# Measurement of the $\alpha$-particle Monopole Transition Form Factor at MAMI

Harald Merkel
Johannes Gutenberg-Universität Mainz
for the A1-Collaboration

25th European Conference on Few-body Problems in Physics
Mainz, August 1st, 2023

- Motivation
  - From first principles to complex nuclei
  - $\chi$EFT and *ab-initio* calculations
- Monopole Transition form factor
  - Experiment at A1
  - Analysis and FF-Extraction
  - Results
- Outlook
  - MAGIX at MESA

S. Kegel *et al.*, Phys. Rev. Lett. 130, 152502 (2023)

# Motivation

**First principles $\Rightarrow$ Complex nuclei**

Huge progress in recent years

- Increasing computational power
- Consistent nuclear forces, *e.g.* NN-, 3N-forces from $\chi$EFT

How can we test this?

- Starting with ground state properties, e.g. masses
- We know much more!
  - Single particle wave functions
  - Resolution dependent observables
  - Dynamics of transitions

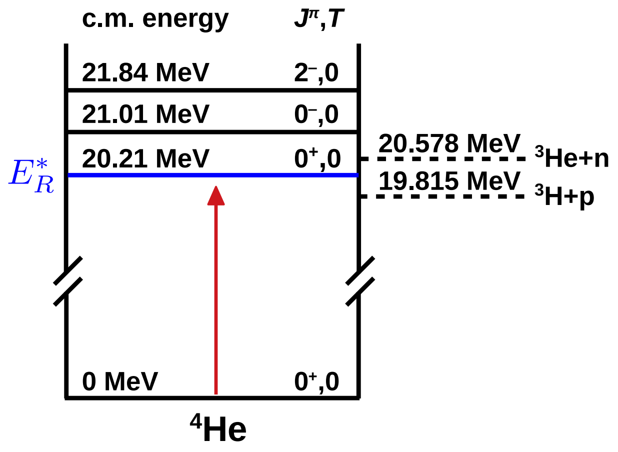
  Clean experiments, but challenging calculations

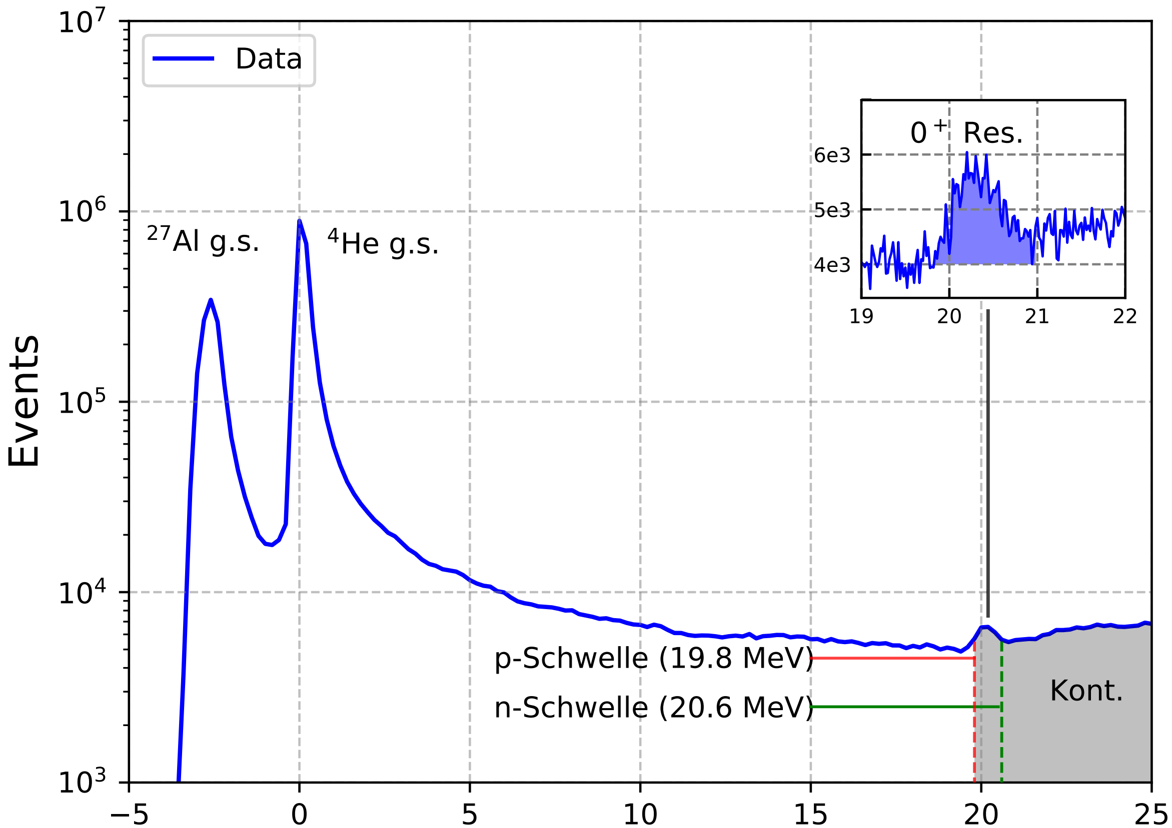
$\Rightarrow$ Starting point: Few Body Physics

# Why $^4$He?

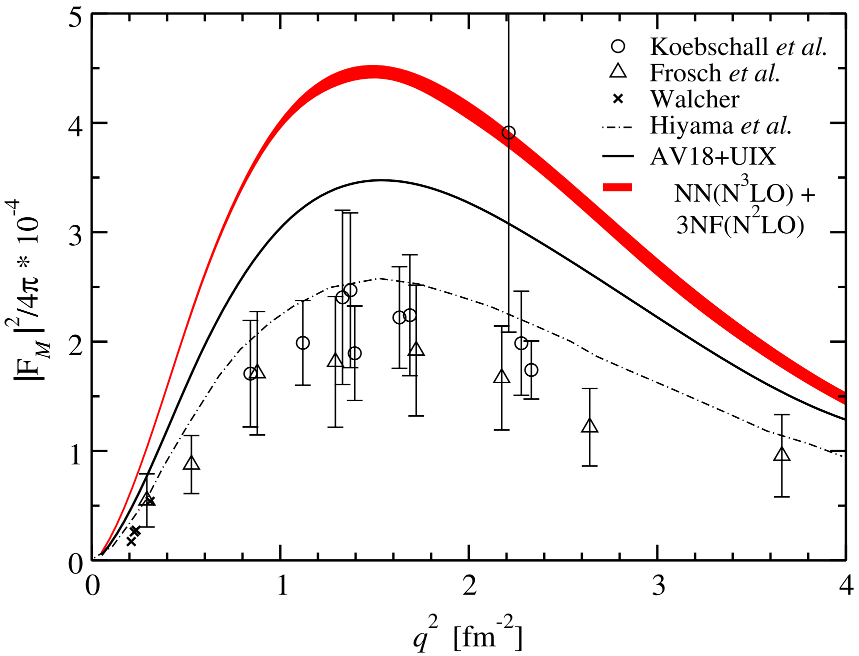
$\chi$EFT and *ab-initio* calculations for A=4

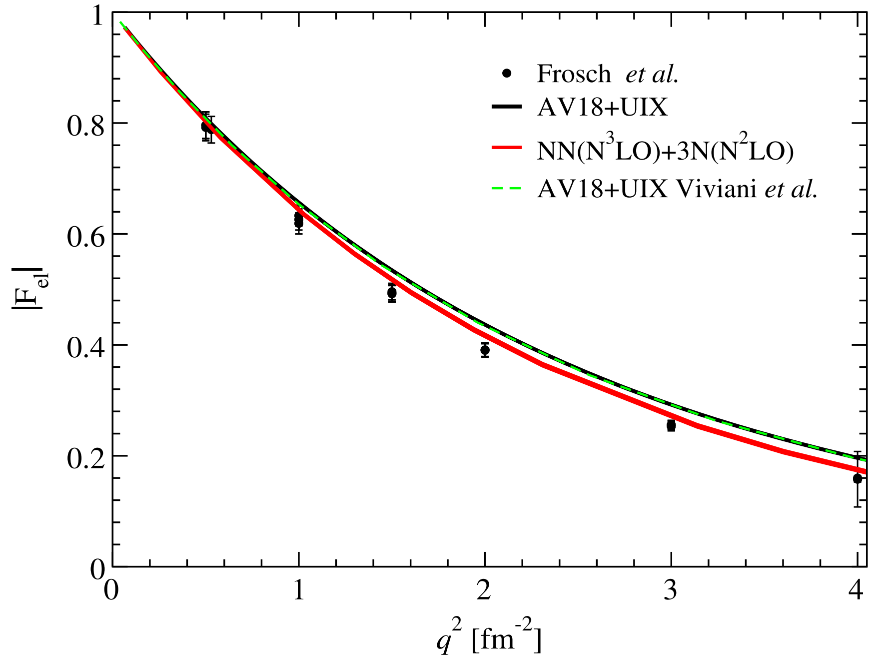
- $\rightarrow$ $^4$He as lightest, stable system with nuclear density, numerical solvable
- $\rightarrow$ Monopole resonance at $E_{0+} = 20.21\,\text{MeV}$
- $\rightarrow$ Electron scattering as pure electromagnetic Interaction
- $\rightarrow$ Transition form factor $F_{M0+}(Q^2)$: $Q^2$ dependence of excitation from ground state to resonance



# Calculations in $\chi$EFT

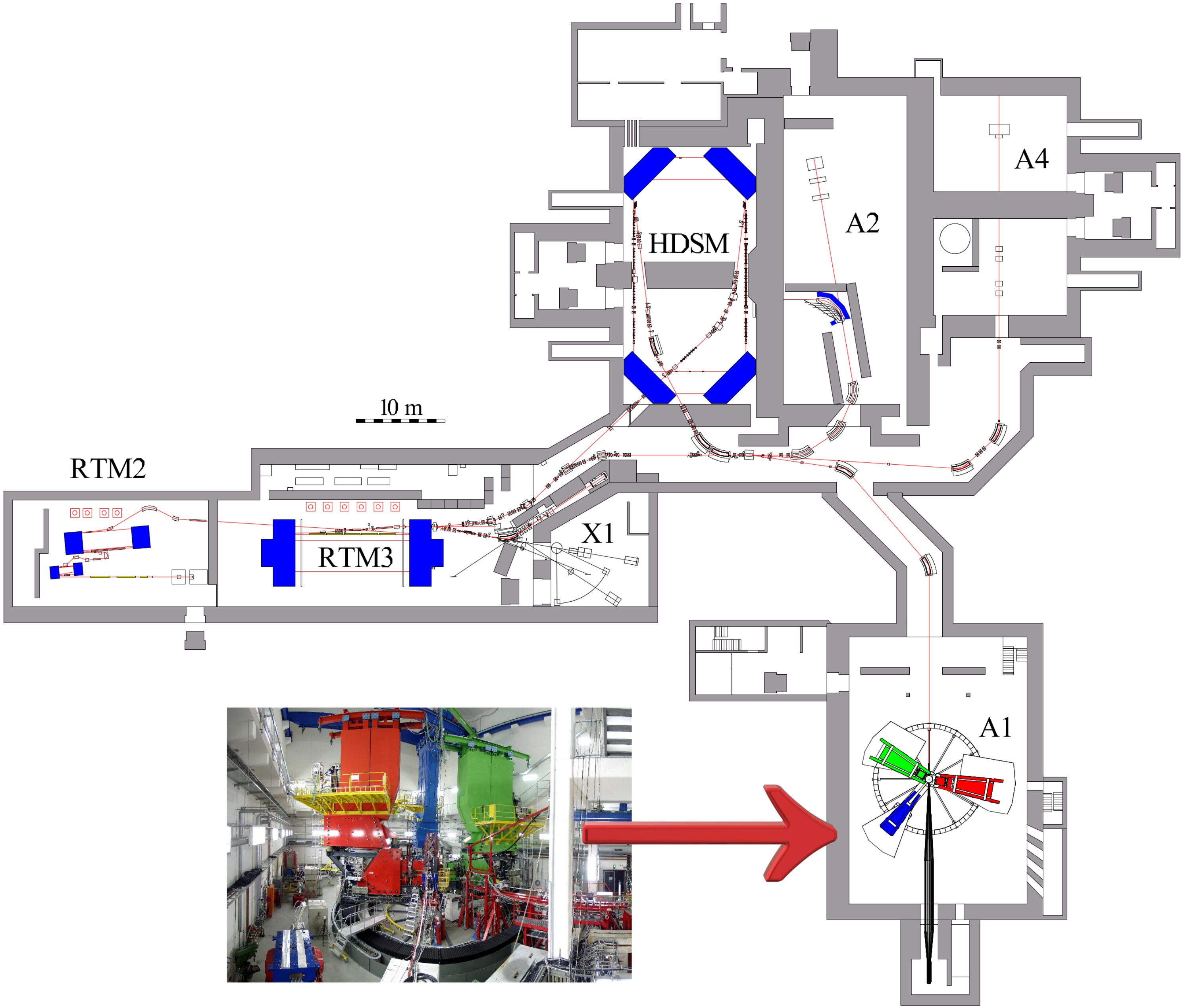


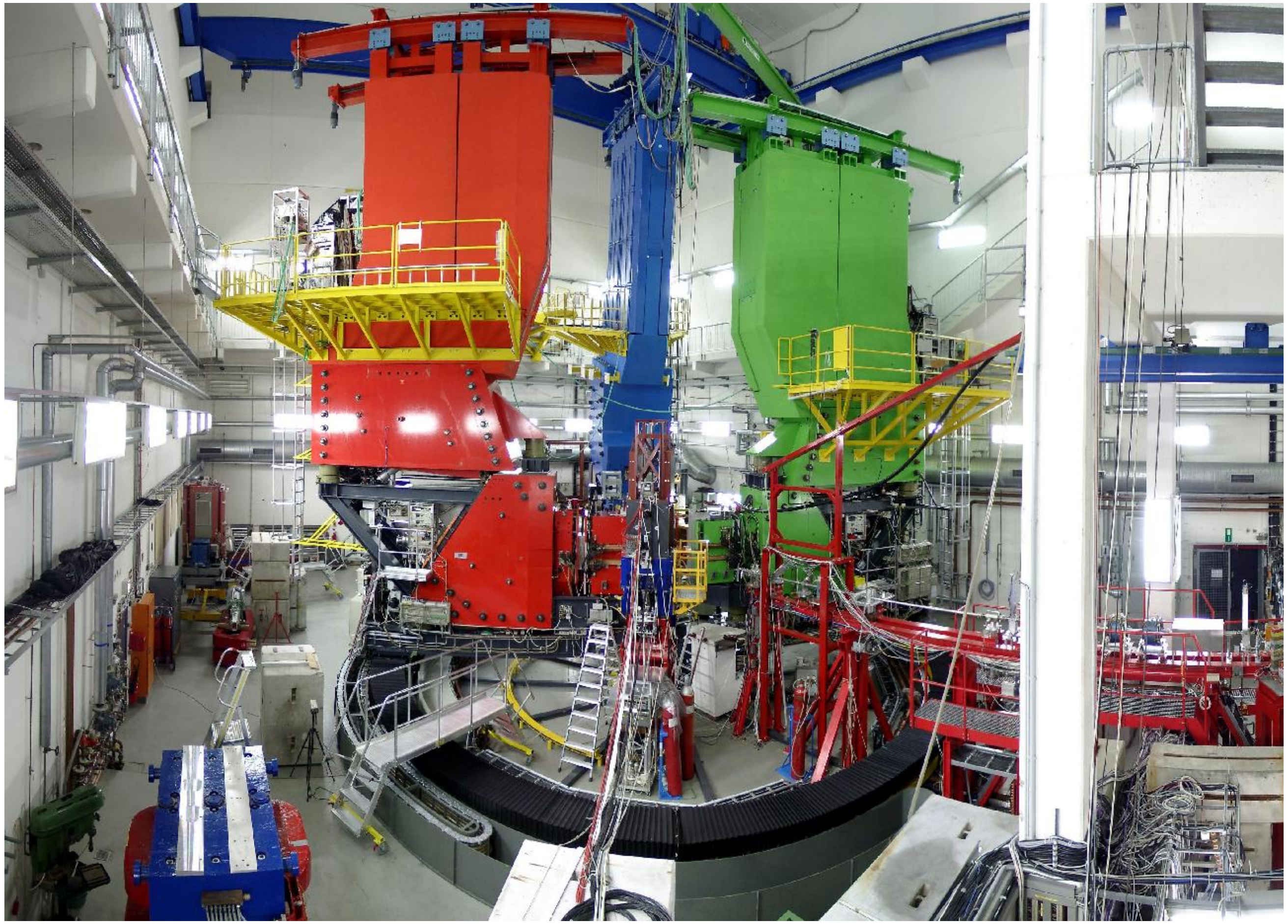

- *Ab initio* calculation of Monopole Form Factor $|F_M(q^2)|^2$ and Electric Form Factor $|F_{el}(q^2)|$
- Realistic nucleon forces
  - Phenomenological potential: Argonne $V_{18}$ + Urbana IX
  - Effective field theory: $NN\ (N^3LO) + 3N\ (N^2LO)$
- Elastic form factor well described (used to fix Low Energy Constants)
- Striking deviation for Monopole Form Factor
- But: poor data quality

S. Bacca, N. Barnea, W. Leidemann, G. Orlandini, Phys. Rev. Lett. 110 (2013), 042503.

# Experiment - MAMI

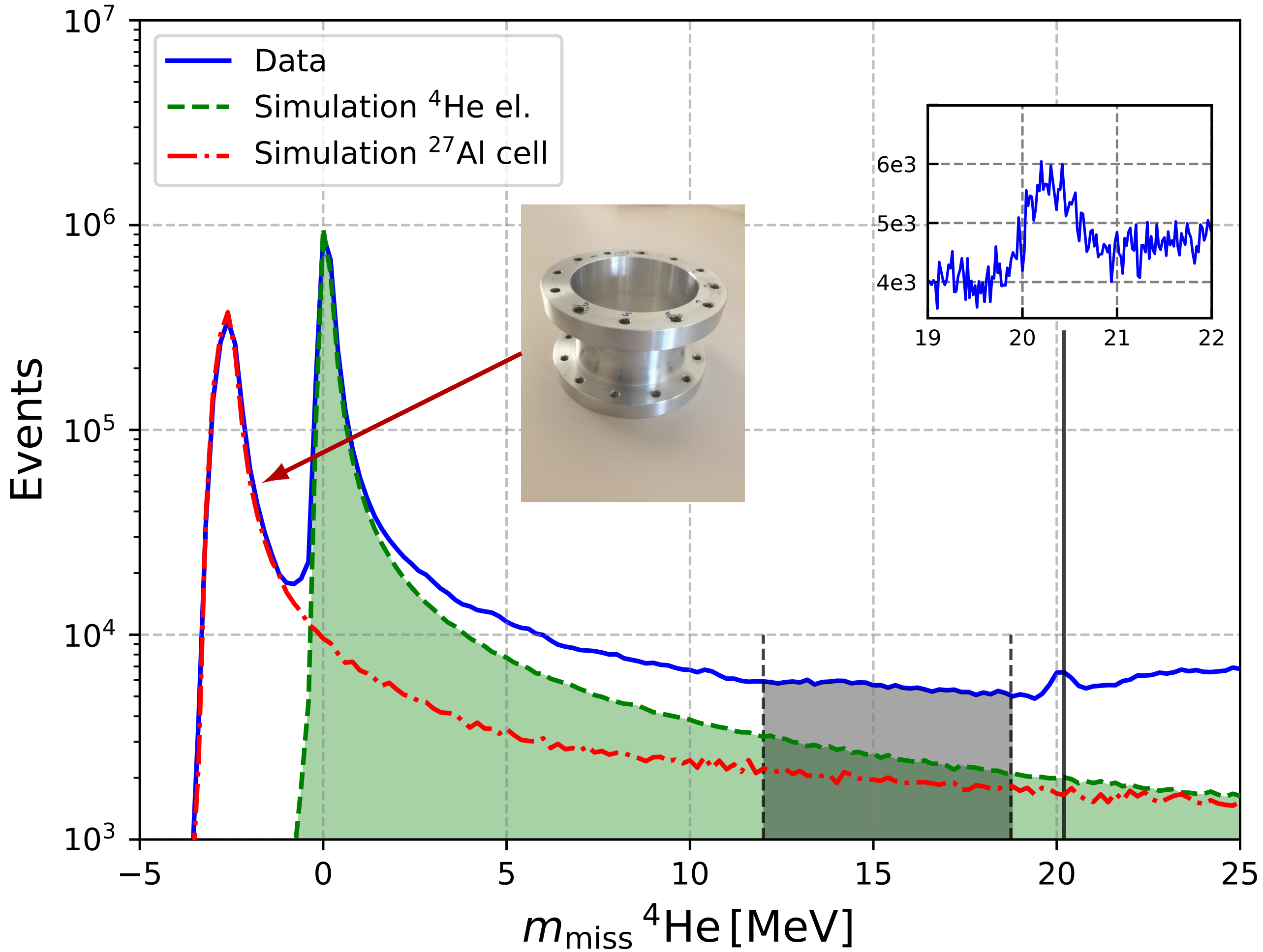


# Experiment - A1



- Single-arm experiment with independent high-resolution spectrometers A and B
- Beam energys: 450 MeV, 690 MeV, 795 MeV
- $0.5\,\mathrm{fm}^{-2} < Q^2 < 5.0\,\mathrm{fm}^{-2}$ with 44 data points
- Empty target cell runs with reduced Helium pressure

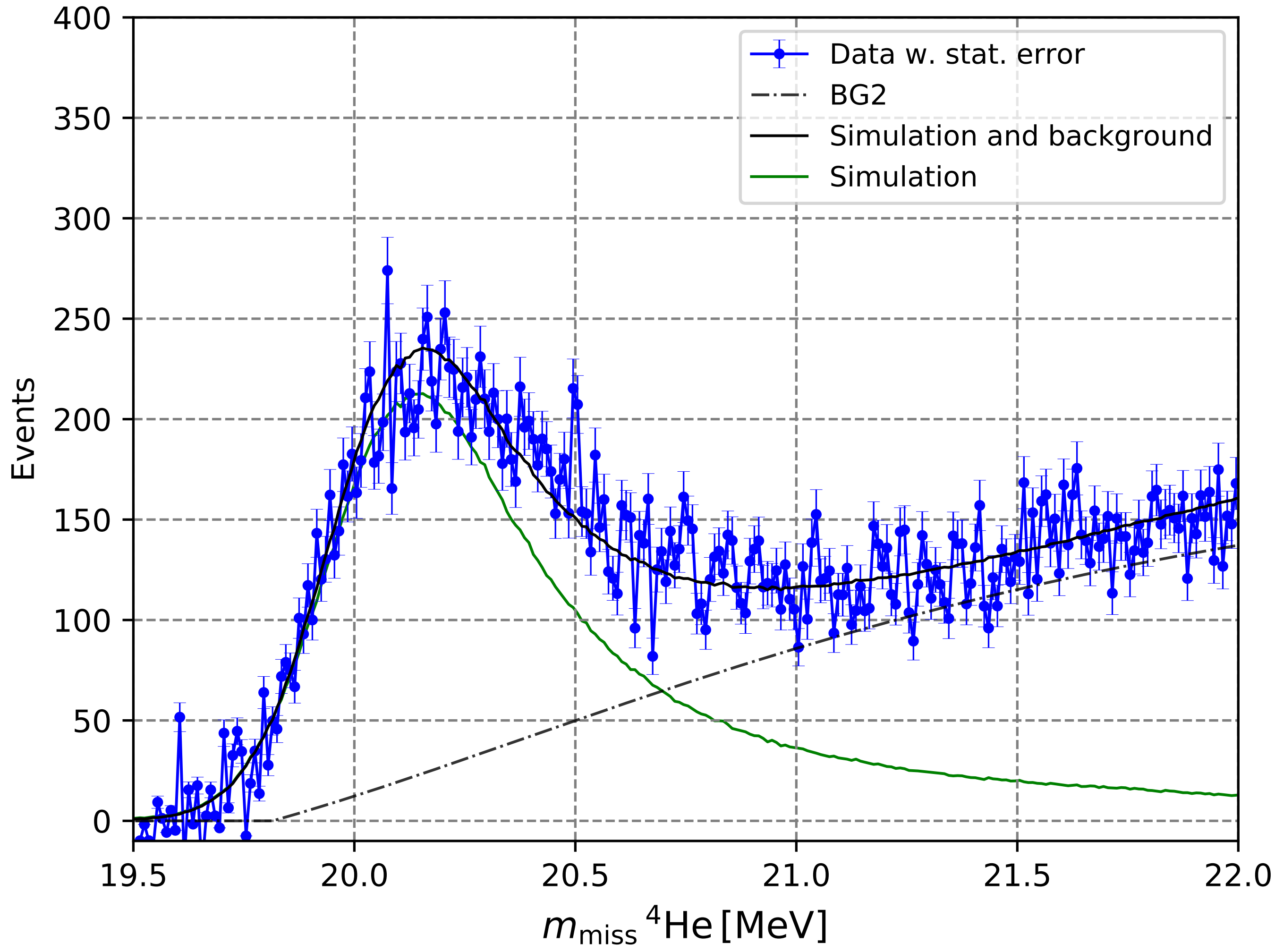
# Background subtraction




- Aluminum target walls: Semi-empirical model of elastic, quasi-elastic, inelastic scattering
  Check with emtpy cell runs!
- Radiative tail of $^3$He elastic line: Elastic Form Factor + radiative corrections
- Check of model-calibration at mass region below break-up channel

# Separation of Break-up Channel

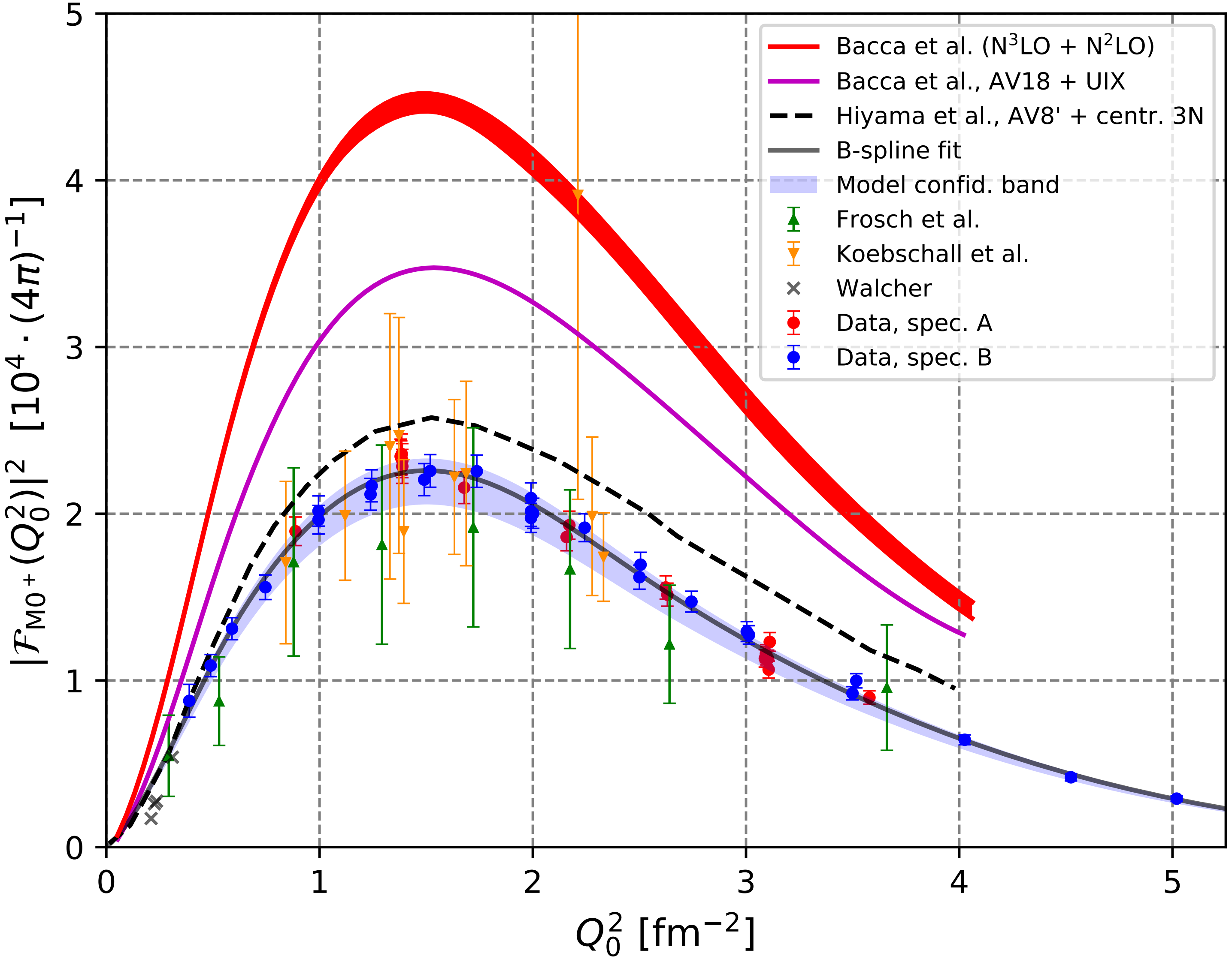
Quasi-free knockout of a proton: $e + {}^{4}\mathrm{He} \rightarrow e' + {}^{3}\mathrm{H} + p$




- Standard quasi-free Model: Spectral function and off-shell cross section
- Fit of Monopole line width (incl. threshold effects)

$$\Gamma_0 = 288 \pm 39\,\mathrm{keV}$$

# Result on Monopole Form Factor

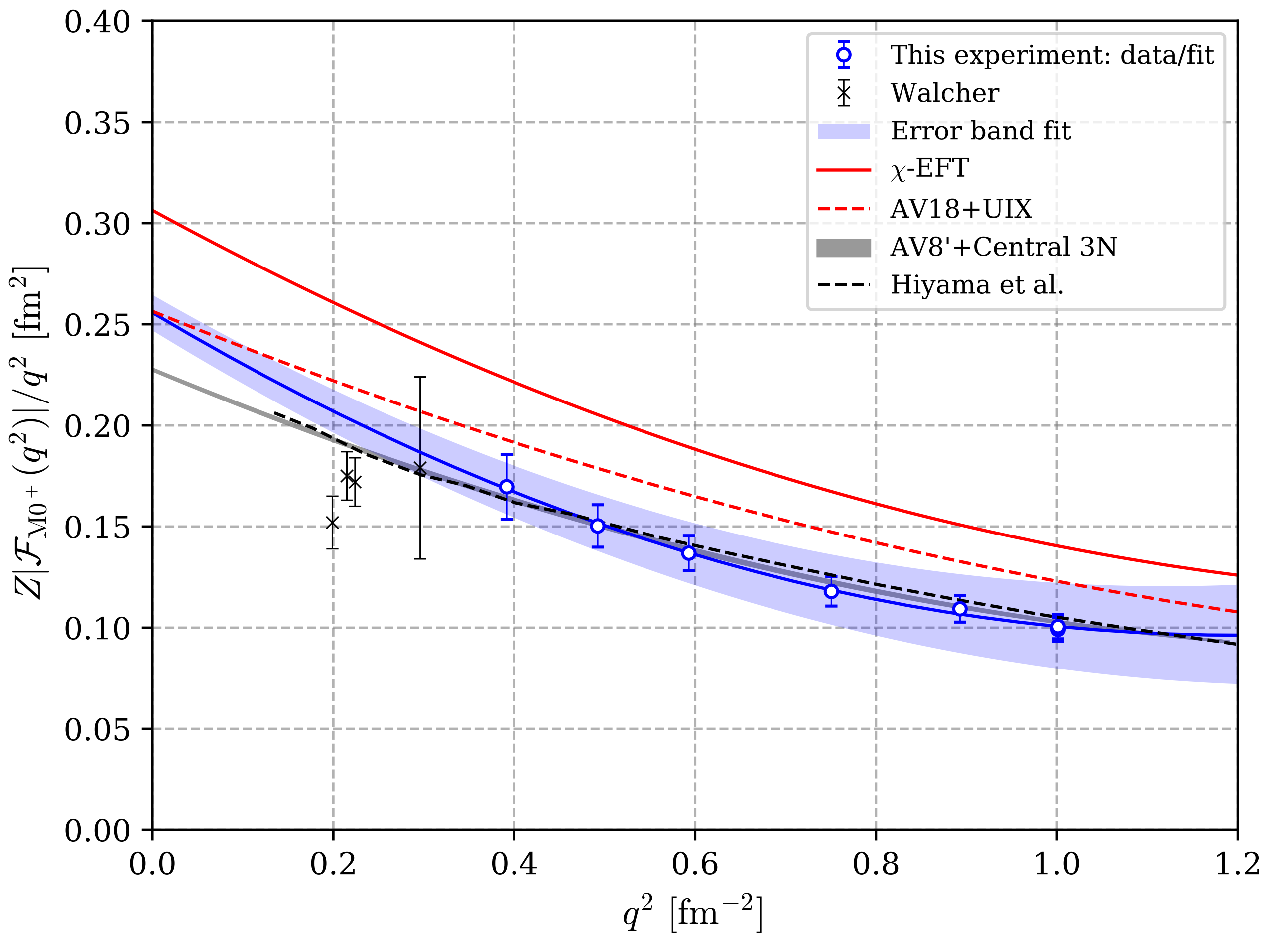



- Consistent with old data
- Significant deviation from models with reduced error 20% – 200%

# Matrix element and Transition Radius

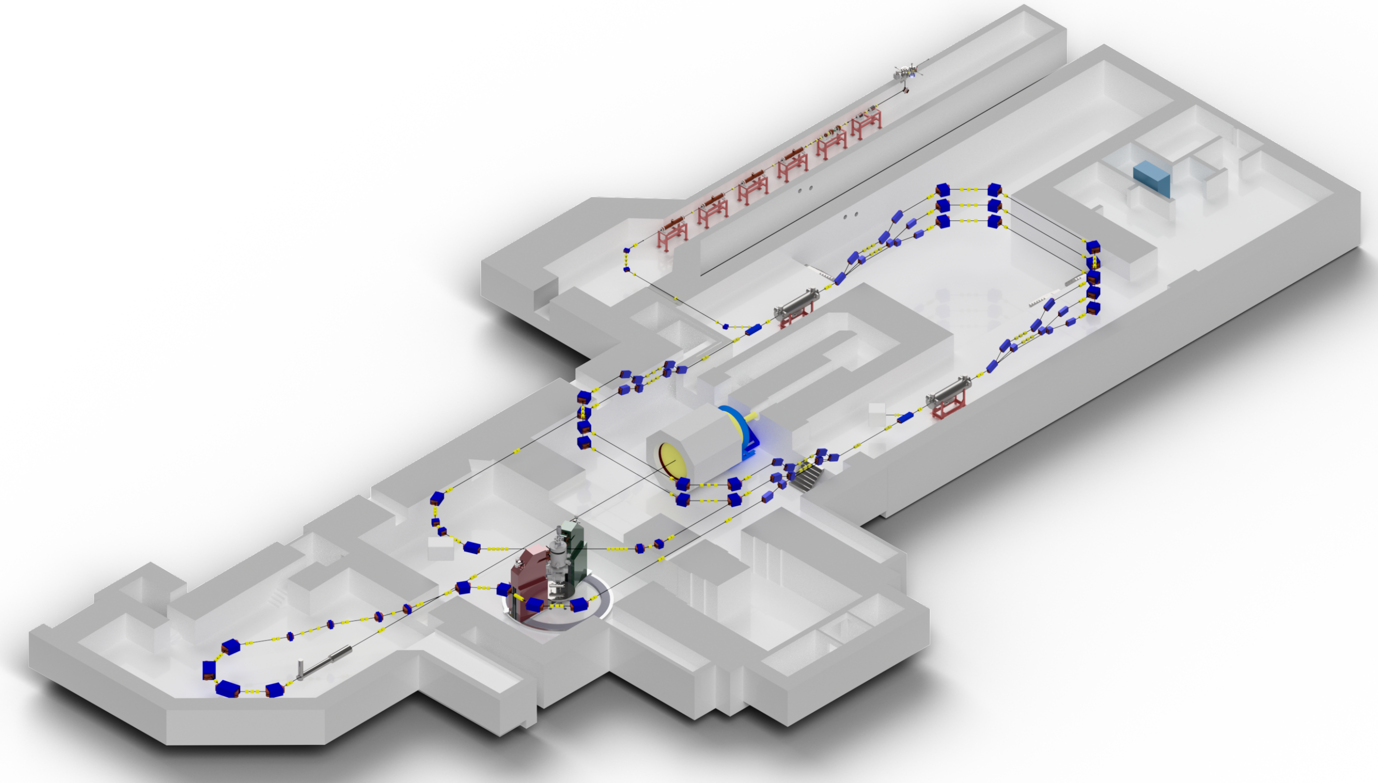
$$\frac{Z|F_{M0+}(q^2)|}{q^2} = \frac{\langle r^2\rangle_{\mathrm{tr}}}{6}\left[1 - \frac{q^2}{20}\mathcal{R}_{\mathrm{tr}} + O(q^4)\right]$$

with Matrix Element $\langle r^2\rangle_{tr}$
Transition Radius $\mathcal{R}_{\mathrm{tr}}$




| | $\langle r^2\rangle_{\mathrm{tr}}$ [fm$^2$] | $\mathcal{R}_{\mathrm{tr}}$ [fm] |
|---|---|---|
| Experiment | 1.53 $\pm$ 0.05 | 4.56 $\pm$ 0.15 |
| Theory (AV8'+ central 3N) | 1.36 $\pm$ 0.01 | 4.01 $\pm$ 0.05 |
| Theory (AV18+UIX) | 1.54 $\pm$ 0.01 | 3.77 $\pm$ 0.08 |
| Theory (χEFT) | 1.83 $\pm$ 0.01 | 3.97 $\pm$ 0.05 |

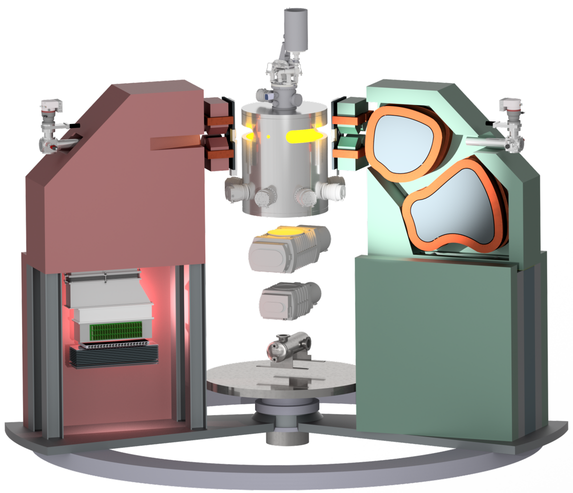
# MESA - Mainz Energy Recovery Superconducing Acclerator

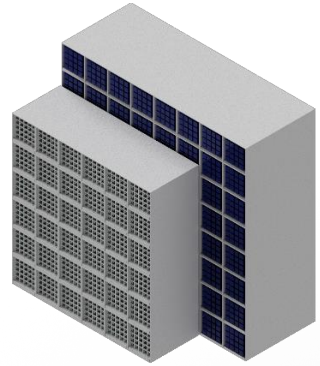


- Super-conducting, recirculating LINAC
- Energy of up to 155 MeV
- Operation for EXTERNAL target, 1 mA, polarized beam
- Operation in ENERGY RECOVERY MODE
  - Energy of up to 105 MeV
  - High beam current (up to 10 mA)
  - Large fraction of the beam can be used for an INTERNAL target

## MAGIX

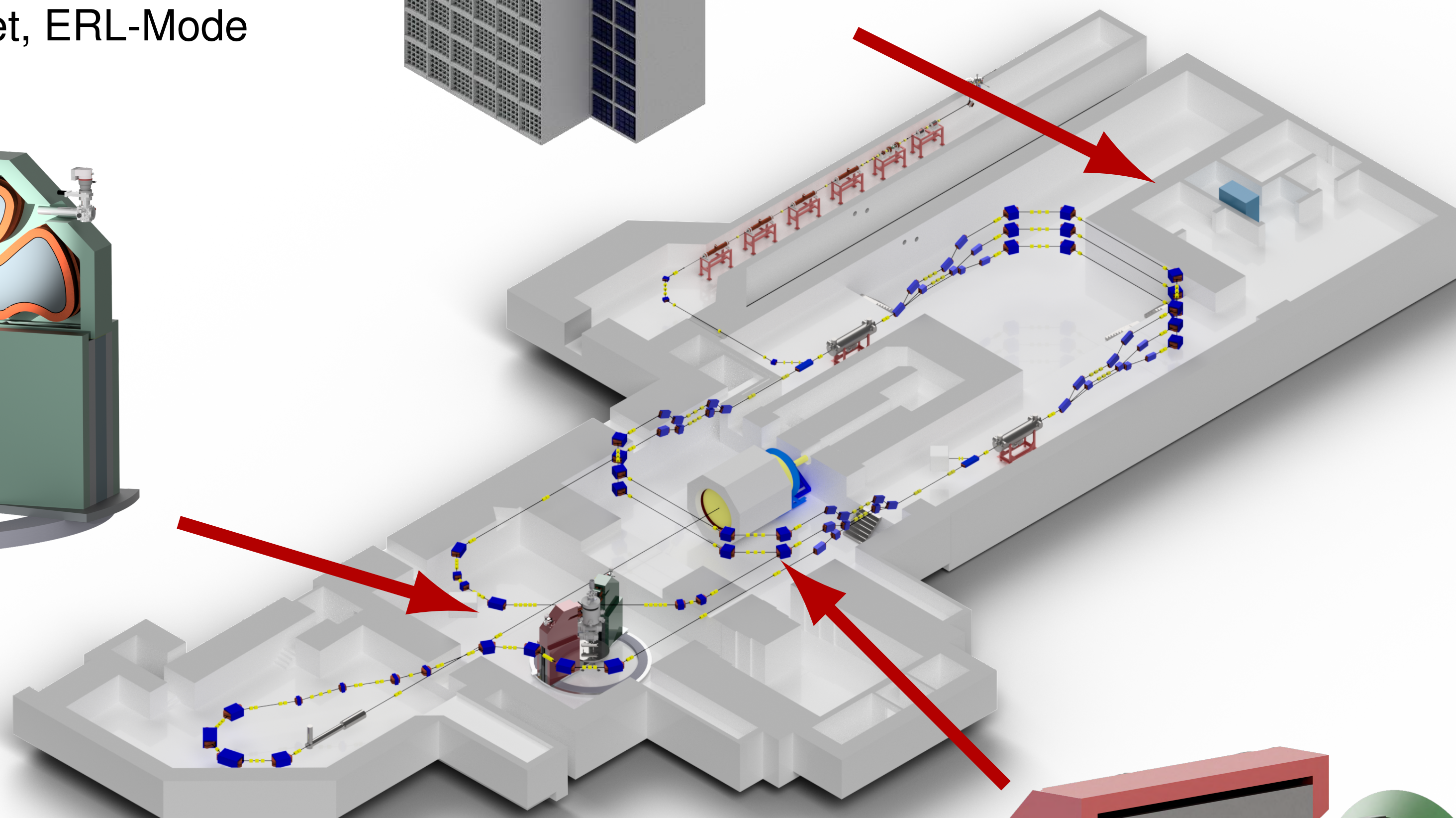
- High Resolution Spectrometers
- Internal Gas Target, ERL-Mode

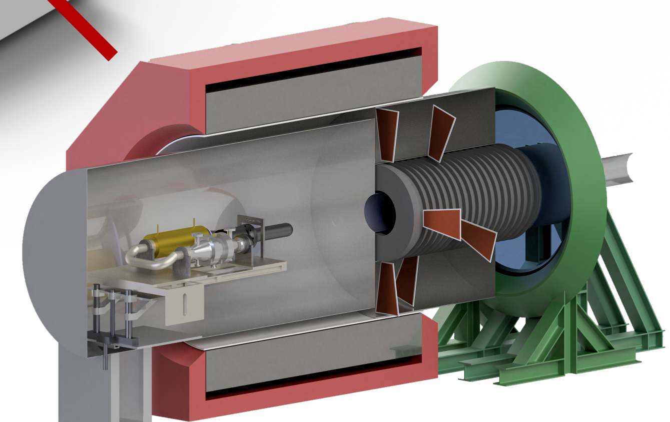




## DarkMESA

- Search for Dark Sector Particles





## P2

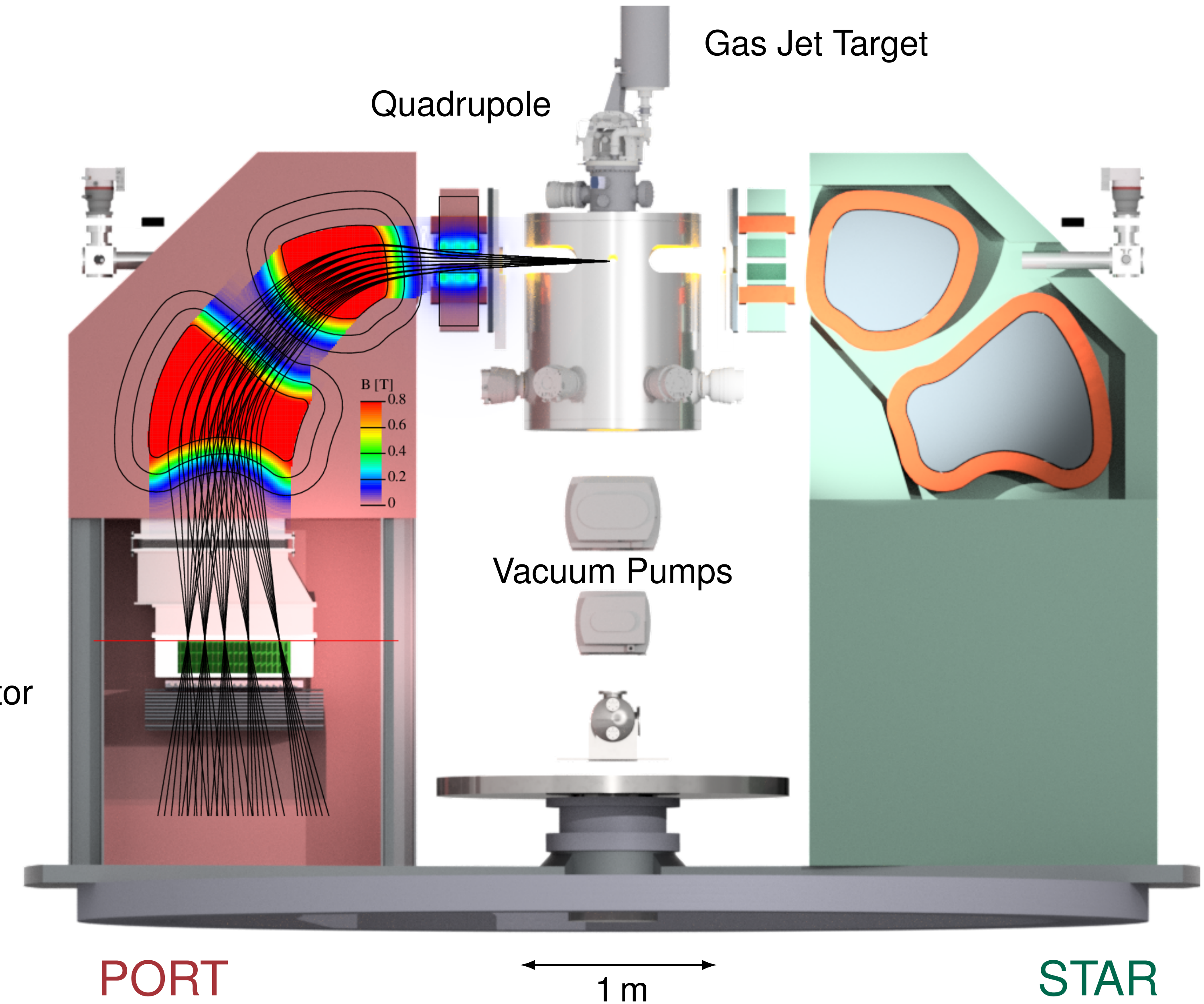
- Parity-Violating $\vec{e}$-scattering
- Extracted Beam (155 MeV, $150\,\mu$A)

# MAGIX - MAinz Gas Injection Target EXperiment

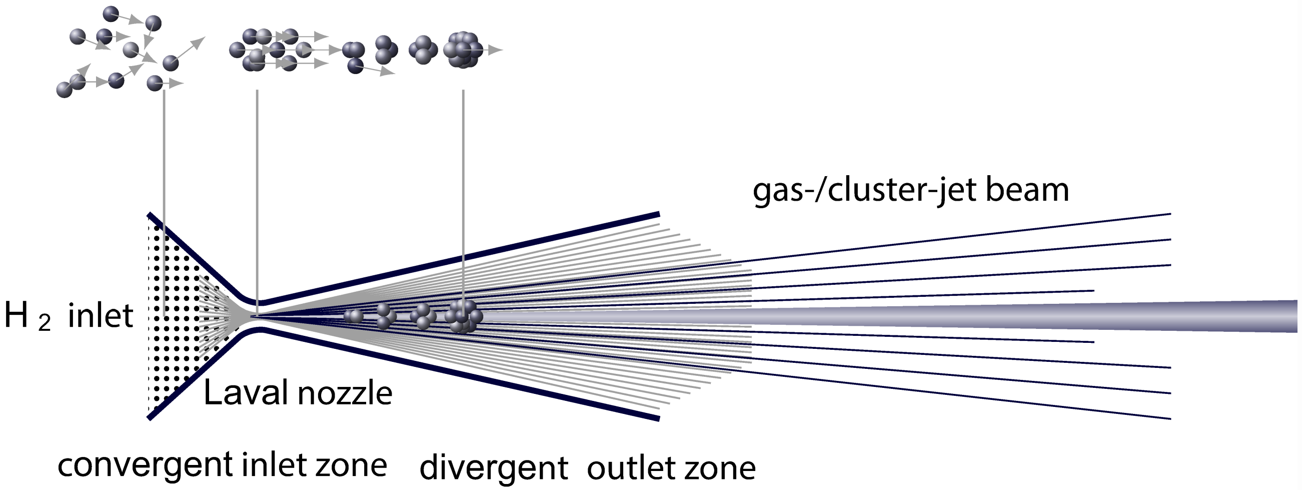
2× Dipole
90° Bending

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

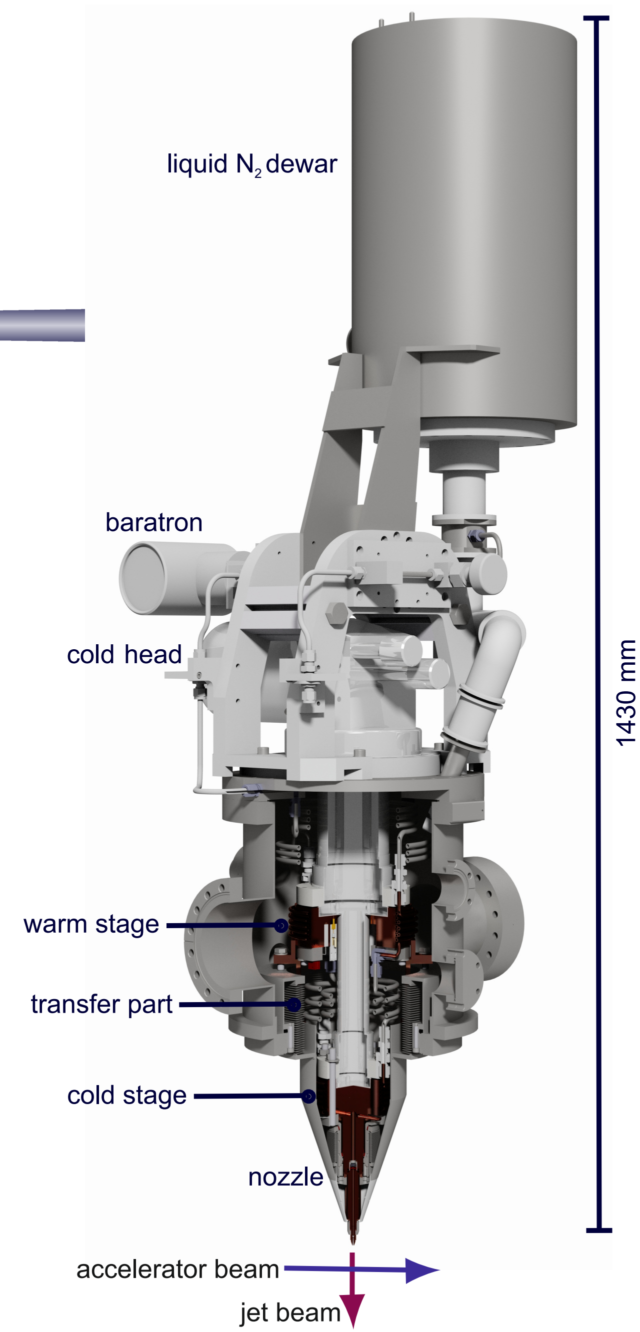
GEM based TPC
Scintillator Detector
Muon Veto



# Supersonic Gas-Jet Target

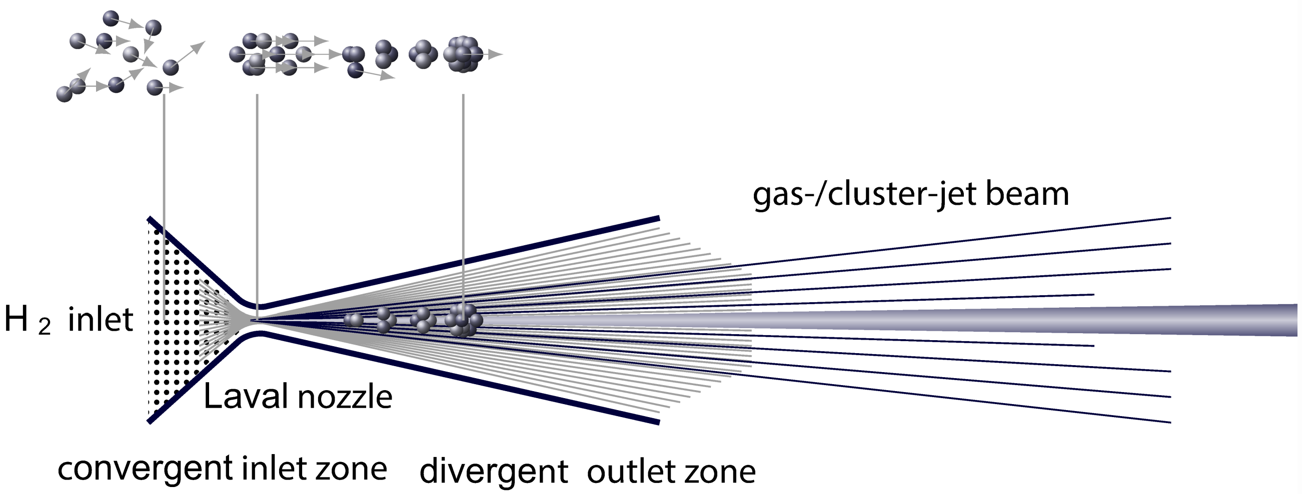


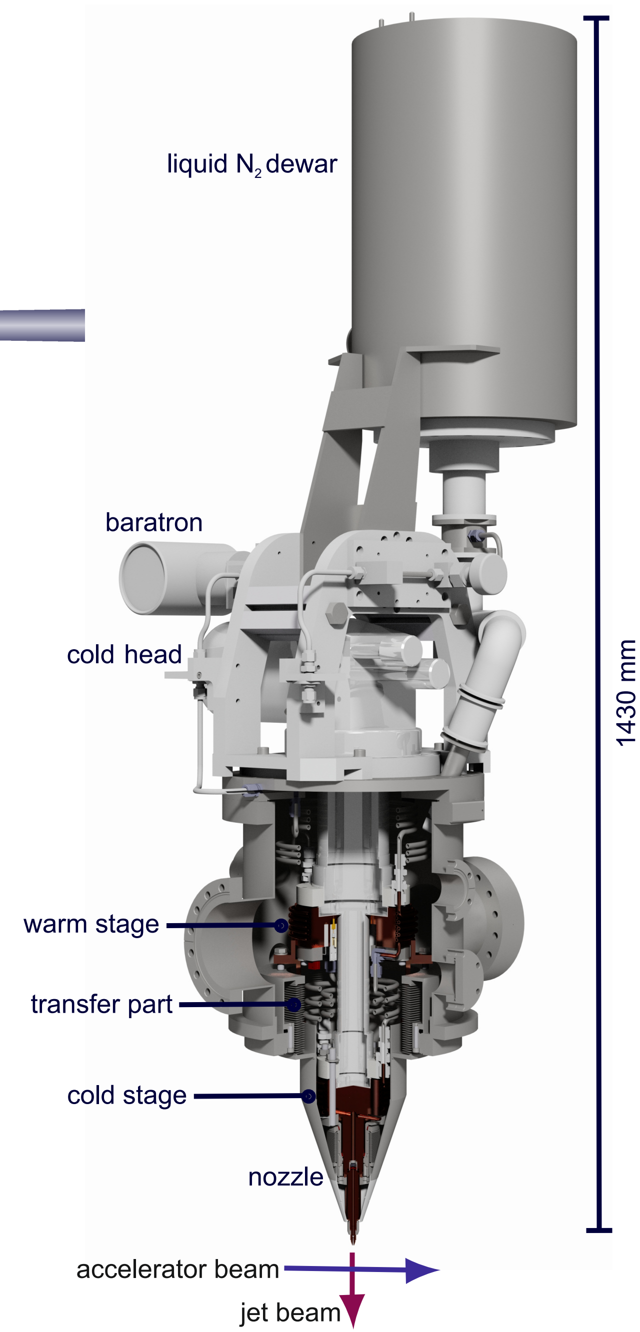

- Laval Nozzle
- Supersonic Gas-Jet
- Temperature drops below freezing point
- Massive Clusters ($\approx$ 10000 atoms)
- $10^{18}$Particles$/$cm$^2$
- Windowless, thin, and pointlike target




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

# Supersonic Gas-Jet Target




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

# MAGIX – Physics Program

**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 | $d\sigma/d\Omega$, 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 | $d\sigma/d\Omega$ |
| $^4$He exclusive | $^4\mathrm{He}(e,e'p/d)$ | $^4$He | $d\sigma/d\Omega$ |

**Dark Sector**

| | | | |
|---|---|---|---|
| Leptonic Decay | $Ar(e,A' \rightarrow e^+e^-)$ | $^{40}$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

- First principles $\rightarrow$ complex nuclei
  - $\chi$EFT for NN and 3N forces
  - Clean observables accessible via electron scattering
  - Starting with few body physics to connect to theory

- $^4$He Monopole transition form factor
  - Sensitive to NN forces
  - Precise data on Form factor, width, transistion radius
  - Large discrepancy between theory and experiment

- Future
  - MESA: Energy recovery linac $\rightarrow$ high current
  - MAGIX: High resolution spectrometers in relevant energy range
  - Full program on few body physics