Proton Form Factor Program at MESA

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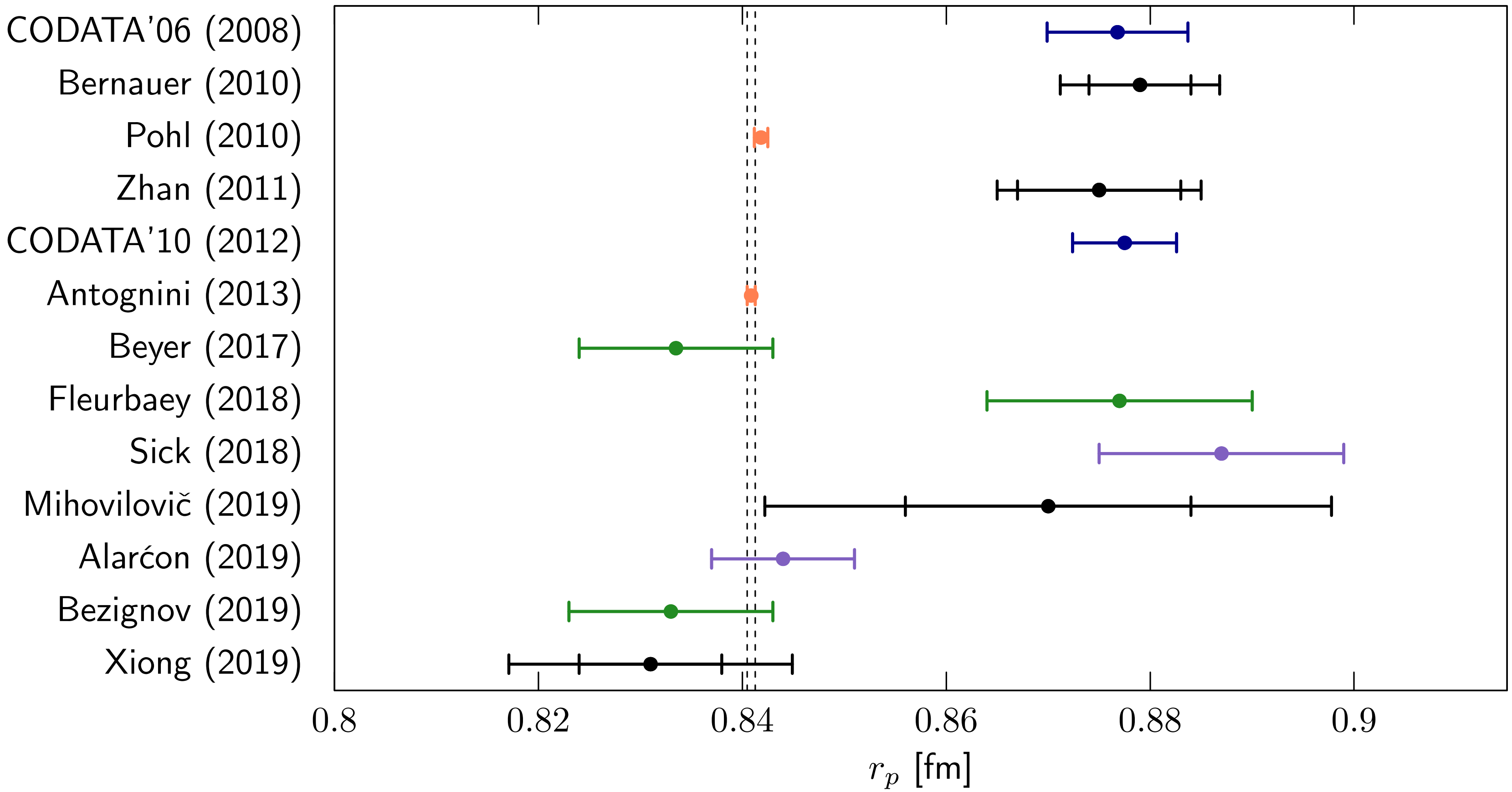
Proton Radius European Network - STRONG 2020 & μASTI
Mainz, June 30^{th}, 2023

- Motivation
  - Current Status
  - How to make progress?
- The MESA Accelerator
  - New low energy machine
  - Energy Recovery Linac
- The MAGIX Setup
  - High-resolution spectrometers
  - Internal gas-jet target
  - Form factor program at MAGIX

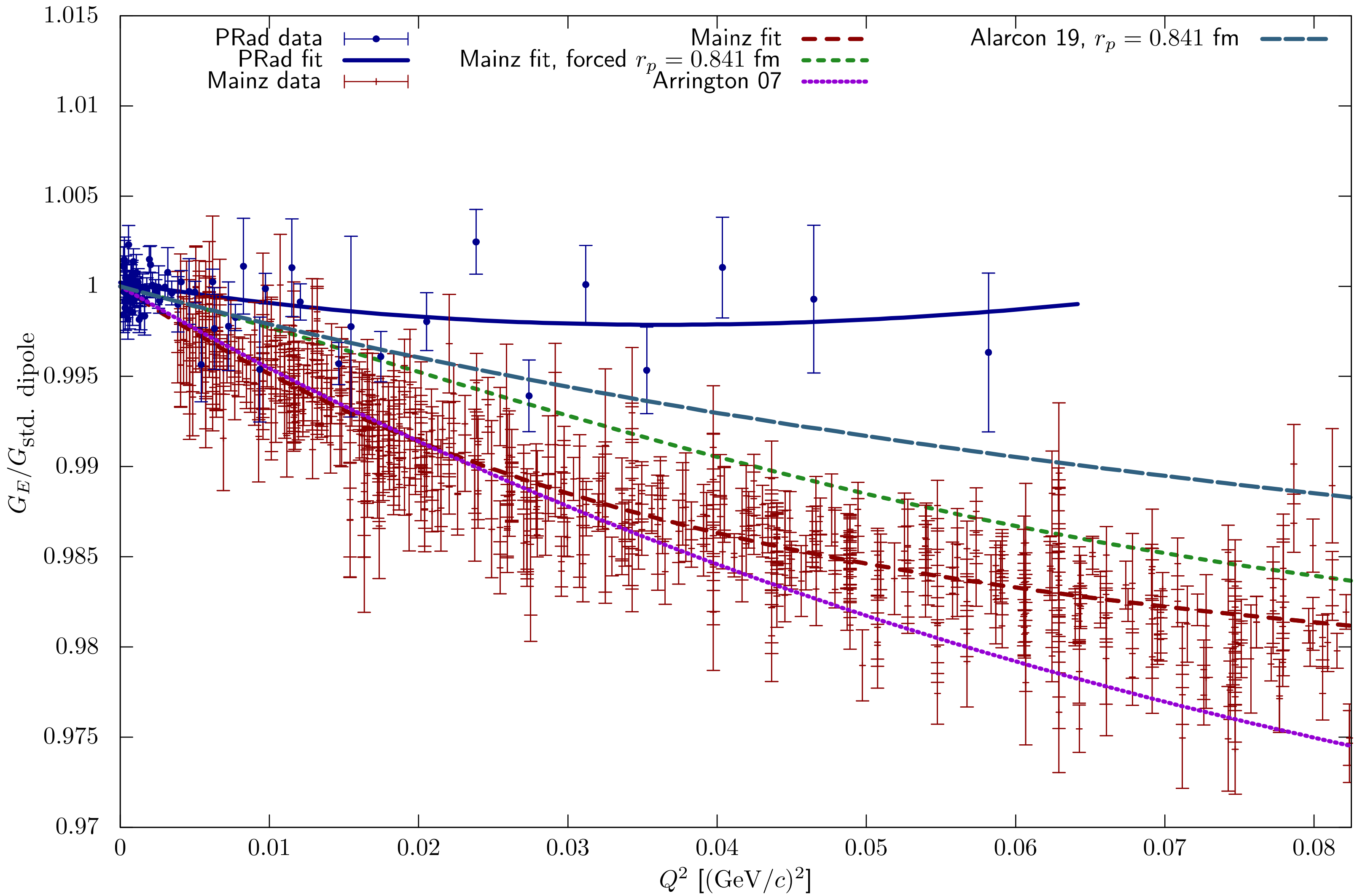
“Proton Radius Puzzle” – How to make progress

Starting 2010... Electron scattering (Bernauer) inconsistent
with spectroscopic results from muonic hydrogen (Pohl)



All electron scattering data now consistent?
Any gain from refitting or interpretation of existing data?
How well do we know the ***form factors*** of the proton?

Data still not consistent...



- Two high quality data sets in electron scattering
- Clearly not consistent
- Older data sets only useful to arbitrarily fine-tune your fits (Rad. corrections, normalization *etc.*)

How to improve the situation

Focus: What might be the problem?

- Radiative corrections
  - Missing Q^2 dependent terms?
- Background
  - Modelling of Q^2 dependent background?
- Efficiency
  - Is there a Q^2 dependent efficiency?
- Normalization
- Resolution/channel identification $\rightarrow$ control of cuts and background

All are definitely different for the two data sets!

GOAL: Reduce systematic error of ALL of these effects

Where to measure

Radius is *defined* at $Q^2 = 0$ but it's impossible to measure *slope* with only 1 point

Small Q^2 required for *normalization*: $Q^2 < 10^{-3}\,\mathrm{GeV}^2$

$$Q^2 = 4EE'\sin^2\frac{\theta}{2} \quad \Rightarrow \quad \text{Should we reduce } \theta \text{ or } E, E'?$$

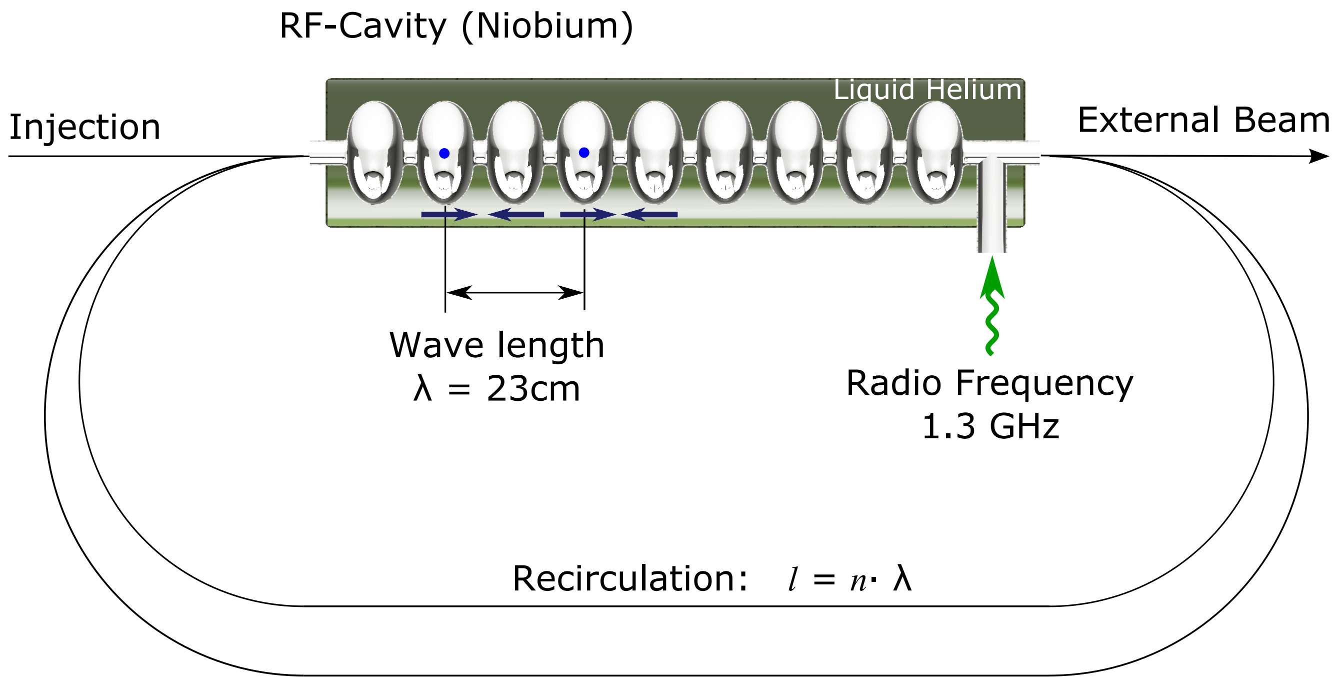
- Cross section $\sim \frac{1}{Q^4} \Rightarrow$ high resolution for Q^2, i.e. E,E',θ necessary
- Relative error of θ is significant reduced at large θ
- E, E' in principle from elastic kinematics,
  but high resolution for cut control etc. necessary
- Physics background is reduced at large θ (Bremsstrahlung, Møller, etc.)

Maximum: at least $Q^2 > 0.02\,\mathrm{GeV}^2$ for lever arm and curvature

The leverage defines the leading error of the radius!

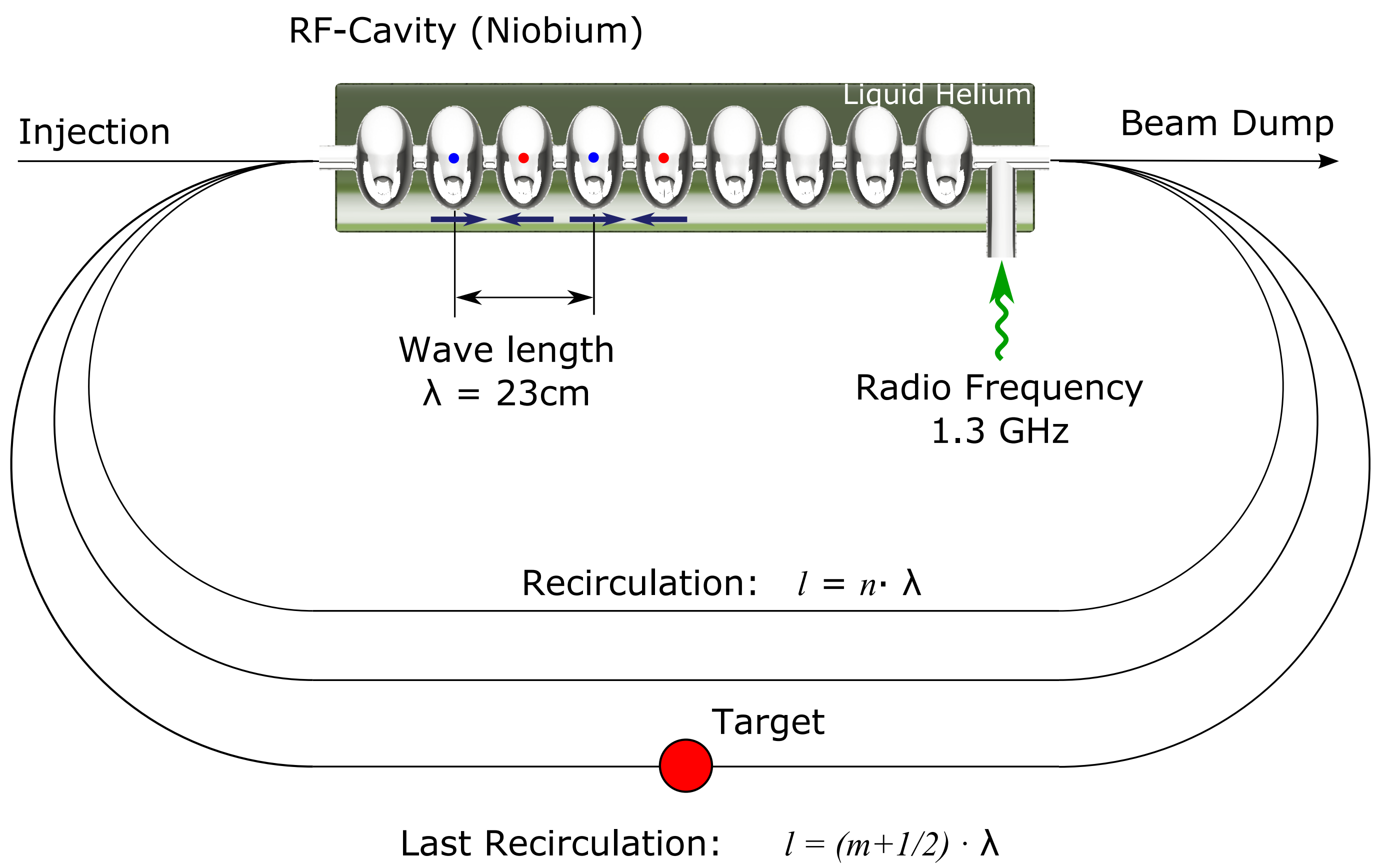
Use a low energy accelerator of a few MeV up to 100 MeV $\Rightarrow$ MESA

Energy Recovery Linac - Idea



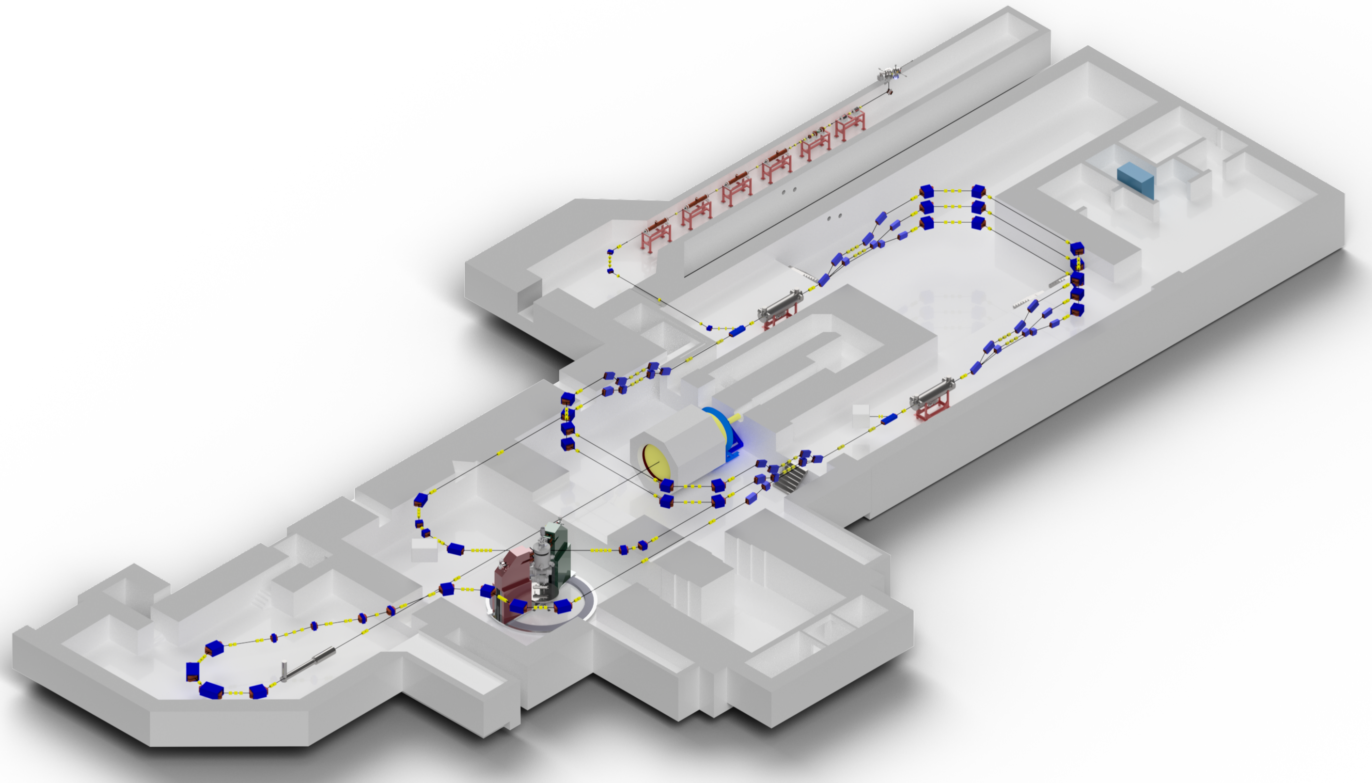
- Recirculating Linear Accelerator $\rightarrow$ increase beam *energy*

Energy Recovery Linac - Idea



- Recirculating Linear Accelerator $\rightarrow$ increase beam *energy*
- Last return path: $l = (m + \frac{1}{2})\lambda \rightarrow$ Phase shift
- Energy feed back to cavities $\rightarrow$ increase beam *current*

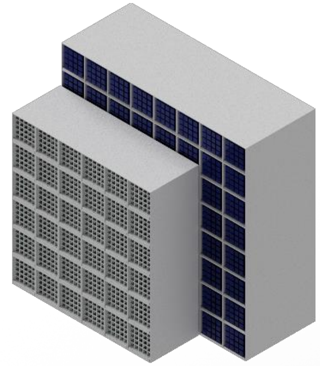
MESA - Mainz Energy Recovery Superconducing Acclerator



- Super-conducting, recirculating LINAC
- Energy of up to 155 MeV
- Operation for EXTERNAL target, 1 mA, polarized beam
- Operation in ENERGY RECOVERY MODE
  - Energy of up to 105 MeV
  - High beam current (up to 10 mA)
  - Large fraction of the beam can be used for an INTERNAL target

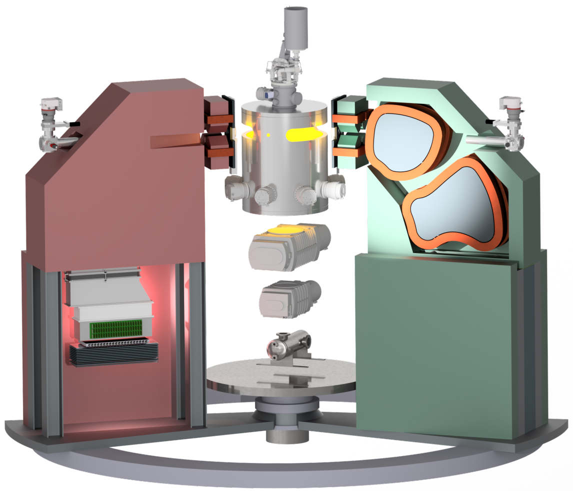
DarkMESA

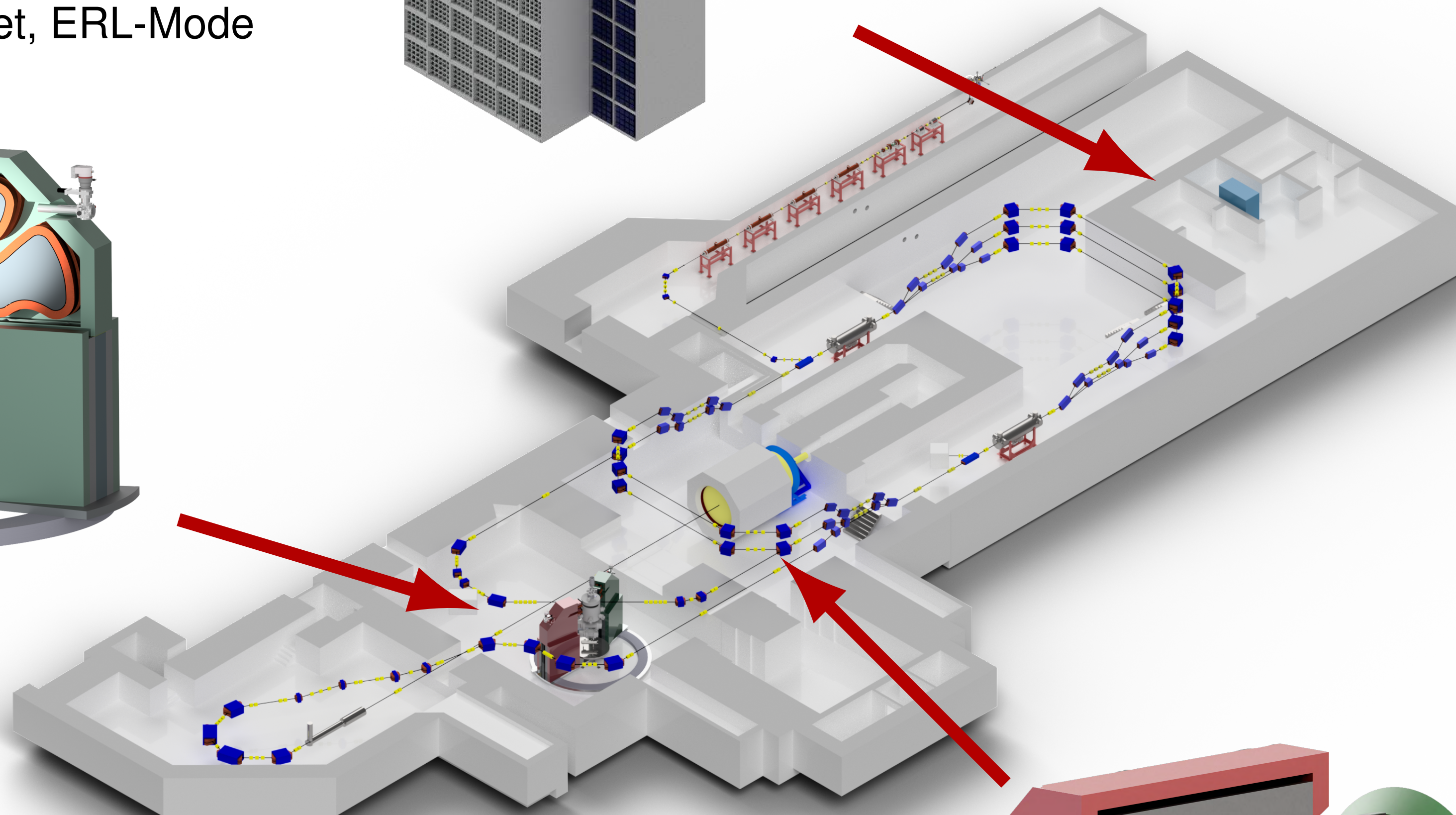
- Search for Dark Sector Particles

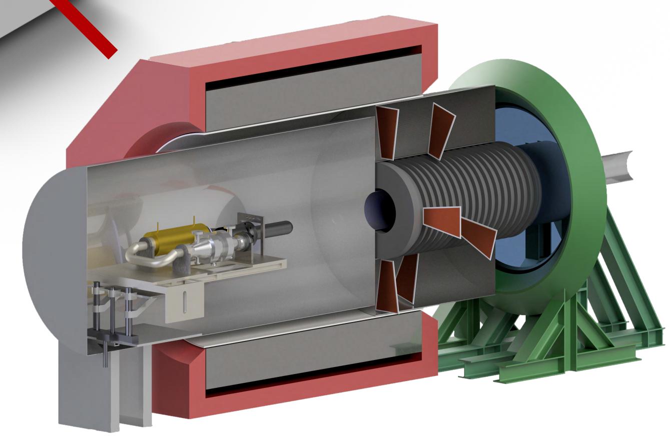


MAGIX

- High Resolution Spectrometers
- Internal Gas Target, ERL-Mode







P2

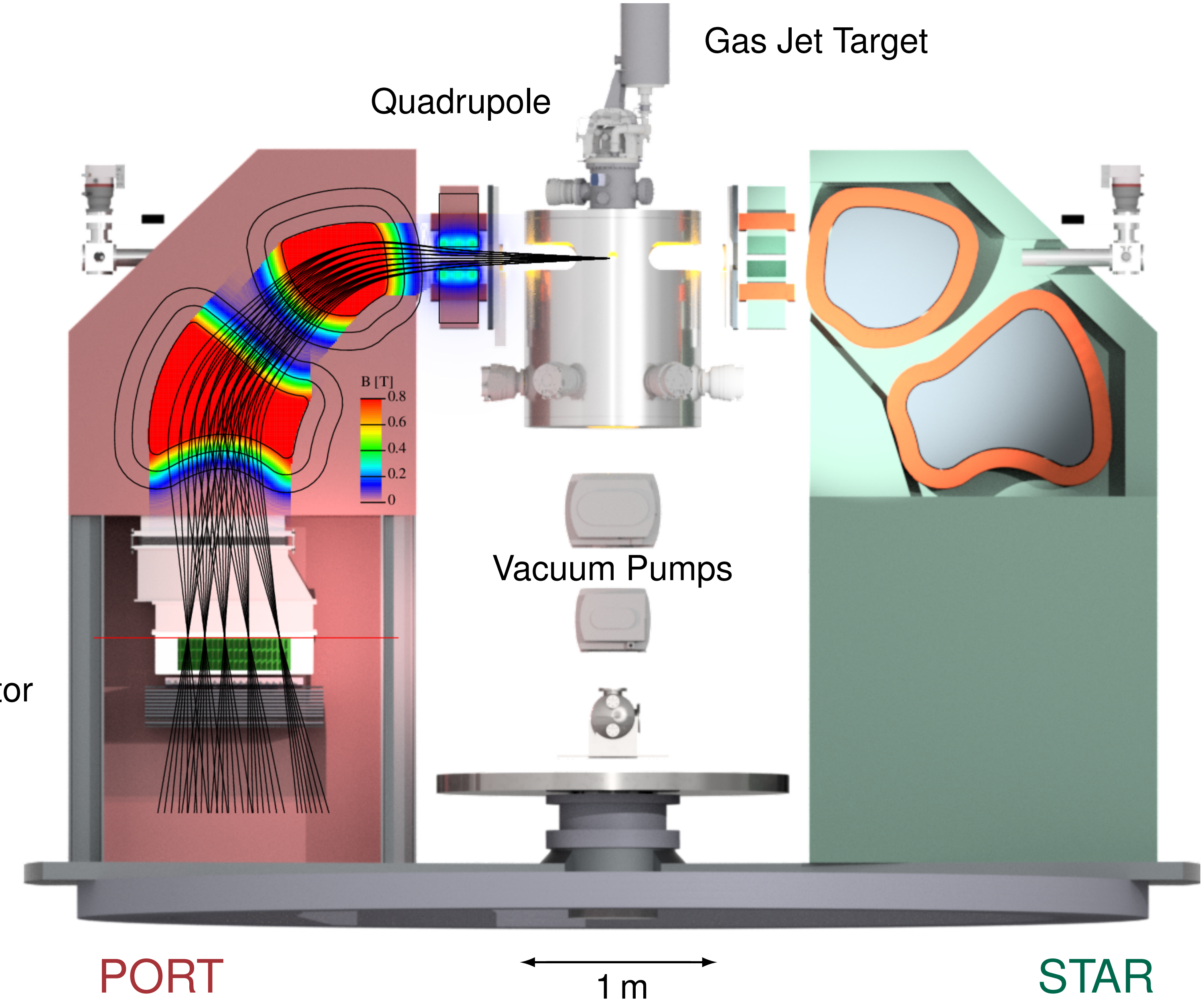
- Parity-Violating $\vec{e}$-scattering
- Extracted Beam (155 MeV, $150\,\mu$A)

MAGIX - MAinz Gas Injection Target EXperiment

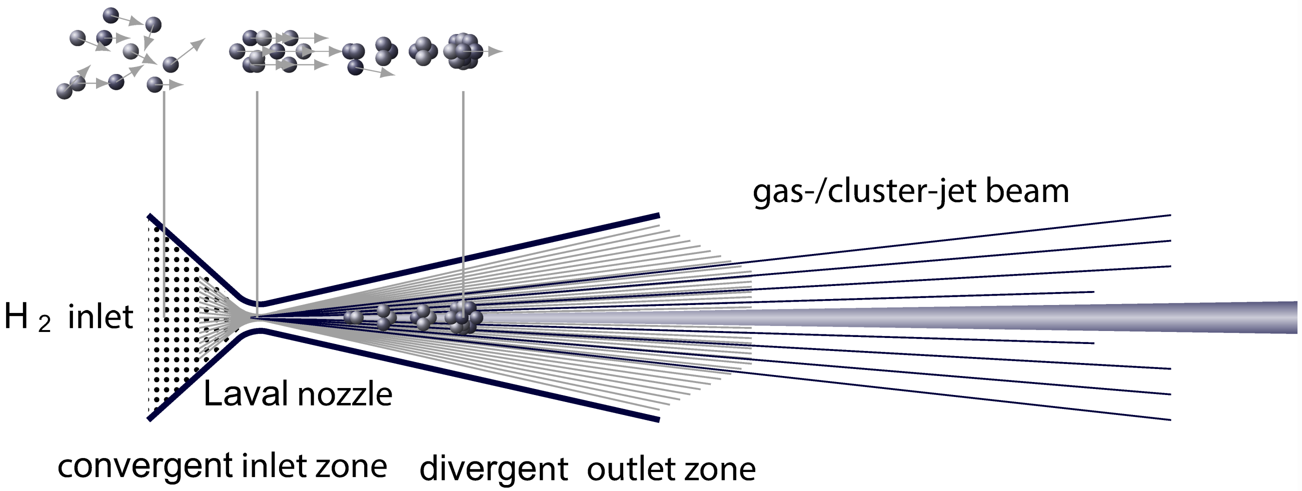
2× Dipole
90° Bending

$$\frac{\delta p}{p} < 10^{-4}$$

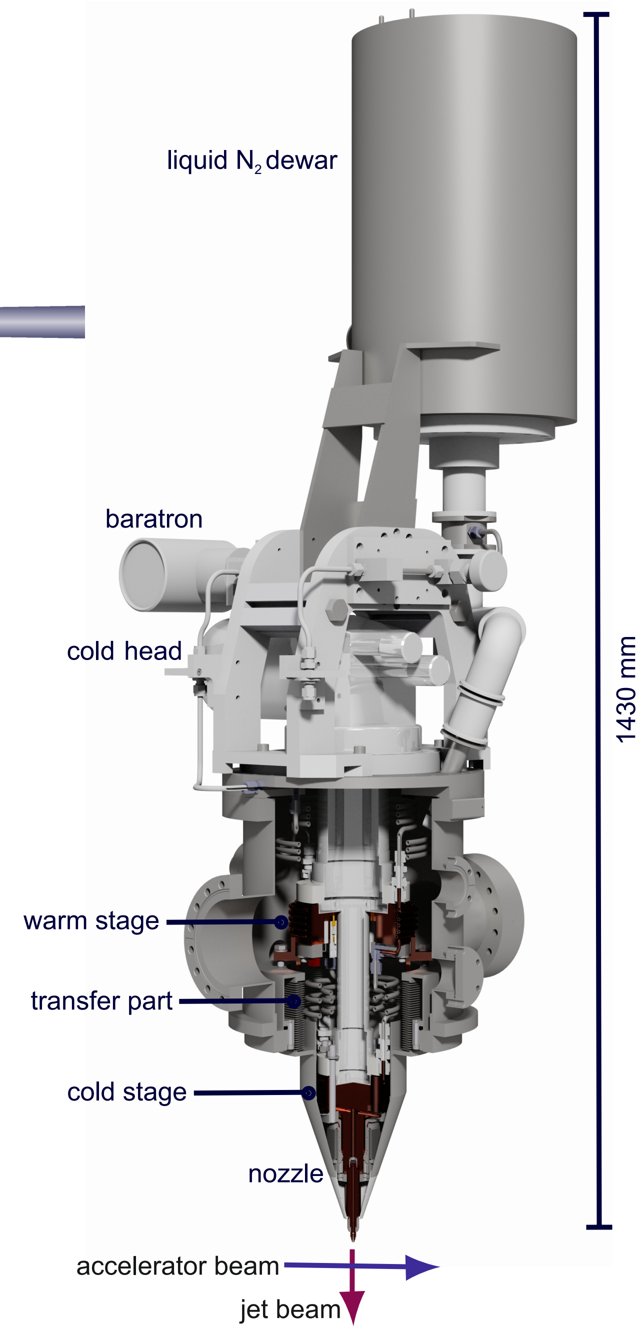
GEM based TPC
Scintillator Detector
Muon Veto



Supersonic Gas-Jet Target

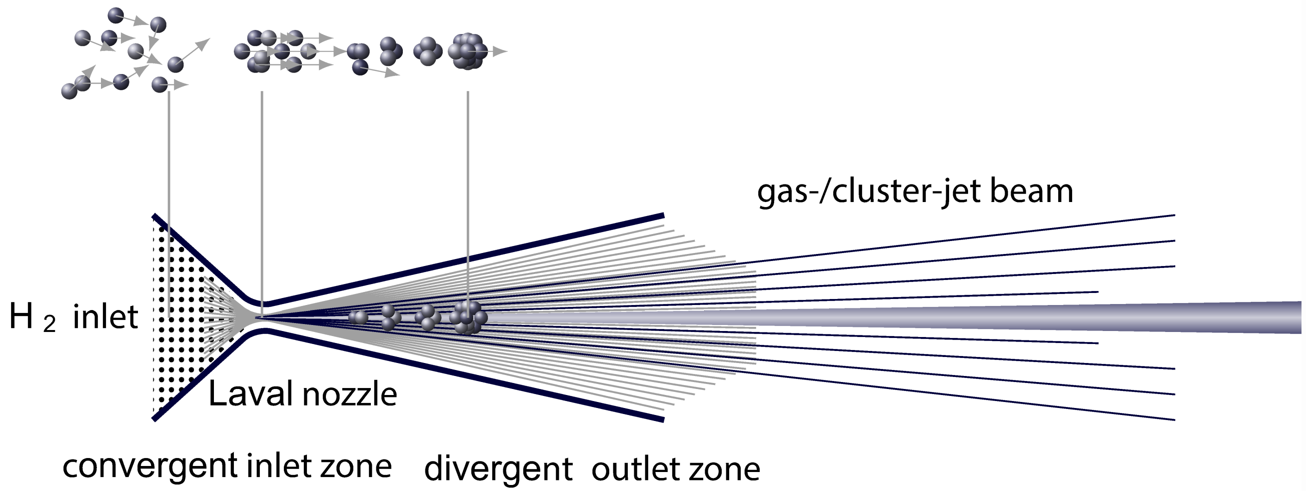


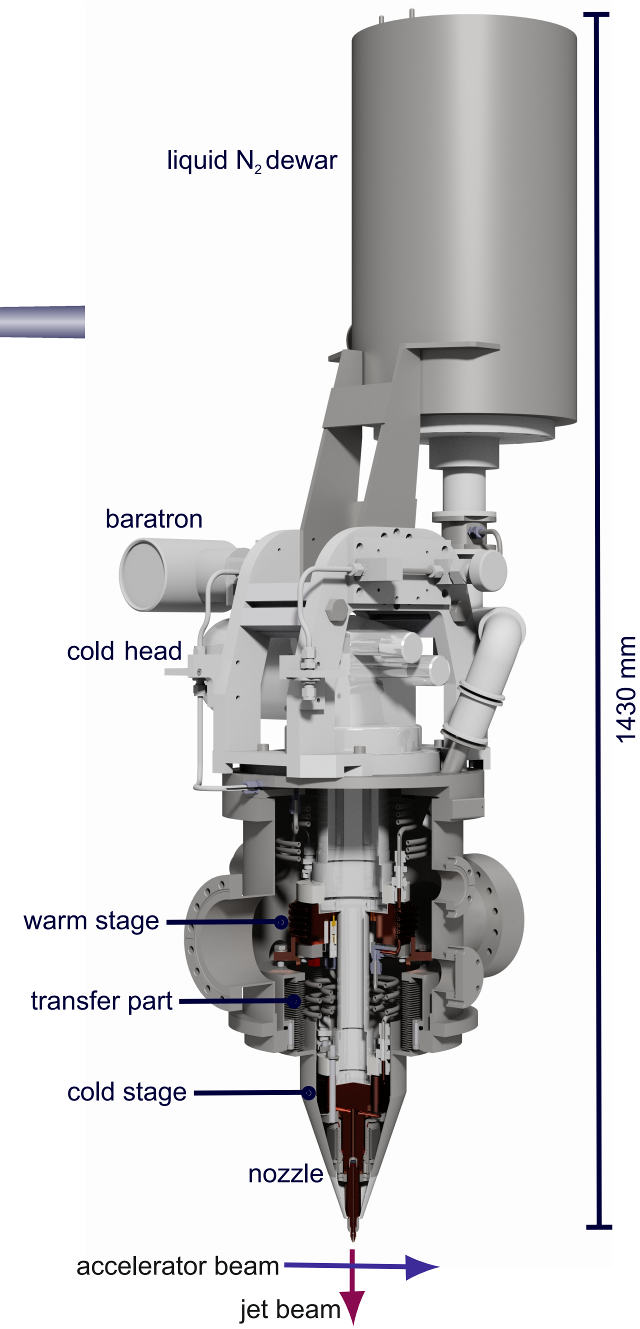
- Laval Nozzle
- Supersonic Gas-Jet
- Temperature drops below freezing point
- Massive Clusters ($\approx$ 10000 atoms)
- 10^{18} Particles/cm^2
- Windowless, thin, and pointlike target



AG A. Khoukaz (Univ. Münster)
S. Grieser *et al.*, NIM A 906 (2018) 120

Supersonic Gas-Jet Target





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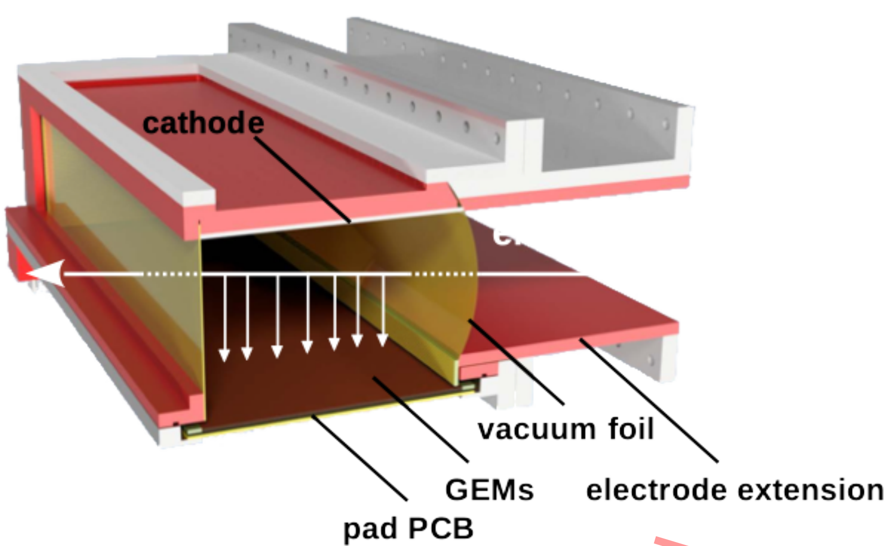
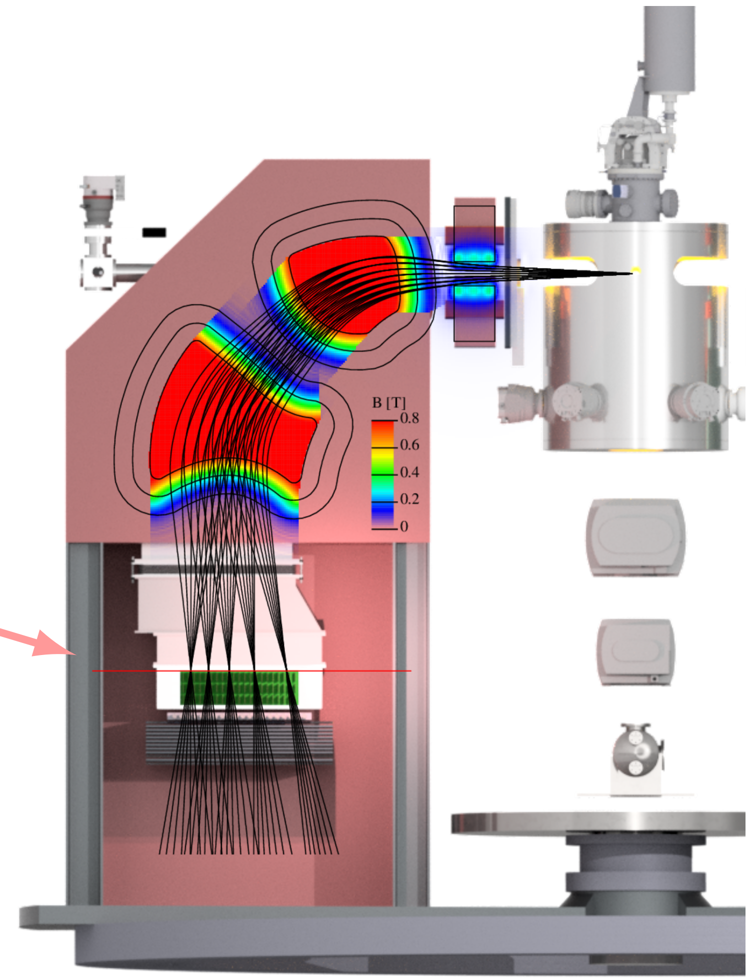
Minimal Material Budget

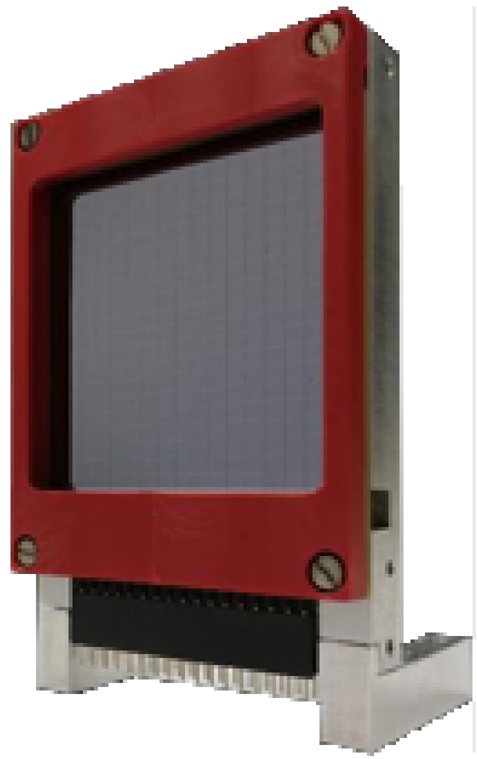




Focal plane tracking detector:

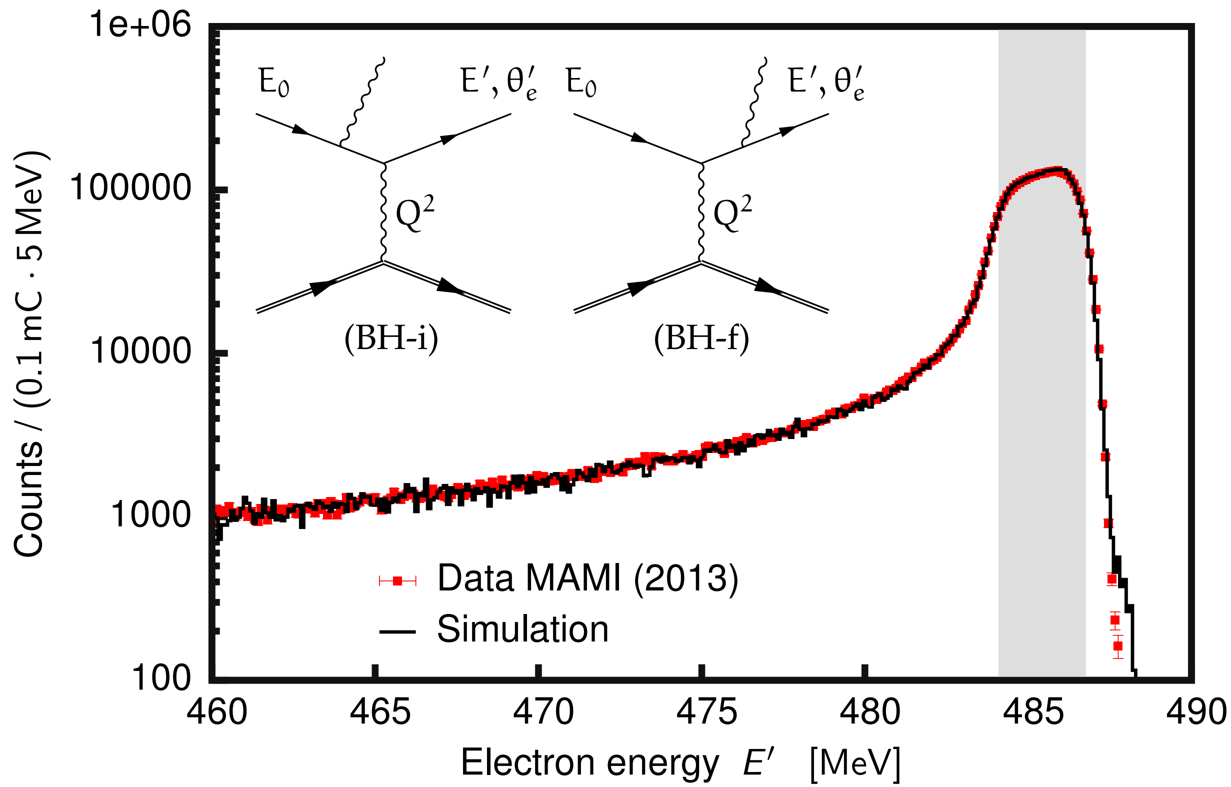
- Time projection chamber
- GEM readout plane
- Open field cage
- Vacuum down to focal plane
- Total material budget: 75 μm Kapton (0.26% X_0)

Silicon Strip Detectors



- Recoil detector for low energetic nuclei and hadrons
- Silicon strip detectors 5 cm$\times$5 cm
- NO material beween reaction vertex and detection volume
- Horizontal resolution by stripes, vertical by two-sided readout
- Cooled, stack with scintillator
- Radiation: will die after a few weeks, but still affordable...
- Recoil-Proton detection for systematics (radiative corrections, efficiency, acceptance,...)

Radiative Corrections: Extensive Test by ISR Experiment

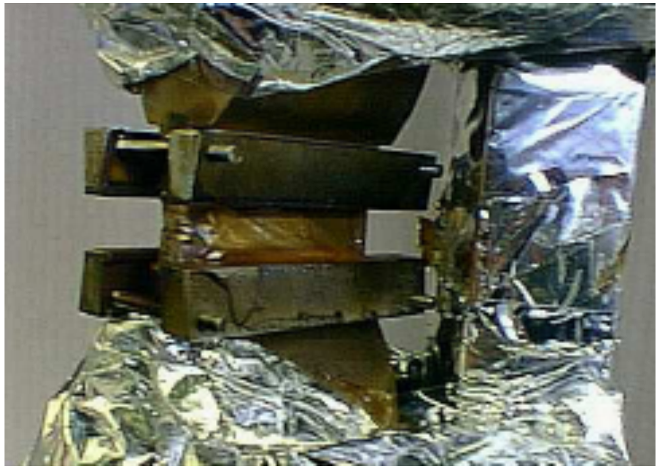


Standards for modern experiments:

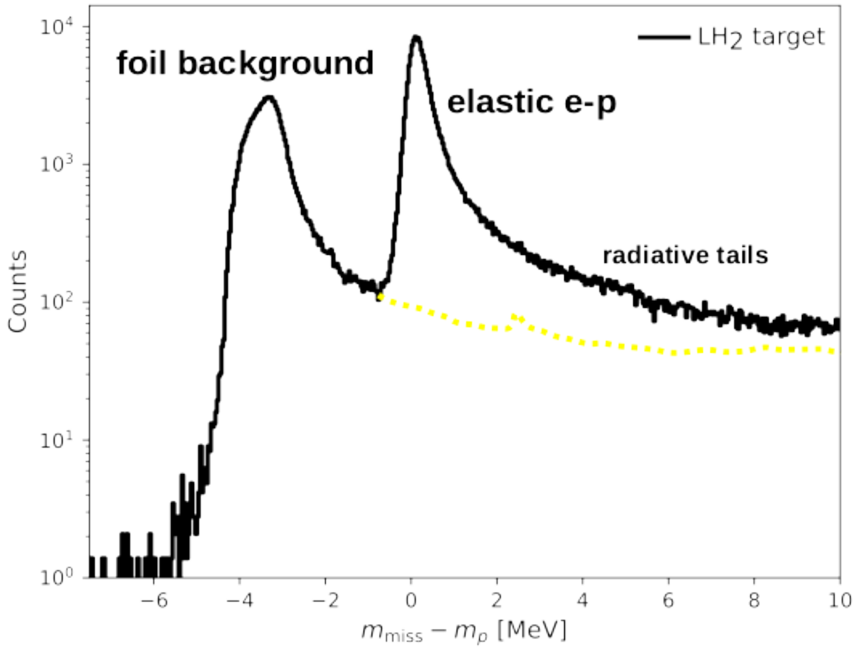
- No peaking approximation, full electron mass, etc.
- Higher order corrections, NNLO
- Correction on an event by event basis by generator
- Experimental verification over required Q^2 range
- Improvement: Reduce contribution of external Bremsstrahlung

M. Mihovilovič, EPJ. A 57, 107 (2021)

Reduction of Background - A1-Target

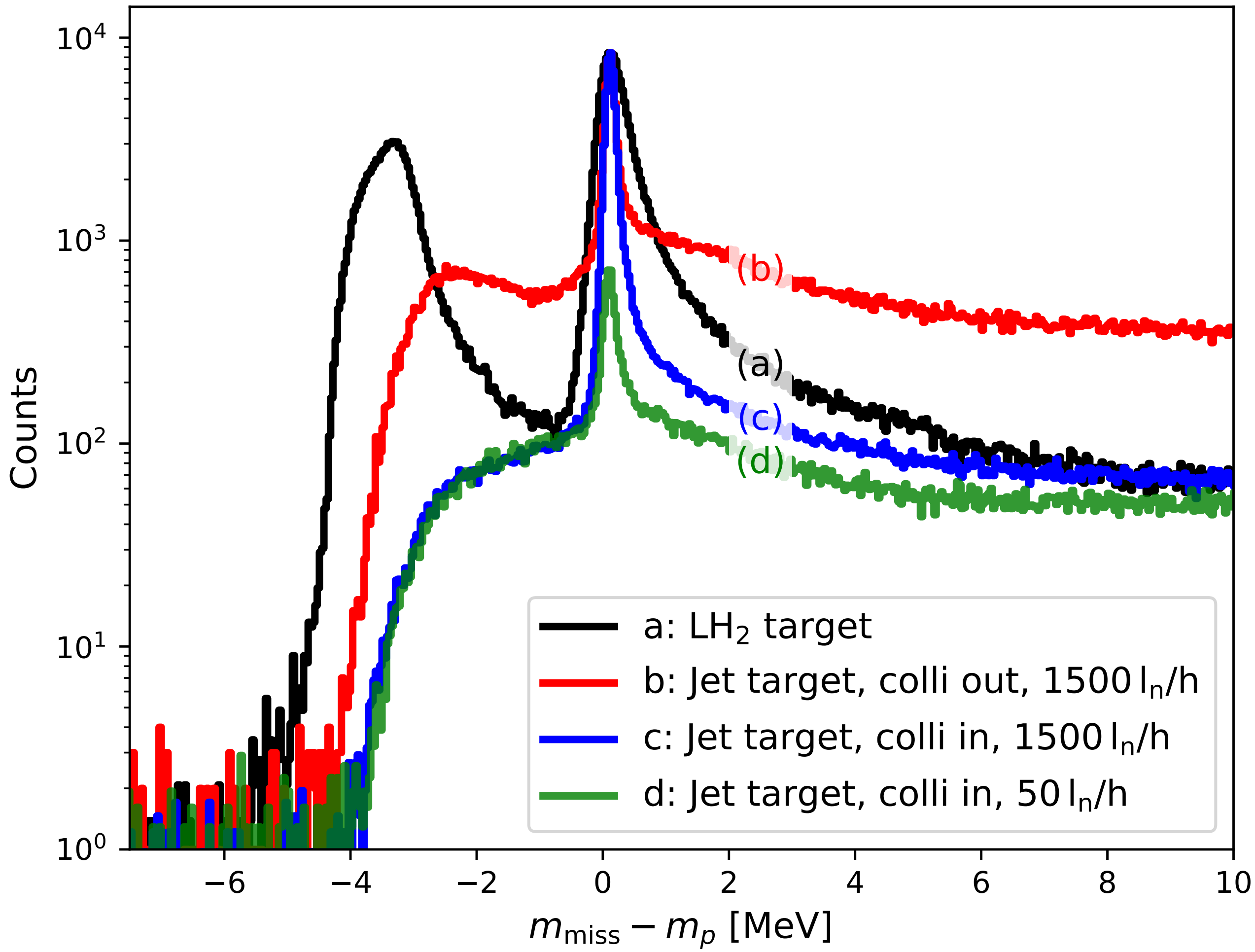


Element	Content (%)
Cobalt, Co	41-44
Chromium, Cr	19-21
Nickel, Ni	12-14
Tungsten, W	2.3-3.3
Molybdenum, Mo	2-2.8
Manganese, Mn	1.35-1.8
Carbon, C	0.17-0.23
Beryllium, Be	0.02-0.06
Iron, Fe	Balance



- Energy loss
- Multiple scattering
- Empty cell measurements
- Simulation with FF-Models
- ...

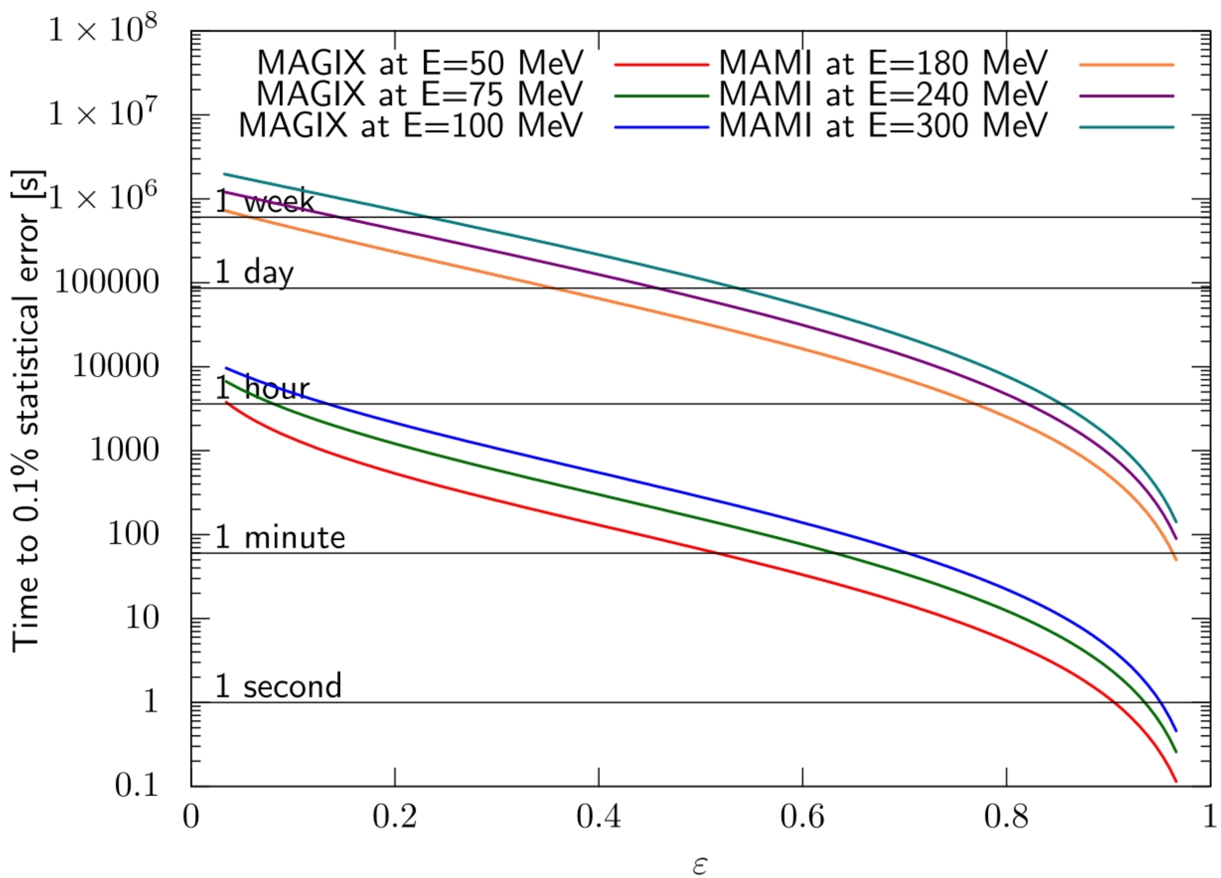
Reduction of Background - Jet Target at A1



- No external radiative corrections!
- Significant reduced background (will be even better at MAGIX)!
- Increased missing mass resolution

B.S. Schlimme et al., NIMA 1013 (2021) 165668

Statistical Error



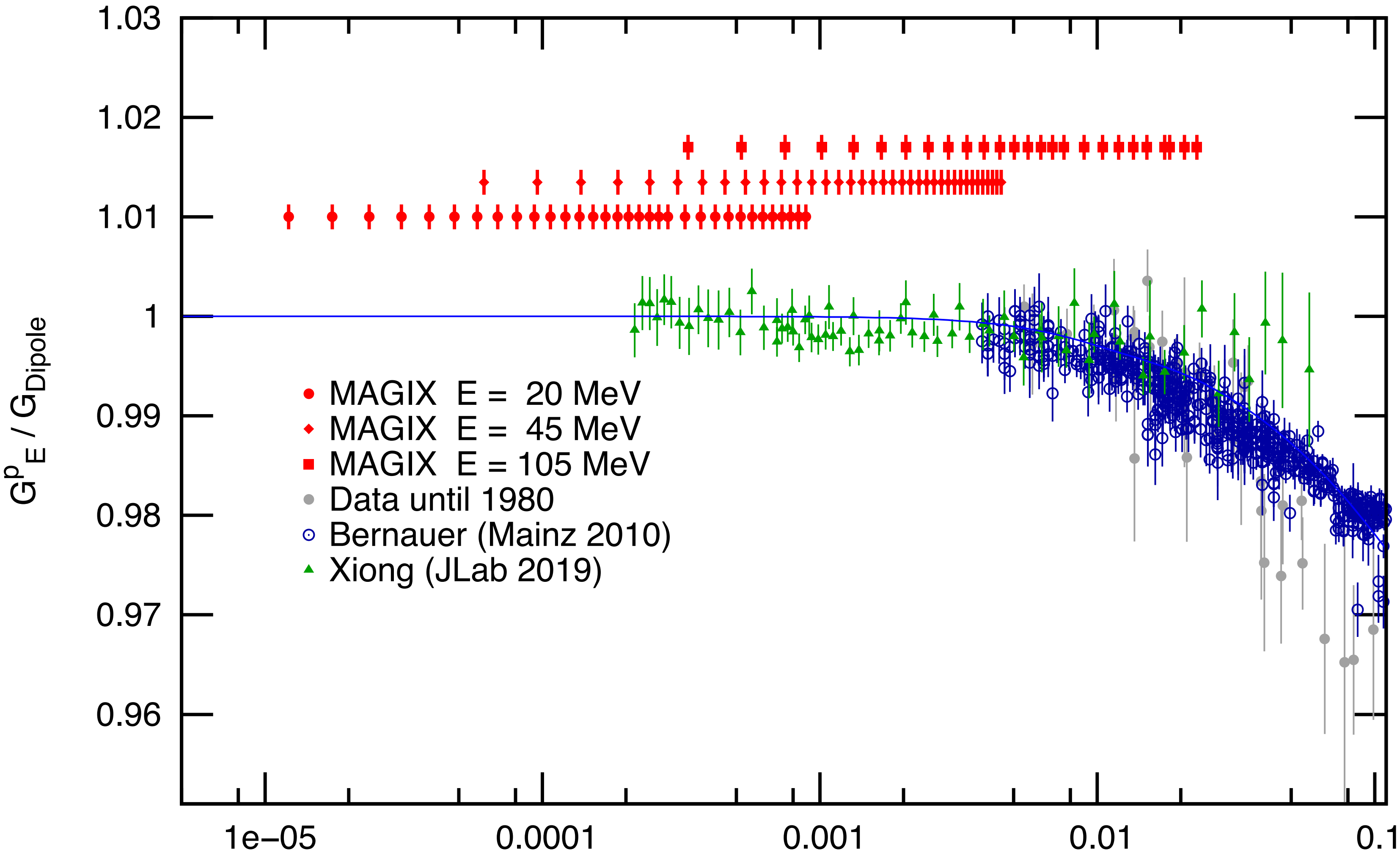
- Run time is negligible!
- Statistical error $\ll$ Systematic error
- Utilize the time for *kinematical overlap* $\rightarrow$ vary spectrometer angle in tiny steps
  $\rightarrow$ **direct measurement of efficiency**

Improvements to existing measurements

All objectives improved by $\approx$ one order of magnitude

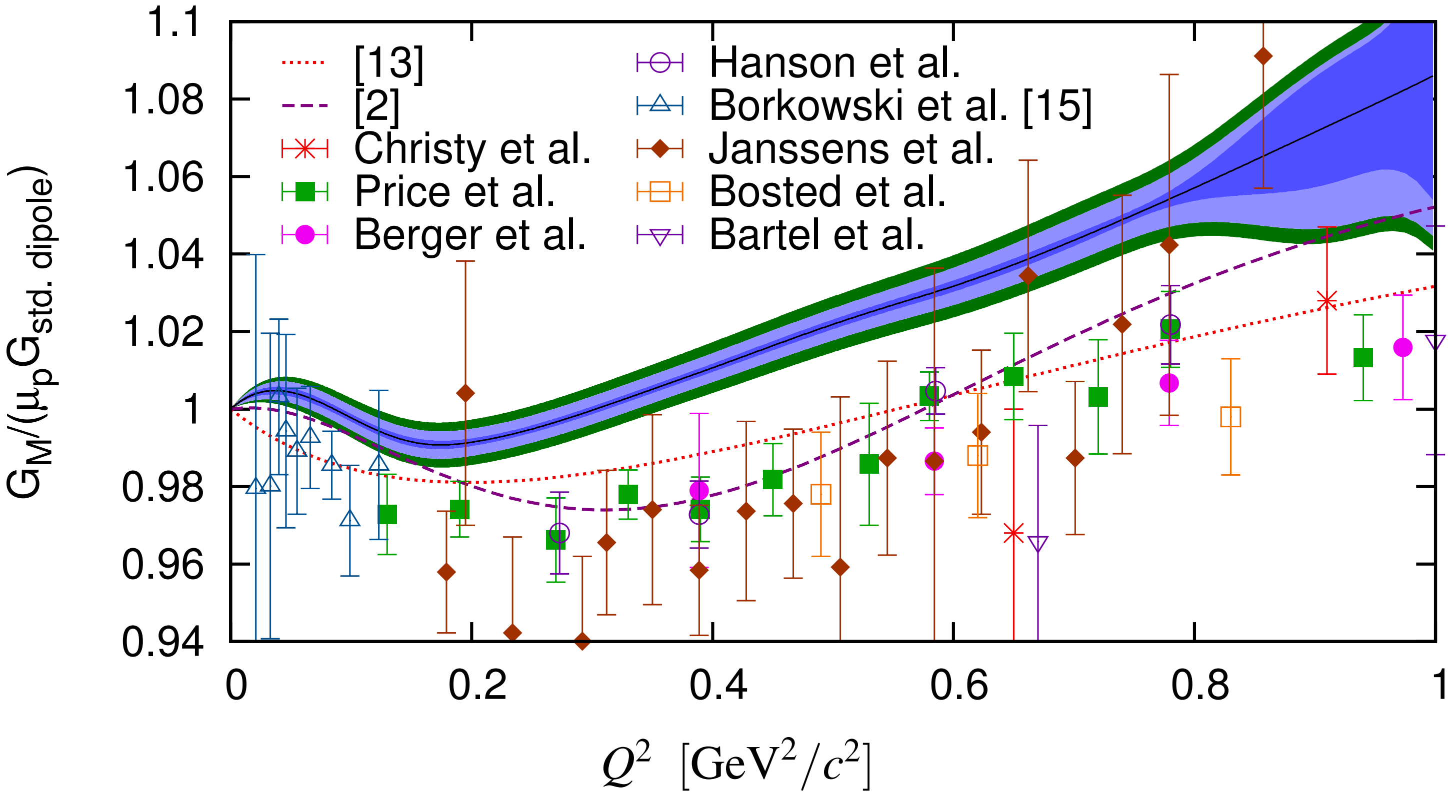
- Radiative corrections ✓
  - No external corrections
  - Small at low Q^2 anyway
  - Clean experimental confirmation of calculations/simulation by ISR experiment
- Background ✓
  - Reduced by at least one order of magnitude
- Efficiency ✓
  - Vaste overlap of measurements
  - Switch between two identical spectrometers
- Normalization ✓
  - Spectrometer as luminosity monitor
  - State-of-the-Art, dead-time free readout
- Resolution/channel identification $\rightarrow$ control of cuts ✓
  - Improved missing mass resolution
  - Reduced missing mass dependent Background

Expected Error Bars



- Coverage up to $Q^2 = 0.03 GeV^2/c^2$
- Dominated by systematic error
- Windowless target, high resolution, high efficiency, negligible background, . . .

Magnetic Radius

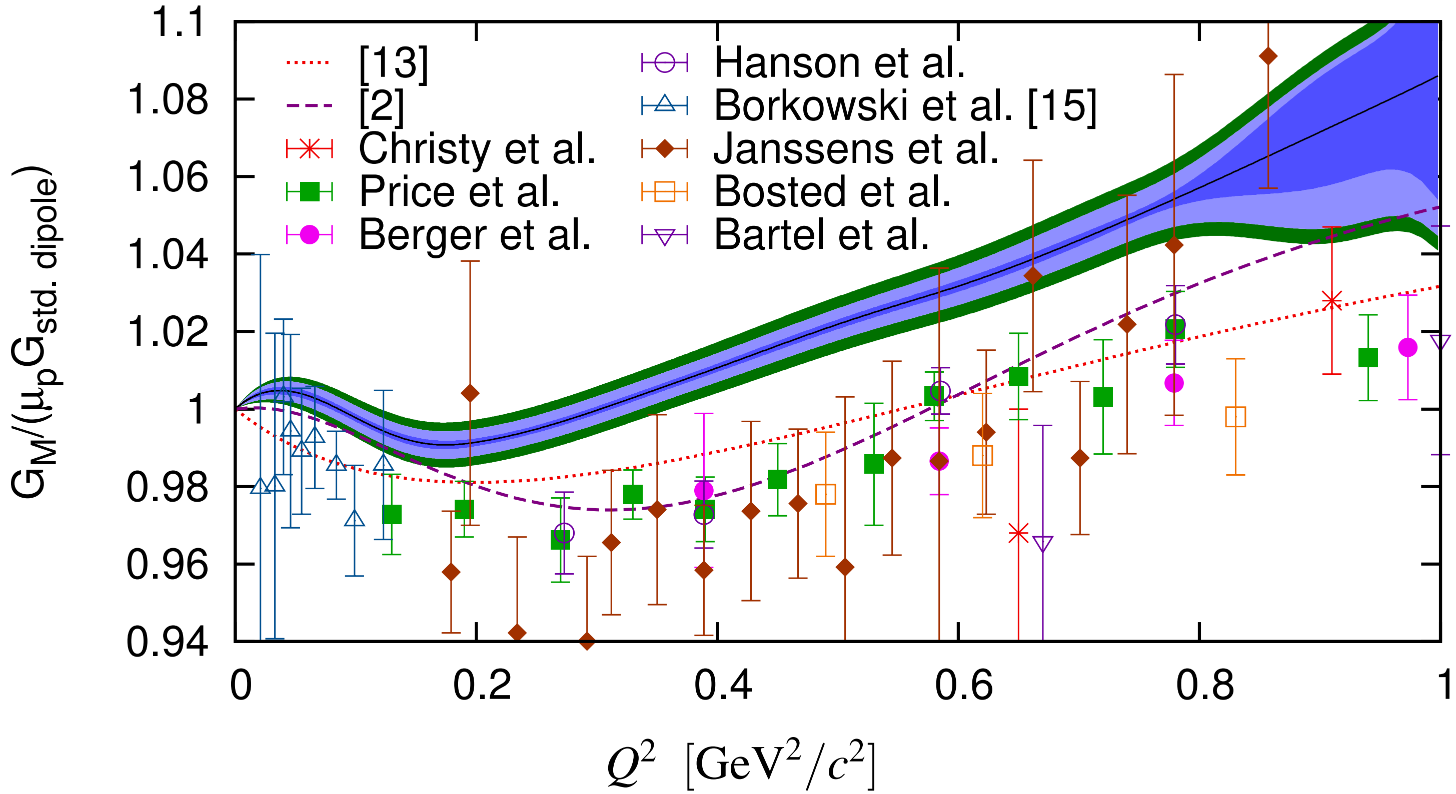


$$\langle r_M \rangle = 0.777(13)_{\text{stat}}(9)_{\text{syst}}(5)_{\text{model}}(2)_{\text{group}}$$

Important e.g. for Zemach radius

$$\langle r_Z \rangle = -\frac{4}{\pi}\int_0^\infty \frac{dq}{q^2}\left(\frac{G_E(q^2)\,G_M(q^2)}{\mu_p} - 1\right)$$

Magnetic Radius

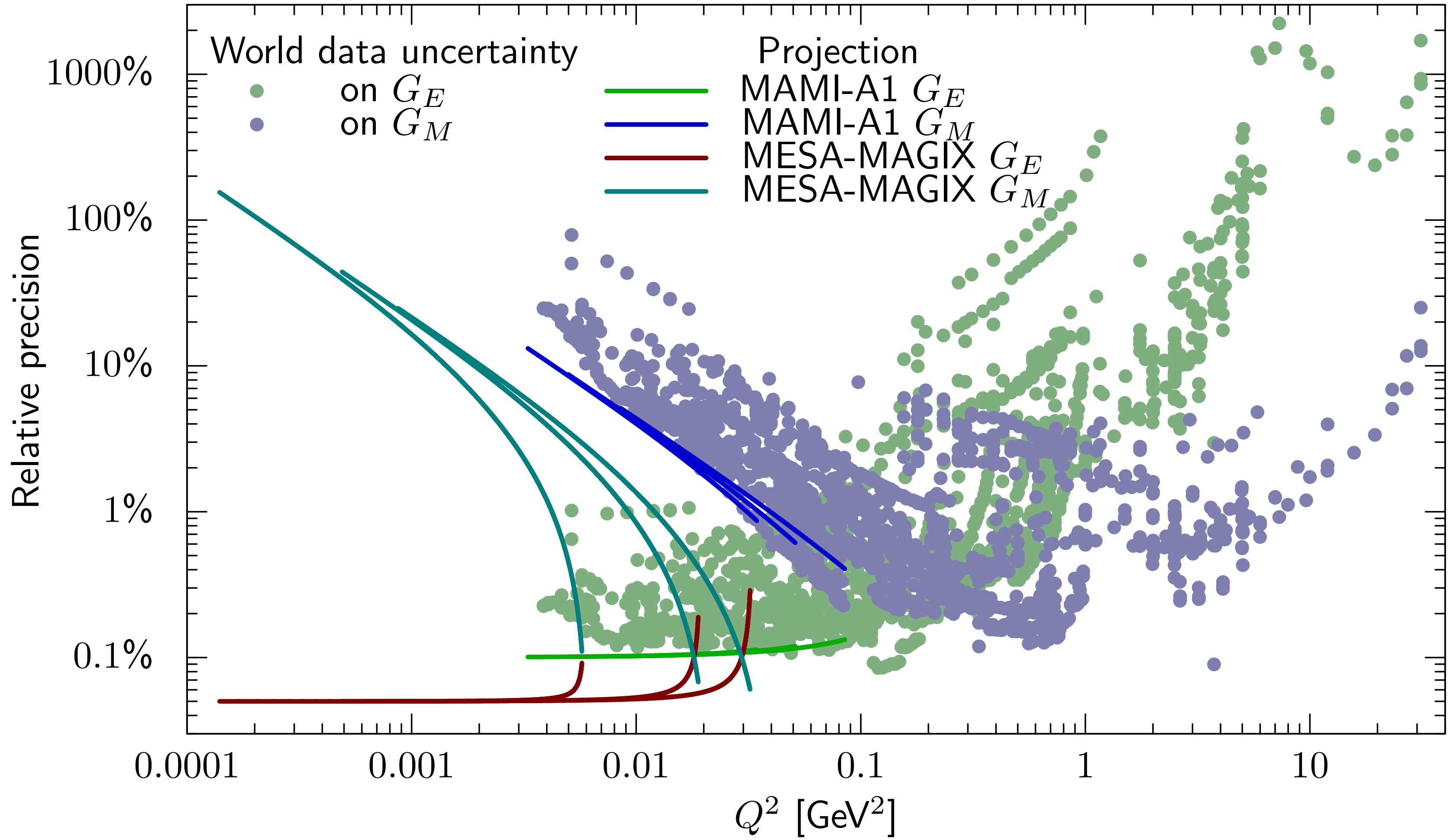


Can we measure this?

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

- G_E dominates for $Q^2 \to 0$
- Except for $\varepsilon \to 0$ backward angles! $\Rightarrow$ MAGIX

Projected Error



- Every beam energy gives a few high quality data points
- Significant improvement possible

MAGIX – What else...

Hadron Structure

Topic	Reaction	Jet	Observables
p Formfactor	$H(e,e')p$	H	$G_E(Q^2)$, $G_M(Q^2)$, r_E, r_M
d Formfactor	$D(e,e')d$	D	$A(Q^2)$, $B(Q^2)$, r_d
^{3}He Formfactor	$^3\mathrm{He}(e,e')^3\mathrm{He}$	^{3}He	r_E
^{4}He Formfactor	$^4\mathrm{He}(e,e')^4\mathrm{He}$	^{4}He	r_E

Few-Body Systems

d Breakup	$D(e,e'p)$	D	$\mathrm{d}\sigma/\mathrm{d}\Omega$, polarizabilities
^{3}He inclusive	$^3\mathrm{He}(e,e')$	^{3}He	Structure functions, R_L
^{4}He inclusive	$^4\mathrm{He}(e,e')$	^{4}He	Structure functions, R_L
^{4}He monopole	$^4\mathrm{He}(e,e')^4\mathrm{He}^*$	^{4}He	Transition Formfactors $E(^4\mathrm{He}^*)$, $\Gamma(^4\mathrm{He}^*)$
^{16}O inclusive	$^{16}\mathrm{O}(e,e')$	^{16}O	Structure functions, R_L
^{40}Ar inclusive	$^{40}\mathrm{Ar}(e,e')$	^{40}Ar	Structure functions, R_L
^{3}He exclusive	$^3\mathrm{He}(e,e'p/d)d/p$	^{3}He	$\mathrm{d}\sigma/\mathrm{d}\Omega$
^{4}He exclusive	$^4\mathrm{He}(e,e'p/d)$	^{4}He	$\mathrm{d}\sigma/\mathrm{d}\Omega$

Dark Sector

Leptonic Decay	$Ar(e,A' \to e^+e^-)$	^{40}Ar, Xe	Lepton pair mass $m_{A'}$ peak search
Invisible Decay	$p(e,e'p)A'$	H	Missing mass $m_{A'}$ peak search

Astrophysical Reactions

S-Factor Phase 1	$^{16}\mathrm{O}(e,e'\alpha)^{12}\mathrm{C}$	^{16}O	$S_{E1}(E)$, $S_{E2}(E)$
S-Factor Phase 2	$^{16}\mathrm{O}(e,e'\alpha)^{12}\mathrm{C}$	^{16}O	$S_{E1}(E)$, $S_{E2}(E)$

Summary

- MESA: a new accelerator for precision physics
- MAGIX
  - High resolution spectrometers
  - Optimized for low energy measurements
  - High count rate capability
- Proton electric radius
  - MESA will start 2025
  - Others will be faster AMBER/MUSE/PRAD2/ULQ2...
  - We will have an impact nevertheless!
- Proton magnetic radius
  - From the planned experiments, only MAGIX can address r_M
- Other radii...
  - All gas targets possible
  - First ones on list: D, He, ...