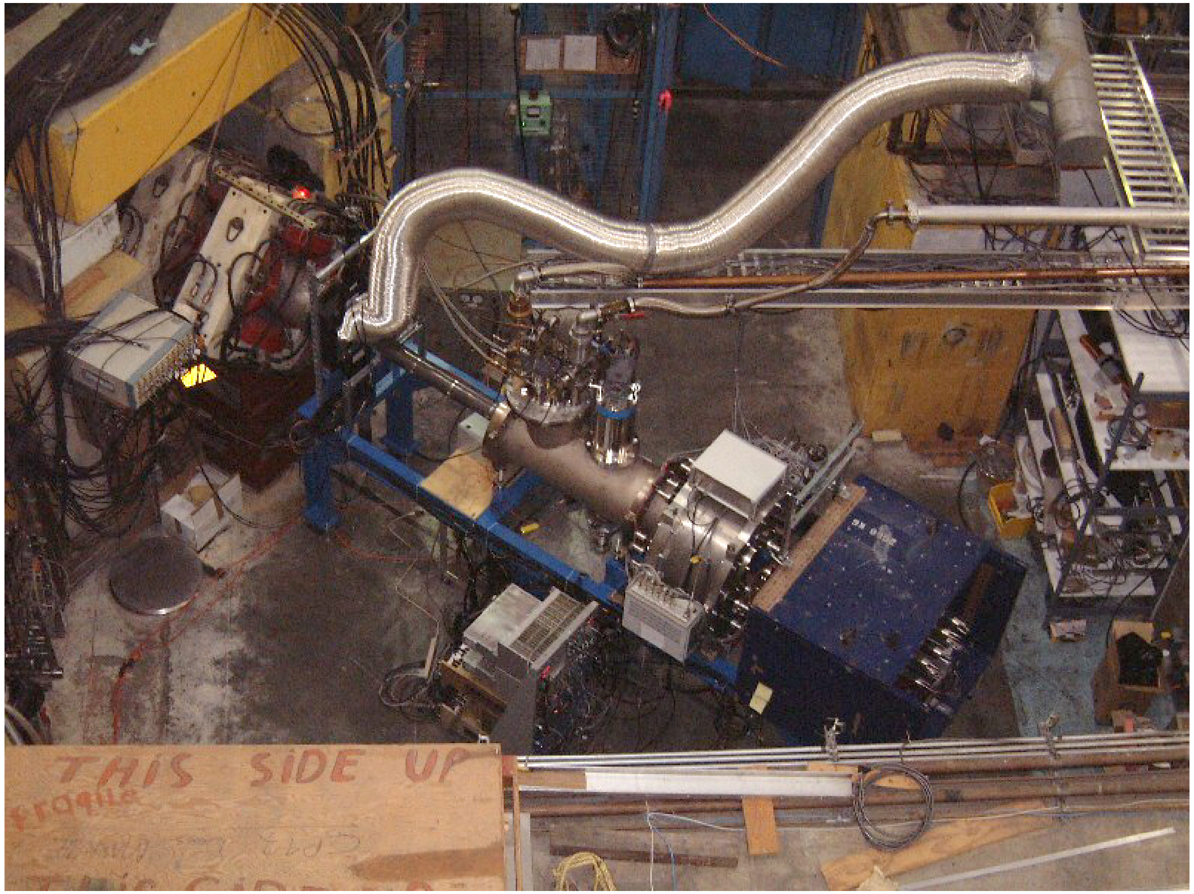
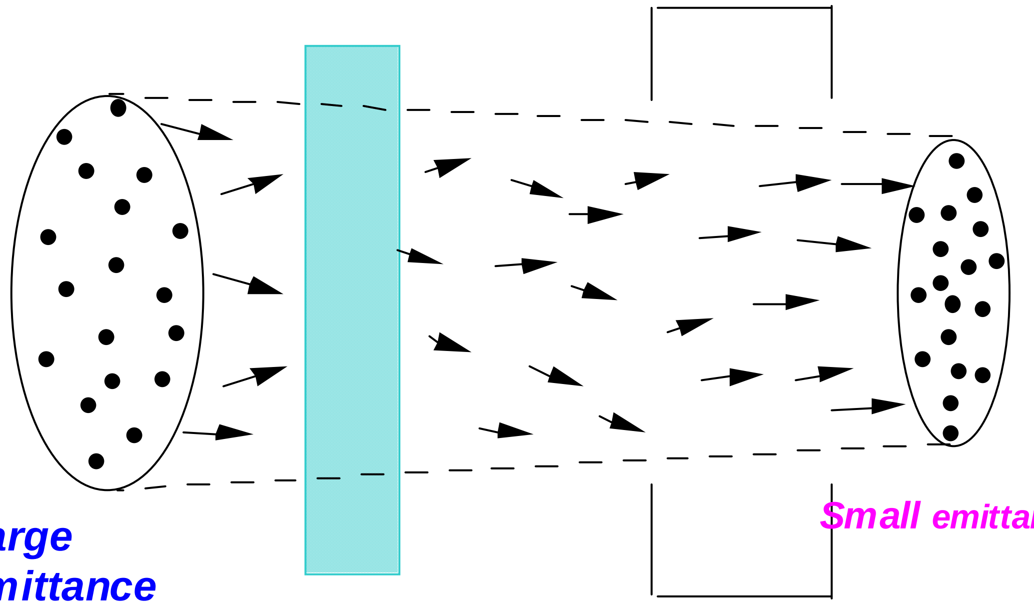
Results from MuScat

- Ionization Cooling
- Motivation
- Beamline and Detector
- Data taken at TRIUMF (2003)
- Analysis
- Comparison of results with GEANT4
- Conclusions



Ionization Cooling

Material	$\langle dE/ds \rangle_{min}$ (MeV $g^{-1}cm^2$)	L_R ($g\,cm^{-2}$)	Merit
GH_2	4.103	61.28	1.03
LH_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18



Momentum loss is opposite to motion, p, p_x, p_y, ΔE decrease

Momentum gain is purely longitudinal

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \text{GeV})^2}{2\beta^3 E_\mu m_\mu L_R}$$

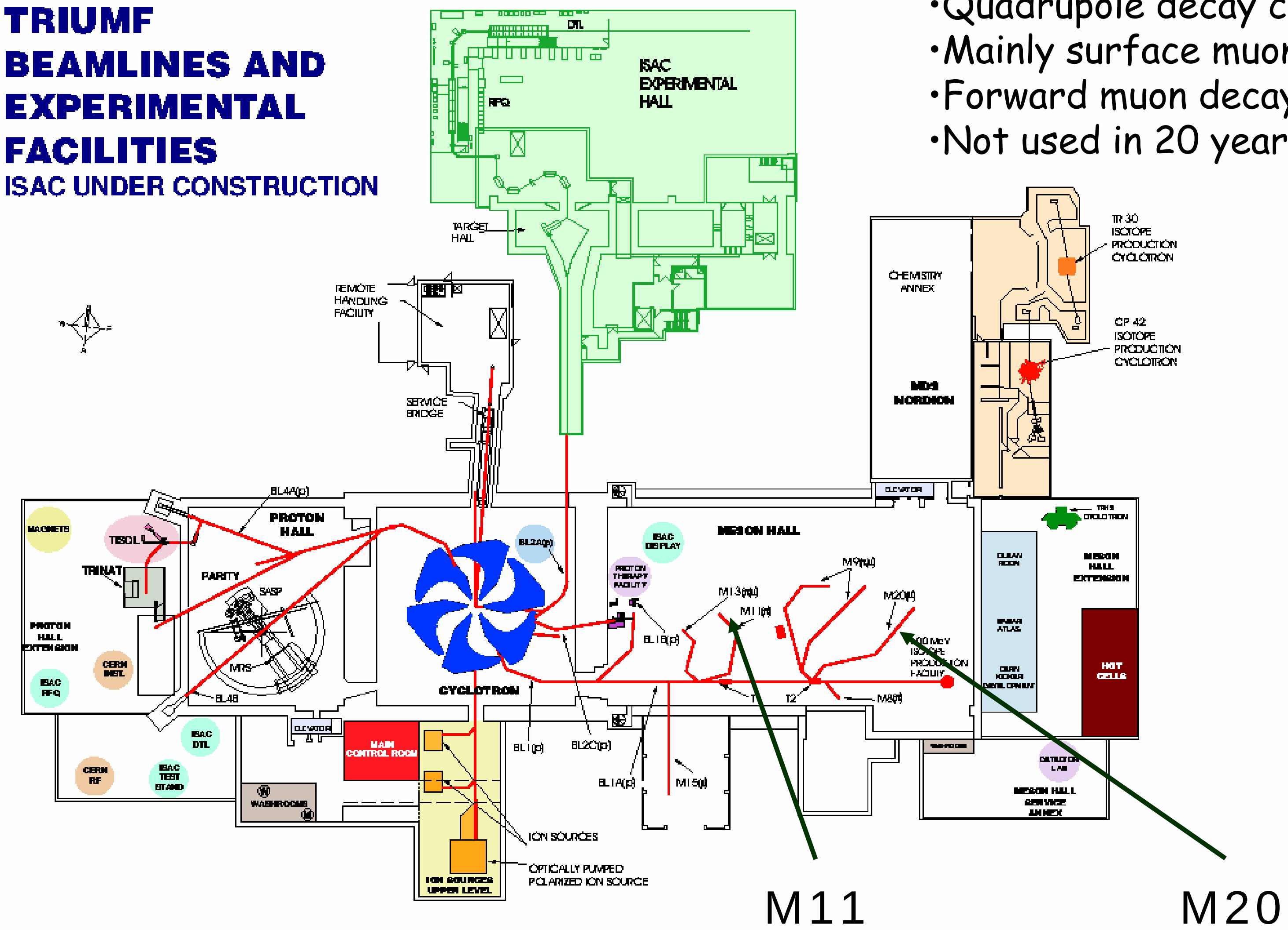
$$\epsilon_{N,\text{min}} = \frac{\beta_\perp (14\ \text{MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}$$

MuScat Motivation

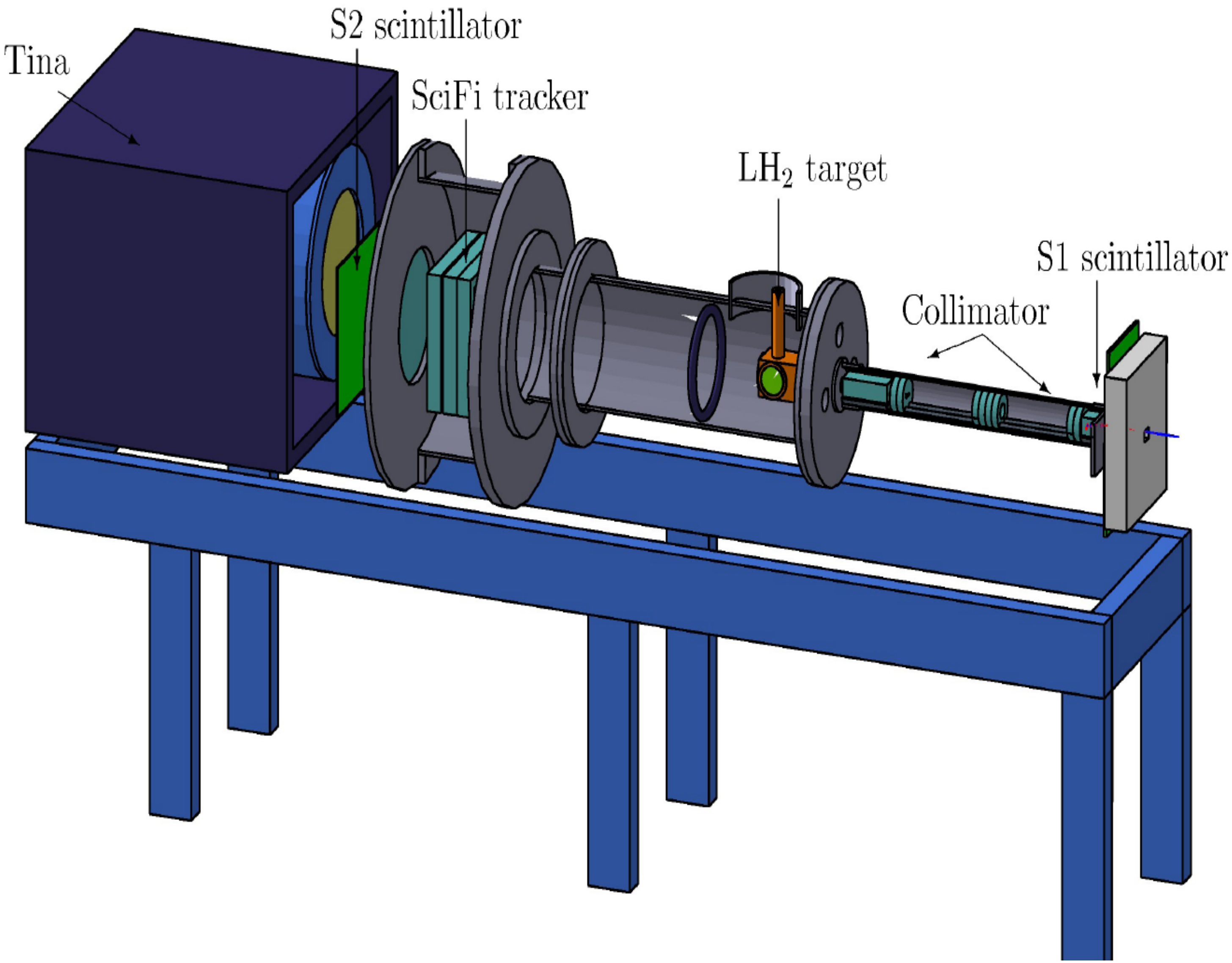
- Difference between theory (Moliere) and old data.
- No direct measurements of muon multiple scattering at energy relevant to ionization cooling.
- Recent theories covering low Z materials (Tollestrup) and Hydrogen specifically (Allison) predict lower rates of high angle scatters than in existing simulations (good for ionization cooling!)
- Need an experiment to measure the scattering distributions over a range of targets and test theories -> MuScat
- Engineering run at TRIUMF (M11) in 2000
- Physics run (M20) in 2003
- Final results are now published in NIMB (Vol 251/1 pp 41-55), preprint: http://arxiv.org/abs/hep-ex/0512005

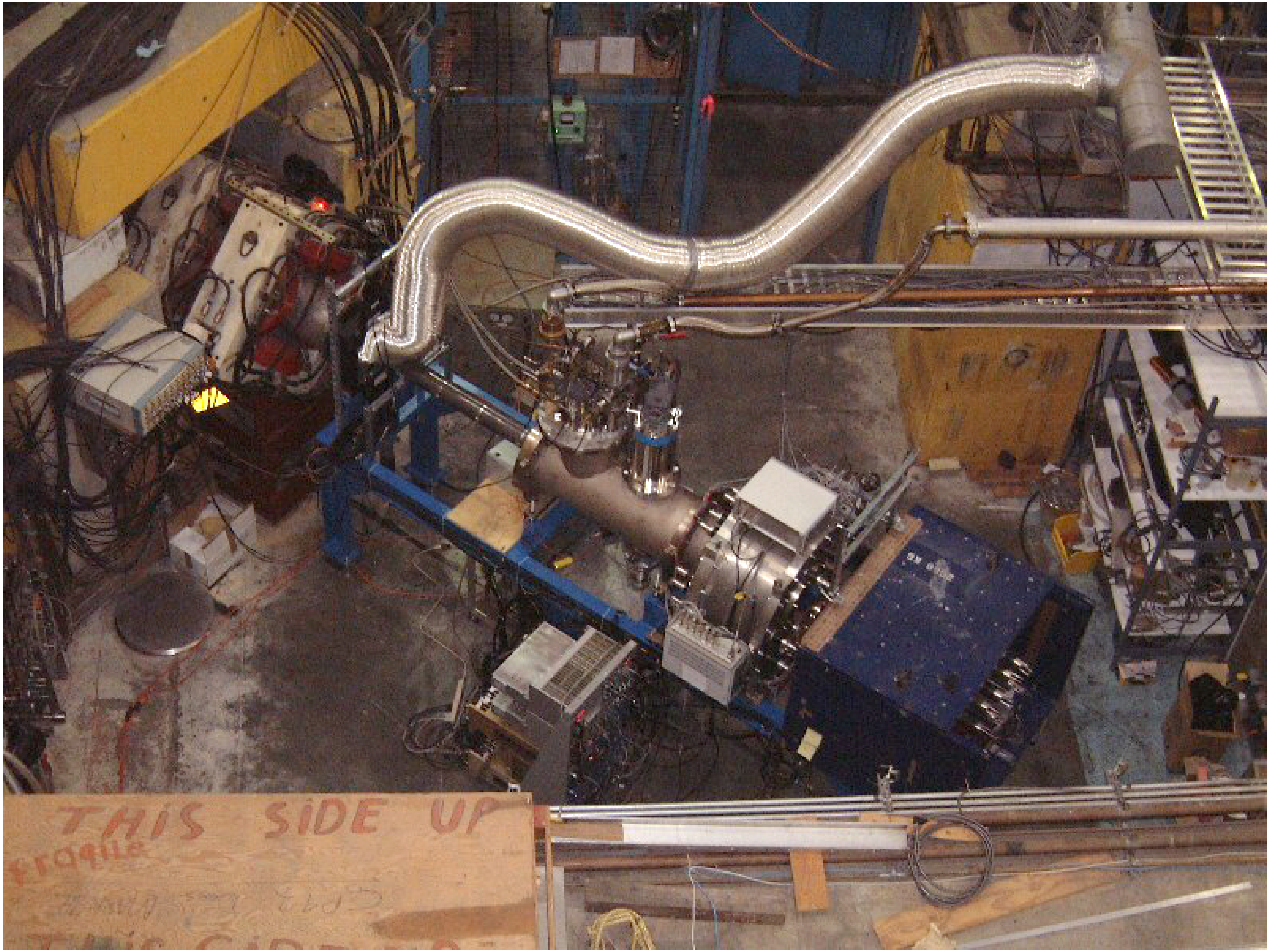
MuScat at TRIUMF

M20 Beamline:
- Quadrupole decay channel
- Mainly surface muons
- Forward muon decays: 175 MeV/c
- Not used in 20 years!



MuScat Detector




THIS SIDE UP
fragile

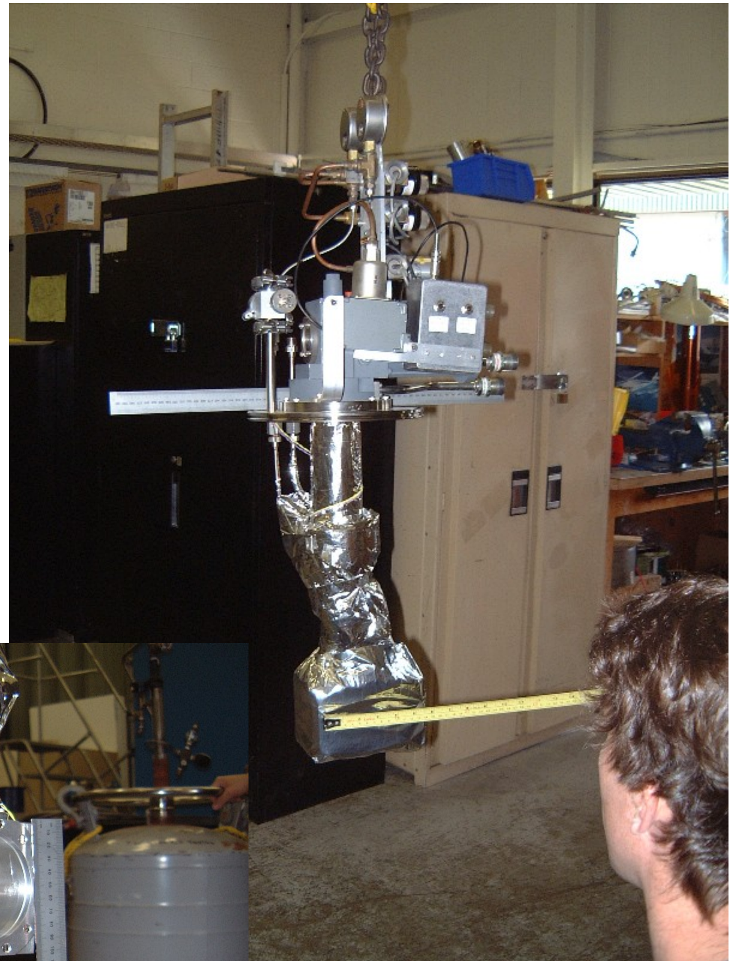
Targets

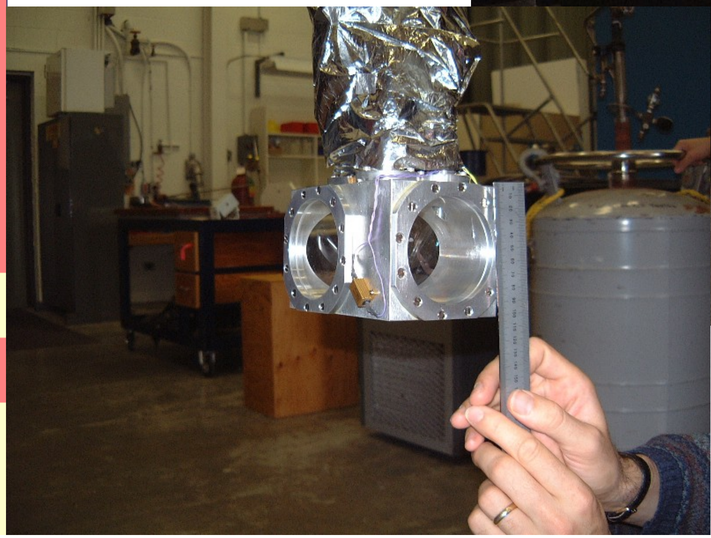
Target	Thickness, mm	X0, %	Events, Millions
Lithium 2	12.78	0.82	2.0
Lithium 1	6.43	0.41	3.0
Lithium 1	6.4	0.41	2.1
Lithium 2	12.72	0.81	3.0
Beryllium	0.98	0.28	3.4
Beryllium	3.73	1.06	3.8
Polyethylene	4.74	0.99	2.0
Carbon	2.5	1.53	2.0
Aluminium	1.5	1.69	3.0
None			6.0
Iron	0.24	1.36	2.2
Iron	5.05	28.68	3.4
Long, empty	150		4.8
Long, full	150	1.53	5.2
short, empty	100		9.5
short, full	100	1.02	6.0

Solid target wheel made in UK

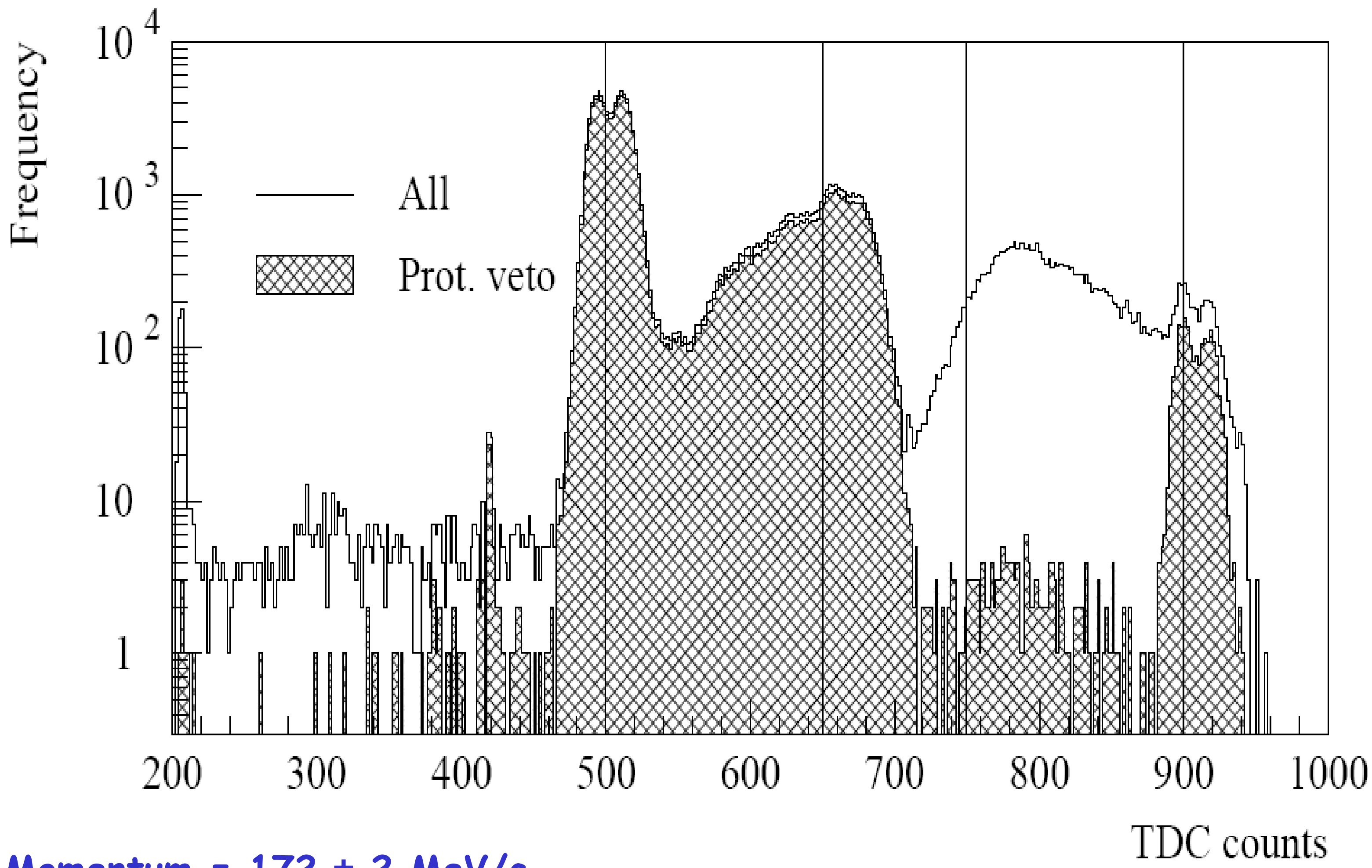
LH2 target made by TRIUMF group

Two lengths: 10cm and 15cm



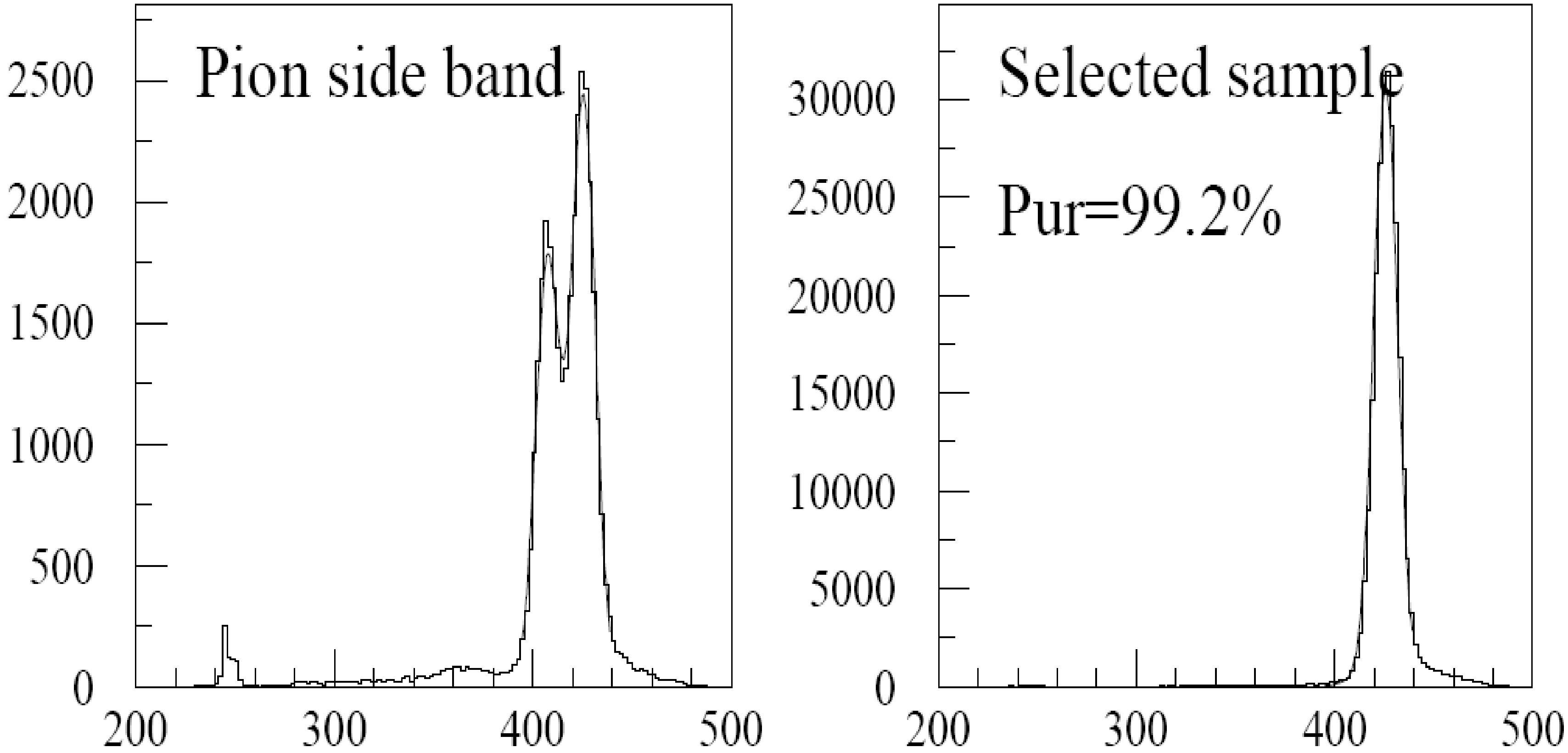


Particle ID



Beam Momentum = 172 ± 2 MeV/c

Checking TOF with TINA



The distribution of the prompt signal in TINA for events selected by TOF as being mixed pions and muons (left) or muons used for analysis (right).

Analysis

- No target data used to tune Monte Carlo description of the beam and collimation system.
- Thick Fe target data used to tune the description of the tracking detectors (in particular efficiency and cross-talk).
- Unfolding algorithm used to extract scattering distribution from raw data:
  - $D = B + D_\pi + R \cdot \varepsilon \cdot \Theta$
    - D is the observed position data
    - B is the background of particles not passing through the target
    - D_π is the contamination from pions
    - R is the response of the detector to a particle deflected through the angle Θ_y
    - ε is the efficiency of the detector for particles deflected through the angle Θ_y
    - Θ is the projected scattering distribution in the target.

Analysis

- The background is found from simulation (muons which can meet the trigger condition without passing through the target) and is typically 0.125%.
- The pion contamination is taken from the pion sideband. The default value is 0.8% pions.
- The response and efficiency matrices are determined from Simulation.
- The deconvolution is achieved using MINUIT to solve for Θ.
- The minimisation used 21 bins and symmetry about $\Theta = 0$ is enforced.

- In the MuScat paper the unfolded scattering distributions are compared with GEANT4 version 7.0.p01.
- There is better agreement with the more recent version 8.1.

Thin Fe

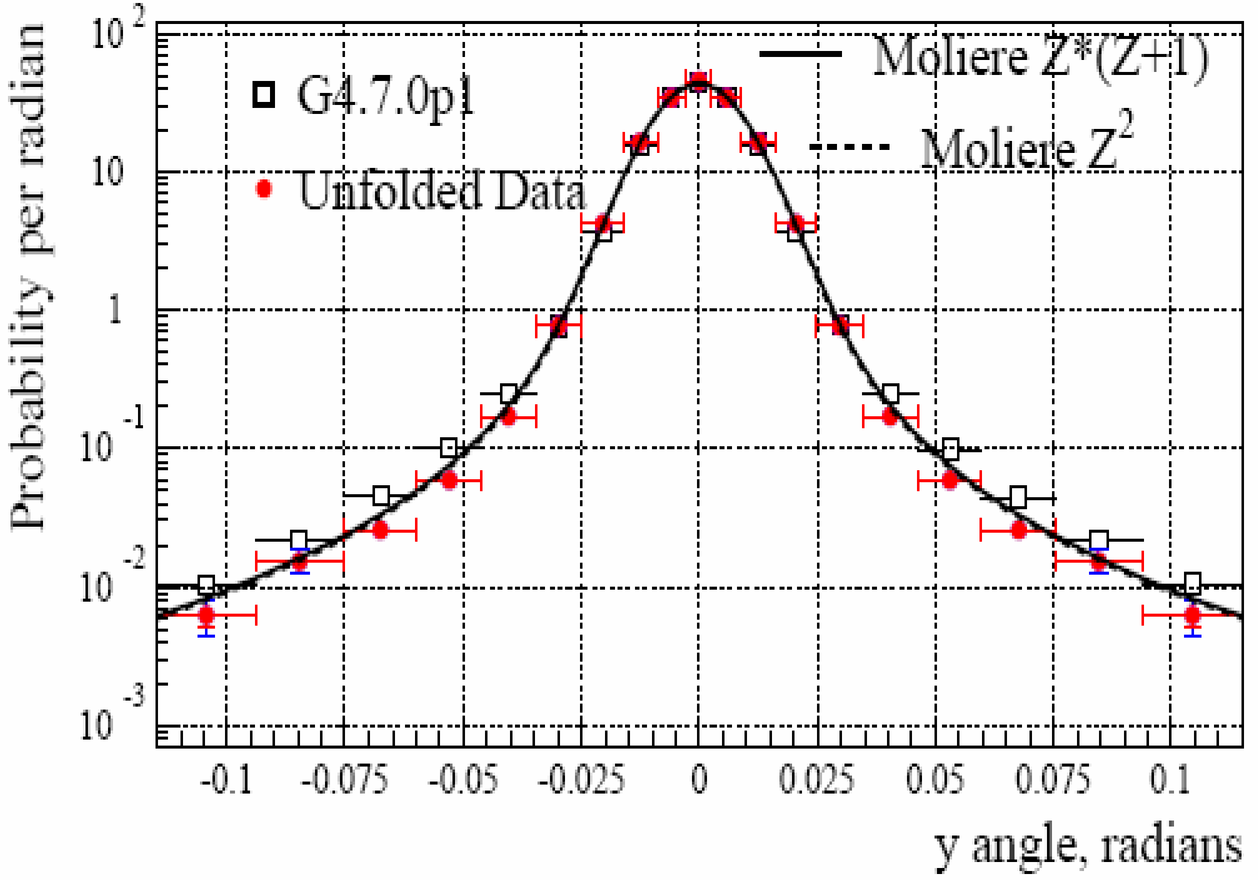
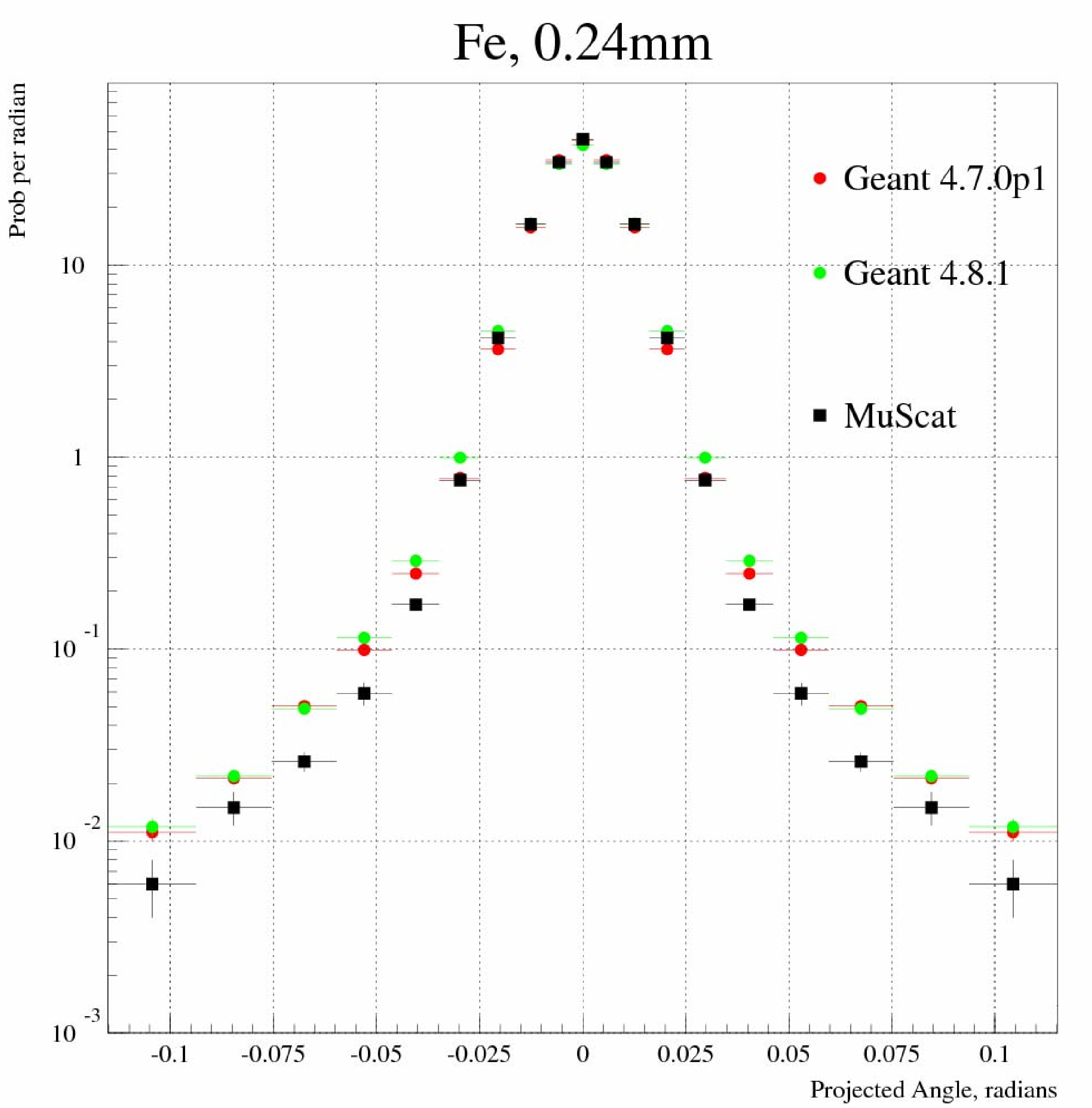


Fig. 16. The projected scattering angle distribution in data and simulation for thin iron, target 10.


Fe, 0.24mm
Prob per radian
Geant 4.7.0p1
Geant 4.8.1
MuScat
10
1
10 -1
10 -2
10 -3
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
Projected Angle, radians

Al

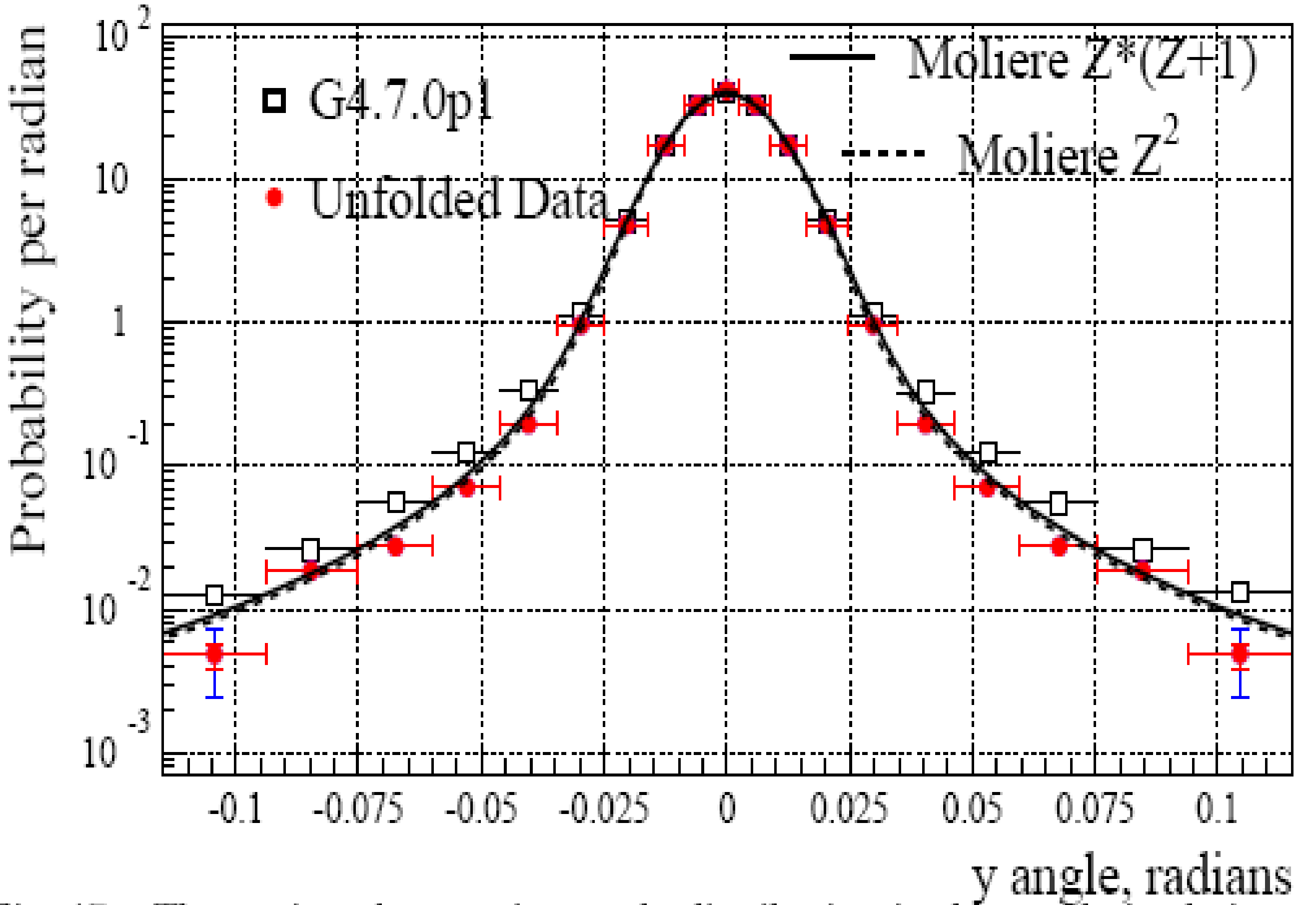
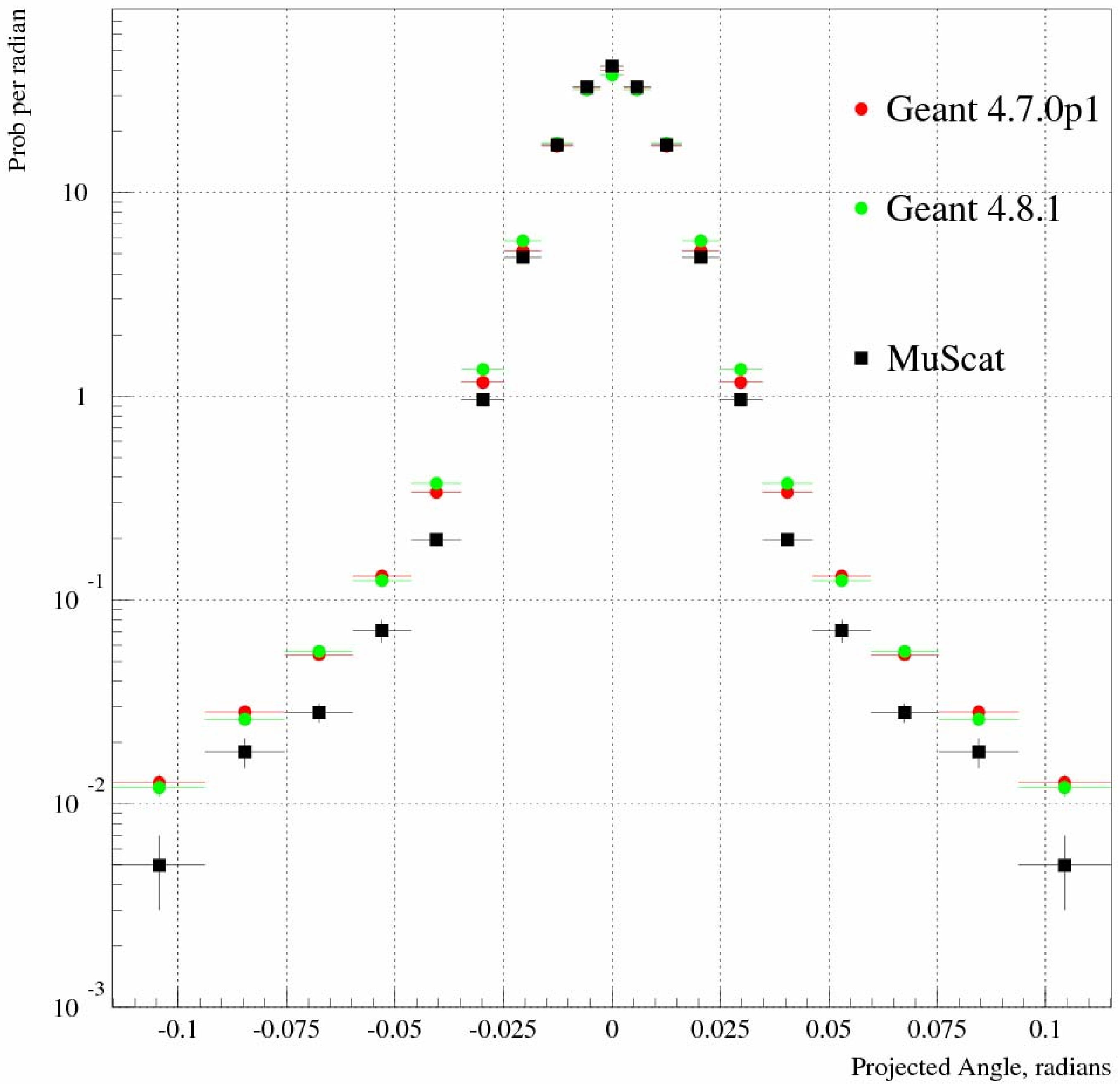
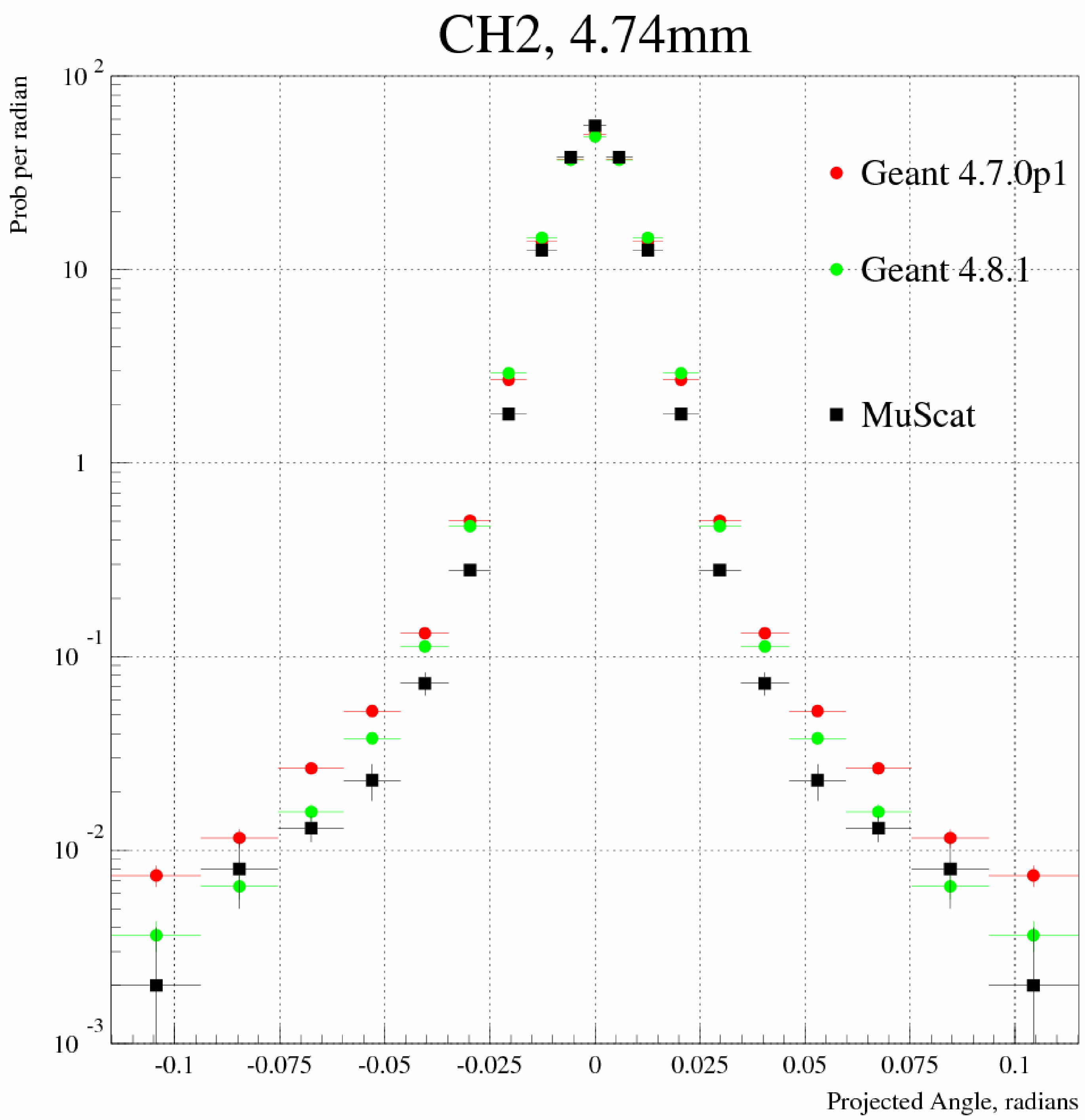


Fig. 17. The projected scattering angle distribution in data and simulation for aluminium, target 8.

Al, 1.5mm



Prob per radian
10
1
10 -1
10 -2
10 -3
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
Projected Angle, radians
Geant 4.7.0p1
Geant 4.8.1
MuScat


CH2, 4.74mm
Prob per radian
Geant 4.7.0p1
Geant 4.8.1
MuScat
Projected Angle, radians
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1

C

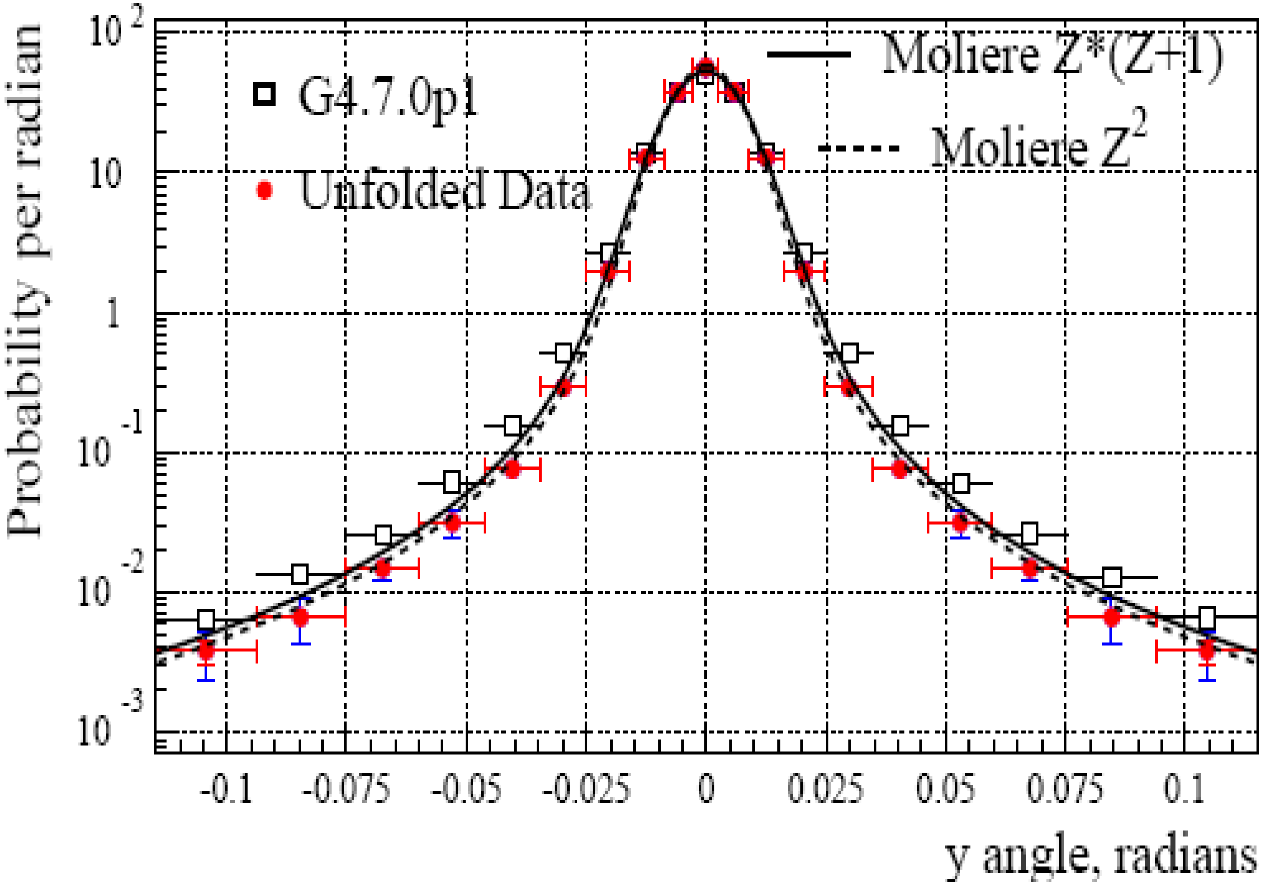
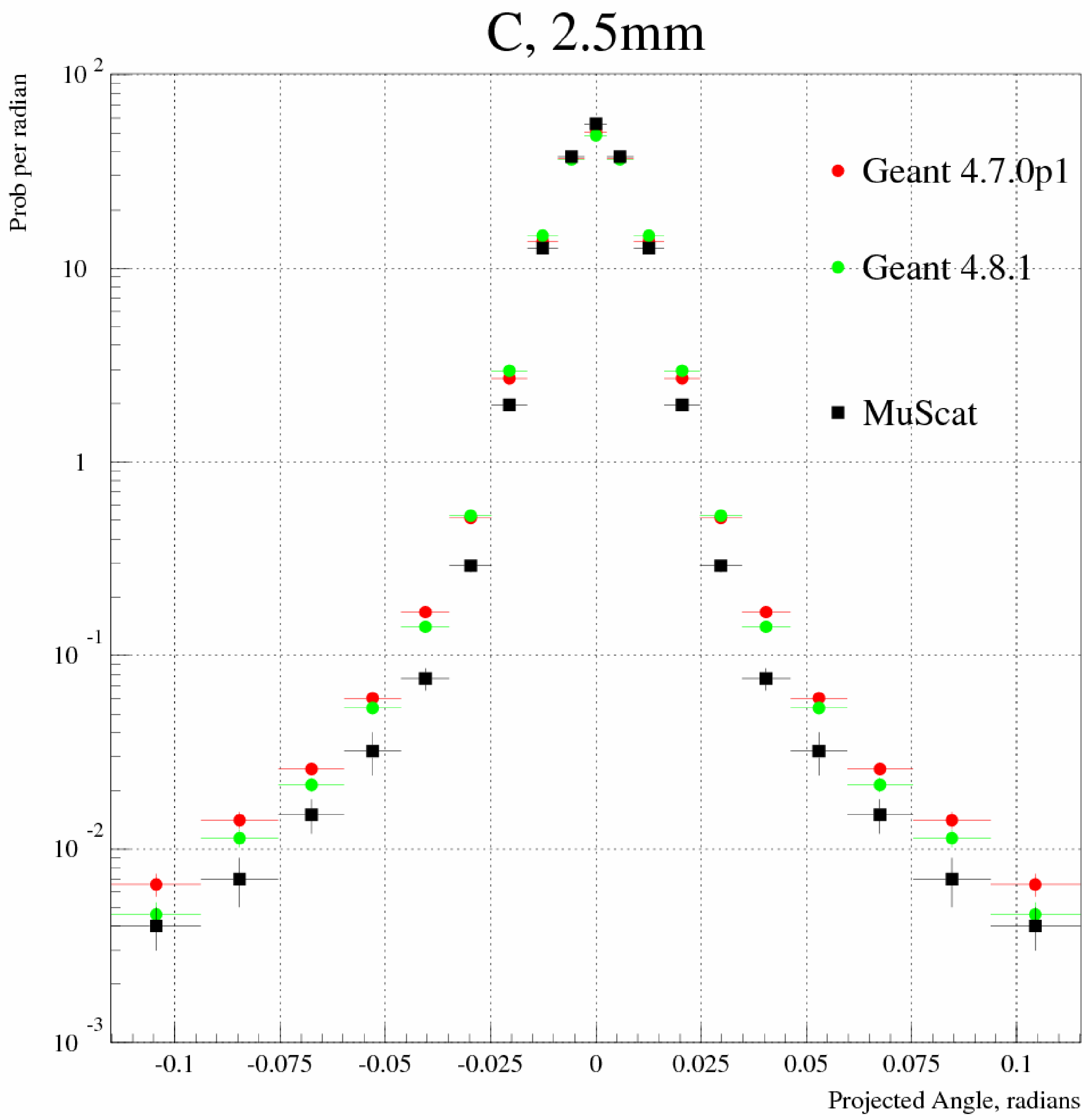


Fig. 18. The projected scattering angle distribution in data and simulation for carbon, target 7.


C, 2.5mm
Prob per radian
10 2
10
1
10 -1
10 -2
10 -3
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
Projected Angle, radians
Geant 4.7.0p1
Geant 4.8.1
MuScat

Thick Be

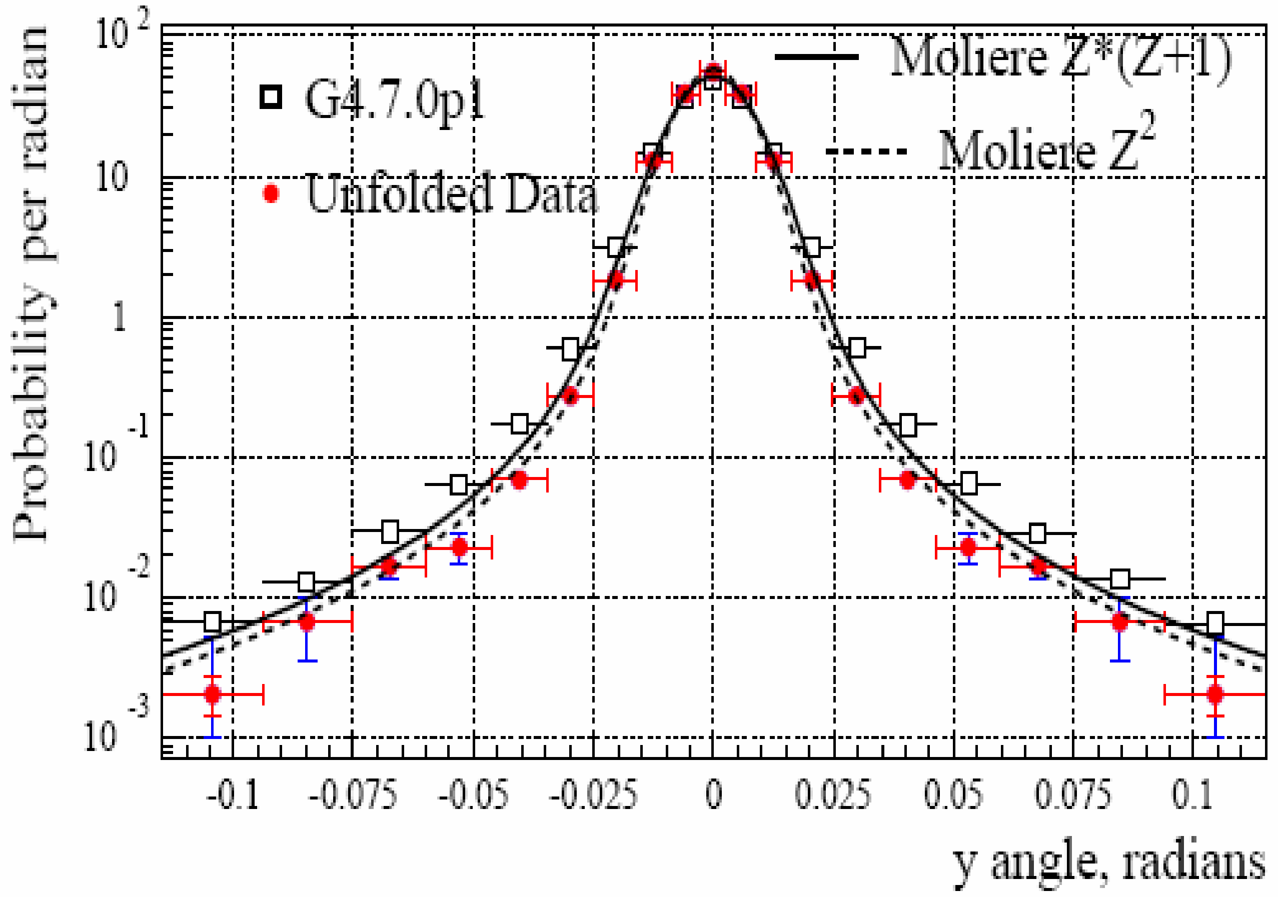
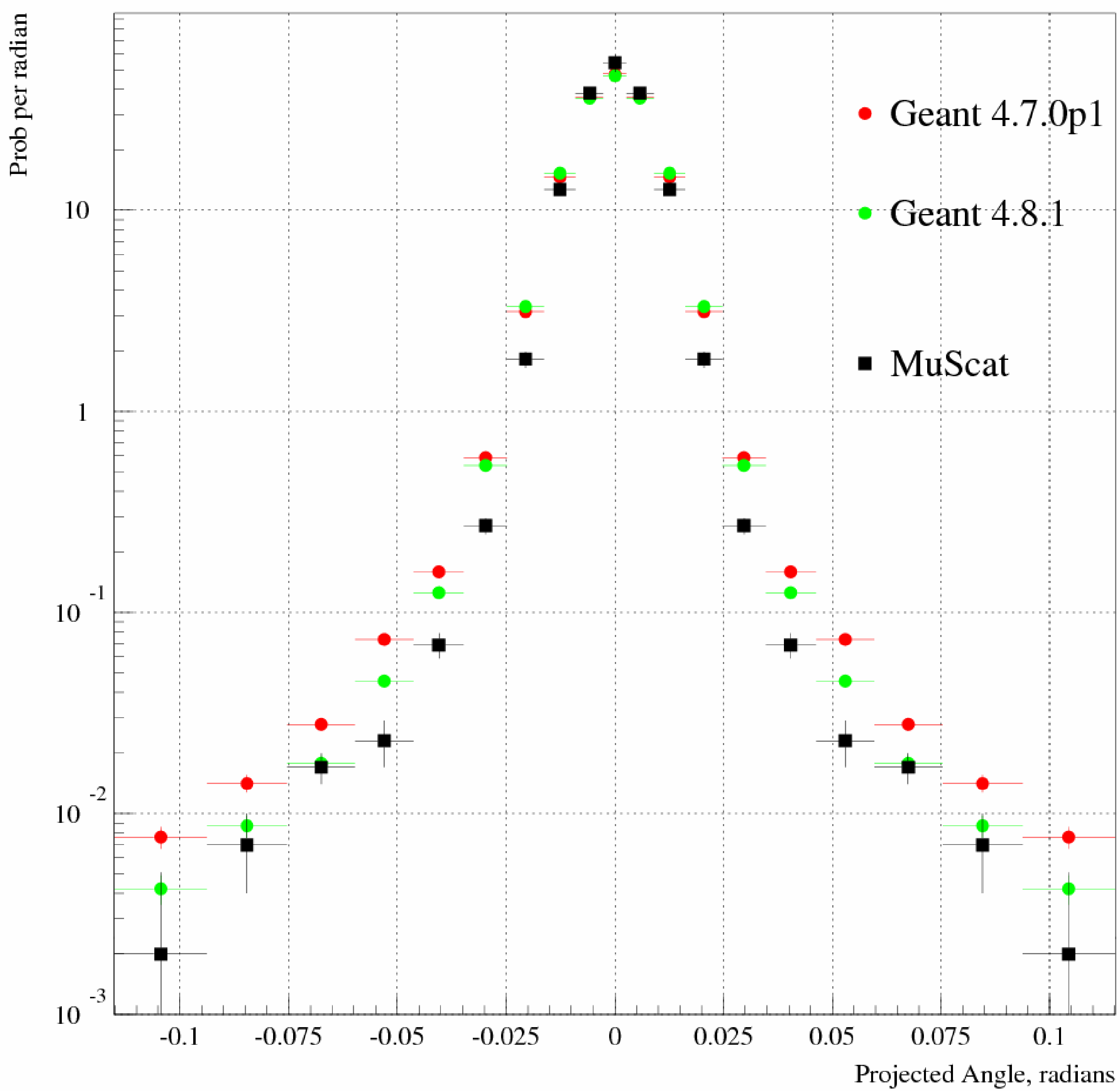
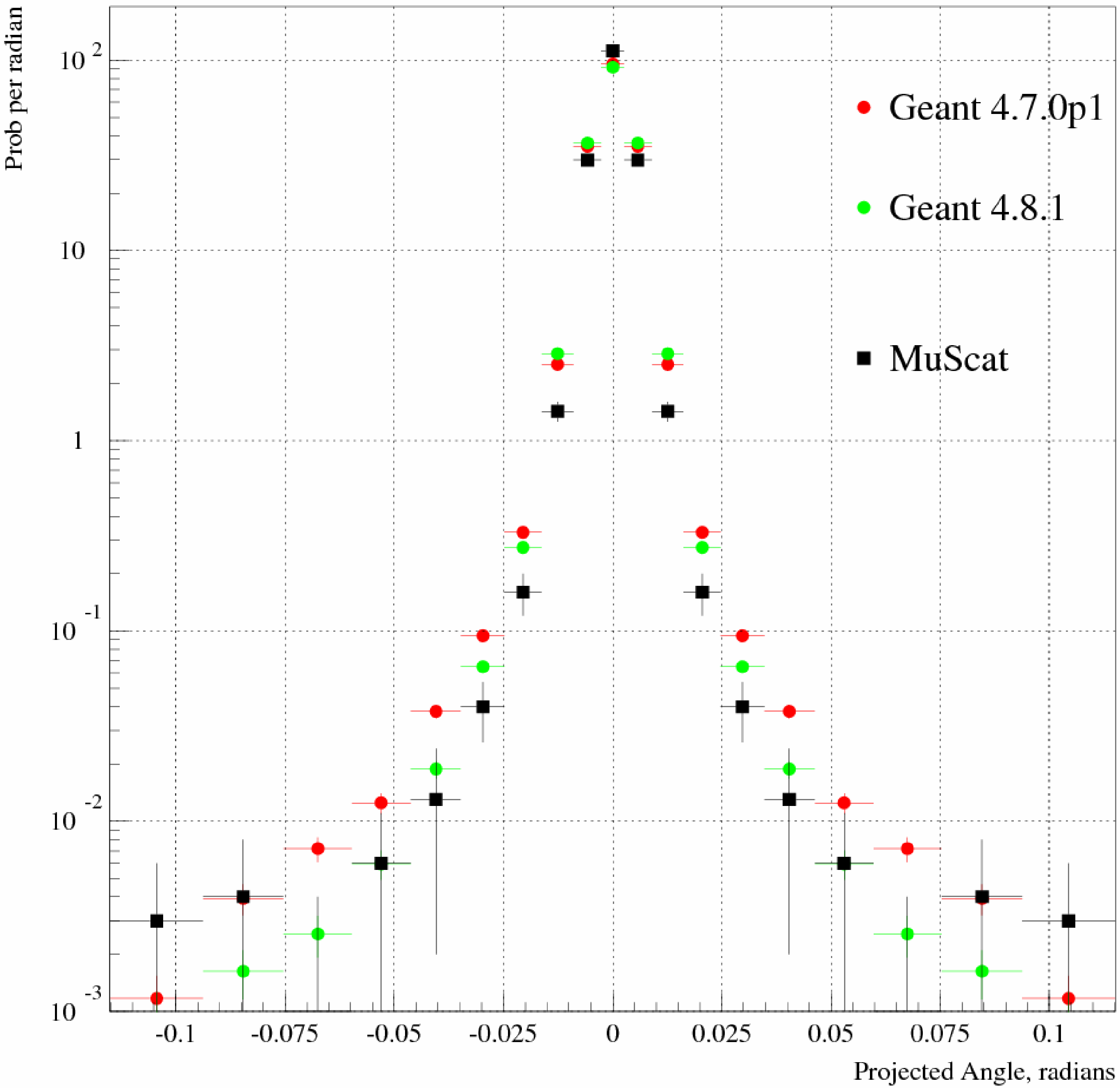


Fig. 19. The projected scattering angle distribution in data and simulation for thick beryllium, target 5.

Be, 3.73mm


Prob per radian
10
1
10 -1
10 -2
10 -3
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
Projected Angle, radians
Geant 4.7.0p1
Geant 4.8.1
MuScat

Be, 0.98mm


Prob per radian
10^2
10
1
10^-1
10^-2
10^-3
Geant 4.7.0p1
Geant 4.8.1
MuScat
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
Projected Angle, radians

Thick Li

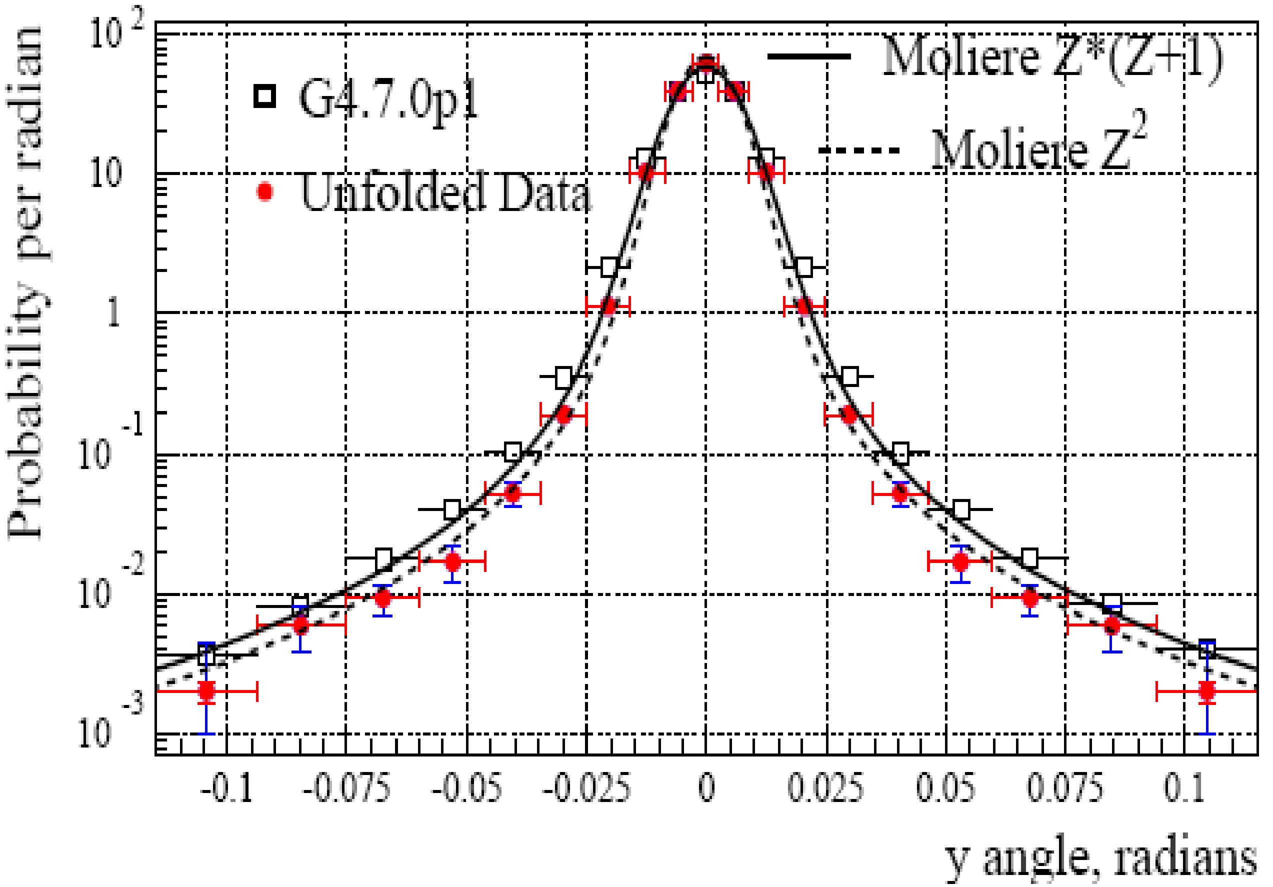
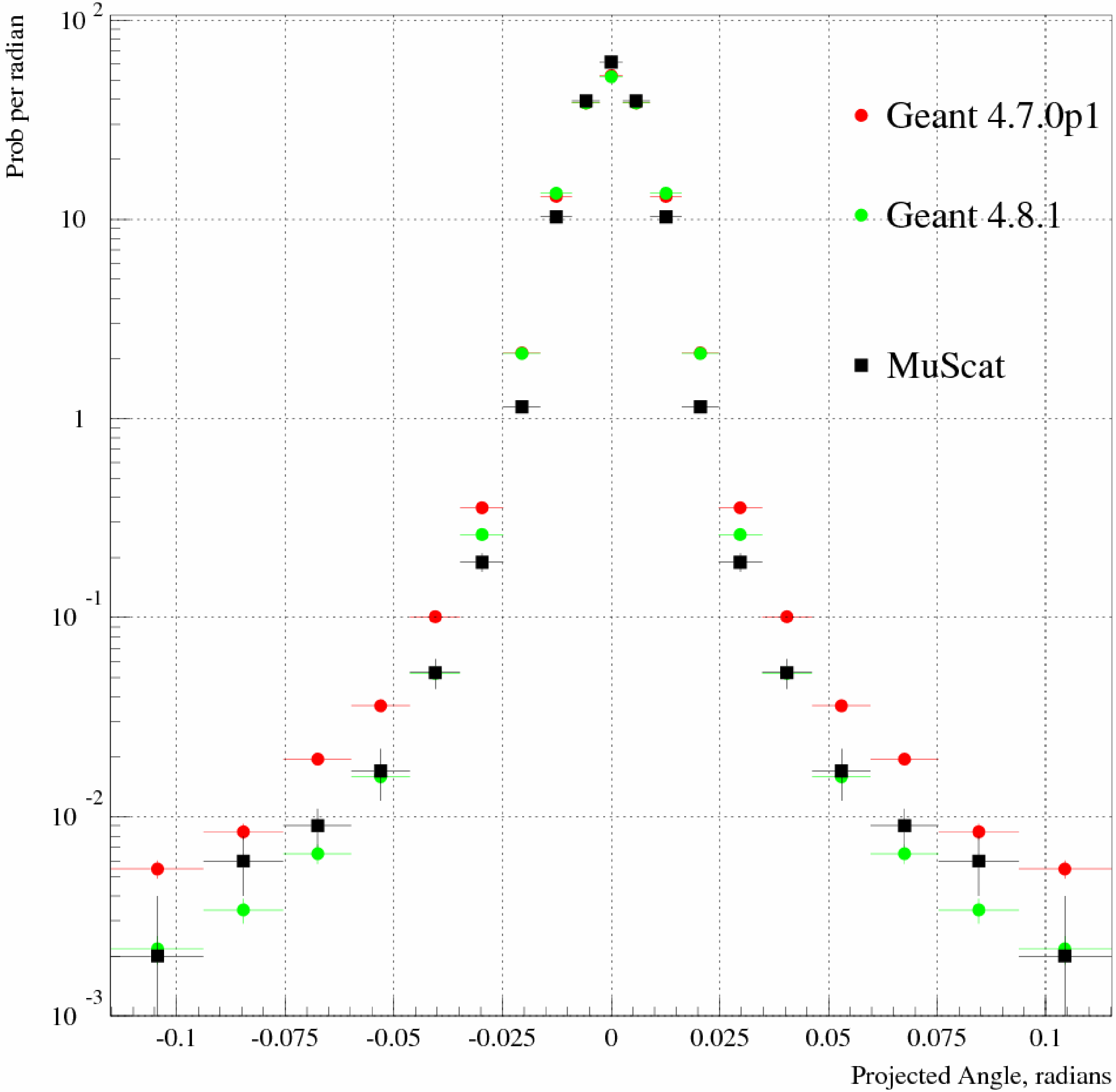
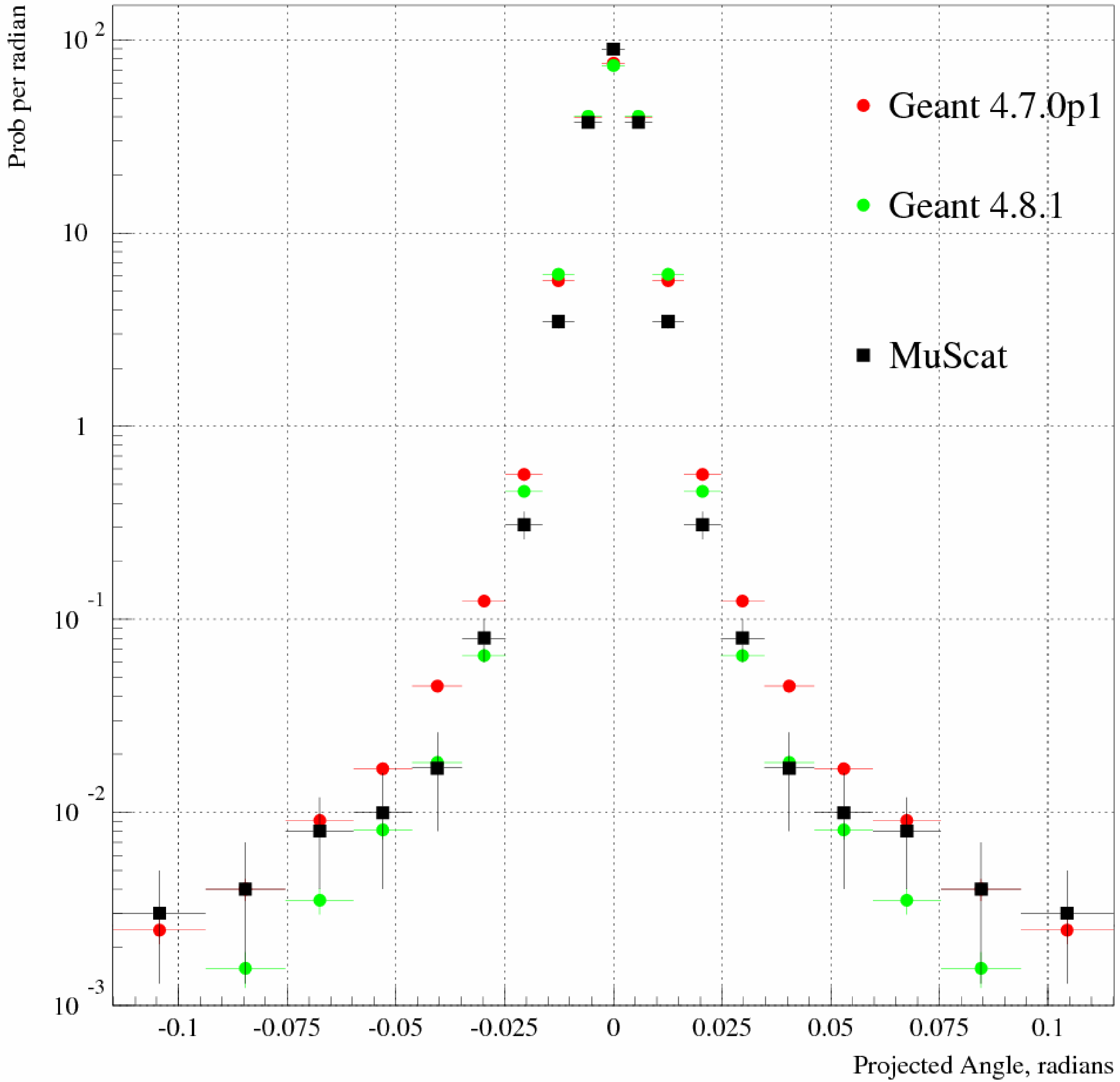


Fig. 20. The projected scattering angle distribution in data and simulation for thick lithium, both targets combined.

Li, 12.75mm


Prob per radian
Geant 4.7.0p1
Geant 4.8.1
MuScat
Projected Angle, radians

Li, 6.41mm


Prob per radian
10 2
10
1
10 -1
10 -2
10 -3
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
Projected Angle, radians
Geant 4.7.0p1
Geant 4.8.1
MuScat

Long LH2

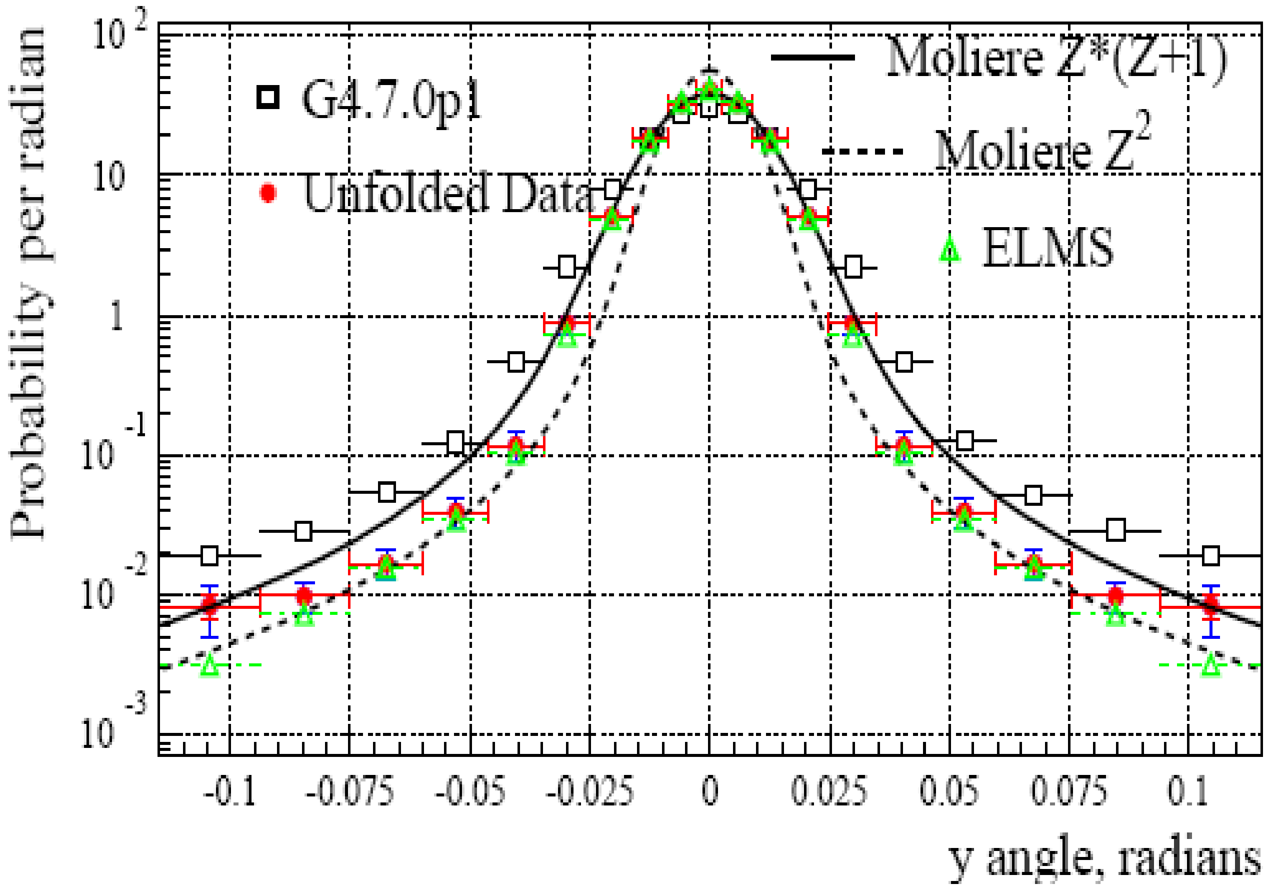
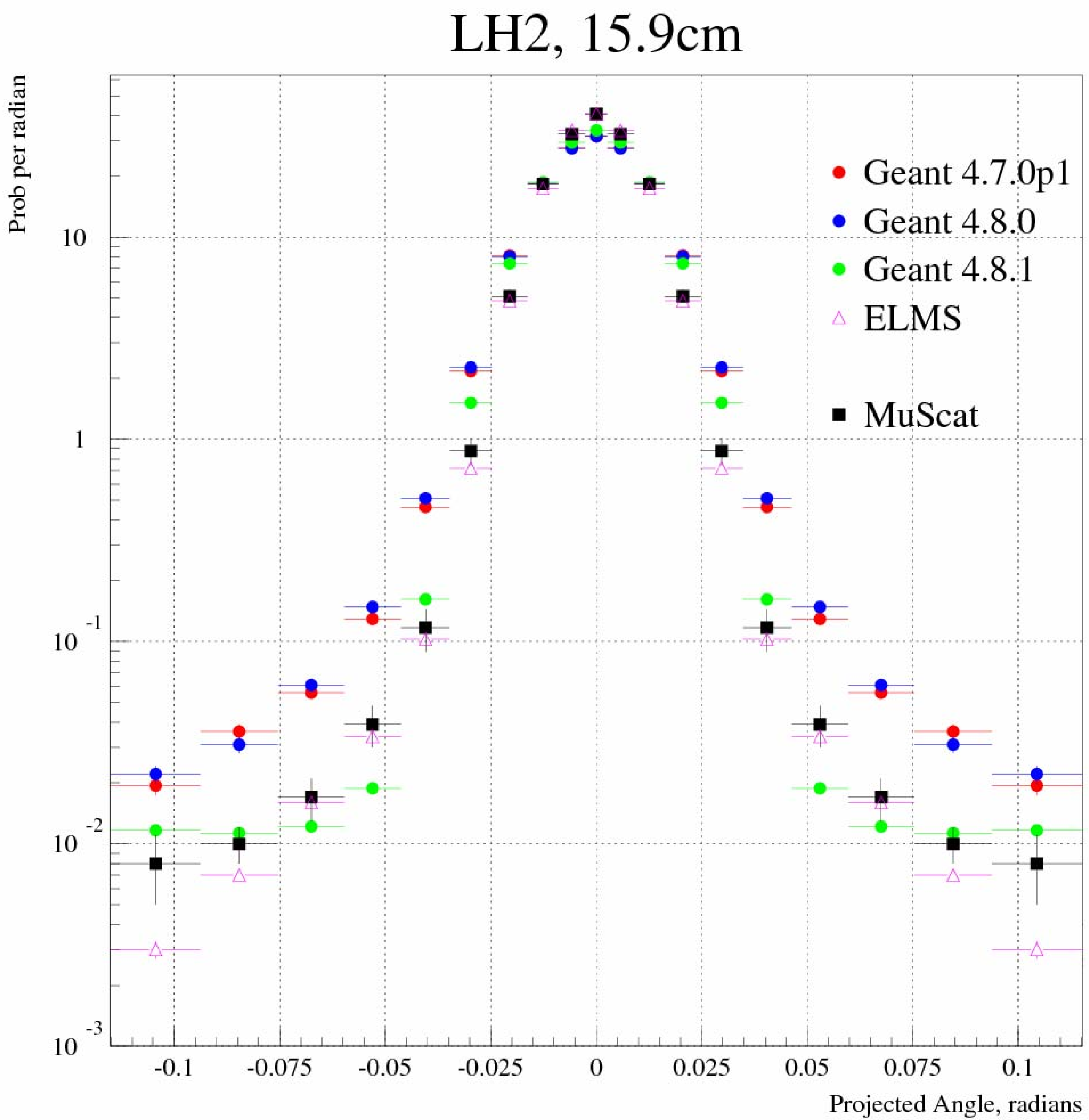


Fig. 22. The projected scattering angle distribution in data and simulation fo: 159 mm of liquid H_2.


LH2, 15.9cm
Prob per radian
Geant 4.7.0p1
Geant 4.8.0
Geant 4.8.1
ELMS
MuScat
10
1
10^-1
10^-2
10^-3
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
Projected Angle, radians

Conclusions

- Final results show less high angle scatters than older data and simulations, particularly for low Z materials.
  - Predicts better performance in Ionisation cooling channels (4D and 6D) than simulations made so far!
- Distributions agree well with ELMS for Hydrogen and are better with GEANT4 8.1 than previous versions.
- Future analysis should allow validation of energy loss/scattering correlations.
- Ongoing testing will compare results with new releases of GEANT4, in particular when new models are added.