# MULTI-LEPTON–PROTON SCATTERING MEASUREMENTS AND THE PROTON RADIUS PUZZLE

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**The Hebrew University of Jerusalem**
**PSAS 2026, 22nd May**

MUSE

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM
الجامعة العبرية في أورشليم القدس

psas 2026

NSF

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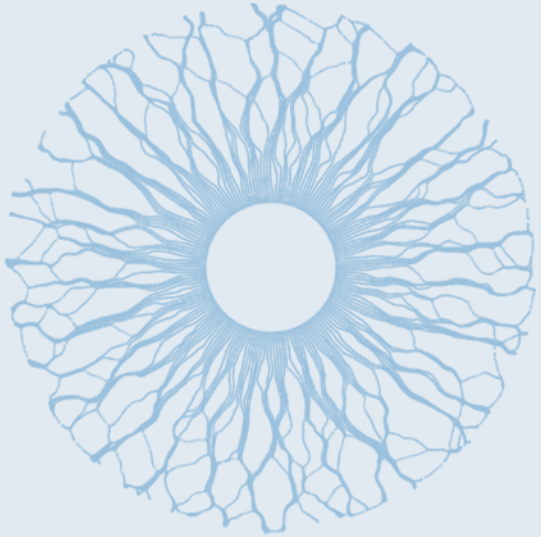
PSI

Fundamental Interactions Group

# OUTLINE





- Proton Radius Puzzle
- MuSE – The Muon Scattering Experiment
- Analysis Challenges
- Current Status

# Proton Radius

$$r_P^2 = \frac{\int r^2 \rho(r) d^3 r}{\int \rho(r) d^3 r}$$

Proton **charge** radius

**Motivation** – Spatial charge distribution parameter

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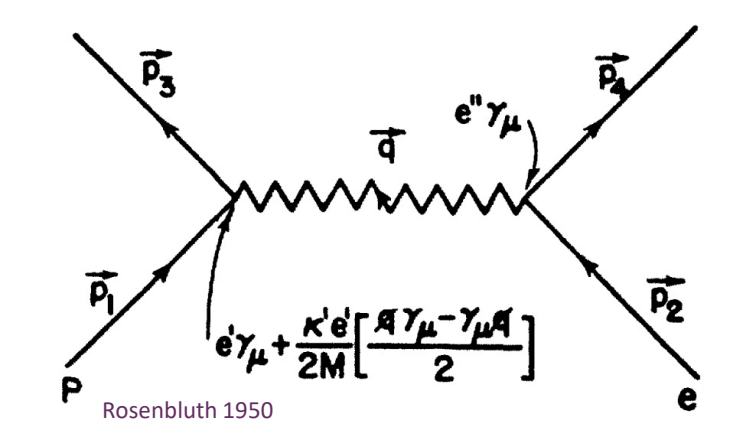
Proton **charge** radius

**Motivation** – Spatial charge distribution parameter

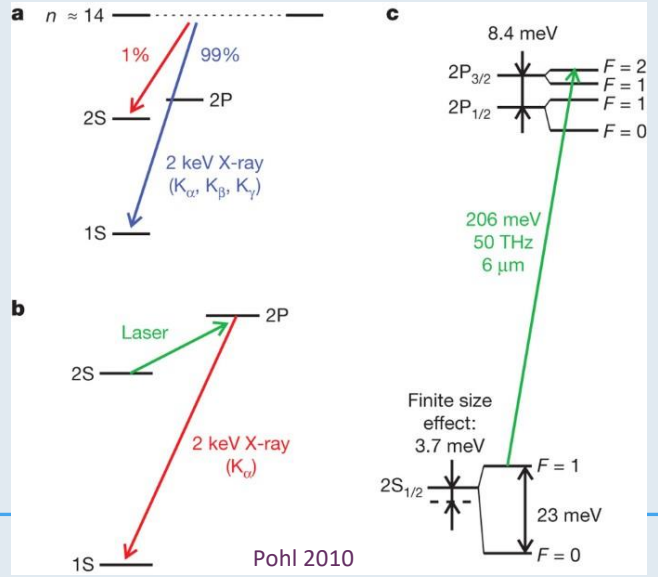
Measured through its interaction with charged particles – e, $\mu$ – **Leptons**

## Scattering




Rosenbluth 1950

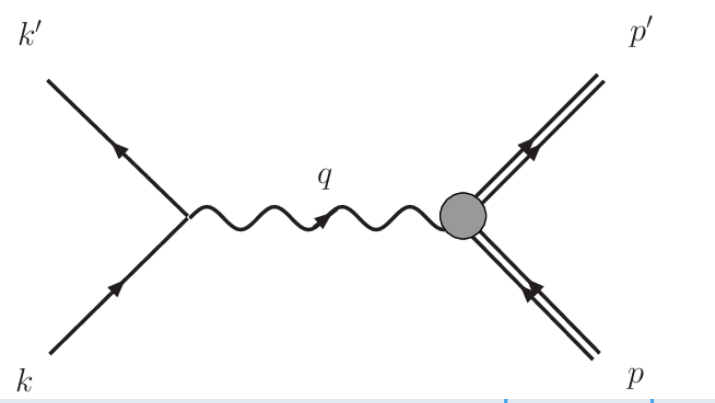
## Spectroscopy




Pohl 2010

# SCATTERING MEASUREMENTS

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{mott} \times \frac{E}{E'}\left[\frac{4m_P^2\left(G_E^2(Q^2) + \frac{Q^2}{4m_P^2}G_M^2(Q^2)\right)}{4m_P^2 + Q^2} + \frac{Q^2}{2m_P^2}G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$




Rosenbluth Deferential Cross Section

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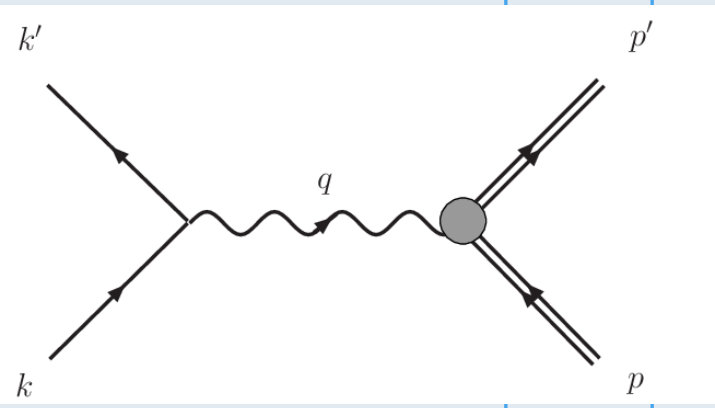


- Mott cross section can be extracted - $(\theta, E, m_l)$
- Lepton energy post scatter $(E')$ can be extracted - $(\theta, E)$
- Momentum Transfer $(Q^2)$ can be extracted - $(\theta, E, E')$
- When $Q^2 \to 0$ then $G_M^2(Q^2)$ is neglected

Measure $\frac{d\sigma}{d\Omega}, \theta, E$ to extract $G_E^2$

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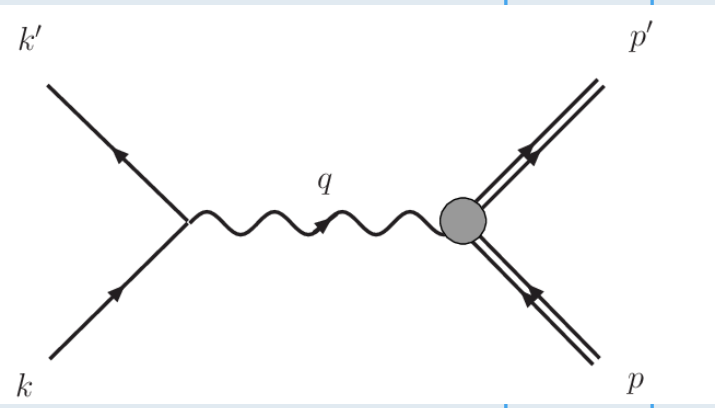


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Measure $\frac{d\sigma}{d\Omega}, \theta, E$ to extract $G_E^2$

$$\langle r_P^2 \rangle = -6\frac{dG_E^2(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

# Proton Radius measurements

$$\frac{\int r^2 \rho(r) d^3 r}{\int \rho(r) d^3 r} \qquad -6 \frac{dG_E^2}{dQ^2}\Big|_{Q^2=0} \qquad \propto \left(\frac{m_l + m_P}{m_l m_P}\right)^3 \Delta E_n$$

| $r_p$ | Scattering | Spectroscopy |
|---|---|---|
| $e$ | | |
| $\mu$ | | |

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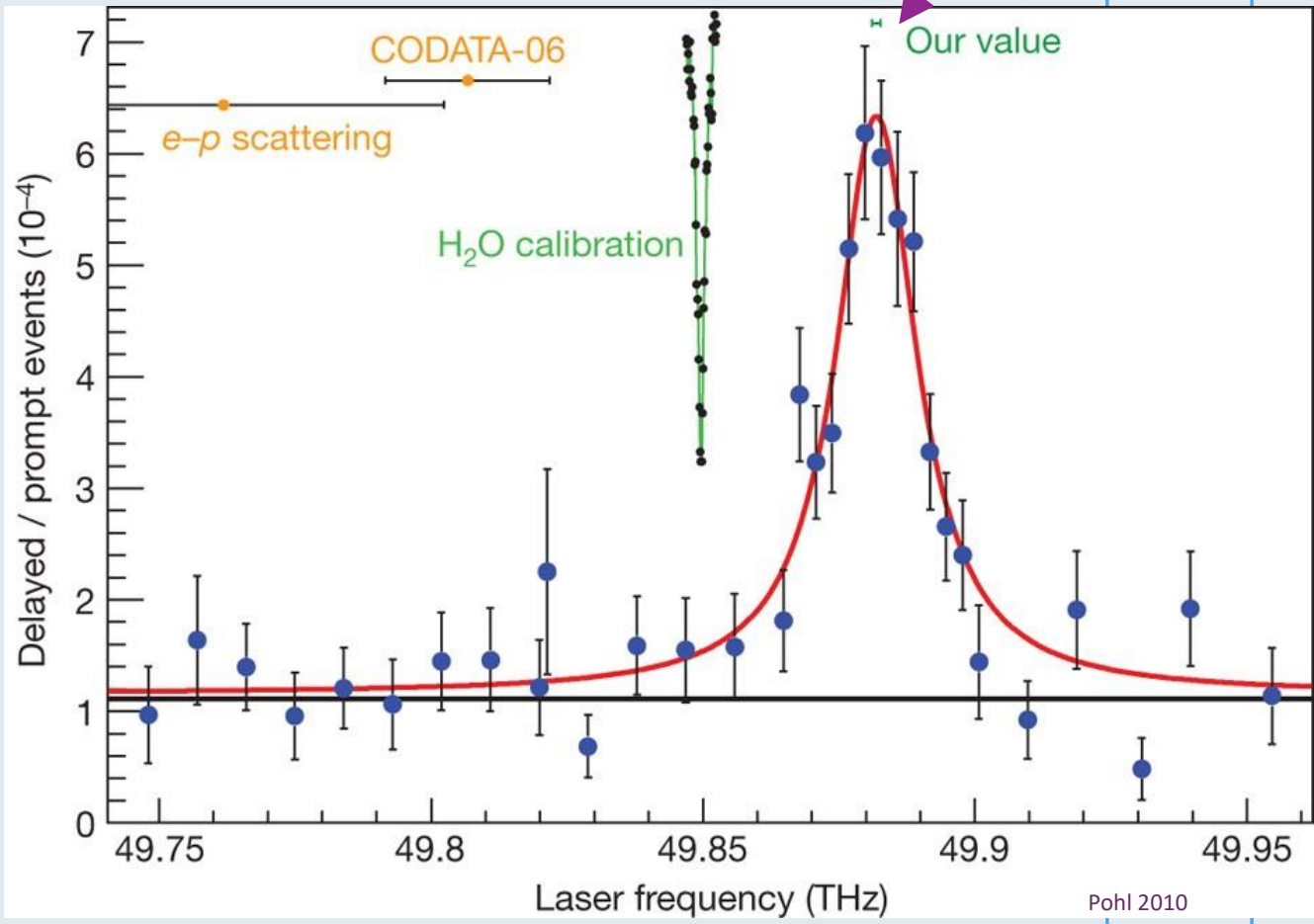
| $r_p$ | Scattering | Spectroscopy |
|---|---|---|
| $e$ | $0.875 \pm 0.0060$ | $0.877 \pm 0.0077$ |
| $\mu$ | | |

Units are in fm ($10^{-15}\ m$)

# Proton Radius Puzzle

$$r_P = 0.841 \pm 0.00039\ fm$$




Pohl 2010

# Proton Radius ~~measurements~~ Puzzle

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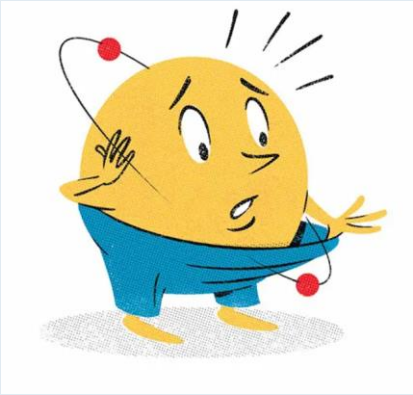

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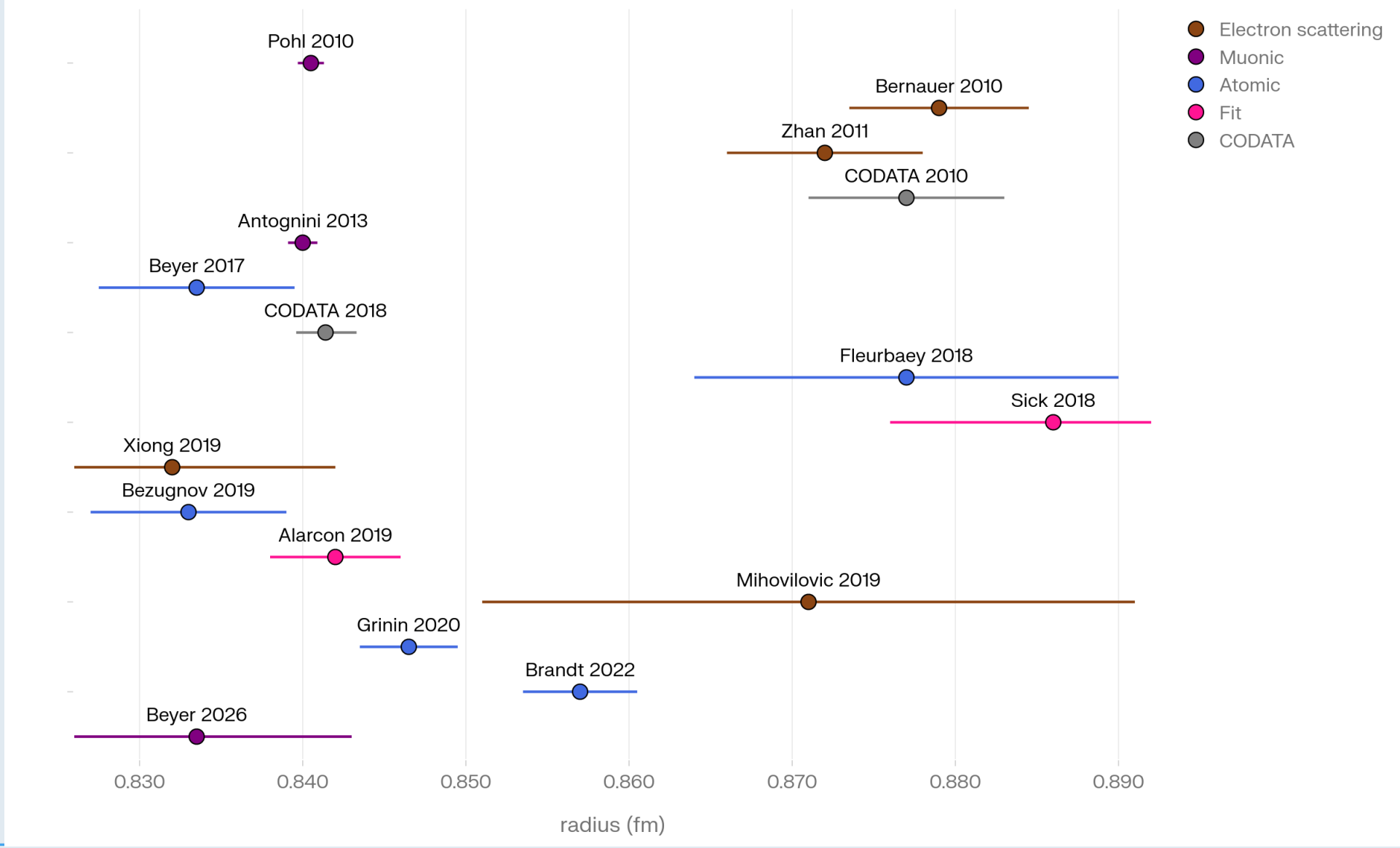

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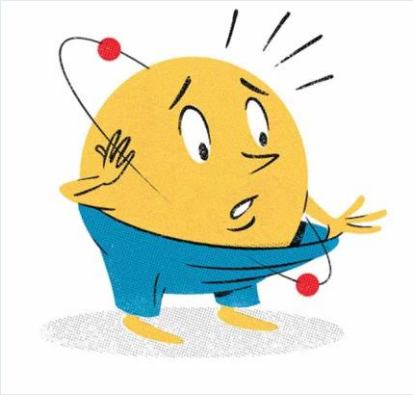

| $r_p$ | Scattering | Spectroscopy |
|---|---|---|
| $e$ | $0.875 \pm 0.0060$<br>$0.831 \pm 0.017$ | $0.877 \pm 0.0077$<br>$0.833 \pm 0.010$<br>$0.8433 \pm 0.0031$ |
| $\mu$ | | $0.841 \pm 0.00039$<br>$0.842 \pm 0.00067$ |

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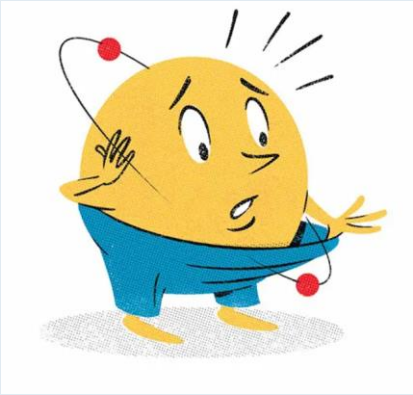

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| $\mu$ | MUSE | $0.841 \pm 0.00039$<br>$0.842 \pm 0.00067$ |

- $e$ and $\mu$ determination do not always **agree**
- No $\mu p$ scattering
- **MUSE** is designed to test this directly

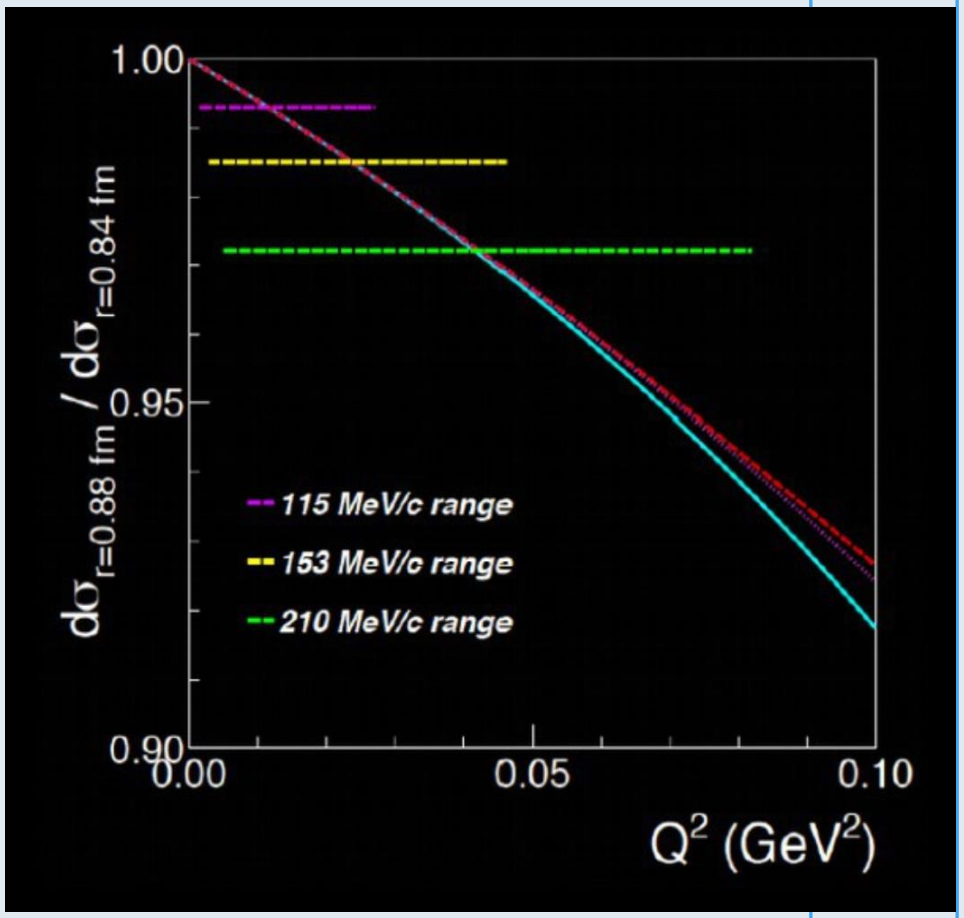
Units are in fm ($10^{-15}\ m$)

# WHAT MUSE DOES DIFFERENTLY?

- Simultaneous $e^{\pm}, \mu^{\pm}$ and $\pi^{\pm}$ beam
- Dual polarity beam: **Lepton universality**, **Two Photon Exchange (TPE)**
- Low-$Q^2$ coverage range

$$(0.002 - 0.08\ GeV^2)$$

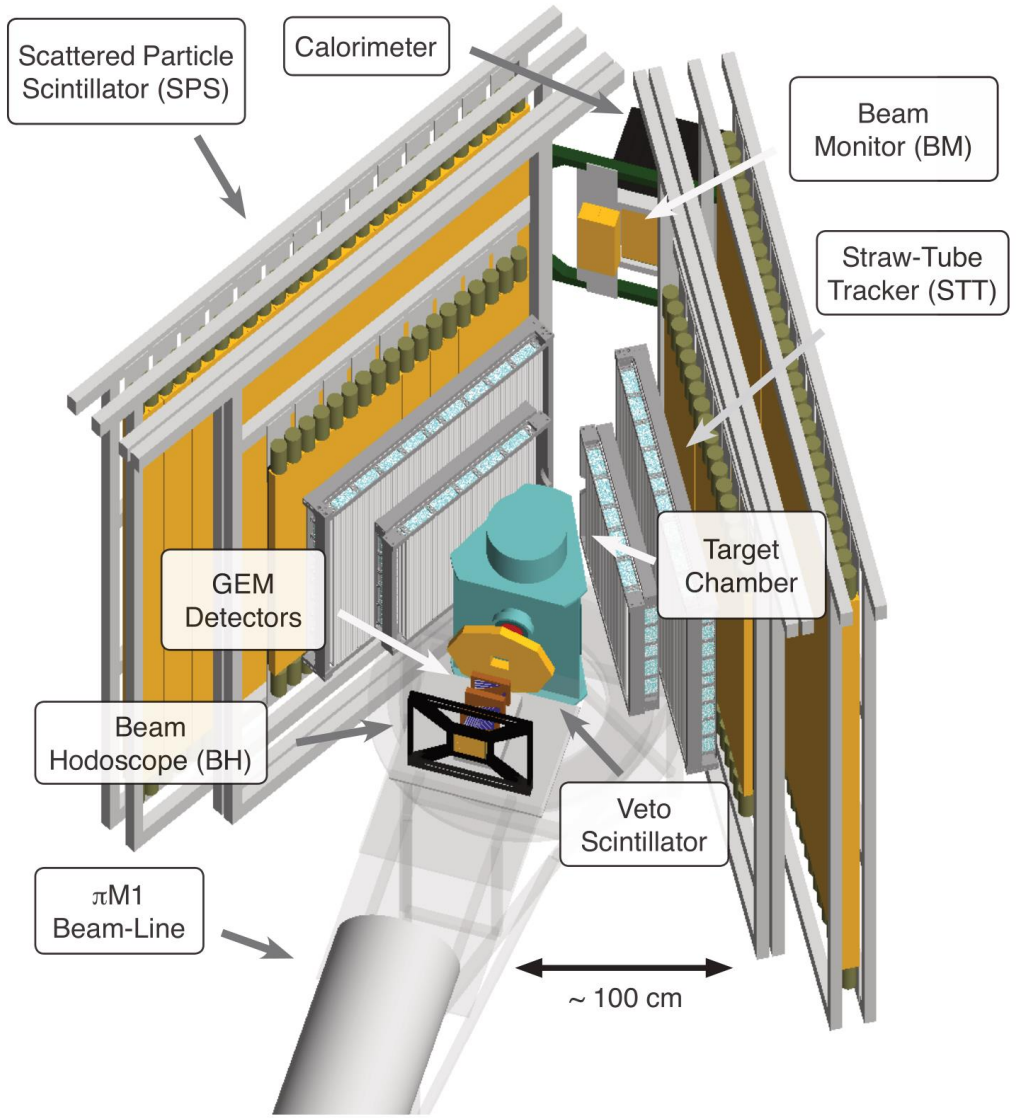
- Systematics: Same apparatus, same target, same kinematics
- High precision
- Scattering angle: $20 - 100$ degrees (2 sides)
- Fully blinded (more later)



# WHAT MUSE DOES DIFFERENTLY? SCATTERING EXPERIMENTS:

| Experiment | Low Energy/ Wide Angles | $e^-$ | $e^+$ | $\mu^-$ | $\mu^+$ |
|---|---|---|---|---|---|
| Mainz 2010 | ✓ | ✓ | | | |
| PRad JLab | | ✓ | | | |
| Mainz ISR | ✓ | ✓ | | | |
| Mainz Jet | ✓ | ✓ | | | |
| MUSE PSI | ✓ | ✓ | ✓ | ✓ | ✓ |
| ULQ2 ELPH | ✓ | ✓ | | | |
| AMBER CERN | | | | ✓ | ✓ |
| MAGIX MESA | ✓ | ✓ | | | |
| PRad II JLab | | ✓ | | | |

# Muse Detectors Setup




Reminder, **per lepton type**:

- Measure $\frac{d\sigma}{d\Omega}, \theta, \boldsymbol{E}$
- Extract $G_E^2$
- Calculate $r_P$

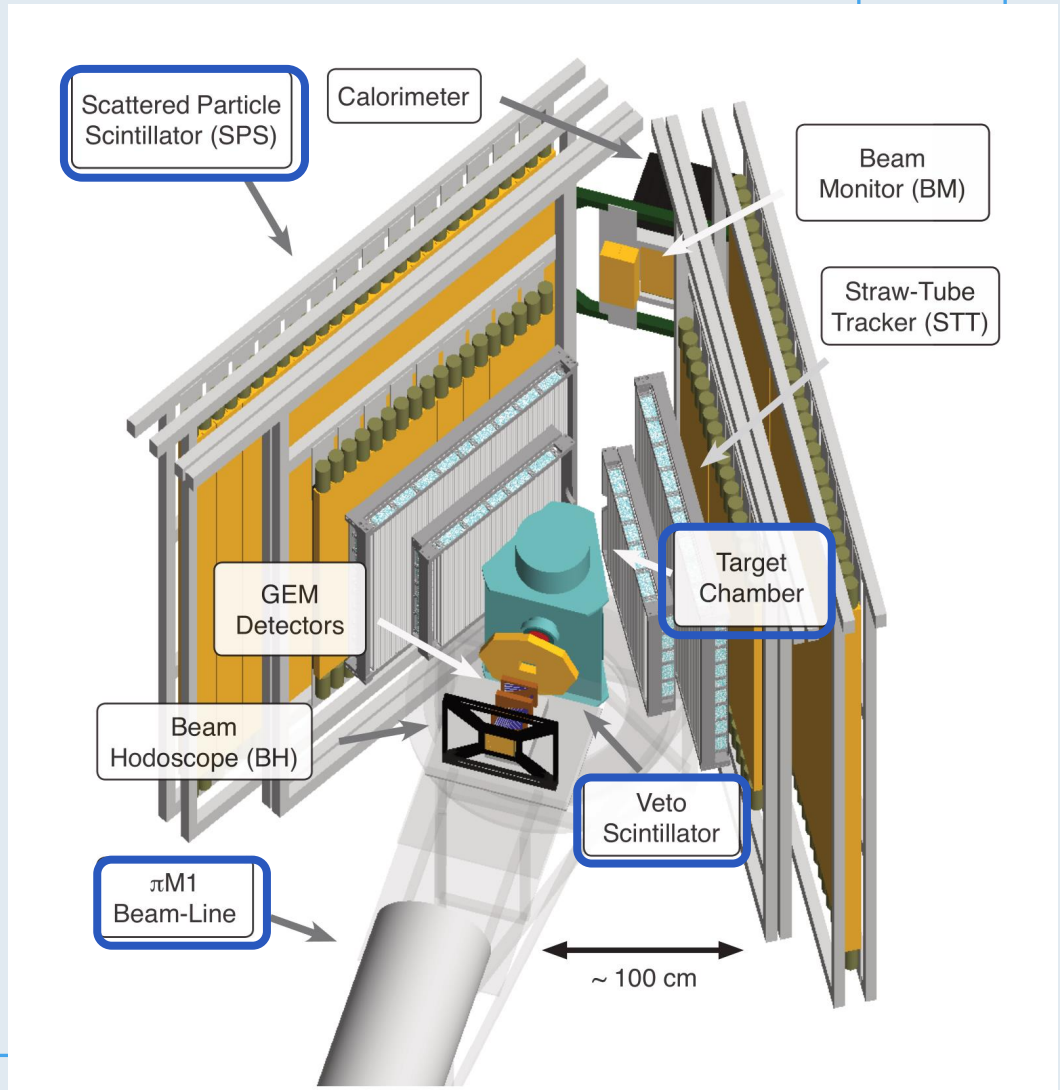
# Trigger

RF timing

‘Hit’ at Scattered Particle Scintillators

No ‘Hit’ at Veto detector

A scattering event recorded

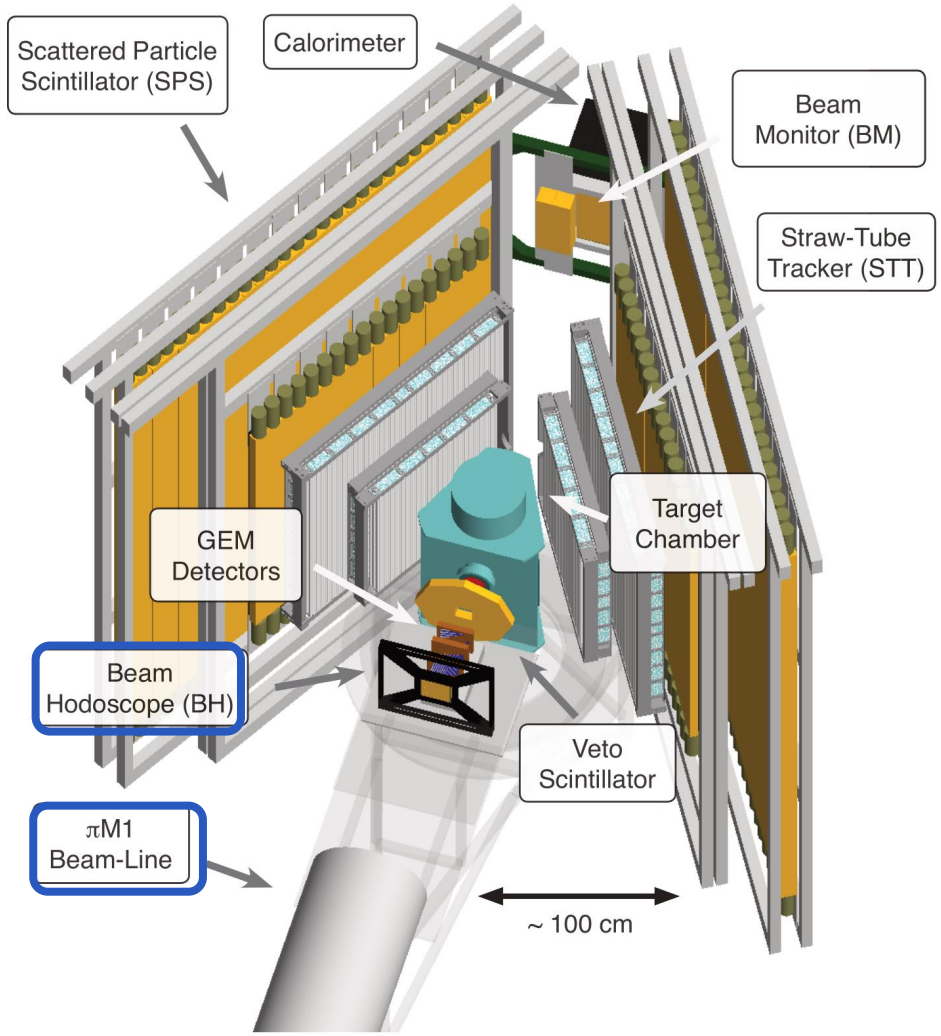


# Particle ID

A scatter event recorded

$$\Delta T = T_{Production} - T_{BH}$$

Particle ID



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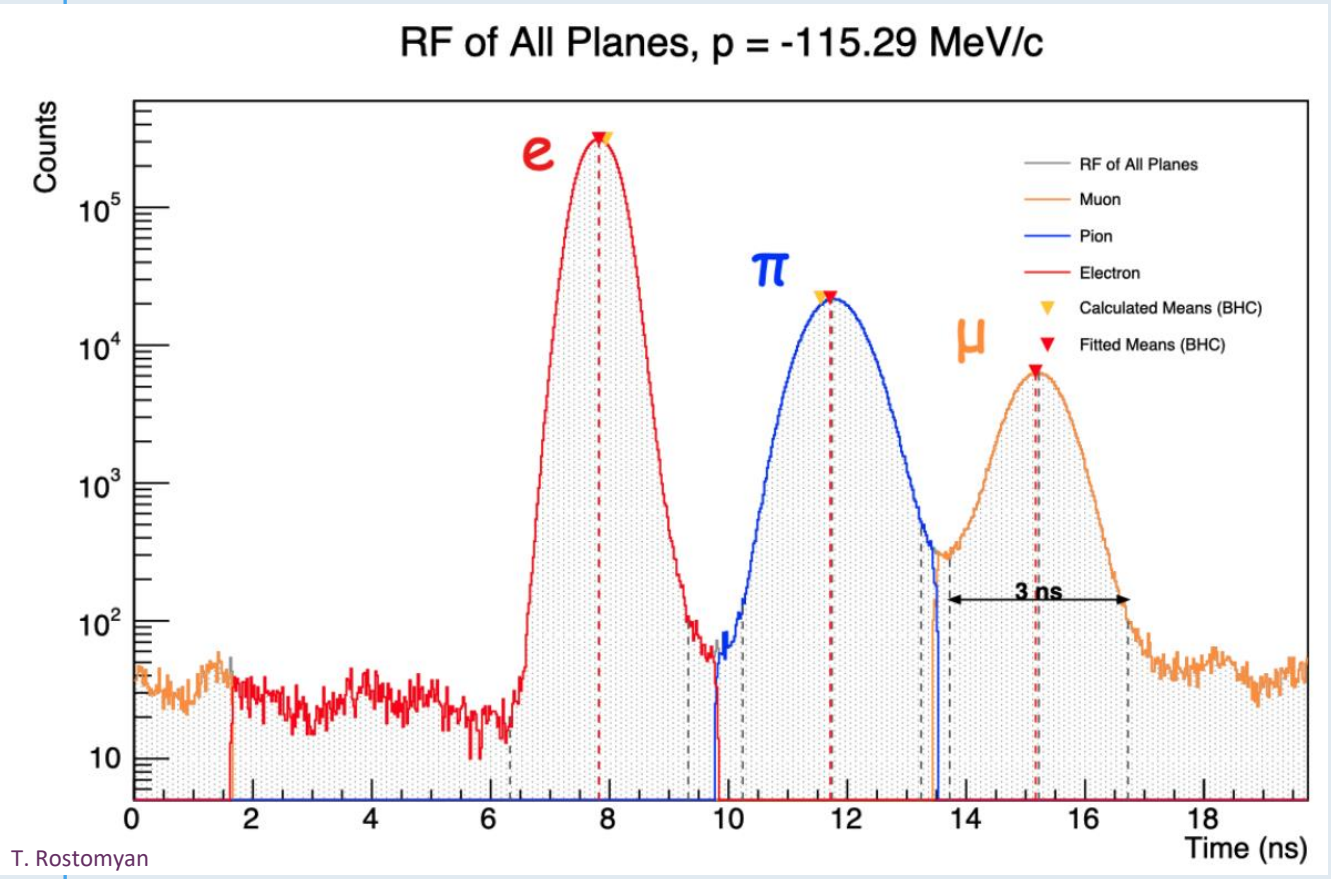
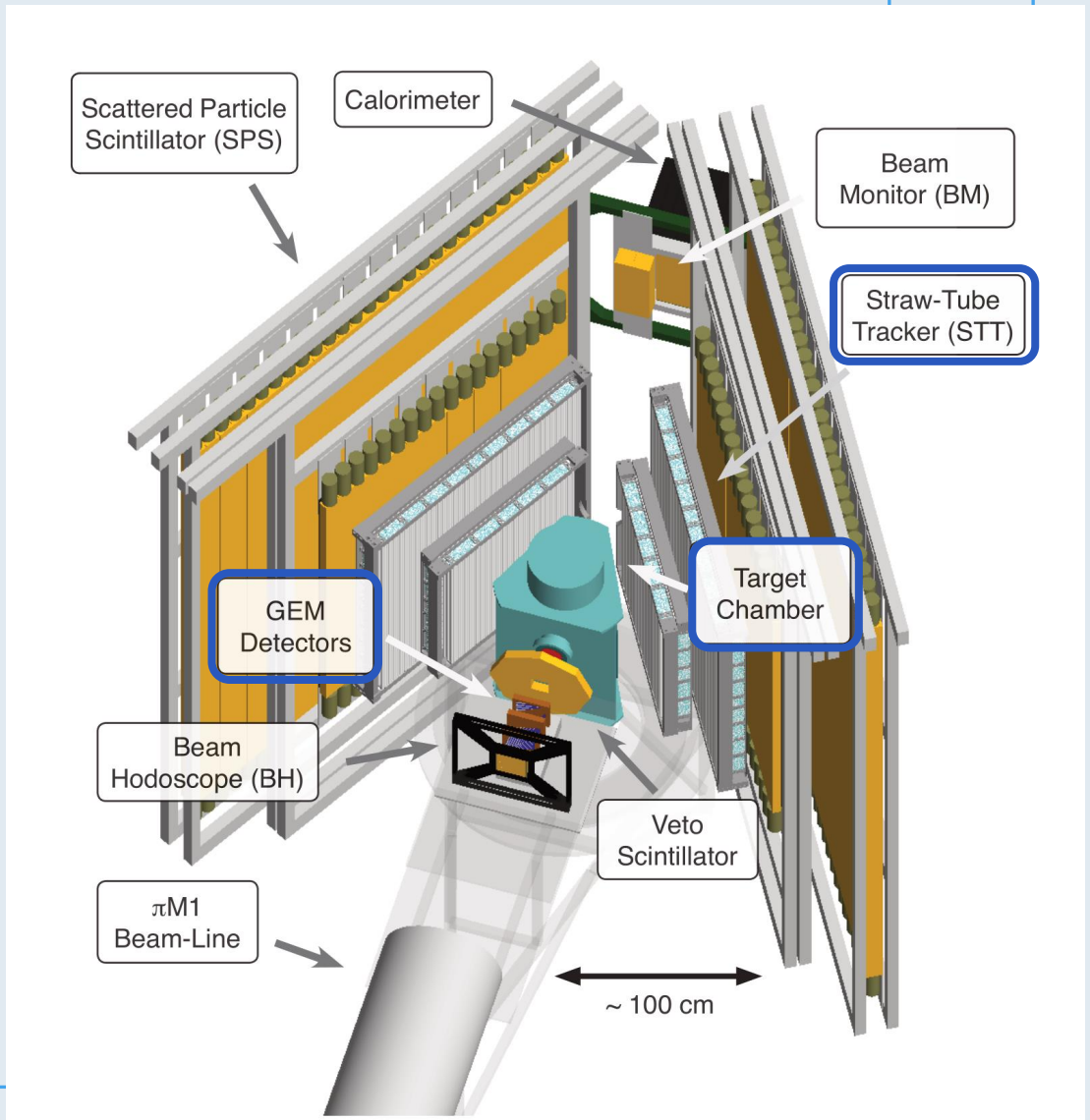



T. Rostomyan

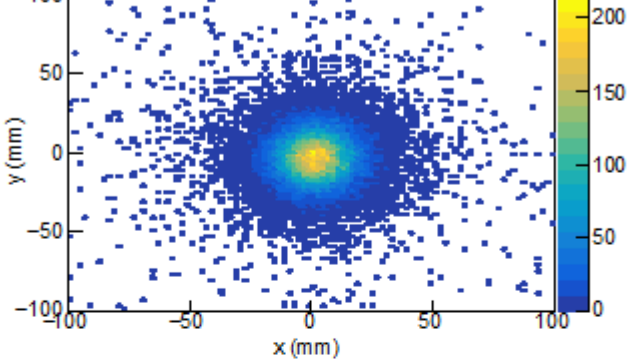
RF: Relative time between **BH** and the **production target**

# Scattering Angle $\theta$

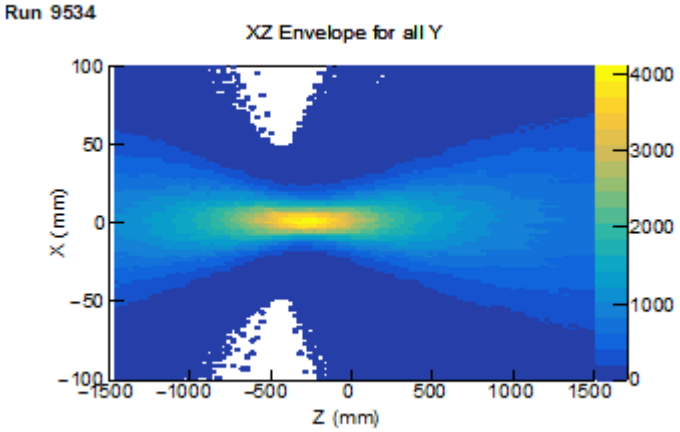
GEM Trajectory extraction → STT Trajectory extraction → Vertex reconstruction → $\theta$

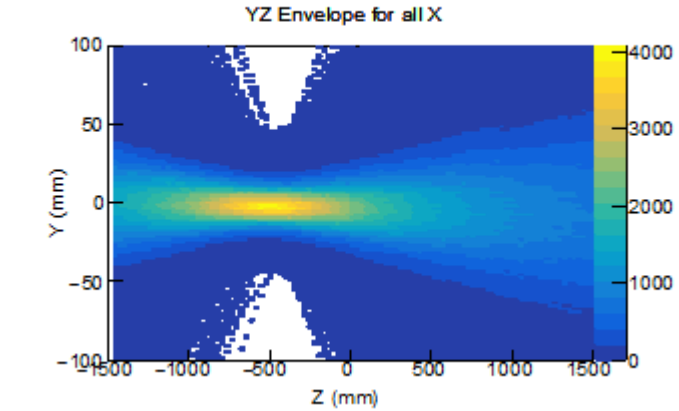


# Scattering Angle $\theta$

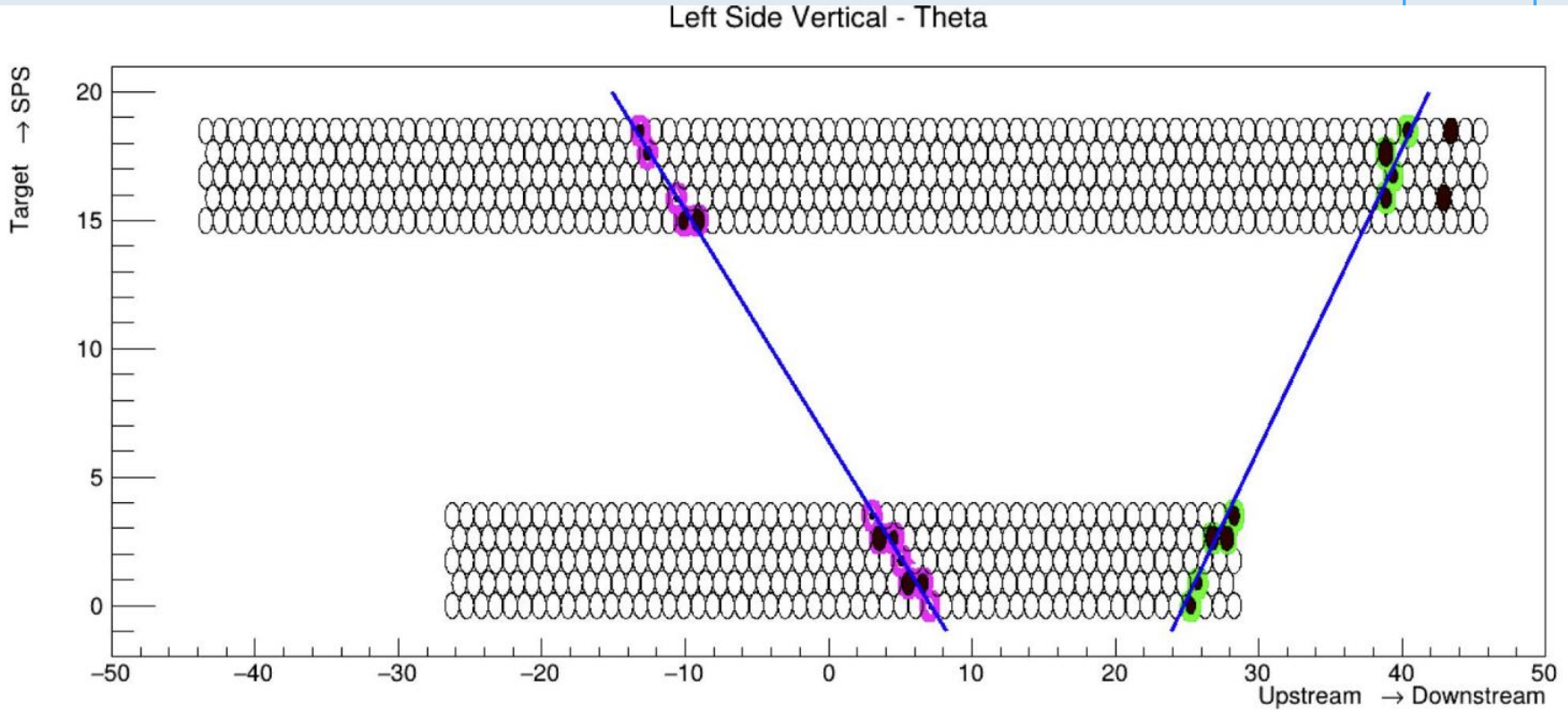



**GEMs - Gas Electron Multiplier**

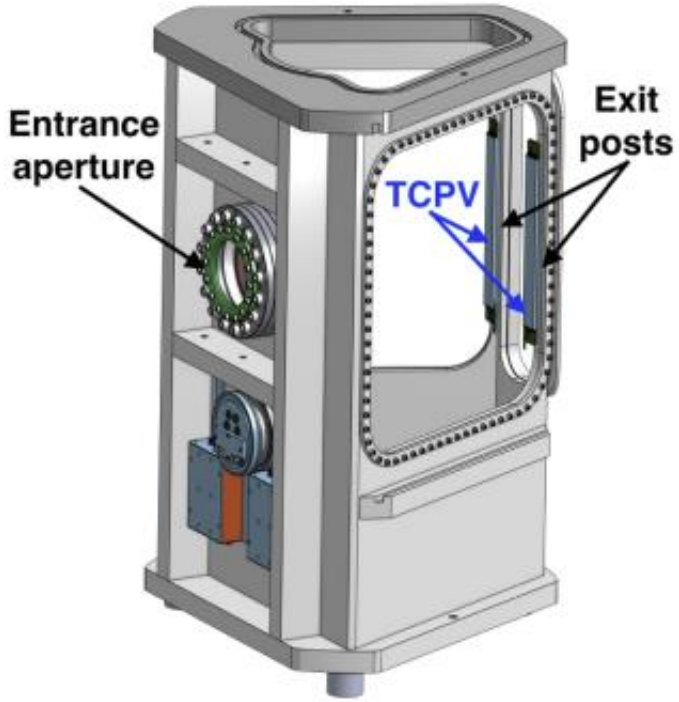


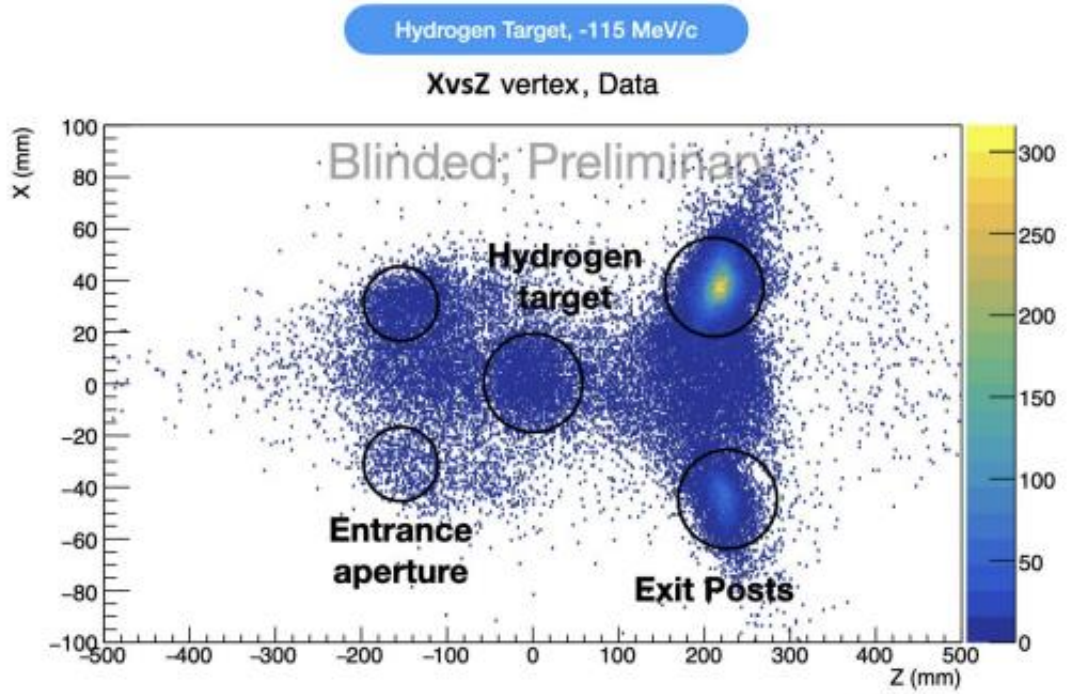




**STT - Straw Tube Tracker**



# Scattering Angle $\theta$ Vertex Reconstruction



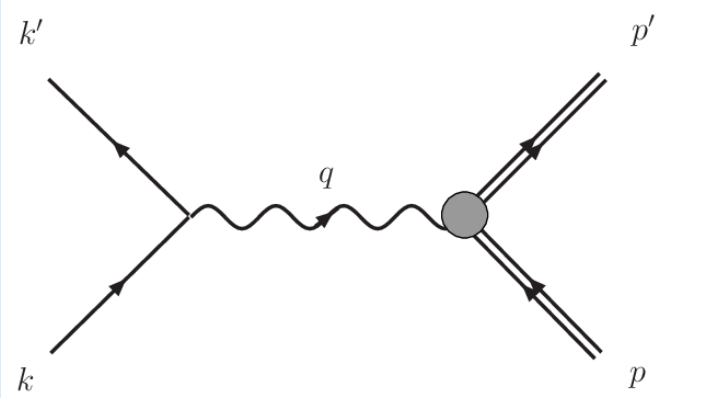



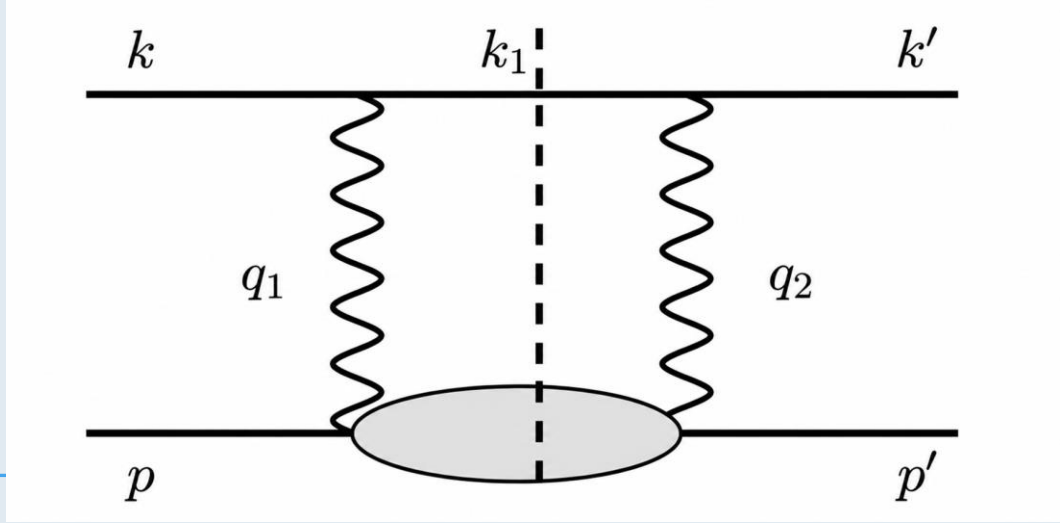

LH2 target reconstruction for p = -115 MeV/c

# TWO PHOTONS EXCHANGE (TPE)

Two-Photon Exchange (TPE) is an **additional term** for cross-section amplitude

Can be extracted by $e^+/e^-$ and $\mu^+/\mu^-$ scatter ratios



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$$M_{1\gamma} \propto e^2$$

$$M_{2\gamma} \propto e_l e^2$$

# TWO PHOTONS EXCHANGE (TPE)

Two-Photon Exchange (TPE) is an **additional term** for cross-section amplitude

**Will** be extracted by $e^+/e^-$ and $\mu^+/\mu^-$ scatter ratios

$$\left(\frac{d\sigma}{d\Omega}\right) \approx \left(M_{(1\gamma)} + M_{(2\gamma)}\right)^2 \approx M_{(1\gamma)}^2 \mp 2\mathbb{R}\left[M_{(1\gamma)} M_{(2\gamma)}\right] + \cdots$$

$$R_{l^+,l^-} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{l^+p}}{\left(\frac{d\sigma}{d\Omega}\right)_{l^-p}} = 1 - 2\Delta_{TPE}$$

# RADIATIVE EFFECTS

Bremsstrahlung radiation - Accelerated charged particle emit radiation

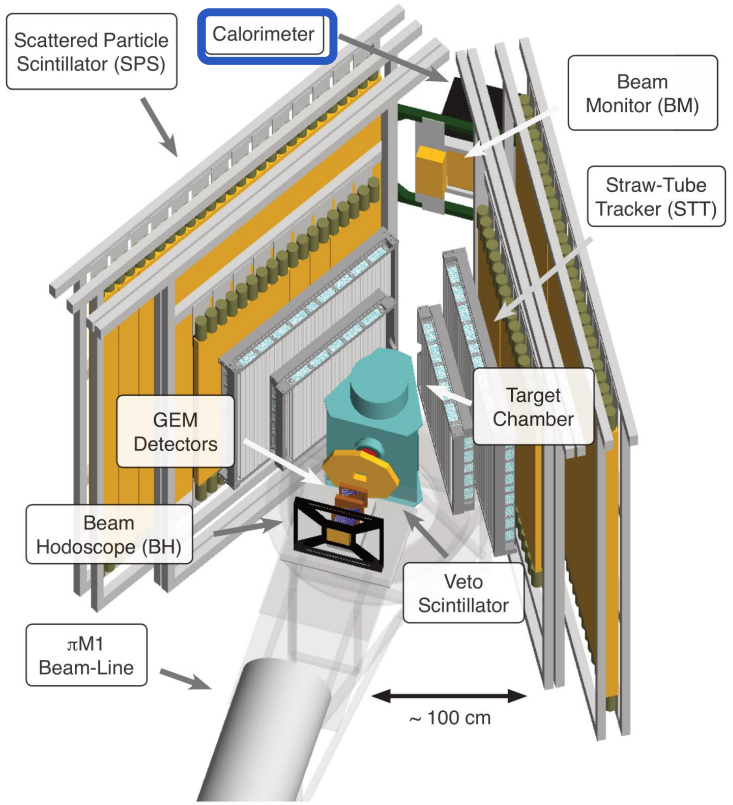
→ Loss energy

Most effective when $\frac{m_l^2}{Q^2} \ll 1$ Ratio is **small** $(e^-, e^+)$

Most effective at large angles

# RADIATIVE EFFECTS @ MUSE

Done with calculation and measurements by the calorimeter detector



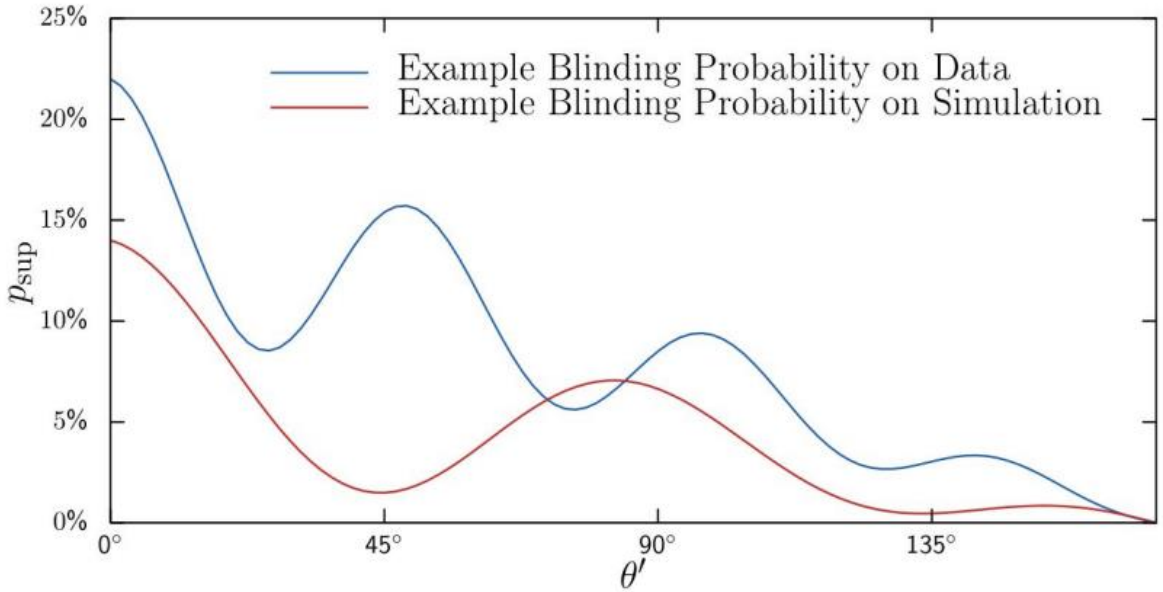

$$lp \rightarrow lp\gamma$$

Important correction for the comparison of $e$ and $\mu$

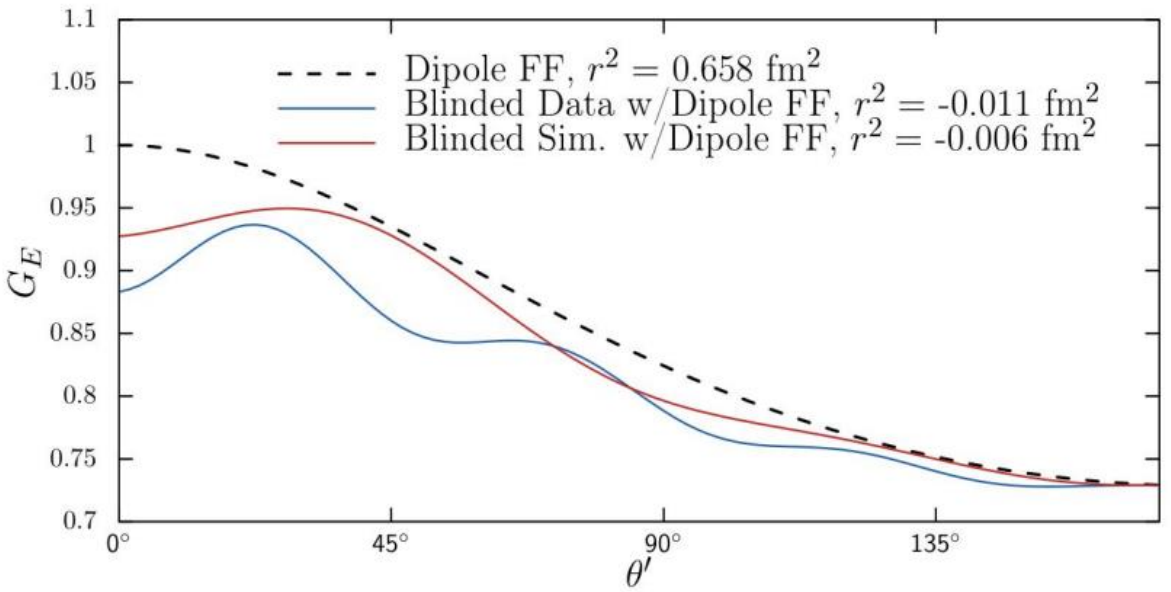
# Blinding

$$P = \frac{1}{15}(3 - \theta')(A + 0.3B \cdot \cos(B + \theta'))$$
$$A = [0.25,1], B = [3,10]$$

Changes **Clusters** of data



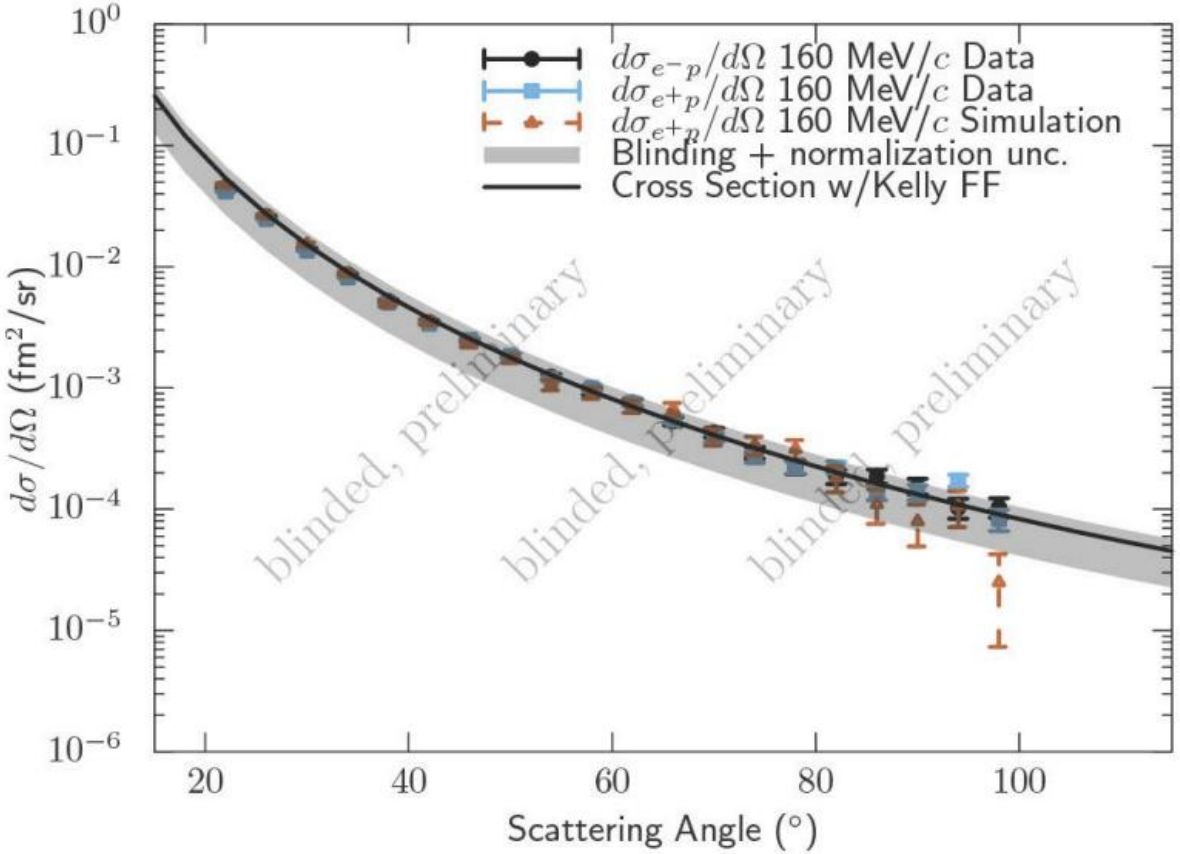

Example blinding distribution for data & simulation,
A = 0.4 (0.8) and B = 4.1 (7.2)

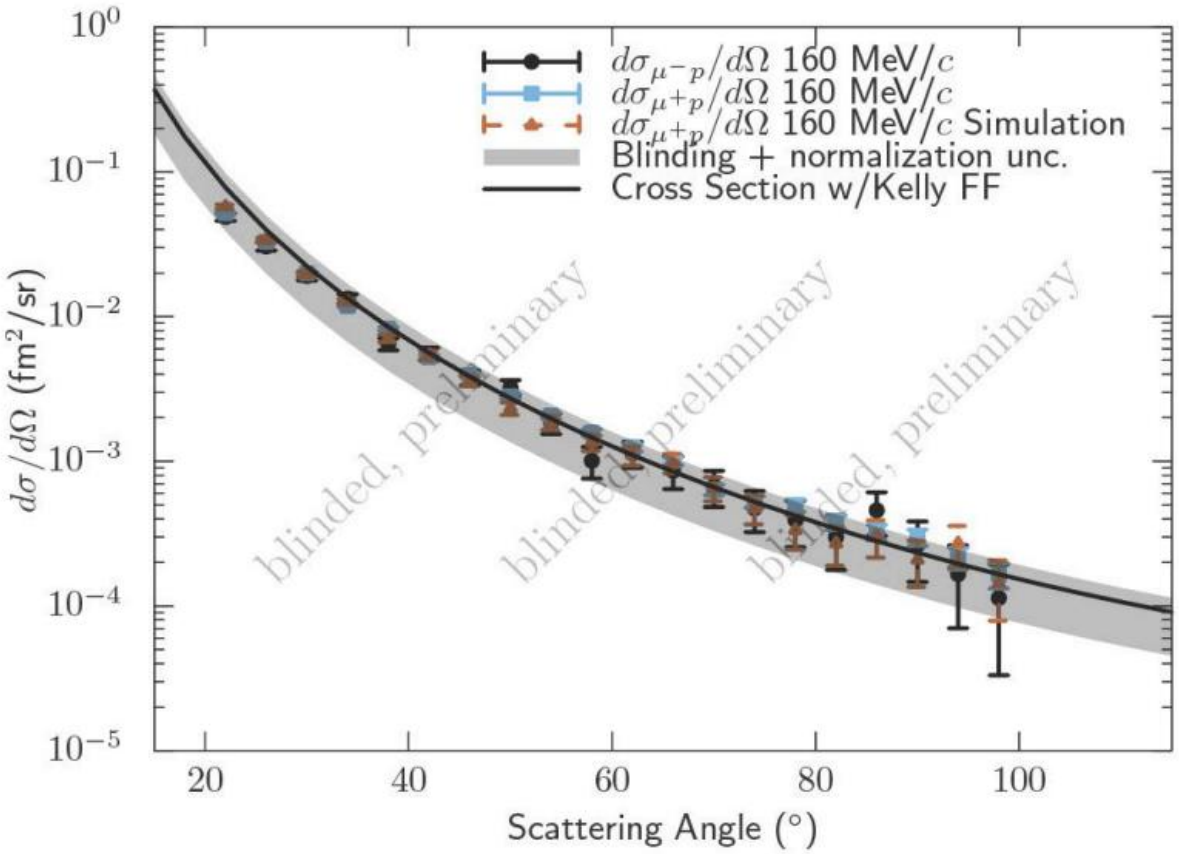


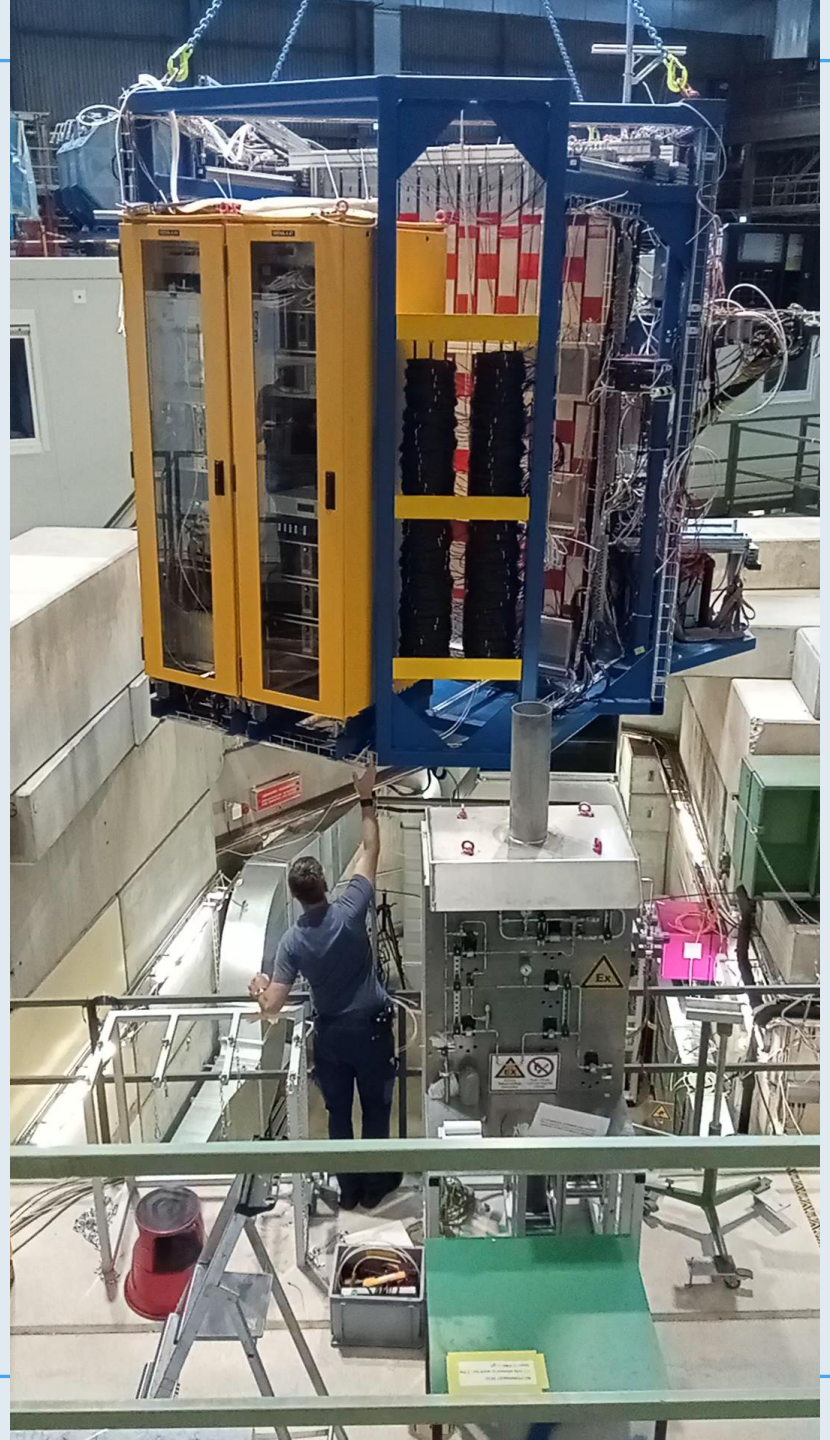

Effect of blinding on Sachs electric form factor $G_E$ for MUSE data & simulation

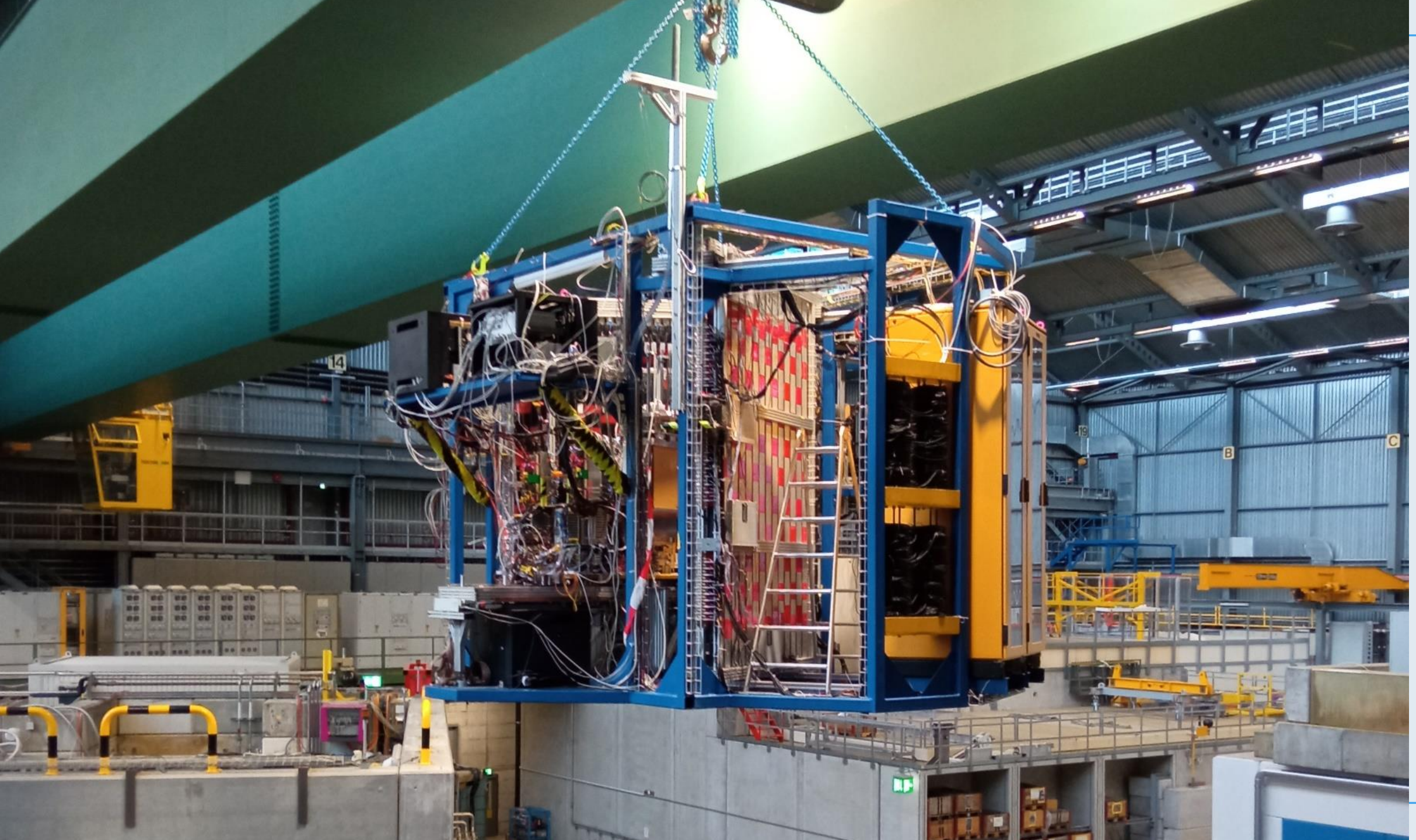
Bernauer, 2023

# Current Analysis Status





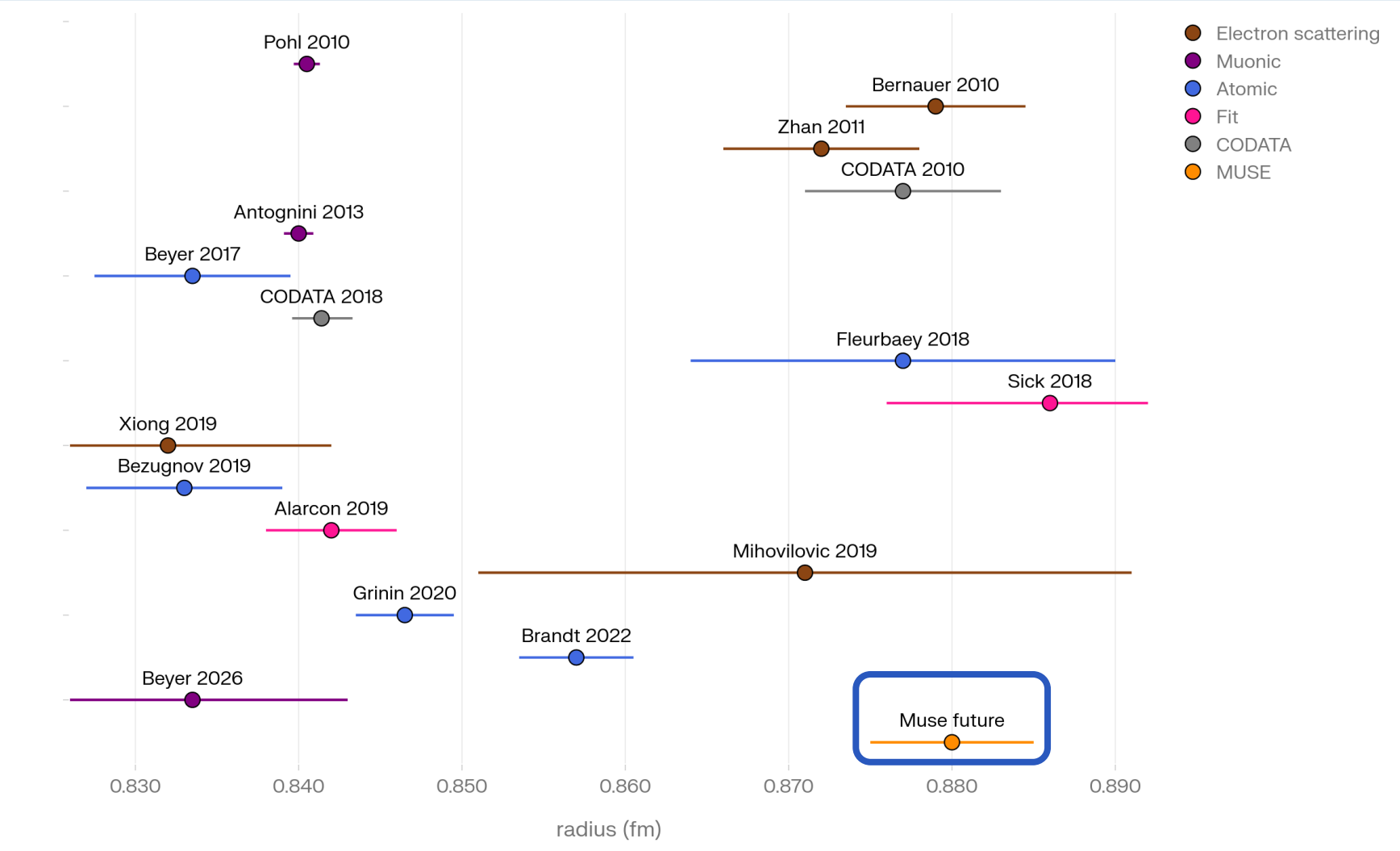



- Production data collected **completed** $\approx 10^{10}$ events
- Started final measurement period **yesterday** (systematics)
- Final analysis stage

- Will provide novel data (TPE, radiative correction)
- Will provide measurements with 2(4) leptons
- Accurate scattering measurements

- Expected uncertainty **below %1**

# Proton Radius measurements With Muse (arbitrary located)



# THANK YOU FOR LISTENING!

*Without a question, a good answer has no place to go…*


Dvir Yaari, **Muse**, HUJI
dvir.yaari@mail.huji.ac.il