Simulating the high-rate performance of MRPC detectors for the CBM TOF wall

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for the CBM TOF group

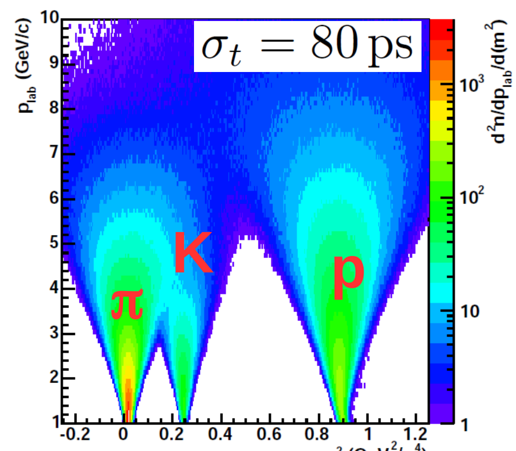
The CBM time-of-flight wall

cf. P. Giubellino, “Status of the FAIR Project”, **PV I**
cf. I. Deppner, “Status of the CBM Time-of-Flight system”, **HK 53.1**

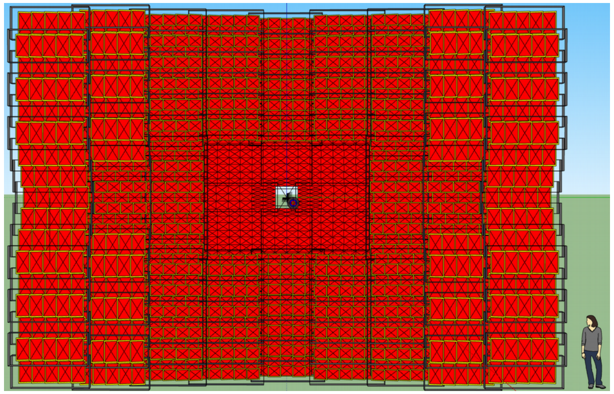
- main hadron identification tool up to momenta of 5 GeV/c in the angular range 2.5° - 25° covered by the S(ilicon) T(racking) S(tation) detector
- dimensions: 9 m high, 13.5 m wide, active area of about 120 m²
- time resolution 80 ps, efficiency > 95%

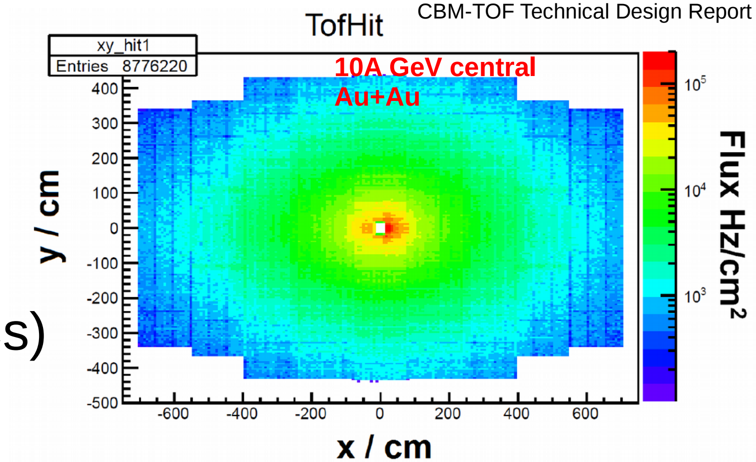
$$m^2 = p^2 \left(\frac{1}{\beta^2} - 1 \right)$$

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



CBM-TOF Technical Design Report


CBM-TOF Technical Design Report



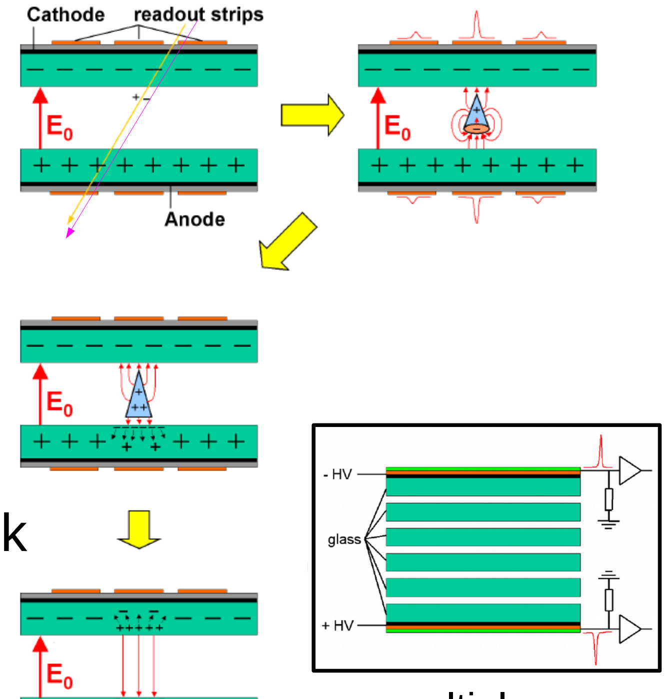
I. Deppner et al., J. Instrum. **9**, C10014 (2014)

- 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 $O(\text{ms}) \leq \tau \leq O(\text{s})$, depending on the glass resistivity.

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



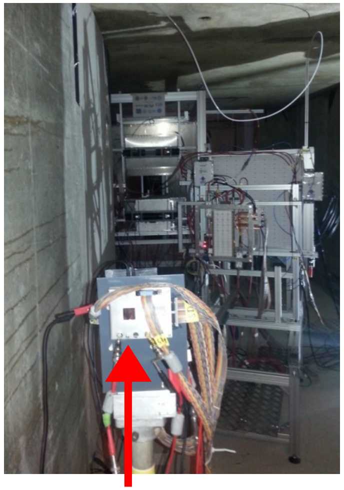
multiple gaps

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

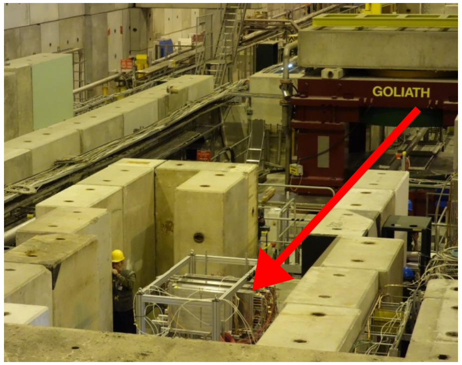
Prototype tests with HI-reaction secondaries

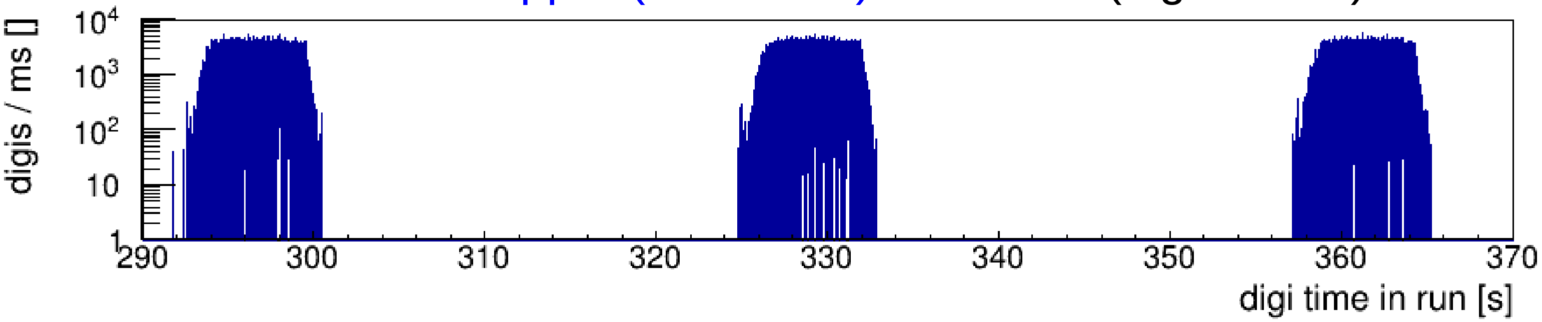
M. Petriş et al., Nucl. Instrum. Meth. A **920**, 100 (2019)
P. Lyu et al., J. Instrum. **12**, C03055 (2017)

- Different MRPC prototypes equipped with float (long relaxation times → slow recovery) and low-resistive glass (short relaxation times → fast recovery) were flood-illuminated at CERN-SPS in 2015/2016.
- Setup in November 2015 at the H4 beam line of the North Area (NA)



  – 30 AGeV/c Pb ions at beam intensities of 1-10 MHz on a 1-4 mm lead target (2-8% interaction probability)
  – CERN-SPS super cycle: 32.4 s (27 BP)
  – slow-extraction time: ca. 8 s, flat-top time: ca. 6 s
  – DAQ (TRB3/DABC) triggered by coincidences of an in-beam diamond start counter with different MRPCs
  – upper (lower rate) and lower (higher rate) branch

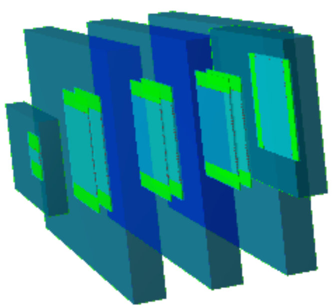


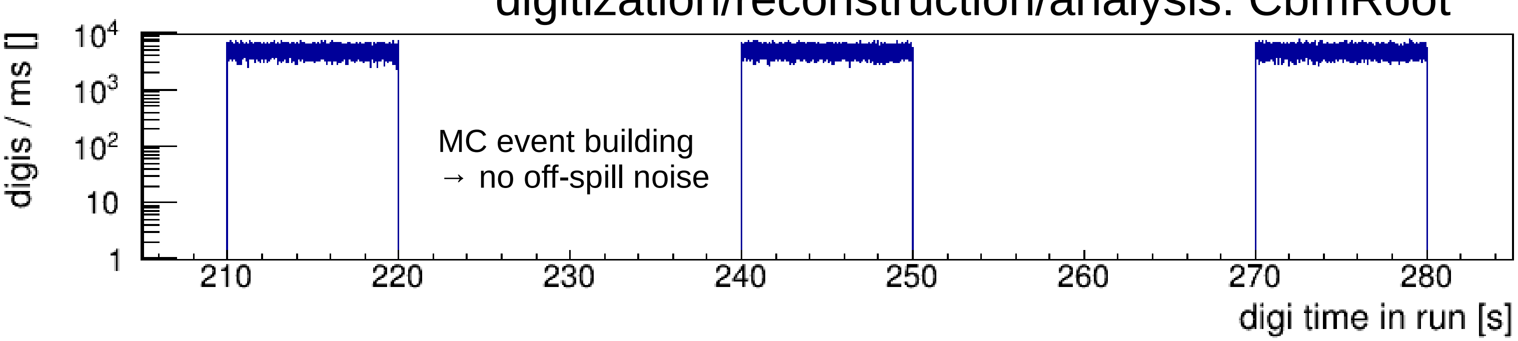


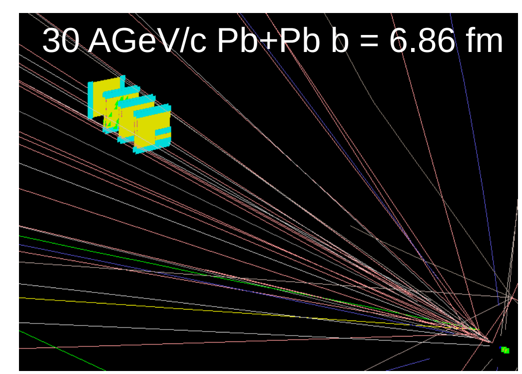
pictures by courtesy of I. Deppner

Full-scale in-beam test simulations

- Goal: Reproduce observed detector response features with maximal realism and minimal computational effort (→ parametrization)
  - implement inter-particle/inter-event signal interference
  - keep track of the full measurement history ("triggerless" simulation)
  - event building with "software" triggers → CBM free-streaming DAQ
- Software infrastructure
  - collision seeds: UrQMD 3.3p2
  - Monte Carlo transport: GEANT 3.21
  - framework: FairRoot v-18.06 with FairSoft may18
  - digitization/reconstruction/analysis: CbmRoot

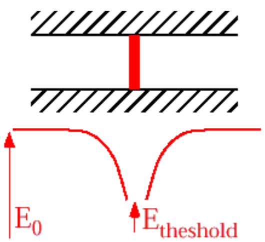






Particle memory and signal interference

- Ansatz: The induced charge spectrum accessible to the n-th particle at coordinates ($\mathbf{x}_n$,t_n) follows the probability distribution of



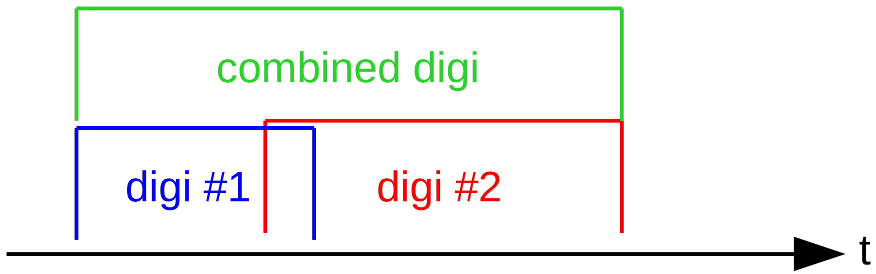
M. Abbrescia, “Improving rate capability of Resistive Plate Chambers”, RPC2016

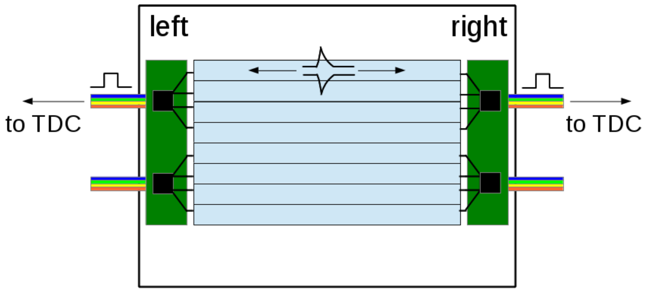
$$Q_{\mathrm{ind},n} = \left[1 - \sum_{i=1}^{n-1} \left\{ \frac{q_{\mathrm{ind},i}}{q_{\mathrm{max},0}} \times \frac{1}{1 + \left(\frac{\mathbf{x}_n - \mathbf{x}_i}{r_{\mathrm{imp}}}\right)^2} \times \exp\left(-\frac{t_n - t_i}{\tau_{\mathrm{MRPC}}}\right) \right\}\right] Q_{\mathrm{ind},0}$$

  - r_{imp}: spatial extent of local E-field reduction
  - τ_{MRPC}: relaxation time of local E-field restoration

- The repeated summation of n-1 terms has complexity $O(n^2)$!

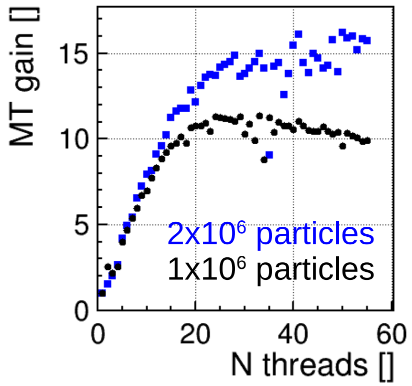
- The (pre-amplified) induced signal is discriminated and digitized yielding a “digi” object with the leading-edge timestamp and the time over discrimination threshold (ToT). Digis overlapping in time are merged.



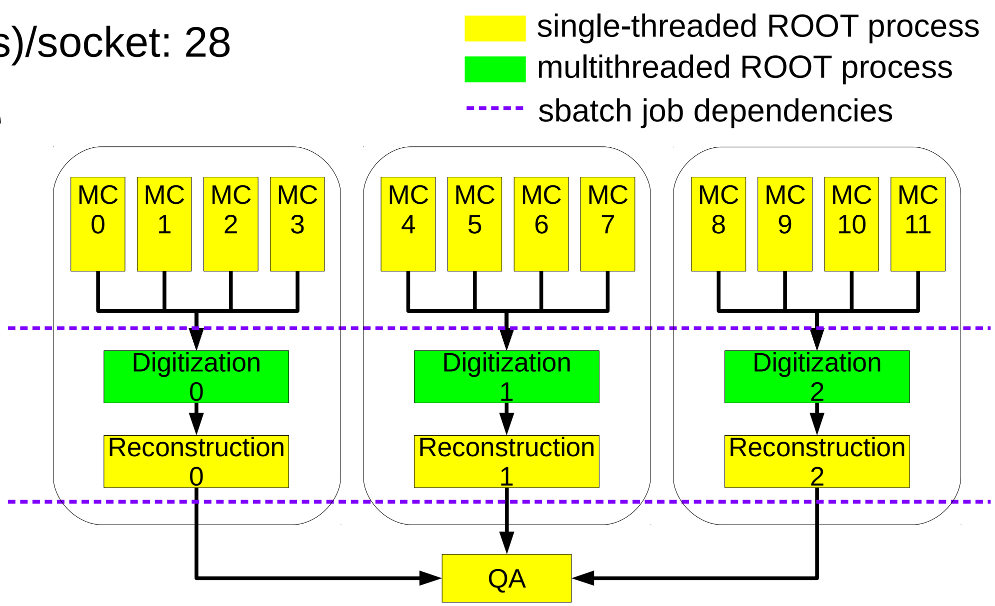


Parallelized spill processing

- The Kronos batch farm at FAIR/GSI provides 534 dual-socket compute nodes for large-scale batch processing of jobs (scheduler: Slurm).
  - 194x 2x Intel® Xeon® E5-2660 v3
    - #(physical) cores/socket: 10
    - #threads (logical cores)/socket: 20
  - 340x 2x Intel® Xeon® E5-2680 v4
    - #(physical) cores/socket: 14
    - #threads (logical cores)/socket: 28



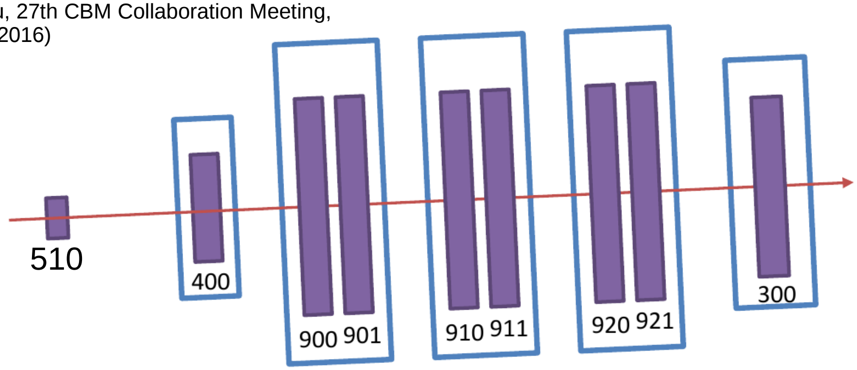
- With sufficiently large spill breaks the charge memory can be reset after each spill, i.e. many spills can be processed in parallel on the cluster.
- Memory limitation: 30×10^{6} particles (7d runtime on Kronos, 40 threads)!

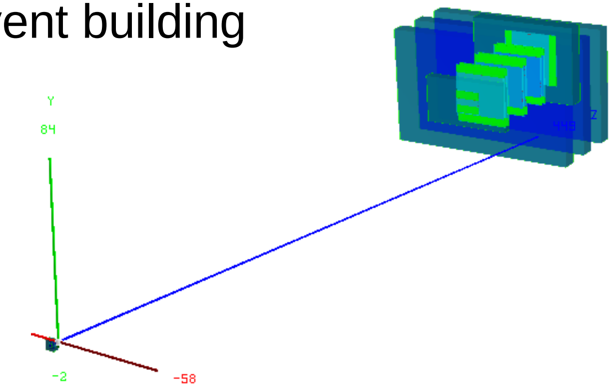


Simulated flux conditions in the SPS setup

- The computational limit for the large-area MRPC prototypes (~900 cm^2) is a sustained 10 s external particle flux of 2.7 kHz/cm^2 (total flux: x1.2).
- In the upper (lower rate) branch of the setup, fluxes of 2.2 kHz/cm^2 on these prototypes (4.5 d) were estimated with scintillation scalars.
- Hits on several such counters are required for reconstructing reference tracks to predict (X, Y, T) coordinates of corresponding hits on a counter declared detector under test (DUT). → start with 1 kHz/cm^2 (3x 23 h)
  - beam intensity: 1.3x10^6 Hz; 10 s flat-top time, 30 s accelerator cycle
  - tracking setup: 5-1-0 – 4-0-0 – 9-0-1 (float glass) – 9-2-0 – 9-2-1
  - pre-calibrated digis, Monte Carlo event building

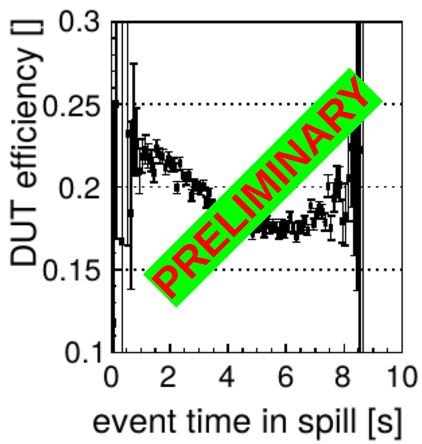
P. Lyu, 27th CBM Collaboration Meeting, GSI (2016)

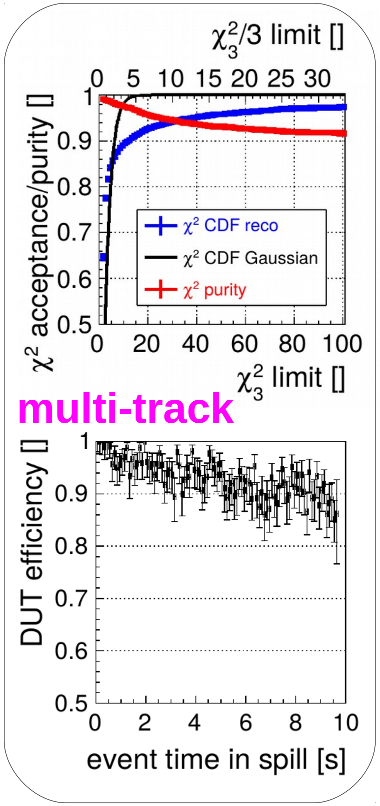


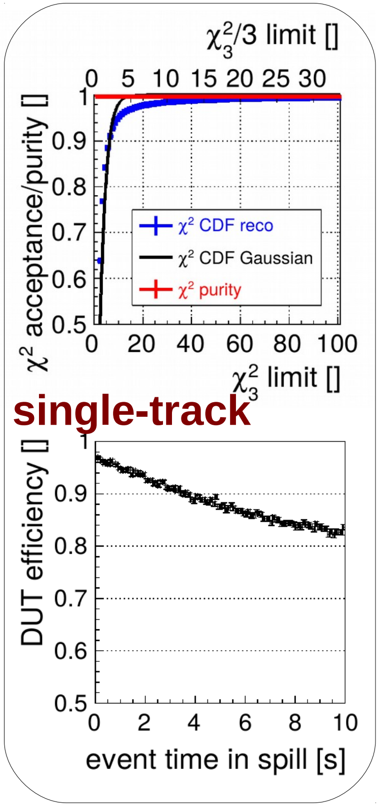


Multi-track flood-illumination response

- Under the CERN-SPS conditions, a large-area counter sees - on average - 8 external charged particles per event.
- To reduce matching impurities between reference tracks and DUT hits the matching acceptance window defined by a χ^2-like distance measure of deviations in (X, Y, T) should be narrow.
  - small χ^2 → lack of statistics!
- The deviations between a purely Gaussian response function and the simulated one can partially be traced back to distortions due to signal interference.
- A degradation effect as a function of time in spill is observed in actual flood-illumination data from CERN-SPS.

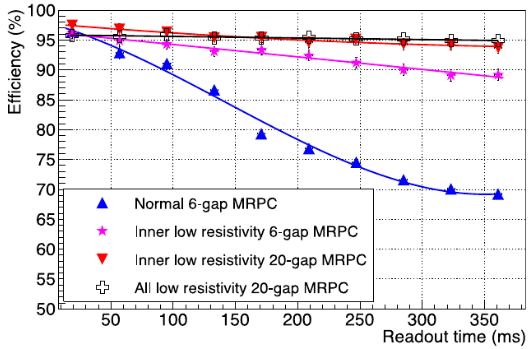




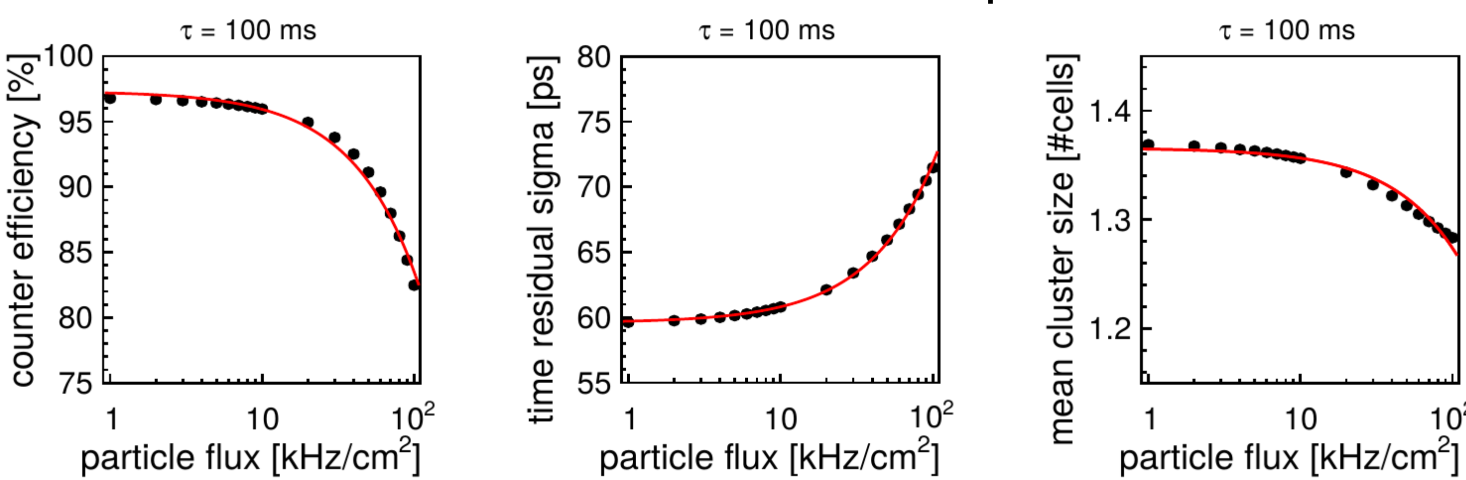


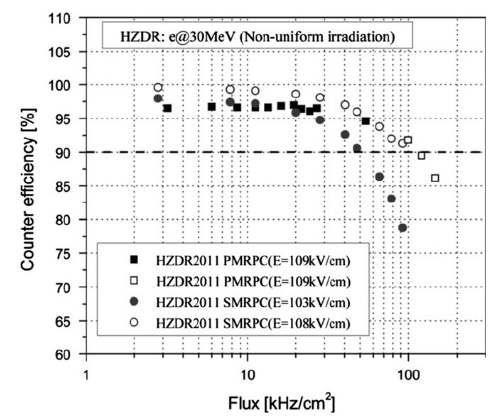
Single-track spot response

- The response degradation as a function of irradiation time can be studied much cleaner with MRPCs which are homogeneously (spot-)illuminated with single electrons/pions.
- The spot illumination removes the particle memory limitation and allows for simulating much higher fluxes.
- Without precisely adjusting counter parameters a qualitative agreement in (linear) response degradation as a function of increasing particle flux is observed with data measured at ELBE in April 2011.



Z. Liu et al., Nucl. Instrum. Meth. A **928**, 7 (2019)





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

C. Simon et al., CBM Progress Report **2017**, 141 (2018)

Summary and Outlook

- An MRPC digitization scheme for time-based (“triggerless”) detector simulations has been developed.
- A particle memory which causes the response function to degrade with irradiation time is a core building block of the computation model.
- On flood-illuminated large-area counters, sustained fluxes of a few kHz/cm^2 can be simulated while spot-illumination studies could be supported in software up to $100\ kHz/cm^2$ and beyond.
- The signal interference feature allows for simulating multi-track reaction environments as in the future CBM experiment at SIS-100.

- TODO: Qualitatively adjust the model parameters to a reference measurement (if possible also to the reaction data taken at CERN-SPS)!

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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- Ingo Deppner

bmb+f Großgeräte der physikalischen Grundlagenforschung

SEVENTH FRAMEWORK PROGRAMME

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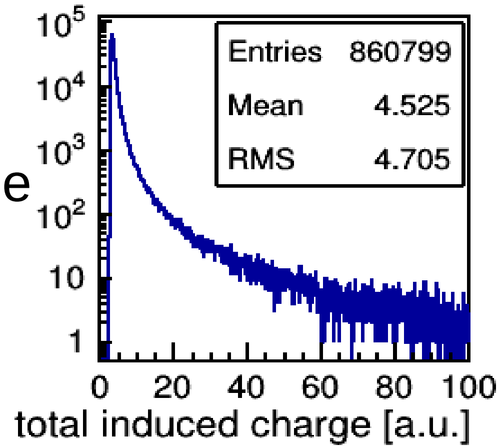
AIDA 2020

Backup

Parametric MRPC response description

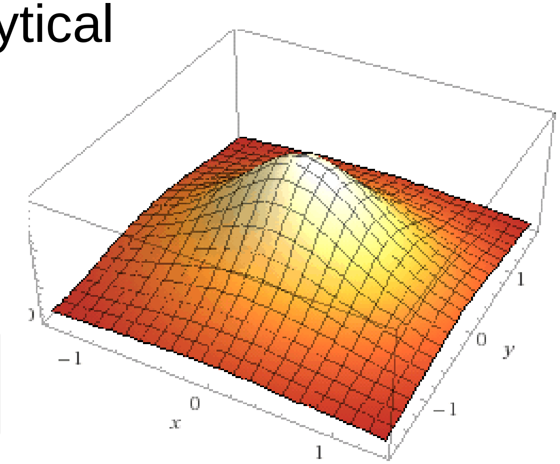
- Assumption: The total induced charge on the (undivided!) readout plane follows a Landau distribution.
  - TMath::Landau(Q_{ind},location,scale,kTRUE)



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

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

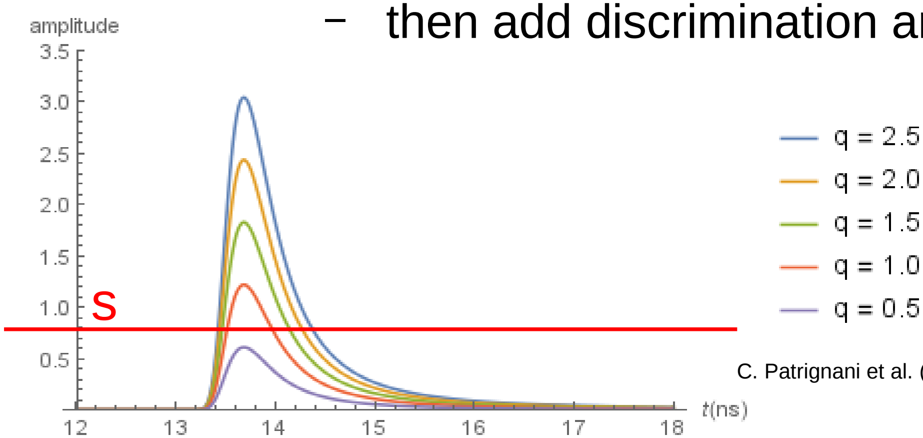
$$q_{\rm strip} = \frac{Q_{\rm ind}}{2\pi}\left[\arctan\left(\frac{x_{\rm high}\, y_{\rm high}}{R\sqrt{R^2+x_{\rm high}^2+y_{\rm high}^2}}\right) - \arctan\left(\frac{x_{\rm low}\, y_{\rm high}}{R\sqrt{R^2+x_{\rm low}^2+y_{\rm high}^2}}\right) - \arctan\left(\frac{x_{\rm high}\, y_{\rm low}}{R\sqrt{R^2+x_{\rm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



Wolfram|Alpha

Parametric MRPC response description

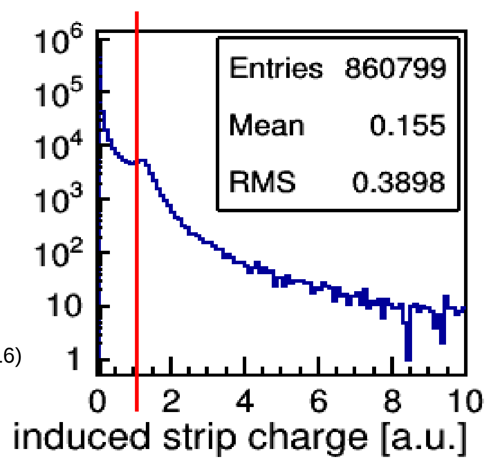
- Assumption: The (amplified!) signal is shaped according to a normalized Landau distribution multiplied by the strip charge.
  - $f(t) = q_{\mathrm{strip}} \times \mathrm{TMath::Landau}(t, \mathrm{mpv}, \mathrm{sigma}, \mathrm{kTRUE})$
- Assumption: Leading and trailing edge discrimination points in 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



Wolfram Mathematica 11

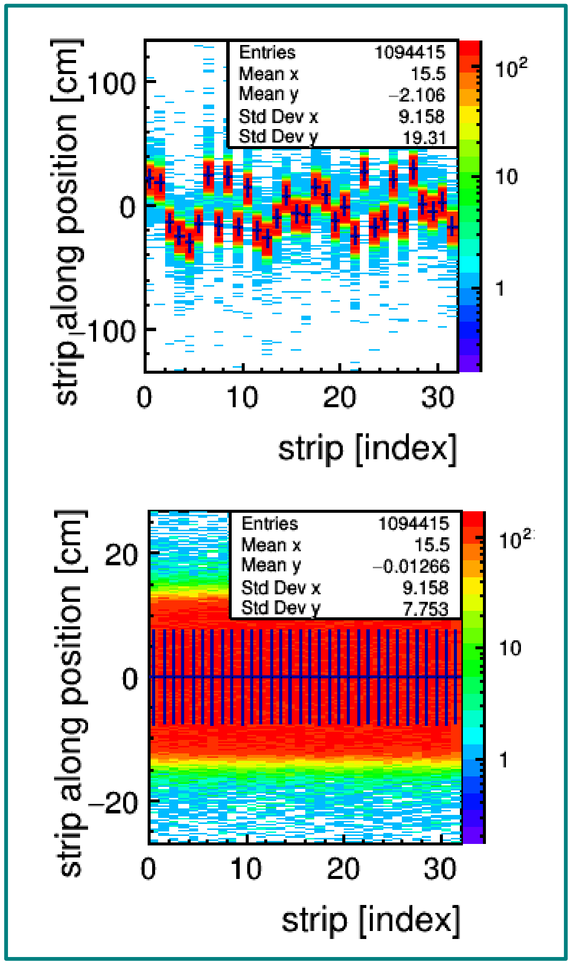
$$\sigma_t = \frac{\sigma_n}{(dS/dt)_{S_T}}$$

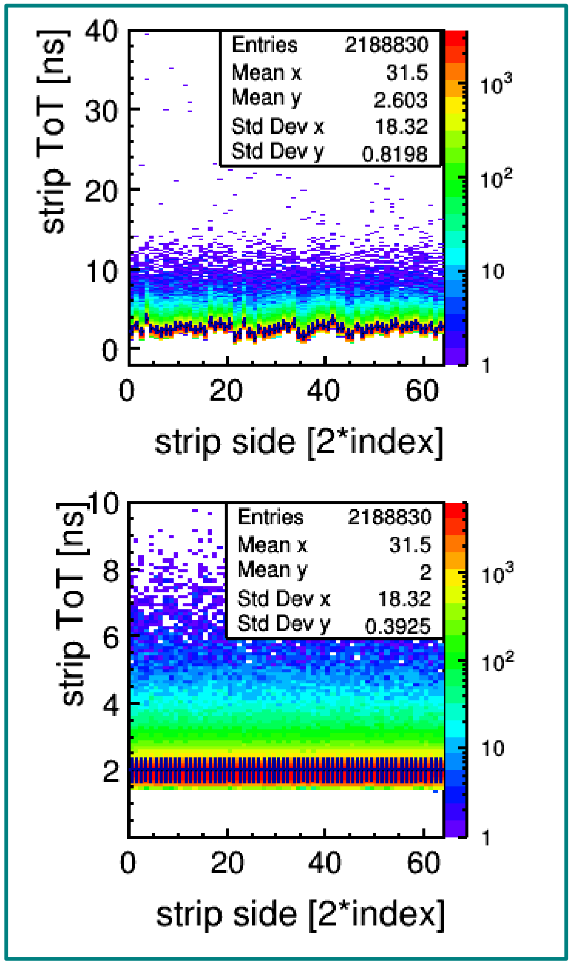
C. Patrignani et al. (Particle Data Group), Chin. Phys. C **40**, 100001 (2016)

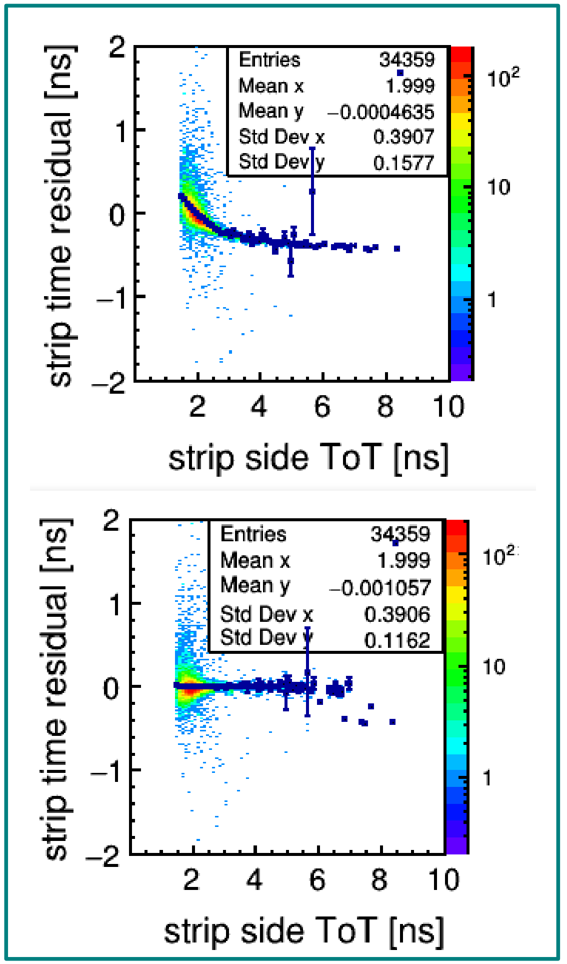


Run time offsets and time walk

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

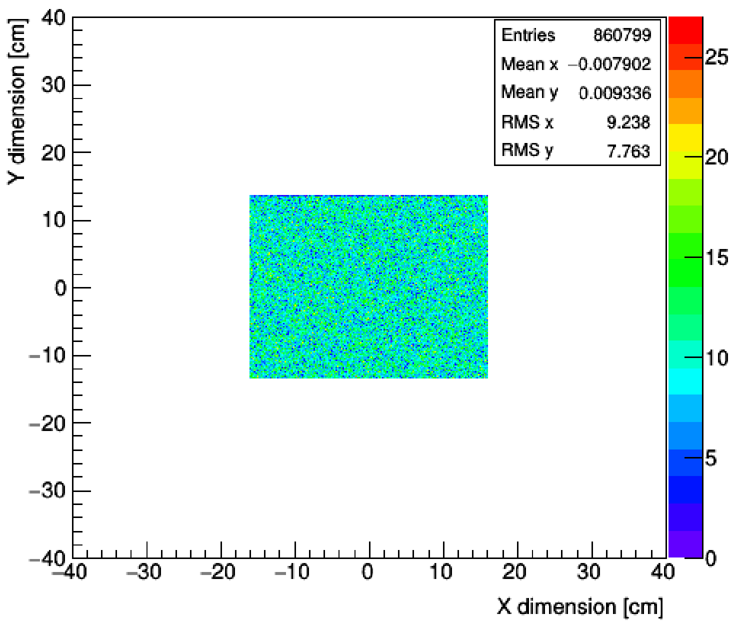






Model parameter adjustment

- 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, …).



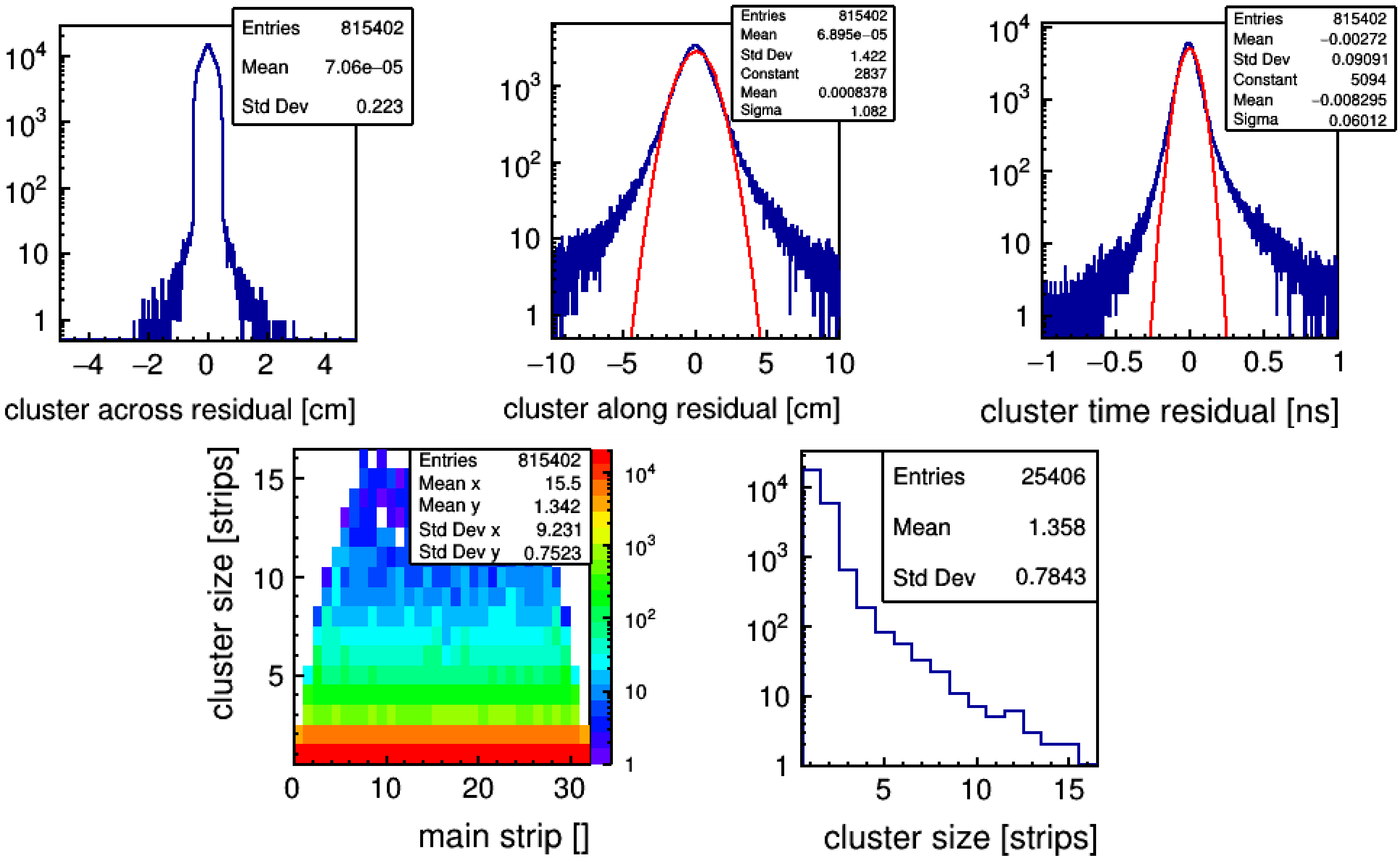

```
Calling chisq function...
      ------------------------------------------------------------------------------------
      total induced charge modus:          3.15677954
      total induced charge scaling:        0.29131190
      total induced charge distance:       0.48694227
      discrimination 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

Response residuals and cluster size

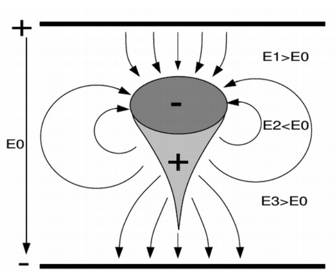


Analytic MRPC response descriptions

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

W. Riegler, C. Lippmann, R. Veenhof, Nucl. Instrum. Meth. A **500**, 144 (2003)

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



C. Lippmann, W. Riegler, Nucl. Instrum. Meth. A **517**, 54 (2004)

- 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

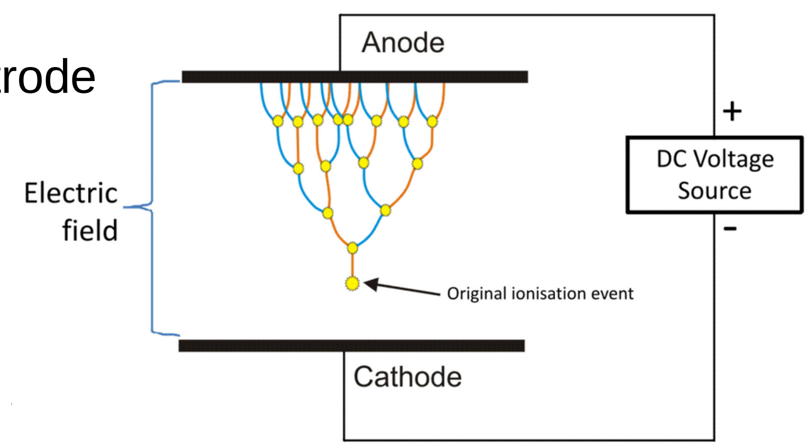
$$Q_{ind}(z) = \frac{E_W}{V_W}\frac{e_0}{\alpha-\eta}\mathrm{e}^{(\alpha-\eta)(d-z)} - 1$$

- timing precision

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

- gap efficiency

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

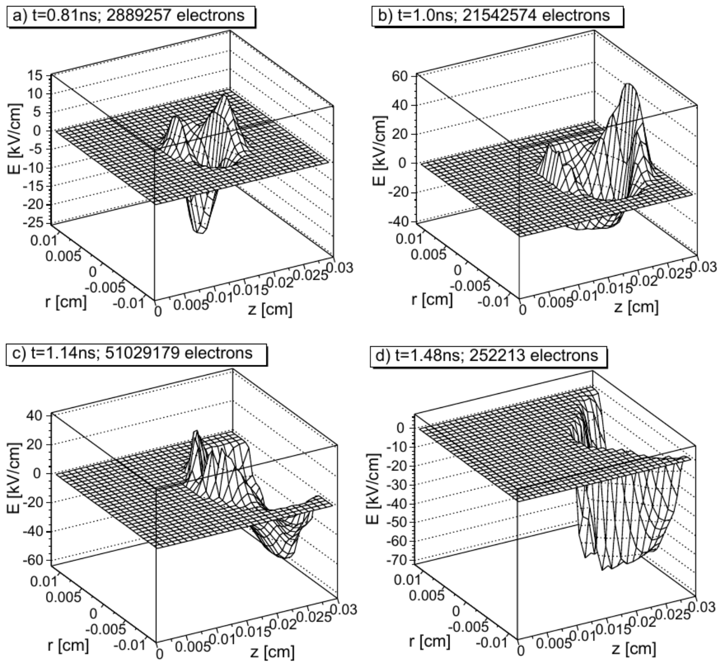


https://en.wikipedia.org/wiki/Townsend_discharge#/media/File:Electron_avalanche.gif

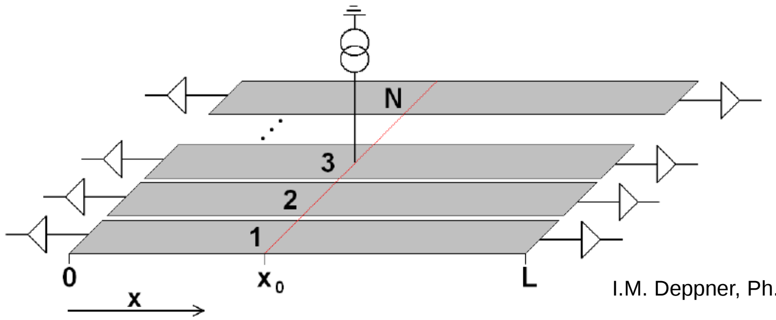
- But some experimental MRPC results (in particular the induced charge) cannot be reproduced by applying these expressions! Space-charge effects play a dominant role in MRPCs.

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



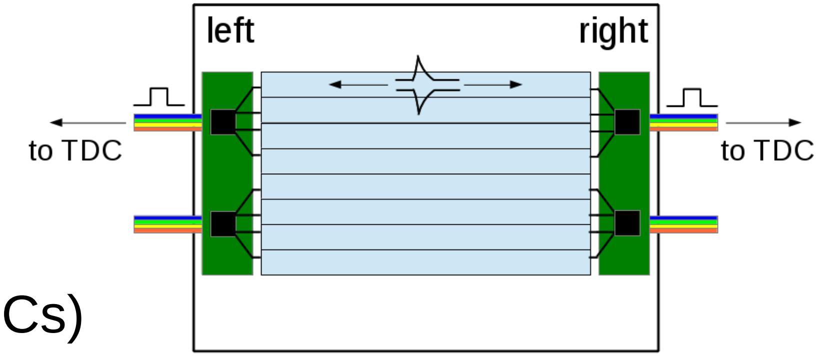
C. Lippmann, W. Riegler, Nucl. Instrum. Meth. A **517**, 54 (2004)

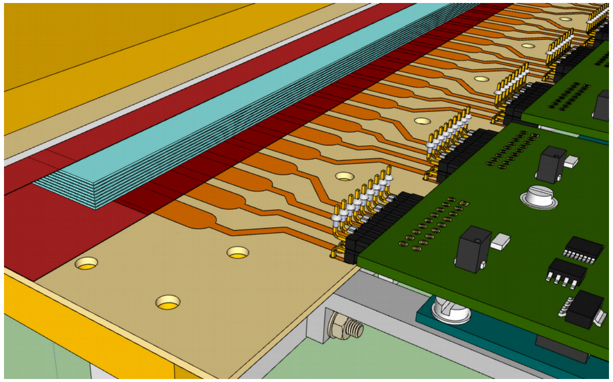


I.M. Deppner, Ph.D. Thesis, Heidelberg University, Heidelberg, Germany, 2013

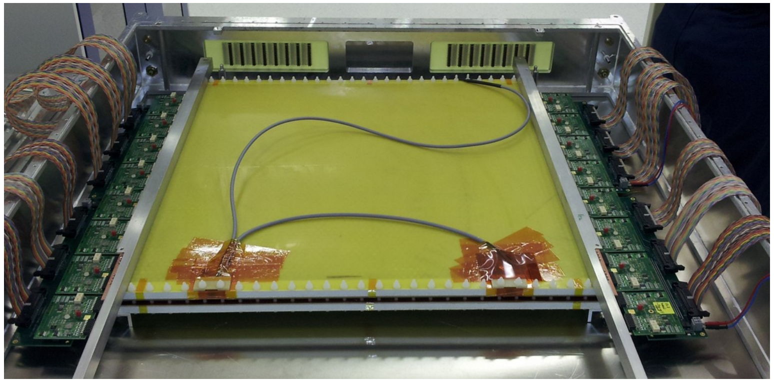
Basic MRPC readout principle

- 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., J. Instrum. **9**, C09028 (2014)



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