Test 1

Test 1

- Test 2

Test 1

- Test 2

Test III

Test 1

- Test 2

Test III

...

Test 1

- Test 2

Test III

...   ...

Test I

- Test 2

Test III

... ...

I know that I am speaking for all of Matey's colleagues at CERN in saying that we will miss him. Particle physics has lost not only an excellent physicist, but also a true gentleman. We shall always remember Matey as a friendly and co-operative colleague with a warm personality, whose loss is felt very deeply by the Bulgarian community and all colleagues at CERN.

Mateev was a key figure in Bulgaria's scientific policy. He was named Minister of Education in 1991 and developed the <National Education Act >, adopted by the National Assembly that very year. He championed the establishment of the National Foundation for Fundamental Research and was elected to the Bulgarian Academy of Sciences in 2003. In 2009 he received the <Cyril and Methodius> medal, a very high Bulgarian distinction. None of these honours changed Mag's modest and friendly ways.

Matey was the key promoter of Bulgaria's membership of CERN, and his country's representative to the CERN Council from 1999 to 2000. Bulgaria's active participation in CERN was among Mateev's greatest services to science.

Matey was a long-standing and faithful friend of CERN. We shall deeply miss him.

Rolf Heuer

Wednesday, 13 April, 2011

Lamb shift in muonic hydrogen

Bound-state QED

&

proton radius

puzzle

A. Antognini

MPQ, Garching, Germany

ETH, Zurich, Switzerland

Lamb shift in muonic hydrogen

Bound-state QED

&

proton radius

puzzle

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MPQ, Garching, Germany

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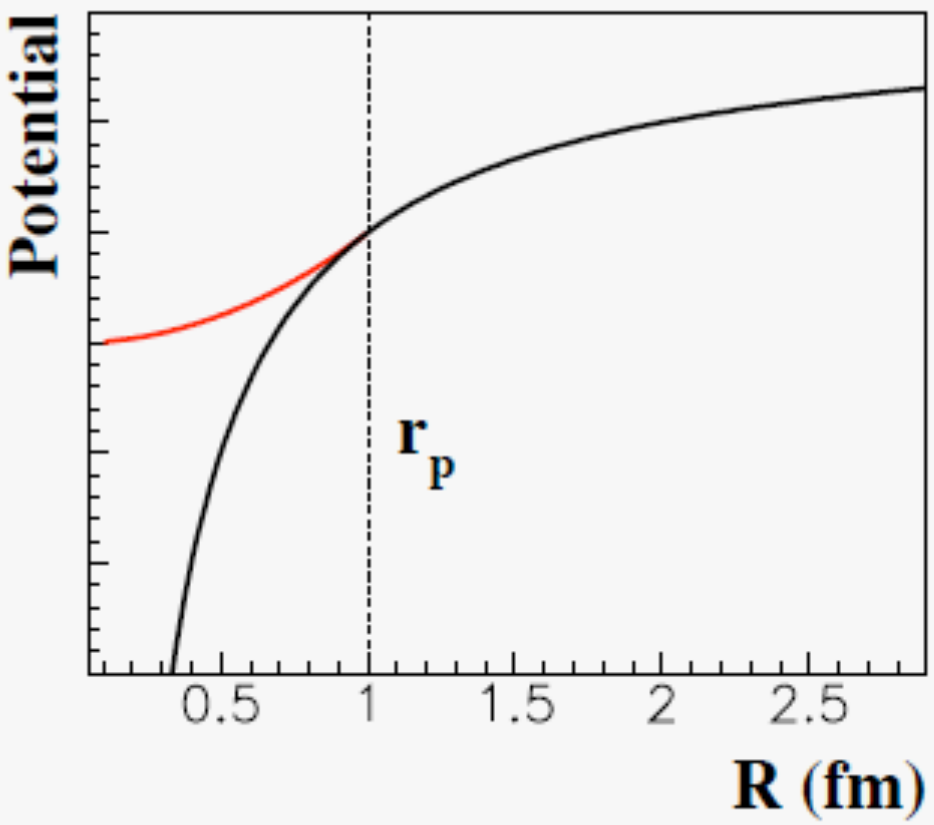
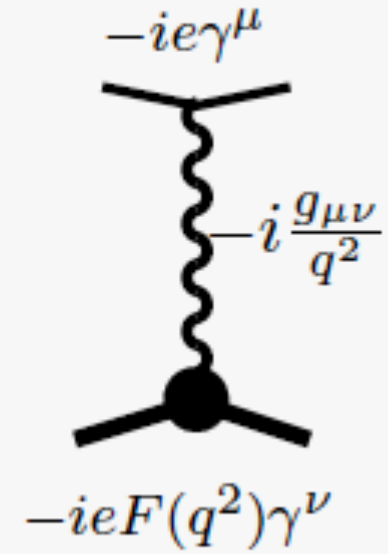
QED
is NOT
endangered
by the proton's
running radii

The leading proton finite size contribution





$$\frac{1}{q^2} \rightarrow \frac{F(q^2)}{q^2}$$

$$r_p^2 \equiv \int d^3r\, \rho(\mathbf{r}) r^2$$

$$F(\mathbf{q}^2) = \int d^3r\, \rho(\mathbf{r}) e^{-i\mathbf{q}\cdot\mathbf{r}} \simeq Z(1 - \frac{\mathbf{q}^2}{6} r_p^2 + \cdots)$$

Maxwell equation: $\nabla E = 4\pi\rho$

$$V = \begin{cases} -\frac{Z\alpha}{2r_p}\left(3 - (\frac{r}{r_p})^2\right) & (r < r_p) \\ -\frac{Z\alpha}{r} & (r > r_p) \end{cases}$$

$$m_r \equiv \frac{m_\ell m_p}{m_\ell + m_p}$$

$$\Delta V = \begin{cases} -\frac{Ze^2}{2r_p}\left(3 - (\frac{r}{r_p})^2 - \frac{2r_p}{r}\right) \\ 0 \end{cases}$$

$$\Delta E^{FS} = \langle \bar\Psi | \Delta V | \Psi \rangle$$

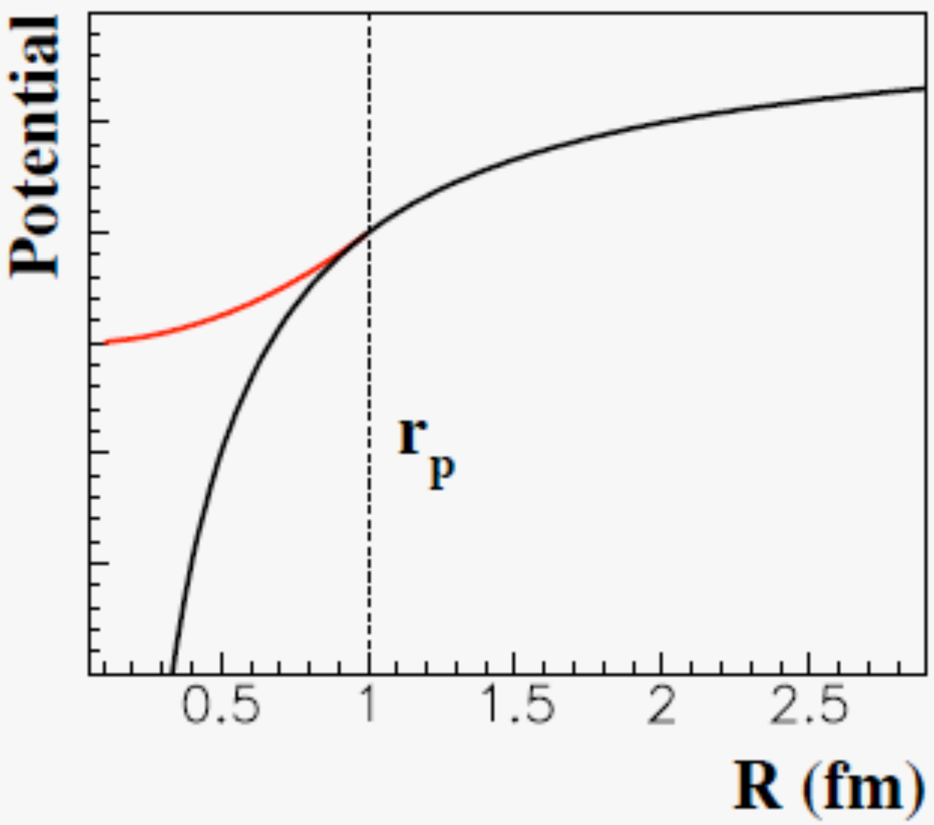
$$\Delta V(r) = V(r) - \left(-\frac{Z\alpha}{r}\right)$$

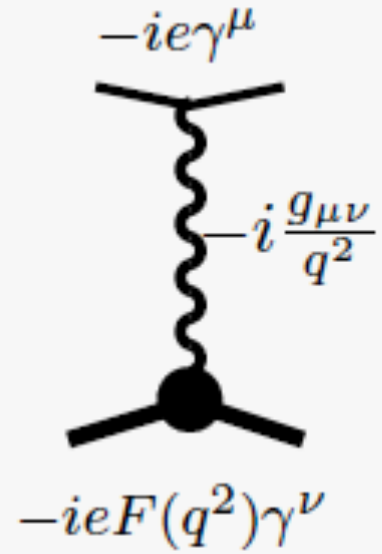
$$\Delta V(\mathbf{q}) = \frac{4\pi Z\alpha}{\mathbf{q}^2}(1 - F(\mathbf{q})) \simeq \frac{2\pi(Z\alpha)}{3} r_p^2$$

$$\Delta V(r) = \frac{2\pi(Z\alpha)}{3} r_p^2\, \delta(r)$$

$$\begin{aligned} \Delta E^{FS} &= \frac{2\pi(Z\alpha)}{3} r_p^2 |\Psi_n(0)|^2 \\ &= \frac{2(Z\alpha)^4}{3n^3} m_r^3 r_p^2 \delta_{l0} \end{aligned}$$

The leading proton finite size contribution





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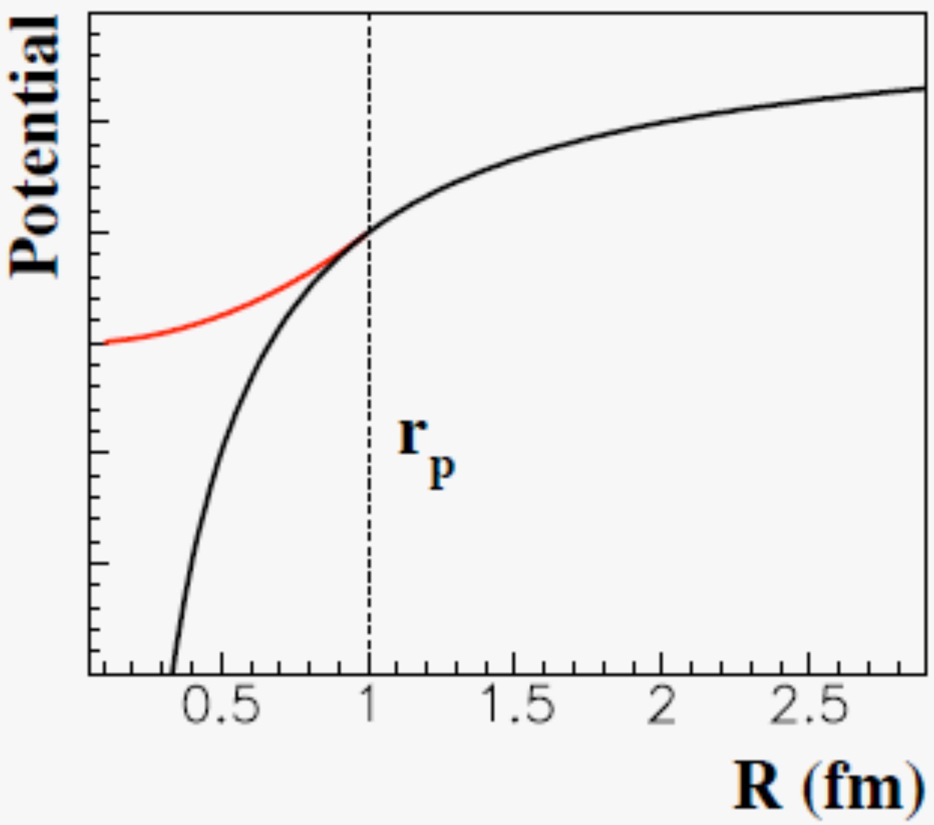

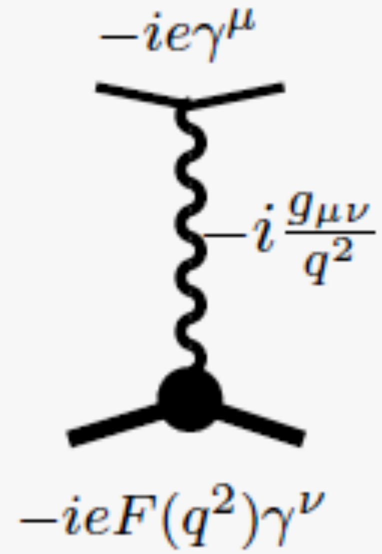

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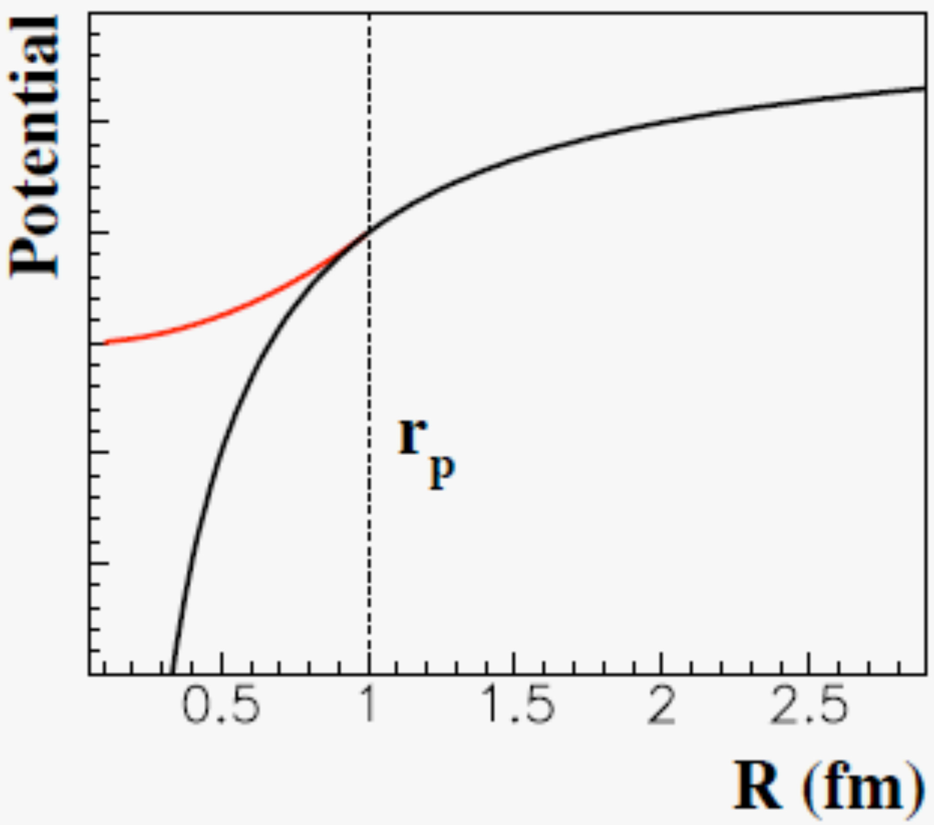

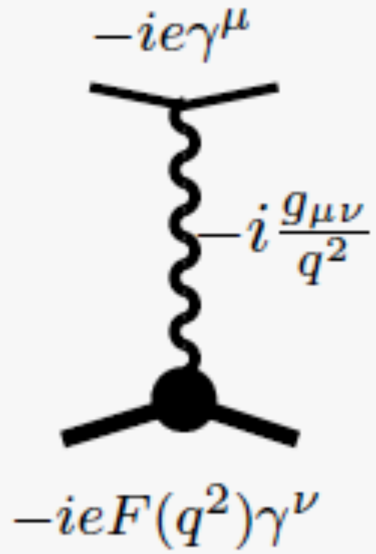

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$$\Delta V(r) = \frac{2\pi(Z\alpha)}{3}\, r_p^2\, \delta(r)$$ Not Quite Right

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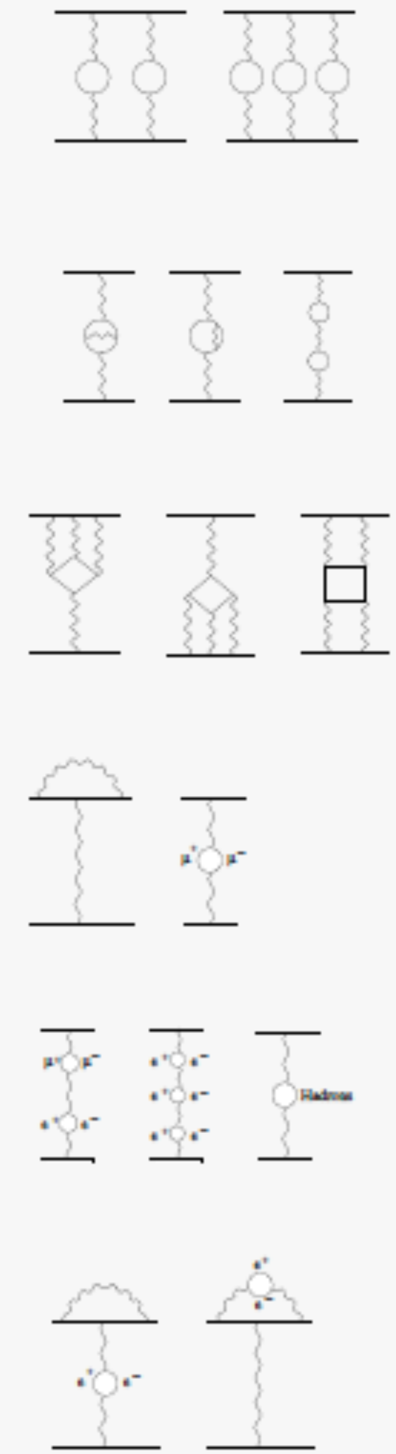
$$\frac{|\Psi_\mu(0)|^2}{|\Psi_e(0)|^2} = \left(\frac{m_\mu}{m_e}\right)^3$$

$$\approx 10^7$$

Contributions to the μp Lamb shift

#	Contribution	Value	Unc.
3	Relativistic one loop VP	205.0282	
4	NR two-loop electron VP	1.5081	
5	Polarization insertion in two Coulomb lines	0.1509	
6	NR three-loop electron VP	0.00529	
7	Polarisation insertion in two and three Coulomb lines (corrected)	0.00223	
8	Three-loop VP (total, uncorrected)		
9	Wichmann-Kroll	−0.00103	
10	Light by light electron loop ((Virtual Delbrück)	0.00135	0.00135
11	Radiative photon and electron polarization in the Coulomb line $\alpha^2(Z\alpha)^4$	−0.00500	0.0010
12	Electron loop in the radiative photon of order $\alpha^2(Z\alpha)^4$	−0.00150	
13	Mixed electron and muon loops	0.00007	
14	Hadronic polarization $\alpha(Z\alpha)^4 m_r$	0.01077	0.00038
15	Hadronic polarization $\alpha(Z\alpha)^5 m_r$	0.000047	
16	Hadronic polarization in the radiative photon $\alpha^2(Z\alpha)^4 m_r$	−0.000015	
17	Recoil contribution	0.05750	
18	Recoil finite size	0.01300	0.001
19	Recoil correction to VP	−0.00410	
20	Radiative corrections of order $\alpha^n(Z\alpha)^k m_r$	−0.66770	
21	Muon Lamb shift 4th order	−0.00169	
22	Recoil corrections of order $\alpha(Z\alpha)^5 \frac{m}{M} m_r$	−0.04497	
23	Recoil of order α^6	0.00030	
24	Radiative recoil corrections of order $\alpha(Z\alpha)^n \frac{m}{M} m_r$	−0.00960	
25	Nuclear structure correction of order $(Z\alpha)^5$ (Proton polarizability)	0.015	0.004
26	Polarization operator induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	0.00019	
27	Radiative photon induced correction to nuclear polarizability $\alpha(Z\alpha)^5 m_r$	−0.00001	
	Sum	206.0573	0.0045



Aim of the experiment

- Measure the $2S-2P$ energy difference (Lamb shift) in μp

  $\Delta E(2S-2P) = 209.978(5) - 5.226\, r_p^2 + 0.0347\, r_p^3$ meV

  with 30 ppm precision.

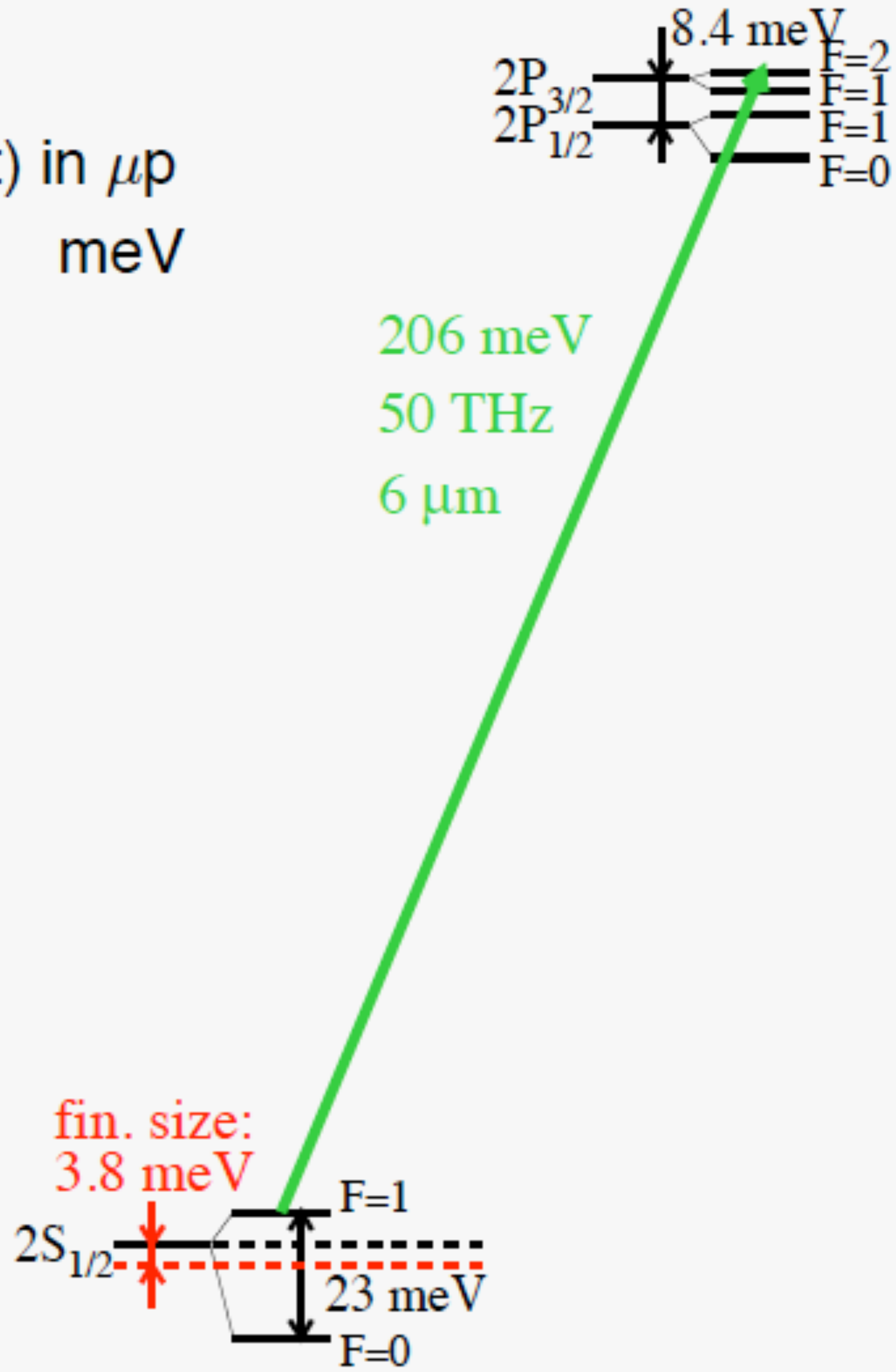
- Extract r_p with $u_r \approx 10^{-3}$ (rel. accuracy)

  $\rightarrow$ bound-state QED test in hydrogen
  to a level of $u_r \approx 3 \times 10^{-7}$ ($10\times$ better)

  $\rightarrow$ improve Rydberg constant ($R_\infty = mc\alpha^2/2h$)
  to a level of $u_r \approx 1 \times 10^{-12}$ ($6\times$ better)

  $\rightarrow$ benchmark for lattice QCD calculations

  $\rightarrow$ confront with electron scattering results



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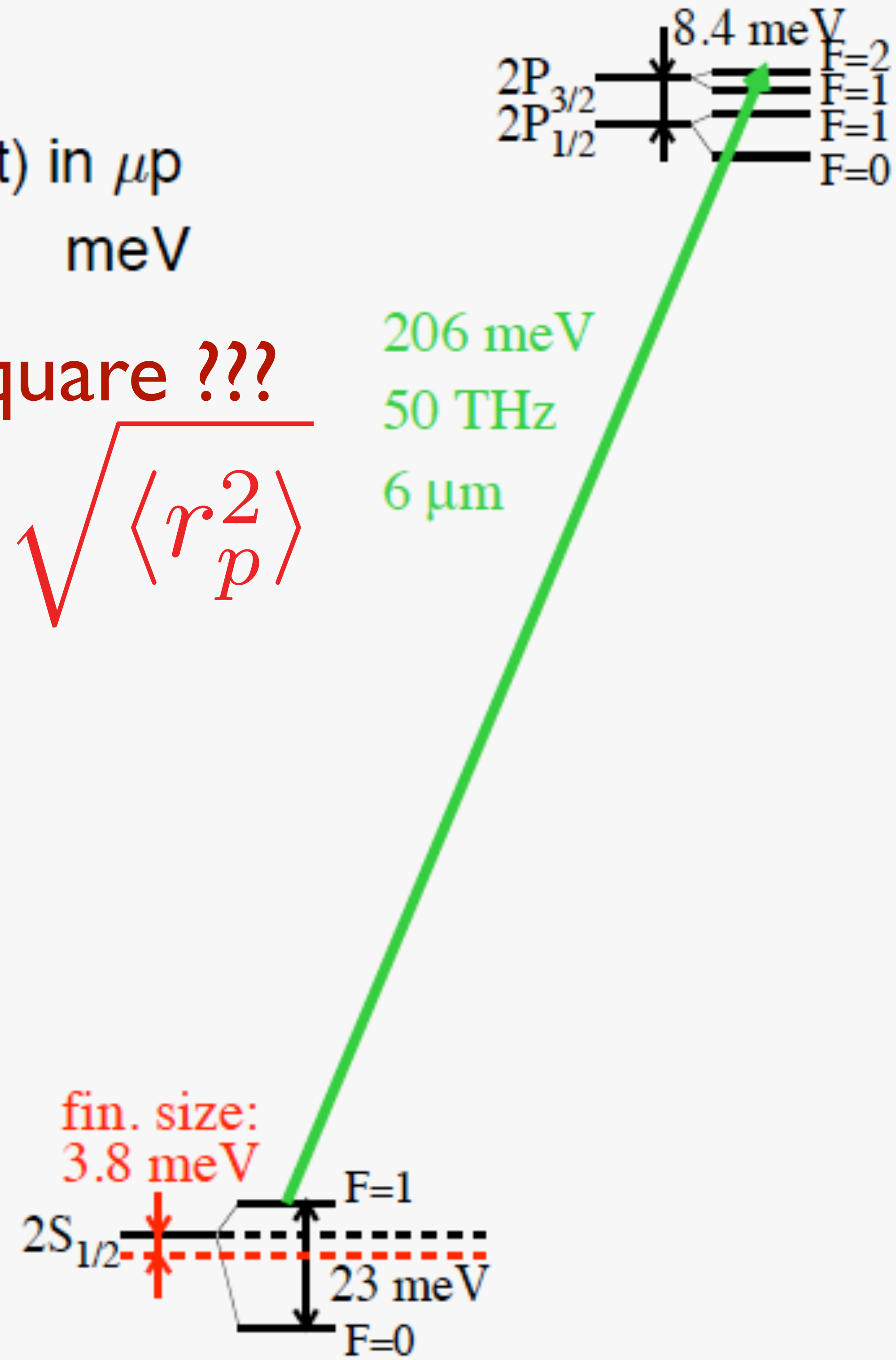

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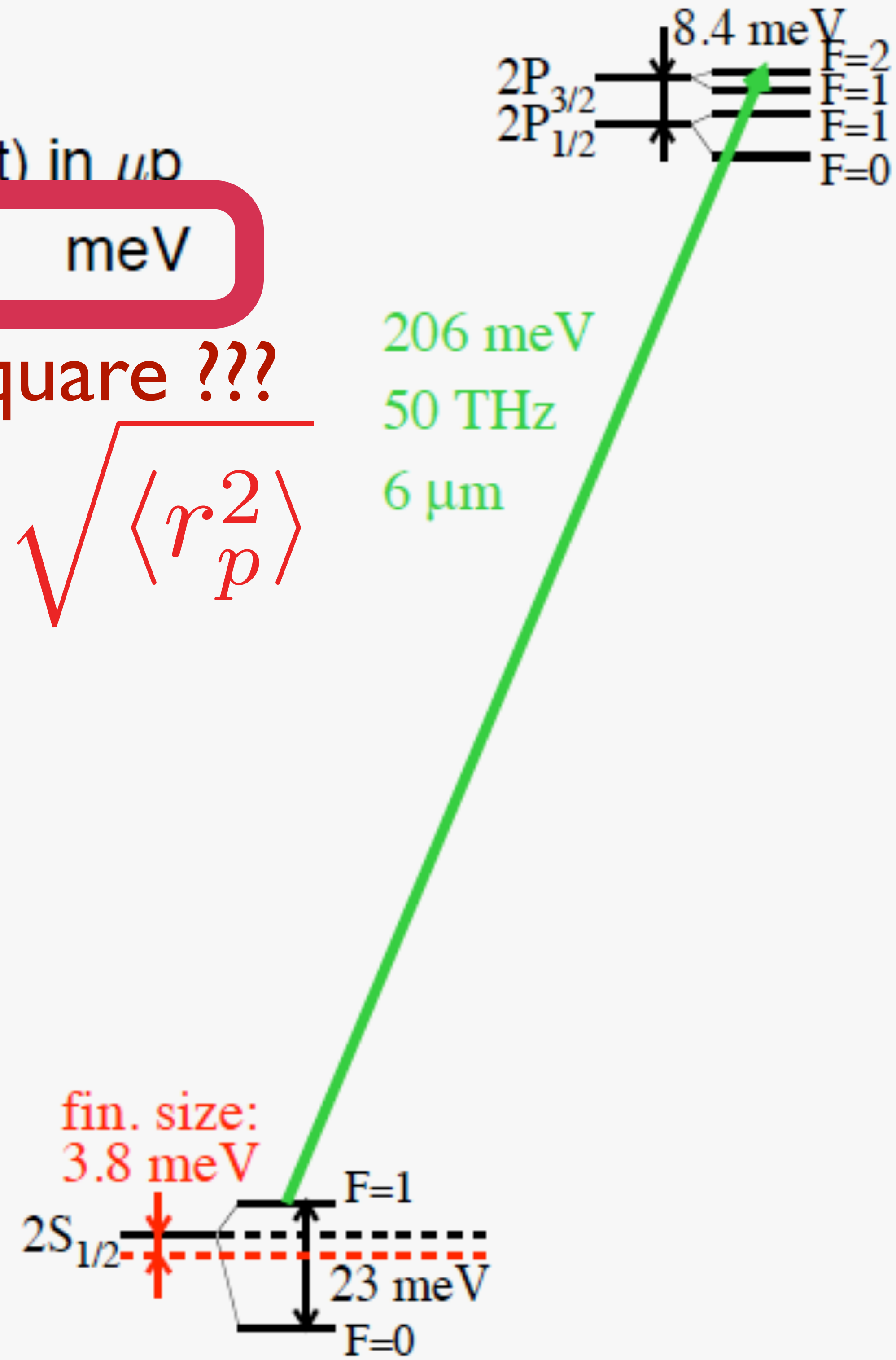
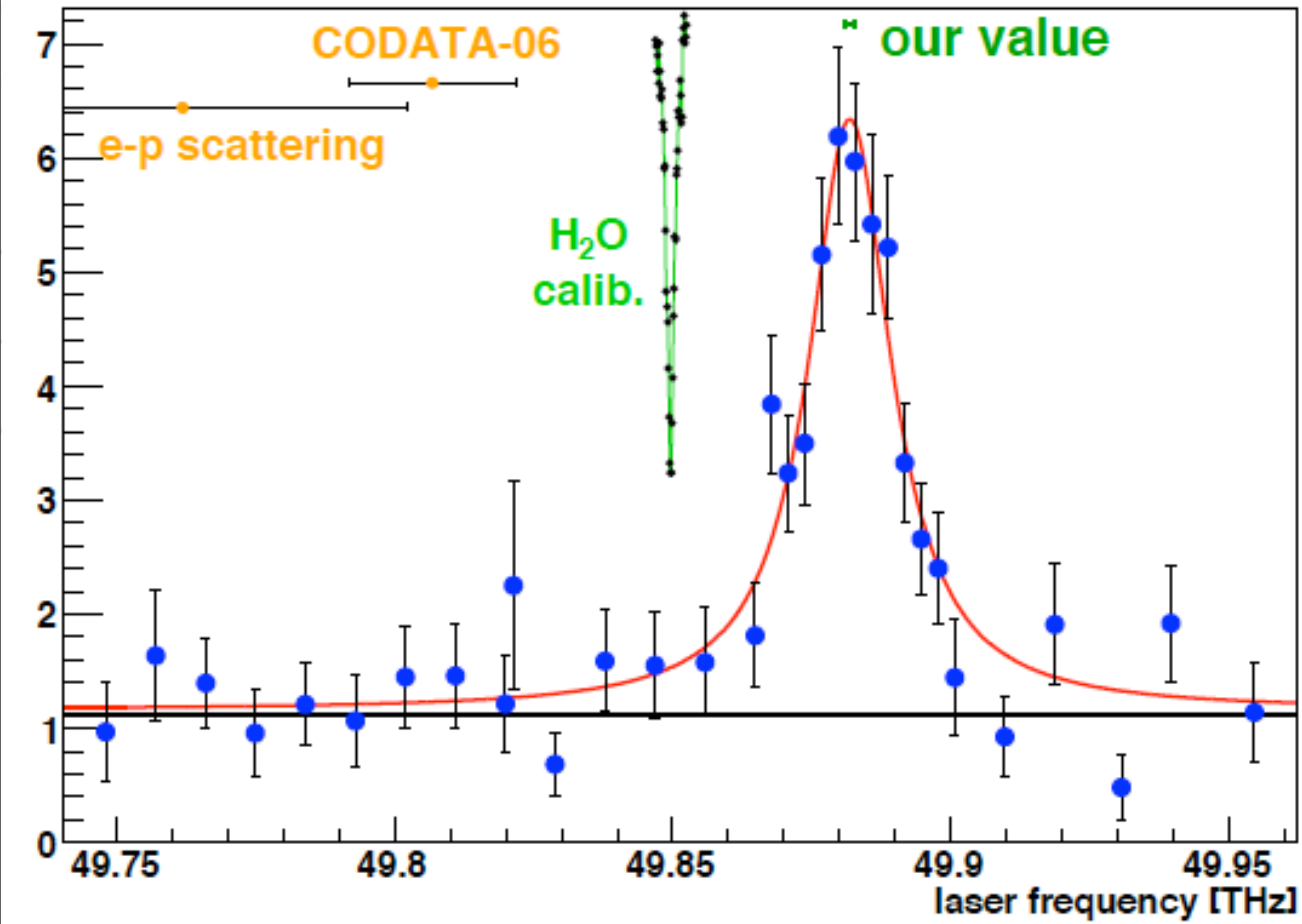
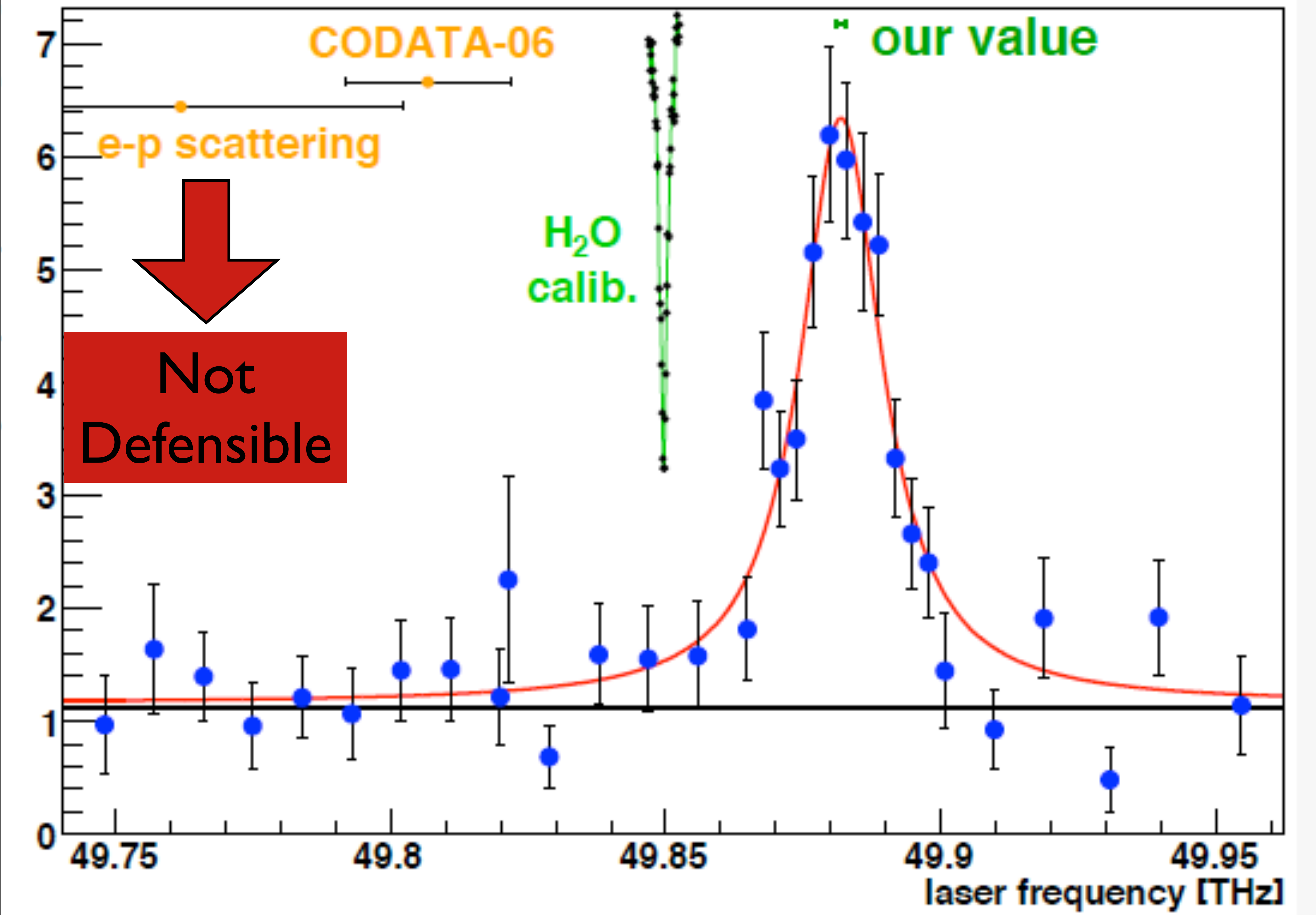




CODATA-06
our value
e-p scattering
H_2O calib.
0
1
2
3
4
5
6
7
49.75
49.8
49.85
49.9
49.95
laser frequency [THz]



CODATA-06
our value
e-p scattering
H_2O
calib.
Not
Defensible
0
1
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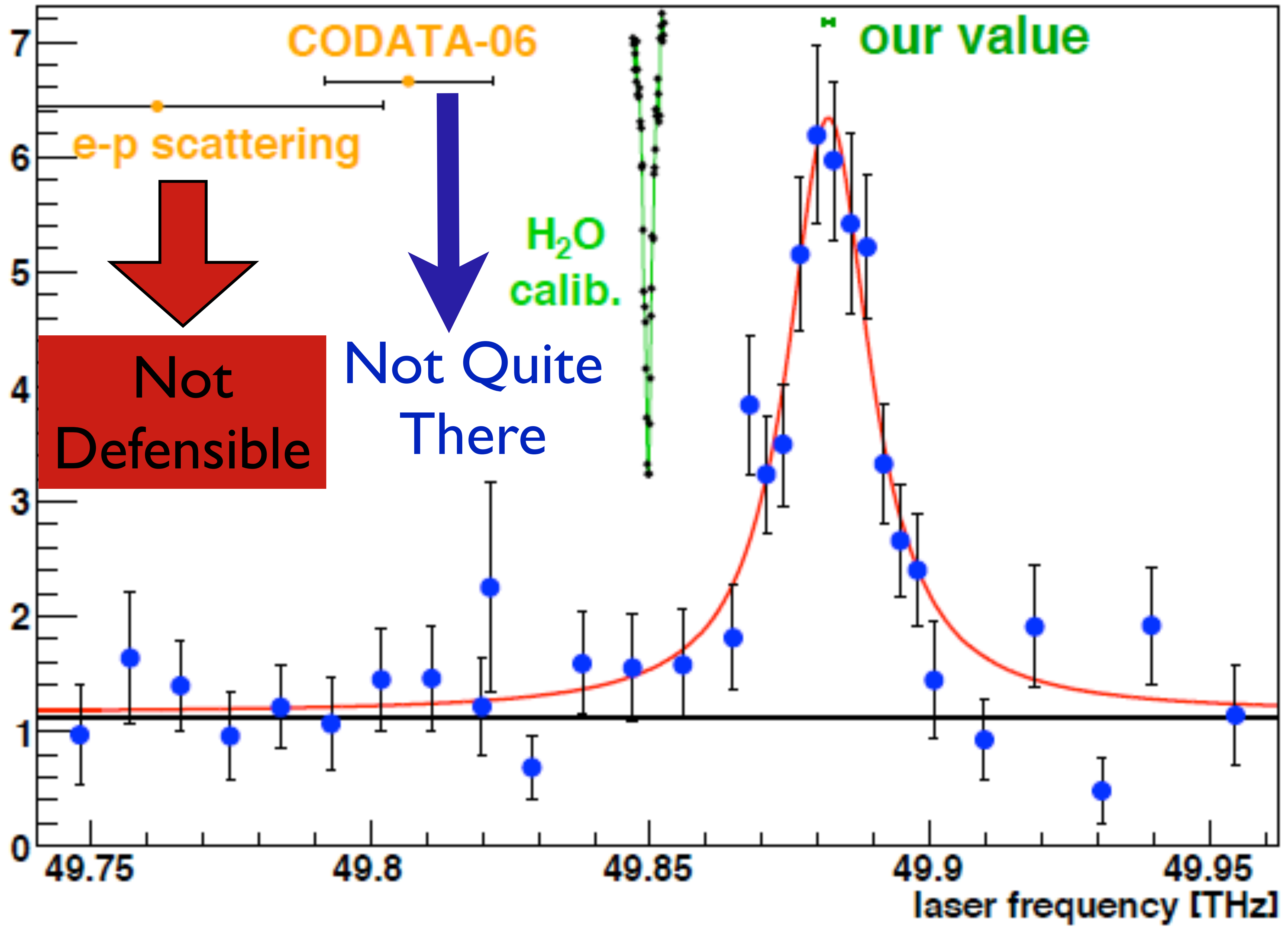
laser frequency [THz]


CODATA-06
our value
e-p scattering
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7
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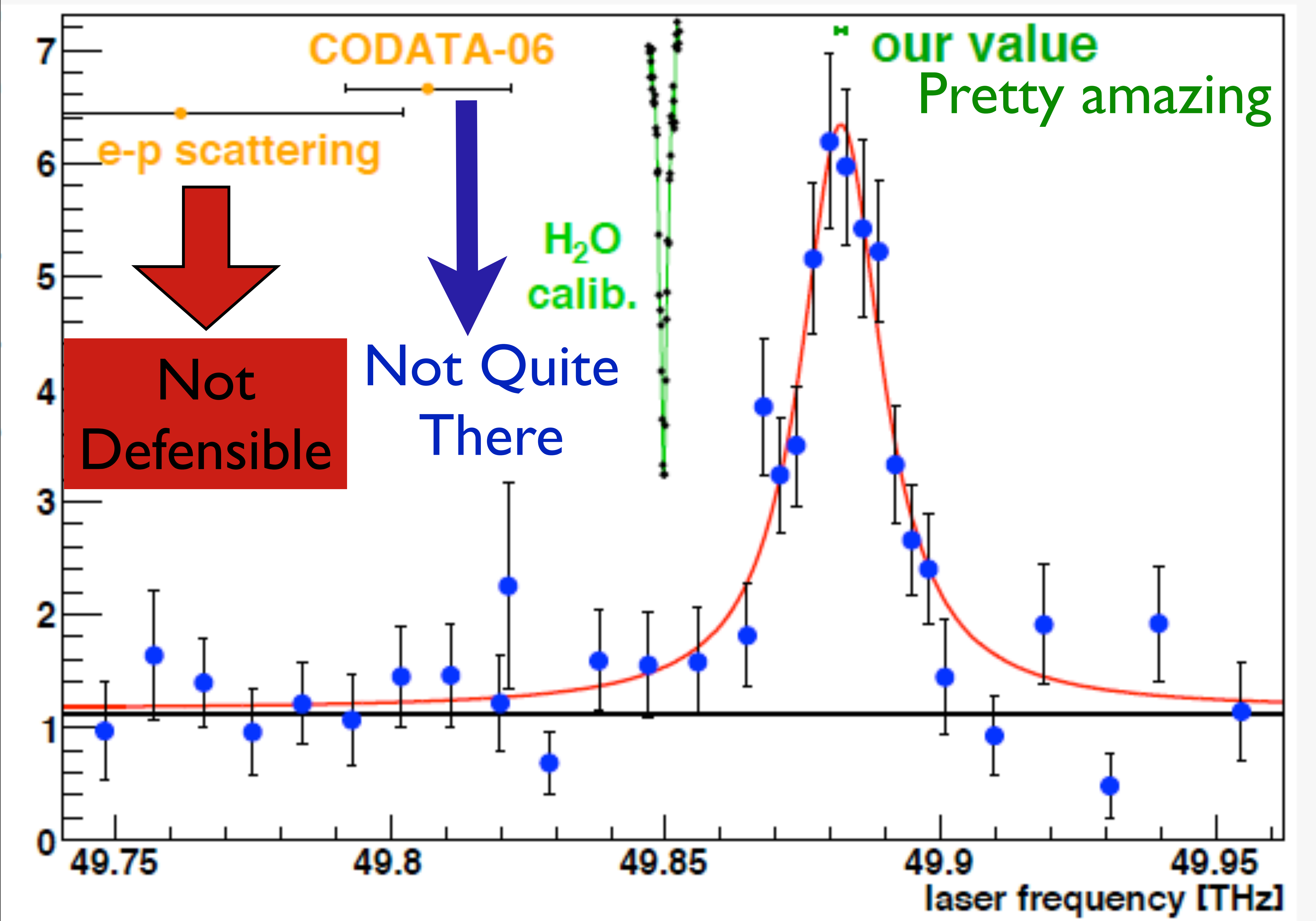

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Pretty amazing
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49.75
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0
1
2
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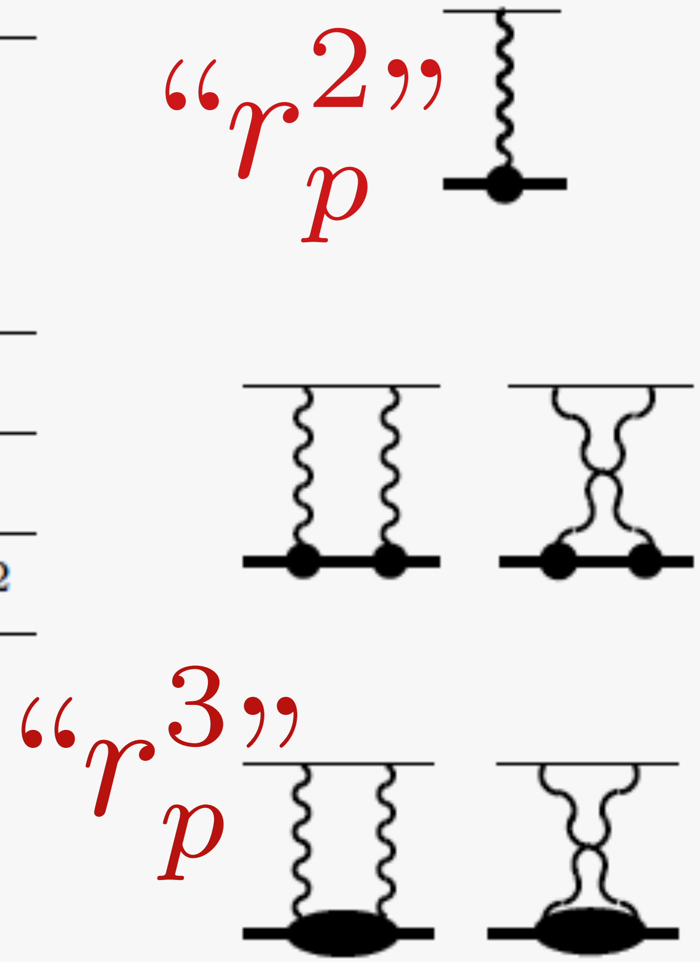
5
6
7

Lamb shift prediction

- radius dependent contributions

Contribution	Value	
Leading nuclear size contribution	-5.19745	$< r_p^2 >$
Radiative corrections to nuclear finite size effect	-0.0275	$< r_p^2 >$
Nuclear size correction of order $(Z\alpha)^6 < r_p^2 >$	-0.001243	$< r_p^2 >$
Total $< r_p^2 >$ contribution	-5.22619	$< r_p^2 >$
Nuclear size correction of order $(Z\alpha)^5$	0.0347	$< r_p^3 >$
Nuclear size correction of order $(Z\alpha)^6 < r_p^4 >$	-0.000043	$< r_p^2 >^2$



- A1 collaboration at MAMI, Mainz has started the reevaluation of the various proton moments: $< r_p^2 >, R_{\text{Zemach}}, < r_p^4 > \ldots$

New evaluations of structure leads to a shift $< 10\%$ of the measured discrepancy.

$$E(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}) = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ meV}$$ (HFS+FS included)

Ladies & Gentlemen

Ladies & Gentlemen

THE THIRD ZEMACH MOMENT

$$L^{\mathrm{th}}\left[\langle r_p^2\rangle, \langle r_p^3\rangle_{(2)}\right] =$$ (in meV, with r in fermi)

$$209.9779(49) - 5.2262\,\langle r_p^2\rangle + 0.00913\,\langle r_p^3\rangle_{(2)}$$

$$\Delta E_3(n) = \frac{\alpha^5}{3\,n^3}\,m_r^4\,\delta_{l0}\,\langle r_p^3\rangle_{(2)}$$

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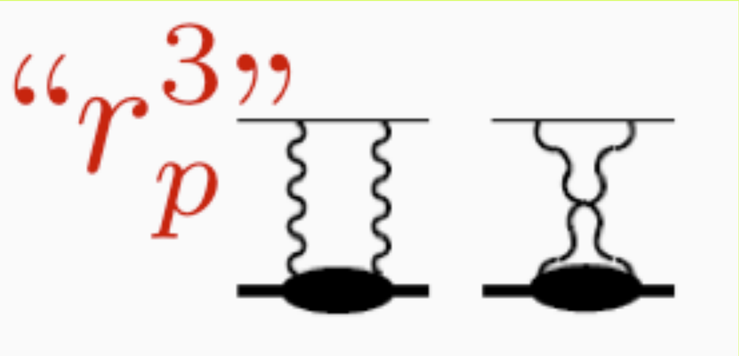

$$\langle r_p^3\rangle_{(2)} \equiv \int d^3r_1 d^3r_2\,\rho(r_1)\rho(r_2)|\mathbf{r}_1 - \mathbf{r}_2|^3$$

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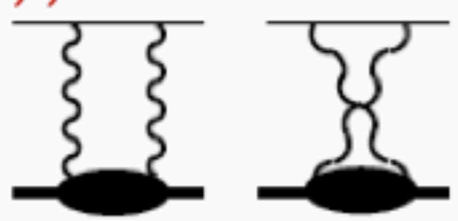
“r_p^3”



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For a dipole form factor

$$\left[\langle r^3\rangle_{(2)}\right]^2 = (3675/256)\left[\langle r^2\rangle\right]^3$$

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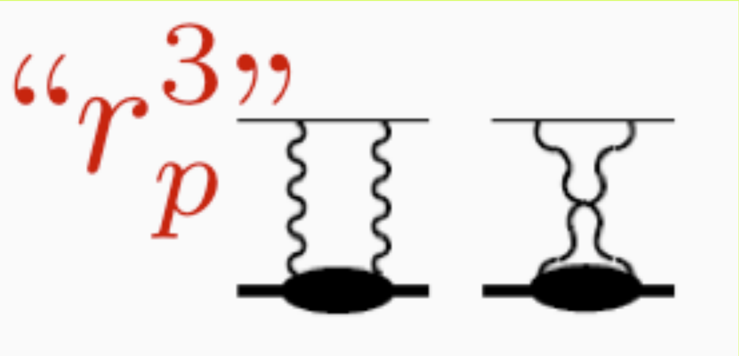

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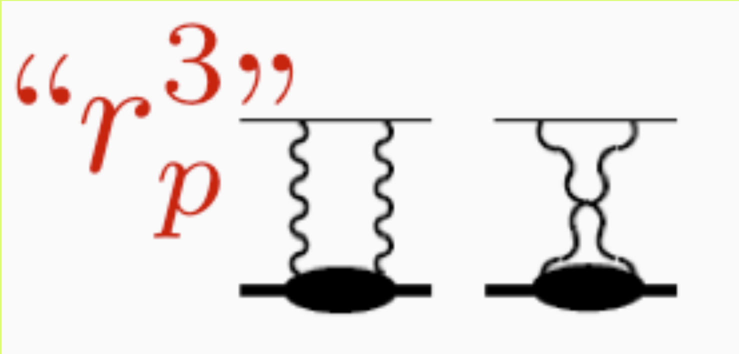

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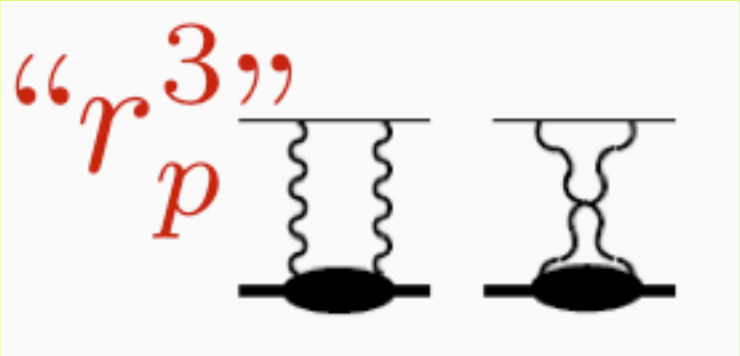

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It is intrepid to use a model of the proton

$$G_E(Q^2) = \frac{1}{\left[1 + \frac{|Q^2|}{0.71\,\mathrm{GeV}^2}\right]^2}$$

... to challenge QED

THE RUNNING RMS P-RADIUS

THE RUNNING RMS P-RADIUS

$$\langle r_p^2 \rangle$$

$$\frac{2\pi\alpha}{3}\langle r_p^2\rangle|\Psi_{2,0}(0)|^2$$

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The slope of FF at $\mathbf{q}^2 = 0$

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The slope of FF at $\mathbf{q}^2 = 0$

the F.T. of $\delta(\vec{\mathrm{r}})$

$$\int_0^\infty e^{i\vec{q}\vec{r}} d^3q \quad (\text{all } q)$$

$$\frac{2\pi\alpha}{3}\langle r_p^2\rangle|\Psi_{2,0}(0)|^2$$

The slope of FF at $\mathbf{q}^2 = 0$

the F.T. of $\delta(\vec{\mathrm{r}})$

$$\int_0^\infty e^{i\vec{q}\vec{r}} d^3q \quad (\mathrm{all}\ q)$$

Rephrase "atomic" result:

$$\langle r_p^2\rangle|_{(0,\infty)} \simeq \frac{\langle r_p^2\rangle|_{(\alpha m_r,m)}}{1 - 4\,\alpha\, m_r\sqrt{\langle r_p^2\rangle|_{(\alpha m_r,m)}/6}}$$

$$\mathbf{q} = \mathcal{O}(\alpha\, m_r)\ \text{up to}\ \mathbf{q} \sim m/4$$

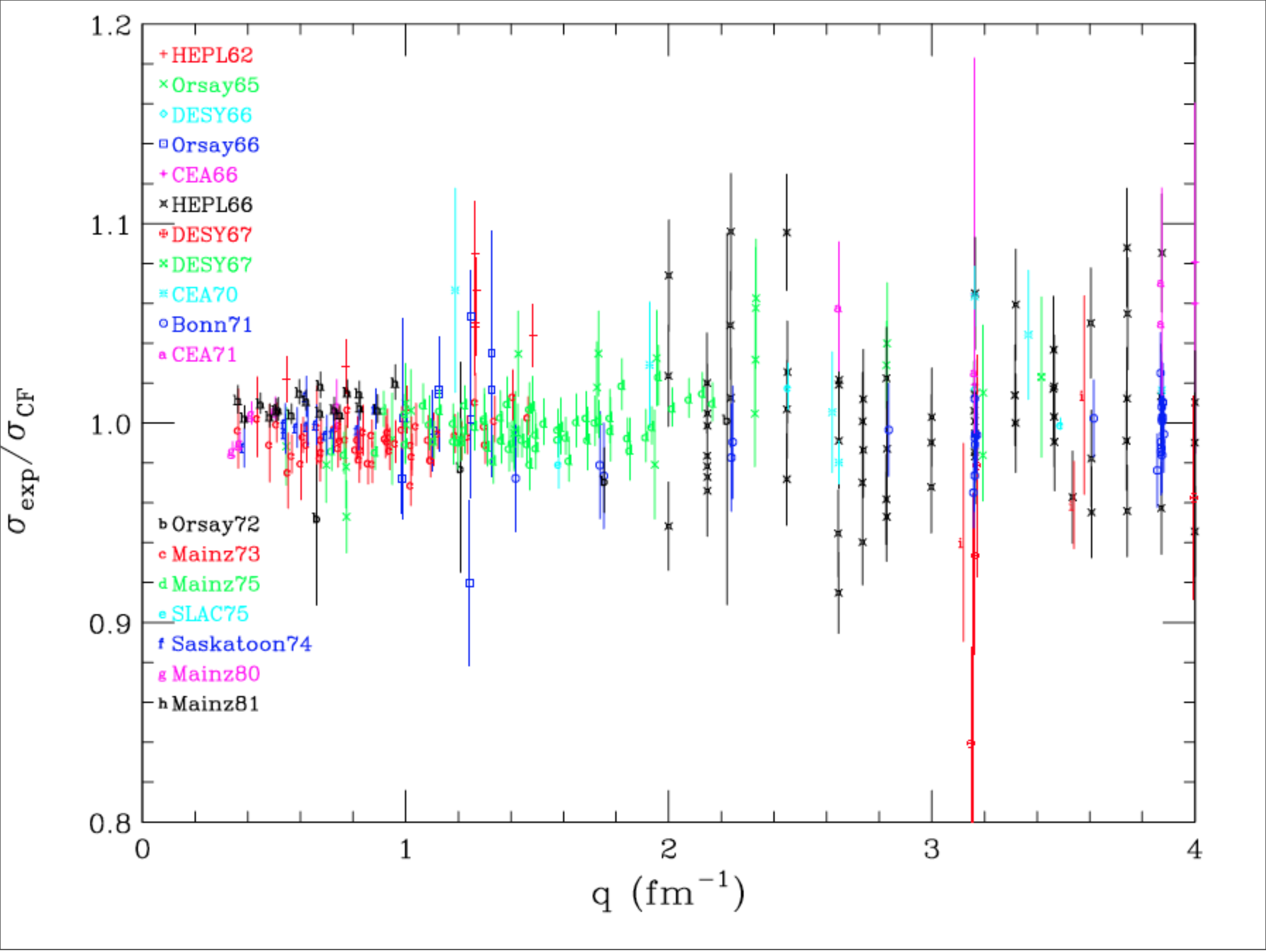
Momentum range is which the proton is "probed" in the atom

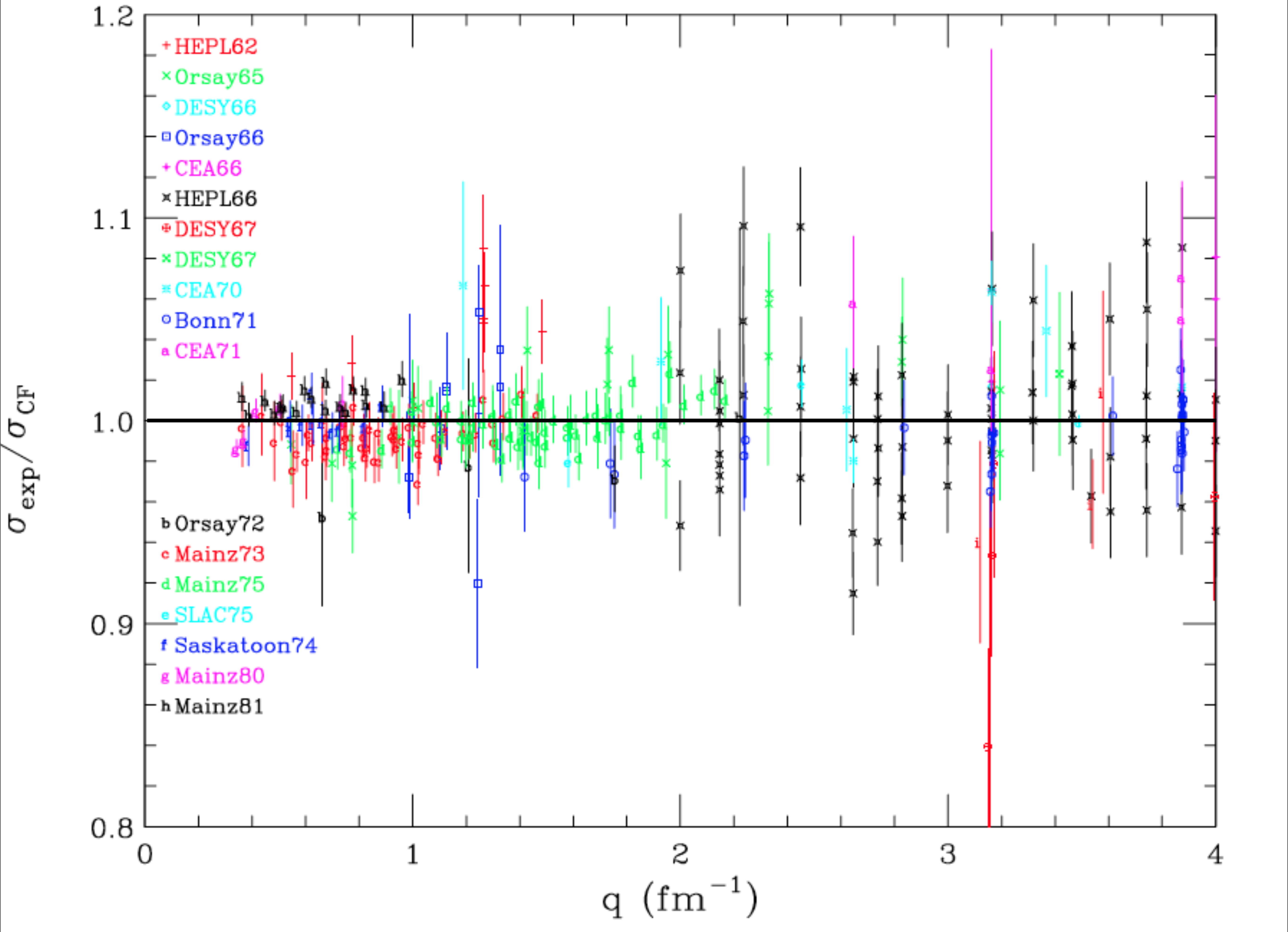
Correction is form-factor dependent

Extracting

$$\langle r_p^2 \rangle$$

from electron-proton scattering data


HEPL62
Orsay65
DESY66
Orsay66
CEA66
HEPL66
DESY67
DESY67
CEA70
Bonn71
CEA71
Orsay72
Mainz73
Mainz75
SLAC75
Saskatoon74
Mainz80
Mainz81
σ_{exp}/σ_{CF}
q (fm^{-1})
1.2
1.1
1.0
0.9
0.8
0
1
2
3
4


HEPL62
Orsay65
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Orsay66
CEA66
HEPL66
DESY67
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CEA70
Bonn71
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Orsay72
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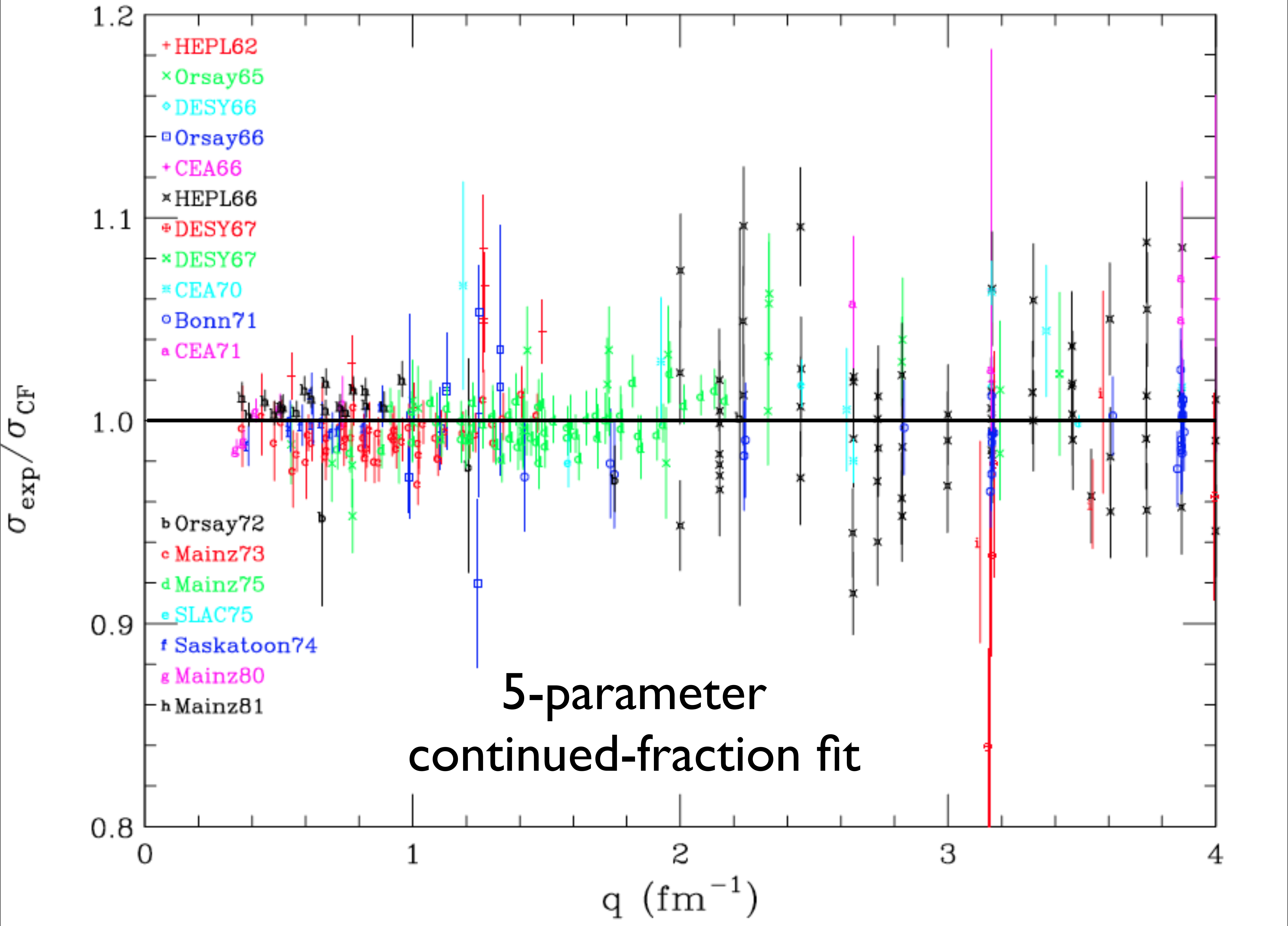
1.2
1.1
1.0
0.9
0.8
0
1
2
3
4
σ_{exp}/σ_{CF}
q (fm^{-1})


HEPL62
Orsay65
DESY66
Orsay66
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DESY67
DESY67
CEA70
Bonn71
CEA71
Orsay72
Mainz73
Mainz75
SLAC75
Saskatoon74
Mainz80
Mainz81
σ_{exp}/σ_{CF}
q (fm^{-1})
5-parameter continued-fraction fit

$$f(z,n) = \frac{2^{-n/2}\ e^{-z/2}\ z^{\frac{n}{2}-1}}{\Gamma\left[\frac{n}{2}\right]}$$

$$f(z,n) = \frac{2^{-n/2}\, e^{-z/2}\, z^{\frac{n}{2}-1}}{\Gamma\left[\frac{n}{2}\right]}$$

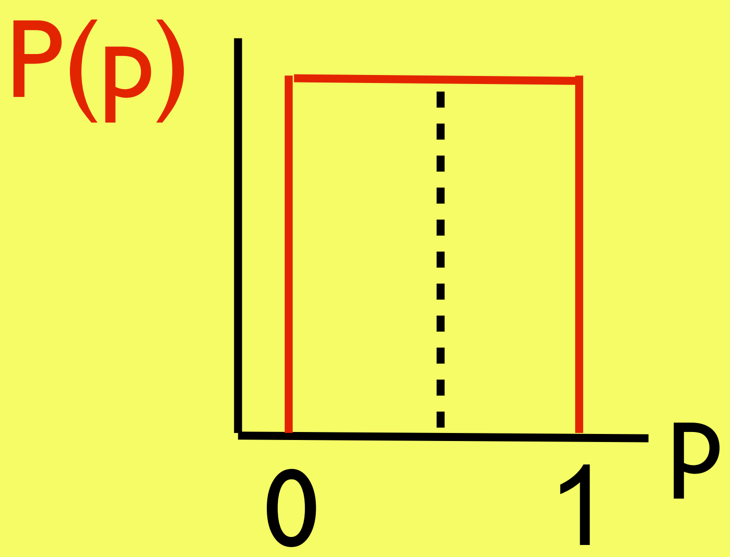
$$p(\chi^2, n_{\mathrm{dof}}) = \int_{\chi^2}^{\infty} f(z, n_{\mathrm{dof}})\, dz =$$

$$f(z,n) = \frac{2^{-n/2}\, e^{-z/2}\, z^{\frac{n}{2}-1}}{\Gamma\left[\frac{n}{2}\right]}$$

$$p(\chi^2, n_{\text{dof}}) = \int_{\chi^2}^{\infty} f(z, n_{\text{dof}})\, dz = \frac{\Gamma(n_{\text{dof}}/2, \chi^2/2)}{\Gamma(n_{\text{dof}}/2)}$$

$$f(z,n) = \frac{2^{-n/2}\, e^{-z/2}\, z^{\frac{n}{2}-1}}{\Gamma\left[\frac{n}{2}\right]}$$

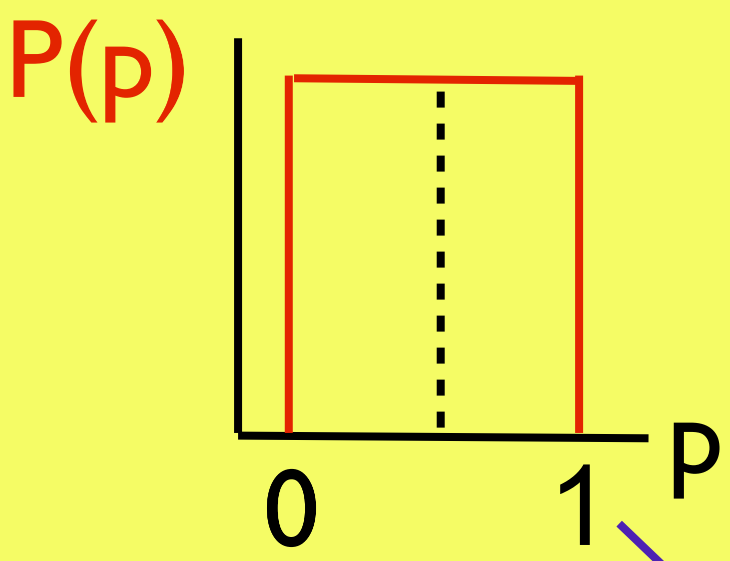
$$p(\chi^2, n_{\rm dof}) = \int_{\chi^2}^{\infty} f(z, n_{\rm dof})\, dz = \frac{\Gamma(n_{\rm dof}/2, \chi^2/2)}{\Gamma(n_{\rm dof}/2)}$$



H correct
Data good

$$f(z,n) = \frac{2^{-n/2}\, e^{-z/2}\, z^{\frac{n}{2}-1}}{\Gamma\left[\frac{n}{2}\right]}$$

$$p(\chi^2, n_{\mathrm{dof}}) = \int_{\chi^2}^{\infty} f(z, n_{\mathrm{dof}})\, dz = \frac{\Gamma(n_{\mathrm{dof}}/2, \chi^2/2)}{\Gamma(n_{\mathrm{dof}}/2)}$$

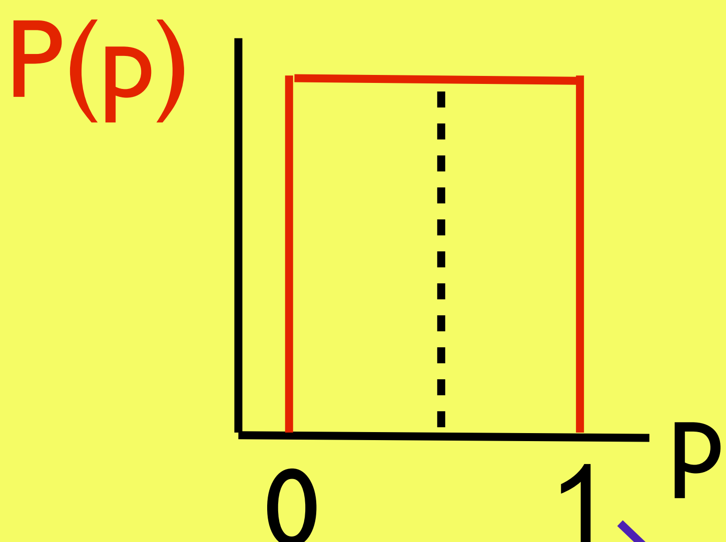


H correct
Data good

The data are tickled to agree with H

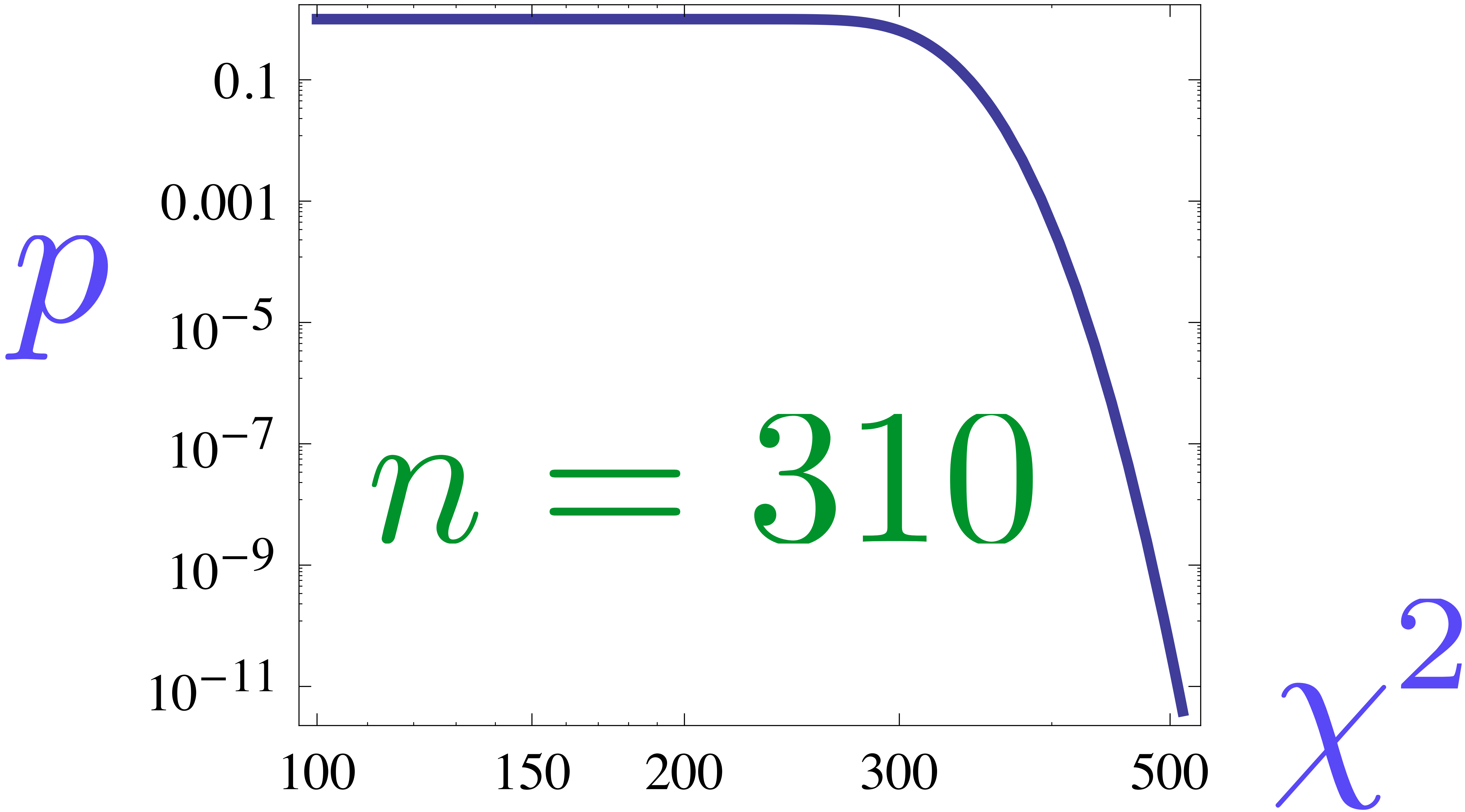
$$f(z,n) = \frac{2^{-n/2}\, e^{-z/2}\, z^{\frac{n}{2}-1}}{\Gamma\left[\frac{n}{2}\right]}$$

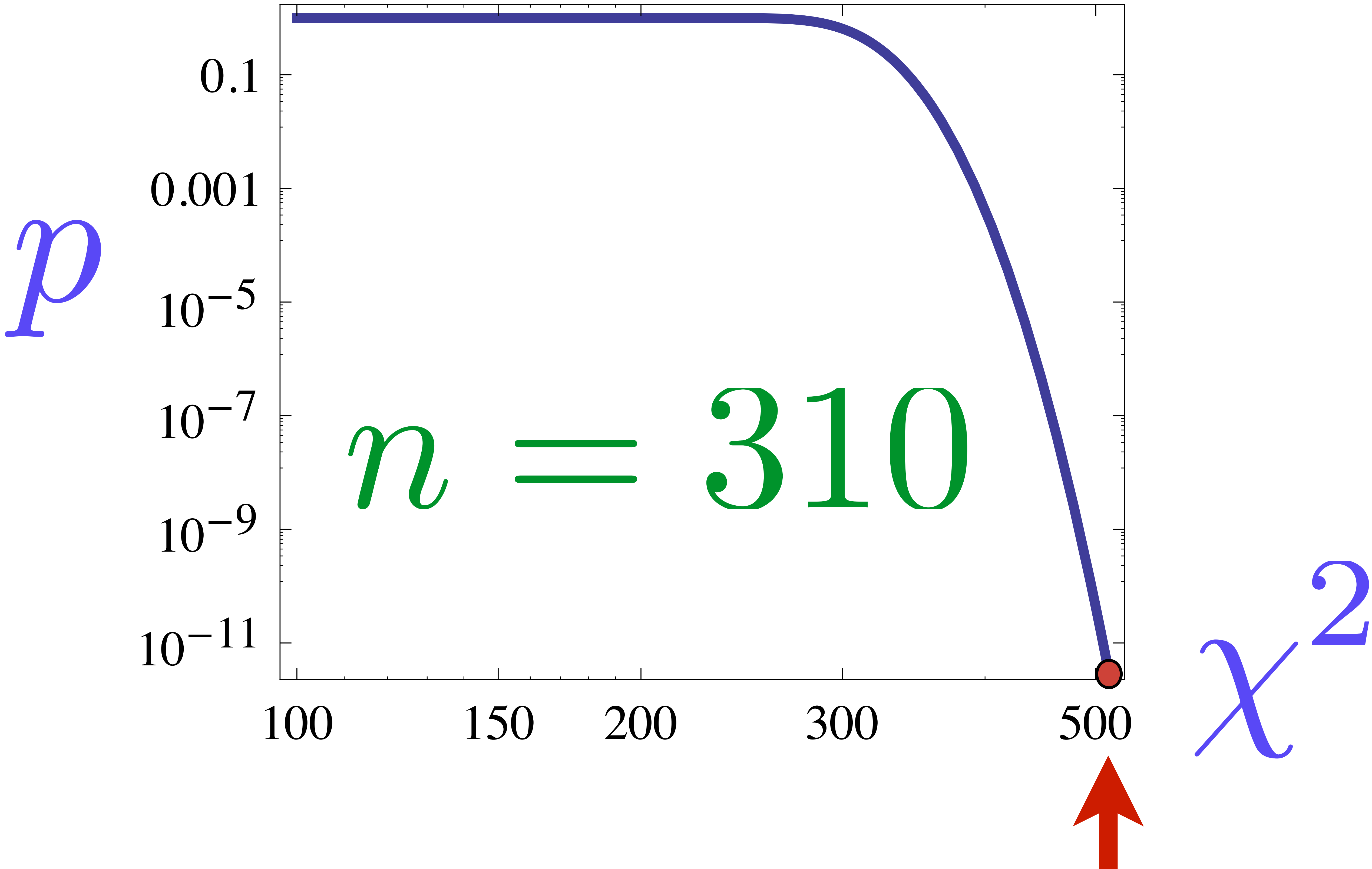
$$p(\chi^2, n_{\mathrm{dof}}) = \int_{\chi^2}^{\infty} f(z, n_{\mathrm{dof}})\, dz = \frac{\Gamma(n_{\mathrm{dof}}/2, \chi^2/2)}{\Gamma(n_{\mathrm{dof}}/2)}$$



H correct
Data good

The data are tickled to agree with H
H and the data do not agree


p
0.1
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
$n = 310$
100
150
200
300
500
χ^2



$$p(512, 310) \simeq 3.92 \times 10^{-12}$$

what to say ??????

what to say ??????

¡¡¡¡ ™

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!!!!!!!!!!!!!!!!!!!!!!

Ig Nobel Peace Prize 2010

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Stephens, Atkins, and Kingston of Keele University, for confirming the widely held belief that swearing relieves pain.

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¡¡¡ $ & # £ ∞ § ¶ !!!

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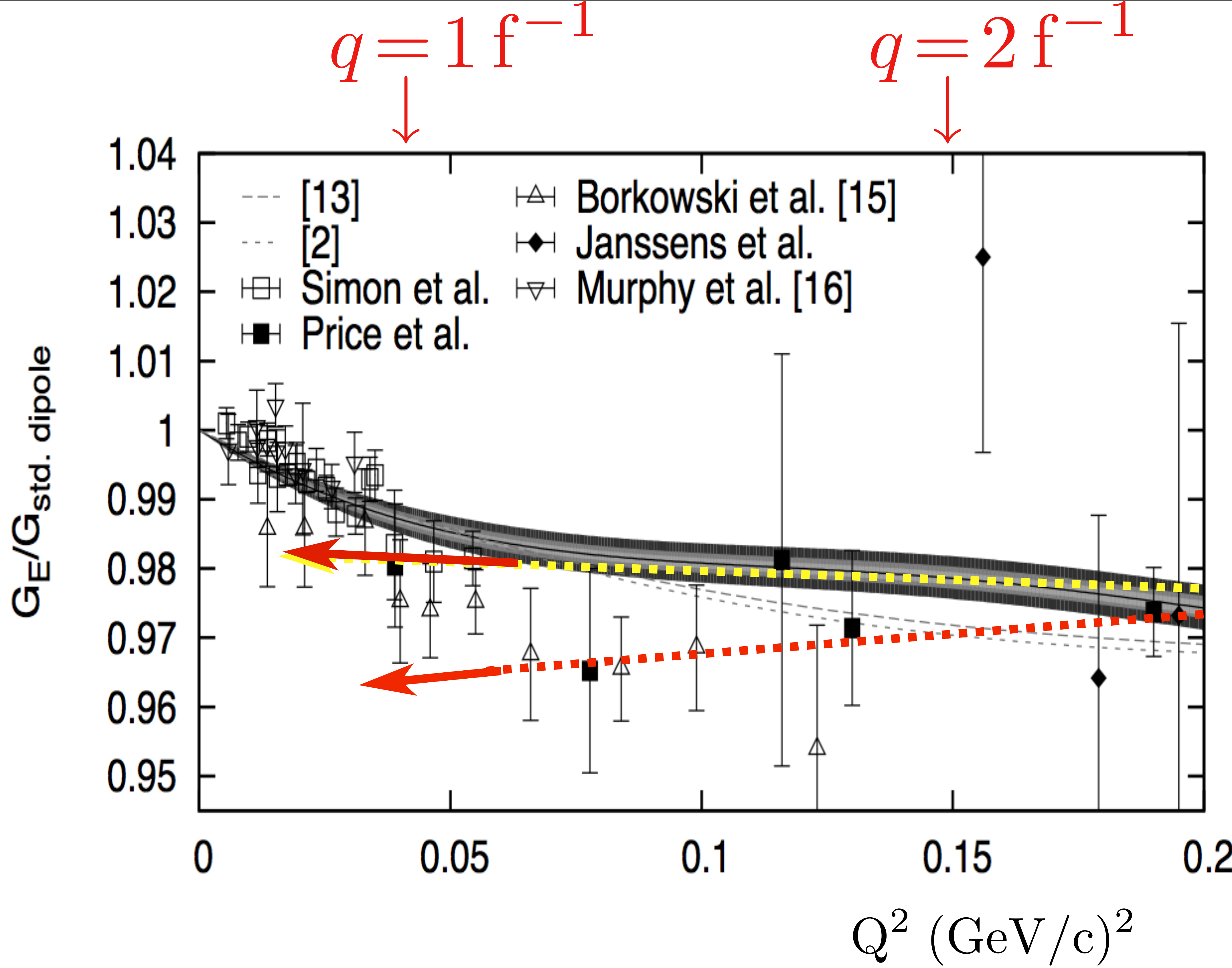
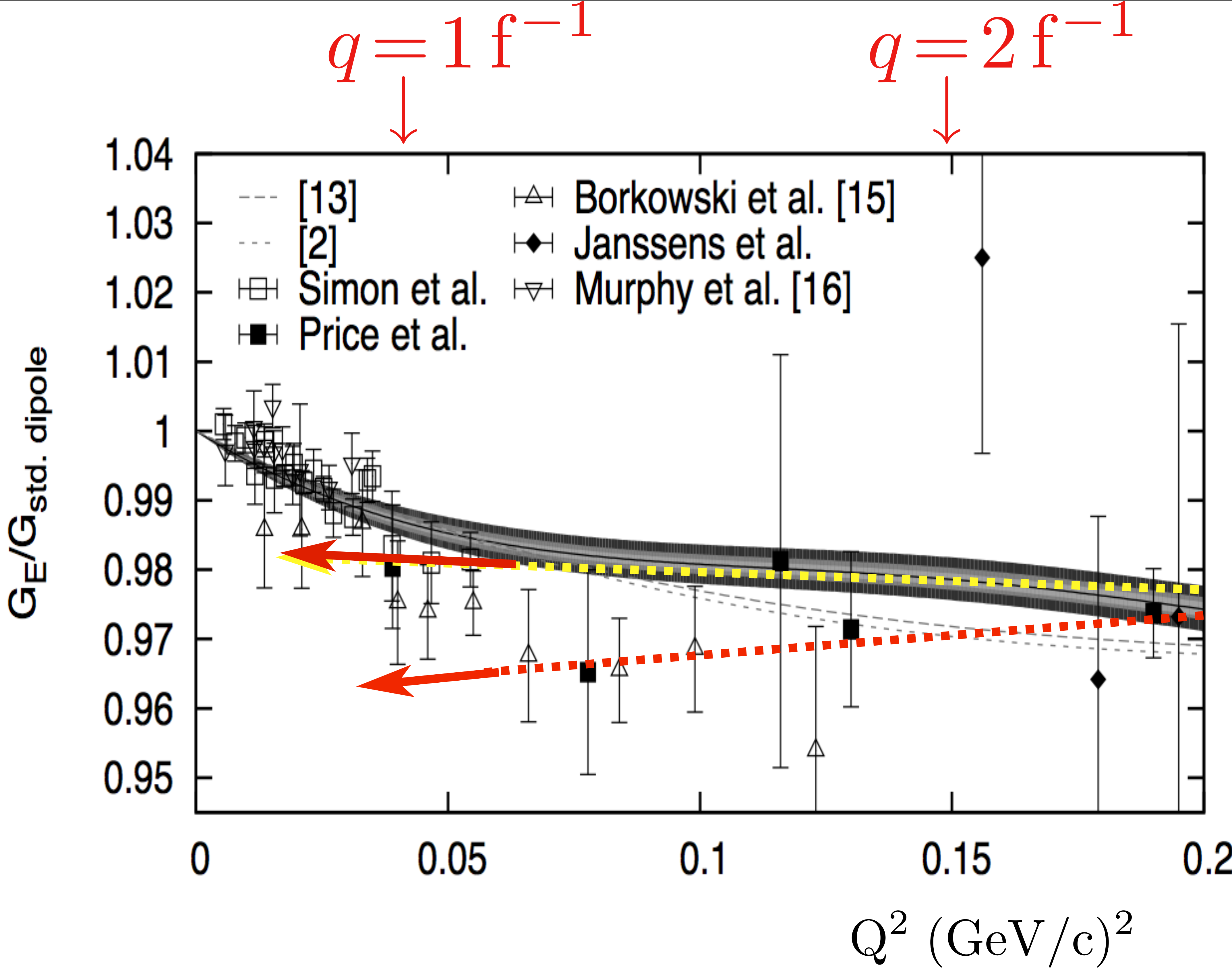
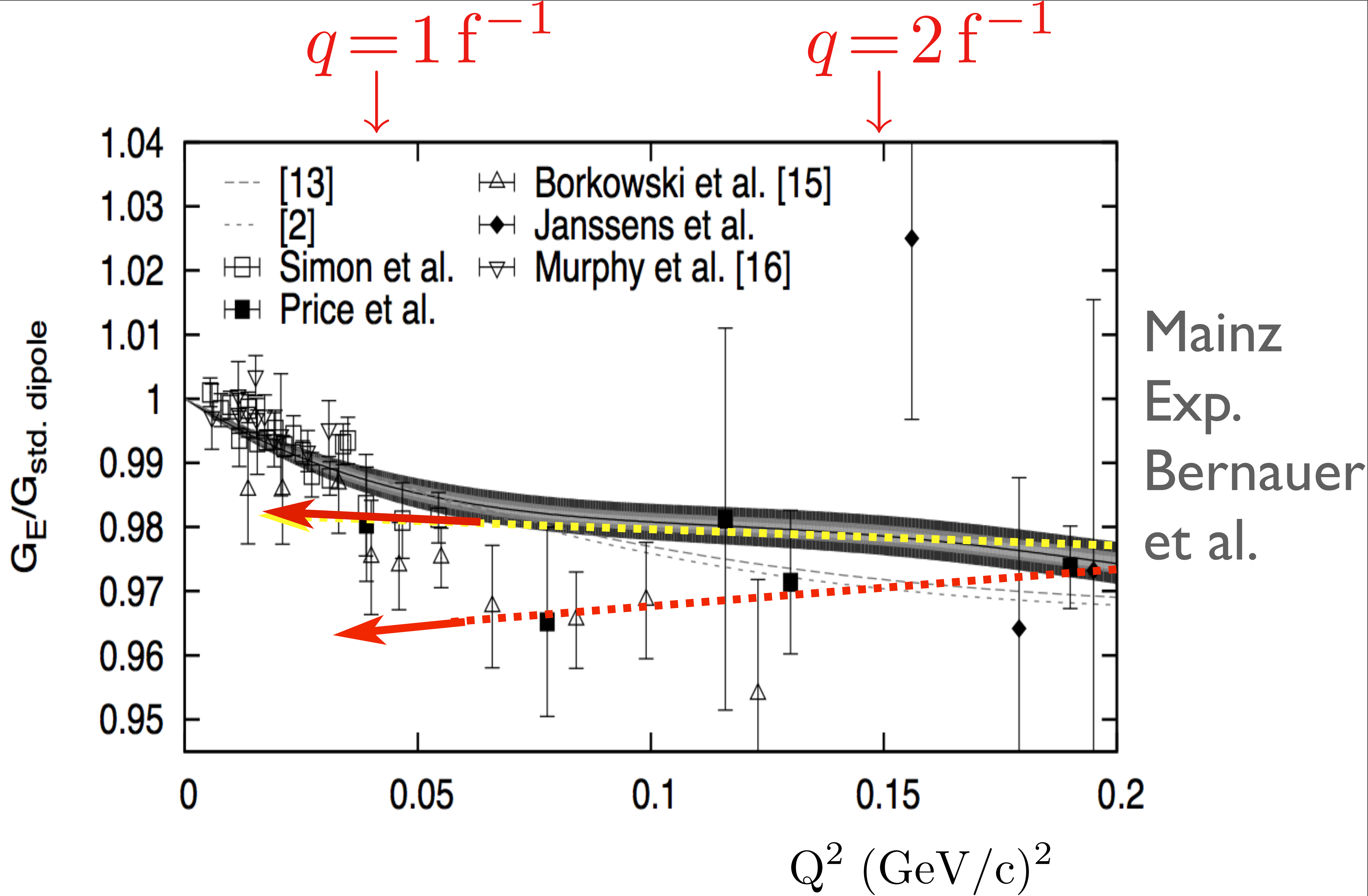
REFERENCE: "Swearing as a Response to Pain," Richard Stephens, John Atkins, and Andrew Kingston, Neuroreport, vol. 20 , no. 12, 2009, pp. 1056-60.



q = 1 f^-1
q = 2 f^-1
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
GE/Gstd. dipole
[13]
[2]
Simon et al.
Price et al.
Borkowski et al. [15]
Janssens et al.
Murphy et al. [16]
0
0.05
0.1
0.15
0.2
Q^2 (GeV/c)^2



Mainz Exp. Bernauer et al.



$$p(\text{most flexible}) = 1.9 \times 10^{-4}$$

$$\sqrt{\langle r_p^2 \rangle}(\text{polynom}) =$$

$$0.883(5)_{\text{stat}}(5)_{\text{syst}}(3)_{\text{model}}\ \text{fm}$$

$$\sqrt{\langle r_p^2 \rangle}(\text{polynom}) =$$

$$0.883(5)_{\text{stat}}(5)_{\text{syst}}(3)_{\text{model}}\ \text{fm}$$

$$\sqrt{\langle r_p^2 \rangle}(\text{spline}) =$$

$$0.875(5)_{\text{stat}}(4)_{\text{syst}}(2)_{\text{model}}\ \text{fm}$$

$$\sqrt{\langle r_p^2 \rangle}(\text{polynom}) =$$

$$0.883(5)_{\text{stat}}(5)_{\text{syst}}(3)_{\text{model}}\ \text{fm}$$

$$\sqrt{\langle r_p^2 \rangle}(\text{spline}) =$$

$$0.875(5)_{\text{stat}}(4)_{\text{syst}}(2)_{\text{model}}\ \text{fm}$$

THEOREM

Extracting $\langle r_p^3 \rangle_{(2)}$ from (the same) electron-proton scattering data

$$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$$

$$=$$

$$(1.394 \pm 0.022)\ \mathrm{fm}$$

$$\langle r_p^3 \rangle_{(2)} \equiv$$

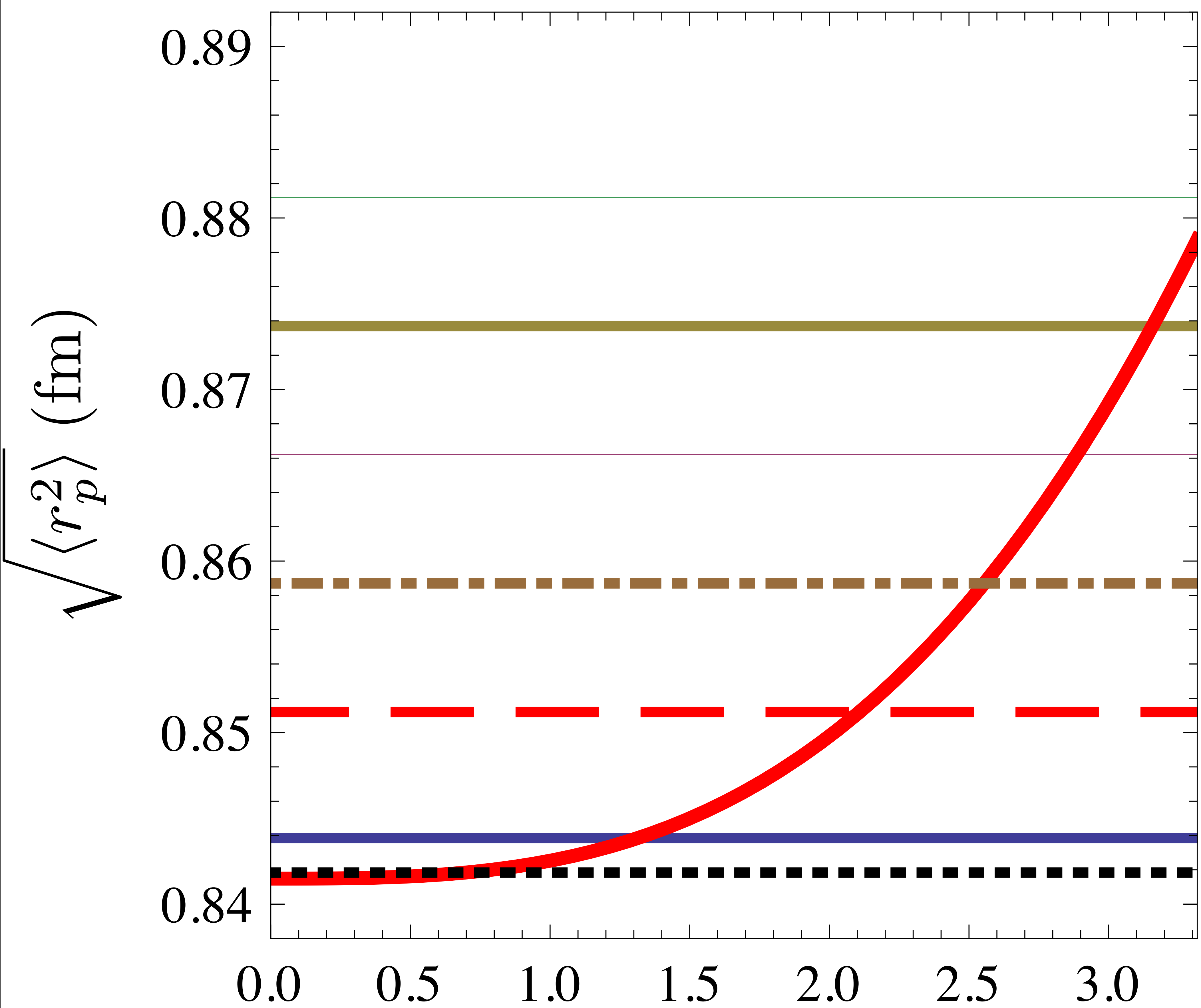
$$\int d^3r_1 d^3r_2\, \rho(r_1)\rho(r_2)|\mathbf{r}_1 - \mathbf{r}_2|^3 =$$

$$\langle r_p^3 \rangle_{(2)} \equiv$$

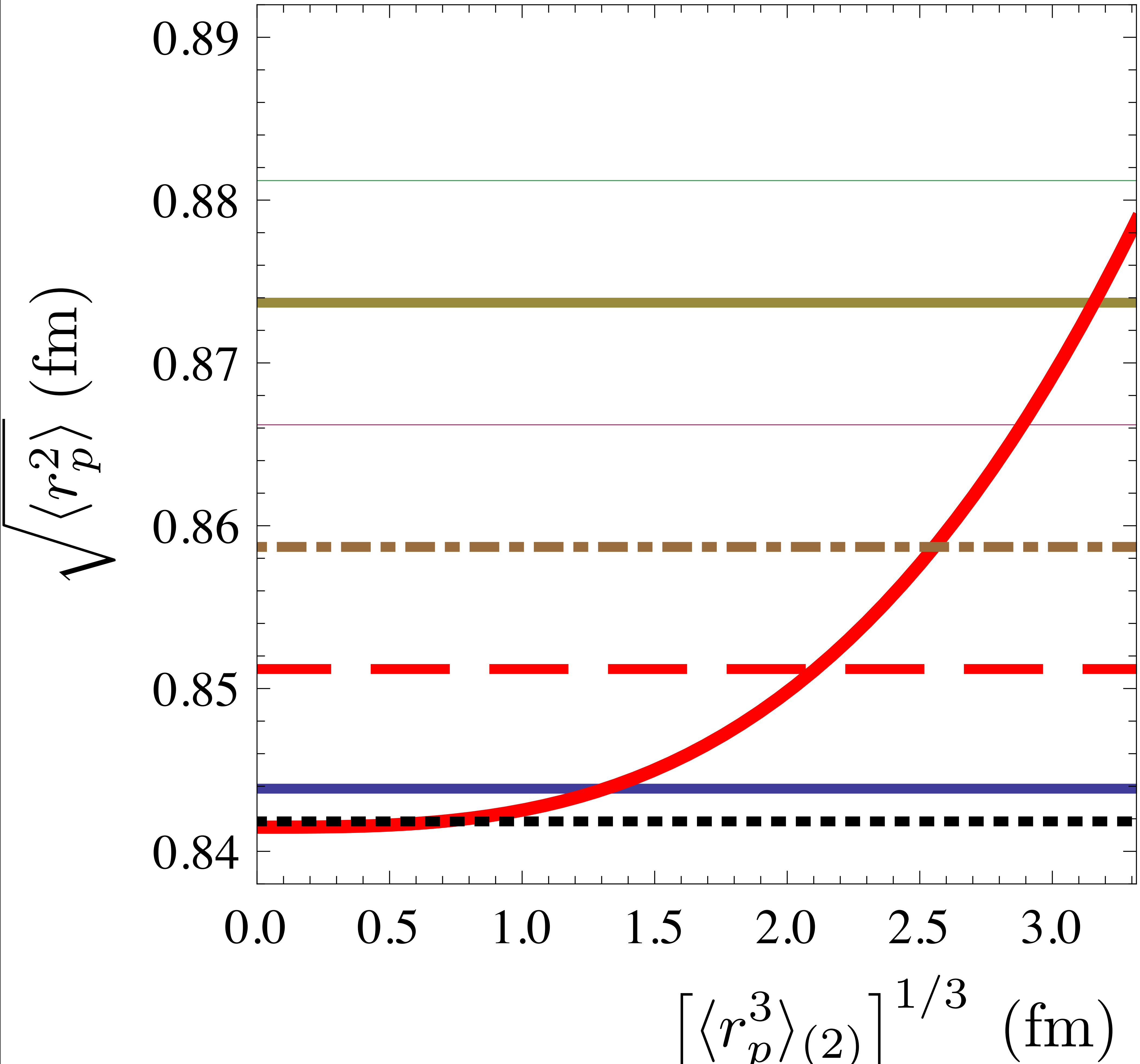
$$\int d^3 r_1 d^3 r_2 \, \rho(r_1) \rho(r_2) |\mathbf{r}_1 - \mathbf{r}_2|^3 =$$

$$\int_0^\infty \frac{dq}{q^4} \, I(q^2)$$

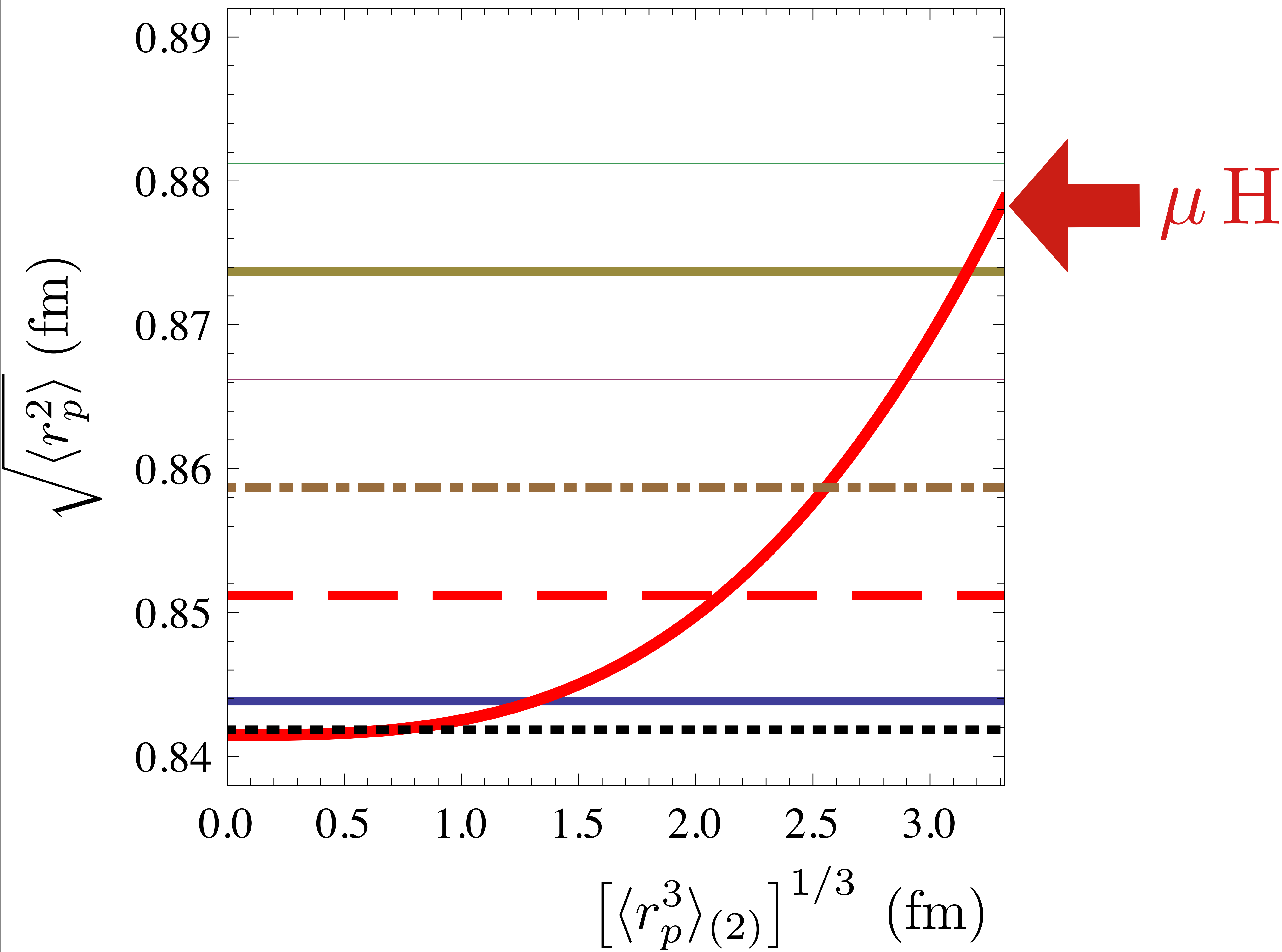
$$I(q^2) \equiv \frac{48}{\pi} \left[G_E^2(\mathbf{q}^2) - 1 + \frac{\mathbf{q}^2}{3} \langle r_p^2 \rangle \right]$$



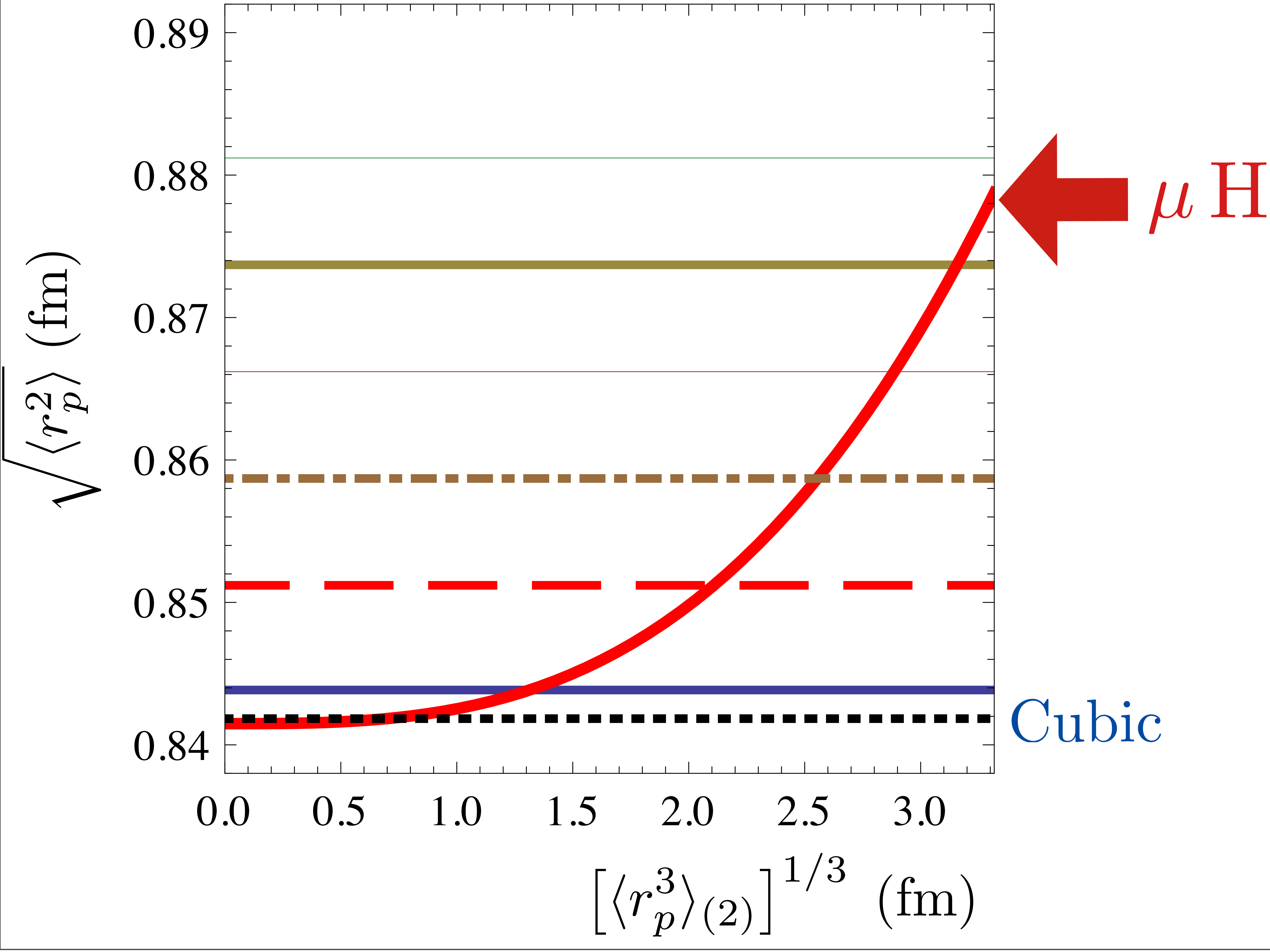
0.89
0.88
0.87
0.86
0.85
0.84
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0



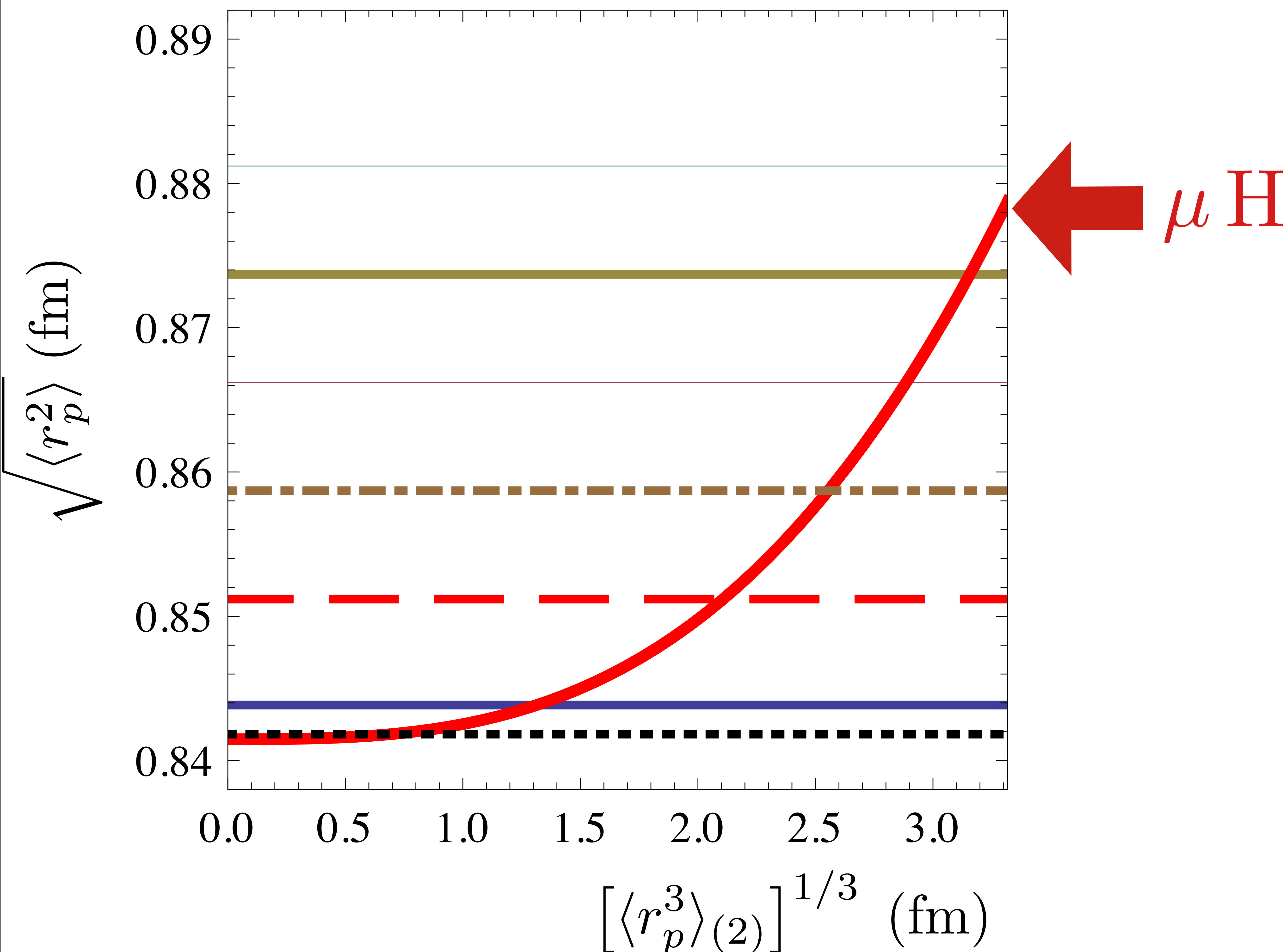
0.89
0.88
0.87
0.86
0.85
0.84
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)



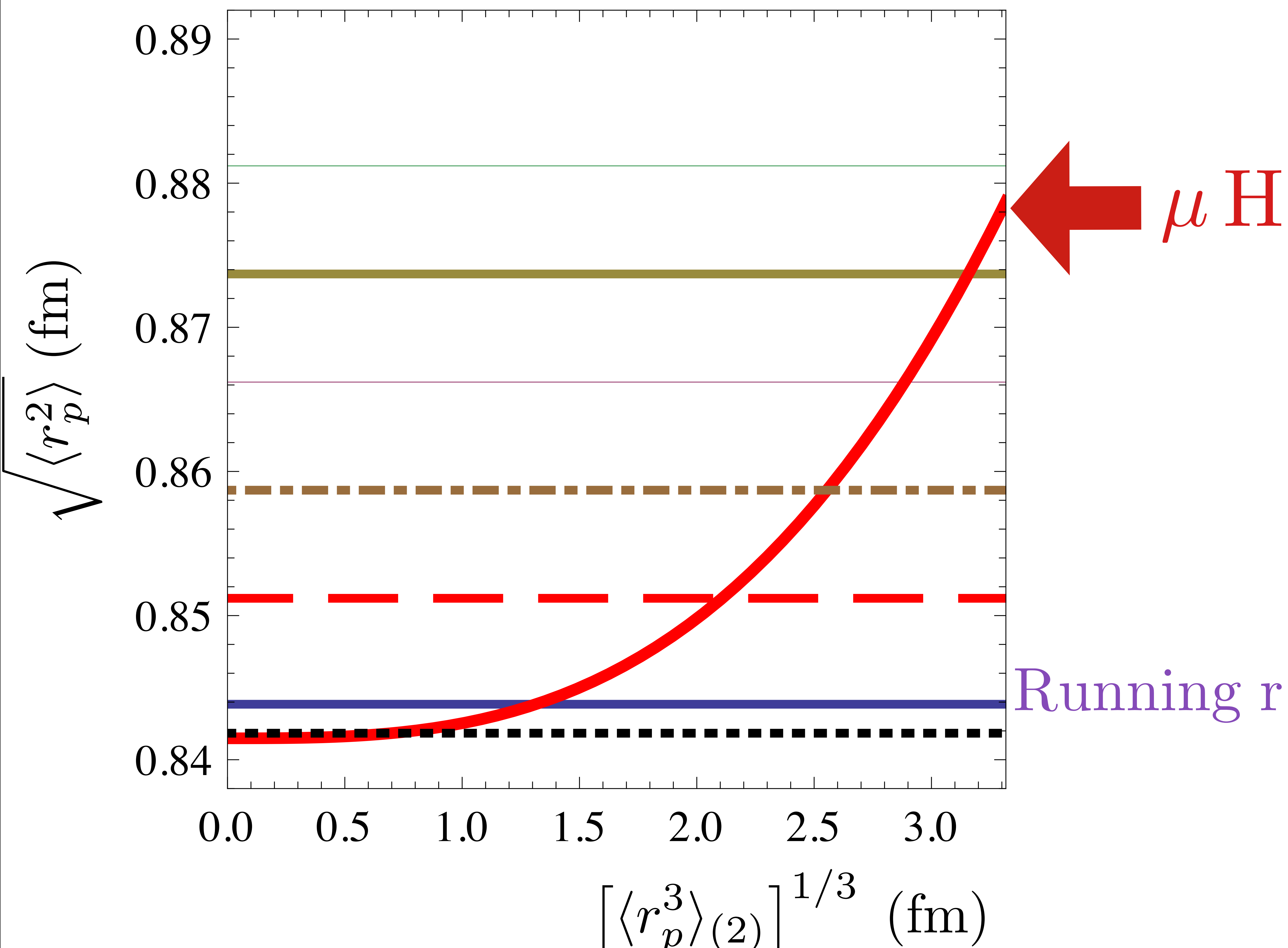
0.89
0.88
0.87
0.86
0.85
0.84
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)
μ H

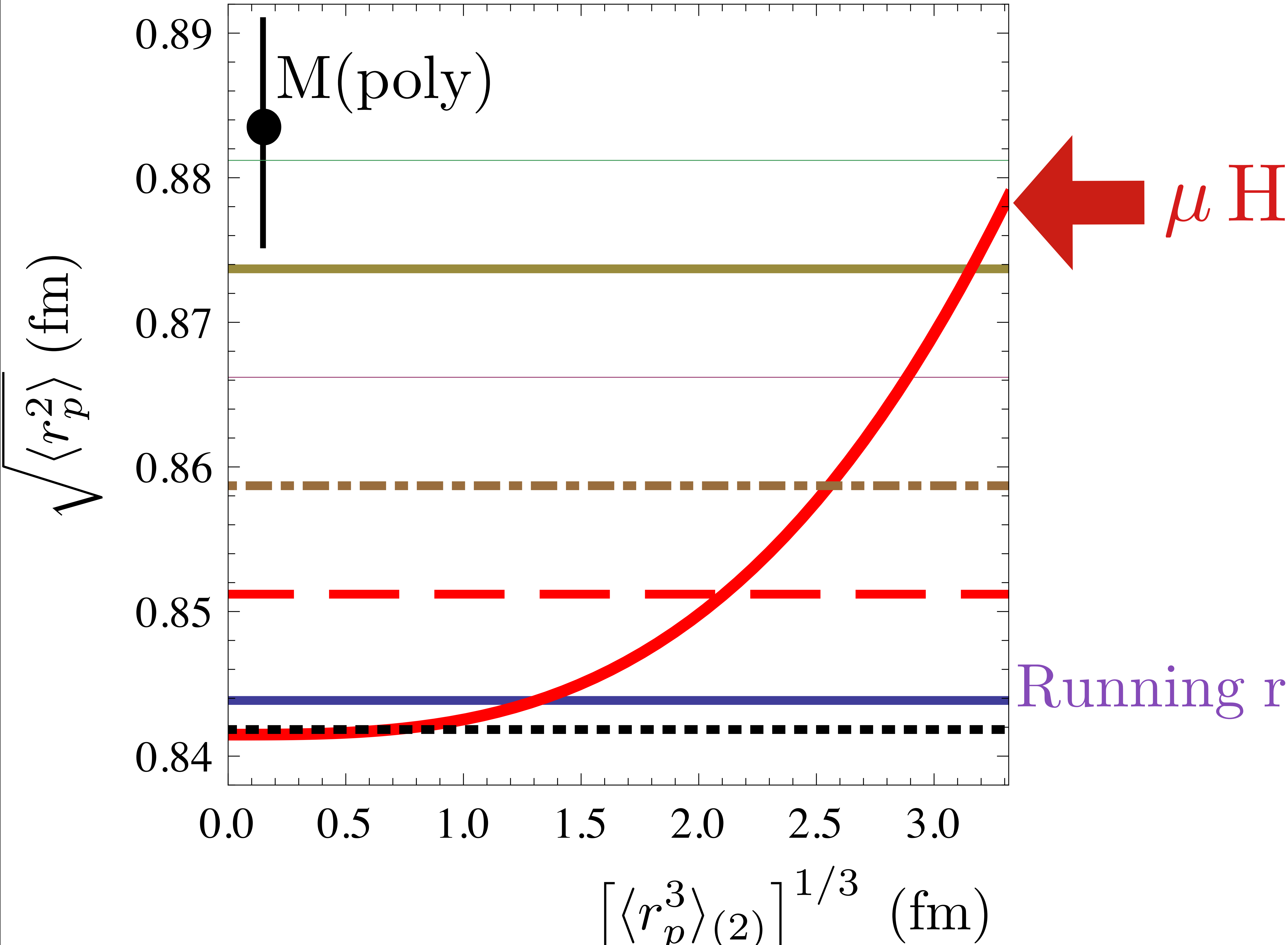


0.89
0.88
0.87
0.86
0.85
0.84
$\sqrt{\langle r_p^2 \rangle}$ (fm)
μ H
Cubic
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)

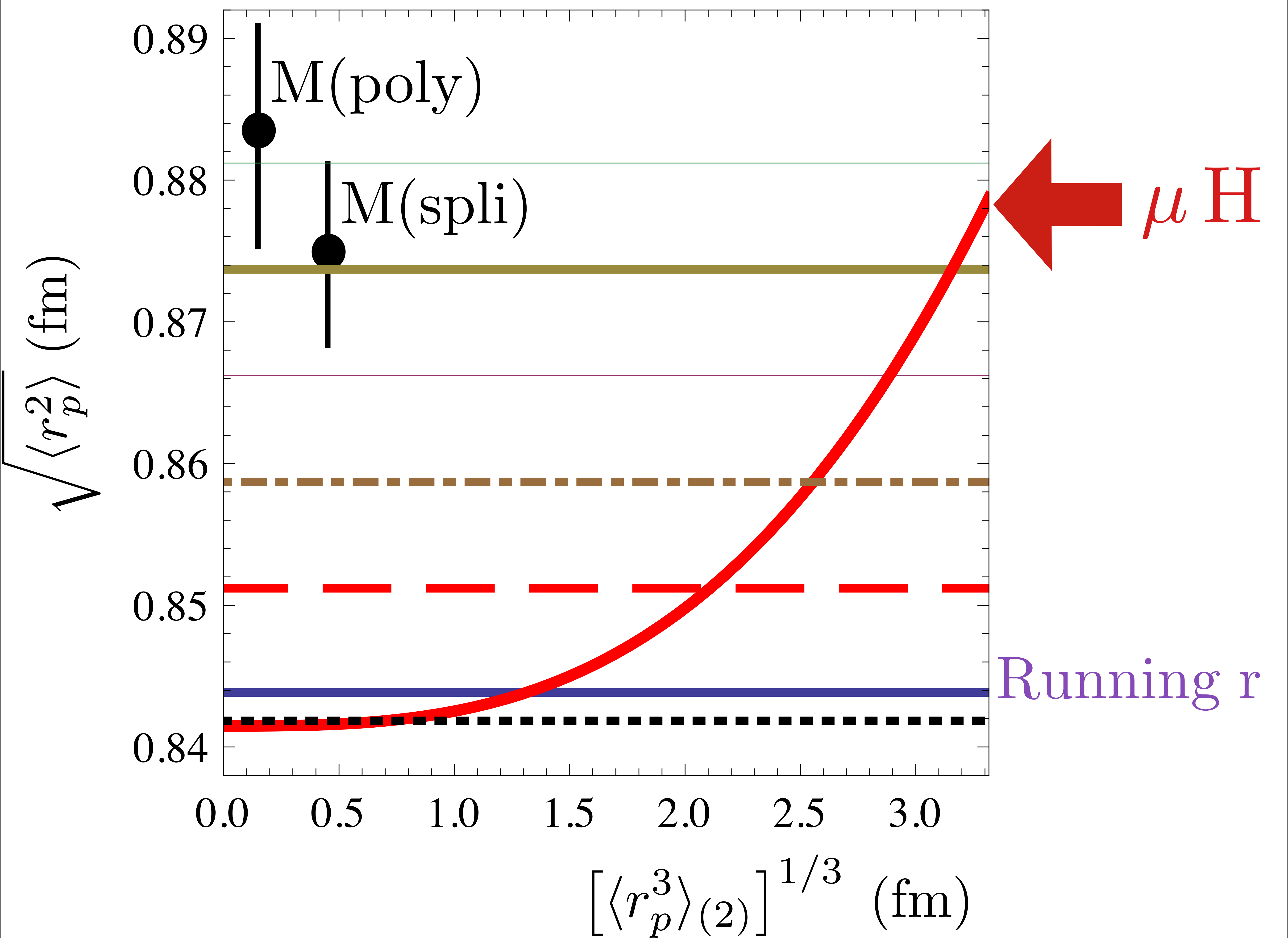


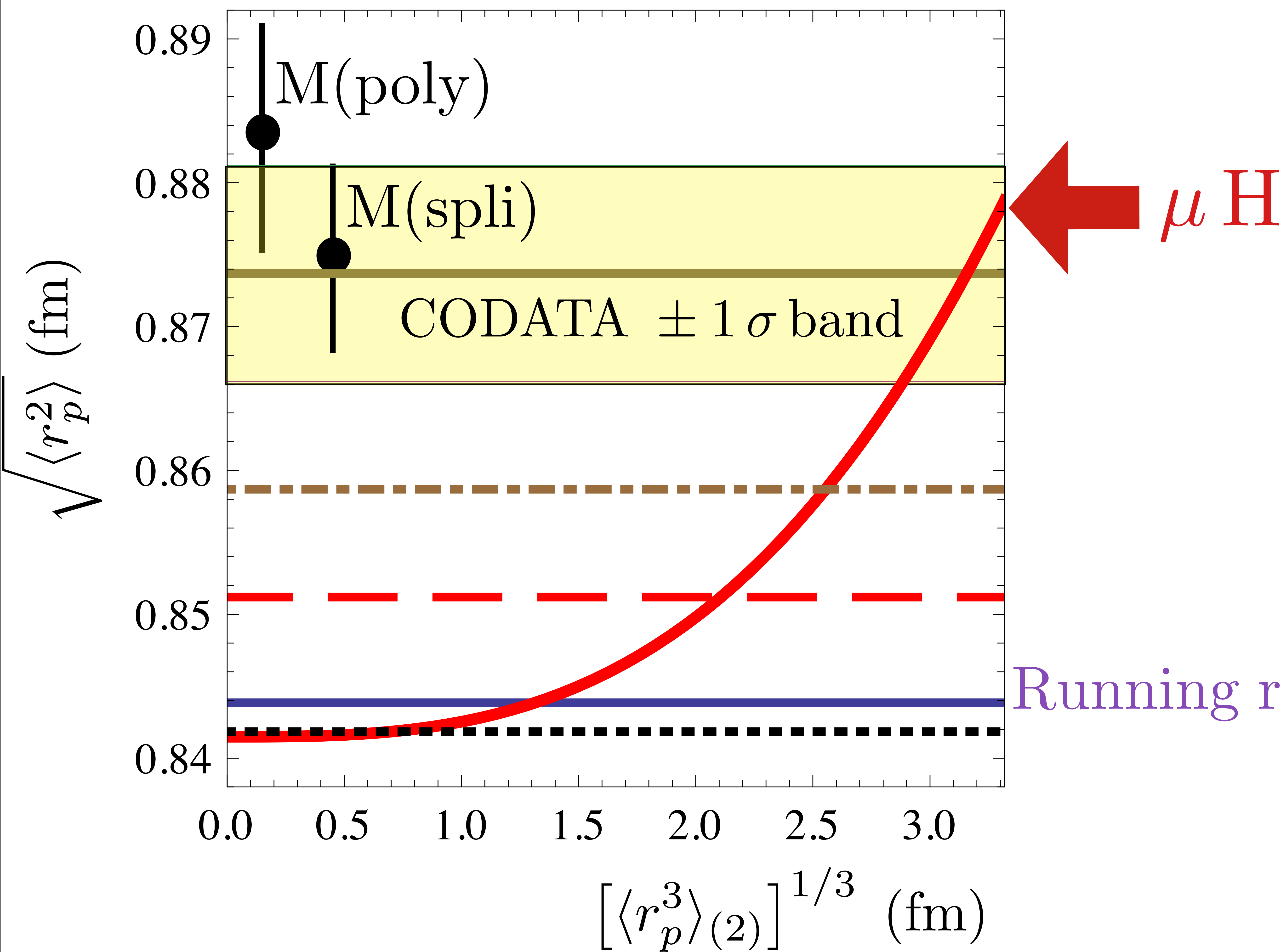
0.89
0.88
0.87
0.86
0.85
0.84
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)
μ H


0.89
0.88
0.87
0.86
0.85
0.84
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)
μ H
Running r

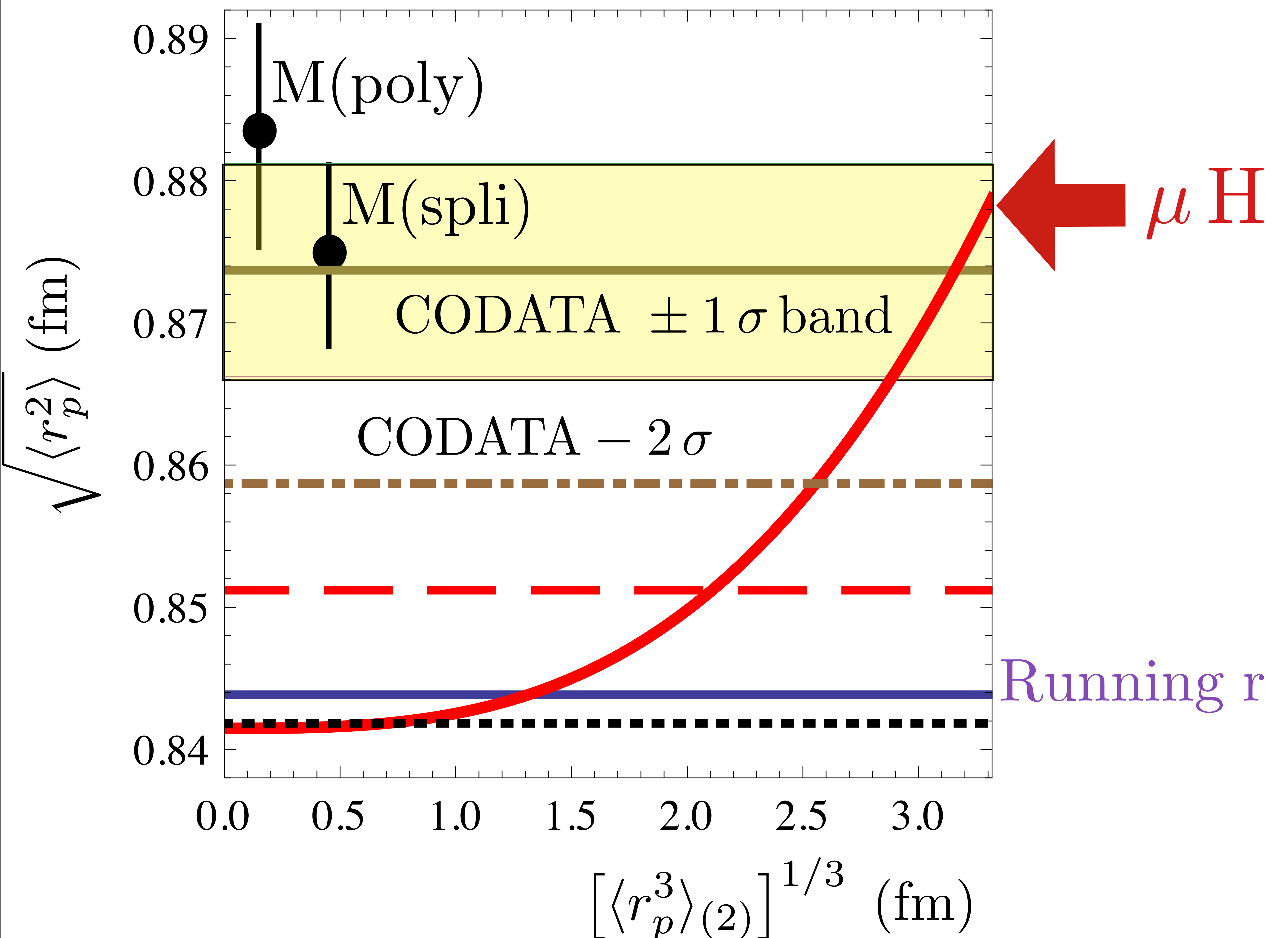


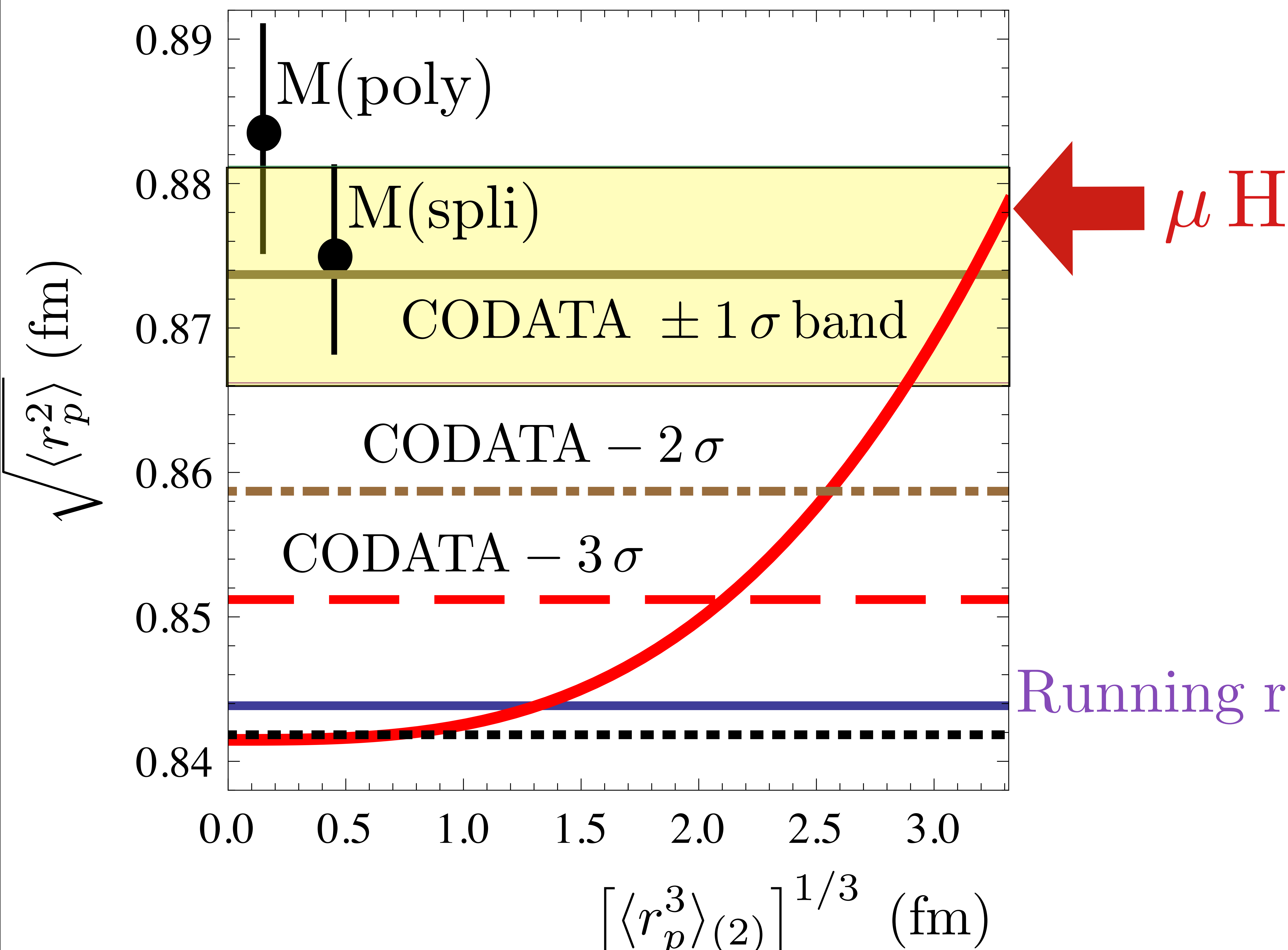
M(poly)
μ H
Running r
0.89
0.88
0.87
0.86
0.85
0.84
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)

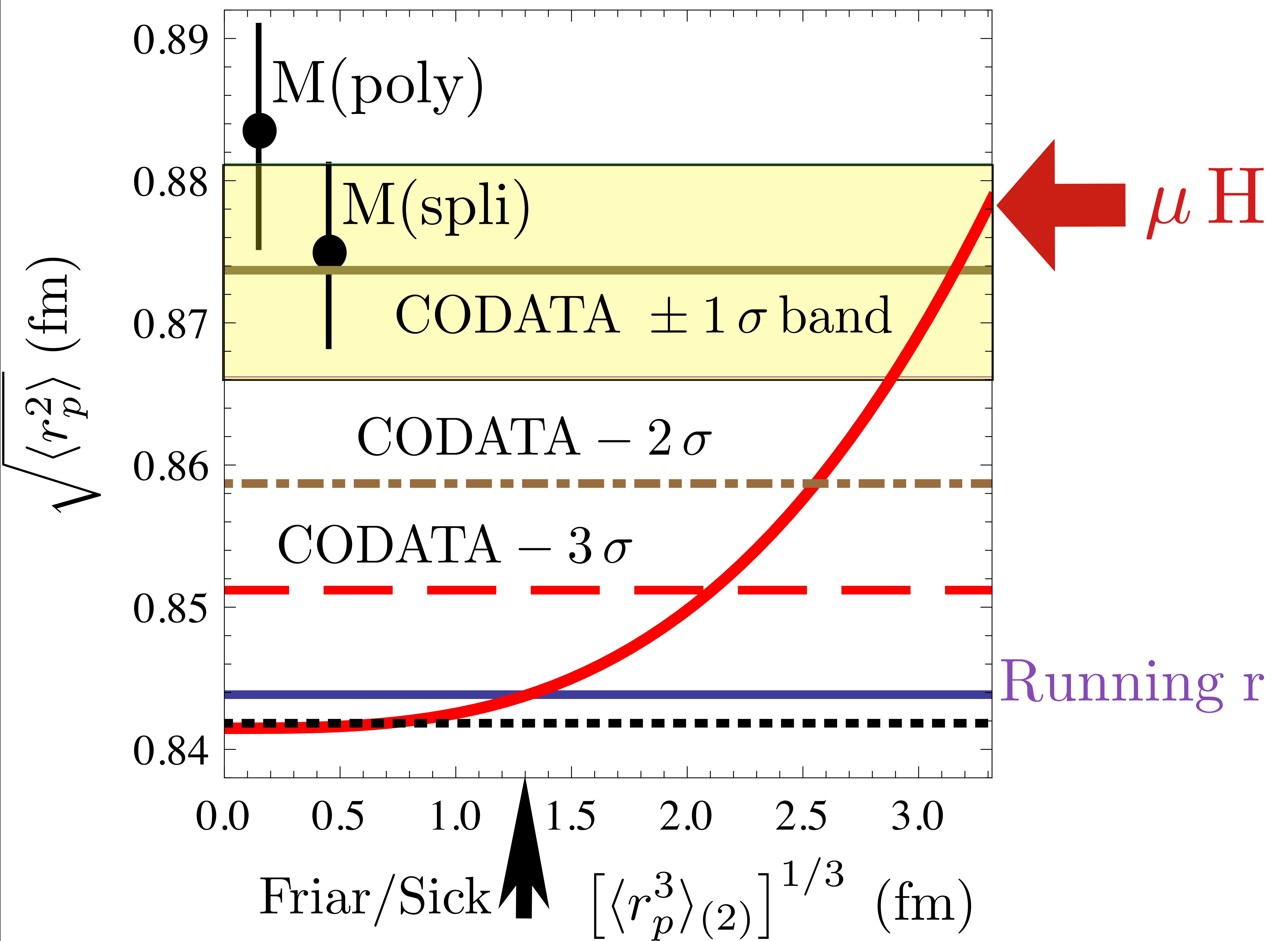

0.89
0.88
0.87
0.86
0.85
0.84
M(poly)
M(spli)
μ H
Running r
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)



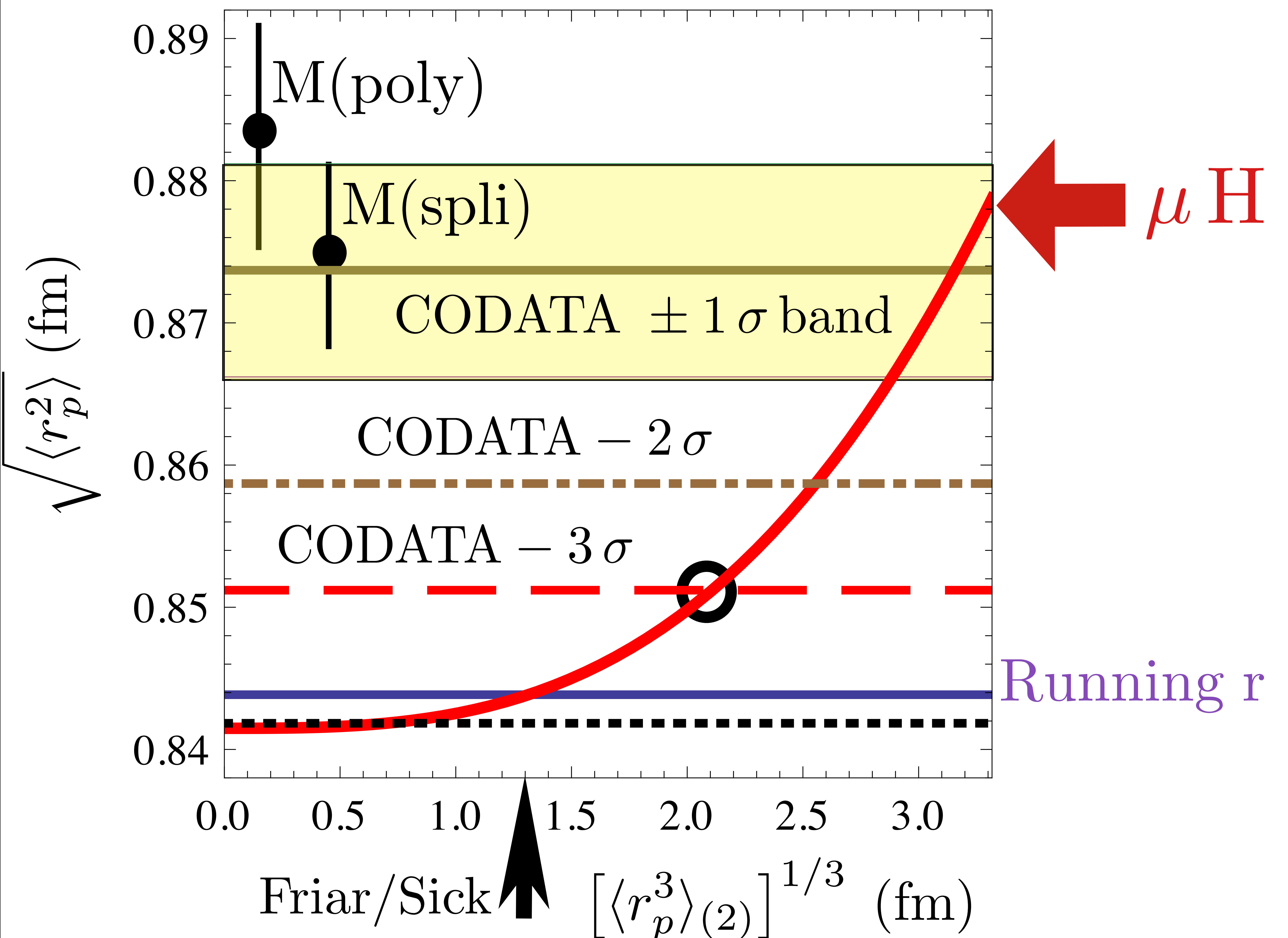
0.89
0.88
0.87
0.86
0.85
0.84
M(poly)
M(spli)
CODATA ± 1 σ band
μ H
Running r
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\sqrt{\langle r_p^2 \rangle}$ (fm)
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)


M(poly)
M(spli)
CODATA ± 1 σ band
CODATA − 2 σ
μ H
Running r
0.89
0.88
0.87
0.86
0.85
0.84
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\sqrt{\langle r_p^2 \rangle}$ (fm)
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)

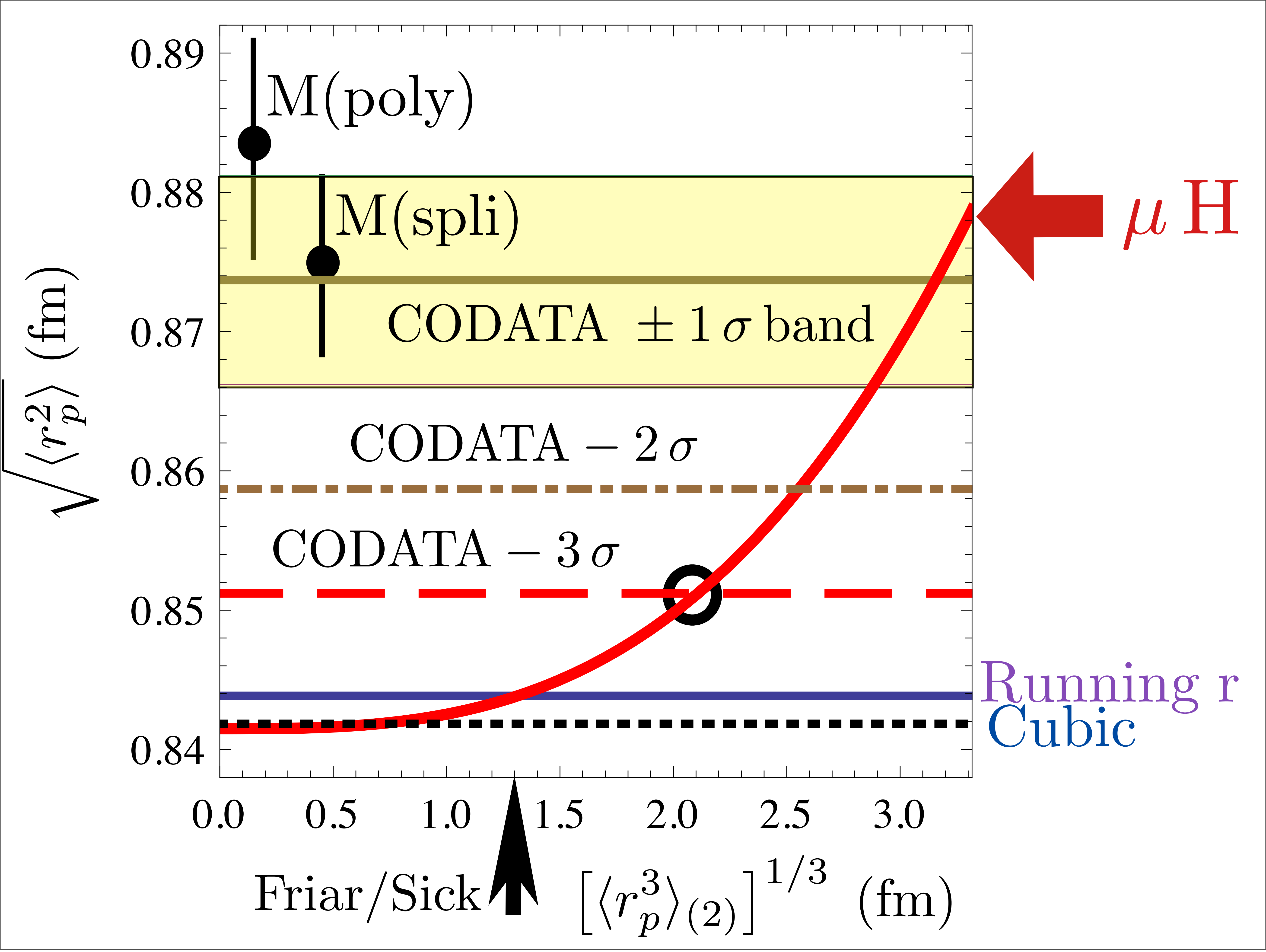

0.89
0.88
0.87
0.86
0.85
0.84
M(poly)
M(spli)
CODATA ±1σ band
CODATA − 2σ
CODATA − 3σ
μH
Running r
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\sqrt{\langle r_p^2 \rangle}$ (fm)
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)



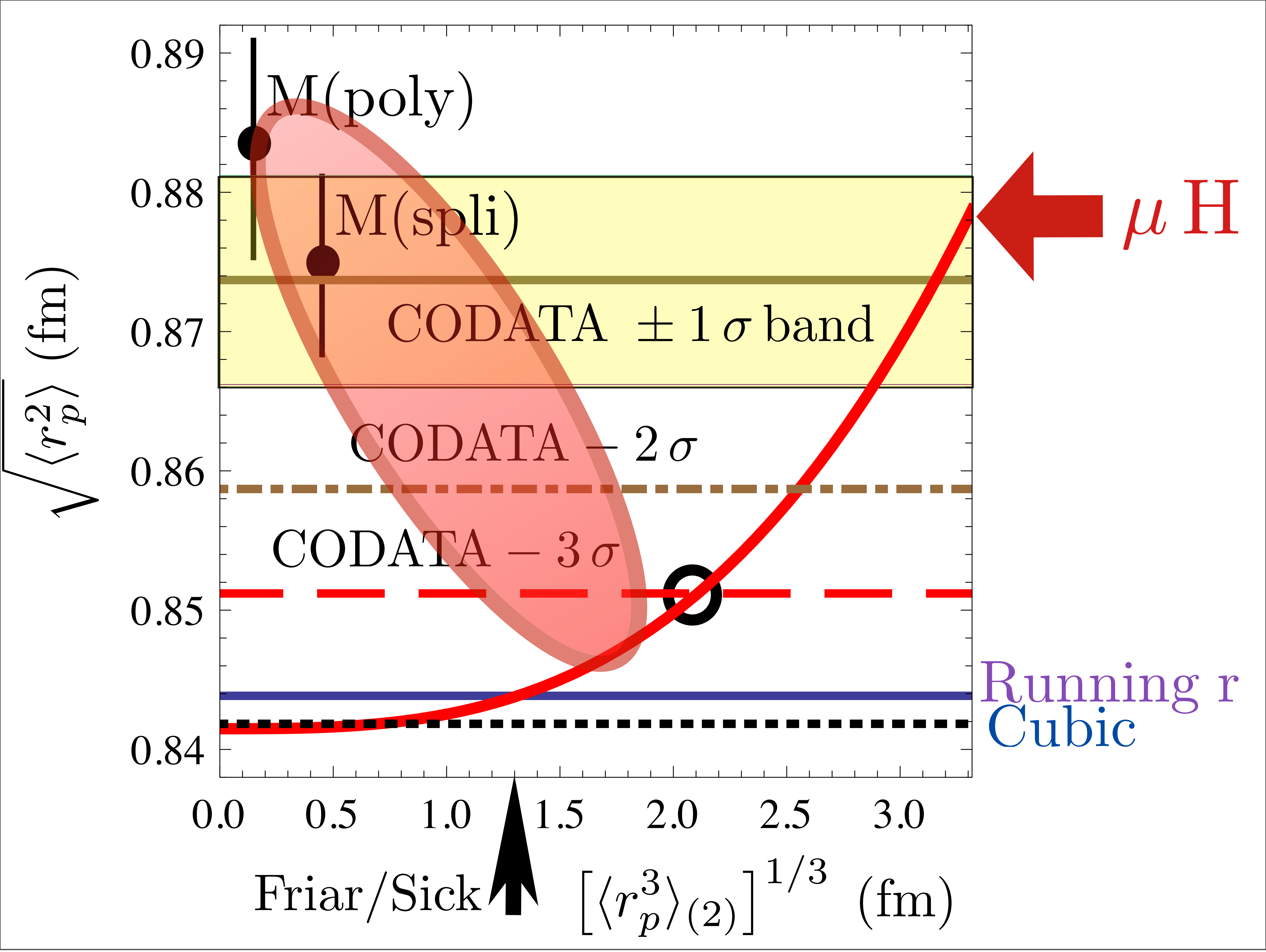
0.89
0.88
0.87
0.86
0.85
0.84
M(poly)
M(spli)
CODATA ±1 σ band
CODATA − 2 σ
CODATA − 3 σ
μ H
Running r
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Friar/Sick
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)



0.89
0.88
0.87
0.86
0.85
0.84
M(poly)
M(spli)
CODATA ± 1 σ band
CODATA − 2 σ
CODATA − 3 σ
μ H
Running r
$\sqrt{\langle r_p^2 \rangle}$ (fm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Friar/Sick
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)



M(poly)
M(spli)
CODATA ±1σ band
CODATA − 2σ
CODATA − 3σ
μ H
Running r
Cubic
0.89
0.88
0.87
0.86
0.85
0.84
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\sqrt{\langle r_p^2 \rangle}$ (fm)
Friar/Sick
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)



0.89
0.88
0.87
0.86
0.85
0.84
M(poly)
M(spli)
CODATA ±1 σ band
CODATA − 2 σ
CODATA − 3 σ
μ H
Running r
Cubic
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\sqrt{\langle r_p^2 \rangle}$ (fm)
Friar/Sick
$\left[\langle r_p^3 \rangle_{(2)}\right]^{1/3}$ (fm)

?

Ig Nobel Management Prize 2010

Ig Nobel Management Prize 2010

Pluchino, Rapisarda, and Garofalo of the Univ. of Catania, for demonstrating **mathematically** that organizations would become more efficient if they promoted people at random.

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REFERENCE: "The Peter Principle Revisited: A Computational Study," Alessandro Pluchino, Andrea Rapisarda, and Cesare Garofalo, Physica A, vol. 389, no. 3, February 2010, pp. 467-72.

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BASTA