Instrumental uncertainties in radiative corrections for the MUSE experiment

Steffen Strauch (University of South Carolina)
for the MUSE Collaboration

The XV International Conference on Beauty, Charm, Hyperons in Hadronic Interactions (BEACH 2024)

3–7 June 2024, Charleston, SC

Supported in parts by the U.S. National Science Foundation: NSF PHY-2111050. 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.

MUon Scattering Experiment (MUSE) at PSI

- MUSE will test lepton universality through the comparison of cross sections, form factors, and proton radii extracted from **electron** and **muon** scattering.
- Beams of both **positive** and **negative** polarity leptons will determine two-photon exchange corrections, testing predictions.
- A forward-angle calorimeter tests initial-state radiative corrections.

MUSE

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

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

MUSE at the secondary beam line πM1

Beam

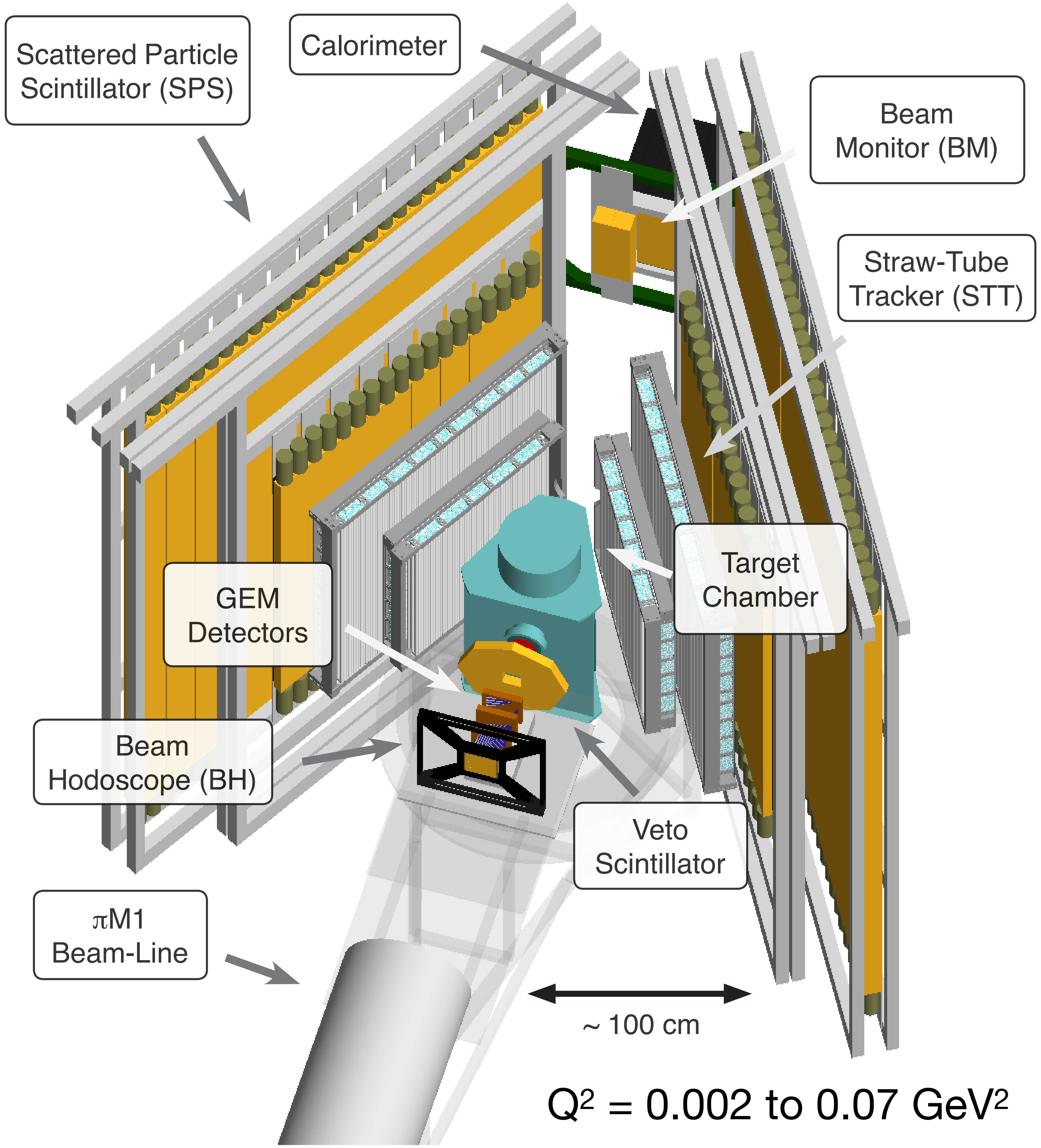
- 50 MHz RF (20 ns bunch separation)
- e, μ, π beams with large emittance
- Flux: 3.3 MHz
- Momentum: 115, 160, 210 MeV/c

Beam line detectors:

- Timing, identifying, and tracking of beam particles to the target and beyond

Scattered particle detectors:

- Timing and tracking of scattered particles with large solid-angle coverage



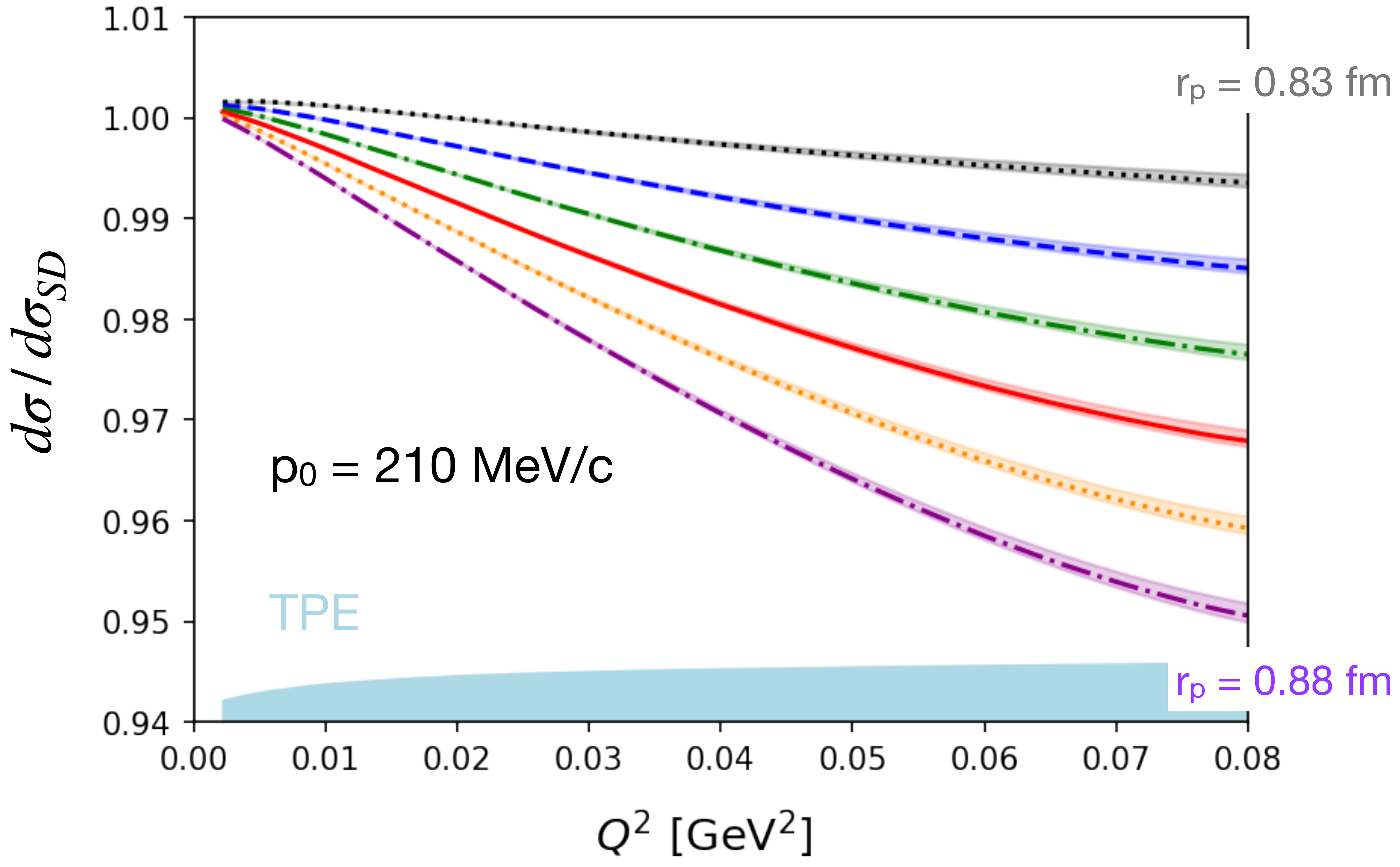
Q^2 = 0.002 to 0.07 GeV^2

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det]
E. Cline et al. (MUSE Collaboration), Phys. Rev. C 105 (2022) 5, 055201.

Proton charge radius extraction from muon scattering at MUSE

- A 0.01 fm change in radius corresponds to about 0.9 % change in cross section.
- Good control of systematic uncertainties is required to achieve the goal of the experiment.
- Radiative corrections are the largest contributor to systematic uncertainties in MUSE.

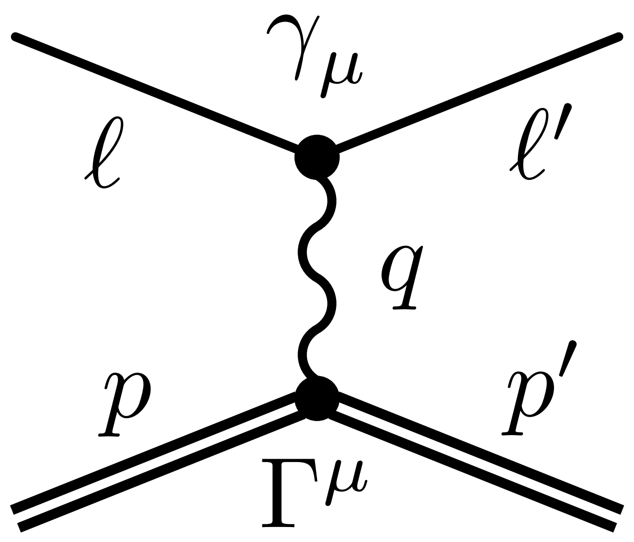
$\mu p \to \mu p$



Dispersively improved chiral effective field theory:
F. Gil-DomÍnguez, J.M. Alarcón and C. Weiss, Phys. Rev. D 108, no.7, 074026 (2023)

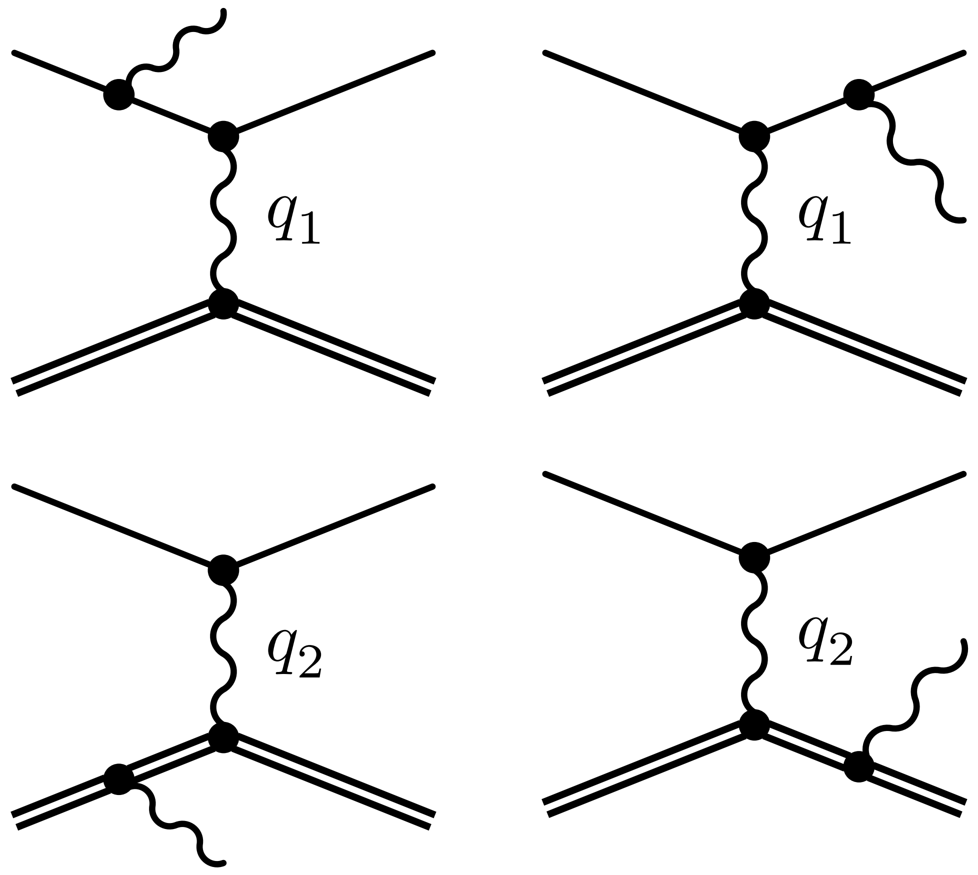
Experimental lepton-proton cross section $\ell^{\pm}p \rightarrow \ell'^{\pm}p'\gamma$

First Born approximation



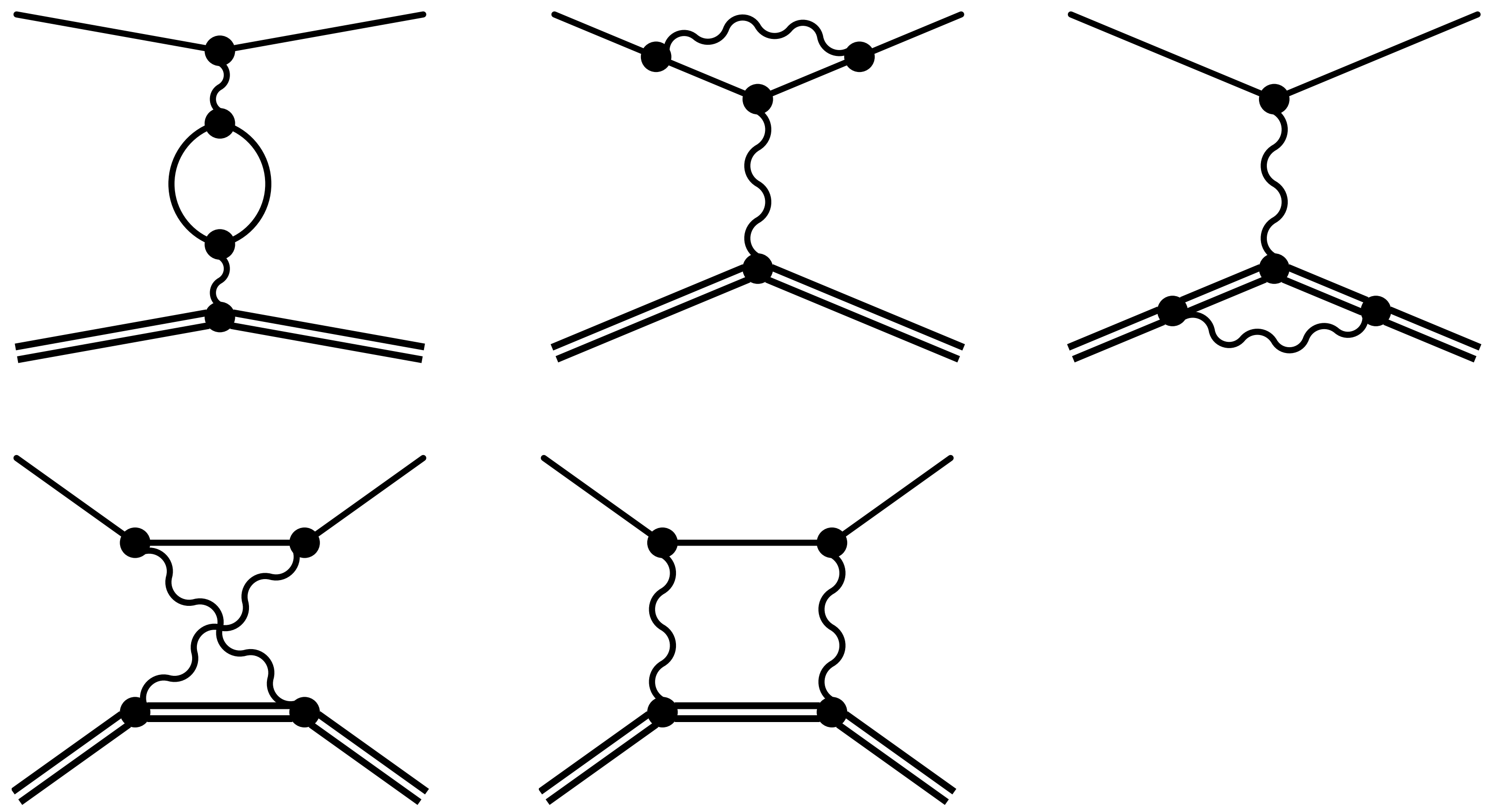
+

First-order bremsstrahlung processes



+

Virtual-photon corrections



+ …

Vacuum polarization
Lepton/proton vertex corrections
Two-photon exchange corrections

Born cross section:

- can be obtained from σ^{exp} with radiative corrections,
- is needed to determine form factors and charge radius.

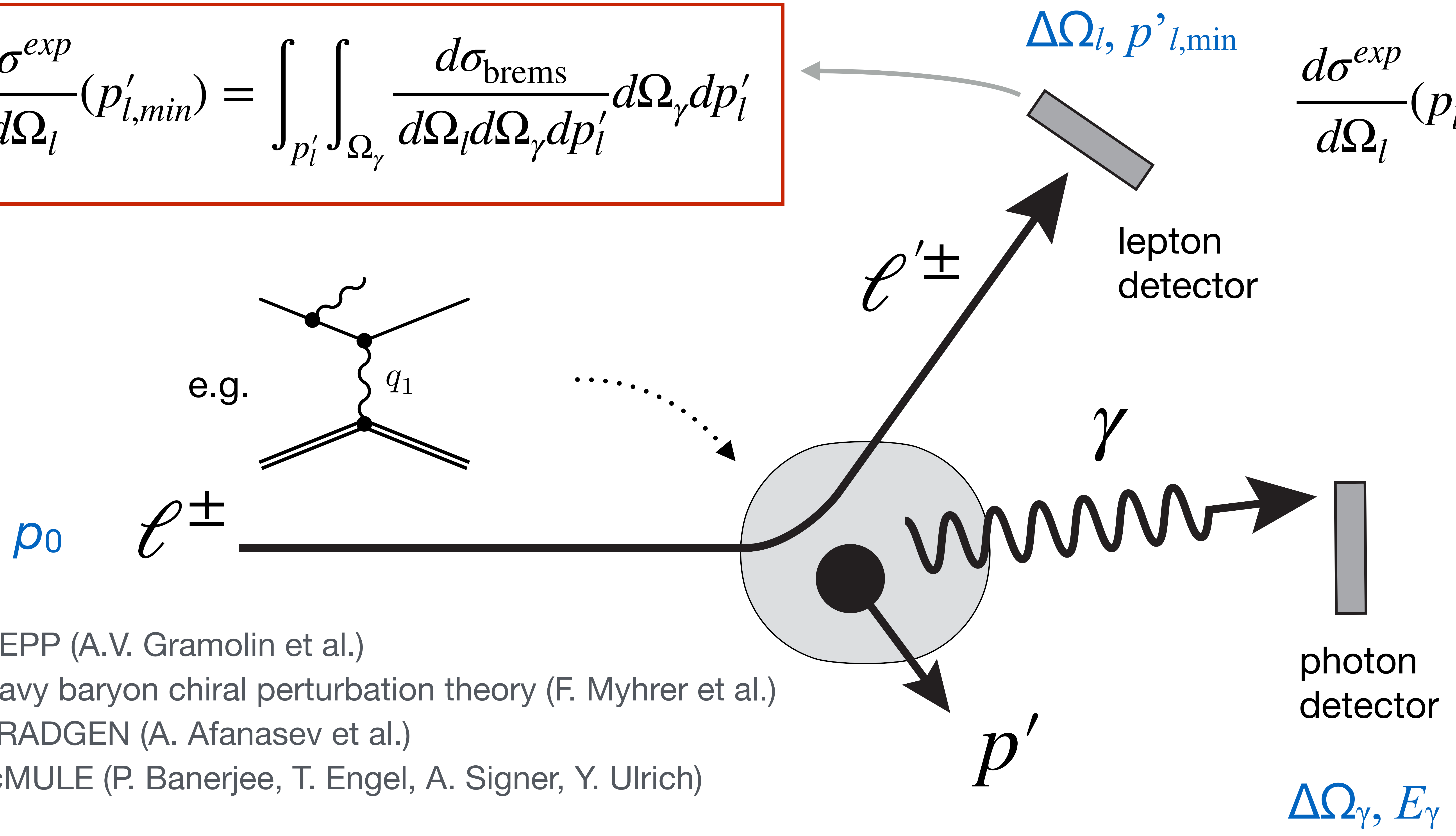
ESEPP includes emission of **hard radiated photon**, beyond soft-photon approximation and the **mass of lepton**.

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

Experimental cross section depends on kinematic setting and acceptance

Experimental bremsstrahlung cross-section

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



Born cross section

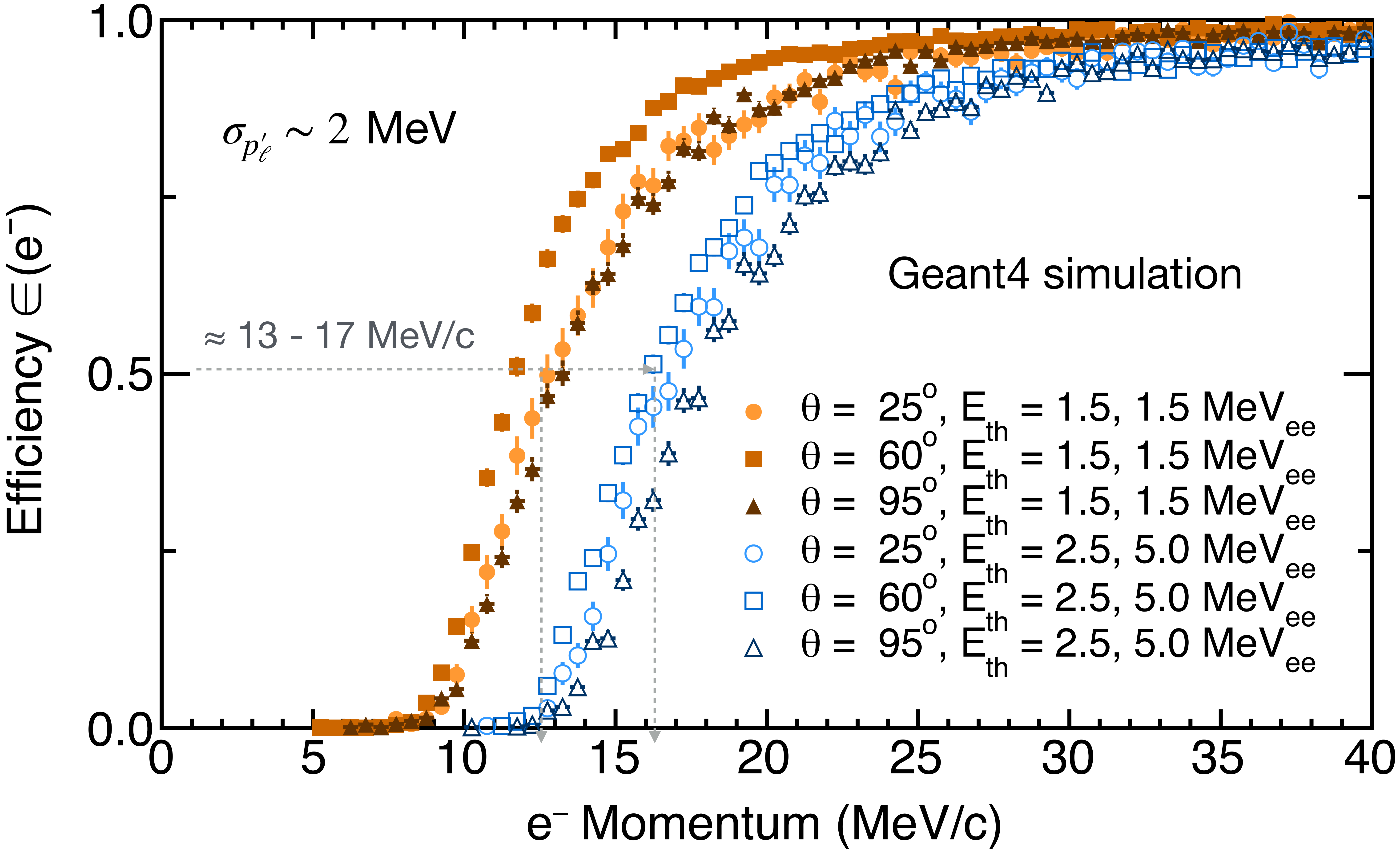
$$\frac{d\sigma^{exp}}{d\Omega_l}(p'_{l,min}) = \frac{d\sigma_0}{d\Omega_l}\left[1 + \delta(p'_{l,min})\right]$$

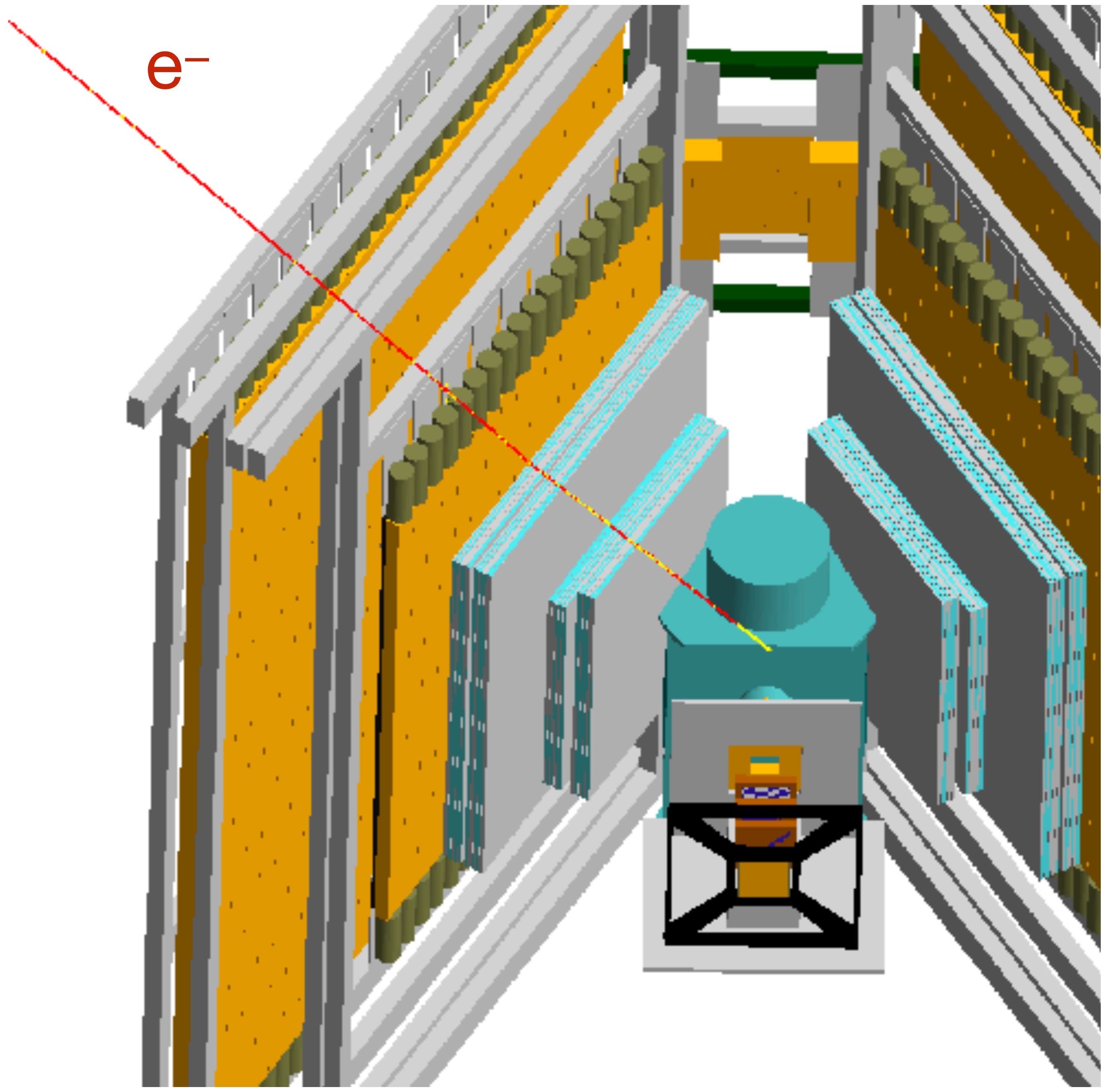
Calculated radiative corrections

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

ESEPP (A.V. Gramolin et al.)
Heavy baryon chiral perturbation theory (F. Myhrer et al.)
ELRADGEN (A. Afanasev et al.)
McMULE (P. Banerjee, T. Engel, A. Signer, Y. Ulrich)
…

Lepton-momentum threshold is primarily determined by the SPS detector





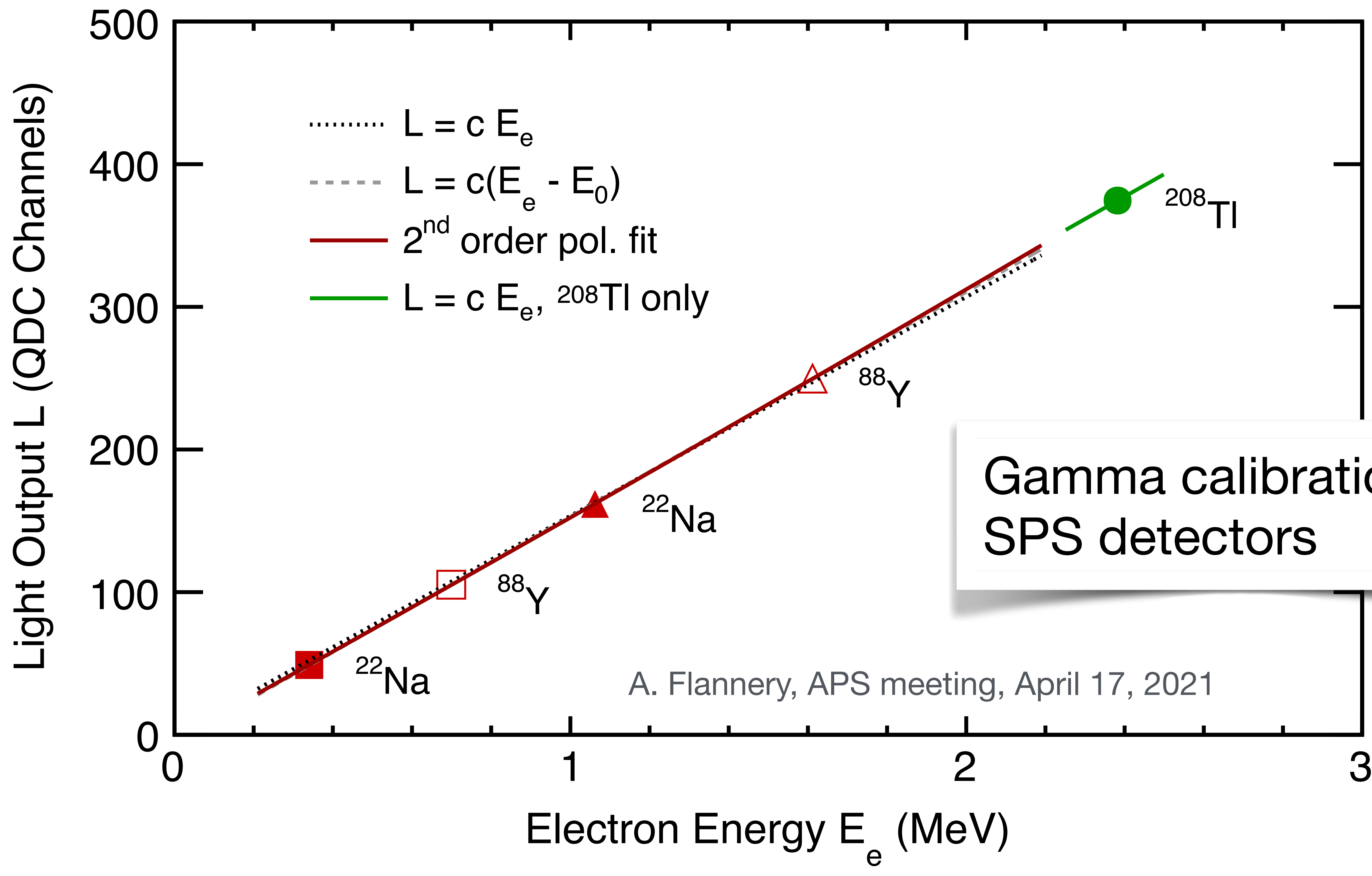
- Function of the SPS discriminator **thresholds** in the front and rear walls
- Function of the lepton **scattering angle**

L. Li et al. (MUSE Collaboration), Eur. Phys. J. A 60:8 (2024)

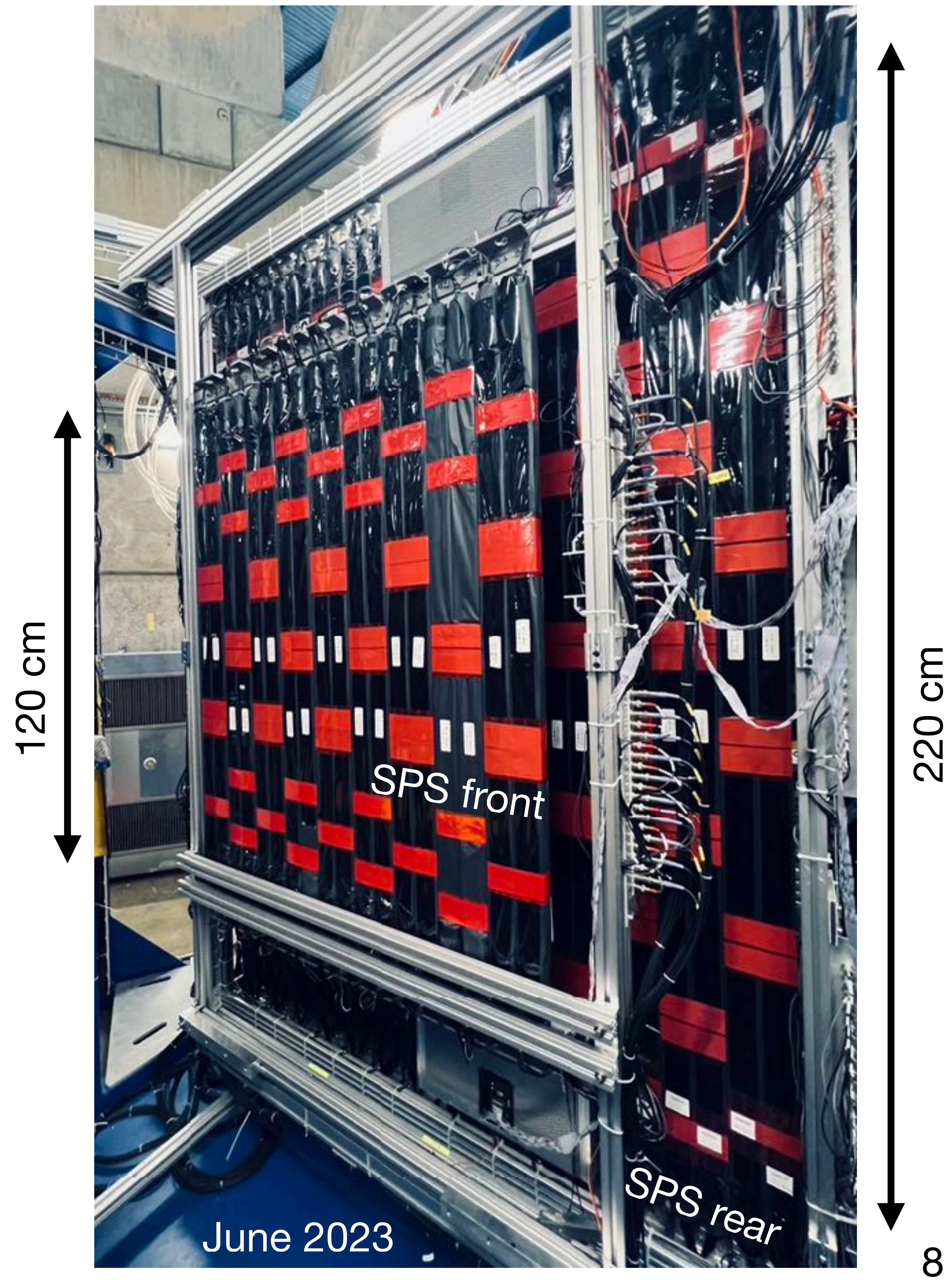
Scattered-particle scintillators as event trigger and for reaction ID

Front wall: 18 bars (6 cm x 3 cm x 120 cm)
Rear wall: 28 bars (6 cm x 6 cm x 220 cm)

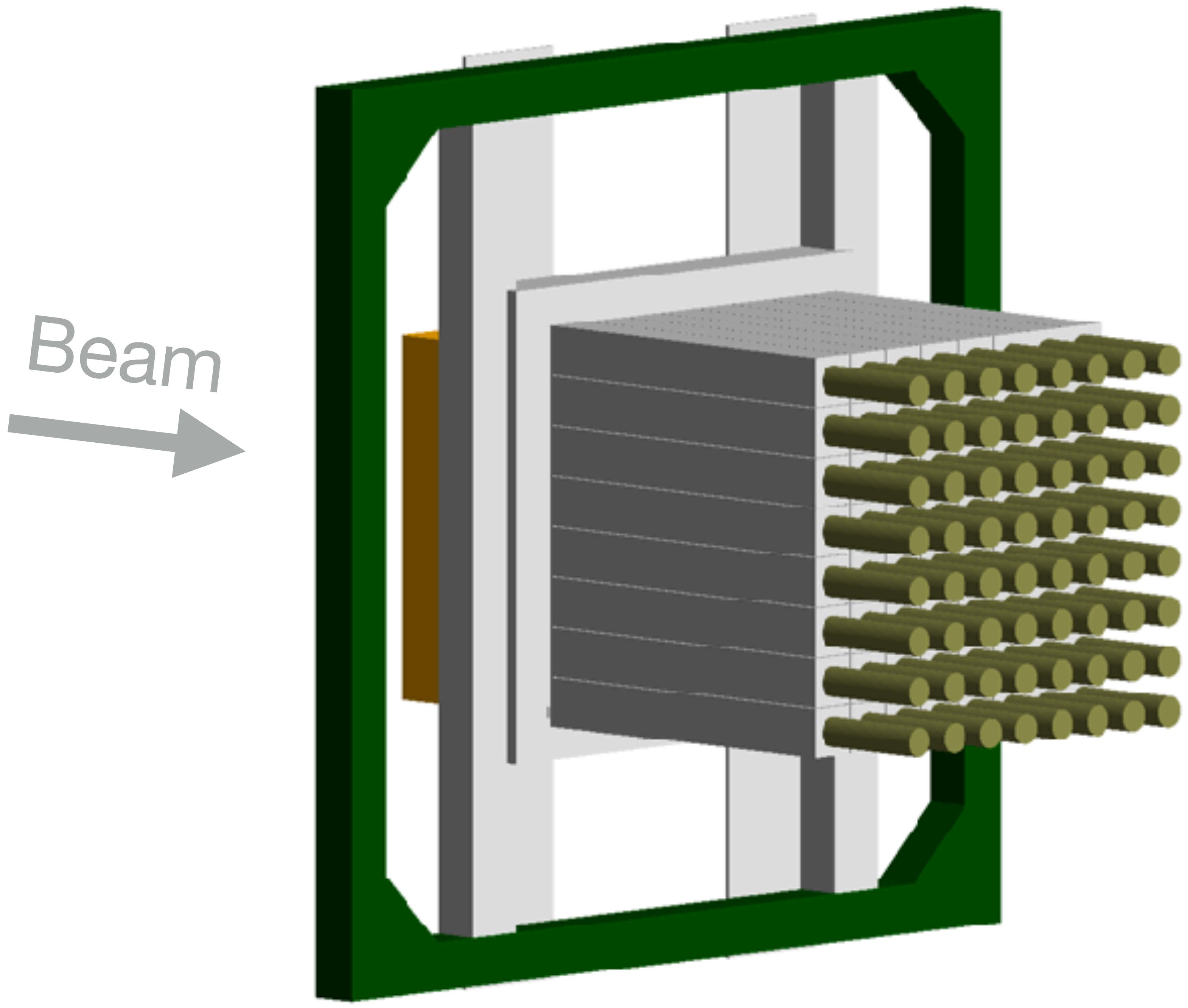
Scattered-particle scintillators exceed required time resolution:
σ(Front) < 50 ps, σ(Rear) < 60 ps



Gamma calibration of SPS detectors

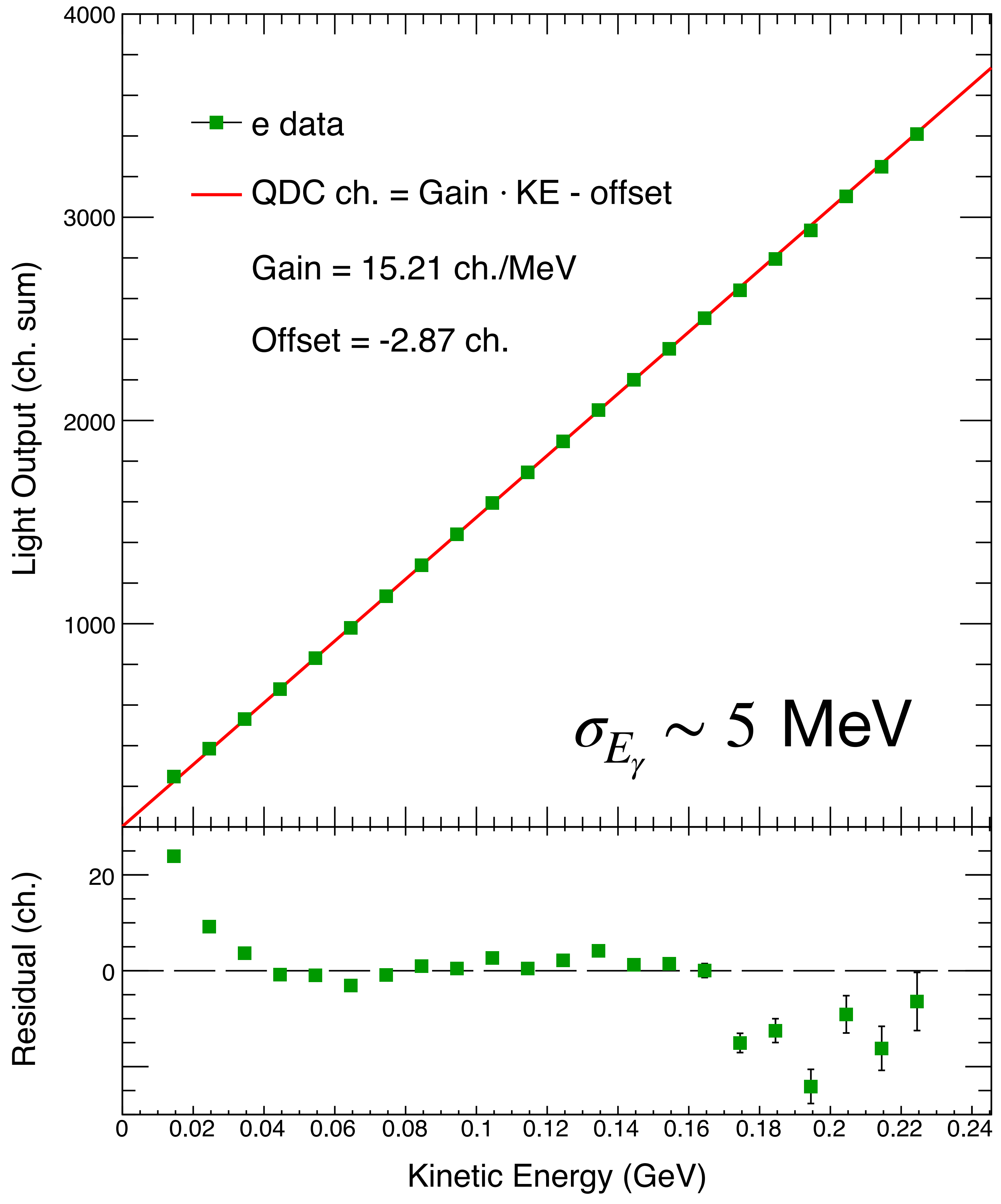


Photon calorimeter is calibrated with electron-beam data

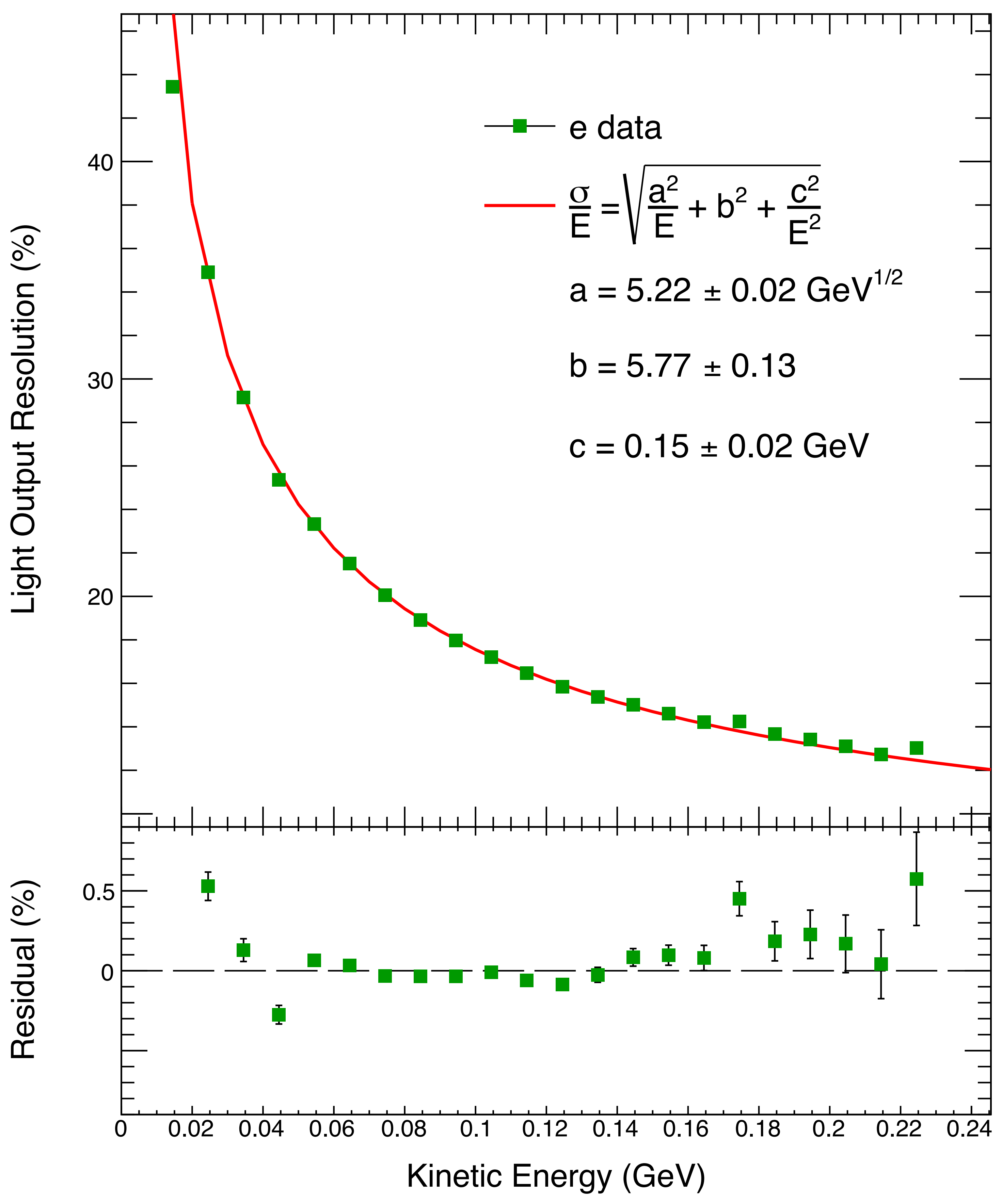


64 lead-glass crystals
(4 cm x 4 cm x 30 cm)

Light output

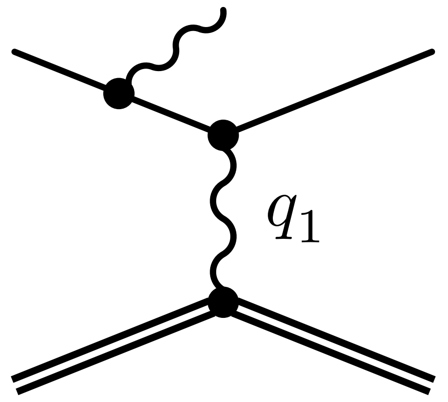


Light output resolution

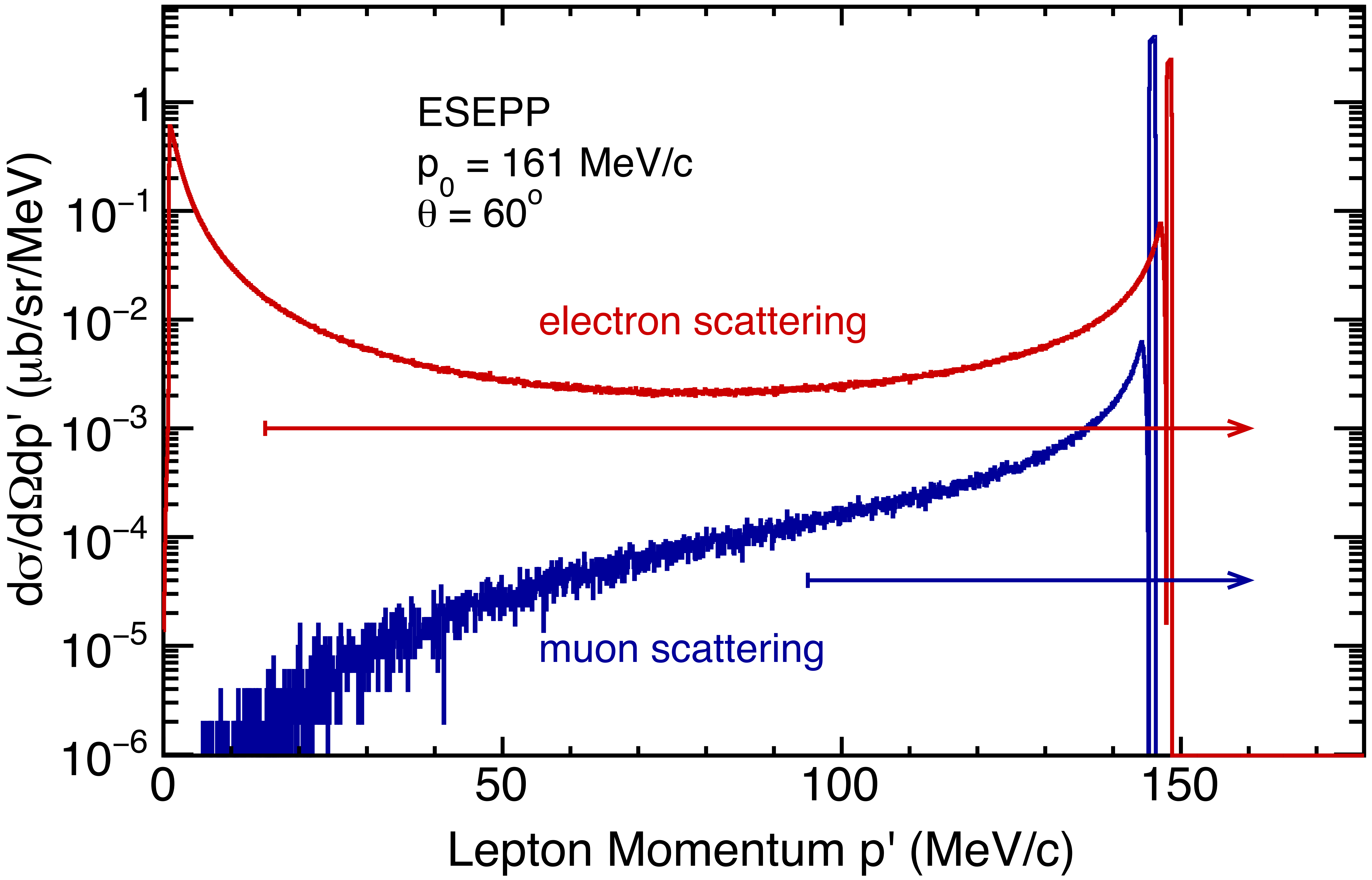


Win Lin (Rutgers) analysis of electron-beam data

$ep \to e'p\gamma$ and $\mu p \to \mu' p\gamma$ cross sections in MUSE kinematics



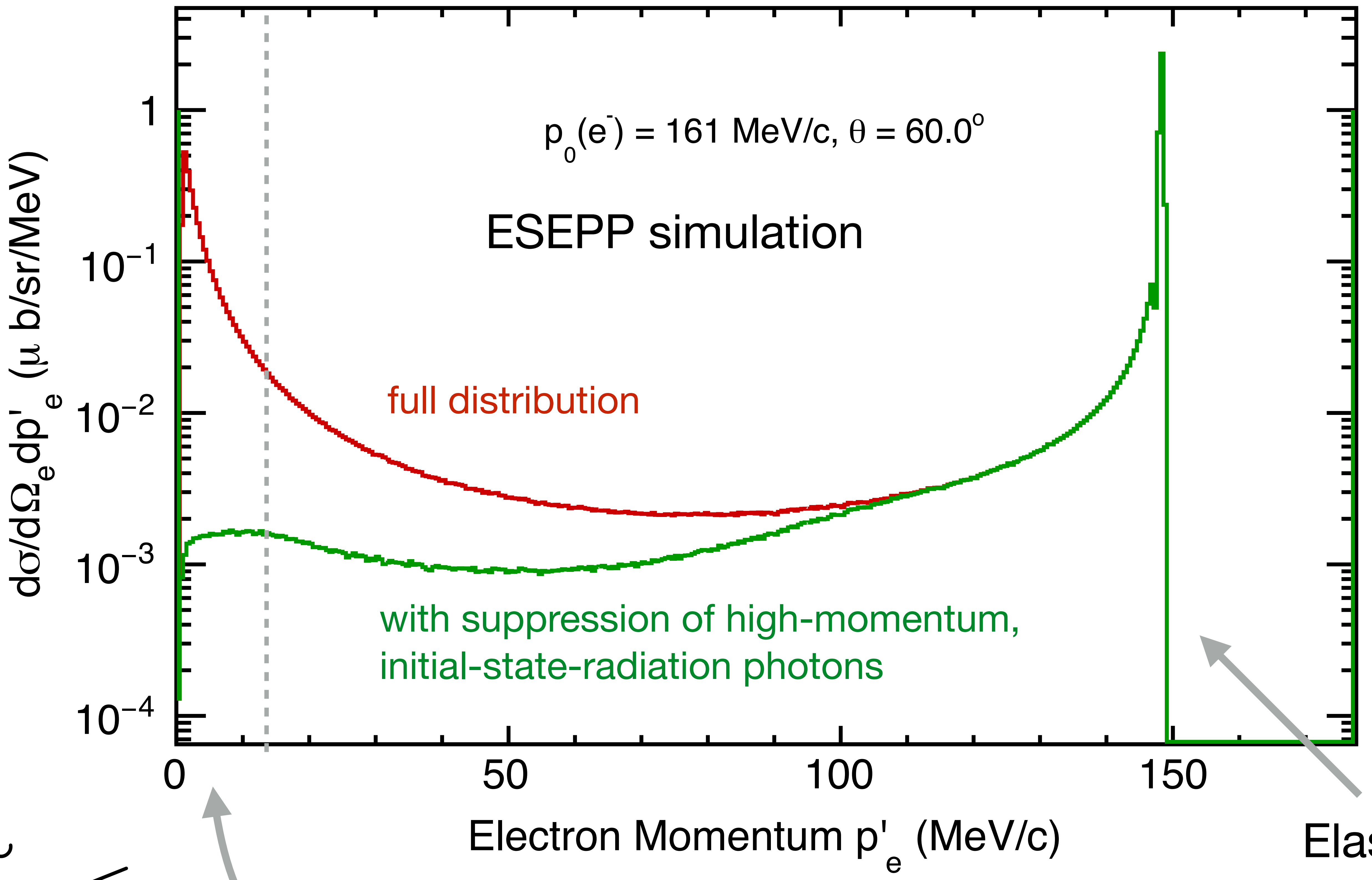
MUSE will integrate over a large momentum range.

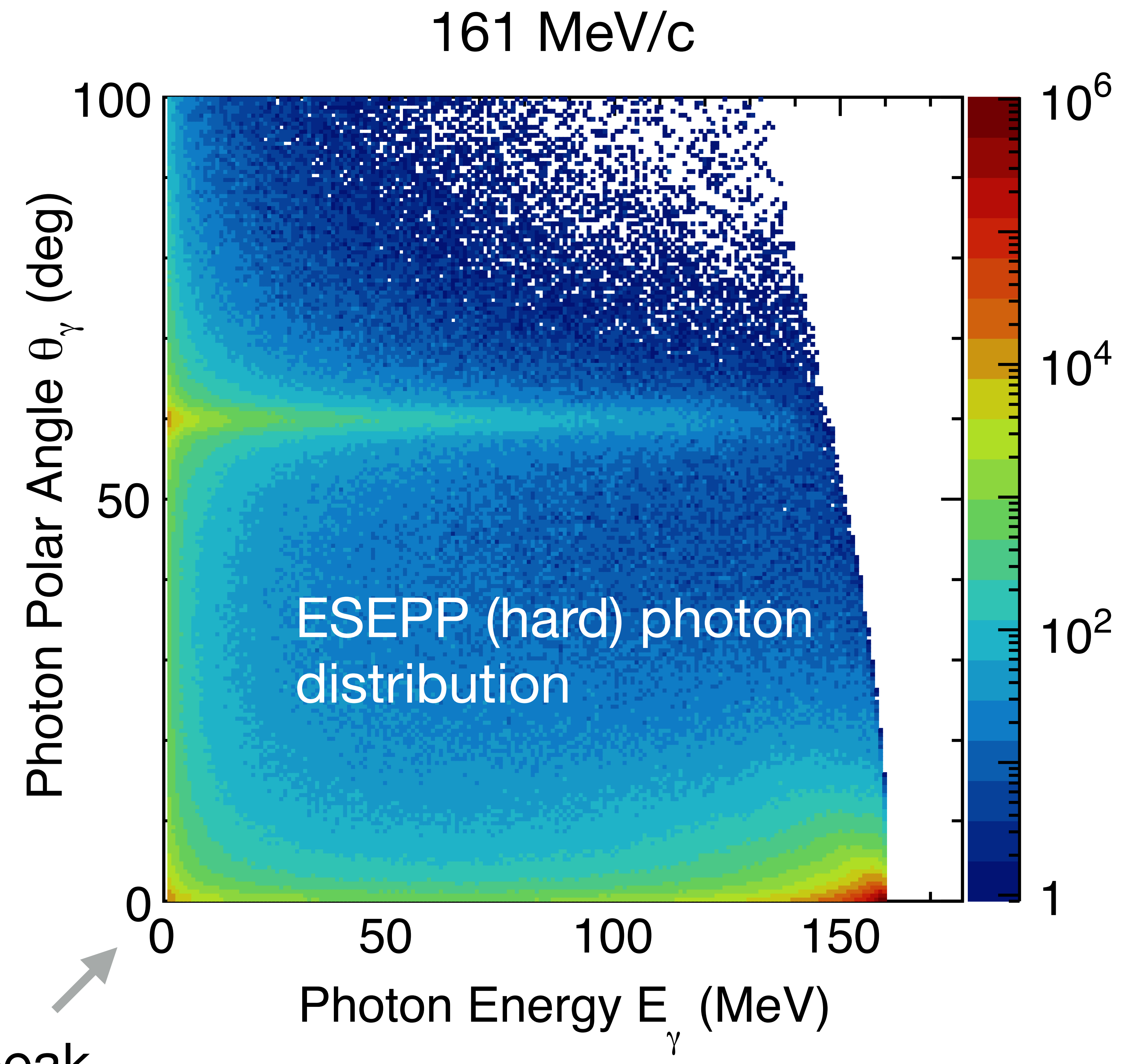


L. Li et al. (MUSE Collaboration), Eur. Phys. J. A 60:8 (2024)

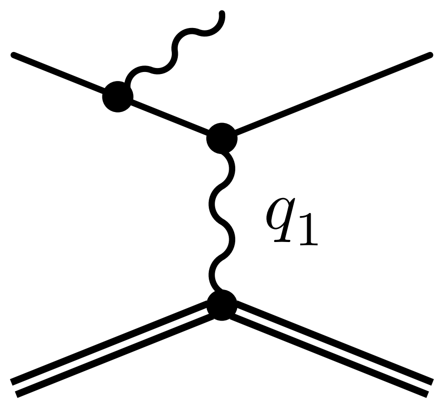
$ep \to e'p\gamma$ photon distribution

MUSE will integrate over a large momentum range





Elastic peak



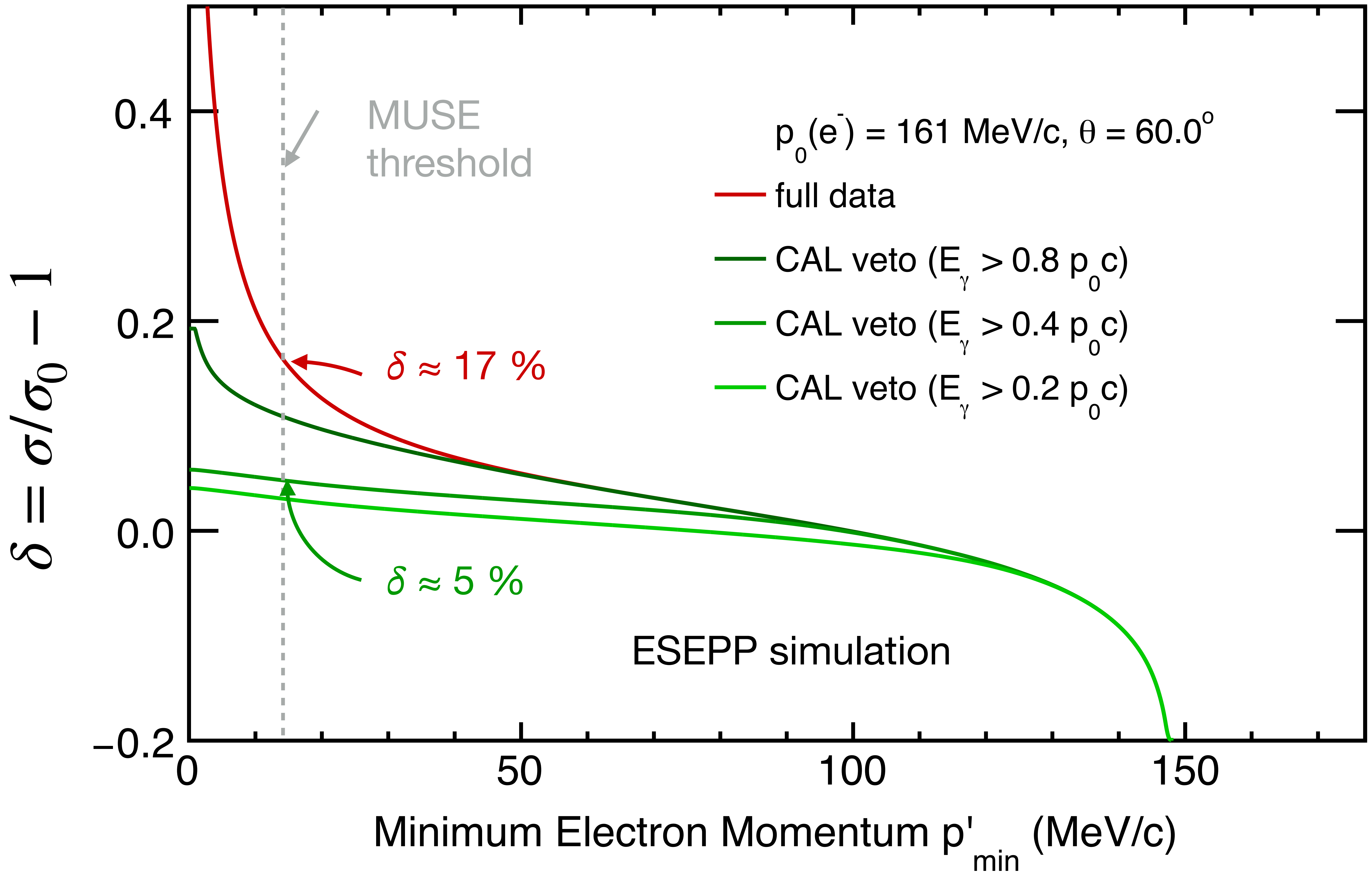
If the incident lepton loses energy due to the emission of a hard photon, then the probability for this lepton to be scattered by the proton increases.

The downstream photon calorimeter will veto events with hard initial-state radiation

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

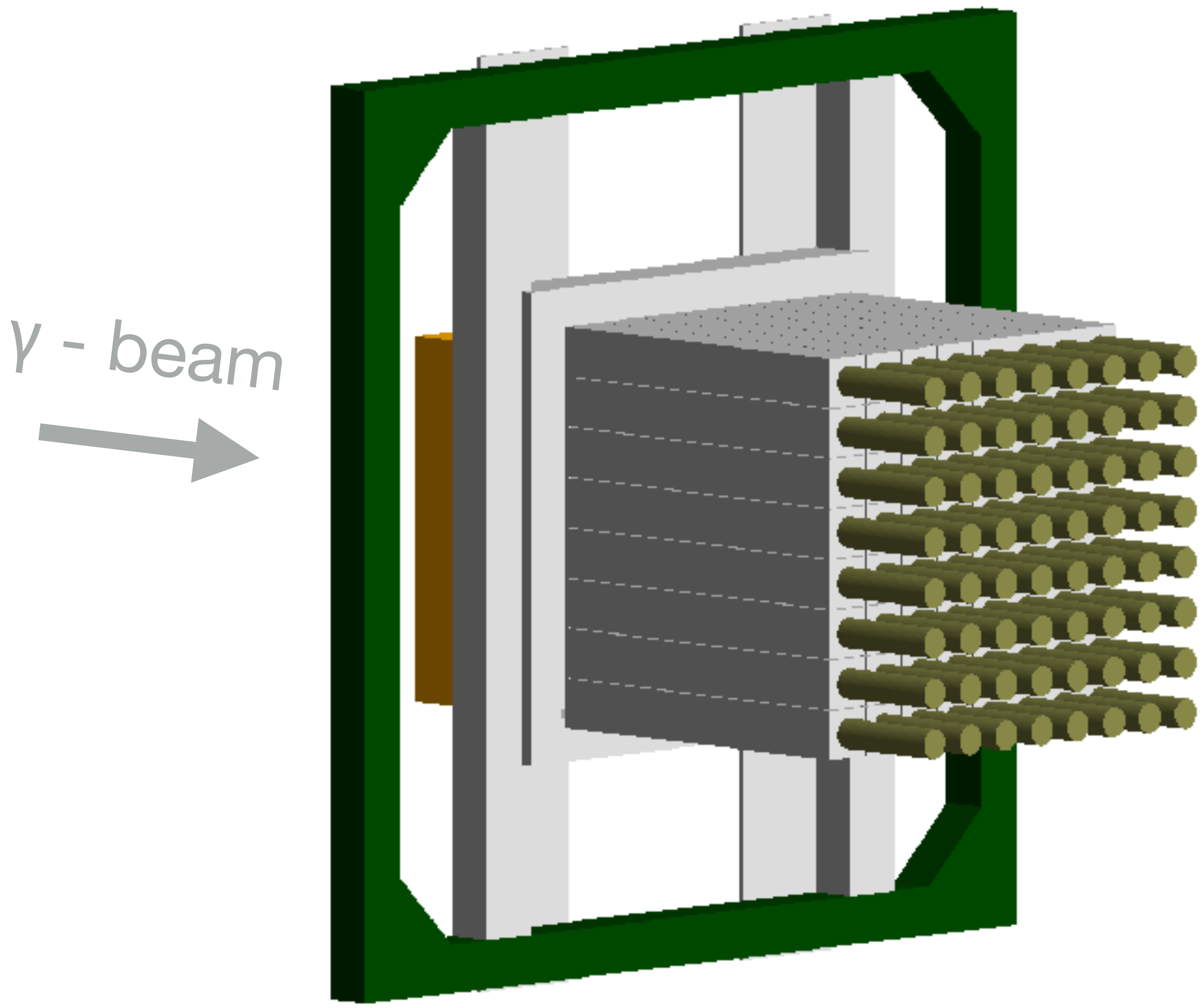
(> 1% change / MeV/c)

CAL veto on initial-state radiation reduces radiative corrections and p'_{min} dependence, reducing uncertainty.

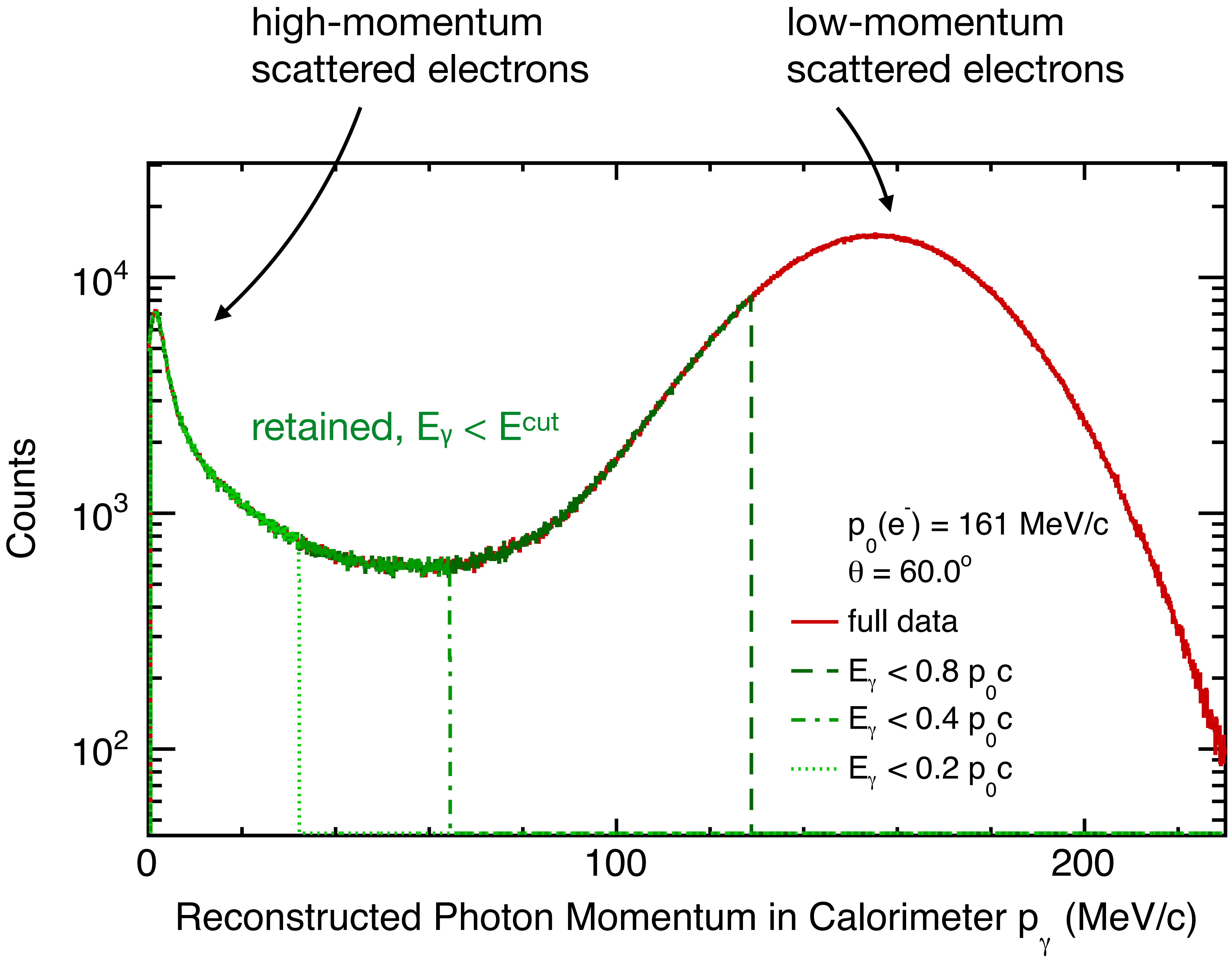


L. Li et al. (MUSE Collaboration), Eur. Phys. J. A 60:8 (2024)

The downstream photon calorimeter will veto events with hard initial-state radiation



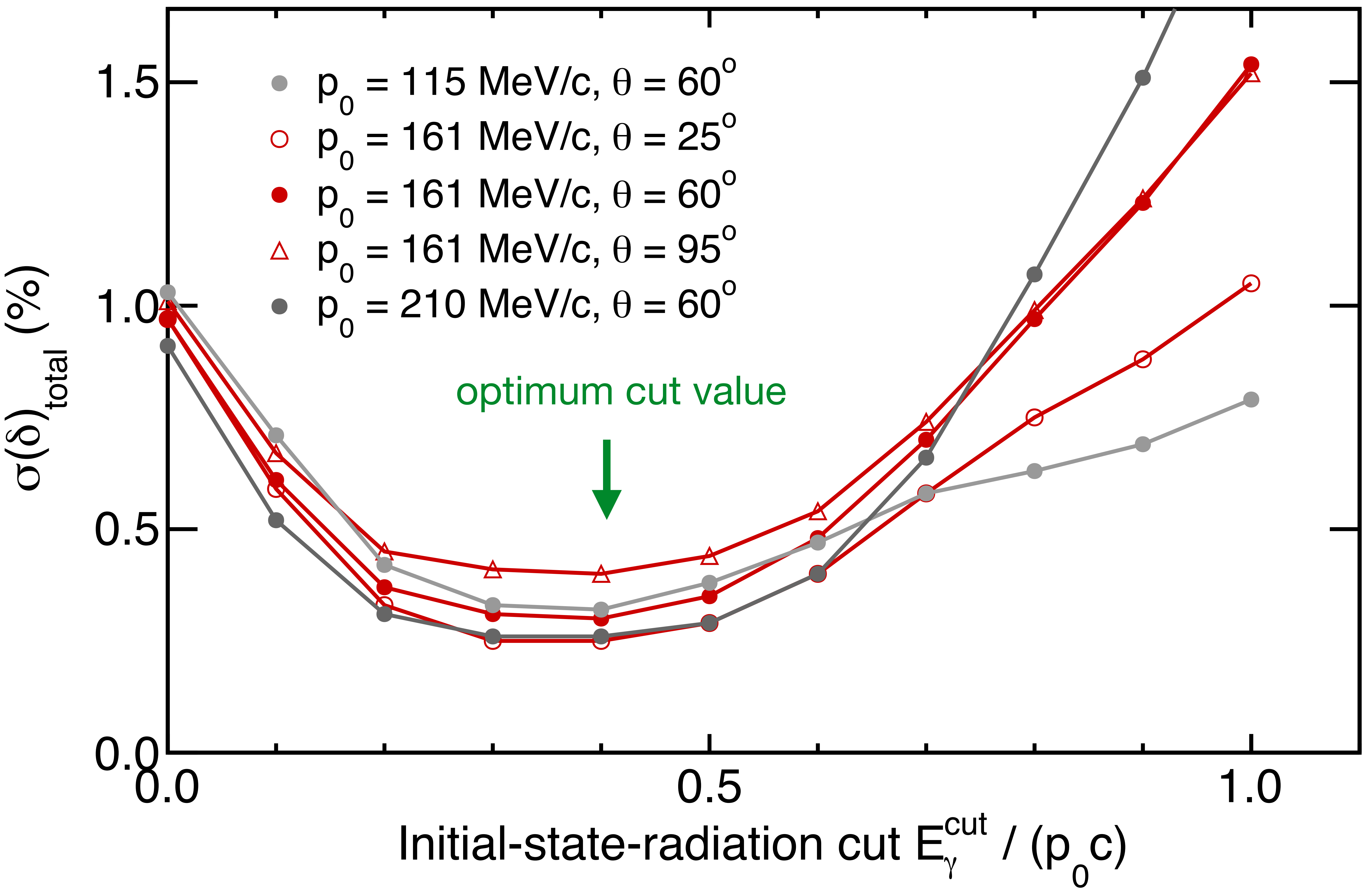
64 lead-glass crystals
(4 cm x 4 cm x 30 cm)



L. Li et al. (MUSE Collaboration), Eur. Phys. J. A 60:8 (2024)

Optimizing the energy cut on the ISR

uncertainty in the **photon-momentum** determination dominates



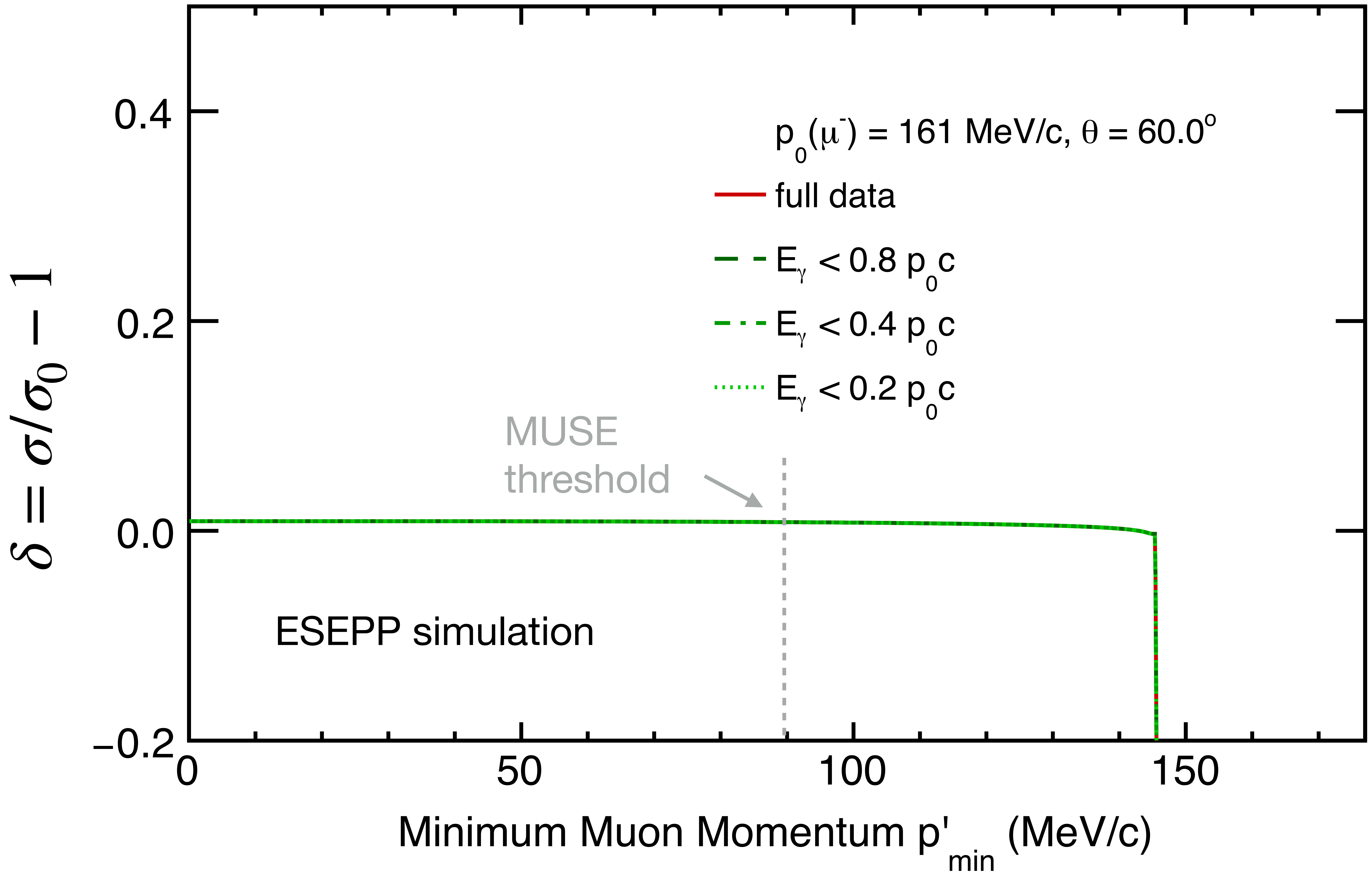
uncertainty in the minimum **electron-momentum** determination dominates

L. Li et al. (MUSE Collaboration), Eur. Phys. J. A 60:8 (2024)

Radiative corrections for $\mu p \to \mu' p \gamma$ are small and well determined

Compared with electron scattering, the radiative corrections for muon scattering are:

- small, $\delta \leq 1$ %,
- (almost) independent of the muon detection threshold,
- independent of any photon veto.



L. Li et al., Eur. Phys. J. A 60:8 (2024)

Instrumental uncertainties in the radiative corrections of the elastic scattering cross sections

- The preliminary estimates of the total instrumental uncertainties in the radiative corrections for **electrons** are 0.2% - 0.5%.*

$\sigma_\delta(e^-)$	115 MeV/c			161 MeV/c			210 MeV/c		
	20°	60°	100°	20°	60°	100°	20°	60°	100°
p'_{min}	0.05%	0.18%	0.30%	0.03%	0.16%	0.31%	0.02%	0.13%	0.31%
θ	0.01%	0.01%	0.00%	0.01%	0.00%	0.00%	0.00%	0.03%	0.01%
p_0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
E_γ	0.32%	0.33%	0.33%	0.25%	0.25%	0.26%	0.20%	0.22%	0.22%
Total	**0.32%**	**0.38%**	**0.45%**	**0.25%**	**0.30%**	**0.40%**	**0.20%**	**0.26%**	**0.38%**

angle-dependent uncertainty, relevant for radius extraction, ≲ 0.3%

angle-independent uncertainty, **not** relevant for radius extraction

- The preliminary estimates of the total instrumental uncertainties in the radiative corrections for **muons** are smaller than 0.01%.*

* Not including model uncertainties.

L. Li et al. (MUSE Collaboration), Eur. Phys. J. A 60:8 (2024)

Summary and Outlook

- **MUSE** measures $\mu^{\pm}p$ and $e^{\pm}p$ scattering cross sections and will directly compare μp and ep interactions, extract the proton charge radius, and study two-photon exchange effects.

- Radiative corrections of electron-scattering cross sections are a leading source of systematic uncertainties in the experiment.

- A dedicated downstream photon detector helps to suppress initial-state radiation effects, and simulations show angular-dependent uncertainties in radiative corrections to the electron cross section be up to 0.3%.