Geant4 Simulations for MUSE

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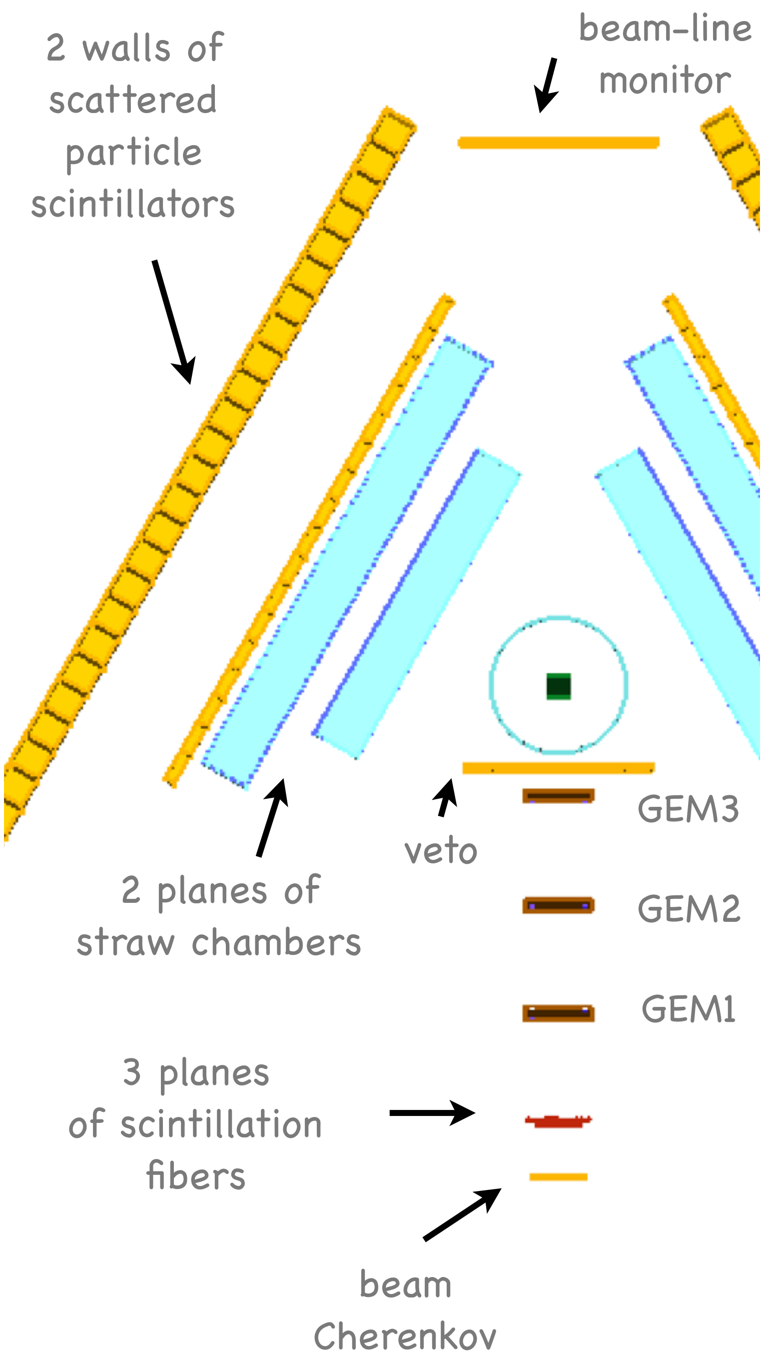


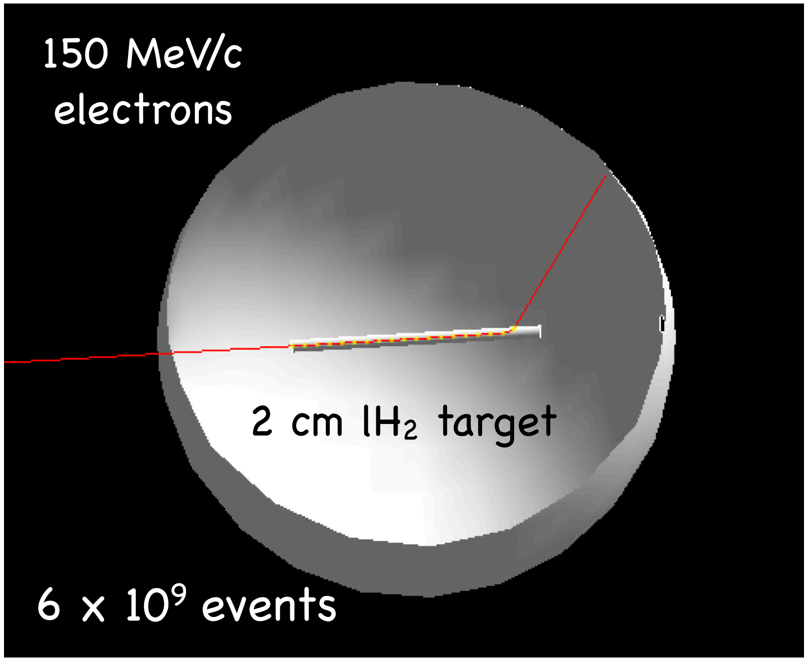
Outline

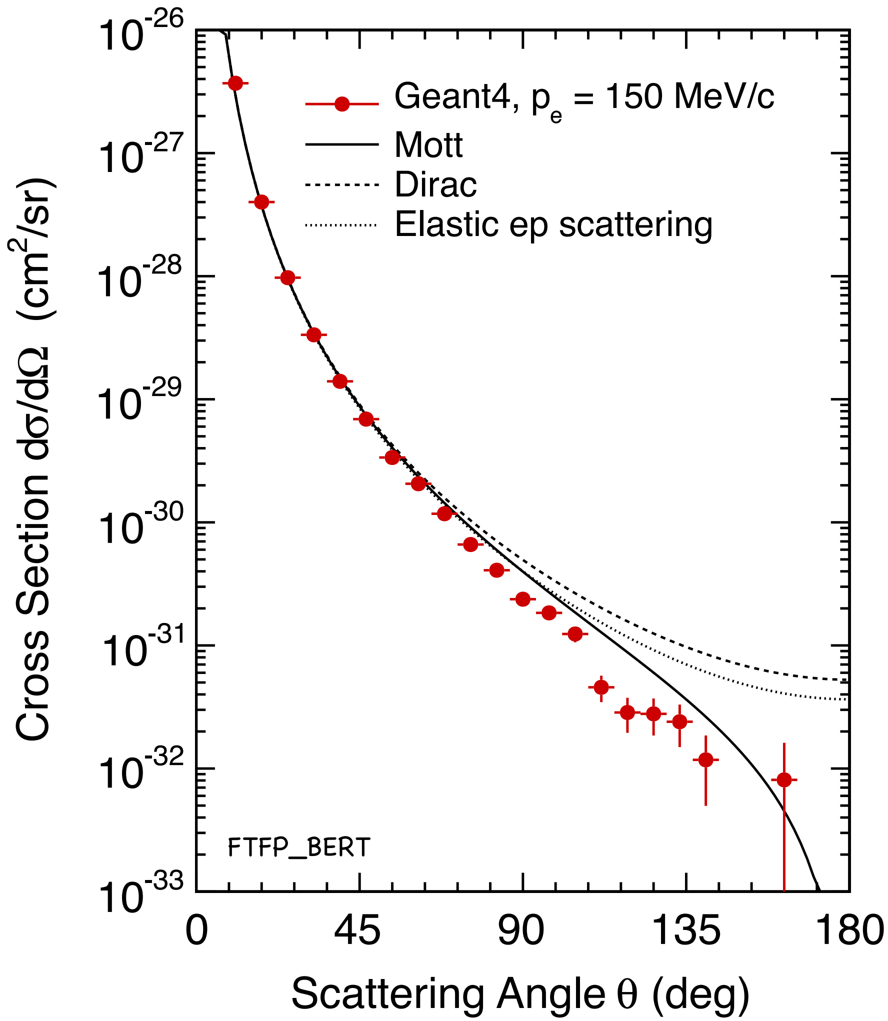
1. Geant4 physics model and simulation verification

2. Simulation of detector and beam properties

3. Preliminary study of analysis topics
   - Particle tracking and scattering-angle reconstruction
   - Møller/Bhabha scattering
   - Muon decay in flight

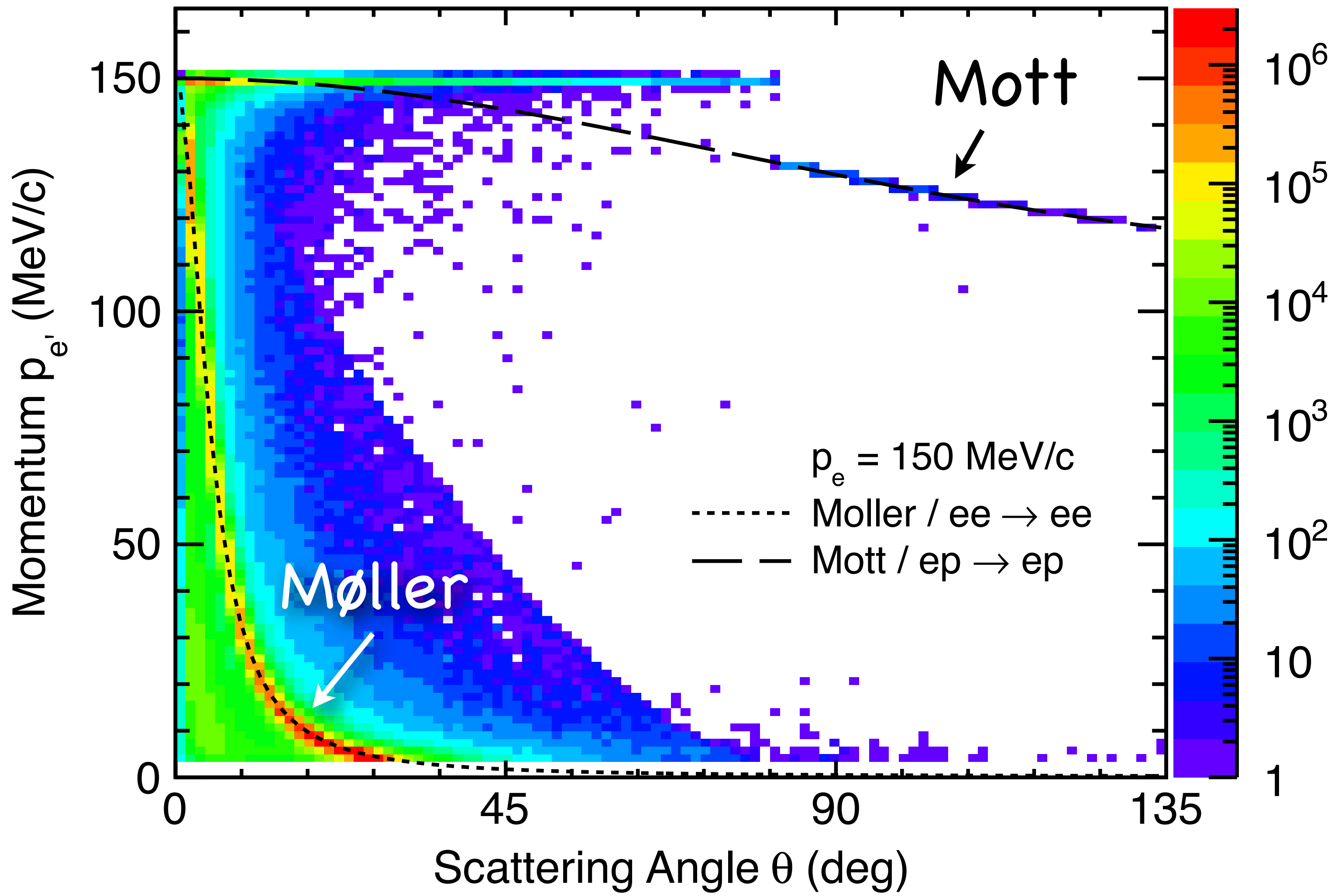
Physics: test of ep - scattering cross section





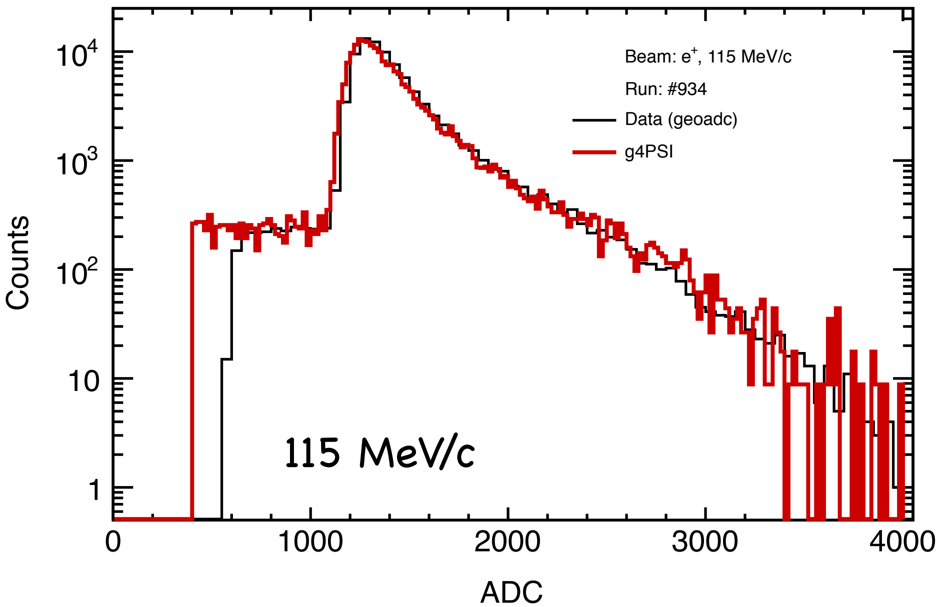
ep elastic cross section **reasonably well** described in Geant4 at 150 MeV/c and 210 MeV/c.

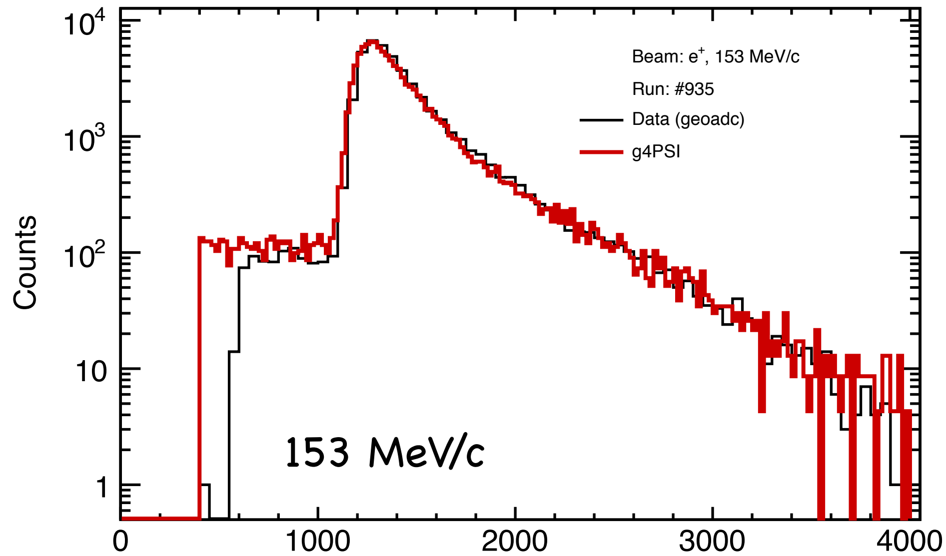
Physics: Mott and Møller scattering

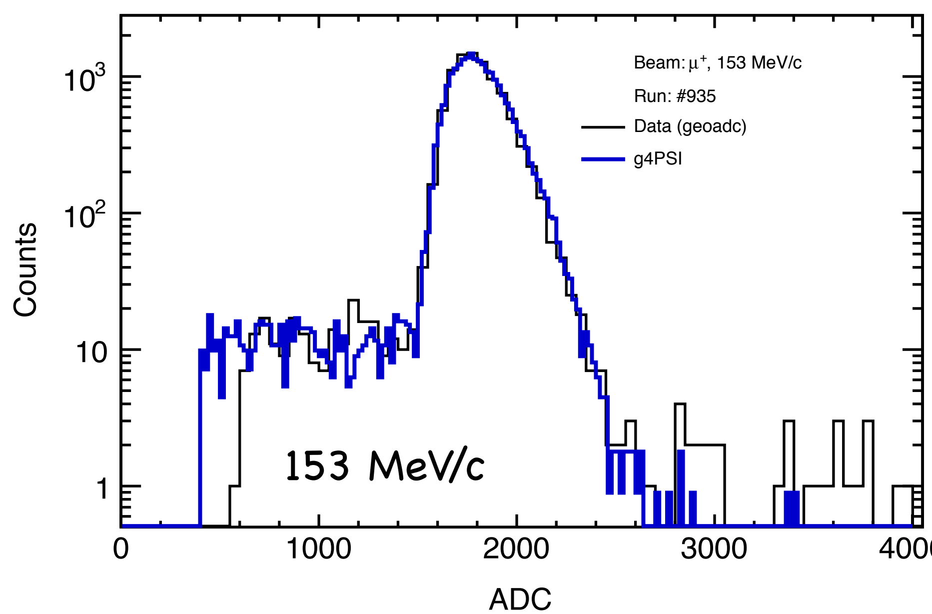


Momentum-angle correlation approximated for forward angle elastic ep scattering.

Pulse-height distribution: electrons and muons







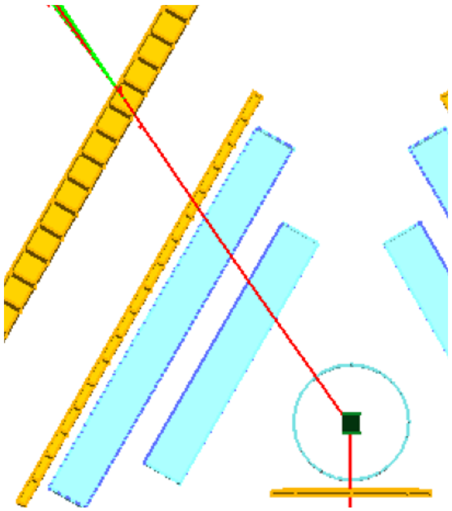
Data (Summer 2013):

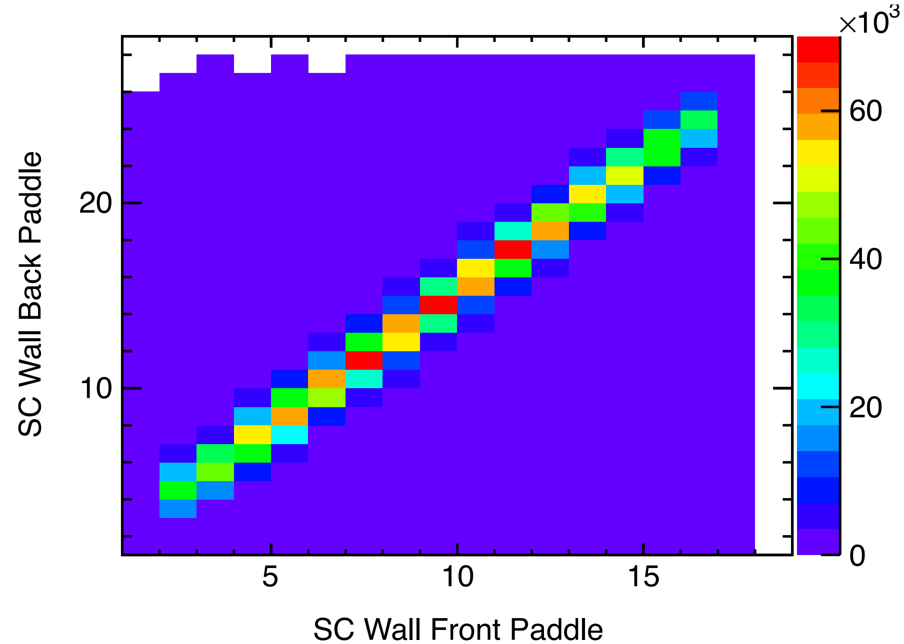
- 5 cm x 5 cm x 50 cm scintillator with 2 PMTs.

Geant4 simulation

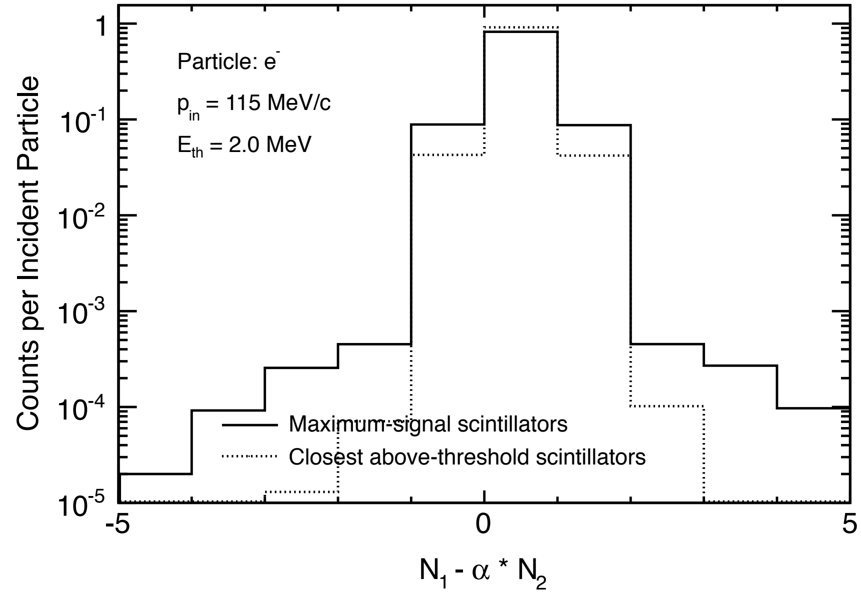
- Universal energy scale of the MC data for all runs and all particle types.
- Histograms normalized for equal number of entries.
- Adjustment of beam parameters in simulation to fit pulse-height spectrum.

Scattered particle scintillator - paddle correlation



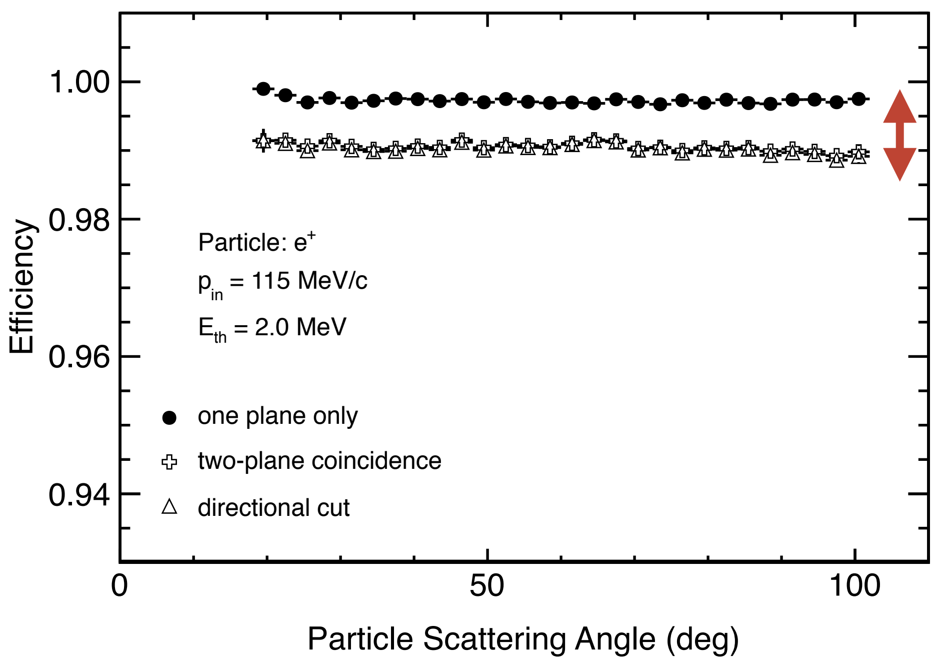


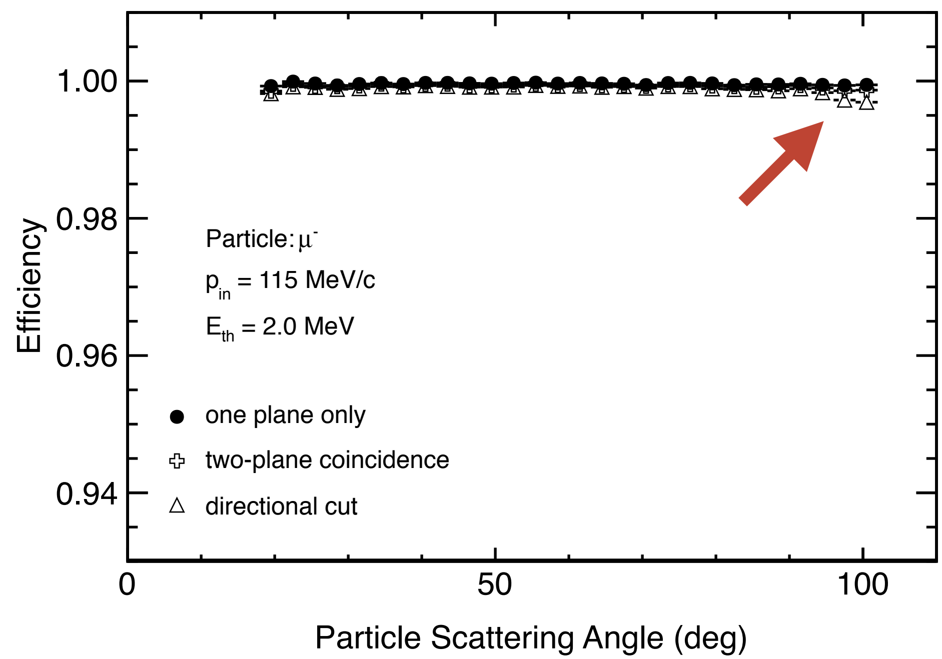
- Front- and back-wall hits are highly correlated if the event originated in the target.
- Imposing a hardware coincidence with the expected correlation does reduce accidental background.
- Measured correlation will help validate the simulation.



Detector efficiency of TOF wall scintillators

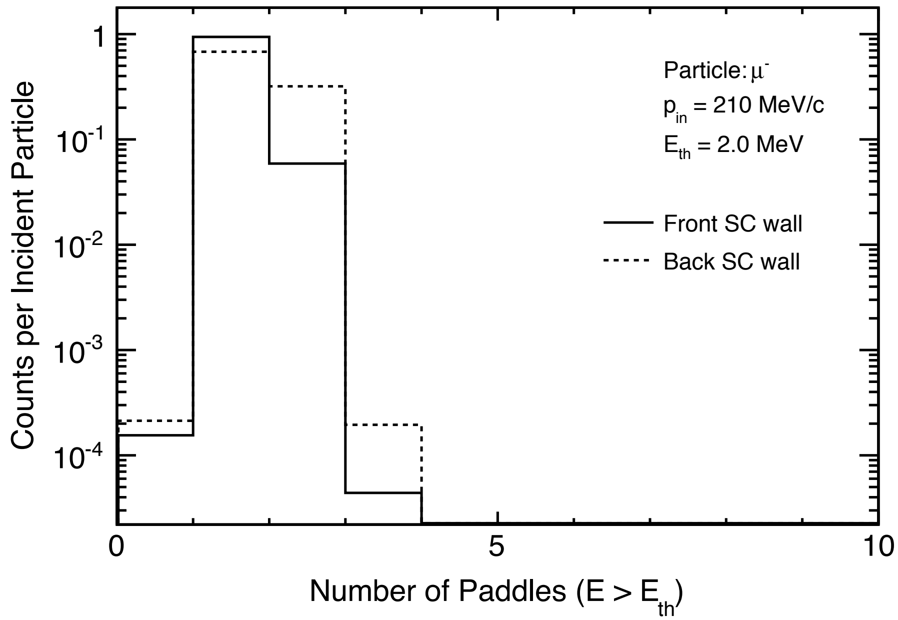
- Efficiency of scattered particle scintillators is ≳ 99%
- Small (< 1%) effects which will be corrected
  - Annihilation of positrons in the front wall
  - Multiple scattering of low-momentum muons (with directional cut)



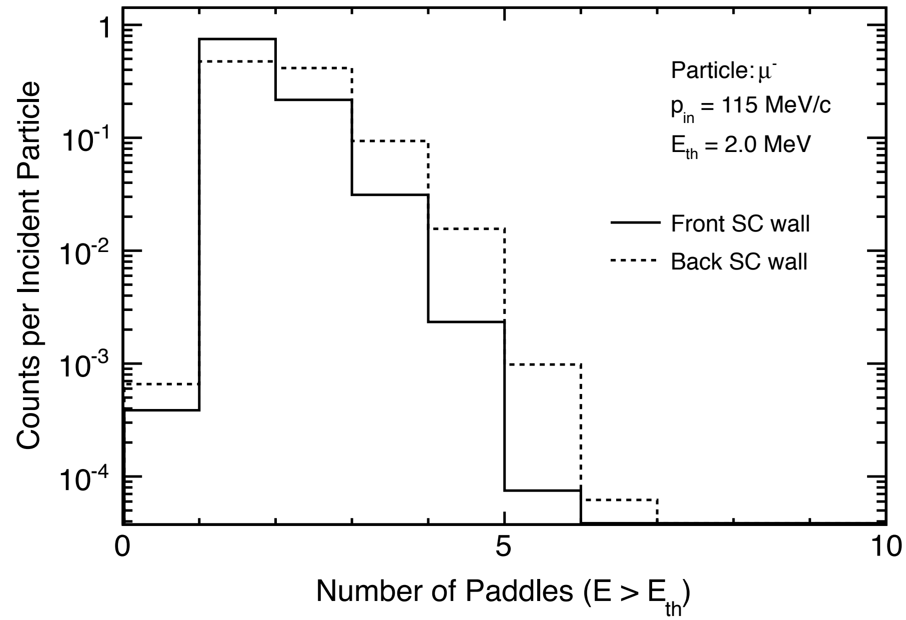


Multiplicity of scintillator-paddle hits

Typically low multiplicity



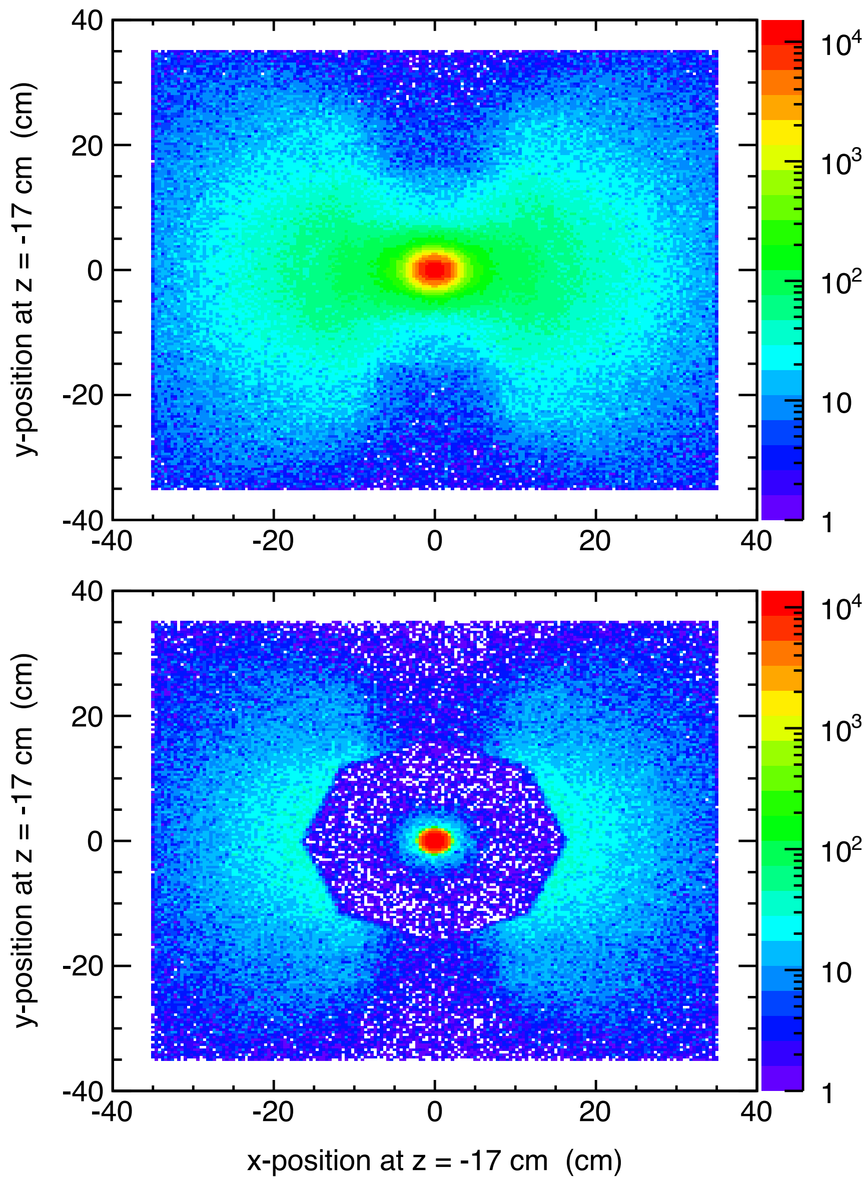
Highest multiplicity

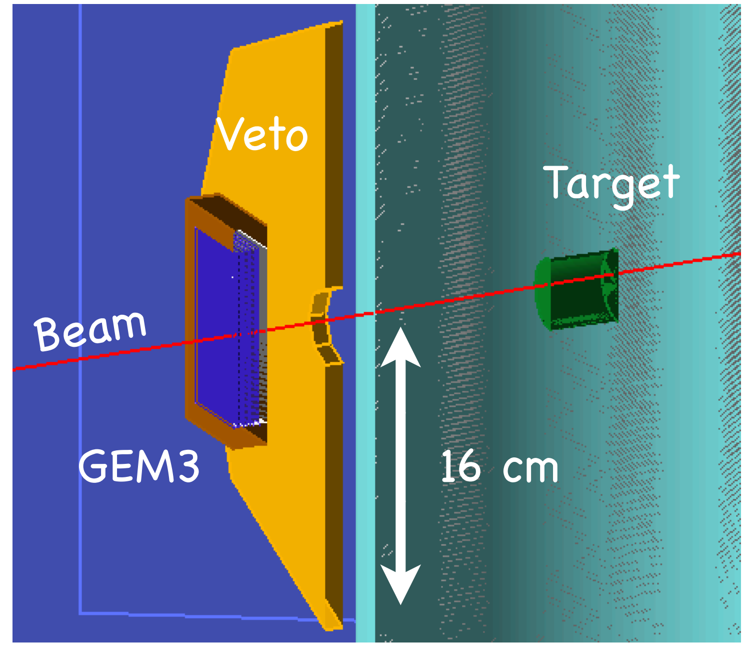


- In most cases one or two bars trigger per scintillator wall.
- Hit multiplicities can be used to validate the simulation.

Veto detector essential to reduce trigger rate

electron beam, p = 153 MeV/c





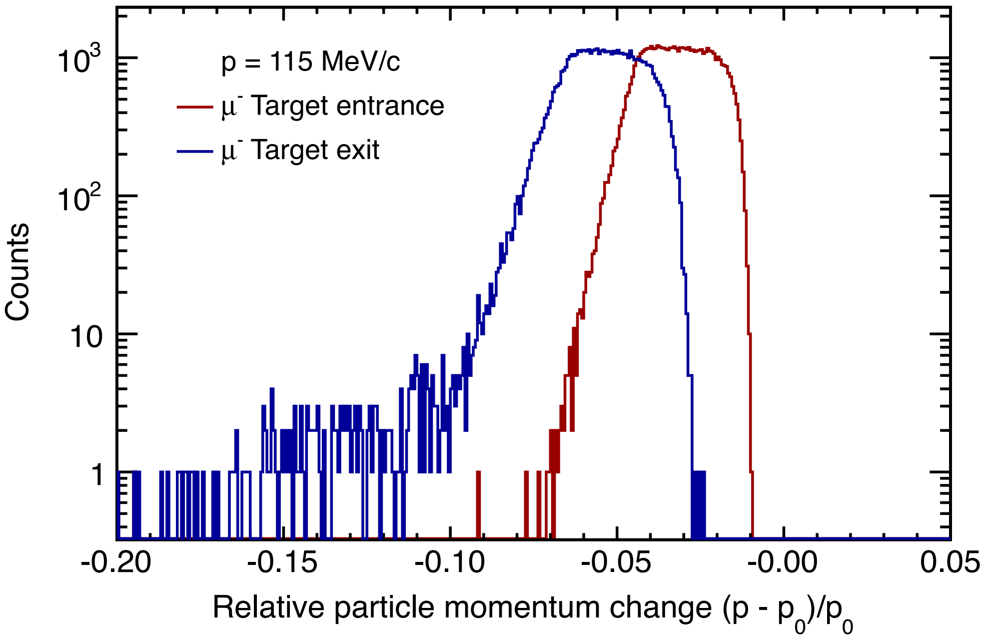
Trigger-rate reduction after veto:

- electrons ≈ 1/3
- muons ≈ 1/2

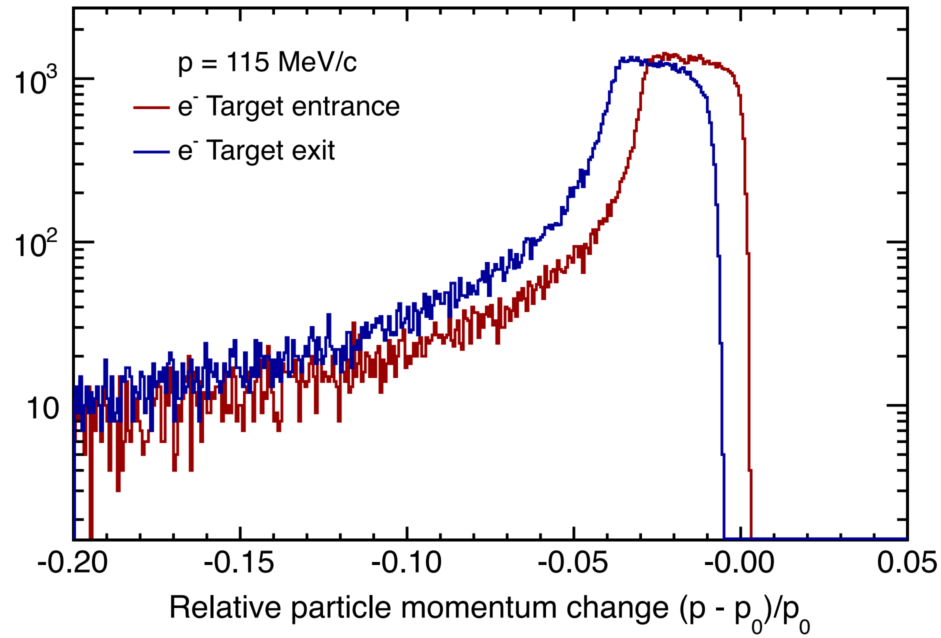
Simulation helps to understand the beam momentum distribution

Incident electron beam with momentum spread, $\Delta p/p = \pm 1.5\%$

Muon beam

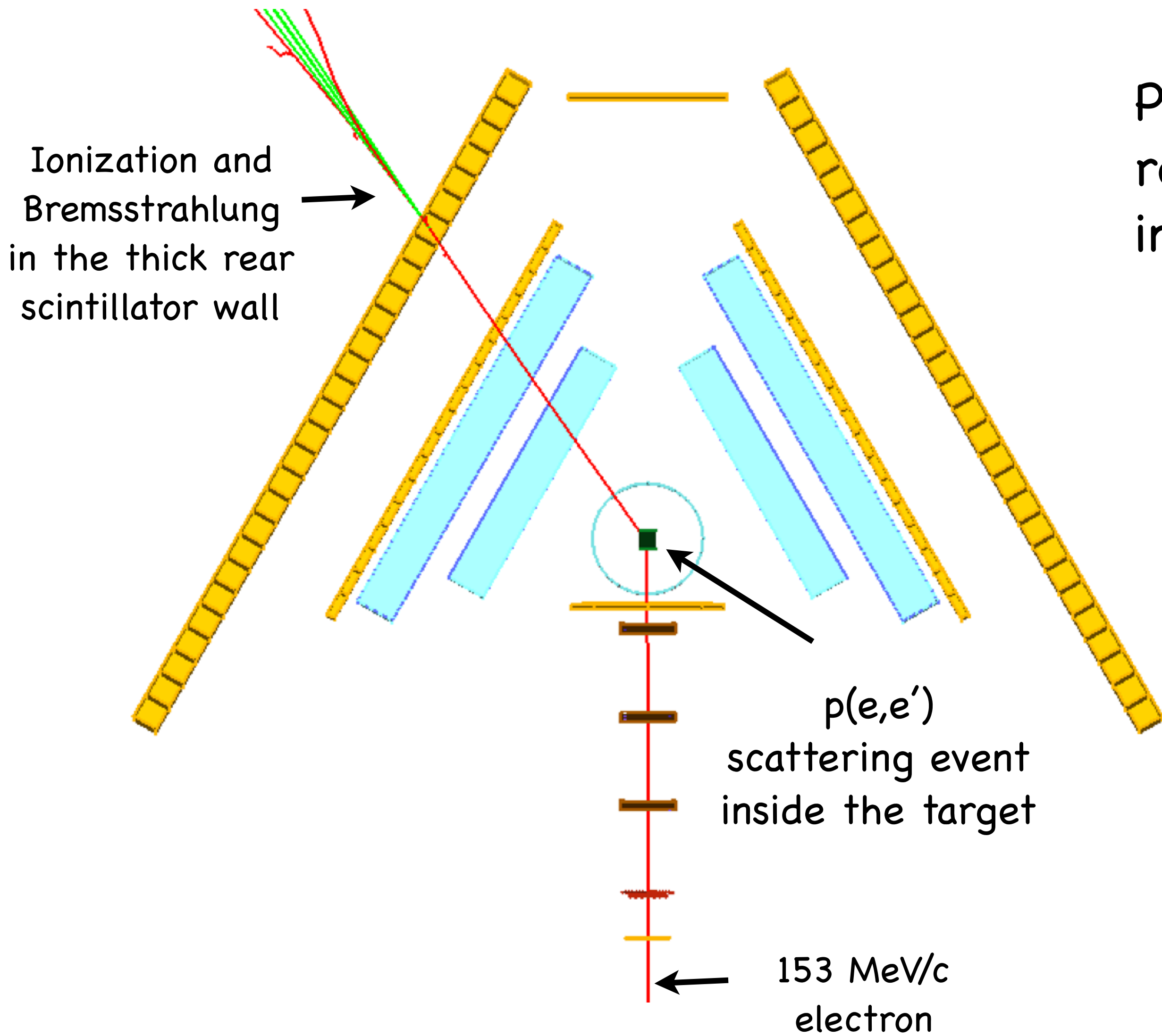


Electron beam



Beam-momentum distributions are an important input to radiative corrections of the scattering cross section.

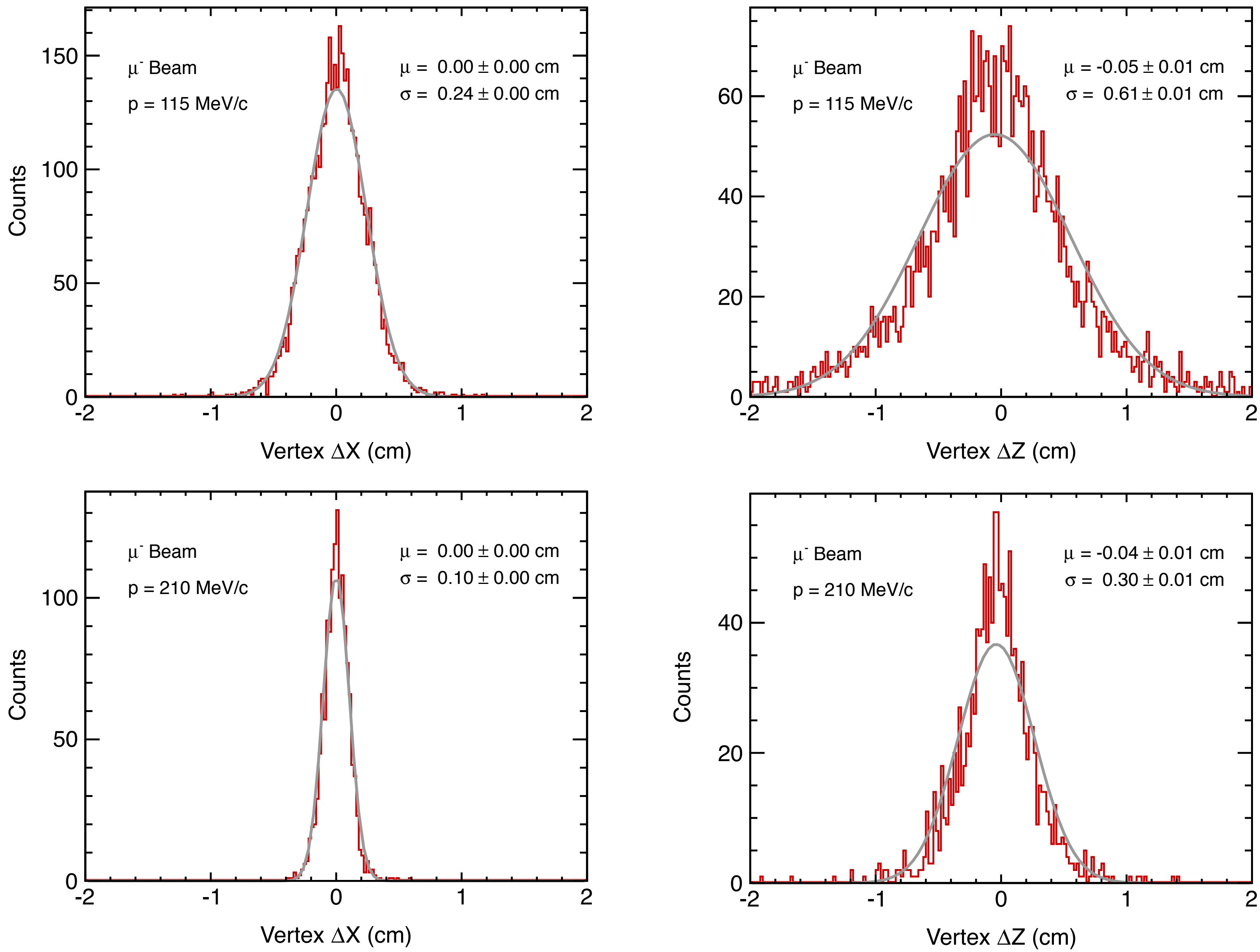
Tracking of simulated events



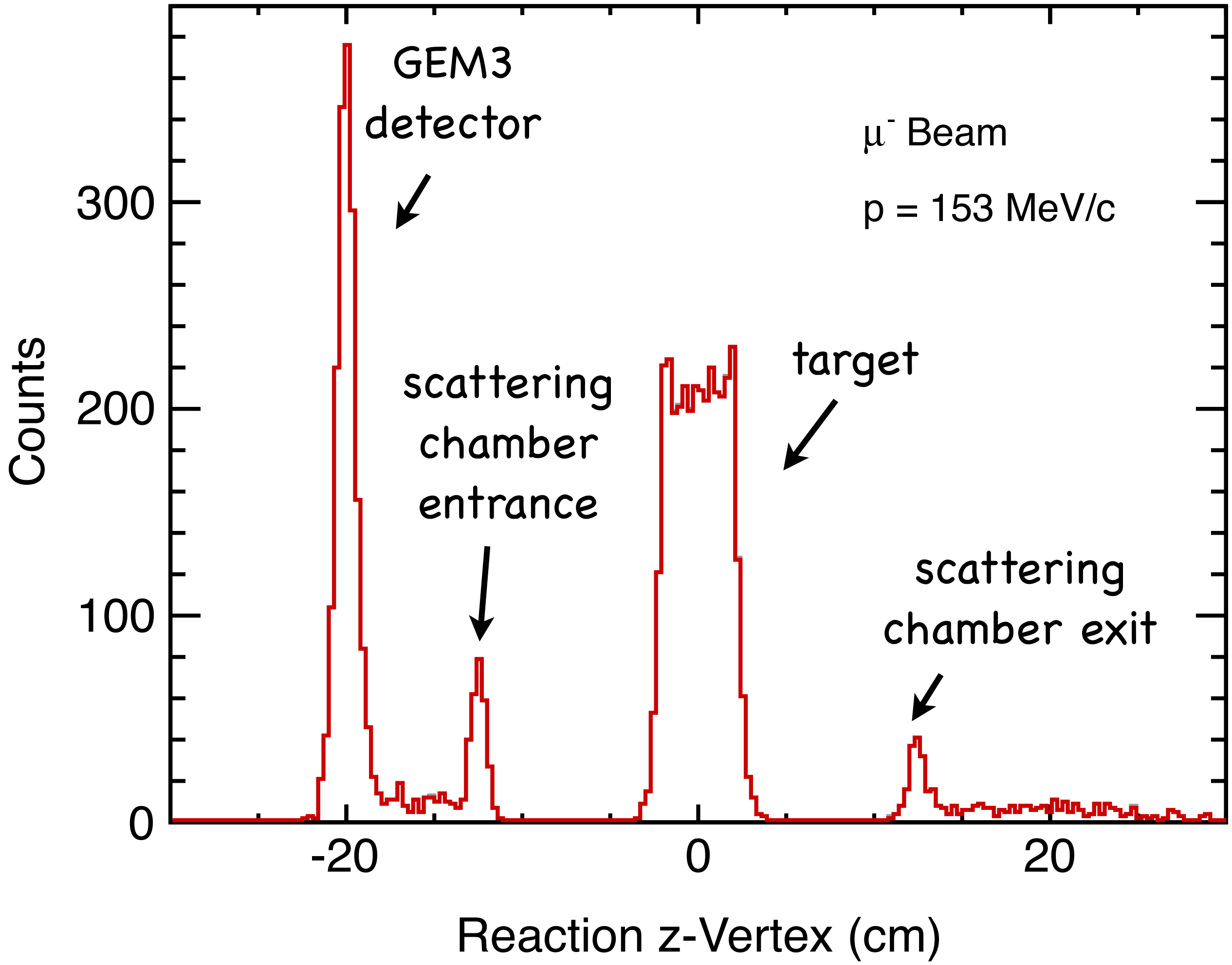
Particle-track reconstruction using hit information from

- hits in GEM detectors (incident) and
- straw chambers (scattered)

Vertex Resolution $\sigma \lesssim 6$ mm

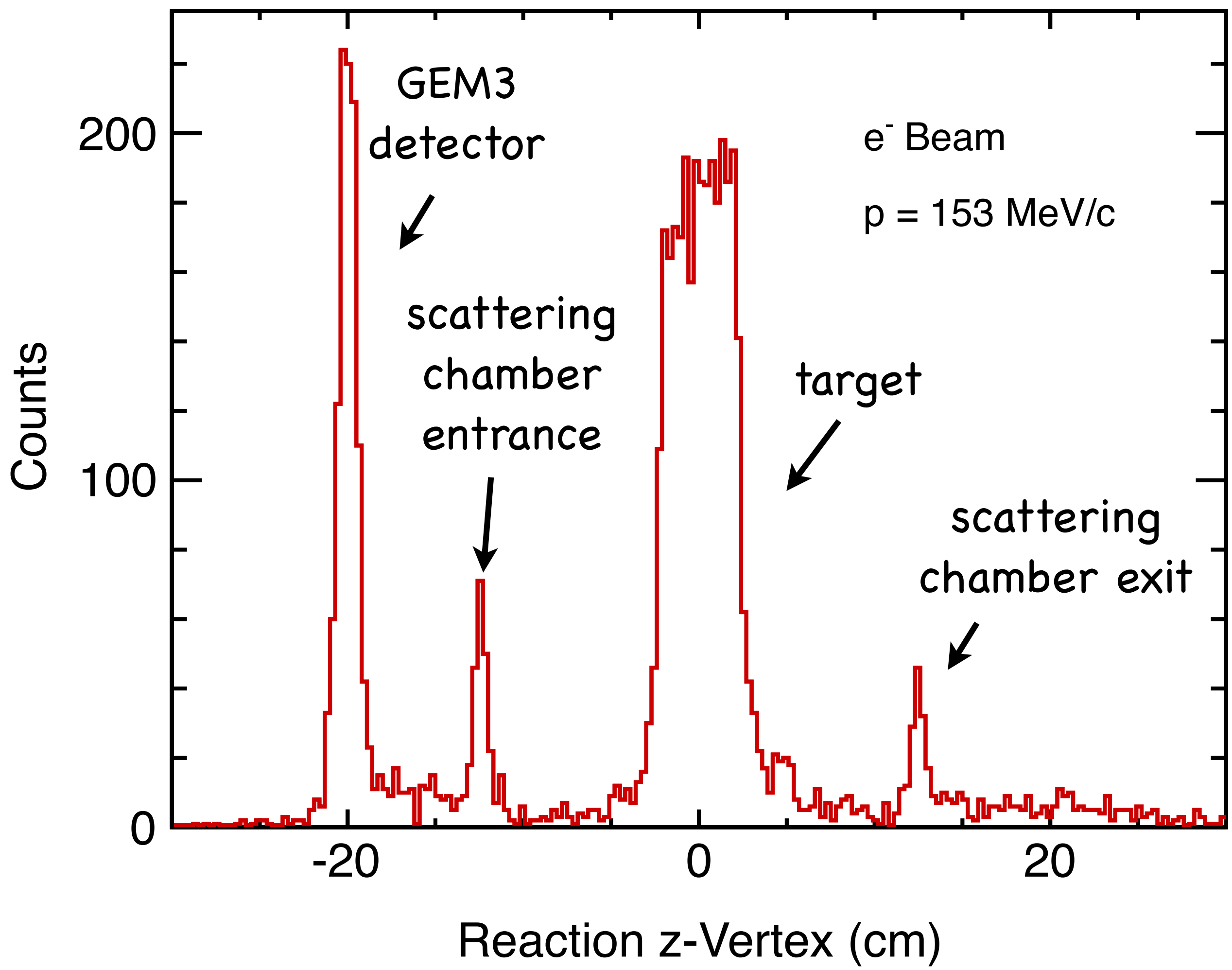


Vertex reconstruction of muon events



Reconstruction of muon scattering vertex is of sufficiently high resolution to cleanly separate scattering events within the target from other sources.

Vertex reconstruction for electrons

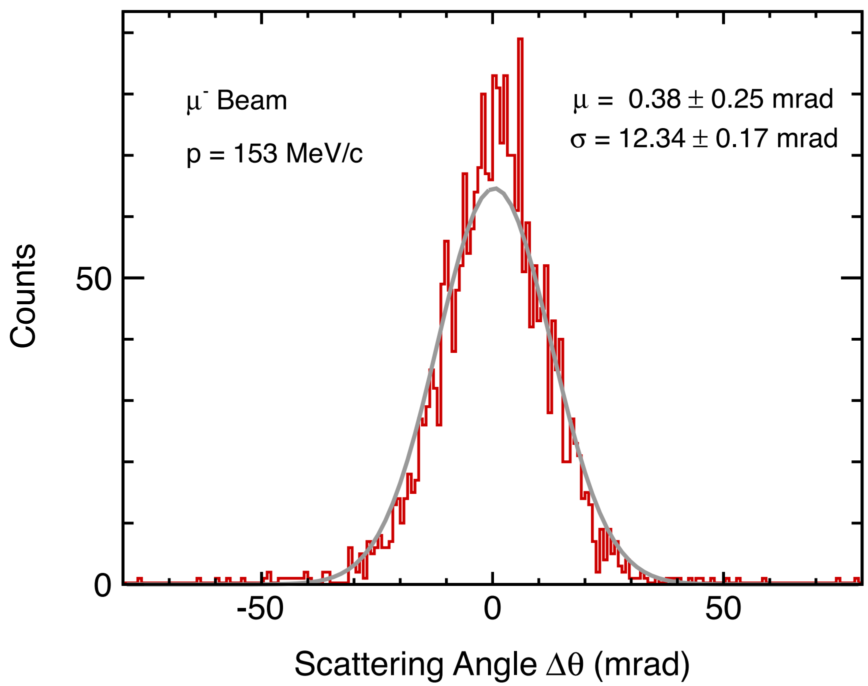


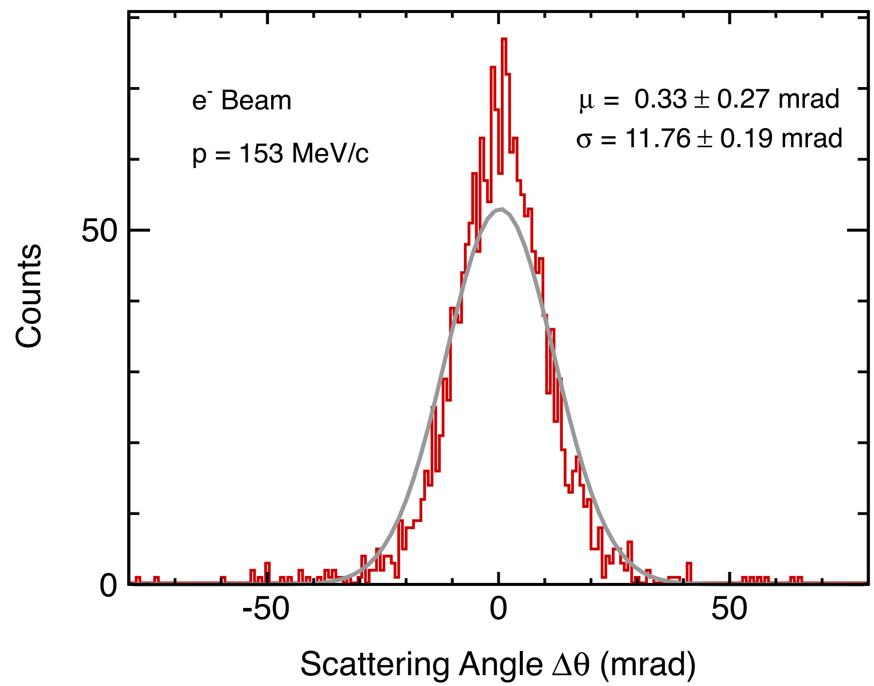
Radiation processes affect vertex reconstruction of electrons. Small background can be studied and corrected for with empty target measurements and simulations.

Sufficient resolution of the scattering angle reconstruction

Reconstruction of the scattering angle for simulated events with reconstructed reaction vertex within the target volume and θ > 20°

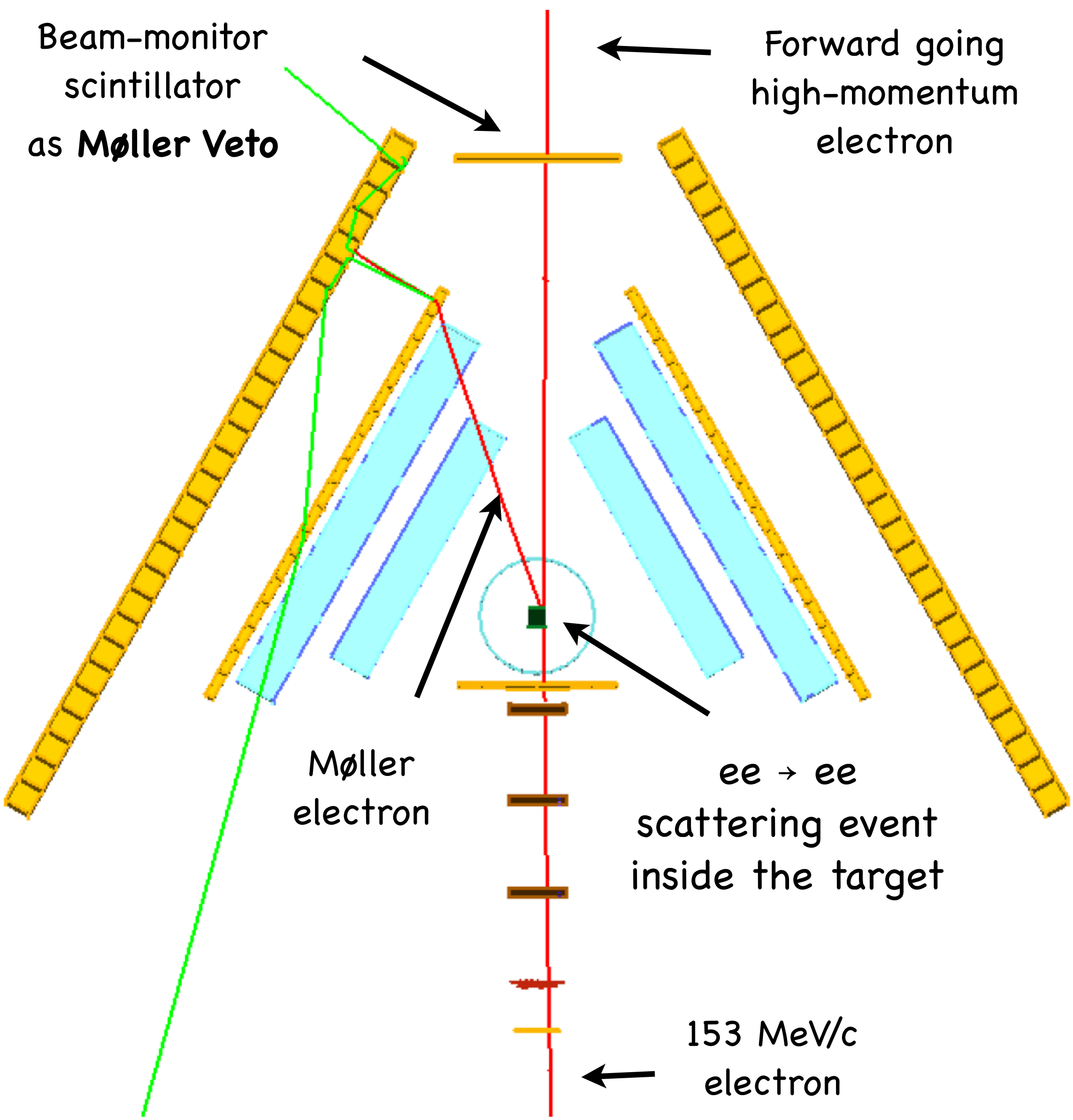
$$\Delta\theta = \theta_{\text{reconstructed}} - \theta_{\text{simulated}}$$





Reconstruction of the scattering angle is unbiased and of sufficient resolution.

Møller scattering background



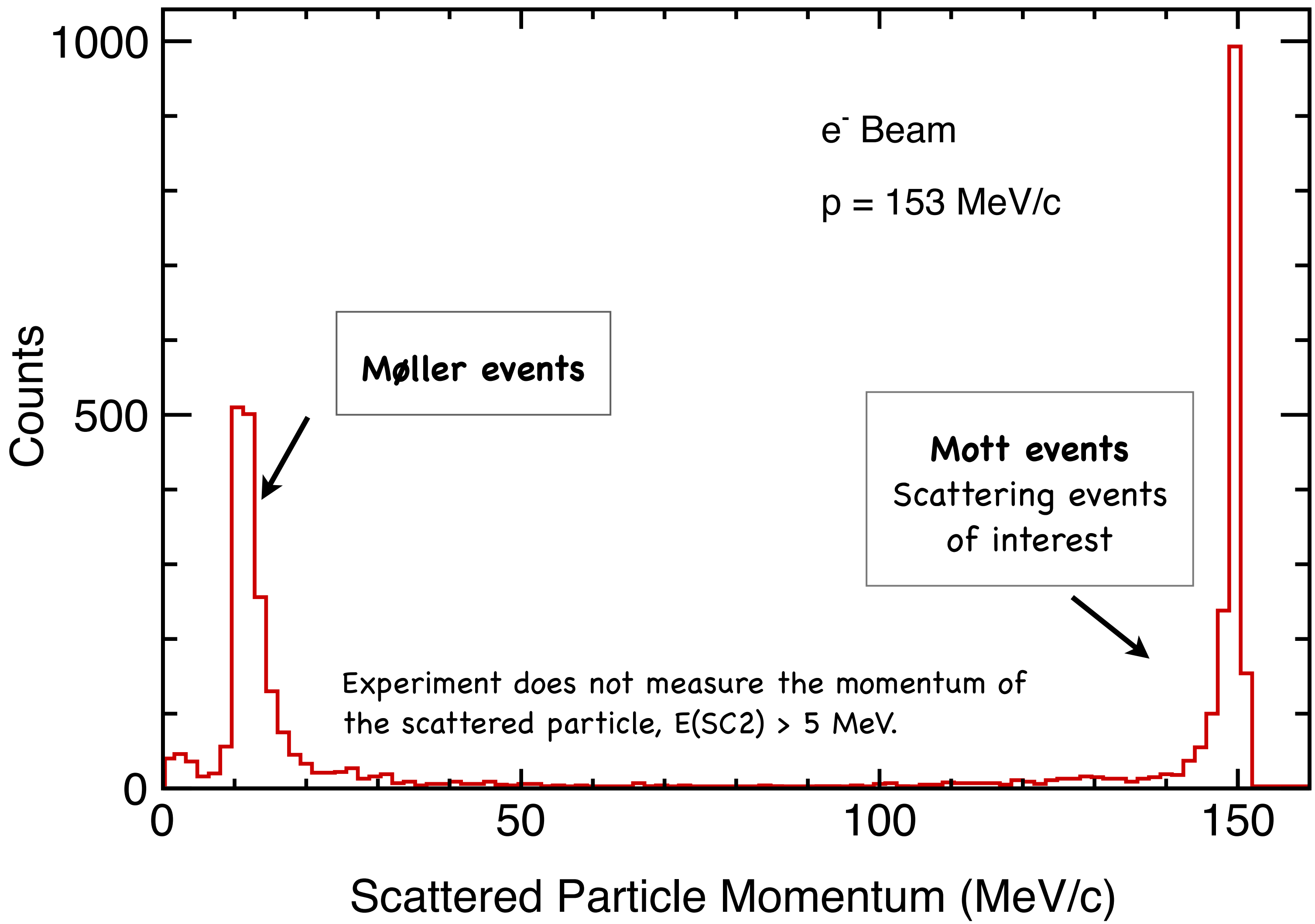
Signatures

- Scattered Møller electron forward peaked
- Scattered electron has low momentum
- Forward going high-momentum beam electron

Suppression

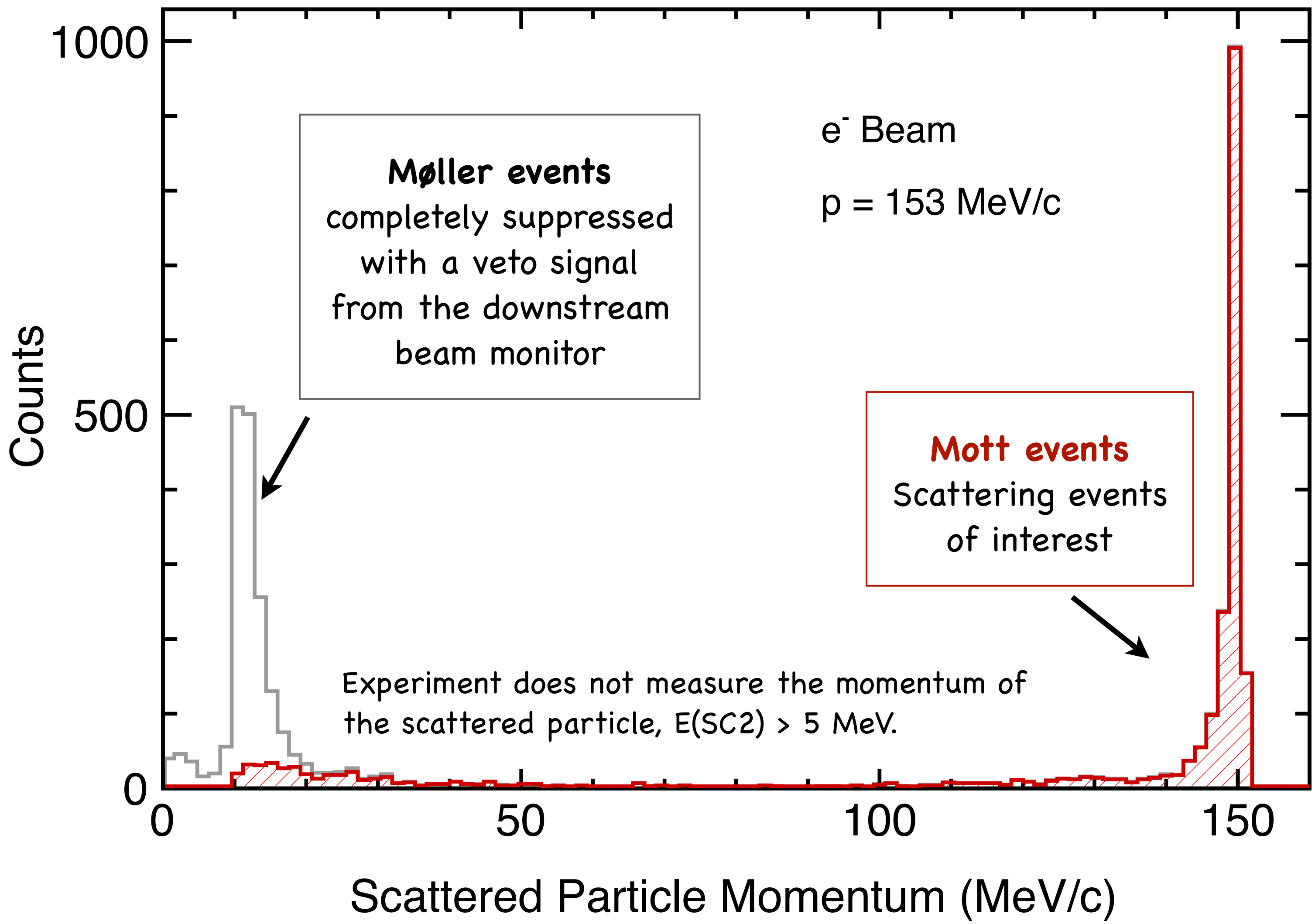
- Beam-monitor scintillator as **Møller Veto**
- **Scintillator Wall** bar combination

Electron momentum distribution dominated by Møller events



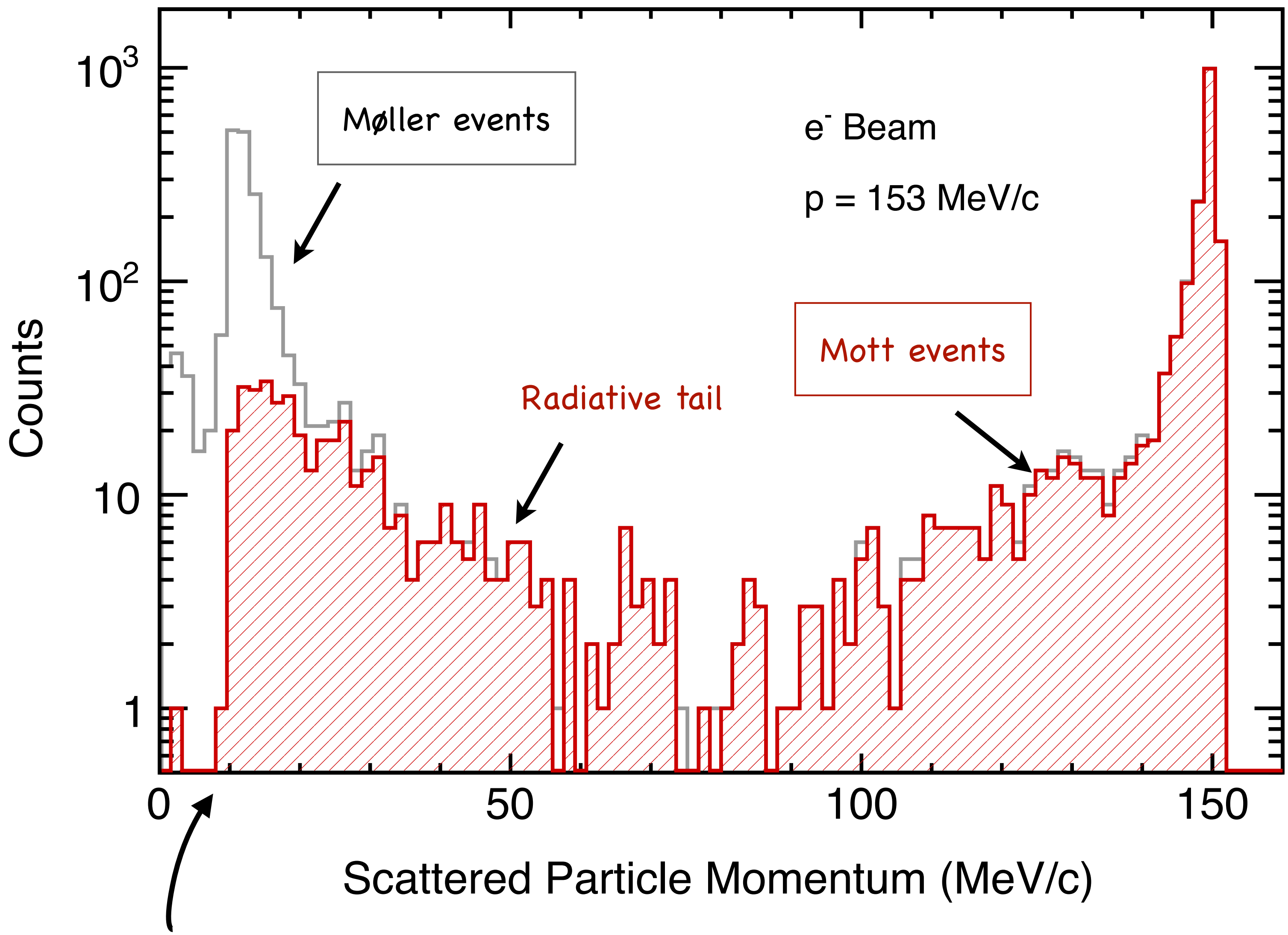
All events have a reaction vertex within the target volume.

Full suppression of Møller events with beam monitor veto



All events have a reaction vertex within the target volume. Events marked in red do **not** have a hit in the downstream beam monitor.

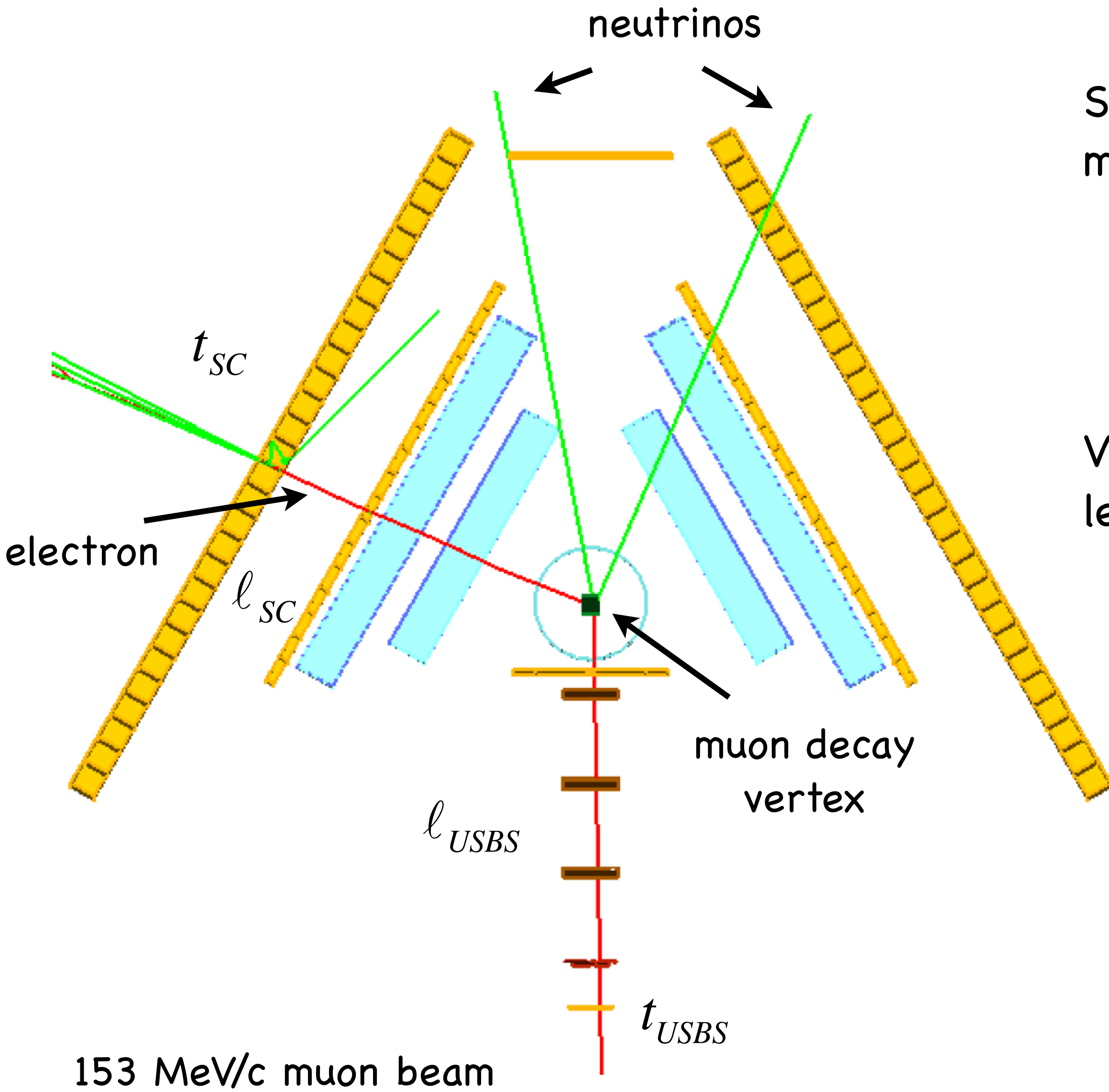
Simulation gives input to calculations of radiative corrections



simulation determines detection threshold, which is an input to the calculations of radiative corrections

Muon decay in flight

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$



Suppression of background from muon decay

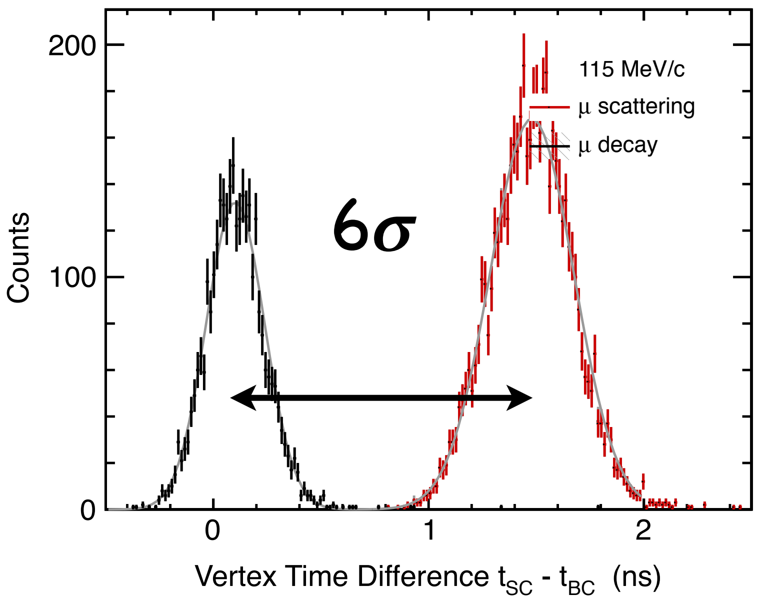
- Target vertex cut
- Time of flight

Vertex-time difference from path lengths and measured times

$$\Delta t = \left(t_{SC} - \frac{\ell_{SC}}{c} \right) - \left(t_{USBS} - \frac{\ell_{USBS}}{\beta_\mu c} \right)$$

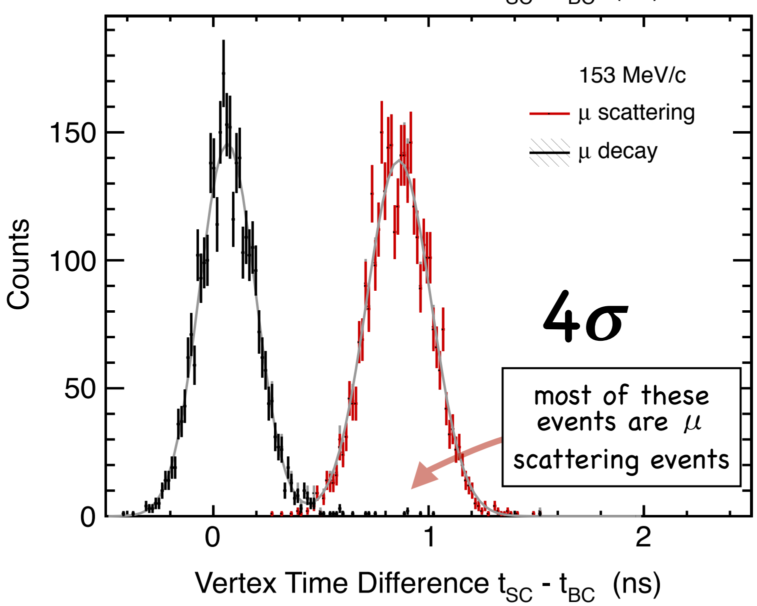
assuming electron after muon decay, $\beta_e = 1$

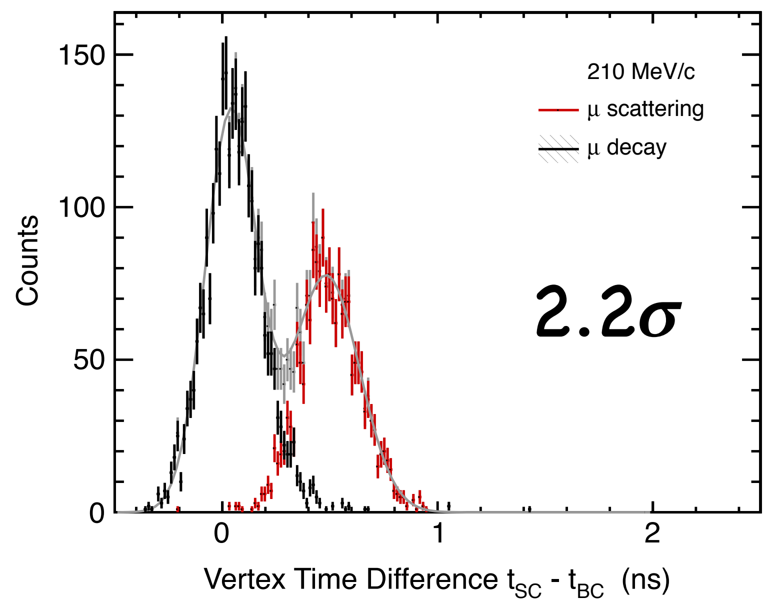
Muon decay in flight — vertex-time difference



Detection of muon decay by path-length corrected time-of-flight:

- time-of-flight walls (t_{SC}, σ = 50 ps)
- upstream beam Cherenkov (t_{BC}, σ = 100 ps)





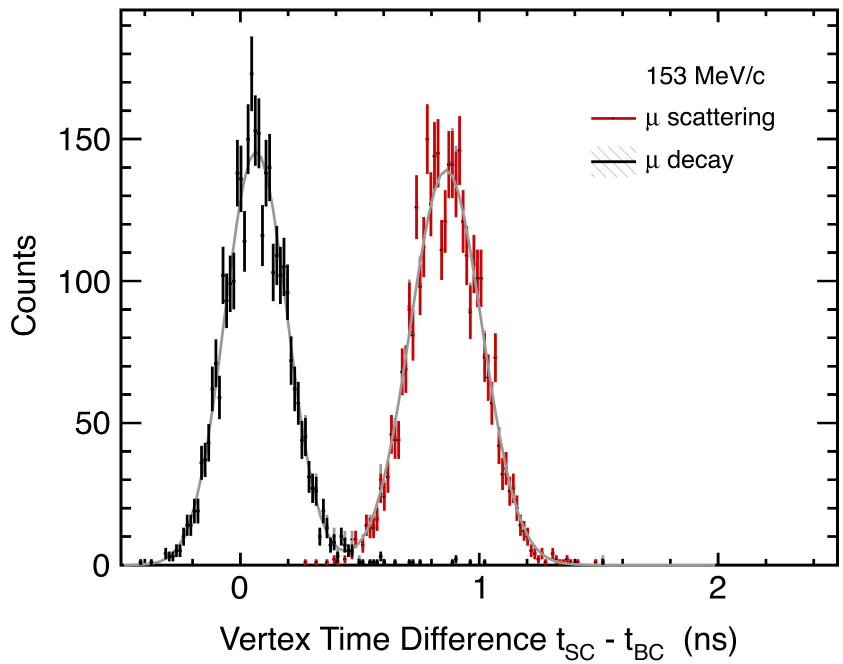
High fraction of scattering events are detectable without significant background contribution

μ momentum	Vertex-time difference cut on scattering event distribution $-\sigma < t_{SC} - t_{BC}$	$-3\sigma < t_{SC} - t_{BC}$
115 MeV/c	Signal 85(2)% Background 0.0(0.0)%	**Signal 100(2)%** **Background 0.0(0.0)%**
153 MeV/c	Signal 87(2)% Background 0.3(0.1)%	**Signal 100(2)%** **"Background" 1.6(0.2)%**
210 MeV/c	**Signal 90(3)%** **Background 3.1(0.2)%**	Signal 100(4)% Background 63(1)%

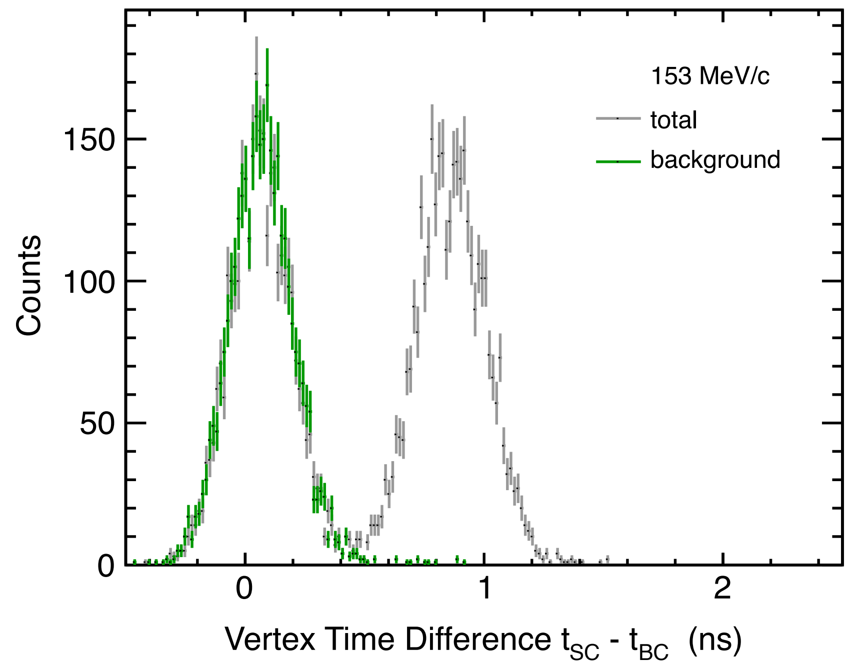
- The time-of-flight technique can reduce the muon-decay in flight background to < 4% prior to any correction of subtraction.
- In practice, vary cut to optimize final uncertainties.

Direct measurement of the muon decay in flight background

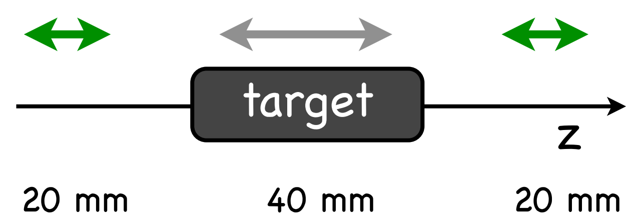
Muon decay flagged in simulation



Muon decay distribution measured



In situ measurement of muon decay-in-flight background from events upstream & downstream of the target.



Summary

- Key physics processes are included in the simulation code.
- Simulation of detector components helped with the optimization of the experimental setup.
- Particle vertex and scattering-angel **reconstruction** is sufficient.
- **Møller/Bhabha scattering** are efficiently suppressed with an event-veto from the beam-line monitor detector.
- **Muon decay-in-flight** background can be removed with time-of-flight measurements, direct measurements of the background up- and downstream of the target, or through empty target measurements.