האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Nuclear Structure Studies with Lepton Probes

Guy Ron

INT, June 2018

Caveat/Disclaimer....

- I am not a neutrino scatterer, nor do I do I study PDFs/DIS/parity/etc...
- My talk will be limited to what I do know.
- Because if I talk about everything you'll still be listening to me tonight.
- I **will** talk about:
  - Charged lepton scattering (muons/electrons).
  - Elastic (and Quasi-Elastic?) scattering.
- With that, the issues we face...

My $0.02 on the main problems (that we can study with lepton scattering scattering)

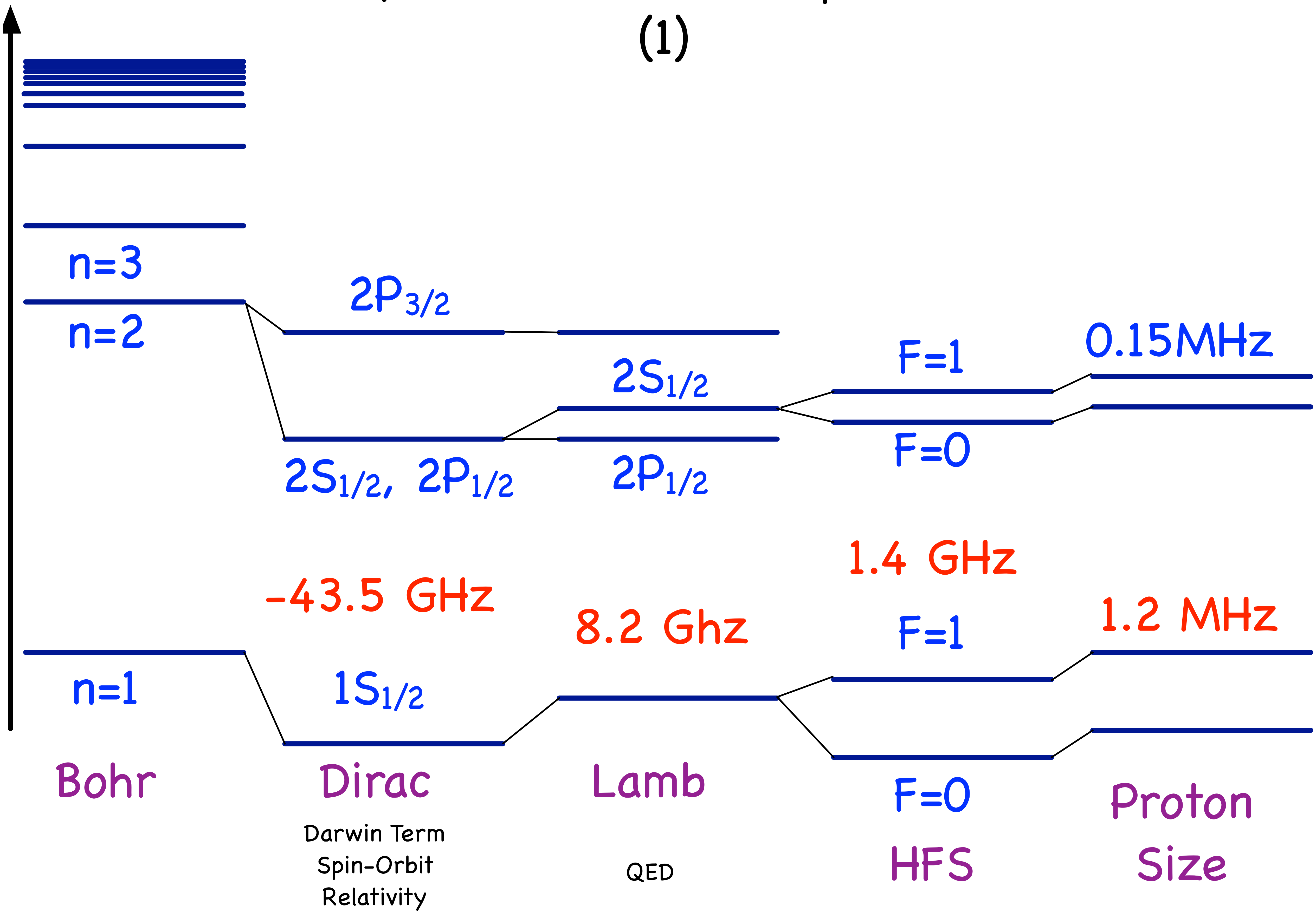
- Proton radius puzzle - and how it relates to experimental analysis, theory, and lepton universality.

- Medium modification of bound nuclei - seen through g_A quenching, EMC effect, CSR, and polarization ratio modifications.

Maybe….
if I have time, and if I feel like an argument

The proton radius puzzle

Two ways to measure the proton radius (1)



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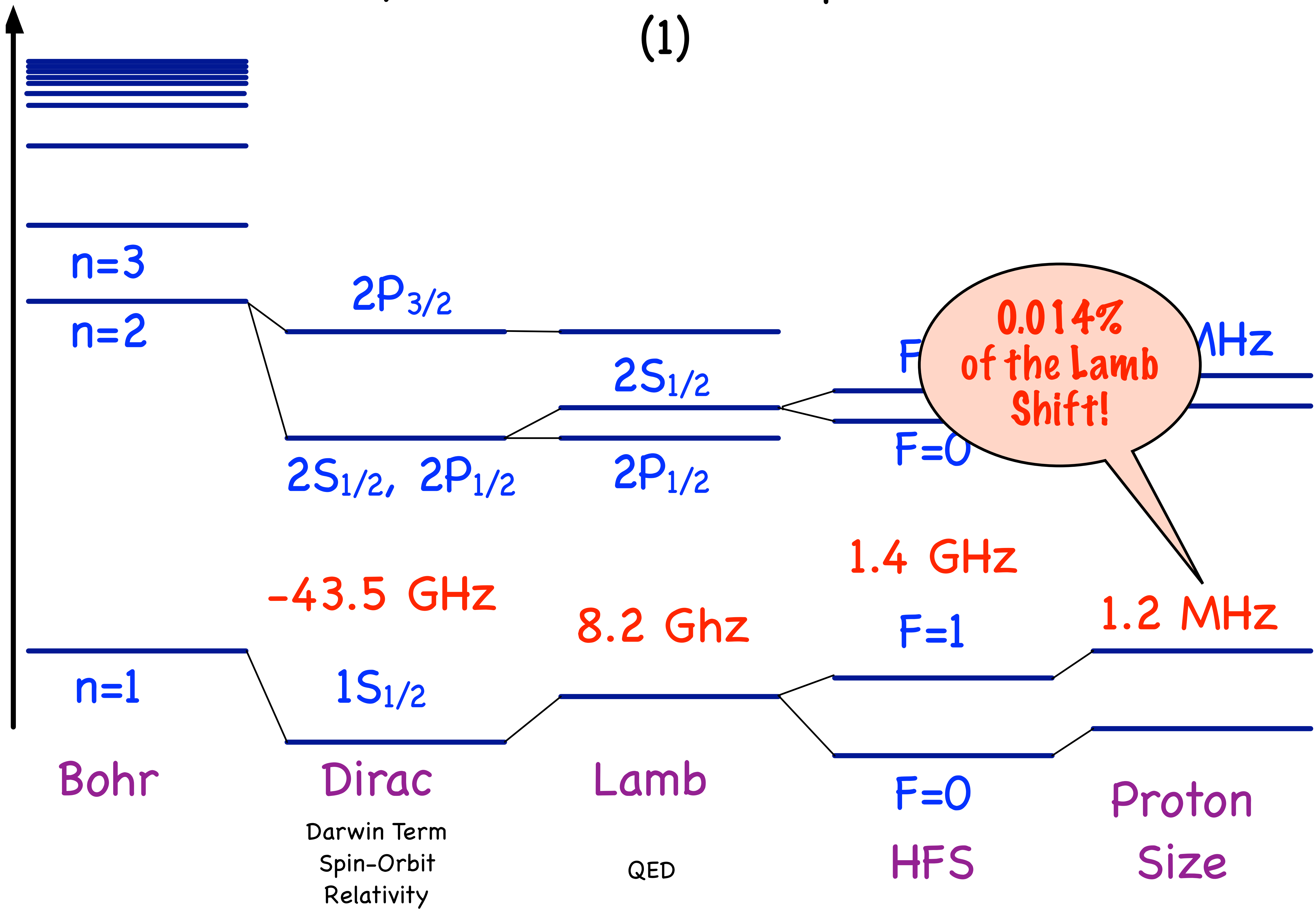

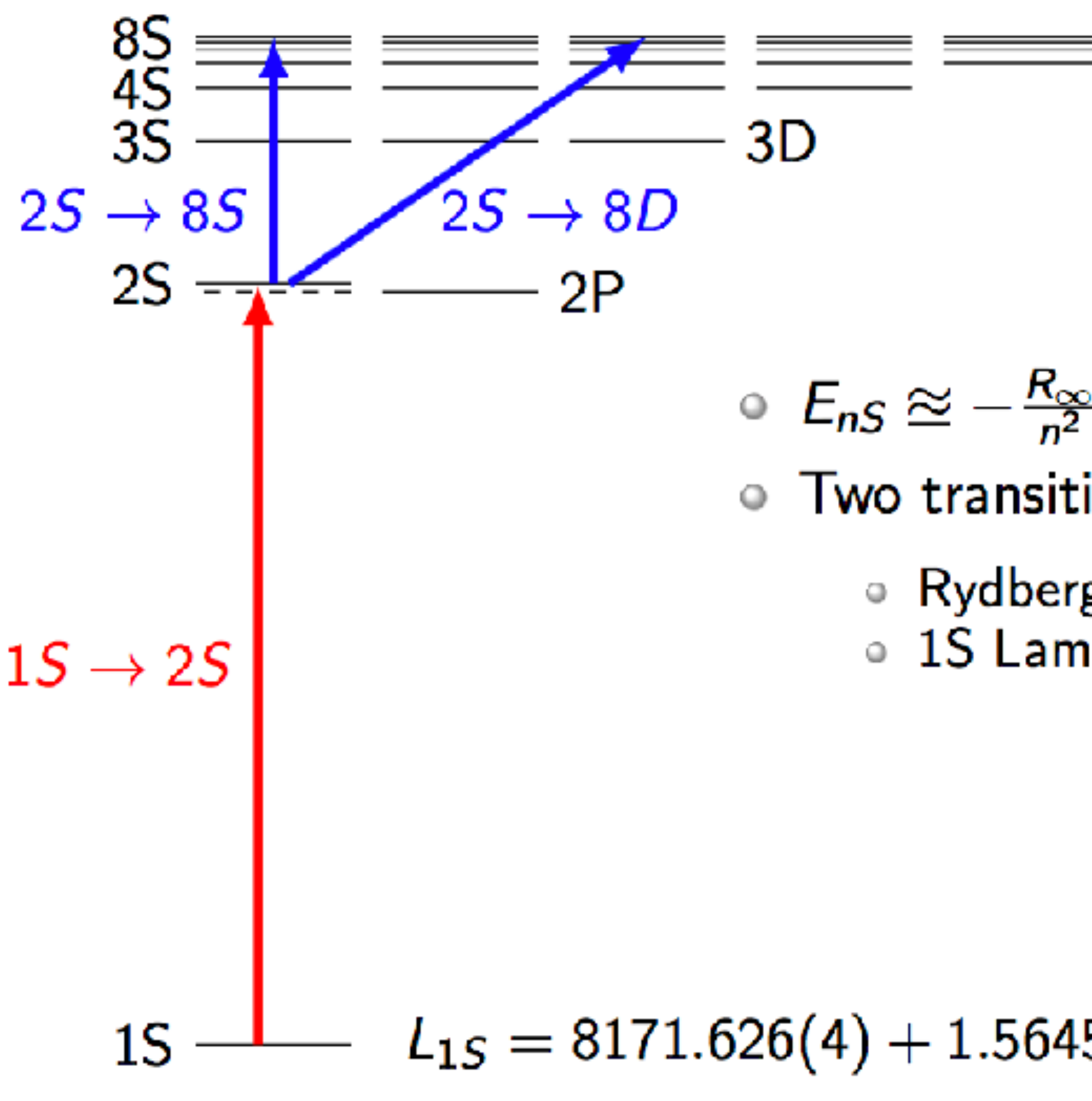

- $E_{nS} \approxeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$
- Two transitions for two unknowns:
  - Rydberg constant R_∞
  - 1S Lamb shift $\Longrightarrow$ radius

$$L_{1S} = 8171.626(4) + 1.5645 \left\langle r_p^2 \right\rangle \text{ MHz}$$

H-Like Lamb Shift Nuclear Dependence

$$\Delta E_{Nucl}(nl) = \frac{2}{3}\frac{(Z\alpha)^4}{n^3}(mR_N)^2\,\delta_{l0}\left(1+(Z\alpha)^2\ln\frac{1}{Z\alpha m R_N}\right)$$

$$\Delta E_{Nucl}(2p_{1/2})\frac{1}{16}(Z\alpha)^6 m\,(mR_N)^2$$

$$\Delta E_{Nucl}(2p_{3/2}) = 0$$

$$L_{1S}^{\mathrm{Hyd}}(r_p) = 8171.636(4) + 1.5645\langle r_p^2\rangle\ \mathrm{MHz}$$

$\Delta E_{Lamb}(1S) = 8172.582(40)$ MHz

$\Delta E_{Nucl}(1S) = 1.269$ MHz for rp = 0.9 fm
$\Delta E_{Nucl}(1S) = 1.003$ MHz for rp = 0.8 fm

$\Delta E_{Lamb}(2S) = 1057.8450(29)$ MHz

$\Delta E_{Nucl}(2S) = 0.1586$ MHz for rp = 0.9 fm
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...ear Dependence

$$\ldots_0 \left(1 + (Z\alpha)^2 \ln \frac{1}{Z\alpha m R_N}\right)$$

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$$L_{1S}(r_p) = \ldots$$

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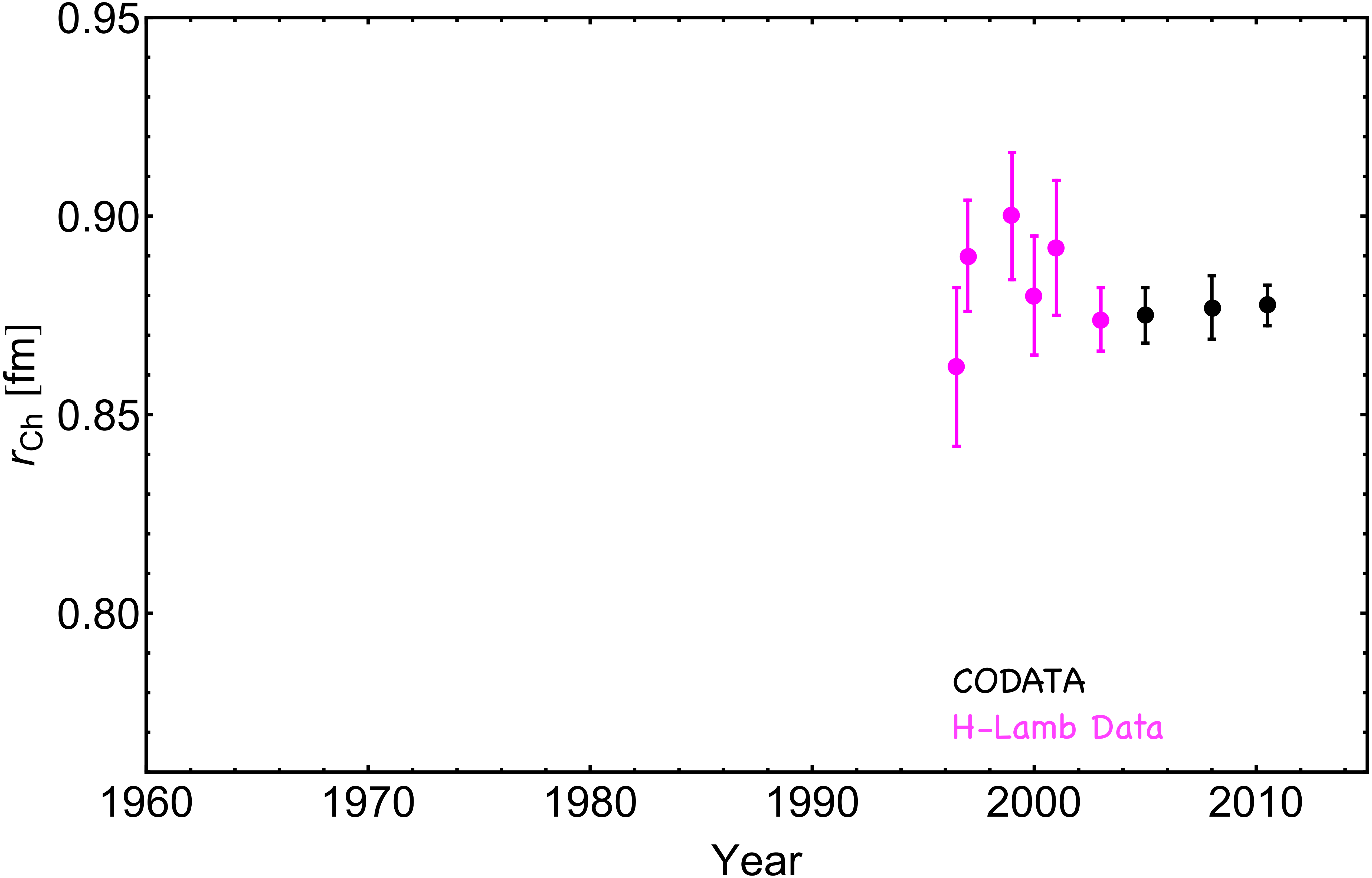
Time evolution of the Radius from H Lamb Shift

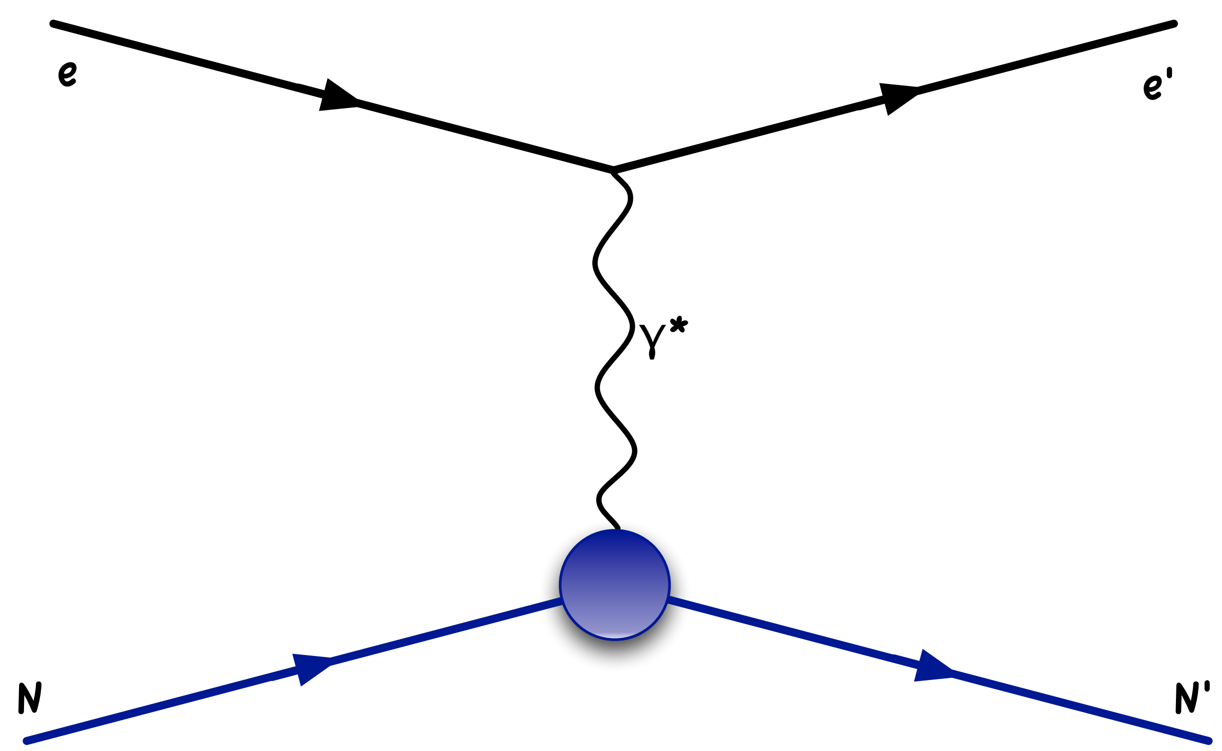


Two ways to measure the proton radius (2)

$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

Rutherford - Point-Like

$$\tau = \frac{Q^2}{4M^2},\ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$



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Mott - Spin-1/2

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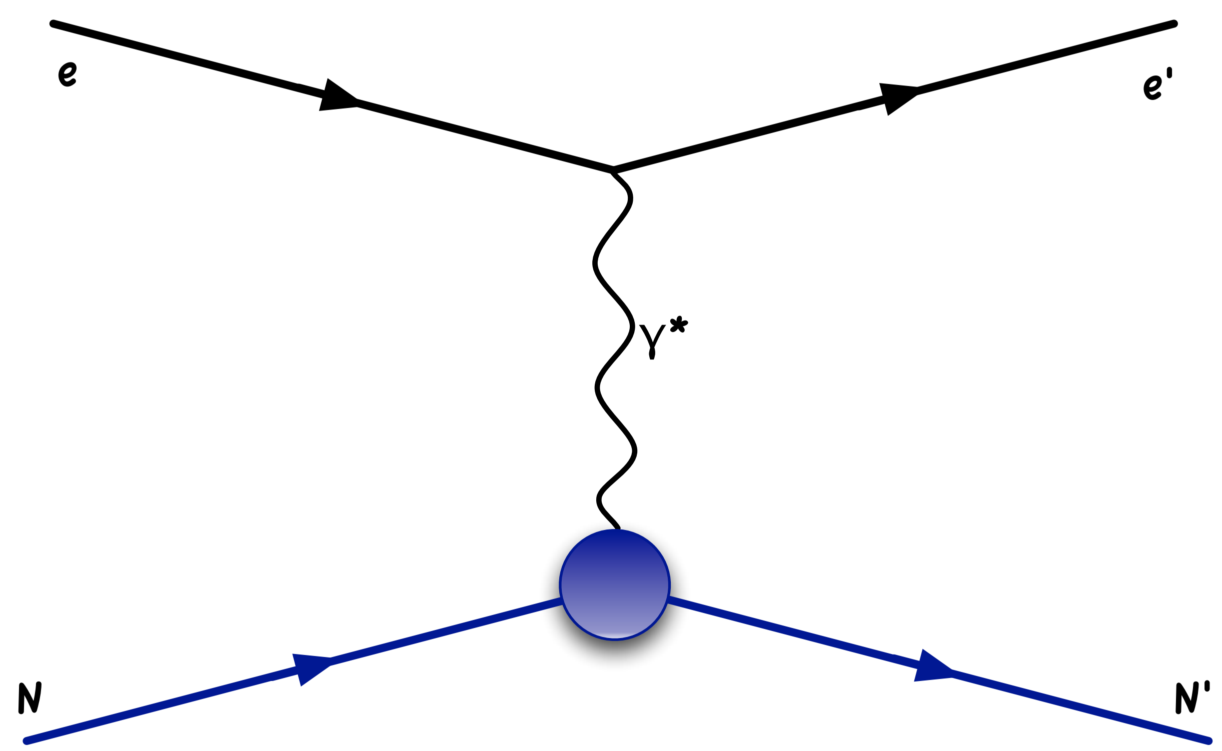

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$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon}G_M^2(Q^2)\right]$$

Rosenbluth - Spin-1/2 with Structure

$$\tau = \frac{Q^2}{4M^2},\ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

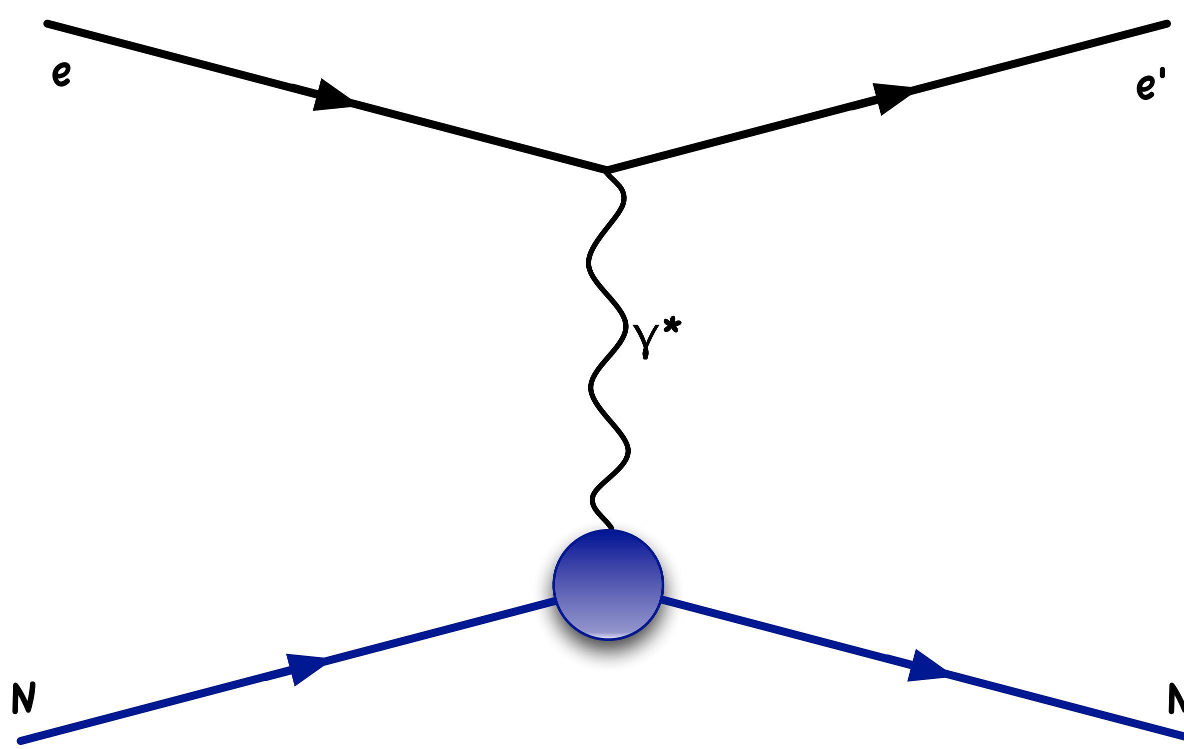
$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

$$G_M^p = 2.793 \quad G_M^n = -1.91$$

Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$



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$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

Everything we don't know goes here!

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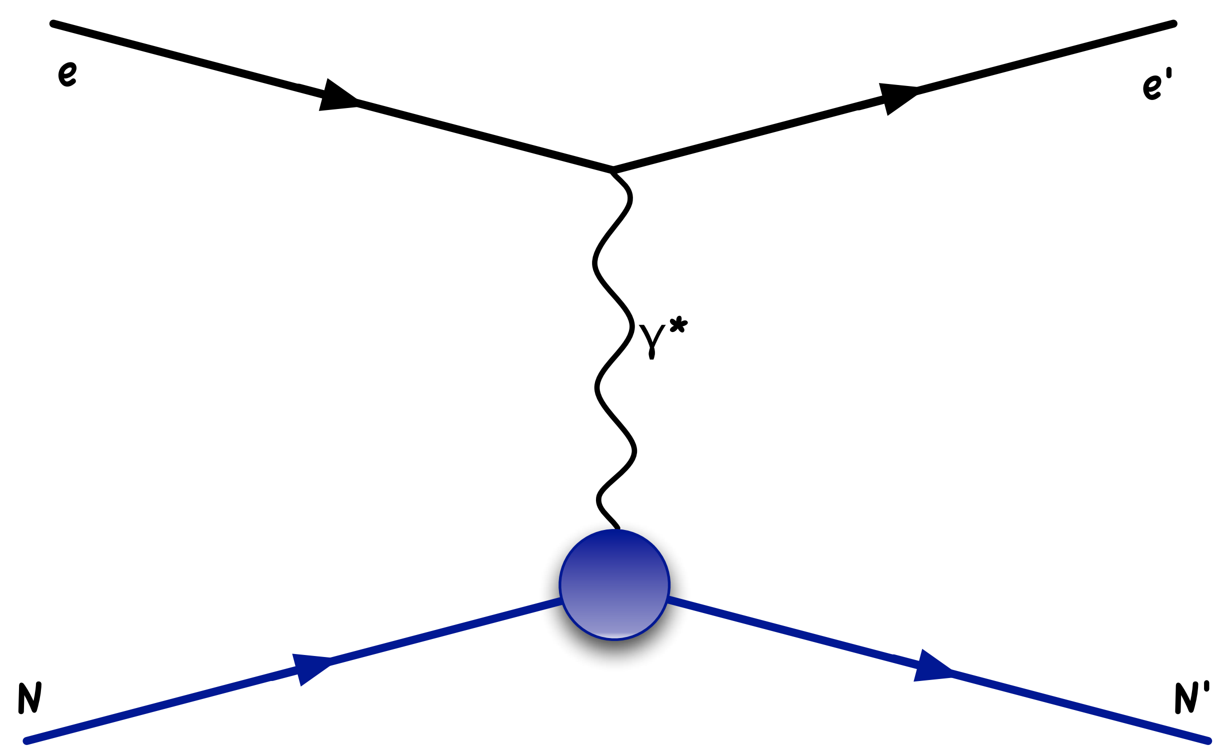

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Form Factor Moments

$$\int e^{-i\vec{k}\cdot\vec{r}}\rho(\vec{r})d^3r \propto \int r^2\rho(r)j_0(kr)dr$$

3d Fourier Transform for isotropic density

$$G_{E,M}(Q^2) = 1 - \frac{1}{6}\left\langle r^2_{E,M}\right\rangle Q^2 + \frac{1}{120}\left\langle r^4_{E,M}\right\rangle Q^4 - \frac{1}{5040}\left\langle r^6_{E,M}\right\rangle Q^6 + \cdots$$

Non-relativistic assumption (only) = k=Q; G is F.T. of density

$$-6\frac{dG_{E,M}}{dQ^2}\bigg|_{Q^2=0} = \left\langle r^2_{E,M}\right\rangle \equiv r^2_{E,M}$$

Slope of $G_{E,M}$ at Q^2=0 defines the radii. This is what FF experiments quote.

Notes

- In NRQM, the FF is the 3d Fourier transform (FT) of the Breit frame spatial distribution, but the Breit frame is not the rest frame, and doing this confuses people who do not know better. The low Q^2 expansion remains.

Boost effects in relativistic theories destroy our ability to determine 3D rest frame spatial distributions. The FF is the 2d FT of the transverse spatial distribution.

The slope of the FF at $Q^2 = 0$ continues to be called the radius for reasons of history / simplicity / NRQM, but it is not the radius.

Nucleon magnetic FFs crudely follow the dipole formula, $G_D = (1+Q^2/0.71\ \text{GeV}^2)^{-2}$, which a) has the expected high Q^2 pQCD behavior, and b) is amusingly the 3d FT of an exponential, but c) has no theoretical significance

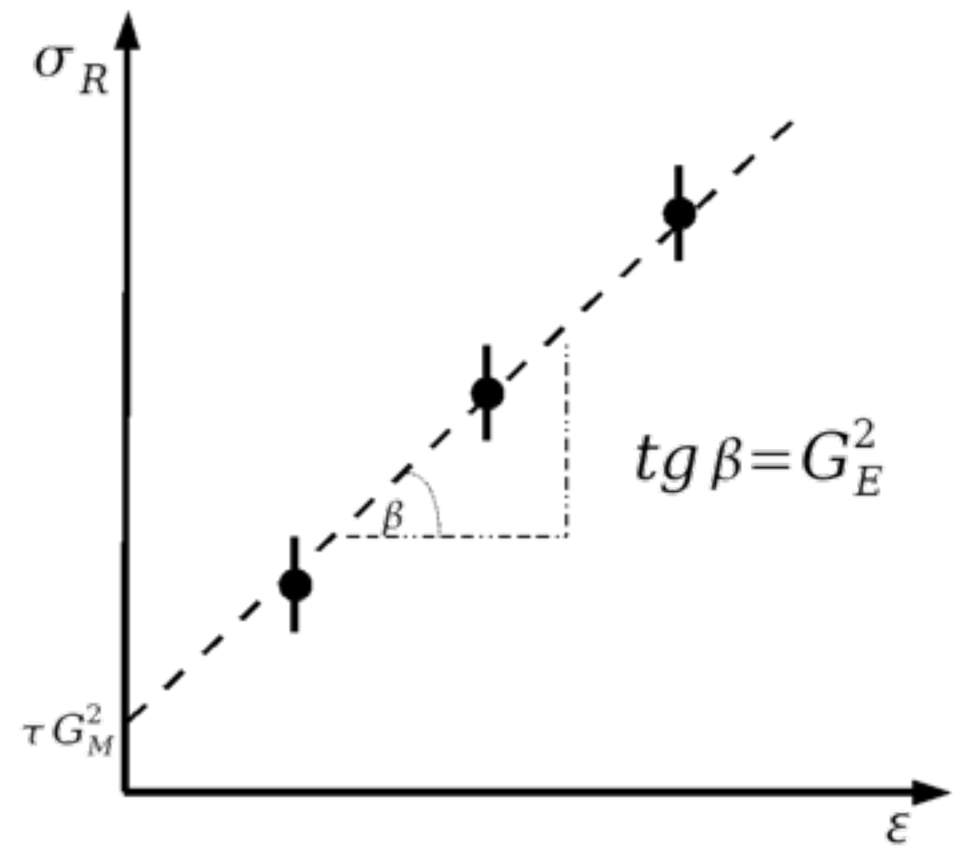
Measurement Techniques

Rosenbluth Separation

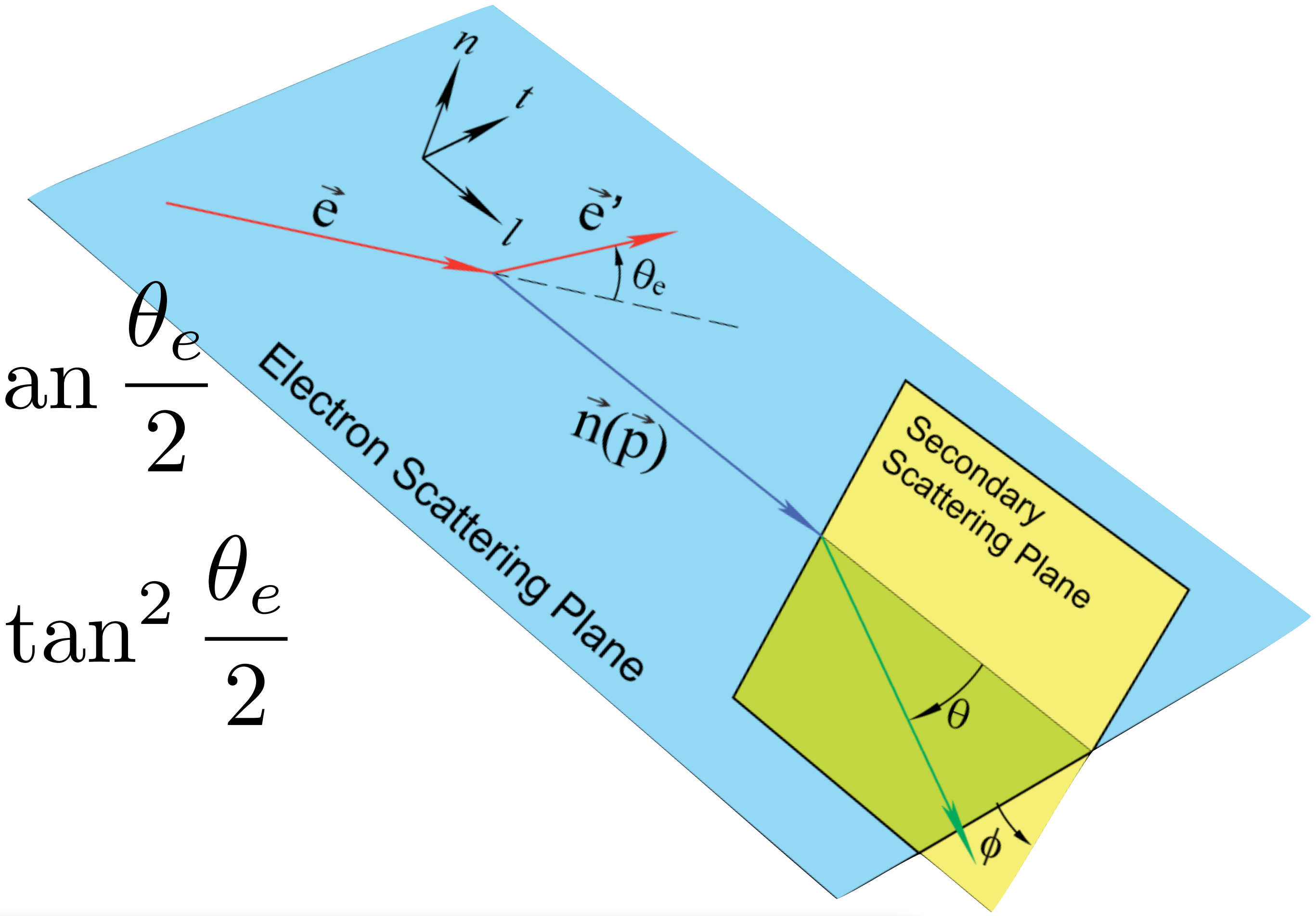
$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right] \;;\; \tau \equiv \frac{Q^2}{4M^2}$$

$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\mathrm{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

- Measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q^2 fixed.
- Linear fit to get intercept and slope.



Measurement Techniques



$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)} G_M^2 \tan^2\frac{\theta_e}{2}$$

$$P_n = 0 \ (1\gamma)$$

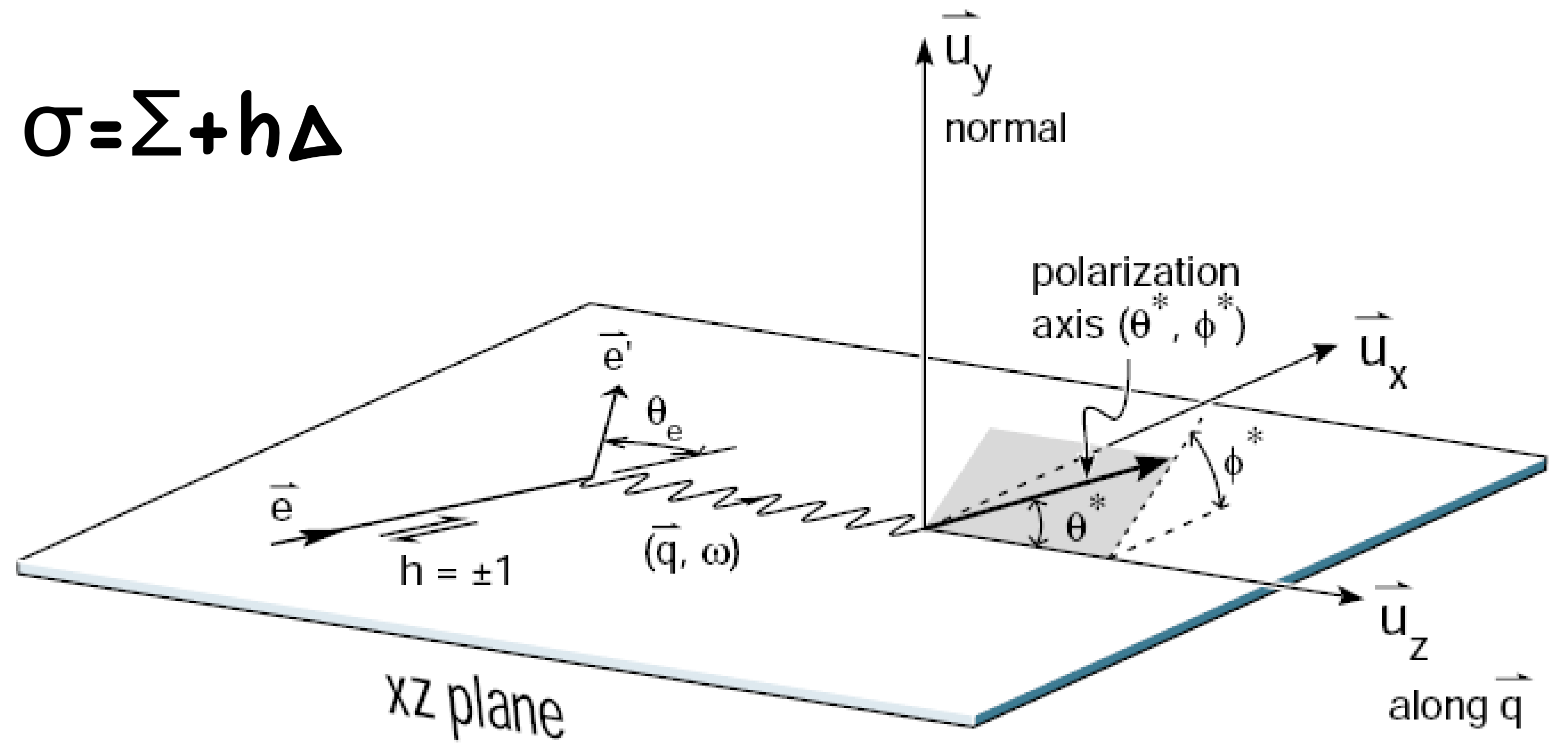
$$\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan\frac{\theta_e}{2}$$

- A single measurement gives ratio of form factors.
- Interference of "small" and "large" terms allow measurement at practically all values of Q^2.

Measurement Techniques

Polarized Cross Section: σ=Σ+hΔ

$$\mathcal{A} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

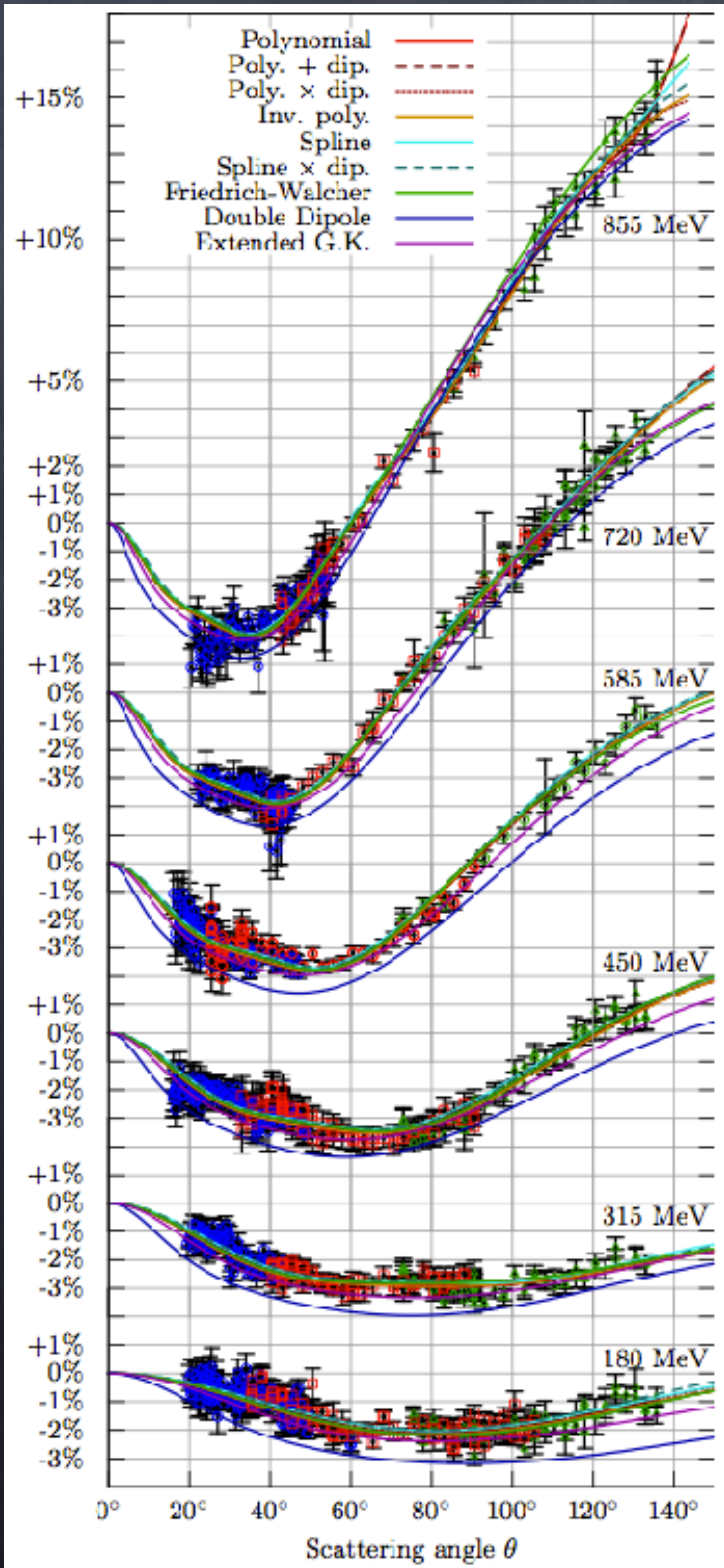


$$\mathcal{A} = f P_b P_t \frac{\overbrace{a\,cos\theta^* G_M^2}^{A_T} + \overbrace{b\,sin\theta^*\,cos\phi^* G_E G_M}^{A_{LT}}}{c G_M^2 + d G_E^2}$$

Measure asymmetry at two different target settings, say θ*=0, 90.

Ratio of asymmetries gives ratio of form factors.

Functionally identical to recoil polarimetry measurements.



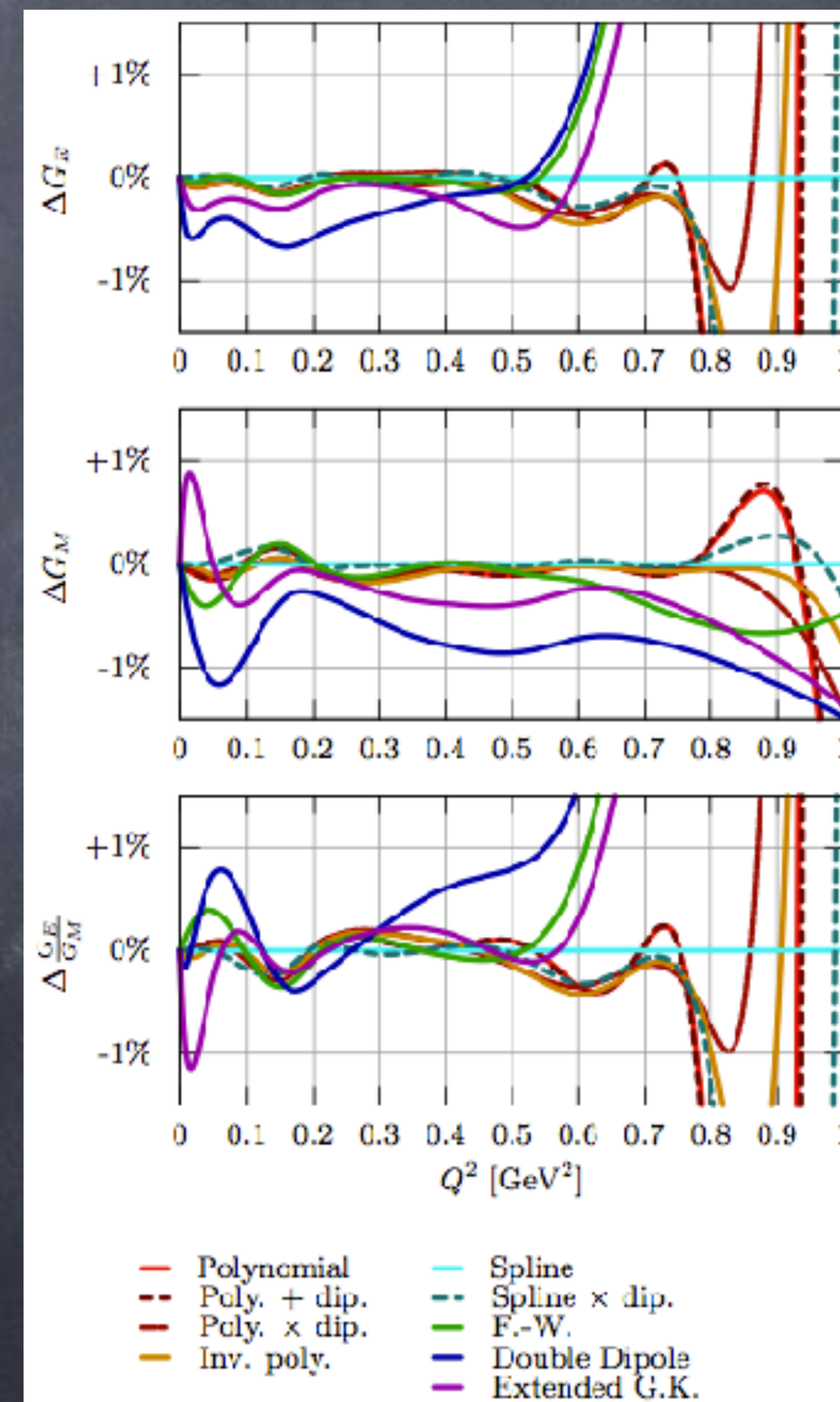
Mainz ep

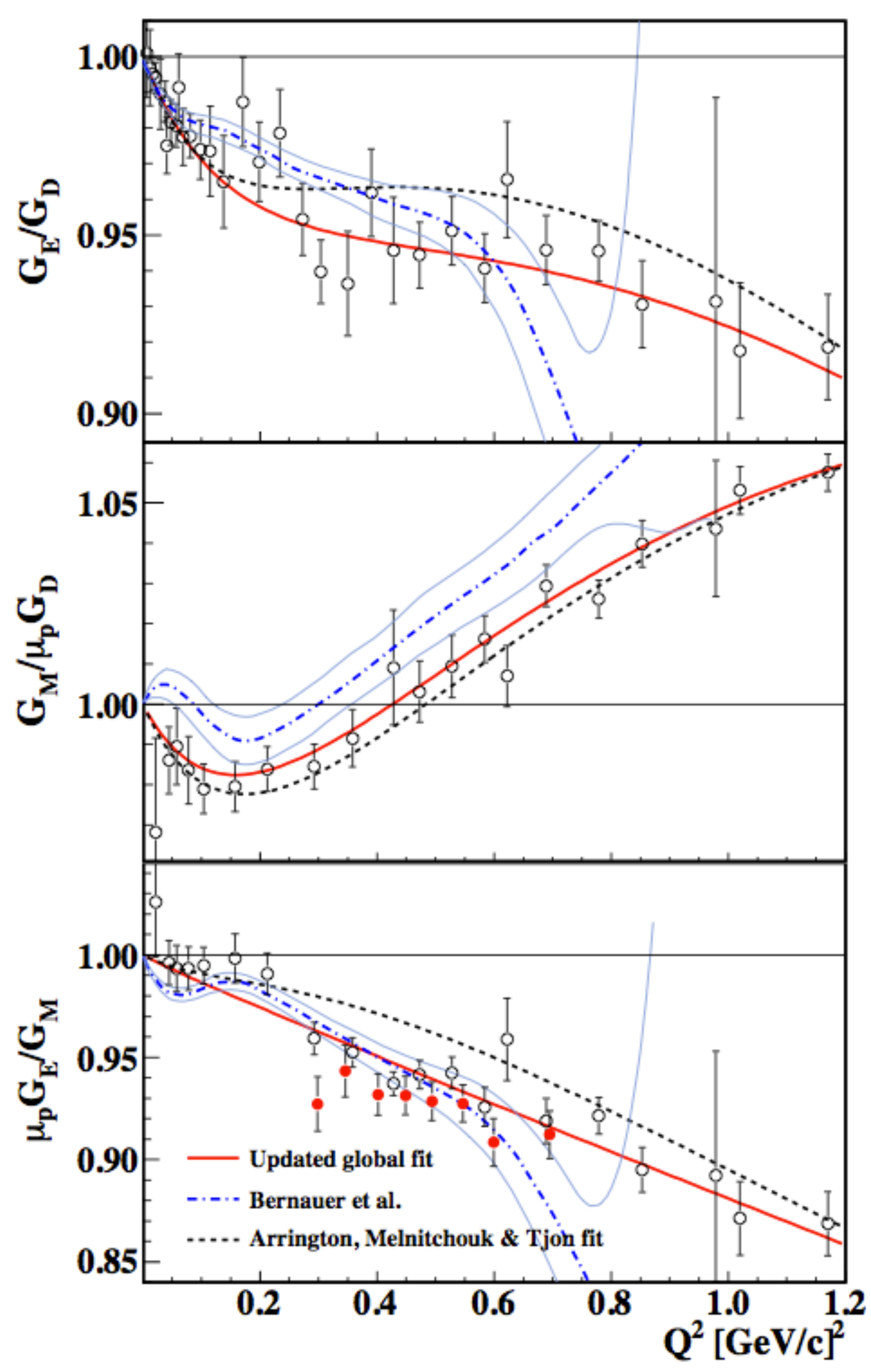
J. Bernauer et al PRL 105, 242001 (2010)

$r_p = 0.879 \pm 0.008$ fm

Left: Cross sections relative to standard dipole

Right: variation in fits to data - some fits have poor χ^2, so uncertainty is overestimated.



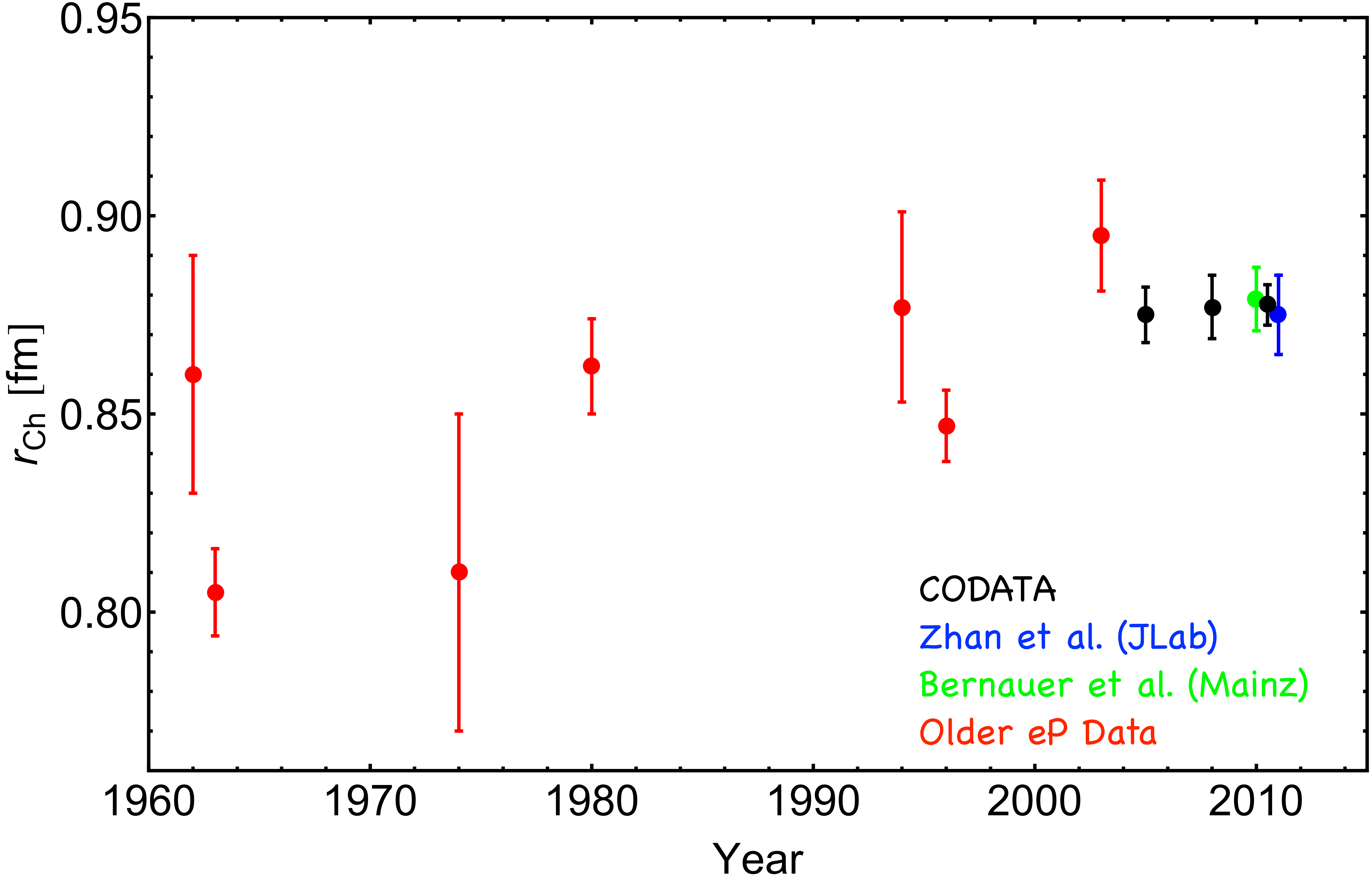


JLab ep E08-007 Part I (GR,...)

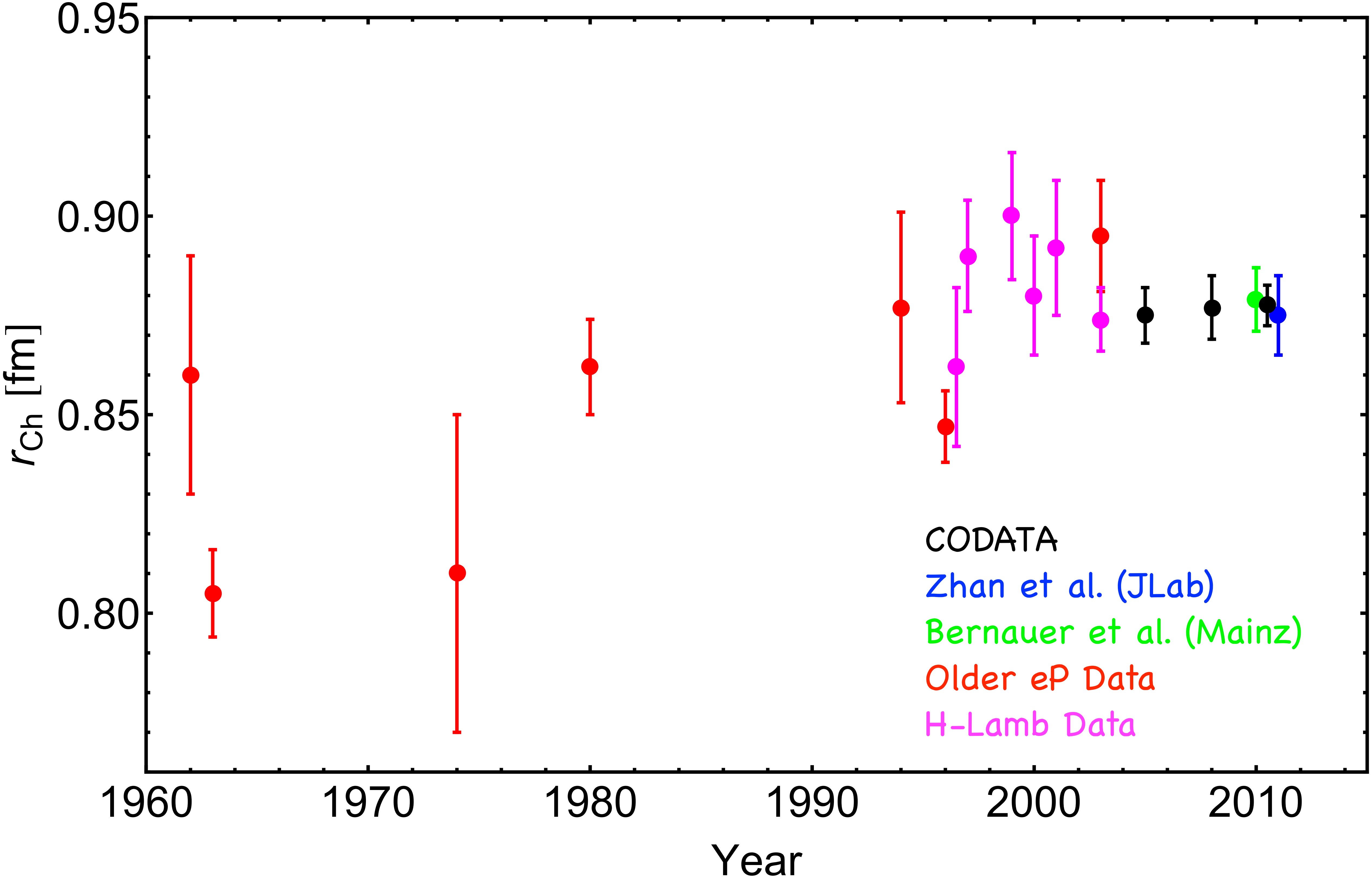
X. Zhan et al PLB 705, 59 (2011)

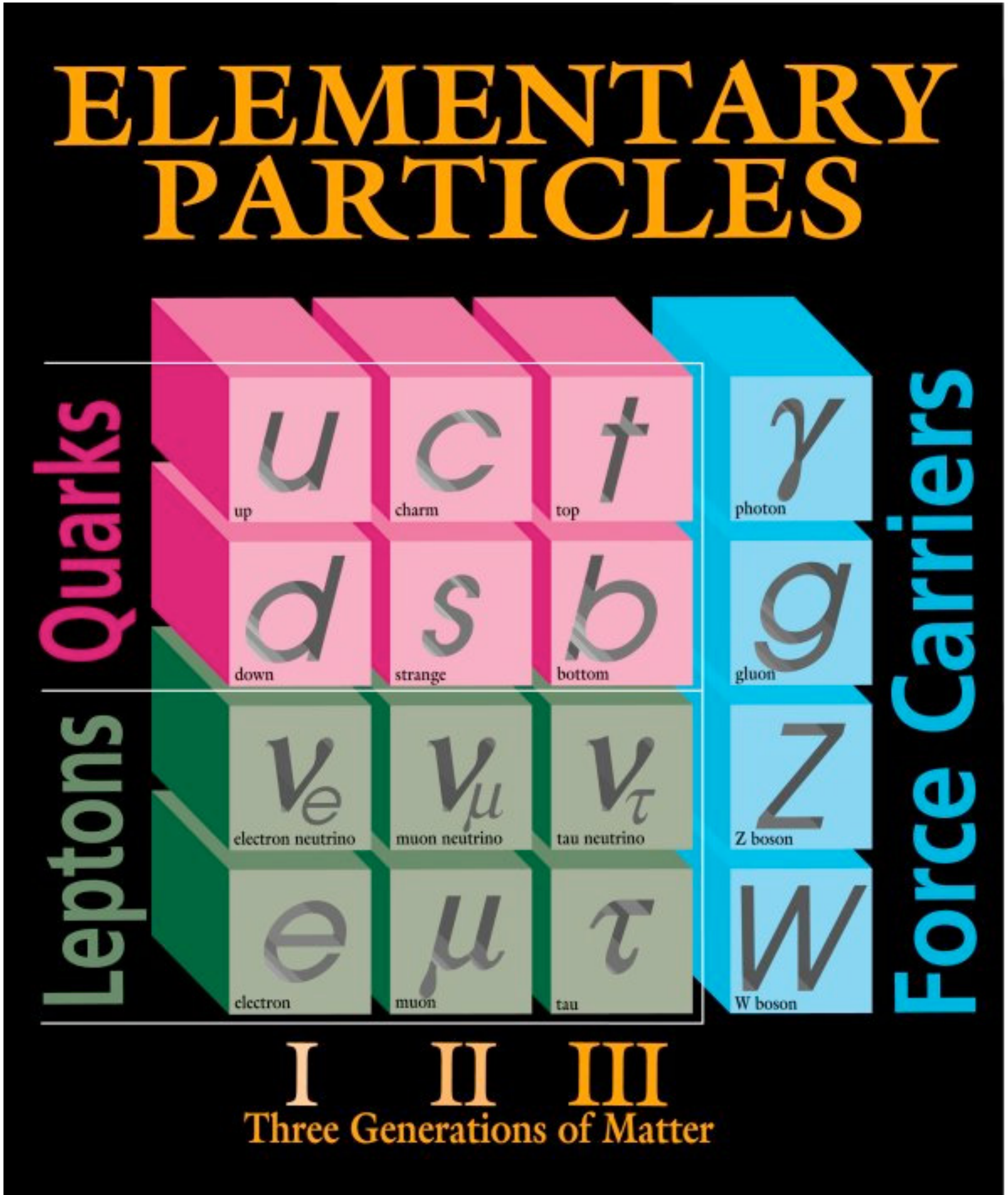
r_p = 0.875 ± 0.009 fm

Time evolution of the Radius from eP data

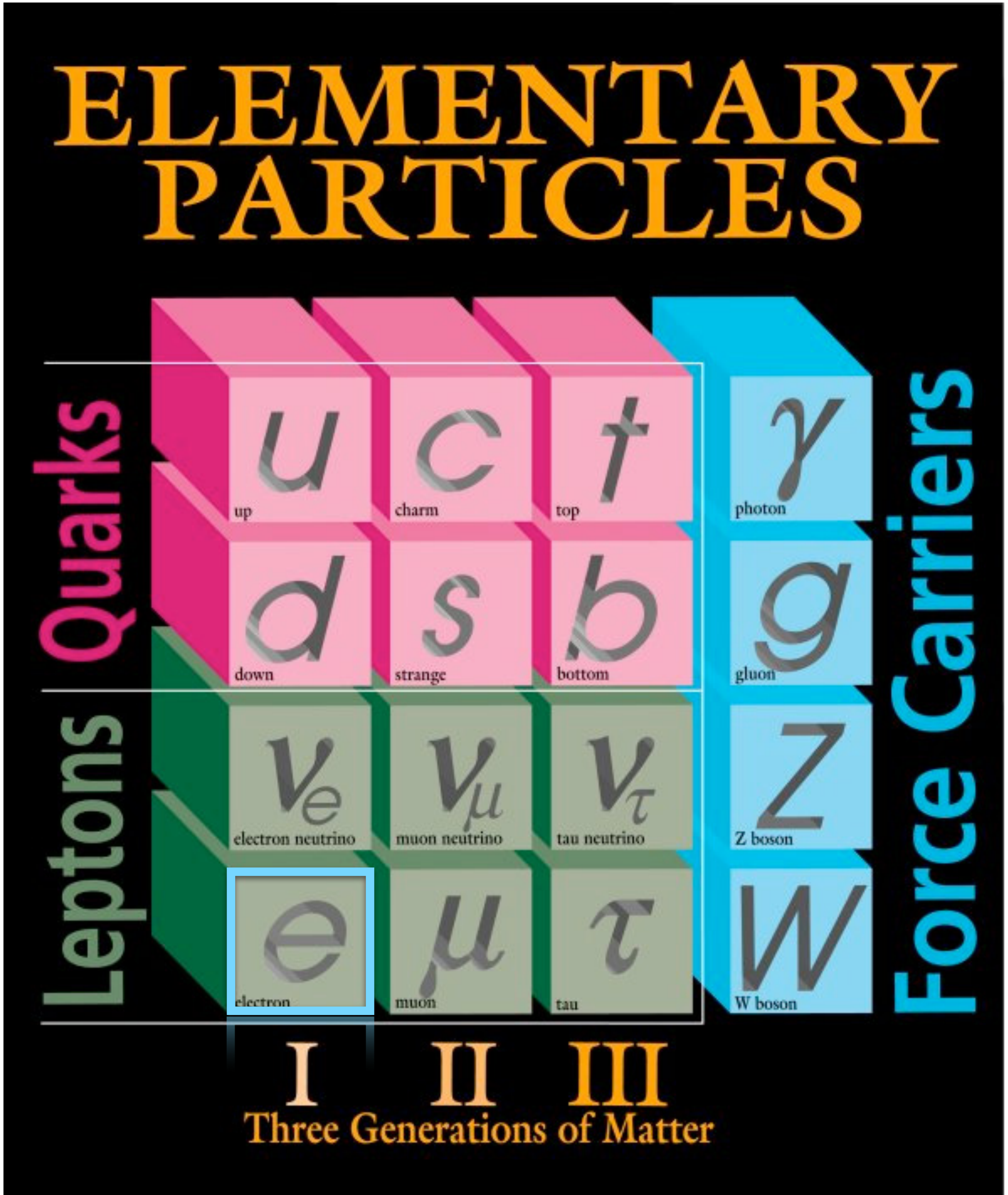


Time evolution of the Radius from H Lamb Shift + eP





Fermilab 95-759



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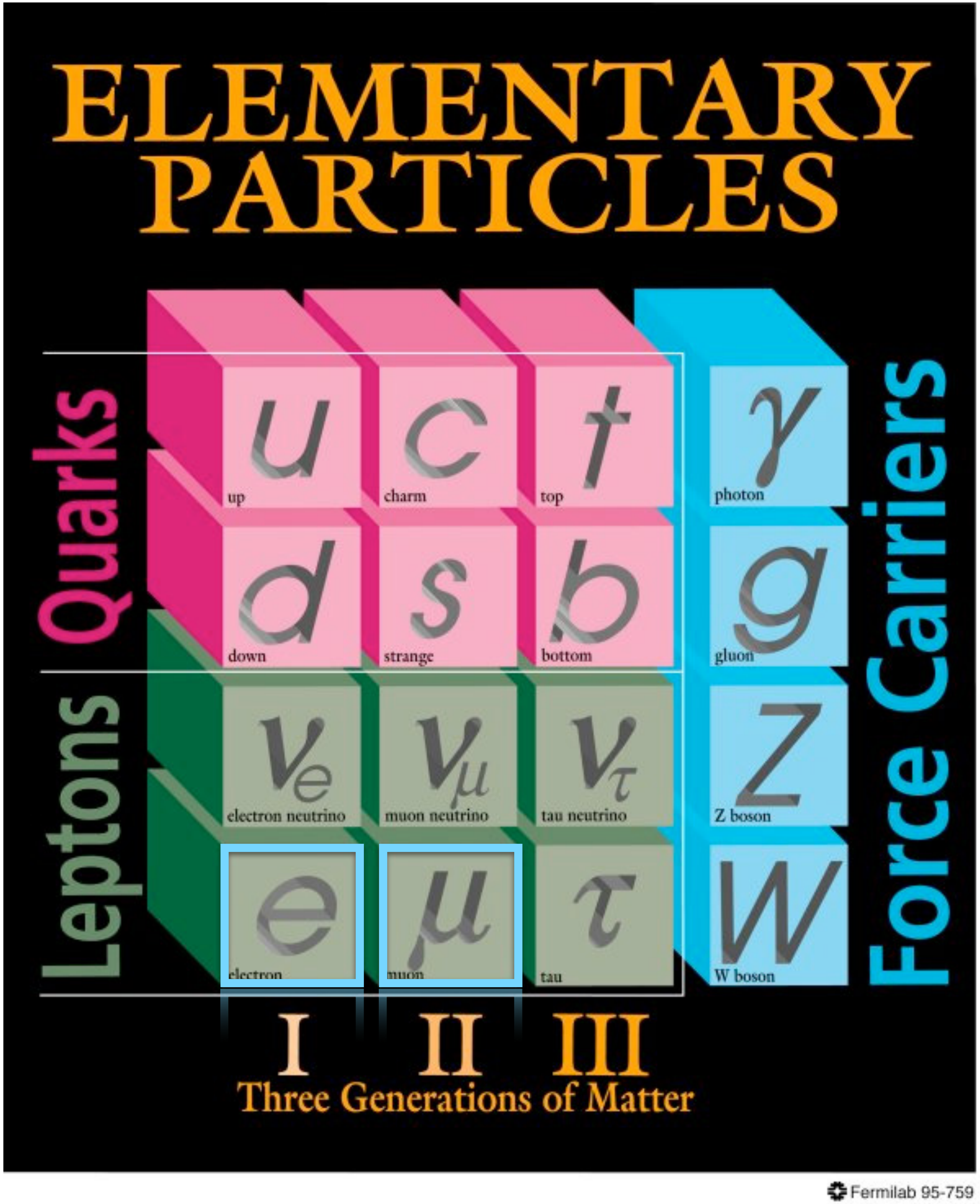


In the standard model the muon is just a heavier version (~200 times) of the electron. The muon decays into an electron (and some neutrinos) with a lifetime of ~2.2 uS.

It has exactly the same interactions…

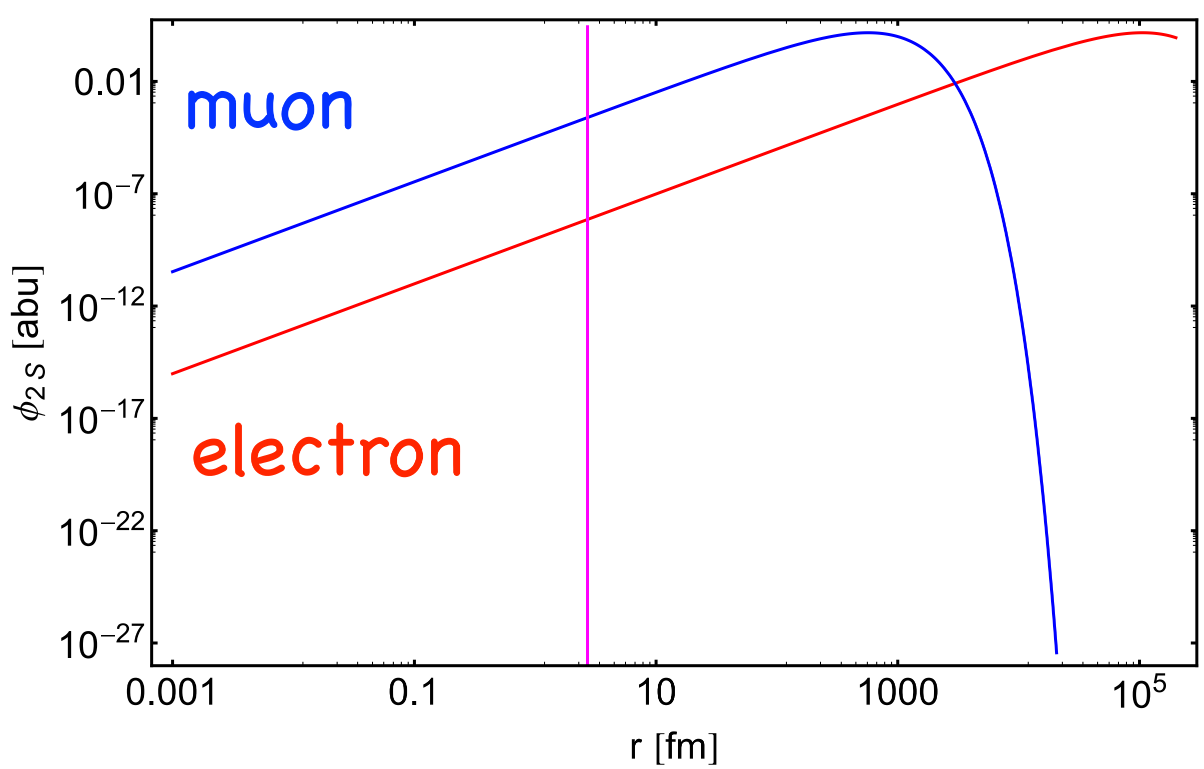
Why atomic physics to learn proton radius?
Why μH?

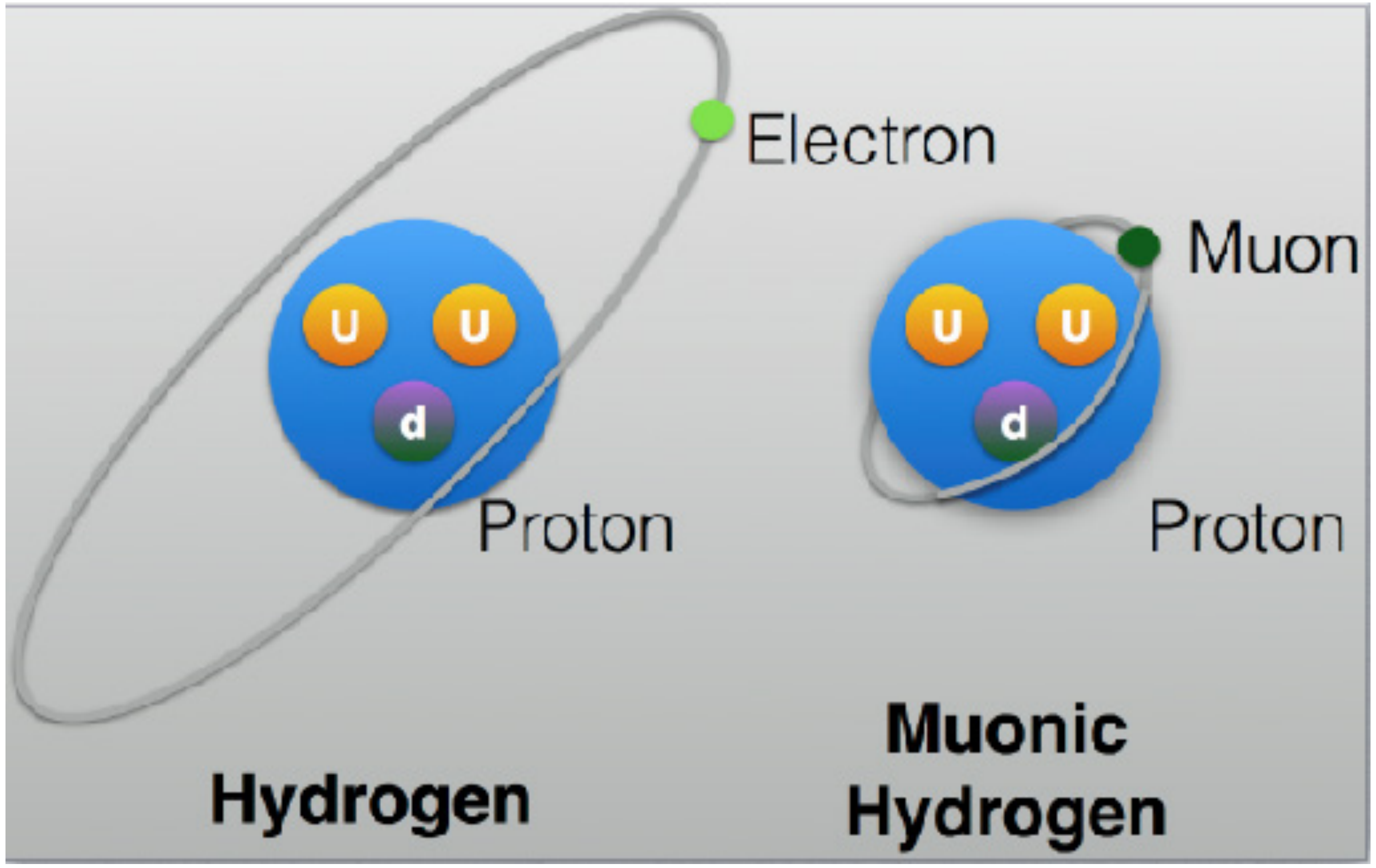
Probability for lepton to be inside the proton:
proton to atom volume ratio

$$\sim \left(\frac{r_p}{a_B}\right)^3 = (r_p\alpha)^3 m^3$$

Lepton mass to the **third** power!

Muon to electron mass ratio ~205 → factor of about 8 million!





Proton charge radius and muonic hydrogen

muonic hydrogen = $\mu^- p$ mass m_μ = 207 m_e

$\Rightarrow$ Bohr: $\langle r^{\mathrm{orbit}} \rangle \sim \dfrac{\hbar}{Z\alpha\, m_r\, c} n^2$

$\Delta E_{\text{finite size}}(nl) \sim r_{\mathrm{p}}^2 \,|\Psi(r=0)|^2$

$$\Rightarrow \boxed{\Delta E_{\text{finite size}}(nl) = \frac{2(Z\alpha)^4 c^4}{3\hbar^2 n^3}\, m_r^3\, r_{\mathrm{p}}^2\, \delta_{l0}}$$

Lamb shift in μp: $\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1})$ =

$$\boxed{209.9779(49) - 5.2262\, r_{\mathrm{p}}^2 + 0.0347\, r_{\mathrm{p}}^3 \;\; [\mathrm{meV}]}$$

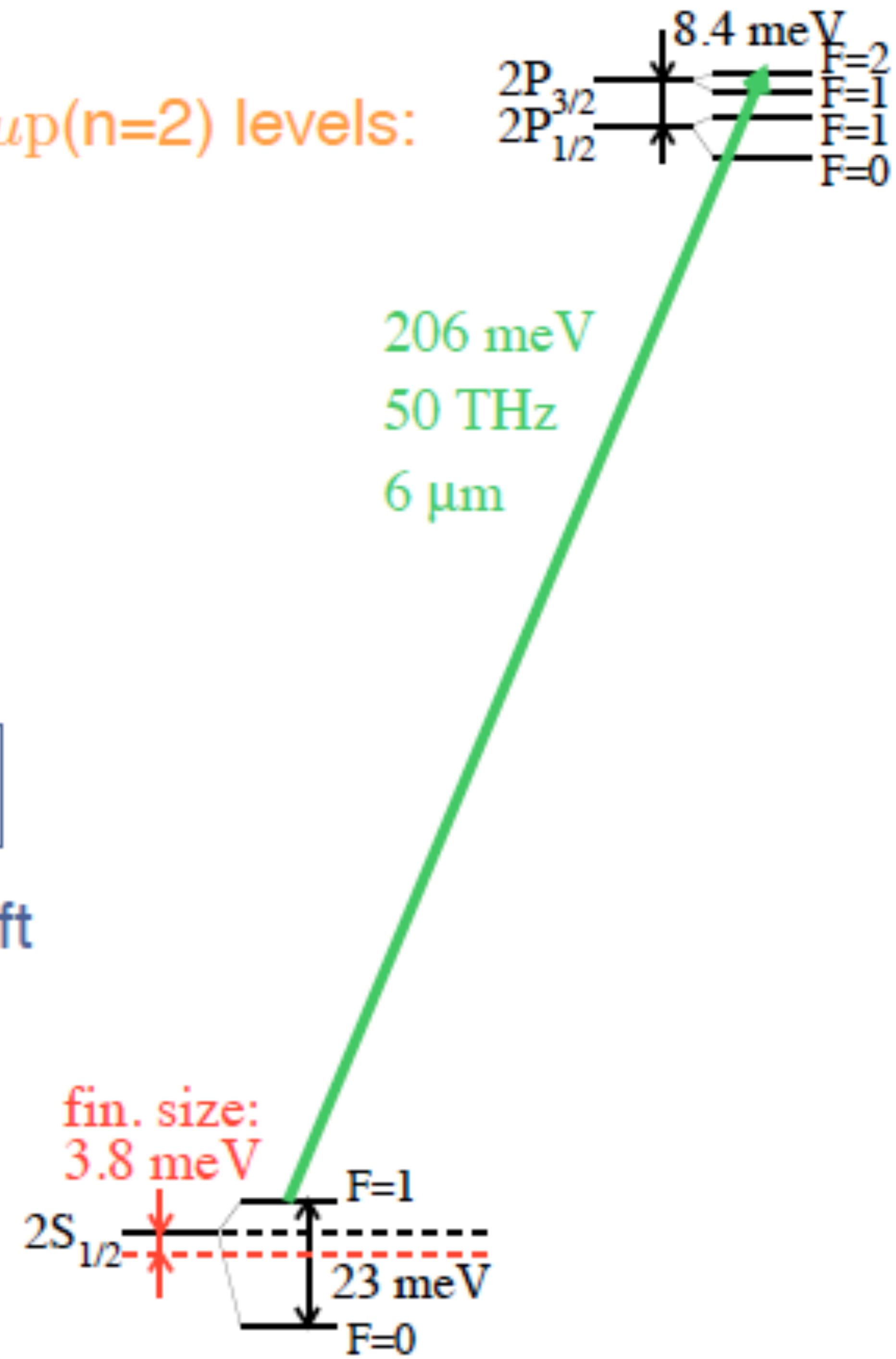
finite size contribution is 2% of the μp Lamb shift

measure ΔE(2S-2P) to 30 ppm = 1.5 GHz

$$\boxed{\Rightarrow r_{\mathrm{p}} \text{ to } 10^{-3}}$$

$$\Gamma_{2P} \;=\; 18.6 \text{ GHz} \qquad (\Gamma_{\mathrm{rad.}})$$

μp(n=2) levels:

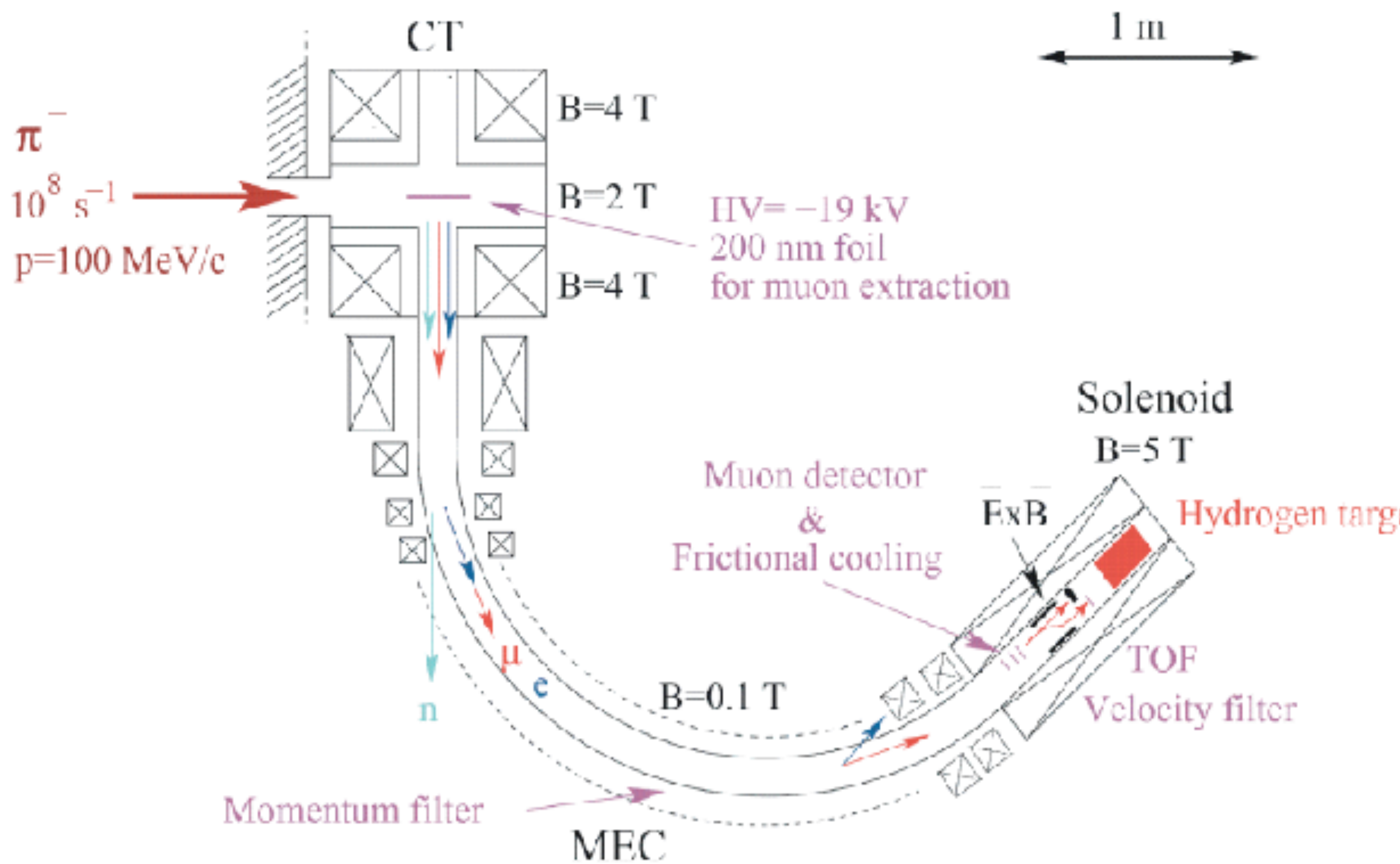


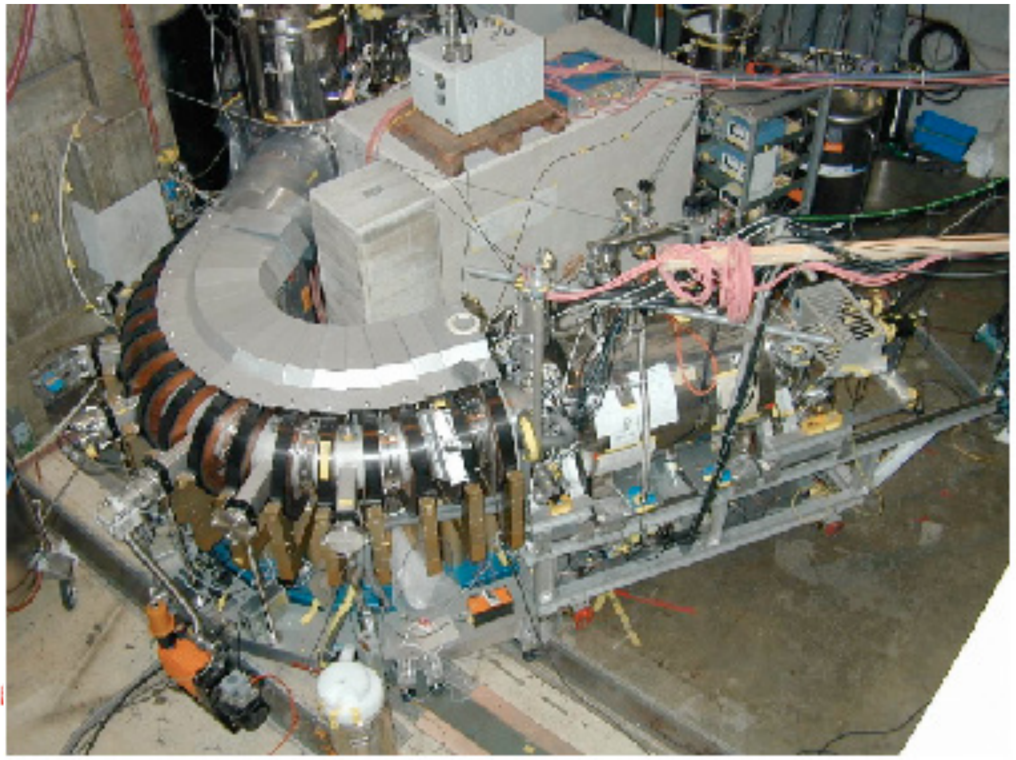
Courtesy of R. Pohl

μP Lamb Shift Measurement

μP Lamb Shift Measurement

- μ from πE5 beamline at PSI (20 keV)





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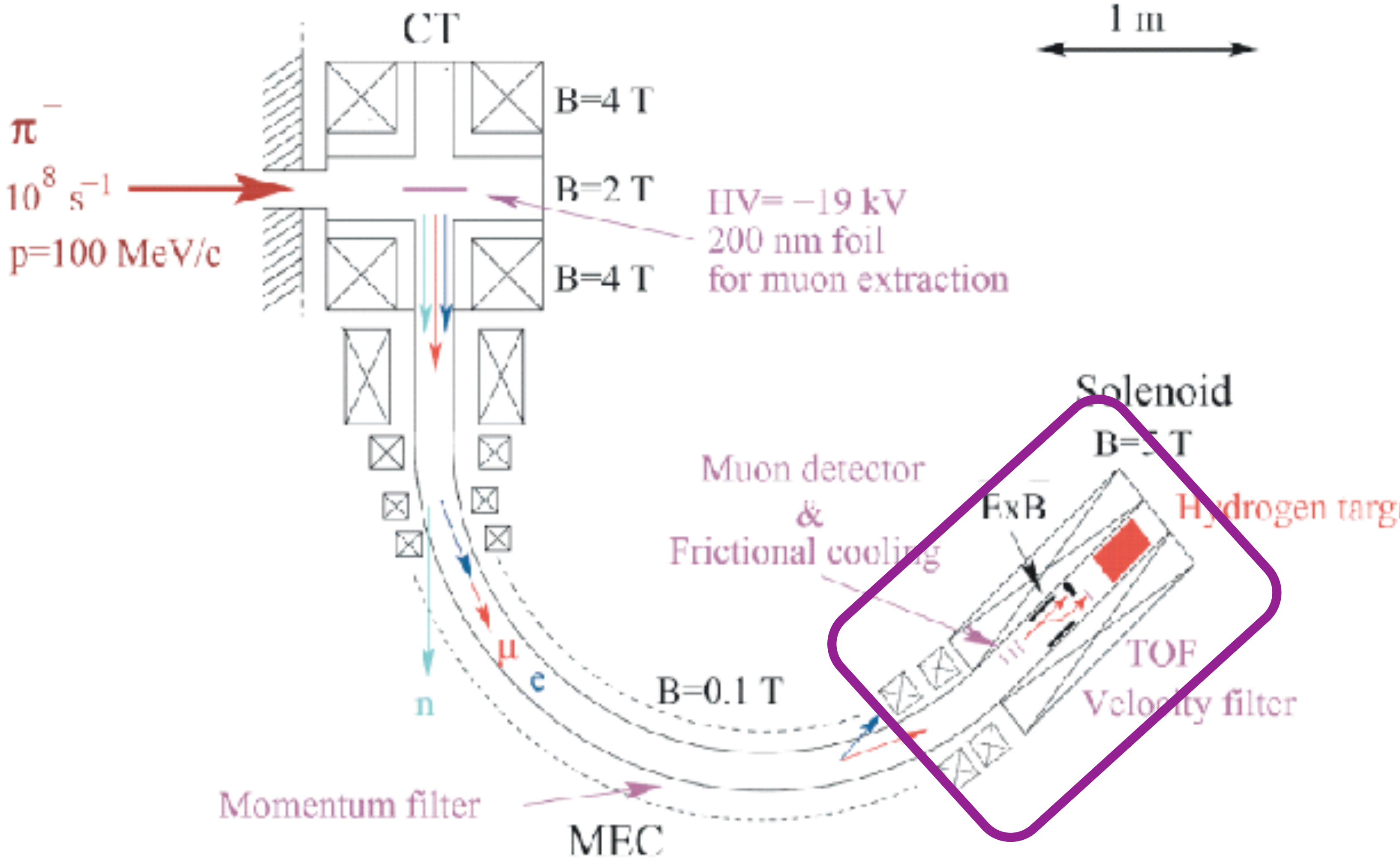

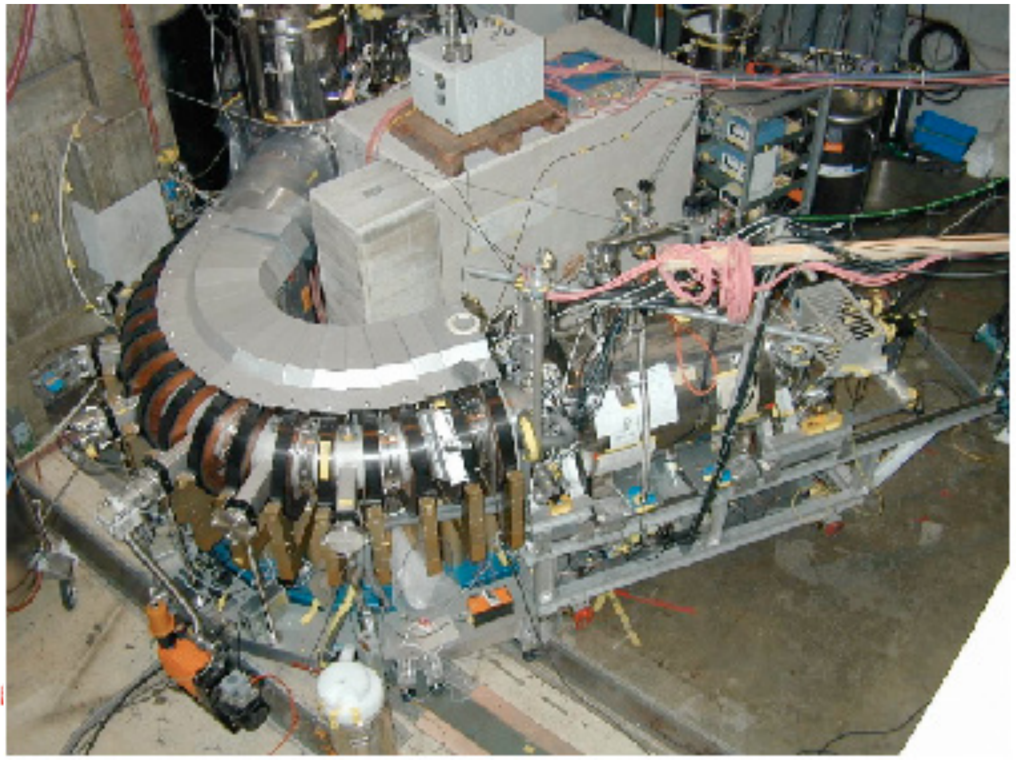

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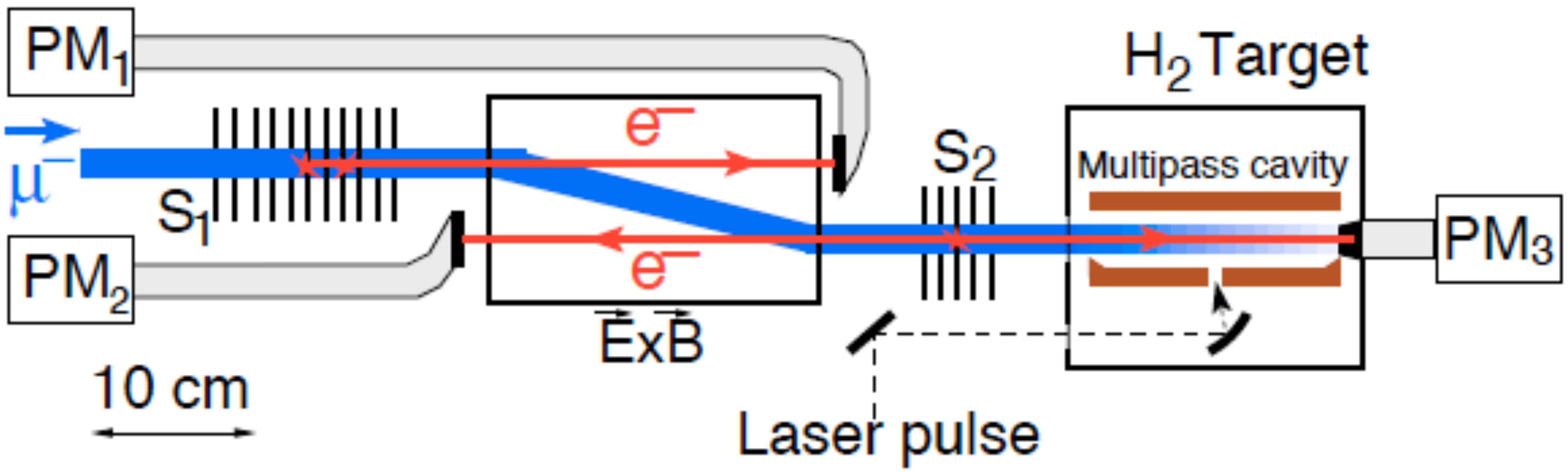
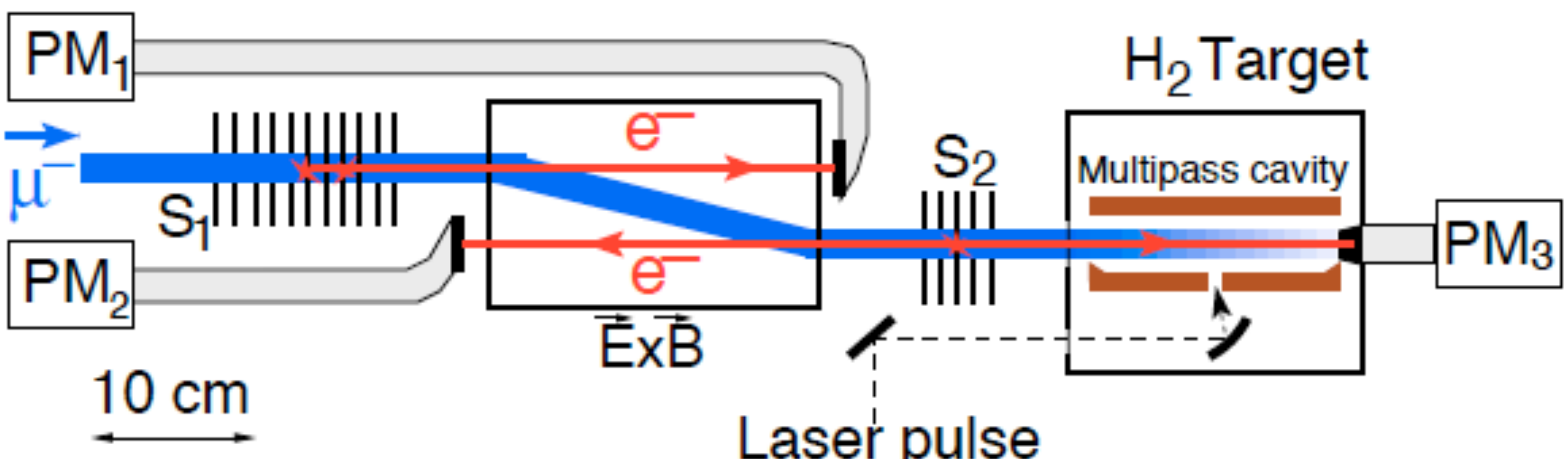


μP Lamb Shift Measurement

- μ from πE5 beamline at PSI (20 keV)
- μ's with 5 keV kinetic energy after carbon foils S1-2
- Arrival of the pulsed beam is timed by secondary electrons in PM1-3



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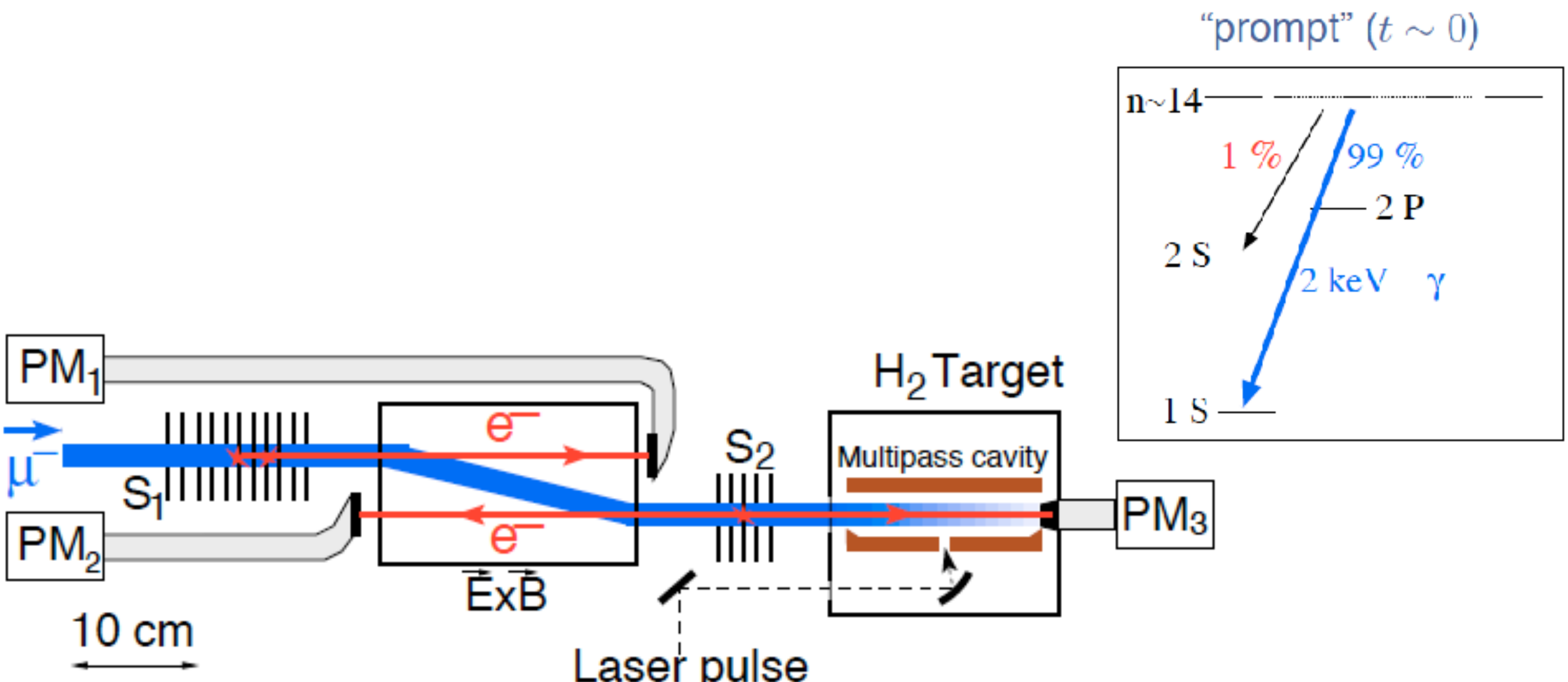

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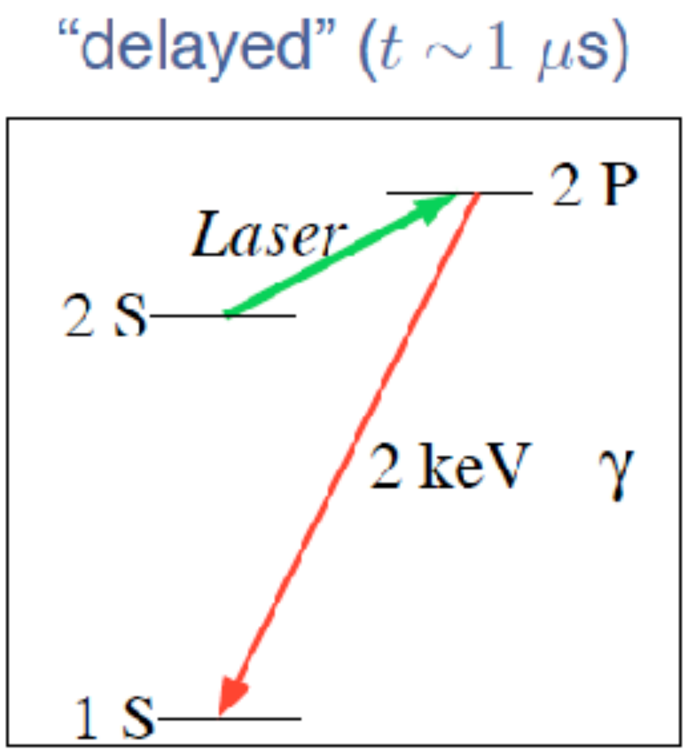
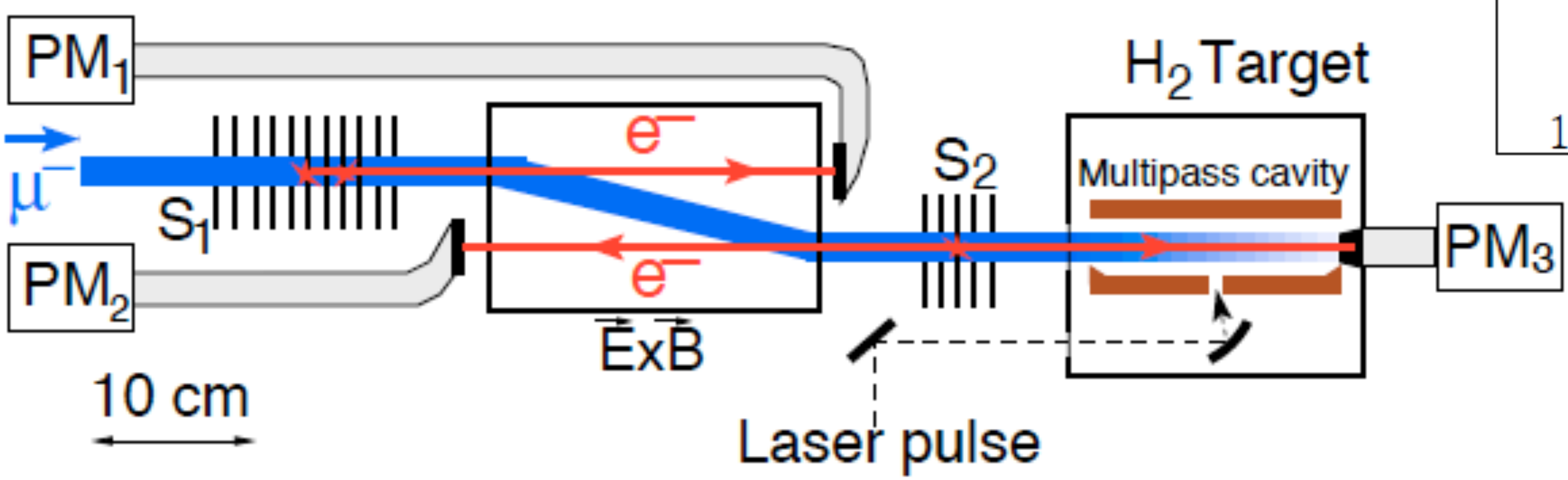
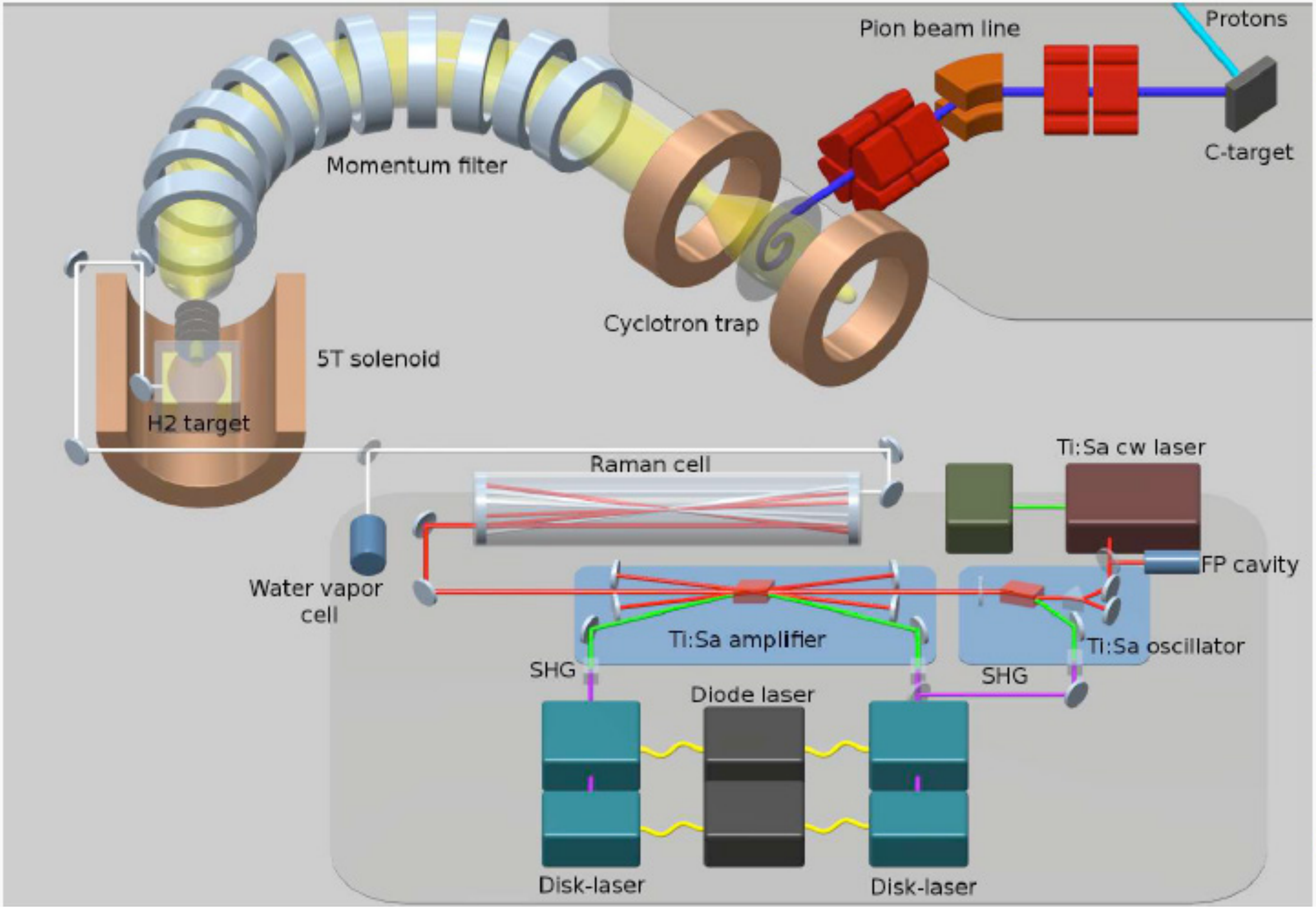
- μ's are absorbed in the H_2 target at high excitation followed by decay to the 2S metastable level (which has a 1 μs lifetime)
- A laser pulse timed by the PMs excites the $2S_{1/2}^{F=1}$ to $2P_{3/2}^{F=2}$ transition
- The 2 keV X-rays from 2P to 1S are detected.



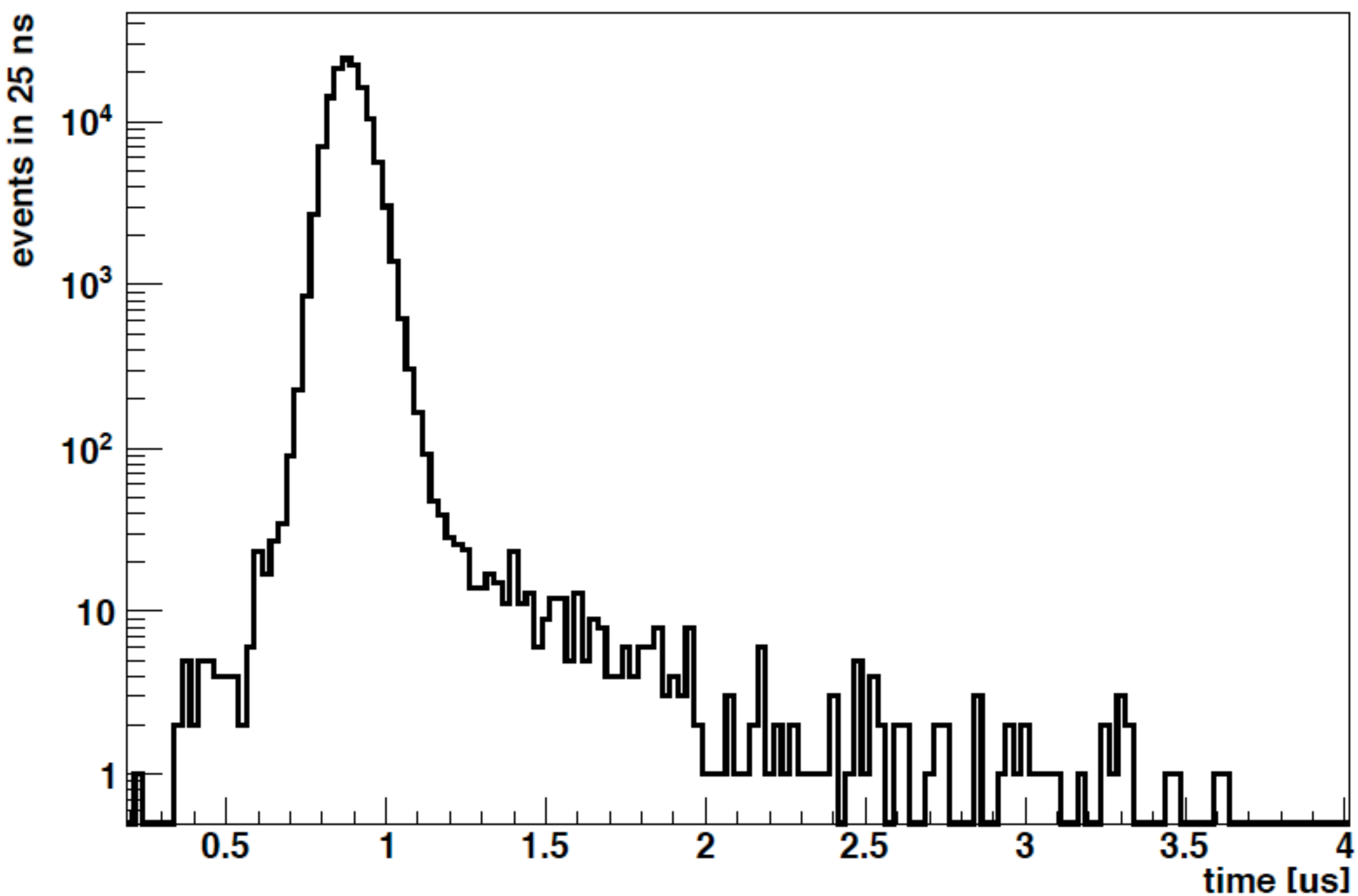


p-beam (1 MW) → π (MeV) → μ (MeV) → μ (keV) → μp(2S) → Laser → X-ray



940 nm (2 kW) → 1030 nm → 515 nm → 708 nm → 1.0 μm → 1.6 μm → 6.0 μm

time spectrum of 2 keV x-rays (∼ 13 hours of data)



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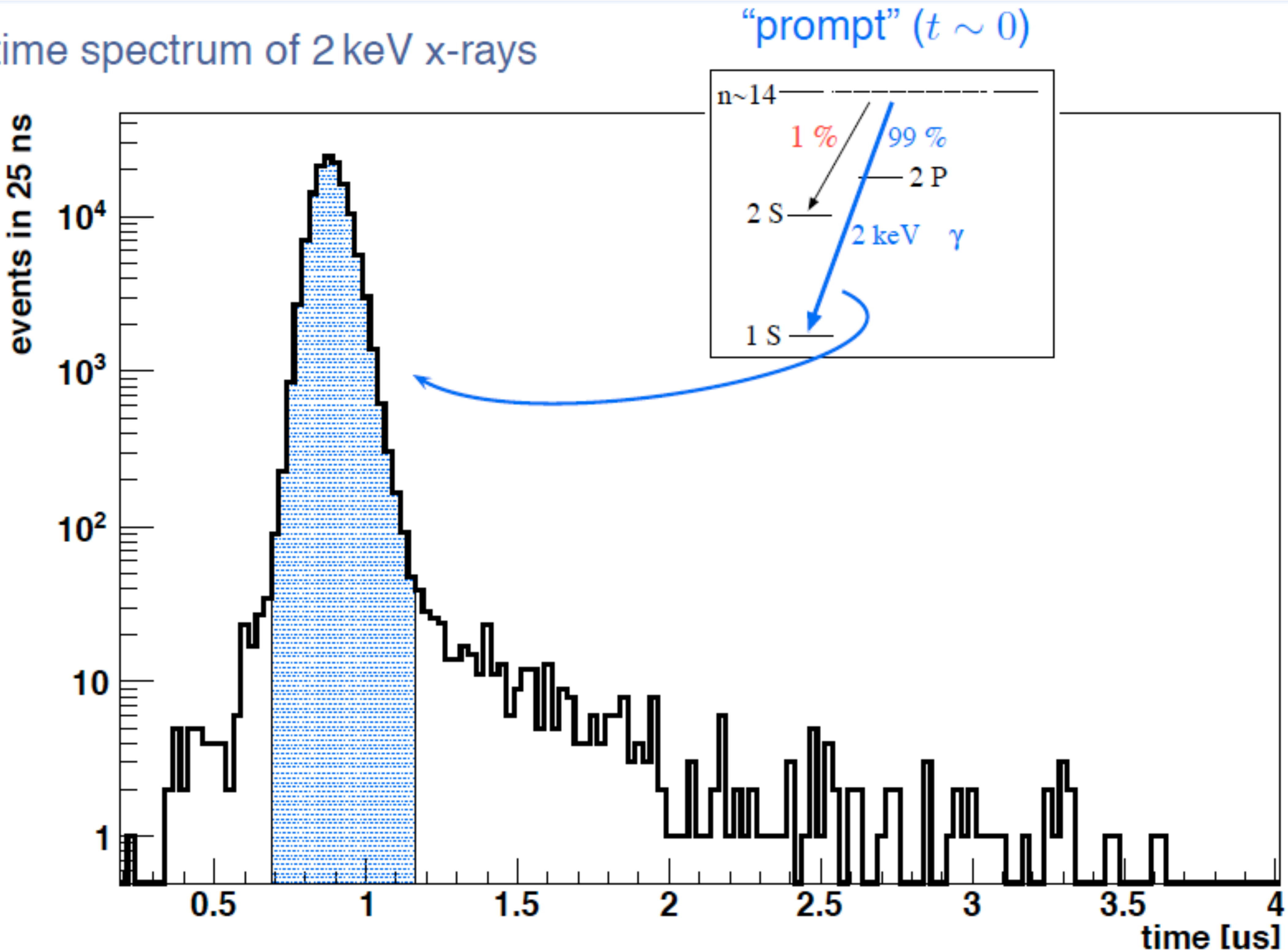

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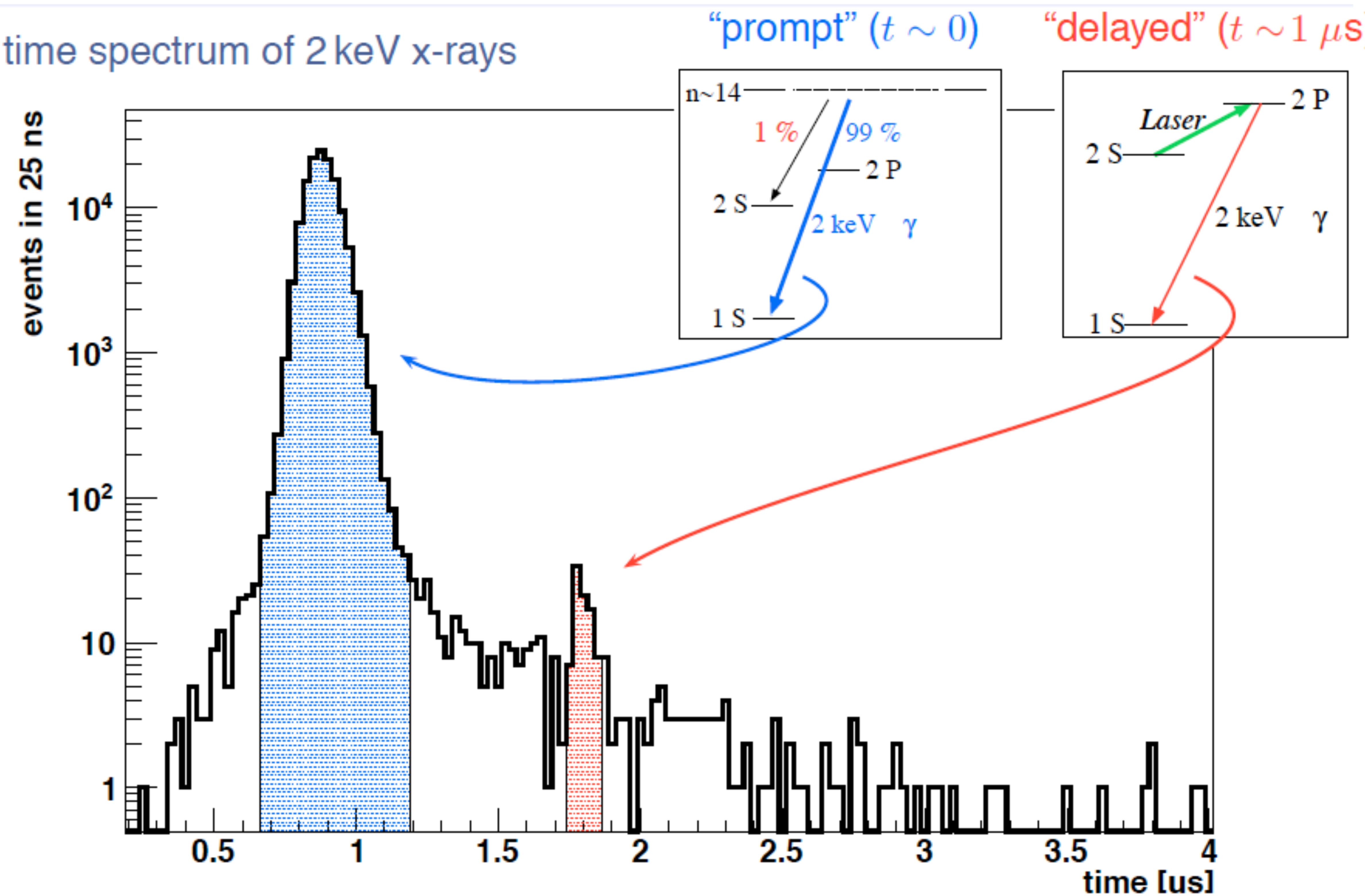

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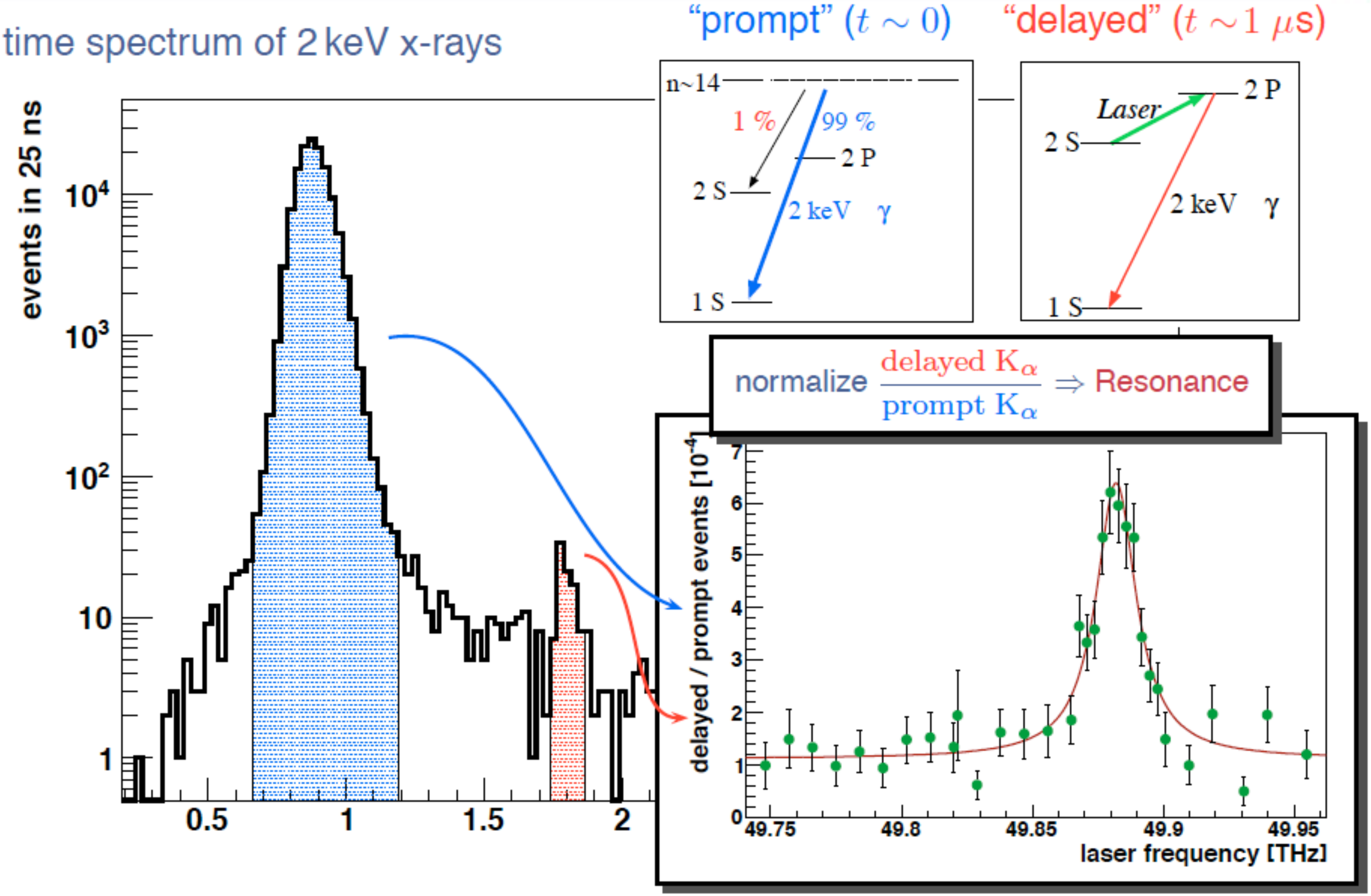
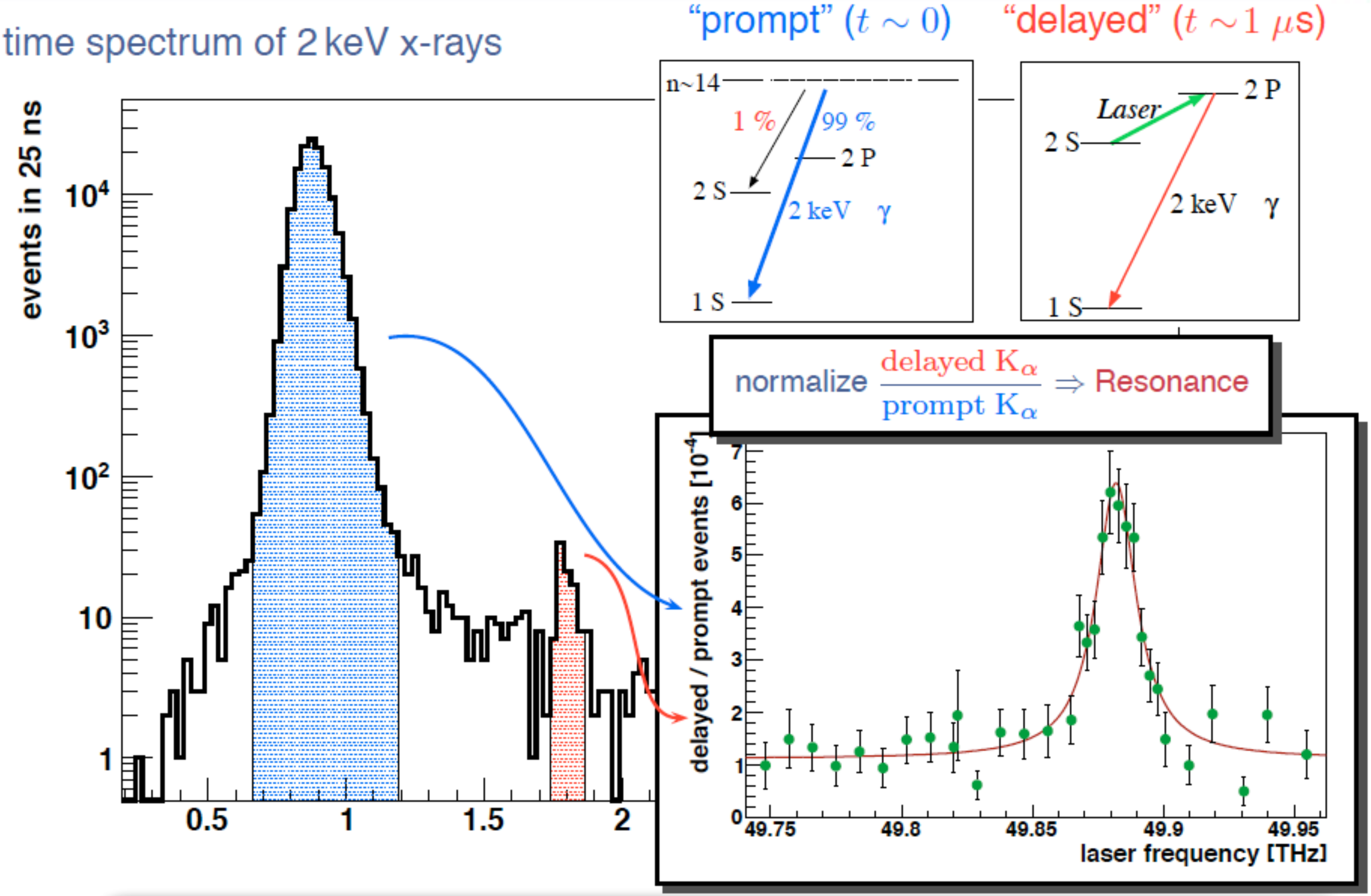
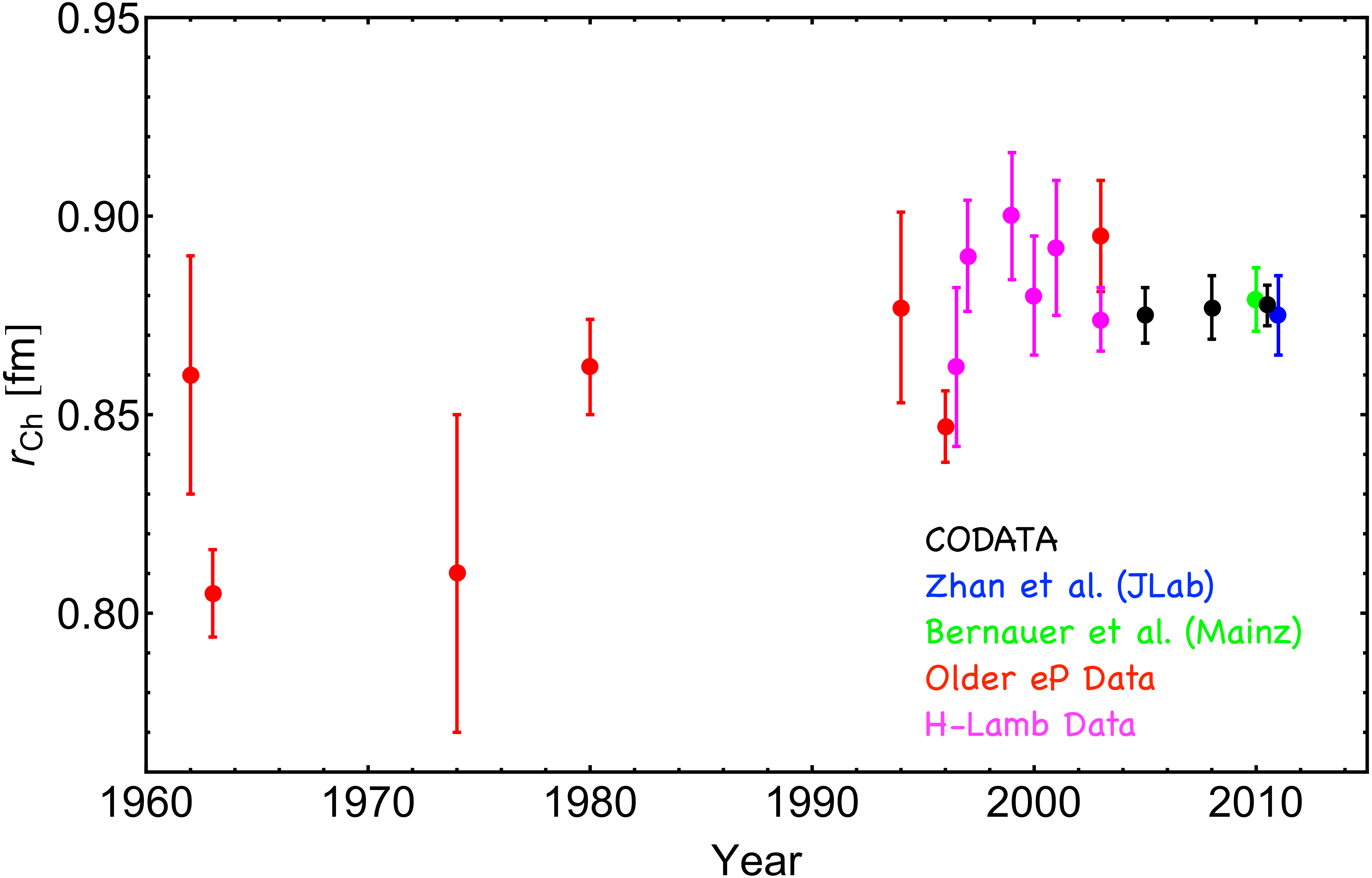


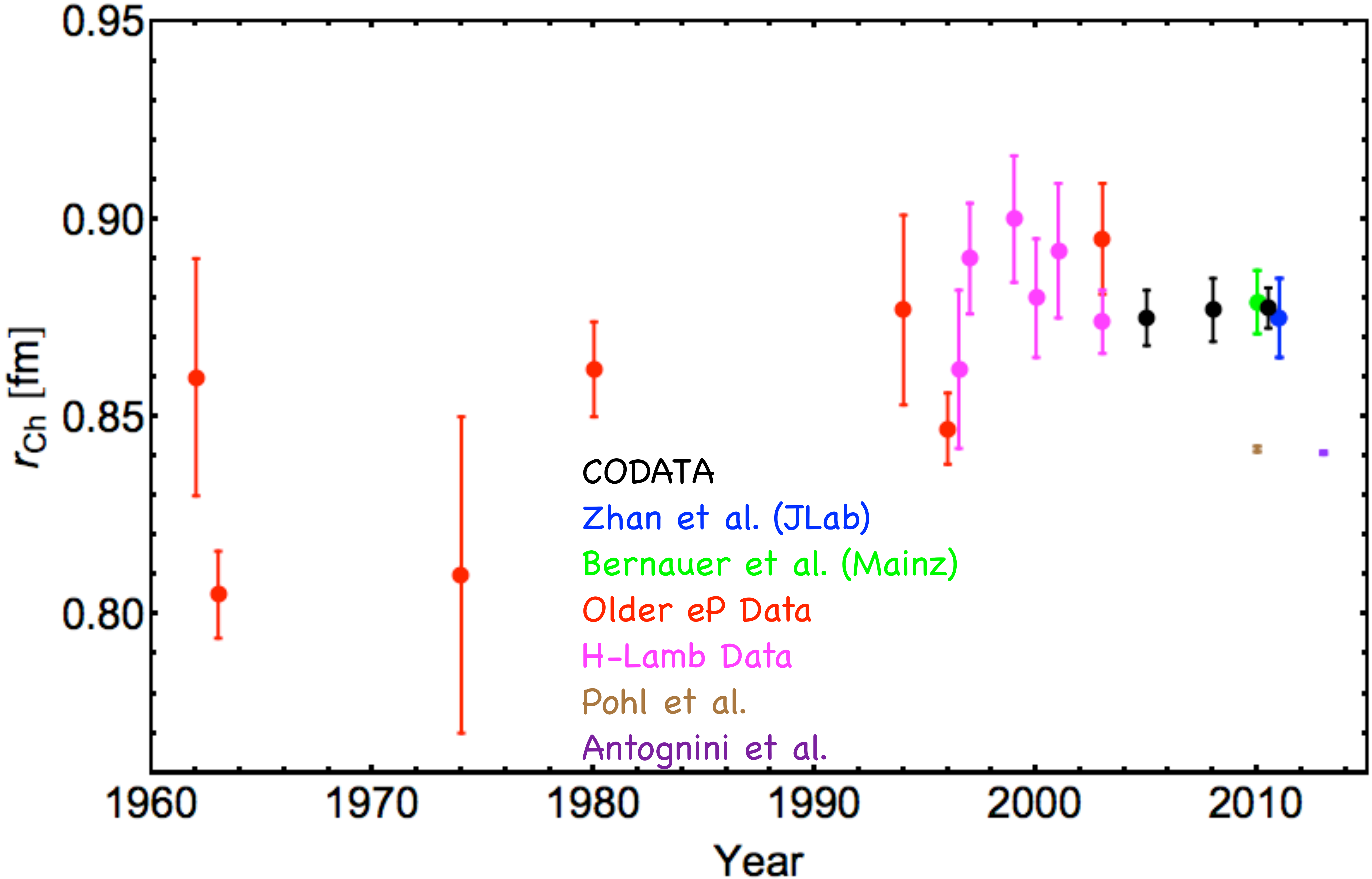


$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \ [\text{meV}]$$

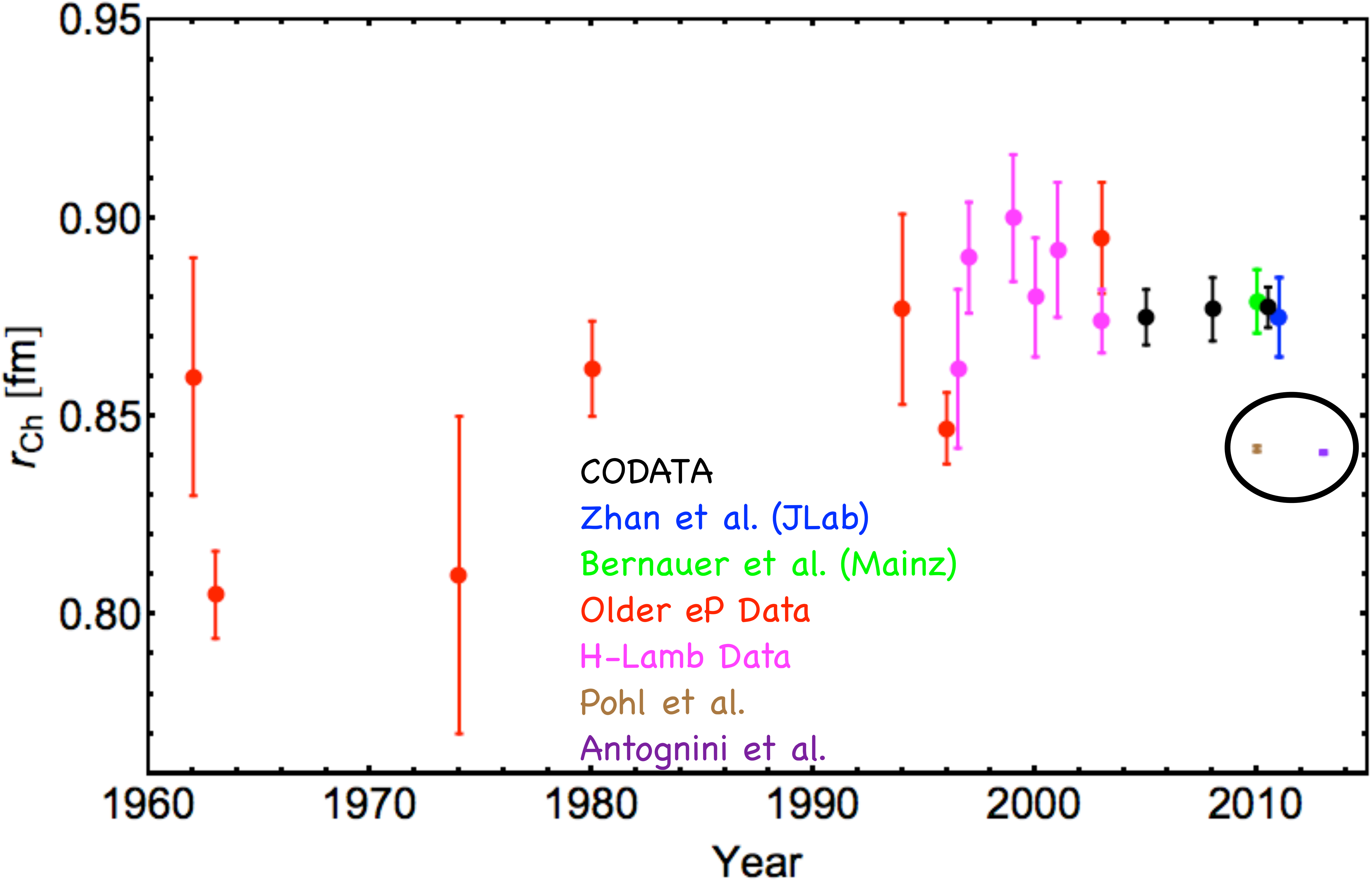
Time evolution of the Radius from H Lamb Shift + eP



Time evolution of the Radius from H Lamb Shift + eP



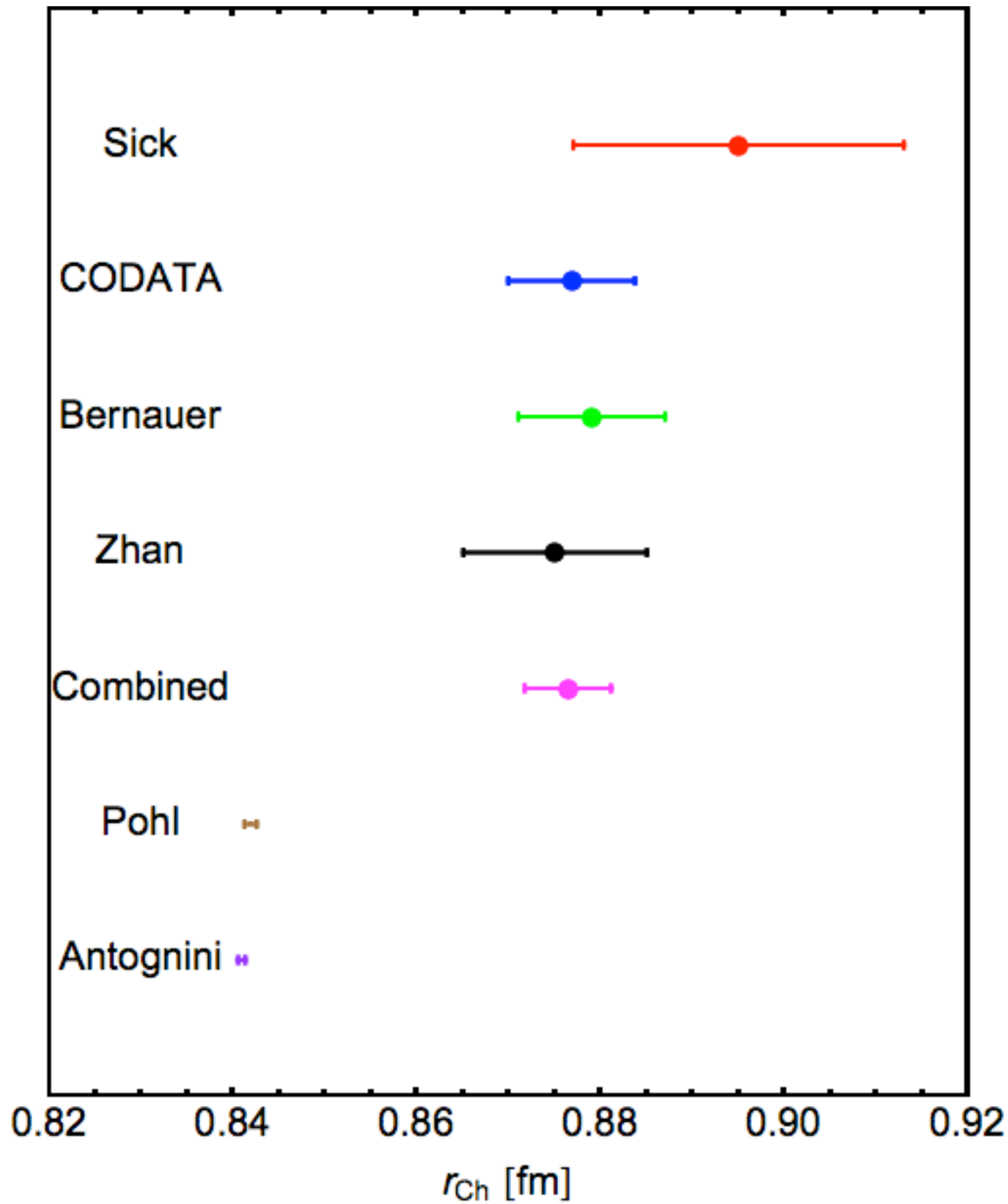
Time evolution of the Radius from H Lamb Shift + eP



Proton Radius Puzzle

Muonic hydrogen disagrees with atomic physics and electron scattering determinations of slope of FF at $Q^2 = 0$

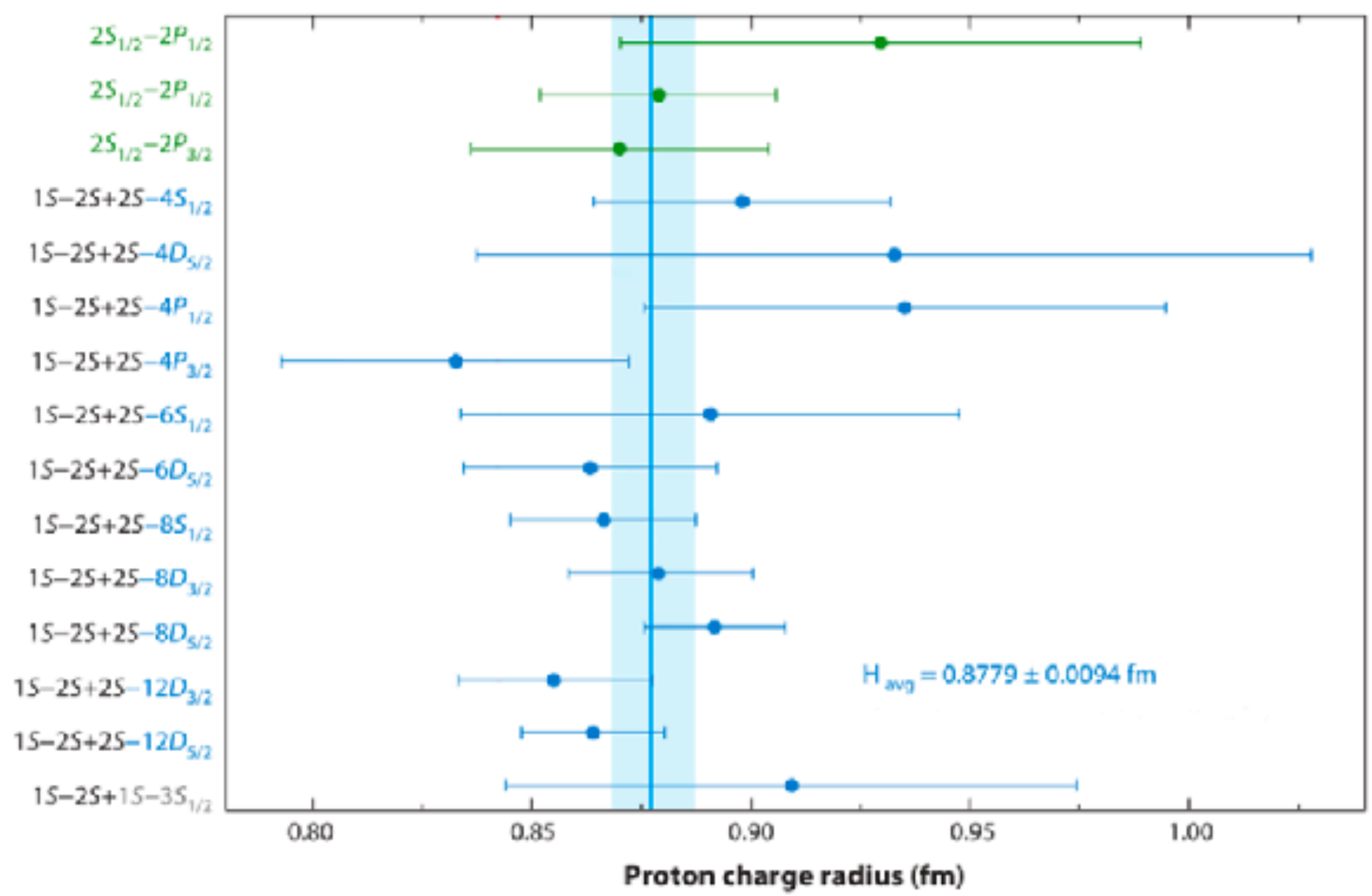
#	Extraction	$\langle r_E\rangle^2$ [fm]
1	Sick	0.895±0.018
2	CODATA	0.8768±0.0069
3	Mainz	0.879±0.008
4	Zhan	0.875±0.010
5	Combined 2–4	0.8764±0.0047
6	Pohl	0.84184 ± 0.00067
7	Antognini	0.84087 ± 0.00039



Experimental Error in the electron (Lamb shift) measurements?

The 1S-2S transition in H has been measured to 34 Hz, that is, 1.4×10^{-14} relative accuracy. Only an error of about 1,700 times the quoted experimental uncertainty could account for our observed discrepancy.

However.....



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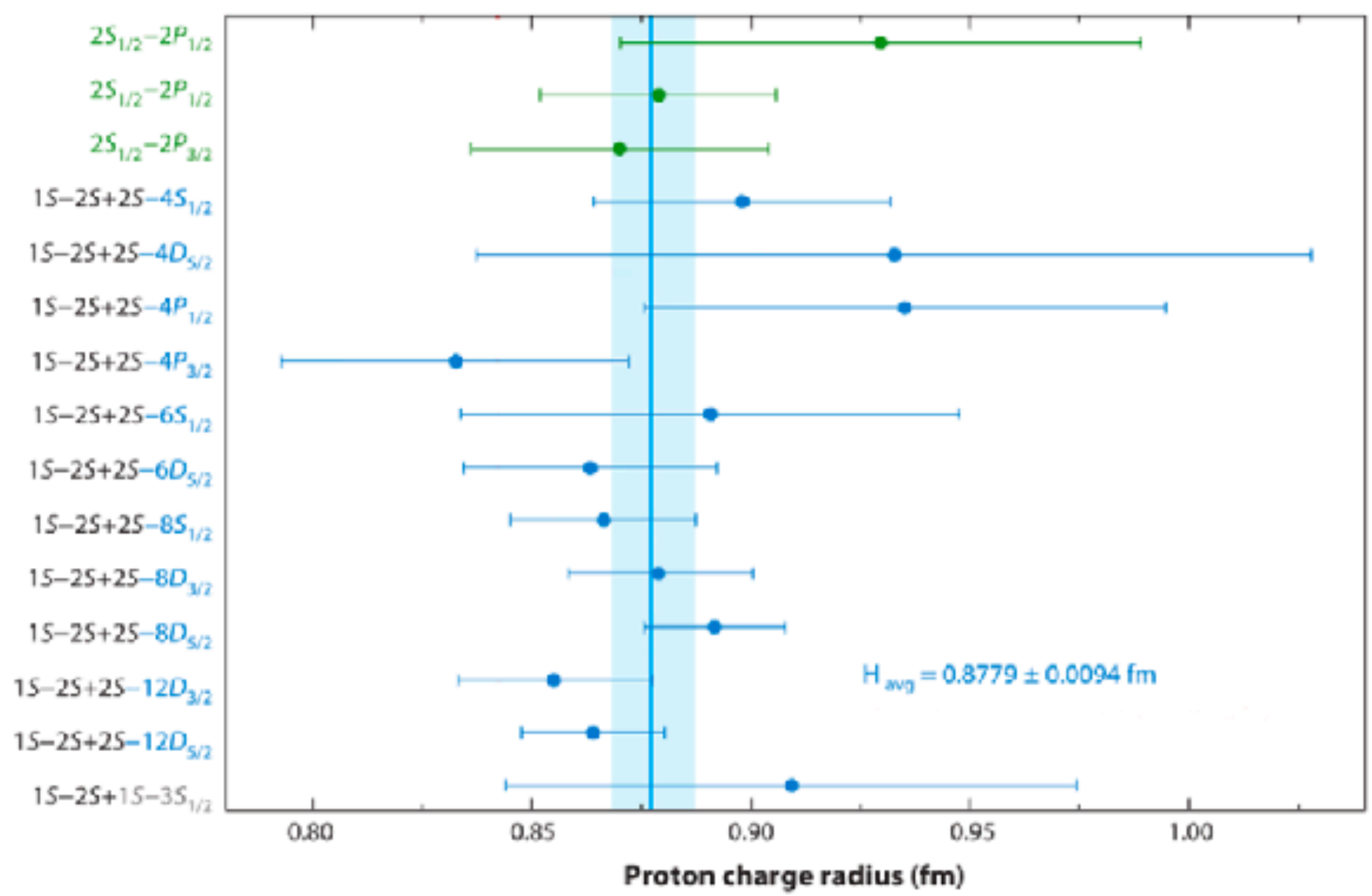
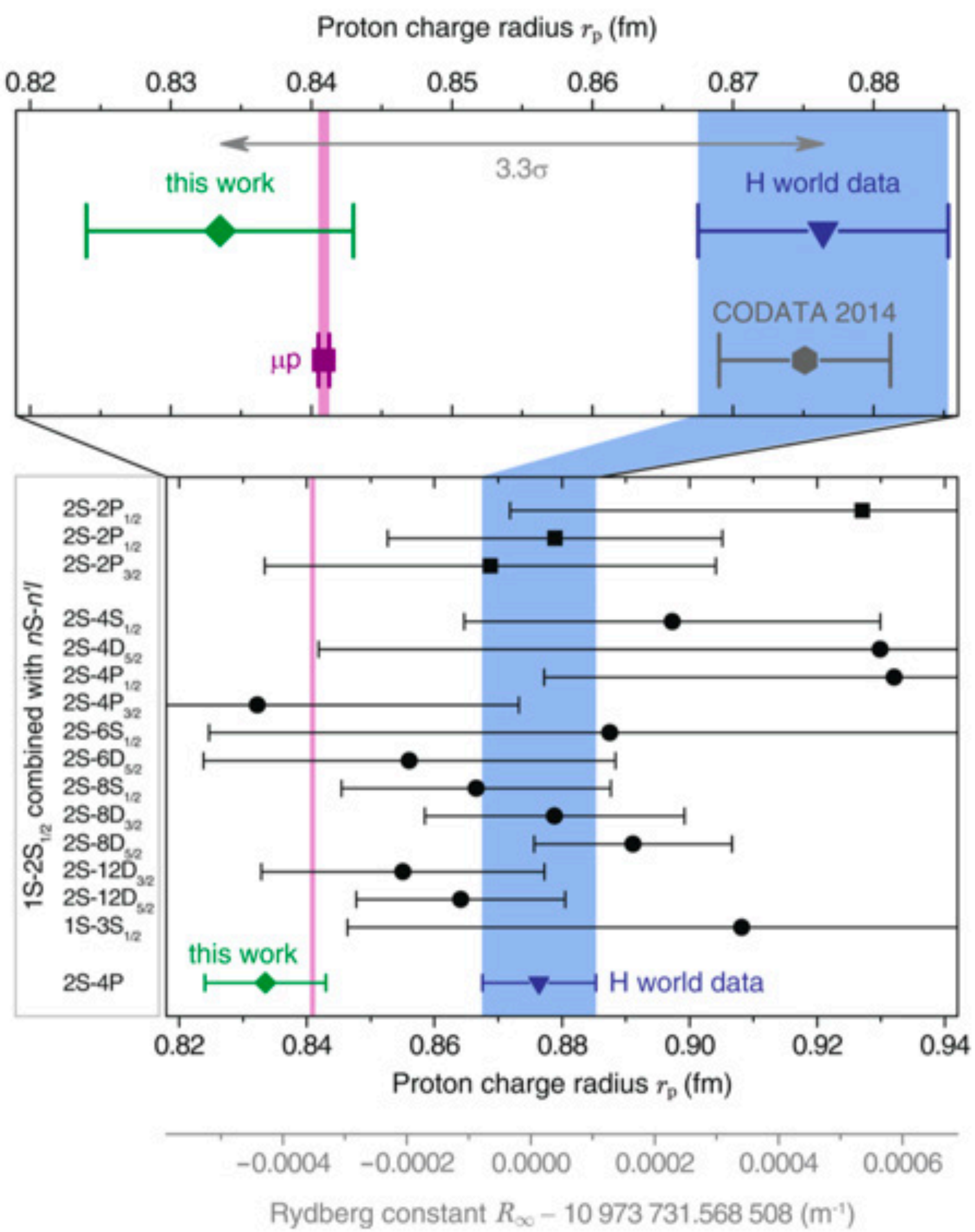
However.....

Important note: This is NOT what CODATA uses to extract the radius!



The plot thickens

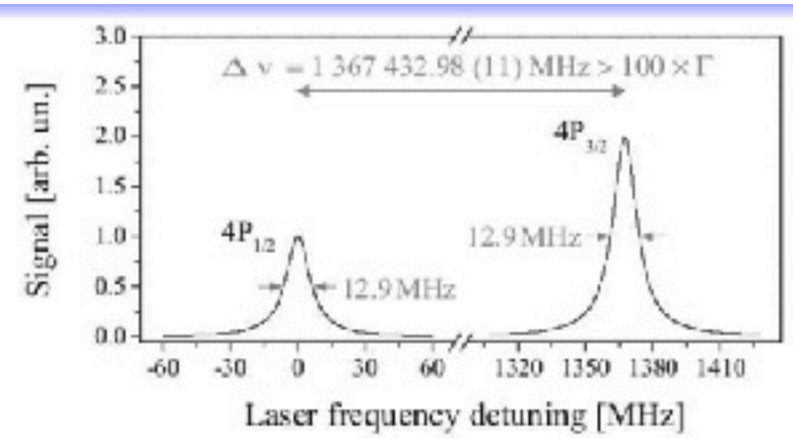
New eH 2s-4P measurement (Beyer et al.)

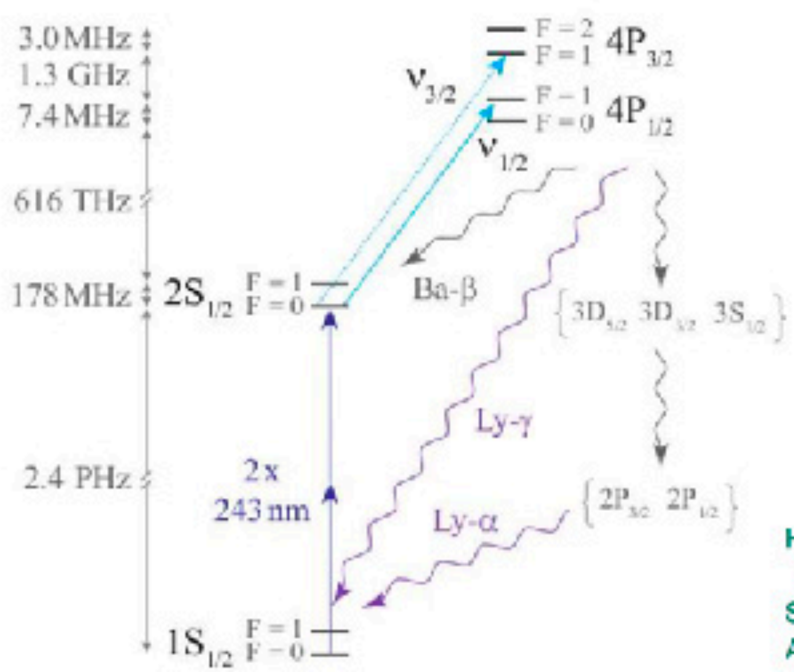


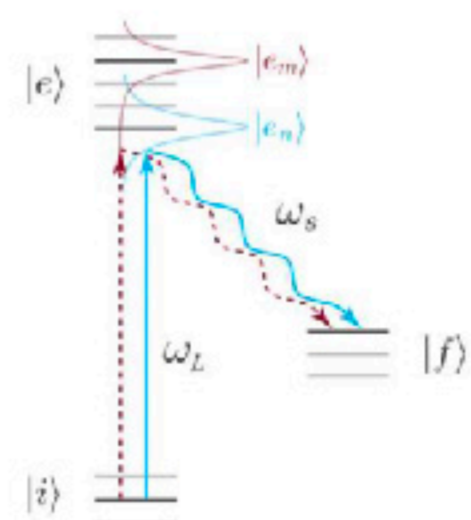
New eH measurement consistent with muonic hydrogen and inconsistent with all previous hydrogen spectroscopy measurements.

A word about Quantum Interference

Line shape distortions due to quantum interference of neighboring atomic resonances lead to a break-down of the simple approximation of natural atomic line shapes by Lorentz functions. They result in apparent geometry-dependent shifts of the observed line centers if not properly taken into account when fitting the experimental data. In the 2s-4p measurement the effect can be several times larger than the proton radius puzzle!





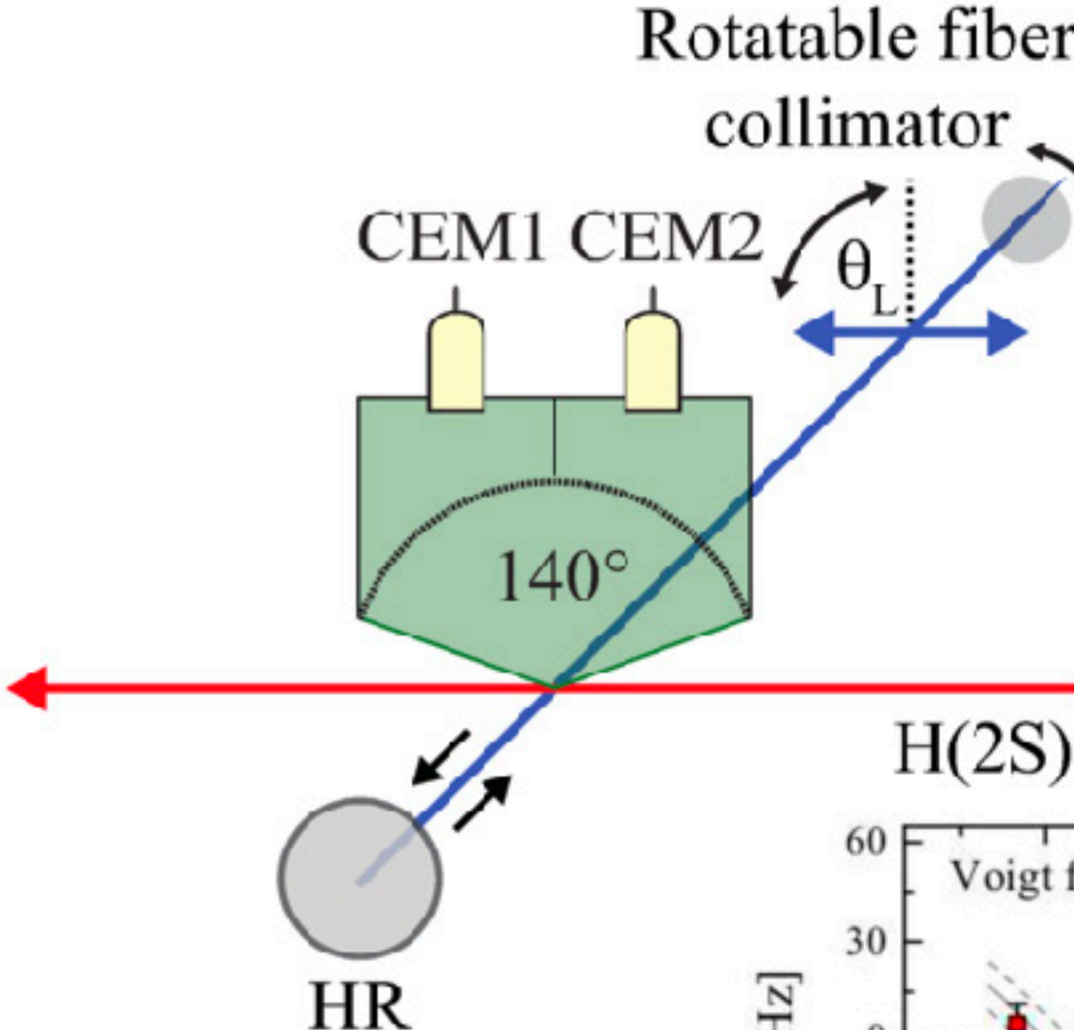


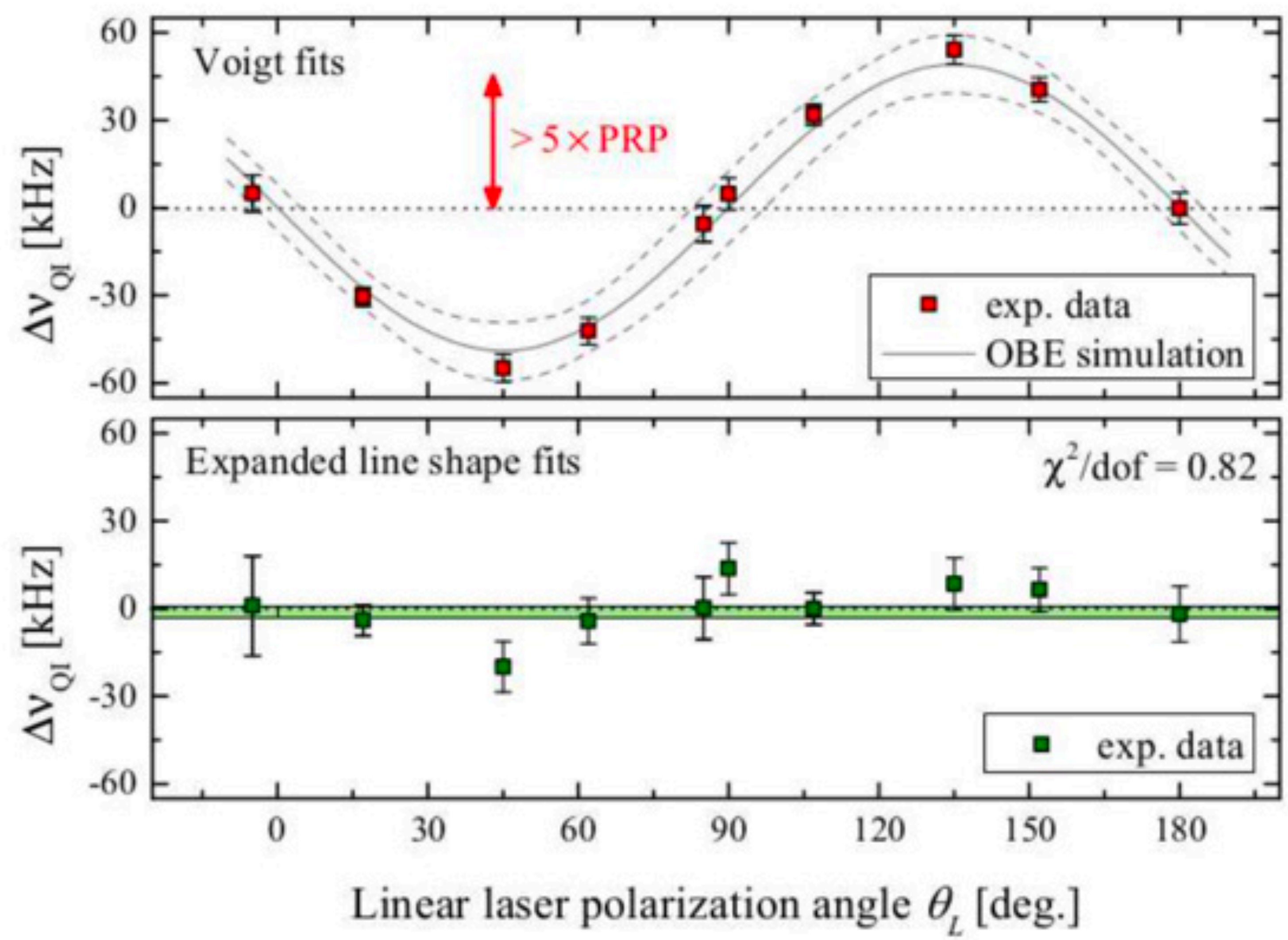
$$P(\omega) \propto \left| \frac{(\vec{d}_1 \cdot \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \cdot \vec{E}_0)\vec{d}_2 e^{i\Delta\phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

= Lorentzian(1) + Lorentzian(2) + cross-term (QI)

Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011), PRA 86, 040501 (2012), etc.
Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)
Amaro, RP *et al.*, PRA 92, 022514 (2015); PRA 92, 062506 (2015)

Slide courtesy R. Pohl.

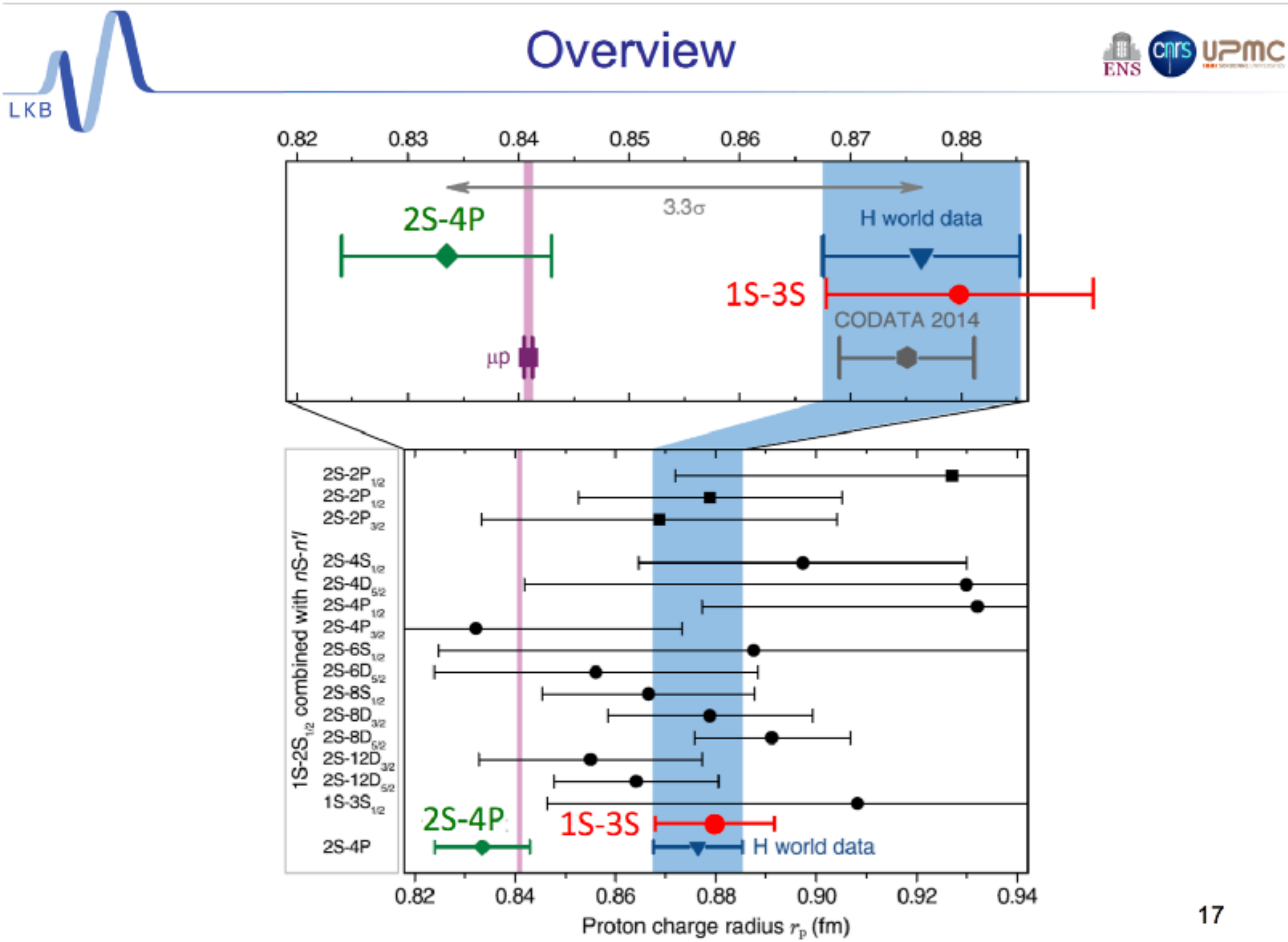


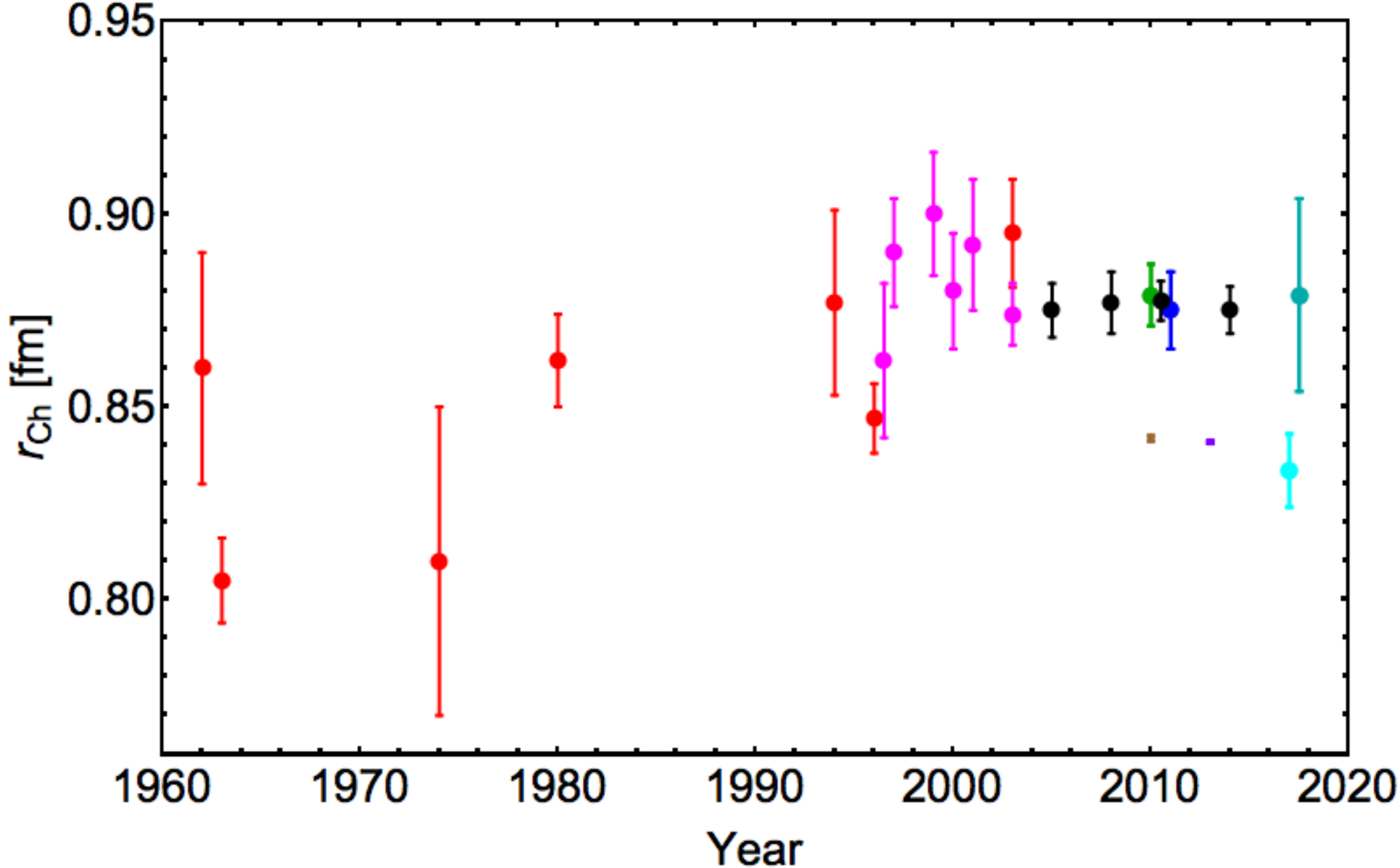


Beyer, RP *et al.*, submitted (2016)

And thickens again

New 1S-3S measurement (Fluerbaey)





0.95
0.90
0.85
0.80
r_{Ch} [fm]
1960
1970
1980
1990
2000
2010
2020
Year

The Scattering Experiments

The scattering knowledge is dominated by the recent Bernauer et al Mainz experiment, plus (our) JLab polarization data and older cross section experiments.

Extracting a radius from the scattering data has been a challenge.

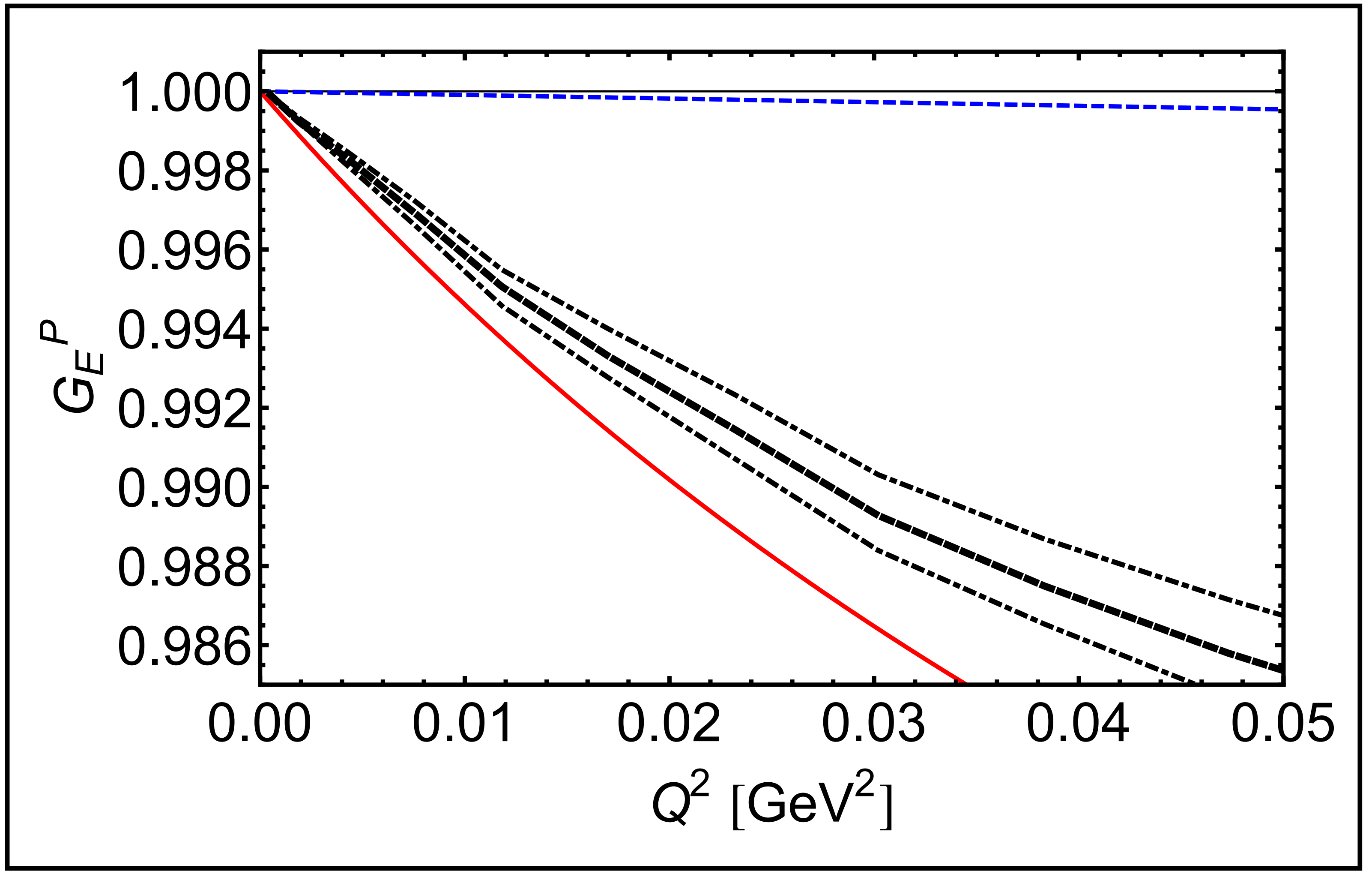
Until recently, all analyses ignored most of the following issues:

- Coulomb corrections
- Two-photon exchange
- Truncation offsets
- World data fits vs radius fits
- Model dependence
- Treatment of systematic uncertainties
- Fits with unphysical poles
- Including time-like data to ``improve'' radius

The good modern analyses tend to have fewer issues.

Experimental Error in the electron scattering measurements?

Essentially all (newer) electron scattering results are consistent within errors, hard to see how one could conspire to change the charge radius without doing something very strange to the FFs.



Examples of Bad Theory Explanations

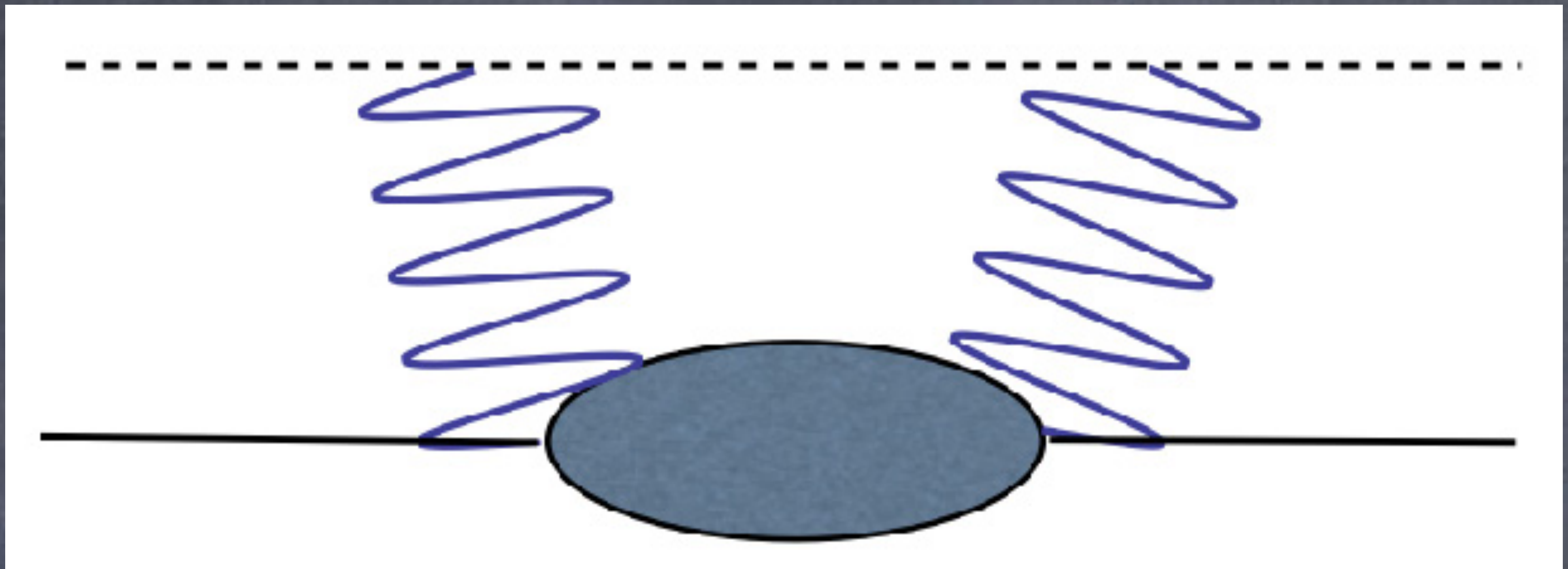
- De Rujula: large 3rd Zemach moment
- Thorns / lumps in form factor
- Quantum gravity!
- Non-commutative geometry
- Large extra dimensions!
- Mart & Sulaksono: oscillating protons
- Robson: rest frame form factor is not scattering form factor
- Giannini & Santopinto: frame dependence of charge radii

Possible Theory Explanations

- What are viable theoretical explanations of the Radius Puzzle?
  - Novel Beyond Standard Model Physics: Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius
  - Novel Hadronic Physics: G. Miller: two-photon correction
  - No explanation with majority support in the community
  - See fall 2012 Trento Workshop on PRP for more details:

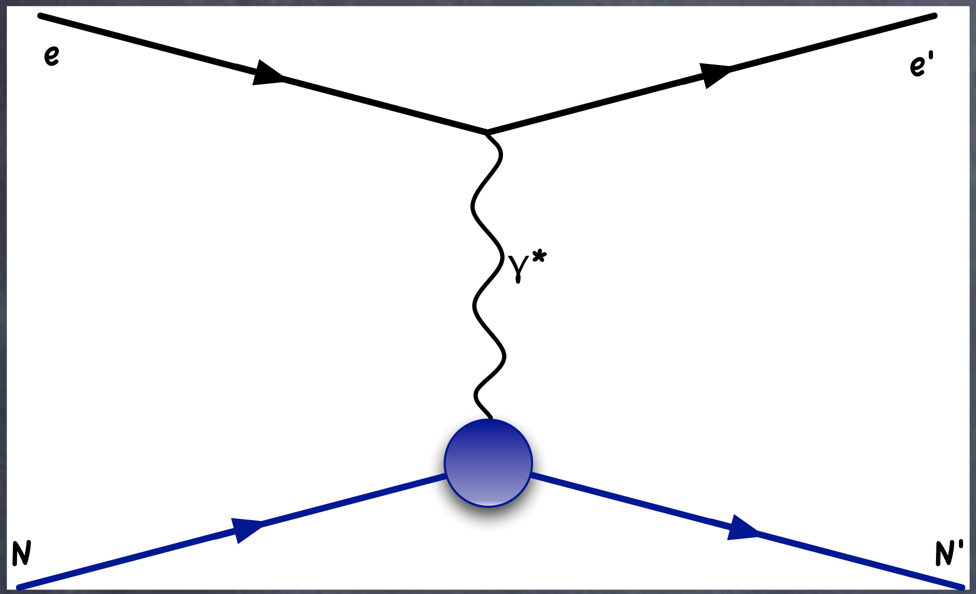
http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento

Theory Explanations: Novel Hadronic Physics



- There is a polarizibility correction that depends on m_l^4, affecting muons but not electrons
- Evaluation uses a model for the Q^2 dependence of the forward virtual Compton tensor for subtractions in dispersion relations
- Prediction: enhanced 2γ exchange in μ scattering: 2–4%
- Calculations using chiral perturbation theory for the low Q^2 behavior coupled to a pQCD inspired inspired Q^{-4} falloff suggest correction is far too small
- Infinite set of possible models allow constraints to be evaded.

Theory Explanations: Novel Beyond Standard Model Physics

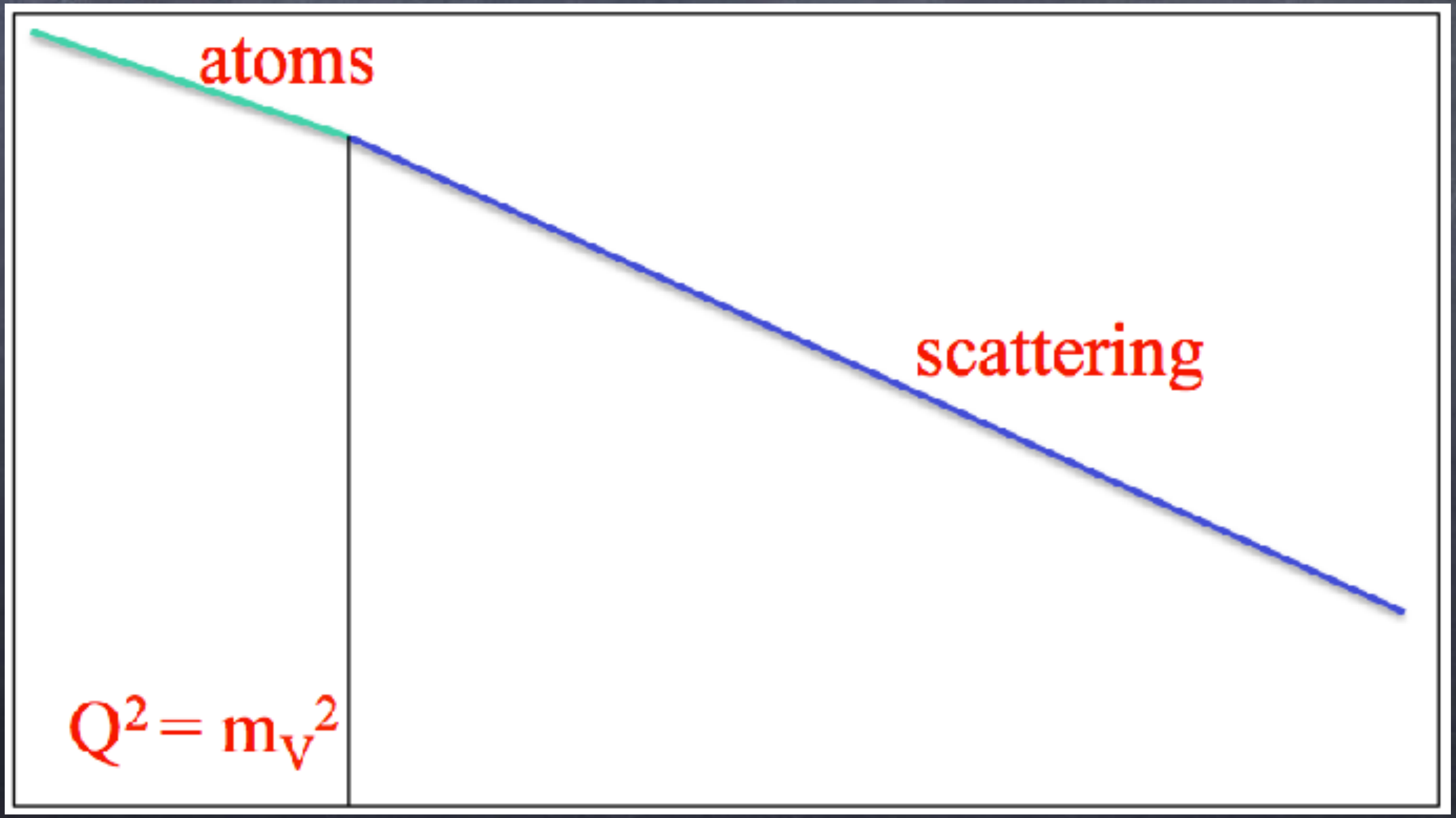


- Ideally (?), one new particle explains (dark photon?) Proton Radius Puzzle, μ g-2, cosmological positron excess / excess γ's from galactic center

- But many constraints from existing physics and the 3 issues may be unrelated
- Most constraints relaxed if you allow flavor dependent coupling.
- Examples follow...

Theory Explanations: Novel BSM Physics

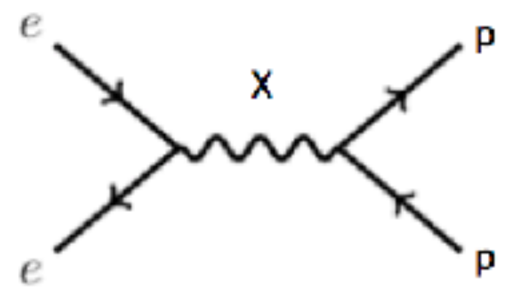
- Pospelov: effect on form factors of new dark photon – would explain scattering vs. atom difference, but not hydrogen vs. muonic hydrogen



Newest idea - Ralston (2016)

A global fit to everything, permitting an alternative

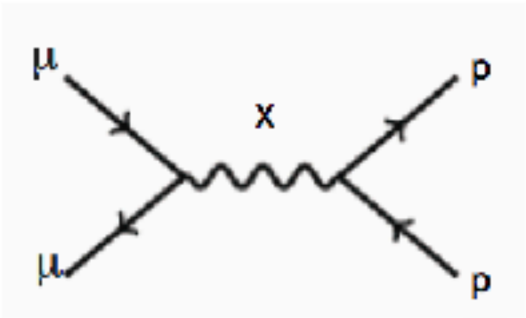
***"no name theory"* of particle X**

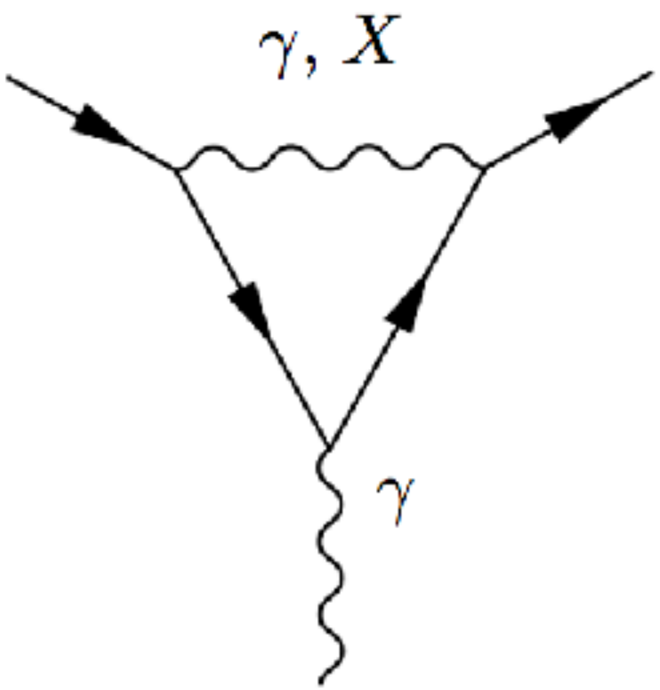


more general than dark photon

$$g_e^2 = g_\mu^2 = g_p^2 = g^2$$

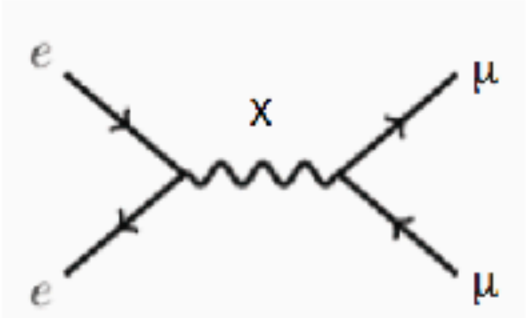
$$\alpha_X = \xi m_X^2 = g^2/4\pi$$





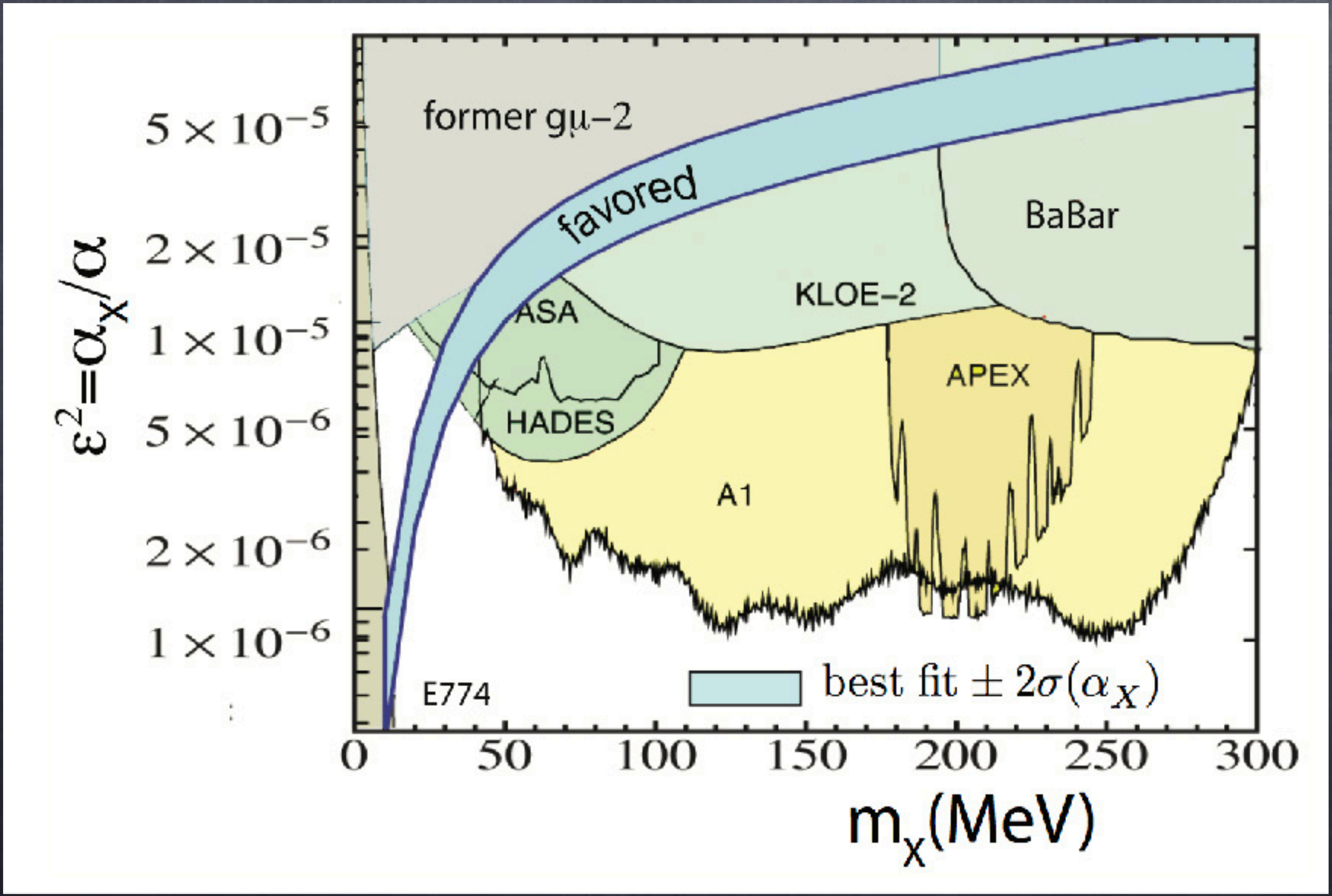
minimal
"bottom-up"
data driven

No other assumptions



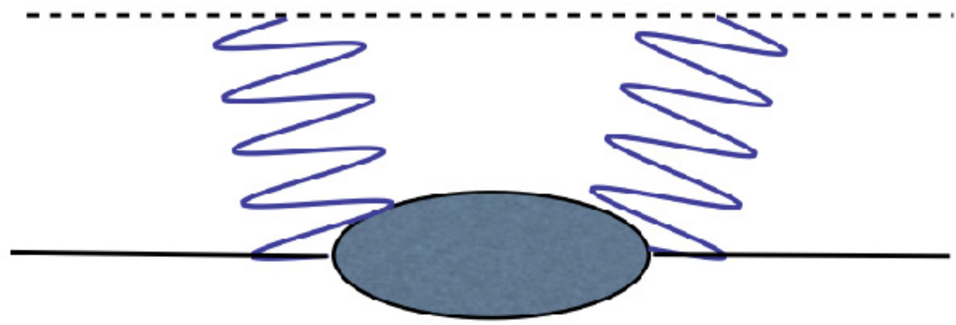
$$a_e^{theory} = 1.7147 \times 10^{-12} + 0.159155\alpha - 0.0332818\alpha^2 + 0.0380966\alpha^3 - 0.0196046\alpha^4 + 0.0299202\alpha^5 + 0.027706\,\xi m_X^2 f(m_X/m_\ell)$$

Newest idea - Ralston (2016)



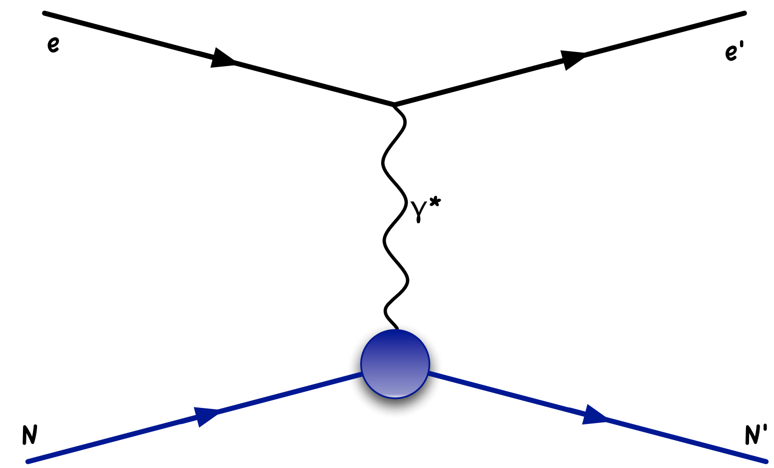
The (surviving) Theory Explanations

- Novel Hadronic Physics



- There is a polarizibility correction that depends on m_l^4, affecting muons but not electrons
- Part of the correction is not (strongly) constrained by data or theory; it might resolve puzzle

- Novel Beyond Standard Model Physics



- There could be unknown particles that couple μp but not ep, in addition to γ
- Evading impacts on known physics requires 2 new particles for cancellations

Status

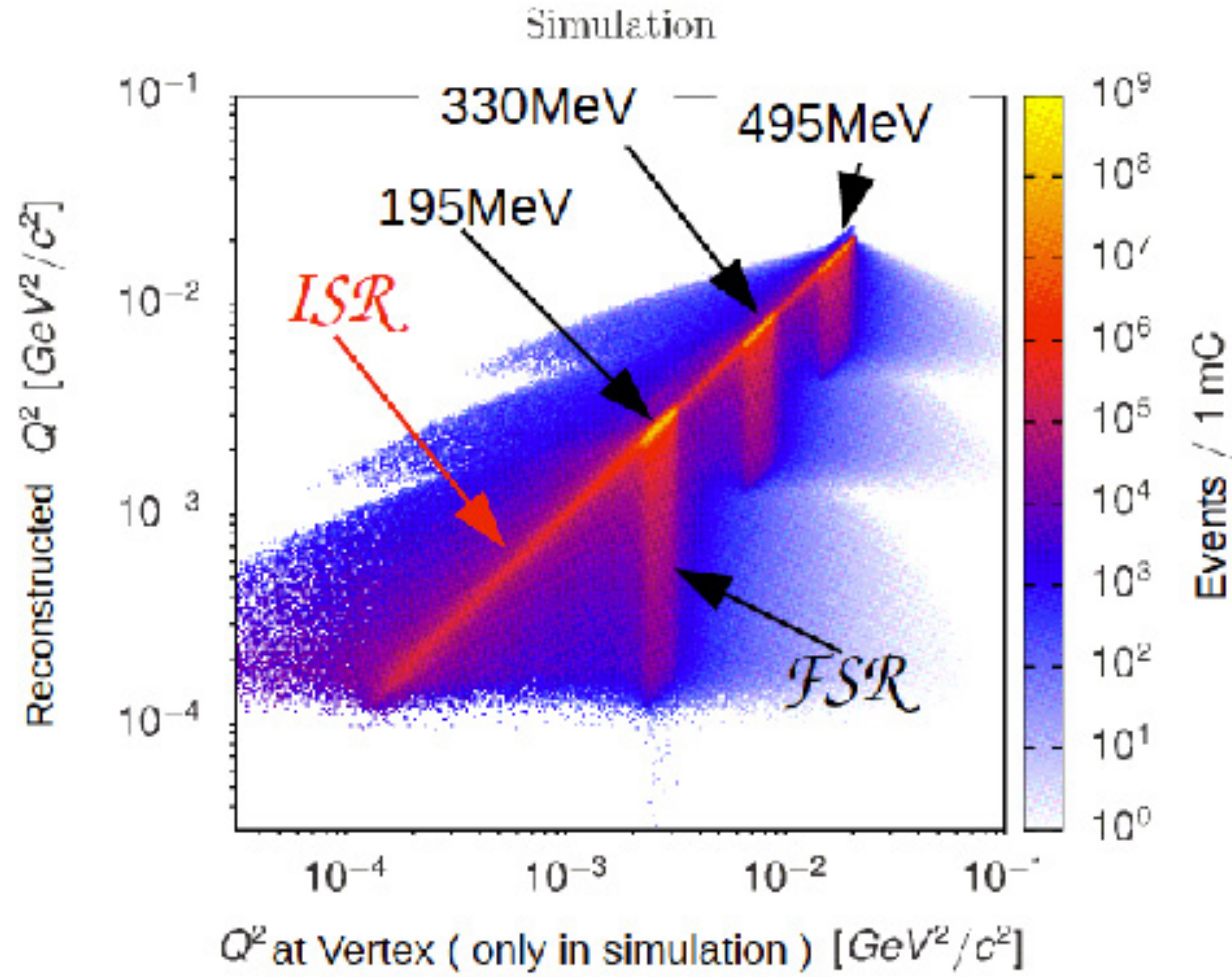
- Up to 2010, we were all happy that atomic hydrogen and electron scattering gave the same proton radius.
- Now we are even happier that muonic hydrogen gives a different proton radius!
- Many possible explanations are ruled out, and the remaining explanations all seem unlikely
  - Experimental error: seems unlikely
  - BSM: not ruled out, but somewhat contrived models
  - Hadronic: not ruled out, but much bigger than most theorists find palatable.
- New data are needed

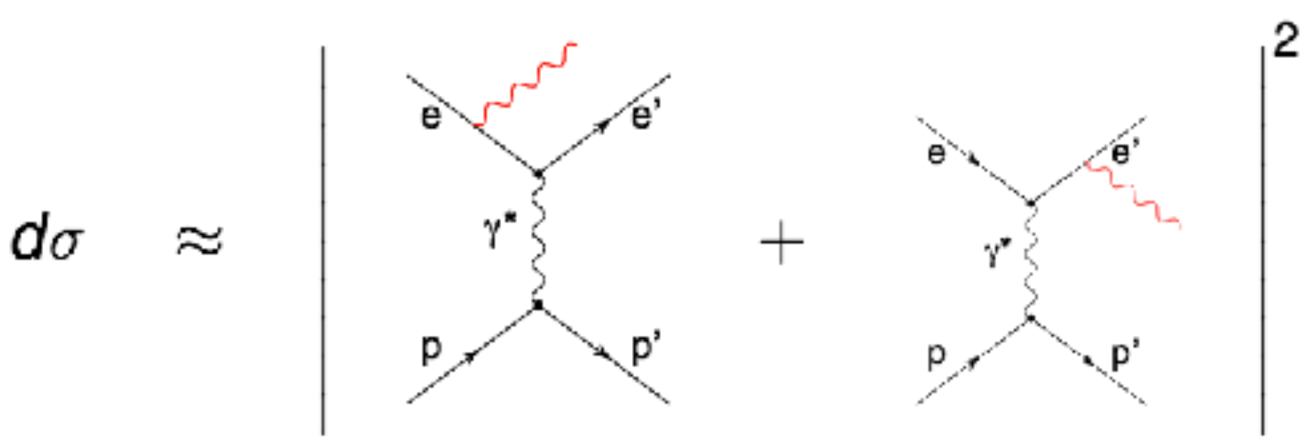
How do we Resolve the Radius Puzzle?

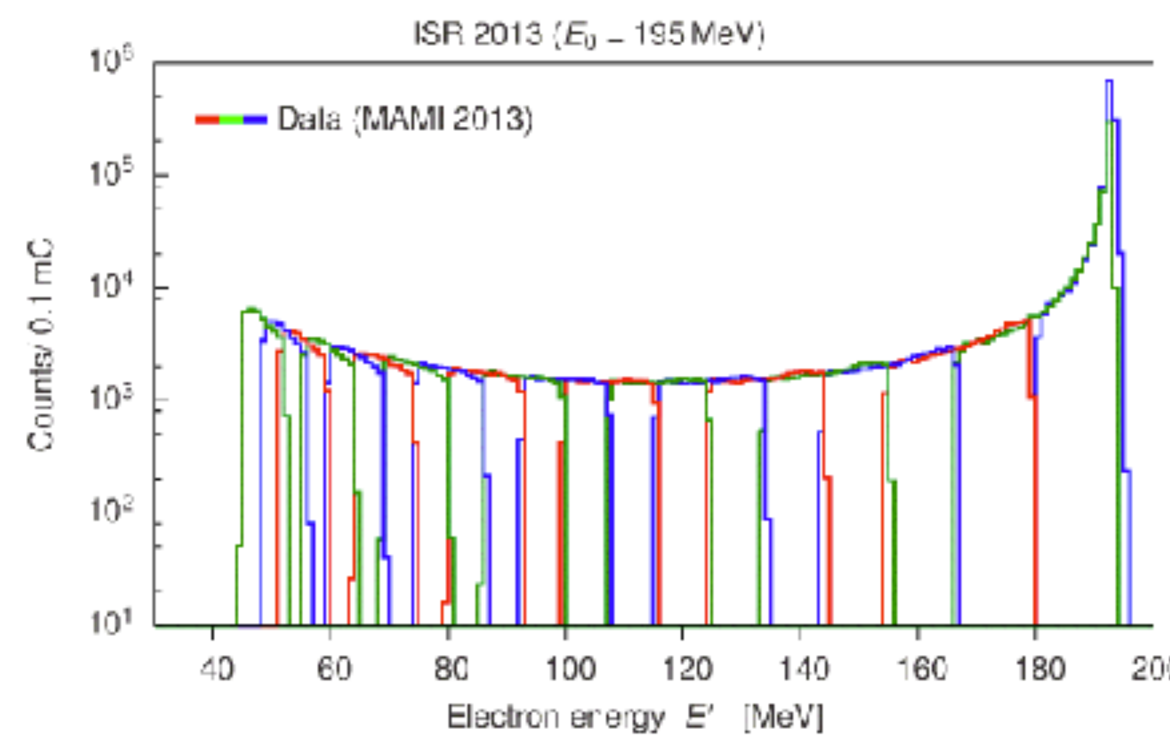
- Theorists keep checking theories
- Experiments check old results, test e / μ differences, new particles, scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation, enhanced 2γ exchange
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2 - Mainz ISR, JLab PRAD, Several more efforts.
  - **Muon scattering!**
  - Rare K decays, etc etc

Where to now? Mainz ISR Experiment

- Use initial state radiation to get effective low Q^2 at vertex.
- Q^2 downto 10^{-4} GeV^2.
- Requires highly accurate radiative models.
- Aiming for 1% cross sections.
- Already took data.

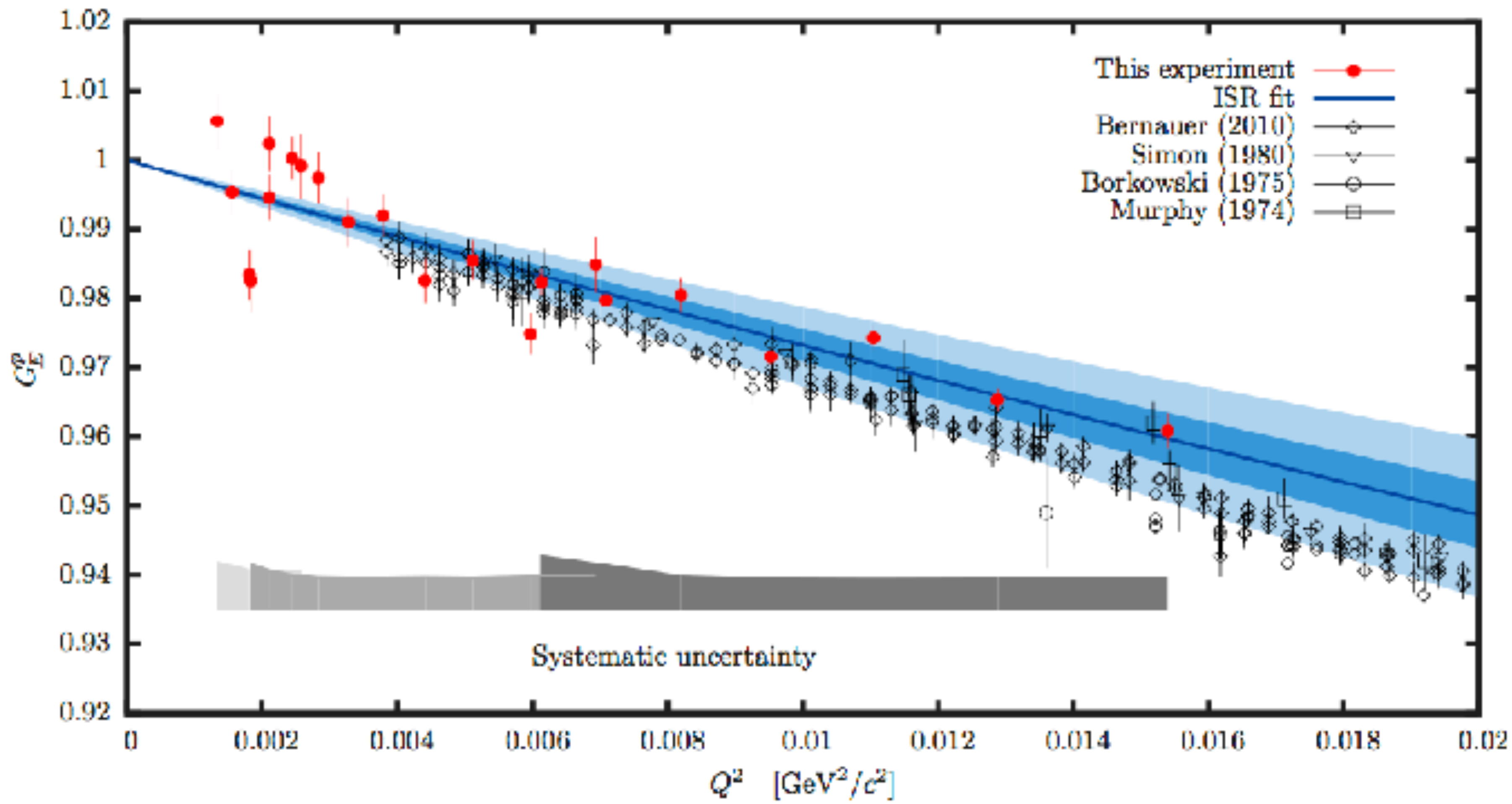






Where to now?

Mainz ISR Experiment



$$r_p = (0.810 \pm 0.035_{\text{stat}} \pm 0.074_{\text{syst.}} \pm 0.003_{\Delta a, \Delta b})\ \text{fm}.$$

nated by systematic effects. Due to the limiting backgrounds and corresponding systematic uncertainties, we are unable to distinguish convincingly between the CODATA and the muonic hydrogen radii. However, we have proven the technique of initial state radiation to be a viable method for investigating the electromagnetic struc-

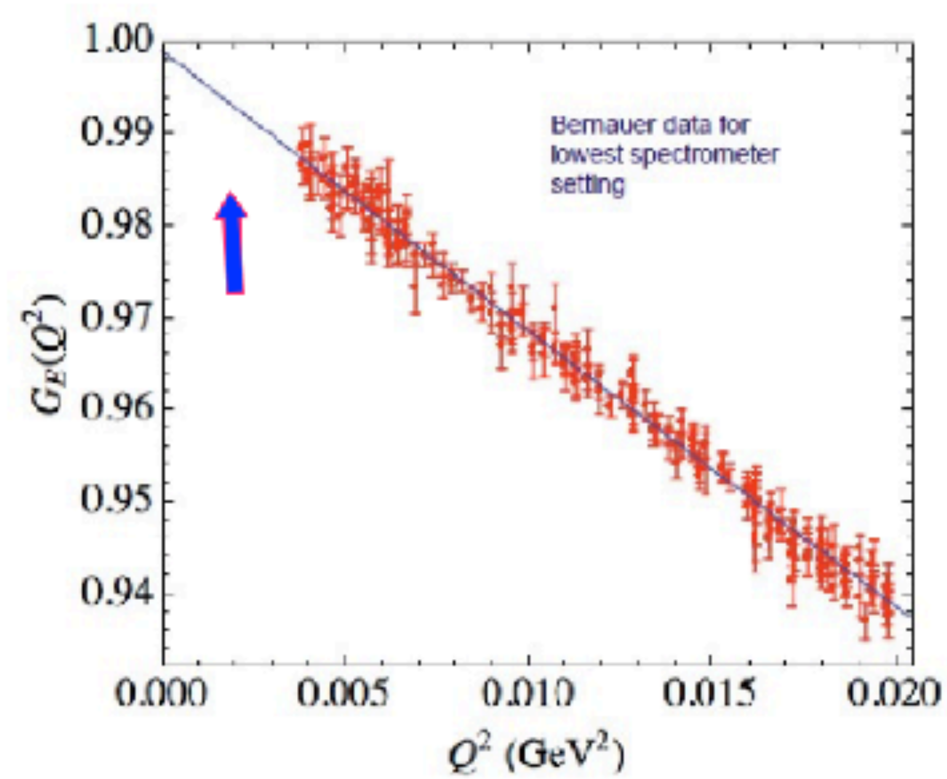
M. Mihovilovič et al., Phys.Lett. B771 (2017) 194-198

Where to now? JLab PRad

The PRad Experimental Approach

- Experimental goals:
  - reach to very low Q^2 range (~ 10^{-4} GeV/C^2)
  - reach to sub-percent precision in cross section
  - large Q^2 range in one experimental setting

- Suggested solutions:
  - ✓ use high resolution high acceptance calorimeter:
    - reach smaller scattering angles: ($\Theta = 0.7^0 - 7.0^0$)
      ($Q^2 = 1\text{x}10^{-4} \div 6\text{x}10^{-2}$) GeV/$c^2$
      large Q^2 range in one experimental setting!
      essentially, model independent r_p extraction
  - ✓ Simultaneous detection of $ee \to ee$ Moller scattering
    - (best known control of systematics)
  - ✓ Use high density windowless H_2 gas flow target:
    - beam background fully under control
    - minimize experimental background



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

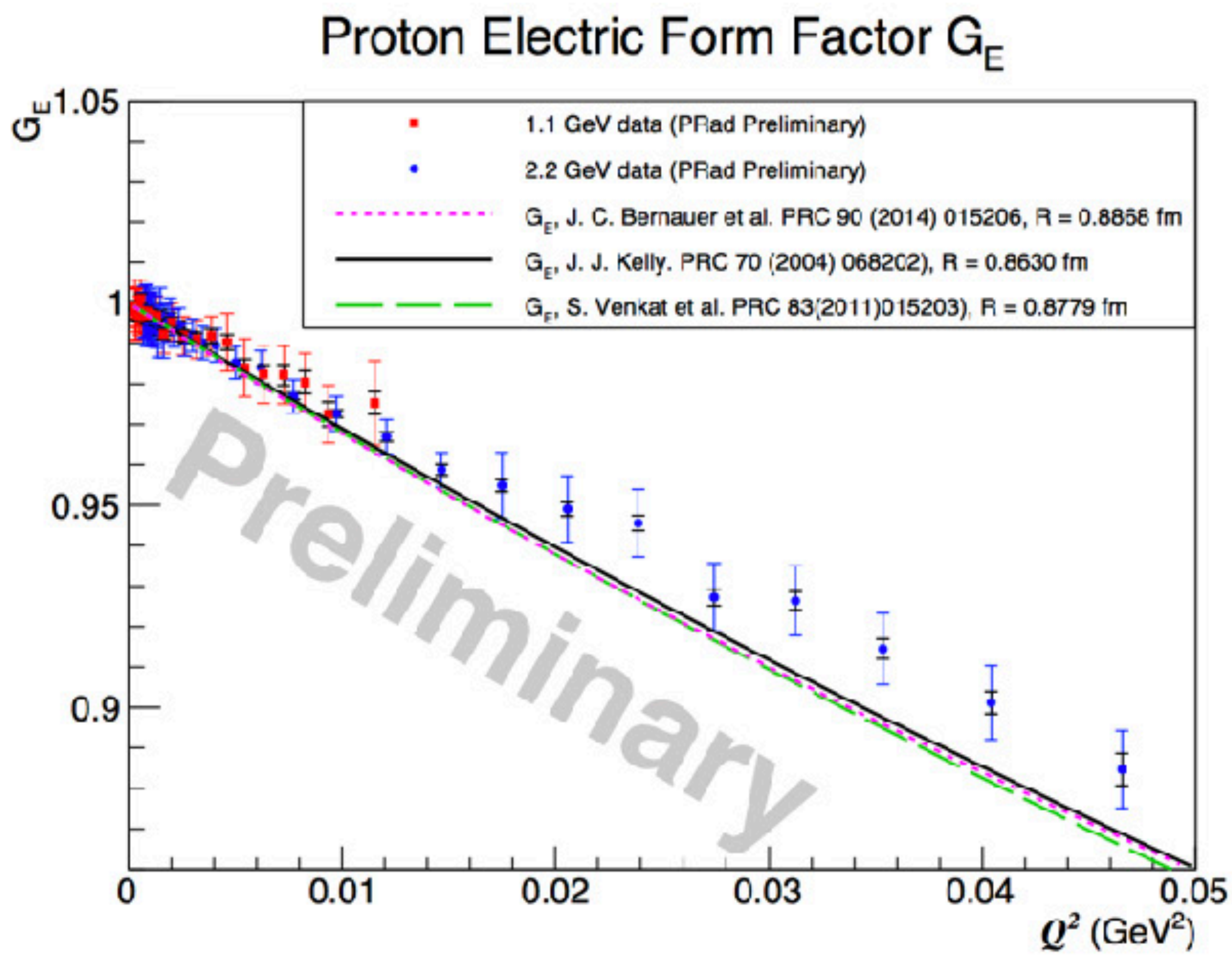
- Two beam energies: E_0 = 1.1 GeV and 2.2 GeV to increase Q^2 range
- Will reach sub-percent precision in r_p extraction
- Approved by JLab PAC39 (June, 2012) with high "A" scientific rating

A. Gasparian Hadron-2016

Where to now?

JLab PRad

- Proton electric form factor G_E v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Systematic uncertainties shown as colored error bars
- Preliminary G_E slope seems to favor smaller radius



Taken from CIPANP PRAD talk (W. Xiong)

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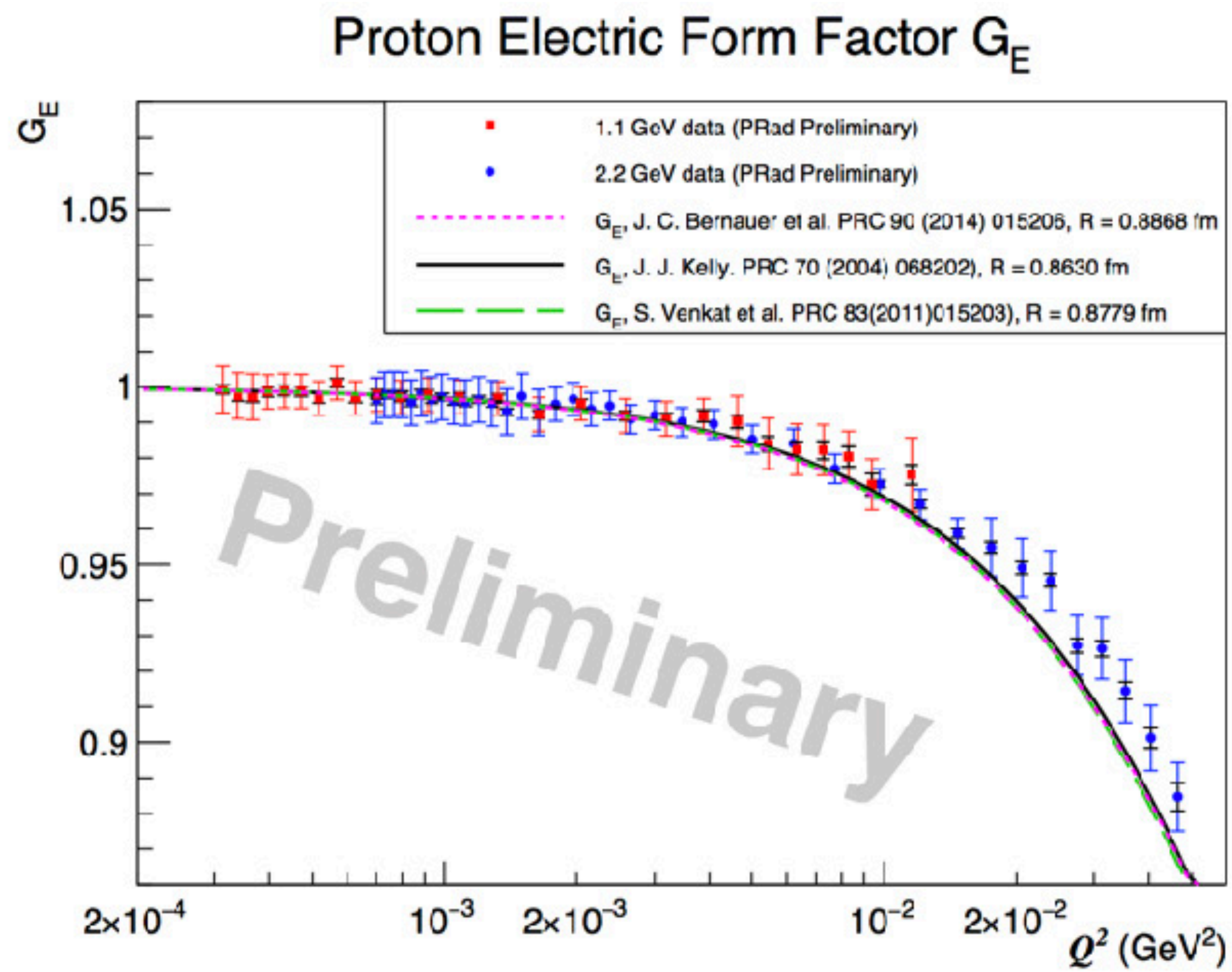

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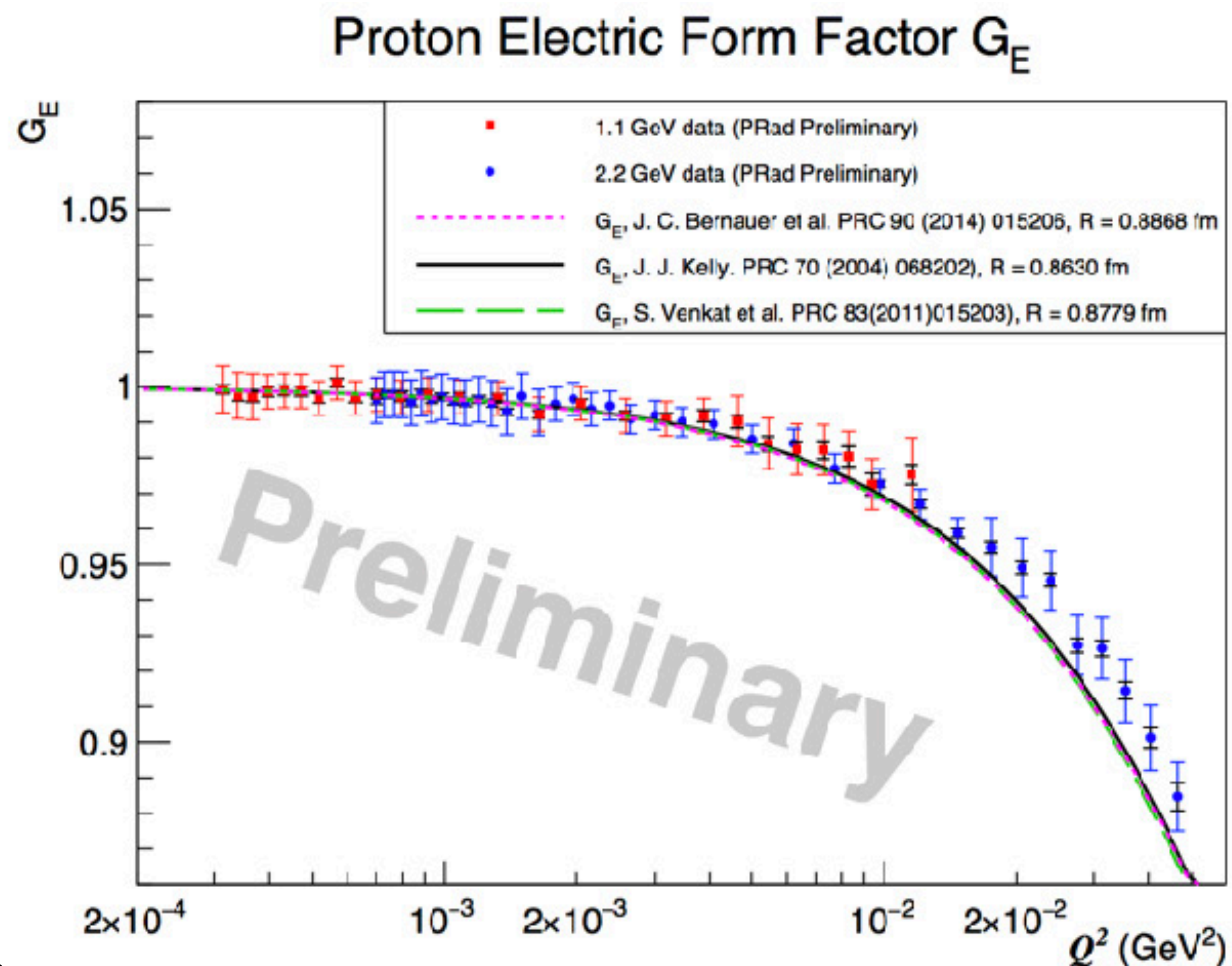


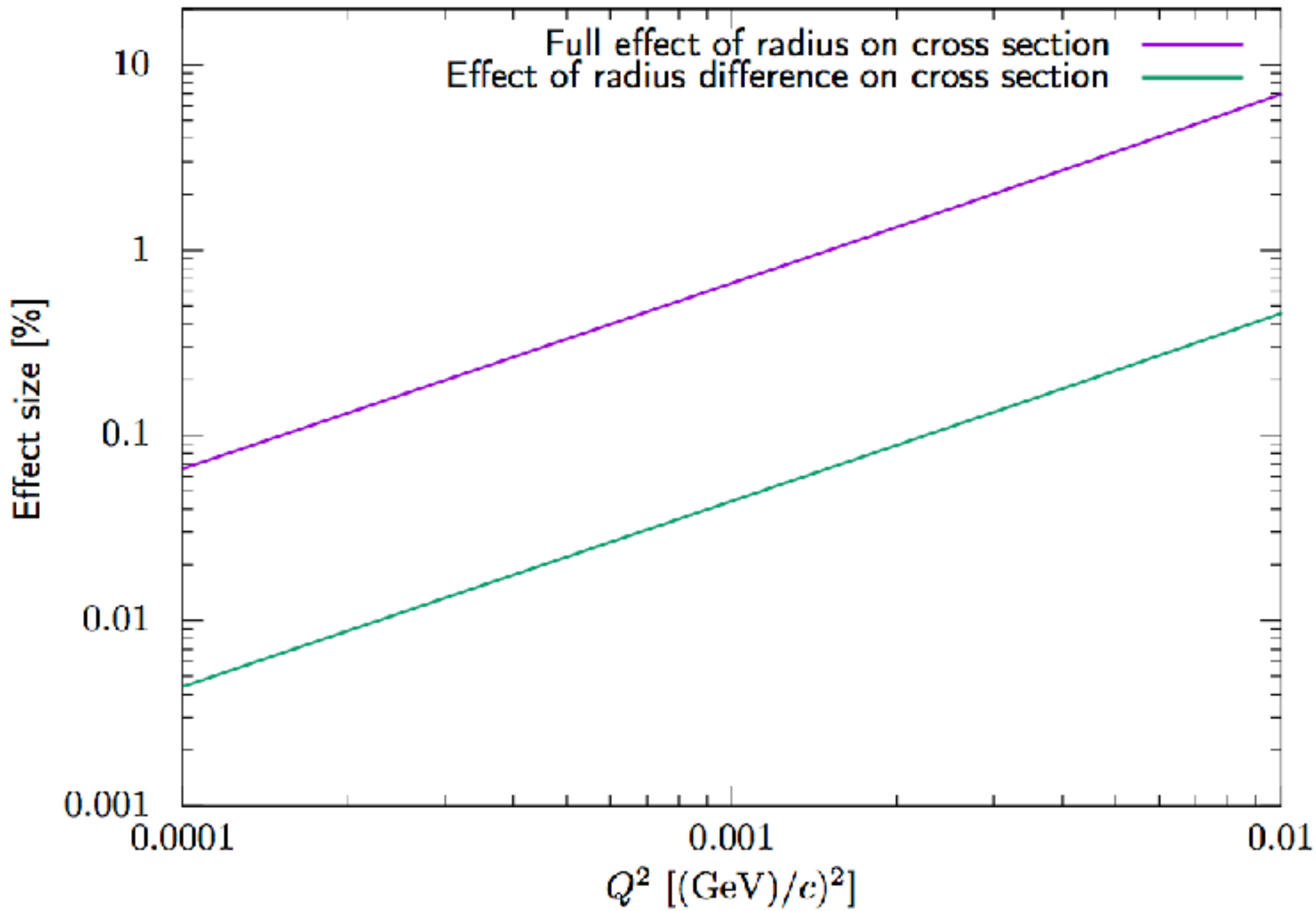
Nope

(higher order terms)

Taken from CIPANP PRAD talk (W. Xiong)

Unfortunately

Low Q^2 Measurements in eP scattering have been pushed about as far as they can go



MUSE - PSI R12-01.1 Technique

r_p (fm)	ep	μp
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	?

$d\sigma/d\Omega(Q^2)$ = counts / ($\Delta\Omega$ N_{beam} $N_{target/area}$ x corrections x efficiencies)

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{d\sigma}{d\Omega}\right]_{ns} \times \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + \left(2\tau - \frac{m^2}{M^2}\right) G_M^2(Q^2)\frac{\eta}{1-\eta}\right]$$

$$\left[\frac{d\sigma}{d\Omega}\right]_{ns} = \frac{\alpha^2}{4E^2}\frac{1-\eta}{\eta^2}\frac{1/d}{\left[1+\frac{2Ed}{M}\sin^2\frac{\theta}{2}+\frac{E}{M}(1-d)\right]} \qquad d = \frac{\left[1-\frac{m^2}{E^2}\right]^{1/2}}{\left[1-\frac{m^2}{E'^2}\right]^{1/2}}$$

$$\eta = Q^2/4EE'$$

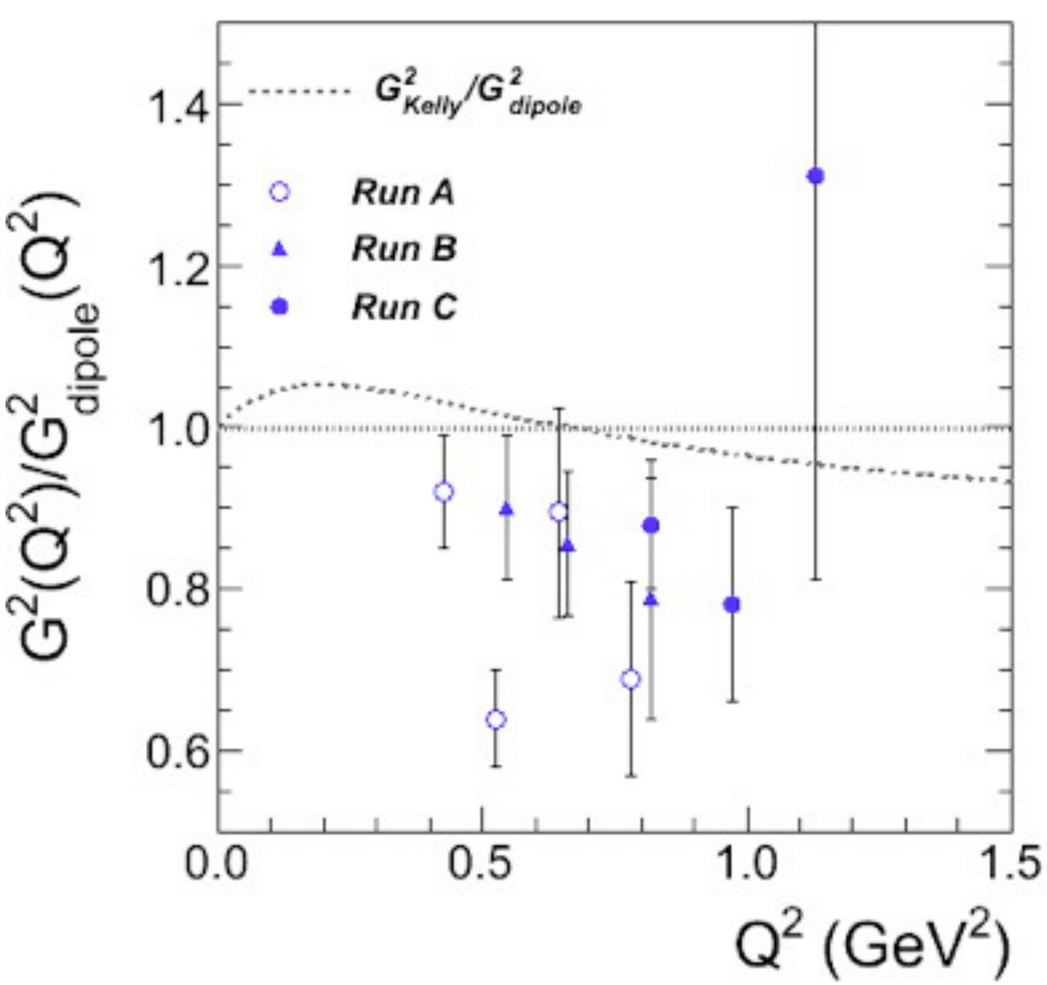
following Preedom & Tegen, PRC36, 2466 (1987)

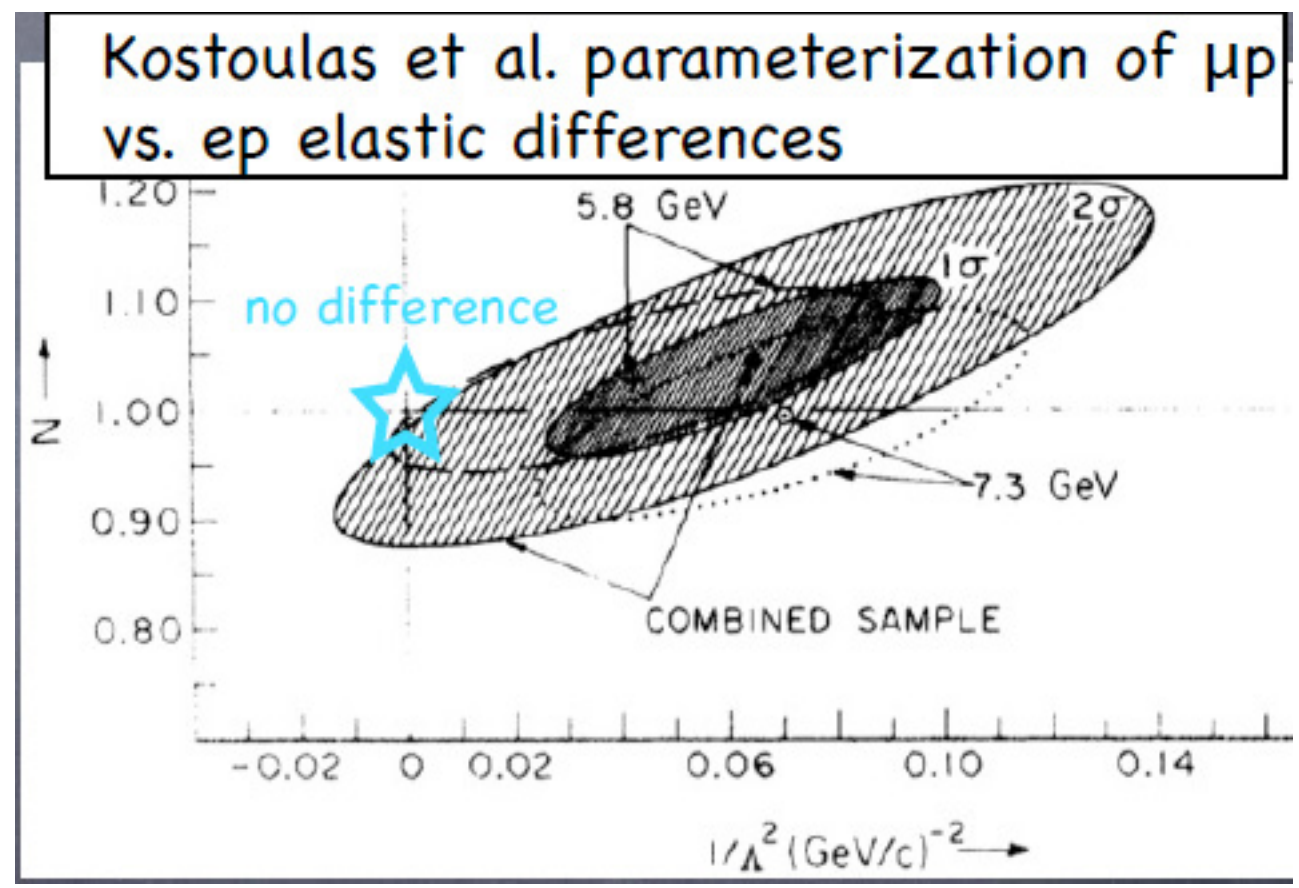
MUSE - PSI R12-01.1 Technique

r_p (fm)	ep	μp
atom	Several new efforts	Heavier light nuclei
scattering	Mainz ISR JLab PRAD LEDEX@JLab	**MUSE**

e-μ Universality

In the 1970s / 1980s, there were several experiments that tested whether the ep and μp interactions are equal. They found no convincing differences, once the μp data are renormalized up about 10%. In light of the proton ``radius'' puzzle, the experiments are not as good as one would like.

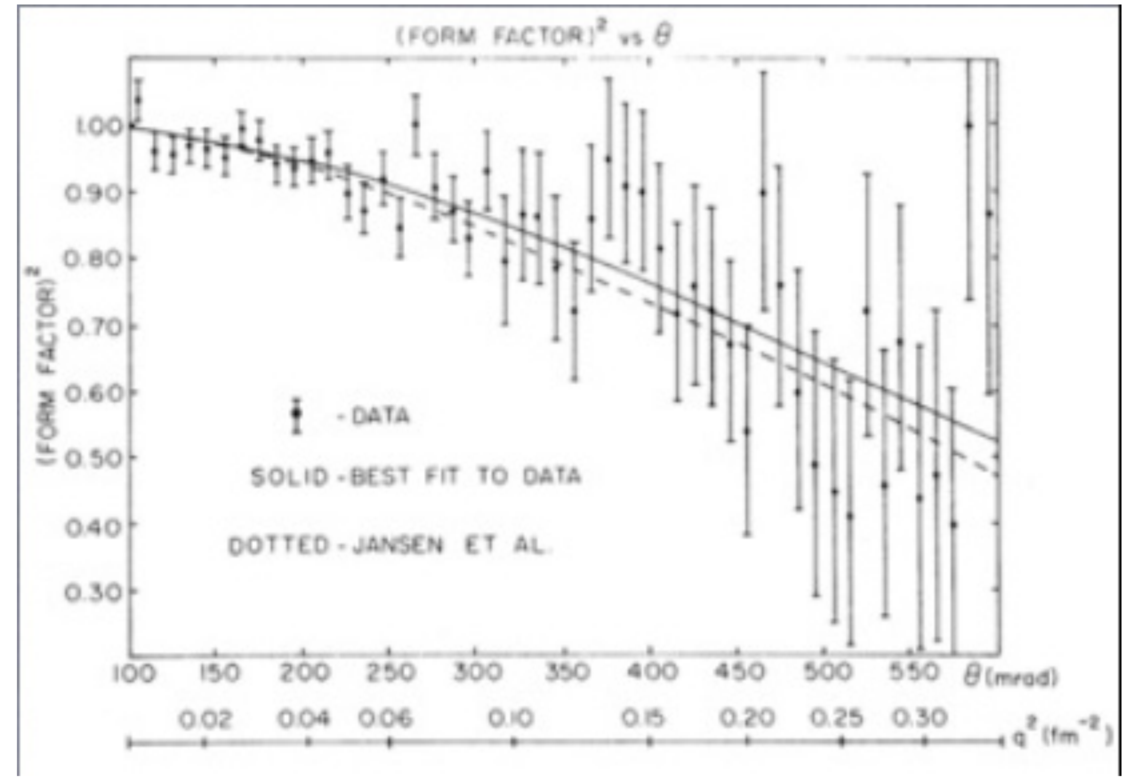




e-μ Universality

The 12C radius was determined with ep scattering and μC atoms.

The results agree:
Cardman et al. eC: 2.472 ± 0.015 fm
Offermann et al. eC: 2.478 ± 0.009 fm
Schaller et al. μC X rays: 2.4715 ± 0.016 fm
Ruckstuhl et al. μC X rays: 2.483 ± 0.002 fm
Sanford et al. μC elastic: 2.32 ± 0.13 fm



Perhaps carbon is right, e's and μ's are the same.
Perhaps hydrogen is right, e's and μ's are different.
Perhaps both are right - opposite effects for proton and neutron cancel with carbon.
But perhaps the carbon radius is insensitive to the nucleon radius, and μd or μHe would be a better choice.

MUSE is not your garden variety scattering experiment

Low beam flux

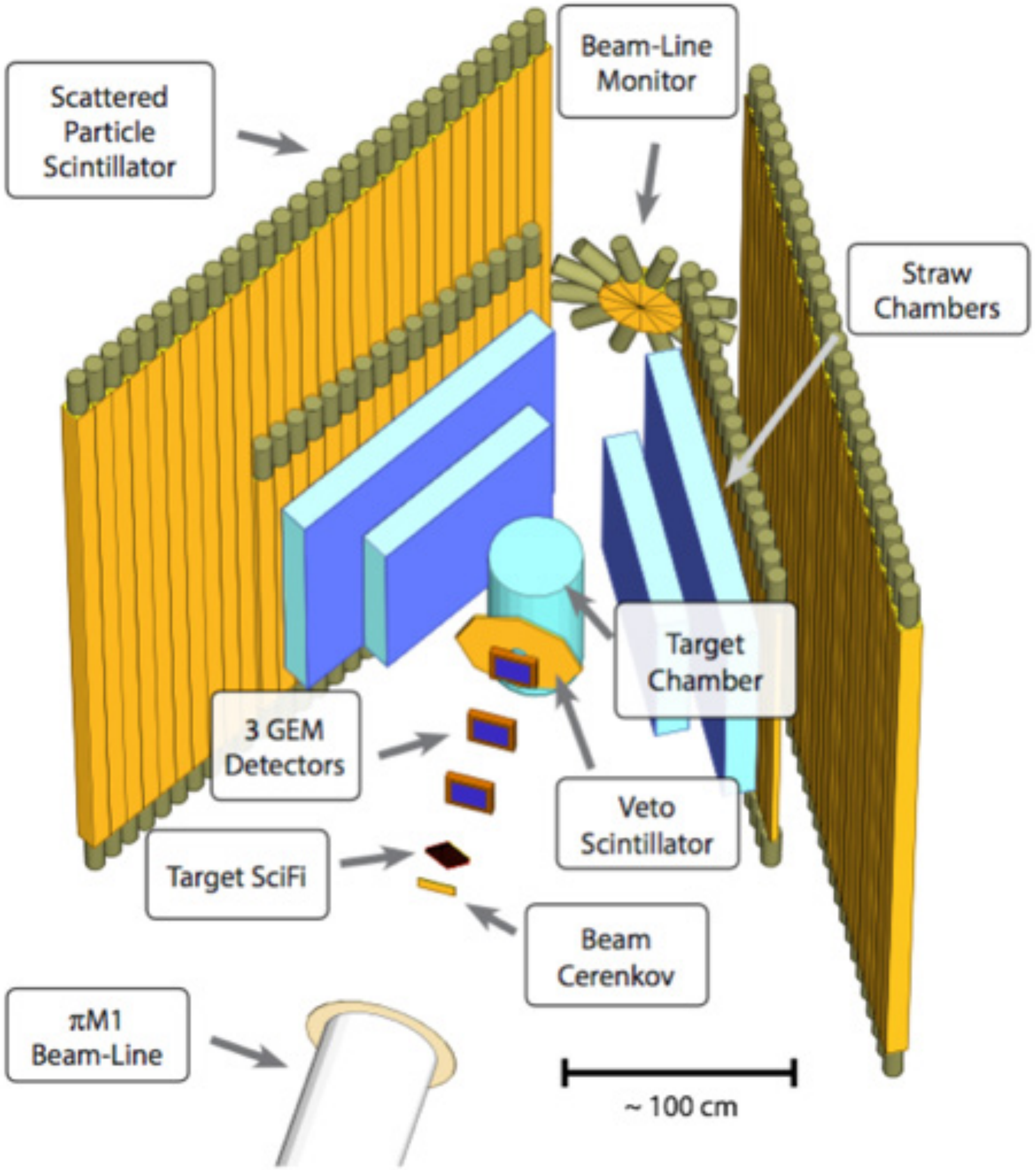
- Large angle, non-magnetic detectors.

Secondary beam (large emittance)

- Tracking of beam particles to target.

Mixed beam

- Identification of beam particle in trigger.



Experiment Overview

PSI πM1 channel

≈115, 153, 210 MeV/c mixed beams of $e^\pm$, $\mu^\pm$ and $\pi^\pm$

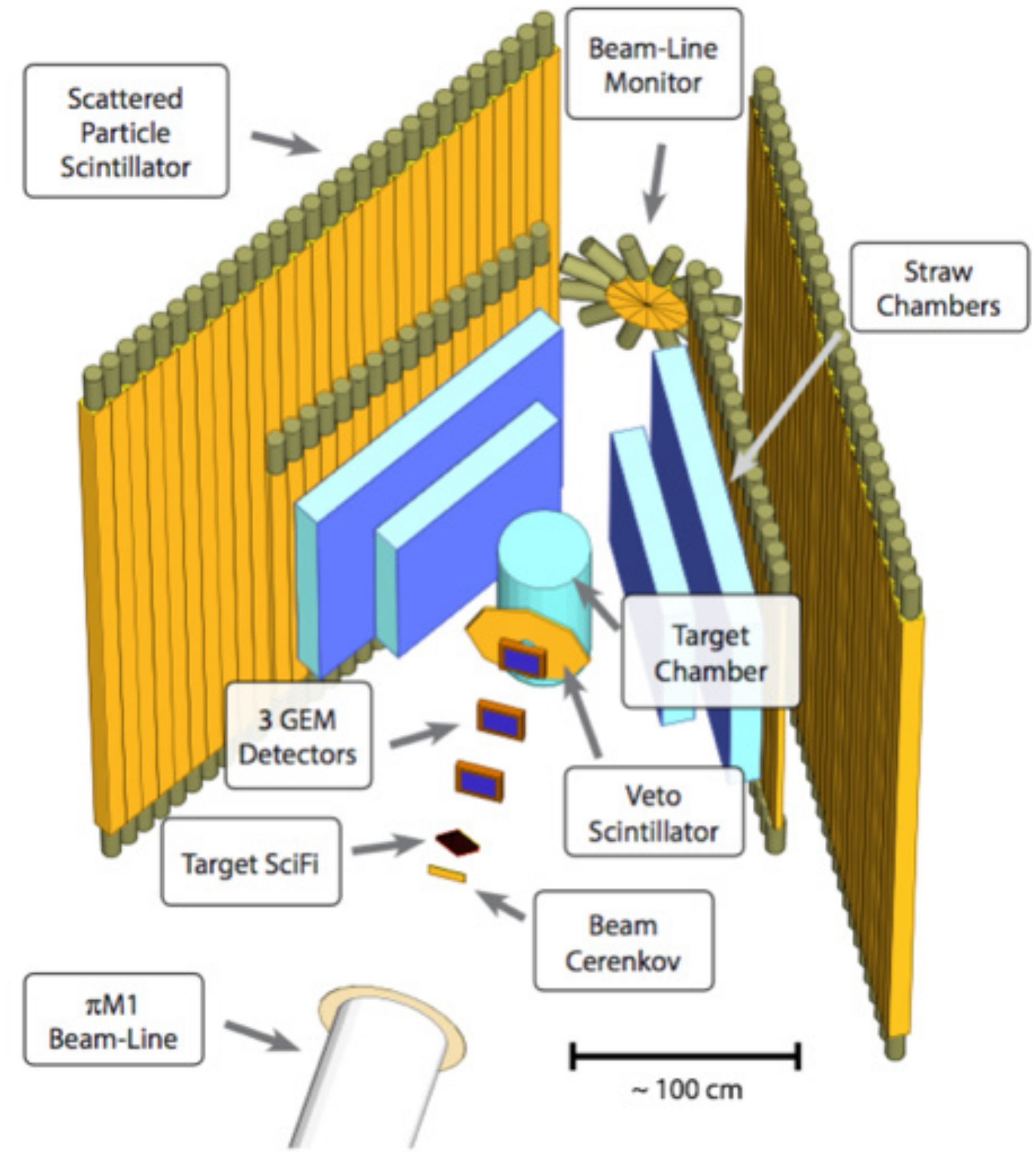
$\theta \approx 20^o - 100^o$

$Q^2 \approx 0.002 - 0.07$ GeV^2

About 5 MHz total beam flux, ≈2-15% μ's, 10-98% e's, 0-80% π's

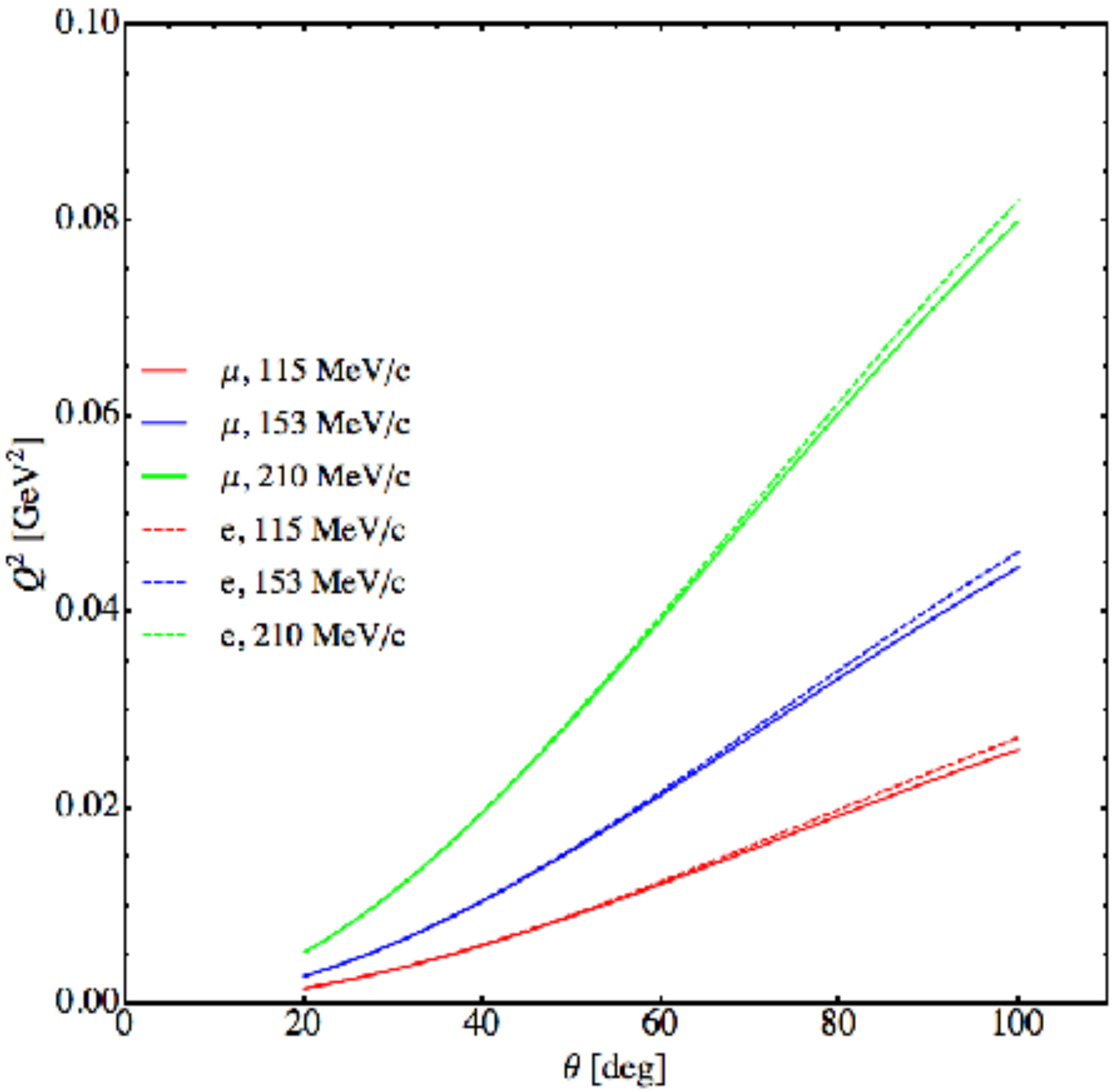
Beam monitored with SciFi, beam Cerenkov, GEMs

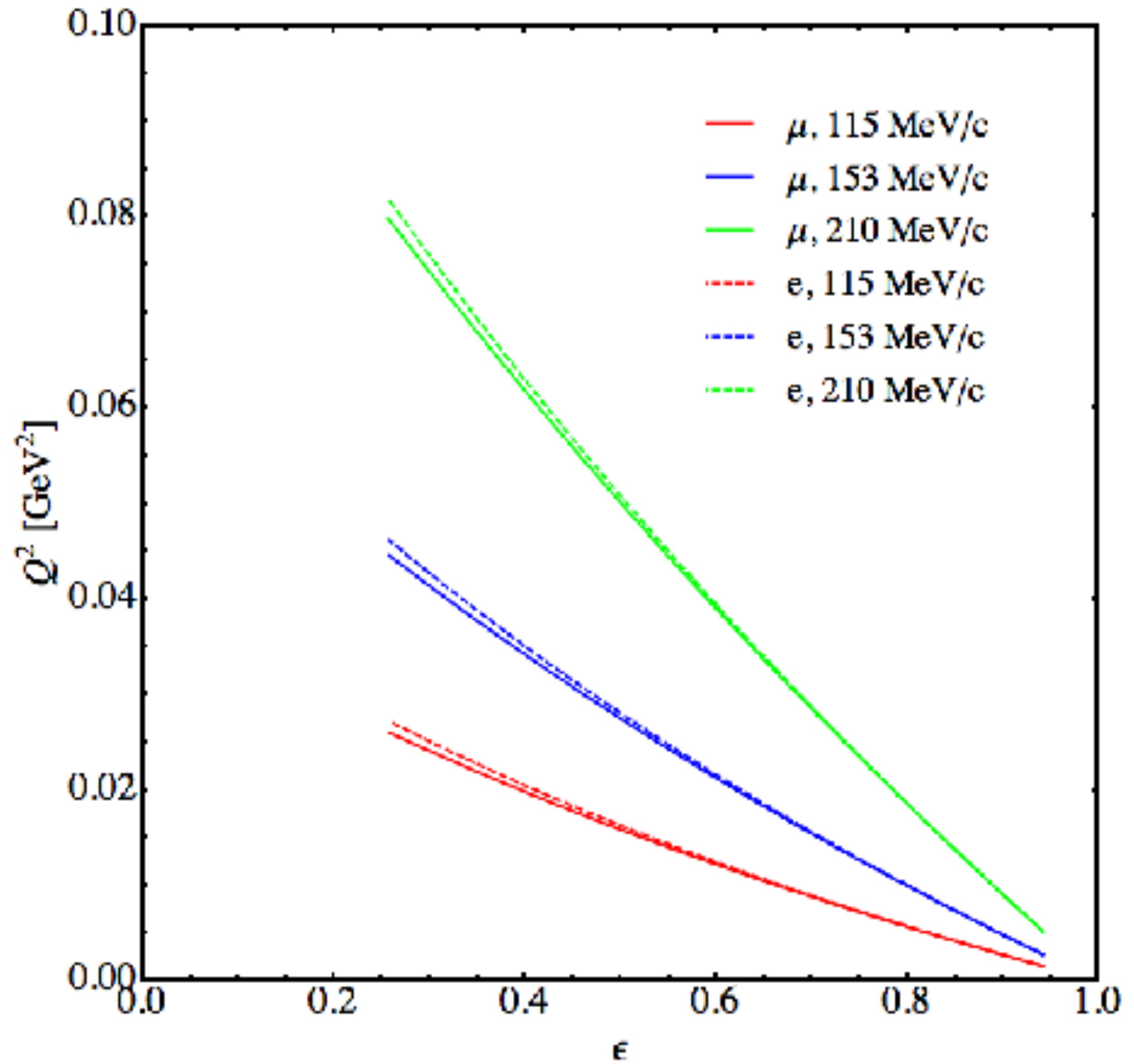
Scattered particles detected with straw chambers and scintillators



Not run like a normal cross section experiment - 7-8 orders of magnitude lower luminosity.
But there are some benefits: count every beam particle, no beam heating of target, low rates in detectors, ...

Experiment Overview





$\theta \approx 20^o - 100^o$

$Q^2 \approx 0.0015 - 0.08\ GeV^2$

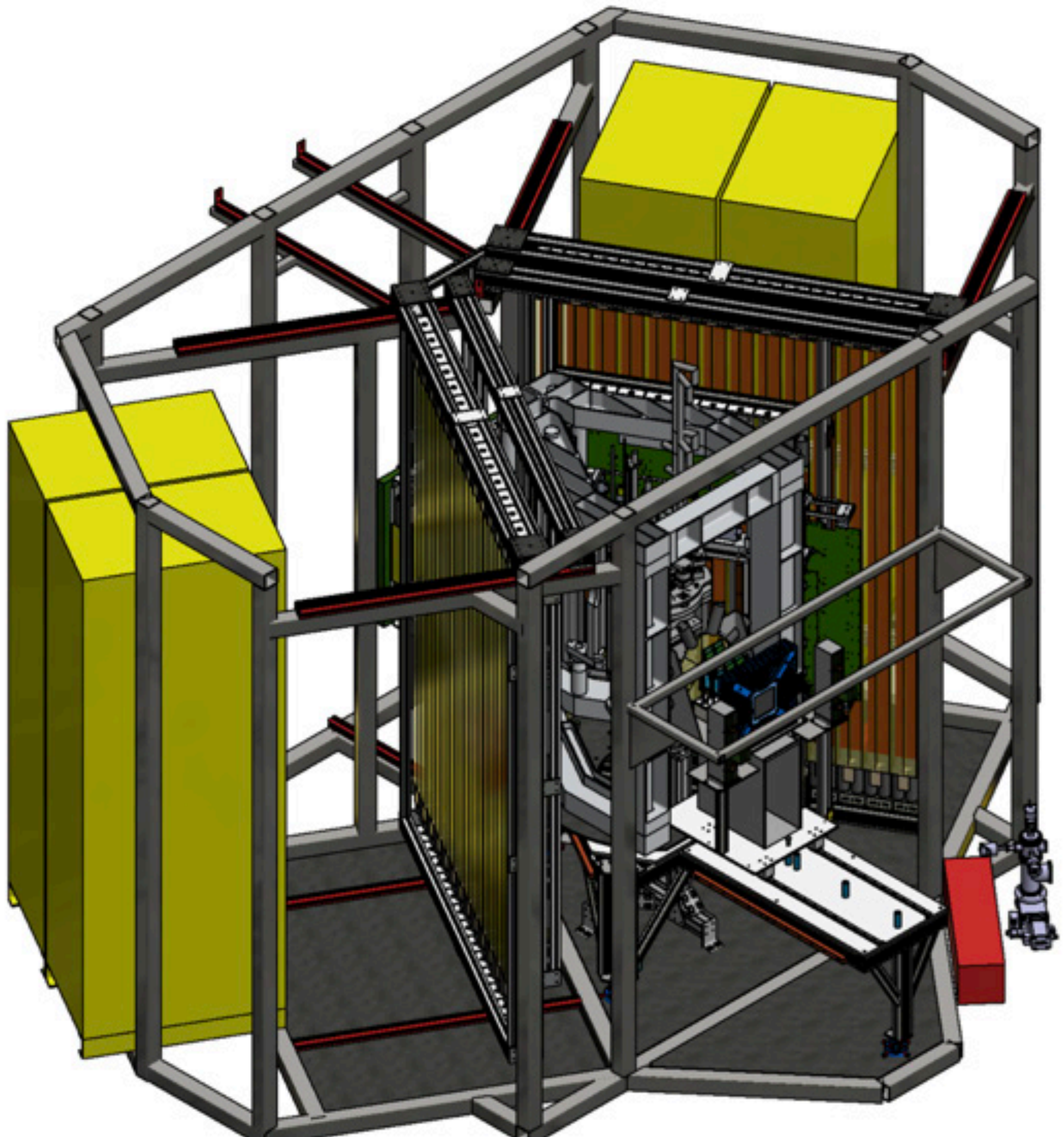
$\varepsilon \approx 0.256 - 0.94$

Allows Rosenbluth separation for some values of Q^2.

Important for controlling G_M

Essentially same coverage for all beam particles.

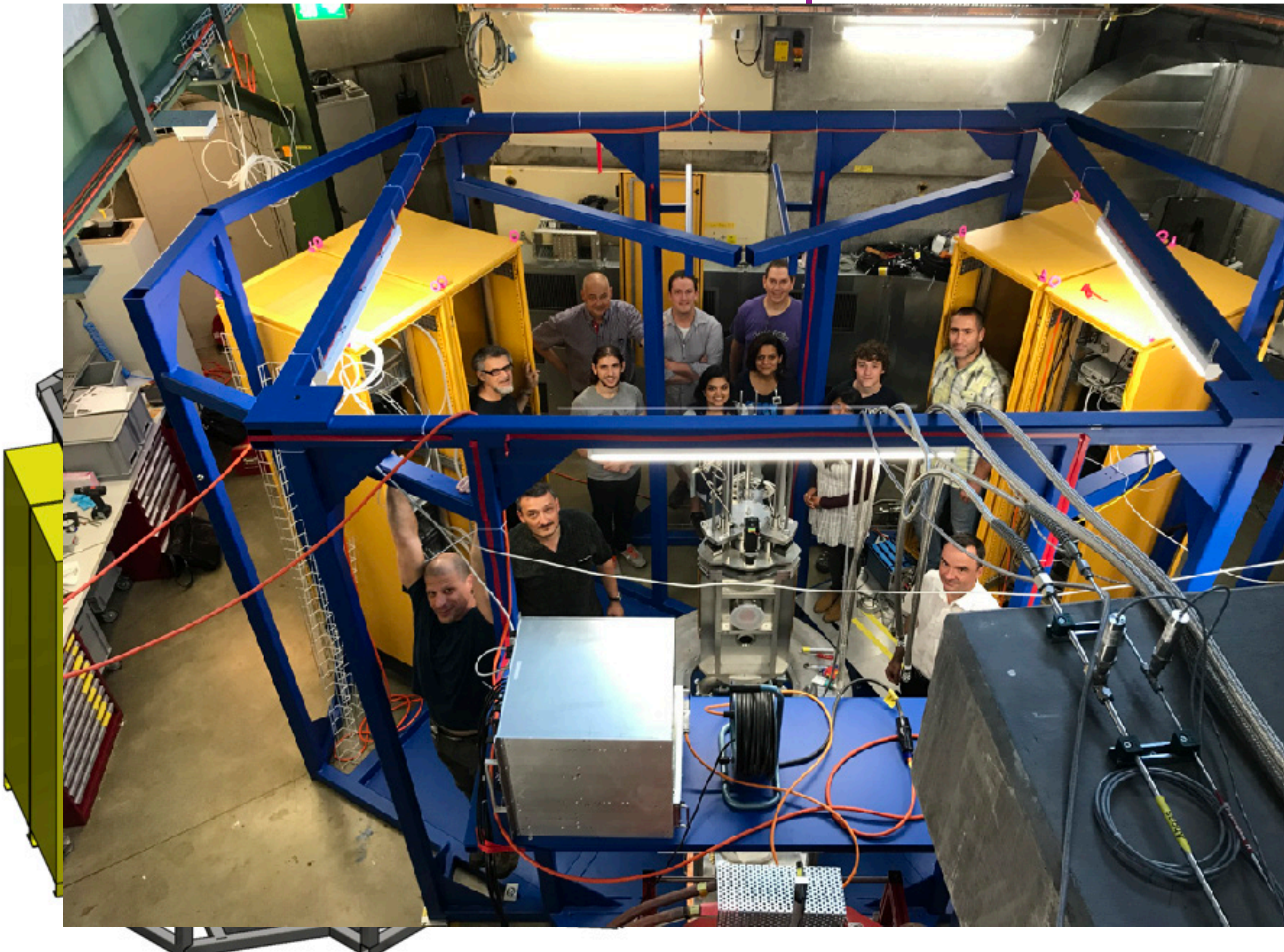
"Final Design"



Component	Weight (lbs)	Weight (kg)
Frame	4200	1680
Table	716	325
Target	508	231
STT	550	250
Large SPS (2 @ 842lb each)	1684	766
Small SPS (2 @ 262lb each)	524	238
Beam Monitor	100	40
Electronics Racks (4 @ 500kg each)	4400	2000
Cables & Misc. (250kg per side)	1100	500
TOTAL	**13782**	**6030**

Experiment on movable (craneable) platform to allow for other uses of the experimental area.

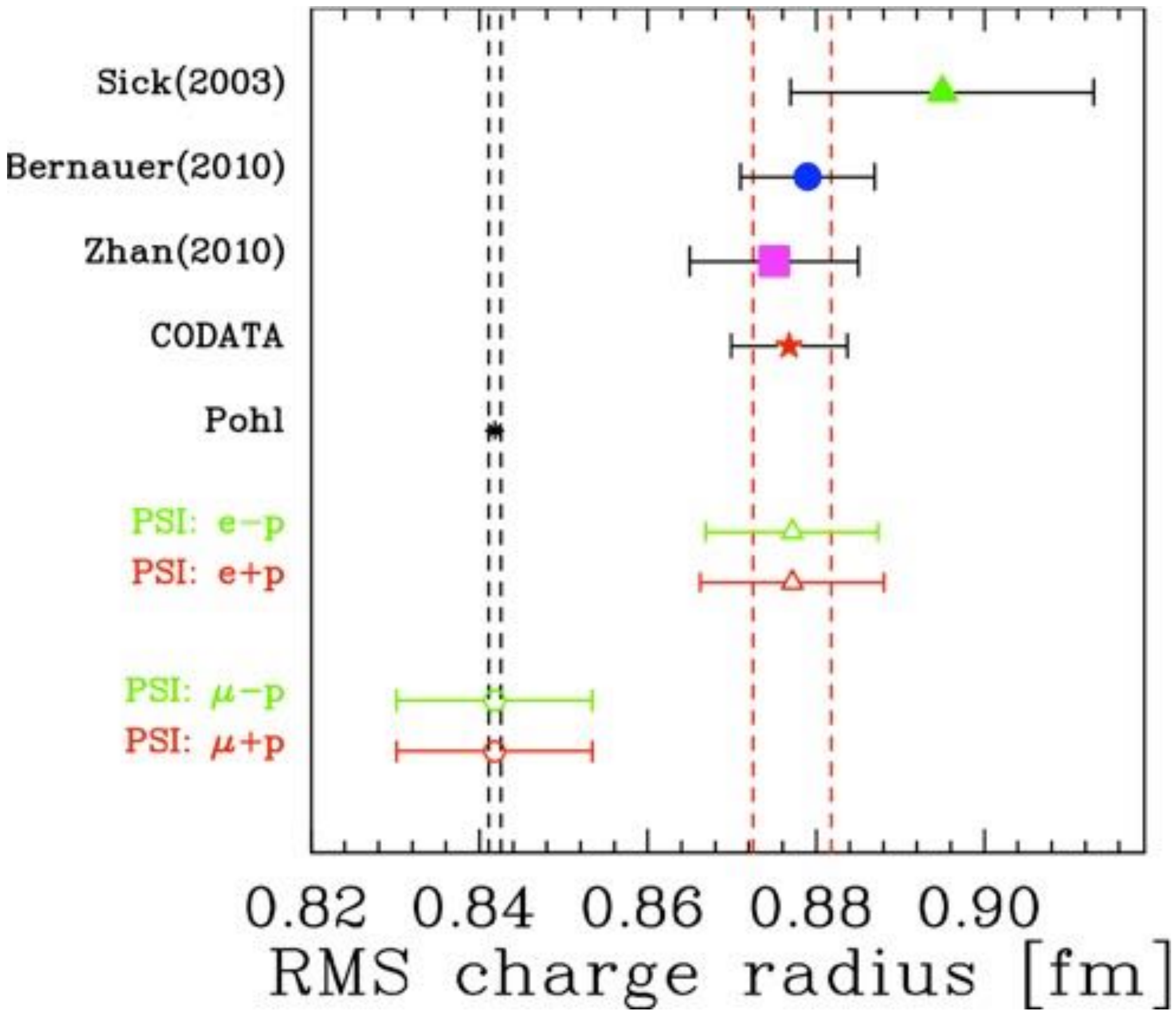
“Final Design”

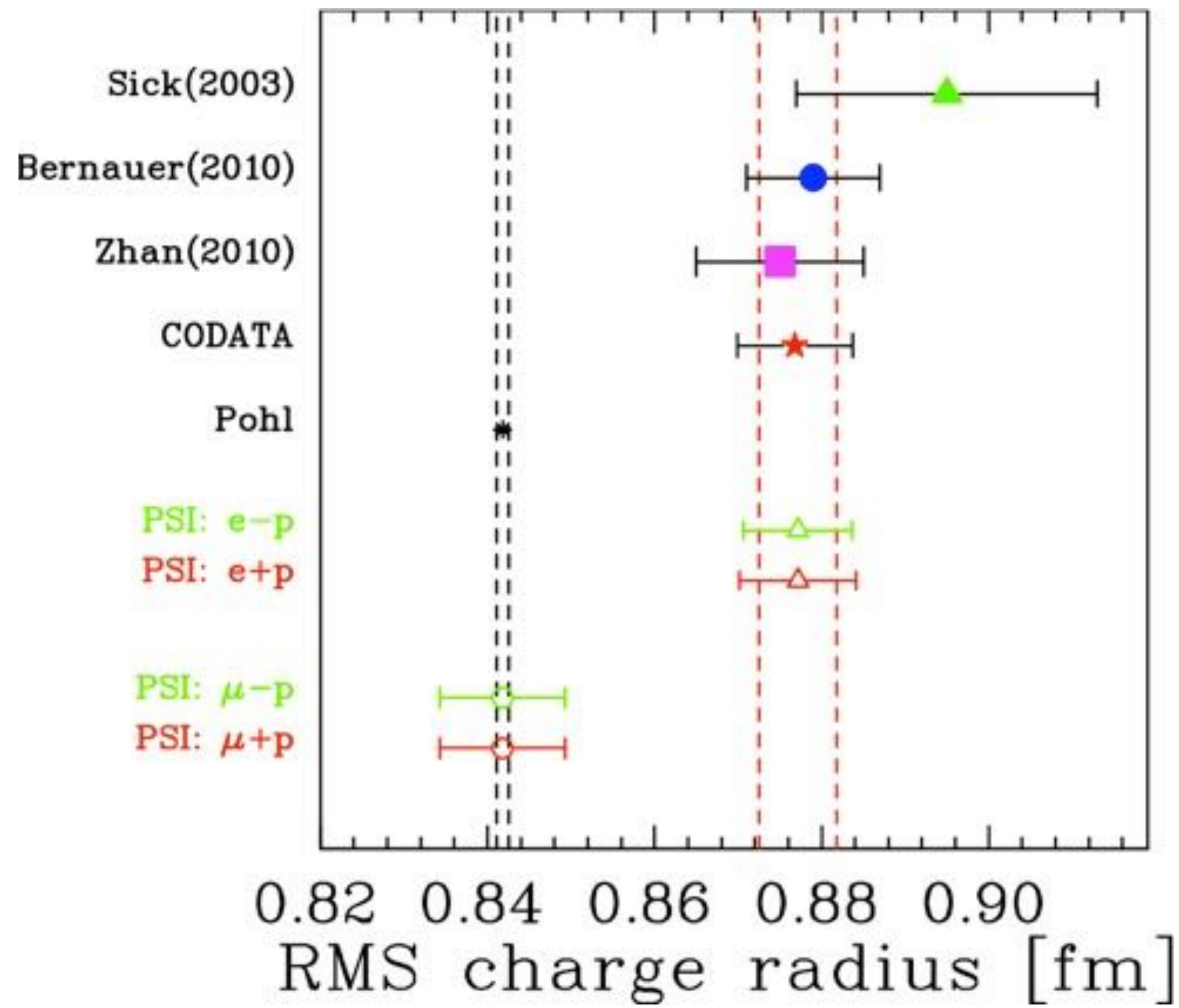


ht (kg)
1680
325
231
250
766
238
40
2000
500
6030

or

Physics





Radius extraction from J Arrington.

Left: independent absolute extraction.

Right: extraction with only relative uncertainties.

The Real Bottom Line

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

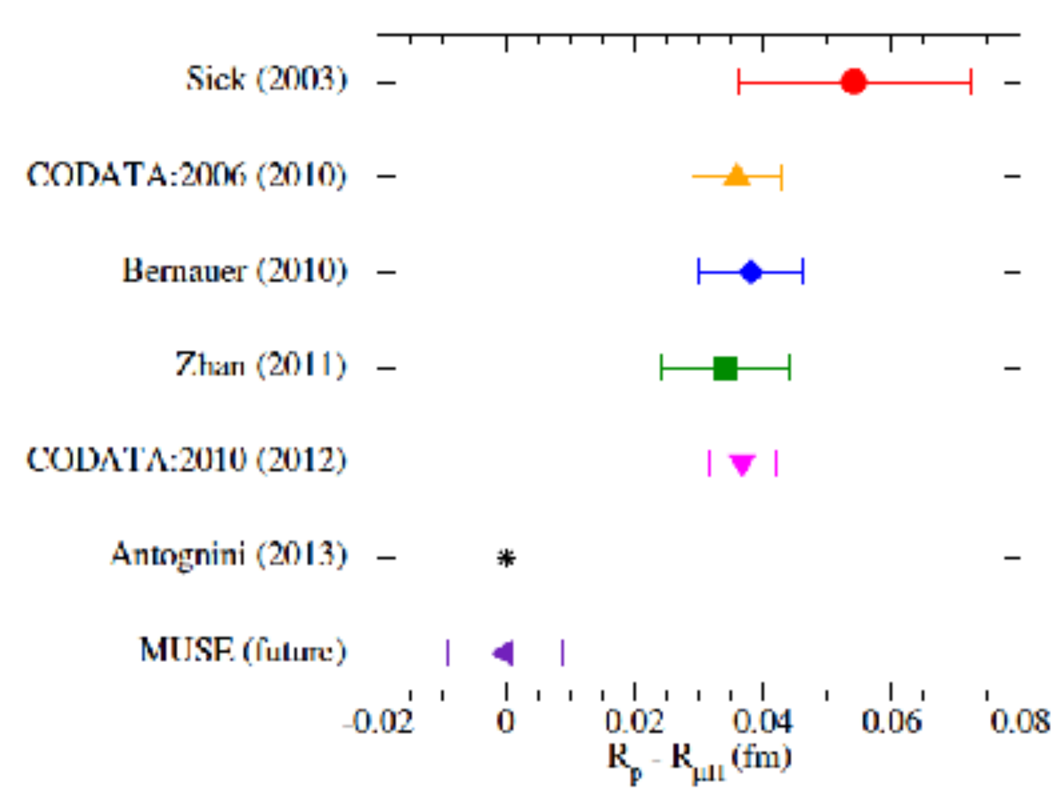
Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, m+/m-, and m/e comparisons

Precise tests of TPE in e-p and m-p or other differences for electron, muon scattering

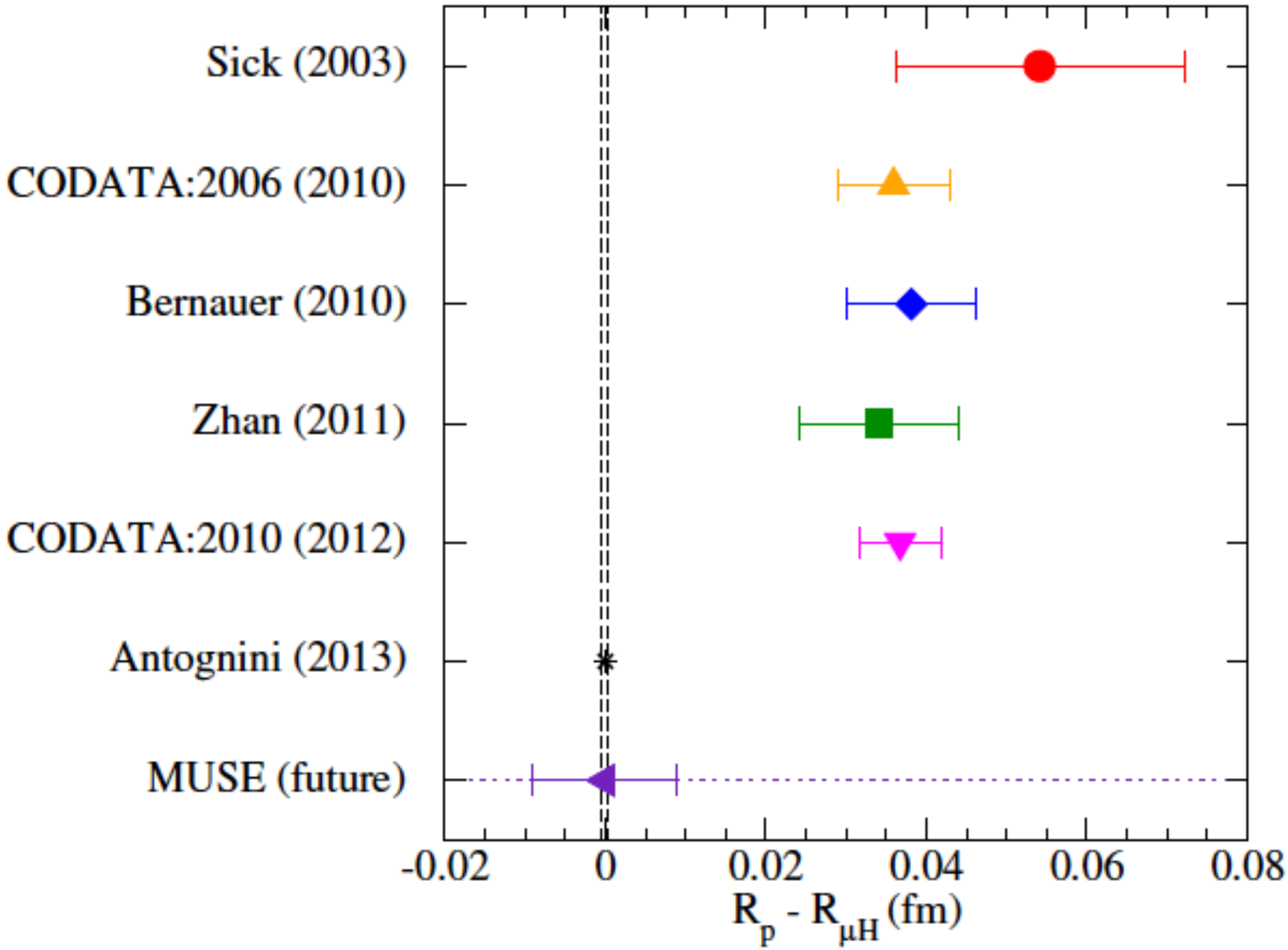
Comparing e/mu gets rid of most of the systematic uncertainties as well as the truncation error.

Projected uncertainty on the difference of radii measured with e/mu is 0.0045.

Test radii difference to the level of 7.7σ (the same level as the current discrepancy)!



The Real Real Botton Line



The Case for MUSE

	Spectroscopy	eP Scattering	MUSE

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State	bound	unbound	unbound

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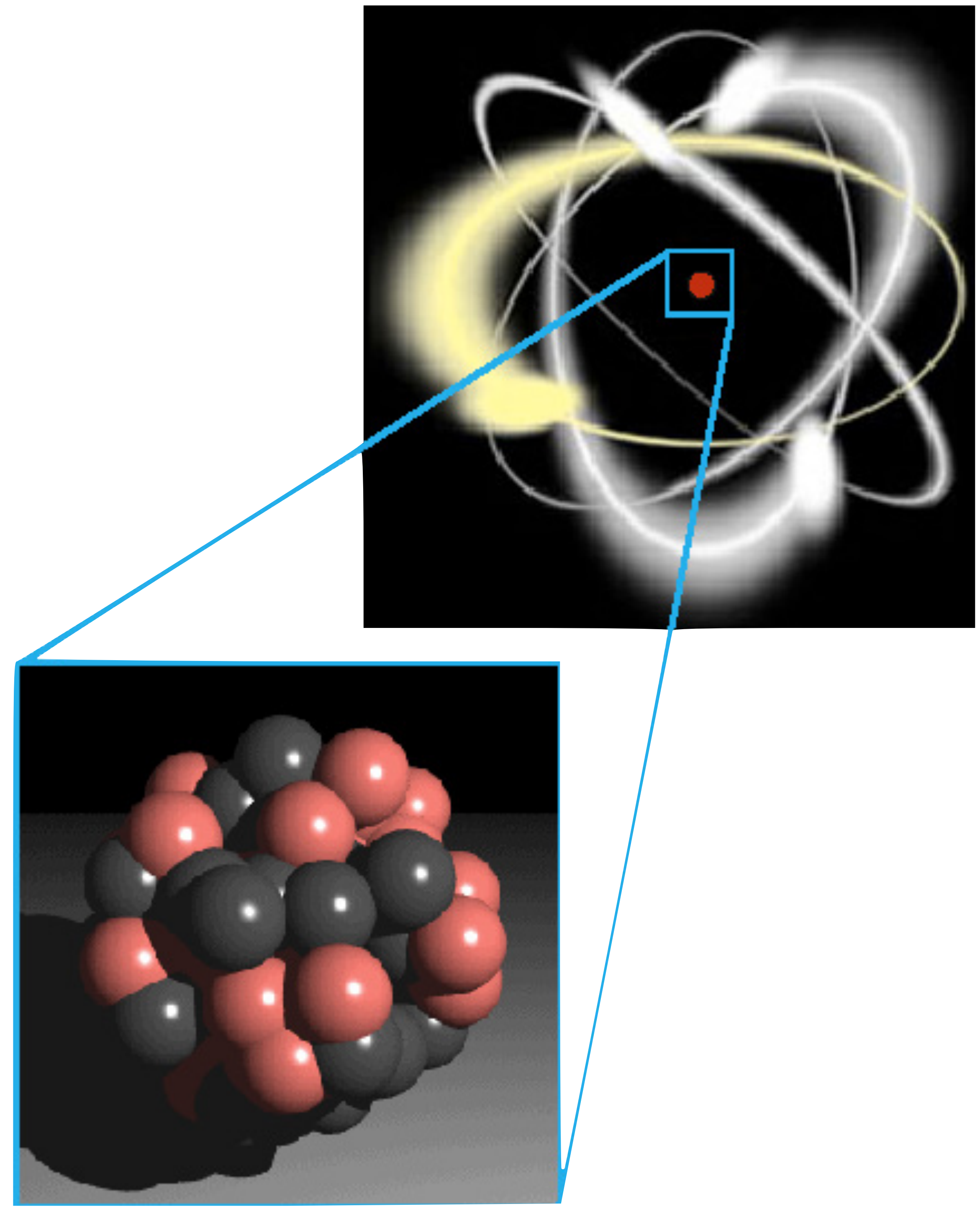
Medium Modification of bound nuclei

The Atom

Standard picture of the atom:

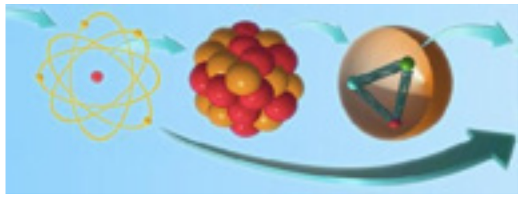
- Electrons zooming around at high velocity, drive the chemistry, interactions of the atom.
- Nuclei are small, static, and uninteresting.



Nuclei are actually complex, dynamic systems.

The Nucleus

Different Things to Different People



- Chemists → Slow, Heavy, and Boring.
- Low Energy Nucl. Phys → Protons + Neutrons, Complex Shell Structure, Angular Momentum.
- Medium Energy Nucl. Phys. → Protons + Neutrons (typically non-interacting).
- High Energy Phys. → Bag of Free Quarks.

Nuclei - Complex, Energetic and Dense

- **Nuclei are incredibly dense**
  - >99.9% of the mass of the atom
  - <1 trillionth of the volume
  - ~10^{14} times denser than normal matter (close to neutron star densities)
- **Nuclei are extremely energetic**
  - "Fast" nucleons moving at ~50% the speed of light
  - "Slow" nucleons still moving at **~10^9 cm/s**, in an object **~10^{-12} cm** in size

Simple picture is totally false, but **extremely effective**

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What happens to the nucleons under these conditions?

Nuclei Are Changed in the Nucleus

Two (and 1/2) examples - out of many

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1. **Neutron lifetime:**

Nuclei Are Changed in the Nucleus

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But this is of course $M_p + M_e < M_n$

a binding effect: $(M_n - M_p - M_e) < B_d$

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$$(M_n - M_p - M_e) < B_d$$

2. **Coulomb Sum Rule Quenching**

Coulomb Sum Rule Quenching?

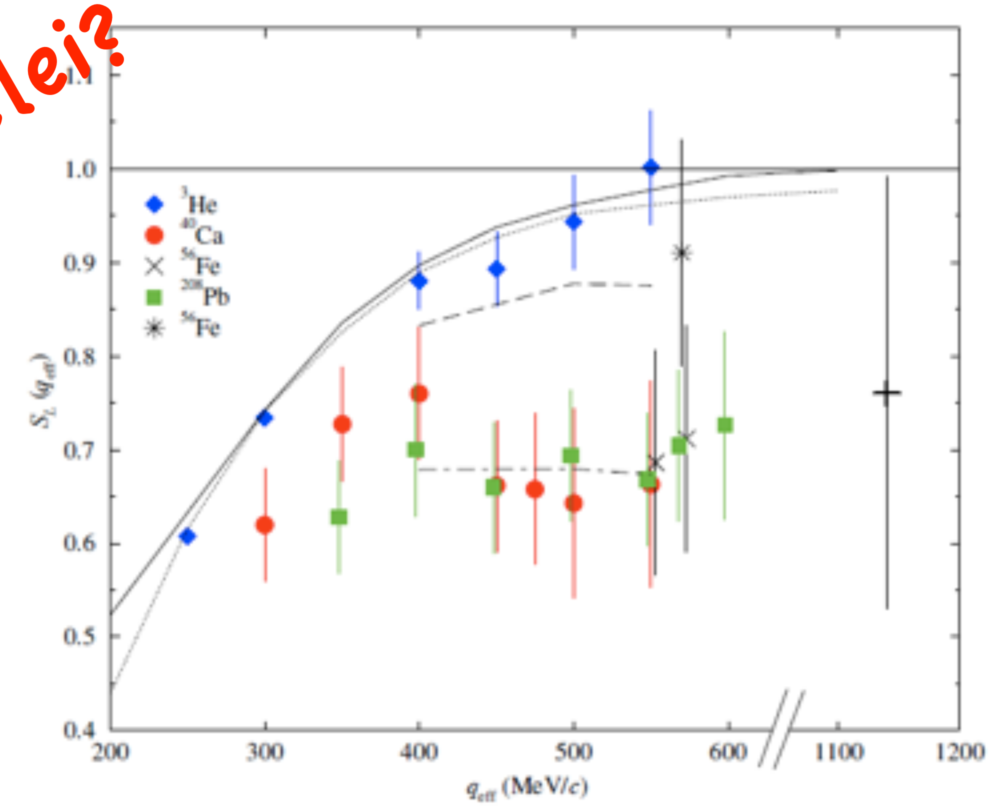
$$S_L(Q^2) = \frac{1}{Z}\int_{0^+}^{\infty} \frac{R_L(\vec{q},\omega)}{\tilde{G}_E(Q^2)} d\omega \rightarrow 1$$

$$\tilde{G}_E(Q^2) = \left(G_E^p(Q^2) + \frac{N}{Z} G_E^n(Q^2) \right) \zeta$$

Sum rule counts the number of interacting components in the nucleus using the longitudinal response function.

Broken in Heavy Nuclei?

Maybe?



$$\frac{d^3\sigma}{d\Omega d\omega} = \sigma_{Mott}\left[\frac{Q^4}{\vec{q}^4} R_L(|\vec{q}|,\omega) + \frac{Q^2}{2\vec{q}^2}\frac{R_T(|\vec{q},\omega)}{\varepsilon}\right]$$

$$\varepsilon(\vec{Q},\omega,\theta)\left[1 + \frac{2\vec{q}^2}{Q^2}\tan^2\frac{\theta}{2}\right]^{-1}$$

J. Morgenstern, Z.-E. Meziani, PLB 515, 269 (2001).

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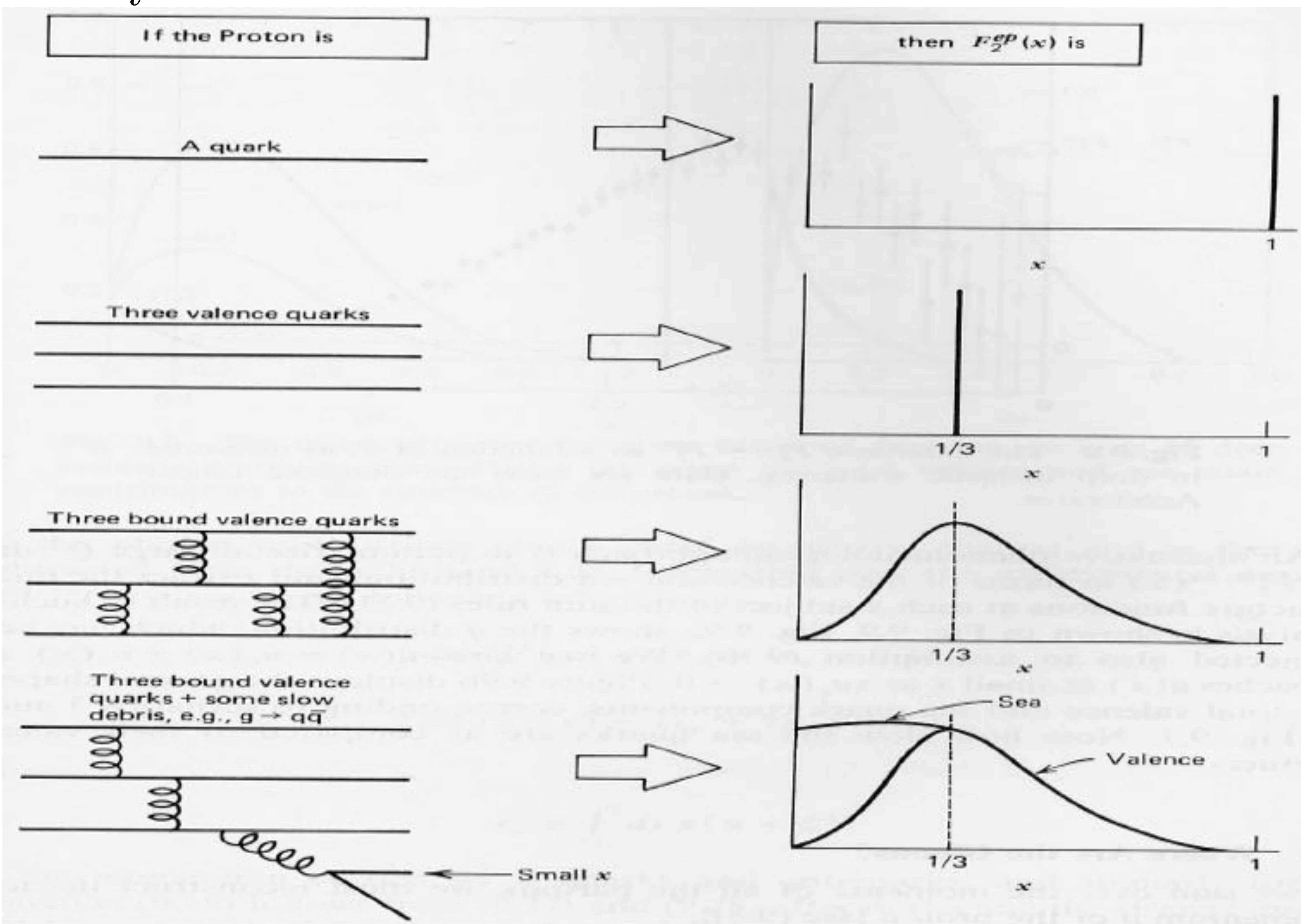
3. **The EMC Effect**

The EMC Effect

$$F_2(x) = \sum_i q_i^2 x f(x)$$

Probability of finding a quark with momentum fraction x in the nucleon.



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FAIL

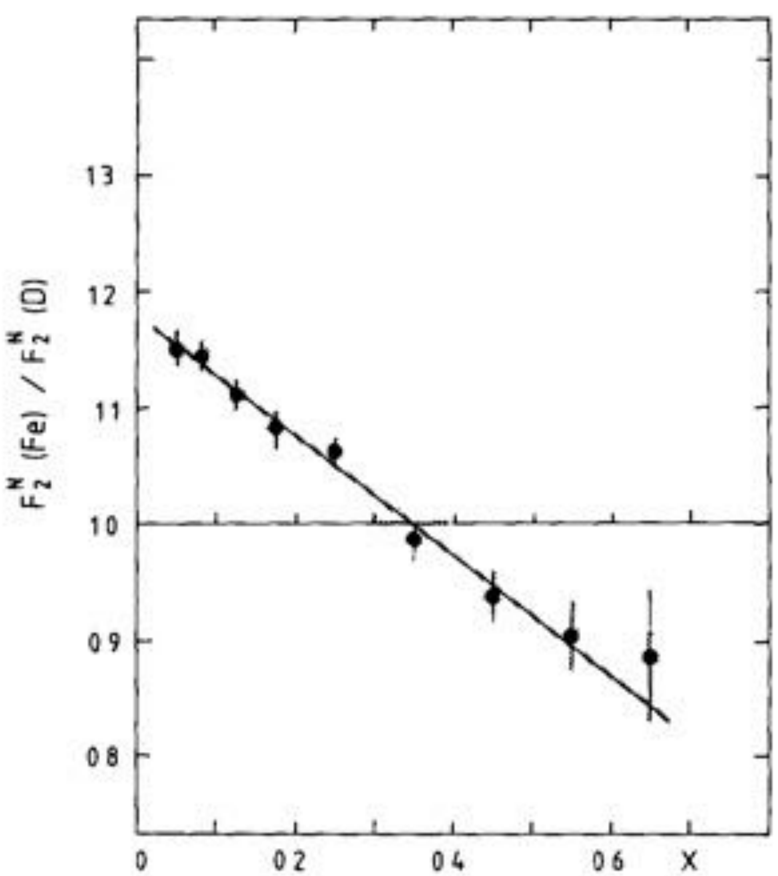
The EMC Effect

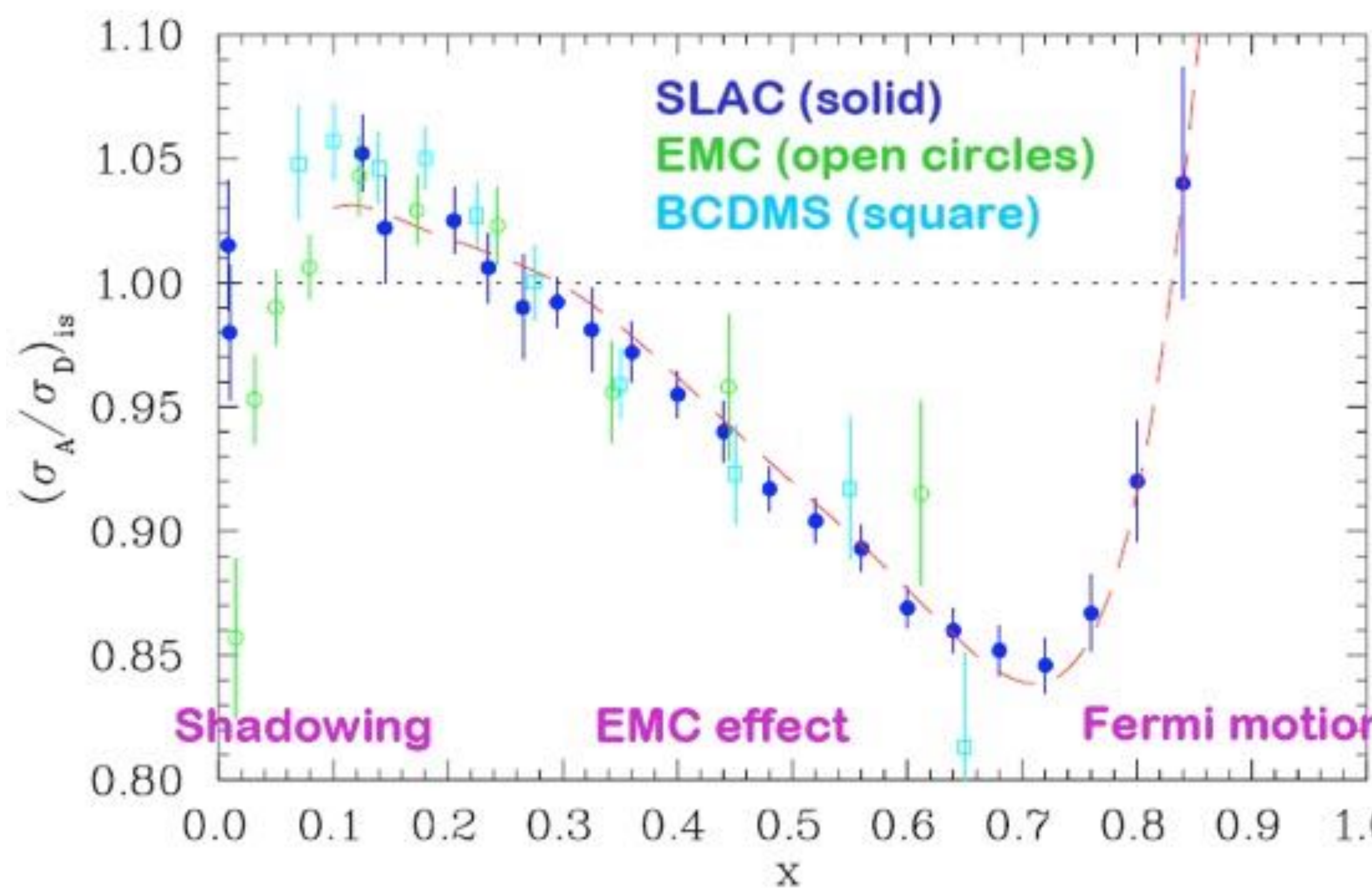
Excess of low momentum quarks and depletion of high momentum quarks in Nuclei.

finding a quark with

ction x in the nucleon.

Expectation: $\ldots + (A - Z)F_2^n$

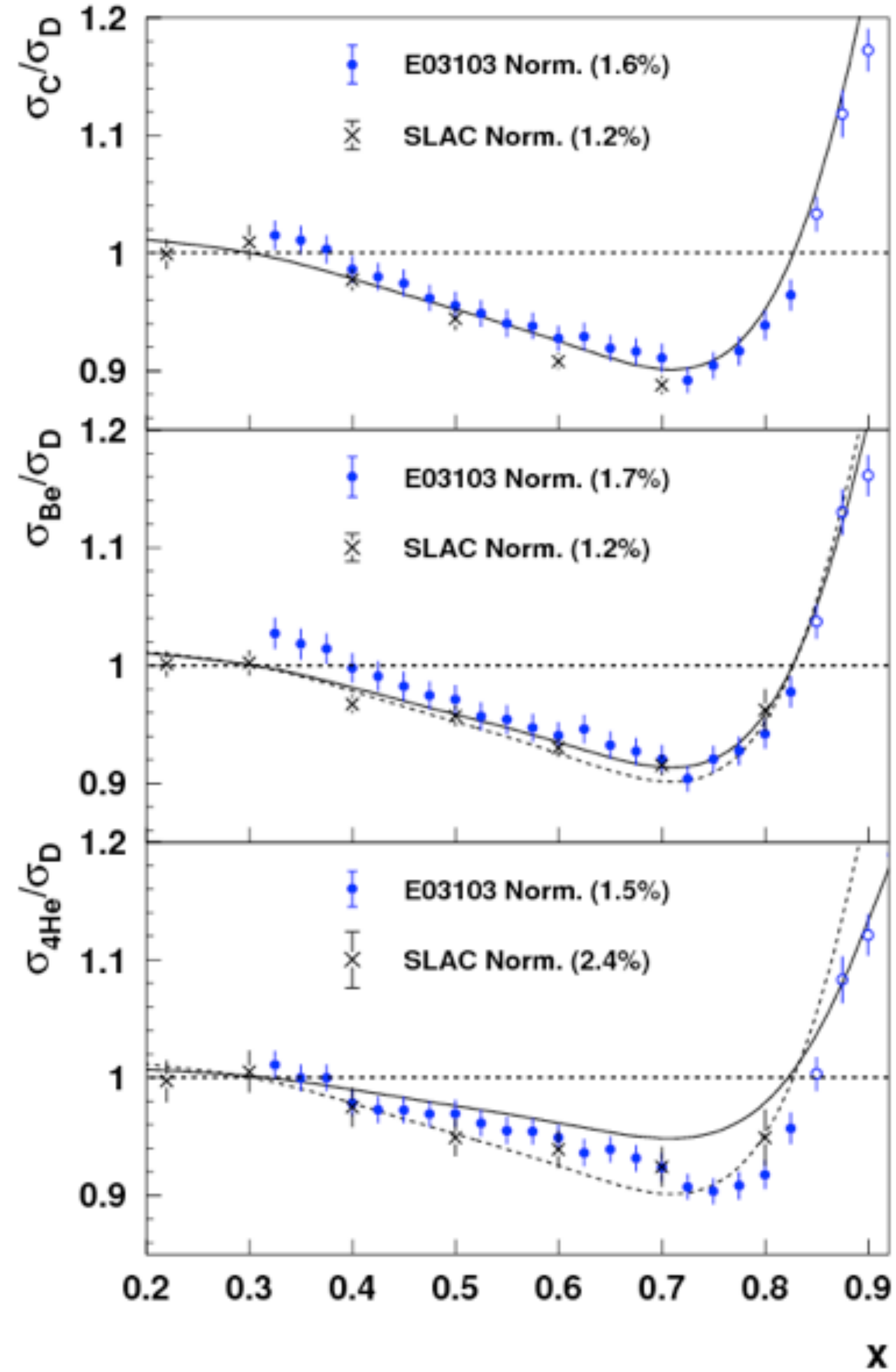




The EMC Effect

A new result

JLab experiment E03-103 (J. Arrington) measured the EMC for light nuclei (and medium-large x).
Results confirm the effect for these nuclei.



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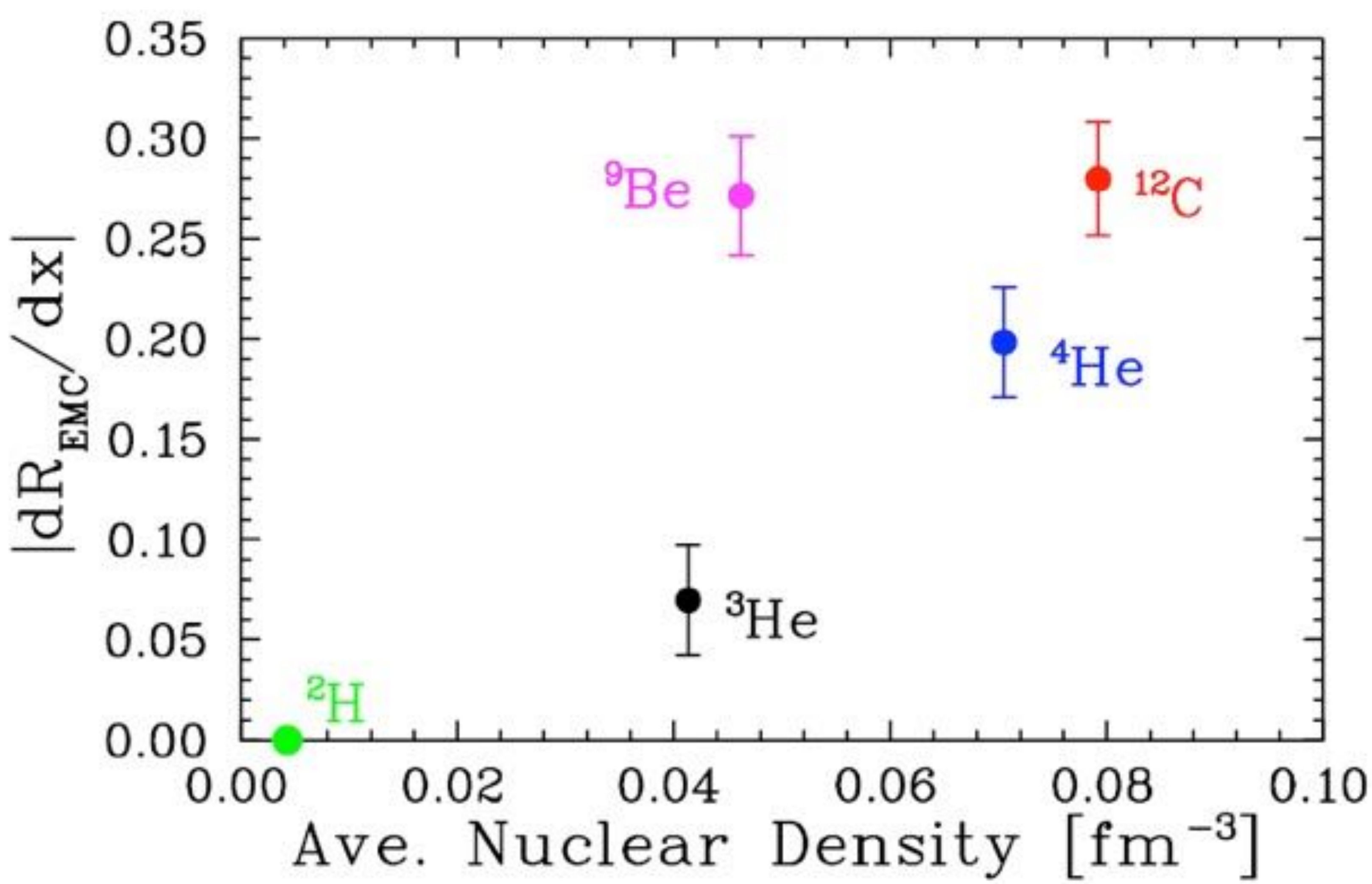

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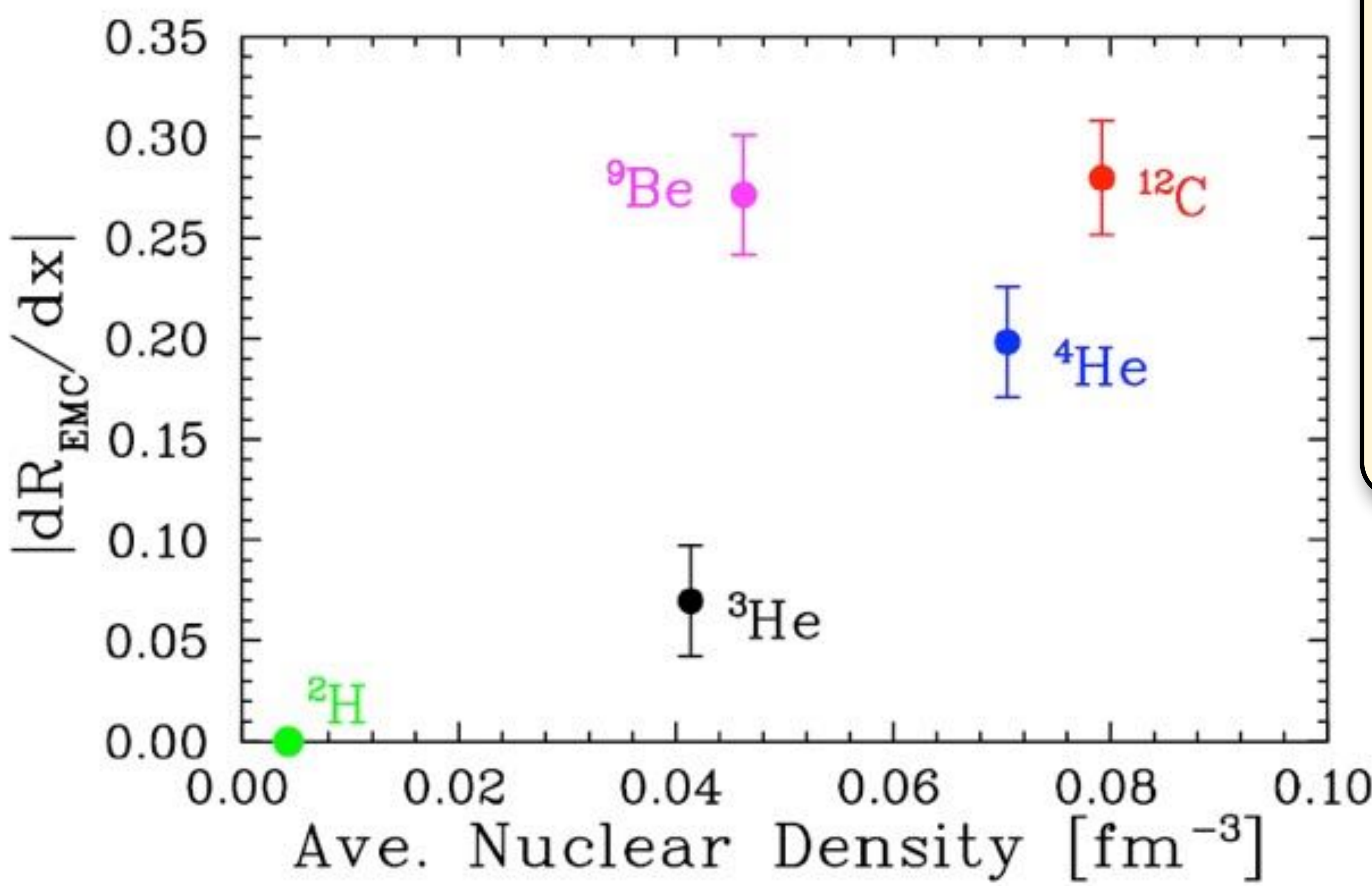

- Plot shows slope of ratio σ_A/σ_D at EMC region.
- EMC effect correlated with ρ not A.
- Local density is important, not average density.

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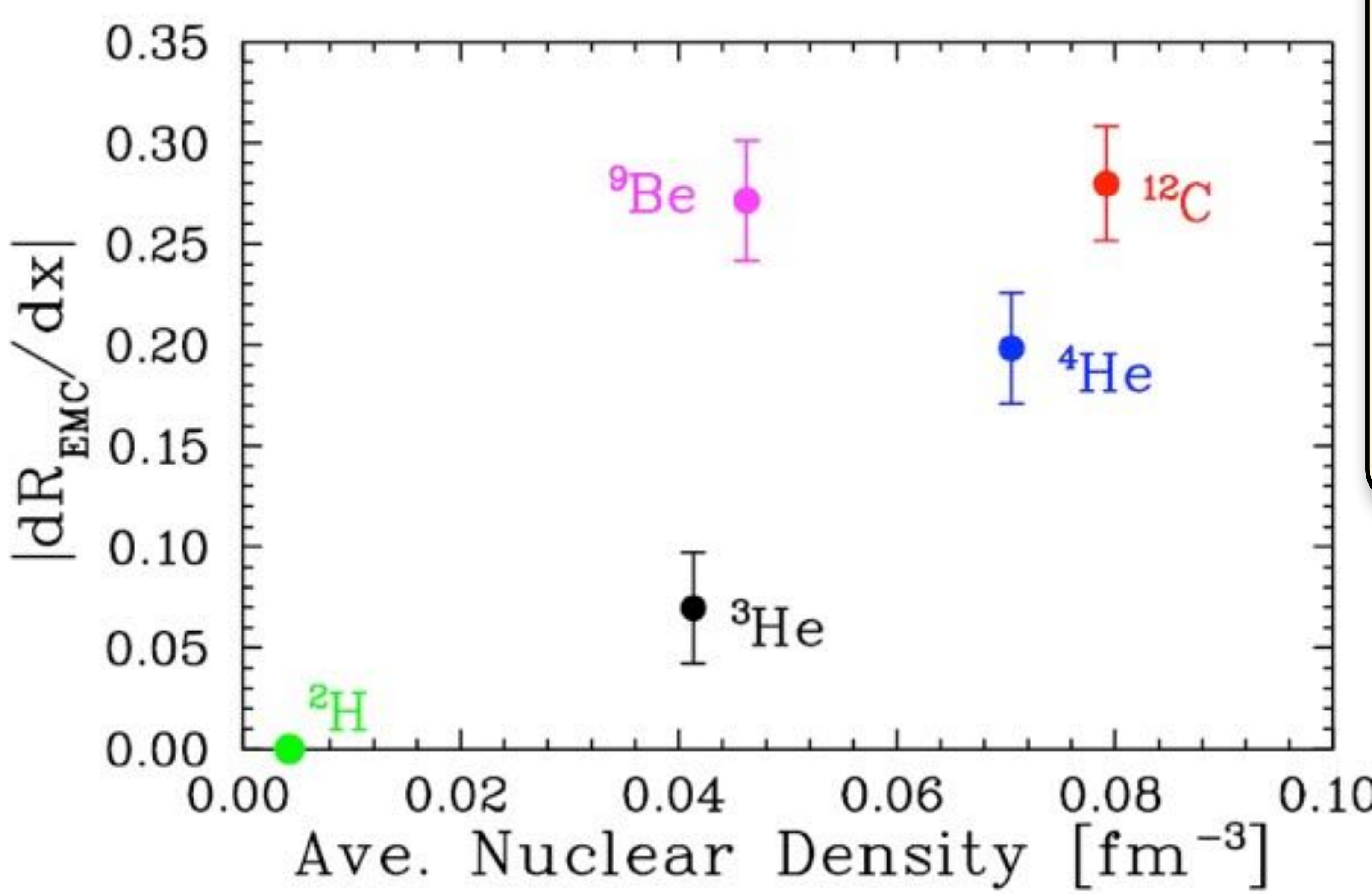

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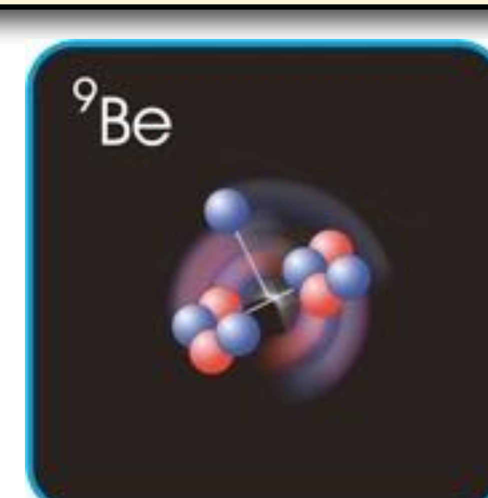
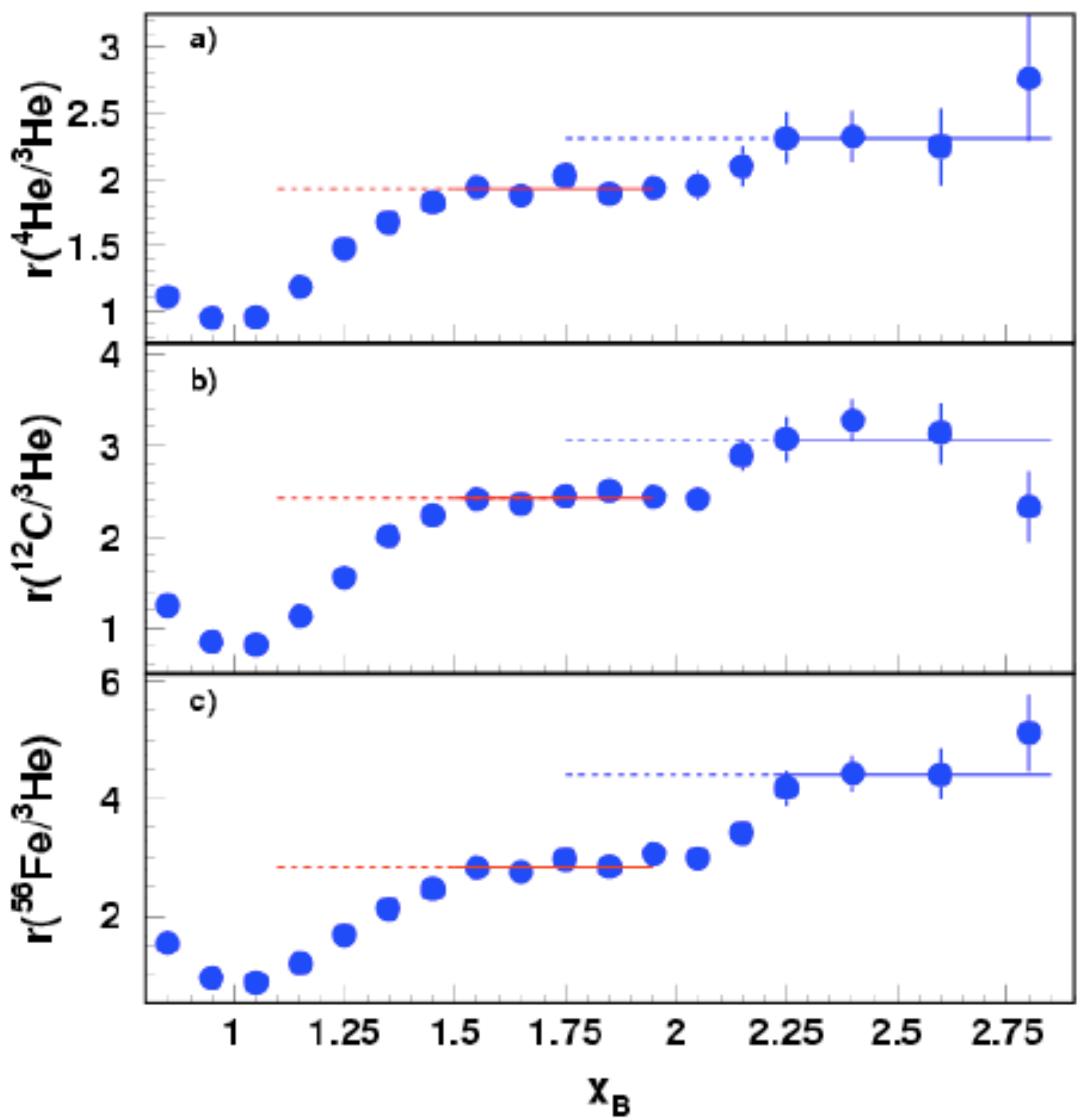


The EMC Effect

A Even Newer "Result"

K. Egiyan et al, PRL96, 082501 (2006)



Is EMC related to Short Range Correlations?

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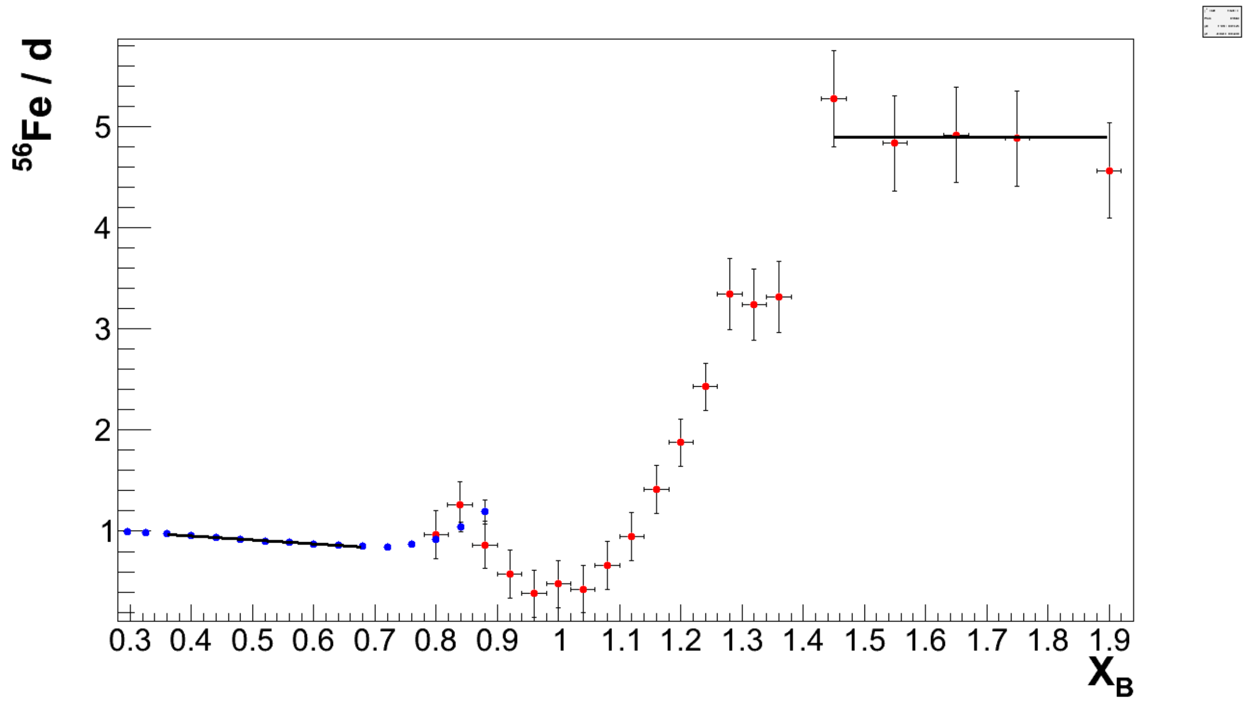

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E. Piasetzky et al., Nuclear Physics A 855, 245 (2011)

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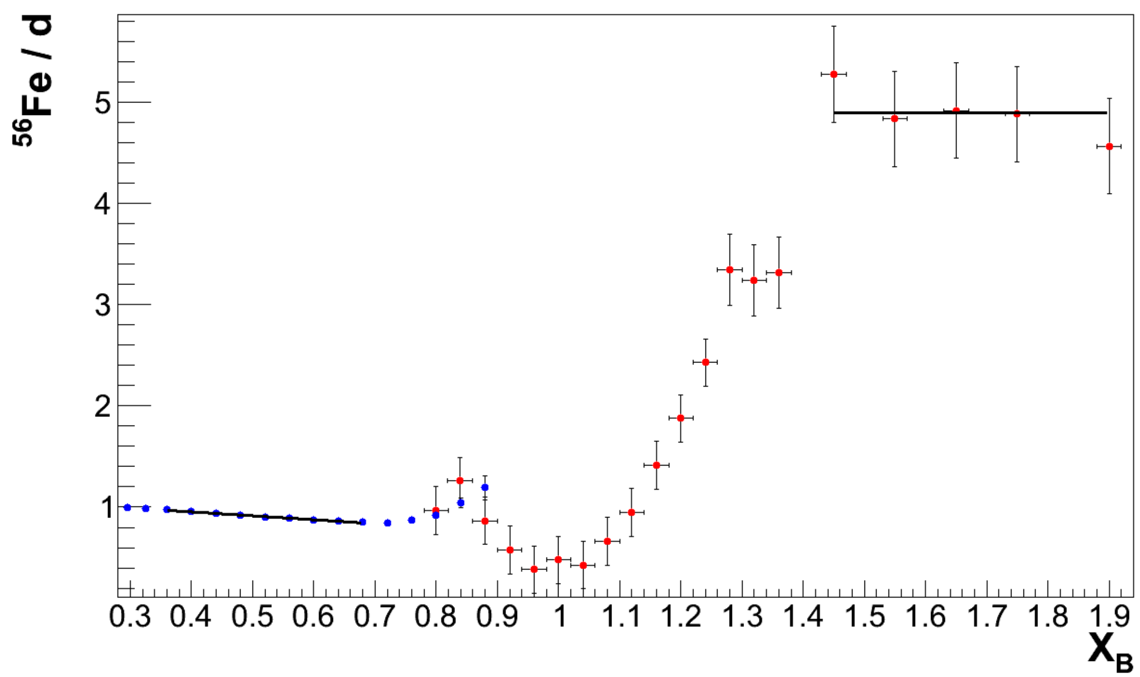

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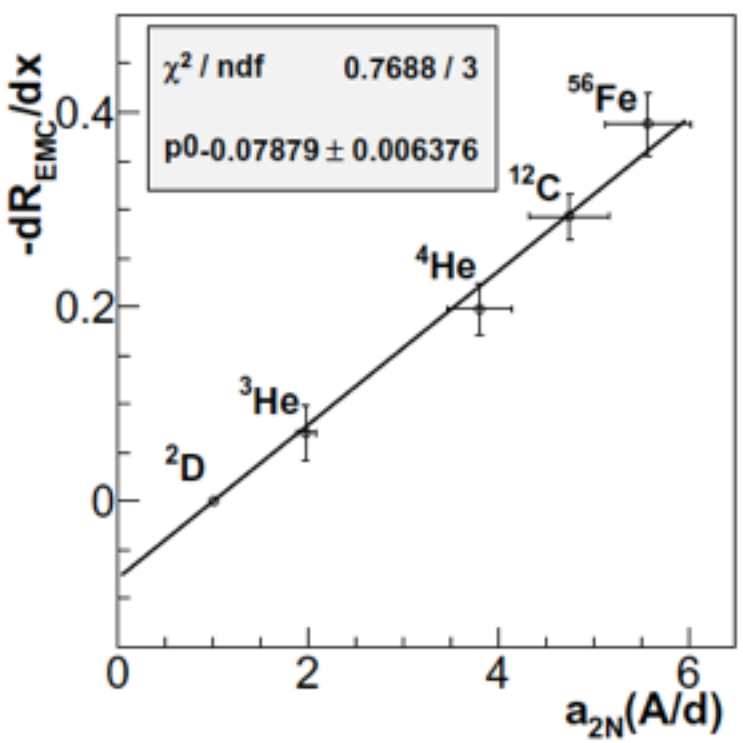
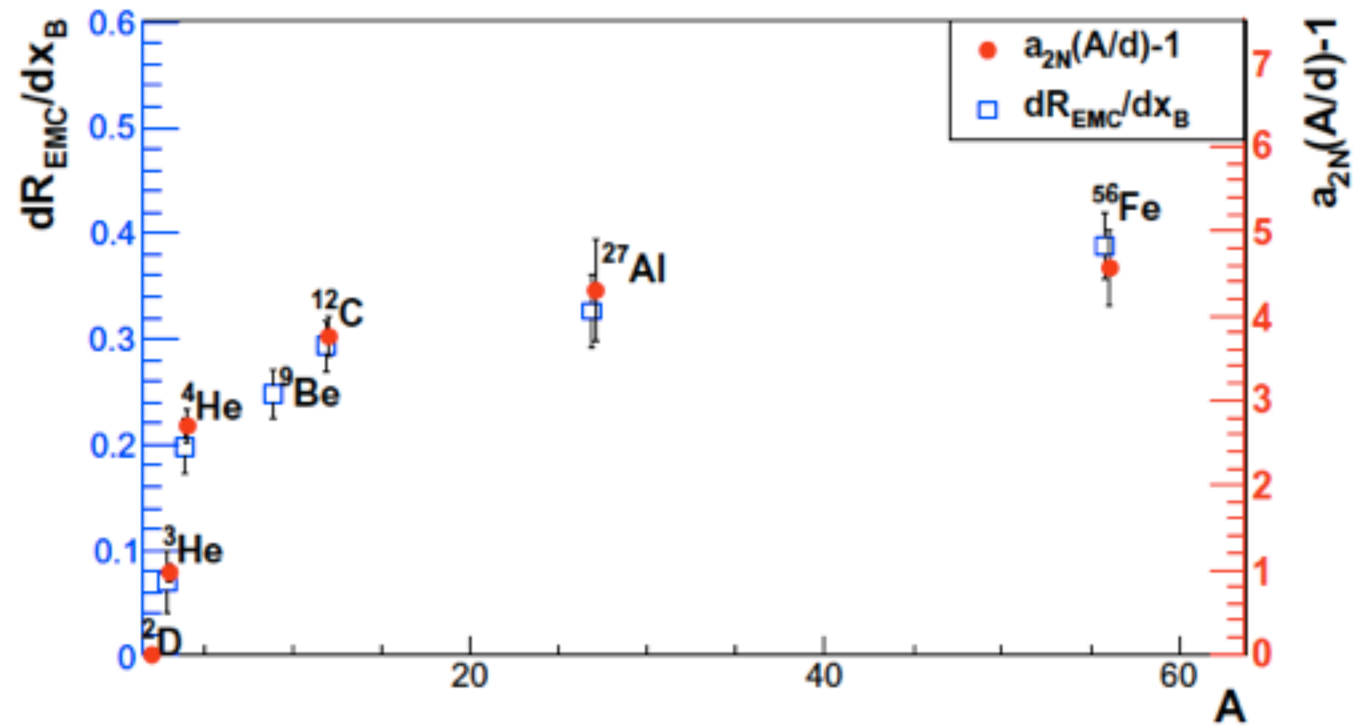




E. Piasetzky et al., Nuclear Physics A 855, 245 (2011)

A Way out?

What we need is...

- Observables sensitive to nucleon structure/size.
- Effect of O(10%) require observable we can measure to 2-3% or better.
- "Different" than previous measurements.

Polarization observables are...

- Related to form factors (Ch/M distributions) - for a free nucleon.
- Can be measured to great precision (<1%).
- Can be shown from calculations to be somewhat insensitive to nuclear effects (*MEC, etc...*).

J. M. Laget, Nucl Phys A579, 333 (1994)

J. J. Kelly, Phys. Rev. C 59, 3256 (1999)

A. Meucci et al., Phys. Rev. C 66, 034610 (2002)

The General Idea

Experiment

- Measure ratio of polarization components for a free nucleon.
- Measure ratio of polarization components for a nucleon extracted from the nucleus in quasi-free scattering.
- Take the super-ratio to remove systematic effects.

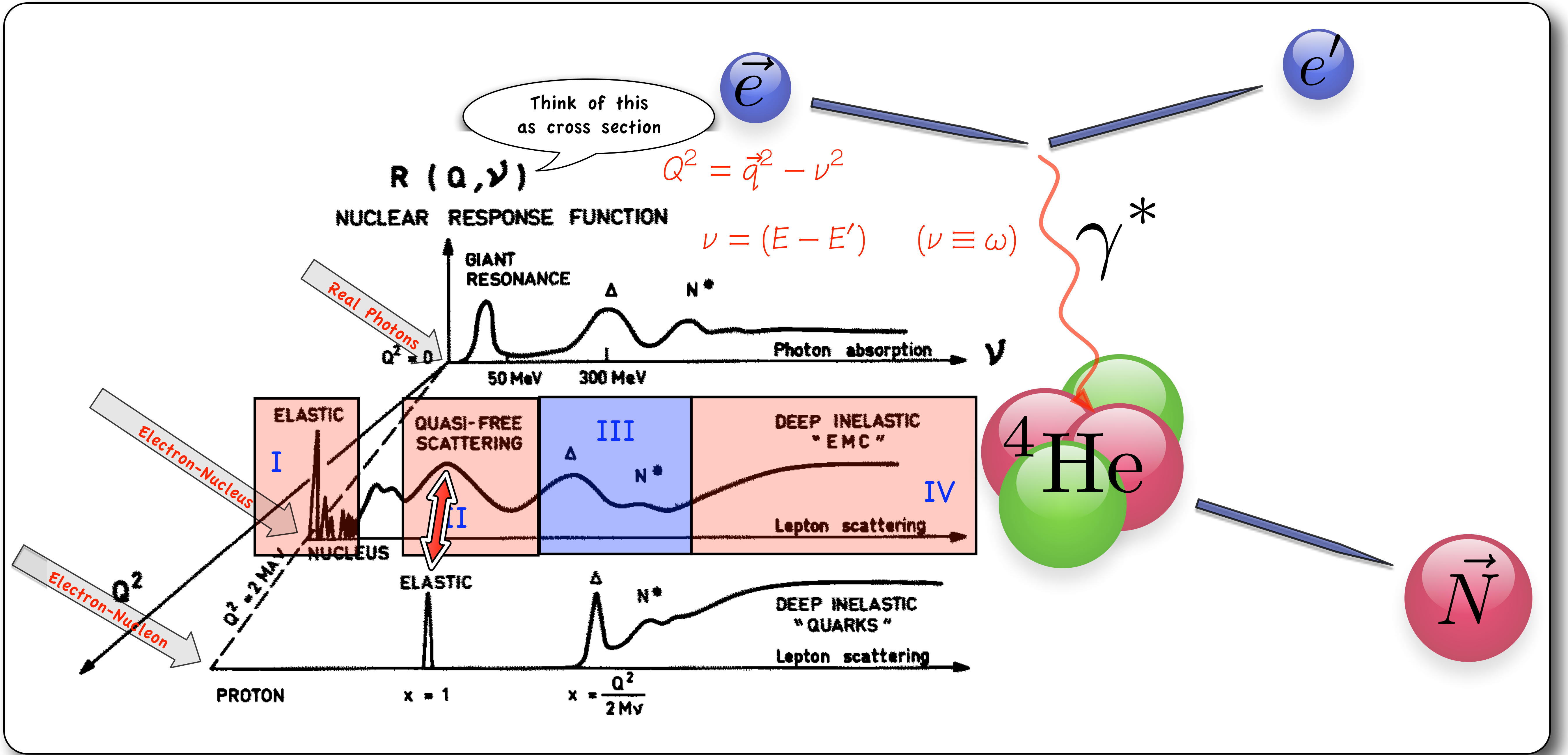
Theory

- Using some model calculate density dependent form factors.
- Integrate over density dist. to get medium modified FF (MMFF).
- Use MMFF to calculate polarization components.
- Add in Final State Interactions, etc...

COMPARE.....

Quasi-Free Scattering

- Electron scatters off Nucleon in the nucleus.
- Data selected to include nucleons with no initial state interactions (i.e., are Quasi-Free).

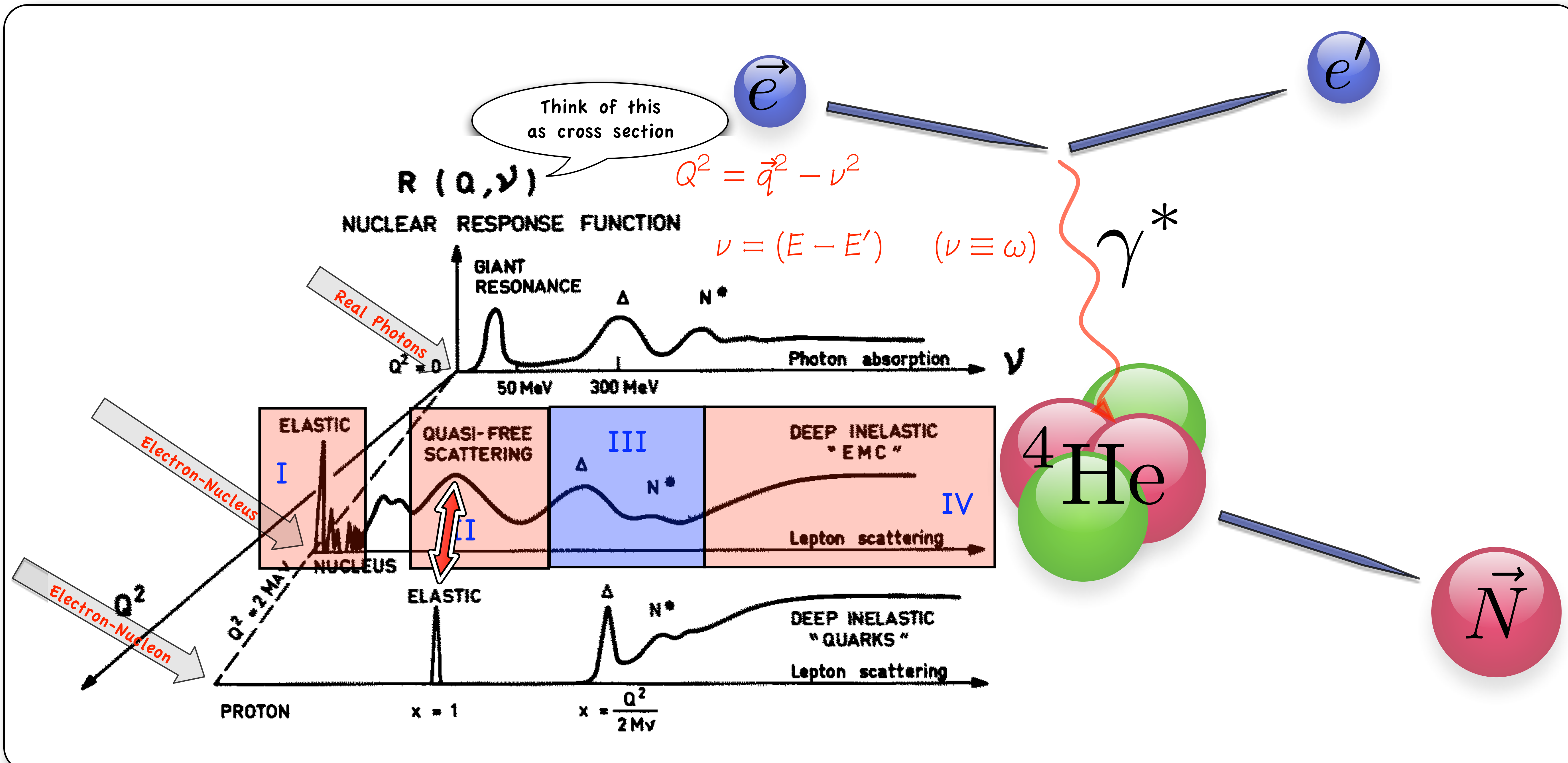


Quasi-Free Scattering

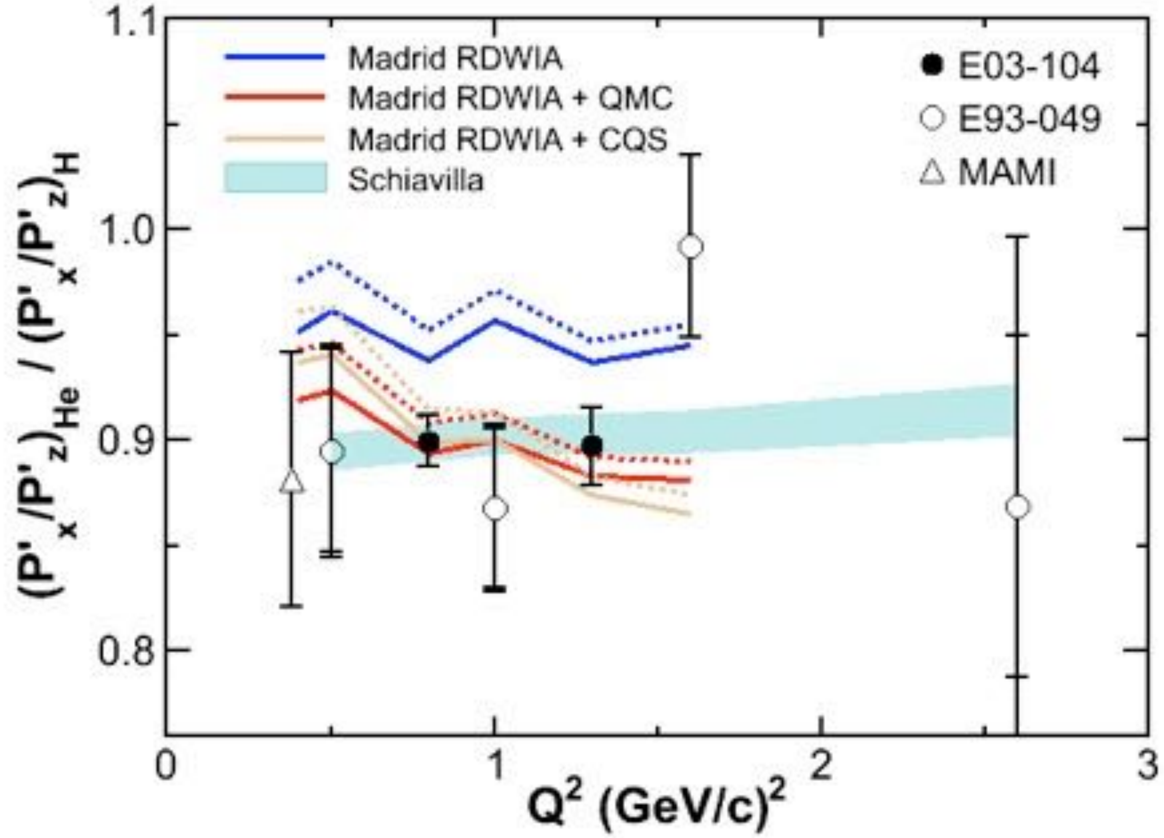
• Electron scatters off Nucleon in the nucleus

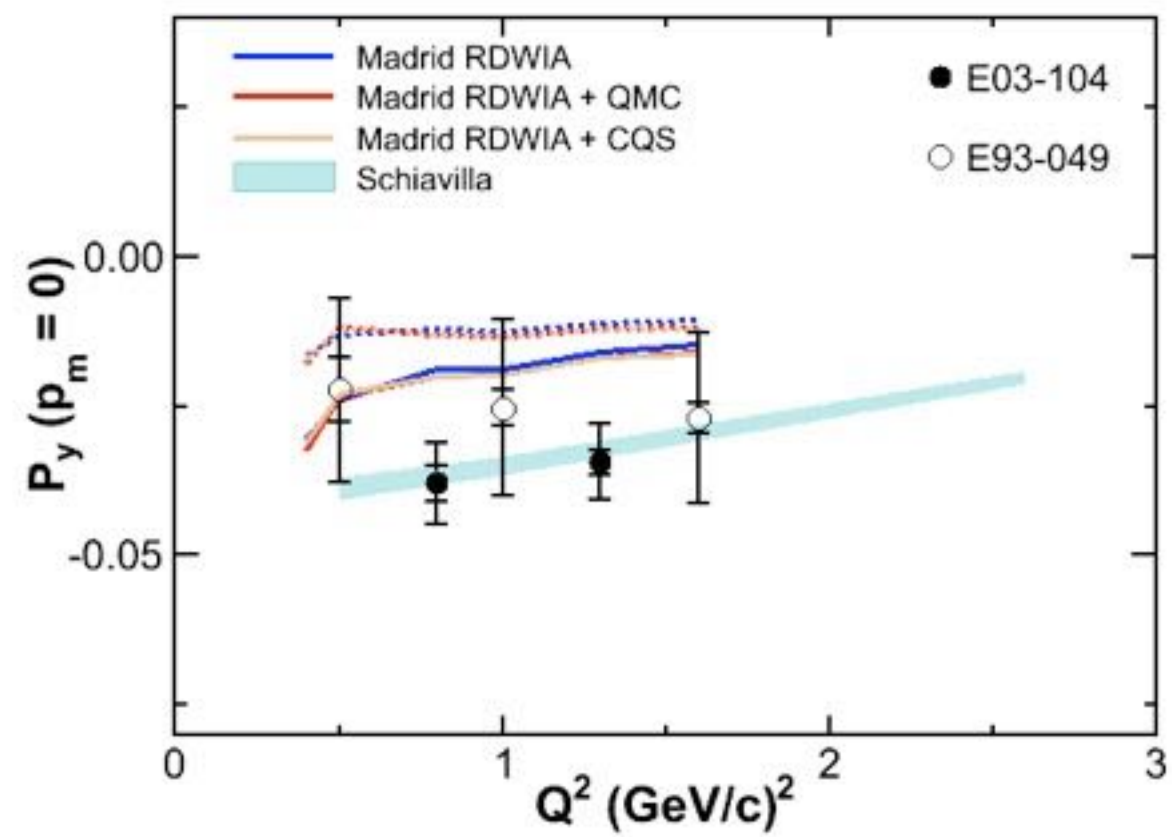
Effectively a "free" nucleon in the mean-field of the nucleus.

interactions (i.e., are Quasi-Free).



$^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ Results





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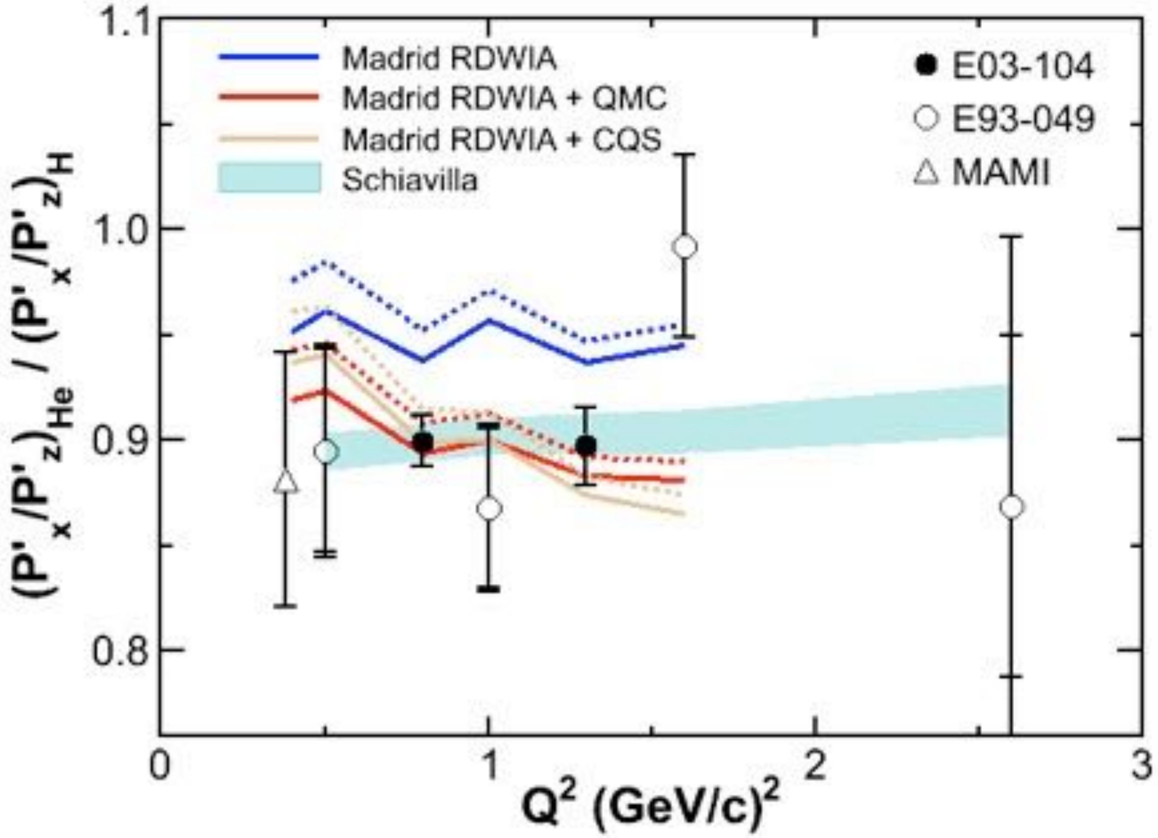

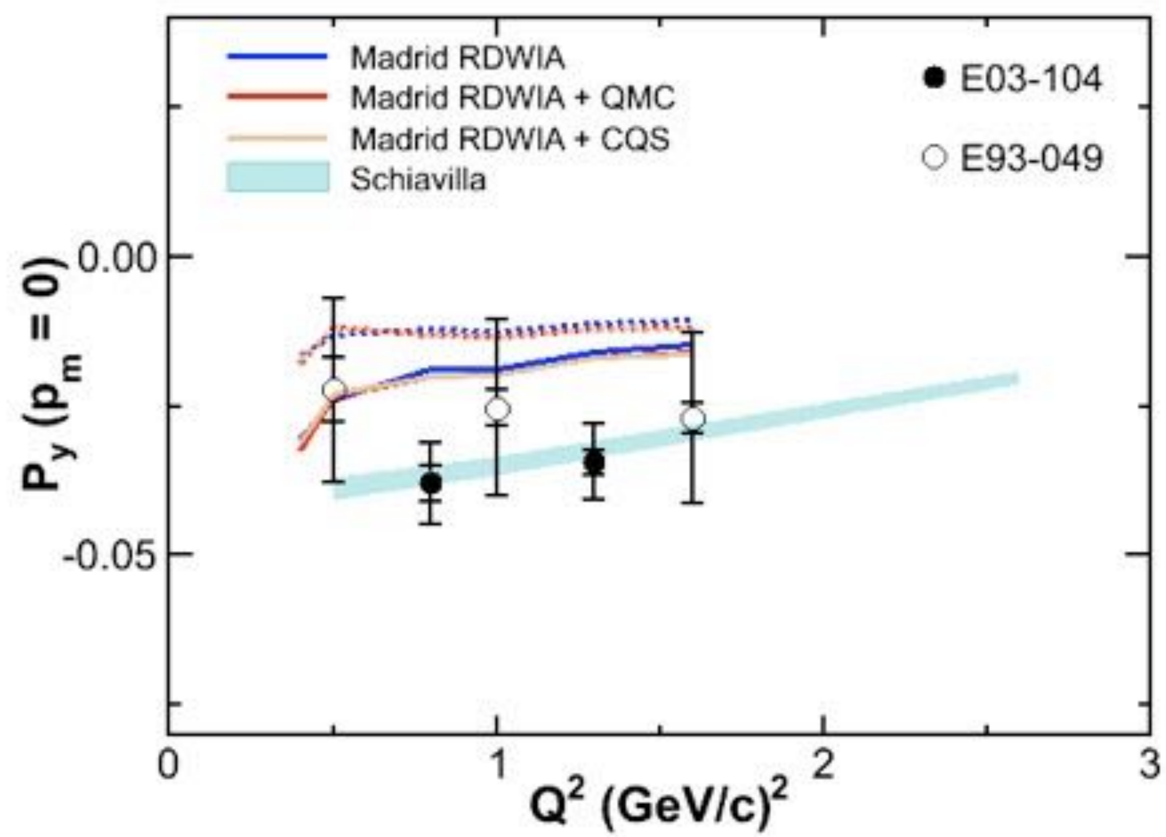

- Is this evidence of modification?

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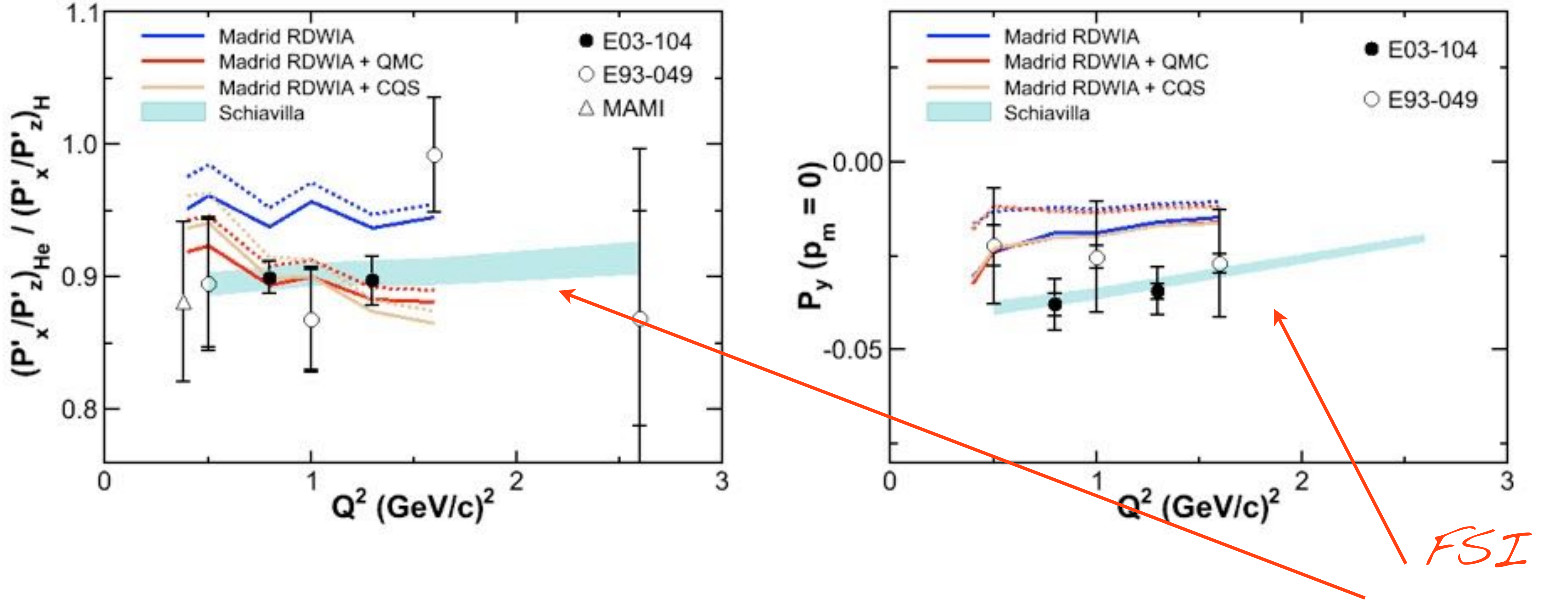

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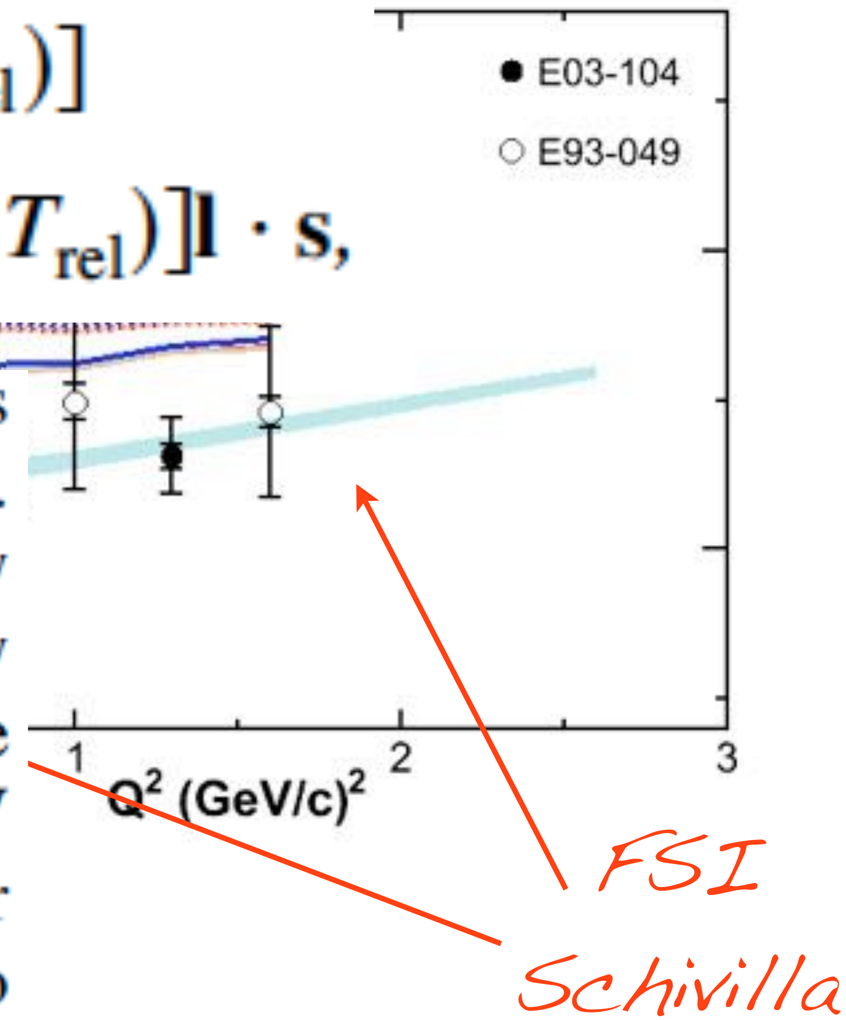
$^4\text{He}(\vec{e}, e'\vec{p})^3\text{H}$ Results

$$v_T^{\text{opt}}(T_{\text{rel}}) = [v^c(r; T_{\text{rel}}) + (4T - 3)v^{c\tau}(r; T_{\text{rel}})] + [v^b(r; T_{\text{rel}}) + (4T - 3)v^{b\tau}(r; T_{\text{rel}})]\mathbf{l} \cdot \mathbf{s},$$

- The central v^c and $v^{c\tau}$, and spin-orbit v^b and $v^{b\tau}$ terms have standard Woods-Saxon and Thomas functional forms. The parameters of v^c, $v^{c\tau}$, and v^b were determined by fitting $p + {}^3\text{H}$ elastic cross section data in the lab energy range $T_{\text{lab}} = (160\text{–}600)$ MeV, and $p + {}^3\text{H} \rightarrow n + {}^3\text{He}$ charge-exchange cross section data at $T_{\text{lab}} = 57$ MeV and 156 MeV (see Refs. [17,18] for a listing of their values). The charge-exchange spin-orbit term is taken to be purely real, with a depth parameter depending logarithmically on T_{lab}, $15.0 - 1.5\log[T_{\text{lab}}(\text{MeV})]$ in MeV, and with radius and diffuseness having the values 1.2 fm and 0.15 fm, respectively. The isospin-independent and



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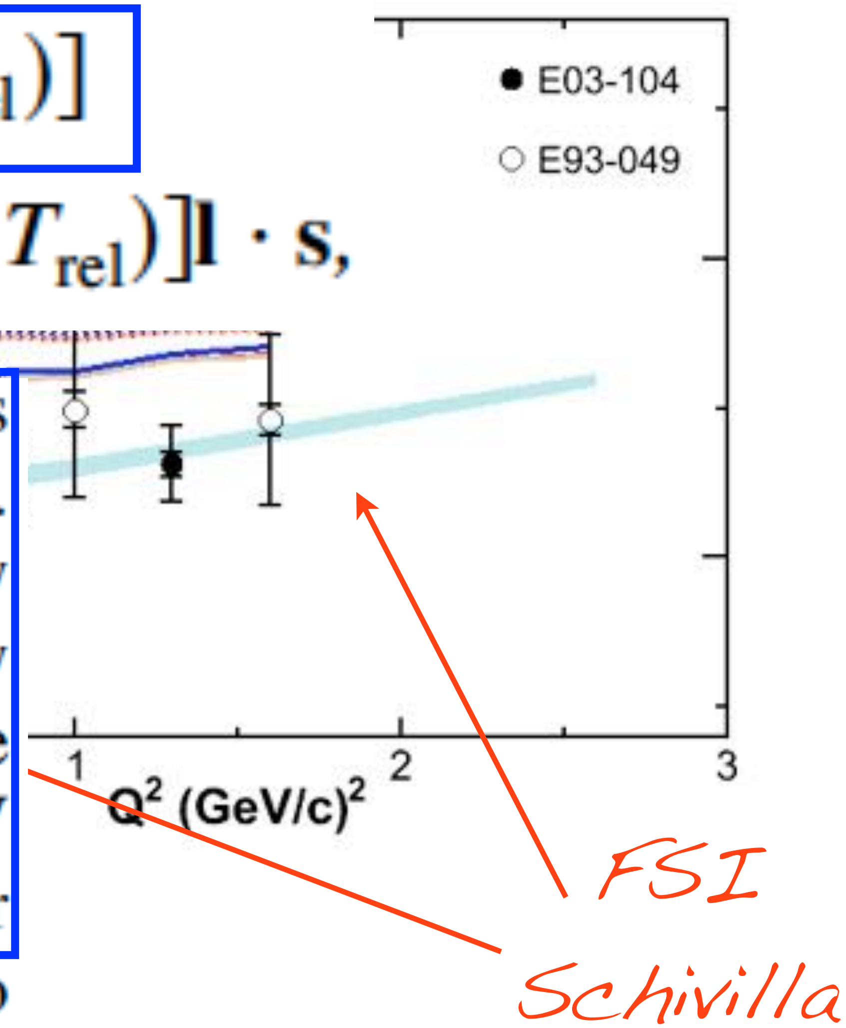
$$v_T^{\mathrm{opt}}(T_{\mathrm{rel}}) = [v^c(r;T_{\mathrm{rel}}) + (4T-3)v^{c\tau}(r;T_{\mathrm{rel}})] + [v^b(r;T_{\mathrm{rel}}) + (4T-3)v^{b\tau}(r;T_{\mathrm{rel}})]\mathbf{l}\cdot\mathbf{s},$$

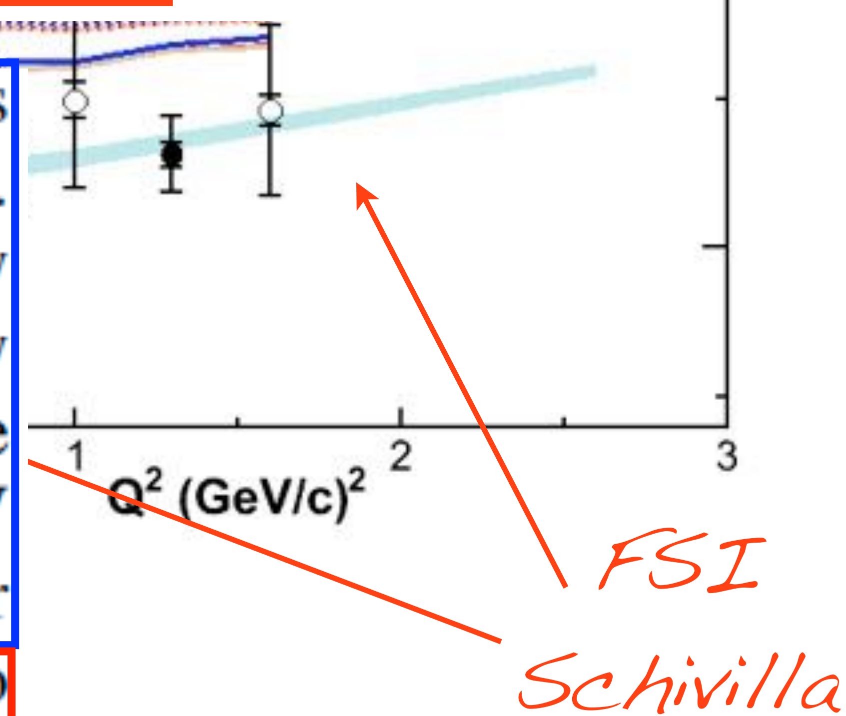


- The central v^c and $v^{c\tau}$, and spin-orbit v^b and $v^{b\tau}$ terms have standard Woods-Saxon and Thomas functional forms. The parameters of v^c, $v^{c\tau}$, and v^b were determined by fitting $p + {}^3\mathrm{H}$ elastic cross section data in the lab energy range $T_{\mathrm{lab}} = (160\text{–}600)$ MeV, and $p + {}^3\mathrm{H} \rightarrow n + {}^3\mathrm{He}$ charge-exchange cross section data at $T_{\mathrm{lab}} = 57$ MeV and 156 MeV (see Refs. [17,18] for a listing of their values). The charge-exchange spin-orbit term is taken to be purely real, with a depth parameter depending logarithmically on T_{lab}, $15.0 - 1.5\log[T_{\mathrm{lab}}(\mathrm{MeV})]$ in MeV, and with radius and diffuseness having the values 1.2 fm and 0.15 fm, respectively. The isospin-independent and

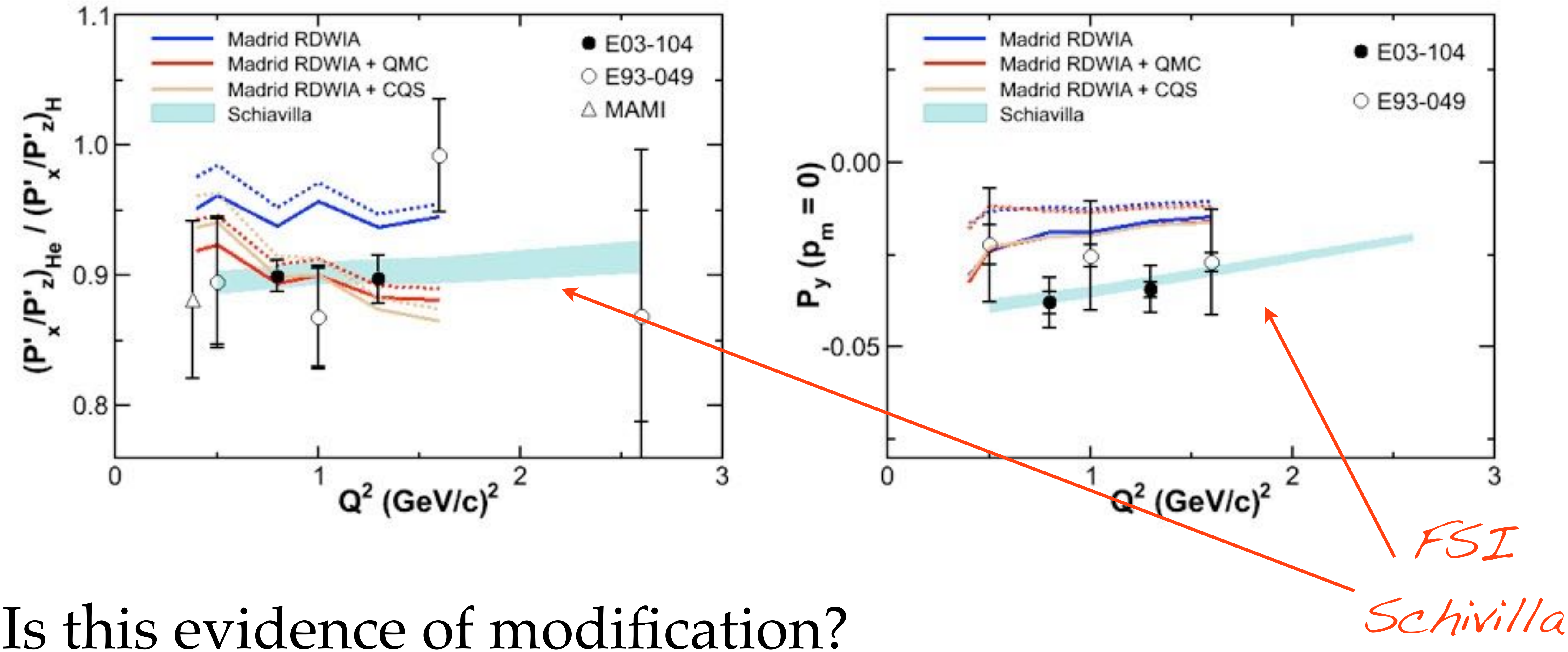
$^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ Results

$$v_T^{\text{opt}}(T_{\text{rel}}) = [v^c(r; T_{\text{rel}}) + (4T - 3)v^{c\tau}(r; T_{\text{rel}})] + [v^b(r; T_{\text{rel}}) + (4T - 3)v^{b\tau}(r; T_{\text{rel}})]\mathbf{l} \cdot \mathbf{s},$$

- The central v^c and $v^{c\tau}$, and spin-orbit v^b and $v^{b\tau}$ terms have standard Woods-Saxon and Thomas functional forms. The parameters of v^c, $v^{c\tau}$, and v^b were determined by fitting $p + {}^3\mathrm{H}$ elastic cross section data in the lab energy range $T_{\text{lab}} = (160\text{–}600)$ MeV, and $p + {}^3\mathrm{H} \rightarrow n + {}^3\mathrm{He}$ charge-exchange cross section data at $T_{\text{lab}} = 57$ MeV and 156 MeV (see Refs. [17,18] for a listing of their values). The charge-exchange spin-orbit term is taken to be purely real, with a depth parameter depending logarithmically on T_{lab}, $15.0 - 1.5\log[T_{\text{lab}}(\text{MeV})]$ in MeV, and with radius and diffuseness having the values 1.2 fm and 0.15 fm, respectively. The isospin-independent and

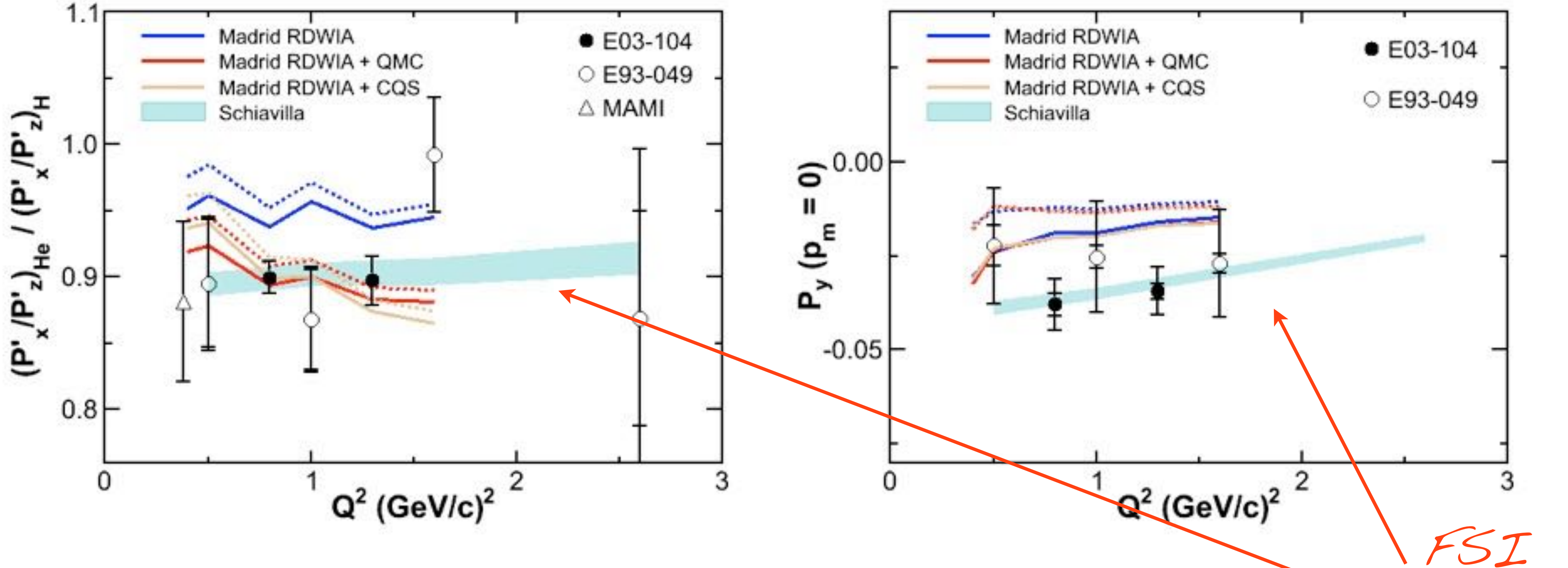


${}^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ Results



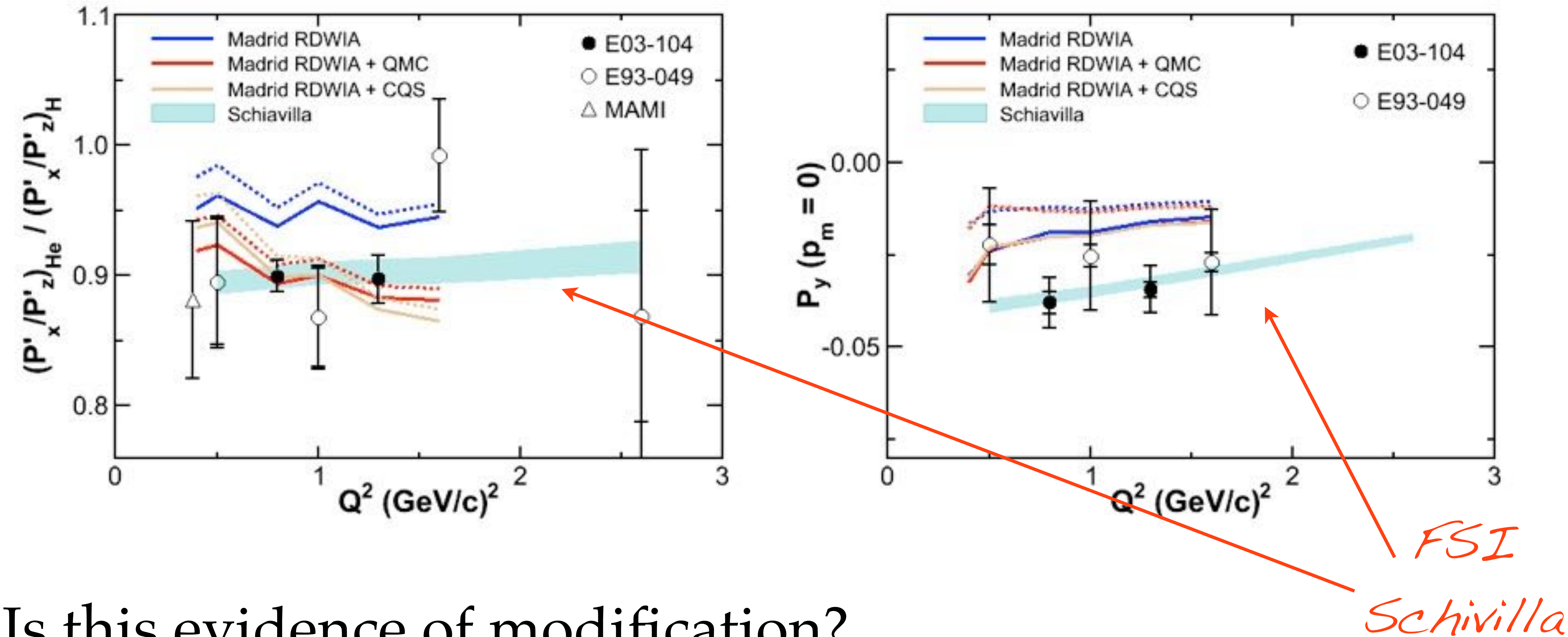
- Is this evidence of modification?

$^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ Results



- Is this evidence of modification?
- FSI in this calculation not constrained by independent measurement! a proof of concept rather than a strong result.

$^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ Results

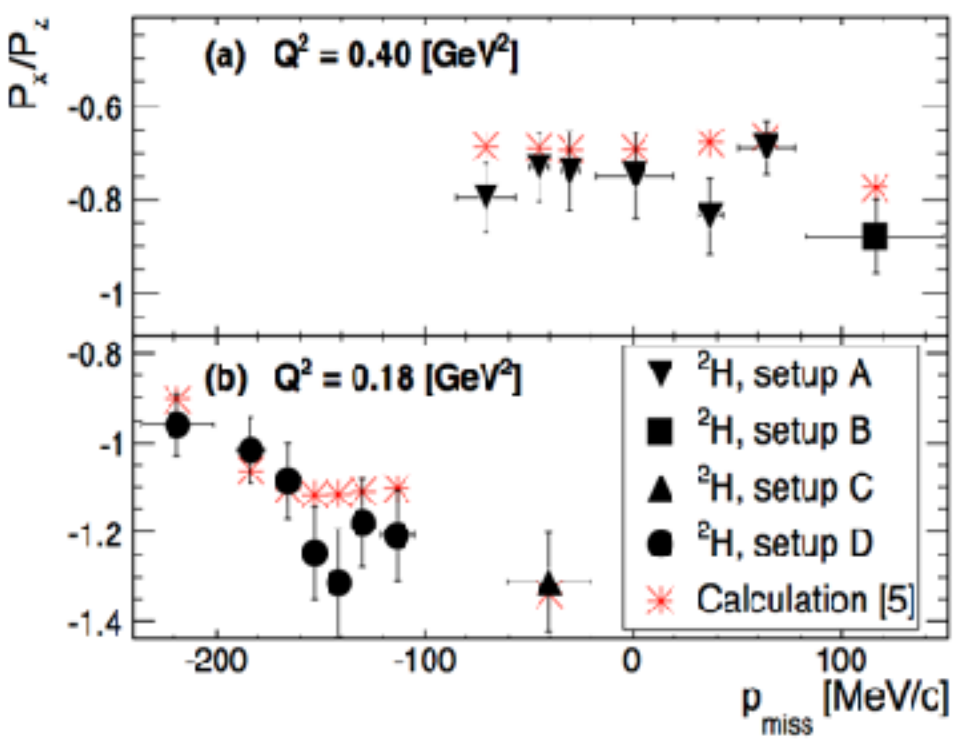


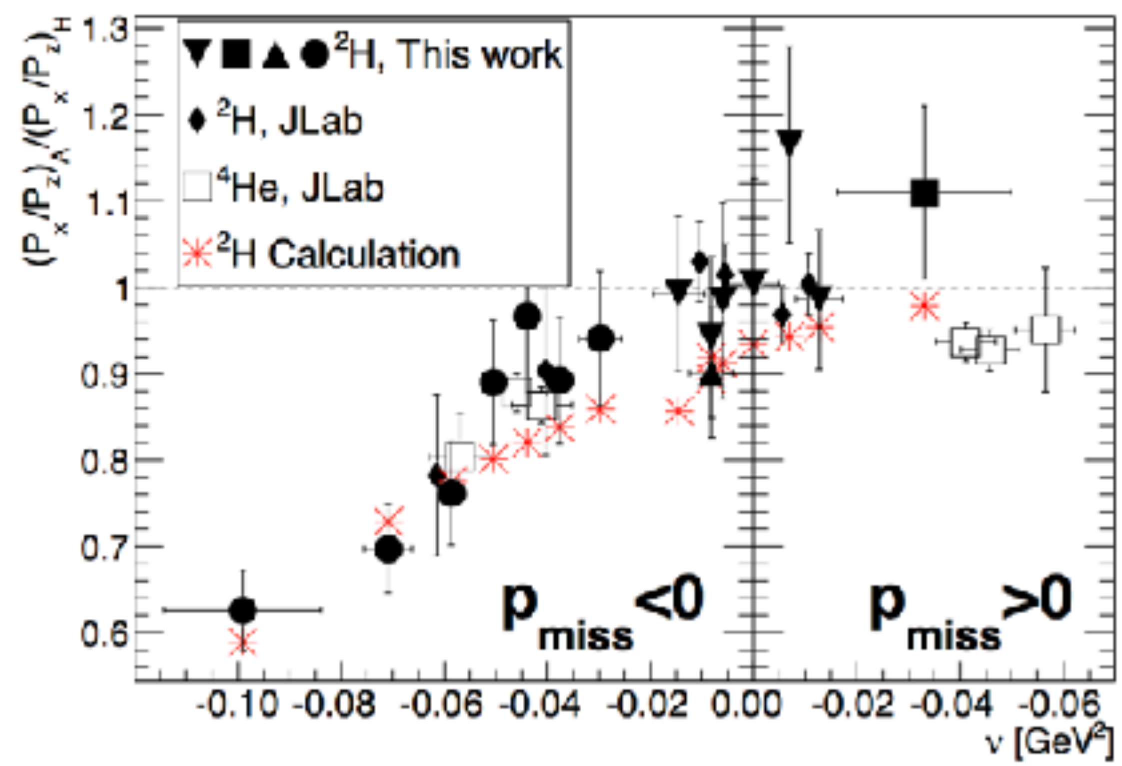
- Is this evidence of modification?
- FSI in this calculation not constrained by independent measurement! a proof of concept rather than a strong result.
- FSI constrained by P_y - independent (of electron scattering) data?

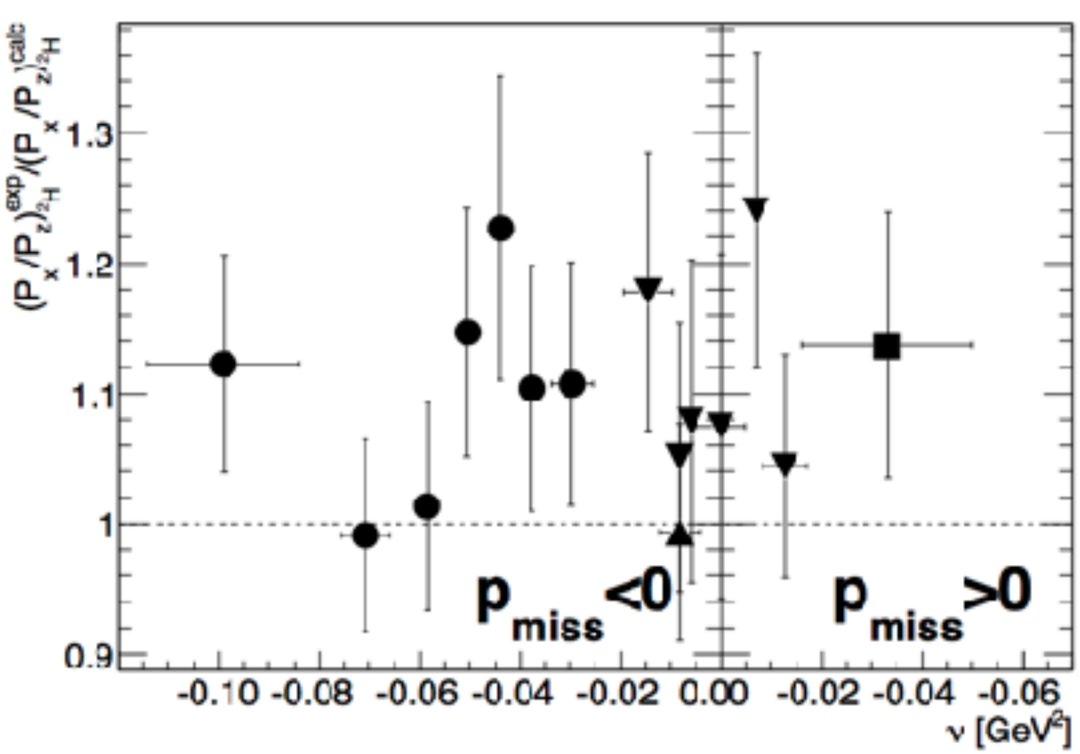
Local vs. Global effect?

- Test in extreme conditions:
  - Nucleon is highly off shell - corresponds to large missing momentum, large virtuality, or tightly bound.
  - Nucleon not tightly bound, but is in an average high density state - can do this by comparing almost on-shell nucleons extracted from different nuclear shells.
- Use polarization observables since they are systematically (relatively) clean.
- So we did....

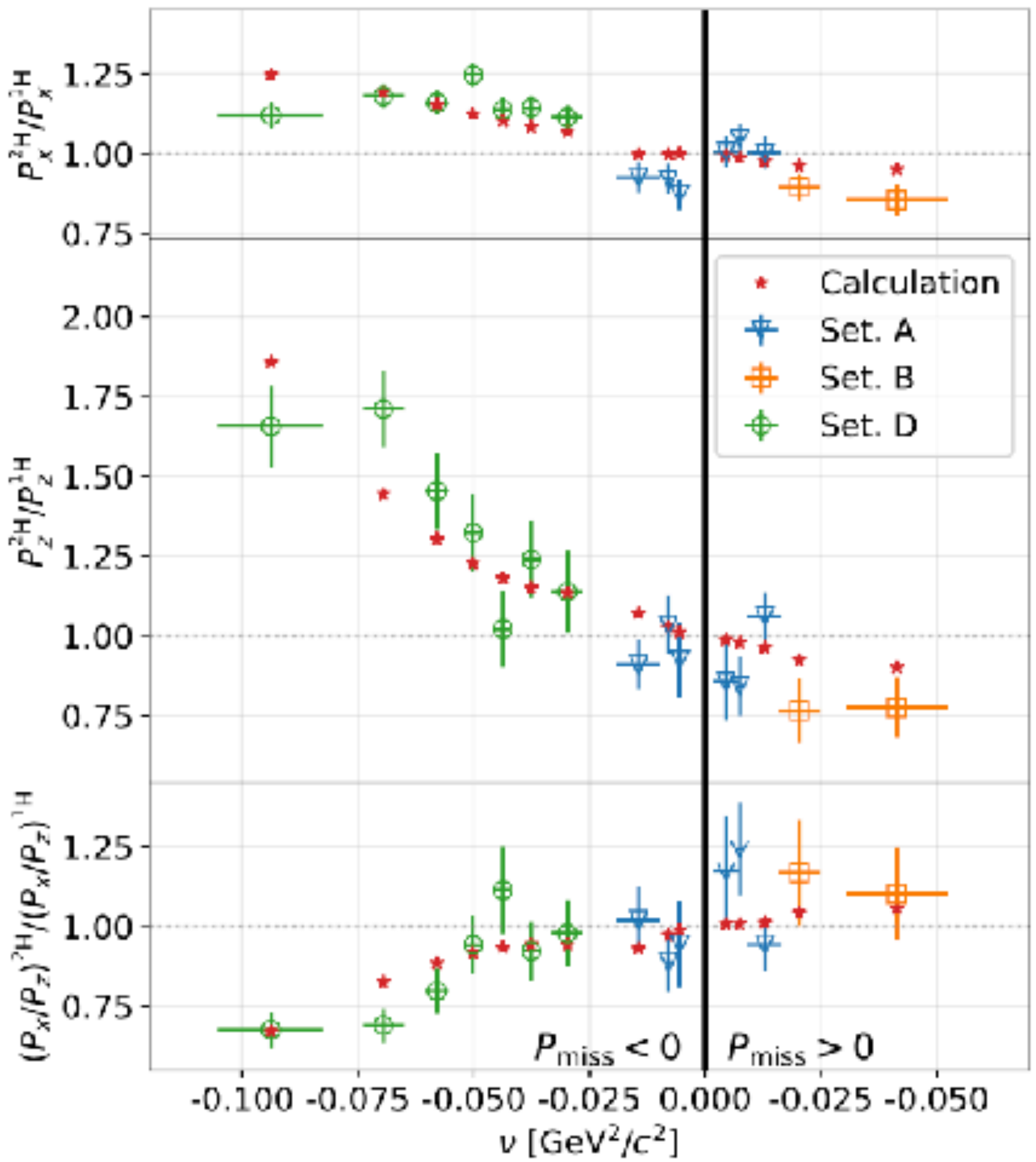
Tightly bound proton in deuteron

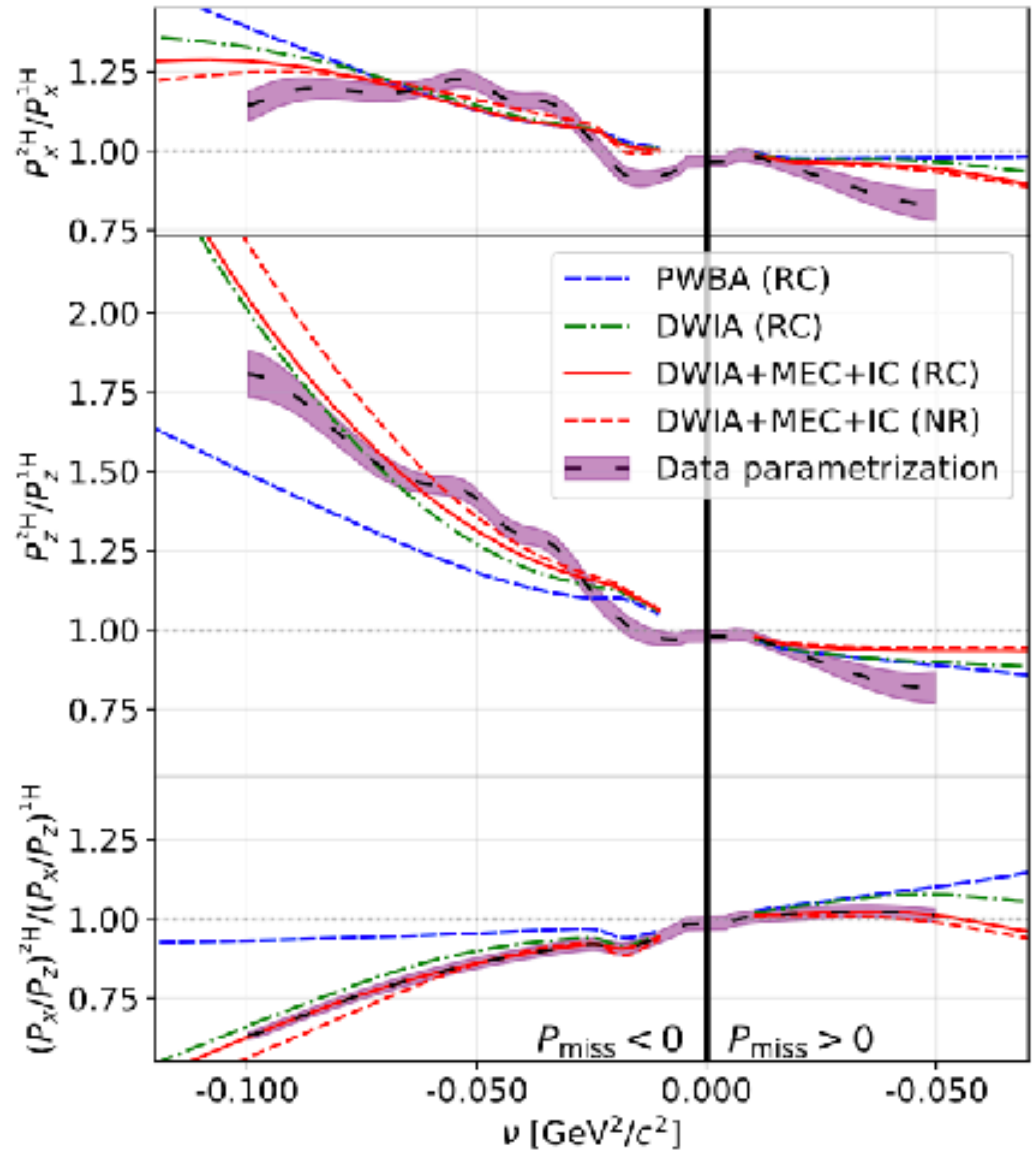






Tightly bound proton in deuteron - Reanalysis





II - s/p shells in ^{12}C (factor of 2 difference in mean density)