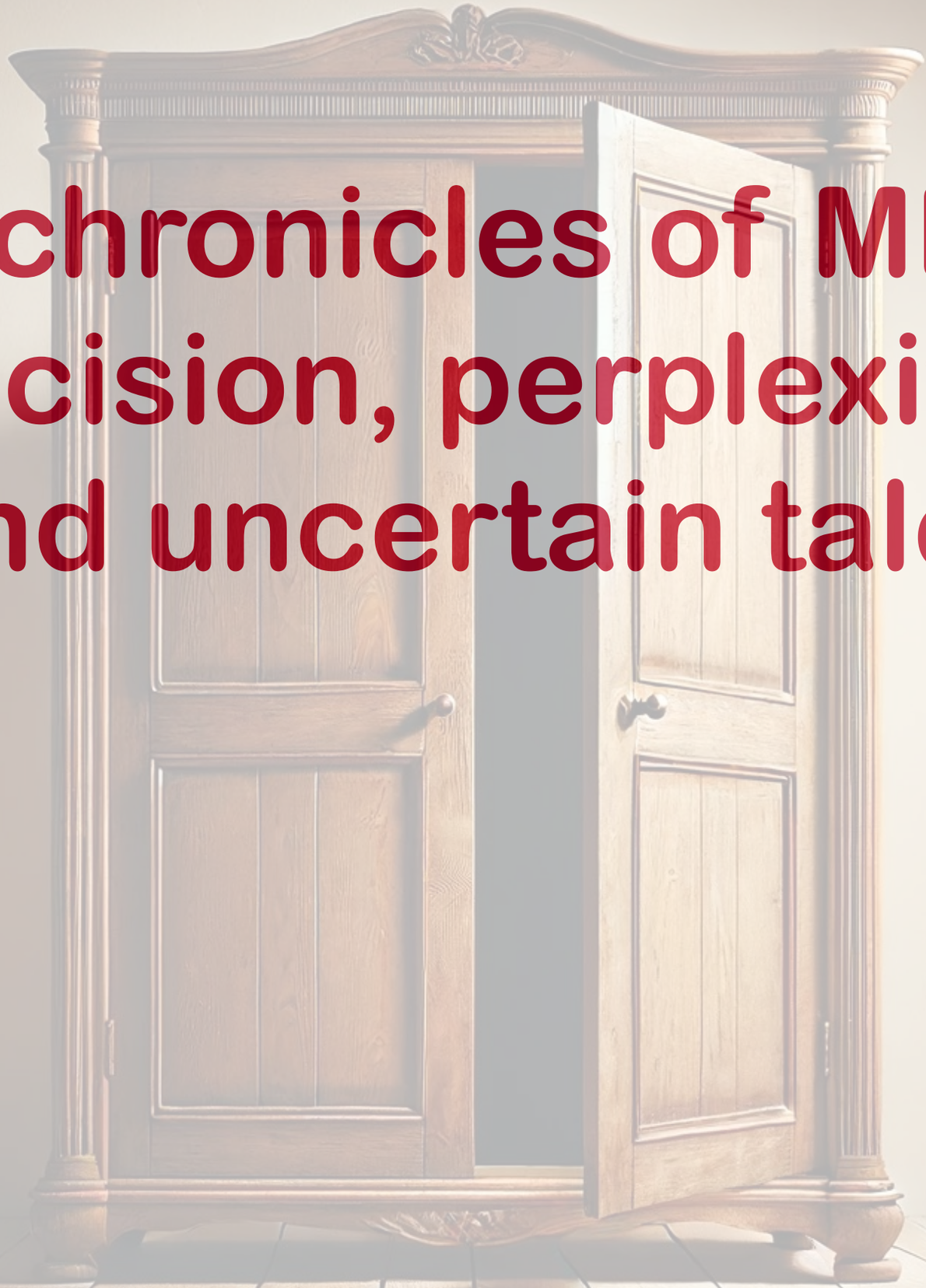
The chronicles of MESA: Precision, perplexities and uncertain tales



Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

The scene features a blend of scientific and fantastical elements. On one side, there's a detailed, **realistic depiction of the MESA accelerator** with **beams of light and particles symbolizing high precision nuclear studies**. In the background, a majestic neutron star is visible, hinting at the physics of neutron stars and the Equation of State of nuclear matter. On the other side, elements of a mystical forest are subtly incorporated, inspired by the Chronicles of Narnia, with an ancient book partially open, showing **diagrams of atomic nuclei and equations**. The overall color scheme is a mix of deep blues and purples, creating an atmosphere of mystery and exploration. The image should evoke a sense of wonder and scientific curiosity, seamlessly blending the real and the fantastical.

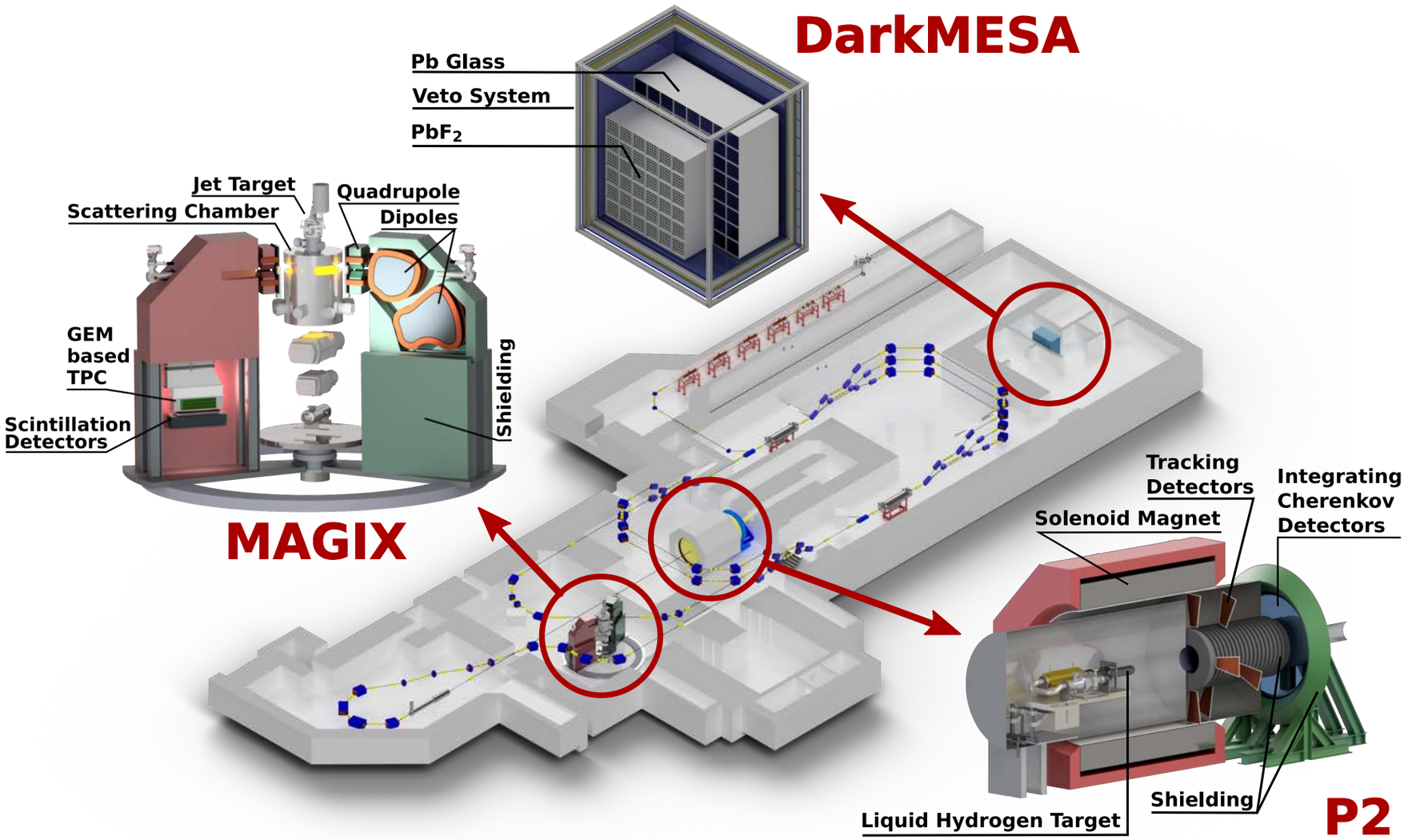
The “Realistic Depiction “

MESA – Mainz Energy-Recovering Superconducting Accelerator

The “Realistic Depiction “

MESA – Mainz Energy-Recovering Superconducting Accelerator

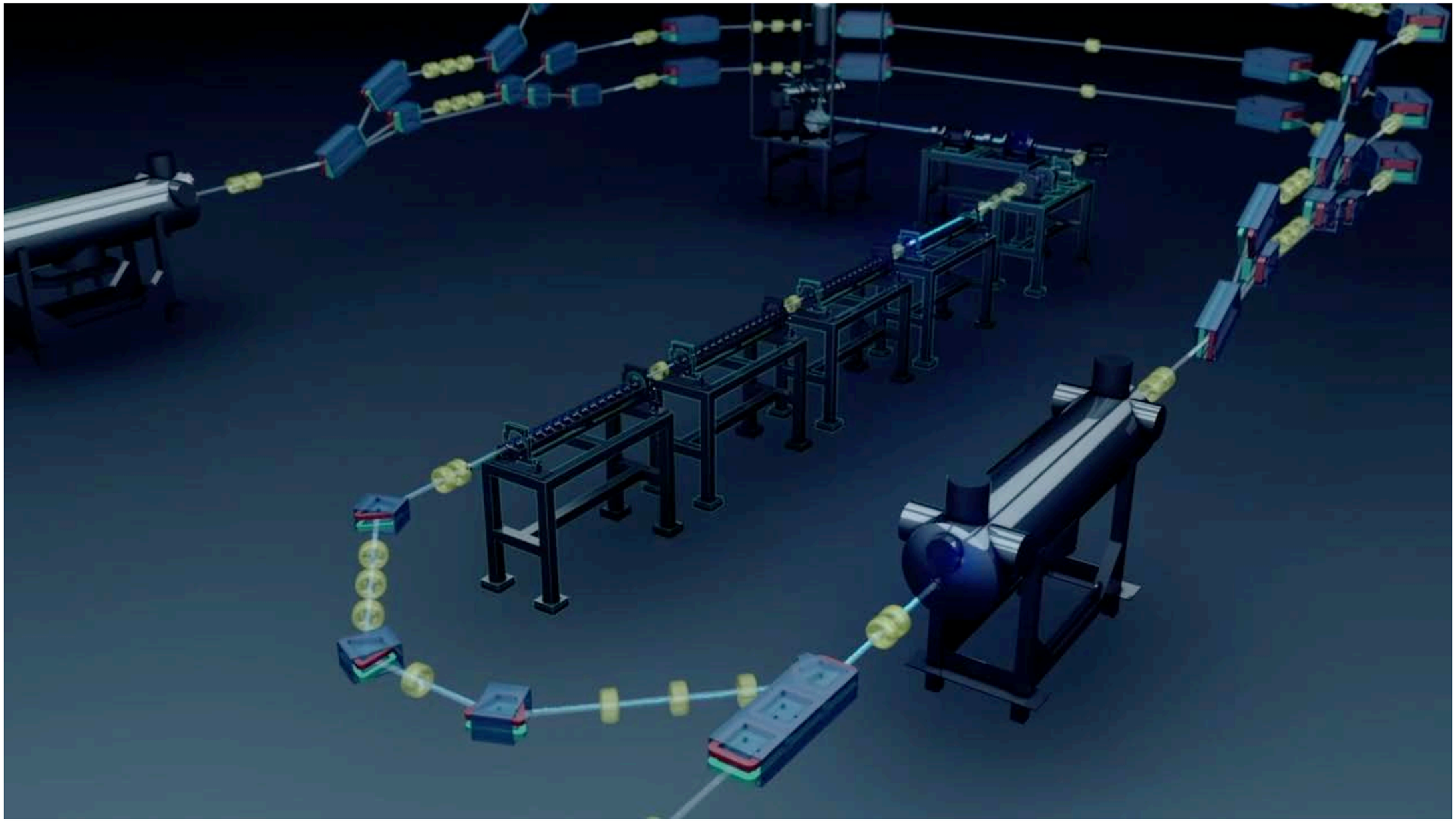
- Energy-recovery mode for **high-intensity** (MAGIX)
- External-beam mode for **high polarisation** (P2)
- Beam dump experiment (**Dark**MESA)



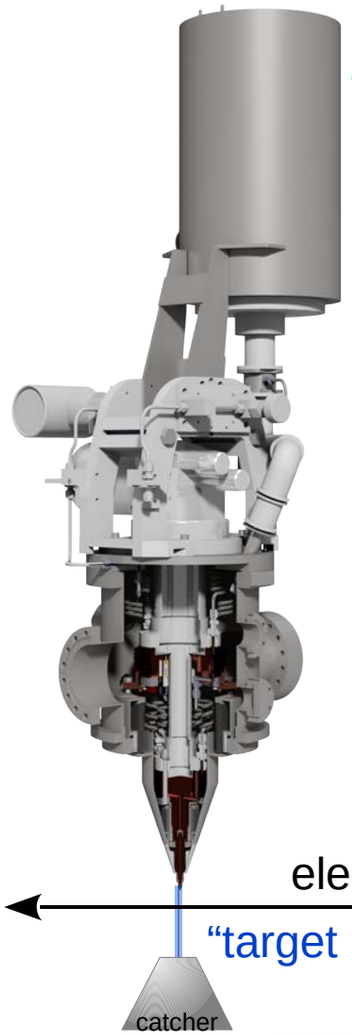
Multi-purpose facility low-energy precision physics experiments

The “Realistic Depiction “

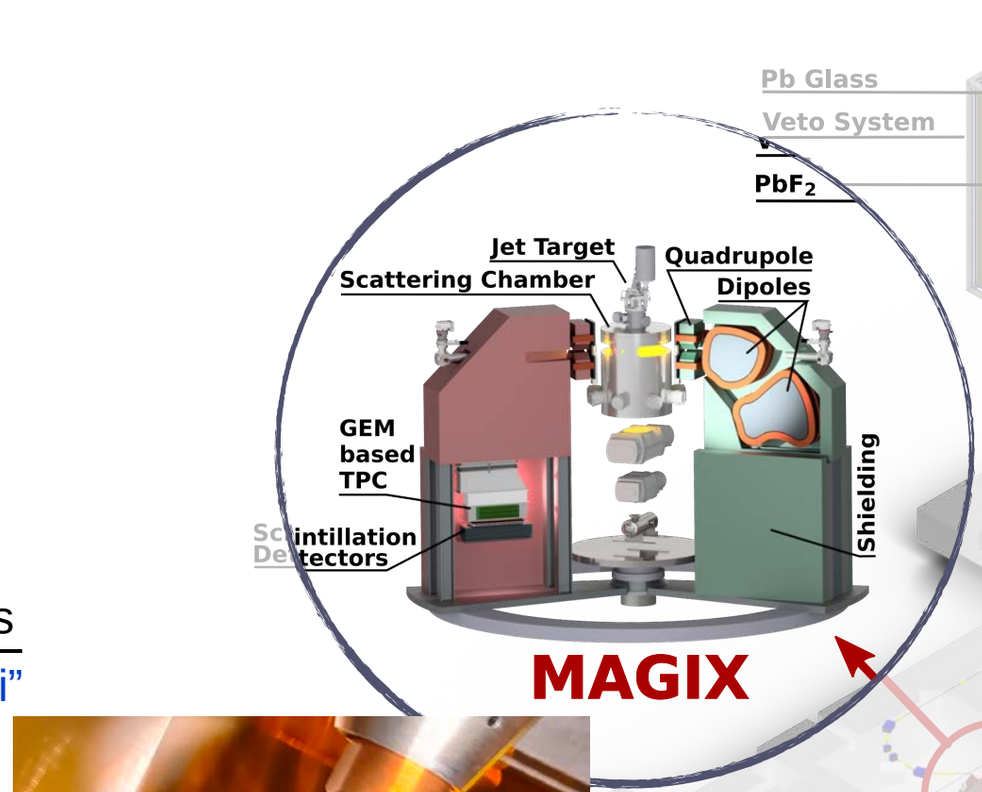
MESA – Mainz Energy-Recovering Superconducting Accelerator

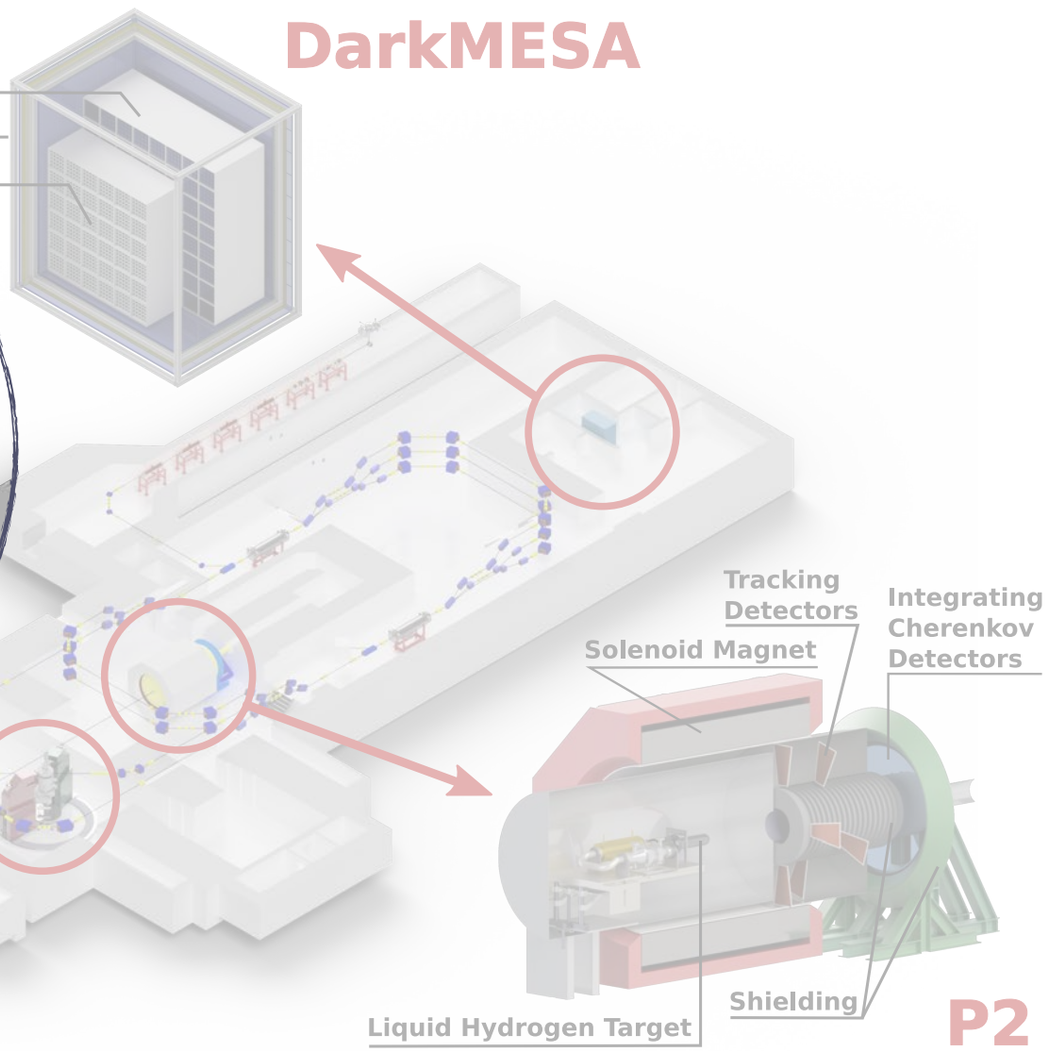


...the "Chronicles of MESA"



NO background, energy loss or multiple scattering from target foils and ice layer and re-scattering from frame, and target length acceptance issues!

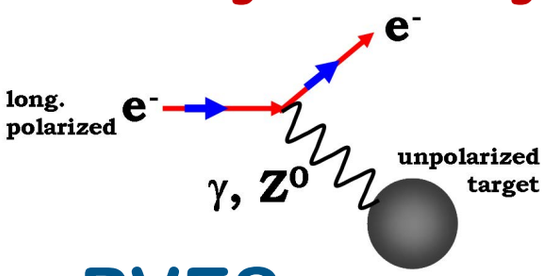




windowless,
thin, point-like

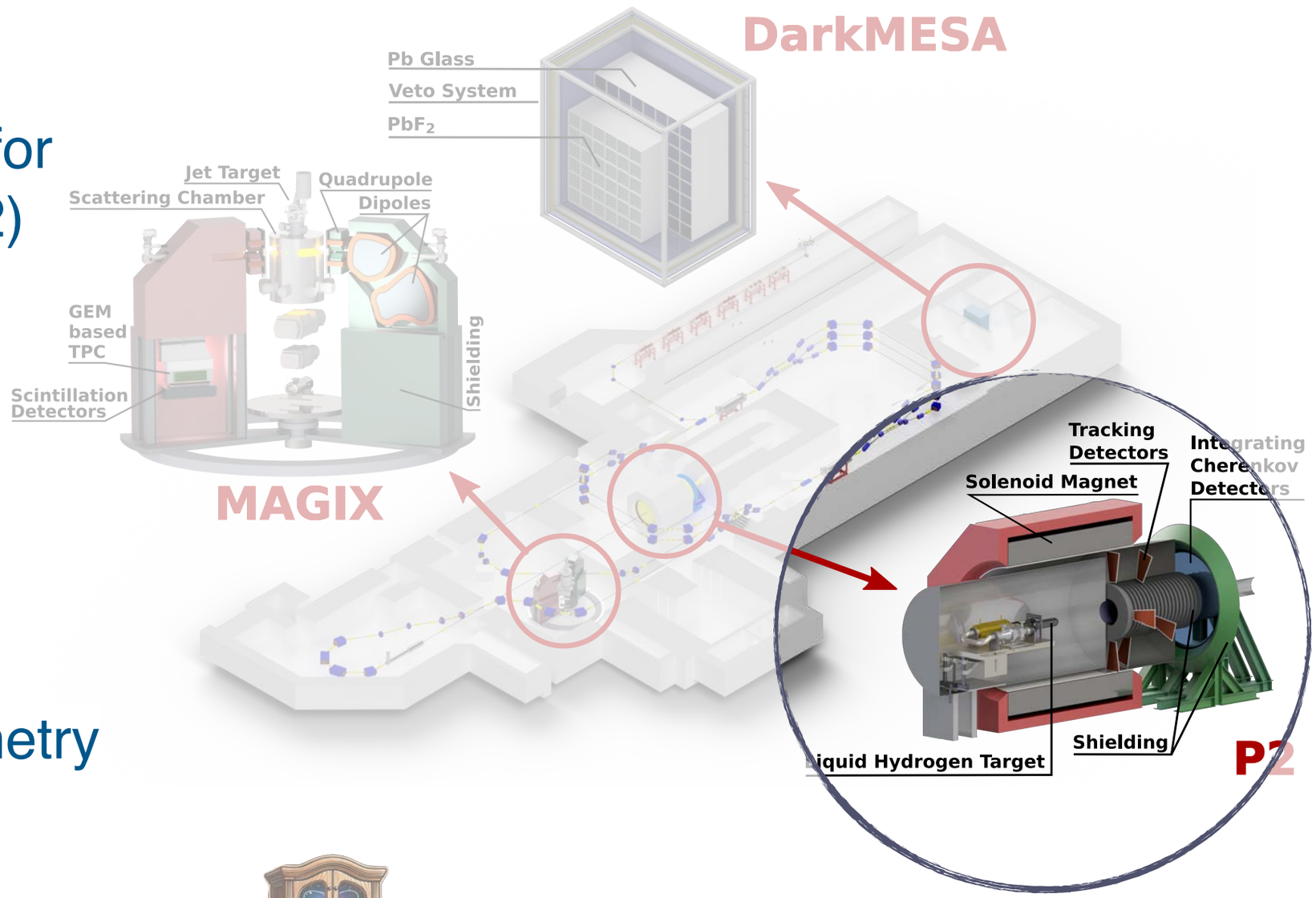
...the "Chronicles of MESA"

PV-Asymmetry



PVES

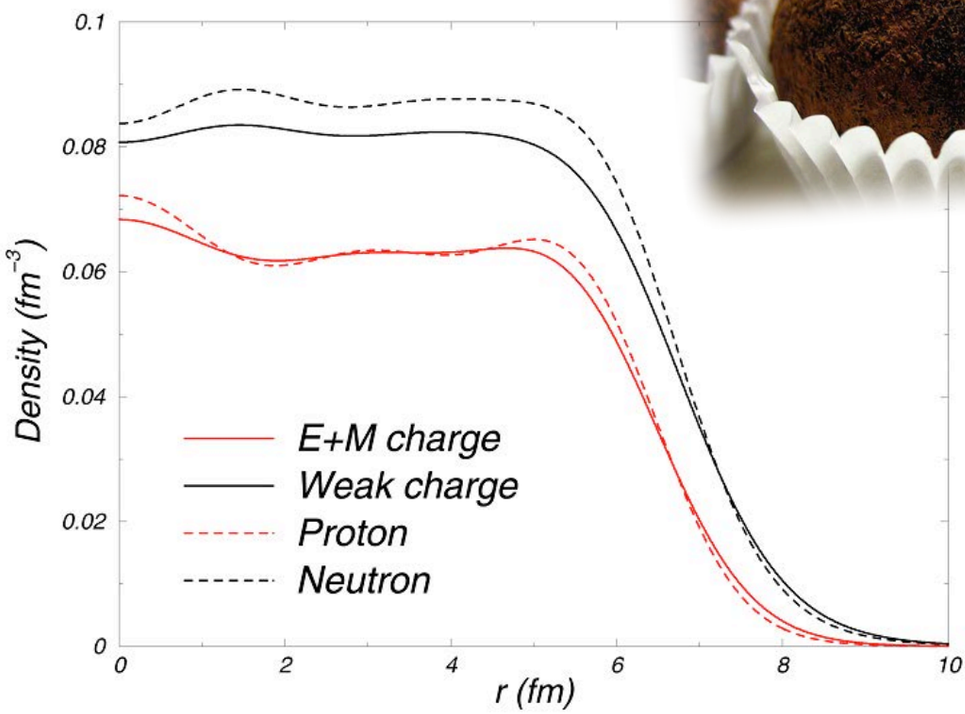
- External-beam mode for **high polarisation** (P2)
- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry



...precision, perplexities and uncertain tales

- Rebellious skins
- The 4 -horsemen of the Apocalypse

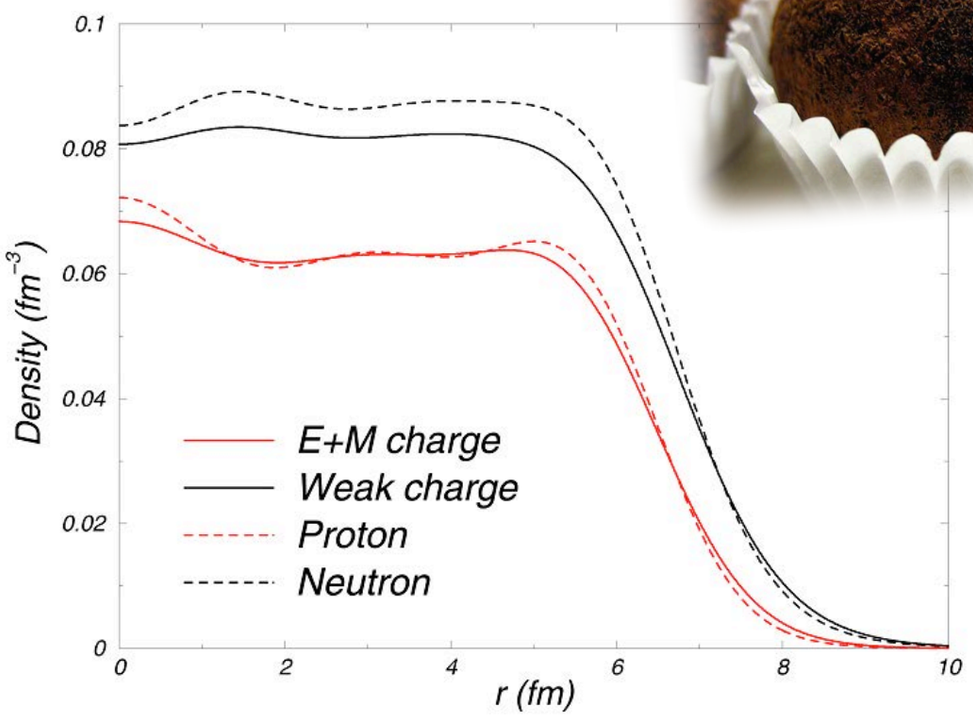
Rebellious skins



Pressure forces neutrons out against surface tension

The neutron skin measures how much neutrons stick out past protons

Rebellious skins



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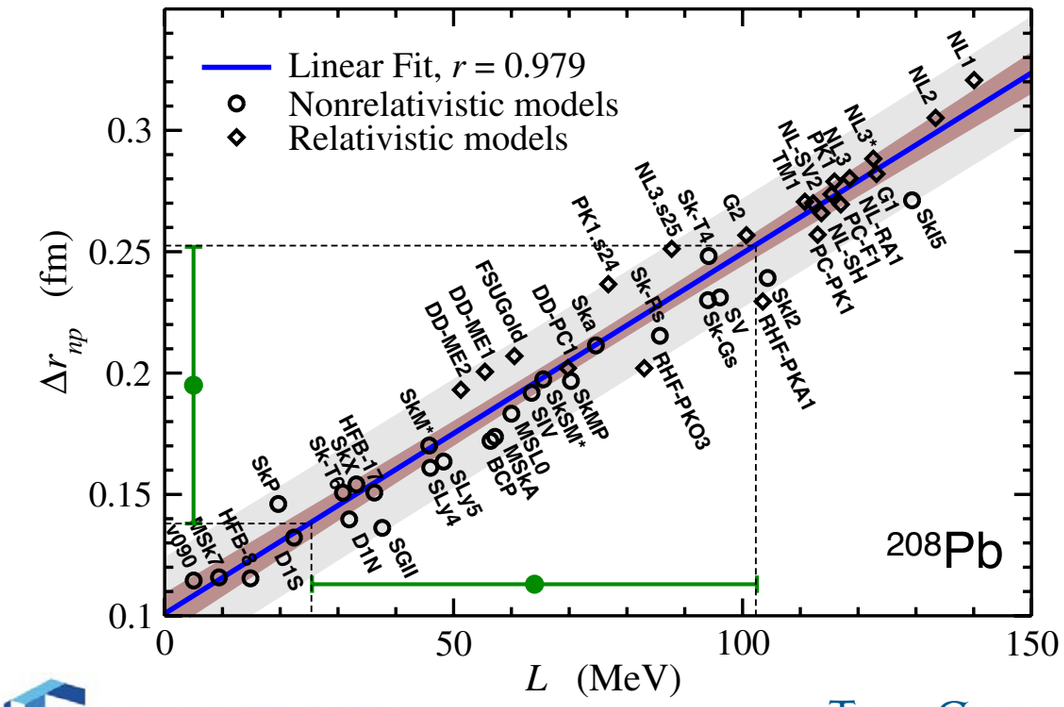
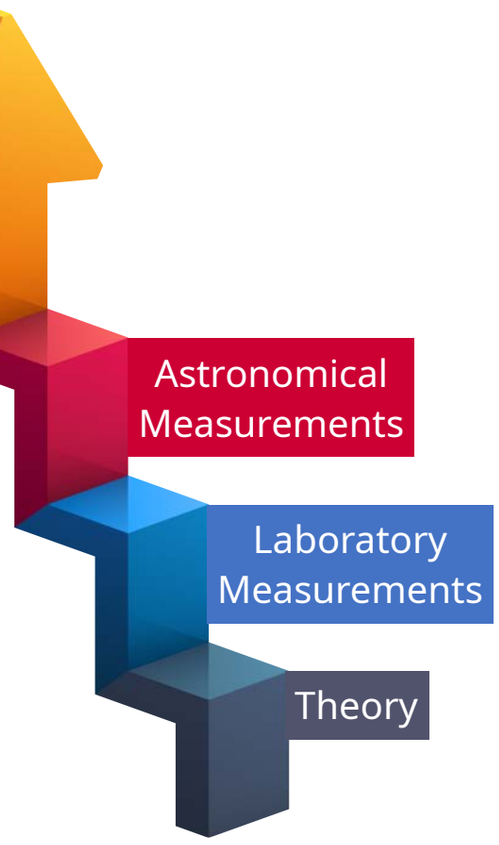
X. Roca-Maza, at al. Phys. Rev. Lett. 106, 252501 (2011)



Credit: NSF/LIGO **Neutron star merger**

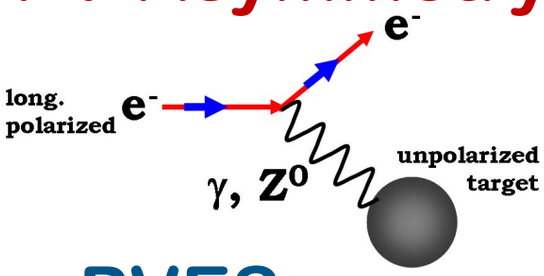


The stairway to heaven

(or the highway to hell, depending on your level of optimism)

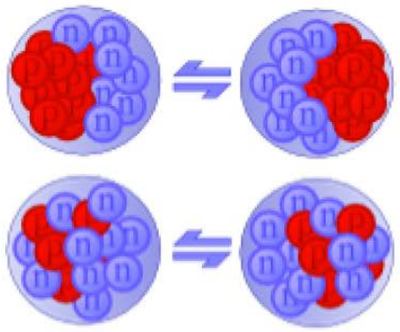
(Personal selection)

PV-Asymmetry



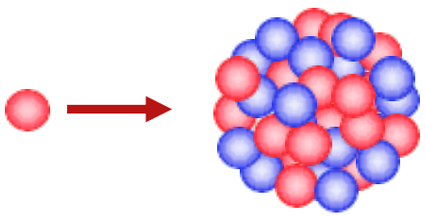
PVES

Resonance Strength

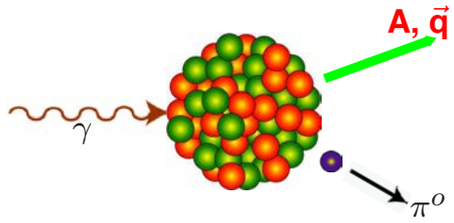


Collective Excitation

Cross-section



Hadronic Probes



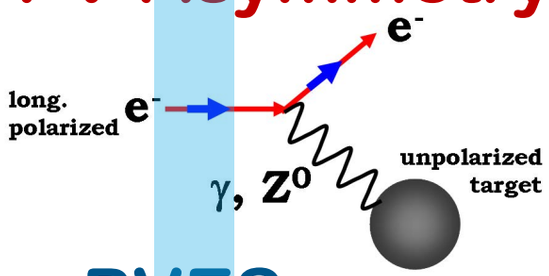
EM Probes

The stairway to heaven

(or the highway to hell, depending on your level of optimism)

(Personal selection)

PV-Asymmetry



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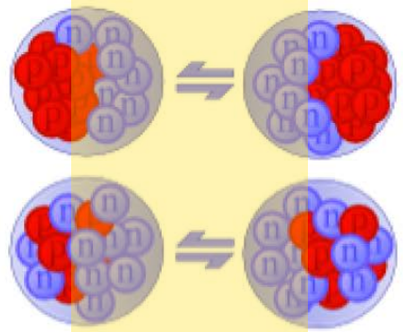

Collective Excitation

????..

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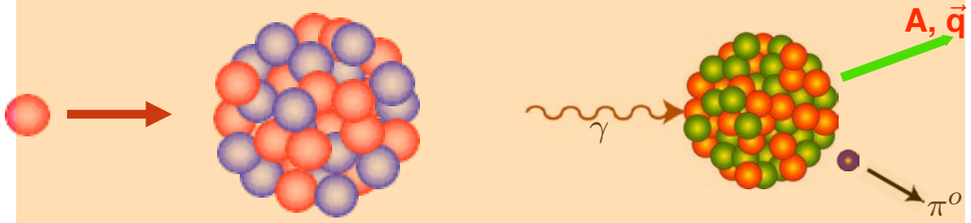
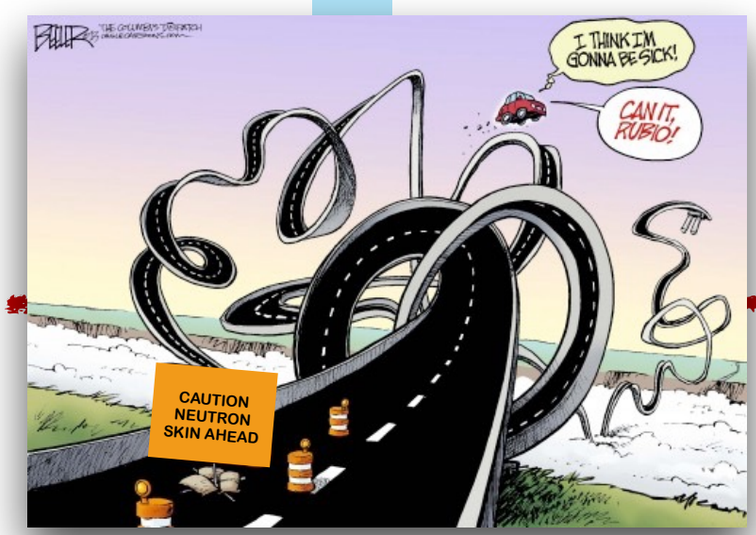


Hadronic Probes

EM Probes



Theo. uncertainties (a.u)

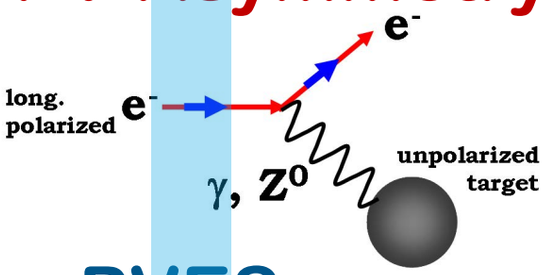
The stairway to heaven

(or the highway to hell, depending on your level of optimism)

(Personal selection)

Experimental Challenges
(in unit of frustration)

PV-Asymmetry



PVES

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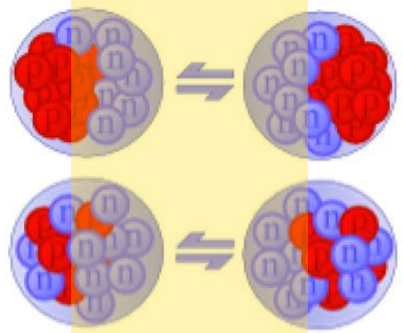

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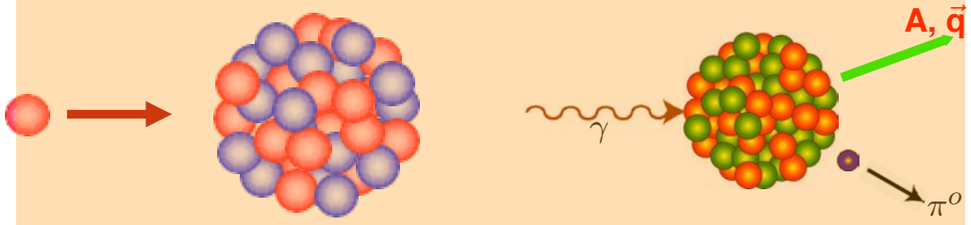

Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

How hellish is hell?

Featured in Physics Editors' Suggestion

Neutron Skin of $^{208}\mathrm{Pb}$ from Coherent Pion Photoproduction

C. M. Tarbert *et al.* (Crystal Ball at MAMI and A2 Collaboration)
Phys. Rev. Lett. **112**, 242502 – Published 18 June 2014

PHYSICS See Synopsis: Neutron Skin Turns Out to Be Soft

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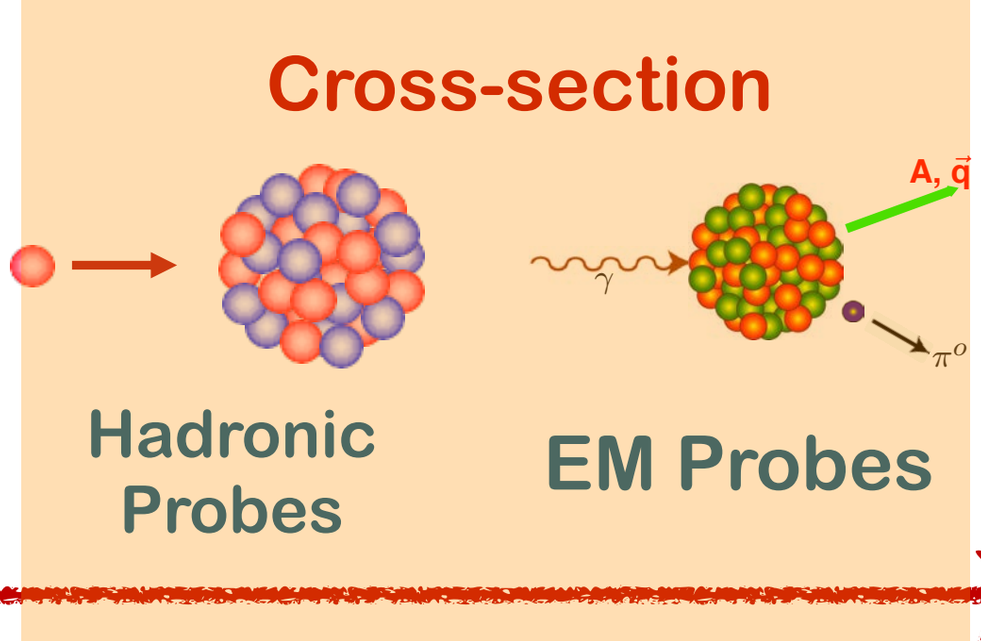
????..



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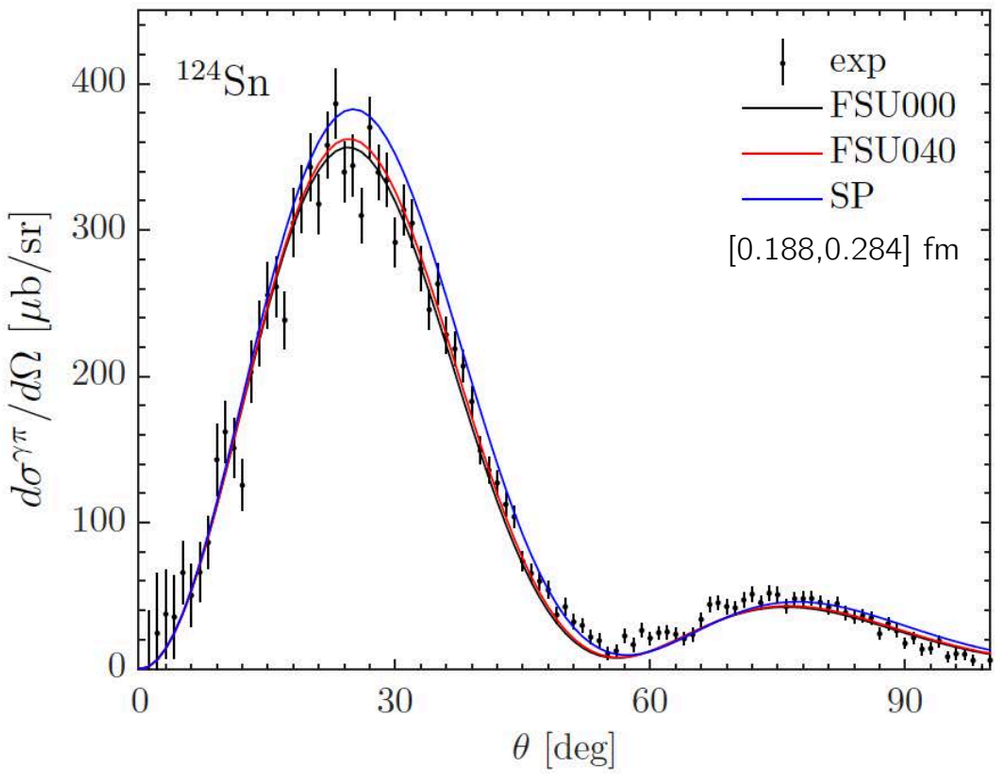

????..

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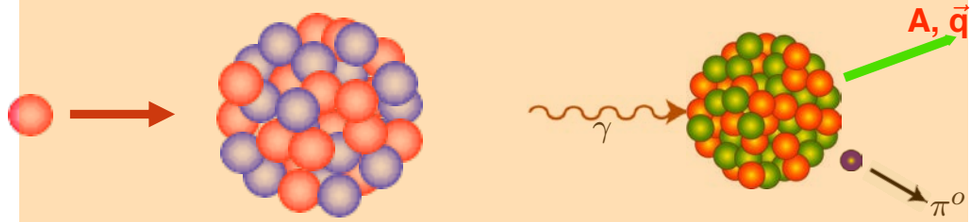

Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

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Theoretical analysis of the extraction of neutron skin thickness from coherent π^0 photoproduction off nuclei

F. Colomer, P. Capel, M. Ferretti, J. Piekarewicz, C. Sfienti, M. Thiel, V. Tsaran, and M. Vanderhaeghen
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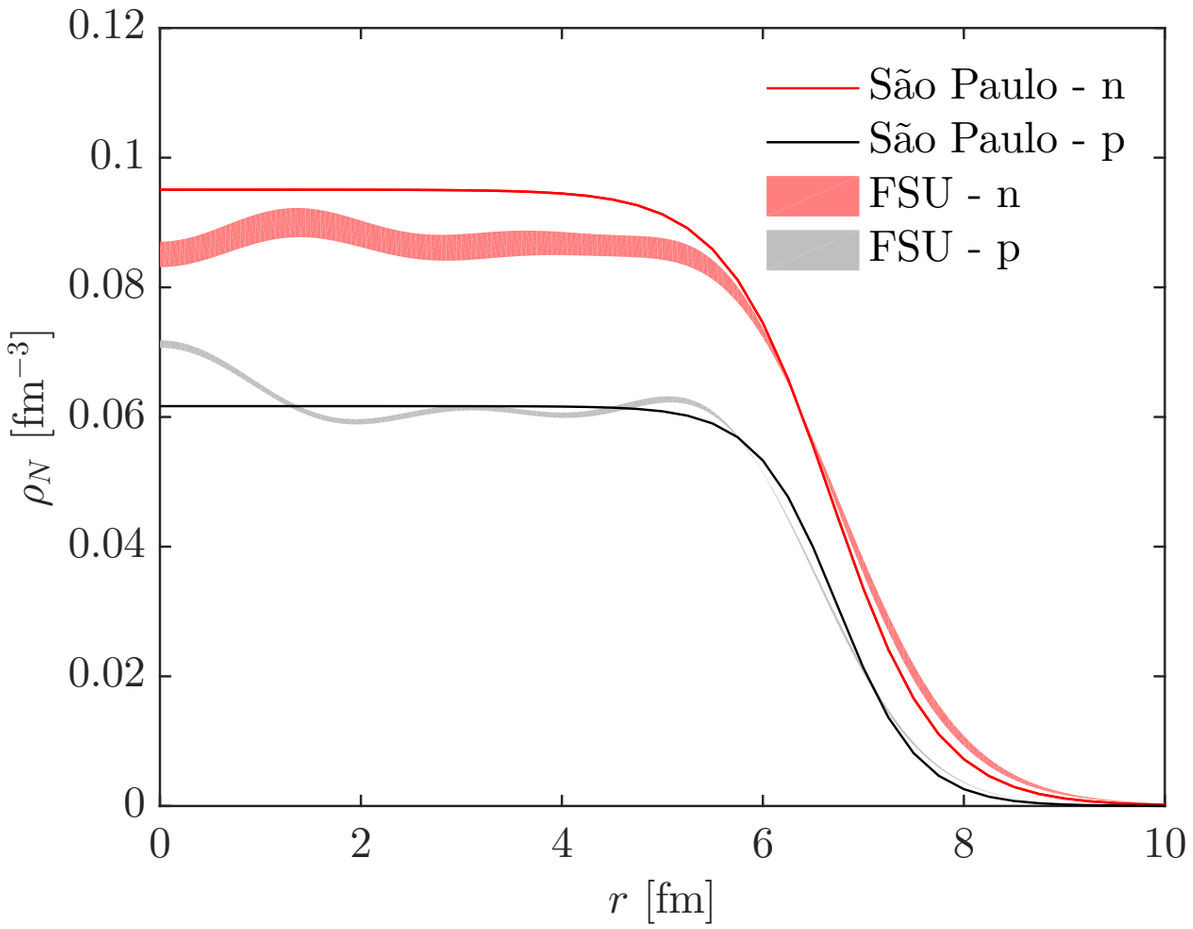

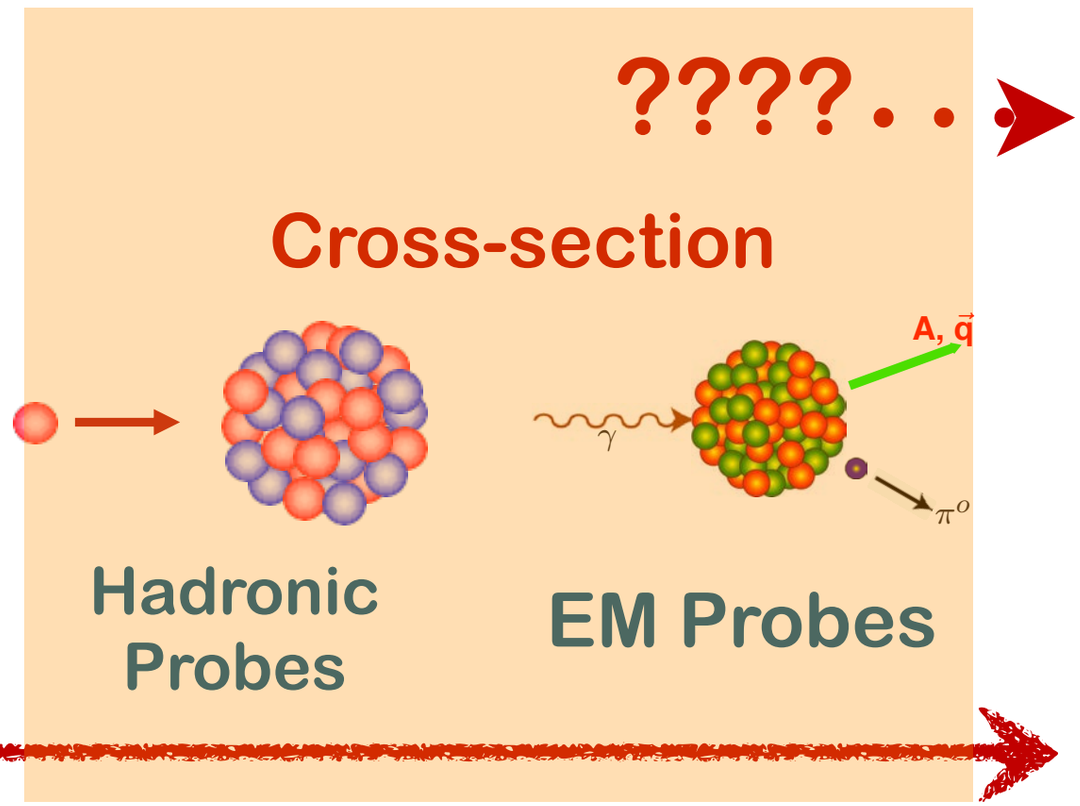

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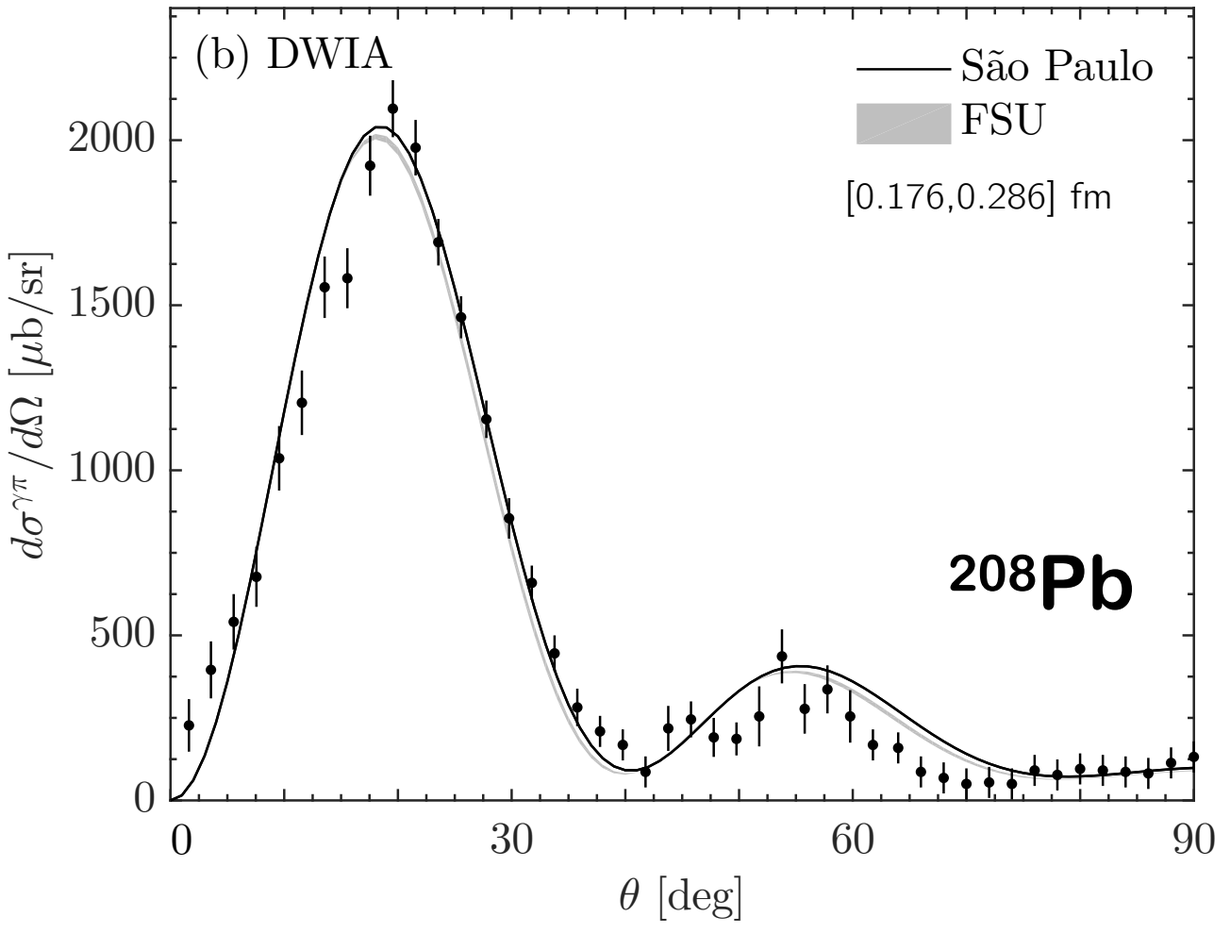

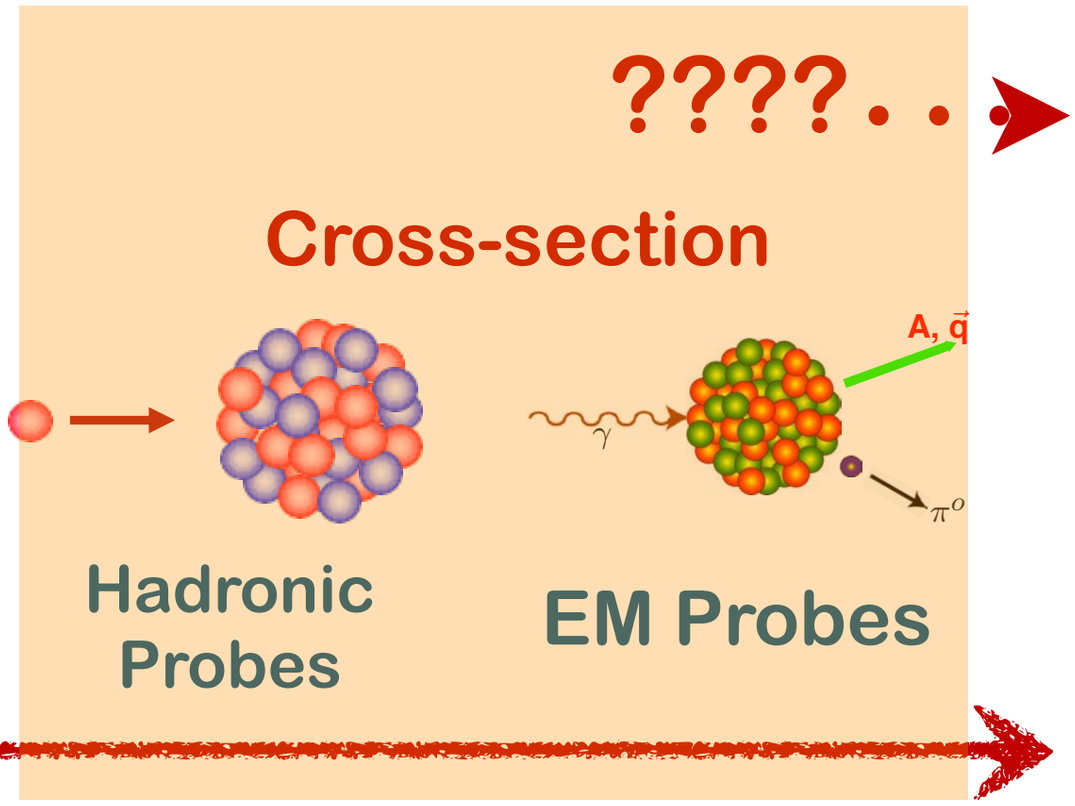

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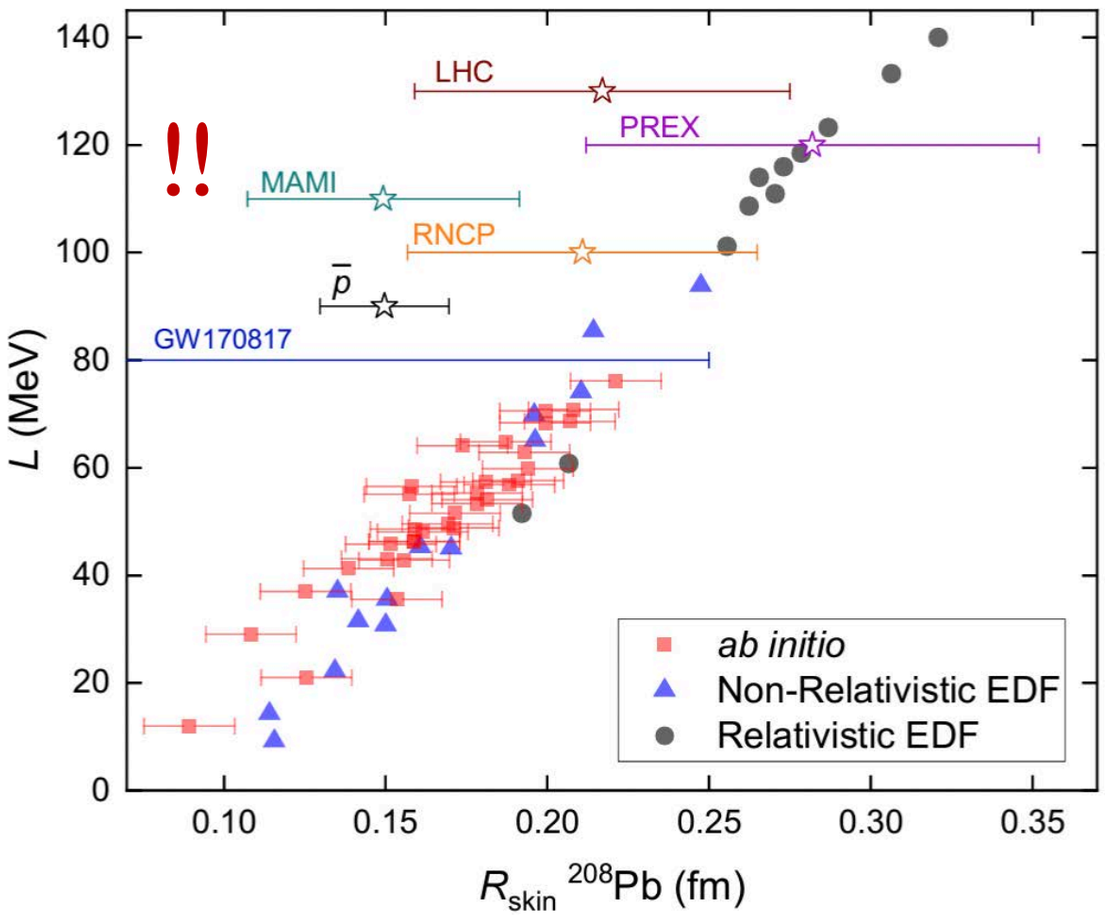
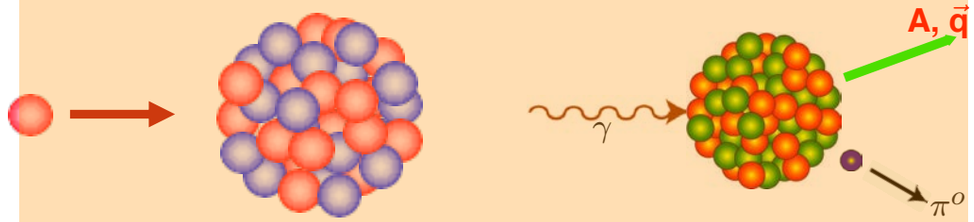
Nuclear Physics Long Range Plan 2024



????..

Cross-section



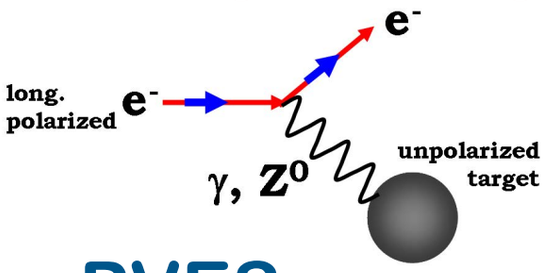
Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

The shortest of the roads …

PV-Asymmetry



PVES

		
electric charge	**1**	**0**
weak charge	**≈0.07**	**1**

Non-PV e-scattering

Electron scattering γ exchange provides R_p through nucleus FFs

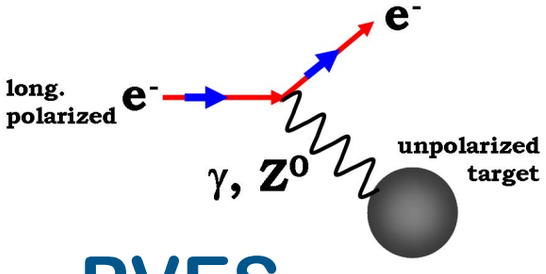
PV e-scattering

Electron also exchange Z, which is parity violating

Primarily couples to neutron

The shortest of the roads ...

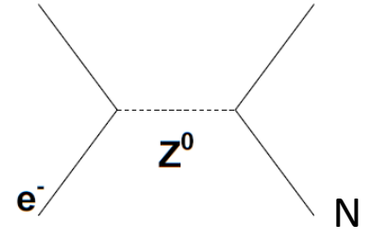
PV-Asymmetry



PVES

$$\sigma \propto \left| \; e^- \xrightarrow{\;\gamma\;} N \; + \; e^- \xrightarrow{\;Z^0\;} N \; \right|^2$$

...to measure ...



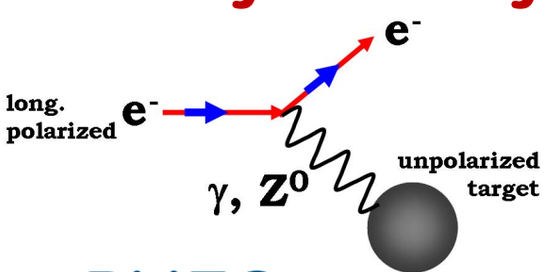
....construct ....

$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-} \approx \frac{\left| e^- \xrightarrow{\gamma} N \right| \cdot \left| e^- \xrightarrow{Z^0} N \right|}{\left| e^- \xrightarrow{\gamma} N \right|^2} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

$$F_{n,p}(Q^2) = \frac{1}{4\pi} \int d^3r \; j_0(qr) \; \rho_{n,p}(r)$$

The shortest of the roads ...

PV-Asymmetry



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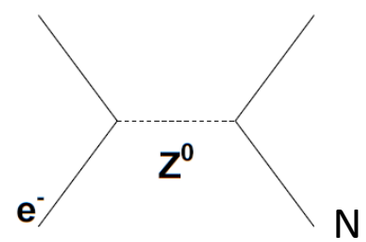

....construct ....

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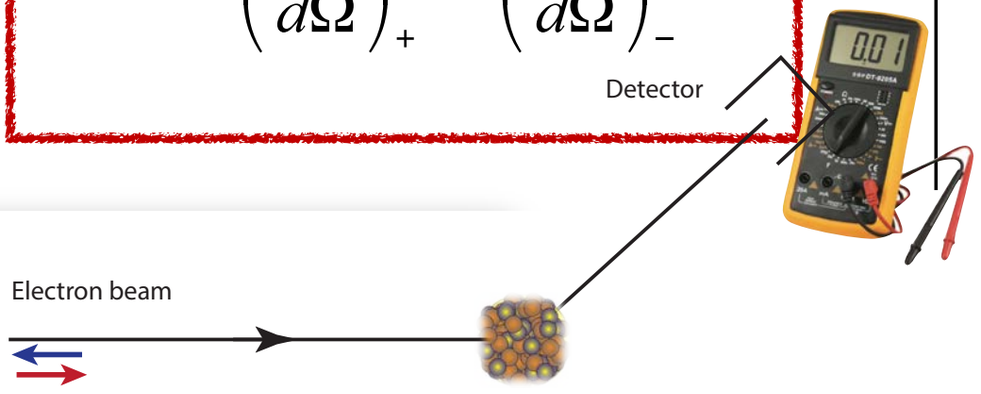
$$\frac{e^- \xrightarrow{\;\gamma\;} N \quad e^- \xrightarrow{\;Z^0\;} N}{2} \; N = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

$$\left| \; e^- \xrightarrow{\;\gamma\;} N \right|^2$$



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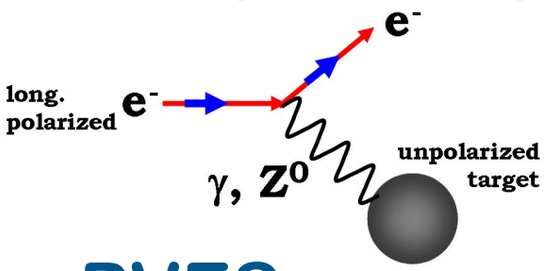
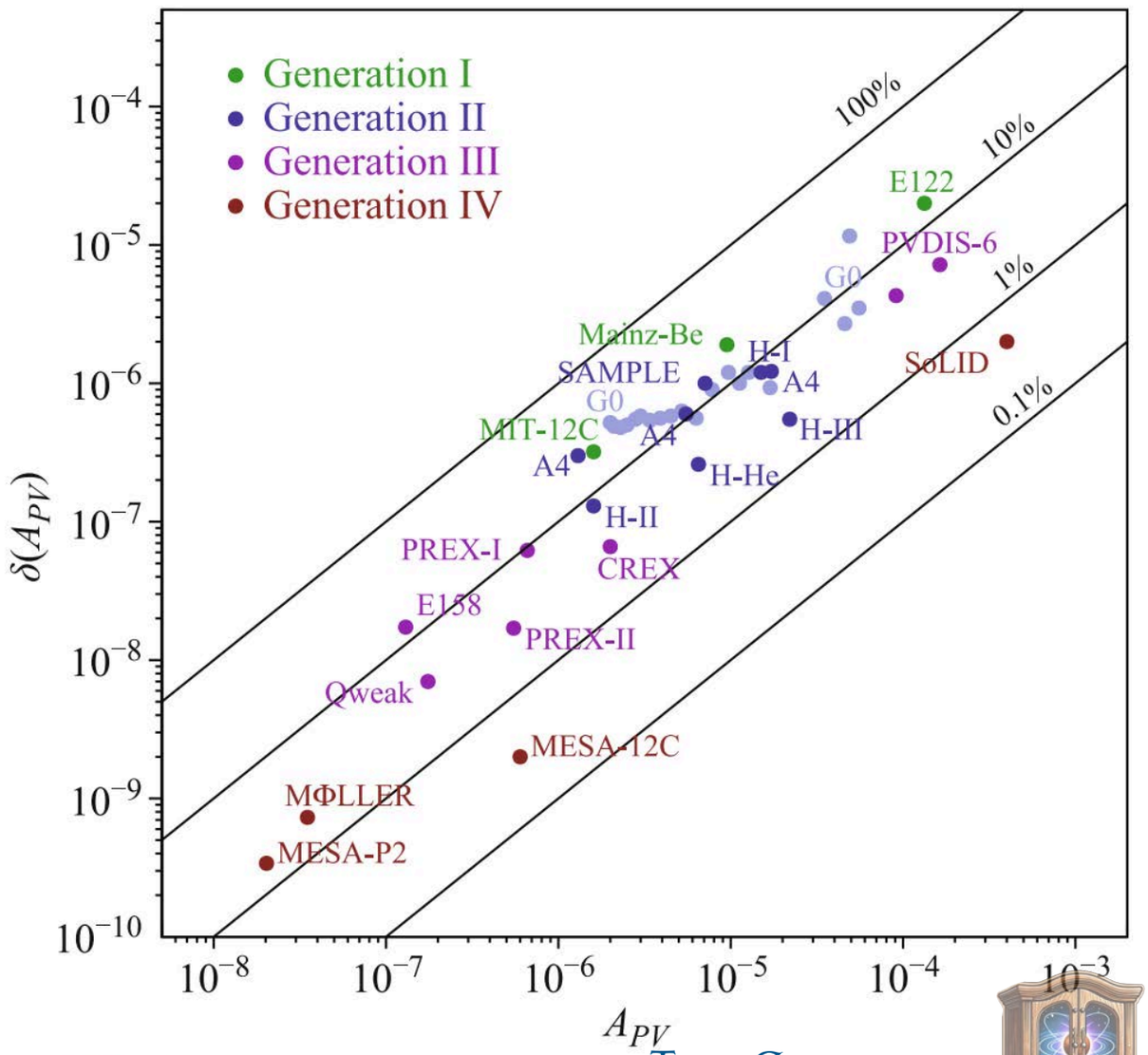
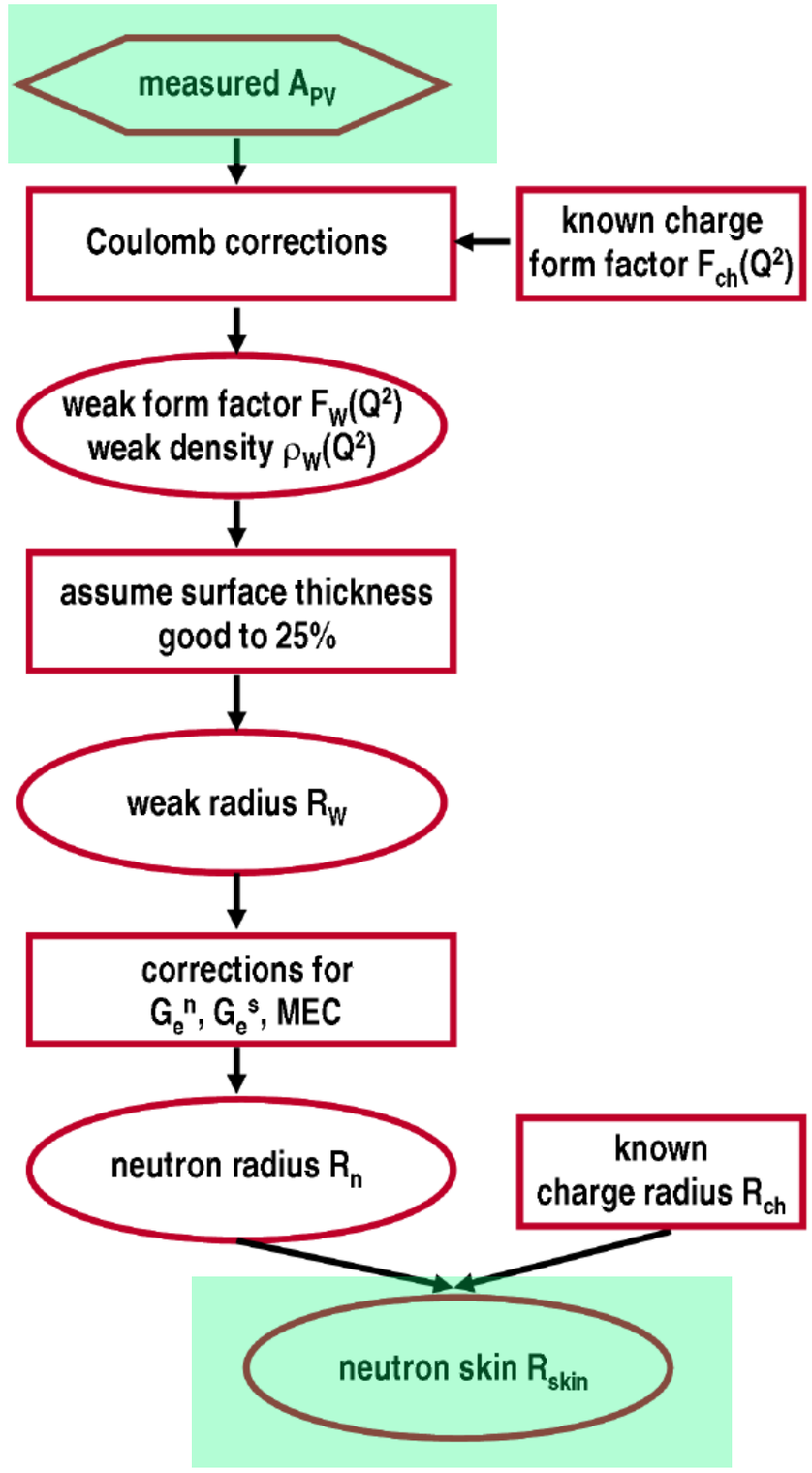
The shortest of the roads ...

PV-Asymmetry



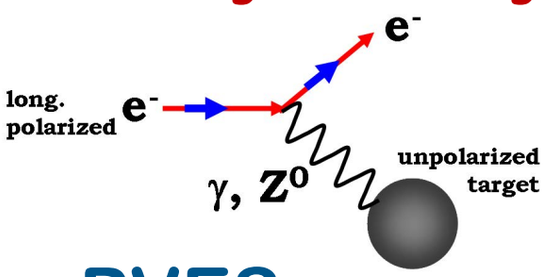
PVES





The shortest of the roads …

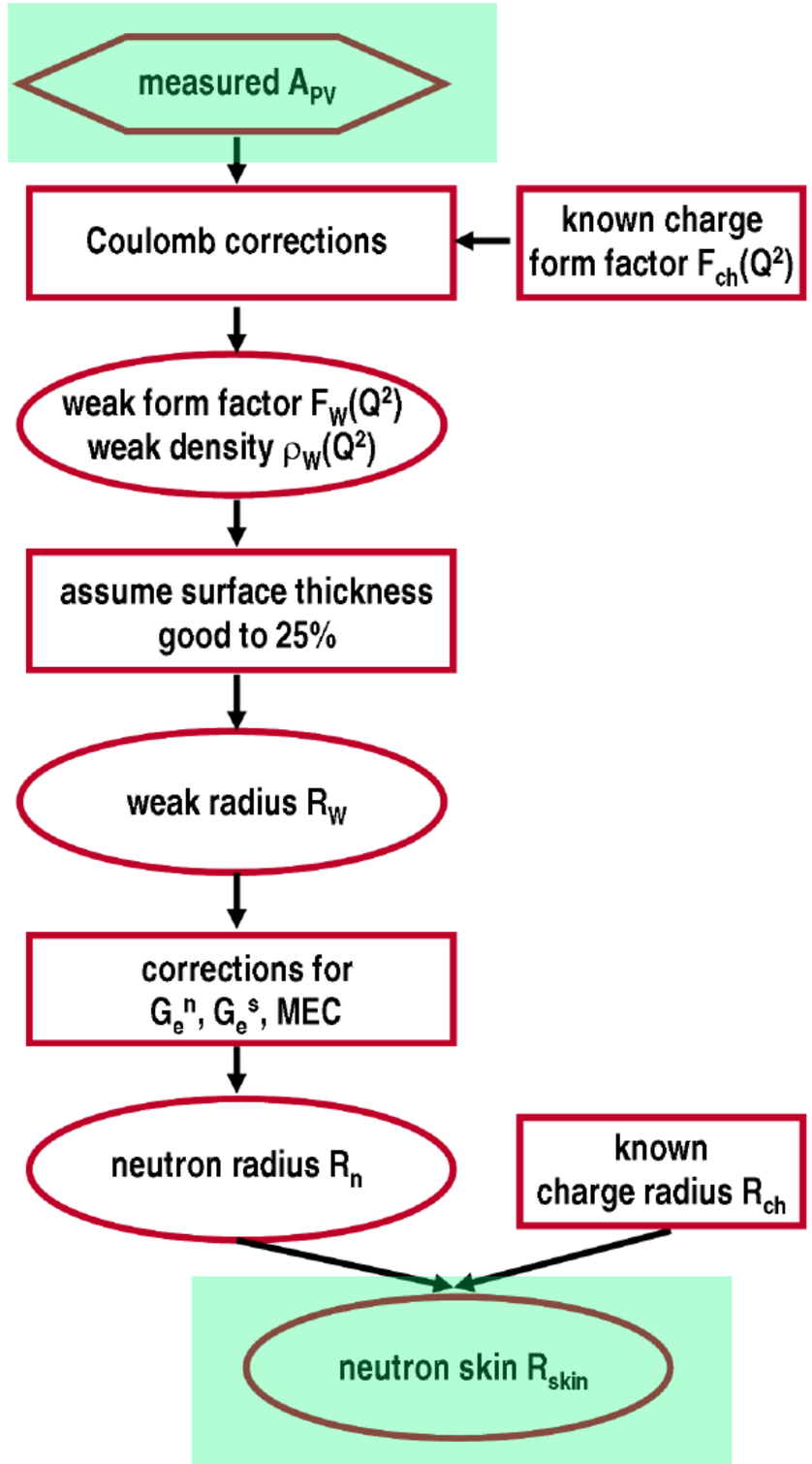
PV-Asymmetry



PVES

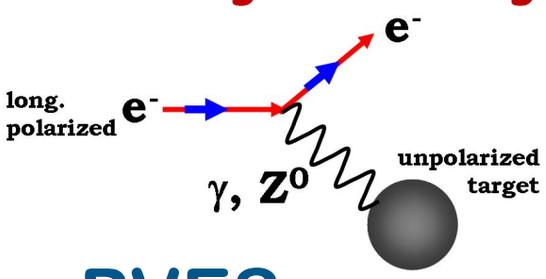
- Essentially means 1.5% on A_{PV}
- A_{PV} is 40 parts per billion
- $\delta(A_{PV})$ is 0.6 parts per billion

$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$



...the "Chronicles of MESA"

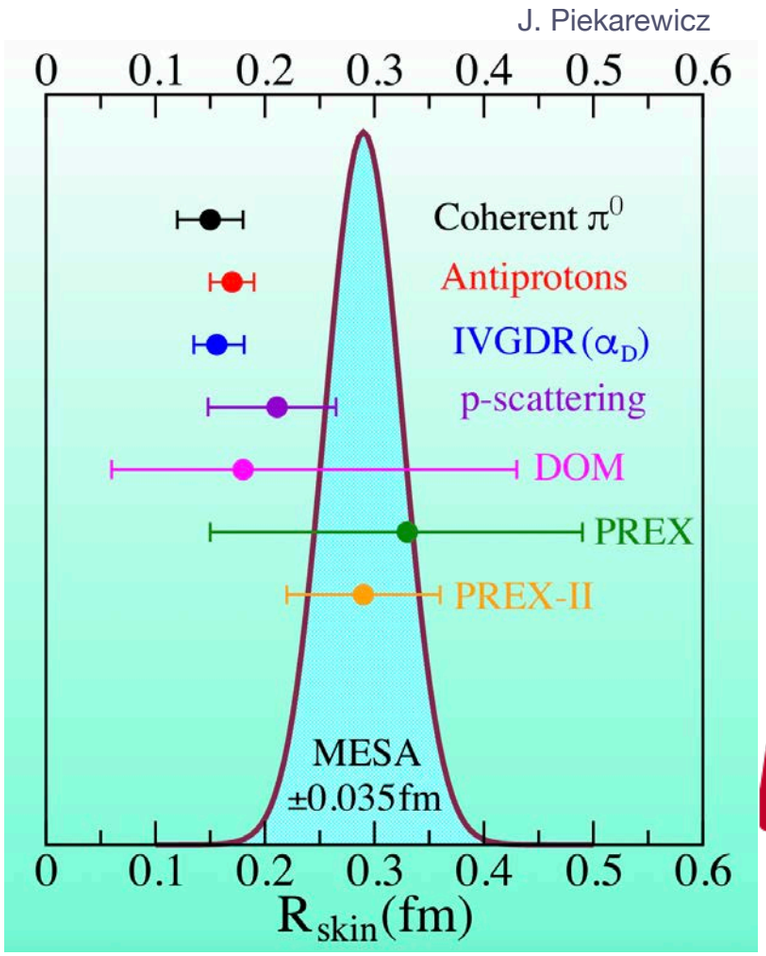
PV-Asymmetry

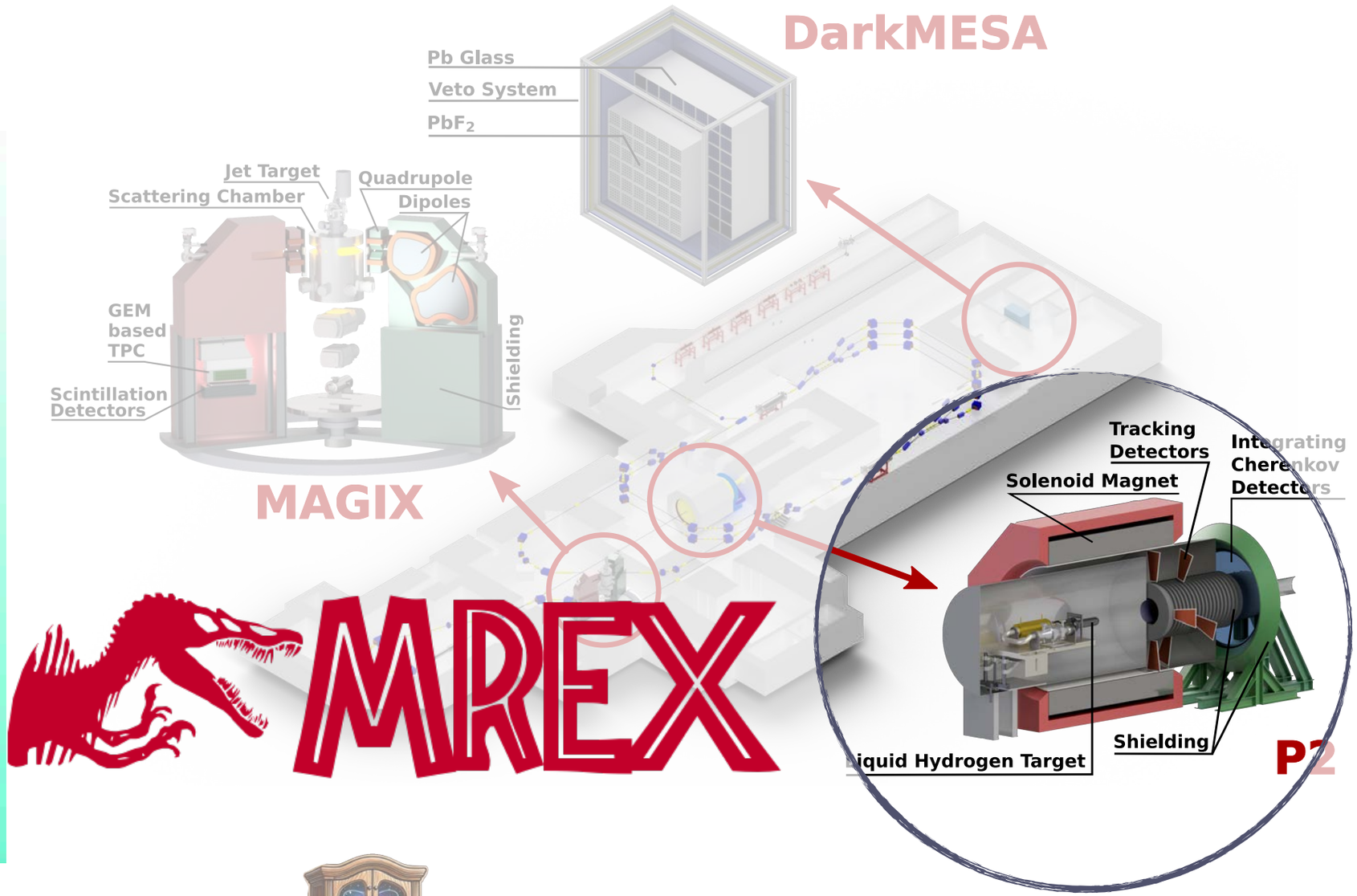


PVES

.... need a few N=10^{18} electrons!

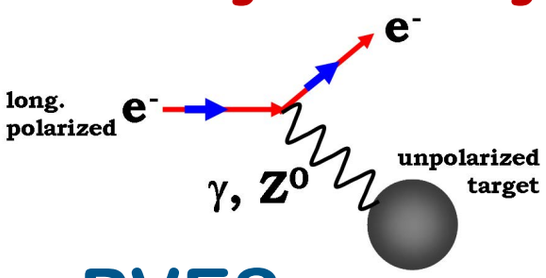
... close to 10^{11} electrons/s



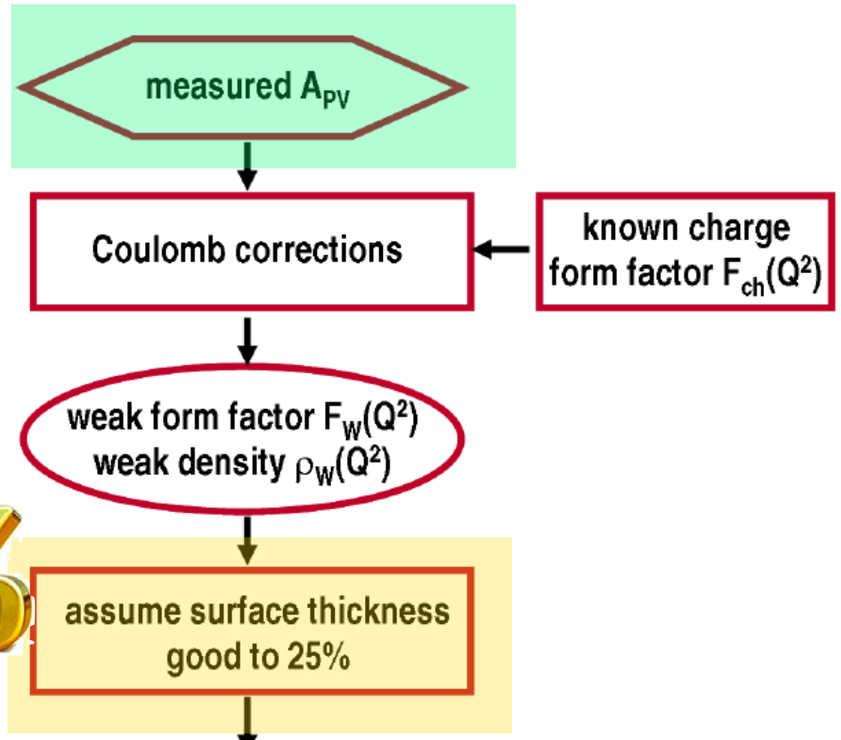


The shortest of the roads ...

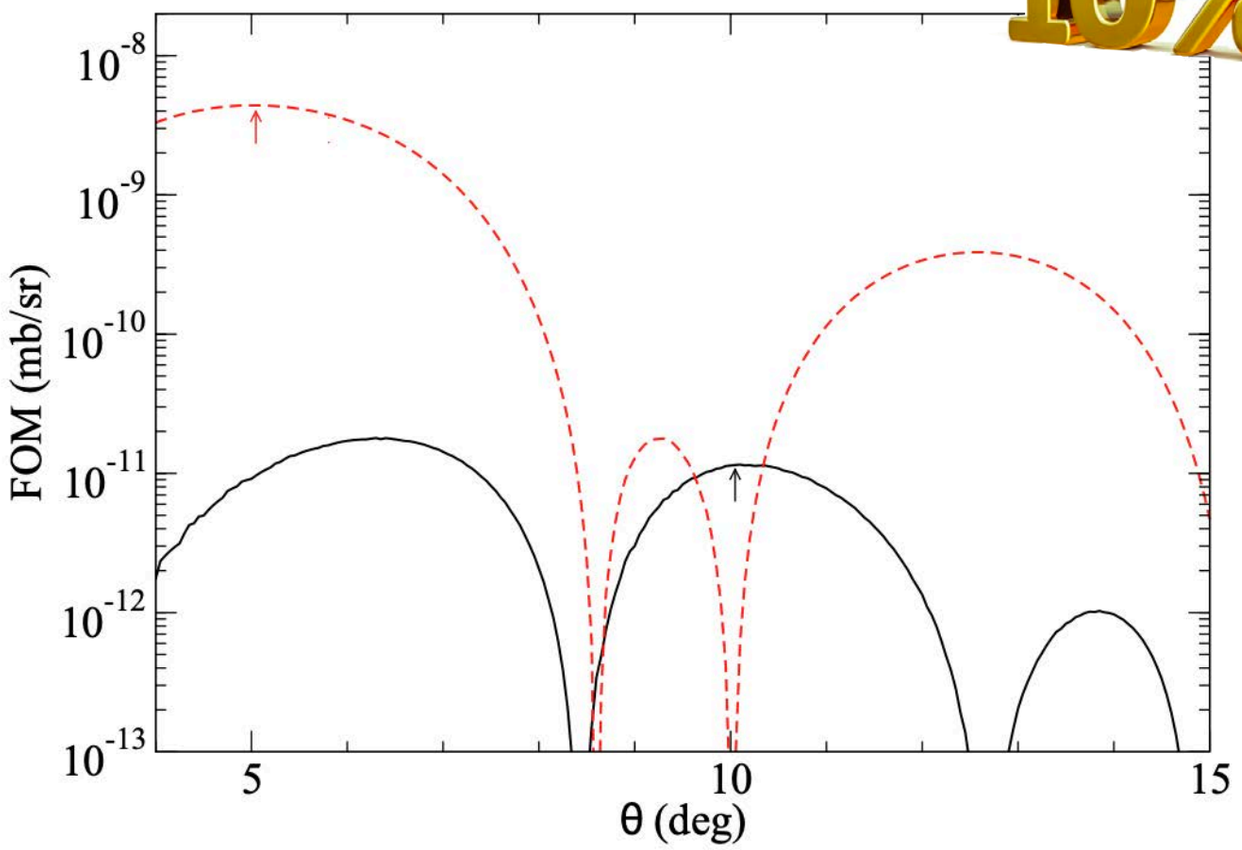
PV-Asymmetry



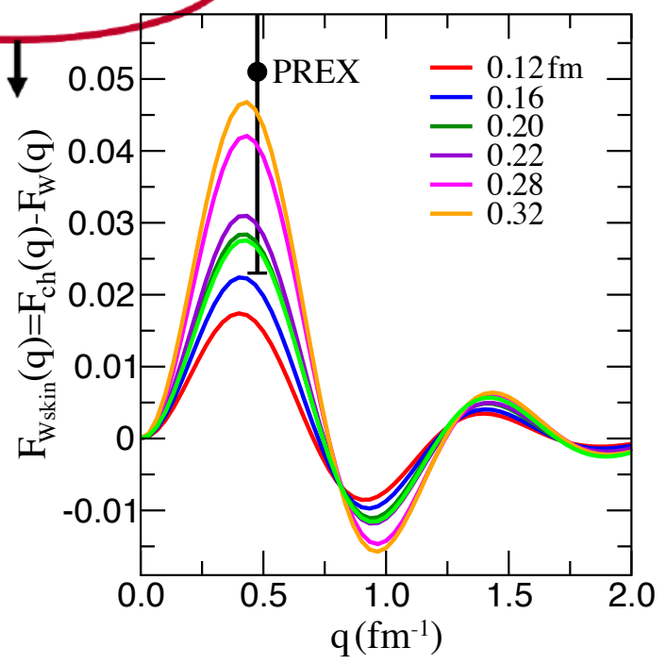
PVES

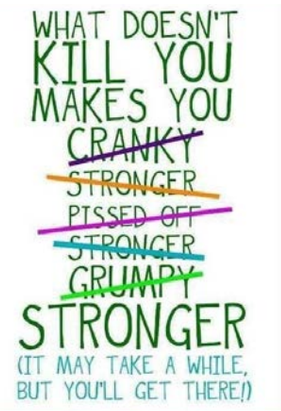


Brendan T. Reed, Z. Jaffe, C. J. Horowitz, **CS** PRC **102**, 064308



J. Phys. G: Nucl. Part. Phys. 46

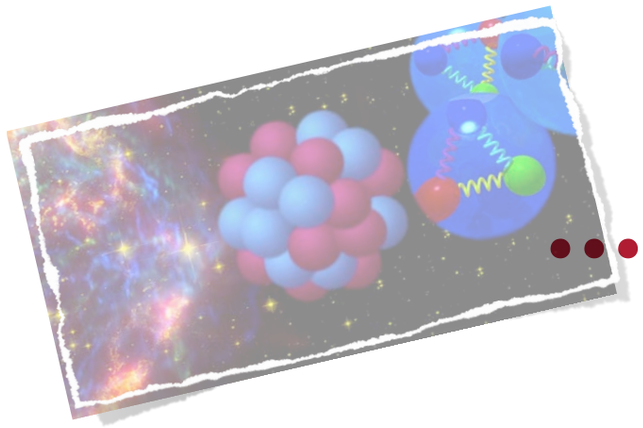




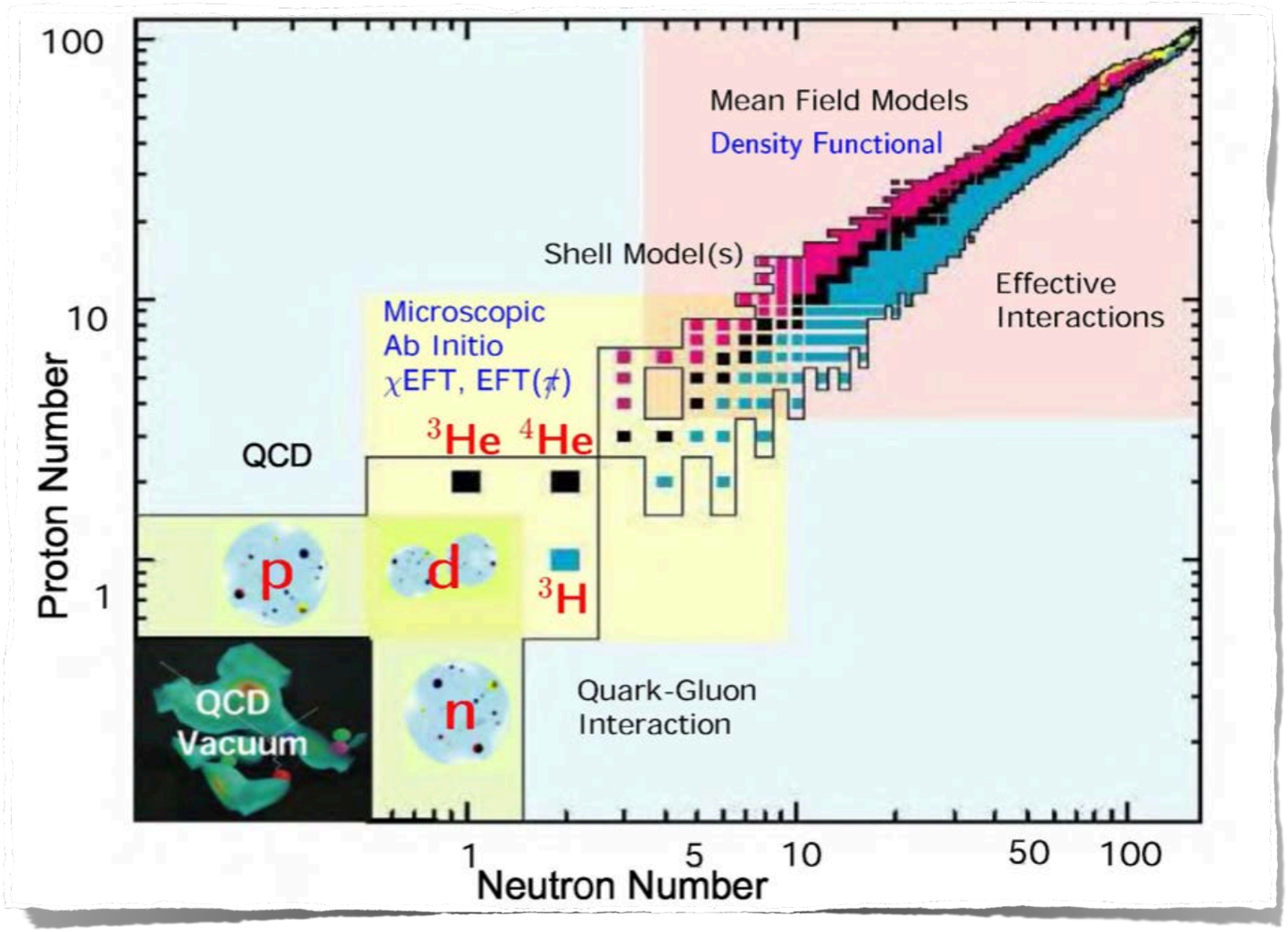
...precision, perplexities and uncertain tales

- Rebellious skins
- The 4 -horsemen of the Apocalypse

Modern nuclear physics is about...

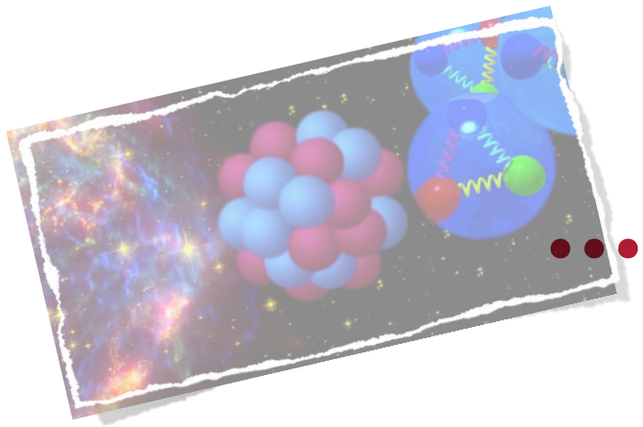


...linking QCD to many-body systems



UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional

A scientific... tango



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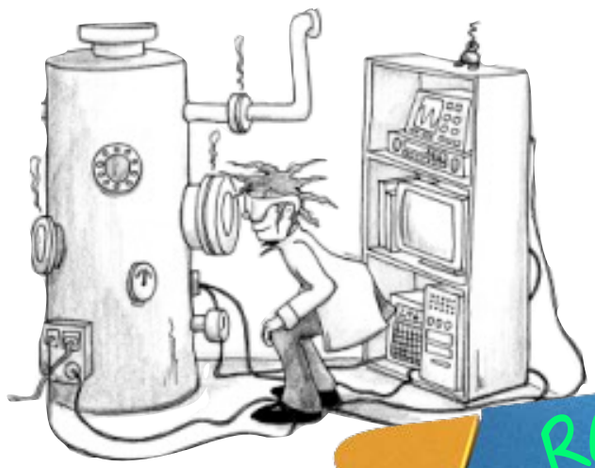

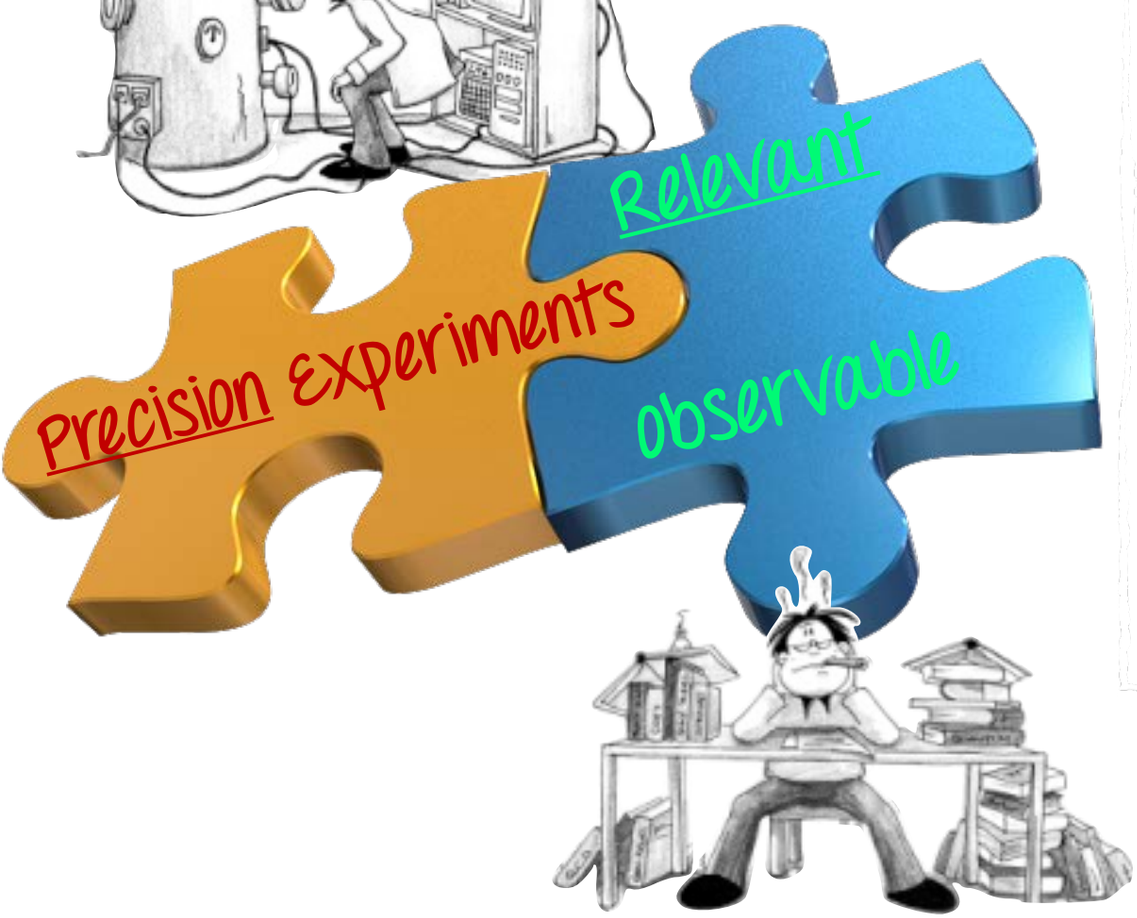

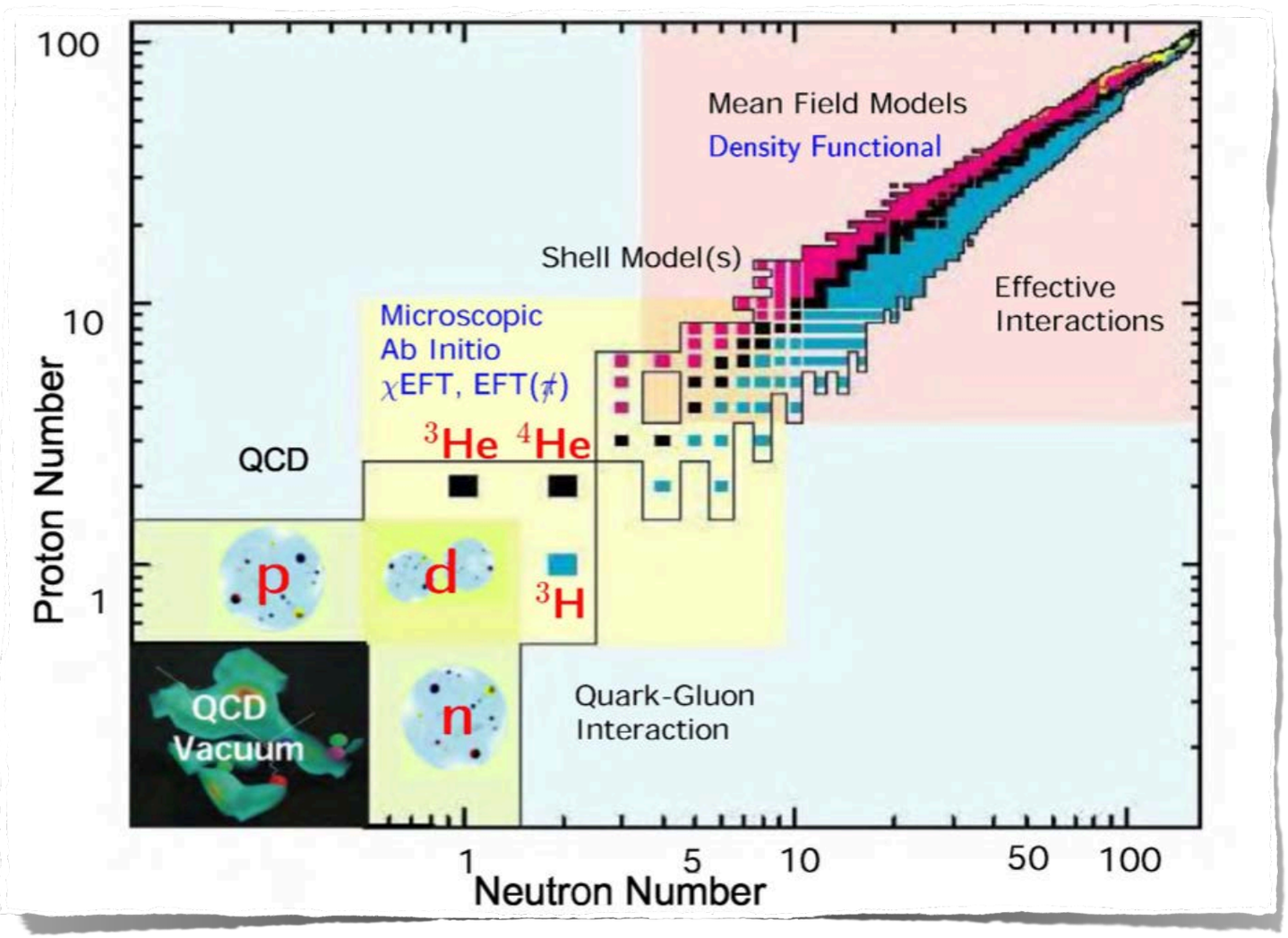

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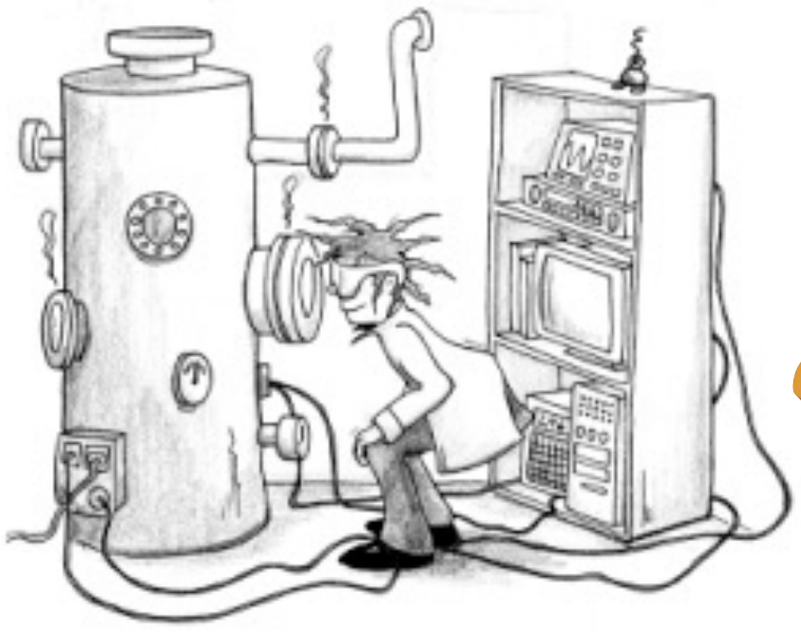
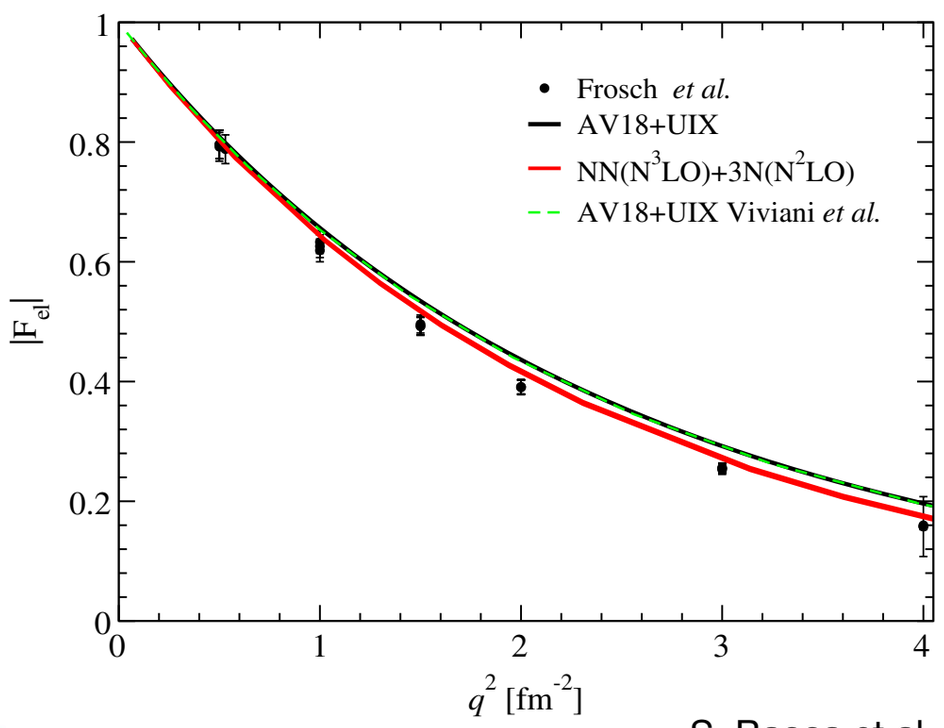
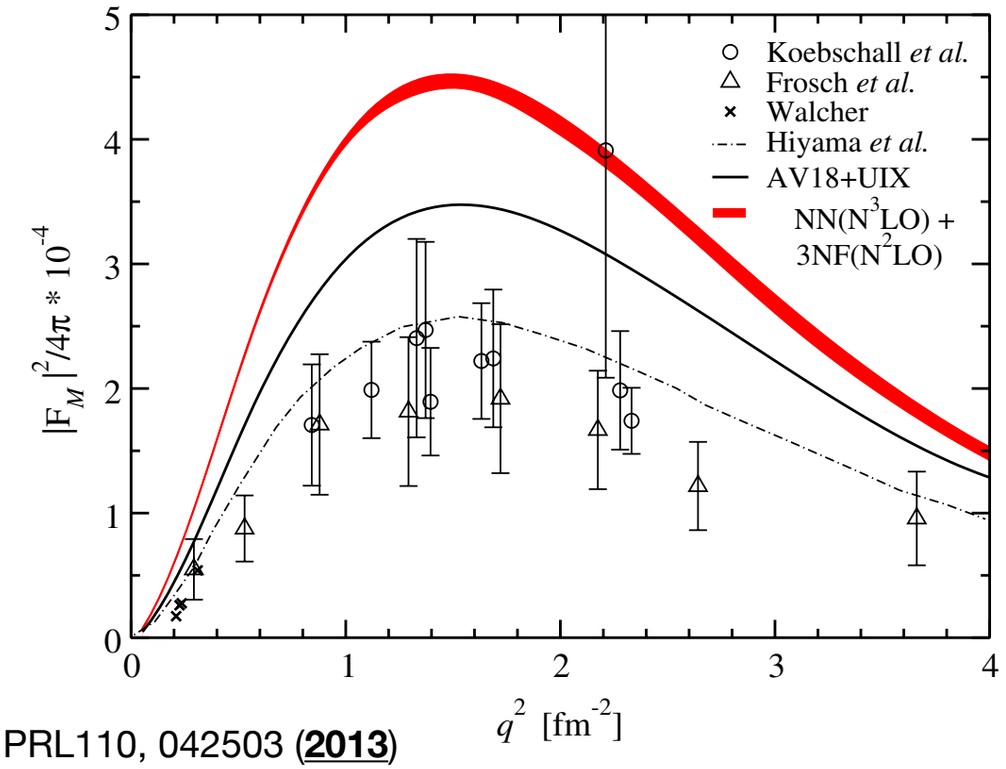


- Exact calculations both for bound and scattering states
- Energy and momentum transfer MUST be consistent with ChEFT predictions!





S. Bacca et al, PRL110, 042503 (**2013**)

The four horsemen of the Apocalypse

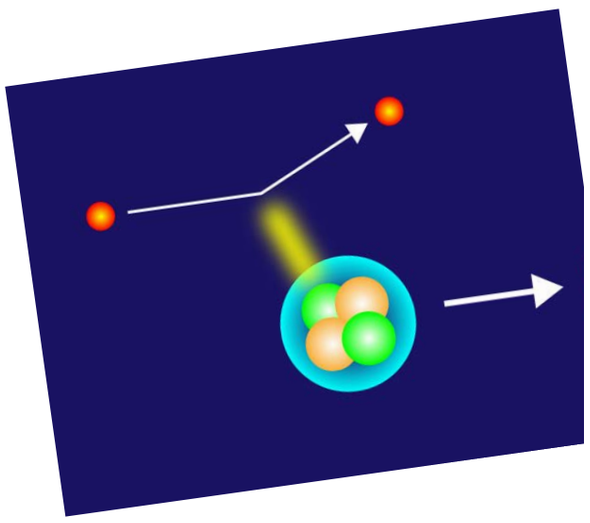
Theory and experiment disagree on alpha particles

Electron-scattering experiments on excited helium nuclei open questions about the accuracy and sensitivity of state-of-the-art nuclear models.

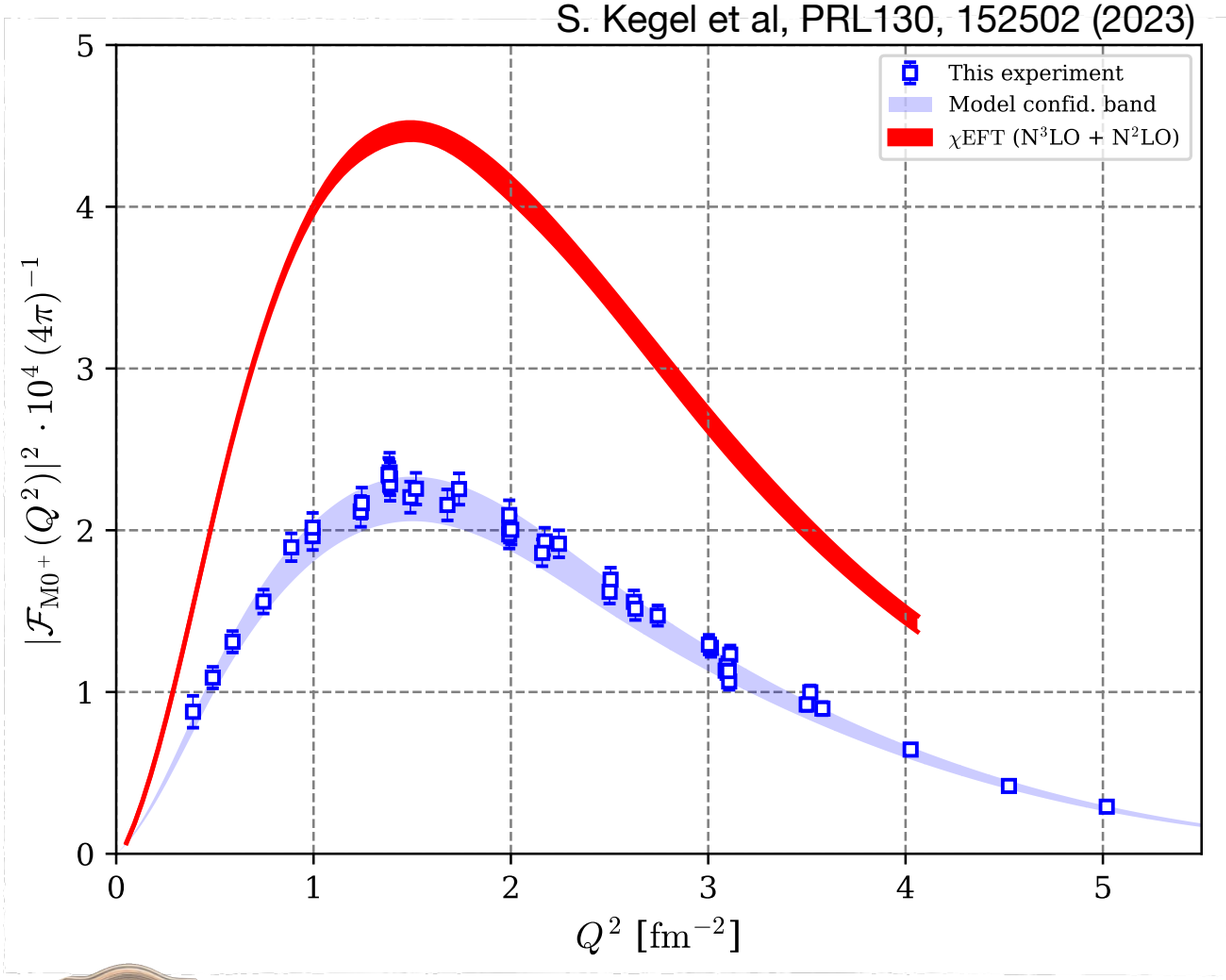
Although the helium nucleus has just four nucleons—two neutrons and two protons—theoretical models fail to replicate some of its properties.

ter. The researchers' calculations of a quantity related to how the nucleons are arranged in the alpha particle's first excited state didn't match the values inferred from electron-scattering experiments. The experiments were primarily from t
the uncertaint
intervening d
and technolog
tor sensitivity
ically, but that

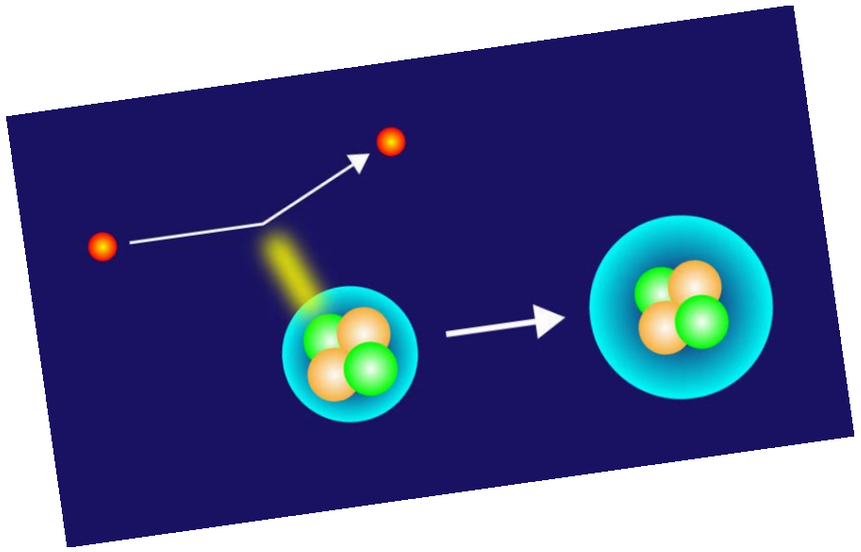
tween theory and expe
and her colleagues deci
and improve experime
tion was warranted. Nov
theory collaborators hav
disagreement and char



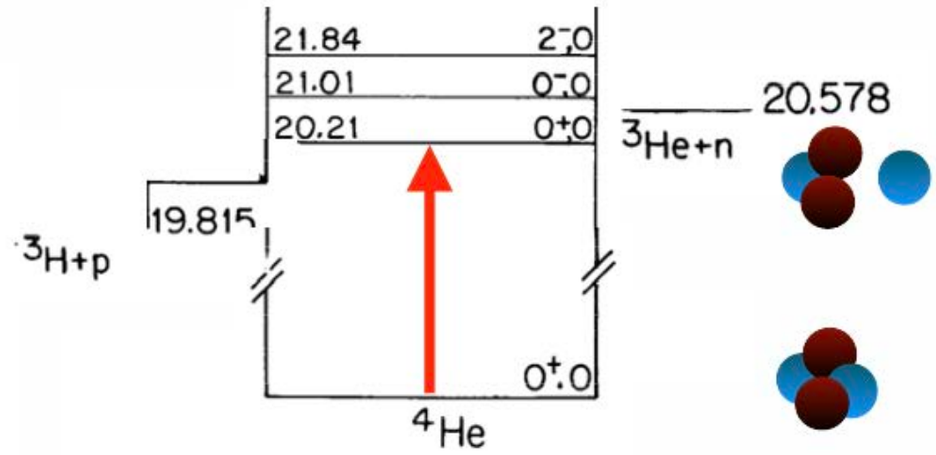
S. Kegel et al, PRL130, 152502 (2023)

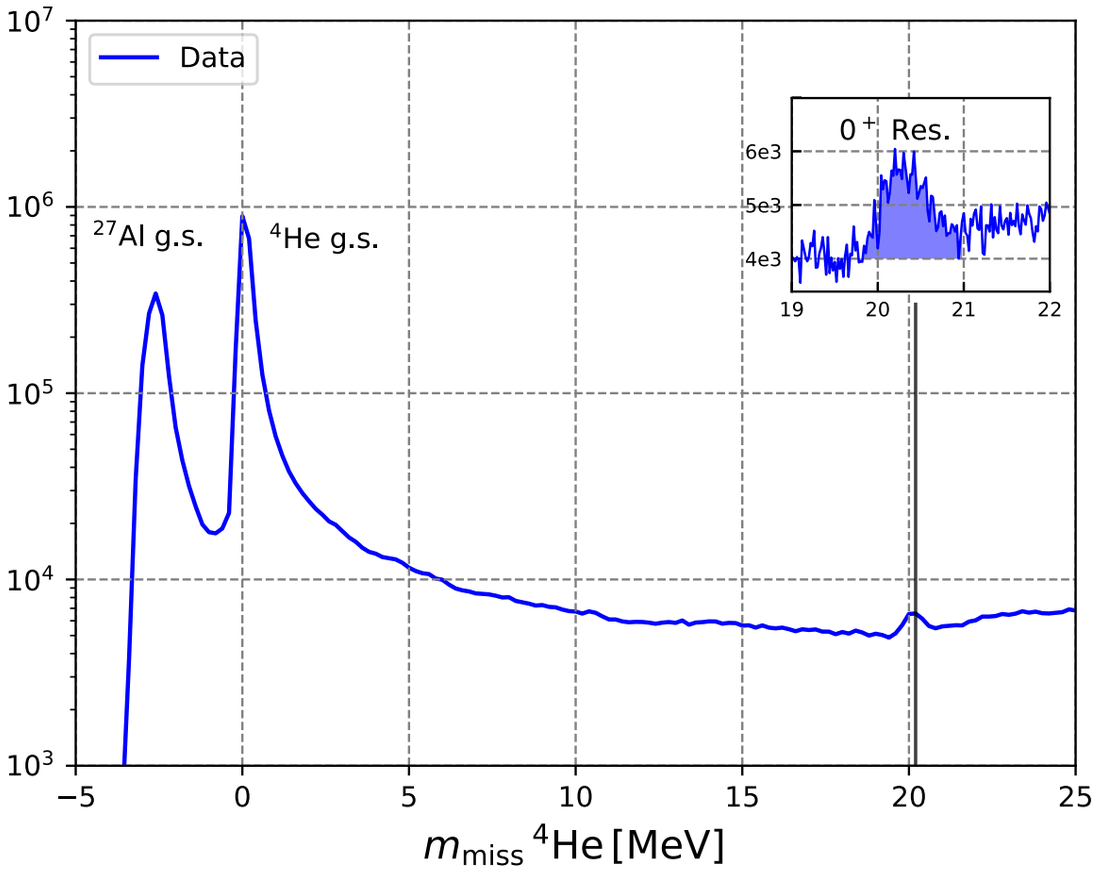


The four horsemen of the Apocalypse



The trans. form factor describes the dynamics of excitation between resonance and ground state depending on Q^2





^{4}He transition form factor

$$\mathcal{F}_{M0+}(Q^2) \propto | < 0_2^+ | \mathcal{M}(Q^2) | 0_1^+ > |$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} \propto |\mathcal{F}_{M0+}(Q^2)|^2 \propto \text{Events}$$

Determination of a form factor

$$|\mathcal{F}(Q^2)|^2 = \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} / \left(\frac{d\sigma}{d\Omega}\right)^*_{\text{Mott}}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \frac{\mathcal{N} - \mathcal{N}_{\text{bg}}}{\mathcal{L}_{\text{int}} \cdot \epsilon_{\text{eff}} \cdot \Omega}$$

Integrated Luminosity

$\mathcal{L}_{\text{int}}$ depends on

- Target density and length
- beam current
- time of the measured setup

$\rightarrow$ **monitored parameters**

Detector Efficiency

ϵ_{eff} depends on

- Deadtime
- Trigger
- VDC parameters (e.g. drift gas density, timing offsets)

$\rightarrow$ **calibrated parameters**

Phase Space

Ω depends on

- Size of Collimator
- central momentum p_{cent}
- scat. angle θ

$\rightarrow$ **simulated parameters**

Determination of a form factor

$$|\mathcal{F}(Q^2)|^2 = \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} / \left(\frac{d\sigma}{d\Omega}\right)^*_{\text{Mott}}$$

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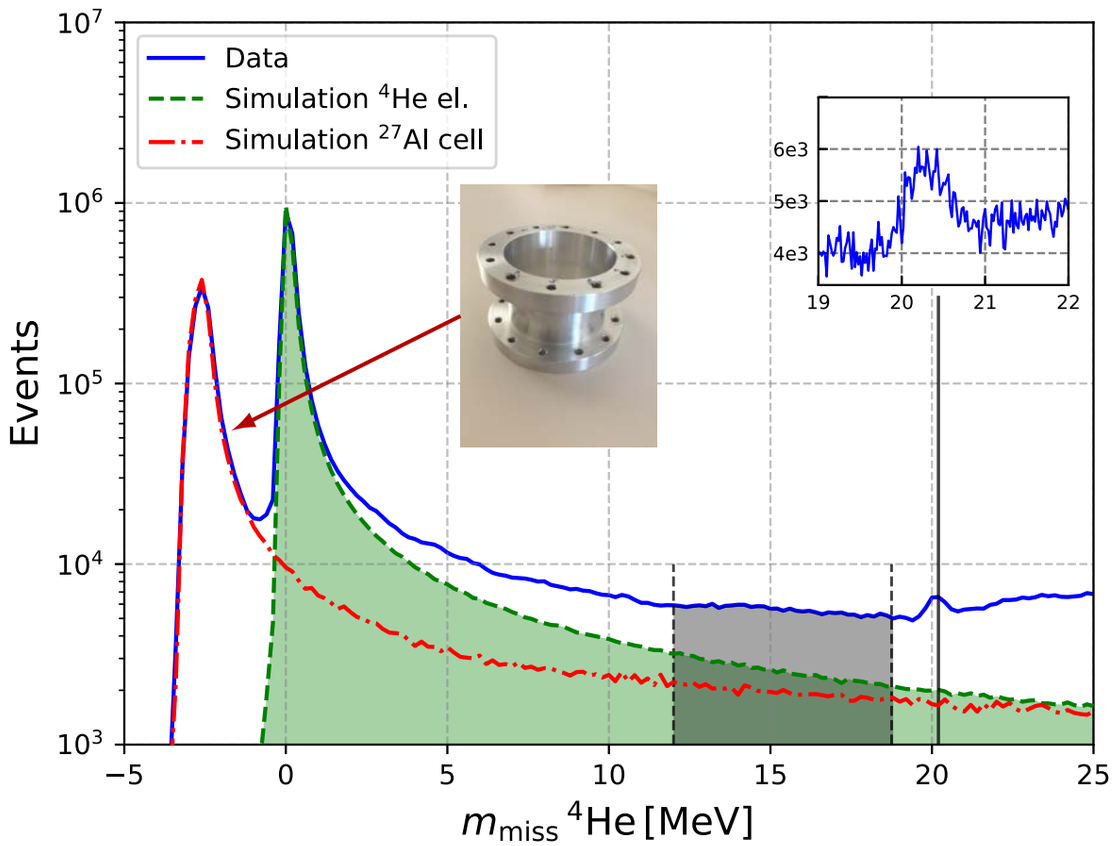
Background subtracted Events

$\mathcal{N}-\mathcal{N}_{\text{bg}}$ depends on

- $\mathcal{N}_{\text{bg}}$: e^- scattering on Target cell Material ^{27}Al
- $\mathcal{N}_{\text{bg}}$: Elastic and Quasi Elastic e^- scattering on ^{4}He
- $\mathcal{N}$: Resonance Model



- Aluminum target walls

Semi-empirical model of elastic, quasi-elastic, inelastic scattering. Check with empty cell runs!

- Radiative tail of ^{4}He elastic line

Elastic Form Factor + radiative corrections

Determination of a form factor

$$|\mathcal{F}(Q^2)|^2 = \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} / \left(\frac{d\sigma}{d\Omega}\right)^*_{\text{Mott}}$$

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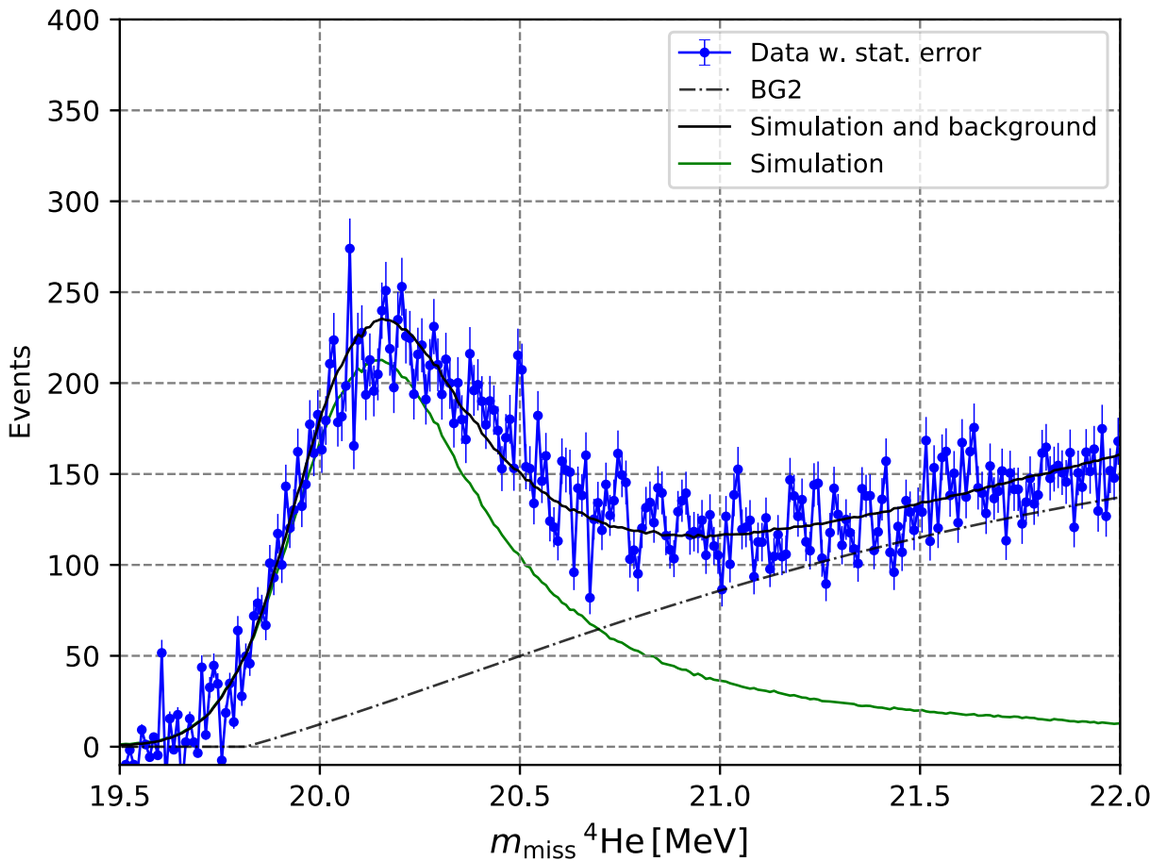

- ^{4}He continuum

Model includes quasi-elastic processes and other resonances (two background models)

- ^{4}He monopole resonance

Parameterisation to simulate the resonance in the spectra (two line shapes)

Results for the transition FF

- Transition form factor fitted with B-Splines and Polynomial x Exp.
- Dependence of background and resonance models embedded by repeating analysis for all combinations of BG1/BG2 and σ1/σ2
  → **model confidence band**
- **At MAGIX we can reduced the uncertainties and measure at lower Q^2**

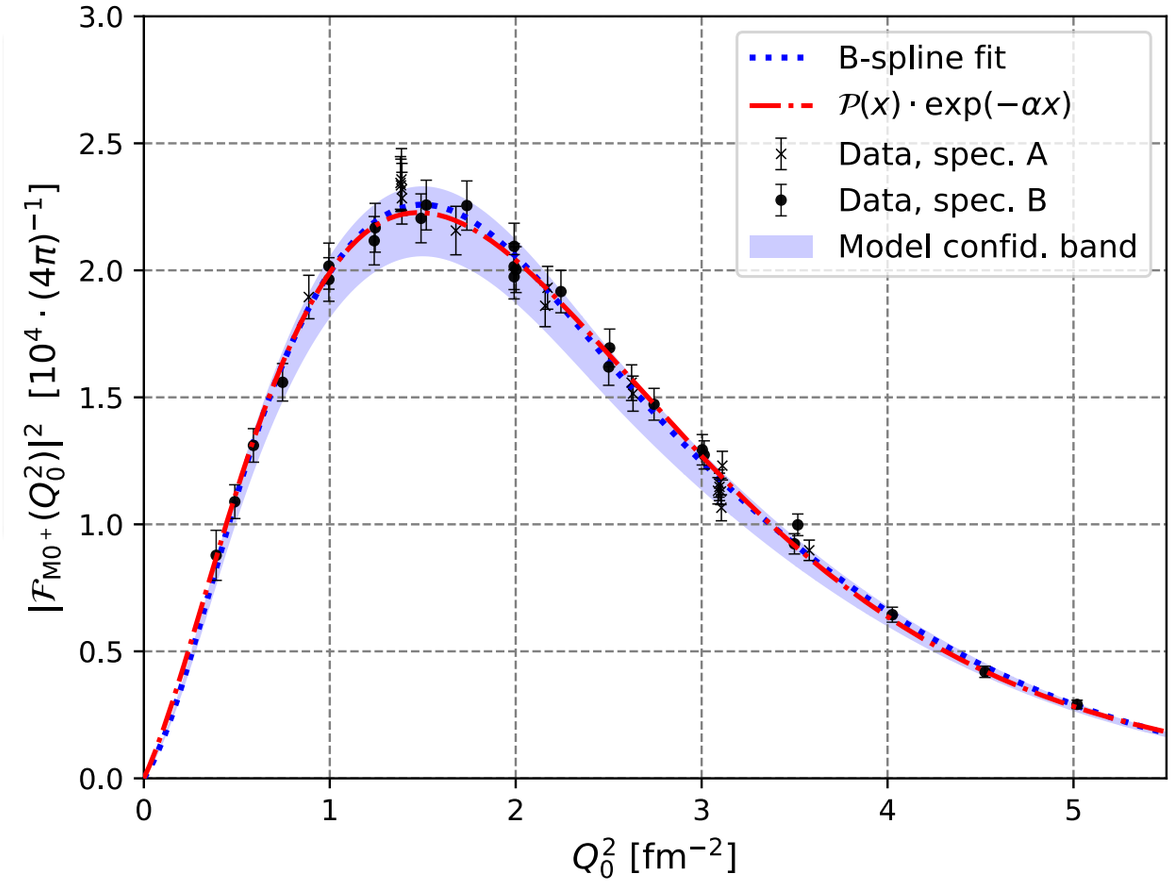

TABLE II. Contributions to the systematic uncertainties of the transition form factor and the model dependencies.

Source	$\Delta\lvert\mathcal{F}_{M0^+}(Q^2)\rvert^2$ (%)
Background	±1
^{4}He ground state form factor	±0.5
$\Delta\Gamma_0$	±4
Model uncertainties	
BG1-BG2	±3.2
$\sigma_1 - \sigma_2$	−5.8

The four horsemen of the Apocalypse

- Transition form factor fitted with B-Splines and Polynomial x Exp.
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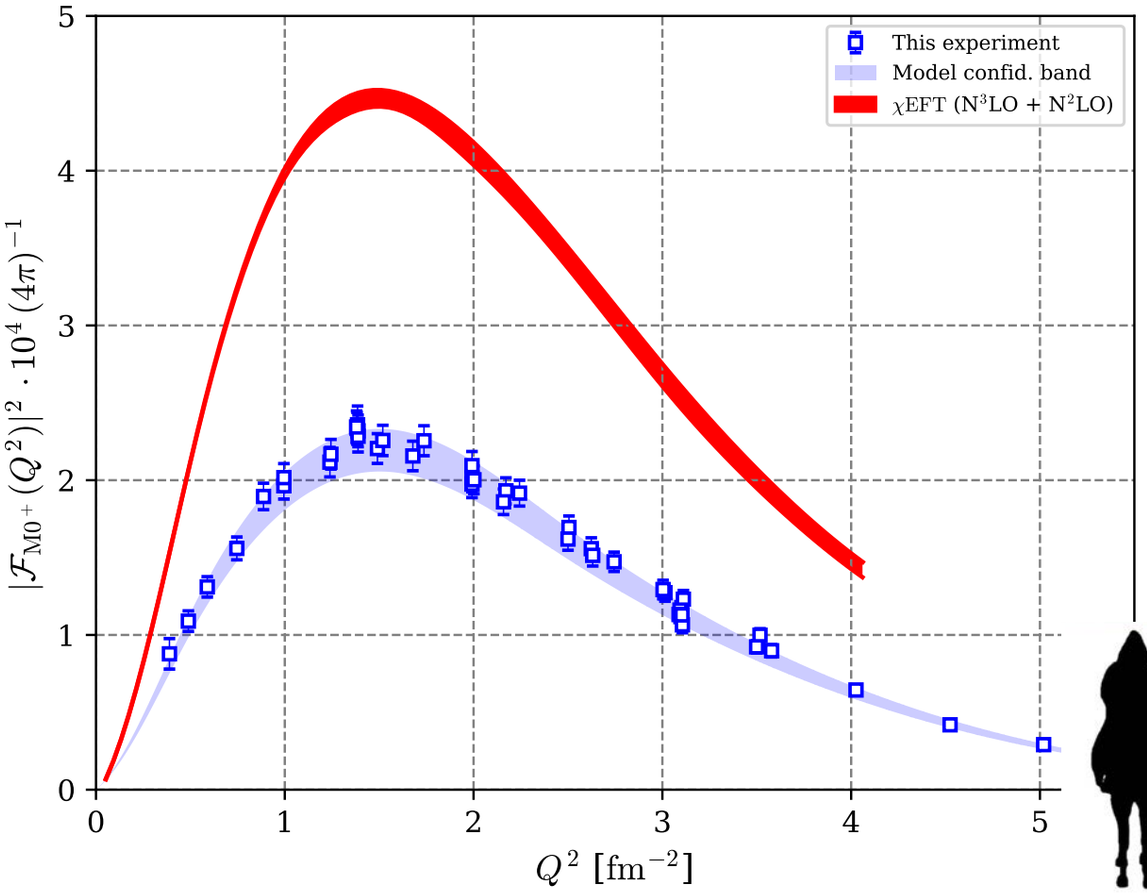


… but would it really help?

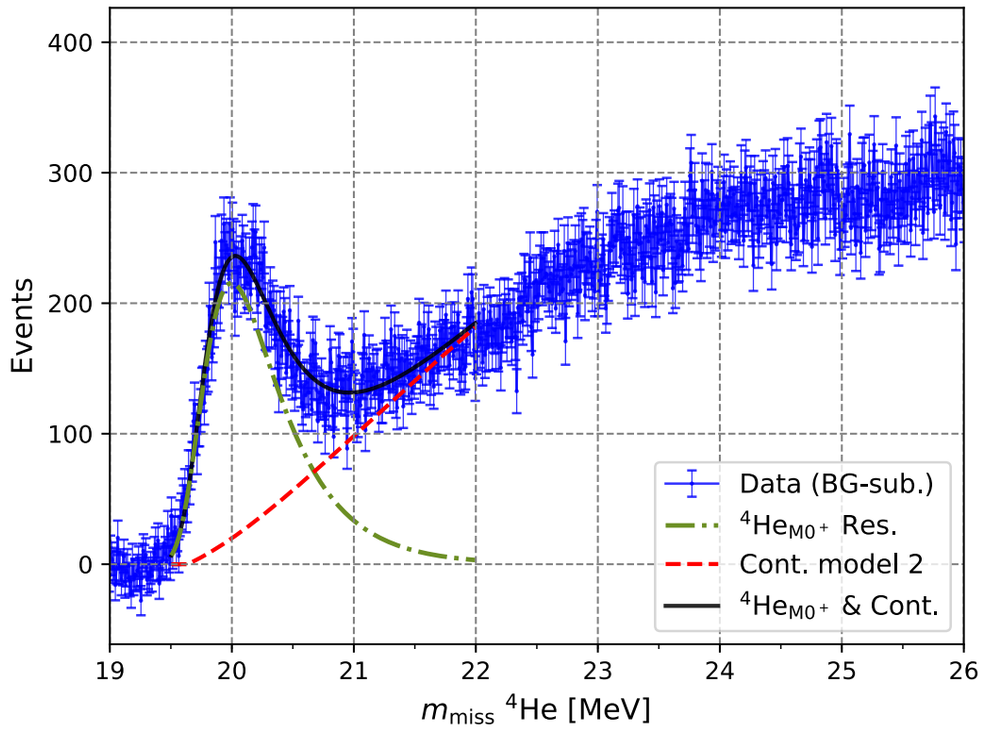
...precision, perplexities and uncertain tales

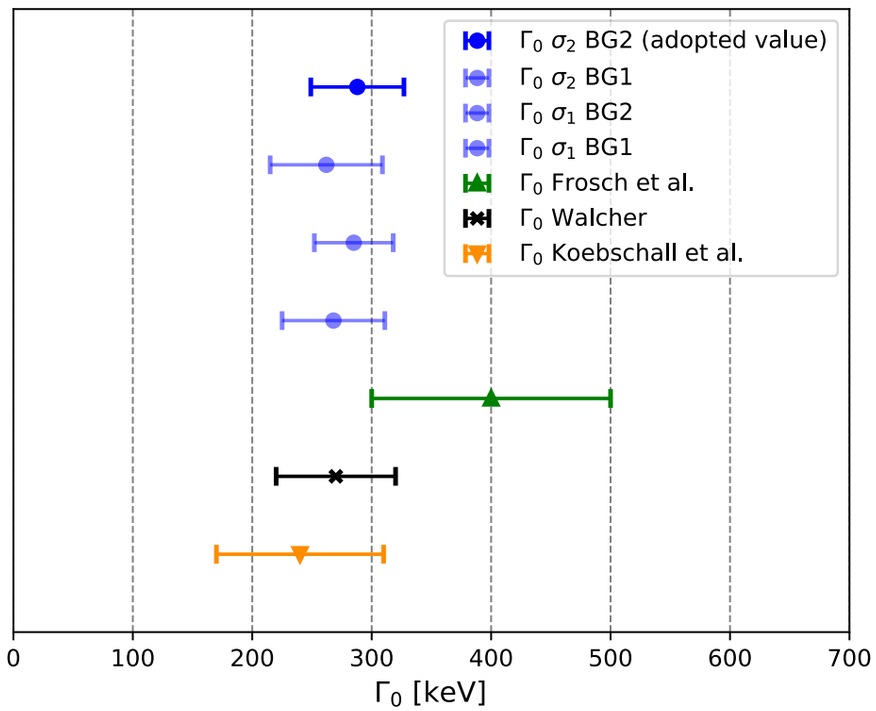
Resonance position

Viviani et al, Phys. Rev. C **102**, 034007 (2020)

Interaction	E_R (MeV)	Γ (MeV)
N3LO500	0.126	0.556
N3LO600	0.134	0.588
N3LO500/N2LO500	0.118	0.484
N3LO600/N2LO600	0.130	0.989
N4LO450/N2LO450	0.126	0.400
N4LO500/N2LO500	0.118	0.490
N4LO550/N2LO550	0.130	0.740
Expt.	0.39	0.50

Large dependence on the nuclear Hamiltonian





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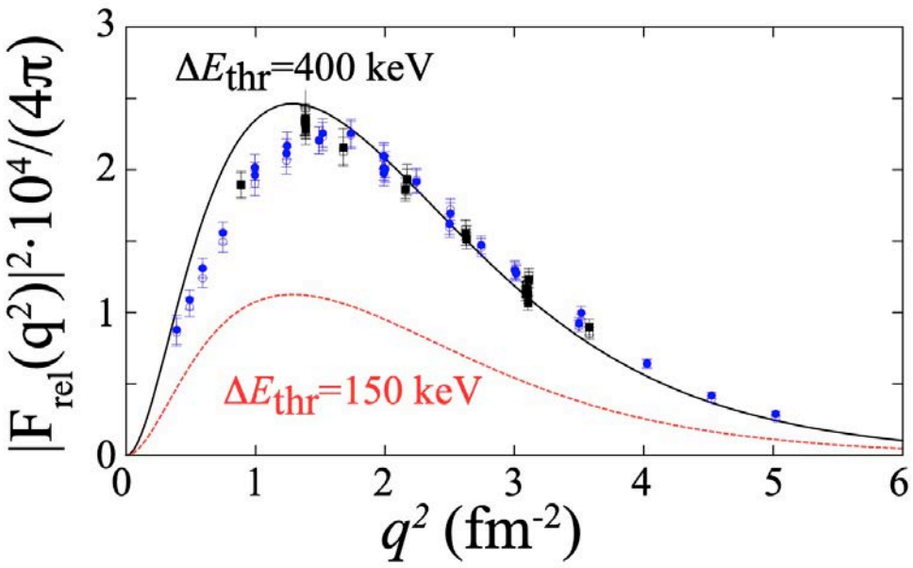
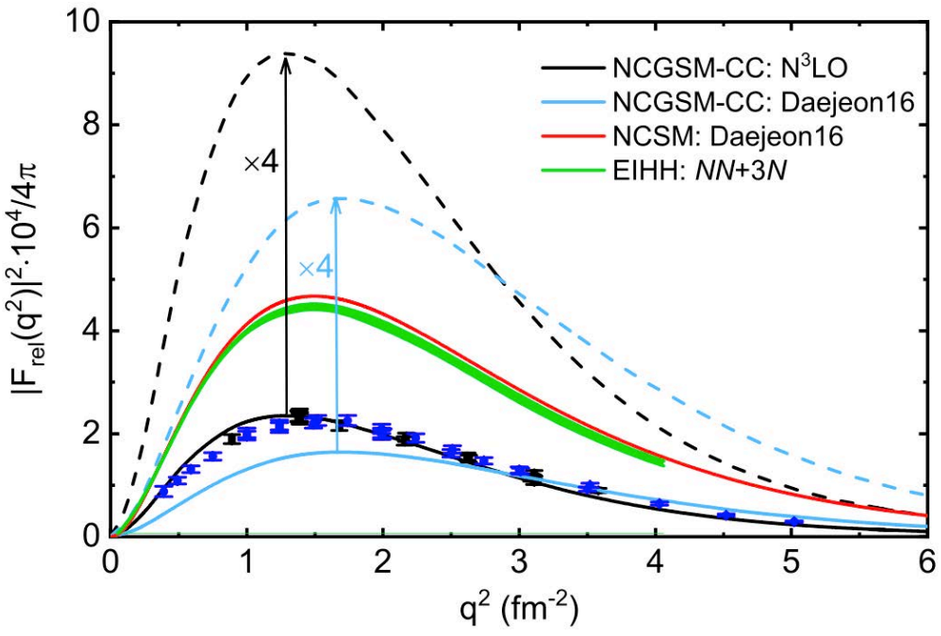
Large dependence on the nuclear Hamiltonian

However, factor potentially wrong, Peng et al, (privat. comm. - comment submitted to PRL)

More calculations

Michel et al., PRL **131**, 242502(2023)





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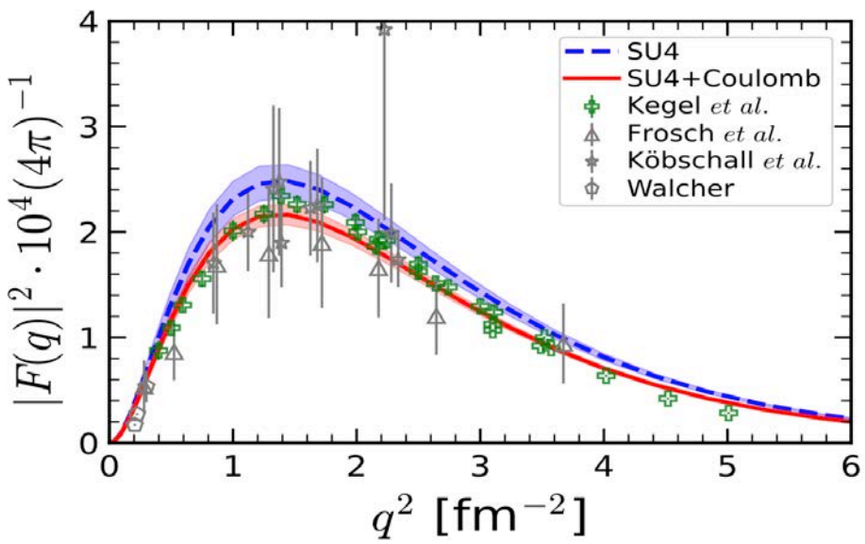
Large dependence on the nuclear Hamiltonian

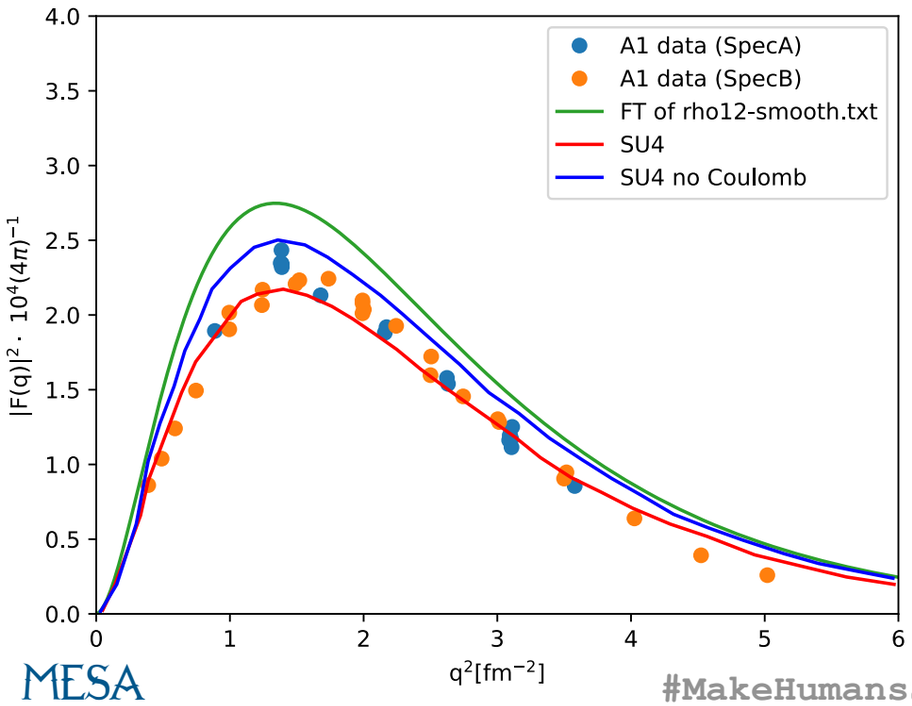
However, factor potentially wrong, Peng et al, (privat. comm. - comment submitted to PRL)

However, Fourier transform of transition density is higher than data (tail was modified)

More calculations

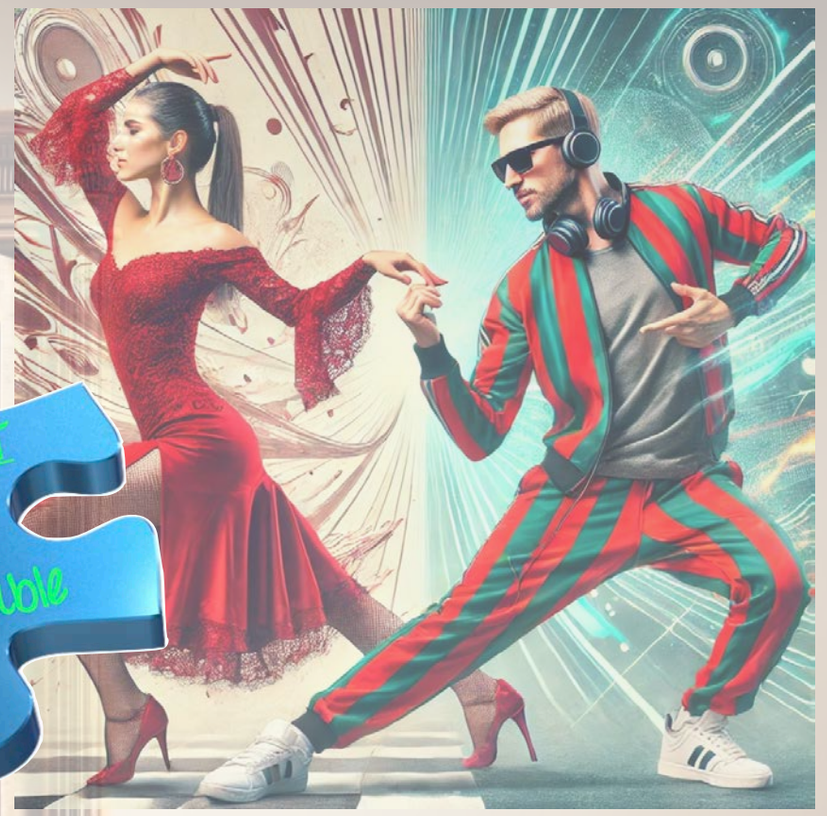
Meißner et al., PRL **132**, 062501 (2024)





… AND UNCERTAIN TALES…

…is it still a tango?



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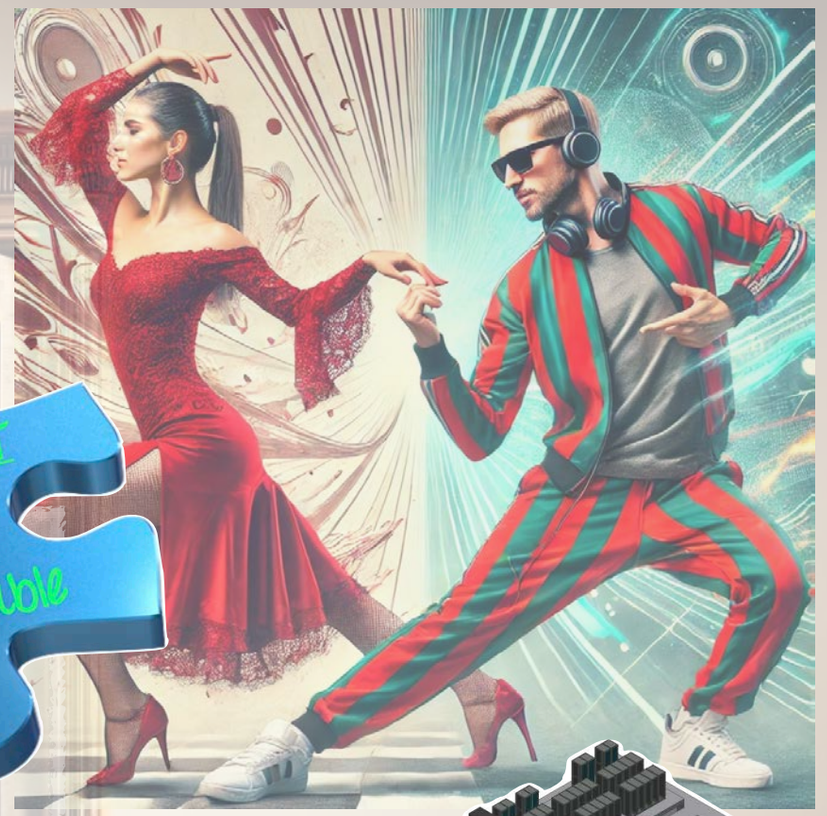
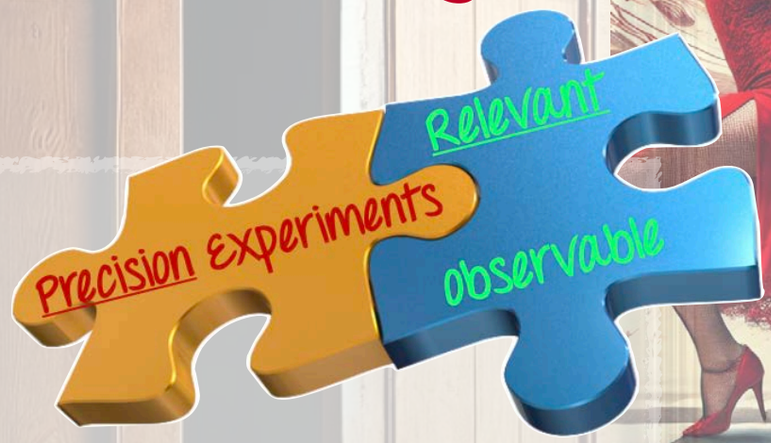
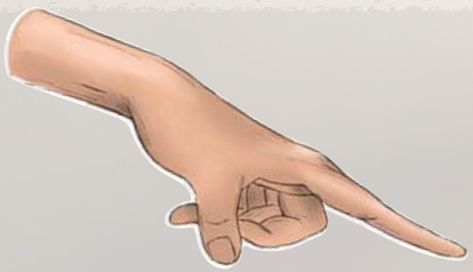




…get all your errors in order! :-)

MESA is the facility to lead precision 2.0

… AND UNCERTAIN TALES…



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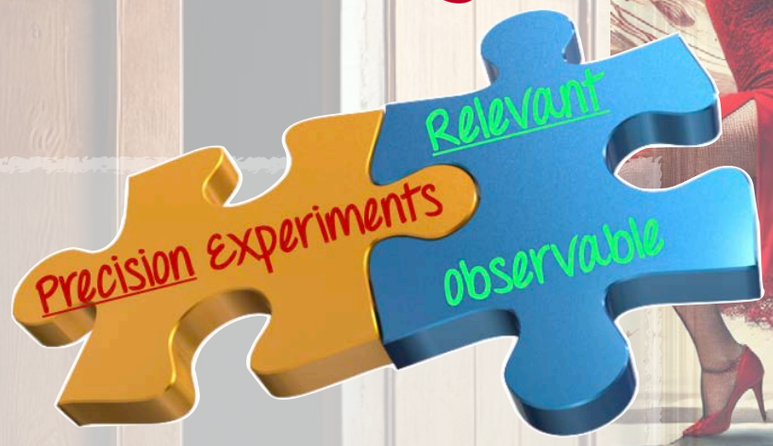

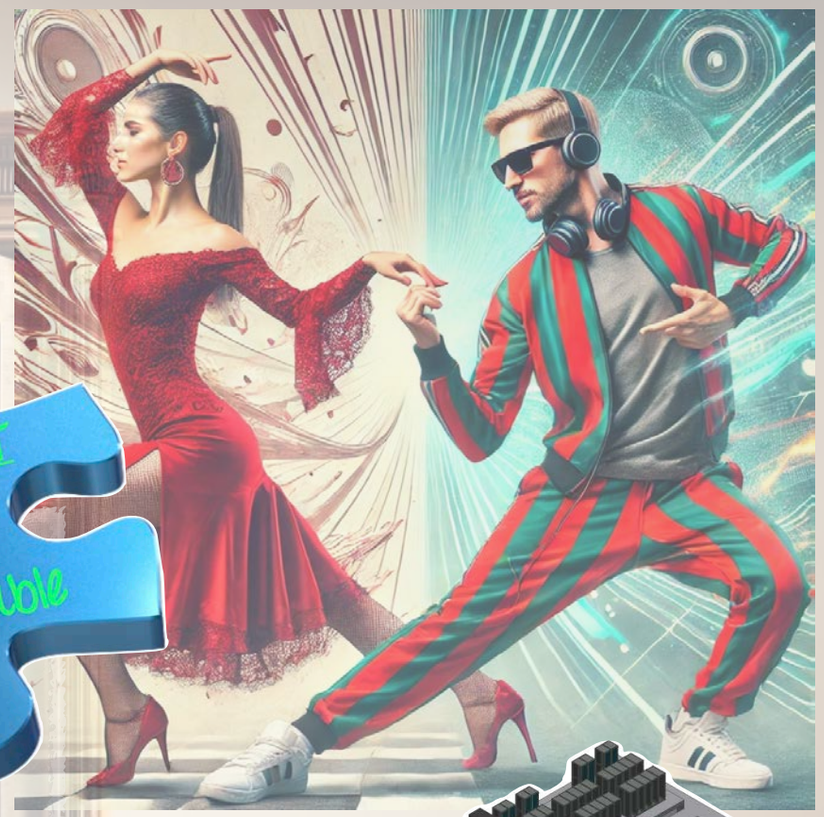

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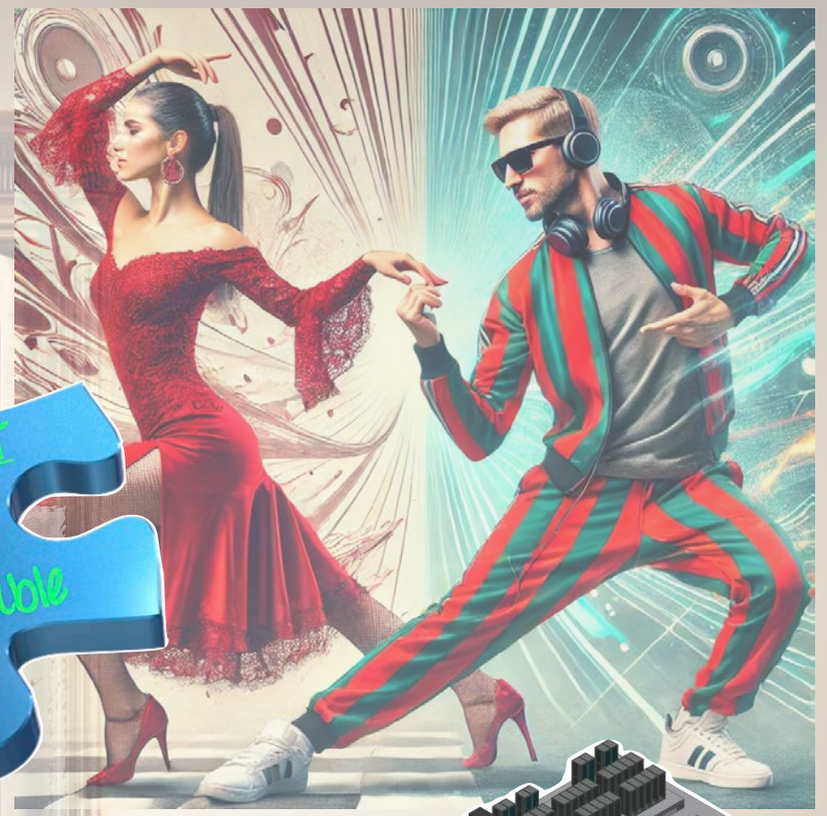
MESA is the facility to lead precision 2.0

Challenge to EFT: Propose a (new) observable and make a prediction!

… AND UNCERTAIN TALES…



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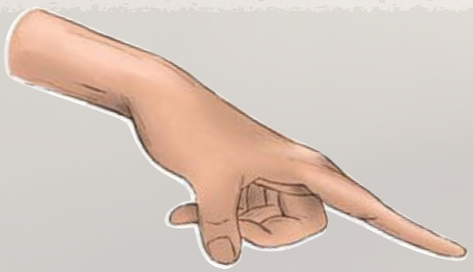

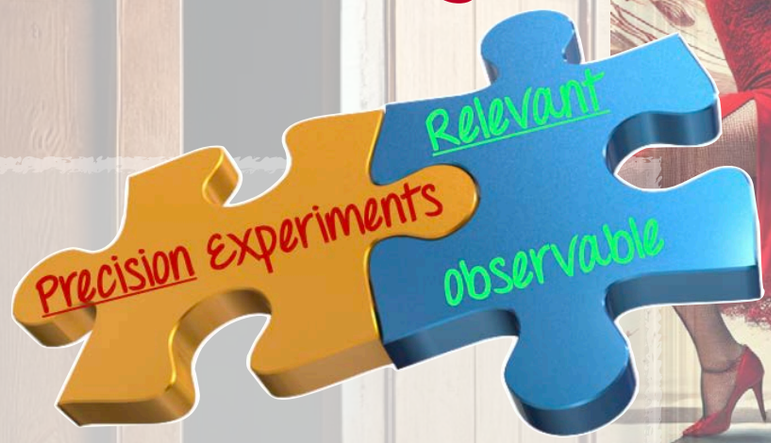

…get all your errors in order! :-)

MESA is the facility to lead precision 2.0

Challenge to EFT: Propose a (new) observable and make a prediction!

…also new data on the proton crisis, search for exotic particles, reactions for astrophysics …

Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.

(Winston Churchill)