Precision physics at MESA

Tyler Kutz
MIT

2024 Joint Photonuclear Reactions and Frontiers & Careers Workshop

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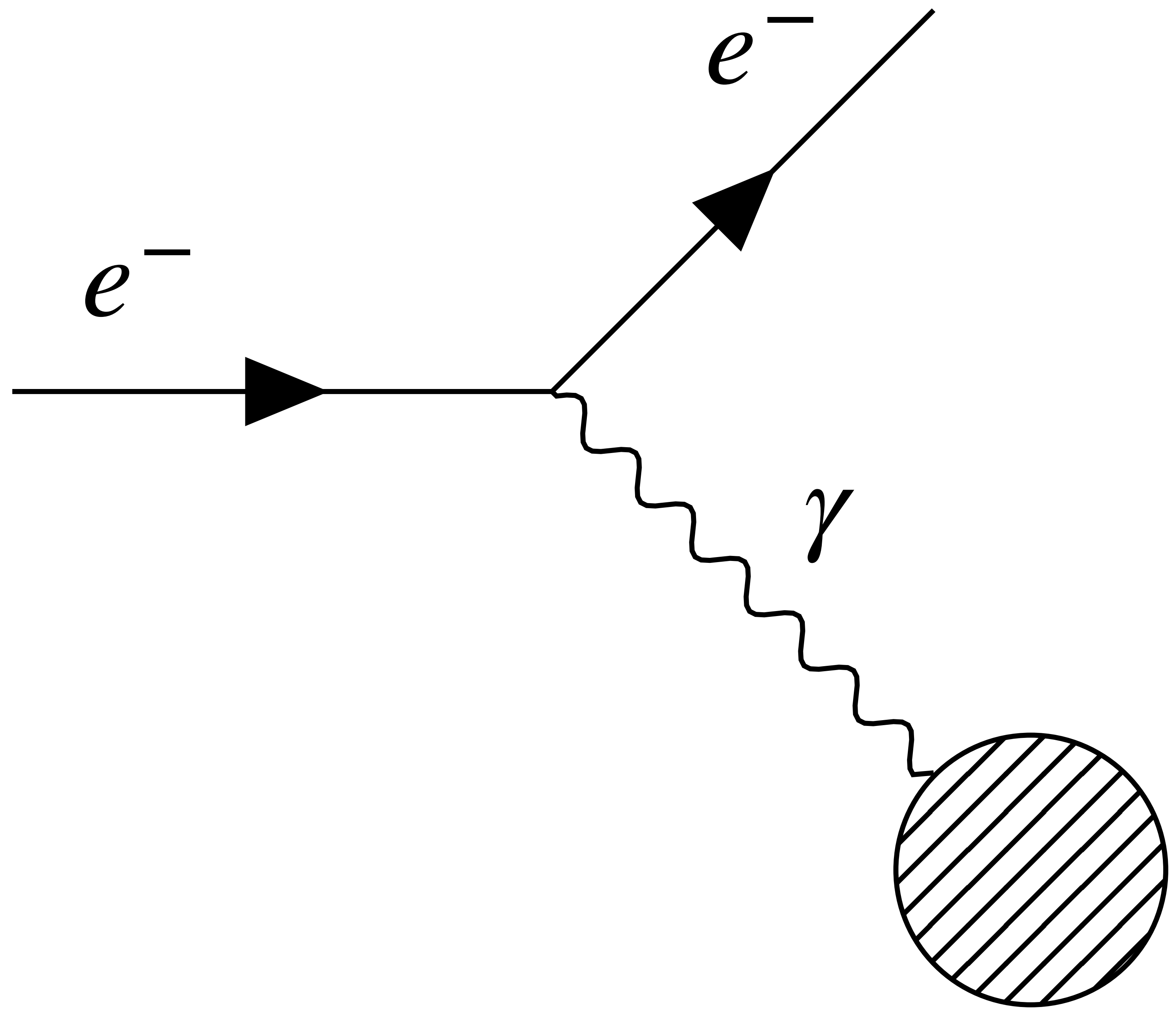
Electron scattering powerful tool for probing nuclear structure and interactions



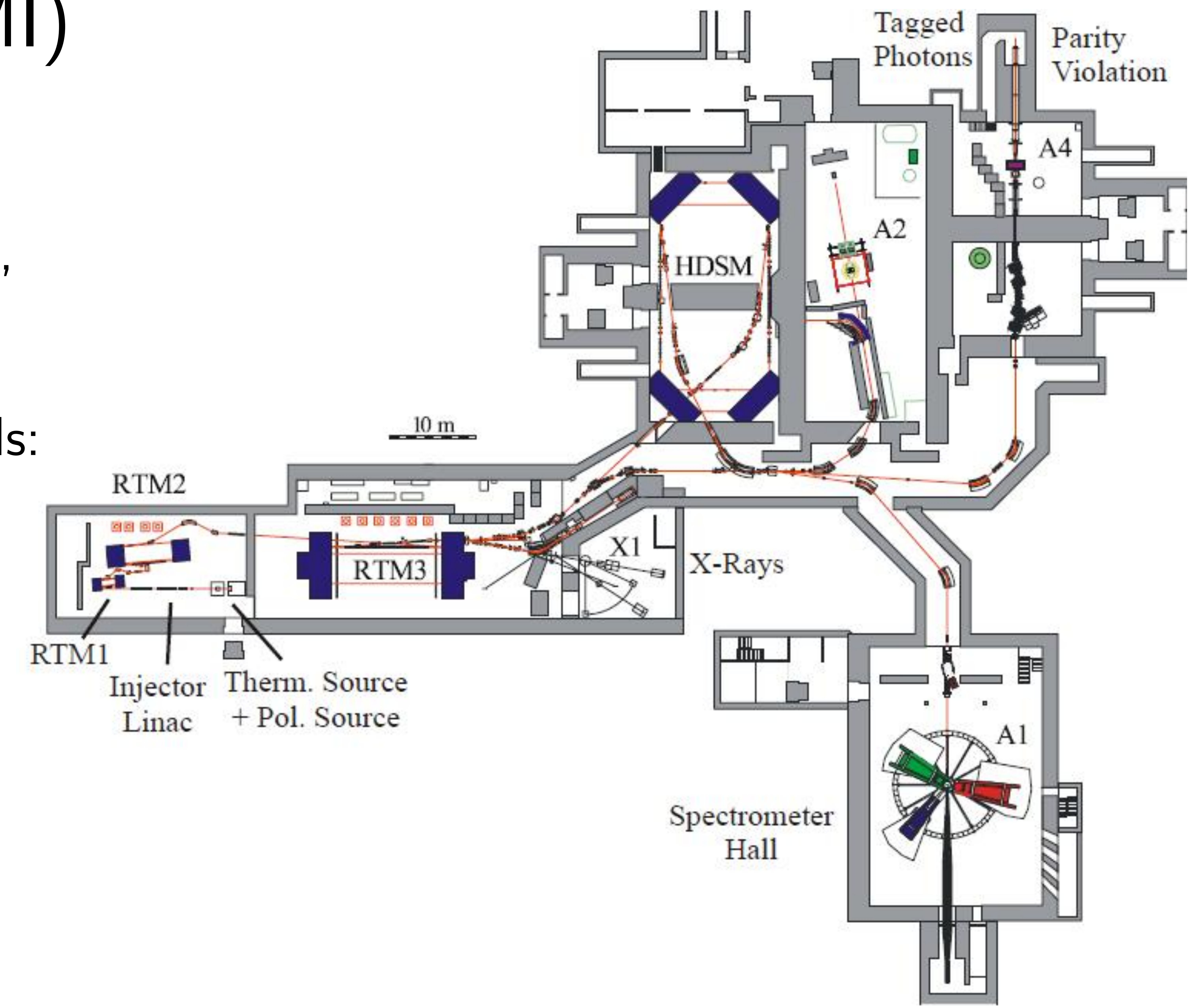
- Convenient to...
  ...produce electron beams
  ...detect scattered electrons
- Nuclear structure measurements frequently interpreted in *Born approximation*
- Study fundamental interactions with processes *beyond one-photon exchange*


D
A
B
C

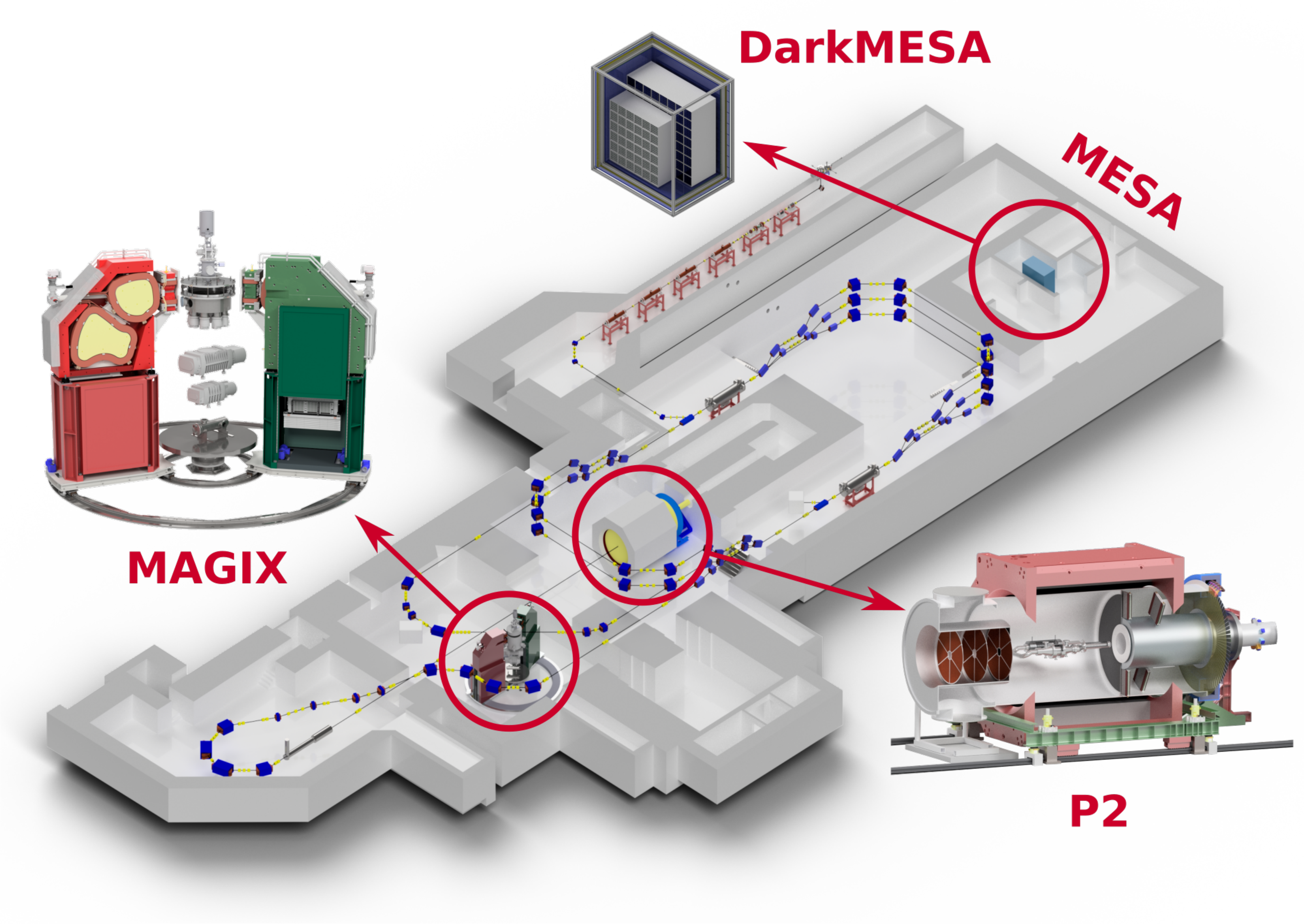

JG|U
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Mainz Microtron (MAMI)

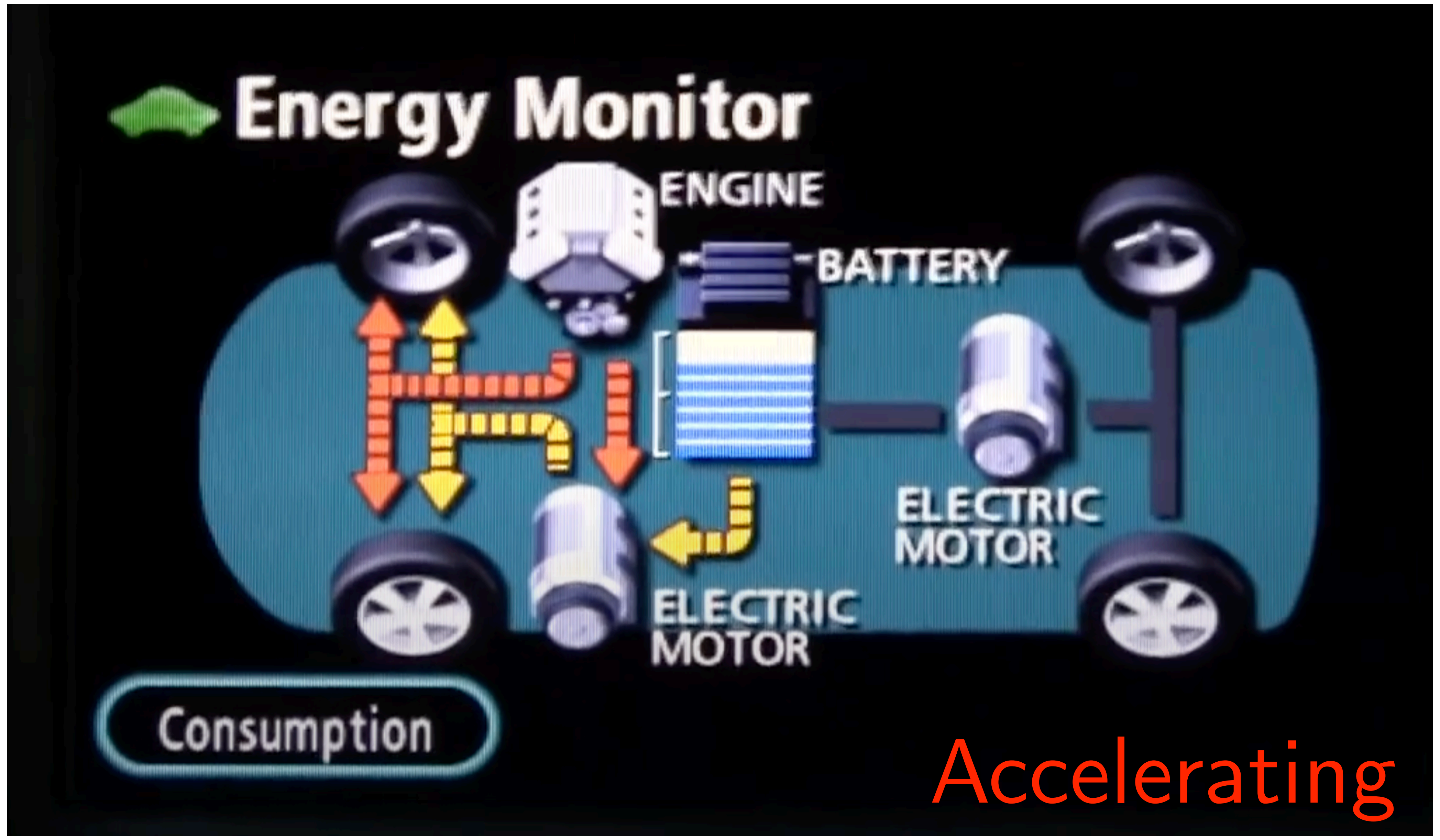
- Beam energy up to 1.5 GeV
- Currents up to 20 μA (polarized), 100 μA (unpolarized)
- Complementary experimental halls:
  - High-resolution spectrometers (A1)
  - Tagged real photon beams (A2)
  - Parity violation (A4)



Mainz Energy-recovery Superconducting Accelerator (MESA)



What is energy recovery?



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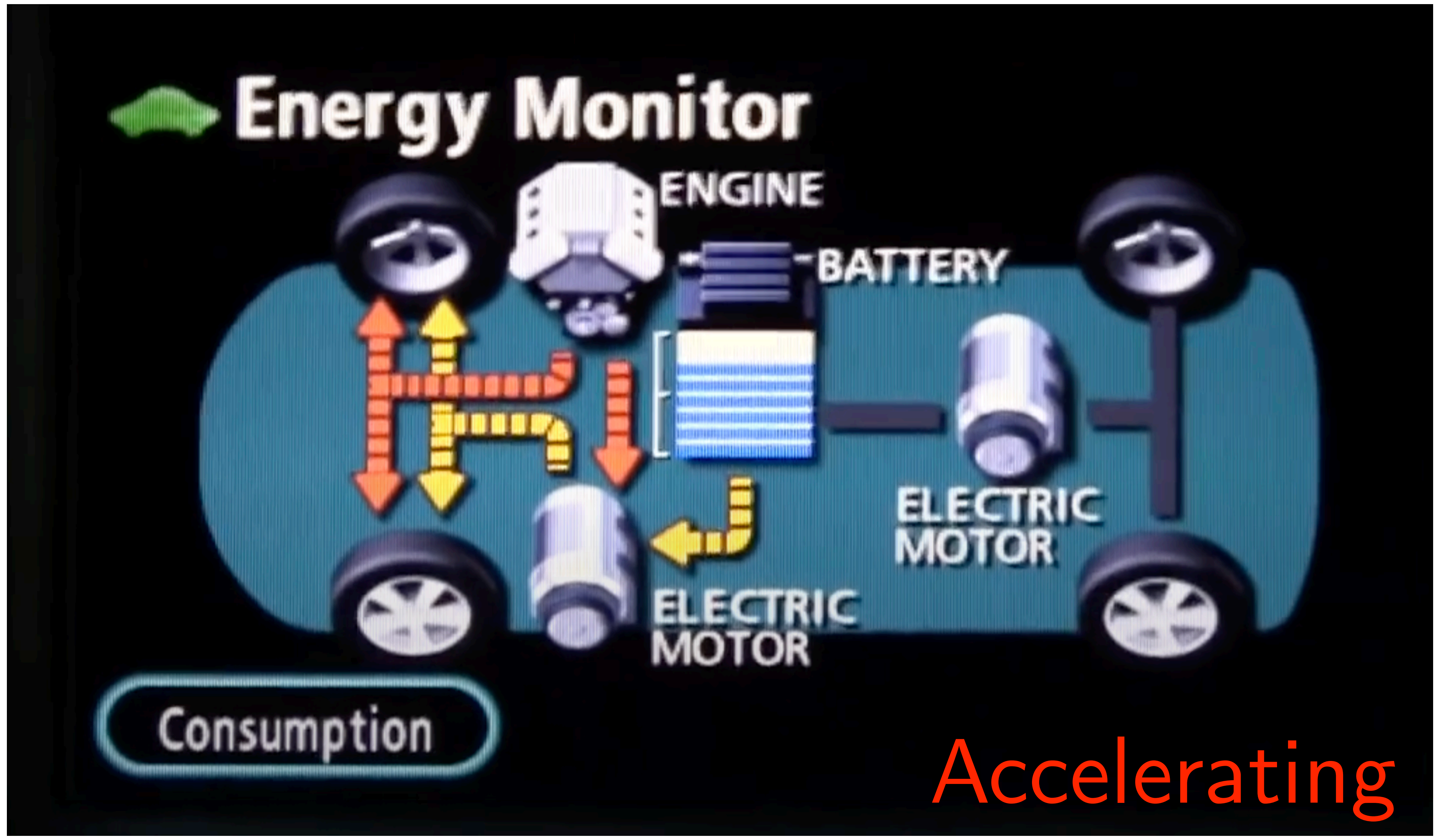

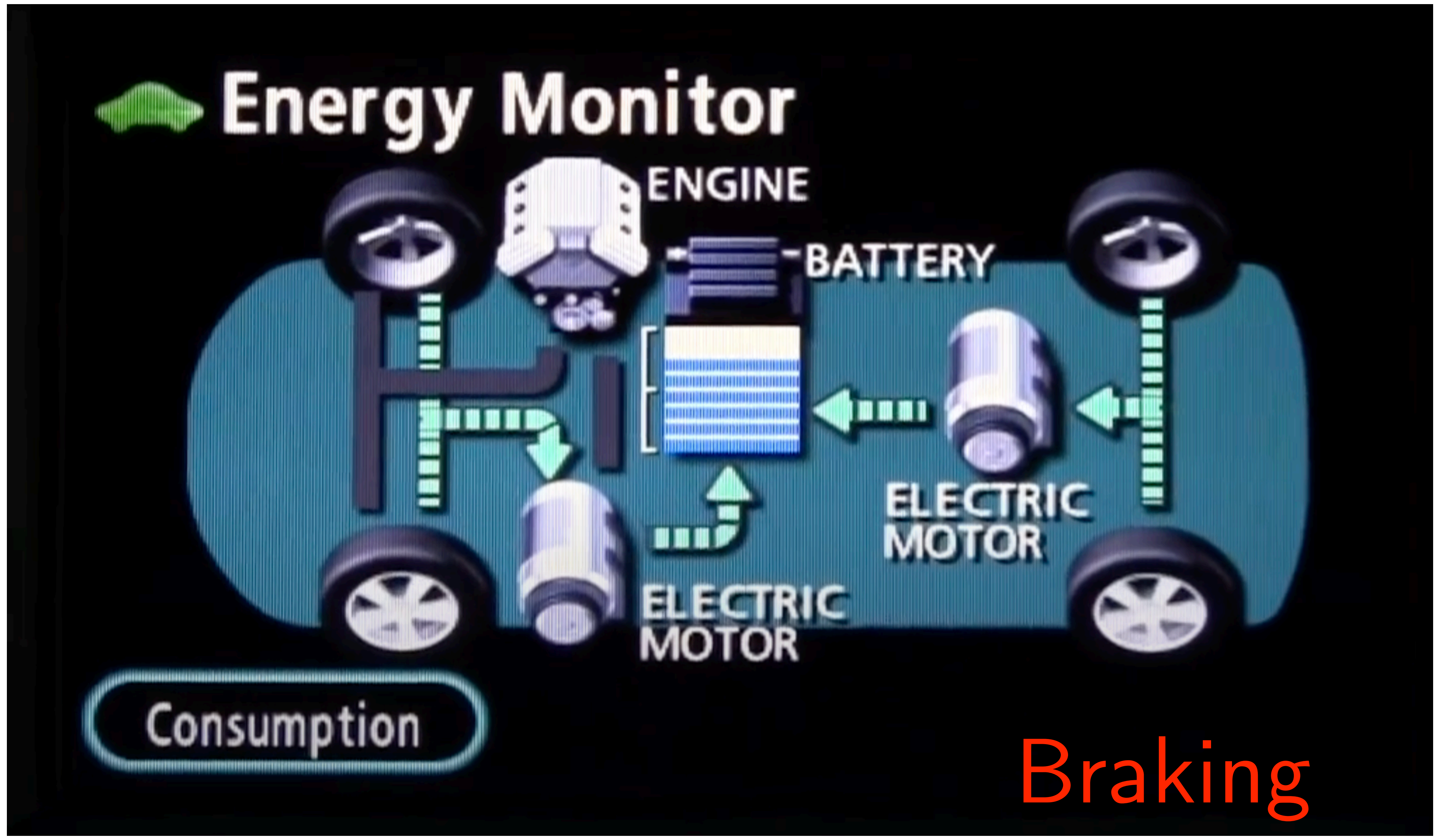

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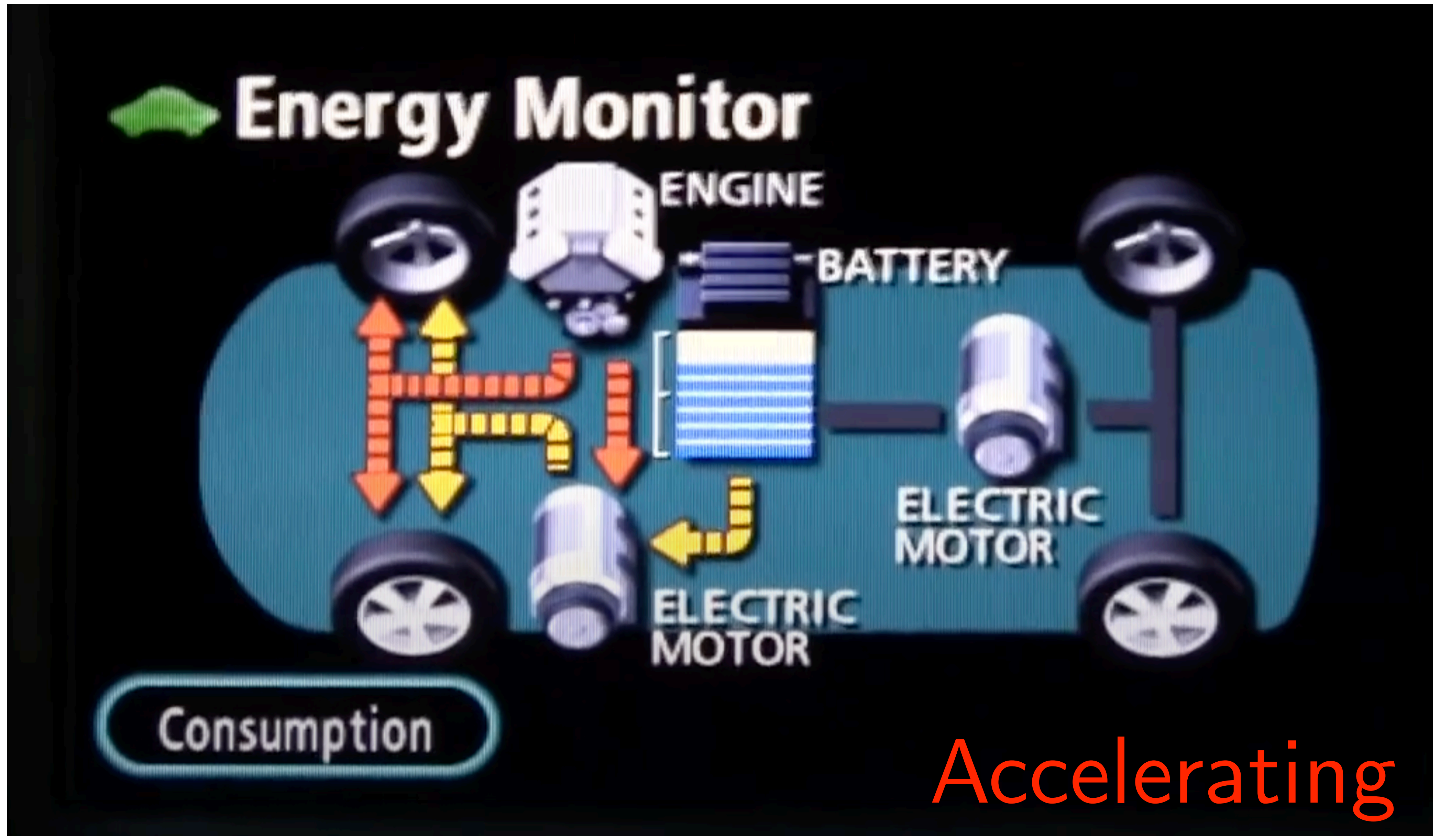
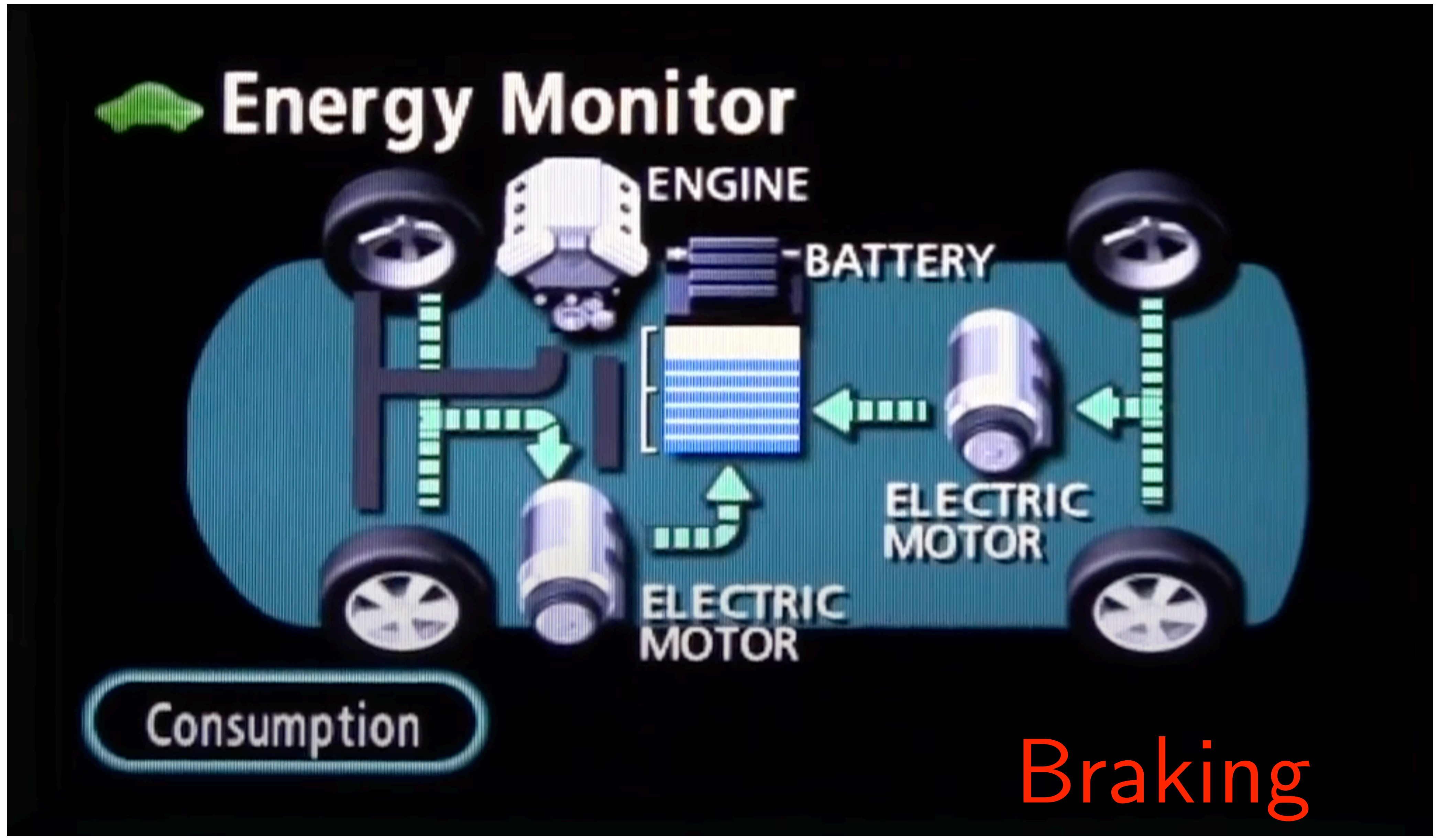
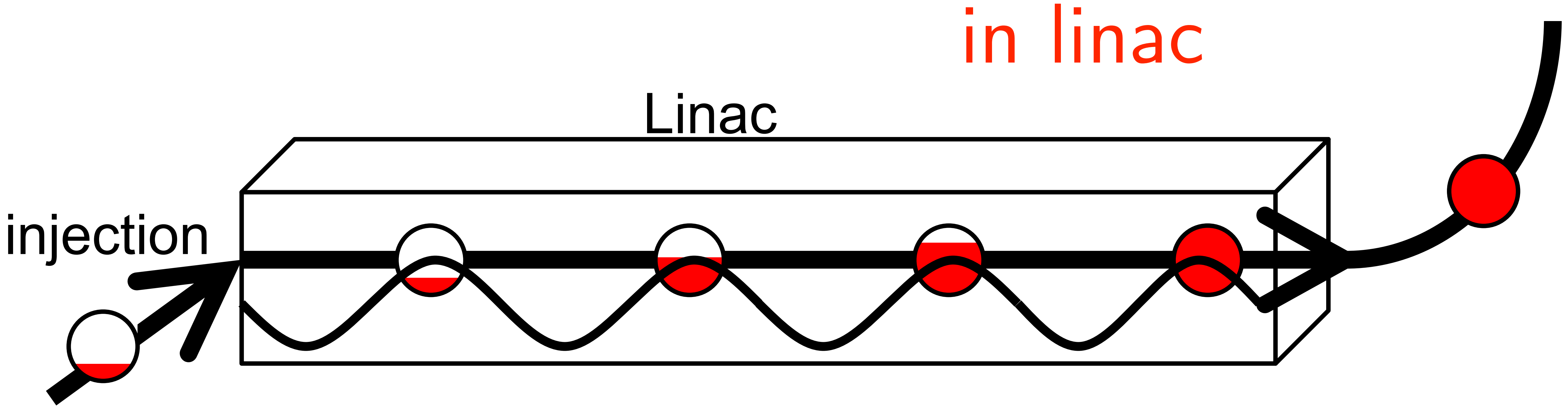




Electron accelerated in linac



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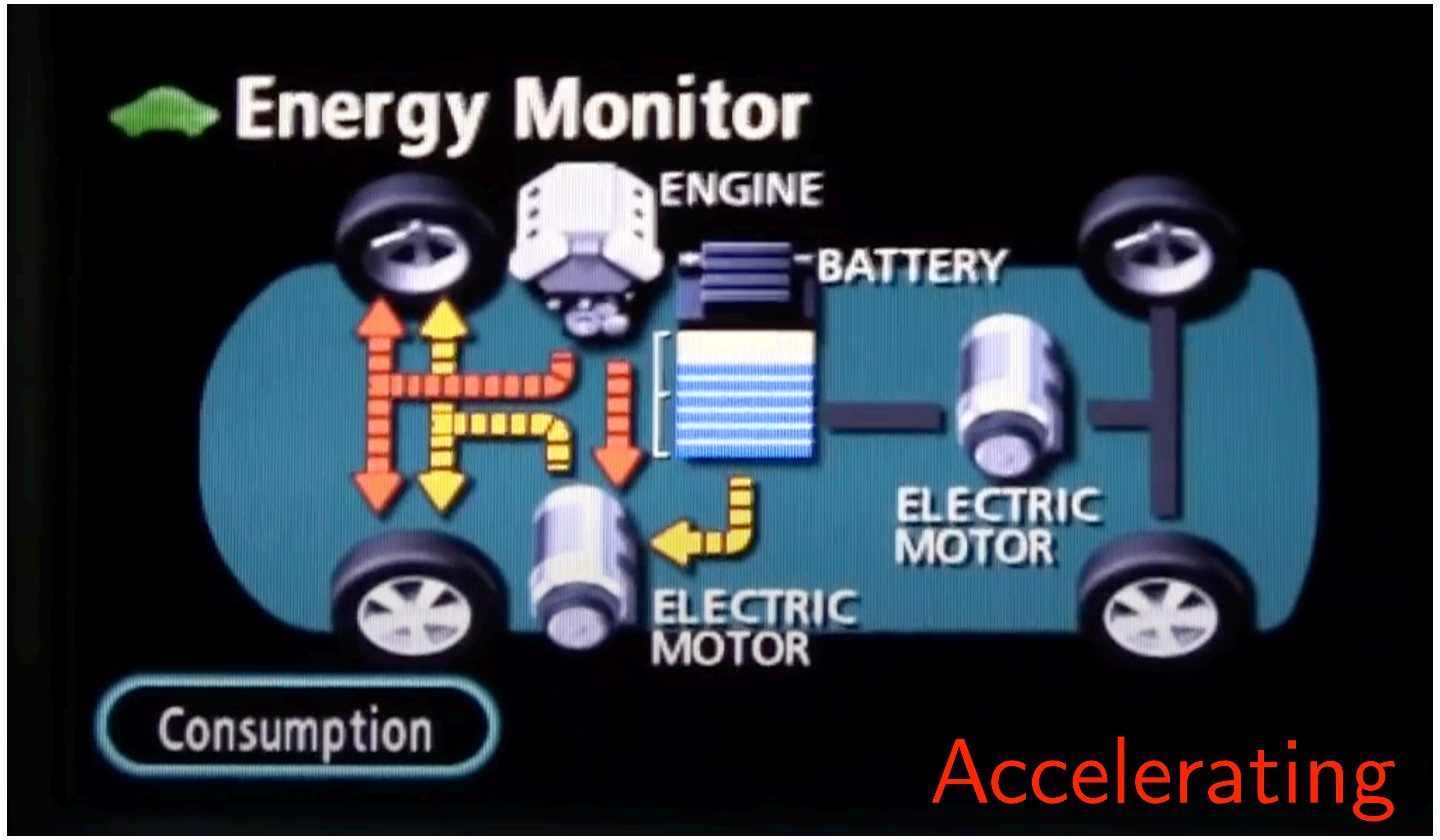
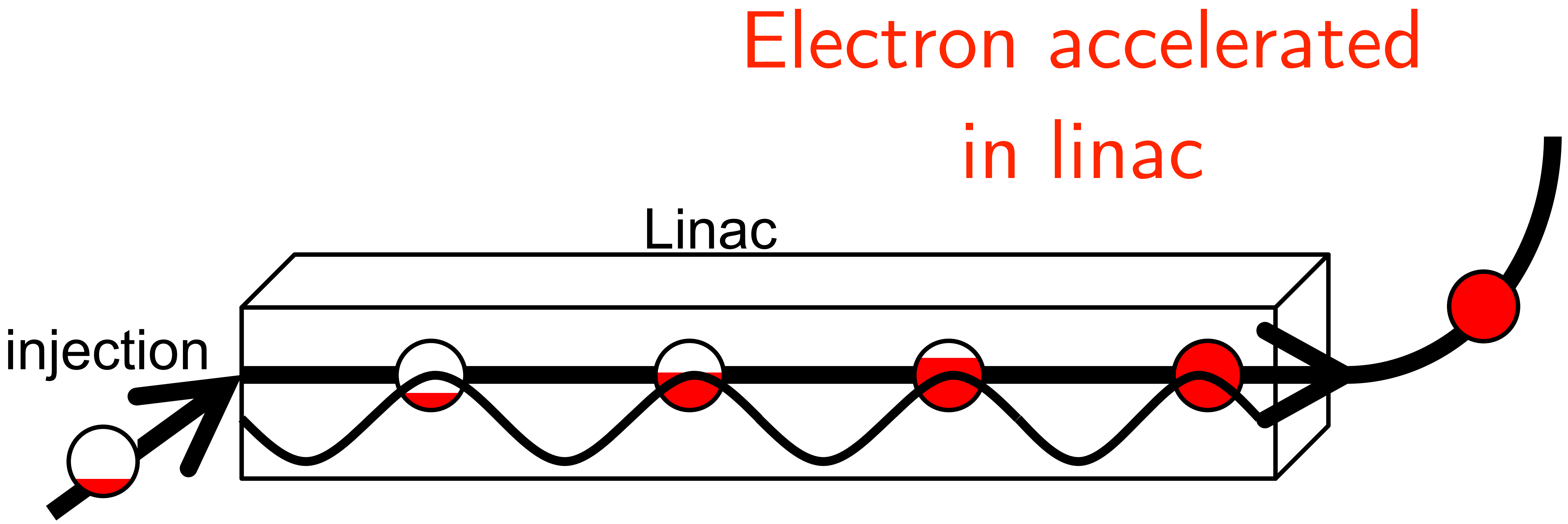
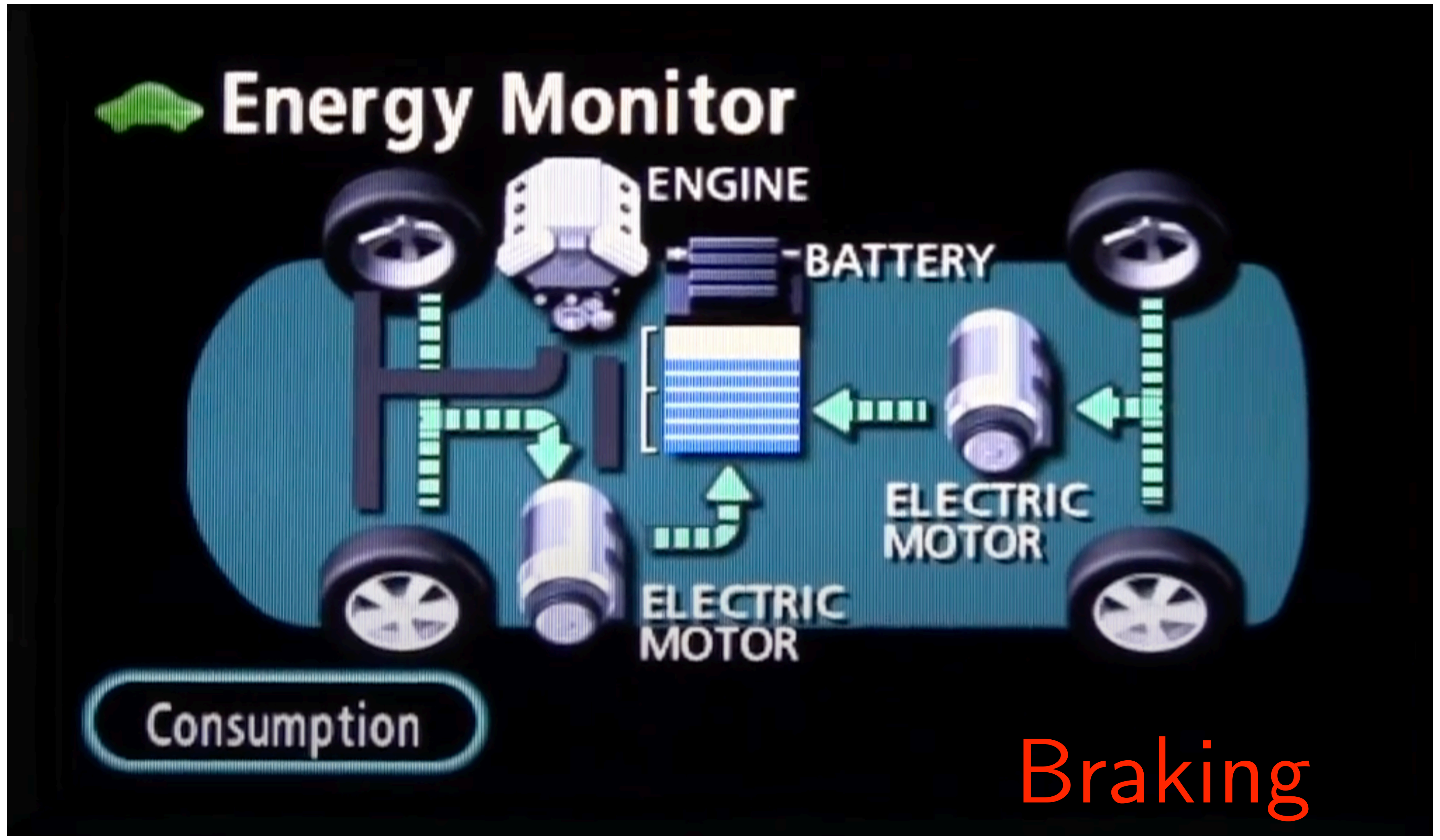
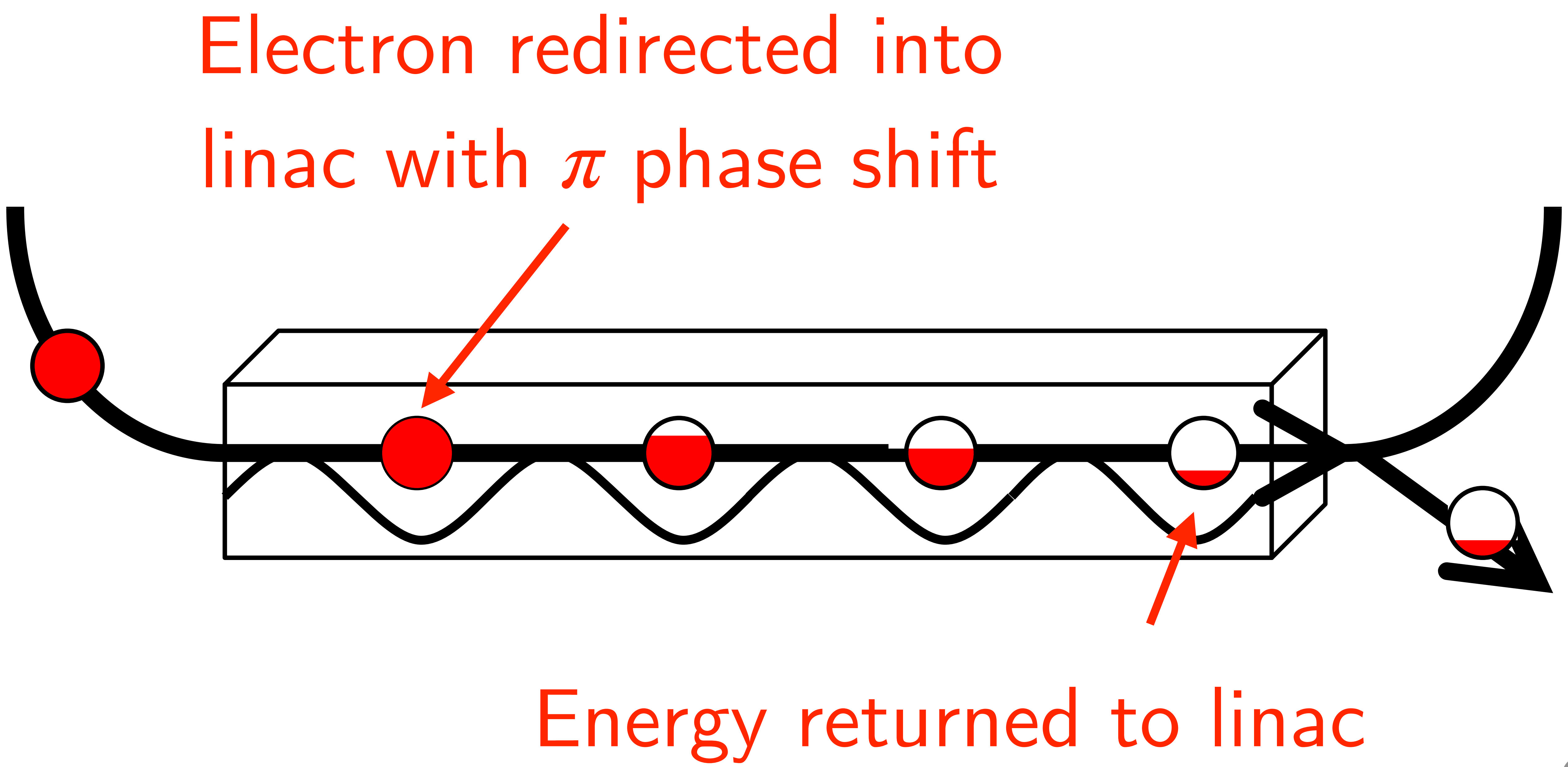


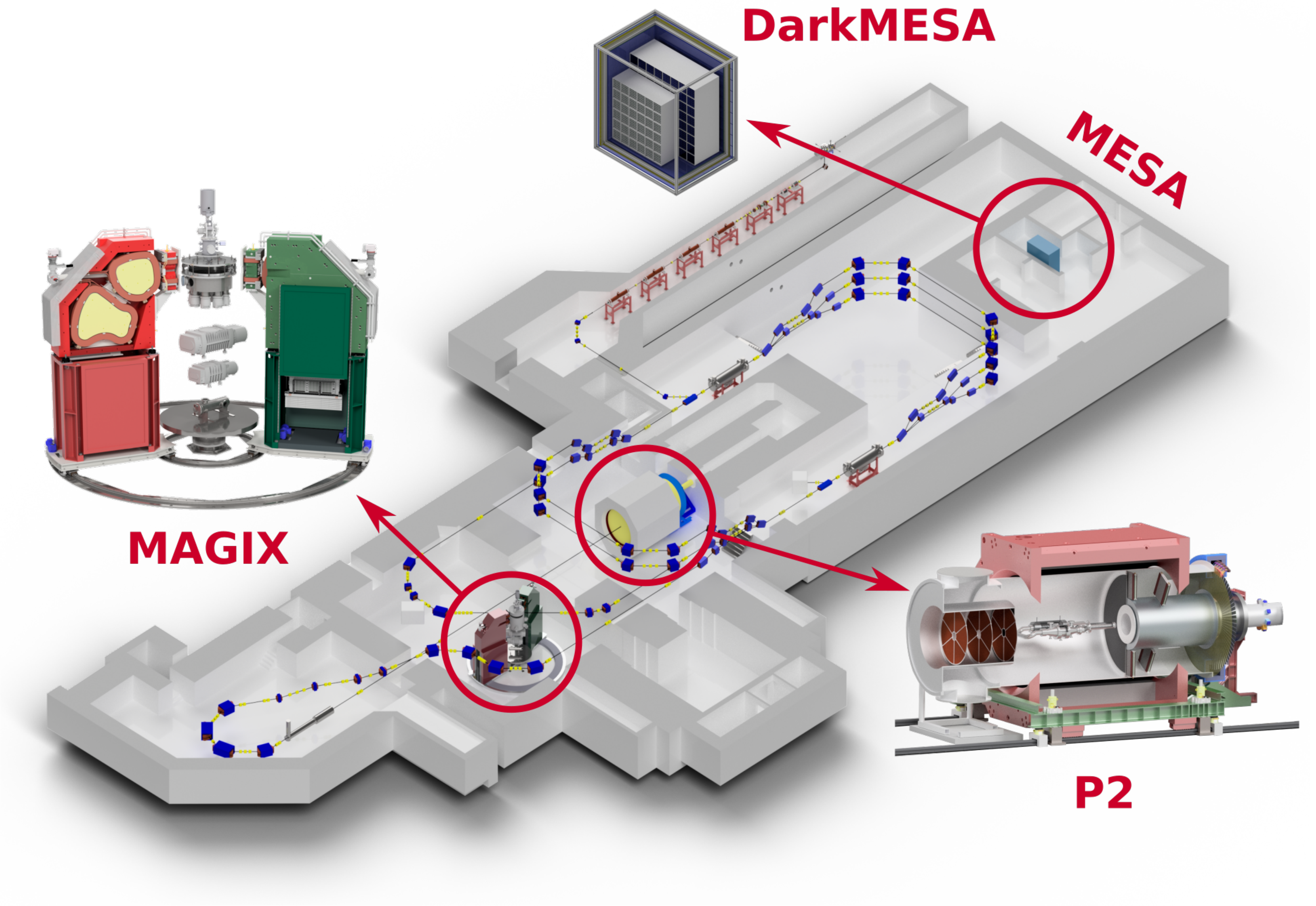






MESA

- In *energy-recovery mode:*
  - Energy up to 105 MeV
  - Currents over *1000* μA



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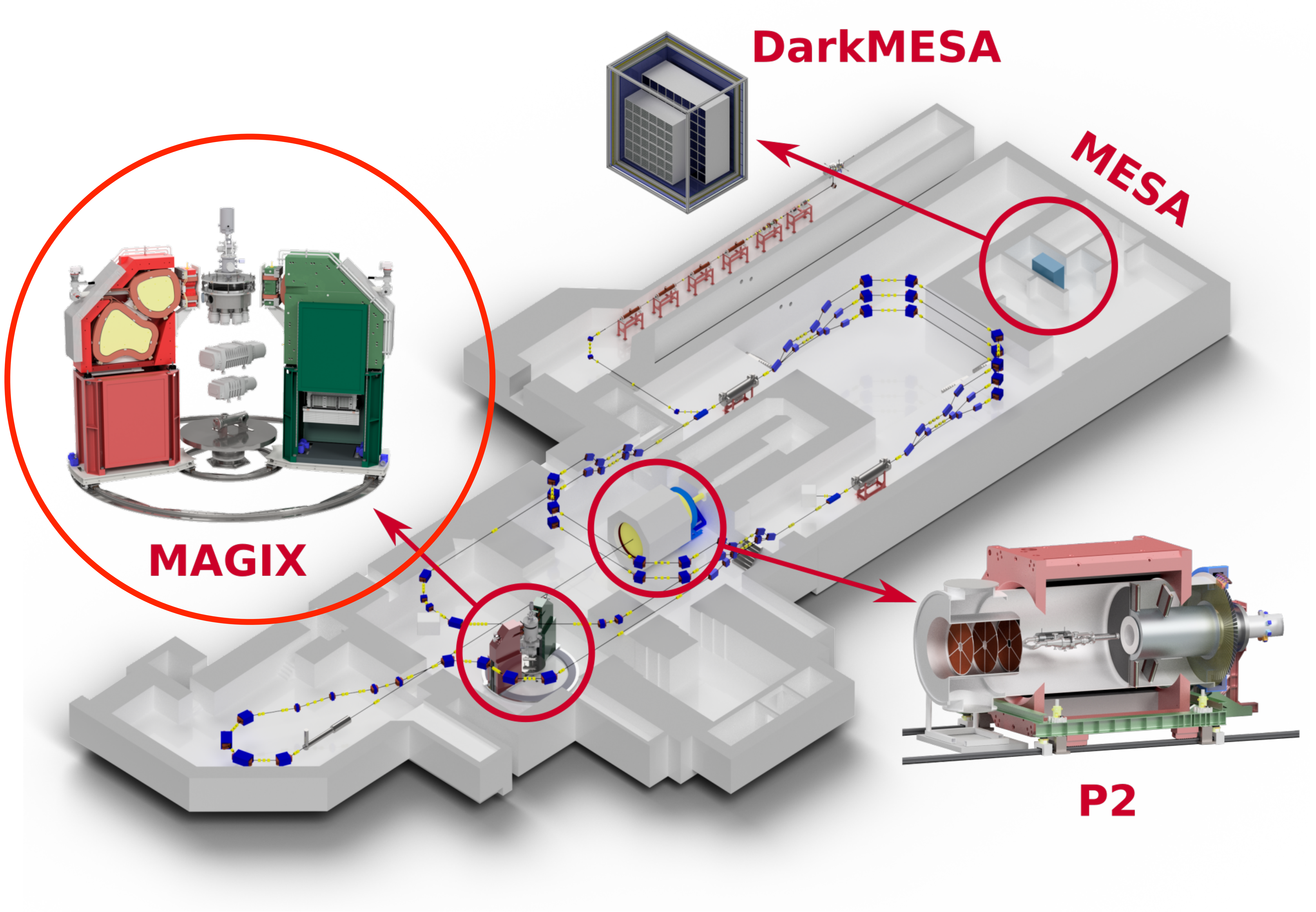

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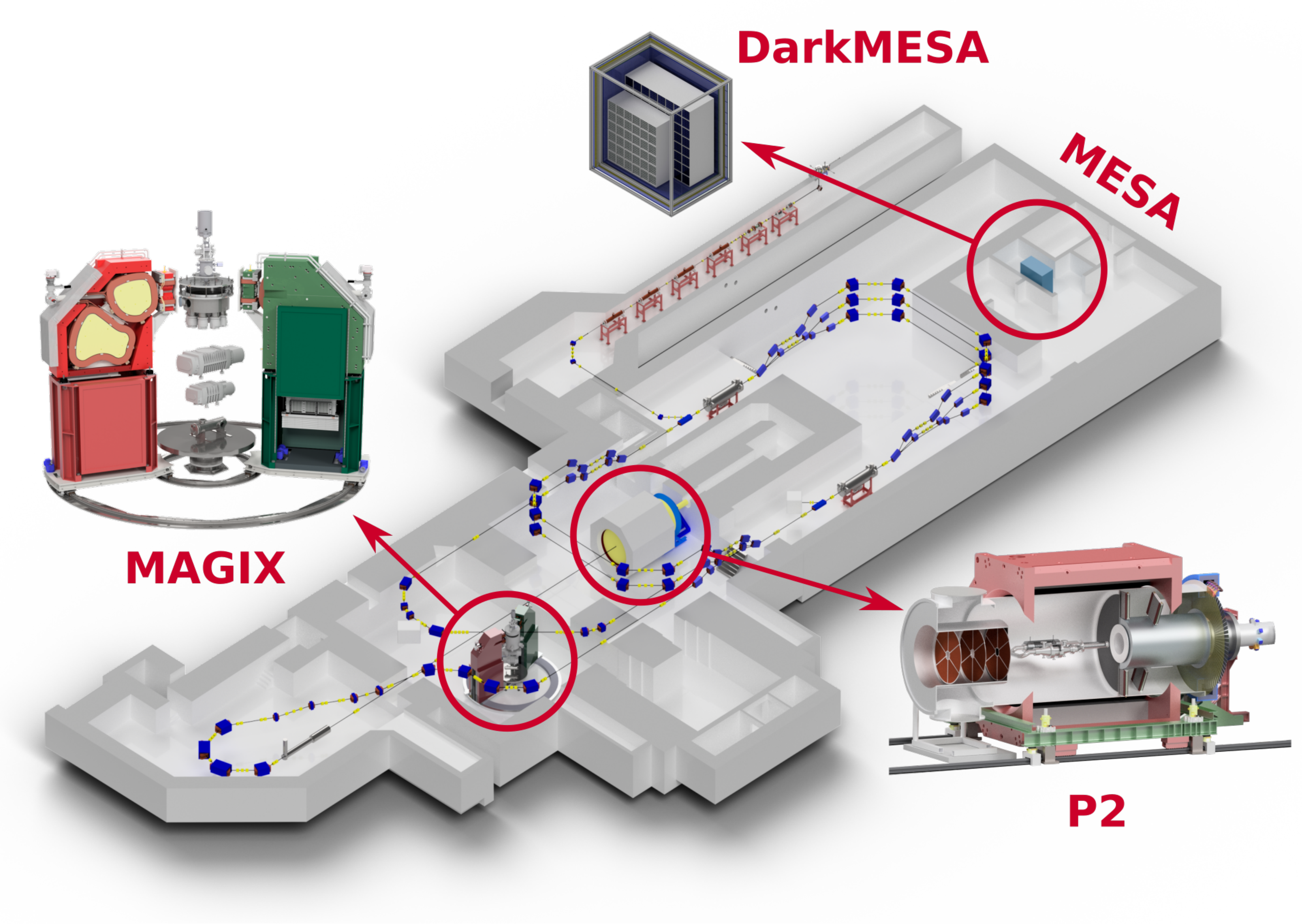
  - Energy up to 155 MeV
  - Current up to 150 μA
  - Polarization up to 80%



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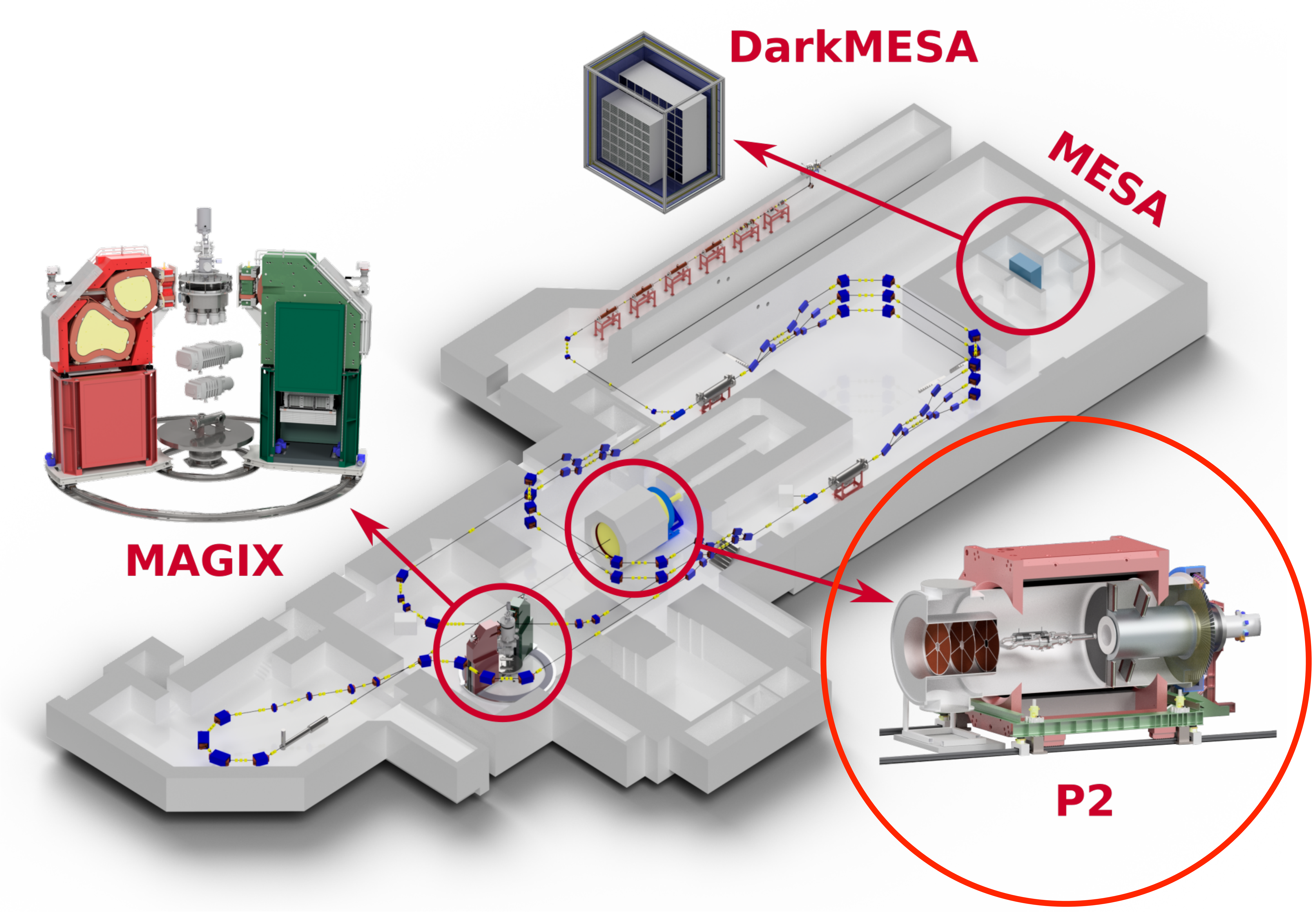

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- MAGIX:
  - Proton form factors
  - Astrophysical S-factor
- P2:
  - Proton weak charge/$\sin^2 \theta_W$
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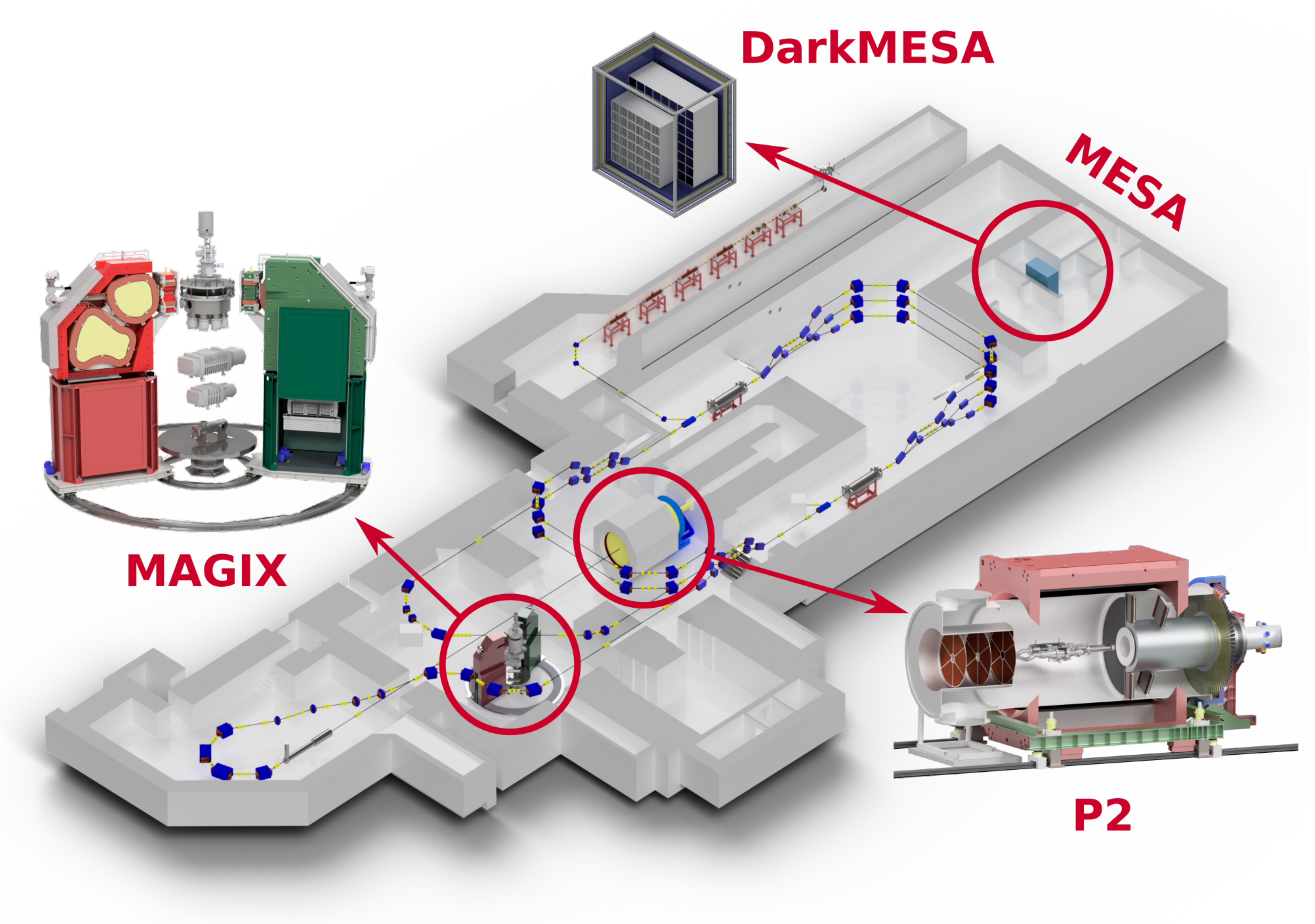
- Both: two-photon exchange



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- High-intensity ERL beam allows (and requires) diffuse targets!
- Primary target: hypersonic gas jet
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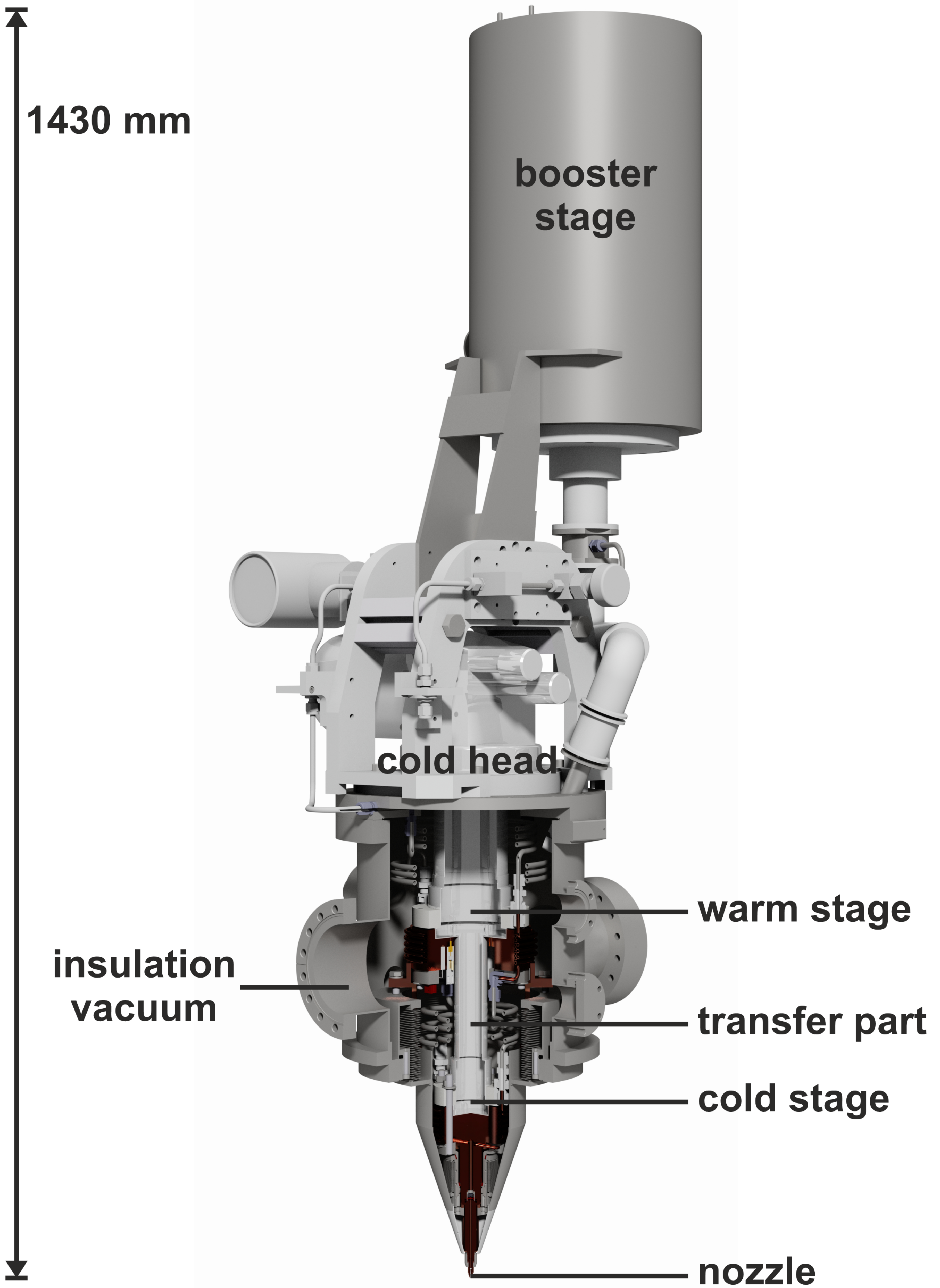

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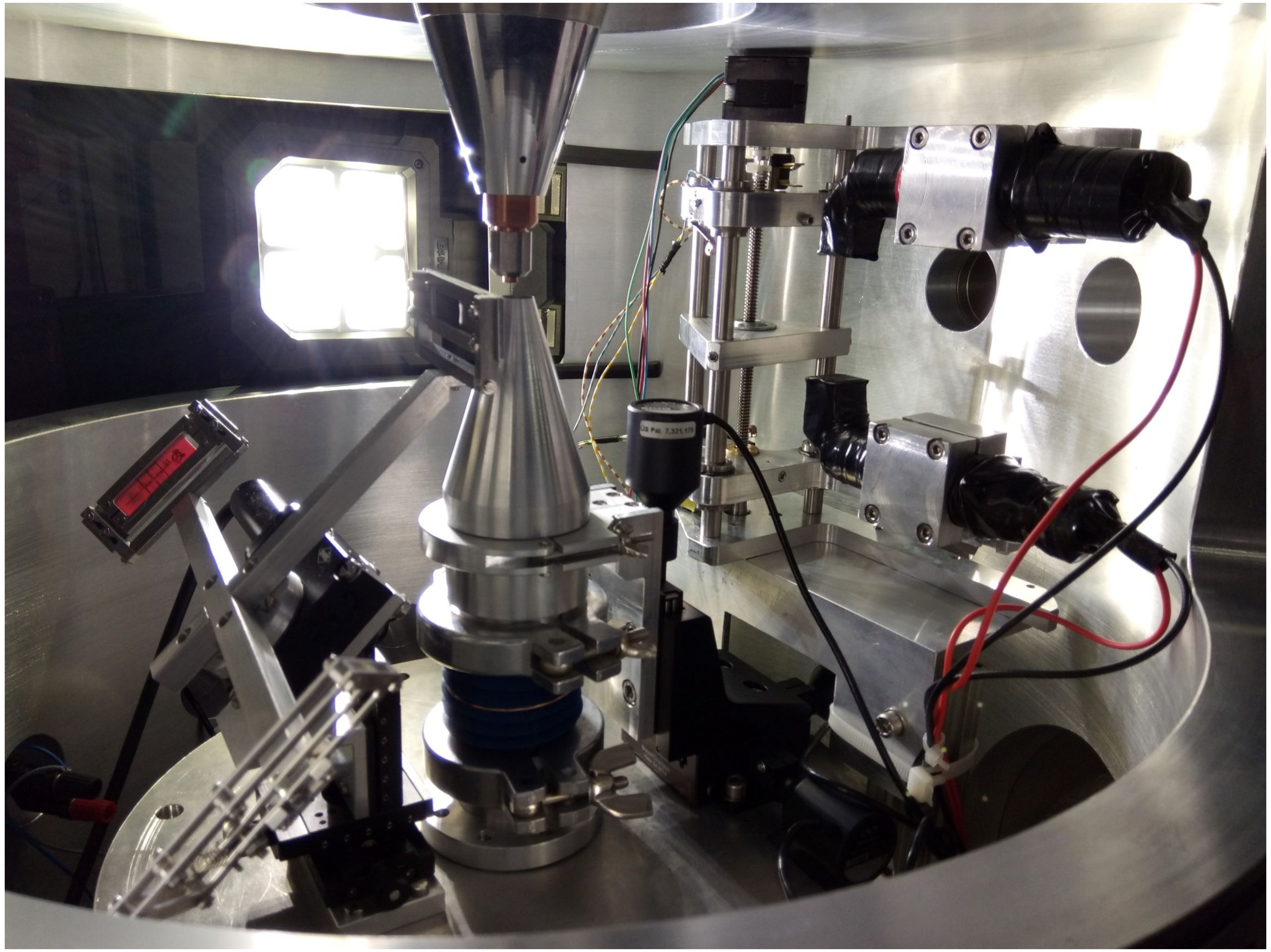
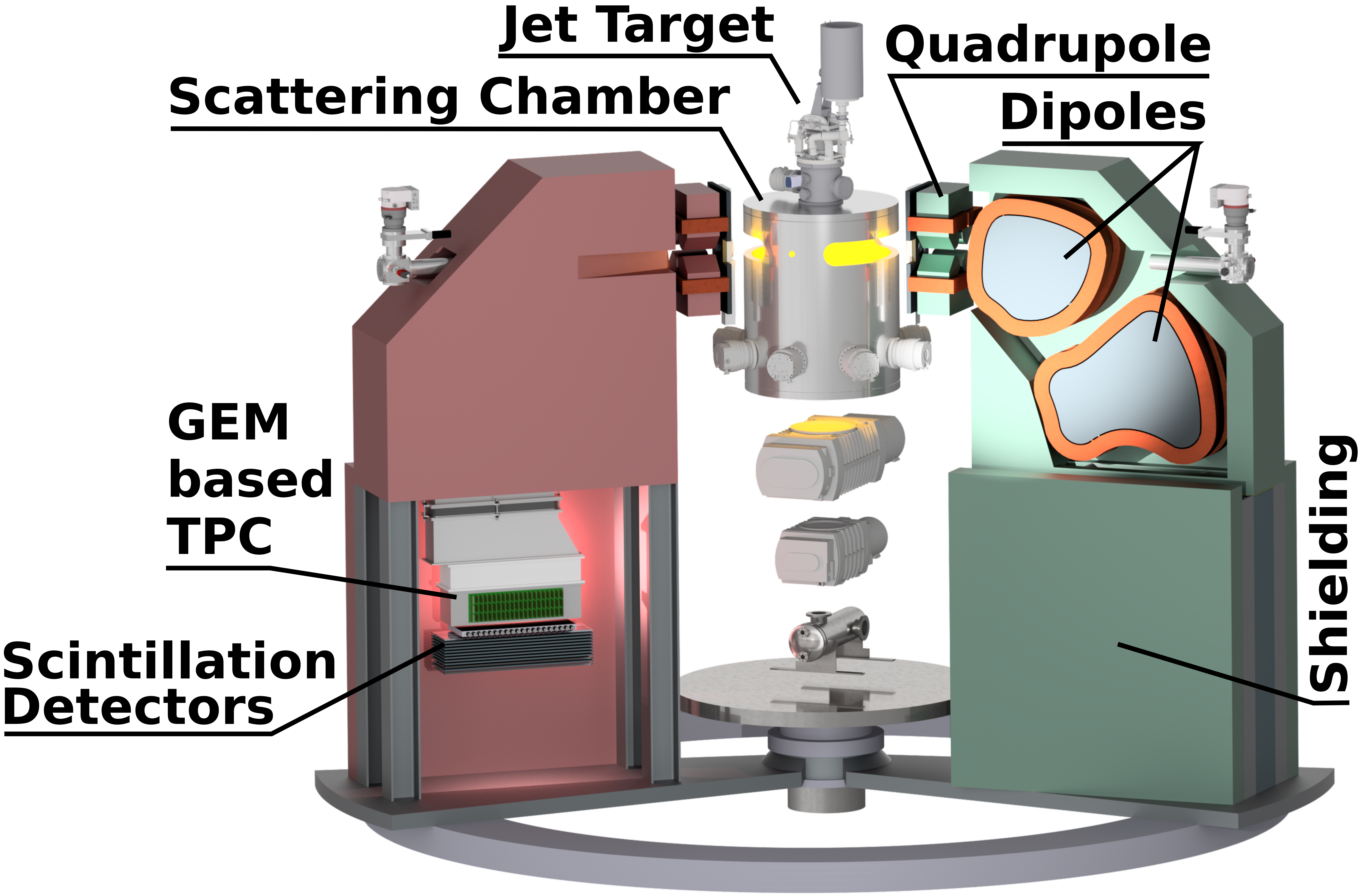


MAGIX spectrometers



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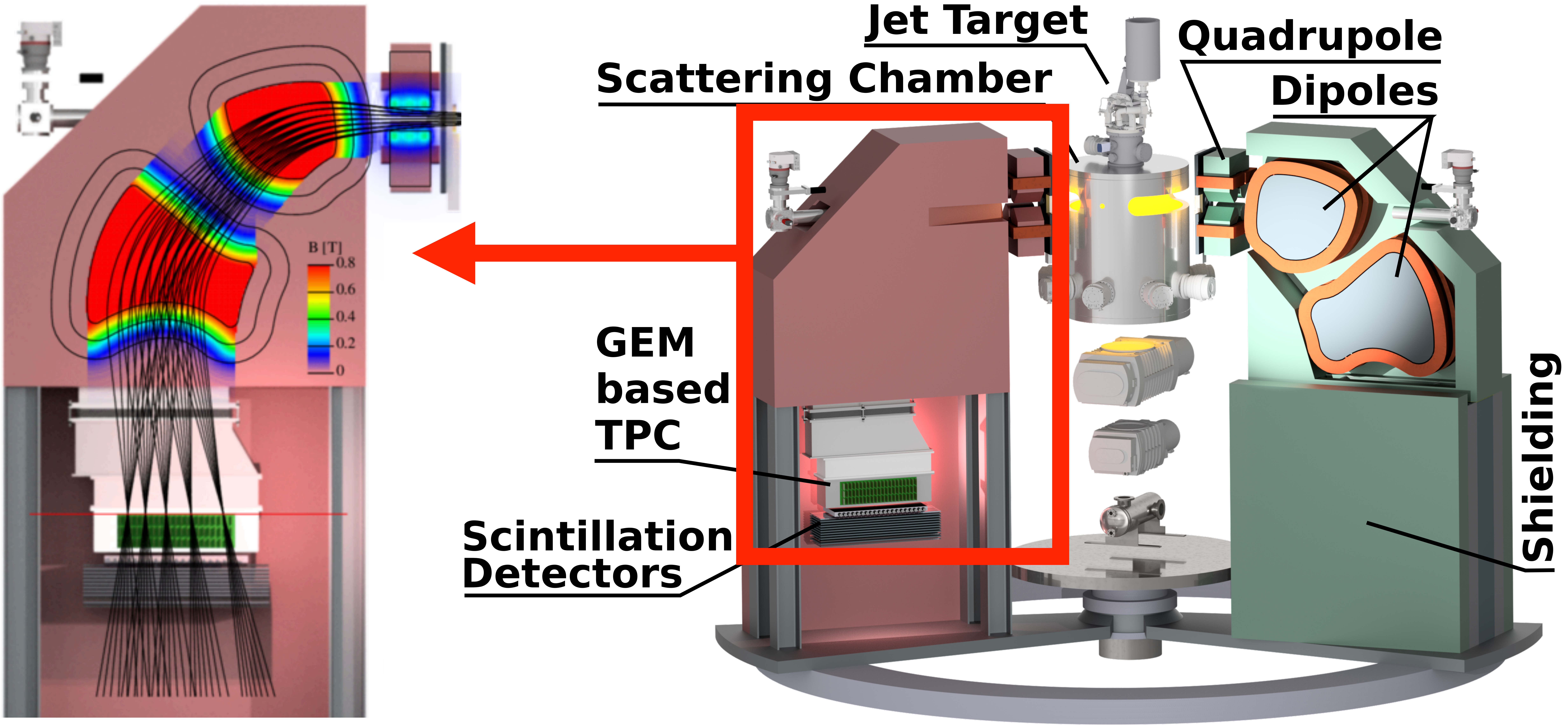

Proton form factors

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \frac{1}{\varepsilon(1+\tau)} \left(\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right), \quad \tau = \frac{Q^2}{4M^2}$$

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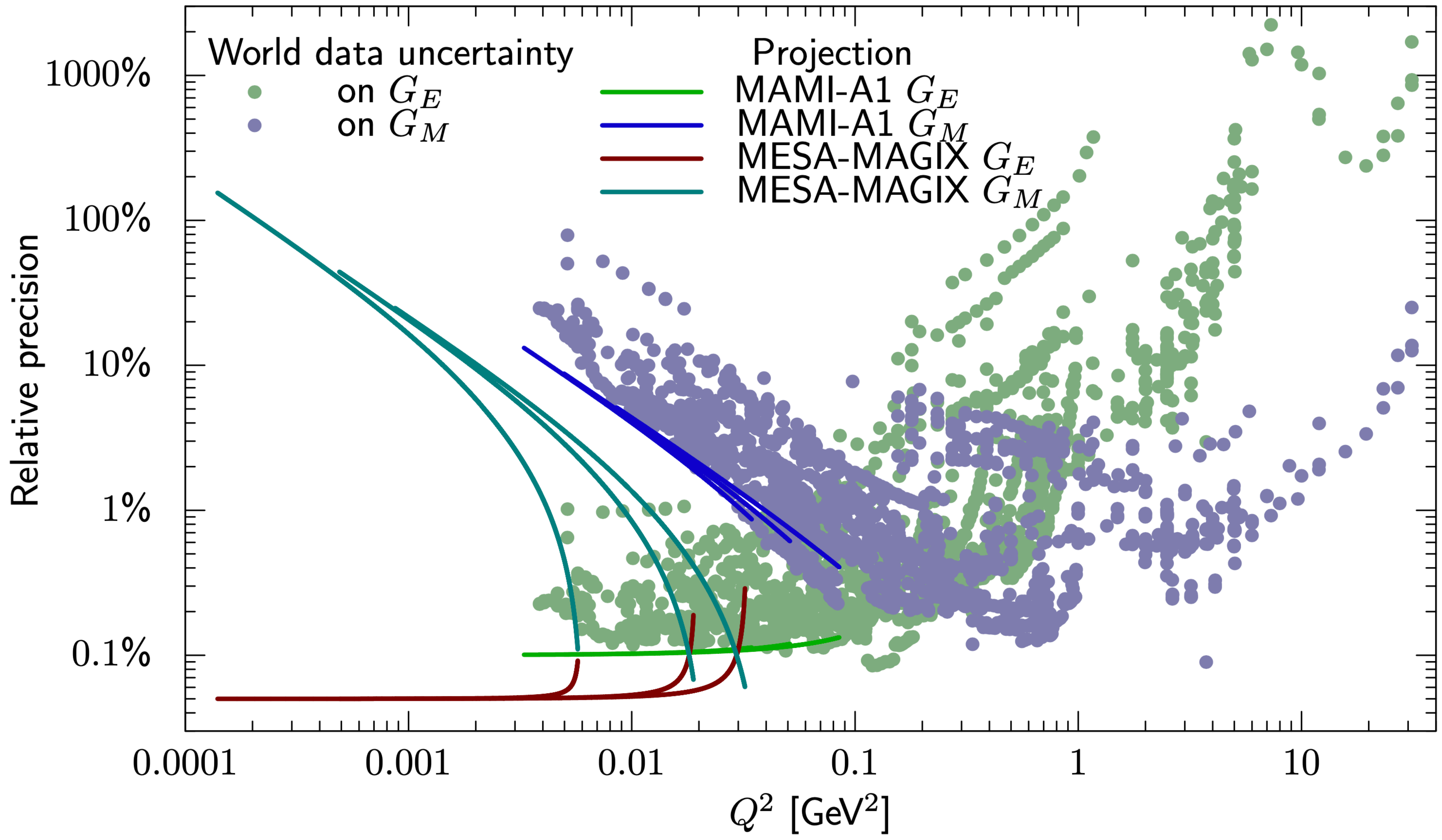
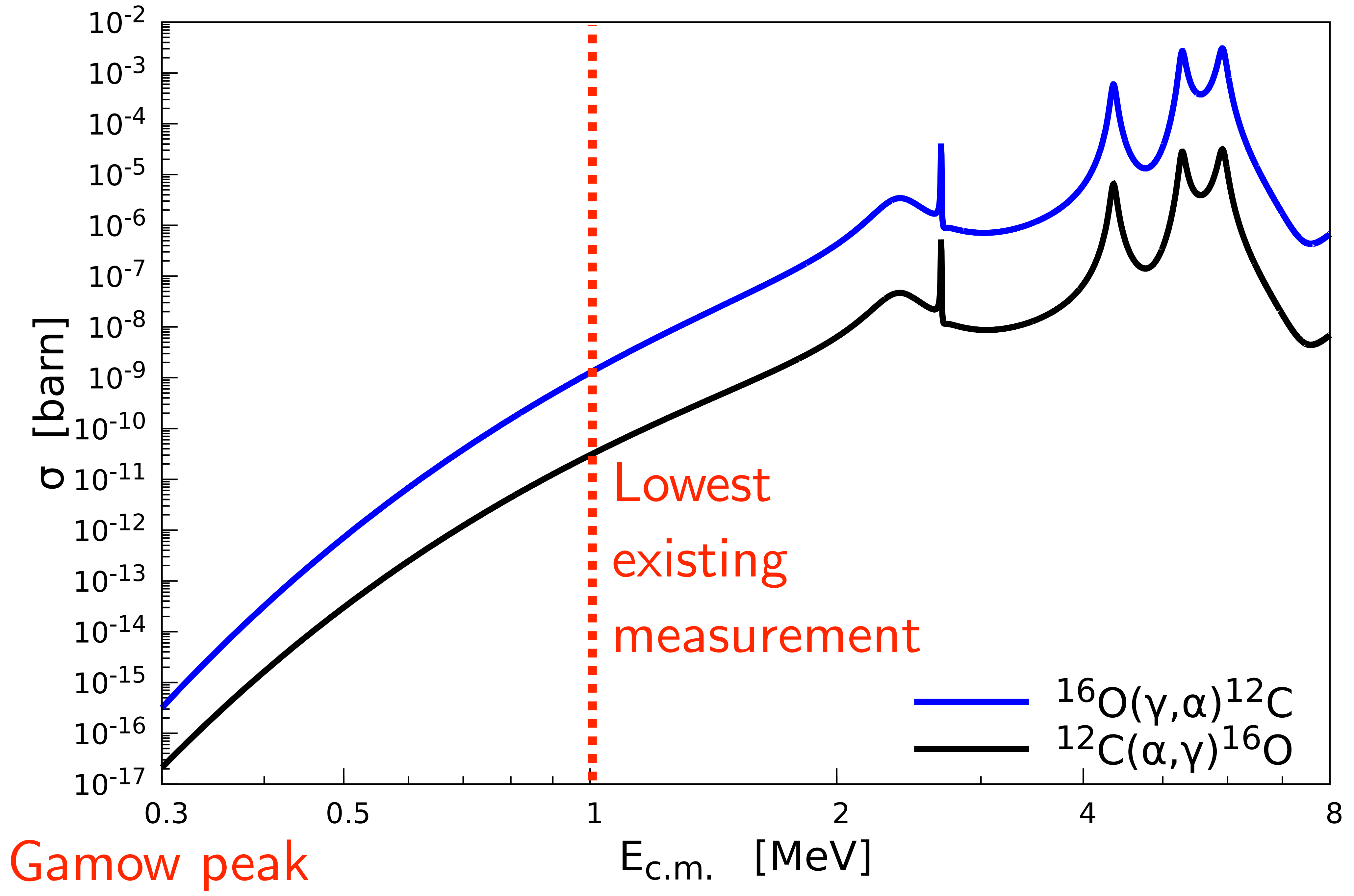
- Reduced uncertainty from internal gas target
- Significant improvement at low Q^2
- Particular impact on G_M, magnetic radius



Astrophysical S-factor

$$\sigma(E_{CM}) = \frac{1}{e^{-2\pi\eta}S(E_{CM})}, \quad \eta \propto Z_1 Z_2$$

- $S(E_{CM})$ factor due to nuclear structure
- $^{12}C(\alpha, \gamma)^{16}O$ of high astrophysical relevance
- Measure time-reversed process in electro-disintegration of of ^{16}O



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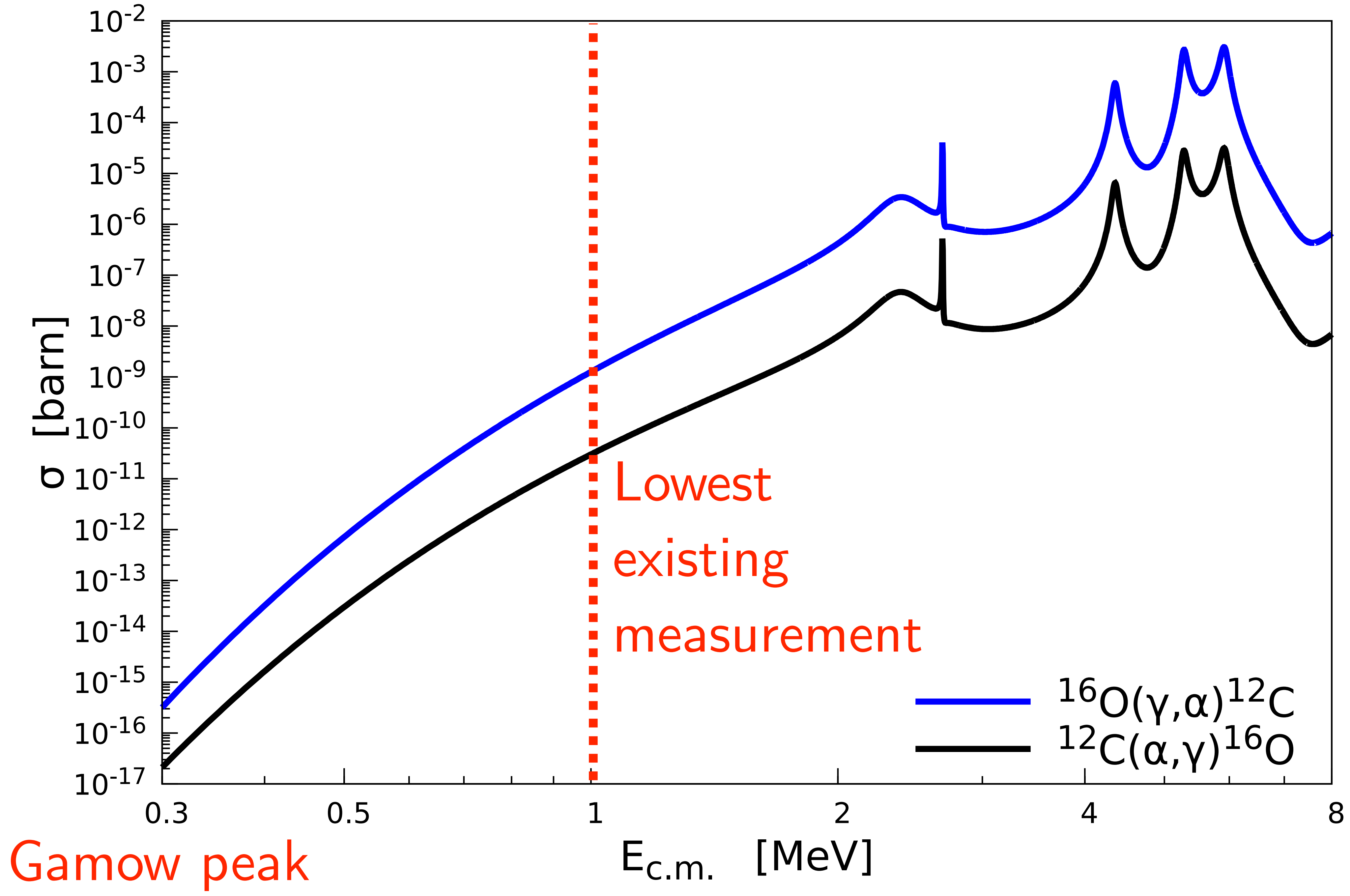

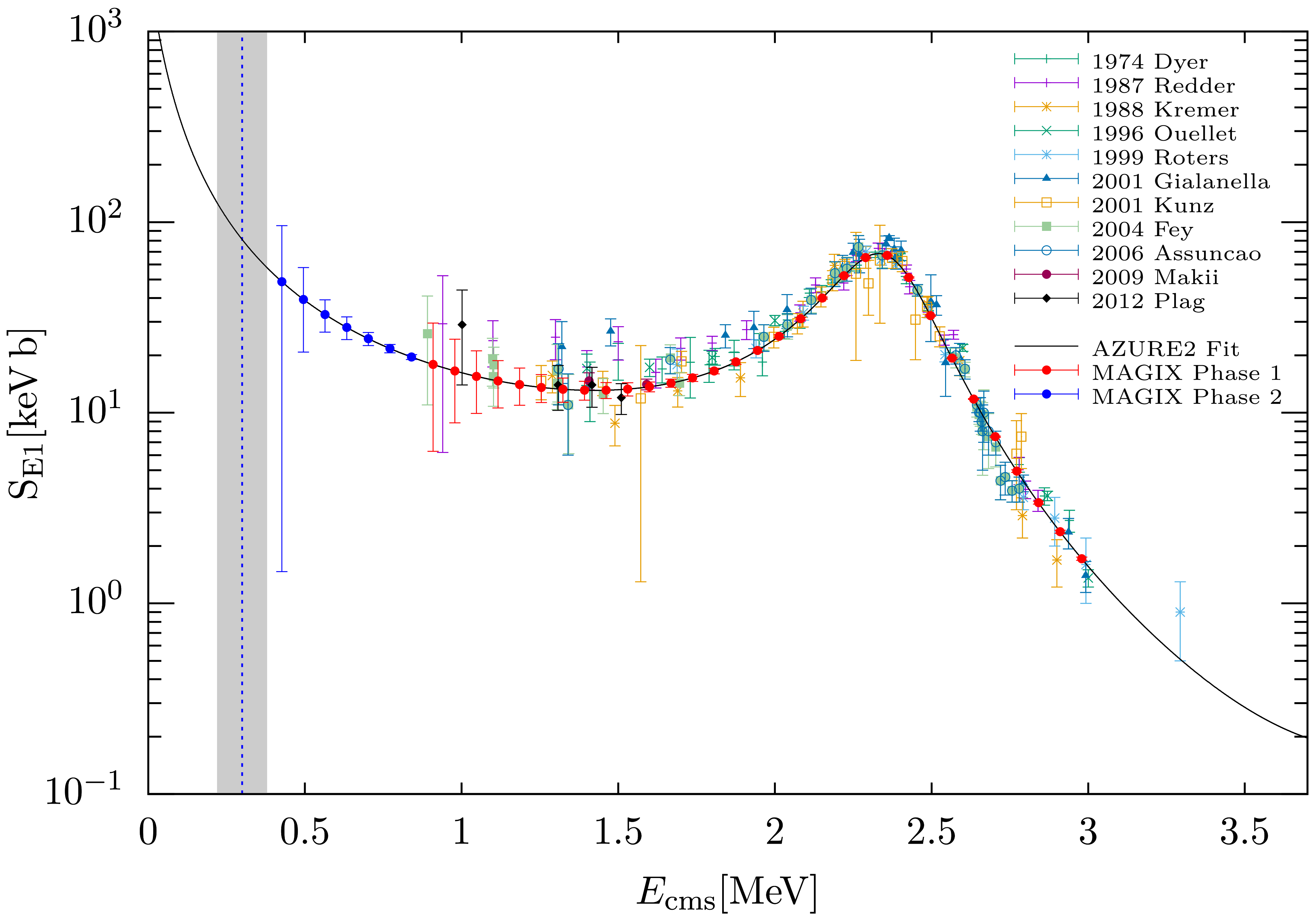

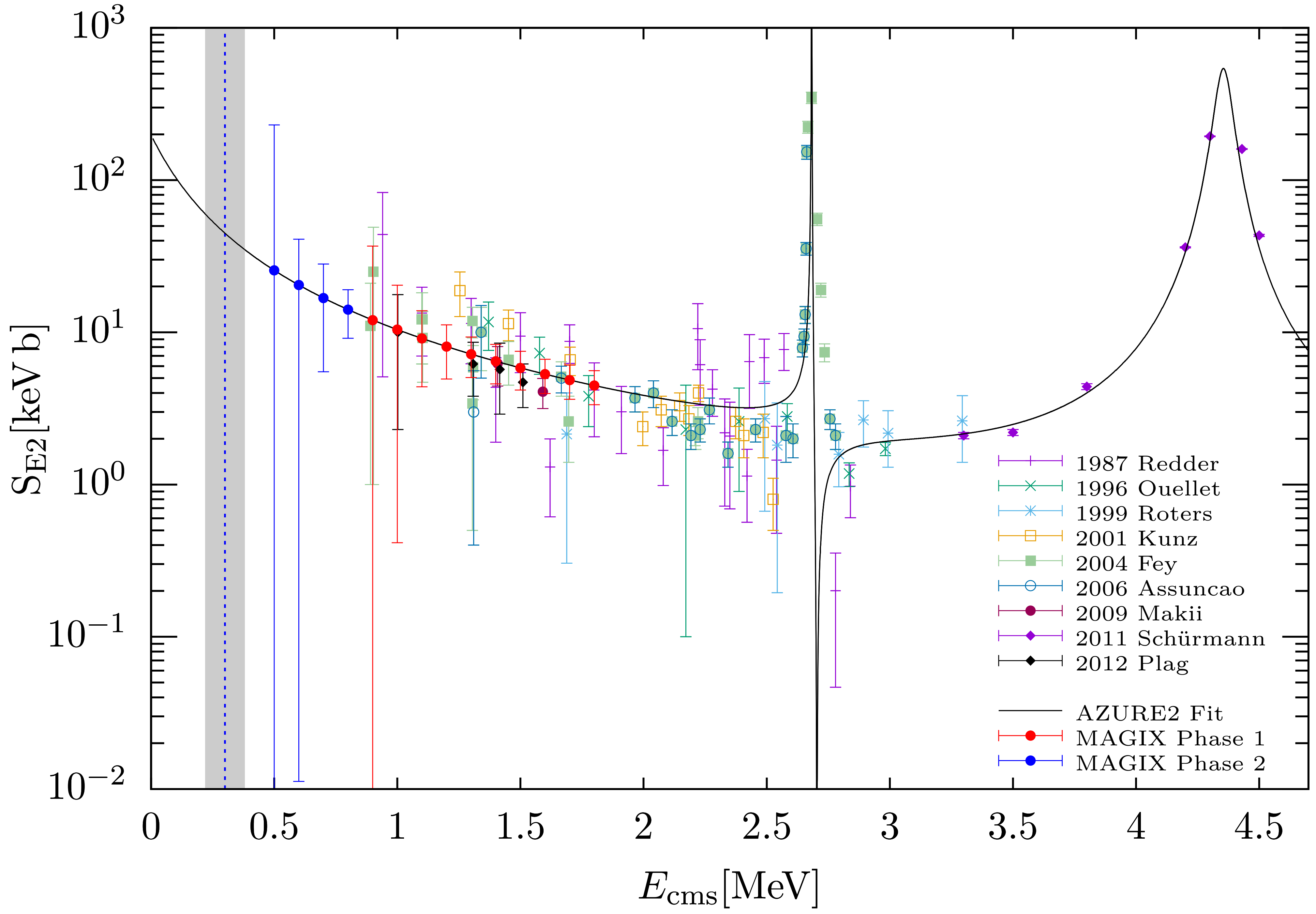

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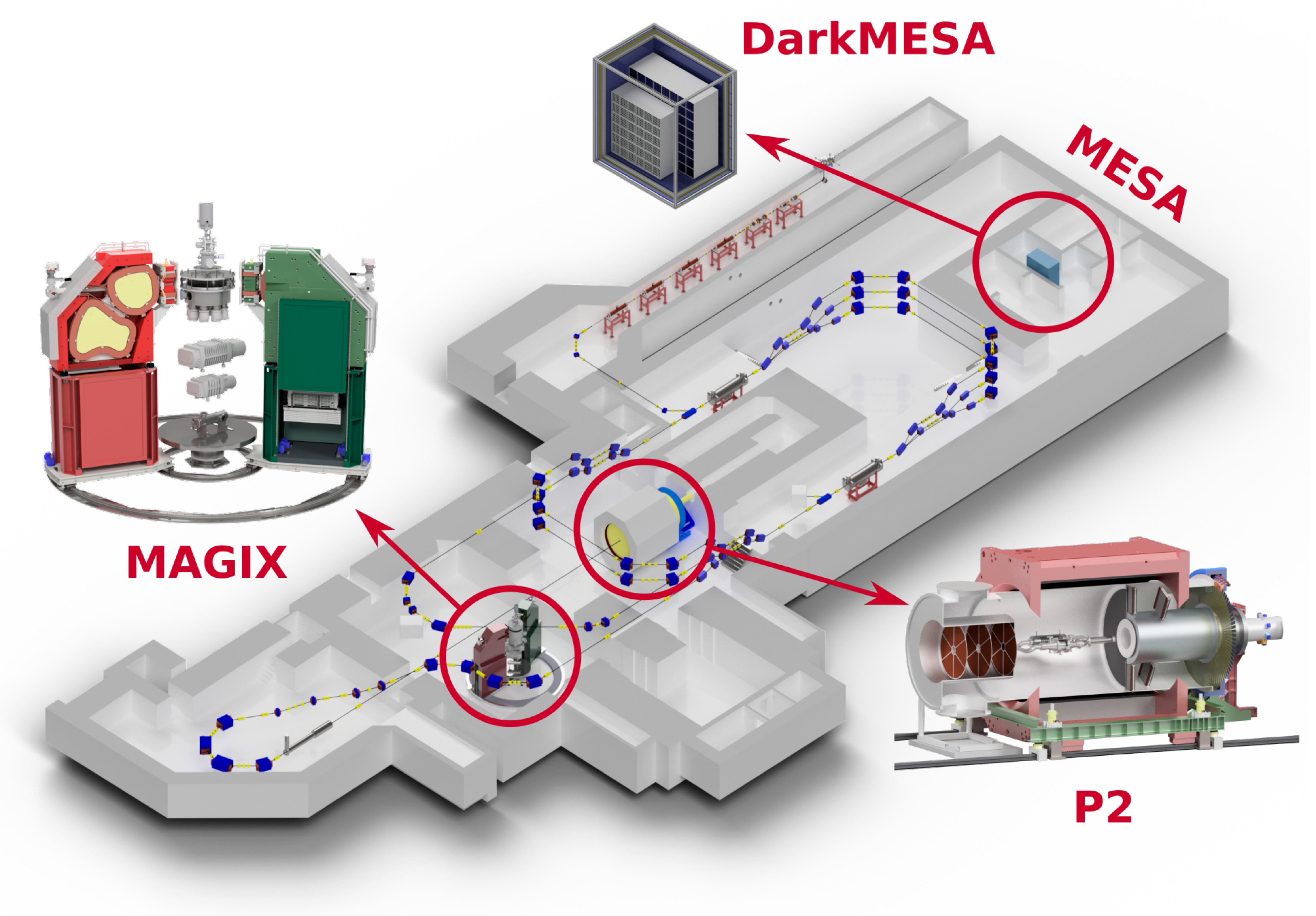
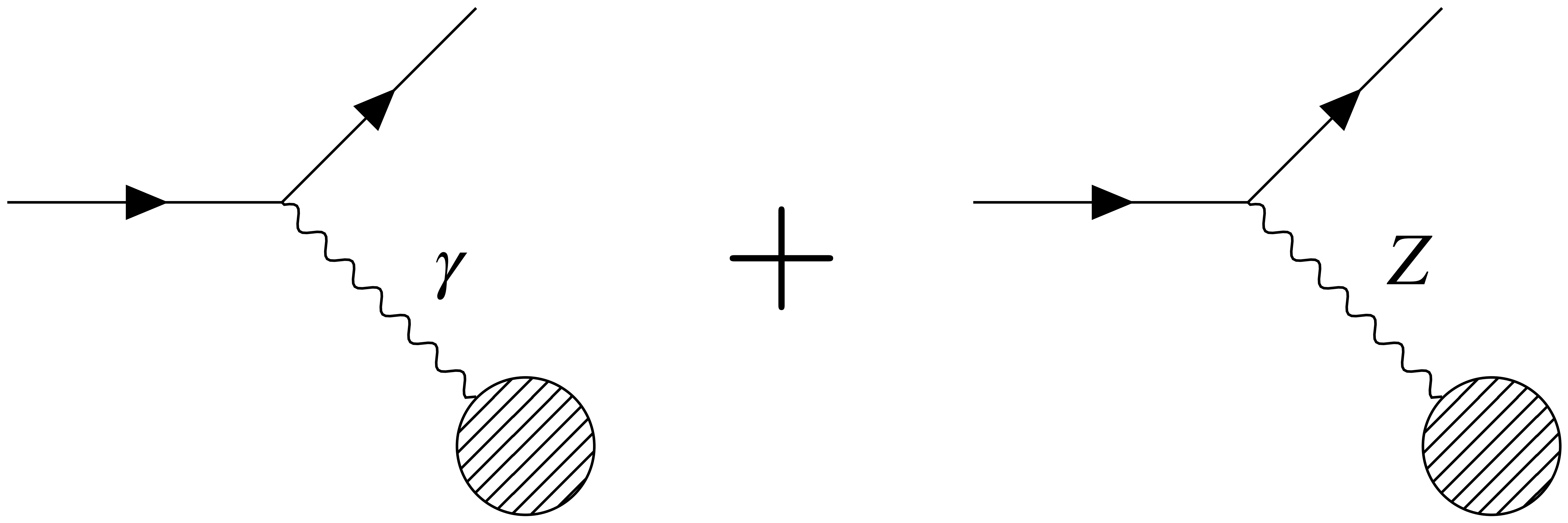


Parity-violating electron scattering (PVES)



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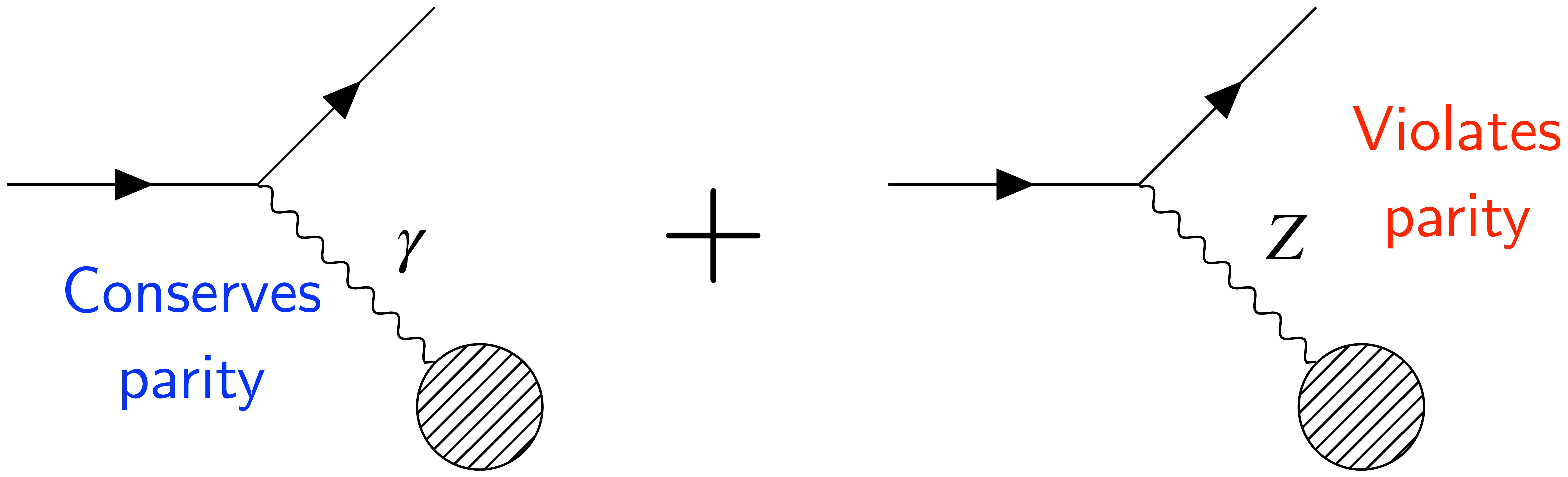

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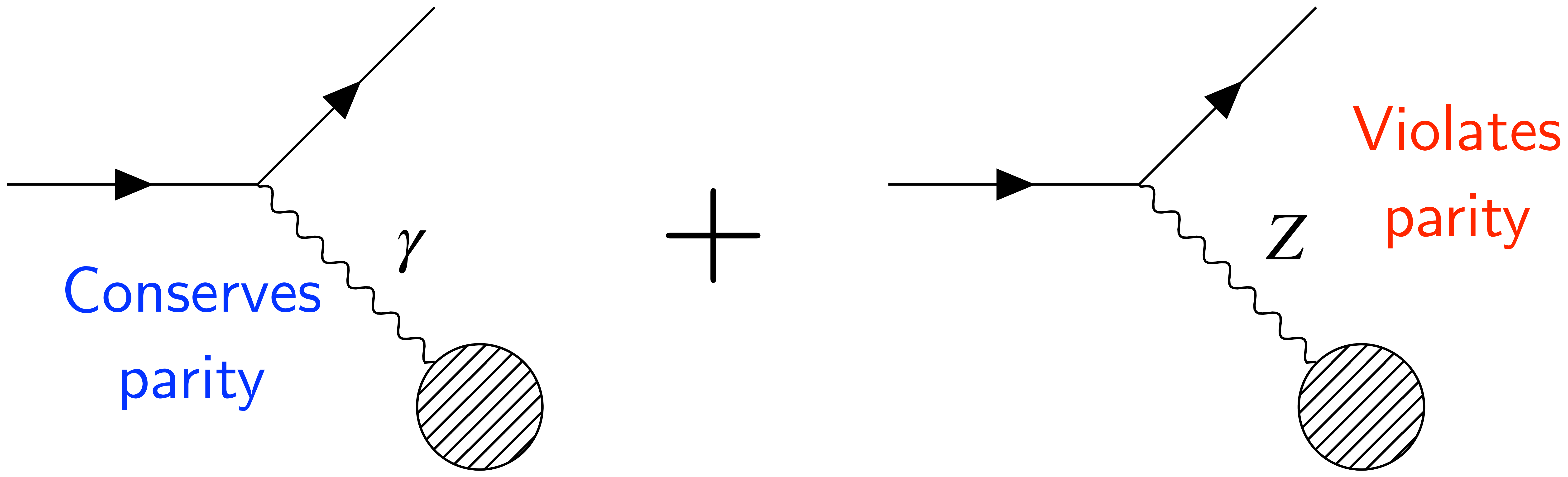

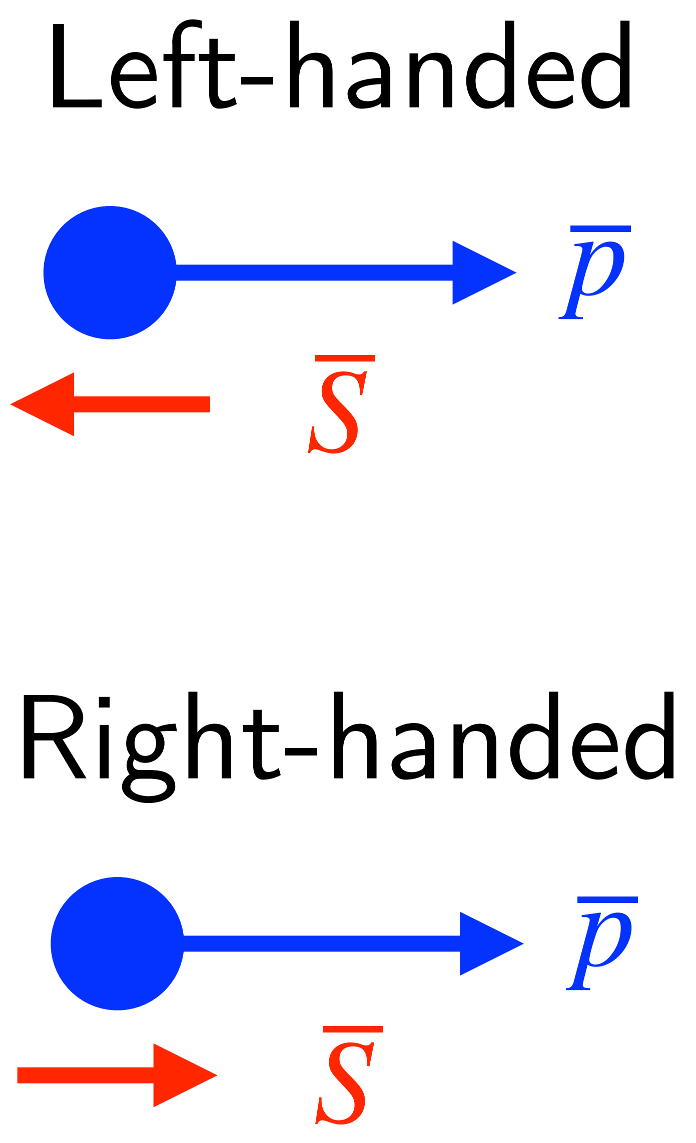

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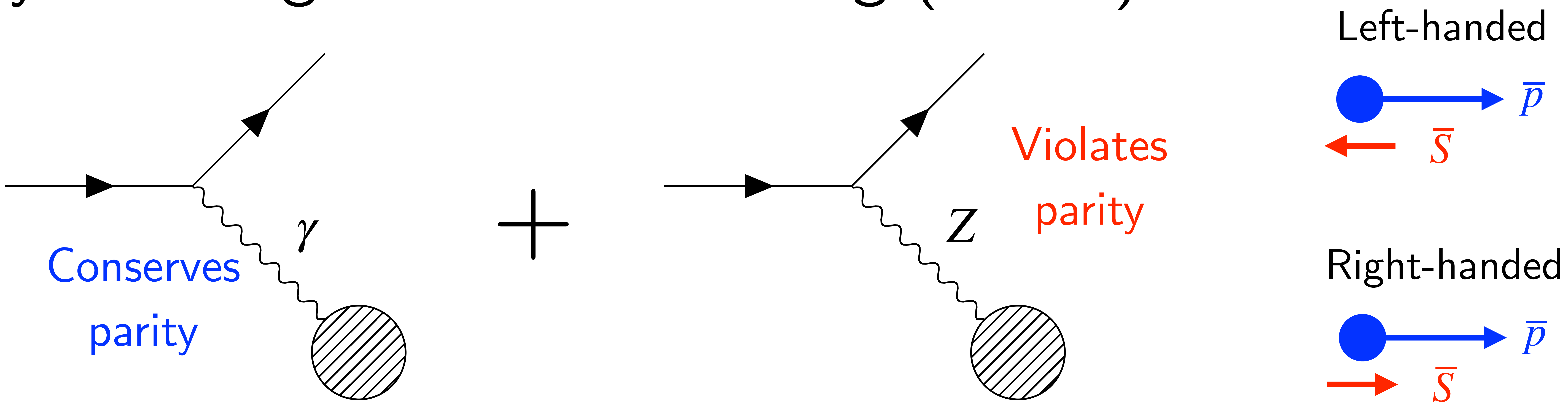

- Interference between γ and Z exchange leads to parity-violating asymmetry

$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto \frac{\mathcal{M}_\gamma^* \mathcal{M}_Z}{\mathcal{M}_\gamma^2} \propto \frac{G_F Q^2}{4\pi\alpha}$$

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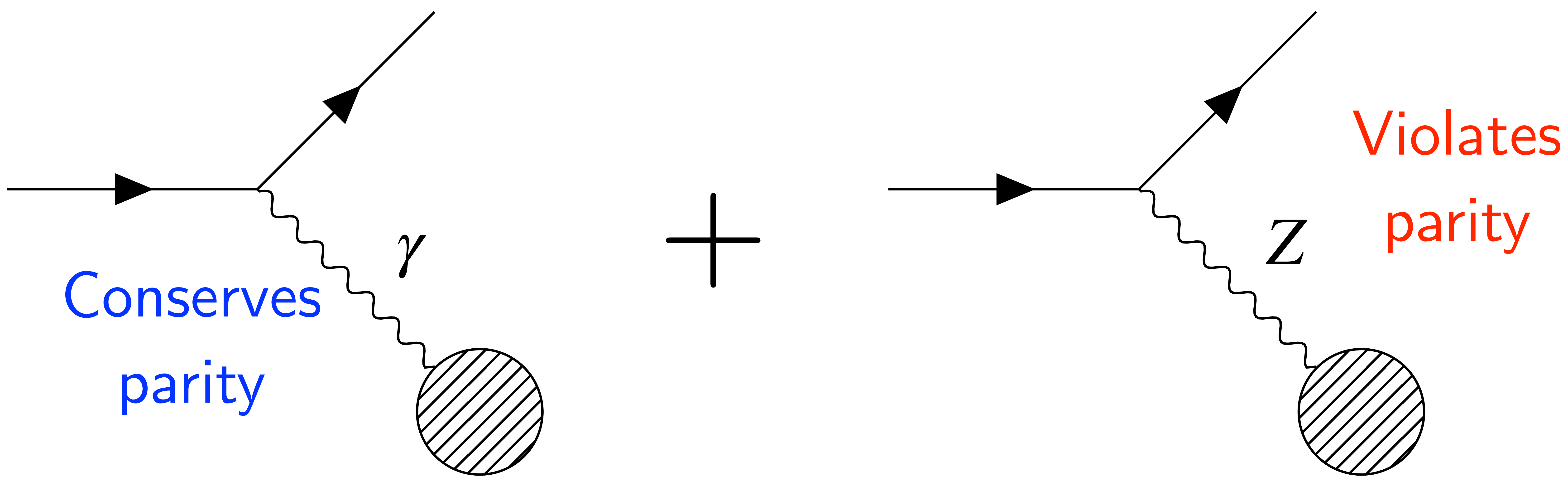

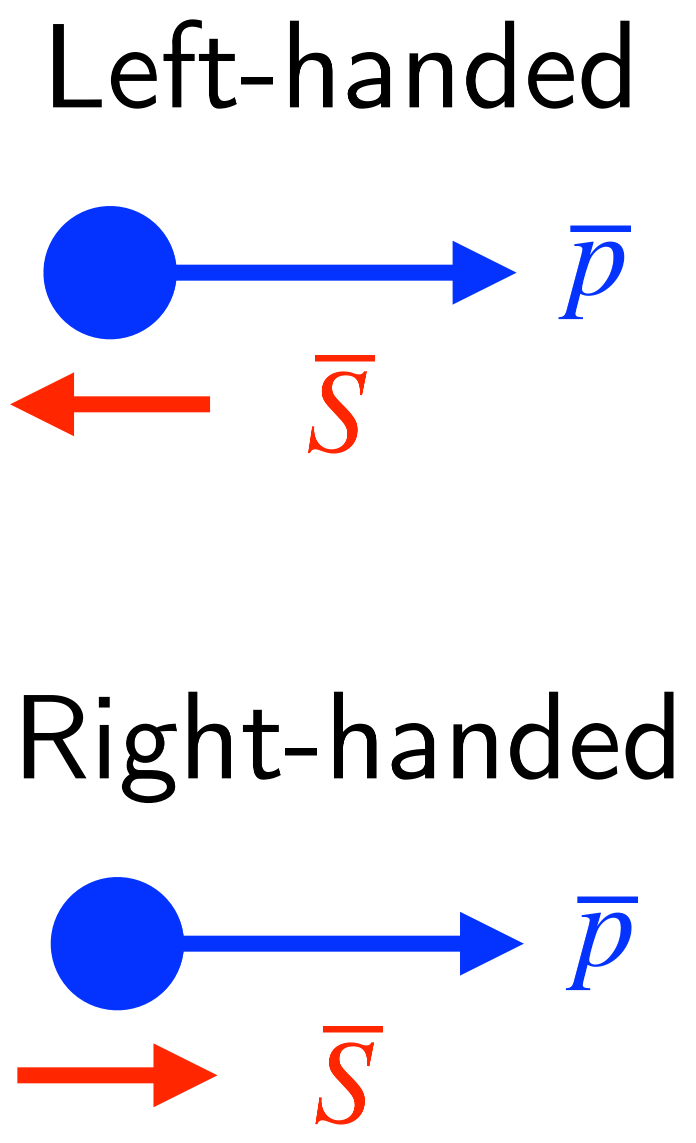

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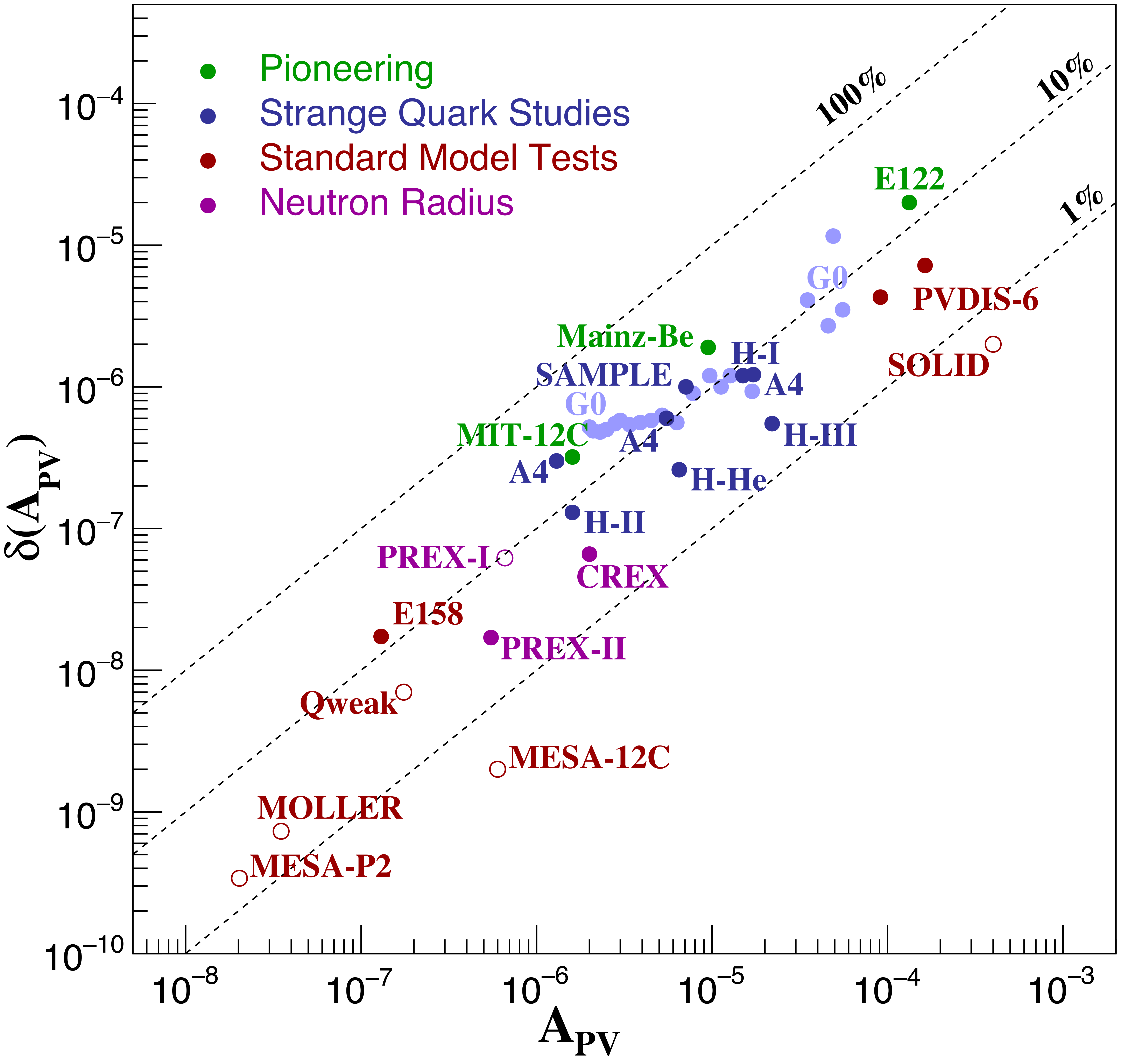
- Typically order parts per million or less
- Sensitive to variety of physics depending on target, kinematics

- History of PVES: continuous improvement in accelerator and detector technology

- State of the art: sub-ppb statistical reach and control of systematics



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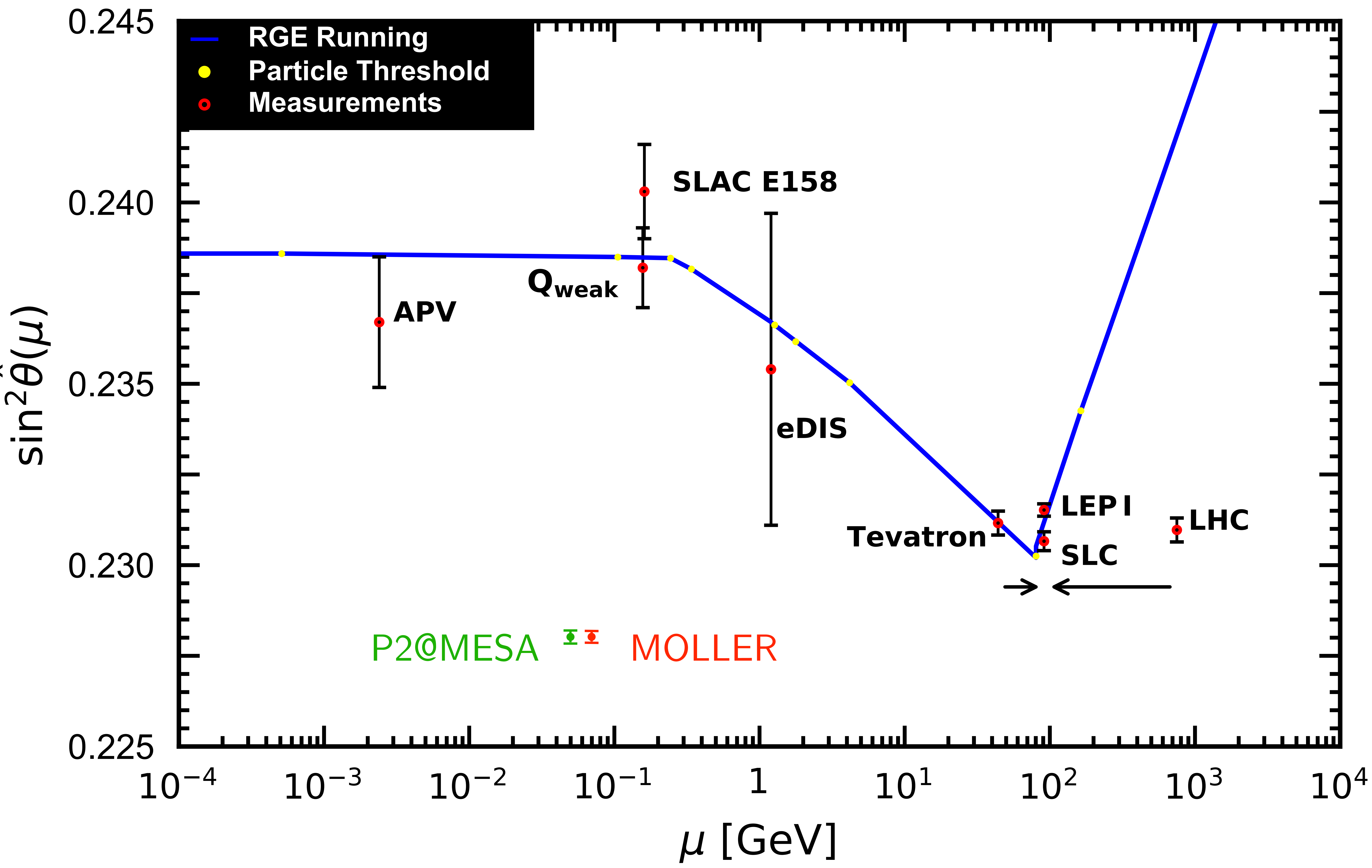

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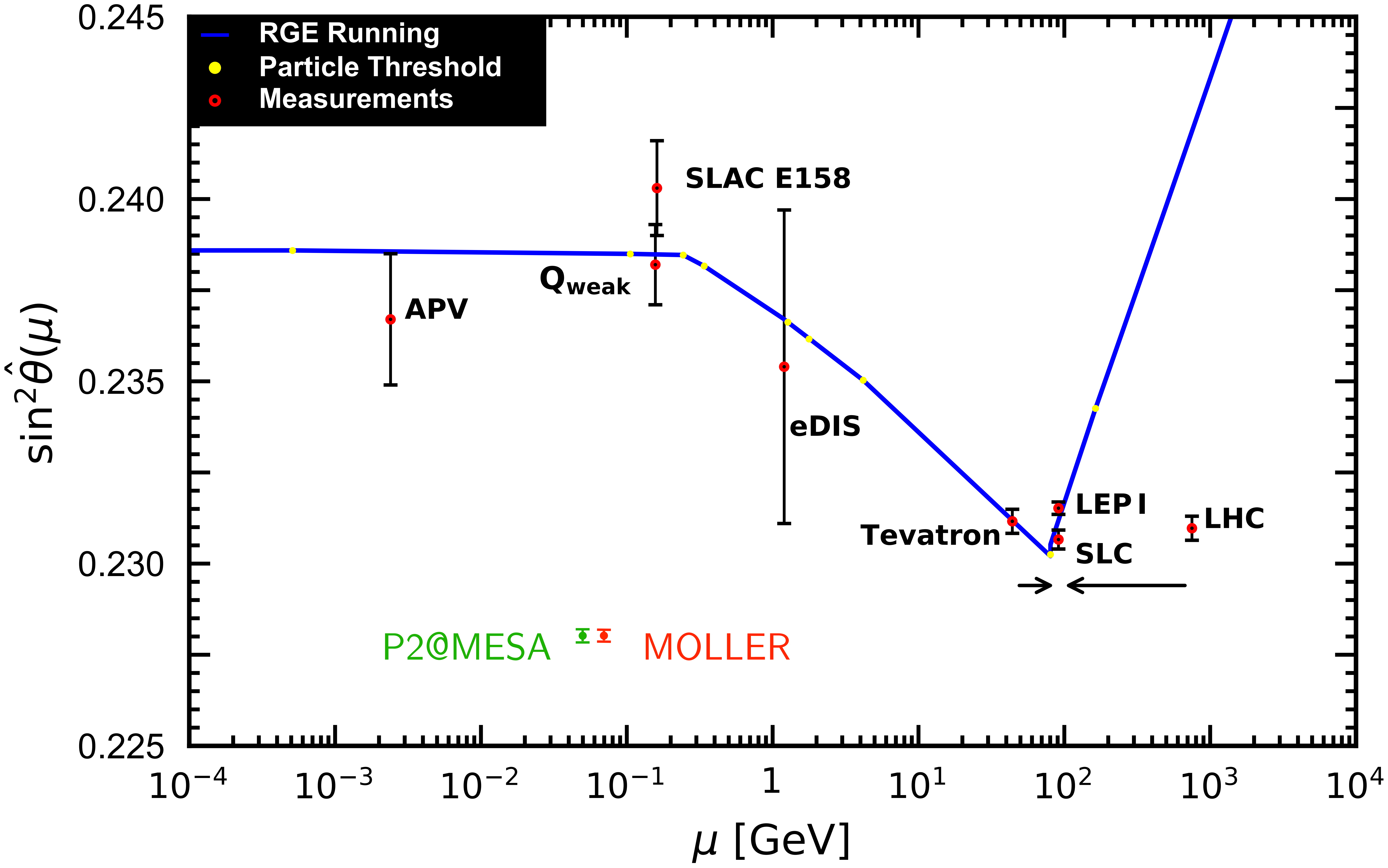

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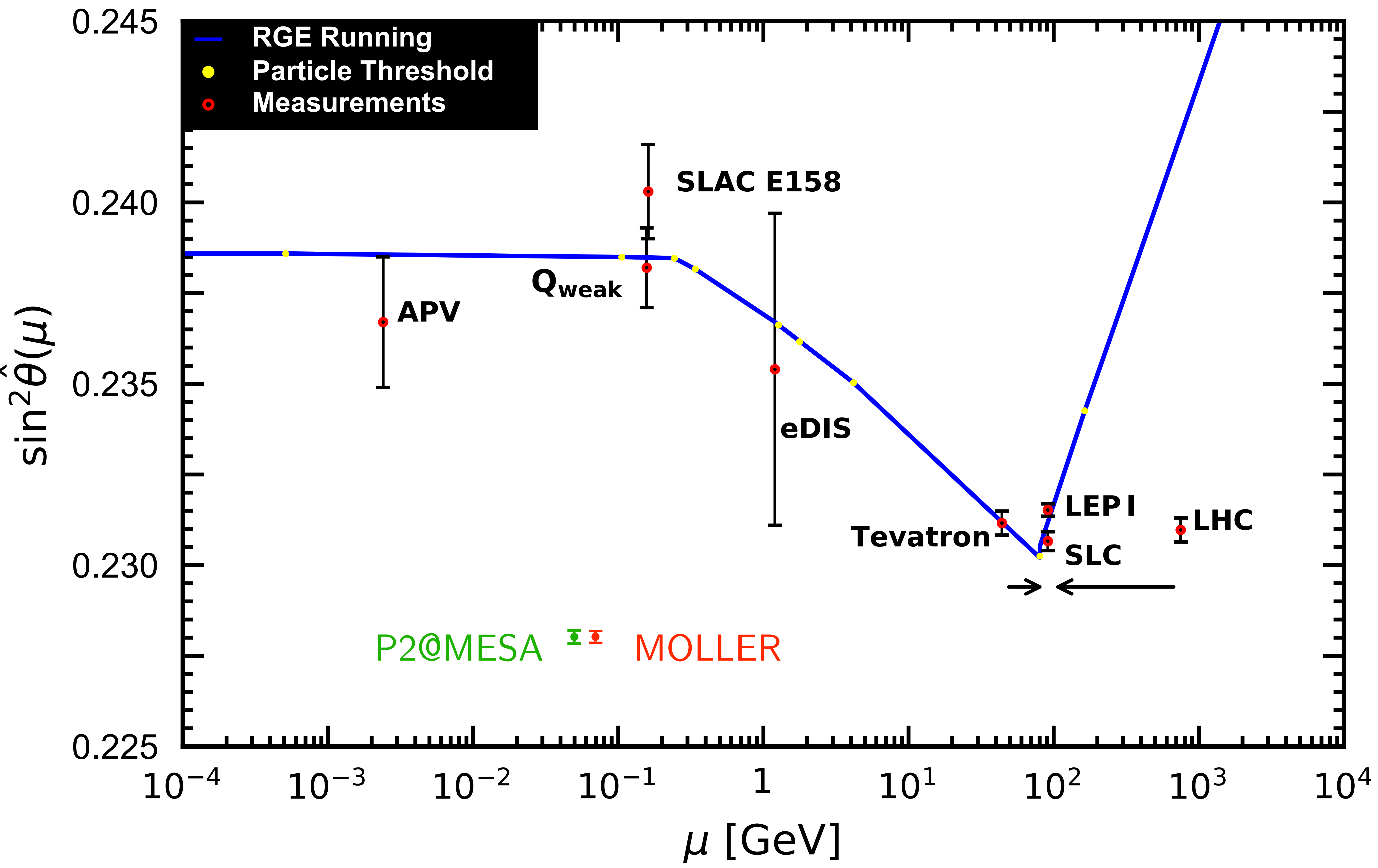
- Constrain BSM physics through effective models → sensitive to mass scales up to $\Lambda \approx 50$ TeV!



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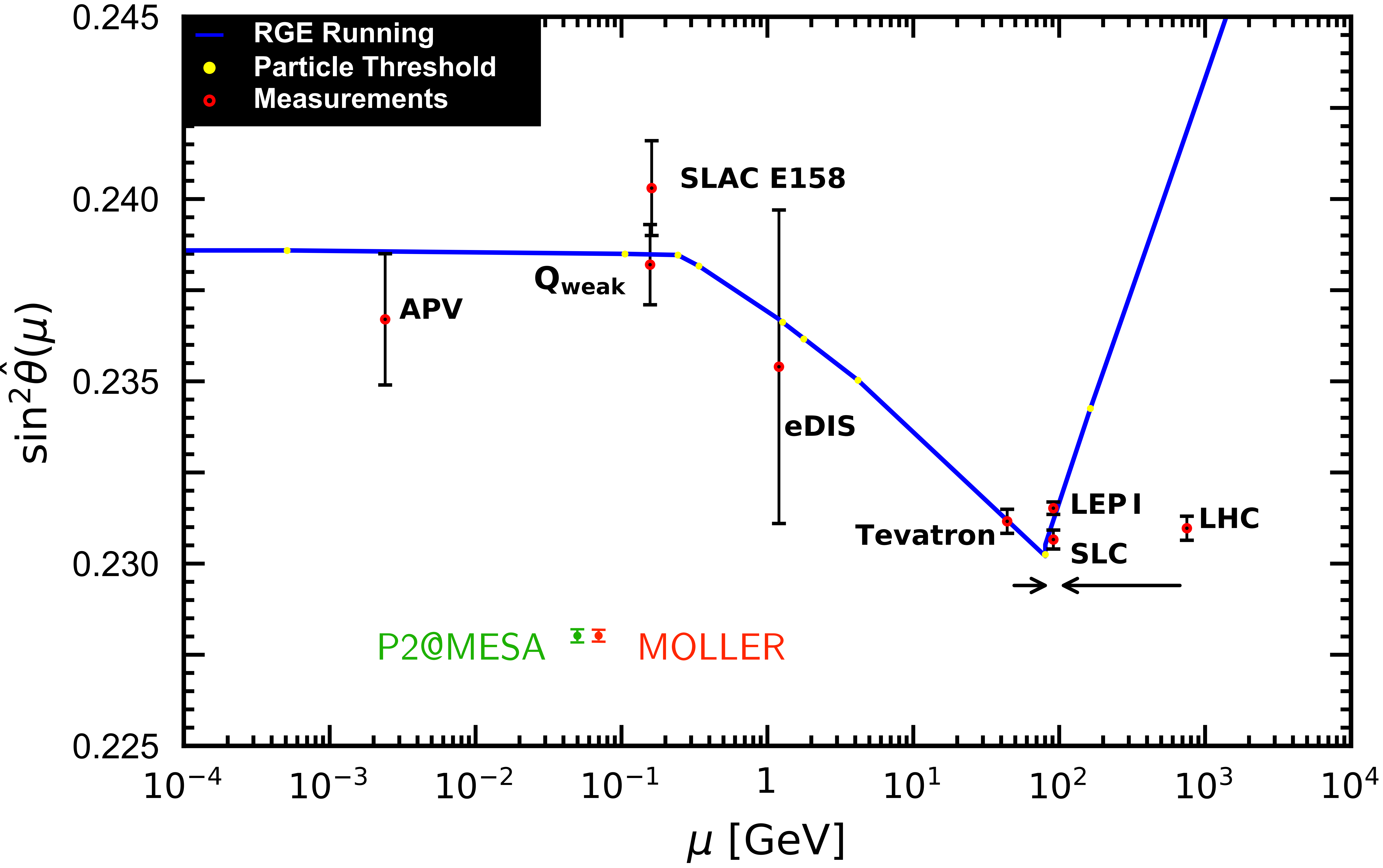

P2: Q_{weak} at MOLLER precision!

Neutron skin measurements with MREX

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  - ^{208}Pb: constrain nuclear EOS
  - ^{48}Ca: bridge between calculations of light and heavy nuclei

Adhikari et al. (PREX collab.), PRL 126, 172502 (2021)
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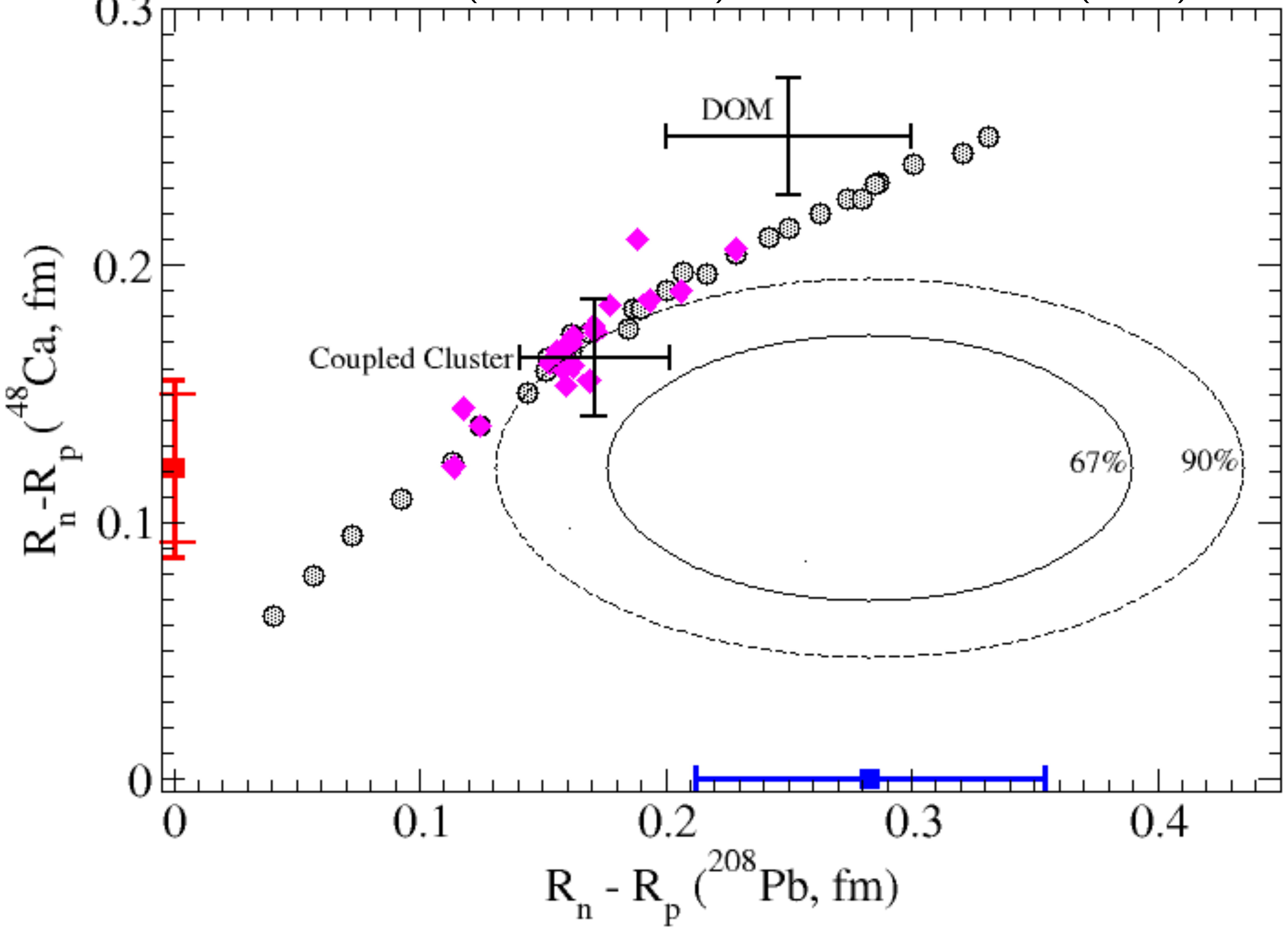

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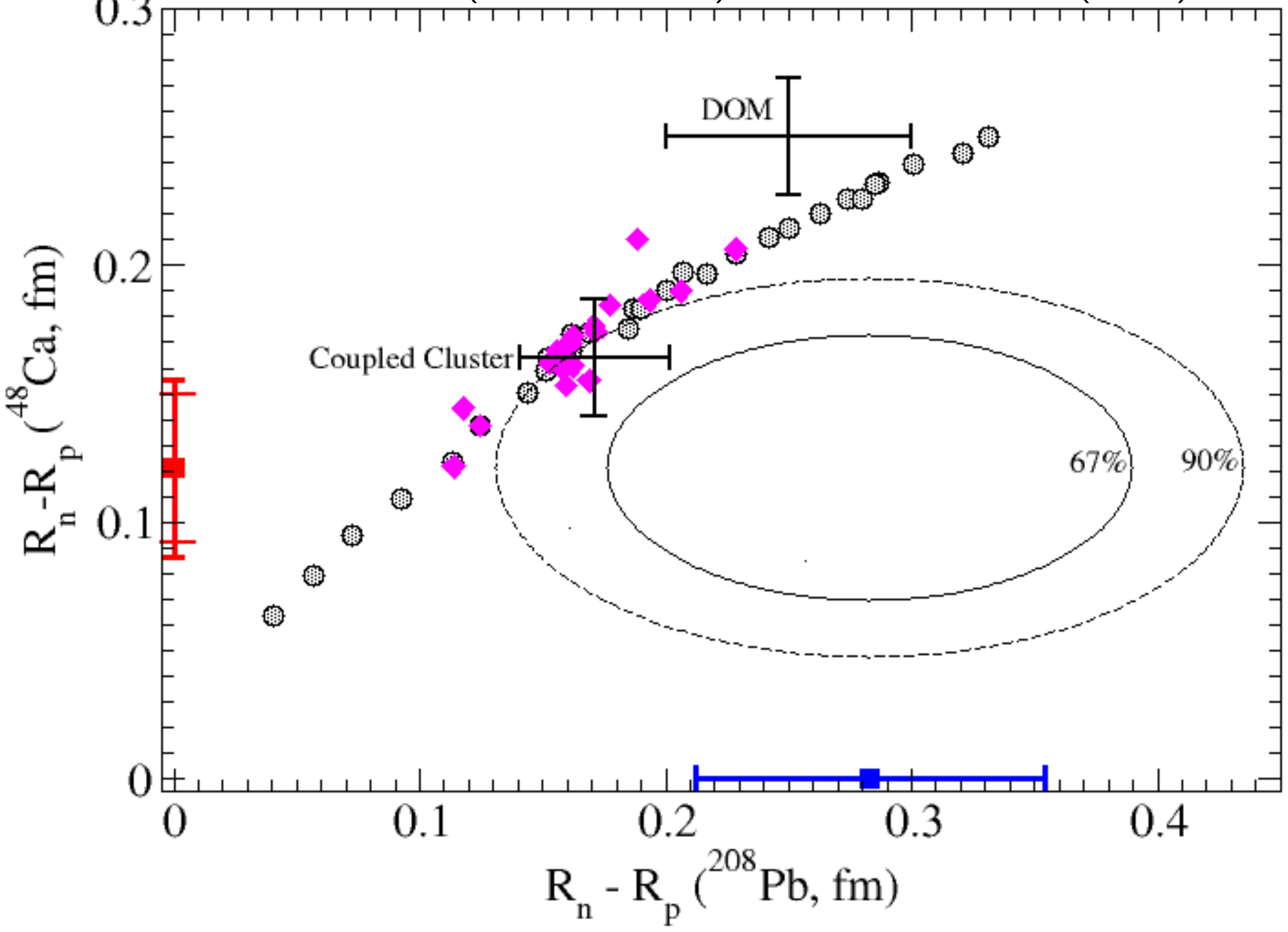
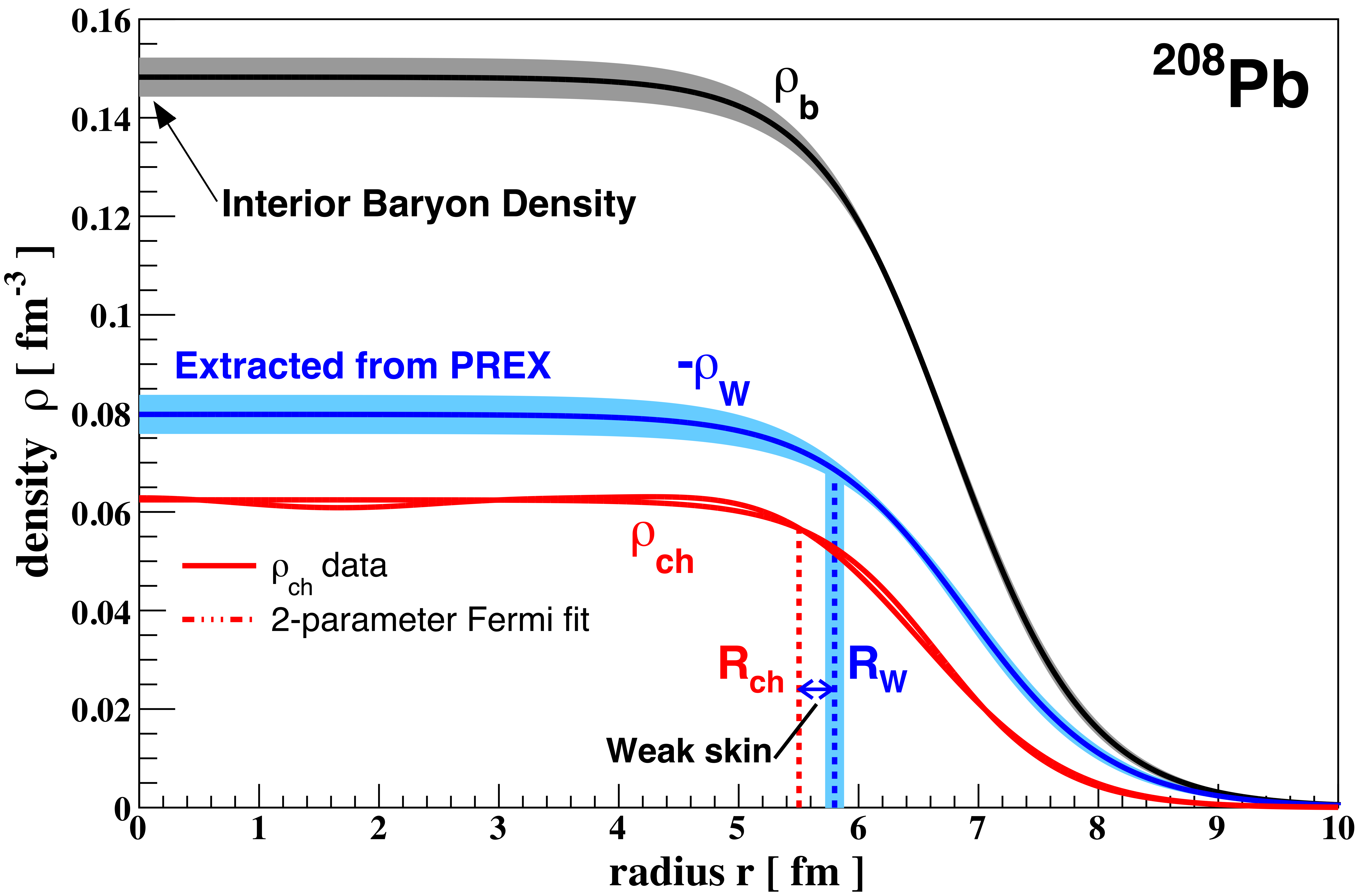


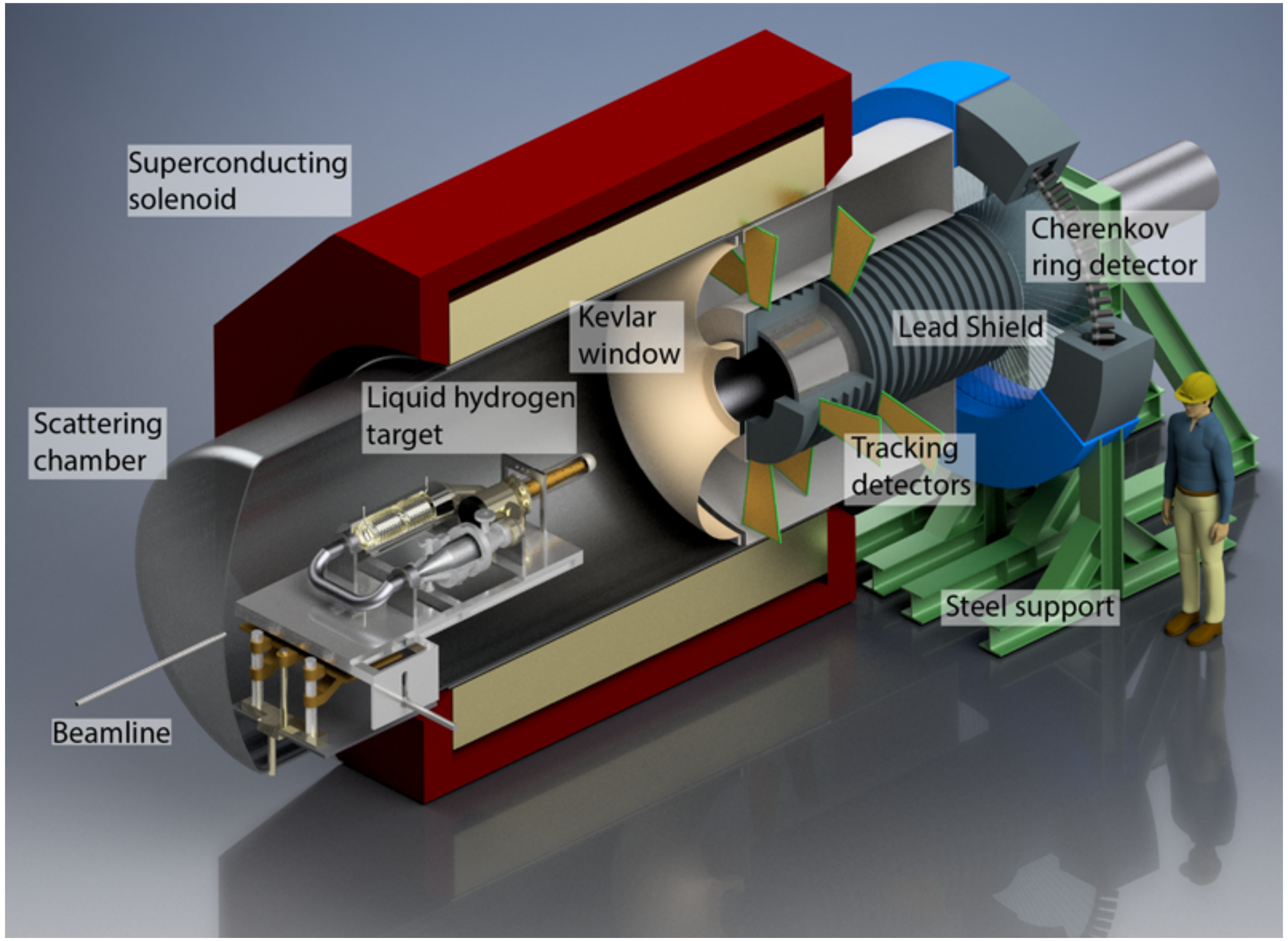
MREX to carry out similar ^{208}Pb measurement with *half the uncertainty*!

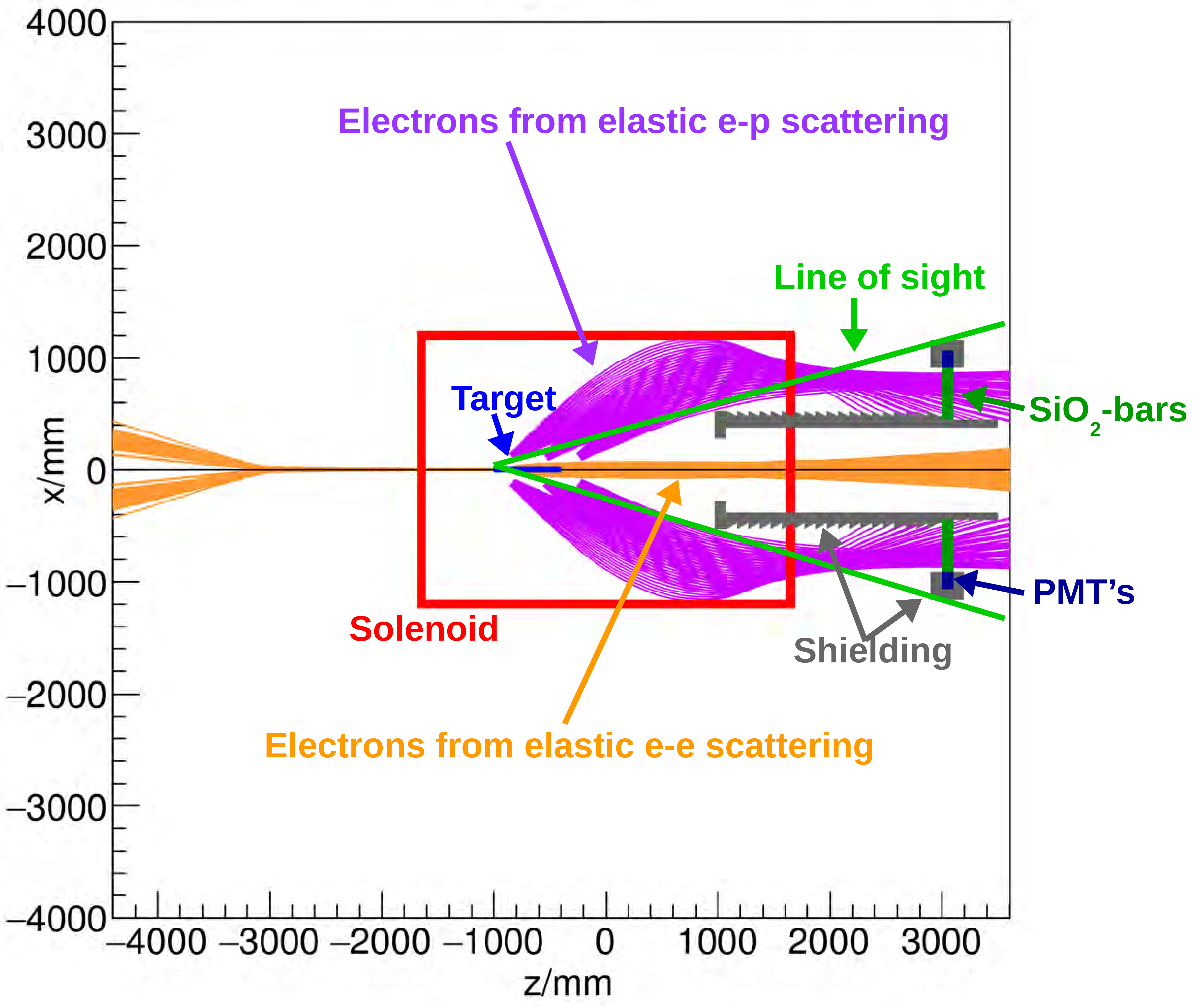
Emergence of saturation density?

- PREX claims extraction of interior baryon density of lead...from *one* data point sensitive to RMS radius
- Possible to measure multiple Q^2 point(s) at MESA



P2 spectrometer





PVES has unique demands for detectors

- Insensitive to low-energy background

  → Pure Cherenkov detector

- Accommodate 100+ GHz event rates to achieve required statistics

  → Radiation-hard material

  → Integrate signal from many simultaneous events (no "counting")

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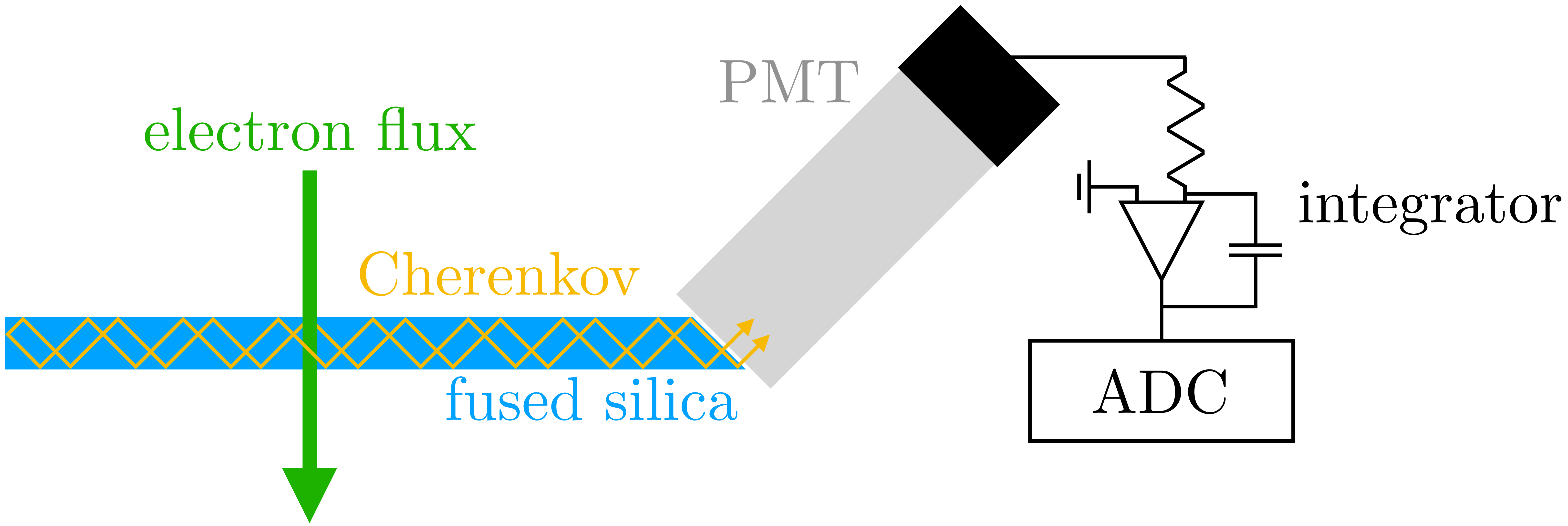
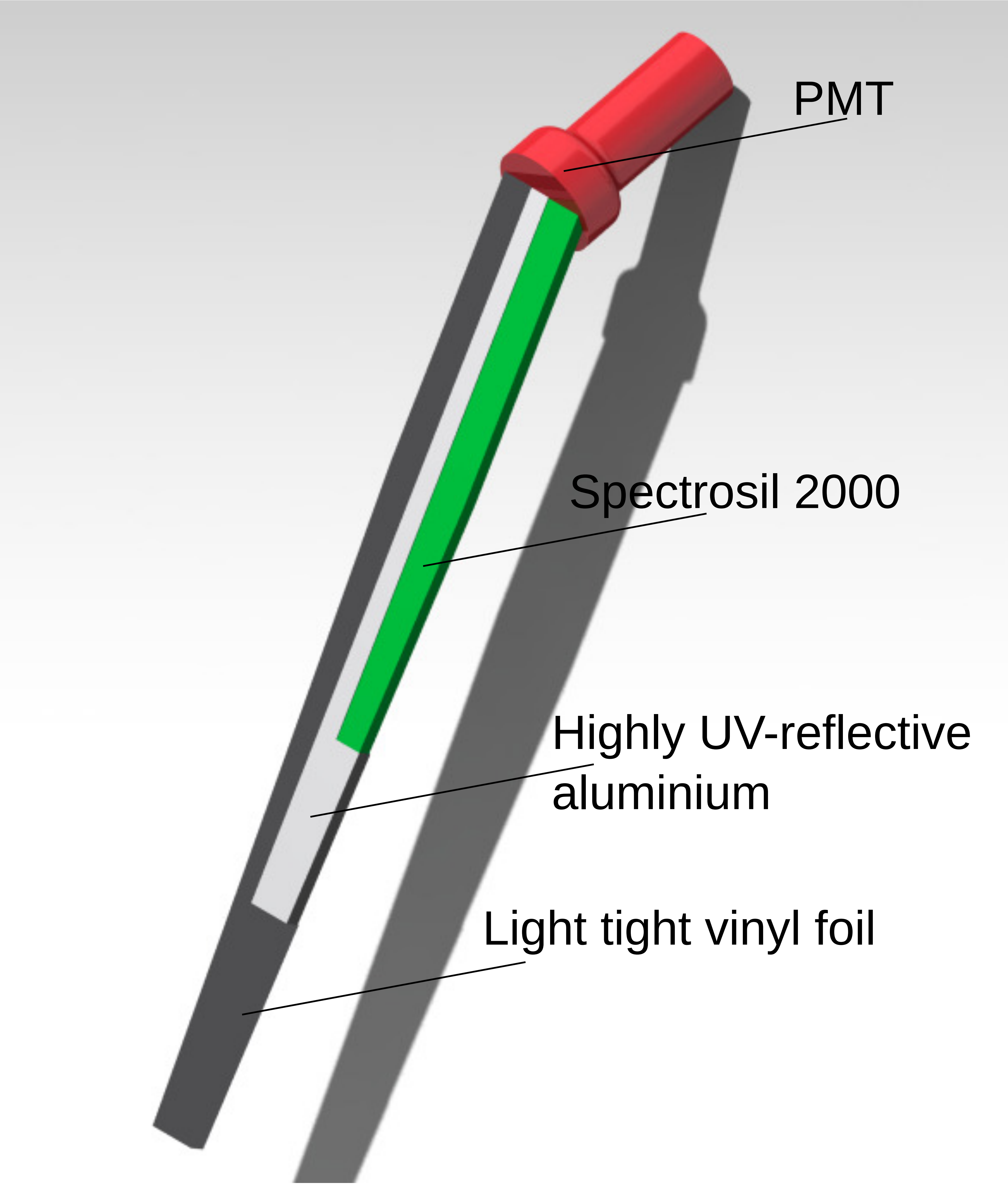
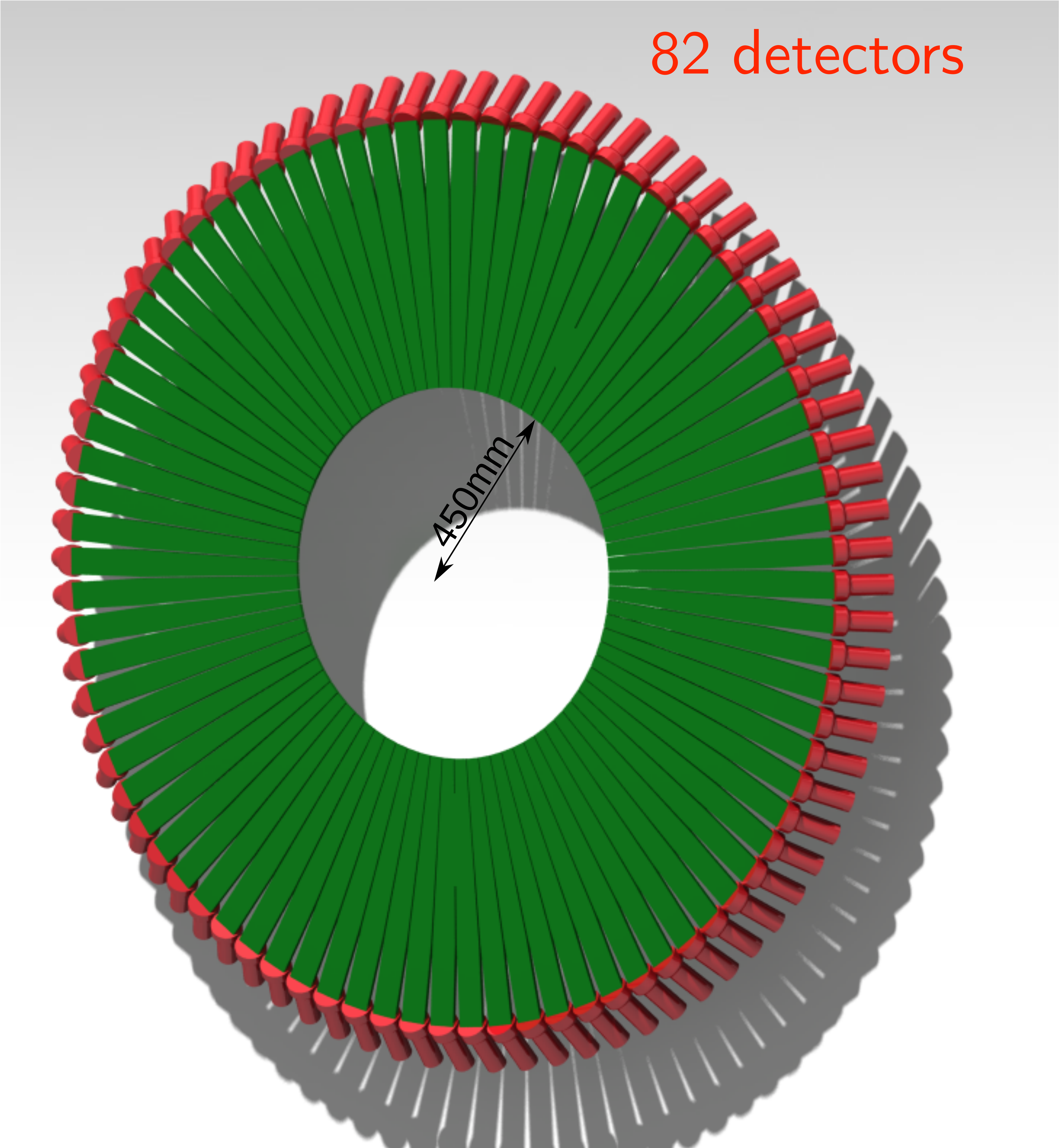
Integrating quartz
Cherenkov detectors



P2 detector ring





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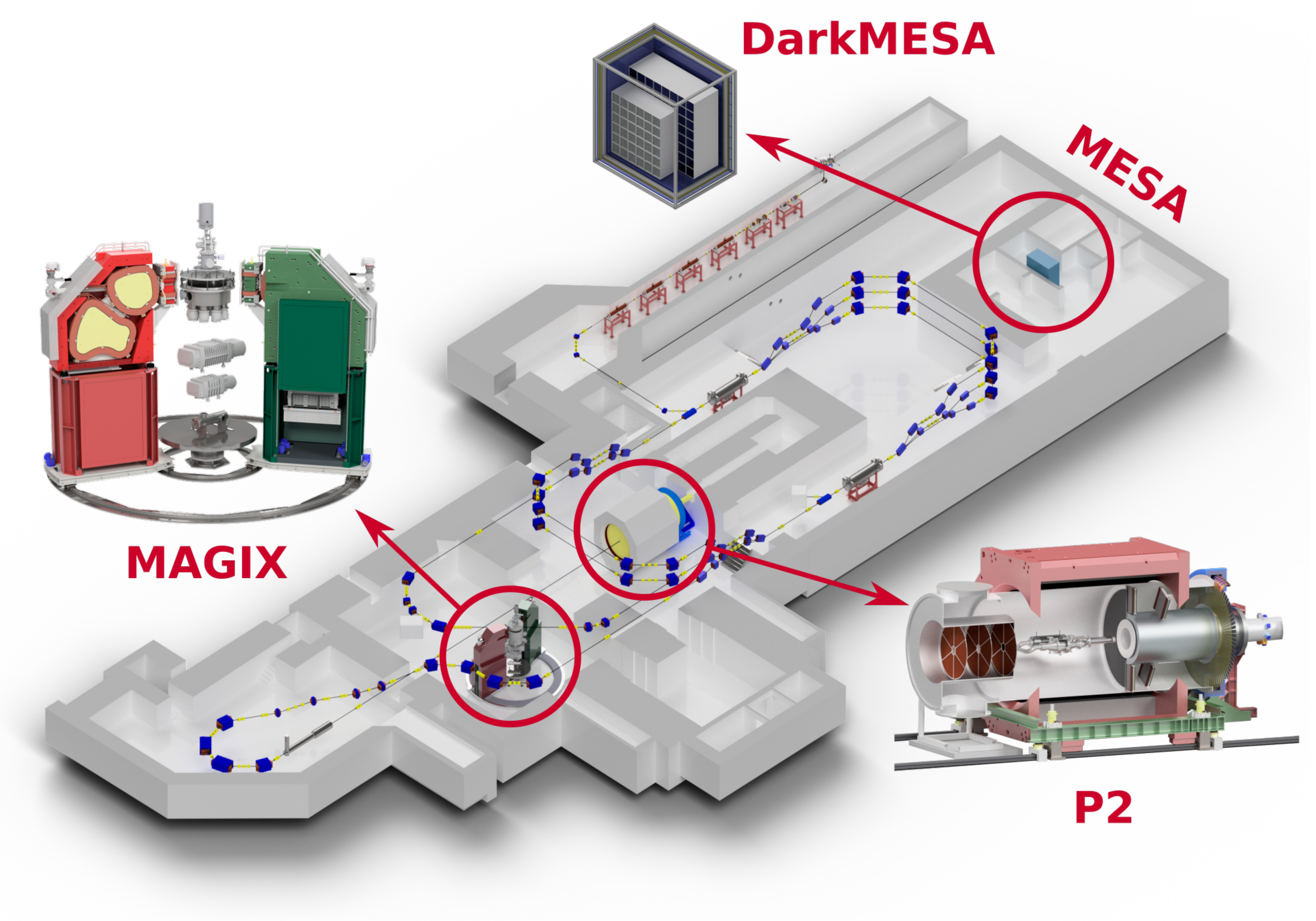
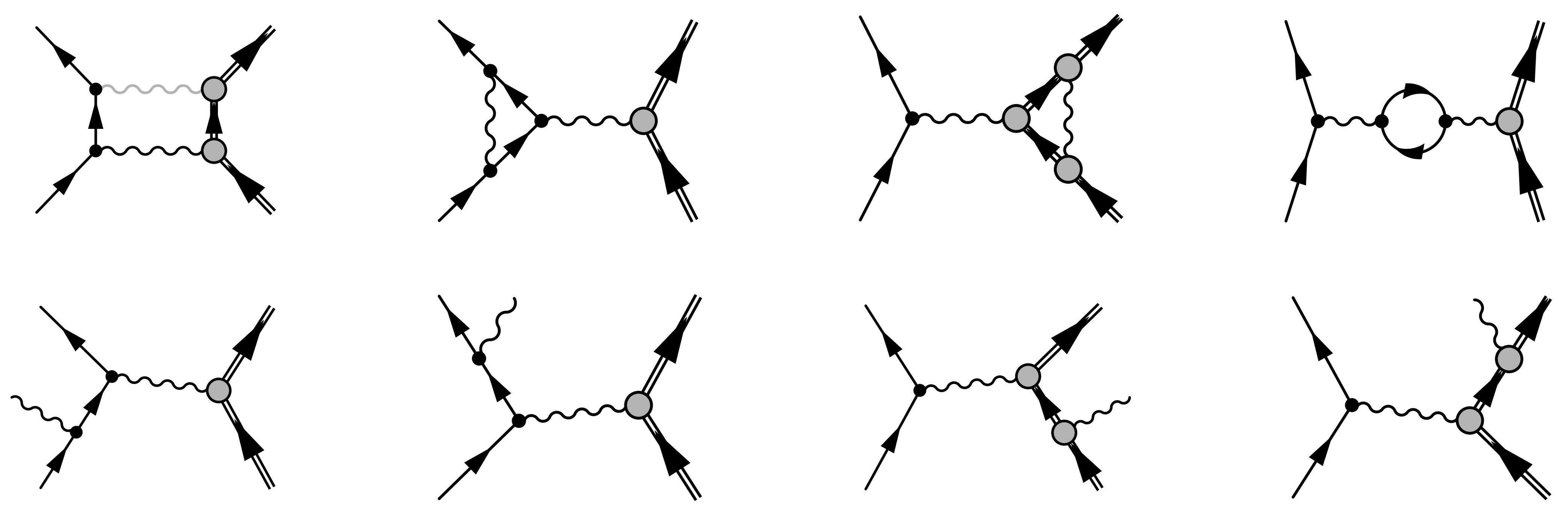


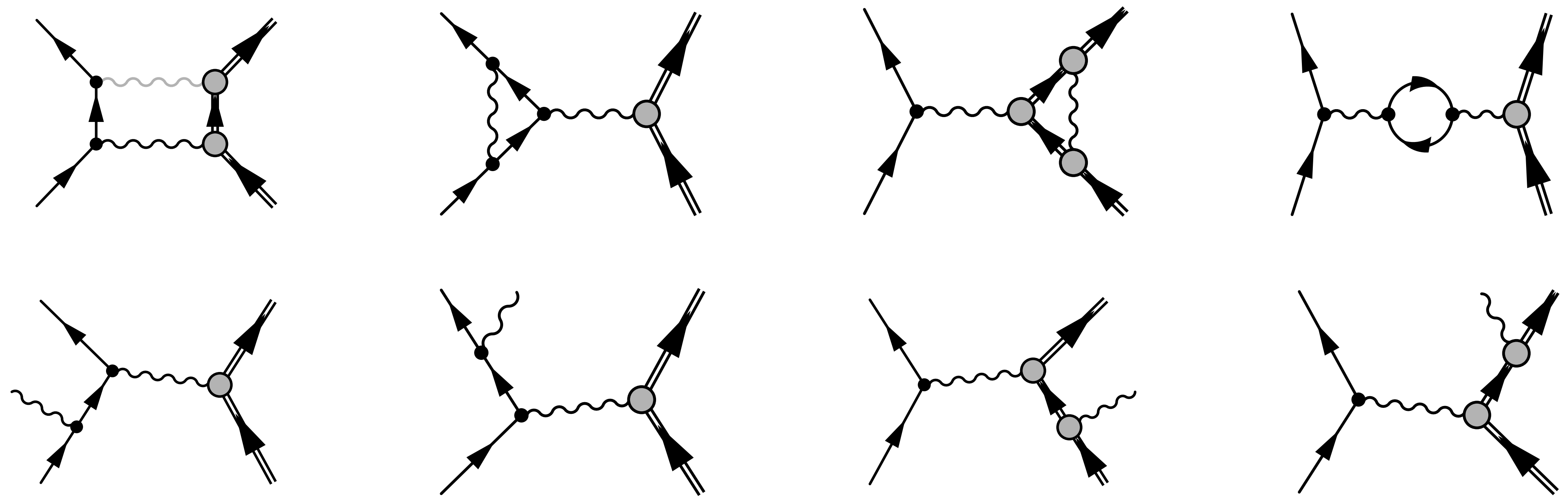
Two-photon exchange

Standard QED radiative corrections

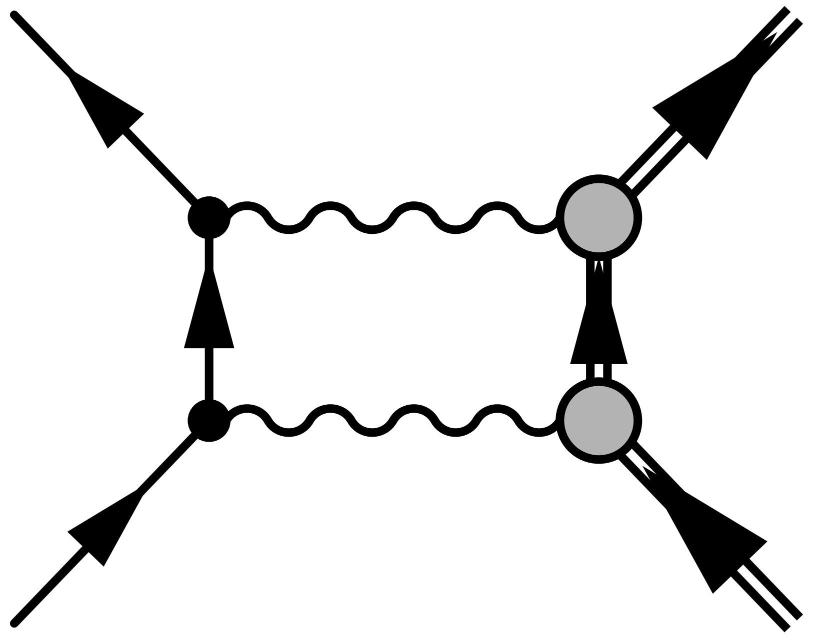


Two-photon exchange

Standard QED radiative corrections



Hard TPE



Excited hadronic states, GPDs...?

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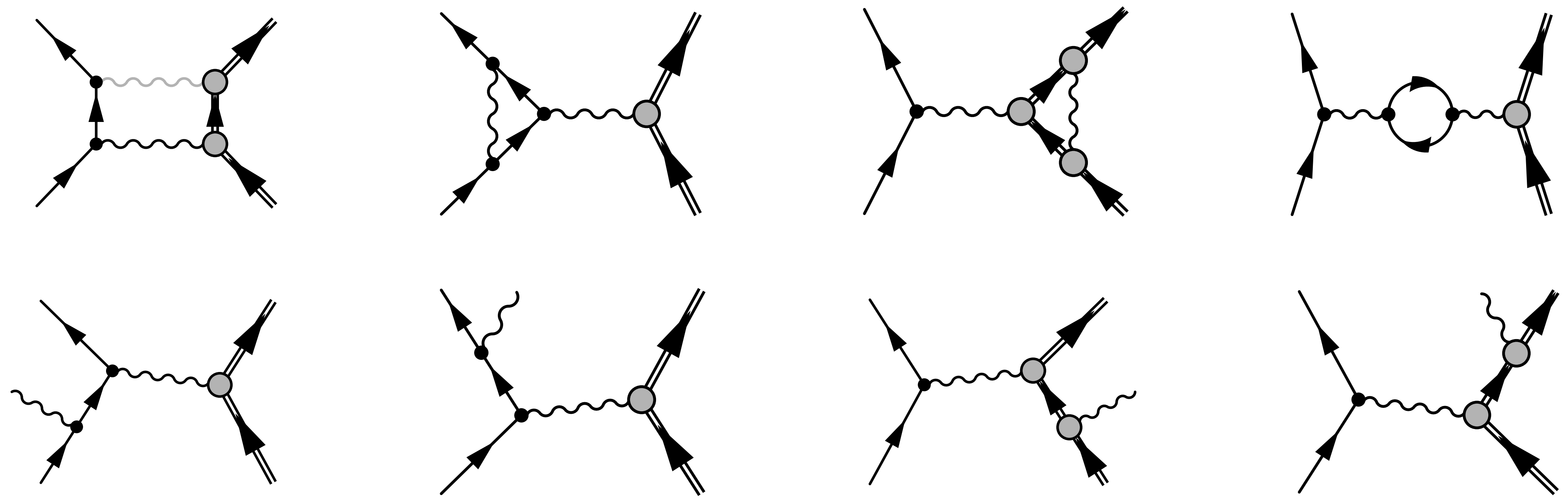

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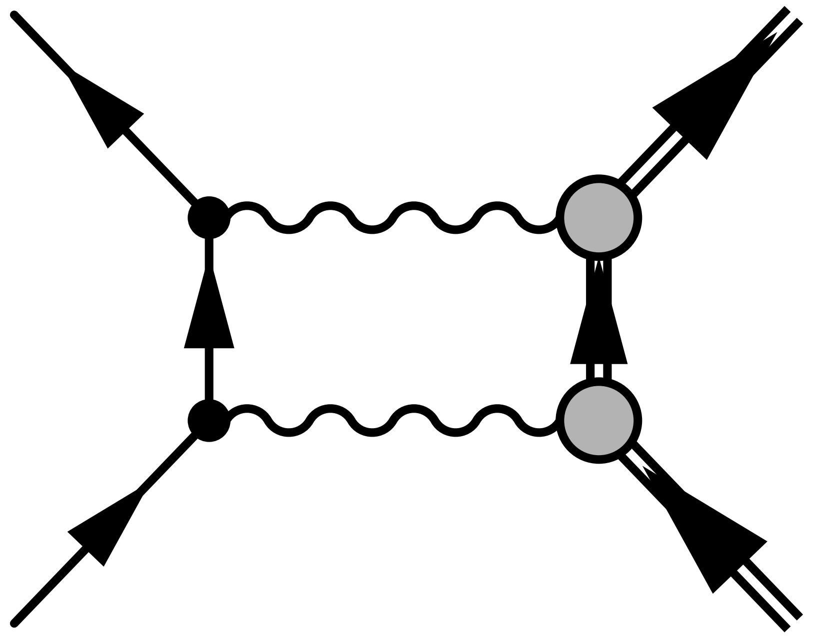

Excited hadronic states, GPDs...?

- TPE is a background to PVES (single-spin asymmetry)

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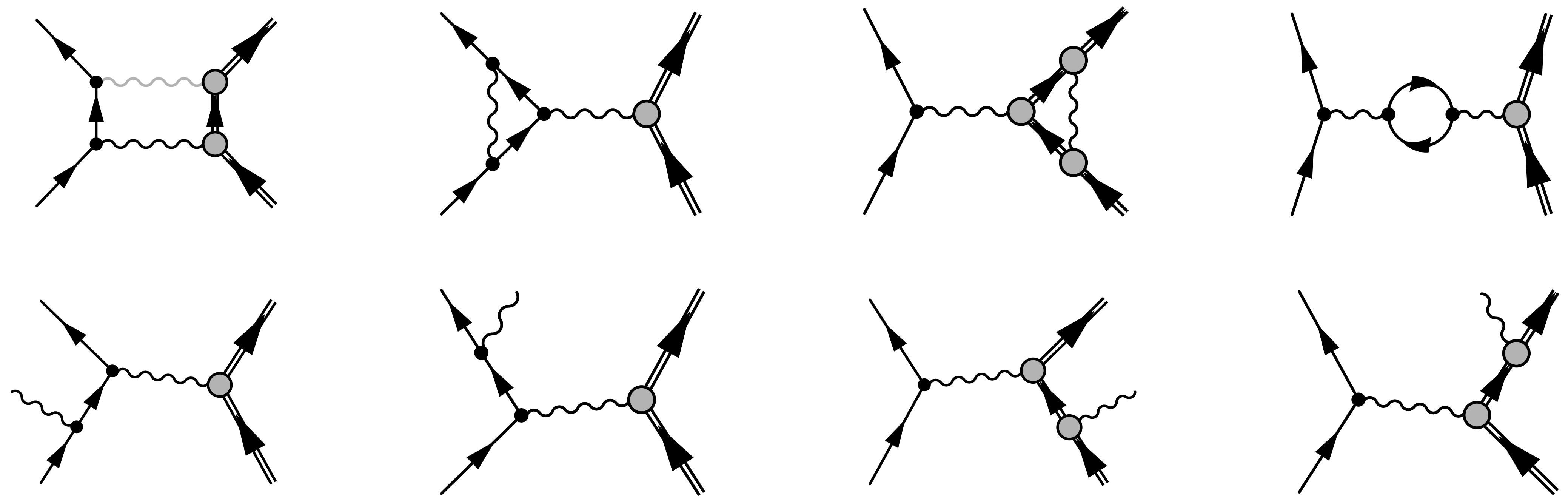
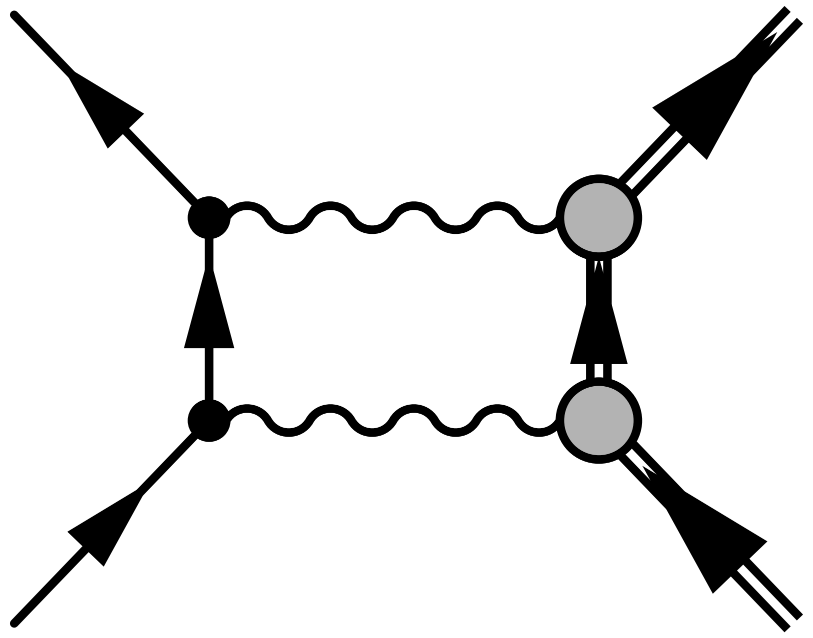


Hard TPE



Excited hadronic states, GPDs...?

- TPE is a background to PVES (single-spin asymmetry)
- TPE is favored hypothesis for proton form factor ratio discrepancy

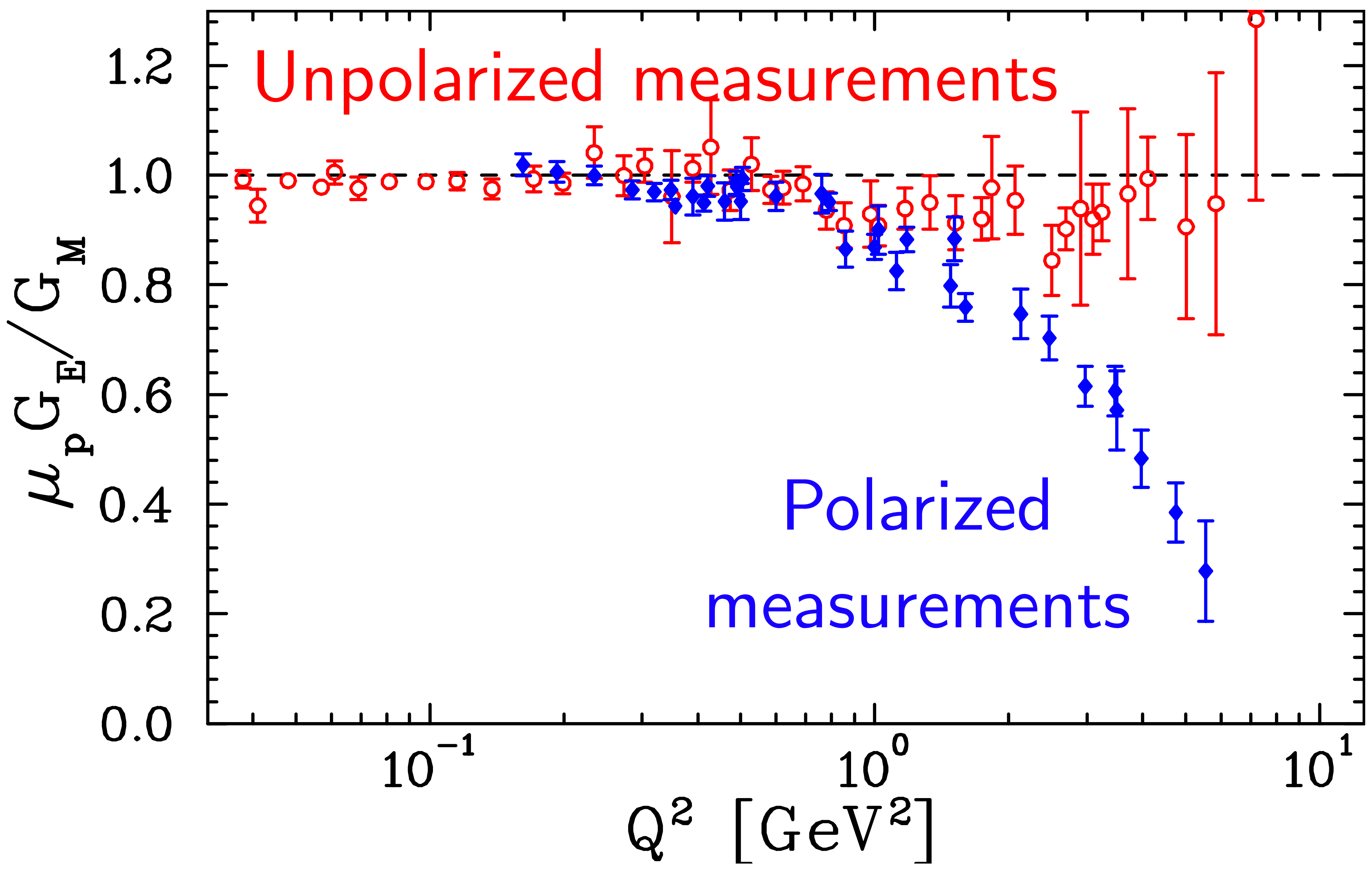


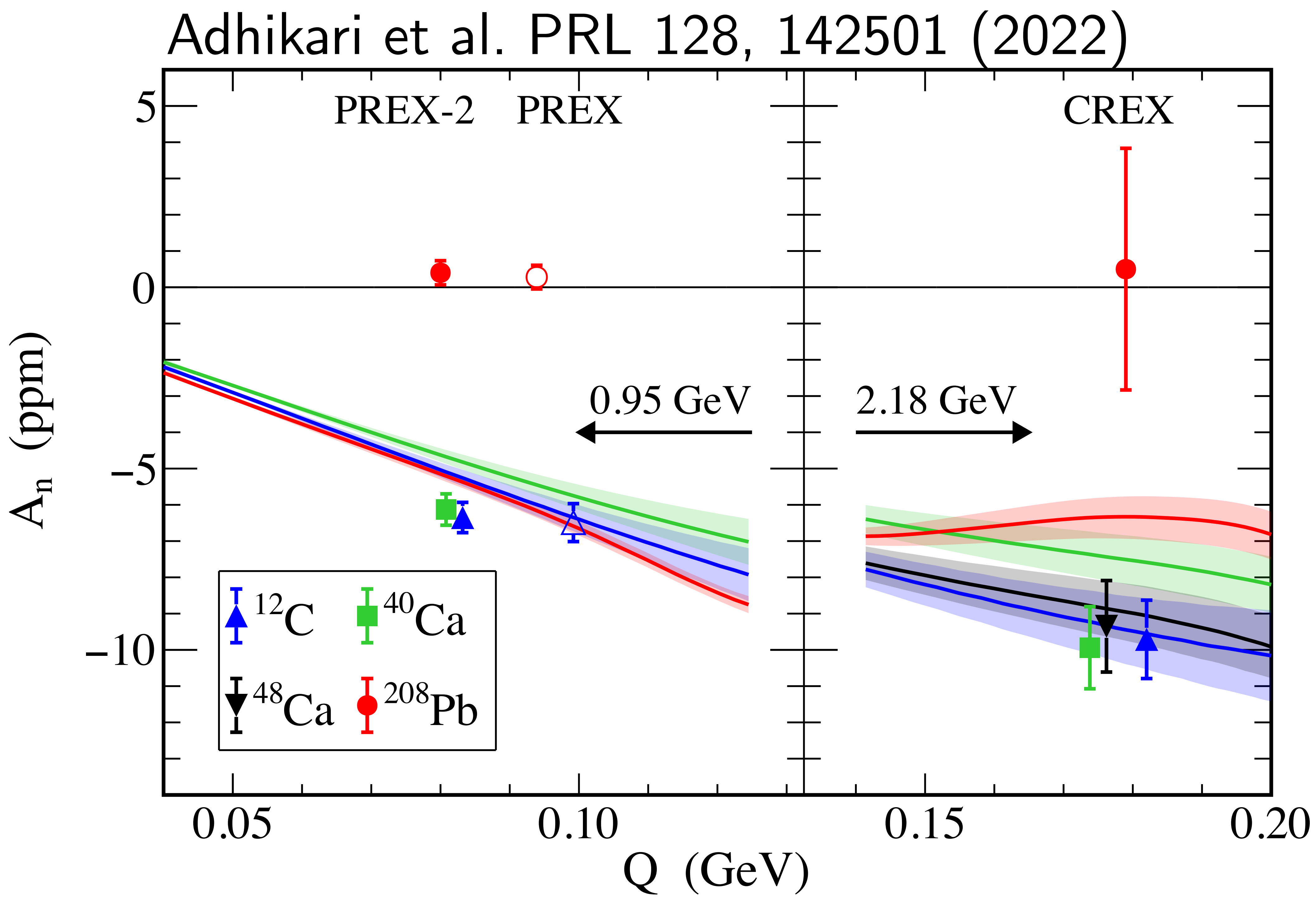
figure from Arrington et al. PRC 76, 035205 (2007)

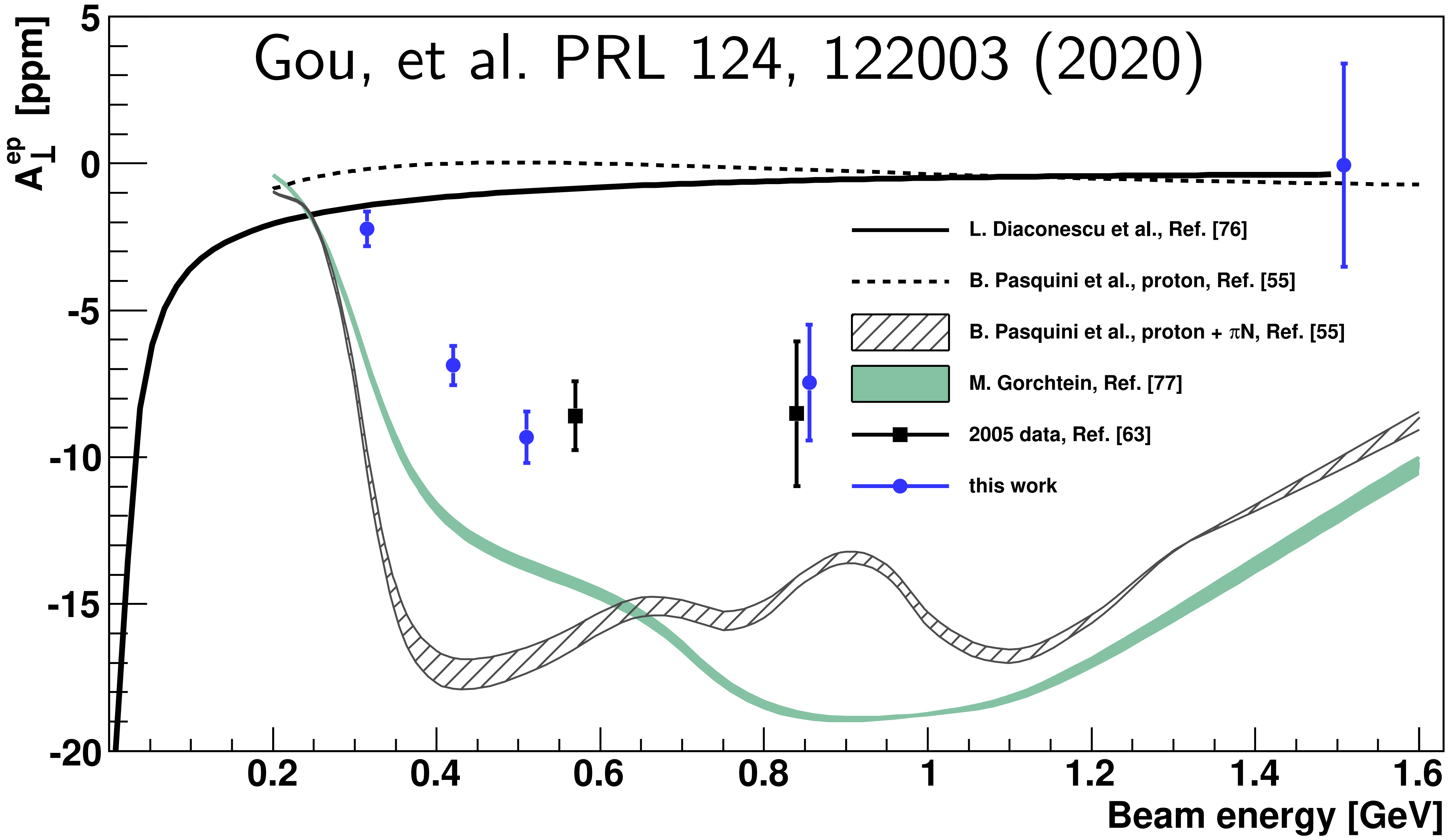
Single-spin asymmetries sensitive to TPE

- Beam- or target-normal SSA:

$$A_\perp = (\sigma^\uparrow - \sigma^\downarrow)/(\sigma^\uparrow + \sigma^\downarrow) \propto \mathrm{Im}[\mathcal{M}_{2\gamma}\mathcal{M}^*_{1\gamma}]$$

- Multiple measurements of beam-normal SSA in *ep* and *eA* scattering disagree with theory





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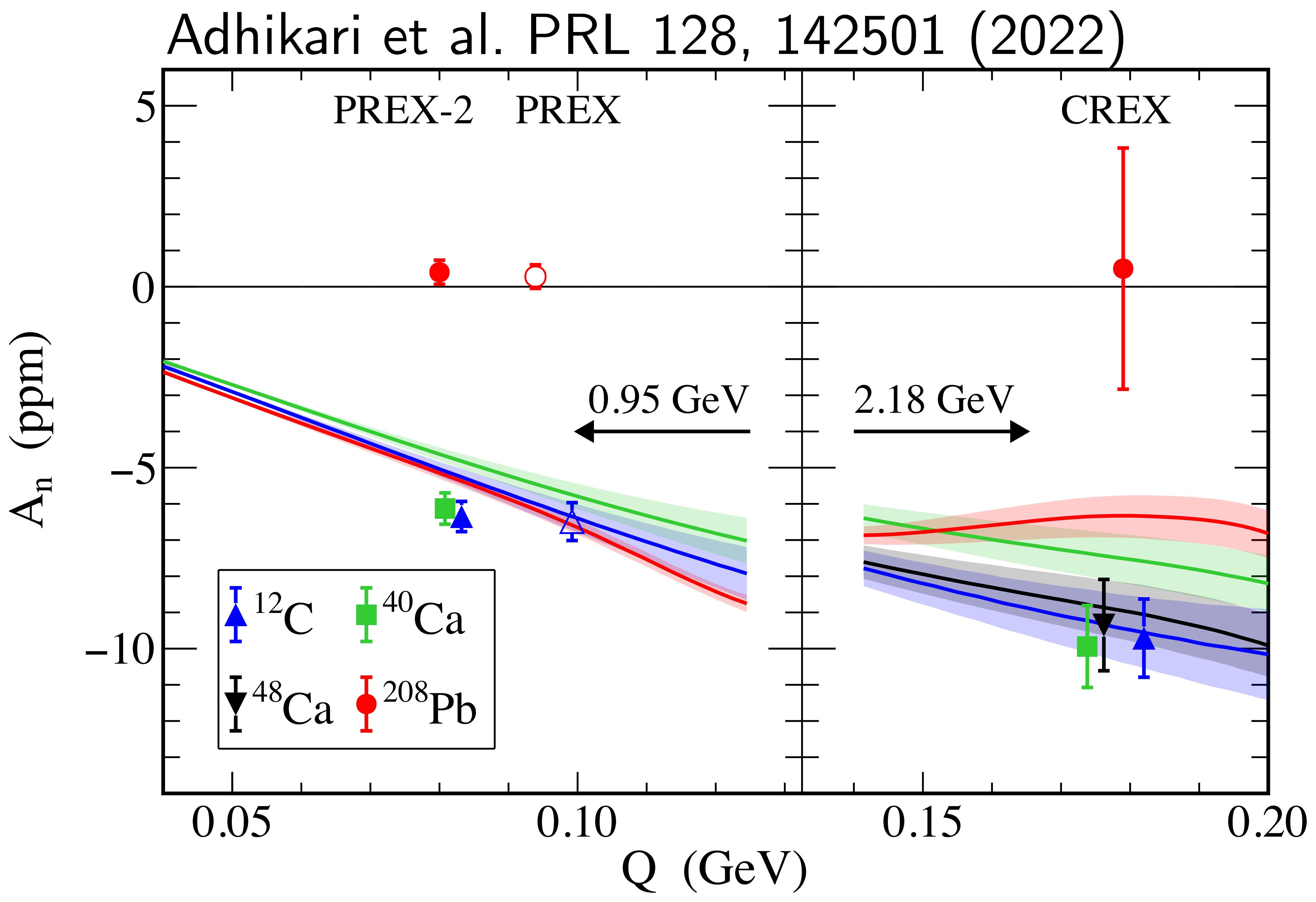
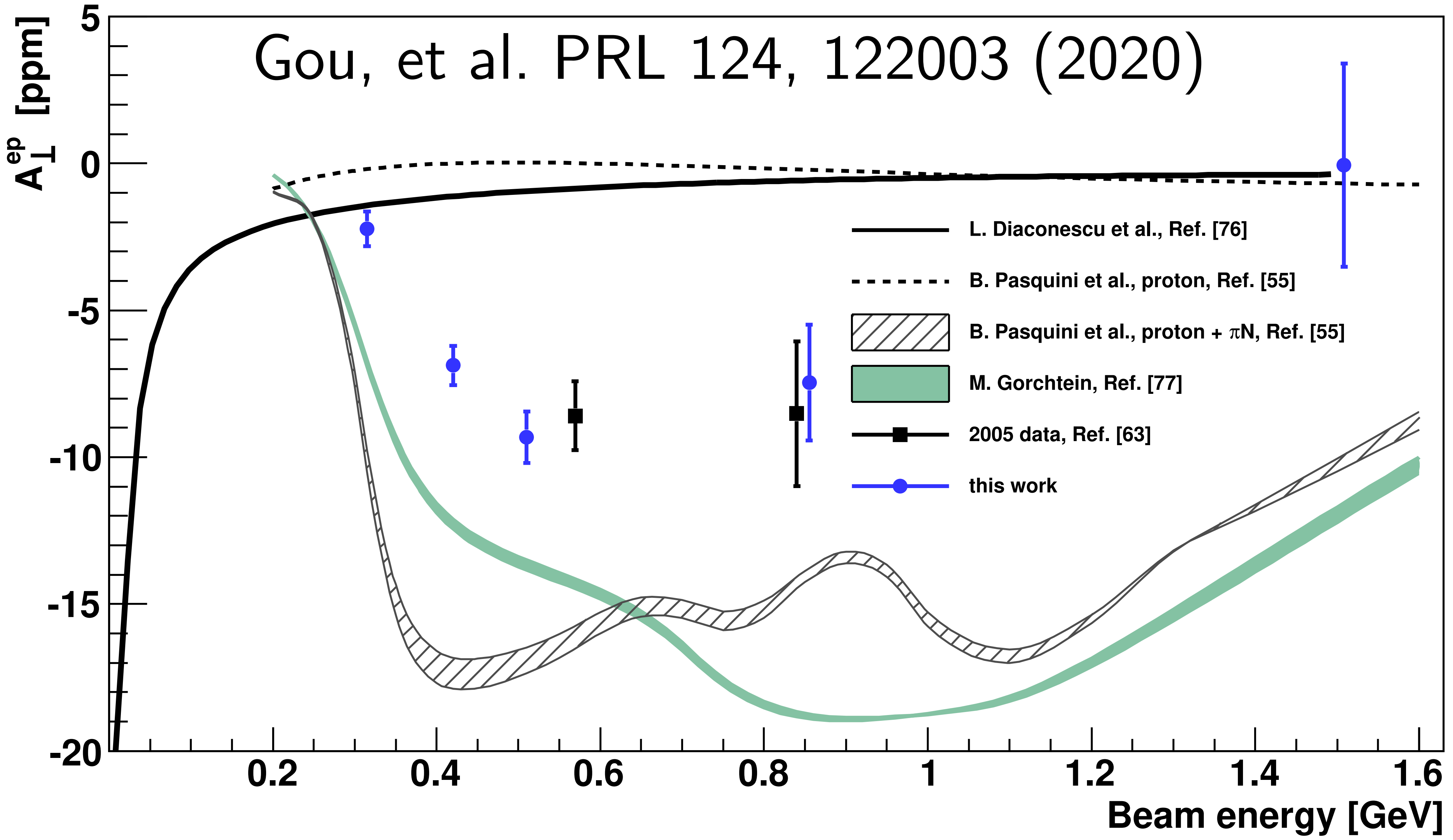
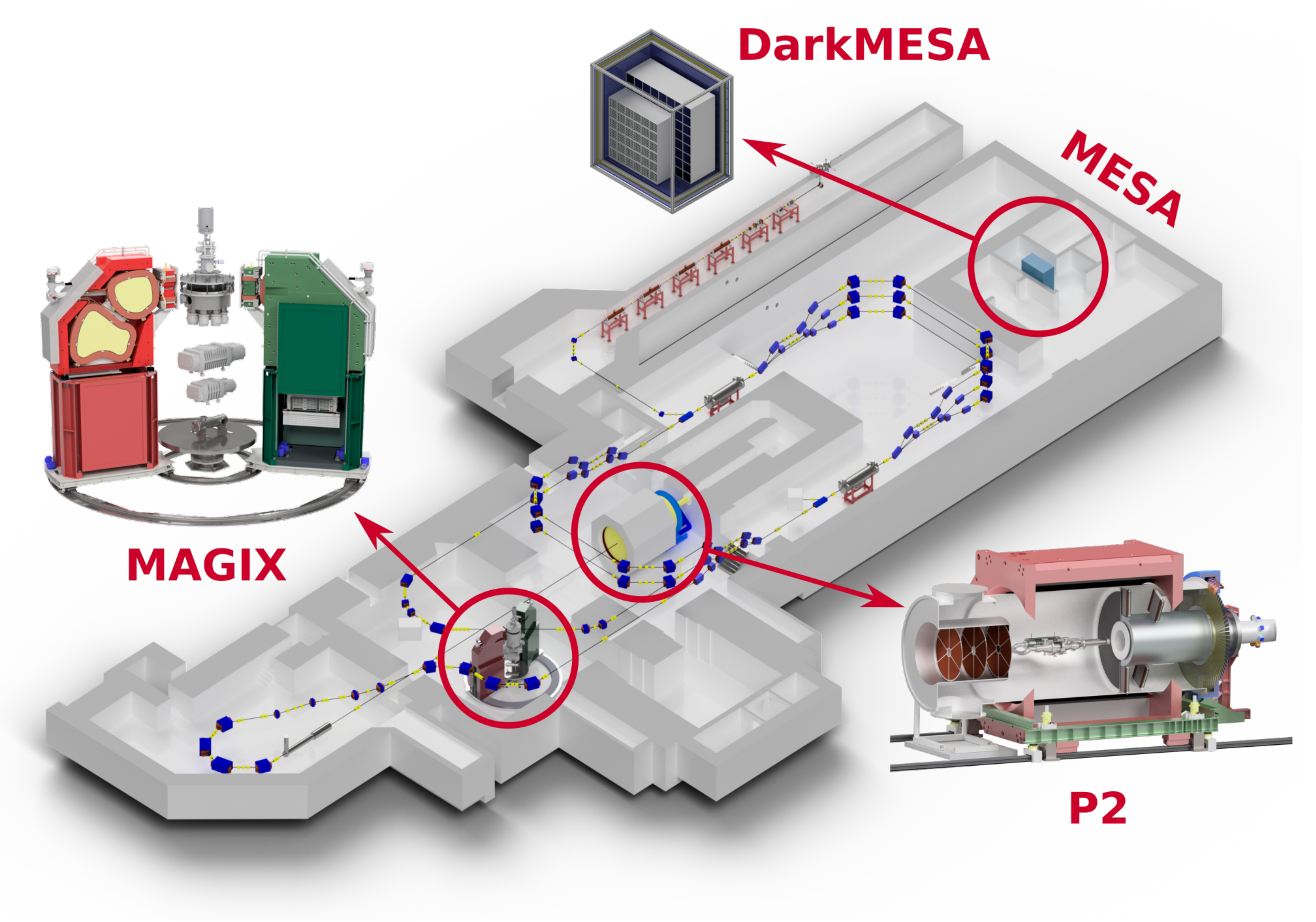
- Multiple measurements of beam-normal SSA in ep and eA scattering disagree with theory
- Possible SSA measurements at MESA:
  - Background measurements for P2
  - Gas jet target? (Avoid matter effects for outgoing electron)



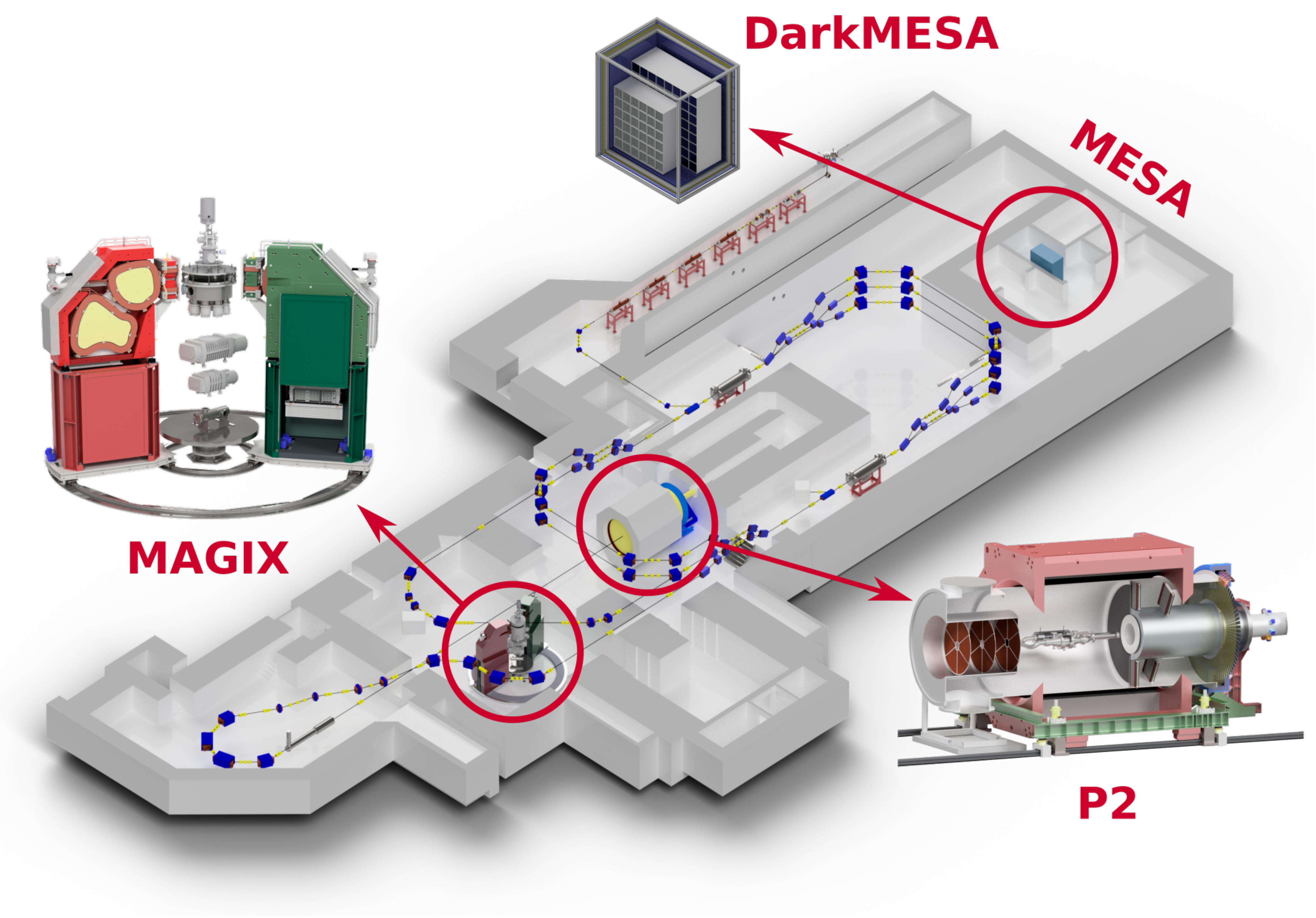


Summary



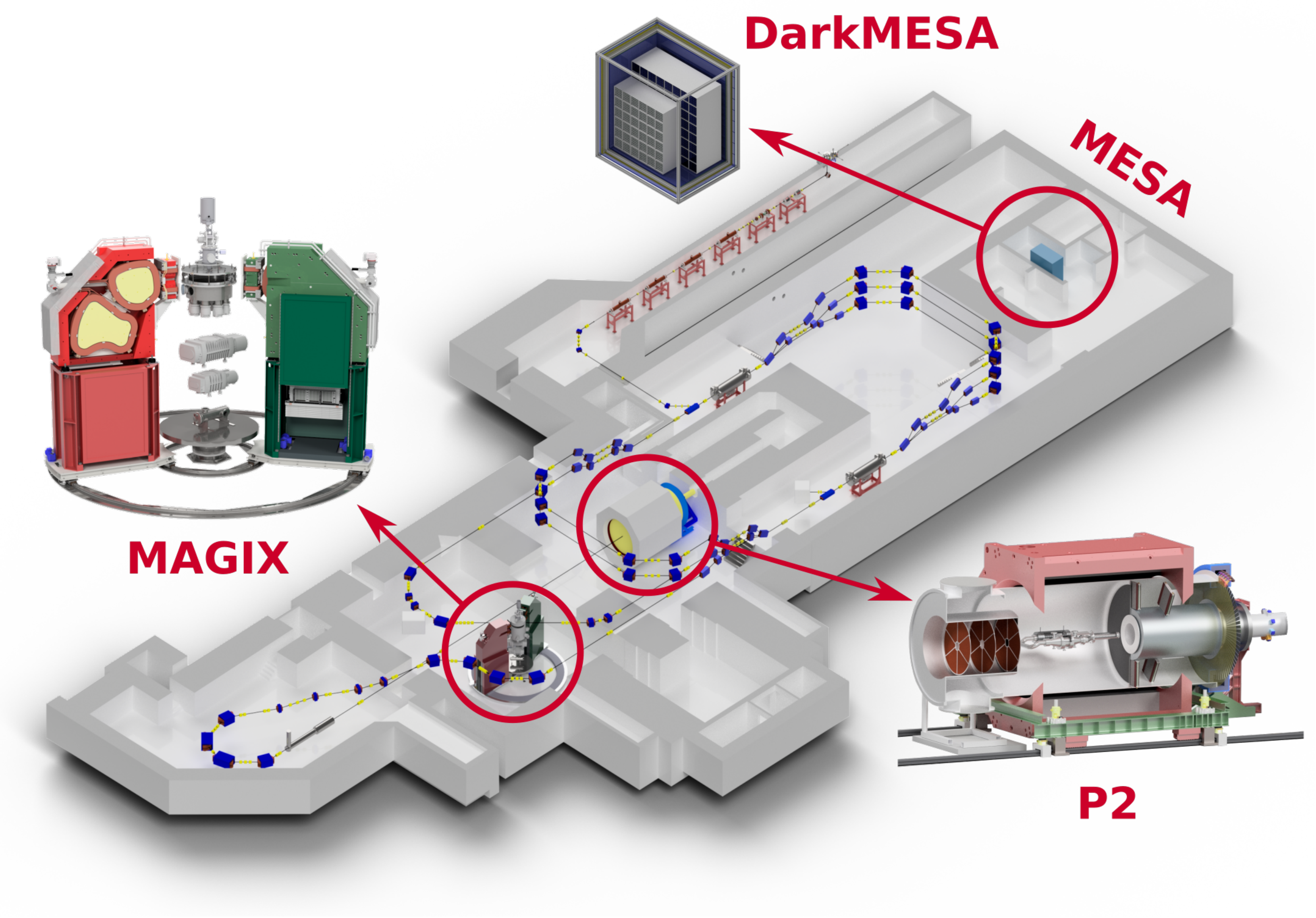
Summary

- MESA is a cutting-edge electron accelerator being built at JGU Mainz



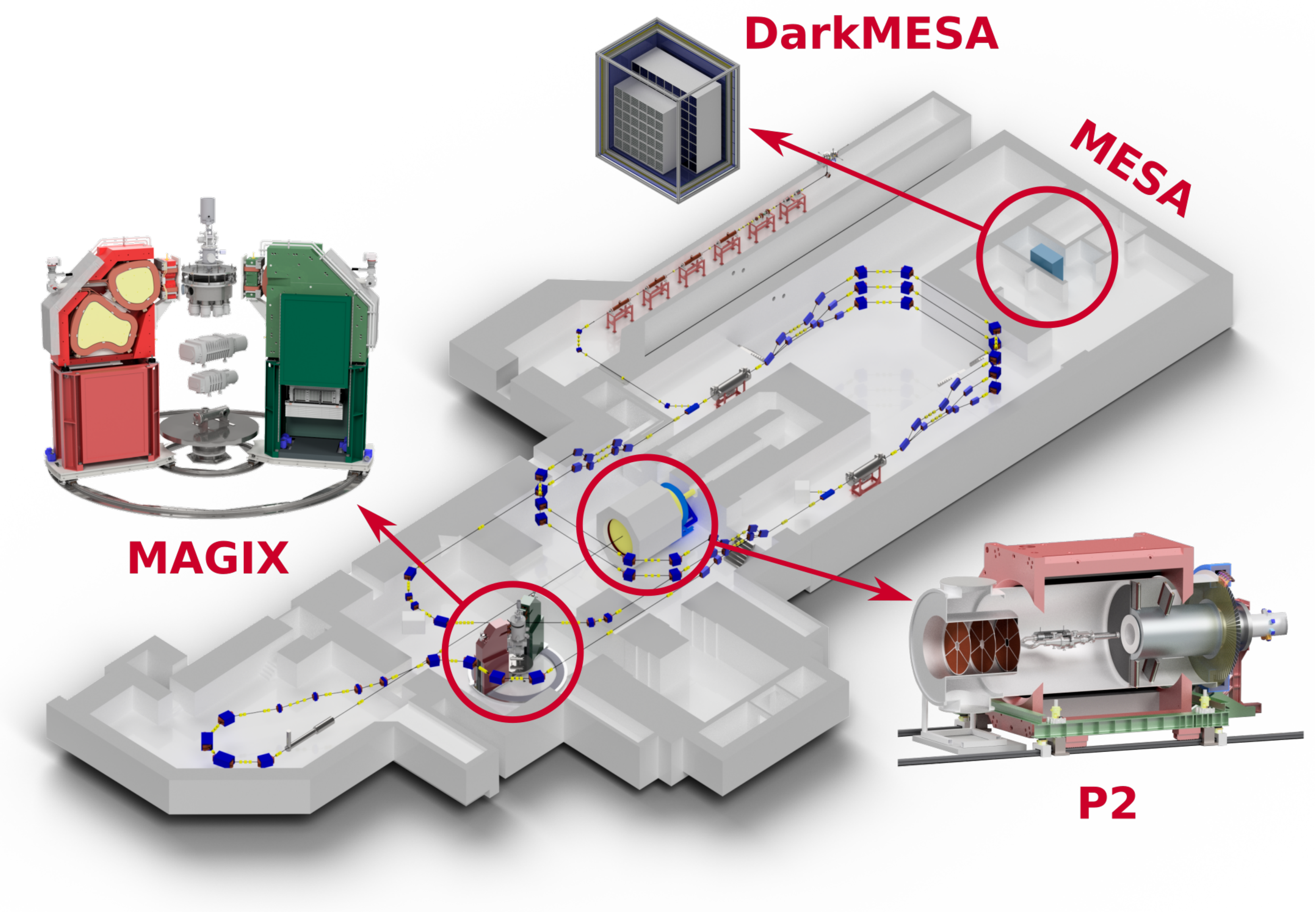
Summary

- MESA is a cutting-edge electron accelerator being built at JGU Mainz
- MAGIX: proton structure, astrophysical processes, few-body systems



Summary

- MESA is a cutting-edge electron accelerator being built at JGU Mainz
- MAGIX: proton structure, astrophysical processes, few-body systems
- P2: high-precision weak mixing angle, neutron skin thicknesses



Summary

- MESA is a cutting-edge electron accelerator being built at JGU Mainz
- MAGIX: proton structure, astrophysical processes, few-body systems
- P2: high-precision weak mixing angle, neutron skin thicknesses
- Currently under construction... set to begin 2025!