The Low-Energy Frontier of the Standard Model:

from Quarks and Gluons to Hadrons and Nuclei

Marc Vanderhaeghen

Colloquium, University of Pavia, May 30, 2013
Frontiers of the Standard Model

New Physics

High-Energy Frontier

Precision Frontier

Low-Energy Frontier

Terra incognita

Fra Mauro (1459)
Frontiers of the Standard Model

LHC
Higgs discovery
Production of new physics particles
Later: ILC

New Physics

High-Energy Frontier

Low-Energy Frontier

Terra incognita

Precision Frontier

Selected diphoton sample

\[
\begin{align*}
\text{Data 2011-2012} & \quad \text{Sig+Bkg Fit (m_{\gamma\gamma} = 126.8 GeV)} \\
\text{ATLAS Preliminary} & \quad \text{Bkg (4th order polynomial)}
\end{align*}
\]

\[
\begin{align*}
\tau_s & = 7 \text{ TeV}, \quad \int Ldt = 4.8 \text{ fb}^{-1} \\
\tau_s & = 8 \text{ TeV}, \quad \int Ldt = 20.7 \text{ fb}^{-1}
\end{align*}
\]
Frontiers of the Standard Model

New Physics

Testing SM at low energies, quantum loop corrections
\( \sin^2 \theta_W \)
\( (g-2)\mu \)
EDM
Flavor physics
Atomic physics

High-Energy Frontier

Low-Energy Frontier

Terra incognita
Hadron physics: Strong interactions, Complex systems

How do quarks/gluons merge into hadrons?
How does hadron structure emerge from basic constituents?
Mass and spin of hadrons?
Central aim of subatomic physics: unraveling the internal structure of hadrons and nuclei.

Physics of Hadrons:
- a) quarks, gluons
- b) constituent quarks
- c) baryons, mesons

Physics of Nuclei:
- d) protons, neutrons
- e) nucleonic densities and currents
- f) collective coordinates

Degrees of Freedom

Energy (MeV)
- 940 neutron mass
- 140 pion mass
- 8 proton separation energy in lead
- 1.32 vibrational state in tin
- 0.043 rotational state in uranium

Complexity:
- Hot and dense quark-gluon matter
- Hadron structure
- Hadron-Nuclear interface
- Nuclear structure
- Nuclear reactions
- Nuclear astrophysics
- Applications of nuclear science
The „Simple“ : unraveling the structure of mesons and baryons

- **Basic question: unraveling strong QCD**
  Origin of mass, spin, imaging of hadrons

- **Precision hadron physics**
  Impact on new physics
  searches: \((g-2)_\mu\) , dark photon search, proton radius puzzle, weak mixing angle

- **Theory tools**
  lattice QCD: ab initio
  EFT/phenomenology: interplay with precision hadron data
The „Complex“: exploring and understanding the nuclear landscape

- **Few-body systems**
  Baryon-baryon interaction from QCD: *ab initio*

- **Neutron-rich matter**
  Nuclear equation of state, neutron stars, supernovae: neutron skin in heavy nuclei

- **Nucleosynthesis**
  Origin of heavy elements: r-process path, production of neutron-rich isotopes
magnetic moment of muon

\[ a_\mu = \frac{(g - 2)_\mu}{2} \]
magnetic moment of muon \( a_\mu = (g-2)_\mu /2 \)

**Magnetic Moment:** \( \vec{m} = \mu_B \, g \, \vec{S} \)

\( \mu_B: \) Bohr magneton,
\( g: \) gyromagnetic factor

**Muon Anomaly:** \( a_\mu = (g-2)_\mu / 2 = \alpha_{em}/2\pi + \ldots = 0.001161 \ldots \)

**Standard Model (SM) prediction** \( a_\mu^{SM} \):
- QED: \( a_\mu^{QED} = (11\,658\,471.896 \pm 0.008) \cdot 10^{-10} \) up to \( \alpha_{em}^5 \)!
- weak: \( a_\mu^{\text{weak}} = (15.4 \pm 0.2) \cdot 10^{-10} \)
- strong: \( a_\mu^{\text{strong}} = (696.7 \pm 5.9) \cdot 10^{-10} \)

\[ a_\mu^{SM} = (11\,659\,184.0 \pm 5.9) \times 10^{-10} \]

Aoyama, Hayakawa, Kinoshita, Nio (2012)

SM prediction entirely limited by strong interactions!

Sensitive test of the Standard Model (SM) and eventually of particles beyond the SM

\[ (a_\mu^{SM} - a_\mu^{exp}) = a_\mu^\text{New Physics} \ (??) \]

Need experimental and theoretical programme in hadron physics to reduce uncertainty of \( a_\mu^{\text{strong}} \)
Hadron physics impact on new physics searches: magnetic moment of muon $a_\mu = (g - 2)_\mu / 2$

**Standard Model predictions $(g-2)_\mu$**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>JN 09 $(e^+e^-)$-based</td>
<td>$-299 \pm 65$</td>
</tr>
<tr>
<td>DHMZ 10 ($\tau$-based)</td>
<td>$-195 \pm 54$</td>
</tr>
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<td>DHMZ 10 $(e^+e^-)$</td>
<td>$-287 \pm 49$</td>
</tr>
<tr>
<td>HLMNT 11 $(e^+e^-)$</td>
<td>$-261 \pm 49$</td>
</tr>
<tr>
<td>BNL-E821 (world average)</td>
<td>$0 \pm 63$</td>
</tr>
</tbody>
</table>

**BNL-E821 2004**

$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (24.9 \pm 8.7) \times 10^{-10}$ (3 $\sigma$)

- **Error(s) or New Physics?**
- $\Rightarrow$ **Clarify situation!**

**E821 measurement of $(g-2)_\mu$**

$a_\mu^{\text{exp}} = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$
Hadron physics impact on new physics searches: magnetic moment of muon $a_\mu = (g - 2)_\mu / 2$

**Standard Model predictions $(g-2)_\mu$**

- JN 09 ($e^+e^-$-based) $-299 \pm 65$
- DHMZ 10 ($\tau$-based) $-195 \pm 54$
- DHMZ 10 ($e^+e^-$) $-287 \pm 49$
- HLMNT 11 ($e^+e^-$) $-261 \pm 49$
- BNL-E821 (world average) $0 \pm 63$

**Error(s) or New Physics?**

$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (24.9 \pm 8.7) \cdot 10^{-10}$ (3 $\sigma$)

→ Clarify situation!

**New FNAL $(g-2)_\mu$ measurement (2016):**

Factor 4 improvement in experimental error

$\delta a_\mu^{\text{exp}} = 1.6 \times 10^{-10}$

→ Improve $a_\mu^{\text{had}}$!
Hadronic contributions to \((g - 2)_\mu\)

**Hadronic vacuum polarization**

\[ a_{\mu, \text{had, VP}} = (692.3 \pm 4.2) \times 10^{-10} \]

will be improved by cross section measurements of \(e^+ e^- \rightarrow \text{hadrons}\)

**BABAR, BES-III**

**Hadronic light-by-light scattering**

\[ a_{\mu, \text{had, LbL}} = (11.6 \pm 4.0) \times 10^{-10} \]

improved by meson transition form factor measurements and further theory developments

**BES-III, MAMI**

Jegerlehner, Nyffeler (2009)
Optical theorem and analyticity allow to relate HVP contribution to \((g-2)_\mu\) with \(\sigma_{\text{had}} = \sigma(e^+e^-\rightarrow\text{hadrons})\)

\[
\alpha^{\text{had,VP}}_\mu = \frac{1}{4\pi^3} \int_{4m^2_\pi}^{\infty} ds \, K(s) \sigma_{\text{had}}
\]

\(\sigma_{\text{had}}: \) Energy range up to 3 GeV essential!
Hadronic vacuum polarization: measurement via ISR at $e^+e^-$ colliders

Approach for measuring hadronic cross section at modern particle factories with fixed c.m.s. energy $\sqrt{s}$: Initial State Radiation (ISR)

**ISR method allows access to mass range $M_{\text{hadr}} < 3$ GeV at BES-III**

→ Continue ISR success story
Hadronic light-by-light scattering

\[ Q_1^2 \quad Q_2^2 \]

\[ pQCD \]

multi-scale problem - mixed soft-hard regions

Non-perturbative hadronic physics input needed!

short distance

chiral expansion

perturbative regime

1/Nc - expansion

\[ \pi^0, \eta, \eta', f_1, f_2 \ldots \]

long distance

\[ \pi^{+-}, K^{+-} \]

u, d, s
**γγ physics: quark structure of mesons**

- **BaBar and Belle data not in agreement!**
  - 
  \[
  F_{\pi^0\gamma^*\gamma} \xrightarrow{Q^2 \to \infty} \frac{2 f_{\pi}}{Q^2}
  \]
  - **γ** - **γ** → **π**
  - spacelike: \( q^2 = -Q^2 < 0 \)
  - timelike: \( q^2 > 0 \)

**Simulations for 1y running at BES-III (10 fb\(^{-1}\))**

**B. Kloss (2011)**
Light-by-light scattering sum sum rules

\[ \int_{s_0}^{\infty} \frac{ds}{s} \left[ \sigma_2(s) - \sigma_0(s) \right] = 0 \]

Euler, Heisenberg (1936)

\[ c_1 \pm c_2 = \frac{1}{8\pi} \int_{s_0}^{\infty} \frac{ds}{s^2} \left[ \sigma_\parallel(s) \pm \sigma_\perp(s) \right] \]

Pauk, Pascalutsa, Vdh (2012, 2013)
light meson production in $\gamma\gamma$ collisions

$$0 = \int_{s_0}^{\infty} ds \left[ \frac{\sigma_2 - \sigma_0}{s} \right](s)$$

$$c_1 \pm c_2 = \frac{1}{8\pi} \int_{s_0}^{\infty} ds \left[ \frac{\sigma_\parallel \pm \sigma_\perp}{s^2} \right](s)$$

<table>
<thead>
<tr>
<th>Isospin = 0 state</th>
<th>$m_M$ [MeV]</th>
<th>$\Gamma_{\gamma\gamma}$ [keV]</th>
<th>$\int \frac{ds}{s} (\sigma_2 - \sigma_0)$ [nb]</th>
<th>$c_1$ [10$^{-4}$GeV$^{-4}$]</th>
<th>$c_2$ [10$^{-4}$GeV$^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>547.853 ± 0.024</td>
<td>0.510 ± 0.026</td>
<td>−191 ± 10</td>
<td>0</td>
<td>0.65 ± 0.03</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>957.78 ± 0.06</td>
<td>4.29 ± 0.14</td>
<td>−300 ± 10</td>
<td>0</td>
<td>0.33 ± 0.01</td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>980 ± 10</td>
<td>0.29 ± 0.07</td>
<td>−19 ± 5</td>
<td>0.020 ± 0.005</td>
<td>0</td>
</tr>
<tr>
<td>$f_0'(1370)$</td>
<td>1200 − 1500</td>
<td>3.8 ± 1.5</td>
<td>−91 ± 36</td>
<td>0.049 ± 0.019</td>
<td>0</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>1275.1 ± 1.2</td>
<td>3.03 ± 0.35</td>
<td>449 ± 52</td>
<td>0.141 ± 0.016</td>
<td>0.141 ± 0.016</td>
</tr>
<tr>
<td>$f_2'(1525)$</td>
<td>1525 ± 5</td>
<td>0.081 ± 0.009</td>
<td>7 ± 1</td>
<td>0.002 ± 0.000</td>
<td>0.002 ± 0.000</td>
</tr>
<tr>
<td>$f_2(1565)$</td>
<td>1562 ± 13</td>
<td>0.70 ± 0.14</td>
<td>56 ± 11</td>
<td>0.012 ± 0.002</td>
<td>0.012 ± 0.002</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td>$-89 \pm 66$</td>
<td>0.22 ± 0.03</td>
<td>1.14 ± 0.04</td>
<td></td>
</tr>
</tbody>
</table>

helicity difference SR: $\eta, \eta'$ contributions entirely compensated by $f_2(1270), f_2(1565)$
Updated Charmonium Spectrum

- Only 2 narrow states remaining unobserved: \(1^1D_1\) and \(1^3D_3\)
- New transitions:
  - \(2^3S_1 \rightarrow \pi^+ \pi^- \eta_c(1S)\)
  - \(1^3D_2 \rightarrow \gamma \eta_c(1S)\) and \(2^3S_1 \rightarrow \gamma \eta_c(1S)\)

Charmonium family:
- \(\psi(4S)\) or hybrid
- \(\psi(3S), \pi^+ \pi^- J/\psi\)
- \(\eta_c(2S), \eta_c(3S)\)
- \(\chi_{c1}(2P), \chi_{c2}(2P)\)

Above \(D\bar{D}\) threshold:
- plethora of new states
- nature? molecules
tetra-quarks, hybrids, ...
BABAR, BELLE, BES-III, PANDA

Narrow states:
- well understood \(c\bar{c}\) states
- only 2 remain to be observed
charmonium production in \(\gamma\gamma\) collisions

### Sum rules evaluated for c\(\bar{c}\) states

<table>
<thead>
<tr>
<th>(m_M) [MeV]</th>
<th>(\Gamma_{\gamma\gamma}) [keV]</th>
<th>(\int \frac{ds}{s} (\sigma_2 - \sigma_0)) [nb]</th>
<th>(c_1) [10(^{-7})GeV(^{-4})]</th>
<th>(c_2) [10(^{-7})GeV(^{-4})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_c(1S))</td>
<td>2980.3 ± 1.2</td>
<td>6.7 ± 0.9</td>
<td>-15.6 ± 2.1</td>
<td>0</td>
</tr>
<tr>
<td>(\chi_{c0}(1P))</td>
<td>3414.75 ± 0.31</td>
<td>2.32 ± 0.13</td>
<td>-3.6 ± 0.2</td>
<td>0.31 ± 0.02</td>
</tr>
<tr>
<td>(\chi_{c2}(1P))</td>
<td>3556.2 ± 0.09</td>
<td>0.50 ± 0.06</td>
<td>3.4 ± 0.4</td>
<td>0.14 ± 0.02</td>
</tr>
<tr>
<td>Sum resonances</td>
<td></td>
<td></td>
<td>-15.8 ± 2.1</td>
<td>0.49 ± 0.03</td>
</tr>
</tbody>
</table>

### Duality estimate for continuum contribution, above D\(\bar{D}\) threshold

\[
\int_{s_D}^{\infty} ds \frac{1}{s} [\sigma_2 - \sigma_0] (\gamma\gamma \to X) \approx \int_{s_D}^{\infty} ds \frac{1}{s} [\sigma_2 - \sigma_0] (\gamma\gamma \to c\bar{c})
\]

**Interplay between hidden charm mesons (c\(\bar{c}\) states) and production of charmed mesons**
search for dark photons in electroweak processes on hadrons
Nature of dark matter / search for dark photons

Recent results from the **Alpha Magnetic Spectrometer** at the International Space Station: Aguilar et al., PRL 110

- **Confirms** $e^+$ excess seen by PAMELA and FERMI


- DM can **explain excess** observed by e.g. PAMELA
- DM must be **charged under new $U(1)_D$ symmetry** to reconcile observations and relic abundance
- no excess of $p$: new gauge boson light ($m_{\gamma'} \lesssim 2 \times m_N$)
Searches for dark photons in electroweak processes

**Kinetic Mixing and $U(1)_D$**

Tree level extensions are strongly constrained, but **loops of heavy particles** are always possible: Holdom, PLB 178

\[
\mathcal{L} \supset -\frac{1}{4} F_{Y,\mu\nu} F_Y^{\mu\nu} - \frac{1}{4} F_{\mu\nu}^I F^I_{\mu\nu} + \frac{\varepsilon_Y}{2} F_{\mu\nu}^I F_Y^{\mu\nu} + e A_{Y,\mu} J_Y^{\mu} + g_D A_{\mu}^I J''^\mu + m^2 A_{\mu}^I A_I^{\mu}
\]

Redefine: $A_Y^{\mu} \rightarrow A_Y^{\mu} + \varepsilon_Y A_I^{\mu}$ and $\varepsilon = \varepsilon_Y \cos \theta_W$

\[
\mathcal{L}_I = \varepsilon e A_{\mu}^I J_{\text{em}}^{\mu}
\]

induced
γ′ search at fixed target electron facilities

Signal

QED background

MAMI test run (2010)

Data and theory in good agreement!

Beranek, Merkel, Vdh (2013)
γ′ search: exclusion limits

Extended program underway:

- **MAMI**: 2010, 2013
- **MESA**: new superconducting ERL (up to 160 MeV) under construction at Mainz
- **Jlab**: APEX, HPS@Hall B, Dark Light
What is the size of the proton?
**What is the size of a proton?**

\[ R_E = 0.8418 \pm 0.0007 \text{ fm} \]

**µH data:**

Pohl et al. (2010)

**ep-data:**

CODATA

\[ R_E = 0.8772 \pm 0.0046 \text{ fm} \]

7.7σ difference !?
Principle of muonic Lamb shift experiment@PSI

Experimental precision ≈ 2 μeV

Energy shift ascribed to finite proton size is 310 μeV less than expected !!!
Proton radius puzzle

Electron scattering facilities MAMI, Jlab: uniquely positioned to deliver high-precision hadron data

recent cross section data \textit{A1@MAMI}

High momentum resolution $\sim 10^{-4}$

MAMI achieved 1\% measurement of $R_E$

Bernauer et al. (2010)
Lamb shift: QED corrections

- Calculated by several groups
  - Pachucki (1996, 1999)
  - Borie (1976, 2005)

- 1 loop electron
  \[ \Delta E = 205.0282 \text{ meV} \]

- 2 loop electron
  \[ \Delta E = 1.5081 \text{ meV} \]

- Muon self-energy, vacuum polarization
  \[ \Delta E = -0.6677 \text{ meV} \]

- Other QED corrections calculated: all of size 0.005 meV or smaller \(< 0.3 \text{ meV}\)
Lamb shift: hadronic corrections

- **Finite-size** correction:
  
  $\gamma\gamma$ box diagram

- Lower blob contains both elastic (nucleon) and in-elastic states
  Information contained in **forward, double virtual Compton scattering**

  - Described by two amplitudes $T1$ and $T2$: function of energy $\nu$ and virtuality $Q^2$
  - Imaginary parts of $T1$, $T2$: unpolarized structure functions of proton

- $\Delta E$ evaluated through an integral over $Q^2$ and $\nu$

\[
\Delta E = \Delta E^{el} + \Delta E^{subtr} + \Delta E^{inel}
\]

- Elastic state: involves **nucleon form factors**
- Subtraction: involves **nucleon polarizabilities**
- Inelastic, dispersion integrals: involves **structure functions F1, F2**

**Hadron physics input required**

*Pachucki (1996, 1999)*
*Faustov, Martynenko (2000)*
*Carlson, Vdh (2011)*
Nucleon polarizability contributions

- Low-energy Compton scattering

Effective Hamiltonian:

\[ \mathcal{H} = -\frac{1}{2} 4\pi \alpha_E E^2 - \frac{1}{2} 4\pi \beta_M B^2 \]

- Electric and magnetic polarizabilities

Evaluation of Lamb shift correction using most recent hadron physics input

Carlson, Vdh (2011)

\[ \Delta E = (-36.9 \pm 2.4) \mu eV \]

PDG values (proton):

- \( \alpha_E = (12.0 \pm 0.6) \times 10^{-4} \text{ fm}^3 \)
- \( \beta_M = (1.6 \pm 0.6) \times 10^{-4} \text{ fm}^3 \)

Baryon ChPT analysis:

- \( \beta_M = (4.0 \pm 0.7) \times 10^{-4} \text{ fm}^3 \)
  - Lensky, Pascalutsa (2010)

Heavy Baryon ChPT analysis:

- Grieshammer et al. (2012)

More precise measurement of \( \beta_M \) underway at A2@MAMI using linearly polarized photons

Present experimental precision: 2 \( \mu \text{eV} \)
Proton radius puzzle: what could it mean?

- unknown correction? ...after known constraints have been built in!

- Change in Rydberg constant?
  
  In absence of further (sizeable) corrections, use of muonic extraction of $R_E$ plugged into electron H Lamb shift yields $R_x$ which is 4.9σ away from CODATA value (and factor 4.6 more precise)

  Pohl et al. (2010)

- New physics?
  
  - explain 3σ $(g-2)\mu$ discrepancy AND 7σ $R_E$ discrepancy from $\mu$H Lamb shift simultaneously invoking a correction by a hypothetical light boson?
  
  - $(g-2)e$ puts strong limit on coupling to e -> much smaller,
    
    Non-universality e – μ?
  
  - New parity violating muonic forces?
  
  - Can rare Kaon decay data help?

Proton radius puzzle: what’s next?

- **Muonic Lamb shift**: muonic D, muonic $^3$He measurements planned
- **Electronic H Lamb shift**: higher accuracy measurement very timely
  - New proposal (York Univ, Canada): $R_E$ to 0.7%
- **new $G_{Ep}$ measurements at very low $Q^2$ down to $Q^2 \approx 2 \times 10^{-4}$ GeV$^2$**
  - **JLAB/Hall B proposal**: magnetic-spectrometer-free experiment (HyCal)
    - $Q^2 = 2 \times 10^{-4} - 2 \times 10^{-2}$ GeV$^2$
    - ep$\rightarrow$ep cross sections normalized to Moller scattering

  ![Diagram of the process](image1)

- **MAMI/A1**: use initial state radiation

  ![Diagram of the process](image2)

- **$\mu - p$ scattering (MUSE) at low $Q^2$ at PSI**
Complementing hadron structure in space- and timelike regions

Proton spacelike form factors
\[ e^- p \rightarrow e^- p \]

Proton timelike form factors
\[ e^+ e^- \rightarrow p \bar{p} \]

\[ q^2 \]

\[ \mu_p G_E / G_M \]

JLab, MAMI

BES-III, PANDA
Precision lattice QCD: ab-initio calculations of hadron structure

- Precision lattice calculations for benchmark hadron structure observables: axial charge, form factors, ...
  
  Capitani et al.

- New vistas in lattice QCD: description of unstable particles, exploration of timelike quantities

\[
N_f = 2
\]

\[
N_f = 2+1
\]

\[g_A\]

ETMC 2010
RBC/UKQCD 2008
LHPC 2010
RBC/UKQCD 2009

This work: plateau
This work: summ.
Spatial imaging of hadrons

Charge, mass, spin densities of quarks in a hadron

$\text{proton} \rightarrow \Delta^+ (1232)$

Generalized Parton Distributions (GPDs): 3D image of hadrons

Deep-Inelastic Scattering
longitudinal quark distribution in momentum space

Unifying concept
fully-correlated quark distributions in both coordinate and momentum space

Elastic Scattering
transverse quark distribution in coordinate space

GPDs: transverse image of hadrons

**GPDs**: quark distributions w.r.t. longitudinal momentum $x$ and transverse position $b_\perp$

$lattice QCD$: moments of GPDs

$\mathbf{x}^n$ moment of u-d GPD

Guidal, Polyakov, Radyushkin, Vdh (2005)

QCD factorization: tool to access GPDs

Q^2 \gg 1 \text{ GeV}^2

GPD (x, \xi, t)

at large Q^2: \textbf{QCD factorization theorem}: hard exclusive process described by GPDs model independent!


KEY Q^2 leverage required to test QCD scaling

world data on proton F2

collider

fixed target

Q^2 / \text{GeV}^2
"complete" picture of nucleon

\[ \xi = 0 \]

Transverse density in momentum space

Transverse density in position space

Lorcé (2011)

\[ \vec{k}_\perp \leftrightarrow \vec{z}_\perp \]

\[ \Delta_\perp \leftrightarrow \vec{b}_\perp \]
Quark orbital angular momentum in proton

\[ \ell_z^q = \int d^2 \vec{b}_\perp (\vec{b}_\perp \times \langle \vec{k}_\perp^q \rangle)_z \]

\[ \langle \vec{k}_\perp^q \rangle = \int dx \ d^2 \vec{k}_\perp \vec{k}_\perp \rho^q_{LU}(x, \vec{b}_\perp, \vec{k}_\perp) \]

Lorcé, Pasquini, Xiong, Yuan (2012)
Energy-luminosity frontier in lepton-nucleon physics

- High-energy, high-luminosity facilities: Compass, JLab@11 GeV, collider projects (EIC, ENC, ...)

- Global nucleon structure analysis effort required: virtual analysis centre
CONCLUSIONS

- Strong interplay between high-energy precision low-energy frontiers

- Impact of hadron physics on new physics searches: \((g-2)_\mu\), \(Q_{\text{weak}}\), new dark photon searches

- Unraveling hadron structure in strong QCD:
  - proton radius puzzle has shaken textbook beliefs
  - combination of new experiments + theory opens perspectives for an imaging of hadrons to an unprecedented level of detail
"Quarks, neutrinos, mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them!"