adriamonje et al., 2014 JINST 5 P02001
S. Aune et al, 2014 JINST 9 P01001
S. Cebrian et al., JCAP (2010) 010

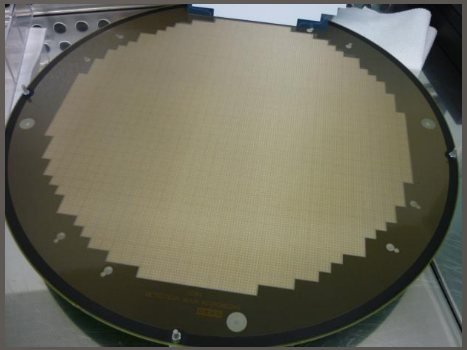
D. Attie et al., 2014 JINST 9 C04013

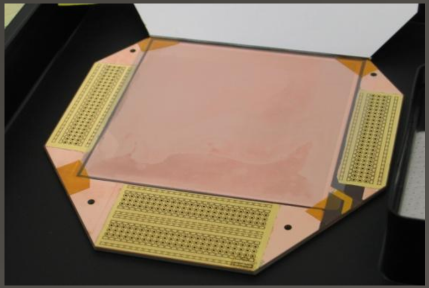
High Pressure TPC: Micromegas



50 μm gap
Ø 35 mm
Non-segmented anode

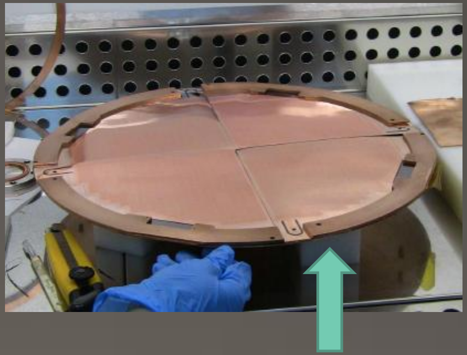
Bulk:
124 μm gap
Ø ~30cm
1152 pixels





50 μm gap
10x10 cm²
Pixelised anode
12x12 pixels

50 μm gap
4 sections
of 288 pixels
(1152 total)



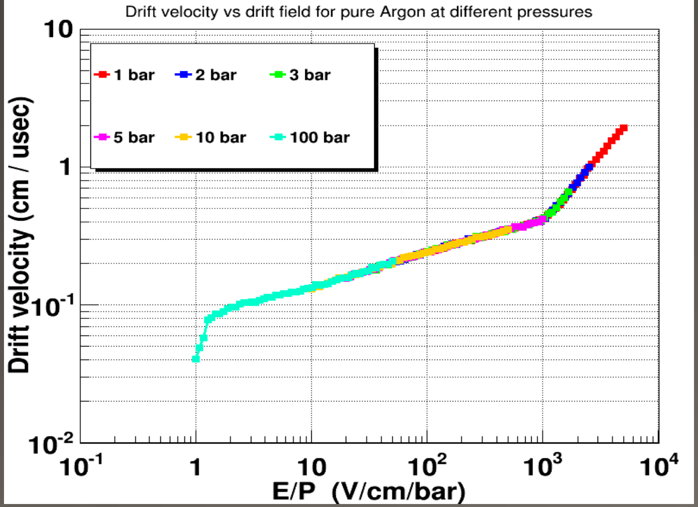
Largest microbulk-covered area so far

Pixels independently read
AFTER-based electronics
1 FEC/sector

High Pressure TPC: Components

- Signal cables
  - Flexible Kapton cables, 300lines
- Feedthroughs
  - HV for the Micromegas meshes
  - High density for the pixel signals
  - EHV for the cathode

Drift velocity depends on E/P



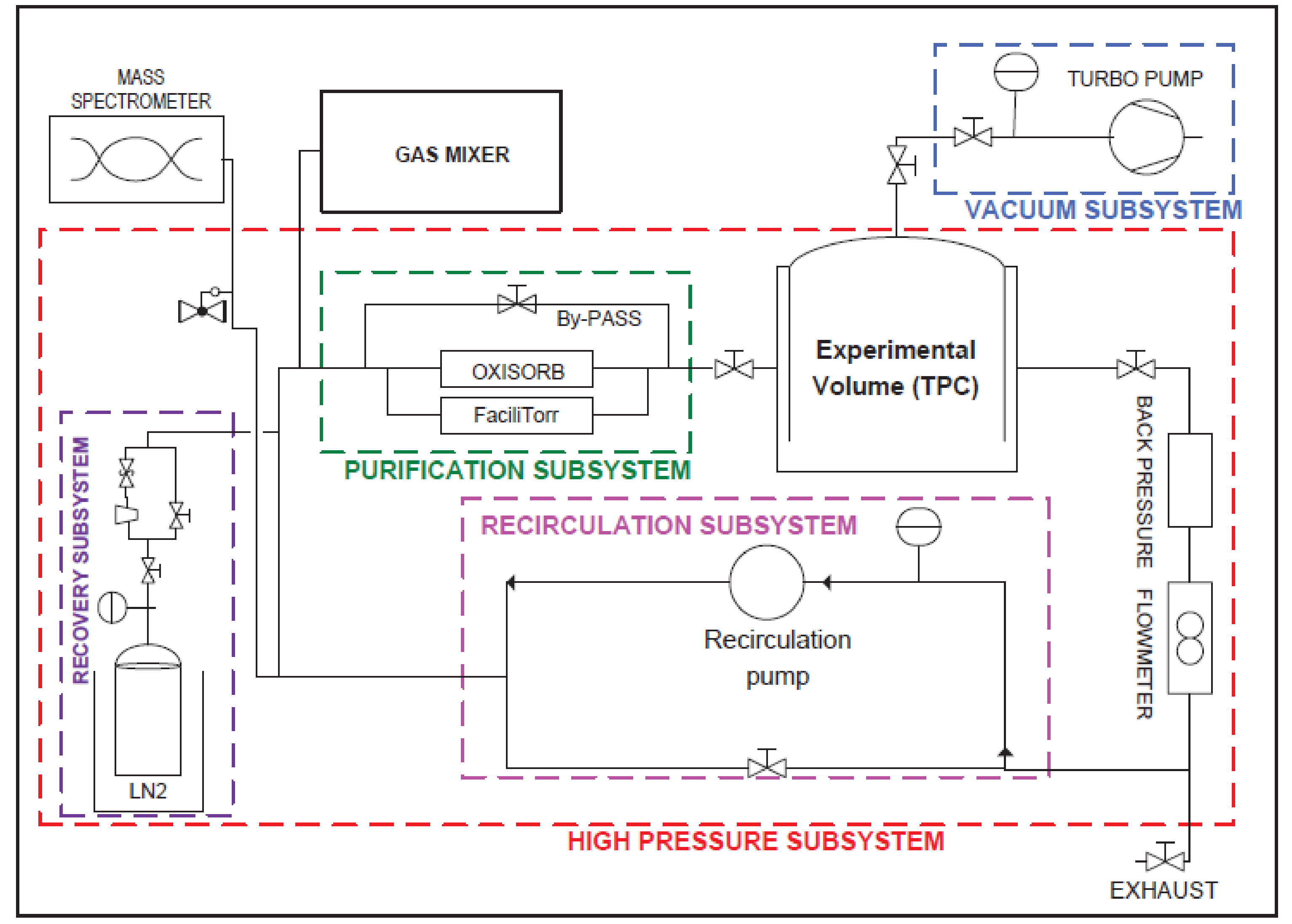
1kV/cm at 1 bar → 10kV/cm at 10 bar

NEXT-MM: could reach 50-100kV… can cause electrical isolation problems

V. Alvarez et al., 2014 JINST 9 C04015

Cirlex screen to avoid sparks to vessel (ground)

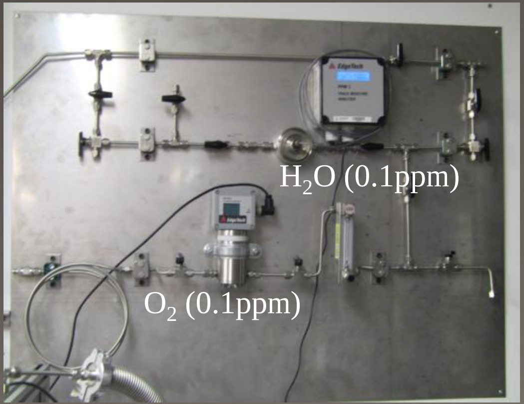
High Pressure TPC: Gas system



High Pressure TPC: Gas system (II)

- Valves that can stand High Pressure but also High vacuum
- Recirculation pump should start at high pressure
- Mass spectrometer measures at vacuum:

  capillary makes it possible at ~ 1 atm
- Limitations of some purifiers and impurities sensors at high pressure
- Mass flow-meters & Back-pressure show unreliable readings > 5bar
- Recovery system with cryo-pumping (compressibility?)



High Pressure TPC: Gas selection

- Depending on the application:
  - Spectrometry: very pure noble gas (Xe)
  - Performance of TPC greatly enhanced with a quencher
- Which quencher ?
  - gain, drift velocity and diffusion
- Does quencher percentage depend on pressure?
  - Yes, but not clear how…
- Other issues:
  - Attachment (purifiers necessary)
  - Recombination
  - (fluorescence)
- To take into account:
  - Vapour pressures of quenchers (liquefaction)
  - Quencher compatibility with purifier

SmallTPC operation: First Tests

- Usual operation procedure:
  - Vessel pumped down to < 10^{-6} after a bake-out cycle
  - Gas enters in the detector (if mixture, first the additive and then base gas)
  - If recirculation (for purification or to make mixture homogeneous), wait for 30min-1 hour
  - Gas measured with mass spectrometer
  - Gas recovered with LN_2

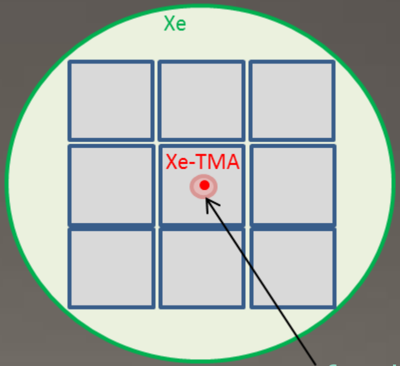
- Tests in Ar-Isobutane, pure Ar and pure Xe

T. Dafni, NIM A 608 (2009) 259-266
T. Dafni et al., J. Phys.:Conf. Ser. 309 (2011)012009

- Looking for a quencher, TMA (C_3H_9N) suggestion:
  - Can form a Penning gas with Xe
  - Reduces electron diffusion
  - Fluorescent (in Xe?)

D. Nygren, 2011 J. Phys.: Conf. Ser. 309 012006

NOT user friendly, but nose can detect it at ppb !
Vapour pressure: ~1bar.



Transverse size of e-cloud after 38cm of drift @1bar

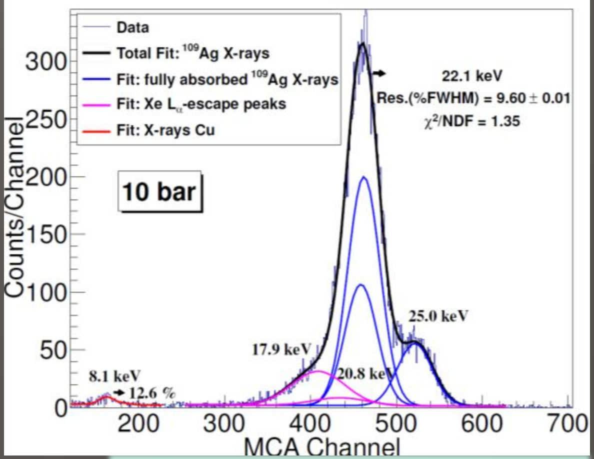
Small TPC operation : Xe-TMA

9.6%(FWHM)
@22.1 keV

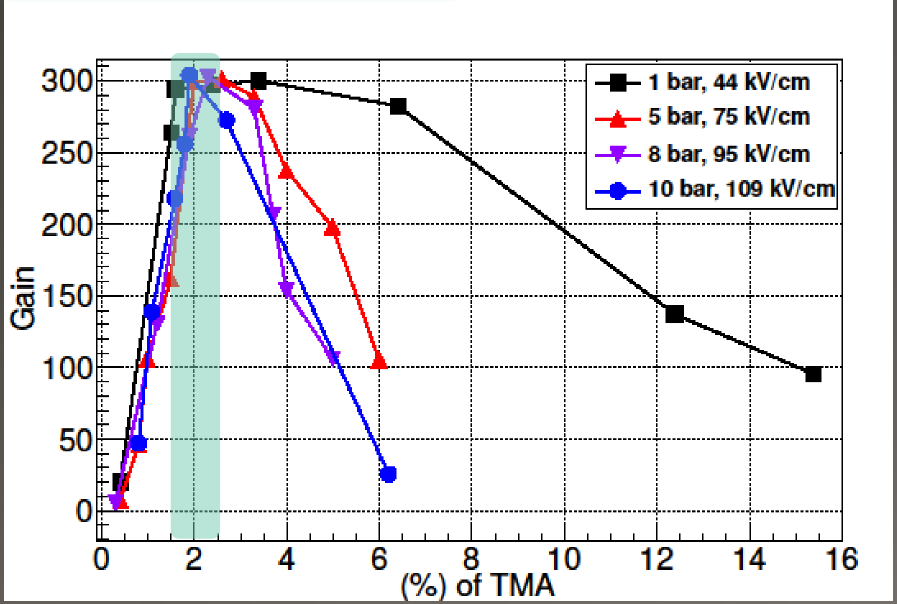
Drastic increase in gain with a small addition of TMA
Narrow optimal range 1-2.5%

The operation point was always well in the plateau.

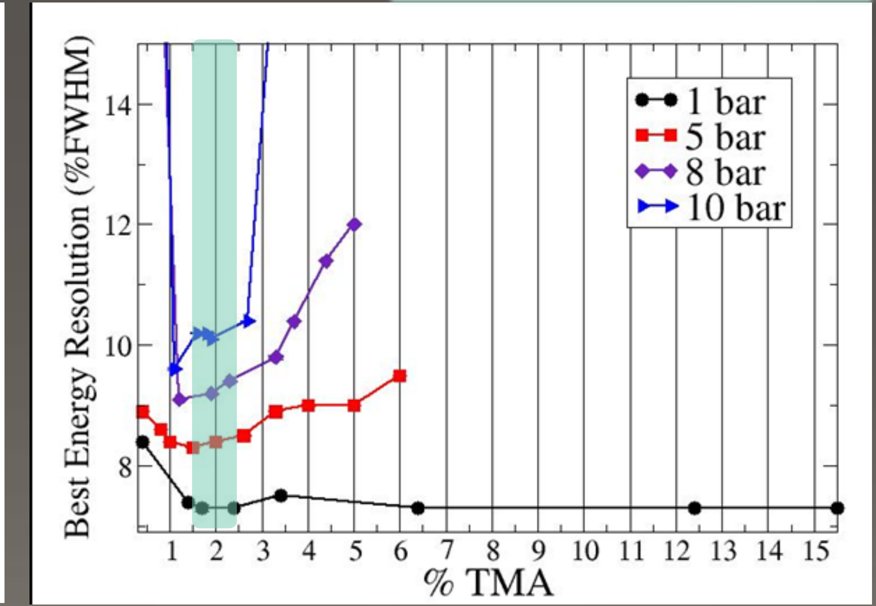
S. Cebrian et al., 2013 JINST 8 P01012
D.C. Herrera , J. Phys. Conf. Ser. 460 (2013) 012012



Gain at constant Vmesh



E_{res} at constant gain (300)



Small TPC operation : Gain & resolution

22.1 keV of ^{109}Cd, Mixtures with (1.5-2.5)% of TMA

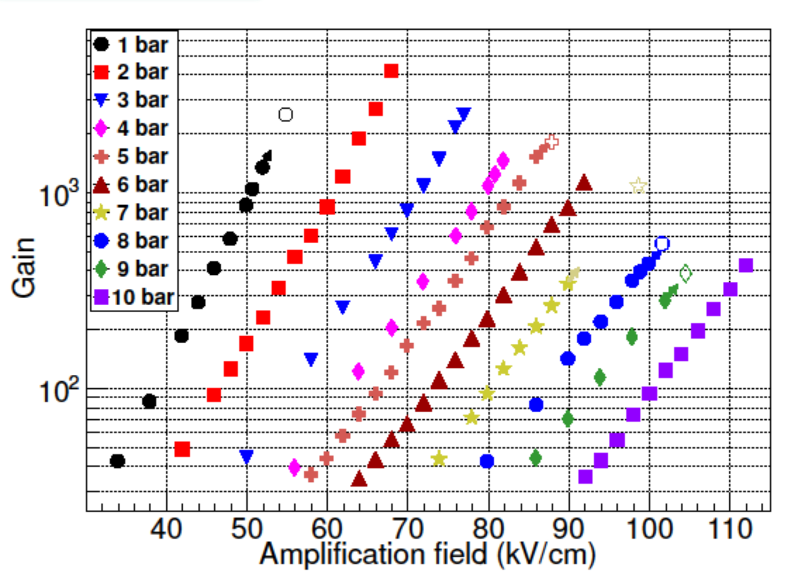
Exponential drop of max. achieved gain at HP

For M=100 at 10 bar, Vmesh= 500V
at 1 bar Vmesh= 200V

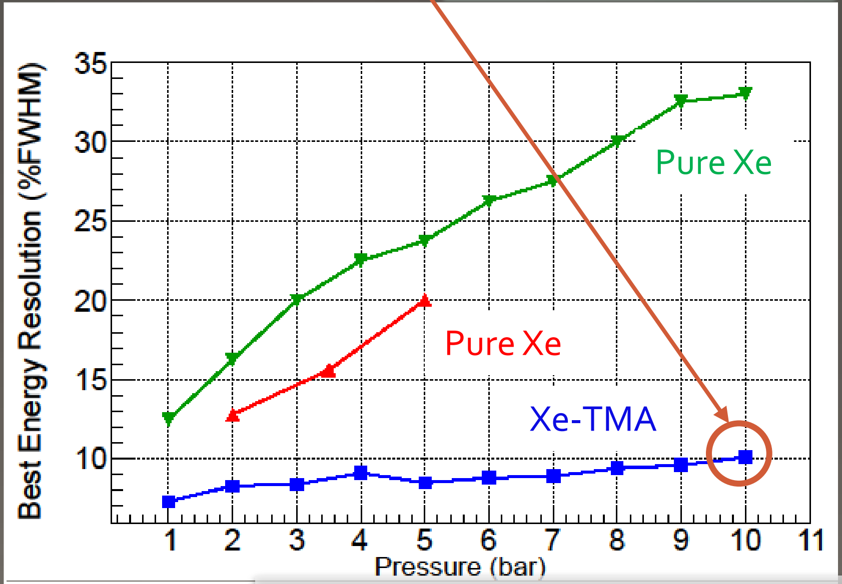
$\alpha \sim P f\left(\frac{E}{P}\right)$ easier than the drift field…

Energy resolution degradation at HP:
Due to intrinsic phenomena, not attachment
Still extrapolates (at 10bar) to
0.9% (FWHM) at $Q_{\beta\beta Xe}$ (2.48MeV)!

Gain 1-10 bar



Best E_{res} comparison



C. Balan et al, 2011 JINST 6 P02006
T. Dafni et al., J. Phys.:Conf. Ser. 309 (2011)012009
S. Cebrian et al., 2013 JINST 8 P01012

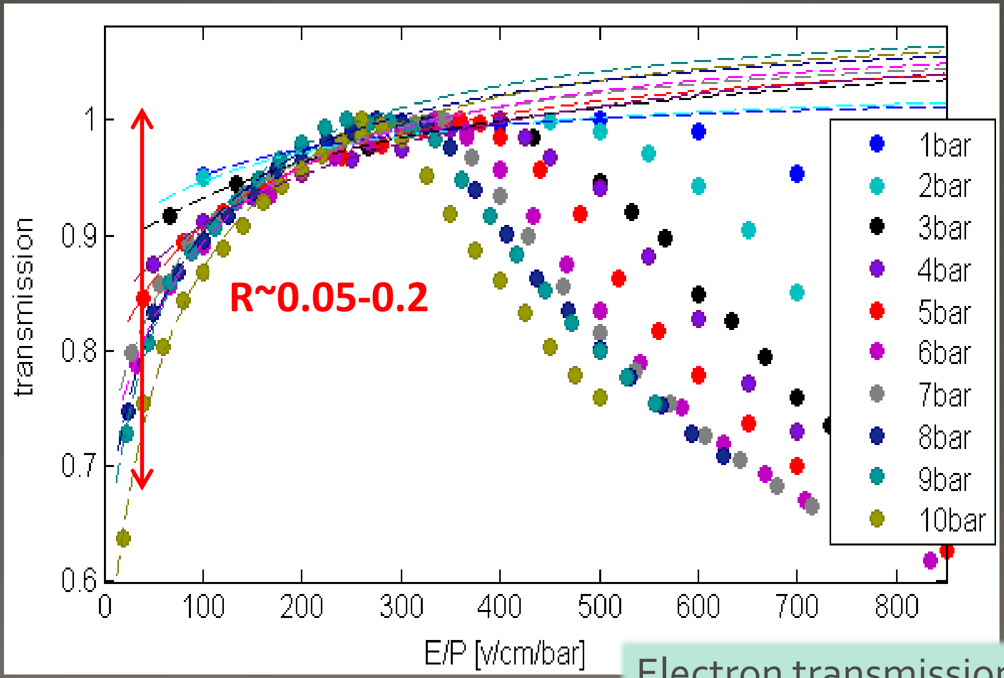
Recombination and ongoing work

Ongoing work on microscopic modelling of the avalanche with Garfield :
Penning, recombination, Fano

Low diffusion allows exotic ideas:
columnar recombination could be used to infer the directionality of dark matter

The left part suffers from recombination (or attachment, but not the case here).

The lower the E/P, the more affected by recombination.



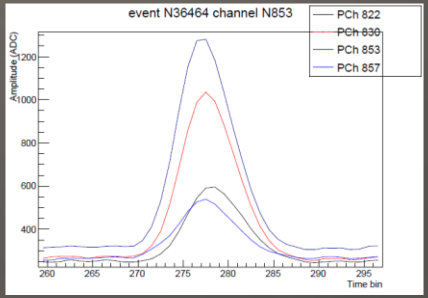
Electron transmission

NEXT-MM: 1-3 bar

V. Alvarez et al , 2014 JINST 9 P03010

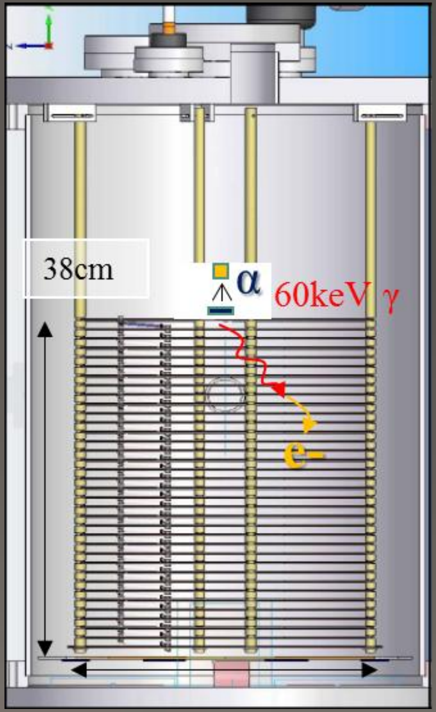
Xe-2%TMA, M= 2000, mesh$_{thr}$~10keV, pixel$_{thr}$~0.5keV
Focus on the 30keV region

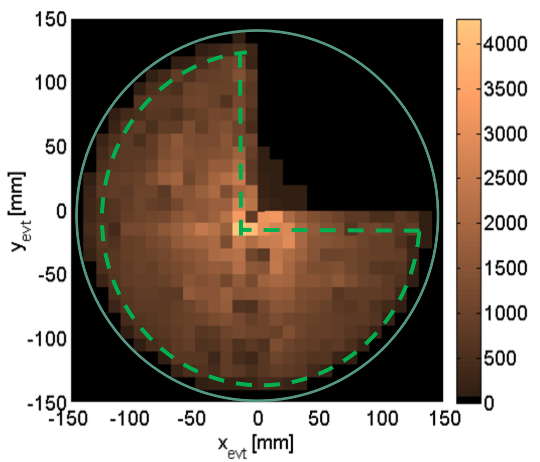
- ✓ Pulse shape analysis:
  - info on t, σ, z
- ✓ Calibrations:
  - sectors, pixels, transient
- ✓ Track:
  - baseline, cosmic, single-cluster
- ✓ Random coincidences suppression
- ✓ XYZ fiducialization

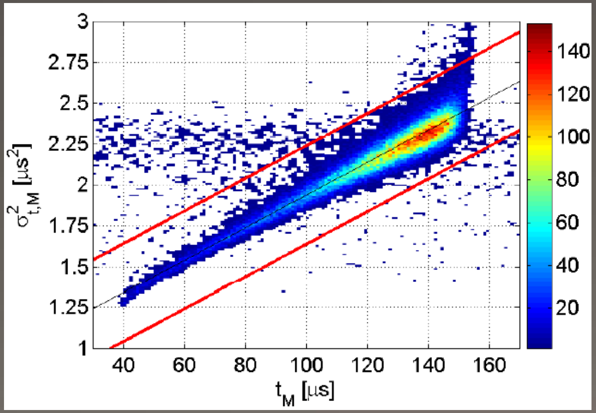


^{241}Am source

(60 keV γ)

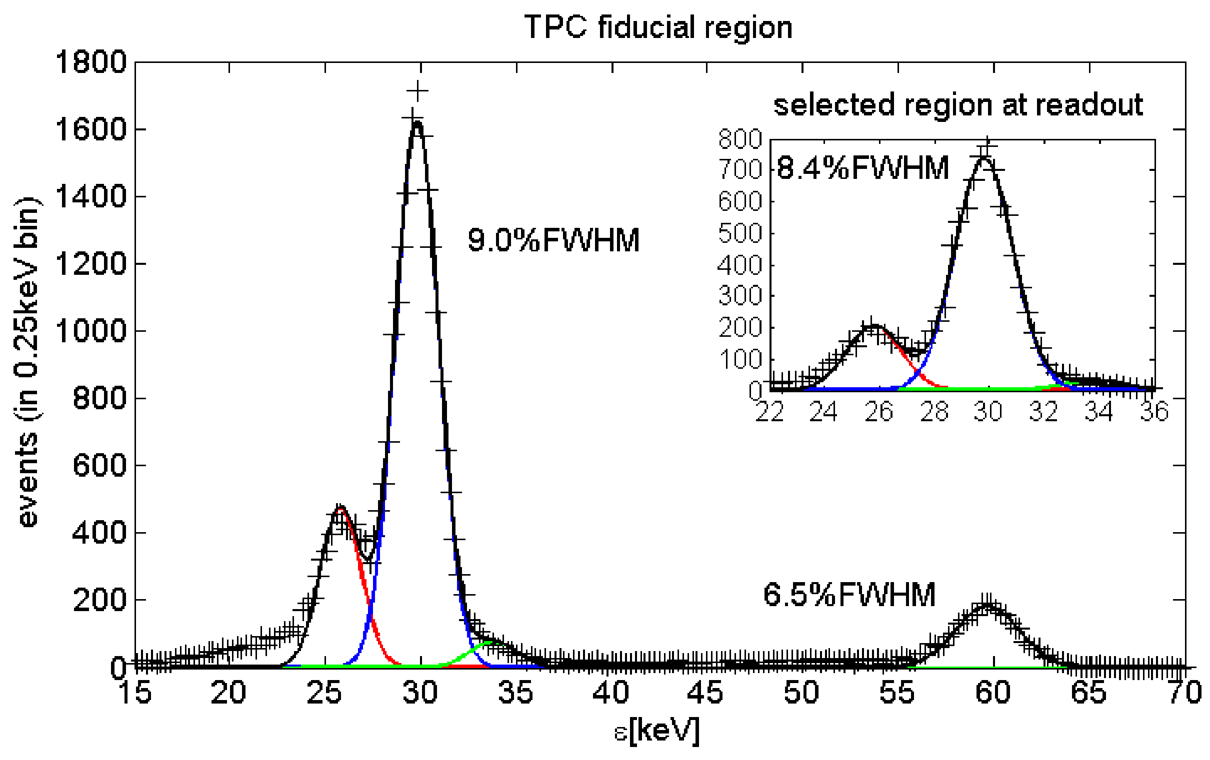






NEXT-MM: 1-3 bar, Energy resolution

Xe-2%TMA, M= 2000, E_{drift} = 145.5V/cm/bar, $mesh_{thr}$~10keV, $pixel_{thr}$~0.5keV

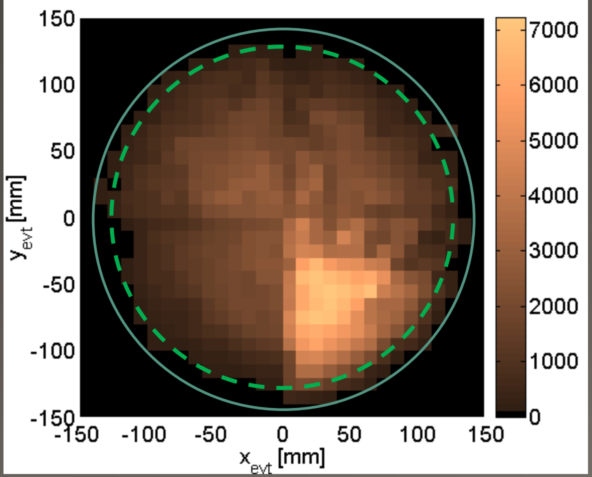


59.5keV	^{241}Am
33.64 keV	Xe K_β
29.80keV	Xe K_α
29.74keV	59.5 - K_α
26.35keV	^{241}Am
25.90keV	59.5- K_β

NEXT-MM: 10 bar

Xe-1%TMA, M~200, mesh$_{thr}$~300keV, pixel$_{thr}$~10keV

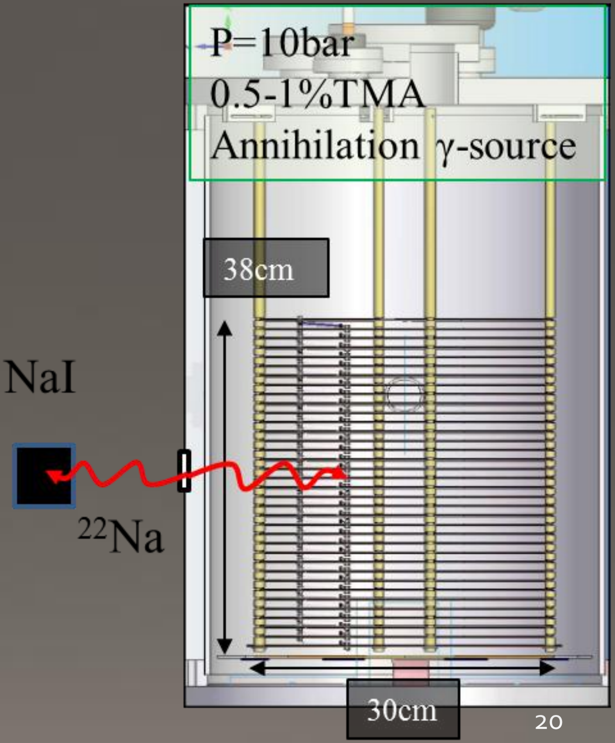
- ✓ Pulse shape analysis:
  - info on t, σ, z
- ✓ Calibrations:
  - sectors, pixels, transient
- ✓ Track:
  - baseline, cosmic, 1-3 clusters
- × Random coincidences suppression
- ✓ XYZ fiducialization



9.5-10 bar

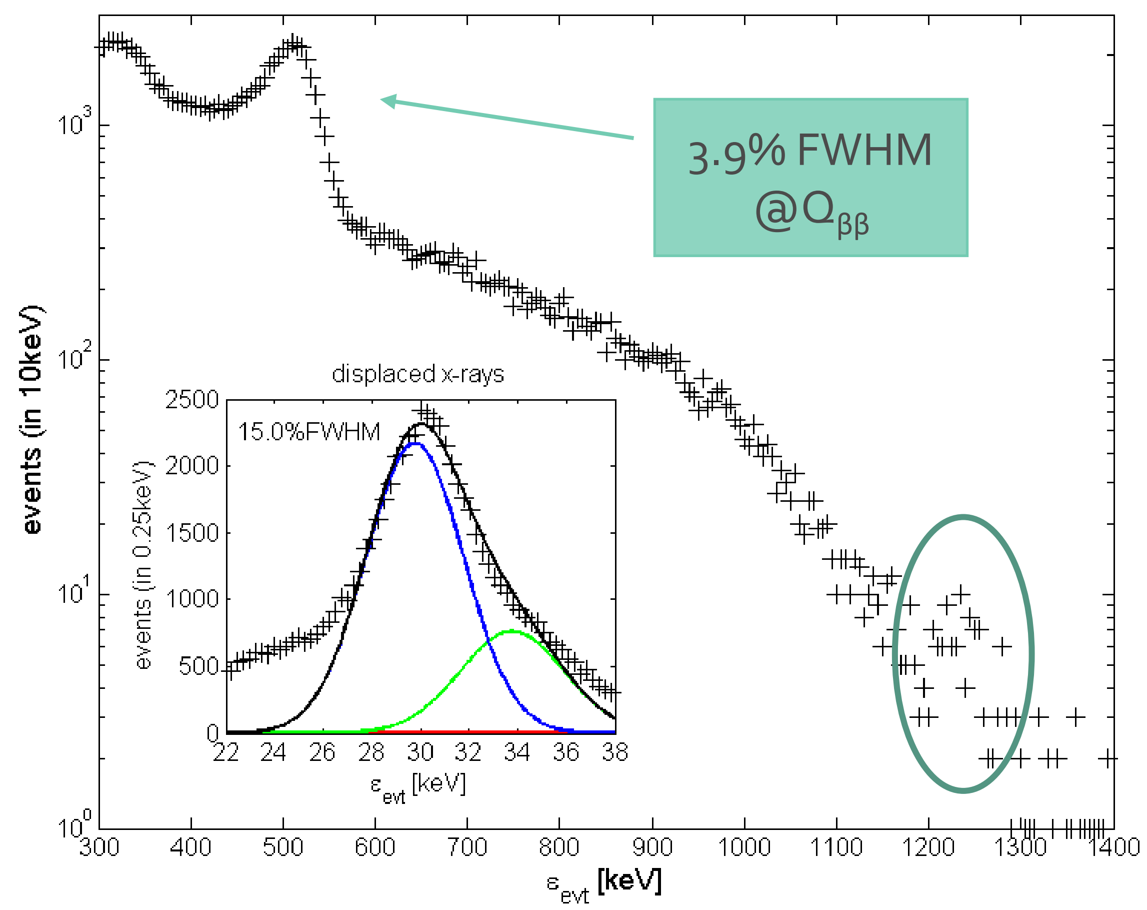
^{22}Na source

(511 keV, 1275 keV)



NEXT-MM: 10 bar, Energy resolution

Xe-1%TMA, M= 200, E_{drift} = 80V/cm/bar, $mesh_{thr}$~10keV, $pixel_{thr}$~0.5keV

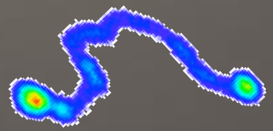


3.9% FWHM @$Q_{\beta\beta}$

15% FWHM @ 30keV

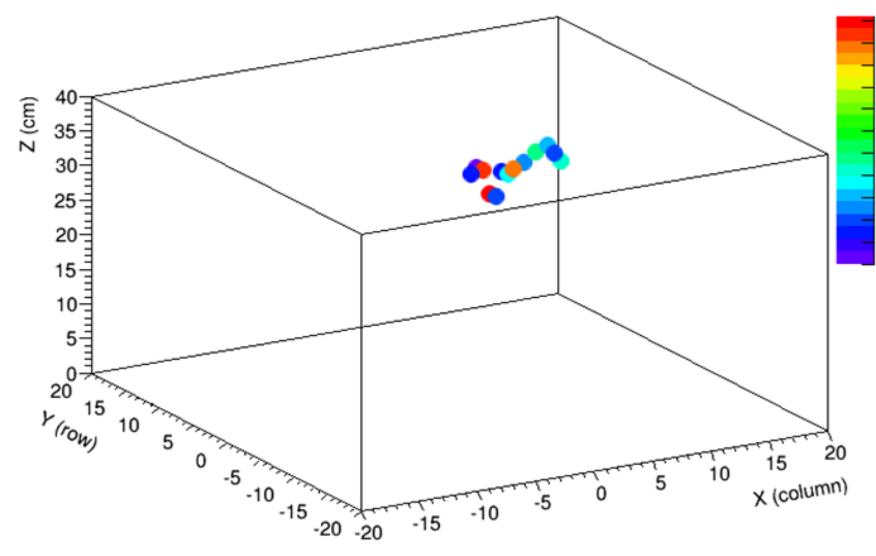
33.64 keV	Xe K_β
29.80keV	Xe K_α
511keV	22Na
1275keV	22Na

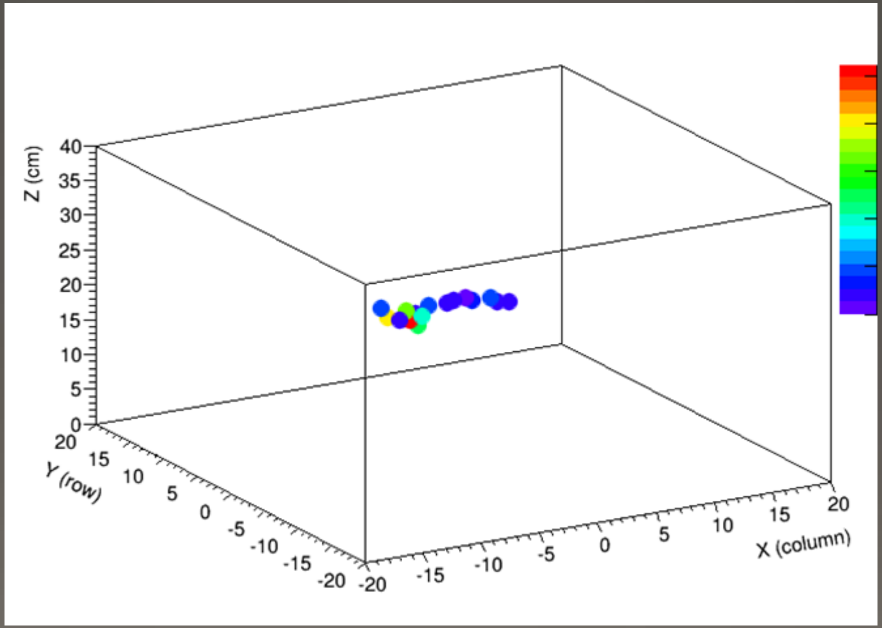
NEXT-MM: 10 bar, tracks



a simulated signal event:
two blobs

1275 keV
The blob is clearly visible.
Data-taking focused on topological aspects already ongoing.



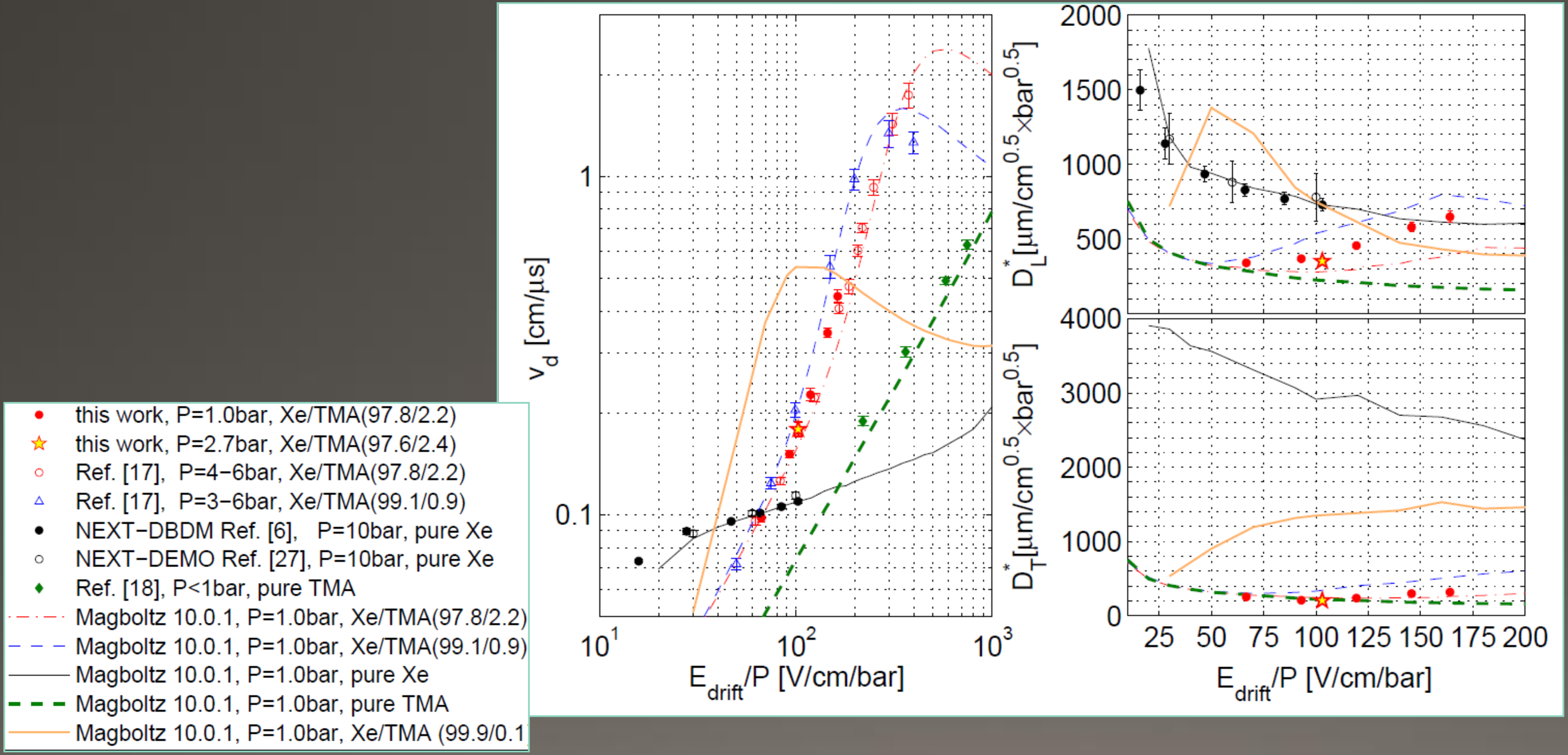


Gas properties

V. Alvarez et al , 2014 JINST 9 P03010

Drift velocity measured in both setups in different Xe-TMA mixtures

NEXT-MM has been the first setup to measure the longitudinal and transverse diffusion of a Xe-TMA mixture



Gas properties

V. Alvarez et al , 2014 JINST 9 P03010

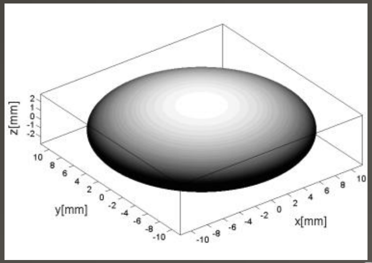
Drift velocity measured in both setups in different Xe-TMA mixtures

NEXT-MM has been the first setup to measure the longitudinal and transverse diffusion of a Xe-TMA mixture

$$\sigma_{L,T} = D^{*}_{L,T}\frac{\sqrt{z}}{\sqrt{P}}$$

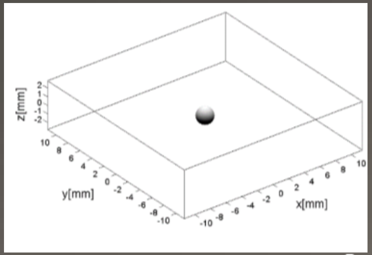
z_{drift} =100cm, P = 10bar

pure Xe

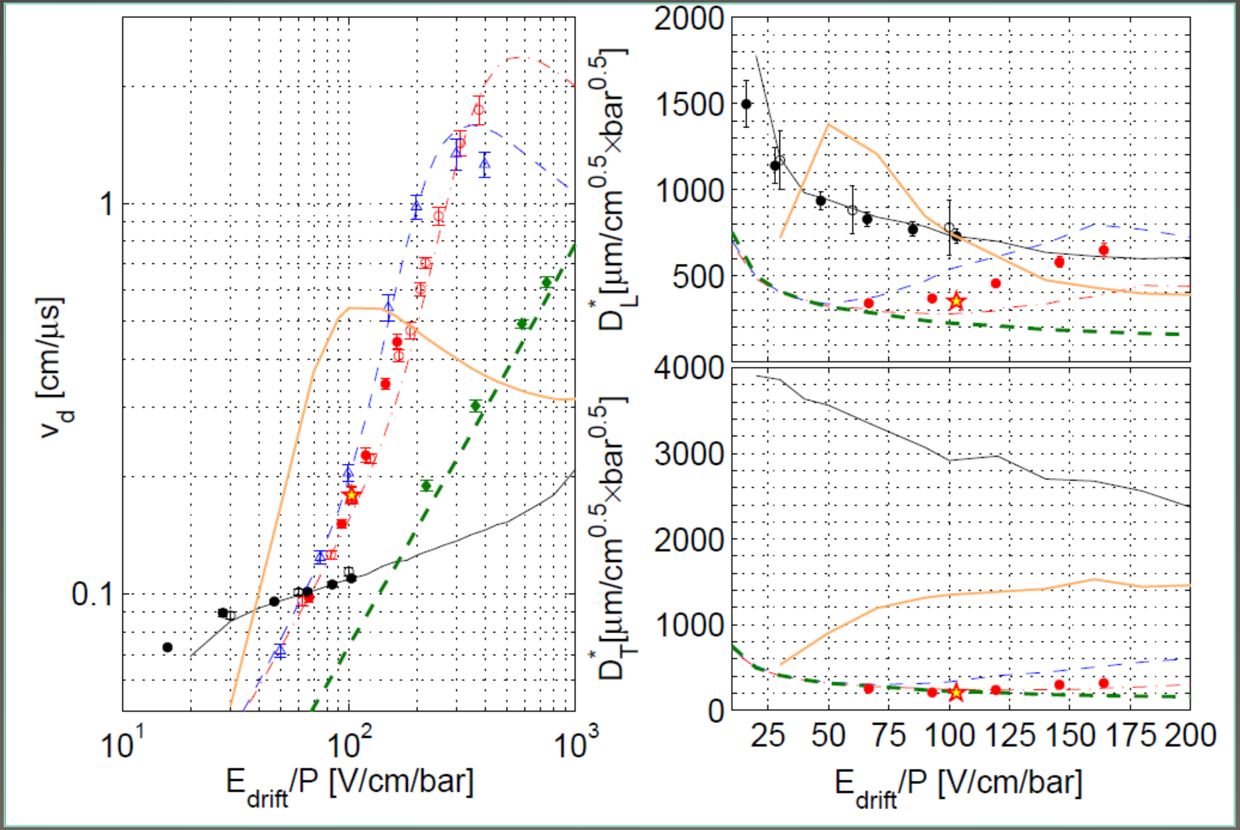


~20×20mm²

Xe/TMA (98/2)

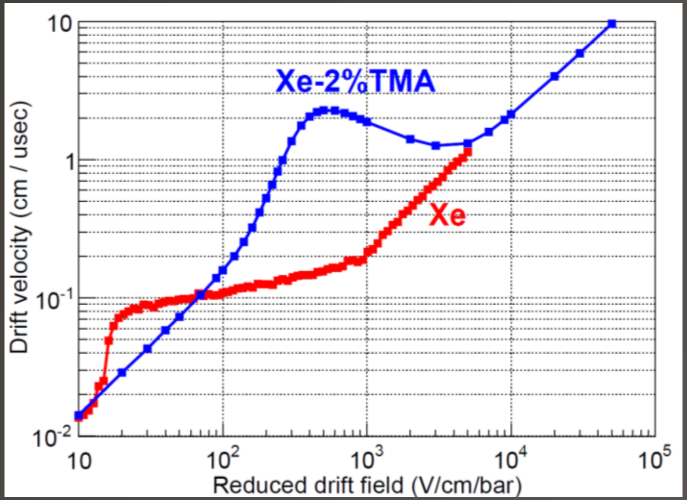


~2×2mm²



Scaling of the relevant parameters

Or how HP translates in TPC performance expectations



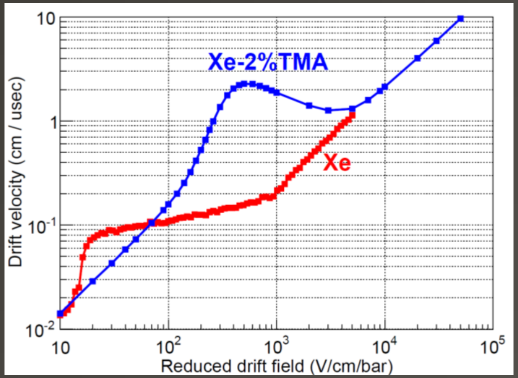
A. Drift velocity fixes several aspects of the TPC, of most importance the time response:
time windows, electronics

$v_d \sim E/P$

one aims at a specific E/P range

Scaling of the relevant parameters

Or how HP translates in TPC performance expectations



A. Drift velocity fixes several aspects of the TPC, of most importance the time response:

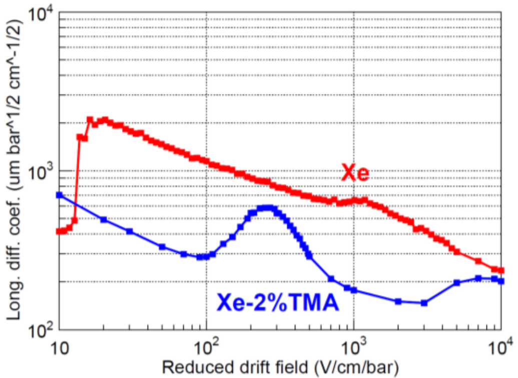
time windows, electronics

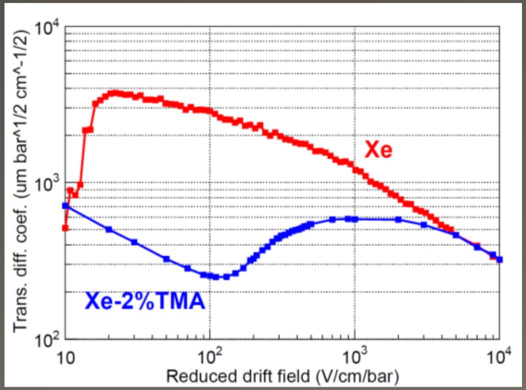
$v_d \sim E/P$

one aims at a specific E/P range

B. Diffusion reduces by factor 3 in each direction for P=10bar

$$\sigma_{L,T} = D^*_{L,T} \frac{\sqrt{z}}{\sqrt{P}}$$





Increases sharpness of the track →
better topology response
Increases charge density in gap →
lower max. achievable gain

Scaling of the relevant parameters

Or how HP translates in TPC performance expectations

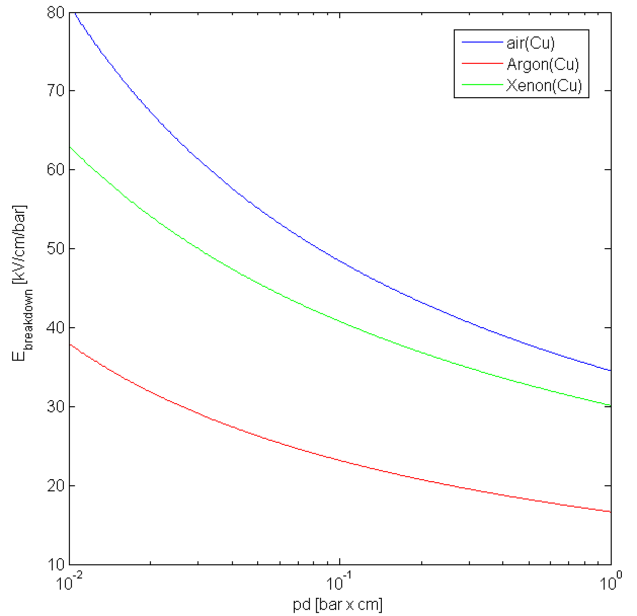
C. Attachment: consequences scale with pressure, or worse: eg. $O_2 \sim P^2$
D. Recombination: higher P, higher probability to reunite

Scaling of the relevant parameters

Or how HP translates in TPC performance expectations

C. Attachment: consequences scale with pressure, or worse: eg. O2 ~ P²

D. Recombination: higher P, higher probability to reunite



E. Keeping same E/P at HP not easy despite higher voltages achievable at HP.

Reduced $E_{breakdown}$ is reduced at higher pressures

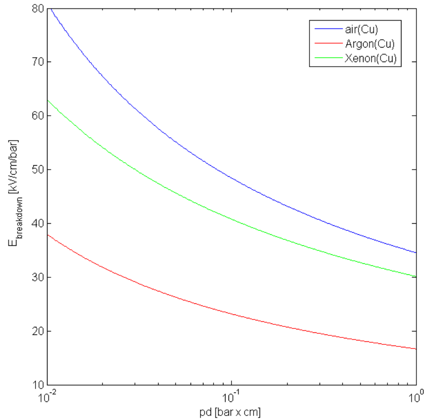
Forces working at lower E/P

Lower E/P means more recombination

Scaling of the relevant parameters

Or how HP translates in TPC performance expectations

C. Attachment: consequences scale with pressure, or worse: eg. O2 ~ P^2
D. Recombination: higher P, higher probability to reunite



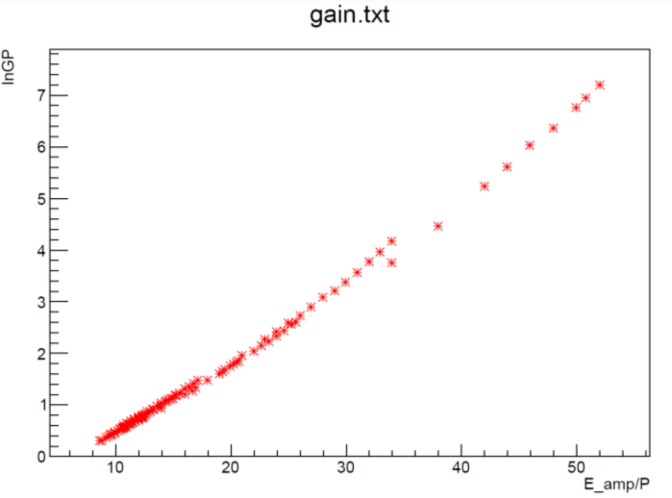
E. Although at HP max. voltages are higher, keeping same E/P at HP not easy

Reduced $E_{breakdown}$ is reduced at higher pressures
Forces working at lower E/P
Lower E/P means more recombination

F. In amplification, one can work at low E_{amp}/P because of the scaling

$$\alpha \sim P f\left(\frac{E}{P}\right)$$

But diffusion lowers max. gain
Avalanche statistics fluctuations worsen energy resolution



Summary and Conclusions (I)

- High pressures are indicated to improve sensitivity, increase target mass and reduce size/volume of detector
- Ultra-high vacuum and HV demand special mechanical components
- Gas system components have to be rated for HP as well: de-pressurization might be necessary in order to use some equipment
- The E/P dependence of drift velocity leads to EHV but is difficult to maintain because of the breakdown limits at HP
- Quenchers are necessary in order to reduce diffusion and increase gain
  - The optimum quencher % for a Penning mixture is not the same as for max gain.
- HP also reduces diffusion, but increases charge density per hole
  - The maximum achievable gain decreases with pressure
- Attachment at HP:
  - If due to impurities in gas, increases (e.g. o_2 ~P^2)
  - If due to outgassing (emanation), not clear, it may even decrease (relatively)
- Recombination is also increased at HP

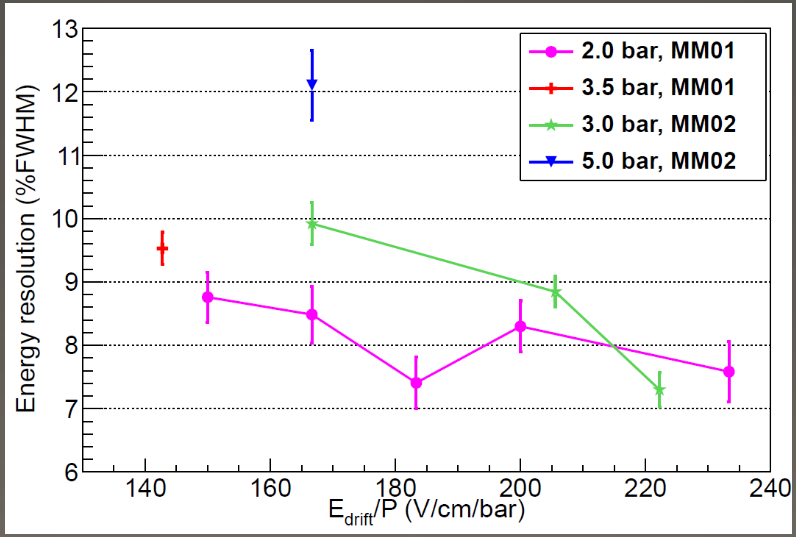
Summary and Conclusions (II)

- At UNIZAR through the T-REX project we are working on the Rare event searches field, bringing together MPGDs and low-background techniques to construct gas TPCs
- We have acquired experience at HP operating mM TPC prototypes, some of them within the NEXT project.
- In the context of the 0νββ decay, Xe-TMA can be of interest
  - Evidence of Penning effect froom gain curves. Drastic increase in gain (at constant field) with the addition of few % TMA
  - Energy resolution results are very encouraging:
    - 9.6% FWHM @22.1keV in a small setup
    - 9% FWHM (2%) and 15% FWHM (3.9%) @ 30 keV (@$Q_{\beta\beta}$) for 1 and 10 bar
  - Gas parameters like the drift velocity, diffusion have been extracted and are in agreement with Magboltz (mostly)
  - Attachment is small in our system and does not seem to be an issue
  - Recombination, however, may be in manifestation in NEXT-1
  - Ongoing:
    - proving topological capabilities as expressed in *J. Phys. G: Nucl. Part. Phys. 40 125203*
    - completing simulation studies on modelling of Xe-TMA mixtures (Penning, recombination, Fano)

end

Some results in pure Xe

- Energy resolution of 60keV γ from ^{241}Am
- Two types of microbulks
- MM02 bigger pitch and hole ø



Small TPC operation : Gas properties

^{241}Am source: Si diode introduced to have info on t_o

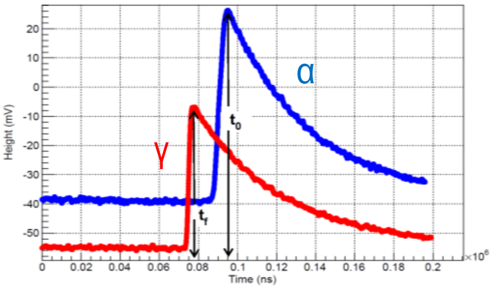
time difference of the two signals: drift velocity

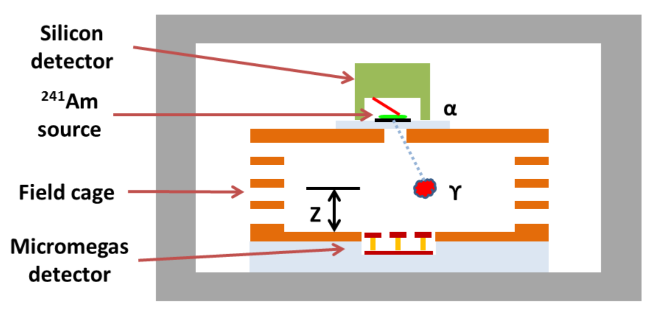
Also information on electron life-time or attachment

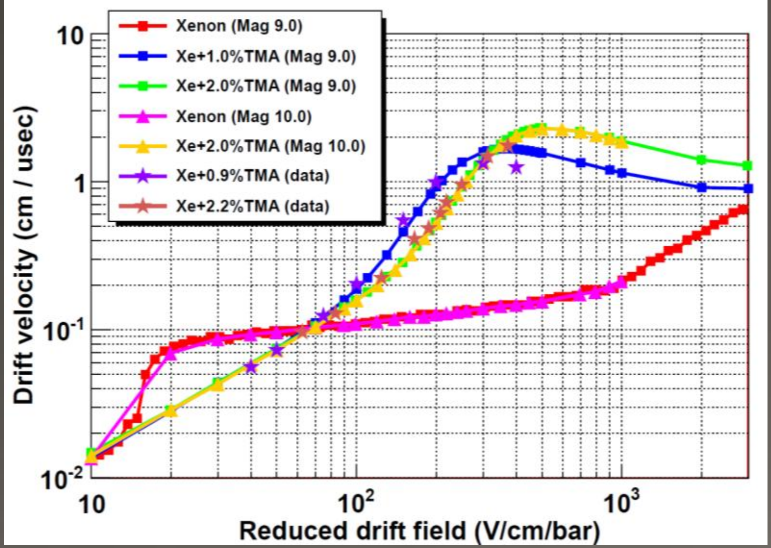
Attachment can be due to:

- impurities in the gas entry
- outgassing of materials

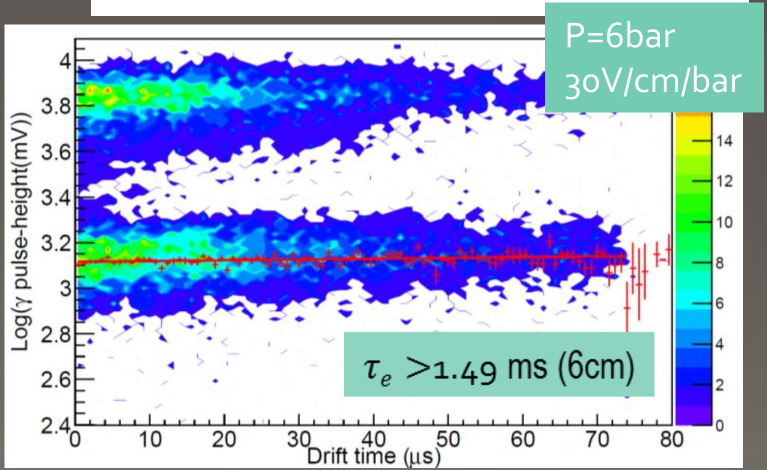
continuous purification limits it.







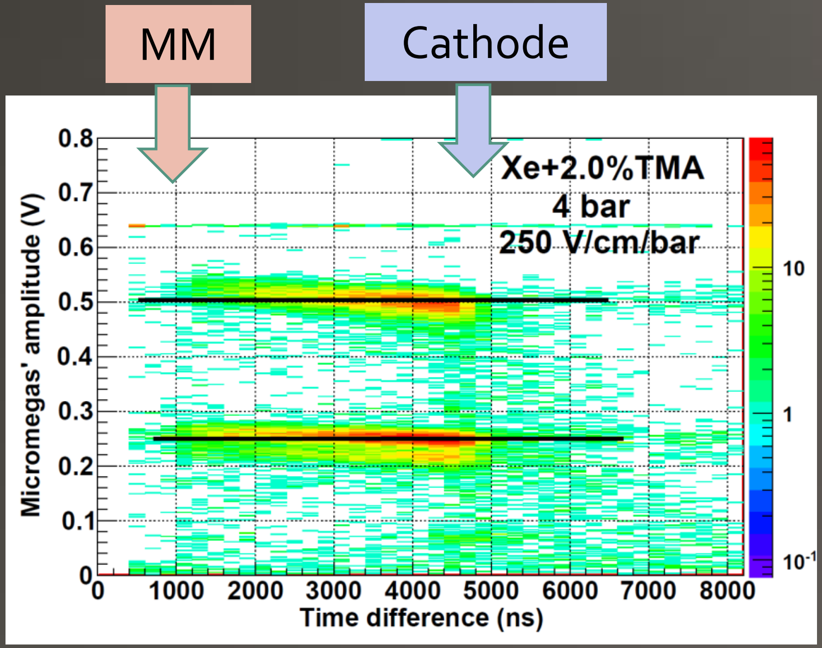
D.C. Herrera , J. Phys. Conf. Ser. 460 (2013) 012012



P=6bar
30V/cm/bar

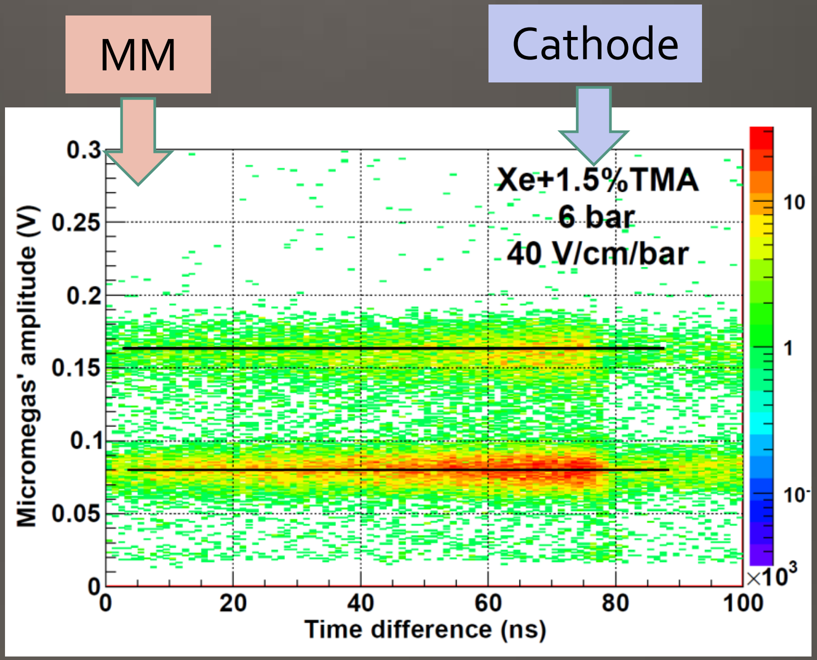
τ_e >1.49 ms (6cm)

Electron life-time



Closed mode, ~2000 ppm O_2

Lifetime: 58 ± 2 μs



Recirculation, 45 ppm O_2

Lifetime > 7.8 ms at 90% CL

$\log(Amp) = log\,(Amp_0) - \frac{1}{\tau}\,\Delta t$ If slope ~0 $\tau > {}^{1}/_{2\,\sigma}$ *at* 90% *CL*

Attachment

Charge loss for slices of the 30keV region

Two examples shown here

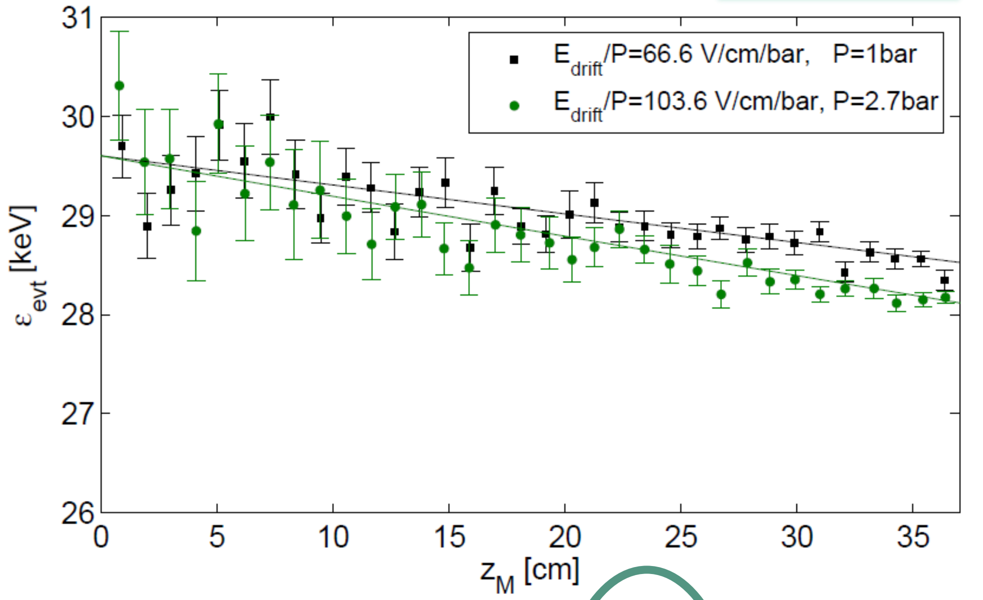
Lowering the threshold the effect is lower

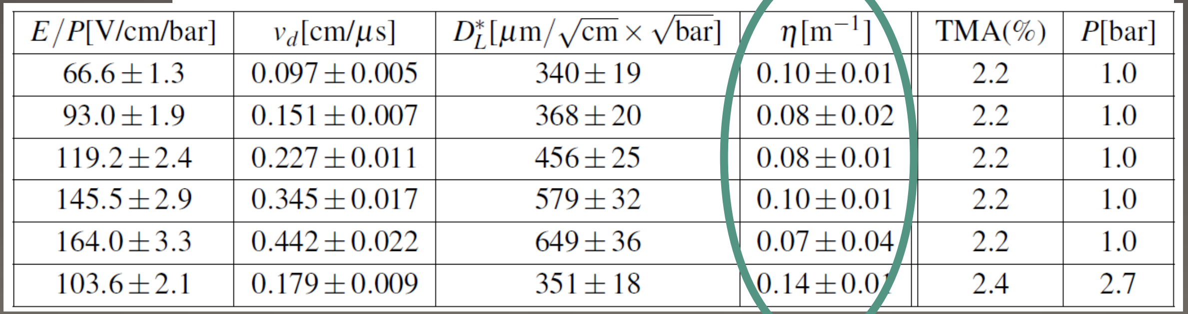
Working on similar study for

the 10 bar campaigns

Attachment cannot be excluded
but should be an upper bound

Charge loss





E/P[V/cm/bar]	v_d[cm/μs]	D_L^*[μm/$\sqrt{\text{cm}}\times\sqrt{\text{bar}}$]	η[m^{-1}]	TMA(%)	P[bar]
66.6 ± 1.3	0.097 ± 0.005	340 ± 19	0.10 ± 0.01	2.2	1.0
93.0 ± 1.9	0.151 ± 0.007	368 ± 20	0.08 ± 0.02	2.2	1.0
119.2 ± 2.4	0.227 ± 0.011	456 ± 25	0.08 ± 0.01	2.2	1.0
145.5 ± 2.9	0.345 ± 0.017	579 ± 32	0.10 ± 0.01	2.2	1.0
164.0 ± 3.3	0.442 ± 0.022	649 ± 36	0.07 ± 0.04	2.2	1.0
103.6 ± 2.1	0.179 ± 0.009	351 ± 18	0.14 ± 0.01	2.4	2.7

Attachment coefficient

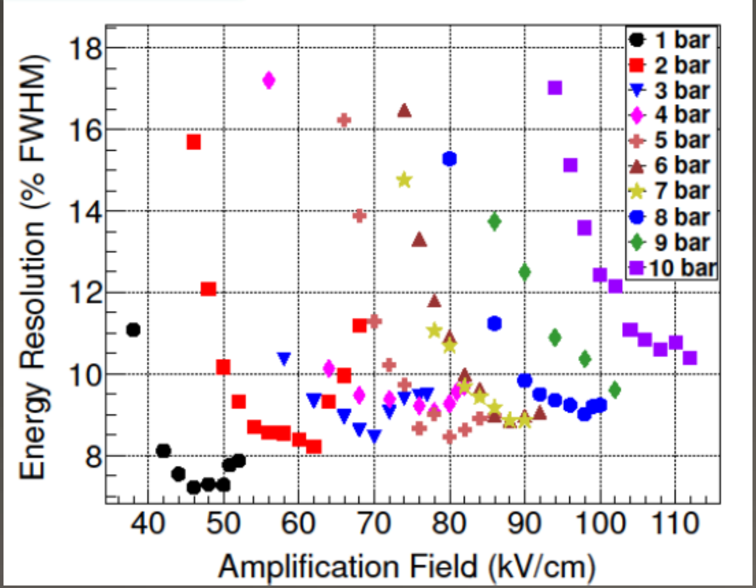
V. Alvarez et al , 2014 JINST 9 P03010

Small TPC operation : Energy resolution

22.1 keV of ^{109}Cd
Mixtures with (1.5-2.5)% of TMA
Energy resolution degradation at HP:
Due to intrinsic phenomena, not attachment!

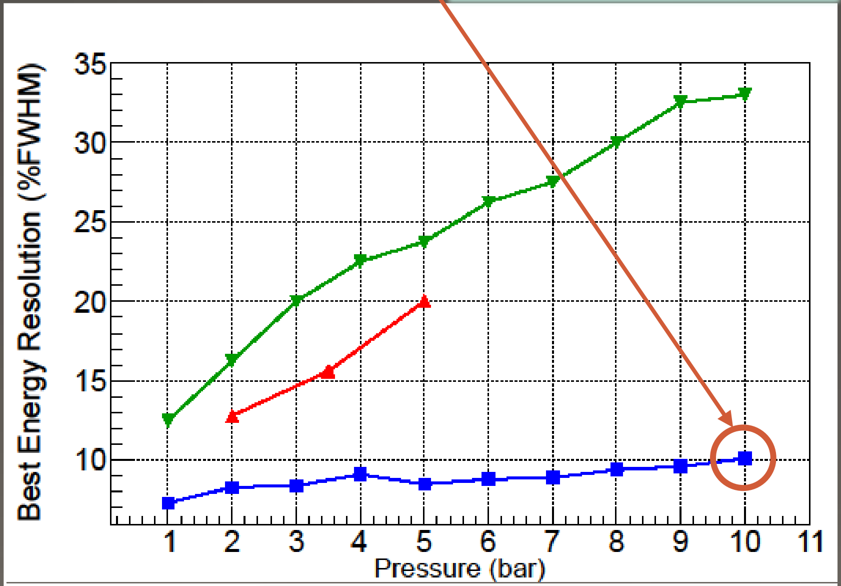
Still extrapolates (at 10bar) to 0.9% (FWHM) at $Q_{\beta\beta Xe}$ (2.48MeV)

E_{res} 1-10 bar



S. Cebrian et al., 2013 JINST 8 P01012
D.C. Herrera , J. Phys. Conf. Ser. 460 (2013) 012012

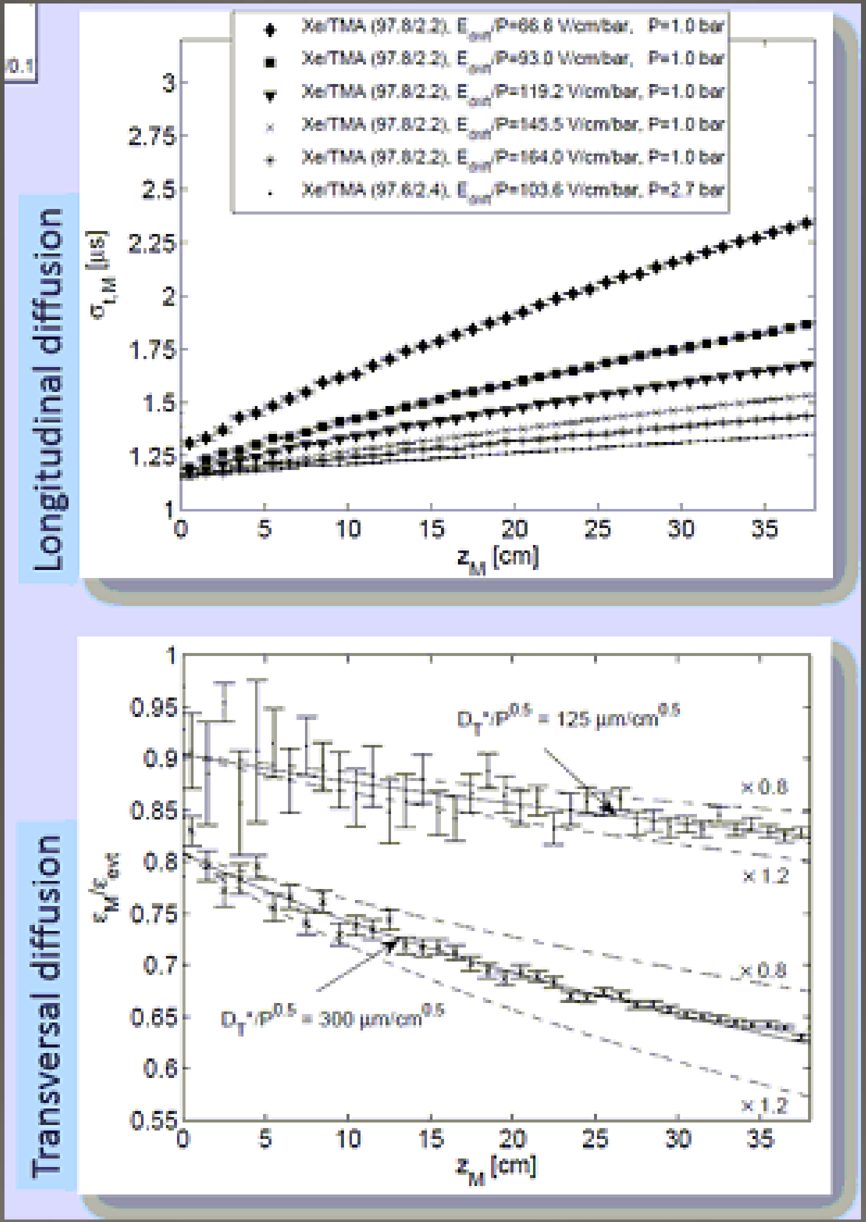
Best E_{res} comparison



C. Balan et al, 2011 JINST 6 P02006
T. Dafni et al., J. Phys.:Conf. Ser. 309 (2011)012009
S. Cebrian et al., 2013 JINST 8 P01012

Diffusion

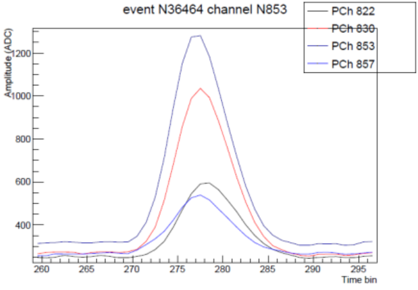
$$D^*_{L,T} = \sqrt{\frac{2PD_L}{v_d}}\left[\frac{\mu m}{\sqrt{cm}} \times \sqrt{bar}\right] \qquad \sigma_{L,T} = D^*_{L,T}\,\frac{\sqrt{z}}{\sqrt{P}}$$



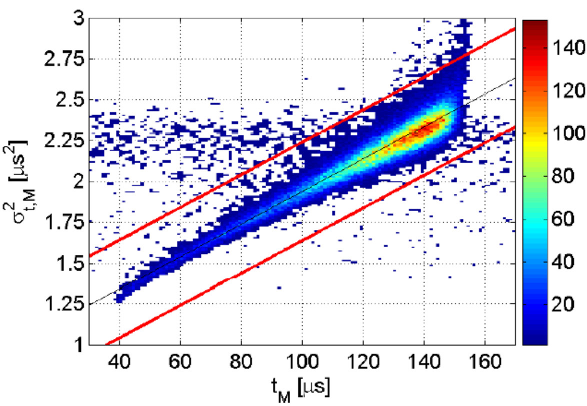
NEXT-MM: 1-3 bar

V. Alvarez et al , 2014 JINST 9 P03010

Xe-2%TMA, M= 2000, mesh$_{thr}$~10keV, pixel$_{thr}$~0.5keV
Focus on the 30keV region

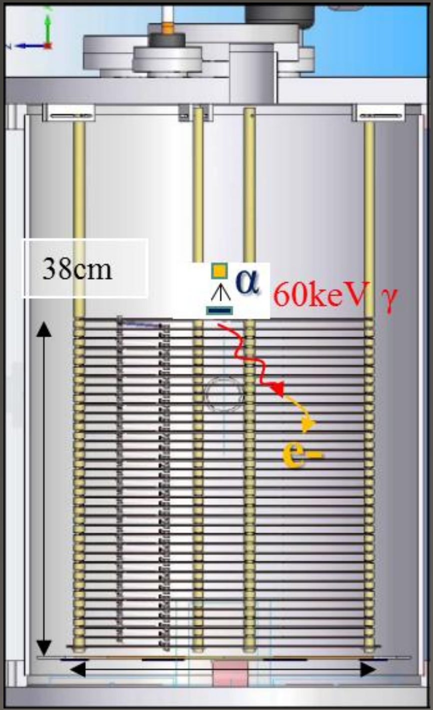


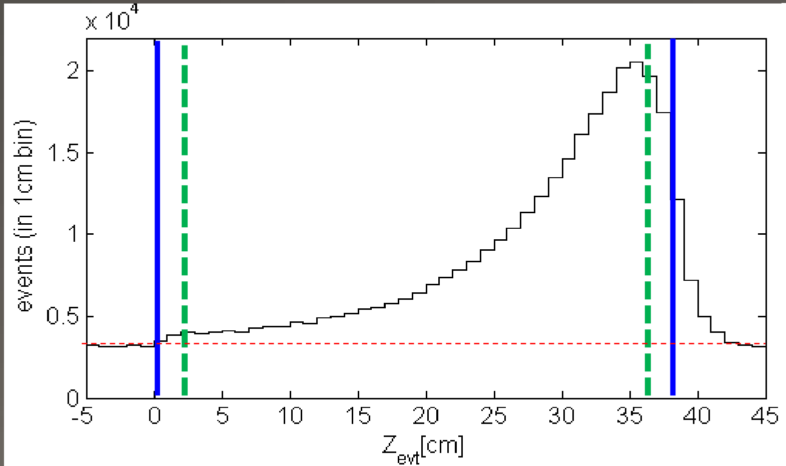
- ✓ Pulse shape analysis:
  info on t, σ, z
- ✓ Calibrations:
  sectors, pixels, transient
- ✓ Track:
  baseline, cosmic, single-cluster
- ✓ Random coincidences suppression
- ✓ XYZ fiducialization

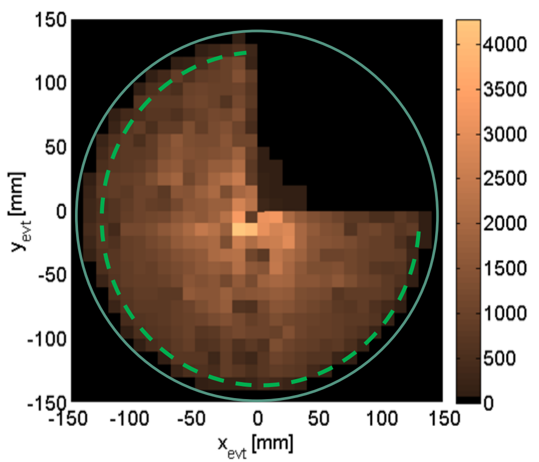


^{241}Am source

(60 keV γ)







NEXT-MM: 10 bar

Xe-1%TMA, M~200, mesh$_{thr}$~300keV, pixel$_{thr}$~10keV

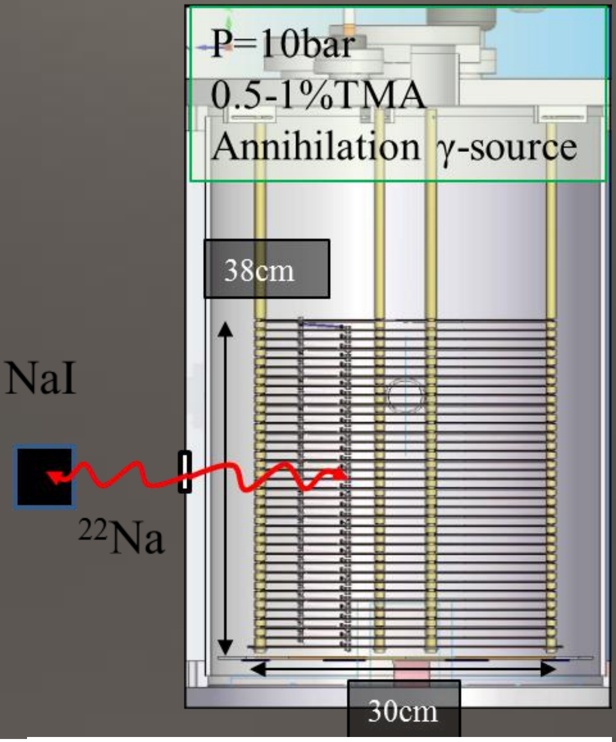
9.5-10 bar

^{22}Na source

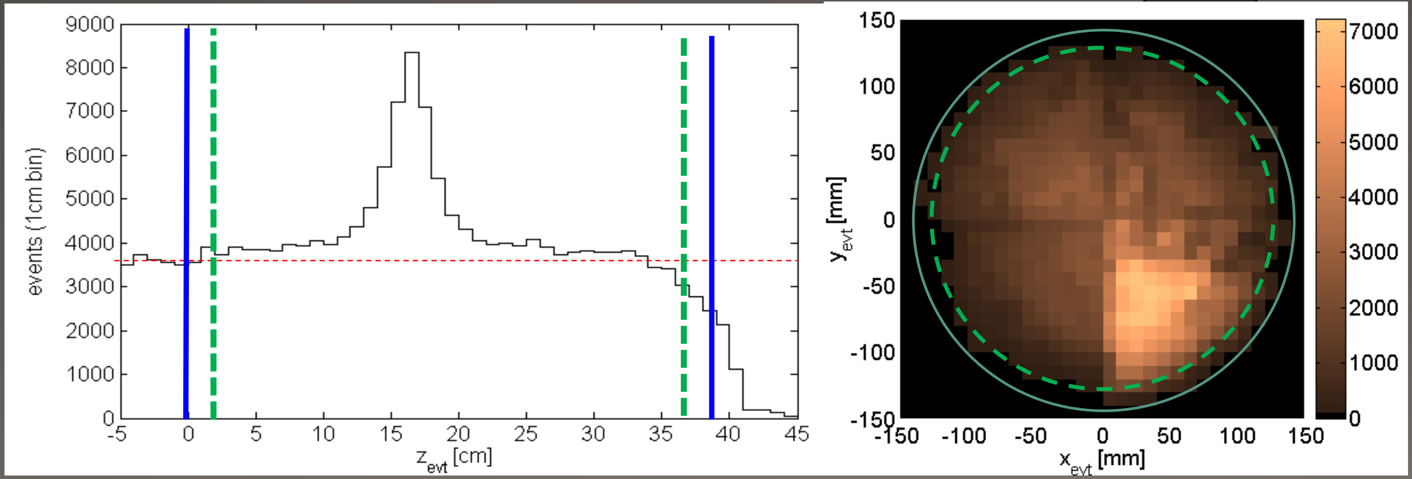
(511 keV,

1275 keV)

- ✓ Pulse shape analysis:
  info on t, σ, z
- ✓ Calibrations:
  sectors, pixels, transient
- ✓ Track:
  baseline, cosmic, 1-3 clusters
- × Random coincidences suppression
- ✓ XYZ fiducialization



Z biased from source position



Small TPC operation : Gain

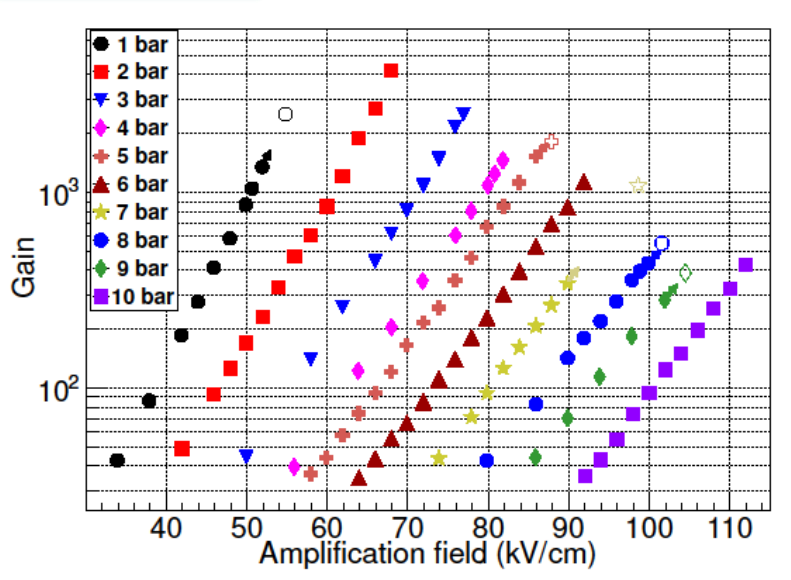
Mixtures with (1.5-2.5)% of TMA

Exponential drop of max. achieved gain at HP

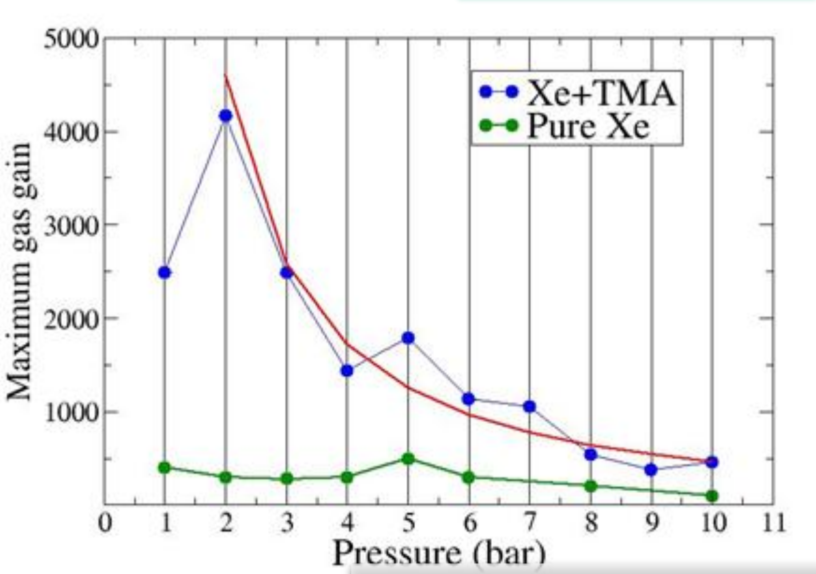
For M=100 at 10bar, Vmesh= 500V while at 1 bar Vmesh= 200V

$\alpha \sim P f\left(\frac{E}{P}\right)$ easier than the drift field…

Gain 1-10 bar



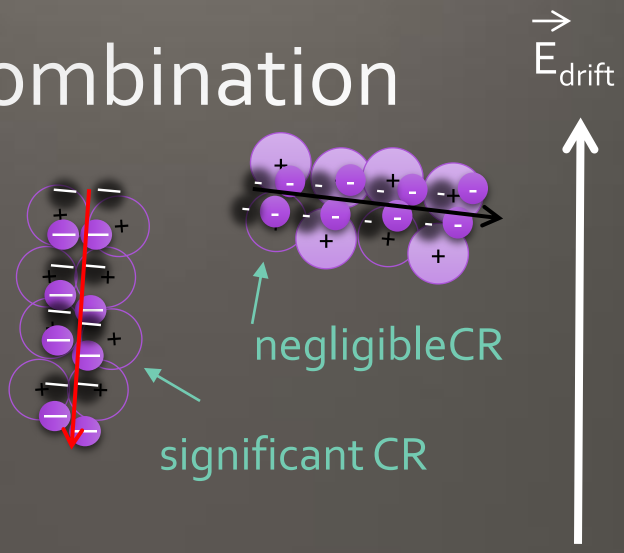
Max. Gain 1-10 bar



S. Cebrian et al., 2013 JINST 8 P01012

C. Balan et al, 2011 JINST 6 P02006

Small TPC operation : Recombination



Recombination:

Geminate (initial): e^- reunites with the parent nucleus

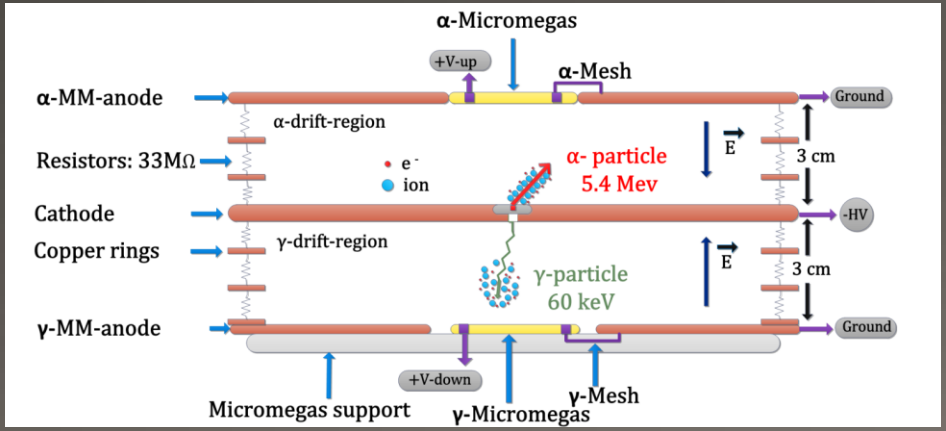
Columnar (volume): e^- escapes from parent but is captured randomly

Could explain left part of electron transmission curves

Dark matter searches:

could help enhance the directionality signal, especially if it minimizes GR

Adapted setup: 3 to 8 bar, TMA (1.2-2.2%) 2%TMA, E/P 10 to 350 V/cm/bar

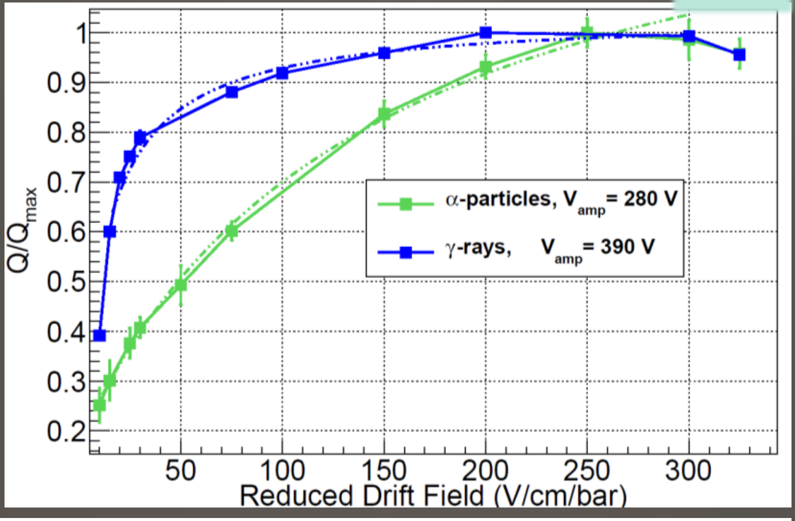


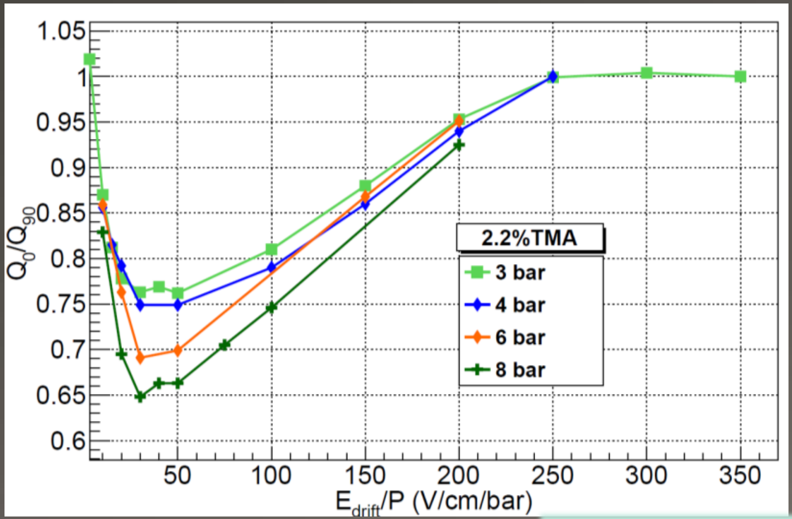
Small TPC operation : Recombination (II)

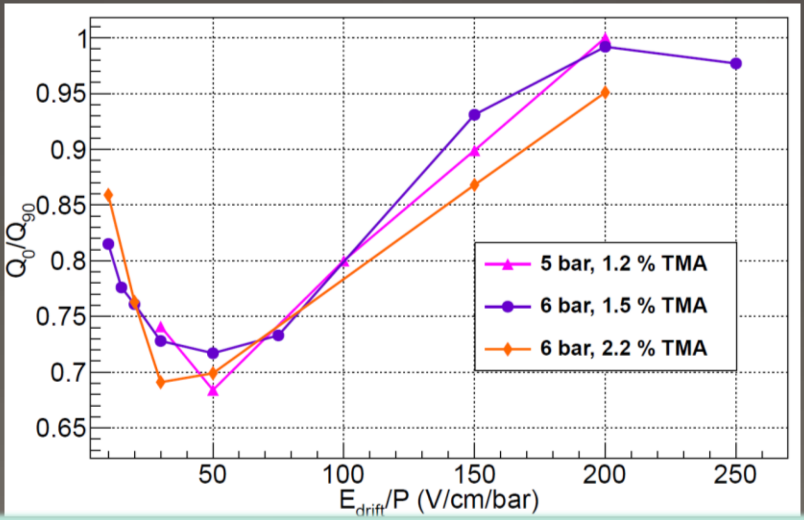
- ➢ α suffer more recombination than γ
- ➢ Decreasing CR indicates GR significant at low E/P (<50V/cm/bar)

Work still ongoing…
(modelling, ..)

6 bar







CR depends on TMA concentration and increases with pressure

On the simulation front

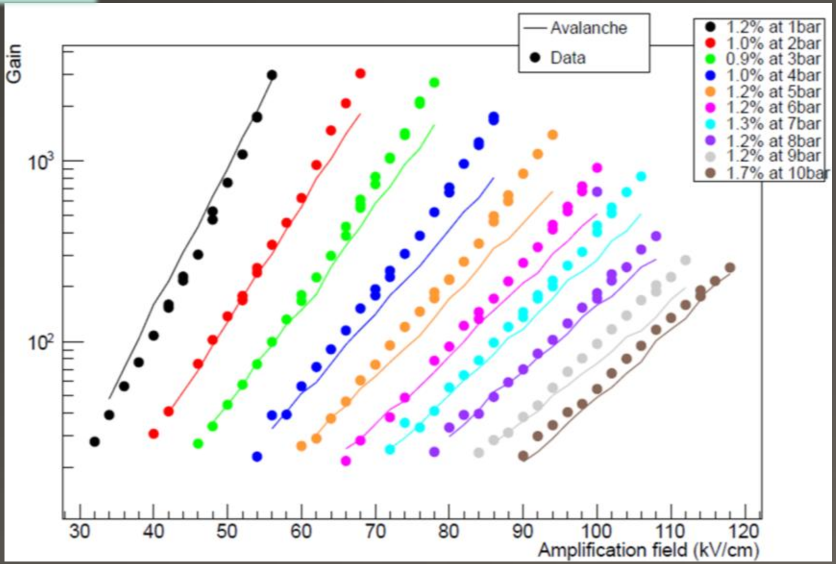
The Penning effect will decrease W as long as recombination stays low and does not over-compensate

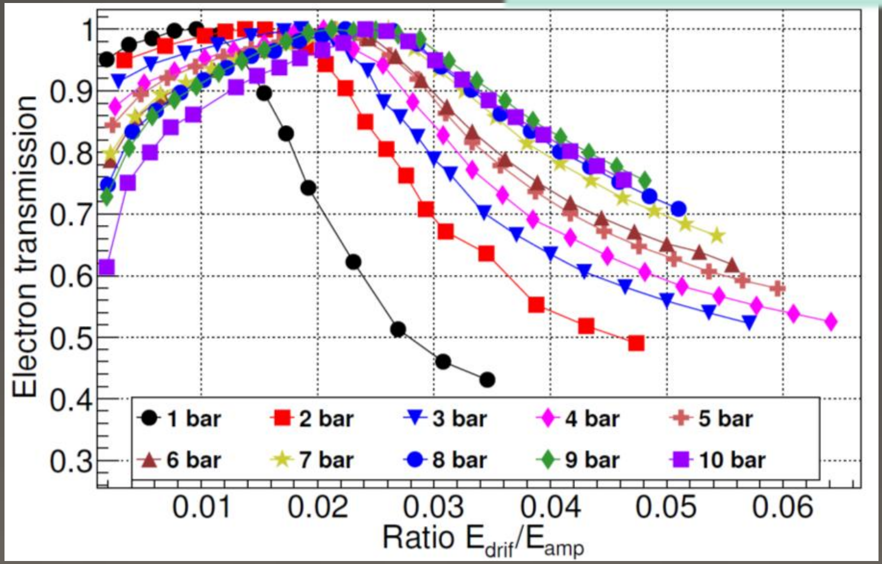
$$\frac{W_{Xe-TMA}}{W_{Xe}} \cong \frac{1}{(1+\color{green}{r}\, N_{exc}/N_I)(1-\color{red}{R})}$$

$$\frac{\sigma_{Xe-TMA}}{\sigma_{Xe}} \geq \sqrt{(1-\color{green}{r}) + \color{red}{R}/F_{Xe}}$$

Gain

Electron transmission





Gain calculations for a parallel-plate geometry
Experimental data taken with the small TPC

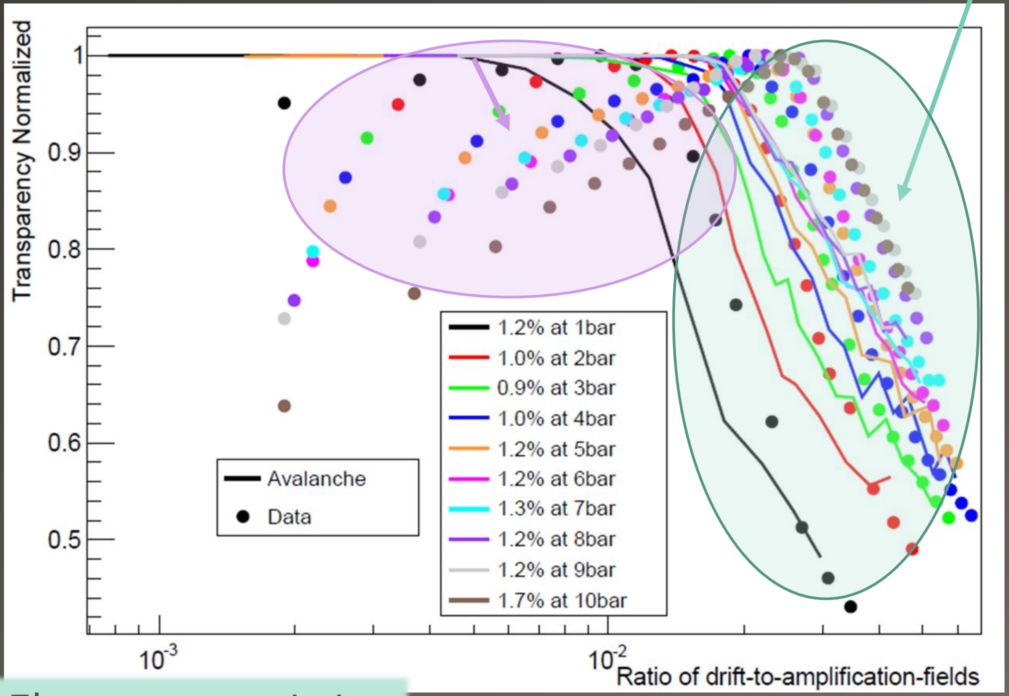
Loss of transmission on left side can be due to recombination, especially at higher pressure

On the simulation front

Ongoing work on microscopic modelling of the avalanche with Garfield
More work on the Fano factor

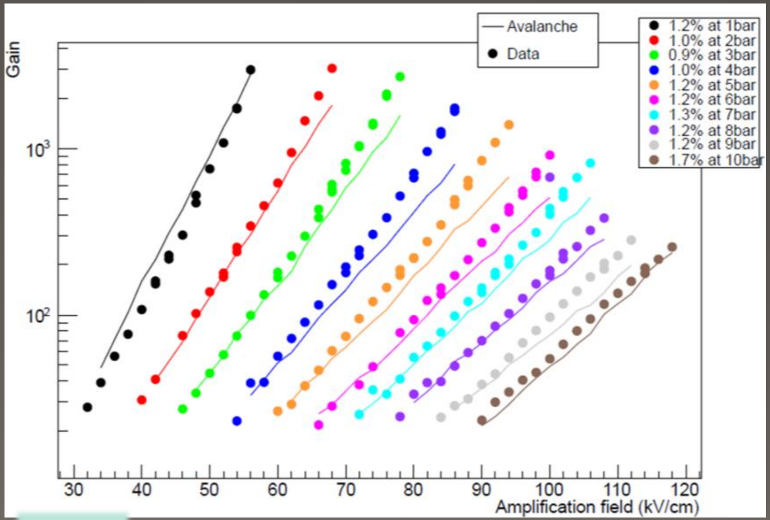
Attachment or recombination, not mM

Low transparency, depending on geometry, diffusion



Electron transmission

Not bad description of the experimental data



Gain