Per aspera ad astra ...

MREX:The Mainz Radius EXperiment

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

The chronicles of MESA: Precision, perplexities and uncertain tales

Book I
MREX:The Mainz Radius EXperiment

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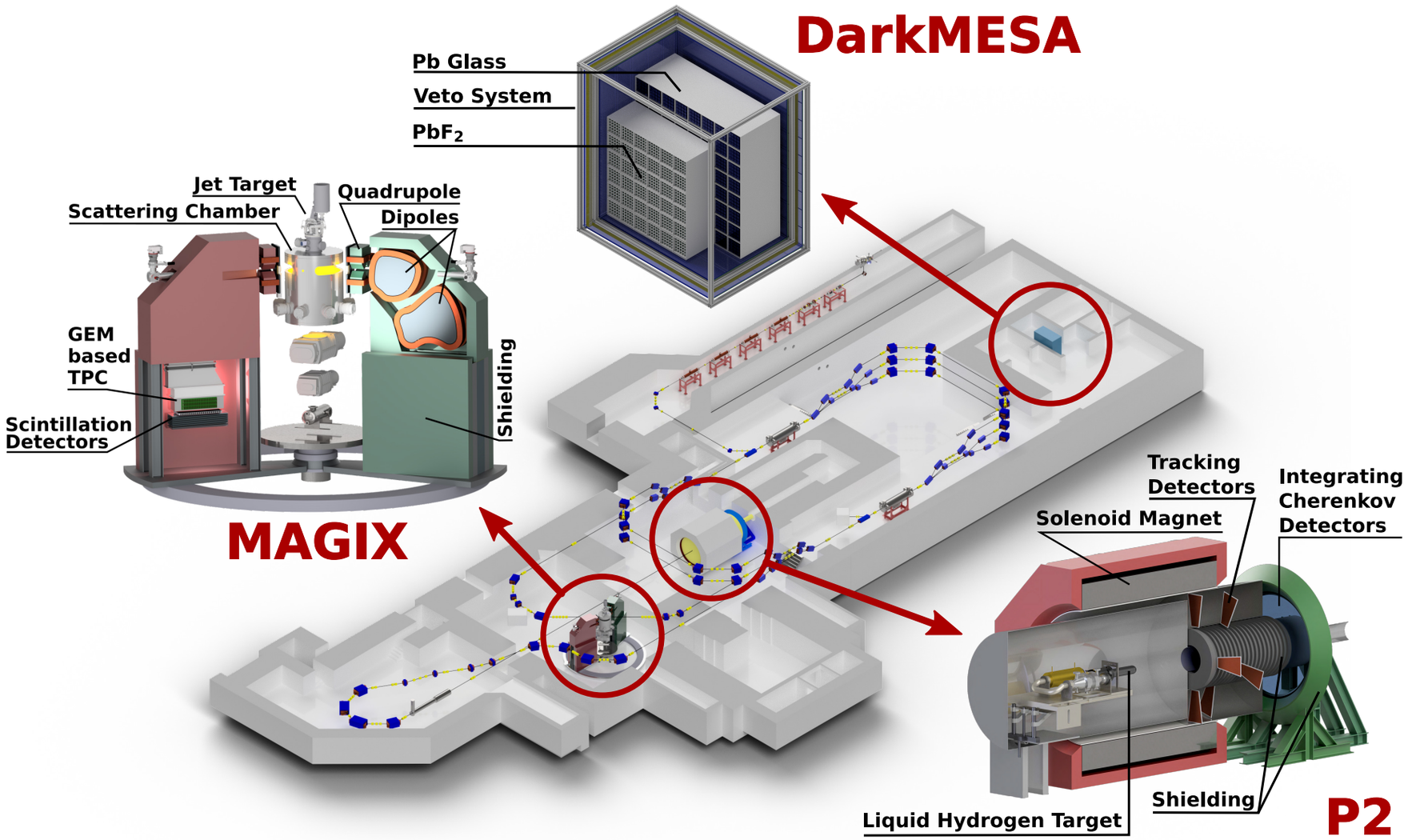
Mainz Energy-recovering Superconducting Accelerator

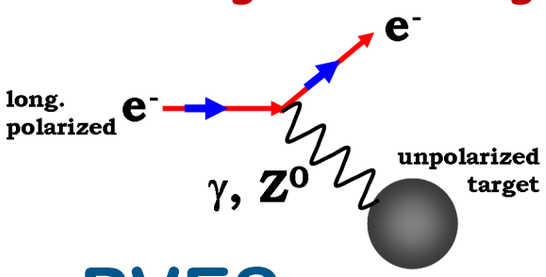
Multi-purpose facility low-energy precision physics experiments

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



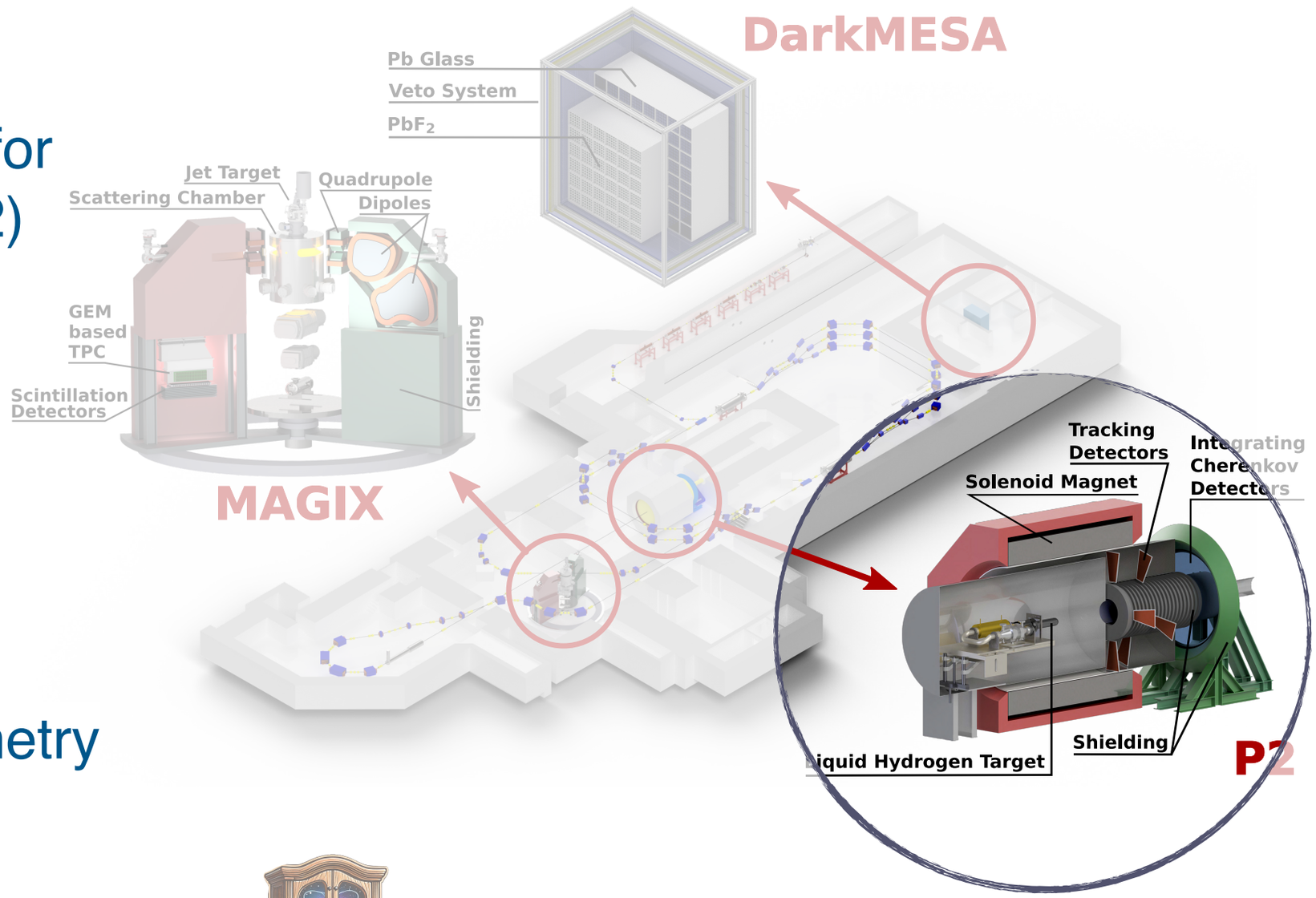
...the "Chronicles of MESA"

PV-Asymmetry



PVES

- External-beam mode for **high polarisation** (P2)



- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry

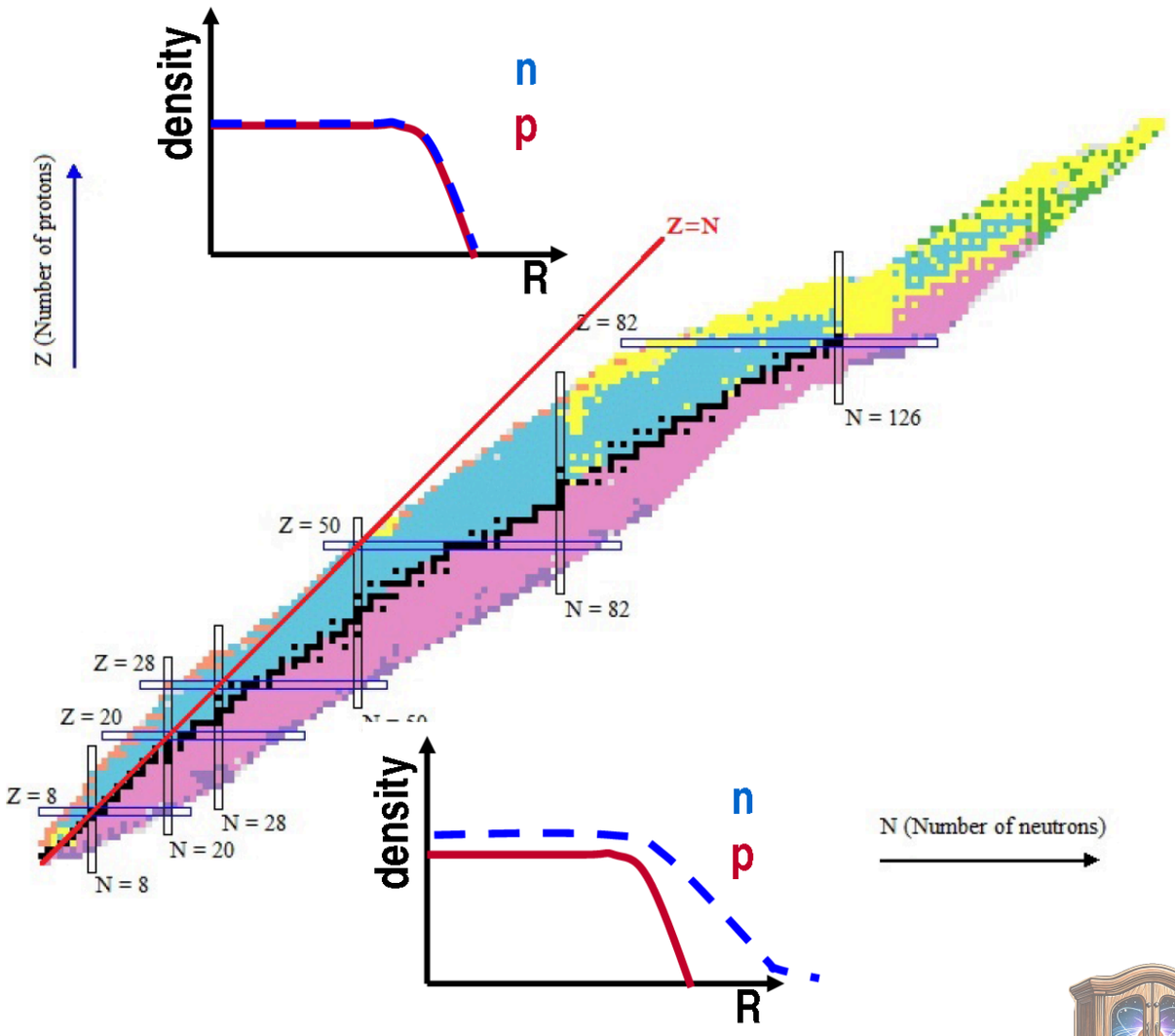
The chronicles of MESA:

Precision, perplexities

and uncertain tales

...did somebody already mentioned neutron-skin to you?

The neutron skin measures how much neutrons stick out past protons

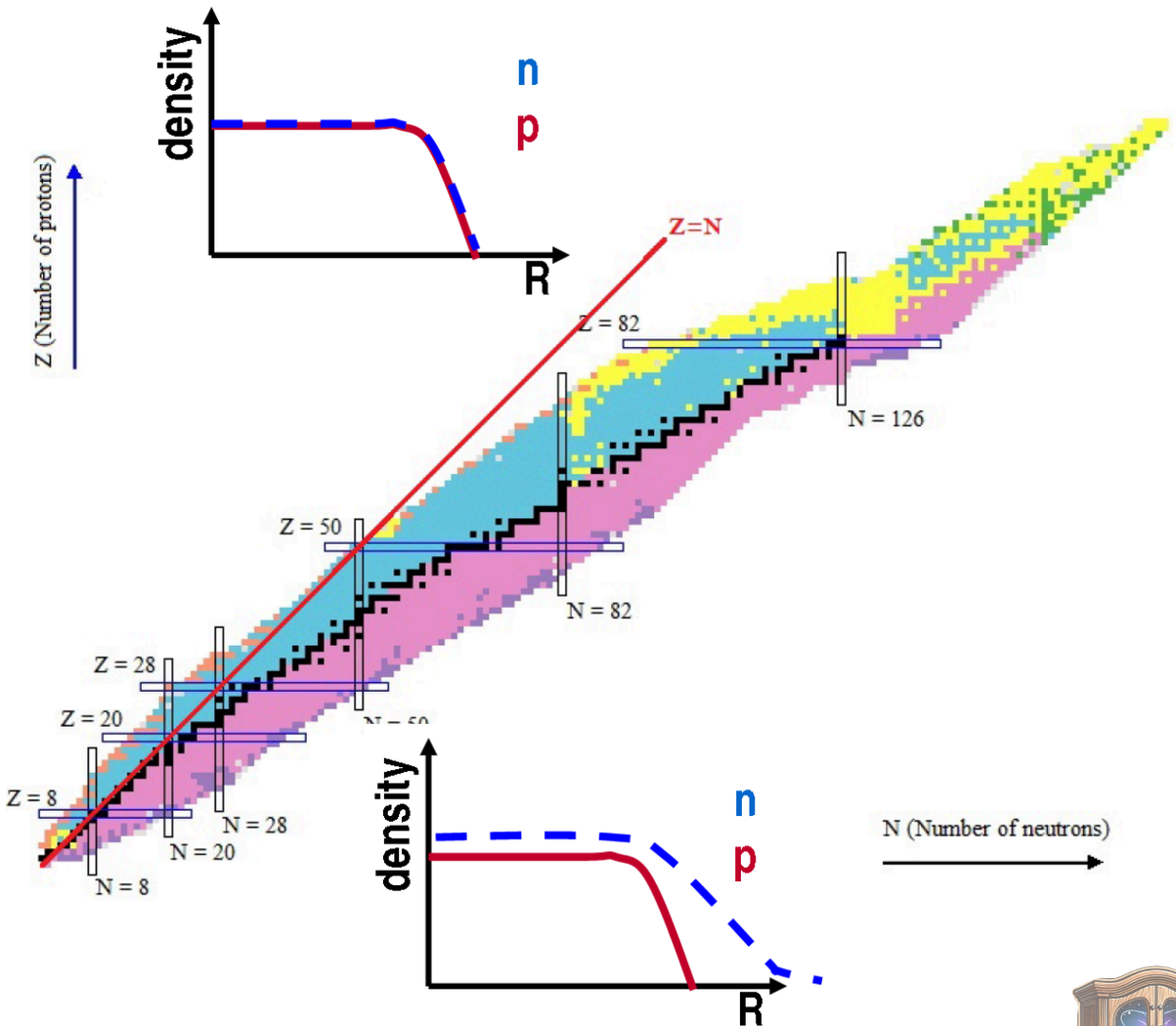


...did somebody already mentioned neutron-skin to you?

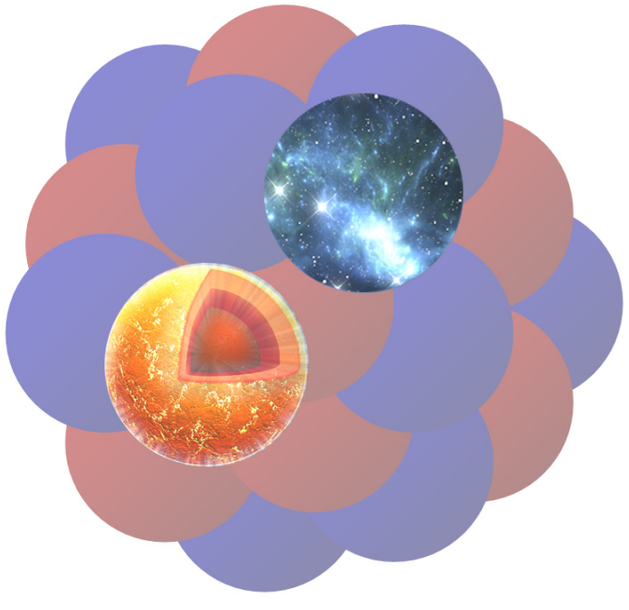
The neutron skin measures how much neutrons stick out past protons

Symmetry energy favours moving them to the surface

Surface tension favours spherical drop of uniform equilibrium density



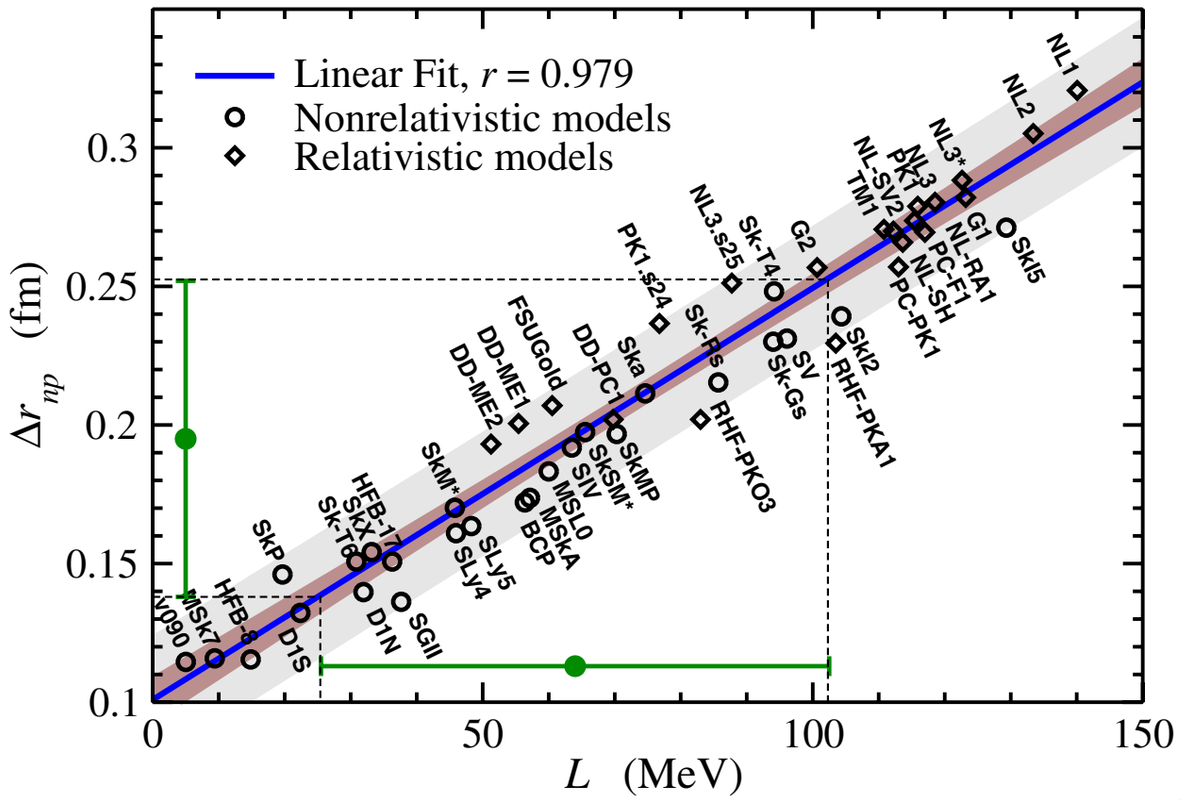
The spoiler: reality!



$$\mathcal{E}(\rho,\alpha) = \mathcal{E}(\rho,\alpha=0) + S(\rho)\,\alpha^2 + \ldots$$

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{1}{2}K_{\text{sym}}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \ldots$$

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



slope parameter

$$L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho_0}$$

curvature parameter

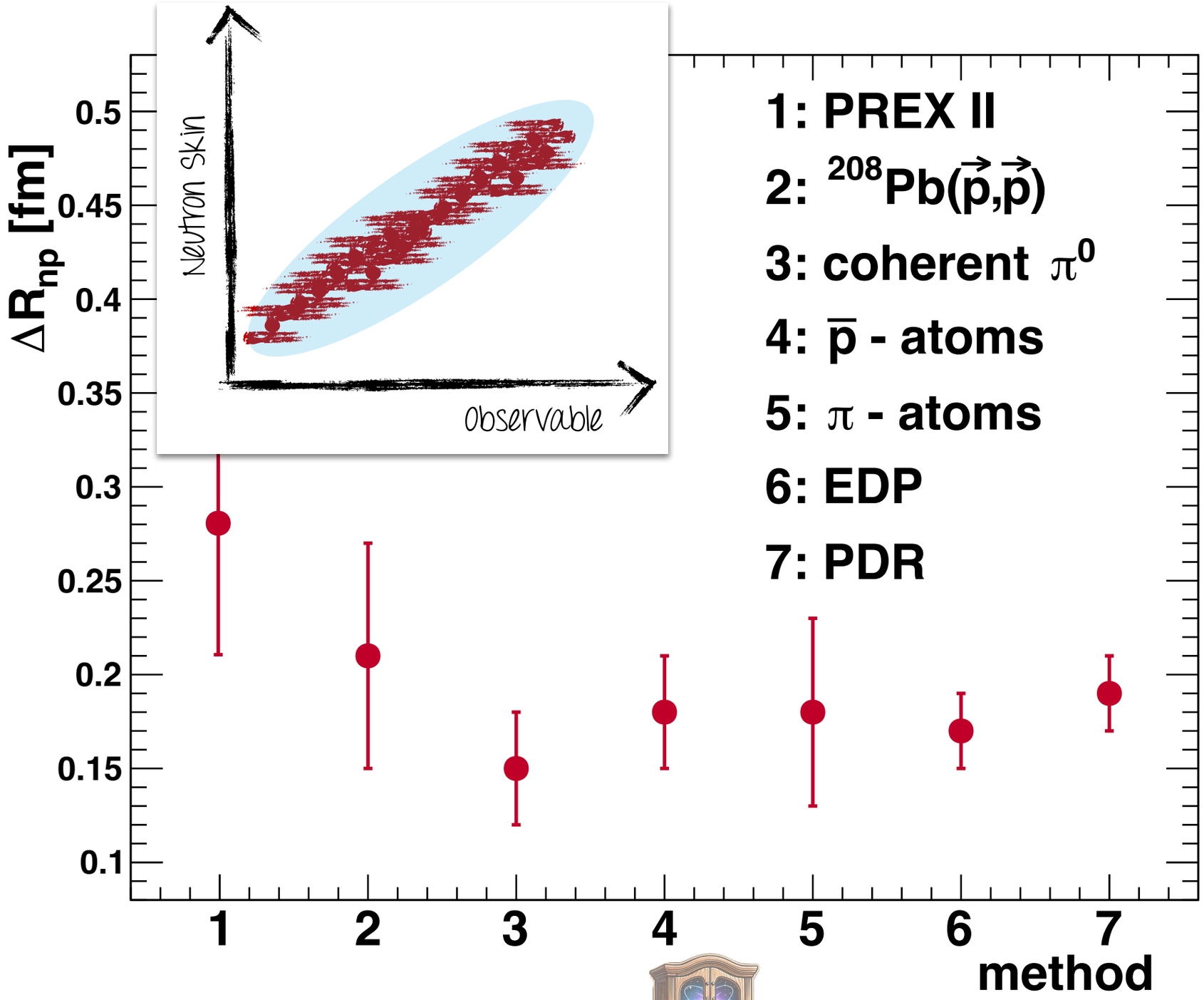
$$K_{sym} = 9\rho_0^2 \left.\frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\right|_{\rho_0}$$

The stairway to heaven

The answer to the ultimate question

The stairway to heaven

NONE is an actual MEASUREMENT of neutron skin!



The stairway to heaven

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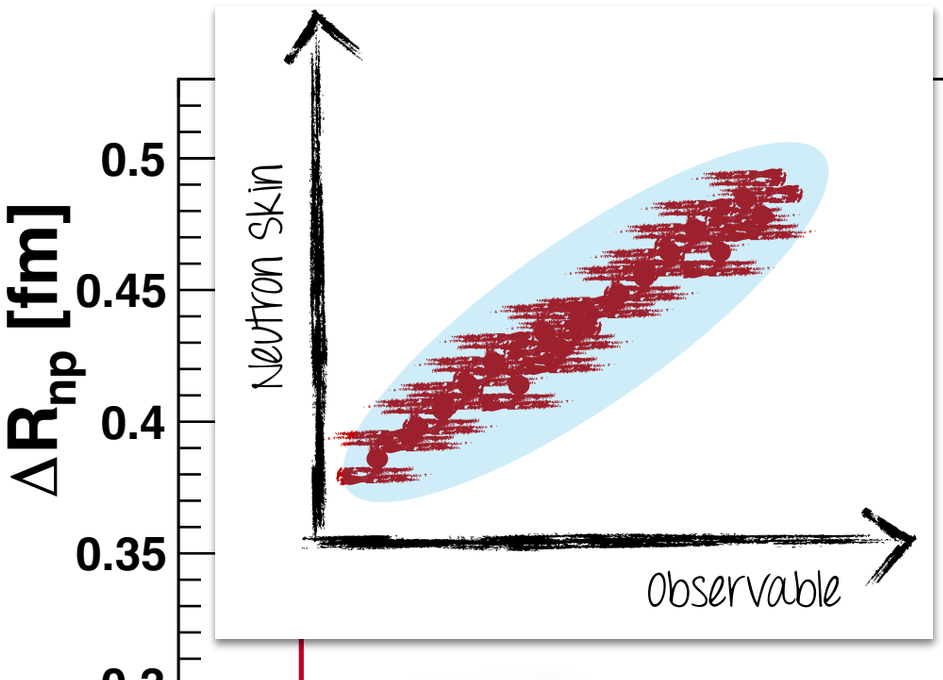
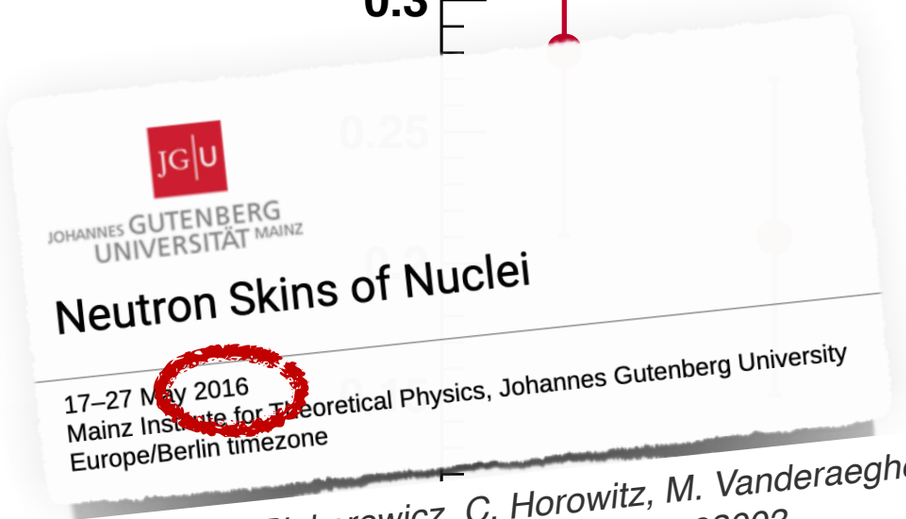




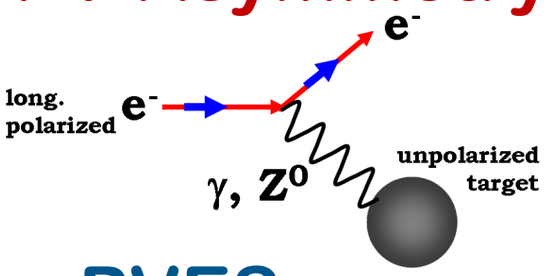
M. Thiel, CS, J. Piekarewicz, C. Horowitz, M. Vanderaeghen
J. Phys. G: Nucl. Part. Phys. 46 093003

The stairway to heaven

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

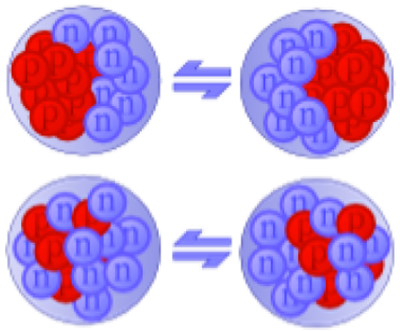
(Personal selection)

PV-Asymmetry



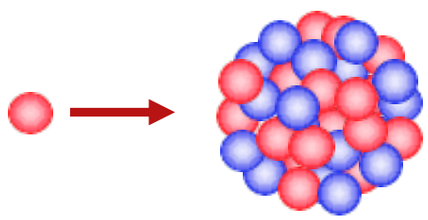
PVES

Resonance Strength

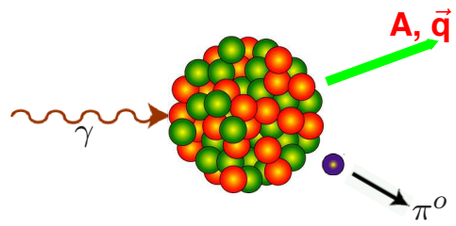


Collective Excitation

Cross-section



Hadronic Probes



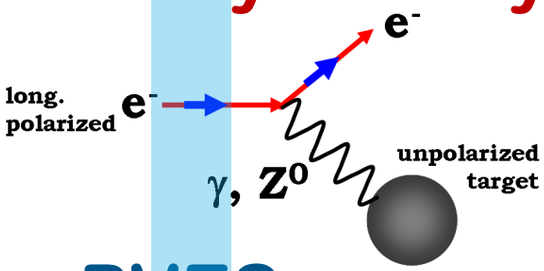
EM Probes

The stairway to heaven

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

(Personal selection)

PV-Asymmetry



PVES

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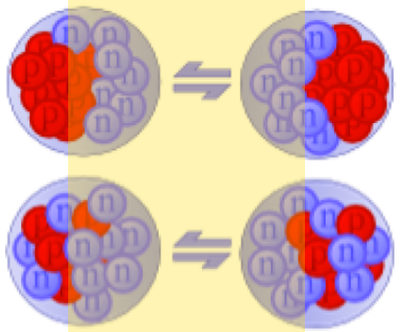
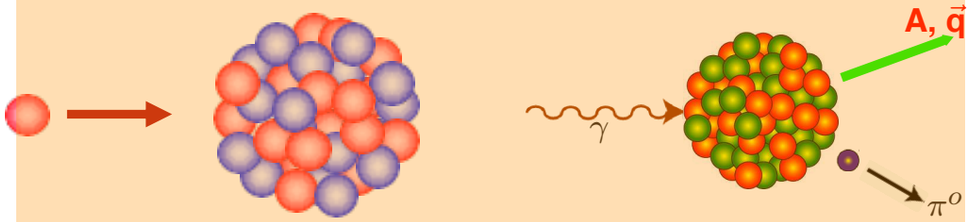


Collective Excitation

see Pierre's talk

????..

Cross-section



Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

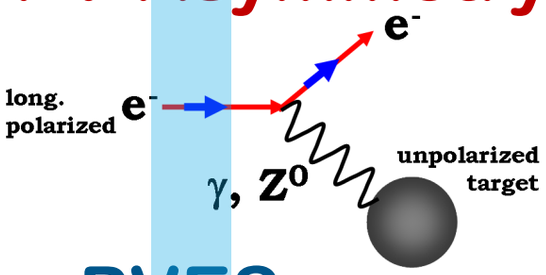
The stairway to heaven

(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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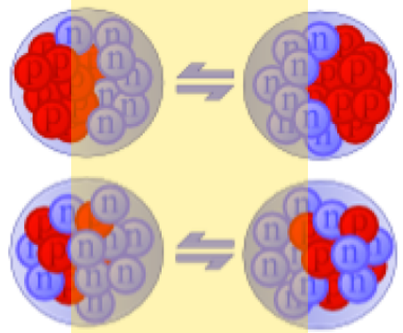

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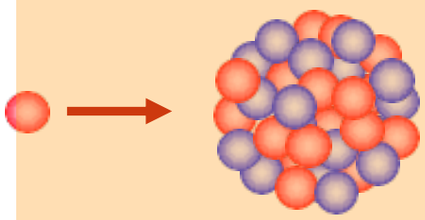
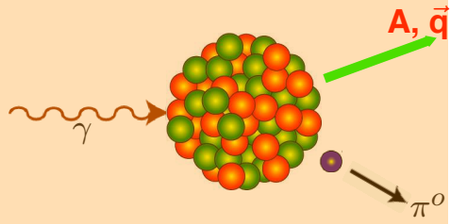


Hadronic Probes

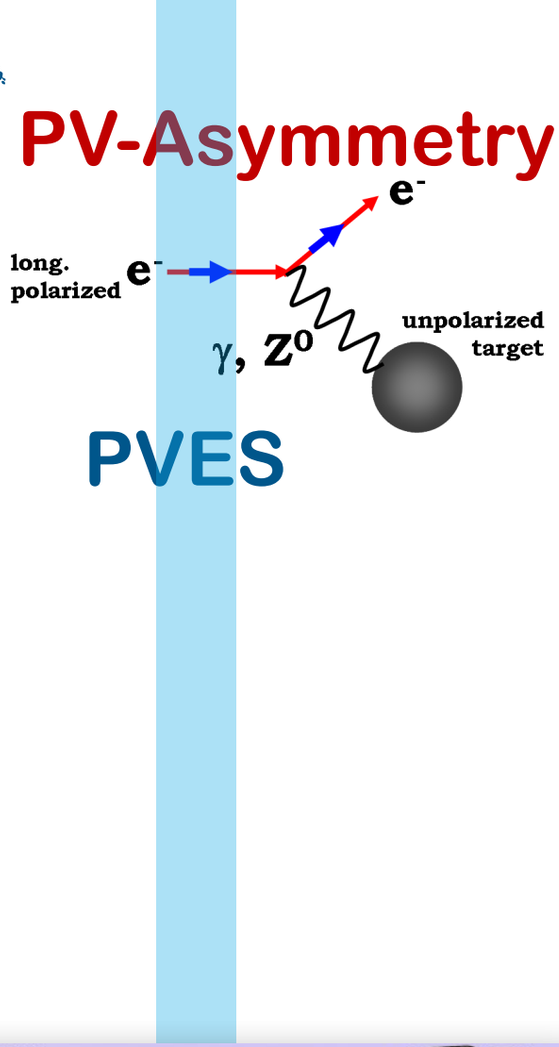


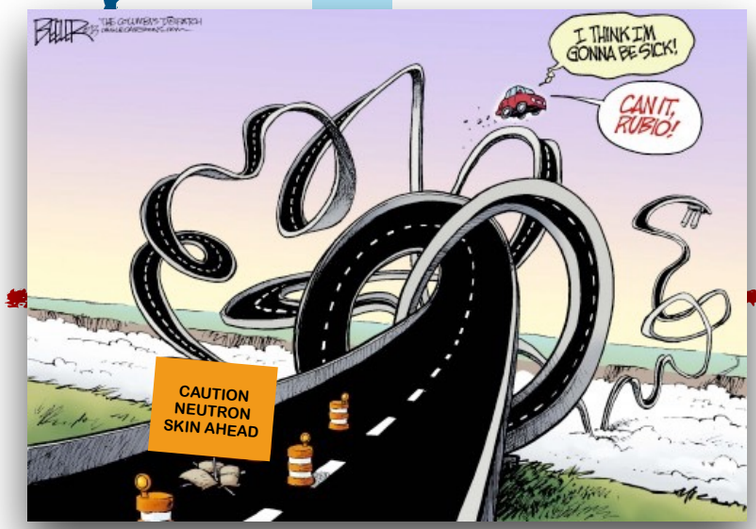
EM Probes

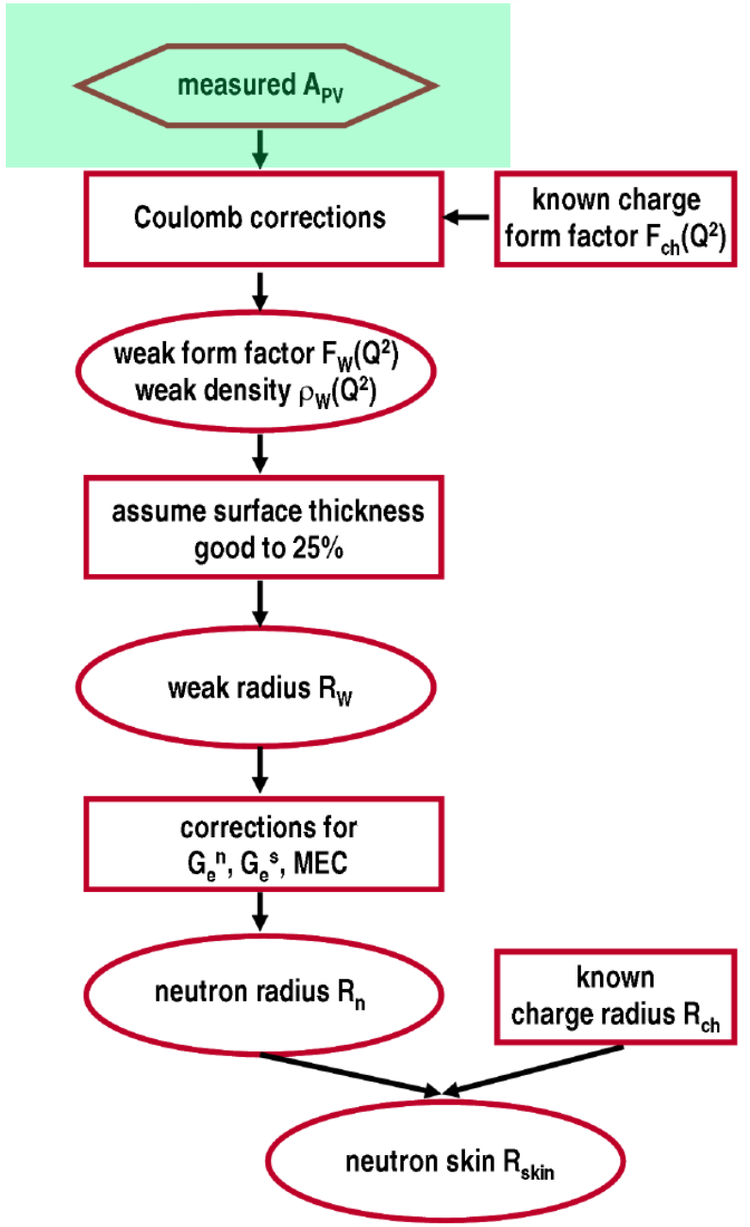
Theo. uncertainties (a.u)

The shortest road ...

Experimental Challenges
(in unit of frustration)



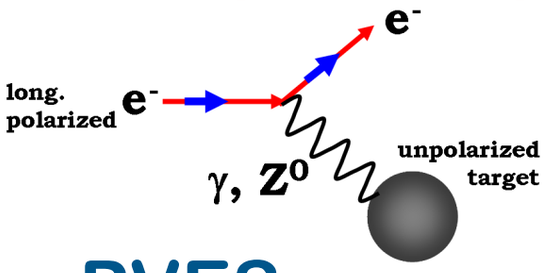




Theo. uncertainties (a.u)

The weak interaction in a nutshell

PV-Asymmetry



PVES

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

Non-PV e-scattering

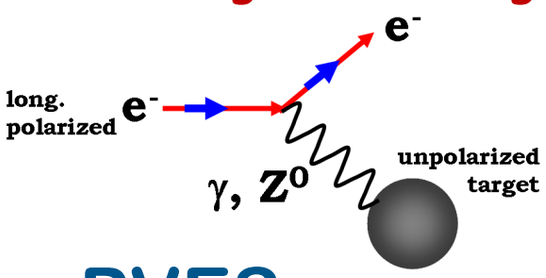
Electron scattering γ exchange provides R_p through nucleus FFs

PV e-scattering

Electron also exchange Z, which is parity violating and primarily couples to neutron

The weak interaction in a nutshell

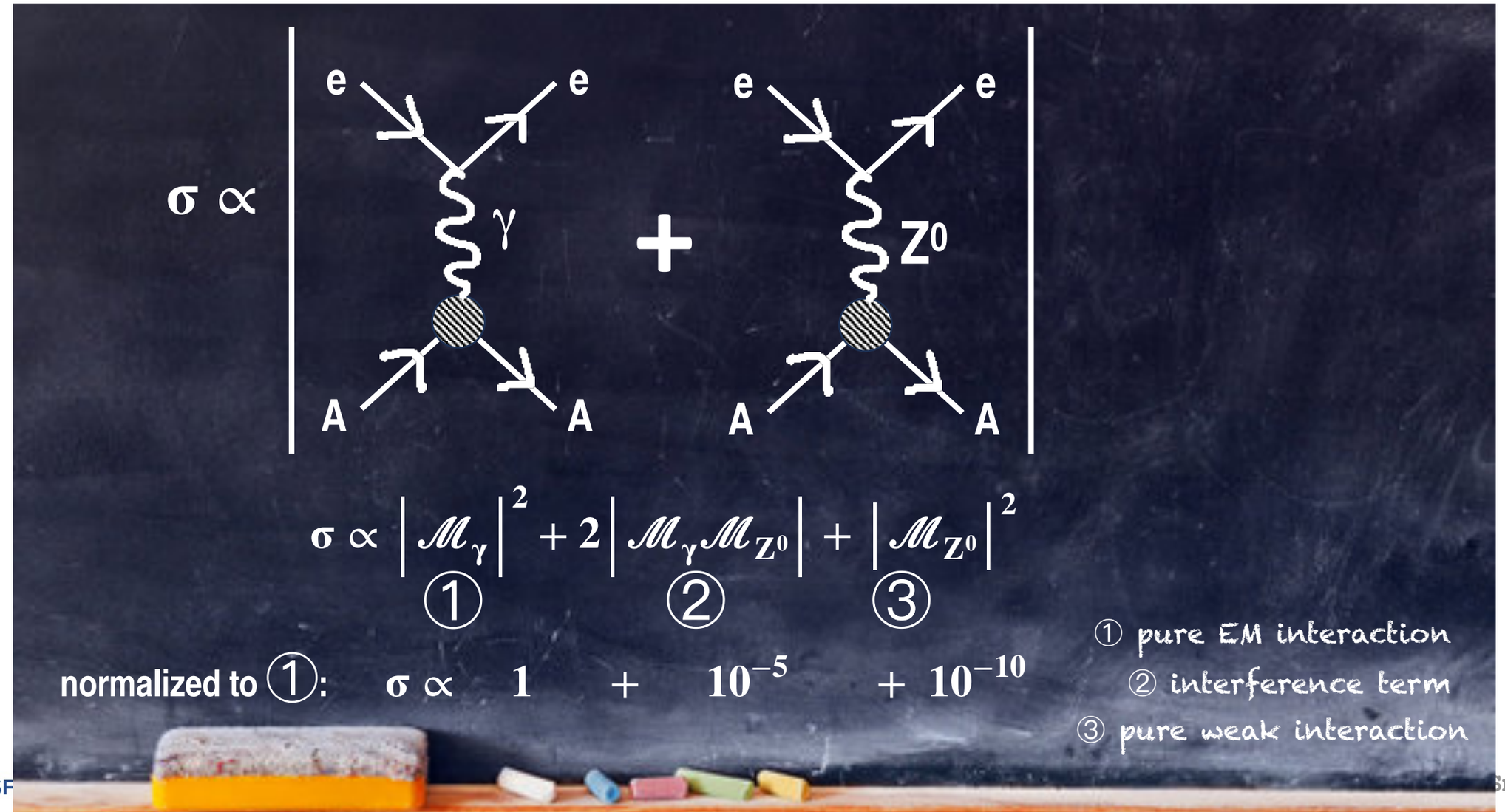
PV-Asymmetry



PVES

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

$$\sigma \propto \left| \mathcal{M}_{\gamma} + \mathcal{M}_{Z^0} \right|^2 = \underbrace{\left| \mathcal{M}_{\gamma} \right|^2}_{①} + \underbrace{2 \left| \mathcal{M}_{\gamma} \mathcal{M}_{Z^0} \right|}_{②} + \underbrace{\left| \mathcal{M}_{Z^0} \right|^2}_{③}$$



normalized to ①: $\sigma \propto 1 + 10^{-5} + 10^{-10}$

① pure EM interaction
② interference term
③ pure weak interaction

Parity violation in electron scattering

LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964-966
(March, 1959)

We assume that besides the weak interaction that causes beta decay,

$$g\,(\bar{P}ON)\,(\bar{e}^{-}O\nu) + \text{Herm. conj.}, \qquad (1)$$

there exists an interaction

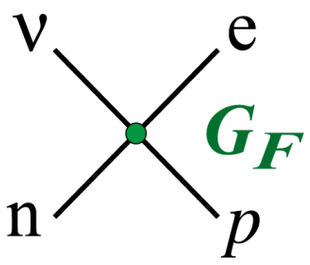
$$g\,(\bar{P}OP)\,(\bar{e}^{-}Oe^{-}) \qquad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu(1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

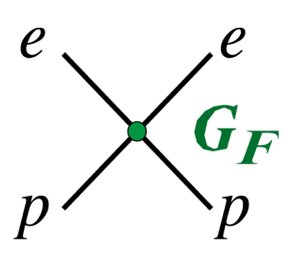
Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

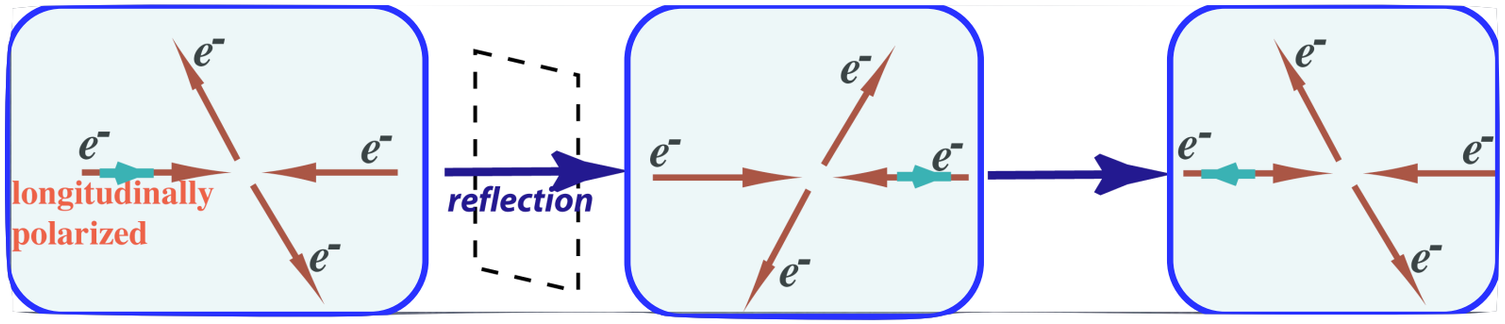
Neutron β Decay



Electron-proton Weak Scattering



PVeS: How to ....



- One of the incident beams longitudinally polarised
- Change sign of longitudinal polarisation
- Measure fractional rate difference

The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity nonconservation effects can be of the order of 0.1 to 0.01 percent.

$$\sigma \propto |A_{EM} + A_{weak}|^2$$

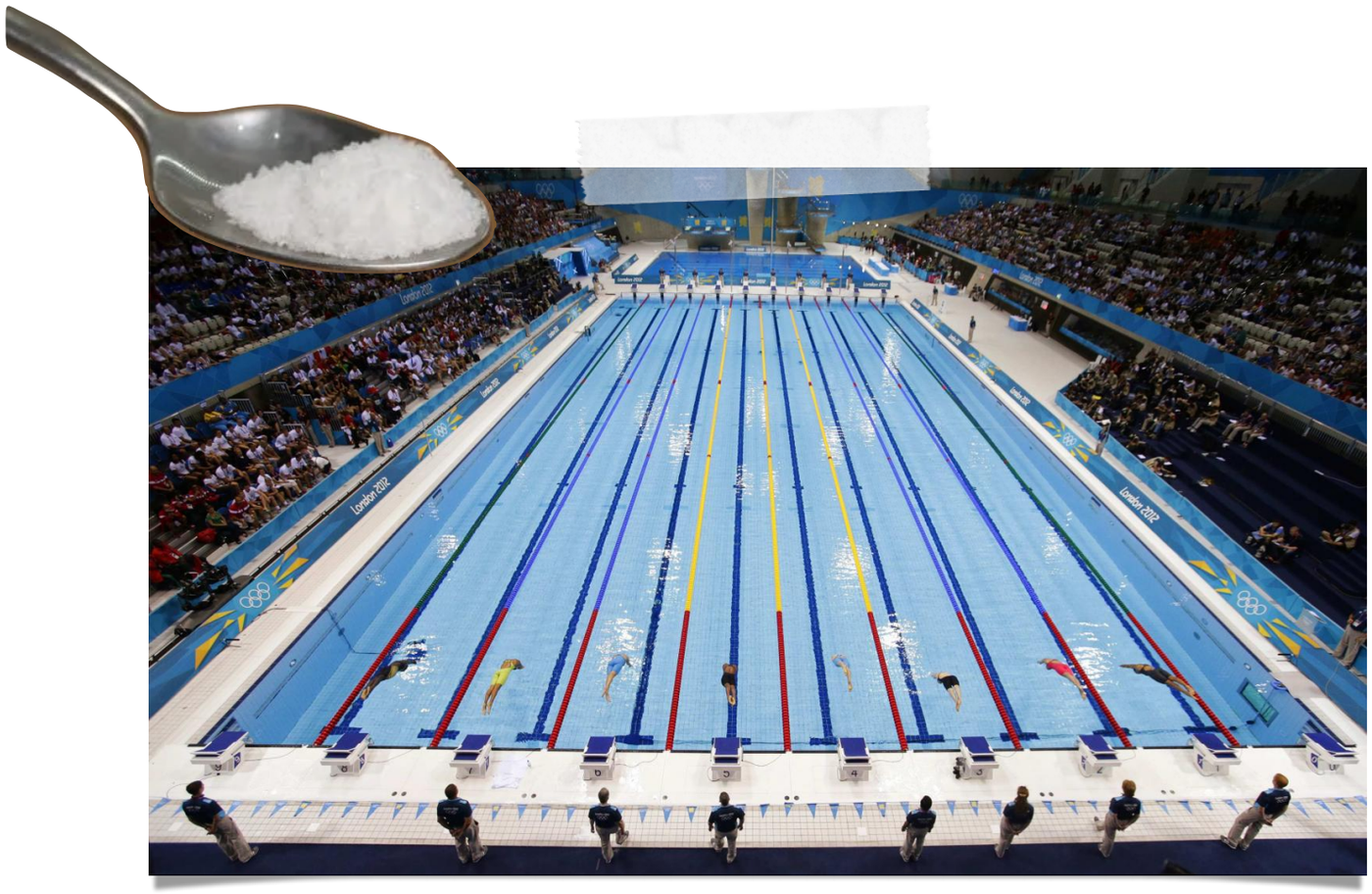
$$\sim |A_{EM}|^2 + 2A_{EM}A^*_{weak} + \dots$$

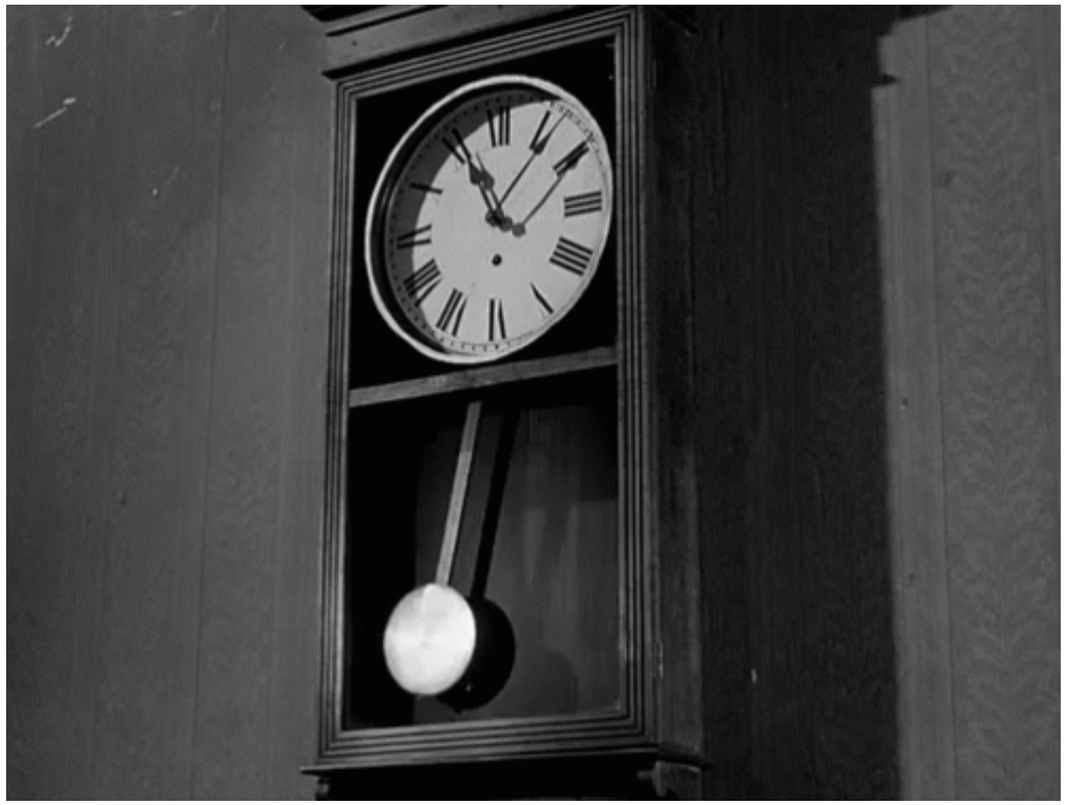
Parity-violating

$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$Q^2 \approx 0.1 - 1\ GeV^2 \rightarrow A_{PV} \leq 10^{-6} - 10^{-4}$

ppm/ppb

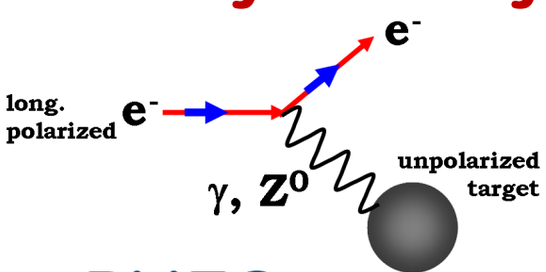




1 sec in 32 years!

PVeS: How to ....

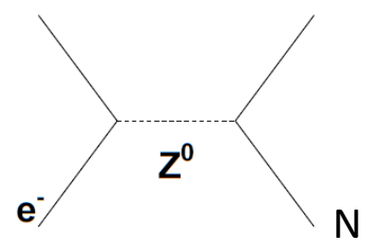
PV-Asymmetry



PVES

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

...to measure ...

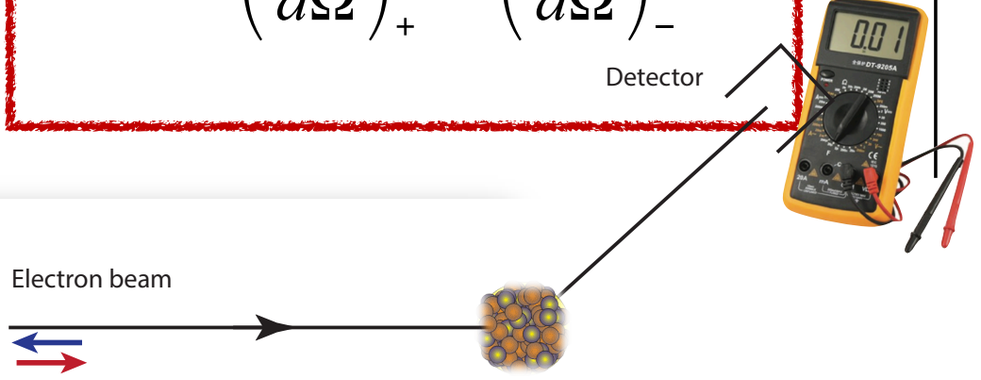


....construct ....

$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-} \approx$$

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

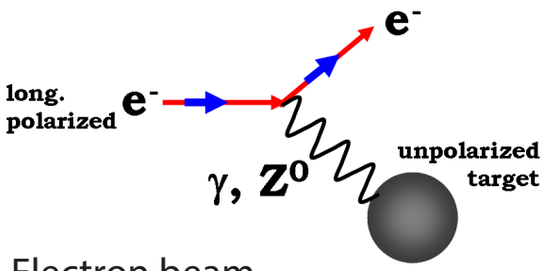
$$= \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \cdot \frac{Q_W}{A} \cdot \frac{F_W(Q^2)}{F_{ch}(Q^2)}$$

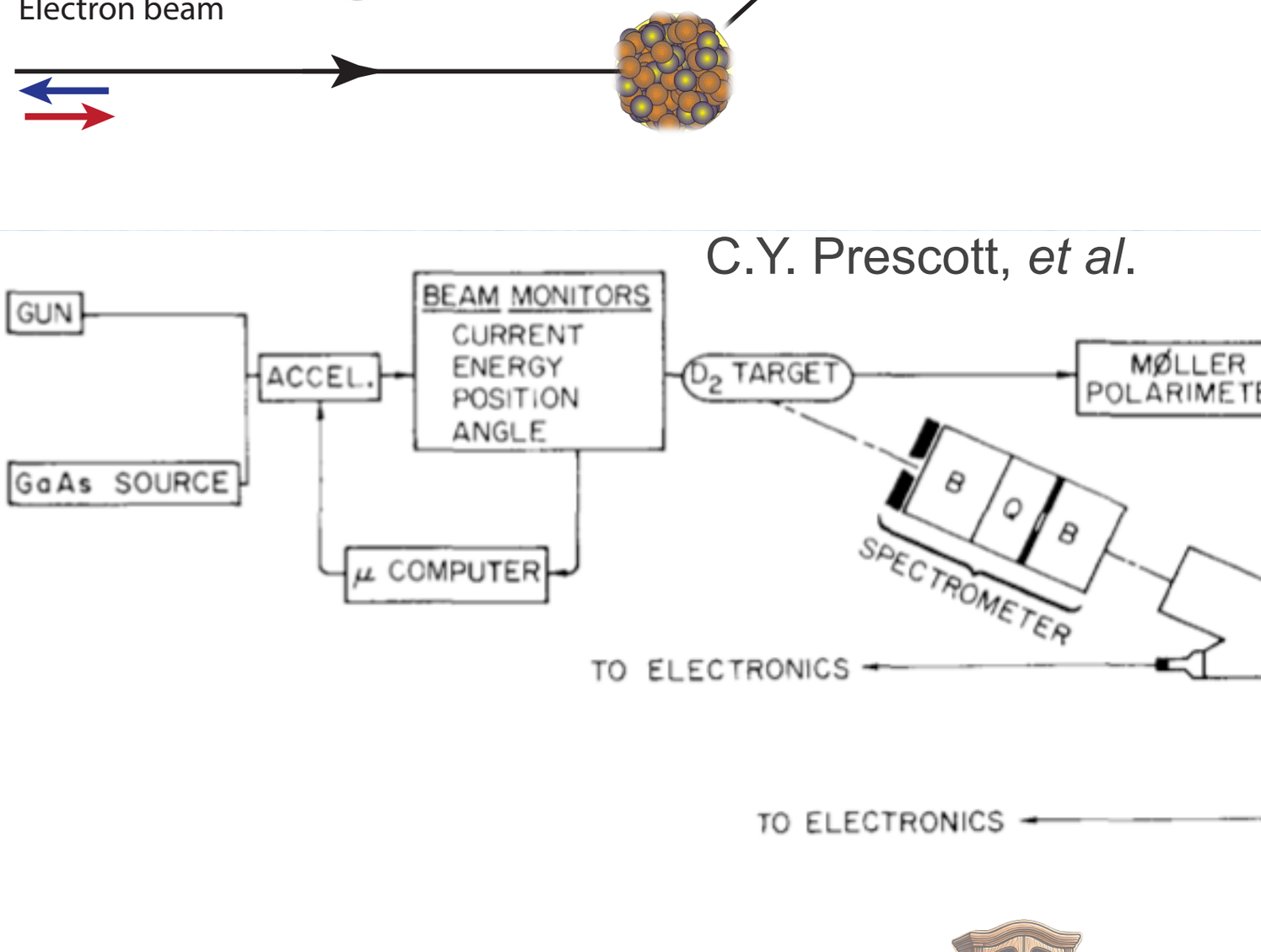


$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

..so where is hell?

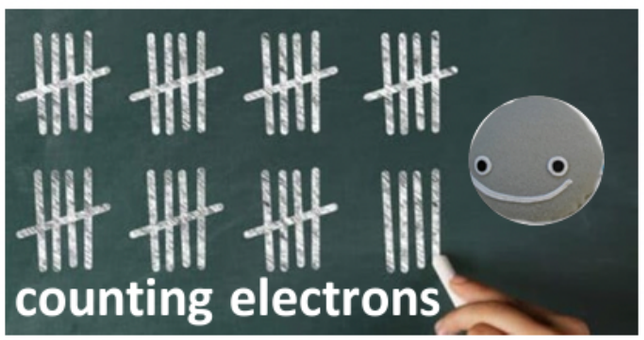
PV-Asymmetry





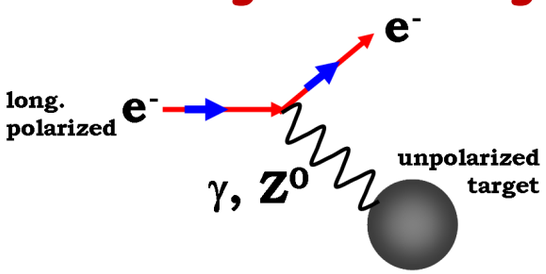
$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-}$$

C.Y. Prescott, *et al*.

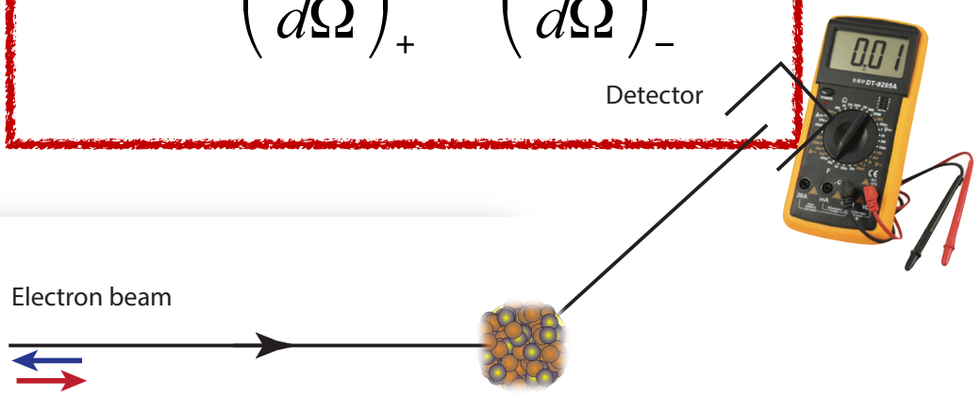


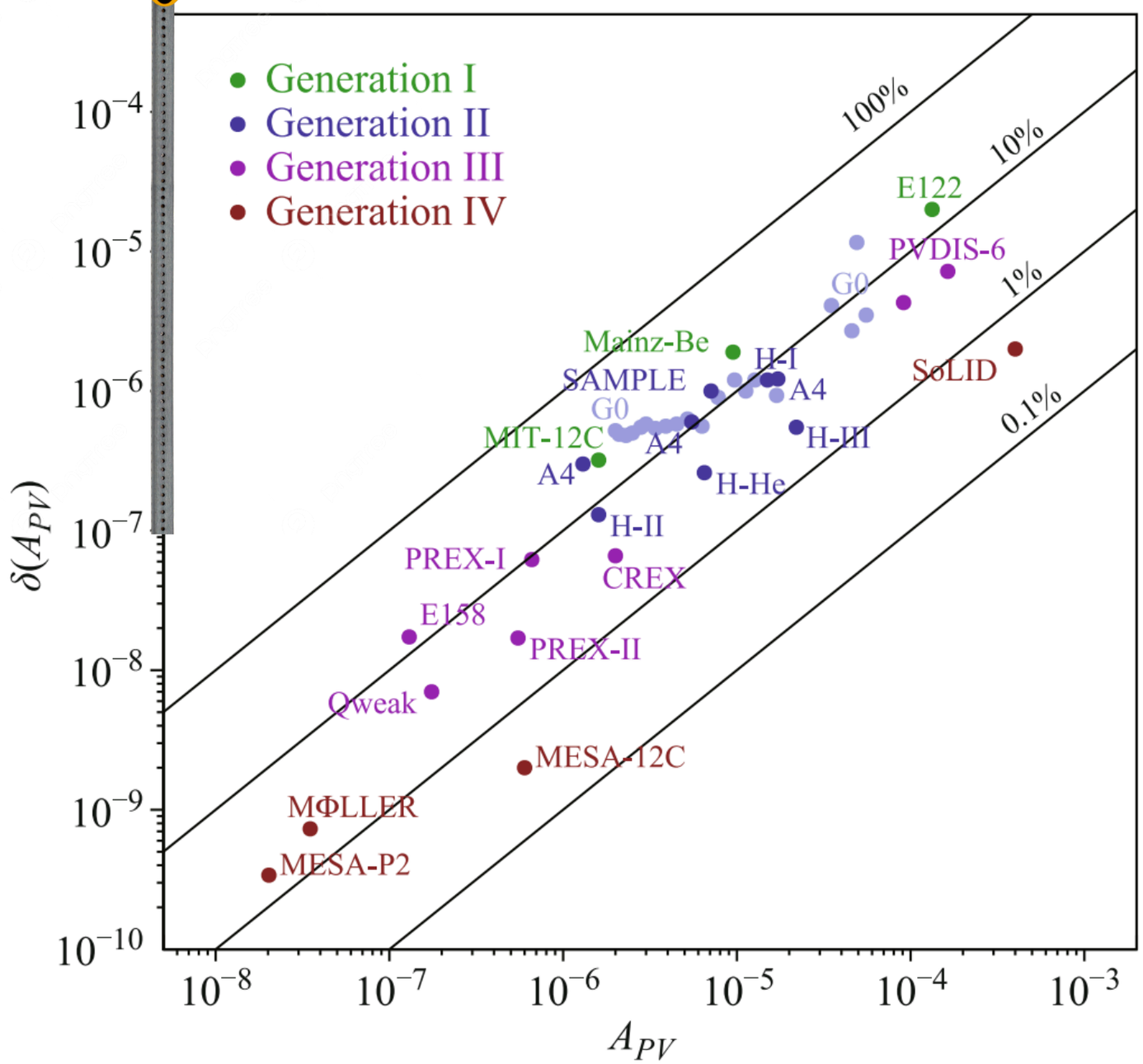
Welcome to Hell!

PV-Asymmetry



$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-} \approx$$

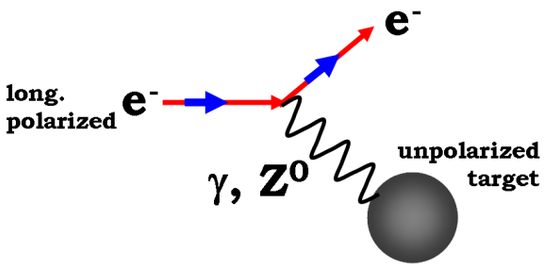




P. Souder and K. Paschke, Front. Phys. 11(1), 111301 (2016)

Welcome to Hell!

PV-Asymmetry



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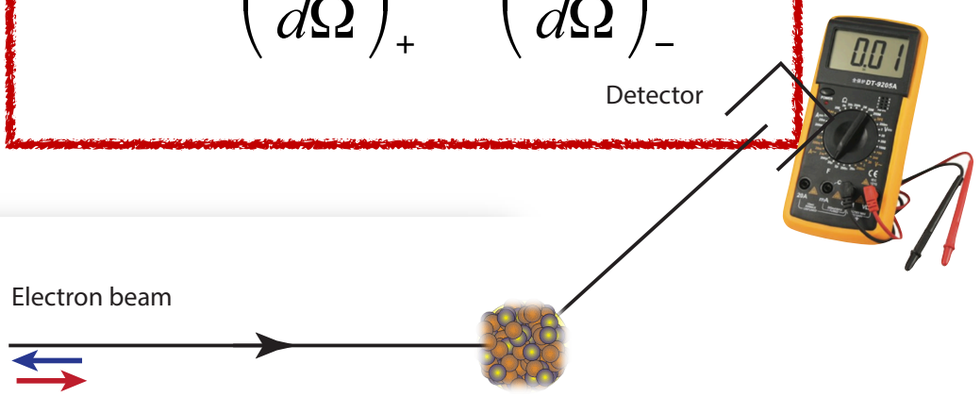
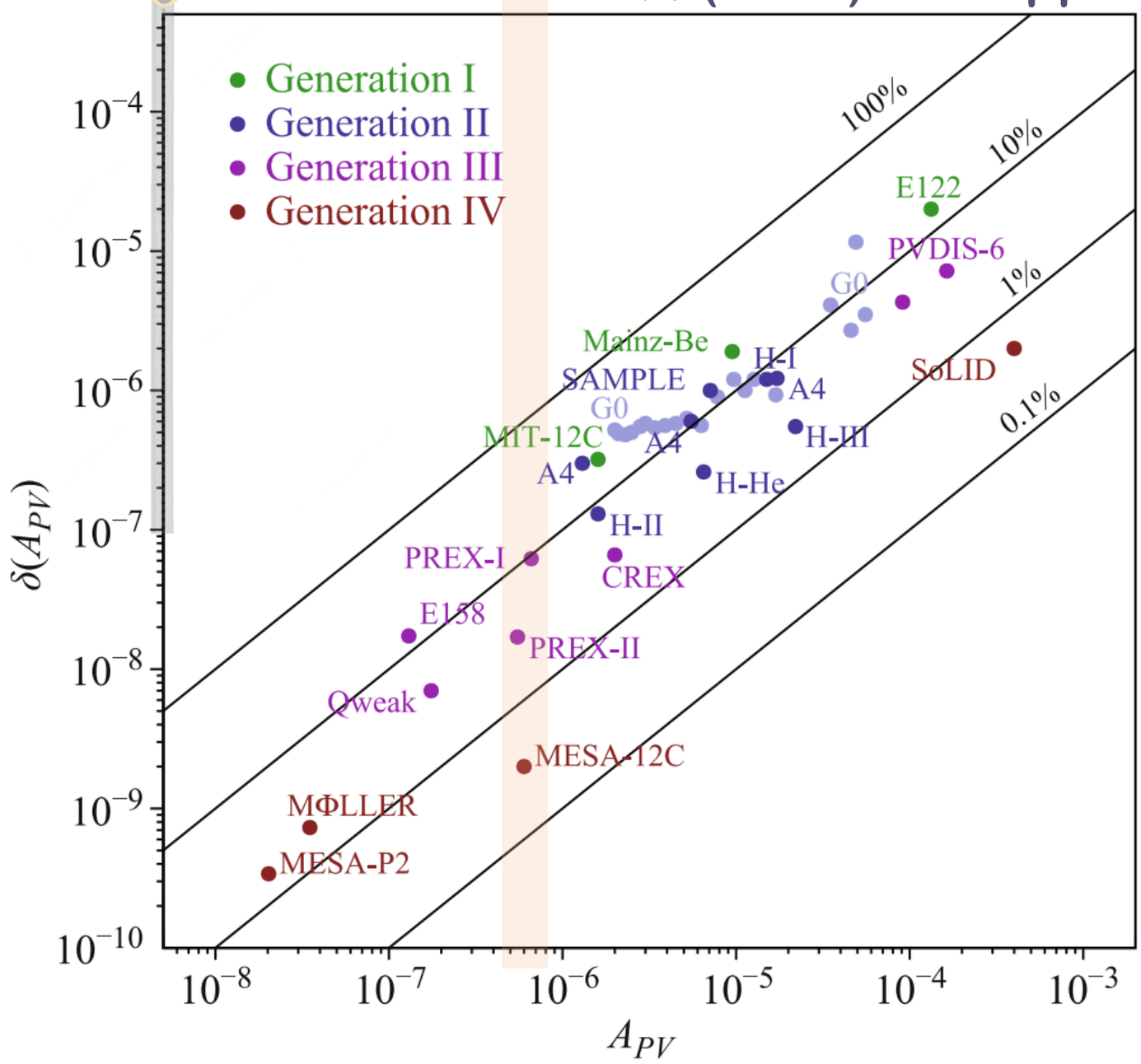


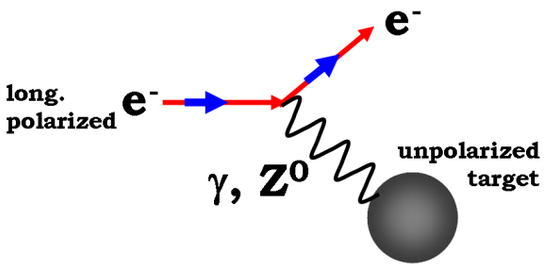
A_{PV} (^{208}Pb) ≈ 550 ppb



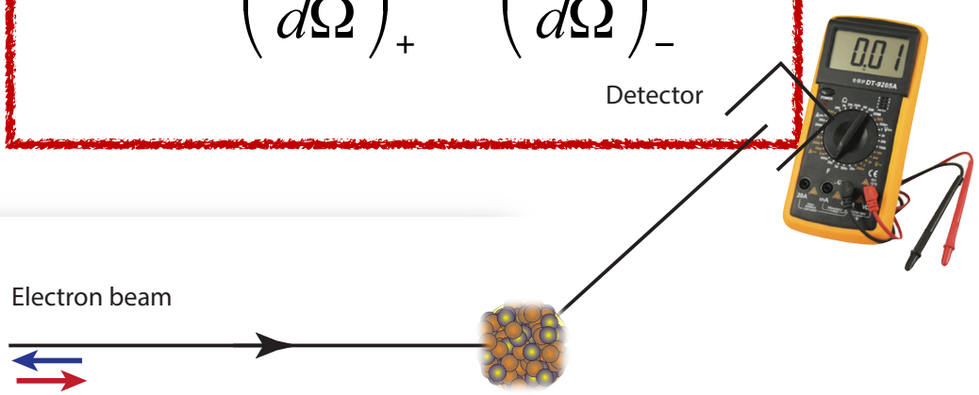
P. Souder and K. Paschke, Front. Phys. 11(1), 111301 (2016)

Welcome to Hell!

PV-Asymmetry



$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-} \approx$$



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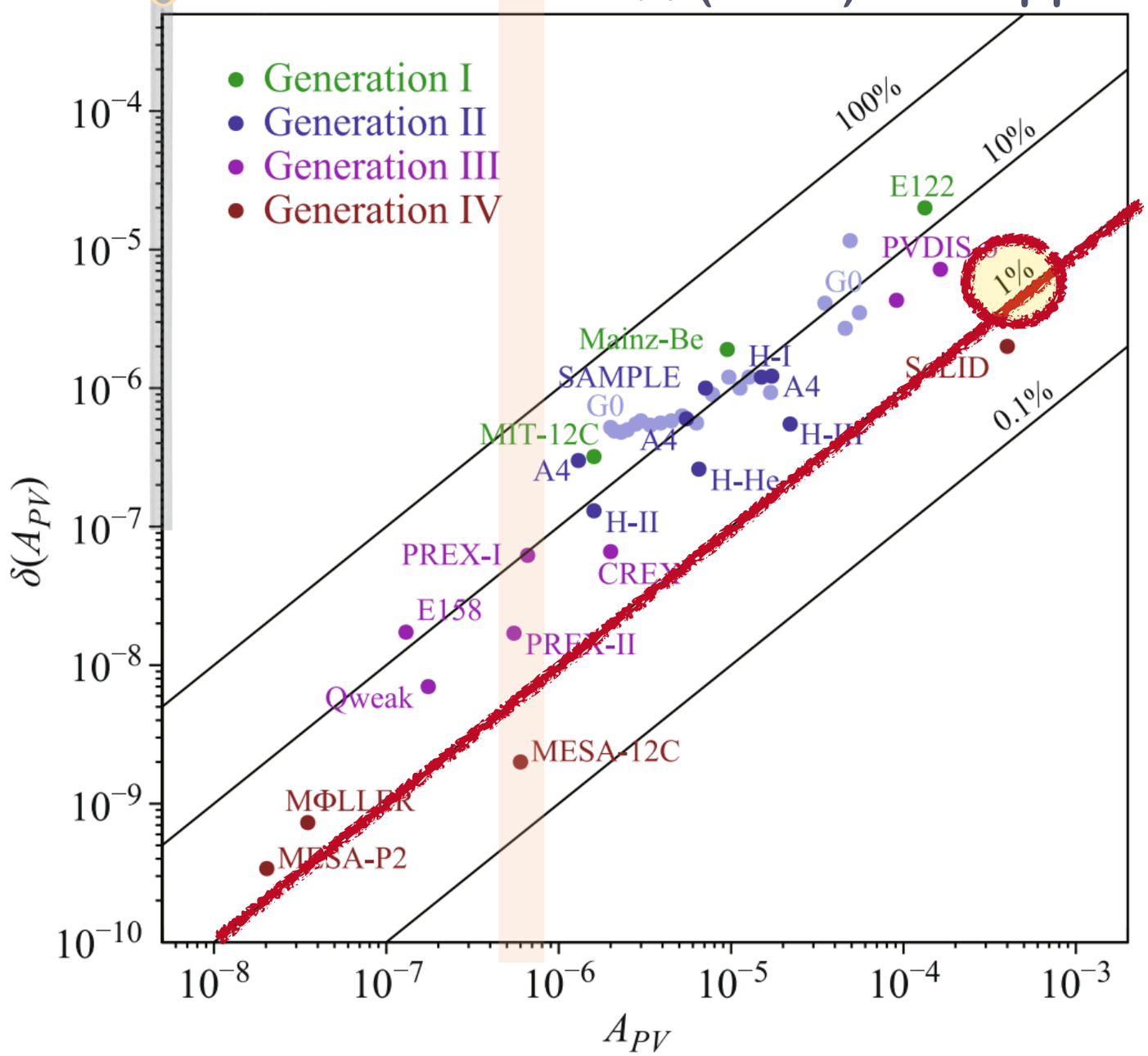
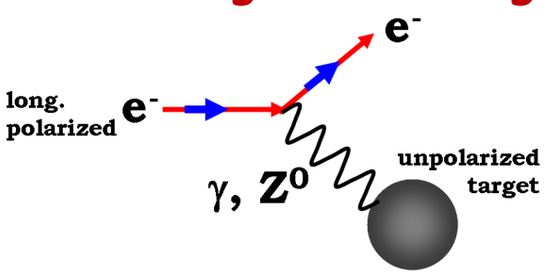


P. Souder and K. Paschke, Front. Phys. 11(1), 111301 (2016)

Welcome to Hell!

PV-Asymmetry

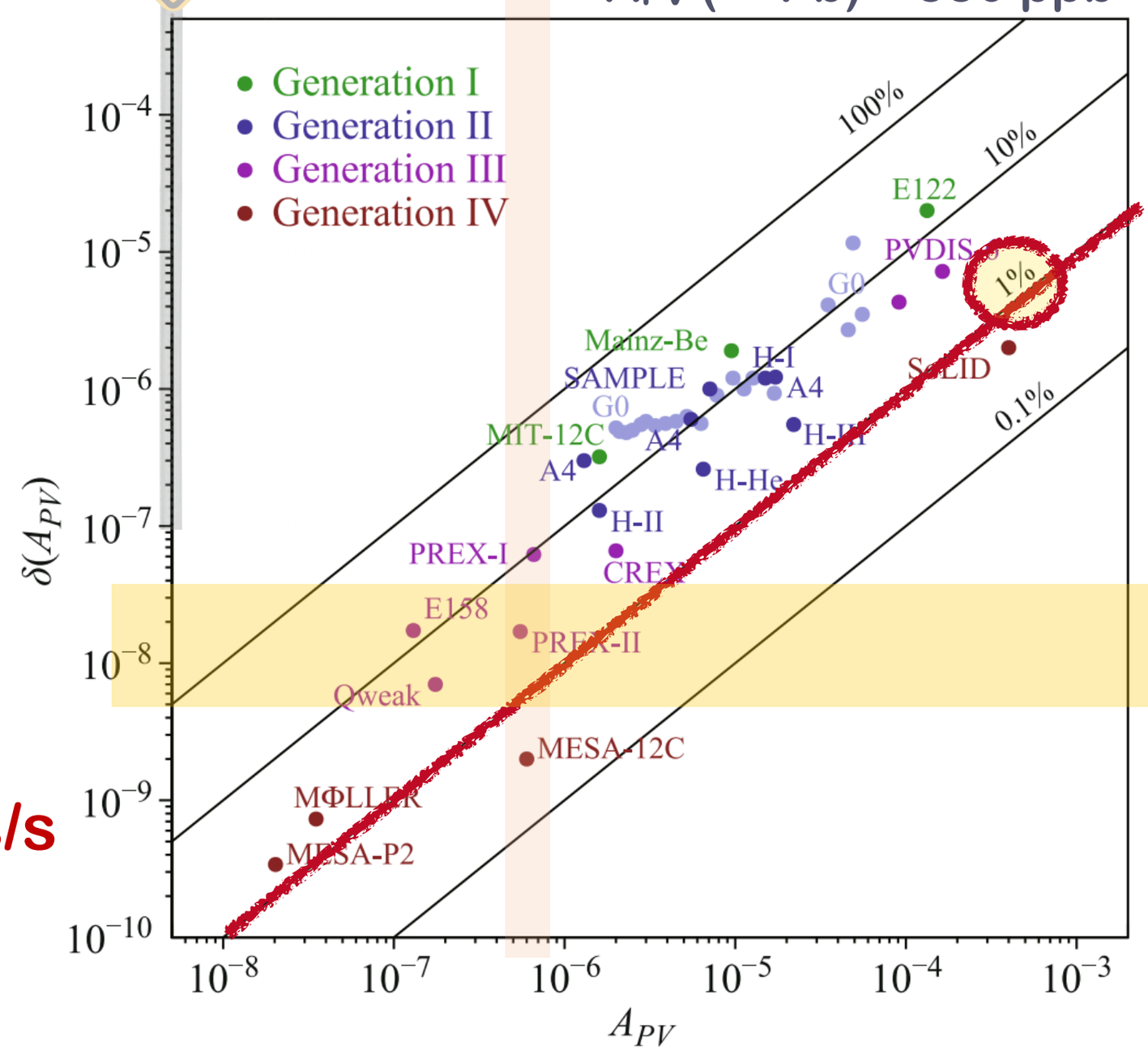


$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

…. need a few N=10¹⁸ e⁻

→ close to 10¹¹ electrons/s

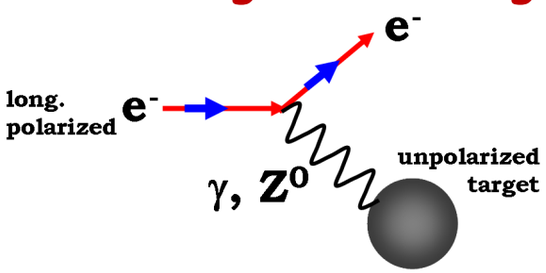
A_{PV} (^{208}Pb) ≈ 550 ppb



P. Souder and K. Paschke, Front. Phys. 11(1), 111301 (2016)

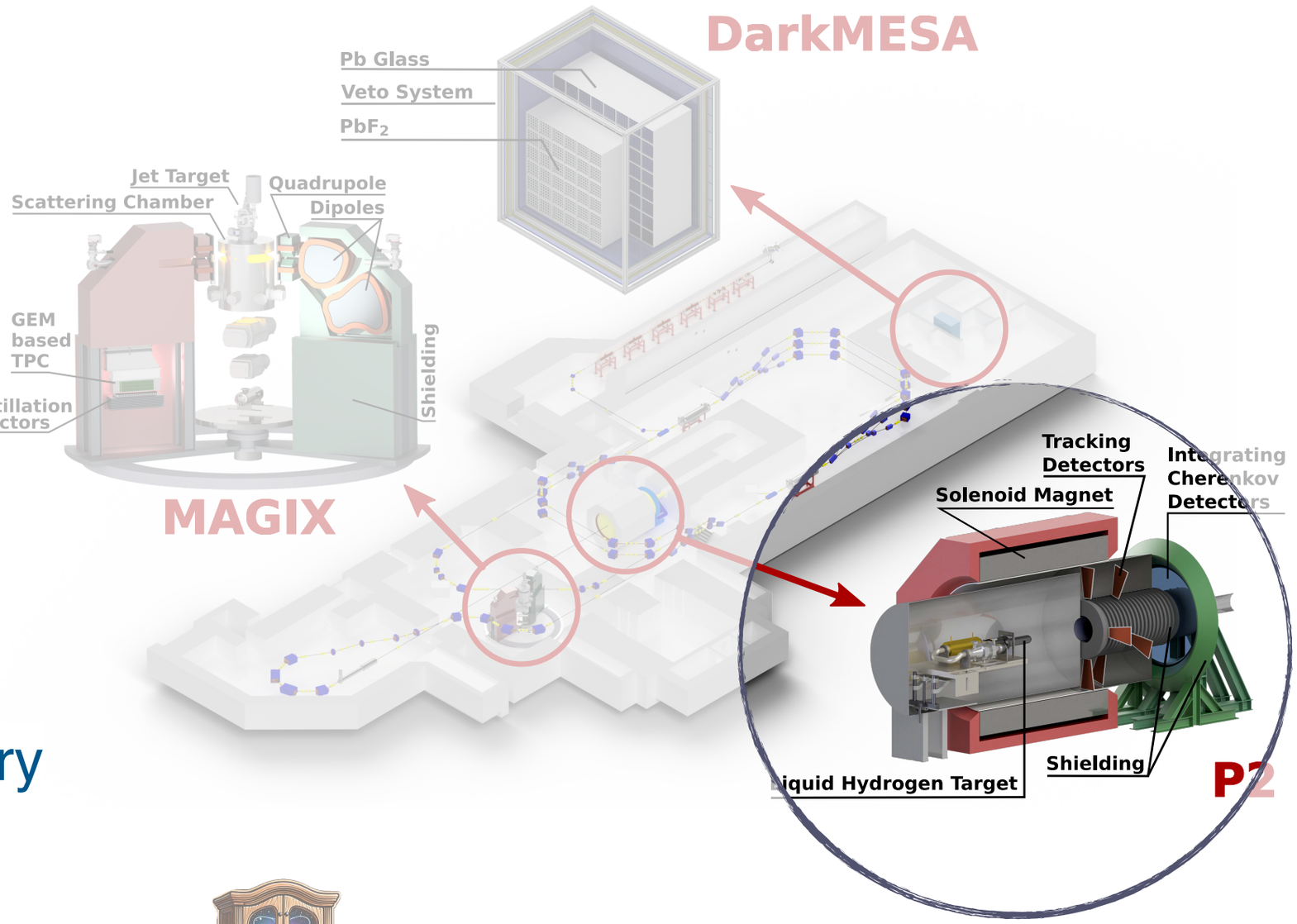
...the "Chronicles of MESA"

PV-Asymmetry



MREX

- External-beam mode for **high polarisation** (P2)

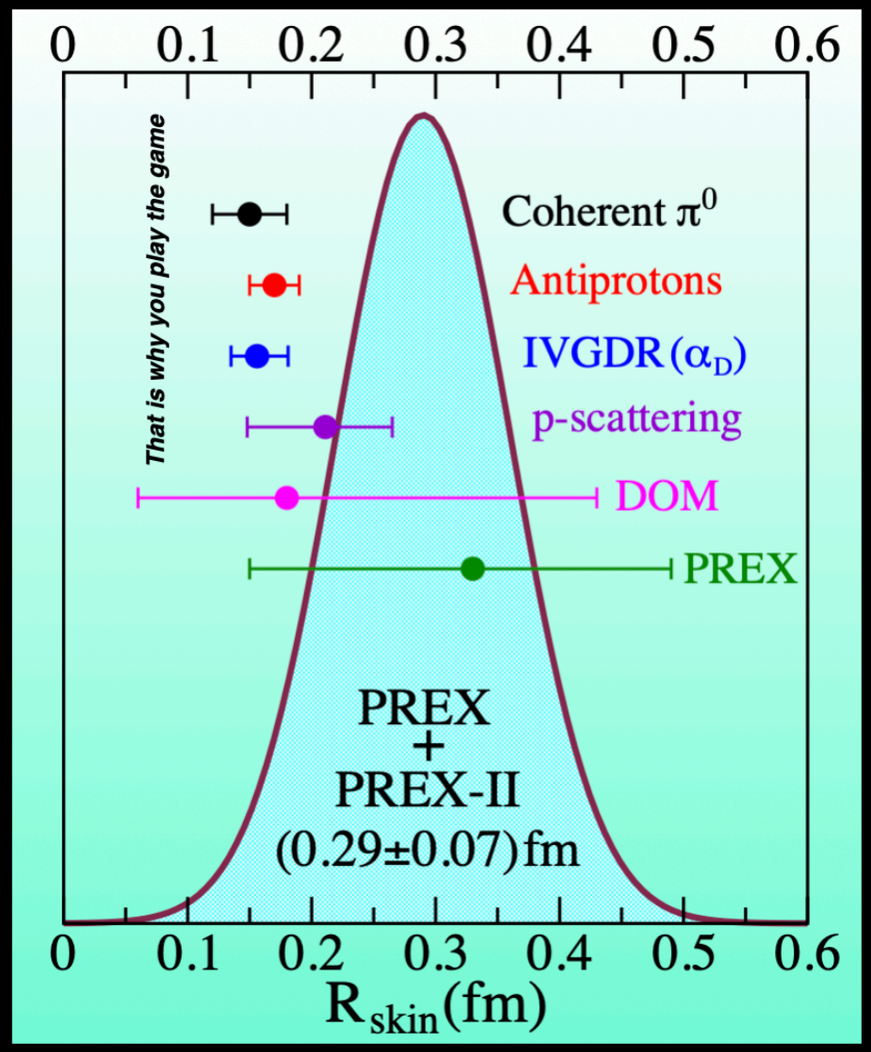


- Beam current 150 μA
- Polarisation > 85%
- High precision polarimetry

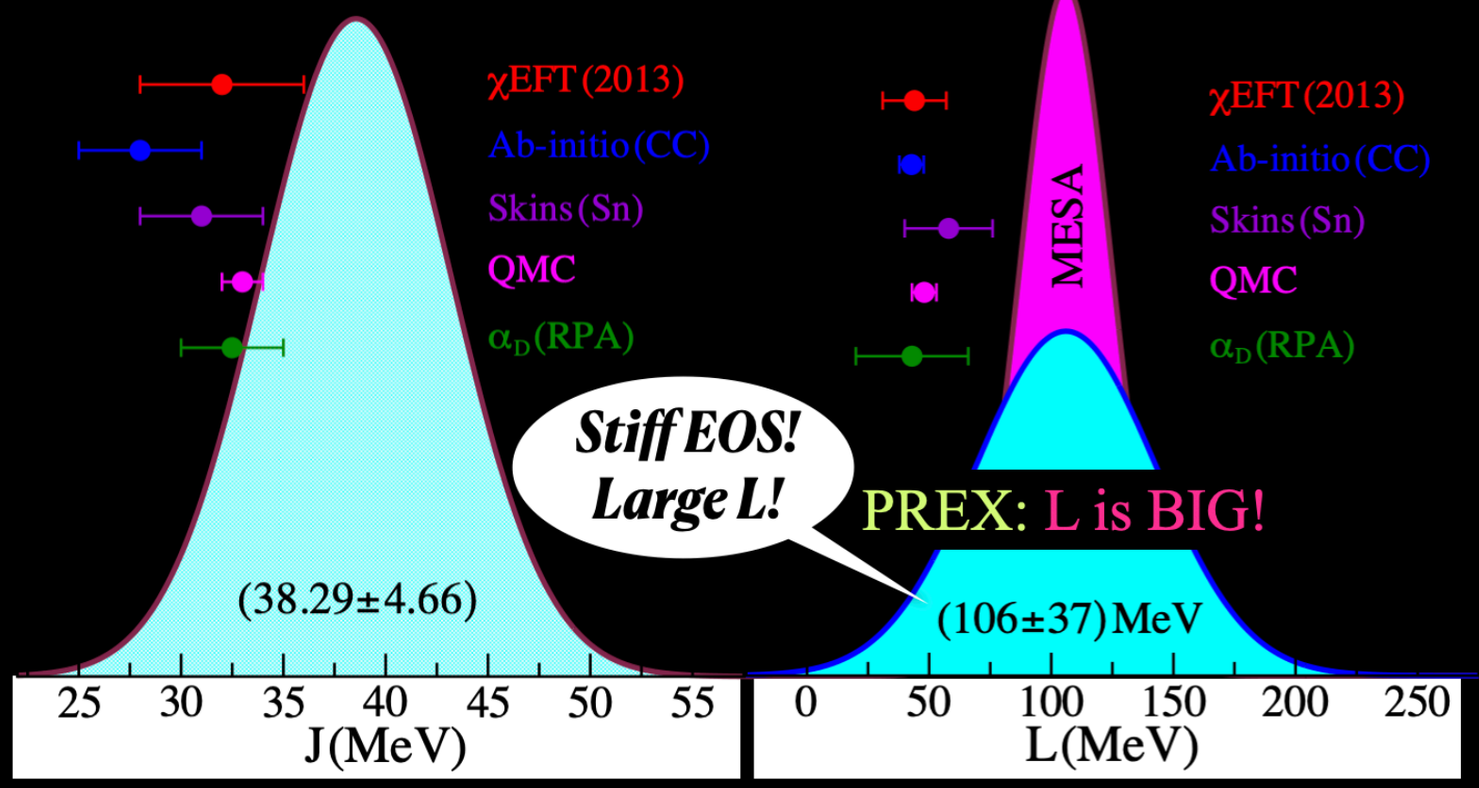
...precision, perplexities and uncertain tales

Jorge Piekarewicz

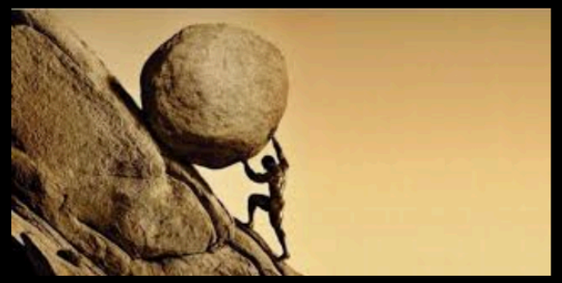
PREX-2 (Oct 29, 2020)
Ciprian Gal - DNP Meeting
Adhikari et al., PRL 126, 172502 (2021)



Conservation of difficulty: PVES provides the cleanest constraint on the EOS of neutron-rich matter in the vicinity of saturation density

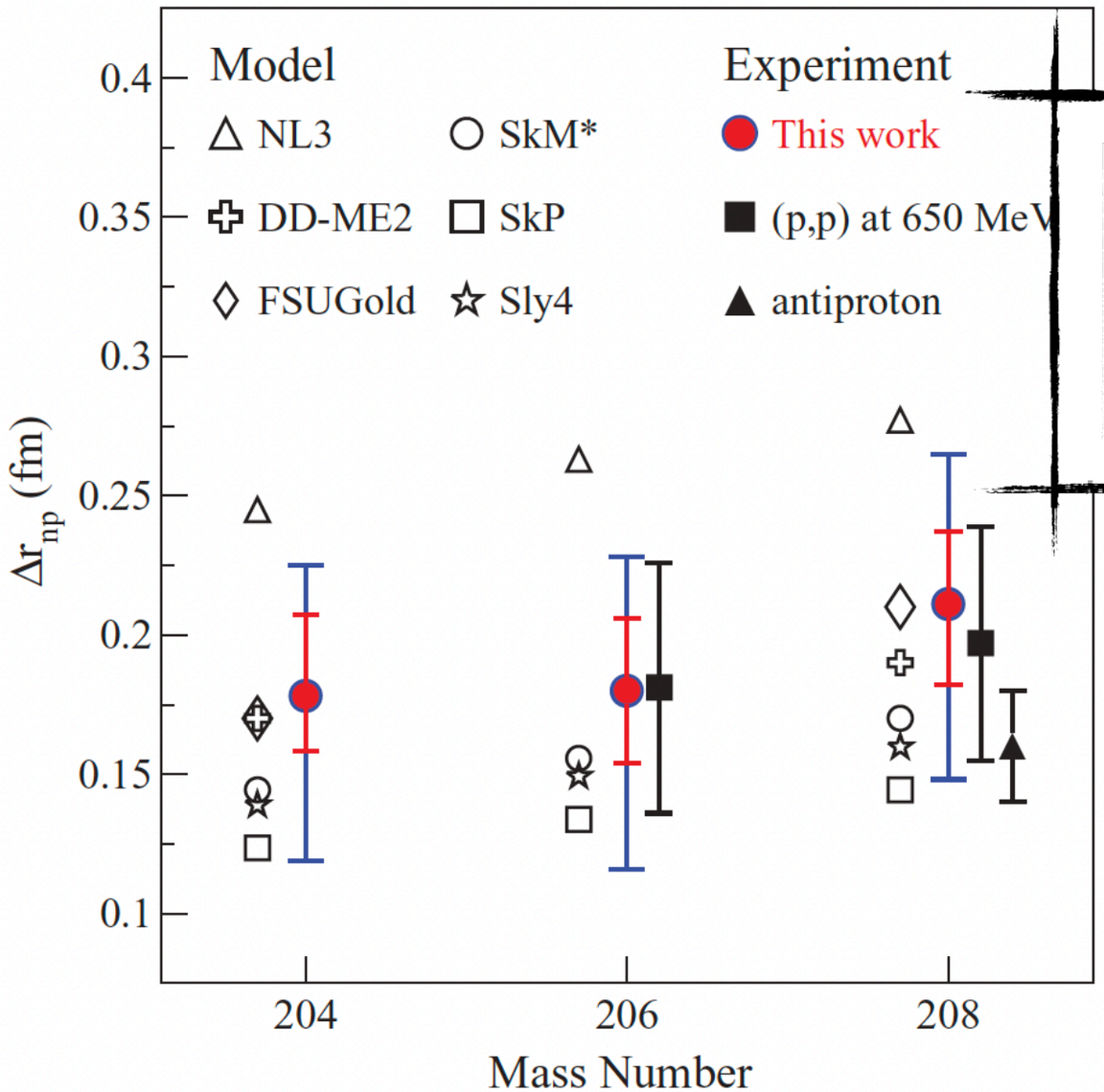


Heroic effort from our experimental colleagues



The stairway to heaven

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



PHYSICAL REVIEW C **82**, 044611 (2010)

Neutron density distributions of ^{204,206,208}Pb deduced via proton elastic scattering at $E_p = 295$ MeV

J. Zenihiro,[1,*] H. Sakaguchi,[1,†] T. Murakami,[1] M. Yosoi,[1,†] Y. Yasuda,[1,†] S. Terashima,[1,‡] Y. Iwao,[1] H. Takeda,[2] M. Itoh,[3,§] H. P. Yoshida,[3,§] and M. Uchida[3,‖]

[1]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

[2]*RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan*

[3]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*

(Received 12 September 2010; published 22 October 2010)

distribution.

Furthermore, we evaluated the error envelopes of the

estimated errors of the neutron rms radii ($\delta r_n^{\mathrm{mdl}} \simeq 0.06$ fm) were found to be relatively small with an accuracy of about 1%, but not so small as to determine the slope coefficient L of the nuclear symmetry energy at saturation density.

Since unknown systematic errors are also included in the model uncertainties, further progress from both the experiment and theory are necessary.

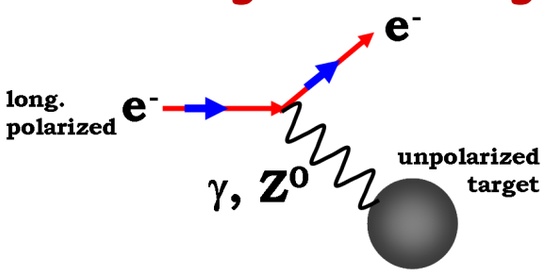
Hadronic Probes

EM Probes

Theo. uncertainties (a.u)

Welcome to Hell!

PV-Asymmetry

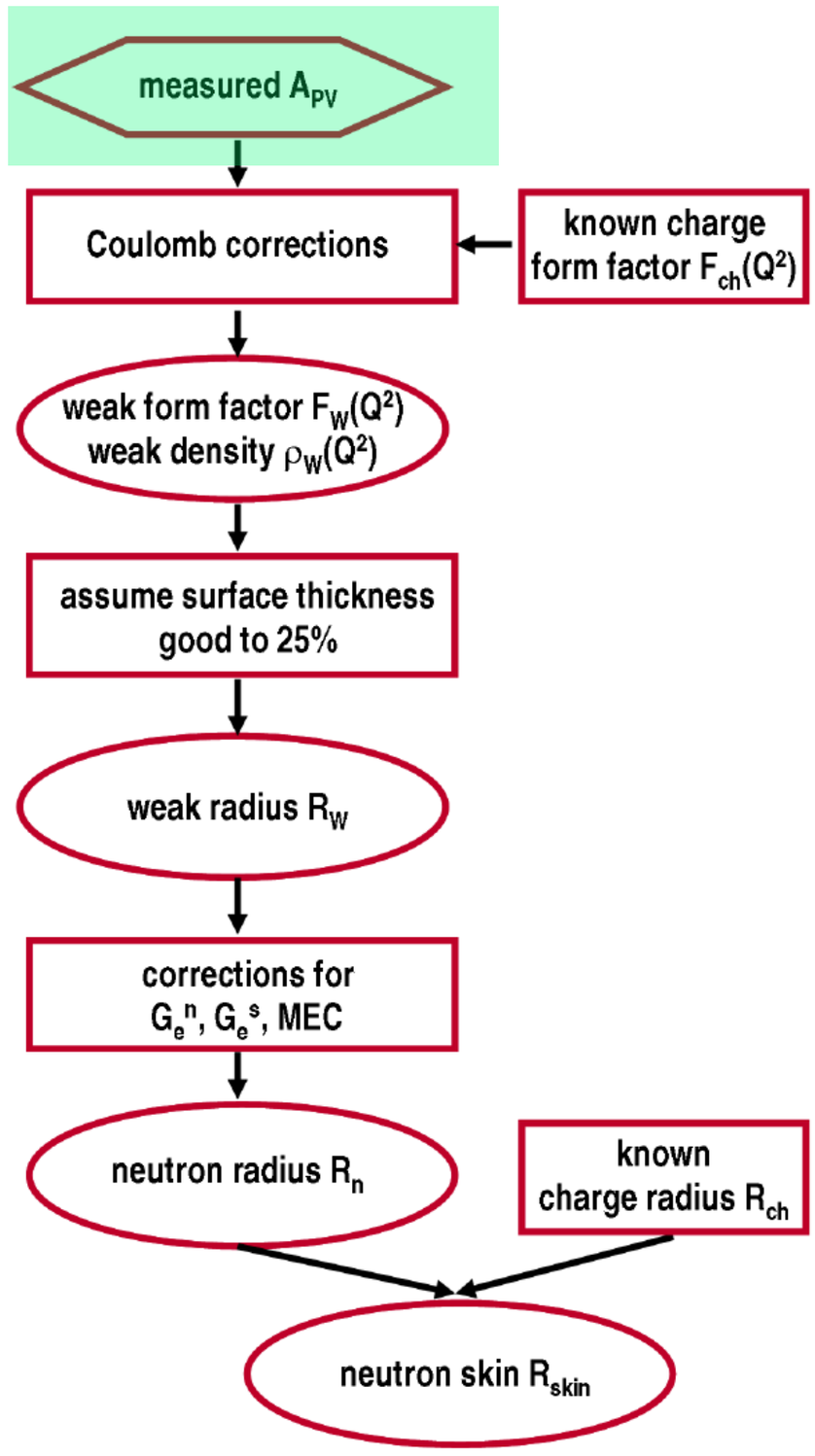


$$\delta(A_{PV}) \propto \frac{1}{\sqrt{N}}$$

…. need a few N=10^{18} e^-

→ close to 10^{11} electrons/s

…but statistics is not everything! 😱



...if you are going through hell keep going!

I think we need to talk about blind analyses!

Blinding factors

$$A_{corr} = A_{det} - A_{beam} - A_{trans} - A_{nonlin} - A_{blind}$$

$$A_{phys} = R_{radcorr}\, R_{accept}\, R_{Q^2} \frac{A_{corr} - P_L \sum_i f_i A_i}{P_L (1 - \sum_i f_i)}$$

Raw Asymmetries (A_{meas})

Typical corrections:

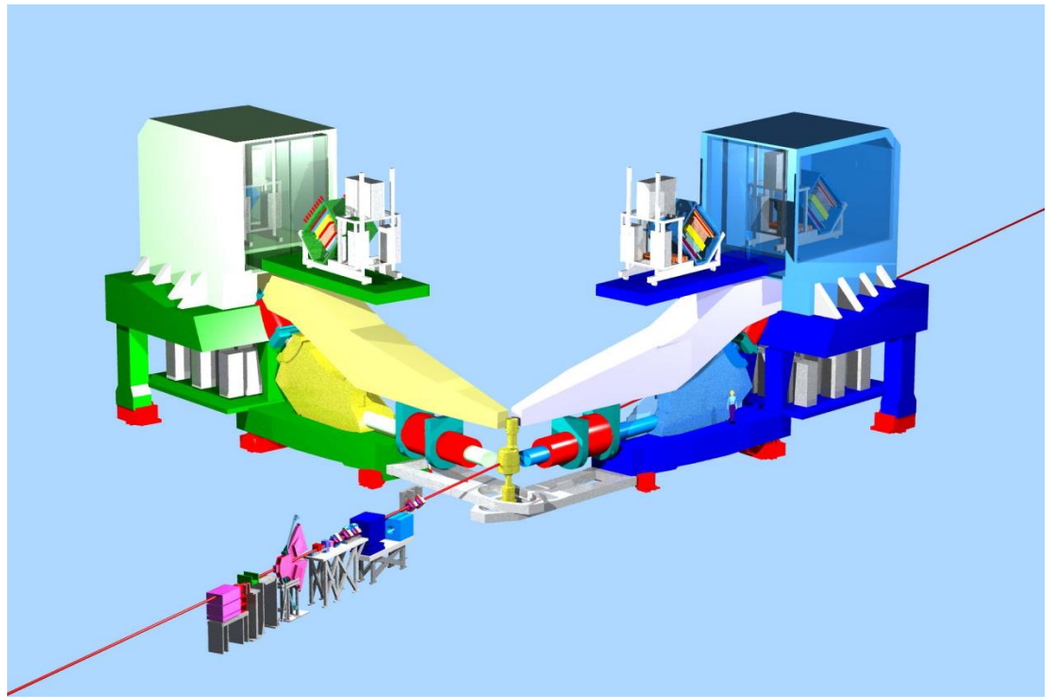
- Helicity correlated corrections
- Background Asymmetry
- Beam polarisation
- EM radiative corrections

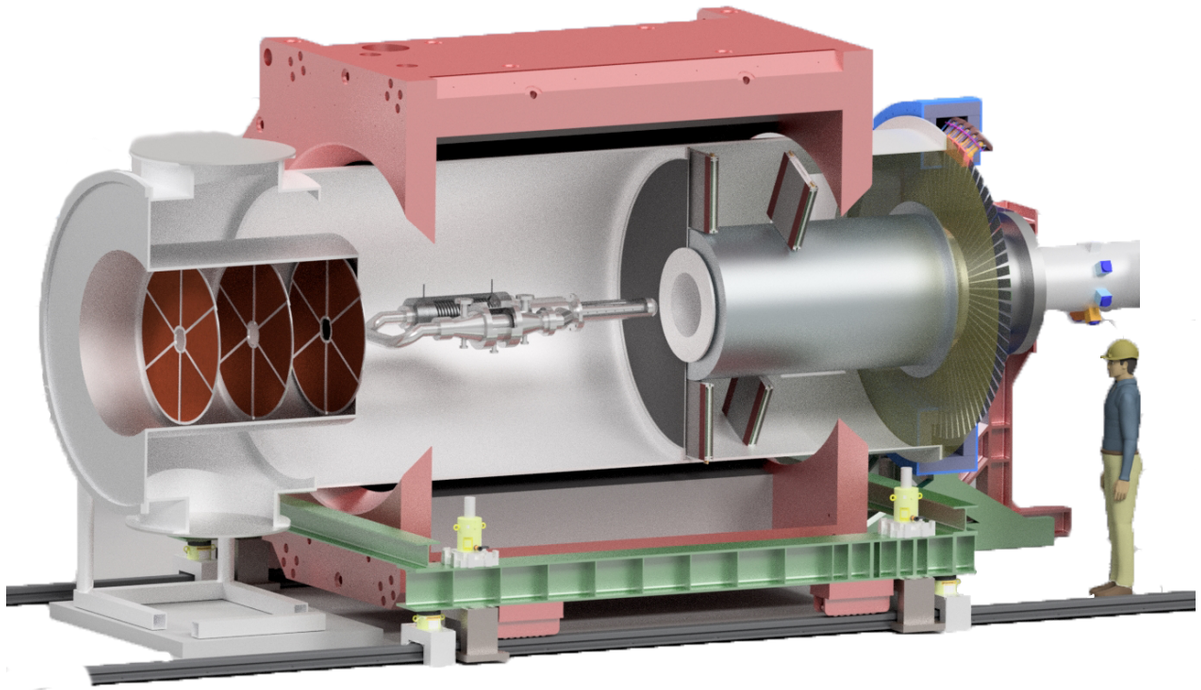
Unblind

Q^2

Phys. Asymmetries (A_{phys})

MREX challenges: 4x statistics has a price!

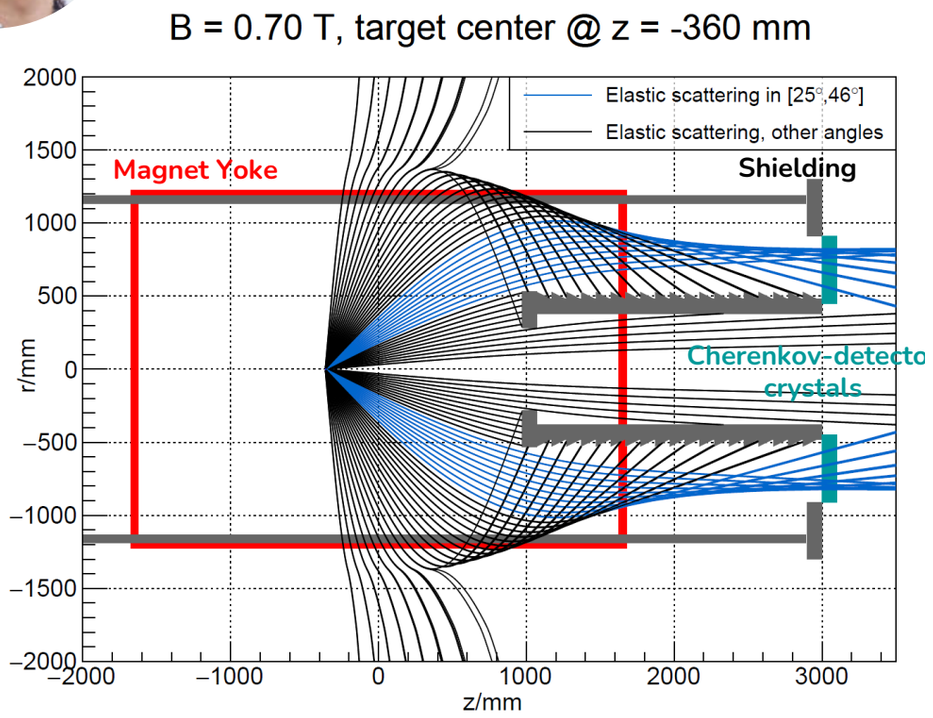


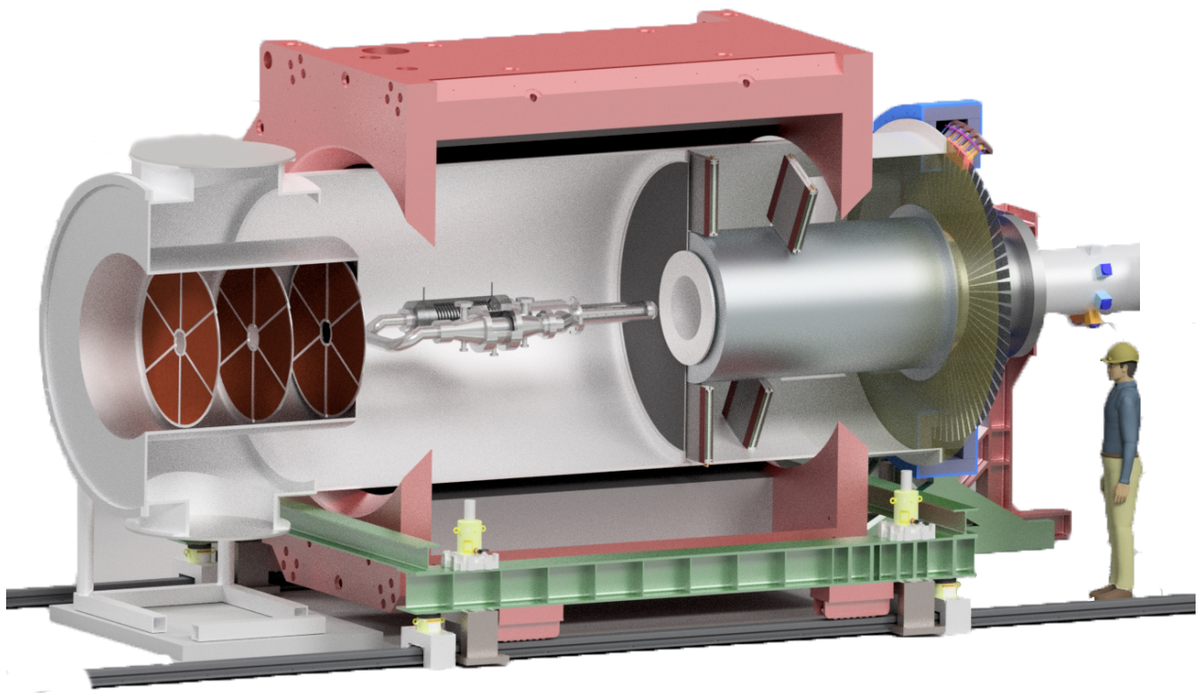


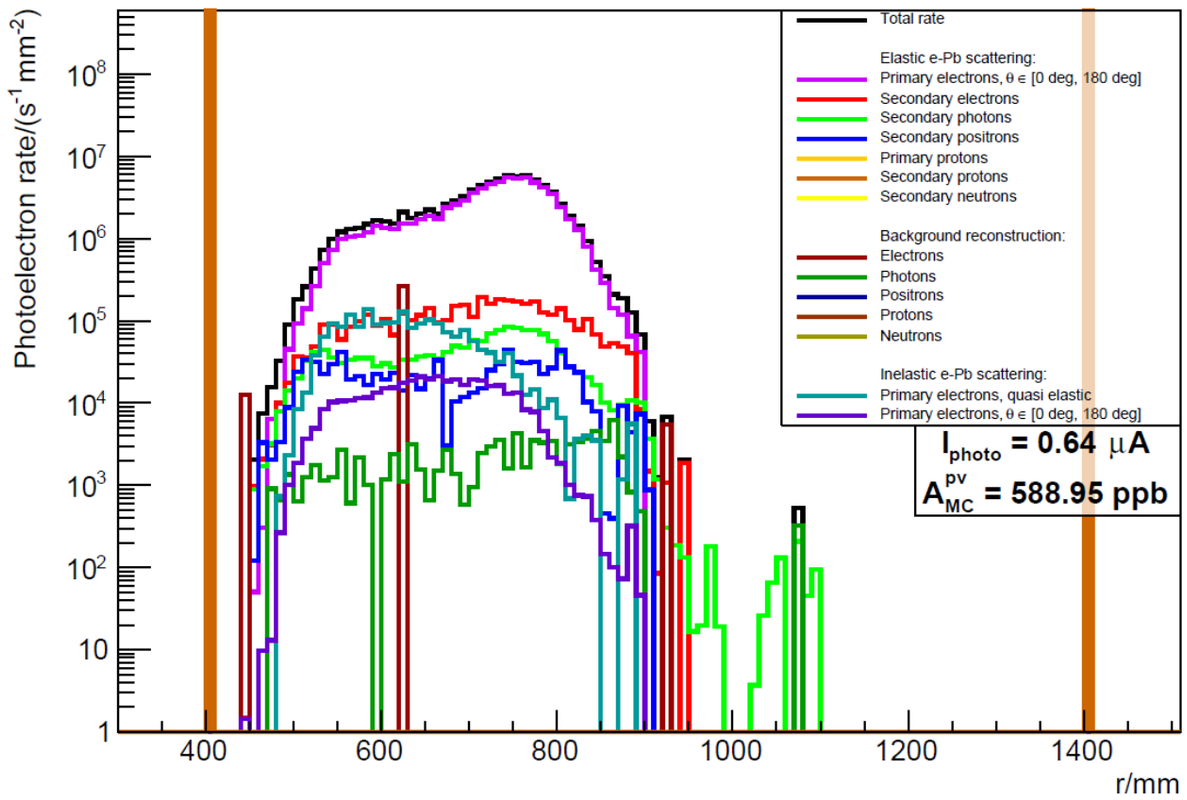
Match momentum transfer while maximising signal from elastic line

precision, perplexities and uncertain tales

Nikita Kozyrev (PhD-JGU)





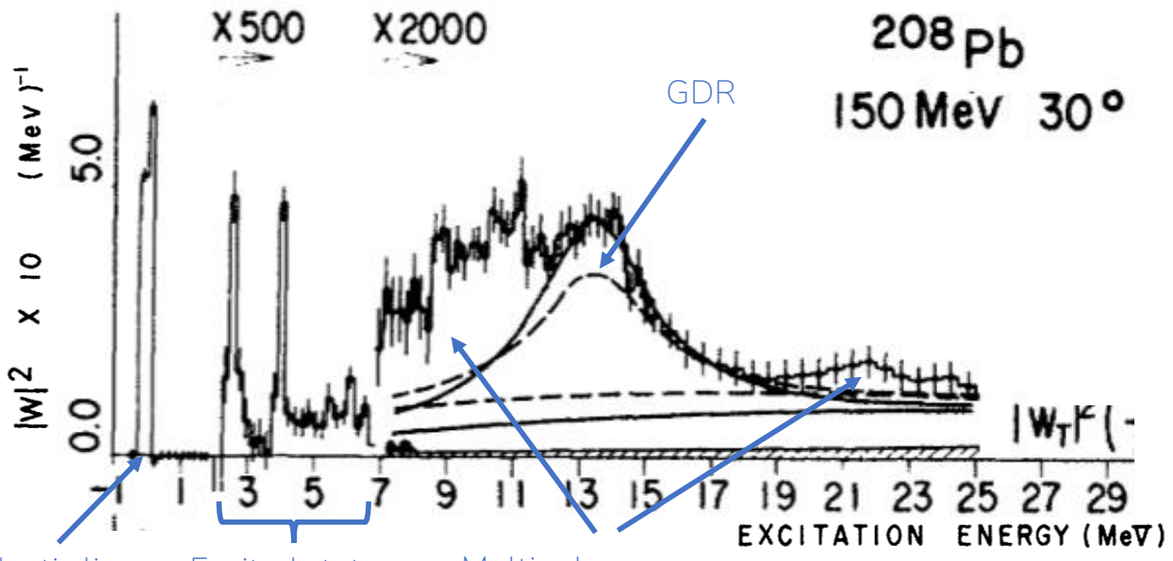


- Solenoid geometry leads to excitation energy acceptance of around 25 MeV
- Each non-elastic contribution has its own asymmetry
- Target background and secondary produced particles changes the measured asymmetry

Nikita Kozyrev (PhD-JGU)

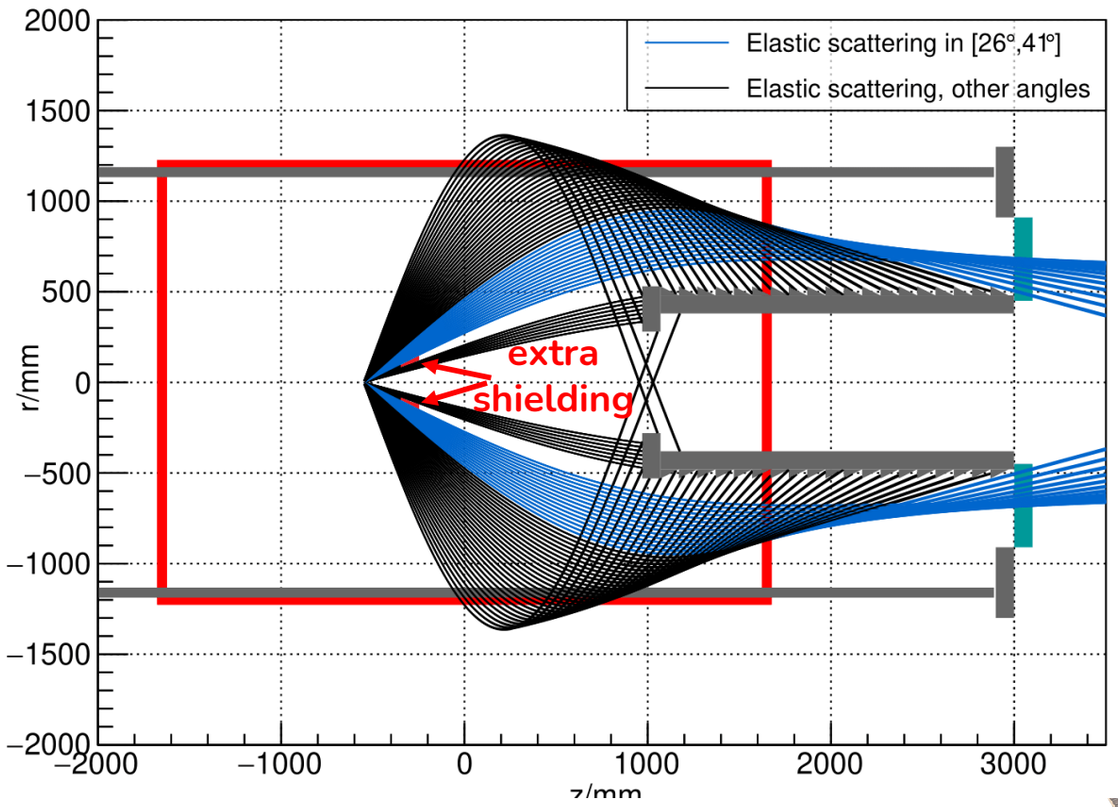
Inelastic contributions

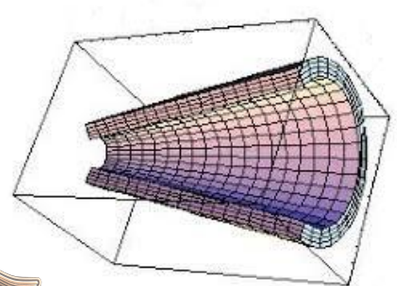
Physical Review C, 1977, 15(1)

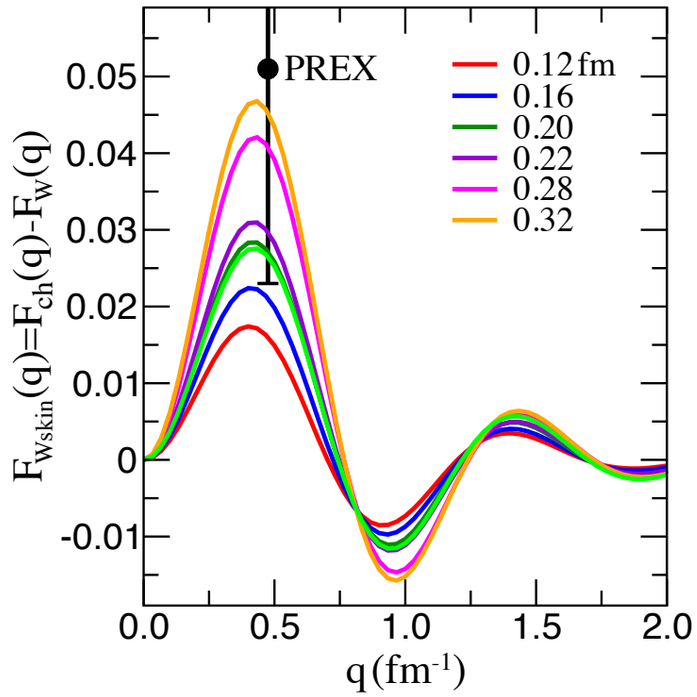


- Need to reduce uncertainty from inelastic
- Moving target would help but also change Q^2

Jorge Piekarewicz







Add conical shielding

Uncertainty from asymmetry correction

Nikita Kozyrev (PhD-JGU)

Uncertainty from asymmetry correction

Define uncertainty from different contributions

Contribution i	3^- and 2^+	MR	Other Inel.	QE	TBG	Secondary
ΔA_i	$0.625 \cdot A_{el}$	$0.625 \cdot A_{el}$	$1.5 \cdot A_{el}$	$A_{el} + \lvert A_{QE}\rvert$	0	$\lvert A_{el} - A_{Secondary}\rvert$
$\Delta f_i / f_i$	20%	50%	100%	100%	10%	10%

$$A^{meas} = (1 - \sum f_i) A^{el} + \sum f_i A_i$$

Extract final uncertainty from each contribution

Contribution i	No additional shielding			With additional shielding		
	ΔA_i^f, ppb	ΔA_i^A, ppb	ΔA_i, ppb	ΔA_i^f, ppb	ΔA_i^A, ppb	ΔA_i, ppb
Secondary electrons	0.06	0.51	0.51	0.01	0.05	0.05
Secondary photons	0.07	0.62	0.63	0.04	0.34	0.34
Secondary positrons	0.01	0.04	0.04	0.01	0.05	0.05
Target background	0.08	0.18	0.20	0.06	0.15	0.16
3^- 2.615 MeV	0.10	0.46	0.47	0.07	0.43	0.44
2^+ 4.085 MeV	0.05	0.35	0.36	0.04	0.34	0.34
MR below GDR	0.18	0.52	0.55	0.14	0.49	0.51
Other Inelastic	0.52	0.72	0.88	0.42	0.59	0.73
Quasielastic electrons	1.20	1.34	1.8	0.73	0.80	1.08
Total ΔA_{ne}, ppb		2.31			1.55	

MREX Q&E

beam
energy: 155 MeV
current: 150μA

target
^{208}Pb 0.56 g/cm^2

A_{PV}: 0.66 ppm
$\Delta\theta$ = 4°
polarization: 85%
q: 86 MeV/c

± **0.03 fm** on the extraction of the neutron skin (65 days BOT)

(assuming 1% systematics - PREX experience)

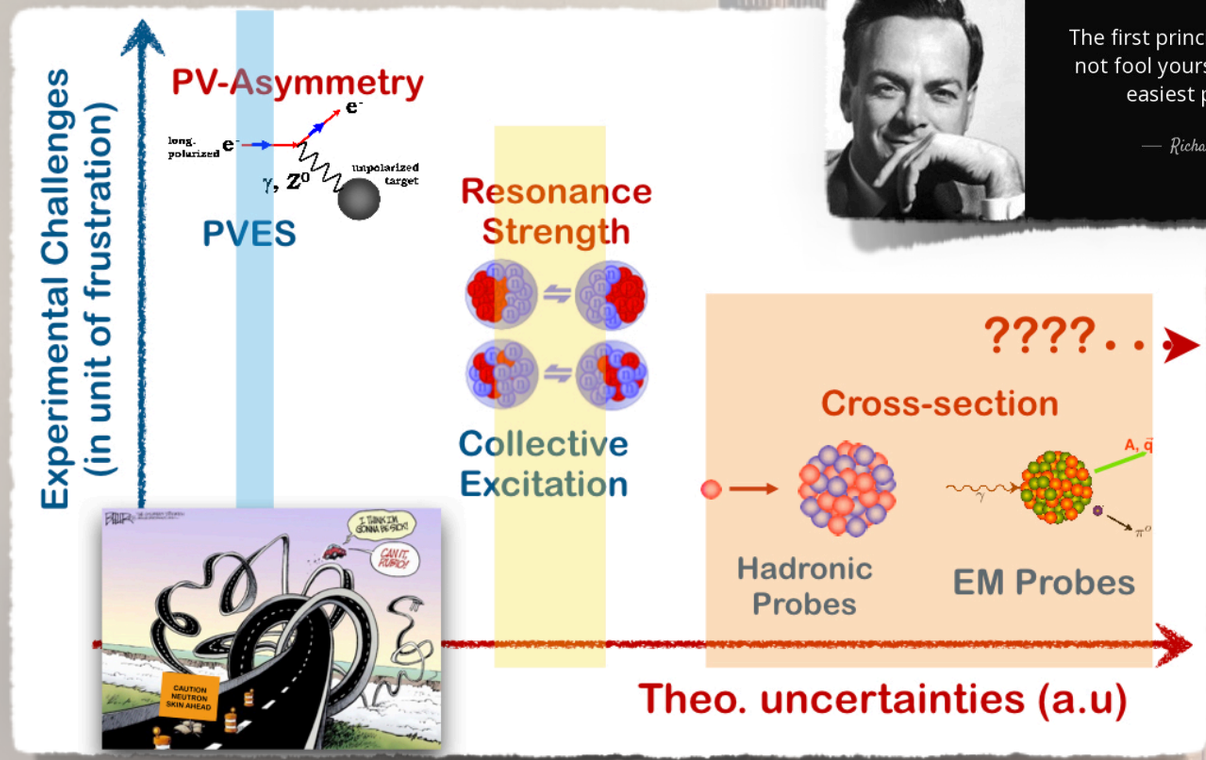
	2024–2027	2028–2031	2032–2035
P2	H Backward	H Forward Data Taking I	H Forward Data Taking II	H Forward Data Taking III
MREX		Neutron-Skin ^{208}Pb	Neutron-Skin ^{48}Ca
DARK MESA	2000 h	6000 h	8000 h
MAGIX	Dark Photon (DP) Beam Dump (BD)	DP Visible BD/ERL	DP Invisible ERL	Dilepton e-prod. ERL	DP Visible Displaced Vertex
		Proton FF, G_E ERL	Proton FF, G_E, G_M ERL
		(γ,α) BD	(γ,n) BD	(γ,α) ERL	(γ,α) ERL + 0° Tagger
	^{12}C transition FF BD	^{4}He transition FF ERL	Deuterium ERL	^{4}He inclusive ERL	^{3,4}He exclusive

Hadrons Nuclei CRC 1660

…we got slightly delayed ….

NO SUCH THING AS A FREE LUNCH

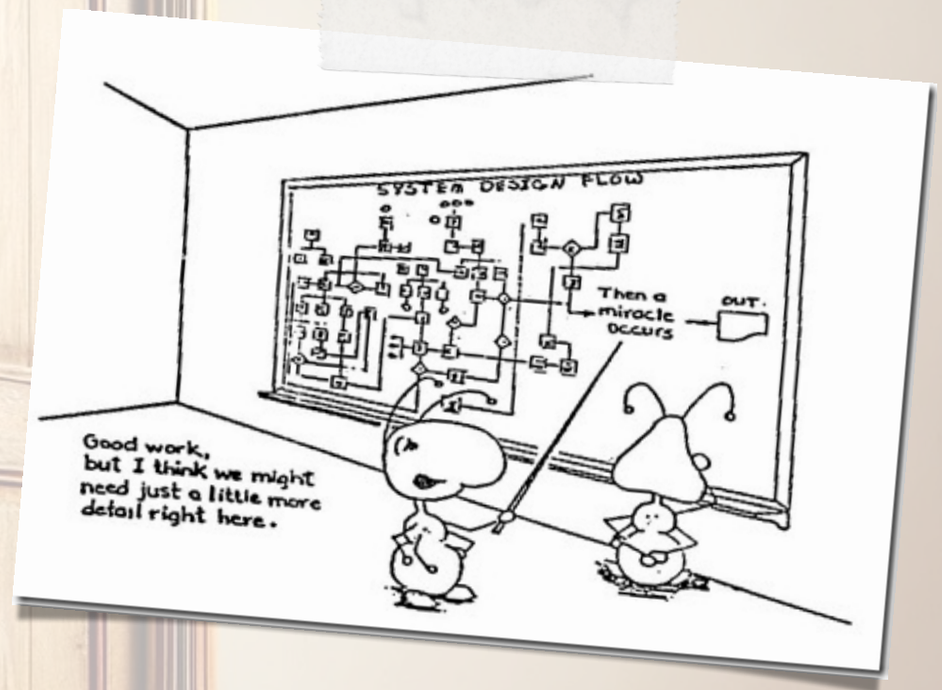
NO SUCH THING AS A FREE LUNCH



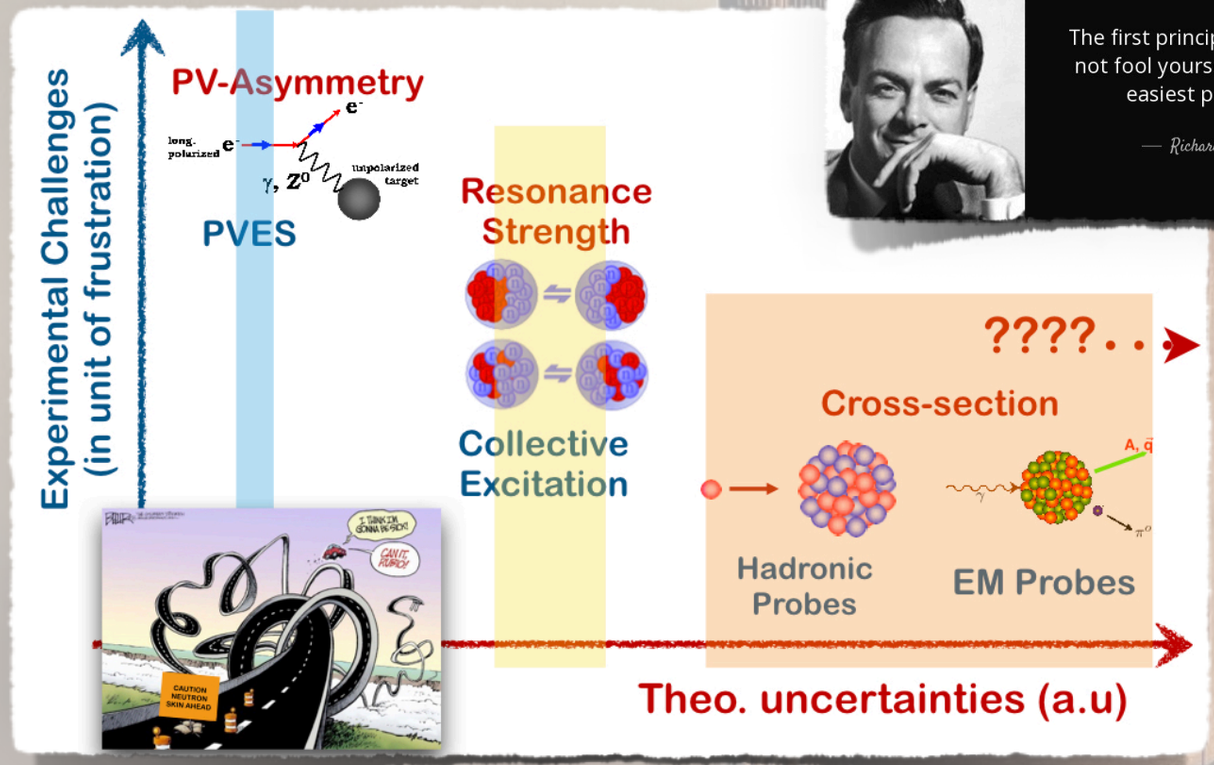
The first principle is that you must not fool yourself and you are the easiest person to fool.

— Richard P. Feynman —

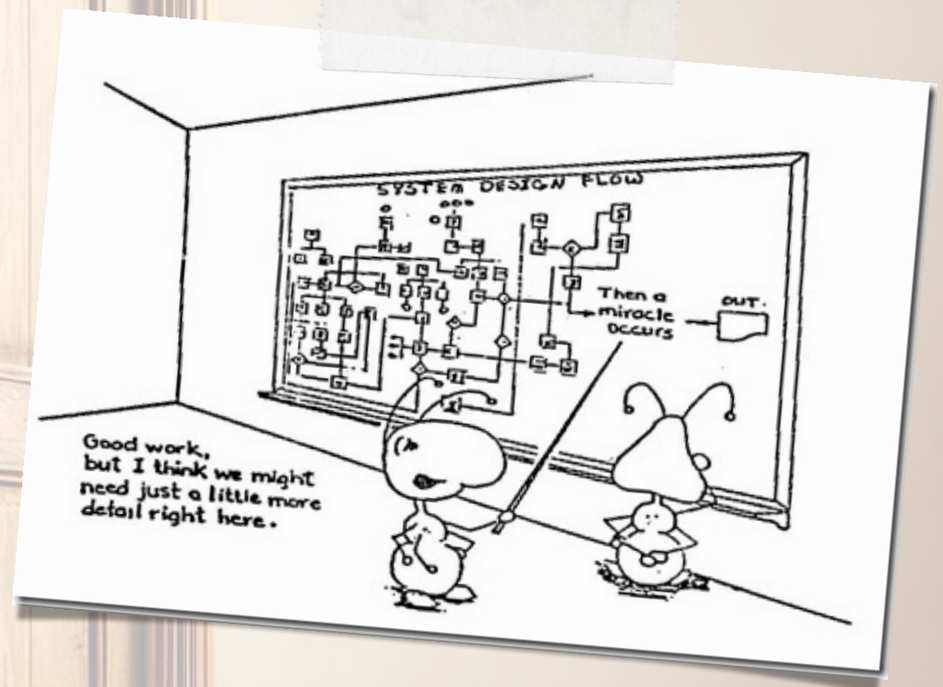
All methods are model-dependent; some are so clingy they miss the neutron skin altogether

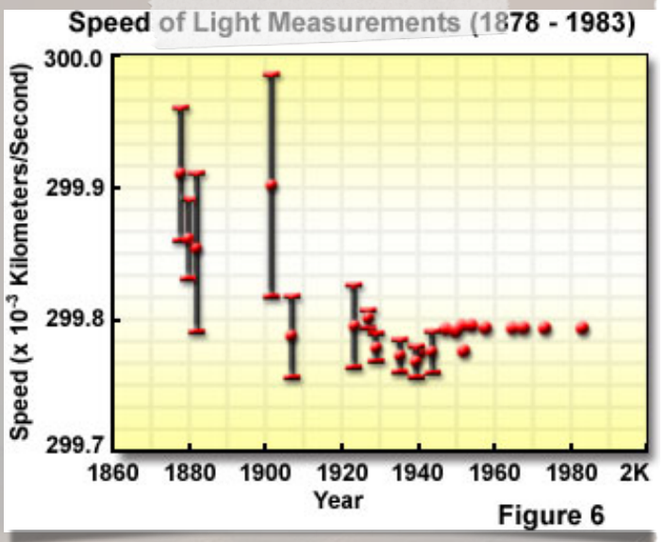


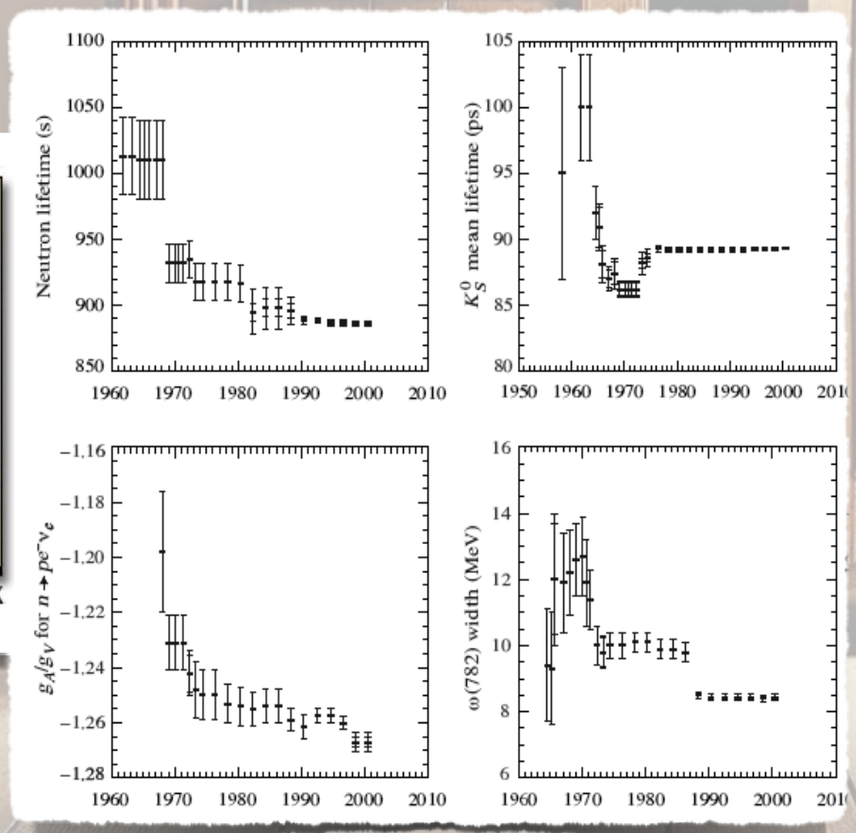
NO SUCH THING AS A FREE LUNCH



All methods are model-dependent; some are so clingy they miss the neutron skin altogether



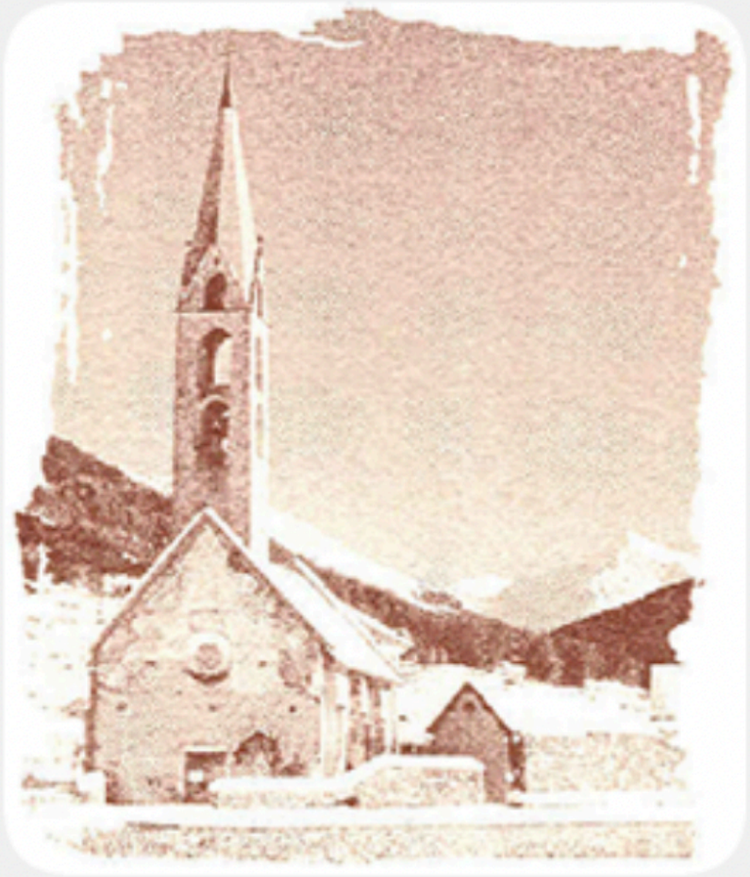




A lesson from the past: it’s time to blind the analysts!

61st International Winter Meeting on Nuclear Physics

January 27 to 31, 2025 Bormio, Italy



Long-standing conference bringing together researchers and students from various fields of subatomic physics.

The conference location is Bormio, a beautiful mountain resort in the Italian Alps.

2025 Edition

The 60th edition of the Bormio conference will be held from January 27 to 31 2025 in Bormio (Italy).

As for previous edition, we are foreseeing two **special** initiatives for **young students**

- **PRE-CONFERENCE SCHOOL**

To improve the participation of students and young researchers at the conference a pre-conference school is taking place on **SUNDAY 26 January 2025**: four topical lectures will be held covering the basis of the main physics topics dealt within the conference. Students are asked to select the proper field in the registration form, if they intend to participate.

- **STUDENTS FELLOWSHIPS**

A limited number of fellowships will be awarded to brilliant students to cover their accommodation and conference fee. Students who intend to apply for the fellowships are asked to send their application (**cover letter, CV and abstract**) in one single pdf file to organizers@bormioconf.org by **OCTOBER 13th**.
Participation to the pre-conference school for students awarded our student fellowships is mandatory.