The proton radius puzzle and the PRad experiment

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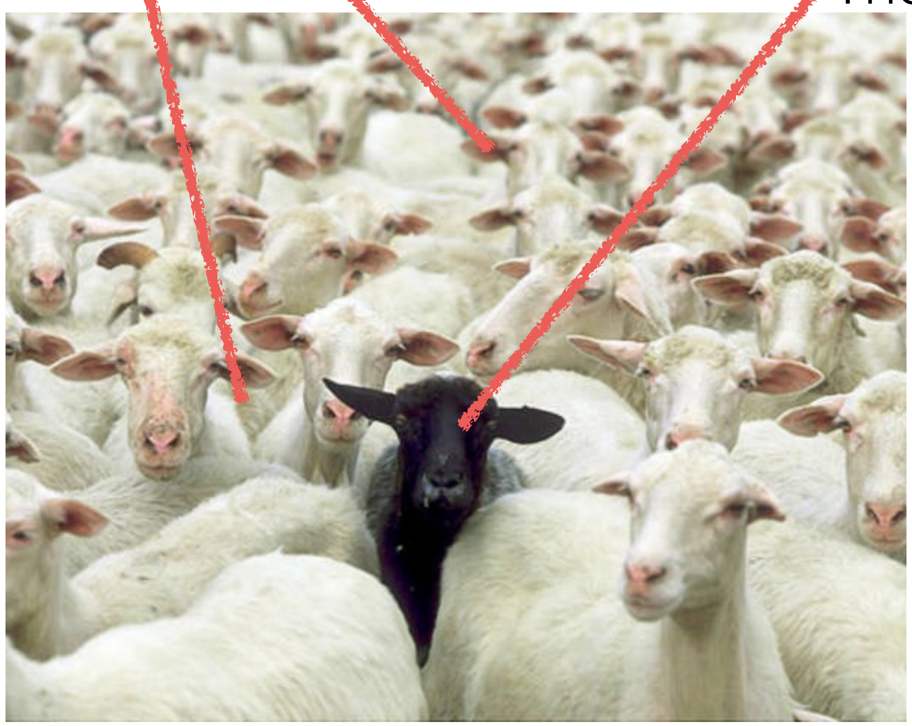
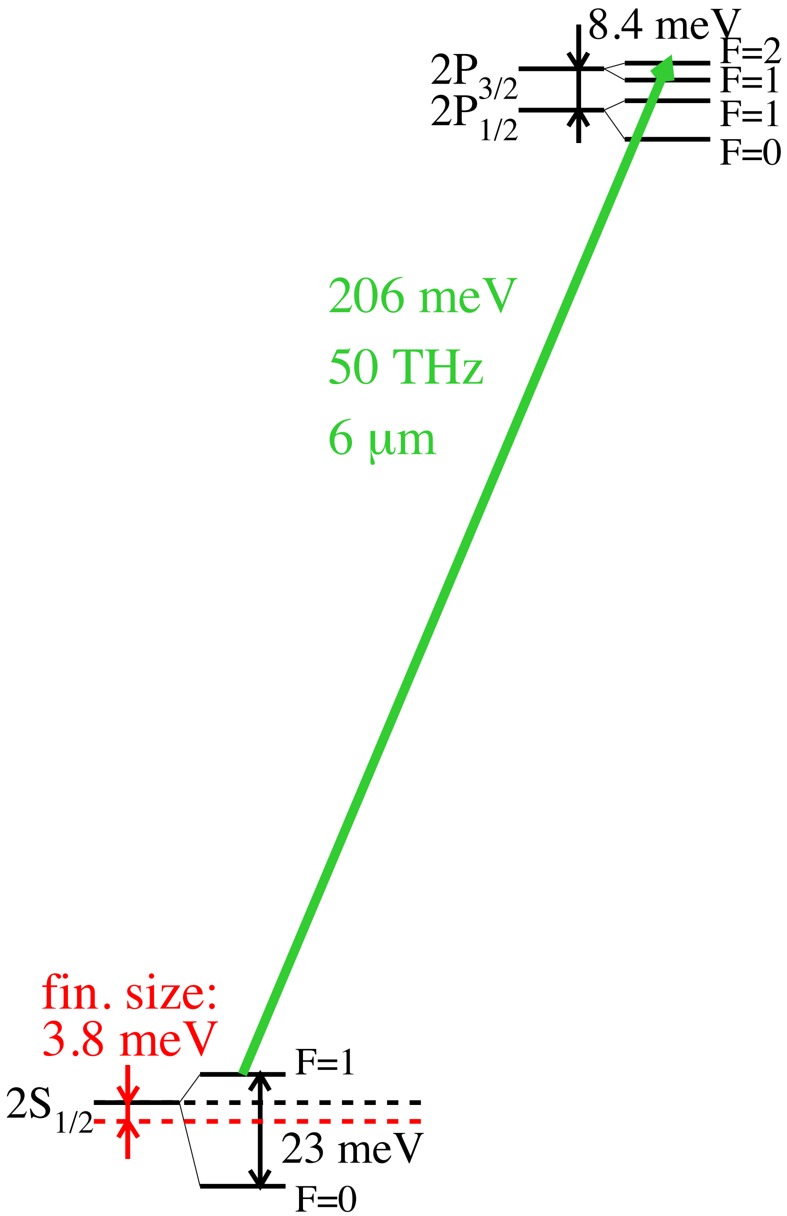
Extracting the proton radius from μp

Measure 2S-2P splitting (20 ppm)
and compare with theory
→ proton radius

$$\Delta E^{\rm th}_{2P-2S} = 206.0336(15) - 5.2275(10)\, R_{\rm p}^2 + 0.0332(20) \quad [\rm meV]$$

The most interesting





$$\Delta E_{\rm size} = \frac{2\pi(Z\alpha)}{3} R_{\rm p}^2 \, |\Psi_{nl}(0)|^2$$

$$= \frac{2(Z\alpha)^4}{3n^3} m_r^3 \, R_{\rm p}^2 \, \delta_{l0}$$

$$m_\mu \approx 200 m_e$$

$$R_{\rm p}^2 = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

Miller,
PRC 99, 035202
(2019)

Principle of the μp 2S-2P experiment

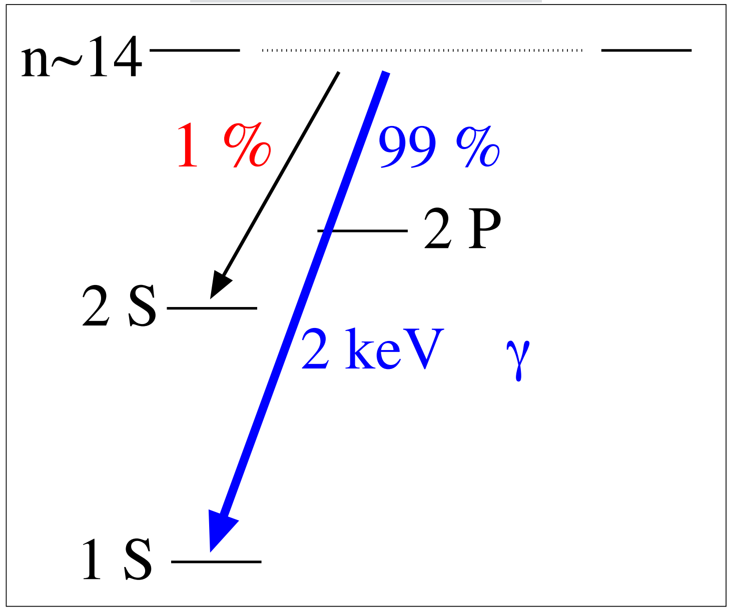
Produce many μ^- at keV energy

Form μp by stopping μ^- in 1 mbar H_2 gas

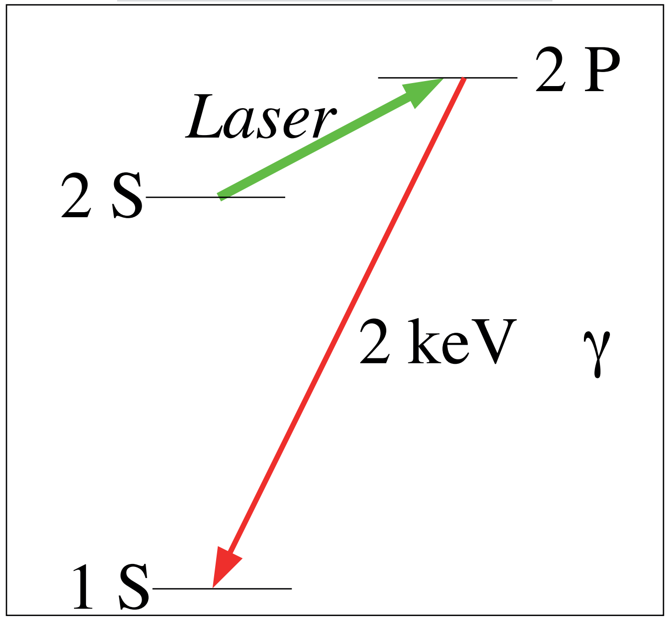
Fire laser to induce the 2S-2P transition

Measure the 2 keV X-rays from 2P-1S decay

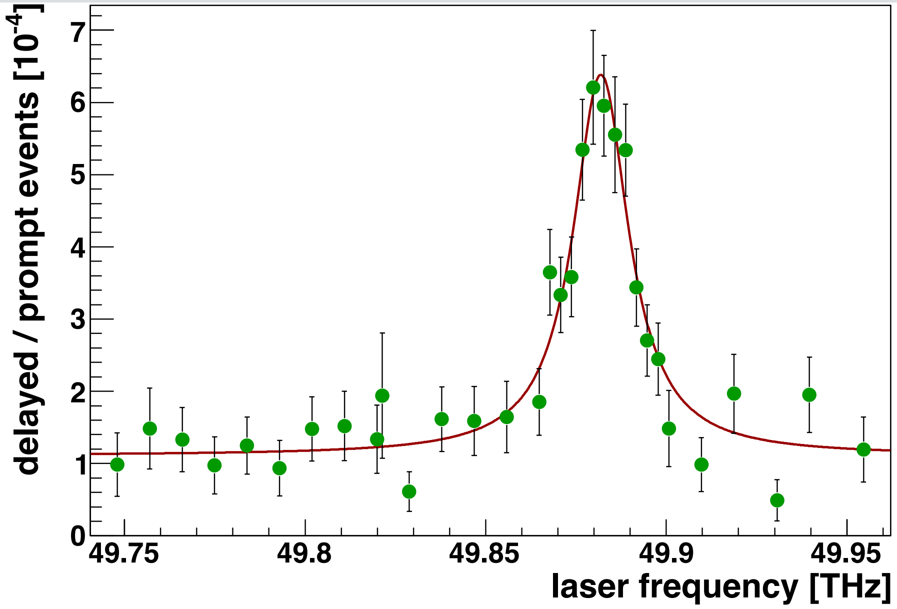
μp formation



Laser excitation

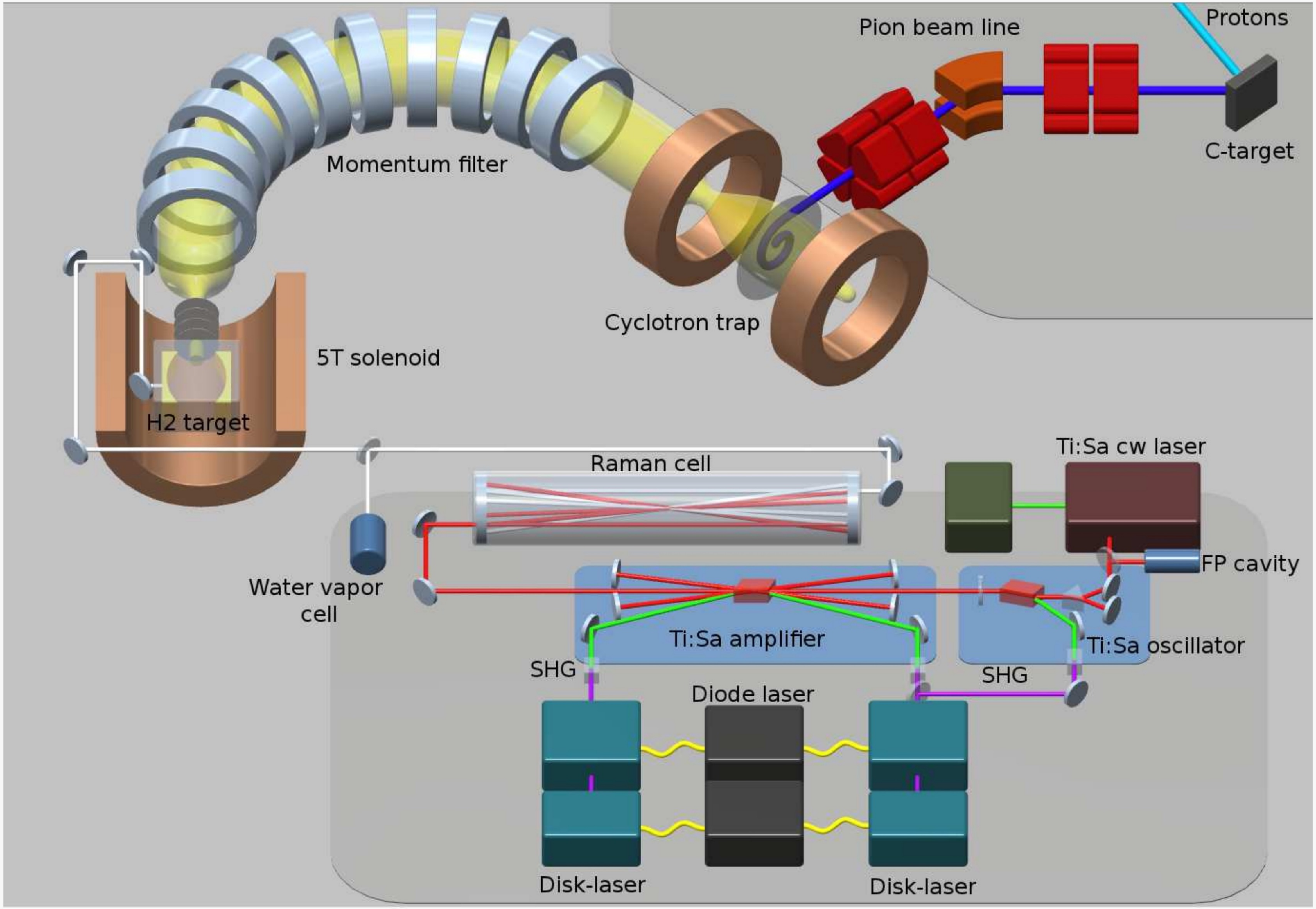


Plot number of X-rays vs laser frequency



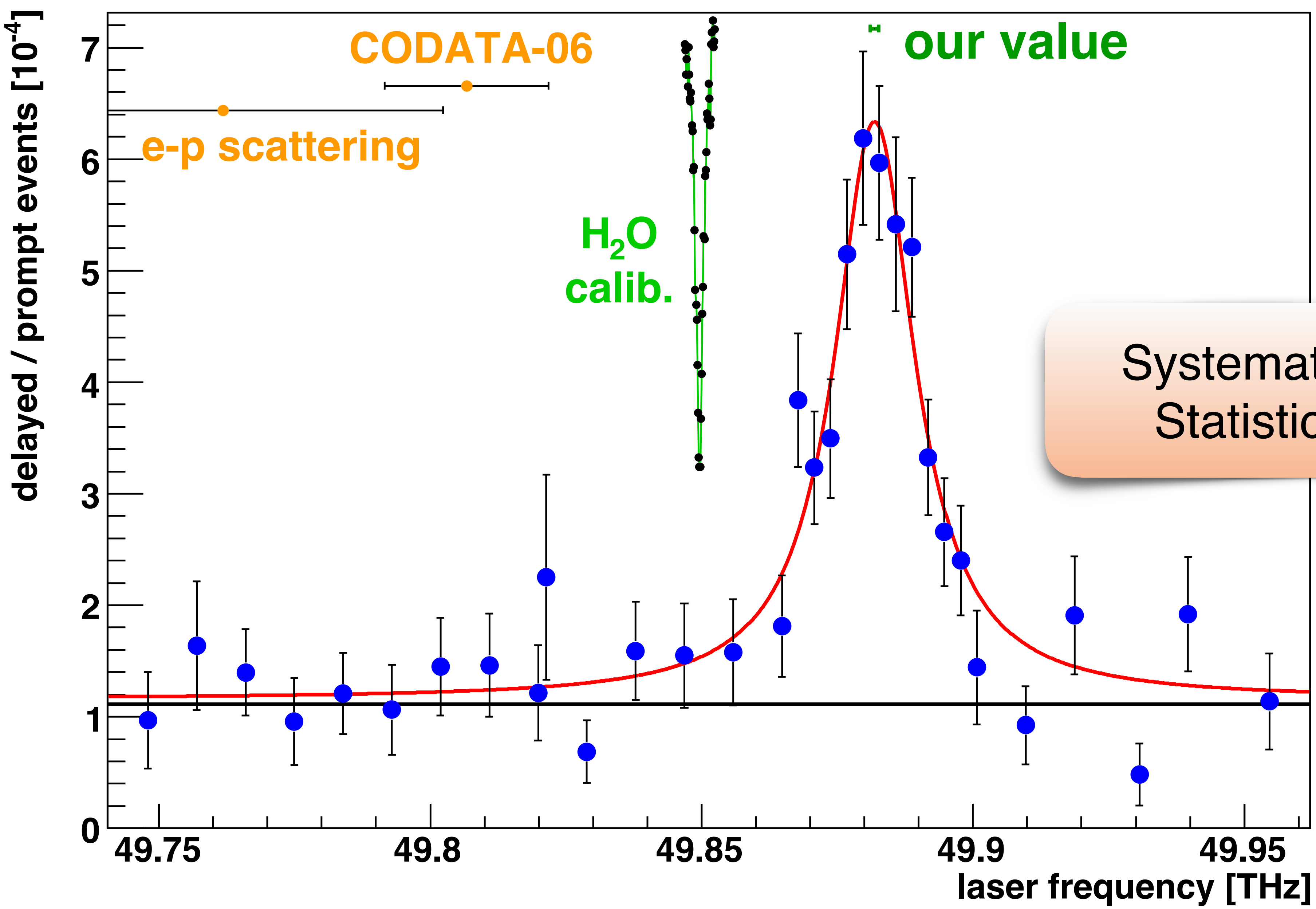
The setup at the Paul Scherrer Institute

p-beam (1 MW)	940 nm (2 kW)
↓	↓
π (MeV)	1030 nm
↓	↓
μ (MeV)	515 nm
↓	↓
μ (keV)	708 nm
↓	↓
μp(2S)	1.0 μm
↓	↓
Laser	1.6 μm
↓	↓
X-ray	6.0 μm



The first μp resonance (2010)

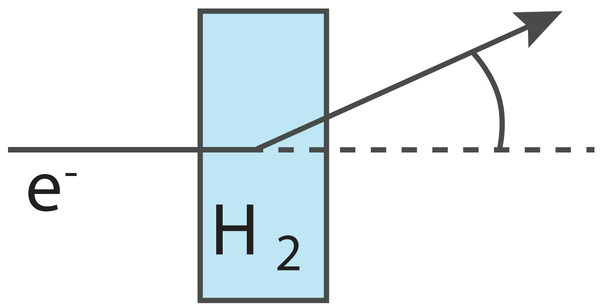
Discrepancy:
$$5.0\,\sigma \;\leftrightarrow\; 75\ \text{GHz} \;\leftrightarrow\; \delta\nu/\nu = 1.5\times10^{-3}$$



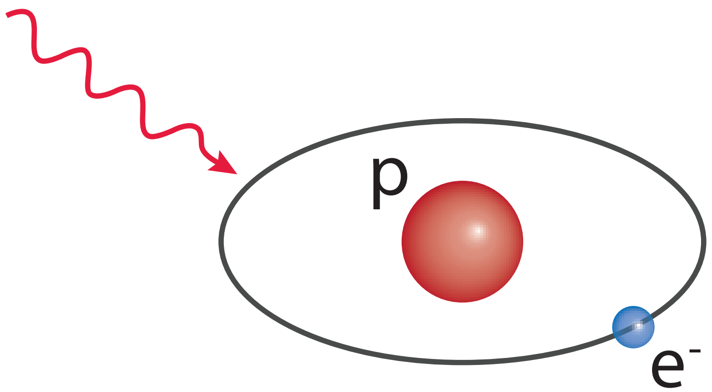
Systematics: 300 MHz
Statistics: 700 MHz

Pohl et al., Nature 466, 213 (2010)

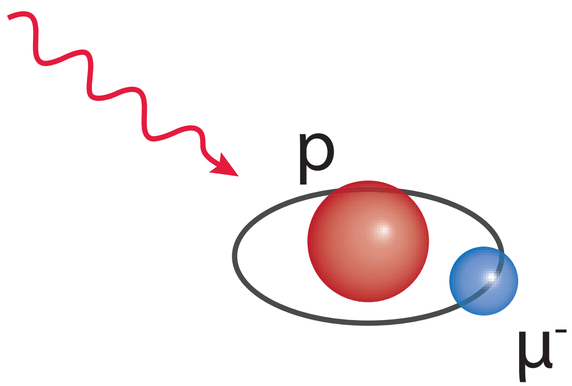
Three ways to the proton radius



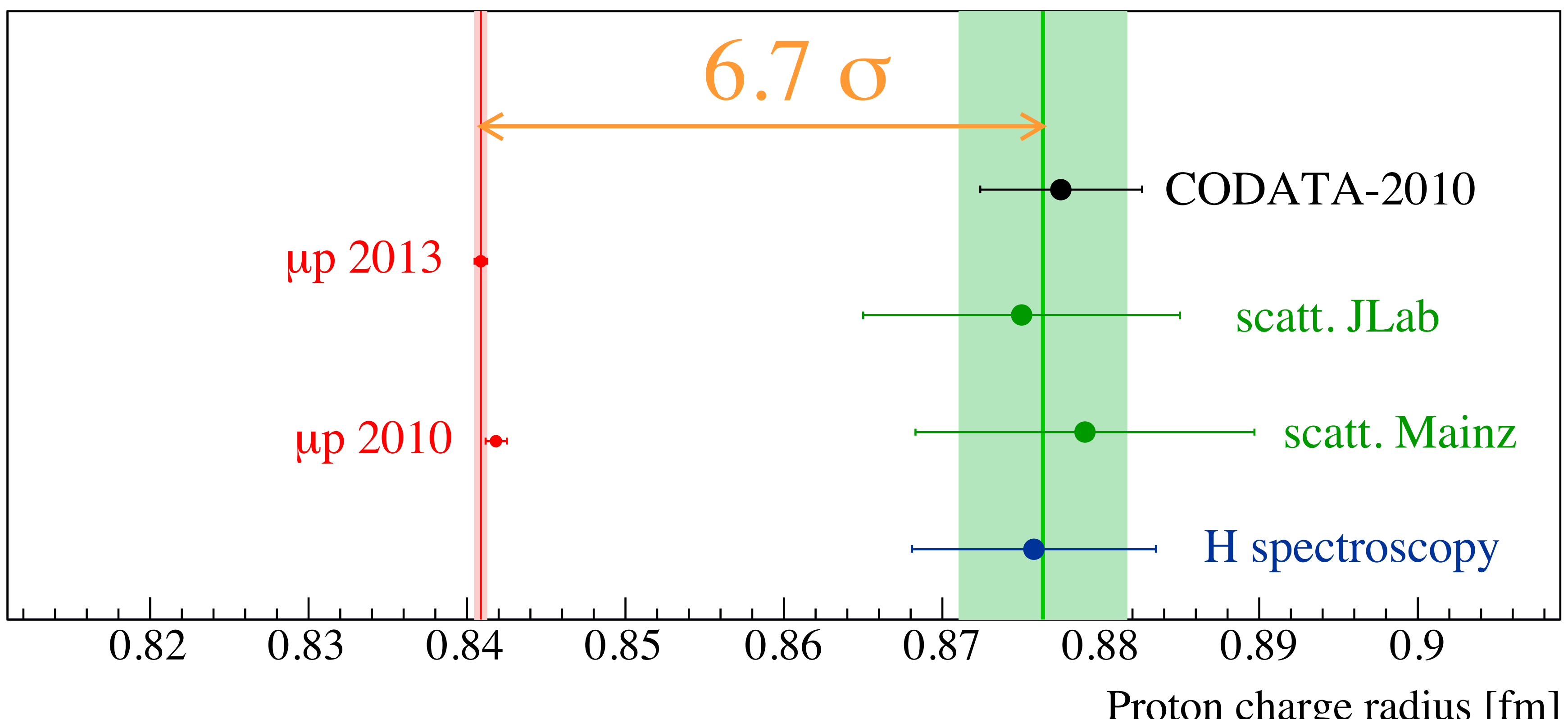
e^--p scattering



H spectroscopy

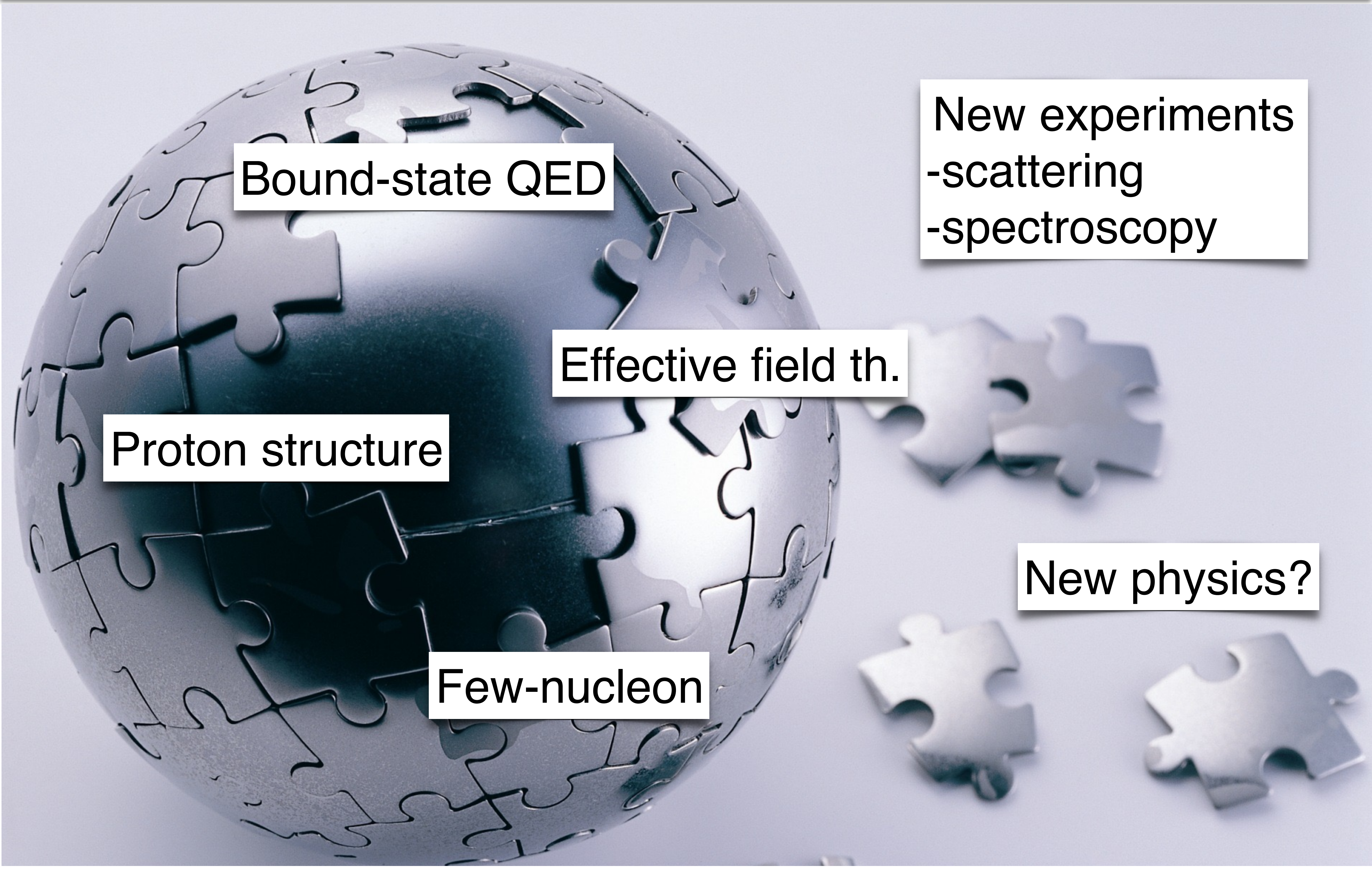


μp spectroscopy



Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

The r_p puzzle has triggered many activities



The proton radius puzzle

- µp experiment
- µp theory
- H experiments
- BSM physics
- e-p scattering

Rarely criticised since:

$m_\mu \approx 200 m_e$

- **sensitive** to the radius

$$\sim m^3 R_p^2 \quad ✓$$

- **insensitive** to systematical effects

$$\sim 1/m \quad ✓$$

The proton radius puzzle

- µp experiment
- **µp theory**
- H experiments
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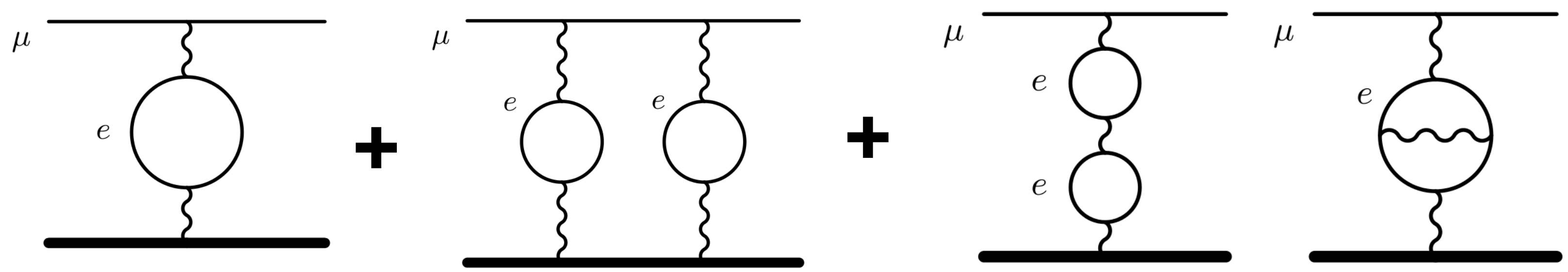
- e-p scattering

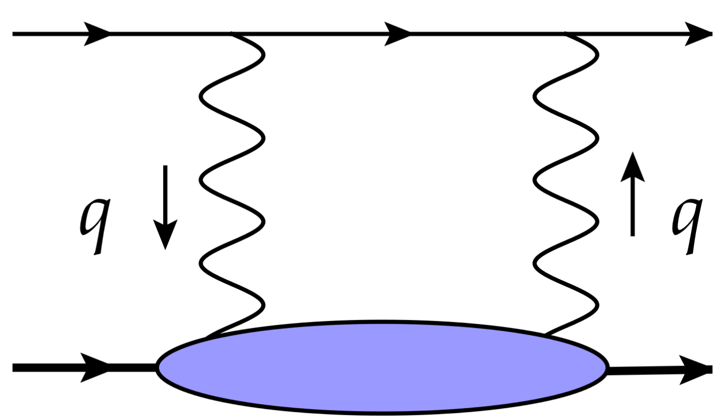
QED ✓✓✓✓

Pachucki, Borie, Eides, Karschenboim, Jentschura, Martynenko, Indelicato Pineda, Peset, Faustov…



+ many more

Two-photon exchange ✓✓✓✓ ✗



Can be computed with dispersion th. + data

But subtraction term is needed
⇒ modelling of proton

Pachucki, Carlson, Birse, McGovern, Pineda, Gorchtein, Pascalutsa, Vanderhaeghen, Alarcon, Miller, Paz, Hill…

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- **µp theory**
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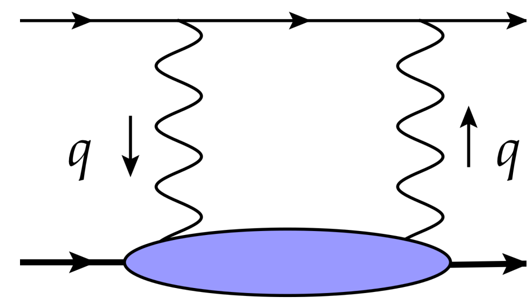
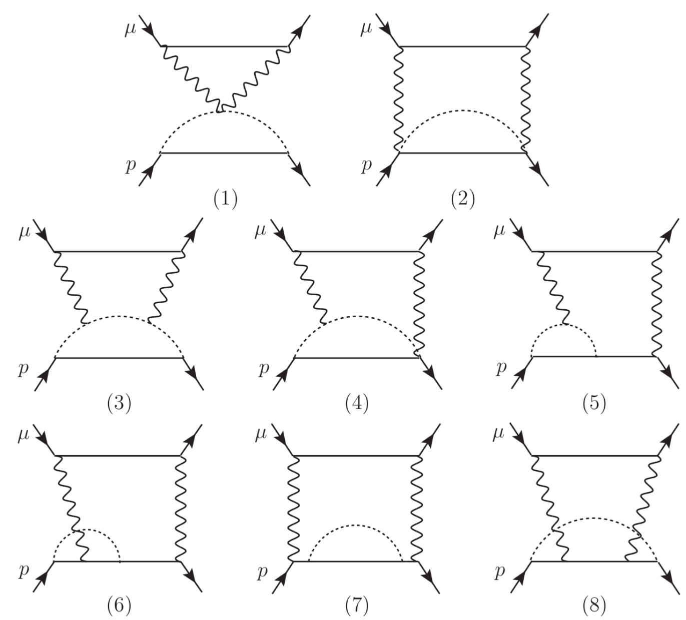
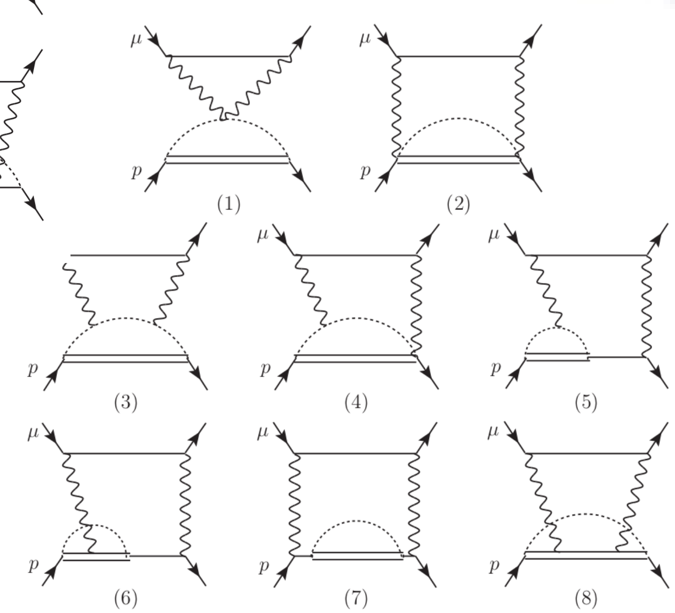


Phenomenological
- dispersion relations
- data
- subtraction term

Chiral EFT

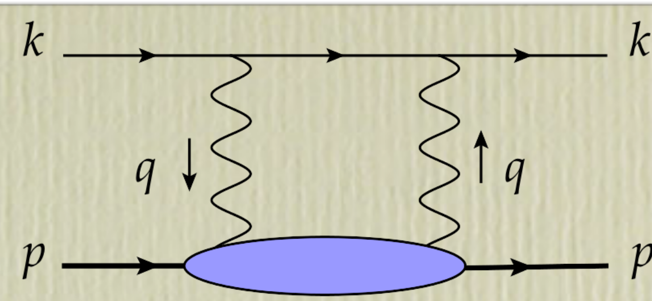




AGREEMENT

Technicalities on TPE in μp

Kinematics: 2 loop variables
q^2 and $\nu=(pq)/M$



+ crossed

$$\mathcal{M} = e^4 \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^4} \bar{u}(k) \left[\gamma^\nu \frac{1}{\not{k} - \not{q} - m_l + i\epsilon} \gamma^\mu + \gamma^\mu \frac{1}{\not{k} + \not{q} - m_l + i\epsilon} \gamma^\nu \right] u(k) T_{\mu\nu}$$

Forward virtual Compton amplitude

$$T^{\mu\nu} = \frac{i}{8\pi M} \int d^4 x e^{iqx} \langle p | T j^\mu(x) j^\nu(0) | p \rangle$$
$$= \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} \right) T_1(\nu, Q^2) + \frac{1}{M^2} (p - \frac{pq}{q^2} q)^\mu (p - \frac{pq}{q^2} q)^\nu T_2(\nu, Q^2)$$

Lamb shift (nS-nP)

$$\Delta E = -\frac{\alpha^2}{2\pi m_l M_d} \phi_n^2(0) \int d^4 q \frac{(q^2 + 2\nu^2) T_1(\nu, q^2) - (q^2 - \nu^2) T_2(\nu, q^2)}{q^4 [(q^2/2m_l)^2 - \nu^2]}$$

Slide stolen from Gorchtein

Technicalities on TPE in μp

T_1, T_2 - the imaginary parts known (Optical theorem)

$$\mathrm{Im}T_1(\nu,Q^2) = \frac{1}{4M}F_1(\nu,Q^2)$$

$$\mathrm{Im}T_2(\nu,Q^2) = \frac{1}{4\nu}F_2(\nu,Q^2)$$

Inelastic structure functions = data

(real and virtual photoabsorption, FF)

Real parts - from forward dispersion relation

$F_1(\nu \to \infty, q^2) \sim \nu^{1+\epsilon}$ - subtraction needed

$F_2(\nu \to \infty, q^2) \sim \nu^{\epsilon}$ - no subtraction

$$\mathrm{Re}T_1(\nu,Q^2) = \bar{T}_1(0,Q^2) + T_1^{pole}(\nu,Q^2) + \frac{\nu^2}{2\pi M}\int_{\nu_0}^{\infty}\frac{d\nu'}{\nu(\nu'^2-\nu^2)}F_1(\nu',Q^2)$$

$$\mathrm{Re}T_2(\nu,Q^2) = T_2^{pole}(\nu,Q^2) + \frac{1}{2\pi}\int_{\nu_0}^{\infty}\frac{d\nu'}{\nu'^2-\nu^2}F_2(\nu',Q^2)$$

Slide stolen from Gorchtein

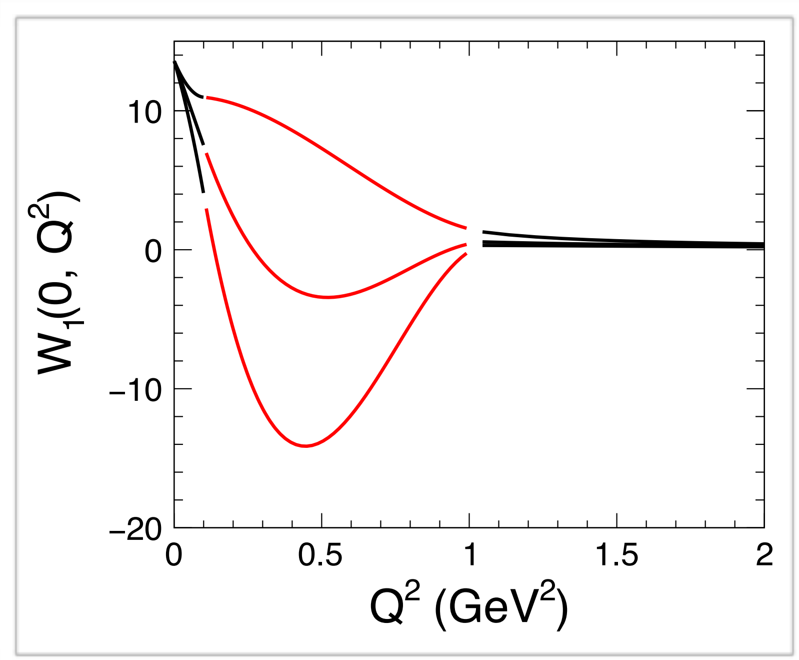
The proton radius puzzle

- µp experiment
- µp theory
- H experiments
- BSM physics
- e-p scattering

Uncertainties and discrepancy

0.3	meV	Discrepancy
0.01	meV:	TPE uncertainty (conservatively, Hill and Paz)
0.0025	meV:	Polarisability-contr. uncertainty (Pascalutsa)
0.0020	meV:	TPE uncertainty (McGovern)
0.0015	meV:	QED uncertainties
0.0023	meV:	Measurement uncertainty

Pachucki, Carlson, Birse, McGovern, Pineda, Peset, Gorchtein, Pascalutsa, Vanderhaeghen, Tomalak, Martynenko, Alarcon, Miller, Paz, Hill…



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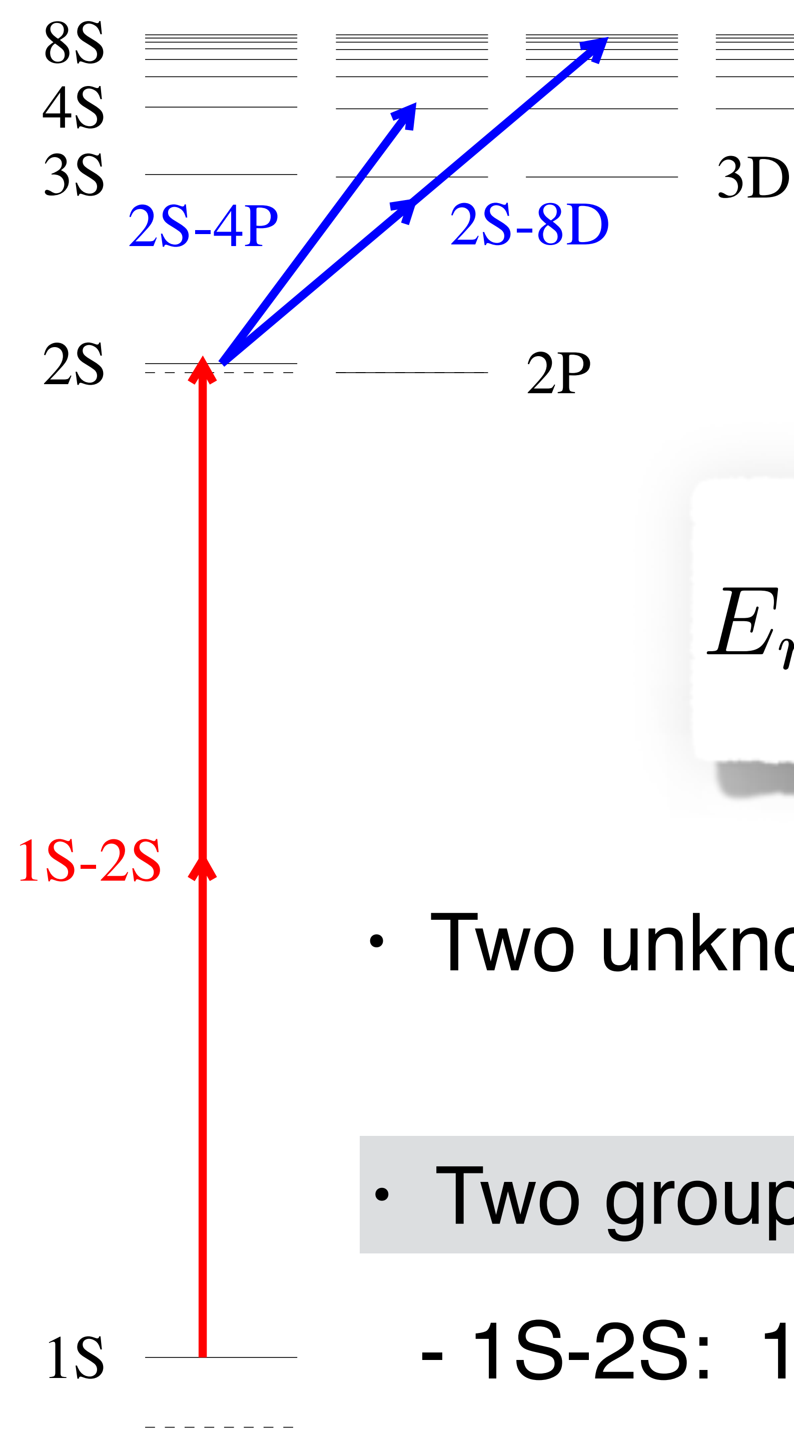

1S-3S: 1801.08816
2S-4P: Science 358, 79–85 (2017)

$$E_{nS} \simeq \frac{R_\infty}{n^2} + \frac{\mathrm{QED} + k R_p^2}{n^3}$$

- Two unknown: R_∞ , R_p

- Two groups of measurements:

  - 1S-2S: 10^{-15} rel. accuracy ✓ ✓
  - others: $<10^{-13}$ rel. accuracy and more prone to systematics ?

The proton radius puzzle (2010)

- µp experiment
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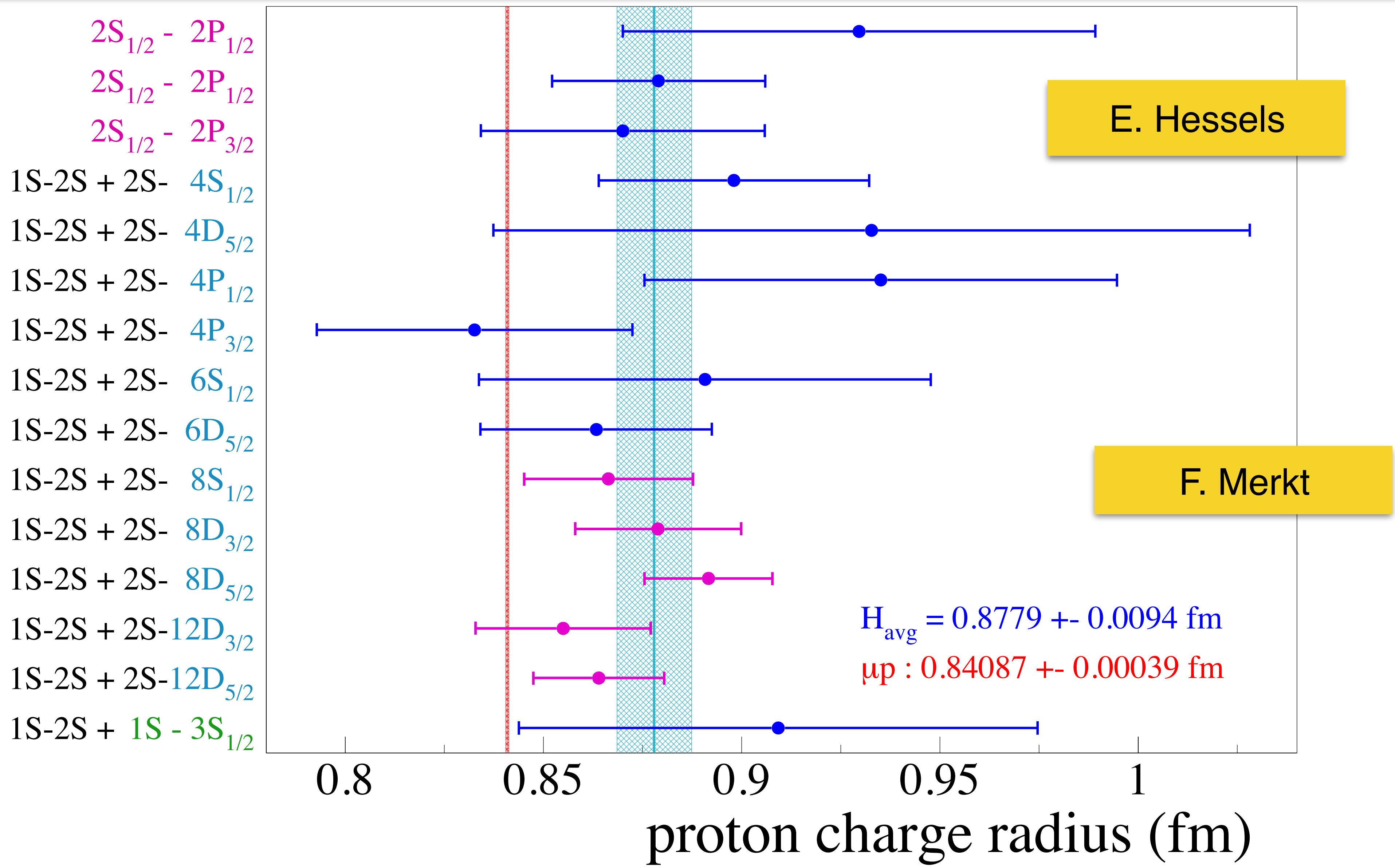

Proton radius discrepancy is $10^{-3}\Gamma$ of 2S-nS transitions

4σ discrepancy only after averaging

The proton radius puzzle

- µp experiment
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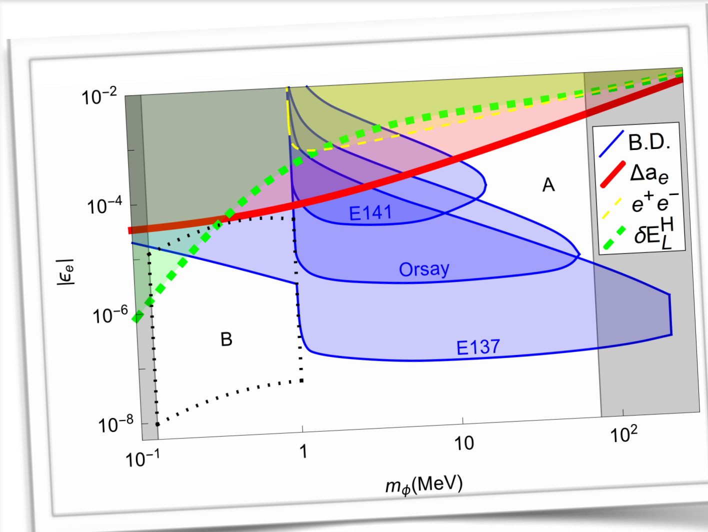
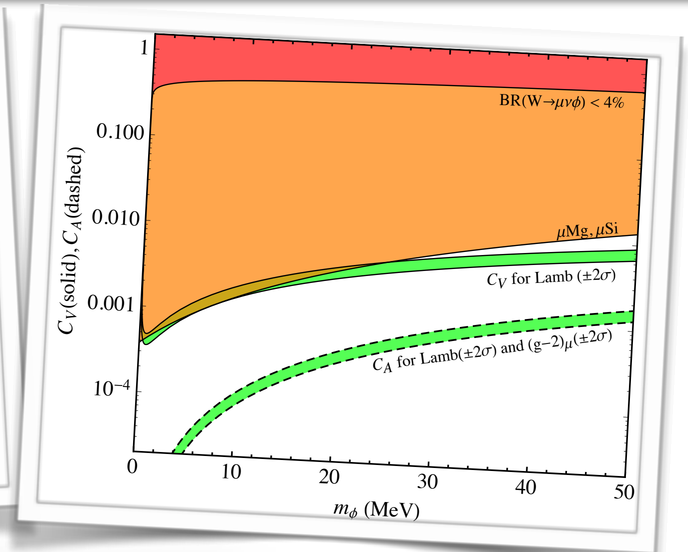
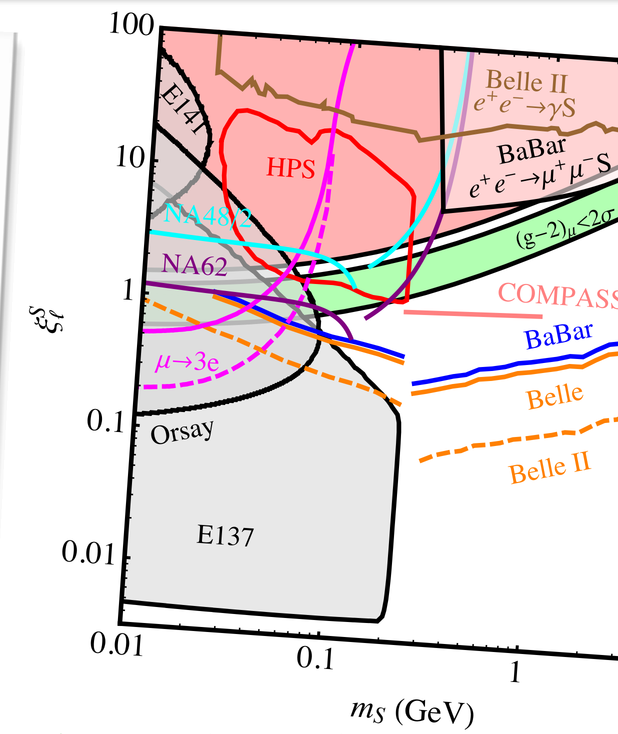
- e-p scattering



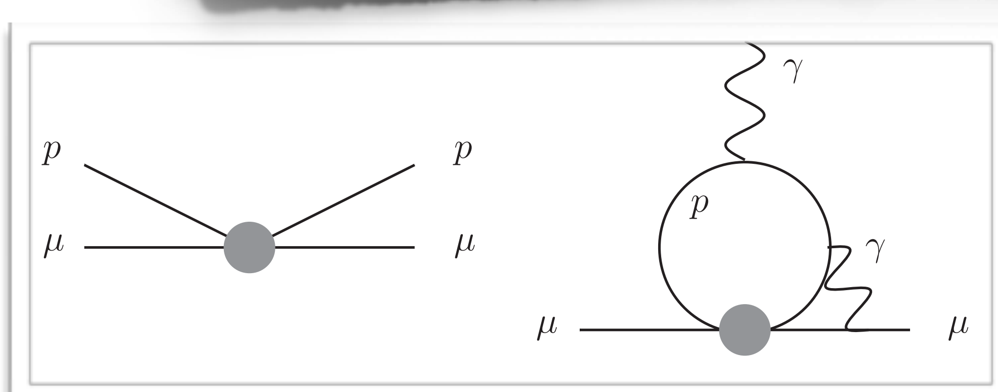




Some open regions for MeV force carrier still resist

Martens & Ralston (2016), Liu, McKeen & Miller (2016), Batell et. al (2016)

- Tuning (e.g. vector vs axial-vector)
- Preferential coupling to μ and p
- No UV completion and no full SM gauge inv.



✓✓✓

✗ ✗ ✗ ✗ ✗

The proton radius puzzle

- µp experiment
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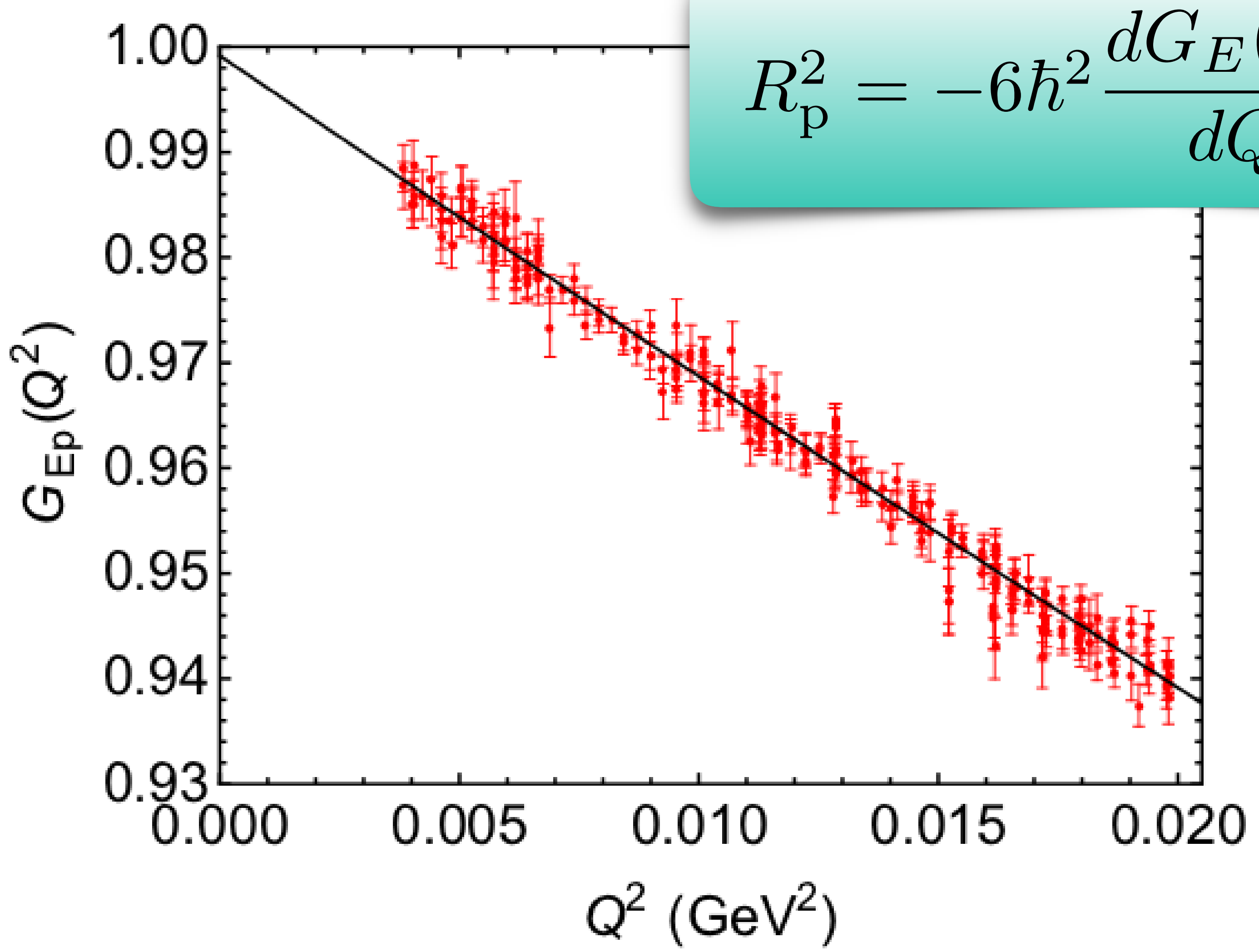
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ros.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{(1+\tau)}\left(\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$

$$R_{\text{p}}^2 = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$



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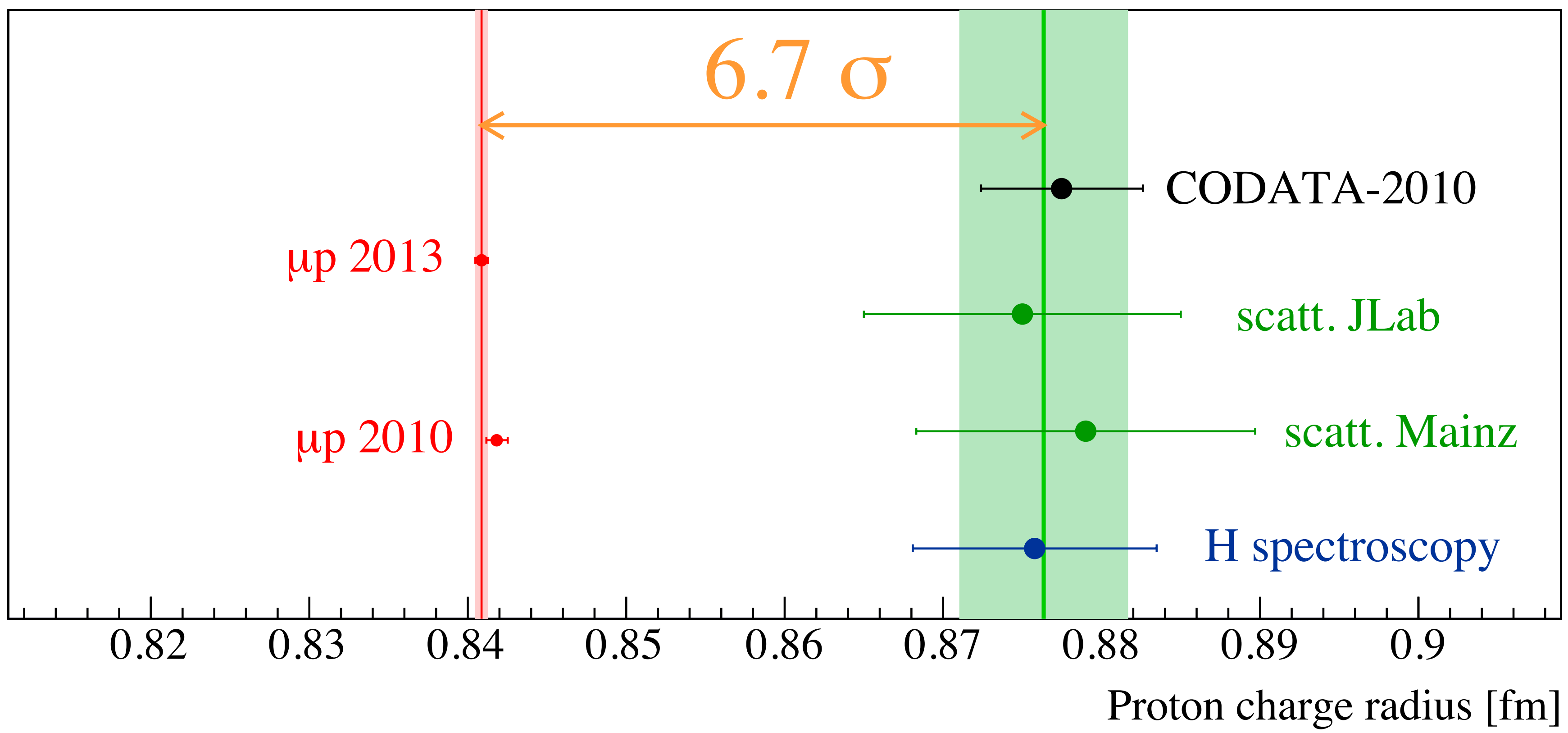
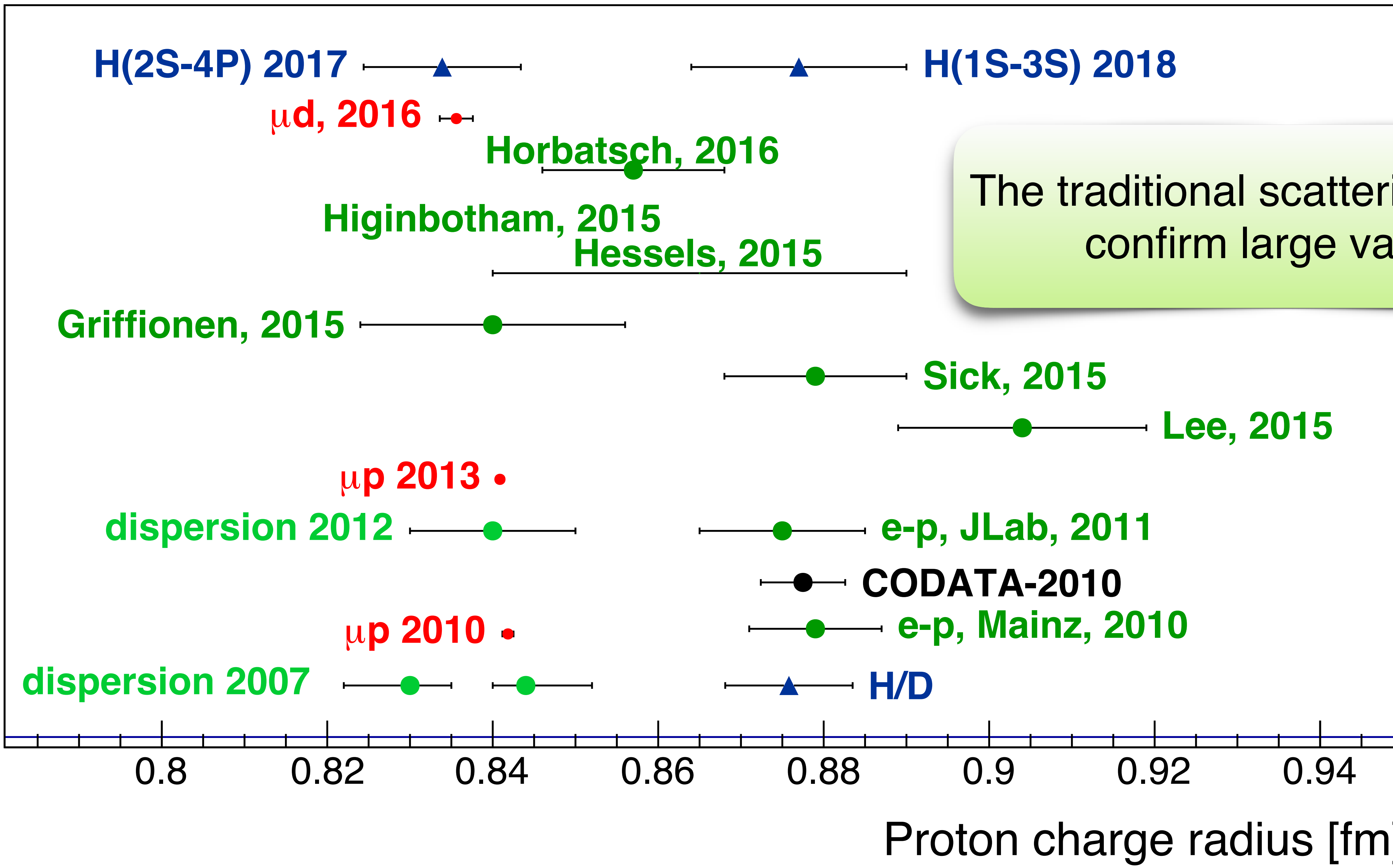
The proton charge radii (2010)



The proton charge radii (2018)

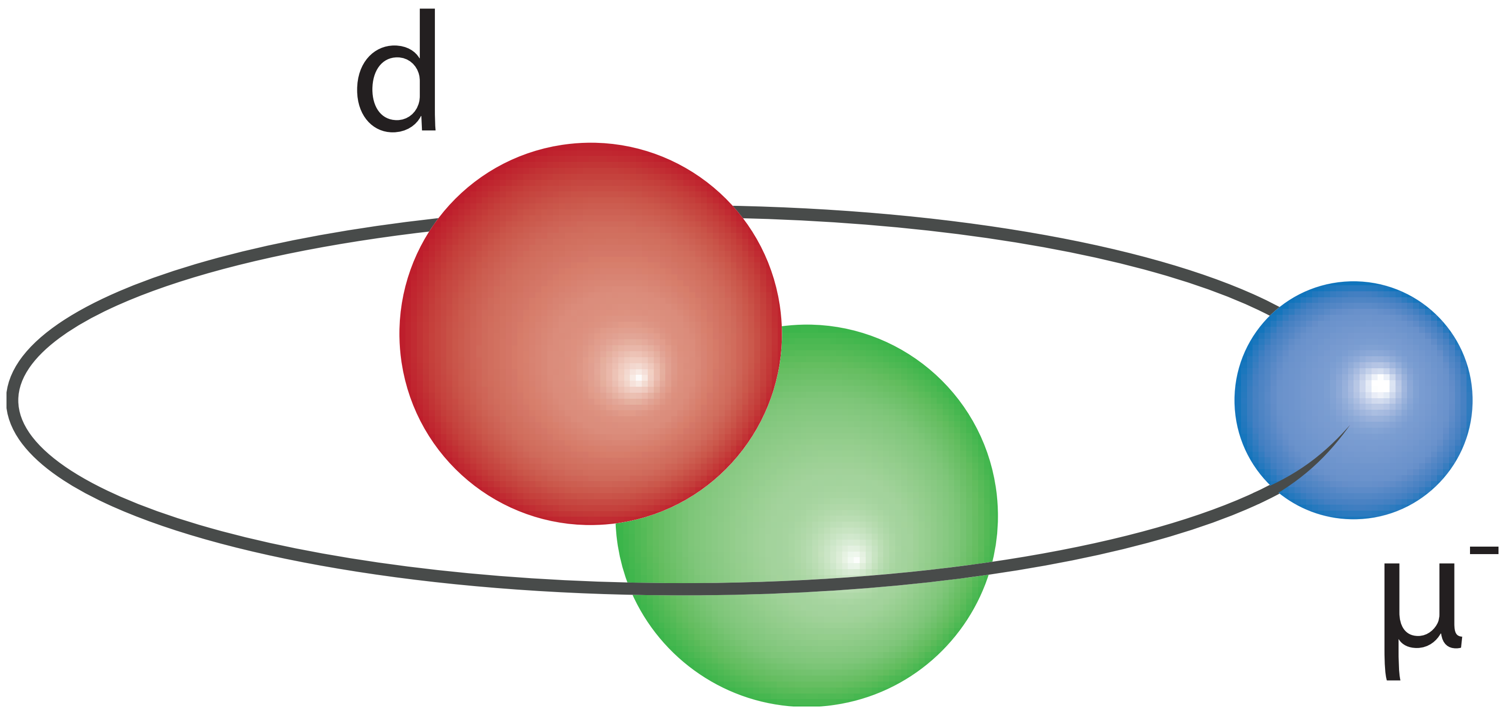
Higinbotham et al.,, arXiv: 1510.01293
Griffioen et al., arXiv:1509.06676
Lorenz et al., PRD 91, 014023 (2015)
Horbatsch, Hessels, Pineda, arXiv:1610.09760
Alarcon, Weiss, PRC 97, 055203 (2018)

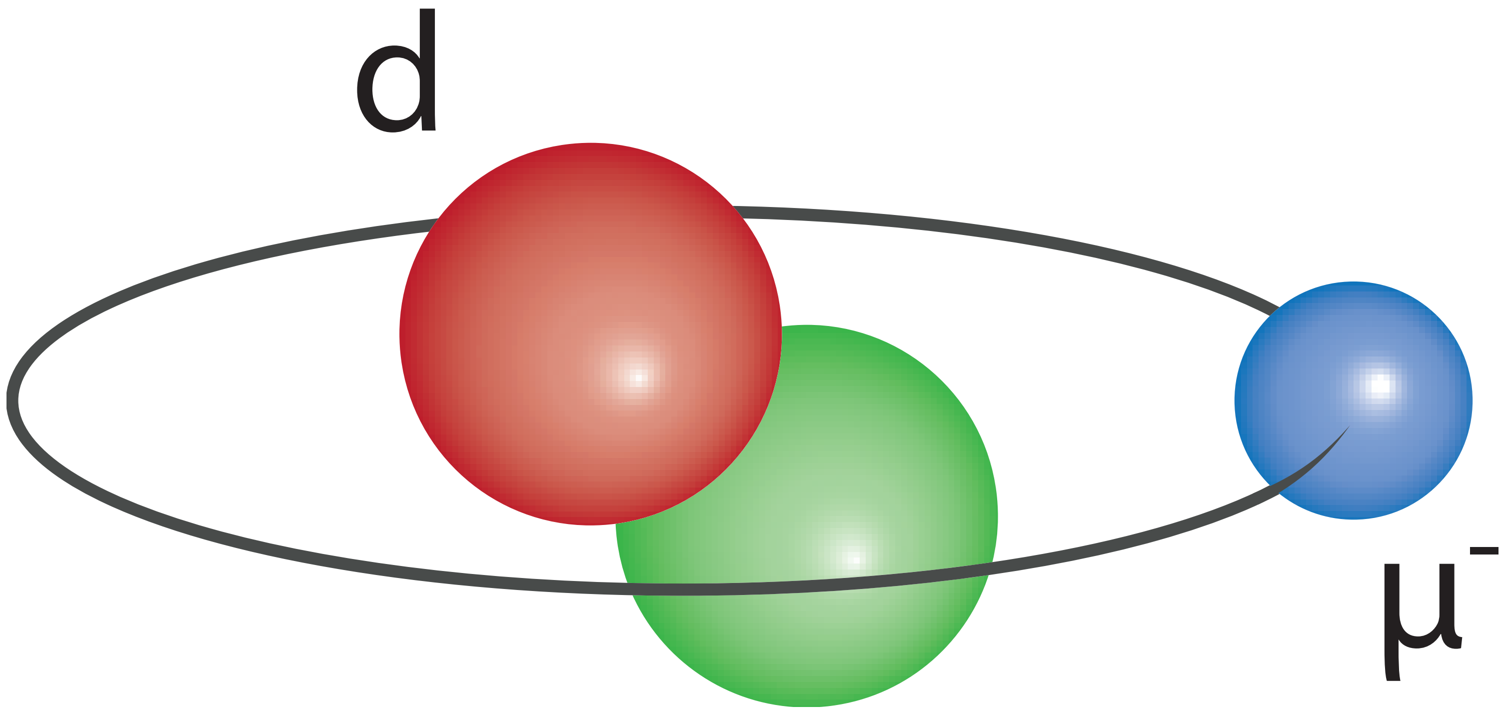
Bernauer, Distler, arXiv:1606.02159
Sick, Trautmann, arXiv:1701.01809
Sick, arXiv:1801.01746
Lee, Arrington, Hill, arXiv:1505.01489
Hoferichter et al., EPJA 52, 331 (2016)
Alarcon et al., arXiv:1809.06373



The traditional scattering experts confirm large values.


LATEST
NEWS


d
μ-



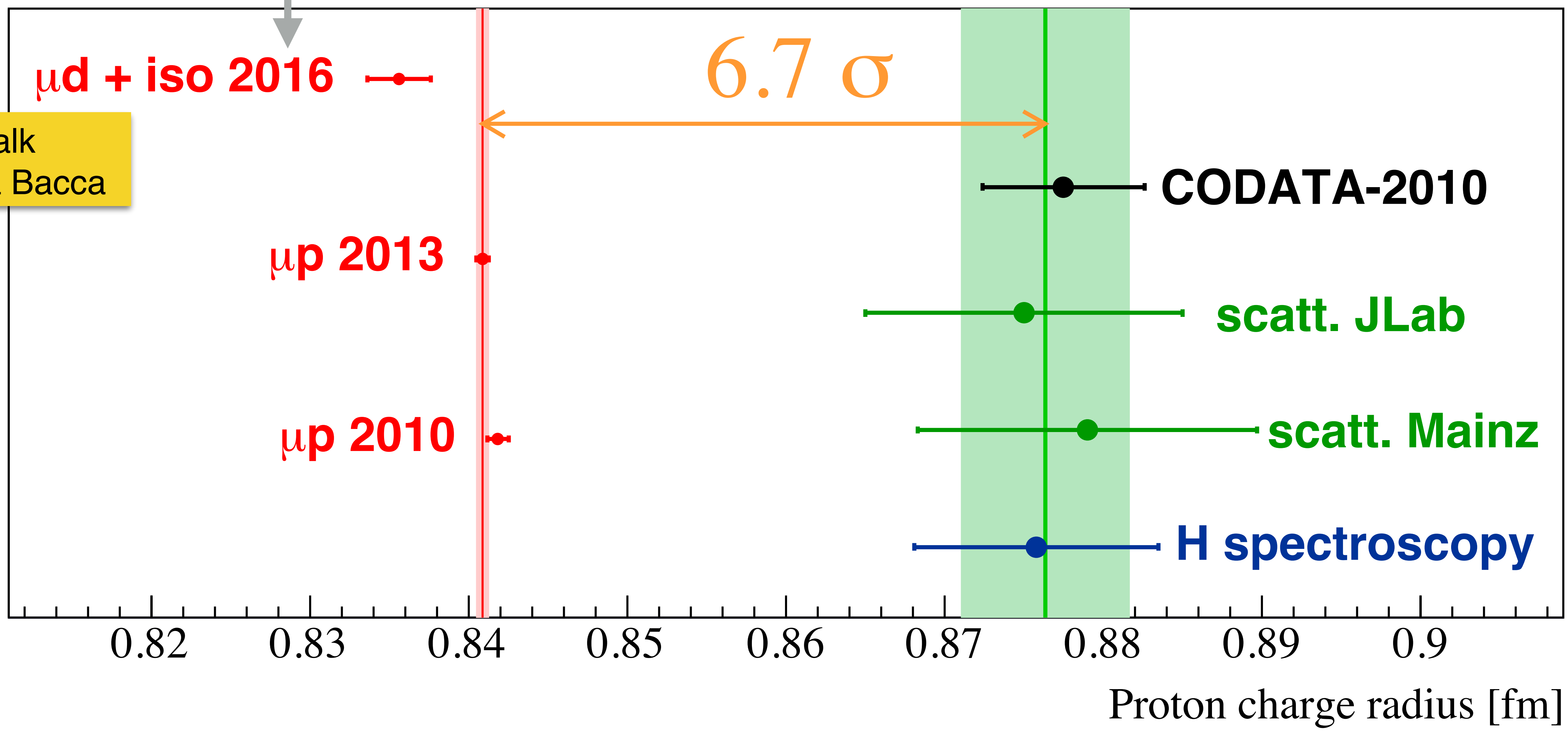
2S-2P energy splitting

$R_d = 2.1256(8)$ fm

The proton charge radius from muonic deuterium

$$\left.\begin{array}{llll} \text{H/D shift:} & R_\mathrm{d}^2 - R_\mathrm{p}^2 & = & 3.820\,07(65)\ \mathrm{fm}^2 \\ \mu d: & R_\mathrm{d} & = & 2.1256(8)\ \mathrm{fm} \end{array}\right\} \Rightarrow \quad R_\mathrm{p} = 0.8356(20)\ \mathrm{fm}$$

talk
Sonia Bacca

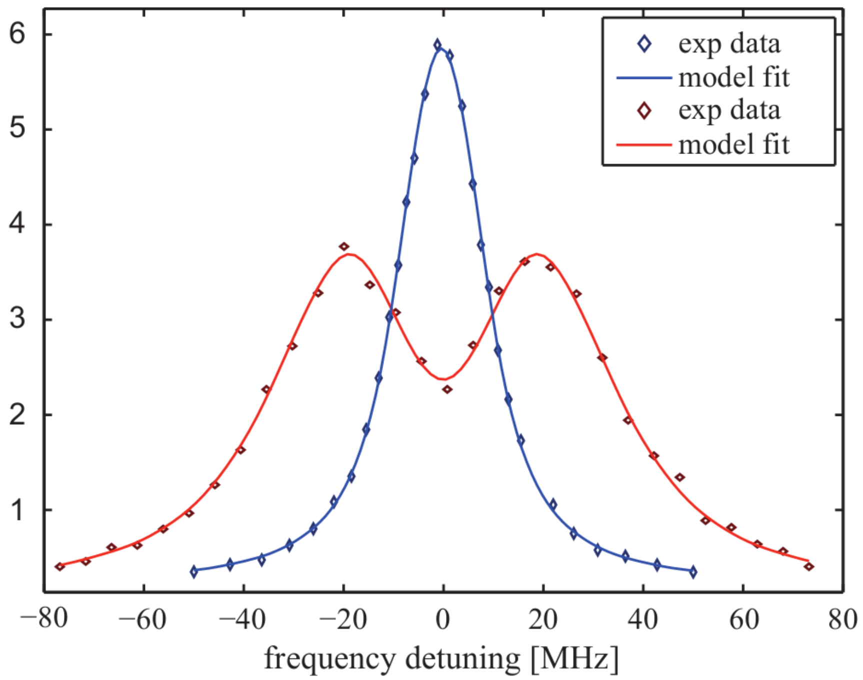


Pohl et al., Science 353, 669 (2016)

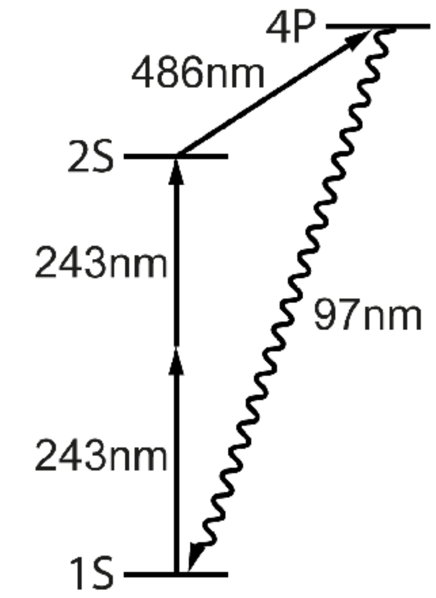
Hernandez et al., Phys. Lett. B 778, 377 (2018)

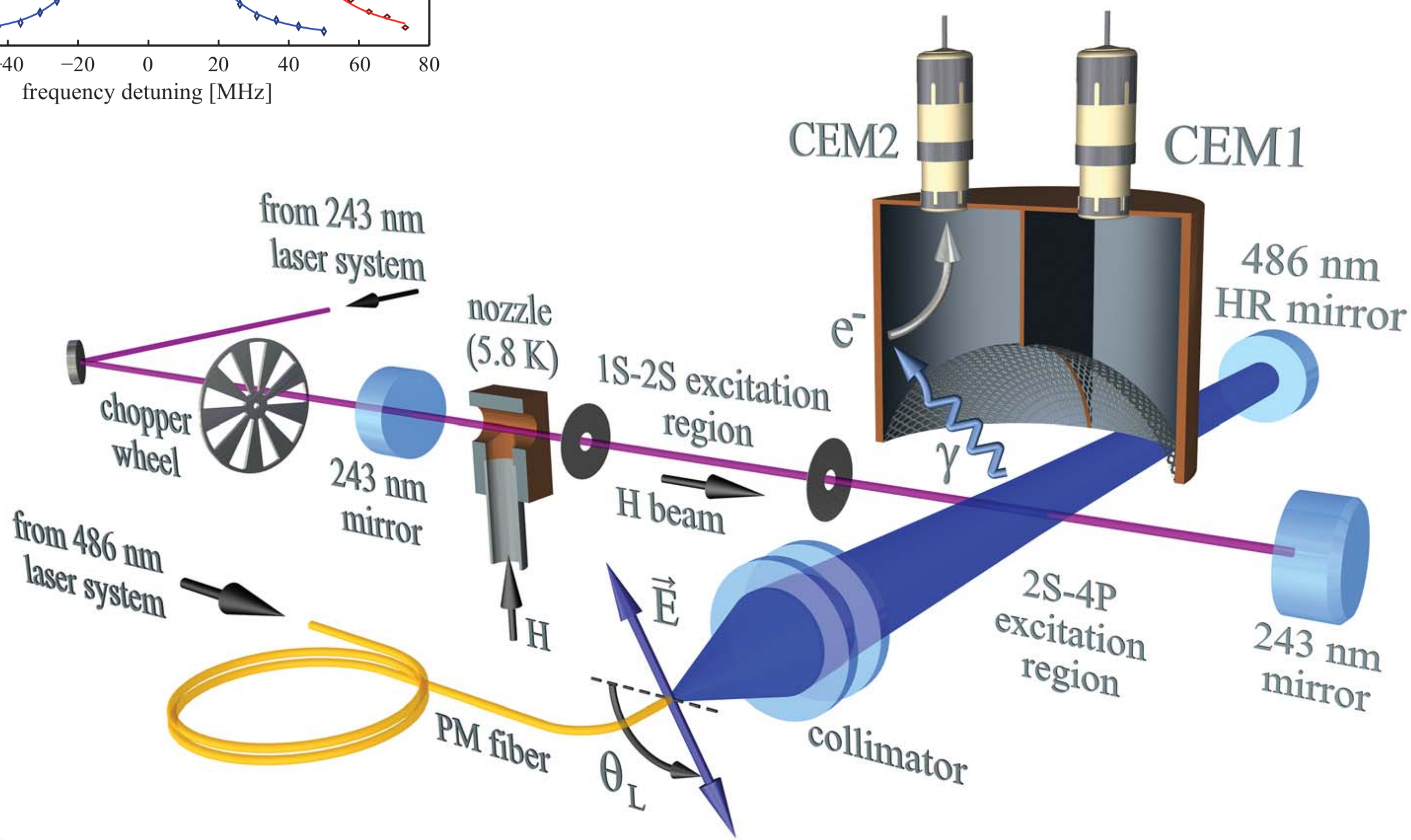
Kalinowski, Phys. Rev. A 99 030501 (2019)

New 2S-4P measurement in H (MPQ, 2017)



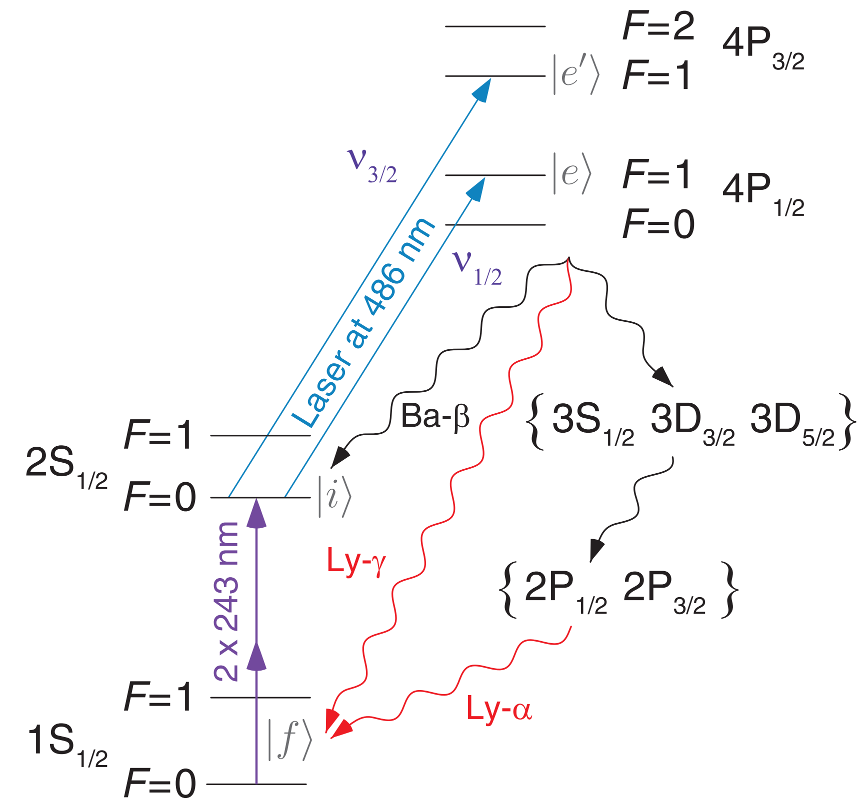
- Produce atomic H beam at cryogenic temp.
- Populate the $2S_{1/2}$ using two-photons excitation
- Excite the $2S_{1/2}$-$4P_{1/2}$ and $2S_{1/2}$-$4P_{3/2}$ transitions
- Detect the 4P-1S decay (velocity resolved)
- Plot number of 4P-1S decays vs. laser freq.





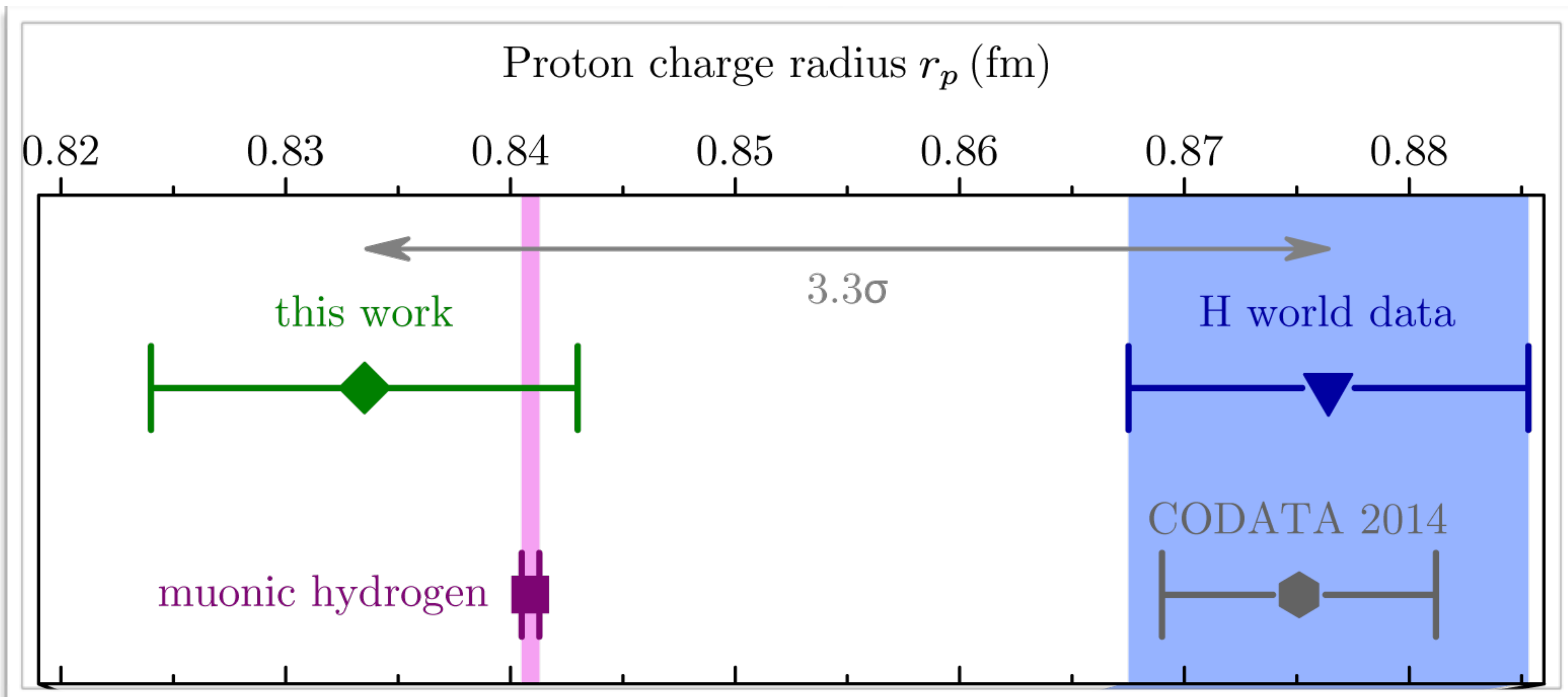
New 2S-4P measurement in H (MPQ, Munich, 2017)

- Limited by residual first order Doppler
- Quantum interference effects (measured)
- Sampling bias
- Subtleties: light force shift, Raman transitions…



- Line width: 20’000 kHz
- Measurement uncert.: 2.3 kHz

⇨ Centroid of an asymmetric line to 10^{-4} of line-width

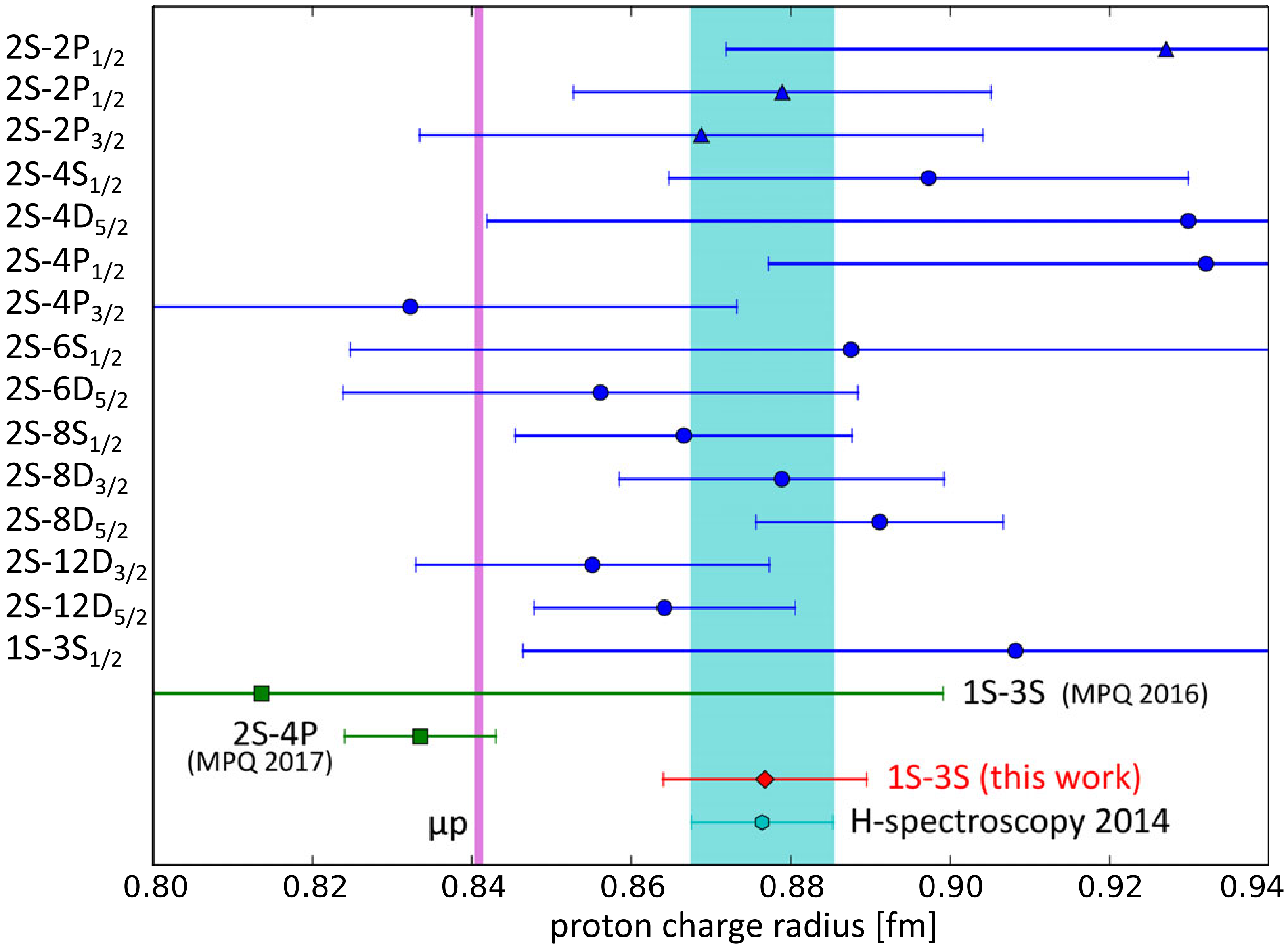


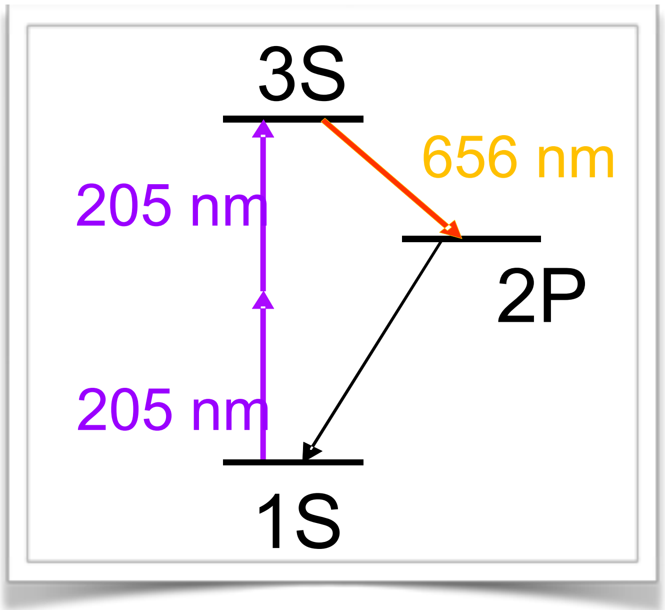
Beyer et al.,
Science 358, 79 (2017)

New 1S-3S measurement in H (LKB, Paris, 2017)

Sources of frequency shifts:
- second-order Doppler (120 kHz)
- light shift
- pressure shift

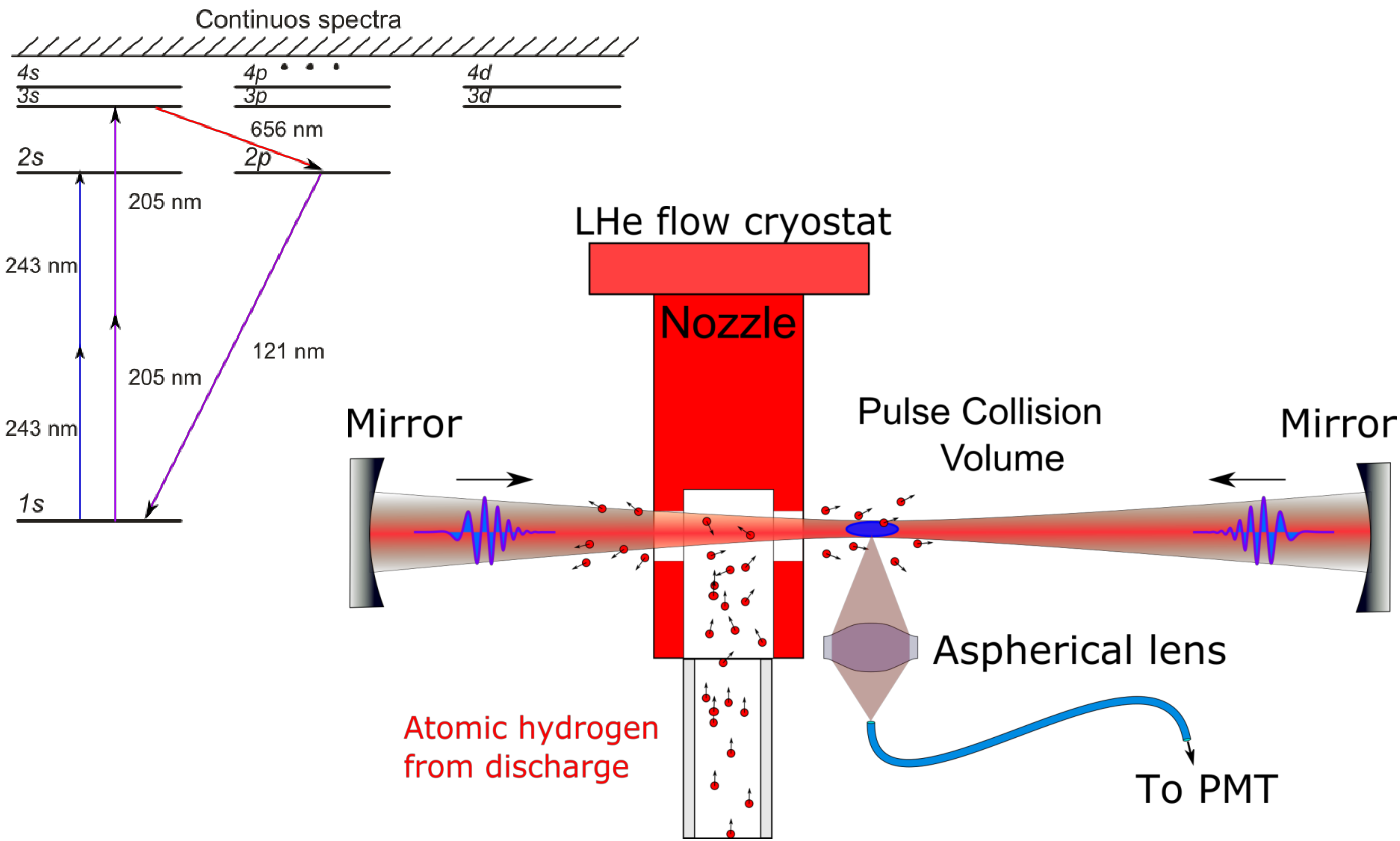
- Line width: 1500 kHz
- Total uncertainty: 2.7 kHz





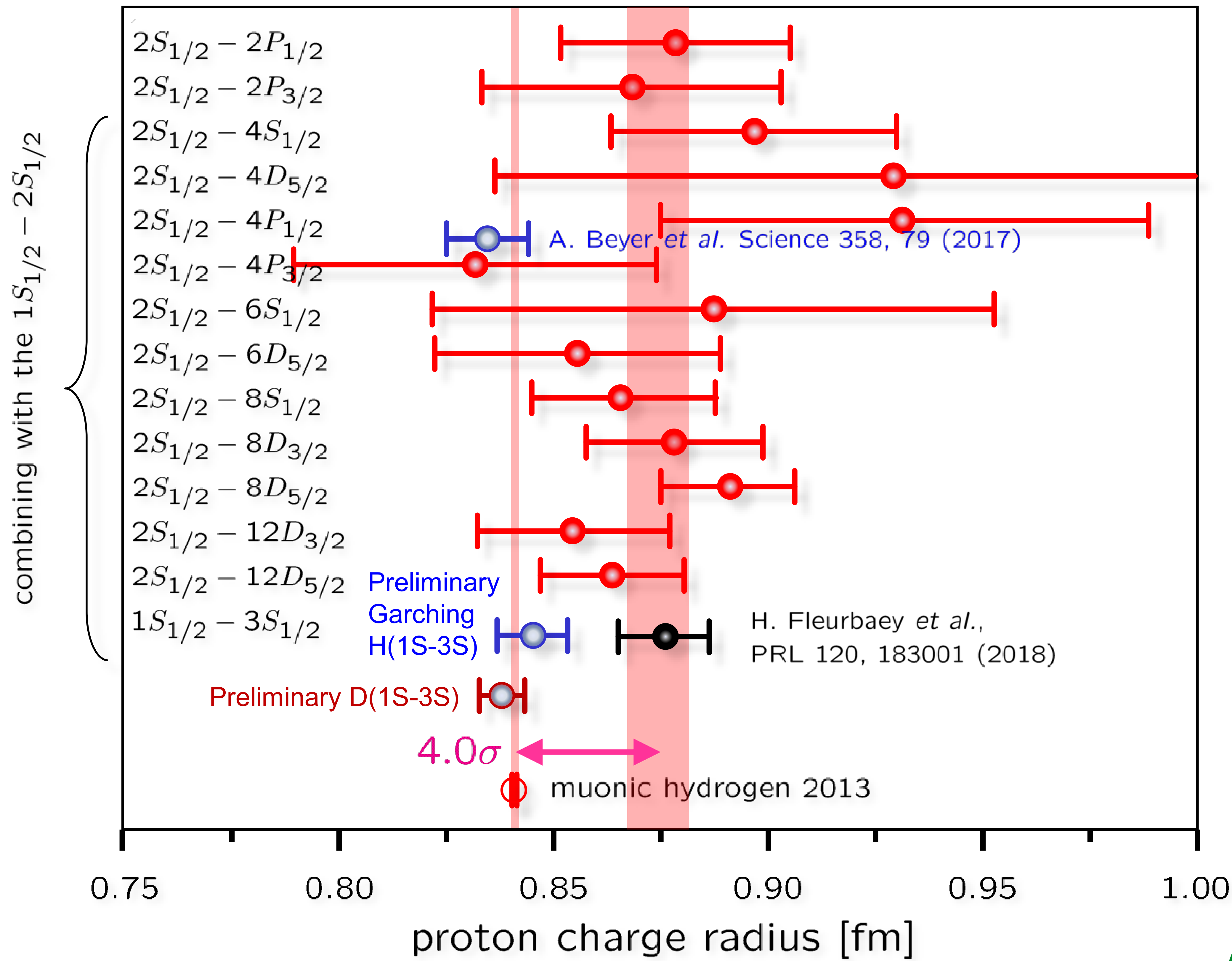
Fleurbaey et al., PRL120, 183001 (2018)

Preliminary 1S-3S measurement in H/D (MPQ, 2018)



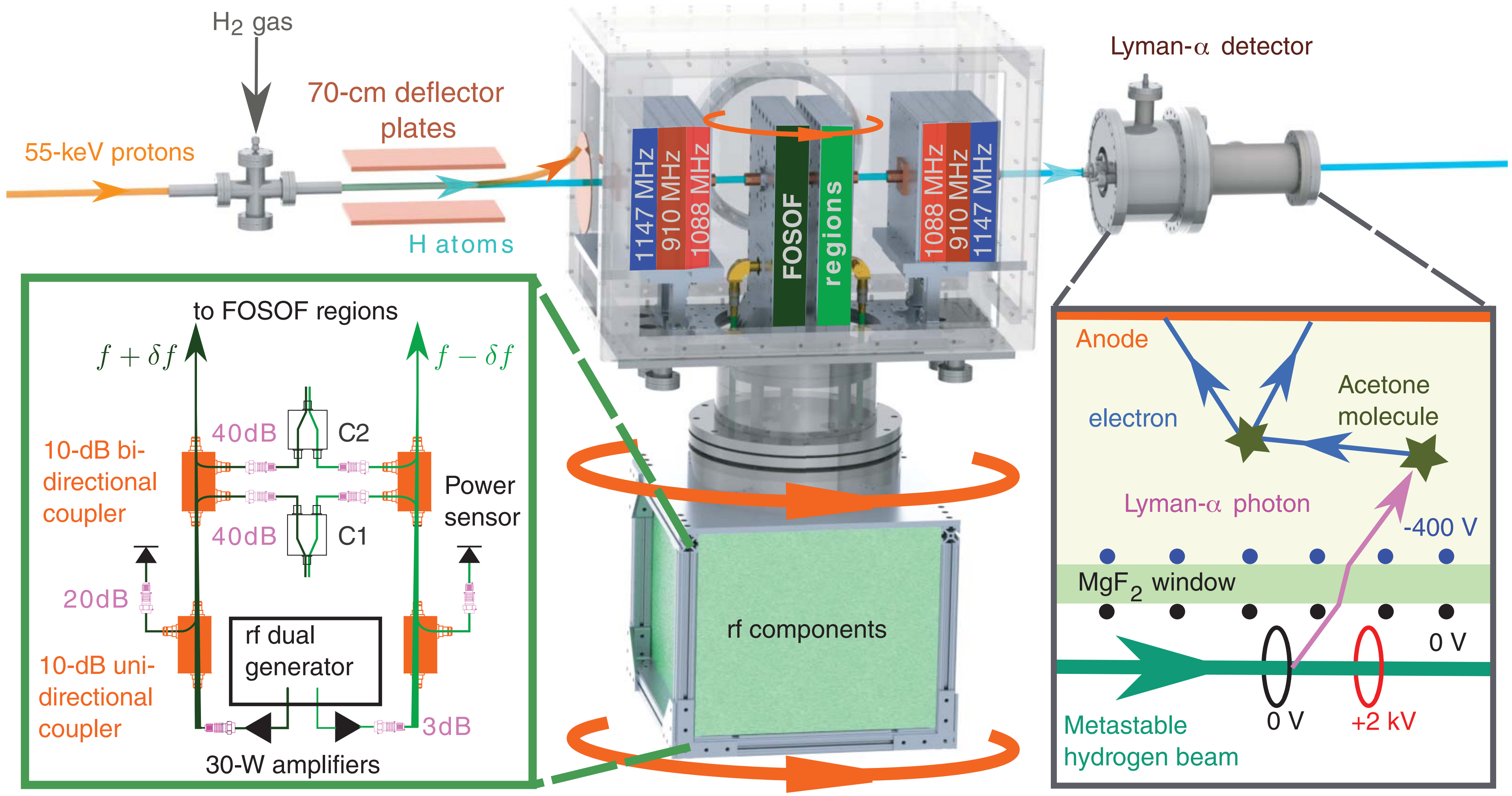
A. Matveev

Preliminary 1S-3S measurement in H/D (MPQ, 2018)

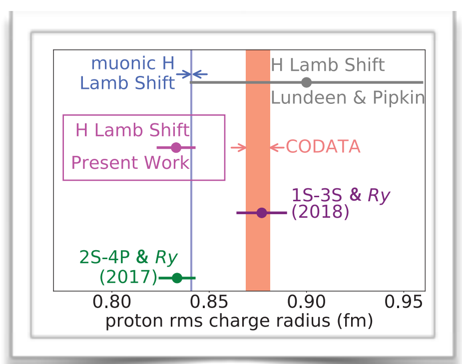


A. Matveev

New 2S-2P measurement in H (Toronto, 2019)



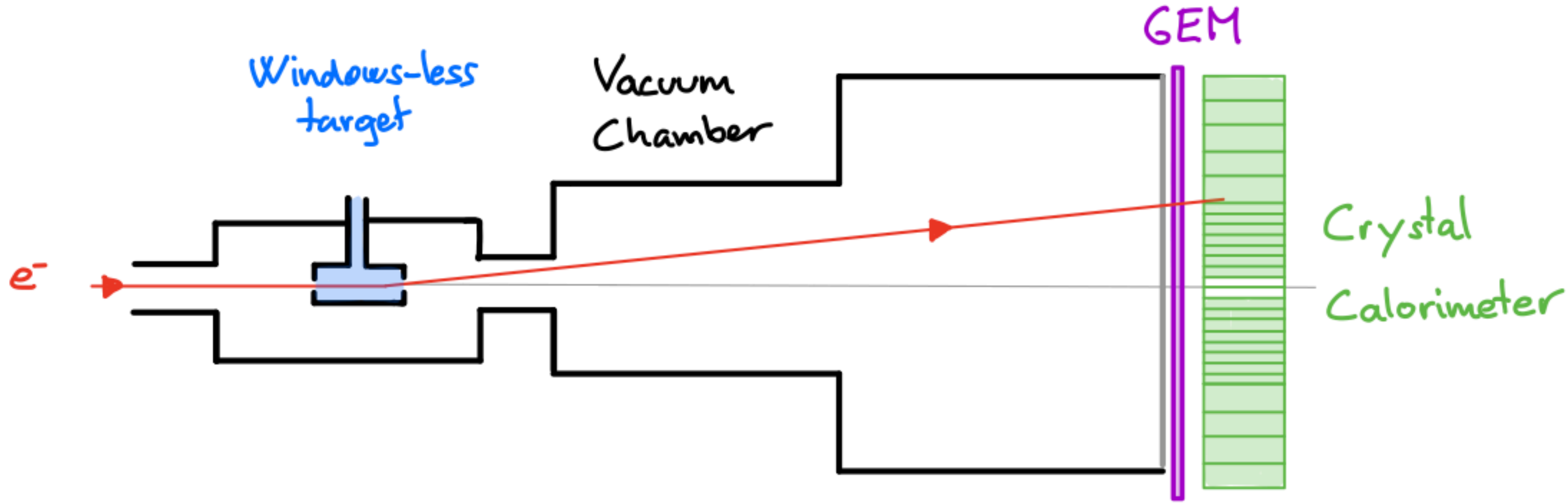
see talk
E. Hessels



N. Bezginov et al.,
Science 365, 1007-1012 (2019)

The PRad experiment at JLAB

I was asked by **A. Gasparian**
to replace him in this workshop



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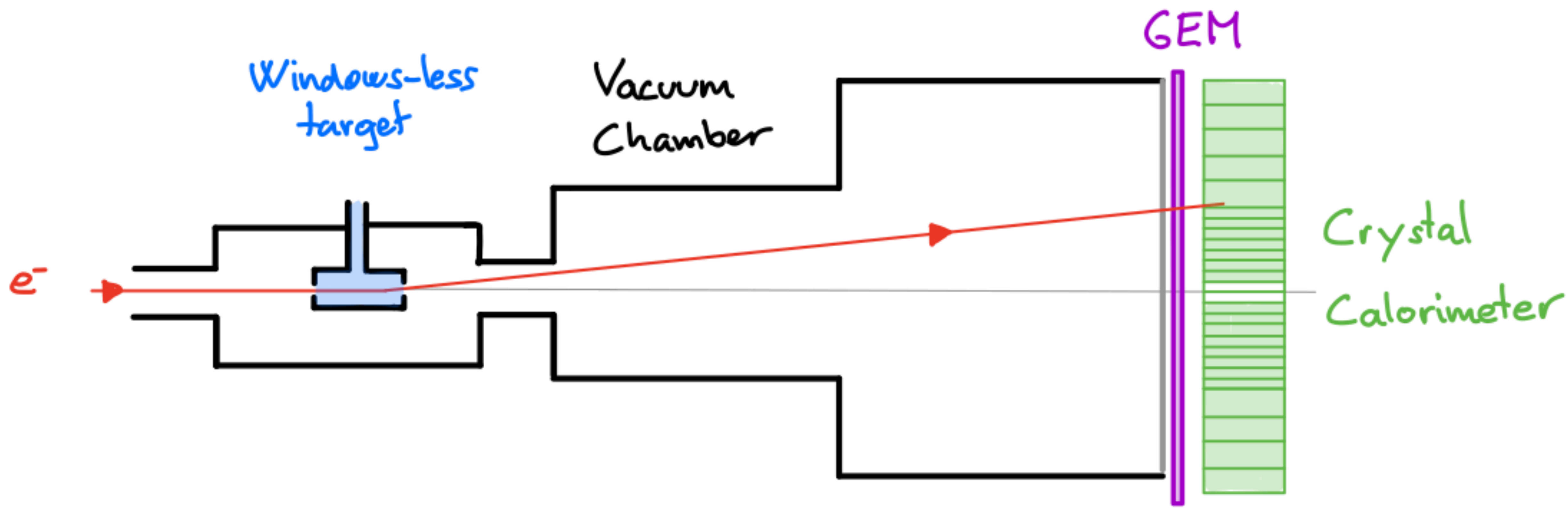

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \frac{N_{exp}(ep \rightarrow ep \, in \, \theta_i \pm \Delta\theta)}{N_{exp}(ee \rightarrow ee)} \cdot \frac{\epsilon^{ee}_{geom}}{\epsilon^{ep}_{geom}} \cdot \frac{\epsilon^{ee}_{det}}{\epsilon^{ep}_{det}} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

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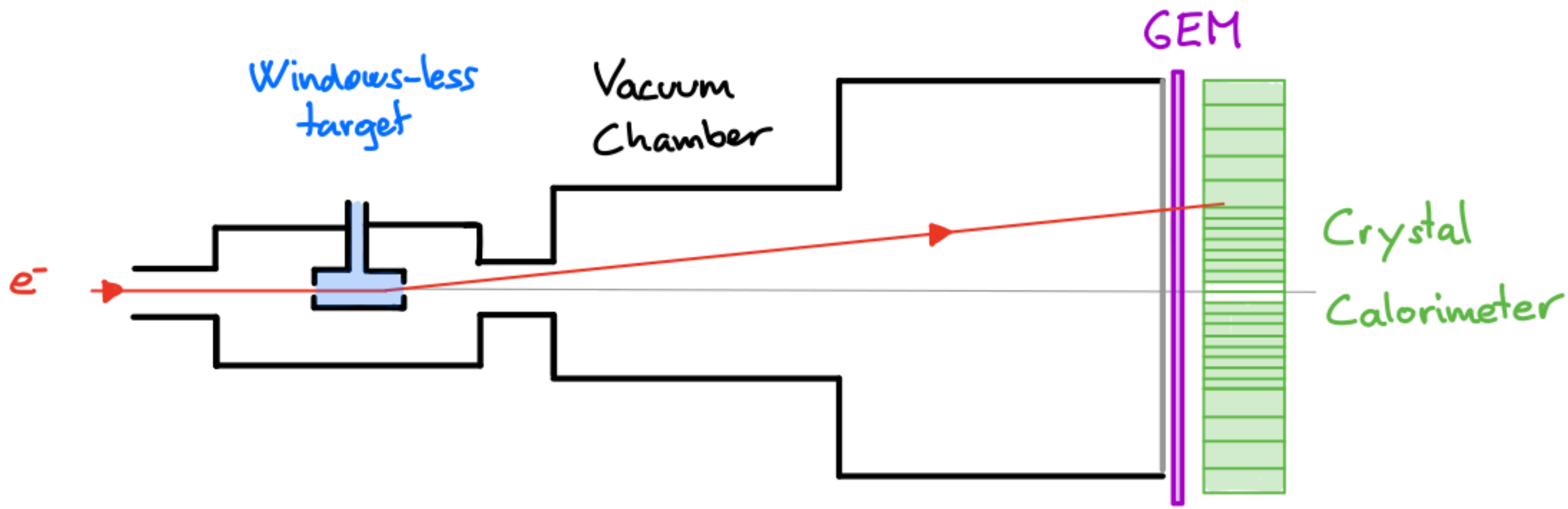
I was asked by **A. Gasparian**
to replace him in this workshop



$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \frac{N_{exp}(ep \rightarrow ep \; in \, \theta_i \pm \Delta\theta)}{N_{exp}(ee \rightarrow ee)} \cdot \frac{\epsilon^{ee}_{geom}}{\epsilon^{ep}_{geom}} \cdot \frac{\epsilon^{ee}_{det}}{\epsilon^{ep}_{det}} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

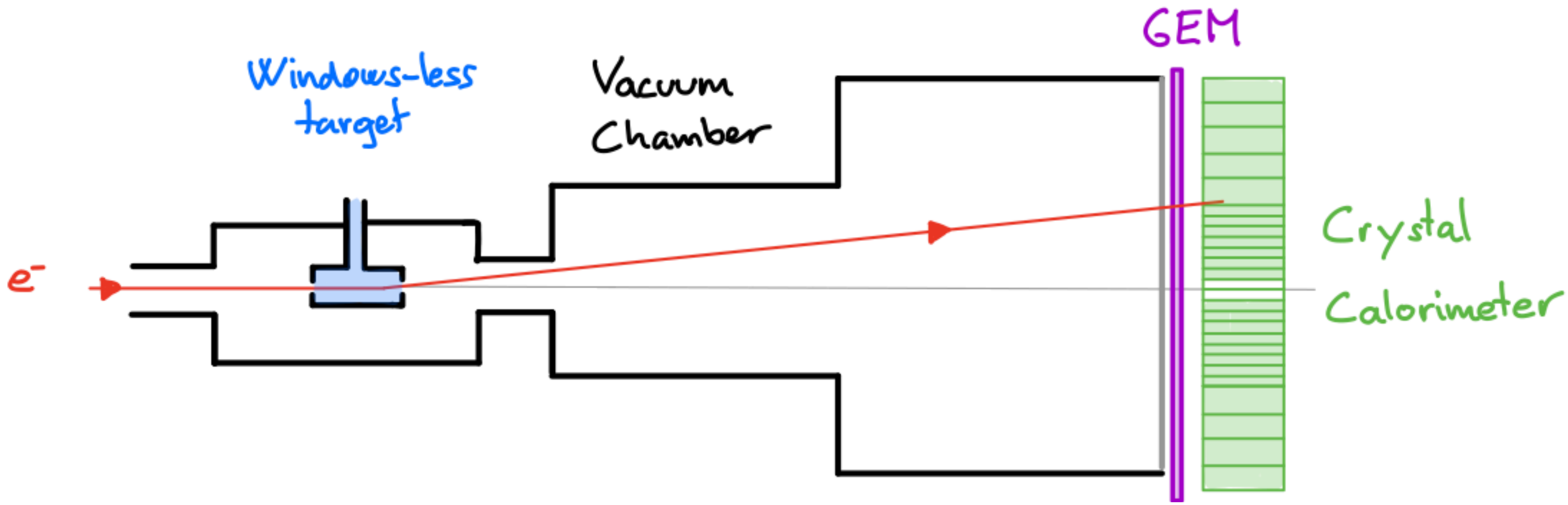
Measured

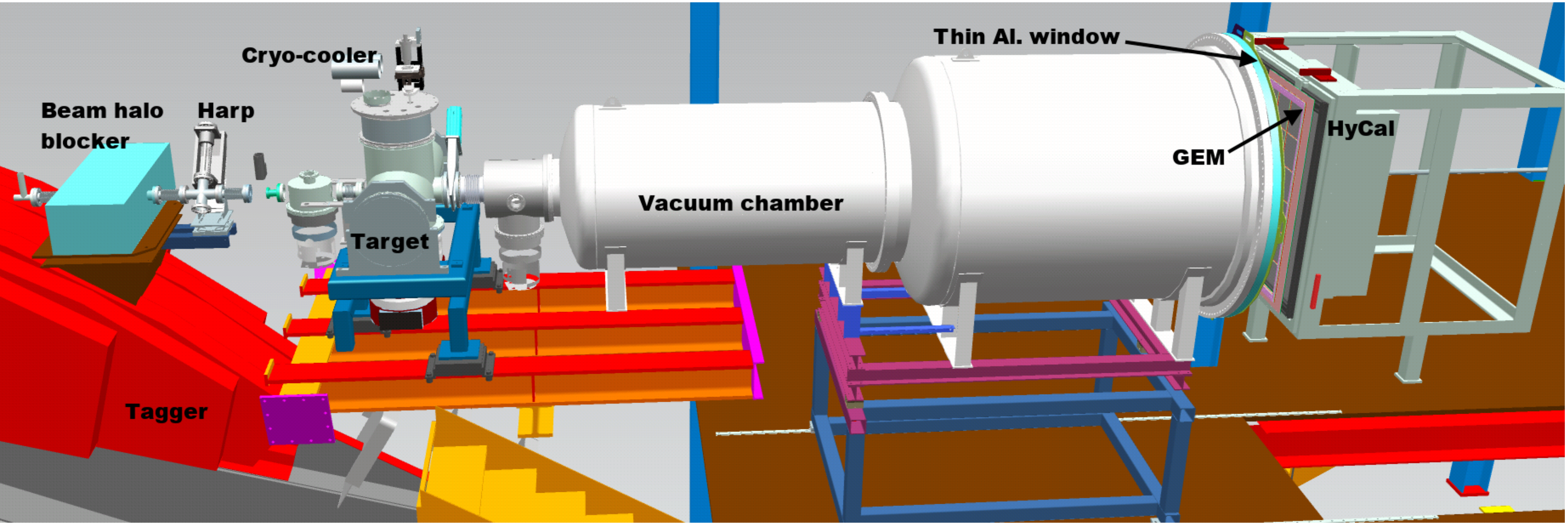
Normalisation of
- Beam intensity
- Proton density

systematic
cancel in first order

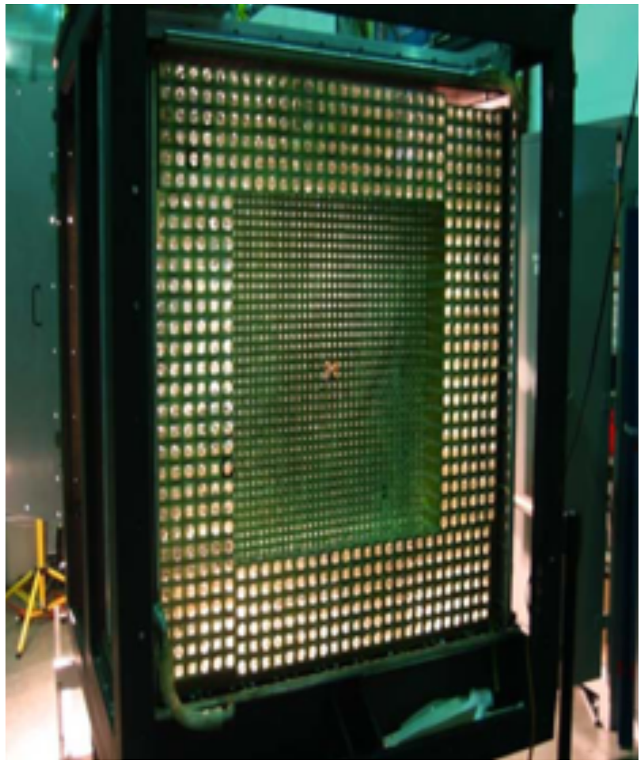
well know
QED process

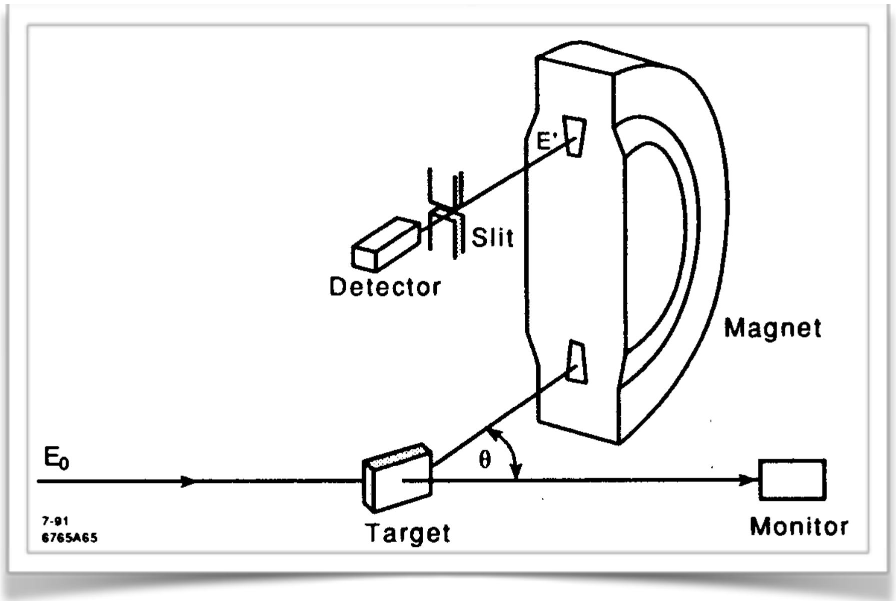
The PRad experiment at JLAB

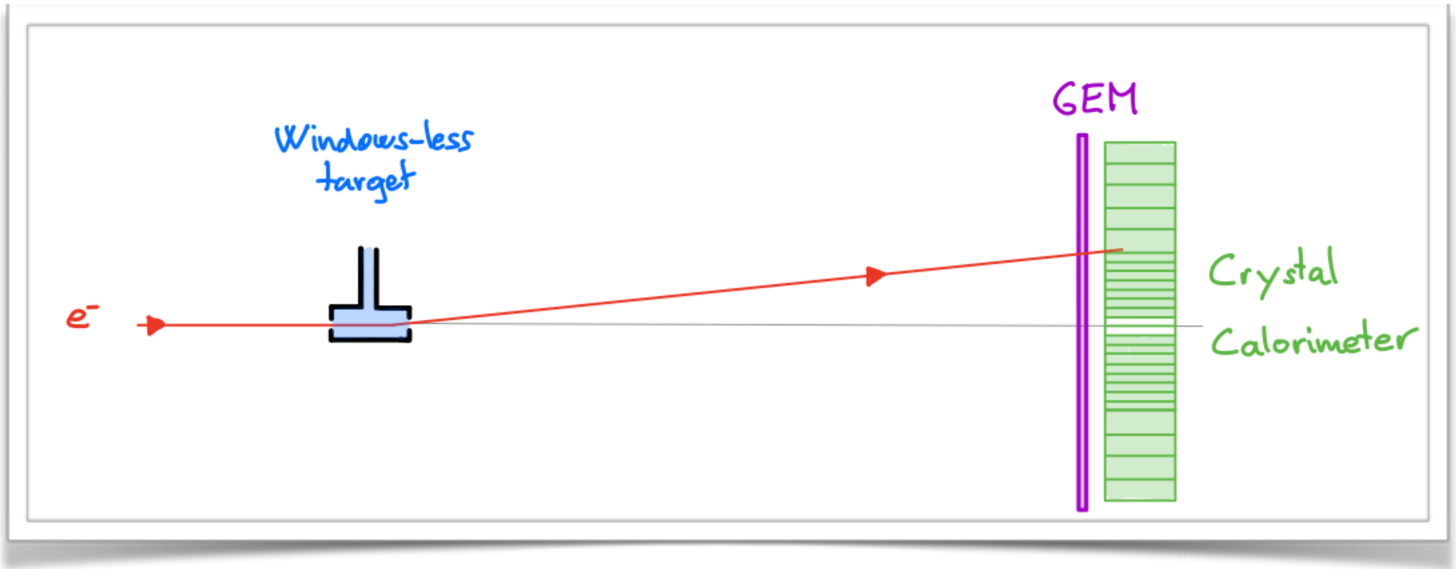




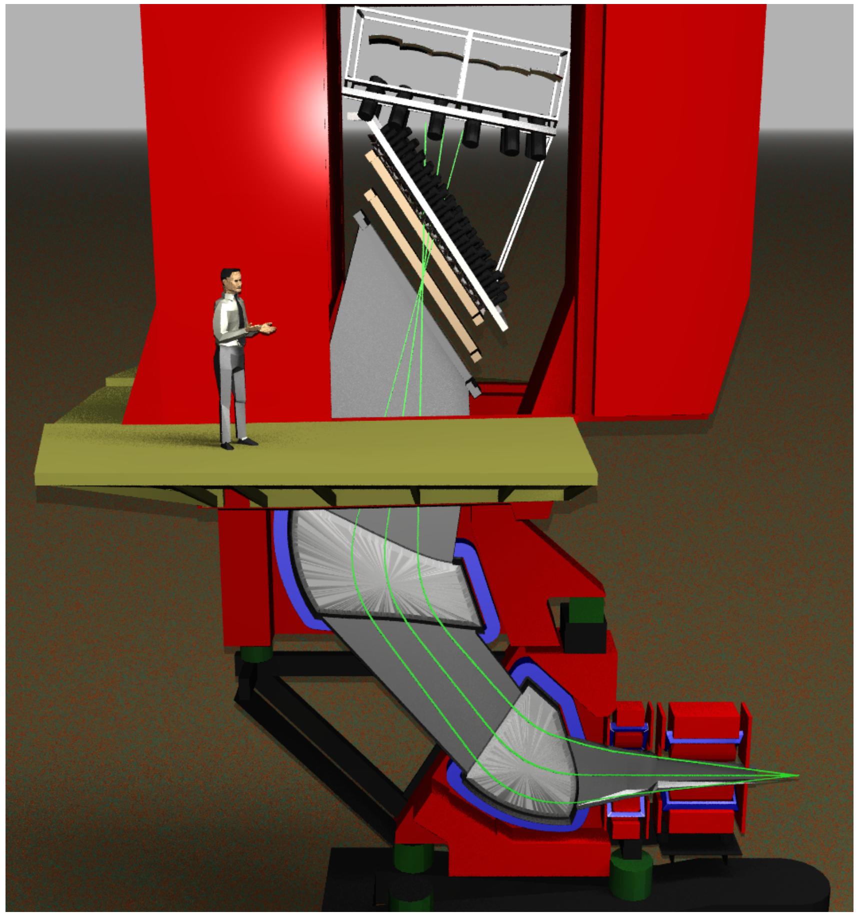
The two approaches: Mainz vs JLAB

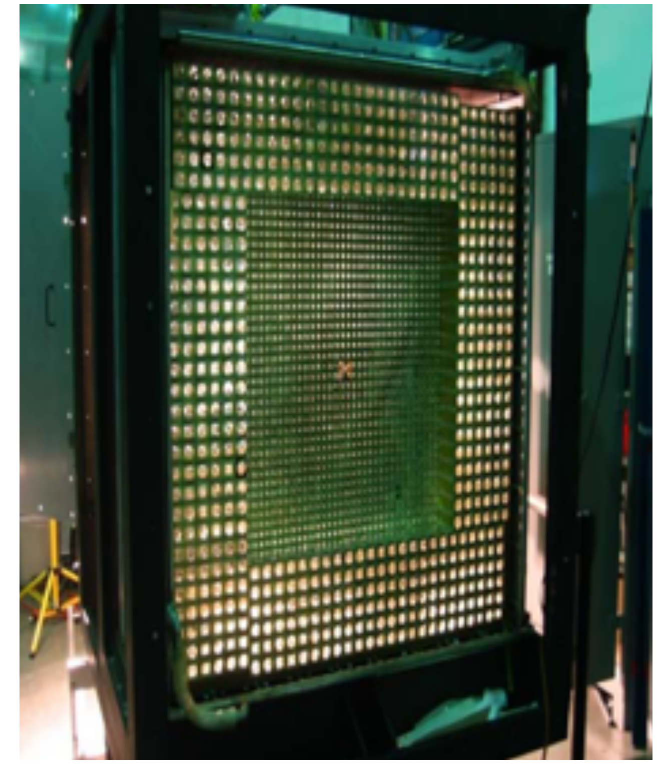


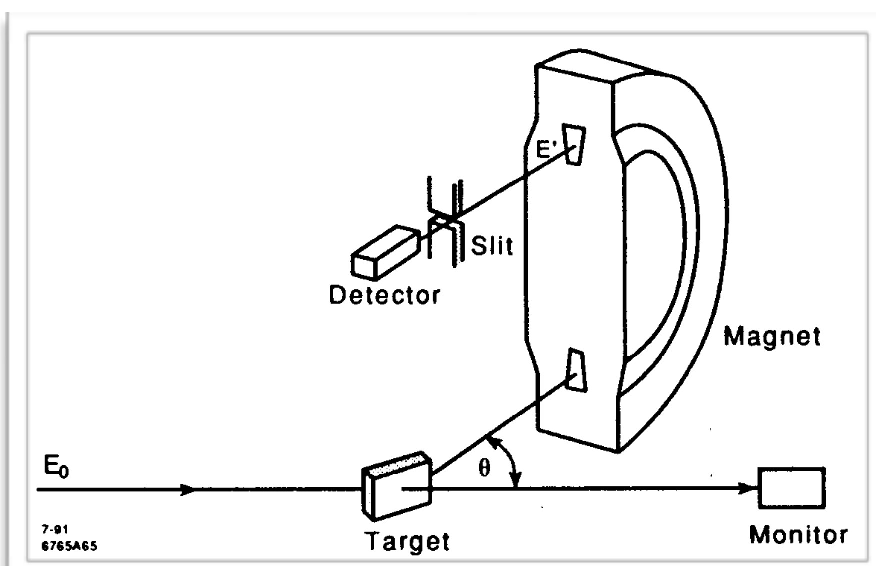




The two approaches: Mainz vs JLAB





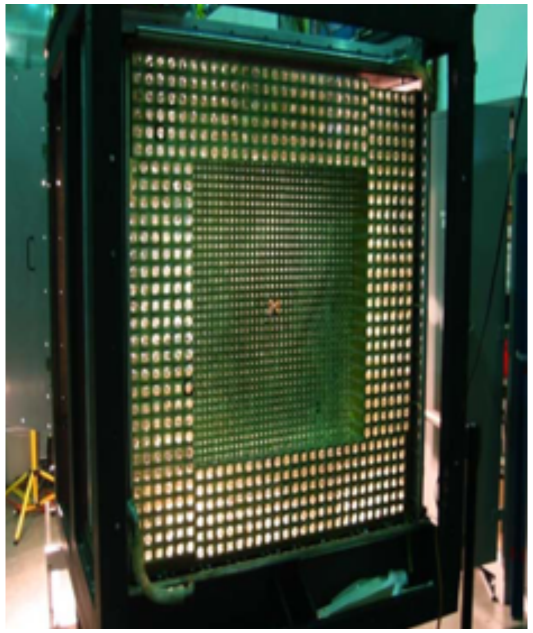


The two approaches: Mainz vs JLAB

Multi-purpose machine

- **Large magnetic spectrometer**
  - high resolution but small acceptances
  - many experimental settings
  - normalisation, efficiencies, systematic

  - minimal scattering angle: 5°
  - minimal Q^{2}: 10^{-3} GeV^{2}
- **Hydrogen target with metallic window**
  - background subtraction using simulation



Dedicated setup

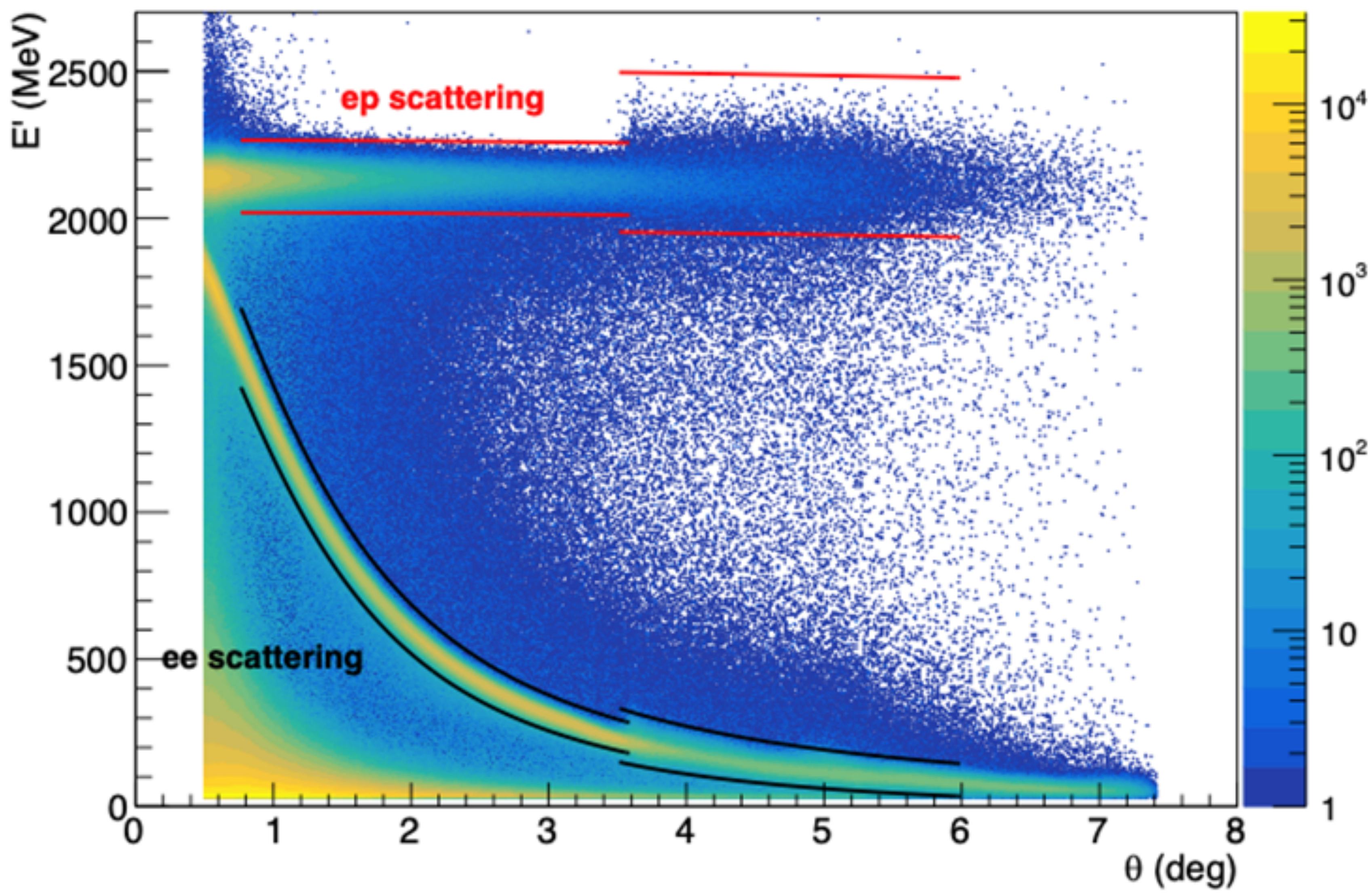
- **Non-magnetic calorimeter**
  - one experimental setting
  - normalisation via well know QED process

  - minimal scattering angle: 0.6°
  - minimal Q^{2}: 10^{-4} GeV^{2}
    (warning: see backup slides)
- **Window-less hydrogen target**
  - residual background measured

Experimental cuts

A. Gasparian

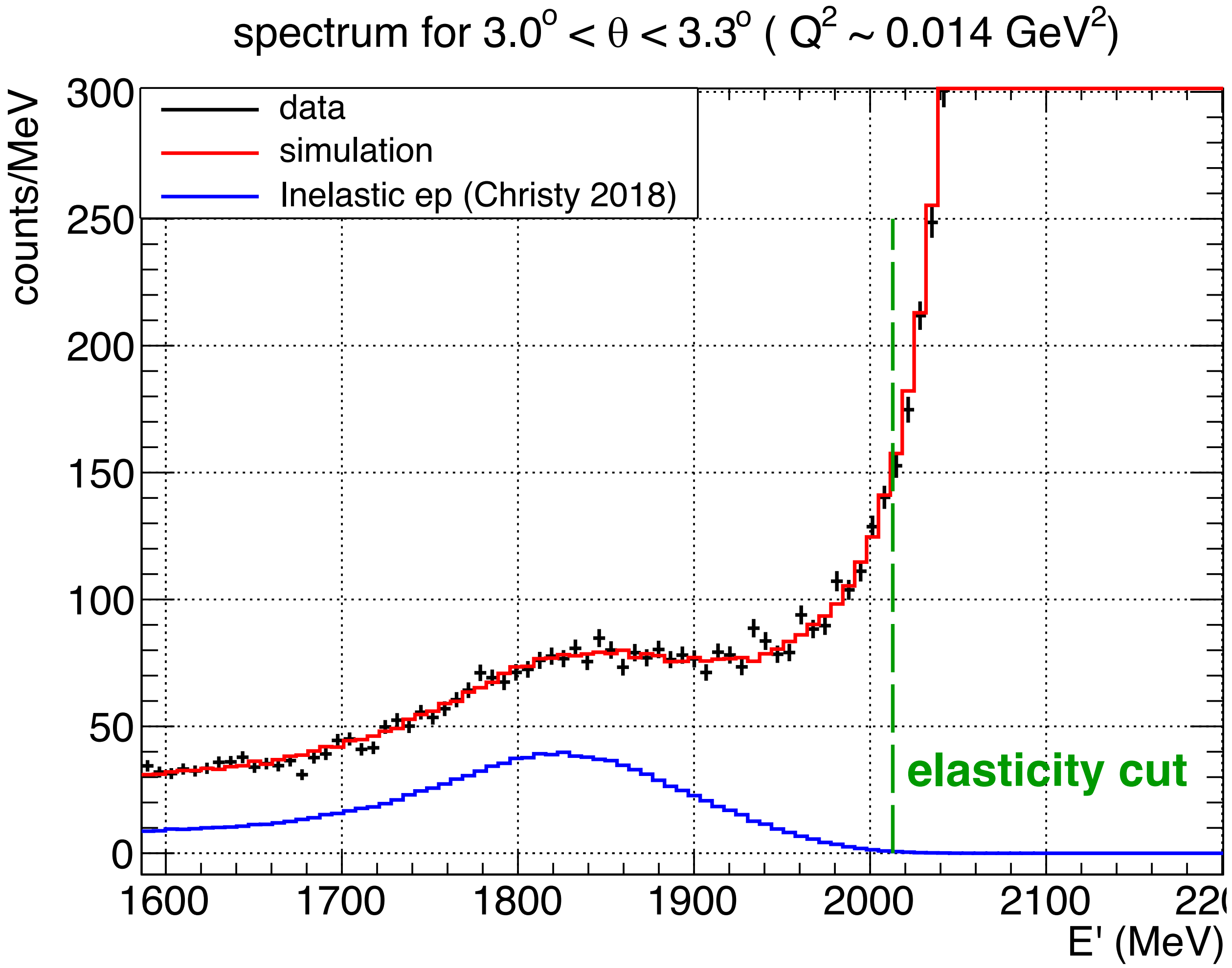
- For all events:
  - hit matching between calorimeter and GEM
- For e-p:
  - angle-dependent energy cut based on kinematic
- For e-e scattering:
  - angle-dependent energy cut
  - elasticity
  - co-planarity
  - vertex z
- e-p background:
  - 10% (< 2% for angles <1.3°)

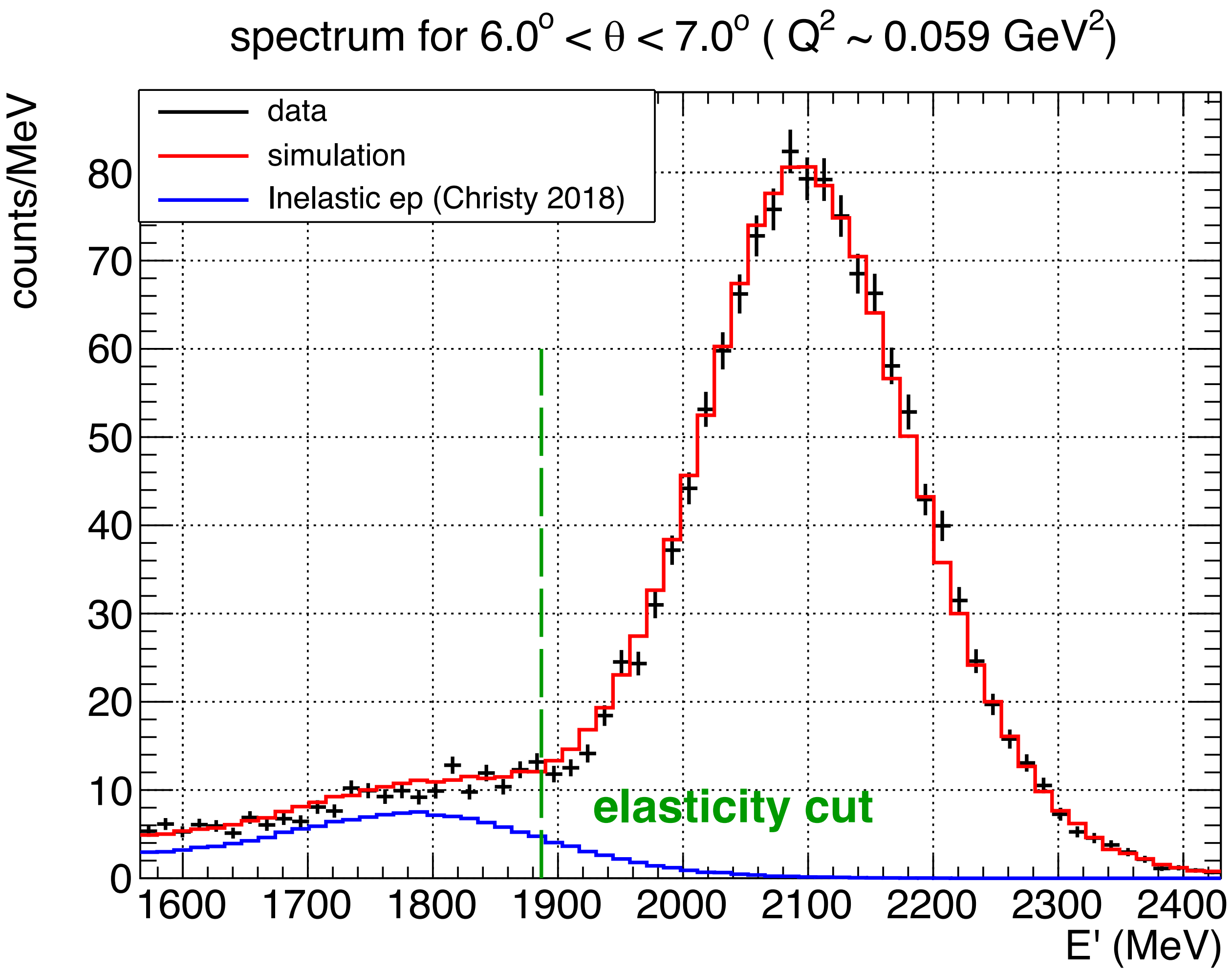


Inelastic contribution

A. Gasparian

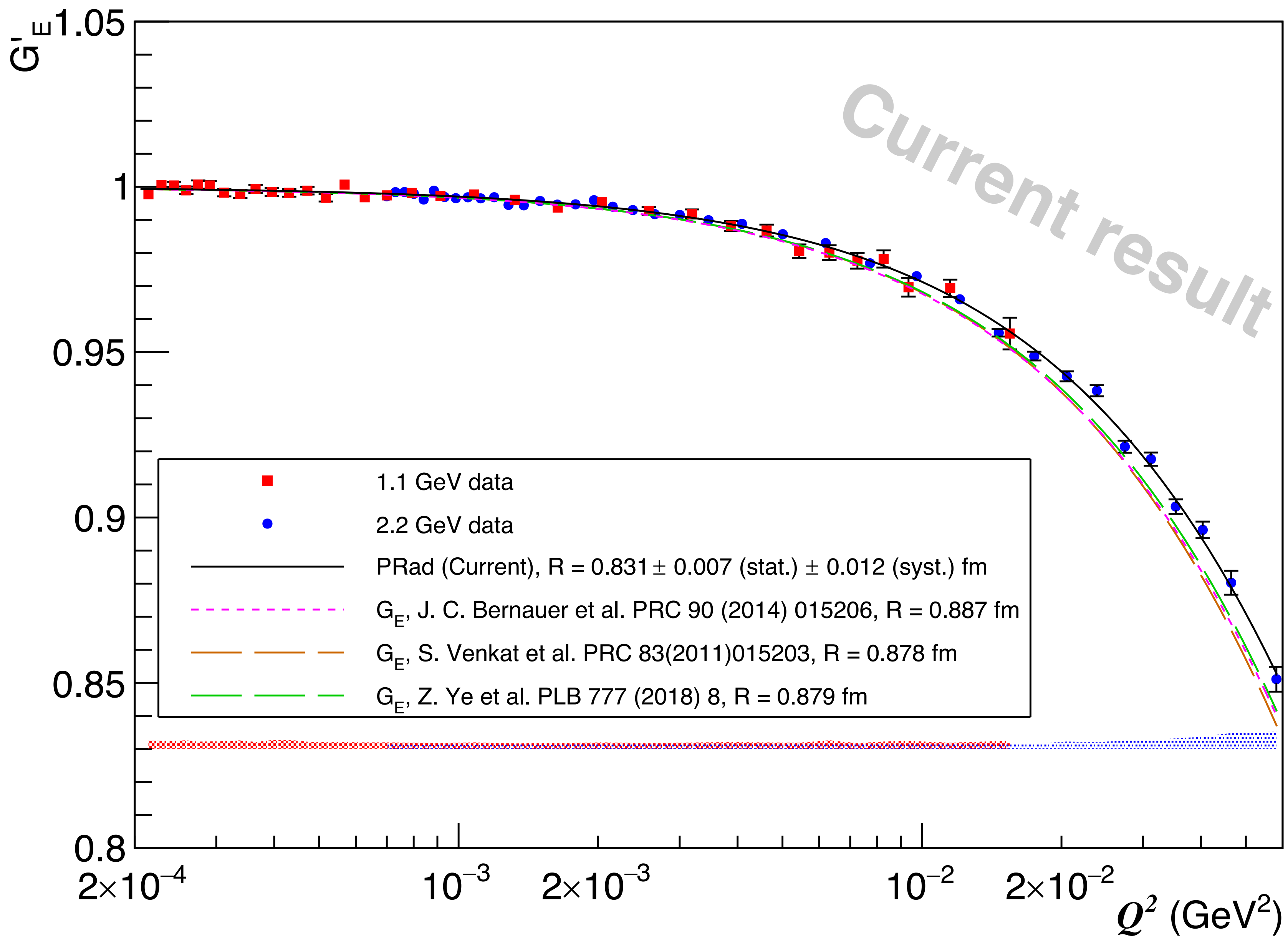
- Inelastic contributions included using Christy 2018 empirical fit
- Good agreement between data and simulation
- Inelastic contribution to elastic peak
  - Negligible for the $PbWO_4$ region (< 3.5°)
  - < 0.2% (2.0%) for 1.1(2.2) GeV in lead glass region





Measured form factor (reduced cross section)

- Statistical uncertainty (per point):
  0.2% for 1.1 GeV and 0.15% for 2.2 GeV
- Systematic uncertainty (per point):
  0.3—0.5 % for 1.1 GeV, 0.3—1.1% for 2.2 GeV



- Normalization:
  n=1.0002 ±0.0002(stat) ±0.0020(sys)
  n=0.9983 ±0.0002(stat) ±0.0013(sys)

A. Gasparian

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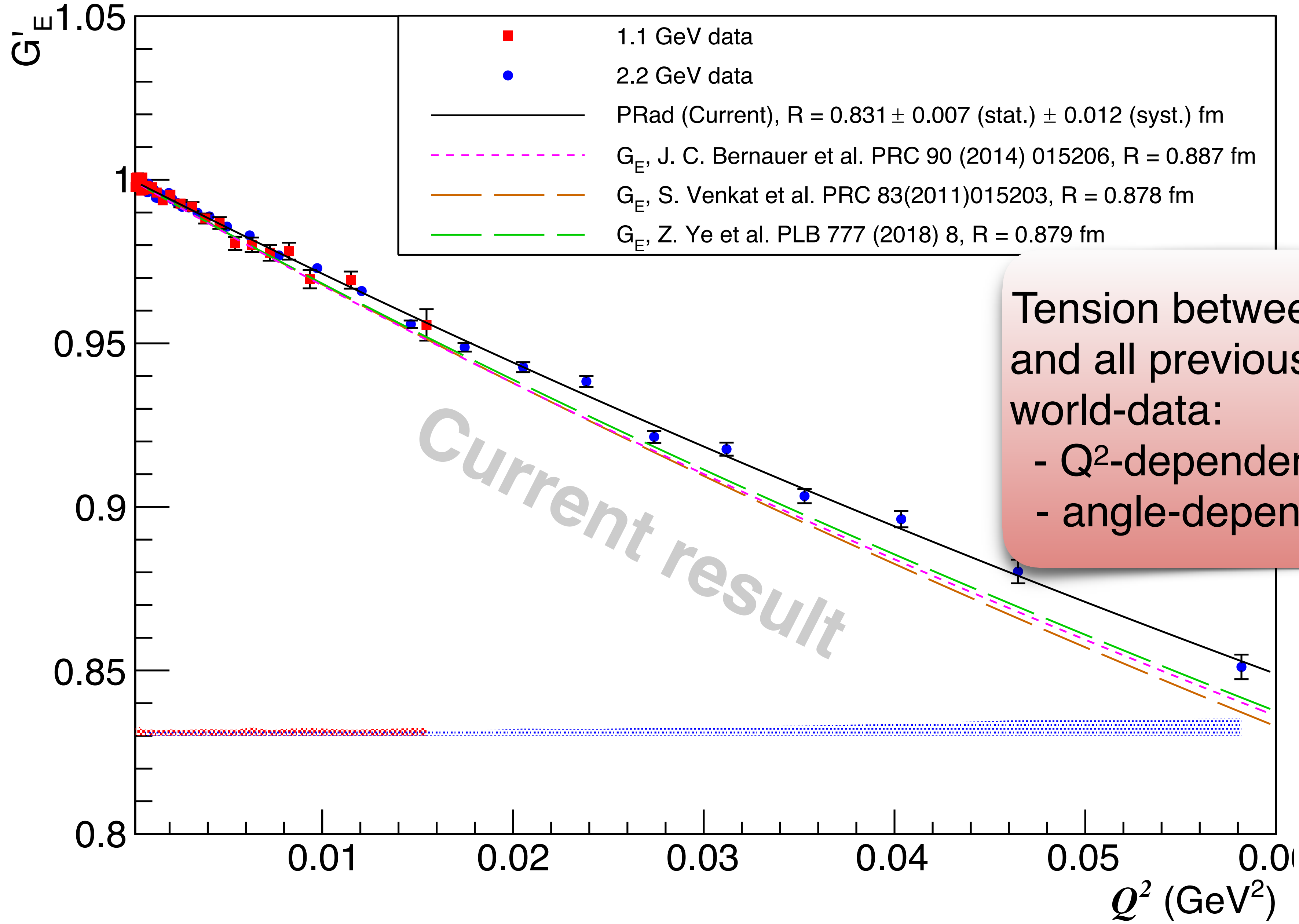


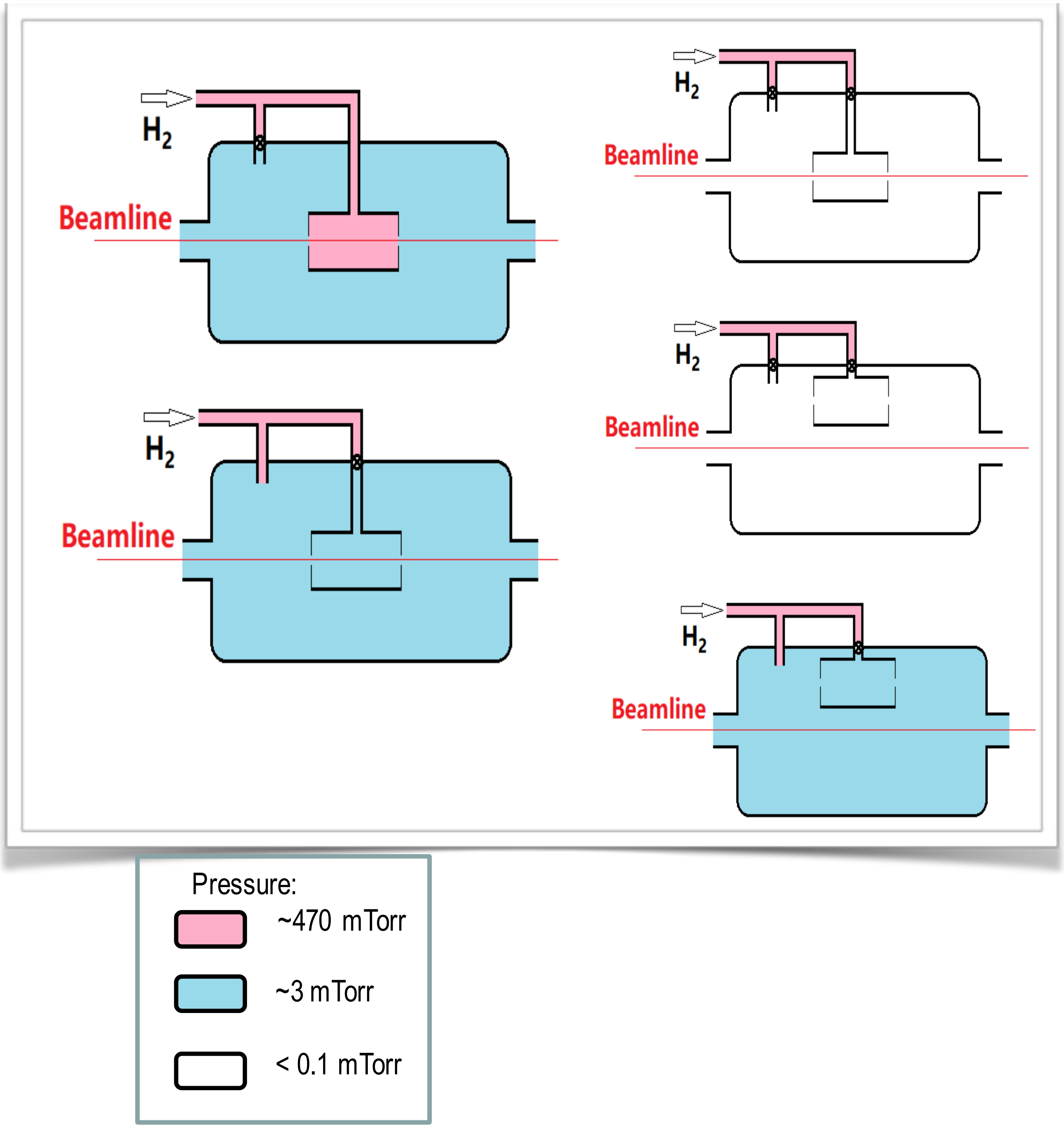
Tension between the PRad data and all previous fits based on world-data:
- Q^2-dependent background?
- angle-dependent systematic?

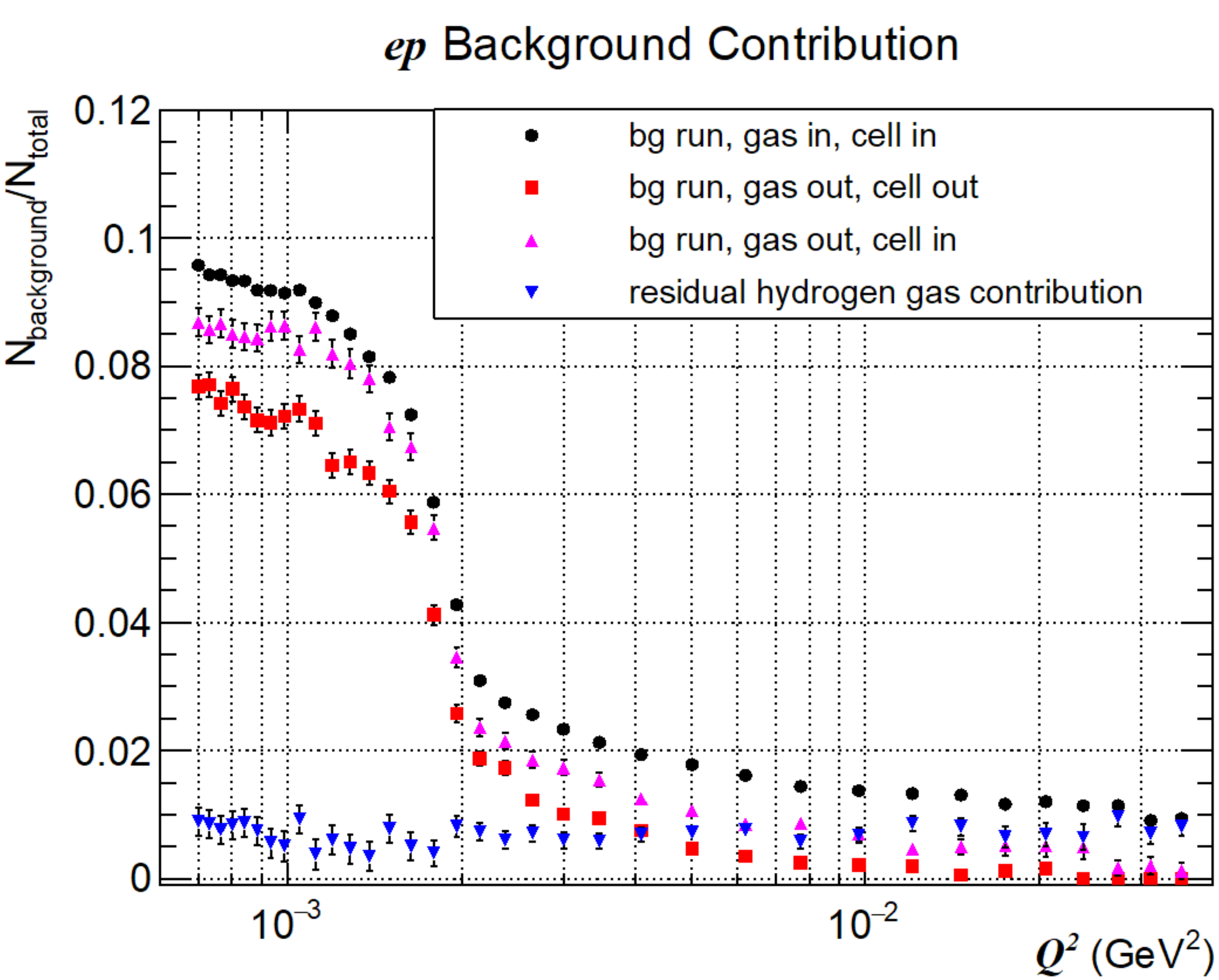
- Normalization:
n=1.0002 ±0.0002(stat) ±0.0020(sys)
n=0.9983 ±0.0002(stat) ±0.0013(sys)

A. Gasparian

Systematic measurements of the background

A. Gasparian





Extrapolation exercise of the PRad collaboration

Systematic study using pseudo data mimicking real data

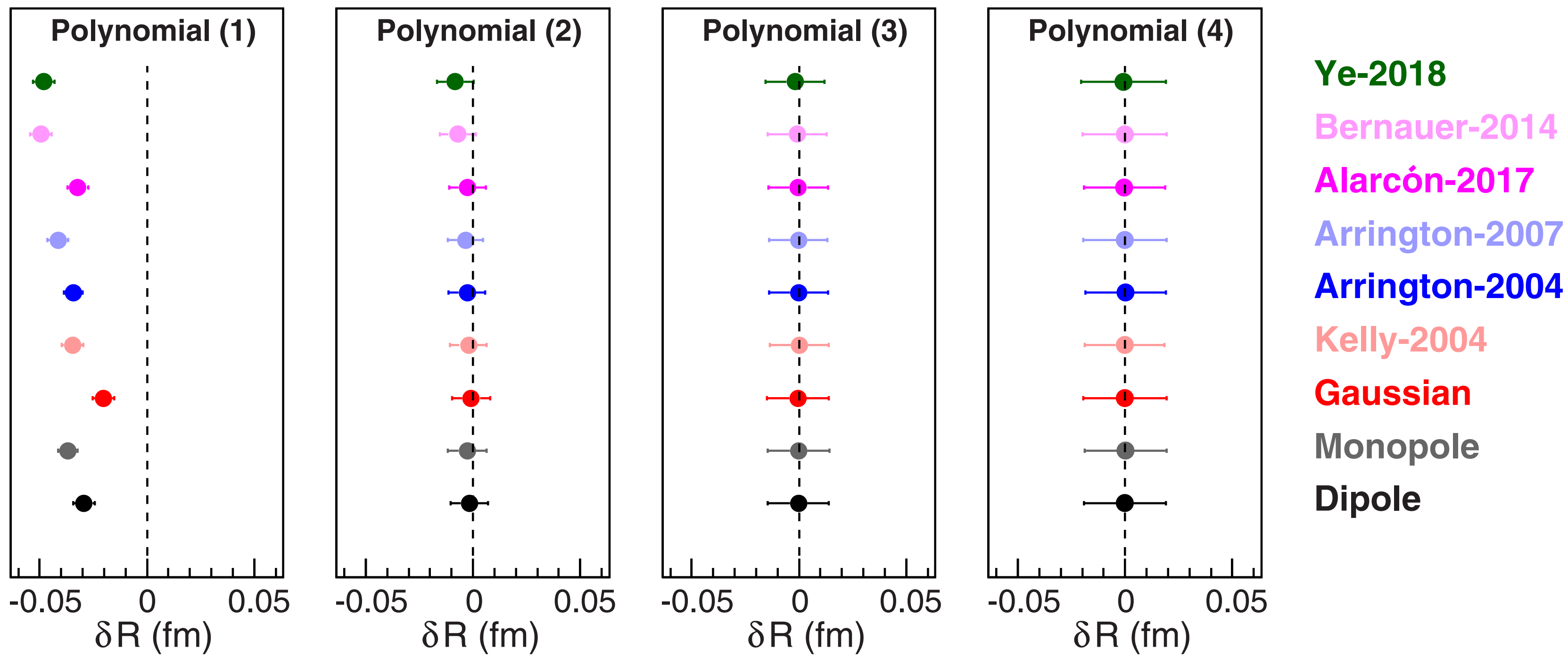


FIG. 4. Polynomial-expansion fits of pseudodata tables generated with nine models.

X. Yan, et al. PRC 98, 2, 025204, 2018

- Generate form factors assuming models for G_E and a R_p value
- Fit form factors to extract R_p

δR = *difference between mean extracted value and true value*

= ***bias***

Extrapolation exercise of the PRad collaboration

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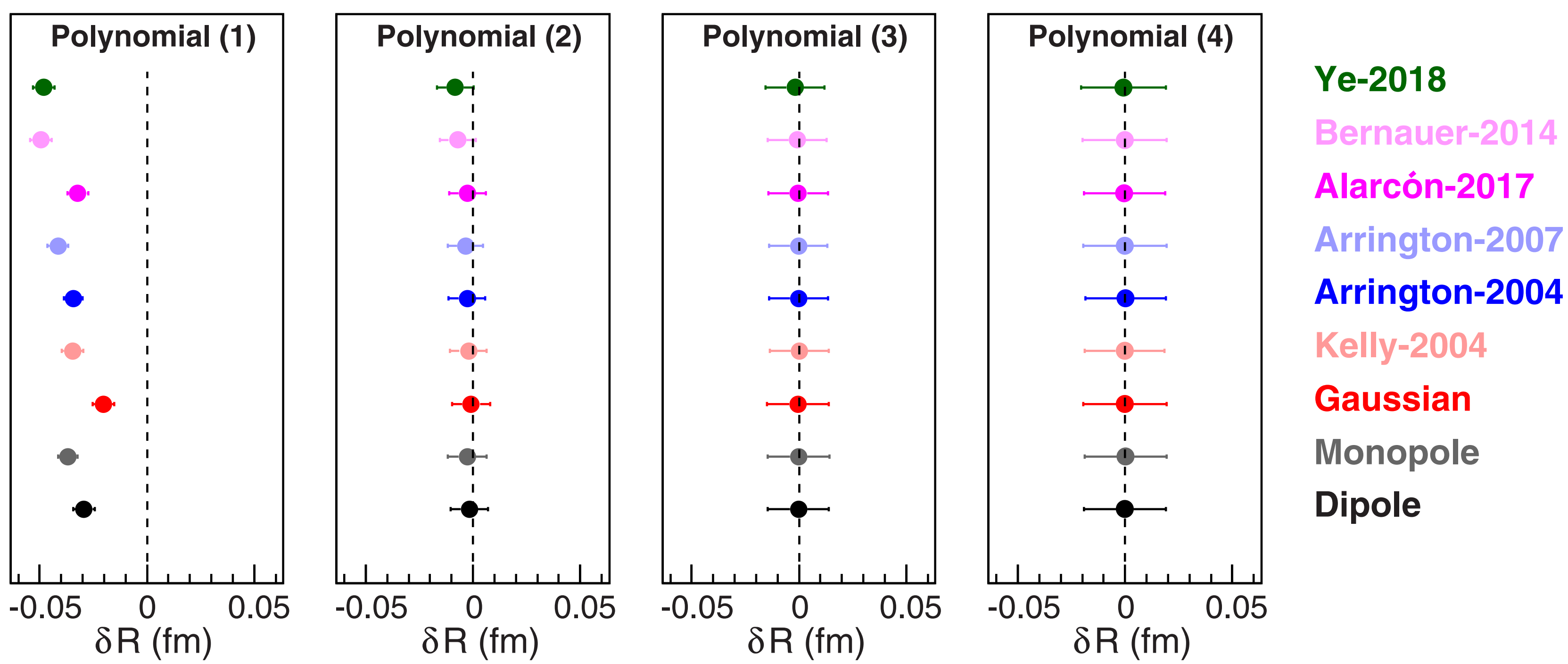

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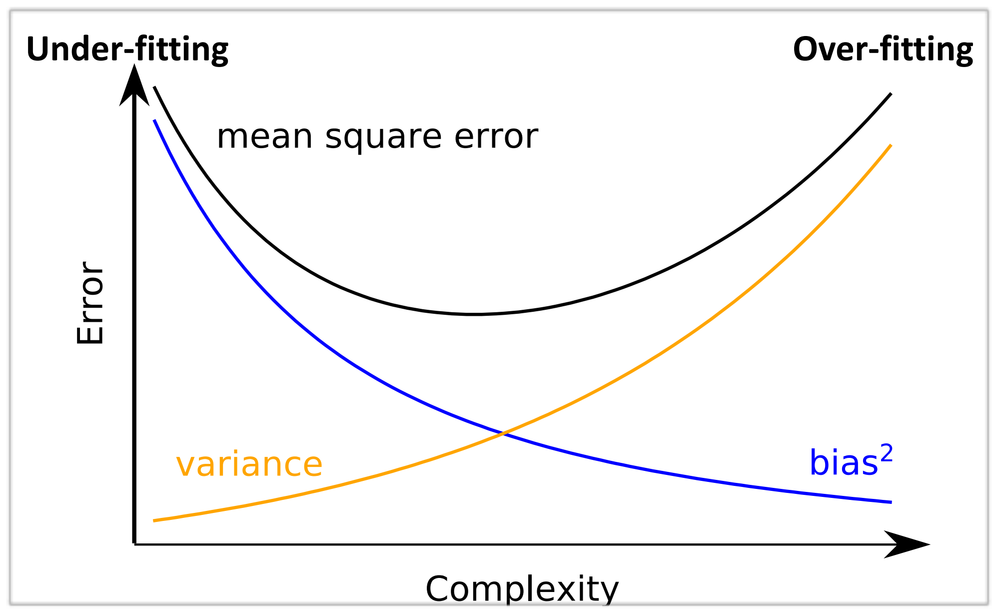
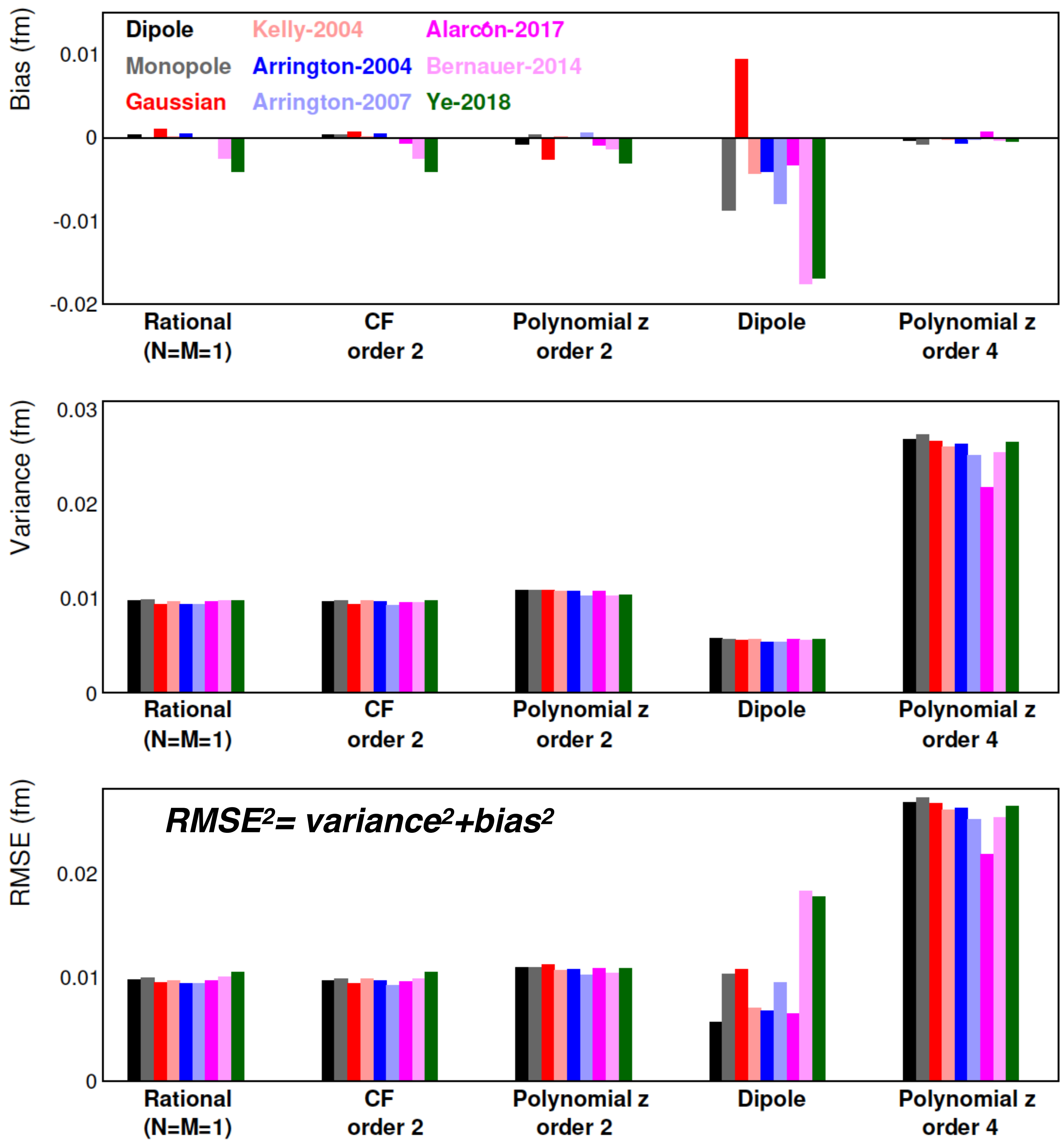
D.W. Higinbotham



- We tend to judge regressions only from χ^2
- Functions with good χ^2 do not necessarily extrapolate well beyond the data

⇨ Find the most suited functional form optimising on **variance (σ)** and **bias (δR)**

Extrapolation exercise of the PRad collaboration



Established the best functional forms
BEFORE
seeing the PRad data

PRC 98, 2, 025204, 2018

PRad results

Accepted in Nature (2019)

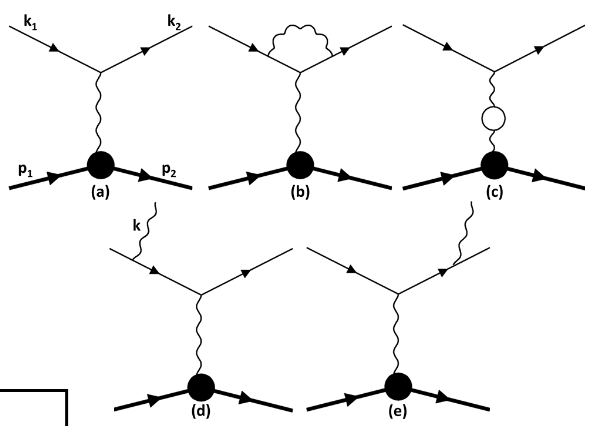
$$R_p = 0.831 \pm 0.007(\text{stat}) \pm 0.012(\text{sys})\ \text{fm}$$

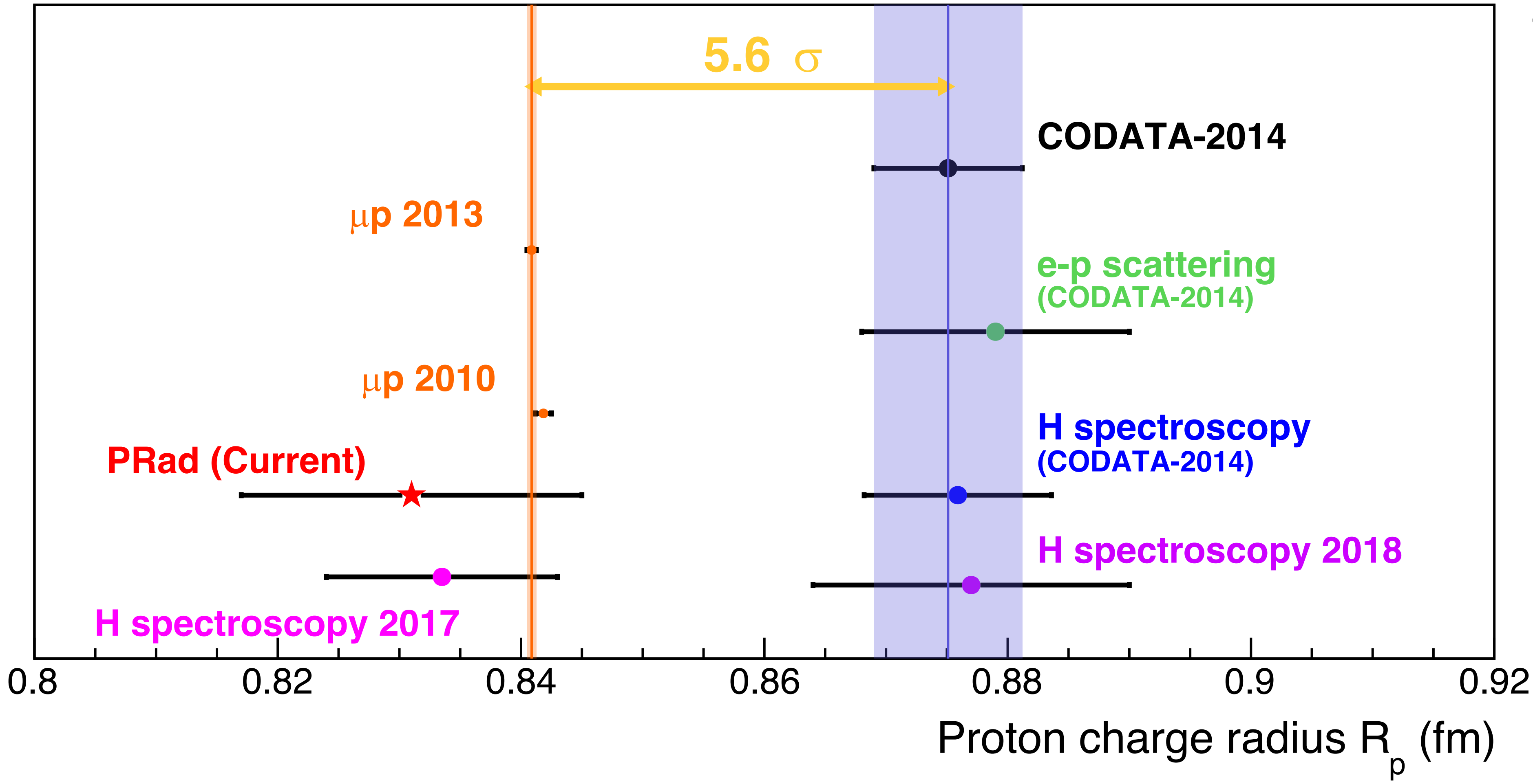
- without ultra-relativistic approximation
- include electron Bremstrahlung
- NLO calculation

I. Akushevich et al., Eur. Phys. J. A 51(2015)1

Main systematic
- radiative corrections to Møller scattering
- background subtraction for the 1.1 GeV data
- event selection

- Result insensitive to G_M
- Extrapolation uncertainty ≪ statistical uncertainty





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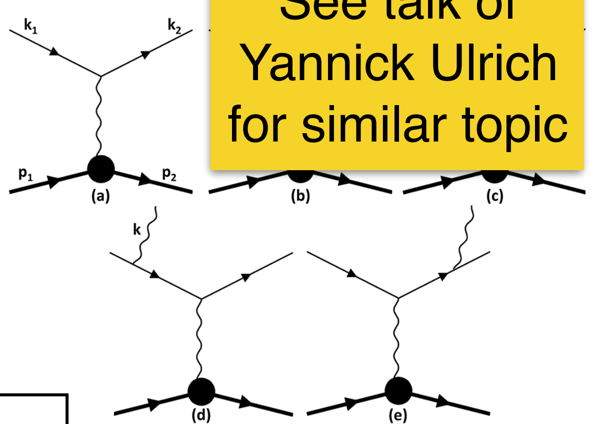
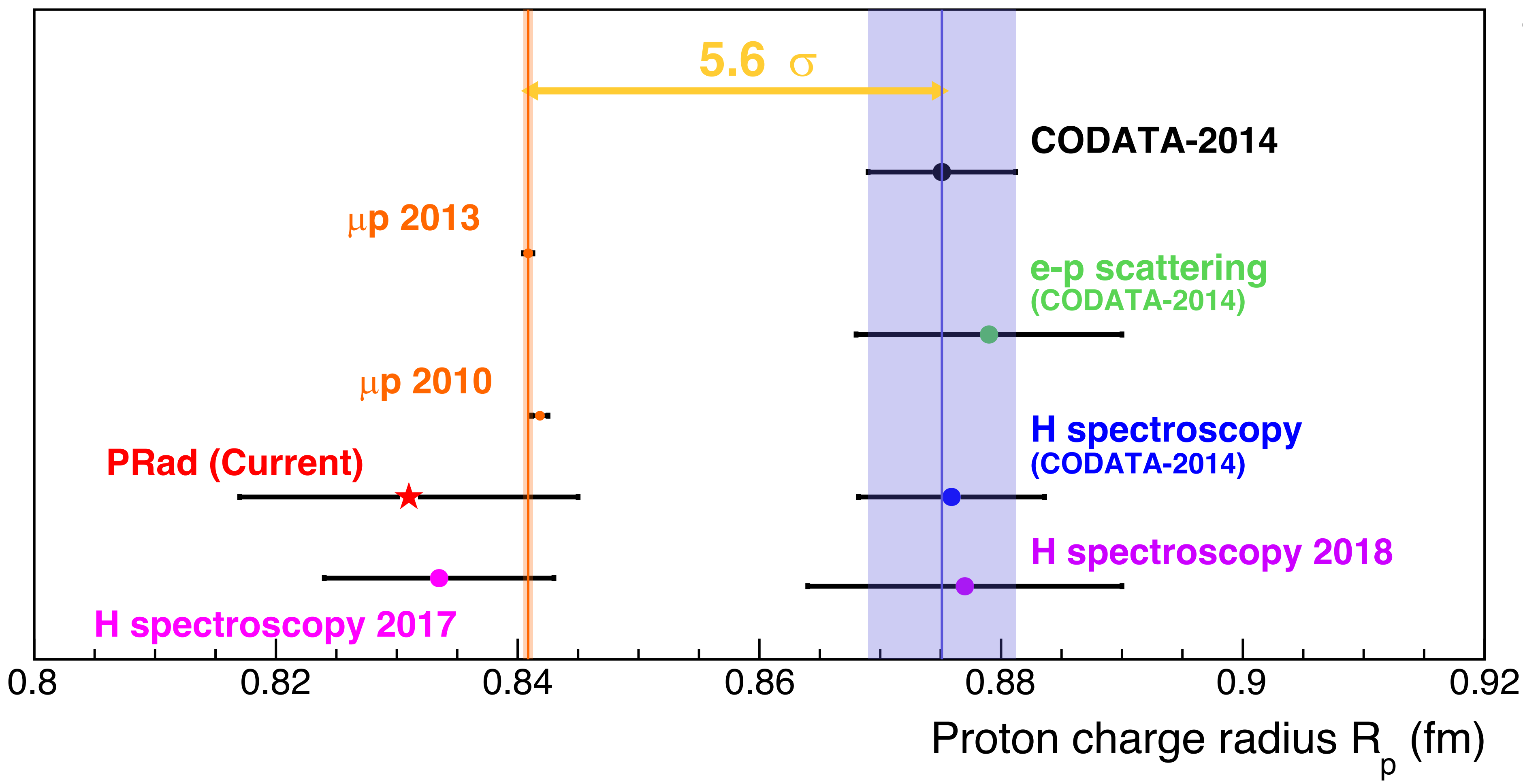
I. Akushevich et al., Eur. Phys. J. A 51(2015)1

See talk of Yannick Ulrich for similar topic



- Result very insensitive to G_M
- Extrapolation uncertainty ≪ statistical uncertainty



Theory guidance?

Is there some ways to “avoid” the extrapolation?

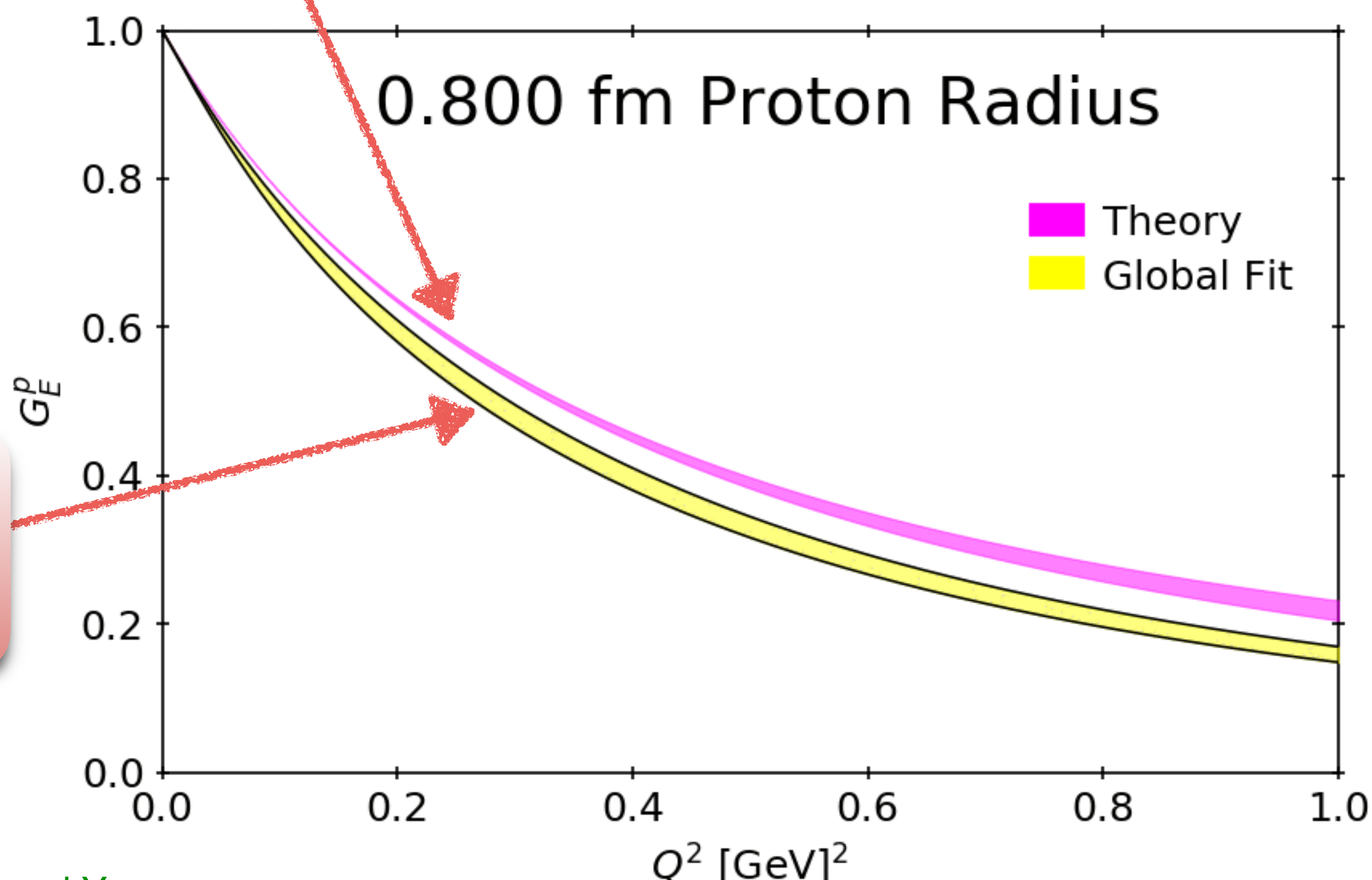
⇨ Using **theory guidance**

The idea is not completely new:

- Dispersion relation, spectral function based on VMD (Meissner)
- Constraining tails of the charge distribution (Sick)
- Chiral perturbation theory to get higher moments (Pineda & Hessels)
- Dispersively improved chiral perturbation theory (Alarcon)

Most recent R_p from e-p reanalysis (my biased choice)

Dispersively improved chiral ChPT
with fixed R_p-value
ChPT: gives spectral functions
Dispersion: correlates various Q^2 regions



Fit of measured cross section and extrapolation **with fixed R_p-value**

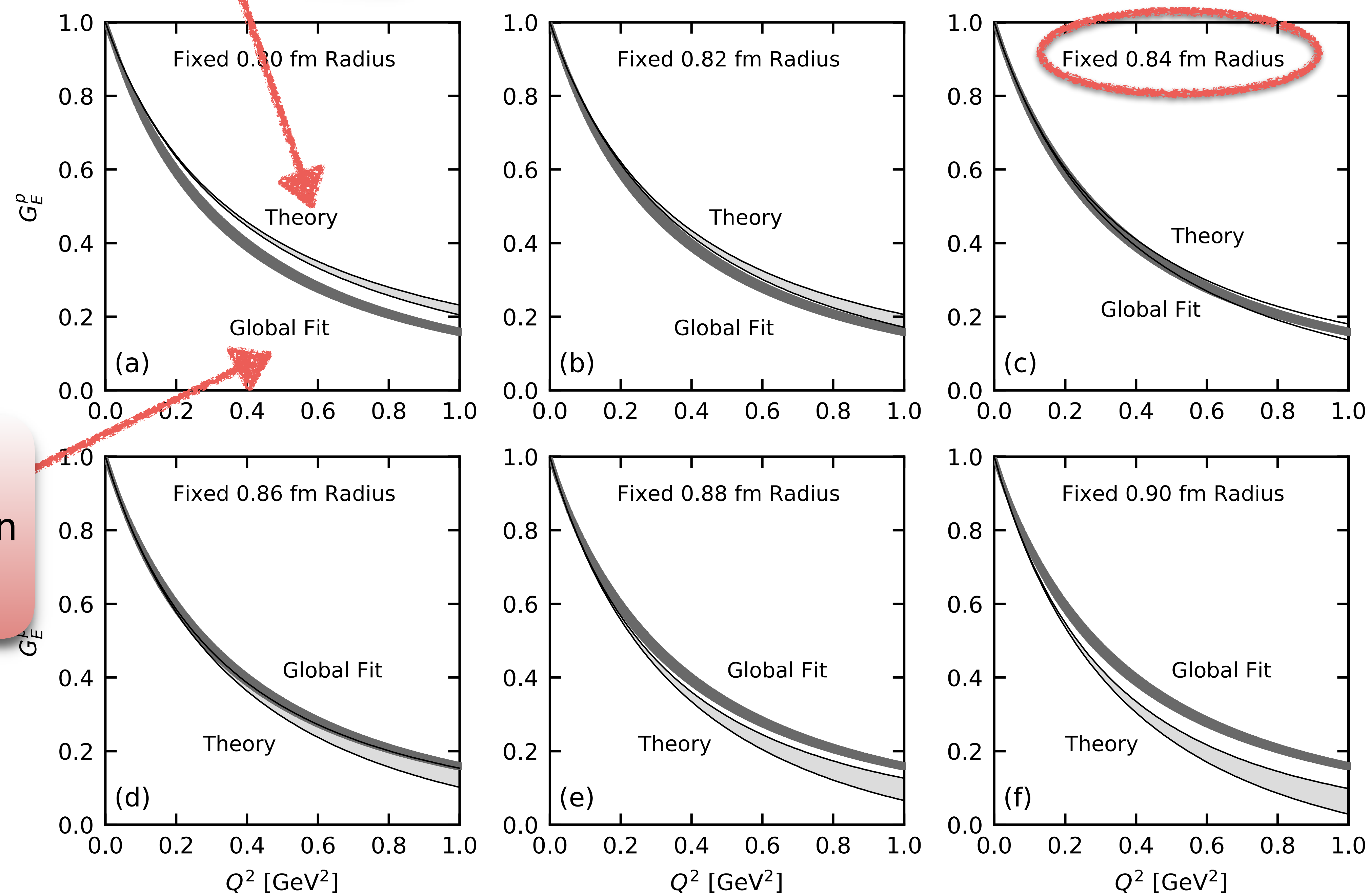
Alarcon, Higinbotham, Weiss and Ye
PRC 99, 044303 (2019)

Most recent R_p from e-p reanalysis (my biased choice)

Dispersively improved chiral ChPT
with fixed R_p-value
ChPT: gives spectral functions
Dispersion: correlates various Q^2 regions

Agreement at the muonic value

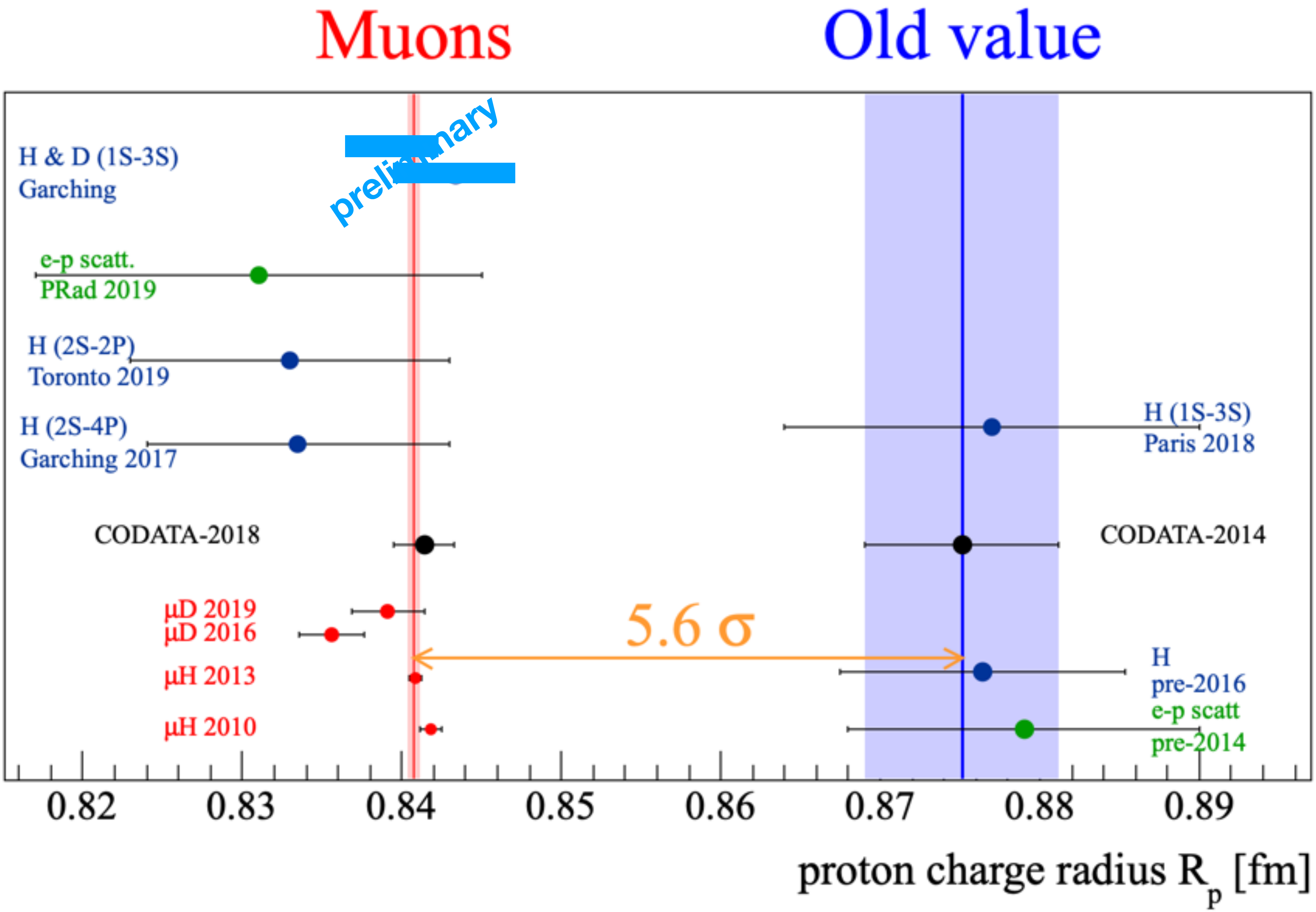
R_p = 0.844(7) fm (e-p scatt.)
R_p = 0.84087(39) fm (μp)



Fit of measured cross section and extrapolation **with fixed R_p-value**

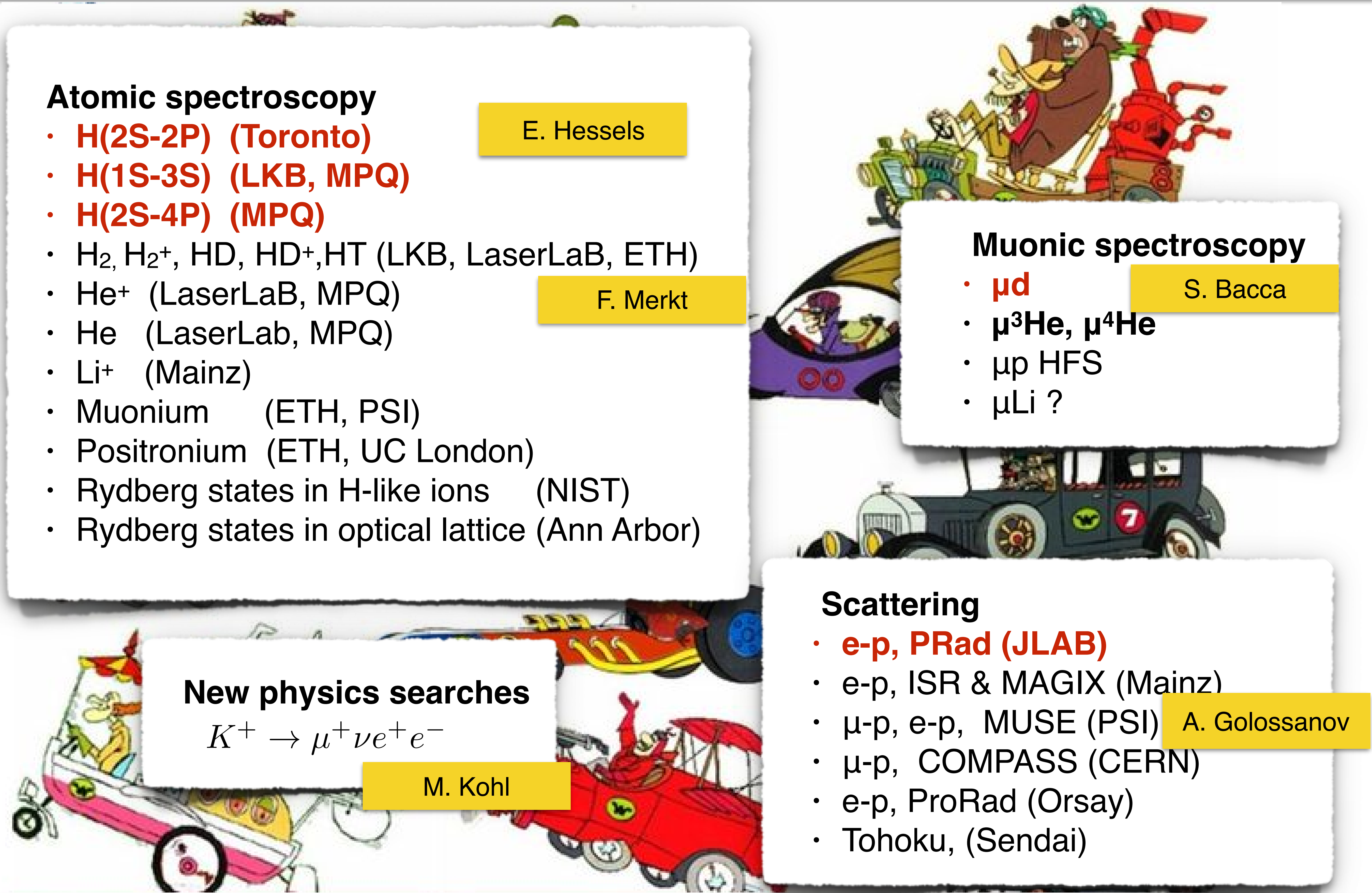
Alarcon et al.
PRC 99, 044303 (2019)

New radii from experiments (excluding re-analysis of scattering data)



The race to the proton radius solution

The race to the proton radius solution



Atomic spectroscopy

E. Hessels

- **H(2S-2P) (Toronto)**
- **H(1S-3S) (LKB, MPQ)**
- **H(2S-4P) (MPQ)**
- H_2, H_2^+, HD, HD^+, HT (LKB, LaserLaB, ETH)
- He^+ (LaserLaB, MPQ)
- He (LaserLab, MPQ)
- Li^+ (Mainz)
- Muonium (ETH, PSI)
- Positronium (ETH, UC London)
- Rydberg states in H-like ions (NIST)
- Rydberg states in optical lattice (Ann Arbor)

F. Merkt

Muonic spectroscopy

S. Bacca

- **μd**
- **μ^3He, μ^4He**
- μp HFS
- μLi ?

Scattering

- **e-p, PRad (JLAB)**
- e-p, ISR & MAGIX (Mainz)
- μ-p, e-p, MUSE (PSI)
- μ-p, COMPASS (CERN)
- e-p, ProRad (Orsay)
- Tohoku, (Sendai)

A. Golossanov

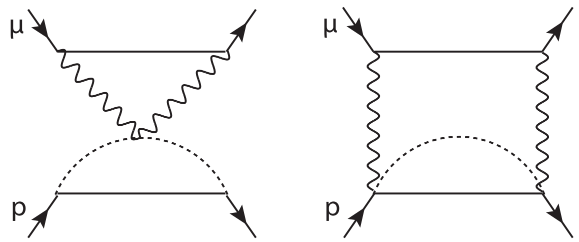
New physics searches

$$K^+ \to \mu^+ \nu e^+ e^-$$

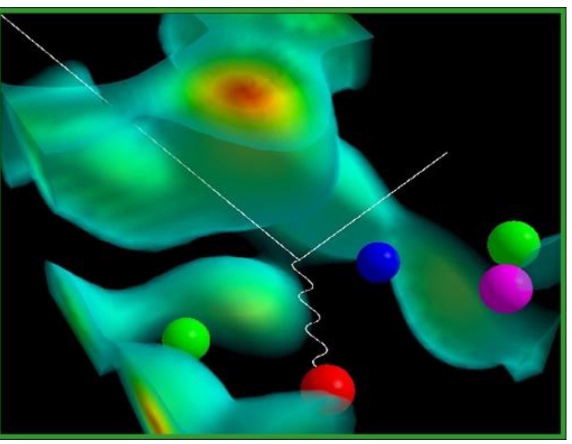
M. Kohl

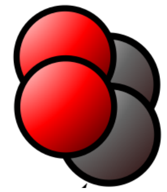
Investiagations prompted by the muonic measurements

Chiral PT

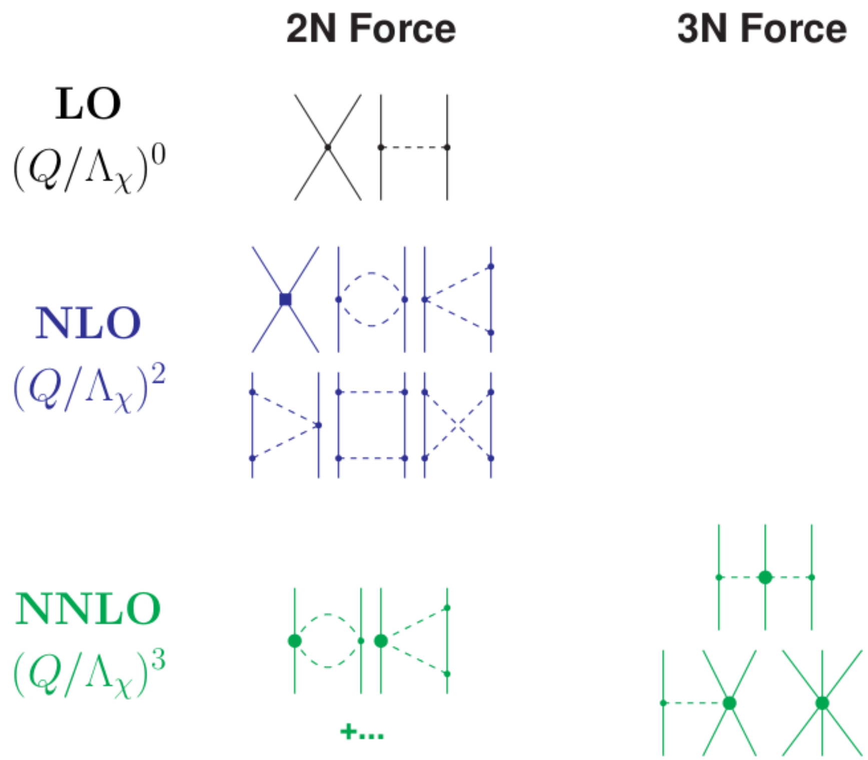


Lattice



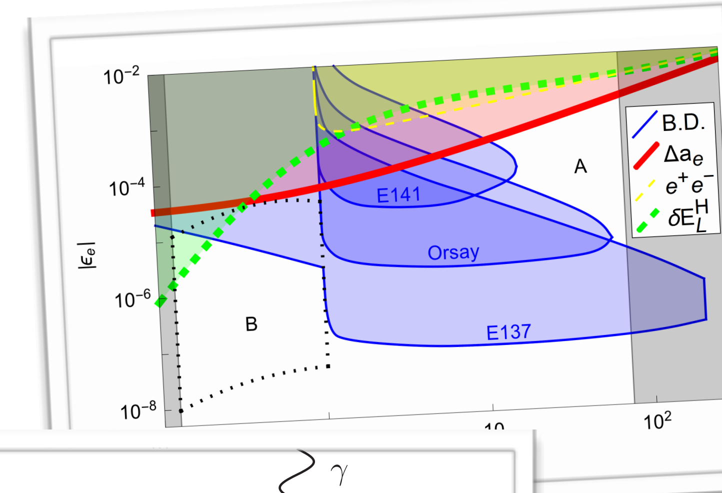


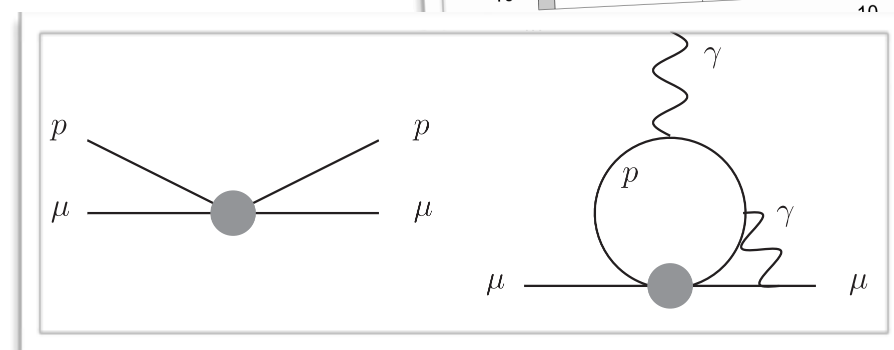
Few-Nucleon EFT



BSM

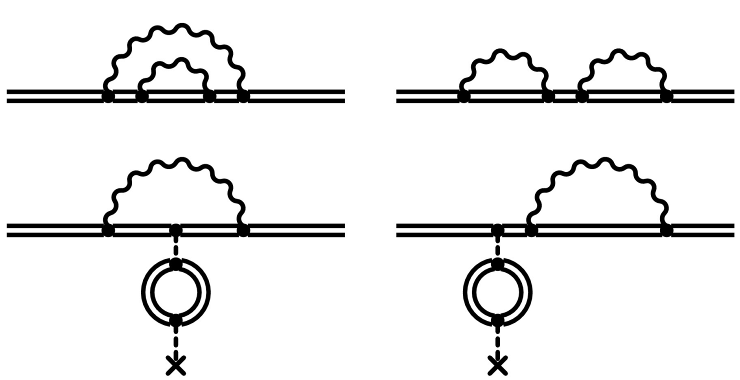
?

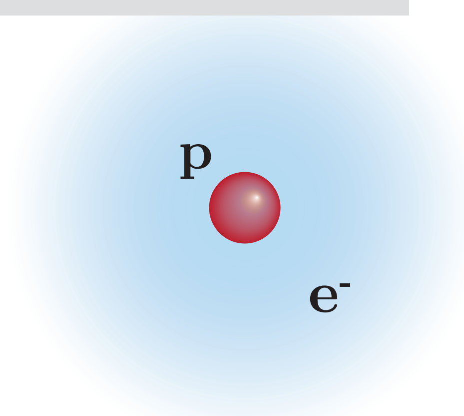




New hadronic effects?

Bound-state QED test and fundamental constant: spectroscopy in hydrogen, molecules, other exotic atoms and Rydberg atoms





Dispersion- and chiral-based approaches to form factors

Polarizabilities, form factors and structure functions program

Analysis of e-p scattering

The same issues are critical for the accelerator neutrino program.

Sensitivity at low Q²

Slide from J. Bernauer

$$G_E(Q^2) = 1 - \frac{Q^2}{6}\langle r_{\mathrm{p}}^2\rangle + \frac{Q^4}{120}\langle r_{\mathrm{p}}^4\rangle + \dots$$

$$\frac{d\sigma}{d\Omega} \propto 1 - \underbrace{A}_{\mathcal{O}(6)} \cdot Q^2 + \underbrace{B}_{\mathcal{O}(30)} \cdot Q^4 + \dots$$

(Q in units of GeV/c)

We want to measure the radius ($\sim\sqrt{A}$) to within 0.5%, without knowing B. So:

$$B/A \cdot Q^2 \ll 0.01 \longrightarrow Q^2 \ll 0.002\,(\mathrm{GeV}/c)^2$$

But: Need to measure A to 1%, so measure $\frac{d\sigma}{d\Omega}$ to $6 \cdot 0.002 \cdot 0.01 = 0.012\%$. Good luck.

Sensitivity to quadratic (proton radius) term

Slide from J. Bernauer

$$G_E(Q^2) = 1 - \frac{Q^2}{6}\langle r_p^2 \rangle + \frac{Q^4}{120}\langle r_p^4 \rangle + \dots$$