Precision Predictions

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Entrée
WHAT is a PRECISION PREDICTION?

● My definition:

A prediction is considered **precise**, if it has a **small (relative) theoretical uncertainty**.

● Remarks

— this does not imply that is agrees with experiment (cf. Popper)
— “small uncertainty” can be best quantified if we have an underlying counting rule
— a prediction without uncertainty makes little sense
— I will mostly consider the interplay of precision predictions with the corresponding precise experiments
EX. 1: MASS of the TOP QUARK and the HIGGS BOSON

- Virtual particles can leave traces
  a cornerstone of precision physics

- This requires precision predictions

- Radiative corrections to $e^+e^-$ collisions (LEP, SLD)
  $\rightarrow m_{\text{top}}$ and $M_{\text{Higgs}}$ could be inferred

- Direct measurements of the top/Higgs 1995/2012 at Fermilab/CERN
EX. 2: The HULSE-TAYLOR PULSAR

- General Relativity predicts the slowing down of pulsar period $P_b$ due to the radiation of gravitational waves.

- Binary system with masses $m_1$, $m_2$ and eccentricity $e$:

$$
\dot{P}_{b,GR} = -\frac{192\pi G^{5/3}}{5c^5} \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)(1 - e^2)^{-7/2}\frac{m_1 m_2}{(m_1 + m_2)^{1/3}}
$$

Peters, Phys. Rev. 136, B1224 (1964)

- A triumph of GR:

Measurements of second- and third-order relativistic effects in the orbit of binary pulsar PSR1913 + 16 have yielded self-consistent estimates of the masses of the pulsar and its companion, quantitative confirmation of the existence of gravitational radiation at the level predicted by general relativity, and detection of geodetic precession of the pulsar spin axis.

Taylor, Fowler, McCulloch, Nature 277, 437 (1979)

$P = 0.059029995269 (2) \ s$

$\dot{P} = 8.64 (2) \cdot 10^{-18} \ s^{-1}$
EX. 2: The HULSE-TAYLOR PULSAR continued

- This has become a true precision test of GR:
  
  → Gravitational waves exist
  
  → Energy as predicted by GR
  
  → Gravity propagates with the speed of light
  
  → GR holds for strongly self-gravitating masses
  
  → Theoretical uncertainty in $P_b$:
    \[ \delta \dot{P}_b = 0.002\% \]
  
- Gravitational waves detected directly by LIGO/VIRGO in 2015 → talk by Giovanni Losourdo

Cumulative shift in periastron time (\(s\))

Year

0.3% (95% C.L.)

[Weisberg & Huang 2016]
Plat principal
EX. 1: From Schwinger’s tombstone to ultrahigh precision

- Dirac’s prediction: a spin-1/2 particle has a Landé factor of $g = 2$

- The dawn of the precision era:

\[
\alpha = \frac{e^2}{4\pi} = \frac{1}{137.03599...}
\]

\[
a_e = \frac{1}{2} (g_e - 2) = \frac{1}{2} \frac{\alpha}{\pi} \simeq 1.1 \cdot 10^{-3}
\]

- The most precise Standard Model prediction [SU(3)$_C$ × SU(2)$_L$ × U(1)$_Y$]:

\[
a_e = a_e(\text{QED}) + a_e(\text{weak}) + a_e(\text{strong})
\]

\[
a_e(\text{QED}) = A_1 + A_2\left(\frac{m_e}{m_\mu}\right) + A_2\left(\frac{m_e}{m_\tau}\right) + A_3\left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}\right)
\]

\[
A_n = \sum_{i=1,2,...} \left(\frac{\alpha}{\pi}\right)^i A_n^{(2i)}
\]

\[
\rightarrow \text{must know } A_1 \text{ to tenth order to achieve sub-ppb precision}
\]
EX. 1: From Schwinger’s tombstone to ultrahigh precision

• Completion of the 10th order (12762 diagrams):

\[ A_1^{(10)} = 6.675(192) \times (\alpha/\pi)^5 \simeq 0.07 \cdot 10^{-12} \]


• Complete SM prediction:

\[ a_e(\text{th'y}) = 1 159 652 182.037 \times 10^{-12} \] using \( \alpha(\text{Rb}) \)

\[ a_e(\text{th'y}) = 1 159 652 181.606 \times 10^{-12} \] using \( \alpha(\text{Cs}) \)


• Best measurement: \( a_e = 1 159 652 182.73(28) \times 10^{-12} \)


• Truely amazing!
EX. 1: From Schwinger’s tombstone to ultrahigh precision

- But a small tension!
  ← a sign of BSM physics?

- Improved measurements of $R_{\infty}$ and $a_e^-$ planned
  Gabrielse et al., 1904.06174 [quant-ph]

- Effects of heavy mass particles are enhanced by $(m_\mu/m_e)^2 \approx 43.000$ in $(g - 2)_\mu$

- Hadronic contribution is the culprit:
  data-driven (VP) and Lattice QCD (LbL) evaluations (many groups world-wide)

- There is a tension → ???

EX. 2: Precision $\sigma$-term physics

- Massless classical QCD is scale-invariant (dilatations)

- Scale invariance broken by quantization: **dimensional transmutation** $\sim \Lambda_{\text{QCD}}$

- **Trace anomaly** = generation of hadron masses (central result of QCD)

$$m_N = \langle N(p) | \theta_\mu^\mu | N(p) \rangle$$

$$= \langle N(p) | \frac{\beta_{\text{QCD}}}{2g} G^a_\mu \gamma^\mu G^\mu a + m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s | N(p) \rangle$$

$[\theta^{\mu\nu} =$ energy-momentum tensor$]$

$\text{field energy}$

$\text{Higgs}$-contribution

Crewther (1972), Chanowitz, Ellis (1972), Collins, Duncan, Joglekar (1977)

- Need to determine

$$\langle N(p) | m_u \bar{u}u + m_d \bar{d}d | N(p) \rangle = \sigma_{\pi N}$$

$$\langle N(p) | m_s \bar{s}s | N(p) \rangle = \sigma_s$$

- The pion-nucleon sigma-term $\sigma_{\pi N}$ can be obtained to high-precision from a Roy-Steiner analysis of pion-nucleon scattering data
EX. 2: Precision $\sigma$-term physics II

- Role of the pion-nucleon $\sigma$-term:
  - Scalar couplings of the nucleon
    \[ \langle N | m_q \bar{q} q | N \rangle = f_q^N m_N \quad (N = p, n) \]
    \[ (q = u, d, s) \]

  ➣ Dark Matter detection

  ➣ $\mu \rightarrow e$ conversion in nuclei

- Condensates in nuclear matter
  \[ \frac{\langle \bar{q} q \rangle (\rho)}{\langle 0 | \bar{q} q | 0 \rangle} = 1 - \frac{\rho \sigma_{\pi N}}{F_\pi^2 M_\pi^2} + \ldots \]

- CP-violating $\pi N$ couplings
  ➣ hadronic EDMs (nucleon, nuclei)

Crivellin, Hoferichter, Procura (2014)
EX. 2: Precision $\sigma$-term physics III

- Roy-Steiner analysis of $\pi N \rightarrow \pi N$
- Important input: precision pionic atom data from PSI
  $\rightarrow$ accurate $\pi N$ scattering lengths (w/ theory)
- First ever dispersive analysis with error bars!
- High-precision determination of $\sigma_{\pi N}$:

\[
\sigma_{\pi N} = (59.1 \pm 1.9_{RS} \pm 3.0_{LET}) \text{ MeV}
\]
\[
= (59.1 \pm 3.5) \text{ MeV}
\]

- Strangeness sigma-term: $\sigma_s \simeq (30 \pm 30)$ MeV
- $m_N$ can be calculated to high precision in lattice QCD

$\Rightarrow$ Only about 100 MeV of the nucleon mass $a$
due to the Higgs! [“mass without mass”]

Wheeler (1962)

Gotta, Prog. Part. Nucl. Phys. 52 (2004) 133
Baru et al., Nucl. Phys. A 872 (2011) 69

Hoferichter et al., Phys. Rept. 625 (2016) 1
EX. 3: Shapiro delay precision physics I

- **Shapiro delay** = 4th test of GR
  - curved space-time reduces $c$
  - Shapiro, Phys. Rev. Lett. 13 (1964) 789

- **Standard approximation (binary):**
  - consider the potential of the receiving mass
  - 2 post-Keplerian parameters
    - $(r_{Sh} \text{ and } s_{Sh} \text{ called “range” and “shape”})$
    - $r_{Sh} = \frac{Gm_{\text{companion}}}{c^3}$, \hspace{0.5cm} $s_{Sh} = \sin i$

- **Well tested in the binary pulsar**
  - PSR J0737-3039A and B
    - $m_A = 1.3381(7)M_\odot$
    - $m_B = 1.2489(7)M_\odot$

Figures courtesy Michael Kramer & Norbert Wex
EX. 3: Shapiro delay precision physics II

- Retardation
- Light bending
- Pulsar rotation

Blandford & Teukolsky (1976), Wex (1995)
Kopeikin & Schäfer (1999)
Schneider (1990)
Doroshenko & Kopeikin (1995)

⇒ lead to modifications in the delay time (residuals)

Figures courtesy Michael Kramer & Norbert Wex
EX. 3: Shapiro delay precision physics III

- Higher order propagation delays in the double pulsar:
  
  \[ \delta_{SD} = 0.019\% \]

- Remarkable agreement between precision theory (GR) and precision experiment

- Theoretical uncertainty in the Shapiro delay prediction: \( \delta_{SD} = 0.019\% \)

Figures courtesy Michael Kramer & Norbert Wex
• Nuclear Lattice Effective Field Theory

\[ \text{\Lähde, Meißner, Lect. Notes Phys. 957 (2019) 1} \]

• First \textit{ab initio} calculation of the Hoyle state in \(^{12}\text{C}\)

\[ \text{Epelbaum et al., Phys.Rev.Lett. 106 (2011) 192501} \]

• Levels calculated with an accuracy of \(\pm 300\) keV

\[ \text{Hoyle (1954)} \]

\[ \text{\Linde (2007)} \]

\[ \text{\Carter (2006)} \]

\[ \text{\textbullet \ Spectrum of \(^{12}\text{C}\)} \]

\[ \text{\textbullet \ Experiment \ NLEFT} \]

\[ \begin{array}{c|c}
\text{Energy [MeV]} & \text{Level} \\
\hline
-92 & 2^+ \\
-90 & 0^+ \\
-88 & 2^+ \\
-86 & 0^+ \\
\end{array} \]

\[ \text{\textbullet \ Precision predictions – Ulf-G. Meißner – JENAS-2019, Orsay, October 16, 2019} \]
How does $\Delta E = E(\text{Hoyle}) - E(3\alpha)$ change, when the fundamental parameters $(m_{\text{quark}}, \alpha)$ of the Standard Model are varied?

Variations of the hadronic/nuclear properties can be computed from chiral EFT plus lattice QCD:


Variations of $\Delta E$ can be investigated in stellar simulations: $r_{3\alpha} \sim \exp(-\Delta E/k_B T)$


Results:

- fine-tunings in the triple-alpha process are correlated
- quark masses can be varied by a few percent (lattice)
- fine structure constant $\alpha$ can be varied by about 7%
Dessert
SUMMARY & OUTLOOK

• Lessons learned / take home:

- Precision predictions rest on scale separations → Effective Field Theories are the tool

- Precision predictions (physics) are of ever growing importance

- Precision physics might be our best take on discovering BSM physics

- Need to sharpen predictions where the SM gives little contribution (e.g. EDMs of nucleons and light nuclei)