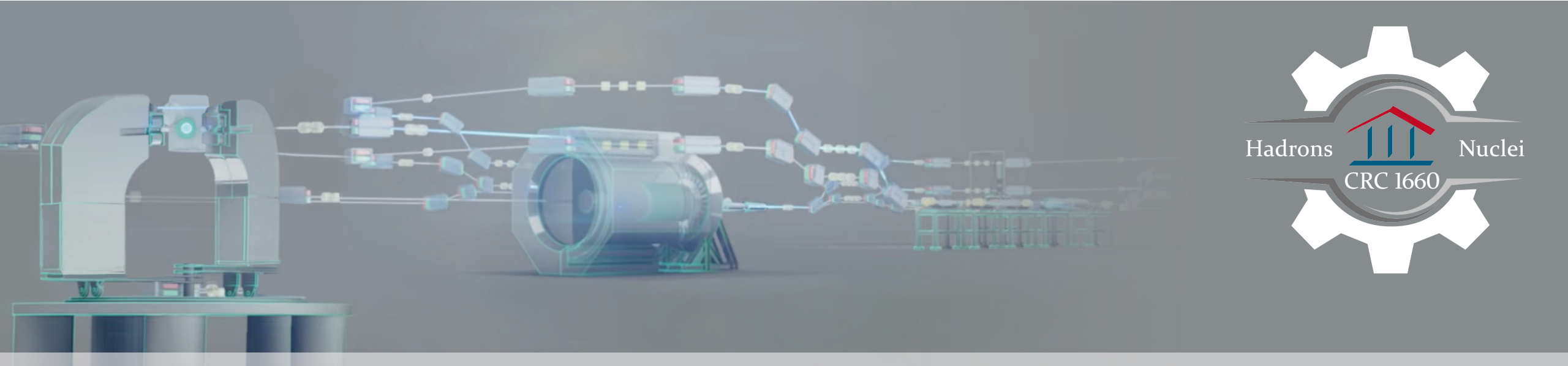


# **A low-energy precision physics program at MESA: Hadrons and Nuclei as discovery tools**

Concettina Sfienti and Marc Vanderhaeghen



JOHANNES GUTENBERG  
UNIVERSITÄT MAINZ

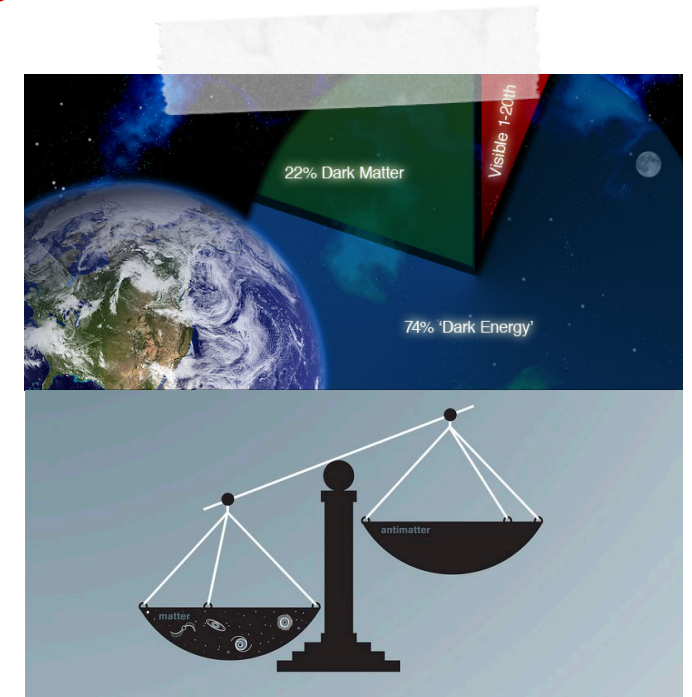
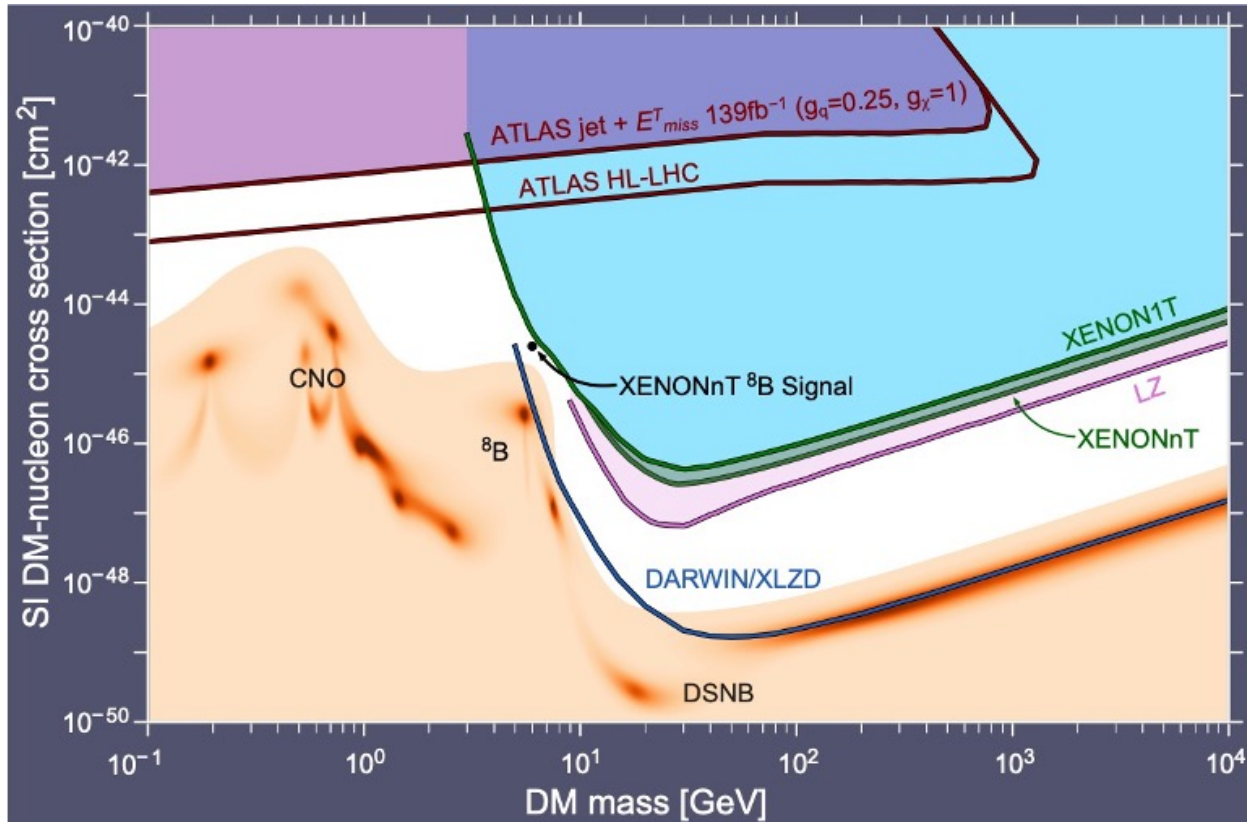


# **THE low-energy precision physics program at MESA: Hadrons and Nuclei as discovery tools**

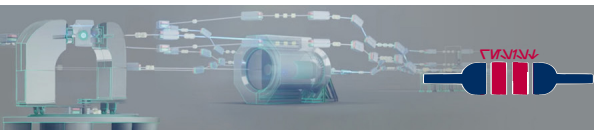
Concettina Sfienti and Marc Vanderhaeghen



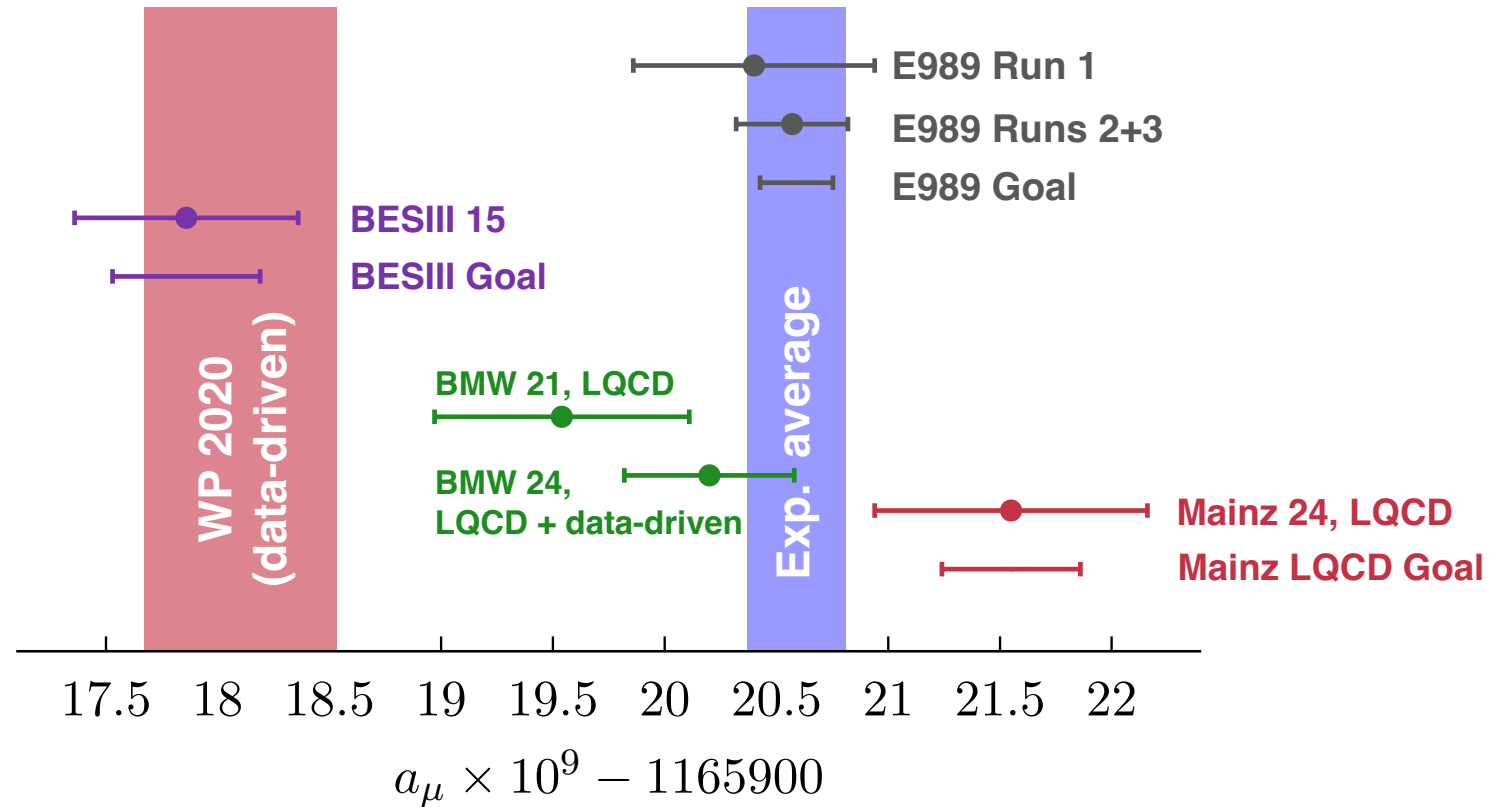
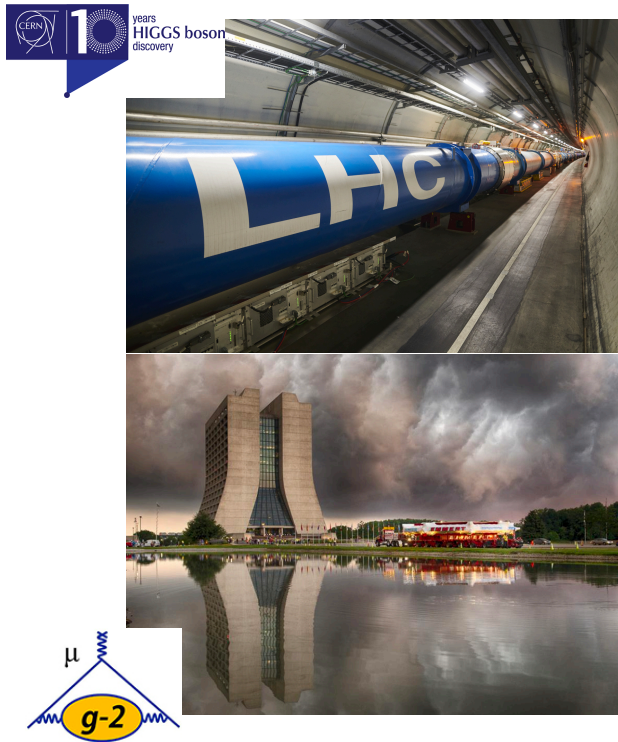
# The landscape: where is the “new” physics?



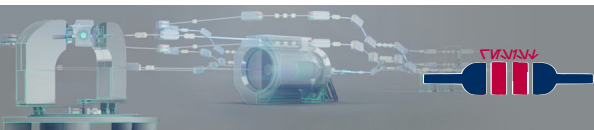
- New particles interact too weakly to be observed?
- Are other mass ranges or new interactions needed?



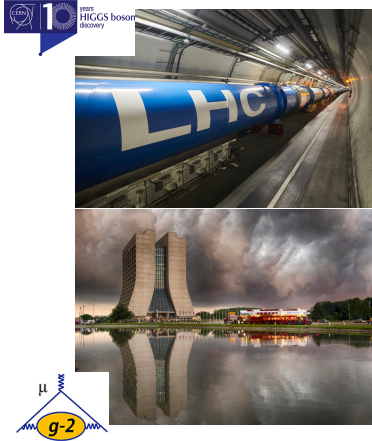
# The landscape: where is the “new” physics?



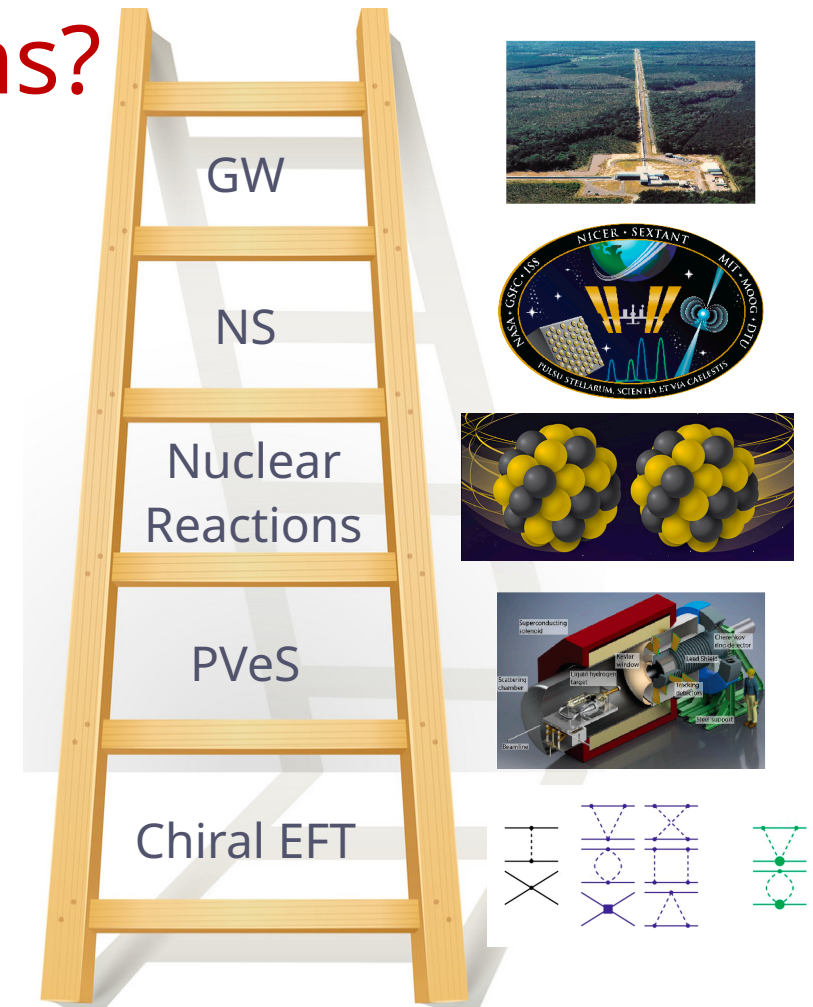
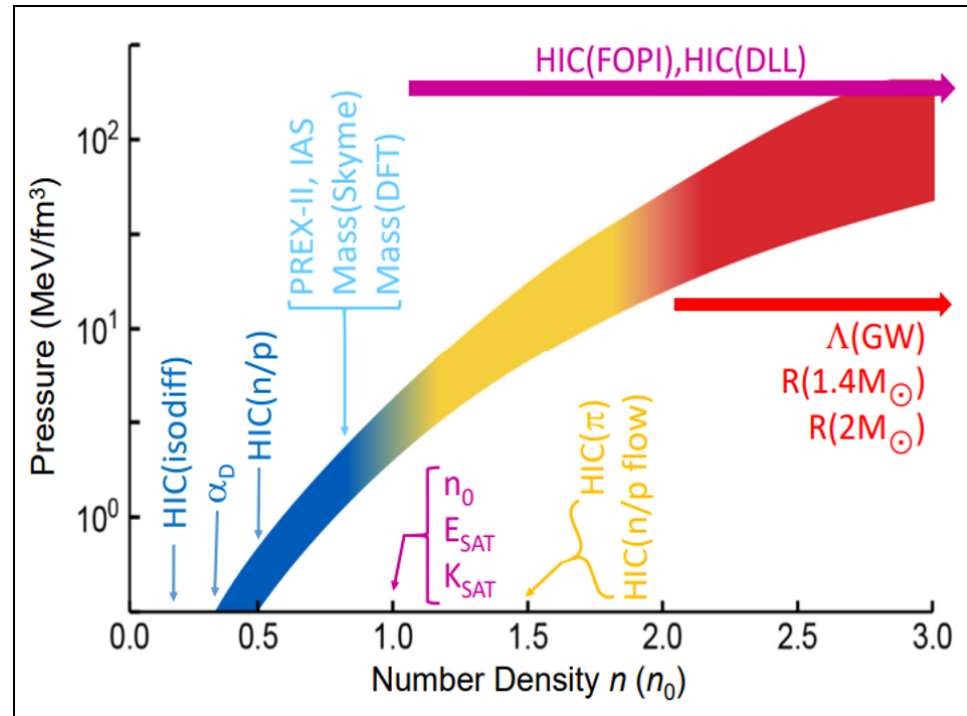
- Are tensions caused by and incomplete understanding of hadronic processes?



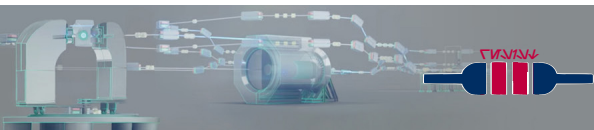
# ... diverse puzzles, common solutions?



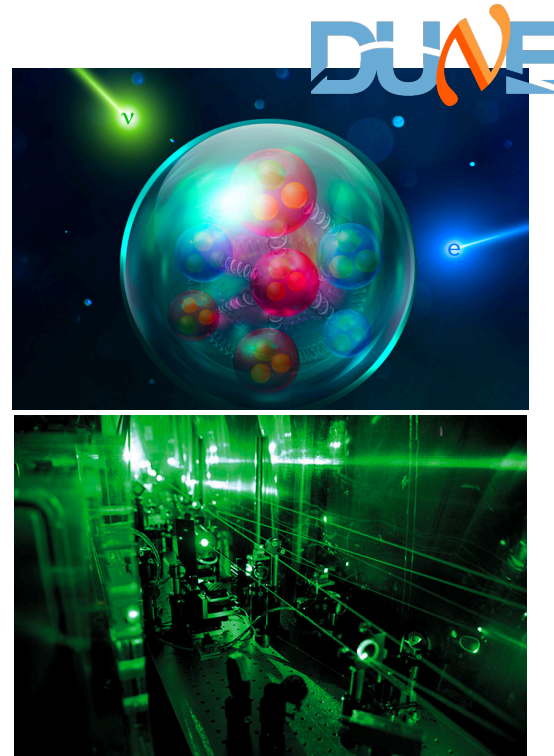
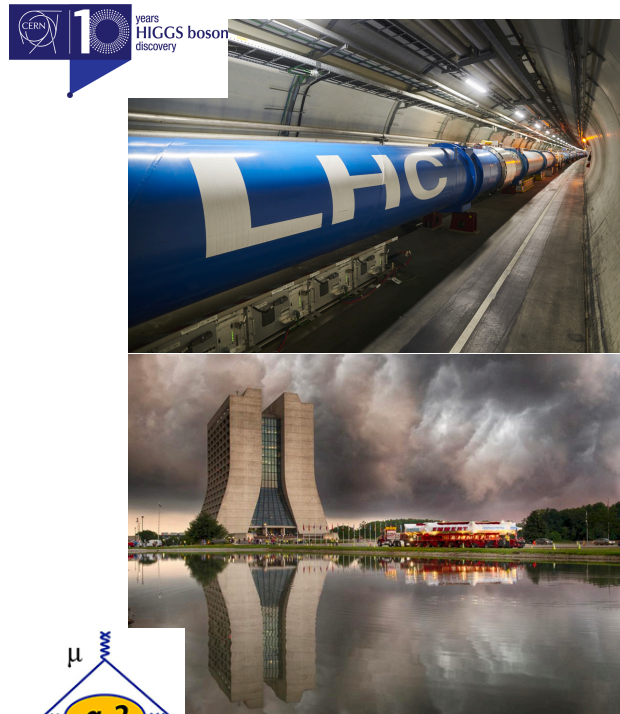
B.Tsang, INT2024



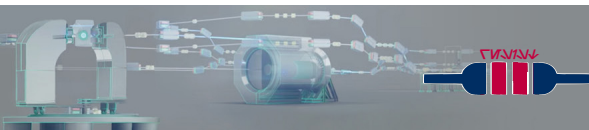
- Only the interplay of theoretical, astronomical observations and experimental laboratory progress will enable a complete understanding!



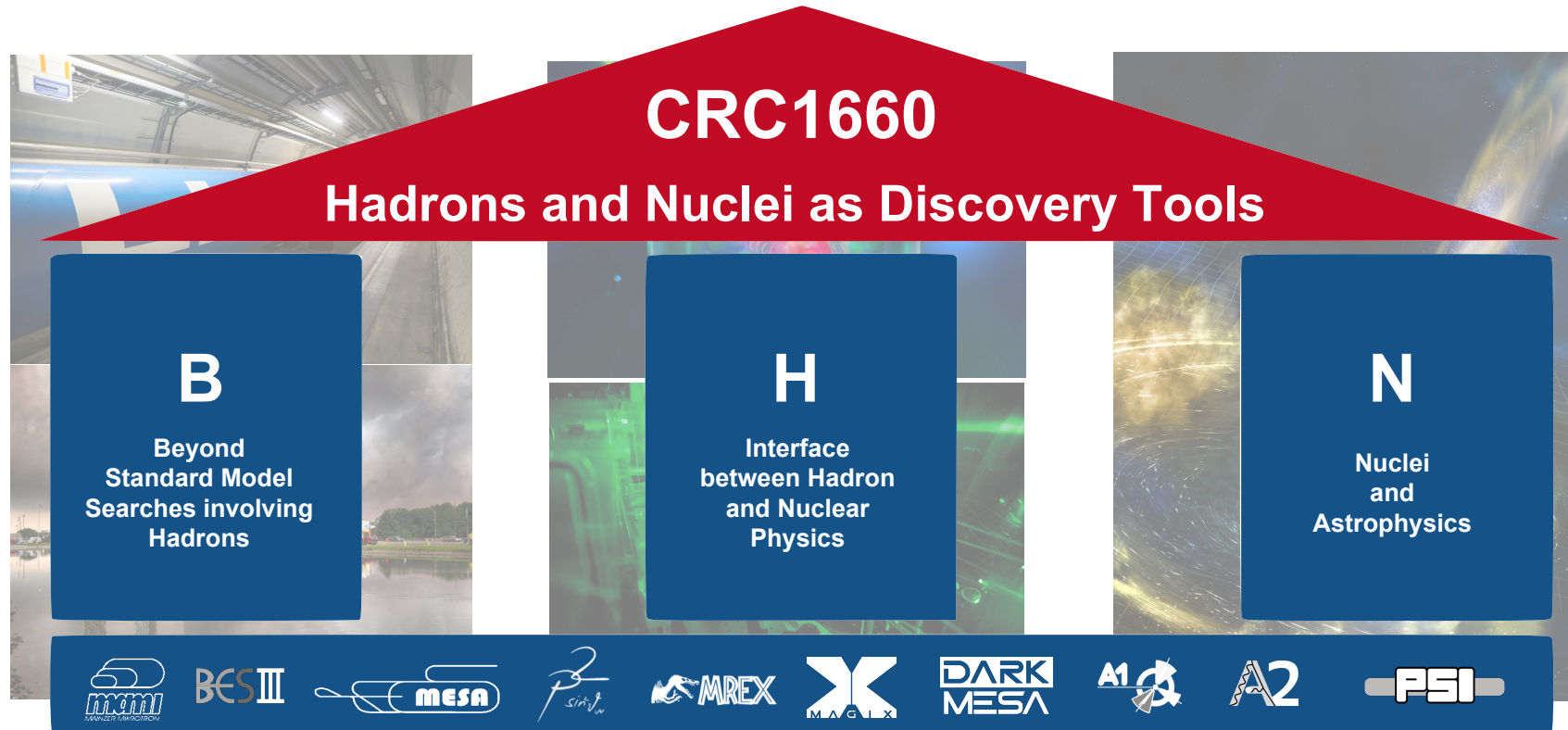
# Similar challenges, common solution



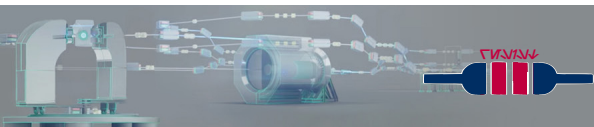
- ▶ Strong **discovery** potential for new physics phenomena
- ▶ Powerful **tools** to sharpen our understanding of strongly interacting systems



# Unlocking physics with hadrons and nuclei



- ▶ Strong **discovery** potential for new physics phenomena
- ▶ Powerful **tools** to sharpen our understanding of strongly interacting systems



# CRC1660

## Hadrons and Nuclei as Discovery Tools

### B

Beyond  
Standard Model  
Searches involving  
Hadrons

### H

Interface  
between Hadron  
and Nuclear  
Physics

### N

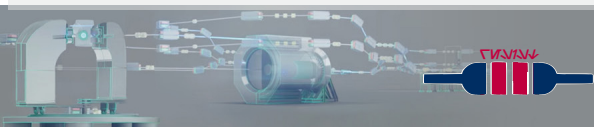
Nuclei  
and  
Astrophysics



BES III



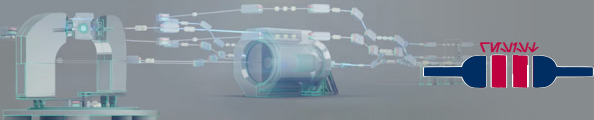
DARK  
MESA

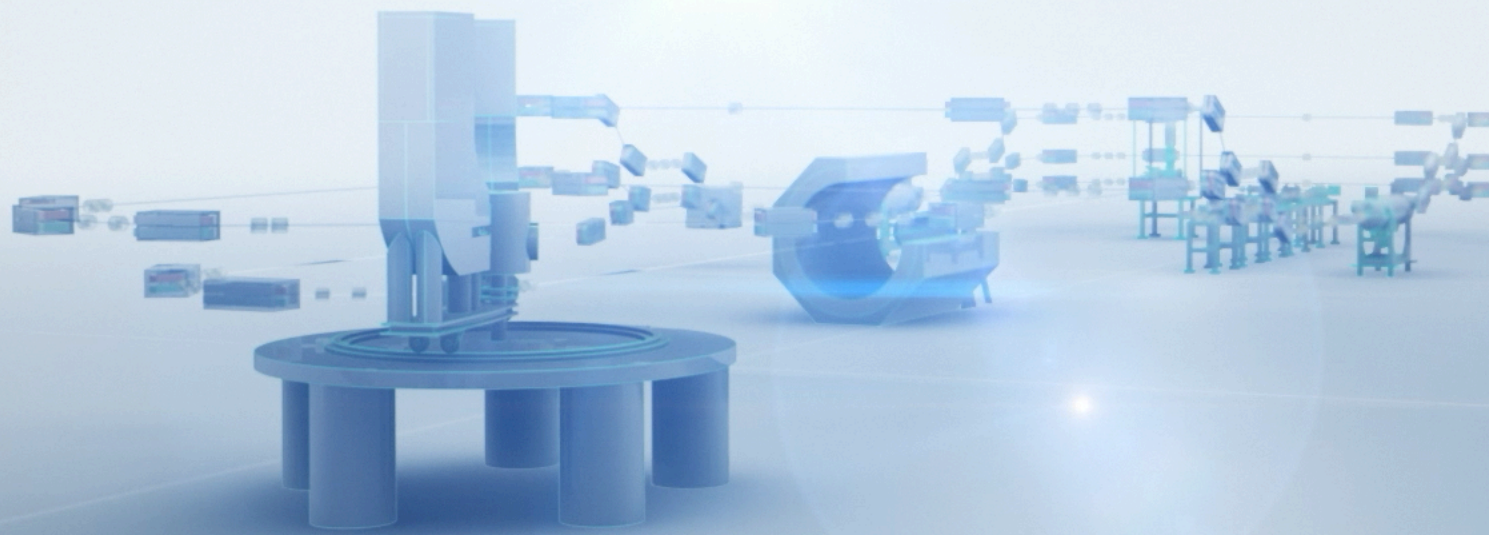




# New experimental opportunities

MESA - Mainz Energy-Recovering Superconducting Accelerator

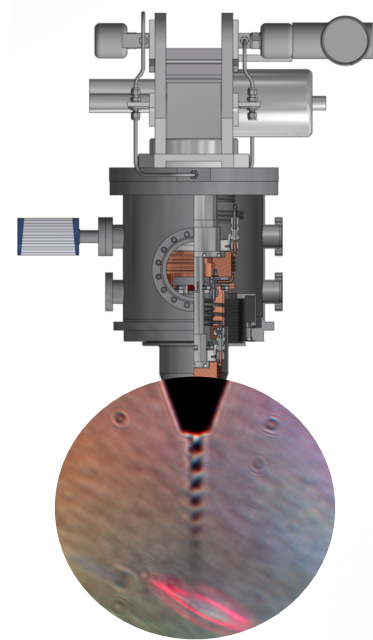
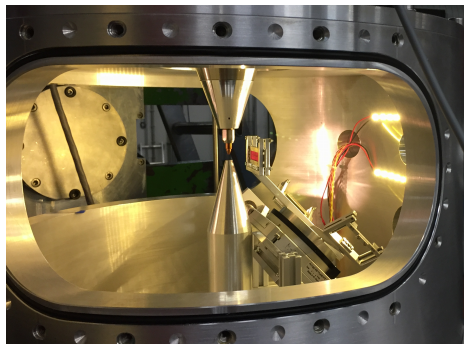




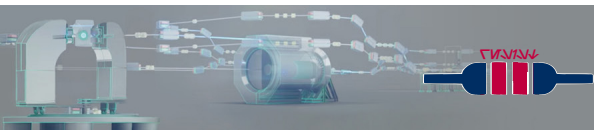
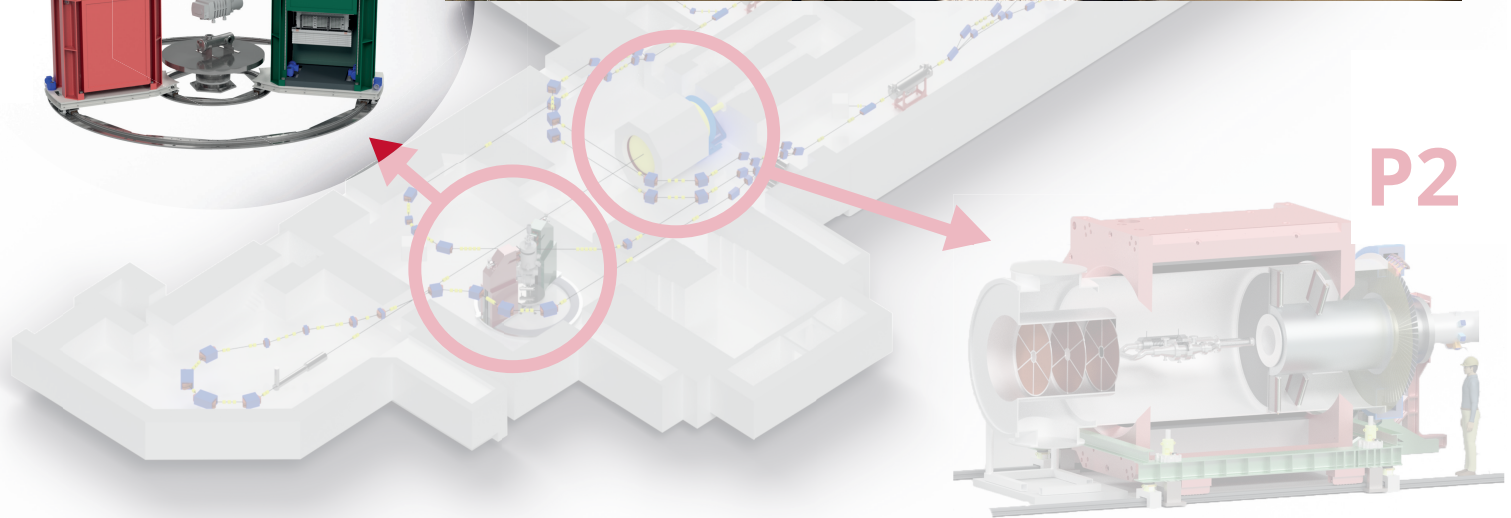
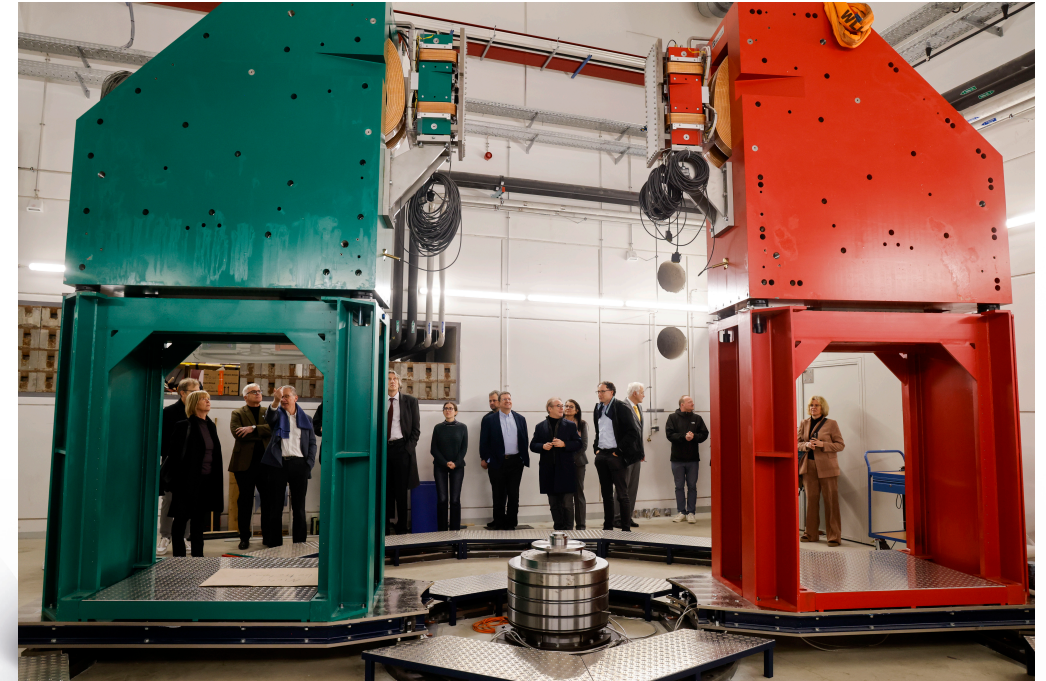
**M**ainz **E**nergy-Recovering **S**uperconducting **A**ccelerator

# MAGIX

- High-resolution spectrometers ( $\Delta p/p \leq 10^{-4}$ )
- Cryogenic **windowless** gas-jet target
- Detection of **low-energy recoil particles**

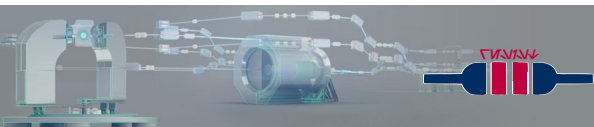
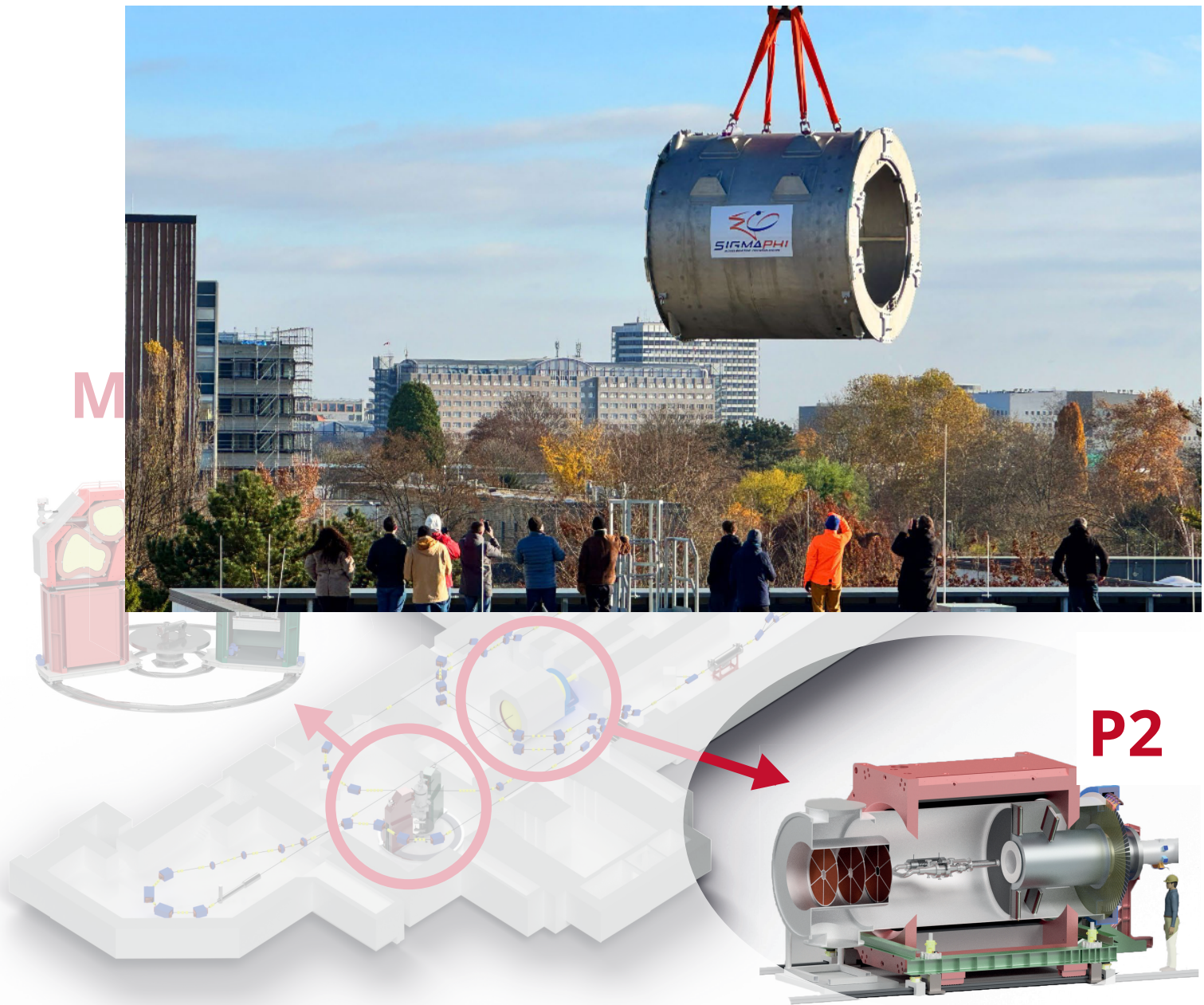


**MAGIX**



# P2

- $L \approx 2.4 \cdot 10^{39} \text{ s}^{-1} \text{ cm}^{-2}$  for 60 cm H target
- **Solenoid spectrometer** with integrating Cherenkov detectors
- State of the art digitization electronics for PV experiment: **transient digitizer**
- Momentum transfer determined by **HV-MAPS tracking detectors**
- **MicroMegas** tracking detectors for asymmetry measurements at backward angles.



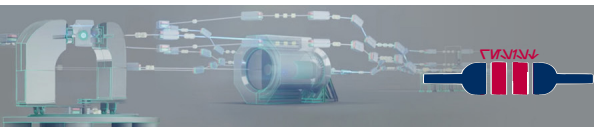


# New experimental opportunities

MESA - Mainz Energy-Recovering Superconducting Accelerator

- Energy-recovery mode for **high intensity** (MAGIX)
- Extracted-beam mode for **high polarisation** (P2)
- Beam dump experiment (**DarkMESA**)

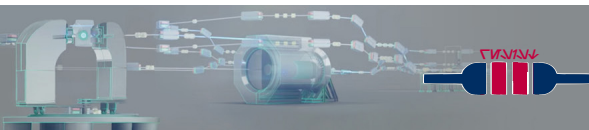
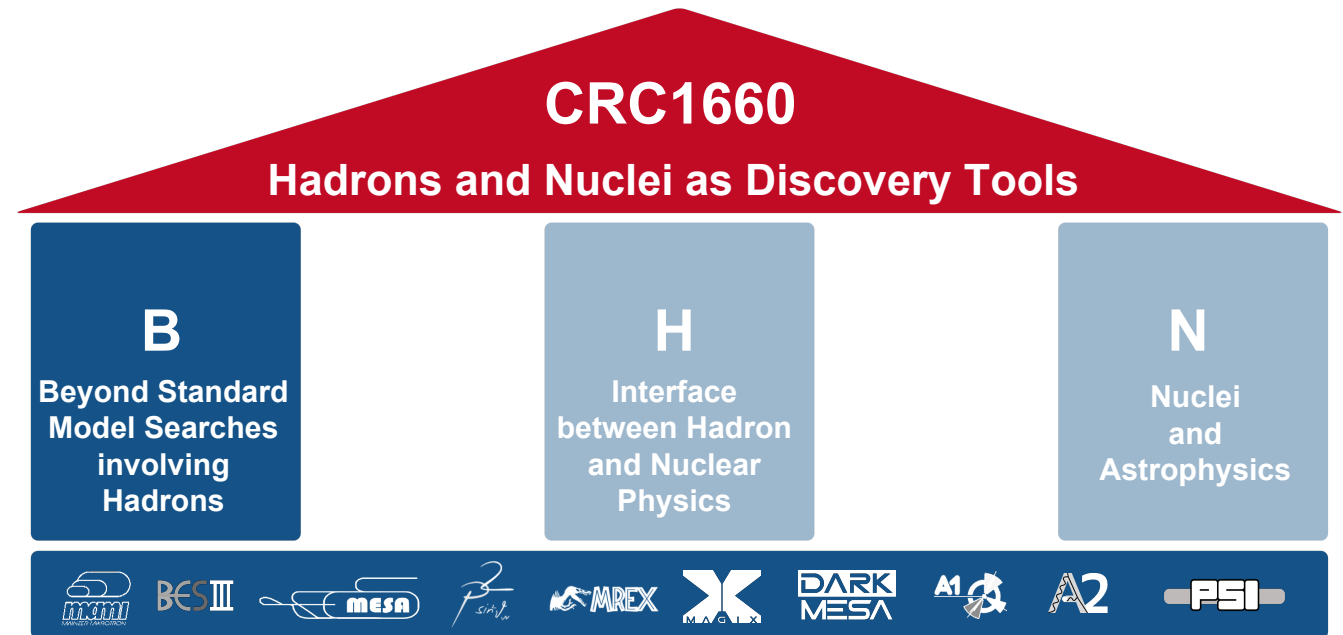
**Multi-purpose facility for next-generation low-energy precision physics experiments**



# Pillar B

## Big questions:

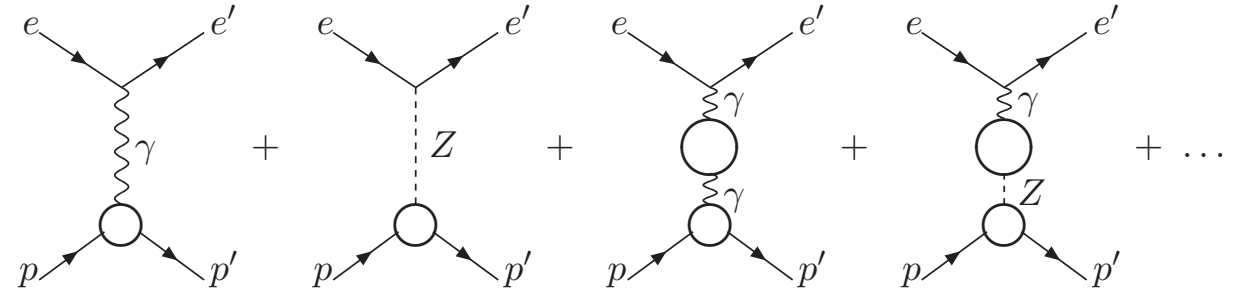
Do we find cracks in the SM, and what is the nature of dark matter?



# Pillar B

## Big questions:

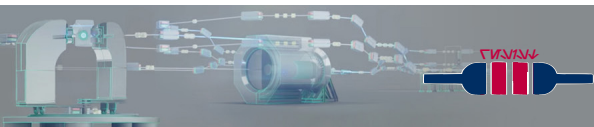
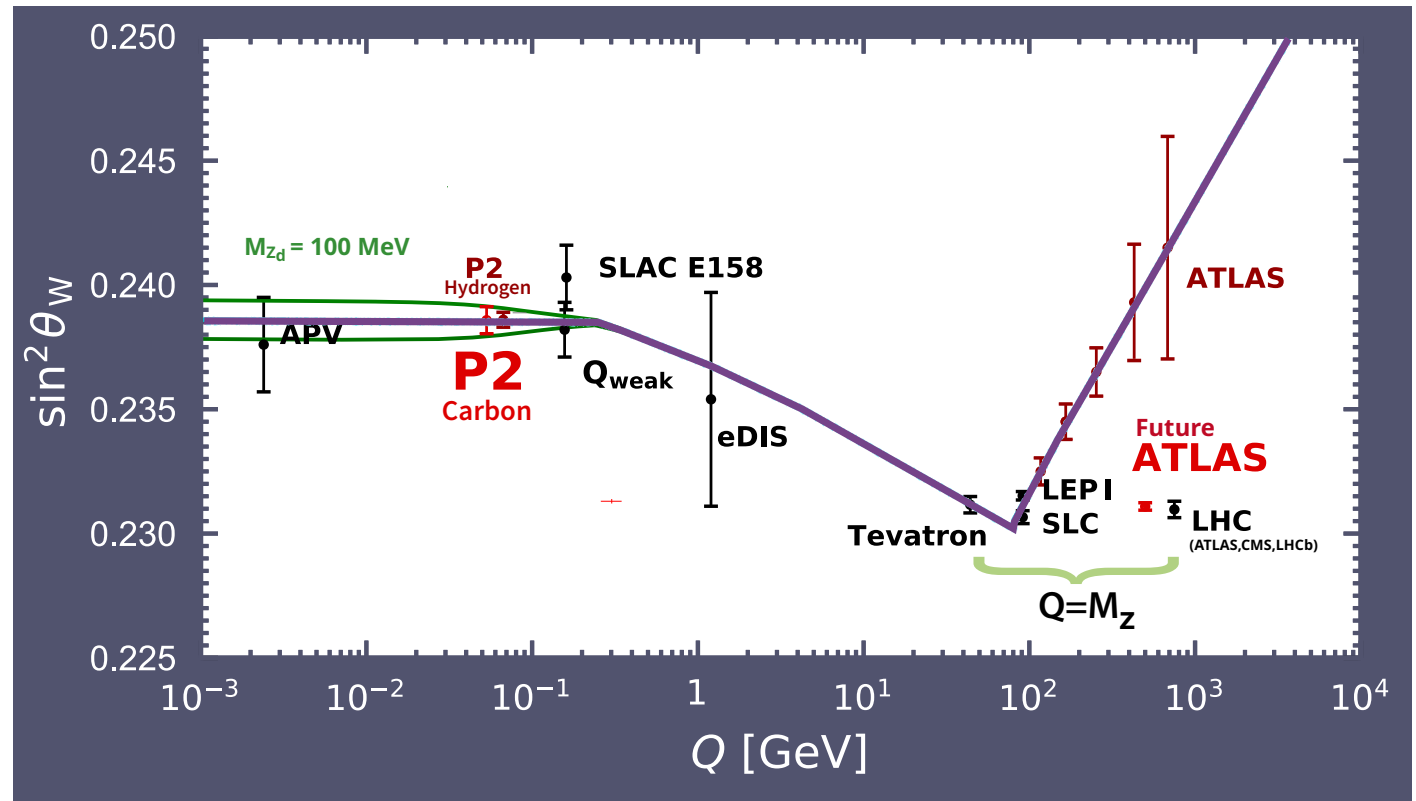
Do we find cracks in the SM, and what is the nature of dark matter?



Dependence on energy scale  
**constrained by SM**

Tension between  
 measurements at **Z-pole**

Low-energy **sensitive to new physics**

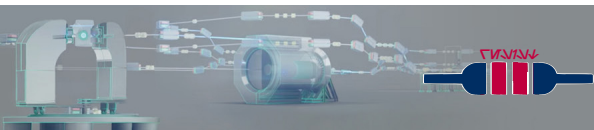
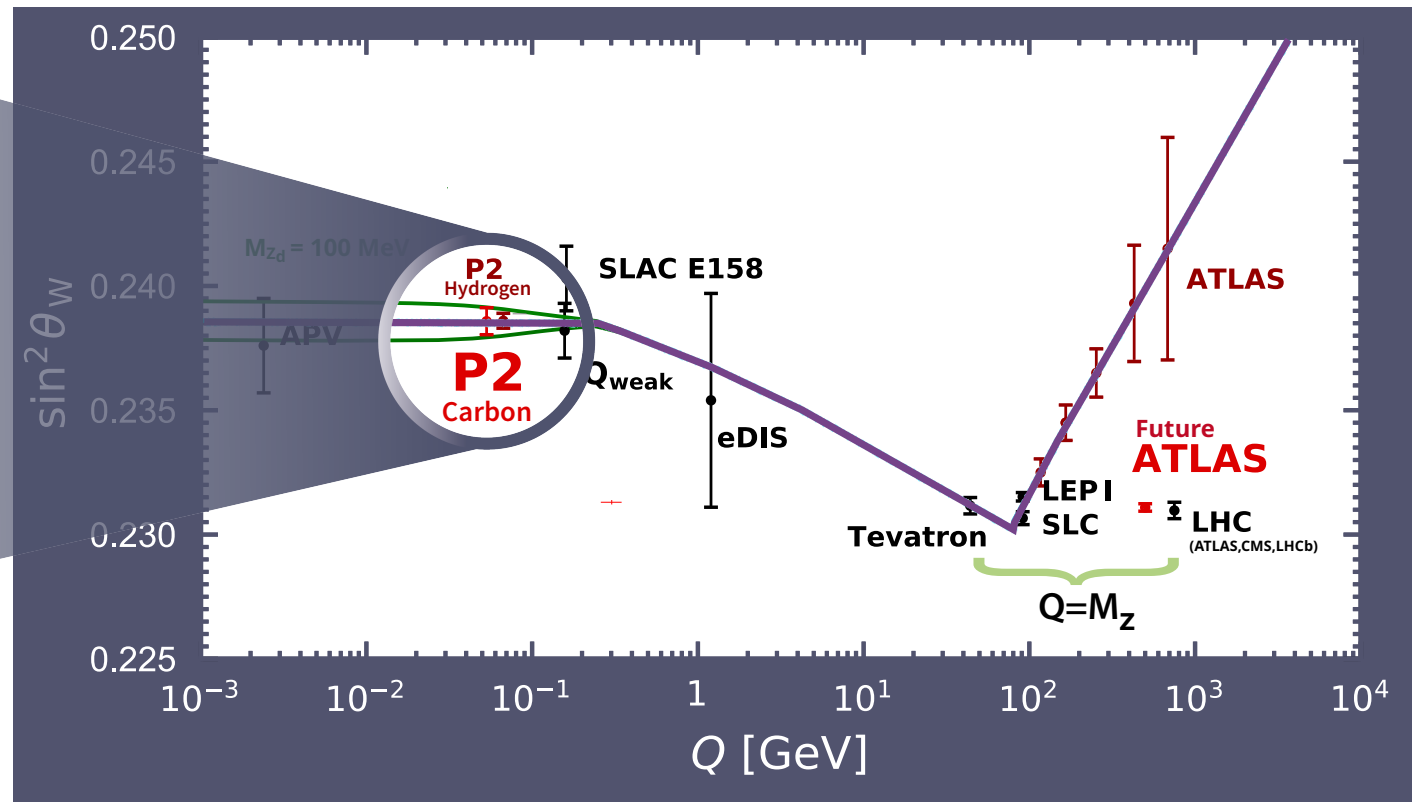
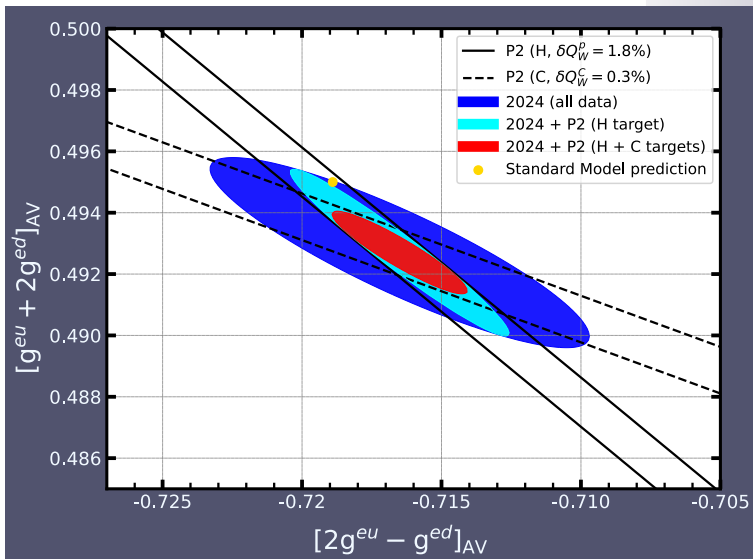
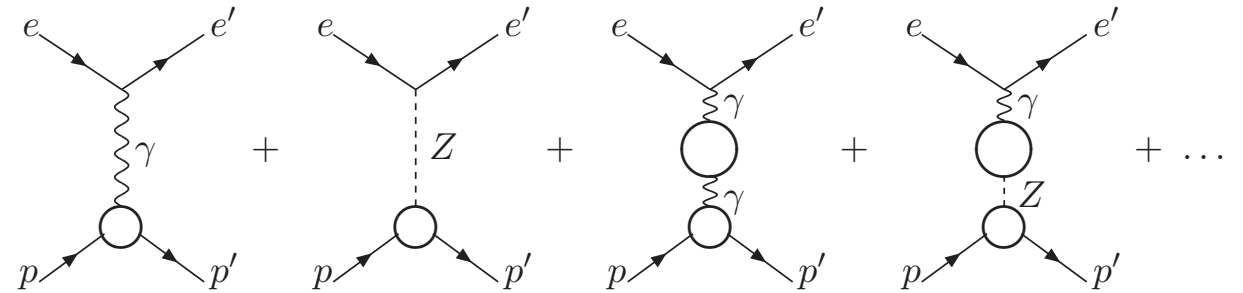




# Pillar B

## Big questions:

Do we find cracks in the SM, and what is the nature of dark matter?

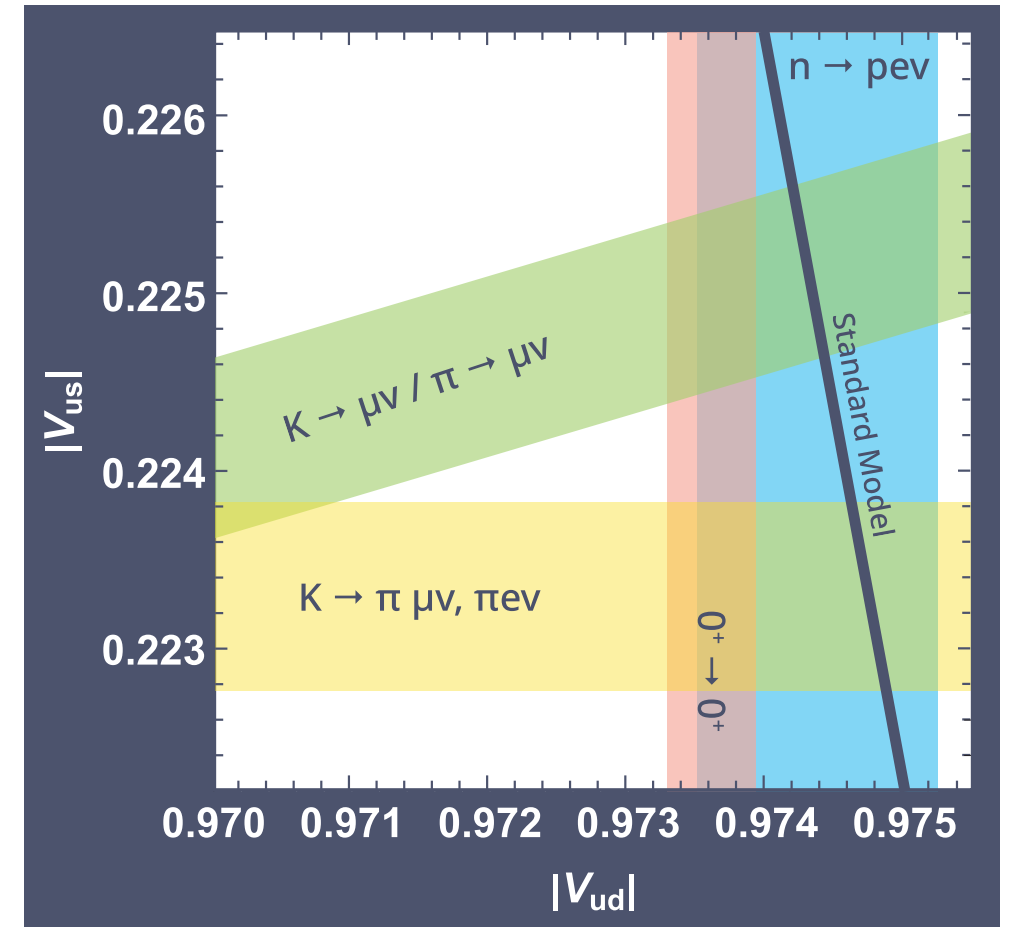
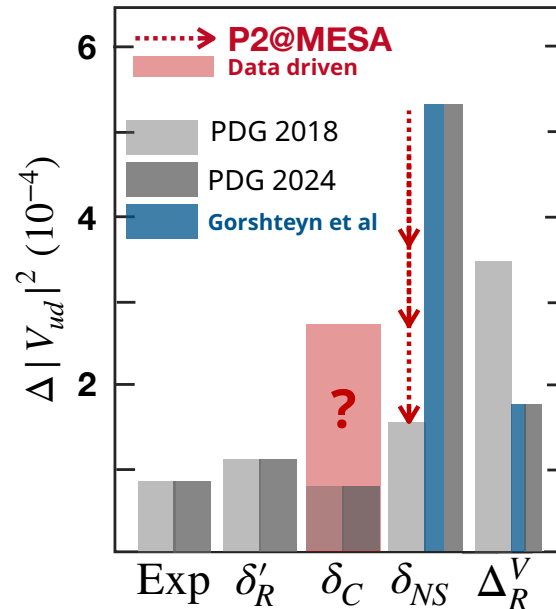


# Pillar B

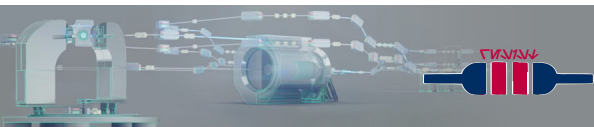
## Big questions:

Do we find cracks in the SM, and what is the nature of dark matter?

- Data driven constraints from **weak radius measurements**
- Complements precision measurement of **neutron lifetime** and improved **branching ratio of kaon decays**



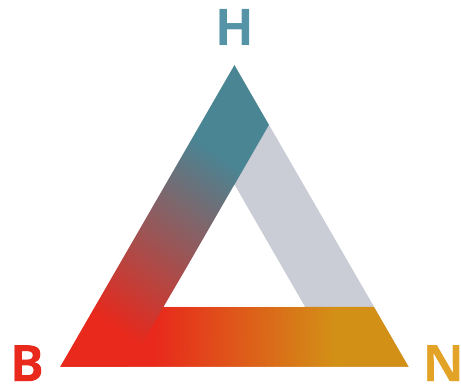
Overconstraining the CKM matrix at the per mille level



# Pillar B

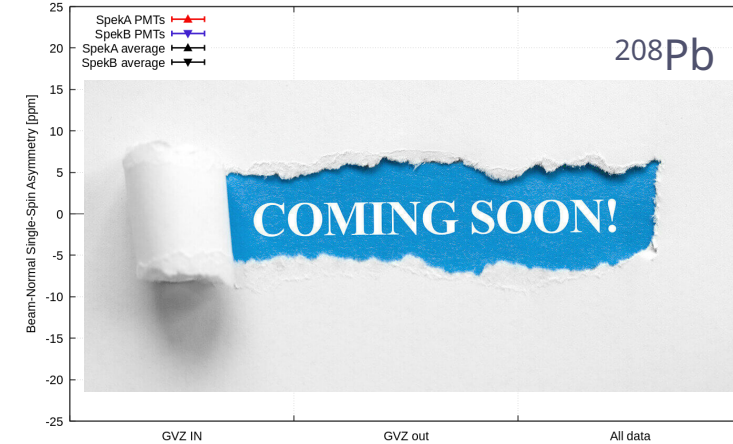
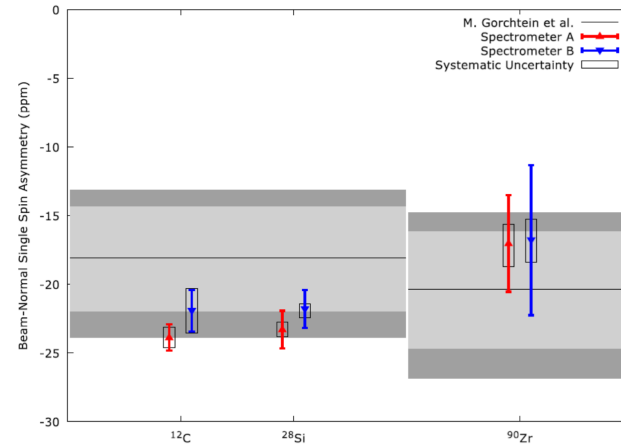
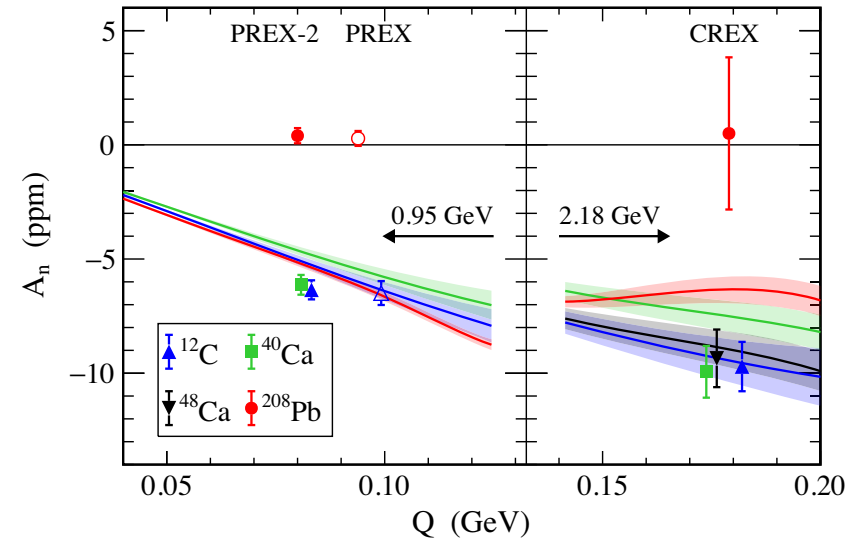
## Big questions:

Do we find cracks in the SM, and what is the nature of dark matter?

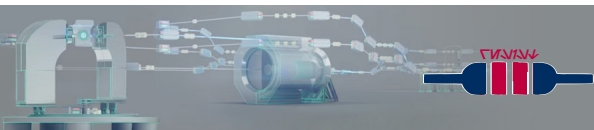


## Interplay with H and N:

Advance precision of hadronic and nuclear processes and properties



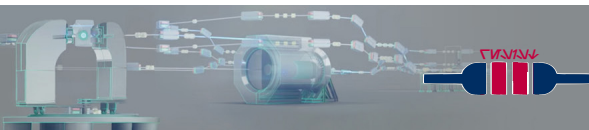
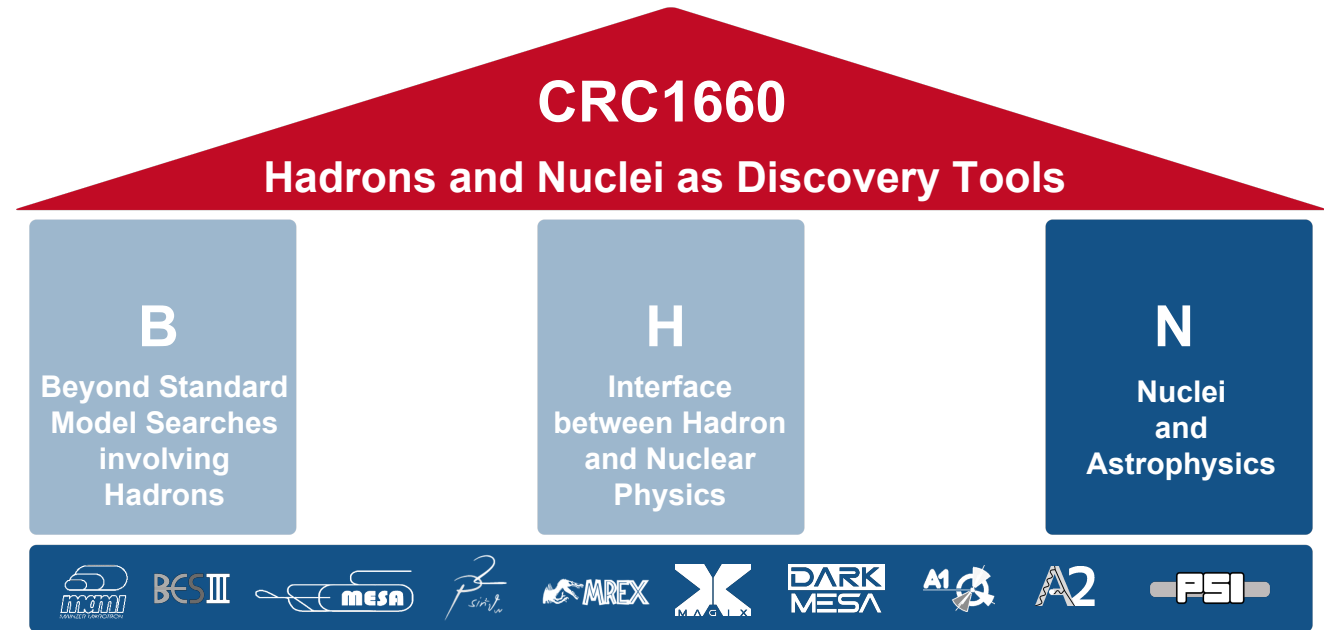
True discrepancy or insufficient understanding?



# Pillar N

## Big questions:

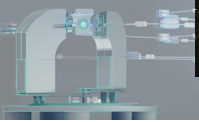
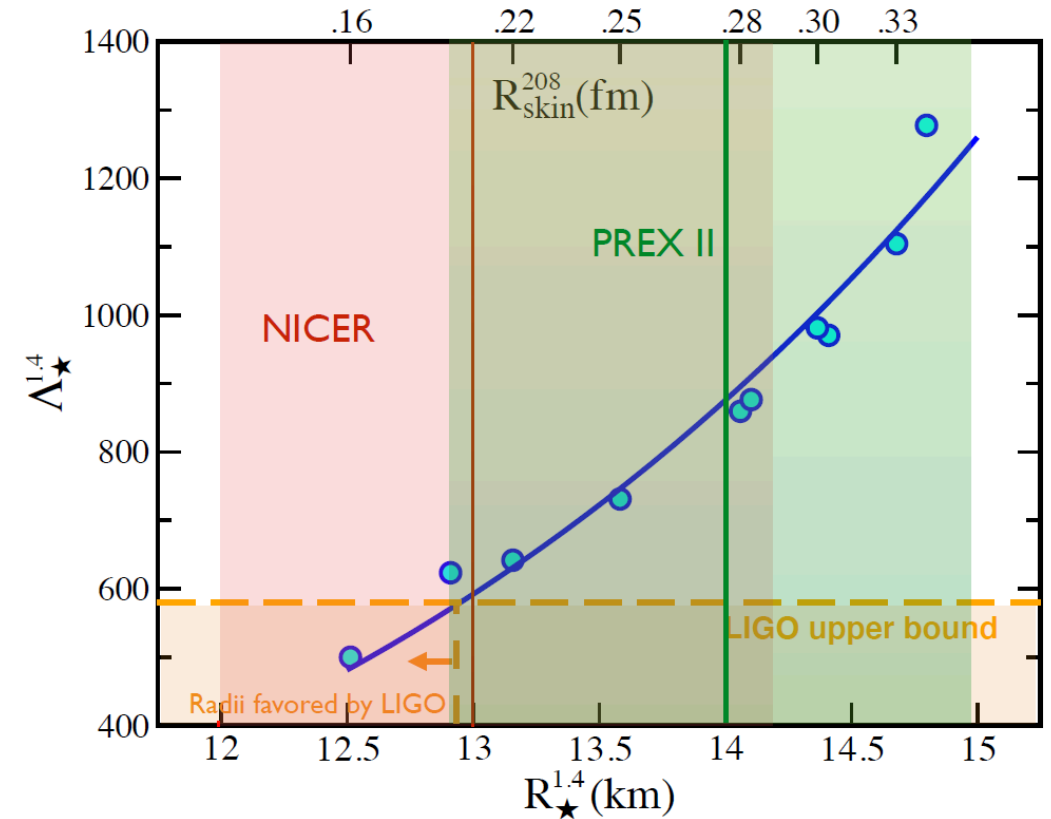
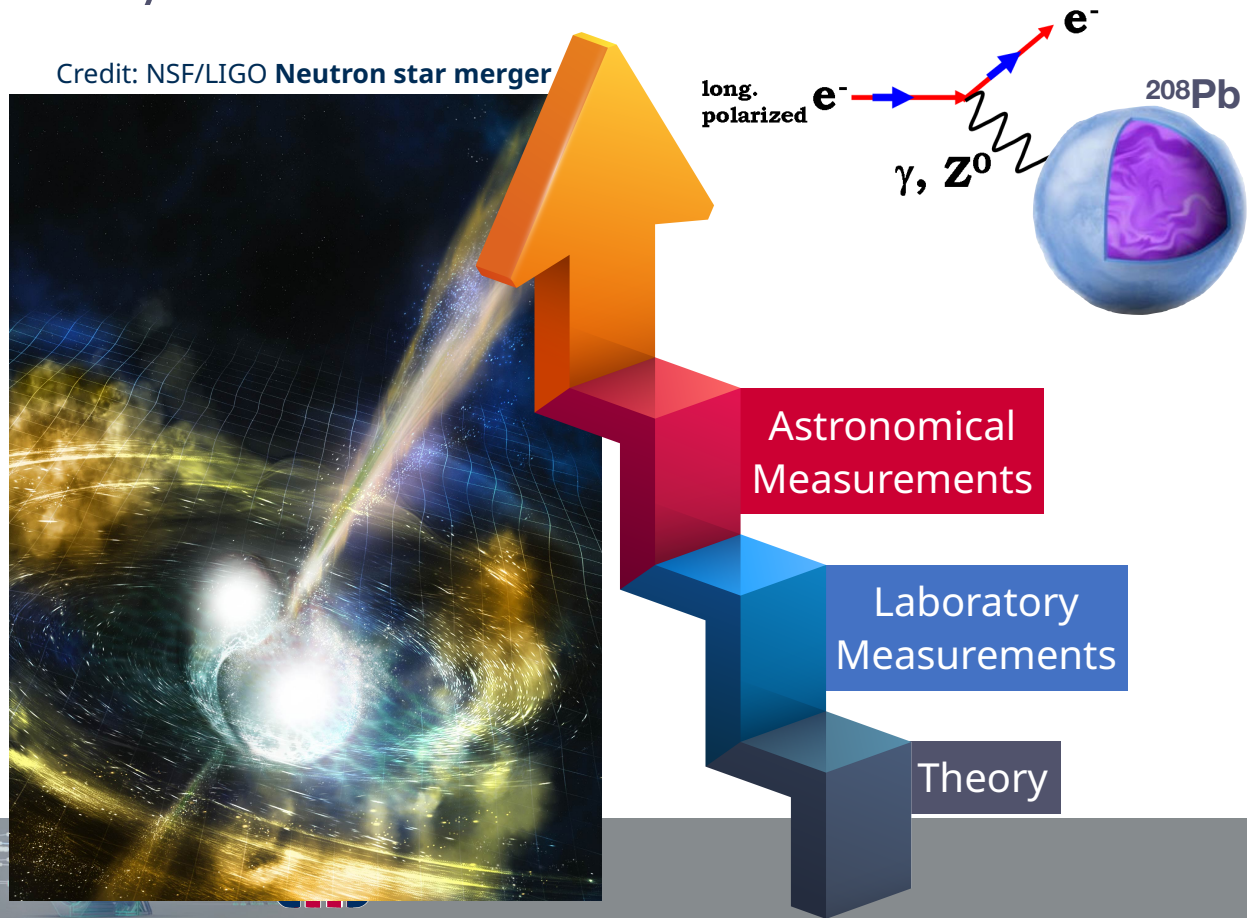
Do we understand nuclear equation of state, stellar nucleosynthesis, few-body nuclear systems?



# Pillar N

## Big questions:

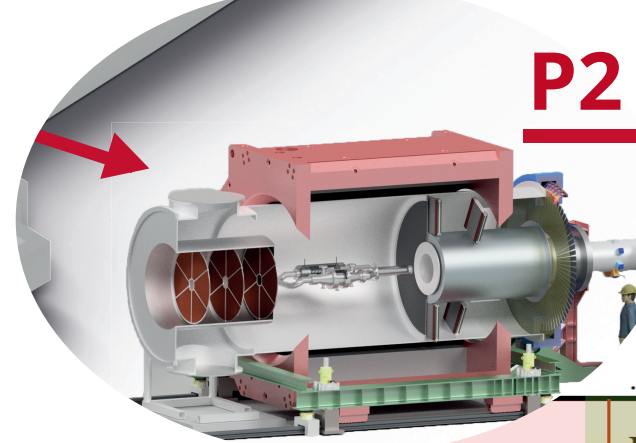
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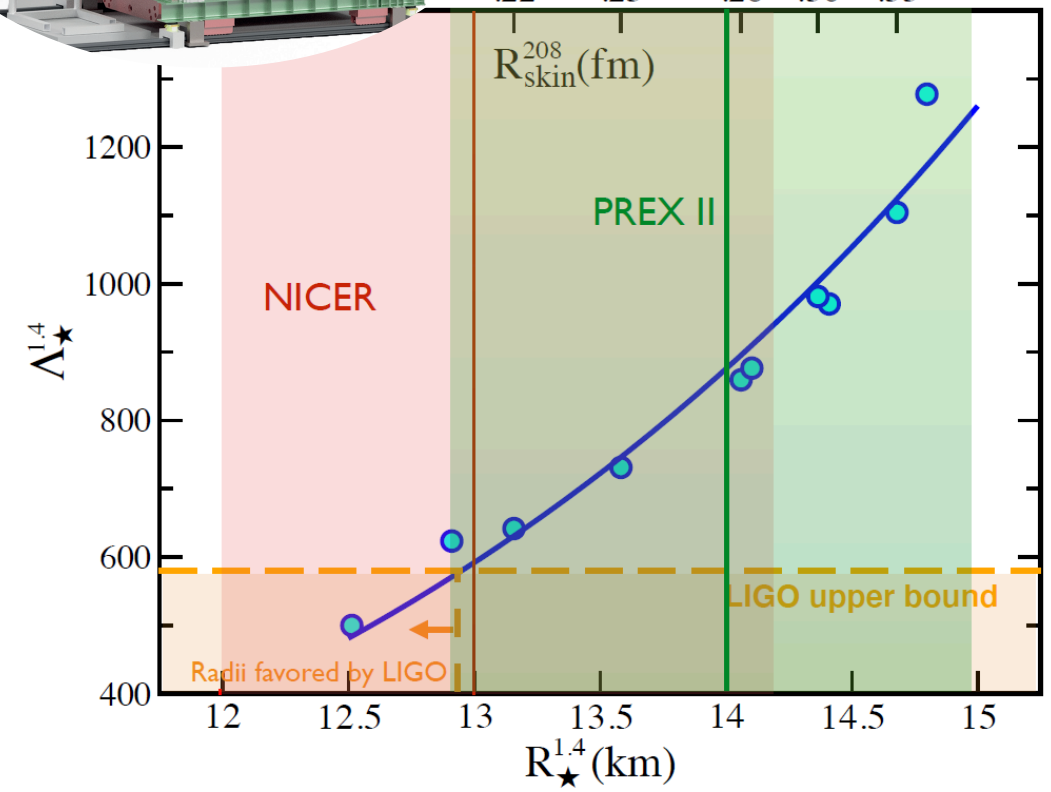
# Pillar N

## Big questions:

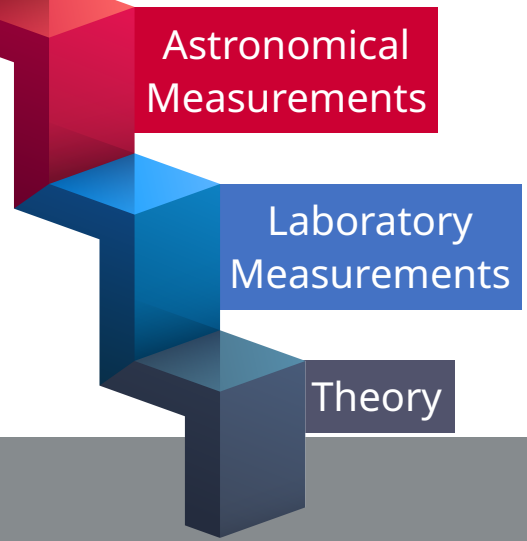
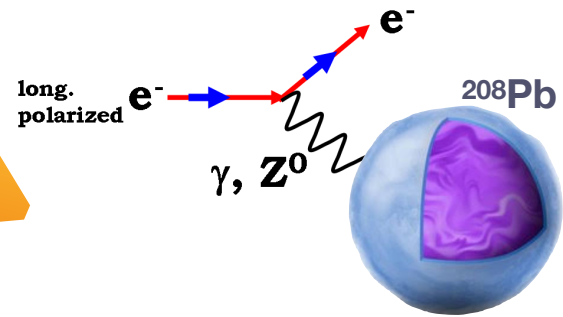
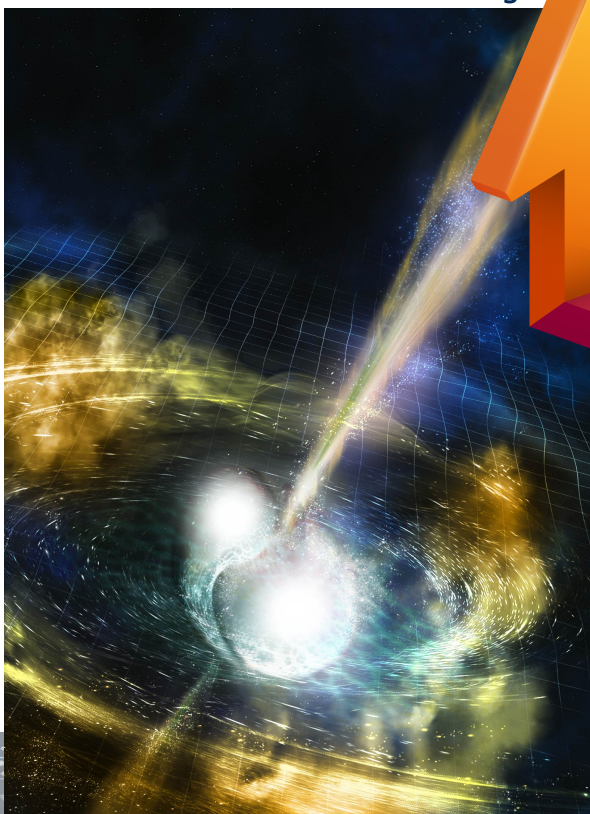
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**P2**



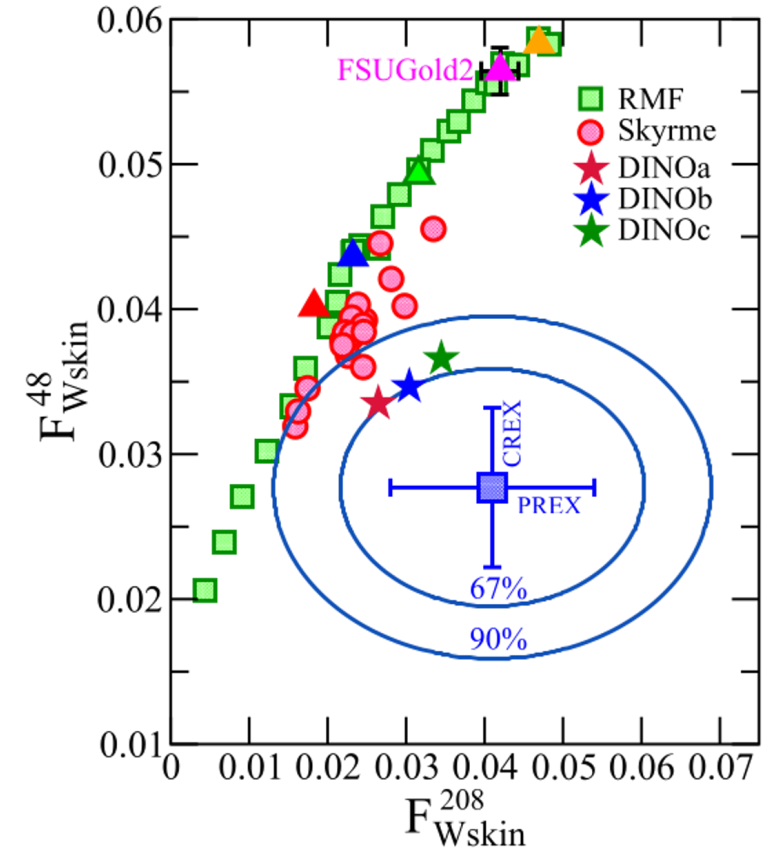
Credit: NSF/LIGO Neutron star merger



# Pillar N

## Big questions:

Do we understand nuclear equation of state, stellar nucleosynthesis, few-body nuclear systems?

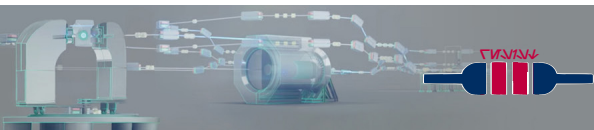


### Combined Theoretical Analysis of the Parity-Violating Asymmetry for $^{48}\text{Ca}$ and $^{208}\text{Pb}$

Paul-Gerhard Reinhard<sup>1,\*</sup>, Xavier Roca-Maza<sup>2,†</sup> and Witold Nazarewicz<sup>3,‡</sup>

*“We conclude that the simultaneous accurate description of the PV asymmetry in calcium and lead cannot be achieved by our models that accommodate a pool of global nuclear properties ...”*

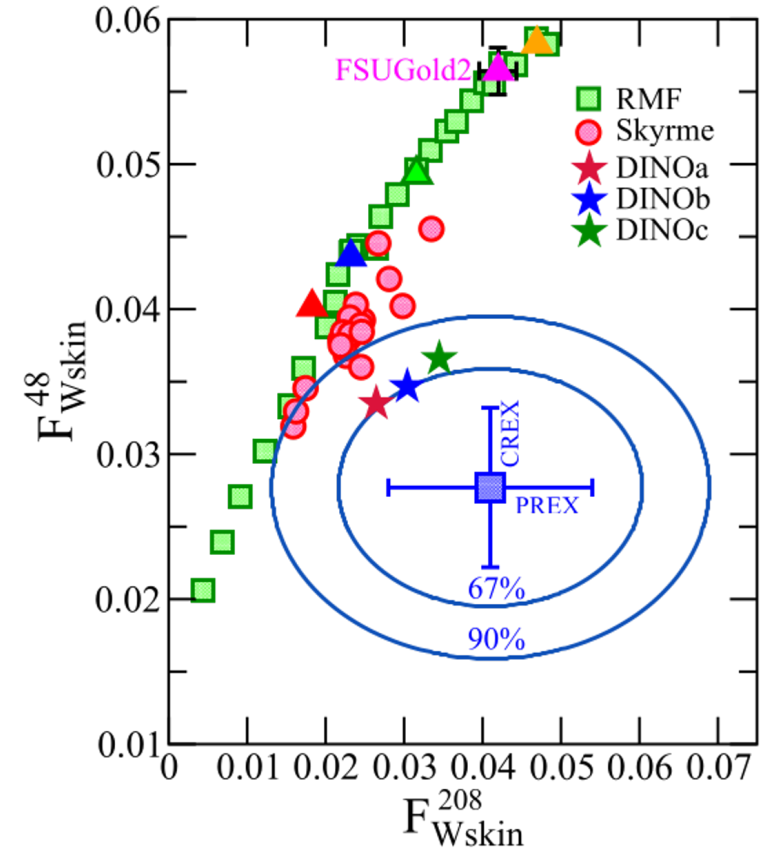
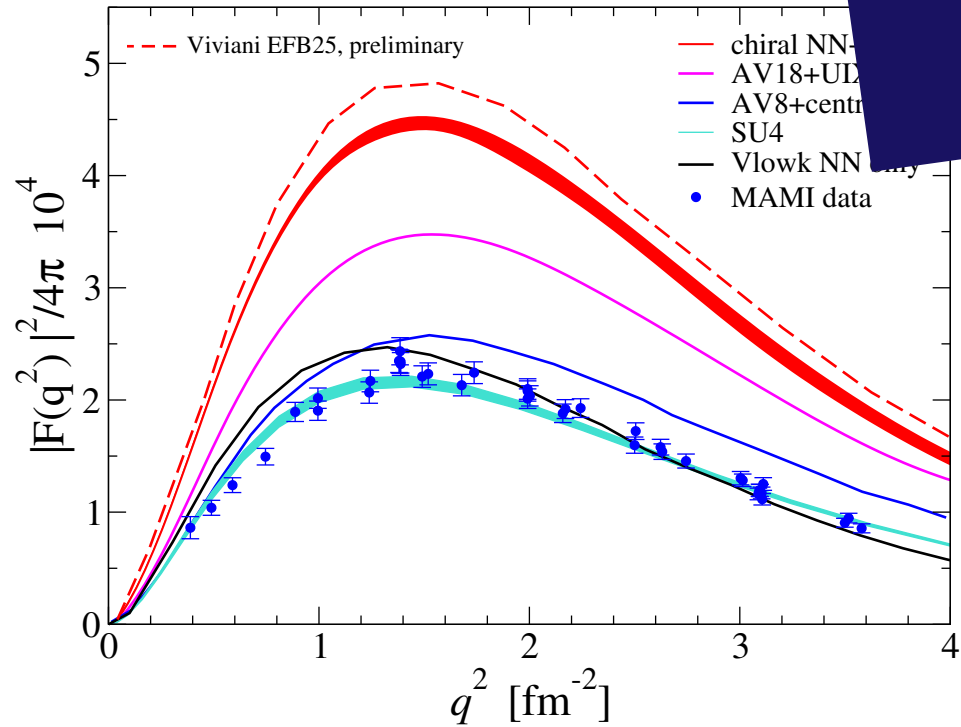
PRL 129, 232501 (2022)



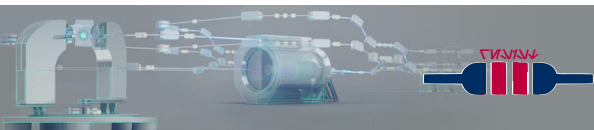
# Pillar N

## Big questions:

Do we understand nuclear equation of state, stellar nucleosynthesis, few-body nuclear systems?



How precisely do we understand the strong interaction to make sense of the differences we see?

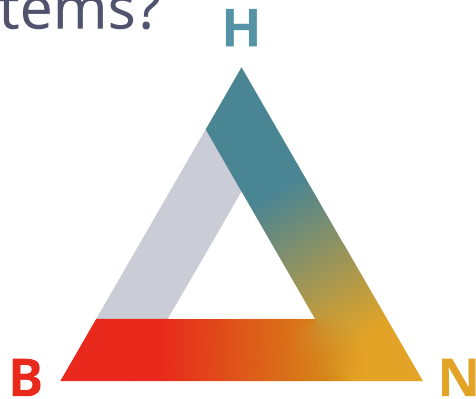




## Pillar N

### Big questions:

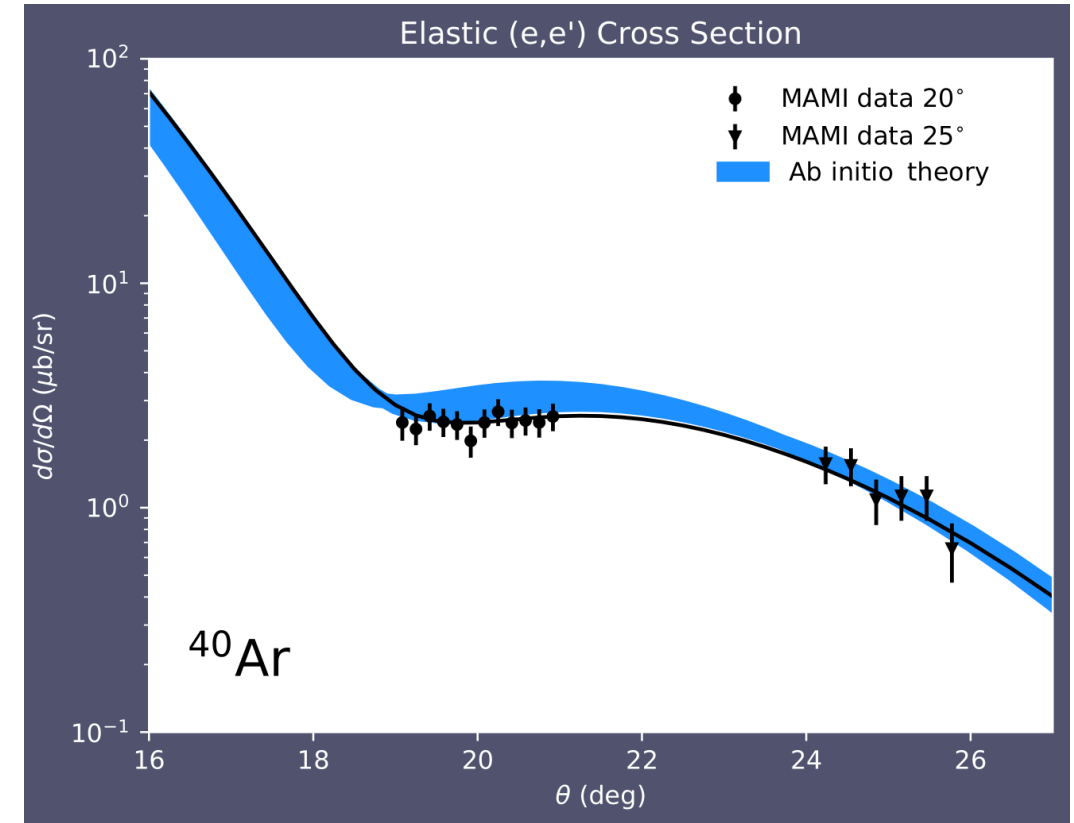
Do we understand nuclear equation of state, stellar nucleosynthesis, few-body nuclear systems?



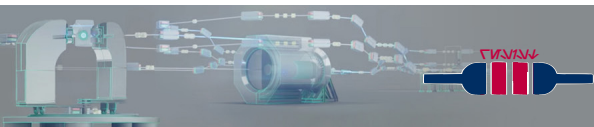
### Interplay with B and H:

Nuclear targets and nuclear theory also crucial in H and B

High-precision experiments anchored by **same underlying theory: QCD, chiral EFT**



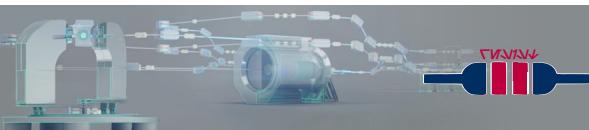
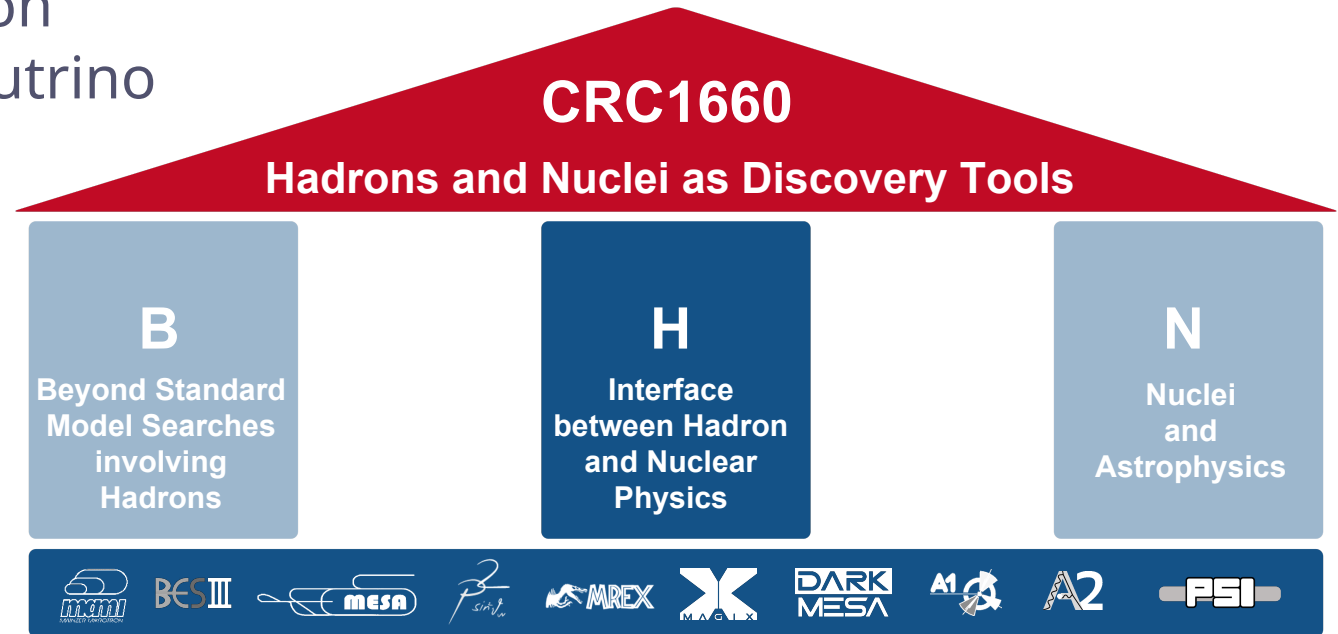
► Interpretation of **neutrino oscillation data** requires precise **neutrino-nucleus cross sections** as input.



# Pillar H

## Big questions:

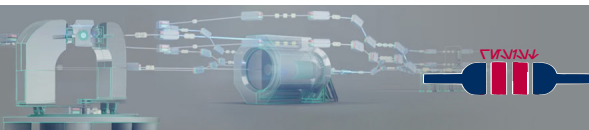
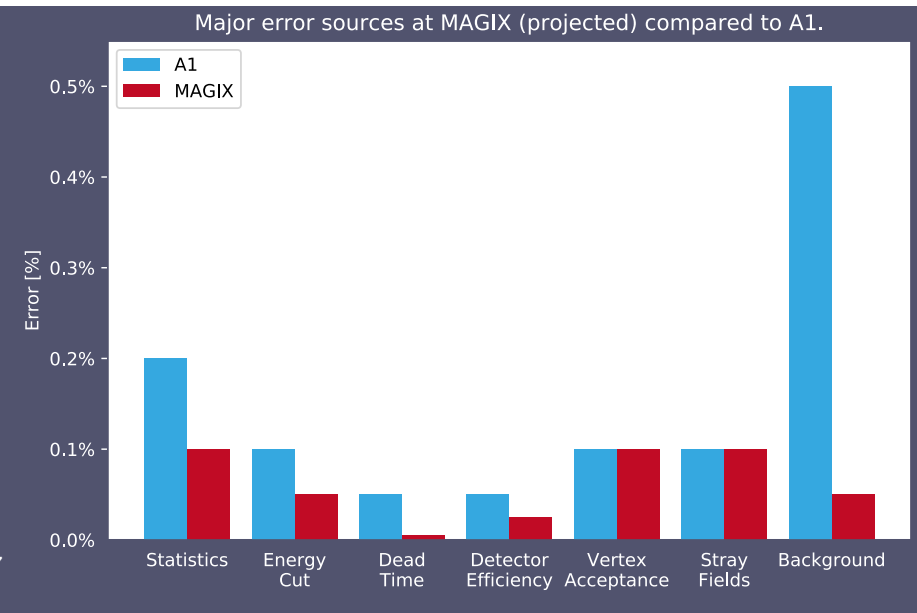
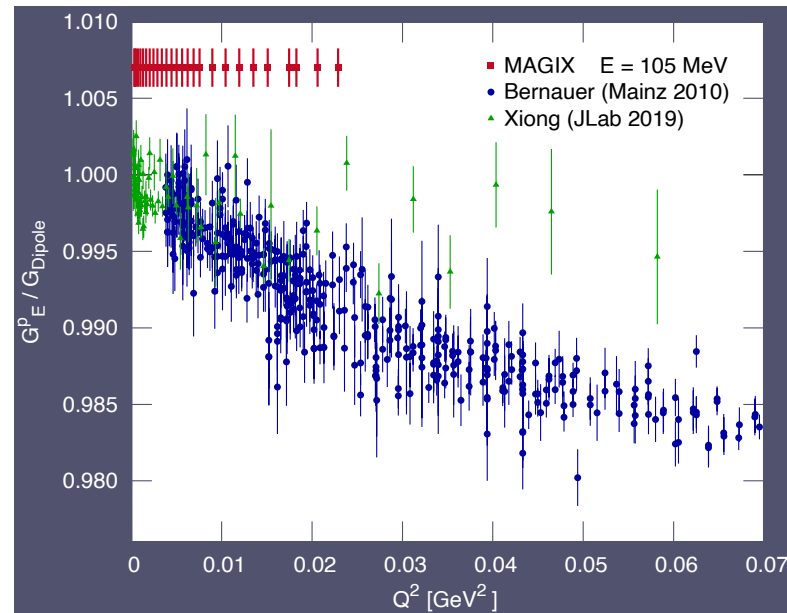
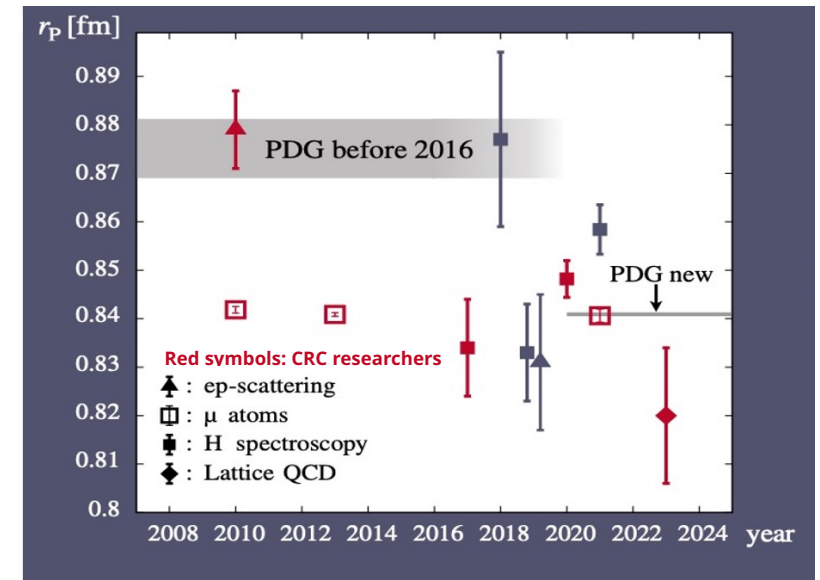
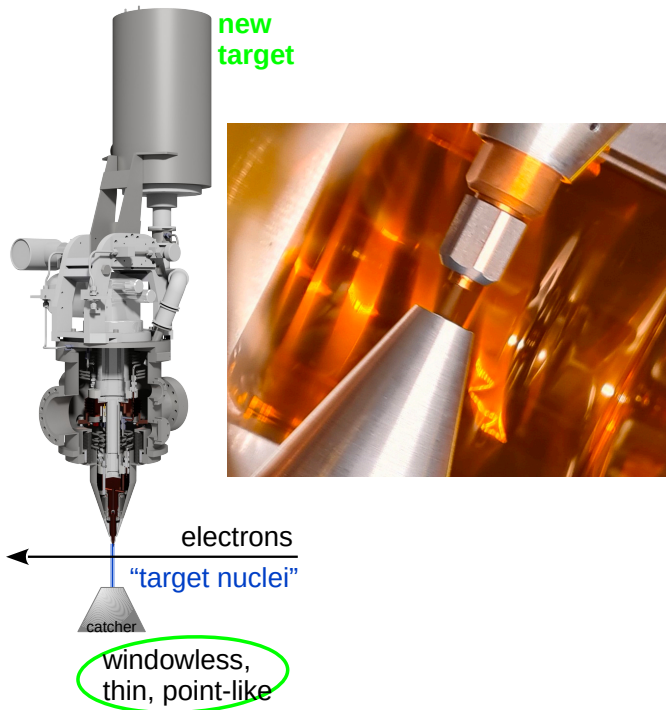
Do we know hadron structure at precision needed for atomic spectroscopy and neutrino cross sections ?



# Pillar H

## Big questions:

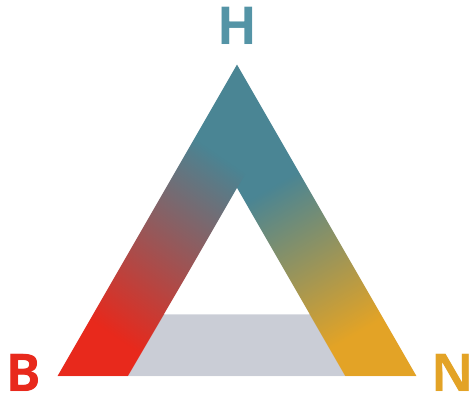
Do we know hadron structure at precision needed for atomic spectroscopy and neutrino cross sections ?



# Pillar H

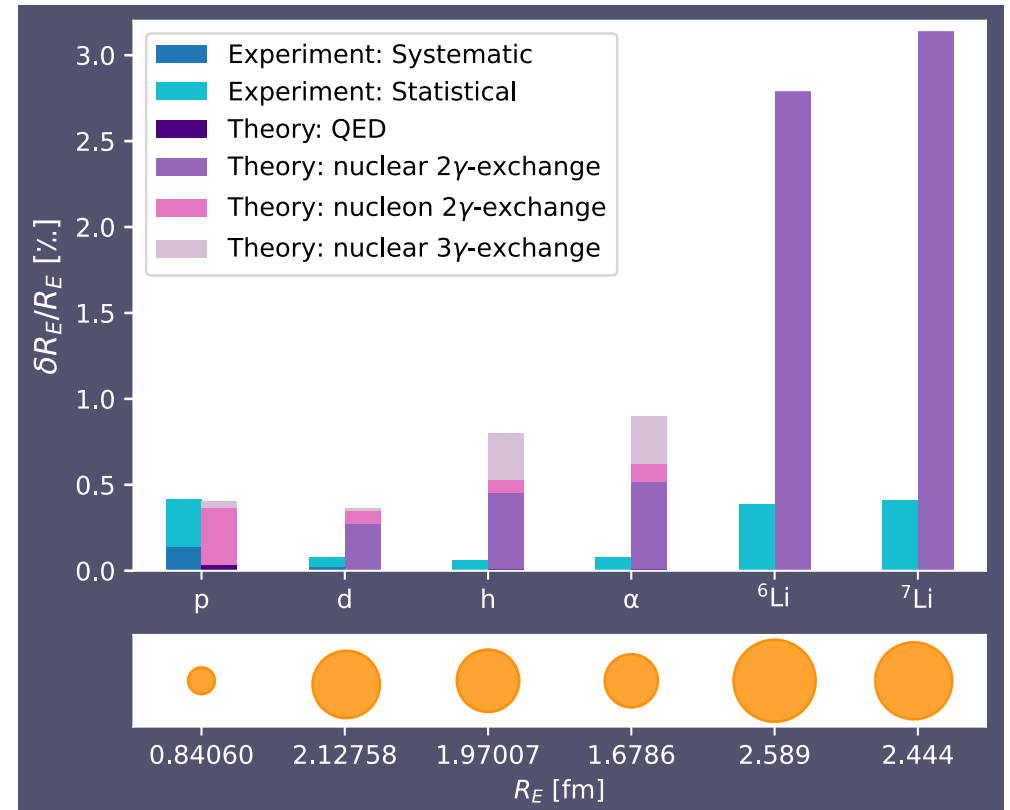
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Do we know hadron structure at precision needed for atomic spectroscopy and neutrino cross sections ?

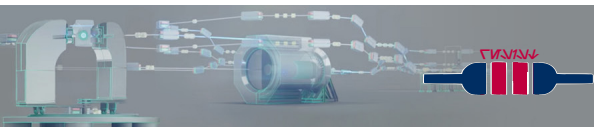


## Interplay with B and N:

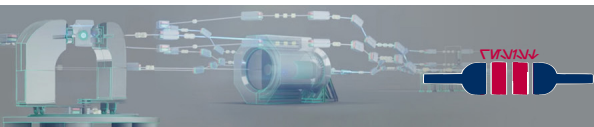
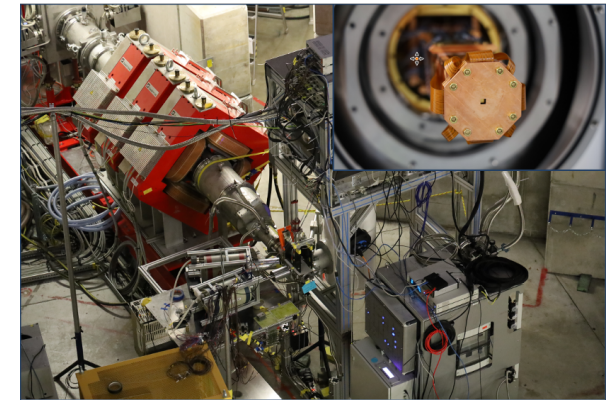
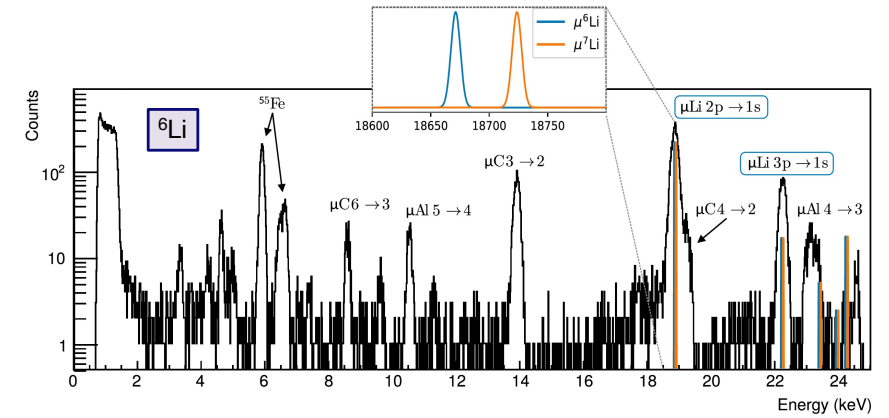
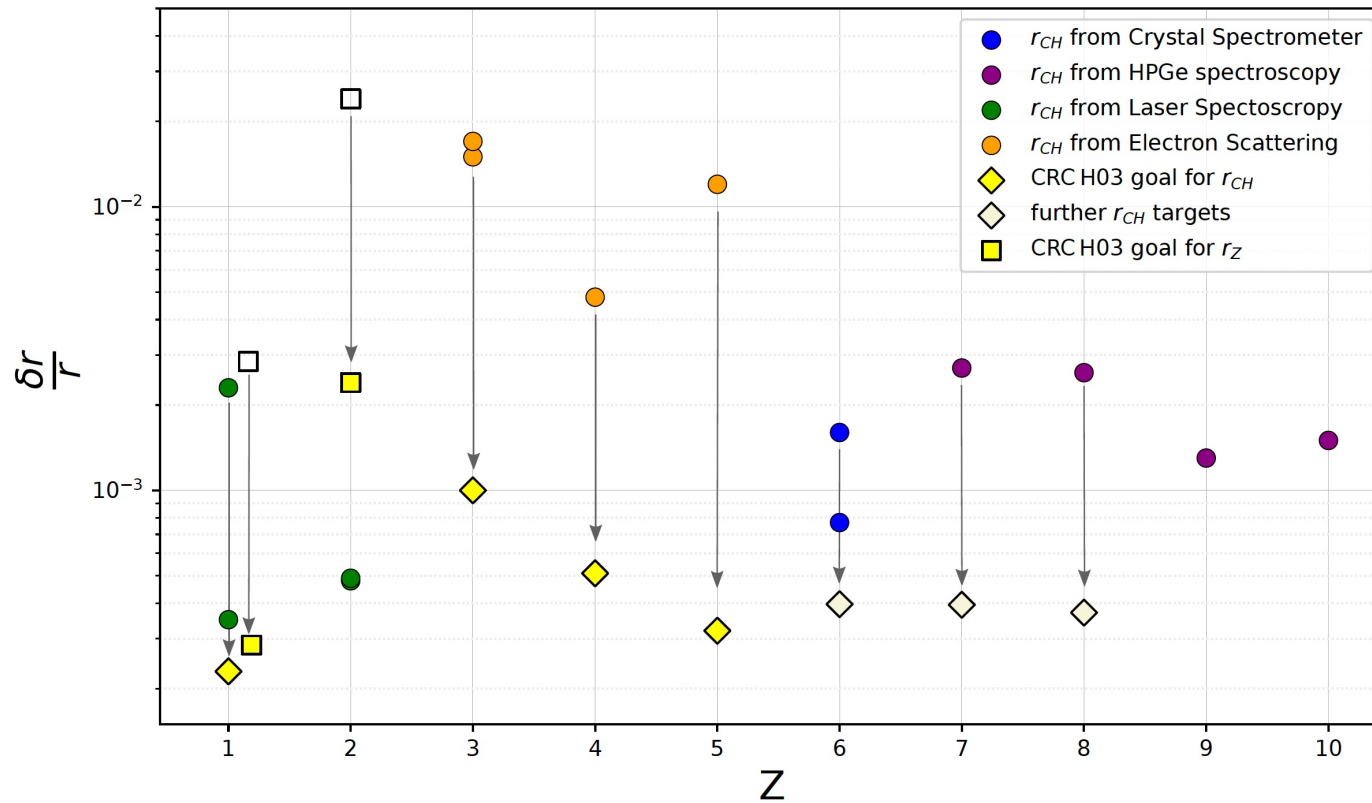
Same theory: lattice QCD, effective field theories (EFTs) used in hadronic corrections in B and benchmarked by N



Nuclear radii measured in **muonic spectroscopy** will benchmark nuclear theory (TPE on nucleon and nuclear targets!)



# Complementing MESA



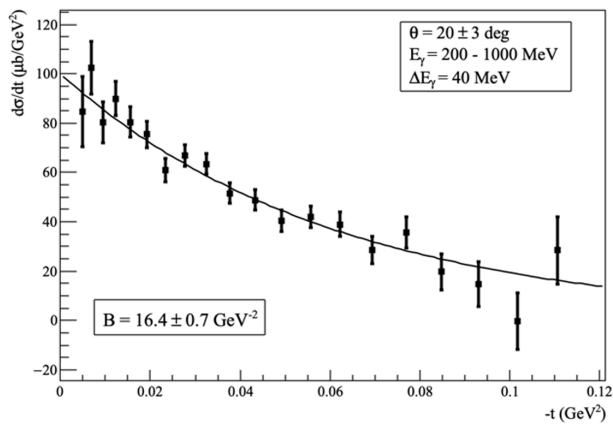
# Complementing MESA



Gorchtein and Horowitz, PRC 77, 044606 (2008).

$$A_n = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \propto g_N(Q^2) \propto e^{-BQ^2/2}$$

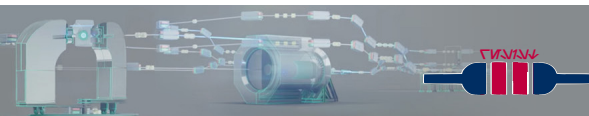
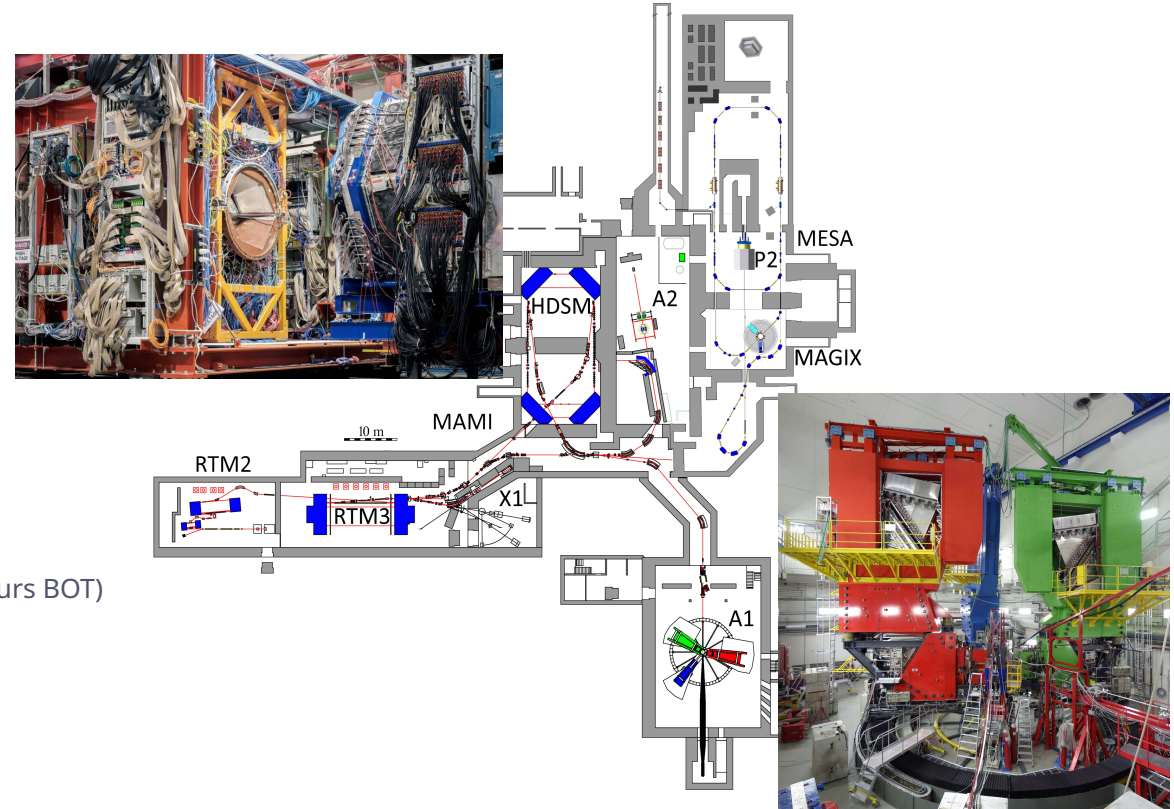
$g_N(Q^2)$  phenomenological Compton Form Factor for nucleus N and B Compton Slope Parameter



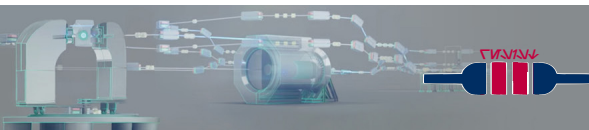
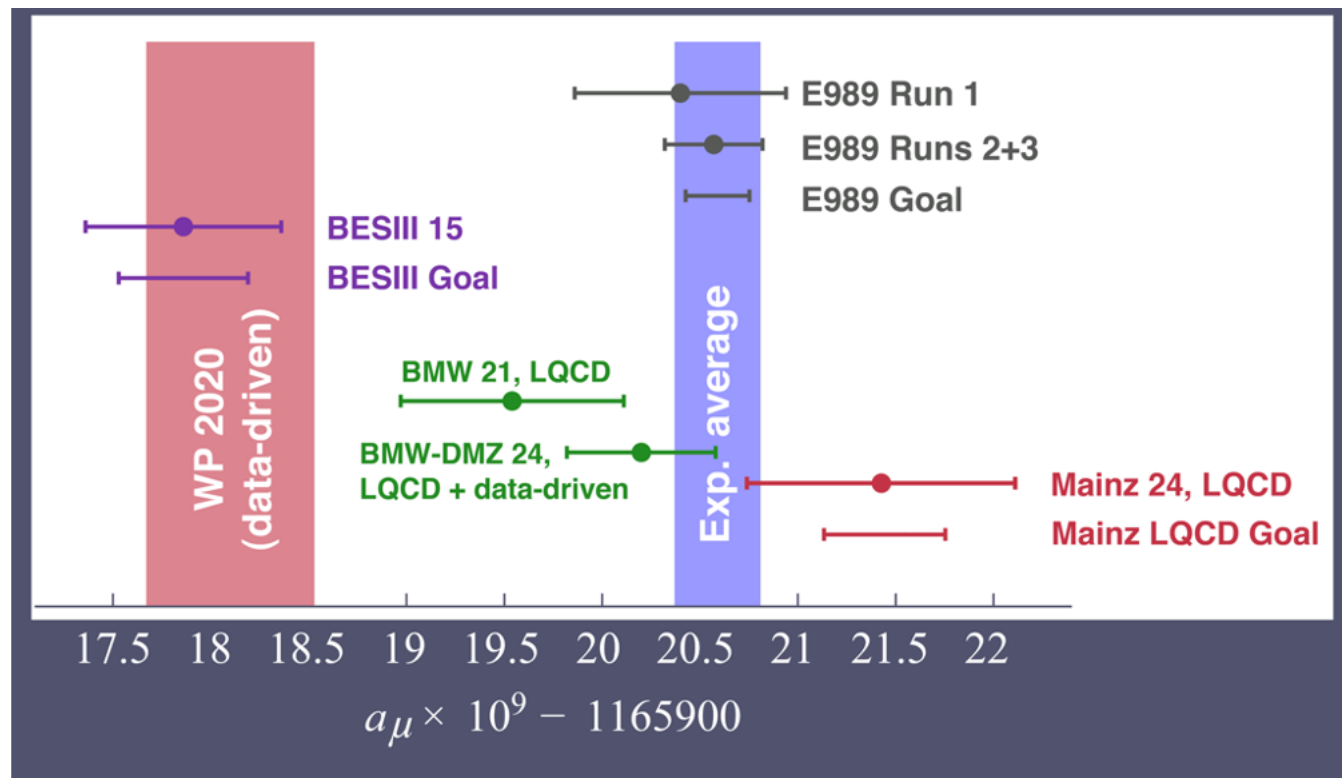
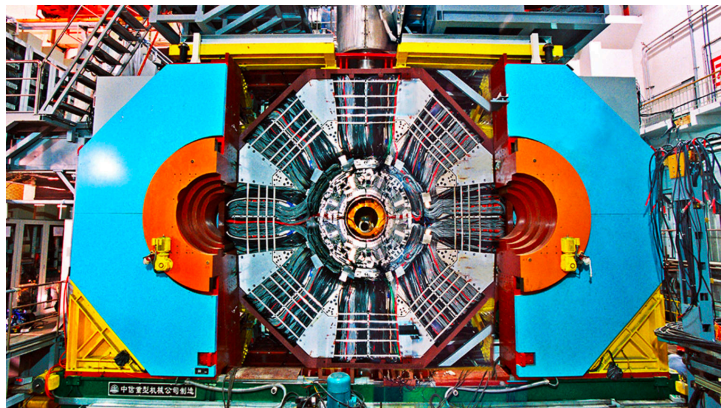
$$\frac{d\sigma}{dt} \approx \left[ \frac{d\sigma}{dt} \right]_{t=0} \times e^{Bt}$$

Projected results CATS@A2 <sup>12</sup>C (200 hours BOT)

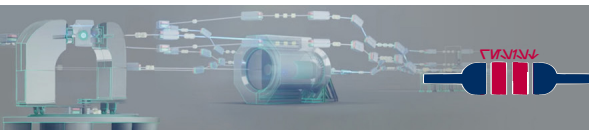
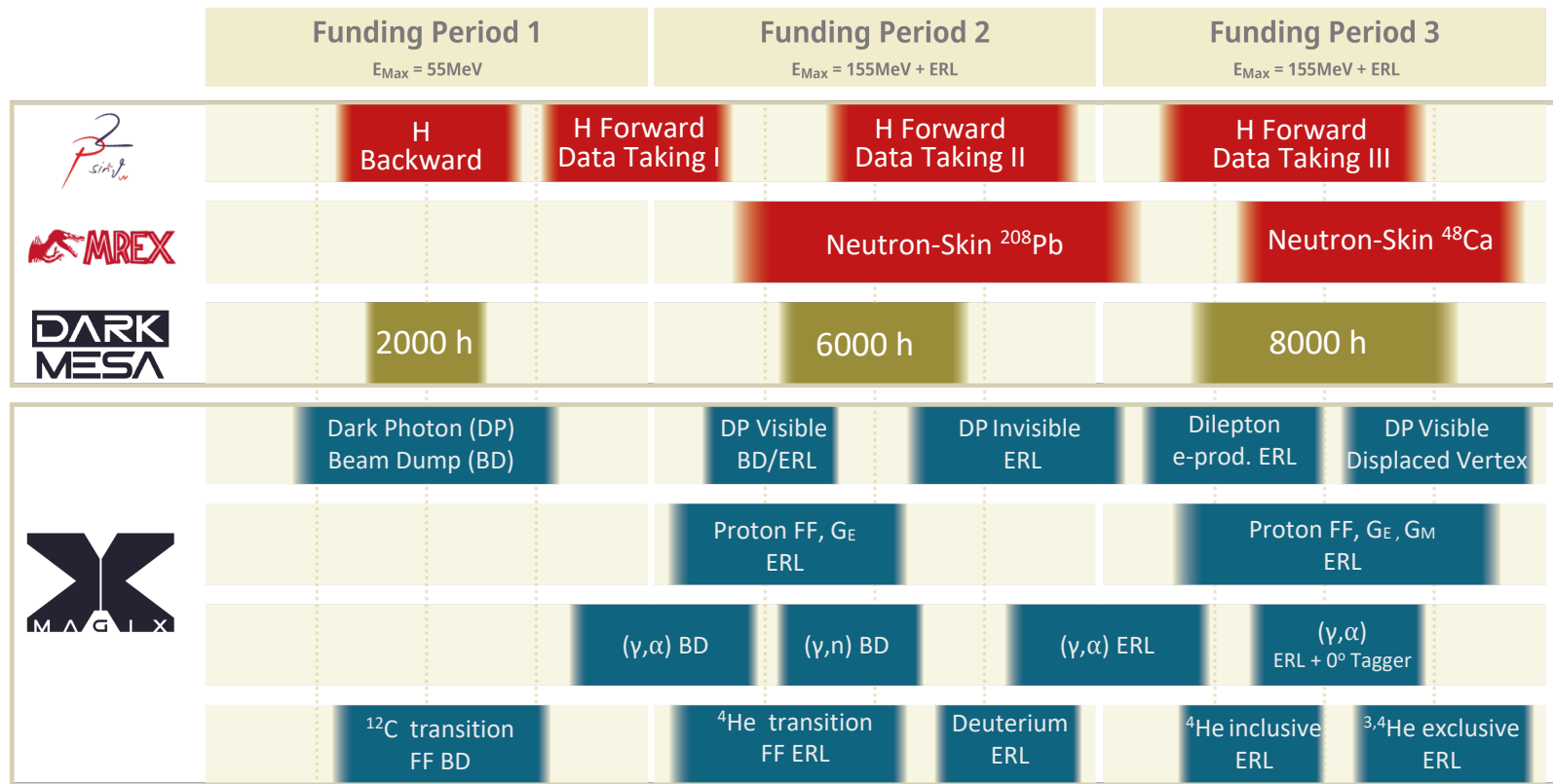
$$\frac{\Delta B}{B} \approx 5\%$$



# Complementing MESA

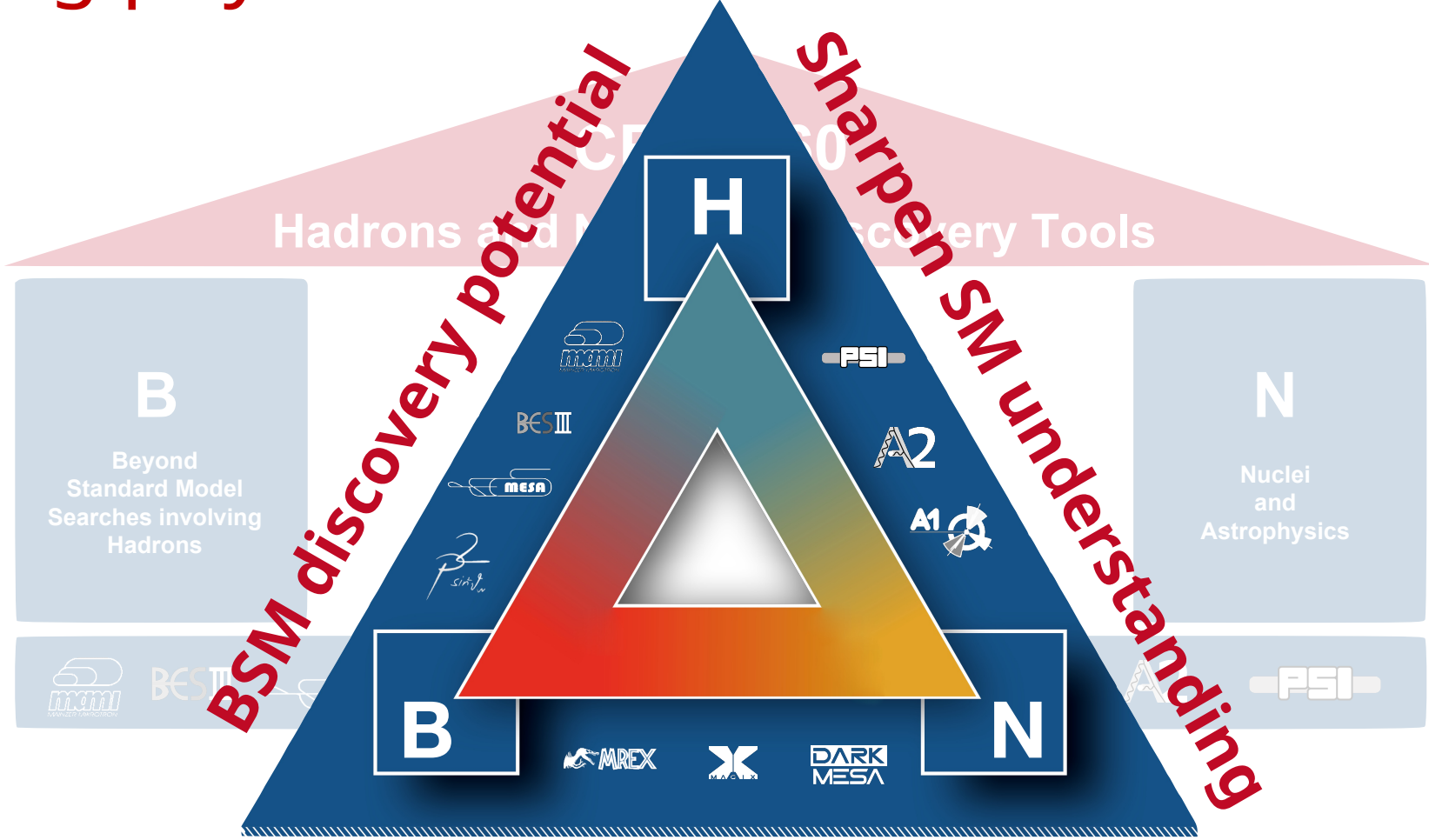


# Timeplan





# Unlocking physics with hadrons and nuclei...



...diversity drives discovery ...

