A parametric response model for the self-triggered MRPC readout scheme of the CBM time-of-flight system

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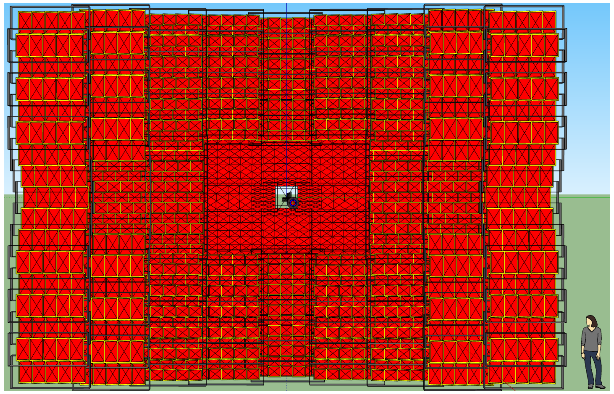
CBM

The CBM time-of-flight wall

cf. J. Lehnert, “The Compressed Baryonic Matter experiment at FAIR”, **HK 30.1**
cf. I. Deppner, “The CBM Time-of-Flight wall”, **HK 16.2**

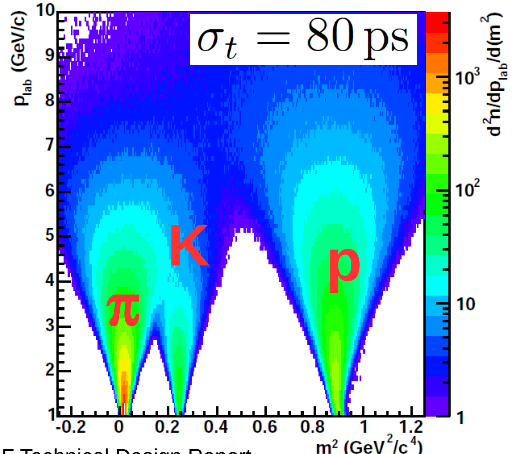
- main hadron identification tool up to momenta of 5 GeV/c in the angular range 2.5° - 25° covered by the S(ilicon) T(racking) S(tation) detector
- dimensions: 9 m high, 13.5 m wide, active area of about 120 m²
- time resolution 80 ps, efficiency > 95%



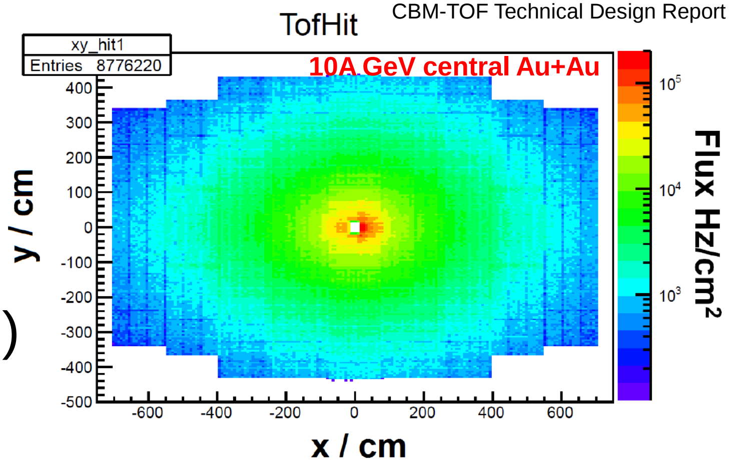
CBM-TOF Technical Design Report

$$m^2 = p^2\left(\frac{1}{\beta^2} - 1\right)$$

$$\sigma_{m^2} = \frac{2p^2}{\beta^2}\frac{\sigma_t}{t}$$



CBM-TOF Technical Design Report



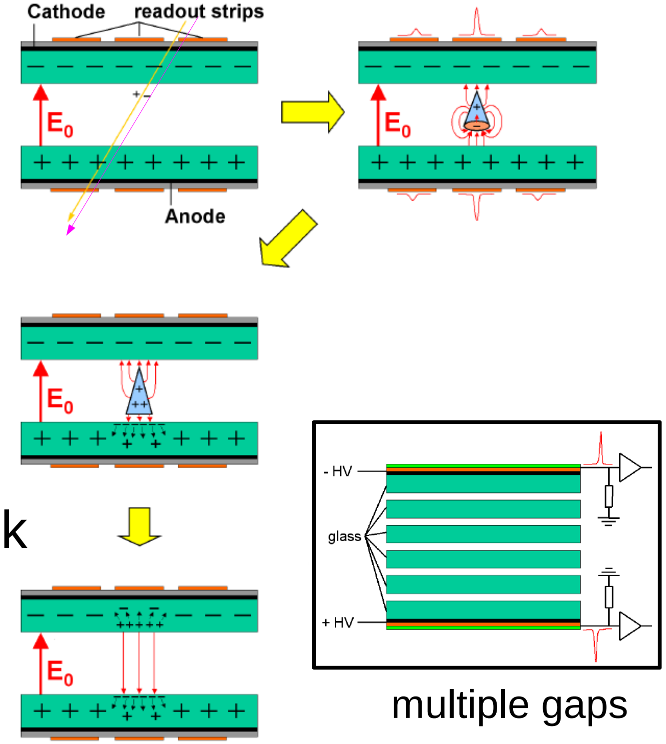
I. Deppner et al., J. Instrum. **9** (2014) C10014

- strongly varying rates (up to 25 kHz/cm²)
- Multi-Gap Resistive-Plate Chambers (MRPCs)

(M)RPC working principle

- gas detectors for timing measurements and trigger applications
- Charged particles traversing the chamber form electron-ion pairs in the gas by ionization.
- Due to the applied high-voltage field the electrons are accelerated and ionize further gas molecules (“avalanche”).
- Avalanche electrons induce mirror charges in the external read-out electrodes (signal formation).
- Electrons and positively charged gas ions drift towards opposing glass plates, accumulate on the surfaces and cause a local reduction of the electric field in the gap.
- Charges compensate one another by means of bulk and surface currents on relaxation time scales of $O(\mathrm{ms}) \leq \tau \leq O(\mathrm{s})$, depending on the glass resistivity.

$$E(t) = E_0\,(1 - \exp(-t/\tau))$$



multiple gaps

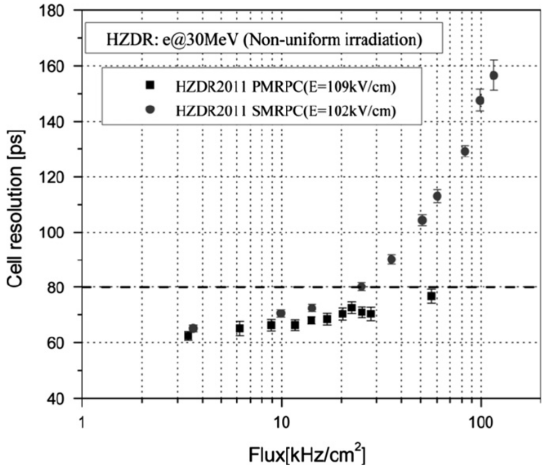
I. M. Deppner, Ph.D. Thesis, Heidelberg University, Heidelberg, Germany, 2013

Flux capability studies in beam

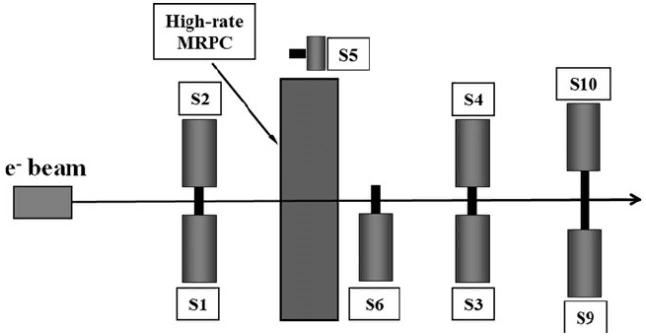
J. Wang et al., Nucl. Instrum. Methods A **713** (2013) 40

(see also: I. Deppner et al., J. Instrum. **7** (2012) P10008; M. Petrovici et al., J. Instrum. **7** (2012) P11003; Z. Weiping et al., Nucl. Instrum. Methods A **735** (2014) 277)

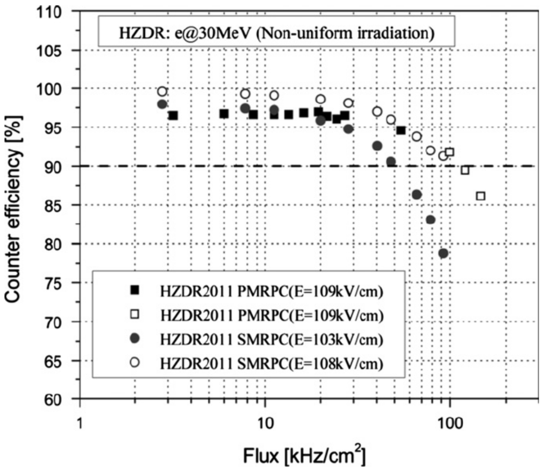
- Exposing the detector to a sustained particle flux should – regarding the operation principle – decrease its detection efficiency until local reduction and recovery of the electric field cancel out.



- The average degradation effect on MRPC detection efficiency and time resolution has been thoroughly studied as a function of incident particle flux.
- example: in-beam test at ELBE in April 2011 with a 30 MeV electron beam (beam spot: a few cm^2)
- conclusion: *“The maximum tolerable particle flux approaches the 100 kHz/cm^2 land-mark.”*

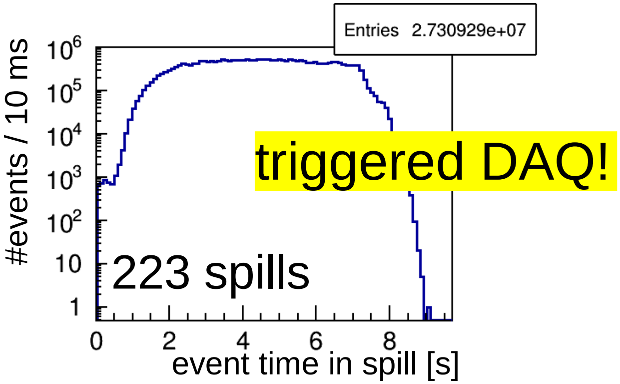


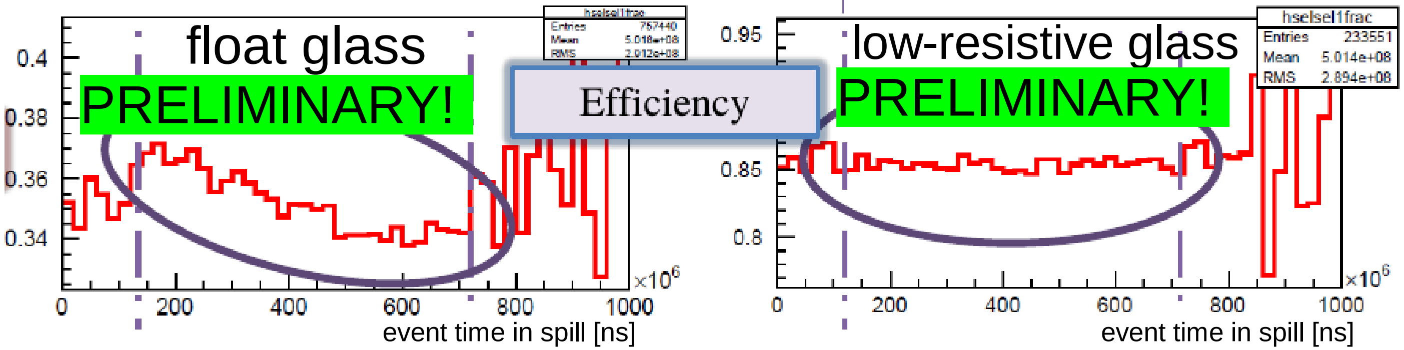
prototype	**PMRPC**	**SMRPC**
glass resistivity	2.5 x 10^{10} Ωcm	2.5 x 10^{10} Ωcm
cell structure	pads	strips
#cells	6 x 2	3
cell length	-	24 cm
cell pitch	2.2 cm (2 cm + 0.2 cm)	2.5 cm (2.2 cm + 0.3 cm)
#gaps	2 x 5	2 x 5
gap width	220 μm	250 μm



Degradation as a function of irradiation time

- In our flux capability studies, detector data were averaged within accelerator spills and across spills.
- Can we observe the MRPC gradually entering field breakdown/recovery equilibrium, i.e. how the degradation of the MRPC response evolves with increasing time in spill? Yes, if
  - events are arranged on a continuous time axis (technical matter)
  - equilibrium is not reached too fast (bin size limited by statistics)
  - incident particle fluxes are sufficiently high
- Some hint at efficiency degradation in spill was reported based on an analysis of data taken at SPS (30 AGeV/c Pb beam on a Pb target).

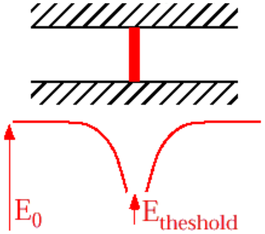



P. Lyu et al., 27th CBM Collaboration Meeting (April 2016)

Simulation of the response degradation

C. Simon et al., CBM Progress Report **2016** (2017) 133

- To model the response degradation in spill a Monte-Carlo simulation including a new parametric digitization scheme (no avalanche dynamics) and memory effects of the MRPC's electric field is being developed.
- Ansatz: Be $Q_{\mathrm{ind},0}$ a random variable which describes the total electric charge spectrum induced by avalanches in the readout plane of an unloaded MRPC. Be $q_{\mathrm{max},0}$ the highest possible value of $Q_{\mathrm{ind},0}$ and $q_{\mathrm{ind},i}$ the charge actually induced by the i-th avalanche at position $\mathbf{x}_i$ and time t_i. Be further r_{imp} an impact radius quantifying the spatial extent of an E-field reduction and τ_{MRPC} the relaxation time for field restoration.
- Then in this approach the induced charge spectrum accessible to the n-th avalanche at coordinates $(\mathbf{x}_n,t_n)$ follows the probability distribution of

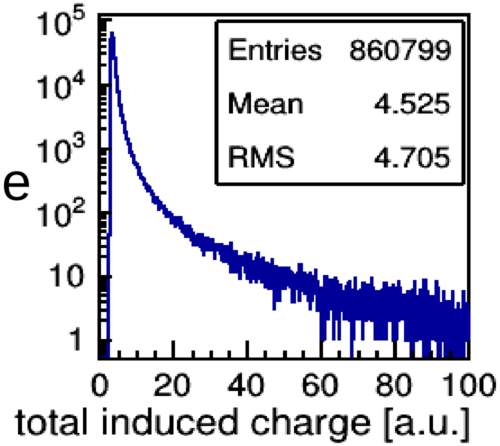


$$Q_{\mathrm{ind},n} = \left[1 - \sum_{i=1}^{n-1}\left\{\frac{q_{\mathrm{ind},i}}{q_{\mathrm{max},0}} \times \frac{1}{1+\left(\frac{\mathbf{x}_n-\mathbf{x}_i}{r_{\mathrm{imp}}}\right)^2} \times \exp\left(-\frac{t_n-t_i}{\tau_{\mathrm{MRPC}}}\right)\right\}\right] Q_{\mathrm{ind},0}$$

M. Abbrescia, “Improving rate capability of Resistive Plate Chambers”, RPC2016

Parametric MRPC response description

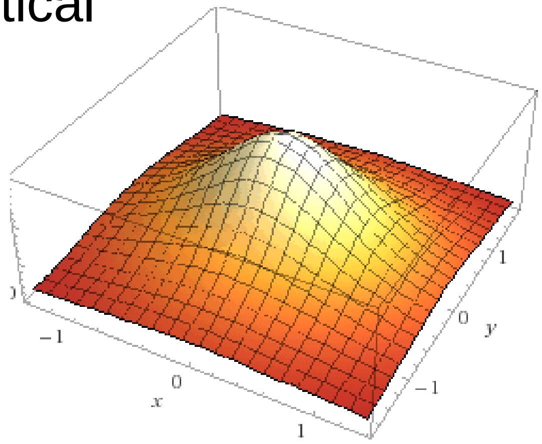
- Assumption: The total induced charge on the (undivided!) readout plane follows a Landau distribution.
    - TMath::Landau(Q_{ind},location,scale,kTRUE)



- Assumption: This charge is distributed in the readout plane according to the electrostatically induced charge density.
    - $$\sigma(x,y) = \frac{Q_{\text{ind}} R}{2\pi(x^2+y^2+R^2)^{3/2}}$$

- Assumption: The strip charges correspond to the analytical integral evaluated at the respective strip boundaries.

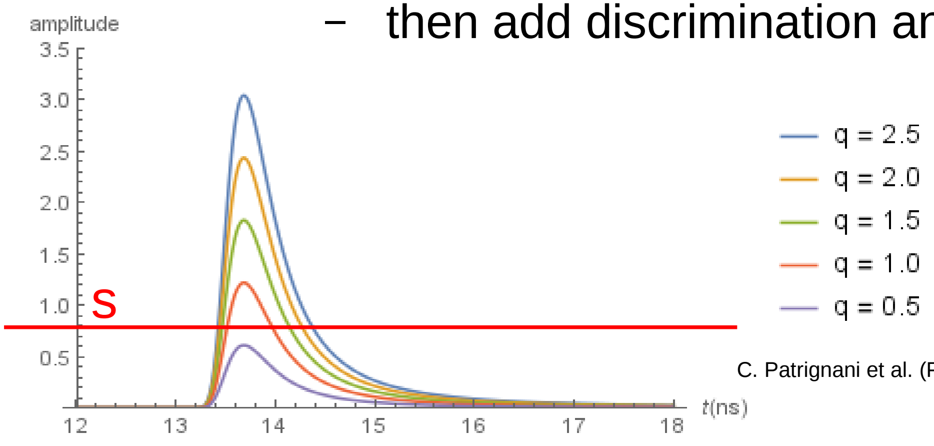
$$q_{\text{strip}} = \frac{Q_{\text{ind}}}{2\pi}\left[\arctan\left(\frac{x_{\text{high}}\,y_{\text{high}}}{R\sqrt{R^2+x_{\text{high}}^2+y_{\text{high}}^2}}\right) - \arctan\left(\frac{x_{\text{low}}\,y_{\text{high}}}{R\sqrt{R^2+x_{\text{low}}^2+y_{\text{high}}^2}}\right) - \arctan\left(\frac{x_{\text{high}}\,y_{\text{low}}}{R\sqrt{R^2+x_{\text{high}}^2+y_{\text{low}}^2}}\right) + \arctan\left(\frac{x_{\text{low}}\,y_{\text{low}}}{R\sqrt{R^2+x_{\text{low}}^2+y_{\text{low}}^2}}\right)\right]$$



Wolfram|Alpha

Parametric MRPC response description

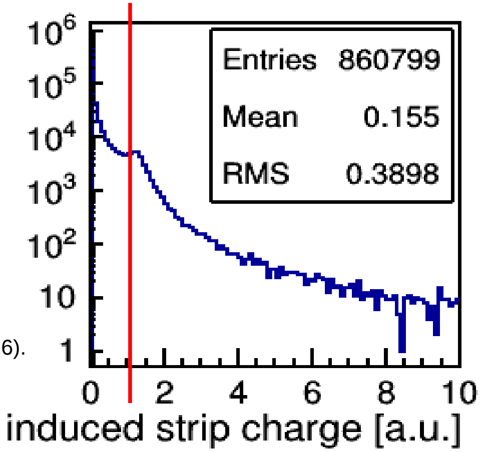
- Assumption: The (amplified!) signal is shaped according to a normalized Landau distribution multiplied by the strip charge.
  - $f(t) = q_{\mathrm{strip}} \times \mathrm{TMath::Landau}(t, \mathrm{mpv}, \mathrm{sigma}, \mathrm{kTRUE})$
- Assumption: Leading and trailing edge discrimination points in time depend on the numerically evaluated intersections of signal f(t) and threshold s.
  - $s = q_{\mathrm{strip}} \times \mathrm{TMath::Landau}(t, \mathrm{mpv}, \mathrm{sigma}, \mathrm{kTRUE})$
  - numerical methods provided by the GNU Scientific Library (GSL)
  - then add discrimination and digitization jitter



$$\sigma_t = \frac{\sigma_n}{(dS/dt)_{S_T}}$$

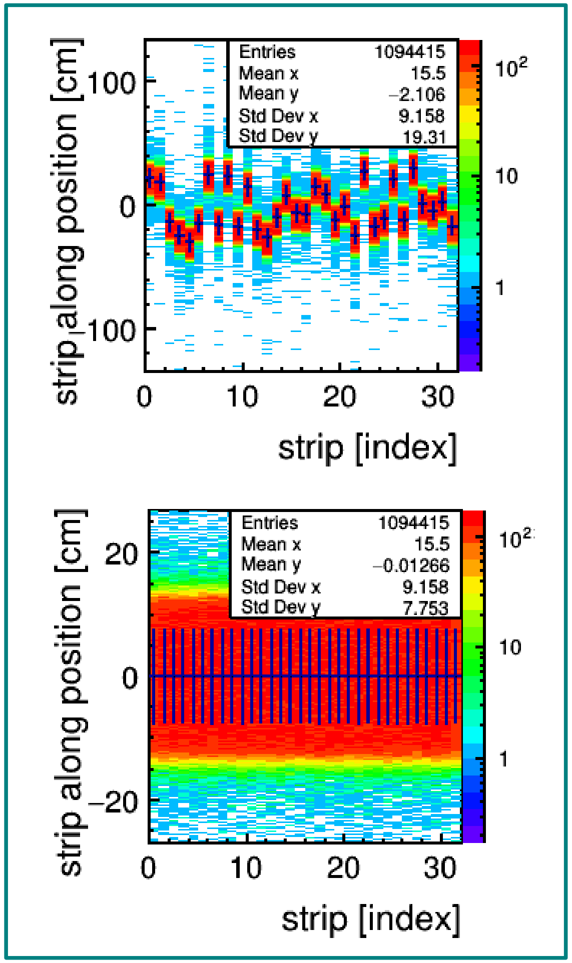
C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

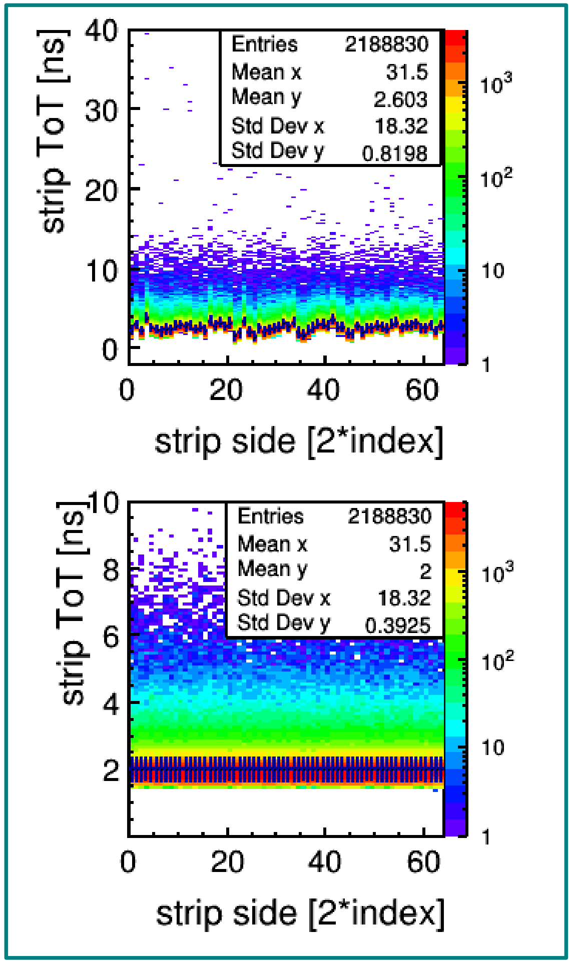
Wolfram Mathematica 11

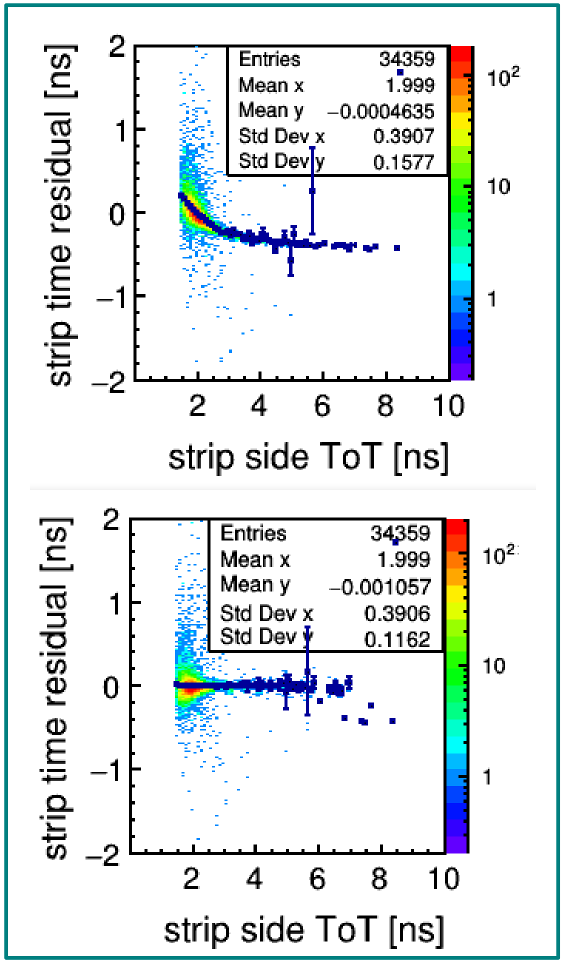


Run time offsets and time walk

- The response parametrization scheme features the main effects an MRPC calibration algorithm needs to flatten.

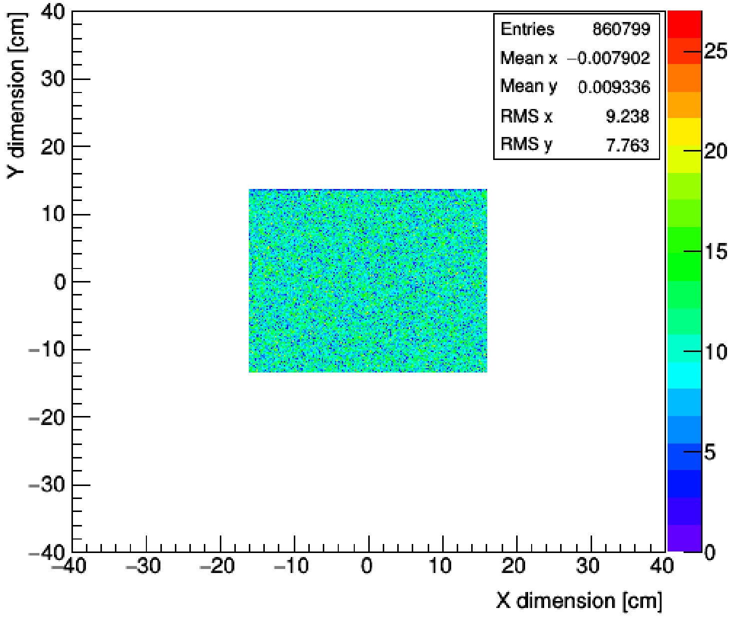


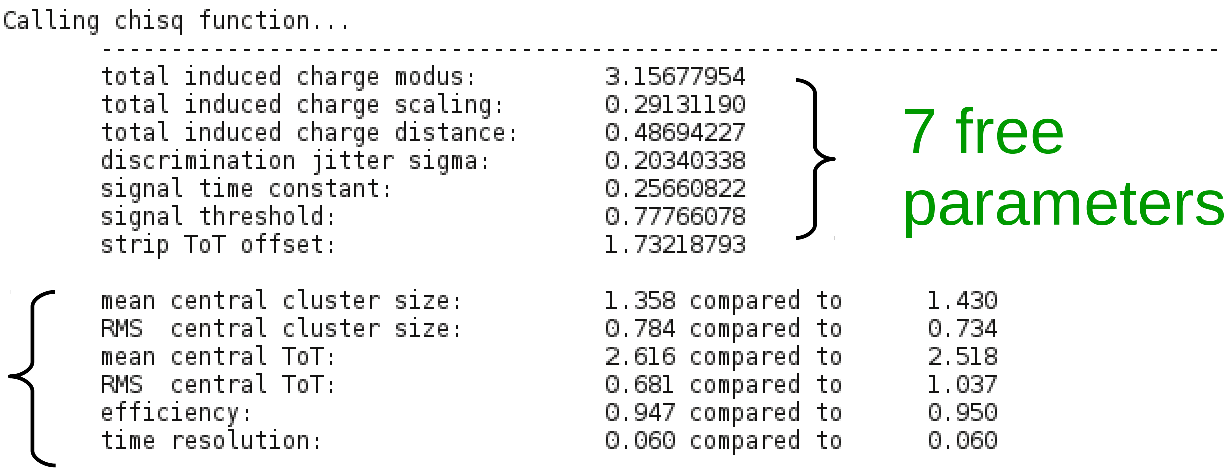




Model parameter adjustment

- The GSL implementation of the downhill simplex minimization algorithm is used to fit the response model to a particular MRPC's characteristics.
- Based on O(10^6) simulated, uniformly distributed hits in the readout plane of an MRPC the simplex algorithm iteratively minimizes a χ^2 value comprising measured constraints (ToT mean and RMS, efficiency, …).





```
Calling chisq function...
       ---------------------------------------------------------------------------------
       total induced charge modus:          3.15677954
       total induced charge scaling:        0.29131190
       total induced charge distance:       0.48694227
       discrimination jitter sigma:         0.20340338
       signal time constant:                0.25660822
       signal threshold:                    0.77766078
       strip ToT offset:                    1.73218793

       mean central cluster size:           1.358 compared to      1.430
       RMS  central cluster size:           0.784 compared to      0.734
       mean central ToT:                    2.616 compared to      2.518
       RMS  central ToT:                    0.681 compared to      1.037
       efficiency:                          0.947 compared to      0.950
       time resolution:                     0.060 compared to      0.060
```

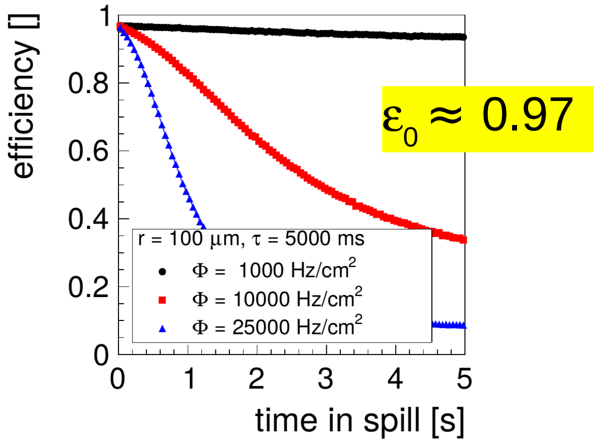
7 free parameters

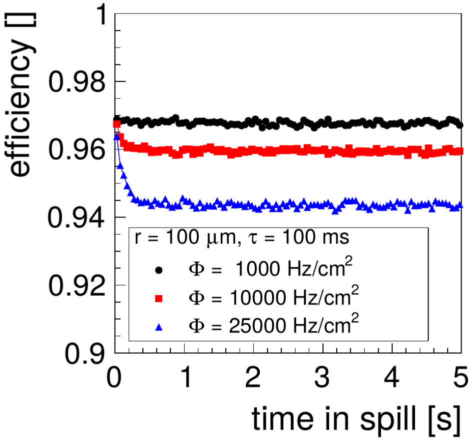
6 constraints

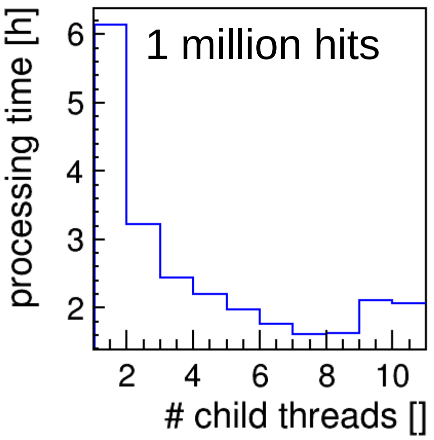
Simulated efficiency degradation

C. Simon et al., CBM Progress Report **2016** (2017) 133

- In a Monte-Carlo parameter study the detection efficiency of a 1 cm^2 spot in the center of an MRPC prototype with dimensions 32 x 27 cm^2 was simulated for low-resistive and float glass electrodes as a function of time in spill at three different incident particle fluxes.







- The (arbitrary) impact radius r_{imp} of 100 µm is the same in both cases. It needs to be fitted to beam time data if the degradation effect can be extracted.

- The run time of the field memory computation grows quadratically with the number of MRPC hits (possible application of multi-threading).

Summary and Outlook

- Recent in-beam test results from SPS (November '15 and '16) might allow for studying the time curve of the MRPC performance degradation. First hints observed with a float-glass prototype need to be reproduced and consolidated.
- A parametrization of the local electric field breakdown/recovery in an MRPC has been developed.
- A self-triggered, front-end driven data acquisition with readout channel dead times of a few nanoseconds (GET4-AFCK-FLIB, used in November '16) – in principle – allows for studying the degradation of the MRPC response as a function of distance in time to the previous hit in a readout channel. Data analysis is ongoing.

cf. D. Emschermann, “A prototype of the free-streaming data acquisition system for the Compressed Baryonic Matter experiment at FAIR”, **HK 15.4**

cf. D. Hutter, “Evaluation of the CBM FLES input interface at 2016 CERN/SPS beam test”, **HK 63.6**

The CBM ToF group

Participating institutes

- THU DEP, Beijing, China
- IFIN-HH, Bucharest, Romania
- GSI, Darmstadt, Germany
- TUD IKP, Darmstadt, Germany
- HZDR ISP, Rossendorf, Germany
- GU IRI, Frankfurt, Germany
- USTC DMP, Hefei, China
- RKU PI, Heidelberg, Germany
- CCNU IOPP, Wuhan, China
- SSC RF ITEP, Moscow, Russia

Special thanks go to

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Großgeräte
der physikalischen
Grundlagenforschung

SEVENTH FRAMEWORK
PROGRAMME

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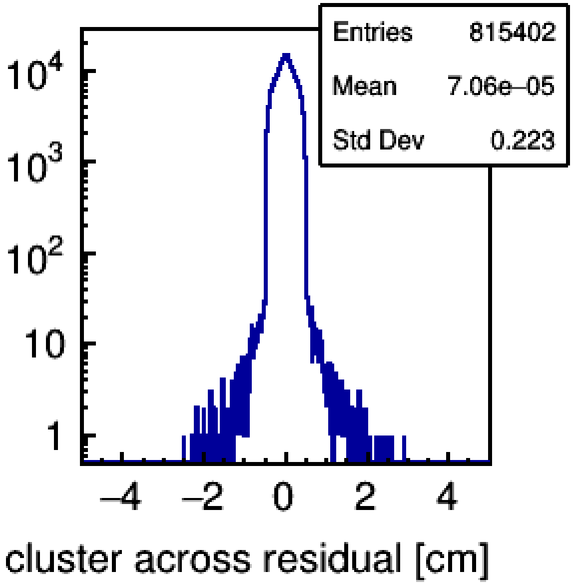
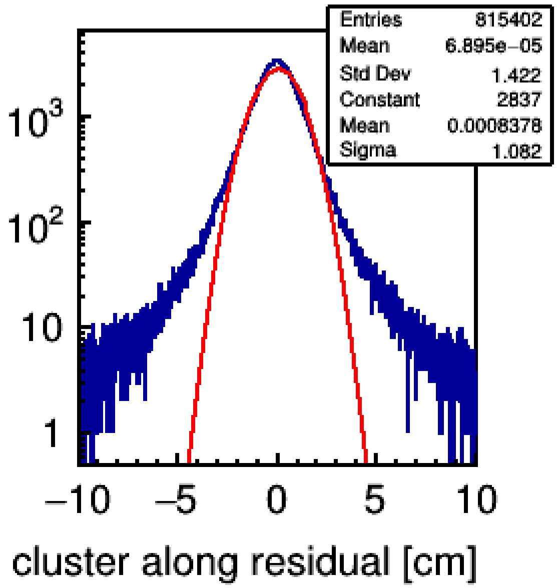
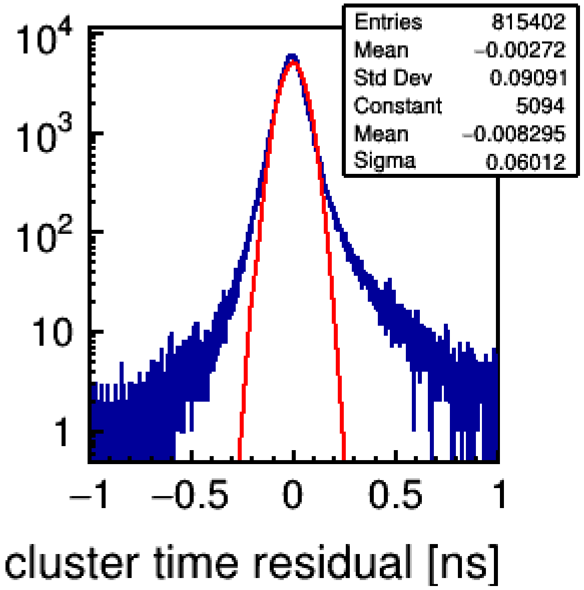
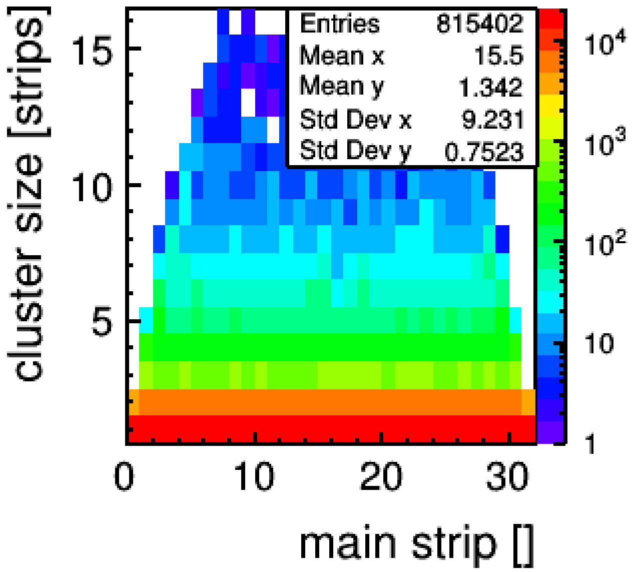
AIDA 2020

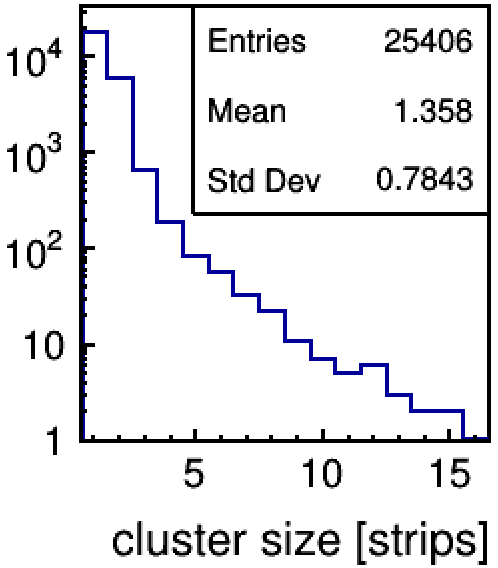
Response residuals and cluster size











Analytic MRPC response descriptions

- Neglecting space-charge effects MRPC characteristics can be expressed rather neatly

W. Riegler, C. Lippmann, R. Veenhof, Nucl. Instr. and Meth. in Phys. Res. A 500 (2003) 144

λ : mean free path
α : Townsend coefficient
η : attachment coefficient
E_W/V_W : weighting field
d : gap size
v : drift velocity
Q_{thr} : threshold charge

  - probability to create a primary charge cluster in the gap at [z,z+dz]

$$P(z) = \lambda^{-1} \exp\left(-\frac{z}{\lambda}\right)$$

  - induced charge in the readout electrode

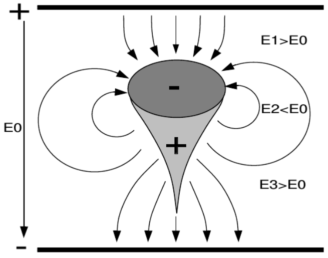
$$Q_{ind}(z) = \frac{E_W}{V_W}\frac{e_0}{\alpha - \eta} e^{(\alpha-\eta)(d-z)} - 1$$

  - timing precision

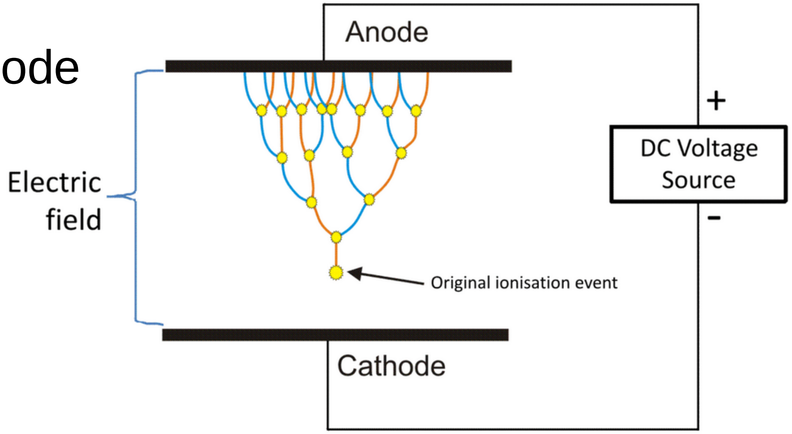
$$\sigma_{RPC} = \frac{1,28255}{(\alpha - \eta)v}$$

  - gap efficiency

$$\varepsilon = 1 - e^{-(1-\frac{\eta}{\alpha})\frac{d}{\lambda}} \left(1 + \frac{V_W}{E_W}\frac{\alpha - \eta}{e_0} Q_{thr}\right)^{\frac{1}{\alpha\lambda}}$$



C. Lippmann, W. Riegler, Nucl. Instr. and Meth. in Phys. Res. A 517 (2004) 54

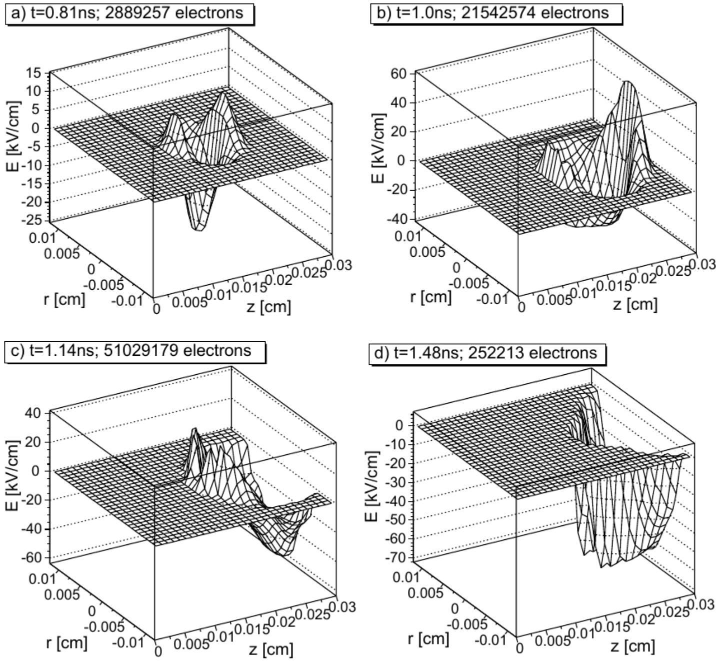


https://en.wikipedia.org/wiki/Townsend_discharge#/media/File:Electron_avalanche.gif

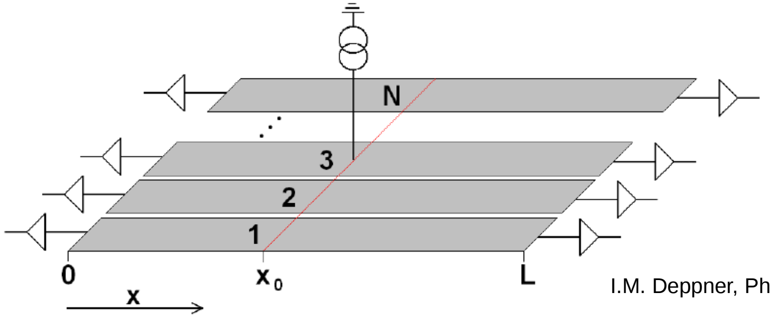
- But some experimental MRPC results (in particular the induced charge) cannot be reproduced by applying these expressions! Space-charge effects play a dominant role in MRPCs.

MRPC space-charge effects

- Space-charge effects which inhibit avalanche growth can be simulated by computationally costly MC methods and might not even converge to experimental findings
- Computing signal propagation, termination, crosstalk and losses in the readout strip electrodes is also rather time consuming
- Thus, a microscopic approach is not feasible for the design of the digitizer class
- Instead, the response function should be parametrized taking into account measured observables from in-beam prototype tests



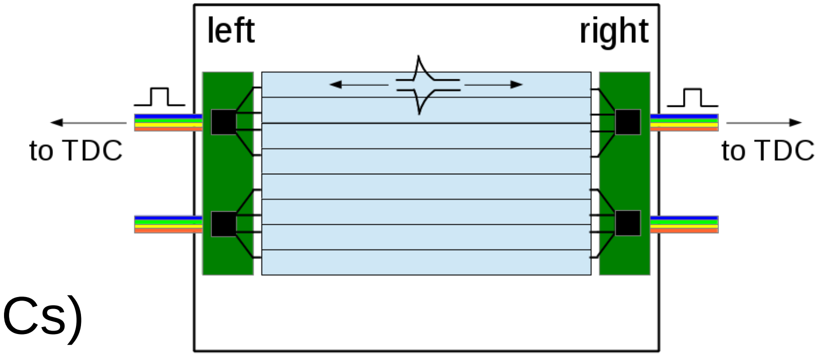
C. Lippmann, W. Riegler, Nucl. Instr. and Meth. in Phys. Res. A 517 (2004) 54

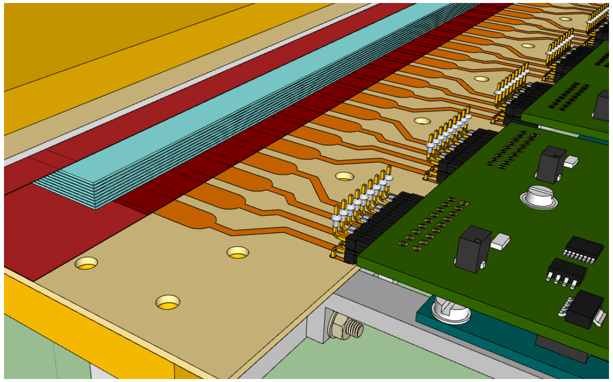


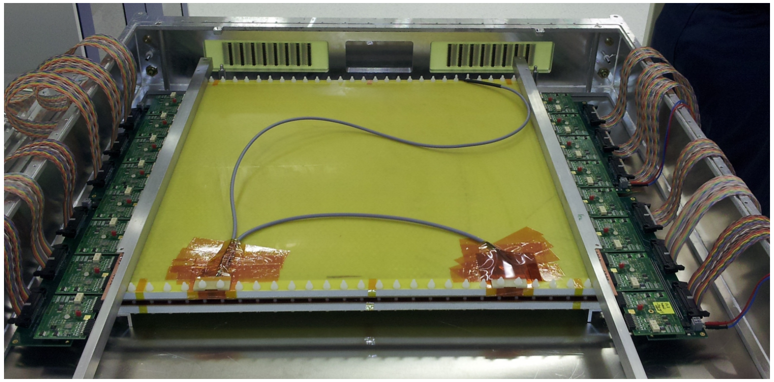
I.M. Deppner, Ph.D. Thesis, Heidelberg University, Heidelberg, Germany, 2013

Basic MRPC readout principle

- differential analog signals on the read-out strips are merged by subtraction, discriminated and converted to LVDS pulses (PADI chip)
- timing quantities:
  - t_L, t_R (leading edge)
  - ToT (pulse width)
- digitization by time-to-digital converters (TDCs)
  - CBM paradigm: **self-triggered digitization and readout**




C. Simon et al., 2014 JINST 9 C09028


CBM-TOF Technical Design Report