The MUSE Beam Line Calorimeter

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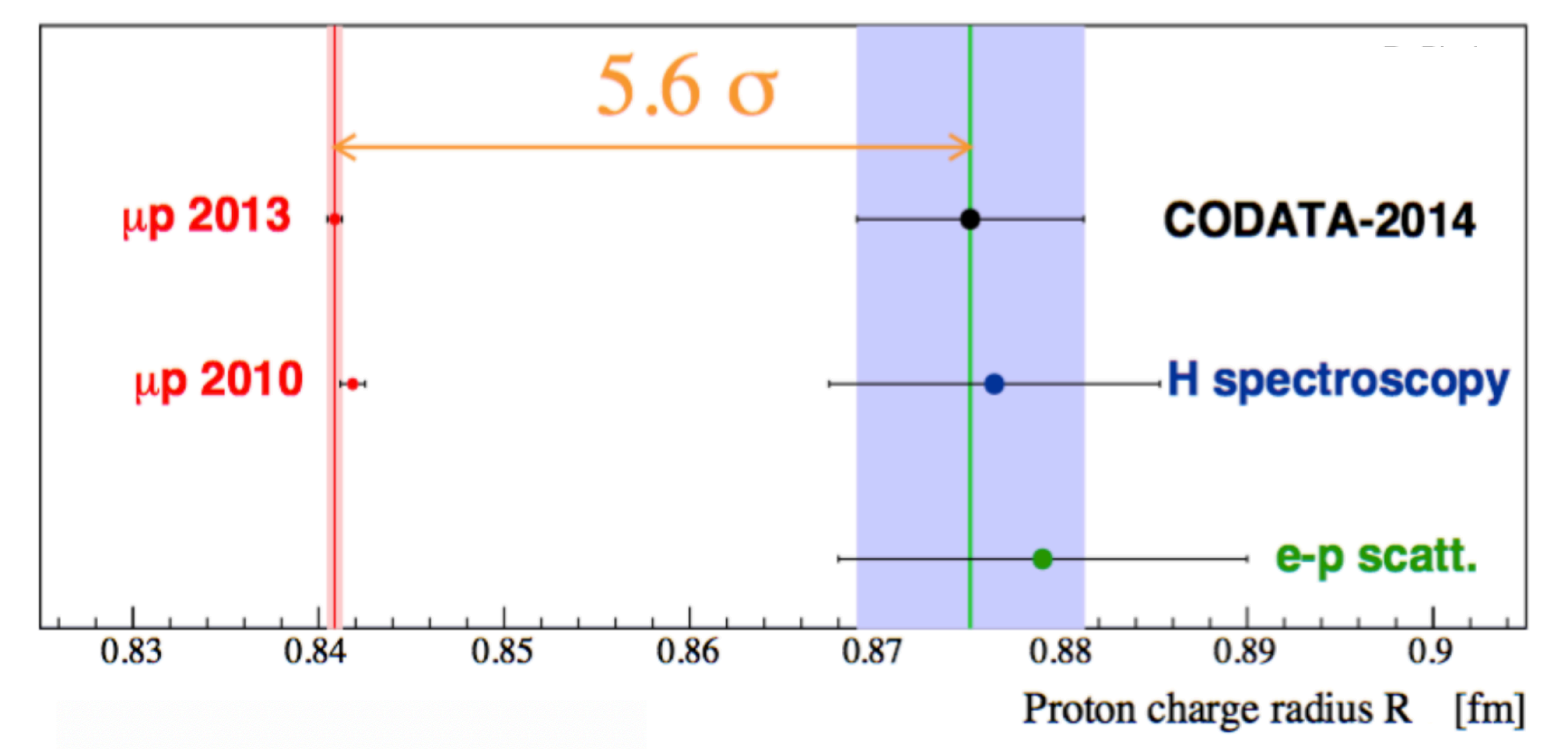
Proton Radius Puzzle



Pohl et al.: 0.84184(67) fm

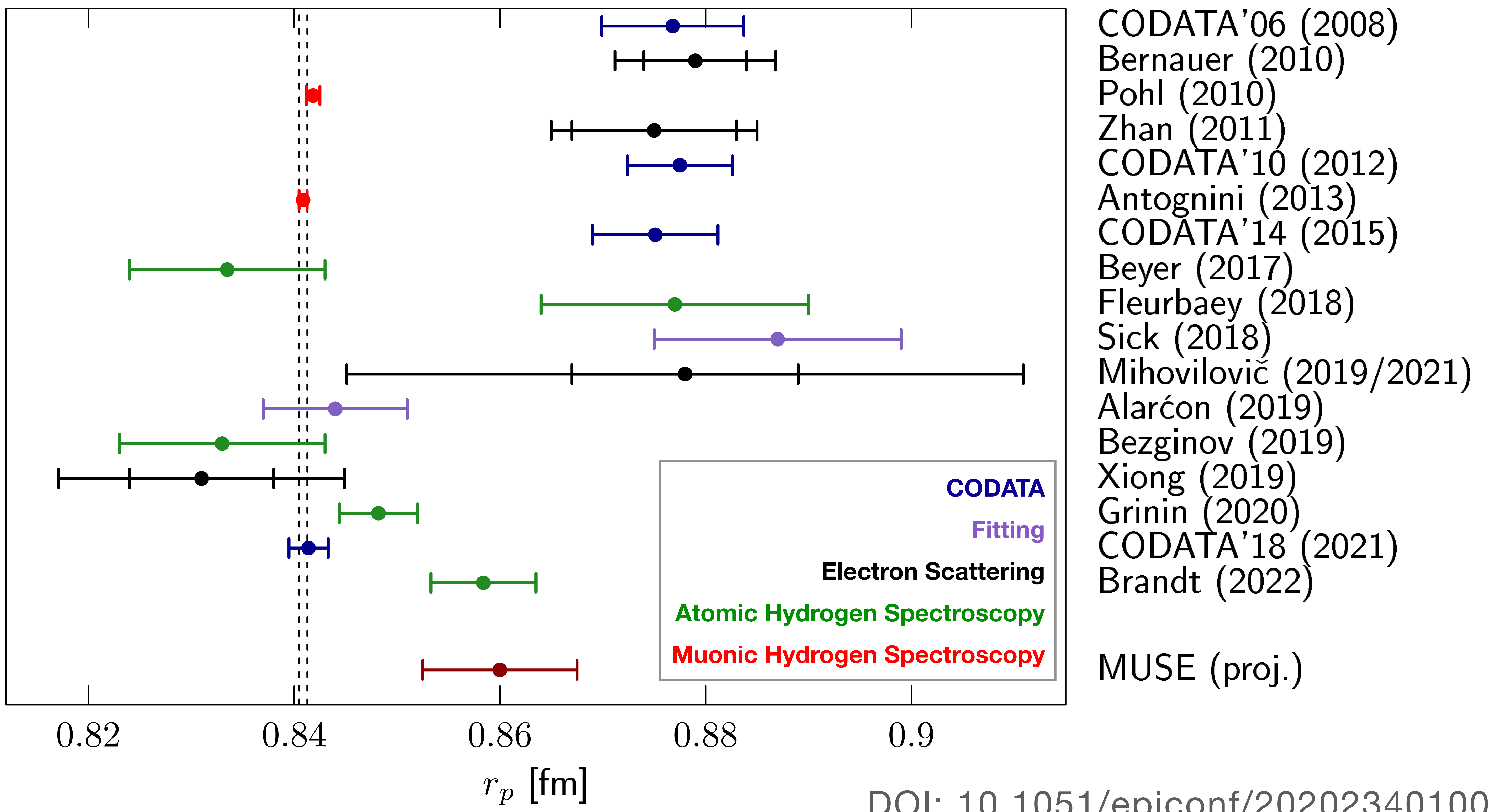
DOI: 10.1038/nature09250

DOI: 10.1126/science.1230016

CODATA: 0.8751(61) fm

DOI: 10.5281/zenodo.22826

Proton Radius Puzzle - Recent Results



DOI: 10.1051/epjconf/202023401001

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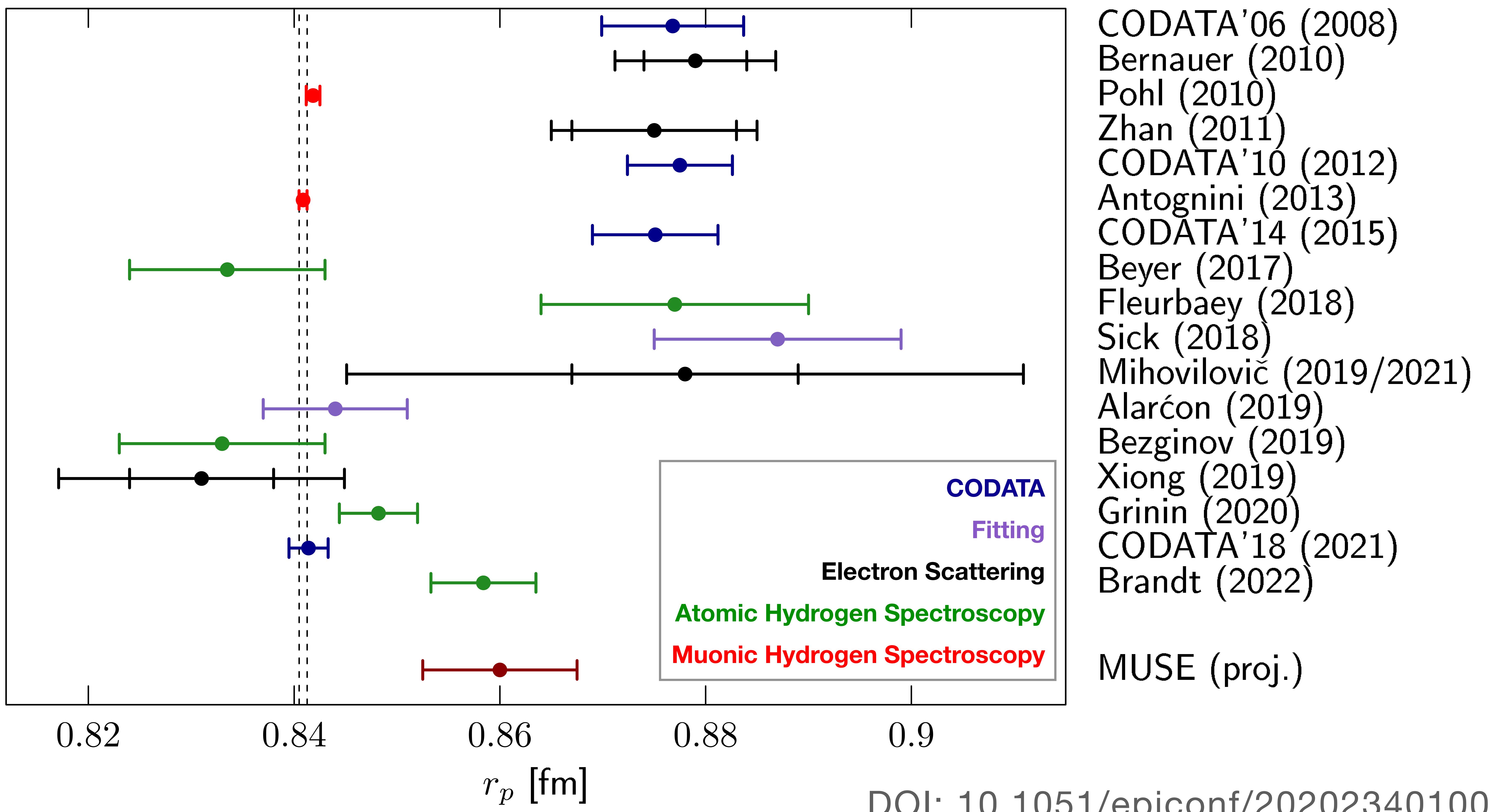

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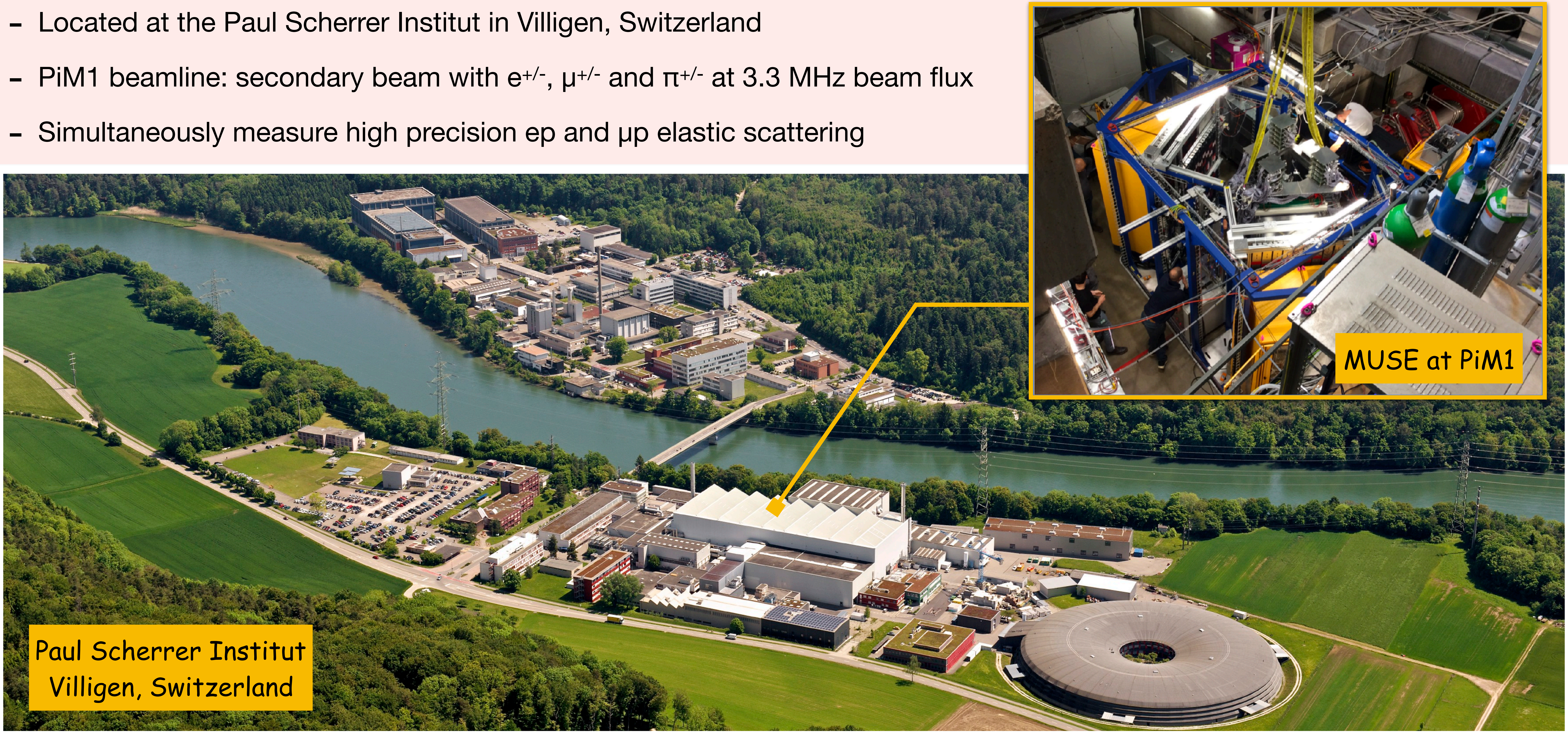
Inconsistencies in recent measurements and analyses → more work to be done, proton radius is still a puzzle!

The MUon proton Scattering Experiment (MUSE)

- Located at the Paul Scherrer Institut in Villigen, Switzerland
- PiM1 beamline: secondary beam with $e^{+/-}$, $\mu^{+/-}$ and $\pi^{+/-}$ at 3.3 MHz beam flux
- Simultaneously measure high precision ep and μp elastic scattering



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Proton Radius ?

* Form factor comparison to other experiments

Lepton Universality

* Direct test by comparing ep and μp form factors

Radiative Correction

* $m_\mu \sim 200 m_e$, hence smaller radiative effects

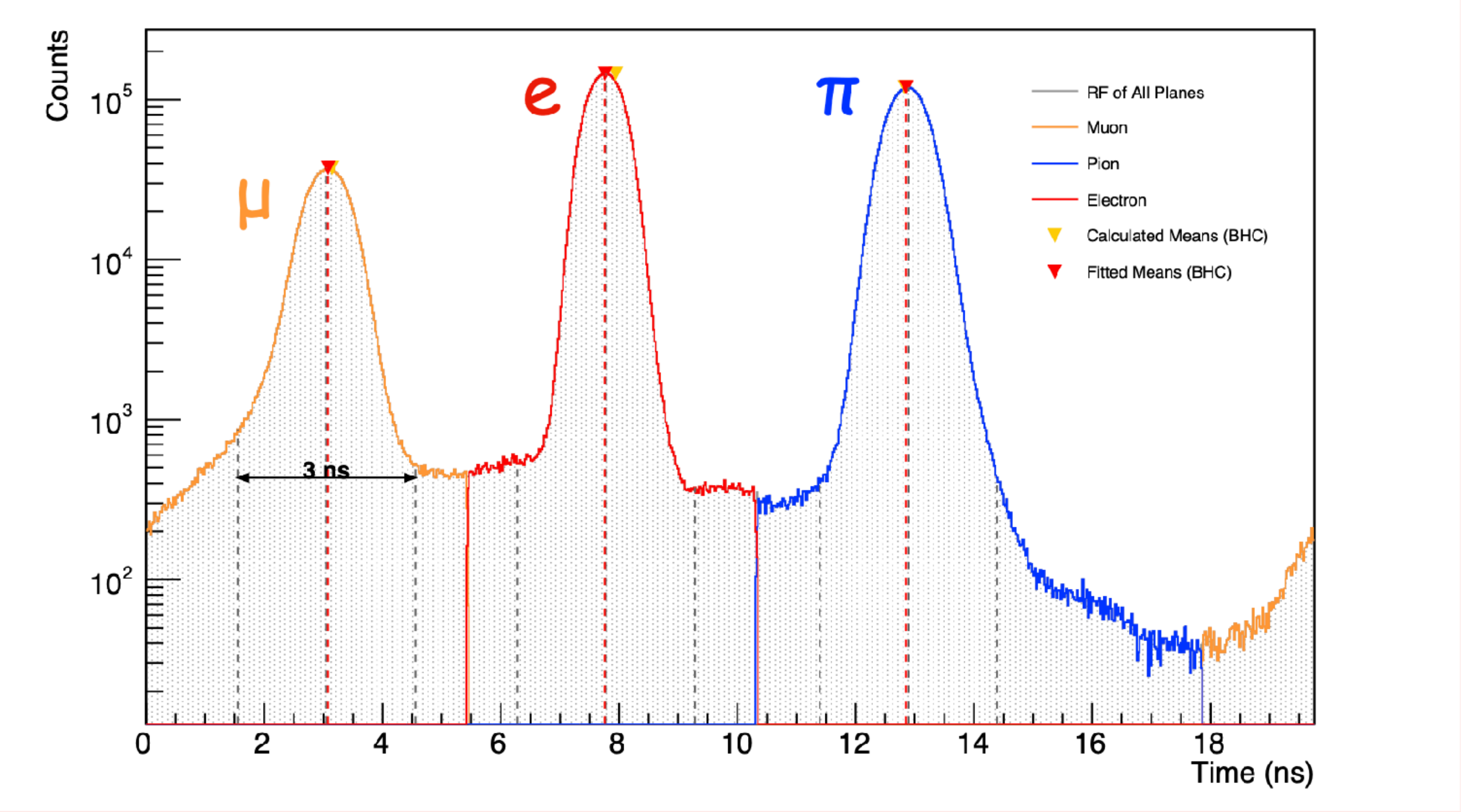
Two Photon Exchange

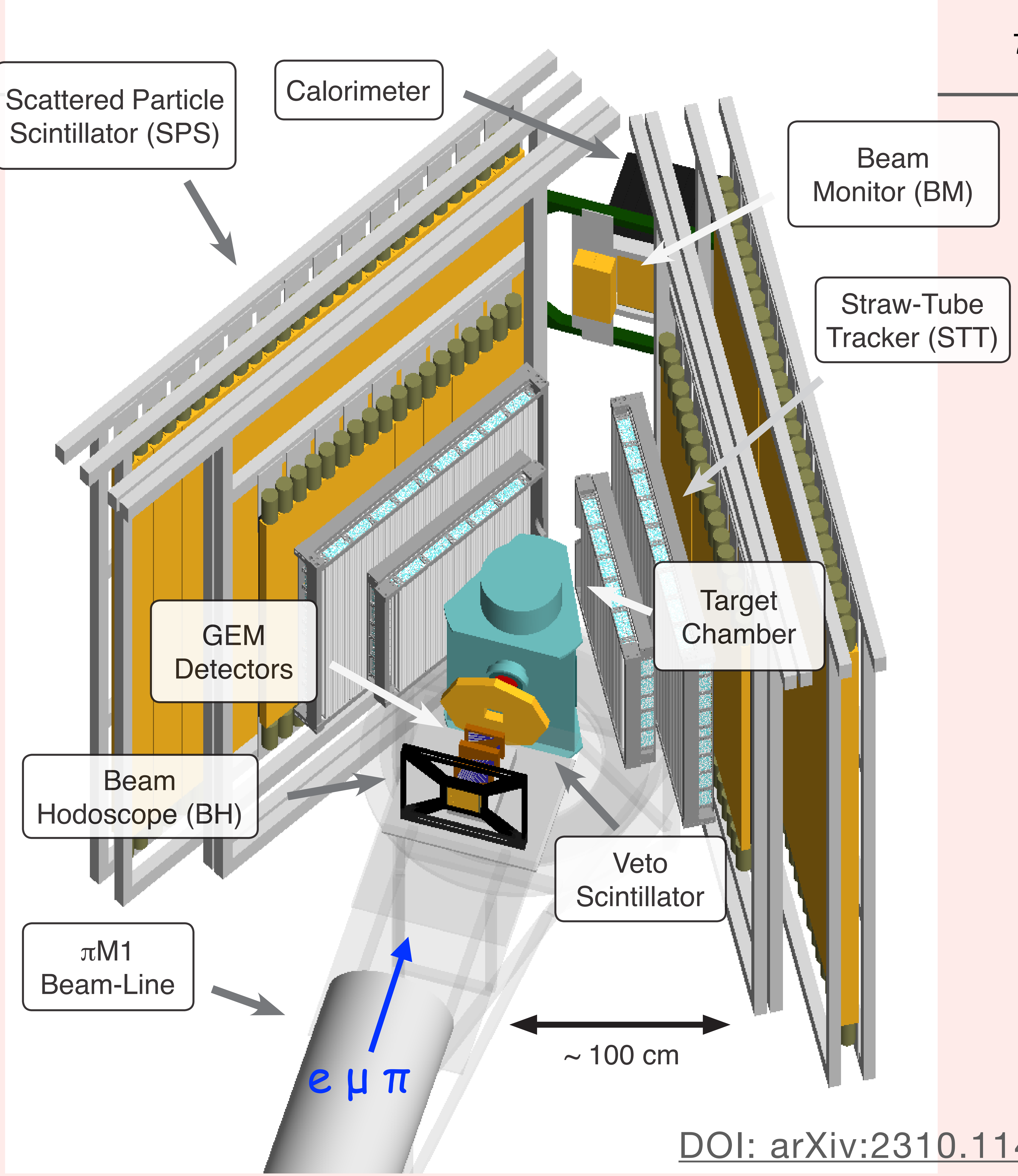
* Using +/- beam allow test for both particles at low Q^2

MUSE Setup

Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle	20 - 100 degrees
Q^2 range for e	0.0016 - 0.0820 $(GeV/c^2)^2$
Q^2 range for μ	0.0016 - 0.0799 $(GeV/c^2)^2$

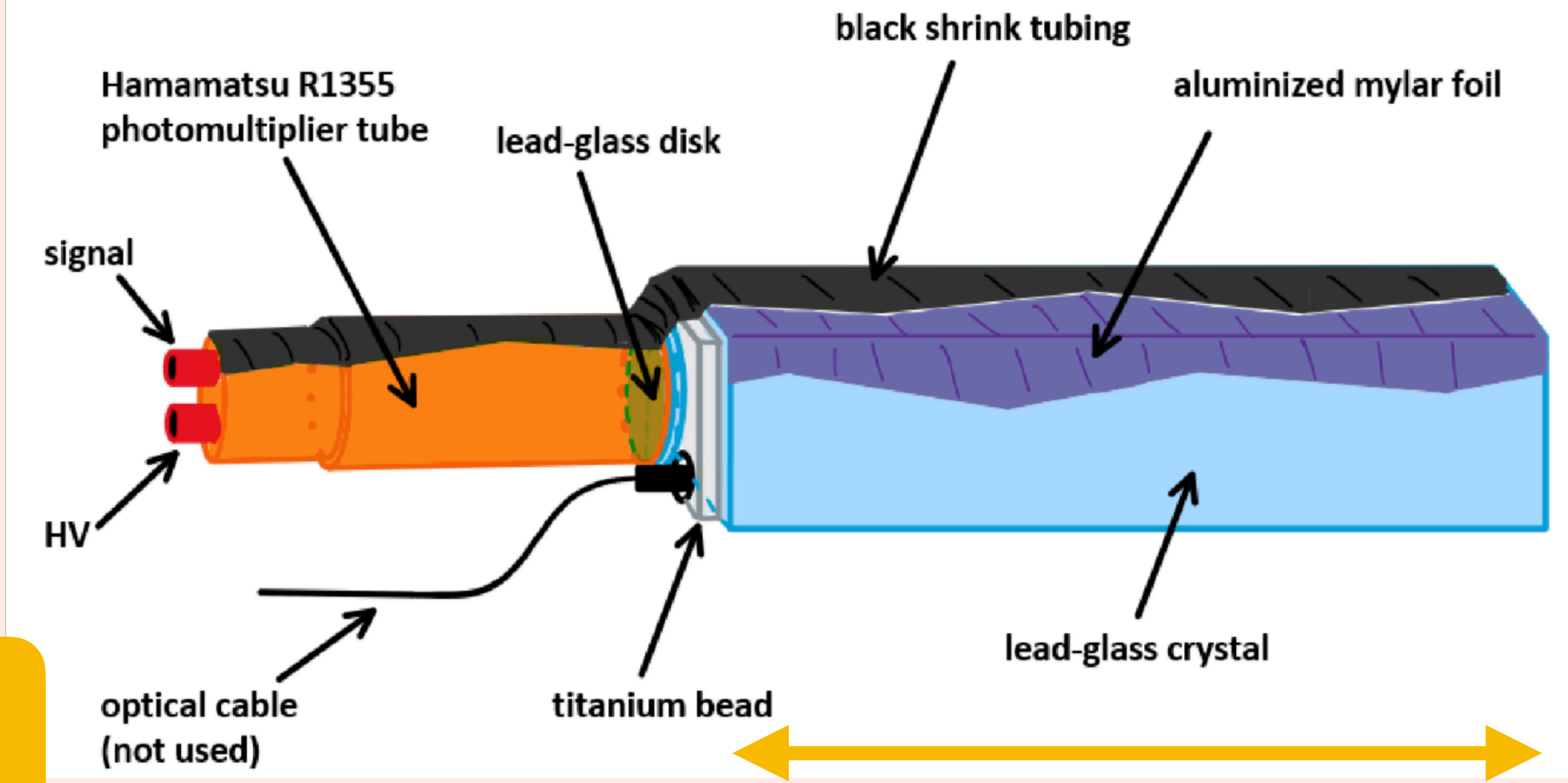
BH RF at 160 MeV/c





DOI: arXiv:2310.11469

MUSE Calorimeter

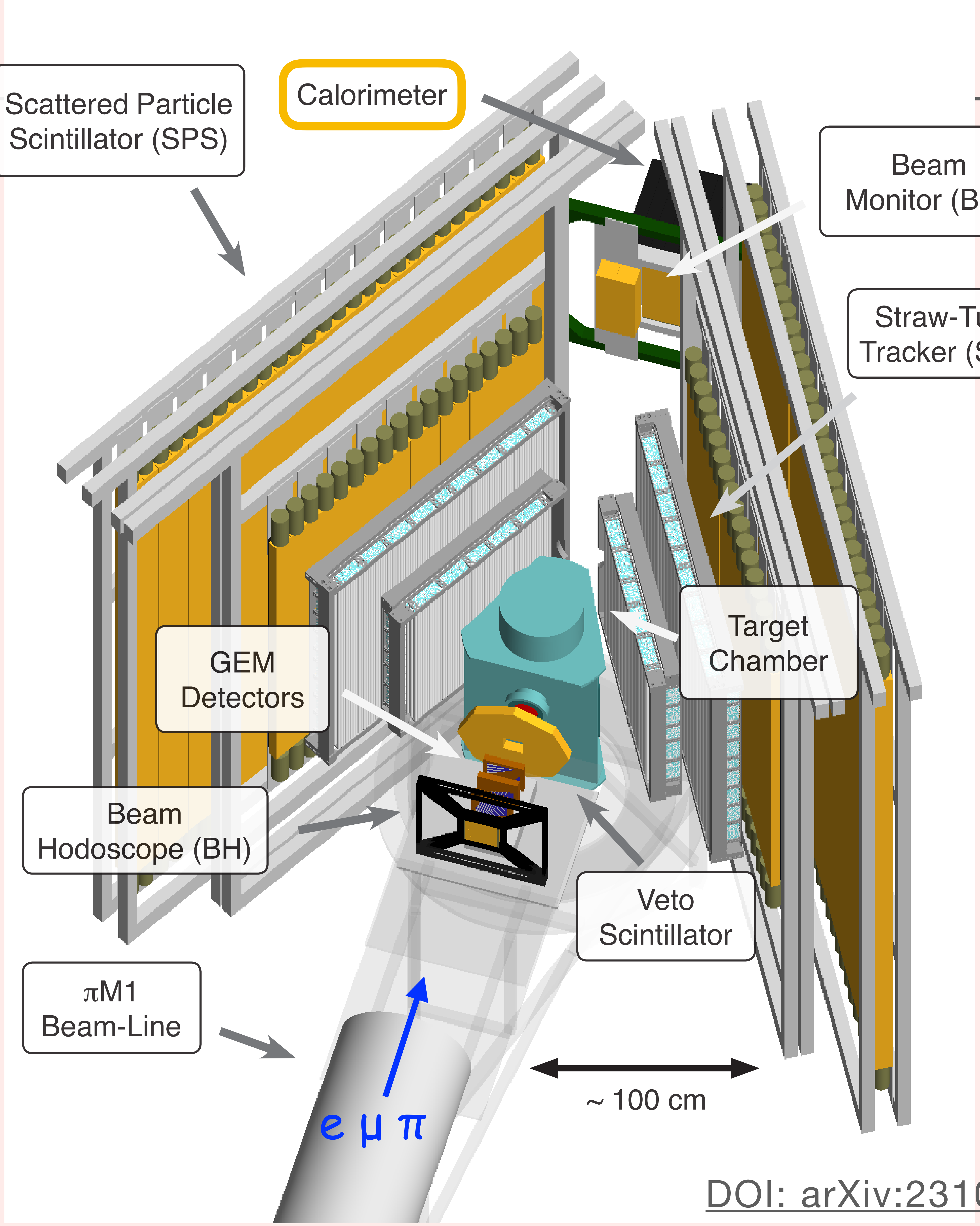


30 cm

Schematic of One Bar

~ 33 cm

Downstream View



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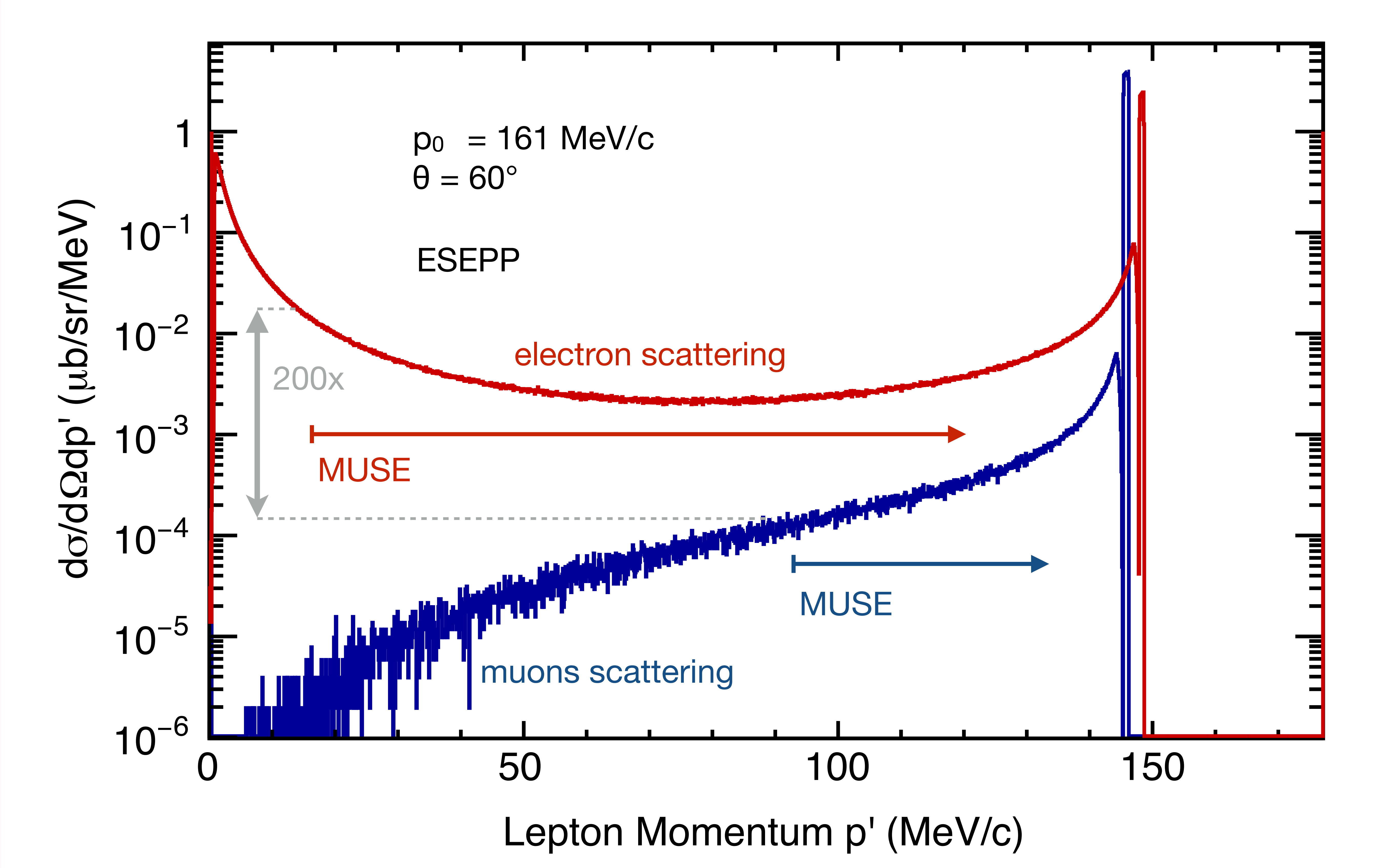
Purpose: Radiative Correction

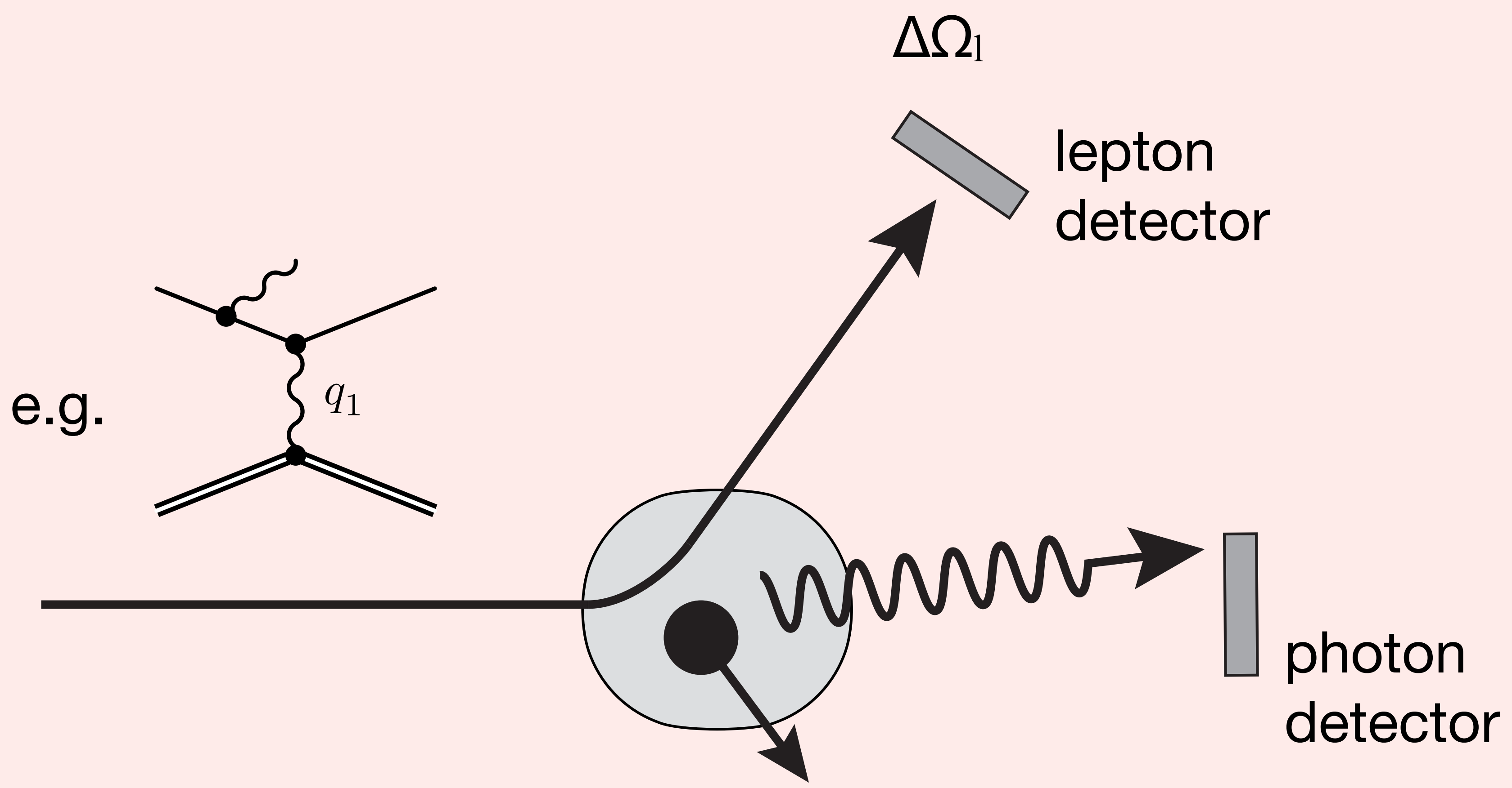
MUSE integrates over a range of outgoing momenta and scattering angles, including the radiative tail.

➡ Need to suppress high energy radiation to limit radiative correction and reduce experimental uncertainty

Differential Cross Section at a MUSE Kinematic Setting



Example of an event with Bremsstrahlung emission:



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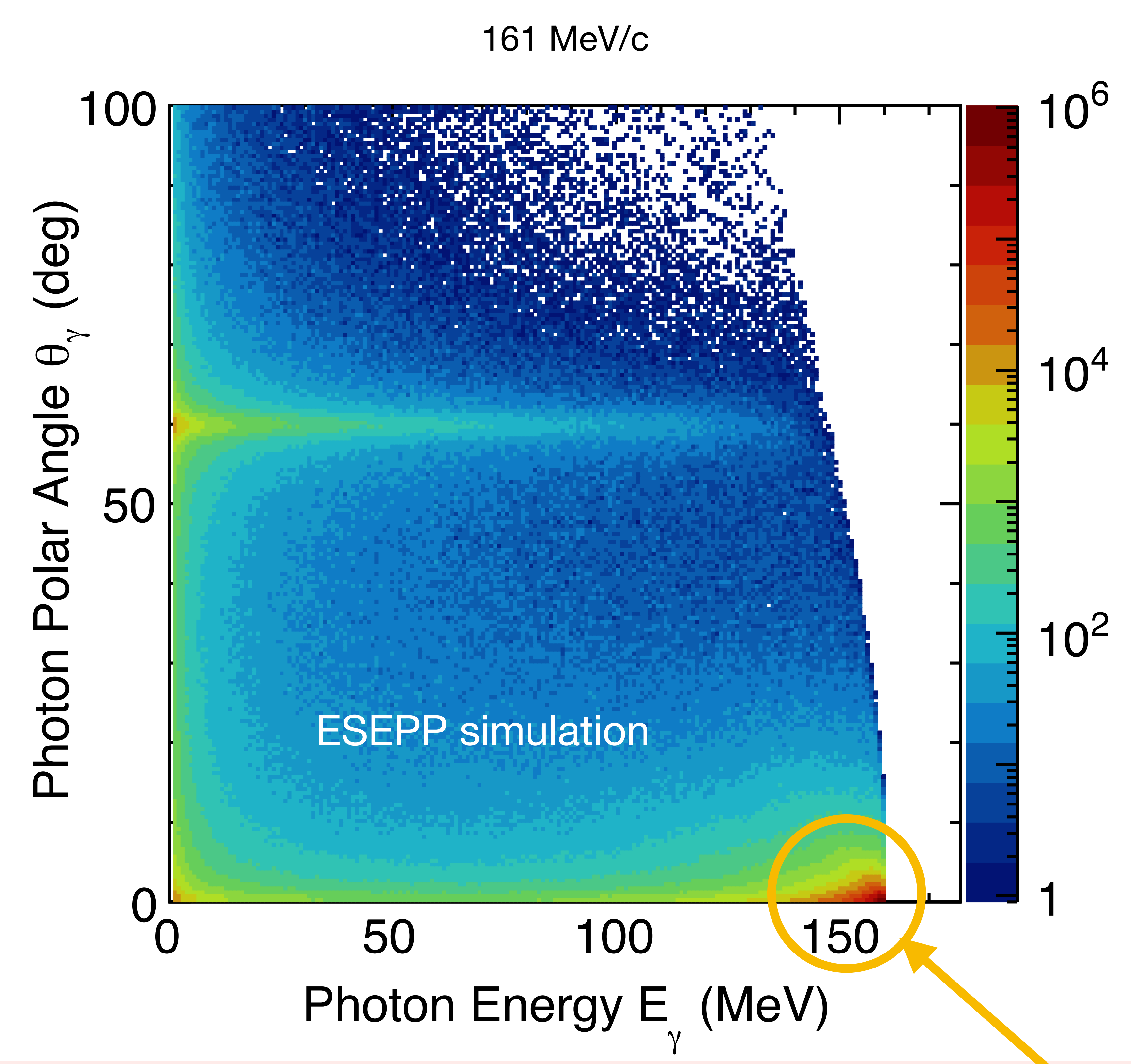
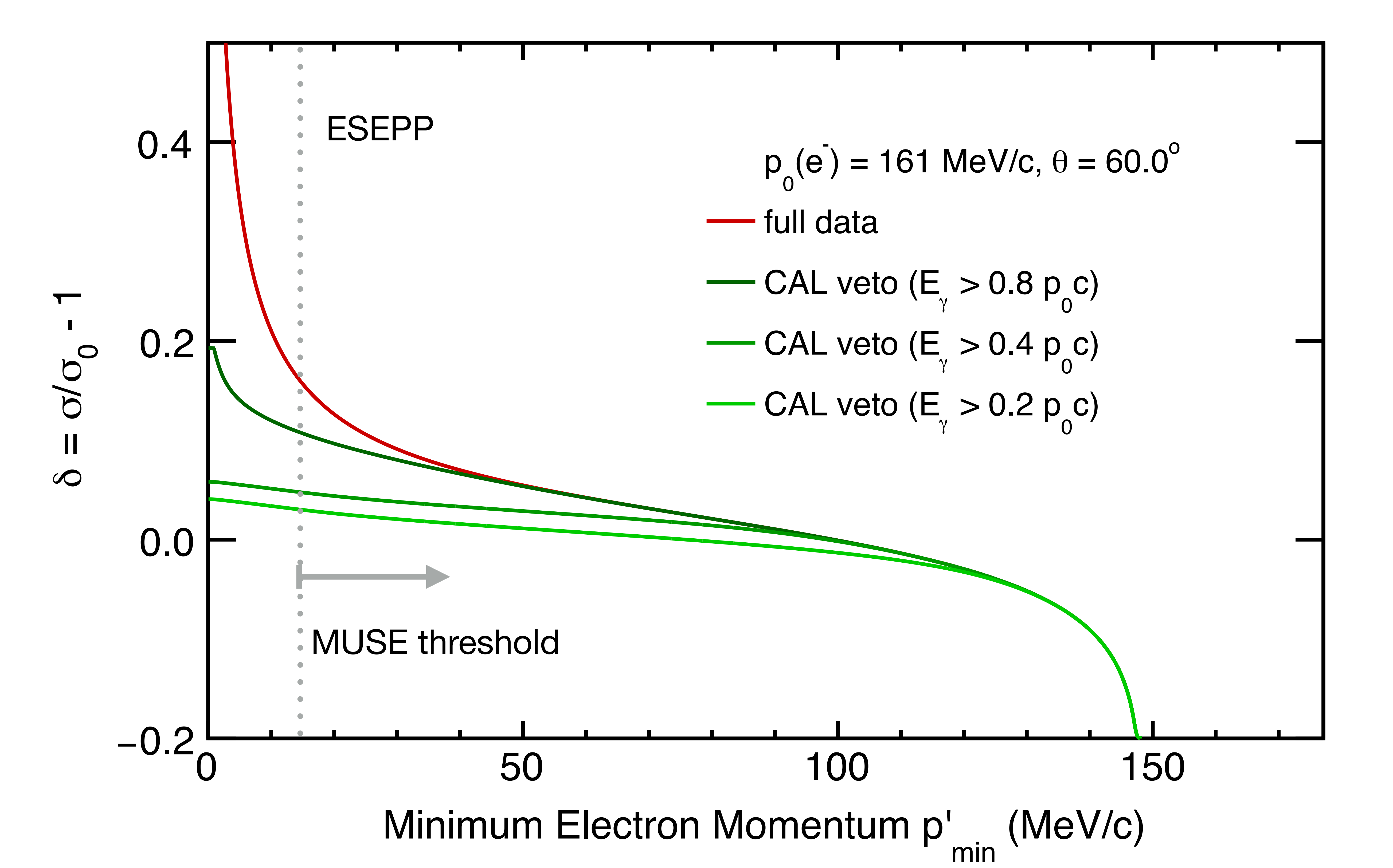
Simulation of Photon Events



Radiative Correction for ep Scattering at a MUSE Kinematic Setting



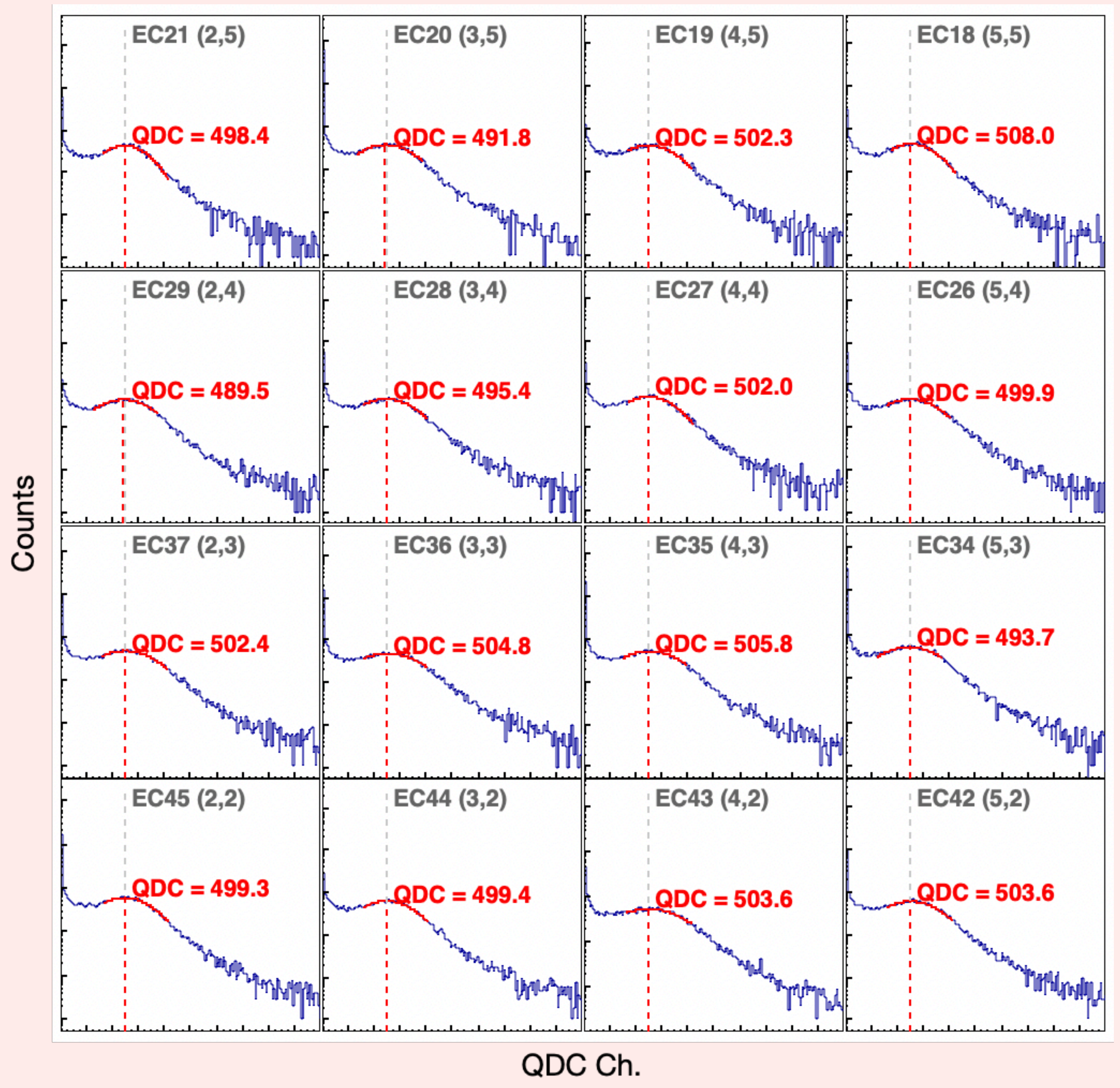
DOI: 10.1088/0954-3899/41/11/115001
DOI: 10.1140/epja/s10050-023-01215-0

Downstream calorimeter vetos events with high E photons
➡ Reduce sensitivity to integration range

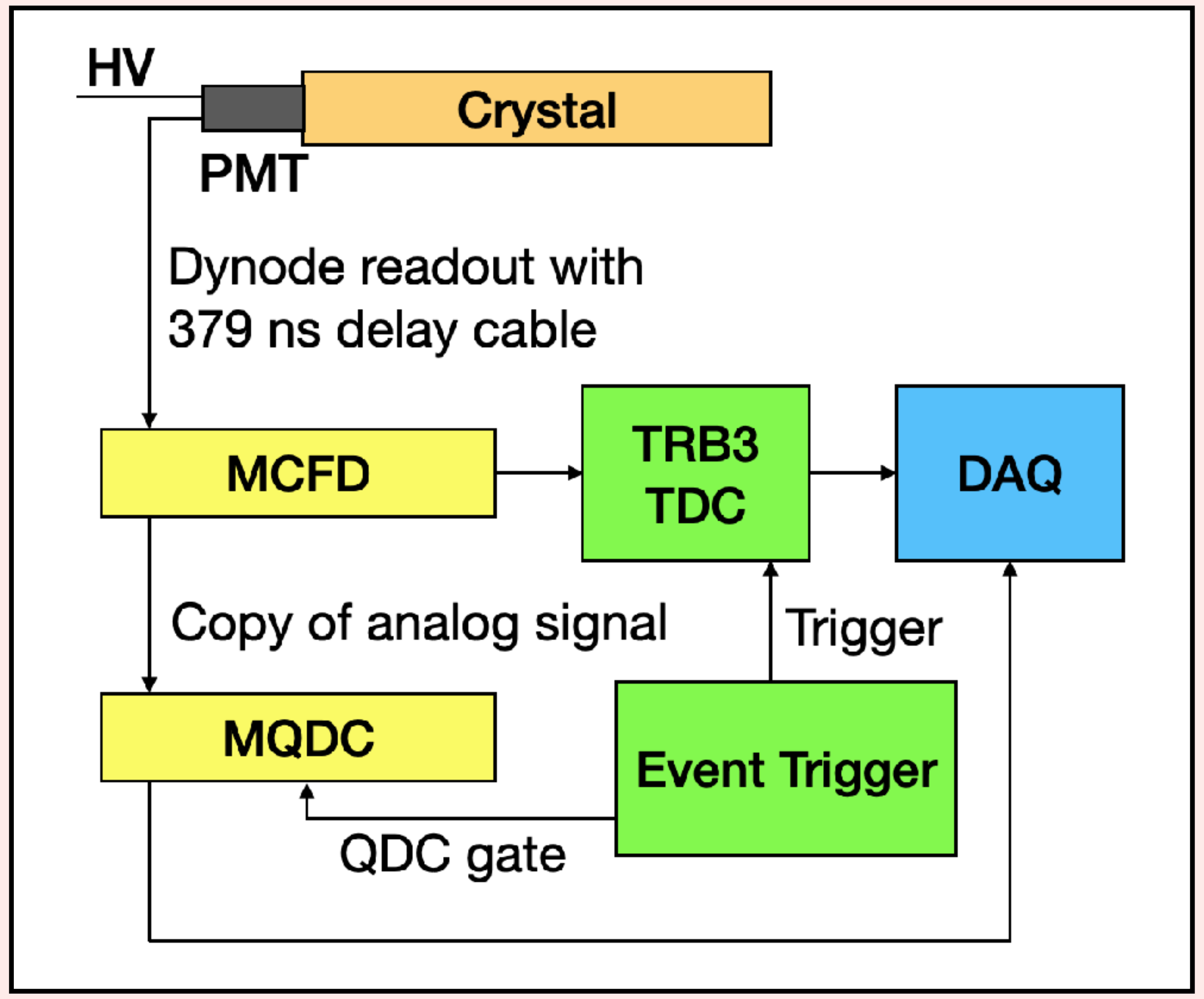
MUSE Calorimeter

- MUSE calorimeter reads out both timing (TDC) and energy (QDC) information
- Match gain using cosmic; calibrate energy using beam

Cosmic Events in the Central 16 Crystals

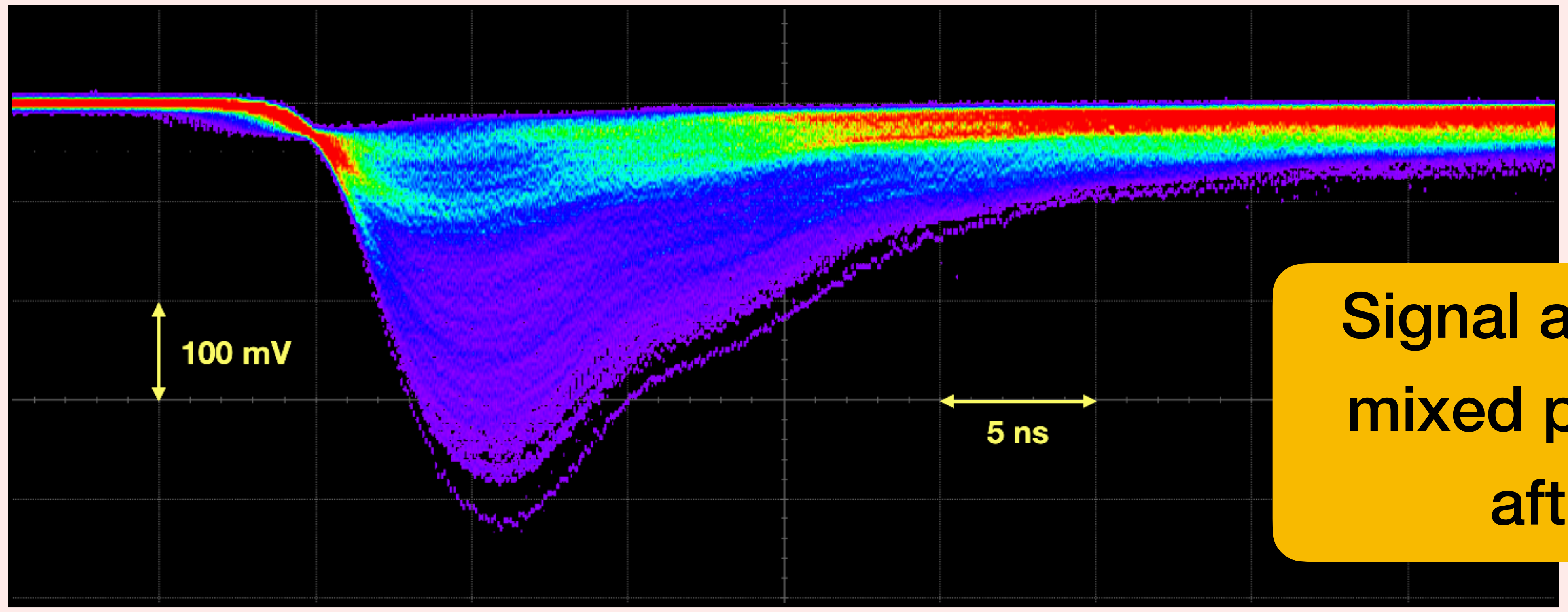


Schematic of readout



TDC for improving cluster finding

QDC for energy reconstruction



Signal at -210 MeV/c mixed particle beam after delay

MUSE Calorimeter

- Energy sum is calculated by highest energy deposited bar + 8 surrounding neighbors

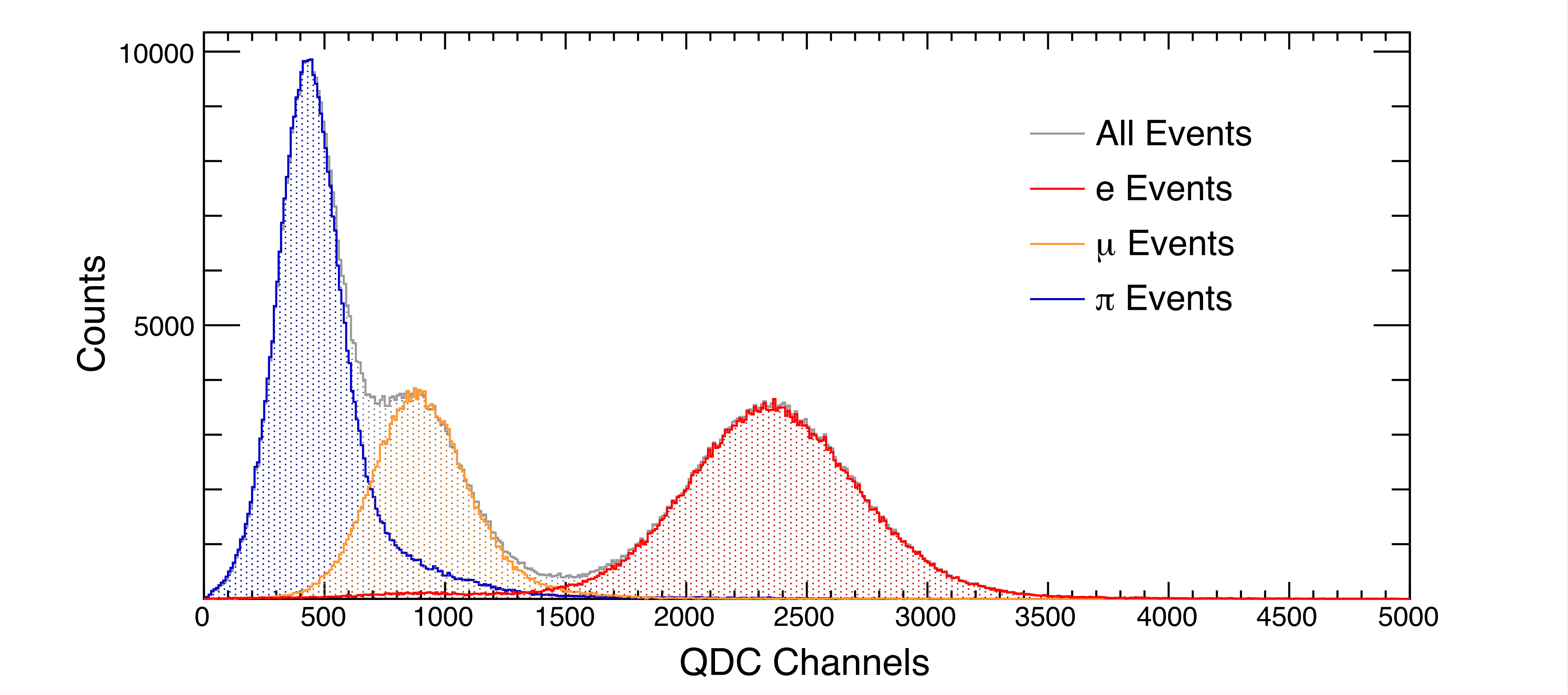
Demonstration of energy sum, star is crystal with highest energy deposited

~ 4 cm

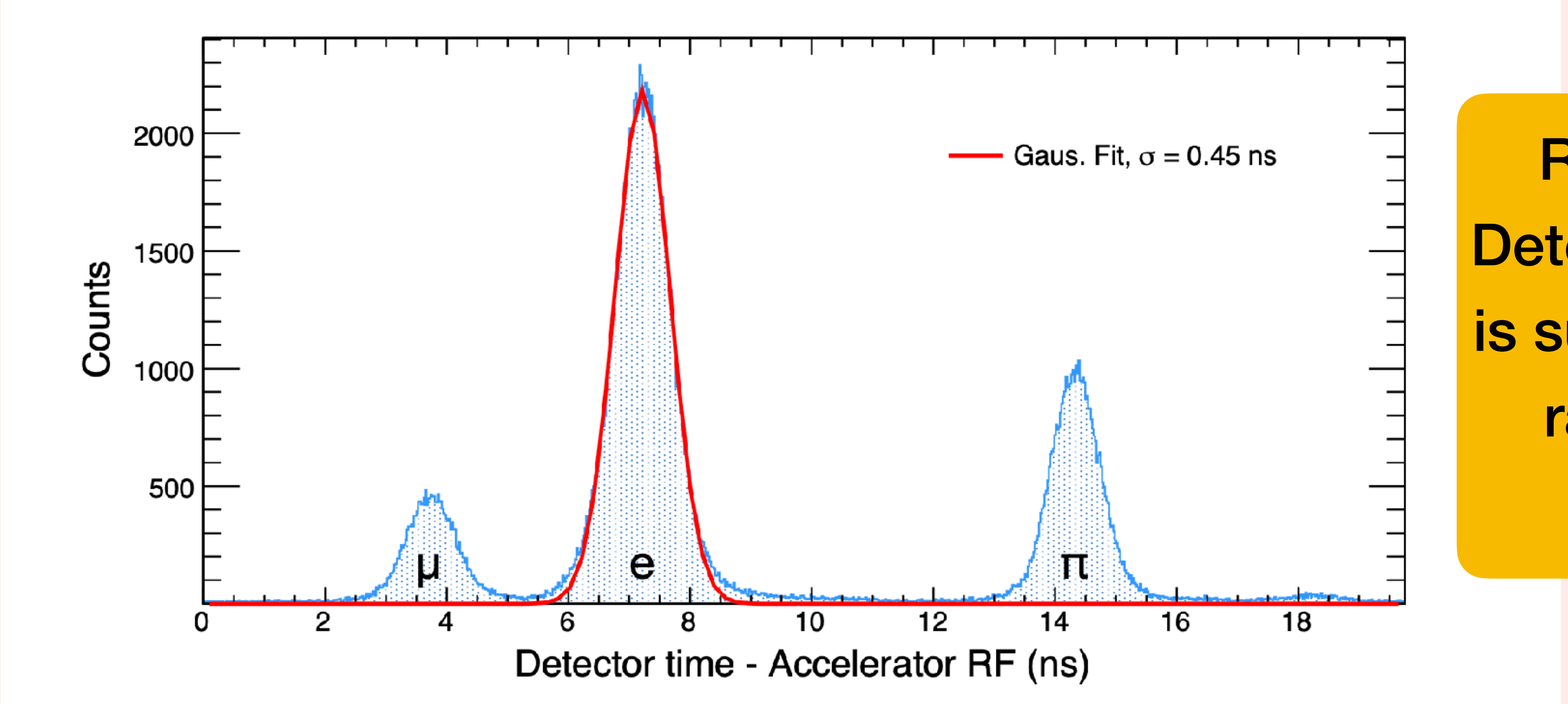
* Radiation length: 1.265 cm
* Molière radius: 2.578 cm

DOI: 10.1093/ptep/ptac097

Energy Distribution at p_{beam} = 160 MeV/c



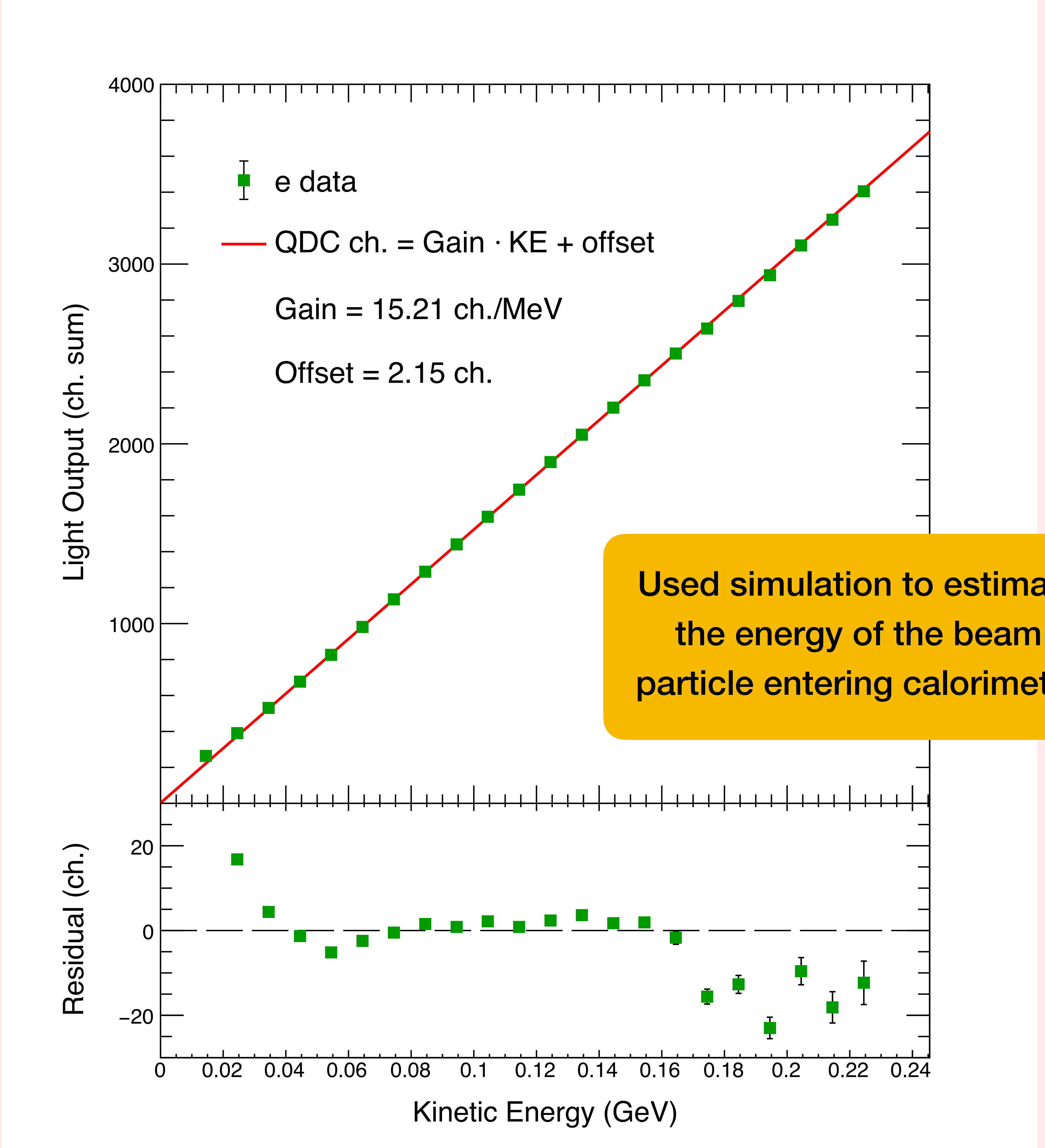
Calorimeter RF time at p_{beam} = 160 MeV/c (Before Walk Correction)



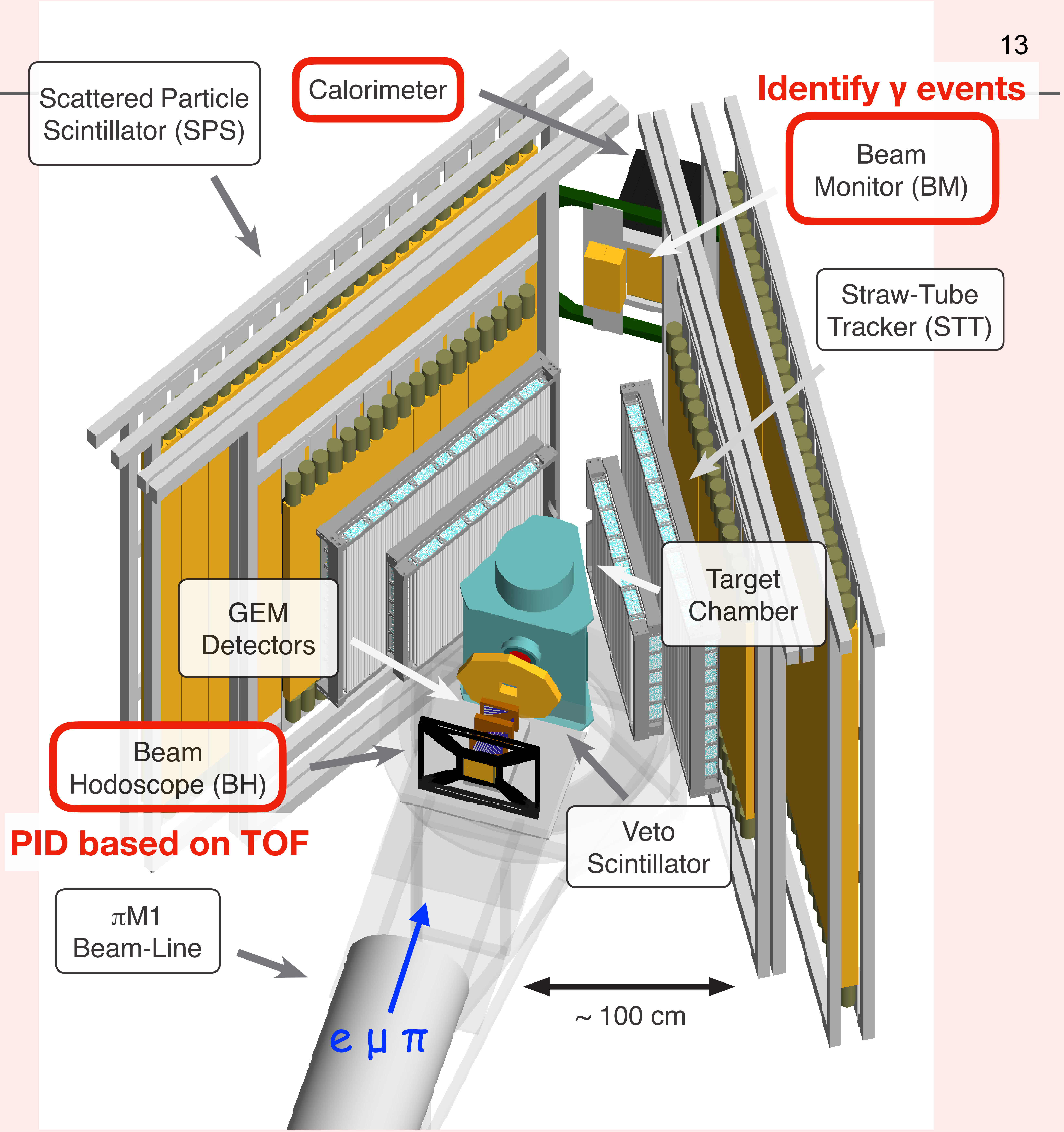
RF Period = 19.75 ns
Detector timing resolution is sufficient for identifying random coincidence beam particles

Detector Response

Light output vs. Average Incident Particle Energy



Used simulation to estimate the energy of the beam particle entering calorimeter



Detector Response

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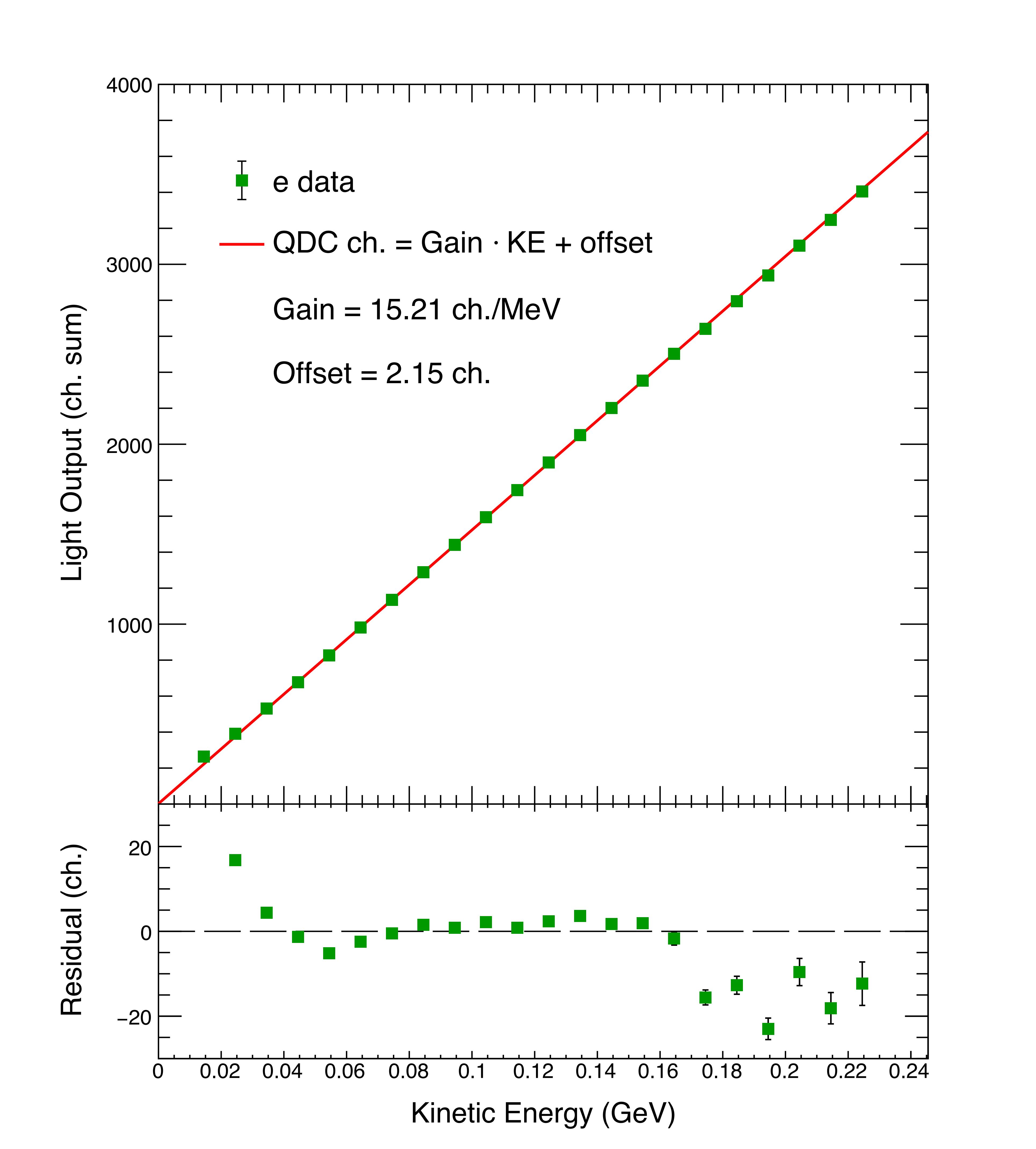
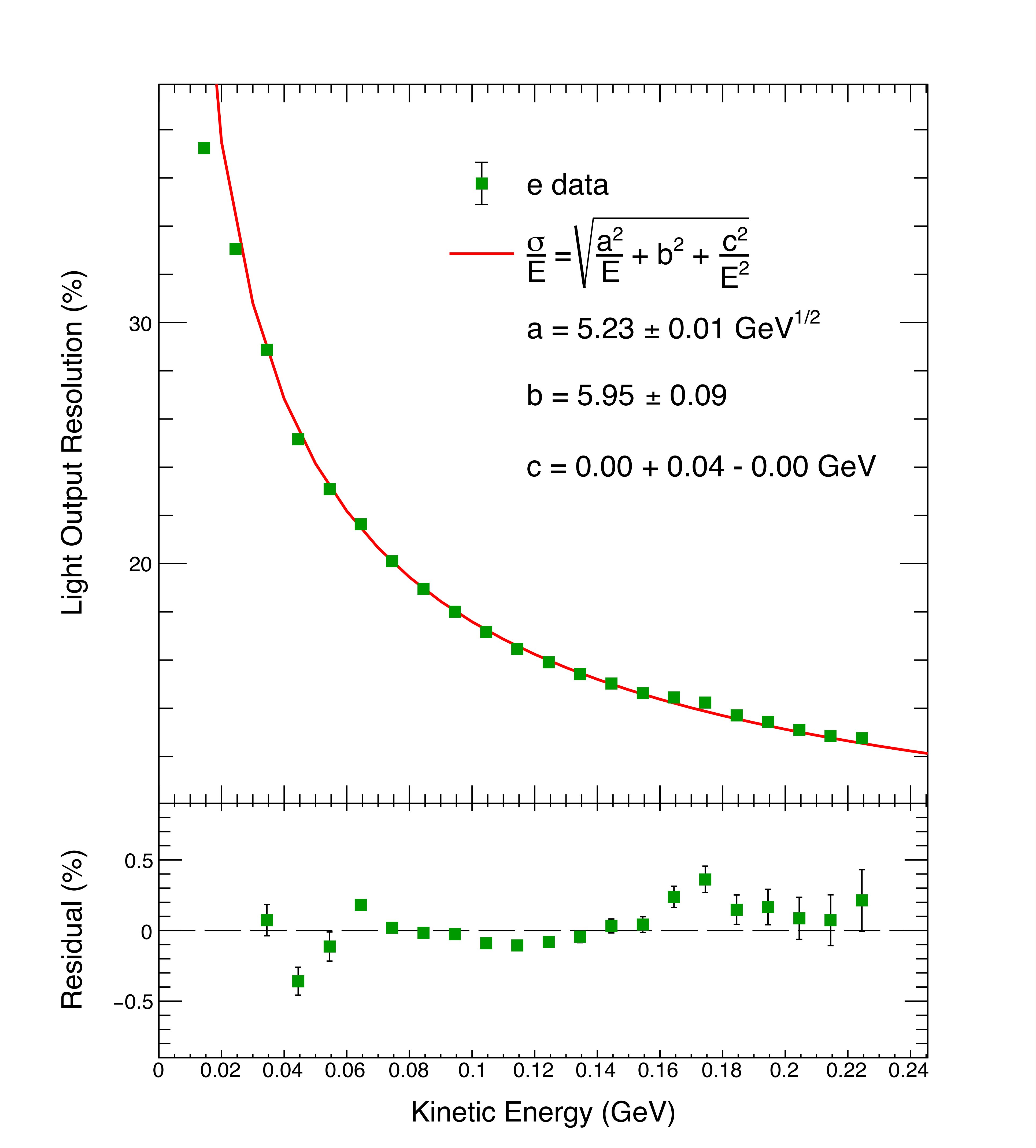


Resolution vs. Average Incident Particle Energy

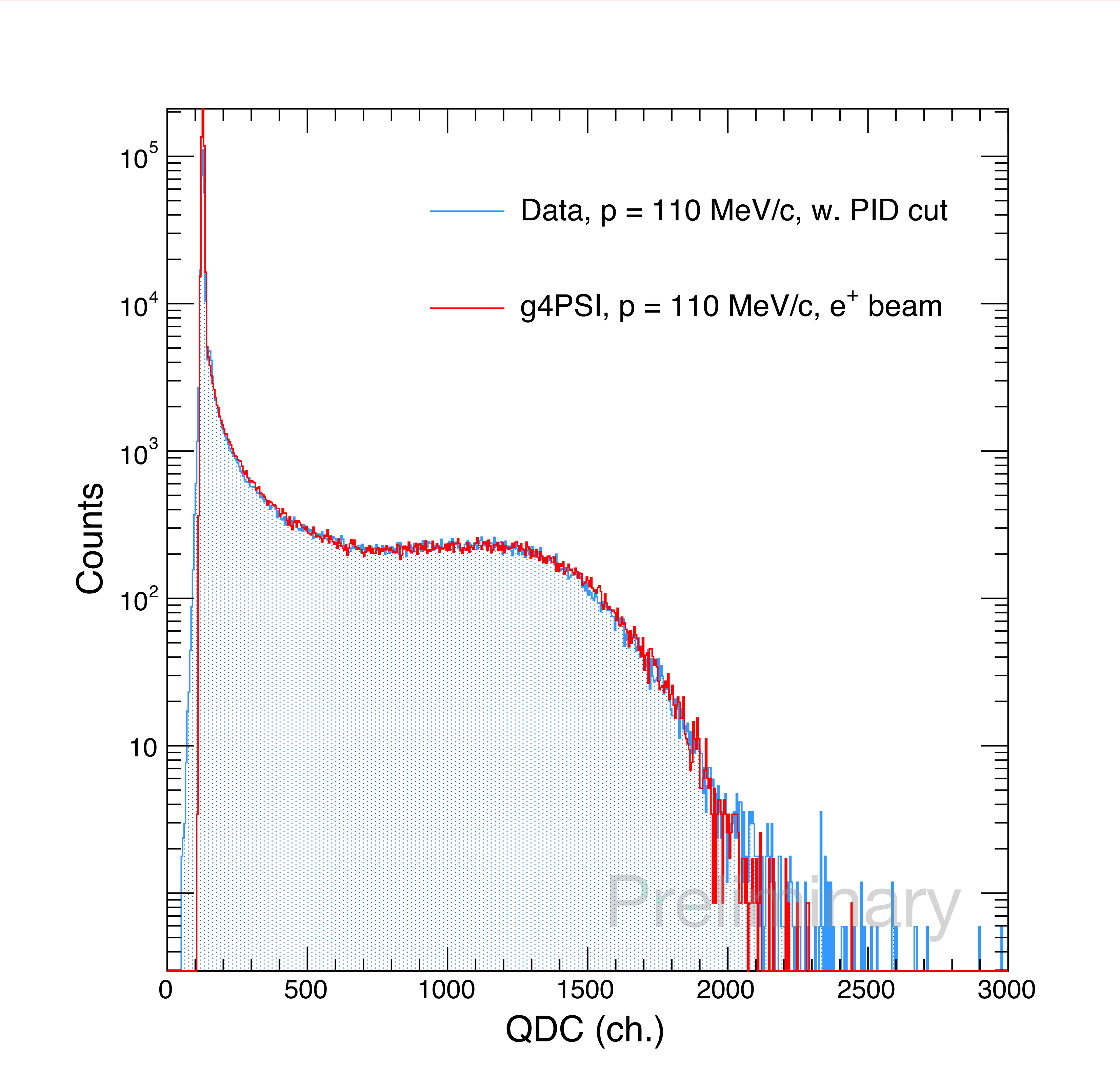


Good energy response with reasonable resolution

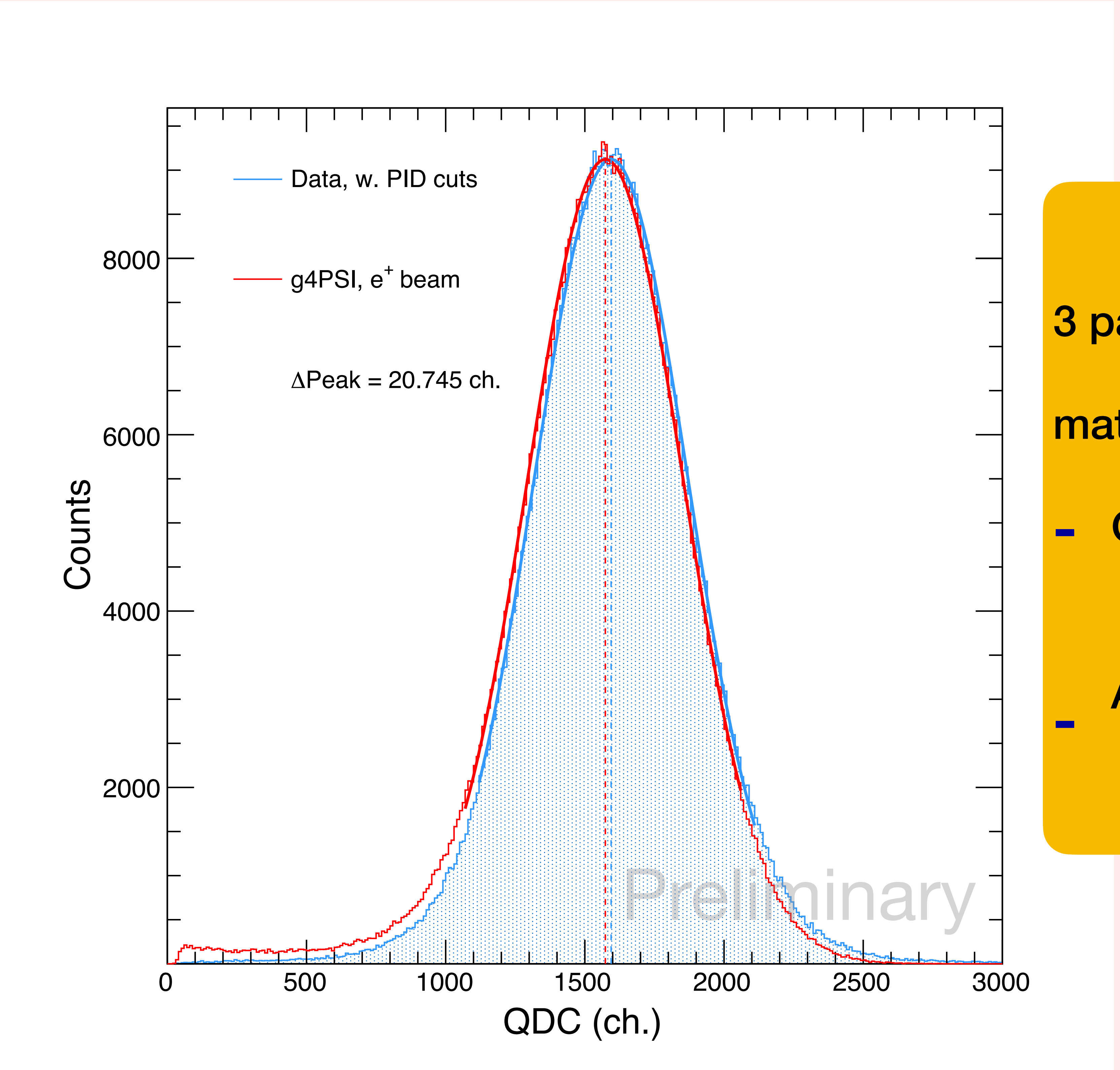
Simulation and Digitization

- Experiment is simulated using Geant4.
- Calorimeter simulation: record Cherenkov light production in the crystals. Two modes of modeling readout:
  - Fast mode: integrates a light yield over the path in the crystal
  - Detailed mode: counts optical photons that reach the PMTs

Electron QDC of a Central Crystal



Electron QDC of a Central Crystal



3 parameters in digitization for additional tuning to match data and simulation for each channel

- Gain parameter
- Additional Resolution: $\sigma = E\sqrt{\frac{\alpha^2}{E} + \frac{\gamma^2}{E^2}}$

Simulation and Digitization

- Tune parameters until data and simulation matches for each bar
- Then look at overall detector response using same analysis.

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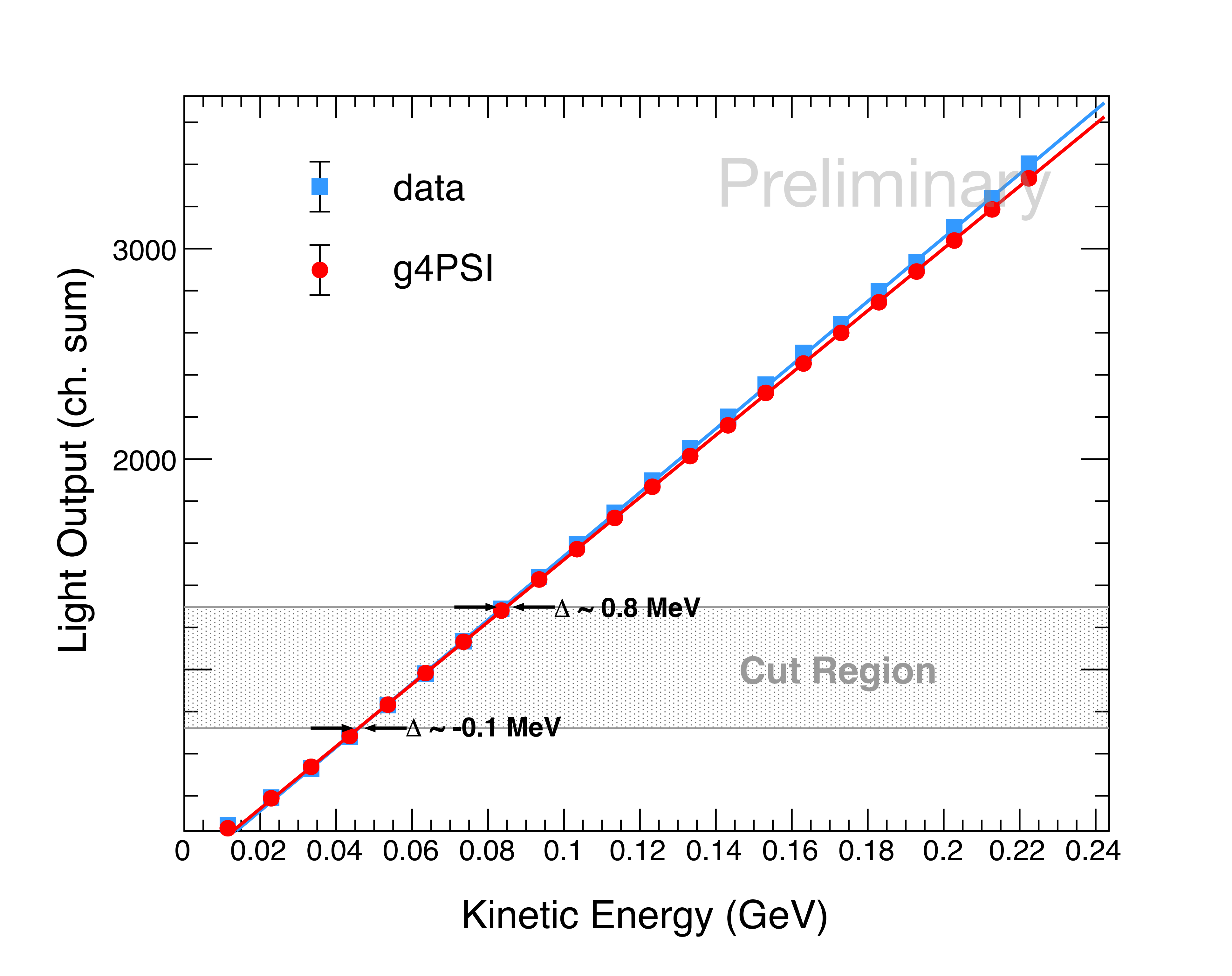

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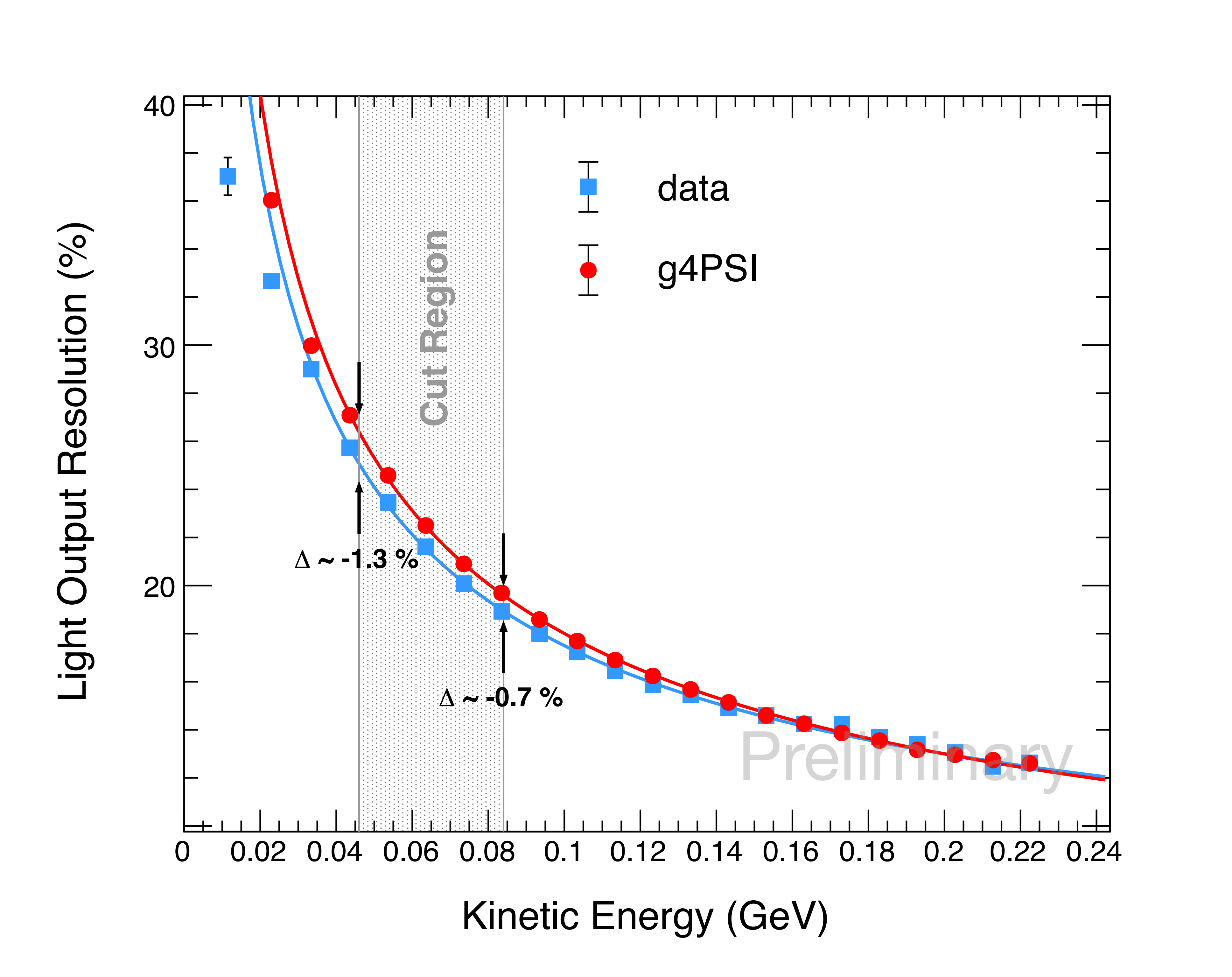
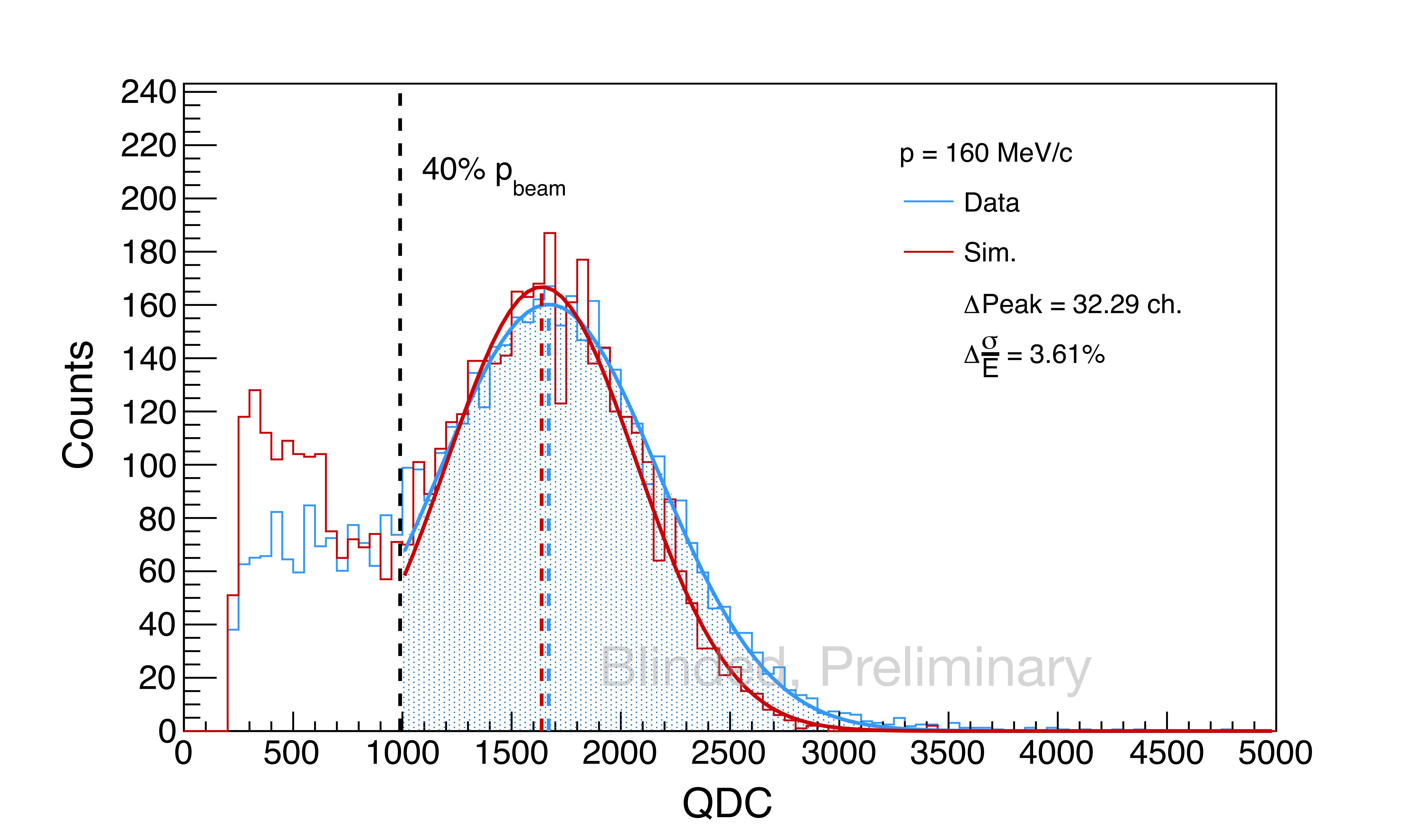


Good agreement between data and simulation, and satisfy requirement (agree within 2 MeV)

Simulation and Digitization

- Tune parameters until data and simulation matches for each bar
- Then look at overall detector response using same analysis

Reconstructed Photon of Scattering Events



- Data and simulation show similar result
- Cut will effectively remove events with large E_γ
- Result is preliminary
  - more tuning in simulation will be done to better model the detector behavior
  - more analysis studies will be done to improve cluster finding

Projected uncertainty on Radiative Corrections

Table 1 Radiative corrections δ for MUSE. Values are given for ep and μp scattering at various kinematic settings and for fully integrated final-state bremsstrahlung photons (full data) and after suppression of photons in the beam direction with the calorimeter ($E_\gamma < 0.4 p_0 c$). The statistical uncertainties in the corrections are of the order 10^{-3}

p_0 (MeV/c) θ	115 25°	115 60°	115 95°	161 25°	161 60°	161 95°	210 25°	210 60°	210 95°
ep									
$p'_{e,\min}$ (MeV/c)	14.8	13.0	14.4	14.8	13.0	14.4	14.8	13.0	14.4
δ_e (full data)	0.091	0.119	0.119	0.130	0.173	0.172	0.173	0.239	0.235
δ_e ($E_\gamma < 0.4 p_0 c$)	0.026	0.042	0.049	0.028	0.049	0.060	0.030	0.056	0.070
μp									
$p'_{\mu,\min}$ (MeV/c)	84.2	82.4	85.8	84.2	82.4	85.8	84.2	82.4	85.8
δ_μ (full data)	0.001	0.005	0.003	0.004	0.009	0.008	0.006	0.010	0.010
δ_μ ($E_\gamma < 0.4 p_0 c$)	0.001	0.005	0.003	0.004	0.009	0.008	0.006	0.010	0.010

Table 2 Uncertainties of radiative corrections σ_δ for ep scattering in MUSE, including the various contributions from the experimental uncertainties in the model input parameters p_0, θ_e, $p'_{\min}$, and E_γ. The values assume a cut on hard photons with $E_\gamma > 0.4 p_0 c$ in the MUSE calorimeter. The total uncertainty does not include model uncertainties in ESEPP

p_0 (MeV/c) θ	115 25°	115 60°	115 95°	161 25°	161 60°	161 95°	210 25°	210 60°	210 95°
$\lvert(\partial\delta_e/\partial p_0)\sigma_{p_0}\rvert$	0.01 %	0.01 %	0.00 %	0.01 %	0.00 %	0.00 %	0.00 %	0.03 %	0.01 %
$\lvert(\partial\delta_e/\partial\theta_e)\sigma_{\theta_e}\rvert$	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
$\lvert(\partial\delta_e/\partial p'_{\min})\sigma_{p'_{\min}}\rvert$	0.05 %	0.18 %	0.30 %	0.03 %	0.16 %	0.31 %	0.02 %	0.13 %	0.31 %
$\lvert(\partial\delta_e/\partial E_\gamma)\sigma_{E_\gamma}\rvert$	0.32 %	0.33 %	0.33 %	0.25 %	0.26 %	0.26 %	0.20 %	0.22 %	0.22 %
σ_{δ_e}	0.32 %	0.38 %	0.45 %	0.25 %	0.30 %	0.40 %	0.20 %	0.26 %	0.38 %

DOI: 10.1140/epja/s10050-023-01215-0

Radiative corrections and uncertainty reduced by a factor of ~2.5 to 5.5 after calorimeter cut

Uncertainty in radiative corrections is 0.33 - 0.22% after calorimeter cut

Conclusion

- MUSE is measuring ep and μp elastic scattering cross section to resolve the proton radius puzzle
- The MUSE calorimeter will reduce uncertainty in radiative corrections by vetoing high energy forward going photons
  - The detector has reasonable detector response
  - Preliminary detector simulation shows promising result matching data
  - Work ongoing for improving cluster finding and multiple beam particle event separation

- MUSE paper on Radiative Corrections: L. Li *et al.* Instrumental uncertainties in radiative corrections for the MUSE experiment. Eur. Phys. J. A 60 8 (2024). DOI: 10.1140/epja/s10050-023-01215-0
- MUSE first calorimeter paper will be published soon: W. Lin *et al.* The MUSE Beamline Calorimeter

Thank you!