The proton radius puzzle

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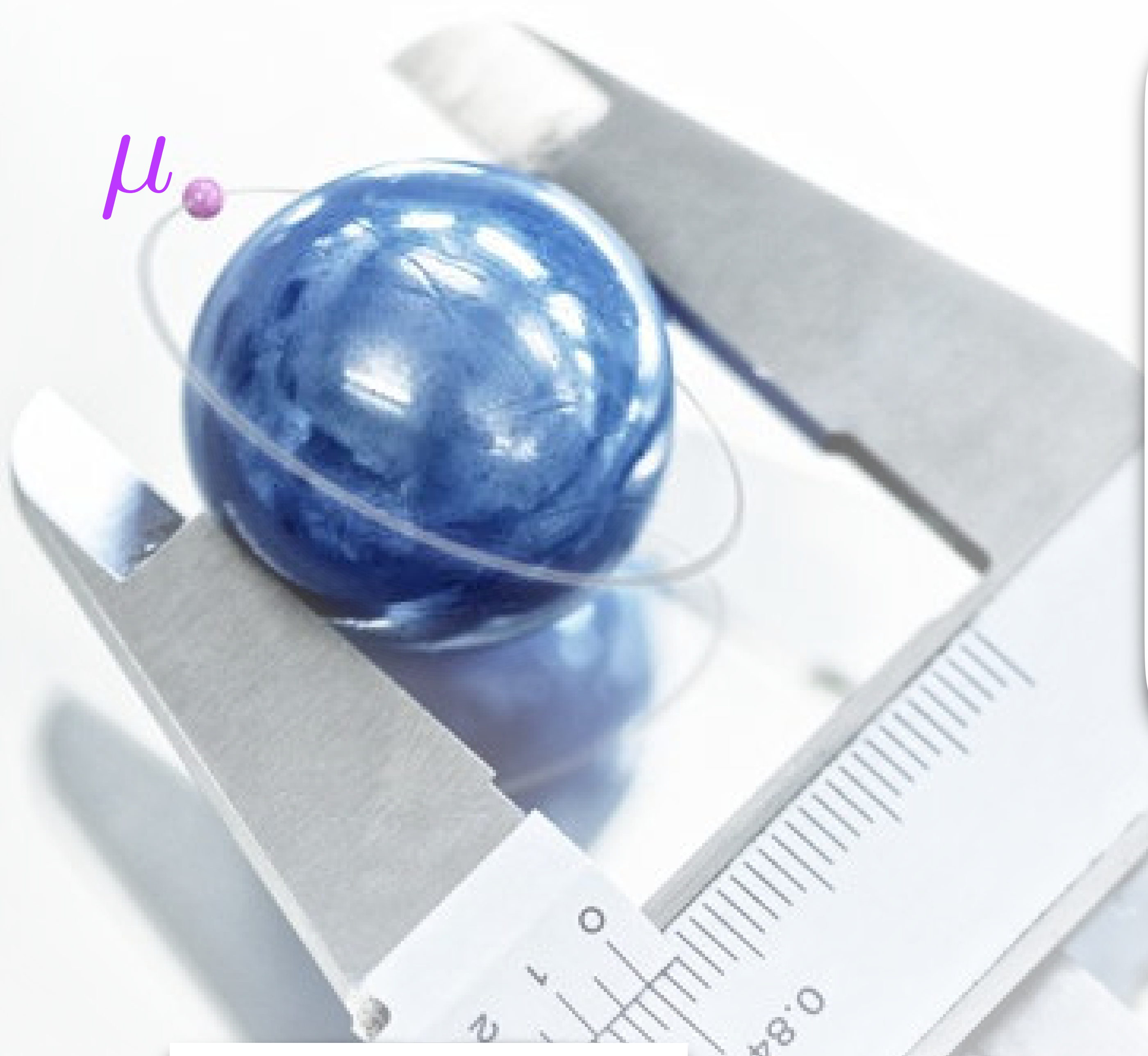
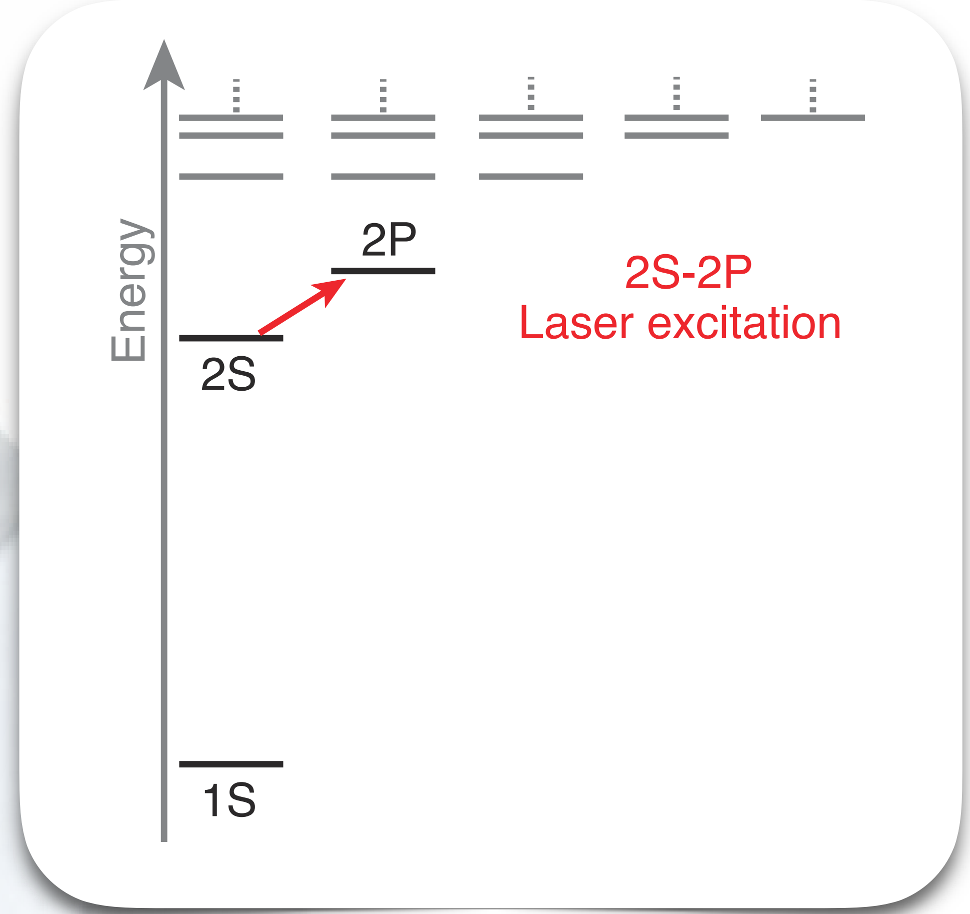
CREMA collaboration

Laser spectroscopy of muonic atoms

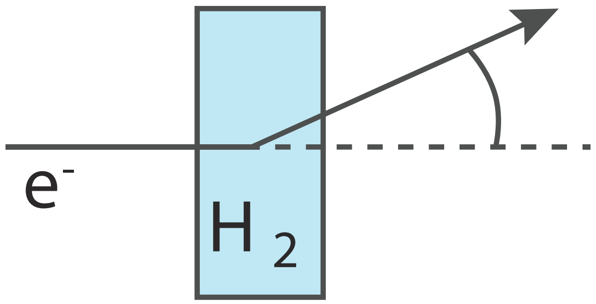




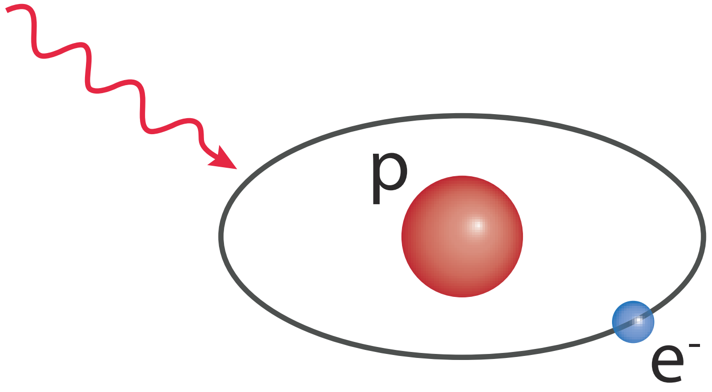
- 2S-2P μp
- 2S-2P μd
- 2S-2P μ³He, μ⁴He

From 2S-2P
⇨ charge radii

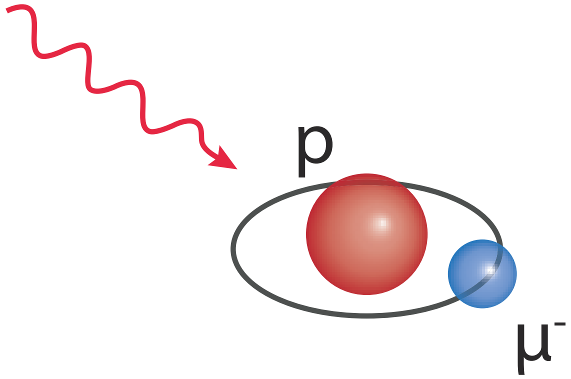
Three ways to the proton radius



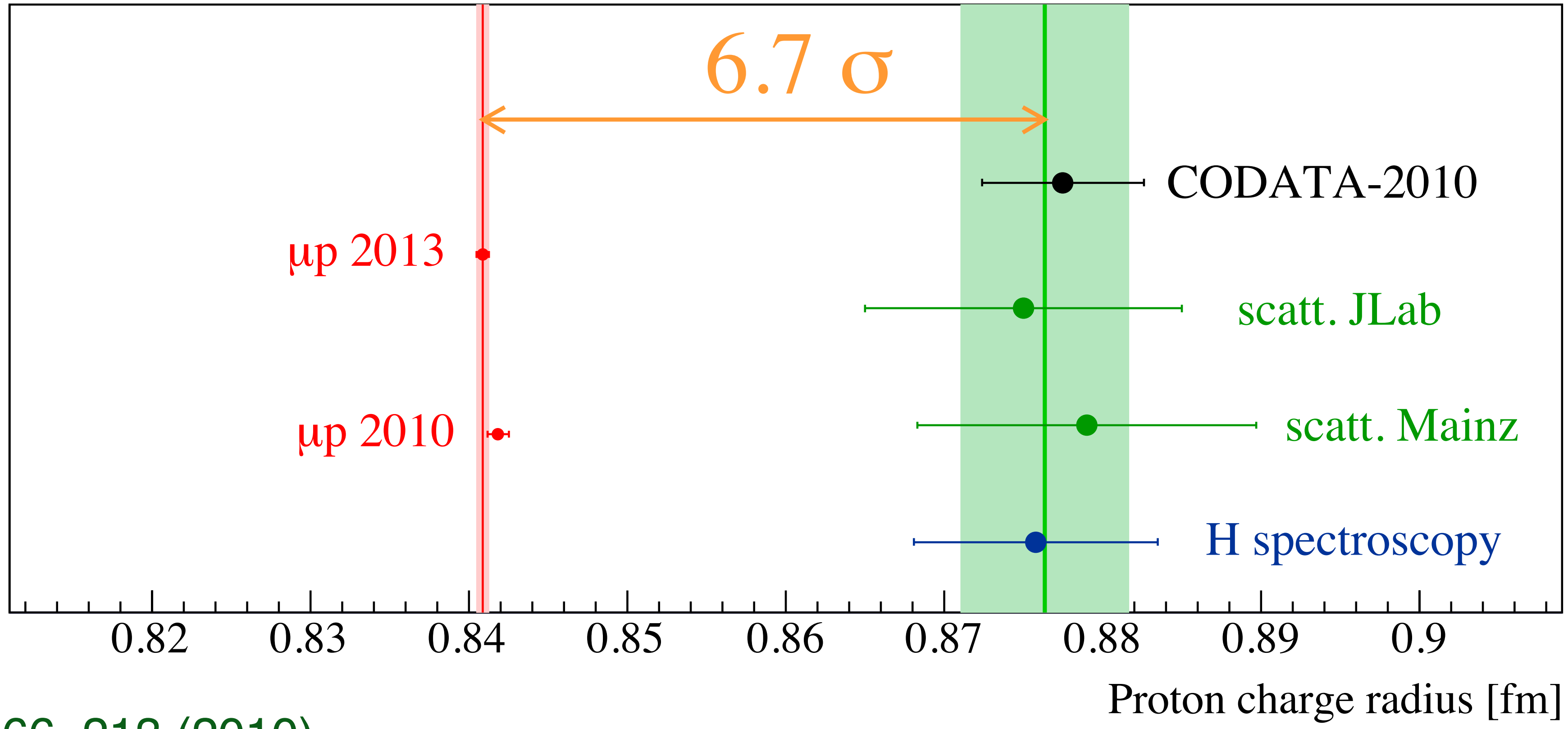
e^--p scattering



H spectroscopy



μp spectroscopy

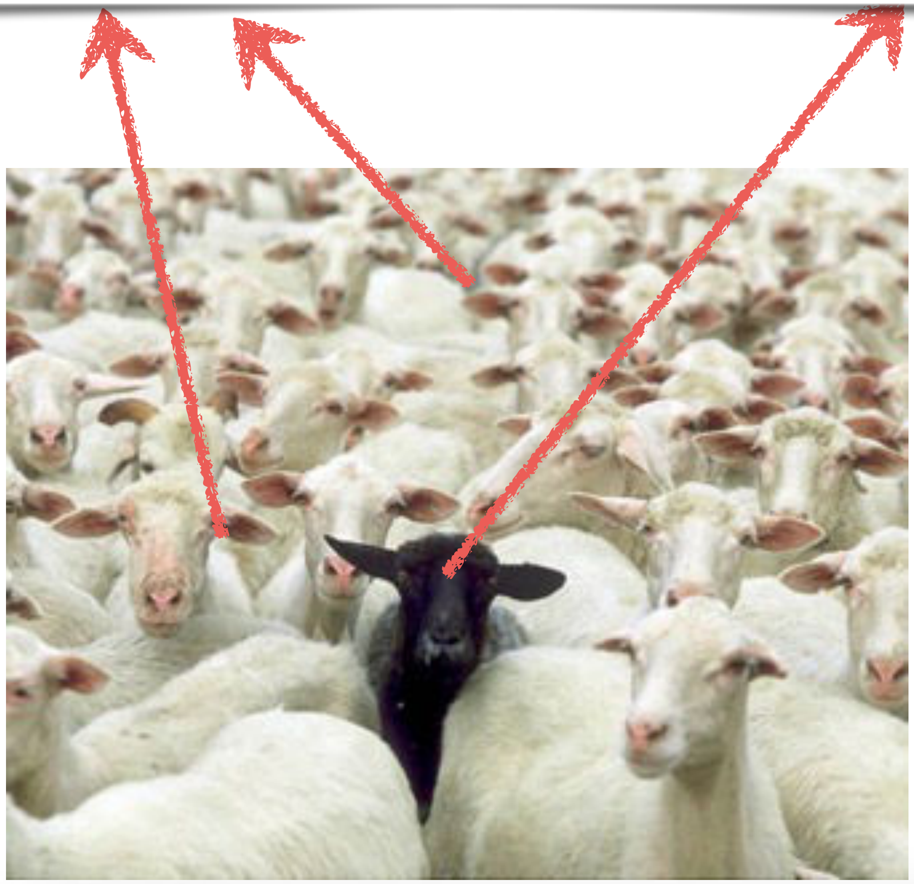


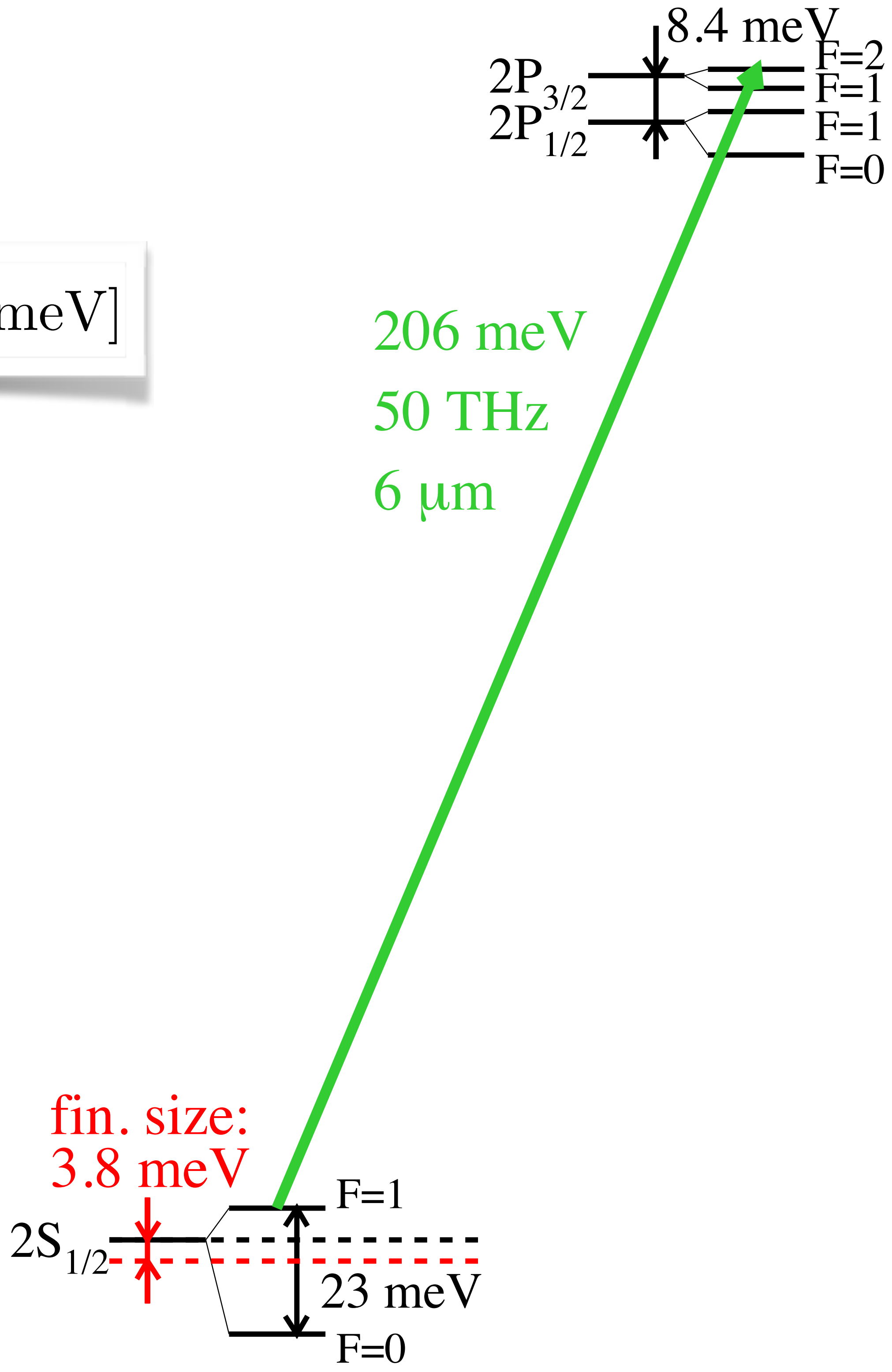
Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

Extracting the proton radius from μp

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

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





$$m_\mu \approx 200 m_e$$

$$\Delta E_{\mathrm{size}} = \frac{2\pi(Z\alpha)}{3}\, r_{\mathrm{p}}^2\, |\Psi_{nl}(0)|^2 = \frac{2(Z\alpha)^4}{3n^3}\, m_r^3\, r_{\mathrm{p}}^2\, \delta_{l0}$$

Principle of the μp 2S-2P experiment

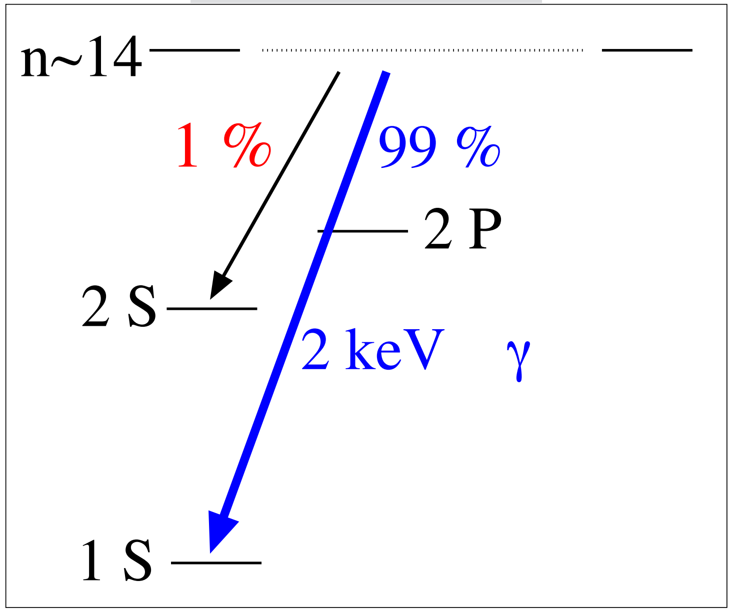
Produce many μ^- at keV energy

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

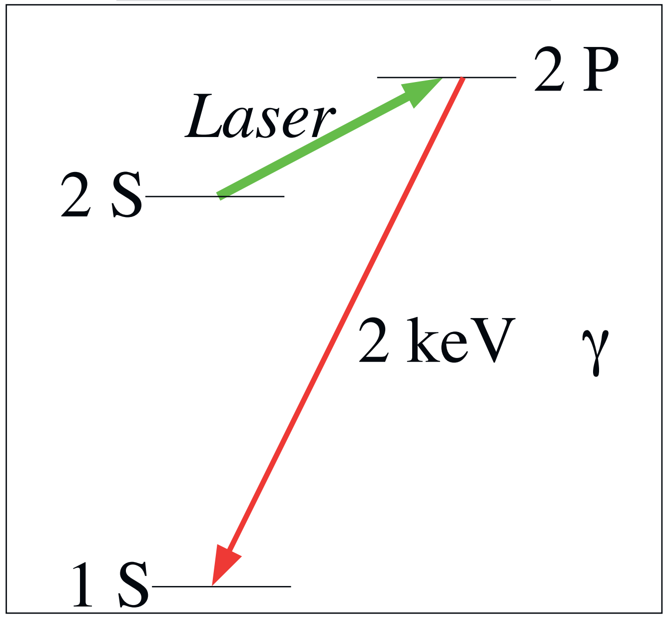
Fire laser to induce the 2S-2P transition

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

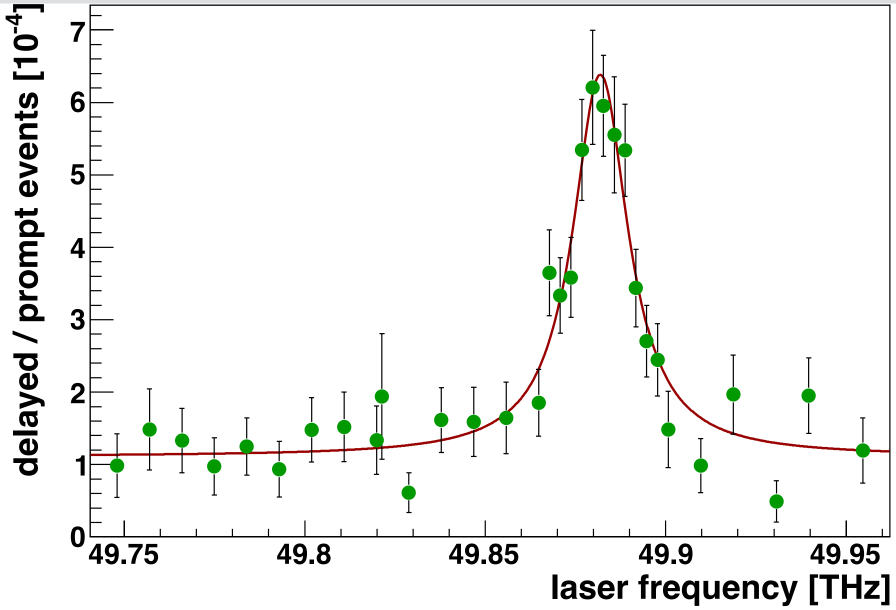
μp formation



Laser excitation

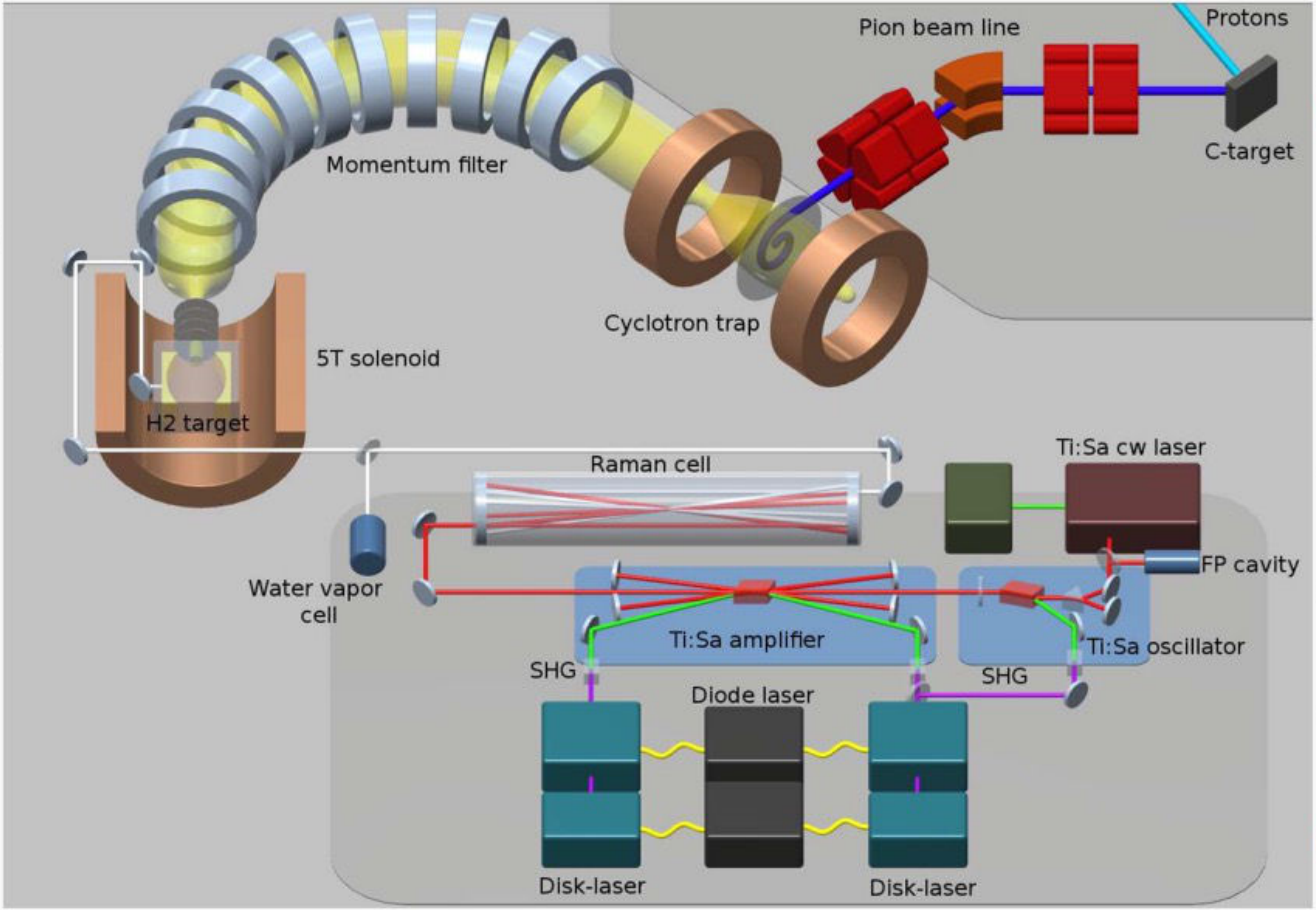


Plot number of X-rays vs laser frequency



The setup at the Paul Scherrer Institute

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

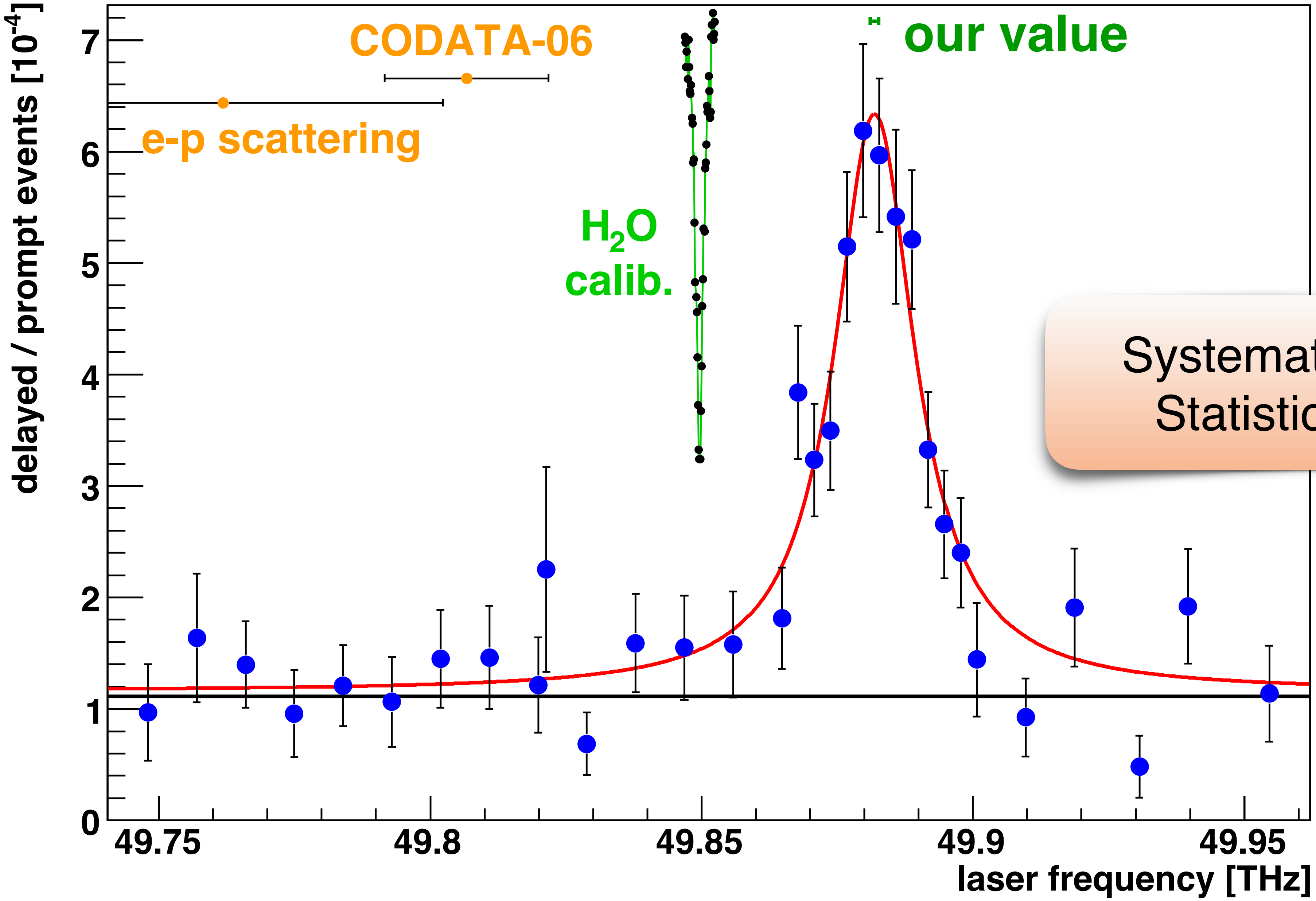


940 nm
(2 kW)
↓
1030 nm
↓
515 nm
↓
708 nm
↓
1.0 μm
↓
1.6 μm
↓
6.0 μm

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)

Politically in-correct discussion

Everybody seems to be right!..?

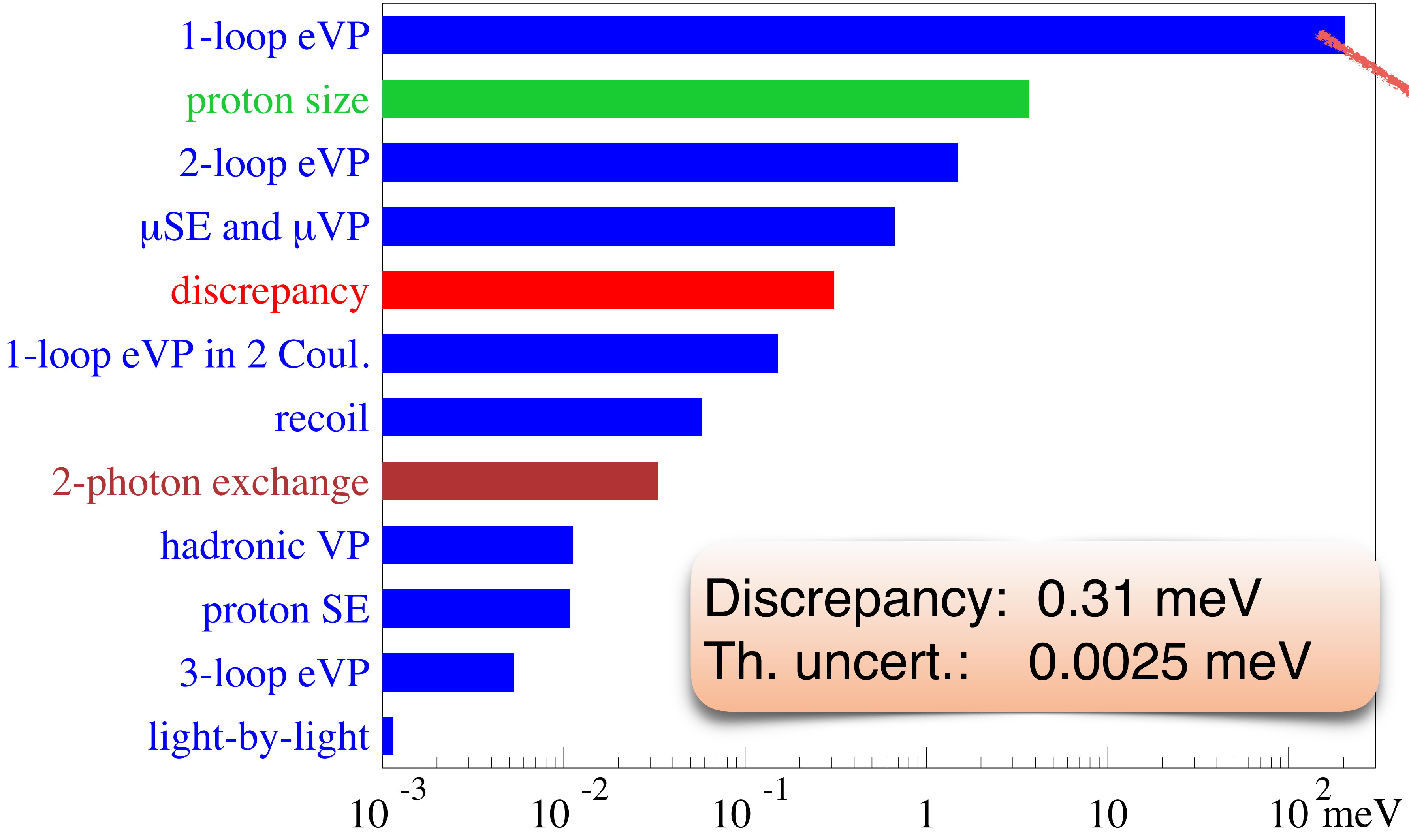
Is the μp experiment wrong?

No!

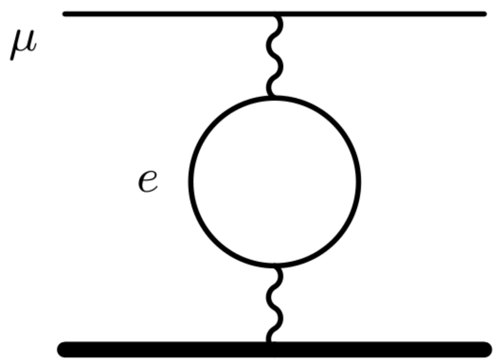
This is what I mean with politically incorrect

Why is the µp theory reliable?

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



Discrepancy: 0.31 meV
Th. uncert.: 0.0025 meV



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

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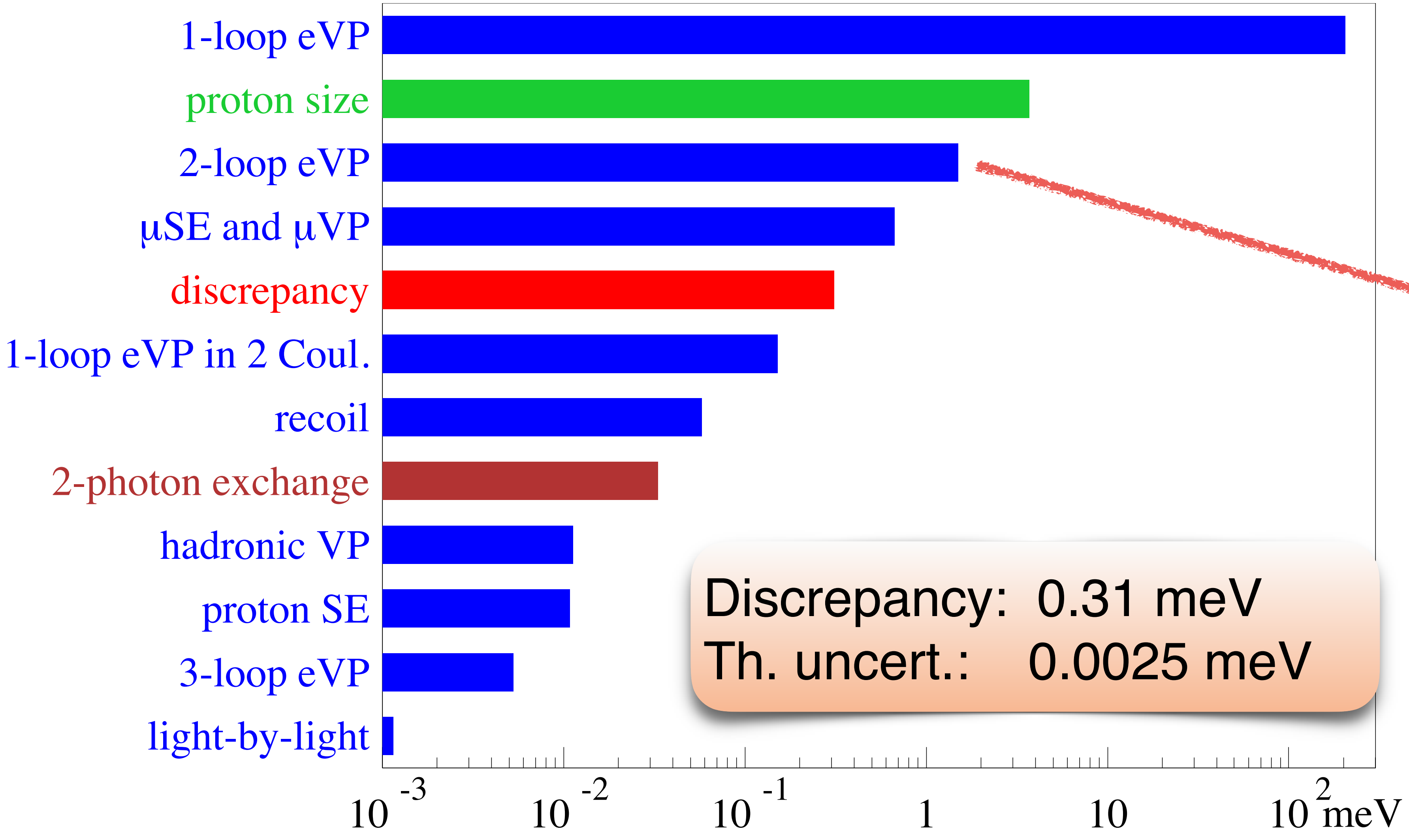

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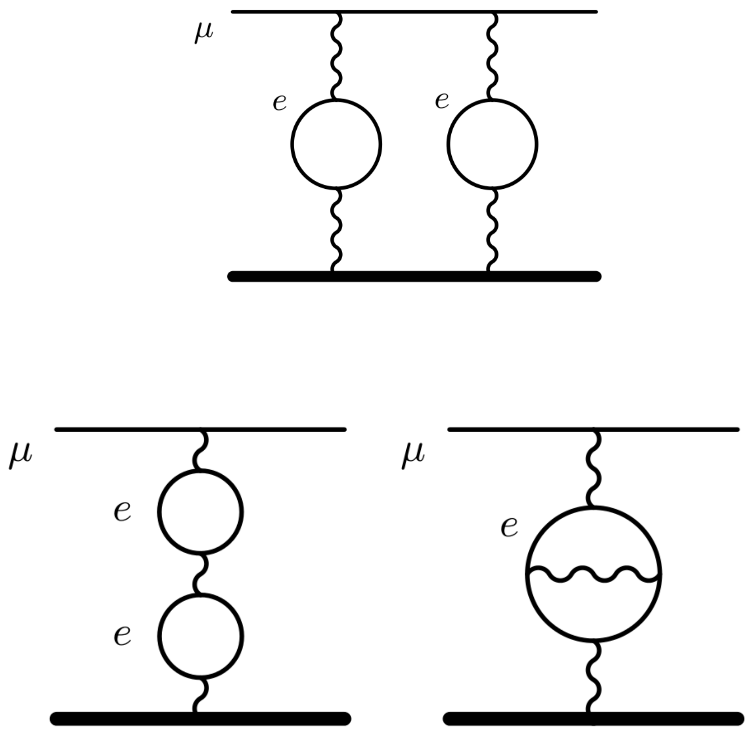

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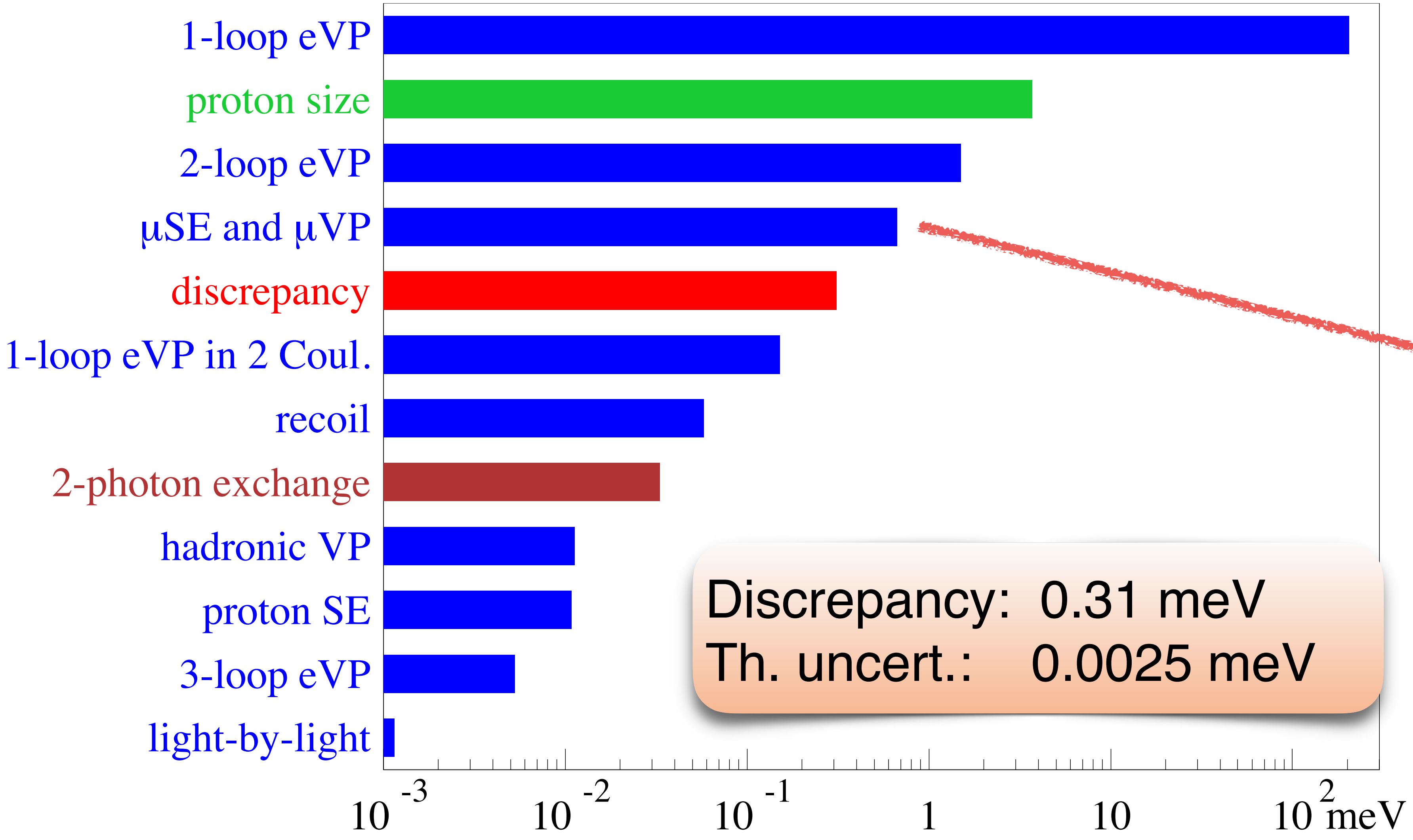

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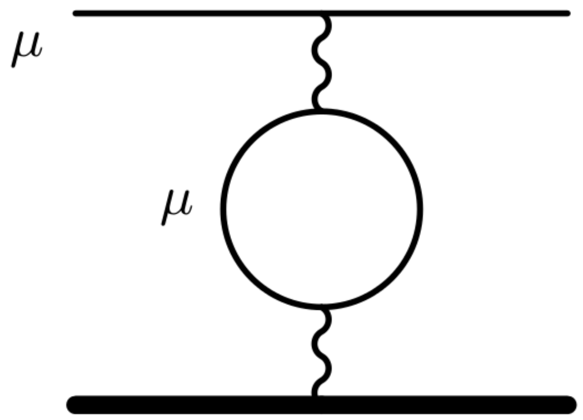

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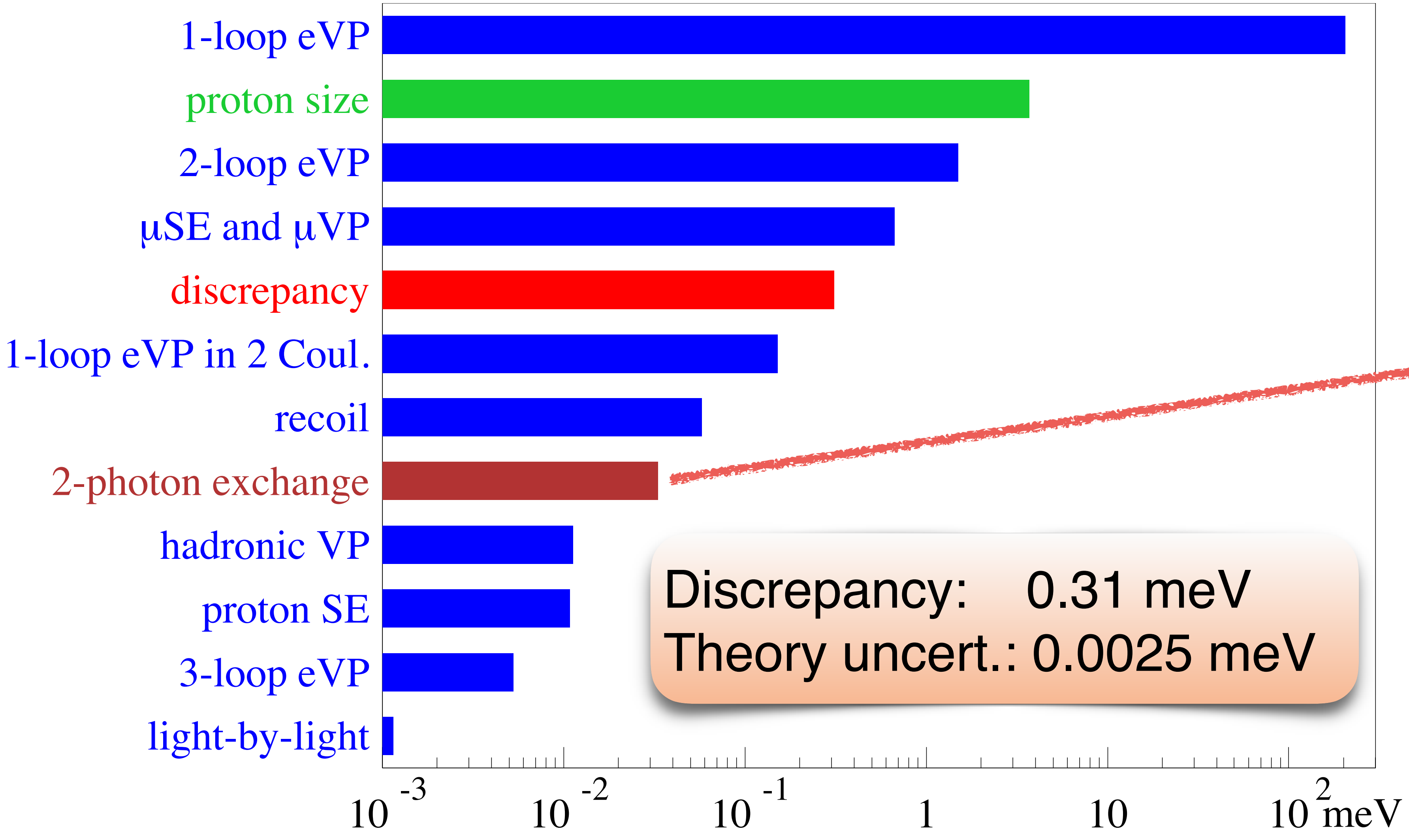
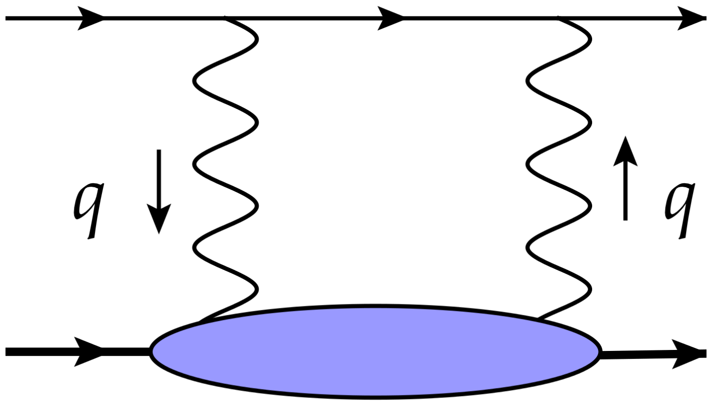


Discrepancy: 0.31 meV
Theory uncert.: 0.0025 meV

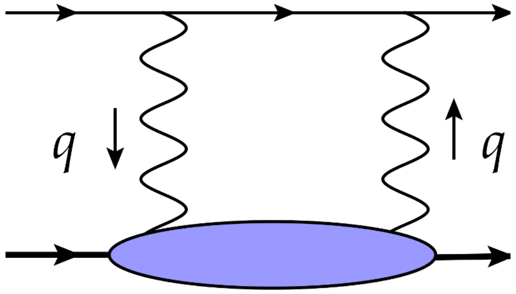


Pachucki, Carlson, Birse, McGovern, Pineda, Gorchtein, Pascalutsa, Vanderhaeghen, Alarcon, Miller, Paz, Hill…

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

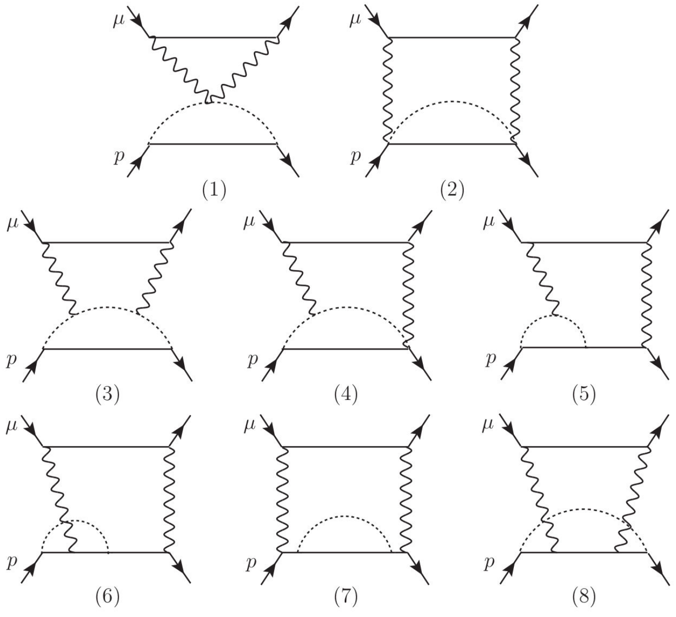
Hill, Paz, arXiv:1611.09917
Birse, McGovern, arXiv1206.3030
Hagelstein et al., arXiv:1512.03765
Peset and Pineda, arXiv:1406.4524

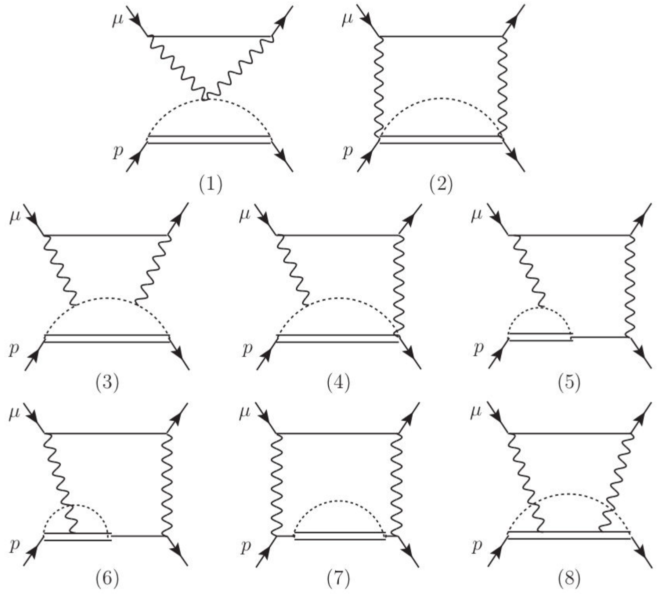
Is the 2γ exchange in μp reliable?



Phenomenological:
- dispersion relations
- data
- subtraction term

Chiral EFT

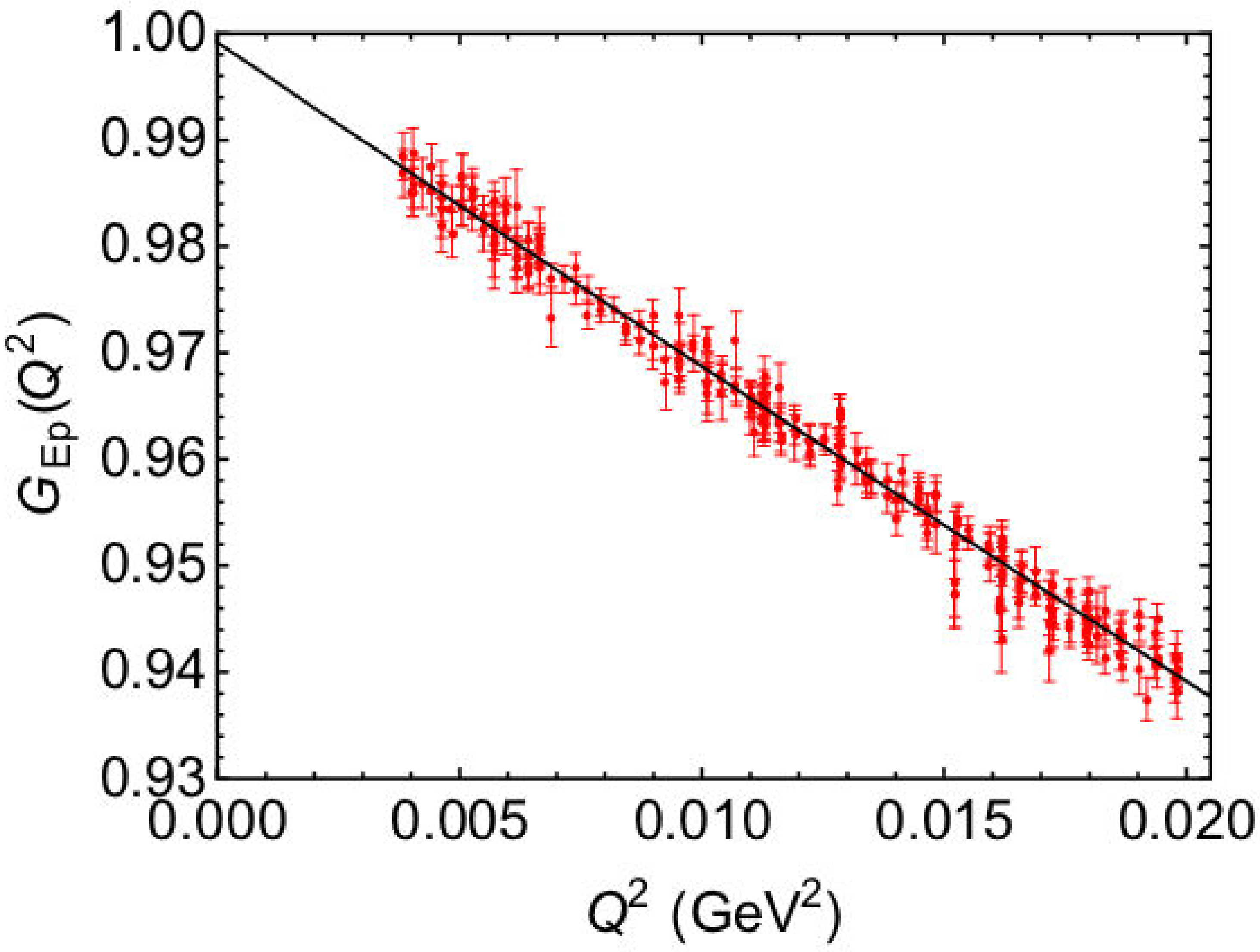




AGREEMENT OF TWO METHODS
Subtraction term=-0.004 (1) meV
Discrepancy=0.3 meV

How reliable is e-p scattering?

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



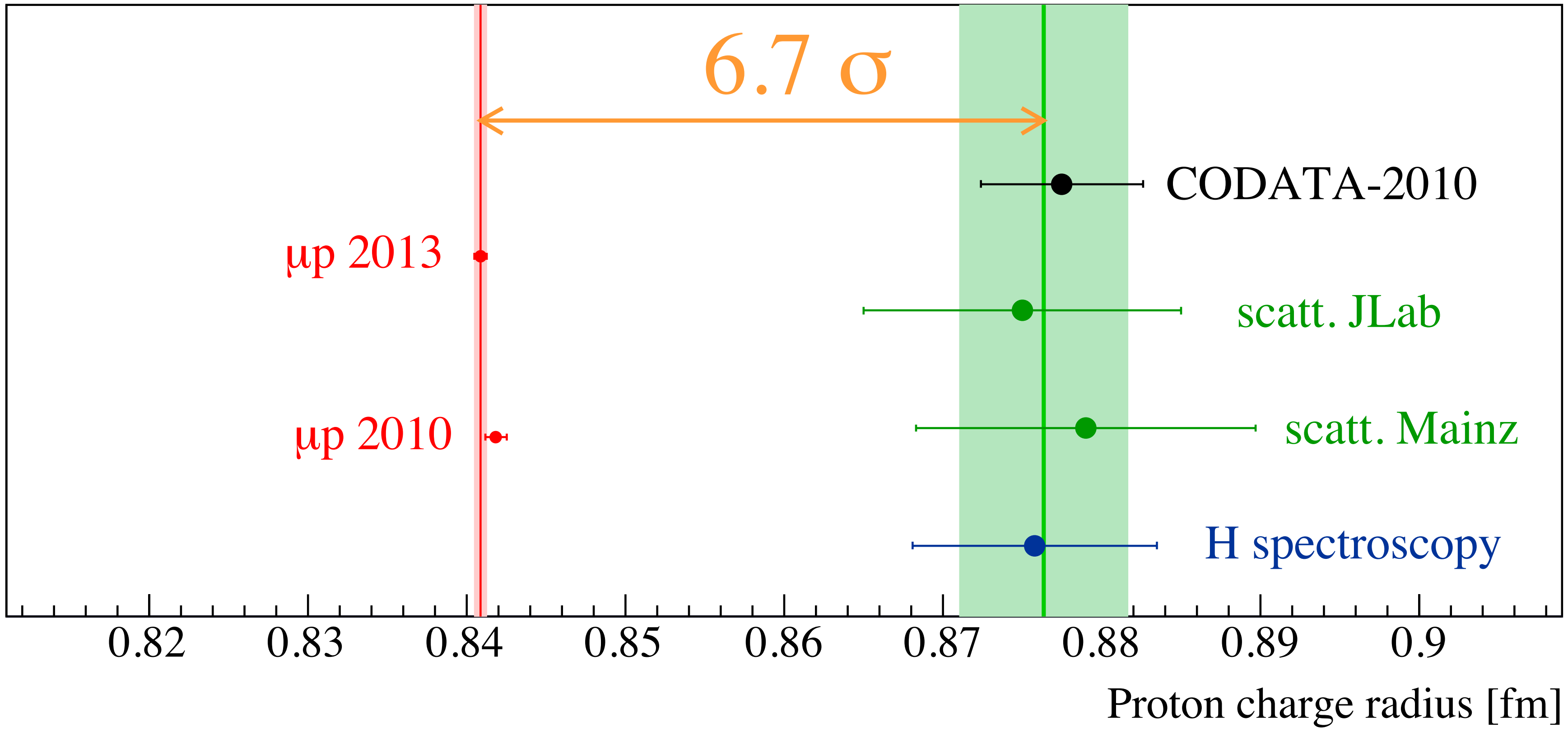
$$\langle r_{\text{p}}^2\rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

Extrapolation:

- which function?
- physical model?
- constraining large-r?
- which Q^2 range?
- sensitivity?

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

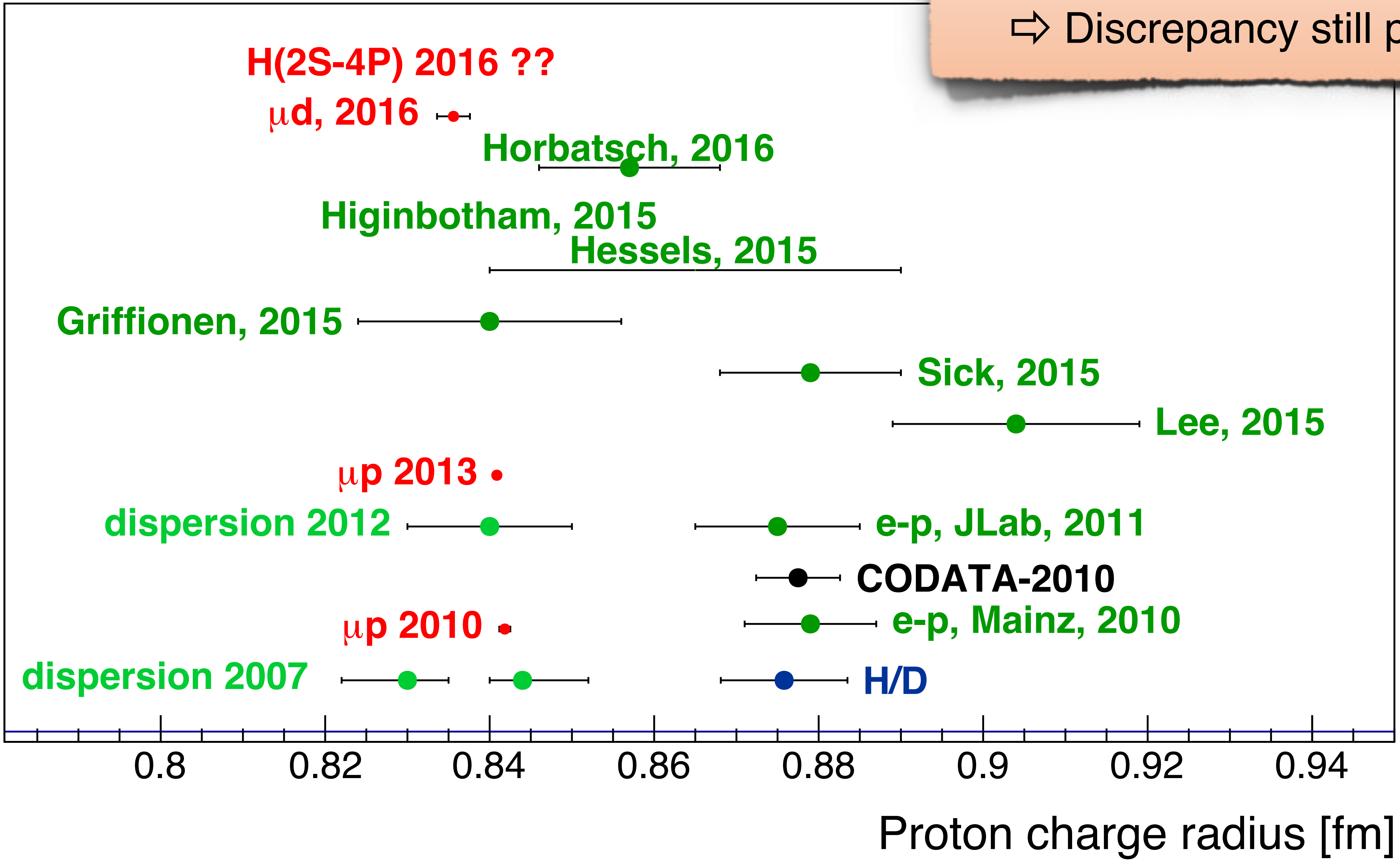
The proton charge radii



The proton charge radii

Bernauer, Distler, arXiv:1606.02159
Sick, Trautmann, arXiv:1701.01809
Horbatsch, Hessels, Pineda, arXiv:1610.09760
Lee, Arrington, Hill, arXiv:1505.01489

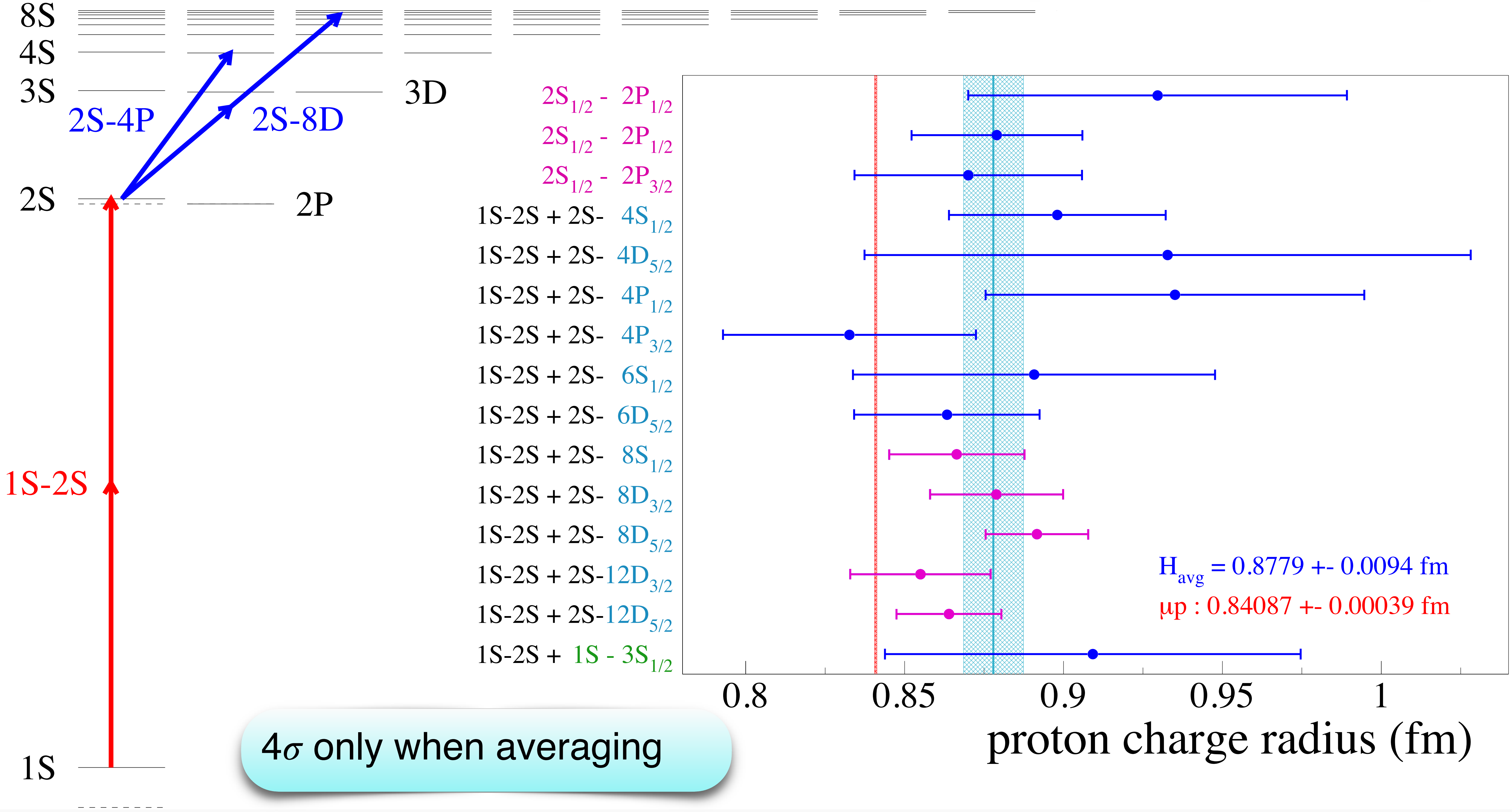
Various e-p scattering analysis in agreement with muonic results **BUT** these analysis are opposed by the experts of the field.
⇨ Discrepancy still persists



How accurate is hydrogen spectroscopy?

$$L^{\mathrm{th}}_{1S}(r_{\mathrm{p}}) = 8171.636(4) + 1.5645\, r_{\mathrm{p}}^2 \quad \mathrm{MHz}$$

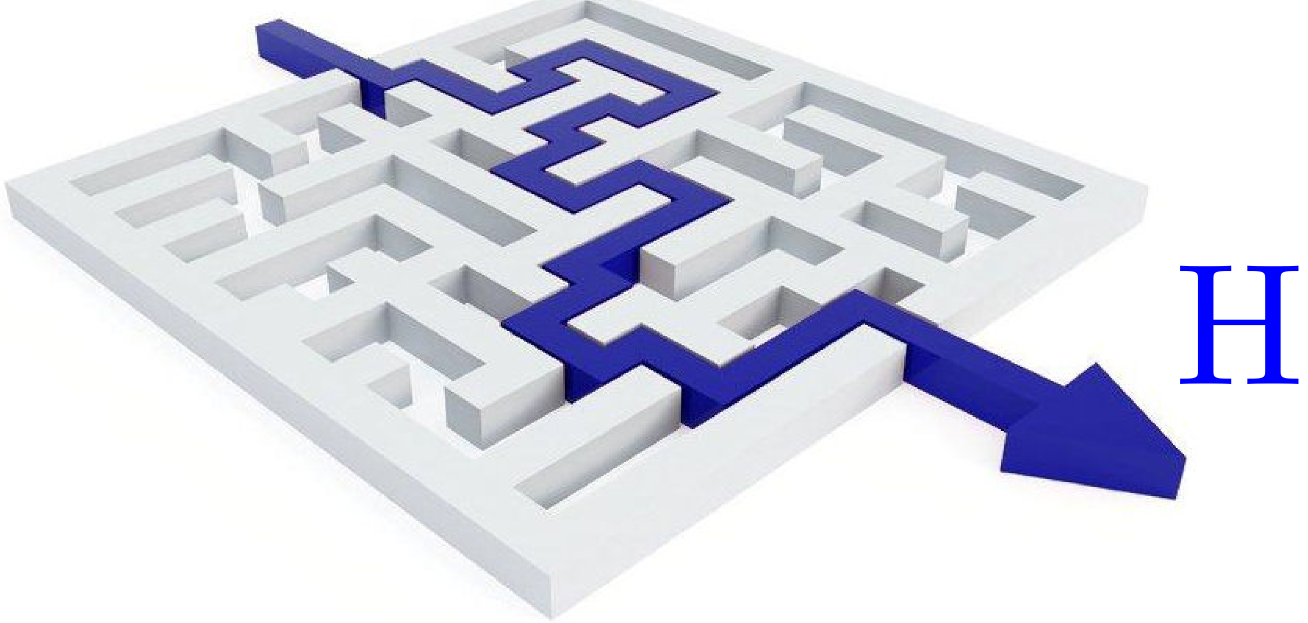
$$E_{nS} \simeq \frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$



4σ only when averaging

How accurate is hydrogen spectroscopy?

Beyer, Ann. d. Phys. 525, 671 (2013)



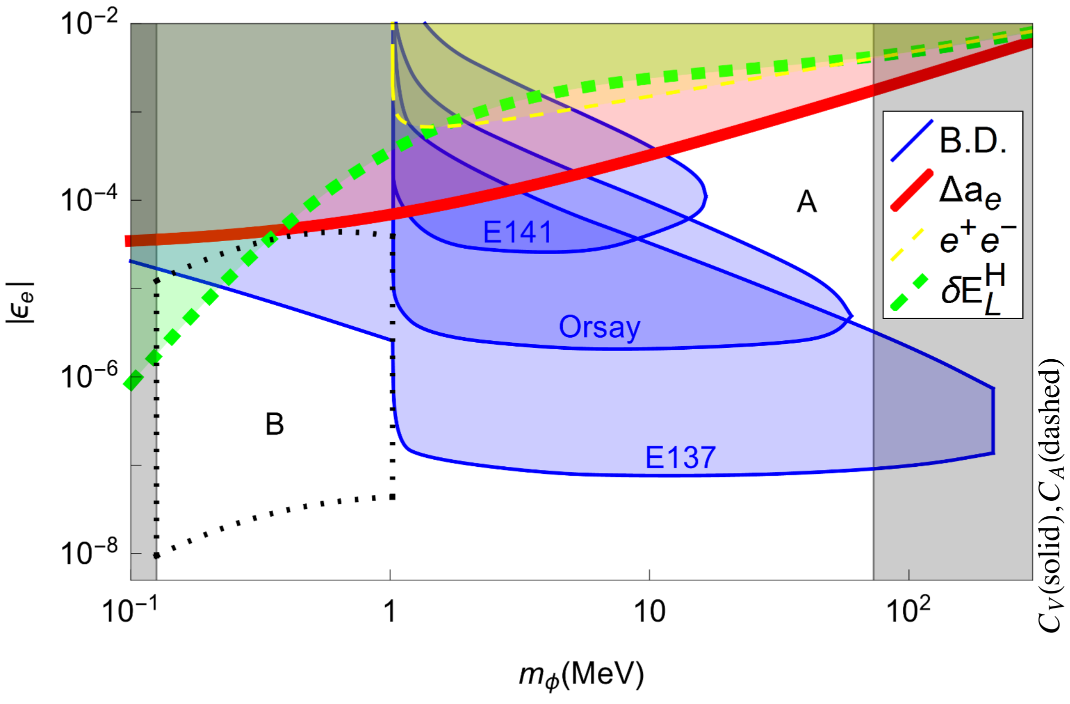
Large sensitivity to R_p
⇨ circumvent high-precision issues
But difficult to see the signal

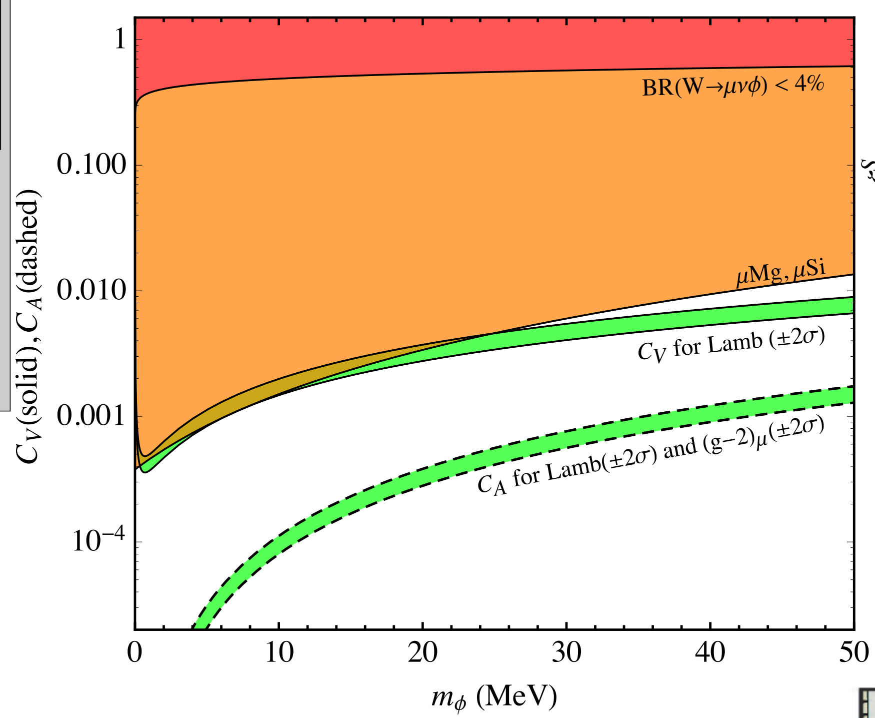
Low sensitivity to R_p
⇨ high-precision frontier
⇨ fight with systematics
But “easy” to see the signal

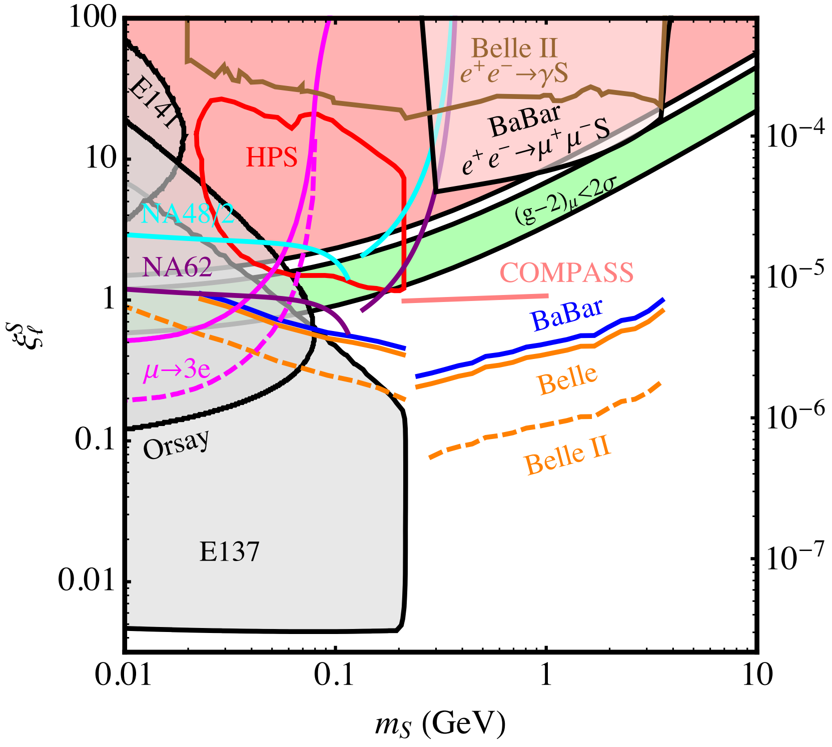
Explain the discrepancy by shifting the			
μp (2S-2P)	$100\,\sigma$	75 GHz	$4\,\Gamma$
H (1S-2S)	4’000 σ	40 kHz	$40\,\Gamma$
H (2S-4P)	$< 1.5\,\sigma$	9 kHz	$7 \cdot 10^{-4}\,\Gamma$
H (2S-2P)	$< 1.5\,\sigma$	5 kHz	$7 \cdot 10^{-4}\,\Gamma$

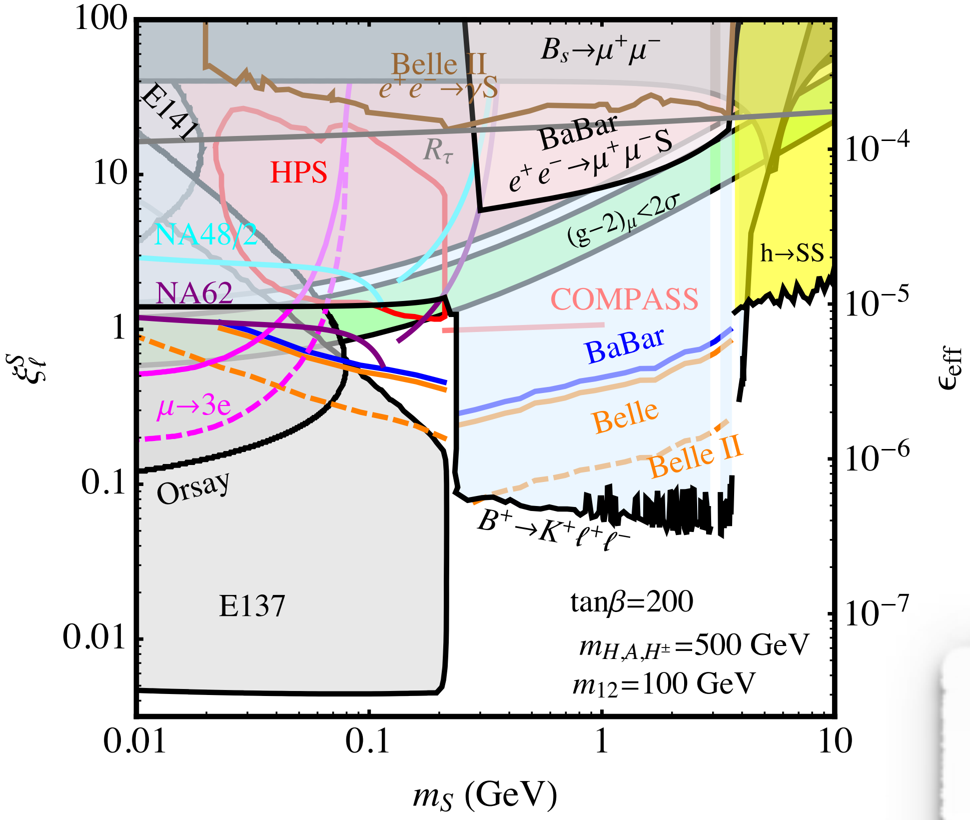
σ : exp accuracy
Γ : line width

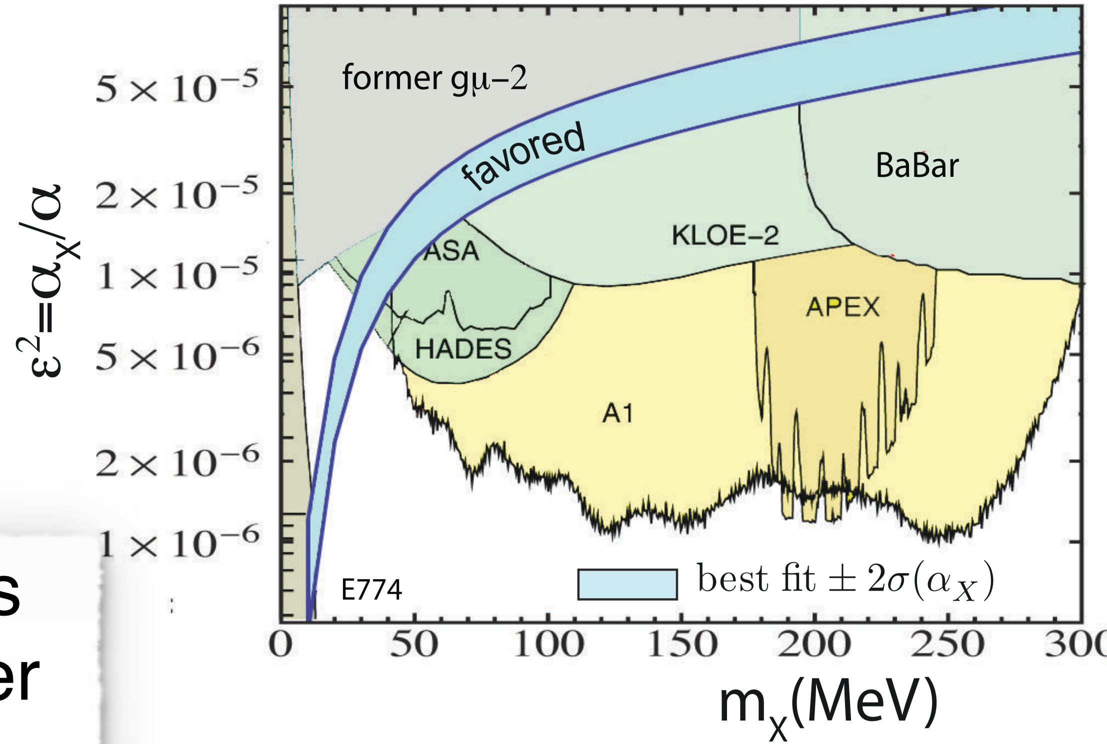
Is there room for BSM physics?











Some open regions for MeV force carrier still resist

Is there room for BSM or unconventional physics?

- Breakdown of Lorentz invariance? Gomes, Kostelecky, & Vargas (2014)
- Unanticipated QCD corrections? G. Miller, (2013)
- Breakdown of Lamb shift expansion due to non-smooth form factor Pascalutsa (2015)
- Light sea fermions in e-p and μ-p interactions. Jentschura, G. Miller
- Beyond perturbative QED: strong field physics. Pachucki, Jentschura (2014)
- Higher-dimensional gravity(?) Dahia & Lemos (2015)
- Renormalization group effects for effective particles. Glazek (2014)
- Point-particle effective theories, Burgess, Haymann, Rummel, Zalavari (2017)
- BSM coupling to muons and protons. Small or no coupling to other particles.

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

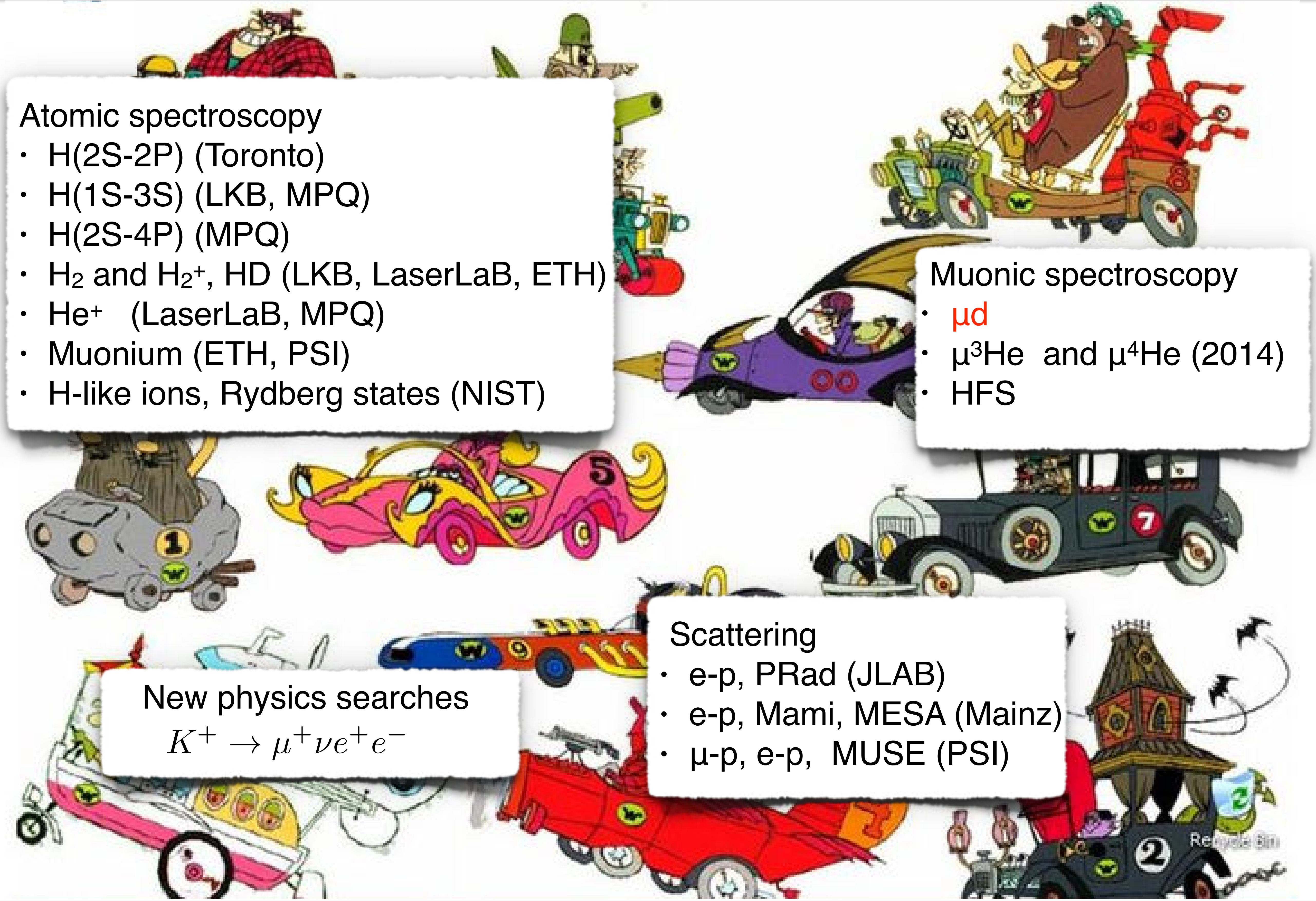
New point-particle EFT
predicts R(μp) < R(H), R(scatt.)
arXiv:1612.07334, arXiv:1612.07313

BSM pessimistic:
Barger, Chiang, Keung, Marfatia (2011, 2012), Karshenboim, McKeen, Pospelov (2014)

BSM optimistic:
Tucker-Smith & Yavin (2011), Batell, McKeen & Pospelov (2011), Brax & Burrage (2011)
Rislow & Carlson (2012, 2014), Marfatia & Keung (2015), Pauk& Vanderhaeghen (2015)
Martens & Ralston (2016), Liu, McKeen & Miller (2016), Batell et. al (2016)

The race to the proton radius solution

The race to the proton radius solution



Atomic spectroscopy

- H(2S-2P) (Toronto)
- H(1S-3S) (LKB, MPQ)
- H(2S-4P) (MPQ)
- H_2 and H_2^+, HD (LKB, LaserLaB, ETH)
- He^+ (LaserLaB, MPQ)
- Muonium (ETH, PSI)
- H-like ions, Rydberg states (NIST)

Muonic spectroscopy

- μd
- μ^3He and μ^4He (2014)
- HFS

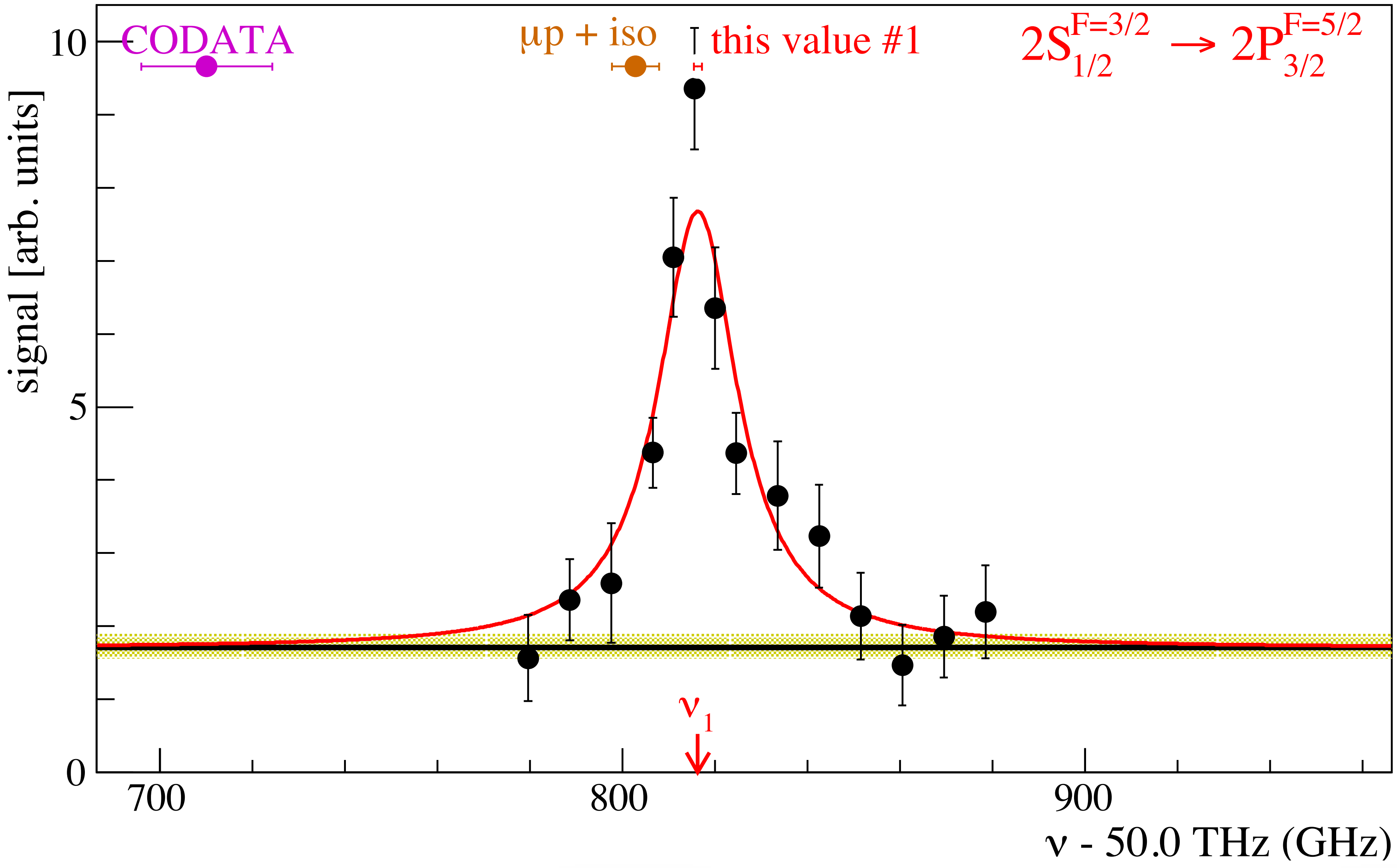
Scattering

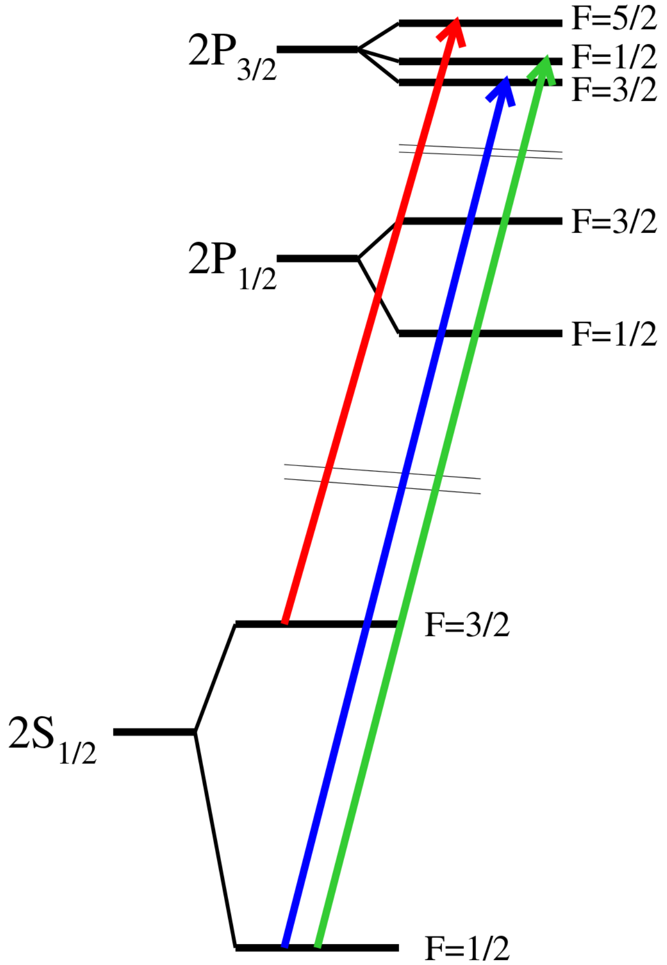
- e-p, PRad (JLAB)
- e-p, Mami, MESA (Mainz)
- μ-p, e-p, MUSE (PSI)

New physics searches

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

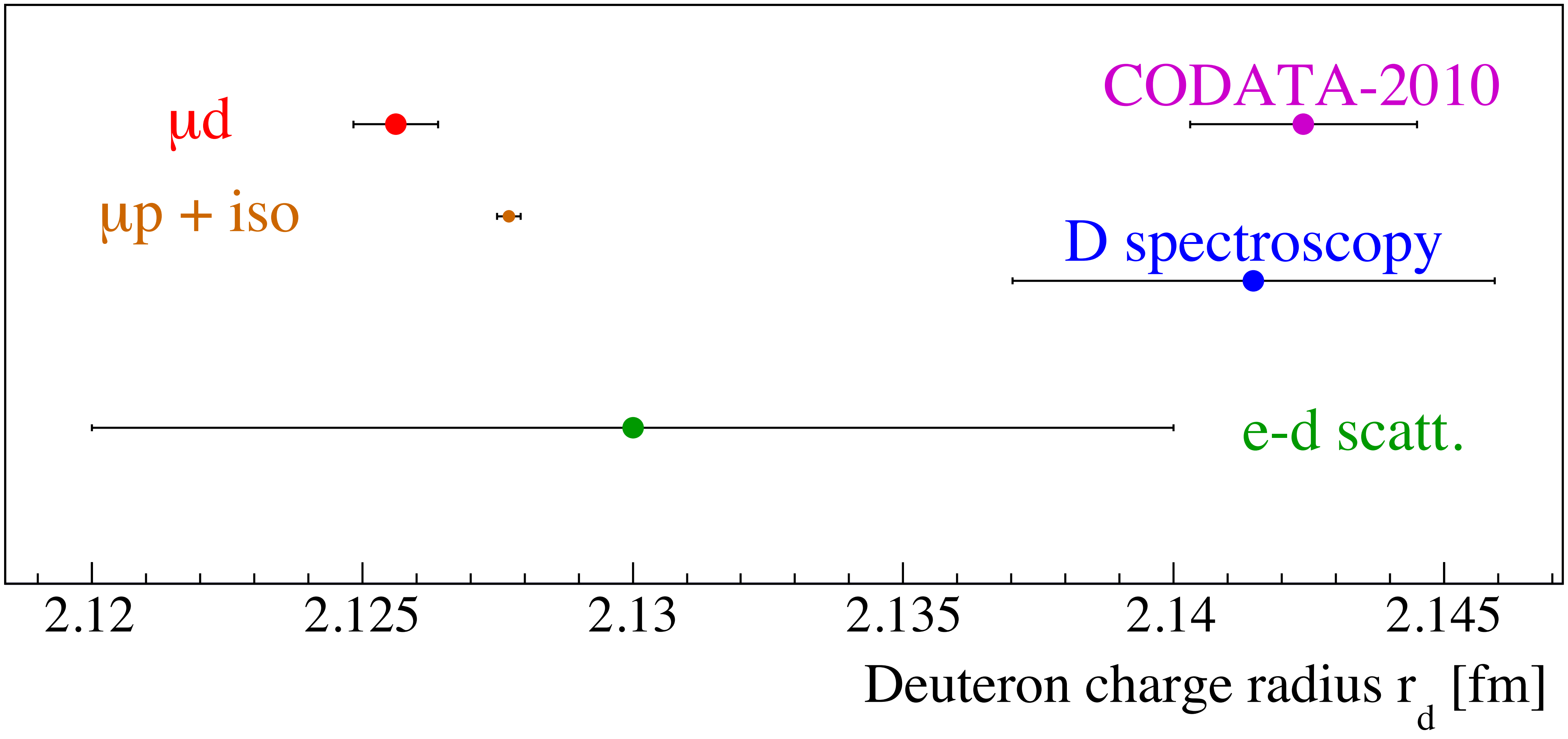
2S-2P spectroscopy of muonic deuterium (μd)





	μp [meV]	μd [meV]	
QED	206	229	$\times 1.1$
$k\langle r^2\rangle$	4	28	$\times 7$
TPE	0.03	1.7	$\times 56$

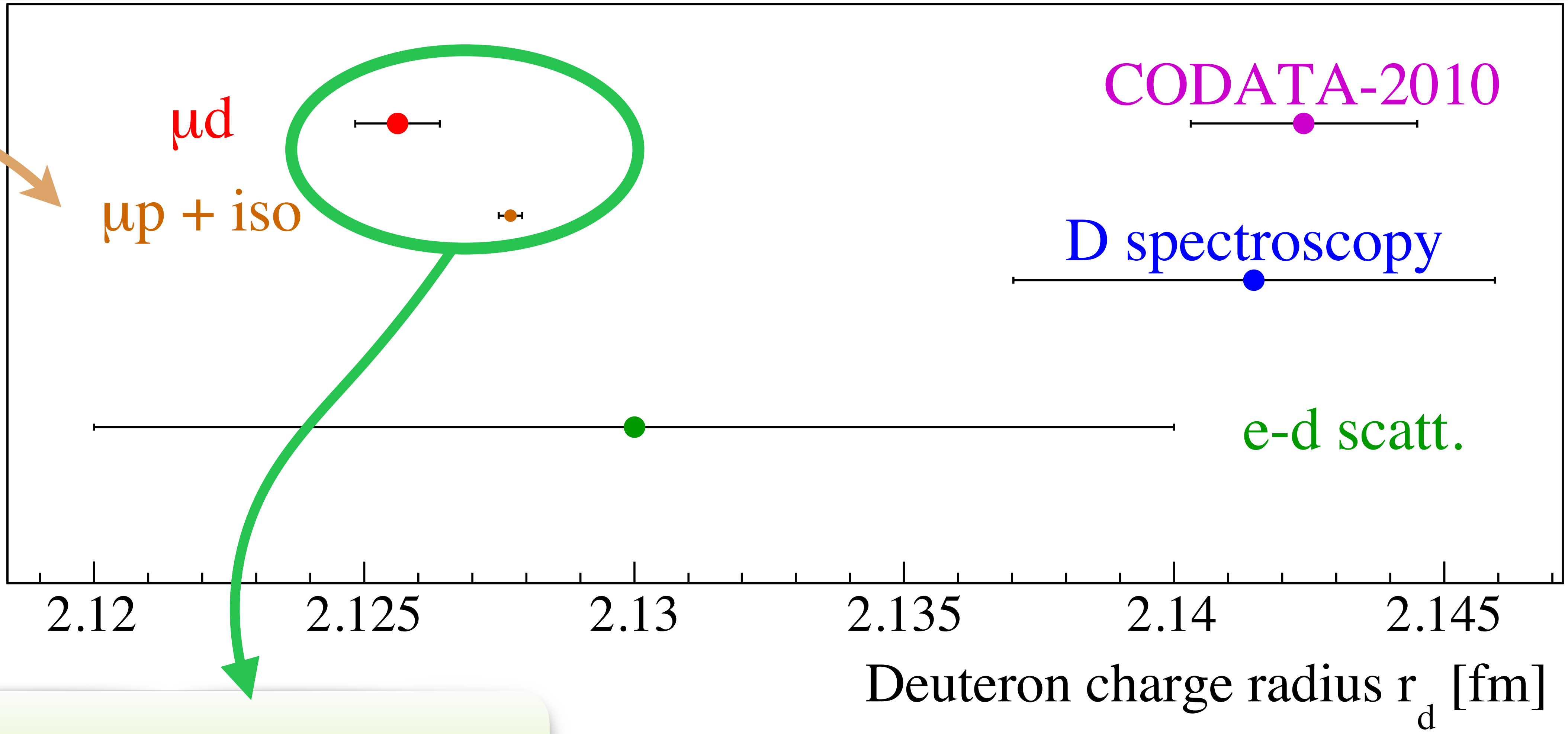
2S-2P spectroscopy of muonic deuterium (μd)



Pohl et al., Science 353, 669 (2016)
Krauth et al., Ann. Phys. 336 168 (2016)
Hernandez et. al., PLB 736, 344 (2014)
Pachucki et al., PRA 91, 040503(R) (2015)

2S-2P spectroscopy of muonic deuterium (μd)

$$\left.\begin{array}{lll} \text{H/D shift:} & r_\mathrm{d}^2 - r_\mathrm{p}^2 & = 3.820\,07(65)\ \mathrm{fm}^2 \\ \mu p: & r_\mathrm{p} & = 0.84087(39)\ \mathrm{fm} \end{array}\right\} \Rightarrow \quad r_\mathrm{d} = 2.12771(22)\ \mathrm{fm}$$



Consistency of muonic results with 1S-2S H/D isotopic-shift

The 2.5σ difference:

- from nuclear polarizabilty?
- BSM physics NOT coupling to n (reduced mass effect)?

Pachucki, Bacca, Barnea, Gorchtein, Carlson….

2S-2P spectroscopy of muonic deuterium (μd)

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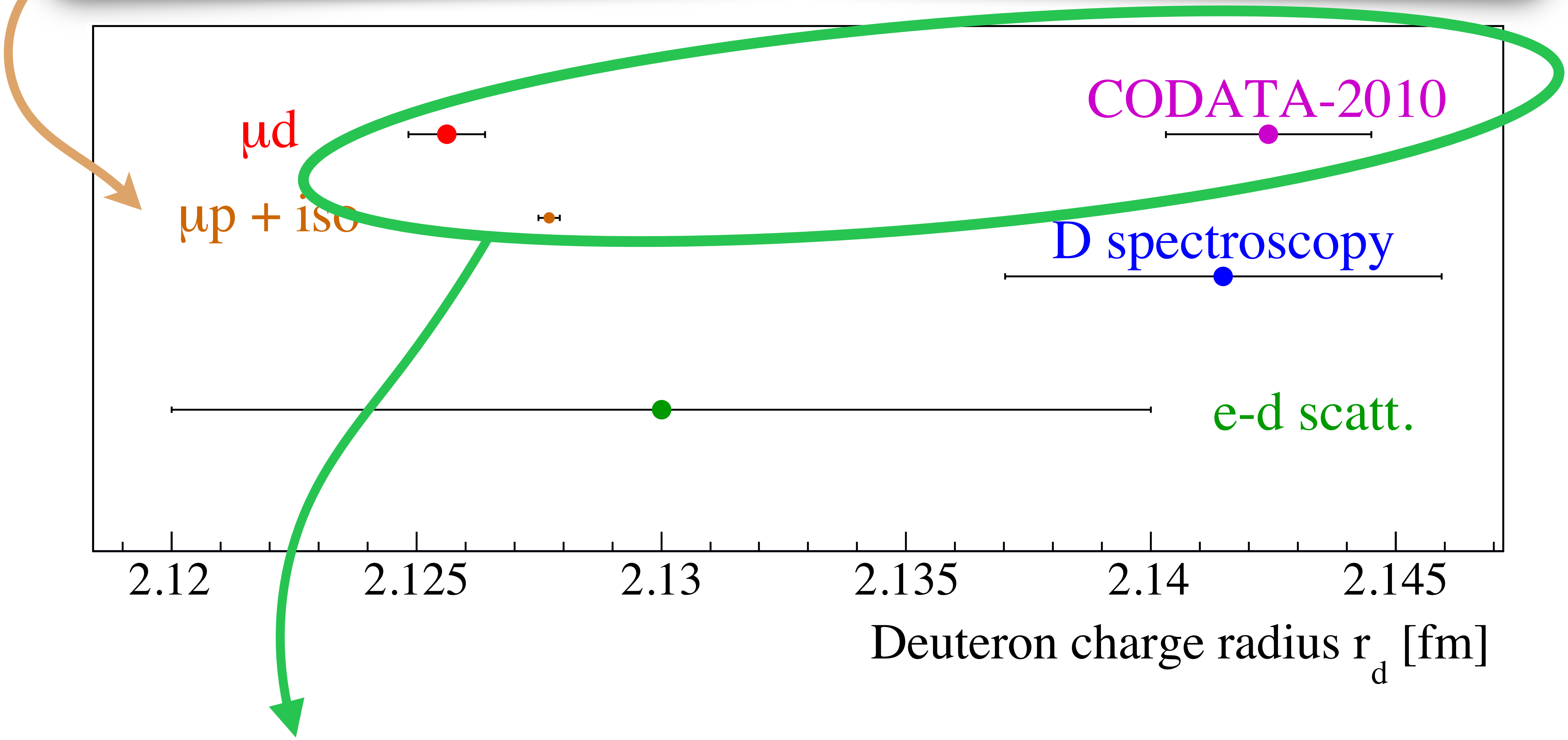

7σ from CODATA

BUT CODATA
contains proton-data

2S-2P spectroscopy of muonic deuterium (μd)

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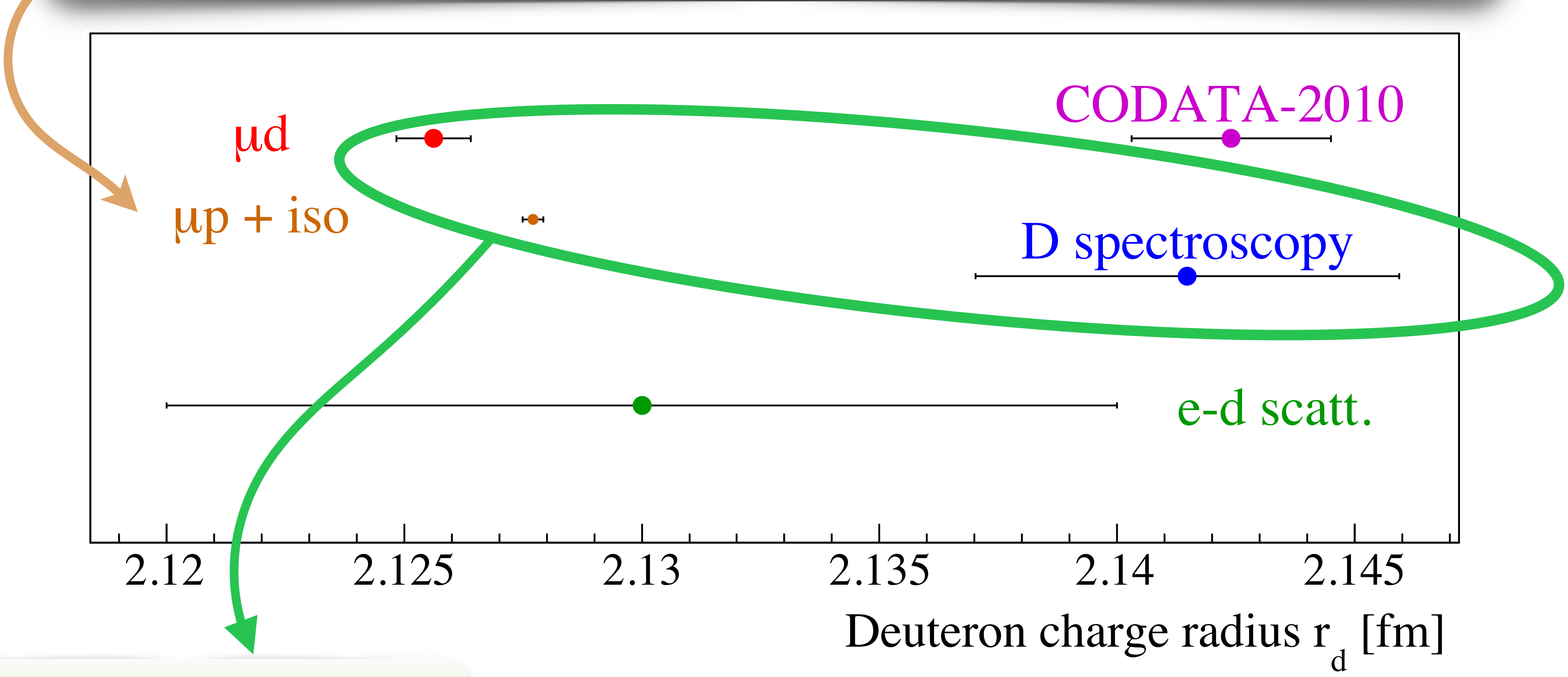


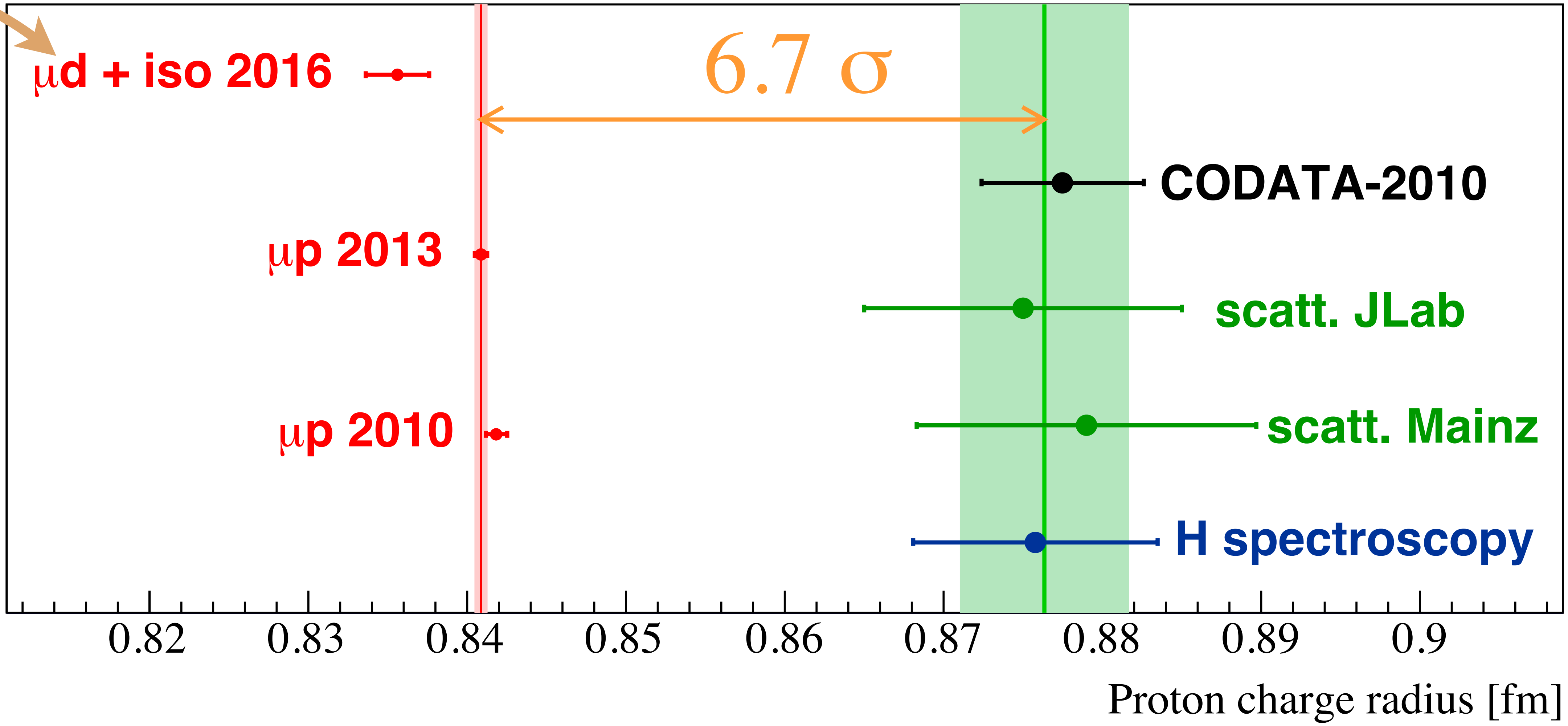
3.5σ from ONLY D-data

⇨ double discrepancy
- proton sector
- deuteron sector

⇨ Problem with H/D exp (R_∞)?
⇨ Problem with H/D th.?
⇨ BSM with no coupling to n?

The proton charge radius from muonic deuterium

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



Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
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Small value of the proton radius is confirmed from *µd*

Radii, polarisability contributions and R_∞

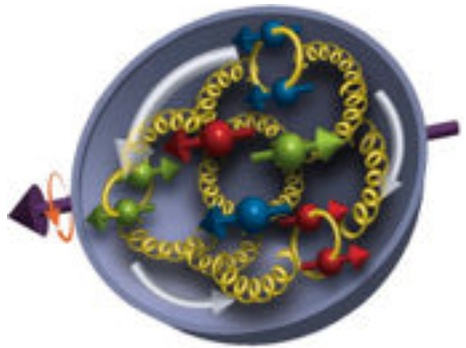
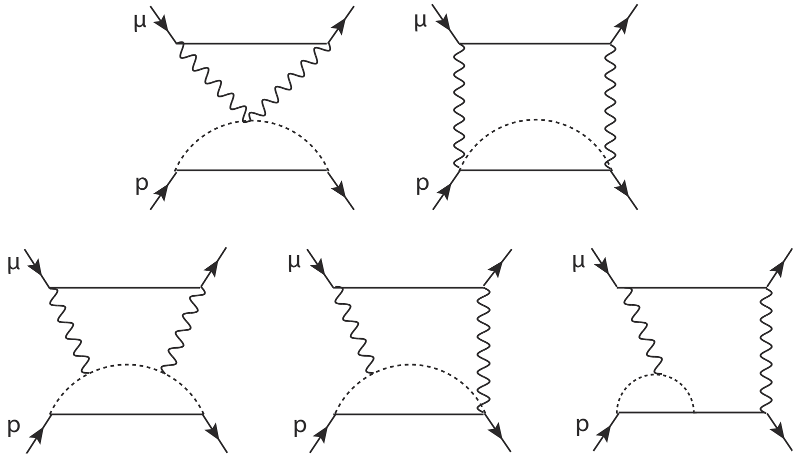


Image: PHENIX coll.

Chiral PT



Lattice

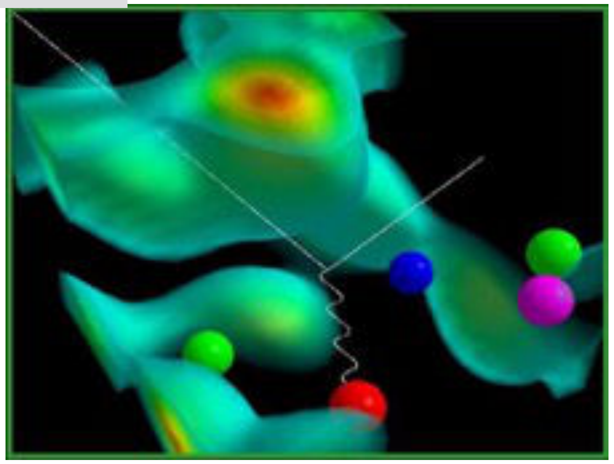
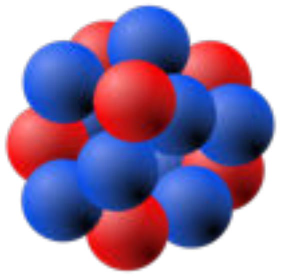
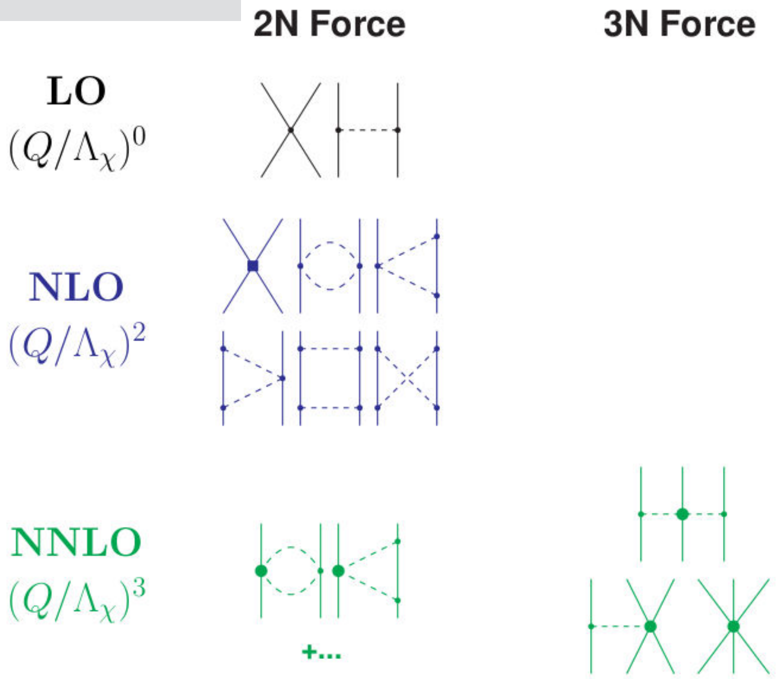


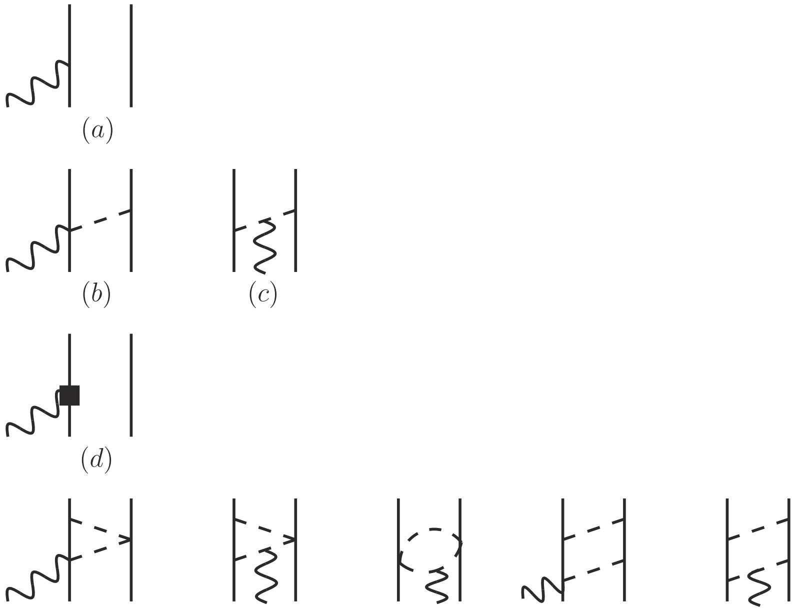
Image: university of Adelaide

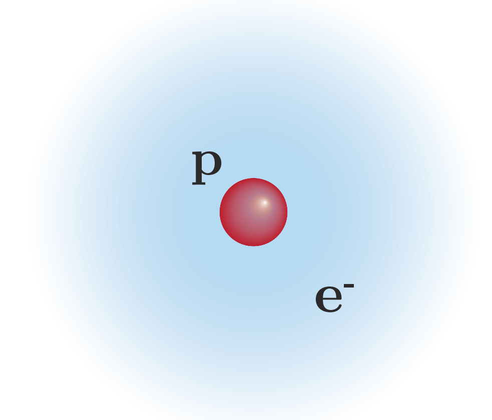


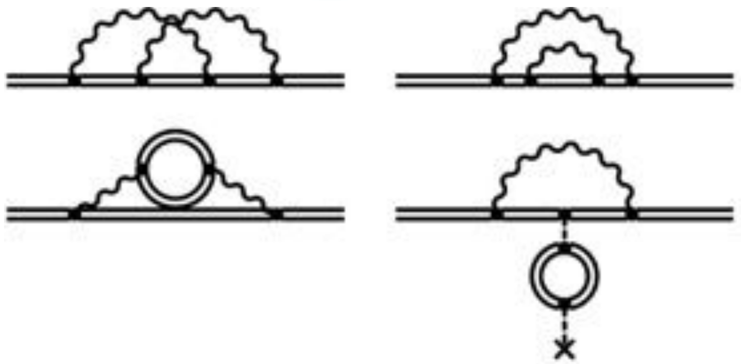
Potential



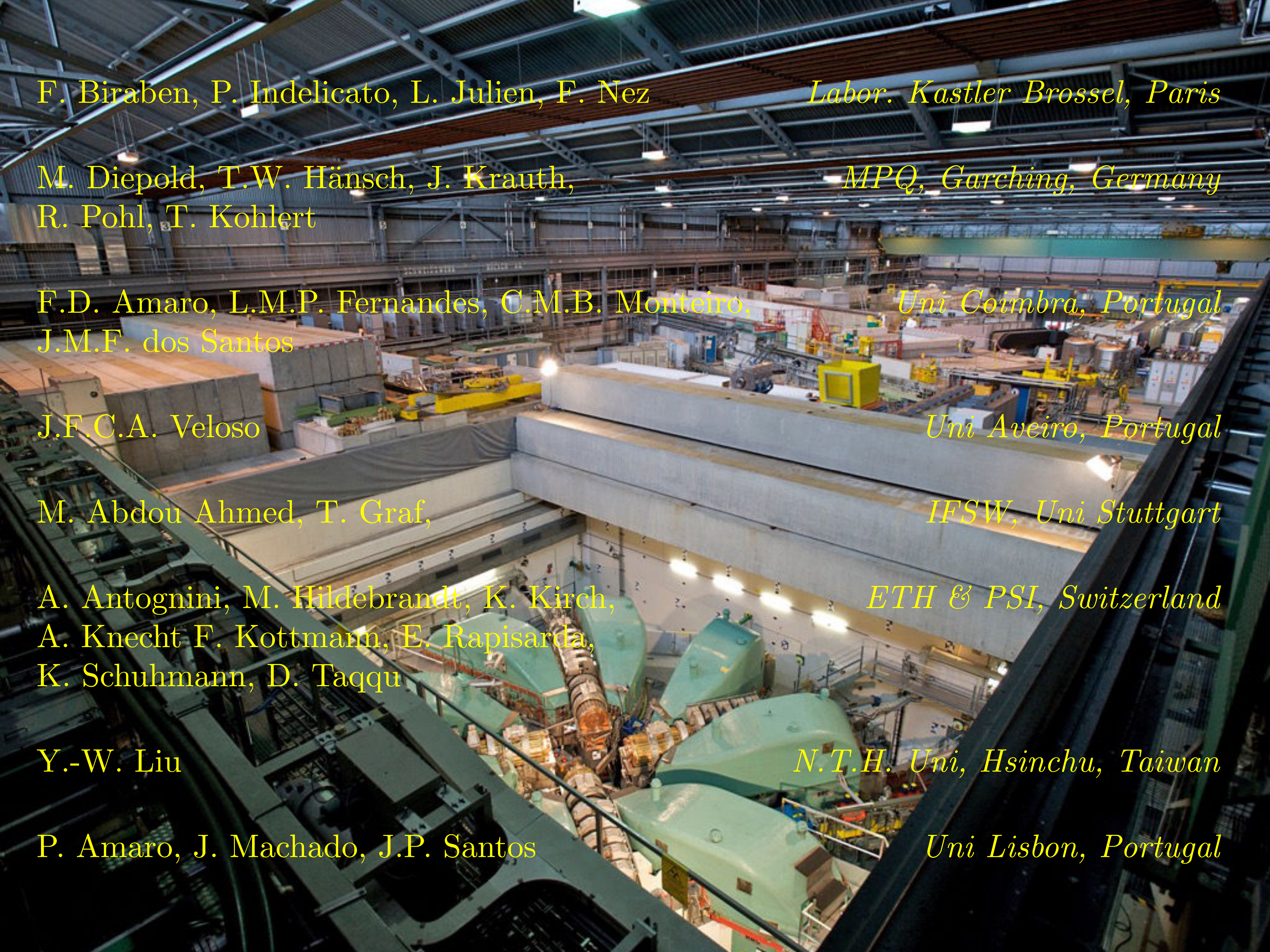
Currents







- Chiral pert. th.
- Lattice
- Dispersion relations
- Few-nucleon th.
- Bound-state QED
- Structure functions
- Spin structure
- Currents
- VMD.....



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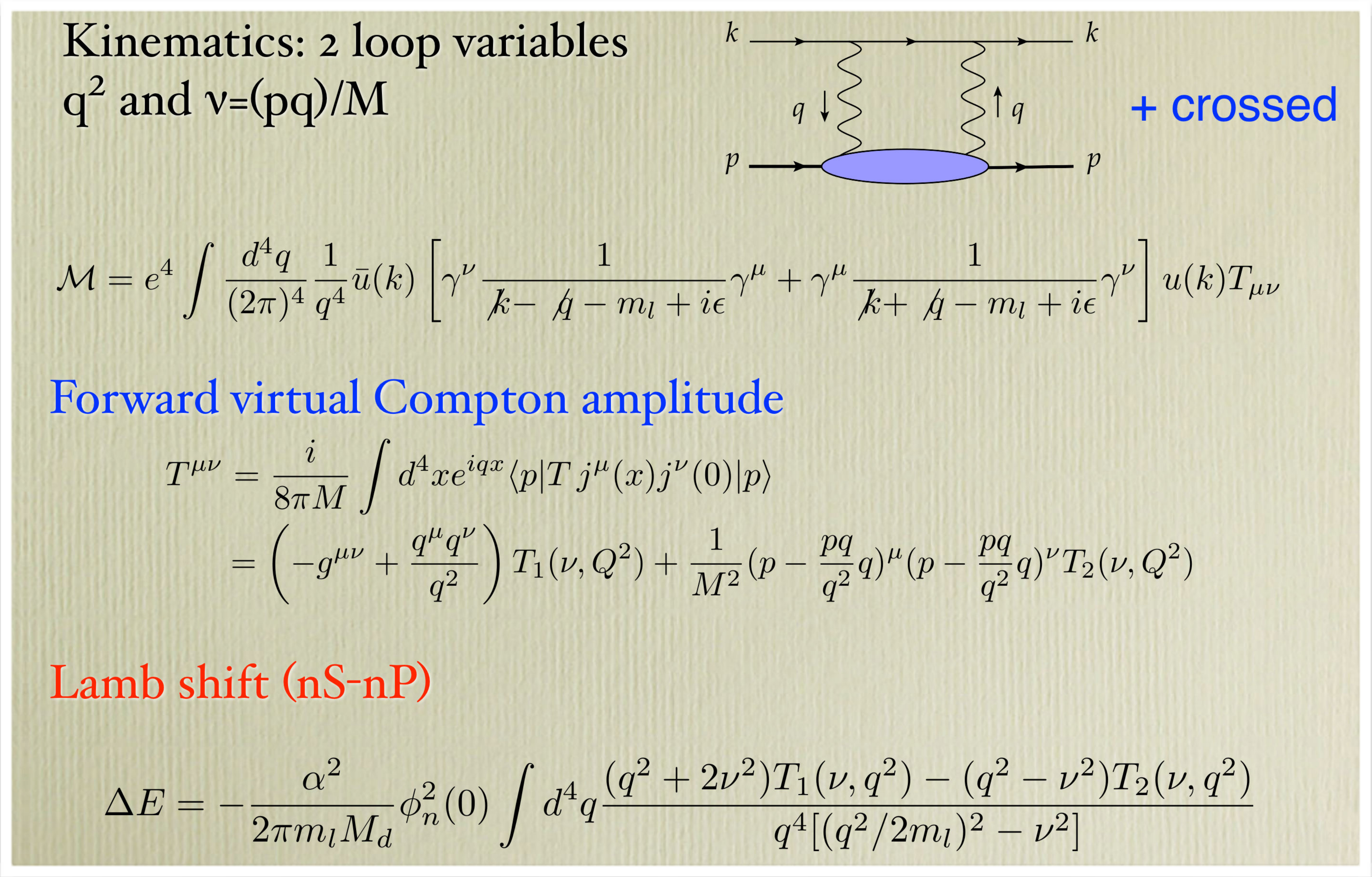
Technicalities on 2γ exchange in μp



Kinematics: 2 loop variables
q^2 and ν=(pq)/M

+ crossed

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

Forward virtual Compton amplitude

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

Lamb shift (nS-nP)

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

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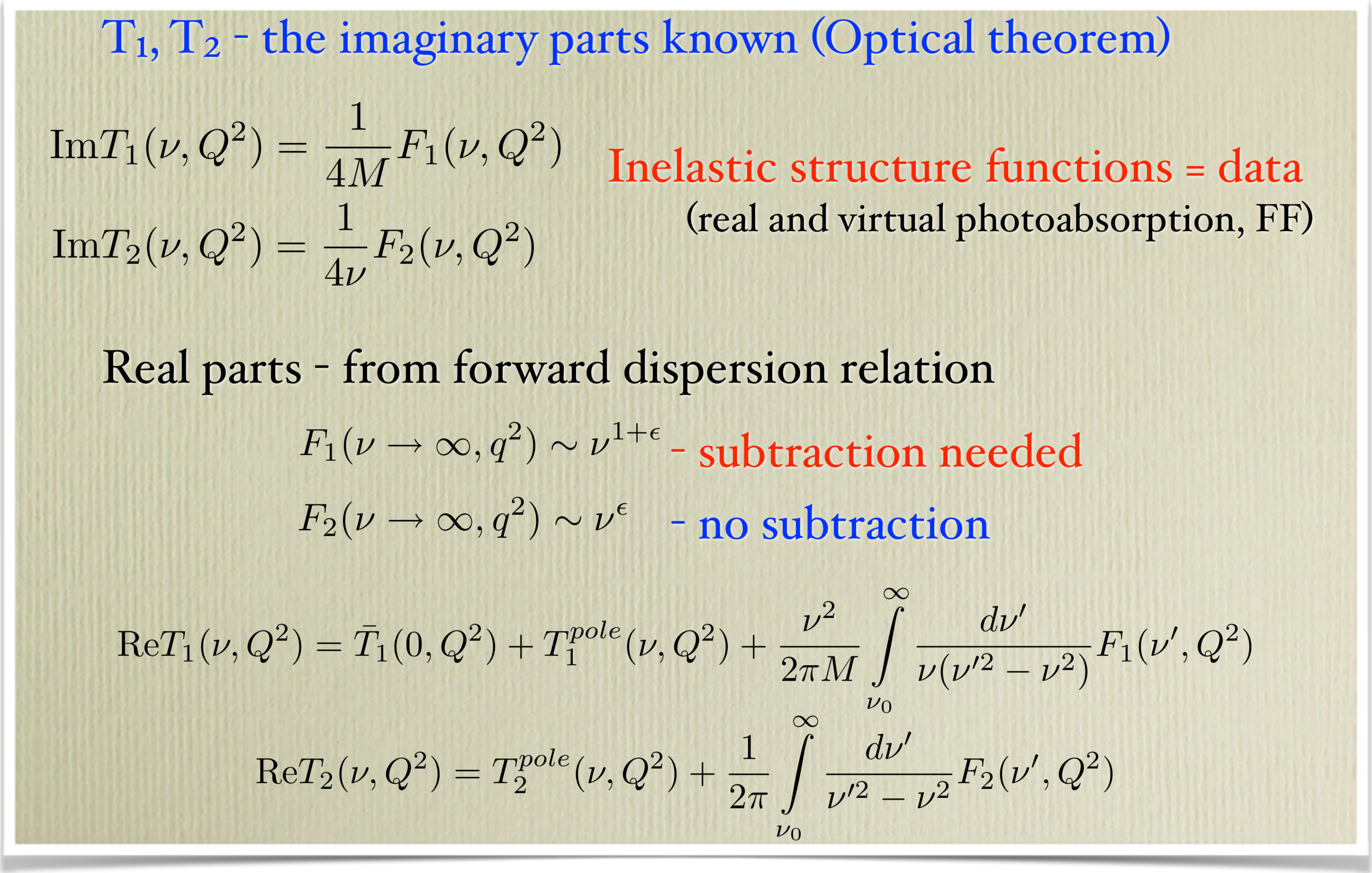
Technicalities on 2γ exchange in µp



T₁, T₂ - 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

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

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

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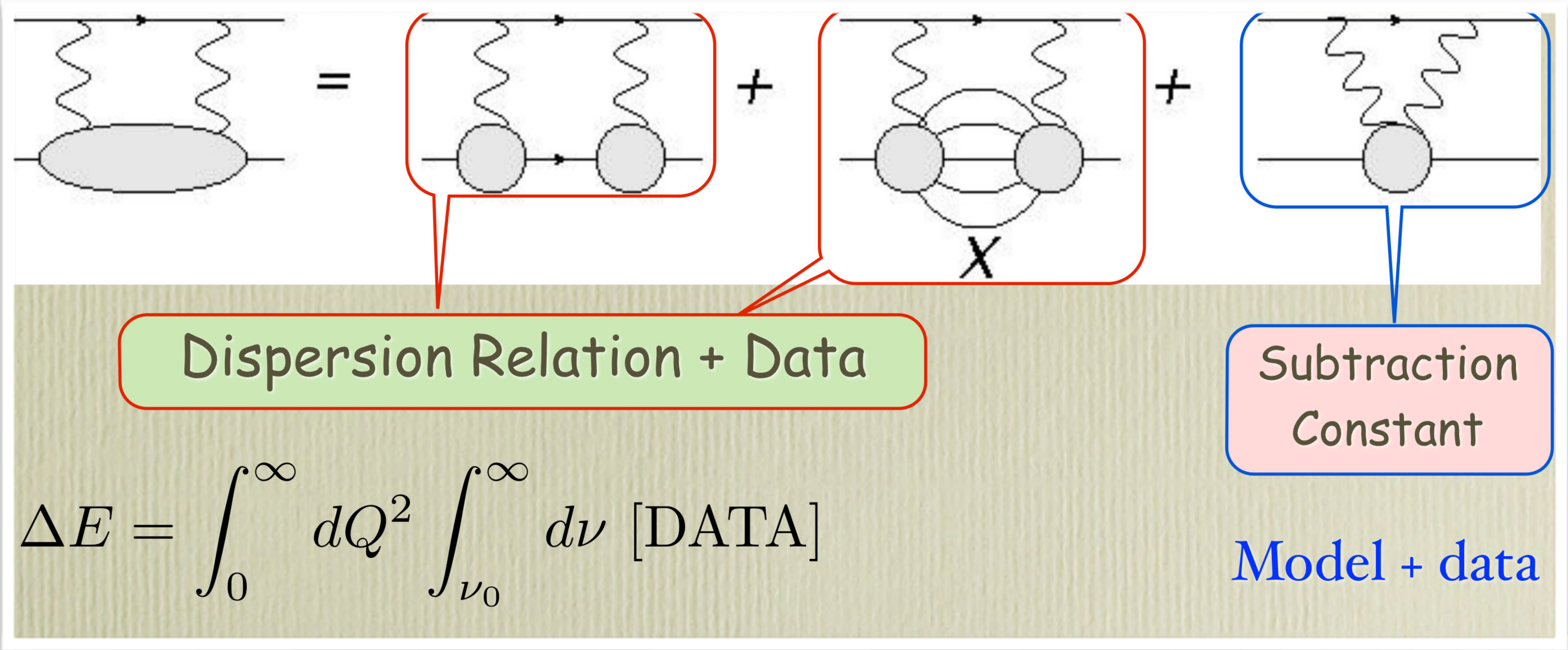
Technicalities on 2γ exchange in μp



$$\Delta E = \int_0^\infty dQ^2 \int_{\nu_0}^\infty d\nu \;[\mathrm{DATA}]$$

Unknown:	Larger than assumed	Hill *and* Paz, PRL 107, 160402 (2011), G. Miller
Under control:	Pion Loops	Vanderhaegen *et al*, PRA 84, 020102 (2011)
Under control:	HBChPT + Dipole	McGovern & Birse, EPJA 48 120 (2012)
Under control:	Finite energy sum rule	Gorchtein *et al*, PRA 84, 052501 (2013)
Under control:	BChPT	Alarćon *et al*, arXiv 1312.1219
Under control:	HBChPT	Peset & Pineda, ArXiv1403.3408 (2014)