Monte-Carlo studies for the *ep*-elastic scattering

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Outline

- Simulation software strategy
  - Goal \ Simulation chain \ Manpower
- Current status
- What’s new?
  - ESEPP generator config https://github.com/nuramatov/esepp/
  - Beam smearing at the exit window (already mentioned by Peter Kravtsov)
  - Electronic signal https://github.com/aleksha/electronic-signal
  - Electronic noise https://github.com/aleksha/electronic-noise
  - Drift velocity experiment
  - Drift in electric field https://github.com/aleksha/pres-electric-field
  - Z-position measurement (angular dependence, power of MVA methods)
  - Recoil ranges for calibration

Run / detector conditions for MC

- Beam model
  - ***Time distribution for incoming electrons***; mean beam frequency – f_b;
  - 2D beam spatial distribution – $Gaus_x(\mu_{bx},\sigma_{bx}) \times Gaus_x(\mu_{by},\sigma_{by})$? Any beam halo?
  - Beam direction distribution – $Gaus_p(\mu_{p\vartheta},\sigma_{p\vartheta}) \times Uniform_{p\varphi}(-\pi,\pi)$?
- Geant-4 (***detector model***) provides ionization
- TPC time resolution model
  - Drift velocities – W_{d1}, W_{d2}; ***Recombination(r_{hit}, f_b)***; ***(x,y)-smearing(r_{hit}, f_b)***
  - **Accepting** due to not clean gas.
  - Signal formation (during grid-anode drift)
  - TDC parameters:
    - N_{ch}, Δt_{ch}; → t_i – TDC channel
    - Energy to TDC response – C_{TDC};
    - ***Noise spectrum***
  - Time-pulse function – $\delta_{Dirac}(t_i)$ → ***Some distribution***$(t, t_i, \boldsymbol{T_j})$

These conditions must be included into Monte-Carlo to have is as closer to the data as possible to mimic operation conditions as a function of (beam)time

Goal: MC can be analyzed as DATA

Software status

- All important parts were investigated
- New studies (done in 2020-03 – 2021-03) will be presented in the main part of the talk

- Software chain of isolated tools, but not a one program ☹

- Manpower:
  - Prof. Vorobyev (ideas, coordination, review)
  - Aleksei Dziuba (with a large input of ideas and settings from PNPI teams)
  - Arsen Nuramatov (bachelor-year student of SPbSU)

Generators

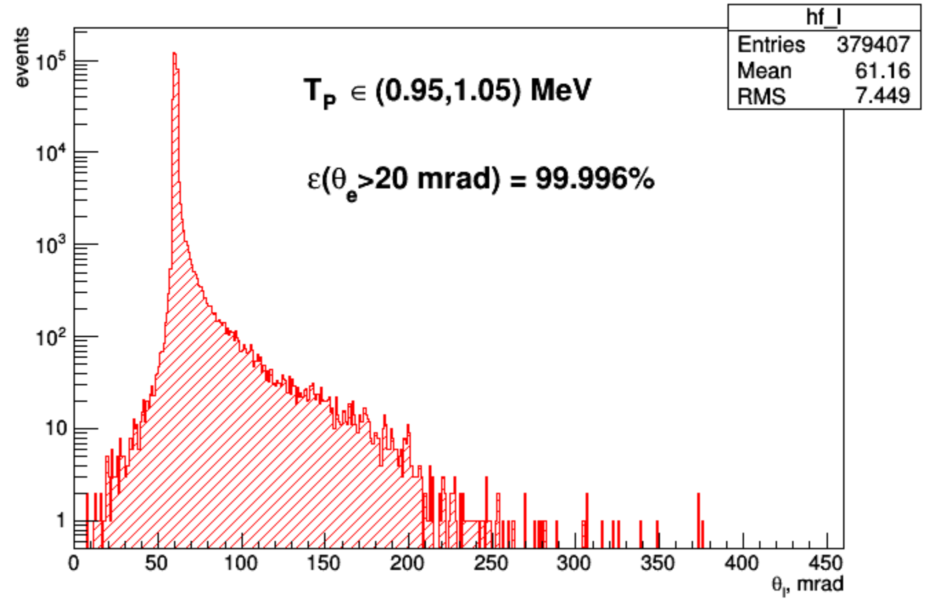
There will be no loss in central (not sensitive) part of CSC

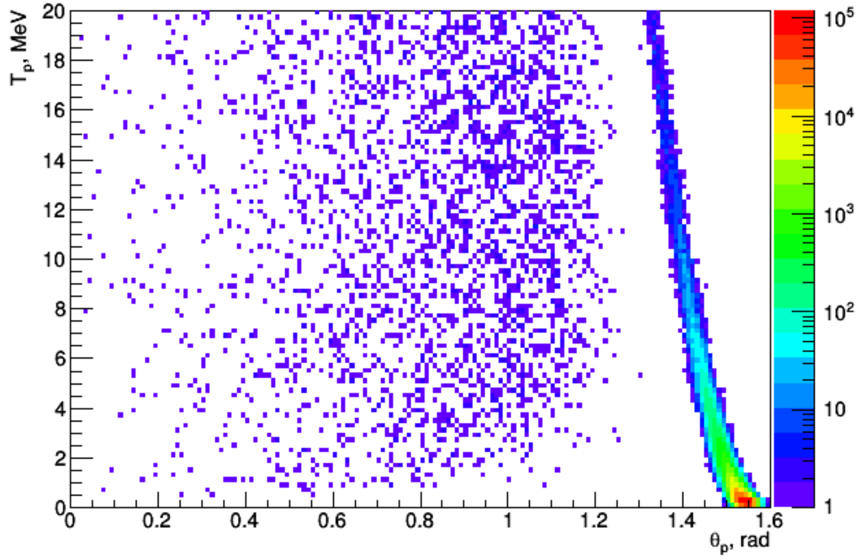
Event generators

- ESEPP https://github.com/gramolin/esepp to account radiative corrections
- We updated a software stack (***conda***) and now there is a way not to build it with a dependencies-hell (use **pres-mc**)
- A nice config-file (not interactive)
  - https://github.com/nuramatov/esepp/

NEW

- "Handmade" Δ production generation for inelastic (there are more realistic approximation in PRad paper)

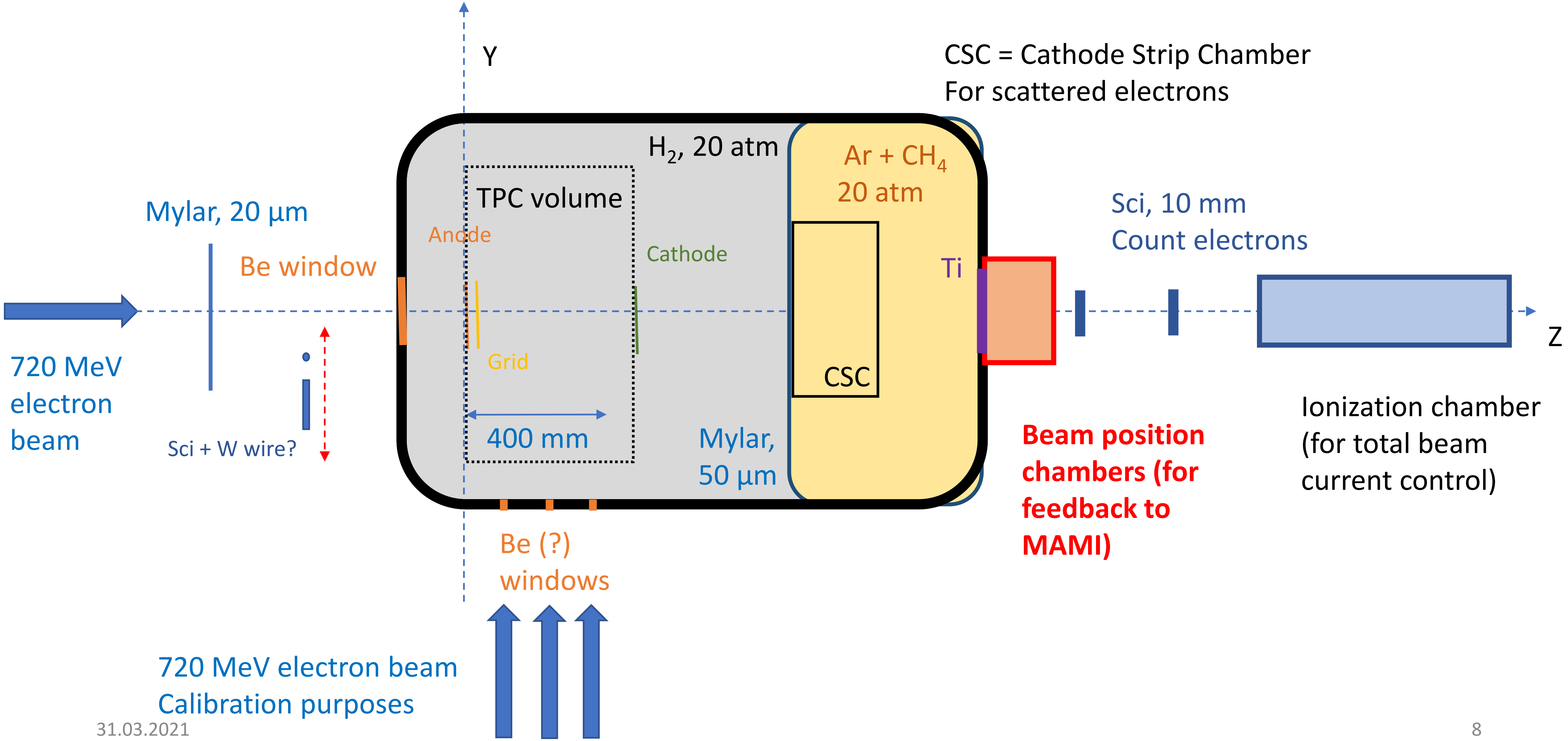




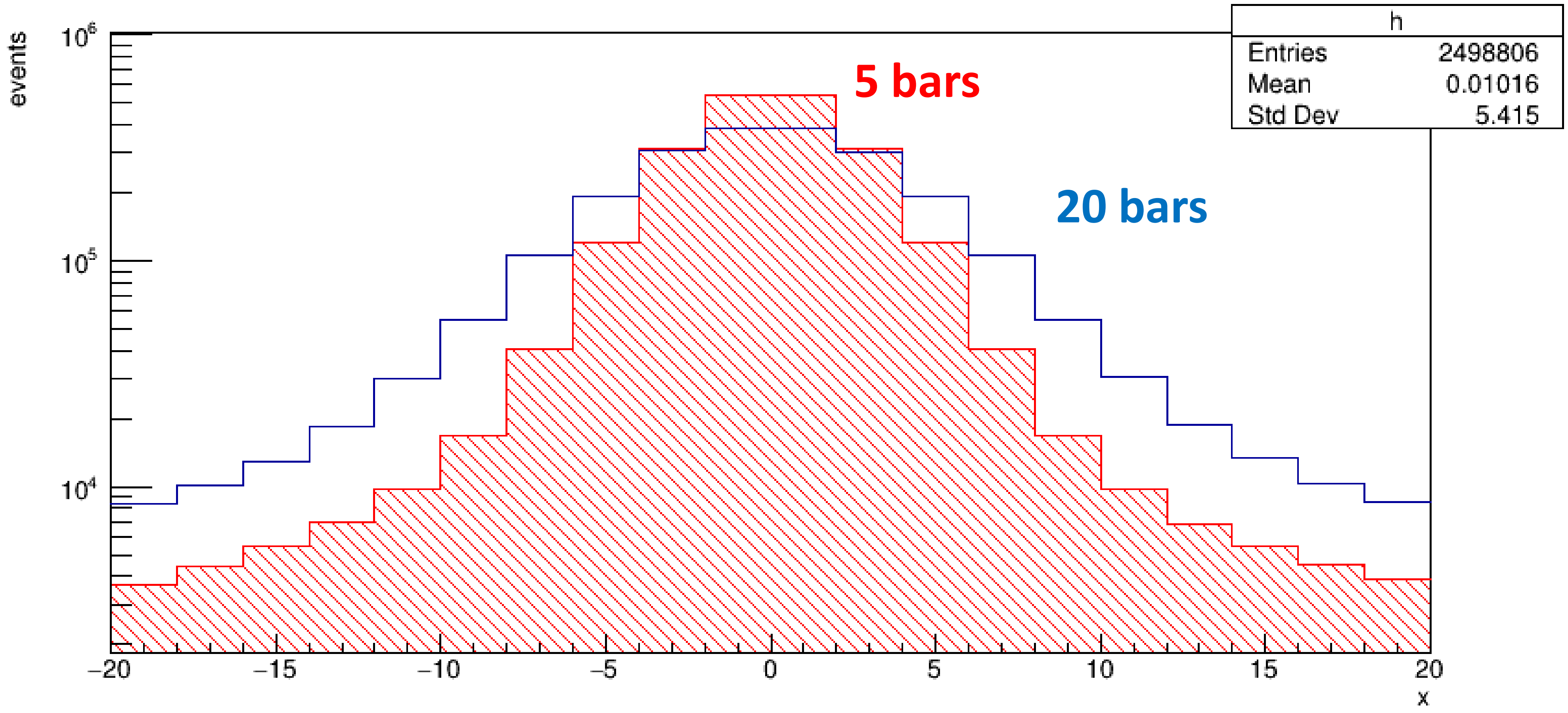
Correlation between T_p and electron and proton angle is powerful tool to reject inelastic background

Beam smearing

Beam smearing by main detector



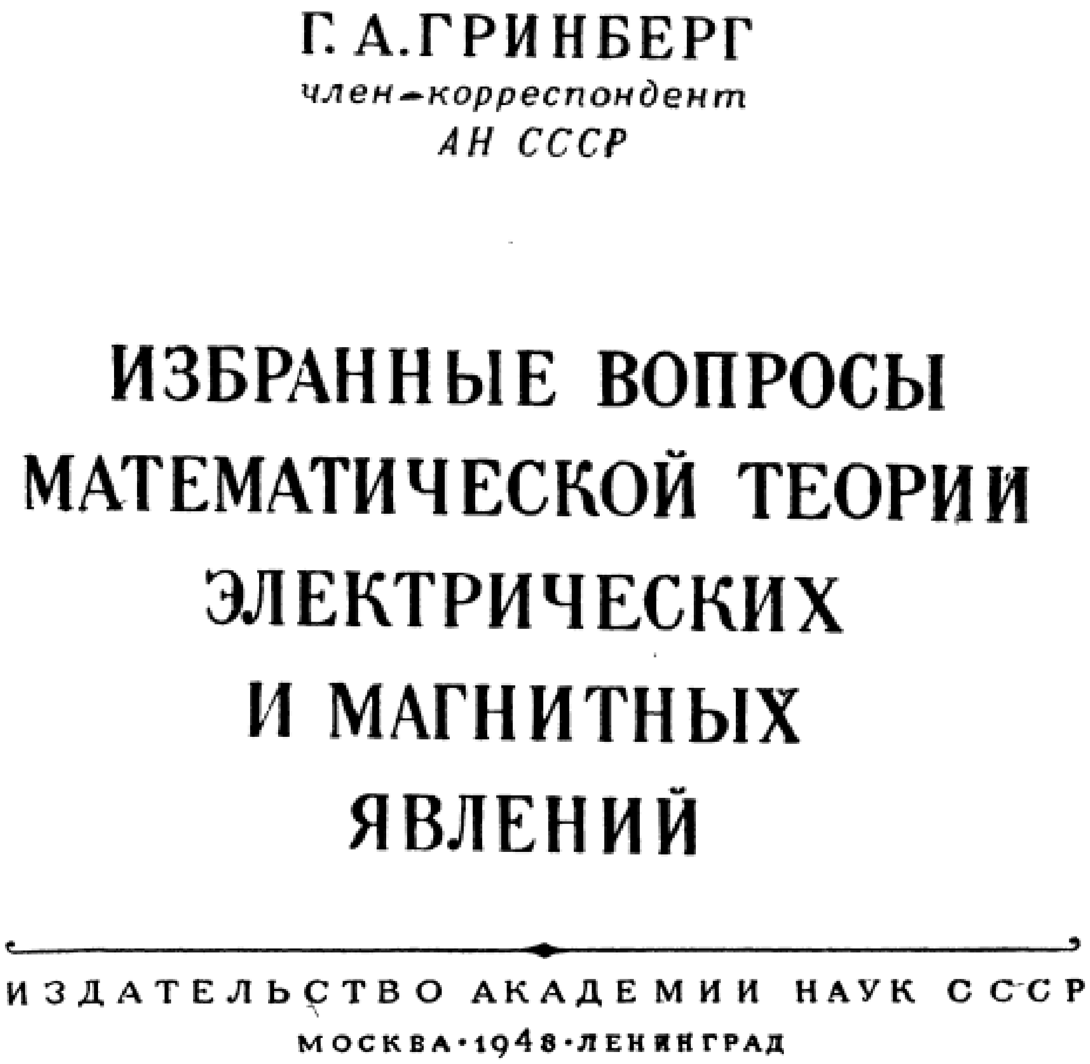
Beam smearing at the exit window



Induced current (during grid-anode drift)

Anode current calculation

- **Problem: signal is created during grid-anode drift. Additional smearing to a signal shaping**
- This method is suggested by **Alexander Dobrovolsky (PNPI)**
  - Добровольский Александр Владимирович
  - dobrovolsky_av@pnpi.nrcki.ru
- Based on Grinberg's textbook
- Simulation tool uses CERN.ROOT framework
  - https://root.cern.ch/



Г. А. ГРИНБЕРГ

член-корреспондент АН СССР

ИЗБРАННЫЕ ВОПРОСЫ МАТЕМАТИЧЕСКОЙ ТЕОРИИ ЭЛЕКТРИЧЕСКИХ И МАГНИТНЫХ ЯВЛЕНИЙ

ИЗДАТЕЛЬСТВО АКАДЕМИИ НАУК СССР

МОСКВА · 1948 · ЛЕНИНГРАД

Electronic signal tool: https://github.com/aleksha/electronic-signal

Charge between two infinite planes

$$\varphi = \frac{4e}{c} \sum_{n=1}^{\infty} K_0\left(\frac{n\pi r}{c}\right) \sin\frac{n\pi\zeta}{c} \sin\frac{n\pi z}{c}.$$

Эта формула дает разложение потенциала точечного заряда, находящегося между двумя проводящими параллельными бесконечными пластинами, в ряд по функциям Макдональда, причем ряд этот сходится весьма быстро для всех тех точек, расстояние r которых от проходящей через заряд оси симметрии поля будет не мало по сравнению с расстоянием c между пластинами.[1]

[1] Это ясно видно из асимптотического выражения для $K_0(t)$ при больших t, которое имеет вид [см. Д$_2$ (61) или Кузьмин, Б. Ф., стр. 77, (31)]:

$$K_0(t) \approx \sqrt{\frac{\pi}{2t}}\, e^{-t},$$

причем погрешность этой формулы уже при значениях t порядка нескольких единиц не превышает немногих процентов и быстро убывает с возрастанием t.

From potential one can go to the induced charge using Gauss theorem

$$\sigma[r\_] := -\frac{q}{L^2} \sum_{n=1}^{k} \left(\text{BesselK}\left[0, \frac{n\,\pi\,r}{L}\right] n\,\text{Sin}\left[\frac{n\,\pi\,h}{L}\right]\right)$$

L – distance between planes
r – radial distance from a charge
h – distance between plane and charge
q – electron charge (q=-1)

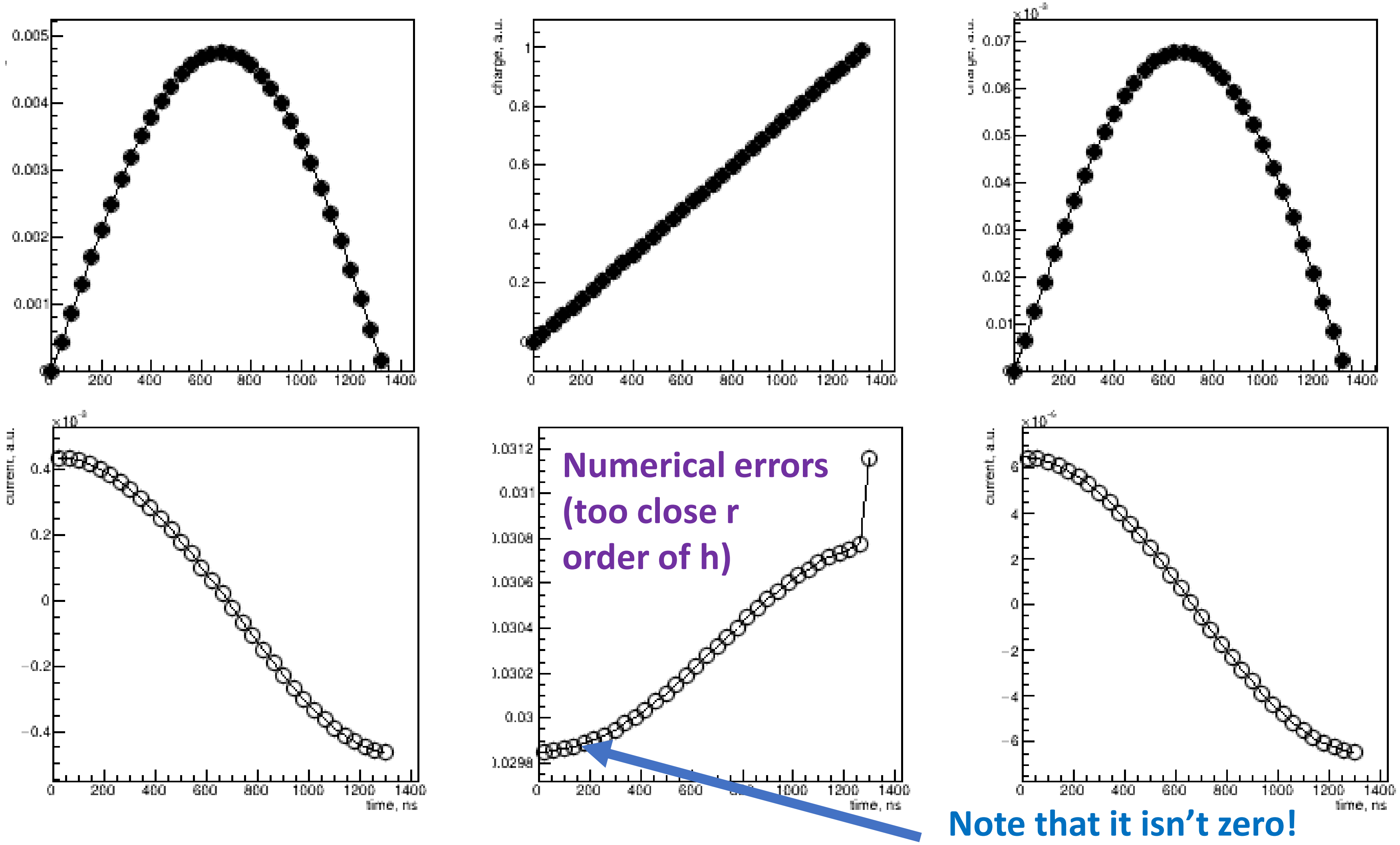
pp.113

The method in a nutshell

- Create a map of induced charge on rings with ***fixed width*** for an electron which is moving perpendicular to anode at ***r=0***.
- Calculate ***induced charge*** and ***induced current*** (as a derivative of the induced charge) with defined anode structure for an electron in point (***x***,***y***) using an overlap of the map and anodes.
- Find which of anode is fired, using the largest integral of current.
- Rescale currents for each of anodes with a common factor, which is evaluated to set the current integral for the fired anode to unity.

Induced charge and current for *x=12mm, y=18mm*

Central pad (r=10 mm) | 1st ring (width 40 mm) | 2nd ring (width 40 mm)



Note that it isn’t zero!

- Example of a tool result
- Agreement with the expected behavior
- Need to speed it up
- As well as integration into a software chain

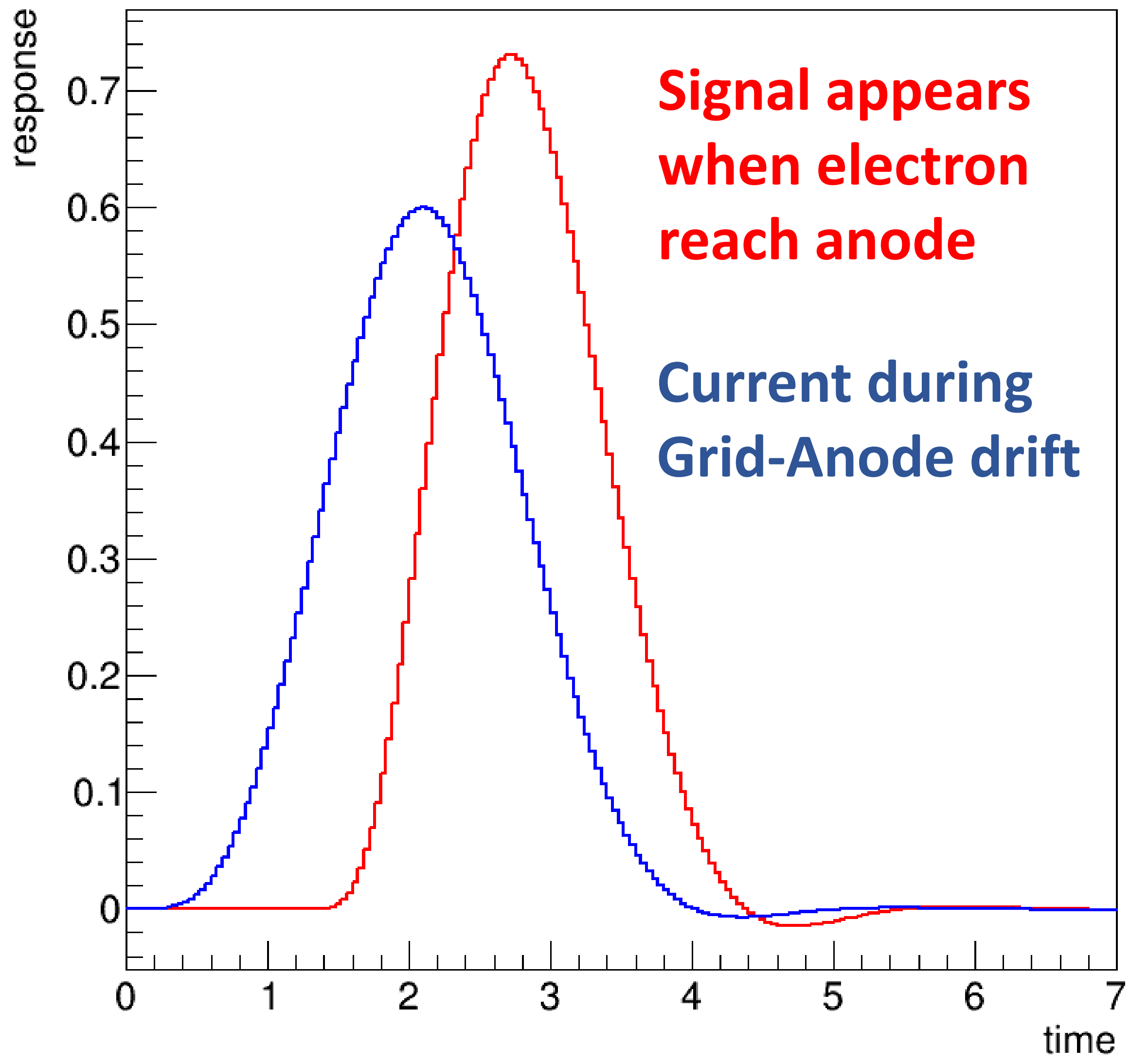
Modification of the response functions

- Many thanks to Alexander Dobrovolsky, who pointed me on the problem!

  - Current is assumed to be constant, while electron drifting between Grid and Anode

  - Zero time – time, when electron is on the grid

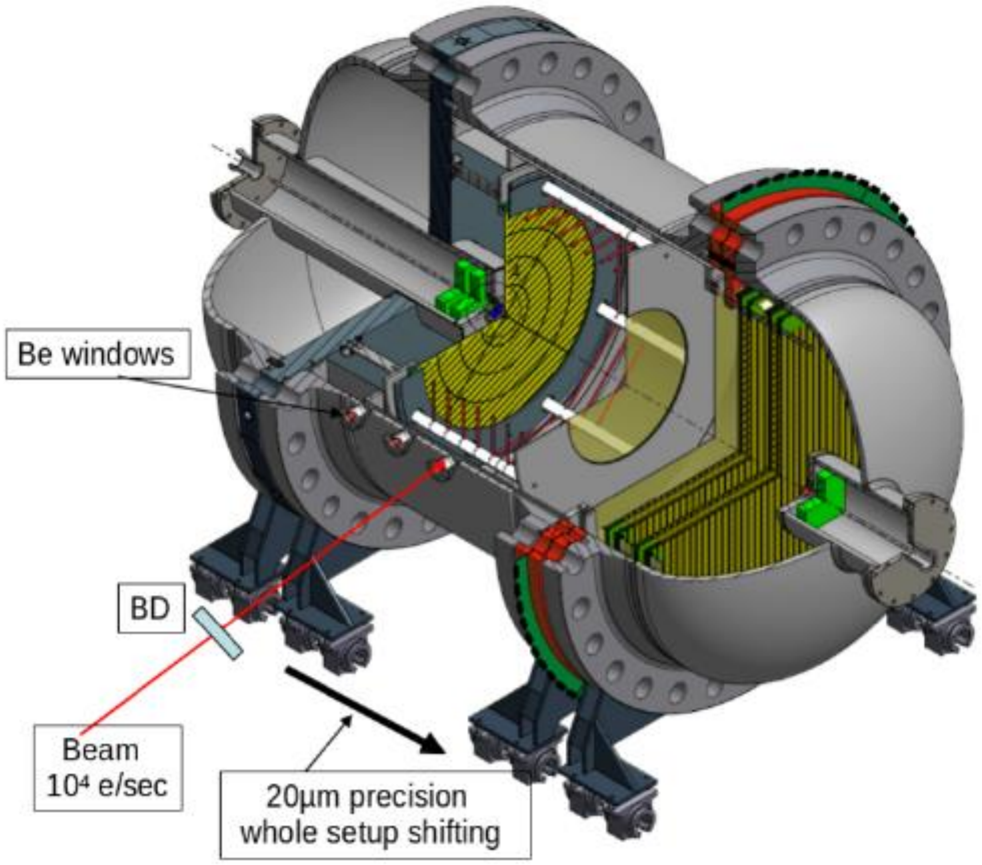
  - $L_{GridAnode}$ = 10 mm; W_2 = 7,5 mm/µs



Drift velocity measurements

Calibration of drift velocities

Calibration setup for main experiment



Idea for drift time measurement: rotate TPC and make a calibration using electron beam, which pass additional ~~beryllium~~ titanium window

Probem: single e^- is invisible in TPC

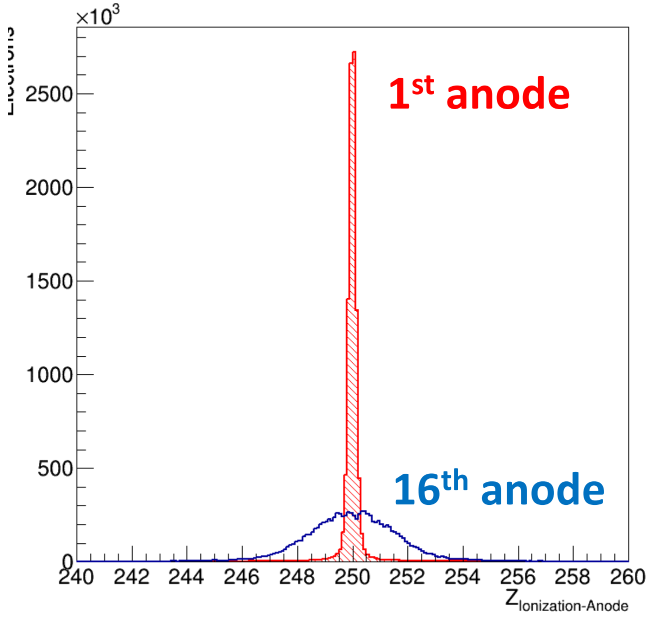
Solution: make integral measurements

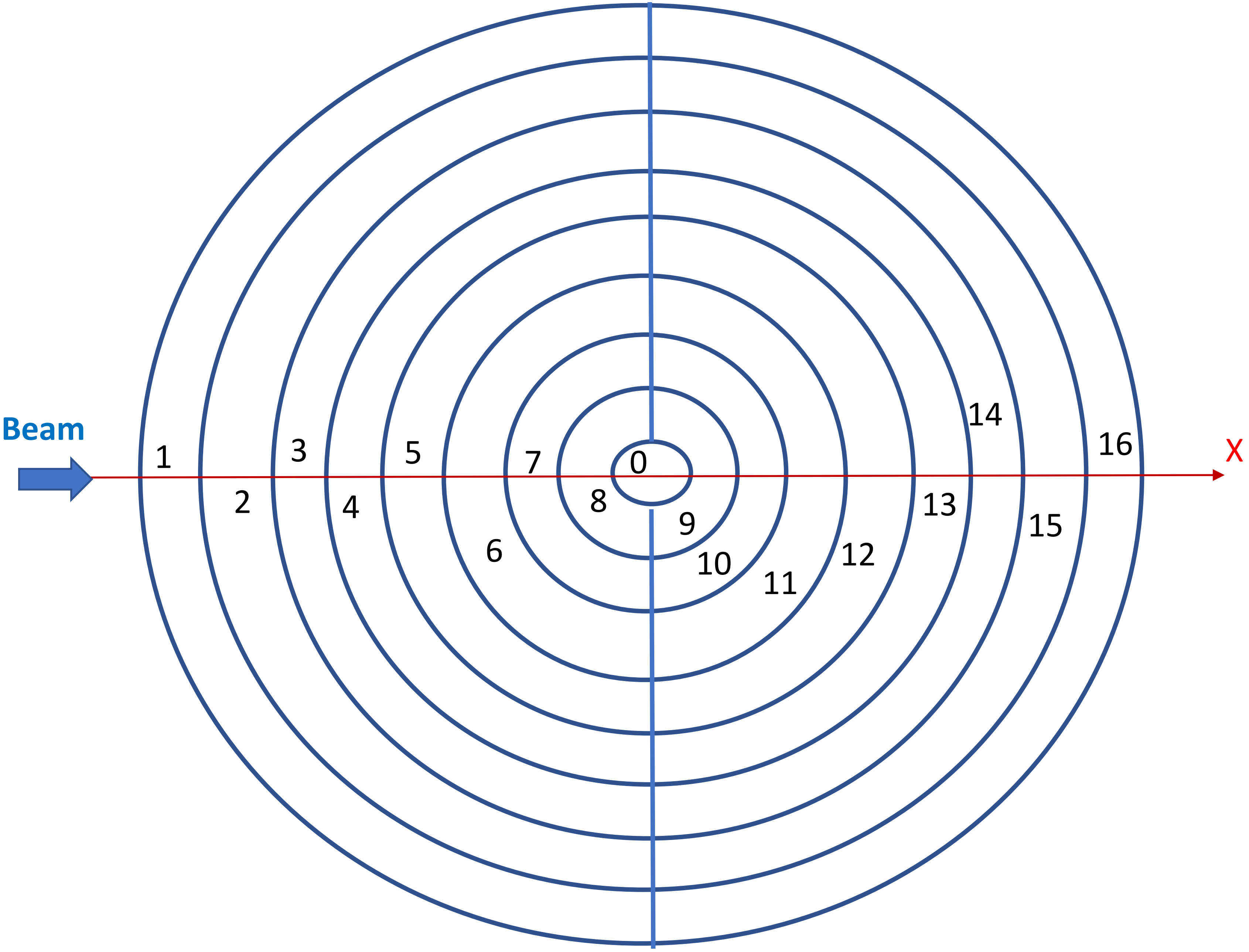
Triggering from incoming beam electron. Time between beam and TPC response is known (with a precision discussed today).

MAMI has excellent beam. The ionization-anode distance is known with 0,1 mm precision.

All pads

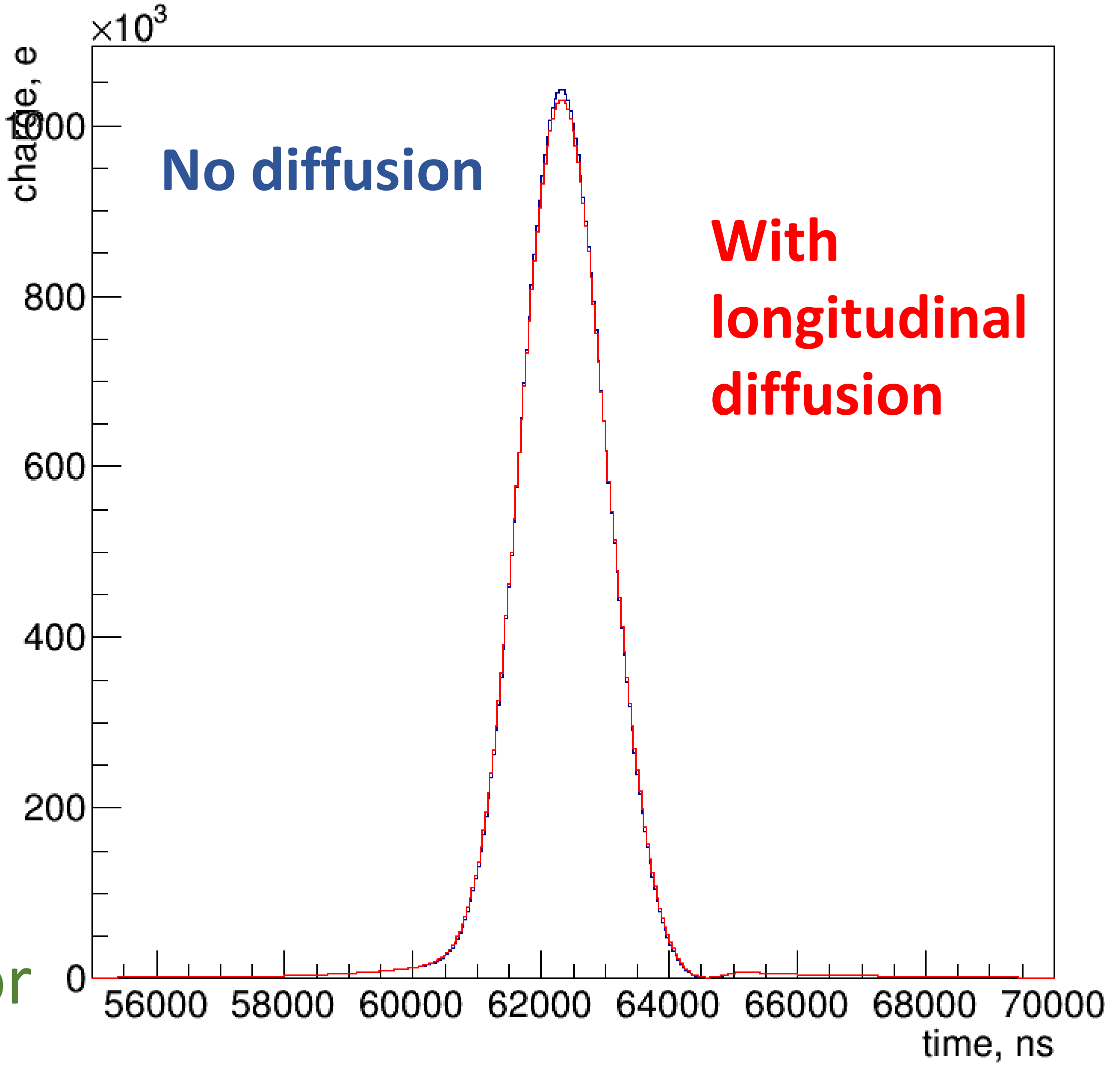
- Central pad is a circle with 1 cm radius
- Others are half-rings with 4 cm width
- Numbering as on sketch

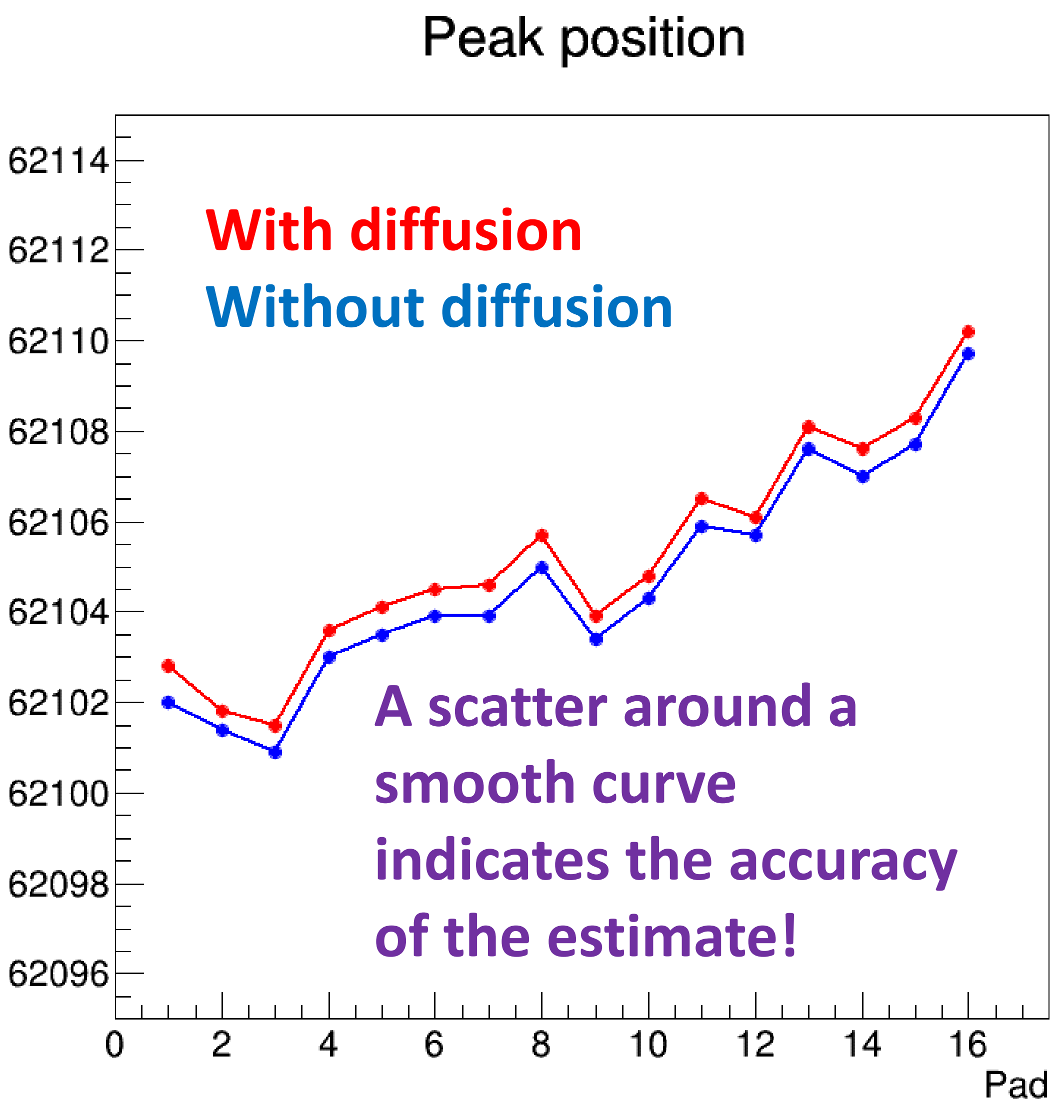


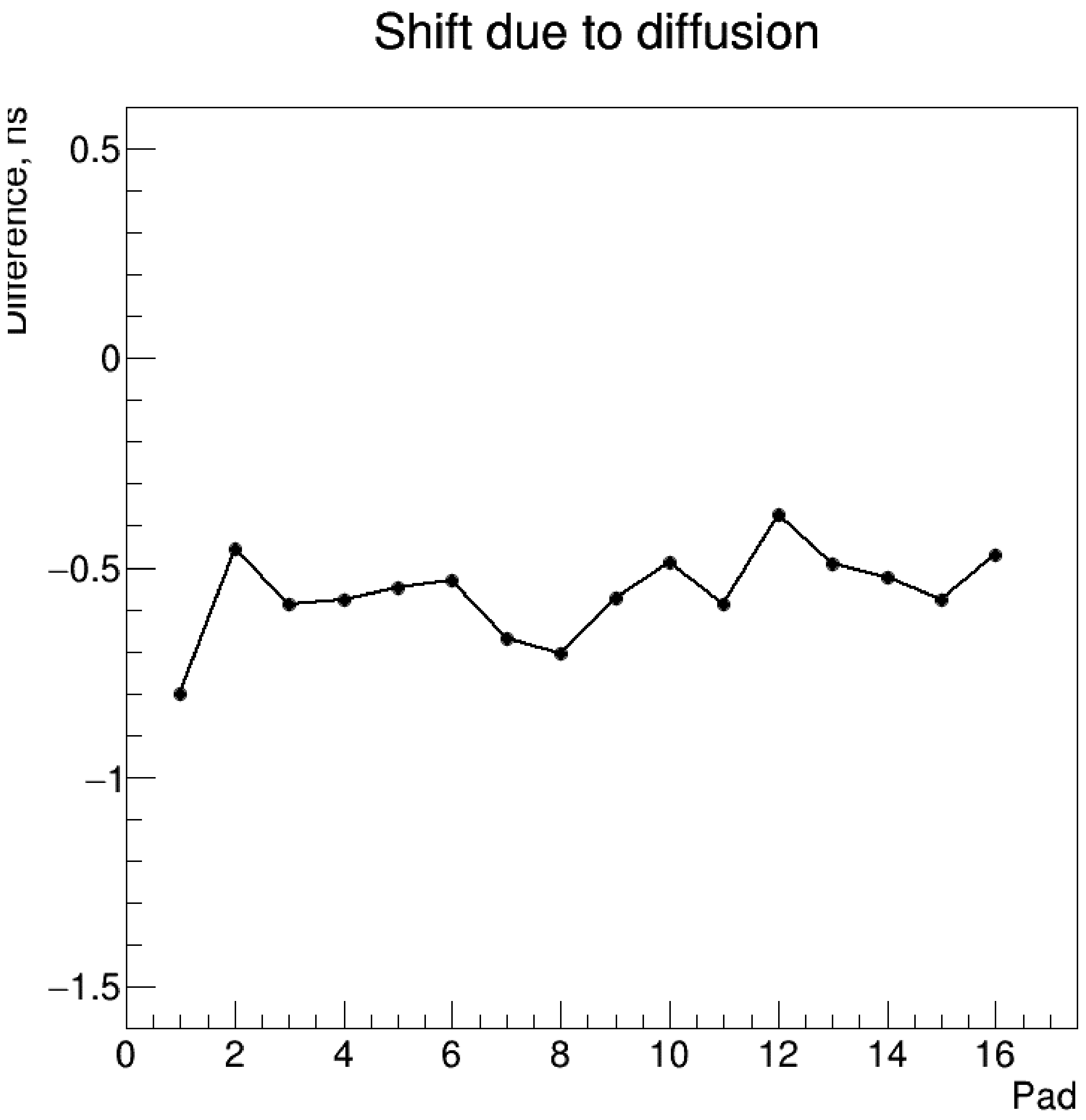


Longitudinal diffusion of electrons

- **$\sigma_Z = 0{,}008 \times \sqrt{L_{TrackGrid}}$**
- $[\sigma_Z] = [L_{TrackGrid}]$ = cm
- Parametrization by German Korolev (private communication *via* Alexey Vorobyev)
- Smear Z-position for each ionization electron by a Gaussian function with **σ_Z**.
- $L_{\mathbf{TrackGrid}}$ = 25 cm
- 10000 of beam electrons (a part of spectrum around the peak is presented)
- Peak maximum as a time-point estimator
- Noise OFF

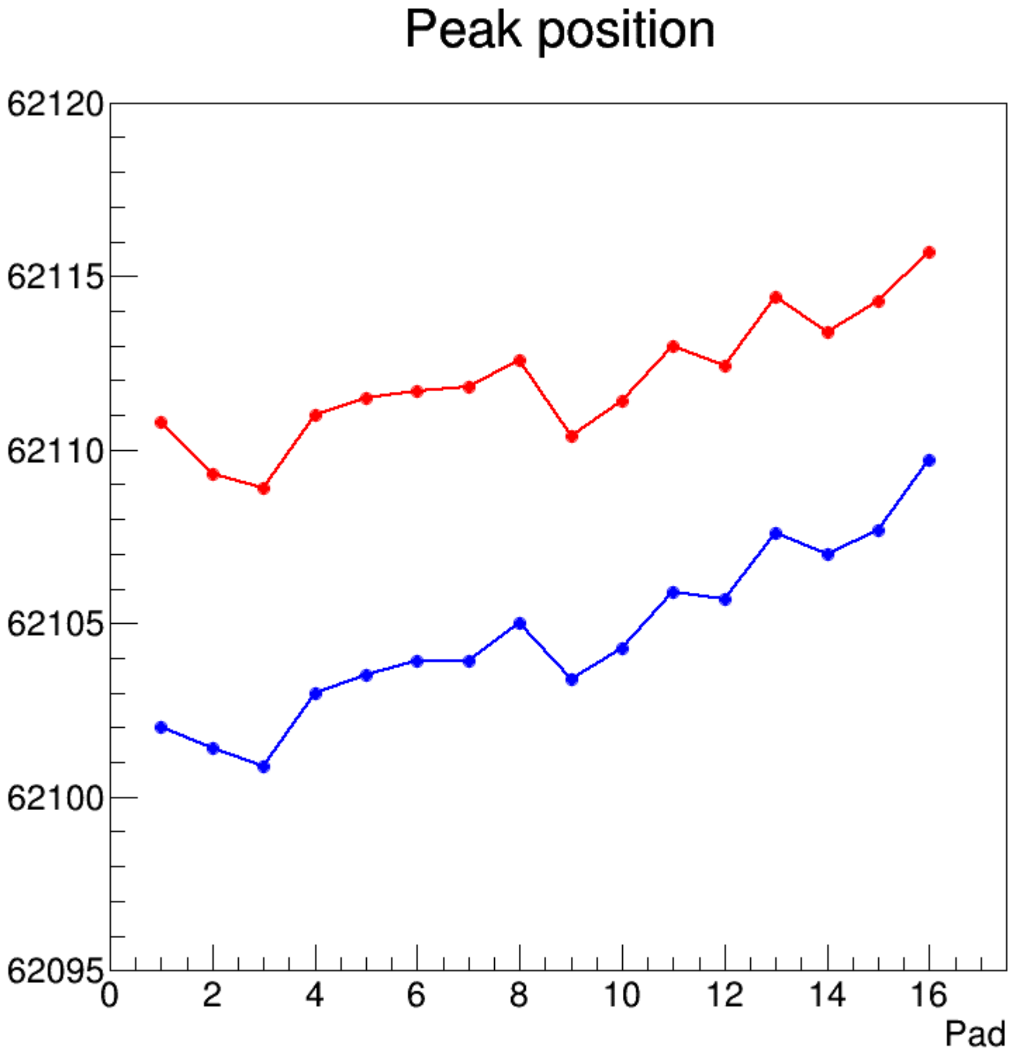


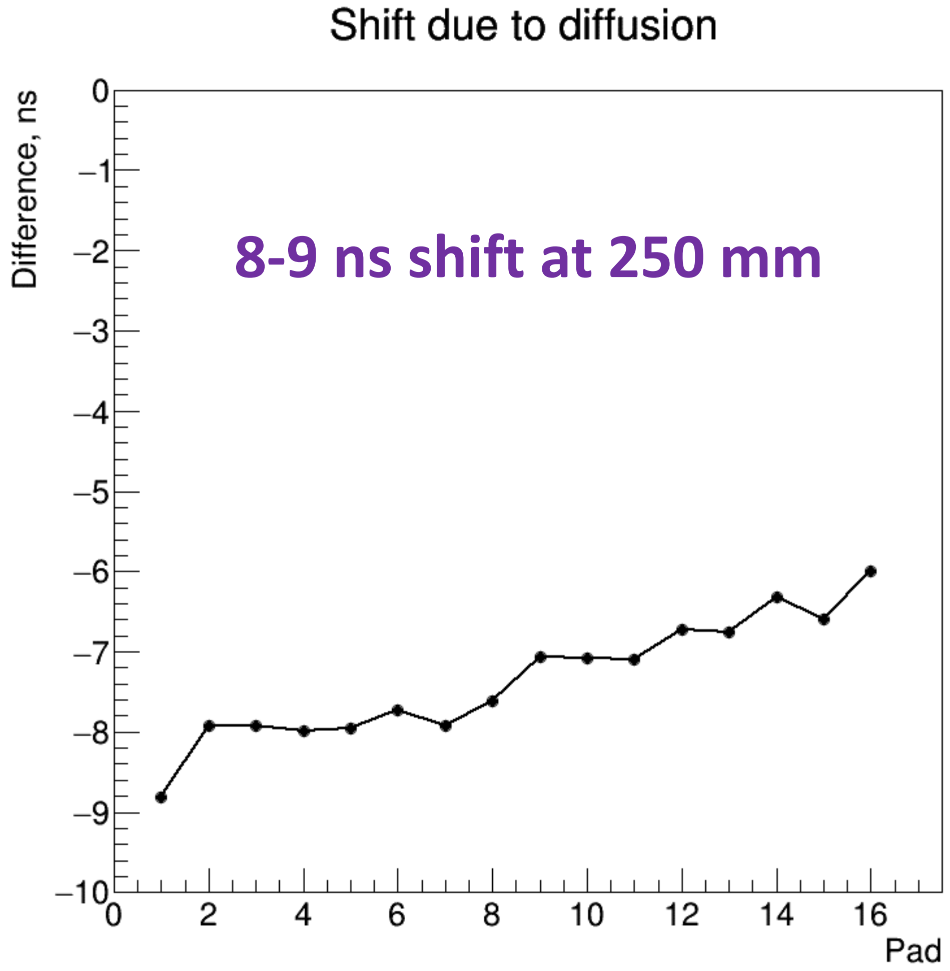




A bias for the maximum position estimator is on nanosecond-scale. Good enough!

Increase diffusion parameter by factor 4





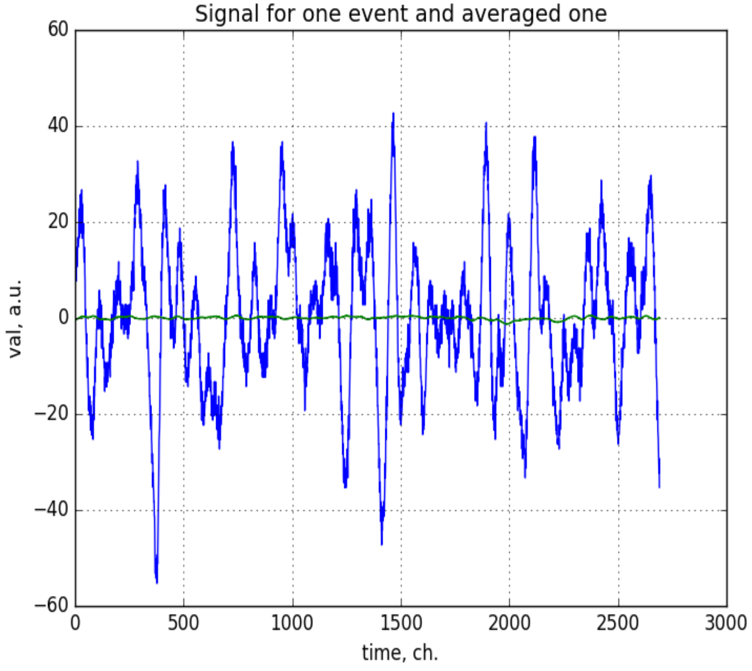
Electronic noise simulation + influence on a drift velocity measurement

See more details https://github.com/aleksha/G4-Models/tree/master/Data/Noise

Further studies of noise + simulation

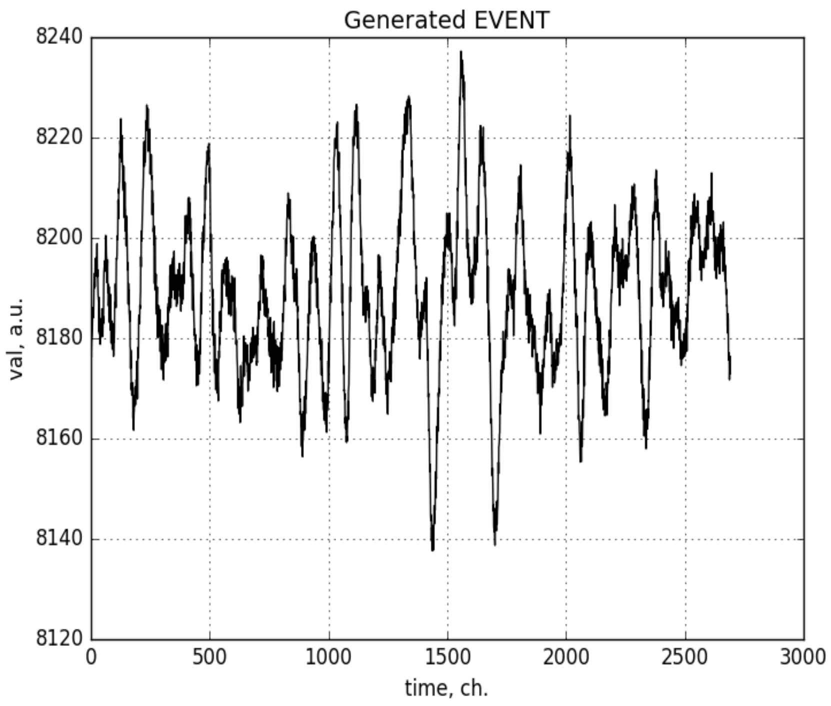
Now it's fast! (factor 1000 wrt 1st version)
Thanks to Arsen Nuramatov

Noise in data (baseline corrected)



1. Obtain distribution for real and imaginary part of frequency spectra using Fourier transformation;
2. Fit these distributions using two gaussian hypotheses;
3. Generate random spectrum out of these distributions;
4. Use inverse Fourier transformation to obtain spectrum of generated events.

Generated noise

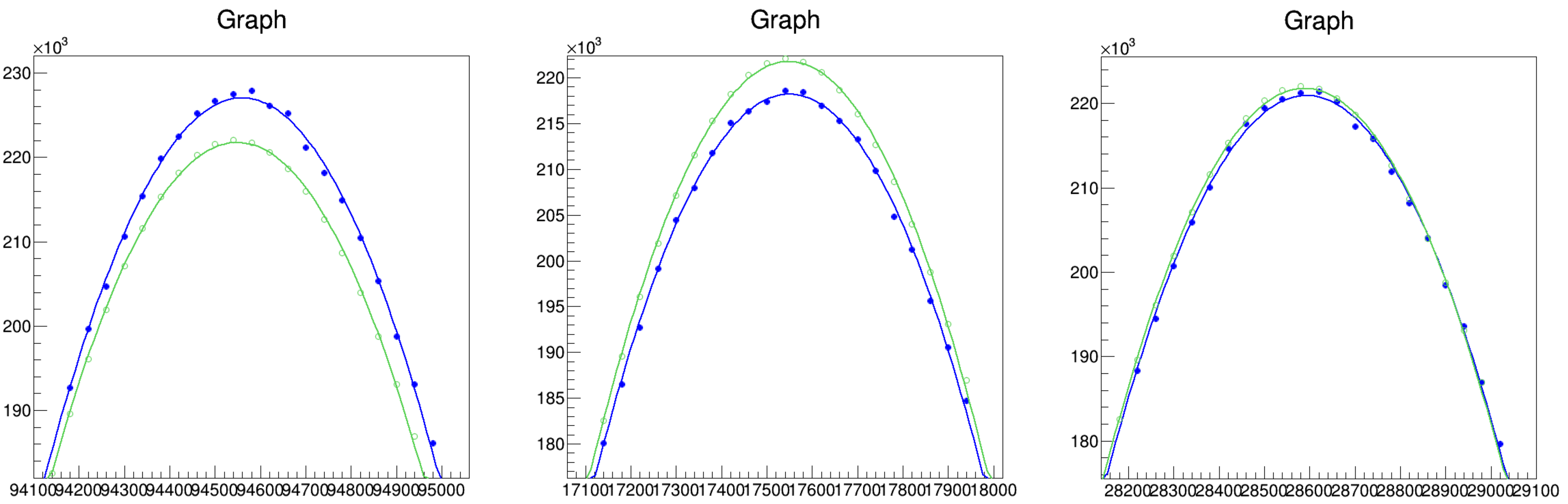


Electronic noise tool https://github.com/aleksha/electronic-noise

Maximum (peak position) shift due to noise

- Peak is placed to the random location of cumulative noise spectrum
- Shift of maximum for signal + noise (blue) wrt. pure signal (green)
- Some fit examples

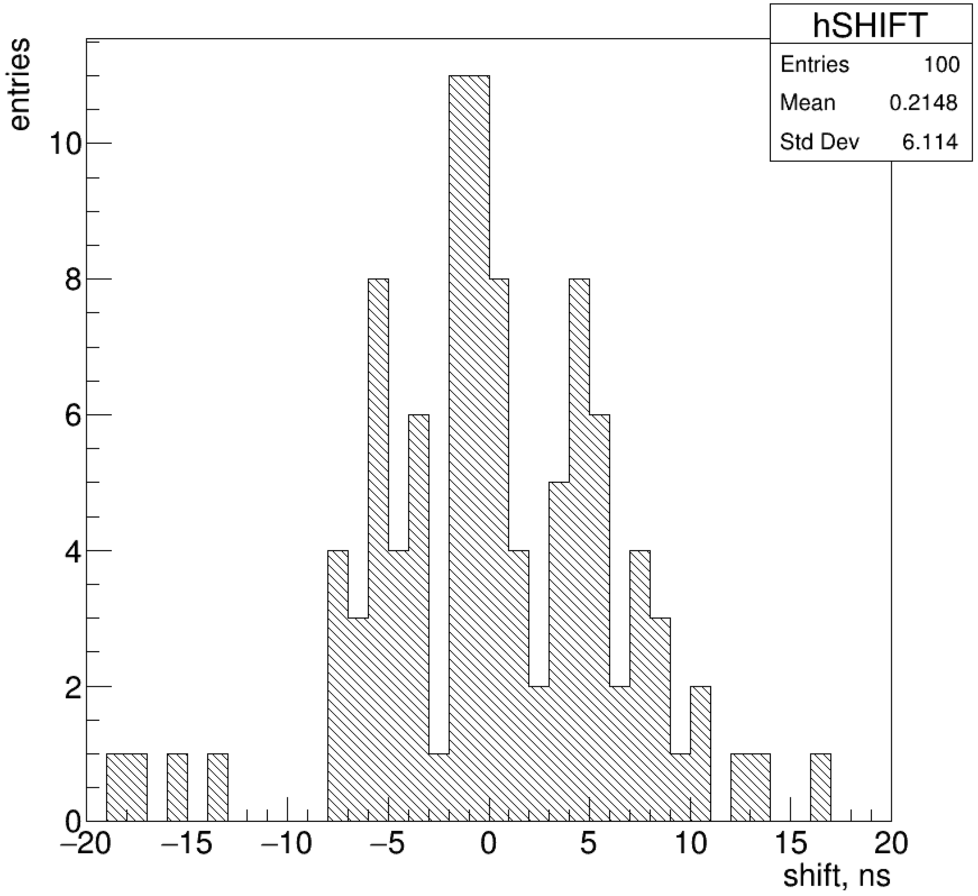
Noise ON



Distribution for shifts for 100k events

- 100 random places for signal peak at the noise spectrum. Signal shape at the peak region and cumulative noise spectra are same, but position is different!

- RMS for maximum with peak position fitting procedure 6,1 ns



Electric field uniformity

Electric field uniformity + drift of electrons

- Electric field calculations are done by **Kuzma Ivshin** using COMSOL package.

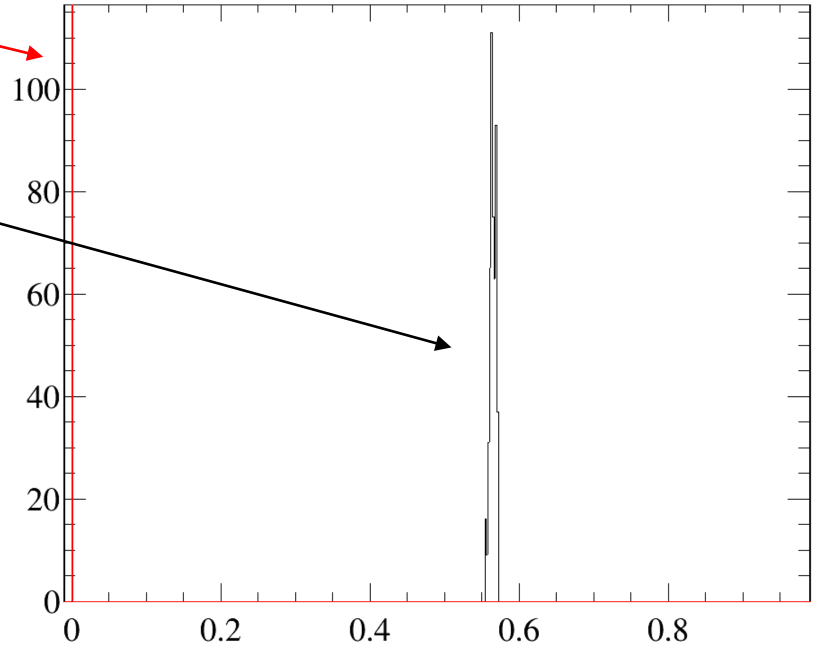
```
wget http://adzyuba.web.cern.ch/adzyuba/d/pres-electric-field.txt
```

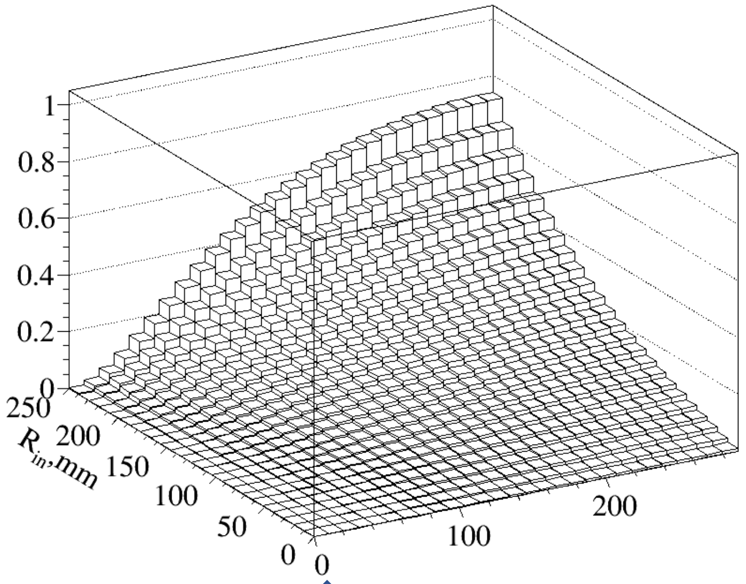
- Electron is drifted in the electric field. Its track is a series of the steps, defined by a step parameter. A typical step size (of 0.1 mm) is order of magnitude less than a spatial grid size for the electric field (5 mm).
- A direction for the step is chosen according to a unit vector parallel to an electric field direction.
- Electric field components in a beginning of a step are inferred by an interpolation procedure (tri-linear interpolation).

Tool to calculate shifts https://github.com/aleksha/pres-electric-field

Electric field uniformity + drift of electrons

- No radial shift if E_x and E_y are set to zero
- Some radial shift for the full field map
- The direction of this is to the center of TPC!
- There is strong R_{in} and Z_{in} dependence





Tool https://github.com/aleksha/pres-electric-field

Further development is needed (interpolation-based shift procedure)

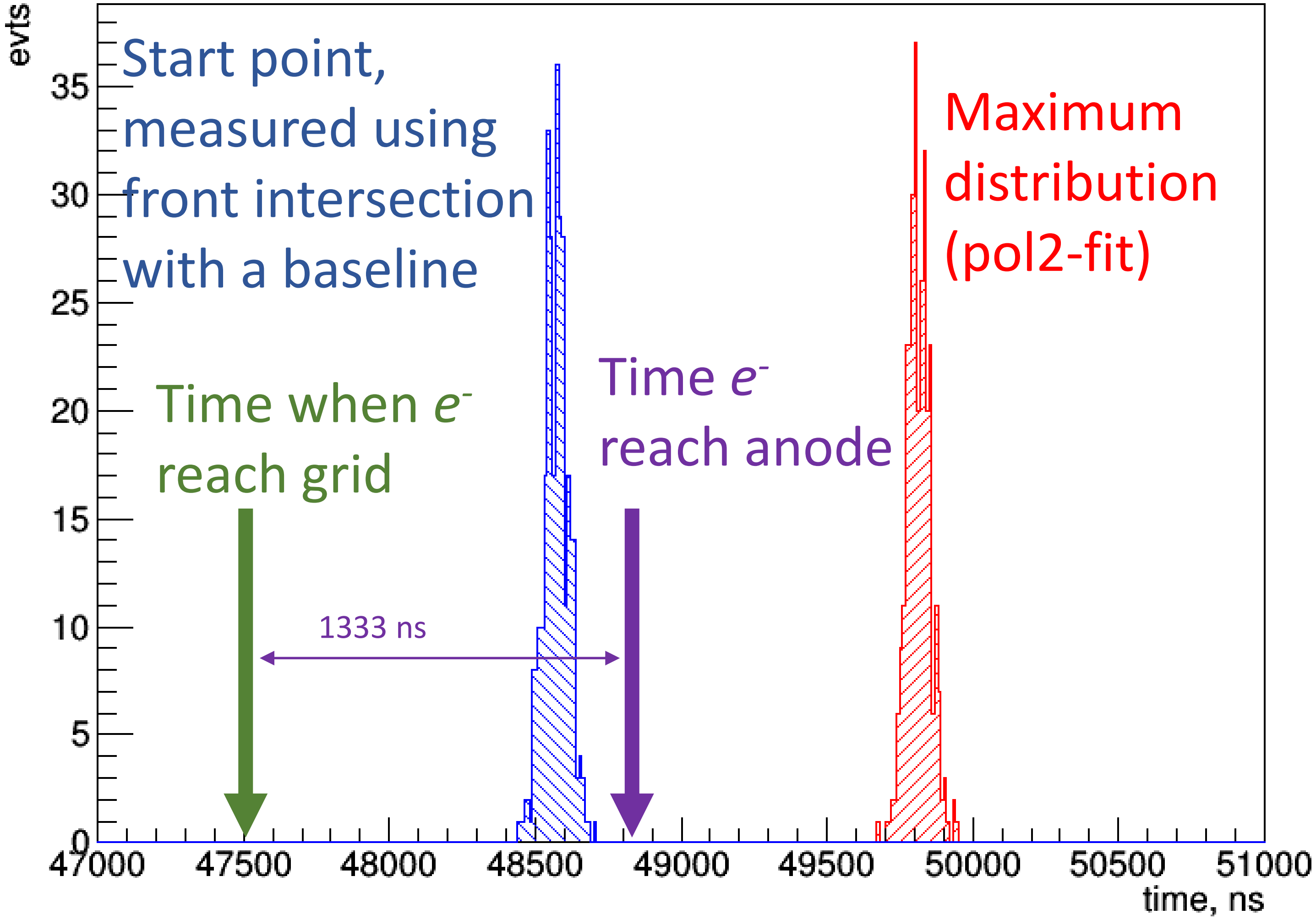
Issue with a Z-positioning

A problem of Z-positioning

- PRES experiment requires a Q^2 scale calibration, which will be done using a measurement of an angle of the scattered electron.
- Measurement will be done with a first layer of multiwire and ***Z*** coordinate of a scattering point measured by a TPC (***X*** and ***Y*** assumed to be zero due to the perfect MAMI beam).
- ***Z*** is measured on the **1st anode ring** by finding of a stable timestamp point from the FADC signal. Central pad has twice worser resolution due it's small size (relatively higher electronic noise) and due to the beam noise.
- Signal shapes depends on a scattering angle of the proton (***T*** fixed)

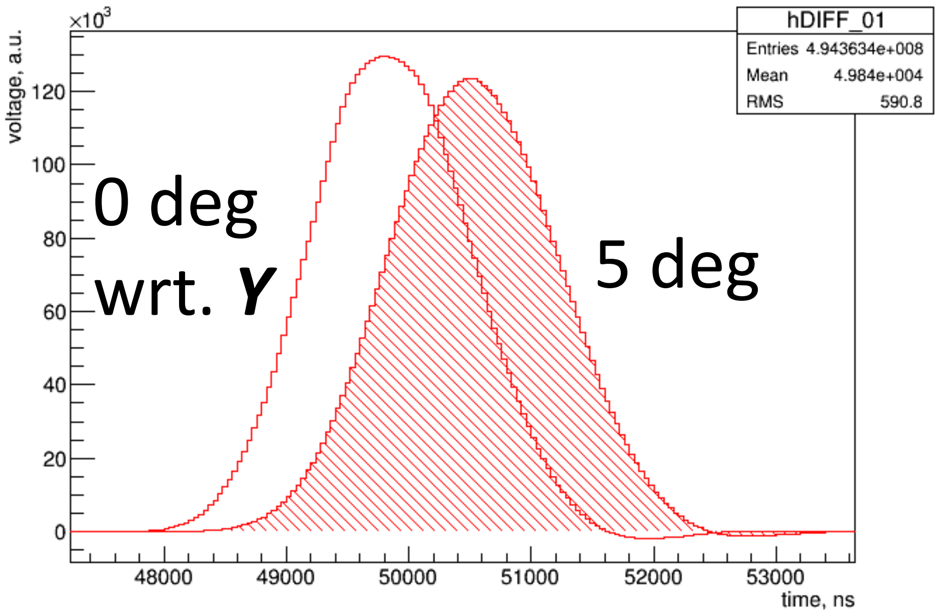
Time point measurement (~40 ns resolution)

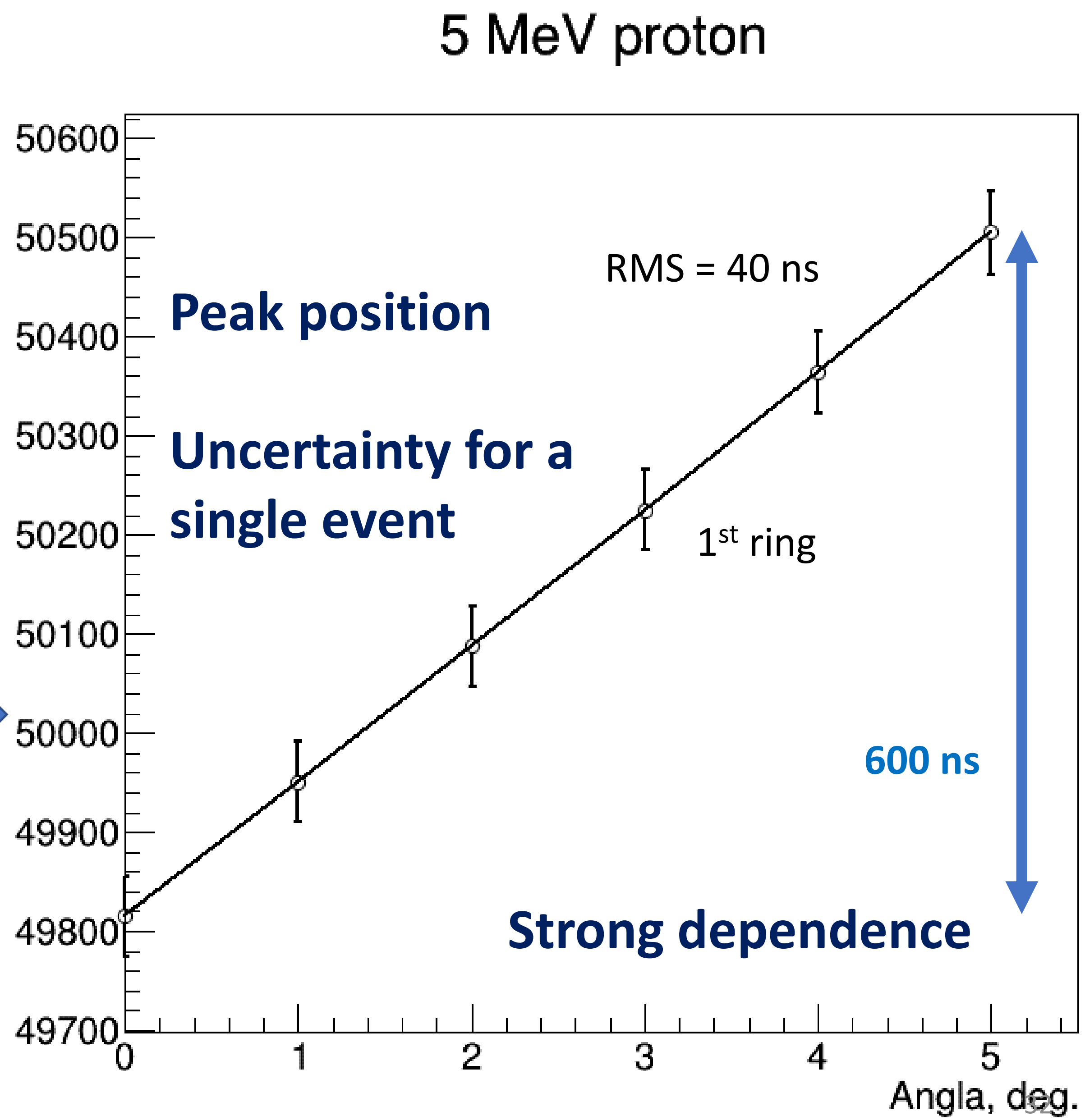
- T = 5 MeV
- Noise ON
- 1^{st} ring



The problem

- T = 5 MeV
- Angle wrt. Y-axis
- Noise OFF
- 1st ring
- Cumulative spectra

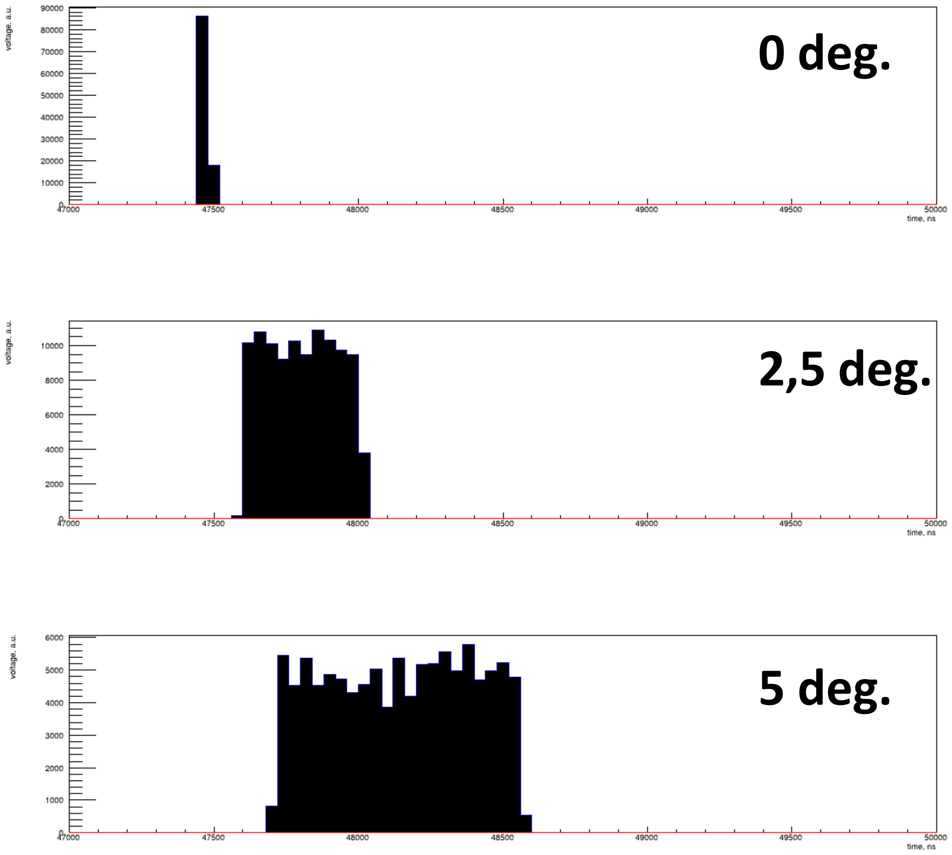




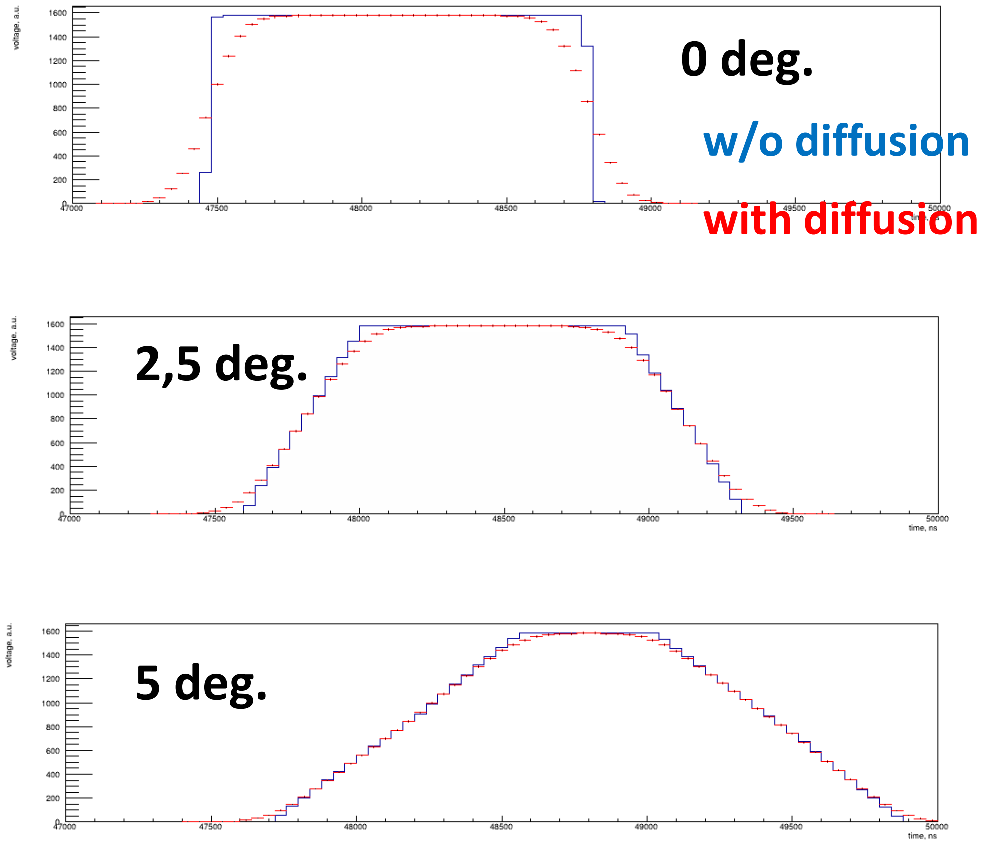
Pure electron signal (a cross check)

Idea by Alexander Inglessi

Electrons arrive at grid



Induced current



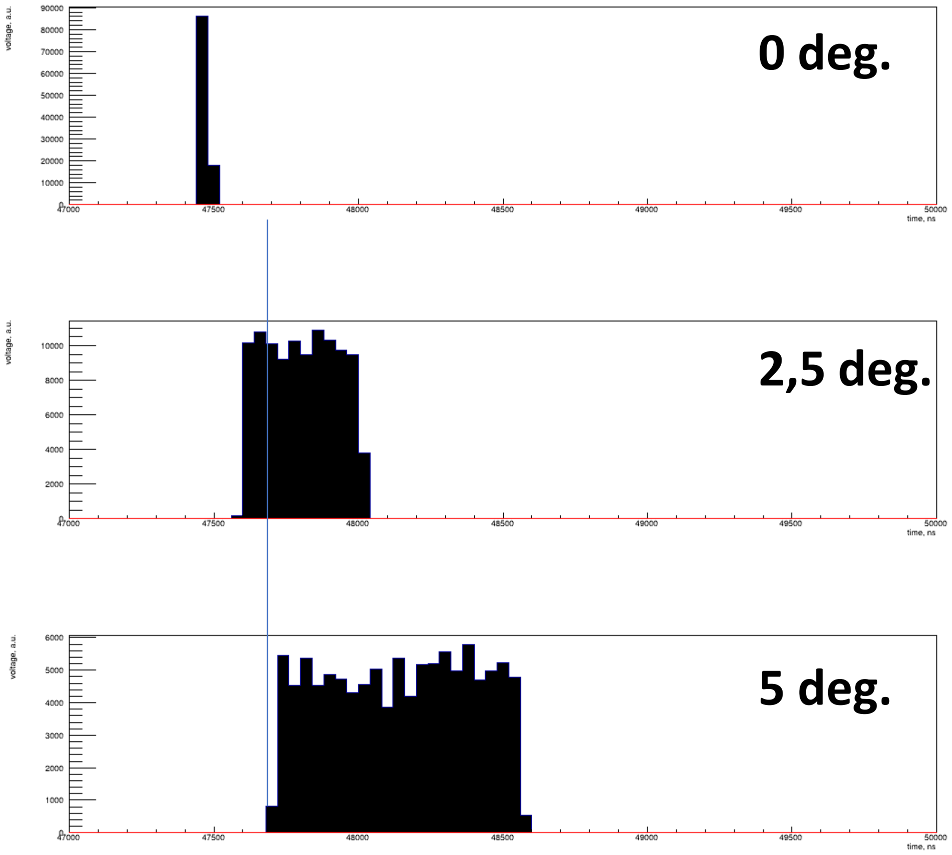
5 deg → Signal projection 0,087*40mm = 3,48 mm → Signal length 870 ns

Note, that y-scale are different, but integrals are the same!

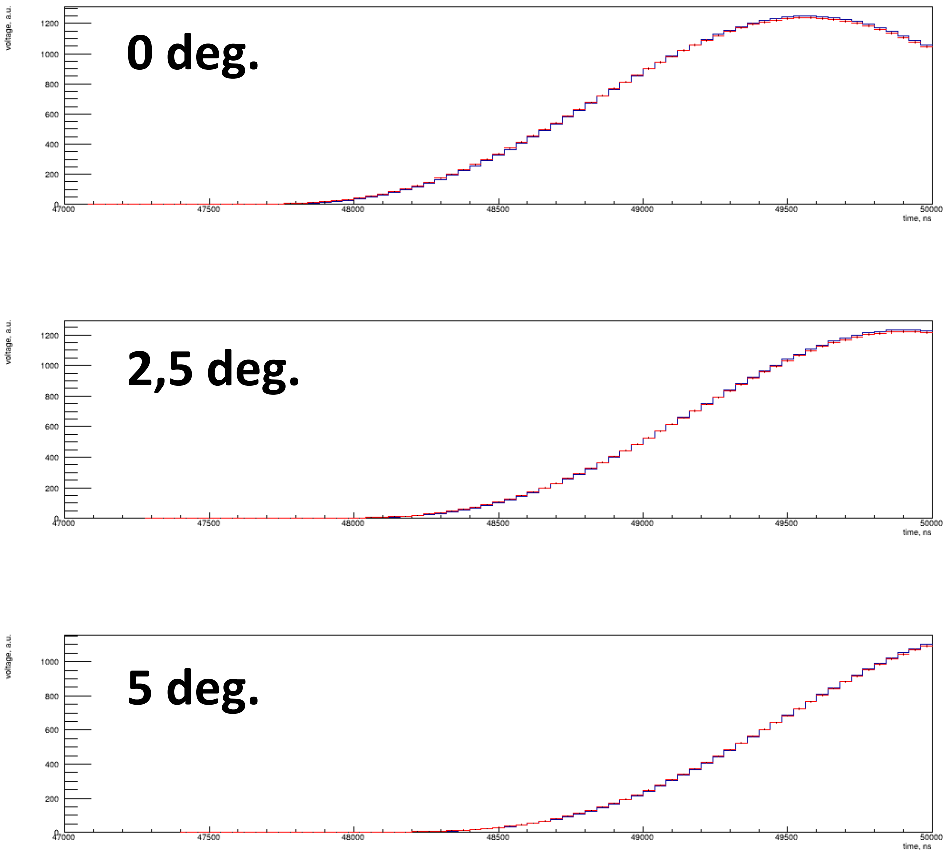
Pure electron signal (a cross check)

Idea by Alexander Inglessi

Electrons arrive at grid



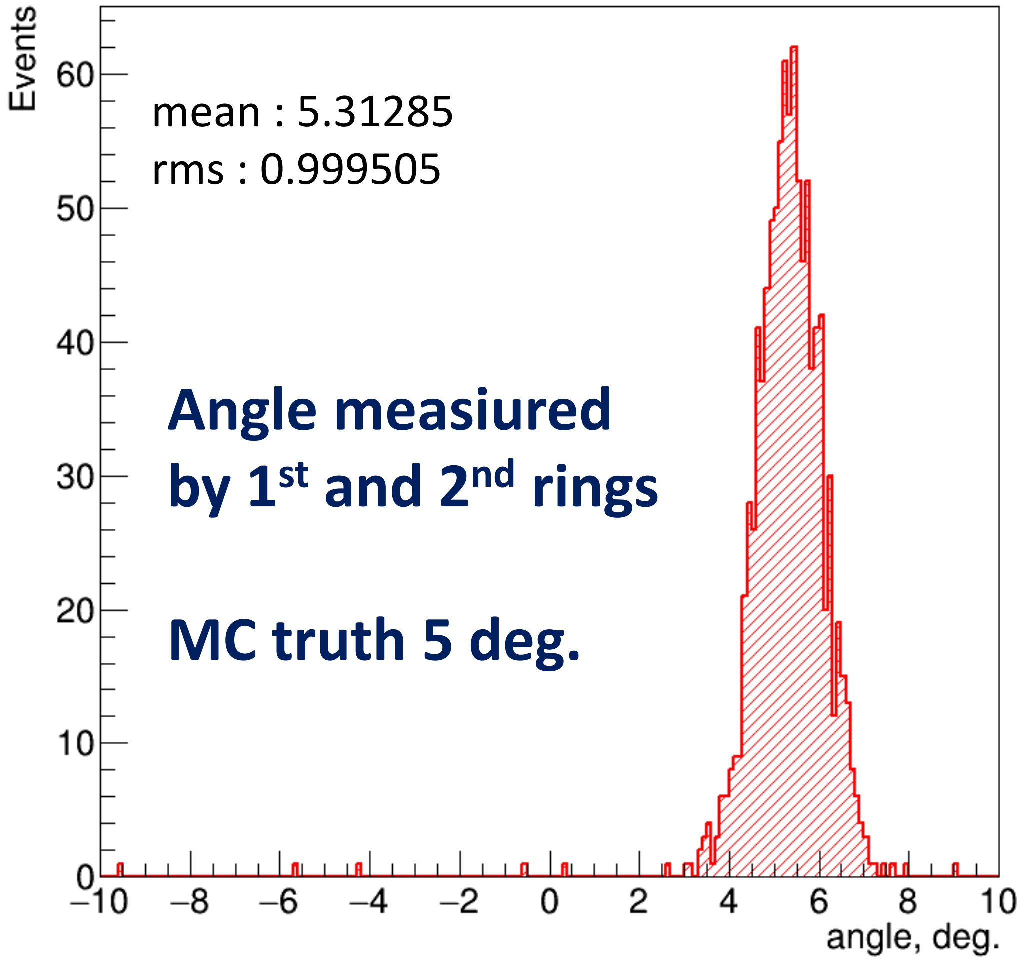
Drift + Electronic response function



5 deg → Signal projection 0,087*40mm = 3,48 mm → Signal length 870 ns

Correction by TPC information

- Recoil angle can be measured by TPC
- Correction on a measured angle
- 0,3-0,4 mm resolution of simple algorithm, when offset is estimated from the measured angle
- Multivariate analysis (MLP) can make 0,2 mm resolution accessible (next slides)



MVA regression as an estimator

- Uniform pdf
  - Z_{TRUE} = (190, 210) mm
  - $Theta_{TRUE}$ = (0, 6) deg
  - T_{TRUE} = (4,5, 5,5) MeV
- Standard ROOT::TMVA example
  - Multi Layer Perceptron (MLP)
  - Boosted decision tree (BDT)
  - Linear discriminant analysis (LD)
- Z or polar angle as target variable
- 800 events for training / 150 for test

To be compared with 0,3-0,4 mm resolution o simple algorithm, when offset is estimated from the measured angle

First MVA results (Z as a target)

```
=====================================================
MVA Method:         <Bias>   <Bias_T>    RMS    RMS_T
=====================================================
9 variables (start, peak, end) from central anode and first two rings
-----------------------------------------------------
MLP              :  -0.0246  -0.0299    0.166    0.140
LD               :  -0.0310  -0.0366    0.174    0.146
BDT              :  -0.0177  -0.0126    0.229    0.191

Indicated by "_T" are the corresponding "truncated" quantities
obtained when removing events deviating more than 2sigma from average.
```

To be compared with 0,3-0,4 mm resolution of simple algorithm, when offset is estimated from the measured angle

Optimization is required

First MVA results (angle as a target)

```
========================================================
MVA Method:          <Bias>   <Bias_T>    RMS     RMS_T
========================================================
9 variables (start, peak, end) from central anode and first two rings
--------------------------------------------------------
MLP             : -0.00304   0.0196     0.538    0.435
LD              :   0.0274   0.0215     0.539    0.451
```

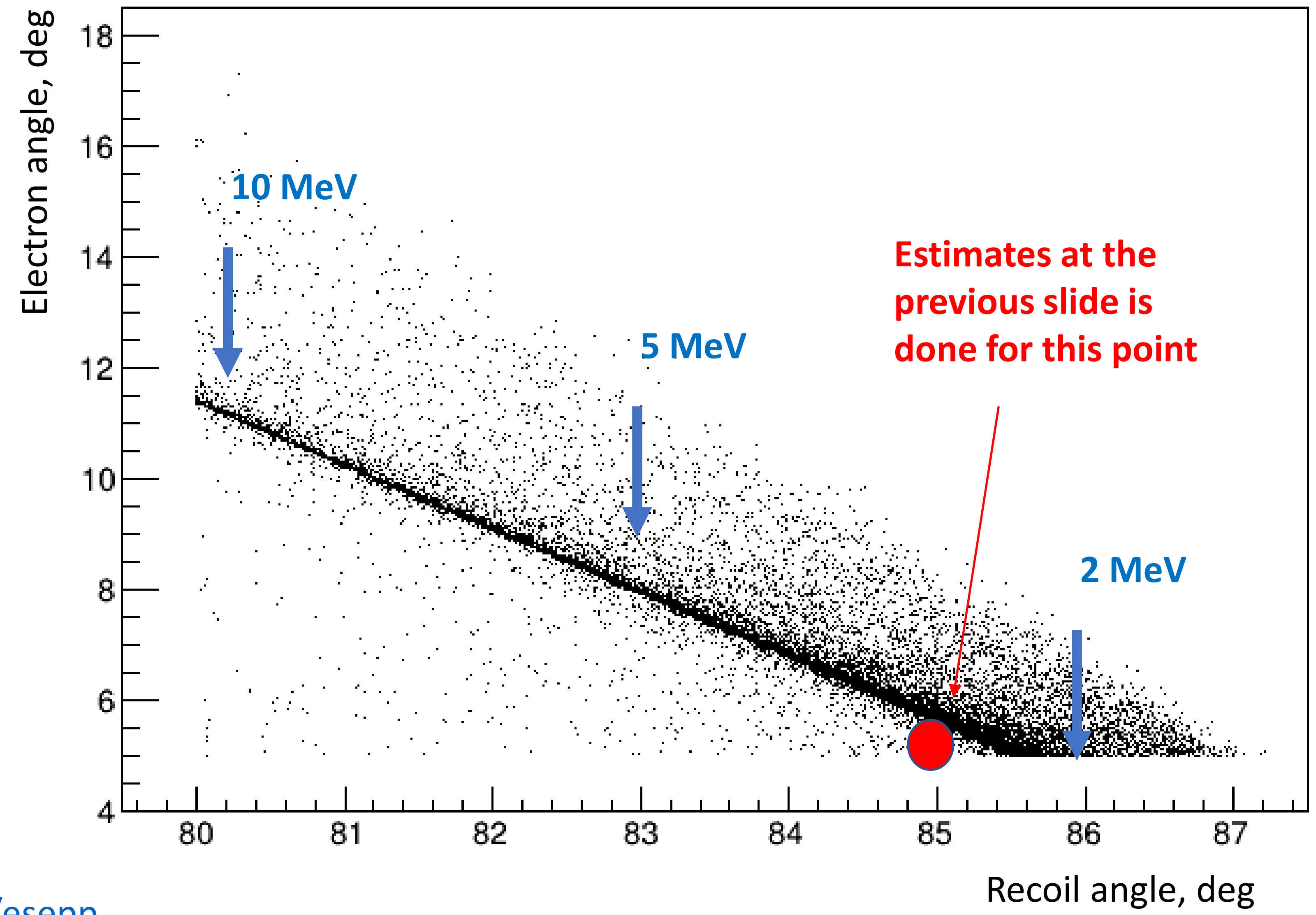
To be compared with ~1,0 deg resolution (see slide 4)

Optimization is required

<u>Conclusion:</u> we have to use full power of MVA in our analysis

Real life (well it's ESEPP)

ESEPP configuration:
- **Photon cut 0,5 MeV**
- **Point-like proton**
- **E=720 MeV**
- **Lepton cut 5 deg.**
- **Maximon & Tjon**
- **Full other rad.calc**



https://github.com/gramolin/esepp

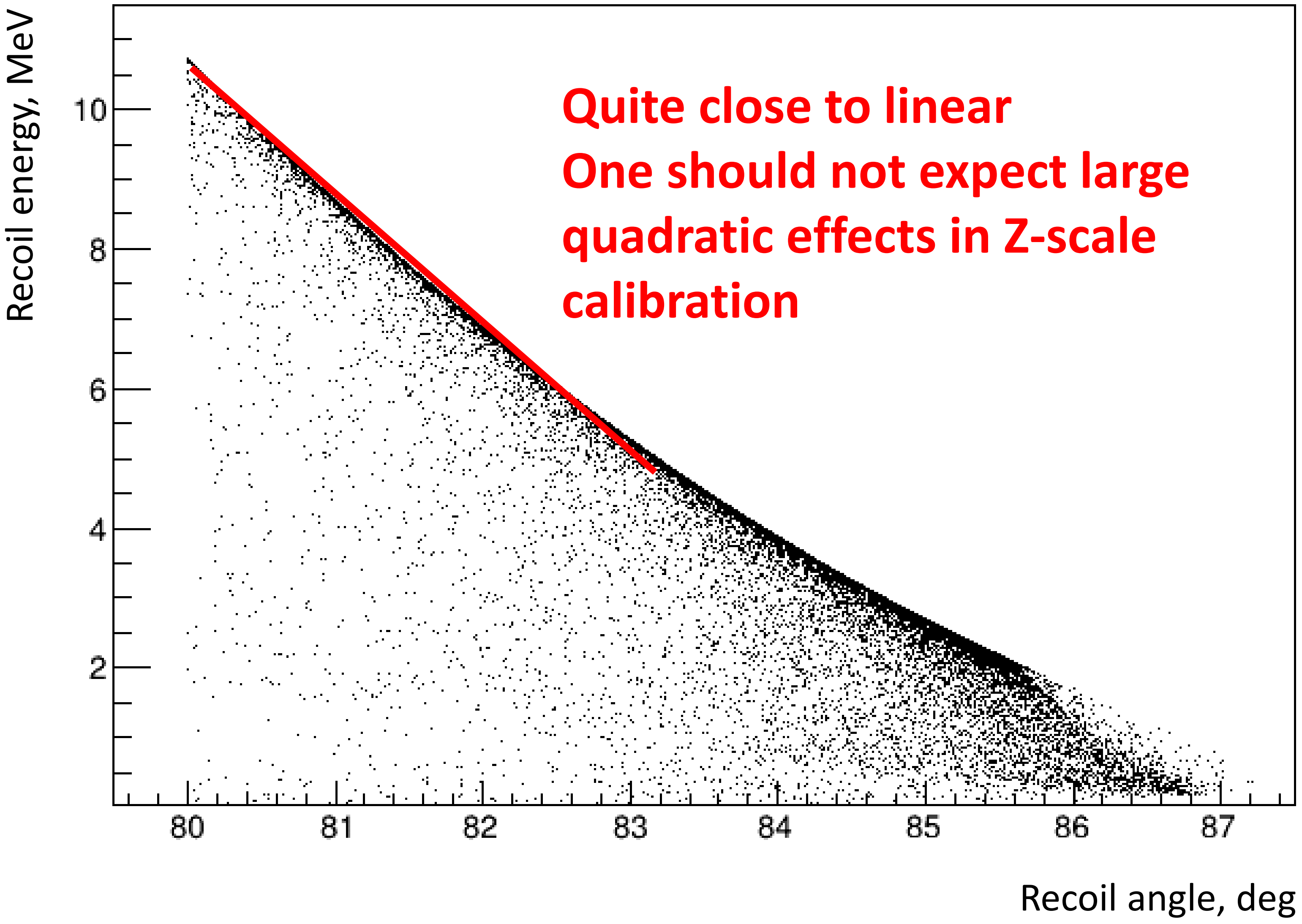
ESEPP

Three problems in the middle:

1. Radiative processes (aka corrections) can create recoils with higher energy which stop between anodes

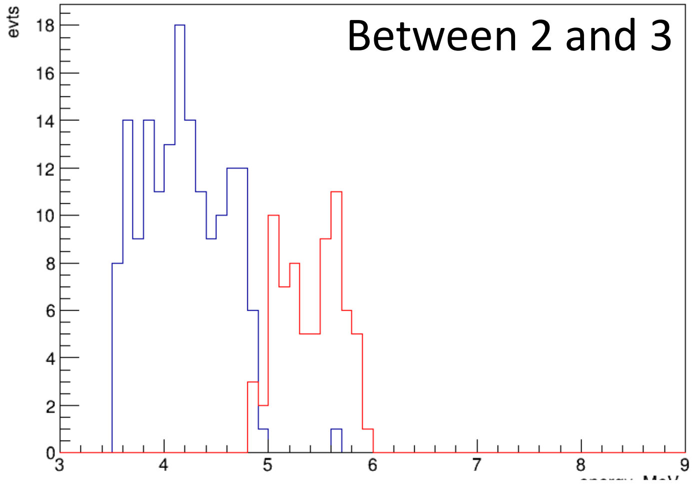
2. Same but via in-elastic processes (with pions)

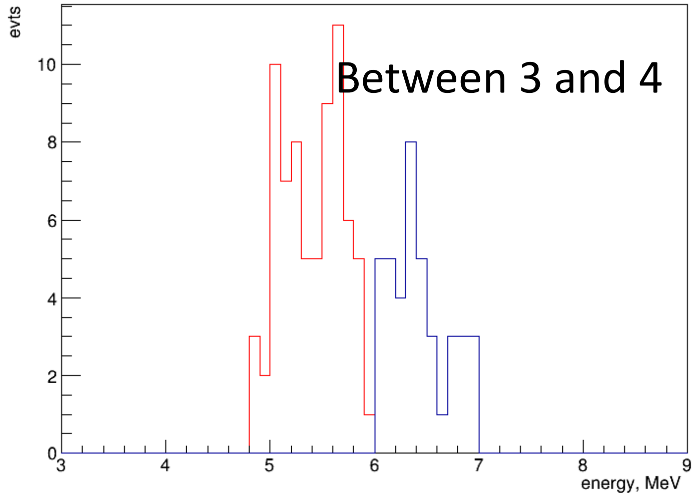
3. A certain signal detection limit can produce bias

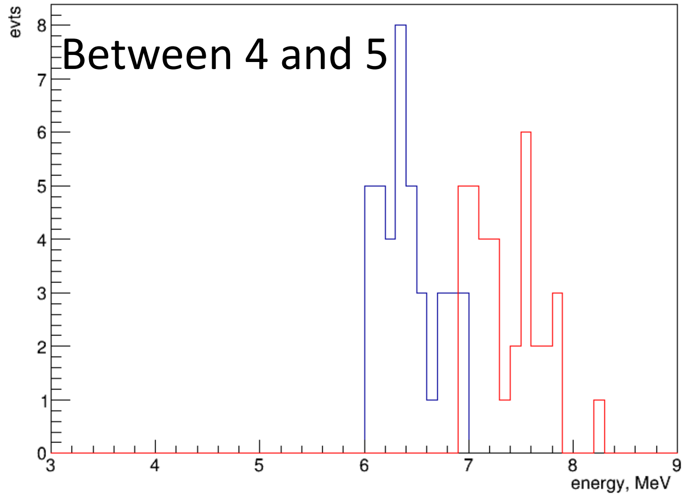


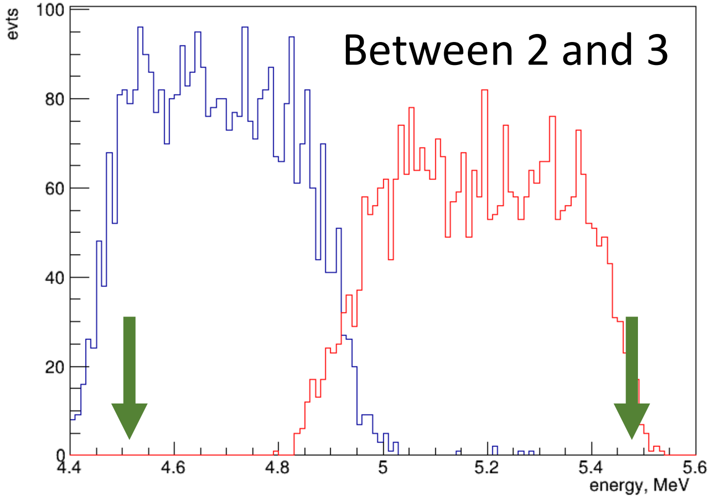
Range measurement

Energy by stop between anodes

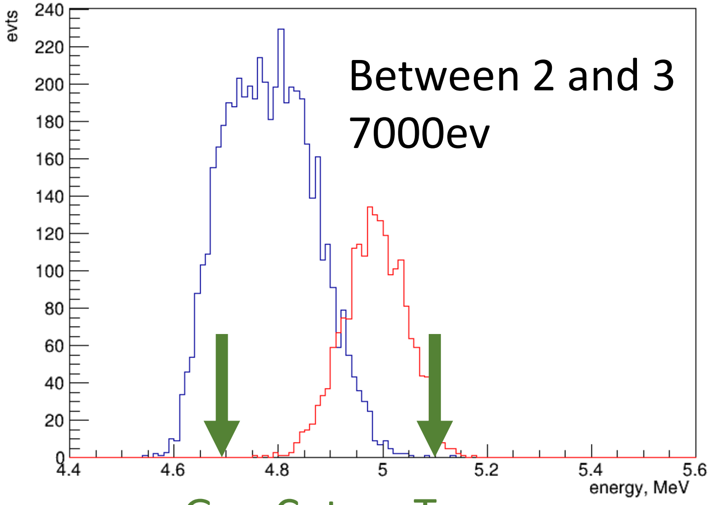








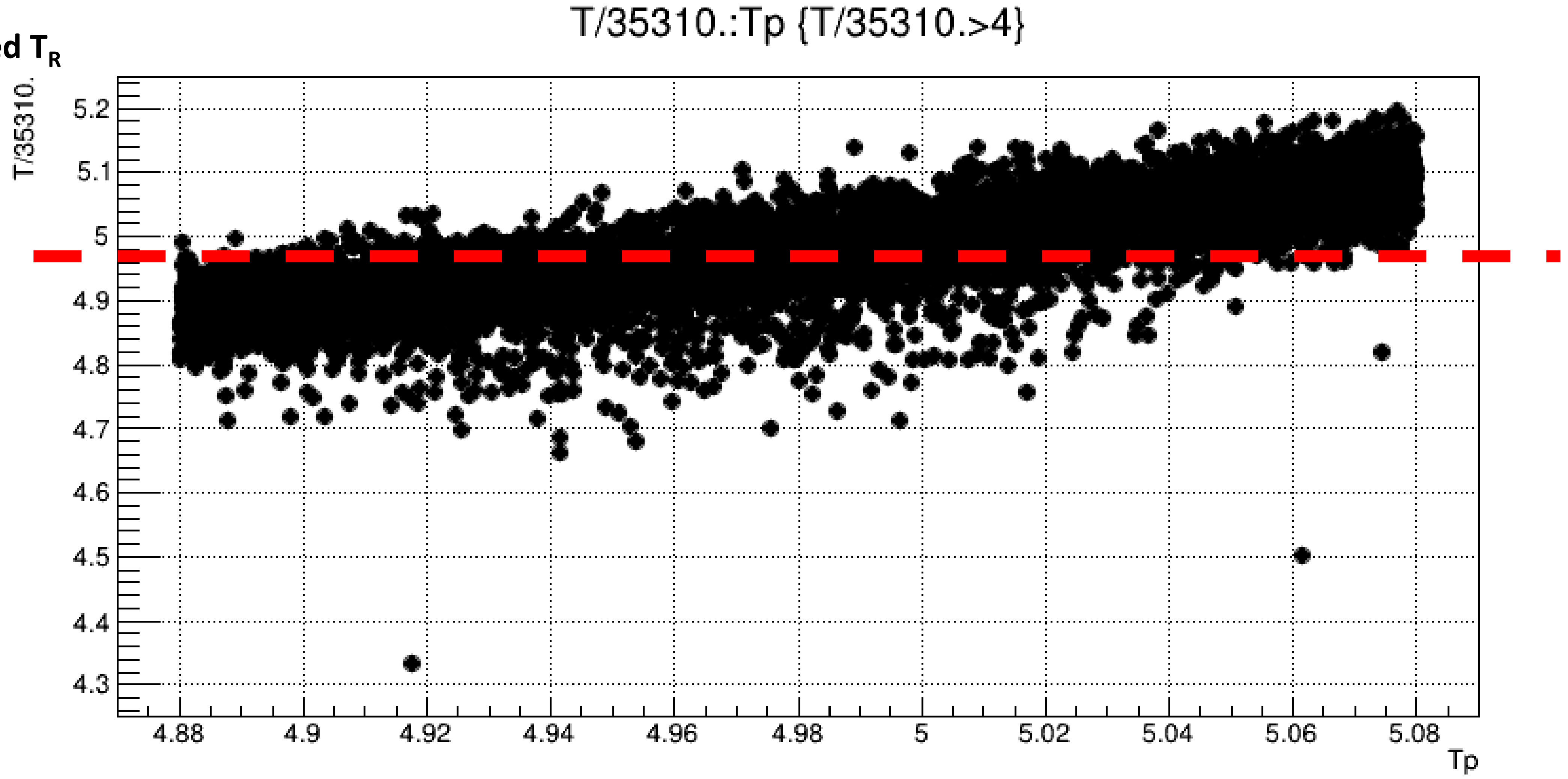
Gen.Cut on T_R



Gen.Cut on T_R

+/- 100 keV range, 7000 events

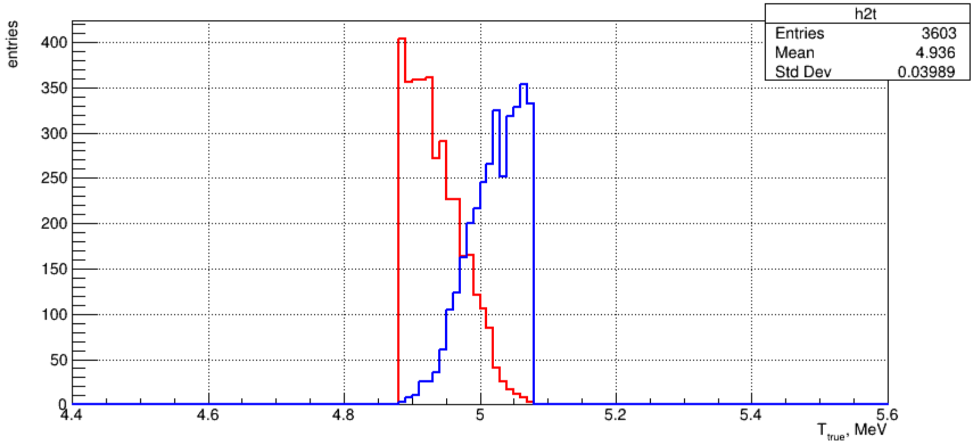
Reconstructed T_R



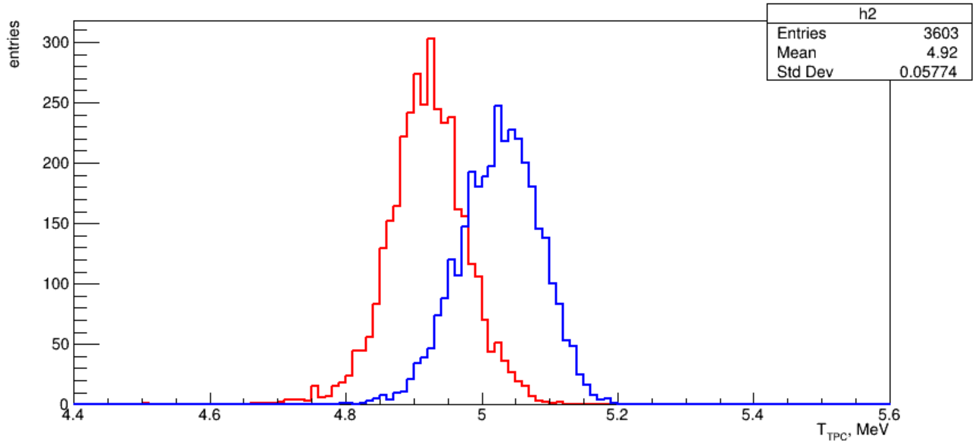
True T_R

Stopped on edge between 2^{nd} and 3^{rd} rings

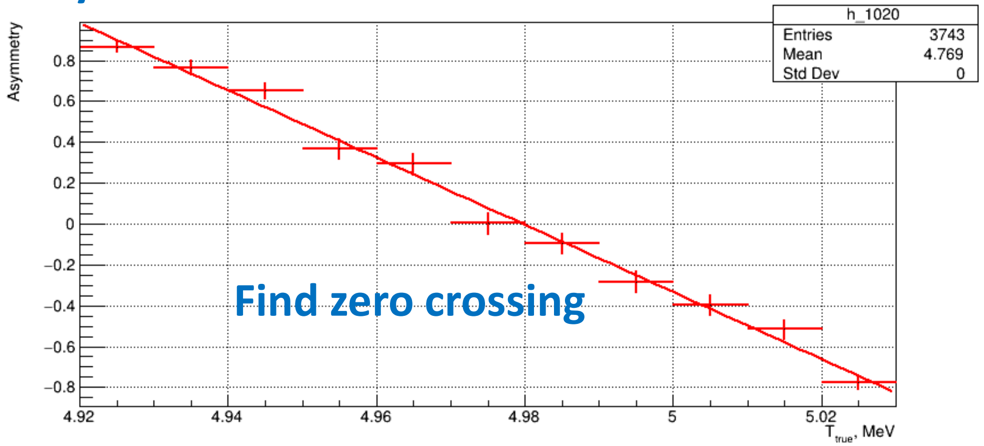
True T_R



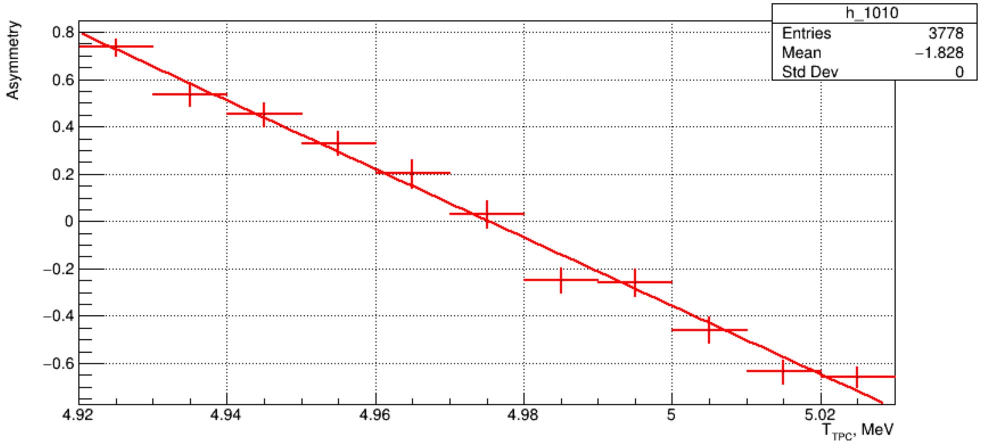
Reconstructed T_R



Asymmetry



Find zero crossing

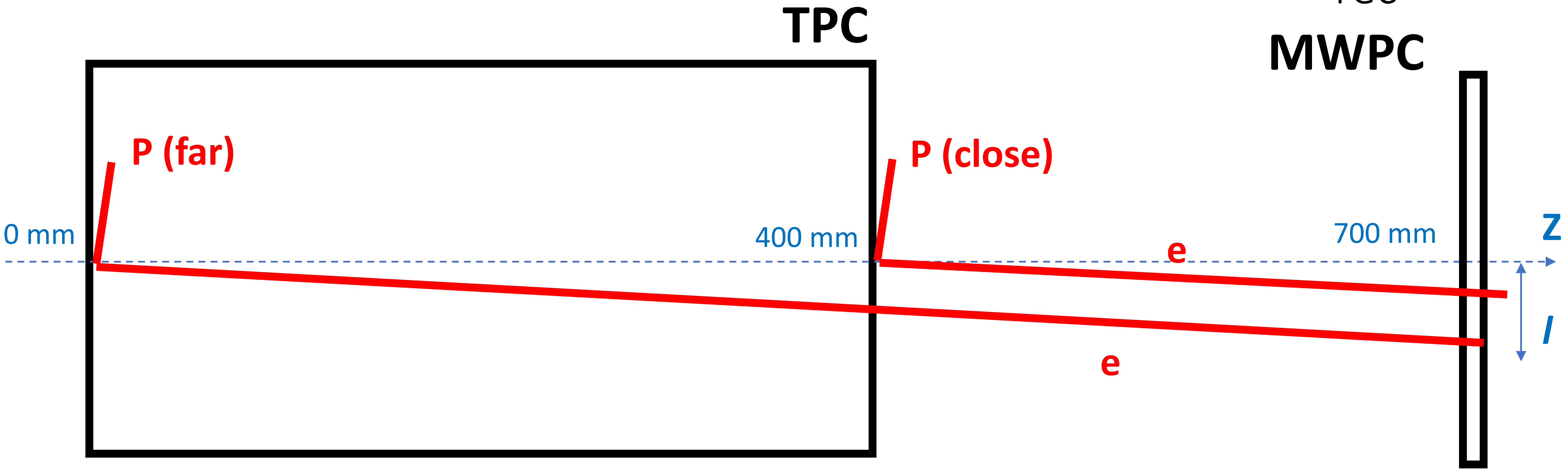


True = 4.9797 +- 0.0008 MeV

Rec. = 4.9753 +- 0.0010 MeV

True − Rec. = -4.4 keV (-4.3σ)

Same energy, same angles, but bias due to Z_{rec}

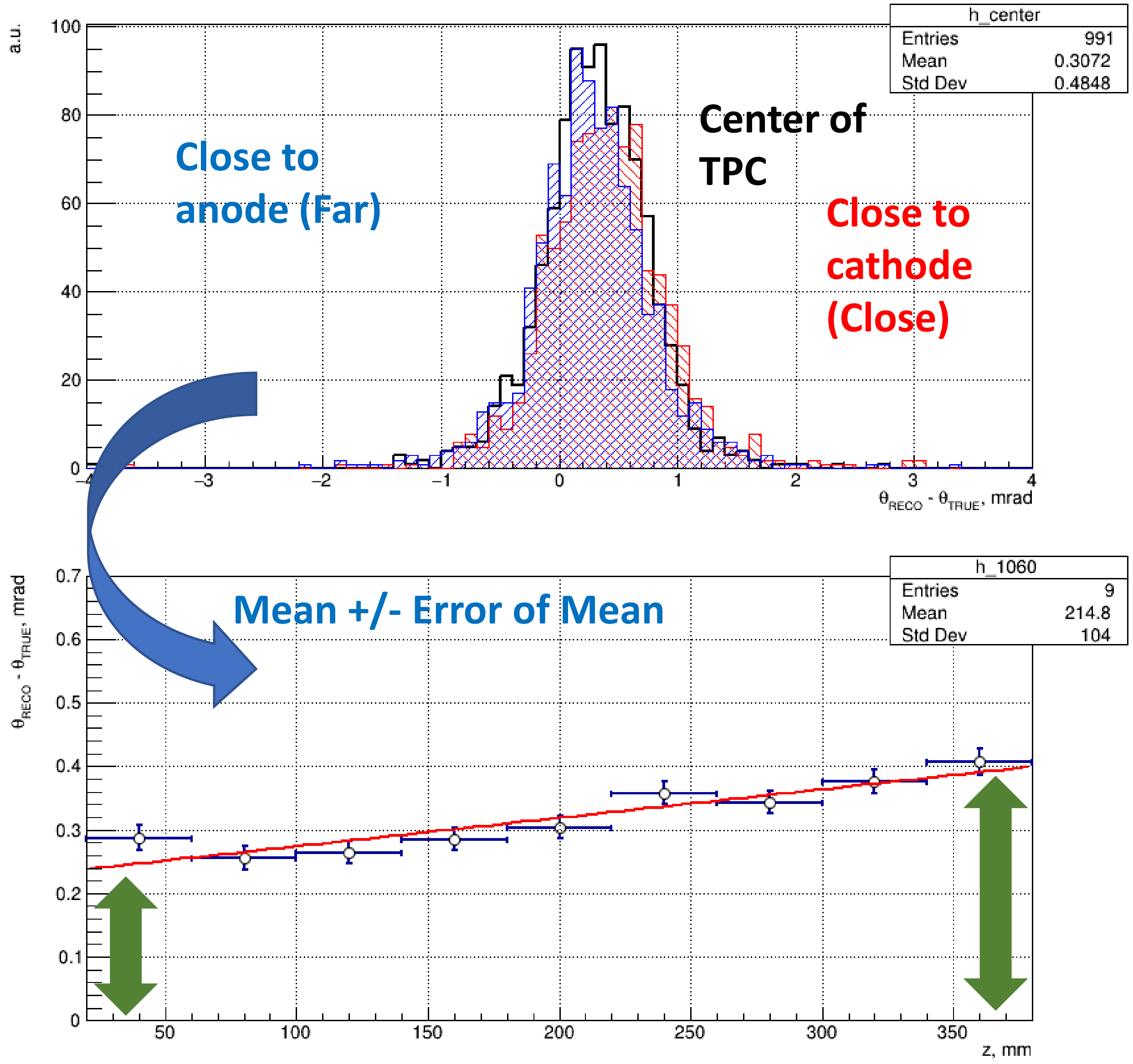


Identical events with θ=5 deg. (87 mrad) → Time bias 600 ns
→ +2,4 mm to a true position wrt. anode

Bias in reconstructed θ → Far: 0,3 mrad (resolution 0,04 mrad)
→ Close: 0,7 mrad (resolution 0,10 mrad)

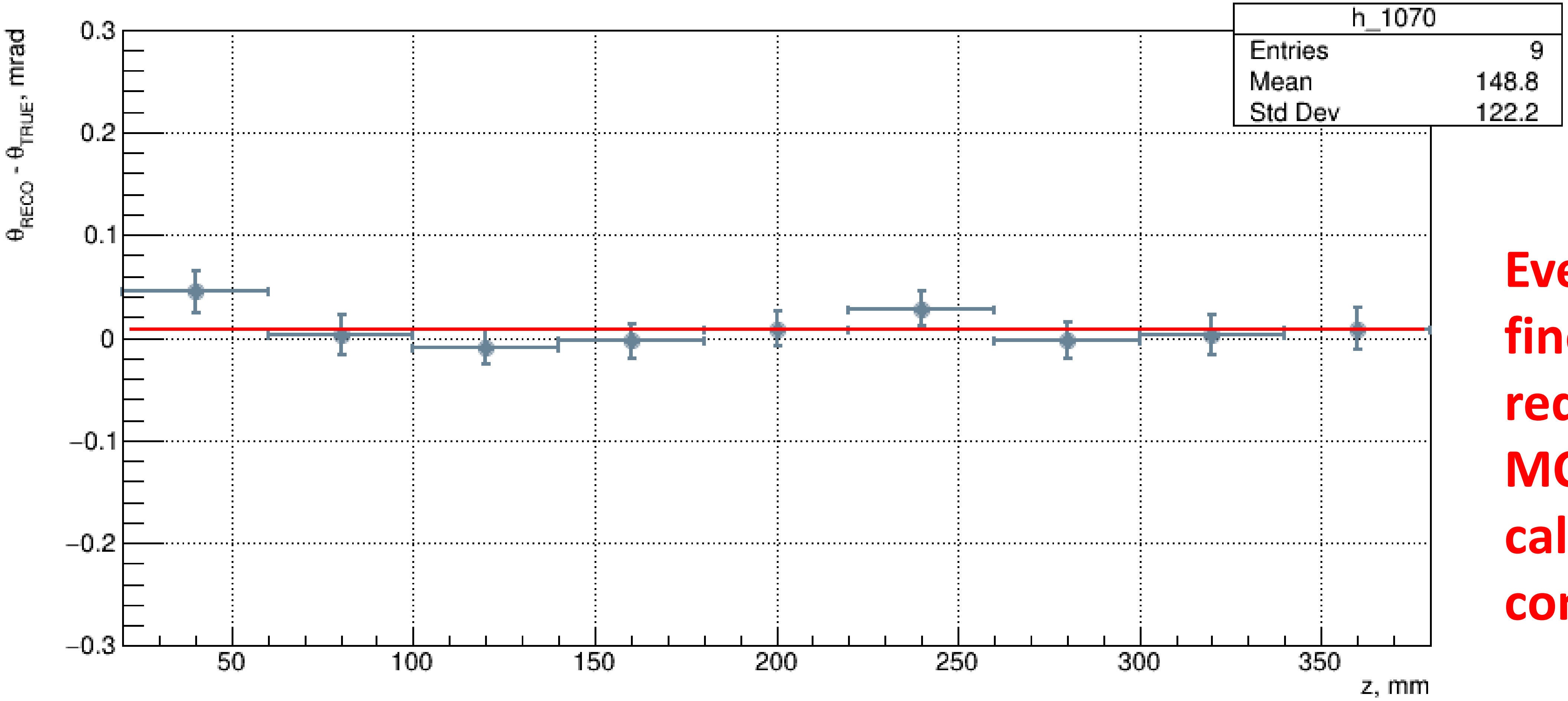
Difference order of 0,4 mrad ← to measure in MC

Z-dependent bias in reconstructed angle



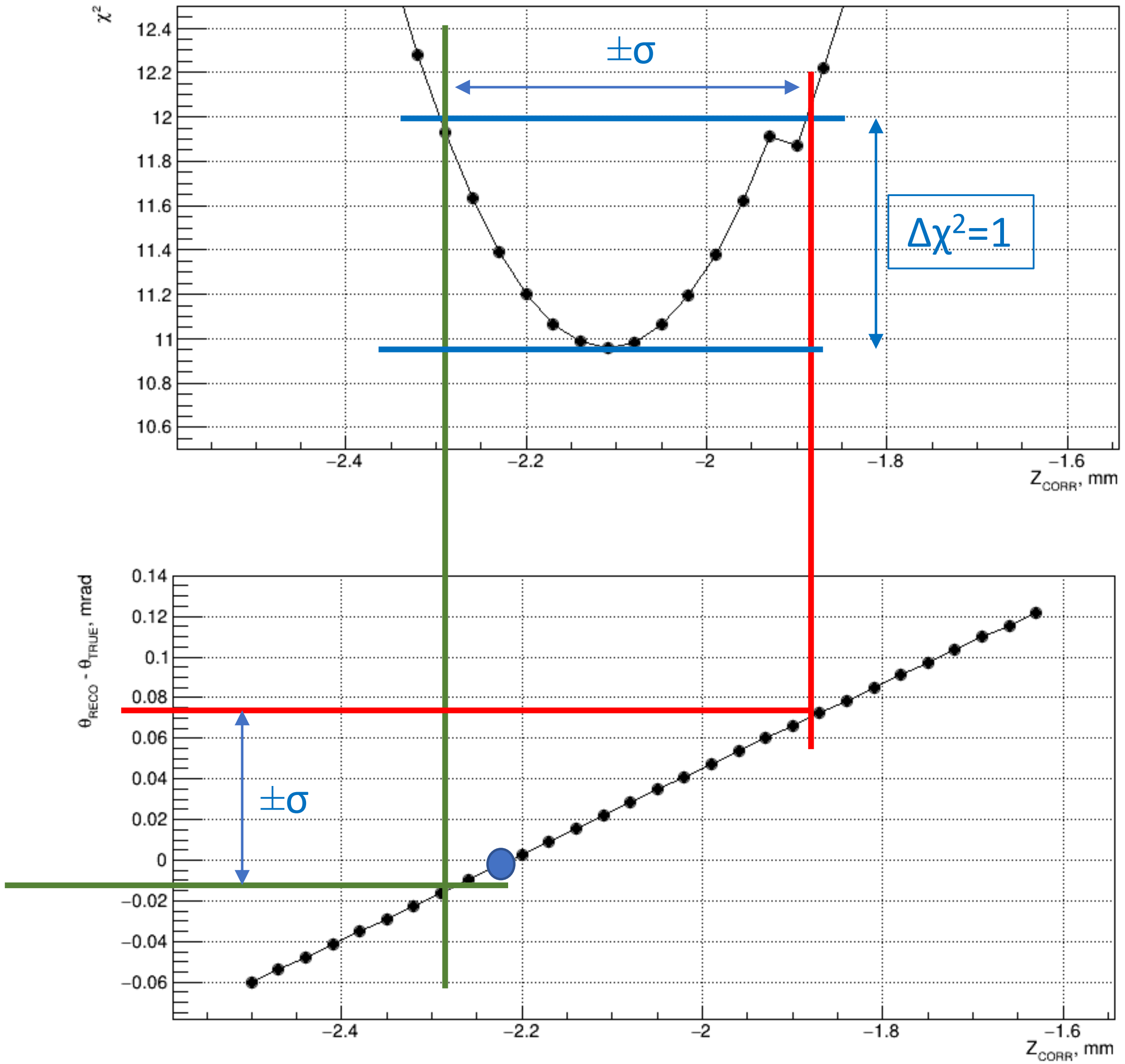
- Mean value of the bias of reconstructed θ (TPC-MWPC based) with respect to a true one depends on Z
- Bias correction → put peak into Z_{TRUE}
- Still some bias, which is higher for higher Z, as expected
- **Why?!! Misalignment?**

Yes! This was a mistype in code → misalignment



Everything fine but requires MC calibration constant!

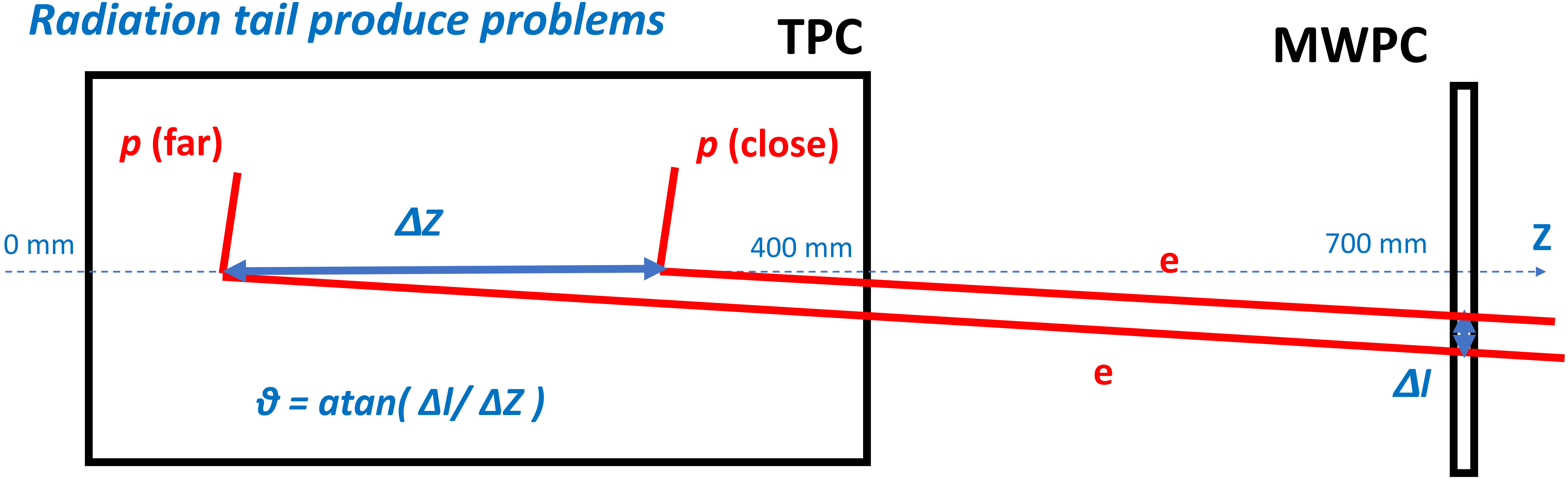
Find tune parameter from best fit by constant



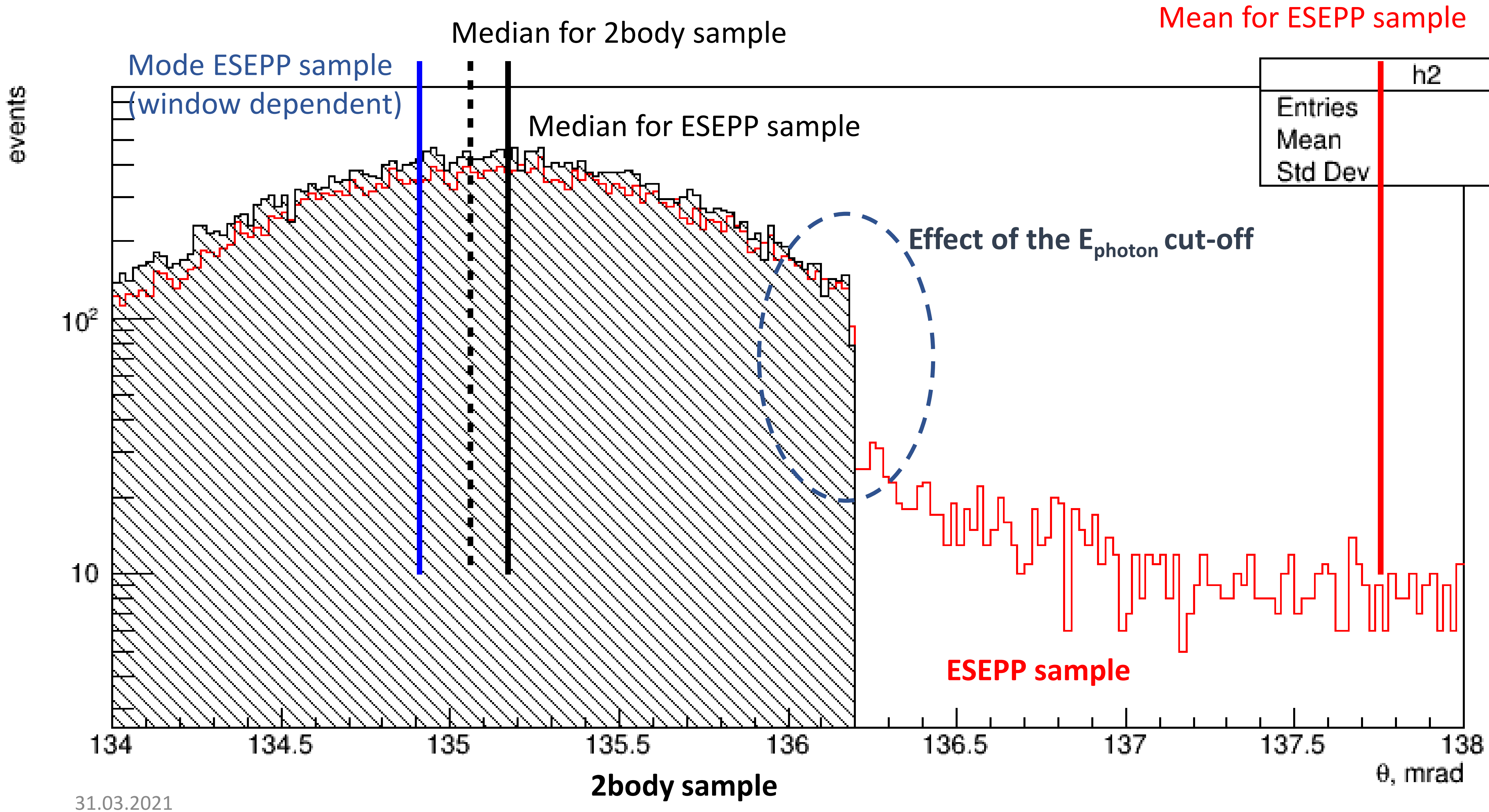
- For each shift calculate χ^2 with respect to a constant hypothesis
- 7000 events,
- Electron scattering angle is calculated in 18 bins along the Z axis
- $\Delta\chi^2=1$ to estimate confidence interval
- Uncertainty of 0,04 mrad, which is $1{,}8*10^{-4}$ relative precision

Absolute measurement of angle

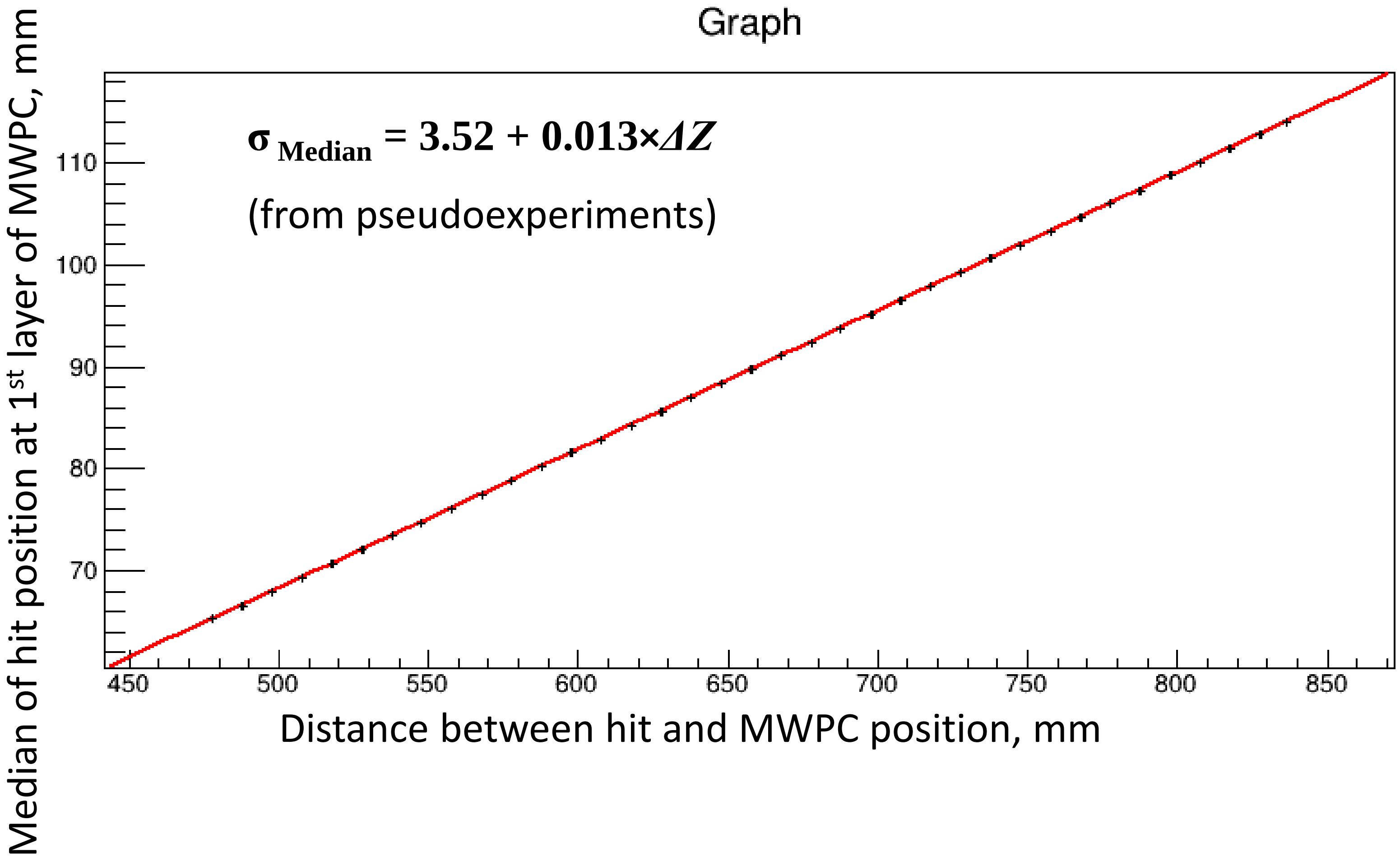
- Identical T_R events using range measurement (T_{23}+/- 50 keV)
- Take ***ΔZ*** to be some large value (I use 180 mm)
- ***ϑ = atan(Δl/ ΔZ)***
- **Idea of Nikolay Voropaev*: Slice on Z and fit Z-l curve to obtain angle***
- ***Radiation tail produce problems***



Median as robust estimator for an angle



Absolute measurement of angle



An angle obtained from the slope

$\theta_{med.est}$ = 135.112 ± 0.021 mrad

was compared with a median true value of scattering angle

θ_{true} = 135.147 mrad.

The relative precision for $\theta_{med.est}$ is 1.5×10^{-4}.

A difference between estimated and true value of the median scattering angle of 0.035 mrad is accounted as a bias introduced by the method.

Expressed in the standard deviation of the procedure it states that the reconstructed angle in in 1.5σ agreement with the true one.

Conclusions

- All the aspects are considered
- Many improvements
  - Signal treatment
  - Noise tool
  - Drift velocity studies
  - Z-position issue
- We are trying to create a single project \ applanation for MC
- Certain lack of manpower