

Mitchell Mesa
Monument Valley
Navajo Nation

MESA and the low-energy precision frontier

Tyler Kutz
JGU Mainz

*16th European Research Conference on Electromagnetic
Interactions with Nucleons and Nuclei*

October 28 - November 1, 2025
Paphos, Cyprus



Surveying the landscape



- **Direct searches for new physics at high energies have come up empty**
 - Possible cracks in Standard model are getting harder to find!
- **Limits on WIMP dark matter approaching neutrino floor**
 - Look for light dark matter in dark sector

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 - Phenomenological interactions and effective field theories require benchmarks from data
- **SM tests limited by hadronic uncertainties**
 - Precision measurements provide critical input to new physics searches

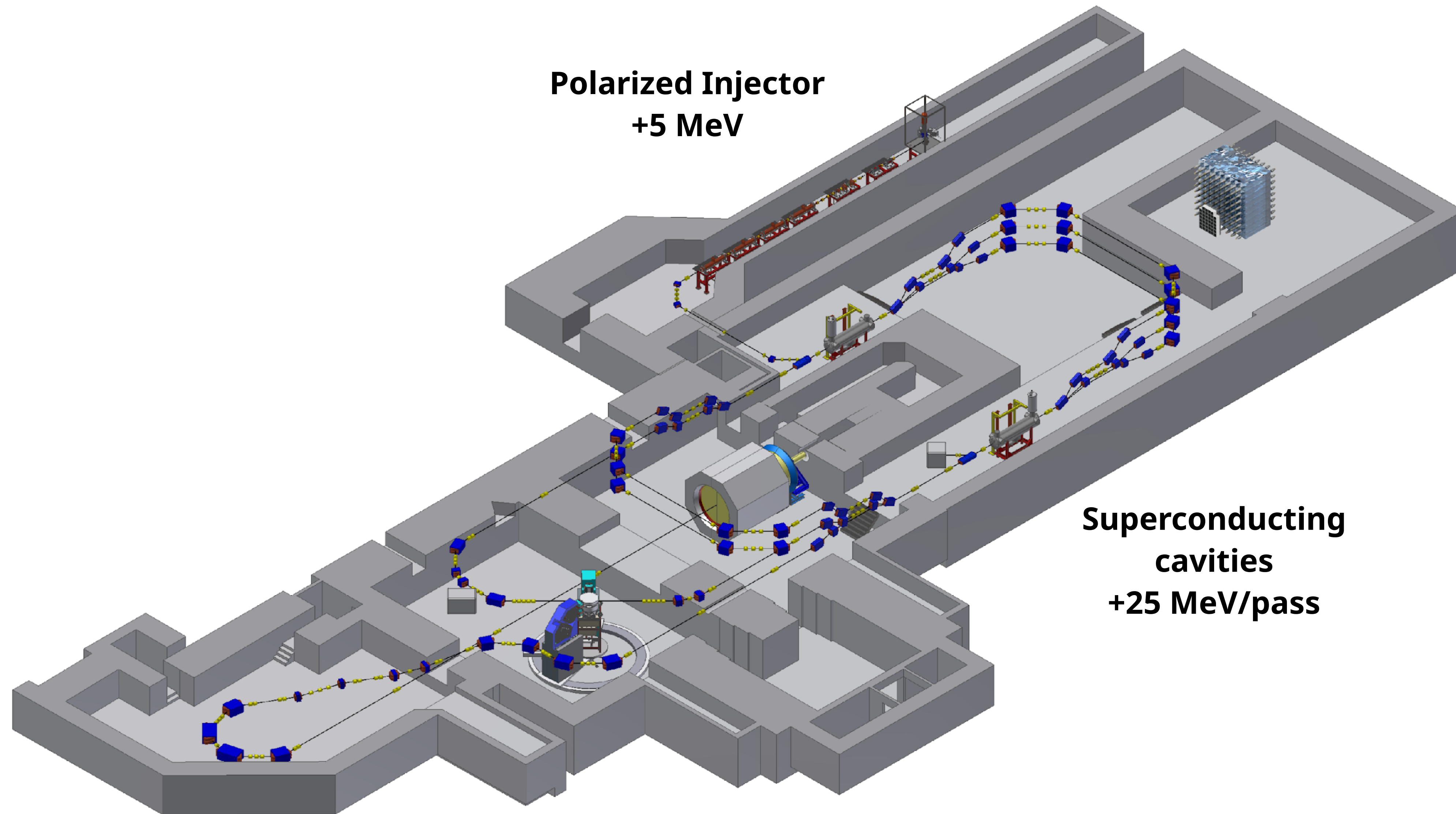
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Diverse challenges → common solution?

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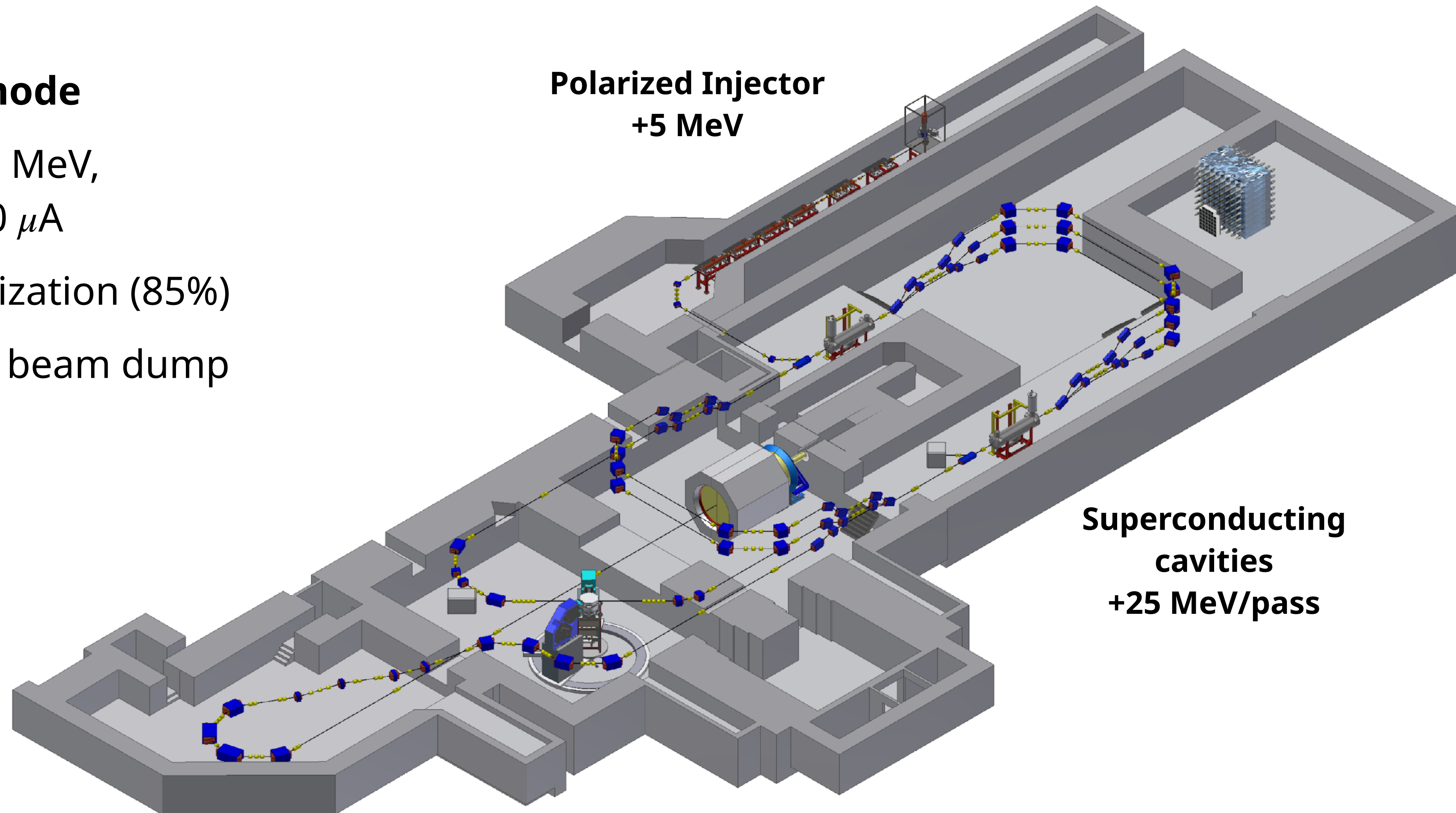
Mainz energy-recovery superconducting accelerator (MESA)



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- Energy up to 155 MeV, current up to $150\ \mu\text{A}$
- High beam polarization (85%)
- Thick target with beam dump



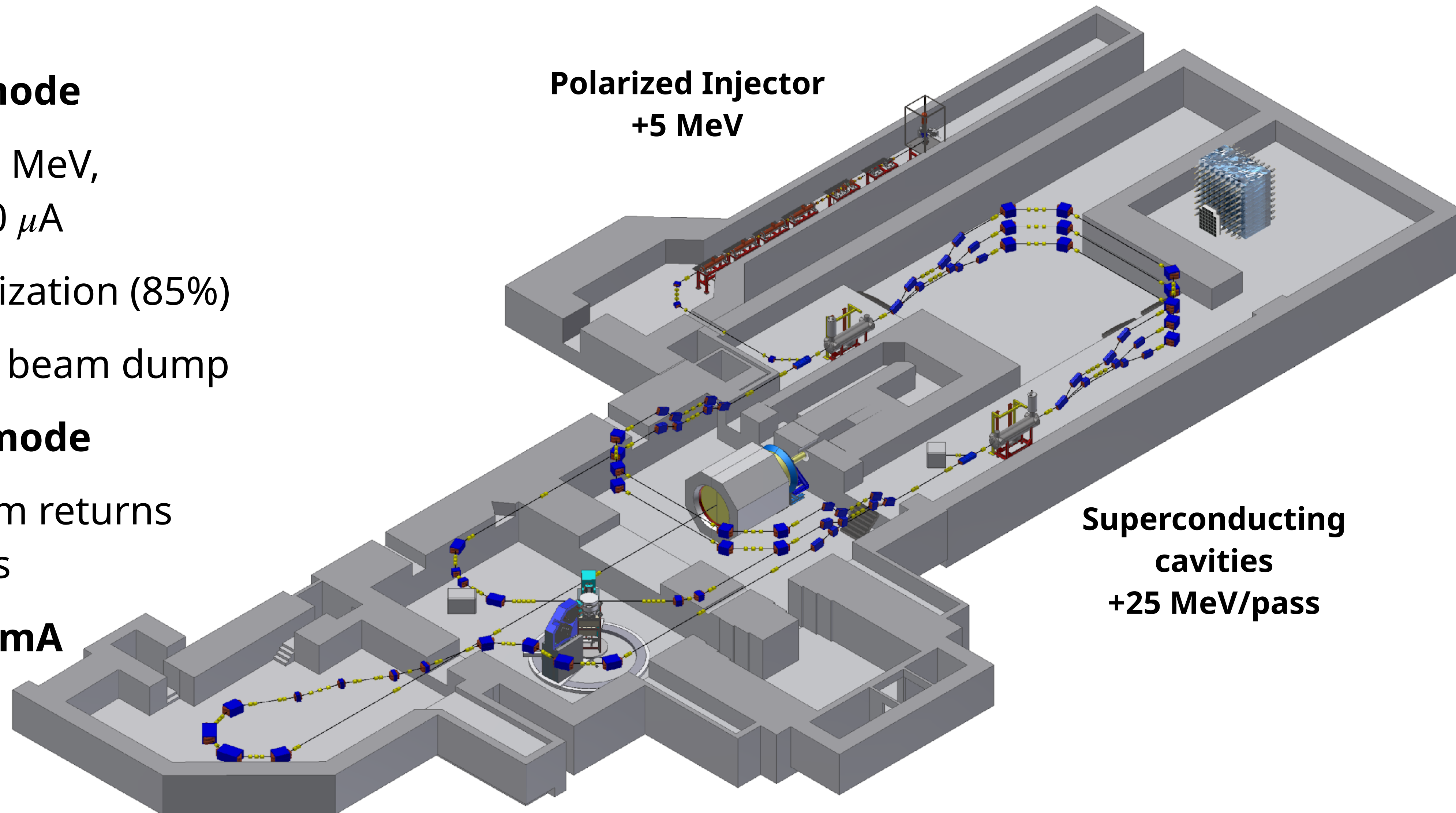
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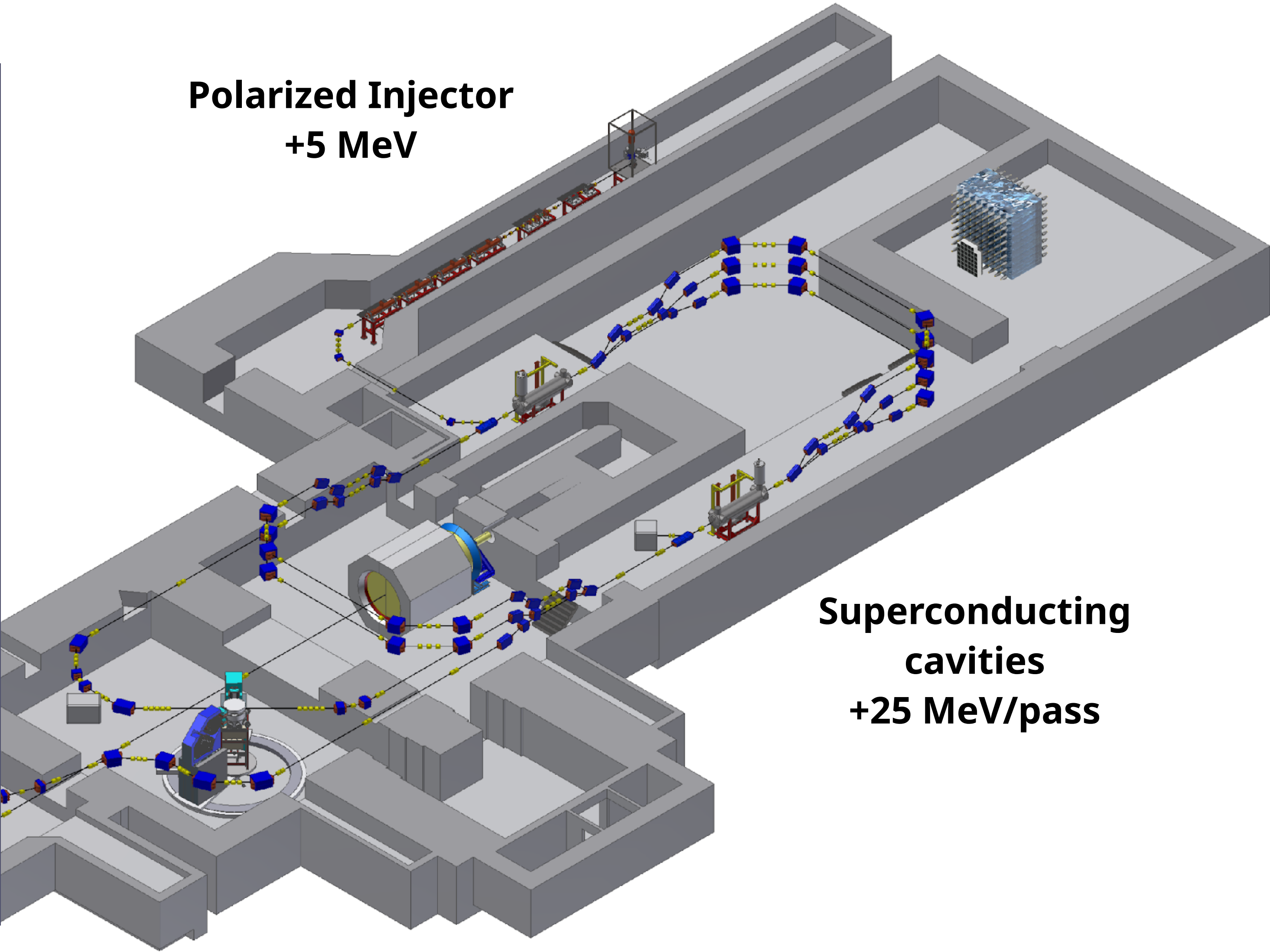
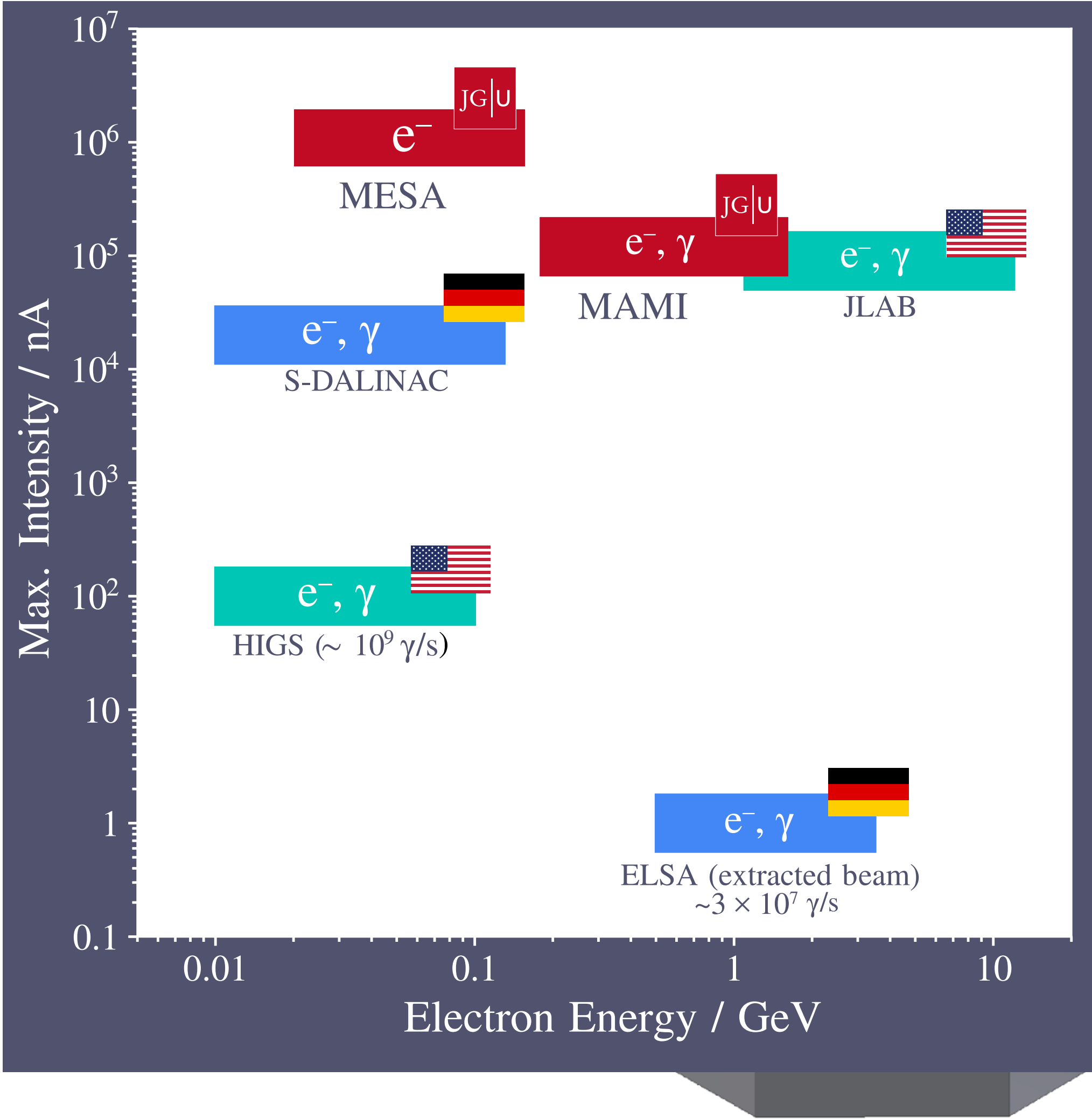
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- **Energy-recovery mode**

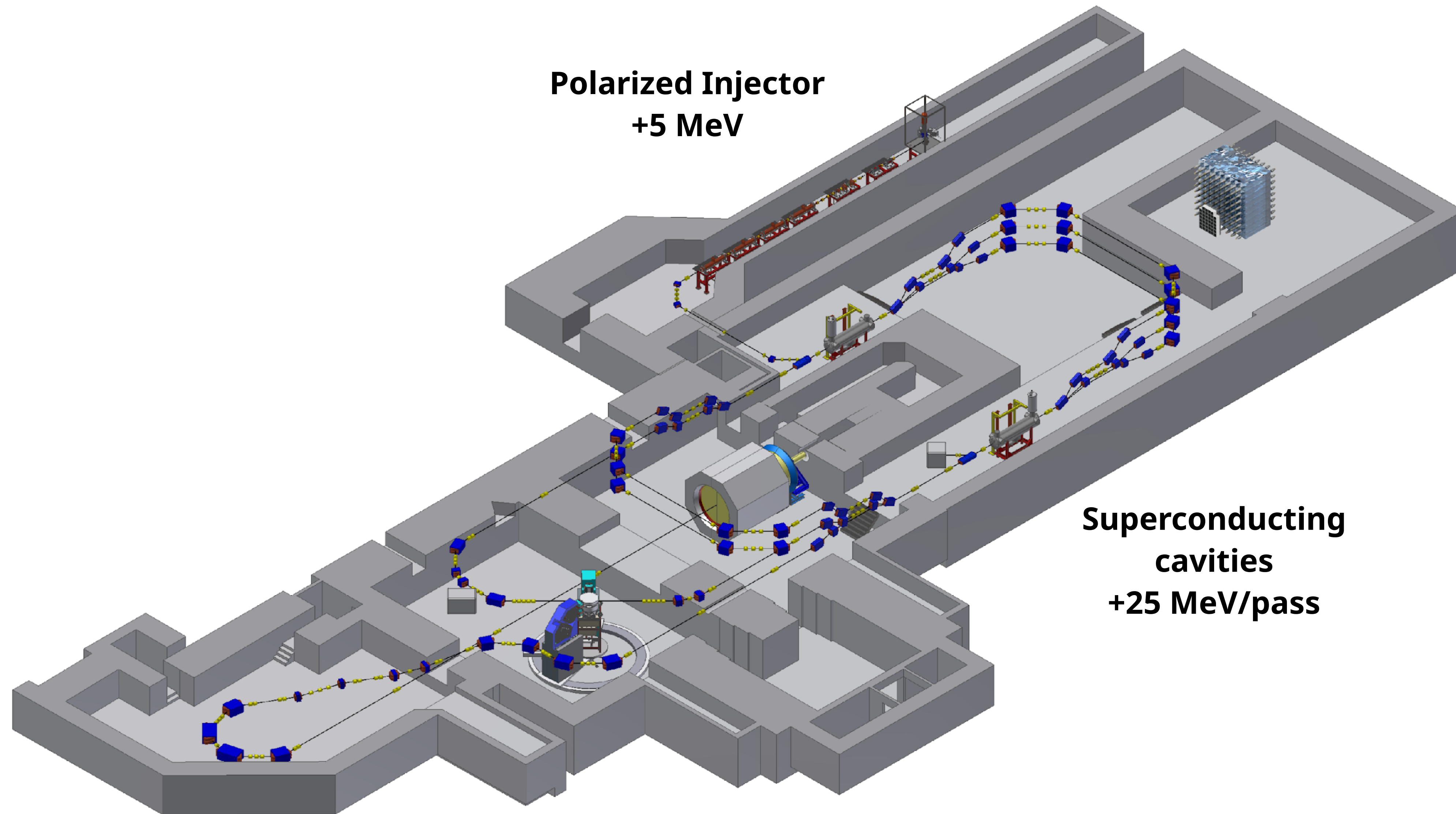
- Unscattered beam returns energy to cavities
- Currents up to **1 mA** (phase I)
- Energy up to 105 MeV



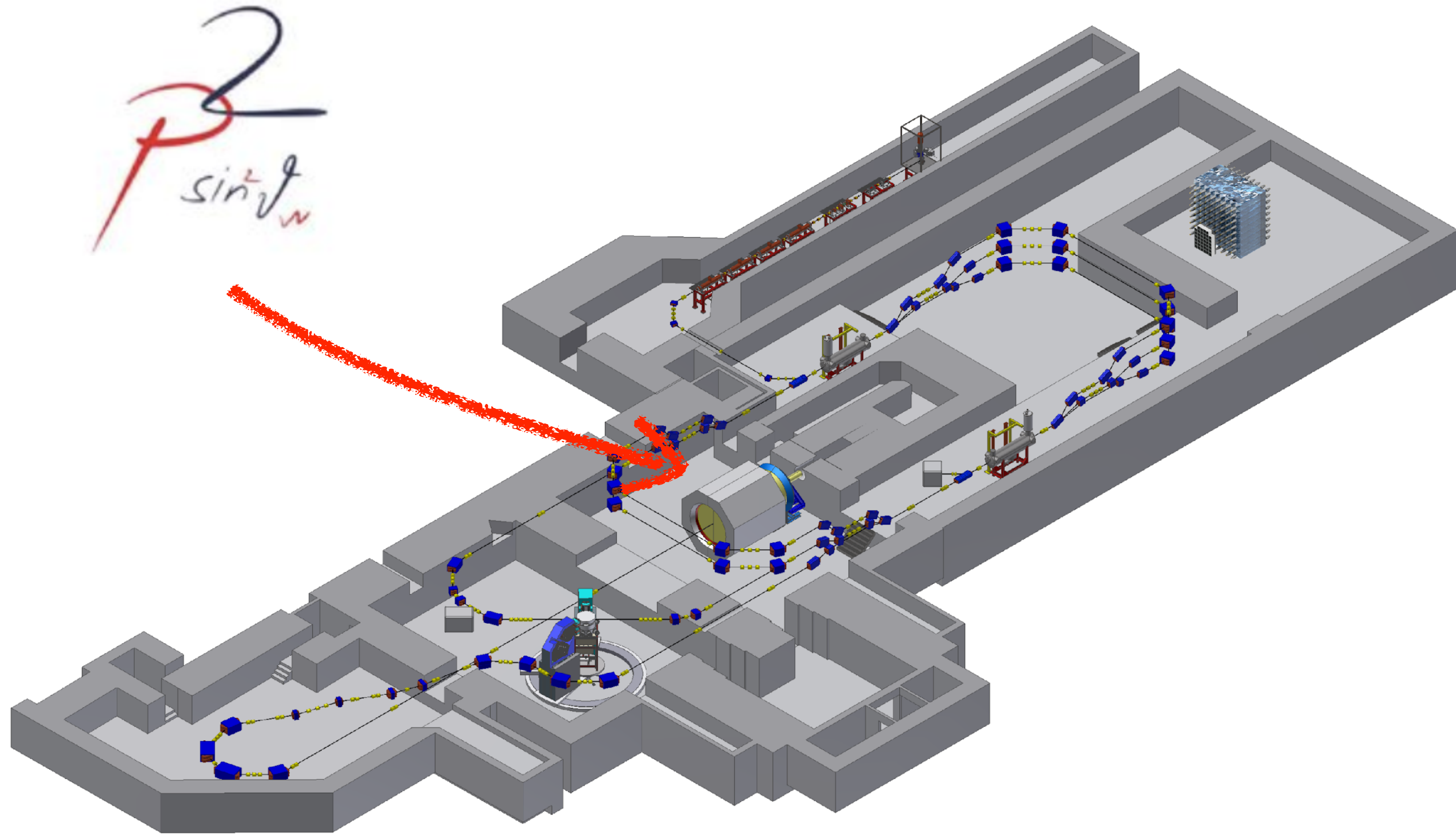
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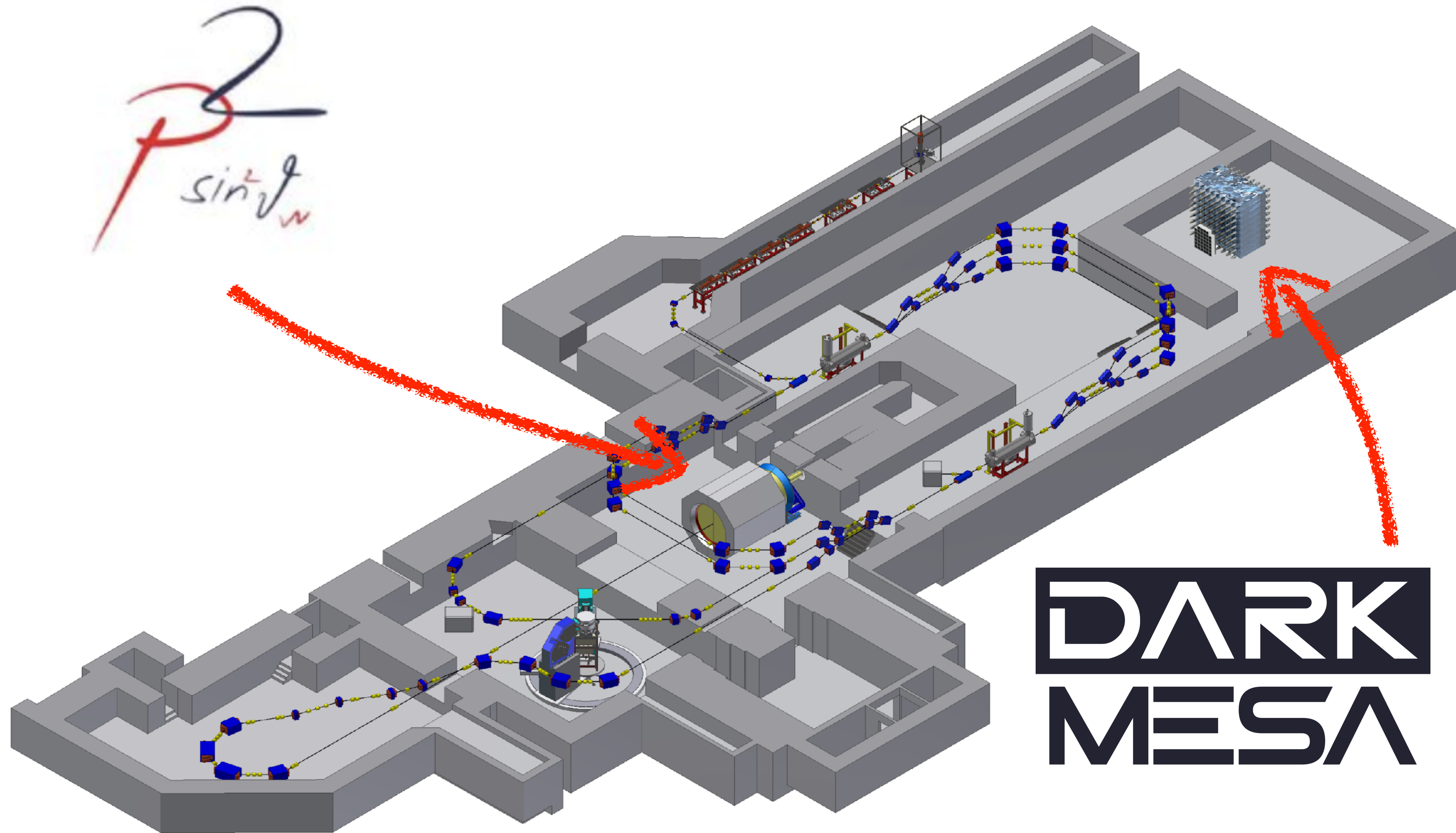
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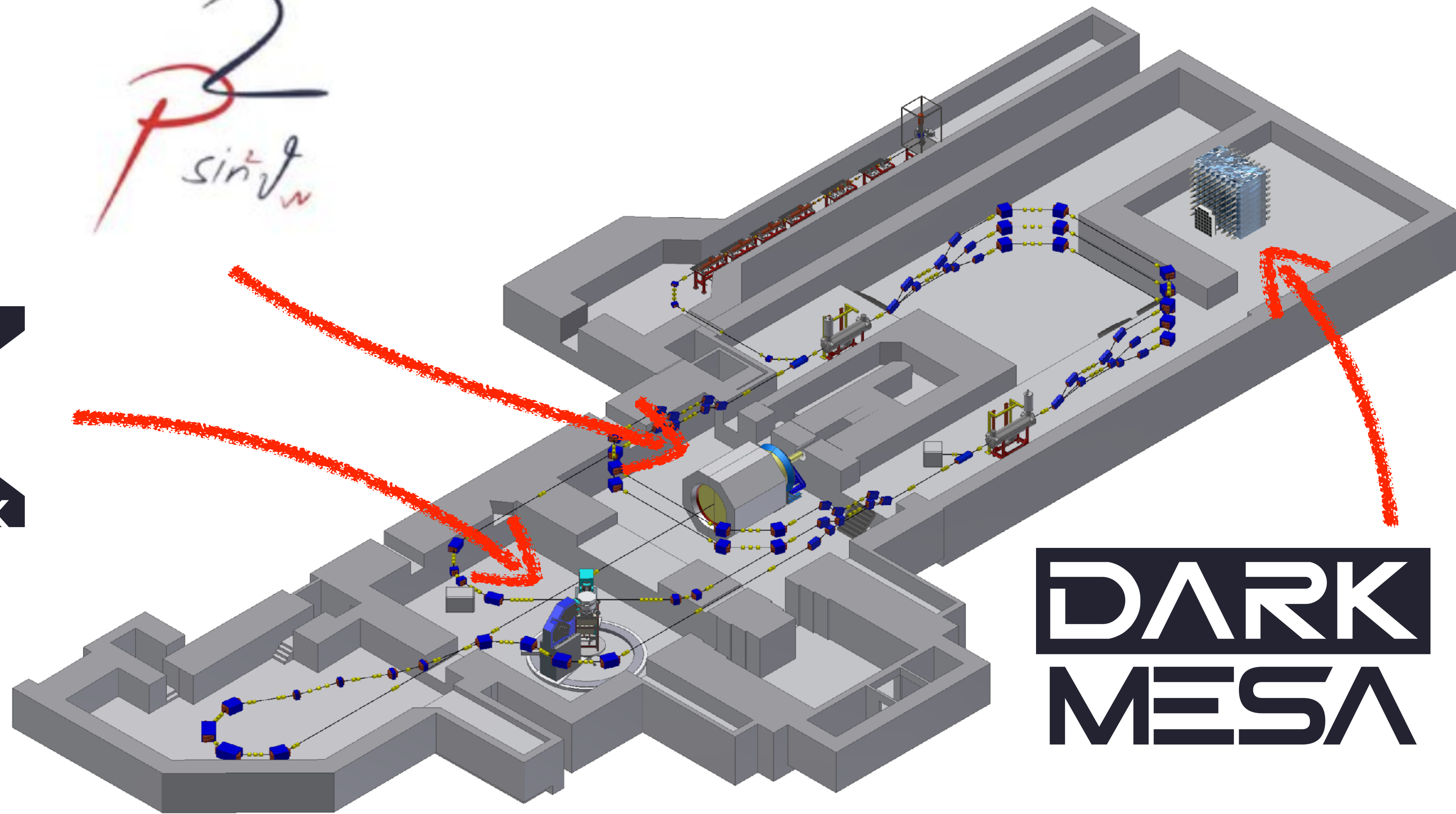


**DARK
MESA**

Mainz energy-recovery superconducting accelerator (MESA)

P^2
 $\sin^2 \theta$

X
MAGIX



DARK
MESA

What will MESA bring to the table?

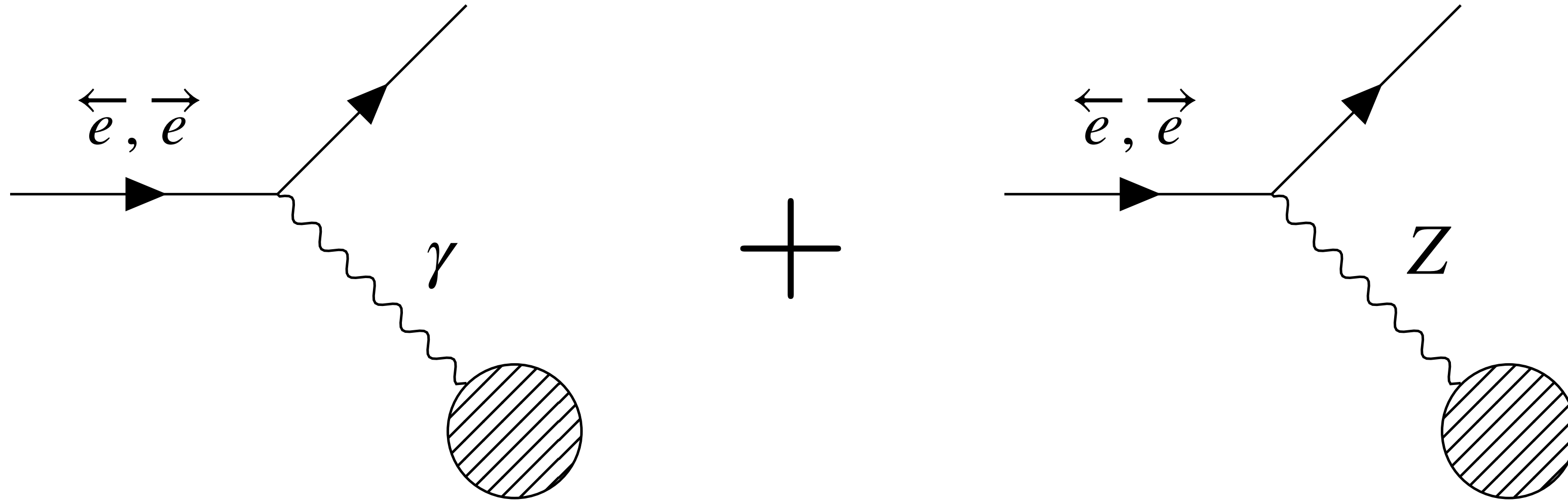
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 - Tests of the Standard Model
 - Weak form factors and neutrons skins
- **Light dark matter search with DarkMESA**
- **Nucleon/nuclear structure with MAGIX**
 - Proton form factors and radii
 - Few-body systems and astrophysical cross sections

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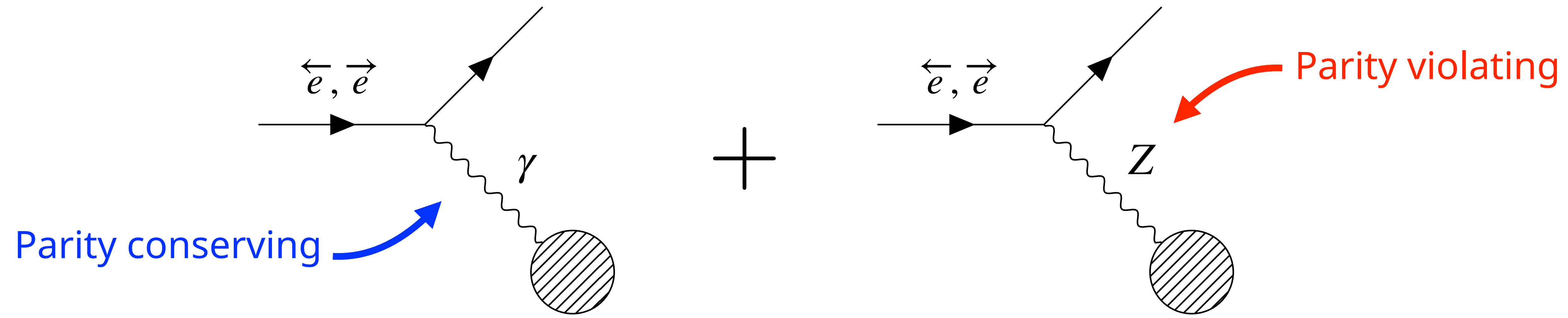
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Many MESA
presentations at EINN!

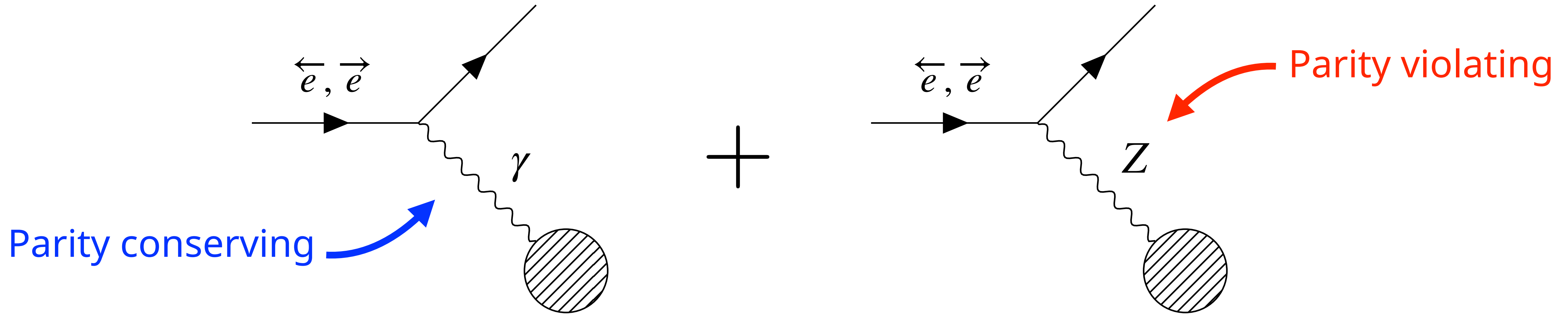
Parity-violating electron scattering



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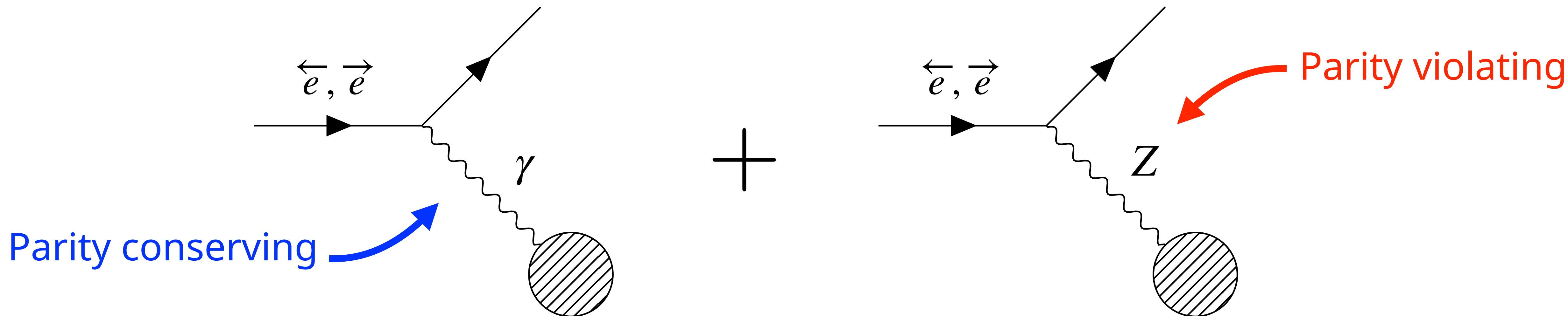
Parity-violating electron scattering



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

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

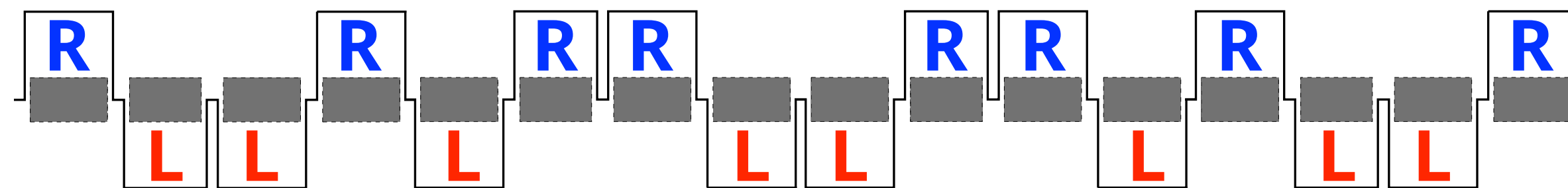
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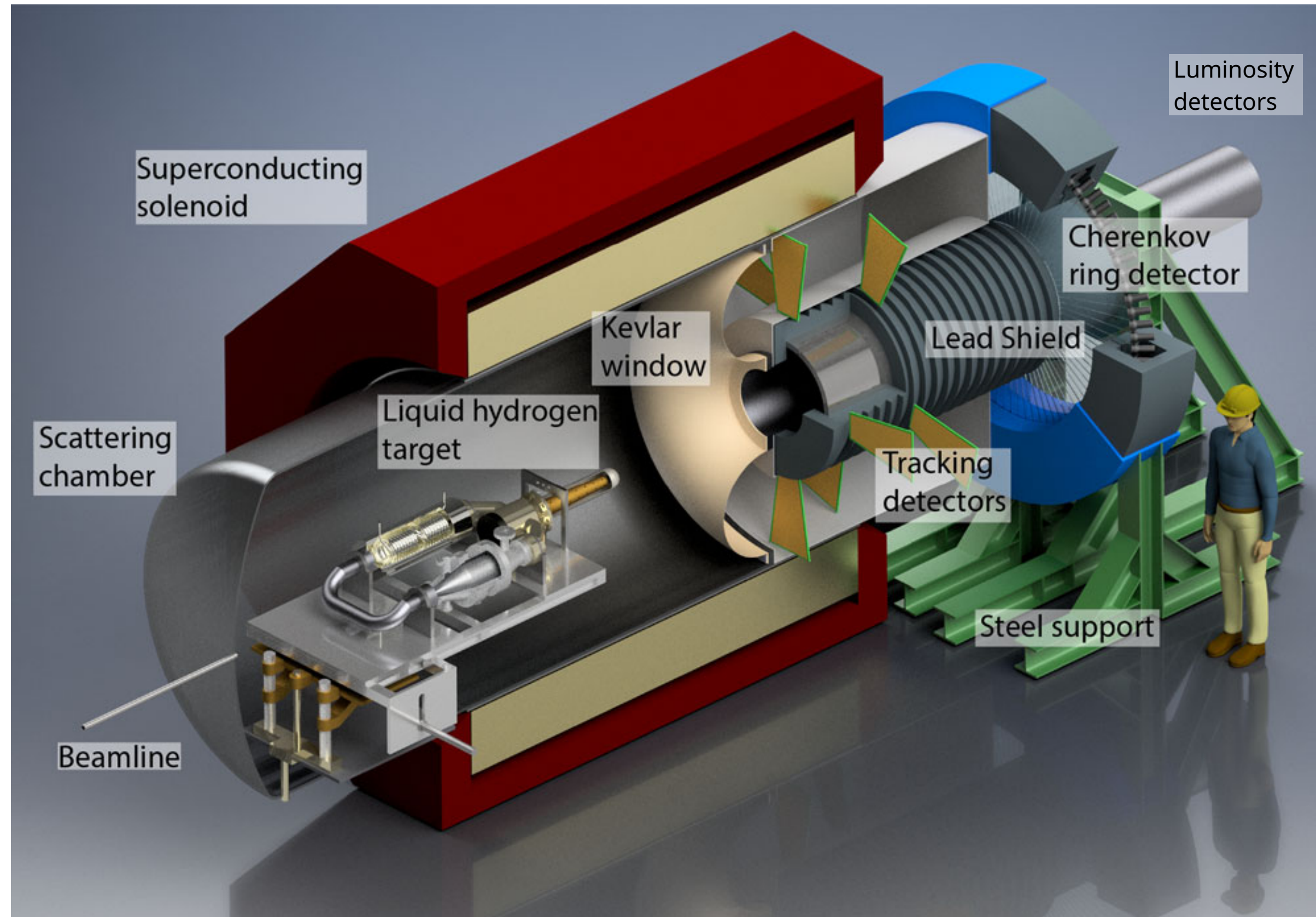
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- Rapid helicity flip (100 - 1000 Hz)
- Measure A_{PV} for pseudo-random quartets

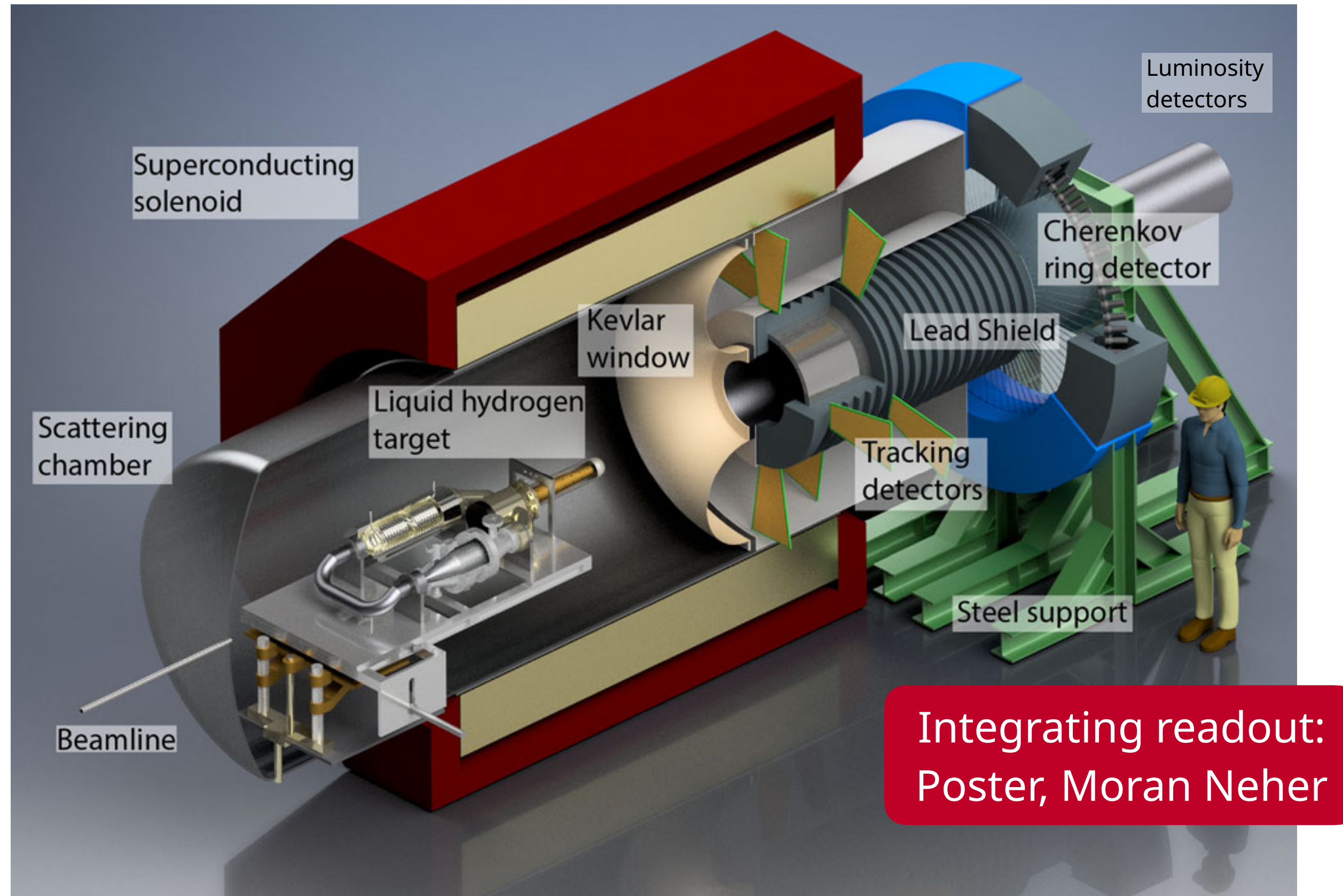


The P2 experiment



- Extracted beam mode:
 - $E = 155 \text{ MeV}, I = 150 \mu\text{A}$
- Targets: LH_2 , ^{12}C , ^{208}Pb
- Superconducting solenoid spectrometer
 - Full azimuthal acceptance
 - Central $\theta_e = 35^\circ$
- Tracking detectors (HV-MAPS)
- Integrating Cherenkov detectors
- Air Cherenkov luminosity monitors

The P2 experiment



Integrating readout:
Poster, Moran Neher

LH2 target:
Poster, Jayanta Naik

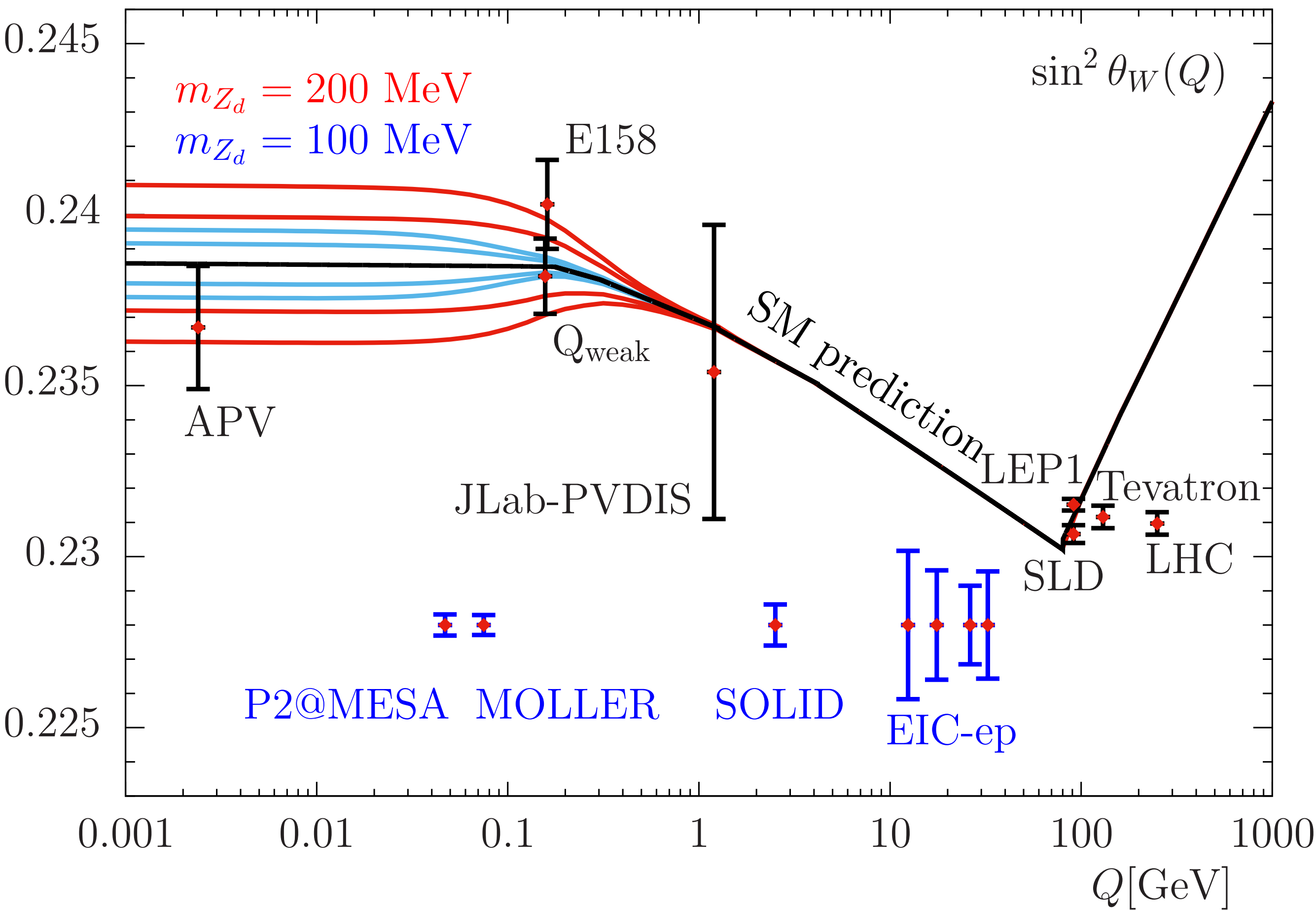
Luminosity monitor:
Poster, Tobias Rimke

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Precision tests of the Standard Model with P2

$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p - F(E, Q^2) \right]$$

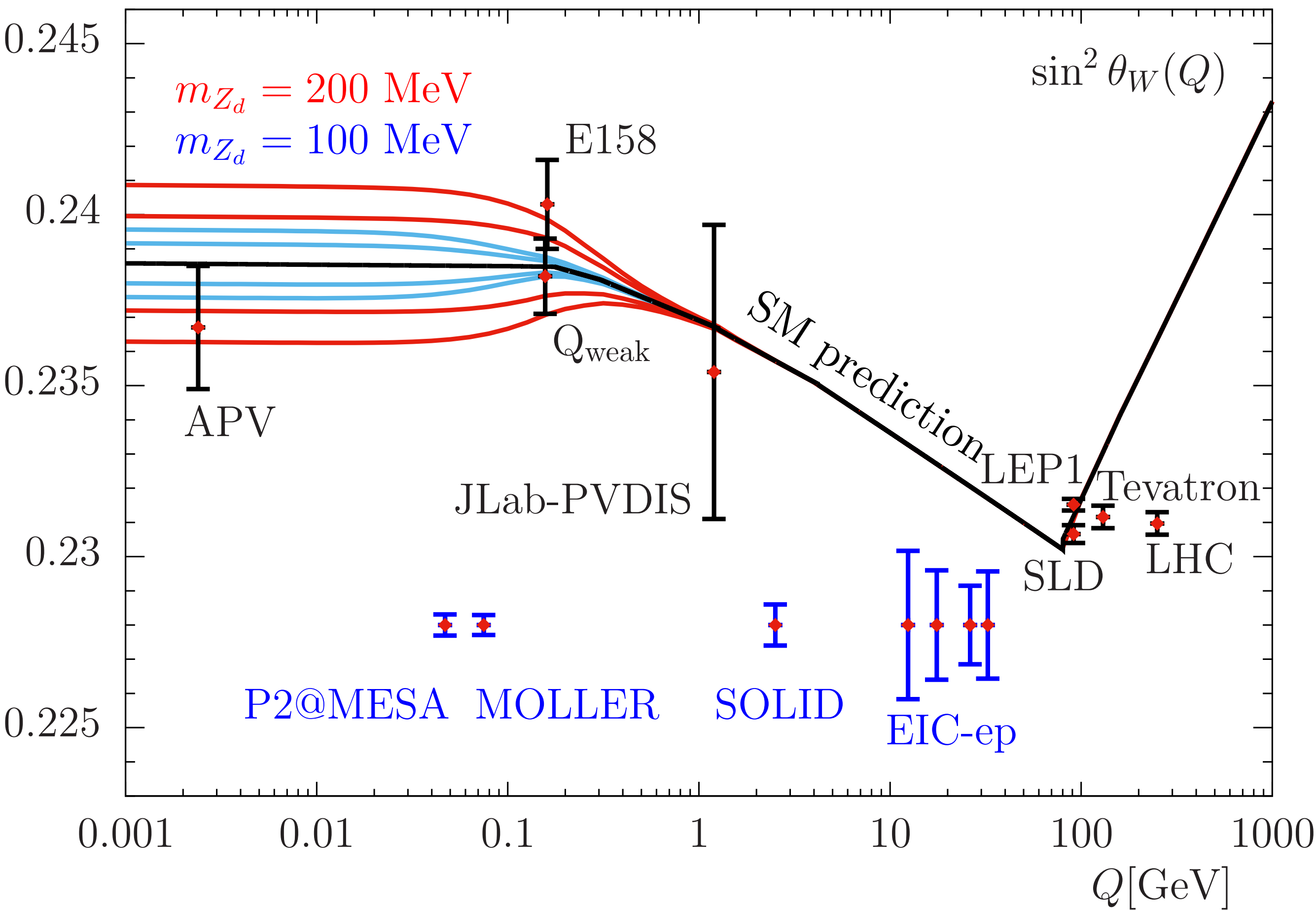
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P2 goal: 40 ppb $\pm$ 0.57 ppb
(0.15% on weak mixing angle)

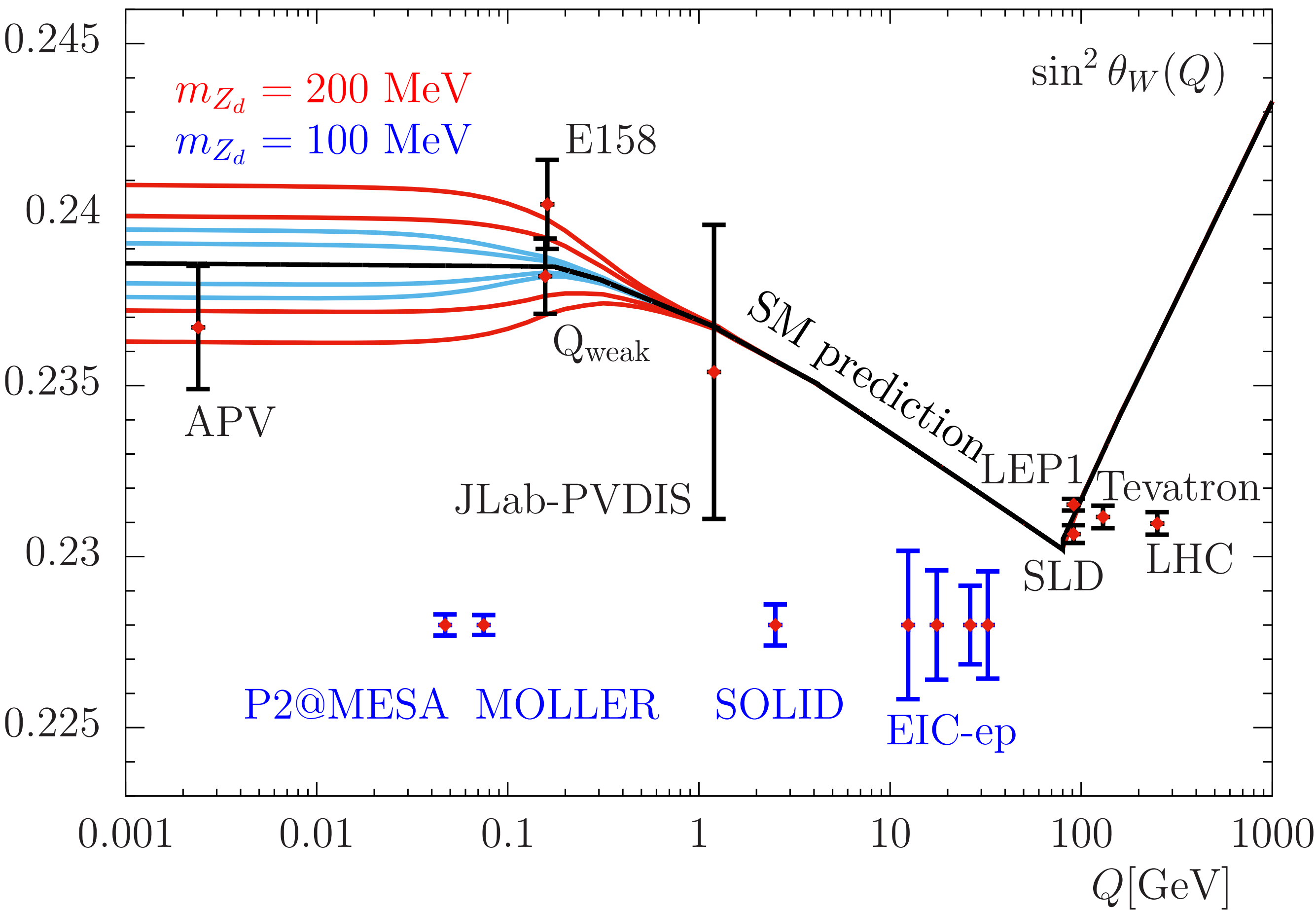
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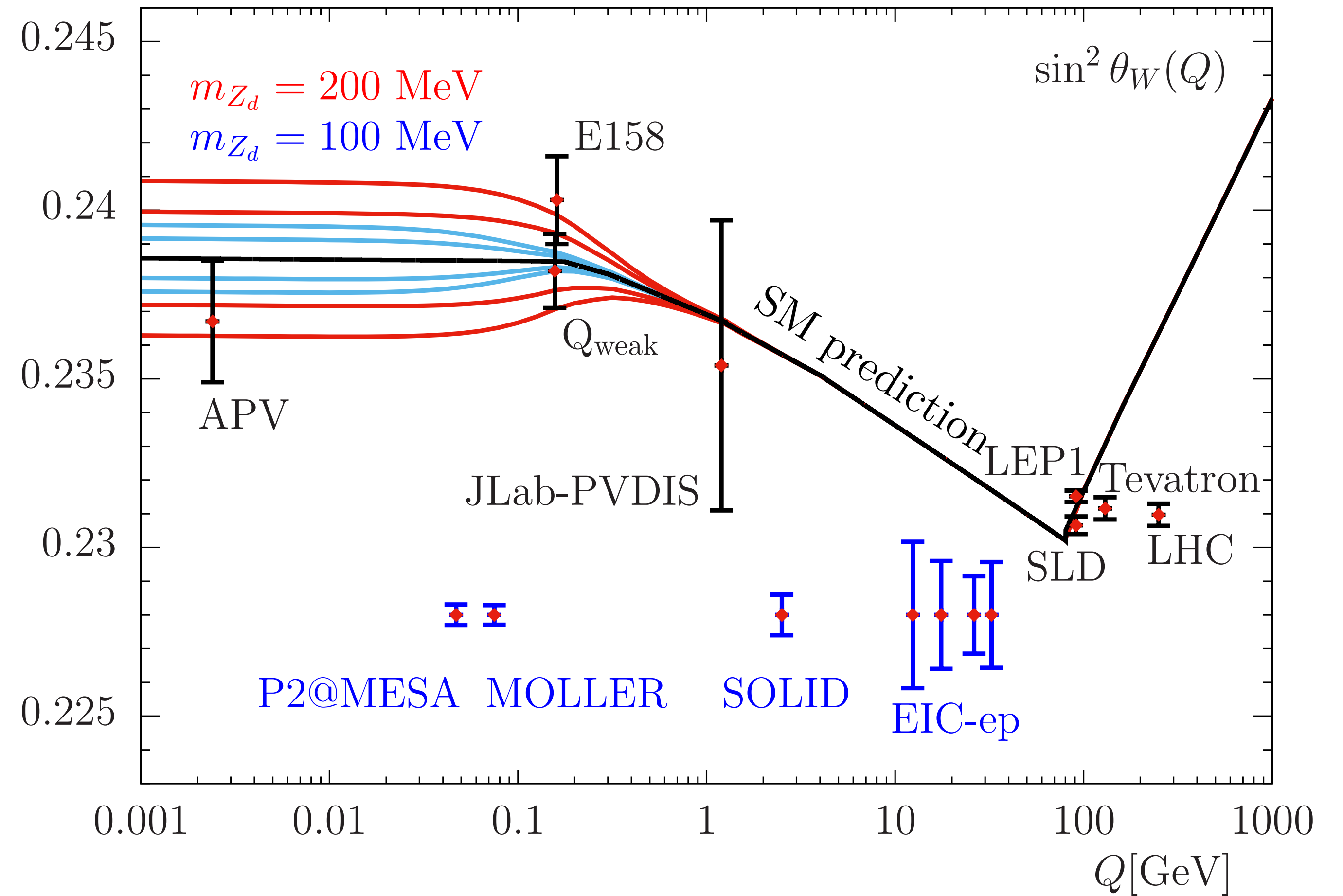
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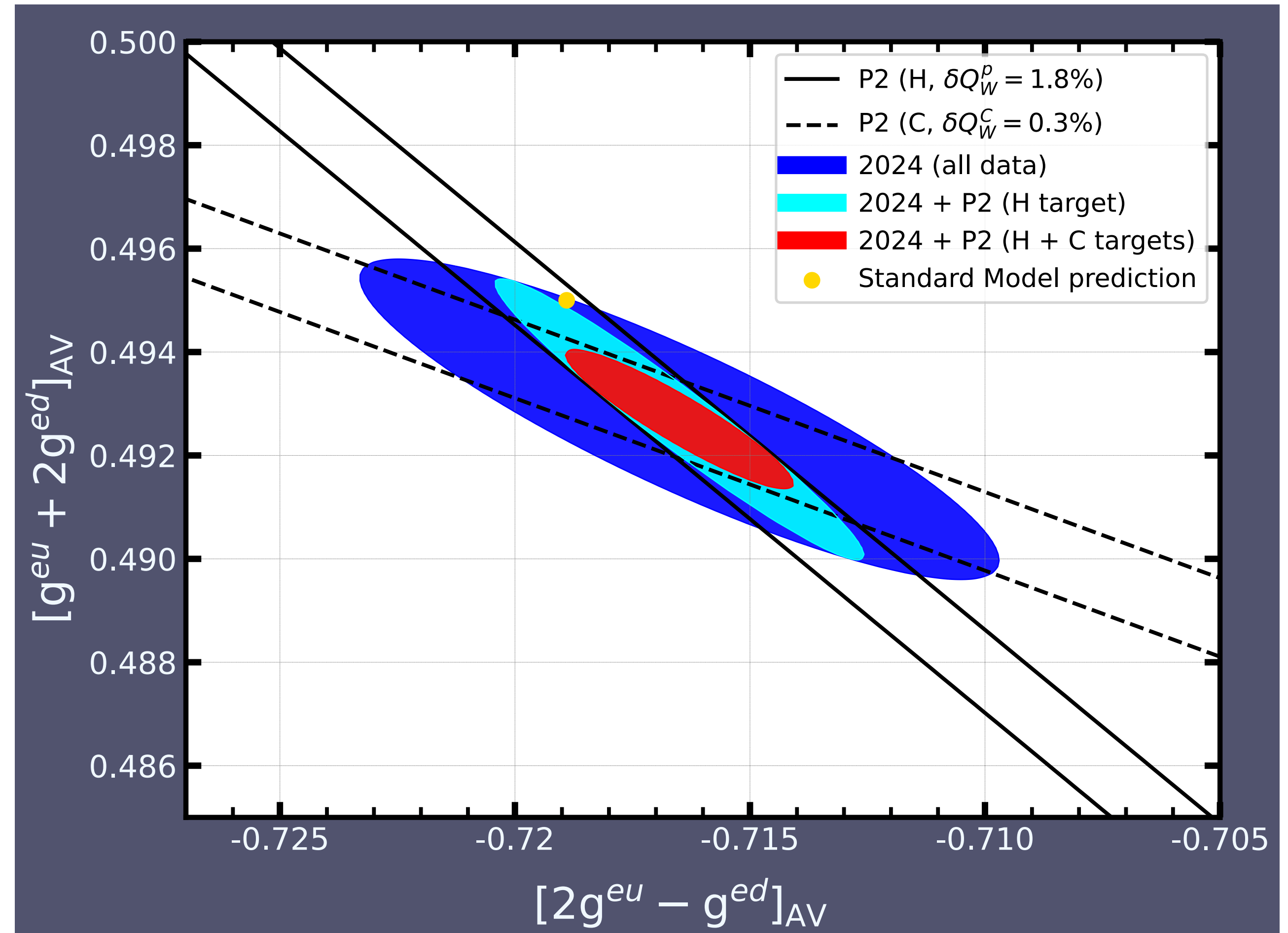
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- Complementary measurements planned on electrons (MOLLER), carbon-12 (P2)



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Weak form factor and neutron skins with MREX

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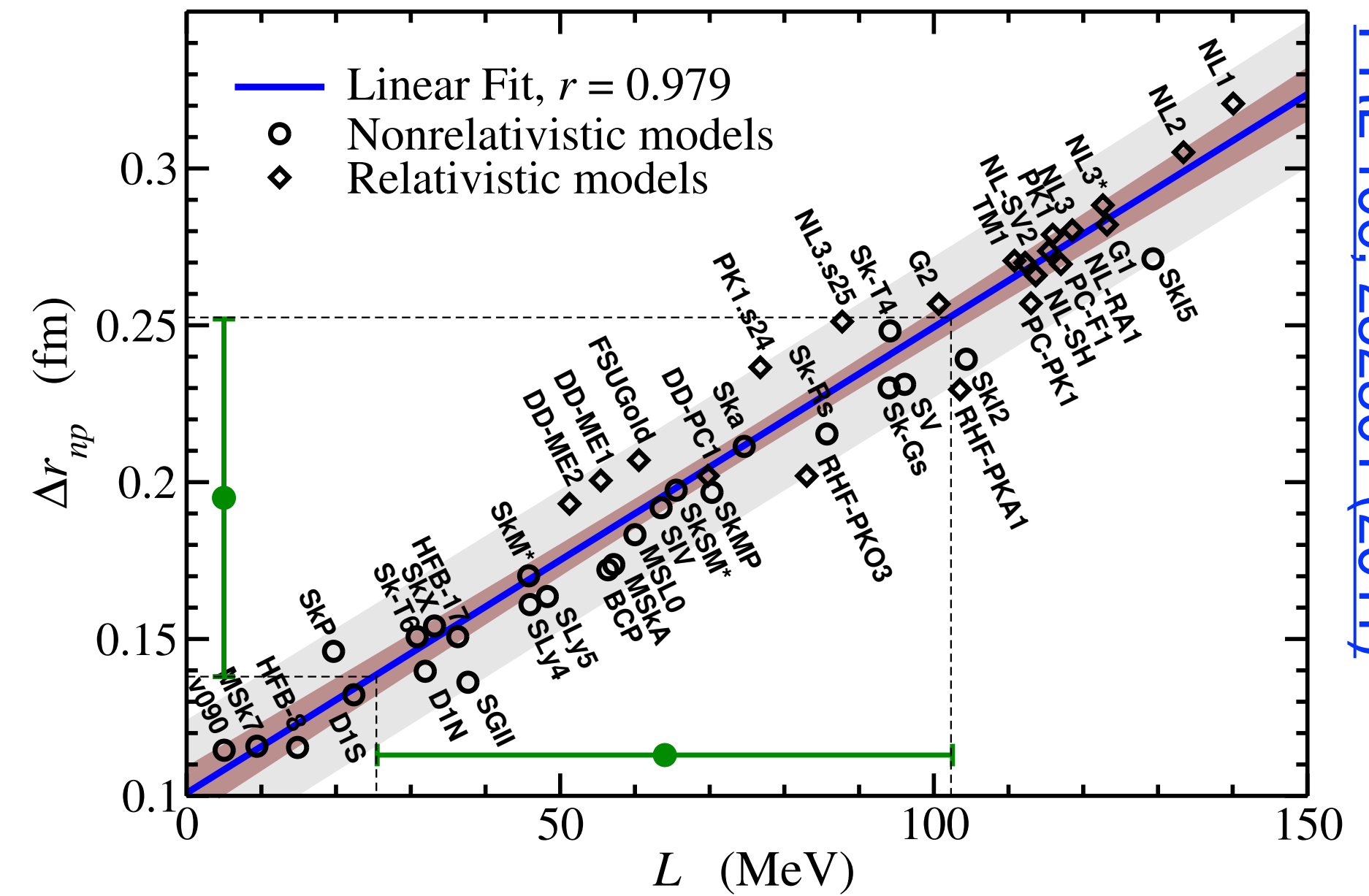
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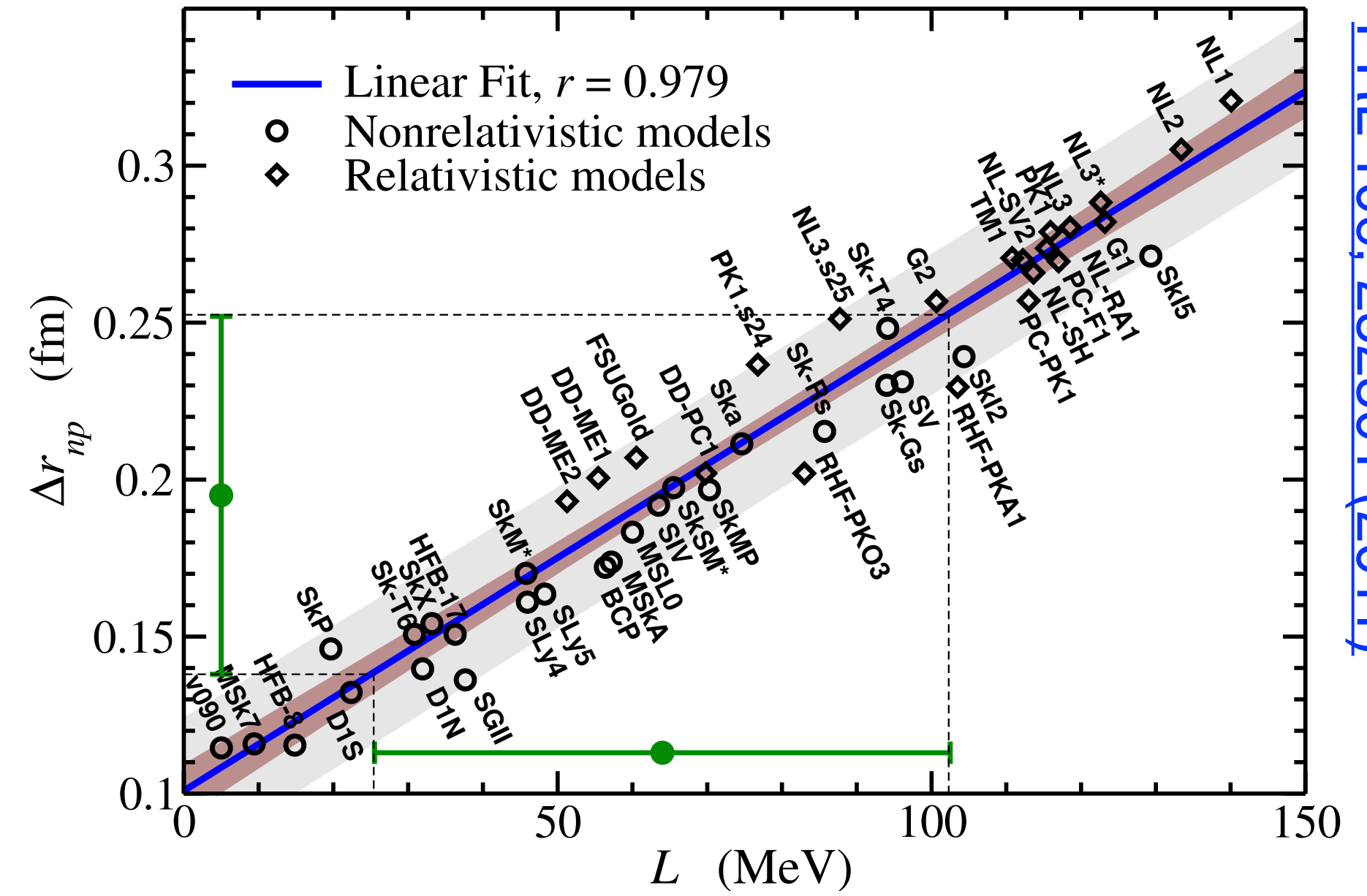


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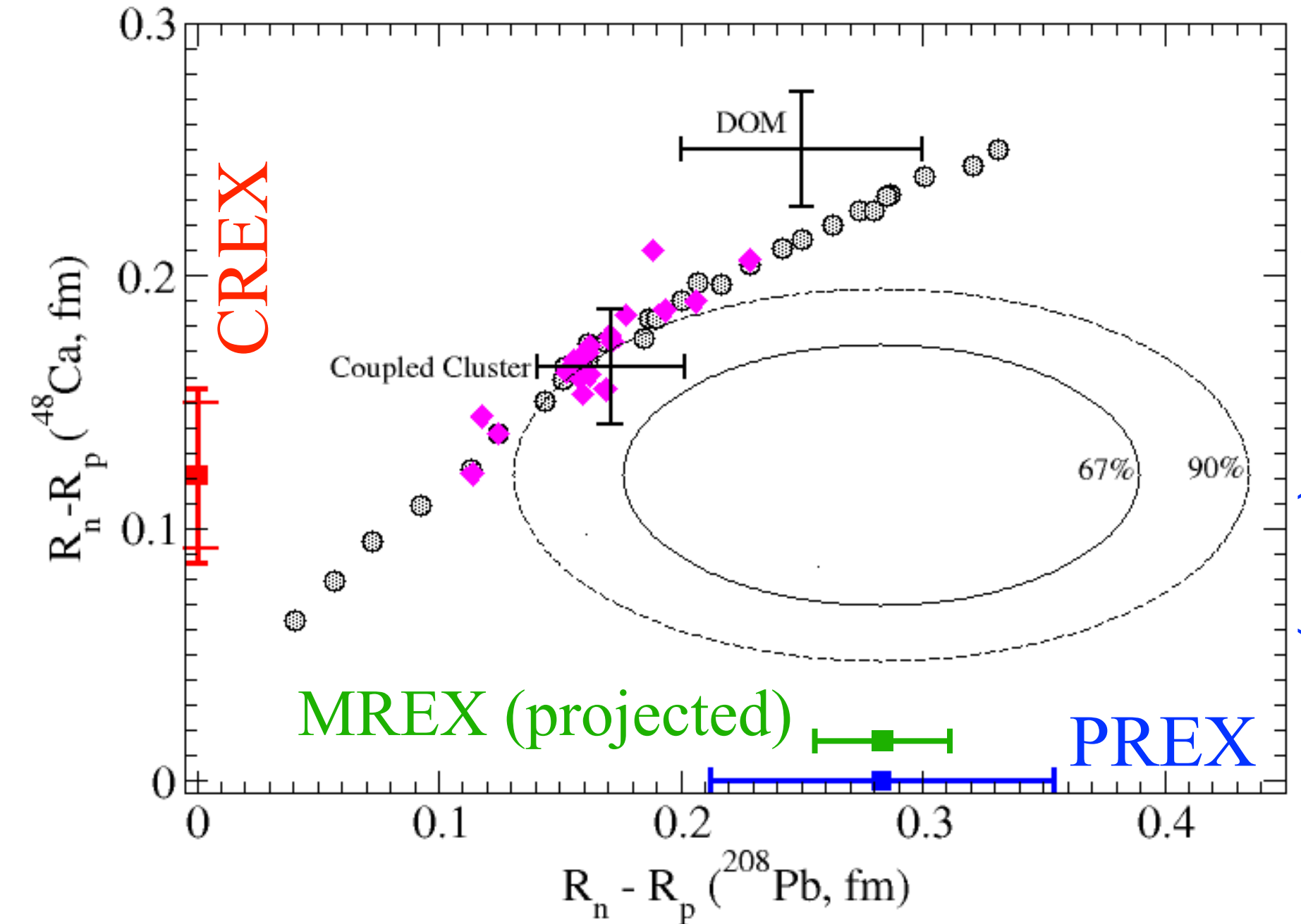
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[PRL 106, 252501 \(2011\)](#)



[PRL 129, 042501 \(2022\)](#)

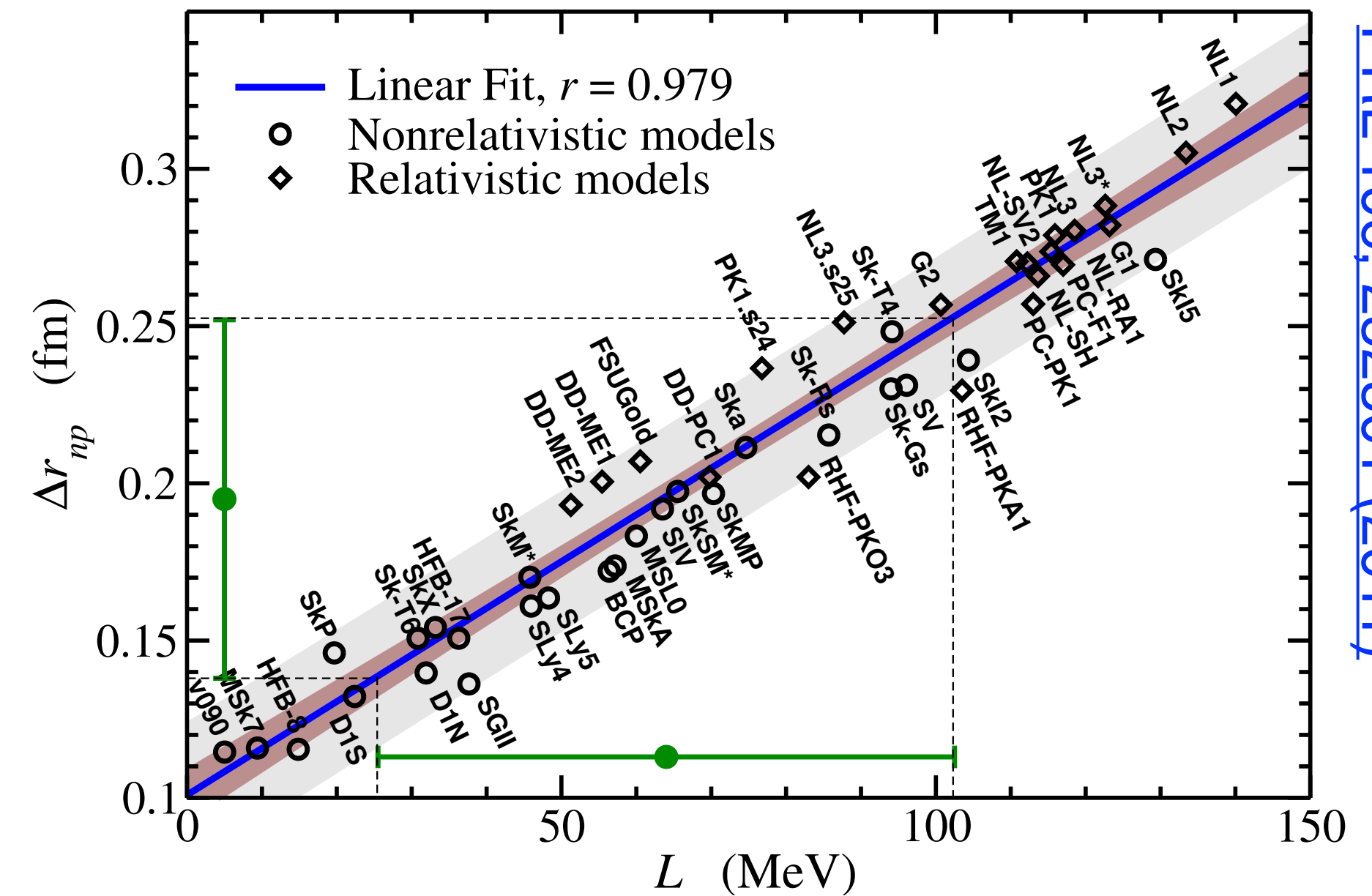
[PRL 126, 172502 \(2021\)](#)

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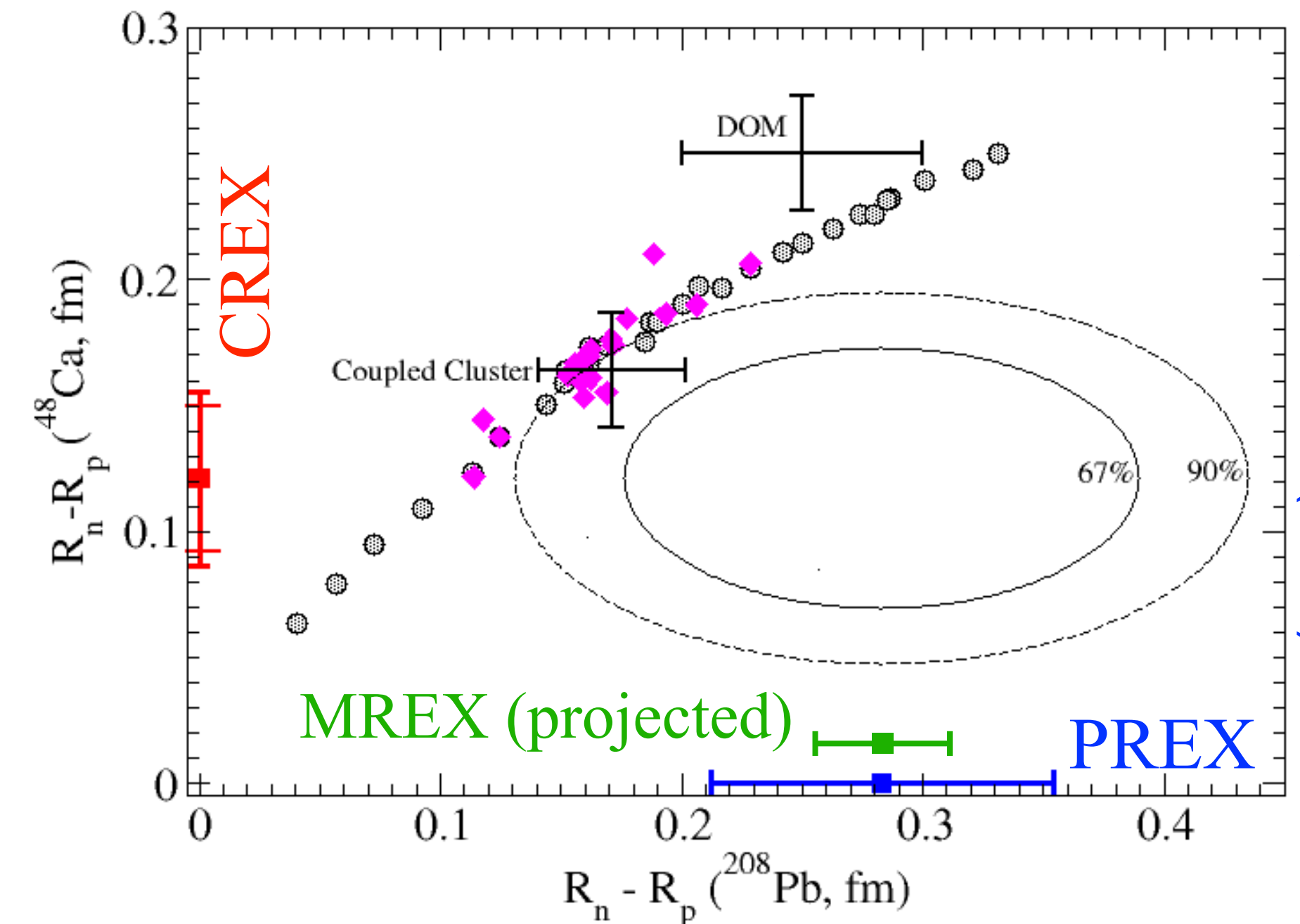
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- ^{26}Mg : Reduce uncertainties in nuclear structure corrections to β -decay (CKM unitarity tests)



[PRL 106, 252501 \(2011\)](#)



[PRL 126, 042501 \(2022\)](#)

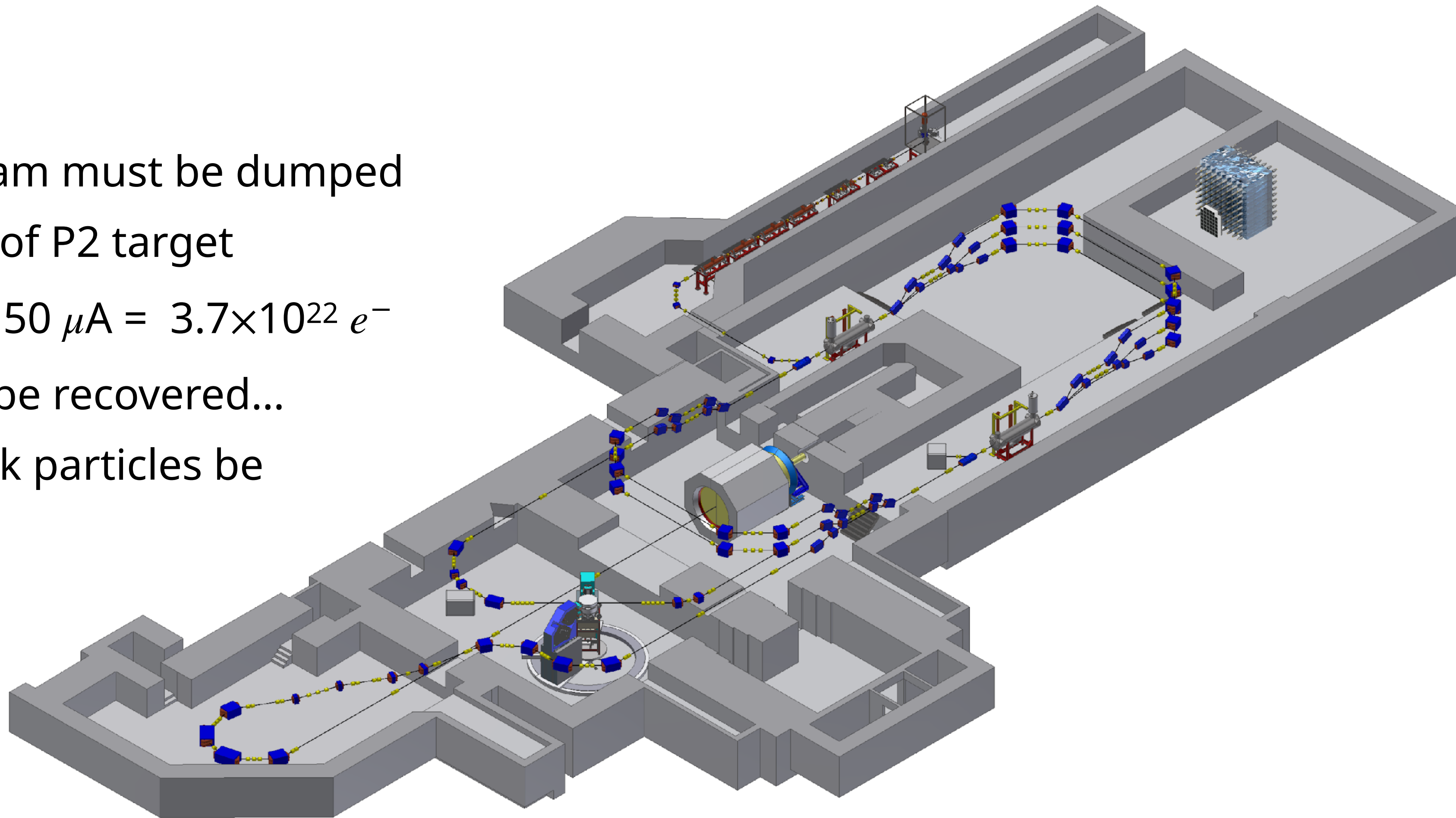
[PRL 126, 172502 \(2021\)](#)

Delivery of the P2 solenoid (November 2024)



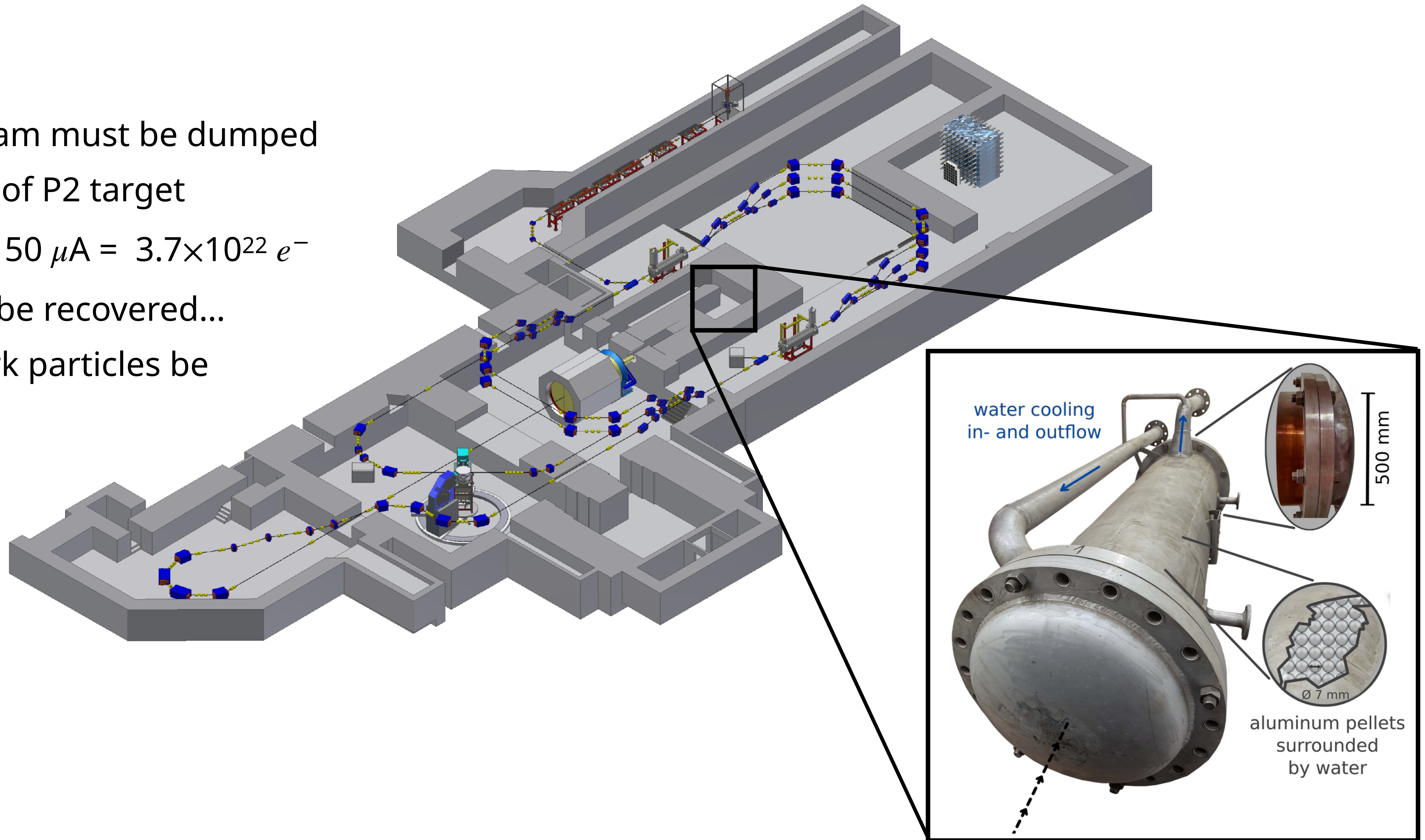
The P2 beam dump

- Extracted beam must be dumped downstream of P2 target
- $11000 \text{ hrs} \times 150 \mu\text{A} = 3.7 \times 10^{22} e^-$
- Energy can't be recovered...
...but can dark particles be produced?



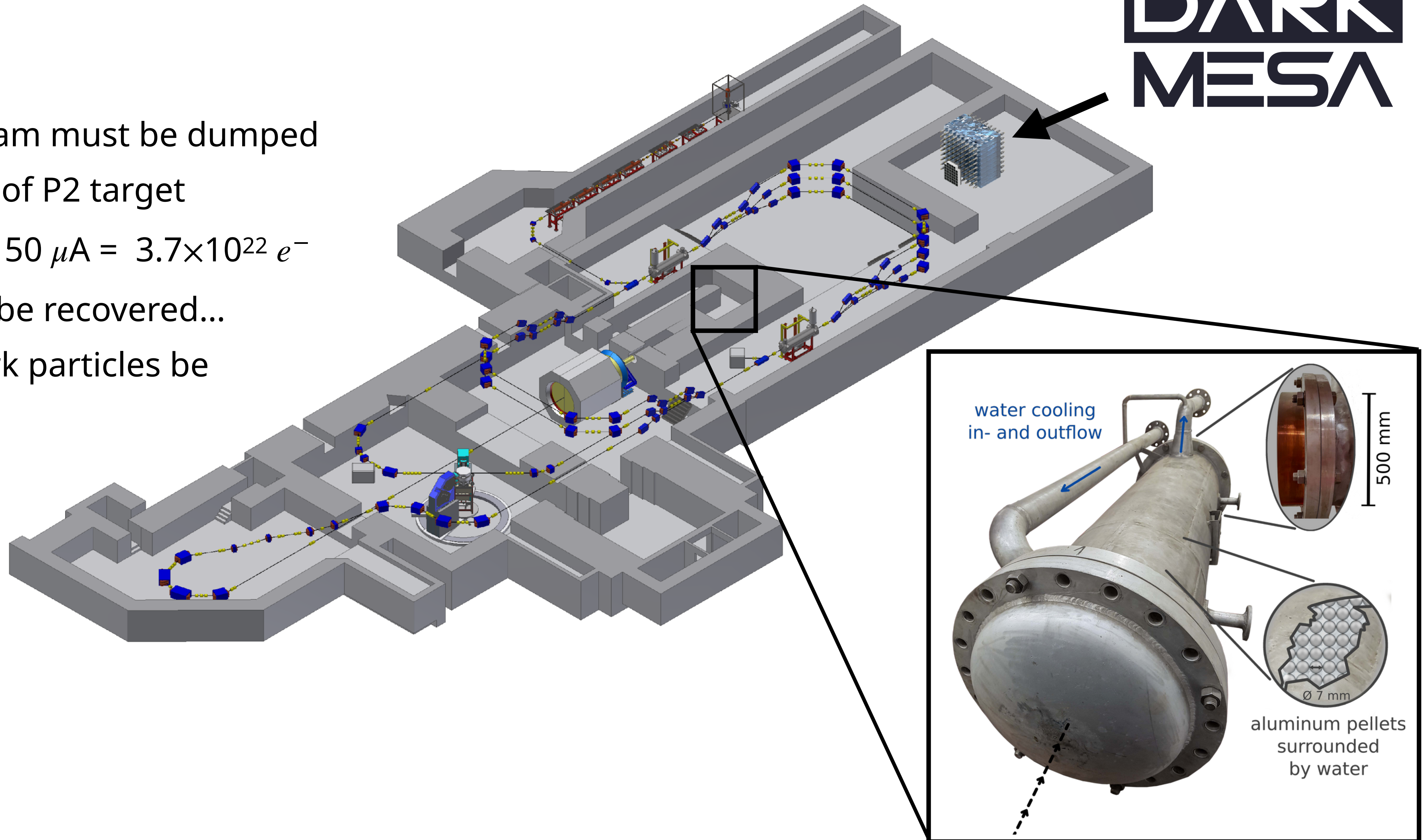
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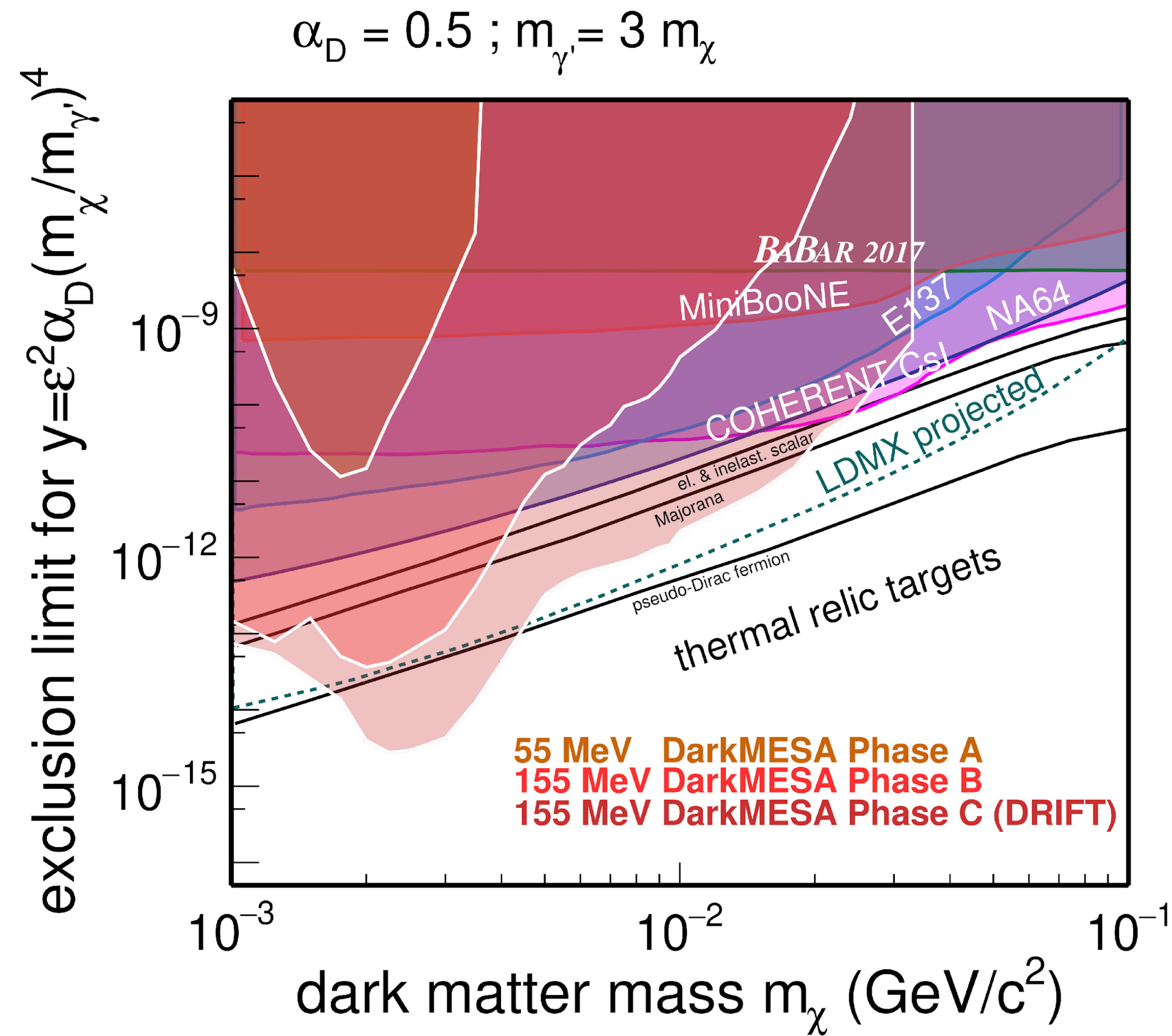


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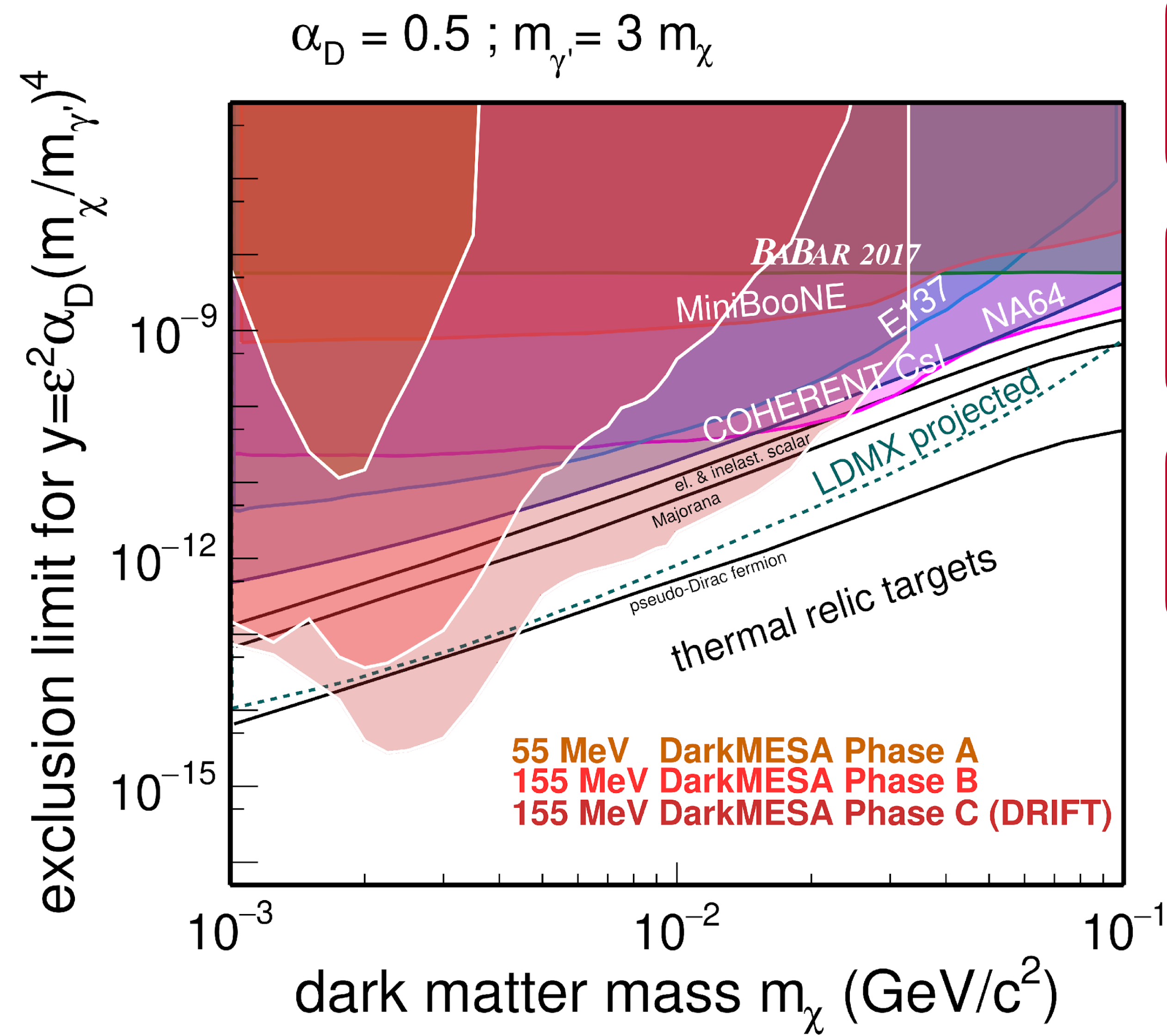
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Projected DarkMESA limits



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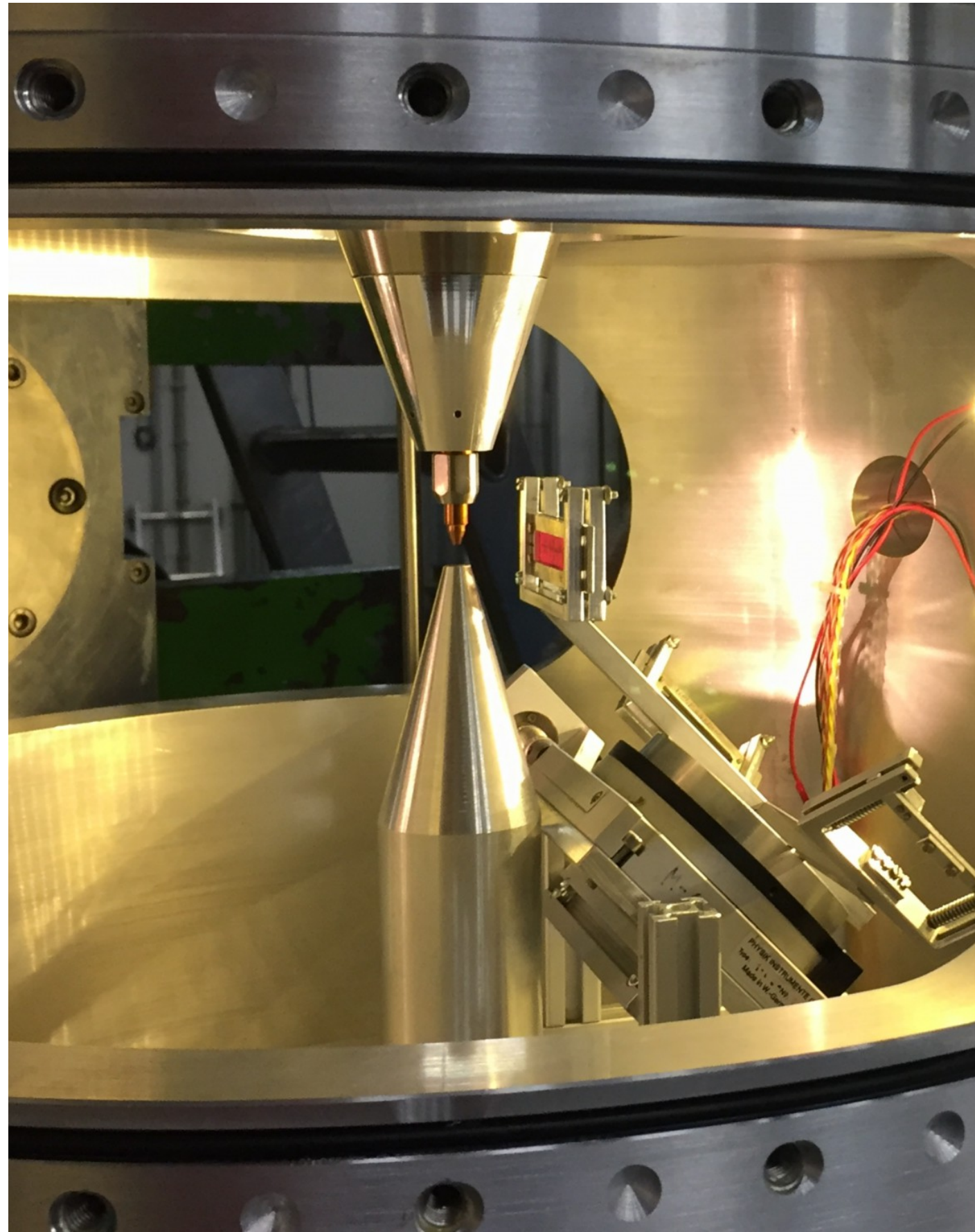
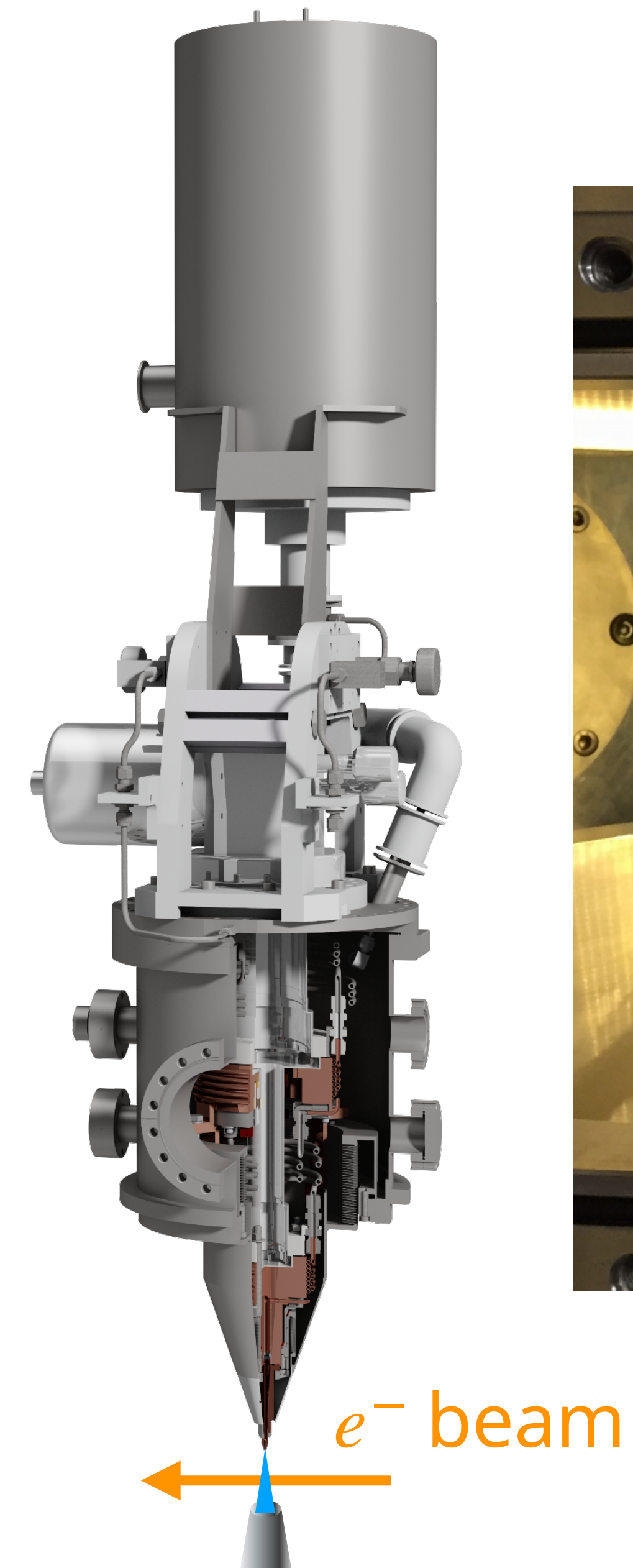
DarkMESA overview:
Parallel Workshop 2,
Mirco Christmann

Liquid scintillator veto:
Poster, Michail
Kontogoulas

Noise reduction:
Poster, Christian Stoß

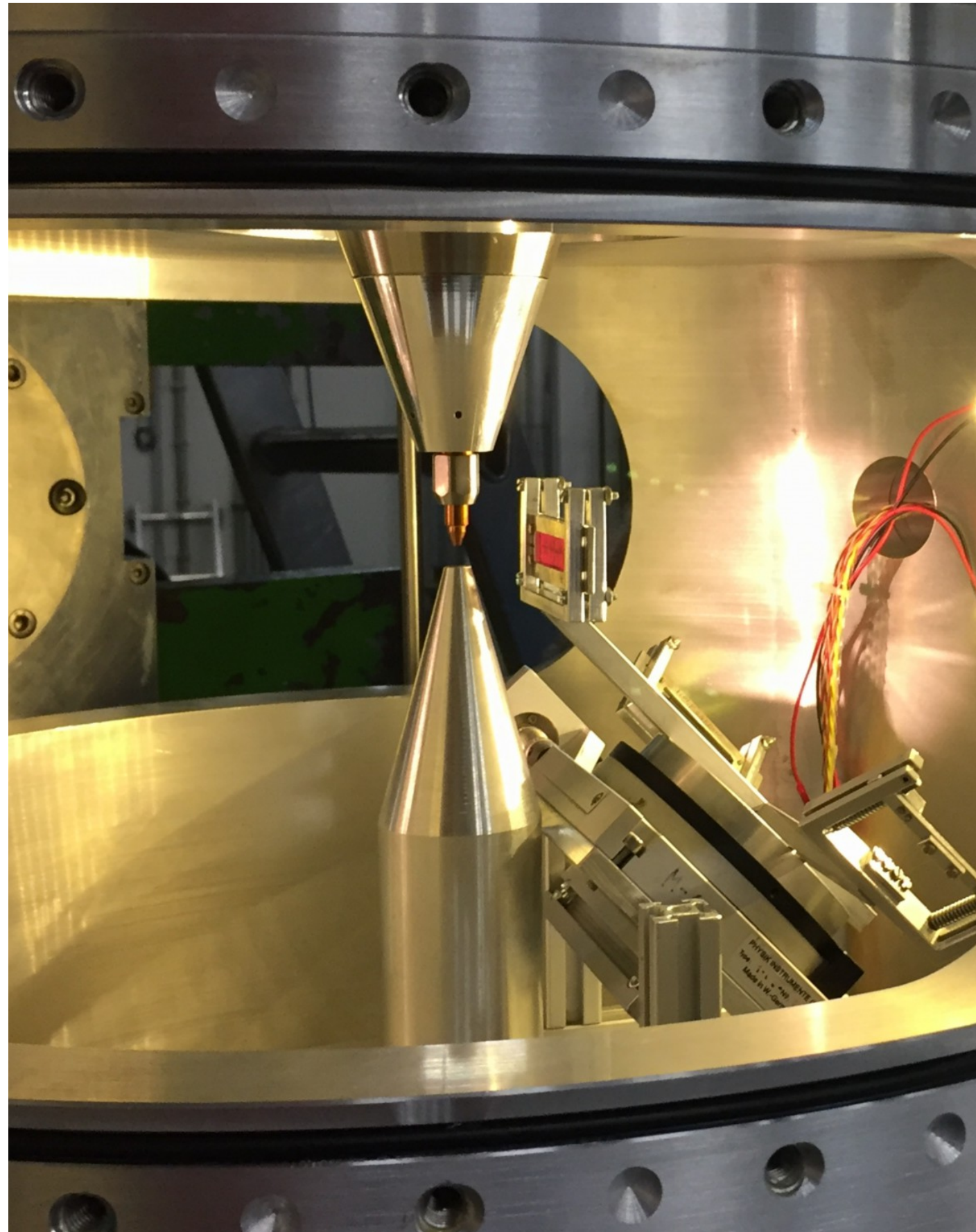
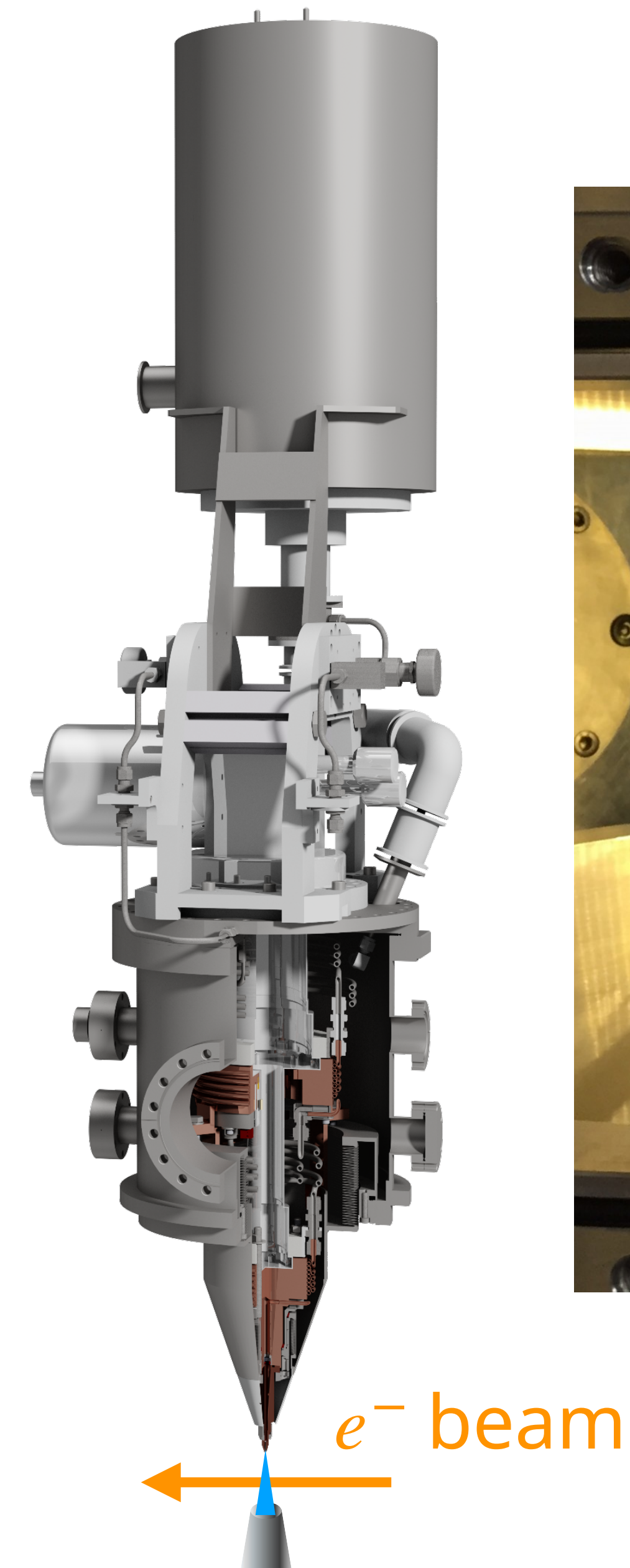
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 - Momentum resolution $\delta p/p = 10^{-4}$
 - GEM-based time projection chamber
 $\mathcal{O}(100 \mu\text{m})$ resolution
 - Scintillator trigger/veto system
- Planned silicon strip detector for low-energy recoils

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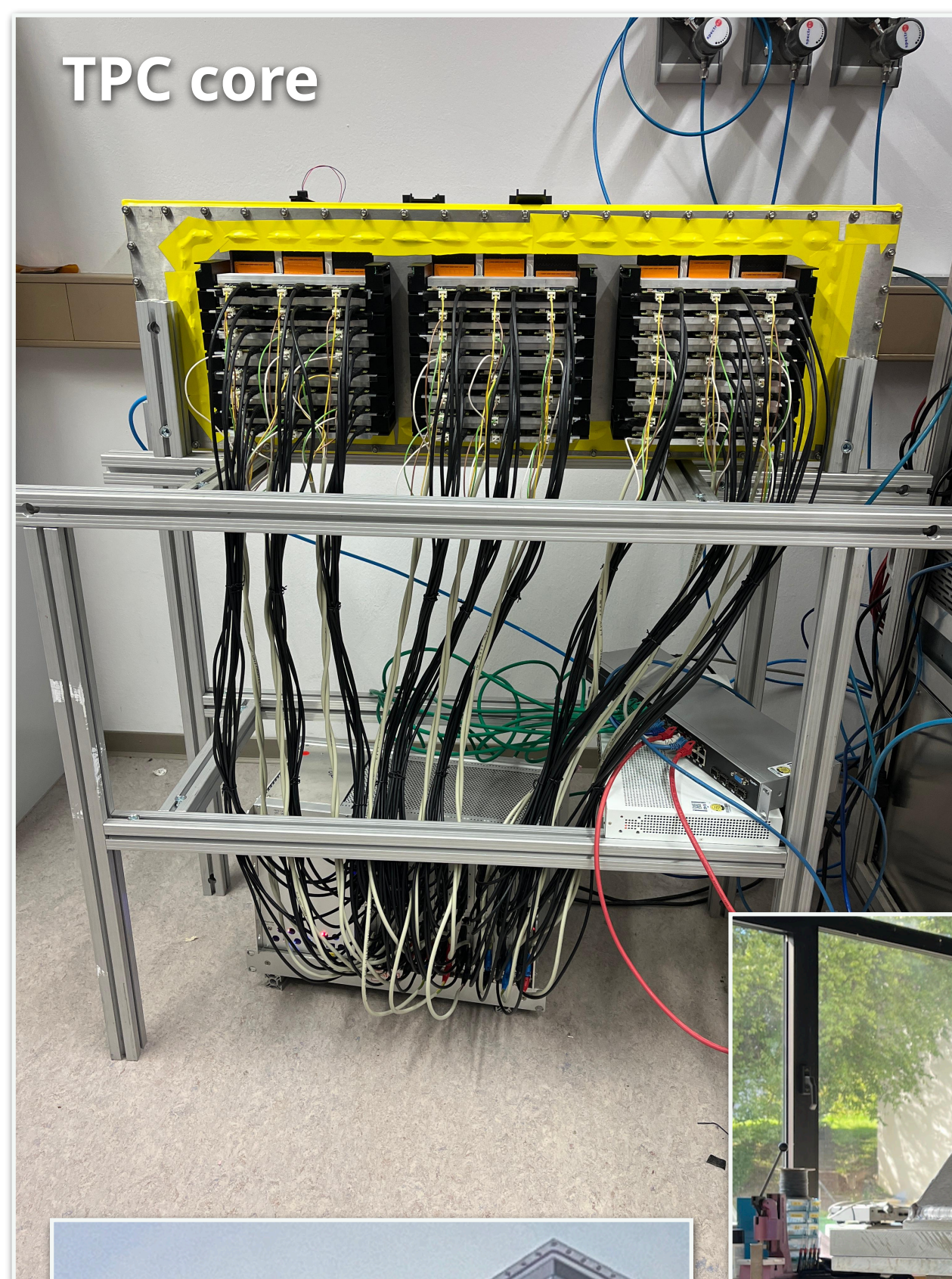
MAGIX overview:
Parallel Workshop 2,
Sebastian Stengel



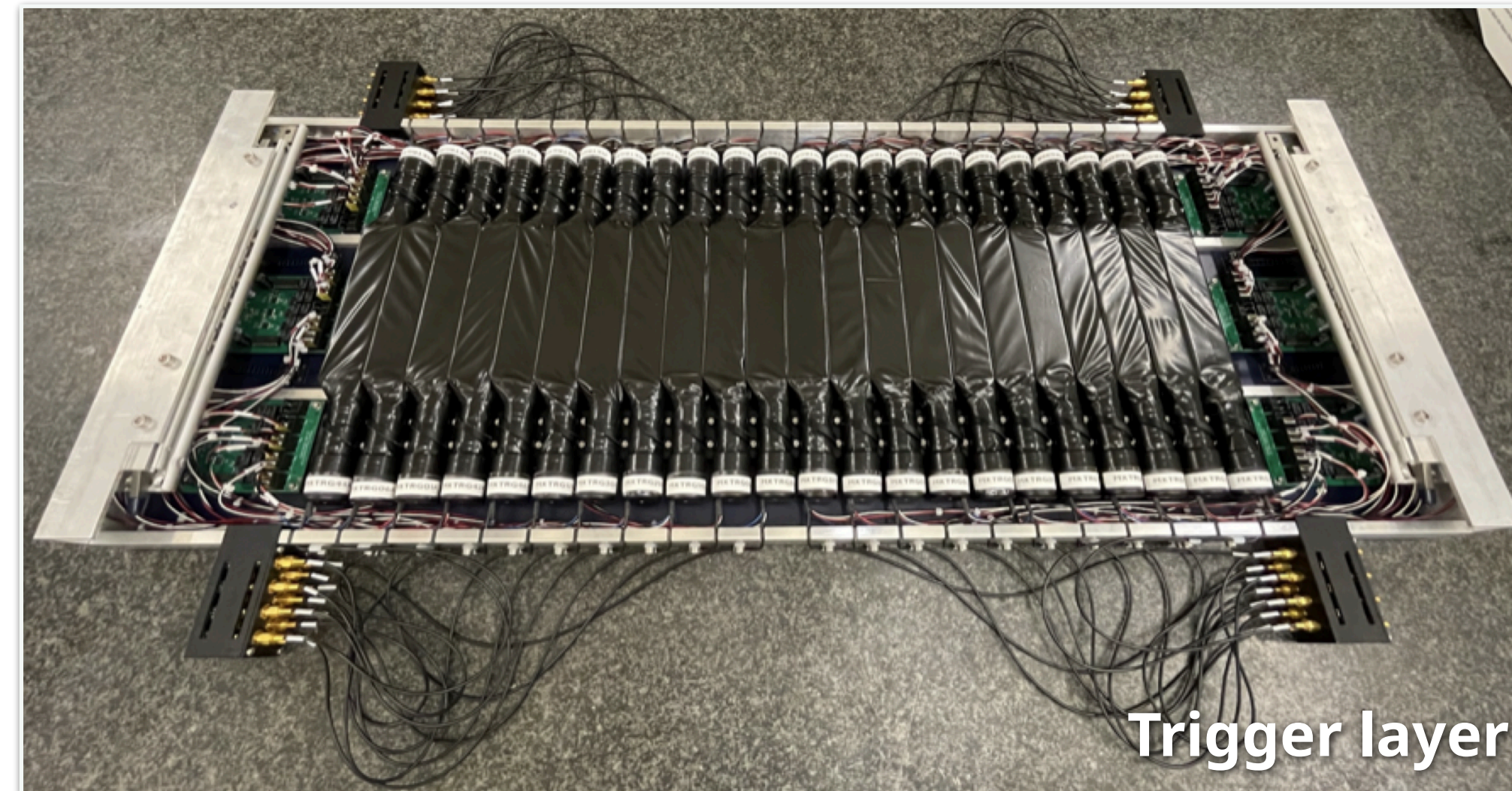
Trigger/veto:
Poster, Hannah Kessler

TPC: Poster,
Lucie Bister

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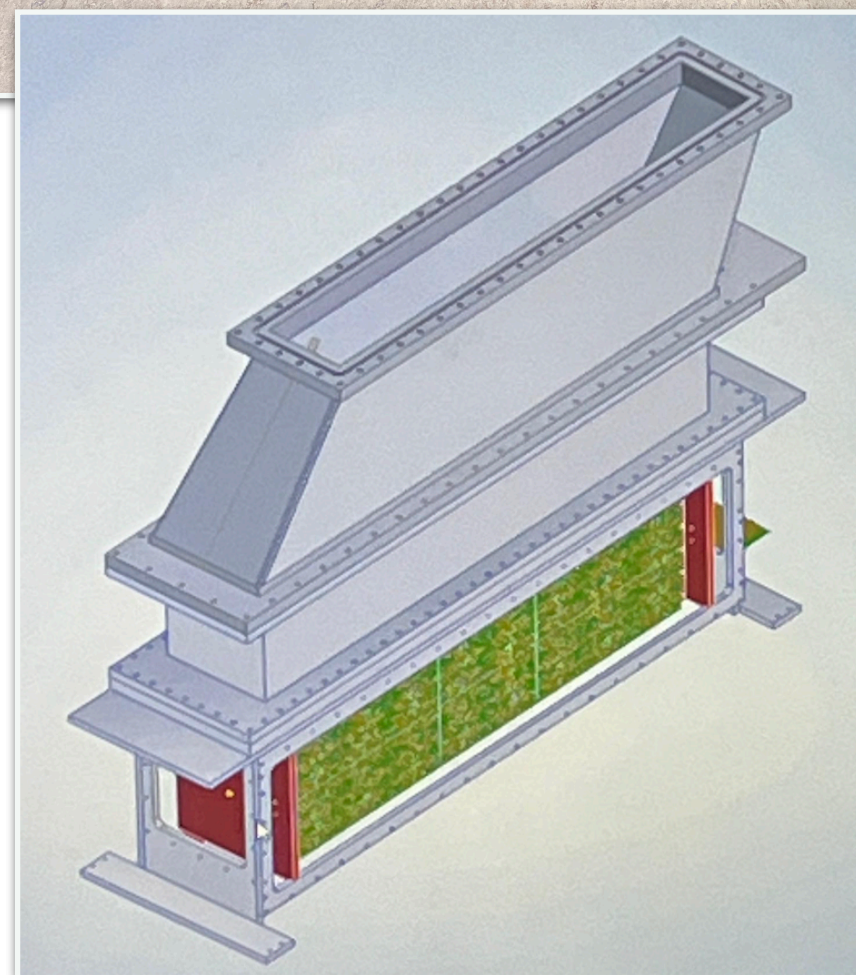


TPC core



Trigger layer

Photos courtesy of
Sebastian Stengel



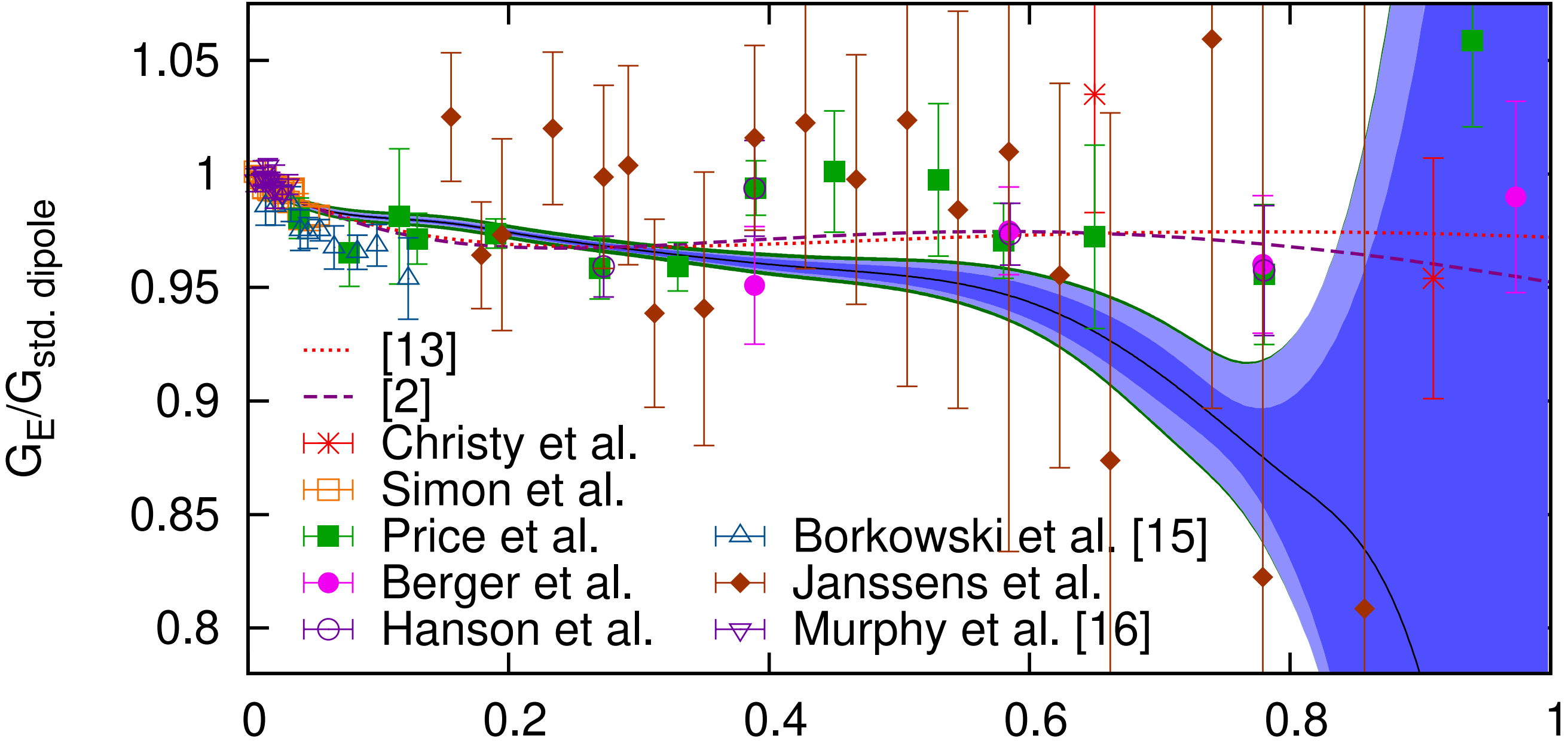
TPC frame



MAGIX hall

Proton elastic form factors

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

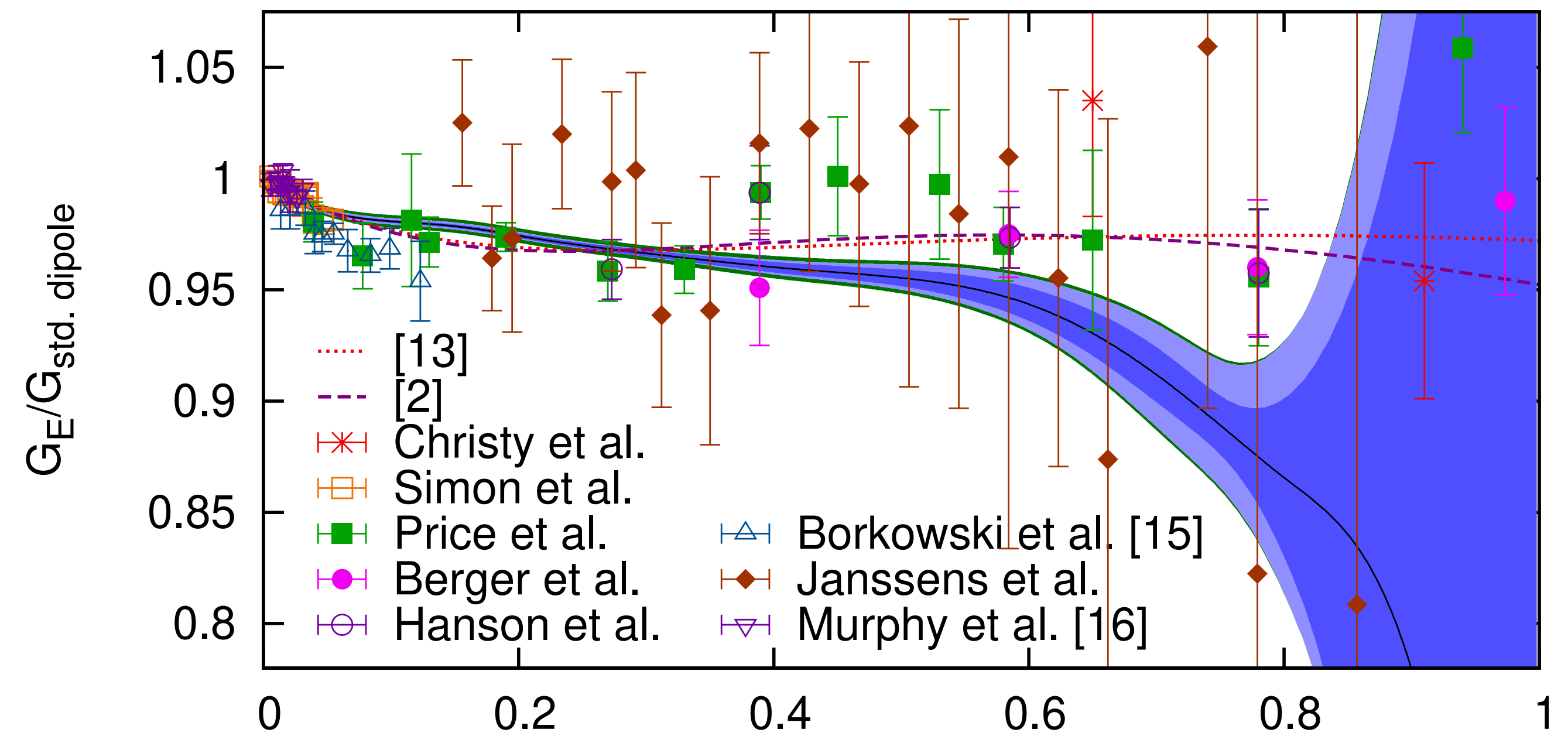


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Low Q^2 expansion:

$$\langle r^2 \rangle \approx -6 \frac{dG(Q^2)}{dQ^2} \bigg|_{Q^2=0}$$

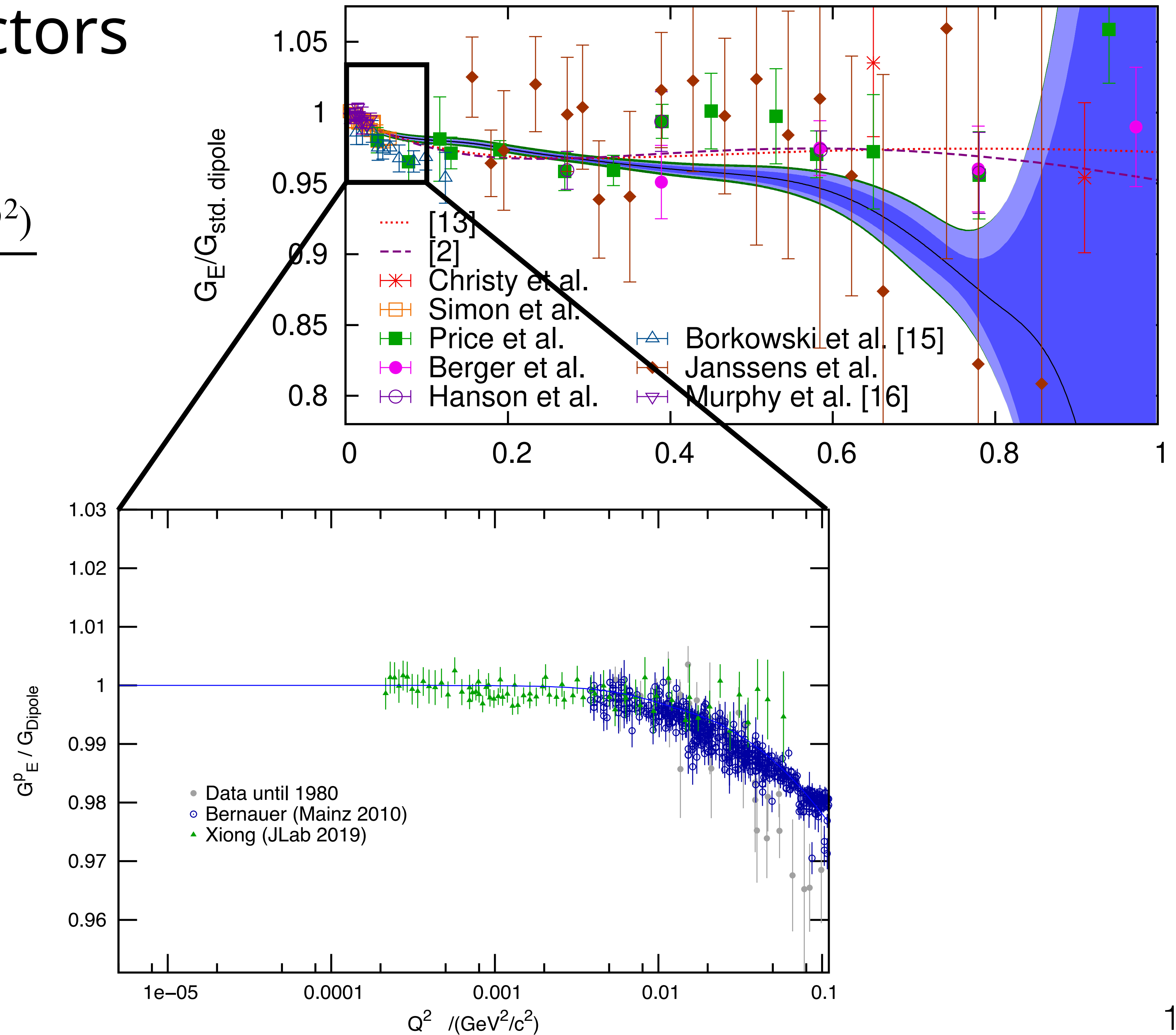


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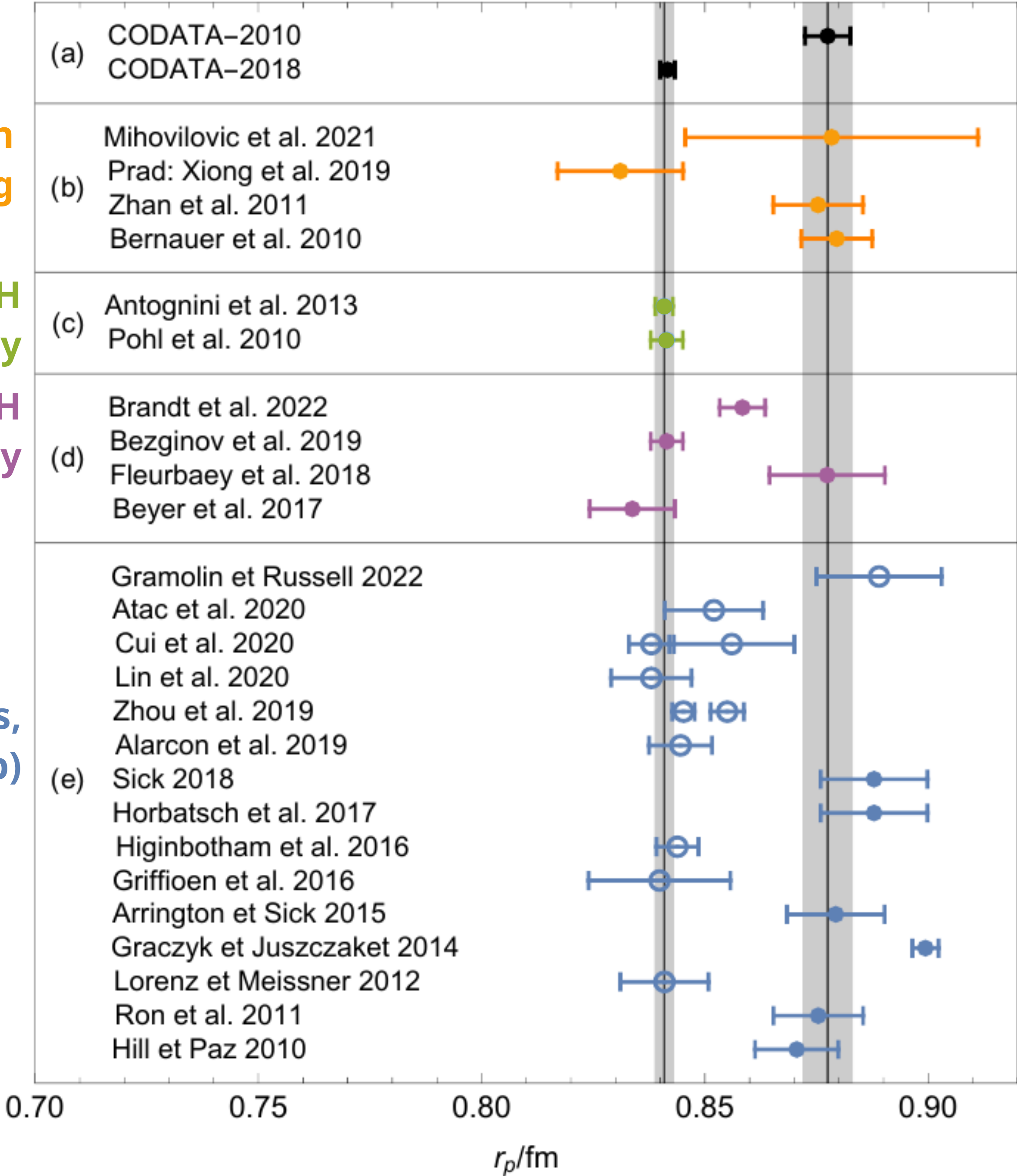
Proton radius puzzle

Electron
scattering

Muonic H
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Electronic H
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Re-analyses,
mostly from (b)



Proton radius puzzle

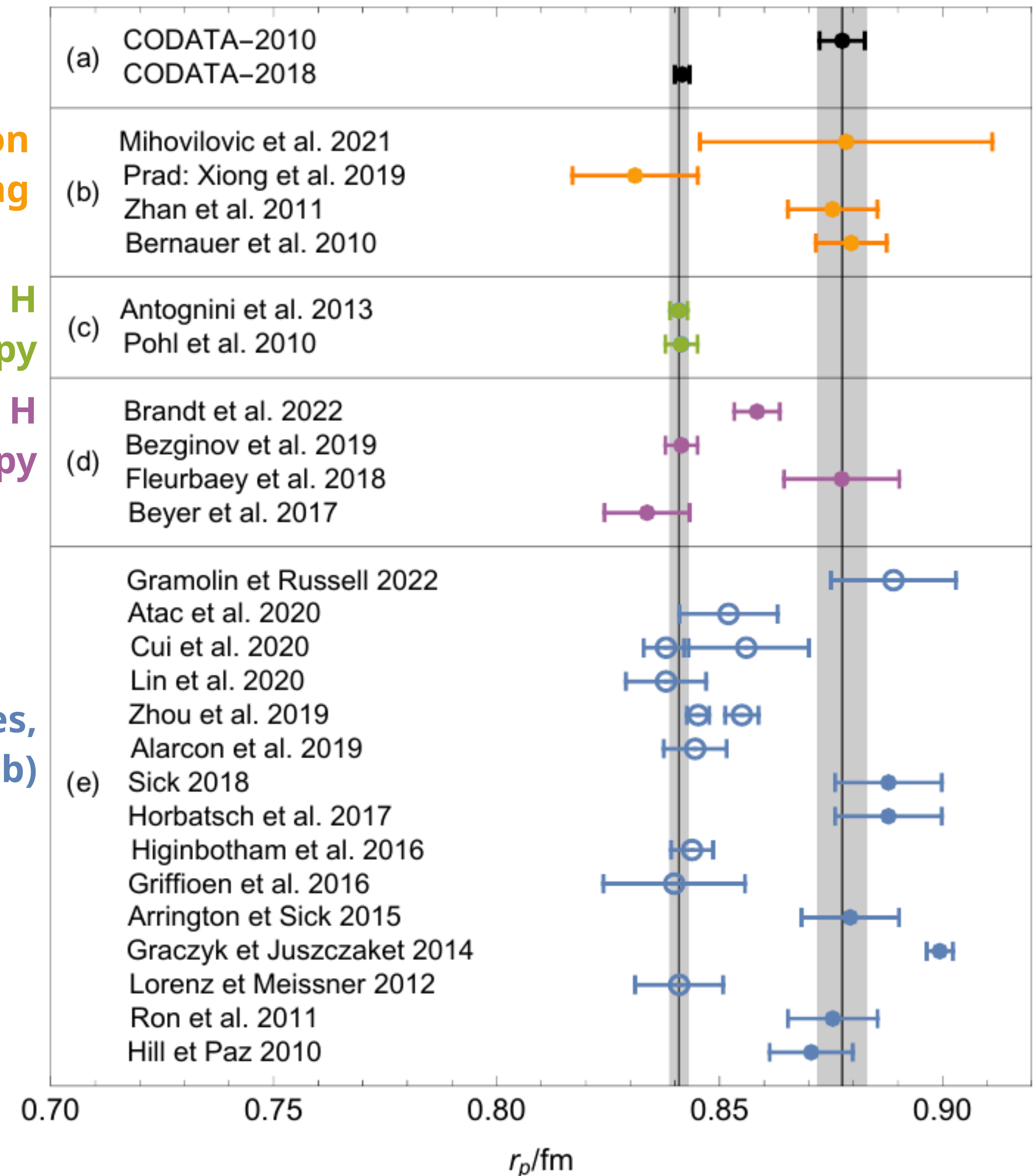
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- **Still no consensus**

"Problem solved!"

"There never was a puzzle!"

" $\langle r_p^2 \rangle$ is not equal to $-6G'(0)$!"

- G. Miller

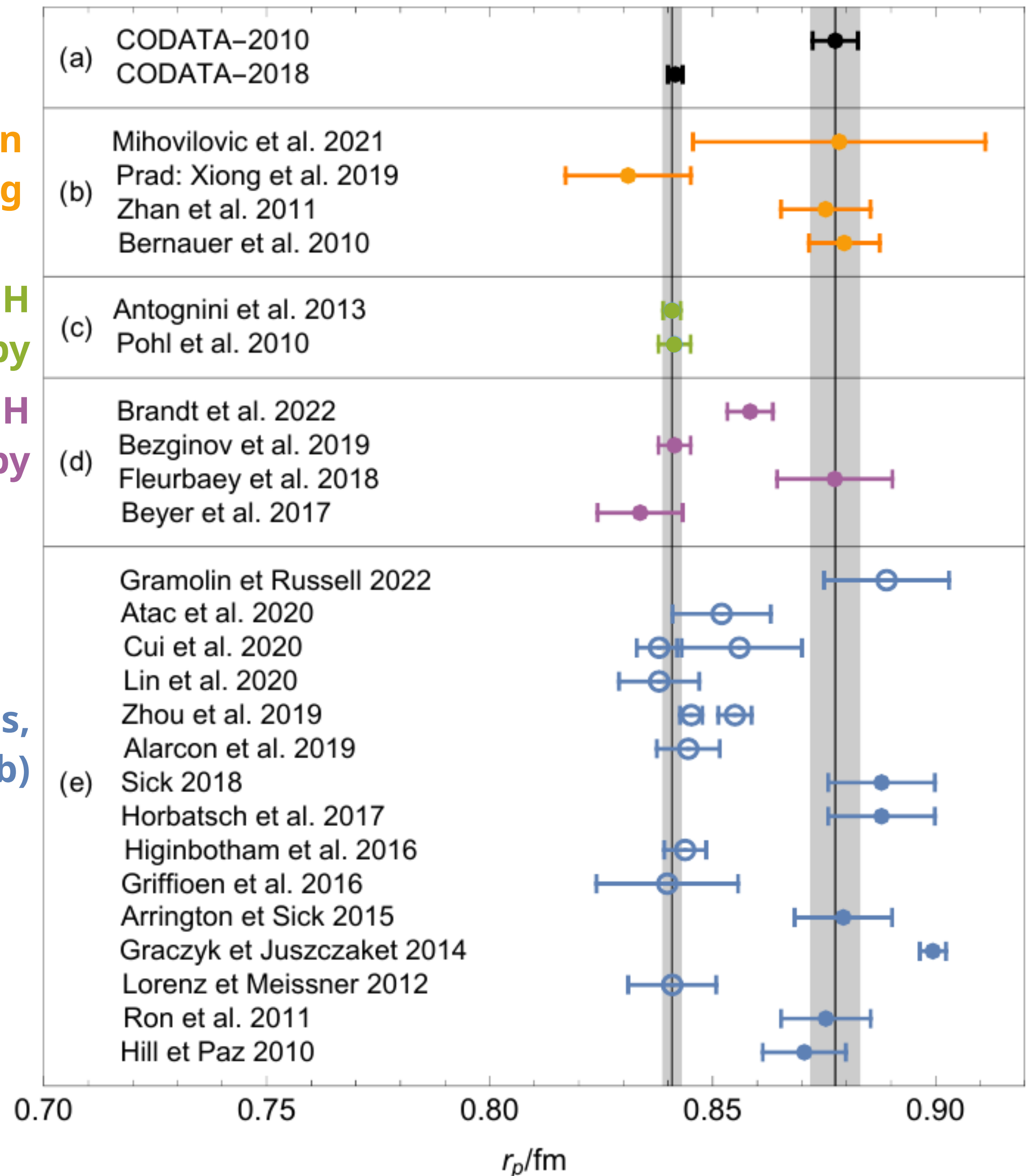
[PRC 99, 035202 \(2019\)](#)

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Neglected corrections? New physics? Experimental/analysis flaws?

Still no consensus

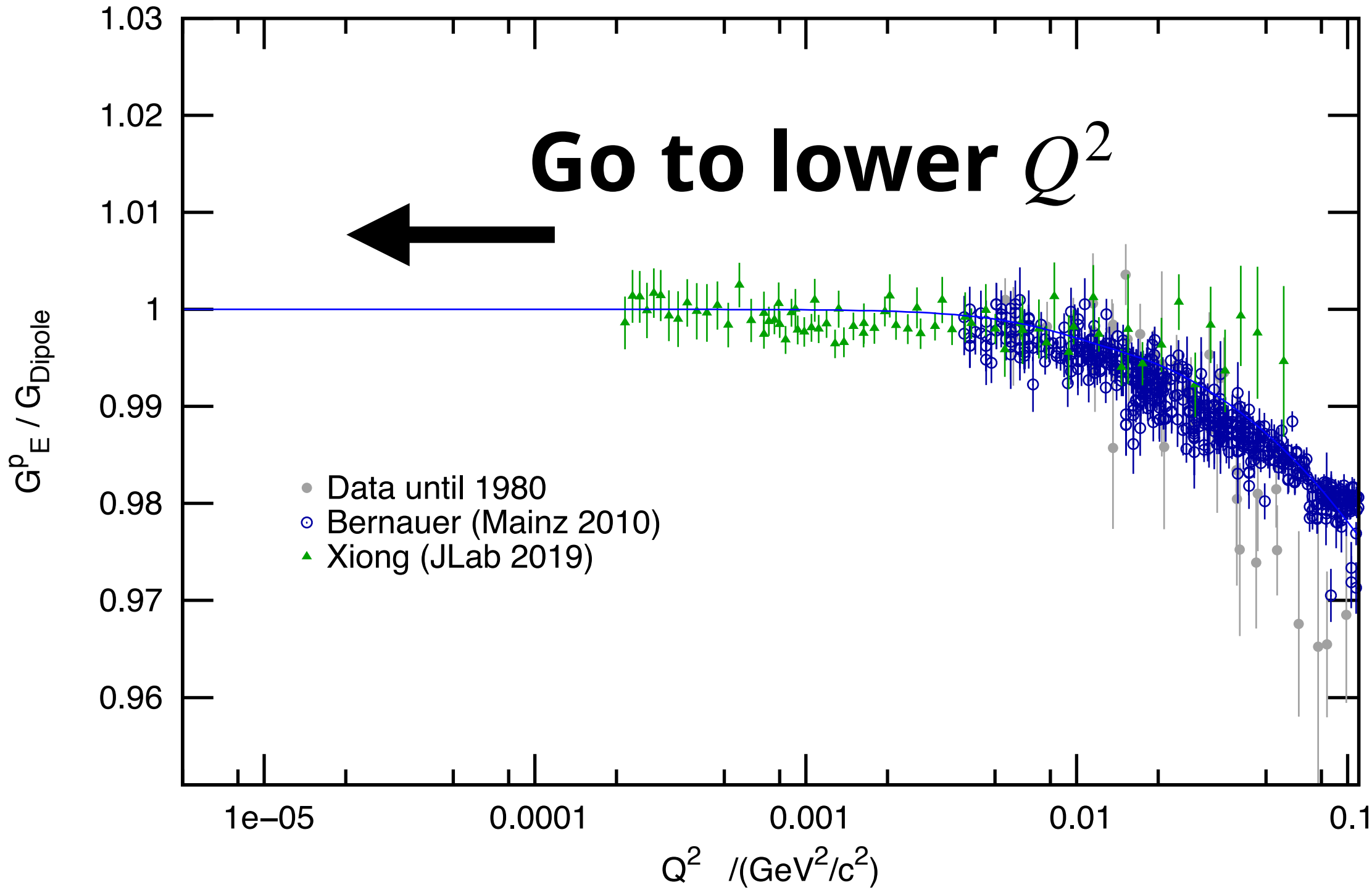
"Problem solved!"
"There never was a puzzle!"
" $\langle r_p^2 \rangle$ is not equal to $-6G'(0)$!"
- G. Miller [PRC 99, 035202 \(2019\)](#)

Electron scattering
Muonic H spectroscopy
Electronic H spectroscopy

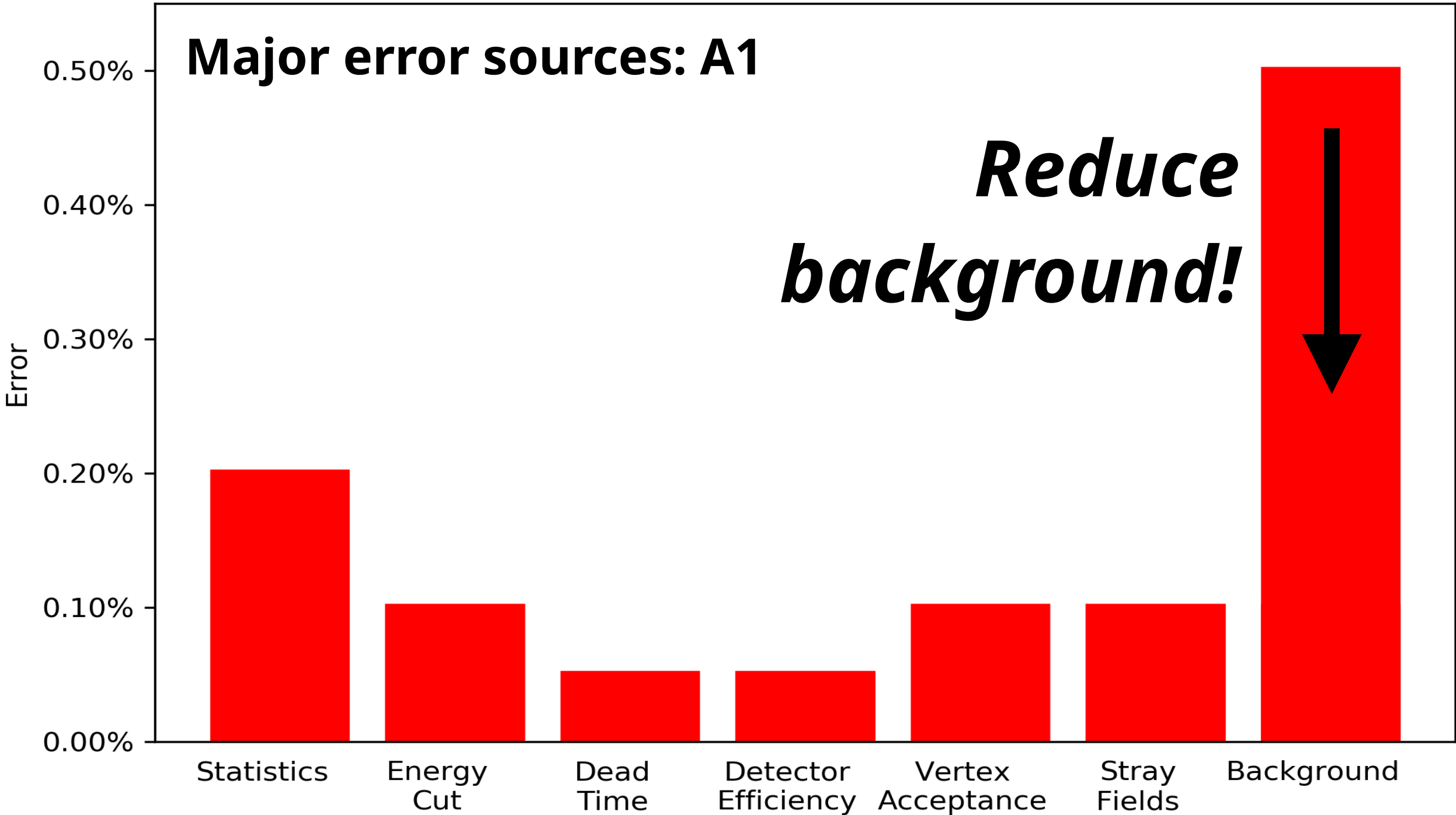
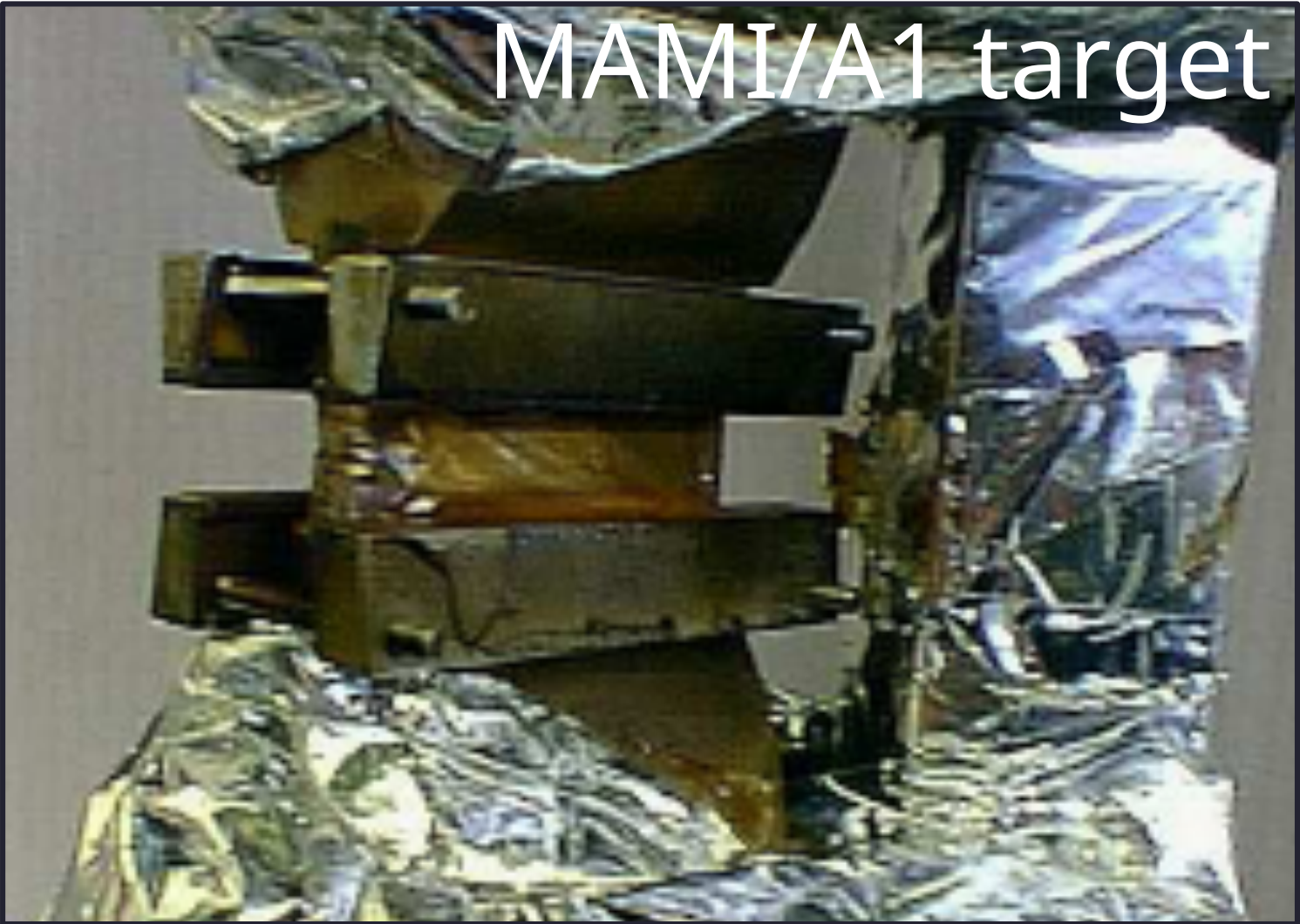
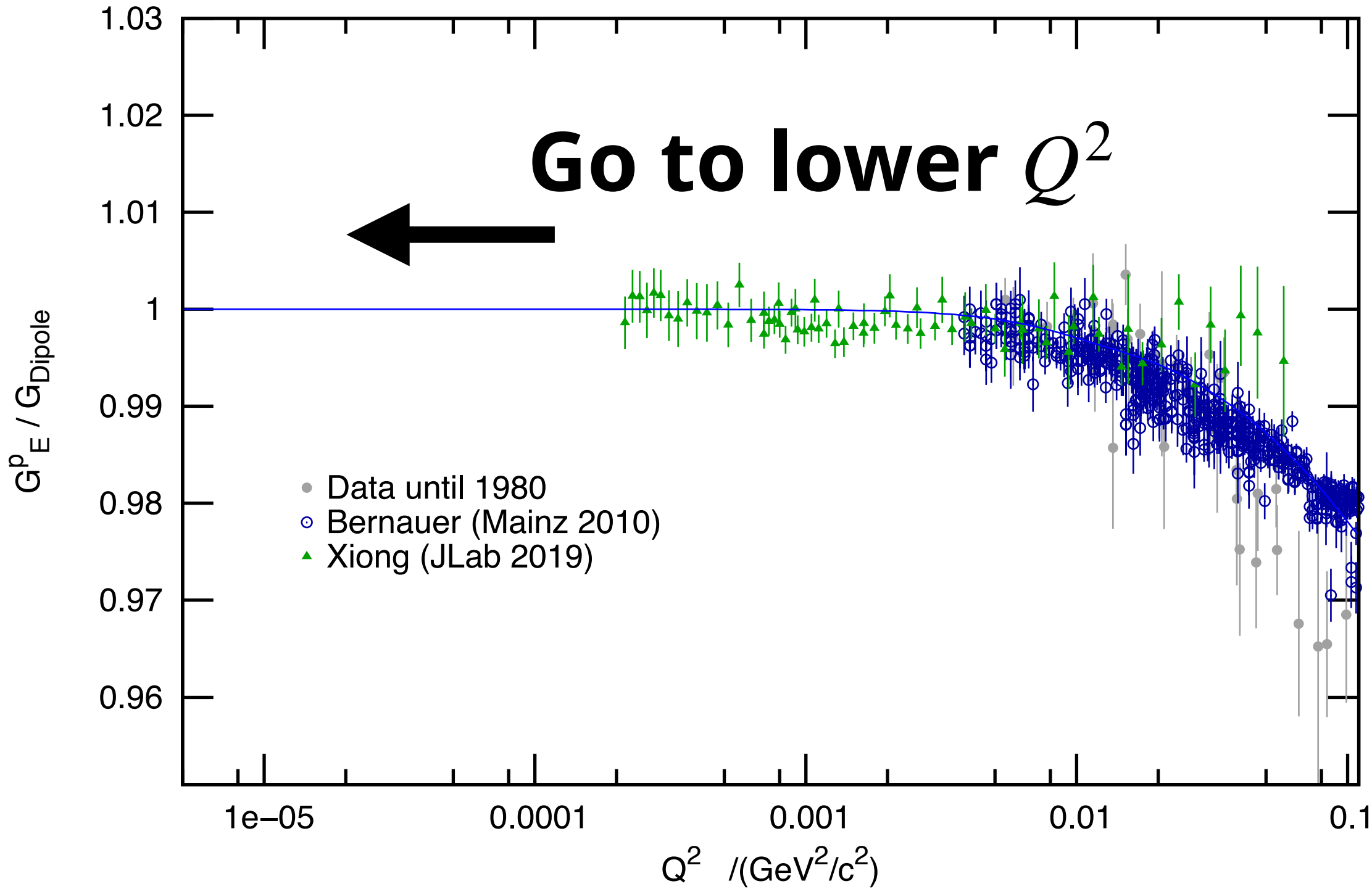
can do better!
- Mainz
Re-analyses, mostly from (b)



How can proton data be improved?

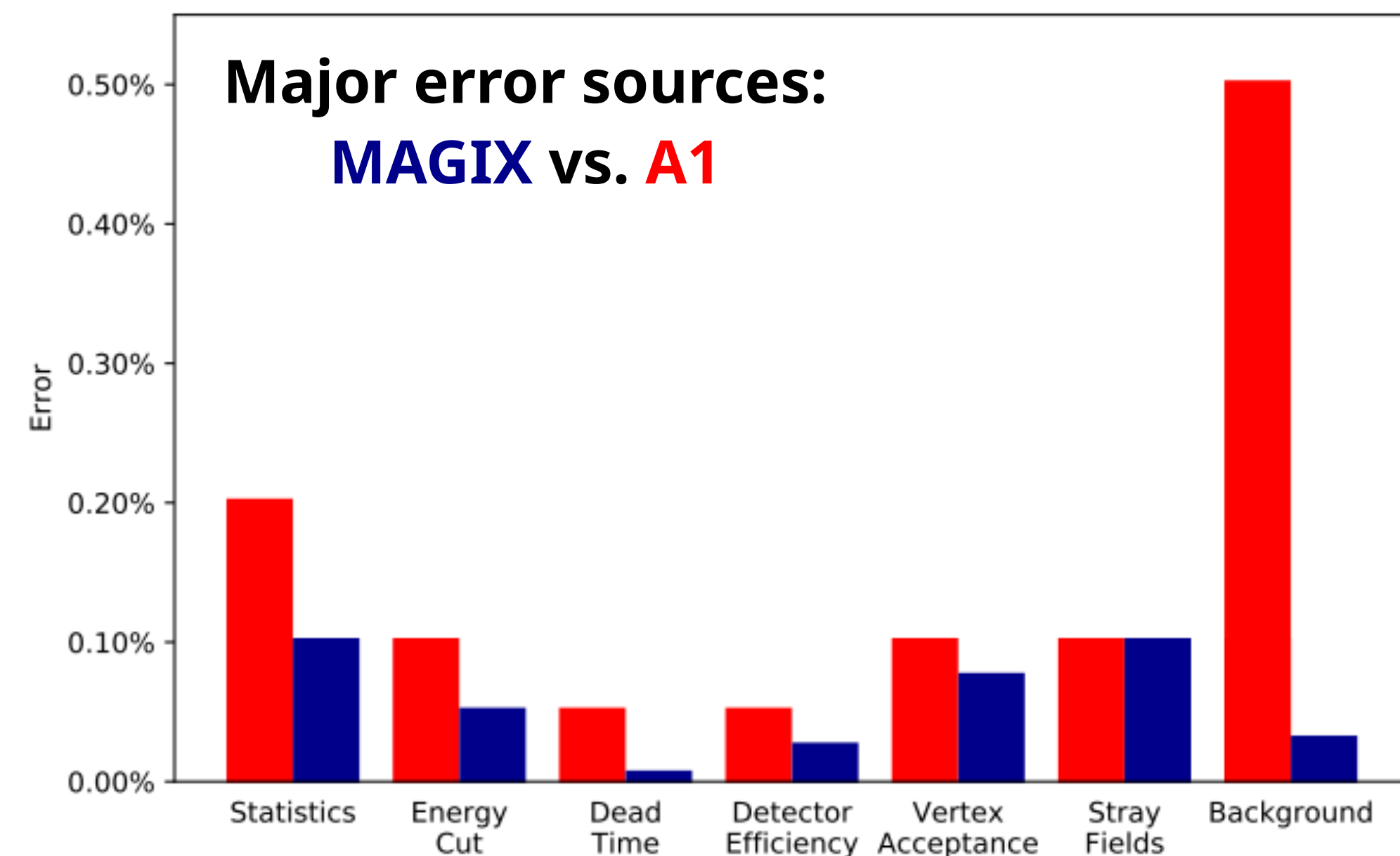
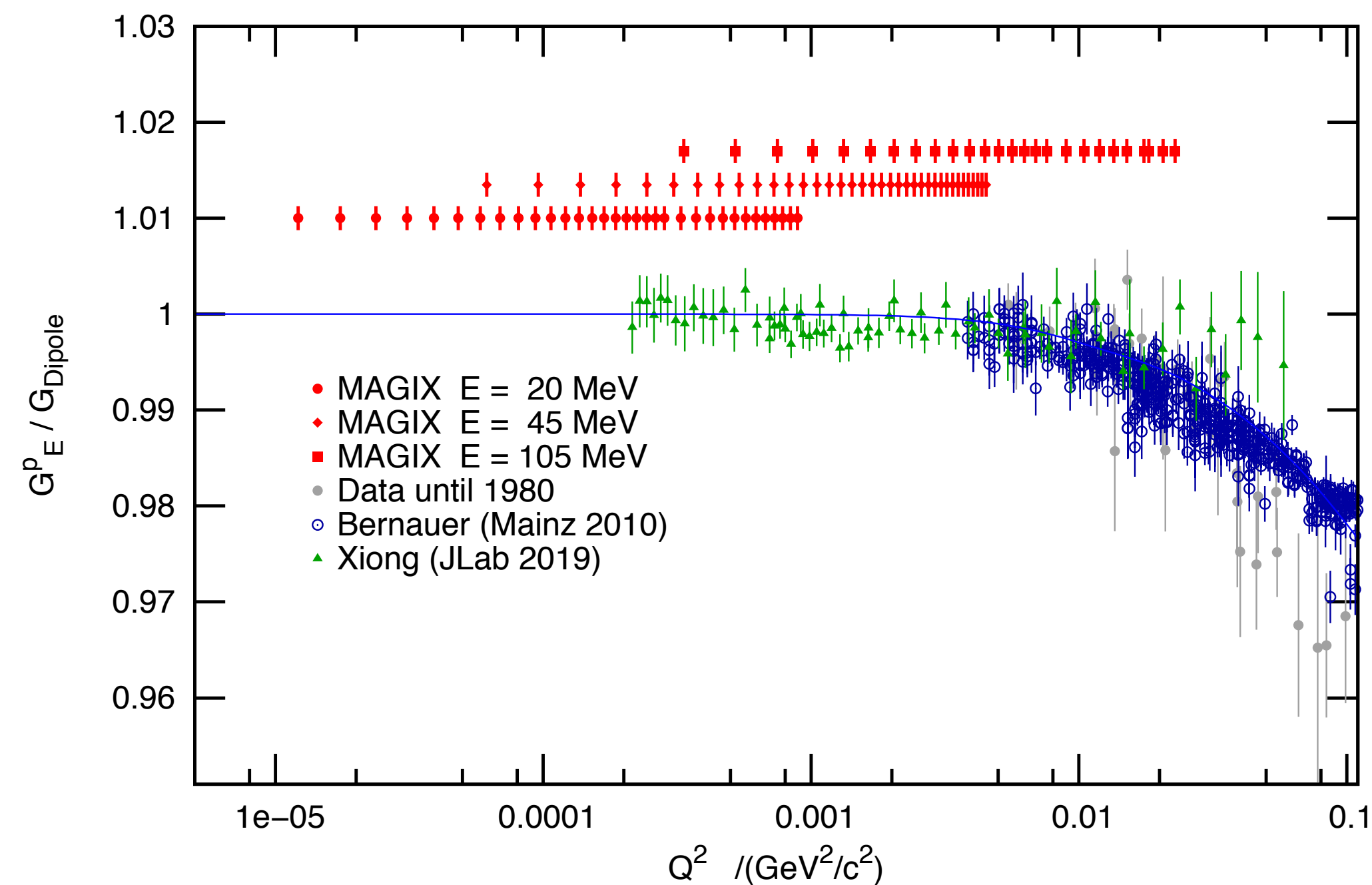
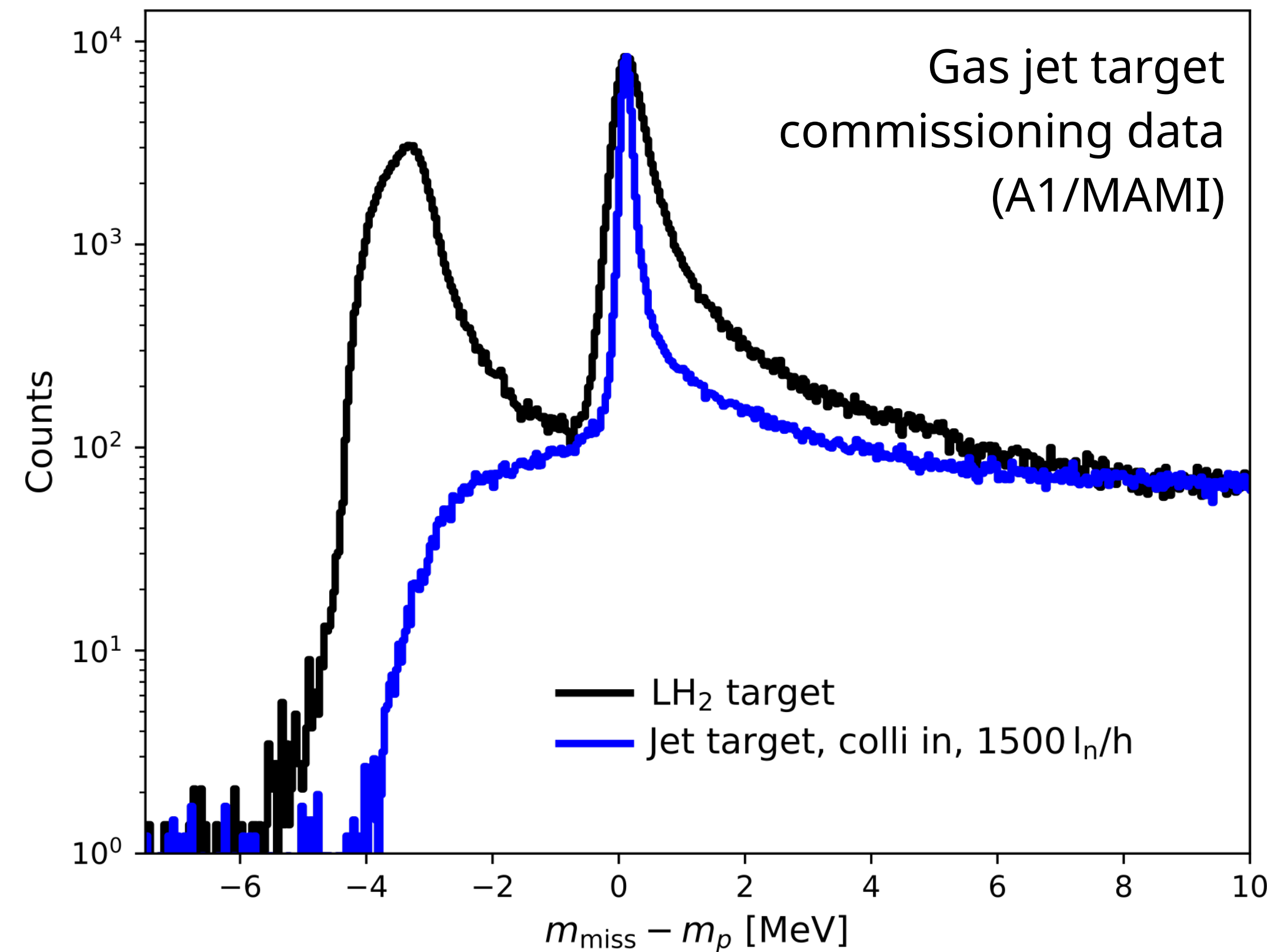


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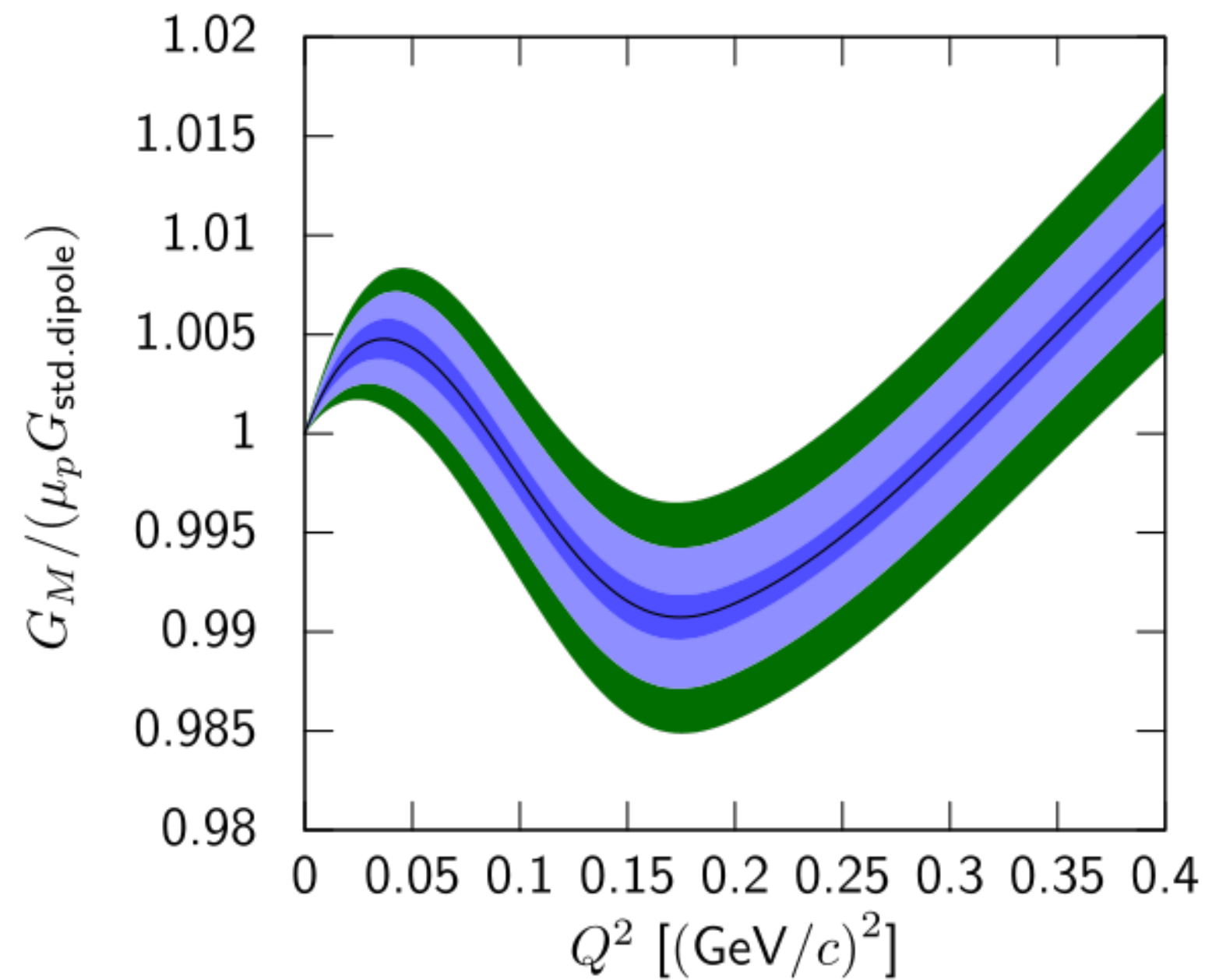


MAGIX can deliver!

- Lower beam energy
- Windowless target



Magnetic form factor: “What about me?!”



MAMI/A1:

$$\langle r_M^2 \rangle^{1/2} = 0.777(13)_{\text{stat}}(9)_{\text{sys}}(5)_{\text{model}}(2)_{\text{group}} \text{ fm}$$

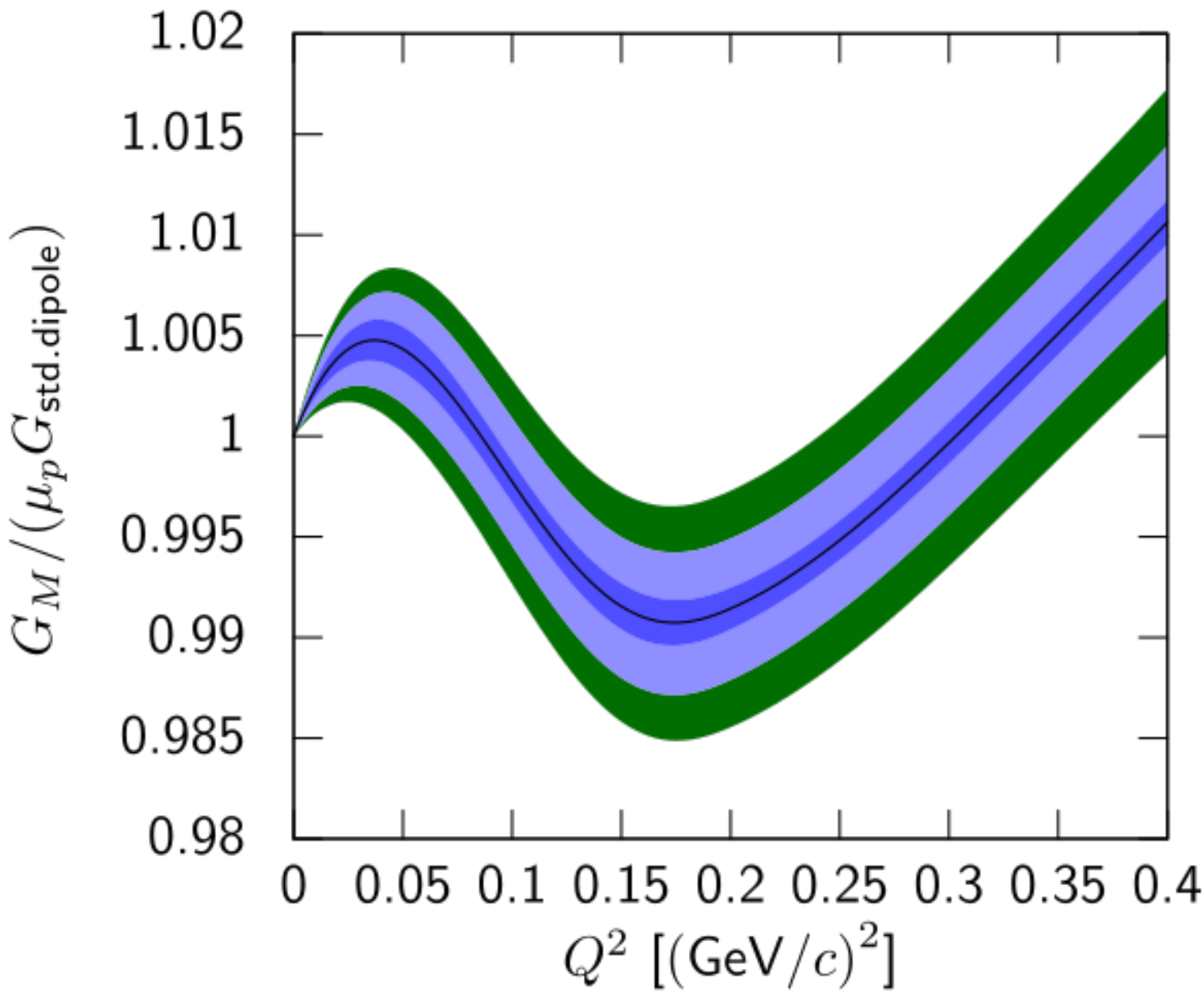
Dispersion theory:

$$\langle r_M^2 \rangle^{1/2} = 0.849 \pm 0.003 \text{ fm}$$

“Such a structure is at odds with unitarity and analyticity.”

[Science Bulletin Volume 69\(4\), 419 \(2024\)](#)

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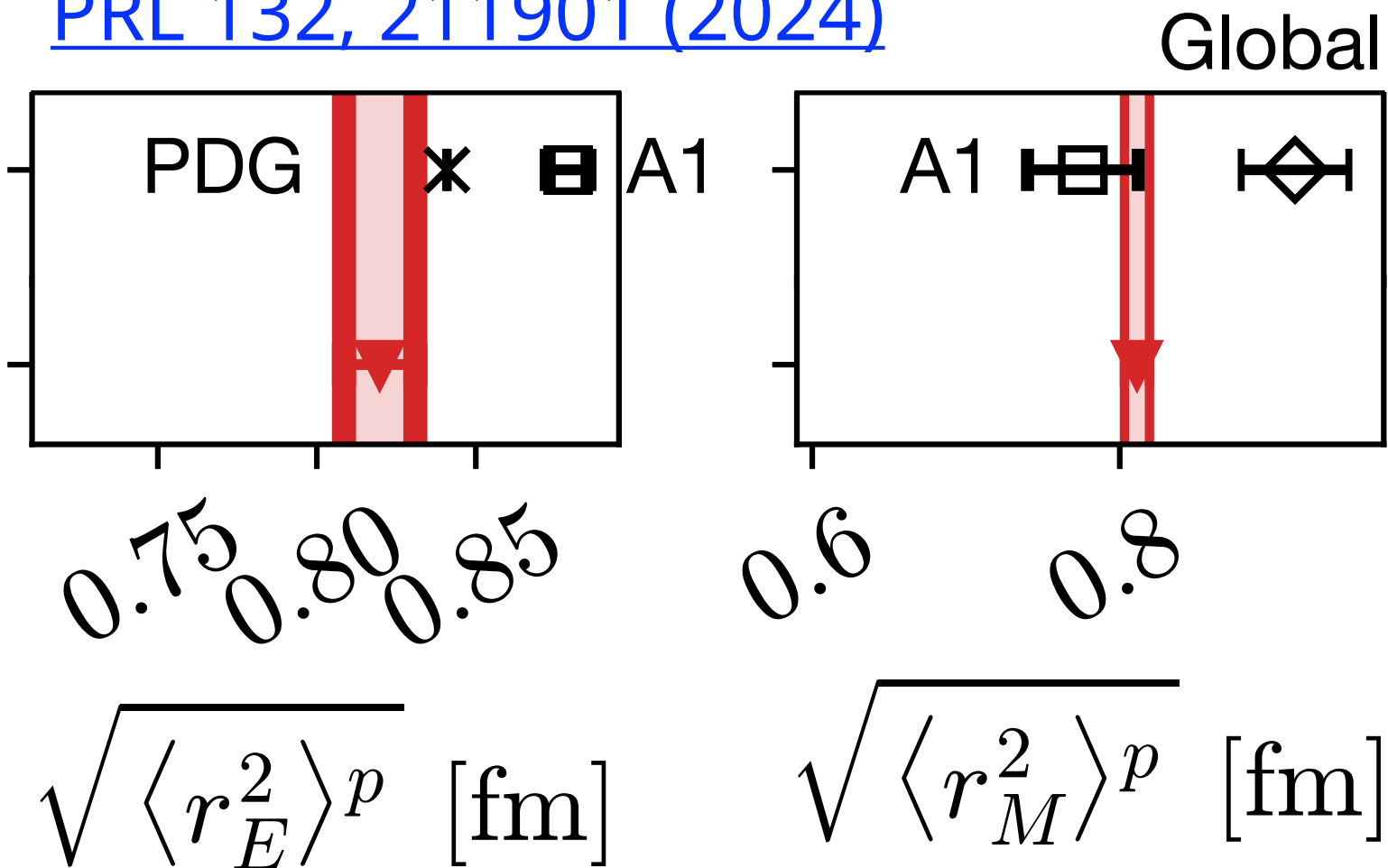
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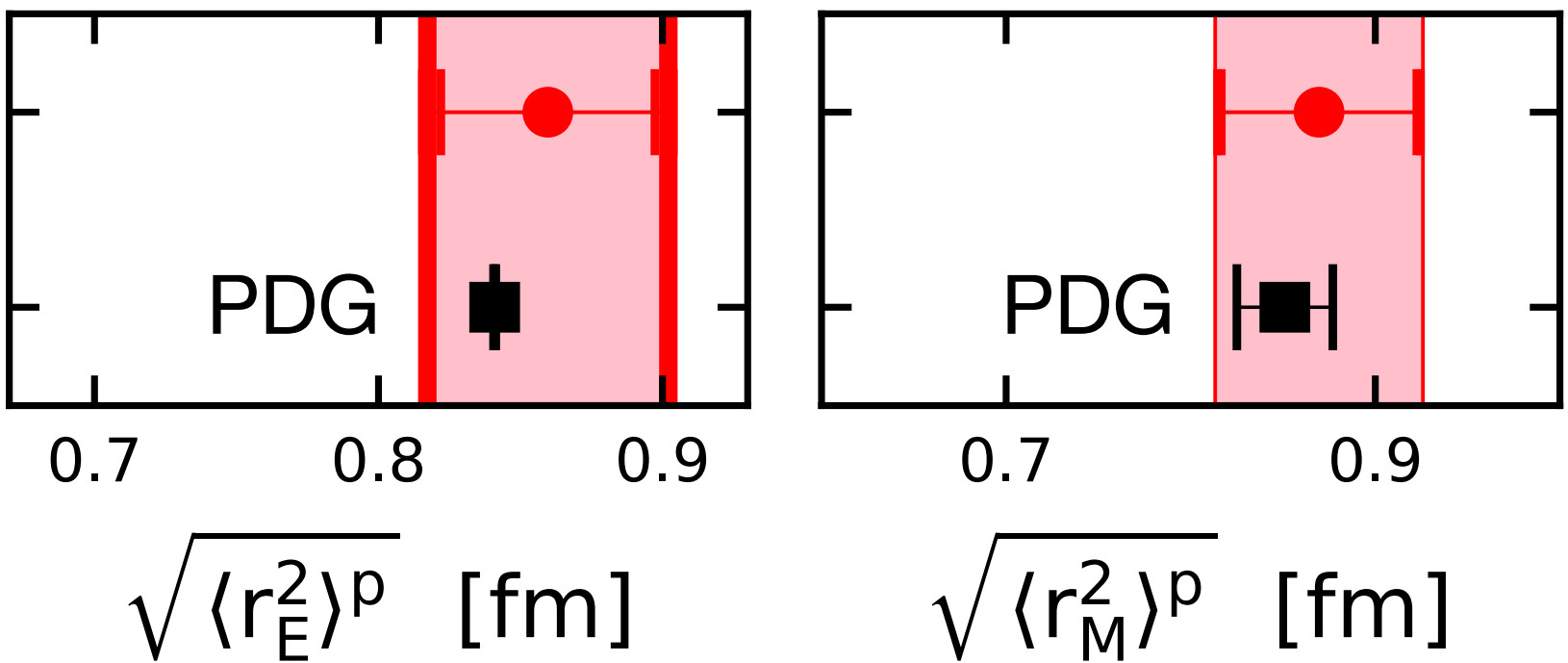
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[PRL 132, 211901 \(2024\)](#)

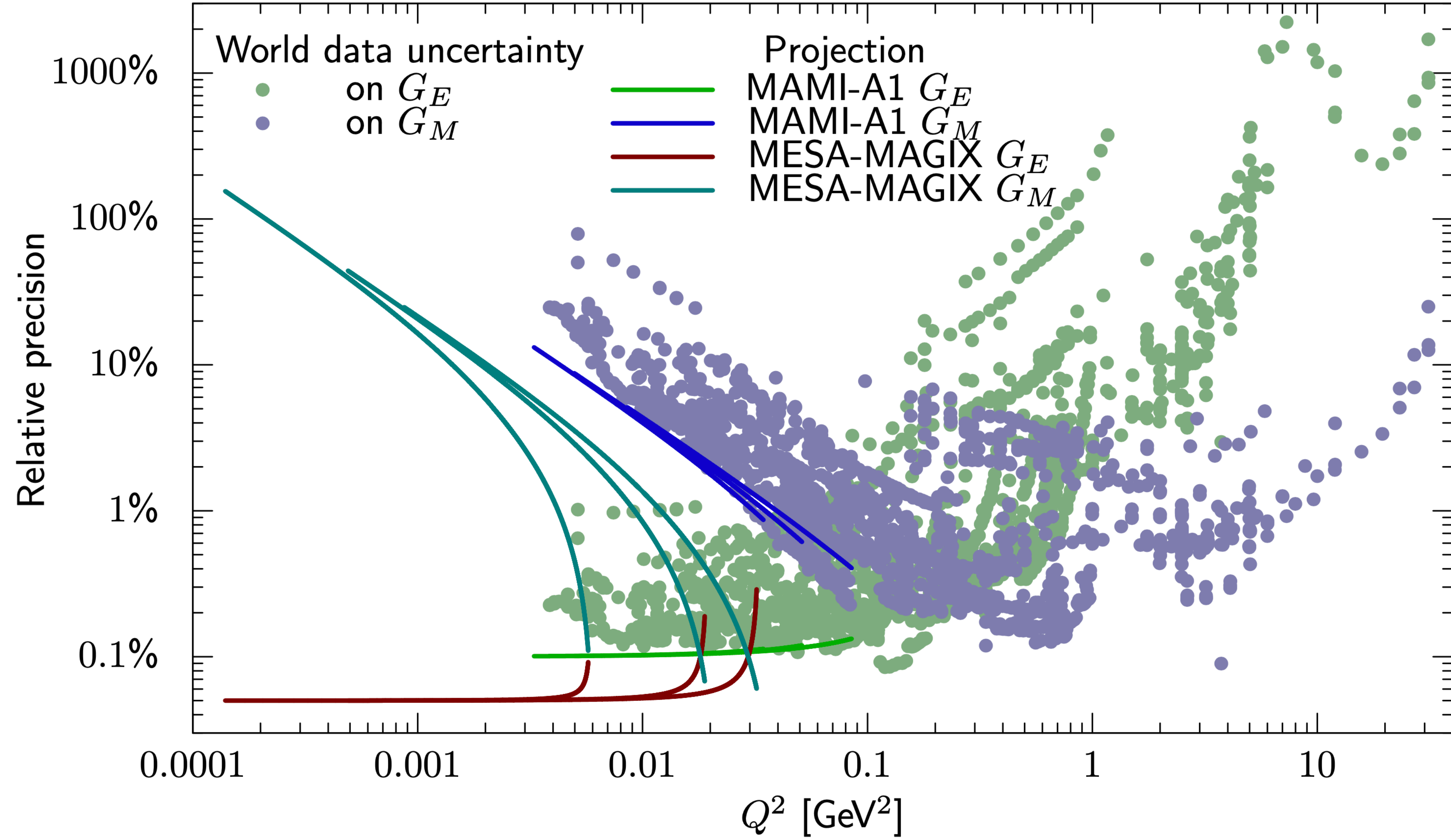


[arXiv:2507.20910v1](#)



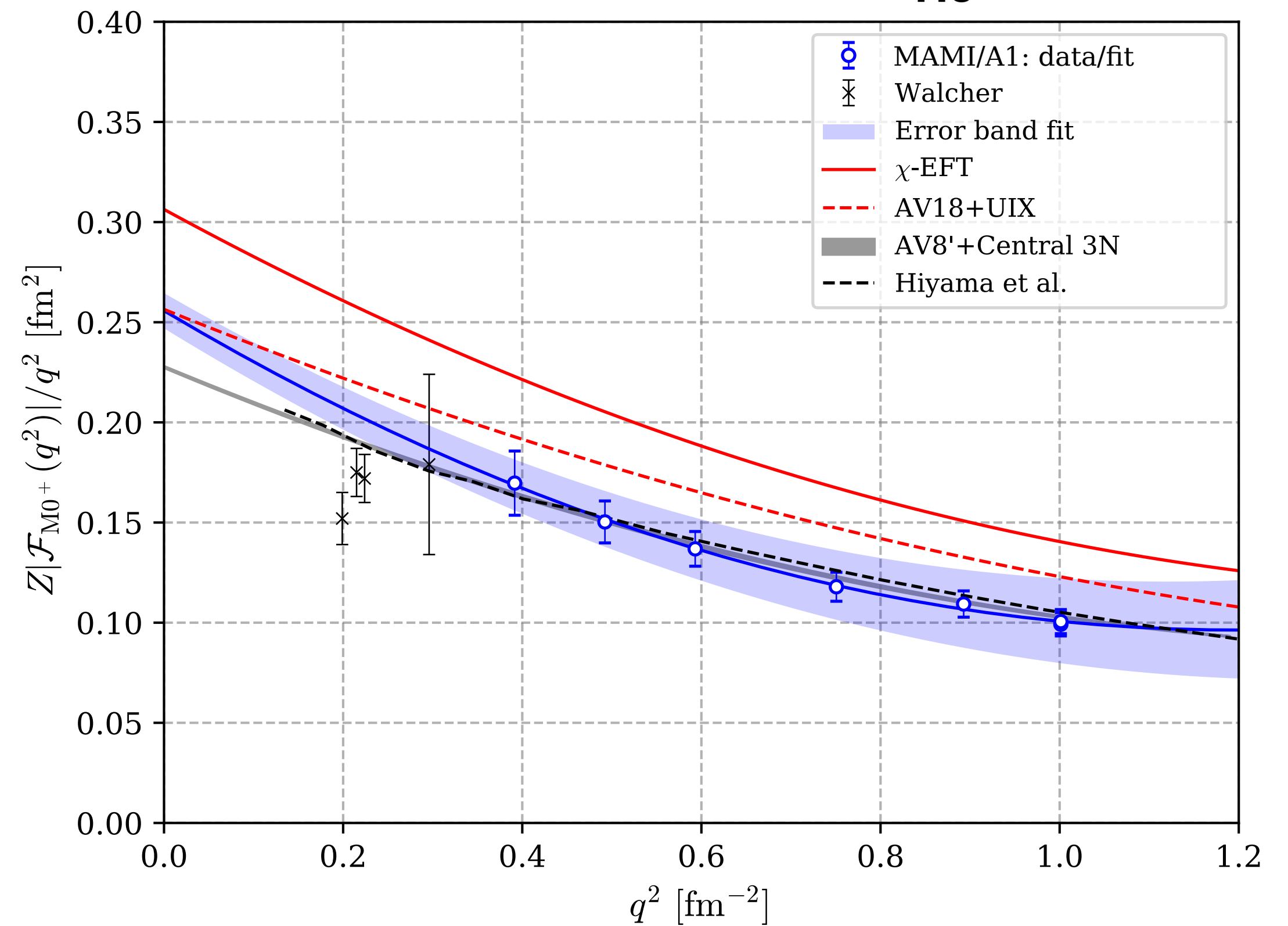
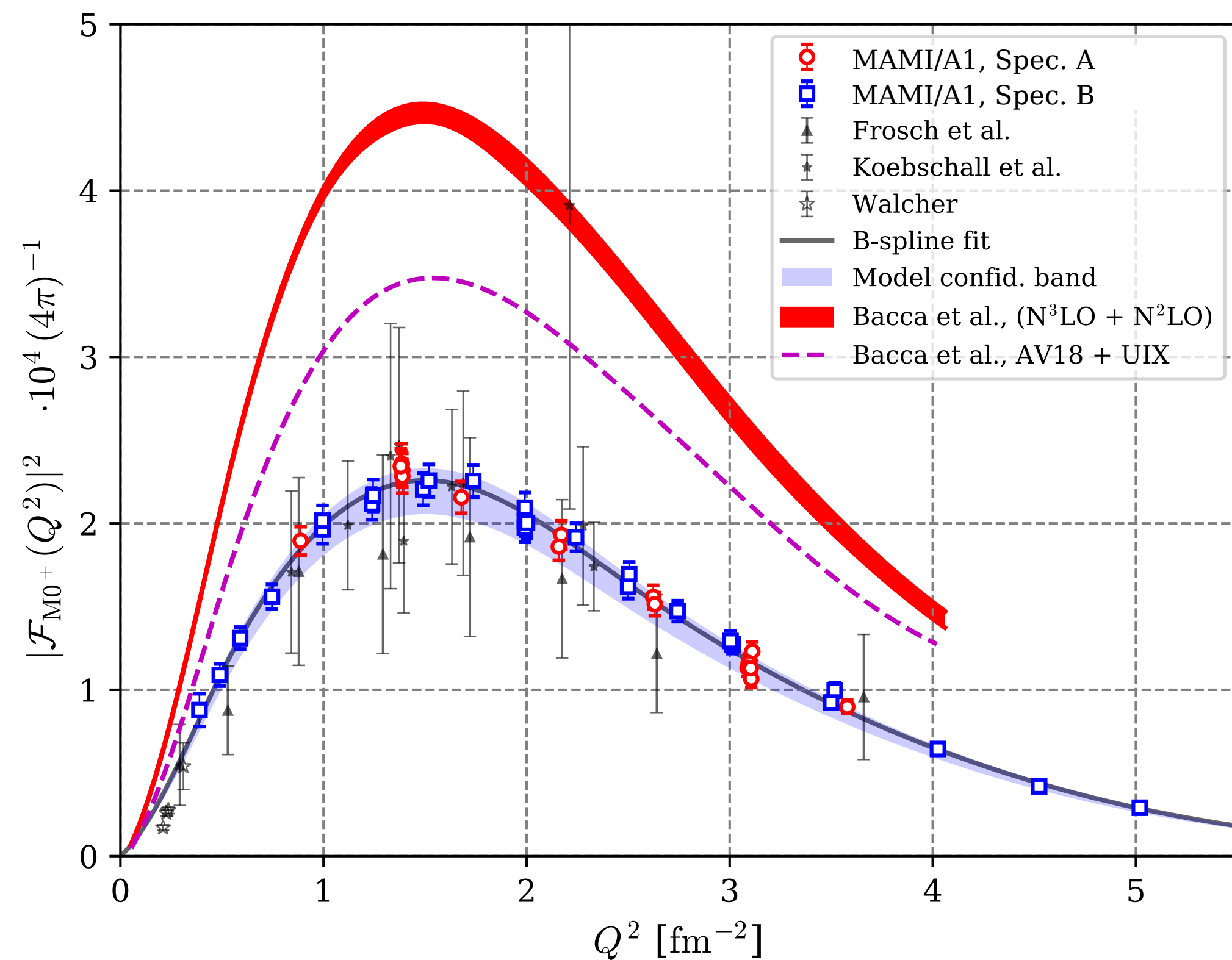
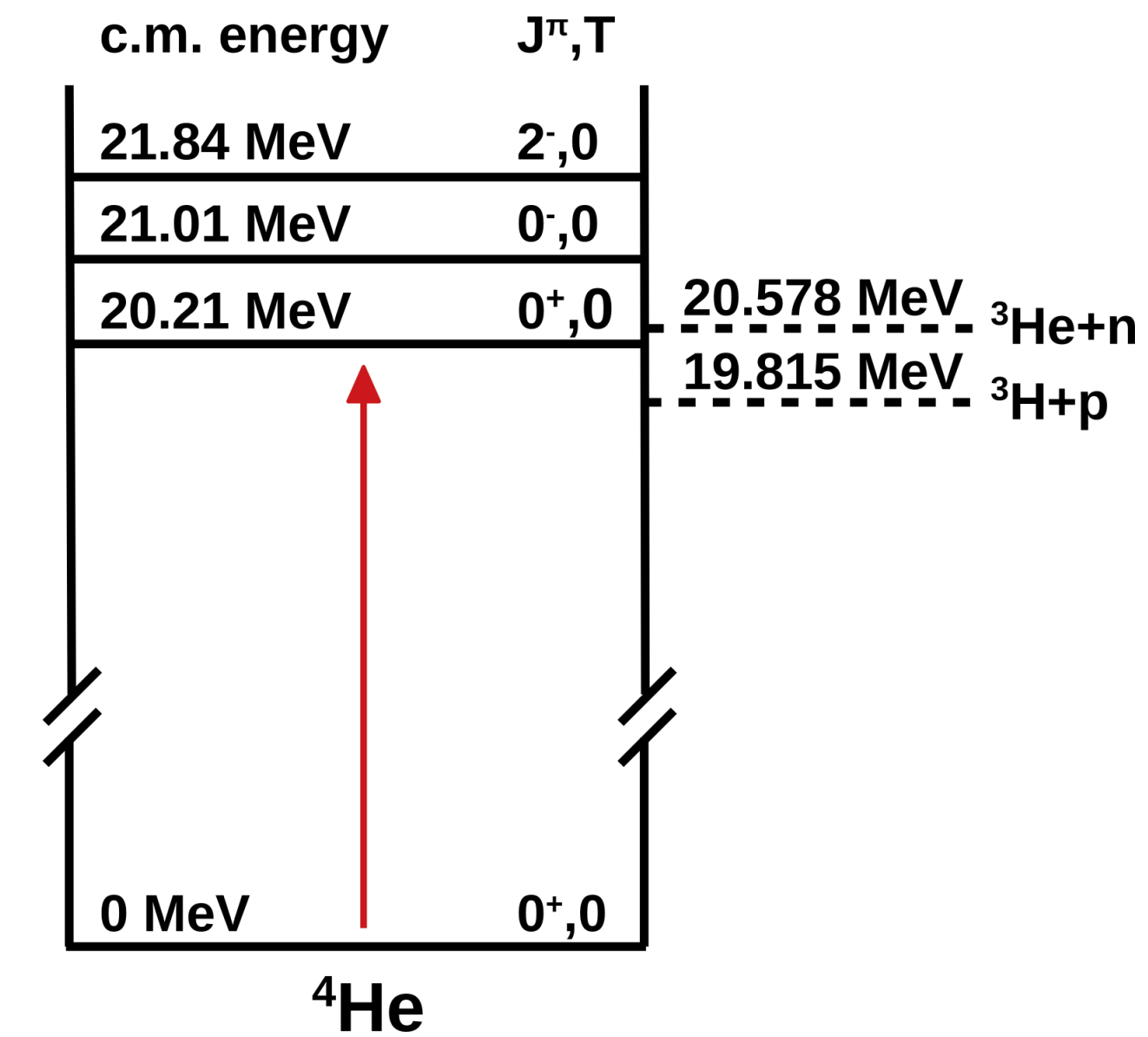
Lattice QCD:

- Mainz: r_E is small, r_M consistent with A1
- Cyprus: r_E consistent with A1, r_M large

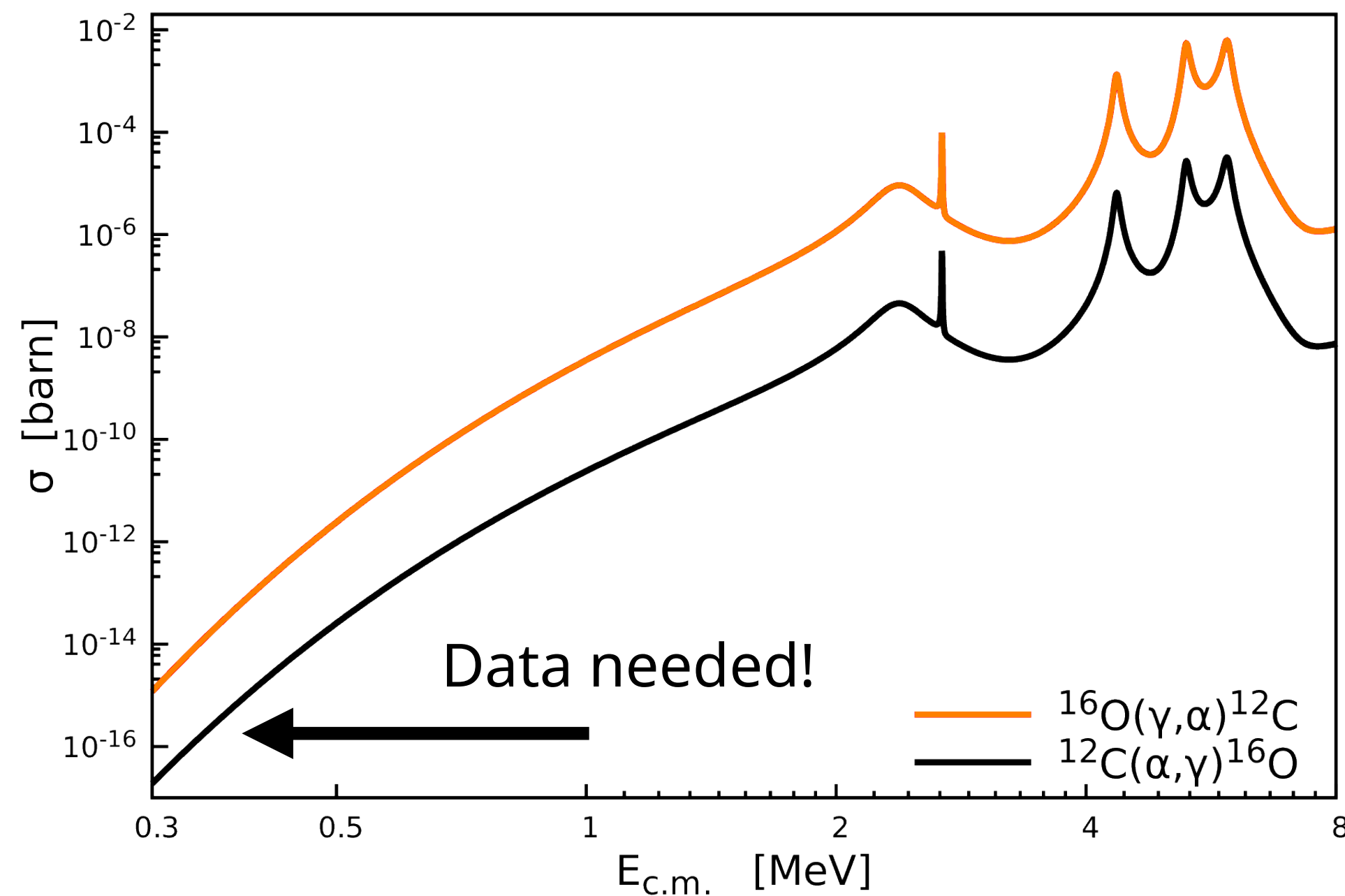
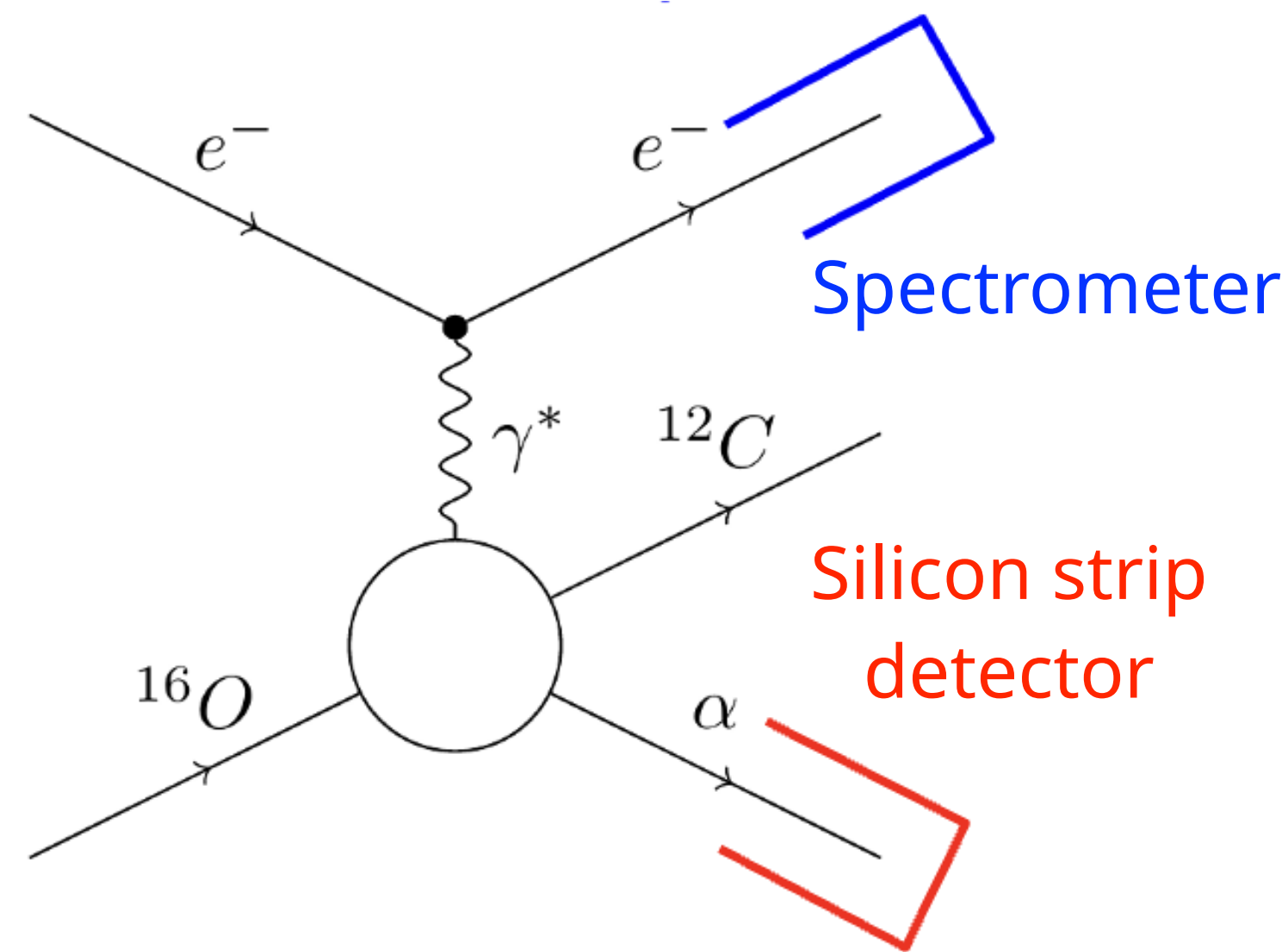


Few-body physics: the nuclear Hamiltonian

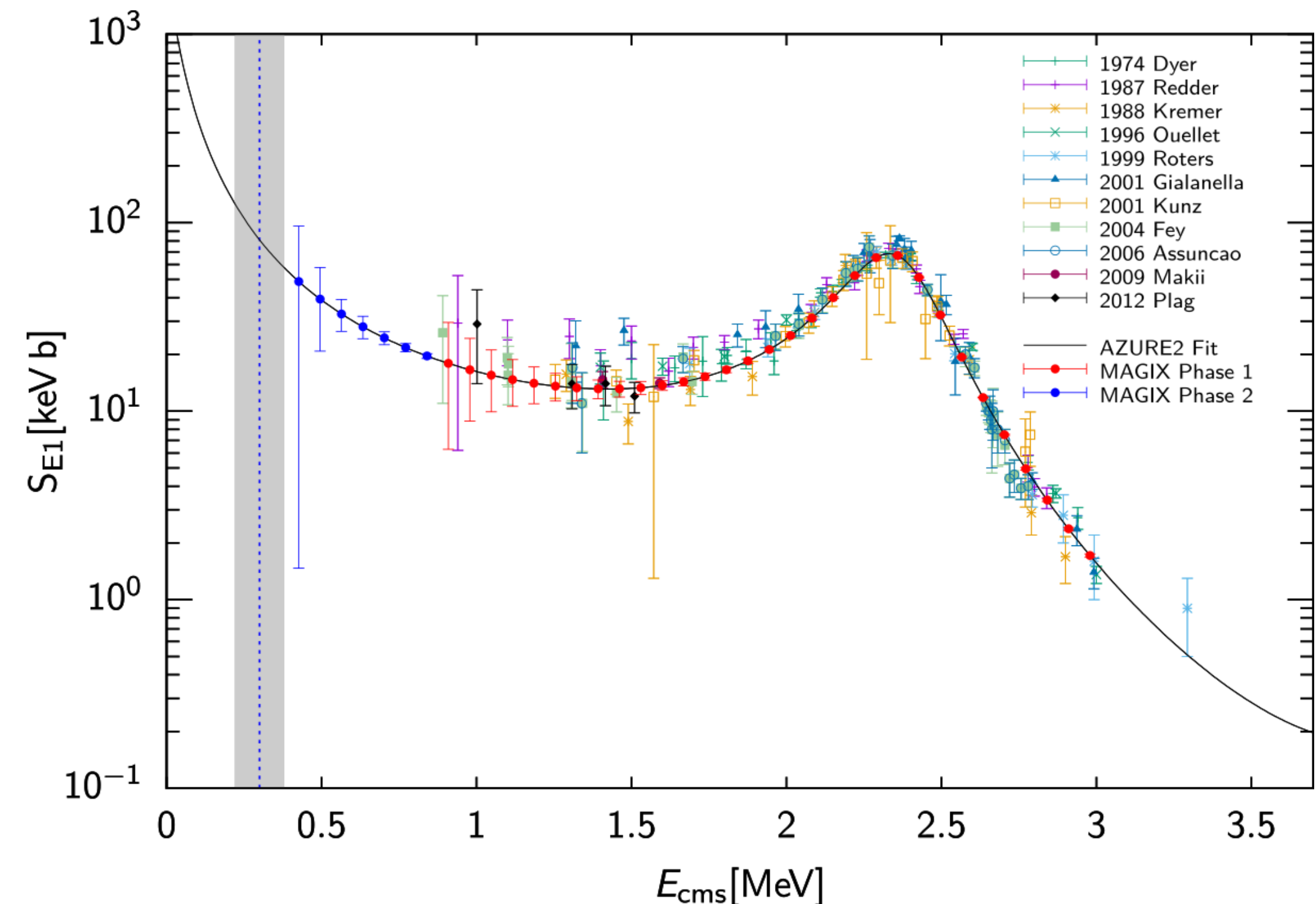
- ^4He monopole transition form factor
- Sensitive to 3N forces
- No agreement between multiple measurements, calculations
- Benchmark order-by-order χEFT expansion



Few-body physics: from Earth to the stars...



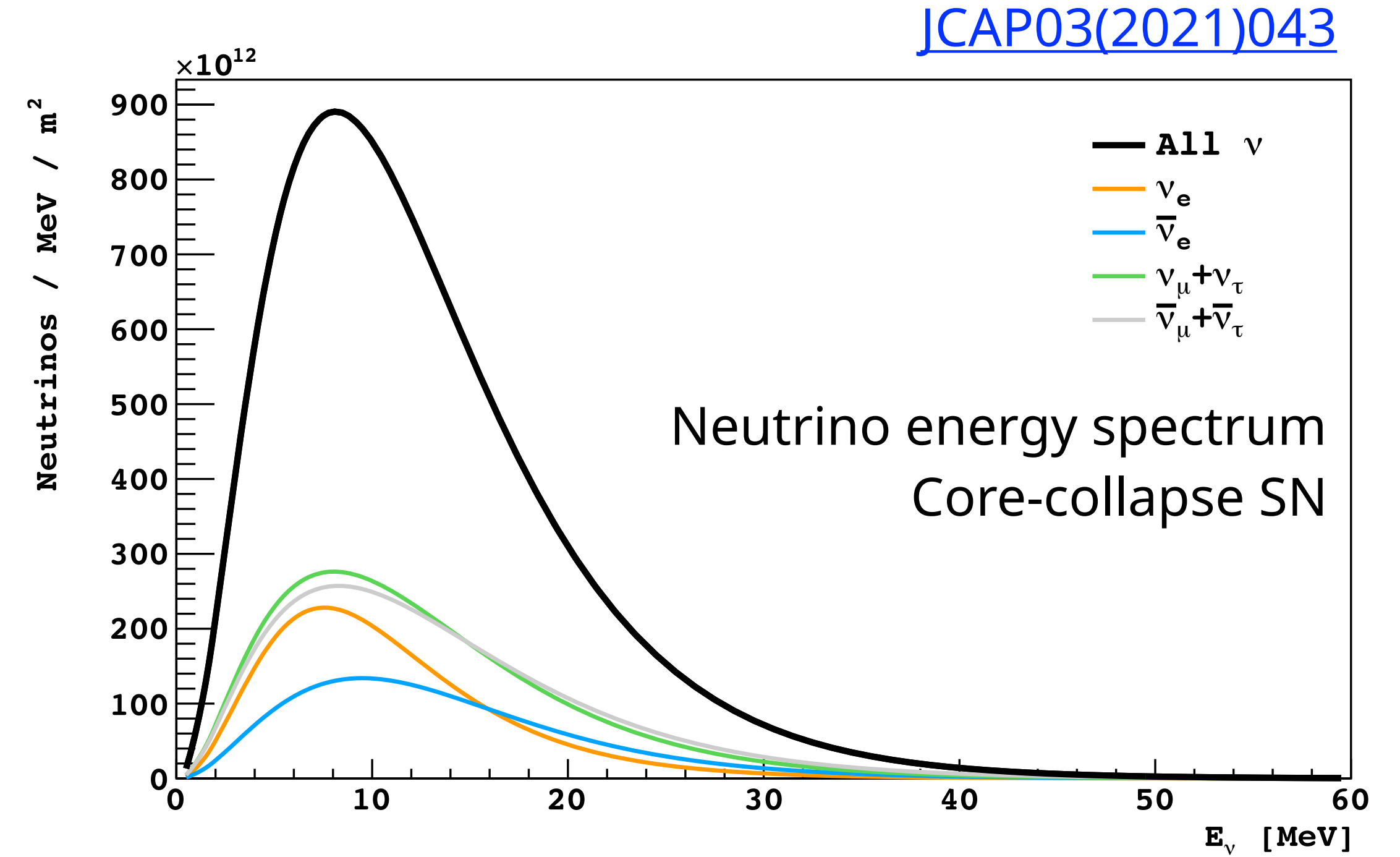
- Photo-dissociation $^{16}\text{O}(e, e'\alpha)^{12}\text{C}$ cross section
- Time-reversed of $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ radiative capture
 - Determines $^{12}\text{C}/^{16}\text{O}$ ratio, influences nucleosynthesis
- Extract S factor for $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ near Gamow peak
- Benchmark calculations from cluster χ EFT



Other MAGIX physics goals

- Electrons for neutrinos

- Benchmark vector part of neutrino-nucleus interactions with electron scattering
- Sub-50 MeV inelastic cross sections relevant for supernova neutrinos



Other MAGIX physics goals

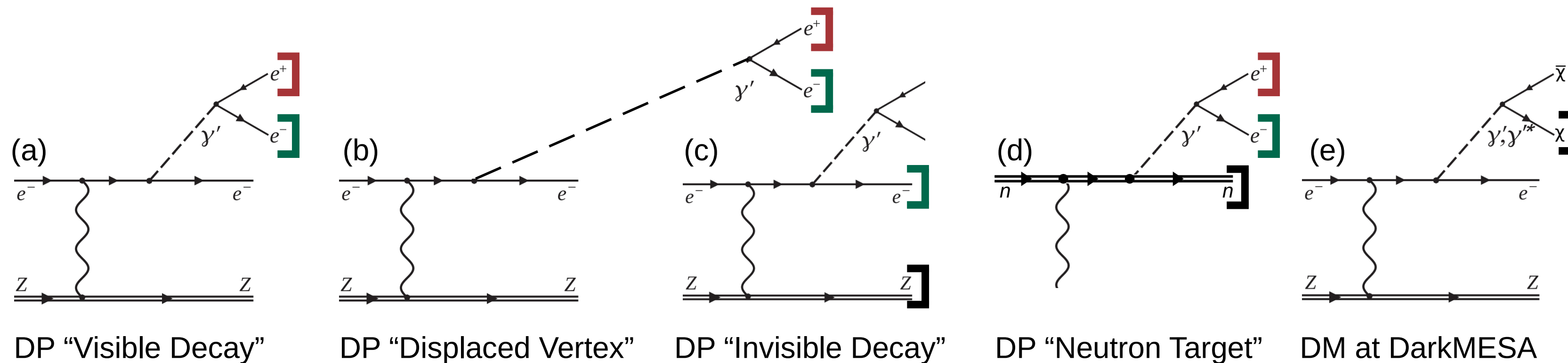
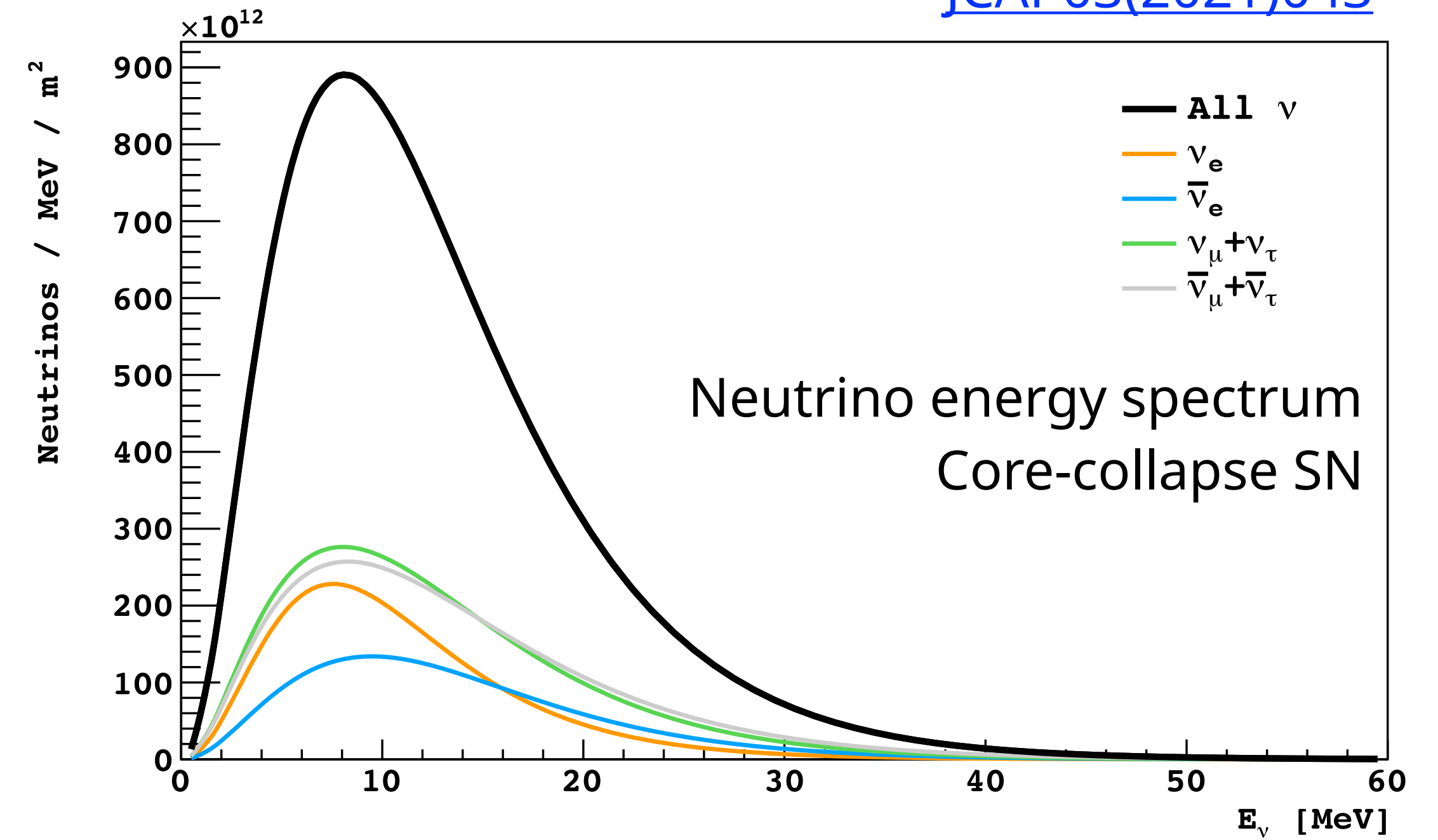
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- Exploit high-resolution spectrometers for coincidence measurements, displaced vertex searches

[JCAP03\(2021\)043](#)



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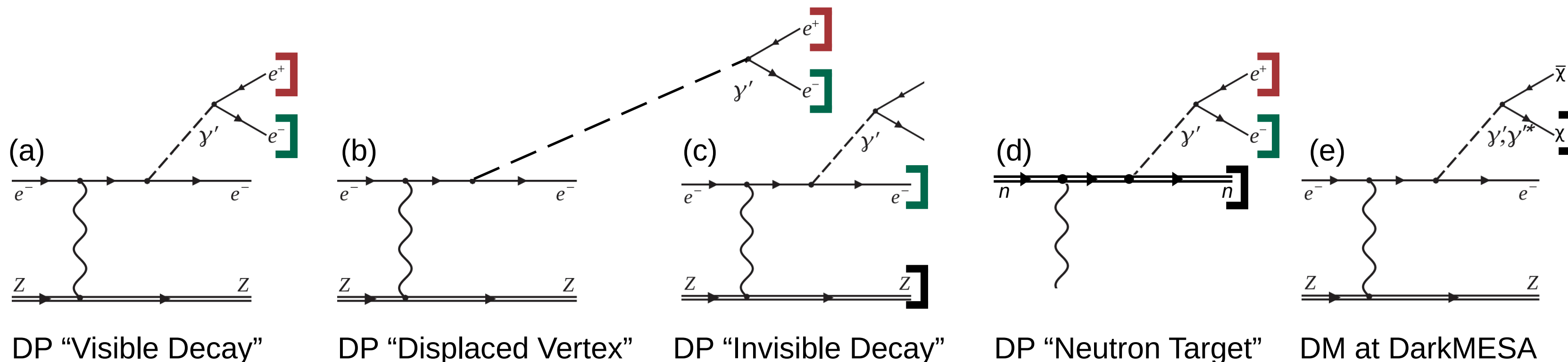
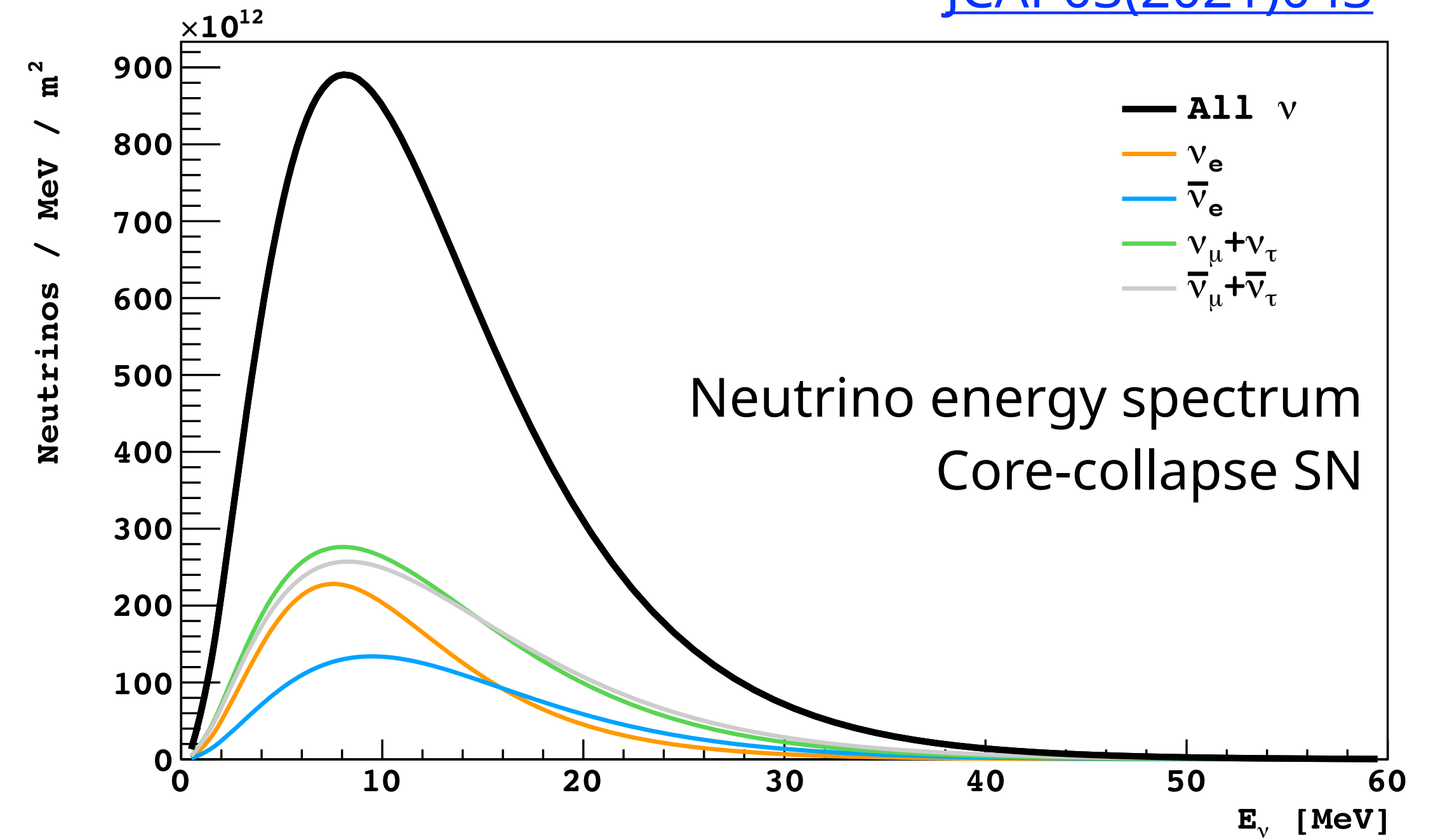
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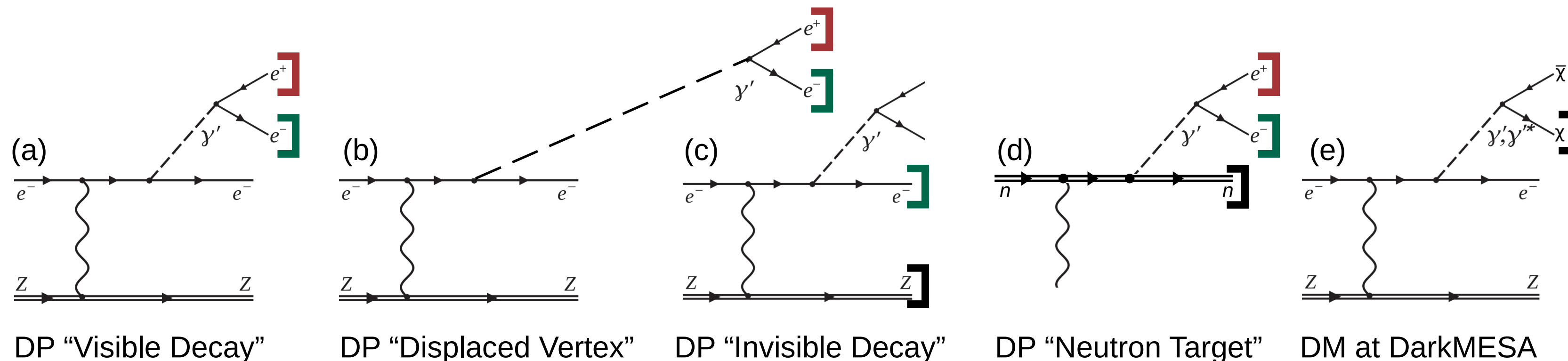
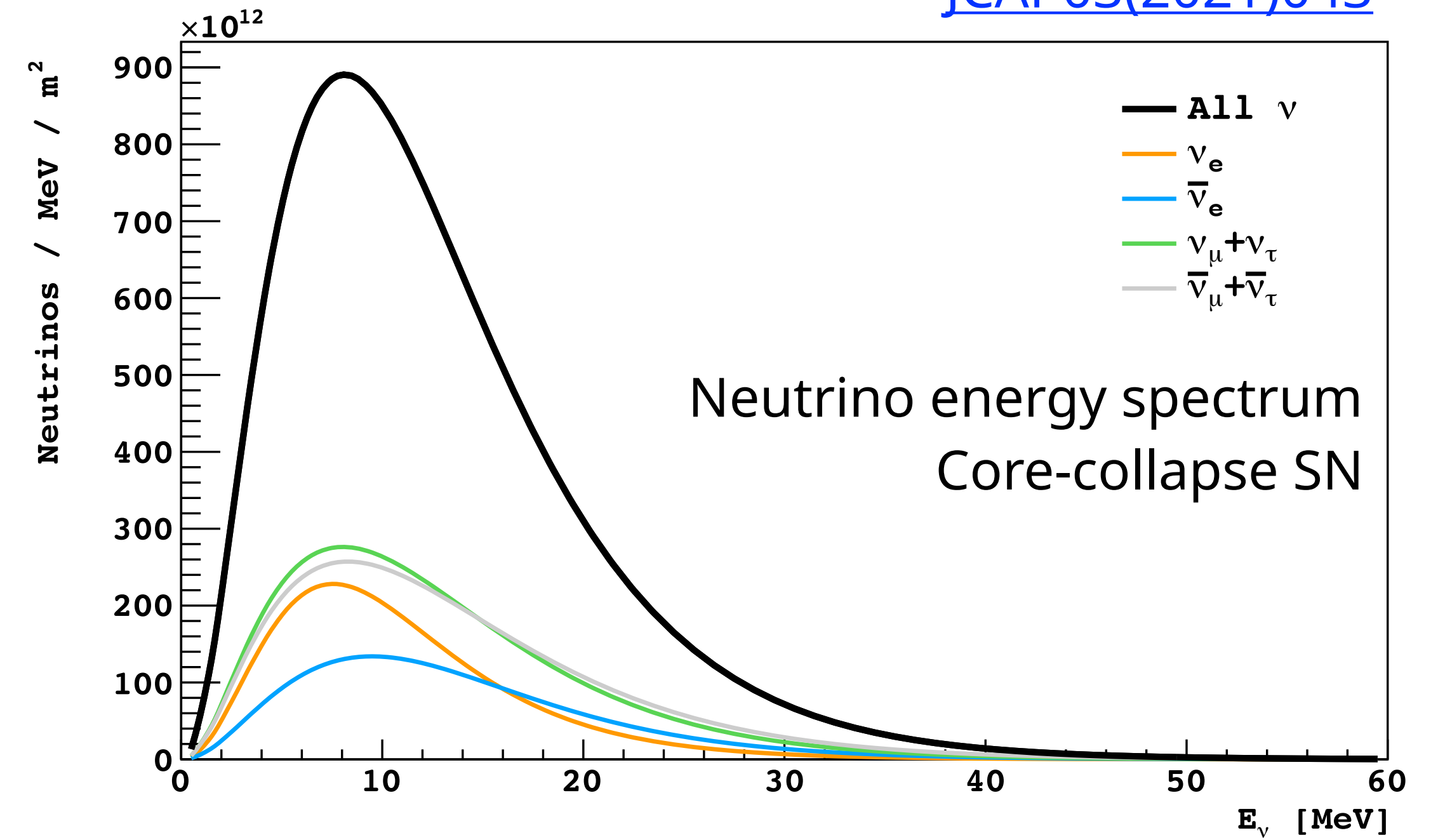
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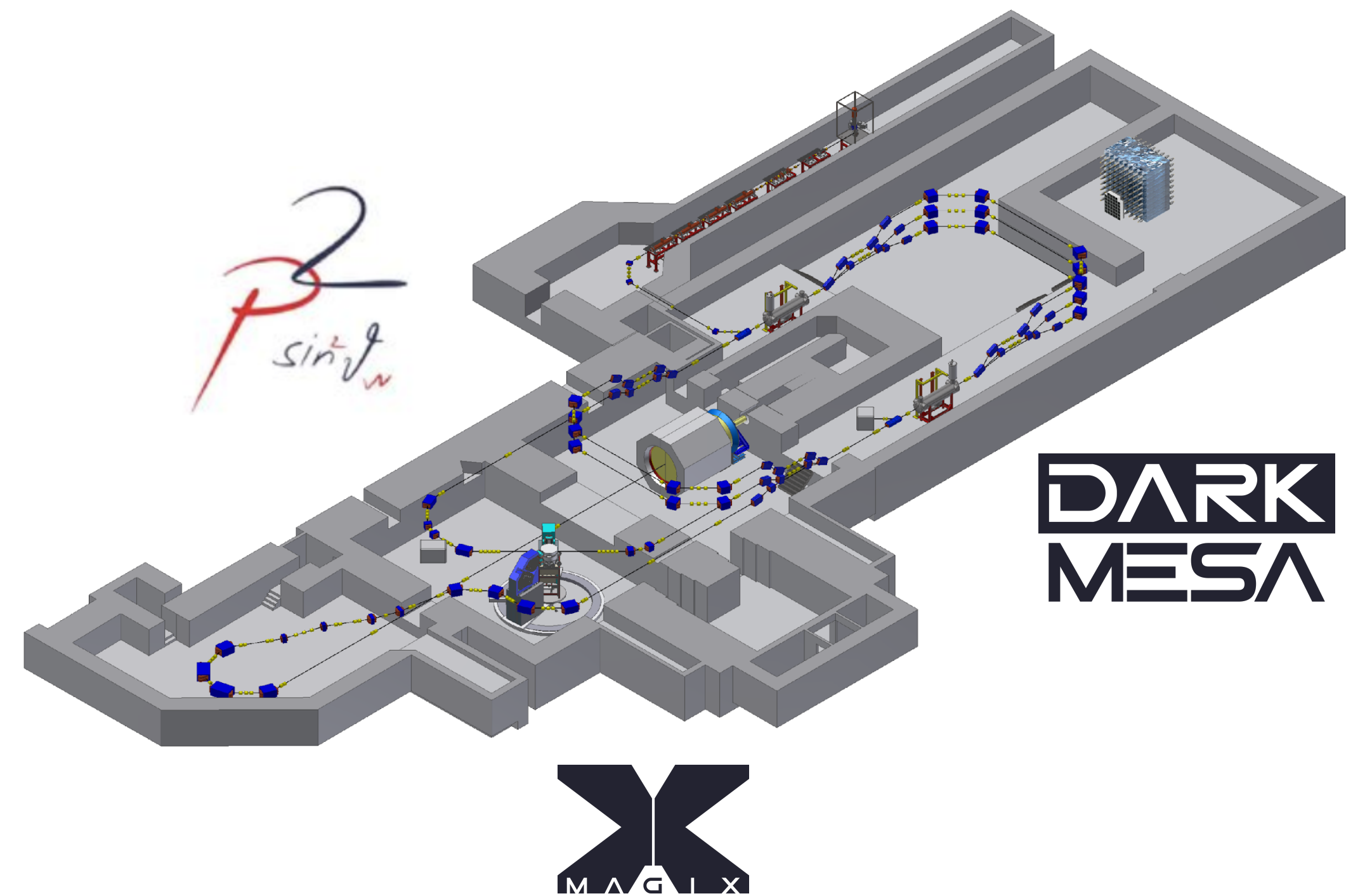
- **Nuclear resonances in neutron-rich nuclei**

[JCAP03\(2021\)043](#)



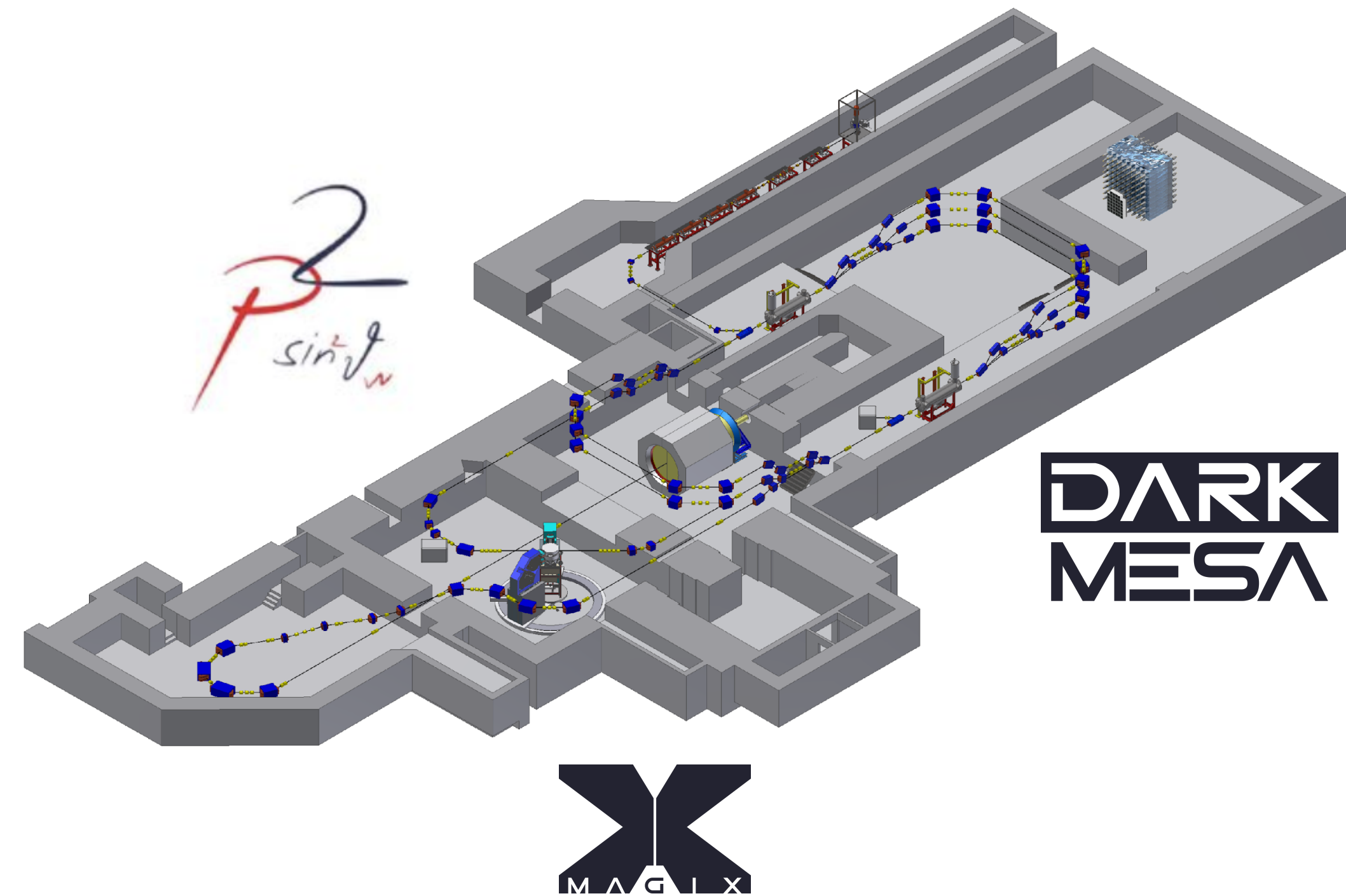
Summary and outlook

- The MESA facility will pioneer *low-energy hadronic measurements* at the *intensity frontier*



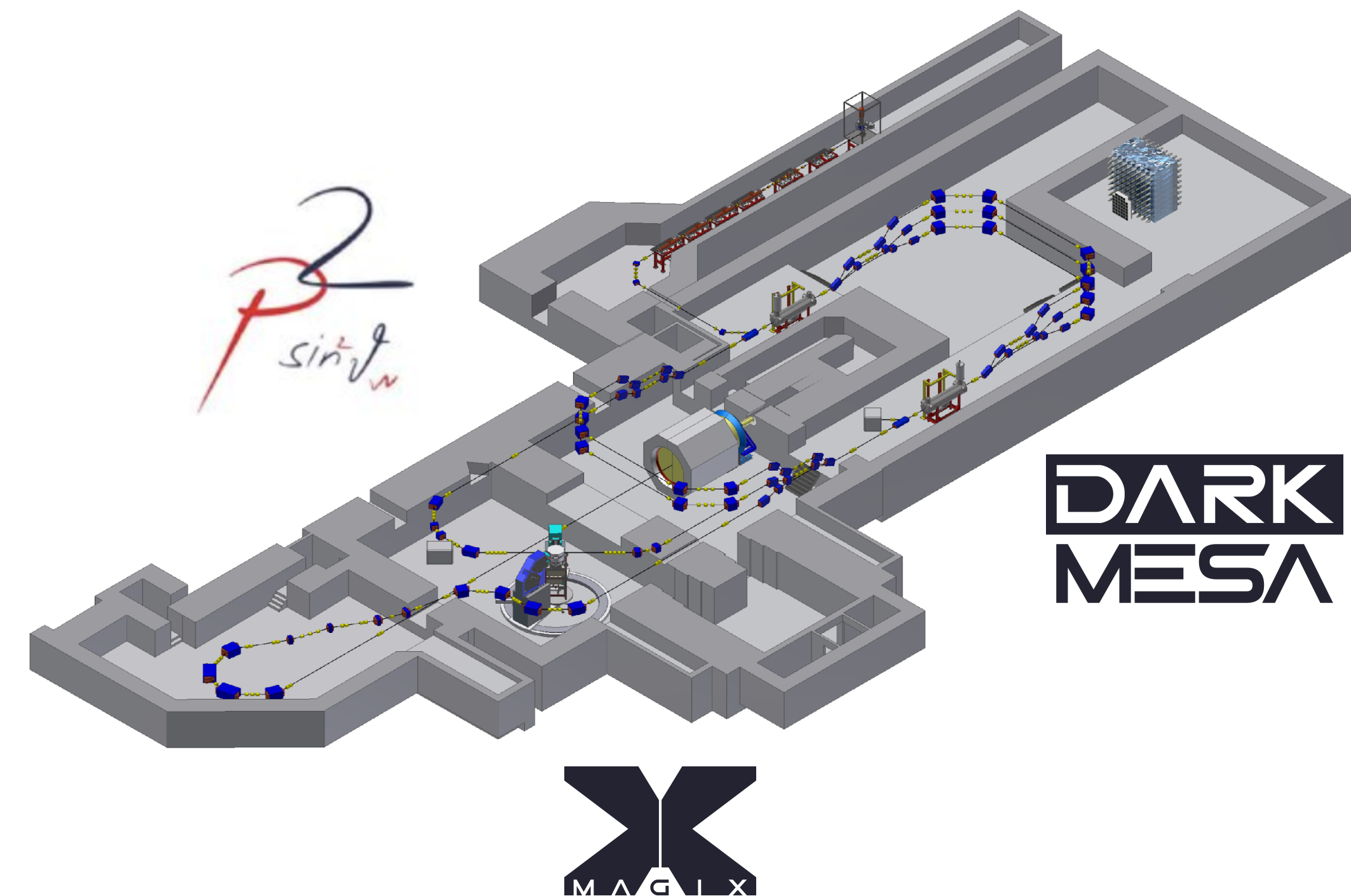
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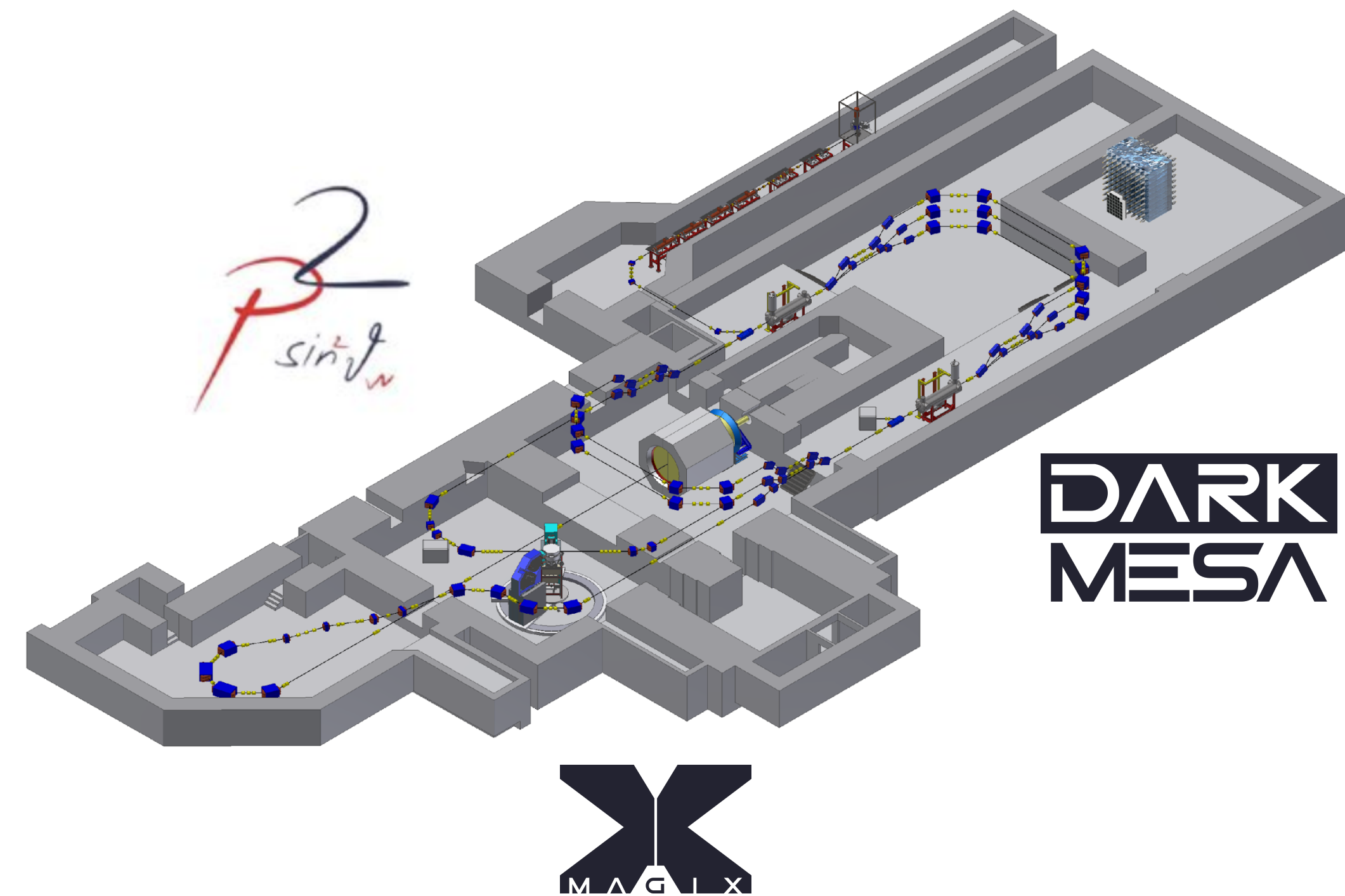
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- Beam on P2 target late 2027
 - Perform first physics measurement of backward asymmetry (sensitive to $G_A^{p,Z}, G_M^s$)

