High resolution tracking with silicon strip detectors for relativistic ions

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Outline

- **Introduction**
- **Experimental setup**
  - ^{12}C **ion beam at 1.5** GeV/u
  - **Strip detectors, 300** μm **thick**
  - **VA high-dynamic range chip**
- **Strip cluster :**
  - **Reconstruction**
  - **Characteristics**
- **Energy loss straggling :**
  - **Landau-Vavilov theory**
- **Spatial resolution**
  - η **spectra**
  - **Tracking simulations**
- **Multiple scattering**
  - **Molière theory**
  - **GEANT Gaussian approximation**
  - ^{12}C **with 1, 2** mm **Pb targets**

Introduction

Ions of charge ze traversing a medium

- **Energy loss :**
  Bethe-Bloch formula
  $$\frac{1}{\rho}\frac{dE}{dx} = z^2 \frac{L}{\beta^2}\left[\ln\left(\frac{2m_e c^2 \beta^2 W_{max}}{l^2(1-\beta^2)}\right) - 2\beta^2\right]$$
  Thick absorber : Gaussian, width $\propto z$
  Thin absorber : Landau-Vavilov theory

- **Multiple Coulumb scattering :**
  Width of the projected angular distribution
  $$\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

- **Production of secondary particles :**
  Delta-ray production
  Nuclear fragmentation

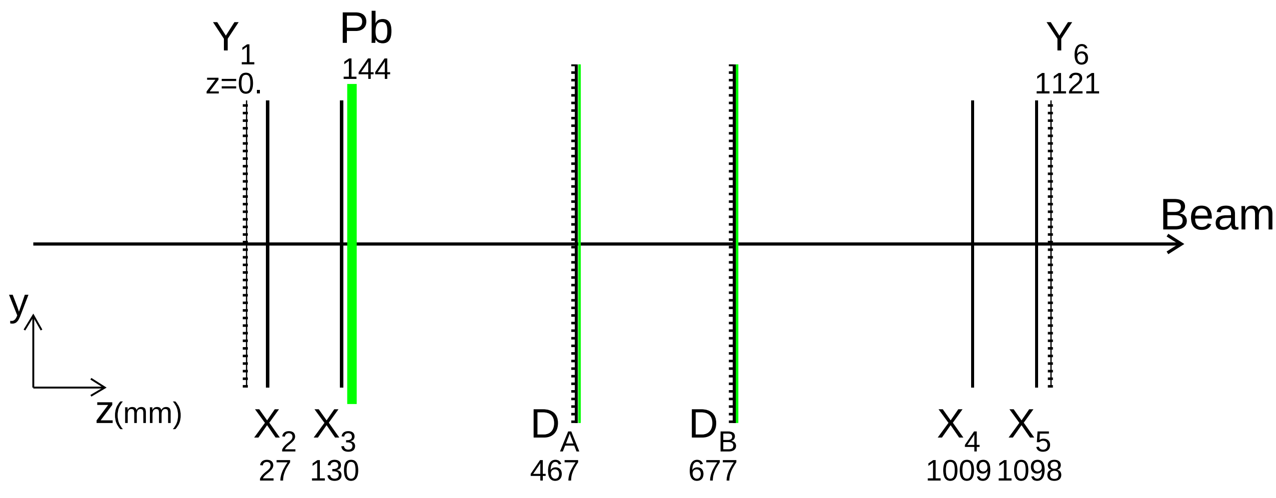
Experimental Setup

^{12}C Ion beam, GSI SIS facility:

- **Beam Energy : 1.5** GeV/u
- $E(^{12}C) = \mathbf{29.18}$ GeV,
  $\gamma = \mathbf{2.16}, \beta = \mathbf{0.92}$
- $\delta p/p < \mathbf{2} \times \mathbf{10}^{-4}$

Detectors :

- **Reference detectors (20×20** mm^2**)**
  20 mm **strips, 100** μm **pitch**
- **Ladders : two wafers (72×41** mm^2**) bounded**
  p^+ **S-side: 2** $\times$ **41** mm **strips, 110** μm **pitch**
  n^+ **K-side: 72** mm **strips, 208** μm **pitch**
  rerouted by kapton cable
- **VA-hdr (AMS version) readout chip**
- **12-bit ADC**

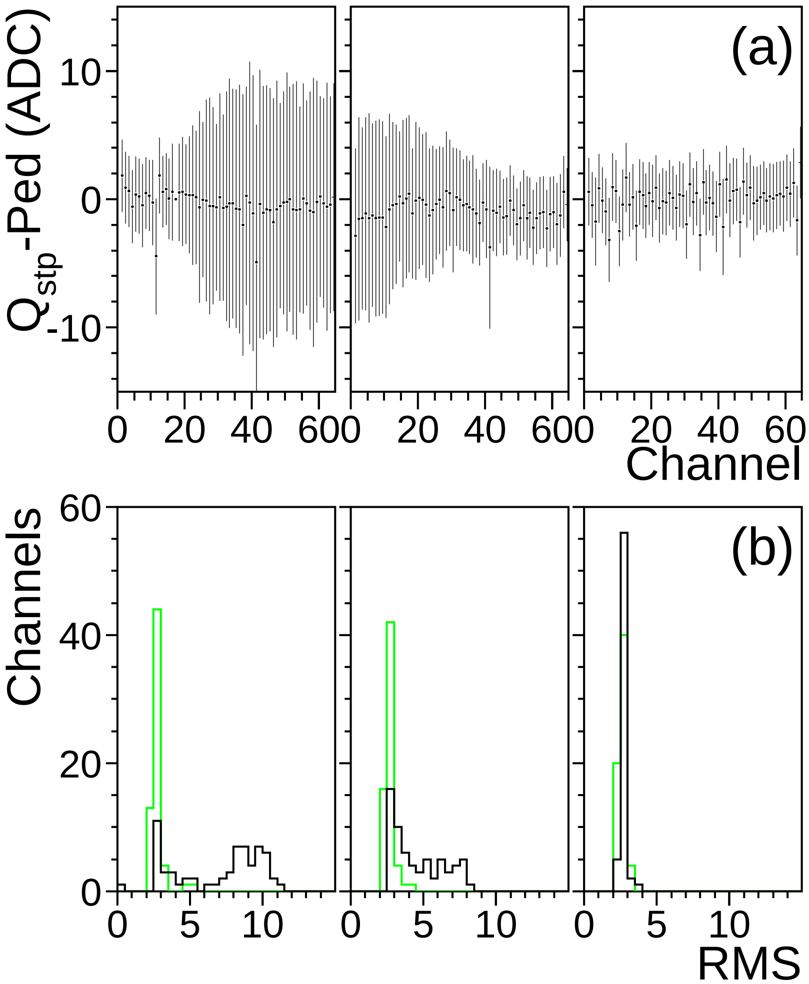


Event Reconstruction

Pedestal of strip signal :

- **Random trigger, off beam-spill**
- $\sigma_N = 2.5$ **ADC counts (green lines)**

VA channels of one reference detector

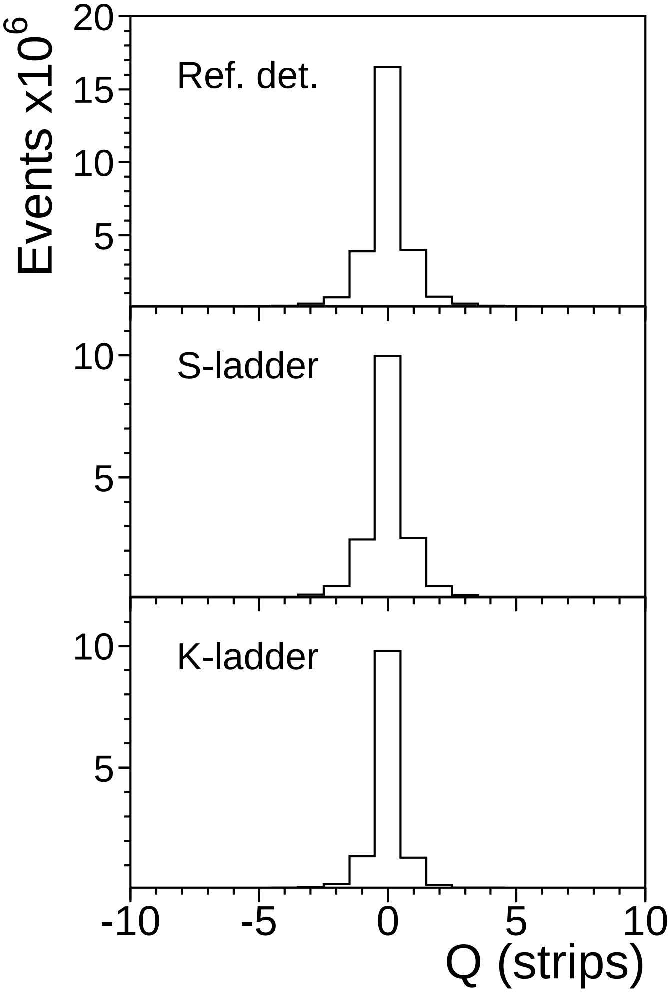


- **Examined by beam trigger**
  Strips of $Q_{stp} > 8\sigma$**+neighboring excluded**
- **The large cluster charge causes local fluctuation**

A Strip Cluster :

- Cut on peak strip charge, total charge
- Neighboring strips of descending charge to 2 σ_N
- Allow climbing up by 10% peak strip charge

Strip charge profile

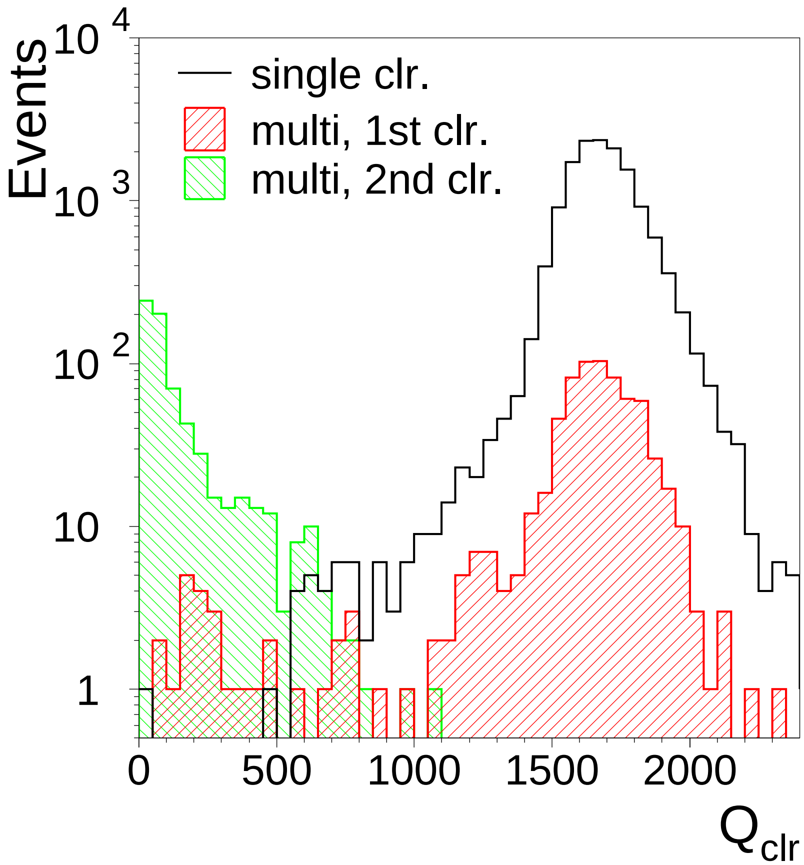


Strip pitch :
Ref.Det.=100 μm, S-ladder=110 μm, K-ladder=208 μm

Purity

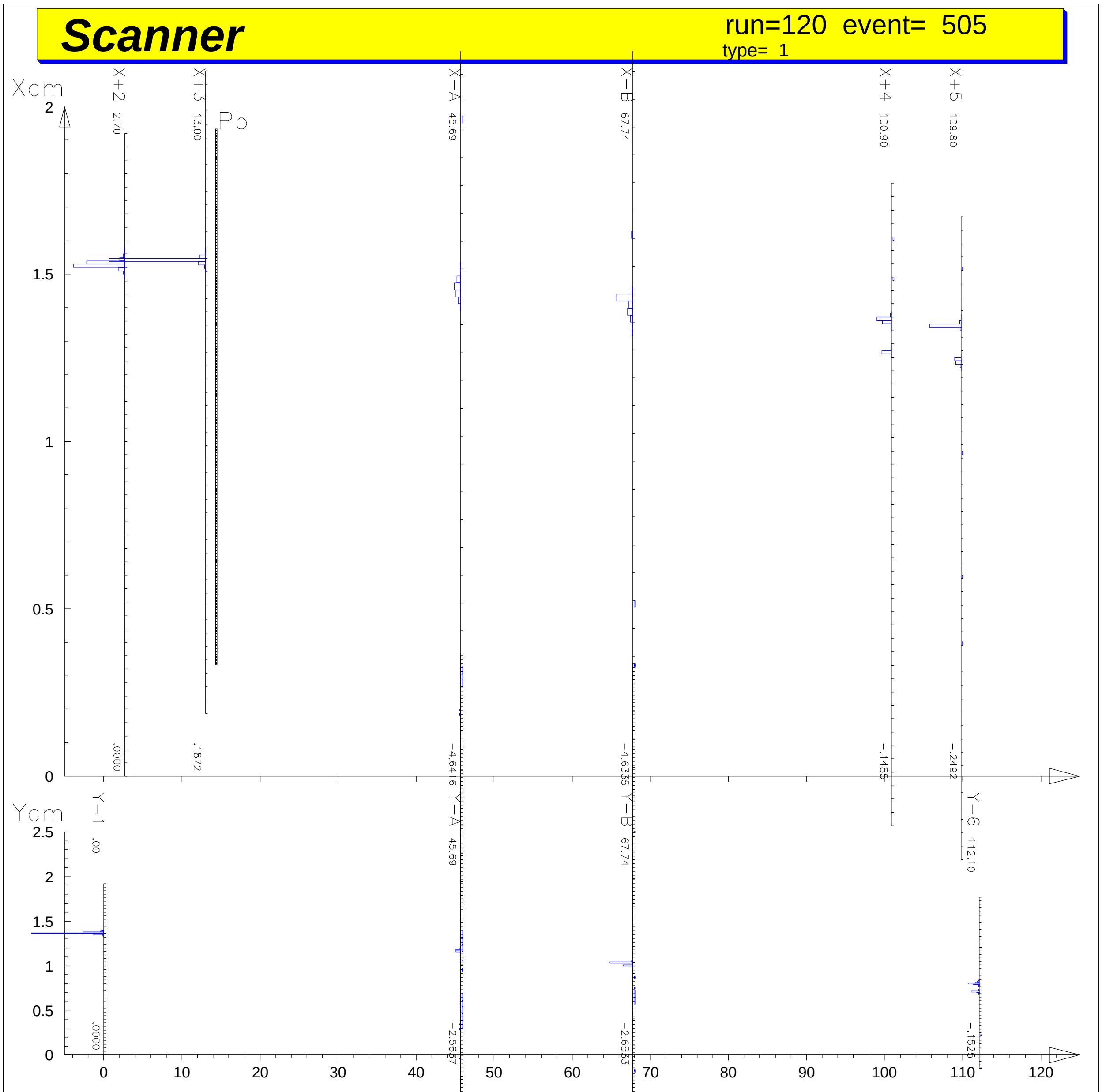
Optimizing cut on total cluster charge

- Q_{clr} of 1 cluster events (black line)
- Multi-cluster events, 1st, 2nd clusters (hatched, $Q^1_{clr} > Q^2_{clr}$)



- Channels of geometrical defects $\sim$ 1%
- Cuts at 20 σ_N
  remnant cluster < 0.5 %
  inefficiency < 0.1 %
- Delta-ray : average $\sim$ 2 δ per wafer
  mostly folded in the 1st cluster
- Nuclear fragmentation : $\sim$ 1 %

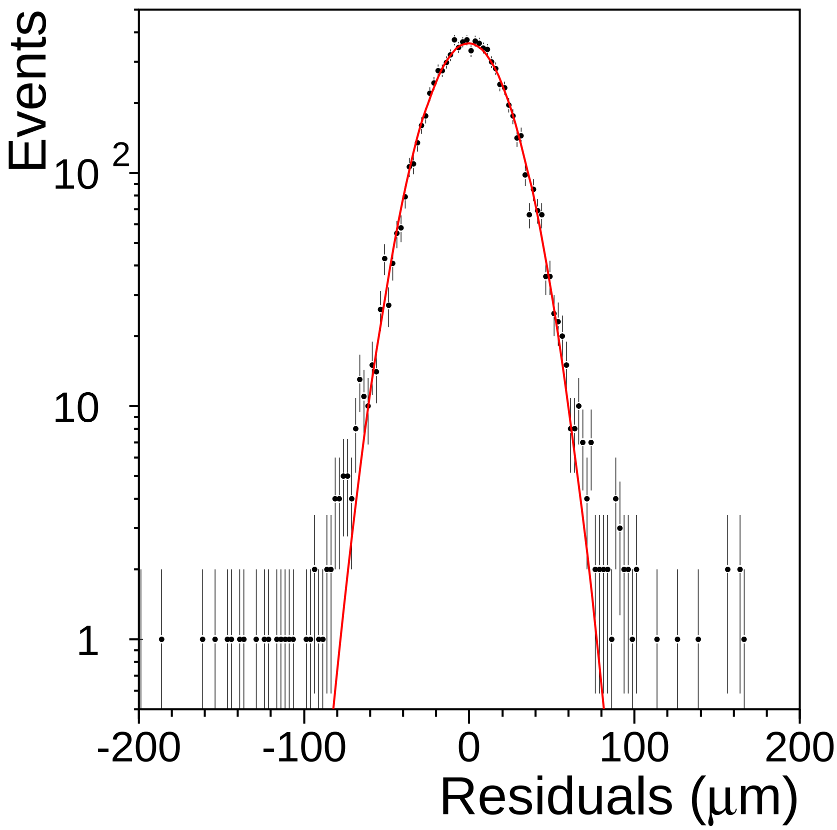
Nuclear fragmentation



Efficiency

Efficiency by linear fit interpolation :

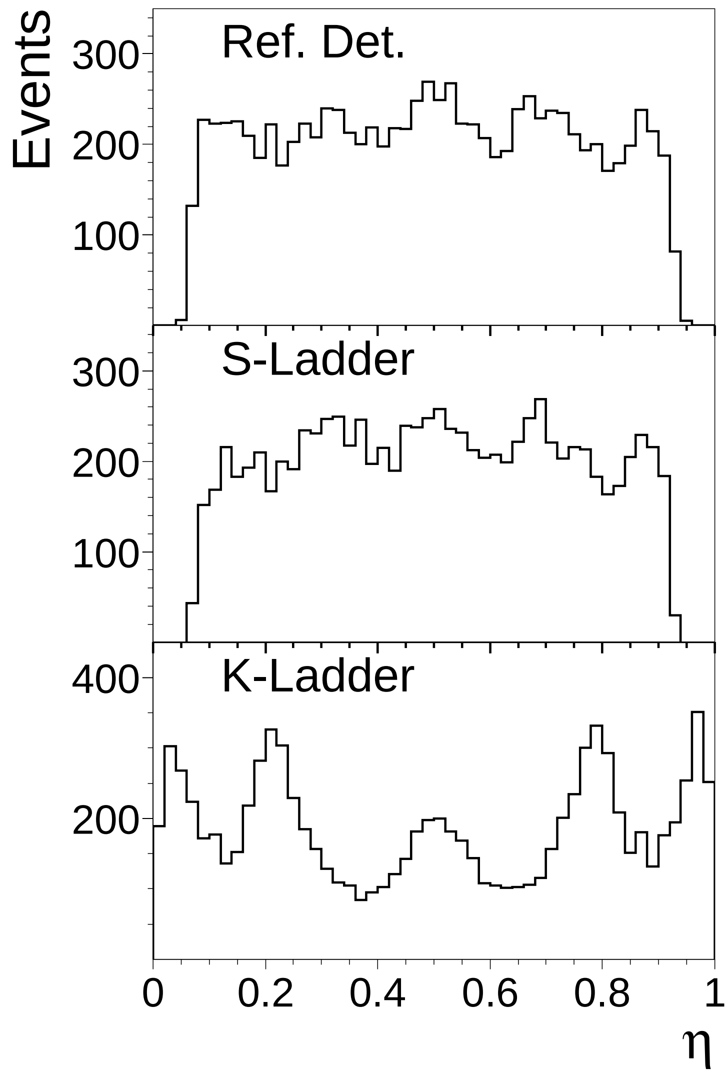
- **Reference detectors for linear fit**
  each has 1 cluster only $Q_{clr} > 500$ ADC
- **Test detector**
  cluster searched w.r.t interpolation position



Within 3σ **range**
Detection efficiency : $\simeq 98.8$ **%**

For a cluster of more than 1 strip

- $\eta = \dfrac{Q_r}{Q_r + Q_l}$
- $Q_{l,r}$ are charge sum of strips left,right to COG
- η spectrum shows the non-linear charge sharing



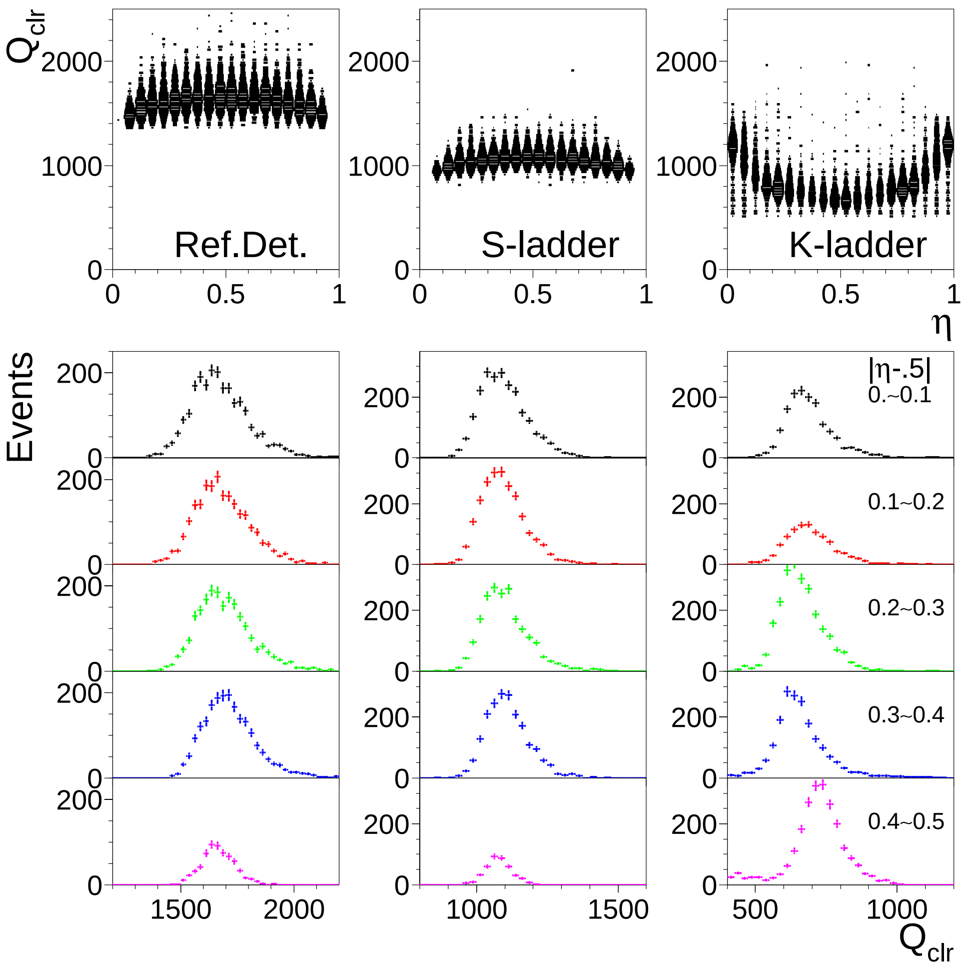
Three floating strips between readouts, contribute to the three bumps

Cluster charge versus η

Corrections to cluster charge :

- Gain of VA chips
- η dependence

Cluster charge versus η,
charge spectra in η intervals



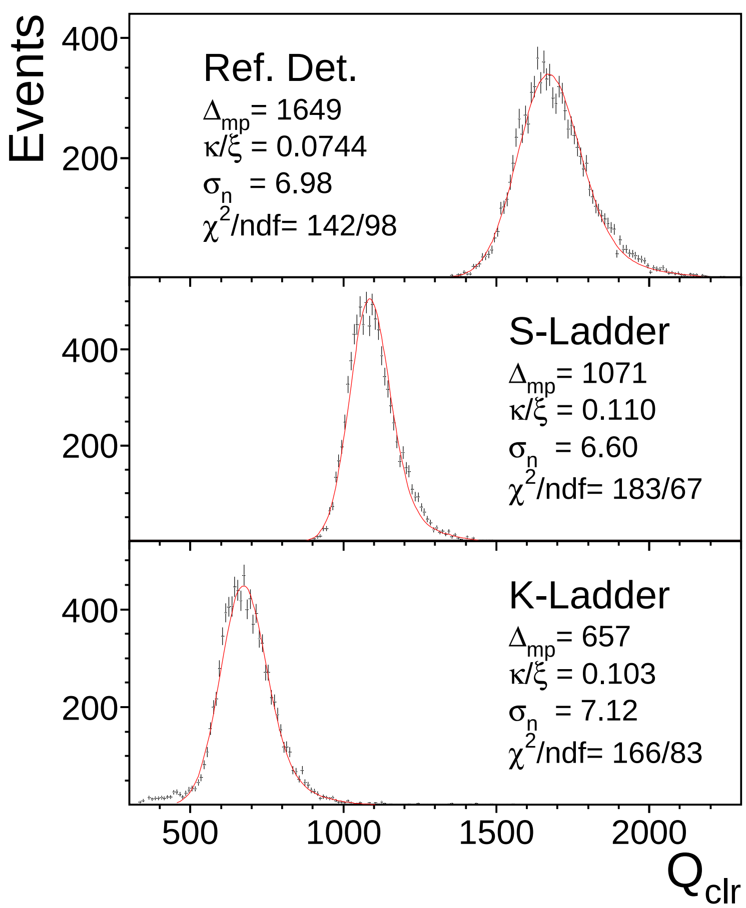
Energy straggling

Energy loss straggling :

- **Momentum of ^{12}C ion is 26.95 GeV**
- **Traversing 300 μm Si wafer**
  Vavilov theory, β^2=0.8532, κ=0.0169
- **Q_{clr} spectra fitted to**
  Gaussian convoluted Vavilov distribution

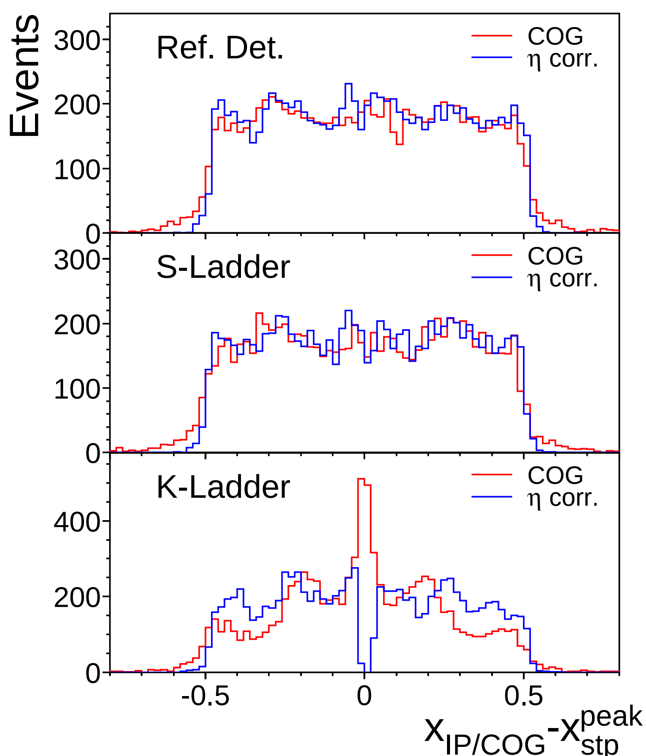
$$f(\Delta, x) = \mathcal{C} \sum_{\Delta-4\sigma}^{\Delta+4\sigma} \exp\left(-\frac{(\Delta-\Delta')^2}{2\sigma^2}\right) \phi_V(\lambda, \kappa, \beta^2)\, \delta\Delta'$$

- **Fitting parameters are Δ_{mp}, κ/ξ, σ**



η correction

- Converting X_{COG} to impact position X_{IP}
- Beam spot is $\gg$ strip pitch, uniform between two strips
- η has the nonlinear charge sharing versus X_{COG}
- $X_{IP} = \dfrac{\int_0^\eta f(\eta)}{\int_0^1 f(\eta)}$



Alignment

- Calibrated by linear track fitting,
- for strip offset, rotation on the wafer plane

Tracking simulated by GEANT

Physics processes

- Multiple Coulomb scattering
- Energy loss
- Delta ray, bremsstrahlung

Strip cluster simulation

- Cluster position :
  mean of (enter/create and exit/stop) positions
- Cluster charge :
  randomly sampled on data spectrum,
  shared to two strips
- Detector resolution :
  Gaussian smearing at impact position

GEANT control

- AUTOmatic tracking parameters
- Step precision EPSIL=100 μm
- Thresholds for γ, $e^{\pm}$ cutoff, bremsstrahlung, δ-ray

CUTGAM	CUTELE	BCUTE	DCUTE
100 keV	100 keV	500 keV	250 keV

Multiple scattering in GEANT

Molière theory

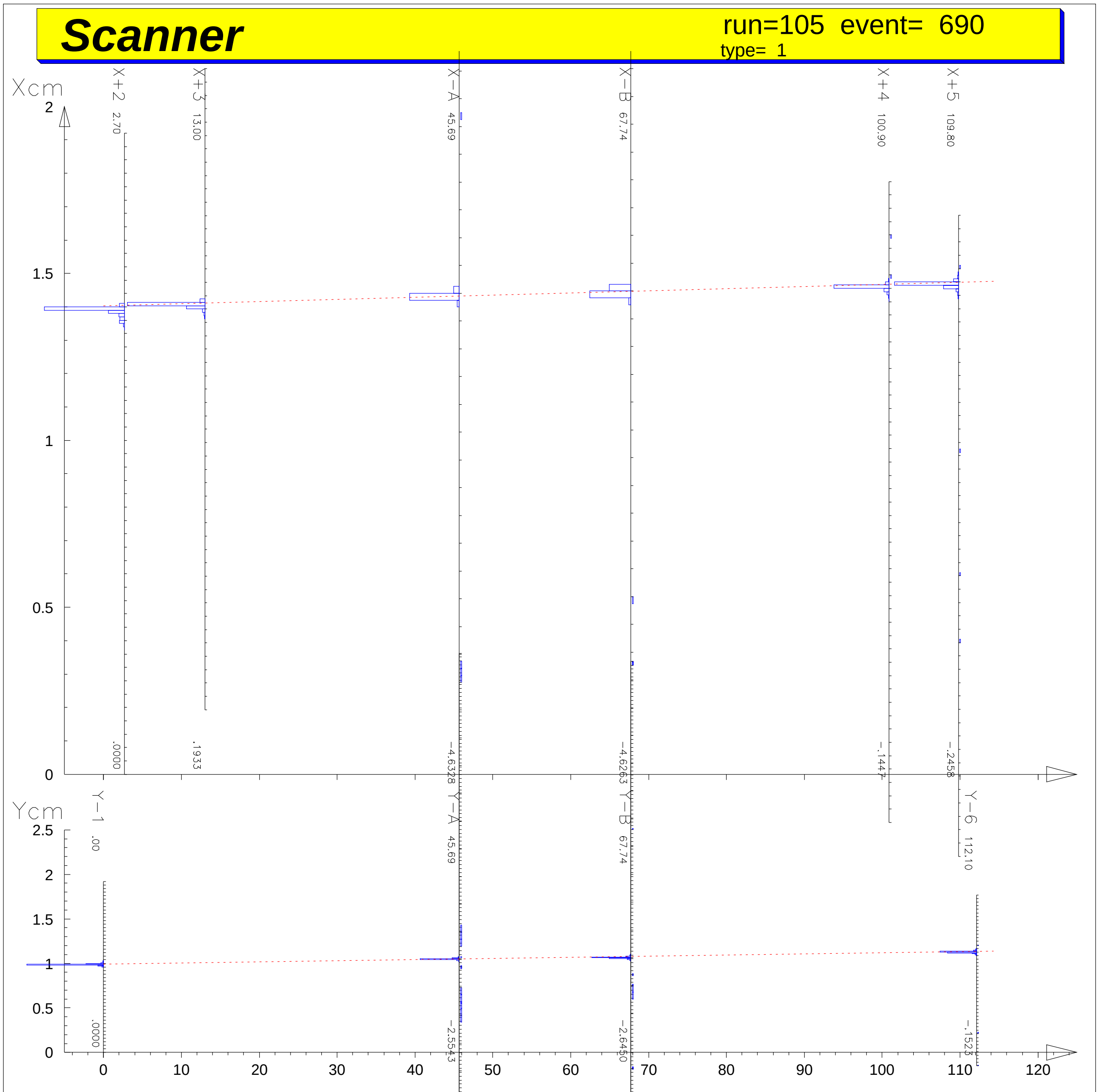
- **Many atomic collisions**
  $\Omega_0 = 10K$ **for** ^{12}C **of** 29.18 GeV **through** $300\ \mu$m **Si**
- **Semi-infinite homogeneous media**
- **No energy loss**

Gaussian approximation

- **The Gaussian width** θ_0 **of PDG,**
  $$\theta_0(t_1 + t_2) \neq \sqrt{\theta_0^2(t_1) + \theta_0^2(t_2)}$$
  limits to simulation steps
- **GEANT Gaussian approximation** [**Lynch,Dahl**]
  $$\theta_0^2 = \frac{\chi_c^2}{1 + F^2} \left[\frac{1+\nu}{\nu} \ln(1+\nu) - 1 \right]$$
  $\nu = \Omega_0 / 2(1 - F)$
  $F =$ **track fraction in the sample**
  Empirical fits for Ω_0

- **Consists with Molière to better than 2%**

Linear track fitting



Spatial resolution

Least square estimate for σ_{IR}

- $\mathbf{LS} = \frac{1}{N} \sum^N \left(1 - \frac{\sigma^i_{data}}{\sigma^i_{MC}}\right)^2$

  $\sigma_{data}, \sigma_{MC}$: residual widths of unweighted linear fit
- Minimizing LS, iteration on σ^i_{IR}

  use setup of target Pb = 0 mm

Pb	Widths of data residuals (μm)						LS estimates			
	X_2	X_3	D_a	D_b	X_4	X_5	$\sqrt{\mathbf{LS}}_0^M$	$\sqrt{\mathbf{LS}}^M$	$\sqrt{\mathbf{LS}}^{ML}$	$\sqrt{\mathbf{LS}}^{GL}$
0 mm	9.9	10.6	–	–	14.4	13.3	0.25	0.011	0.014	0.040
0 mm	28.5	14.5	40.2	40.4	18.6	29.4	0.13	0.021	0.021	0.030
1 mm	76.9	47.7	56.9	46.8	23.1	37.6	0.13	0.059	0.052	0.063
2 mm	92.7	58.5	63.2	49.0	24.4	41.2	0.11	0.046	0.048	0.057

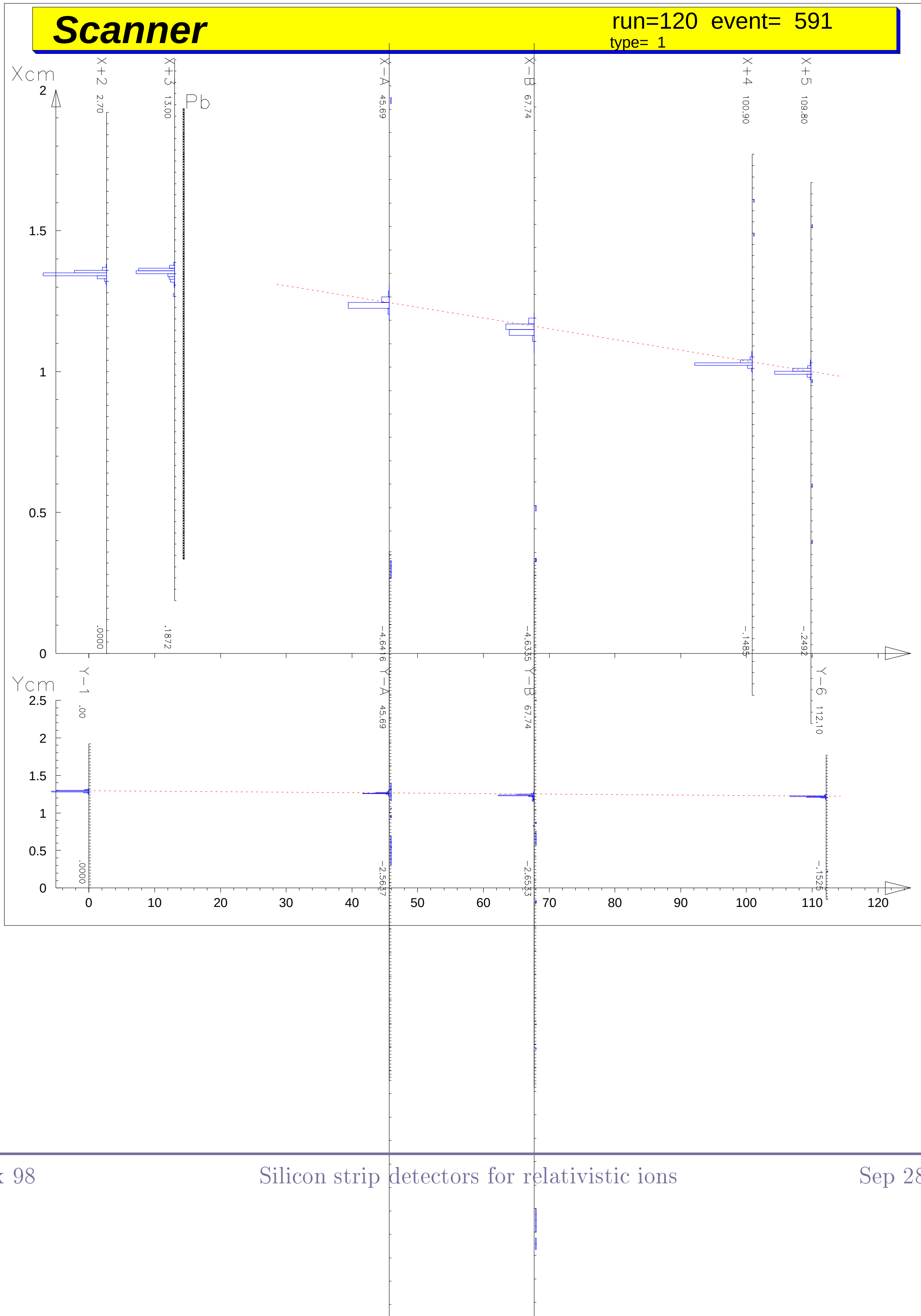
$\sqrt{\mathbf{LS}}_0^M$: MC with Molière only, $\sigma_{IR} = 0$
$\sqrt{\mathbf{LS}}^M$: MC with Molière only
$\sqrt{\mathbf{LS}}^{ML}$: MC with Molière + Energy loss
$\sqrt{\mathbf{LS}}^{GL}$: MC with Gaussian + Energy loss

Intrinsic resolution determined

- Reference detectors: **7** μm
- S-ladder : **8** μm
- K-ladder : **14** μm

- Uncertainty : **3** μm

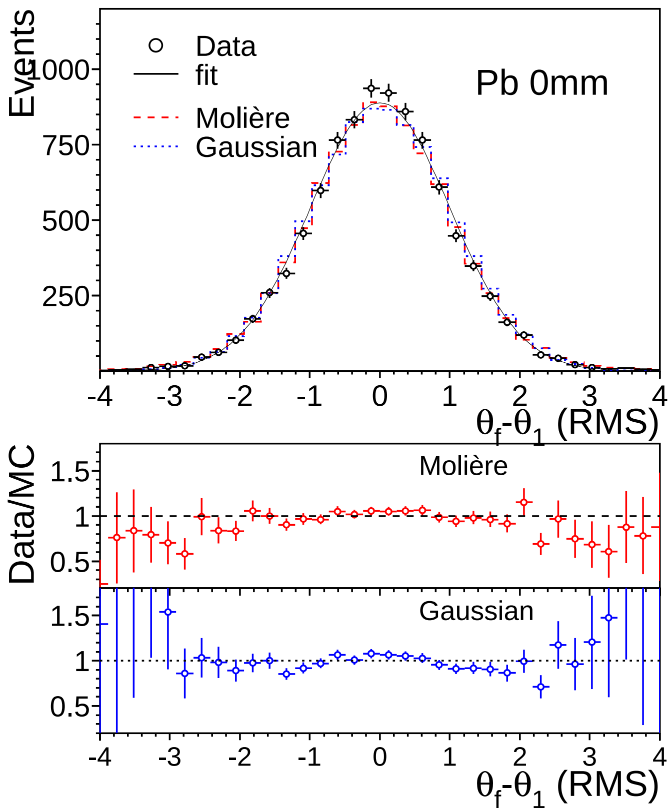
  Tracking, geometry of simulations,
  cutoff values, physics processes
  Alignment, clustering in reconstruction


Scanner
run=120 event= 591
type= 1
Xcm
Ycm
Pb
X+2 2.70
X+3 13.00
X−A 45.69
X−B 67.74
X+4 100.90
X+5 109.80
Y−1 .00
Y−A 45.69
Y−B 67.74
Y−6 112.10
0 10 20 30 40 50 60 70 80 90 100 110 120

Multiple scattering

Projected angle :

- **Target :** **Pb = 0** mm
- **Incident angle θ_1:**
  by the front two detectors
- **Scattering angle θ_f:**
  linear fit to the four down stream detectors

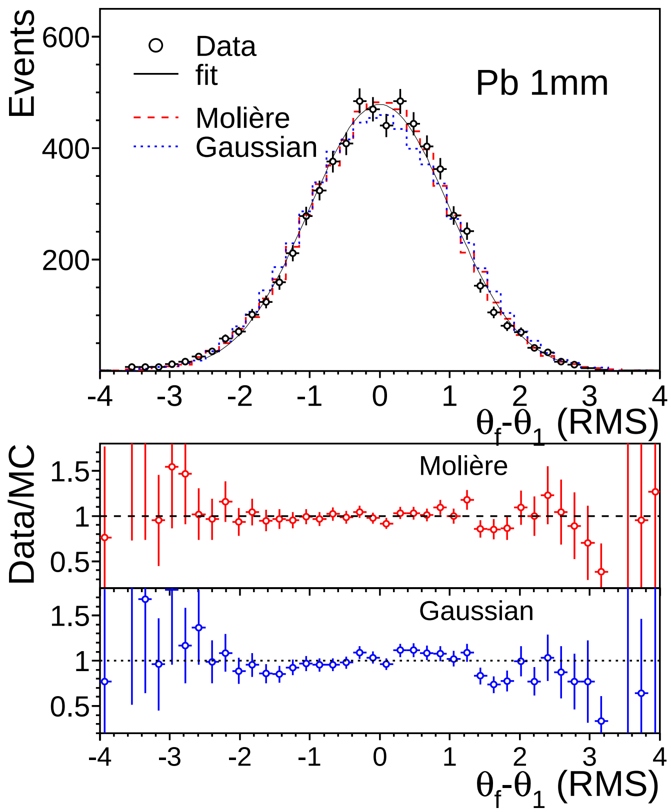


- $$\frac{\sigma(\text{data})}{\sigma(\text{Molière})} = 1.010 \pm 0.010 \pm 0.030 \qquad \chi^2/df = 1.59$$
- **Uncertainties :**
  Detector resolution : 2%
  Simulation of geometry : 2%
  Reconstruction : 1%

Multiple scattering

Projected angle

- Target : **Pb = 1** mm
- Incident angle θ_1:
  by the front two detectors
- Scattering angle θ_f:
  linear fit to the four down stream detectors

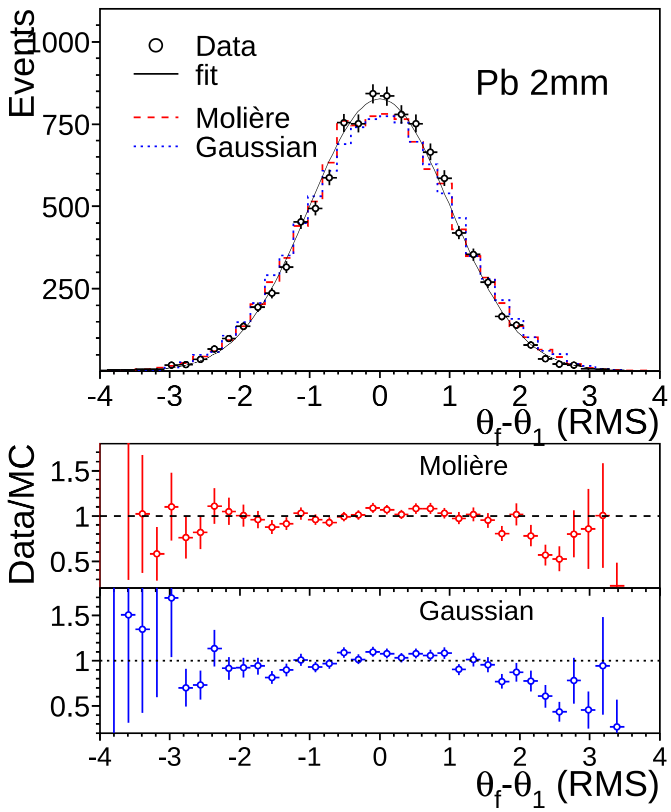


- $\dfrac{\sigma(\text{data})}{\sigma(\text{Molière})} = 0.997 \pm 0.011 \pm 0.024 \qquad \chi^2/df = 1.08$
- **Uncertainties :**
  Detector resolution : 1%
  Simulation of geometry : 2%
  Reconstruction : 1%

Multiple scattering

Projected angle

- **Target :** **Pb = 2** mm
- **Incident angle θ_1:**
  by the front two detectors
- **Scattering angle θ_f:**
  linear fit to the four down stream detectors



- $\dfrac{\sigma(\text{data})}{\sigma(\text{Molière})} = 0.956 \pm 0.008 \pm 0.024 \qquad \chi^2/df = 2.28$
- **Uncertainties :**
  Detector resolution : 1%
  Simulation of geometry : 2%
  Reconstruction : 1%

Multiple scattering

- **Pb = 0 mm**
  σ_0**(data) = 330 ± 3** μ**Rad**

	σ(data)/σ(MC)	χ^2/d.f
Molière+Loss	**1.010**$\pm 0.009 \pm 0.030$	**1.59**
Gaussian+Loss	**0.976**$\pm 0.010 \pm 0.030$	**2.23**

- **Pb = 1 mm**
  σ_0**(data) = 1275 ± 13** μ**Rad**

	σ(data)/σ(MC)	χ^2/d.f
Molière+Loss	**0.997**$\pm 0.011 \pm 0.024$	**1.08**
Gaussian+Loss	**0.970**$\pm 0.011 \pm 0.024$	**2.03**

- **Pb = 2 mm**
  σ_0**(data) = 1561 ± 11** μ**Rad**

	σ(data)/σ(MC)	χ^2/d.f
Molière+Loss	**0.956**$\pm 0.008 \pm 0.024$	**2.28**
Gaussian+Loss	**0.952**$\pm 0.008 \pm 0.024$	**3.74**

Conclusion

- **Silicon strip detectors**
  can provide high precision tracking
  for relativistic ion
- **Multiple scattering agrees well with**
  Molière theory and
  GEANT Gaussian approximation