Numerical Simulation of μSR Position-Sensitive Detectors

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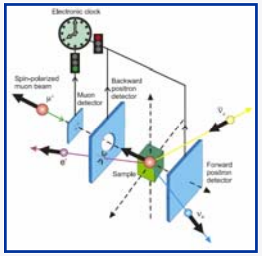
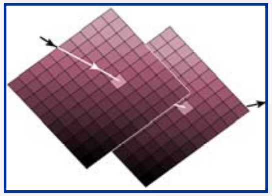
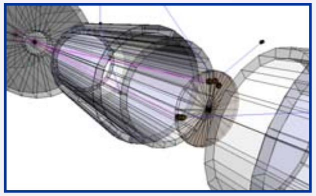
Visual overview



Current limitations
of the μSR technique



Position-sensitive
detectors (PSD) for μSR



Numerical simulations as
a test & optimisation tool

Motivation: Extend μSR to new domains

- Current μSR relies on scintillation counting: scintillators – light guides – photomultipliers

Advantages

- ✓ Fast response
- ✓ High detection efficiency
- ✓ High flexibility
- ✓ Inexpensive
- ✓ Etc…

Not suitable with

- ✗ High magnetic fields
- ✗ Low-energy muons
- ✗ Tiny samples
- ✗ Etc…

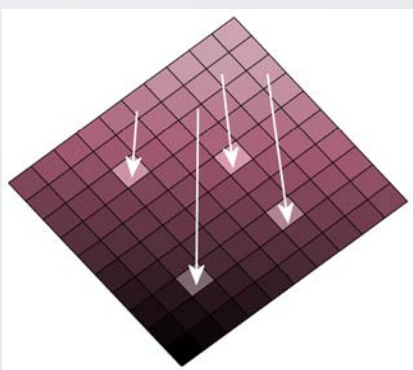
Objective

Development of position-sensitive detectors (PSD) and electronics readout based on new solid-state and integrated technologies – **NMI3 JRA8**

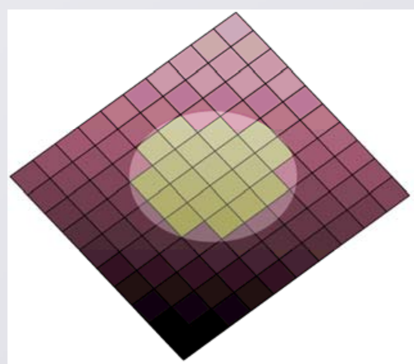
PSD – New development ideas

Problem		Proposed solution
▸ Pile-up effects	→	Detector segmentation
▸ Small samples / high backgr.	→	Particle origin reconstruction
▸ High magnetic fields	→	Segmentation / tracking

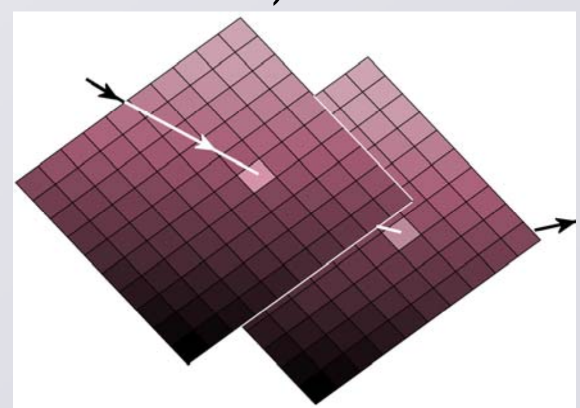
Requirements: High spatial resolution (1 mm or better)
High positron detection efficiency (> 95%)
Good time resolution (1 ns or better)



Pixel detector
for count splitting



Software defined
pixel geometry



Full particle
tracking ?

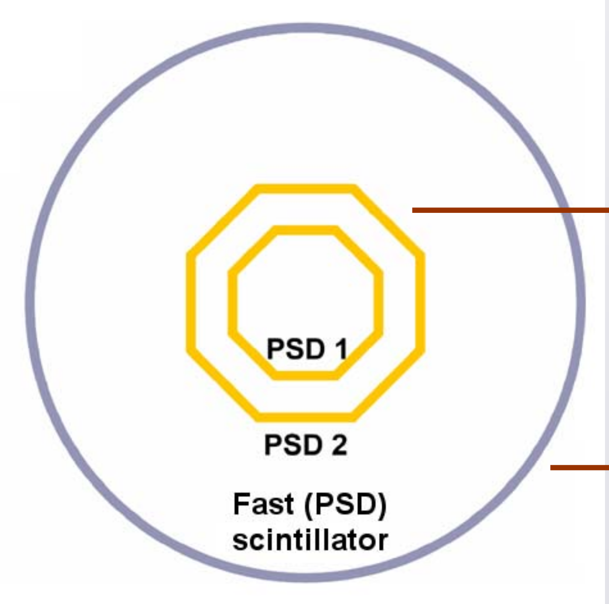
Possible detector layout: Physics

Mixed type detectors successfully used in: NA58, FAROS, etc.

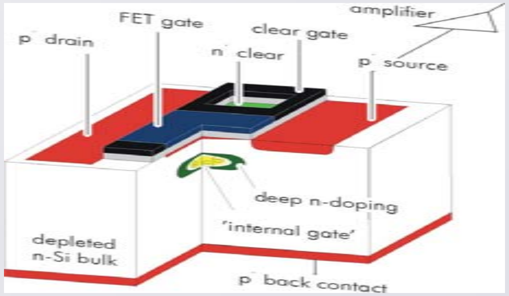
Detector = Silicon devices (position) + Scintillating fibres (timing)

⬇

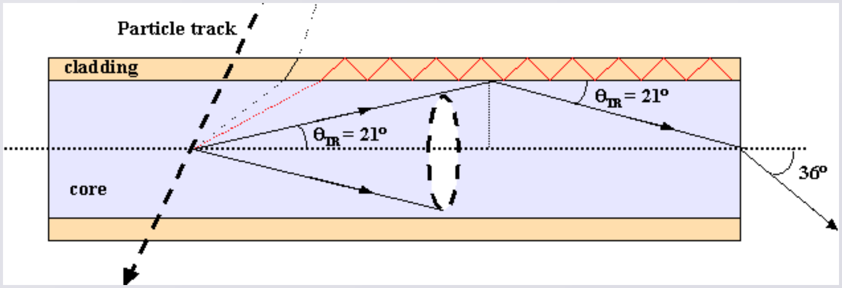
Improved overall performance due to complementary advantages



PS detector layout



Silicon DEPFET



Scintillating fibre – SciFi

Exploring PSD using simulations

Real tests: **complex** and **difficult** ➔ Use simulations to establish and optimize preliminary detector **performance**

Establish detector limits

- Muons

  Longitudinal and radial ranges, dispersion

- Positrons

  Exit fraction, energies, angle & coord. dispersion

Optimize performance

- Parameter optimization

  Detector number, thickness, angles, distances, extension, position, pixel size, etc.

T. Shiroka, et al., *Physica B* **374** (2006) 494

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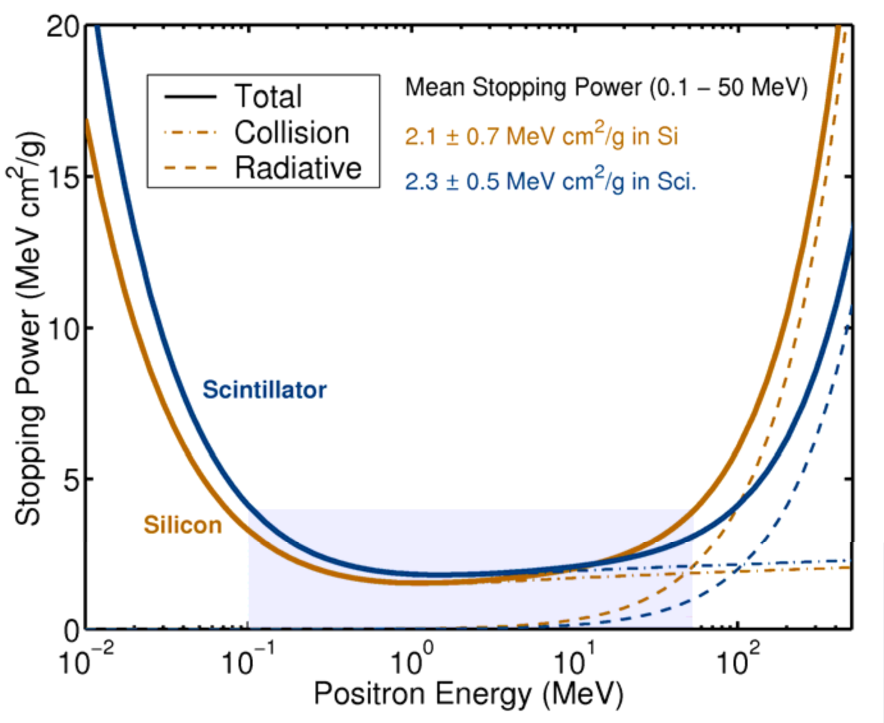
Peculiarities of decay positrons



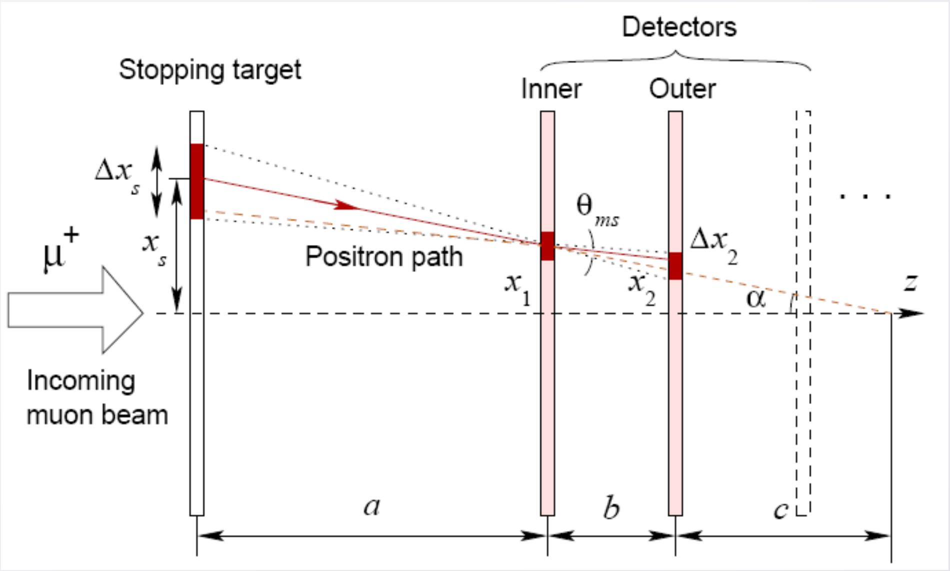
Stopping power vs. positron energy in silicon and scintillating fibres

http://physics.nist.gov/PhysRefData/

Positrons in μ^+ decay:

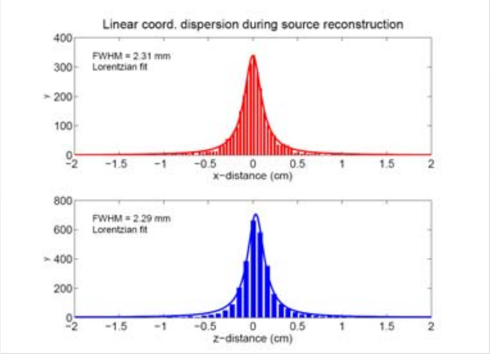
- $T = 37 \pm 11$ MeV, much different from particles in colliders ($T \sim 1$ GeV)
  ➔ large multi. scattering
- Behave as minimum ionising particles (MIPs)
  ➔ low signal levels
- Radiation level is low
  ➔ very limited damage

PSD Simulation method

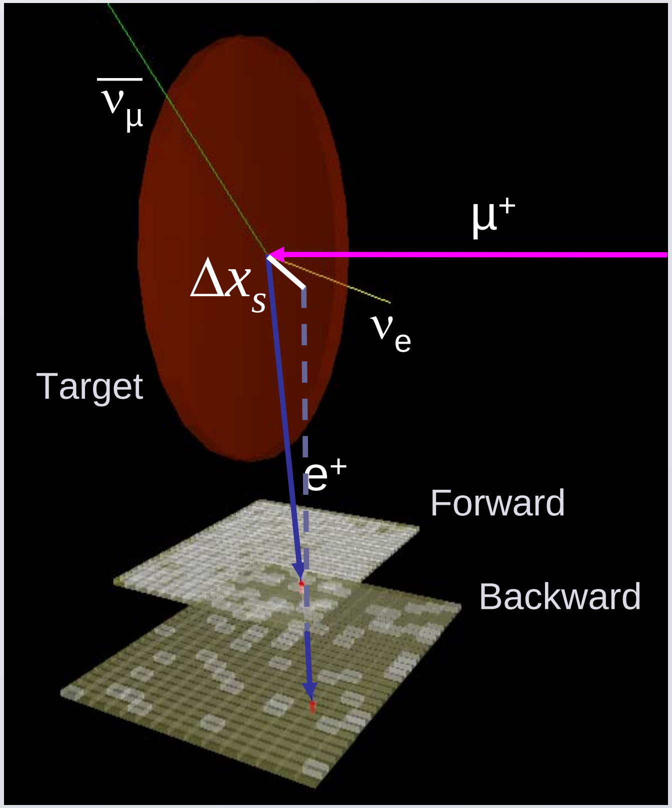


Detector schematics and …

Statistical analysis



… GEANT4 Simulation



Theoretical uncertainty predictions

Simplified case: $\Delta x_p = 0$ (no pixel structure)

$$\Delta x_s = a \cdot \theta \cdot 1/\cos^2\alpha$$

Distance — Mult. Scatt. — Position & extension — No dependence on *b*!

Real case: $\Delta x_p > 0$ (with pixel structure)

$$\Delta x_s = [(a/\mathbf{b}+1)^2 \cdot \Delta x^2_{1p} + (a/\mathbf{b})^2 \cdot (b^2\, \theta^2/\cos^4\alpha + \Delta x^2_{2p}]^{1/2}$$

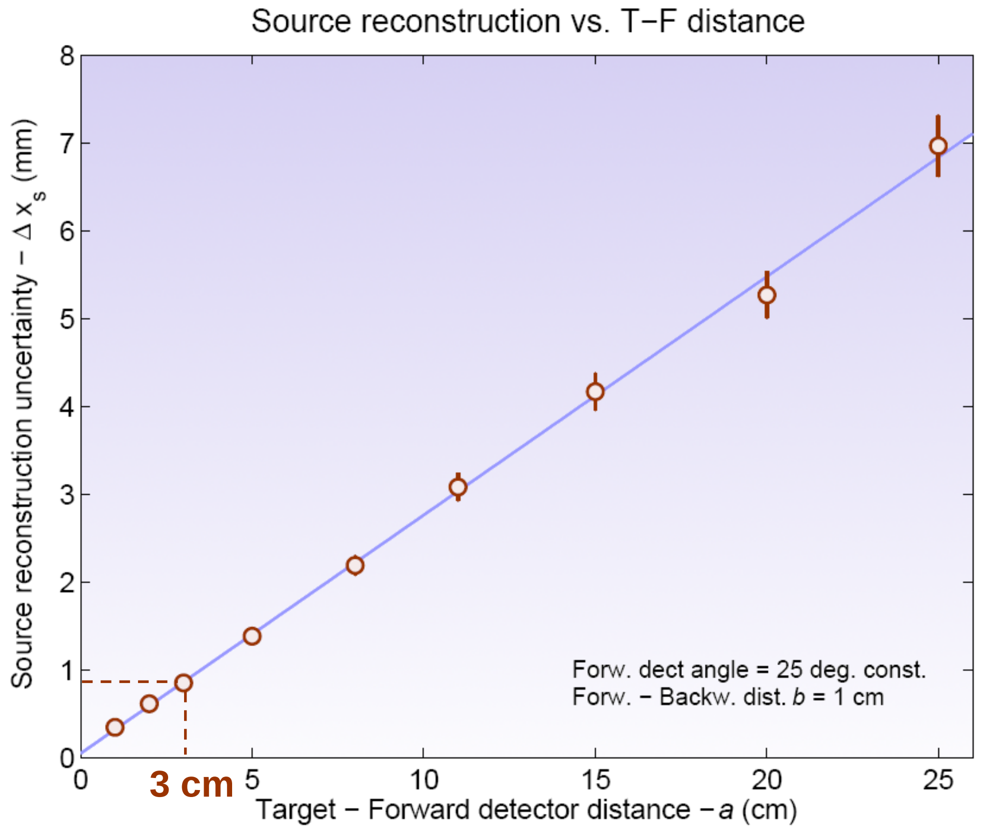
$$\Delta x_2 = [\Delta x^2_{2p} + (b \cdot \theta \cdot 1/\cos^2\alpha)^2]^{1/2}$$

← Dependence on *b*

Pixel error — Mult. Scatt.

What do simulations predict ?

Detector-to-target distance effect



A **linear** error is expected with the first detector-to-source distance:

$$\Delta x_s = \boldsymbol{a} \cdot \theta \cdot 1/\cos^2\alpha$$

Conclusion: Put the first detector as closely as possible to the target!

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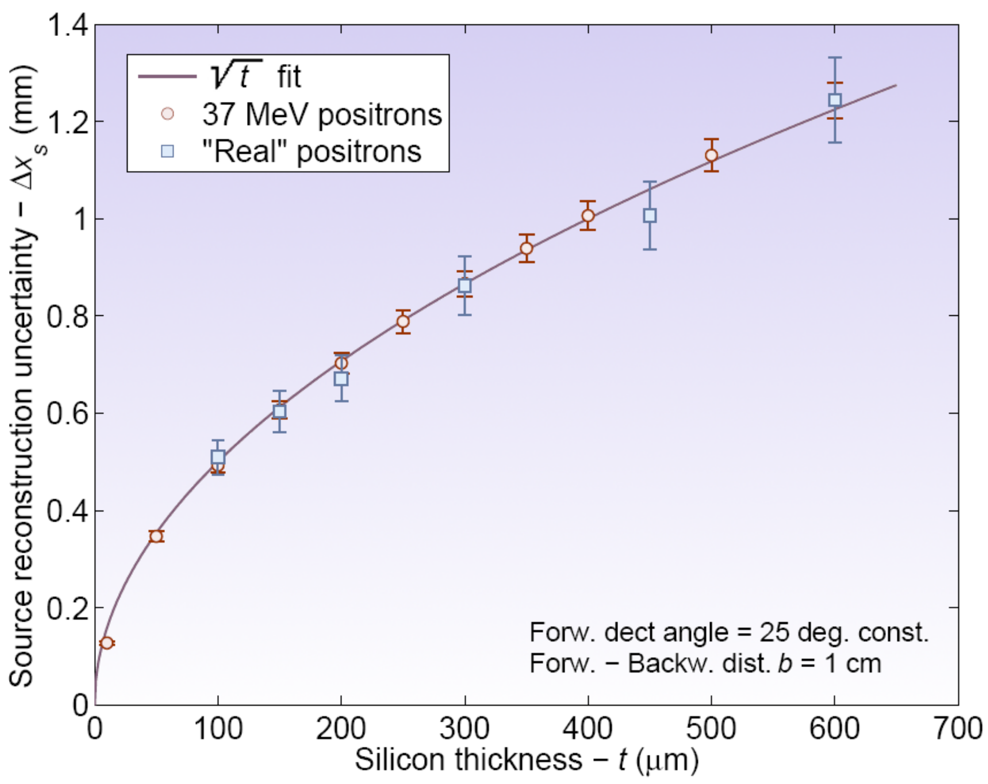
Multiple scattering (thickness) effect



An **increased** error expected for thicker detectors, with large multiple scattering:

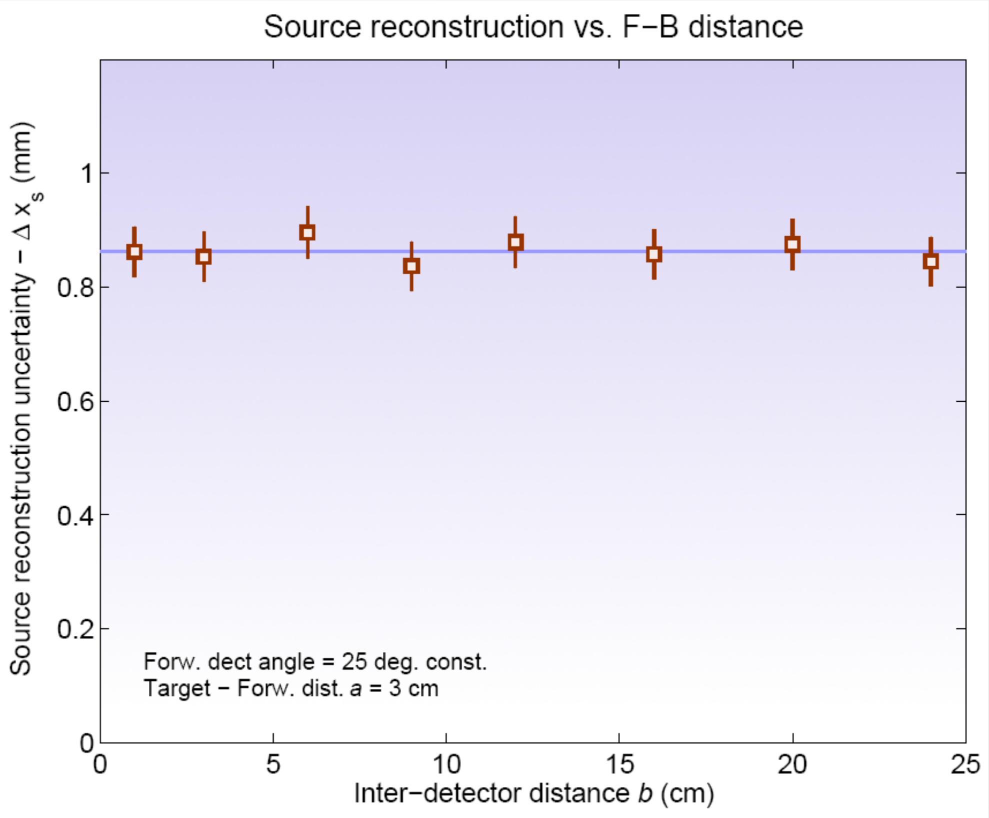
$$\theta \sim \sqrt{t}$$

If: $\Delta x_s = a \cdot \theta \cdot 1/\cos^2\alpha$

$$\Delta x_s \sim \sqrt{t}$$

Conclusion: Use a detector as **thin** as possible (~300 μm) compatibly with the S/N level

Inter-detector distance effect



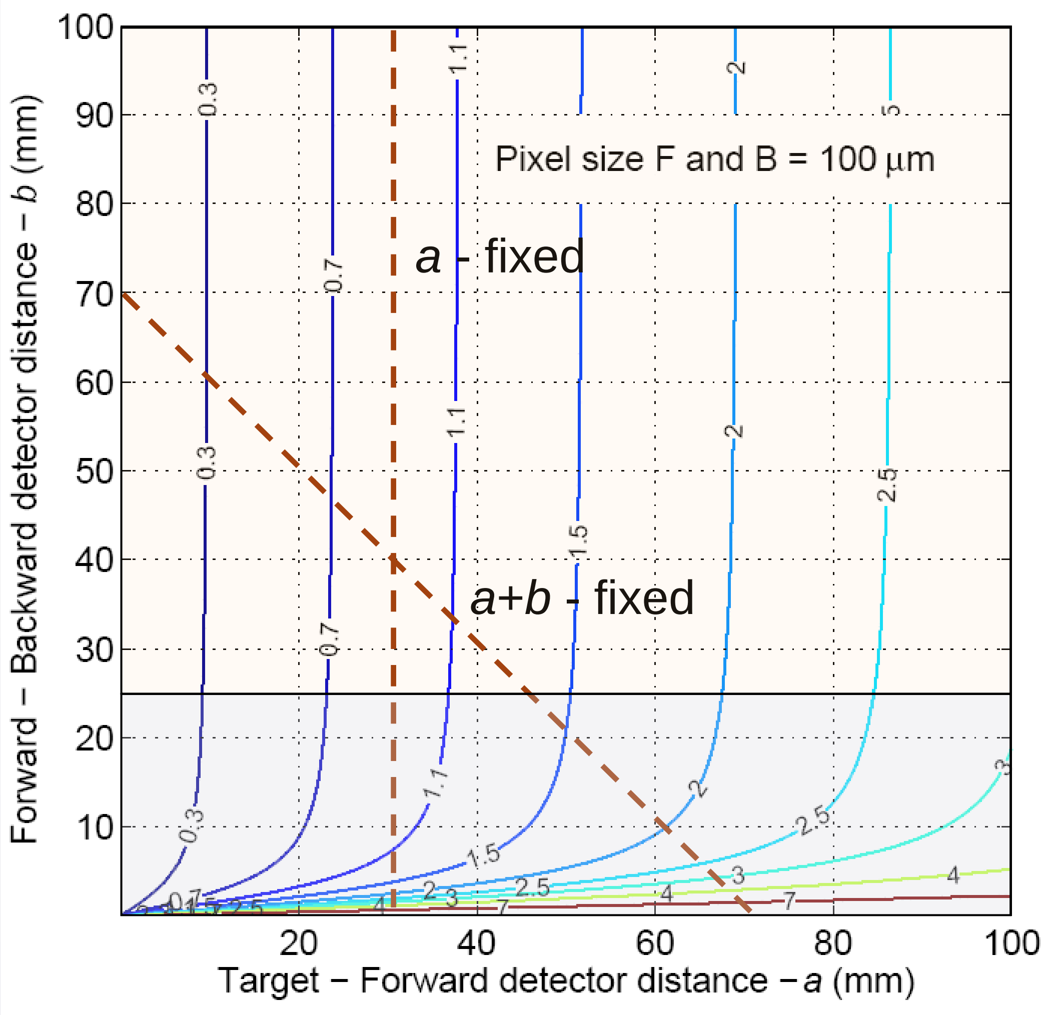
If the inner detector has **no pixel** structure a constant error with F–B dist. expected:

$$\Delta x_s = a \cdot \theta \cdot 1/\cos^2\alpha$$

Conclusion: Calculate errors also for a pixelated detector!

2D uncertainty map (Pixel size > 0)

Source location error vs. ***a*** and ***b*** distances



Errors due to
Multiple scattering

Errors due to
Finite PIXEL size

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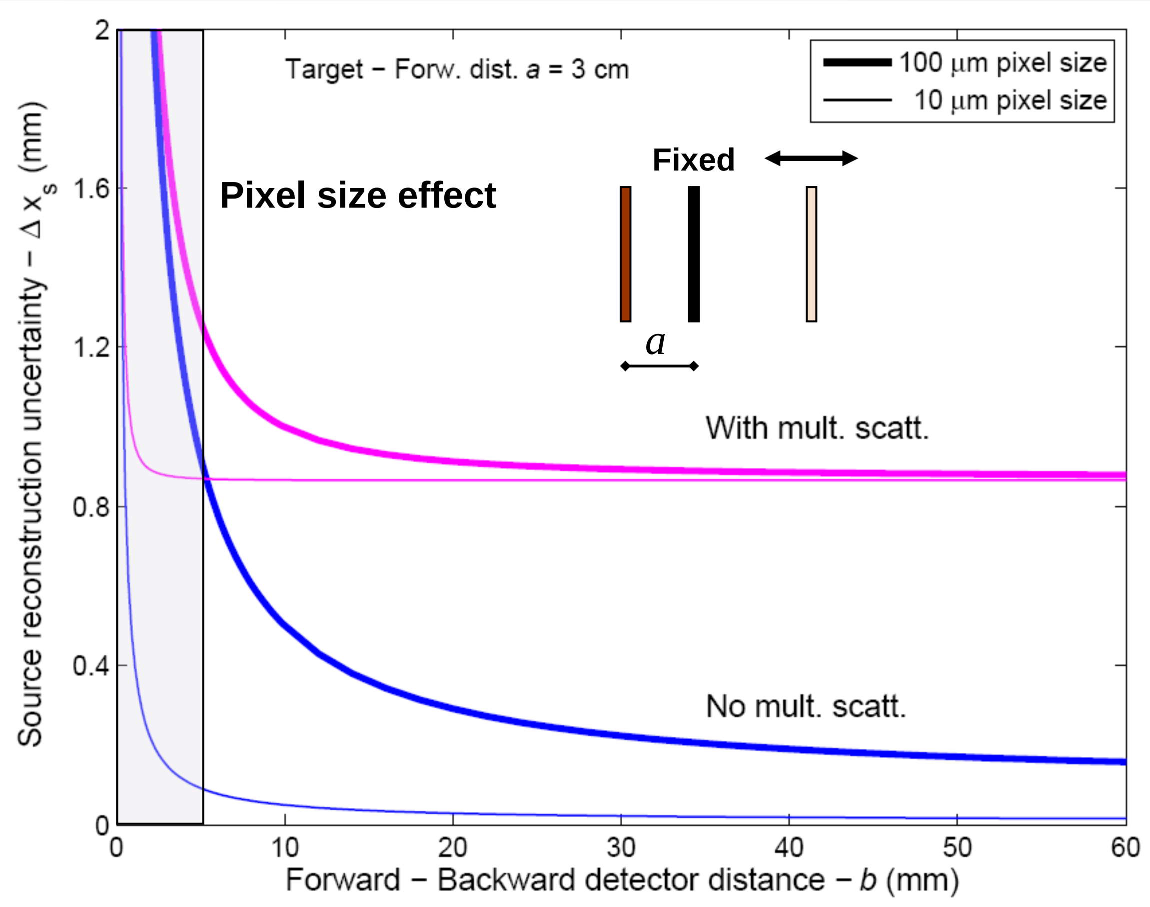
Source reconstruction error: fixed *a*



a = const: mimics a **fixed inner detector** position

- Multiple scattering is unavoidable. Big detectors won't improve resolution
- Pixel errors very important at short distances. Small pixels allow for a smaller detector
- At large distances, the error is constant and independent of pixel size

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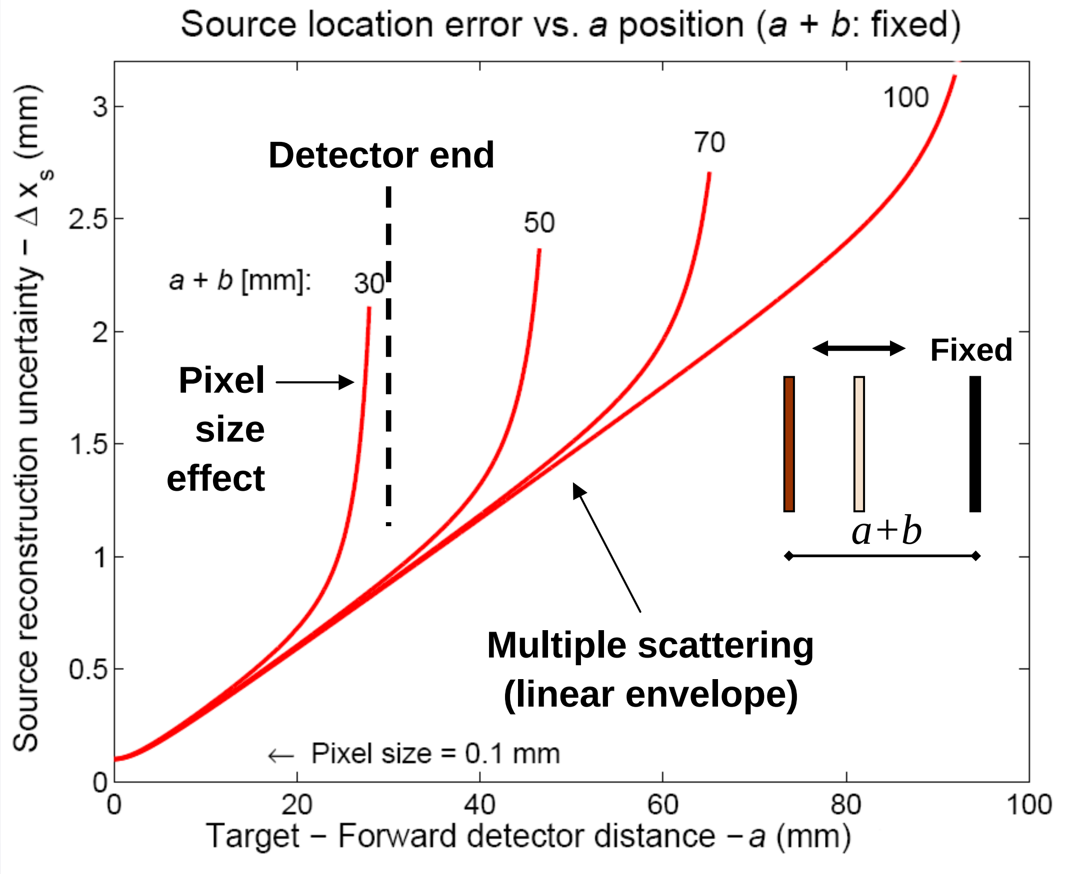
Source reconstruction: fixed *a* + *b*



- **No position** can overcome the intrinsic pixel size error
- An **acceptable error** is found for $a \sim b$ or less.

  Best solution for $a \sim 0$.

$a + b =$ const: mimics the **limited space** available for the detector

Conclusions and future work

- Detector simulation is crucial in optimizing detector performance and guiding the building of prototypes:

  Critical param.: Detector thickness, extension, distance to target

  Important param.: Pixel size, inter-distance, number of layers

- The desired resolution (~1 mm) is achievable. Further improvements are limited by intrinsic effects

Future work

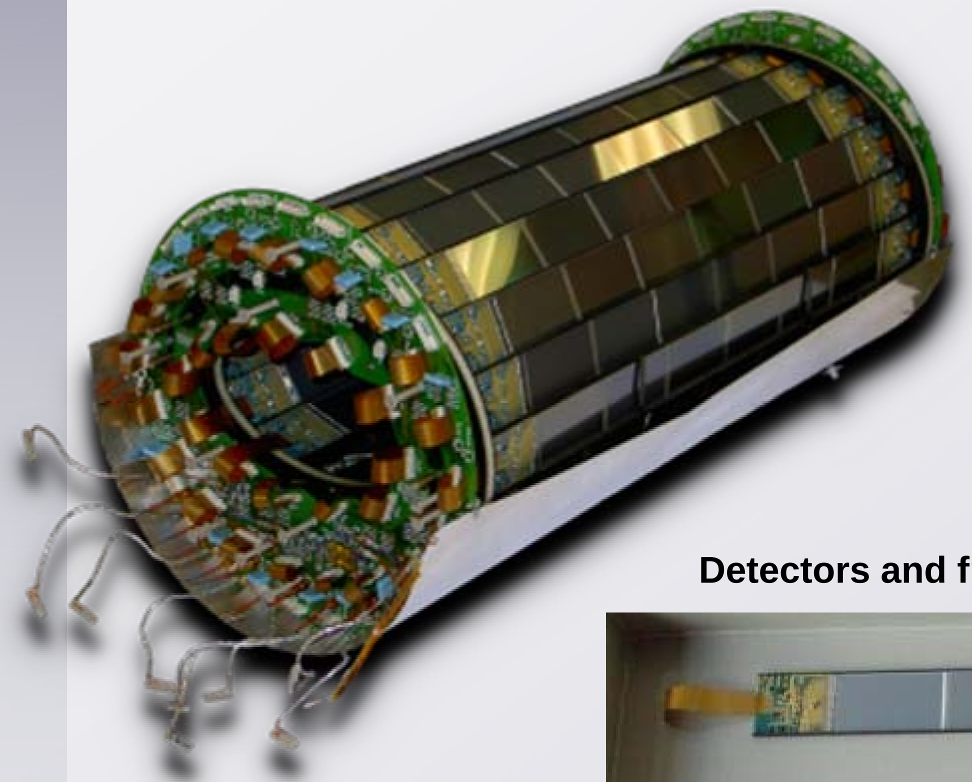
- Testing of prototypes: assess position sensing capabilities and timing in realistic conditions

Simulation testing

H1 CST – silicon detectors

H1 CST: HERA Central Silicon Tracker

Overall detector view



Top view of front-ends

Detectors and front-ends

One ladder:
6 double sided sensors
+ 2 hybrid front-ends

H1 CST detector: features and plans

Main detector features:

- 34 mm x 59 mm x 300 µm ($0.3X_0$) *double sided* p-n sensors
- 12 µm strips: 25 µm pitch on *p* side and 88 µm pitch on *n* side
- 37 µm impact parameter resol.
- 640 readout lines per side
- 10 MHz speed (100 ns rise time)
- 32 channel – PRO/A ASIC
- On-board preamp/shaper/discrim.
- Four step adjustable gain
- 2 l/min water cooling

Timetable:

- Check for good modules
- Assembly the test detector
- Test air or water **cooling**
- Write MIDAS DAQ software
- Data collection and analysis
- Development of μ^+ beam monitor?

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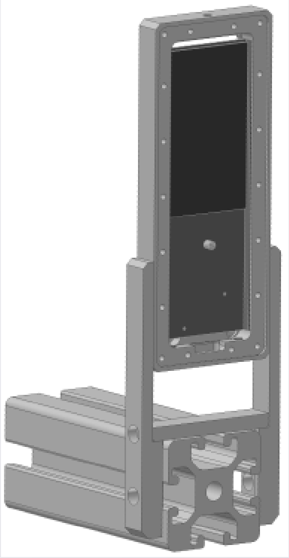
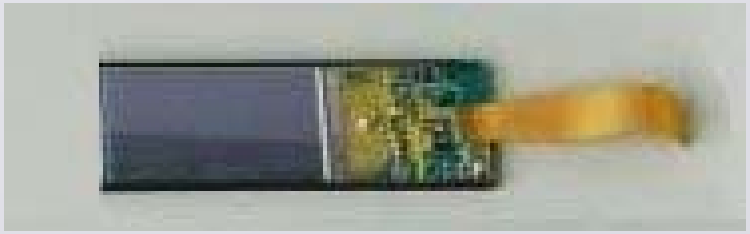
PSD Performance testing

New data acquisition control system
(Etrax – Altera Cyclone FPGA)

PS detector holder
(light-tight & cooled)





Solid-state Si pixel detector
(adapted from HERA H1 CST)

Acknowledgements

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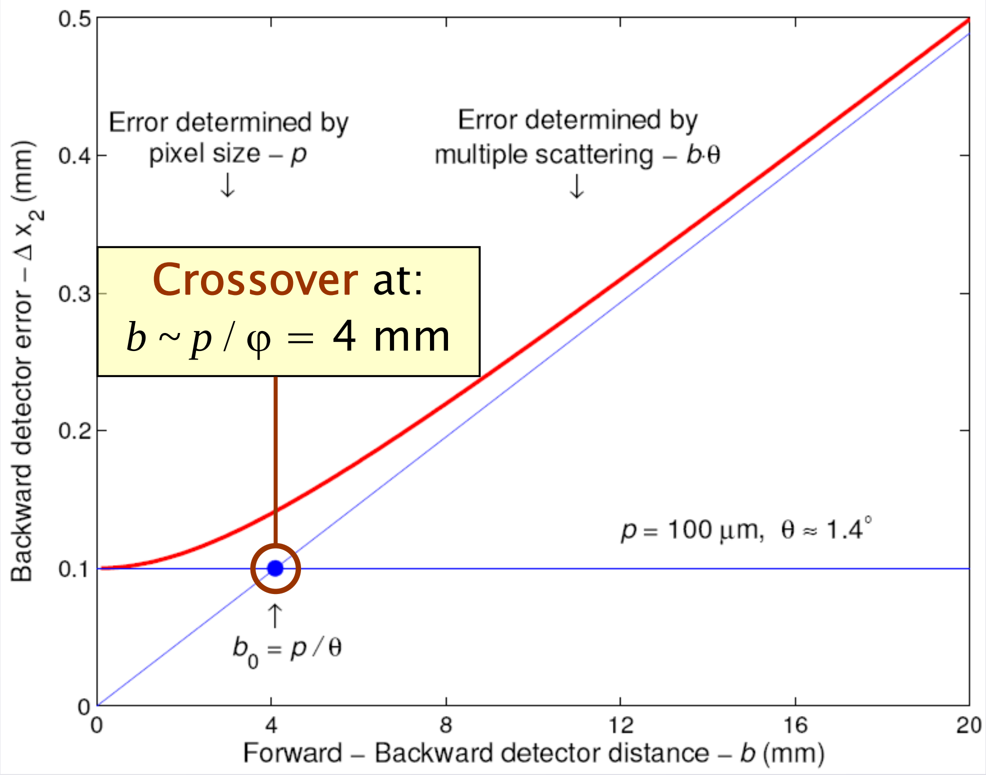
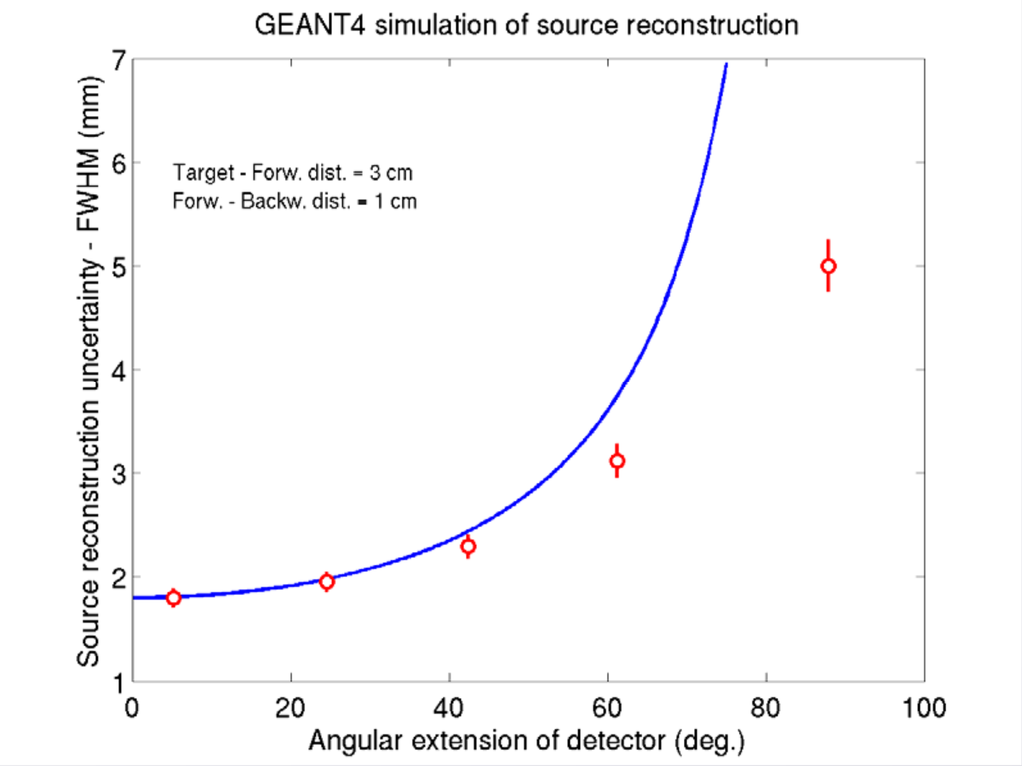
Linear error in backward detector

$$\Delta x_2 = [\Delta x^2_{2p} + (b \cdot \theta \cdot 1/\cos^2\alpha)^2]^{1/2}$$

↓ Pixel error ↓ Mult. Scatt.



Detector angular extension (position)



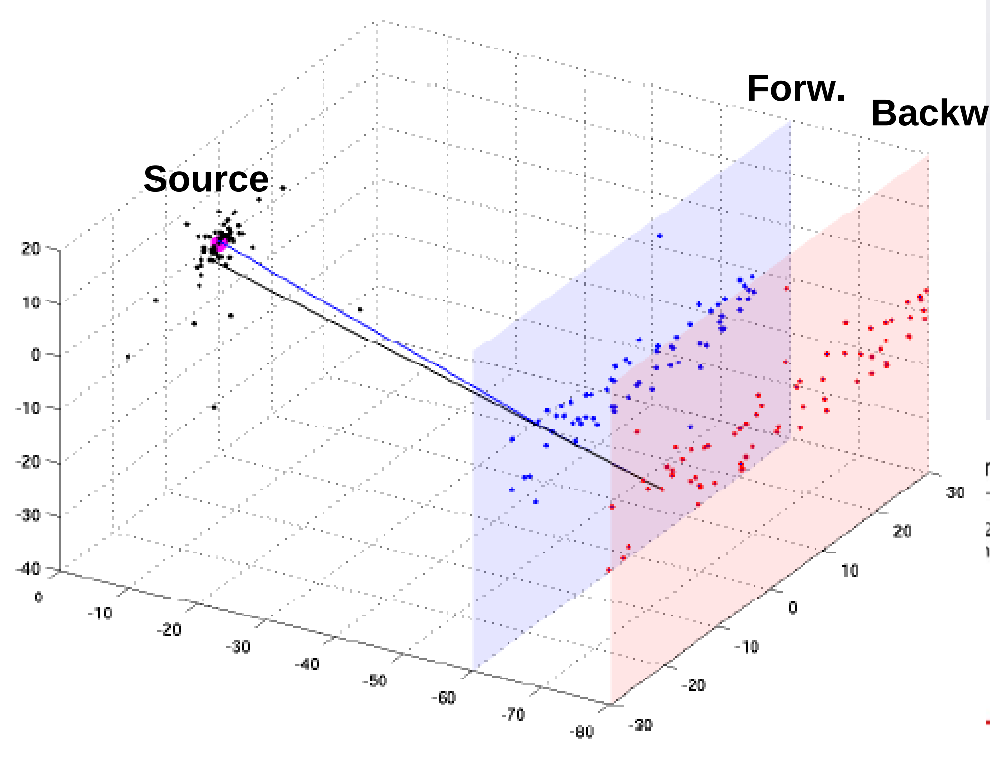
A very steep increase in error is expected for detectors at (or spanning) large angles:

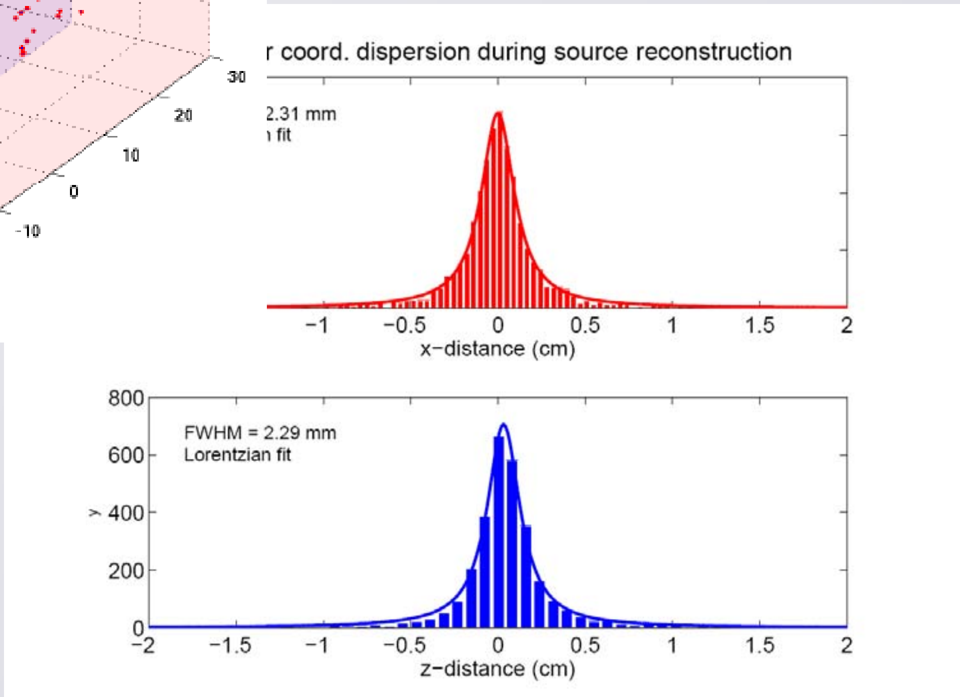
$$\Delta x_3 = a \cdot \varphi/2 \cdot \mathbf{1/cos^2\alpha}$$

$$1/\cos^2\alpha = \begin{cases} 1 & \text{for } \alpha = 0° \\ 4/3 & \text{for } \alpha = 30° \\ 2 & \text{for } \alpha = 45° \end{cases}$$

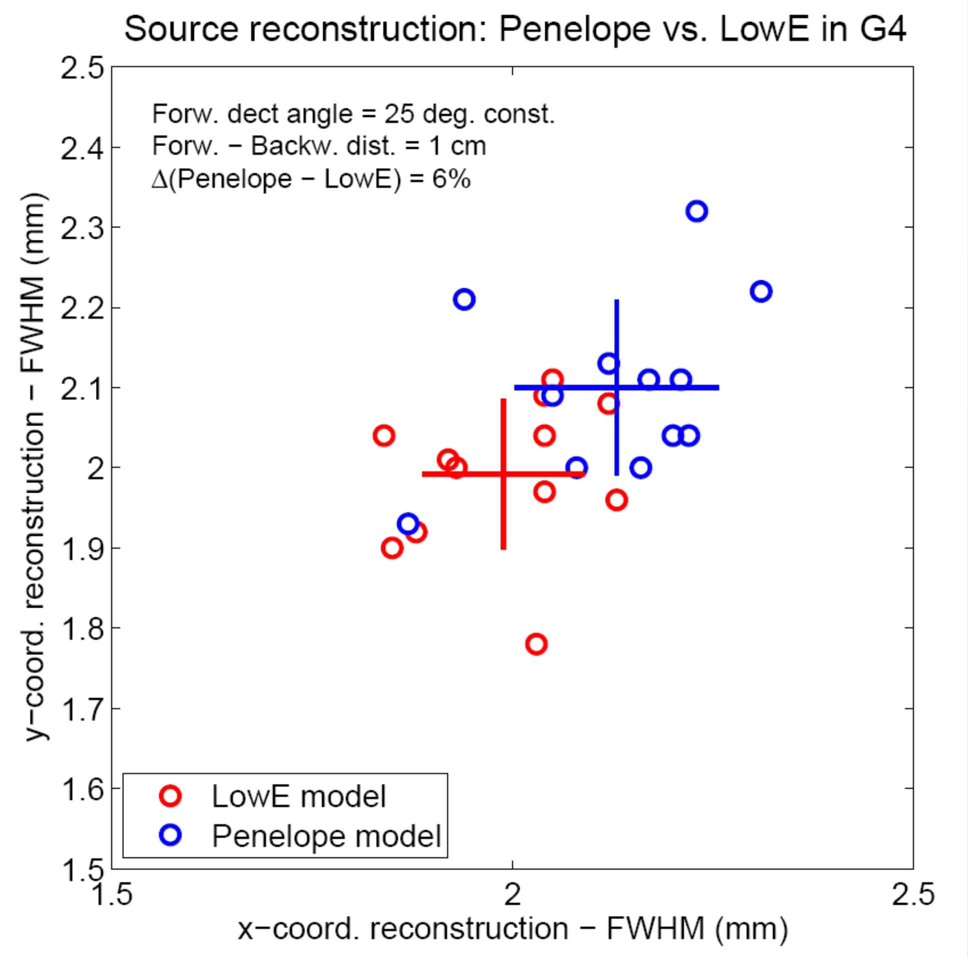
Conclusion: Use a detector covering **30° or less**.

Source position reconstruction





Checks of simulation stability



- Most calculation performed using **LowE** and **PENELOPE**: Only minor differences (< 6%)!
- The use of different **cut values** (0.1 and 1 mm) also did not affect significantly the results.

Conclusion: The reported results are **stable** and **reliable**.

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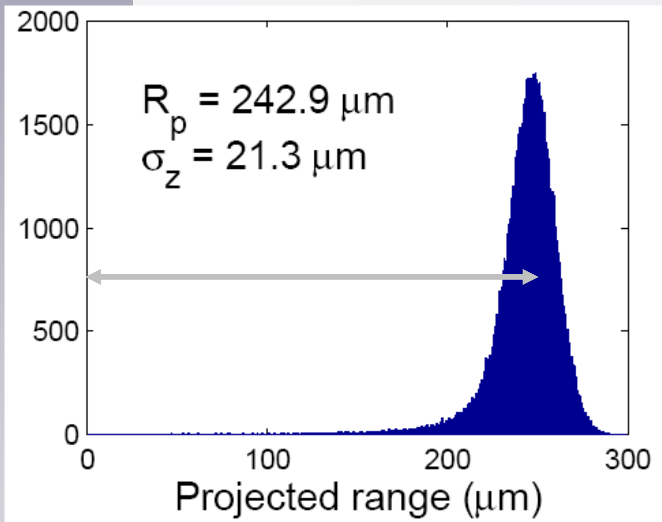
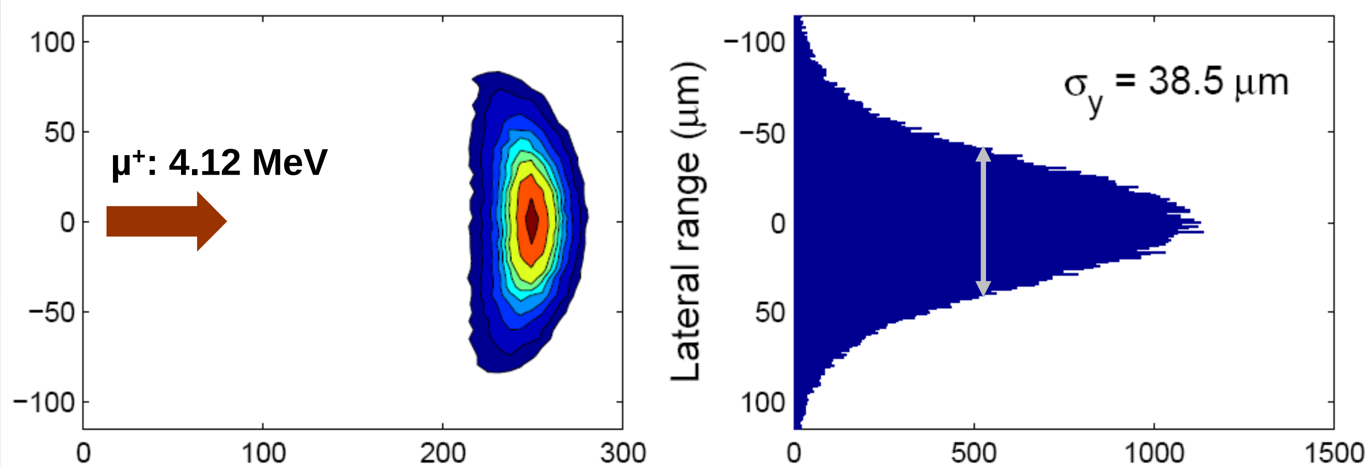
Projected and lateral μ^+ range in Ag



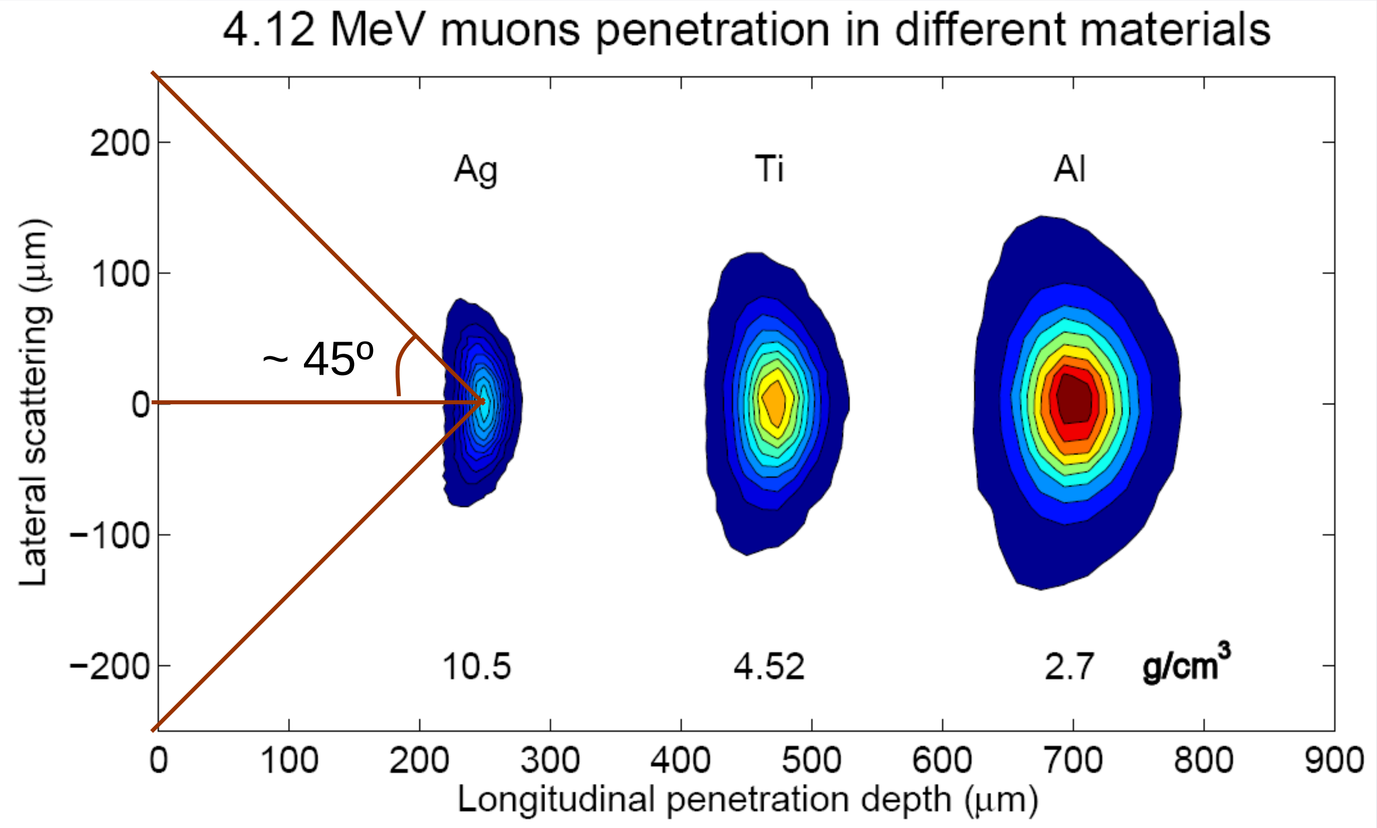
- The **projected** range relates to S_p, but how?
- Is **lateral** range important with respect to S_p?
- Can we **ignore the details** in a quick GEANT4 simulation?



Quick answer:

Yes, for Ag: $13\sigma_y = S_p$
Further studies for other elements.

Projected and lateral μ^+ ranges



Muon lateral range increases proportionately with projected range

Positrons are mainly (HWHM) emitted within ~ 45º from muon beam direction