Radiative-corrections for the MUSE experiment

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for the MUSE Collaboration

Supported in parts by the U.S. National Science Foundation: NSF PHY-1812382. The MUSE experiment is supported by the U.S. Department of Energy, the U.S. National Science Foundation, the Paul Scherrer Institute, and the US-Israel Binational Science Foundation.

Radiative Corrections Workshop, Stoney Brook (online), July 9–10, 2020

MUon Scattering Experiment (MUSE) at PSI

Direct test of μp and ep interactions in a scattering experiment:

- higher precision than previously for μp,
- low-Q^2 region for sensitivity to the **proton charge radius**, Q^2 = 0.002 to 0.07 GeV^2,
- with μ^+,μ^- and e^+,e^- to study possible **2γ mechanisms**,
- with μp and ep to have direct **μ/e comparison**.

MUSE

$$e^- p \to e^- p$$
$$e^+ p \to e^+ p$$
$$\mu^- p \to \mu^- p$$
$$\mu^+ p \to \mu^+ p$$

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

Projected MUSE proton charge-radius results

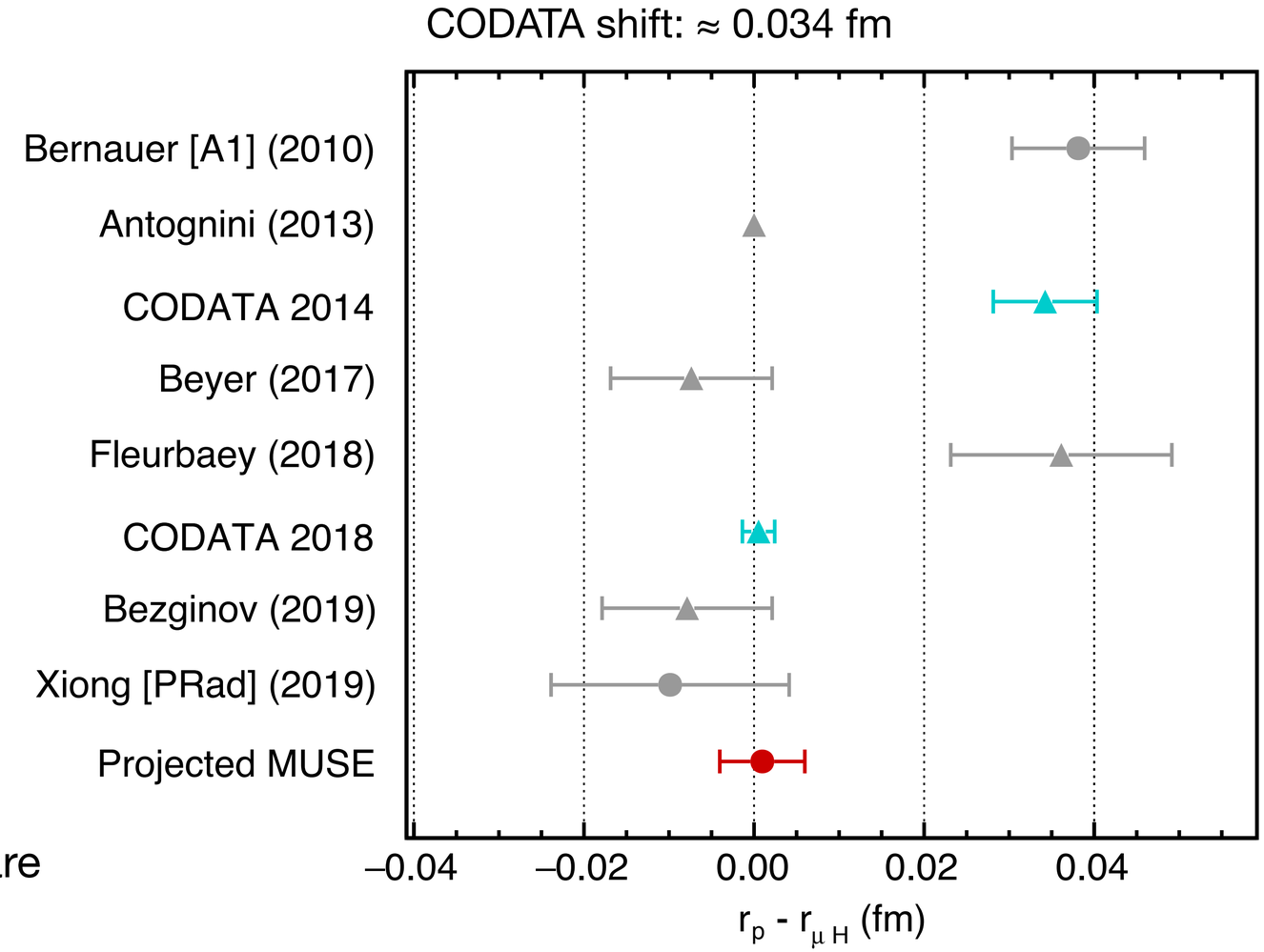
How different are the e/μ radii?
(truncation error largely cancels)
Sensitivity to differences in extracted e/μ radii:

$\sigma(r_e - r_\mu) \approx 0.005$ fm

What is the radius?
Absolute values of extracted e/μ radii (assuming no +/- difference seen):

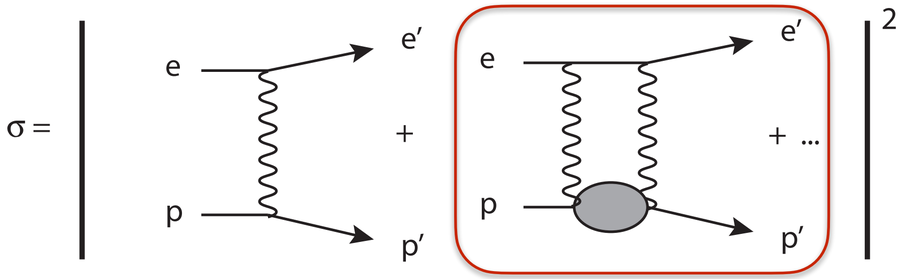
$\sigma(r_e), \sigma(r_\mu) \approx 0.008$ fm

Comparisons of, e.g., **e to μ** or of **μ^+ to μ^-** are insensitive to many of the systematics



The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE provides a high precision test of two-photon exchange for electrons and muons at low Q^2



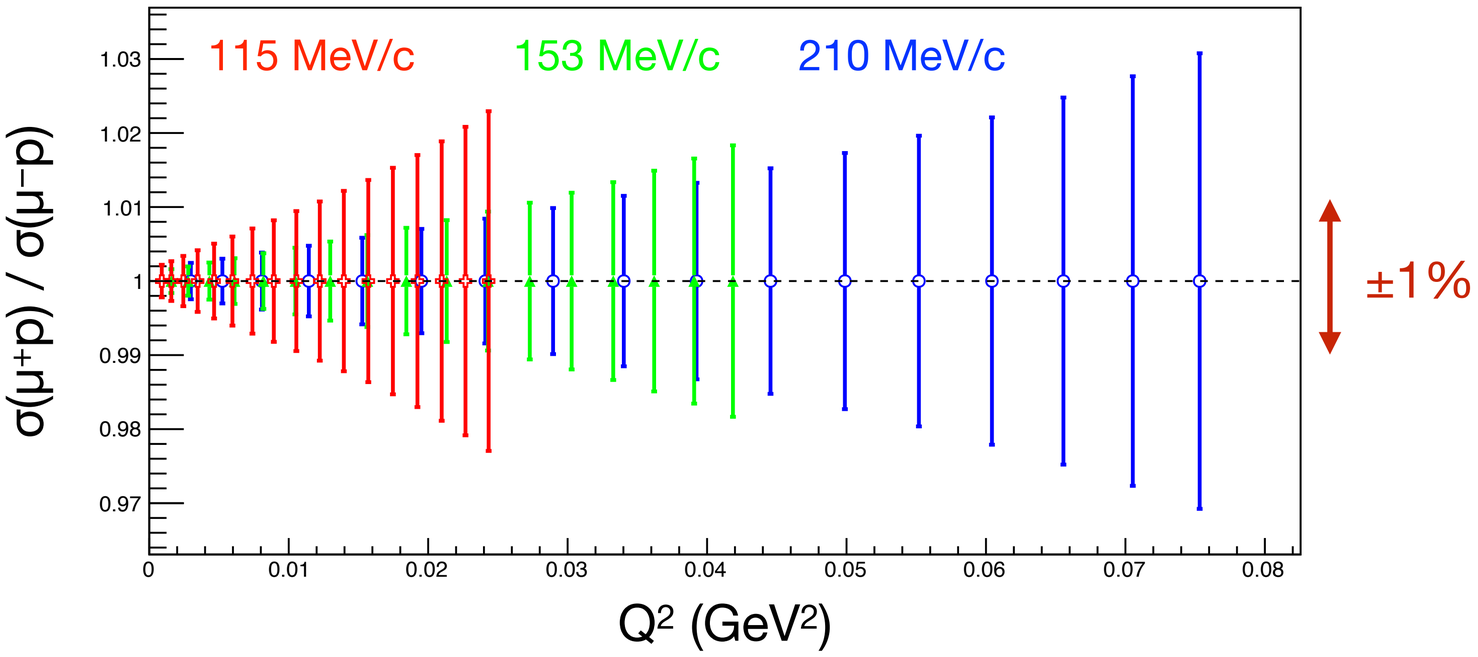
TPE: largest theoretical uncertainty in low-energy proton structure.

Projected relative uncertainty in the ratio of μ^+p to μ^-p elastic cross sections. Estimated systematics: 0.2%.

$$\sigma_{e^\pm p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}^\dagger{}_{1\gamma}\mathcal{M}_{2\gamma}\} + \cdots$$

sign change with lepton-charge

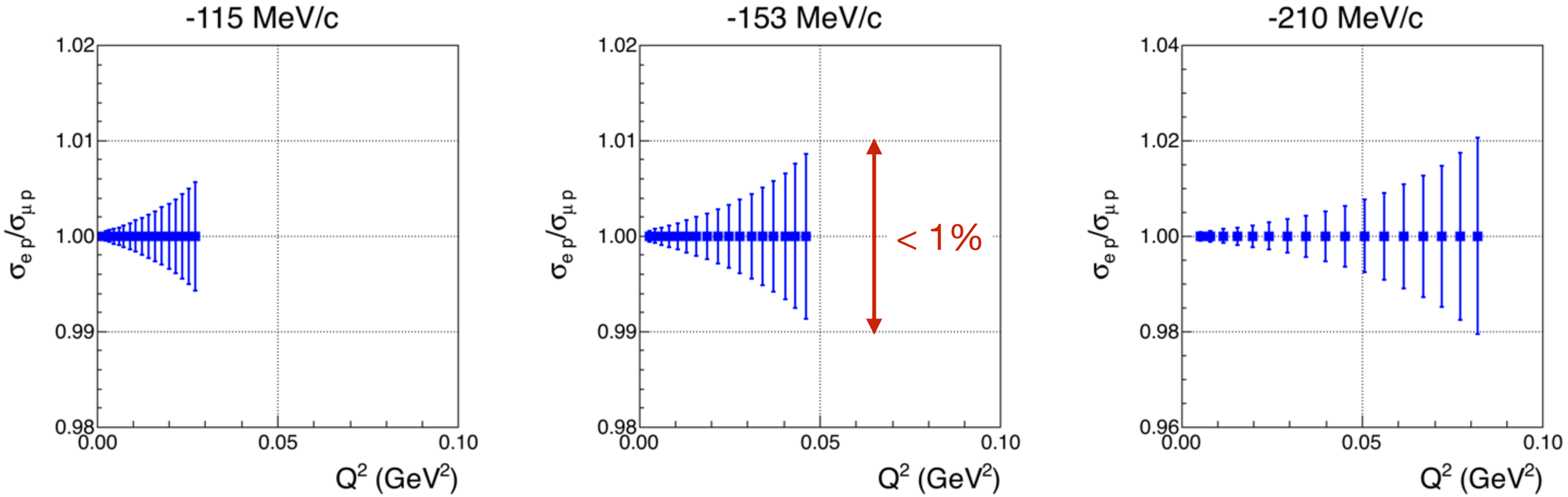
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 + 4\frac{\Re\{\mathcal{M}^\dagger{}_{1\gamma}\mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$



MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE directly compares ep to μp cross-sections

Projected relative statistical uncertainties in the ratio of ep to μp elastic **cross sections**.
Estimated systematics ≈ 0.5%.



The relative statistical uncertainties in the **form factors** are half as large.

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

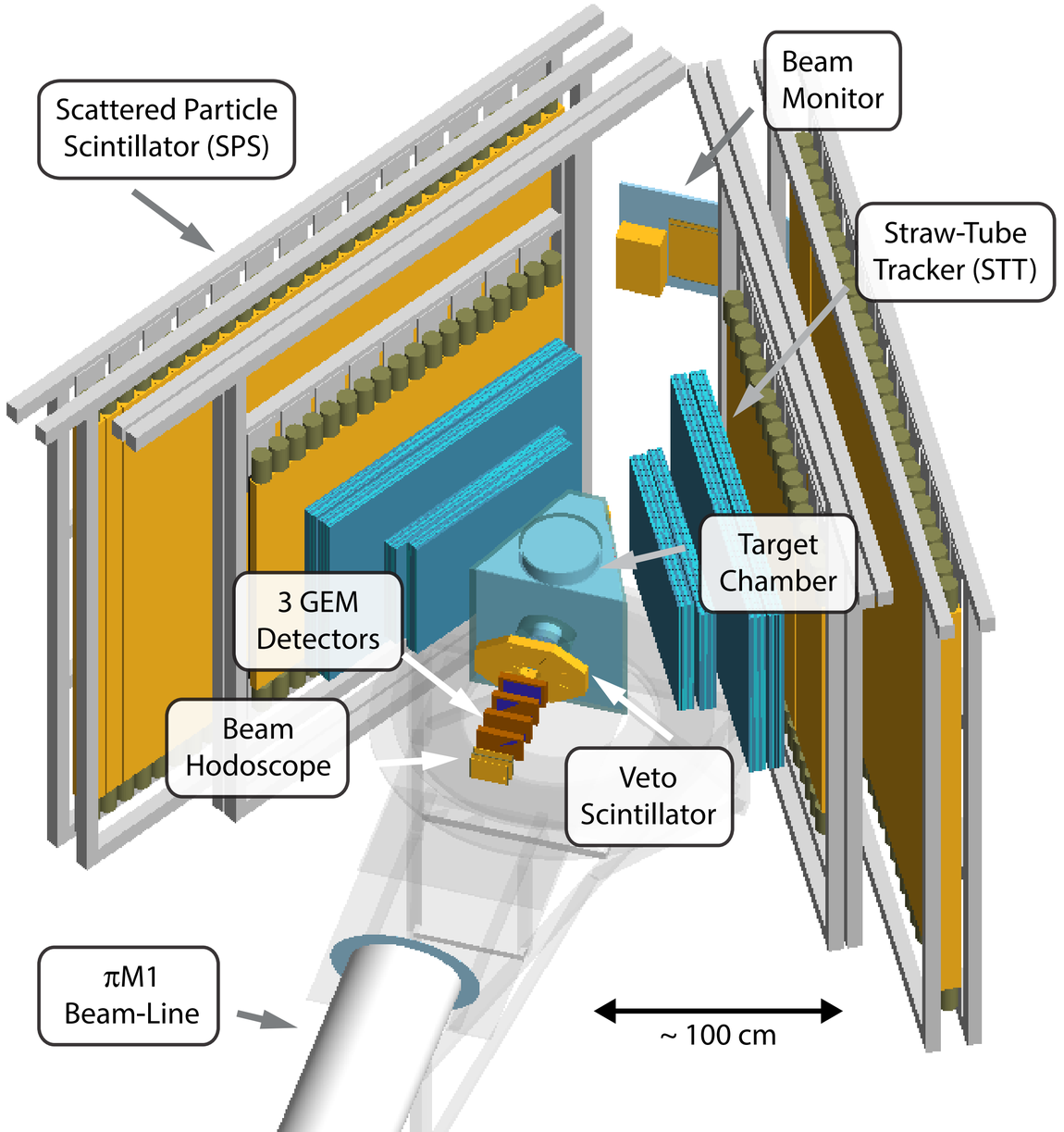
MUSE is an unusual scattering experiment

Measure $e^{\pm}$ and $\mu^{\pm}$ elastic scattering off a liquid hydrogen target.

$$20^\circ < \theta < 100^\circ$$
$$-45^\circ < \phi < 45^\circ$$
$$p = 115,\ 161,\ 210 \text{ MeV/c}$$

Challenges

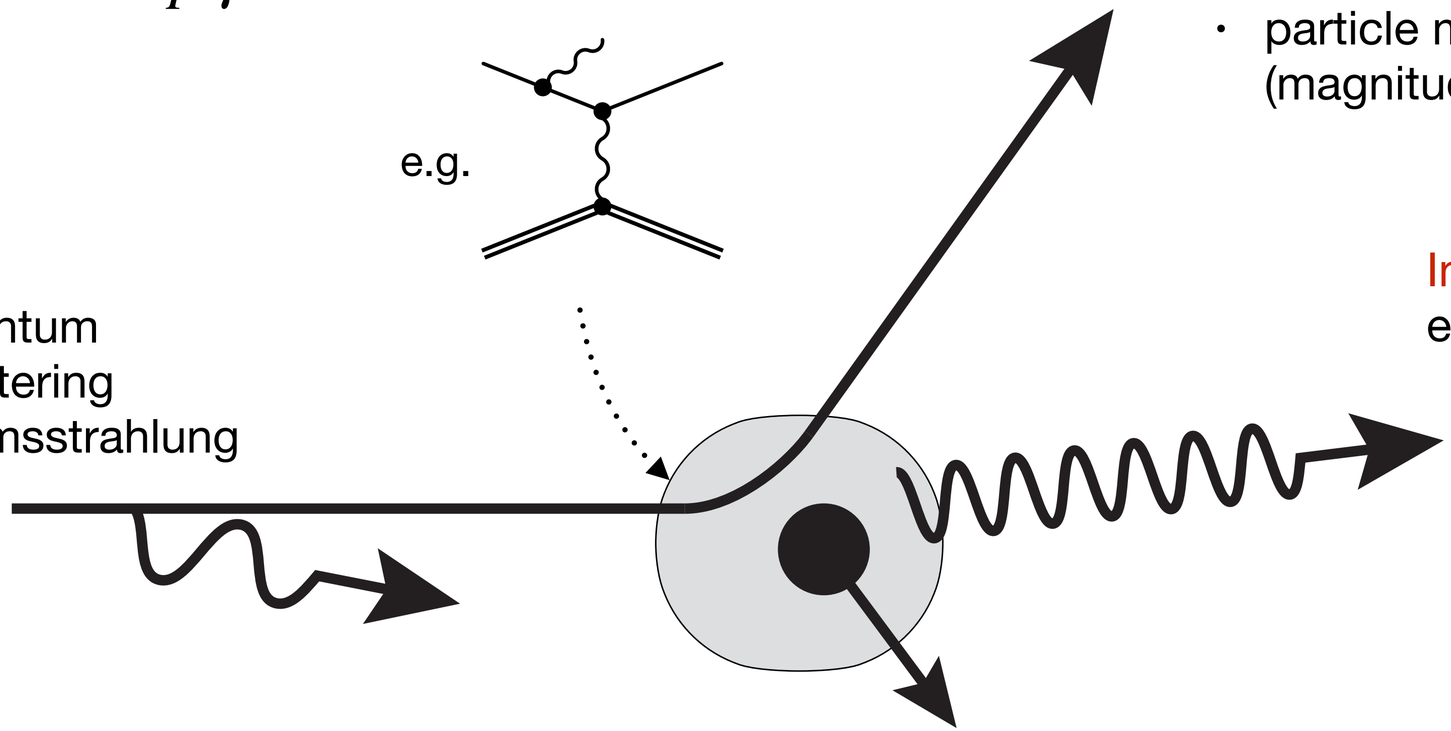
- Secondary beam: identifying and tracking beam particles to target,
- Low beam flux: large angle, non-magnetic spectrometer,
- Background: e.g., Møller scattering and muon decay in flight.



The MUon Scattering Experiment at PSI (MUSE),
MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

The size of the radiative corrections depends on the detector properties and event selection

$$\ell^{\pm} p \to \ell'^{\pm} p' \gamma$$



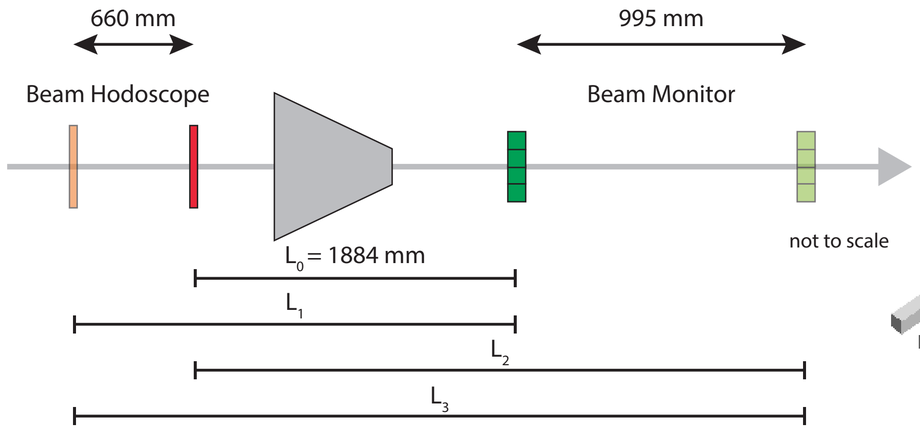
Scattered lepton
- angular acceptance
- particle momentum
  (magnitude not precisely measured)

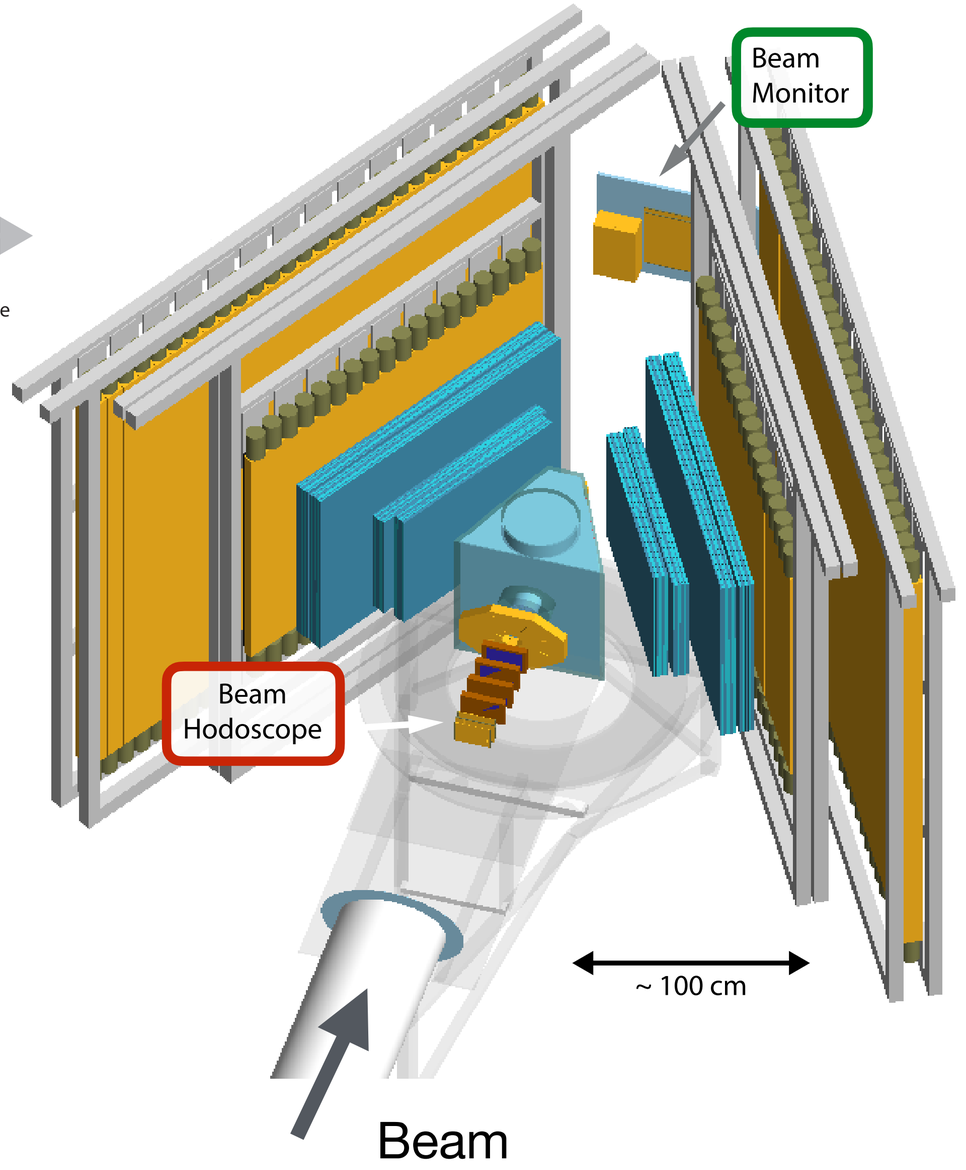
Incident lepton
- beam momentum
- multiple scattering
- external Bremsstrahlung

Internal Bremsstrahlung
e.g., initial-state radiation

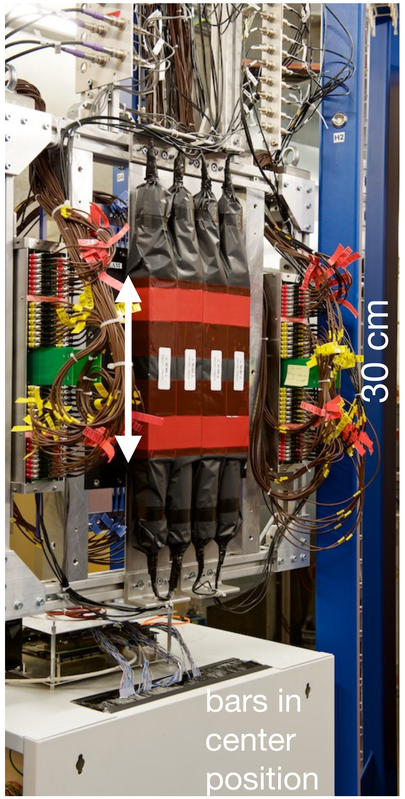
Recoiling proton
remains unobserved

MUSE detector system for TOF measurements

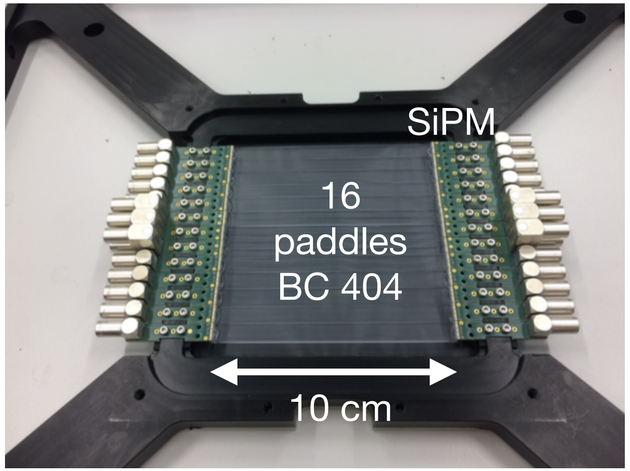




Beam monitor
SC bars (UofSC)



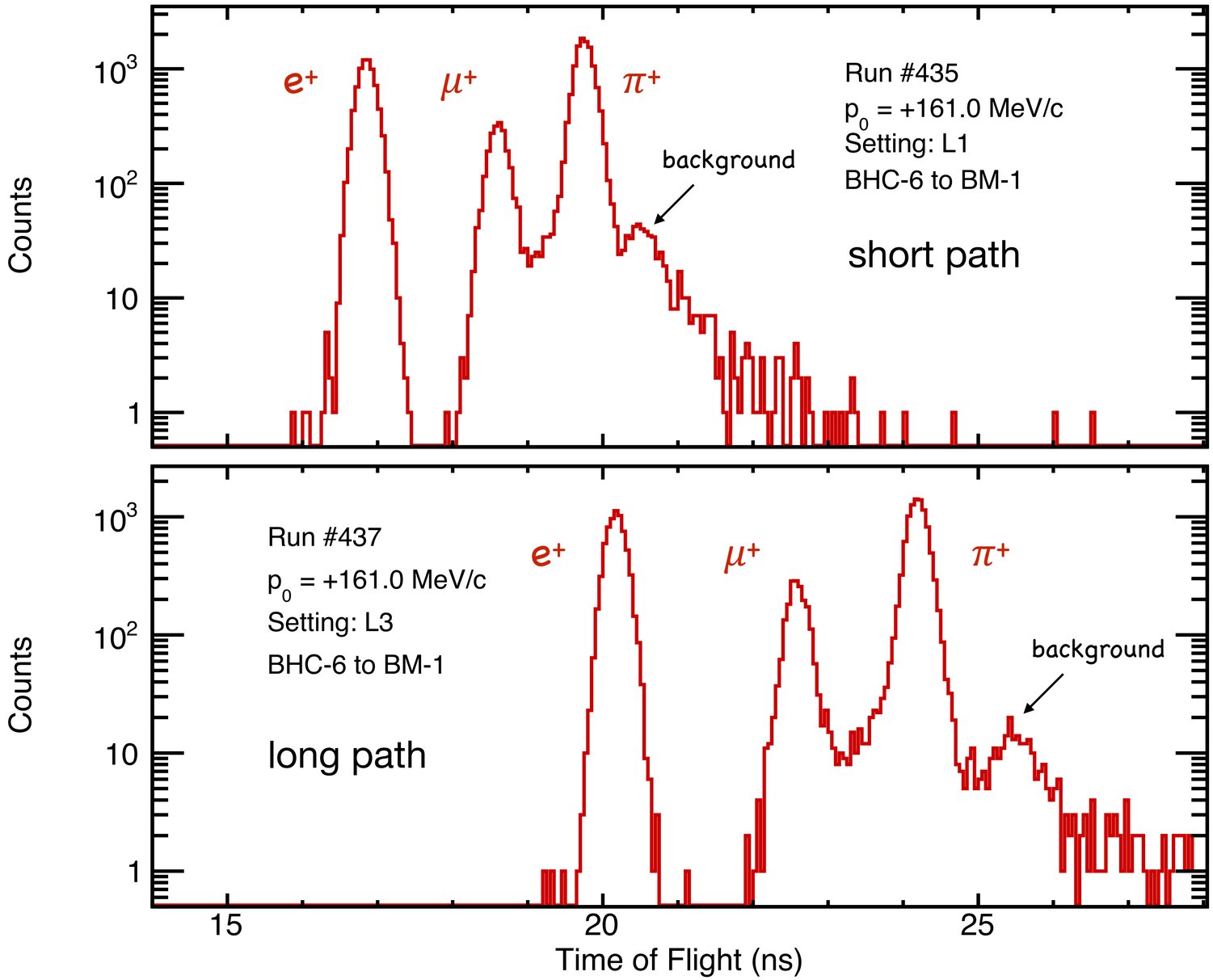
Beam hodoscope
planes C & D (Rutgers)



Examples of two experimental time-of-flight distributions

The agreement of the measured and calculated πM1 channel momenta is at the desired 0.2 – 0.3% level.

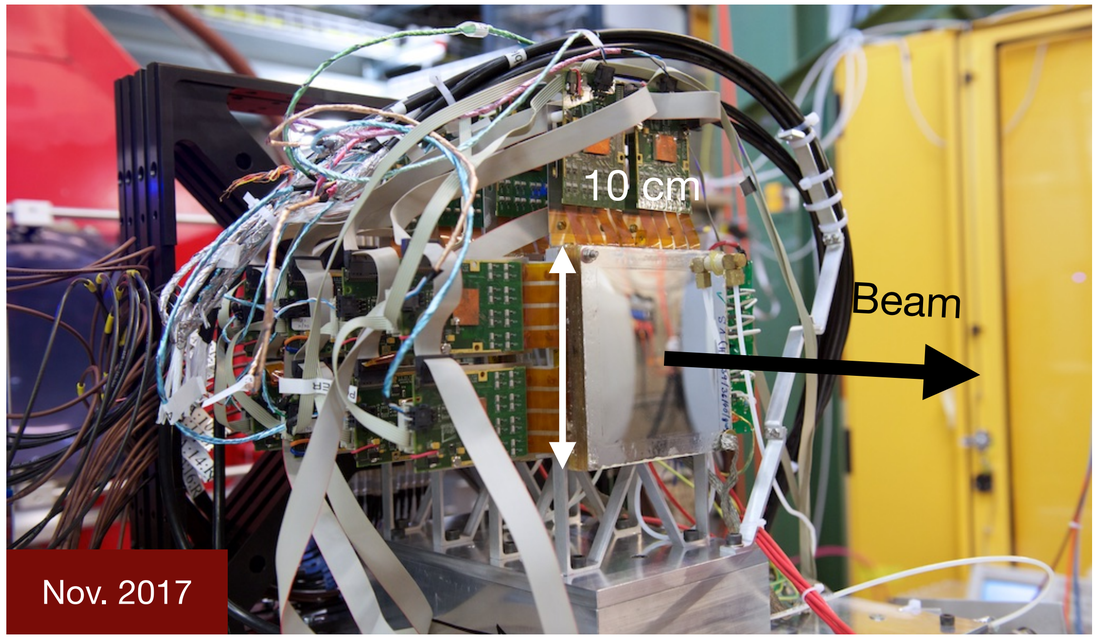
$$\sigma_{p_0} = 0.002 \cdot p_0$$

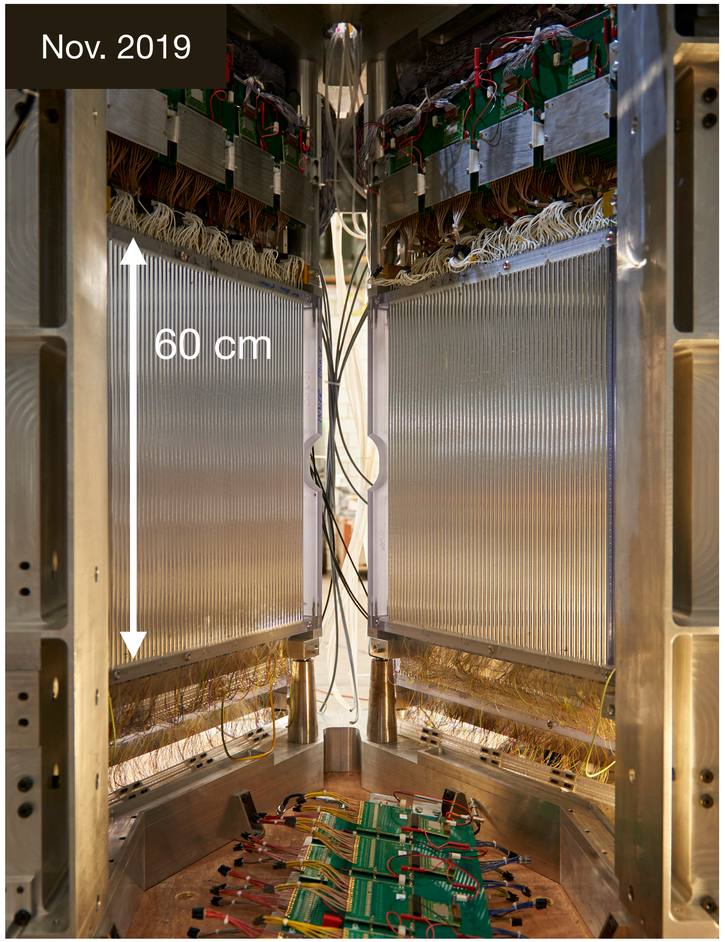


MUSE tracking detectors

GEM detectors (Hampton Univ.)

- Set of three GEM detectors built for & run in OLYMPUS.
- Measure trajectories into the target to reconstruct the scattering kinematics.

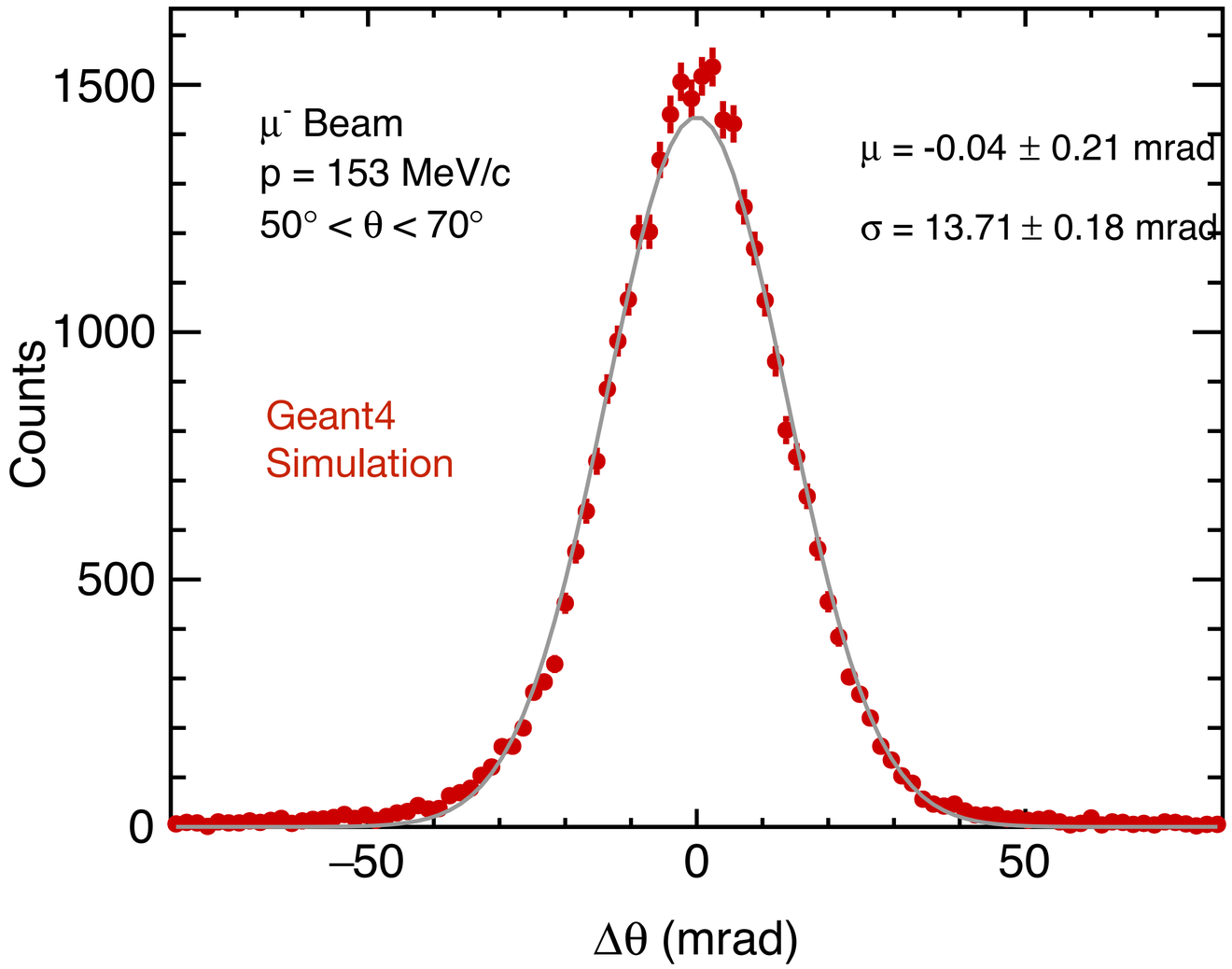




Straw-tube tracker
(Hebrew University of Jerusalem + Temple)

- Two STT chambers with 5 vertical and 5 horizontal planes each (3000 straws total).
- The Straw Tube Tracker provides high-resolution and high-efficiency tracking of the scattered particles from the target.

Reconstruction of scattering angle



Position resolution:
GEM 70 μm and STT 120 μm.

Full Geant4 simulation including detector material and target.

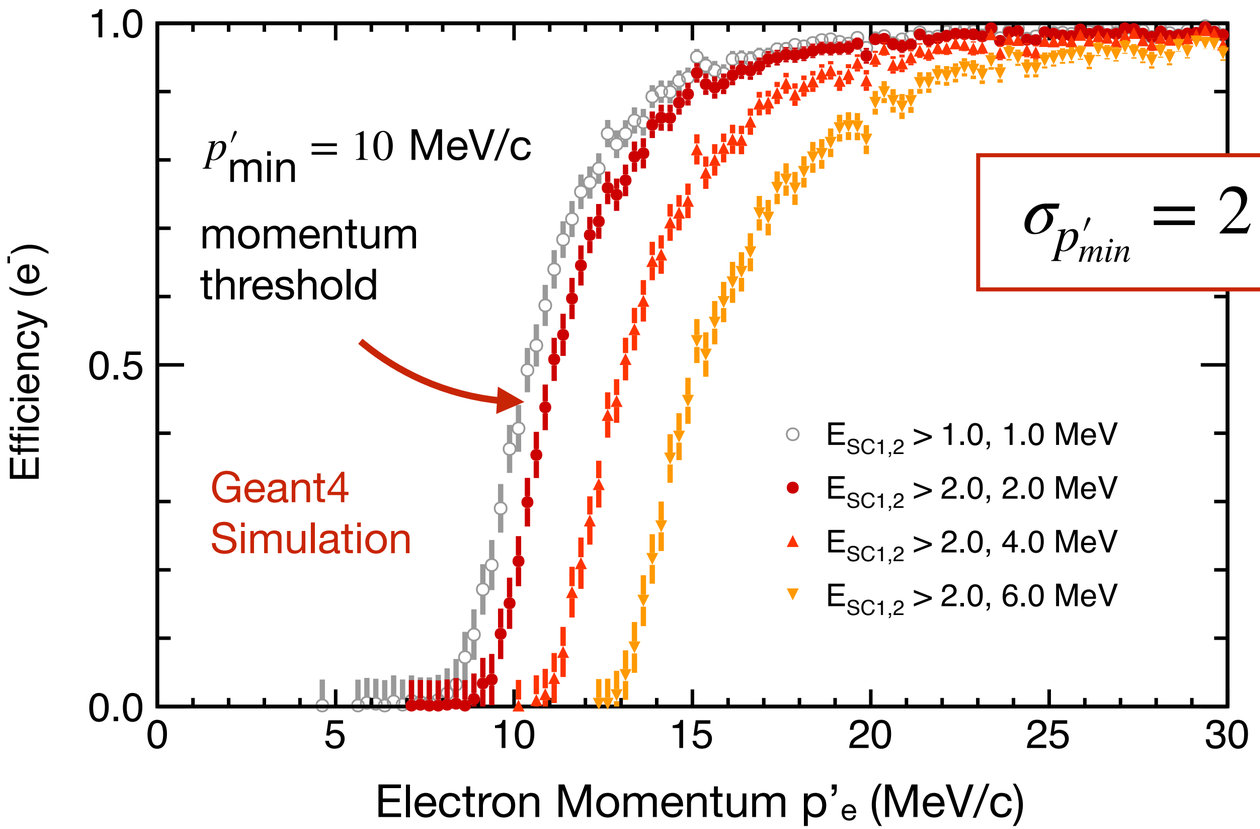
Scattering-angular resolution is dominated by multiple scattering and ≤ 20 mrad.

$$\sigma_\theta = 20 \text{ mrad}$$

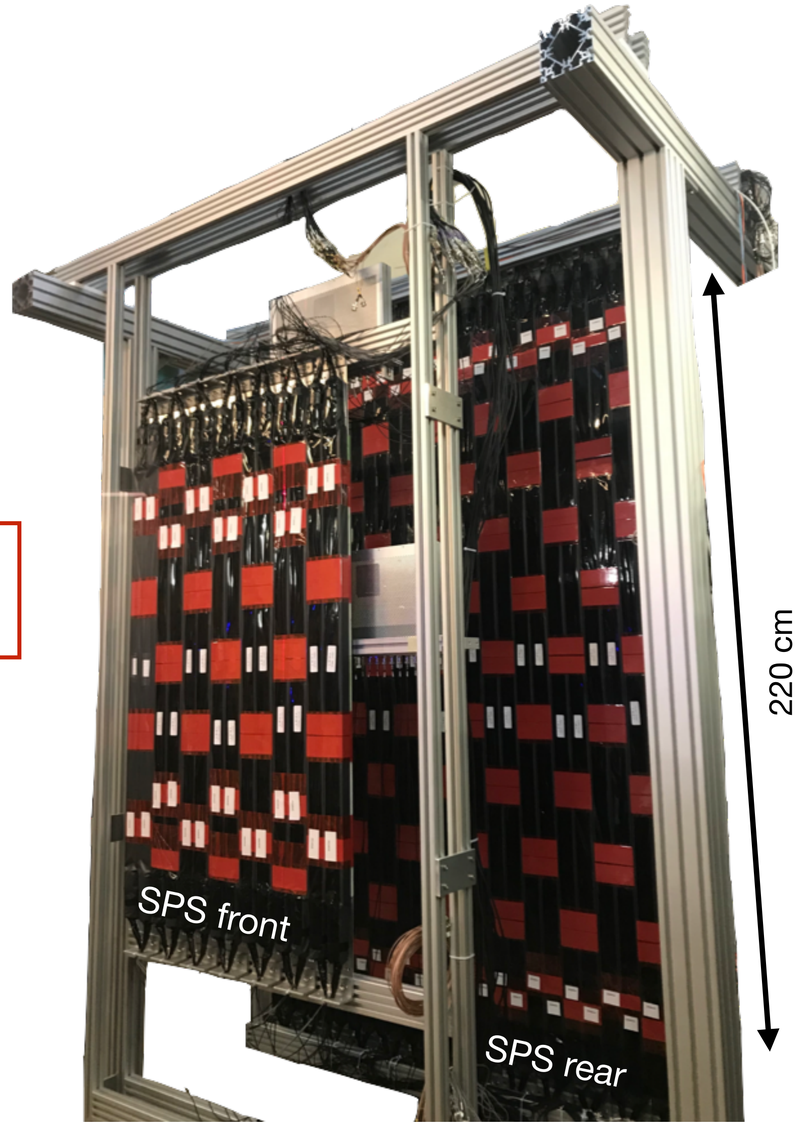
Detection of scattered lepton in SPS

Fast and efficient **scattered-particle scintillators (SPS)** (University of South Carolina) provide event trigger and particle ID

- Front wall: 18 bars (6 cm x 3 cm x 120 cm), $\sigma_t < 50$ ps
- Rear wall: 28 bars (6 cm x 6 cm x 220 cm), $\sigma_t < 60$ ps

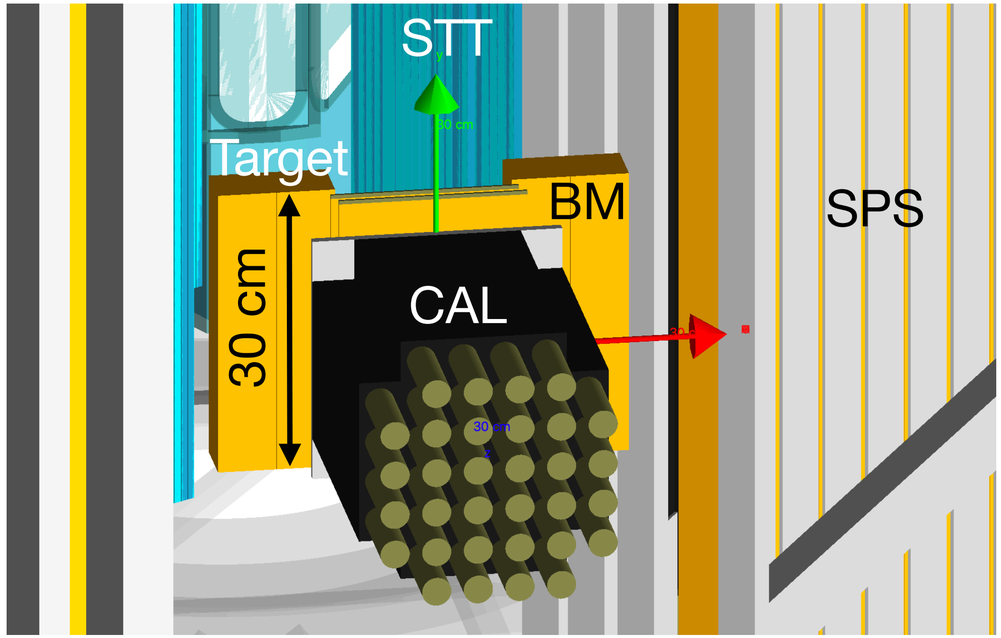


$$\sigma_{p'_{min}} = 2 \text{ MeV/c}$$



Calorimeter

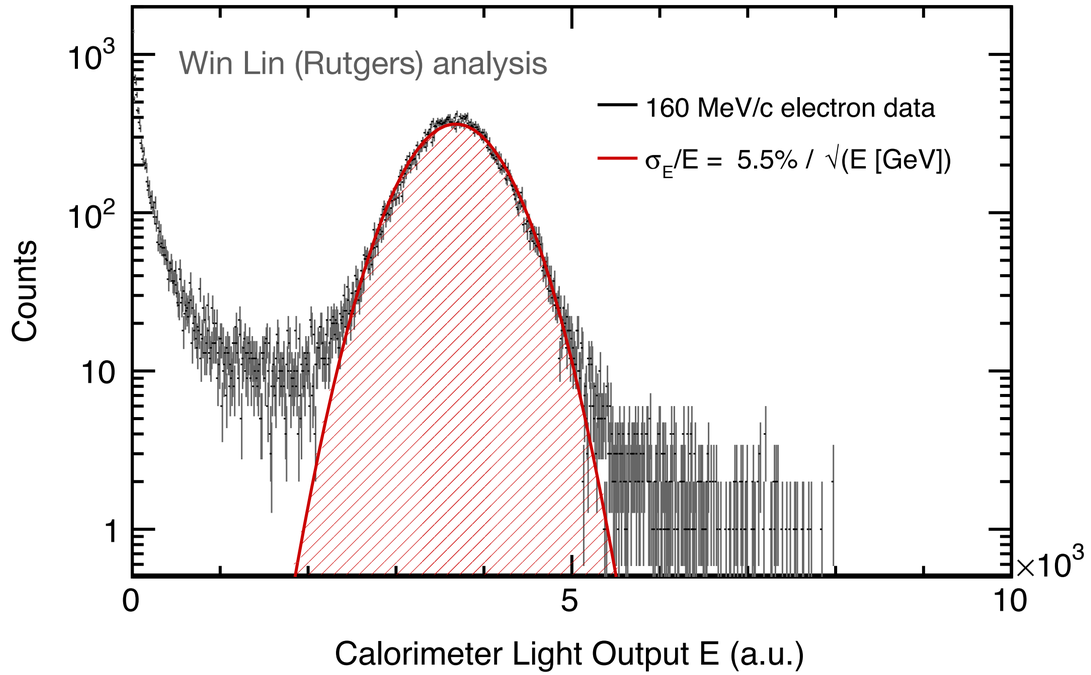
Beam line view from downstream side of MUSE



Calorimeter in beamline downstream of BM

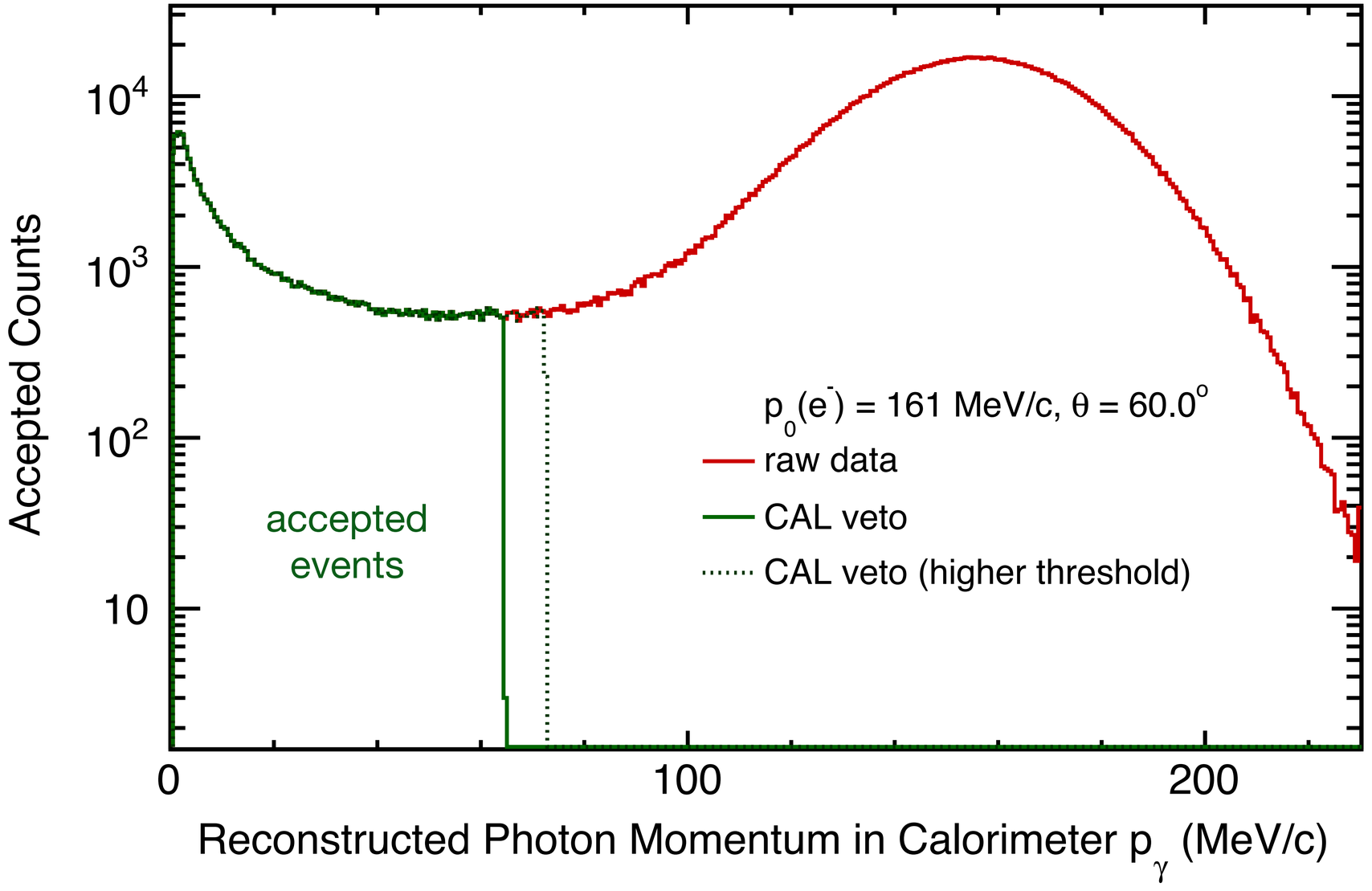
32 lead-glas crystals (4 cm x 4 cm x 30 cm)

Preliminary performance tests
Sum of light output of set of nine calorimeter blocks



$$\frac{\sigma_E}{E} = \frac{5\,\%}{\sqrt{E\ (\mathrm{GeV})}}$$

Calorimeter can be used to suppress initial-state bremsstrahlung



Simulated bremsstrahlung spectrum, folded with expected detector resolution

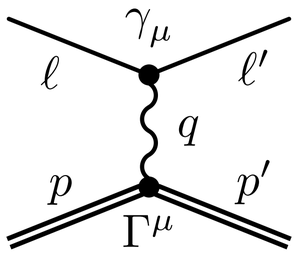
$\sigma_{E_\gamma} \approx 10$ MeV

Event-Generator Requirements

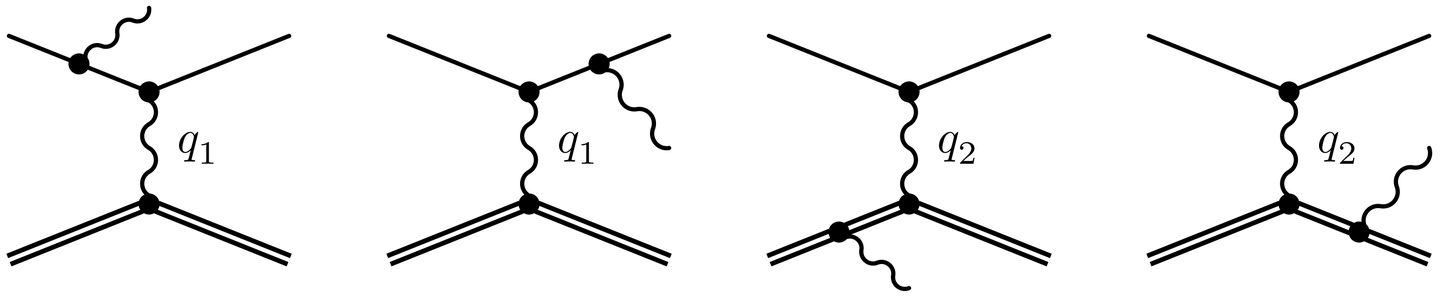
- Include emission of **hard radiated photon**, beyond soft-photon approximation.
- Include the **mass of lepton**:
  - Not using approximation $-q^2 \gg m^2$.
  - Accurate calculation of the event kinematics.
- Suitable for Monte Carlo simulations
- Models
  - **ESEPP** (Gramolin et al.)
  - Olympus / Darklight
  - Heavy baryon chiral perturbation theory (F. Myhrer and collaborators)
  - ELRADGEN (A. Afanasev et al.)
  - …

Elastic Scattering of Electrons and Positrons on Protons (ESEPP)

first Born approximation

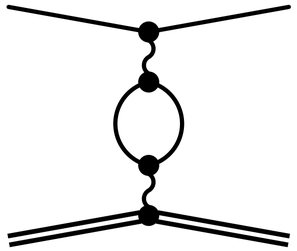


first-order bremsstrahlung process $l^{\pm}p \to l'^{\pm}p'\gamma$

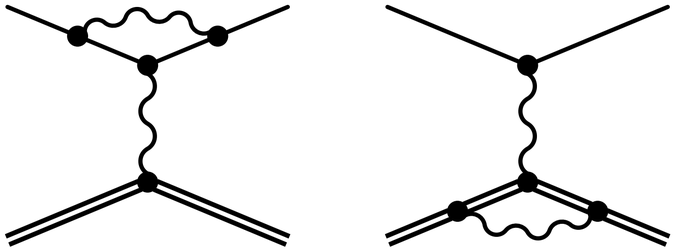


virtual-photon corrections

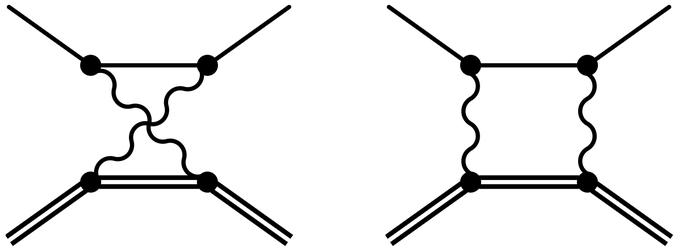
vacuum polarization



lepton/proton vertex corrections



TPE corrections



A.V. Gramolin et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 115001 (28pp)

Lepton-charge dependence

Cross section of charged lepton scattering on protons:

$$\sigma(\ell^{\pm}p) \propto |\mathcal{M}_{\text{Born}}|^2 +$$
$$2\Re\left[\mathcal{M}^{\dagger}_{\text{Born}}\left(\mathcal{M}_{\text{vac}} + \mathcal{M}^{\ell}_{\text{vert}} + \mathcal{M}^{p}_{\text{vert}}\right)\right] +$$
$$2\Re\left[\mathcal{M}^{\dagger}_{\text{Born}}\left(\mathcal{M}_{\text{box}} + \mathcal{M}_{\text{xbox}}\right)\right] +$$
$$\left|\mathcal{M}^{\text{li}}_{\text{brems}} + \mathcal{M}^{\text{lf}}_{\text{brems}}\right|^2 + \left|\mathcal{M}^{\text{pi}}_{\text{brems}} + \mathcal{M}^{\text{pf}}_{\text{brems}}\right|^2 +$$
$$2\Re\left[\left(\mathcal{M}^{\text{li}}_{\text{brems}} + \mathcal{M}^{\text{lf}}_{\text{brems}}\right)^{\dagger}\left(\mathcal{M}^{\text{pi}}_{\text{brems}} + \mathcal{M}^{\text{pf}}_{\text{brems}}\right)\right] + \mathcal{O}(\alpha^4)$$

Charge-odd terms:

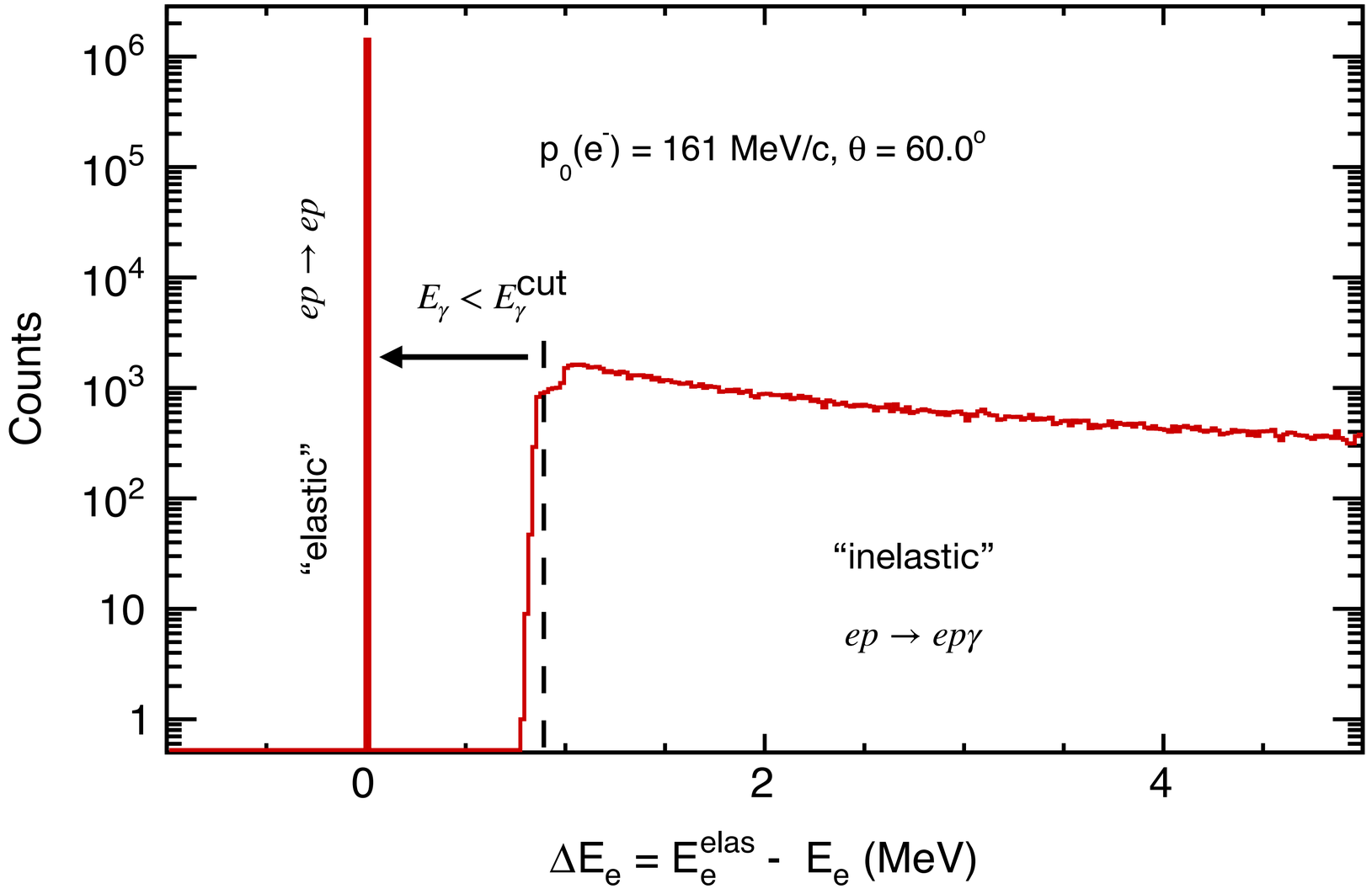
Interference TPE term

Interference bremsstrahlung term

The interference-TPE term and the interference-bremsstrahlung terms change sign depending on the sign of the lepton's charge.

A.V. Gramolin et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 115001 (28pp)

The ESEPP event generator



- ESEPP generates unweighted events
- Two types of events: elastic (analytical integration) and inelastic (numerical integration)
- First-order bremsstrahlung is taken into account in both cases

A.V. Gramolin et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 115001 (28pp)

Minimalistic MUSE simulation

Numerical integration of Bremsstrahlung cross-section

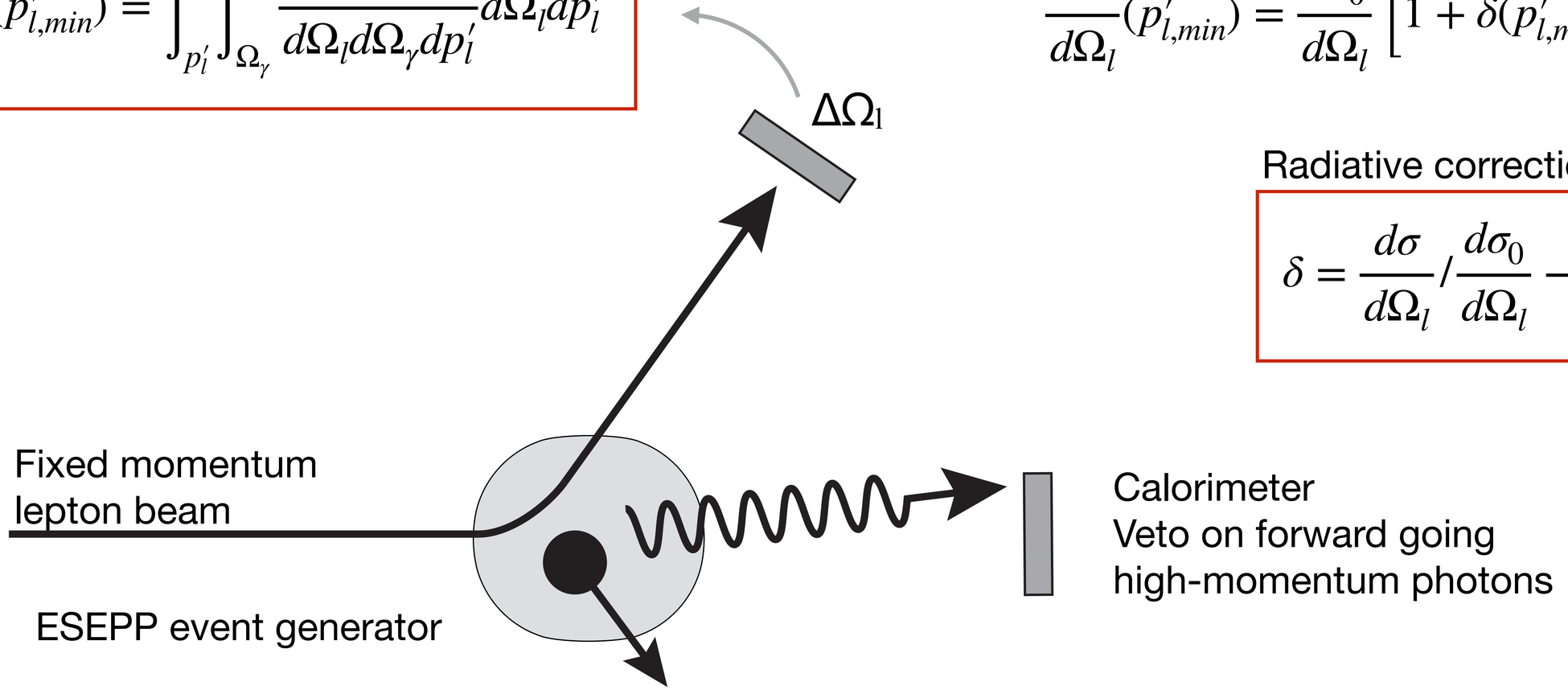
$$\frac{d\sigma}{d\Omega_l}(p'_{l,min}) = \int_{p'_l}\int_{\Omega_\gamma} \frac{d\sigma_{\text{brems}}}{d\Omega_l d\Omega_\gamma dp'_l} d\Omega_l dp'_l$$

Born cross-section

$$\frac{d\sigma}{d\Omega_l}(p'_{l,min}) = \frac{d\sigma_0}{d\Omega_l}\left[1 + \delta(p'_{l,min})\right]$$

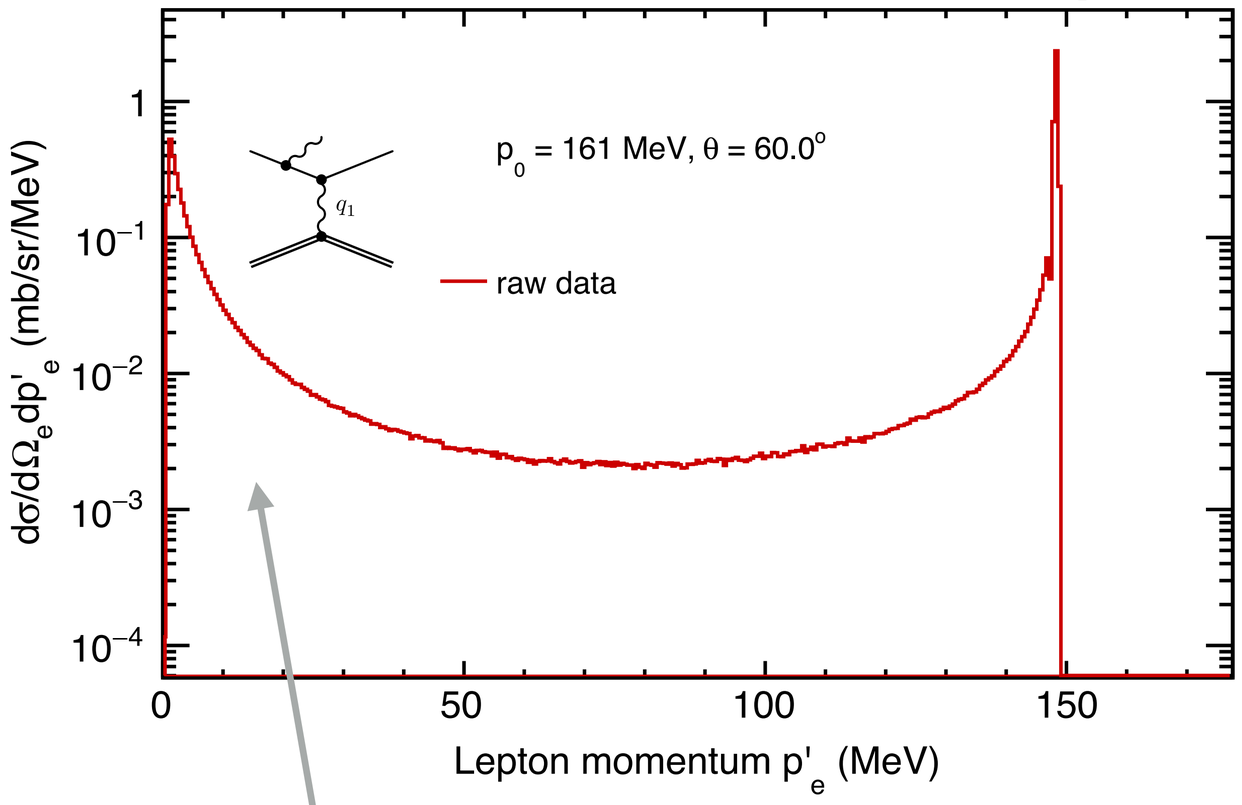
Radiative correction

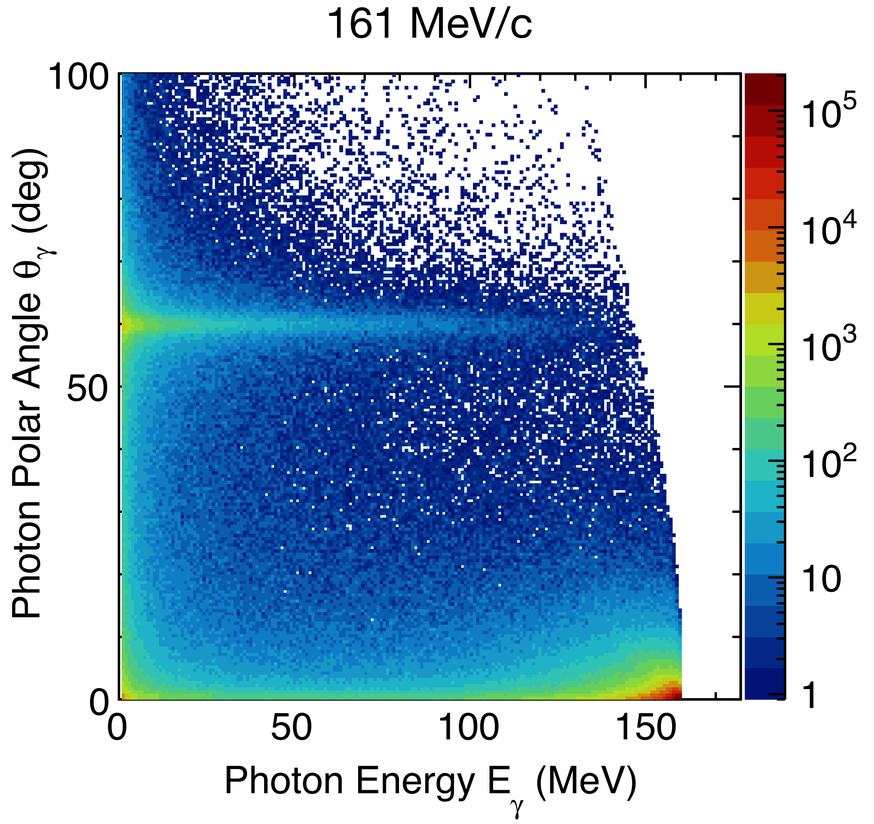
$$\delta = \frac{d\sigma}{d\Omega_l} / \frac{d\sigma_0}{d\Omega_l} - 1$$



$ep \rightarrow e'p\gamma$ Cross section in MUSE kinematics

MUSE will integrate over a large momentum range



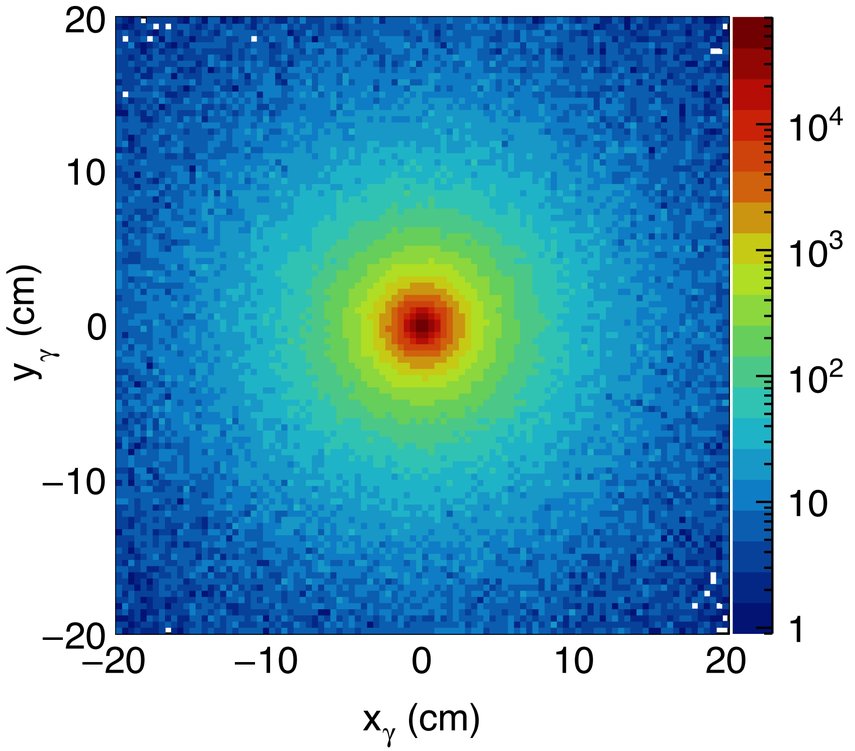


If the incident lepton loses energy due to emission of a hard photon then the probability for this lepton to be scattered by the proton increases.

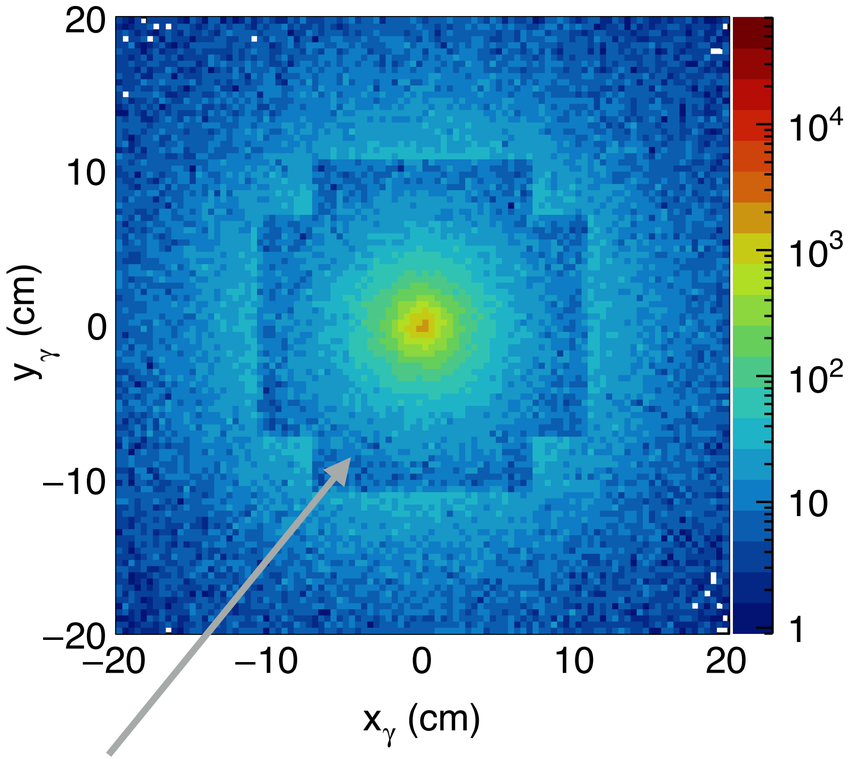
Simulated downstream $ep \rightarrow e'p\gamma$ photon distribution

p_0 = 161 MeV/c

full distribution



distribution after cut on calorimeter signal



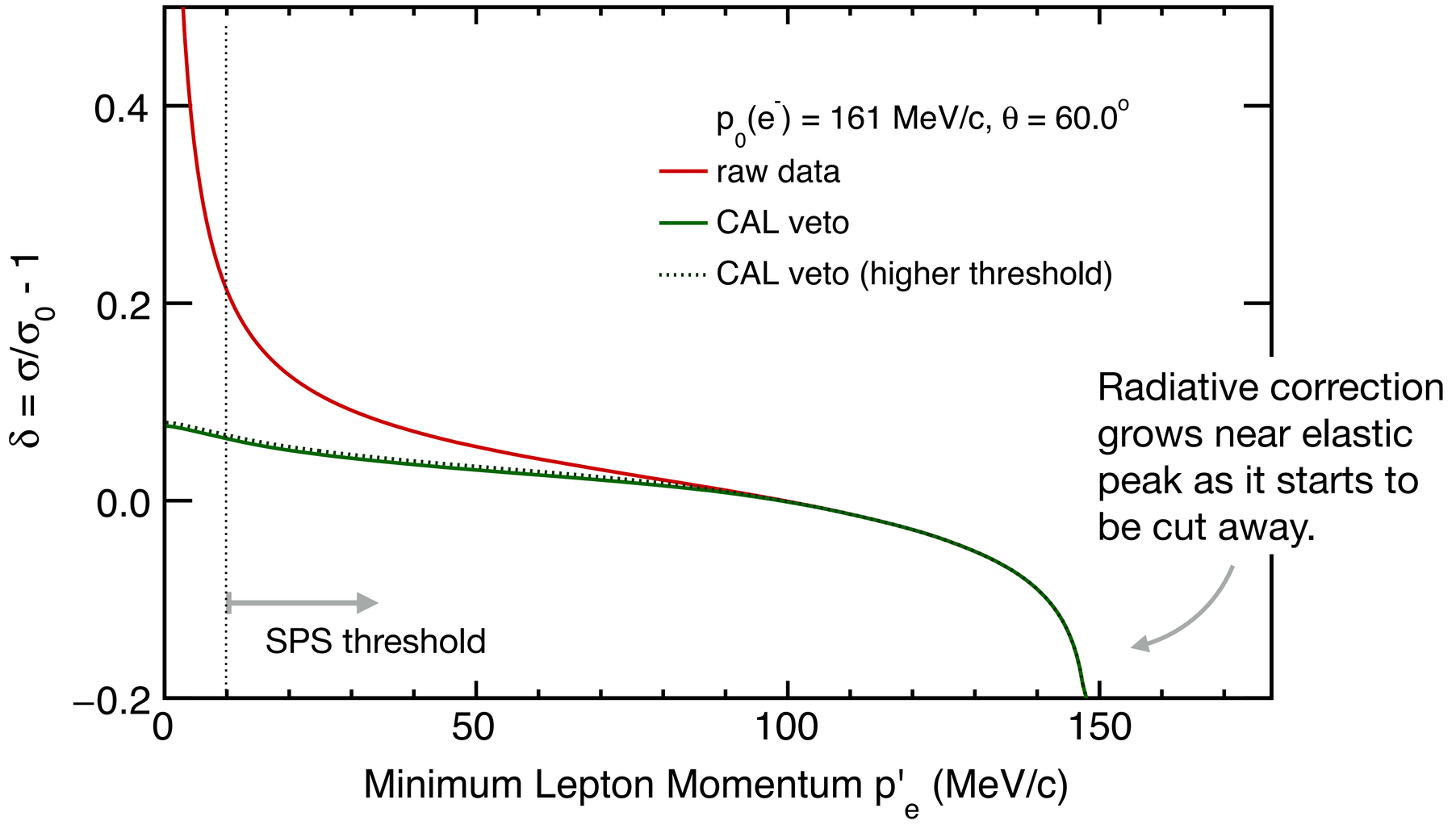
low-momentum photons,
below calorimeter threshold

Radiative corrections for electron-scattering data in MUSE kinematics

Rapidly changing radiative corrections for small p'_{min}.

(> 1% change / MeV/c)

Veto on downstream photons keep corrections small and reduces p'_{min} dependence.

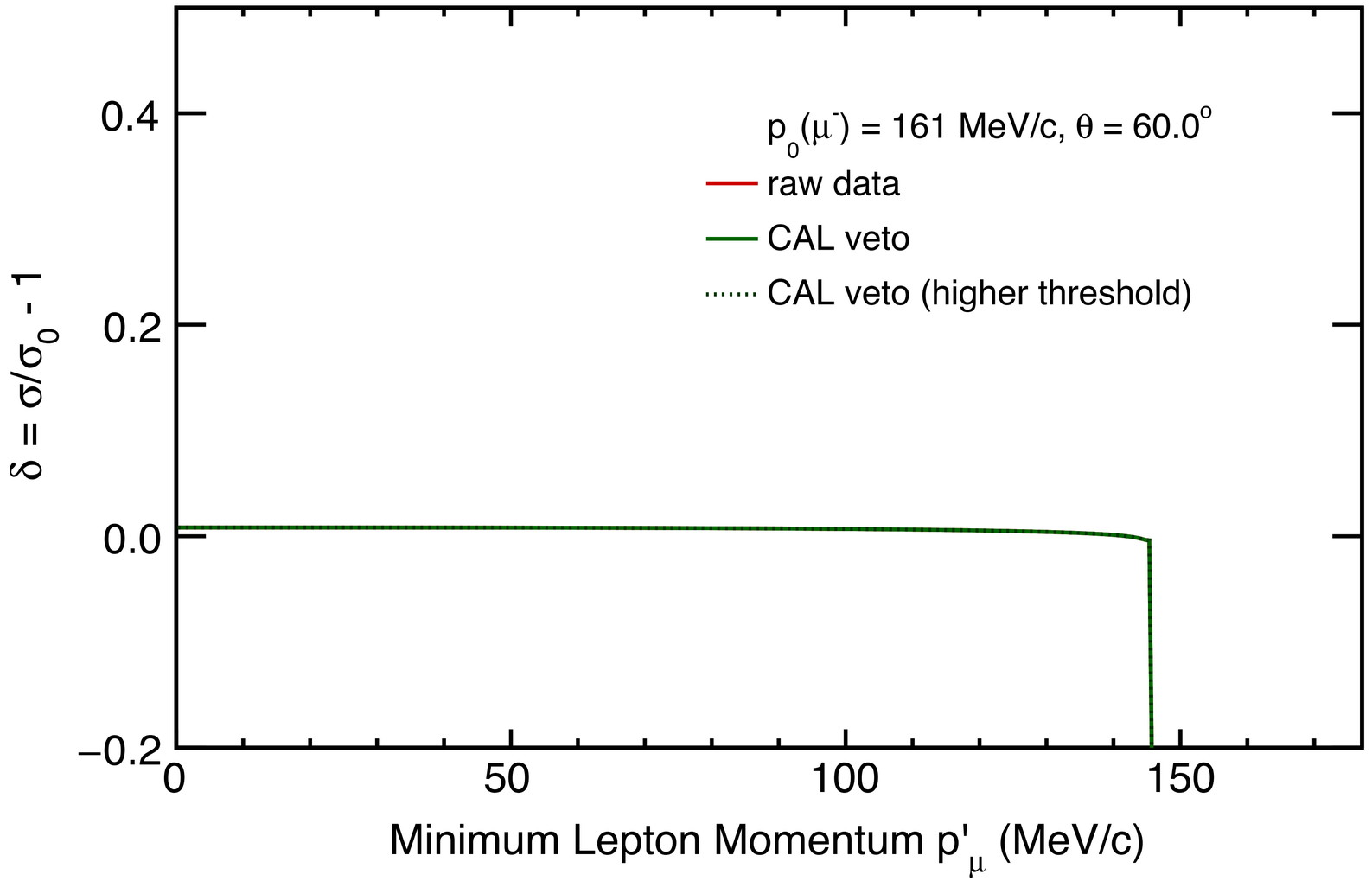


Radiative corrections for muon-scattering data in MUSE kinematics

Small radiative corrections

Corrections nearly independent of p'_{min}

Calorimeter cut without effect on the data



Uncertainties in the radiative corrections: ep

Preliminary results

$\sigma_\delta(e^-)$	115 MeV			210 MeV		
	20°	60°	100°	20°	60°	100°
p'_{min}	0.05%	0.29%	0.56%	0.03%	0.23%	0.63%
p_0	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%
θ	0.13%	0.07%	0.05%	0.10%	0.14%	0.01%
E_γ	0.55%	0.57%	0.58%	0.35%	0.40%	0.38%
Total	**0.57%**	**0.65%**	**0.81%**	**0.37%**	**0.48%**	**0.74%**

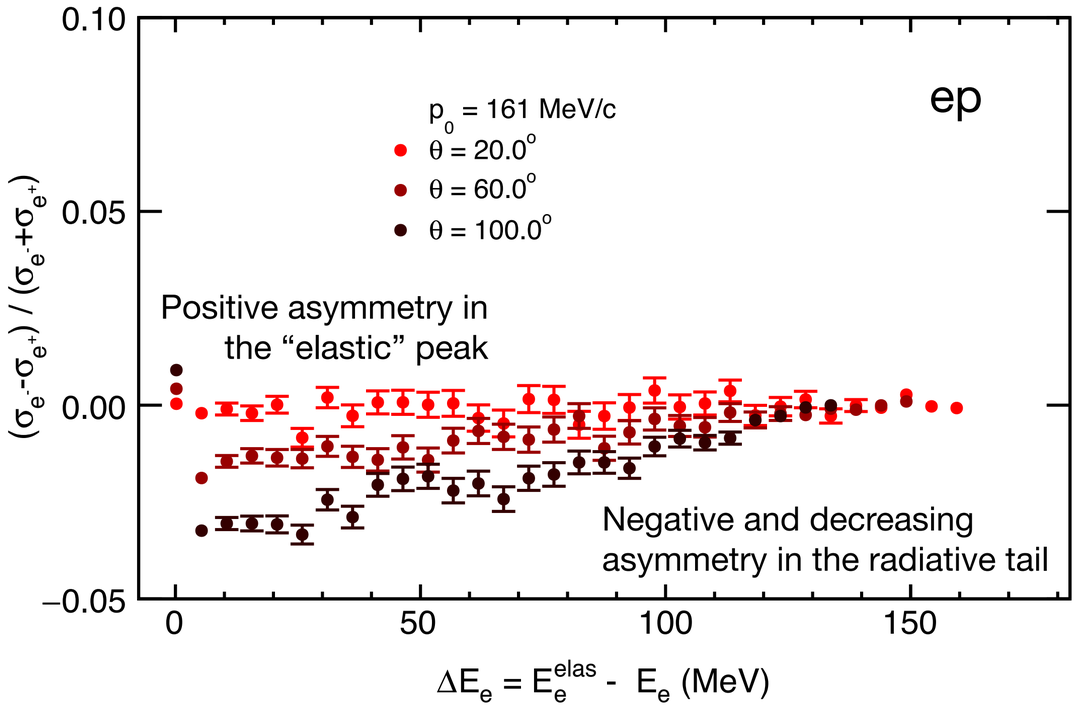
Uncertainties in the radiative corrections: μp

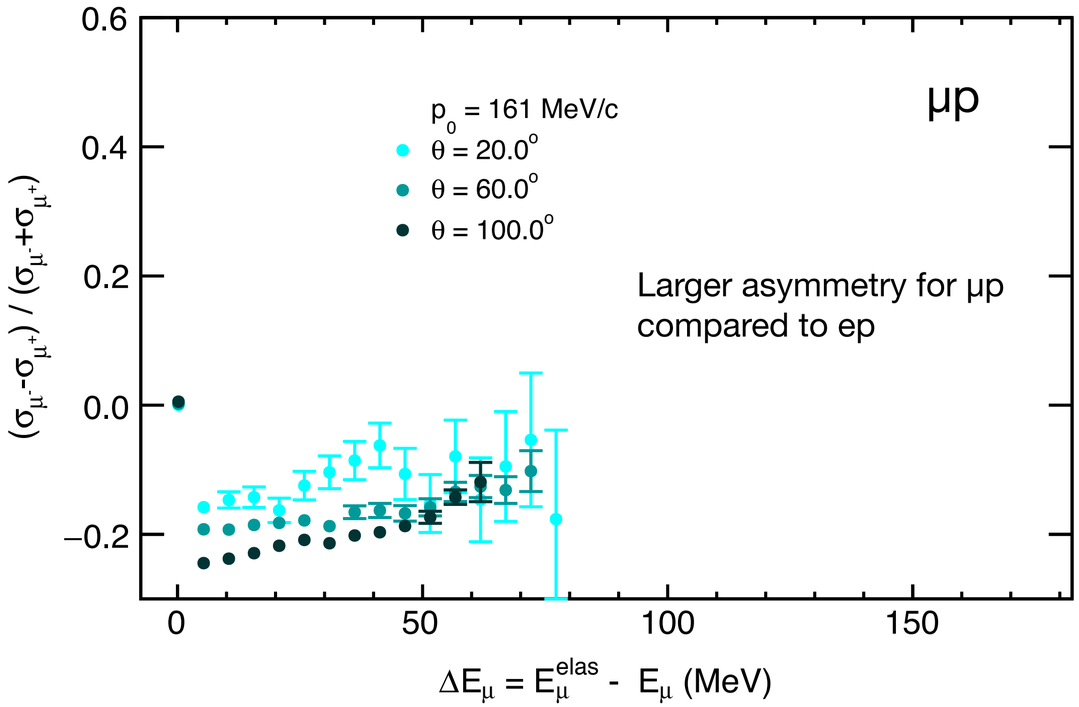
Preliminary results

$\sigma_\delta(\mu^-)$	115 MeV			210 MeV		
	20°	60°	100°	20°	60°	100°
p'_{min}	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
p_0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
θ	0.06%	0.02%	0.04%	0.04%	0.03%	0.04%
E_γ	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	**0.06%**	**0.02%**	**0.04%**	**0.04%**	**0.03%**	**0.04%**

Cross-section asymmetries

The interference-TPE term and the interference-bremsstrahlung terms change sign depending on the sign of the lepton's charge.





More work needs to be done

- Improvement of the event sampling to more efficiently cover the full angular acceptance of the MUSE setup.
- Inclusion of the event generator in a full MUSE simulation.
- Understand the theoretical uncertainties, model dependence, and possible improvements in the calculations deep in the radiative tail.
- Separating the overall vs. the point-to-point radiative correction.
- Perform more dedicated calorimeter calibrations.

Summary

- **MUSE is a high-precision experiment** to measure the proton charge radius, study possible 2γ mechanisms, and have a direct μ/e comparison of the elastic cross-sections.
- **The MUSE setup** has unique implications for the determination of radiative corrections:
  - Without a magnetic spectrometer, MUSE does not measure the final-state lepton momentum precisely.
  - A dedicated downstream photon detector helps to suppress initial-state radiation effects.
- ESEPP simulations show uncertainties in radiative corrections to be lower than 1%.