MUSE Overview

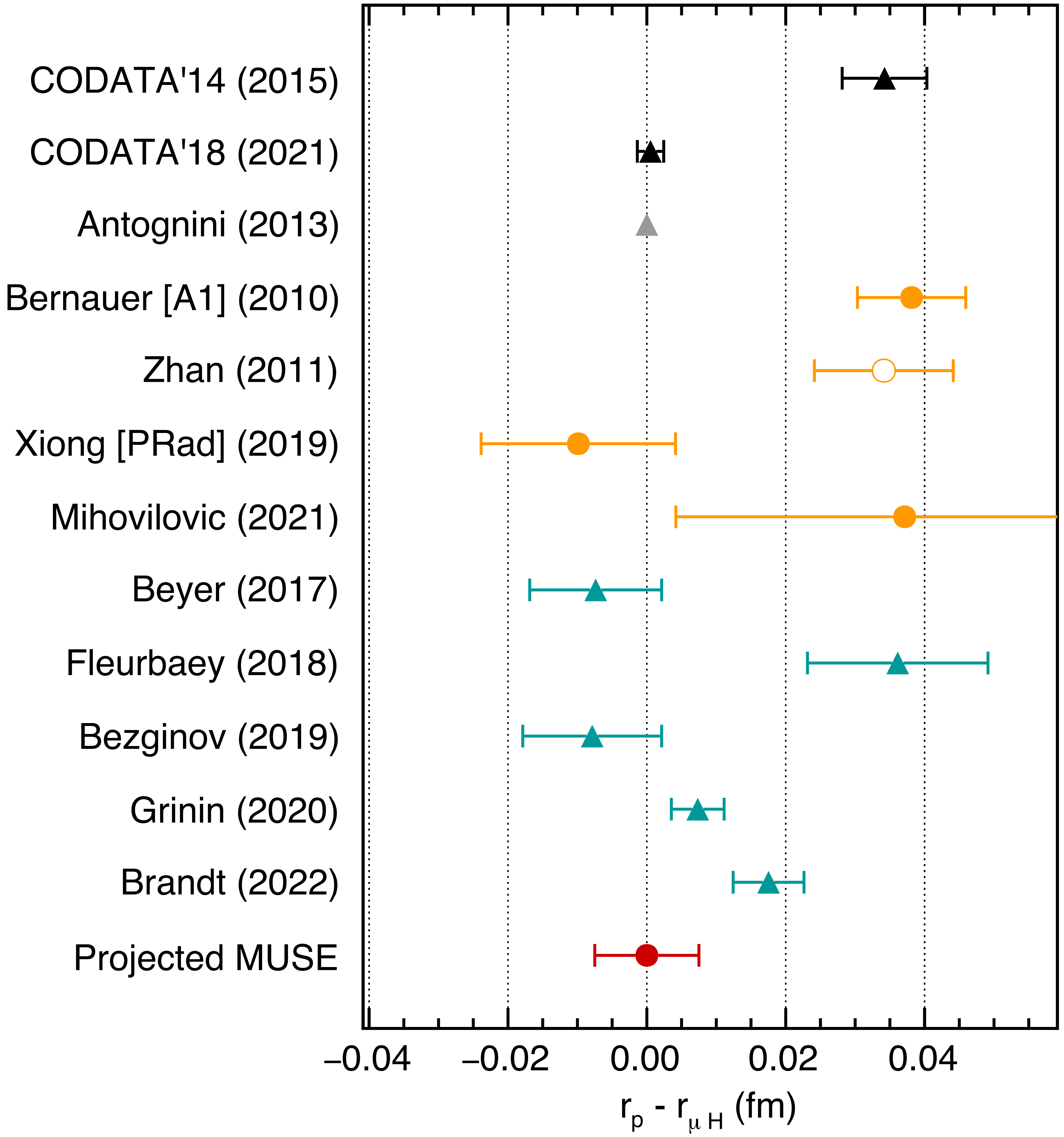
Steffen Strauch
University of South Carolina

for the MUSE Collaboration

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

MUSE Review, BVR 55, PSI, February 5, 2024

MUSE and The Proton Radius Puzzle



Inconsistent electron-scattering data

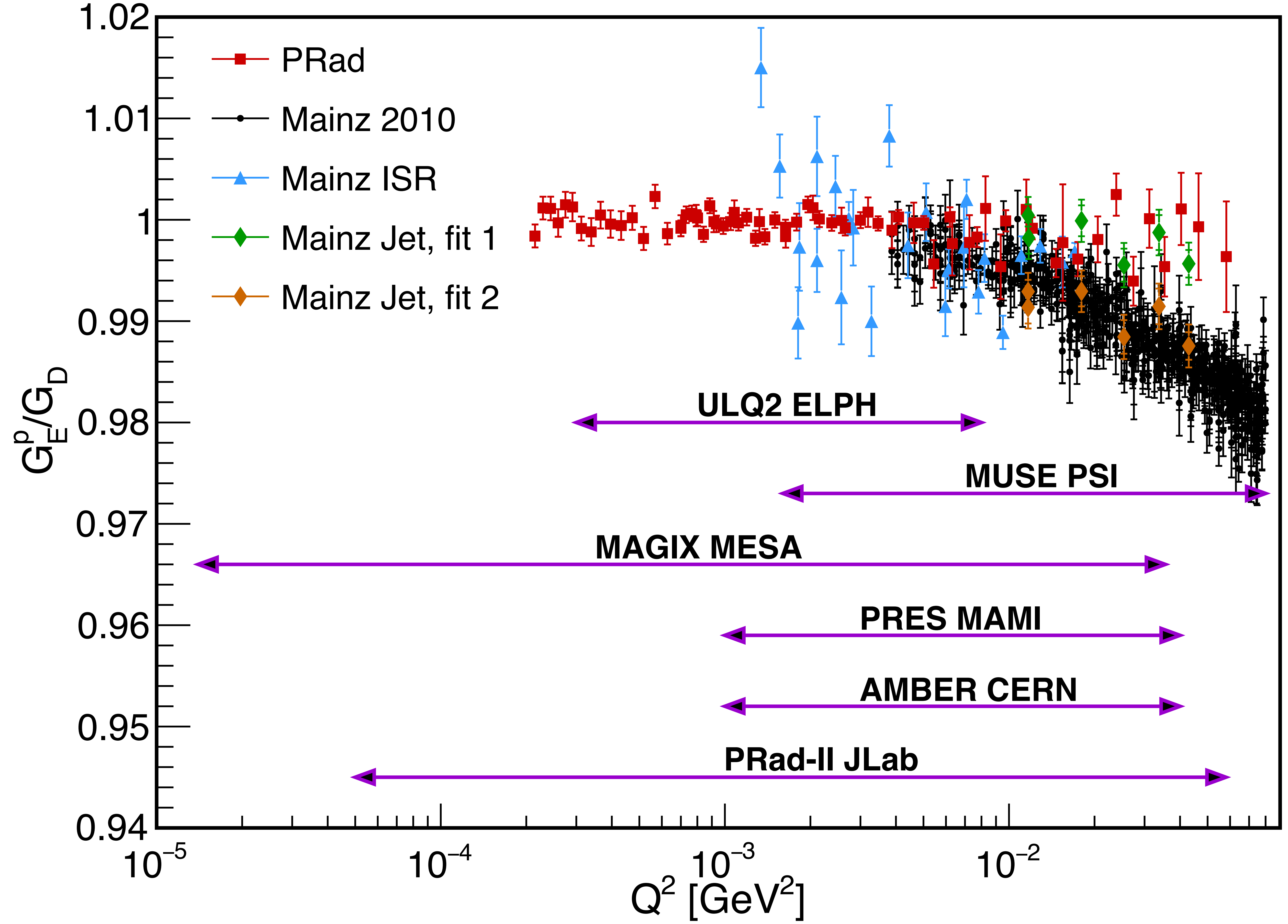
Inconsistent hydrogen-spectroscopy data

No adequate muon-scattering data available yet

MUSE

$$e^{\pm}p \rightarrow e^{\pm}p$$
$$\mu^{\pm}p \rightarrow \mu^{\pm}p$$

Update on scattering experiments



Beam	e⁻	e⁺	μ⁻	μ⁺	
PRad	✓				completed
Mainz 2010	✓				
Mainz ISR	✓				
Mainz Jet	✓				
MUSE PSI	✓	✓	✓	✓	running
ULQ2 ELPH	✓				
AMBER CERN			✓	✓	future
MAGIX MESA	✓				
PRES MAMI	✓				
PRad-II JLab	✓				

W. Xiong and C. Peng, ``Proton Electric Charge Radius from Lepton Scattering,'' Universe **9**, no.4, 182 (2023), doi:10.3390/universe9040182, [arXiv:2302.13818 [nucl-ex]].

W. Xiong and C. Peng, Review (2023):
Proton Electric Charge Radius from Lepton Scattering

“This unique experiment [MUSE] will provide valuable insights into the proton charge radius puzzle.

> Firstly, a comparison between electronic and muonic measurements will be a direct test for **lepton-universality violation and any related new physics**.
>
> Secondly, this comparison can test our understanding of **radiative corrections (RC)**. Muons have nearly 200 times the mass of electrons and thus have much smaller radiative effects. …
>
> Furthermore, the use of both positive and negative polarities of the incoming lepton beam allows control of the contribution from the **two-photon exchange (TPE)** diagrams.”

W. Xiong and C. Peng, ``Proton Electric Charge Radius from Lepton Scattering,'' Universe **9**, no.4, 182 (2023), doi:10.3390/universe9040182, [arXiv:2302.13818 [nucl-ex]].

MUSE in the literature in the past year

Reviews

- **Proton Electric Charge Radius from Lepton Scattering**
  W. Xiong and C. Peng, Universe 9, no.4, 182 (2023), doi:10.3390/universe9040182, [arXiv:2302.13818 [nucl-ex]].
- **Radiative Corrections: From Medium to High Energy Experiments**
  A. Afanasev et al., arXiv:2306.14578 [hep-ph]

Experiment

- **Blinding** for precision scattering experiments: The MUSE approach as a case study
  [arXiv:2310.11469v1 [physics.data-an]]
- Instrumental uncertainties in **radiative corrections** for the MUSE experiment
  [L. Li et al., Eur. Phys. J. A 60:8 (2024)]

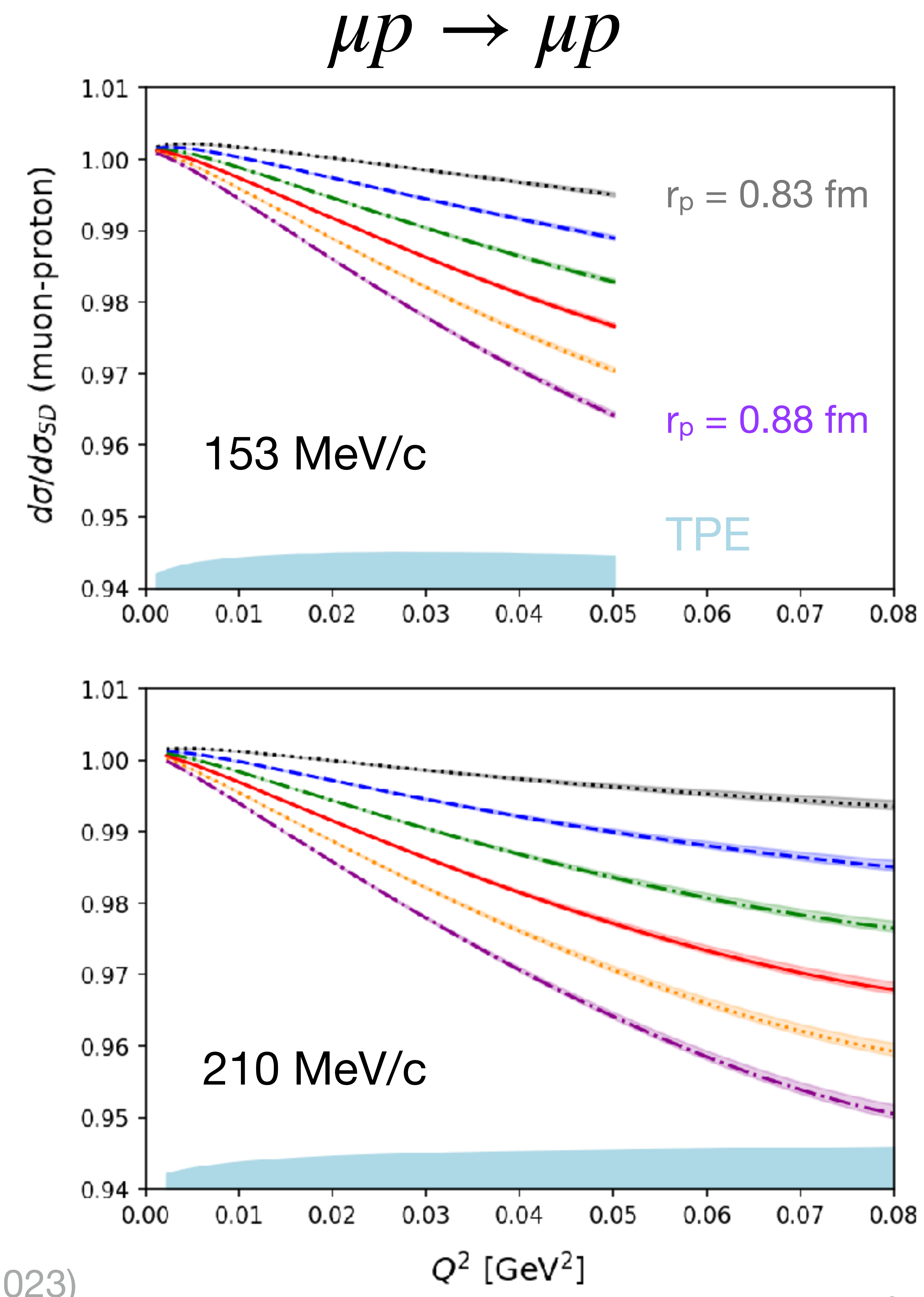
Theory

- Proton charge **radius extraction** from muon scattering at MUSE using dispersively improved chiral effective field theory
  F. Gil-DomÍnguez, J.M. Alarcón and C. Weiss, Phys. Rev. D 108, no.7, 074026 (2023)
- Impact of **NNLO QED corrections** on lepton-proton scattering at MUSE
  T. Engel, F. Hagelstein, M. Rocco, V. Sharkovska, A. Signer and Y. Ulrich, Eur. Phys. J. A 59, no.11, 253 (2023)
- Analytical Evaluation of Elastic Lepton-Proton **Two-Photon Exchange** in Chiral Perturbation Theory
  P. Choudhary, U. Raha, F. Myhrer and D. Chakrabarti, [arXiv:2306.09454 [hep-ph]]
- Contribution of **π^0 Exchange** in Elastic Muon-Proton Scattering
  A. Naik and A. Afanasev, [arXiv:2401.13892 [nucl-th]]

2023 Long Range Plan for Nuclear Science

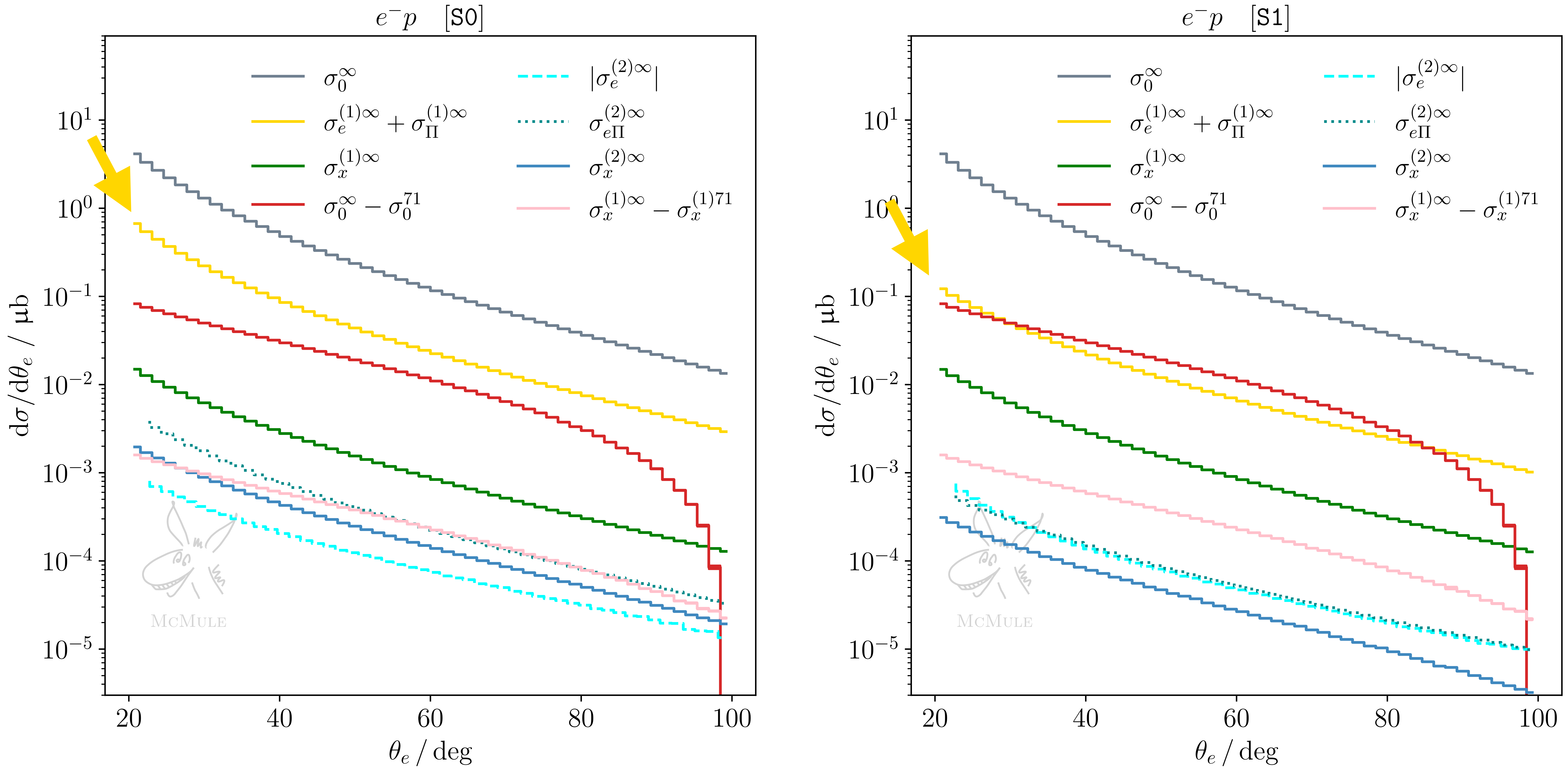
Proton charge radius extraction from muon scattering at MUSE

- Dispersively improved chiral effective field theory
- The paper quantifies
  - the **sensitivity of the μp cross section to the proton charge radius**,
  - the **theoretical uncertainty** of the cross section predictions, and
  - the size of **two-photon exchange** corrections.
- The optimal kinematics for radius extraction at MUSE is at momenta 210 MeV/c and $Q^2 \sim 0.05$–$0.08\ \mathrm{GeV}^2$.



F. Gil-DomÍnguez, J.M. Alarcón and C. Weiss, Phys. Rev. D **108**, no.7, 074026 (2023)

Impact of NNLO QED corrections on lepton-proton scattering at MUSE



p_{beam} = 210 MeV/c

kinematical scenarios
S0 : without inelasticity cut
S1 : with inelasticity cut

pure NLO leptonic and fermionic corrections

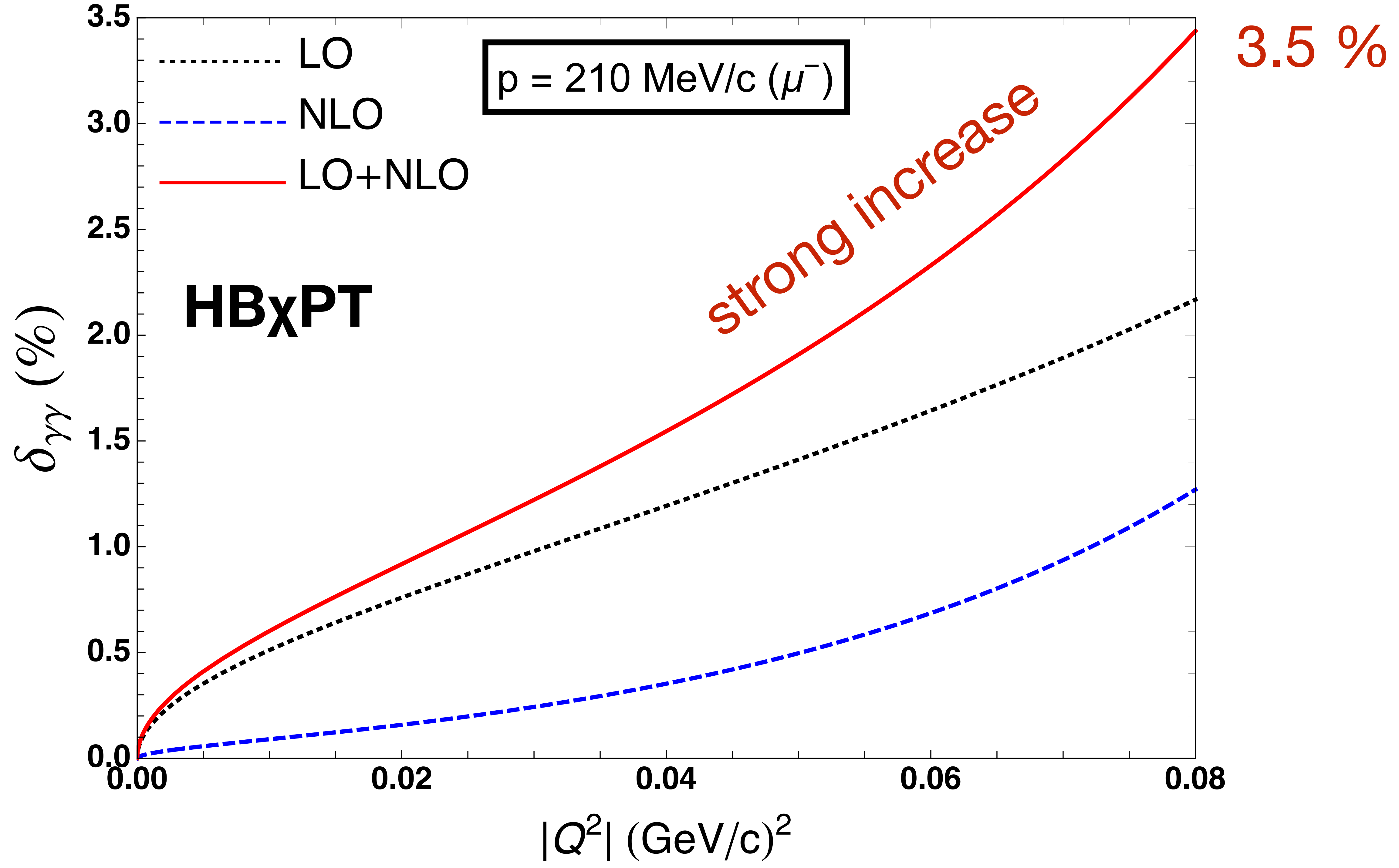
LO effects with and without inclusion of the proton form factors

NLO mixed corrections, TPE

“The availability of both electrons and muons, with both polarities, is a **remarkable advantage** for the MUSE experiment, as it allows to **analyze a diversified phenomenology and to keep under control QED radiative corrections**, if needed.”

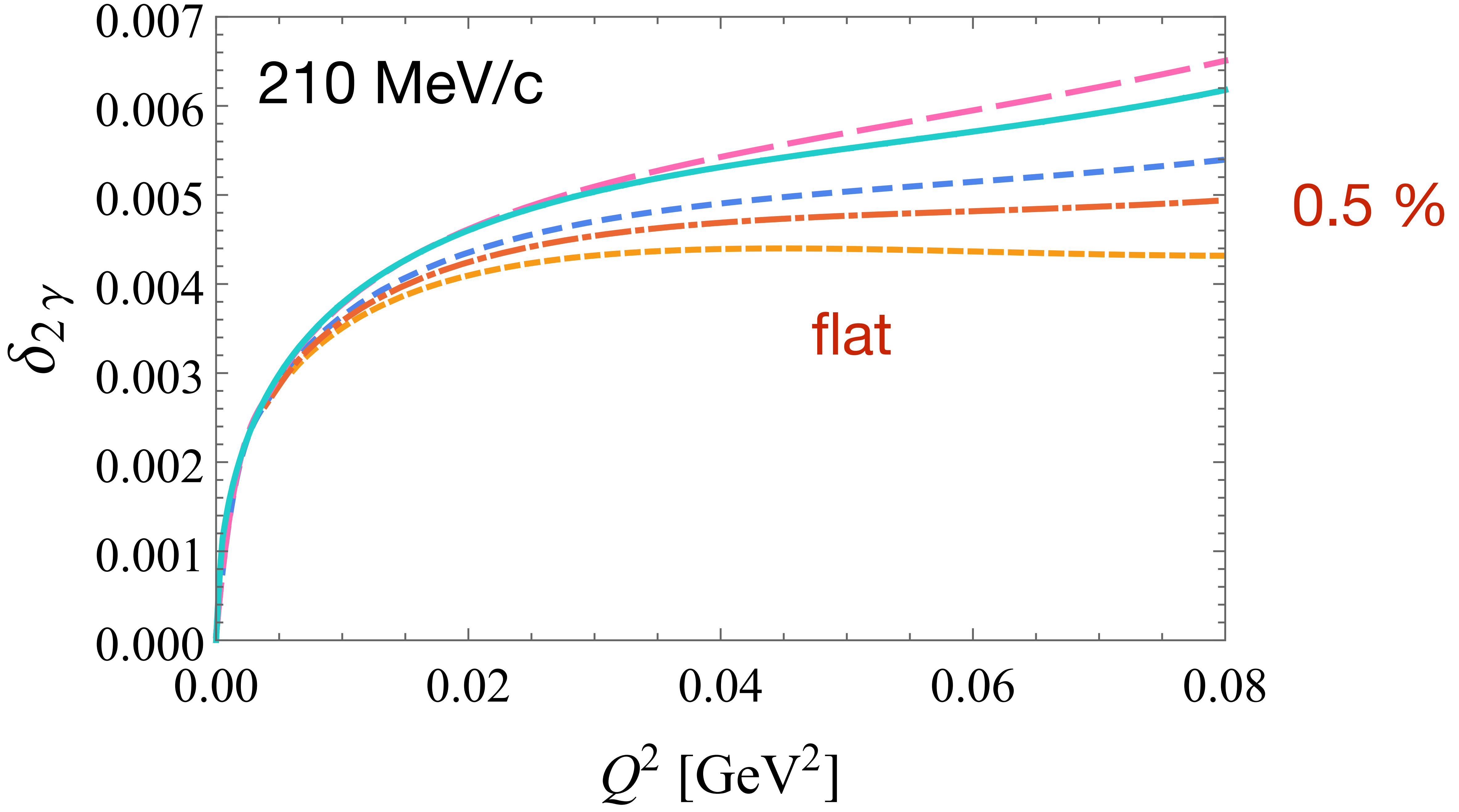
T. Engel, F. Hagelstein, M. Rocco, V. Sharkovska, A. Signer and Y. Ulrich, Eur. Phys. J. A **59**, no.11, 253 (2023)

Two-Photon Exchange in Chiral Perturbation Theory



McMule μ^- results for comparison

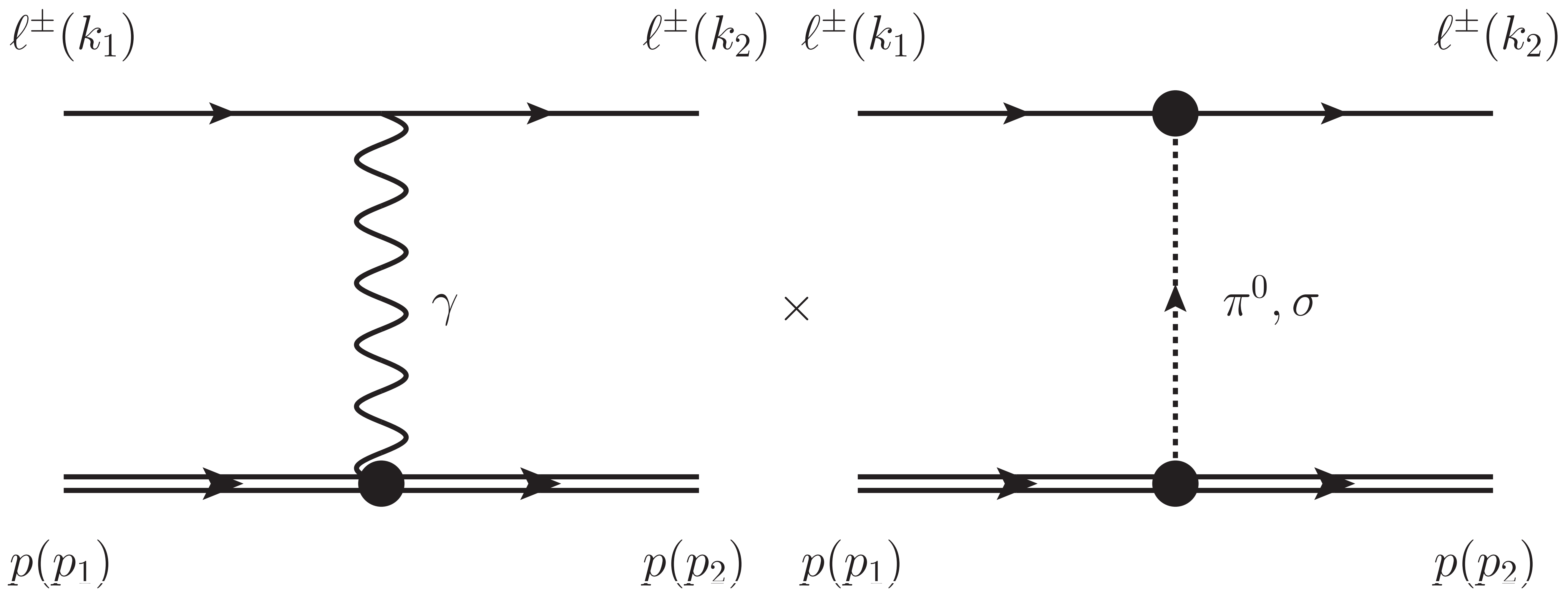
O. Tomalak and
M. Vanderhaeghen



- Evaluation of the TPE loop contributions using **heavy baryon chiral perturbation theory** (HBχPT) without taking recourse to soft photon approximation (SPA) methods
- Authors find **sizable TPE contributions beyond the expected SPA results** ⇒ MUSE will test those

P. Choudhary, U. Raha, F. Myhrer and D. Chakrabarti, [arXiv:2306.09454 [hep-ph]].

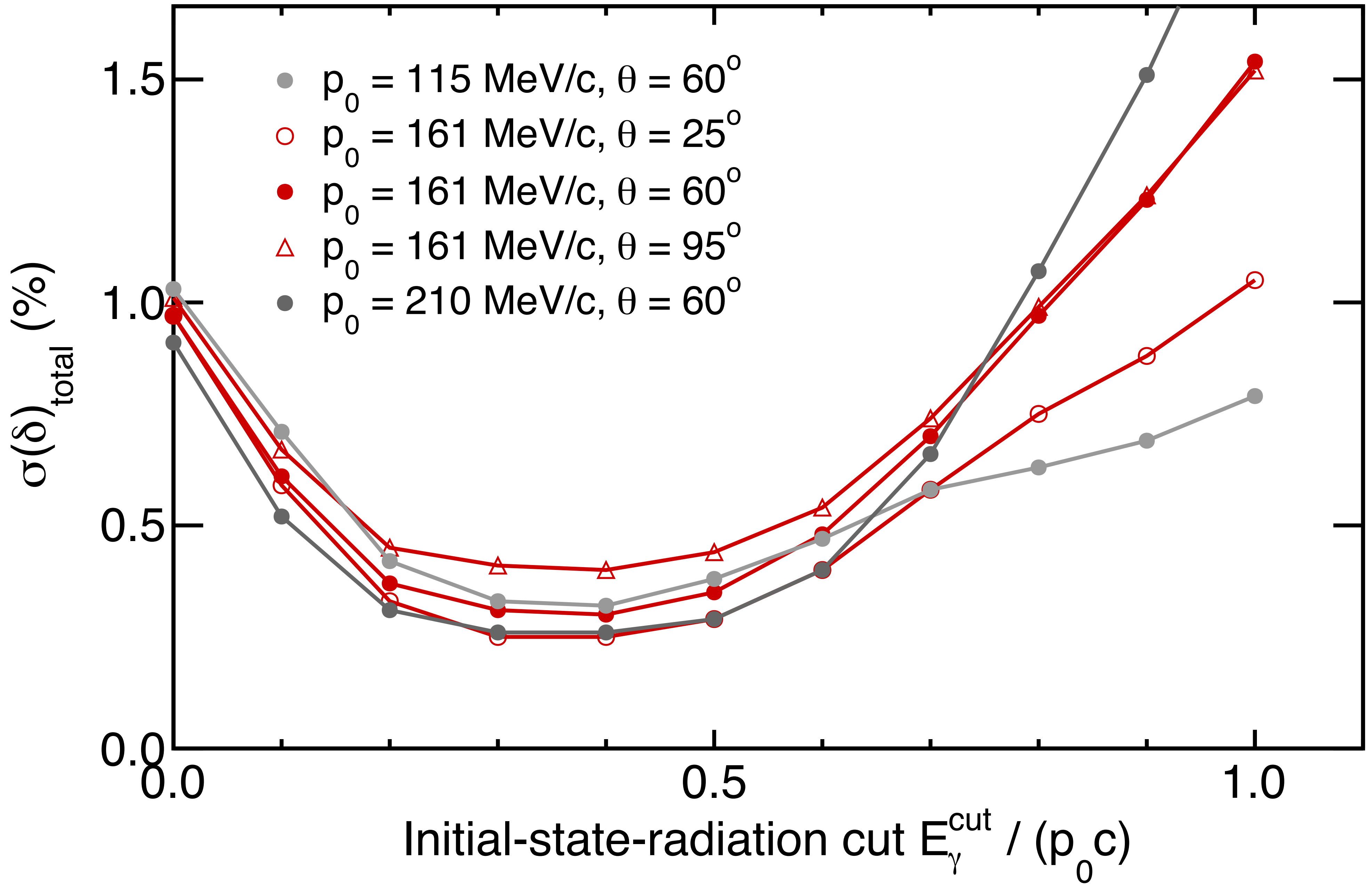
Contribution of π^0 Exchange in Elastic Muon-Proton Scattering



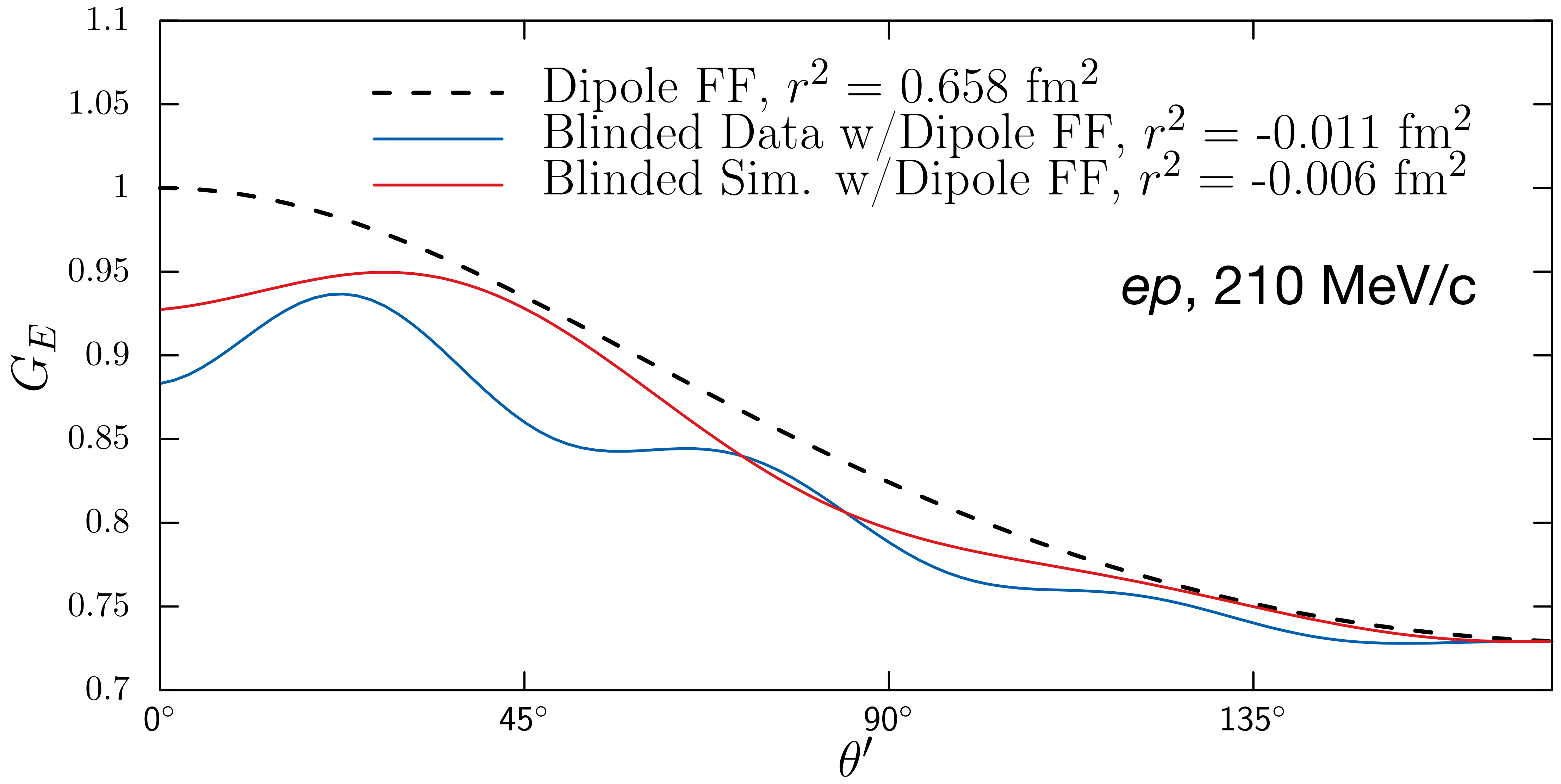
- Hadronic contributions to the anomalous magnetic moment of the muon have the largest uncertainties. Helicity-flip meson exchange may provide insight into those calculations.
- **π^0-exchange** contributes for the case of a transversely polarized proton target (the contribution was found to be on the order of ~ 0.15% for muons in the kinematic region of the MUSE experiment) but
- **does not contribute to the unpolarized cross section** in the first order correction of QED.

A. Naik and A. Afanasev, [arXiv:2401.13892 [nucl-th]]

2023 MUSE collaboration papers



L. Li et al., “**Instrumental uncertainties in radiative corrections for the MUSE experiment**”,
Eur. Phys. J. A 60:8 (2024).

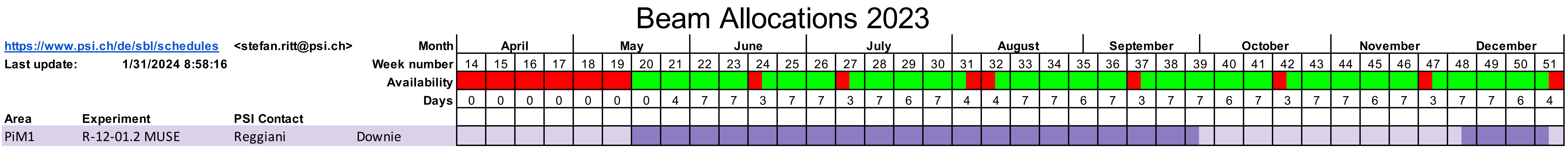


$(e, \mu, \pi) \otimes (+, -) \otimes$ (115, 160, 210 MeV/c) $\otimes$ (data, sim)

J.C. Bernauer et al., “**Blinding for precision scattering experiments: The MUSE approach as a case study**”,
arXiv:2310.11469v1 [physics.data-an]

MUSE calorimeter paper under collaboration review

Accomplishments in 2023



Beam Allocations 2023

https://www.psi.ch/de/sbl/schedules <stefan.ritt@psi.ch>

Last update: 1/31/2024 8:58:16

Month	**April**				**May**				**June**				**July**					**August**	
Week number	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Availability	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟩🟥	🟥🟩
Days	0	0	0	0	0	0	0	4	7	7	3	7	7	3	7	6	7	4	4
PiM1 R-12-01.2 MUSE Reggiani Downie							🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪

Month			**September**				**October**					**November**				**December**			
Week number	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
Availability	🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟩	🟥🟩	🟩	🟩	🟩	🟩🟥
Days	7	7	6	7	3	7	7	6	7	3	7	7	6	7	3	7	7	6	4
PiM1 R-12-01.2 MUSE Reggiani Downie	🟪	🟪	🟪	🟪	🟪	🟪	🟪									🟪	🟪	🟪	🟪

Area	**Experiment**	**PSI Contact**	
PiM1	R-12-01.2 MUSE	Reggiani	Downie

- Maintained and improved the experimental setup
  ⇒ Paul Reimer’s presentation
- Staffed shifts and **ran MUSE for over 150 days** with improved efficiency, and obtained the highest-quality data set yet
- Developed and refined analyses
  ⇒ Ethan Cline’s presentation
- Continued work on the simulation
  ⇒ Matt Nicol’s presentation

	Scattering Data
2021	1.4×10^9
2022	1.0×10^9
2023	2.9×10^9

Total Goal	$12 - 15 \times 10^9$

plus additional calibration data

Experiment Challenges in 2023

- TCPV was found displaced and needed to be repositioned
- Requirement of humidity control to address STT currents
- STT gas leaks needed to be tightened which led to much-improved performance in December
- SPS glue joints needed to be repaired
- Cooling-water interruption led ultimately to damage to the empty hydrogen-target cell
- One of the four GEMs could not be read out during the December run period

⇒ Konrad Deiter’s and Paul Reimer’s presentations

Significant Results since 2023

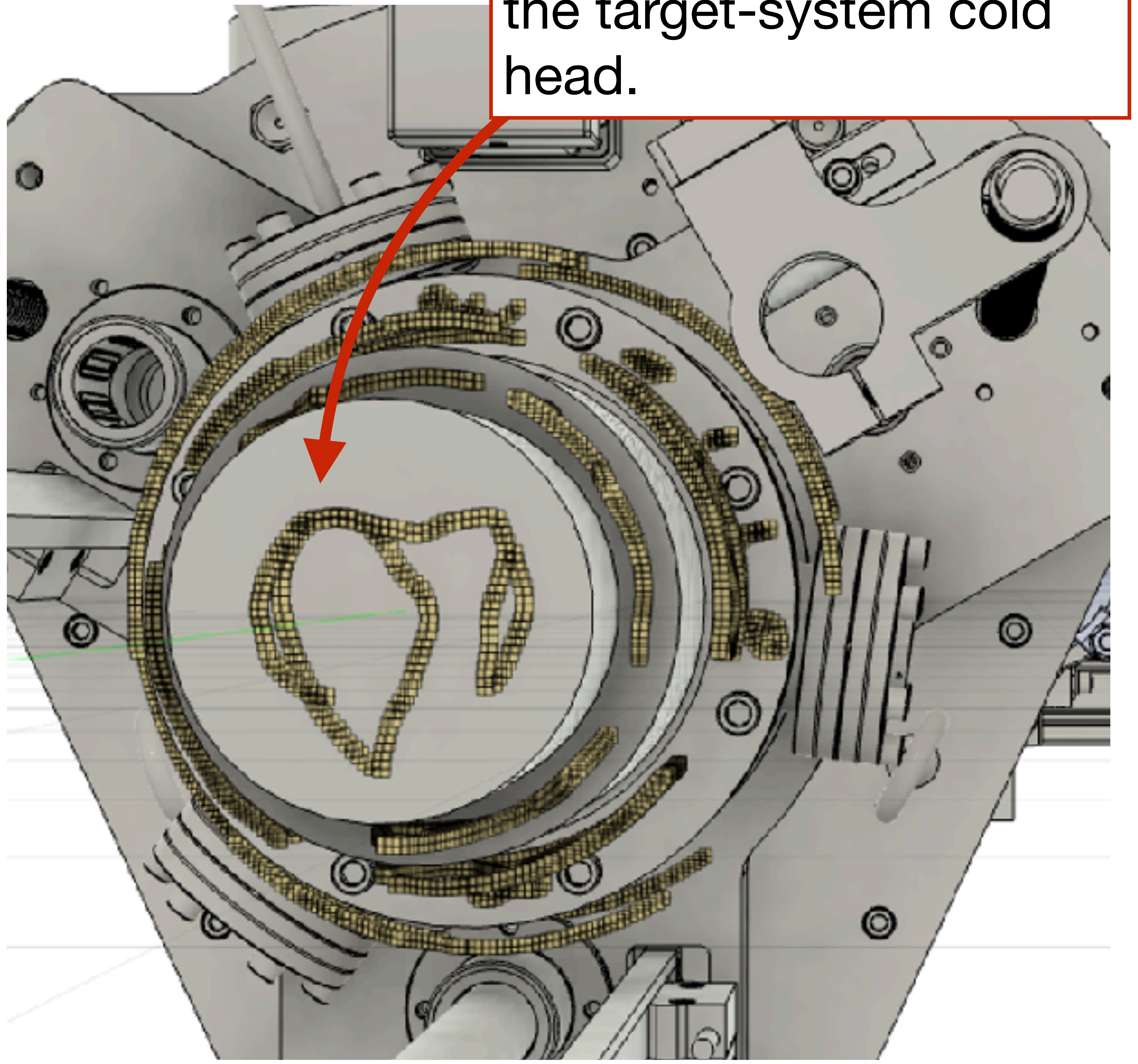
- Students graduated
  - **Shraddha Dogra (Ph.D., Rutgers)**, “Studying Two-Photon Exchange with ep and μp Elastic Scattering in the MUSE Experiment”
  - **Anne Flannery (M.S., USC)**, “Gamma calibration of scintillators for the muon scattering experiment”
  - **Win Lin (Ph.D., Rutgers)**, “Testing Lepton Universality with ep and μp Elastic Scattering in the MUSE Experiment”
  - **Jesmin Nazeer (Ph.D., HU)**, “Construction and Commissioning of Gas Electron Multiplier (GEM) Detectors in Advanced Assembly Design for Low-Energy Applications at High Rates and Analysis of GEM Data from the MUSE Experiment at PSI”
  - **Dvir Yaari (M.S., HUJI)**, “Characteristics of Straw Tube Trackers & Gas Distribution System”
- Two Papers published or submitted for publication
  - L. Li et al., Eur. Phys. J. A 60:8 (2024), J.C. Bernauer et al., arXiv:2310.11469v1 [physics.data-an]
- Analysis report submitted on December 31, 2023
- Status report submitted on January 22, 2024

Collaboration – Personnel Update

Michael Paolone (New Mexico State University) with Ph.D. student, **Mohammad Ali**, joined the collaboration in April 2023 with contributions to the analysis of survey data and detector alignment.

Graduate Students: Mohammad Ali (NMSU), Angel Christopher (HU), Subham Das (RU), Anne Flannery (HU), Tanvi Patel (HU), Rachel Ratvasky (GW), Haley Reid (UM), Kyle Salamone (SBU), Dvir Yaari (HUJI)

Postdocs: Alexander Golossanov (HU), Stefan Lukenheimer (UM), Hamza Atac (TU, ~50 %), Ethan Cline (SBU, ~50 %), Ievgen Lavrukhin (UM, ~50 %), Matthew Nicol (USC), Ryan Richards (HU, ~50 %)



> 20k survey points on the cylindrical parts of the target-system cold head.

Mohammad Ali (NMSU)

Plans for 2024

PAUL SCHERRER INSTITUT

Beam-Time Request Form 2024

R - Experiments with Muon, Pion and UCN Beams at the CHRISP facility
for Particle Physics and Beam Tests

Period: May – December 2024

Please complete in block letters!

1. TYPE OF REQUEST, TITLE

This beam-time request is for a: ☐ new proposal / addendum / test ☒ continuation[1] of experiment: R- 12-01.2

[1] Continuation must be accompanied by a progress report

Short Title:
MUSE

2. CONTACT PERSON

One *(1)* person only. All correspondence concerning this proposal will only be sent to the *Contact Person*. Indicate if Contact Person is also a Spokesperson. Supply international dialing codes.

First Name(s): Ronald Last Name: Gilman
Institute: Rutgers the State University of New Jersey
Street / No.: 136 Frelinghausen Road
City / Postal Code: Piscataway, NJ 08854 Country: USA
Telephone: +1-848-445-8775 E-Mail: rgilman@physics.rutgers.edu

☐ Spokesperson

3. REQUESTED BEAM TIME INCLUDING SETUP TIME

Give weeks (= 16 -19 shifts of 8h each, average 125 real hours per week) or days for small tests.

BEAM - AREA	DURATION	PREFERRED DATES
PiM1	6 months	We would appreciate a beamtime allocation similar to that of our 2023 beam time.

Dead-line for submission of beam-time requests: January 22, 2024

Date: January 21, 2024

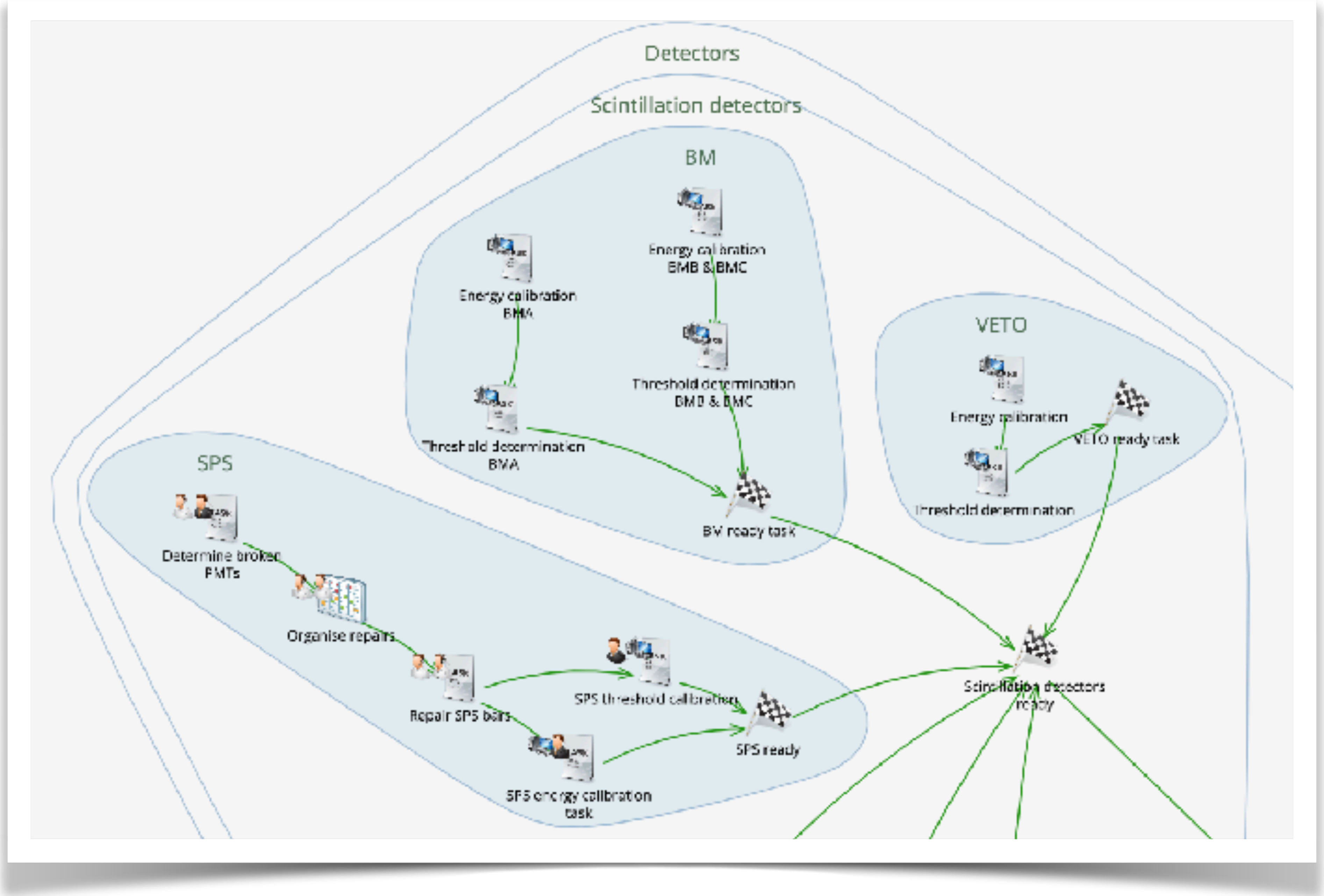
Name: Ronald Gilman Ronald Gilman

Please submit this form to:
Paul Scherrer Institut
Stefan Ritt
CH-5232 Villigen / Switzerland

Telephone: +41 (0)56 310 37 28
Telefax: +41 (0)56 310 31 20
E-mail: stefan.ritt@psi.ch

Beam-Time Request Form Date printed: 25/01/2023

MUSE project in gameplan.global



- Requested **6 months** of beamtime, with preference for a beamtime allocation similar to that of our 2023 beamtime
- Work on experiment readiness
- Take production data

Agenda of the Review Meeting

14:00	**Overview**	Steffen Strauch
	MUSE: Equipment Status	Paul Reimer
	LH_2 Target Operation	Konrad Deiters
15:30	Break	
	Simulations	Matthew Nicol
	High-Level Analysis and lp Cross Sections	Ethan Cline
	Projected Results	Ron Gilman