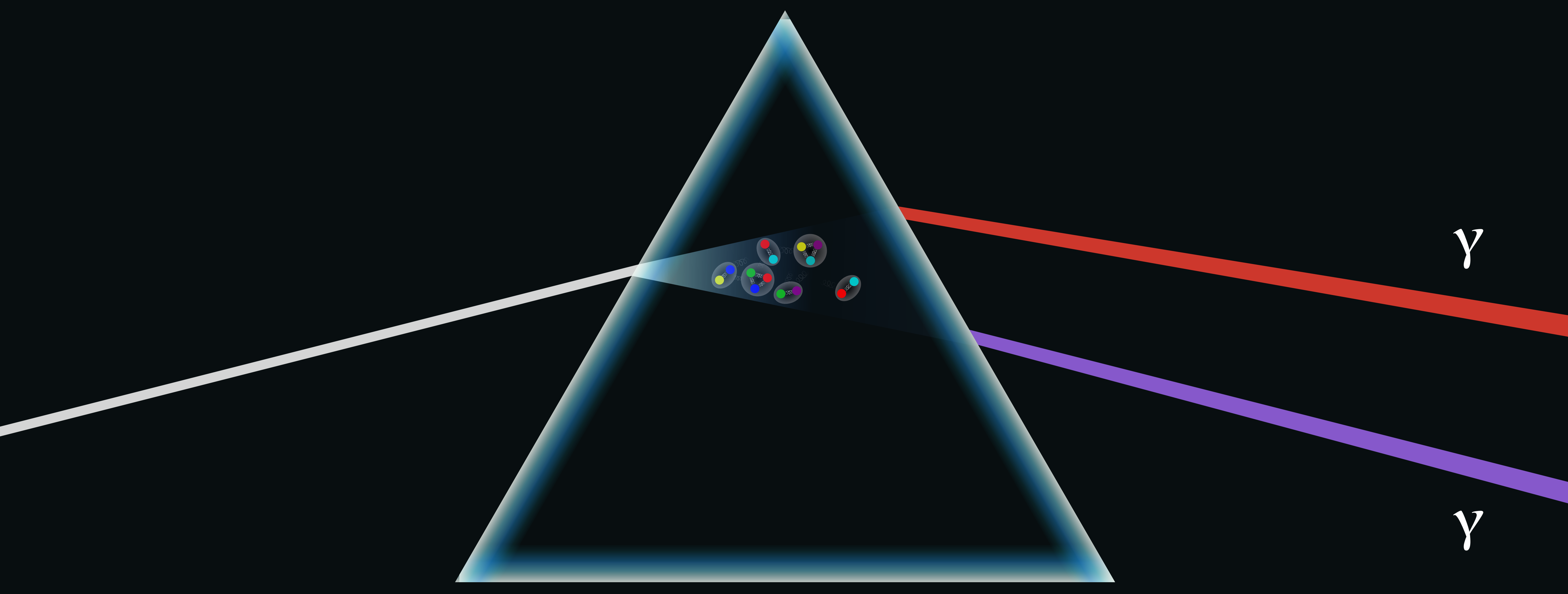
The Dark Side of the Proton



Franziska Hagelstein (JGU Mainz & PSI Villigen)

The Standard Model and Beyond

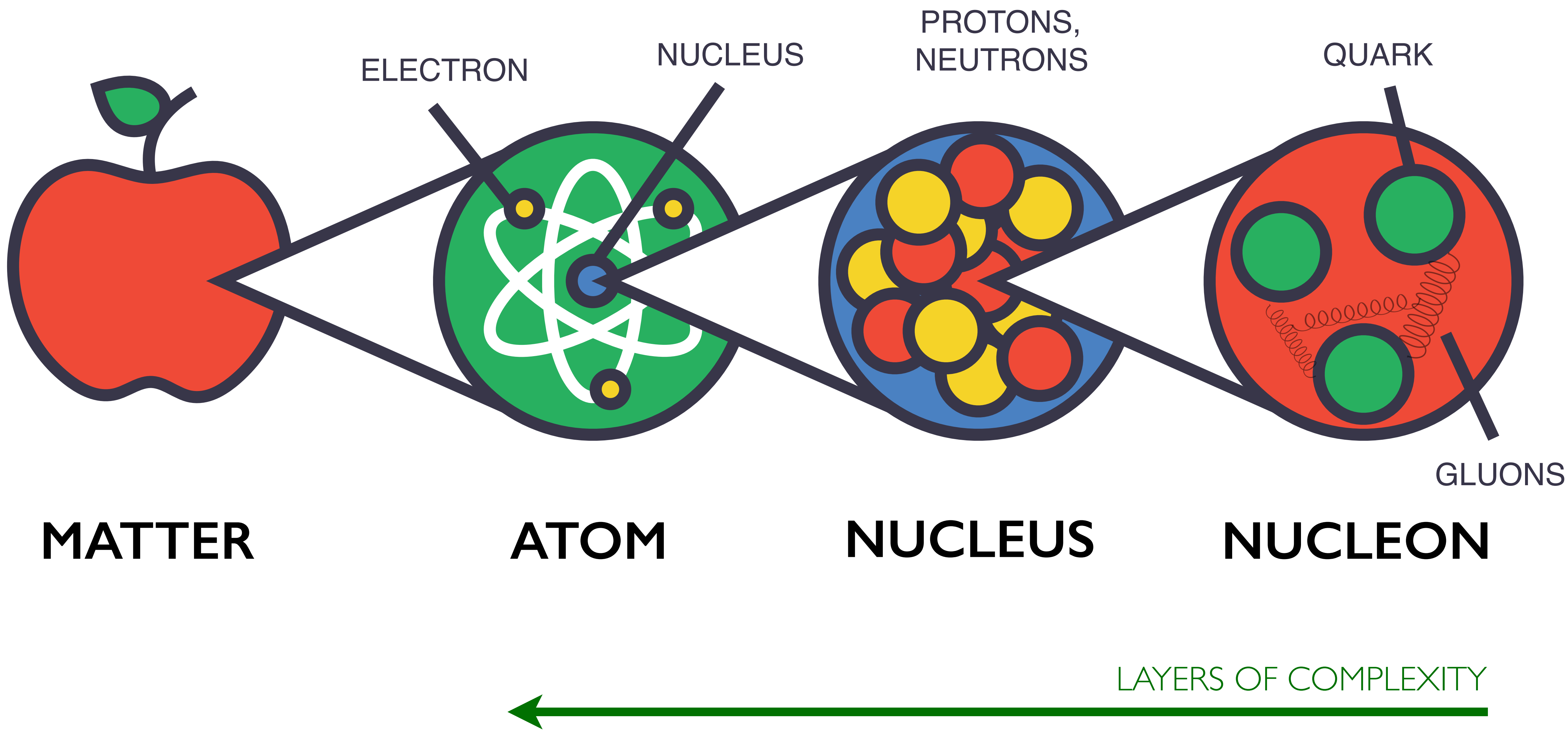
On the “bright” side

- Standard Model of Particle Physics (SM) — very successful
- Proton — difficult but calculable

On the “dark” side

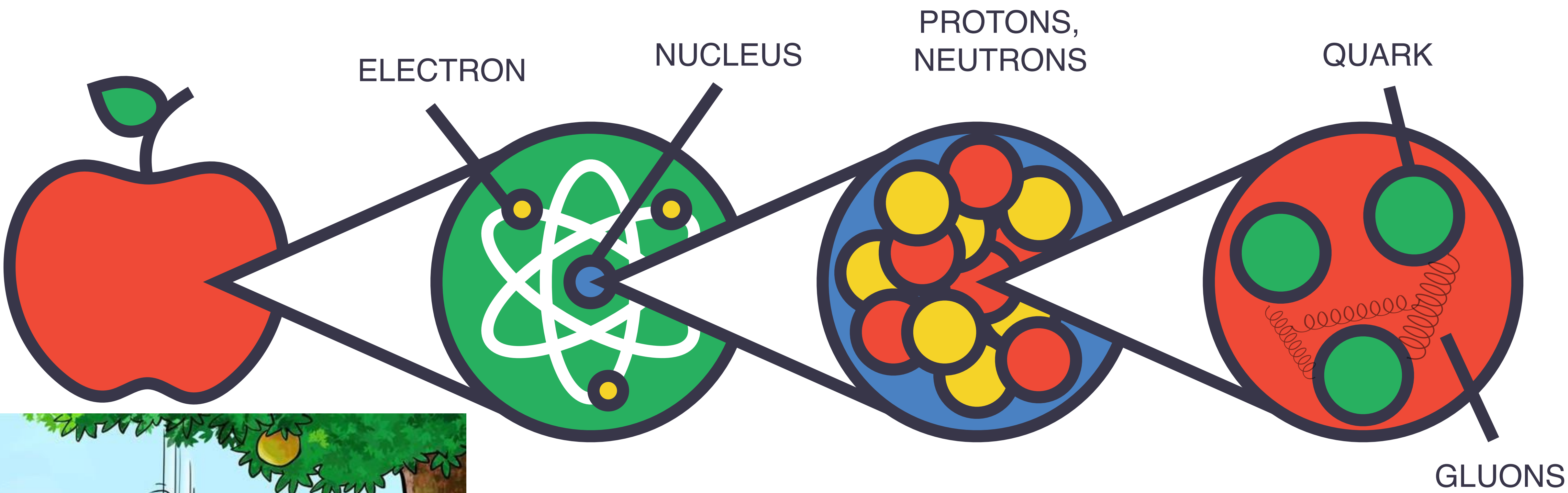
- Evidence for New Physics — Physics beyond the SM (BSM)
- Hadrons (e.g., the proton) are often involved in “puzzles” — disagreement between SM predictions and experiments

ATOMIC, NUCLEAR AND PARTICLE PHYSICS



Research at the intersection of atomic, nuclear and particle physics

ATOMIC, NUCLEAR AND PARTICLE PHYSICS



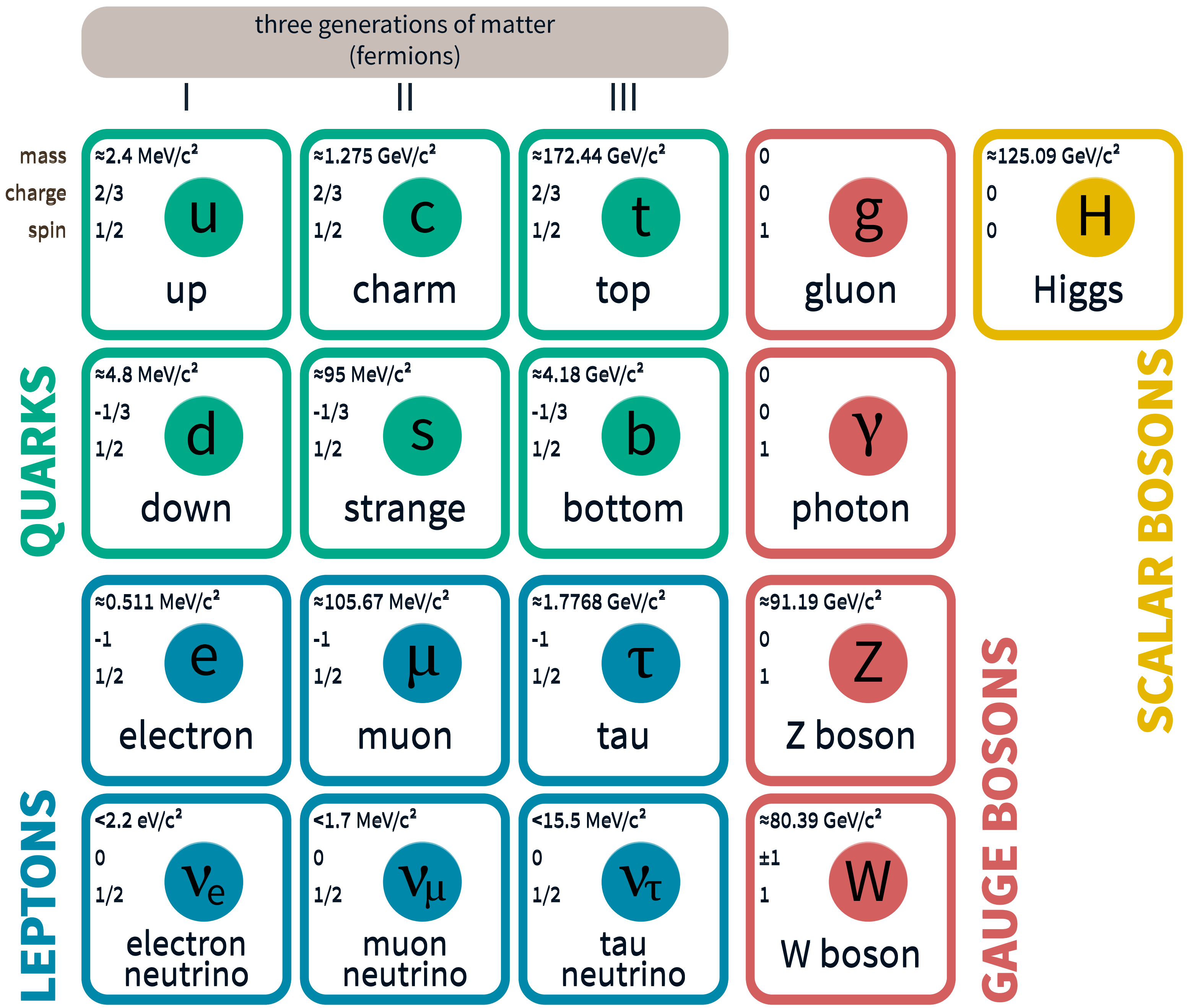
ATOM **NUCLEUS** **NUCLEON**

LAYERS OF COMPLEXITY

Research at the intersection of atomic, nuclear and particle physics

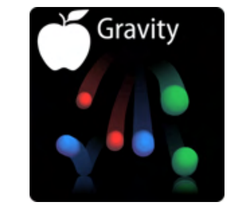
Our aim: understanding physics at the femtoscale (proton radius ~1 fm)

STANDARD MODEL OF PARTICLE PHYSICS

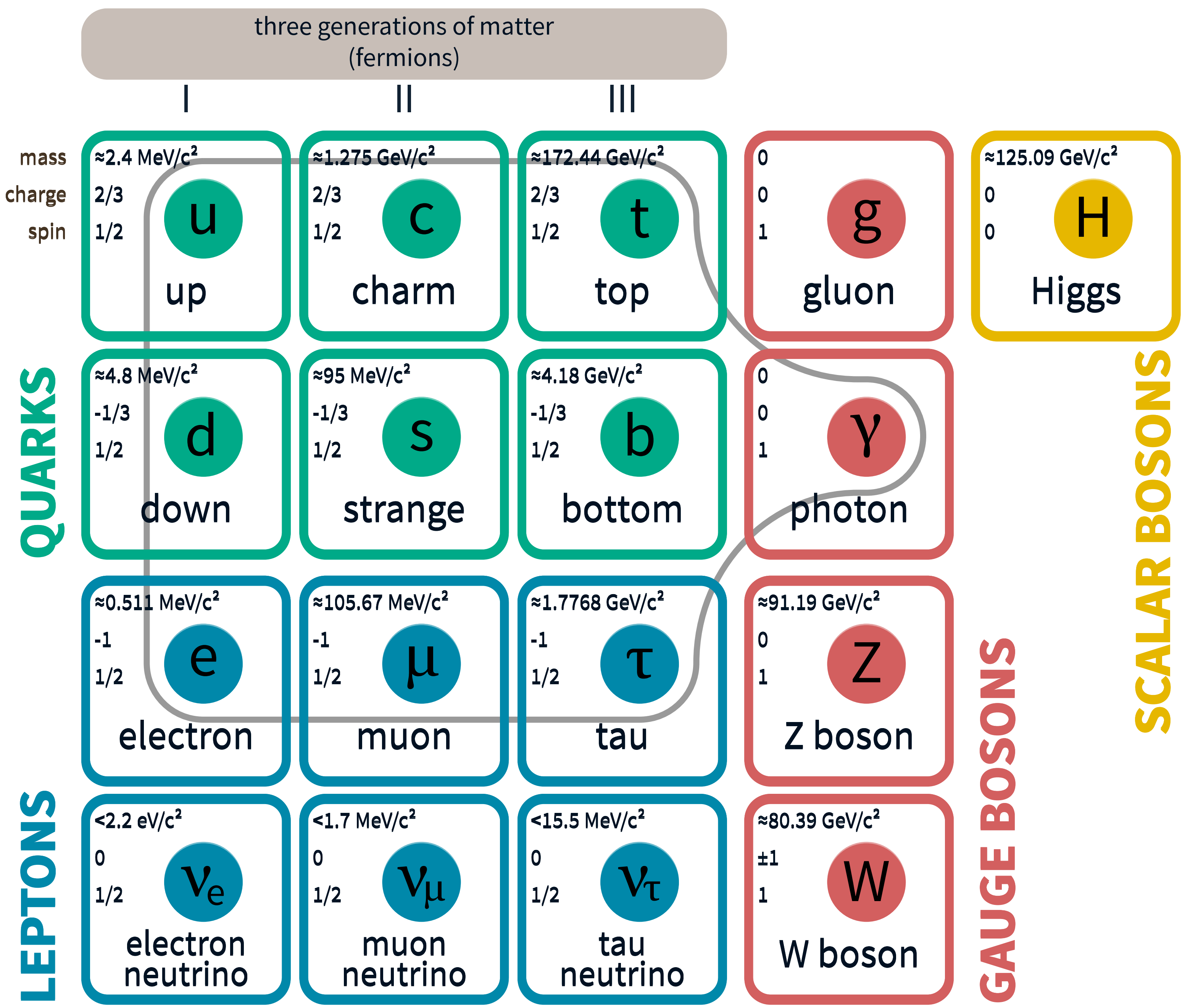


combines 3 of 4 fundamental interactions:

- Gravity is not part of the Standard Model



STANDARD MODEL OF PARTICLE PHYSICS



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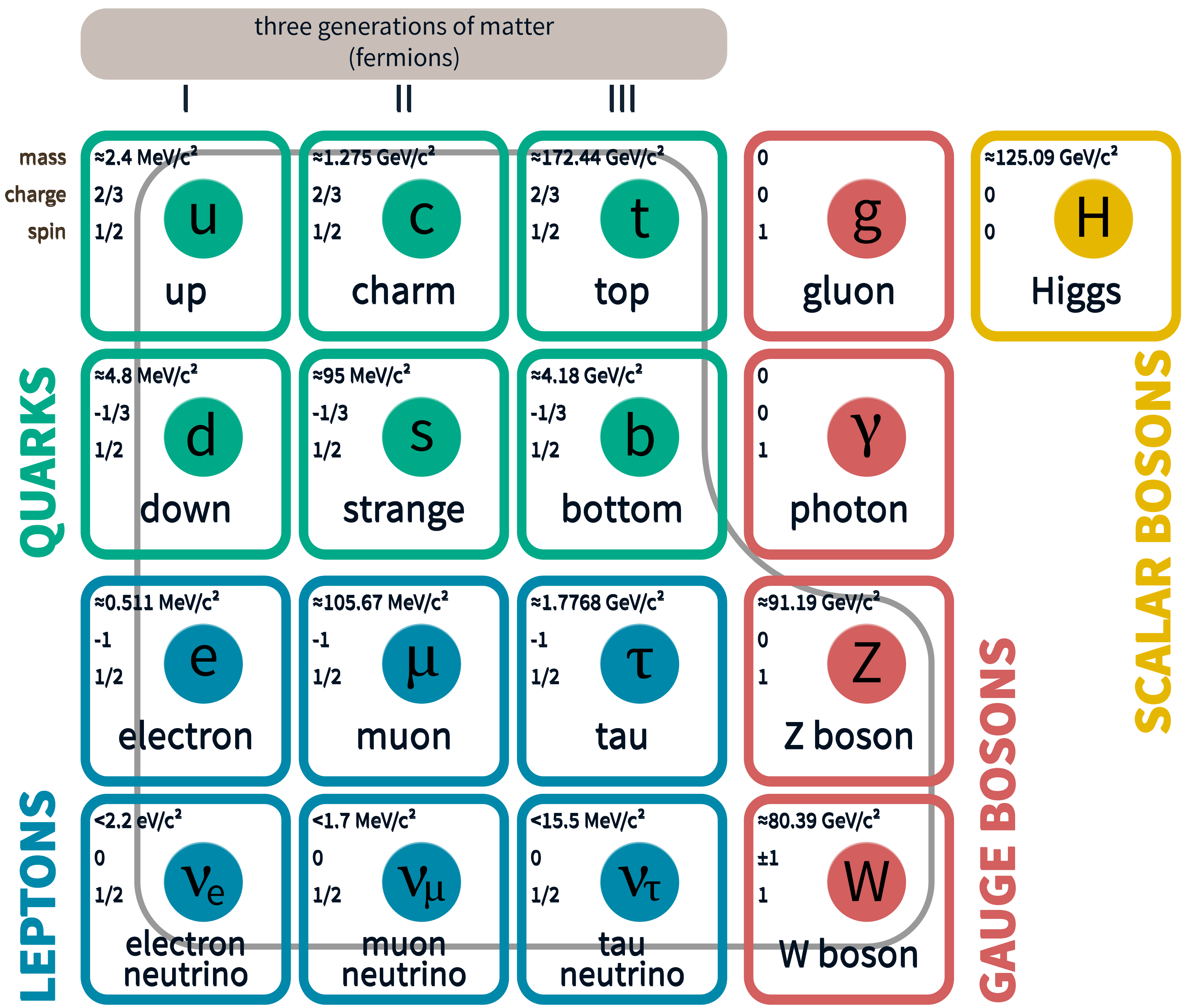

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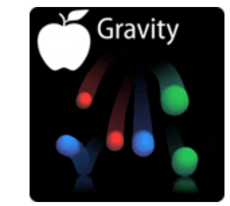

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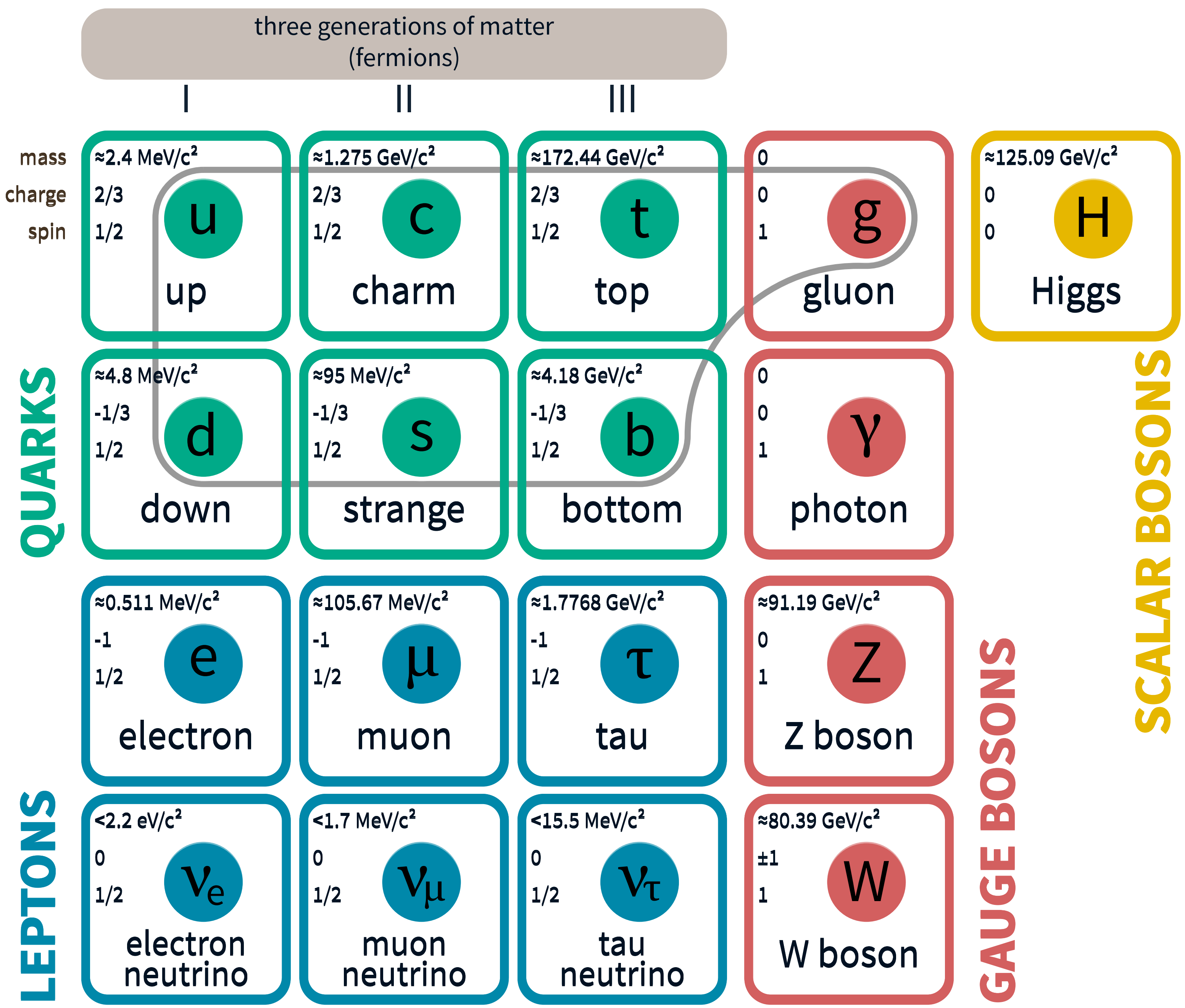
- Weak interaction responsible for β decay (mediated by Z and W bosons)

STANDARD MODEL OF PARTICLE PHYSICS



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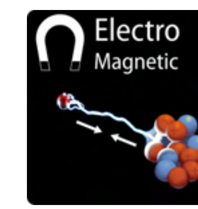
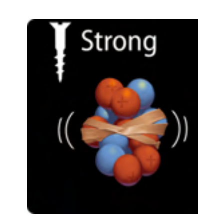


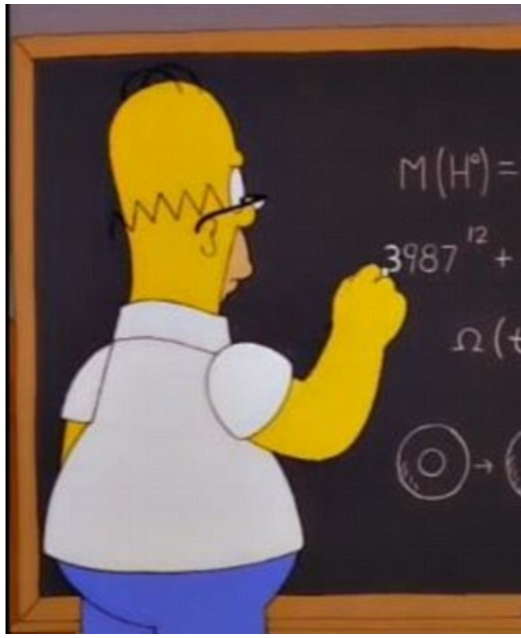
- Weak interaction responsible for β decay (mediated by Z and W bosons)

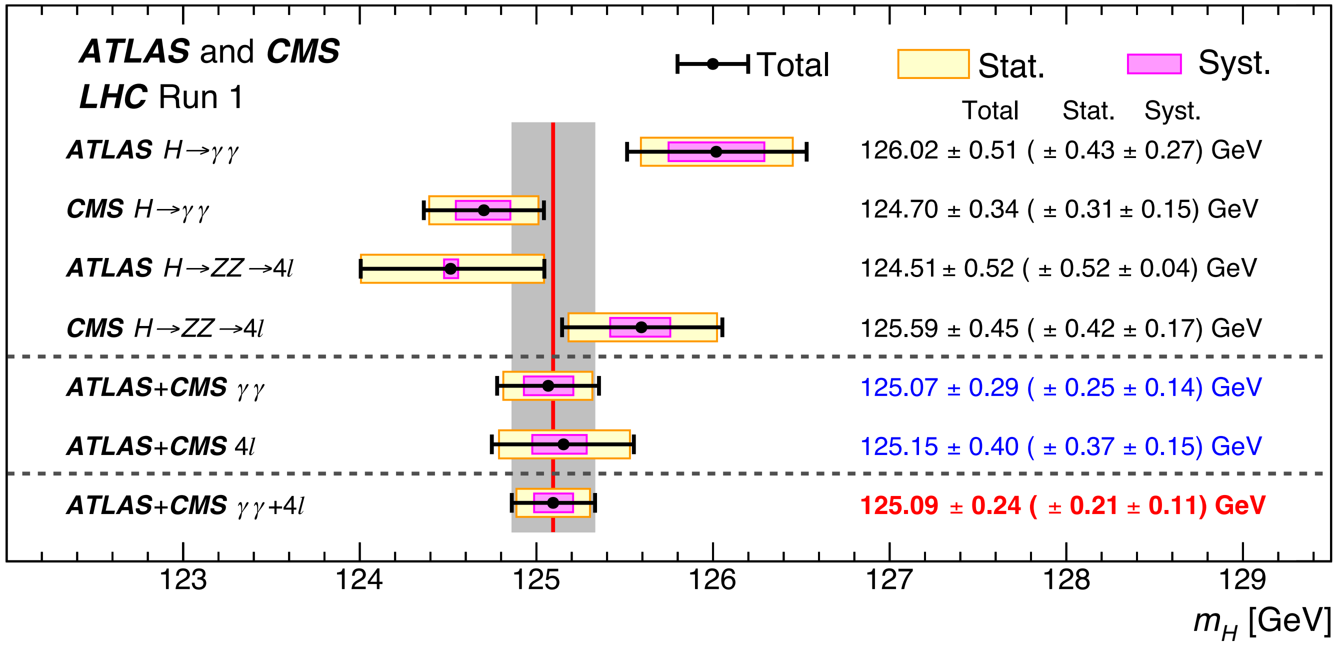
- Strong interaction (QCD) between quarks (mediated by 8 gluons)

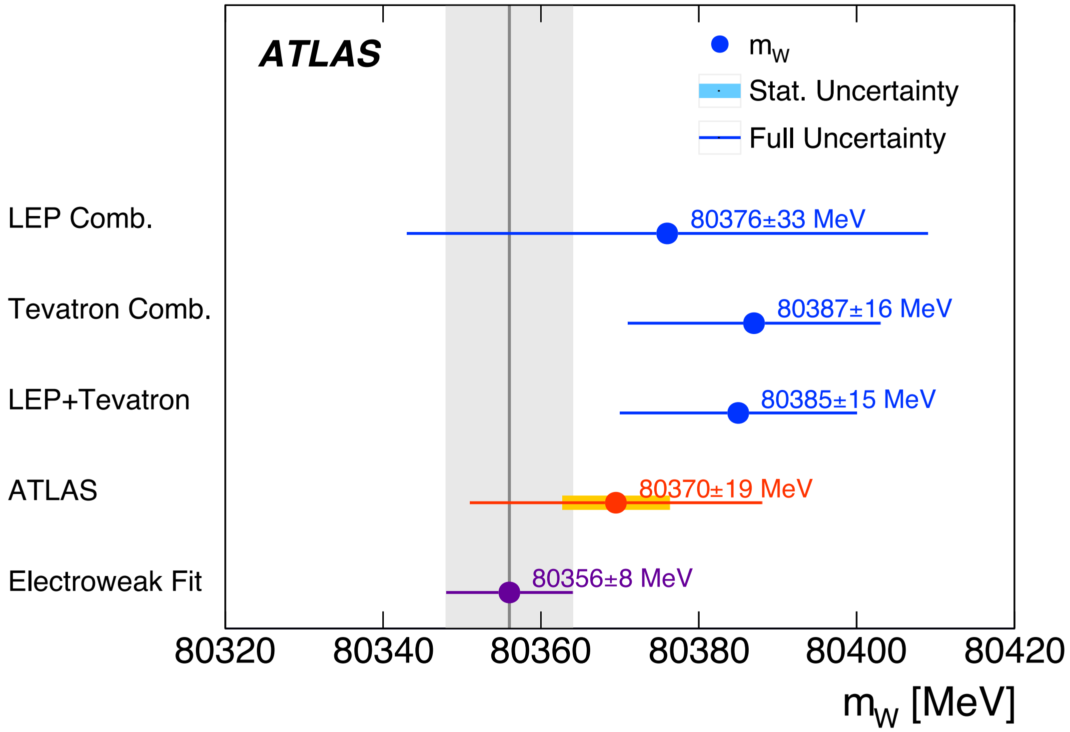


SUCCESS OF THE STANDARD MODEL

- The Standard Model (SM) of particle physics is a remarkably successful theory
- Many incredible predictions of the SM confirmed by experiment:
  - Higgs boson @ CERN (ATLAS, CMS), 2012
  - W and Z boson @ CERN (SPS), 1983







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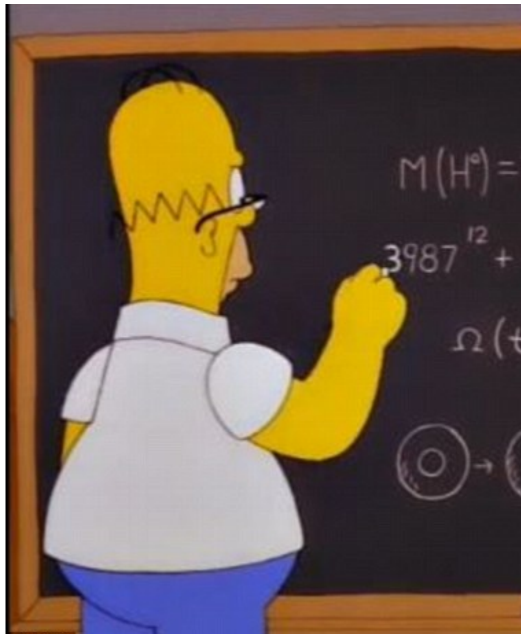
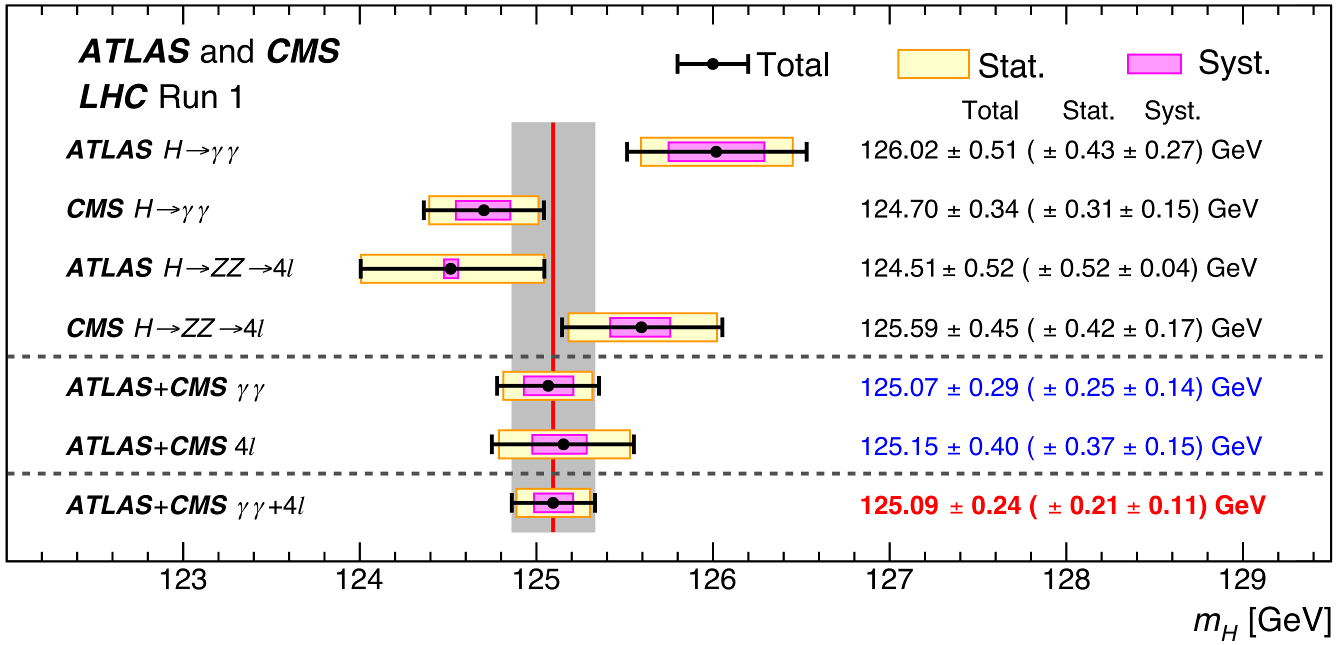
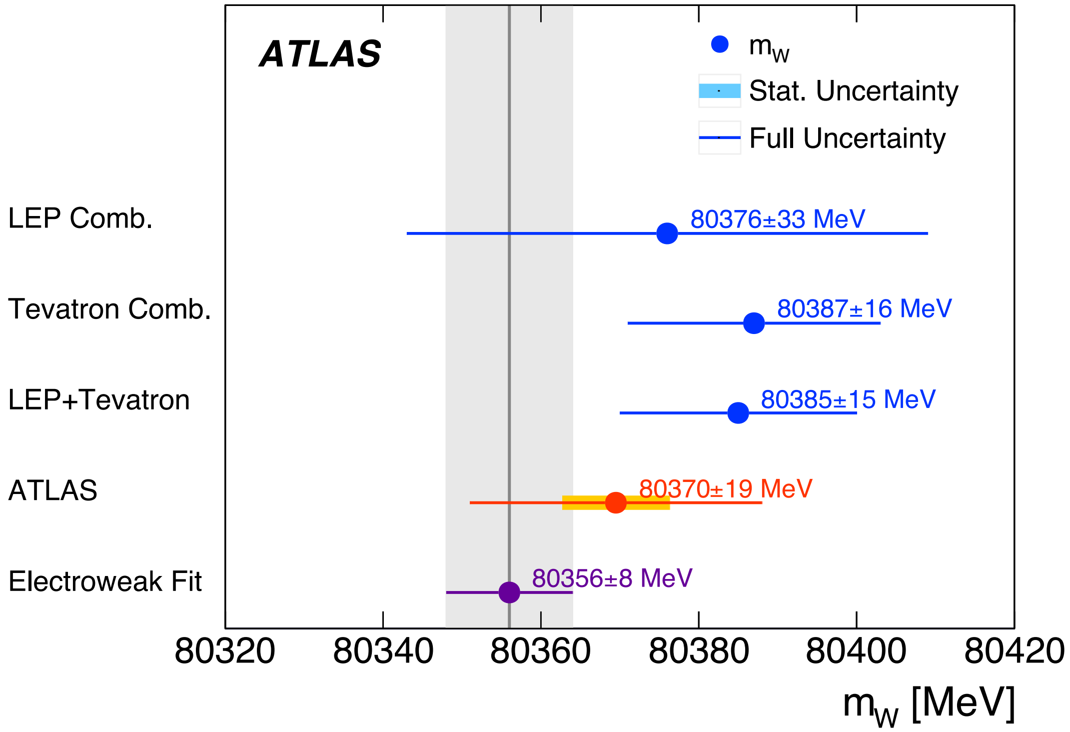


- *Yet, not complete ?*





ASTROPHYSICAL OBSERVATIONS

- Many indications for physics beyond the SM (BSM)

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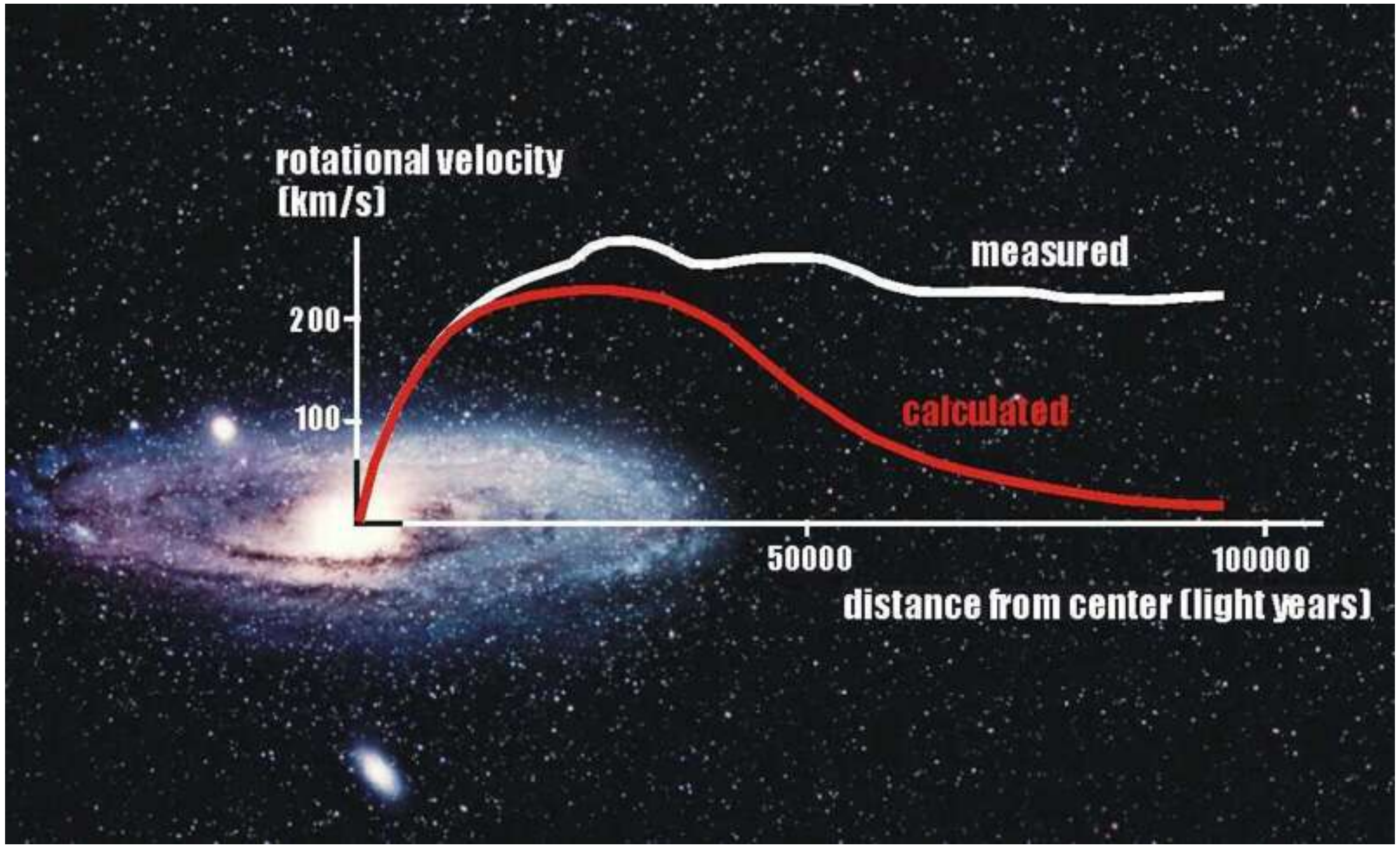
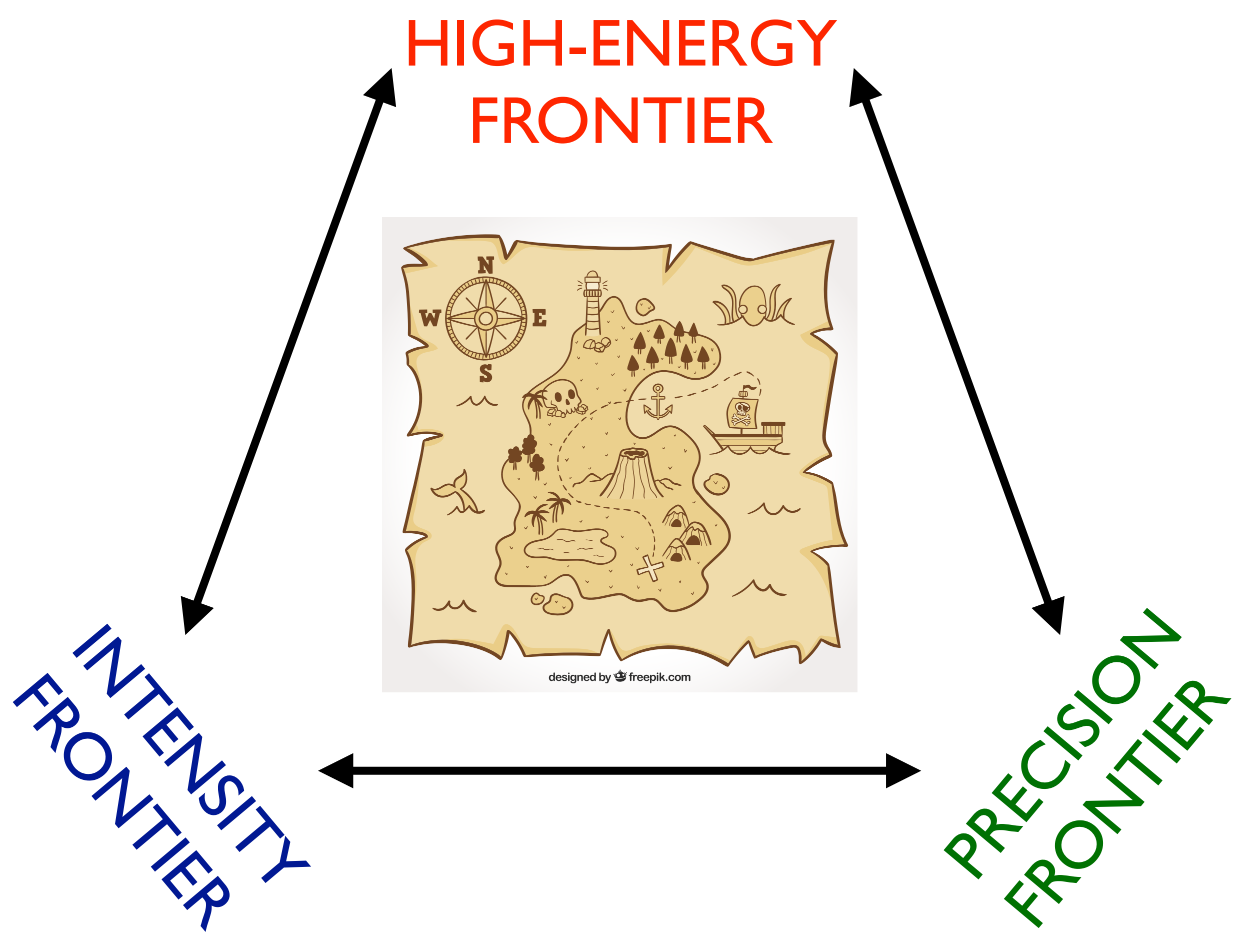
- Many indications for physics beyond the SM (BSM)
  - Baryon asymmetry
  - Rotation curves of disc galaxies → Dark Matter and Dark Energy



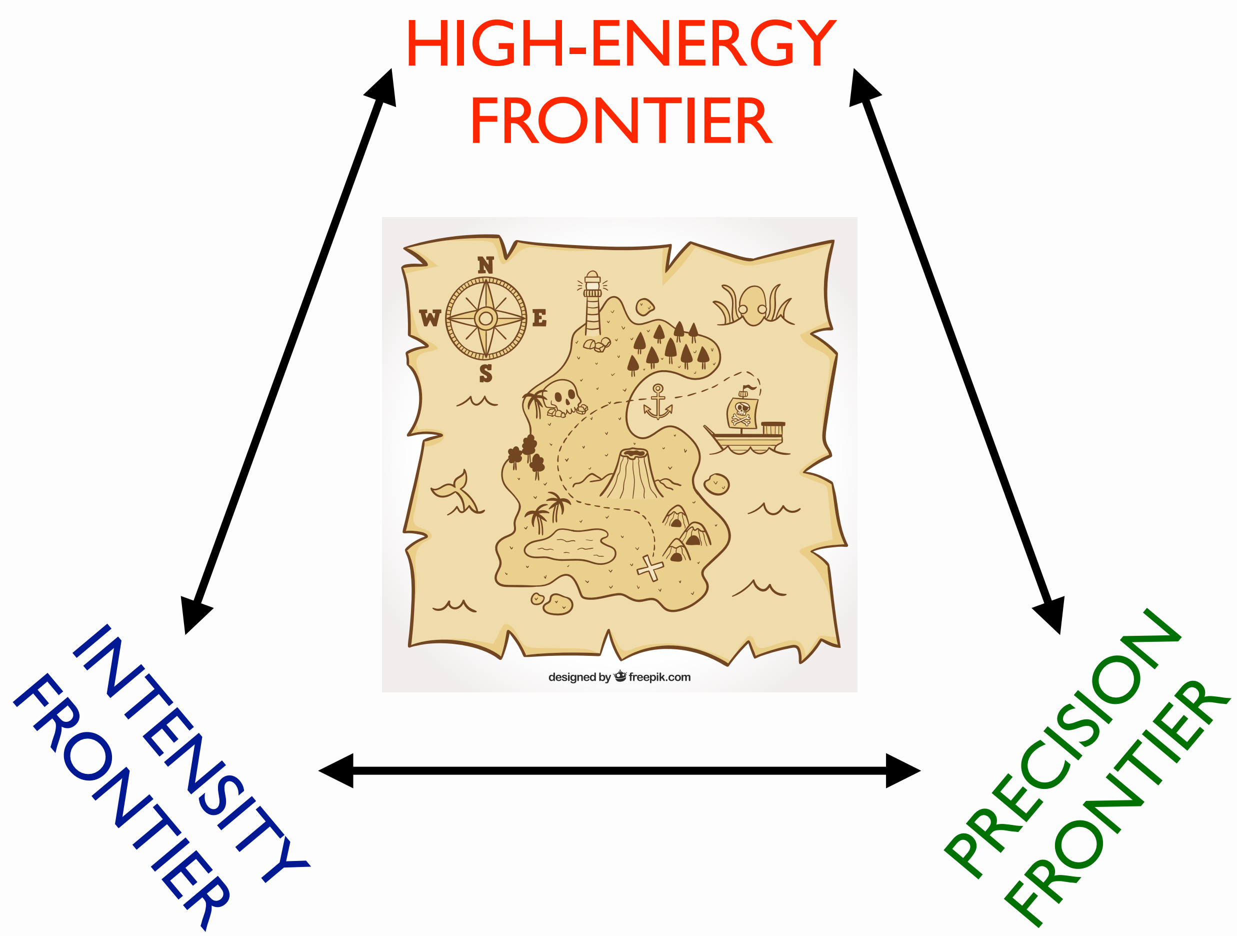
NEW PHYSICS SEARCHES

- Freeman Dyson: *"There is no illusion more dangerous than the belief that the progress of science is predictable.* ***If you look for nature's secrets in only one direction, you are likely to miss the most important secrets****, those which you did not have enough imagination to predict."*



NEW PHYSICS SEARCHES

- Lab searches for New Physics proceed along 3 frontiers:



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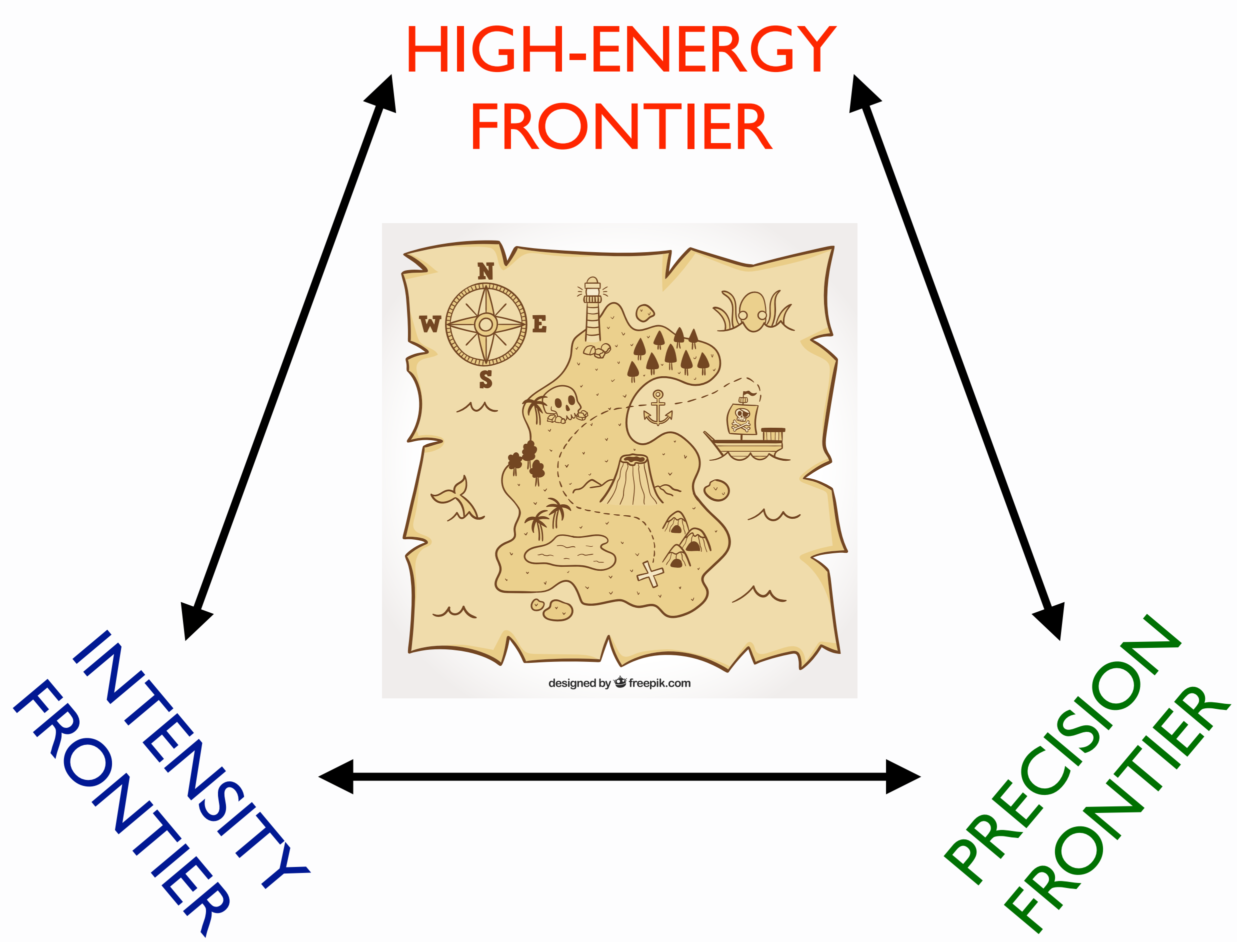

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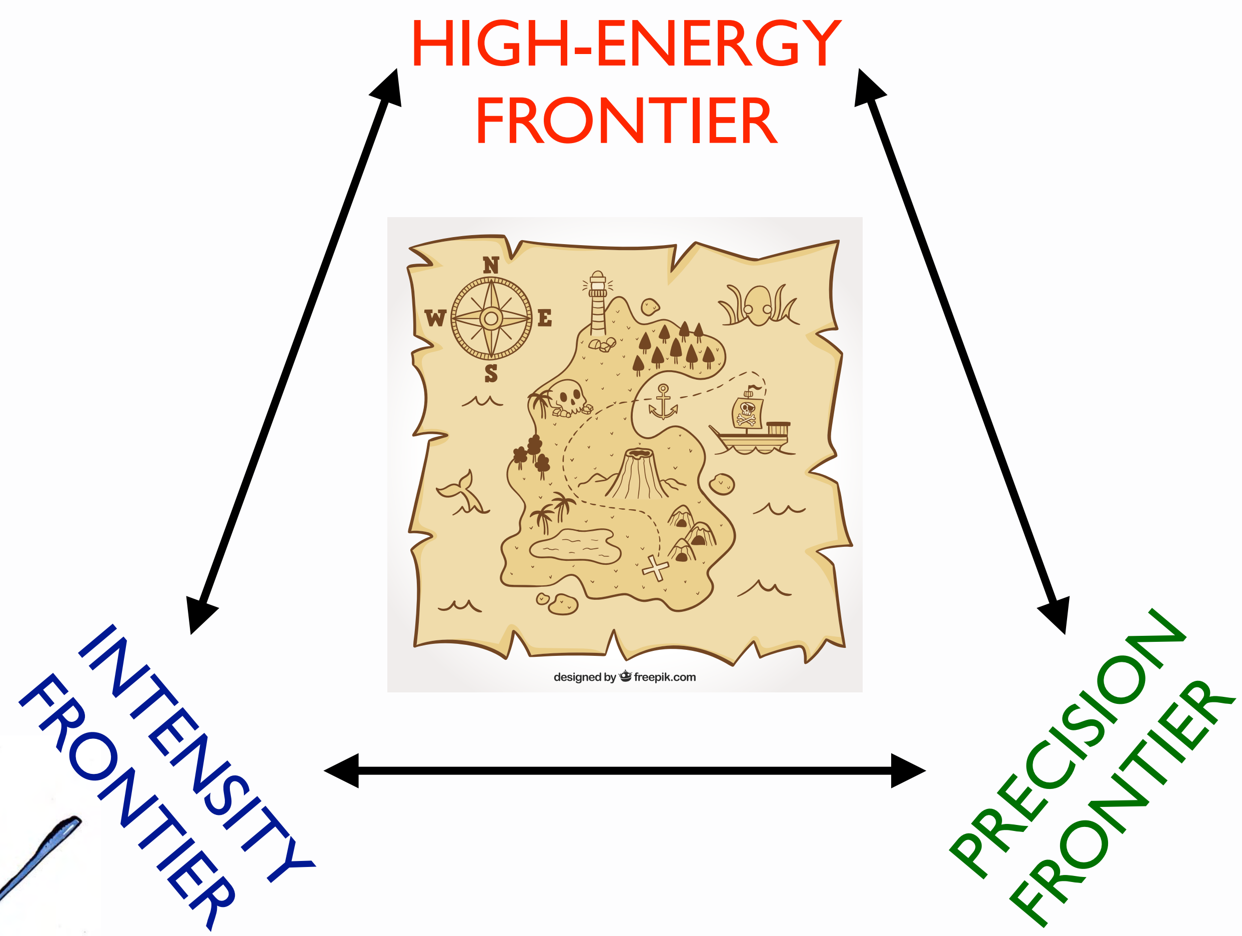

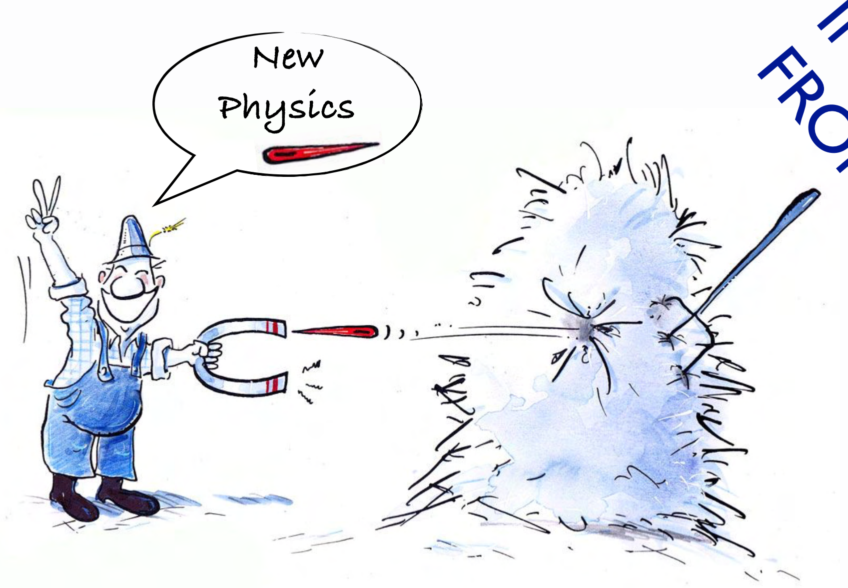

NEW PHYSICS SEARCHES

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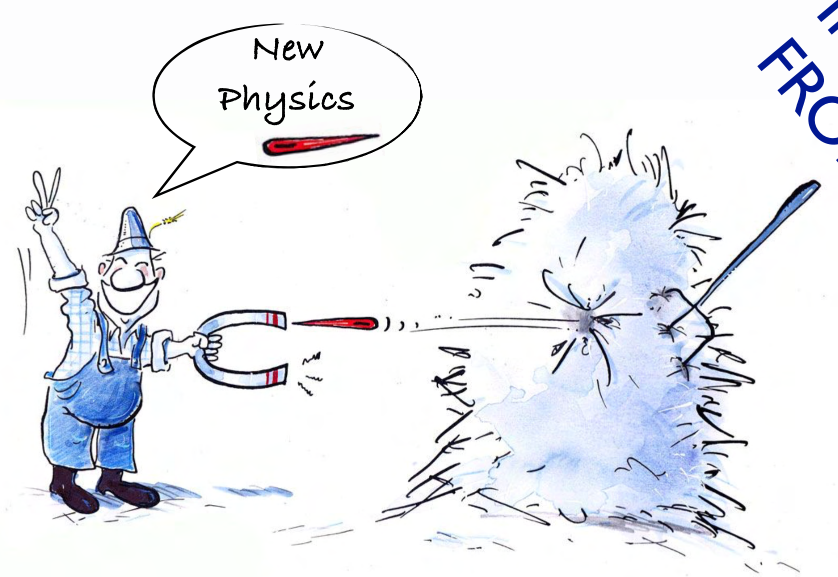
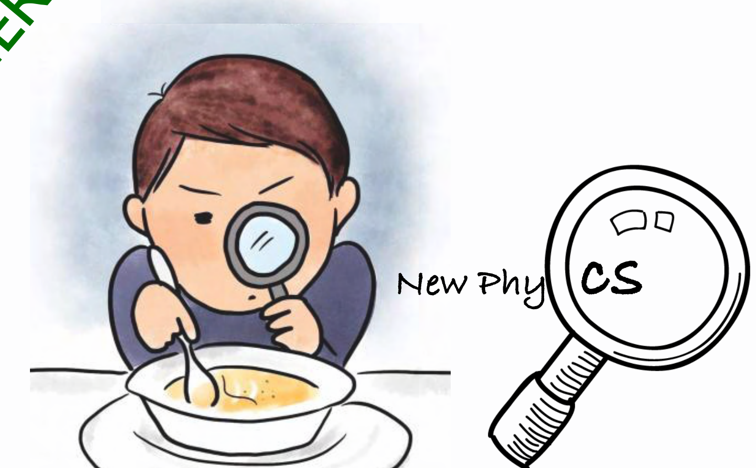
HIGH-ENERGY FRONTIER



INTENSITY FRONTIER

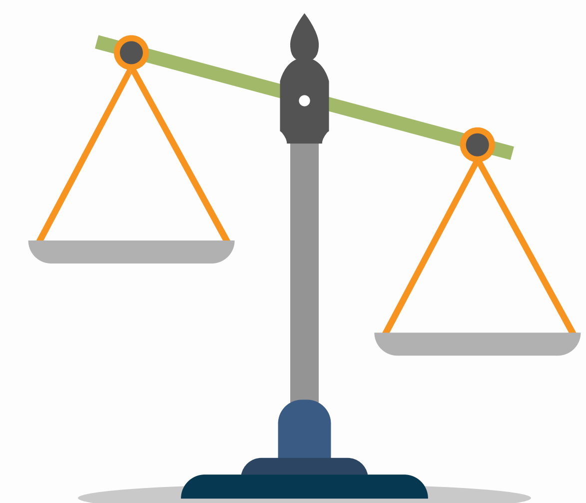
PRECISION FRONTIER



NEW PHYSICS SEARCHES

- Lab searches for New Physics proceed along 3 frontiers:

SM prediction vs. experimental observation



HIGH-ENERGY FRONTIER

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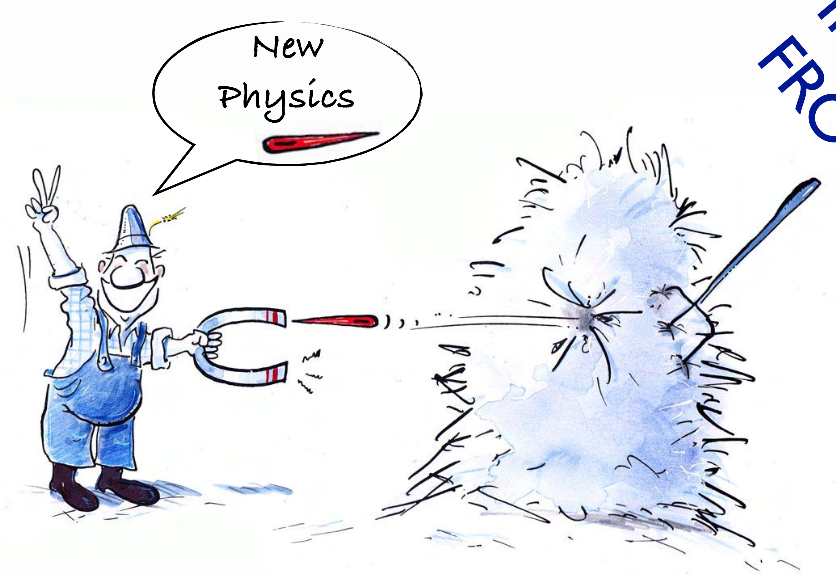
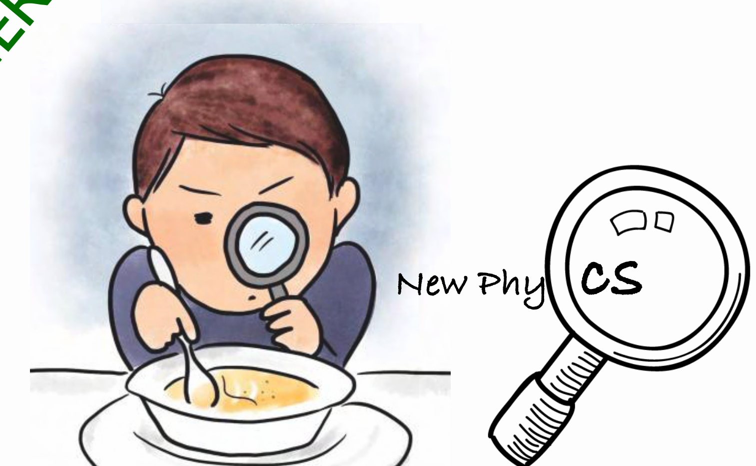
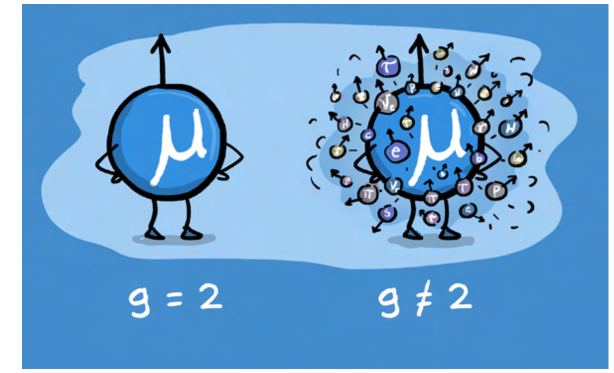


PRECISION FRONTIER



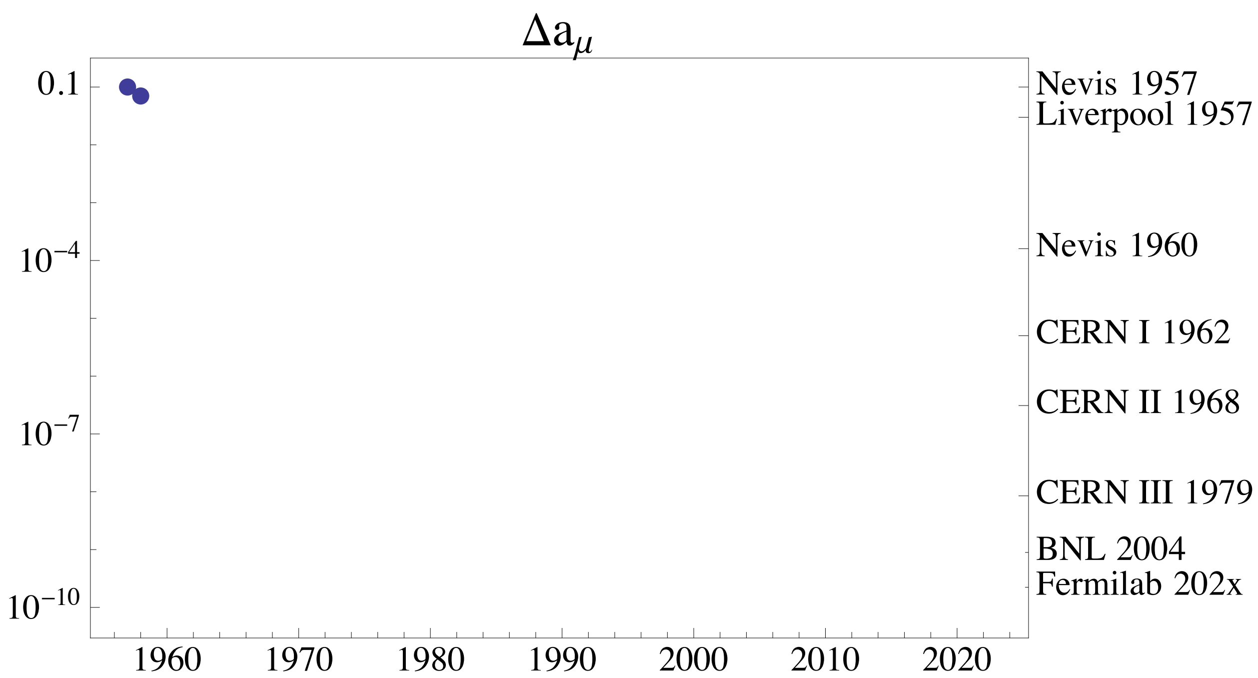
MUON g-2

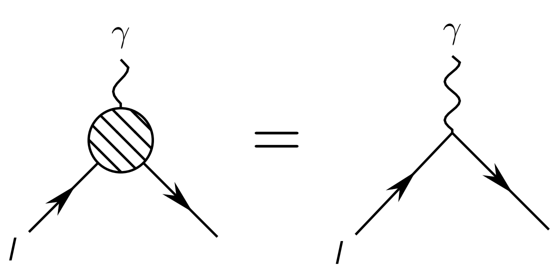


- Electrostatic properties of charged spin-1/2 particles:
  - Charge Q and electric dipole moment $\vec{d}$
  - Magnetic moment $\vec{\mu} = g\frac{e}{2m}\vec{s}$
- Anomalous magnetic dipole moment: $a_\mu = \frac{g_\mu - 2}{2} = 0.0011659181$

  $\Longrightarrow$ deviation of the gyromagnetic factor from its value (2) in Dirac theory
- a_e : QED test, precise determination of $\alpha = e^2/4\pi$
- a_μ : less precisely measured than a_e but 43000 more sensitive to possible contributions from New Physics $a_\ell \sim \left(m_\ell/m_{\mathrm{NP}}\right)^2$

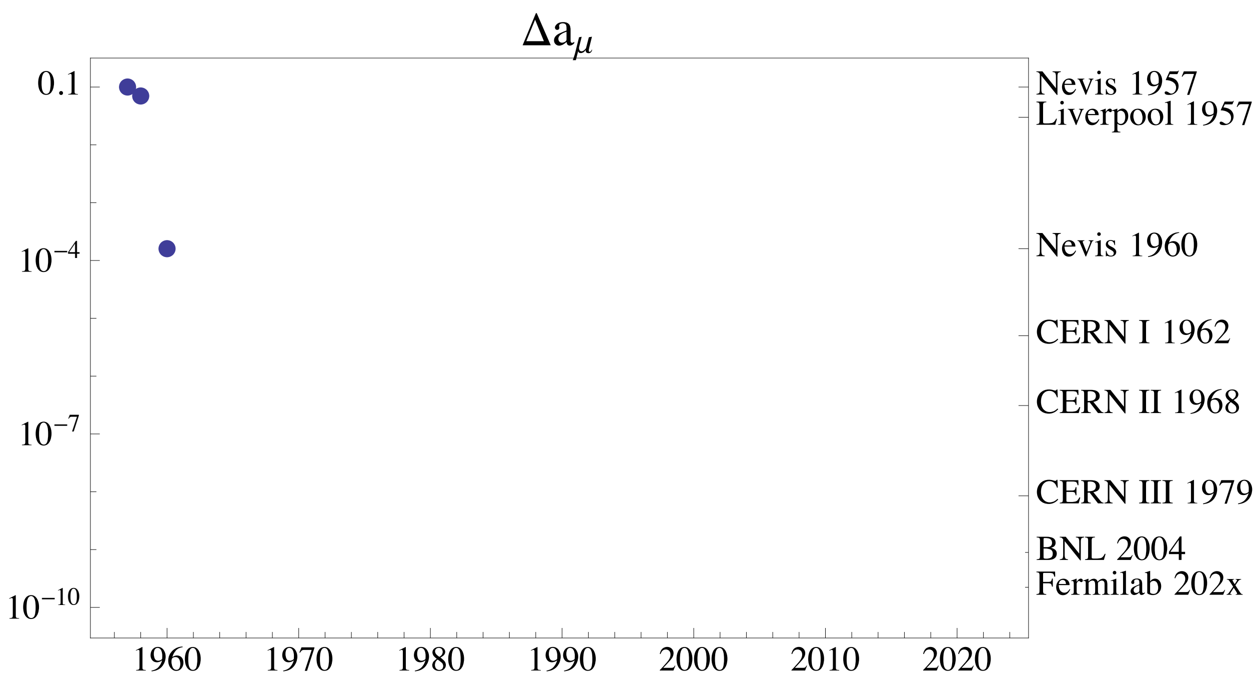
PRECISION PHYSICS





- Anomalous magnetic moment of the muon: $a_\mu = (g-2)/2 = 0.0011659181$

PRECISION PHYSICS



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Schwinger term
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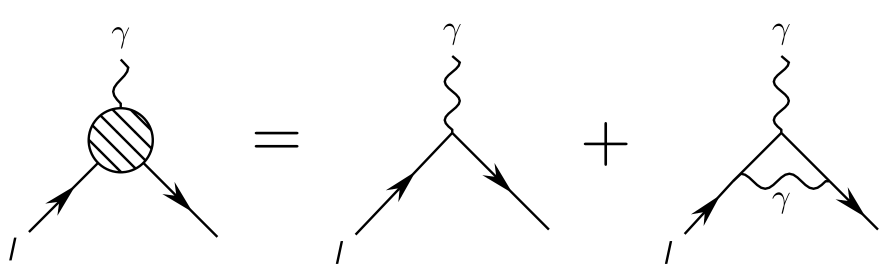
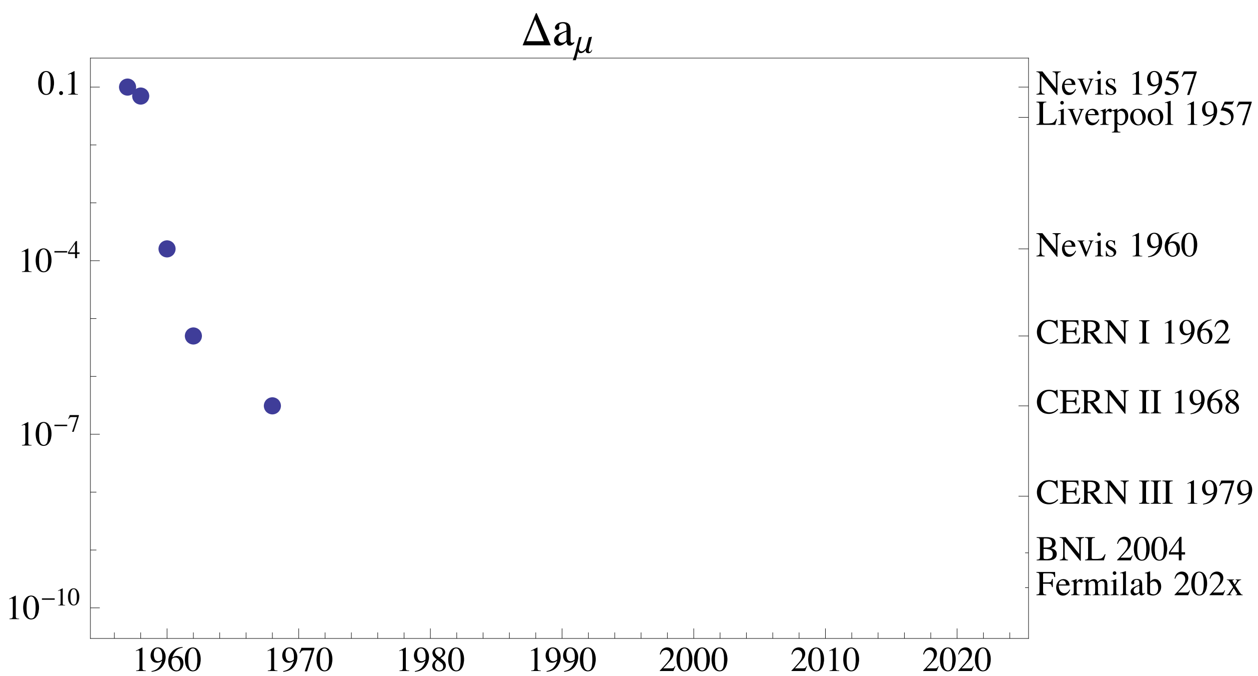


1-loop QED [1 diagram]

PRECISION PHYSICS



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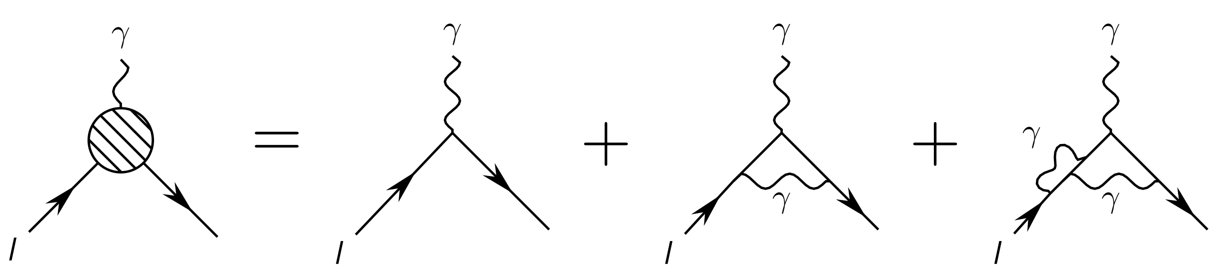
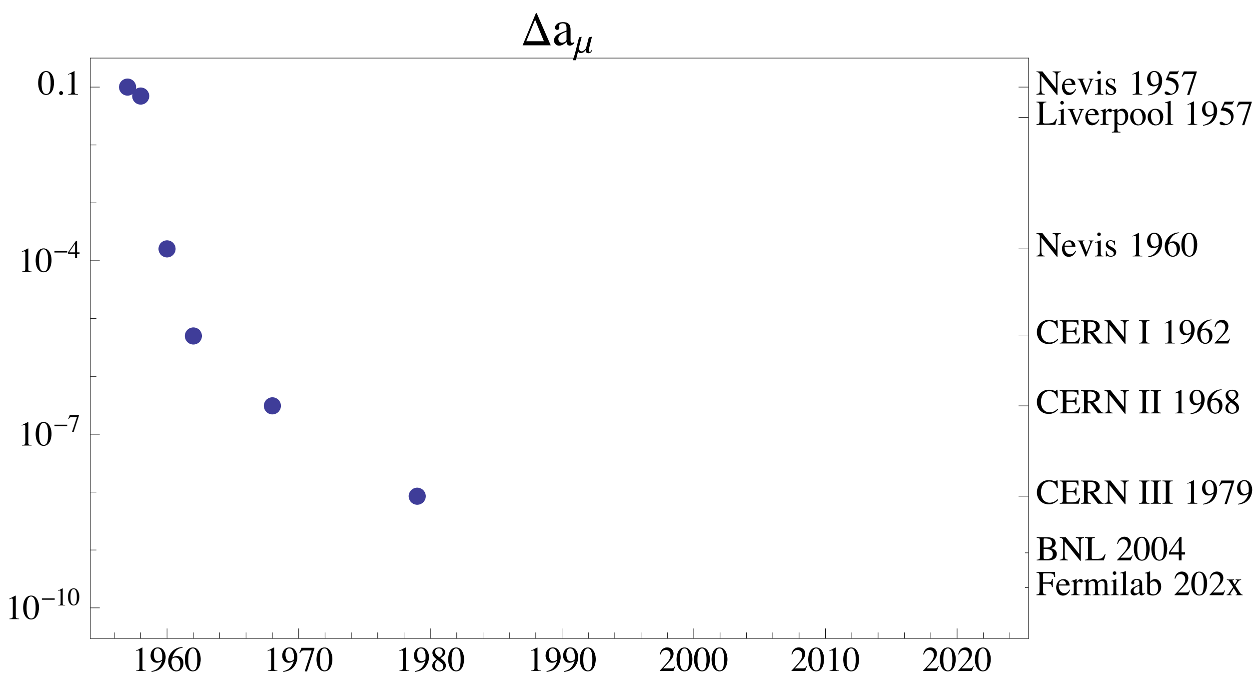


1-loop QED [1 diagram]

2-loop QED [7 diagrams]

3-loop QED [72 diagrams]

PRECISION PHYSICS



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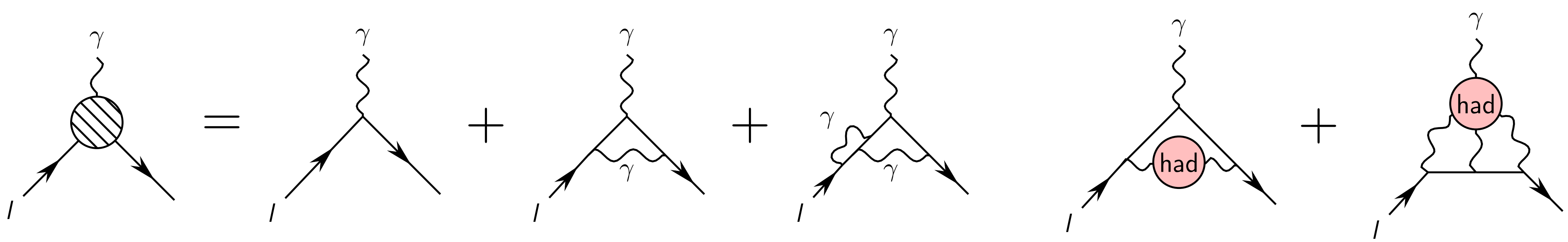

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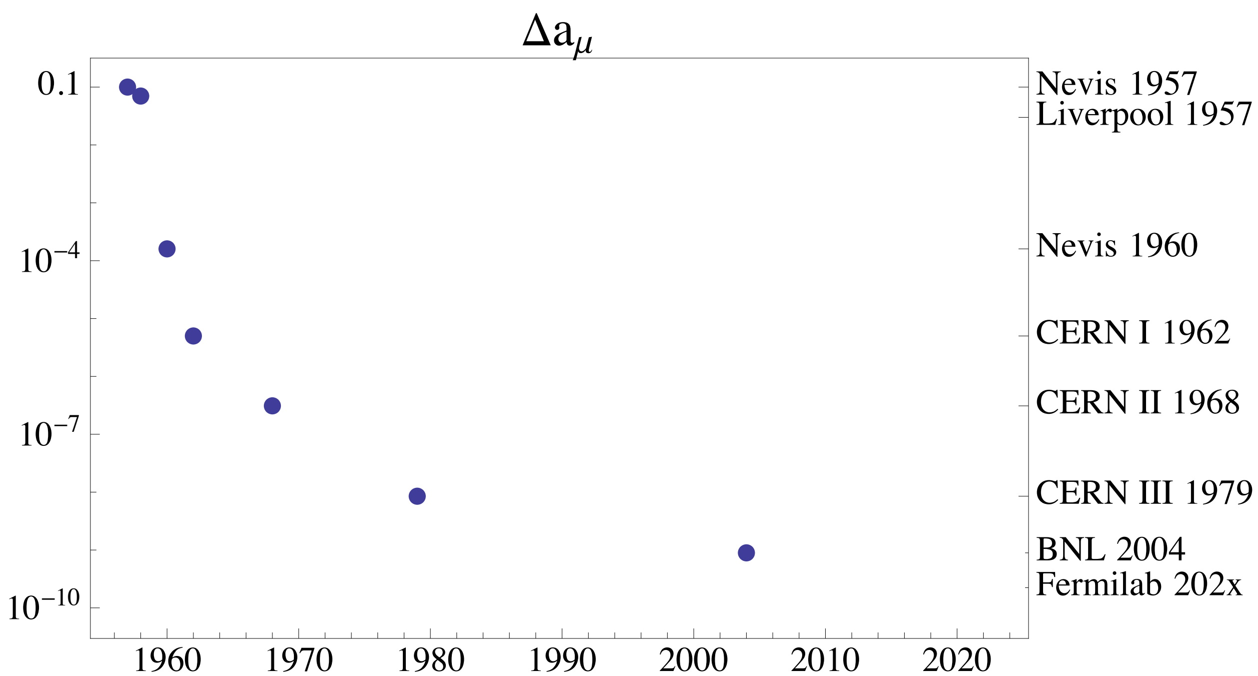

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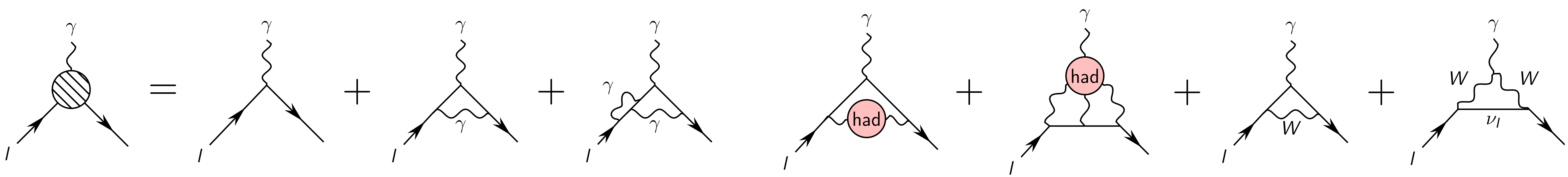

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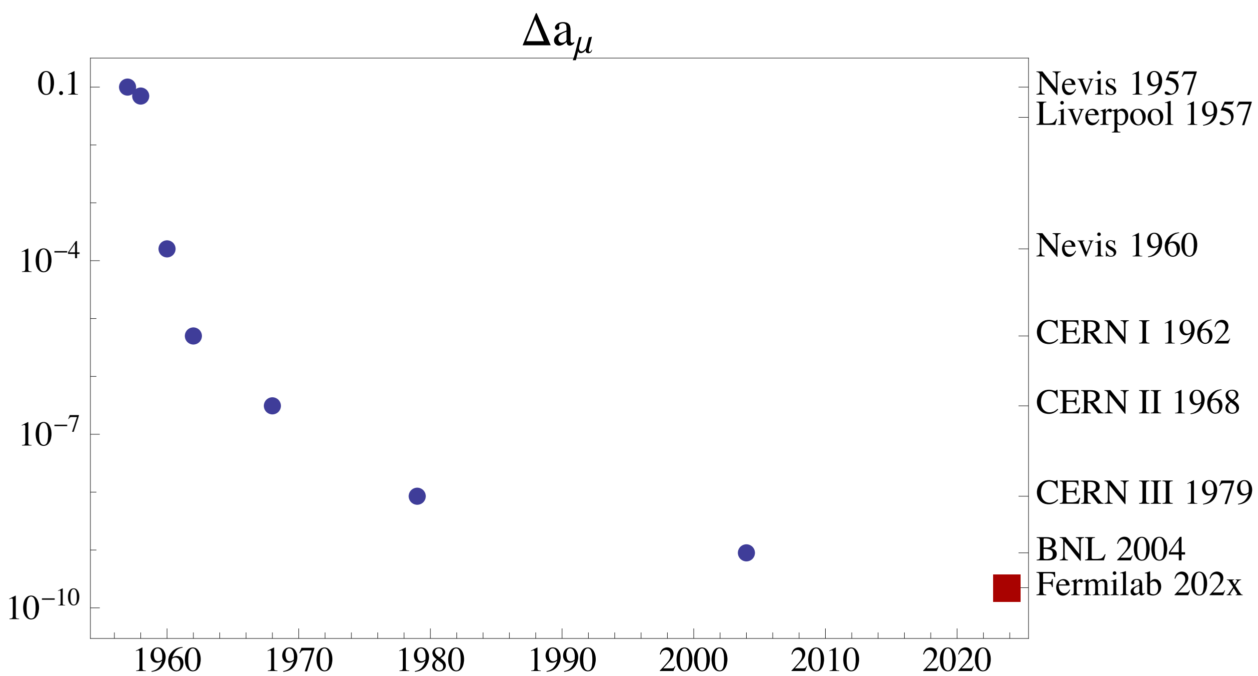
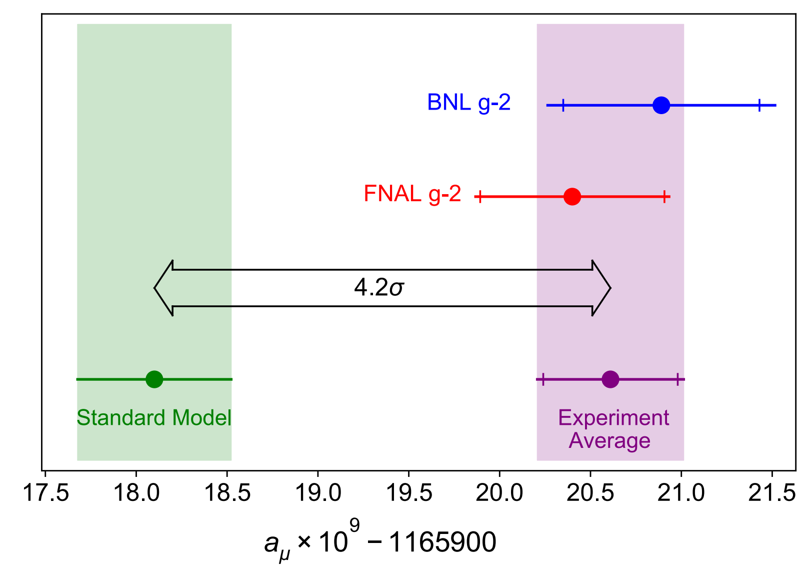
5-loop QED [12 672 diagrams]

PRECISION PHYSICS



- Anomalous magnetic moment of the muon: $a_\mu = (g-2)/2 = 0.0011659181$
- Factor of 2 reduction of experimental uncertainty expected



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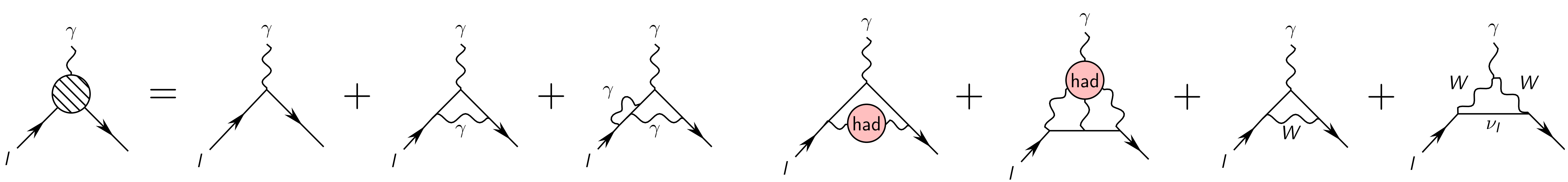

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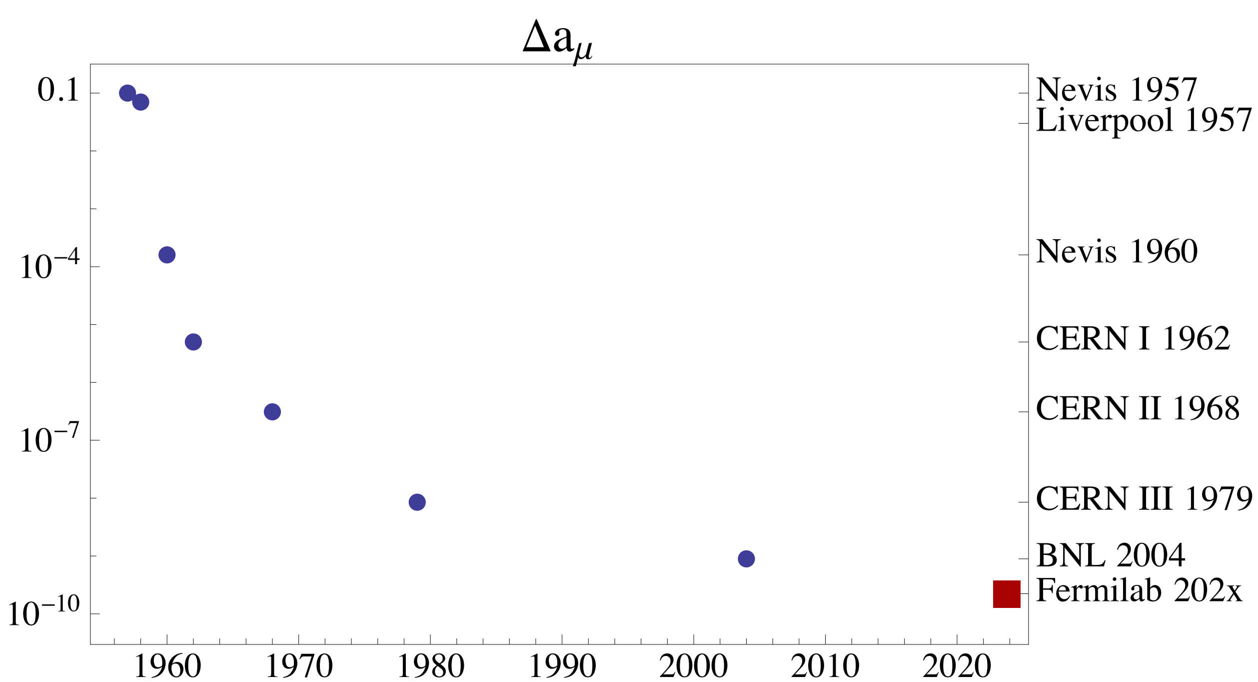

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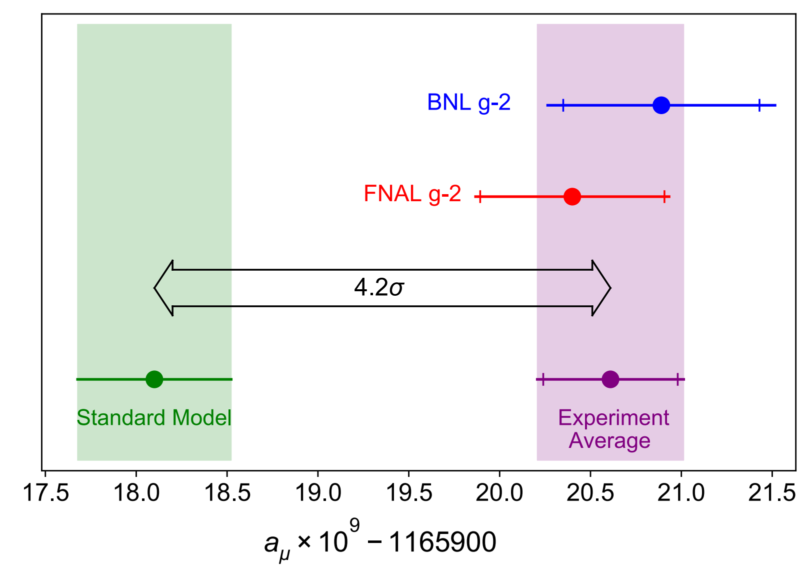

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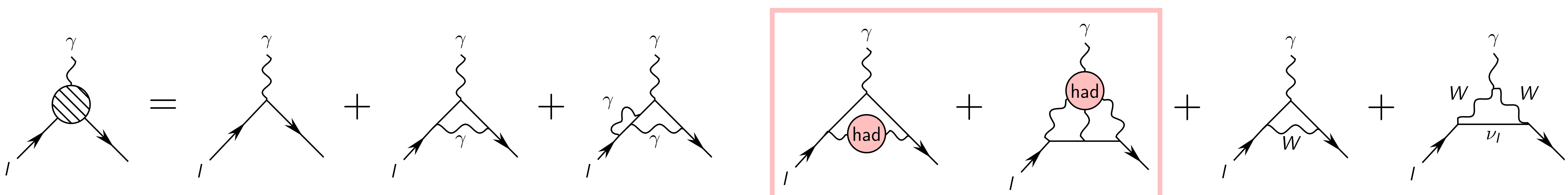

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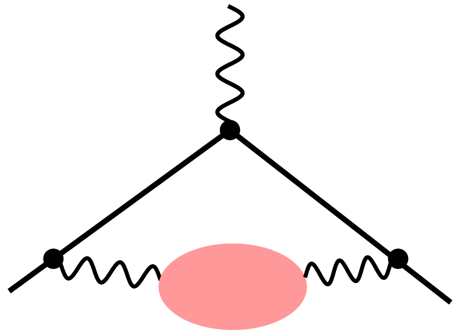
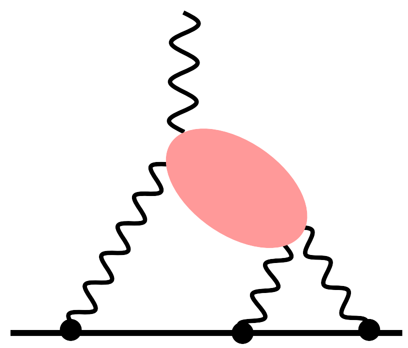
- *Mismatch implies "New Physics" or insufficient understanding of the SM!*
- *SM prediction has to improve yet again!*

HADRONIC CORRECTIONS

Hadronic vacuum polarization (HVP)



Hadronic light-by-light scattering (HLbL)

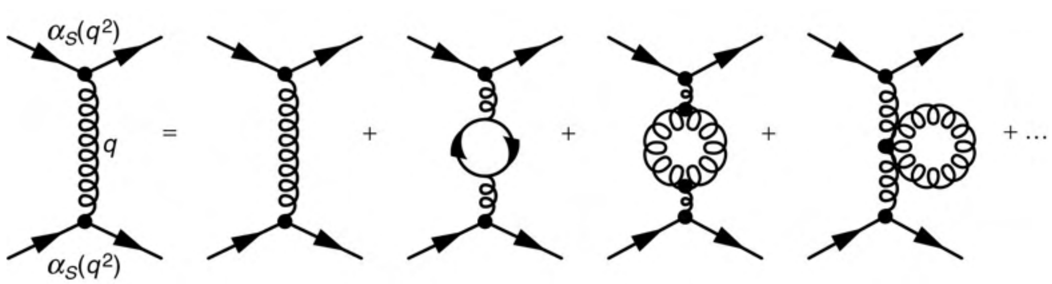


	$a_\mu \times 10^{14}$	$\Delta a_\mu \times 10^{14}$	$\Delta a_\mu / a_\mu$
HVP	6 845 000	40 000	6×10^{-3}
HLbL	92 000	18 000	2×10^{-1}
Electroweak	153 600	1 000	7×10^{-3}
QED	116 584 718 931	104	9×10^{-10}
SM prediction	116 591 810 000	43 000	4×10^{-7}

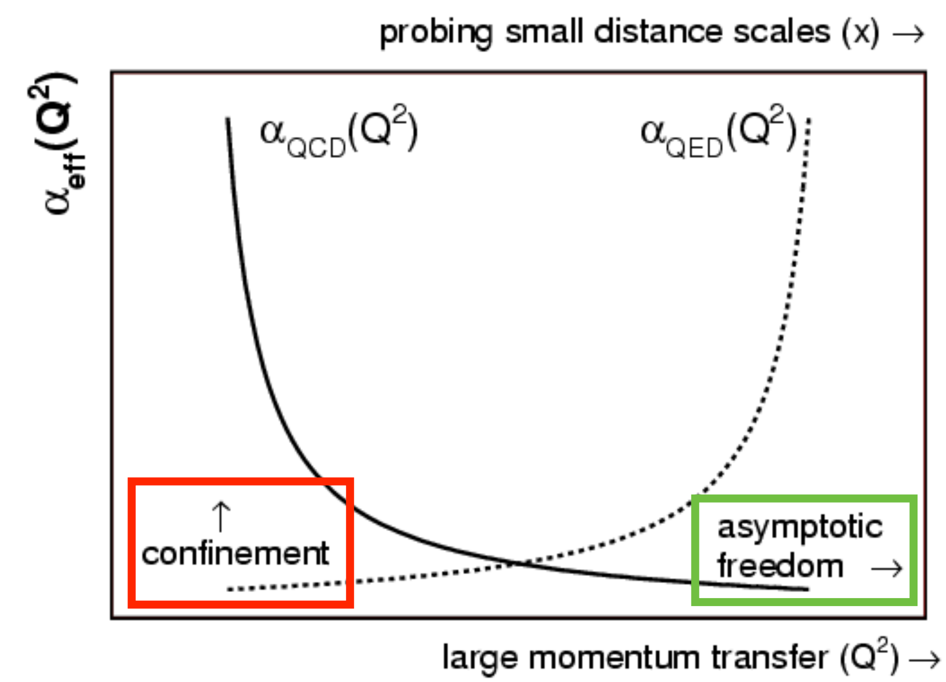
- Hadronic contributions are the stumbling block … often limiting factor in precision of SM predictions

QUANTUM CHROMODYNAMICS

running of the coupling constant



gluon self-interaction



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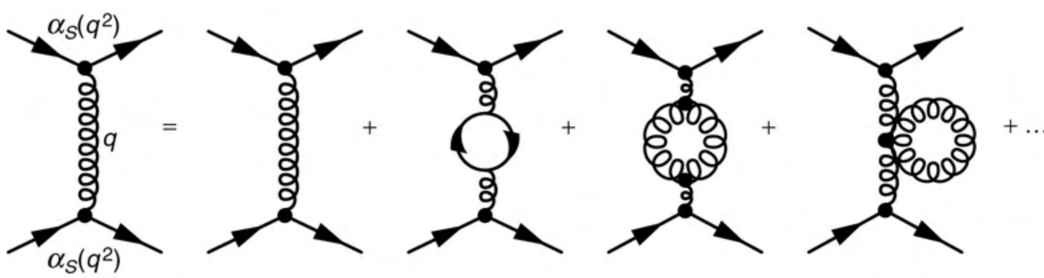

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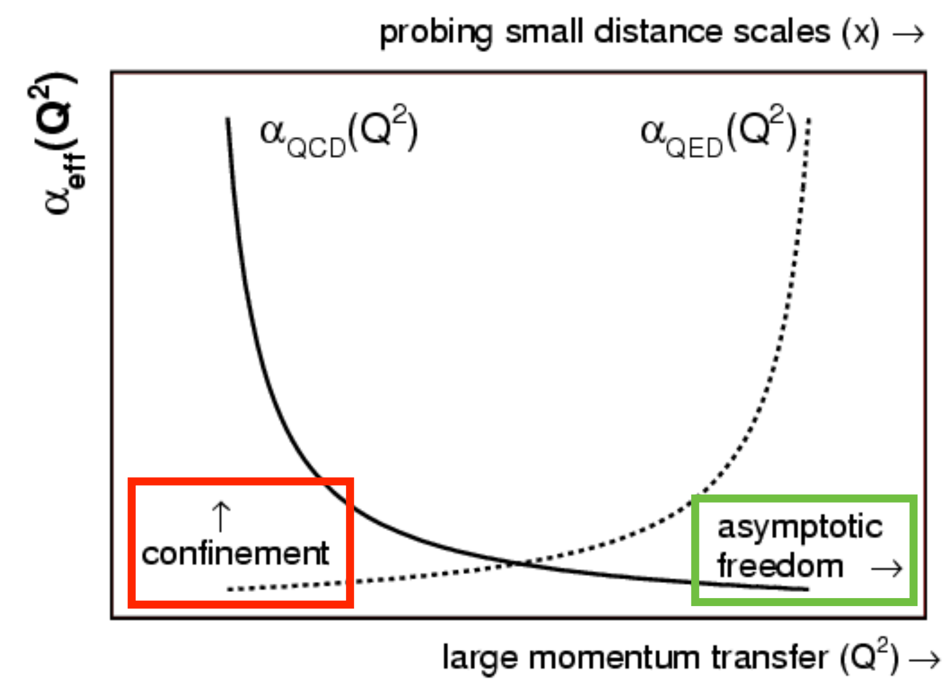
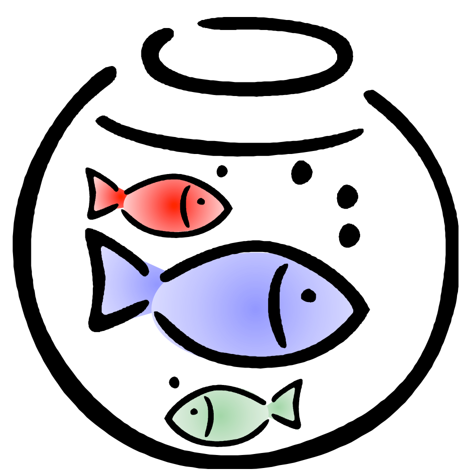
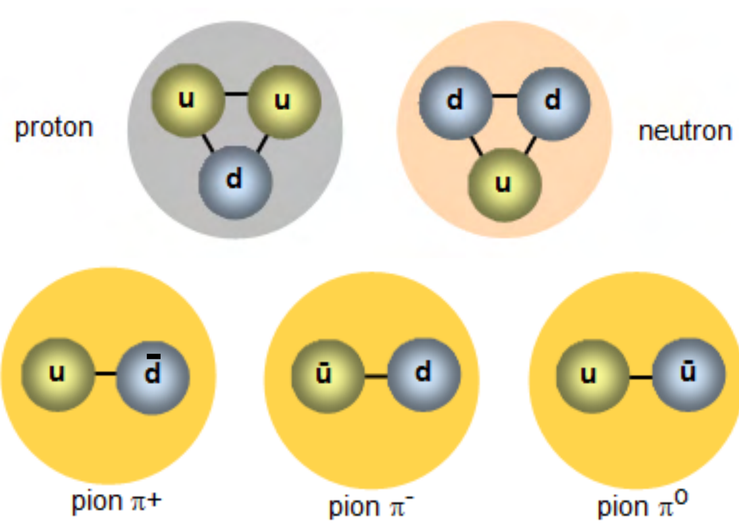
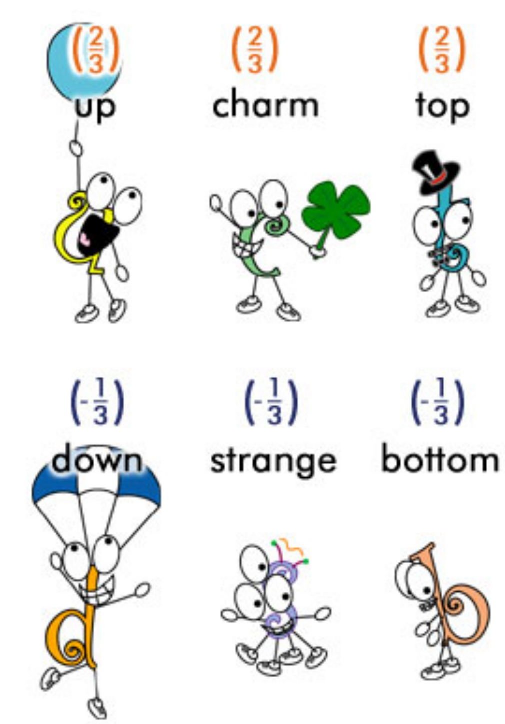


color confinement
at low energies hadrons are the effective degrees of freedom



asymptotic freedom
at high energies quarks and gluons are the degrees of freedom and QCD is treated perturbative

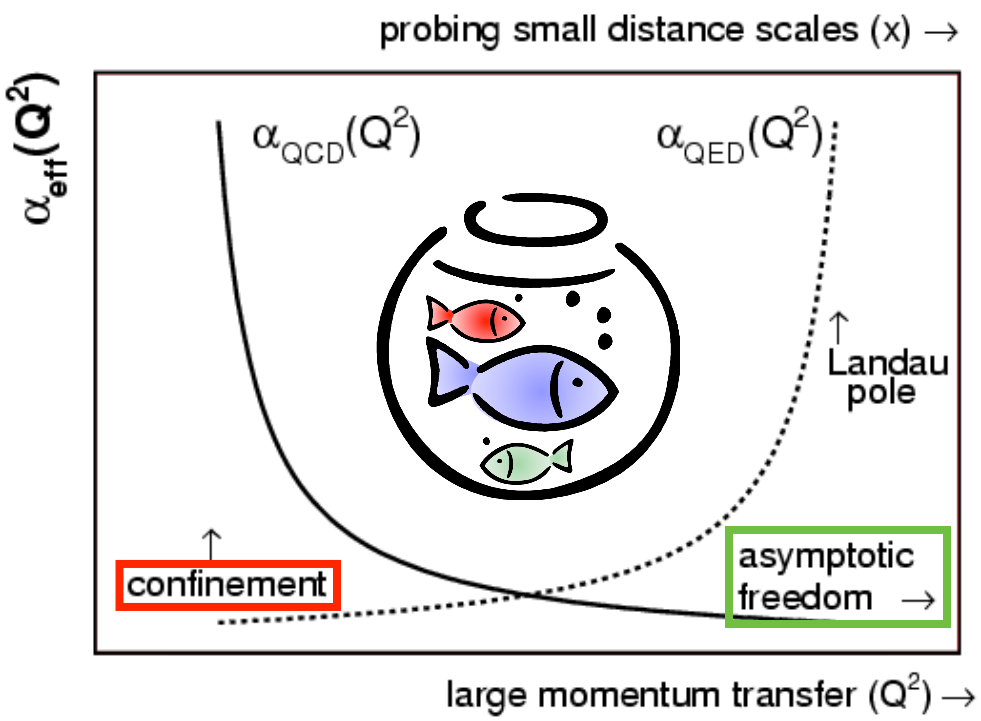




HADRONIC CORRECTIONS

- QCD is non-perturbative at low energies, due to strong coupling

running of the coupling constant



- Hadronic corrections are challenging to calculate:
  - Effective field theories, e.g., chiral perturbation theory (ChPT) or pionless EFT
  - Lattice QCD
  - Dispersion relations (unitarity, causality) — basis for data-driven evaluations

The Puzzling Proton

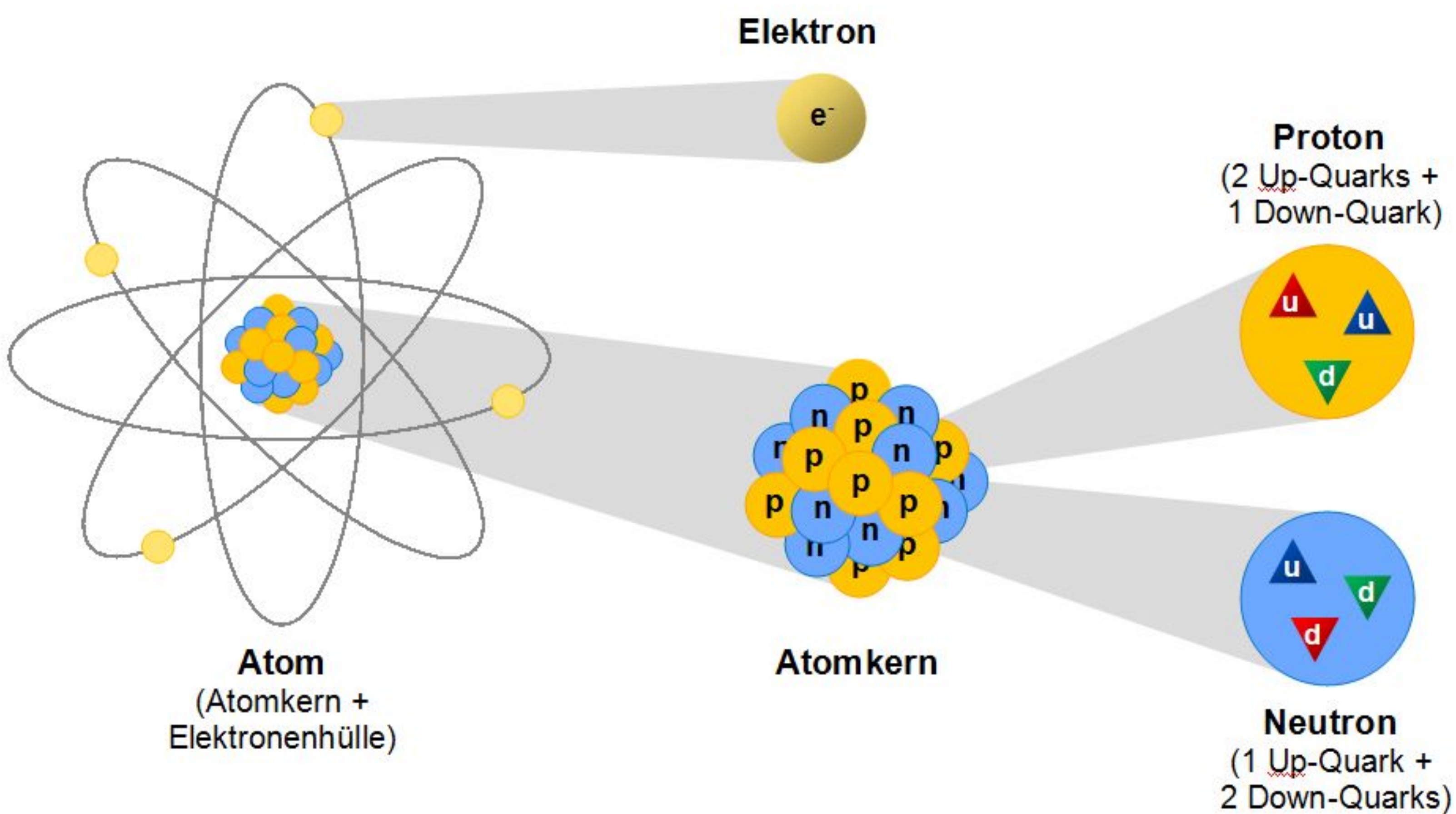
https://www.sciencenews.org

FROM COMPTON SCATTERING TO MUONIC HYDROGEN AND BACK TO THE FUTURE

- low-energy nucleon structure is seen through:

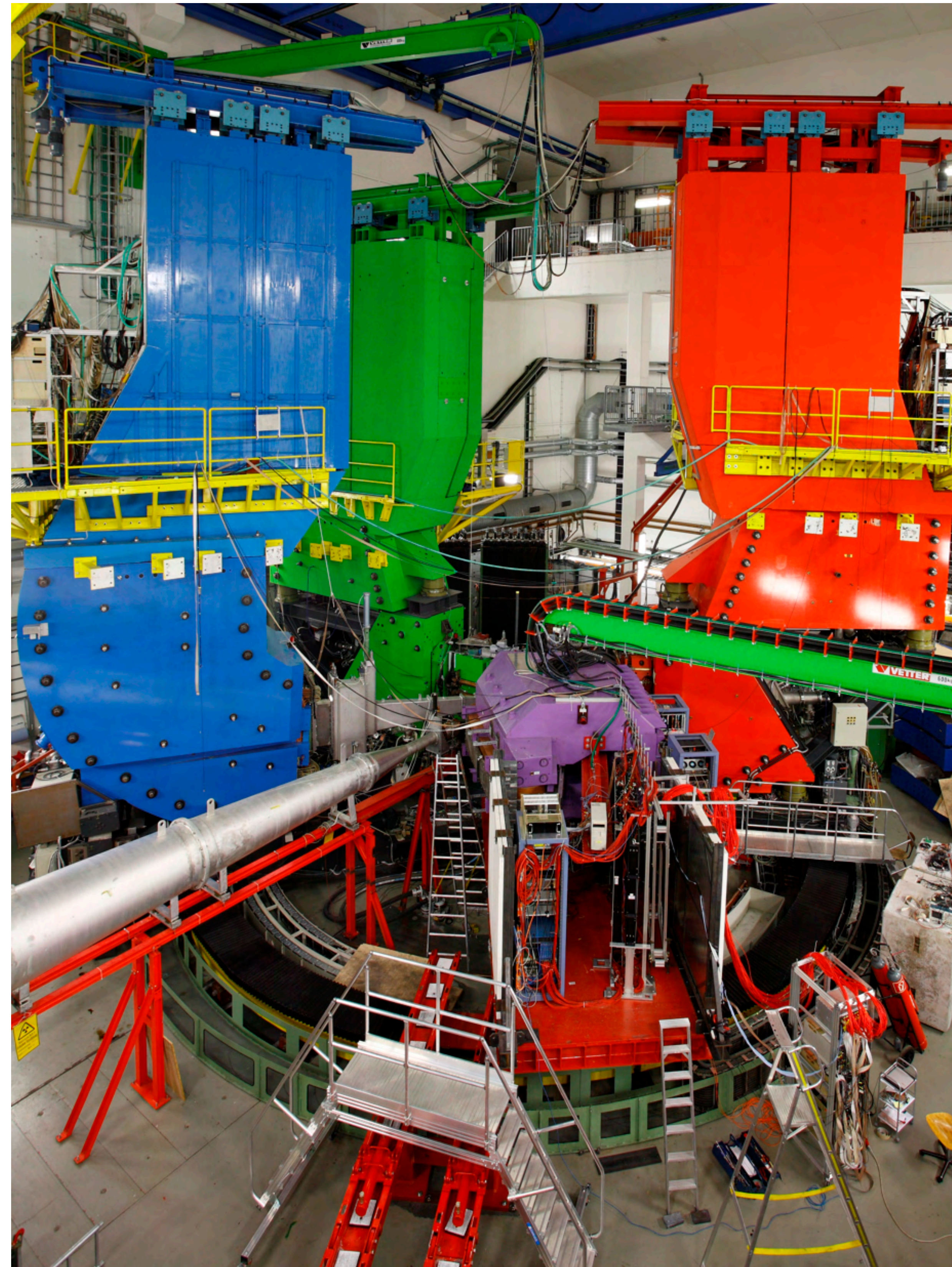
  a) electromagnetic probes (e.g., electron and Compton scattering)

  b) nucleon-structure effects in atoms

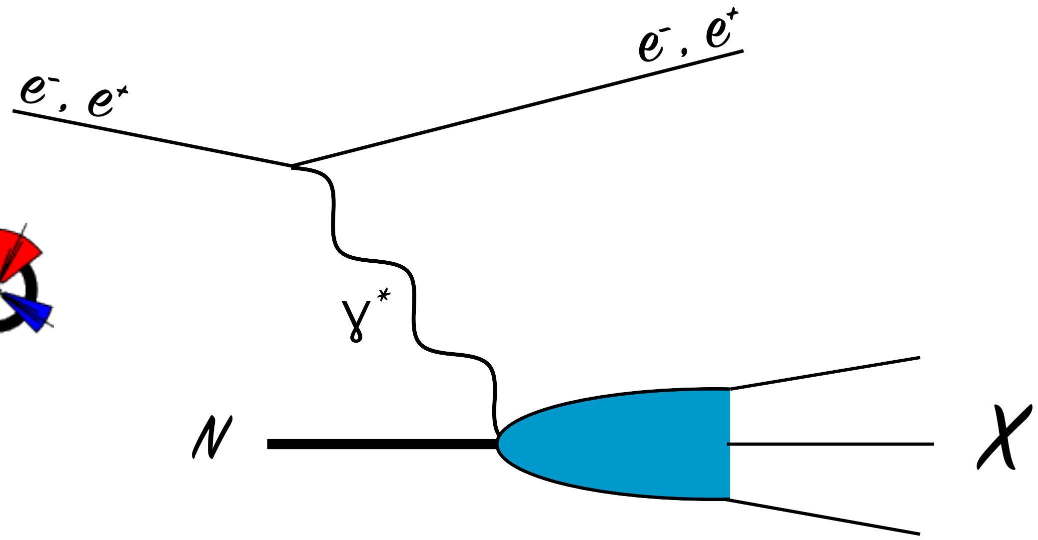


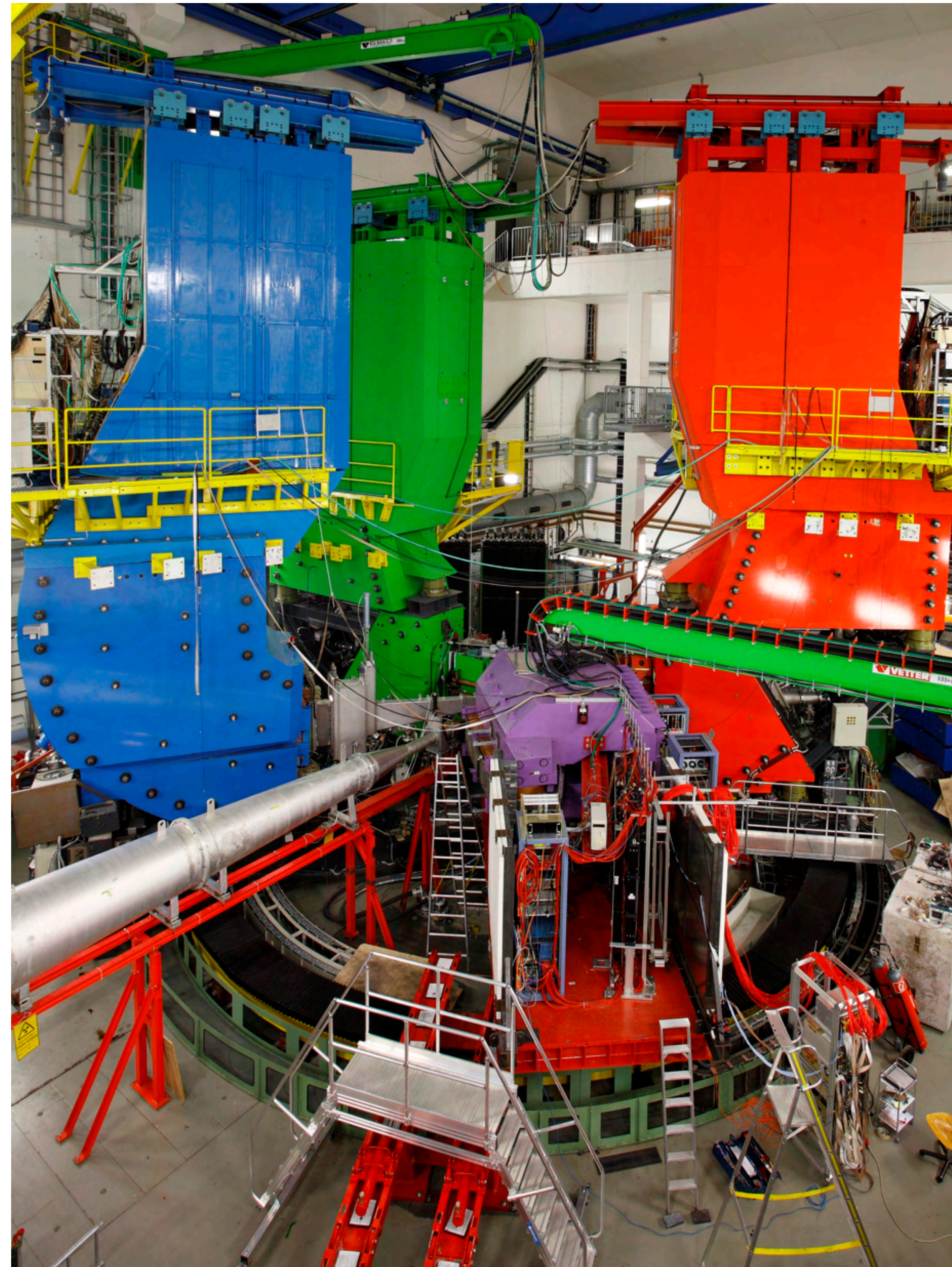
intersection of nuclear, particle and atomic physics

ELECTRON AND COMPTON SCATTERING

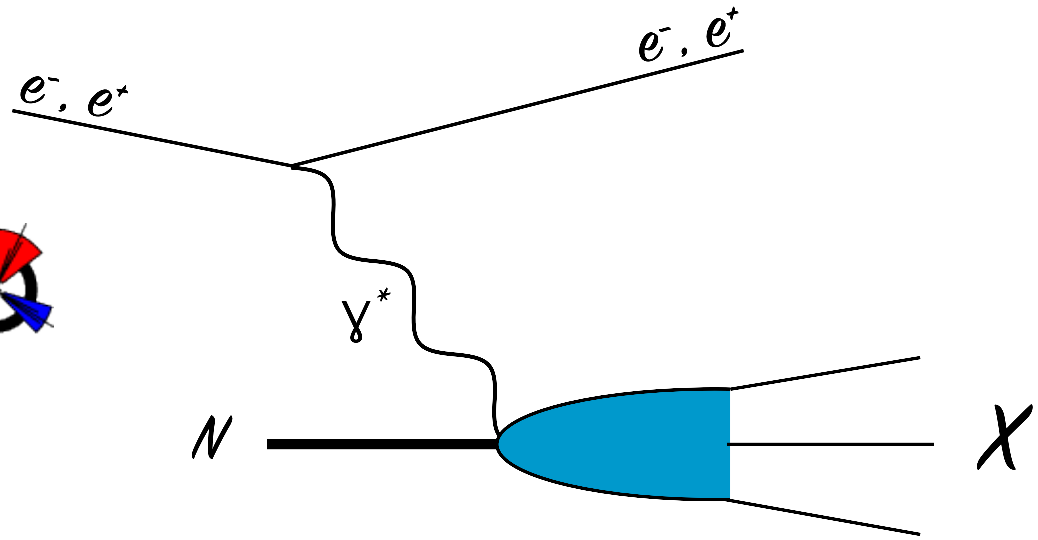


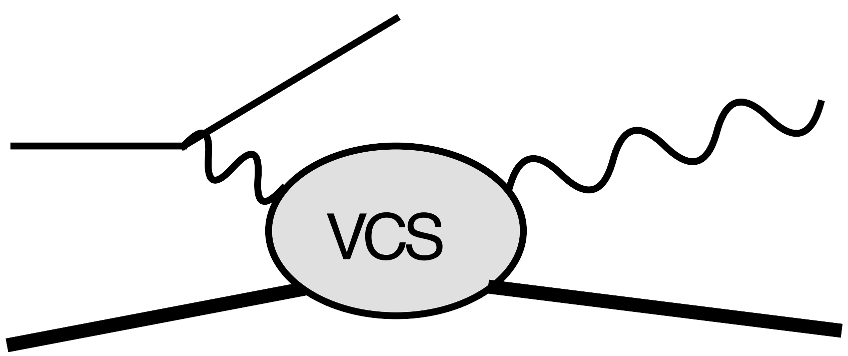
ELECTRON AND COMPTON SCATTERING

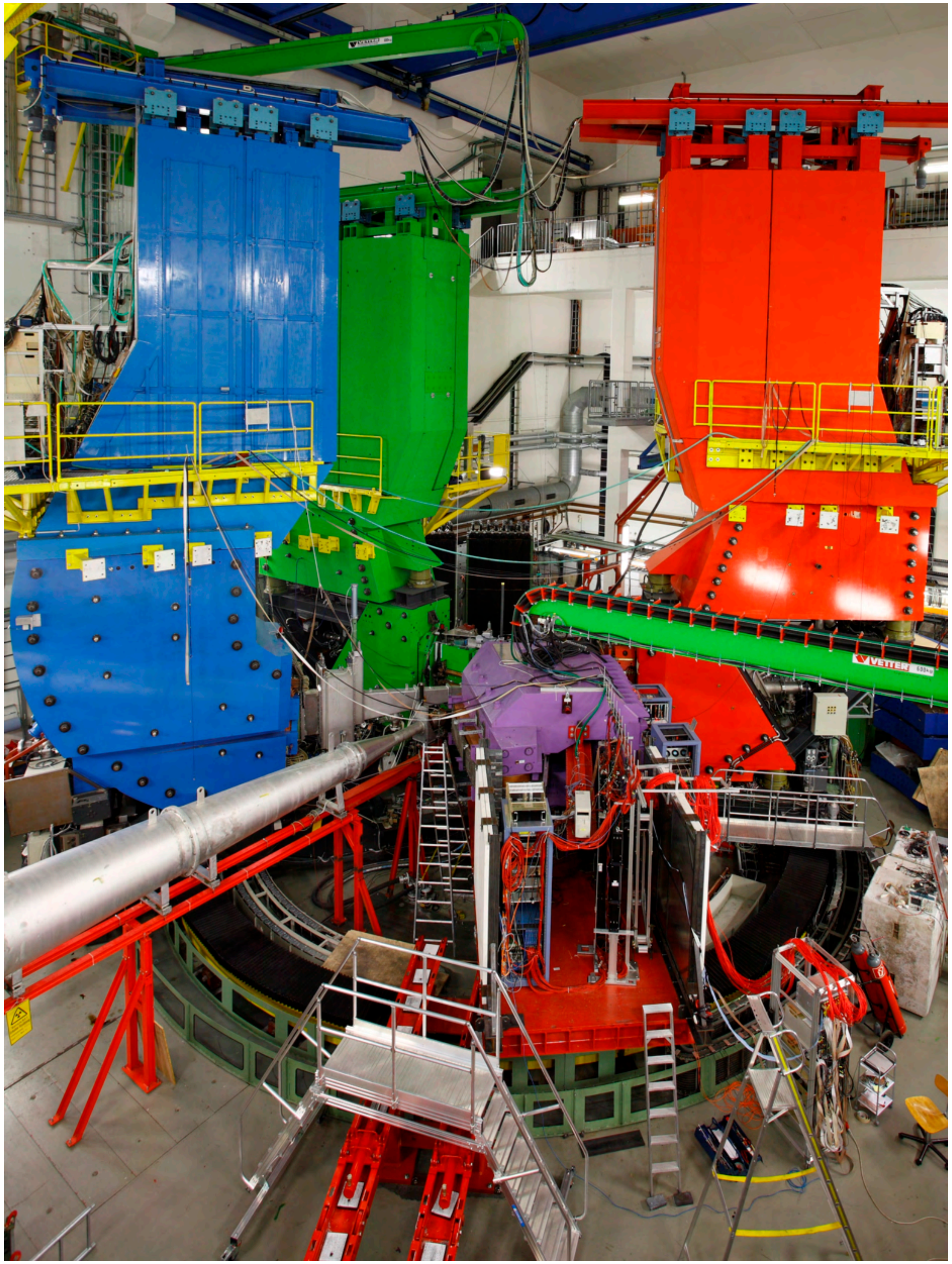




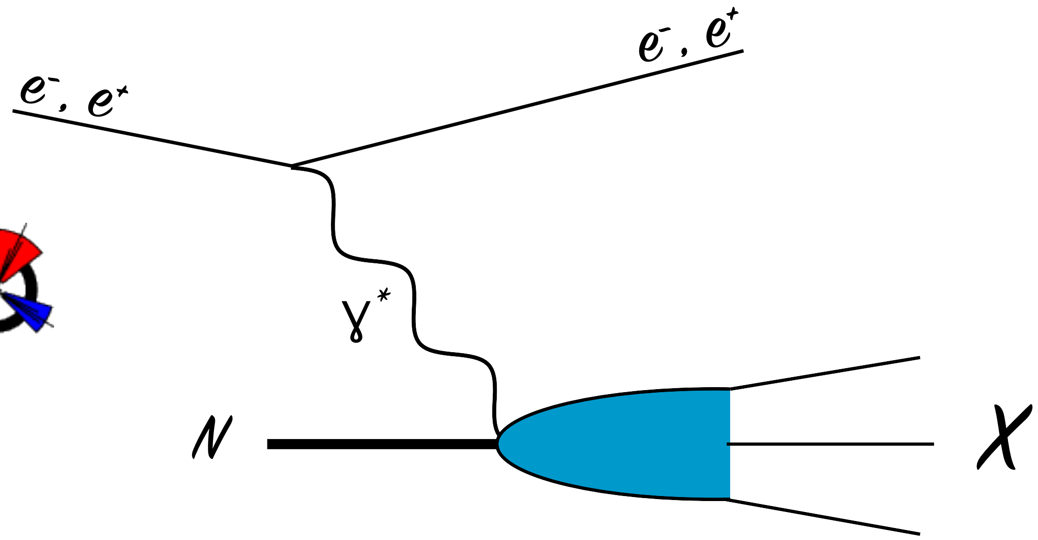
ELECTRON AND COMPTON SCATTERING

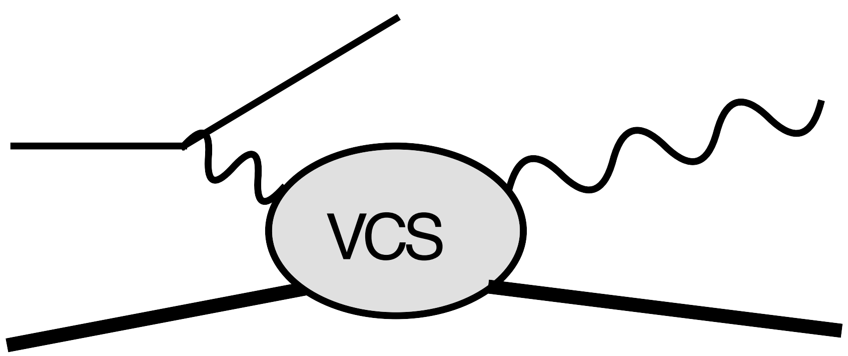


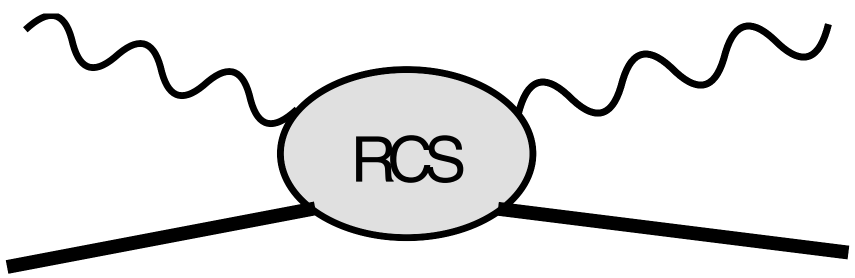


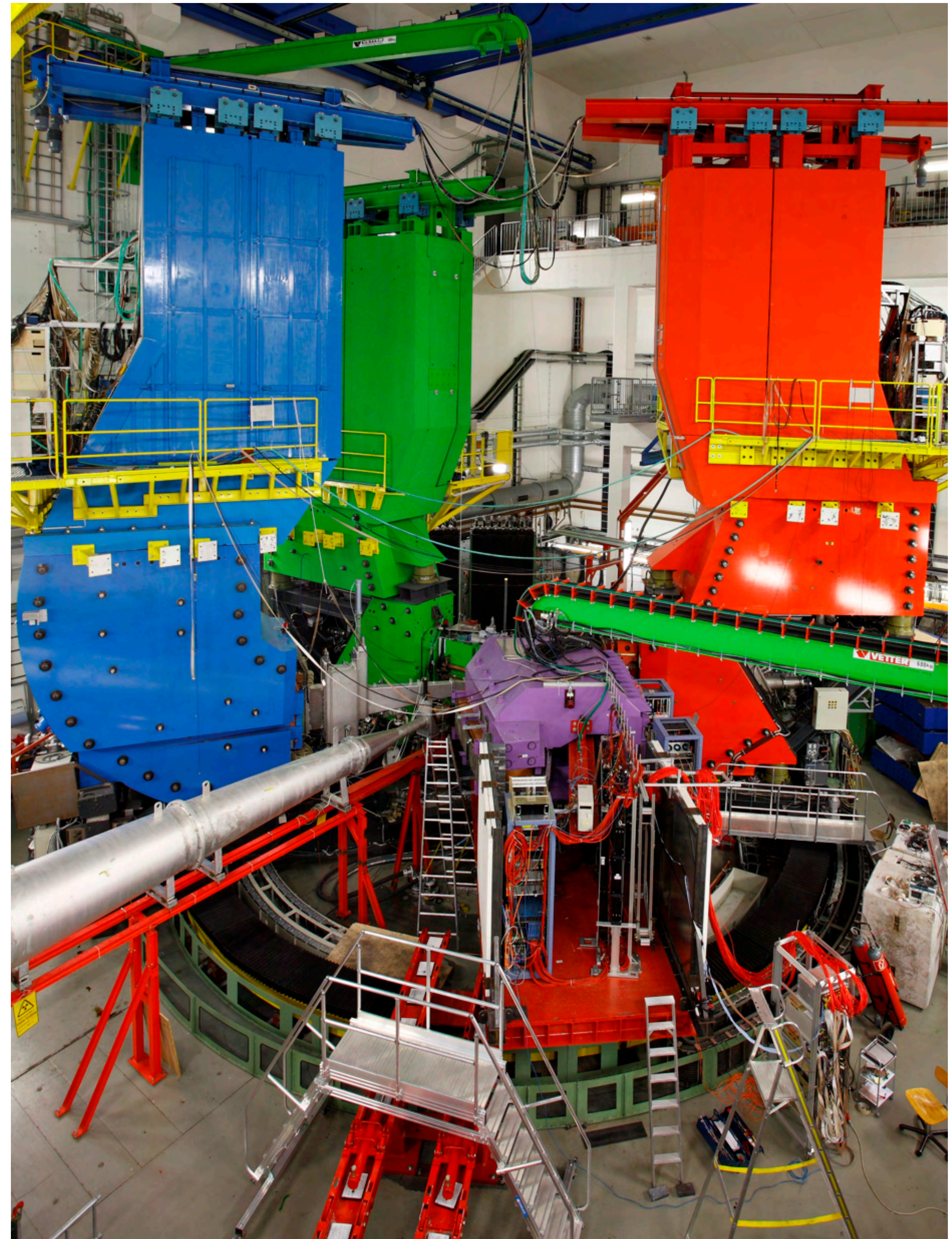


ELECTRON AND COMPTON SCATTERING

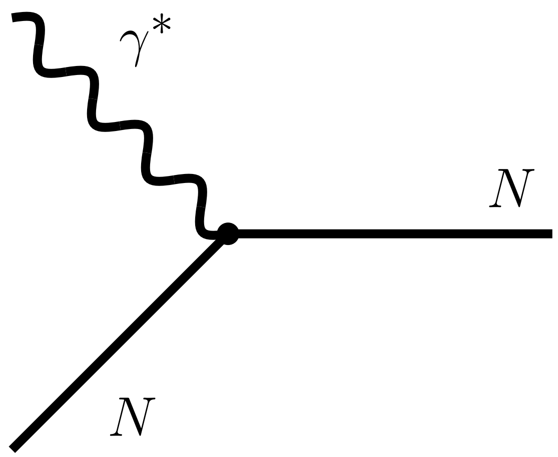








ELECTROMAGNETIC FORM FACTORS



ρ(r)	$\lvert F(\boldsymbol{q}^2)\rvert$	Beispiel
punktförmig	konstant	Elektron
exponentiell	Dipol	Proton
gaußförmig	gaußförmig	^{6}Li
homogene Kugel	oszillierend	–
Kugel mit diffusem Rand	oszillierend	^{40}Ca
r ⟶	$\lvert \boldsymbol{q} \rvert$ ⟶	

- Form factors (FF): Fourier transforms of charge and magnetization distributions:

$$\rho(r) = \int \frac{\mathrm{d}\boldsymbol{q}}{(2\pi)^3} G(\boldsymbol{q}^2) e^{-i\boldsymbol{q}\boldsymbol{r}}$$

- Root-mean-square (rms) charge radius:

$$R_E = \sqrt{\langle r^2 \rangle_E}$$

$$\langle r^2 \rangle_E \equiv \int \mathrm{d}\boldsymbol{r}\, r^2\, \rho_E(\boldsymbol{r}) = -6 \frac{\mathrm{d}}{\mathrm{d}Q^2} G_E(Q^2)\Big|_{Q^2=0}$$

$$G_E(Q^2) = 1 - \frac{1}{6}\langle r^2 \rangle_E Q^2 + \frac{1}{120}\langle r^4 \rangle_E Q^4 + \dots$$

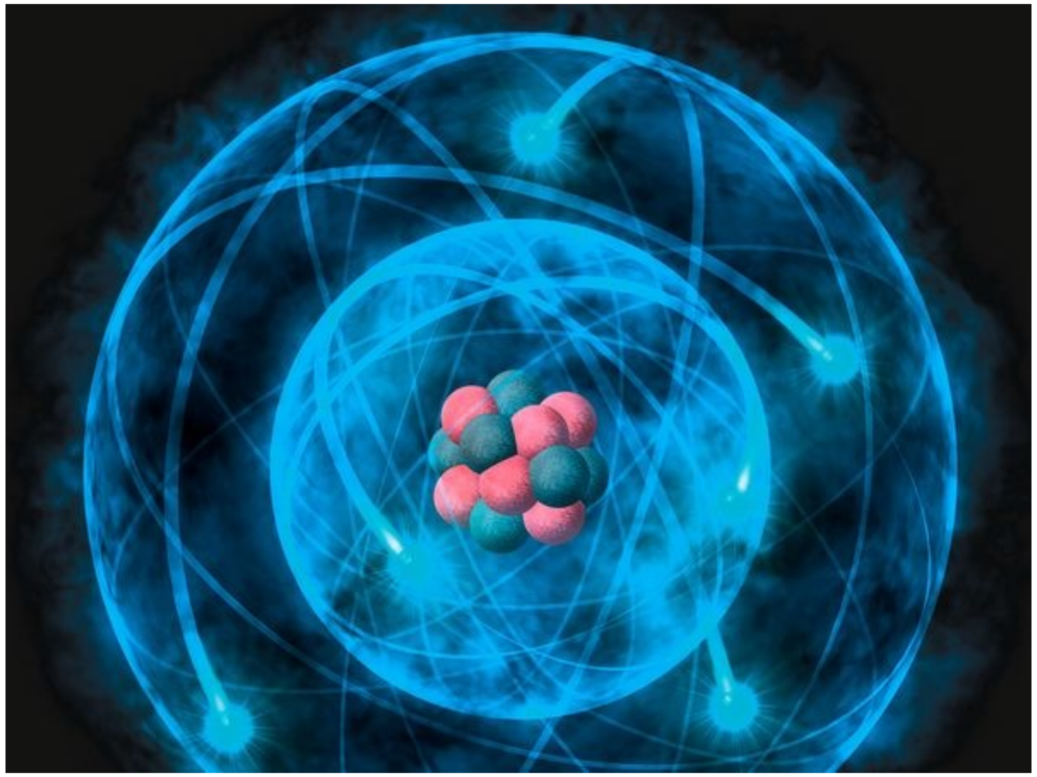
- Extraction of the proton charge radius from ep scattering requires extrapolation of FF data to zero momentum transfer

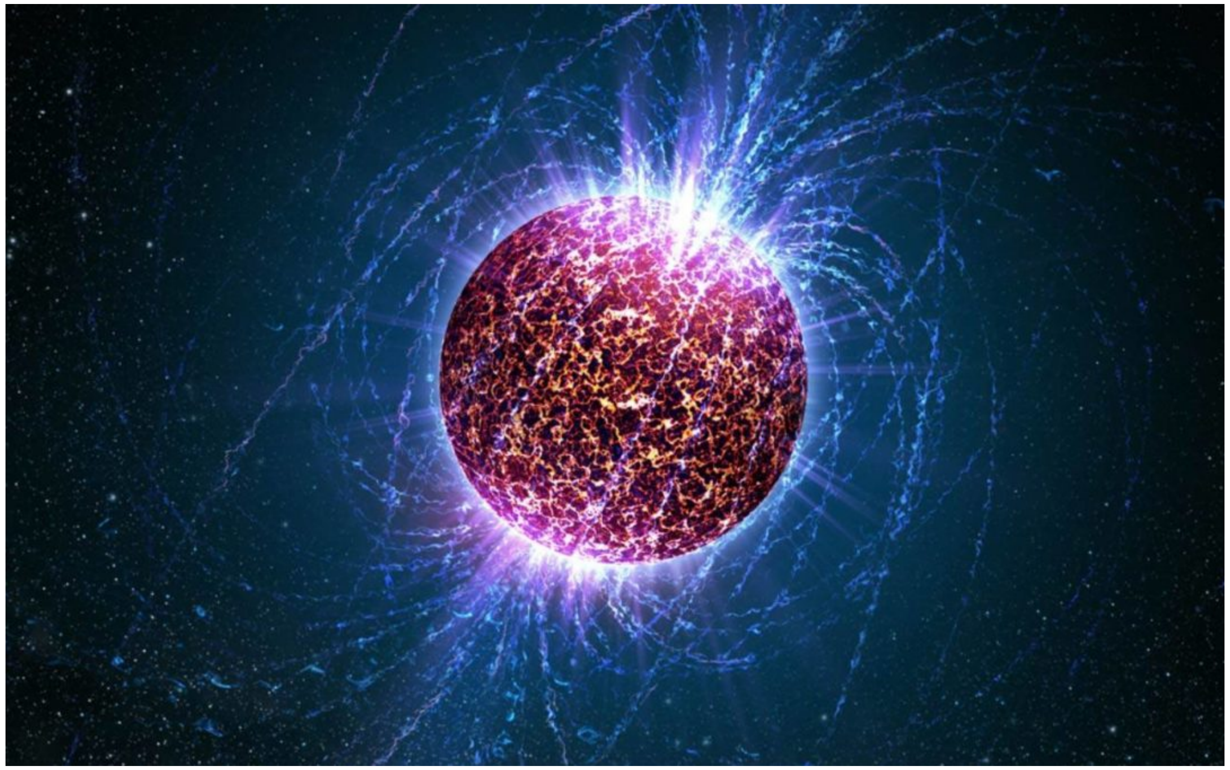
POLARIZABILITIES

- Fundamental characteristics of inelastic structure, complementary to the elastic form factors

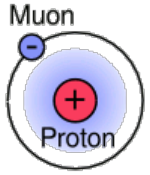
e.g., polarizabilities of nuclei, atoms, molecules are comparable to their volume, whereas the nucleons are much more rigid (polarizabilities are of the size $10^{-4}\,\mathrm{fm}^3$)

- affect properties of nuclei, atoms, … , neutron stars





- e.g., precise input required in muonic hydrogen

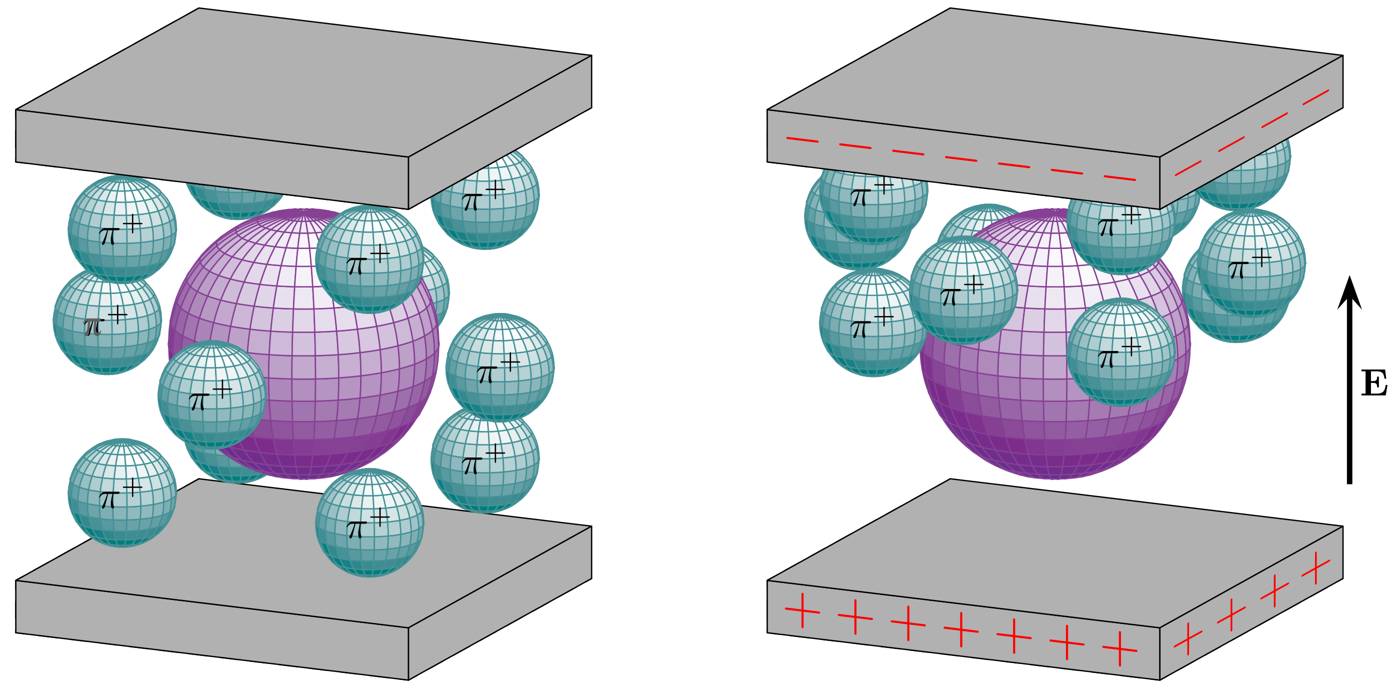


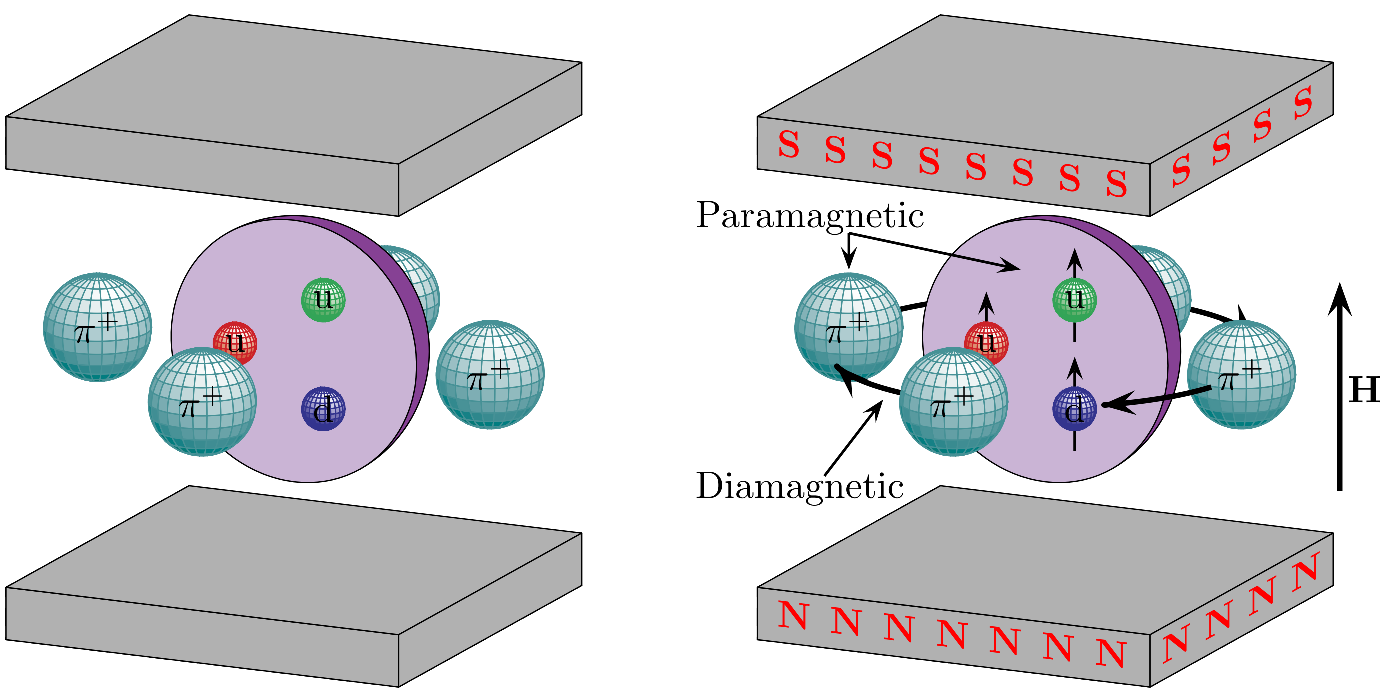
NUCLEON POLARIZABILITIES

Electric dipole polarizability:

$$\vec{P} = \alpha_{E1}\,\vec{E}$$

induced electric dipole polarization





Magnetic dipole polarizability:

$$\vec{P} = \beta_{M1}\vec{H}$$

polarization induced by magnetic field

diamagnetic: $\beta_{M1} < 0$
paramagnetic: $\beta_{M1} > 0$

DIAMAGNETIC OR PARAMAGNETIC ?

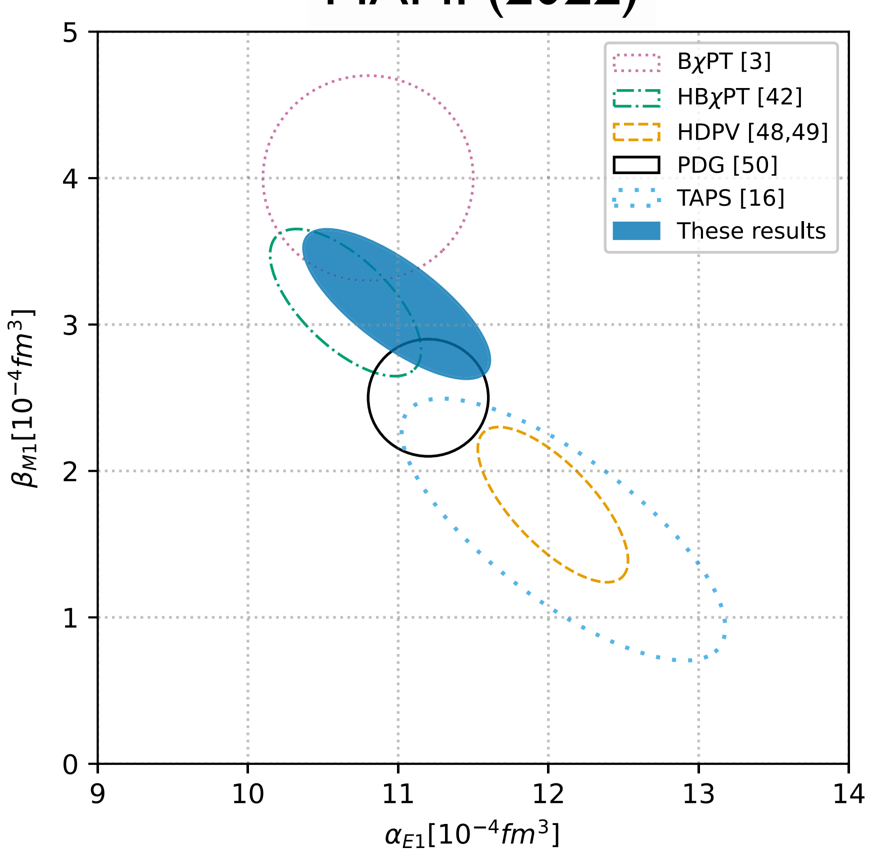
- Baldin sum rule constrains the sum of electric and magnetic dipole polarizabilities through photoabsorption data

$$\alpha_{E1} + \beta_{M1}\,(\text{Baldin}) = 14.0(2) \times 10^{-4}\,\text{fm}^3$$

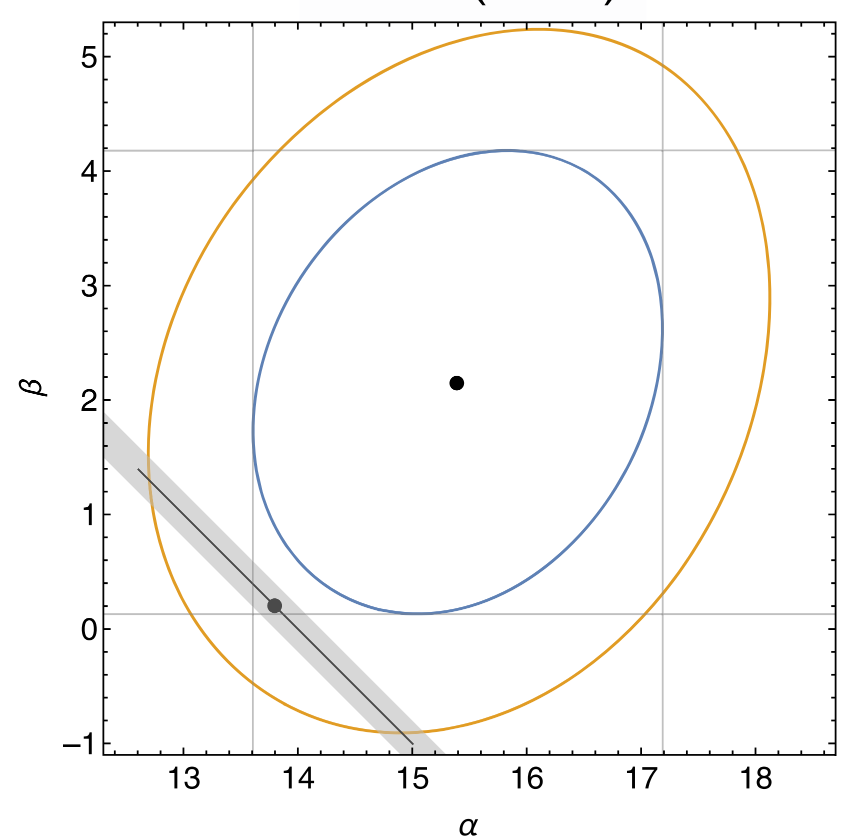
O. Gryniuk, FH, V. Pascalutsa, Phys. Rev. D 92, 074031 (2015)

- Is the proton dia- or paramagnetic?

MAMI (2022)



HIGS (2022)

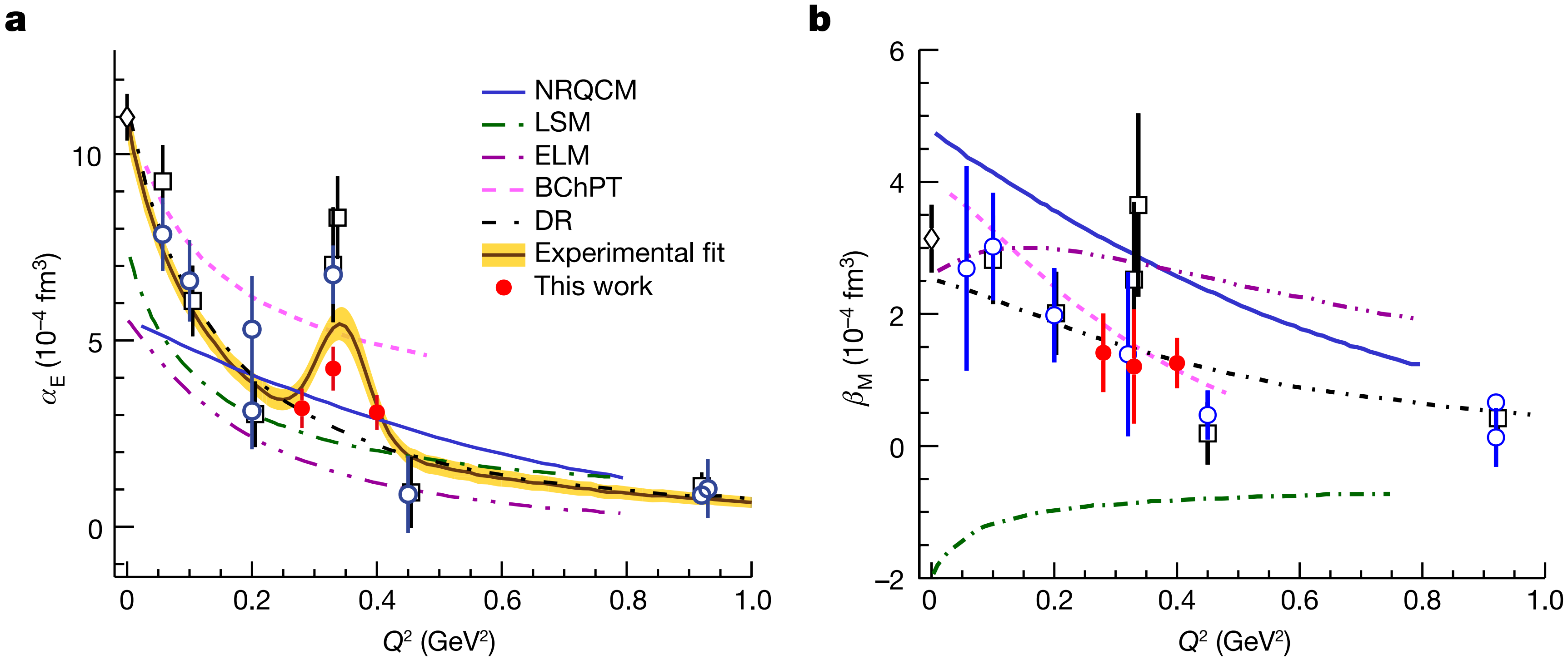


$$\beta_{M1}\,(\text{ChPT}) = 3.9(0.7) \times 10^{-4}\,\text{fm}^3$$
$$\beta_{M1}\,(\text{DR}) = 2.4(0.6) \times 10^{-4}\,\text{fm}^3$$
$$\beta_{M1}\,(\text{MAMI}) = 3.14(0.51) \times 10^{-4}\,\text{fm}^3$$
$$\beta_{M1}\,(\text{HIGS}) = 0.2(1.2) \times 10^{-4}\,\text{fm}^3$$

Eur. Phys. J. C75 (2015) 604
Phys. Rev. Lett. 129 (2022) 10, 102501
Phys. Rev. Lett. 128 (2022) 13, 132502
Phys. Rev. Lett. 128 (2022) 13, 132503

PROTON "STRECHINESS" ?

- Electric dipole polarizability extracted from virtual Compton scattering differs from theoretical expectation



nature

Nikolaos Sparveris: *"It is certainly puzzling for the physics of the strong interaction, if this thing persists … **So, the ball now is on the side of the [standard model] theory**."*

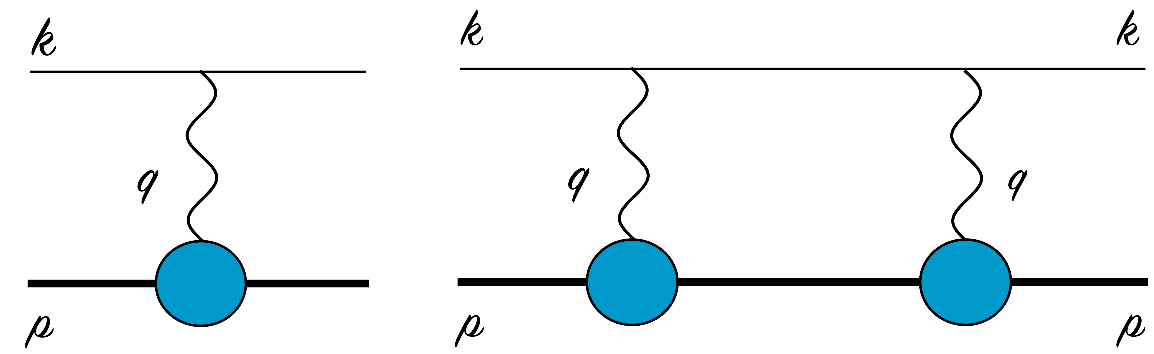
NewScientist

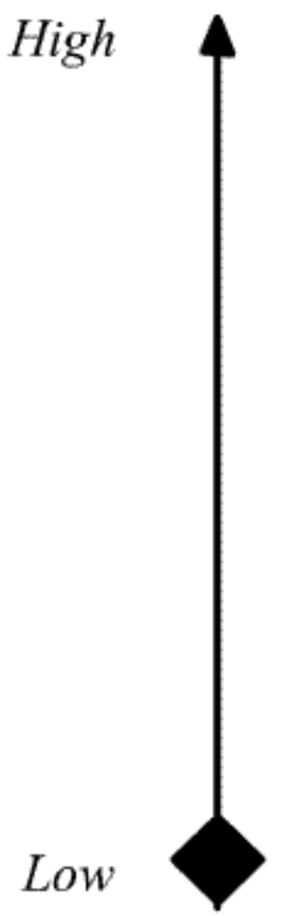
Judith McGovern: *"I don't think most people took [the 2000 result] really seriously, I think they assumed that it would go away, and, **if I'm quite honest, I think most people will still assume that it will go away**."*

ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

Vladimir Pascalutsa: *"Usually, behaviors of these things are quite, let's say, smooth and there are no bumps … **don't want to kill the buzz, but yeah, I'm quite skeptical as a theorist that this thing is going to stay**."*

Proton
~~Atom~~ in an external electric field

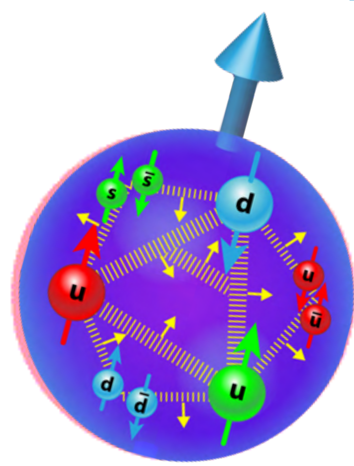


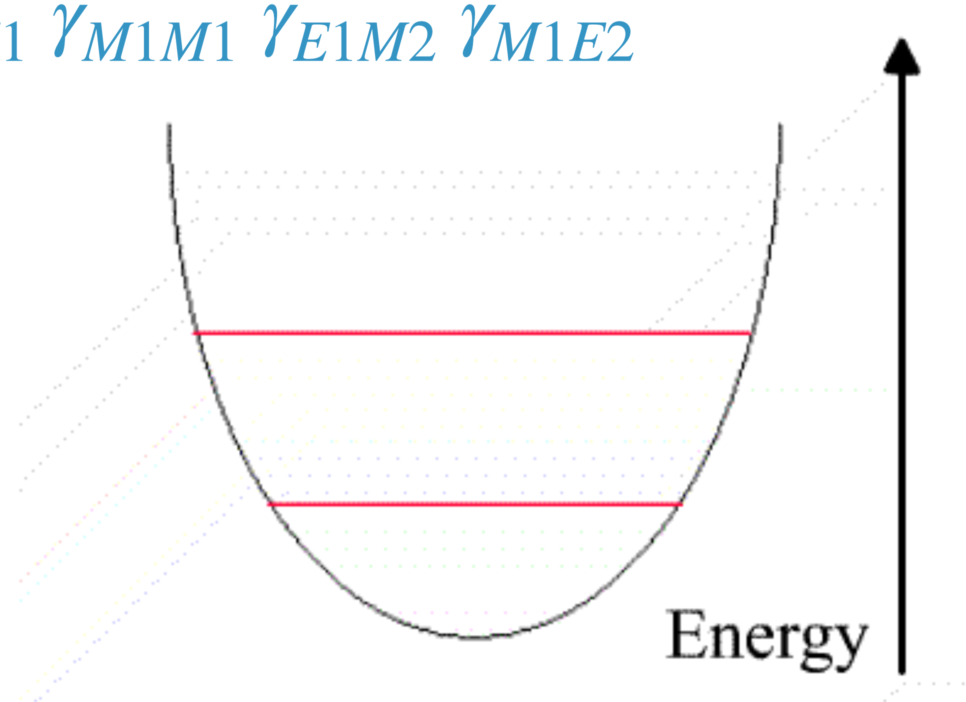


Electrical Field Intensity and Direction

spin polarizabilities

$\gamma_{E1E1}\ \gamma_{M1M1}\ \gamma_{E1M2}\ \gamma_{M1E2}$





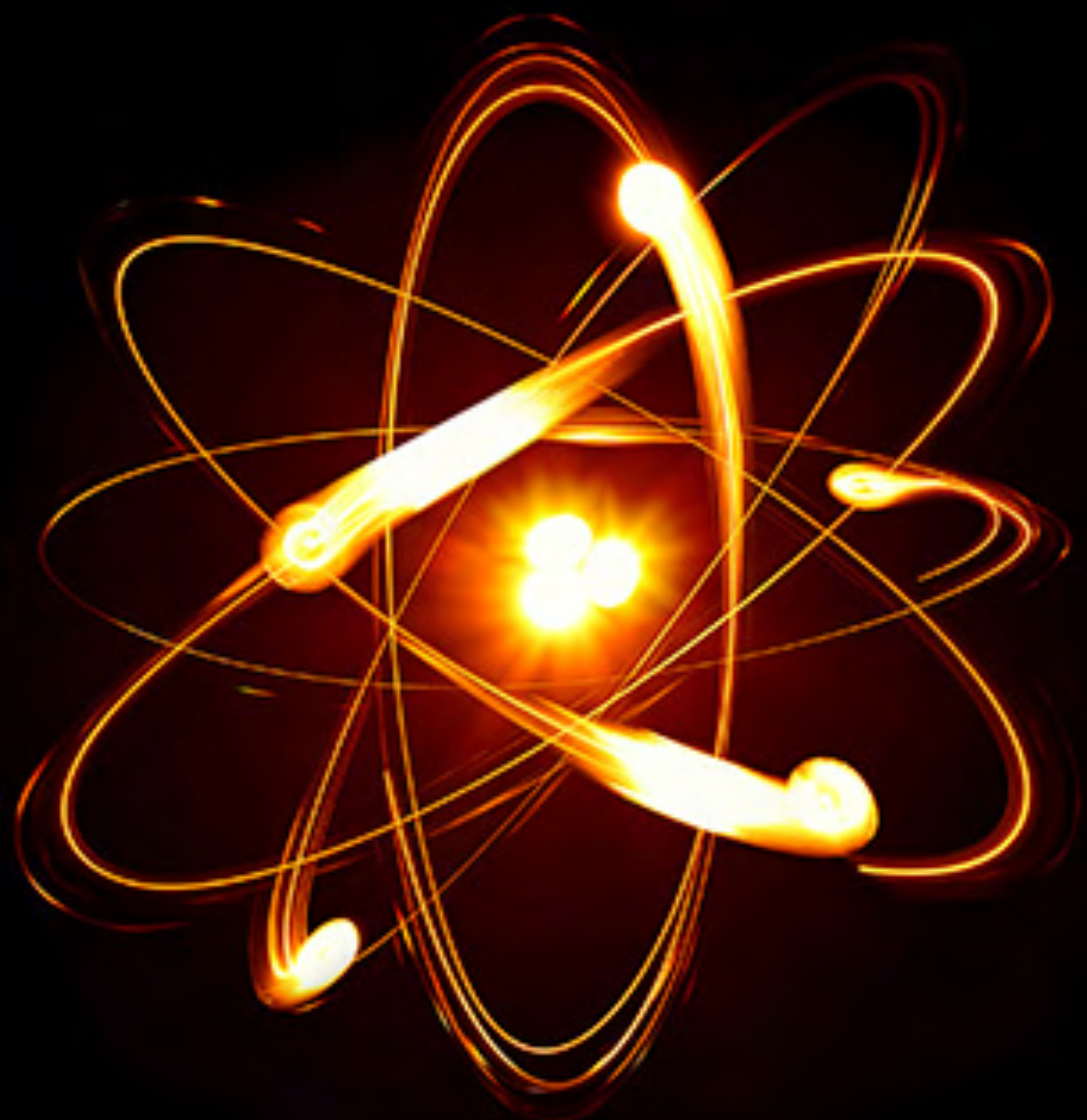
$$\vec{P} = e\vec{d}_E = \alpha_{E1}\vec{E}_{\text{external}}$$

Polarity — induced electric dipole — electric dipole polarizability

$$\vec{\mu}_{\text{ind.}} = \beta_{M1}\vec{B}_{\text{external}}$$

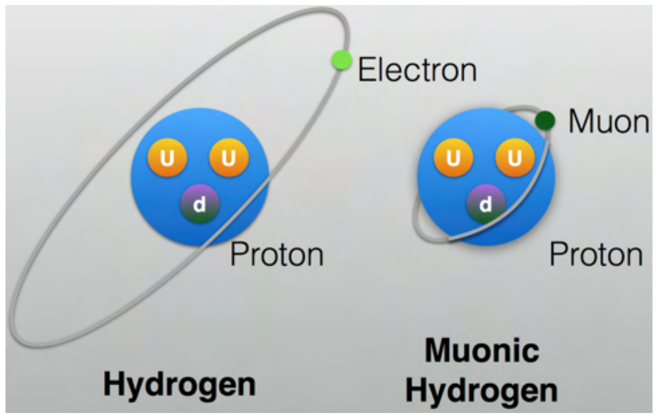
magnetic dipole polarizability

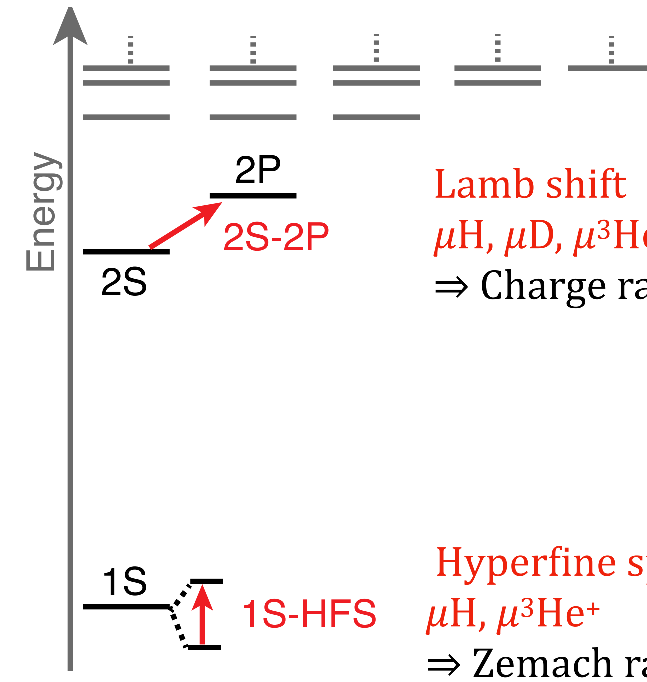
Nuclear Structure from Spectroscopy



https://arstechnica.com

NUCLEAR/NUCLEON STRUCTURE EFFECTS





Lamb shift
μH, μD, μ^3He$^+$, μ^4He$^+$
$\Rightarrow$ Charge radii

Hyperfine splitting (HFS)
μH, μ^3He$^+$
$\Rightarrow$ Zemach radii, magnetic properties

- **Lamb shift:**

wave function at the origin

$$\Delta E_{nl}(\mathrm{LO{+}NLO}) = \delta_{l0}\,\frac{2\pi Z\alpha}{3}\,\frac{1}{\pi(an)^3}\left[R_E^2 - \frac{Z\alpha m_r}{2}R^3_{E(2)}\right]$$

NLO becomes appreciable in μH

- **HFS:**

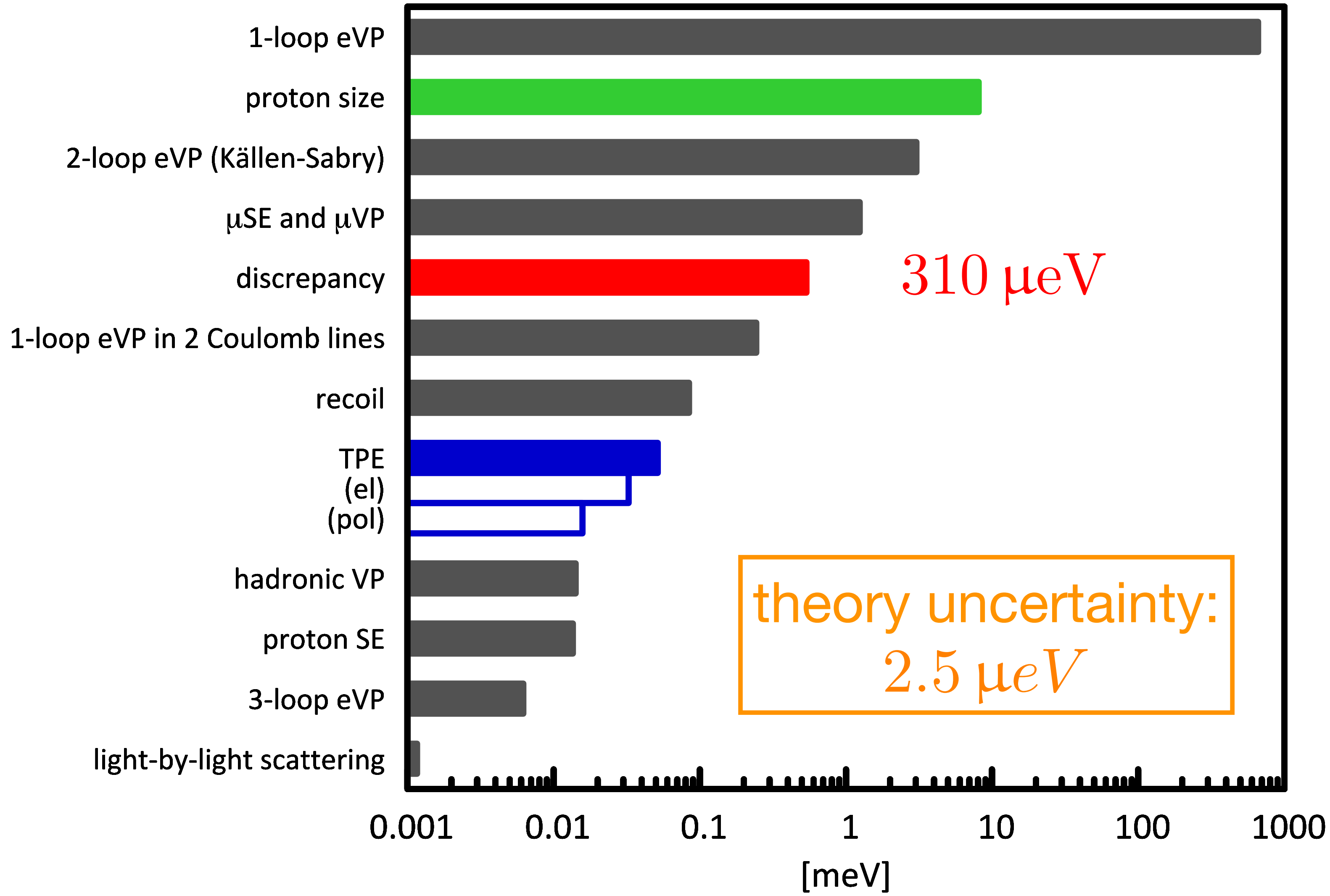
$$\Delta E_{nS}(\mathrm{LO}+\mathrm{NLO}) = E_F(nS)\,[1-2\,Z\alpha m_r\,R_Z]$$

Fermi - Energy:

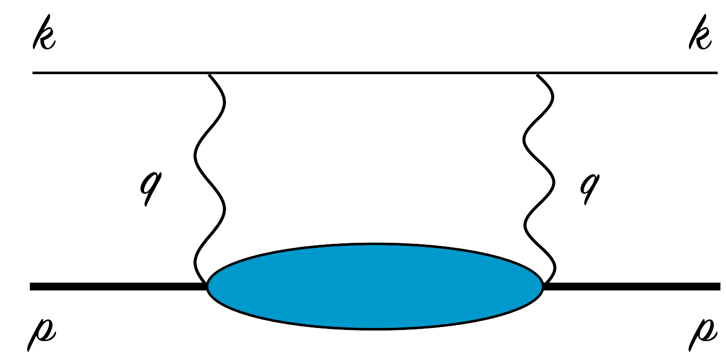
$$E_F(nS) = \frac{8}{3}\frac{Z\alpha}{a^3}\frac{1+\kappa}{mM}\frac{1}{n^3}$$

with Bohr radius $a = 1/(Z\alpha m_r)$

THEORY OF μH LAMB SHIFT



subleading effects of proton structure



$$\delta V^{(2\gamma)} = \delta V^{(2\gamma)}_{\text{elastic}} + \delta V^{(2\gamma)}_{\text{polariz.}}$$

$$E_{\text{LS}}^{\mu\text{H th.}} = 206.0336(15) \boxed{- 5.2275(10) \left(\frac{R_E}{\text{fm}}\right)^2} \boxed{+ E_{\text{LS}}^{2\gamma}}$$

[values in meV]

$$E_{\text{LS}} = \boxed{-\frac{\alpha}{12a^3} R_E^2} + \mathcal{O}(\alpha^5)$$

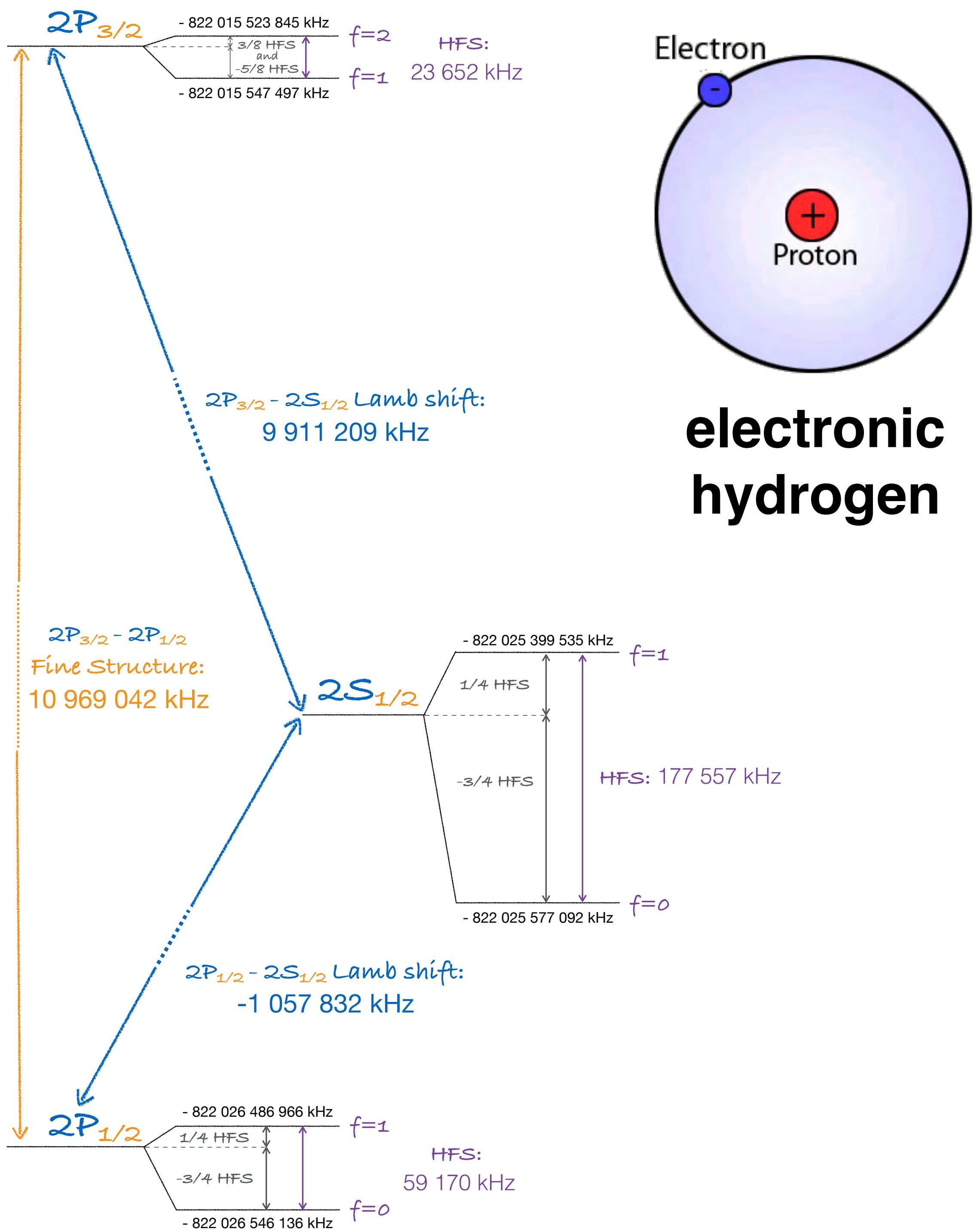


Figure II.4.: Spectrum of electronic hydrogen. The energy levels are extracted from Ref. [185].

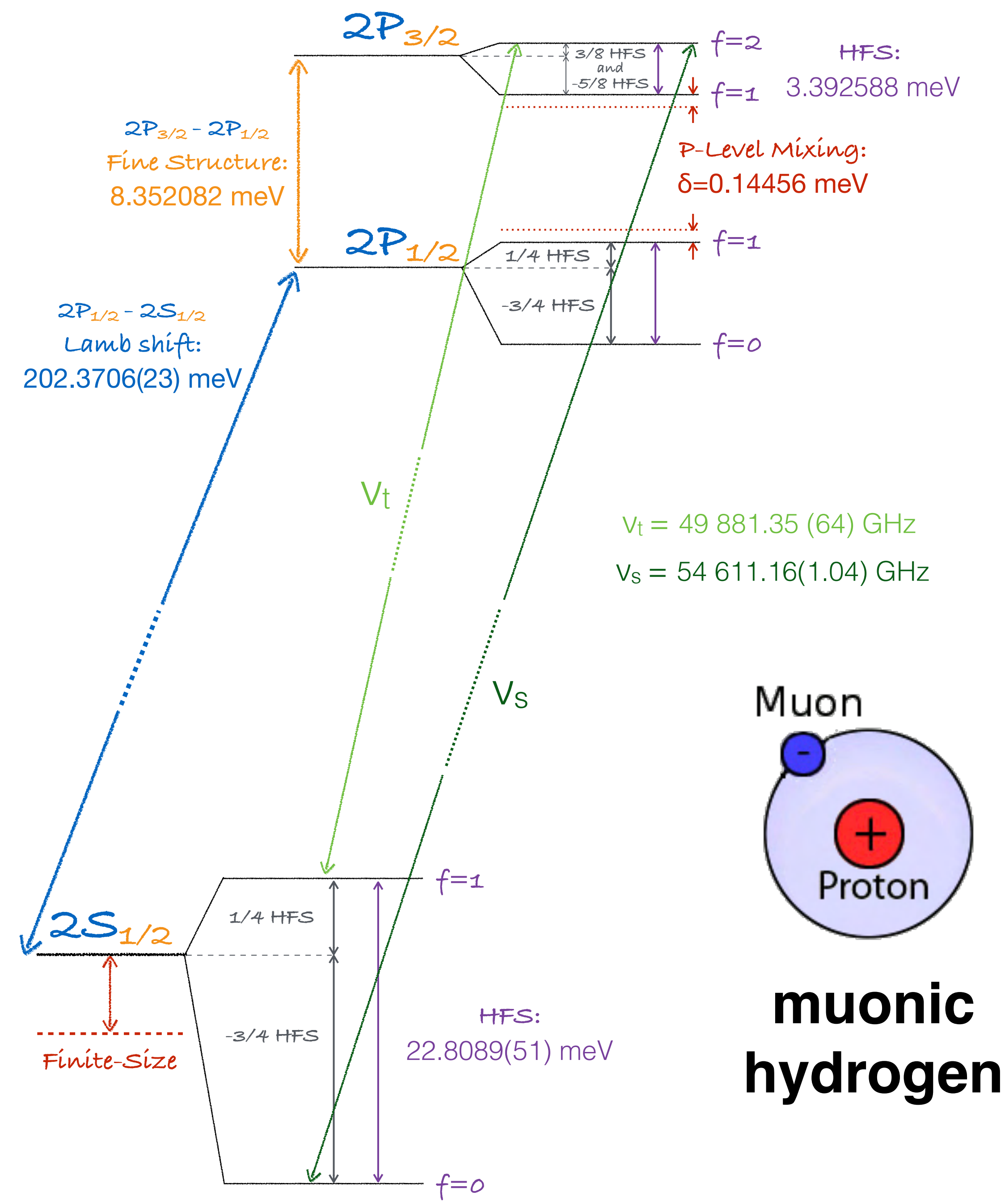
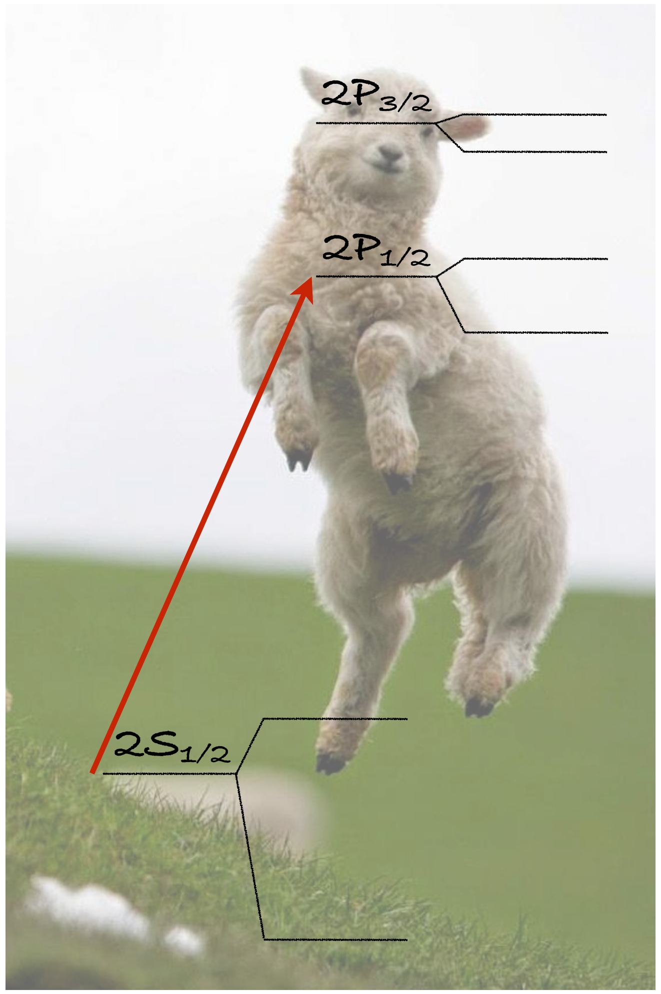


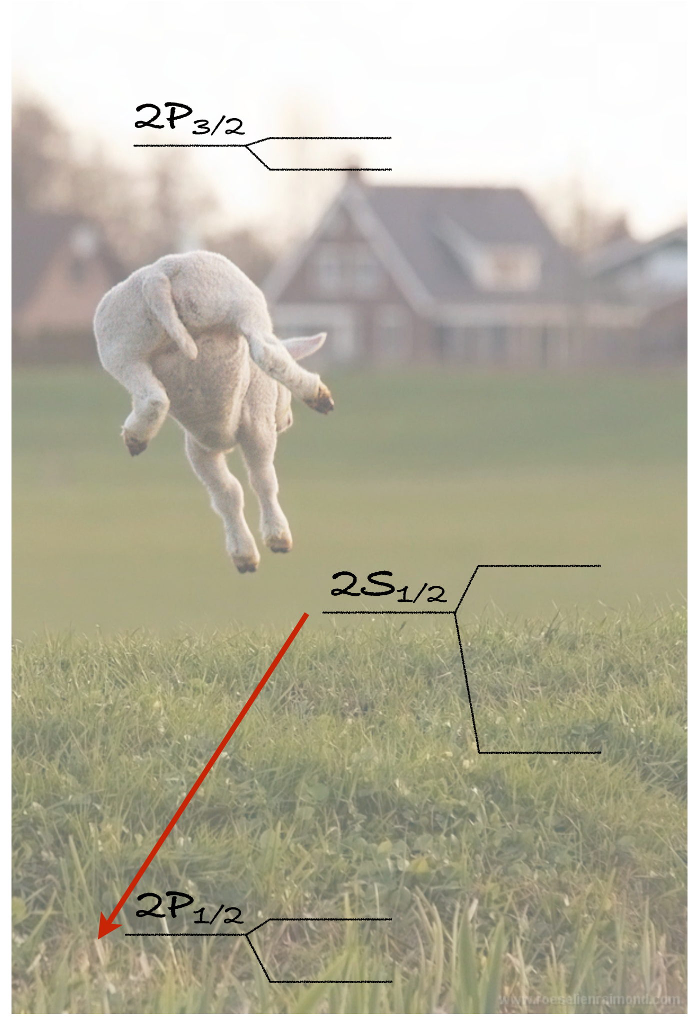
Figure II.3.: Spectrum of muonic hydrogen. The $2P$ fine structure, the $P_{3/2}$ hyperfine splitting and the P-level mixing are taken from the theory summary of Ref. [111]. The two transition frequencies, ν_t and ν_s, are experimental results from Refs. [68, 101]. The $2S$ hyperfine splitting and the classic $2P_{1/2} - 2S_{1/2}$ Lamb shift are reconstructed from the measurements and the theoretical shifts [68, 101, 111].

H precision spectroscopy: 'easy' to see a signal, **'hard' to interpret**

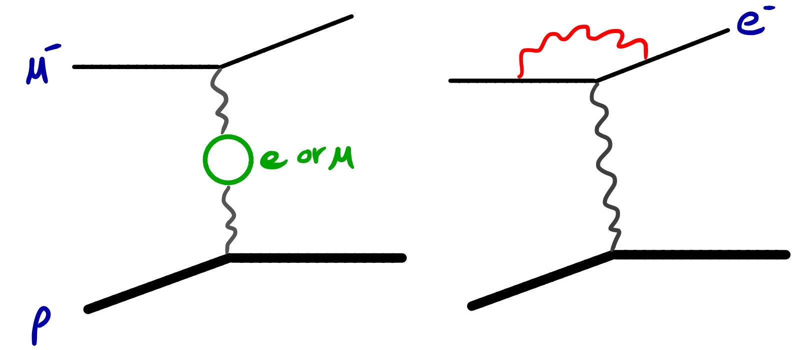
μH spectroscopy: **'hard' to see a signal**, 'easy' to interpret muonic hydrogen:



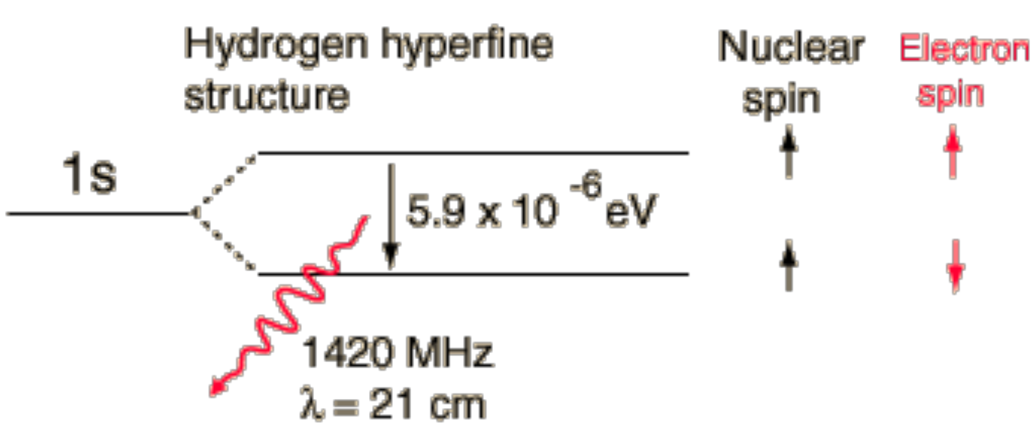
normal hydrogen:

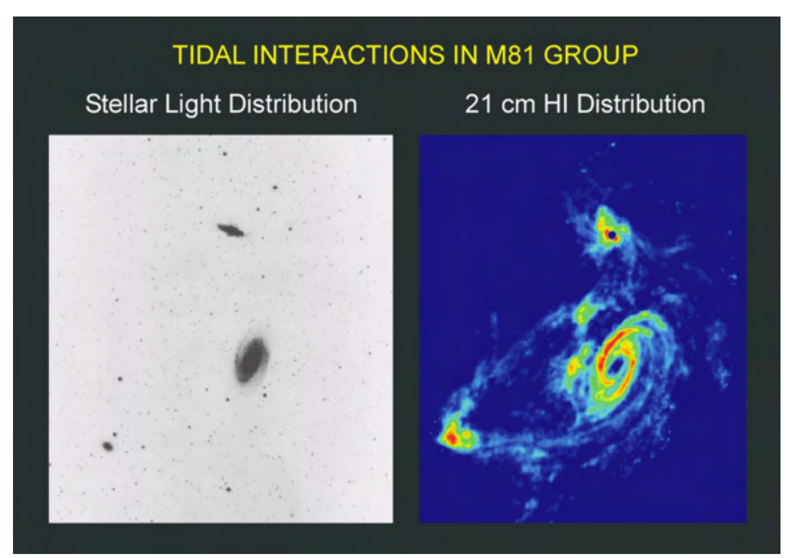


Lamb shift



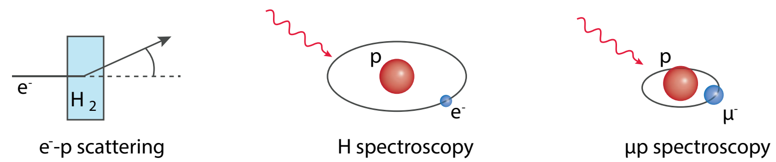
dominant QED contributions

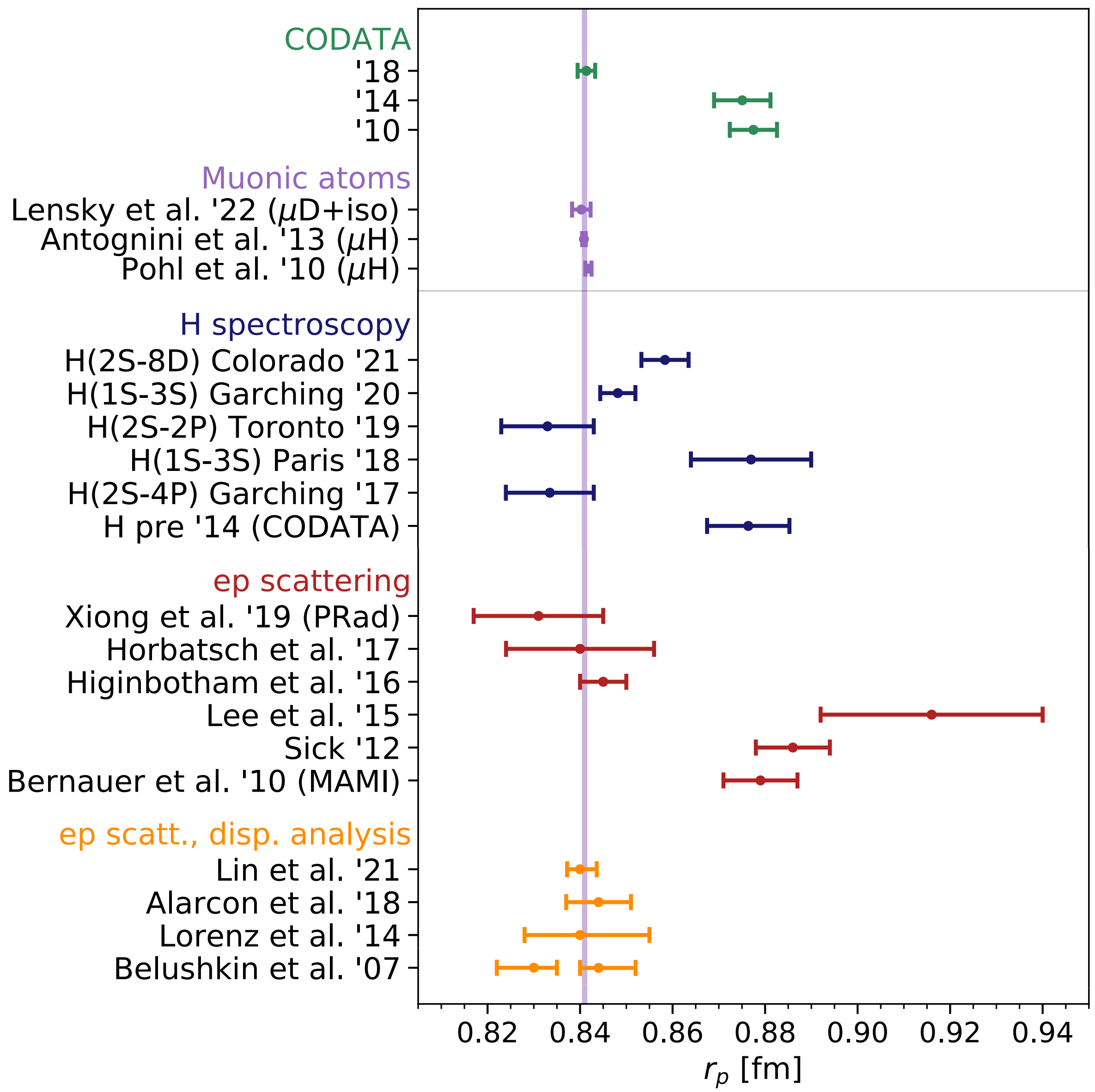




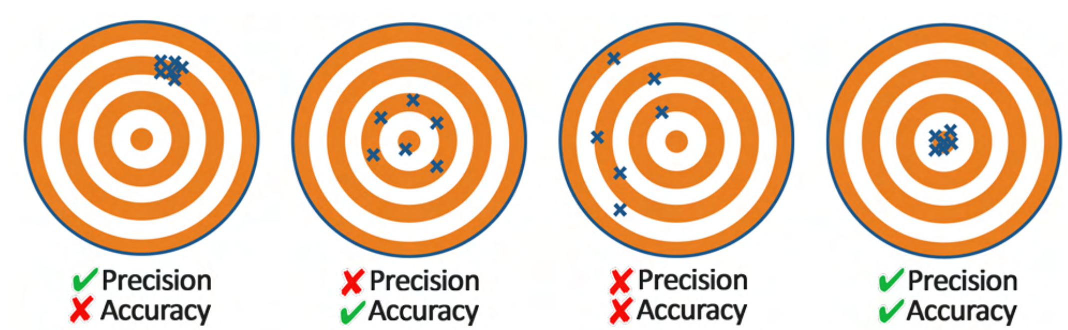
Hyperfine splitting

FROM PUZZLE TO PRECISION





- Muonic atoms allow for PRECISE extractions of nuclear charge and Zemach radii
- CODATA since 2018 included the μH result for r_p
- Still open issues: H(2S-8D) and H(1S-3S)
- Precise and accurate!



FROM PUZZLE TO PRECISION

- Several experimental activities ongoing and proposed:
  - 1S hyperfine splitting in μH (ppm accuracy) and μHe
  - Improved measurement of Lamb shift in μH, μD and μHe^+ possible ($\times 5$)
  - Medium- and high-Z muonic atoms
- **Theory Initiative** is needed!

FROM PUZZLE TO PRECISION

- Several experimental activities ongoing and proposed:
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  - Improved measurement of Lamb shift in μH, μD and μHe^+ possible ($\times 5$)
  - Medium- and high-Z muonic atoms

- **Theory Initiative** is needed!

- Charge radius extractions from Lamb shift in muonic atoms:

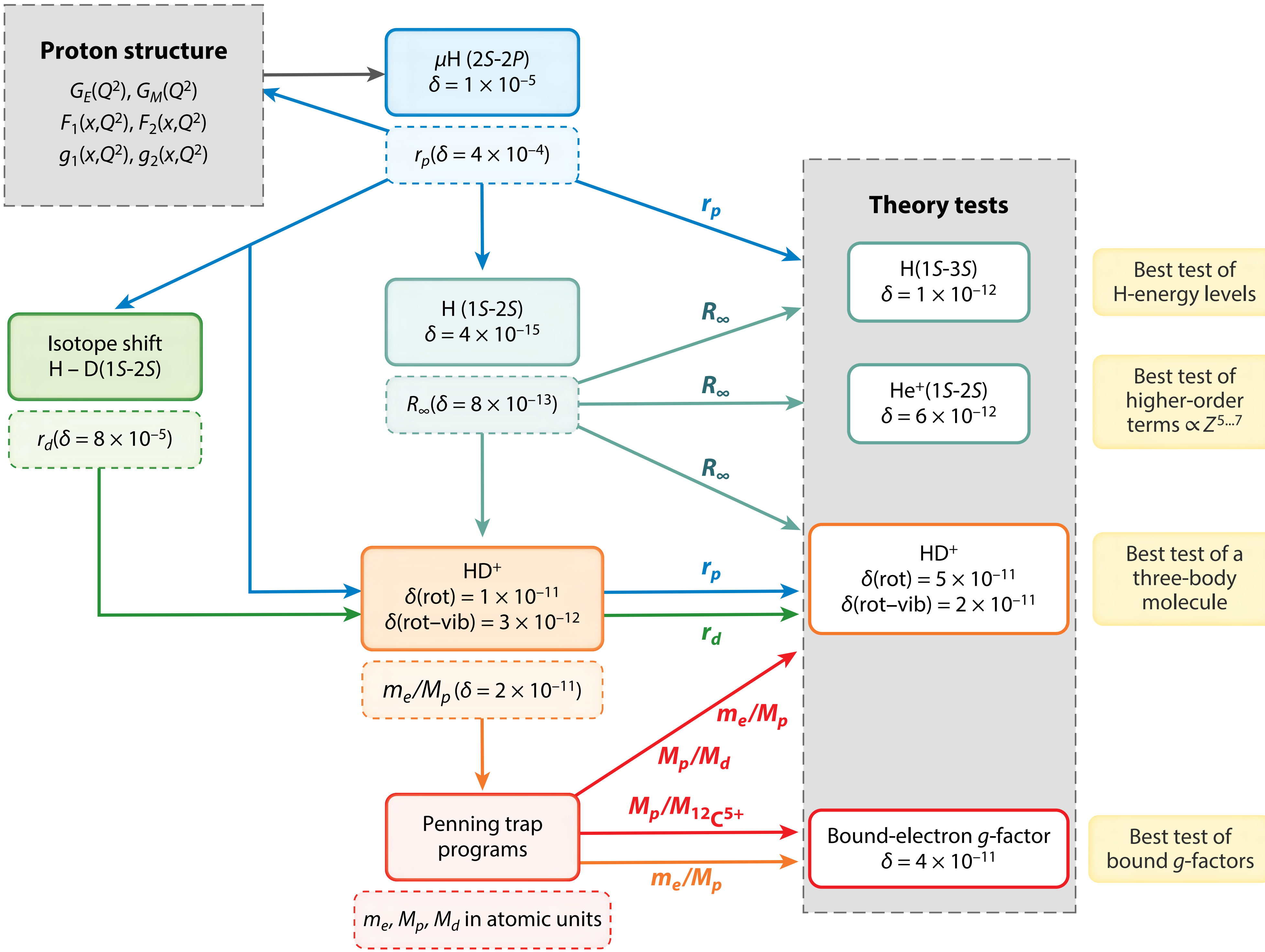
$$r_p = 0.84087(12)_{\rm sys}(23)_{\rm stat}(29)_{\rm theory} \ \ \rm fm$$

$$r_d = 2.12562(5)_{\rm sys}(12)_{\rm stat}(77)_{\rm theory} \ \ \rm fm$$

$$r_\alpha = 1.67824(2)_{\rm sys}(13)_{\rm stat}(82)_{\rm theory} \ \rm fm$$

- μH: present accuracy comparable with experimental precision
- μD, μ^3He^+ and μ^4He^+: present accuracy factor 5-10 worse than experimental precision

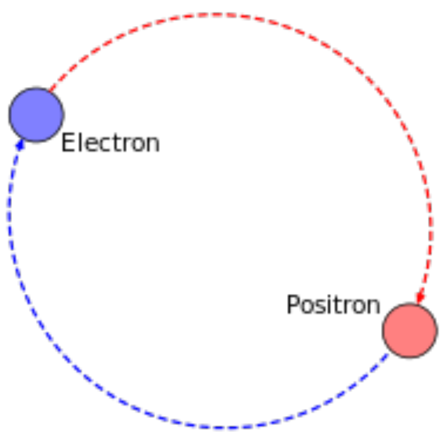
COMBINING μH, H, HE, HD+, ...



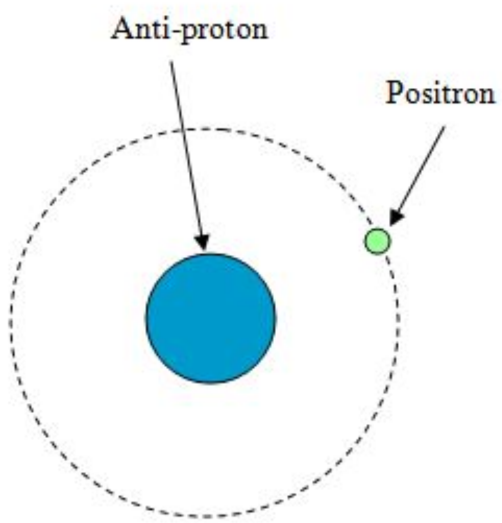
A. Antognini, FH, V. Pascalutsa, Ann. Rev. Nucl. Part. **72** (2022) 389-418

EXOTIC ATOMS

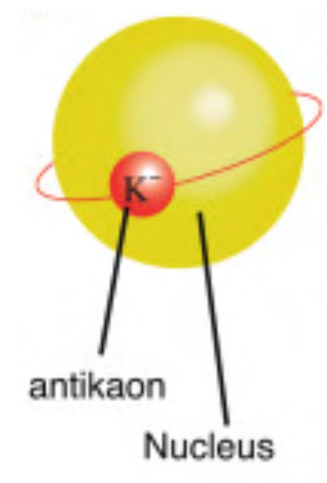
Positronium (1951) or
Muonium (1960):
LEMING @ PSI
Mu-MASS @ ETH-Z



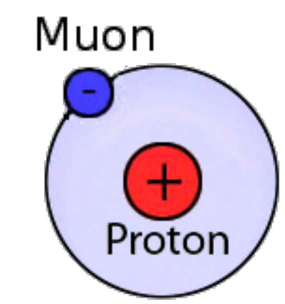
Anti-hydrogen:
LEAR (1995)
ALPHA @ CERN



Mesonic atoms:
kaonic hydrogen (1970)
pionic helium (PSI)

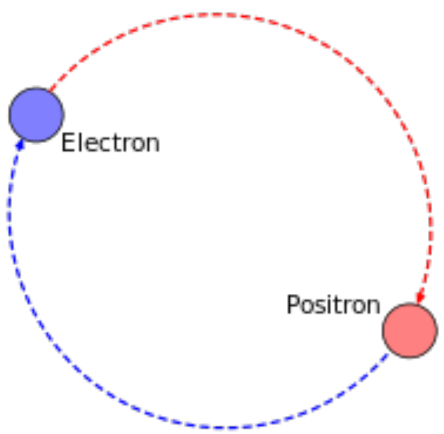


muonic atoms:
μH, μD, μHe$^{(+)}$, …

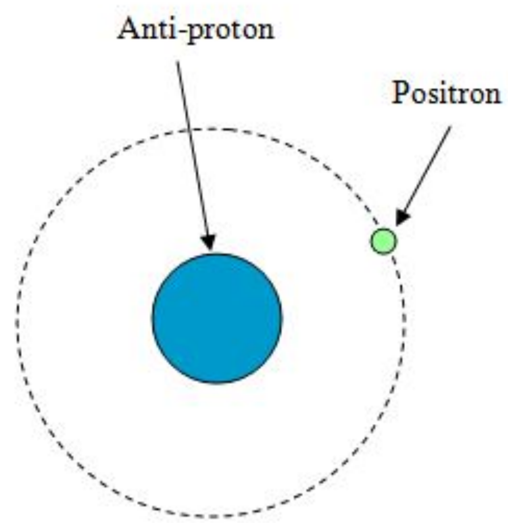


EXOTIC ATOMS

<u>Positronium</u> (1951) or <u>Muonium</u> (1960):
LEMING @ PSI
Mu-MASS @ ETH-Z



<u>Anti-hydrogen</u>:
LEAR (1995)
ALPHA @ CERN



<u>Mesonic atoms</u>:
kaonic hydrogen (1970)
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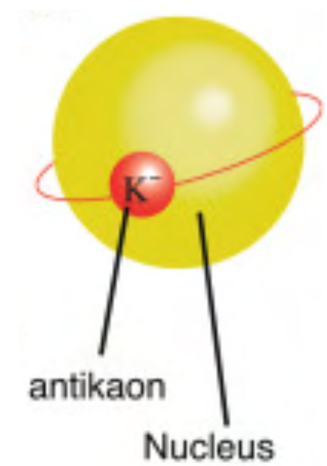
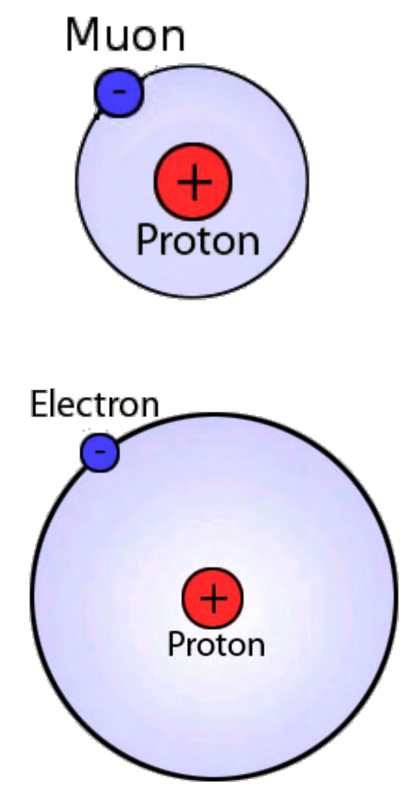
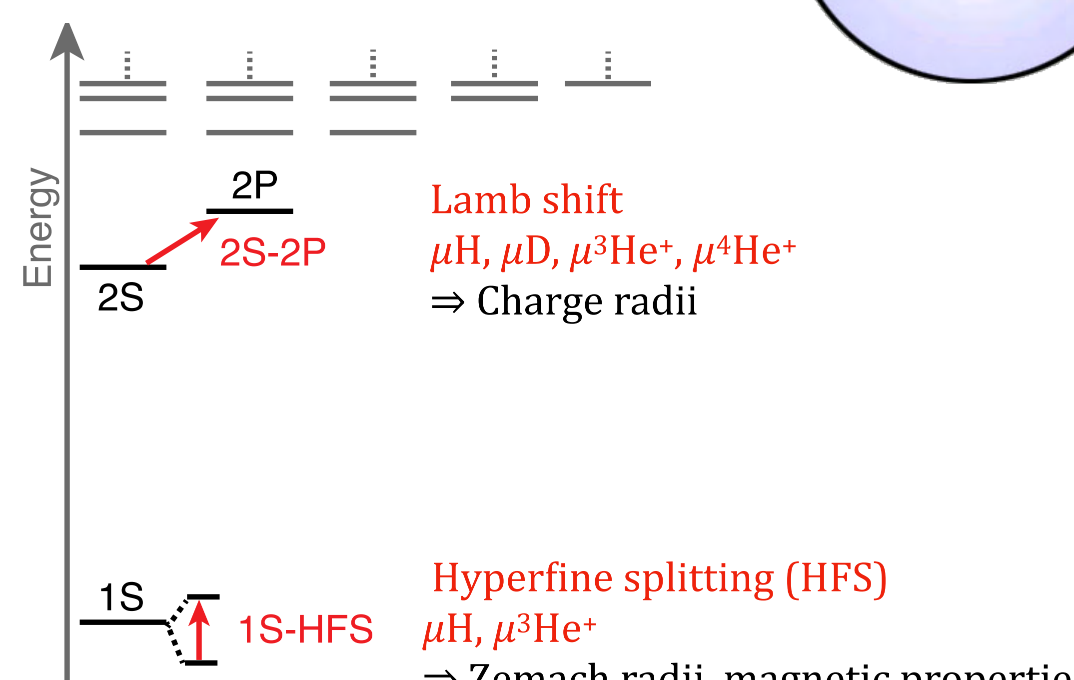


<u>muonic atoms</u>:
μH, μD, $\mu\mathrm{He}^{(+)}$, …



- Muonic atoms are more sensitive to nuclear structure than ordinary atoms — Muon probes the nucleus at a smaller distance



Theory Group
Institute for Nuclear Physics

Possible Bachelor and Master Thesis Projects

https://wwwth.kph.uni-mainz.de/thesis-projects/