Overview of Nuclear Physics Program @MAMI and MESA

Concettina Sfienti

PRISMA

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JG|U

The MAMI Legacy

Upgrade to ...

MAMI-C

Harmonic Double Sided Microtron (2007)

up to E = 1.6 GeV

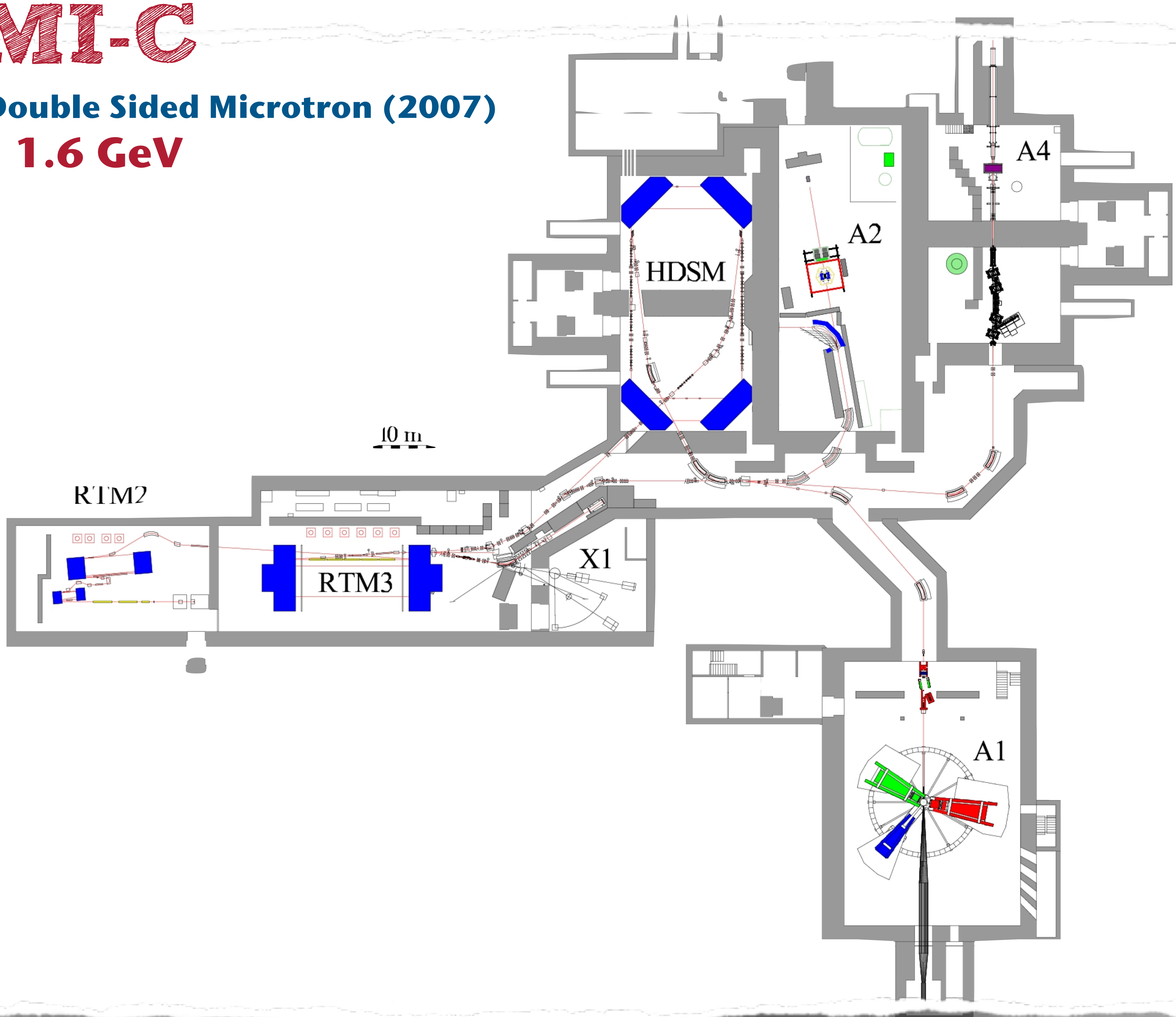
HIGH

Intensity
up to 100 μA

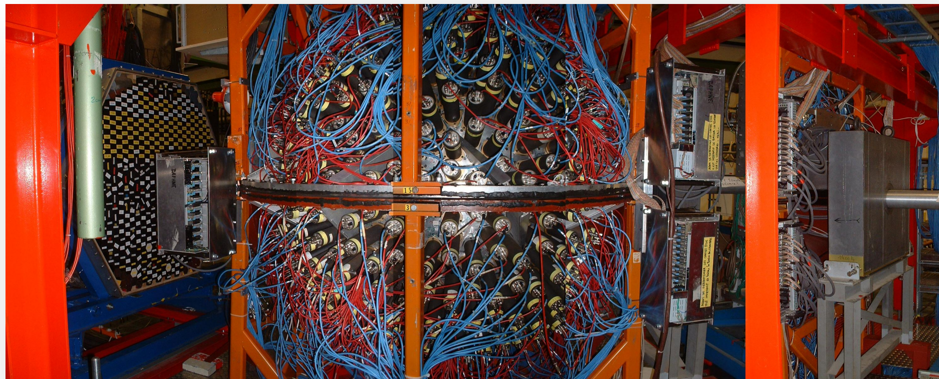
Resolution
σ_E < 0.100 MeV

Polarization
up to 80% @ 40μA

Reliability
85% (7000 h/y)



The Wheelers

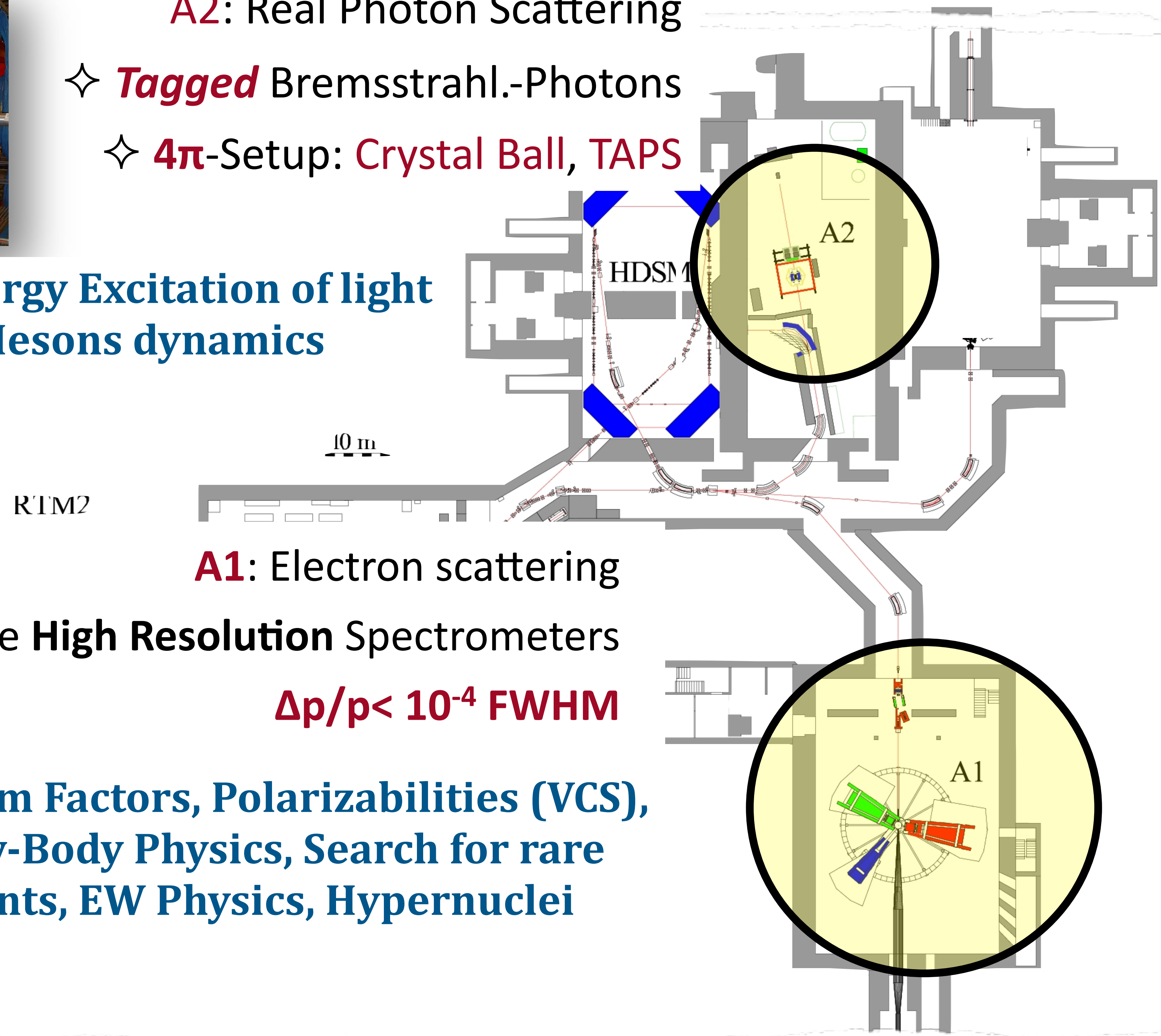


A2: Real Photon Scattering

✧ ***Tagged*** Bremsstrahl.-Photons

✧ **4π**-Setup: Crystal Ball, TAPS

Polarizabilities (RCS), Low Energy Excitation of light hadrons, Neutron Skin, Light Mesons dynamics



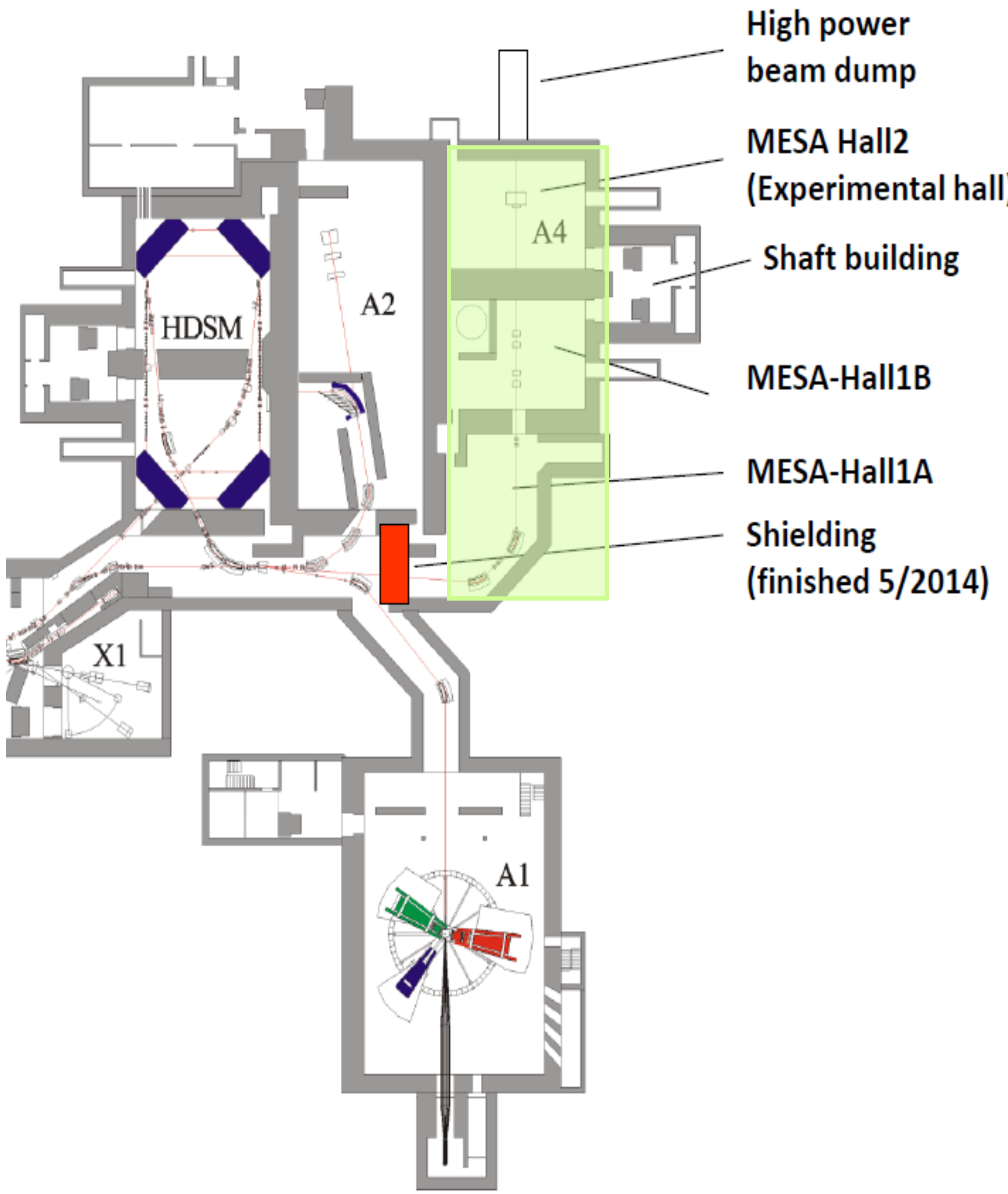
A1: Electron scattering

Three **High Resolution** Spectrometers

$\Delta p/p < 10^{-4}$ FWHM

Form Factors, Polarizabilities (VCS), Few-Body Physics, Search for rare events, EW Physics, Hypernuclei

The Mainz Energy Superconducting Accelerator



The Mainz Energy Superconducting Accelerator

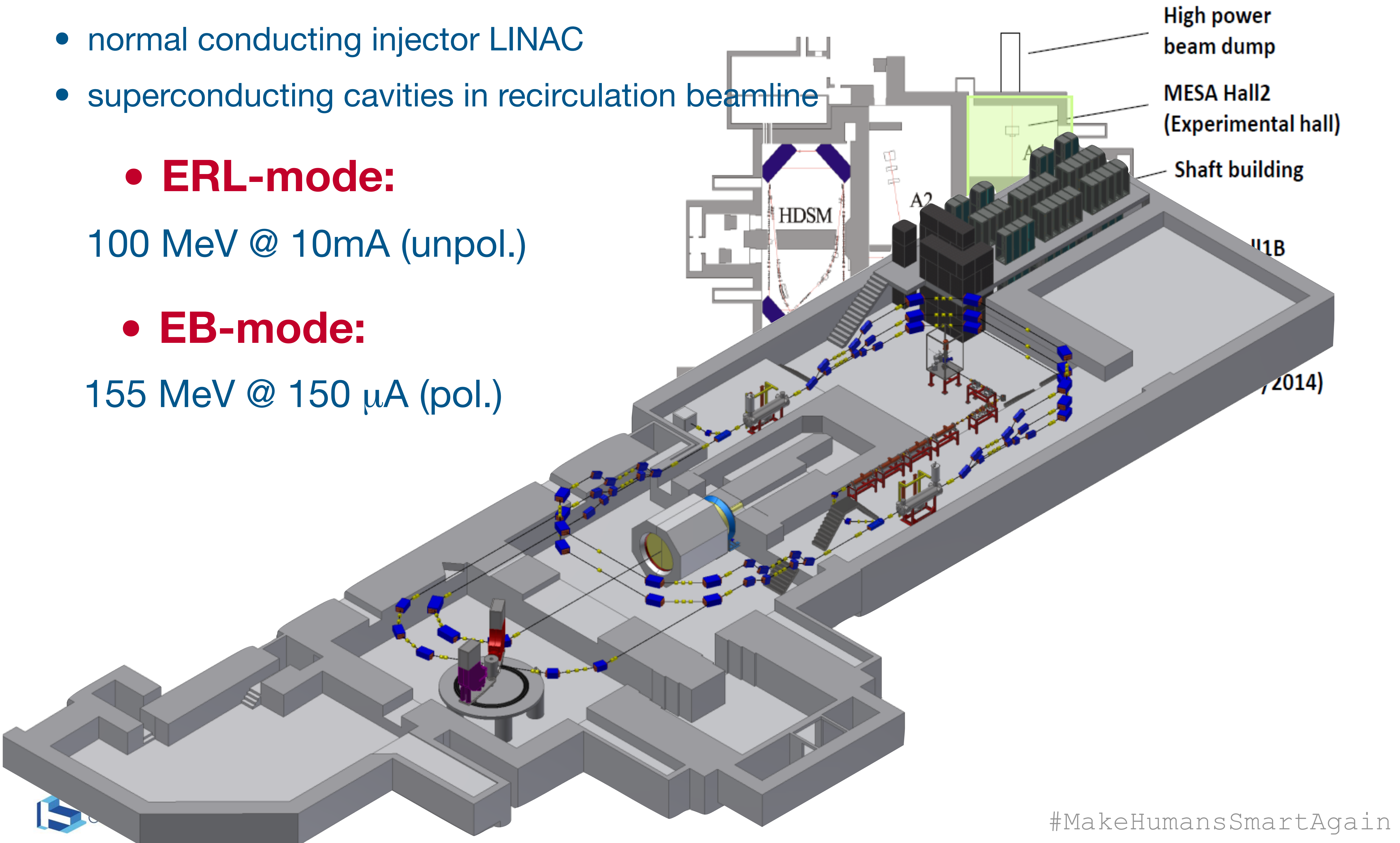
- 1.3 GHz c.w. beam
- normal conducting injector LINAC
- superconducting cavities in recirculation beamline

  - **ERL-mode:**

100 MeV @ 10mA (unpol.)

  - **EB-mode:**

155 MeV @ 150 µA (pol.)



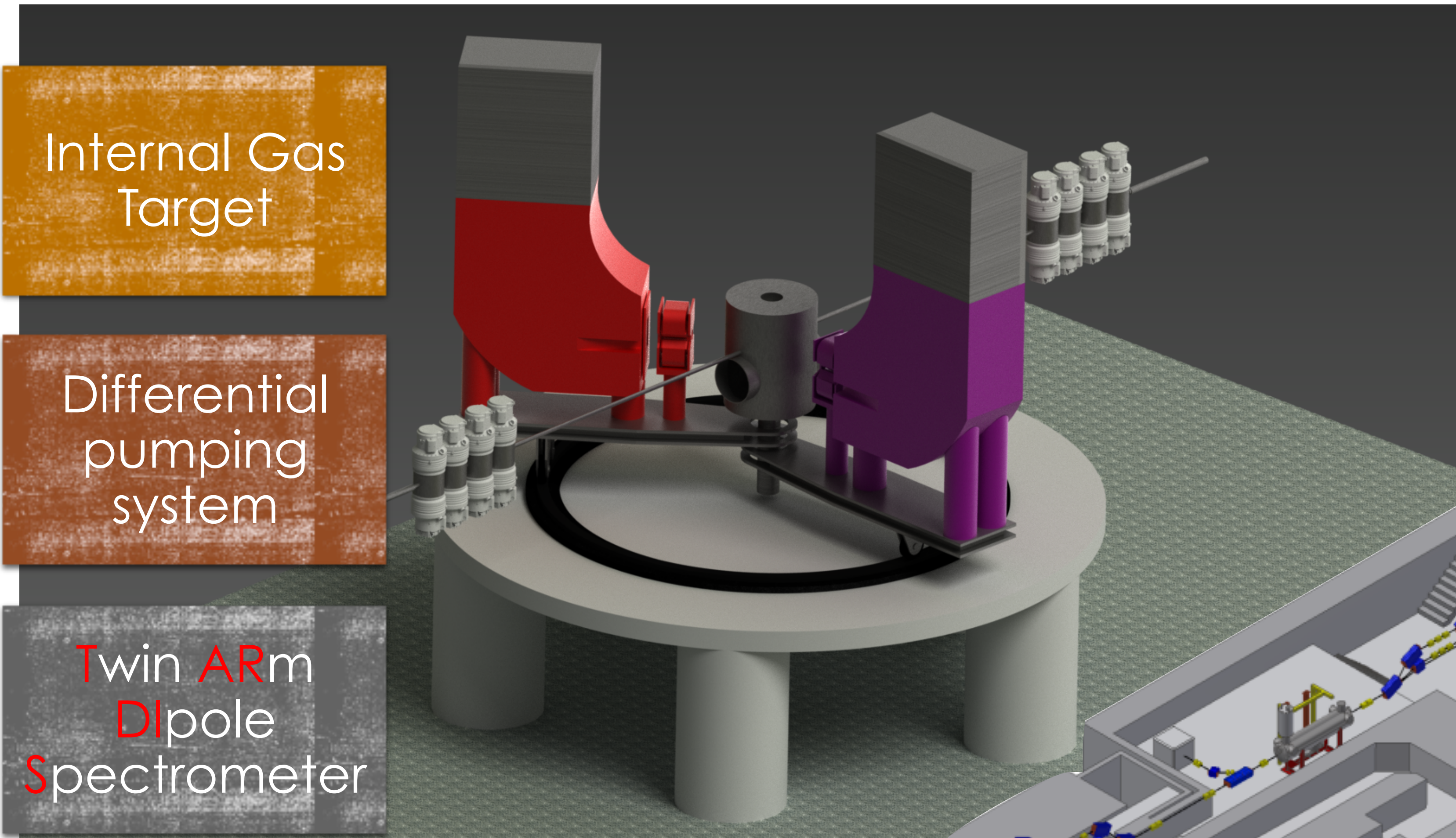
#MakeHumansSmartAgain

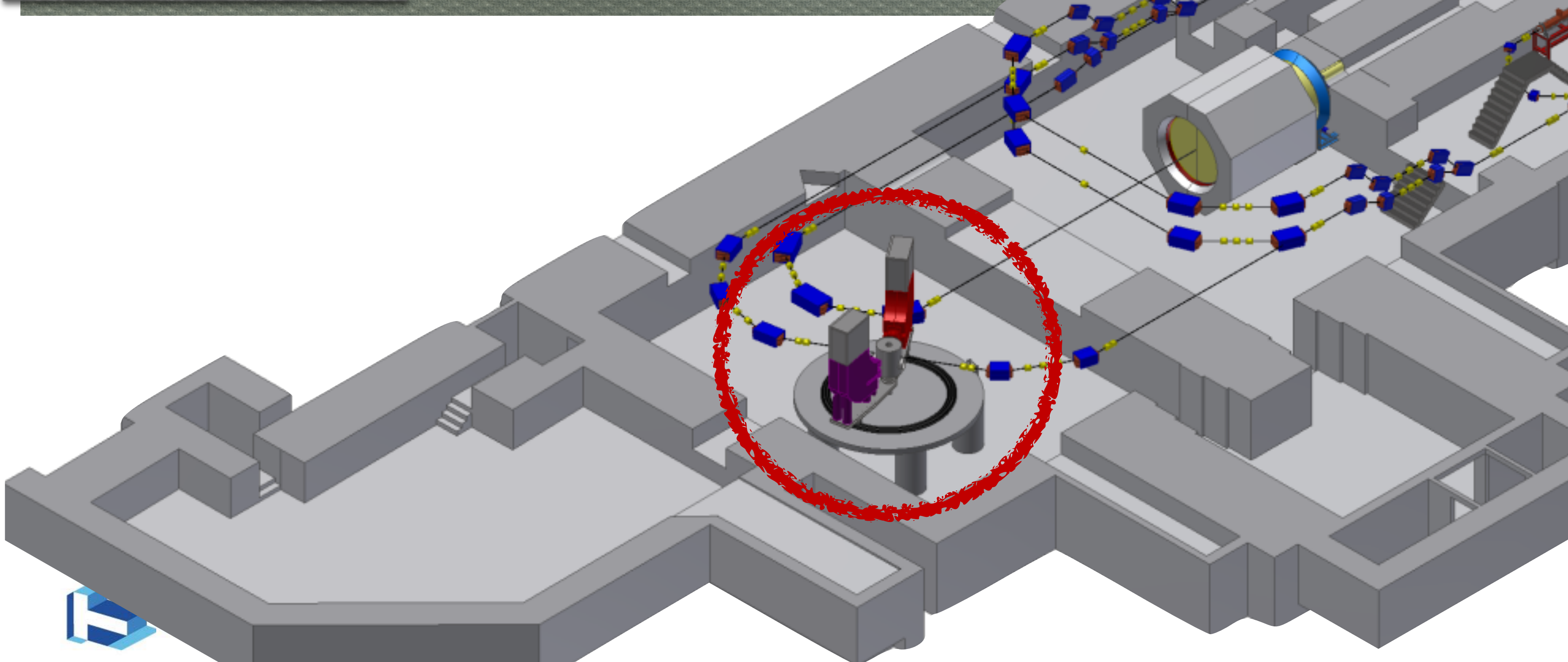
The MESA Wheelers

Internal Gas Target

Differential pumping system

Twin ARm DIpole Spectrometer





High resolution on low momentum electrons
- 1 < p < 100 MeV
- $\frac{\Delta p}{p} \approx 10^{-4}$
- $\Delta\theta \cong 5 * 10^{-2}\,°$

Material reduction
- No window before the magnet
- Thin detector

Large sensitive surface
- $120 * 30\ cm^2$ focal plane surface

Good point resolution
- $50\ \mu m$ point resolution along the in the dispersive plane

Multiple samples
- At least 2 points to reconstruct the full kinematics

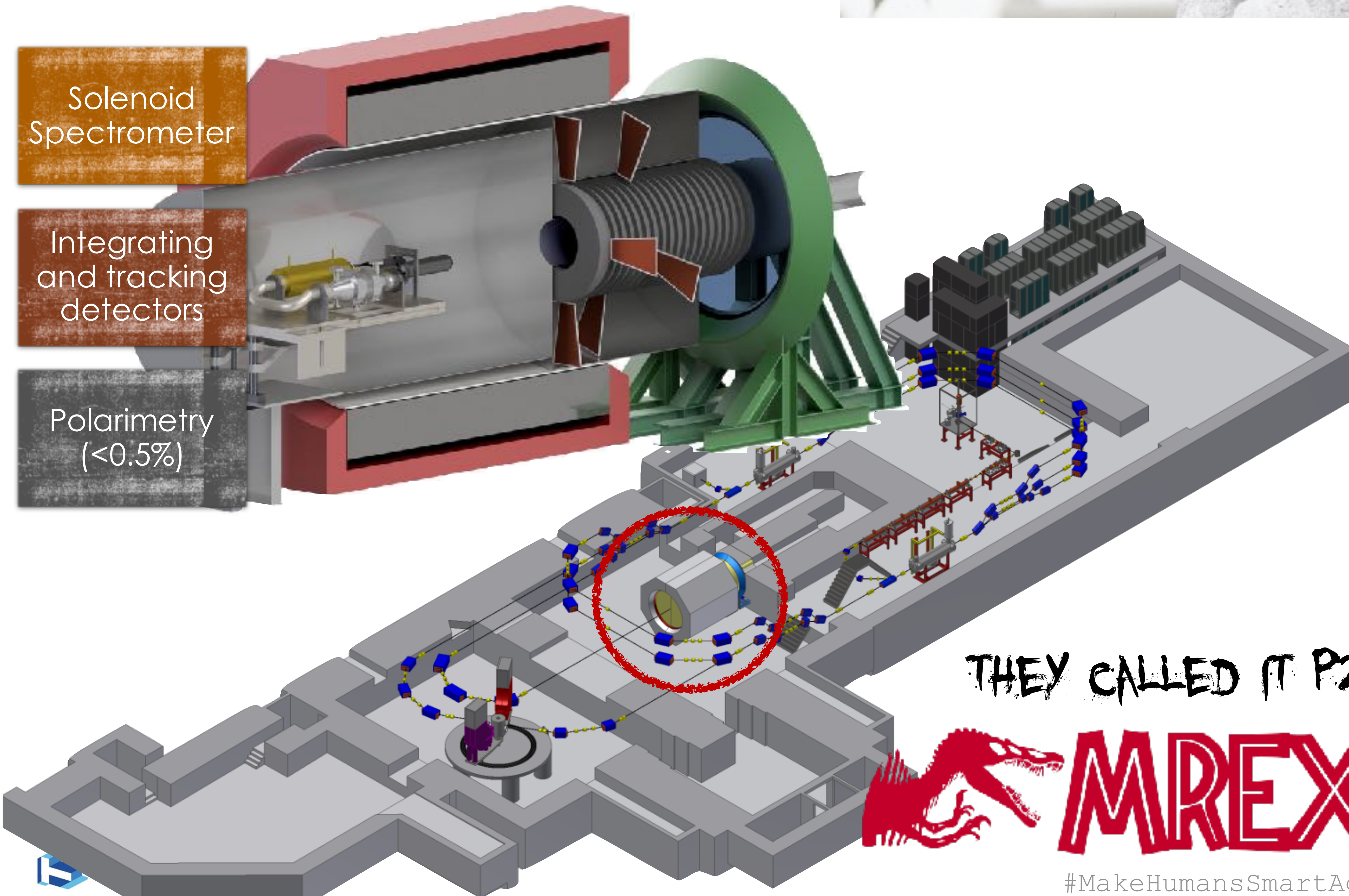
High rate capability
- With a CW operation rates up to $O(1\ MHz)$

The MESA Wheelers

Solenoid Spectrometer

Integrating and tracking detectors

Polarimetry (<0.5%)



THEY CALLED IT P2...

MREX

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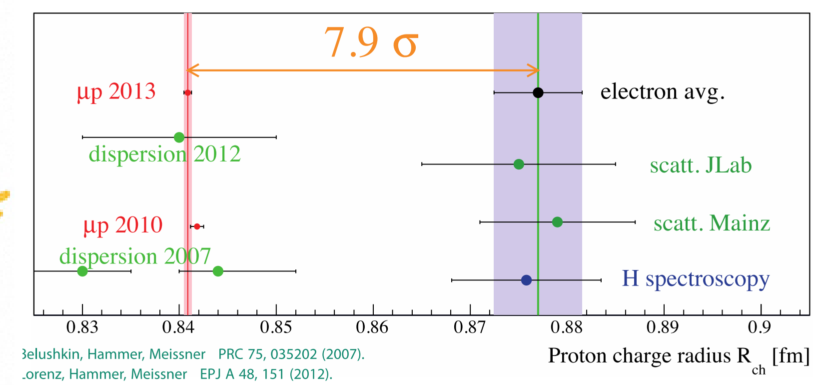
The physics cases

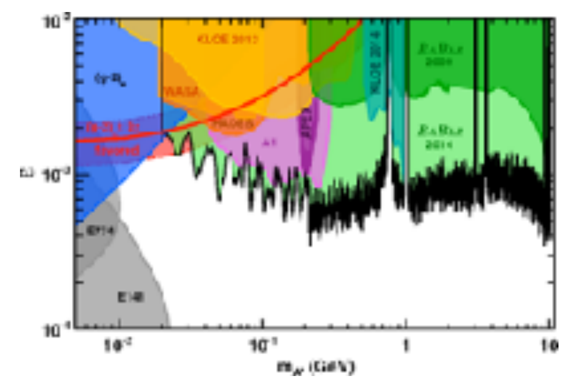
Low energy nuclear physics

High luminosity + high resolution + polarized beam and target



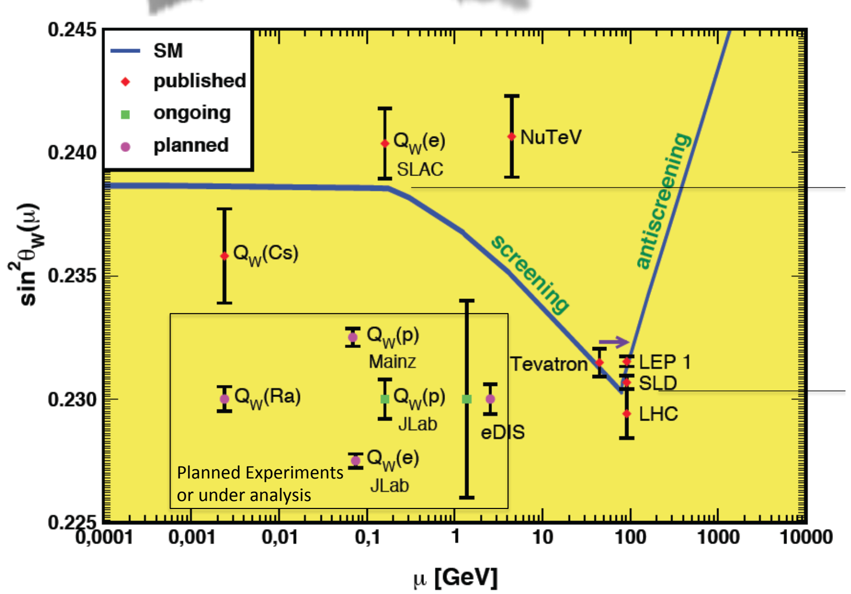
Search for rare events

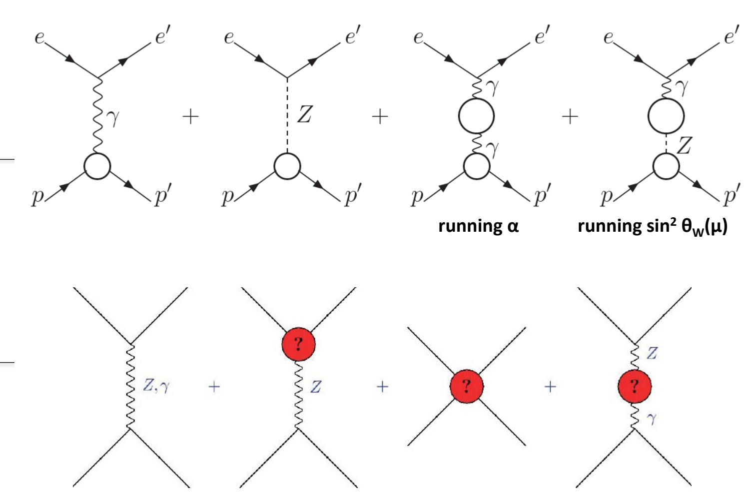
High luminosity + high resolution



Precision EW physics

High luminosity + polarized beam

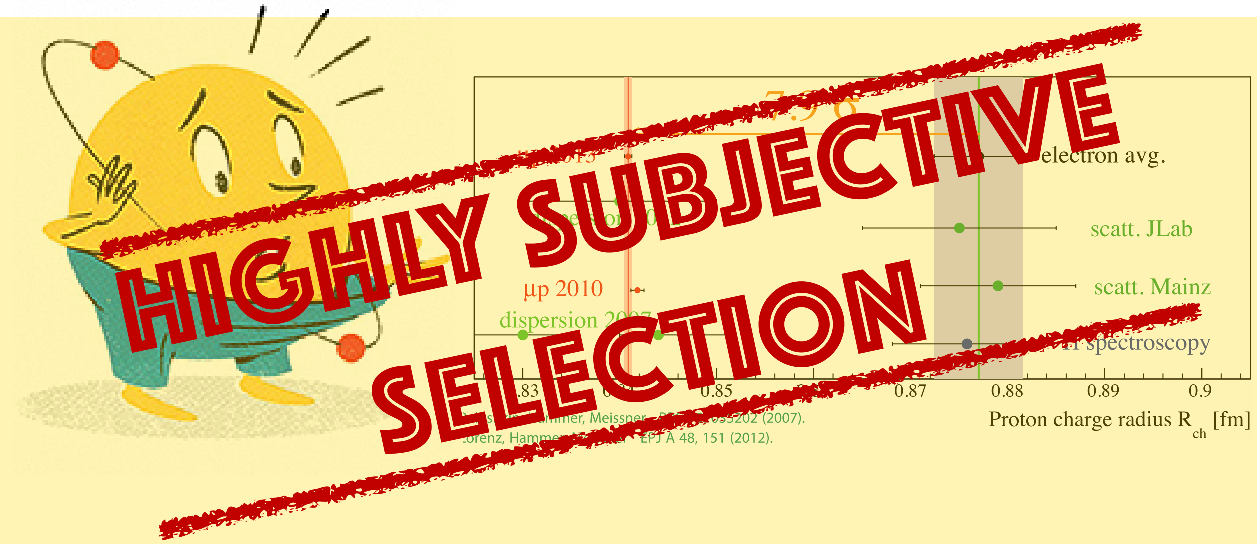




The physics cases

Low energy nuclear physics

High luminosity + high resolution + polarized beam and target



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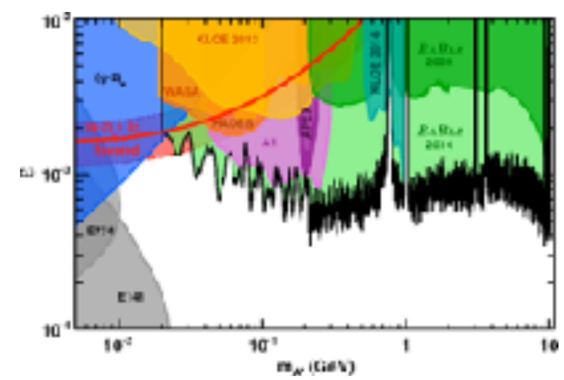

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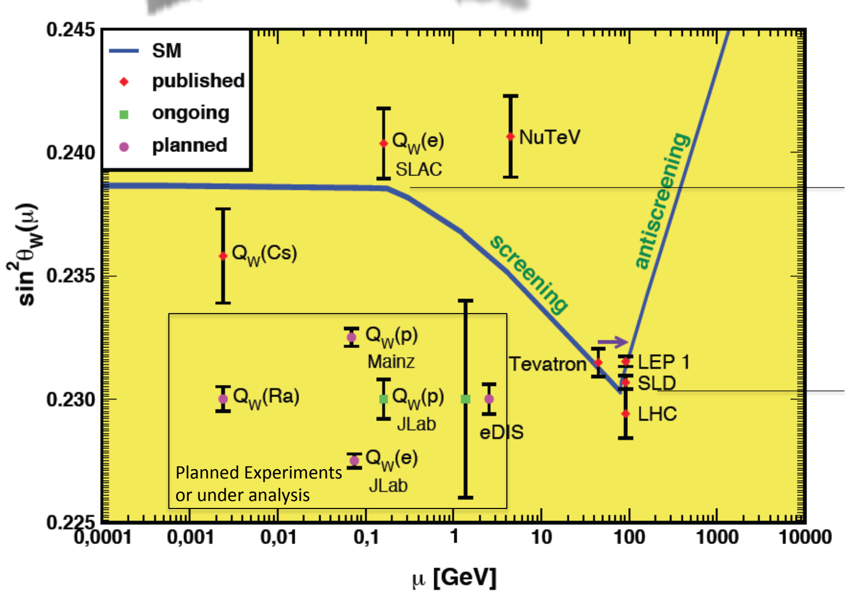

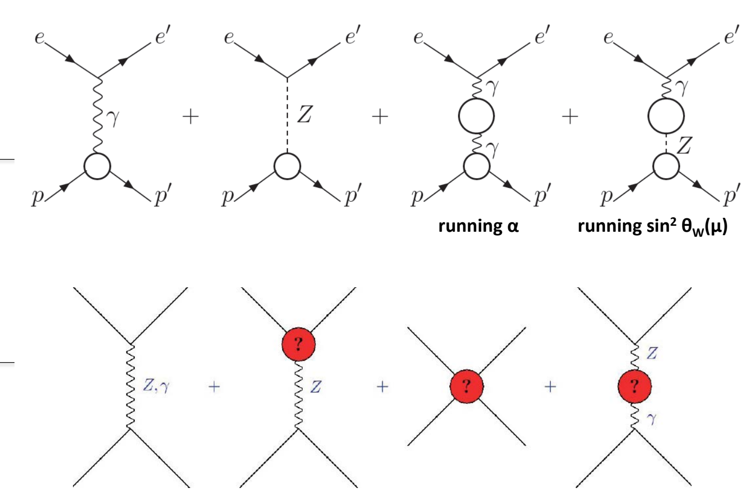

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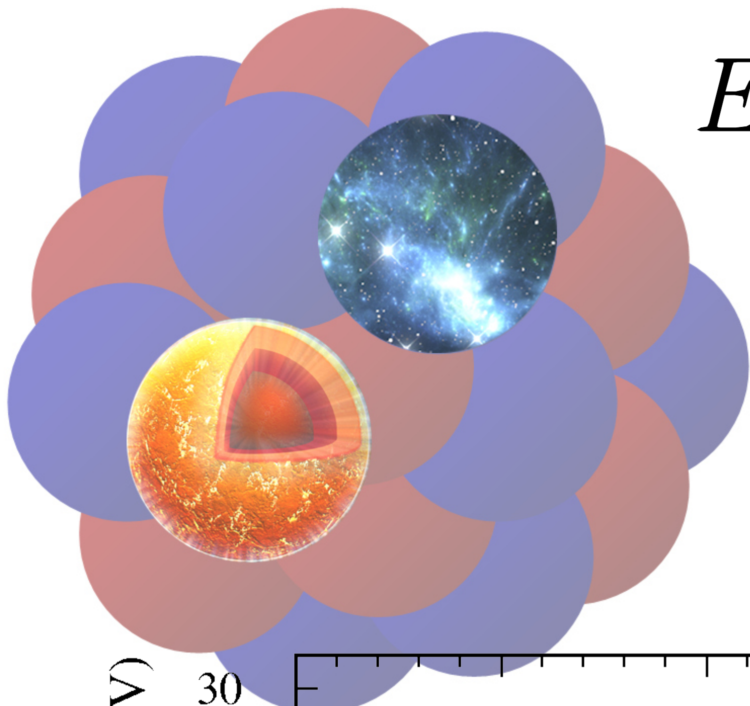
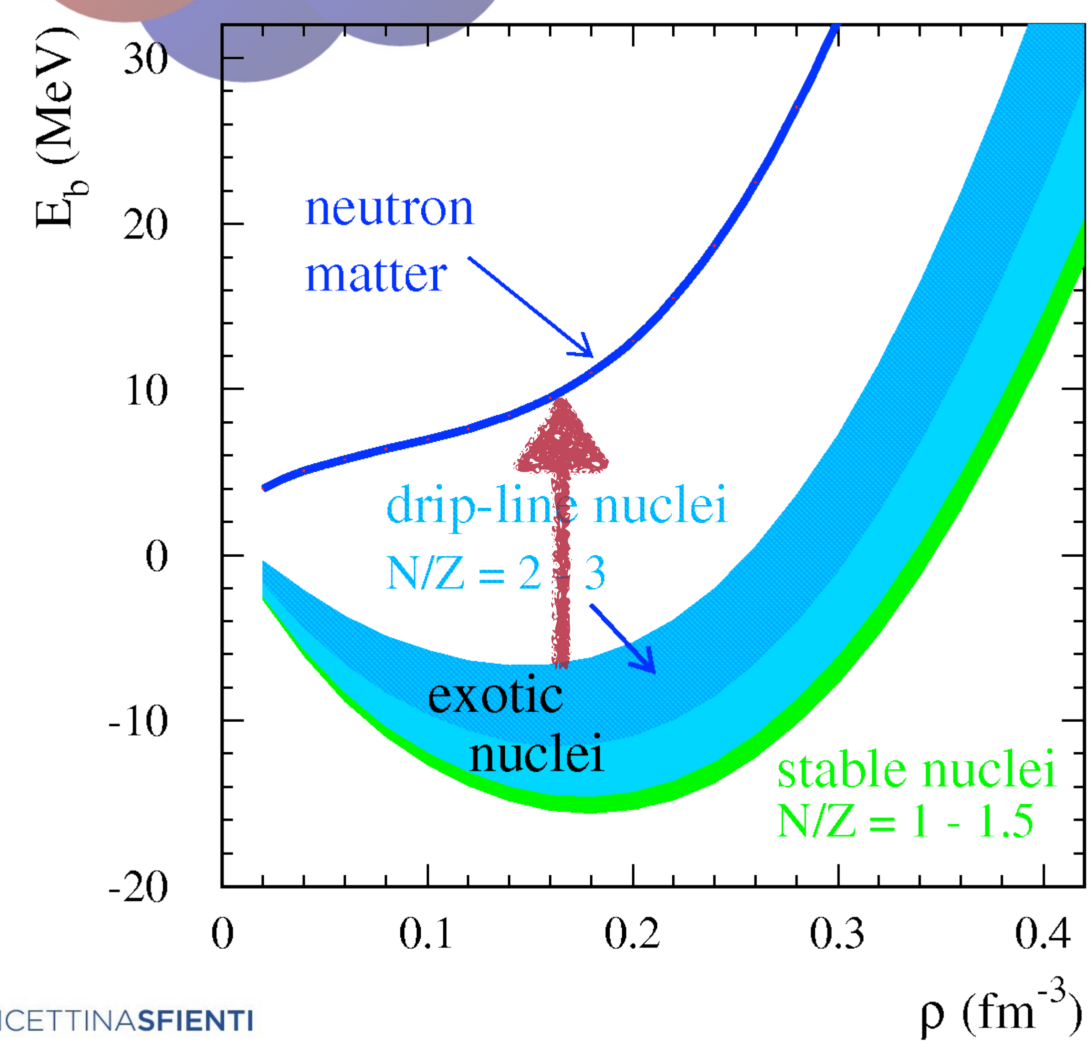
#MakeHumansSmartAgain

“The Search for the Nuclear Symmetry Energy” (*Theory-Vision*)



$$E(\rho,\delta) = E(\rho,0) + \boxed{E_{sym}(\rho)}\,\delta^2 + \mathcal{O}(\delta)^4$$

$$E_{sym}(\rho) = \left[S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2\right] + \ldots$$



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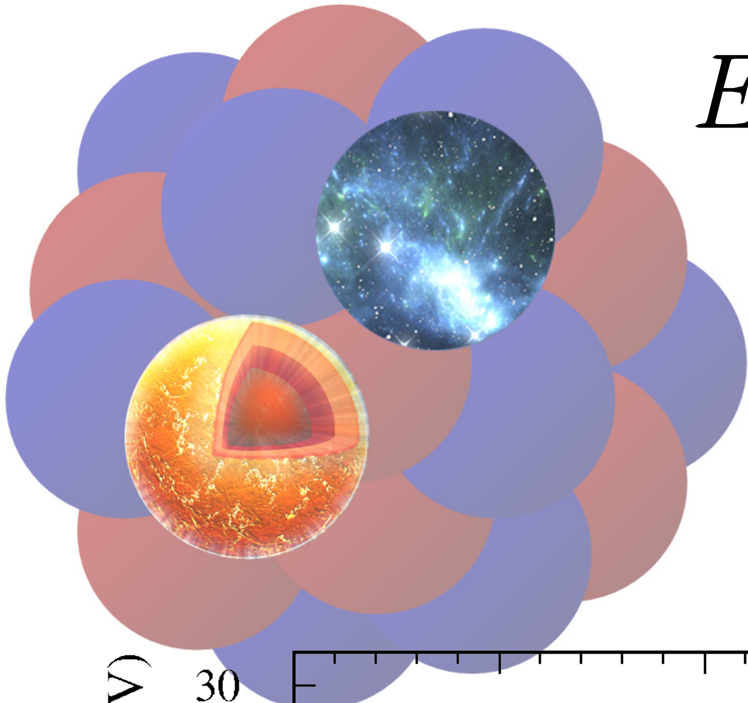

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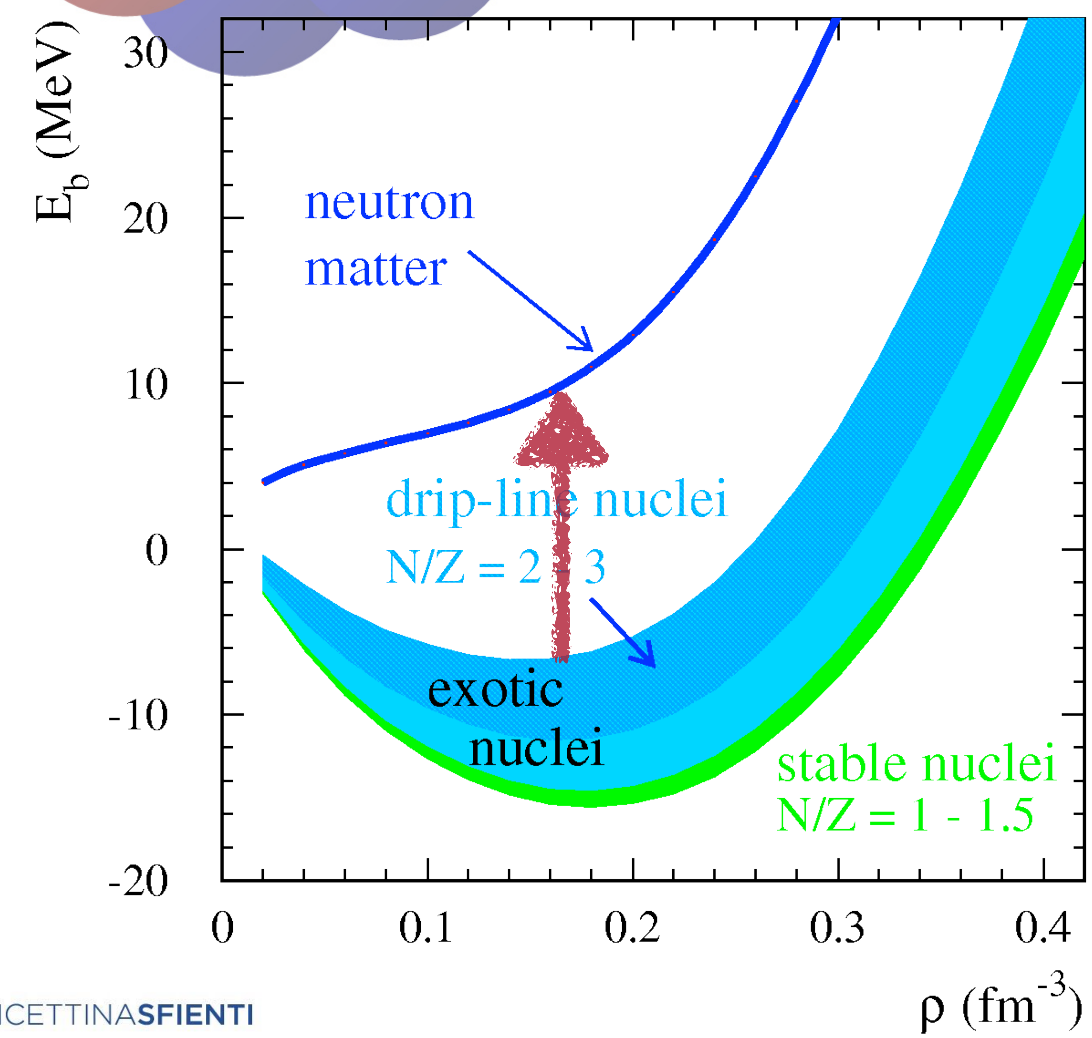


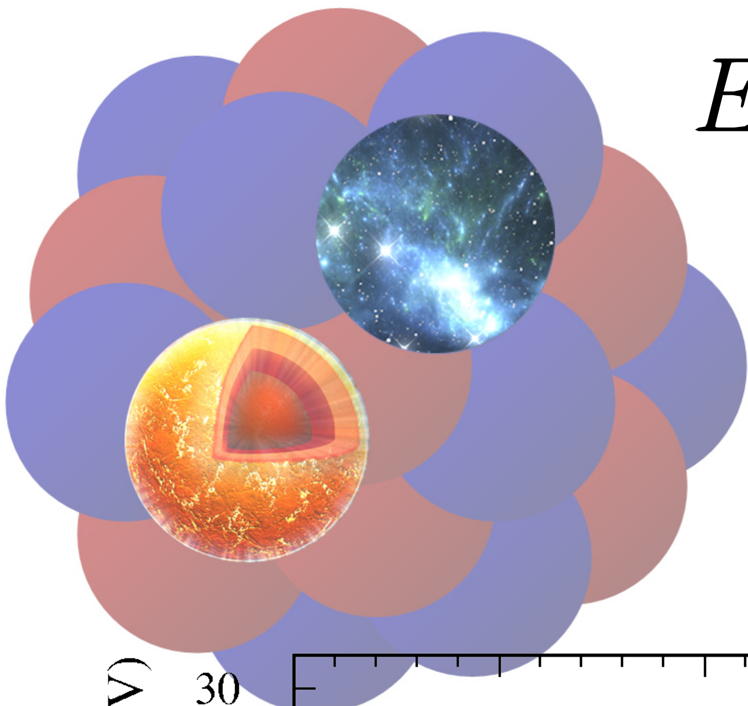
slope parameter

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

curvature parameter

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

...the (blind!?) search for the Nuclear Symmetry Energy



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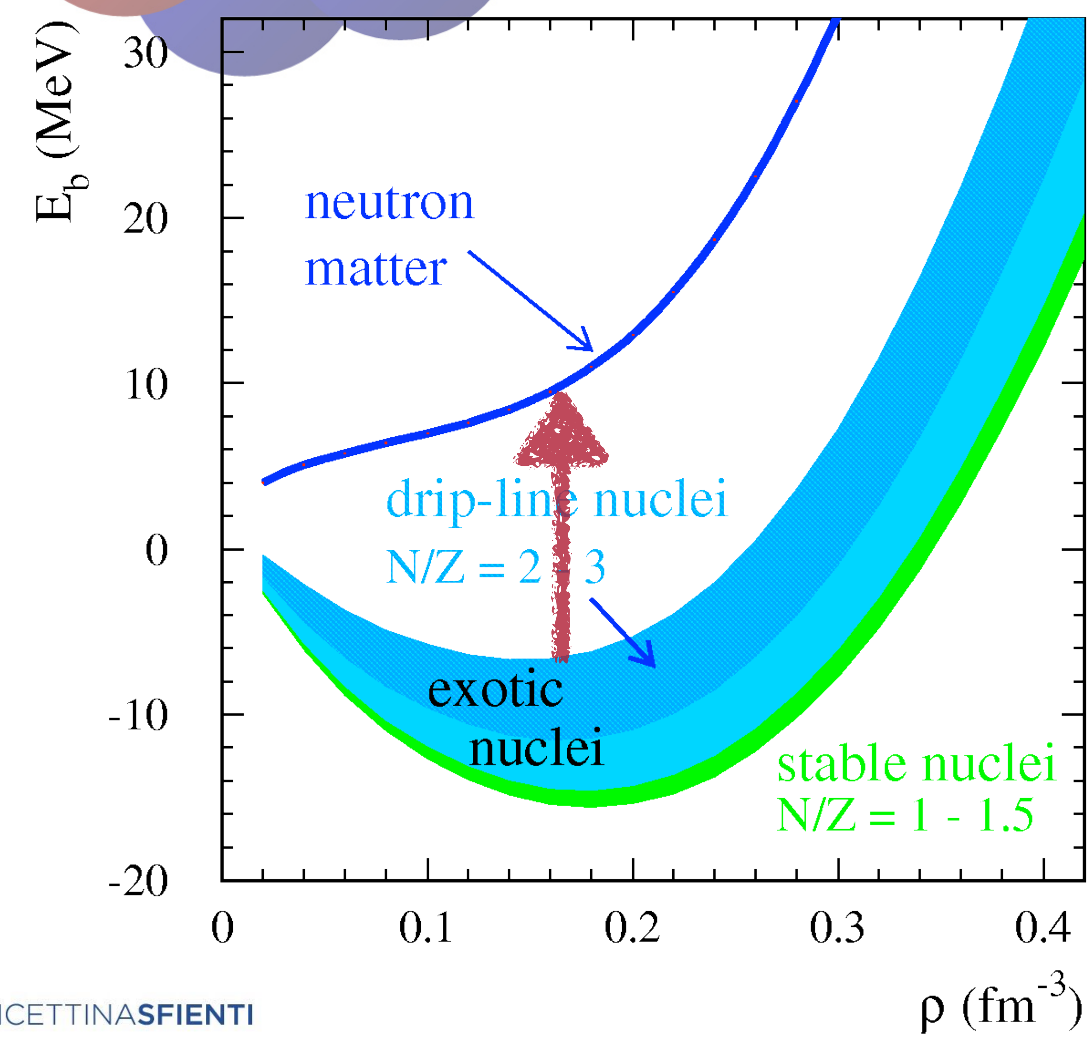
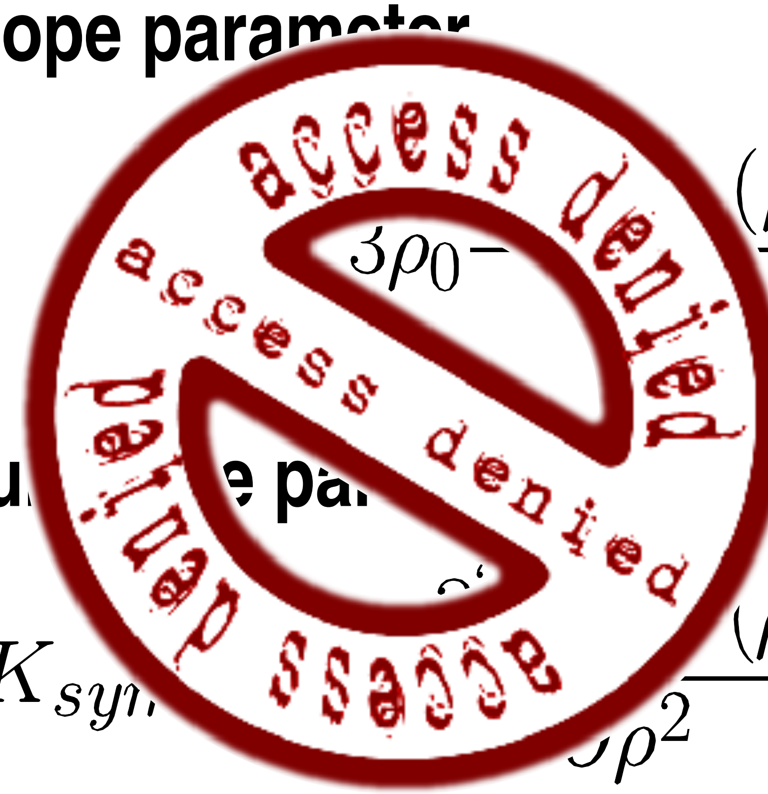


slope parameter

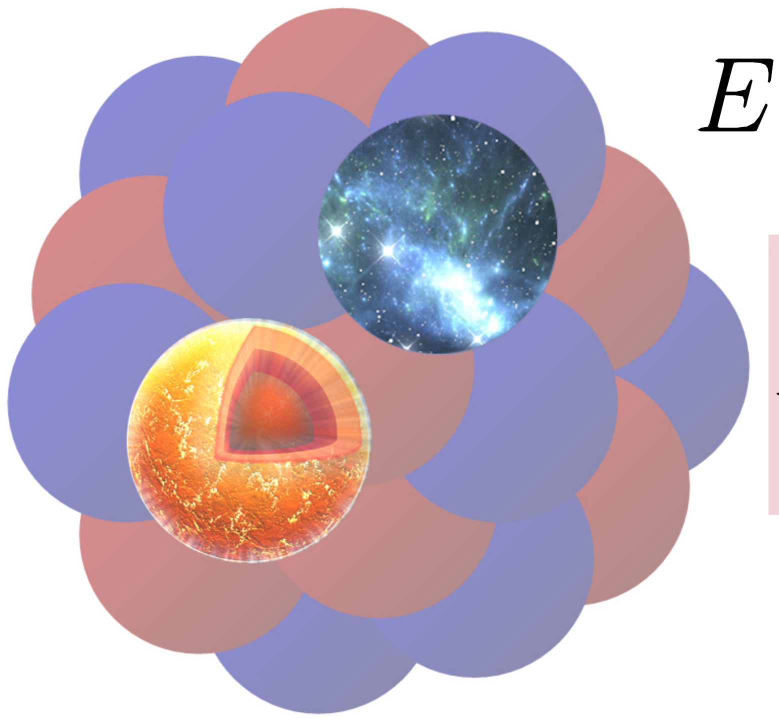
$3\rho_0$ $(\rho)\Big|_{\rho_0}$

cu... e pa...

K_{sym} ... $\partial\rho^2$ $(\rho)\Big|_{\rho_0}$



...the (blind!?) search for the Nuclear Symmetry Energy



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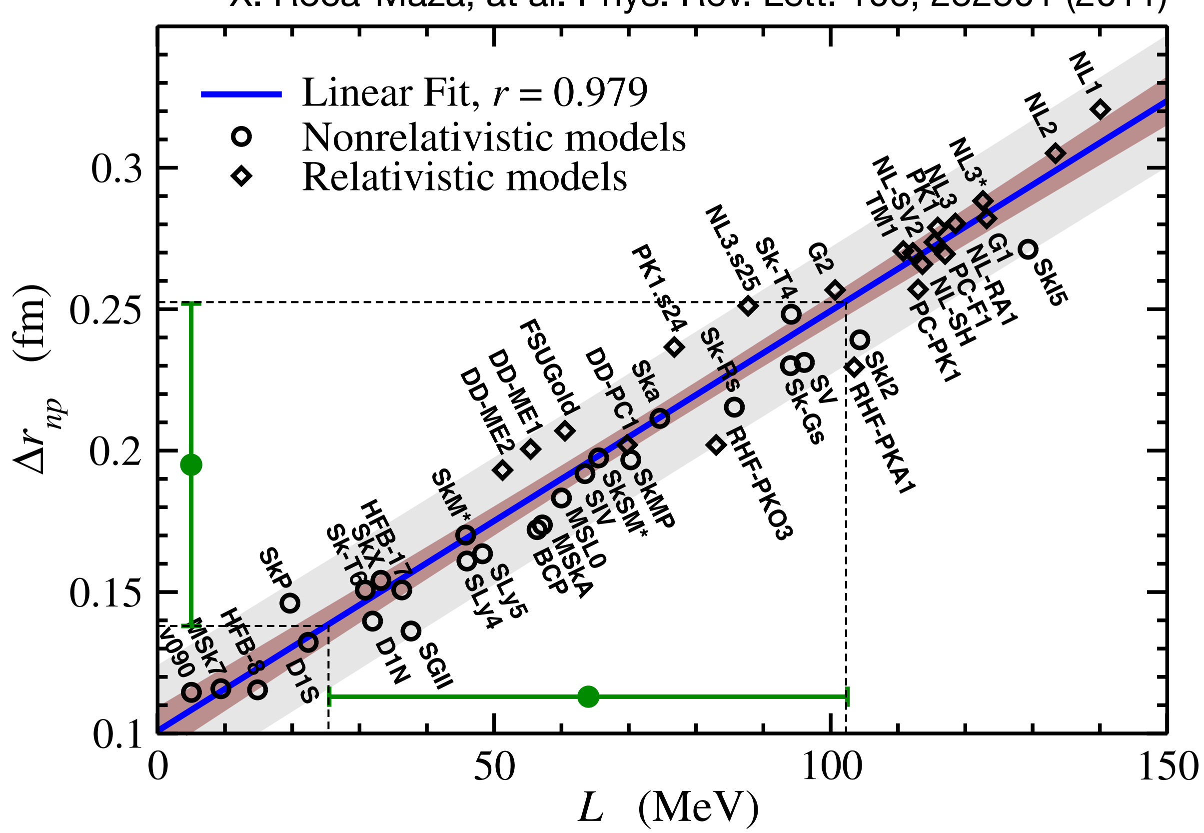
X. Roca-Maza, at al. Phys. Rev. Lett. 106, 252501 (2011)



slope param

(ρ)

$3\rho_0$

ρ_0

cu

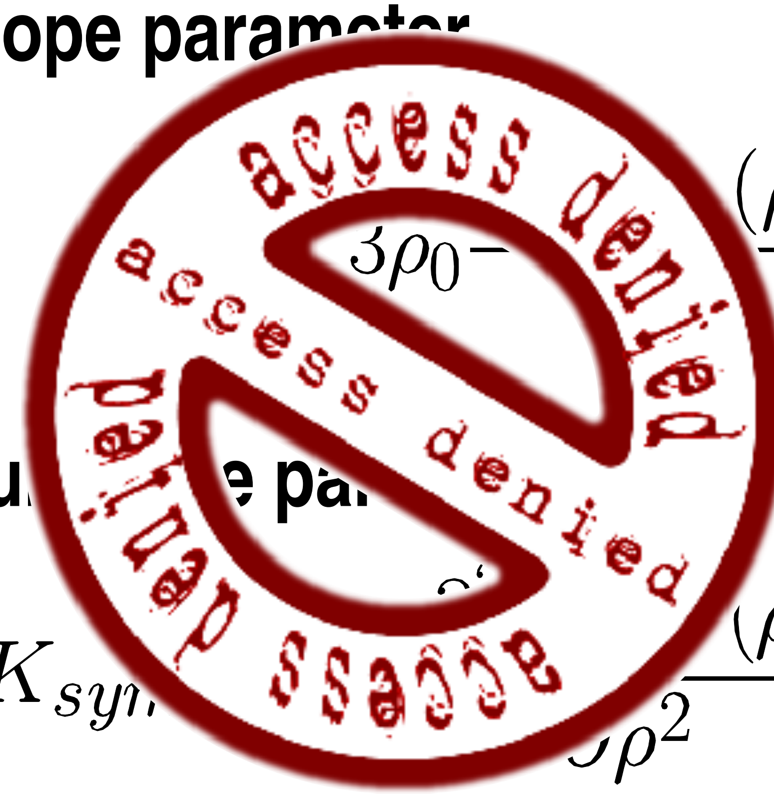
e pa

K_{sym}

ρ^2

(ρ)

ρ_0

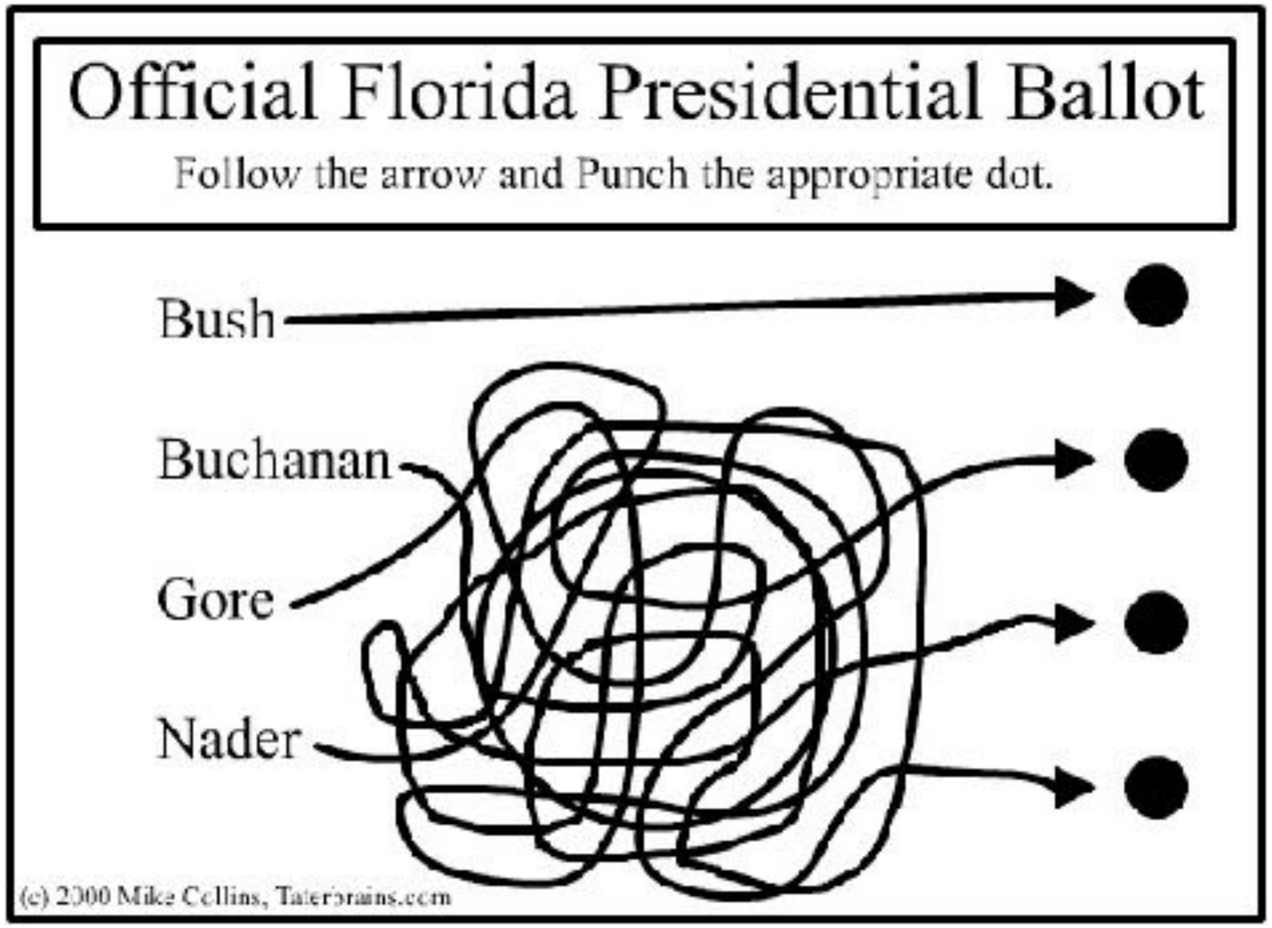


The long winding road ....

...FROM MEASURABLE OBSERVABLES TO THE NEUTRON SKIN

All observables are equal, but some observables are more equal than others … Pedigree!

The long winding road ....



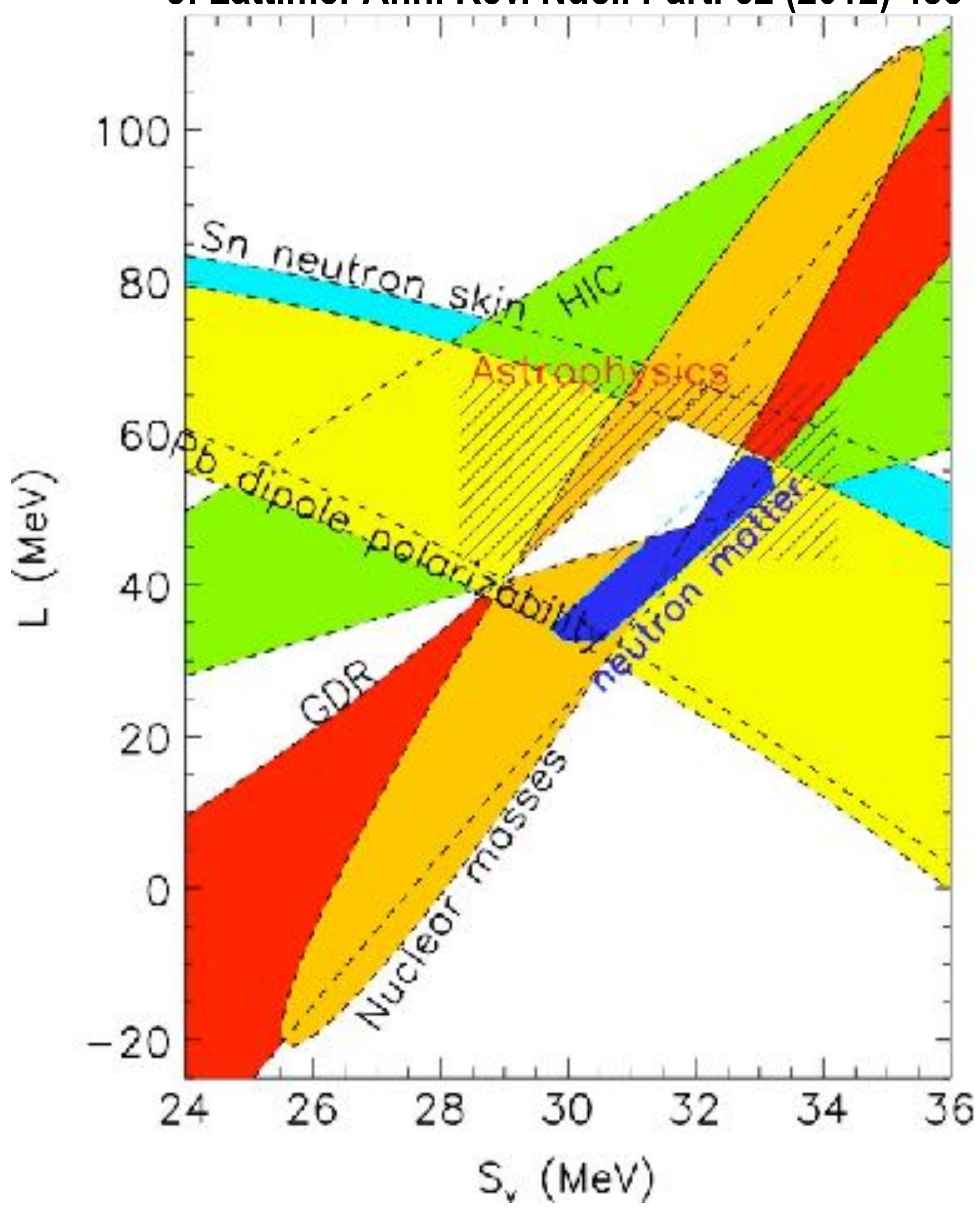
...from measurable observables to the neutron skin

- What is actually measured?
  Cross section, asymmetry, spin observables, …
- How is the measured observable connected to the neutron skin?
- What are the assumptions implicit in making this connection?
  Impulse approximation, off-shell ambiguities, distortion effects, …
- How sensitive is the extraction of the neutron radius/skin to these assumptions?
- Quantitative assessment of both statistical and systematic errors

C. Horowitz, J. Piekarewicz, CS (to appear JPG)

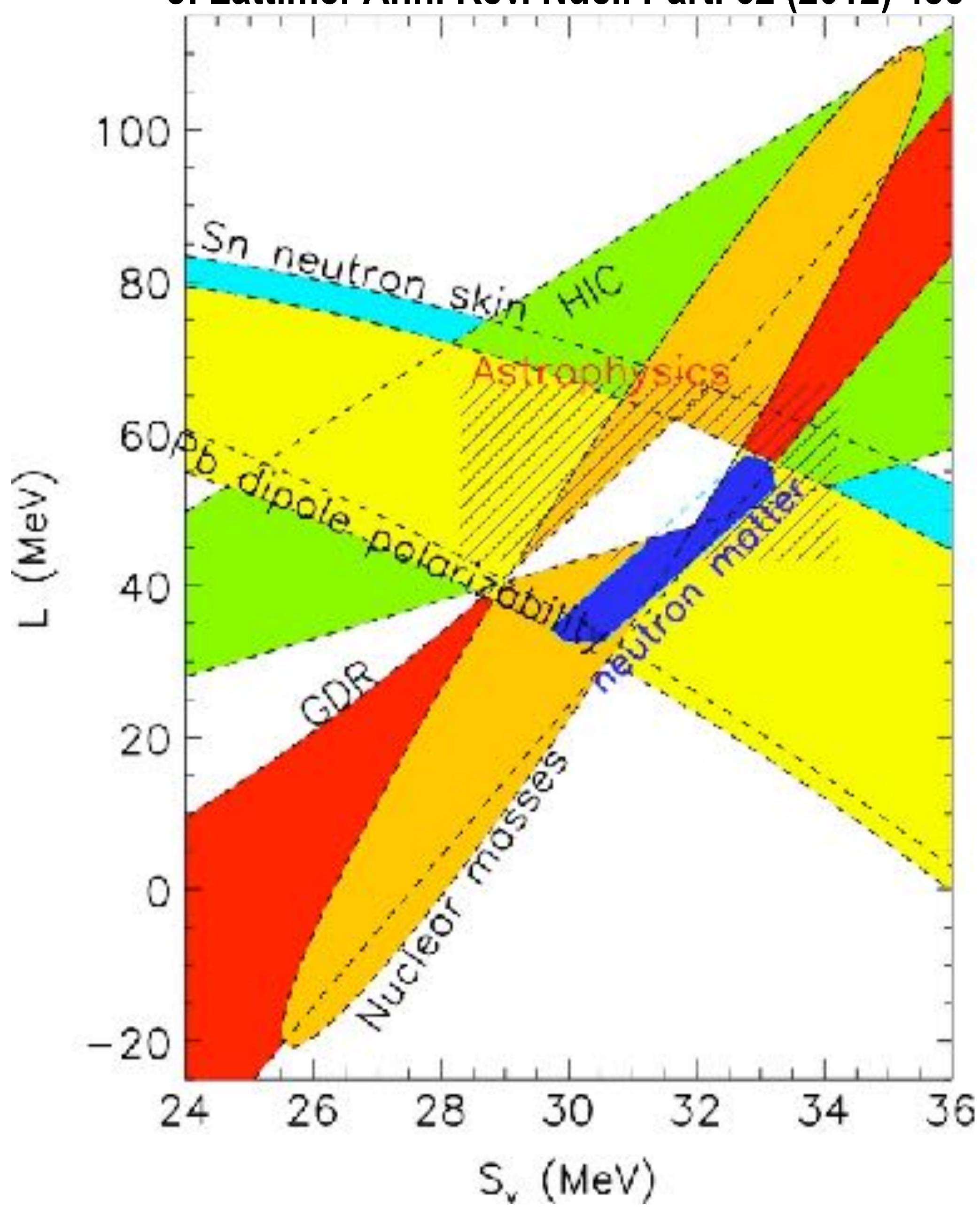
The long winding road ….

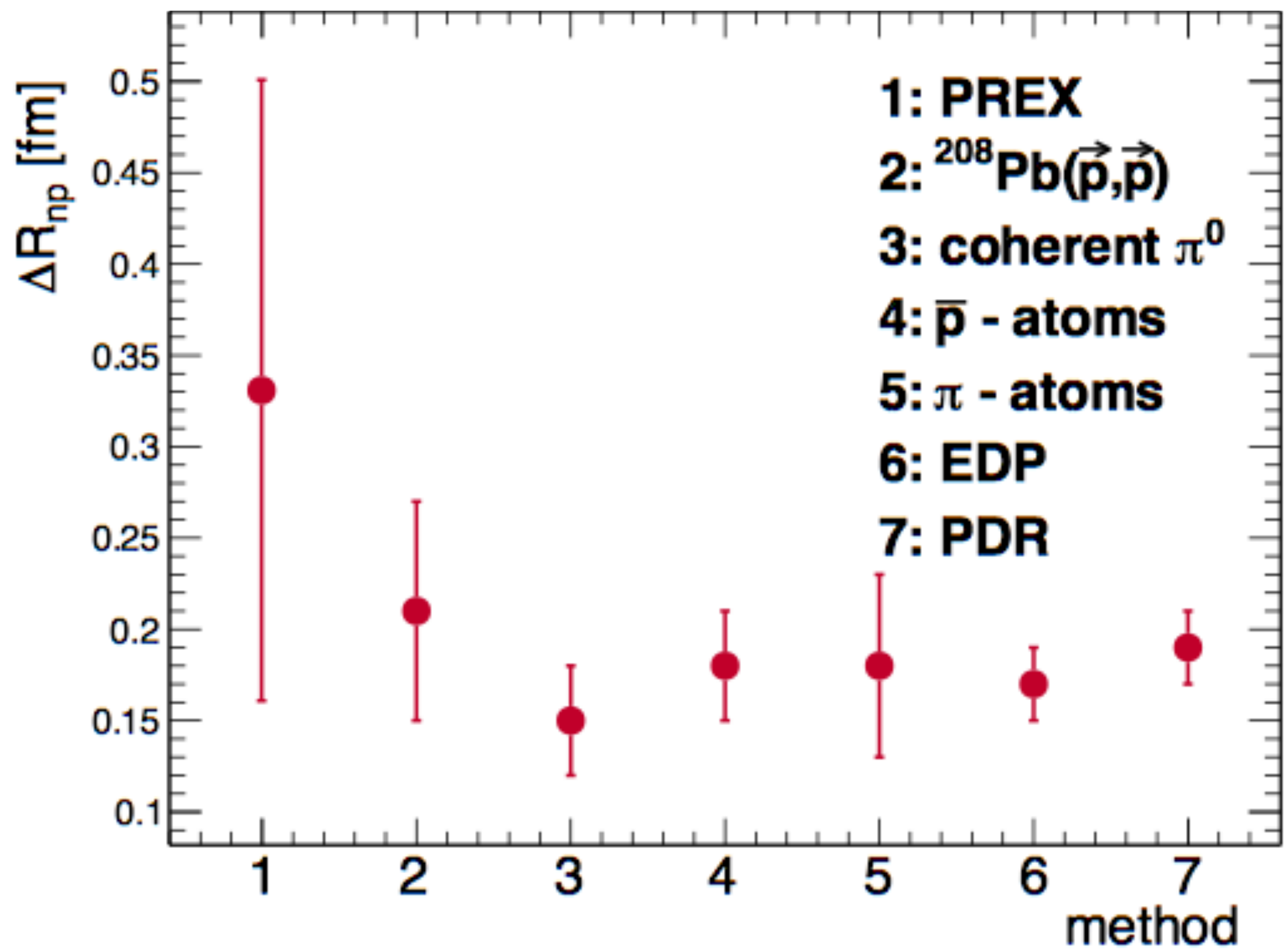
J. Lattimer Ann. Rev. Nucl. Part. 62 (2012) 485



The long winding road ....

J. Lattimer Ann. Rev. Nucl. Part. 62 (2012) 485





The long winding road ….

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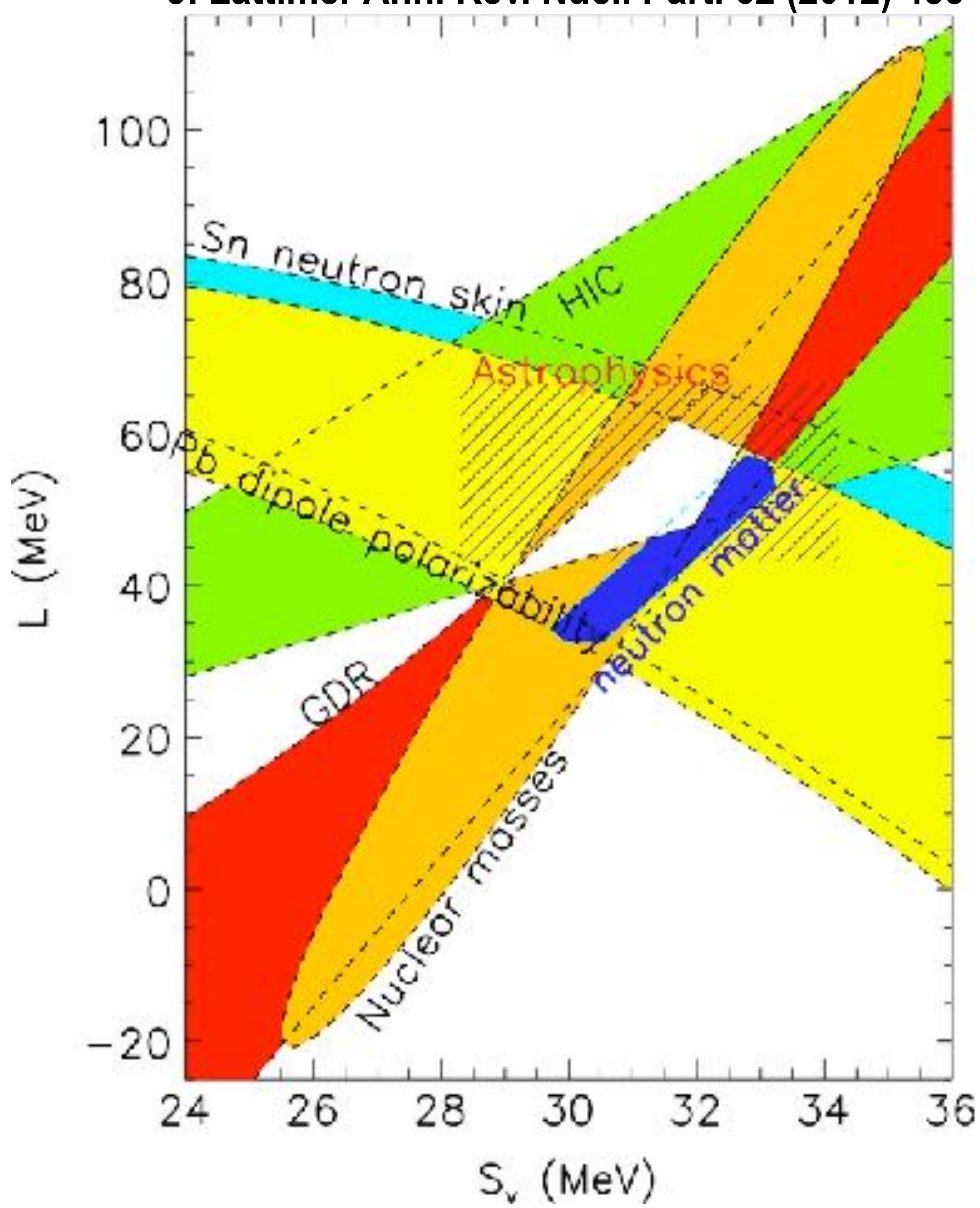

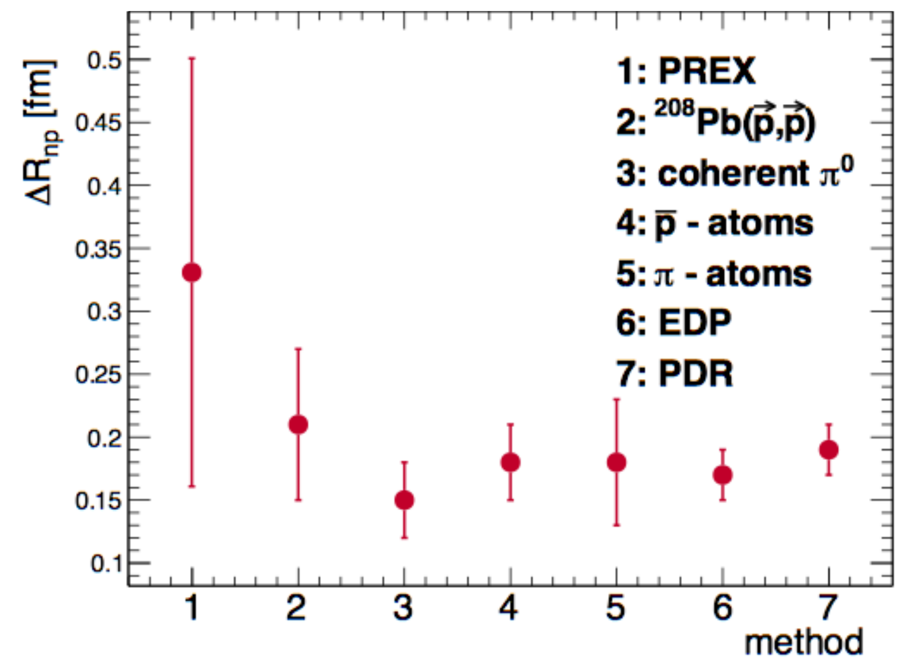

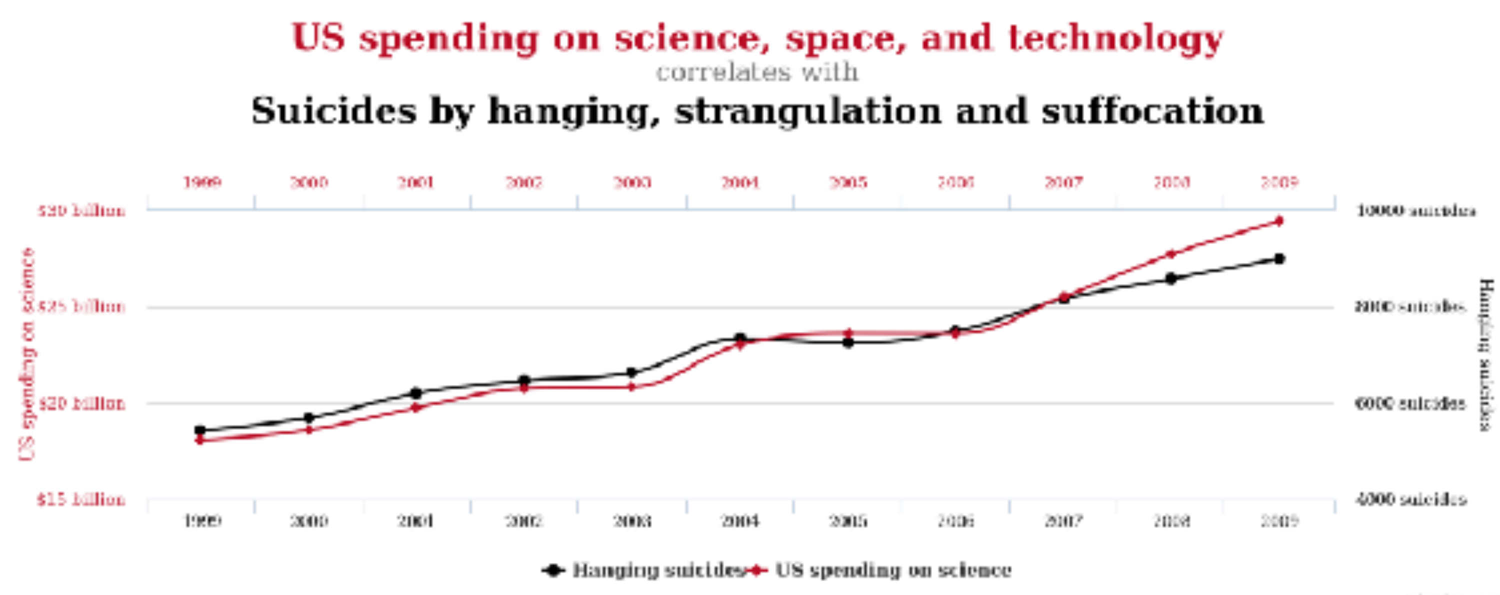

…. could not lead to Rome…

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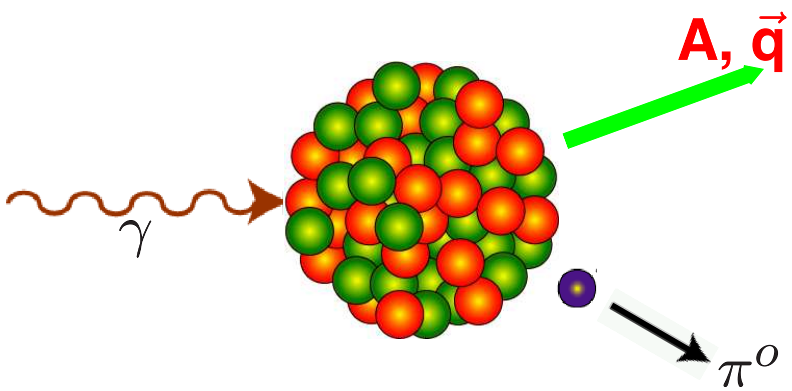
#MakeHumansSmartAgain

One MZ-Example

Coherent π^0 photoproduction: easy and quick *(A2 Coll. Phys. Rev. Lett. 112, 242502)*



… *shine light* on the nucleus!

$$\gamma + A_{(g.s.)} \rightarrow \pi^0 + A_{(g.s.)}$$
$$\hookrightarrow \gamma\gamma$$

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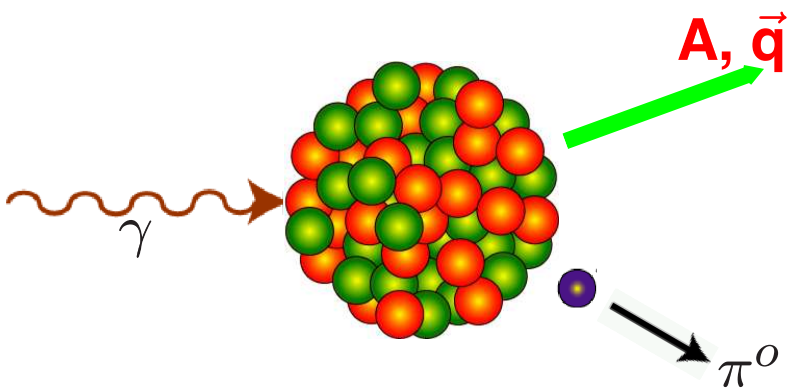

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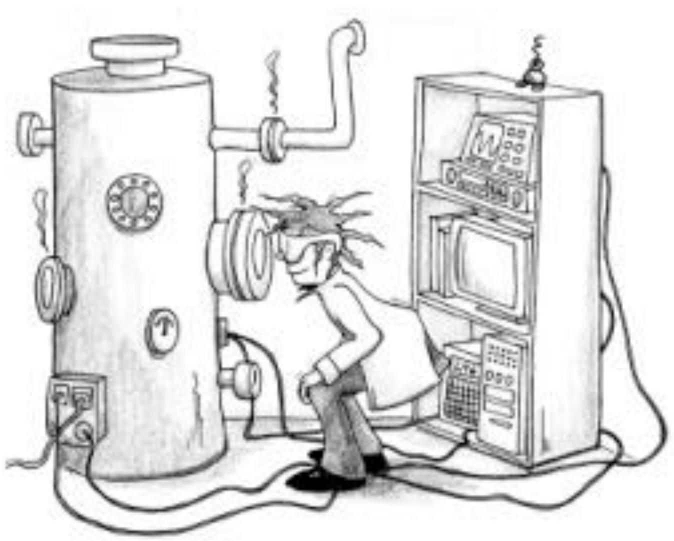


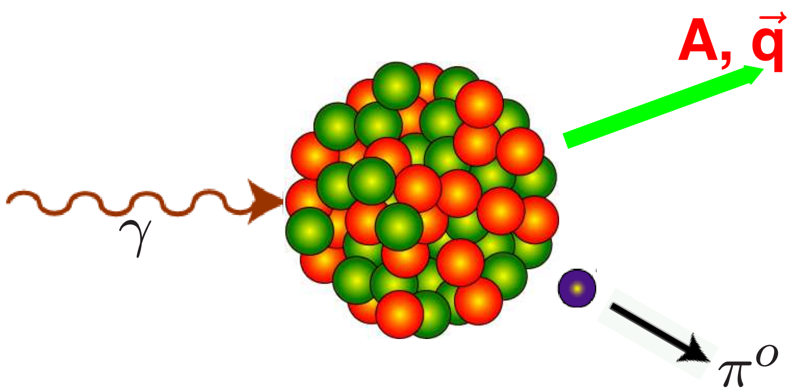
Photon probe interaction well understood: No ISI

π^0 meson produced with ≈ probability on **p AND n**

TO DO: Reconstruct π^0 from $\pi^0 \rightarrow 2\gamma$ decay

One MZ-Example

Coherent π^0 photoproduction: easy and quick *(A2 Coll. Phys. Rev. Lett. 112, 242502)*



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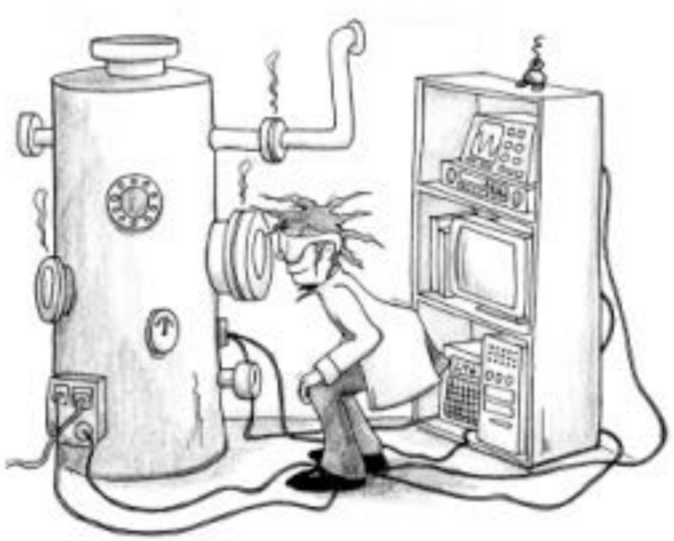
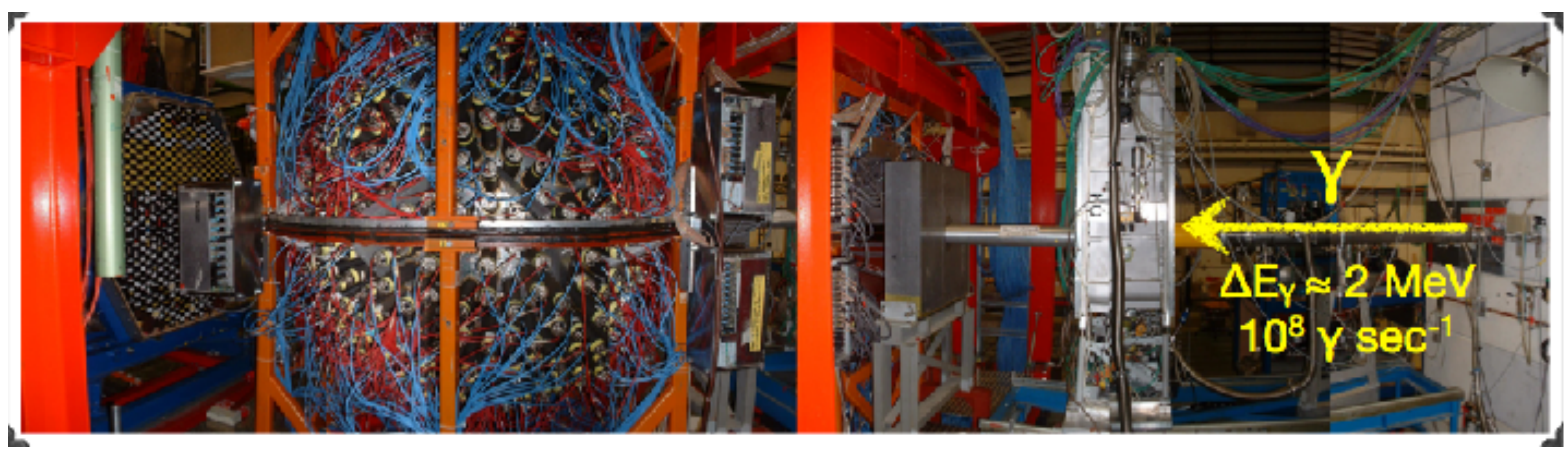
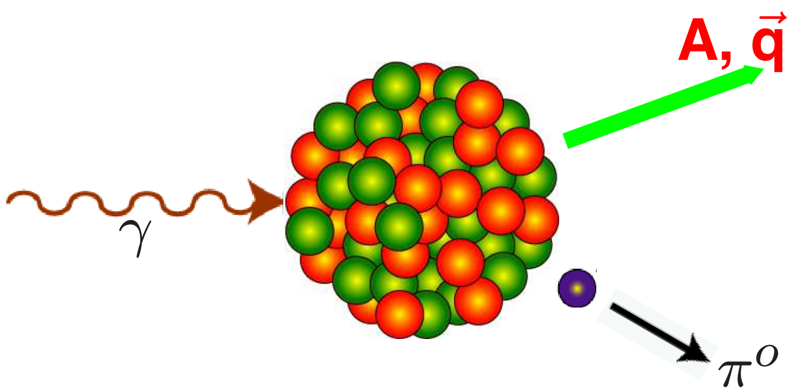




One MZ-Example

Coherent π⁰ photoproduction: easy and quick *(A2 Coll. Phys. Rev. Lett. 112, 242502)*



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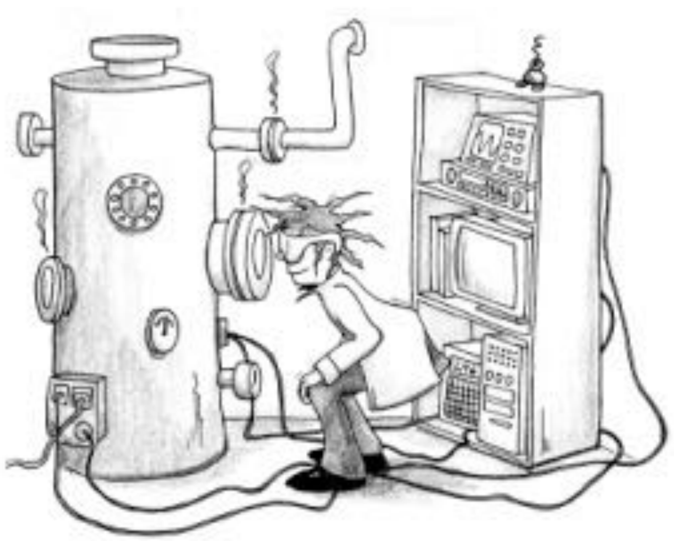
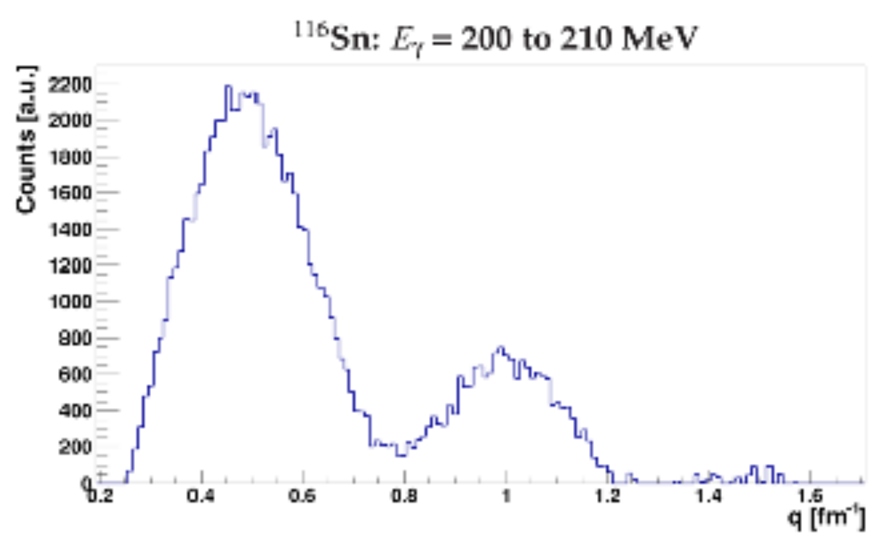
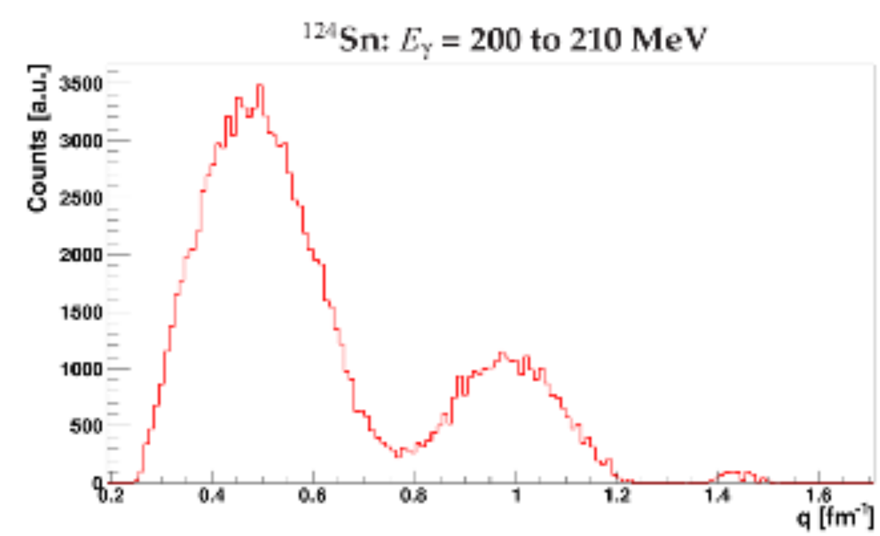
$$\hookrightarrow \gamma\gamma$$







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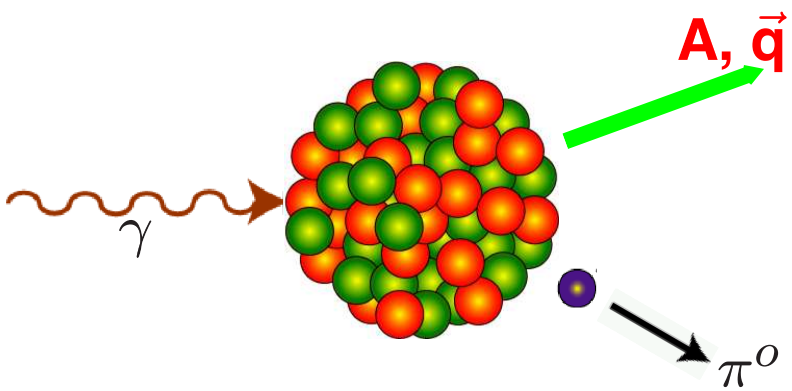


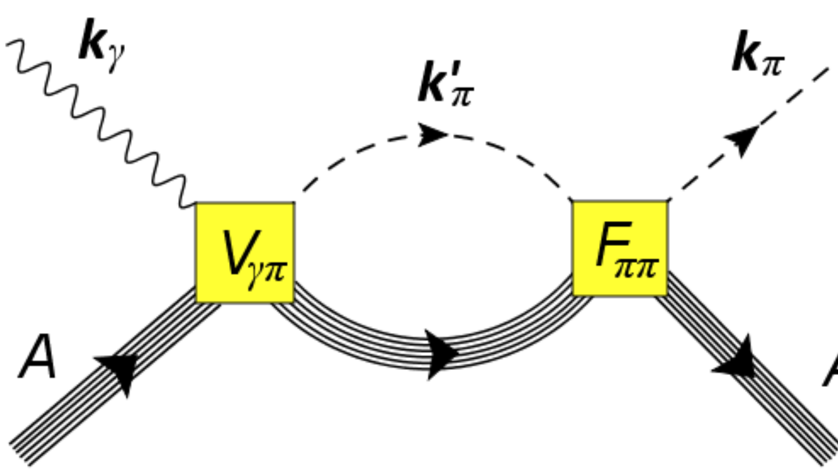
… *shine light* on the nucleus!

$$\gamma + A_{(g.s.)} \rightarrow \pi^0 + A_{(g.s.)}$$
$$\hookrightarrow \gamma\gamma$$

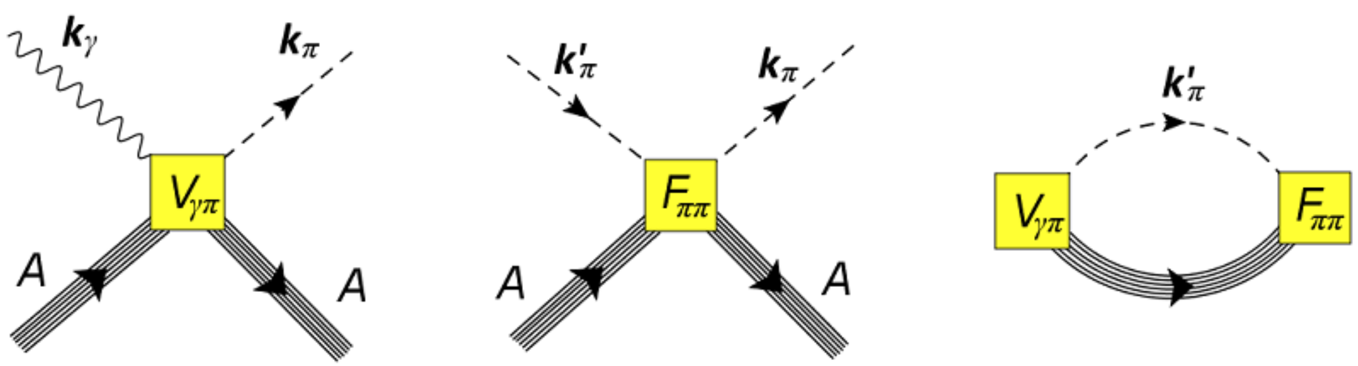
$$\frac{d\sigma}{d\Omega}(\mathrm{PWIA}) \propto sin^2\left(\theta_\pi^*\right) A^2 F^2(q)$$

One MZ-Example

P. Capel, F. Colomer, S. Tsaran, M. Vanderhagen



- ■ Working code for PWIA amplitudes for photoproduction $V^{(\lambda)}_{\pi\gamma}(\mathbf{k}_\pi, \mathbf{k}_\gamma)$
- ■ Working code for scattering matrix $F_{\pi A}$ of π^0
  - Resolution of the Lippmann-Schwinger equation
  - Singularity of Coulomb solved : better constrains on $U^{\mathrm{Nucl}}(k', k)$
- □ DWIA amplitudes calculation
  - Off-shell photoproduction amplitudes $V^{(\lambda)}_{\pi\gamma}(\mathbf{k}'_\pi, \mathbf{k}_\gamma)$
- □ Devise a better form for $U^{\mathrm{Nucl}}(k', k)$



+ Treatment of Resonances,

+ Use Effective Potentials (J. Piekarewicz)

+ Sensitivity of $\sigma_{\mathrm{coherent}}$ to neutron density

+ Benchmark theory with A/Z and Z variation

...it is a long way till Rome ...

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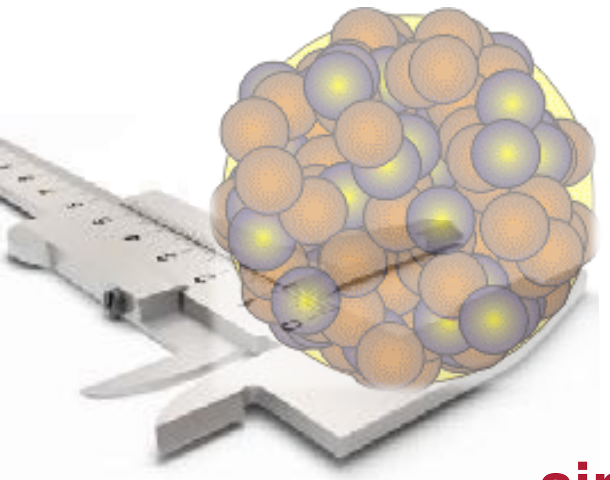
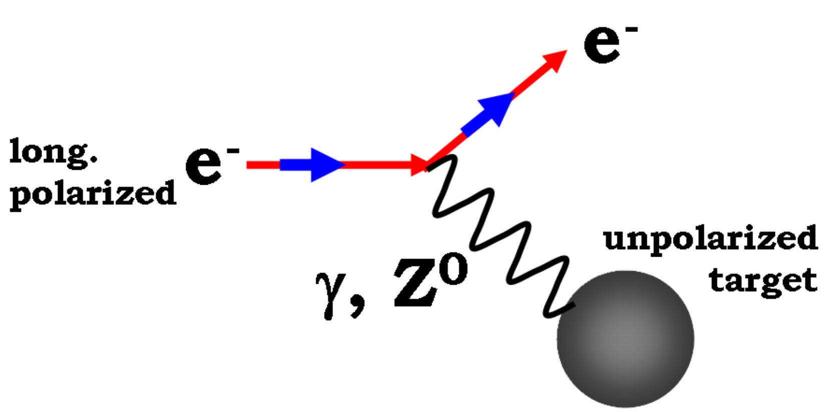
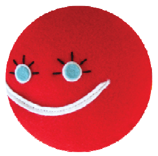
#MakeHumansSmartAgain

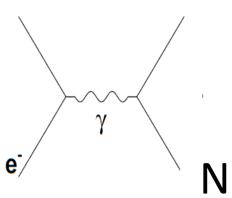
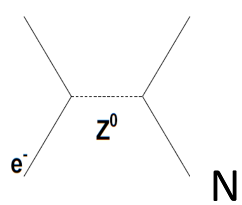
The shortest of the roads ...



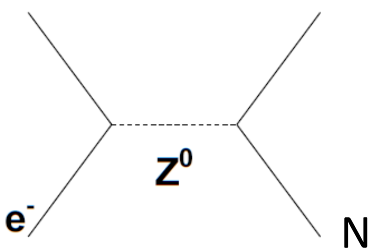


		
electric charge	**1**	**0**
weak charge	**≈0.07**	**1**

...since...

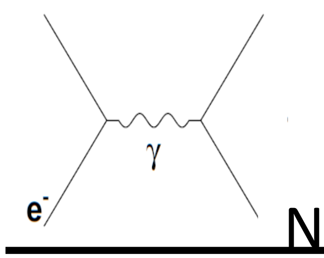
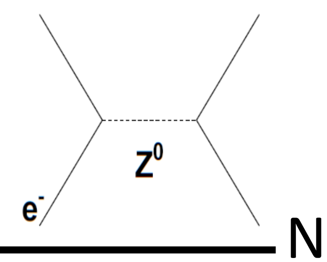
$\sigma \propto \Big|$  $+$  $\Big|^2$

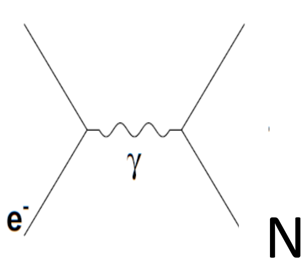
...to measure ...



....construct ....

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

$\Big|$  $\Big|^2$

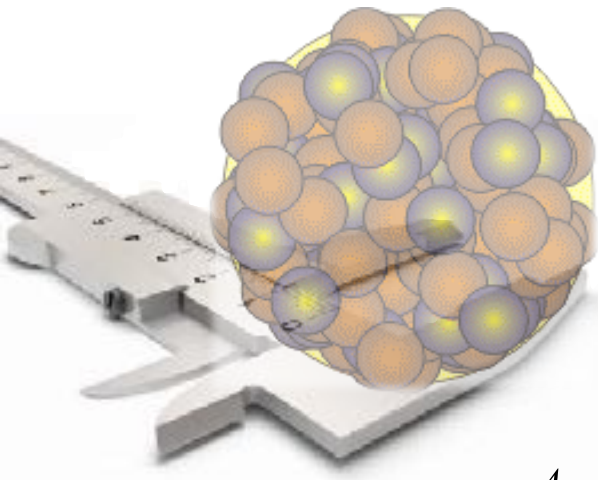
$$= \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

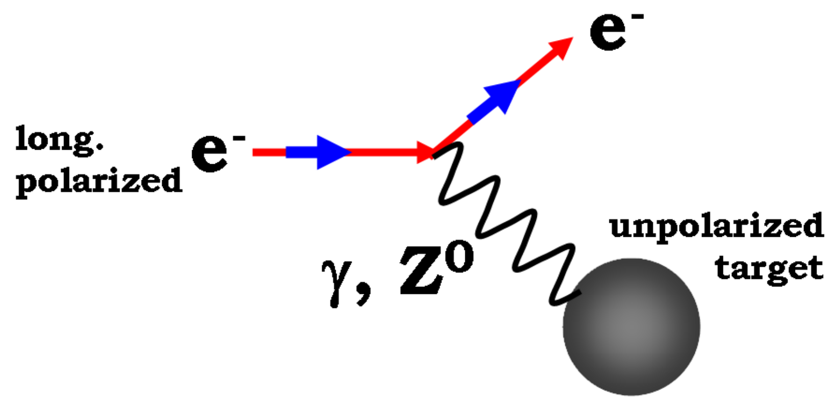
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\; \rho_{n,p}(r)$$

CONCETTINASFIENTI

#MakeHumansSmartAgain

The shortest of the roads …





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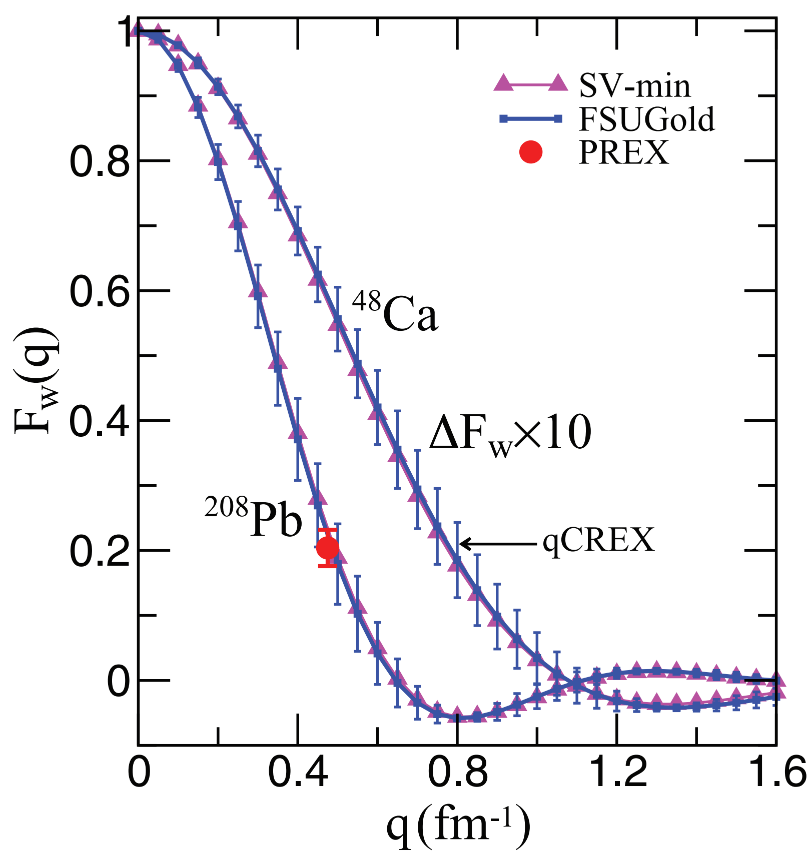
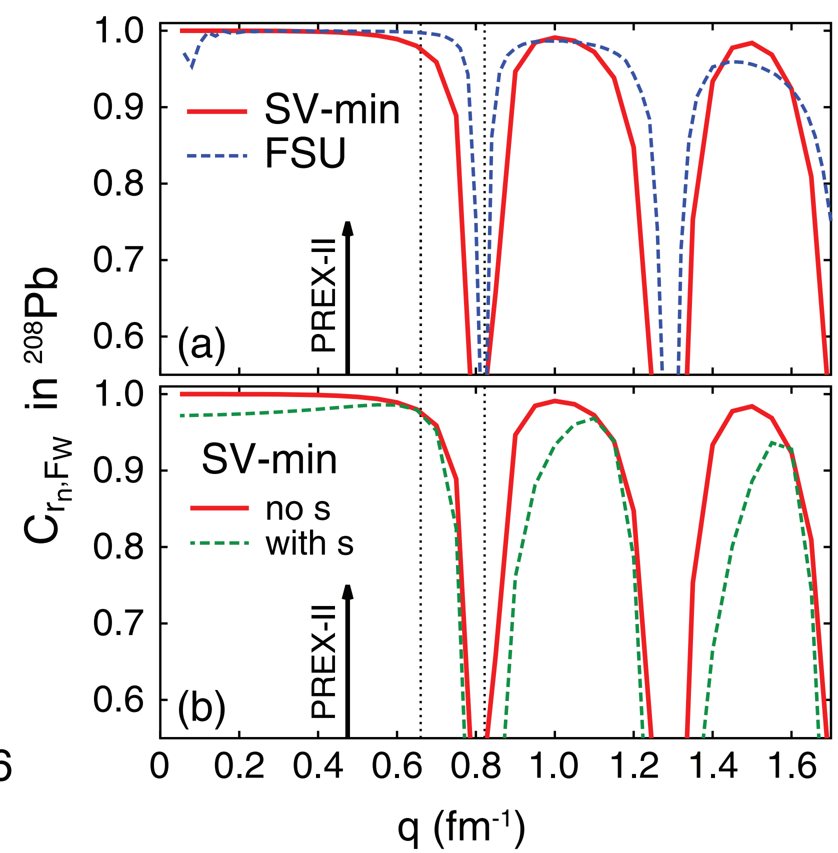




Measured A_{PV}

Correct for Coulomb Distortions

Weak density at one Q^2

Small corrections for G_E^n G_E^s MEC

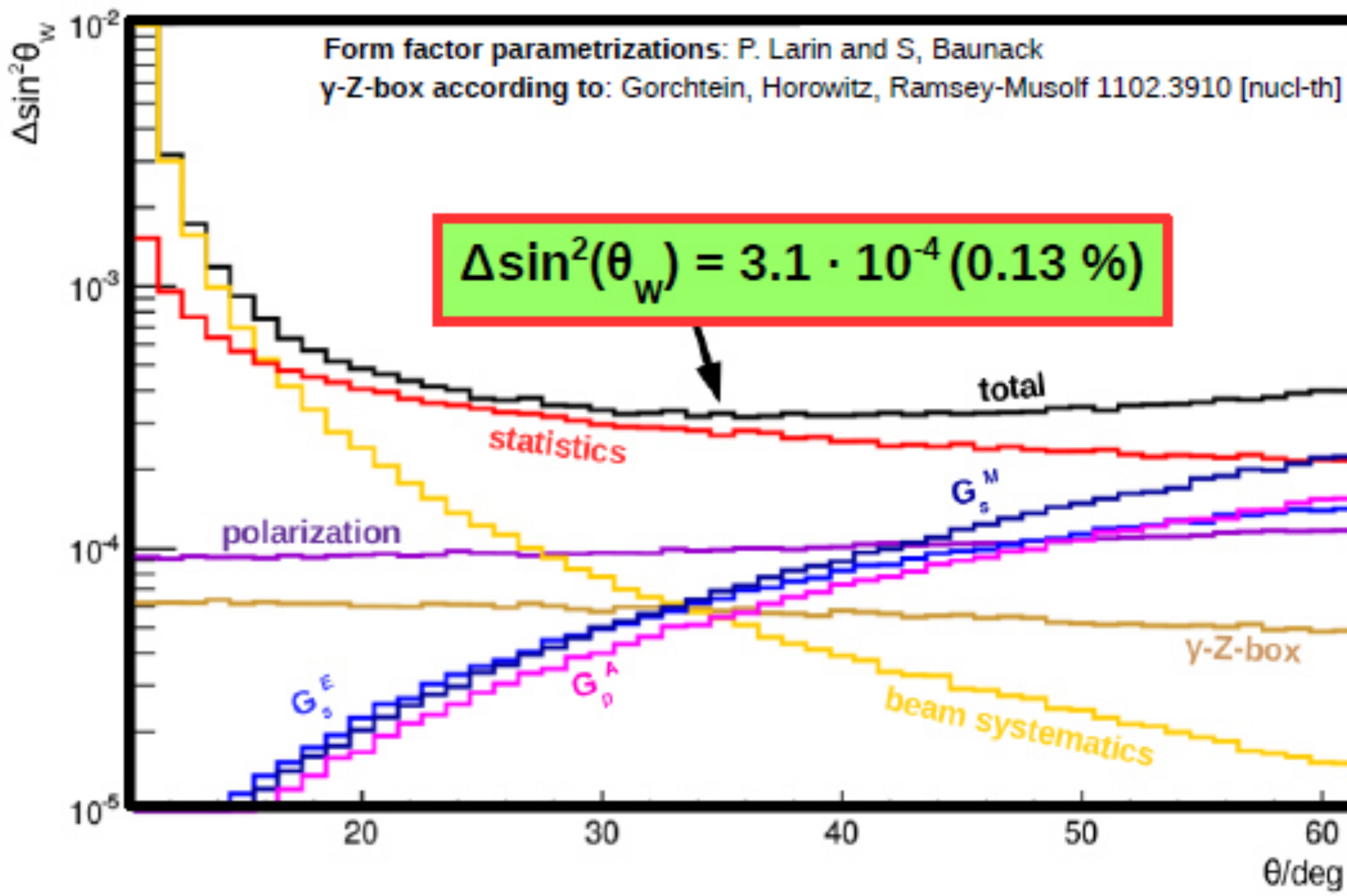
Neutron density at one Q^2

Assume surface thickness good to 25% (MFT)

R_n

PHYSICAL REVIEW C88, 034325 (2013)

#MakeHumansSmartAgain



Beam energy: 155 MeV

Beam current: 150 μA

Polarization: (85±0.5)%

Target: 60 cm lH2

Acceptance: $2\pi\cdot(35°\pm10°)$

Rate: 0.5 THz

Runtime: 10000 h

ΔA^{app}: 0.1 ppb

$\langle A^{exp}\rangle = -28.35$ ppb | $\langle Q^2\rangle = 4.49\text{e-}3\ \mathrm{GeV}^2/c^2$

	Total	Statistics	Polarization	Apparative	FF	Re($\square_{\gamma ZA}$)
$\Delta\sin^2(\theta_W)$	3.1e-4 (0.13 %)	2.6e-4 (0.11 %)	9.7e-5 (0.04 %)	7.0e-5 (0.03 %)	1.4e-4 (0.04 %)	6e-5 (0.03 %)
ΔA^{exp}/ppb	0.44 (1.5 %)	0.38 (1.34 %)	0.14 (0.49 %)	0.10 (0.35 %)	0.11 (0.38 %)	0.09 (0.32 %)

$\Delta A(sys) \approx 0.8\%$

Dominik Becker

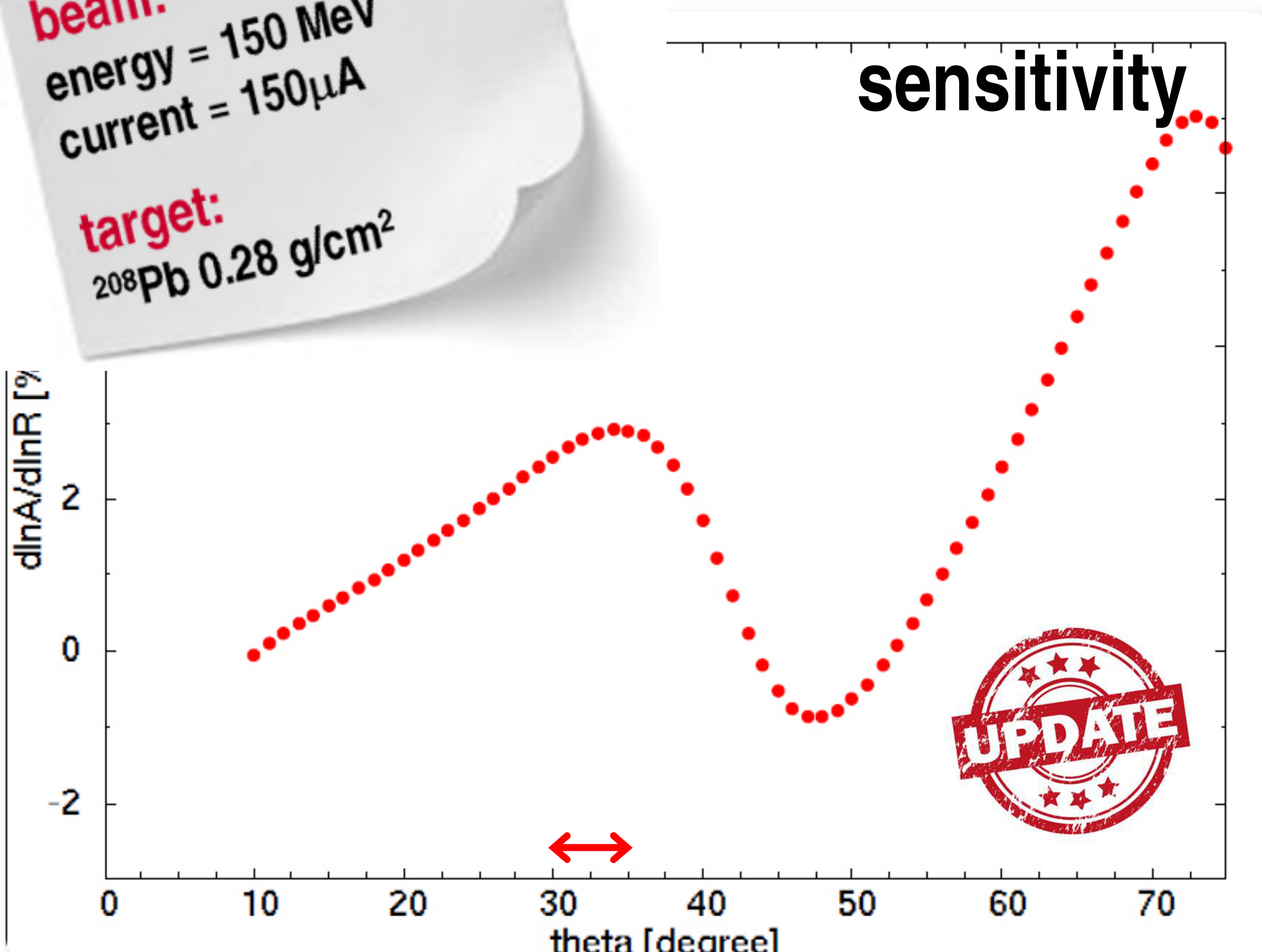
CONCETTINASFIENTI

#MakeHumansSmartAgain

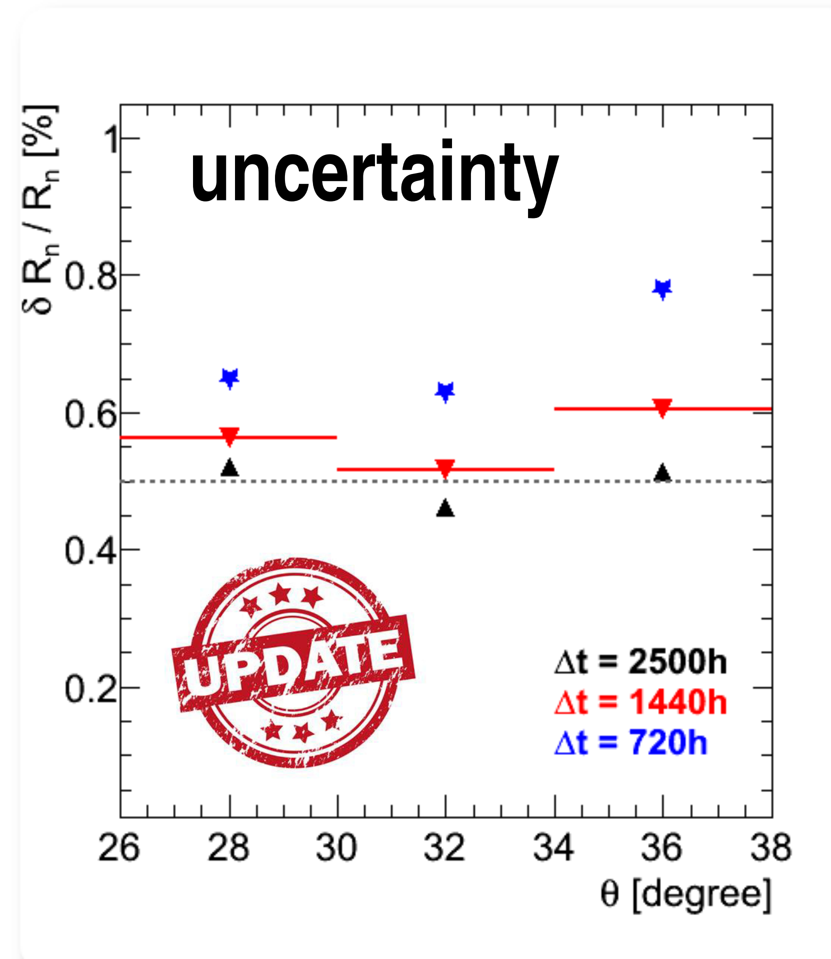
General condition:

beam:
energy = 150 MeV
current = 150μA

target:
^{208}Pb 0.28 g/cm^2



Chuck Horowitz

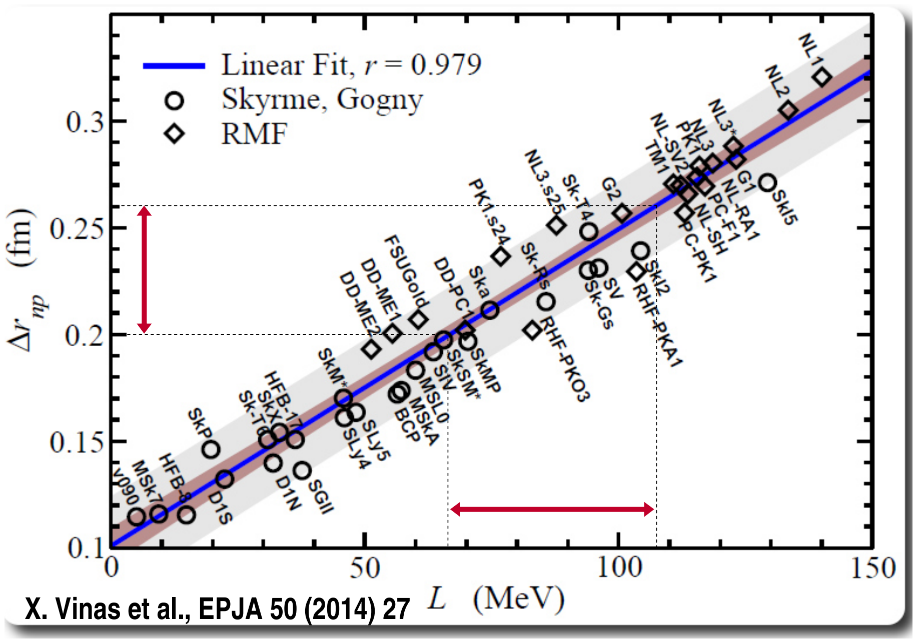


Michaela Thiel

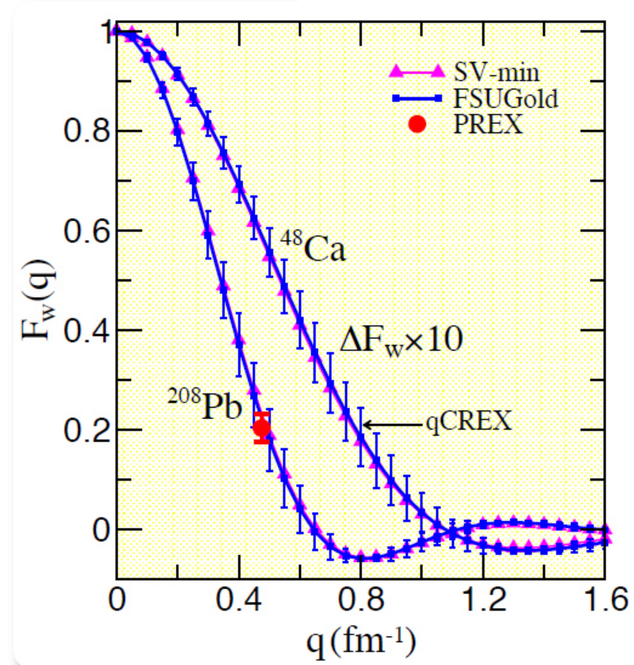
$\Delta\theta = 4°$: expected rate = 8.25 GHz, A_{PV} = 0.66 ppm, P = 85%, Q ≈ 86 MeV

1440h → $\delta R_n/R_n$ = 0.52% (^{208}Pb @ 155 MeV)

MREX



X. Vinas et al., EPJA 50 (2014) 27



P.-G. Reinhard et al.. Phys. Rev. C 88 (2013) 034325

- ➢ **PREX-II & CREX Results needed**
- ➢ **$\delta R_n/R_n$ = 0.5%**
  → L ± 20 MeV

	^{208}Pb @ MREX	^{48}Ca @ MREX	PREX-II	CREX
E_{beam}	155 MeV / 105 MeV	155 MeV / 105 MeV	≈ 1 GeV	2.2 GeV
Q	86 MeV / 58 MeV 0.44 fm^{-1} / 0.29 fm^{-1}	143 MeV / 75 MeV 0.73 fm^{-1} / 0.38 fm^{-1}	86 MeV 0.44 fm^{-1}	154 MeV 0.78 fm^{-1}
$\delta A_{PV}/A_{PV}$	1.3%	1.3%	3.6%	2.4%
$\delta R_n/R_n$	0.52%	0.38%	1.0%	0.5%

“Background” measurements at MAMI

Beam normal (single-spin) asymmetry

- Count rate asymmetry in elastic e-scattering for transverse polarisation (normal to scattering plane)
- No PV effects BUT:

➢ Helicity-correlated background contribution in PV experiments caused by transversal polarisation component

➢ Necessary to measure for all targets used in PV experiment

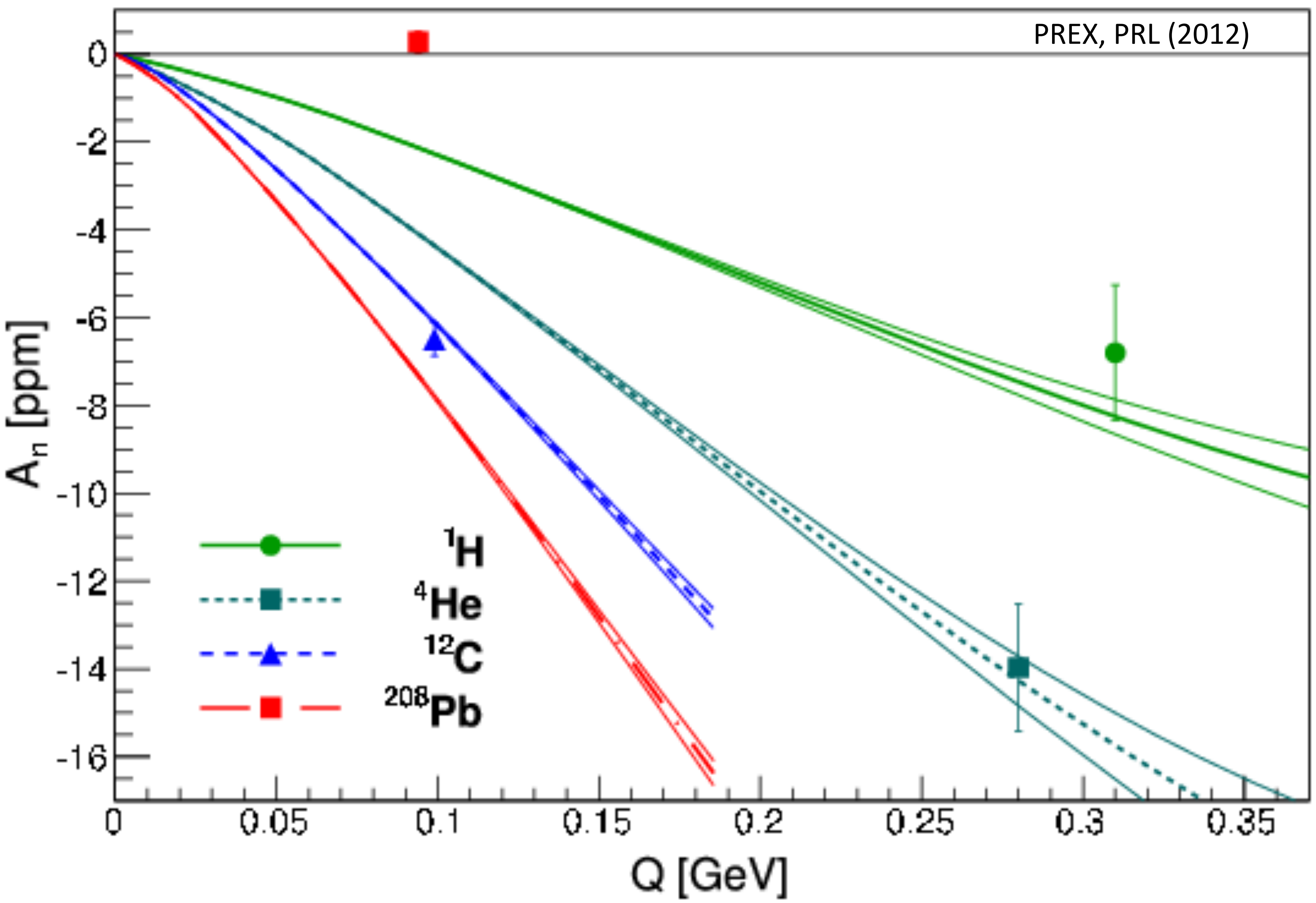
"Background" measurements at MAMI

Beam normal (single-spin) asymmetry

- Count rate asymmetry in elastic e-scattering for transverse polarisation (normal to scattering plane)
- No PV effects BUT:

- Interference term between one- and multi-photon exchange

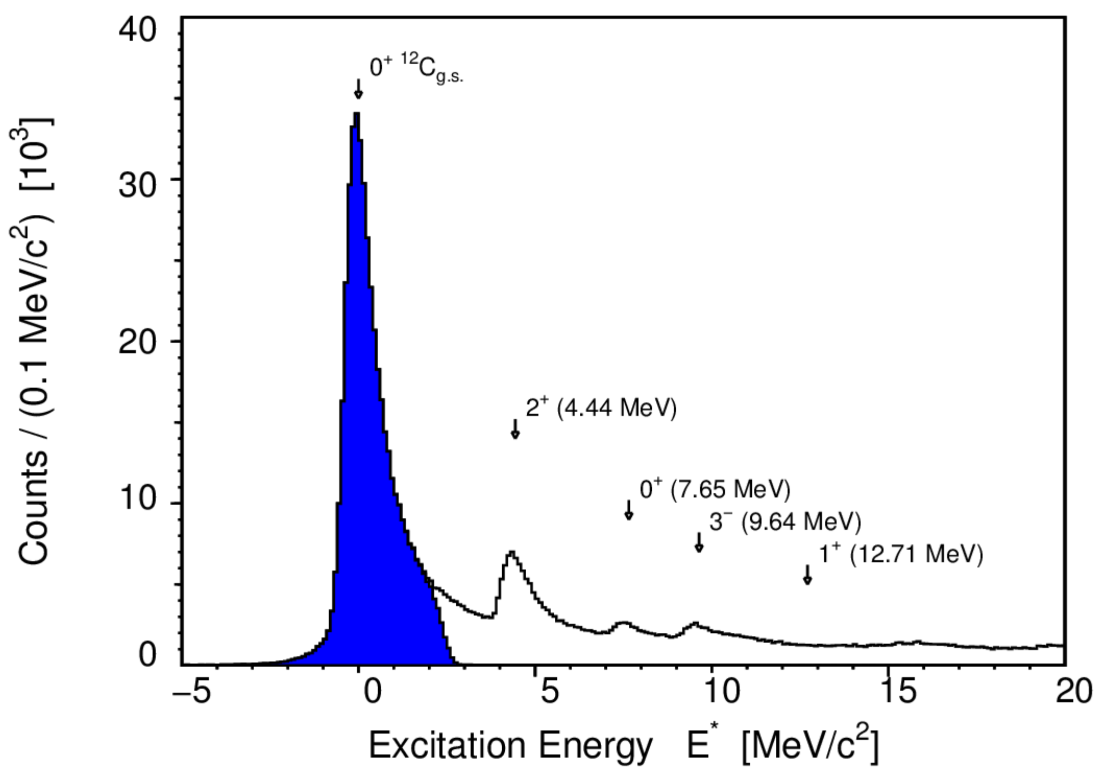
➢ First phase: MAMI



“Background” measurements at MAMI

Beam normal (single-spin) asymmetry

- Elastic peak is well-separated in precision spectrometers



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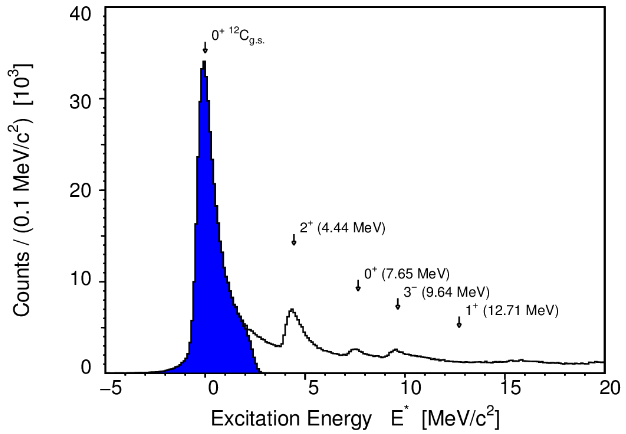
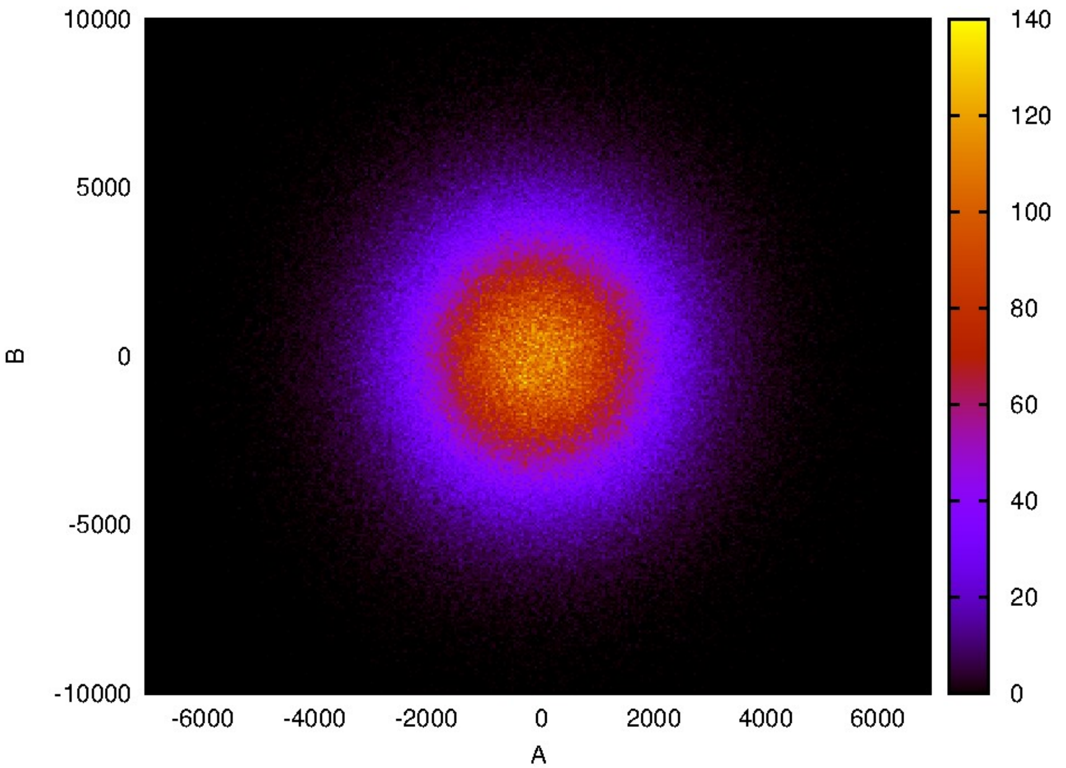


- Raw data is uncorrelated between left/right spectrometers: highly stabilised beam!



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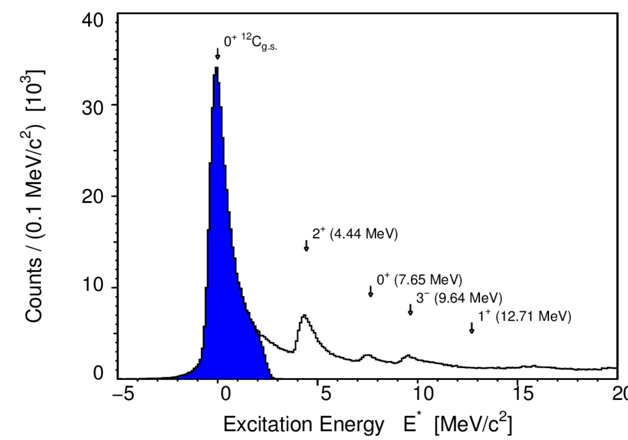

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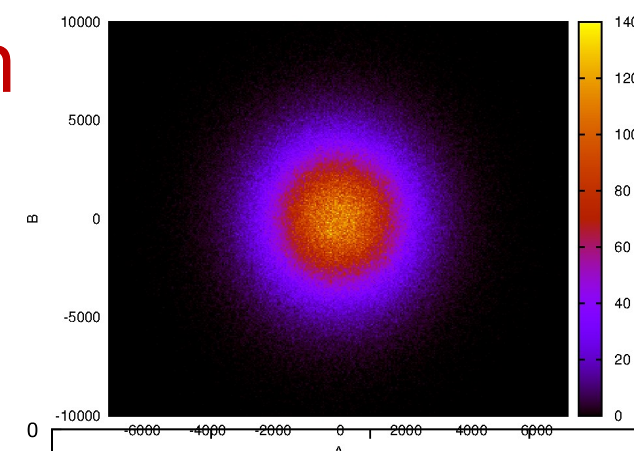
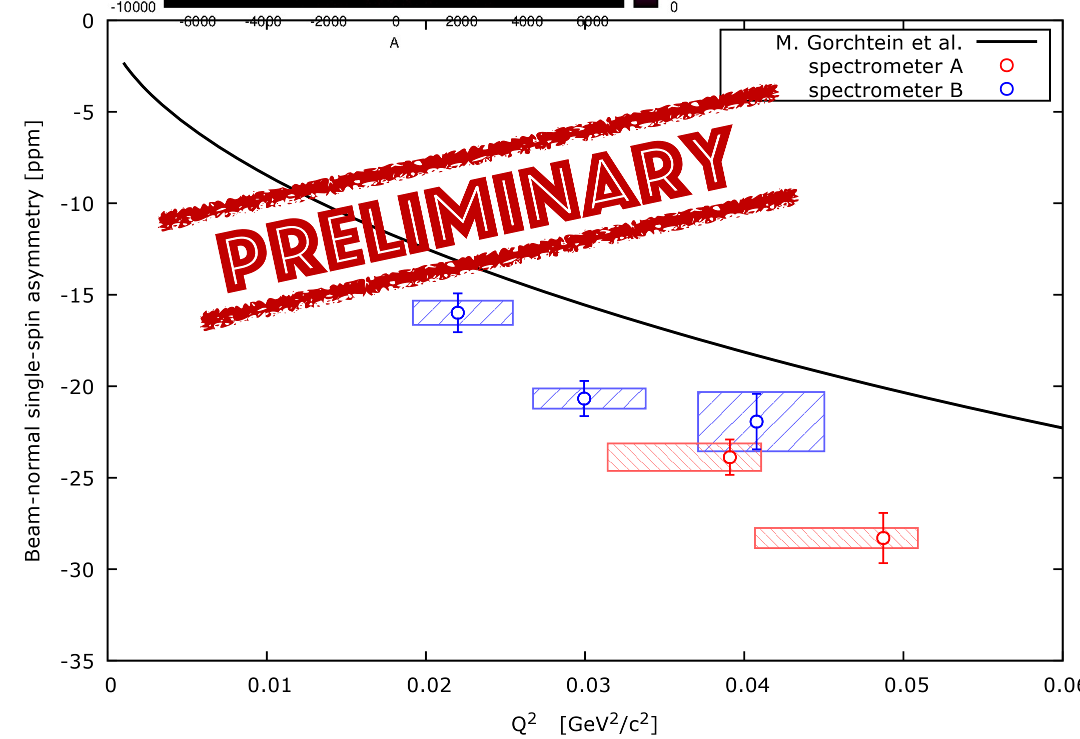


- Systematic study on ^{12}C: future studies on other targets

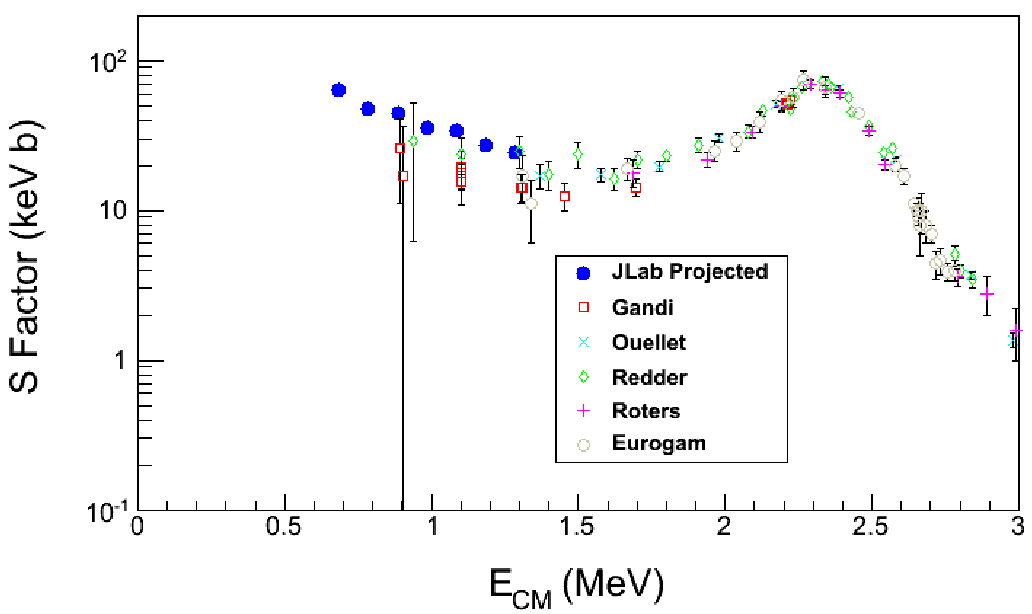
➢ Improving theory
➢ Lowest Q@MAGIX

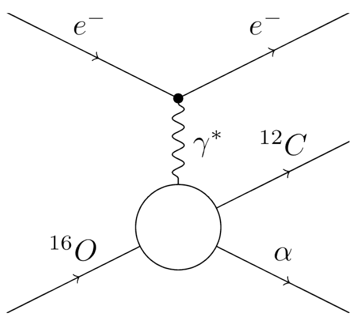


Extension to Nuclear Astrophysics

Jefferson Lab

Astrophysical S-Factor of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$





1. Timereversal $\quad \gamma + {}^{16}O \rightarrow {}^{12}C + \alpha$
2. Covering the Threshold: Electroproduction in limit $Q^2 \rightarrow 0$

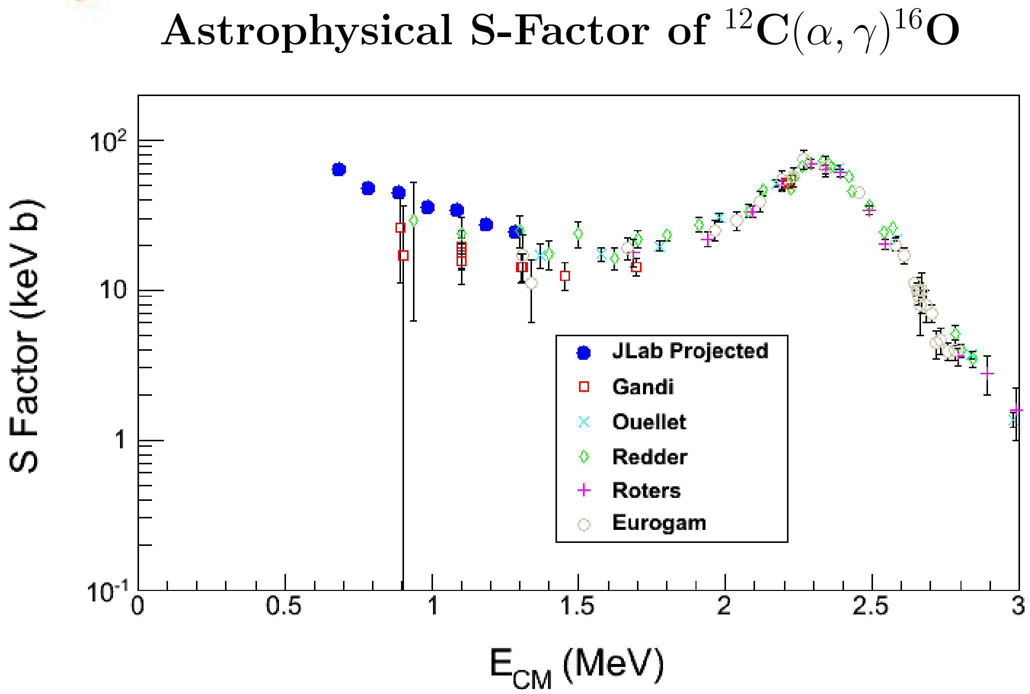
$$e + {}^{16}O \rightarrow e' + {}^{12}C + \alpha \quad \Leftrightarrow \quad \gamma^* + {}^{16}O \rightarrow {}^{12}C + \alpha$$

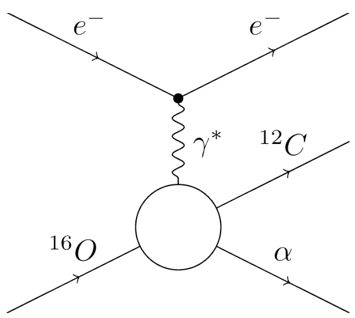
   Electron has large momentum, but virtual photon energy goes to zero!

3. Detection of slow recoil $\alpha \Rightarrow$ gas target, recoil detector

Extension to Nuclear Astrophysics

Jefferson Lab





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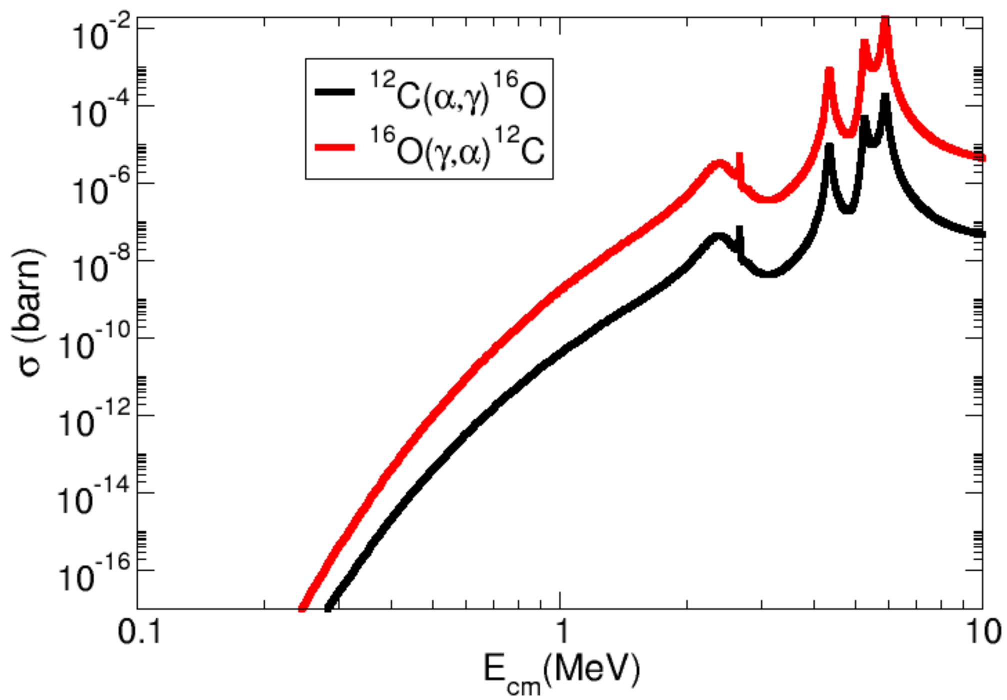


- $\sigma(E_0) \sim 10^{-17}\mathrm{barn}$
- Time reversed reaction:

$$\sigma(E_0) \sim 10^{-15}\mathrm{barn}$$

➢ Simulations ongoing
➢ Commissioning of method for higher E_{cm} @ MAMI

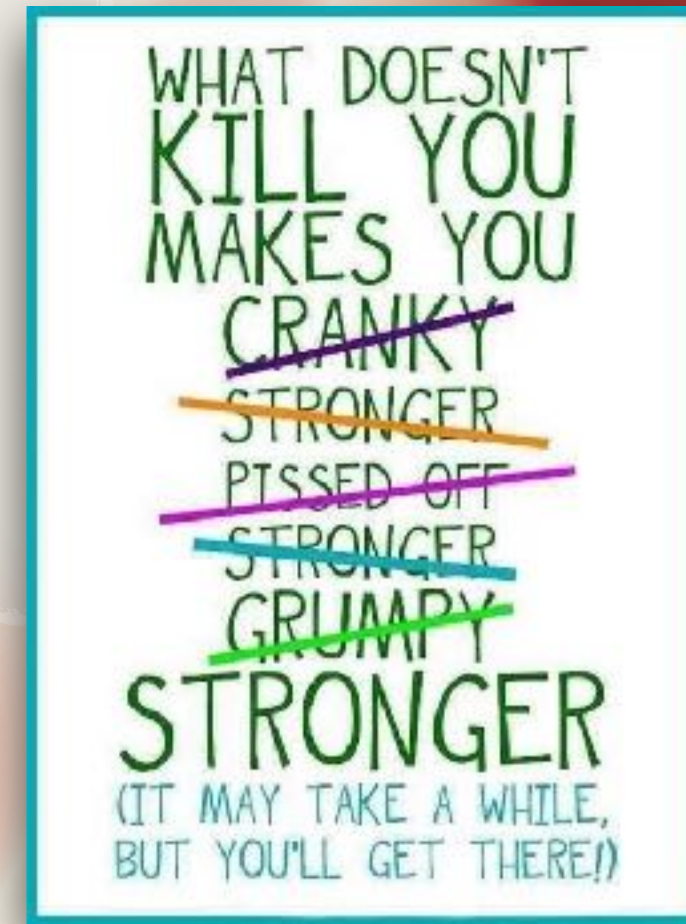
Current and future programs on:

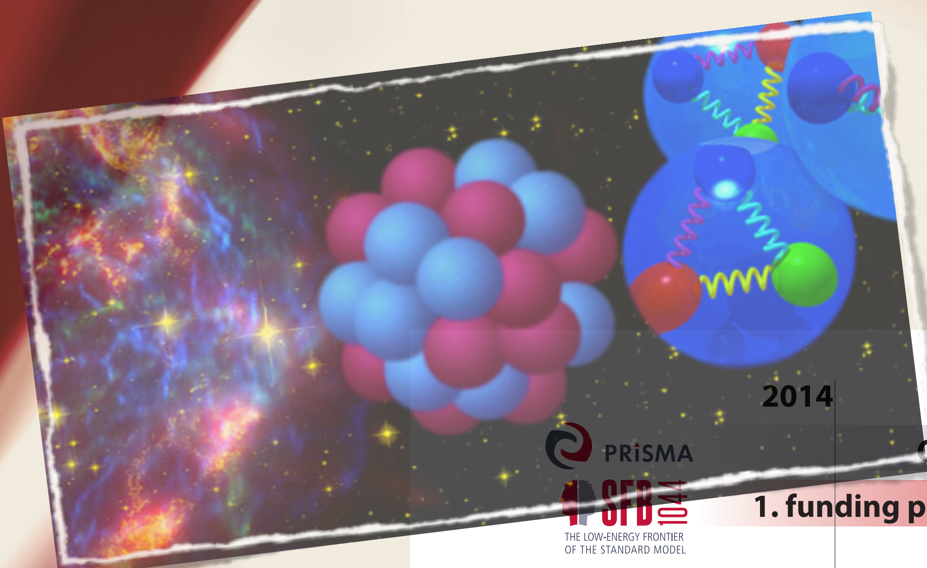
The proton crisis: ISR, d-FF, p-FF at lowest Q

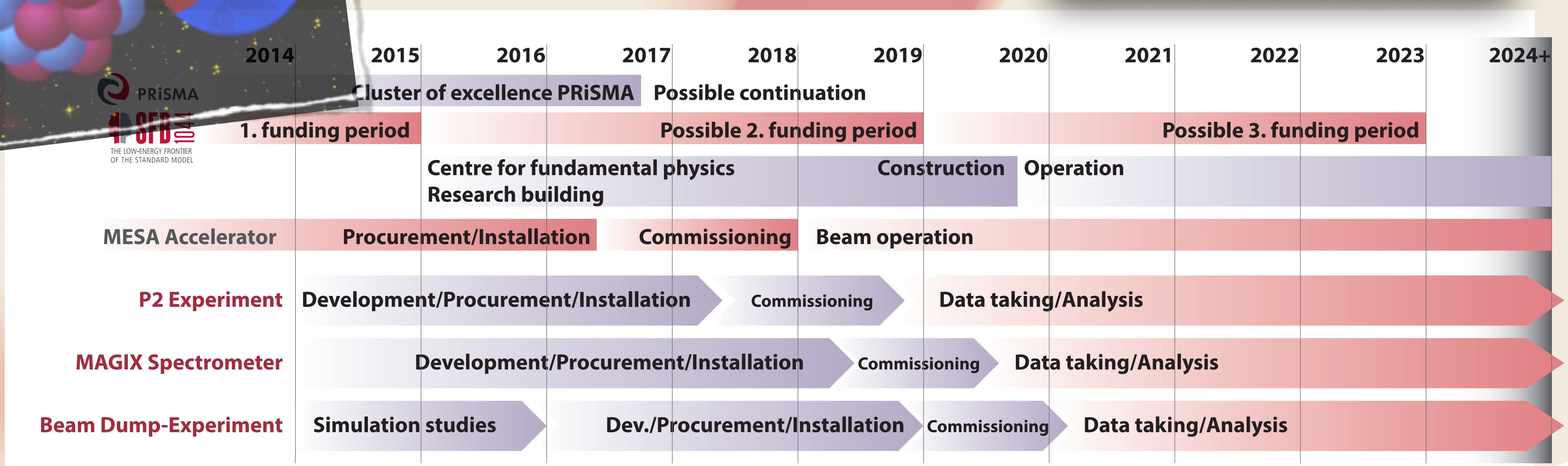
Few-body systems, Search for exotic particles…

and new data on…

n-FF, ^{3,4}He-FF, d-breakup, eLi ….







"Wen Gott strafen will, dem erfüllt er seine Wünsche"

Concettina Sfienti

Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter PRiSMA

SFB 1044

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DEADLINES

October 29: Student's fellowship application

October 29: Registration and abstract submission

December 1 : Notification of abstract acceptance and accommodation

PRISMA

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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