Eötvös bounds on coupling of fundamental parameters to gravity

0805.0318 [hep-ph]

Thomas Dent

Institut für Theoretische Physik, University of Heidelberg

3. Kosmologietag, IBZ, Bielefeld 2008
Introduction

Astrophysical measurements

Atomic clocks and LPI

Gravitational effects of variation

Theory and bounds part 1

Theory part 2

Reviews, previous work:

- V. Flambaum and E. Shuryak, “How changing physical constants and violation of local position invariance may occur?”, physics/0701220
- D. Shaw, ”Detecting seasonal changes in the fundamental constants”, gr-qc/0702090
- TD, “Composition-dependent forces from varying $m_p/m_e$”, JHEP hep-ph/0608067
Motivation

Constancy of “constants” (couplings, mass ratios) is an assumption of particle physics and GR

Should be tested!

- Does it make sense to consider variation?
  Different fundamental “constants” at different points in spacetime breaks Einstein equivalence principle (Local Position Invariance)

- Generally covariant theories with “varying constants” can easily be constructed
  GR plus scalar field weakly coupled to radiation and matter

- Doing physics with “varying constants”
  1. Look for signals and set limits
  2. Look for related effects (WEP violation)
  3. A nonzero signal can rule out unified theories, test models of quintessence etc.

- Consider many probes: different $z$, different environments, spatial variation? ...
Motivation

Constancy of “constants” (couplings, mass ratios) is an assumption of particle physics and GR

Should be tested!

- Does it make sense to consider variation?
  Different fundamental “constants” at different points in spacetime breaks Einstein equivalence principle (Local Position Invariance)

- Generally covariant theories with “varying constants” can easily be constructed
  GR plus scalar field weakly coupled to radiation and matter

- Doing physics with “varying constants”
  1. Look for signals and set limits
  2. Look for related effects (WEP violation)
  3. A nonzero signal can rule out unified theories, test models of quintessence etc.

- Consider many probes: different $z$, different environments, spatial variation? . . .

Motivation

Constancy of “constants” (couplings, mass ratios) is an assumption of particle physics and GR
Should be tested!

- Does it make sense to consider variation?
  Different fundamental “constants” at different points in spacetime breaks Einstein equivalence principle (Local Position Invariance)

- Generally covariant theories with “varying constants” can easily be constructed
  GR plus scalar field weakly coupled to radiation and matter

- Doing physics with “varying constants”
  1. Look for signals and set limits
  2. Look for related effects (WEP violation)
  3. A nonzero signal can rule out unified theories, test models of quintessence etc.

- Consider many probes: different $z$, different environments, spatial variation? …
Alpha: measurement methods

\[ \omega_z = \omega_0 + q \left[ \left( \frac{\alpha_z}{\alpha} \right)^2 - 1 \right] \]

“Many-multiplet” method: different species with different \( q \) coefficients enhance sensitivity (Murphy et al., astro-ph/0209488)

Latest published result, 143 systems (astro-ph/0310318)

\[ \frac{\Delta \alpha}{\alpha} = (-0.57 \pm 0.11) \cdot 10^{-5}, \quad 0.2 < z_{\text{abs}} < 4.2 \]
Alpha: measurement methods

QSO absorption system, \( z = z_{\text{abs}} \)

\[
\omega_z = \omega_0 + q \left[ \left( \frac{\alpha_z}{\alpha} \right)^2 - 1 \right]
\]

“Many-multiplet” method: different species with different \( q \) coefficients enhance sensitivity (Murphy et al., astro-ph/0209488)

Latest published result, 143 systems (astro-ph/0310318)

\[
\frac{\Delta \alpha}{\alpha} = (-0.57 \pm 0.11) \cdot 10^{-5}, \quad 0.2 < z_{\text{abs}} < 4.2
\]
Alpha data

Fractional look–back time

Still controversial, spectra still being analyzed...
A new mu?

\[ \mu \equiv \frac{m_p}{m_e} \]

Vibro-rotational transitions of molecular hydrogen H\textsubscript{2}, different dependences on reduced mass

\[
2005 : \frac{\Delta \mu}{\mu} = (3.05 \pm 0.75) \cdot 10^{-5} \text{ (A)}, \quad (1.65 \pm 0.74) \cdot 10^{-5} \text{ (B)} \quad \text{Ivanchik et al.}
\]

Two different sets of lab wavelengths!

New lab measurements:

\[
\frac{\Delta \mu}{\mu} = (2.4 \pm 0.6) \cdot 10^{-5}, \quad z_{abs} = 3.02, 2.59 \quad \text{Reinhold et al. PRL 2006}
\]

Recently: NH\textsubscript{3} spectrum constraint on \(\Delta \mu/\mu\)

\[
\frac{\Delta \mu}{\mu} = (0.6 \pm 1.9) \cdot 10^{-6}, \quad z = 0.685 \quad \text{Flambaum and Kozlov, PRL 2007}
\]
A new mu? 

$\mu \equiv \frac{m_p}{m_e}$

Vibro-rotational transitions of molecular hydrogen $\text{H}_2$, different dependences on reduced mass

$$2005 : \frac{\Delta \mu}{\mu} = (3.05 \pm 0.75) \cdot 10^{-5} \text{ (A)}, \ (1.65 \pm 0.74) \cdot 10^{-5} \text{ (B)} \quad \text{Ivanchik et al.}$$

Two different sets of lab wavelengths!

New lab measurements:

$$\frac{\Delta \mu}{\mu} = (2.4 \pm 0.6) \cdot 10^{-5}, \ z_{abs} = 3.02, \ 2.59 \quad \text{Reinhold et al. PRL 2006}$$

Recently: $\text{NH}_3$ spectrum constraint on $\Delta \mu/\mu$

$$\frac{\Delta \mu}{\mu} = (0.6 \pm 1.9) \cdot 10^{-6}, \ z = 0.685 \quad \text{Flambaum and Kozlov, PRL 2007}$$
Atomic clocks

Absolute frequency standard: $^{133}$Cs ground state hyperfine transition

Measure some other transition in the lab over years ⇒ bound on fundamental “constant” variations (up to variation of $\mu_{\text{Cs}}$)

Example

- Atomic hydrogen 1S-2S transition $\nu_H \propto \text{Ry}$
- Mercury electric quadrupole transition $\nu_{\text{Hg}} \propto \text{Ry} \alpha^{-3.2}$
- Caesium hyperfine transition $\nu_{\text{Cs}} \propto \text{Ry} \alpha^2 \frac{\mu_{\text{Cs}}}{\mu_B} \alpha^{0.8}$

Eliminate $\mu_{\text{Cs}}$ to obtain $\dot{\alpha}/\alpha = (-0.9 \pm 2.9) \cdot 10^{-15} \text{ y}^{-1}$, \(\text{Fischer et al. PRL 2004}\)

Update: Peik et al. physics/0611088

\[ d \ln \alpha/dt = (-0.26 \pm 0.39) \times 10^{-15} \text{ y}^{-1}, \quad d \ln \mu/dt = (-1.2 \pm 2.2) \times 10^{-15} \text{ y}^{-1} \]
Atomic clocks

Absolute frequency standard: $^{133}\text{Cs}$ ground state hyperfine transition

Measure some other transition in the lab over years $\Rightarrow$ bound on fundamental “constant” variations (up to variation of $\mu_{\text{Cs}}$)

Example

- Atomic hydrogen 1S-2S transition $\nu_H \propto \text{Ry}$
- Mercury electric quadrupole transition $\nu_{\text{Hg}} \propto \text{Ry}\alpha^{-3.2}$
- Caesium hyperfine transition $\nu_{\text{Cs}} \propto \text{Ry}\alpha^2 \frac{\mu_{\text{Cs}}}{\mu_B} \alpha^{0.8}$

Eliminate $\mu_{\text{Cs}}$ to obtain $\dot{\alpha}/\alpha = (-0.9 \pm 2.9) \cdot 10^{-15} \text{ y}^{-1}$  \hspace{1cm} \text{Fischer et al. PRL 2004}

Update: Peik et al. physics/0611088

$$d \ln \alpha/dt = (-0.26 \pm 0.39) \times 10^{-15} \text{ y}^{-1}, \quad d \ln \mu/dt = (-1.2 \pm 2.2) \times 10^{-15} \text{ y}^{-1}$$
Seasonal variations and coupling to gravity

Recent bounds on spatial variation from atomic clocks

Earth elliptical orbit $\Rightarrow$ annual variation $\Delta U \simeq 3.3 \times 10^{-10}$

Consider variation of dimensionless parameters with $U \ e.g.$

$$\frac{\Delta \alpha}{\alpha} = k_\alpha \Delta U$$

Motivation: if variation occurs due to light scalar $\varphi$

$$\nabla^2 \varphi \simeq \lambda_s \rho$$

near massive source $\Rightarrow \varphi$ varies with $U$. 
Seasonal variations and coupling to gravity

Recent bounds on *spatial* variation from atomic clocks

Earth elliptical orbit $\Rightarrow$ annual variation $\Delta U \simeq 3.3 \times 10^{-10}$

Consider variation of dimensionless parameters with $U$ *e.g.*

$$\frac{\Delta \alpha}{\alpha} = k_\alpha \Delta U$$

Motivation: if variation occurs due to light scalar $\varphi$

$$\nabla^2 \varphi \simeq \lambda_s \rho$$

near massive source $\Rightarrow \varphi$ *varies with* $U$. 
Recent limits on couplings

S. Blatt et al., PRL vol. 100, 0801.1974

New Limits on Coupling of Fundamental Constants to Gravity Using $^{87}$Sr Optical Lattice Clocks

Three independent clocks measure $\nu_{\text{Sr}} = 429\,228\,004\,229\,874$ Hz over 3 years: width 2.1 Hz, agree to within $10^{-15}$ (fractional variation)

Relative to Cs standard definition of the second!

Use also Hg$^+$, Yb$^+$, H maser:

- $k_\alpha = (2.3 \pm 3.1) \times 10^{-6}$
- $k_\mu = (-1.1 \pm 1.7) \times 10^{-5}$
- $k_q = (-1.7 \pm 2.7) \times 10^{-5}$

$k_q \rightarrow (m_u + m_d)/\Lambda_c$

To do better: Send atomic clocks into space, increase $\Delta U$ to order $10^{-8}$?

Technically difficult
Recent limits on couplings

S. Blatt et al., PRL vol. 100, 0801.1974

**New Limits on Coupling of Fundamental Constants to Gravity Using $^{87}$Sr Optical Lattice Clocks**

Three independent clocks measure $\nu_{\text{Sr}} = 429\,228\,004\,229\,874$ Hz over 3 years: width $2.1$ Hz, agree to within $10^{-15}$ (fractional variation)

Relative to Cs standard definition of the second!

Use also Hg$^+$, Yb$^+$, H maser:

- $k_\alpha = (2.3 \pm 3.1) \times 10^{-6}$
- $k_\mu = (-1.1 \pm 1.7) \times 10^{-5}$
- $k_q = (-1.7 \pm 2.7) \times 10^{-5}$

$k_q \rightarrow (m_u + m_d)/\Lambda_c$

To do better: Send atomic clocks into space, increase $\Delta U$ to order $10^{-8}$?

Technically difficult
LPI vs. WEP

LPI concerns \emph{non-gravitational} experiments

But variations have dynamical effect:

Mass-energy of a body $M_b$ depends on space-time

$\Rightarrow$ Bodies sit in a “potential” $V(x) = M_b(x)$

do not follow geodesics: extra acceleration

\[
\vec{a} = -\frac{\vec{\nabla} M}{M} \quad \Rightarrow \quad \frac{|a|}{g} = \frac{\Delta \ln M}{\Delta U}
\]

Expand $M_b$ as function of varying parameters $G_i$:

\[
\Delta \ln M = \sum_i \frac{\partial \ln M}{\partial \ln G_i} \Delta \ln G_i
\]

therefore

\[
\frac{|a|}{g} = (-) \sum_i \lambda^b_i k_i \quad (k_i \equiv \Delta \ln G_i/\Delta U)
\]

define sensitivity parameter

\[
\lambda^b_i \equiv \frac{\partial \ln M_b}{\partial \ln G_i}
\]
LPI vs. WEP

LPI concerns *non-gravitational* experiments

But variations have dynamical effect:
Mass-energy of a body $M_b$ depends on space-time
⇒ Bodies sit in a “potential” $V(x) = M_b(x)$

do not follow geodesics: extra acceleration

$$\vec{a} = -\frac{\nabla M}{M} \quad \Rightarrow \quad \frac{|a|}{g} = \frac{\Delta \ln M}{\Delta U}$$

Expand $M_b$ as function of varying parameters $G_i$:

$$\Delta \ln M = \sum_i \frac{\partial \ln M}{\partial \ln G_i} \Delta \ln G_i$$

therefore

$$\frac{|a|}{g} = (-) \sum_i \lambda_i^b k_i \quad (k_i \equiv \Delta \ln G_i/\Delta U)$$

define sensitivity parameter

$$\lambda_i^b \equiv \frac{\partial \ln M_b}{\partial \ln G_i}$$
Eötvös experiment

Can we measure $\vec{a}$?

Same direction as $\vec{g}$ but $10^{-5}$ times smaller . . . No

WEP: objects of different composition free-fall the same way

consider test bodies $M_b, M_c$, measure

$$\eta \equiv \frac{a_b - a_c}{g}$$

can be done to $10^{-13}$ precision (Schlamminger (2008) PRL)

NB bodies not freely falling, use $\vec{a}_b - \vec{a}_c$ in direction of Sun or Earth centre

($\neq$ vertical due to rotation)

Find:

$$\eta = \sum_i \frac{\partial \ln(M_b/M_c)}{\partial \ln G_i} k_i \equiv \sum_i \lambda_i^{b-c} k_i$$
Can we measure $\vec{a}$?

Same direction as $\vec{g}$ but $10^{-5}$ times smaller . . . No

WEP: objects of *different composition* free-fall the same way

can be done to $10^{-13}$ precision *(Schlamminger (2008) PRL)*

NB bodies *not* freely falling, use $\vec{a}_b - \vec{a}_c$ in direction of Sun or Earth centre

(≠ vertical due to rotation)

Find:

$$\eta = \sum_i \frac{\partial \ln(M_b/M_c)}{\partial \ln G_i} k_i \equiv \sum_i \lambda_{b,c}^i k_i$$
Nuclear parameters

What is the mass of a body?

\[ Z \text{ protons} + \text{electrons}, A - Z \text{ neutrons}, \text{nuclear binding energy (strong & electromagnetic)} \]

Consider \( \Delta \ln((M_b/Am_N)/(M_c/Am_N)) \)

\[
\frac{M}{Am_N} = 1 \left( f_p - \frac{1}{2} \right) \frac{\delta_N}{m_N} + f_p \frac{m_e}{m_N} + \frac{Z(Z-1)}{A^{4/3}} \frac{a_C}{m_N} - \frac{a_V}{m_N} + A^{-1/3} \frac{a_S}{m_N} + \cdots 
\]

\( (f_p = Z/A) \) with

\[
\delta_N \equiv m_n - m_p \simeq 1.29 \text{ MeV}, \quad a_C \simeq 0.7 \text{ MeV} \propto \alpha \quad a_V \simeq 16 \text{ MeV} \simeq a_S
\]

We find

\[
\Delta \ln \frac{M_b}{M_c} \simeq \left( -\frac{\delta_N}{m_N} \Delta \ln \frac{\delta_N}{m_N} + \frac{m_e}{m_N} \Delta \ln \frac{m_e}{m_N} \right) \hat{\Delta}_{b-c} f_p \\
+ \frac{a_C}{m_N} \Delta \ln \alpha \hat{\Delta}_{b-c} \frac{Z(Z-1)}{A^{4/3}} + \frac{a_S}{m_N} \Delta \ln \frac{a_S}{m_N} \hat{\Delta}_{b-c} A^{-1/3} + \cdots
\]

\( \hat{\Delta} \) means difference between bodies \( b \) and \( c \)

combine \( \delta_N \) and \( m_e \) as \( Q_n \equiv m_n - (m_p + m_e) \) with coupling \( k_{Q_n} \)
Nuclear parameters

What is the mass of a body?

\( Z \) protons + electrons, \( A - Z \) neutrons, nuclear binding energy (strong & electromagnetic)

Consider \( \Delta \ln((M_b/Am_N)/(M_c/Am_N)) \)

\[
\frac{M}{Am_N} = 1 - \left( f_p - \frac{1}{2} \right) \frac{\delta_N}{m_N} + f_p \frac{m_e}{m_N} + \frac{Z(Z-1)}{A^{4/3}} \frac{a_C}{m_N} - \frac{a_V}{m_N} + A^{-1/3} \frac{a_S}{m_N} + \ldots
\]

(\( f_p = Z/A \)) with

\[ \delta_N \equiv m_n - m_p \simeq 1.29 \text{ MeV}, \quad a_C \simeq 0.7 \text{ MeV} \propto \alpha \quad a_V \simeq 16 \text{ MeV} \simeq a_S \]

We find

\[
\Delta \ln \frac{M_b}{M_c} \simeq \left( -\frac{\delta_N}{m_N} \Delta \ln \frac{\delta_N}{m_N} + \frac{m_e}{m_N} \Delta \ln \frac{m_e}{m_N} \right) \hat{\Delta}_{b-c} f_p \\
+ \frac{a_C}{m_N} \Delta \ln \alpha \frac{Z(Z-1)}{A^{4/3}} + \frac{a_S}{m_N} \Delta \ln \frac{a_S}{m_N} \hat{\Delta}_{b-c} A^{-1/3} + \ldots
\]

\( \hat{\Delta} \) means difference between bodies \( b \) and \( c \)

combine \( \delta_N \) and \( m_e \) as \( Q_n \equiv m_n - (m_p + m_e) \) with coupling \( k_{Q_n} \)
Experiments and materials

- **Schlamminger et al.** 2008: Be–Ti, \( \eta = (0.3 \pm 1.8) \times 10^{-13} \)
- **Baeßler et al.** 1999: Fe–SiO\(_2\), \( \eta = (0.5 \pm 9.4) \times 10^{-13} \)
- **Braginsky and Panov** 1972: Pt–Al, \( \eta = (-0.3 \pm 0.4) \times 10^{-12} \)

<table>
<thead>
<tr>
<th>Material</th>
<th>( A )</th>
<th>( Z )</th>
<th>( f_p - 0.5 )</th>
<th>( \frac{Z(Z-1)}{A^{4/3}} )</th>
<th>( A^{-1/3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>9</td>
<td>4</td>
<td>-0.0556</td>
<td>0.64</td>
<td>0.481</td>
</tr>
<tr>
<td>Al</td>
<td>27</td>
<td>13</td>
<td>-0.0185</td>
<td>1.93</td>
<td>0.333</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>21.6</td>
<td>10.8</td>
<td>0</td>
<td>1.74</td>
<td>0.365</td>
</tr>
<tr>
<td>Ti</td>
<td>47.9</td>
<td>22</td>
<td>-0.042</td>
<td>2.65</td>
<td>0.275</td>
</tr>
<tr>
<td>Fe</td>
<td>56</td>
<td>26</td>
<td>-0.0357</td>
<td>3.03</td>
<td>0.261</td>
</tr>
<tr>
<td>Pt</td>
<td>195.1</td>
<td>78</td>
<td>-0.1</td>
<td>5.31</td>
<td>0.172</td>
</tr>
</tbody>
</table>
Bounds on “nuclear” couplings

Derive $\chi^2$ as function of couplings $(k_{Qn}, k_\alpha, k_{aS})$

Project likelihood onto each direction: null bounds

\[
\{\sigma(k_{Qn}), \sigma(k_\alpha), \sigma(k_{aS})\} = \{38, 2.3, 1.0\} \times 10^{-9}
\]

May also include nuclear asymmetry energy $a_A \propto a_S$ (coupling $k_{aA} = k_{aS} = k_{nuc}$), similar results

3 orders of magnitude tighter than atomic clock bounds

Clocks killed by $\Delta U \sim 10^{-10}$, WEP affected by $a_C/m_N \sim 8 \times 10^{-4}$

Space-based WEP experiments (MICROSCOPE, STEP) may improve by 2+ orders of magnitude
Bounds on “nuclear” couplings

Derive $\chi^2$ as function of couplings $(k_{Qn}, k_\alpha, k_{aS})$

Project likelihood onto each direction: null bounds

$$\{\sigma(k_{Qn}), \sigma(k_\alpha), \sigma(k_{aS})\} = \{38, 2.3, 1.0\} \times 10^{-9}$$

May also include nuclear asymmetry energy $a_A \propto a_S$ (coupling $k_{aA} = k_{aS} = k_{nuc}$), similar results

3 orders of magnitude tighter than atomic clock bounds

Clocks killed by $\Delta U \sim 10^{-10}$, WEP affected by $a_C/m_N \sim 8 \times 10^{-4}$

Space-based WEP experiments (MICROSCOPE, STEP) may improve by 2+ orders of magnitude
Fundamental parameters

We bounded couplings to \( Q_n/m_N = (m_n - m_p - m_e)/m_N, \alpha, a_S/m_N \)

Change basis to elementary particle physics (SM) parameters

\[
k_i = F_{ik} k'_k, \quad F_{ik} = \frac{\partial \ln G_i}{\partial \ln G'_k}
\]

parameters to consider:

- \( \alpha \) (coupling \( k'_\alpha \))
- electron mass \( m_e/\Lambda_c \) (\( k'_e \))
- light quark mass \( m_q/\Lambda_c \equiv (m_u + m_d)/2\Lambda_c \) (\( k'_q \))
- up-down mass difference \( \delta_q/\Lambda_c \equiv (m_d - m_u)/\Lambda_c \) (\( k'_{\delta q} \))
- strange quark mass \( m_s/\Lambda_c \)

normalise to the QCD strong interaction scale \( \Lambda_c \)

Use QCD (chiral perturbation theory) to find dependence of \( m_N \equiv (m_n + m_p)/2 \) and \( m_n - m_p \)

Dependence of nuclear binding energy on QCD parameters is unclear

\( \ldots \) dependence of almost everything on \( m_s/\Lambda_c \) is unclear, need to assume \( \Delta \ln (m_s/\Lambda_c) \rightarrow 0 \)
Fundamental parameters

We bounded couplings to \( Q_n/m_N = (m_n - m_p - m_e)/m_N, \alpha, a_S/m_N \)

Change basis to elementary particle physics (SM) parameters

\[
k_i = F_{ik} k'_k, \quad F_{ik} = \frac{\partial \ln G_i}{\partial \ln G'_k}
\]

parameters to consider:

- \( \alpha \) (coupling \( k'_\alpha \))
- electron mass \( m_e/\Lambda_c \) (\( k'_e \))
- light quark mass \( m_q/\Lambda_c \equiv (m_u + m_d)/2\Lambda_c \) (\( k'_q \))
- up-down mass difference \( \delta_q/\Lambda_c \equiv (m_d - m_u)/\Lambda_c \) (\( k'_{\delta q} \))
- strange quark mass \( m_s/\Lambda_c \)

normalise to the QCD strong interaction scale \( \Lambda_c \)

Use QCD (chiral perturbation theory) to find dependence of \( m_N \equiv (m_n + m_p)/2 \) and \( m_n - m_p \)

Dependence of nuclear binding energy on QCD parameters is unclear

\( \ldots \) dependence of almost everything on \( m_s/\Lambda_c \) is unclear, need to assume

\( \Delta \ln(m_s/\Lambda_c) \to 0 \)
Fundamental parameters and bounds

Deuterium binding dependence on $m_{\pi}/\Lambda_c \propto \sqrt{m_q/\Lambda_c}$ calculated in effective field theory:

$$\Delta \ln \frac{B_D}{\Lambda_c} = r \Delta \ln \frac{m_{\pi}}{\Lambda_c}, \quad -10 < r < -6$$

We estimated (TD/Stern/Wetterich 2007)

$$\frac{\partial B_i}{\partial m_{\pi}} \sim (A_i - 1) \frac{\partial B_D}{\partial m_{\pi}} = (A_i - 1) r \frac{B_D}{m_{\pi}}$$

may have error of 100% plus . . .

Transform from “nuclear” couplings ($k_{Qn}$, $k_{\alpha}$, $k_{aS}$) to “fundamental” couplings ($k'_{\delta f}$, $k'_{\alpha}$, $k'_{q}$) via $F_{ik}$:

$$F = \begin{pmatrix} 2.6 & -0.97 & -0.05 \\ 0 & 1 & 0 \\ 0 & 0 & -0.9 \end{pmatrix}$$

$k'_{\delta f} \equiv k'_{\delta q} - 0.25k'_{e}$ from dependence of $m_n - m_p$

Bounds

$$\{\sigma(k'_{\delta f}), \sigma(k'_{\alpha}), \sigma(k'_{q})\} = \{14, 1.7, 0.9\} \times 10^{-9}.$$
Fundamental parameters and bounds

Deuterium binding dependence on $m_\pi/\Lambda_c \propto \sqrt{m_q/\Lambda_c}$ calculated in effective field theory:

$$\Delta \ln \frac{B_D}{\Lambda_c} = r \Delta \ln \frac{m_\pi}{\Lambda_c}, \quad -10 < r < -6$$

We estimated (TD/Stern/Wetterich 2007)

$$\frac{\partial B_i}{\partial m_\pi} \sim (A_i - 1) \frac{\partial B_D}{\partial m_\pi} = (A_i - 1)r \frac{B_D}{m_\pi}$$

may have error of 100% plus...

Transform from “nuclear” couplings ($k_{Qn}, k_\alpha, k_{aS}$) to “fundamental” couplings ($k '_{\delta f}, k '_{\alpha}, k '_{q}$) via $F_{ik}$:

$$F = \begin{pmatrix} 2.6 & -0.97 & -0.05 \\ 0 & 1 & 0 \\ 0 & 0 & -0.9 \end{pmatrix}$$

$k '_{\delta f} \equiv k '_{\delta q} - 0.25k '_e$ from dependence of $m_n - m_p$

Bounds

$$\{\sigma(k '_{\delta f}), \sigma(k '_{\alpha}), \sigma(k '_{q})\} = \{14, 1.7, 0.9\} \times 10^{-9}.$$
Outlook

Bounding couplings to scalar $\varphi$: also consider coupling to source $\lambda_s$

Done in (TD, hep-ph/0608067) for specific classes of model relating values of $k_i$

Not done for general $k_i$ or including nuclear binding energy effects

With bounds on $\partial \ln G_i / \partial \varphi$ can use cosmology to determine/limit $\varphi$ time evolution

$\Rightarrow$ cosmic history of “constants”

Ongoing project with S. Stern, C. Wetterich to “unify” high-z / recent / local probes of variation
Bounding couplings to scalar $\varphi$: also consider coupling to source $\lambda_s$

Done in (TD, hep-ph/0608067) for specific classes of model relating values of $k_i$

Not done for general $k_i$ or including nuclear binding energy effects

With bounds on $\partial \ln G_i / \partial \varphi$ can use cosmology to determine/limit $\varphi$ time evolution

$\Rightarrow$ cosmic history of “constants”

Ongoing project with S. Stern, C. Wetterich to “unify” high-z / recent / local probes of variation