Comparison of Reconstruction Methods for a TPC with GEM Amplification and Pad Readout

Ralf Diener, FLC TPC Group

Outline:

- Data Sets and Measurement Setup
- Reconstruction Software and Resolution Calculation
- Resolution Results
- Monte Carlo Simulation: Performance and Systematics
- Conclusion and Outlook

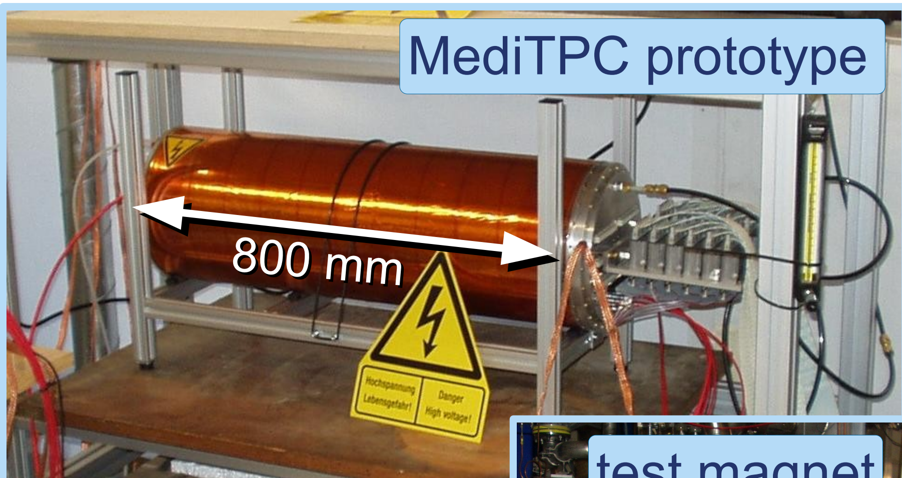
Universität Hamburg

bmb+f - Förderschwerpunkt Elementarteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

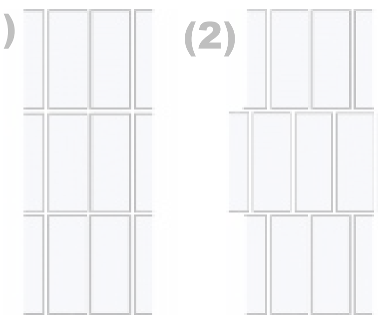
Measurement Setup and Data Sets

- Length: 800 mm , Ø : 270 mm
- Sensitive volume: 666.0 x 49.6 x 52.8 mm^3

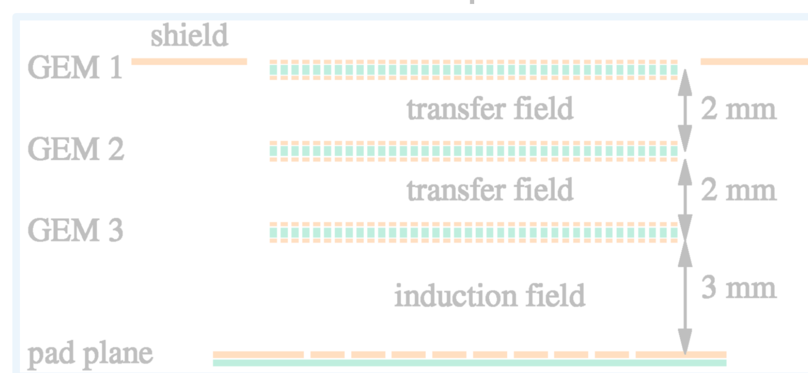


- Magnetic field up to 5.25 T (deviation<7%)
- Data Sets for 0, 1, 2 and 4 T

- Studies with cosmic muons
- Gas: TDR $Ar:CH_4:CO_2$ 93:5:2
  P5 $Ar:CH_4$ 95:5
- Pad layouts:
  - non-staggered (1)
  - staggered (2)
  24 columns, 8 rows
  pitch: 2.2 x 6.2 mm



- Triple GEM amplification setup:
  - Transfer fields : 1500 V/cm
    Induction field : 3000 V/cm
  - About 320 - 335 V per GEM



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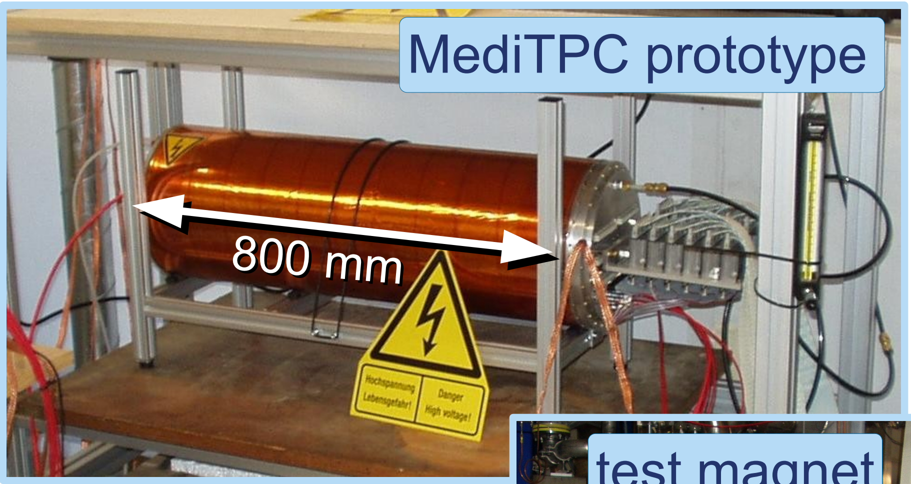

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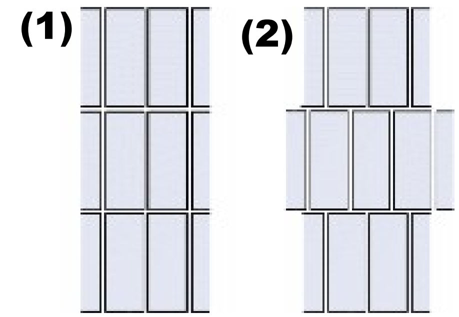

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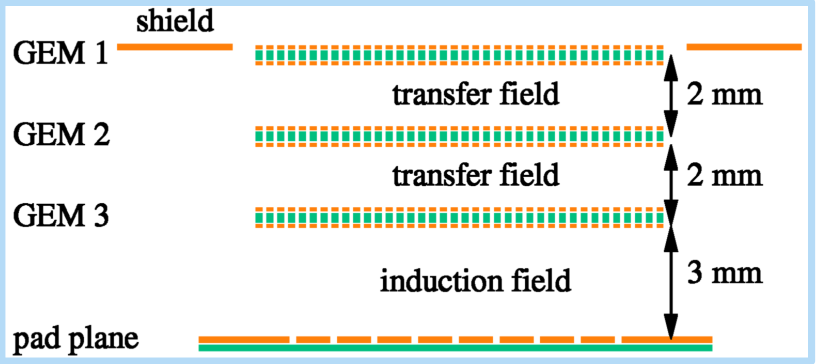


Reconstruction and Resolution

- **Reconstr. Software MultiFit**
  - 3 Step process: Hit Reconstruction → Track Finding → Track Fitting
- 2 Track Fit Methods implemented: (both straight line and circular arc)
  - Chi Squared Method: fits track hyphothesis to reconstructed hits ← Pad Response Correction (PRC) implemented in hit reconstruction
  - Global Fit Method(*): fits track hyphothesis to measured pulses (signals on the pads) → built-in PRC

(*): *"TPC Performance in Magnetic Fields with GEM and Pad Readout"* D. Karlen, P. Poffenberger, G. Rosenbaum (University of Victoria and TRIUMF, Canada) Nucl.Instrum.Meth. A555 (2005) 80-92

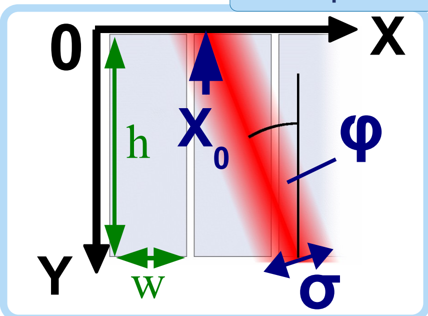
- Fit results: Intercept X_0, Slope X, Circ. Arc: Curvature, Global Fit: Width σ (can be fixed during fit)

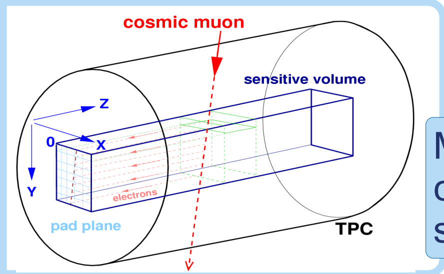
- **Point Resolution**
  - True track position not known → *Geometric Mean Method*
  - Two residuals calc. by MultiFit:
    - for track fit including the point (denoted "*distance*")
    - for track fit without the point (denoted "*residual*")
  - Resolution calculated from geometric mean of the width of both residual distributions:

$$\sigma = \sqrt{\sigma_{distance} \cdot \sigma_{residual}}$$

Proven for
-straight tracks: analytically
-curved tracks : MC studies

track parameters





MultiFit: coordinate system

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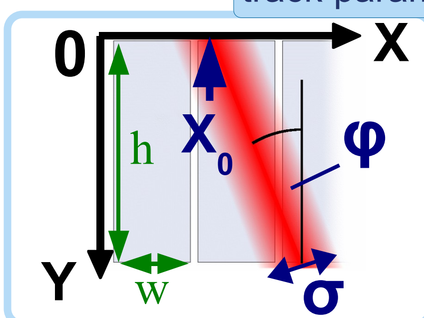

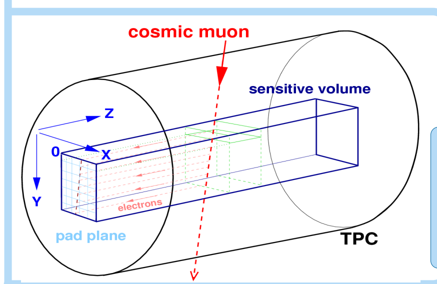

MultiFit: coordinate system

Point Resolution Studies: Introductory Remarks

- Cuts:
  - Angle: $\varphi <$ 0.1 rad (5.73°)
    $\Theta <$ ~0.44 rad (25.0°)
  - Exclude outer columns:
    only hits taken into account with (*nearly*) complete charge measured
  - Minimum of 6 hits per track

- Gas mixtures: TDR (Ar-CH4-CO2: 93-5-2)
  P5 (Ar-CH4: 95-5)

diffusion coefficient D
defocussing constant σ_0

$$\sigma = \sqrt{D z + \sigma_0}$$

derived from GARFIELD7 simulation (0ppm water content)

	P5		TDR	
B (T)	D (mm) 10^{-4}	σ_0 (mm²)	D (mm) 10^{-4}	σ_0 (mm²)
0	571	0,288	202	0,180
1	24,05	0,227	34,1	0,142
2	7,24	0,190	11,5	0,110
4	1,92	0,140	3,00	0,070

- Problem of measured data: top and bottom row (#1 and #8) show crosstalk with the surrounding shield →
  - resolution calculated with all 8 rows too pessimistic (contains not perfect hits)
  - resolution calculated with only 6 inner rows too optimistic (relation between fit parameters and data points too small)
- Both values will be presented
- 8 rows deliver more conservative results (upper limit)

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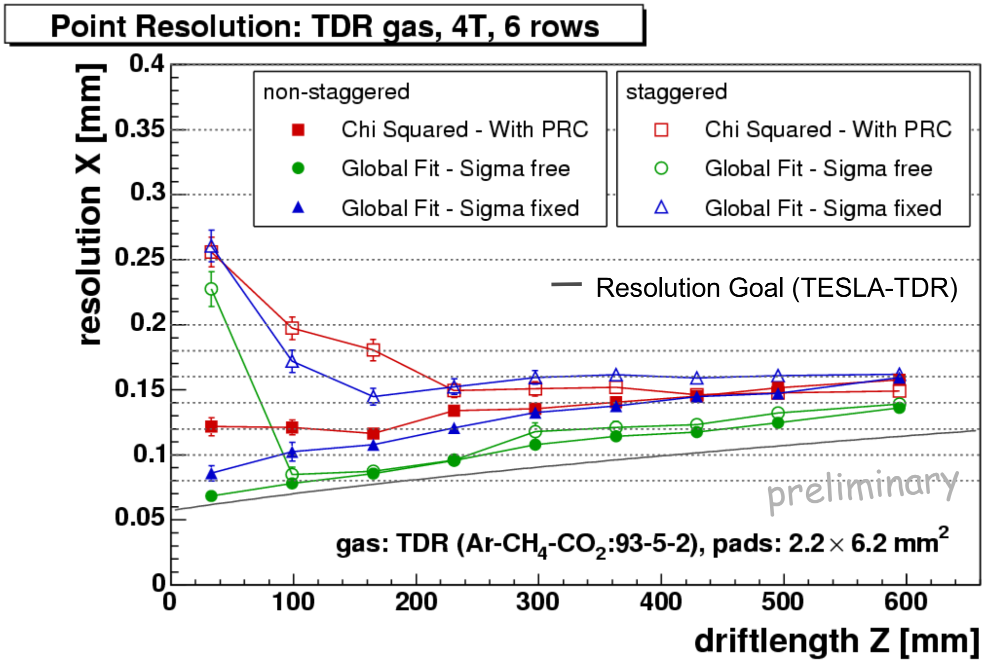
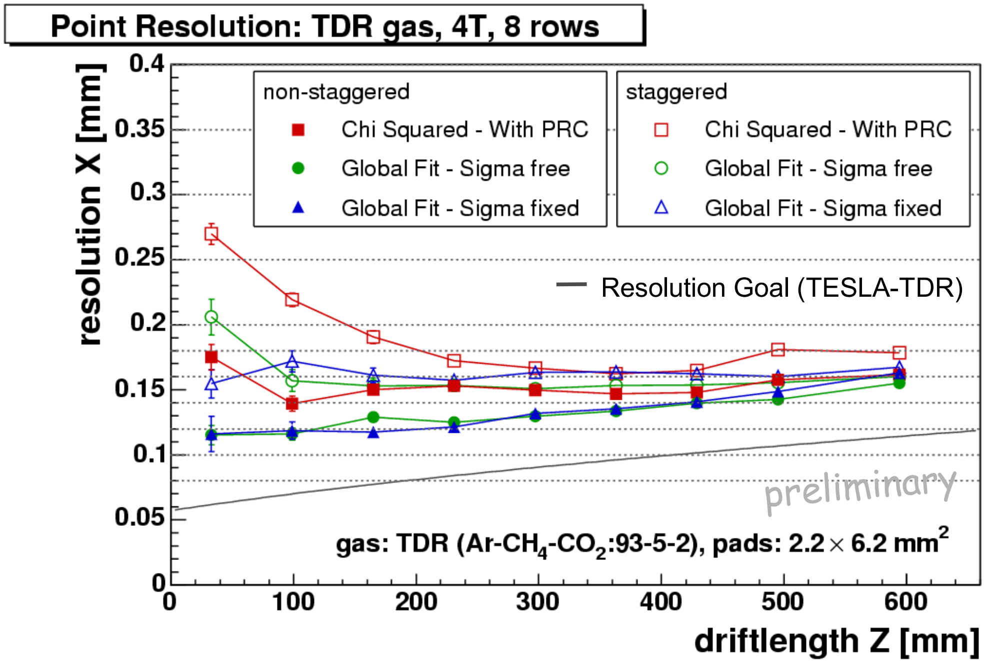
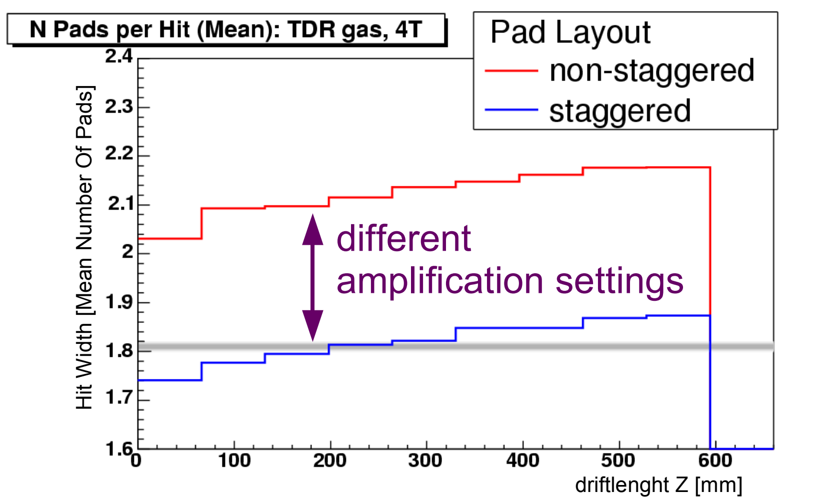
Point Resolution Results: TDR gas



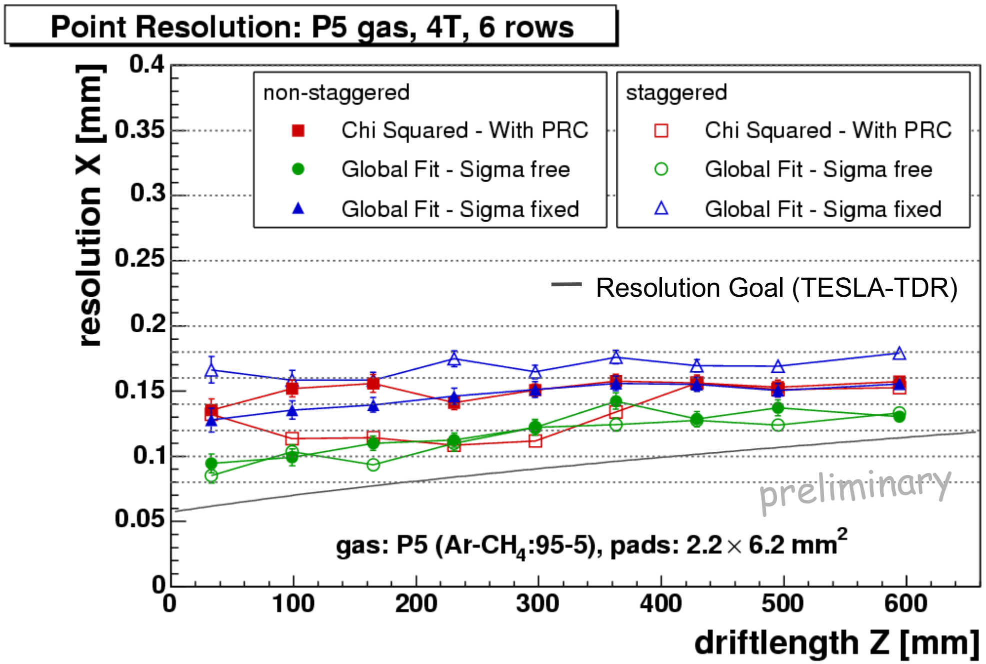


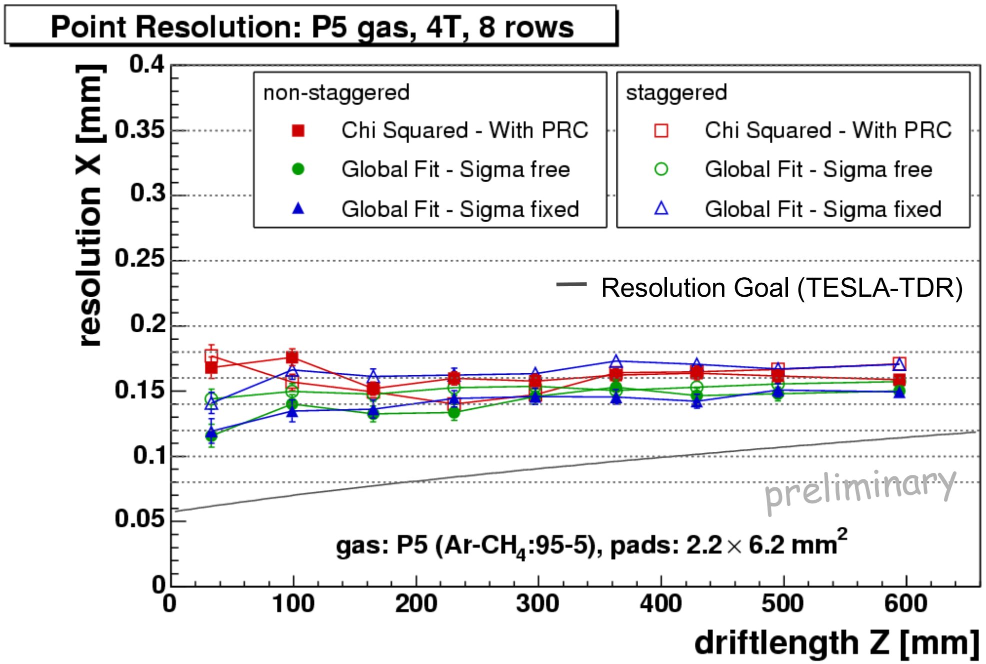
- Deviation between non-staggered and staggered results ← charge sharing too small
- Especially at short drift distances: results from staggered layout affected by charge sharing limit
- Results for 6 rows unreasonably good esp. Global Fit with free σ
- Resolution: ~ 120-180 μm (Z = 0-660 mm)



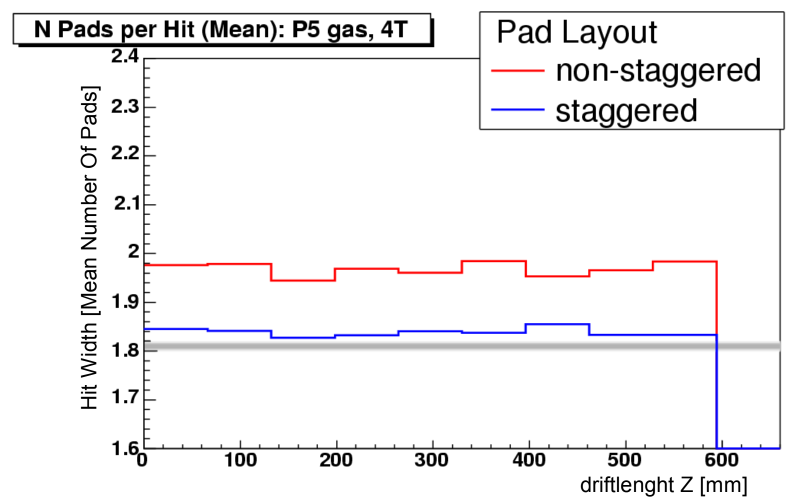
extracted from measurement runs

Point Resolution Results: P5 gas





- Again deviation between non-staggered and staggered results, but here smaller ← charge sharing too small
- Some results from staggered layout also increase at short drift distances, but much less (no big drift dependence of width)
- Results for 6 rows a bit better than for 8, but spread of results smaller for 8 rows
- Resolution: ~ 120-170 μm (Z = 0-660 mm)



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Monte Carlo Simulation

- Working Principle
  - Cosmic muons with realistic angular and energy spectra
  - Detector and trigger geometry

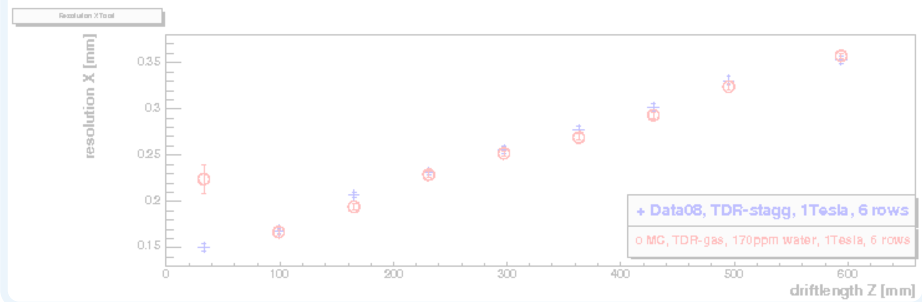
Gas properties: mixture, pressure, water

  - Primary ionization simulated with HEED ➔ 3D e⁻ distribution

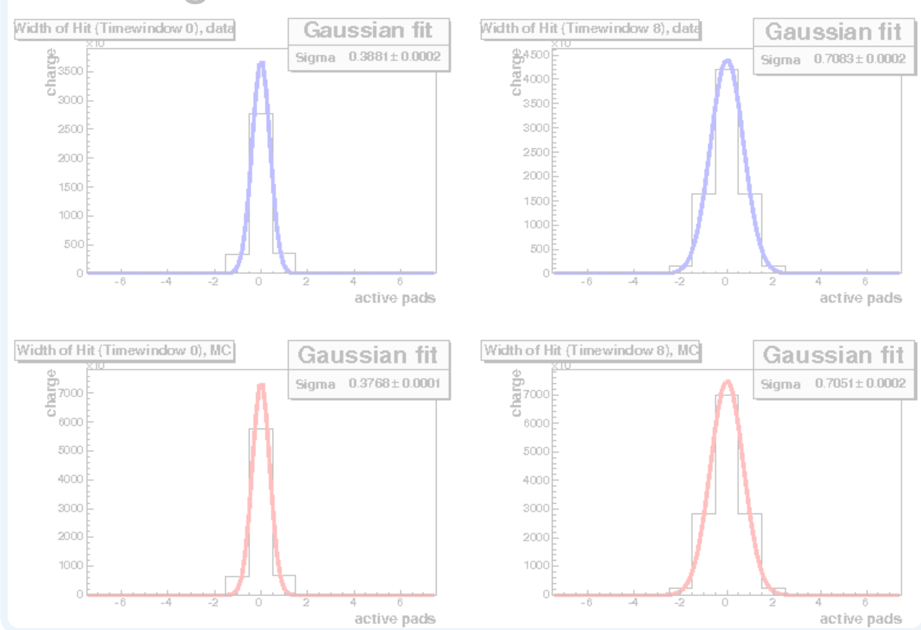
E- & B-field

  - Drift: Gaussian position smearing
    Parameters from GARFIELD
  - GEM amplification:
    - Electrons forced in nearest hole
    - Effective gain applied with Polya distributed smearing
    - Drift between GEMs as above
  - Collection on pad plane and readout
- Simulation for P5 gas, staggered pad layout and up to 19 rows available

- Performance:
  Red: Monte Carlo / Blue: Data
  - Resolution in X:



  - Signal Width:



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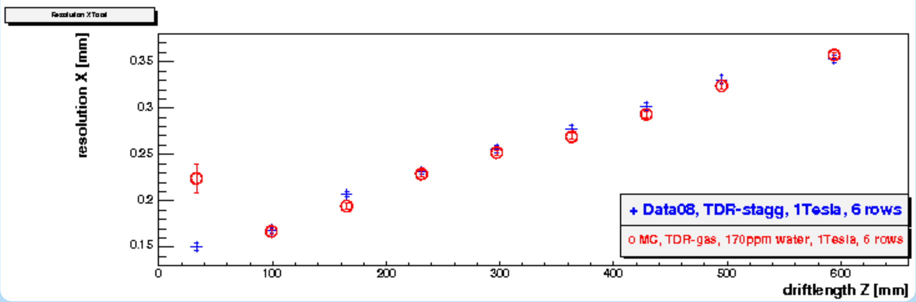

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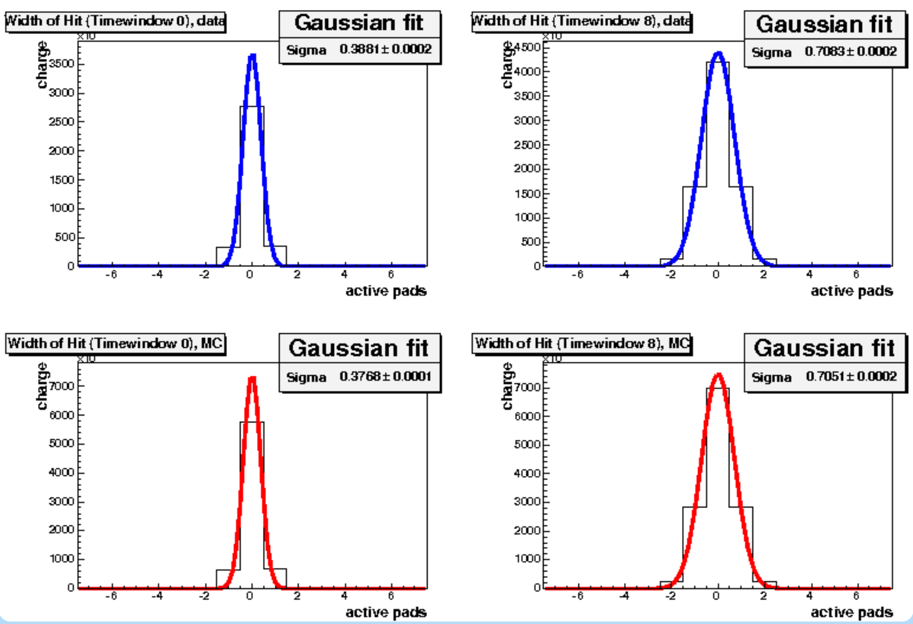
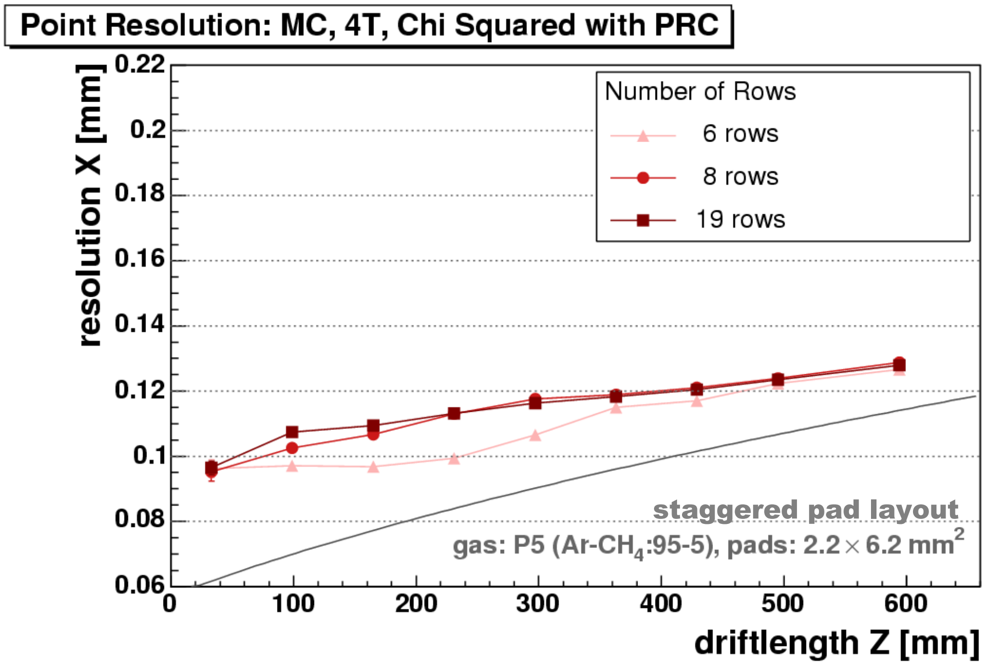
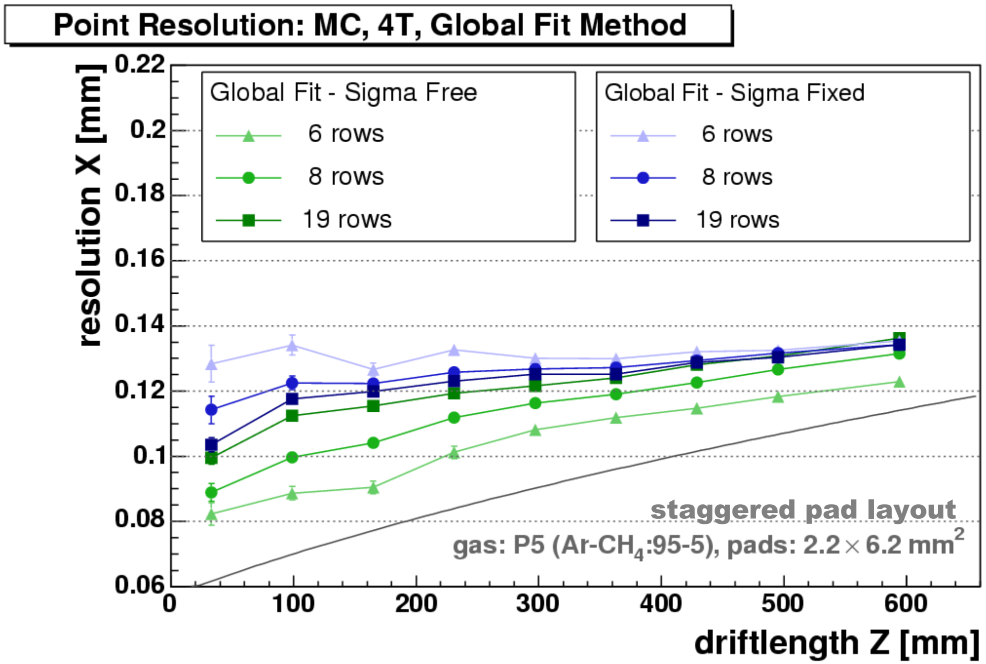


Influence of the Number of Rows



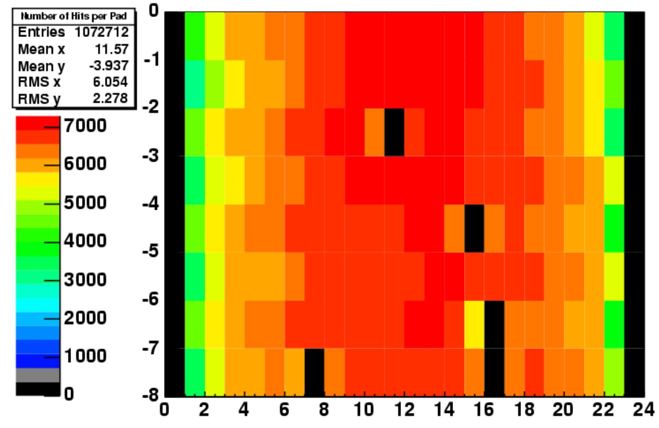


- Chi Squared Method:
  - 6 rows in comparison too good (impact of charge sharing and binning effect in Monte Carlo result in step at ~300mm: 2→3 pads per hit)
  - 8 rows already reasonable
  - 19 rows results show expected shape and are comparable with Global Fit results for 19 rows
- Global Fit with free σ:
  - 6 rows unreasonably good
  - 8 and 19 rows tend to more reasonable results
- Global Fit with fixed σ:
  - results conservative and scale with increasing number of rows
- Both flavors comparable at 19 rows

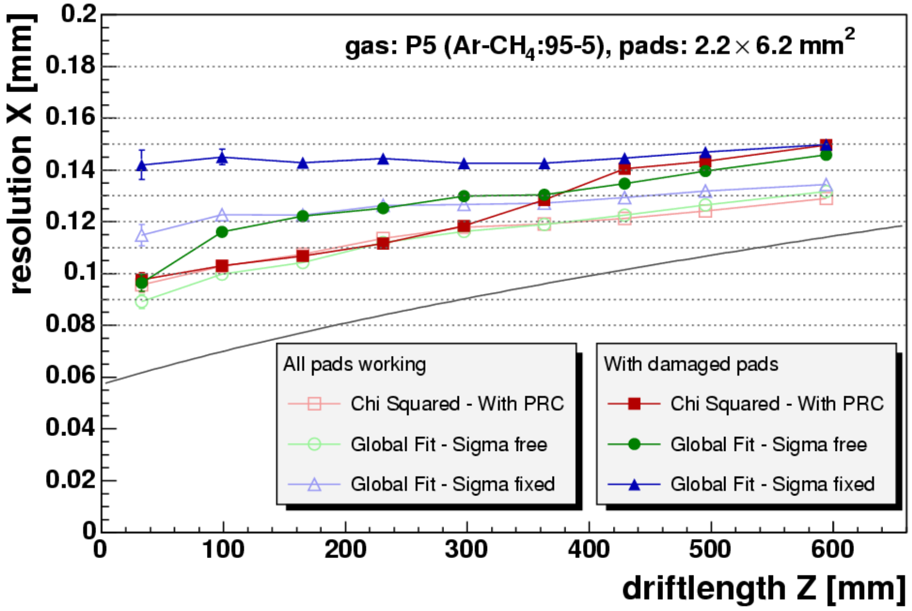
Influence of the Dead Channels

- 8 rows with dead channels
  (same 5 channels that were damaged in the corresponding measurement run)
- Chi Squared stable at low charge sharing, but deviation up to 20 μm at longer drift
  (strong step from binning effect in MC: at ~300 mm step from 2→3 pads per hit)
- Global Fit results also worsened up to 20-30 μm

Charge per Pad – 8 rows



Monte Carlo, 8 rows, 4T, staggered pad layout



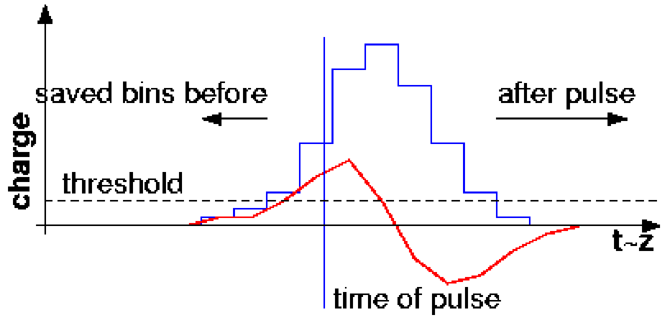
Conclusion and Outlook

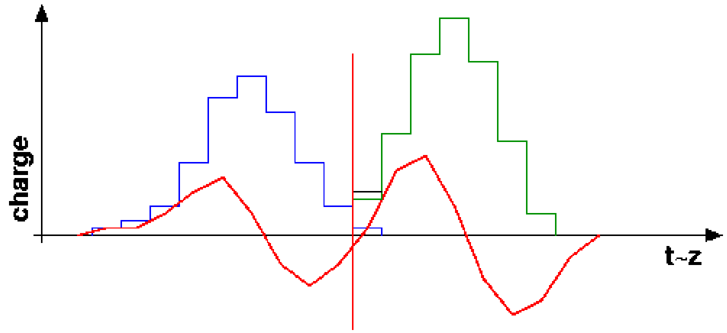
- Both the Chi Squared and the Global Fit Method seem to be applicable
- Chi Squared Method more stable at smaller number of rows
- Global Fit Method with free σ produces better resolution results, while with fixed σ it produces stable but conservative results
- Global Fit needs more CPU time
- The achieved resolution (~120-180 μm) is still quite far from the requirements, but there is a lot of room for improvement:
  - Pad size, number of rows, dead channels, ...
    (and gas mixture, amplification setup etc.)
- Point resolution below 100 μm seems achievable with adequate setup
- Setup with new pad plane is being built at the moment:
  - Pad pitch = 1.27 x 6.985 mm^2 , 14 rows
- New measurements start beginning 2007

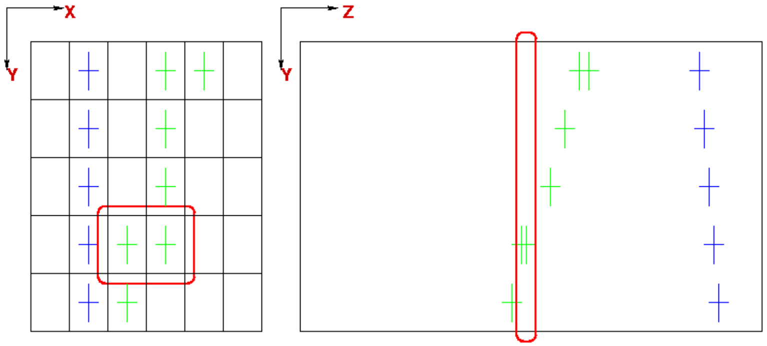
Appendix

MultiFit: Hit Reconstruction

- Find pulses in raw data:
  - detect pulses by threshold
  - time: inflexion point of rising slope
- Separation of pulses:
  - Change in slope
    (ignore variations in the order of noise)
- Combine pulses to hits:
  - start with biggest pulse
  - use recursive method in a time window
    - add the pulse if it is smaller
    - take care of damaged pads
  - calculate hit coordinates
    - x: center of gravity (charge)
    - y: center of the row
    - z: error weighted mean of time of pulses







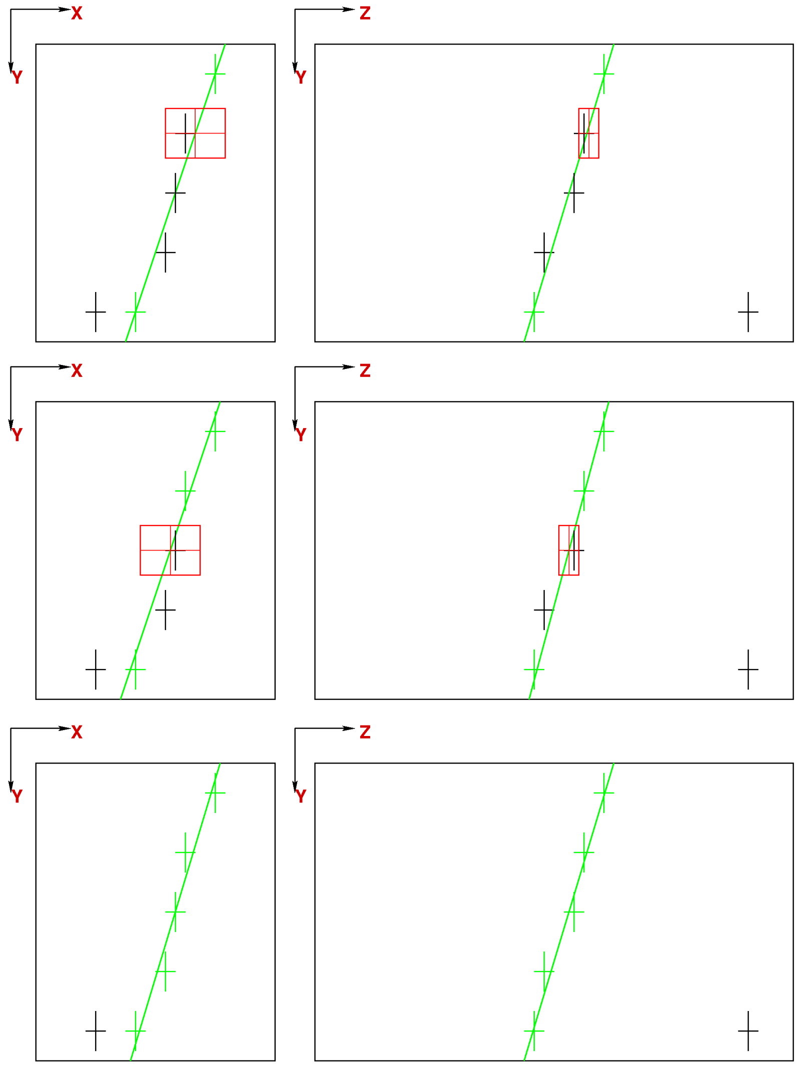
MultiFit: Track Finder

1) First track hypothesis from two points -> fit straight track search in a time window for a hit in the next row

2) After adding the hit:
   - re-fit the track with new hit
   - repeat this procedure in the next row...

3) ... until reaching the last row.

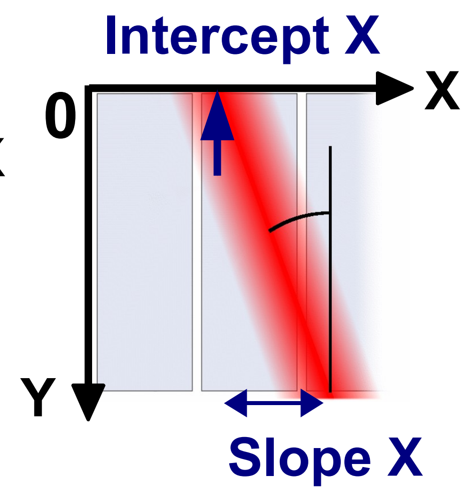
To avoid false tracks:
- only small gaps
- minimal number of hits



Track Fitting: Chi Squared Method

- **Straight line** $x = f(y) = a\,y + b$

  a: SlopeX
  b: InterceptX



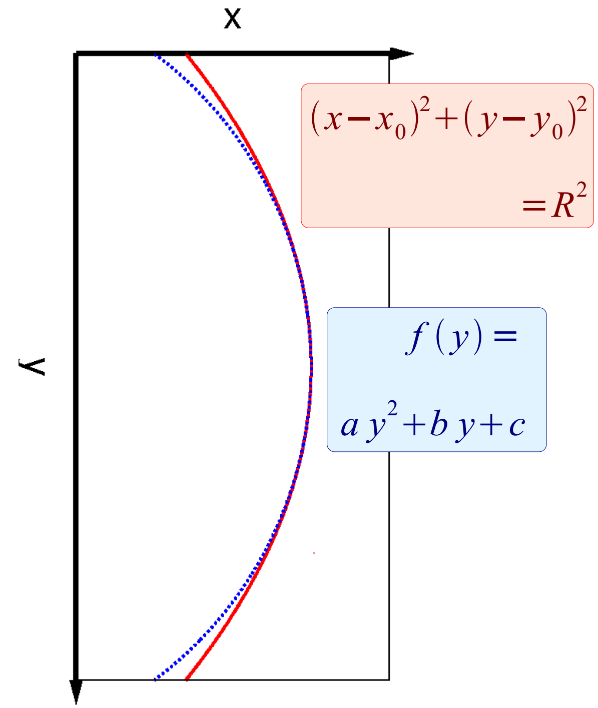
- **2nd degree polynomial:** $x = f(y) = a\,y^2 + b\,y + c$
  - rotated coordinate system

$$Radius\ R = \frac{a}{2}\ ,\ Curvature\ C = \frac{1}{R}$$

$$Center\ (x_0, y_0) \rightarrow solve\ equation\ system:$$

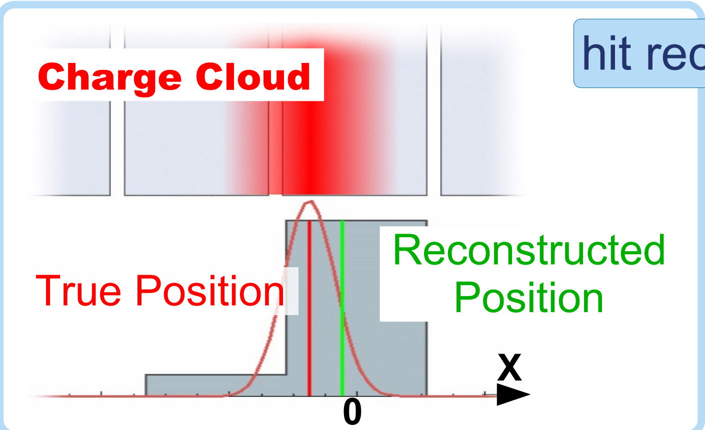
$$(x - x_0)^2 + (y - y_0)^2 = R^2 \quad for\ 2\ points\ (x_1, y_1), (x_2, y_2)$$

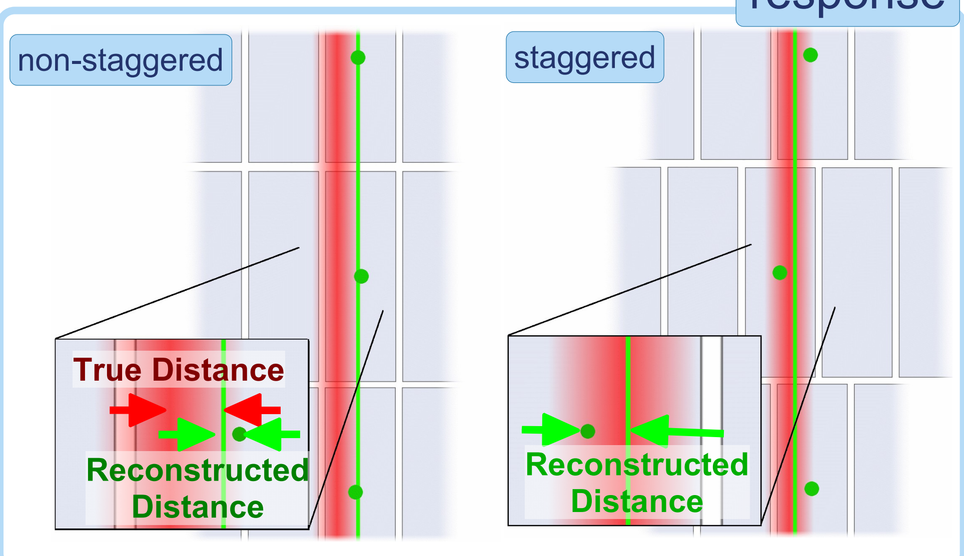
- **Circular arc:** $(x - x_0)^2 + (y - y_0)^2 = R^2$
  - rotated coordinate system
  - initialized with results from polynomial method
  - Fit function: $x = f(y) = x_0 \pm \sqrt{\frac{1}{C^2} - (y - y_0)^2}$



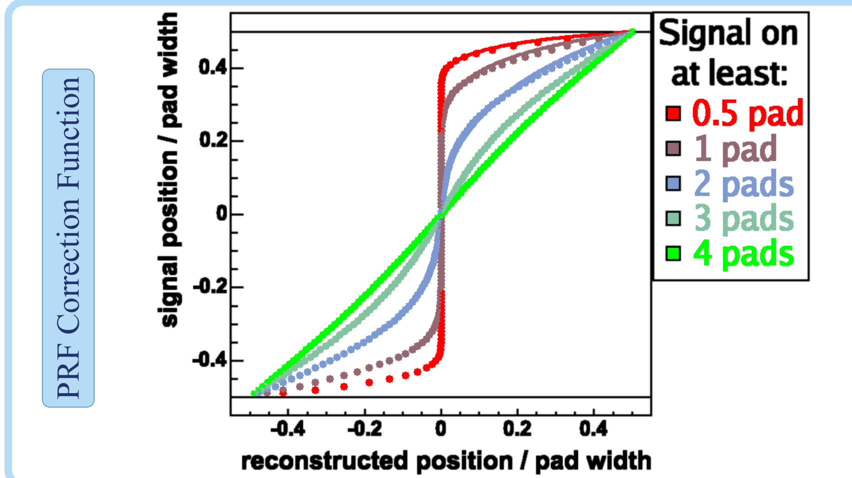
Chi Squared Fit Method: PRF Correction (PRC)

- Pad Response Function (PRF):
  not enough charge sharing →
  Center of Gravity method reconstructs hit towards the pad with the highest signal

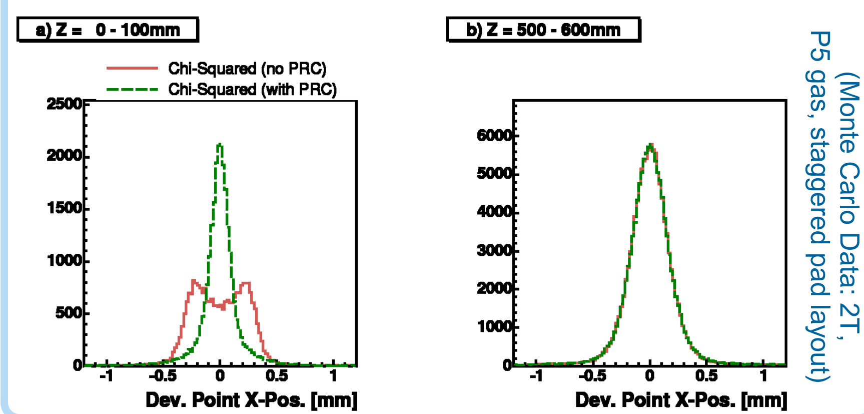




- Correction of the PRF by function depending on charge cloud width
  (→ needs diffusion and defocussing coefficients as input (*MAGBOLTZ* simulation))



- Performance: deviation: hit position ↔ MC track



PRC Implementation in MultiFit

- Pad Response Function (Gaussian charge cloud)

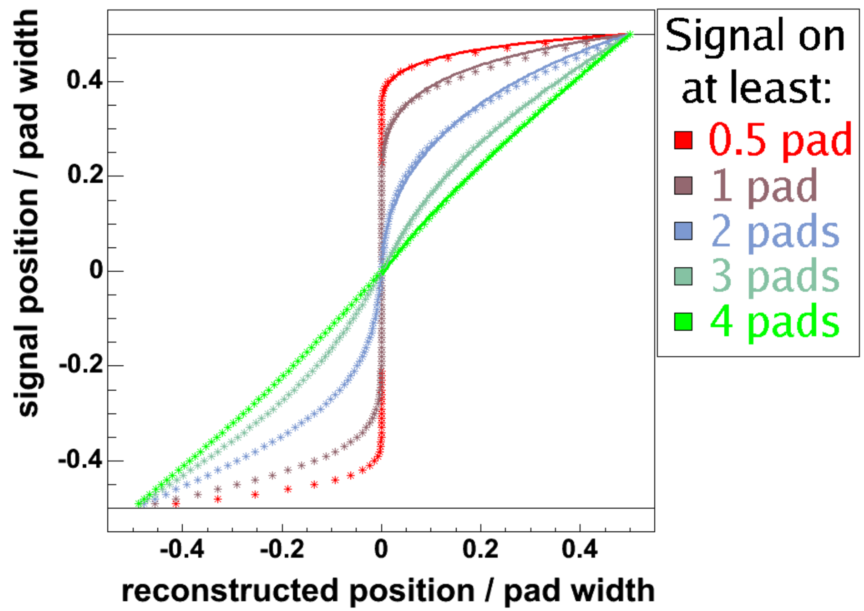
$$Q_{pad}(y)=\int_{-\infty}^{+\infty}\left(\Theta(\psi-\frac{\Delta}{2})*\Theta(-\psi+\frac{\Delta}{2})\right)\times\left(\frac{Q_{max}}{\sqrt{2\pi}\,\sigma_S}*\exp\left[\frac{-(y-\psi)^2}{2\sigma_S^2}\right]\right)d\psi$$

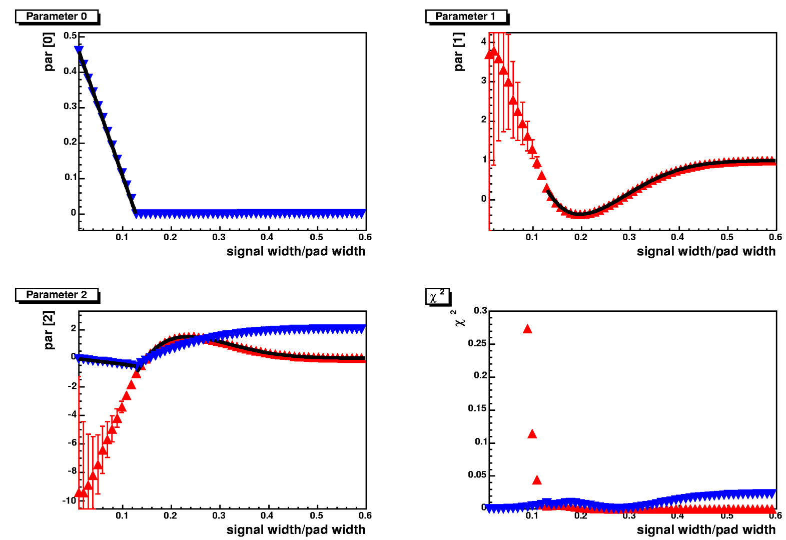
- Pad Response Correction

$$F_{noflat}=P_1x+P_2\sqrt{x}+\left(\frac{1-P_1}{2}-\frac{P_2}{\sqrt{2}}\right)\cdot\sqrt[3]{2x}$$

$$F_{flat}=P_0x+P_2\sqrt{x}+\left(\frac{1-2P_0}{2}-\frac{P_2}{\sqrt{2}}\right)\cdot\sqrt[3]{2x}$$

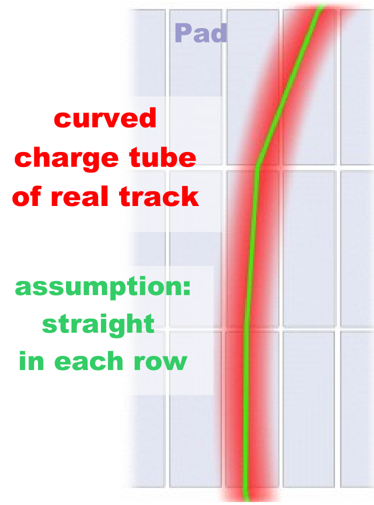
- Parameters: dependent on width σ
  - → fit appropriate polynomials to the parameter curves
  - → polynomials implemented in MultiFit
    needed input: diffusion and defocussing coefficients



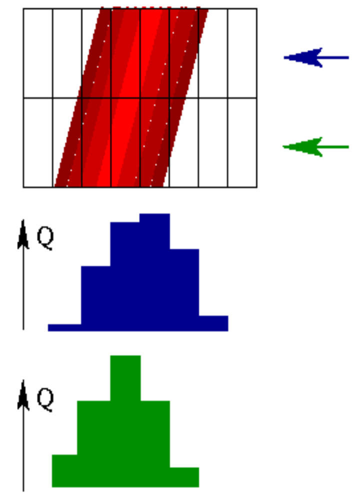


Global Fit Method: Basics

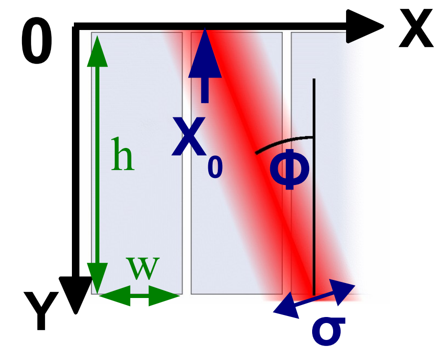
- Assumptions:
  - In each row the track can be described by a straight line



  - XY track fit uses a Gaussian model for charge cloud



- Three (four) parameter fit:
  - Intercept X_0 (x at y=0)
  - Azimuthal angle ϕ
  - Width of the charge cloud σ (can be fixed: calculated dependent on drift length per track and per row from diffucion and defocussing coefficient)
  - Curvature **C** (in case of curved track hypothesis)



Global Fit Method: Principle

- Likelihood function describing charge deposition per pad:

$L_i = p_i^{n_i}$, with $n_i = \frac{N_i}{G}$: number of primary e$^-$, N_i

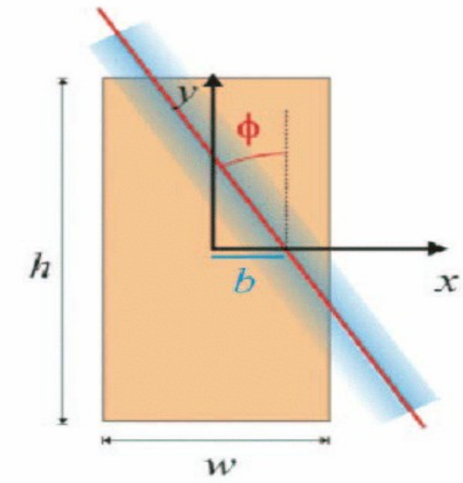
G : gain factor

and $p_i = \frac{Q_{\exp}}{\sum_{n=1}^{pads/row} Q_{\exp}}$ (probability function)

- Product of likelihood functions of all pads:

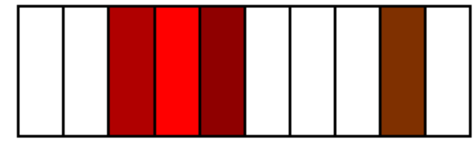
$$\ln L = \sum_{Pad} Q_{measured} \ln \left[\frac{Q_{expected}}{\sum_{Row} Q_{expected}} \right]$$

, with $Q_{\exp} = \int_{\frac{-h}{2}}^{\frac{h}{2}} dy \int_{\frac{-w}{2}}^{\frac{w}{2}} dx \; \frac{1}{2\pi\sigma} e^{\frac{[(x-X_0)\cos(\phi)+y\sin(\phi)]^2}{2\sigma^2}}$



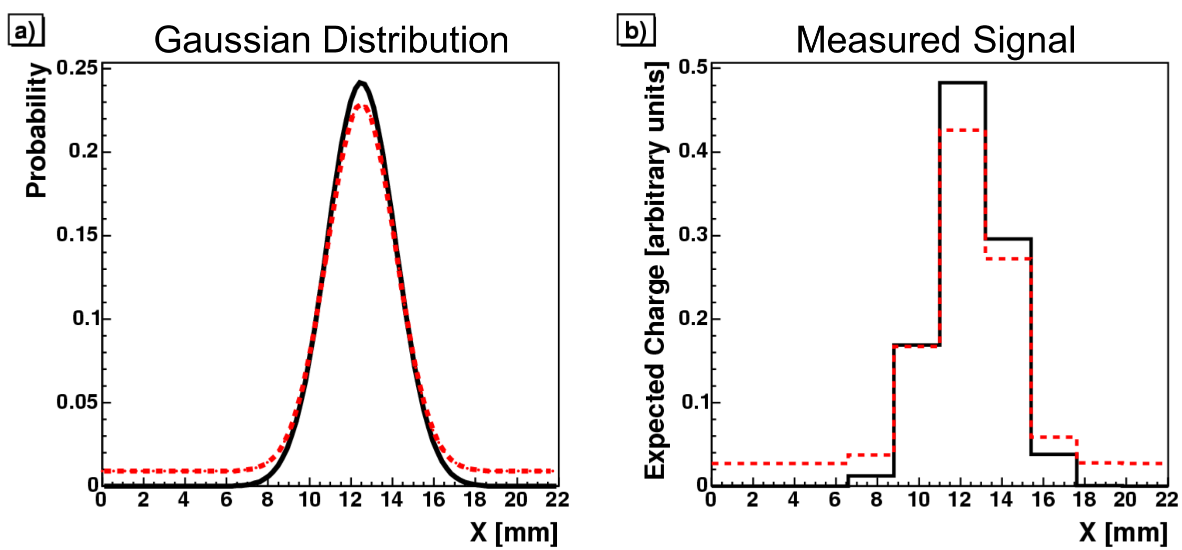
Global Fit Method: Noise Value

- In original, Canadian implementation (JTPC): no clustering → problems with noise pulses



- To make fit more robust, assign a higher probability for measuring a signal to all pads by introducing a constant offset: noise value N

$$p_i \rightarrow \frac{p_i + N}{1 + N \cdot n_{row}} \qquad \rightarrow \qquad \ln L = \sum_{Pad} Q_{measured} \ln\left[\left(\frac{Q_{expected}}{\sum_{Row} Q_{expected}} + N \right) / (1+N) \right]$$



Example: pad row with 10 pads, pitch: 2.2mm

—— without noise value
---- with noise value N=0.01