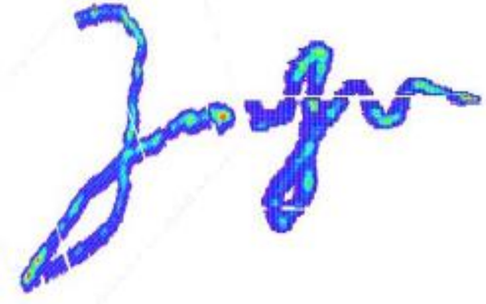


7th symposium on large TPCs for low energy rare event detection

operation of a 10bar/1kg Penning-Fluorescent Xenon TPC:

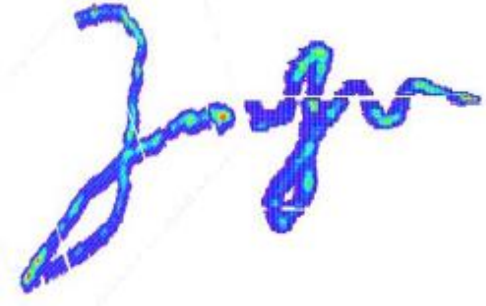
x- and γ-ray reconstruction in charge mode

Diego Gonzalez Diaz
for the NEXT collaboration

next

Universidad Zaragoza
1542

16/12/2014



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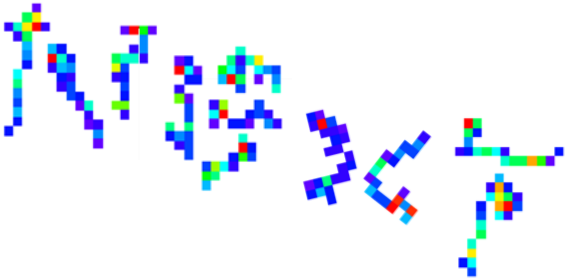
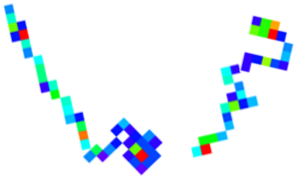




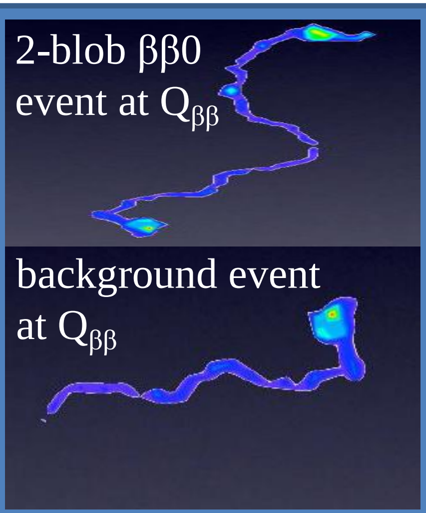
16/12/2014

The 'classical' approach for ^{136}Xe ββ0-searches: **(T$_0$–less TPC read in charge mode)**

the idea

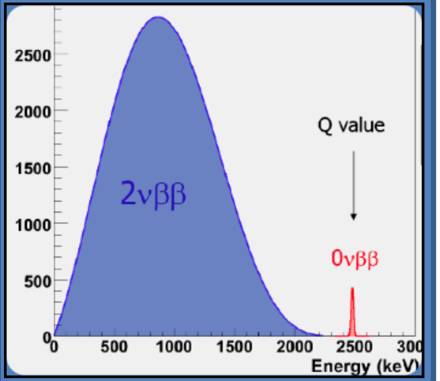
…and the pioneers (Gotthard TPC)

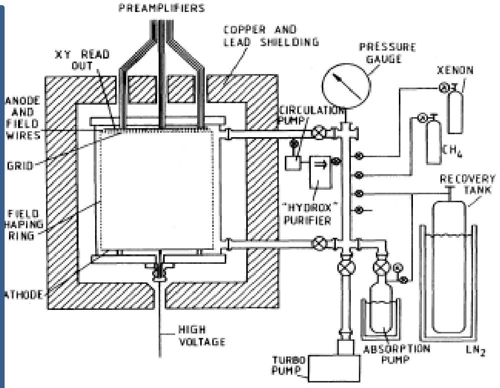
typical electron tracks with energy $\varepsilon = Q_{\beta\beta 0}/2 \sim 1.25$MeV for 10bar Xe in a T$_0$–less TPC read in charge mode

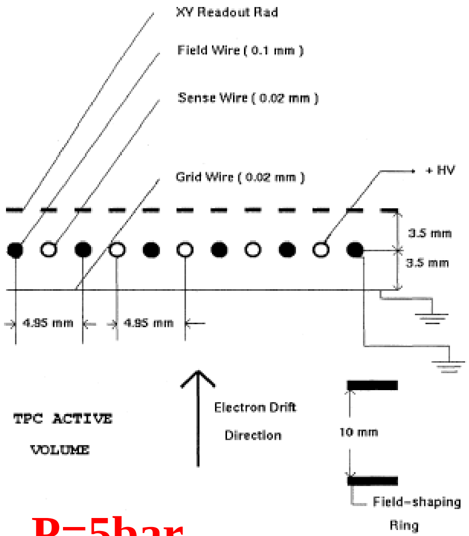


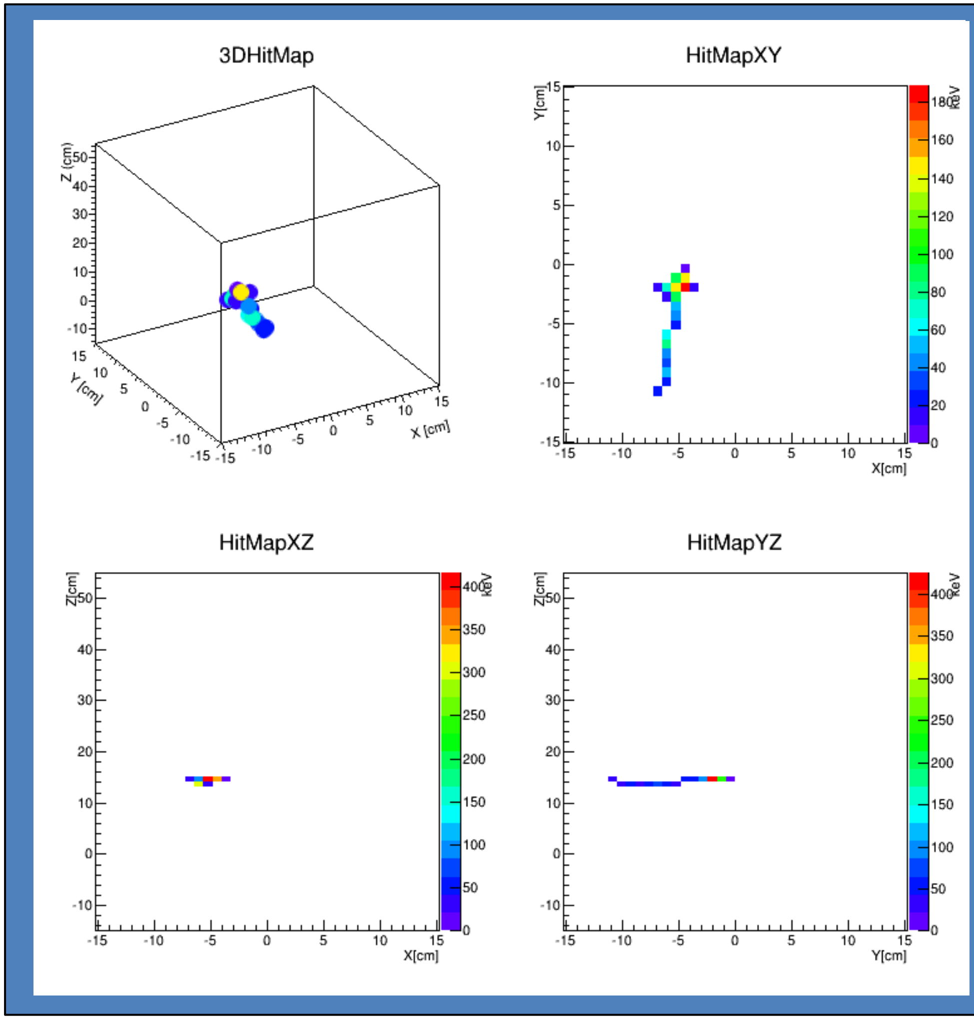
2-blob ββ0 event at $Q_{\beta\beta}$

background event at $Q_{\beta\beta}$









P=5bar,

Xe/CH$_4$ (96.1/3.9)

3.3kg Xe(fid)

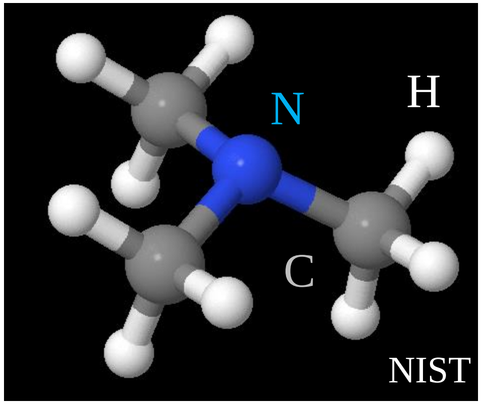
E$_d$ =200V/cm/bar

This is **not** a simulation**!**

TMA

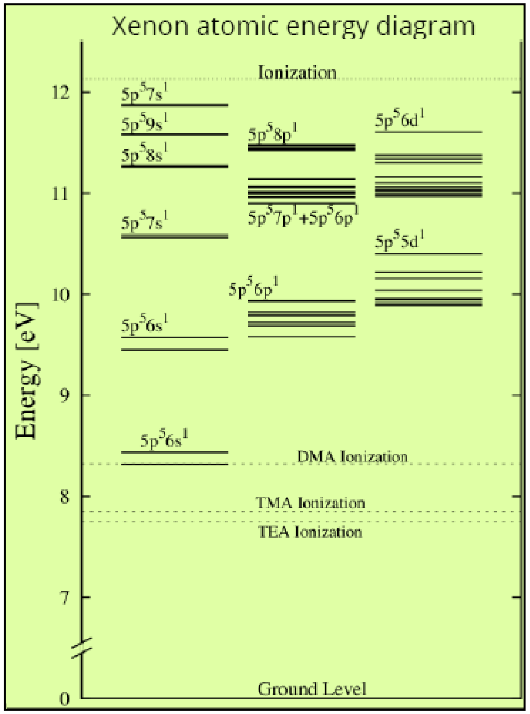
A family of mixtures with potential in ββ0-searches: ‘Penning-Fluorescent mixtures’

(Dave Nygren)



Trimethylamine (TMA)

(the most readily usable at HP in virtue of its relatively high v.p.)



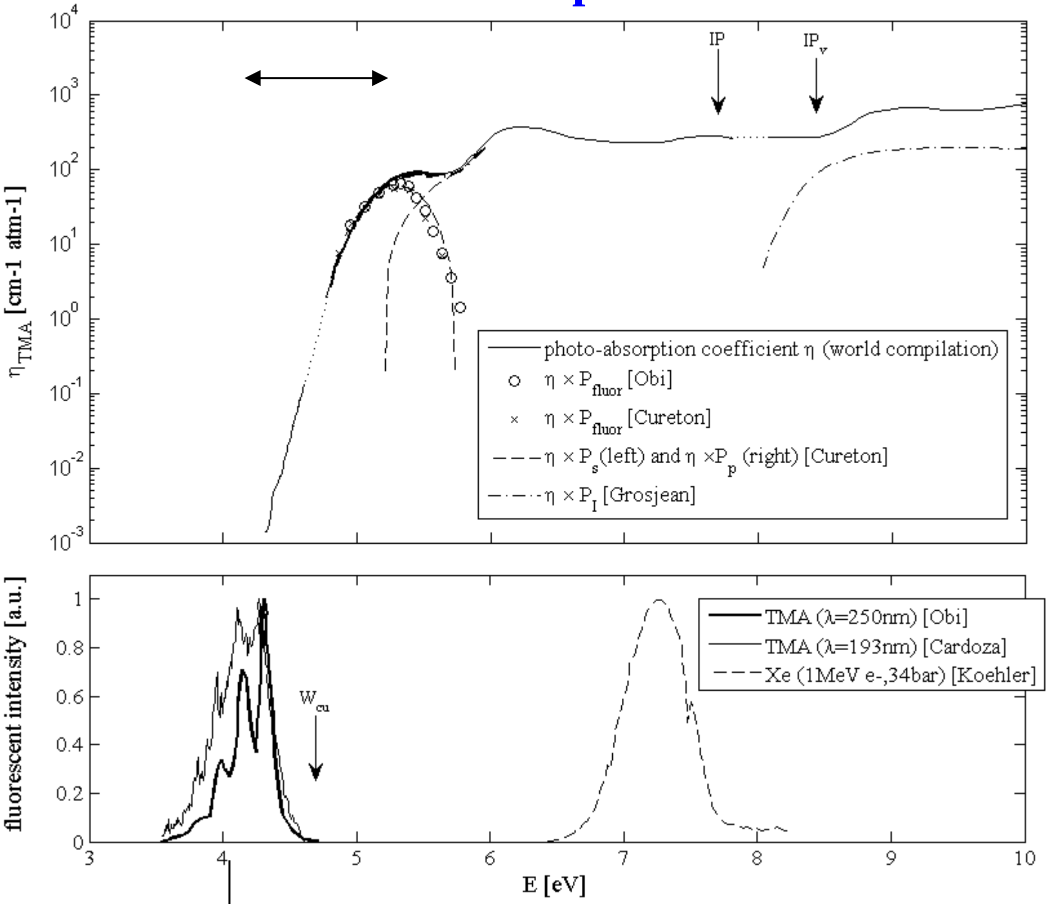
1. Suitable for **Penning** transfer. Can potentially reduce Fano factor.
2. Strongly **fluorescent** with large Stokes shift (self-transparent).
3. Able to **reduce electron diffusion** in gas.
4. **UV-quencher**, eases the imaging of the e- cloud via charge ampl.
5. Allows for **EL at lower field** due to low-lying TMA excited states.

Fluorescence and Penning transfer rate in Xe-TMA (from ionization chamber)

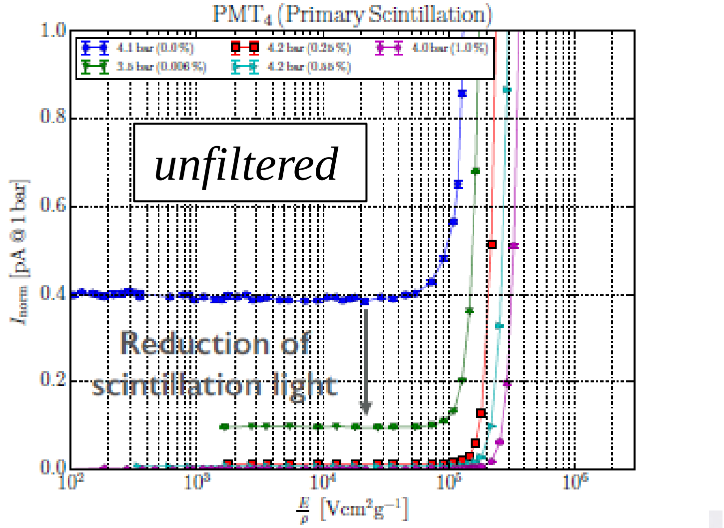
(a reminder of the main idea…)

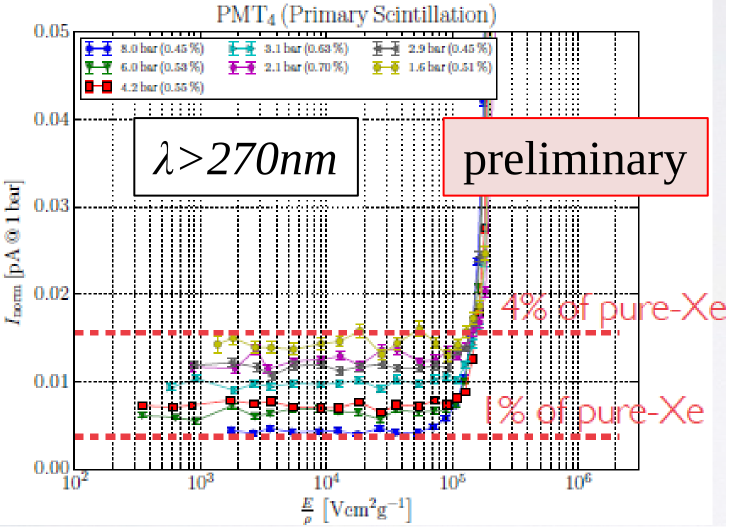
->systematic S_1 measurements in previous talk by Yasu Nakajima (LBL)

absorption



emission



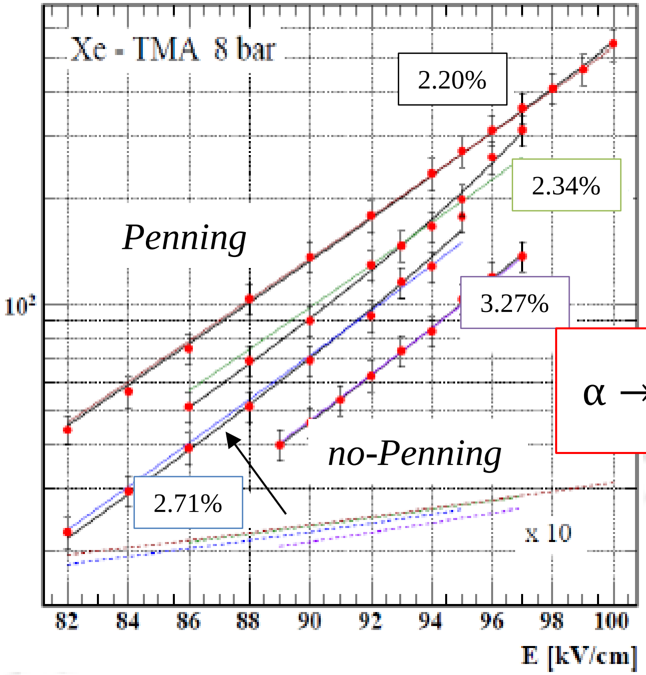


Large Stokes shift: self-absorption mean-free path ~100m for 1% Xe-TMA admixtures!!

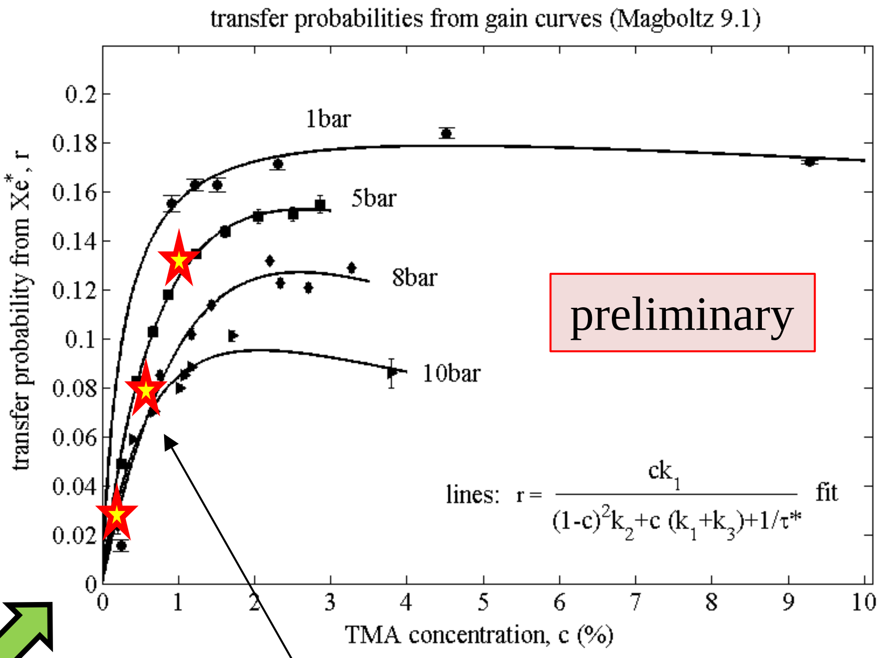
$$N_{S1,Xe-TMA}(8\text{bar}) \sim \frac{QE_{300nm}}{QE_{170nm}} \frac{L.Y._{Xe-TMA}}{L.Y._{Xe}} \frac{Q_{\beta\beta0}}{W_{exc,Xe}} \Omega \sim \mathbf{800\Omega}$$

from Magboltz modeling
(PPC approximation)

Fluorescence and Penning transfer rate in Xe-TMA (from Micromegas chamber)



$$\alpha \rightarrow \alpha\left(1 + r\frac{N_{ex}}{N_I}\right)$$



preliminary

simplified 'toy-model'

$$r = \frac{c k_1}{(1-c)^2 k_2 + c(k_1 + k_3) + \frac{1}{\tau^*}}$$

Penning transfer rate (~P)

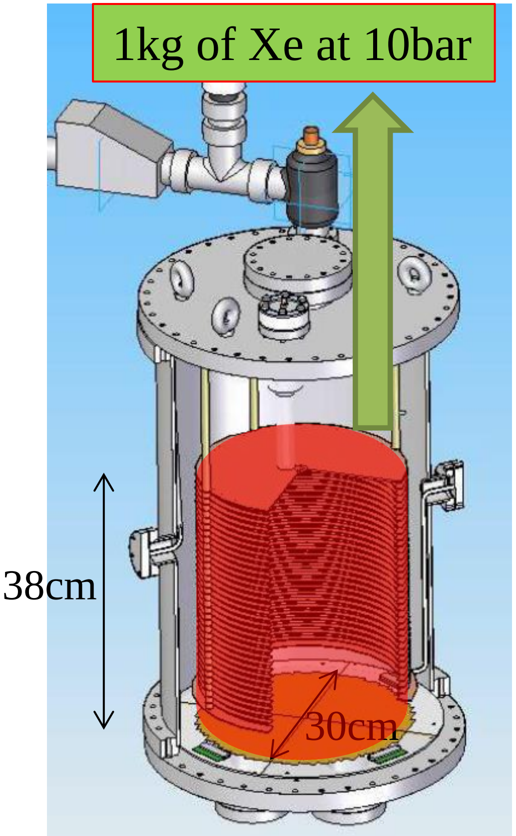
Excimer formation rate $(\sim P^2)$

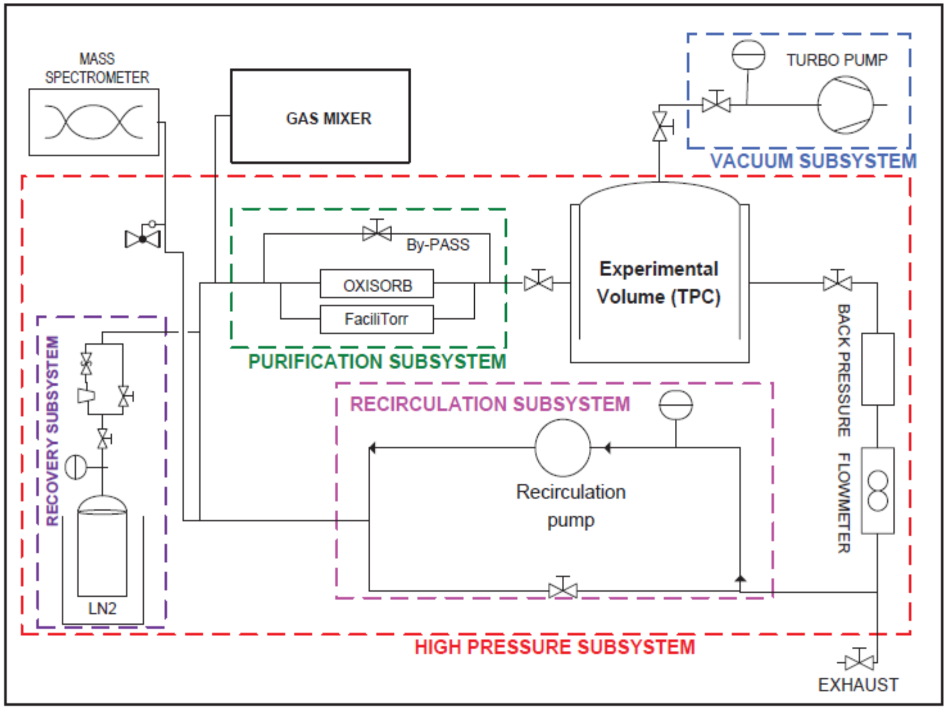
quenching rate (~P)

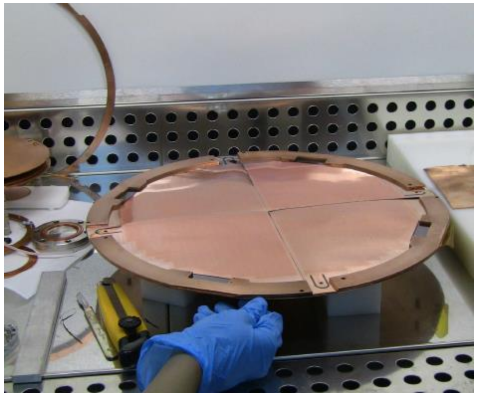
effective life-time

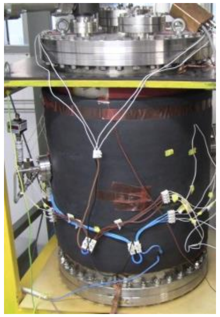
->systematic measurements in previous talk by Yasu Nakajima (LBL)

with O. Sahin, R. Veenhof, S. Biagi
(CERN-Bursa group)





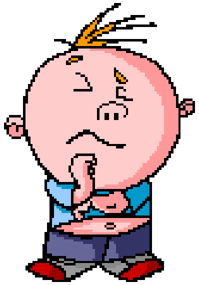


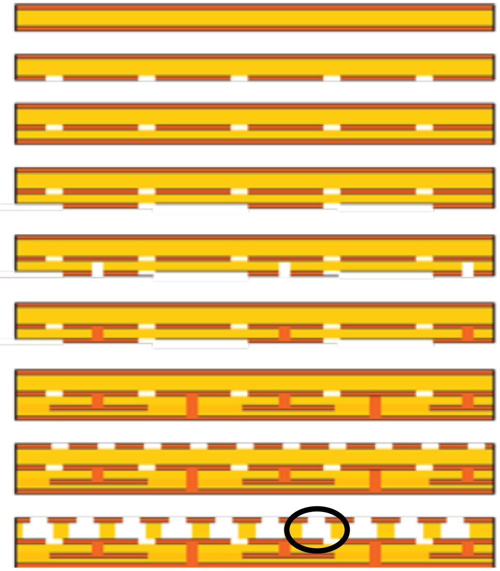


details in:

JINST 9(2014)P03010, JINST 9(2014)C04015

micro-pattern hole-amplification structure
('microbulk MicroMegas')

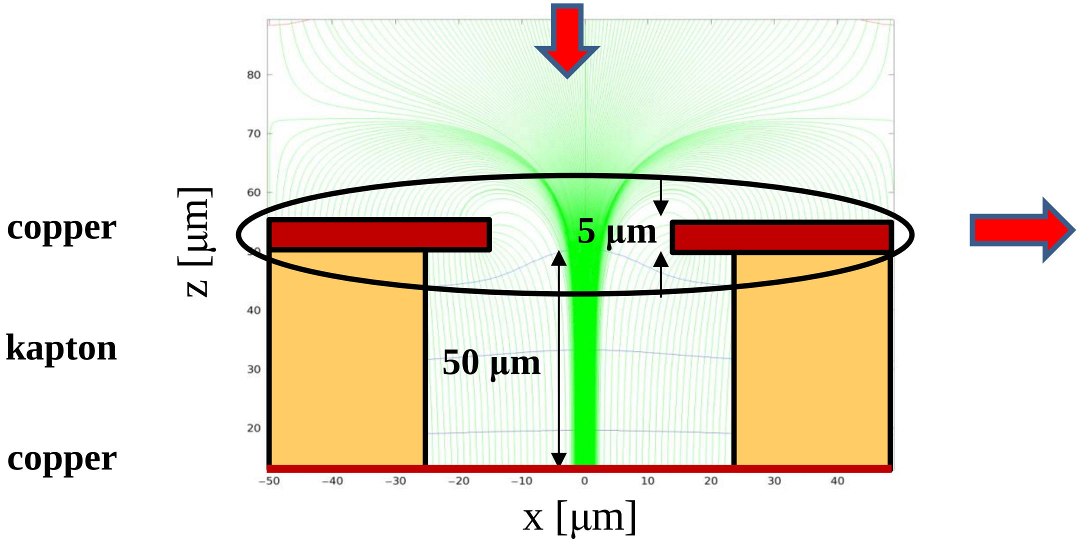


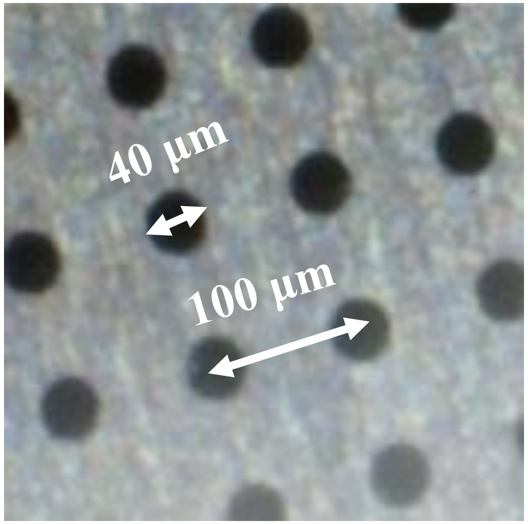


- Double side Cu-coated (5 μm) Kapton foil (50 μm),
- Construction of readout strips/pads (photolithography)
- Attachment of a single-side Cu-coated kapton foil (25/5 μm)
- Construction of readout lines
- Etching of kapton
- Vias construction
- 2^{nd} Layer of Cu-coated kapton
- Photochemical production of mesh holes
- Kapton etching / Cleaning

CERN workshop:
Rui de Oliveira et al

JINST 5(2010)P12001



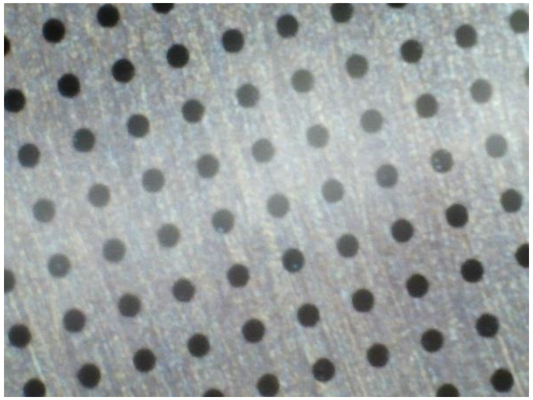


(highly radiopure: <30 µBq/cm^2 for ^{235}U, ^{238}U, ^{232}Th chains)

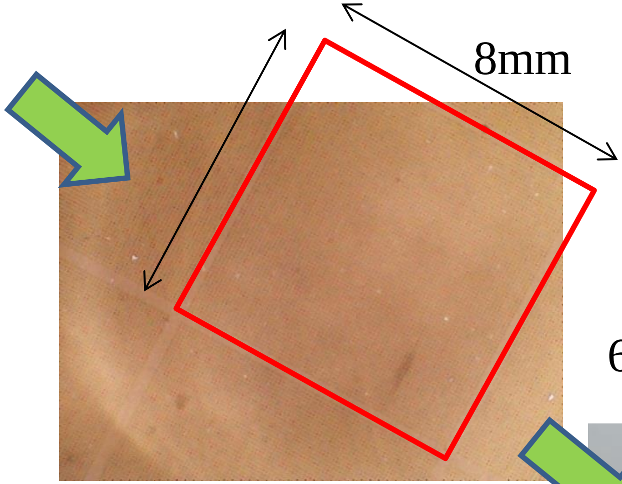
Astropart.Phys. 34 (2011) 354-359

Largest Micromegas manufactured in the microbulk.
No existing experience in a similar system.

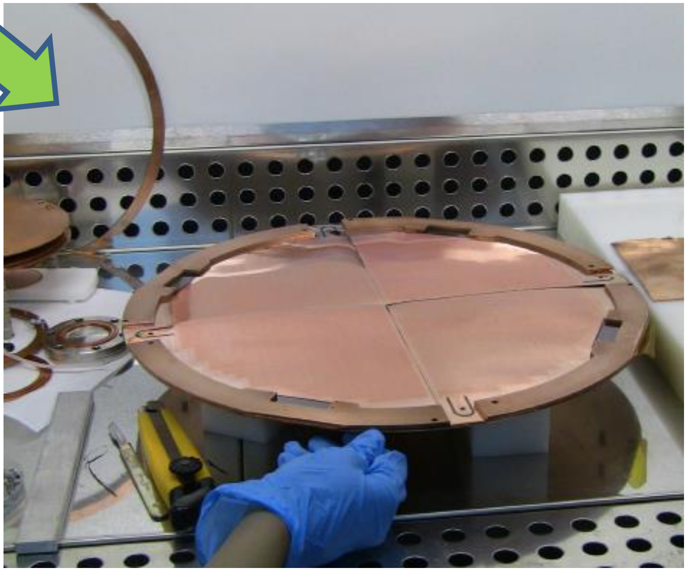
~100 holes



5900 holes/pixel



6796800 holes, 1152 pixels, 700cm^2



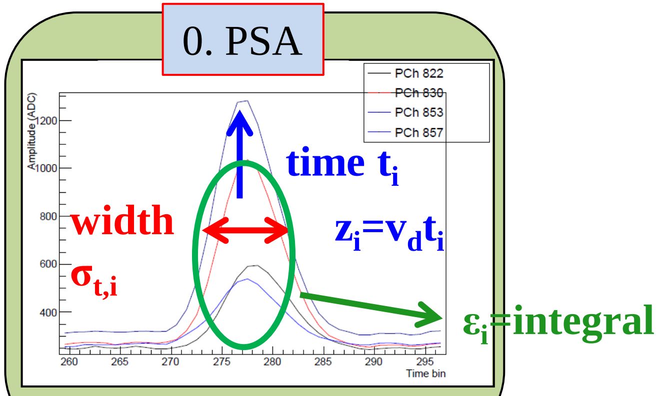
Would the technology allow extending to **m^2** and **γ-tracks** the excellent energy resolution that is achieved under localized x-ray irradiation in R&D setups (~1%$Q_{\beta\beta,Xe}$ (extrap.)) ? JINST 8(2013)P01012

calibration and analysis strategy

procedure analogous to:
JINST 9(2014)C04015

based on Gaussian fits

0. PSA



typical x-ray event

$$\vec{r}_{evt} = \sum_{i=1}^{N_{pixels}} \frac{\varepsilon_i}{\varepsilon_{evt}} \vec{r}_i$$

start-time obtained from coincidence with ancillary detector

1. Calibration

(*on ~20keV<ε<~40keV isolated charge deposits*)

1. Determination of v_d and D_L.
2. Sector equalization (10-20%)
3. Pixel equalization (10%)
4. Transient correction (5-10%)

2. Track quality cut

(*on the sample to analyze*)

1. Cosmic ray cut.
2. Baseline quality.
3. Event energy in expected range.

3. Suppression of random coincidences

Impose a physical criteria (longitudinal diffusion) for the correlation between signal width and drift distance.

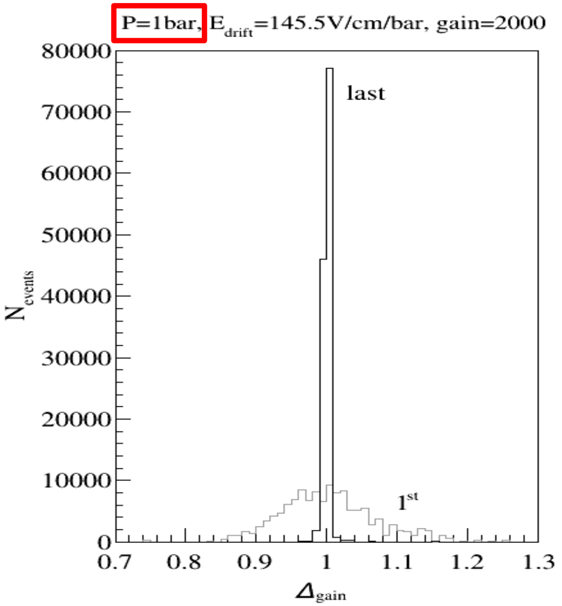
4. XYZ-fiducialization

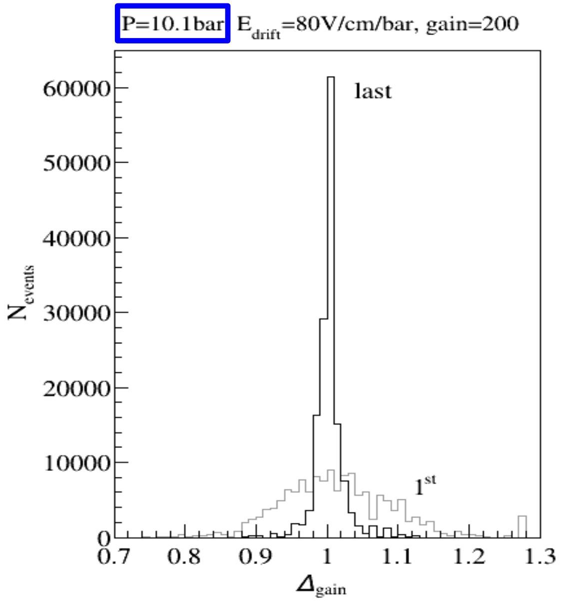
Cut out external 2cm in z and R.

x-rays

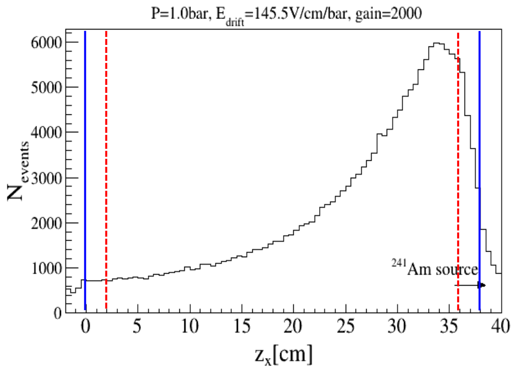
energy resolution for x-rays in the **30keV** region after calibration

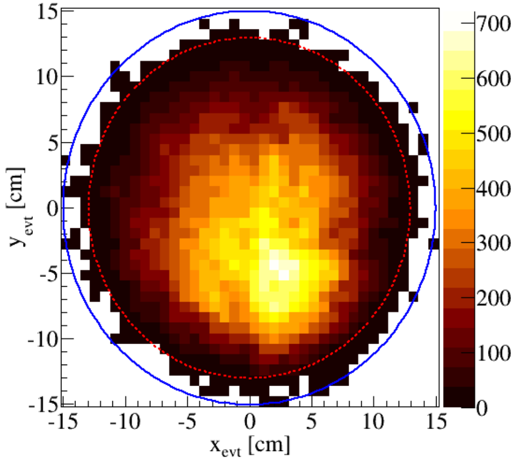
0-1.PSA+calibration

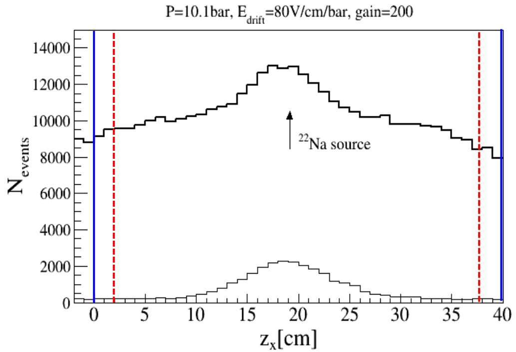




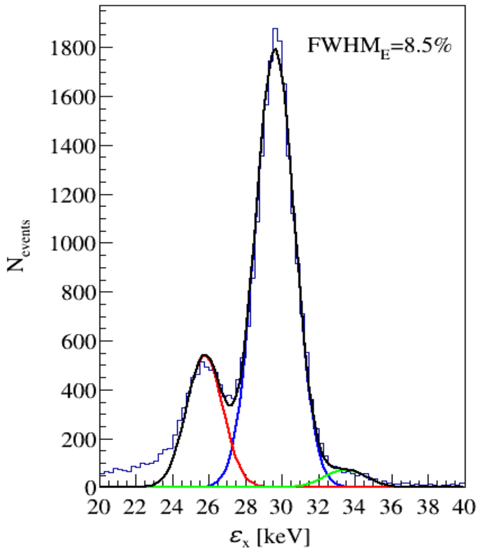
2-4. Track QC + suppress. random coinc. + fiducialization

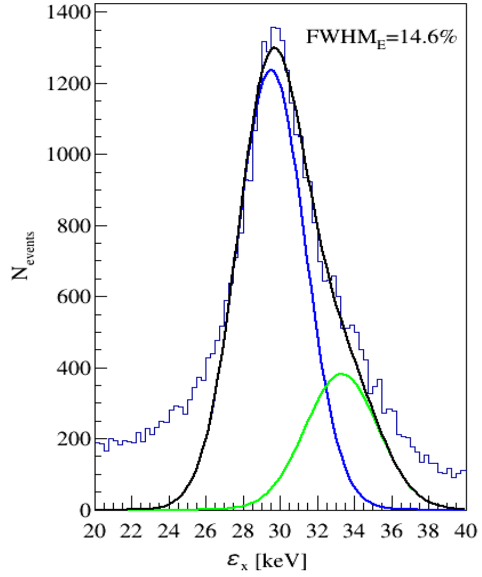






Final result (for isolated x-rays)





Final result
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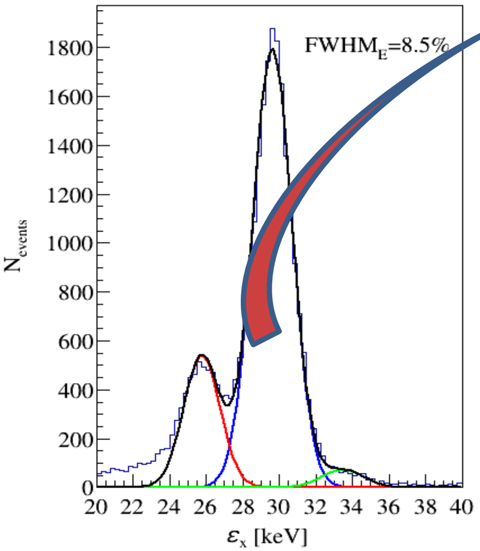
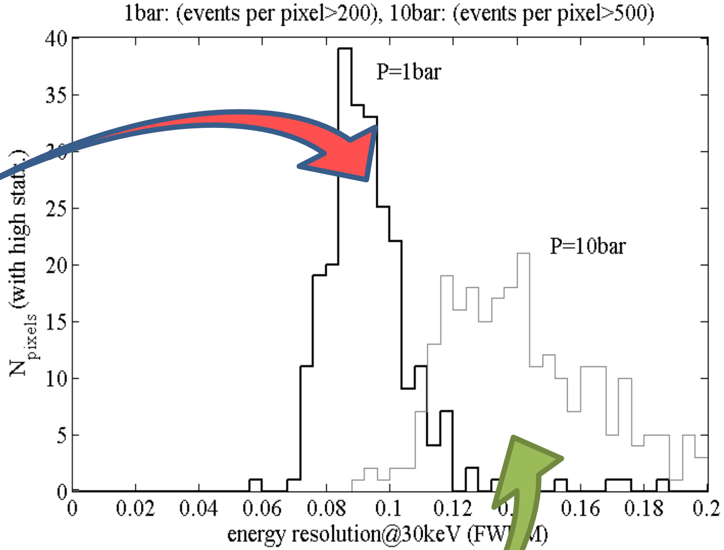
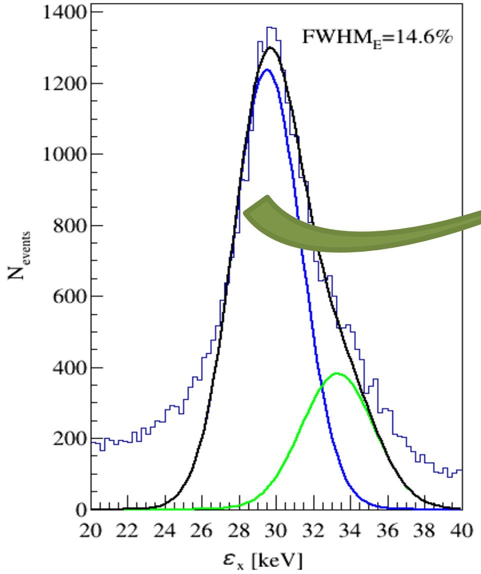
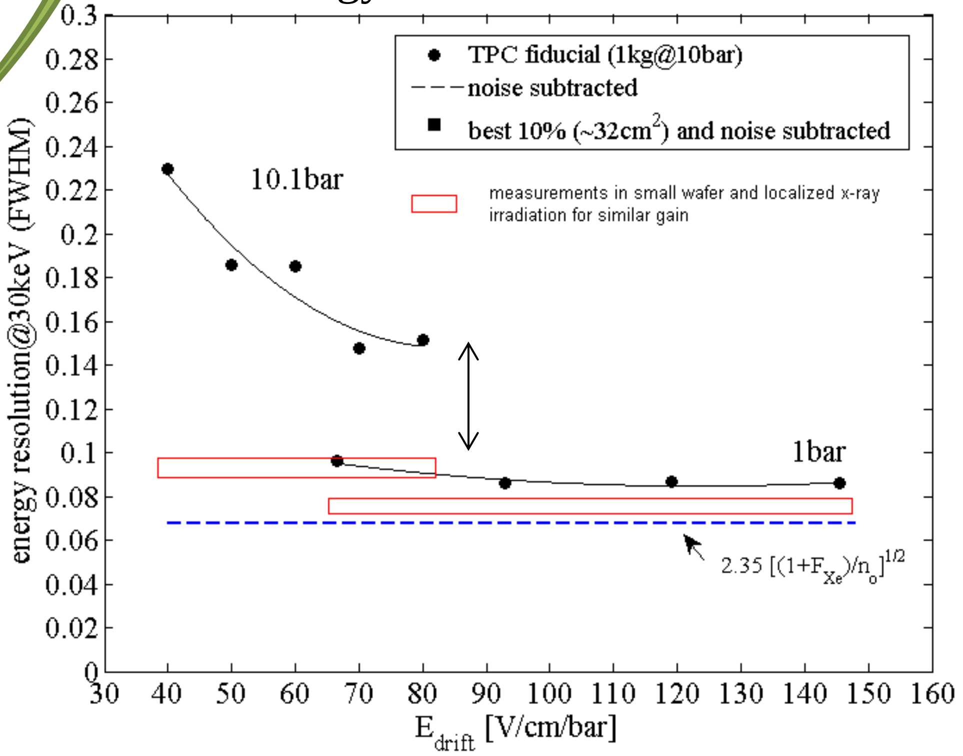




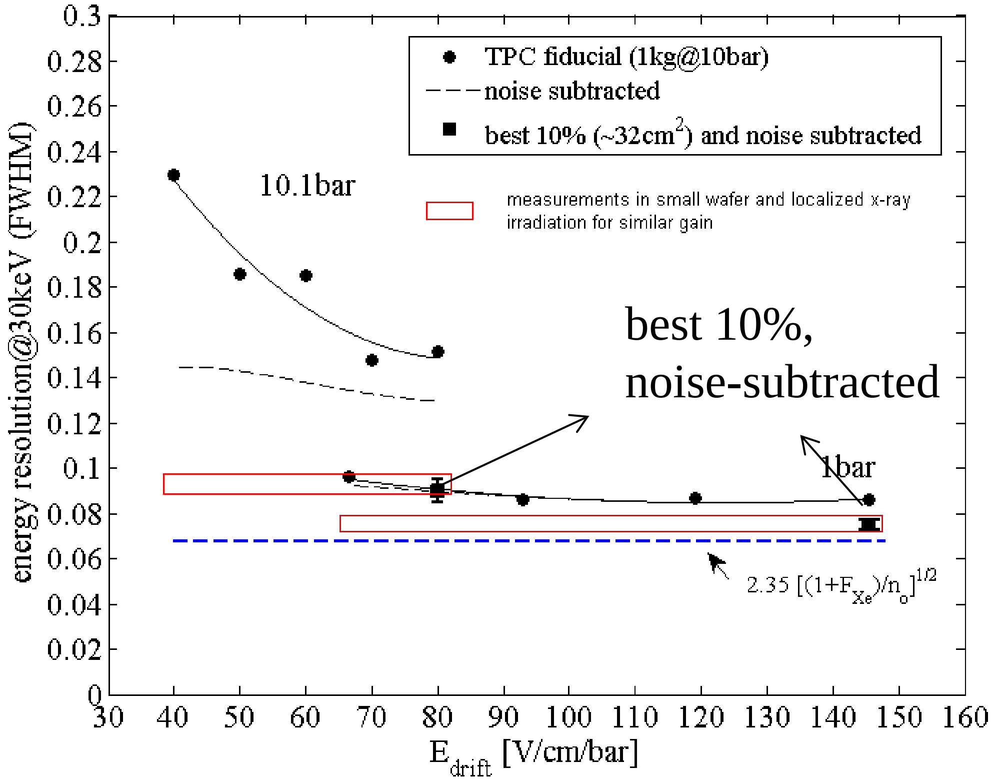
Energy resolution not just a number:
Strong pixel-to-pixel variations



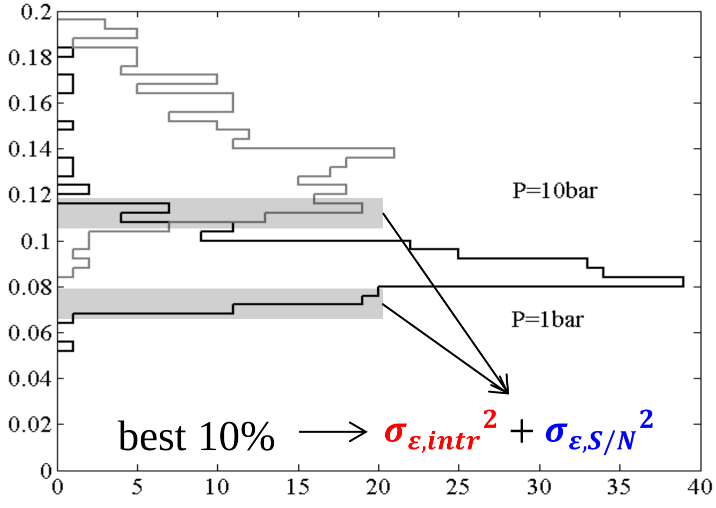
energy resolution vs drift field



energy resolution for x-rays in a nutshell

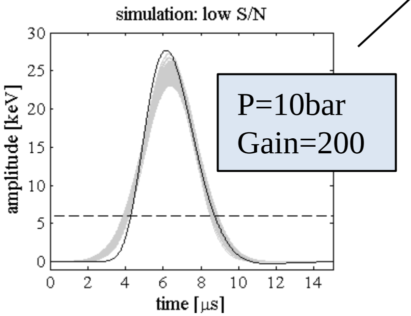


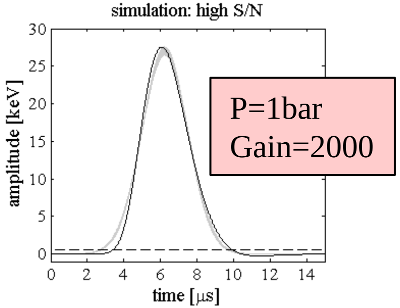
energy resolution pixel by pixel



1bar $\sigma_{\varepsilon}{}^{2} = \sigma_{\varepsilon,intr}{}^{2} + \sigma_{\varepsilon,S/N}{}^{2} + \sigma_{\varepsilon,pixel-to-pixel}{}^{2}$ (0.075, 0.002, 0.035)

10bar $\sigma_{\varepsilon}{}^{2} = \sigma_{\varepsilon,intr}{}^{2} + \sigma_{\varepsilon,S/N}{}^{2} + \sigma_{\varepsilon,pixel-to-pixel}{}^{2}$ (0.09, 0.07, 0.09)





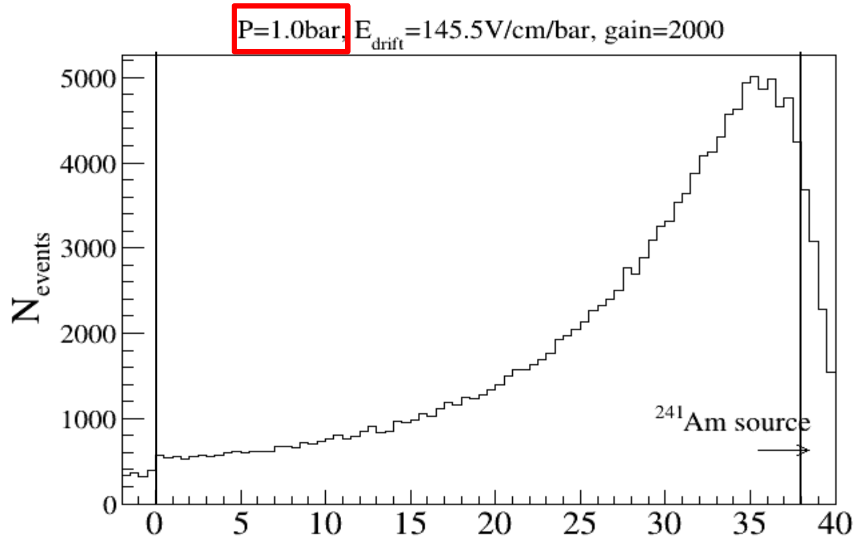
being **point-like** events and their response reasonably **understood**, use them to characterize the TPC

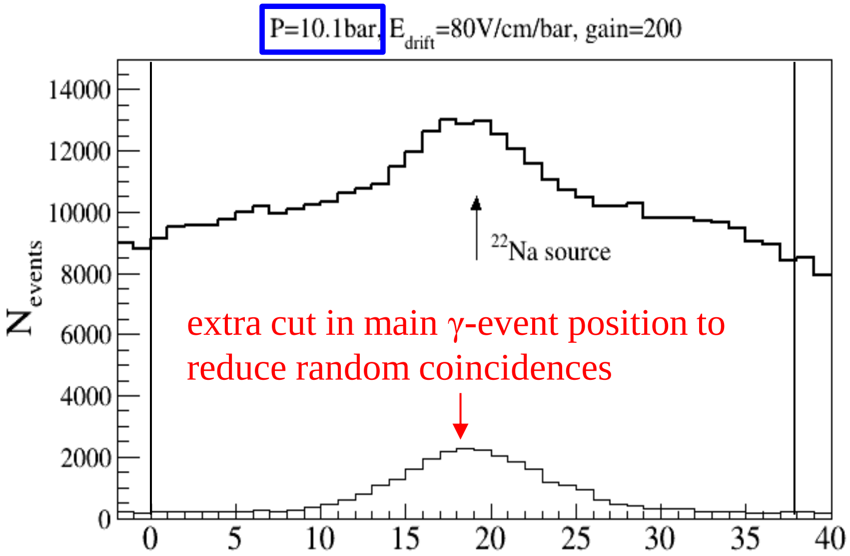
electron drift properties in Xe-TMA (I)

procedure analogous to:

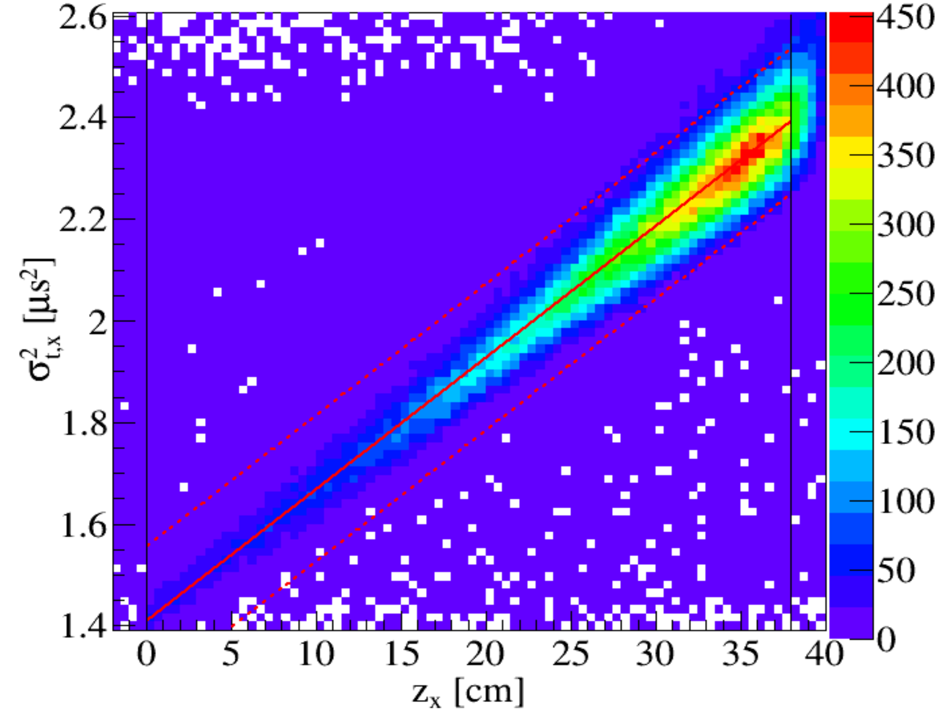
JINST 9(2014)C04015

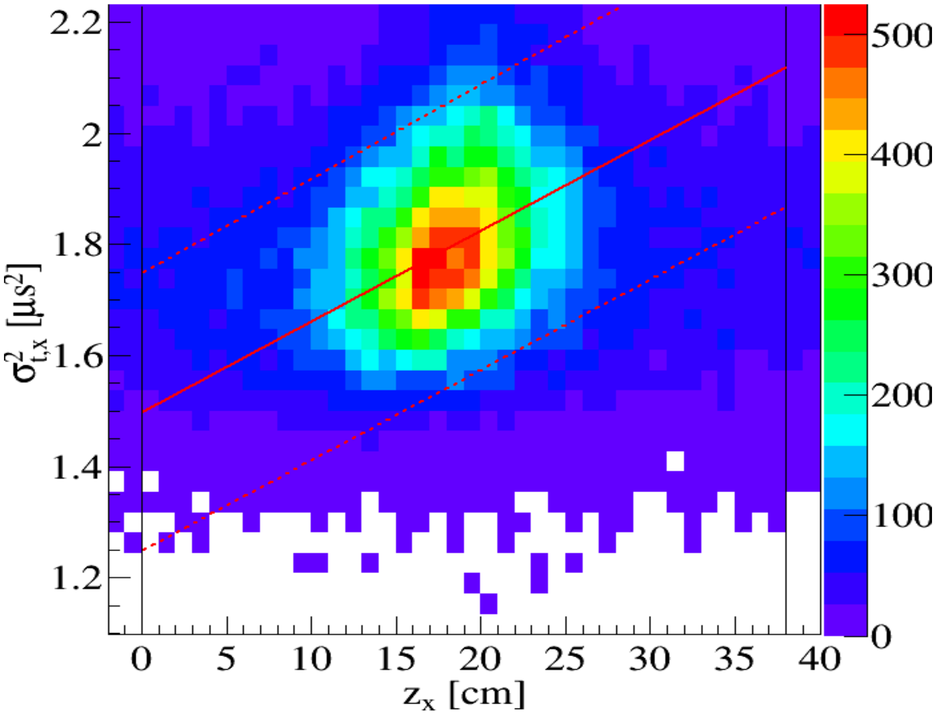
$$\sigma_t^2 = \sigma_0^2 + \left[\frac{D_L^*}{v_d}\right]^2 \frac{z_x}{P}$$


P=1.0bar, E_{drift}=145.5V/cm/bar, gain=2000


P=10.1bar, E_{drift}=80V/cm/bar, gain=200

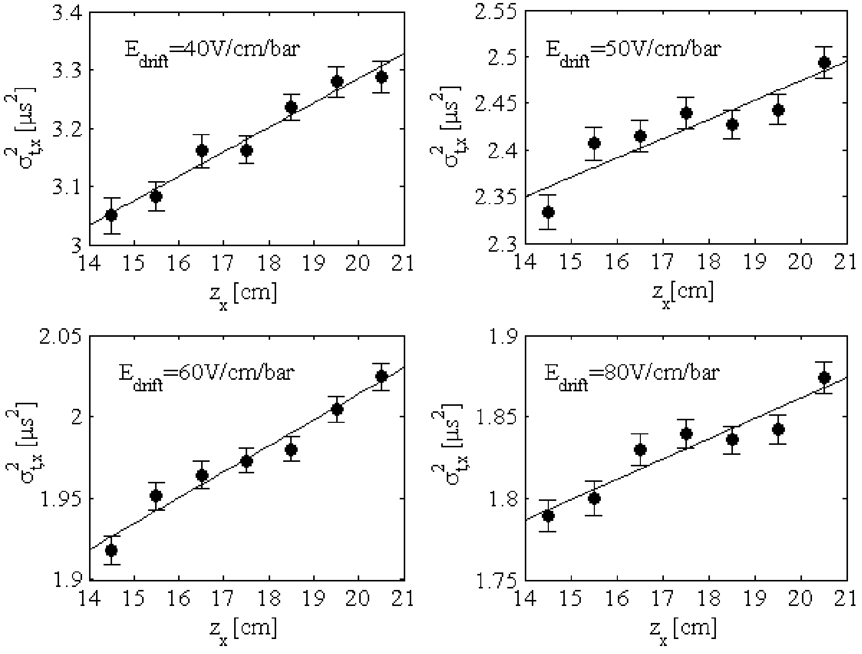
extra cut in main γ-event position to reduce random coincidences



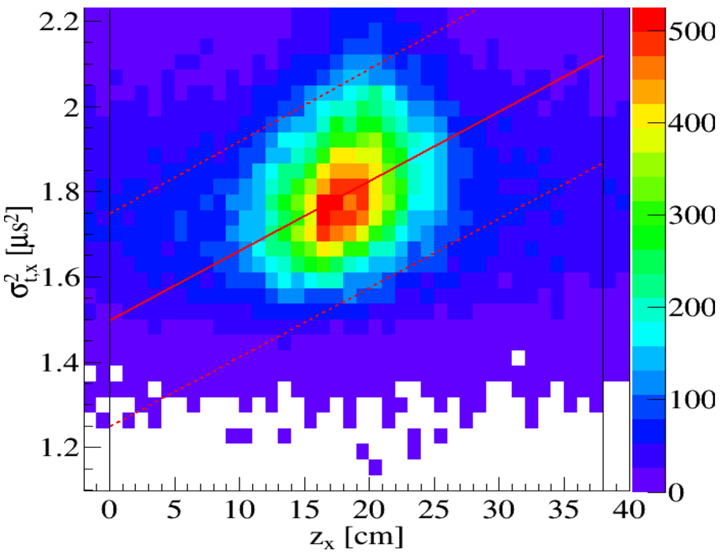


electron drift properties in Xe-TMA (II)

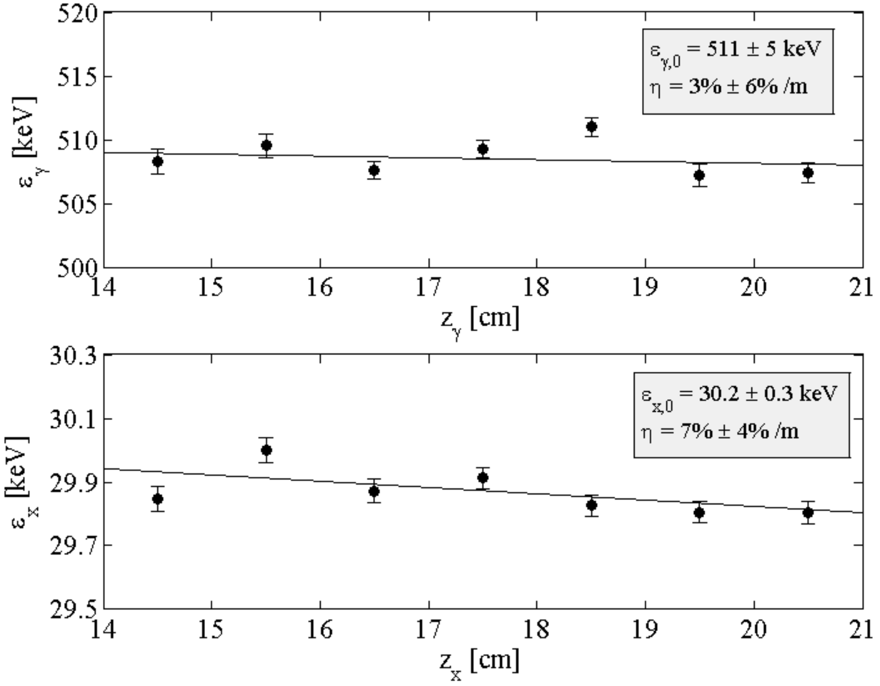
$$\sigma_t^{\,2} = \sigma_0^{\,2} + \left[\frac{D_L^{\,*}}{v_d}\right]^2 \frac{z_x}{P}$$



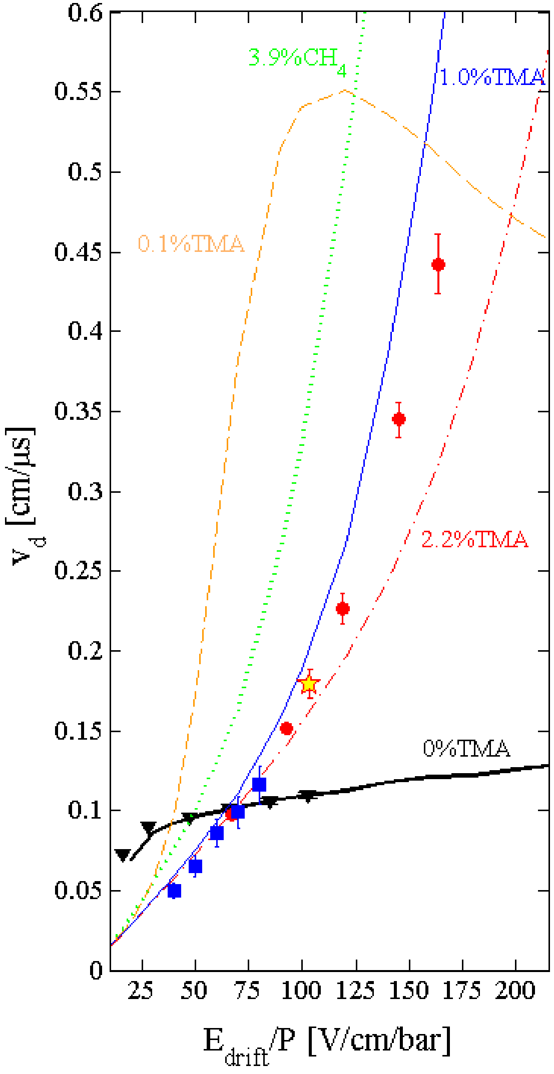
suppress random coincidences
with σ-z correlation cut

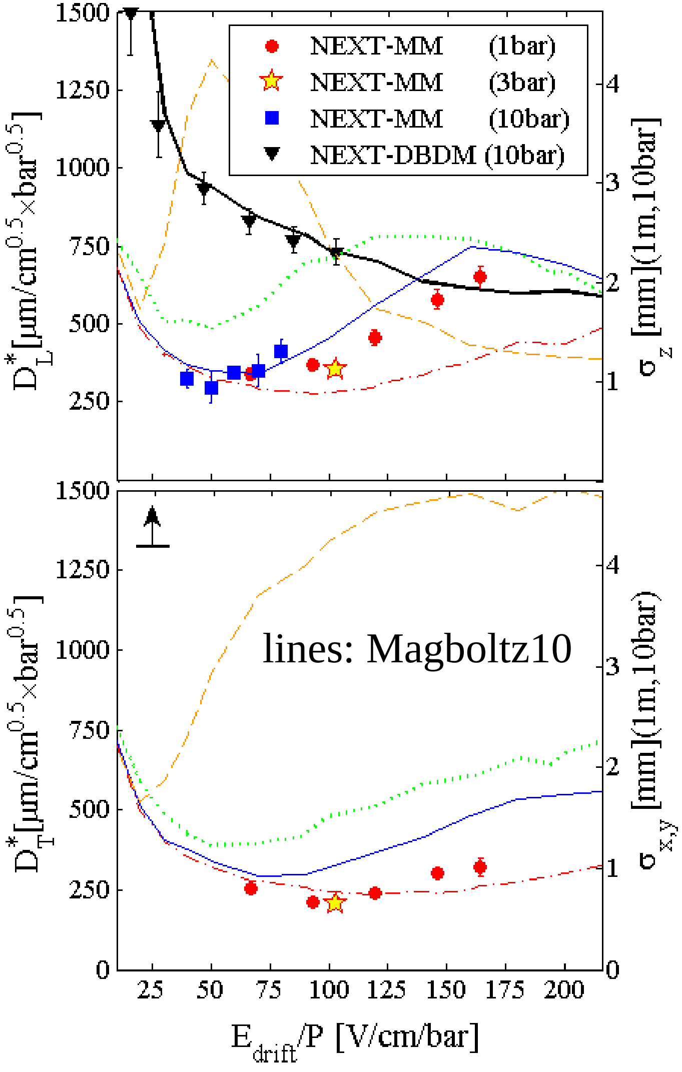


extract electron life-time/attachment



electron drift properties in Xe-TMA in a nutshell





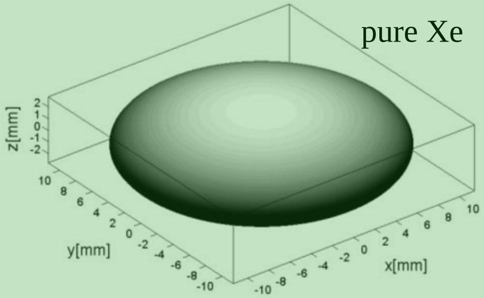
Xe-TMA introduces a very tiny electron diffusion for the relevant drift fields and concentrations!

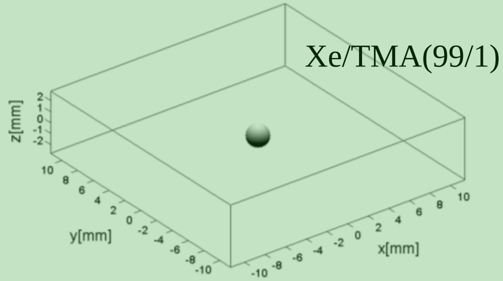
η<10%/m for any of the explored fields and TMA admixtures

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

Spatial spread of point-like charge deposits

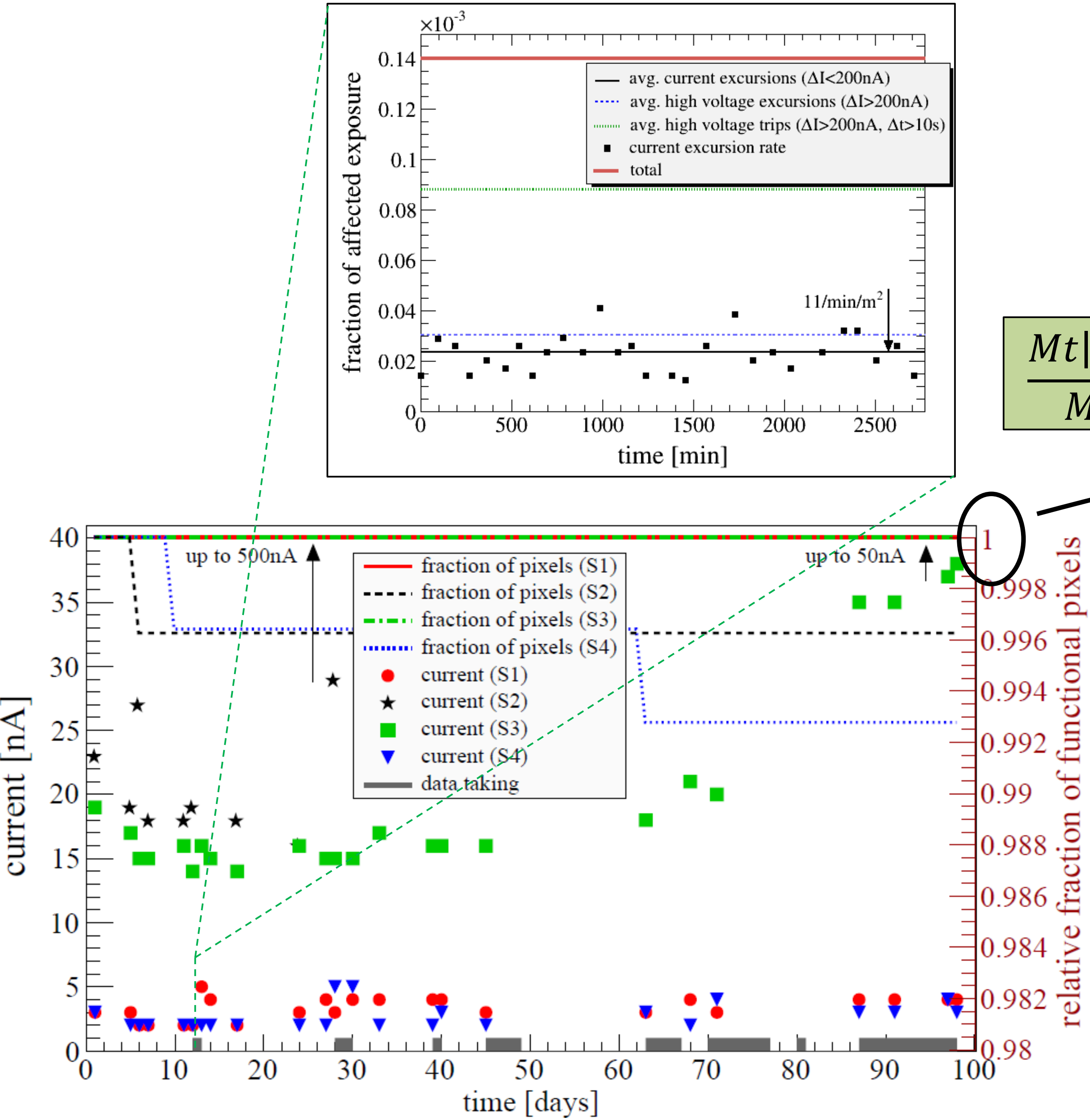
z_{drift}=100cm, P=10bar





↑ E_{drift}~50-100V/cm/bar

stability of readout plane (continuously running for 100days+)



$$T_{1/2}^{-1} \propto a\cdot\epsilon\cdot\sqrt{\frac{\boxed{Mt}}{\Delta E\cdot B}}$$

Fraction of affected exposure due to instrumental problems

$$\frac{Mt|_{loss}}{Mt} \cong \frac{A_{affected}\times\Delta t_{affected}}{A\times t}$$

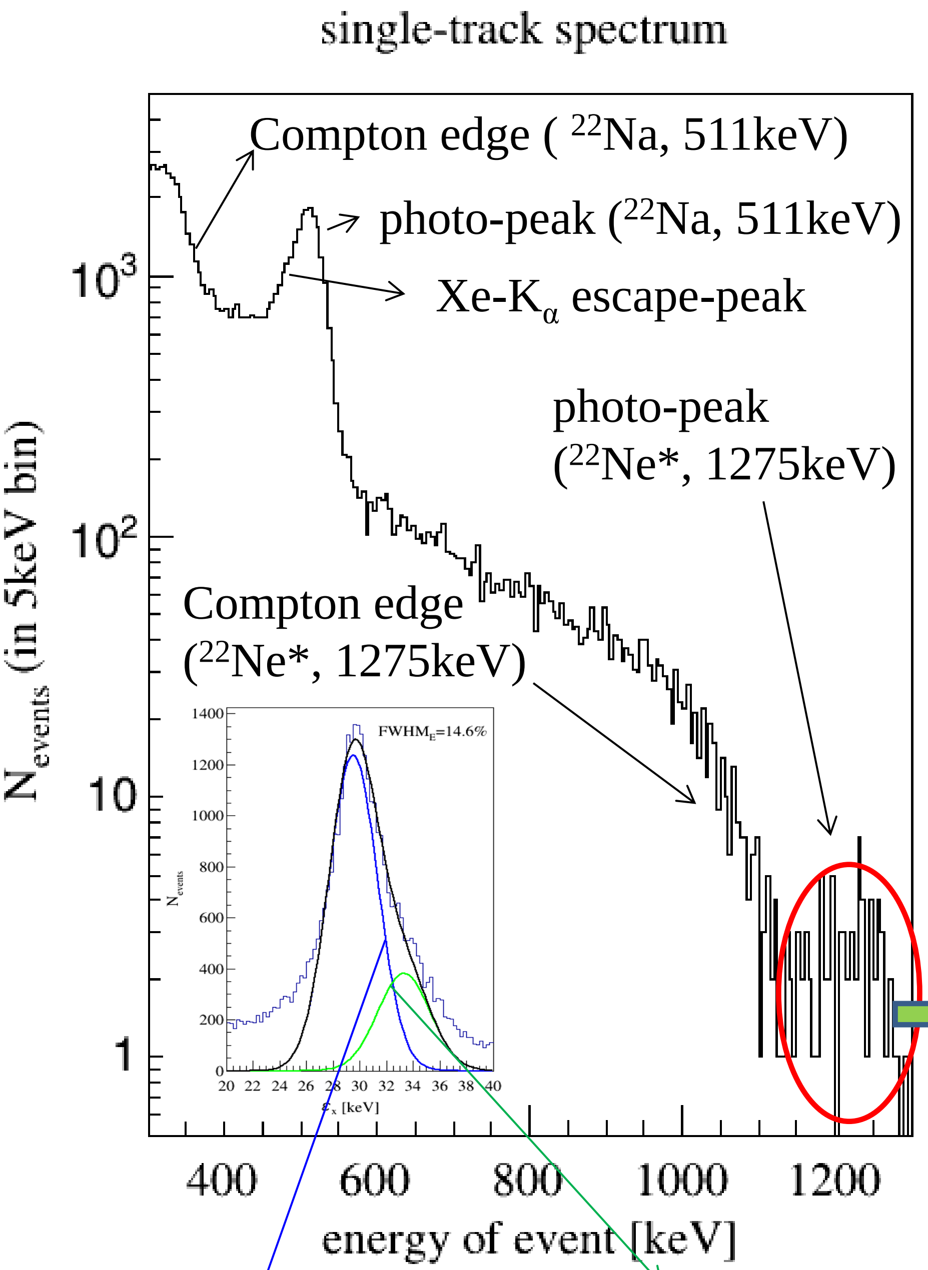
level of instrumented pixels at start of 10bar campaign: ~90%

non-instrumented pixels: ~10%

unclear origin: 1%
connections + cables: 4.5%
damaged pixels: 4.5%

rate of new damage: ~1%/yr
(with calibration source on)

γ-rays


single-track spectrum

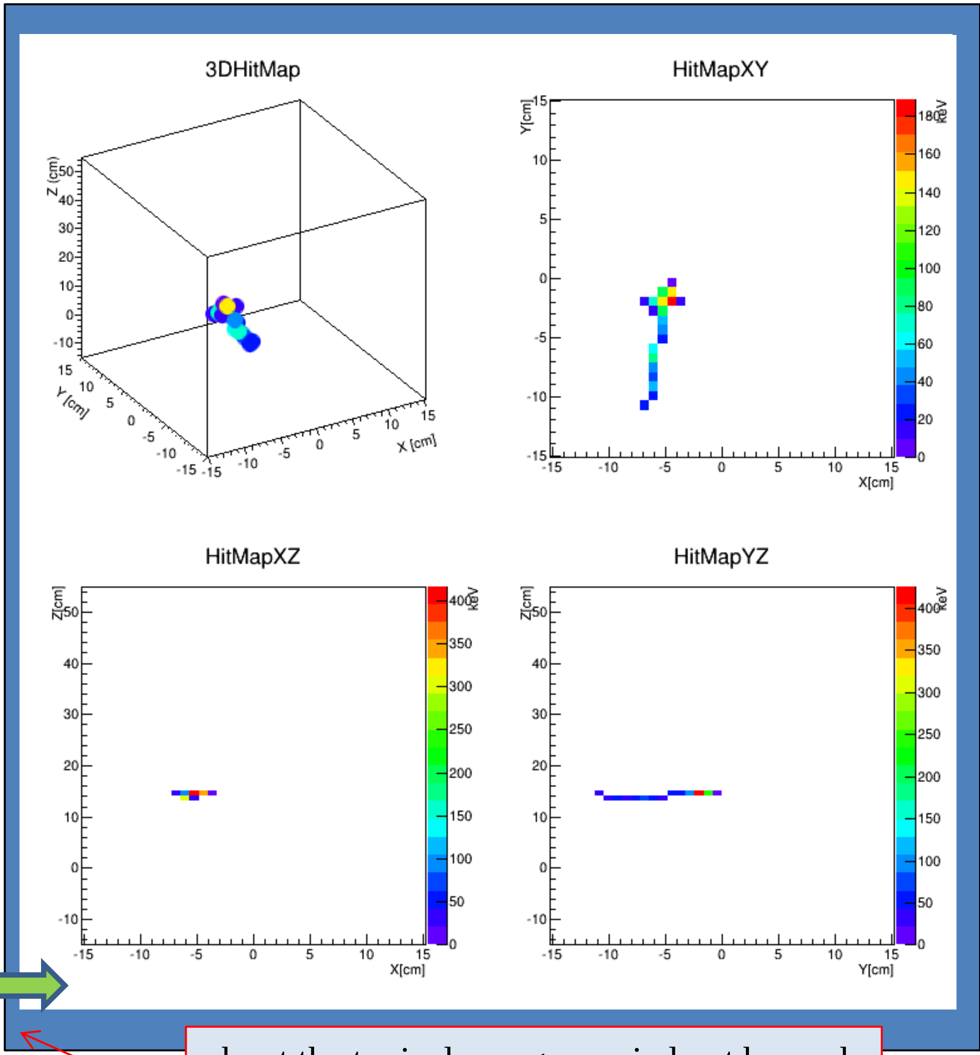
Compton edge (^{22}Na, 511keV)

photo-peak (^{22}Na, 511keV)

Xe-K$_\alpha$ escape-peak

photo-peak (^{22}Ne*, 1275keV)

Compton edge (^{22}Ne*, 1275keV)



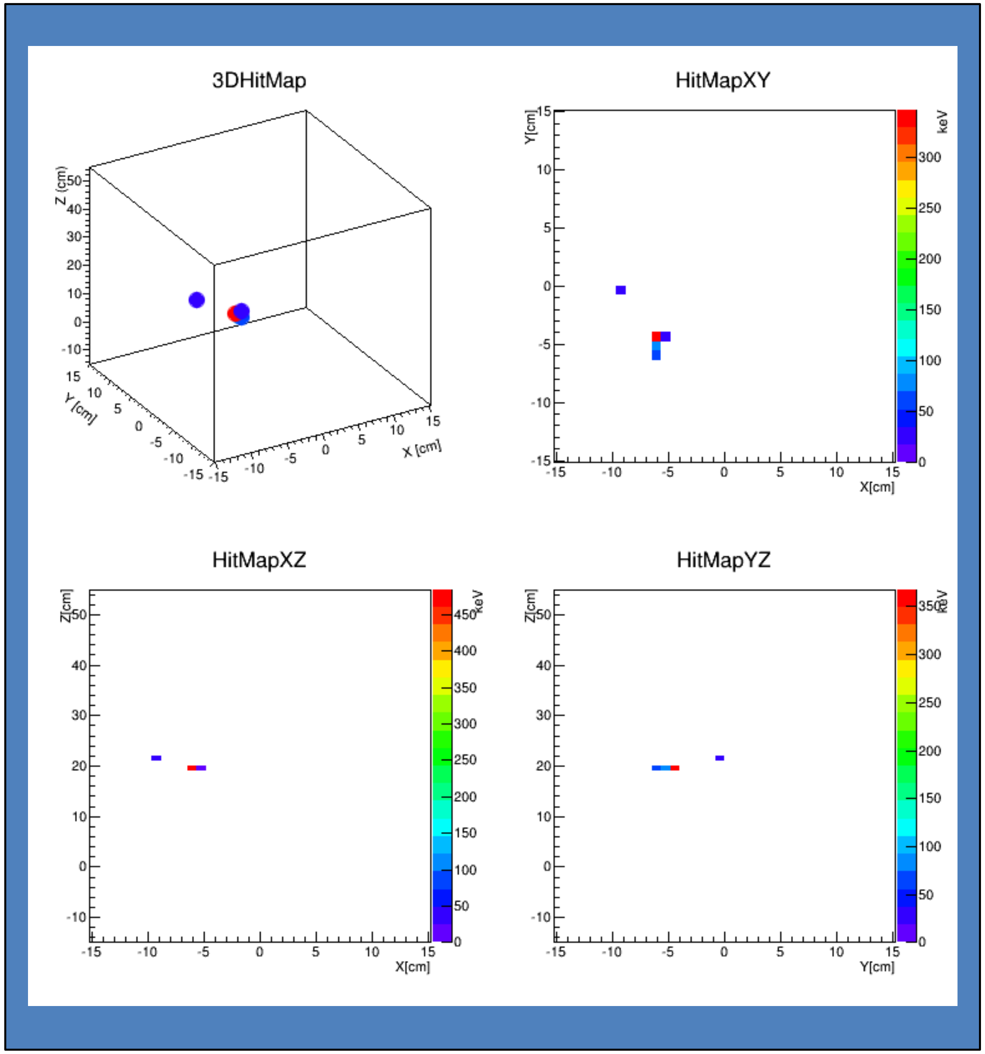
about the typical energy carried out by each electron at Xe^{136} Q$_{\beta\beta0}$!.

(29.8keV Xe-K$_\alpha$ emission)

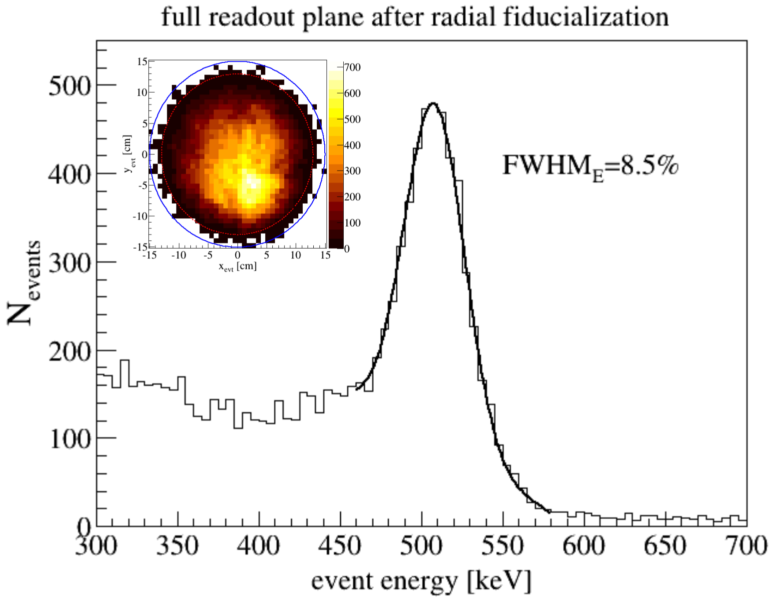
(33.64keV Xe-K$_\alpha$ emission)

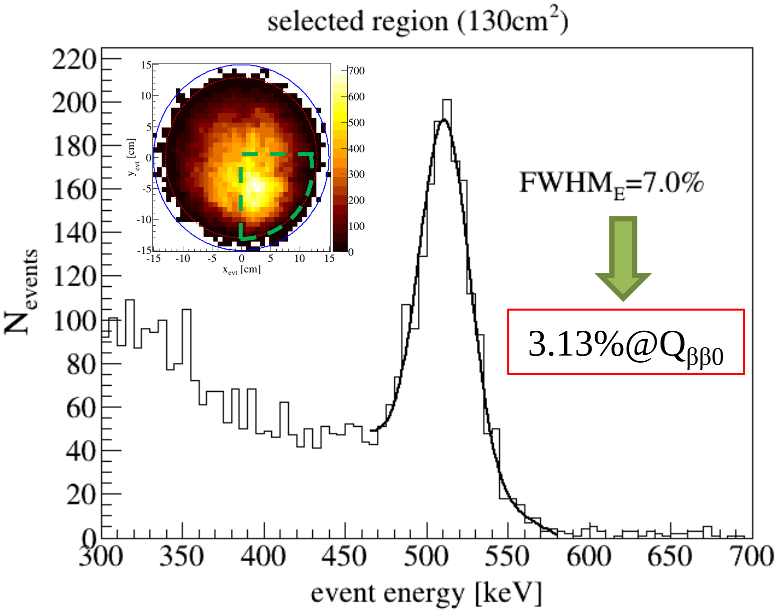
All peak energies correctly reproduced after calibration within 2%

for detailed analysis… select 511keV events with displaced x-ray

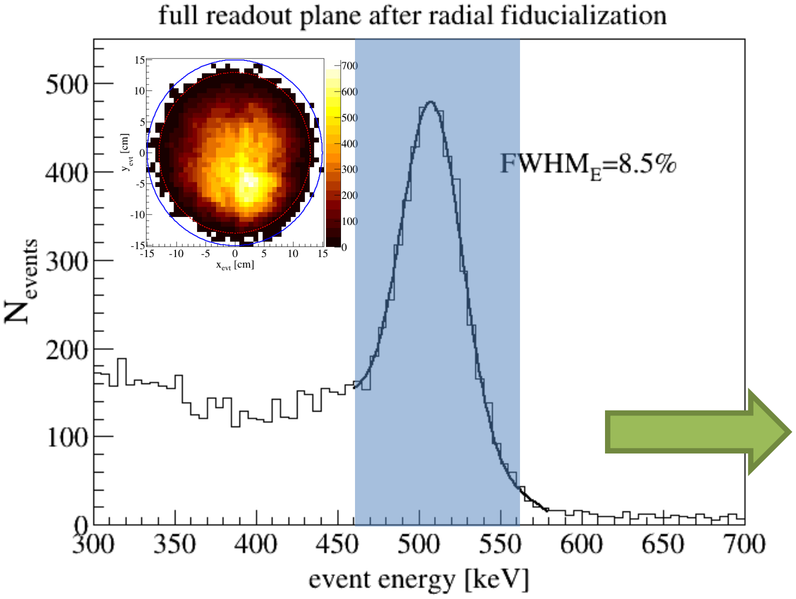


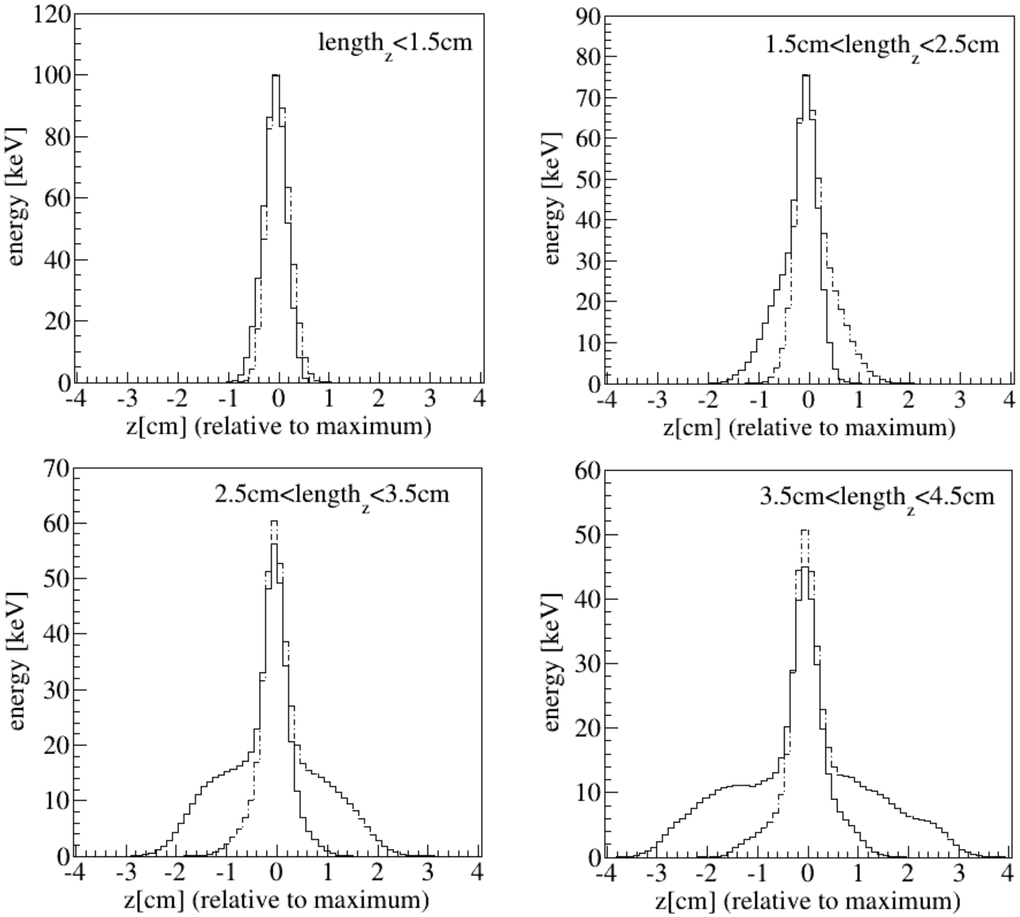
they allow for a simpler estimate of energy resolution (no escape peak) and higher purity (*through σ-z correlation-cut on x-ray*)


full readout plane after radial fiducialization

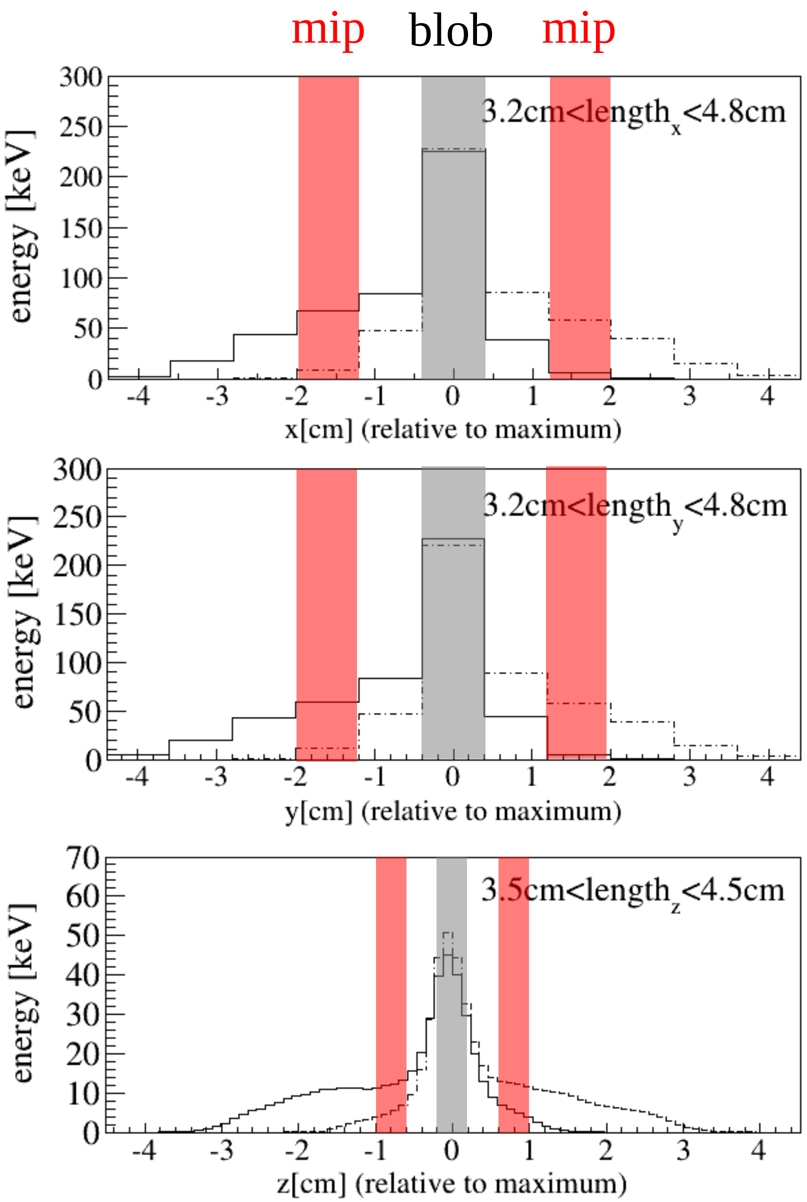

selected region ($130cm^2$)

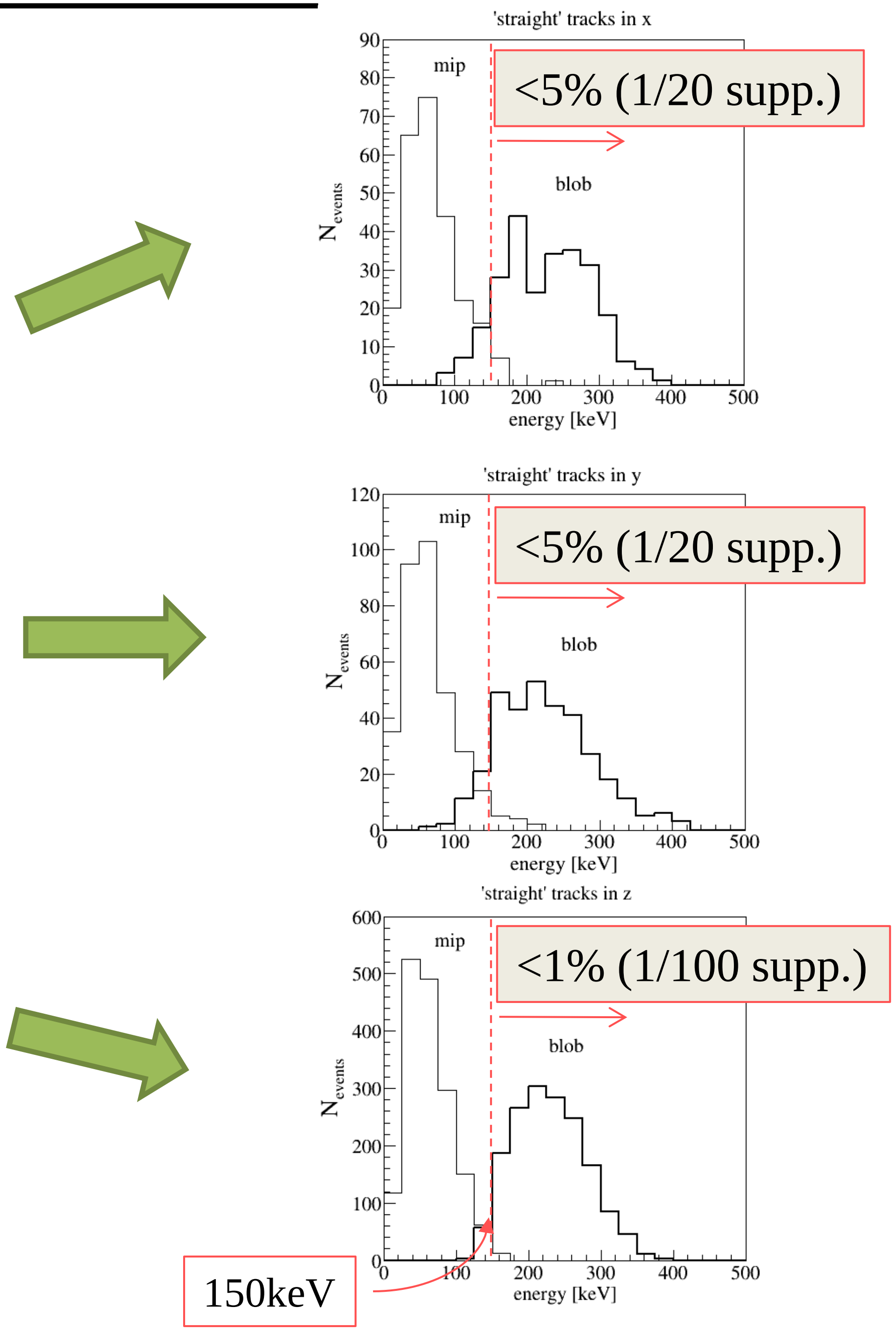
Separation between blob and mip region for straight tracks (I)





Separation between blob and mip region for straight tracks (II)





<5% (1/20 supp.)

<5% (1/20 supp.)

<1% (1/100 supp.)

150keV

Very simplified analysis: compare equal slides in ‘blob’ and ‘mip’ regions

conclusions

1. **NEXT-MM** is **truly a 'Penning-fluorescent Xenon-TPC'**, housing **1kg of Xenon** in its active region, and operating at 10bar.

2. As compared to Gotthard's approach, **Xe-TMA + Micromegas + AFTER-FEE** offers lower electron-diffusion (x2(z), x2(r)), better energy resolution (a factor x2 at 511keV), better z-sampling (x5) true x-y readout and (limited, ~1/100supp.) **primary scintillation** at ~300nm, as well as ability to work at **higher pressure**. Since the **readout is naturally voxelized in x,y,z** (with small influence of diffusion and shaping times), a clear mip-blob separation is visible in all space-projections for 511keV straight tracks.

3. The achieved energy resolution for 511keV electron tracks extrapolates to **3.1%$Q_{\beta\beta0}$**. The deterioration with respect to the anticipated scaling from the K_α resolution (1.6%$Q_{\beta\beta0}$) is probably due to the effect of noise, threshold and the fraction of unconnected pixels (10%) in the reconstruction of extended γ-tracks.

   a) **S/N**: minimum workable threshold at 10bar is **4-8keV**. If the nominal ENC noise of the AFTER chip (x3 lower) could be achieved by **proper cable+connection design (not done)**, a value closer to the anticipated 1-1.5%$Q_{\beta\beta0}$ (and ε_{th}=1.5-3keV**)** might be obtained. MM-optimization (e.g. geometrical gain-compensation 'a la' Giomataris) could bring this value slightly down.

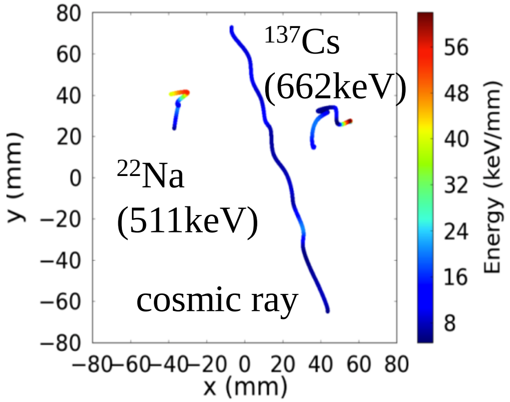
   b) **Dead area**: about **5%** of the readout plane was damaged during commissioning but the **rate of further damage was as low as 1%/year** (source on), with **large stability over more than 100 days of continuous operation (and more than 99% unaffected exposure)**. The observed damage rates, together with the observed variations in response from pixel-to-pixel suggest the implementation of tighter QA procedures.

4. **Blob and mip region clearly recognizable for straight 511keV tracks** already after a very simple analysis: at least **x100** background suppression for z-extended tracks and **x20** for x/y-extended tracks can be anticipated. **It seems that a finer segmentation would help** to improve the blob-identification capabilities as well as proportionally decrease the fraction of damaged area and damage rates.

scope

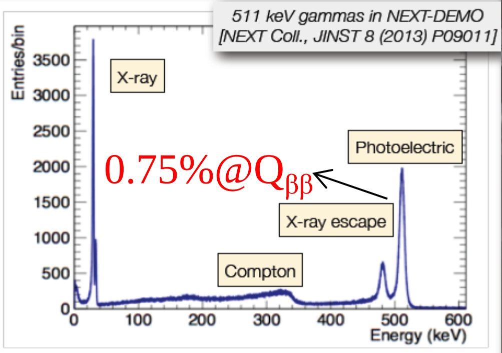
1. Microbulk-Micromegas a fantastic device for tracking γ's in high pressure Xenon-TMA with today's performance. It would be great to include them in a future NEXT-1T based on electroluminescence, if the remaining performances (electroluminescence yield and variance, S_1 sensitivity and low charge-recombination) could be kept for admixtures. Instrumental effects (dead area, noise and threshold) seem to limit presently the energy resolution for extended tracks, but only marginally the experiment exposure.

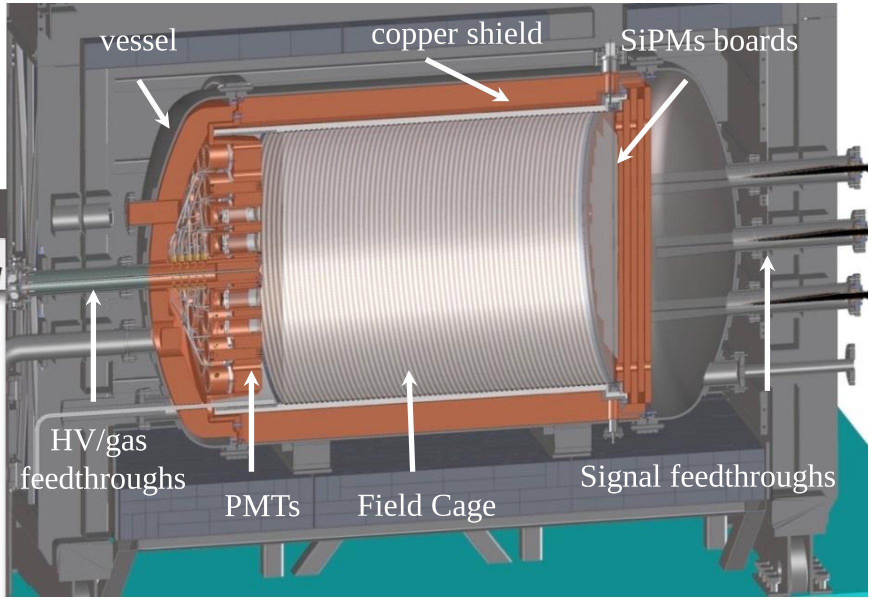
2. These results suggest that in order to obtain near-intrinsic energy resolutions in gas and over large areas one has to operate in conditions where dead channels and noise have no impact on performance. Electroluminescence suffers only marginally from those.



ββ0ν (100 meV)

(2016-2020)


511 keV gammas in NEXT-DEMO
[NEXT Coll., JINST 8 (2013) P09011]

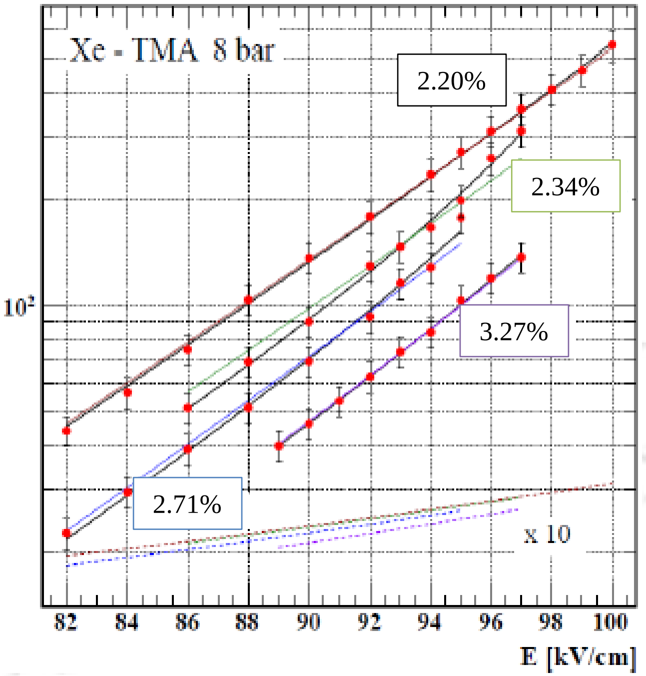


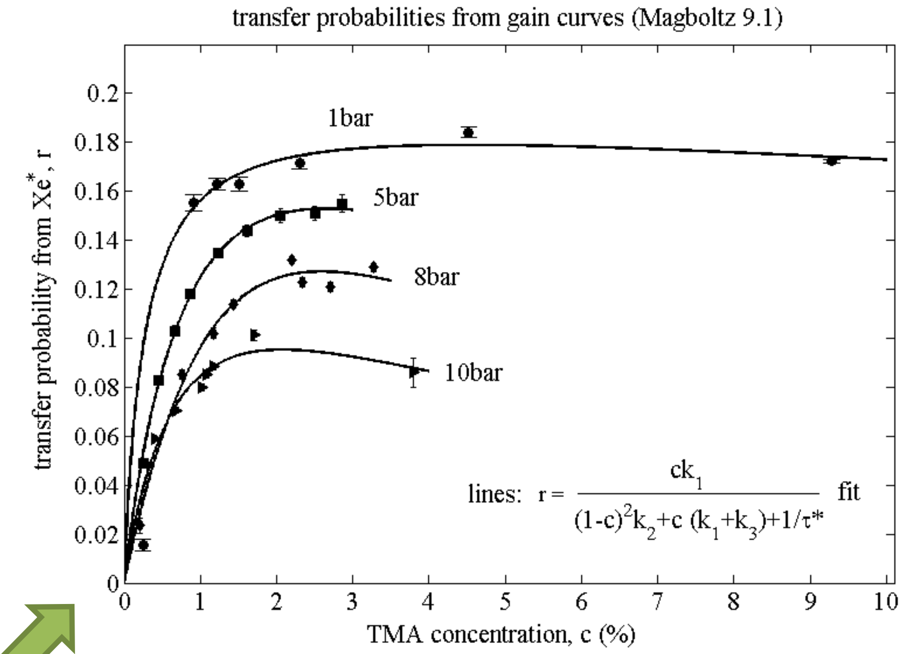
Thanks for your attention!

appendix

Penning transfer rate in Xe-TMA

from Magboltz modeling
(PPC approximation)





simplified 'toy-model'

$$r = \frac{ck_1}{(1-c)^2k_2 + c(k_1 + k_3) + \frac{1}{\tau^*}}$$

Penning transfer rate (~P)

Excimer formation rate (~P^2)

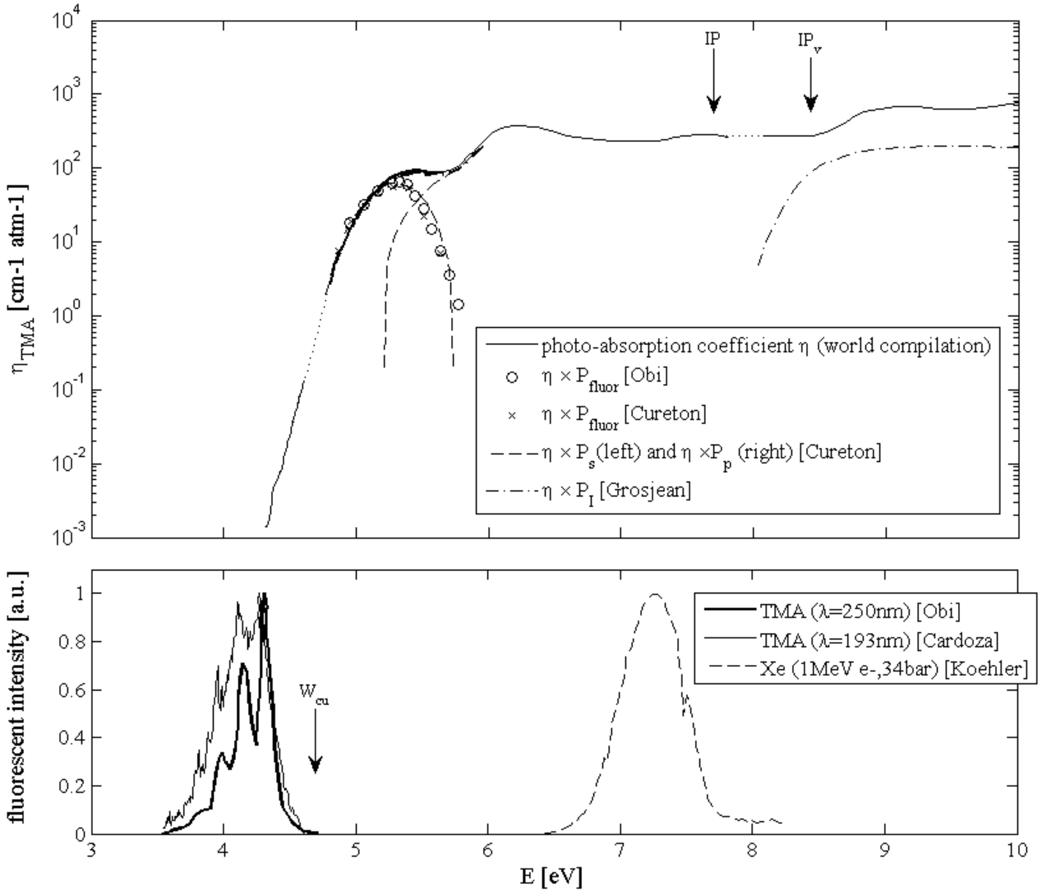
quenching rate (~P)

effective life-time

- Non-trivial decrease with P can be reproduced by the fit.
- Natural explanation in that Penning transfer from excimers disfavored due to energetic considerations (E<IP$_v$).
- Two-body collisions effectively represent a quenching channel for Penning transfer!!.

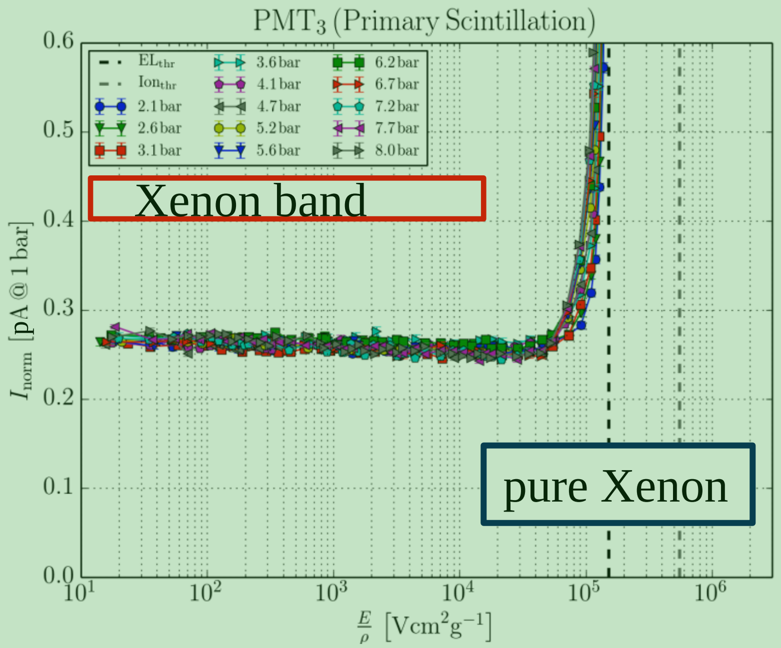
with O. Sahin, R. Veenhof (CERN-Bursa group)

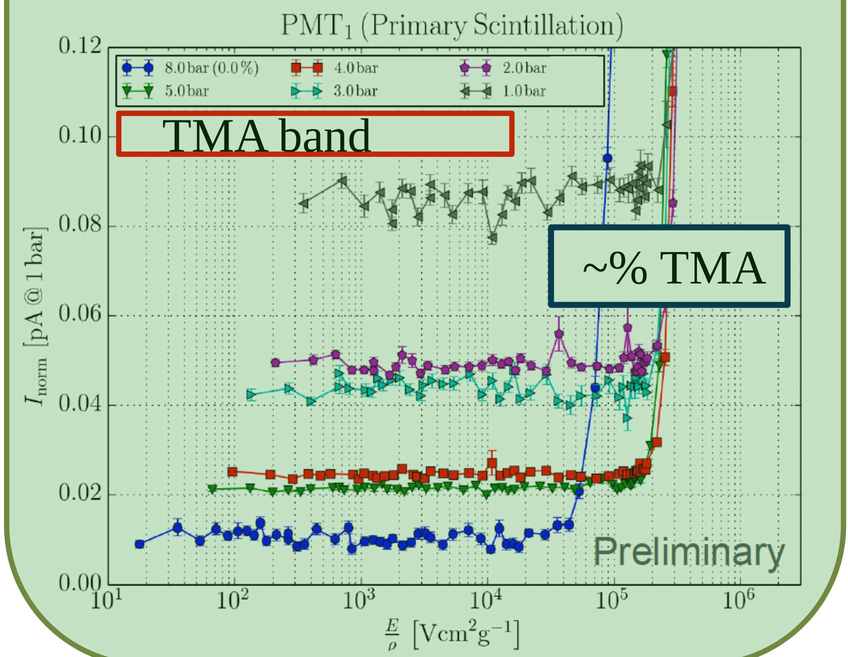
primary scintillation light in Xe-TMA mixtures



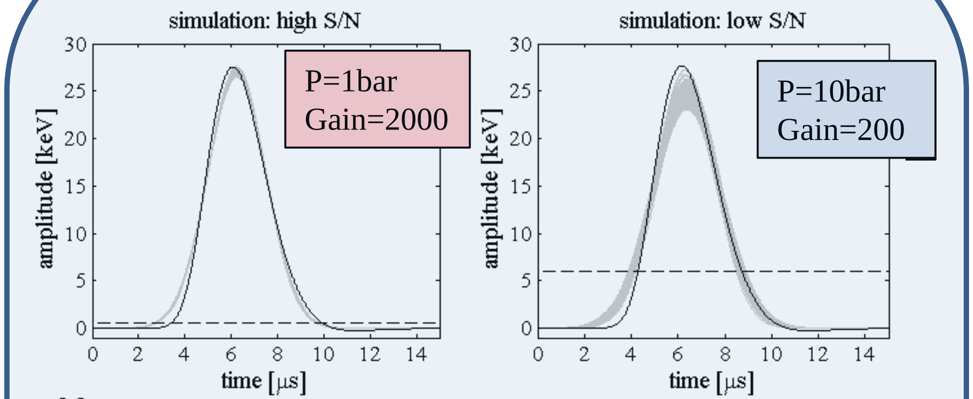
C. Oliveira, A. Goldschmidt, Y. Nakajima et al (LBL group)

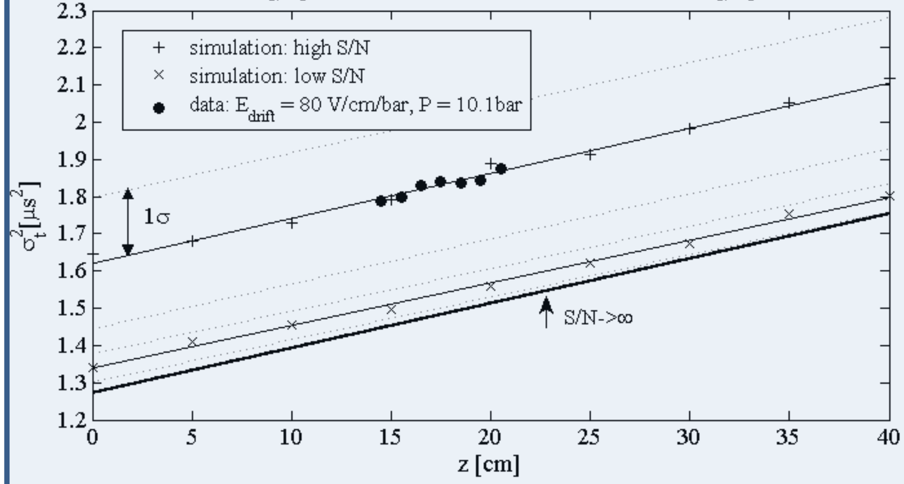
primary light (S_1)



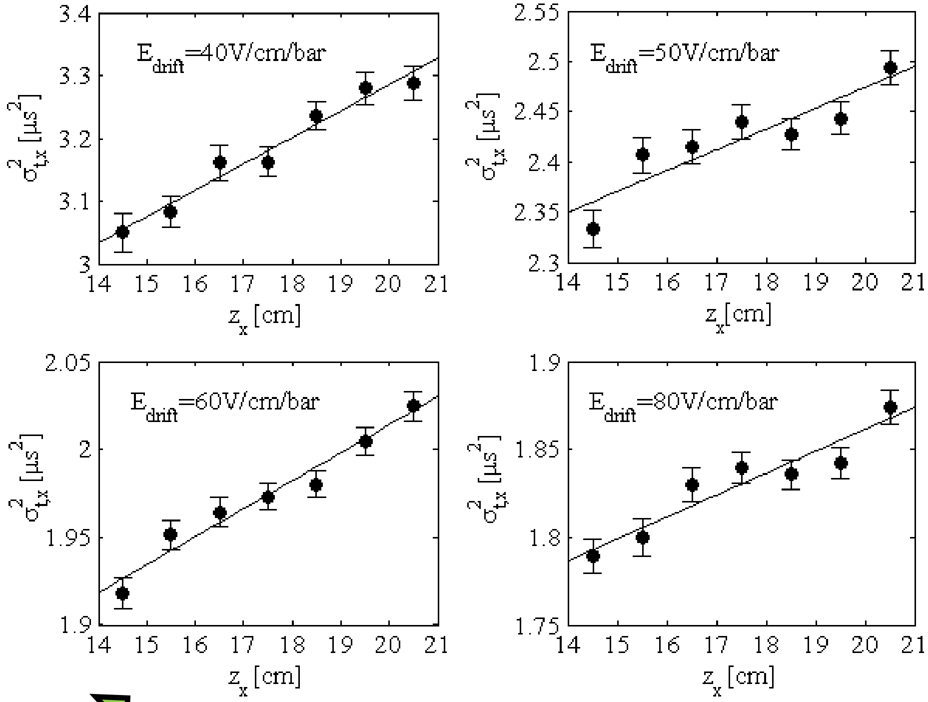


electron drift properties (analysis)

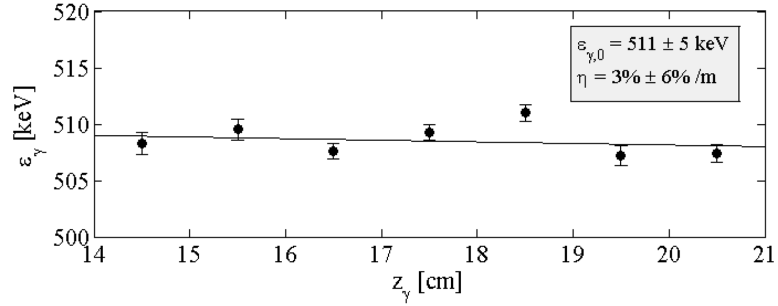


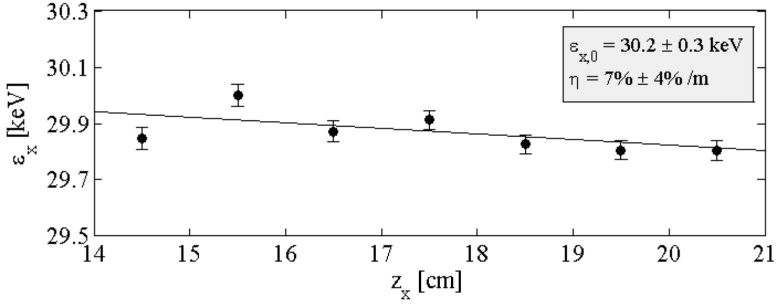


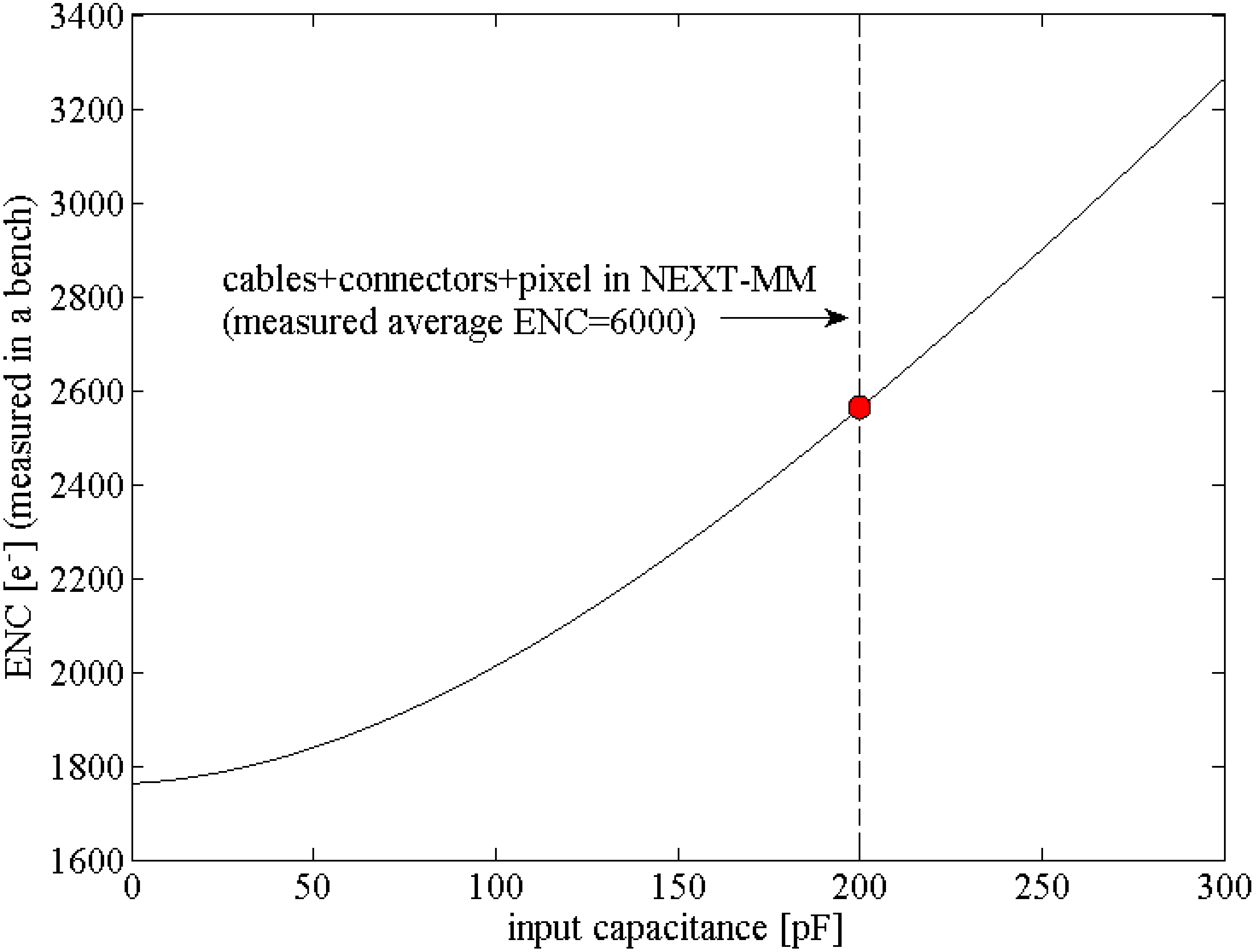
reduced S/N at high P increases minimum signal width and widens correlation stemming from diffusion, but leaves it unaffected.



Suppress random coincidences with σ-z correlation cut

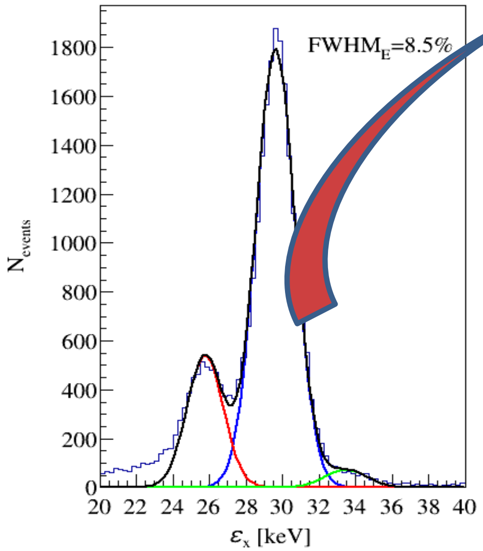


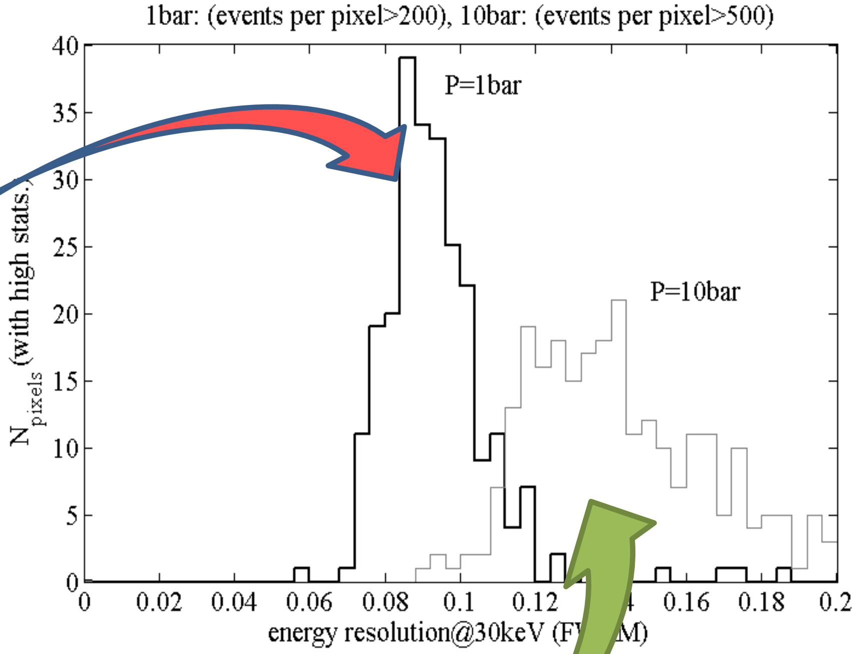




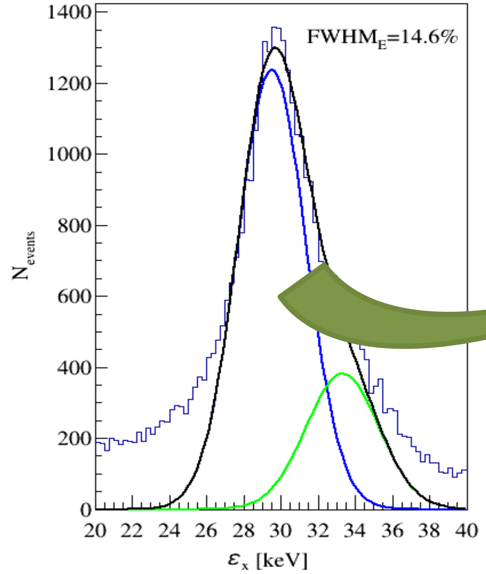
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
ENC [e⁻] (measured in a bench)
cables+connectors+pixel in NEXT-MM
(measured average ENC=6000)
0
50
100
150
200
250
300
input capacitance [pF]

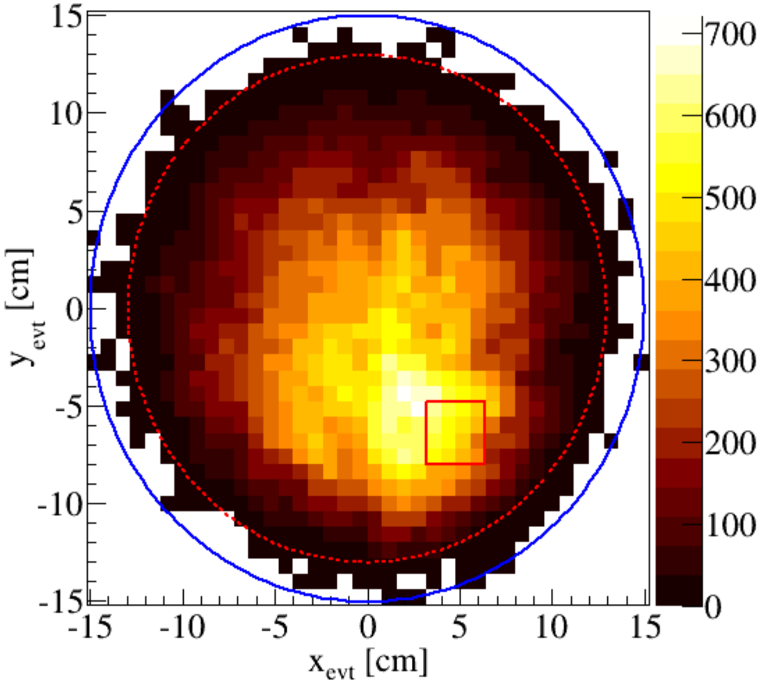
Final result
(for isolated x-rays)



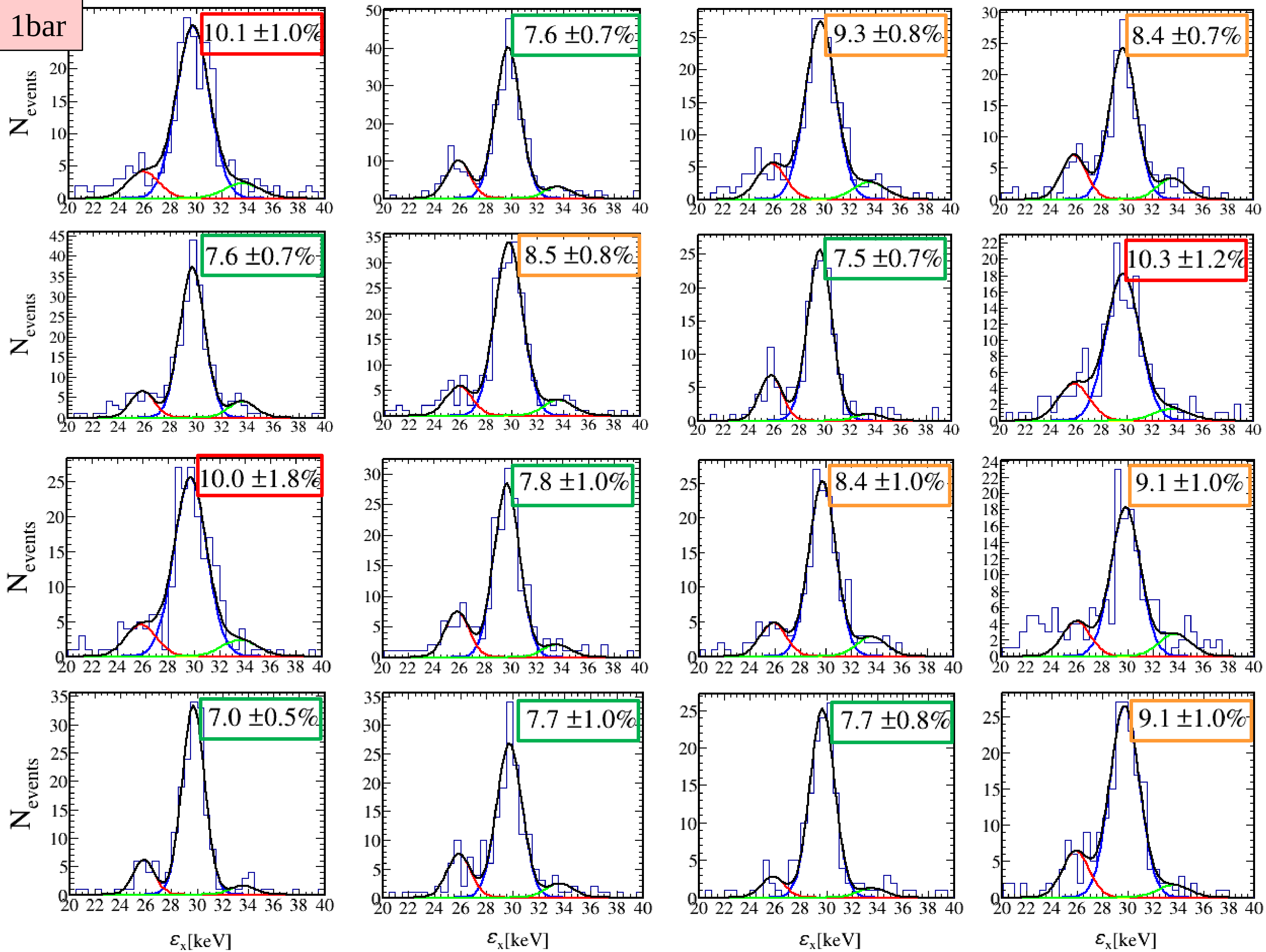


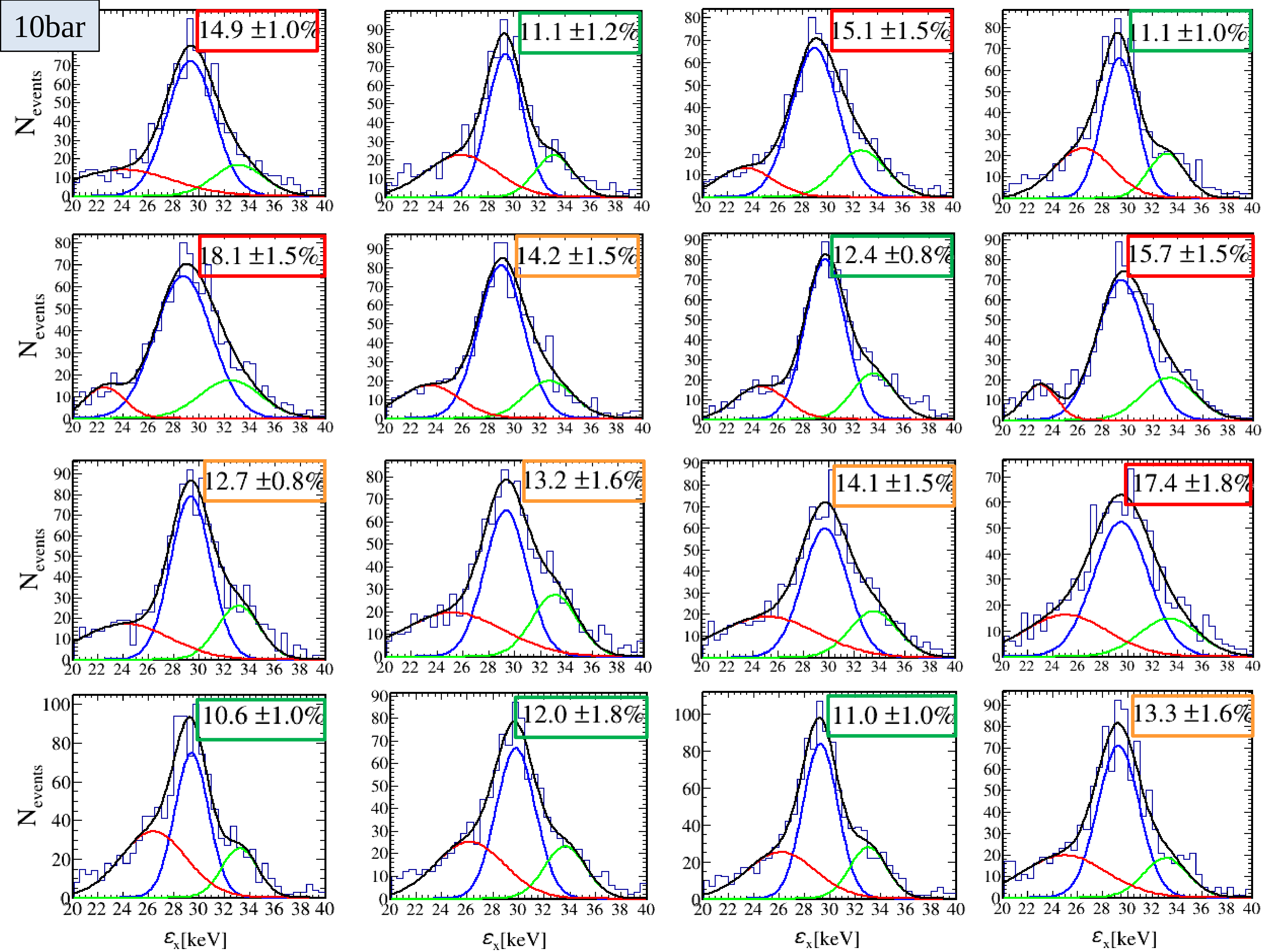
Energy resolution not just a number





1bar

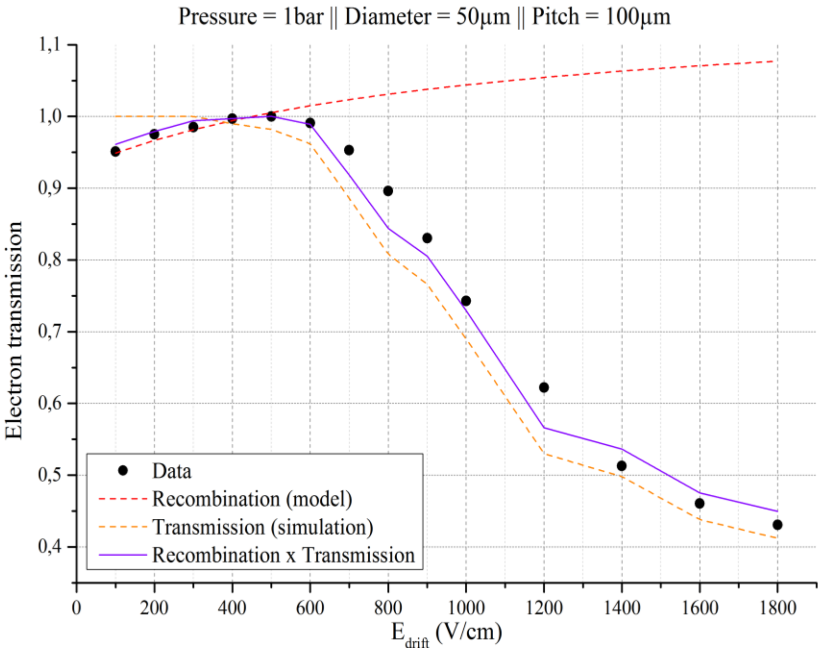

10.1 ±1.0%
7.6 ±0.7%
9.3 ±0.8%
8.4 ±0.7%
7.6 ±0.7%
8.5 ±0.8%
7.5 ±0.7%
10.3 ±1.2%
10.0 ±1.8%
7.8 ±1.0%
8.4 ±1.0%
9.1 ±1.0%
7.0 ±0.5%
7.7 ±1.0%
7.7 ±0.8%
9.1 ±1.0%
N_{events}
ε_x[keV]
20 22 24 26 28 30 32 34 36 38 40


10bar
14.9 ±1.0%
11.1 ±1.2%
15.1 ±1.5%
11.1 ±1.0%
18.1 ±1.5%
14.2 ±1.5%
12.4 ±0.8%
15.7 ±1.5%
12.7 ±0.8%
13.2 ±1.6%
14.1 ±1.5%
17.4 ±1.8%
10.6 ±1.0%
12.0 ±1.8%
11.0 ±1.0%
13.3 ±1.6%
N_{events}
ε_x[keV]
20 22 24 26 28 30 32 34 36 38 40

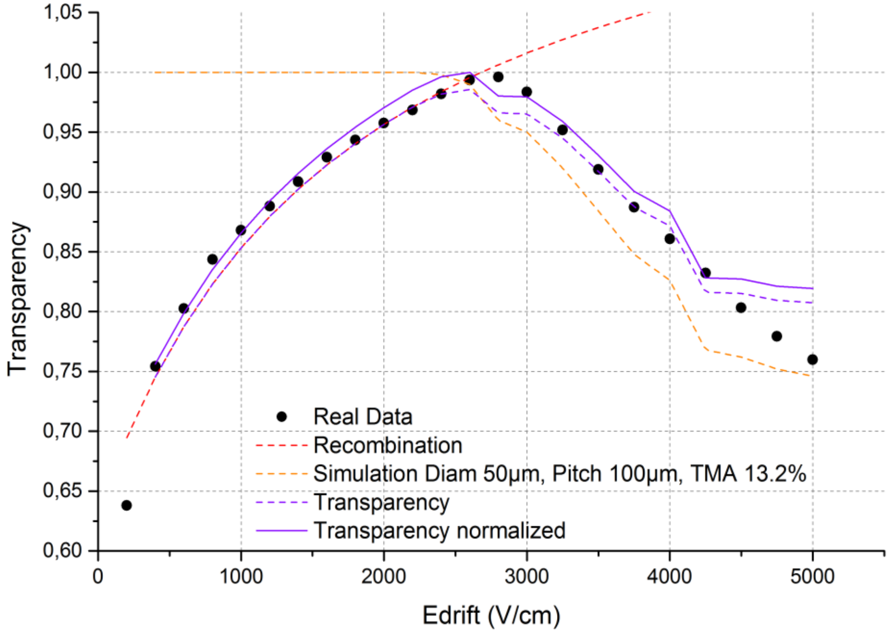
Intrinsic energy resolution

$$\sigma_{\varepsilon,intr}{}^{2} = \sigma_{\varepsilon,MM-gain}{}^{2} + \underbrace{\sigma_{\varepsilon,Fano}{}^{2} + \sigma_{\varepsilon,reco}{}^{2}}_{\text{inherent to the mixture}}$$

1bar

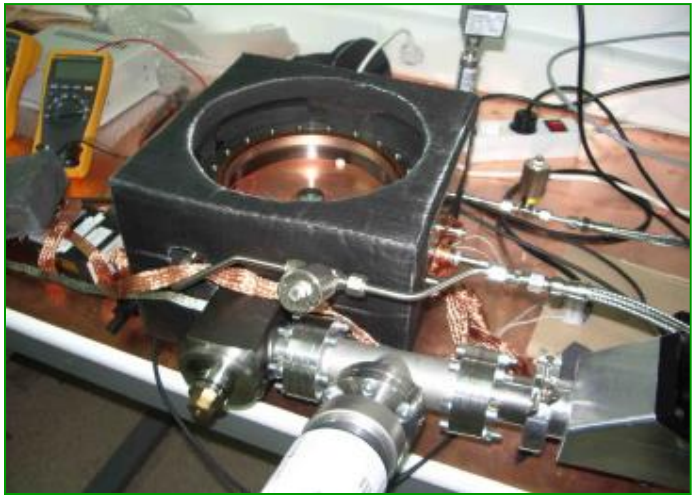


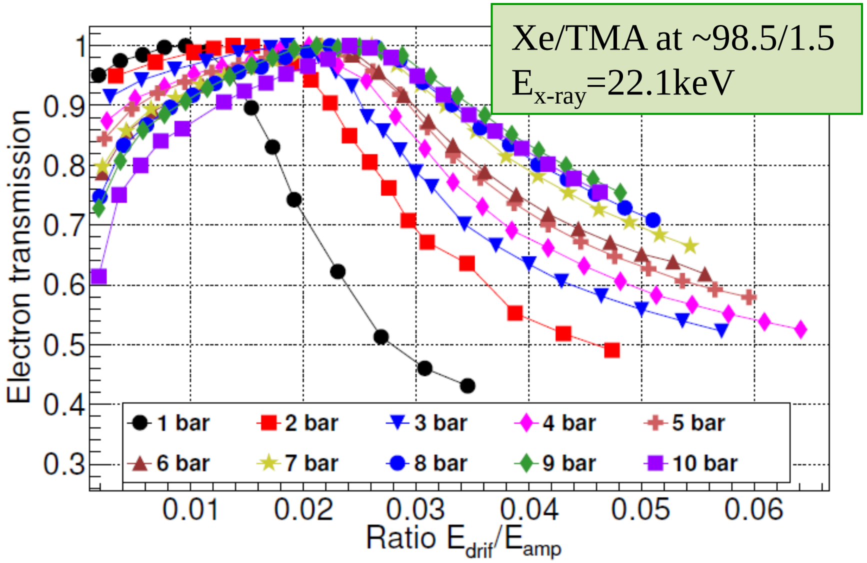
10bar



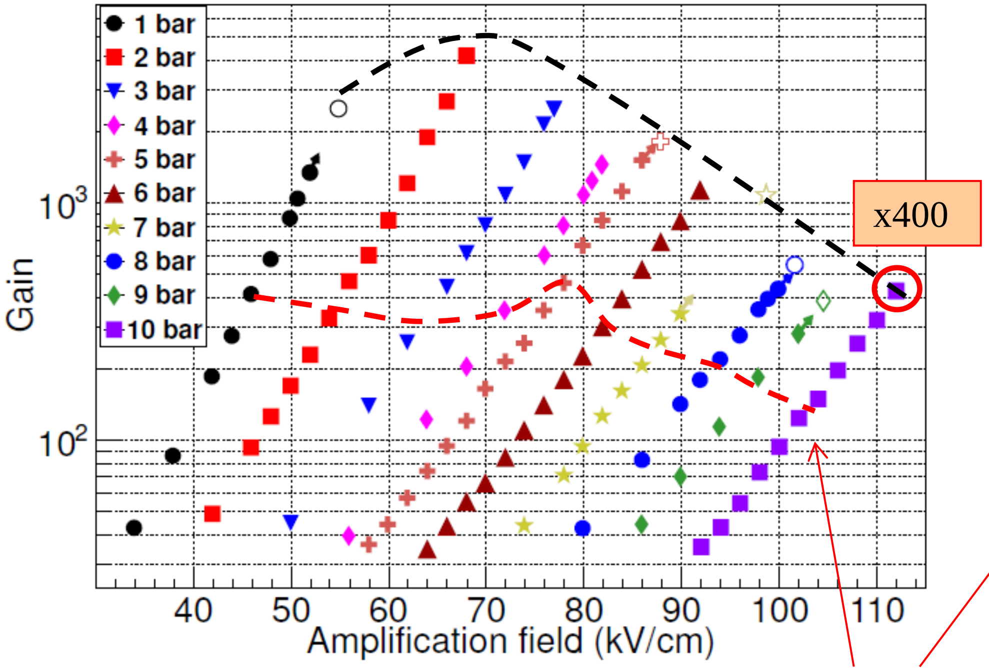
E. Ruiz-Choliz (Zaragoza group)

step 0: measurements in a small setup and general behavior

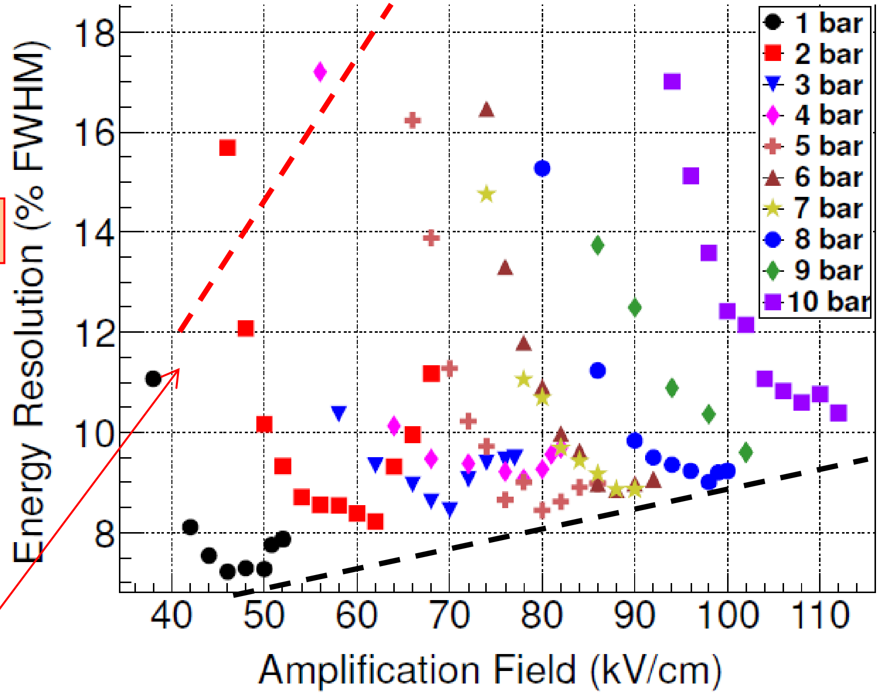




Xe/TMA at ~98.5/1.5
$E_{x\text{-ray}}$=22.1keV

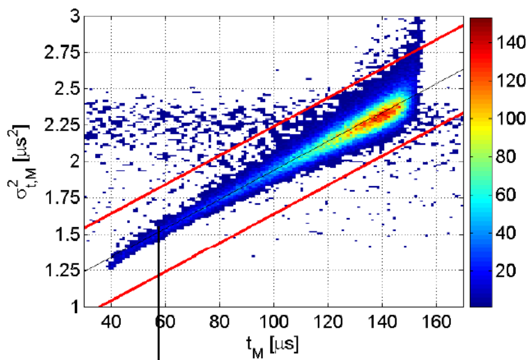


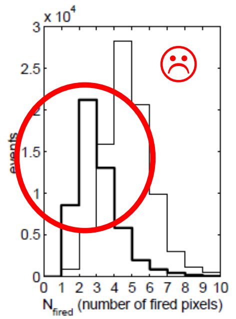
x400



Measurements in pure Xe (Coimbra+Saclay)

Extraction of diffusion coefficients at 1-3bar

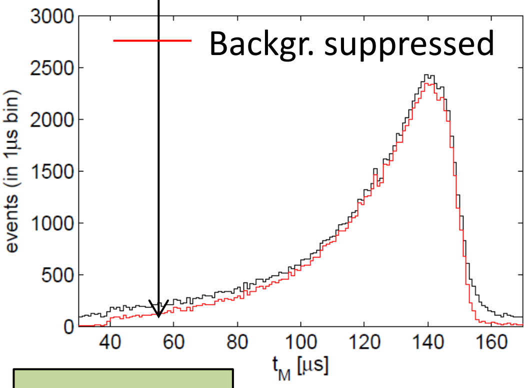




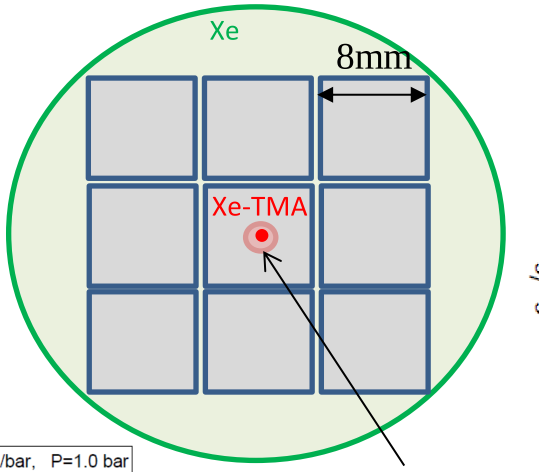
use the following convention

$$D_L^* = \sqrt{\frac{T_0}{T}\frac{2P\,D_L}{v_d}} \quad \left[\frac{\mu\text{m}}{\sqrt{\text{cm}}}\times\sqrt{\text{bar}}\right]$$

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

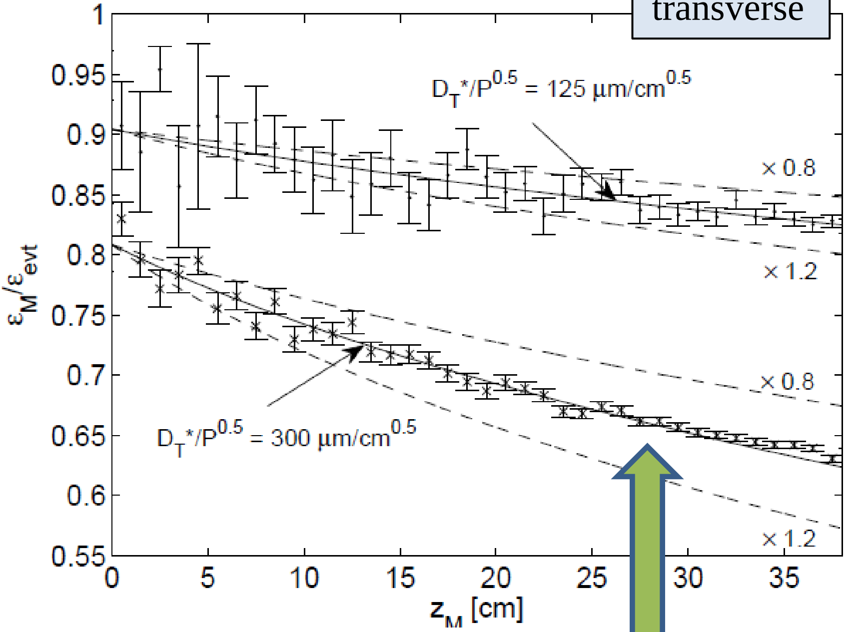


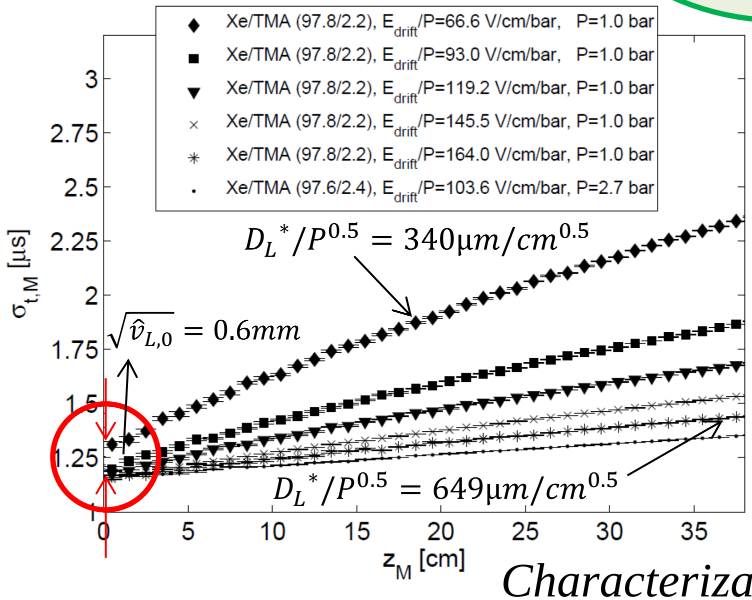
longitudinal



Typical transverse size of the ionization cloud for 38cm drift @1bar (1-σ)

transverse





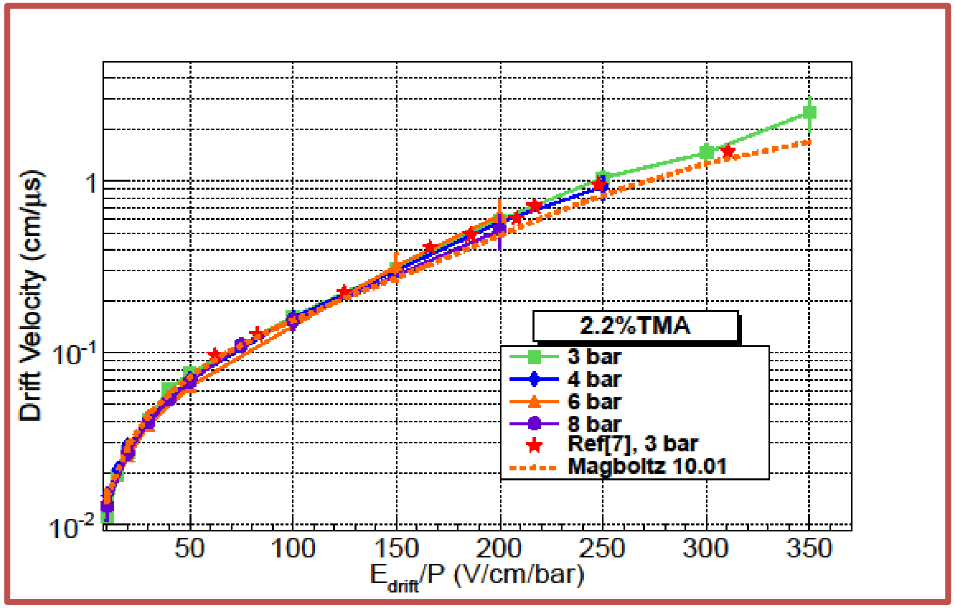
$$<\frac{\varepsilon_M}{\varepsilon_{evt}}> = \left[\frac{1}{L}\int_{-L/2}^{L/2}dx\int_{-L/2}^{L/2}\frac{1}{\sqrt{2\pi\hat{v}_r}}\,e^{-\frac{(x-x_0)^2}{2\hat{v}_r}}\,dx_0\right]^2$$

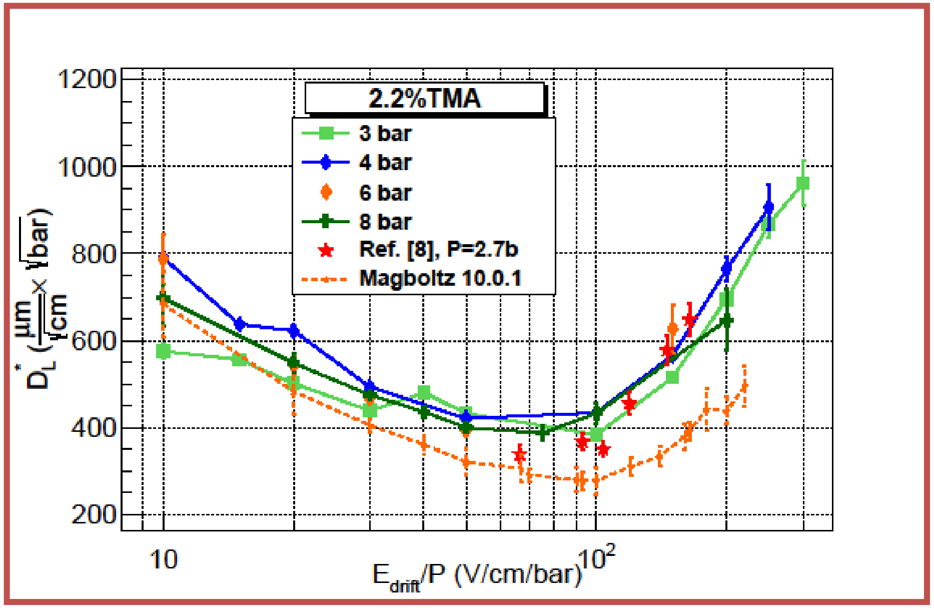
$$<\frac{\varepsilon_M}{\varepsilon_{evt}}> = \frac{\left[2\hat{v}_r\left(e^{-\frac{L^2}{2\hat{v}_r}}-1\right)+\sqrt{2\pi}L\sqrt{\hat{v}_r}\,\text{erf}\left(\frac{L}{\sqrt{2\hat{v}_r}}\right)\right]^2}{2\pi L^2\hat{v}_r}$$

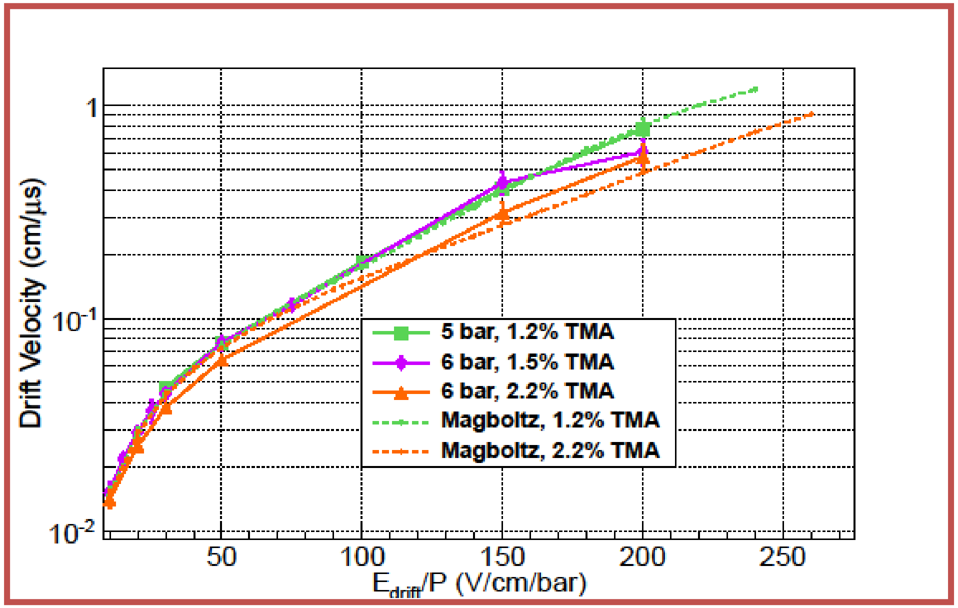
$$\hat{v}_r = D_T^{*\,2}\times\frac{z_M}{P}+\hat{v}_{r,0} \longrightarrow \sqrt{\hat{v}_{r,0}} = 1\pm 0.1mm$$

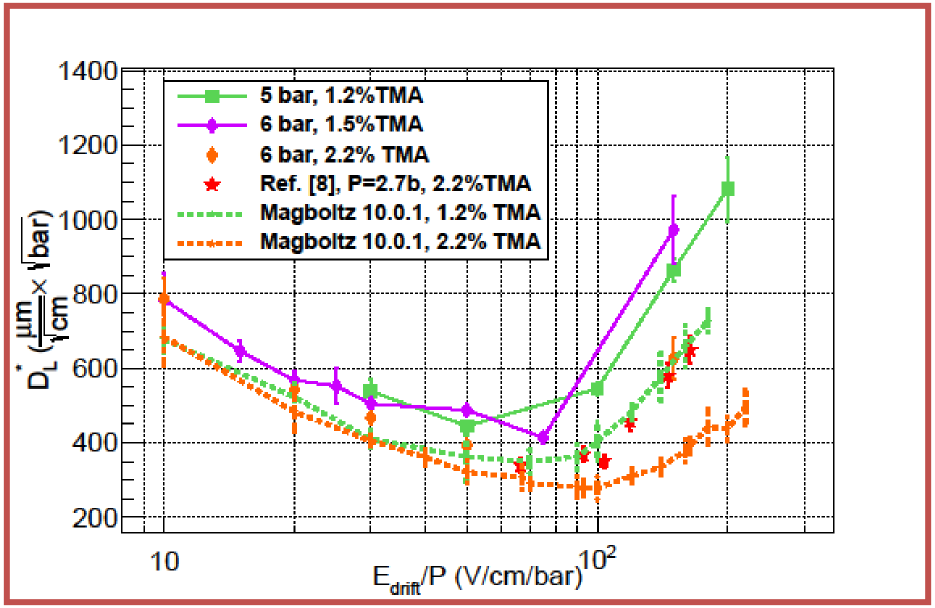
Characterization of a medium size Xe-TMA TPC, JINST 9(2014)C04015

columnar recombination (with α-tracks)





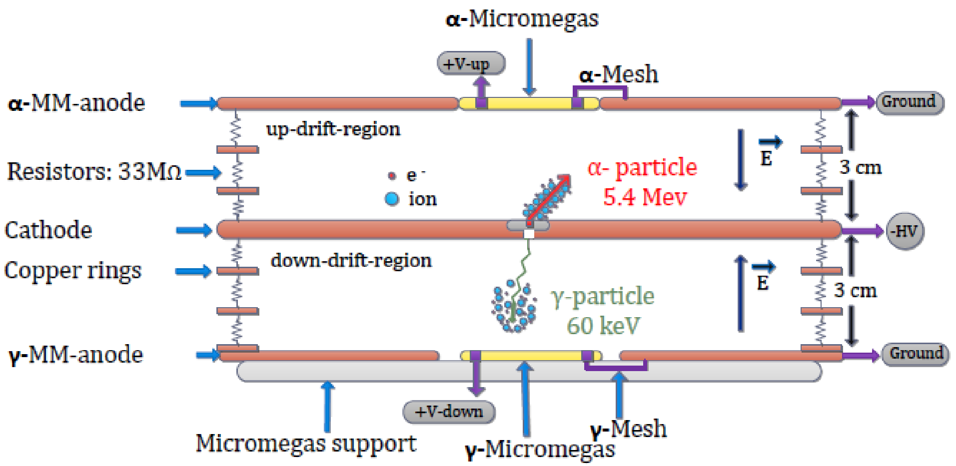


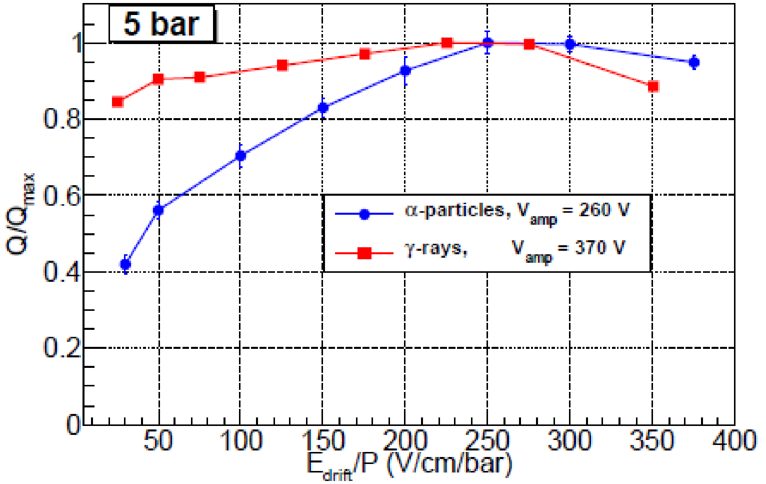


[7] D.C. Herrera , J. Phys. Conf. Ser. **460** (2013) 012012

*[8] V Álvarez et al, JINST **9** C04015 (2014)*

columnar recombination (with α-tracks)





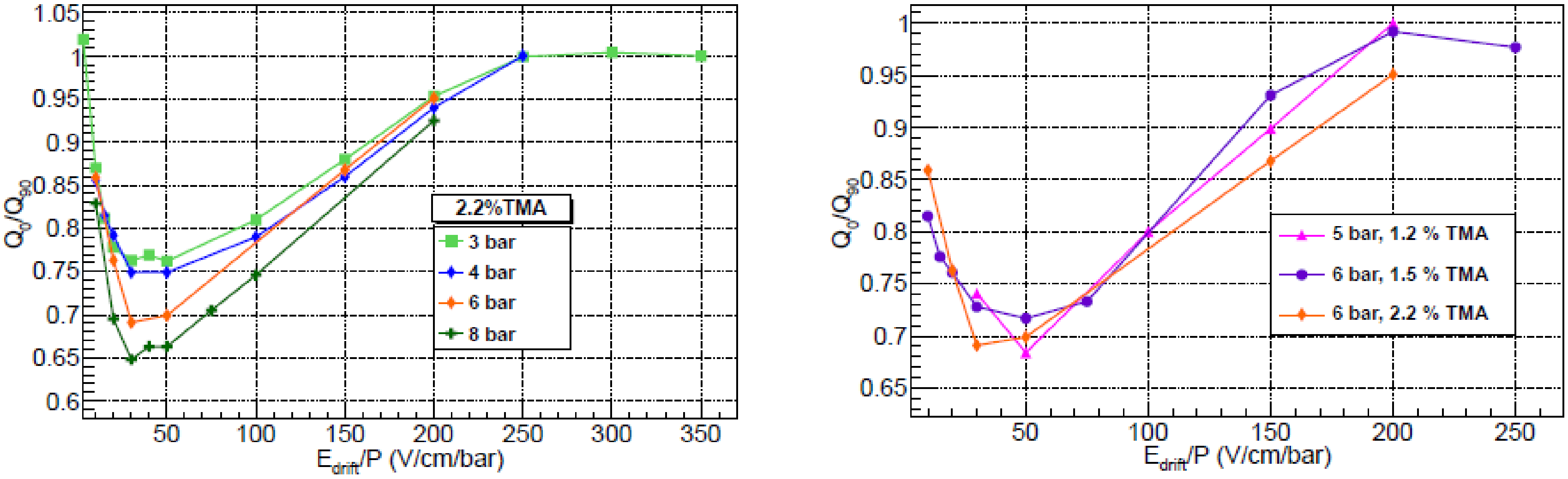


Figure 6: Dependence of Q_0/Q_{90} on E_d/P for different pressures in a mixture of 2.2%TMA (left) and for various TMA concentrations at 5 and 6 bar (right).

Supra-intrinsic energy resolution in Xe-TMA

The basic idea (details omitted)

$$\boxed{\frac{W_{xe-TMA}}{W_{xe}} \cong \frac{1}{(1+rN_{ex}/N_I)(1-R)}}$$

Recombination (electron dynamics)

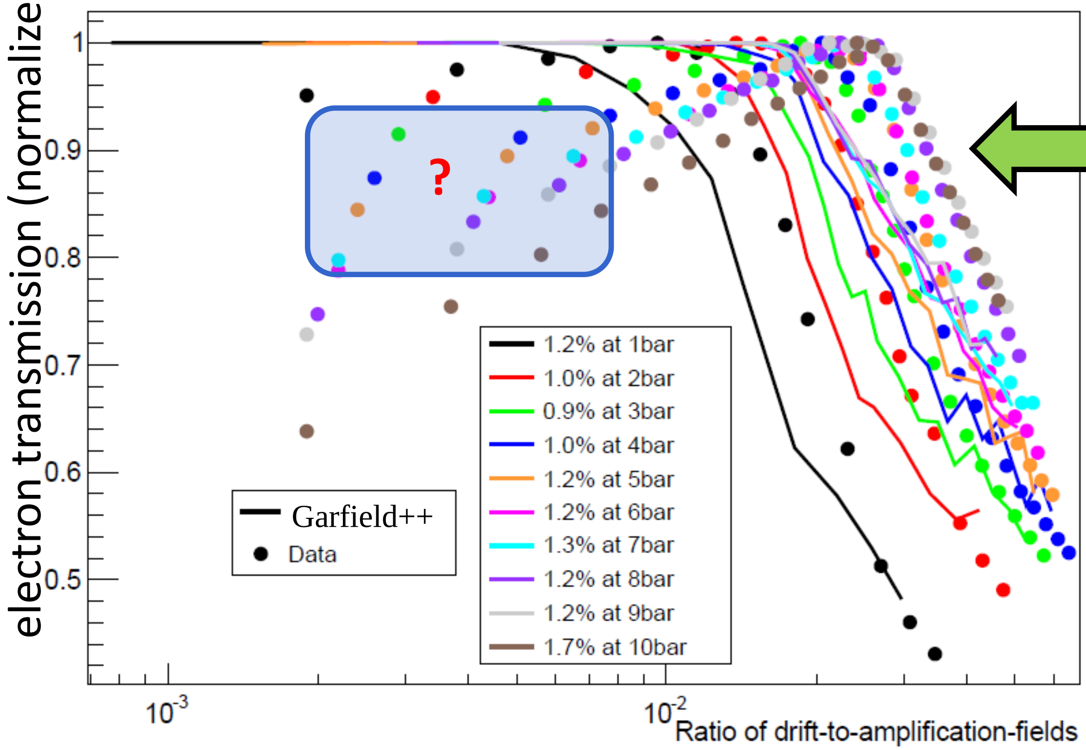
Penning transfer (ion dynamics)

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

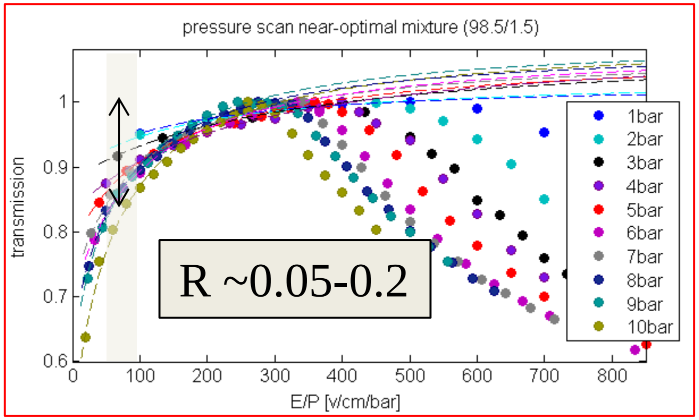
$$\boxed{\frac{\sigma_{xe-TMA}}{\sigma_{xe}} \geq \sqrt{(1-r)+R/F_{Xe}}}$$

Behavior in the drift region (recombination)

~(1-R)



Reasonable description of electron transmission at high fields, but some tweak seems to be needed (x-sections or geometry?)



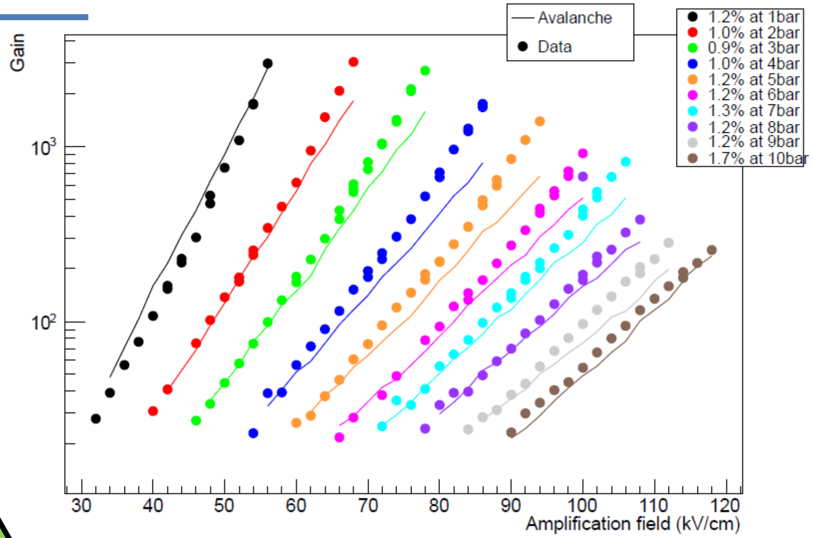
R ~0.05-0.2

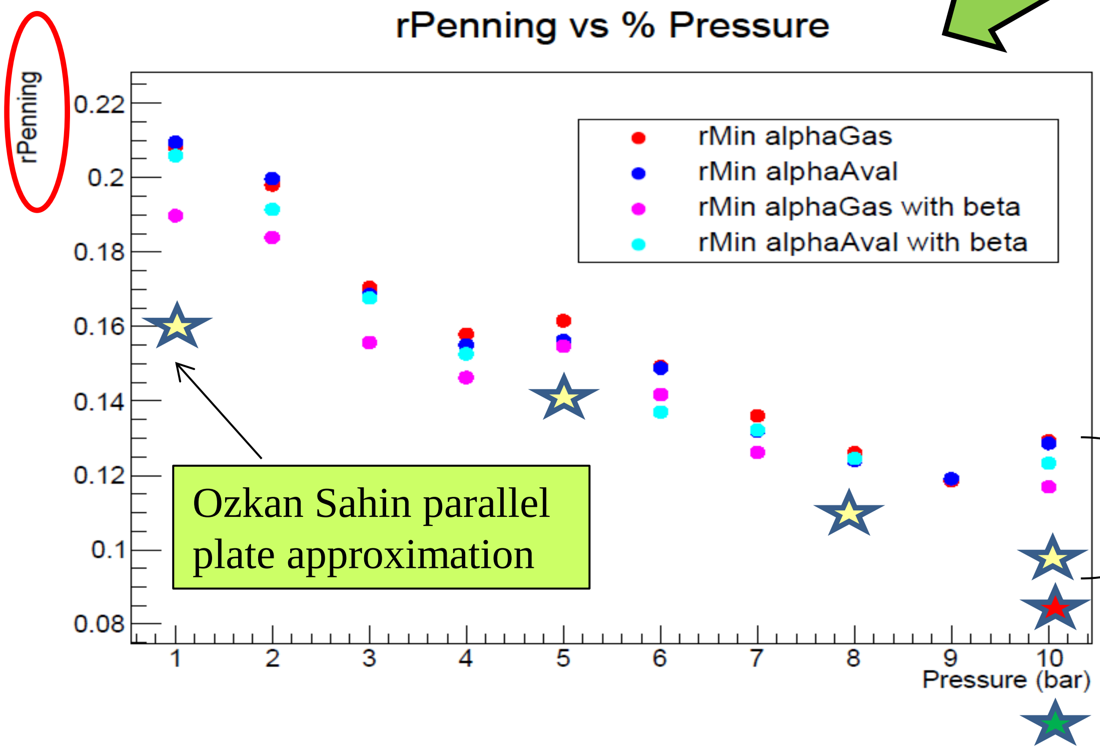
Region at low fields connected to recombination (see talk of D. C. Herrera at WG2).

Behaviour in the gain region (Penning)

reasonable description of gain curves if including Penning transfer!

r~0-0.2





Ozkan Sahin parallel plate approximation

Decreasing trend with pressure!

%TMA=1.5%

%TMA=3.8%

%TMA=0.4%

the Zaragoza group

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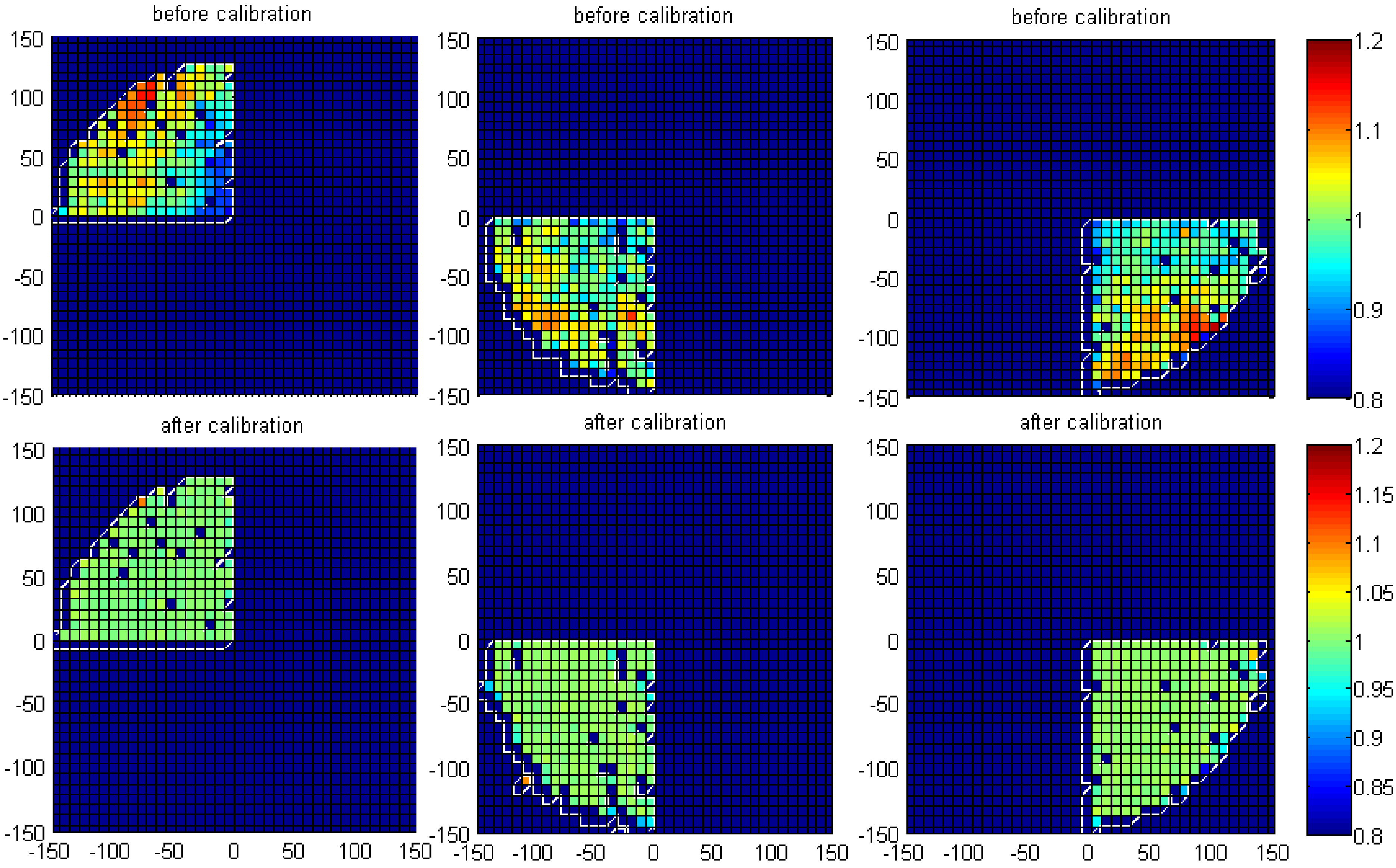
special thanks to Saclay-IRFU and to the CERN workshop

appendix

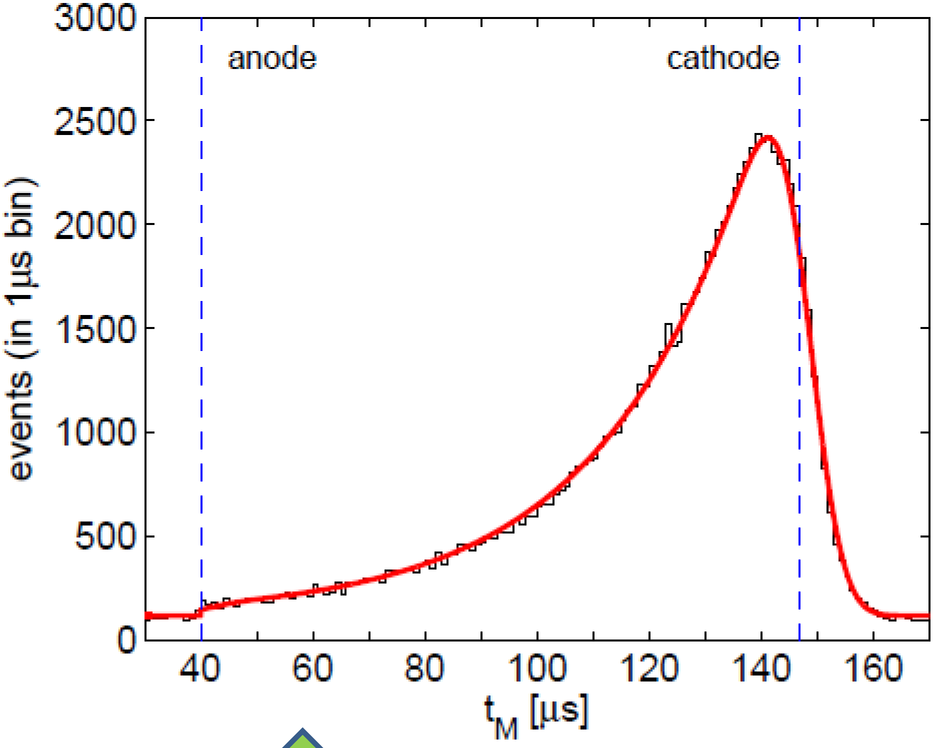
gain maps are necessary in order to achieve ultimate resolution

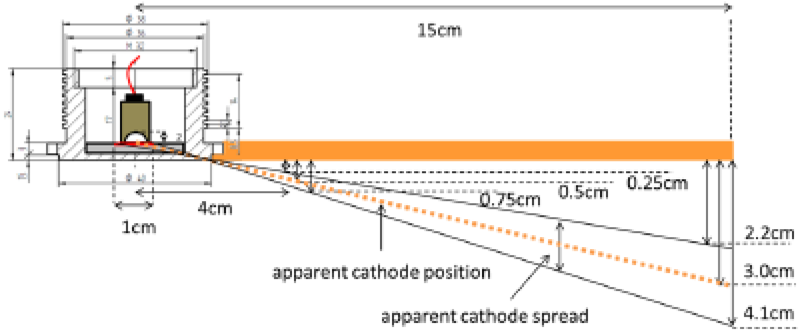


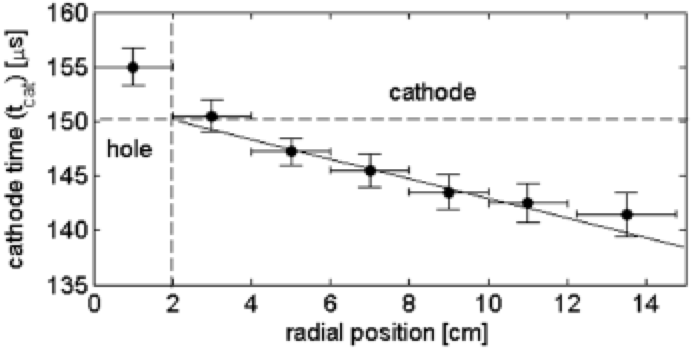
obtained by aligning the 30keV peak pixel by pixel

determining the total drift time (and hence the drift velocity)

(sharp) (smeared due to extended source)





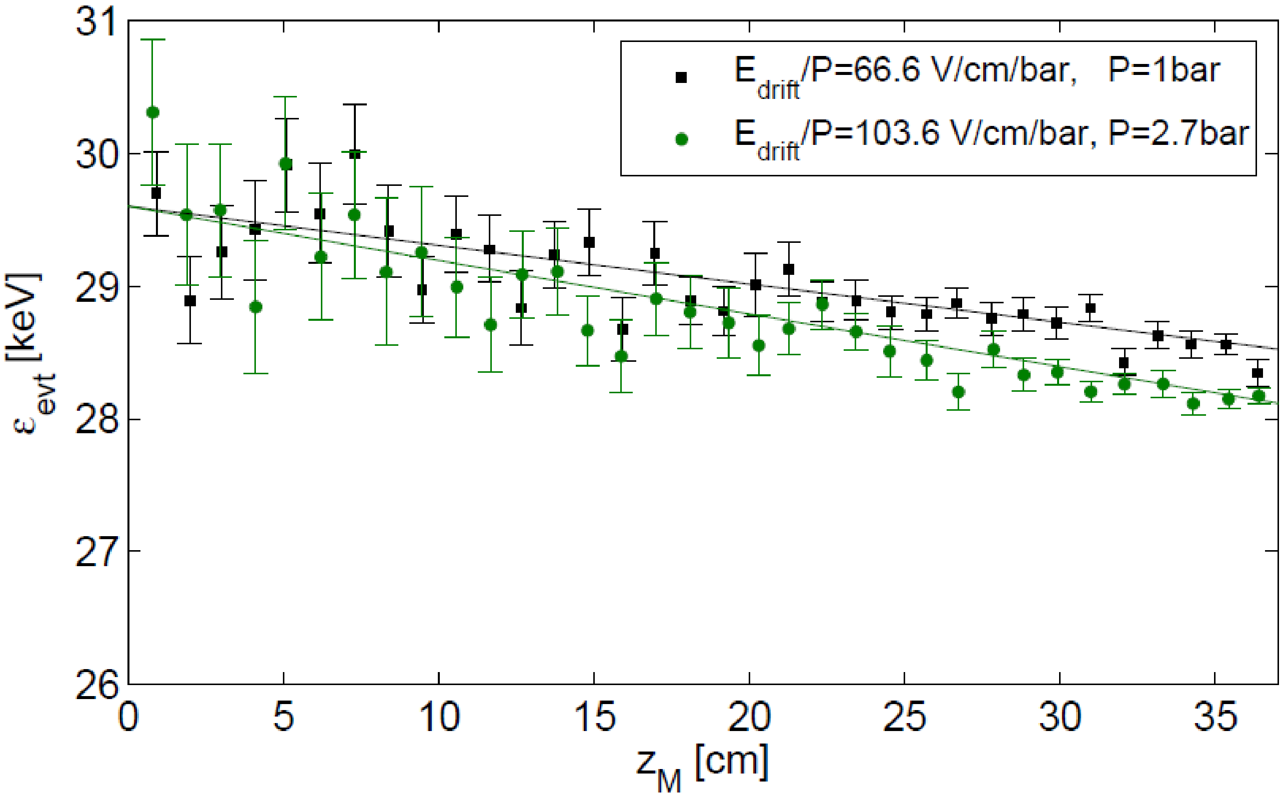


operational fit to exponential convoluted with Gauss

$$v_d = \frac{t_{cat} - t_{ano}}{D(= 38cm)}$$

$$f(t_M) = \mathscr{C} e^{t_M/\tau^*} \left[\mathrm{erf}\left(\frac{t_{cat} - \sigma_g^2/\tau^* - t_M}{\sqrt{2}\sigma_g} \right) - \mathrm{erf}\left(\frac{t_{ano} - \sigma_g^2/\tau^* - t_M}{\sqrt{2}\sigma_g} \right) \right] \Theta(t_M - t_{ano}) + B$$

attachment coefficient



E/P[V/cm/bar]	v_d[cm/μs]	$D_L^*[\mu\text{m}/\sqrt{\text{cm}}\times\sqrt{\text{bar}}]$	$\eta[\text{m}^{-1}]$	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

new hardware

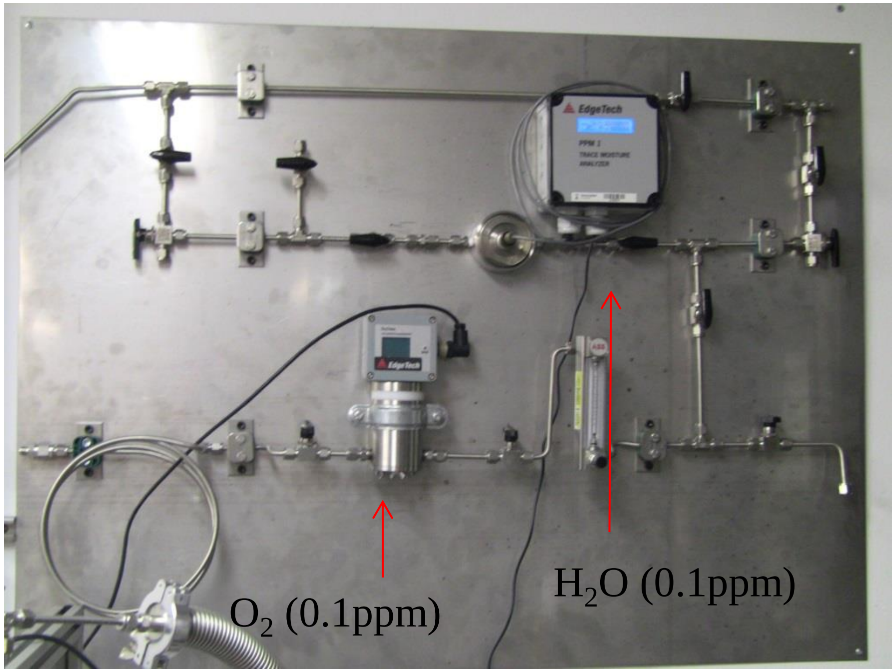
new bottles and piping

TREX-light (pure Xenon line)

NEXT-MM recovery bottle

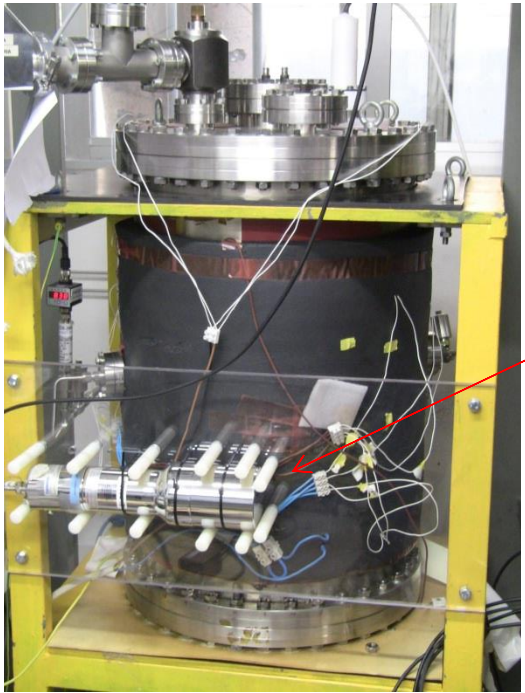
NEXT-MM expansion chamber

sensor panel



O_2 (0.1ppm)

H_2O (0.1ppm)



NaI detector
and Na source