Hunting for new physics with precision Lattice Calculations

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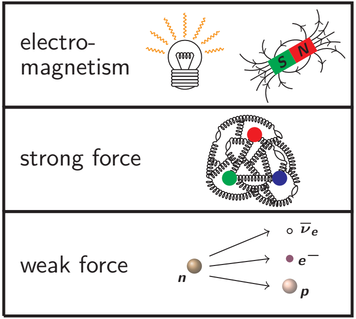
The Standard Model of Particle Physics

quarks	u up	c charm	t top	γ photon	H Higgs boson
quarks	d down	s strange	b bottom	g gluon	
leptons	e electron	μ muon	τ tau	$W^{\pm}$ W boson	
leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson	
				gauge bosons	



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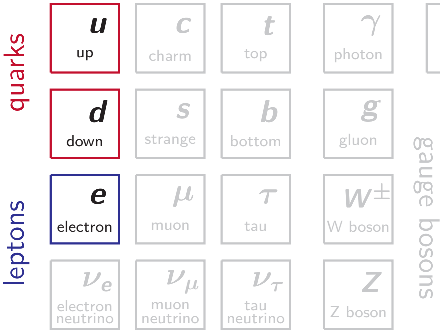

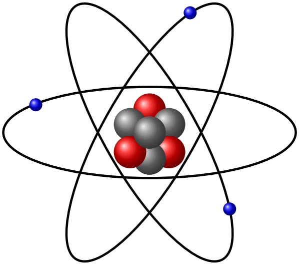

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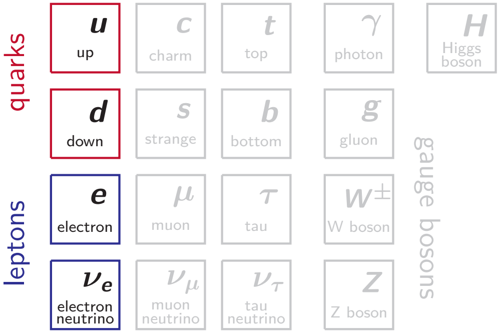

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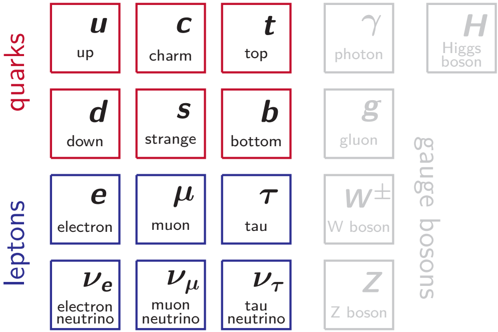

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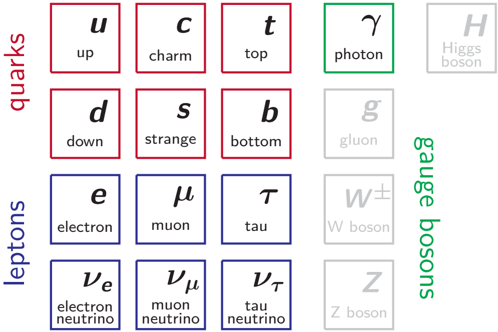

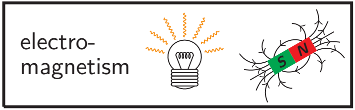

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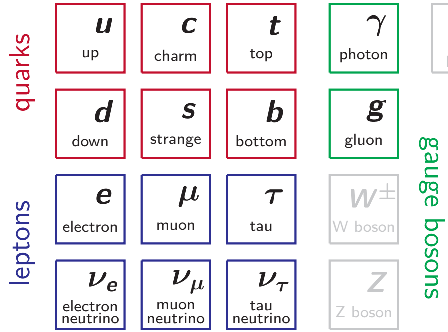

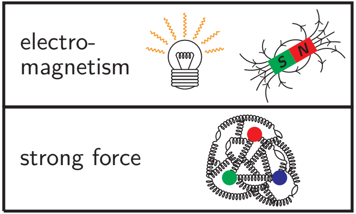

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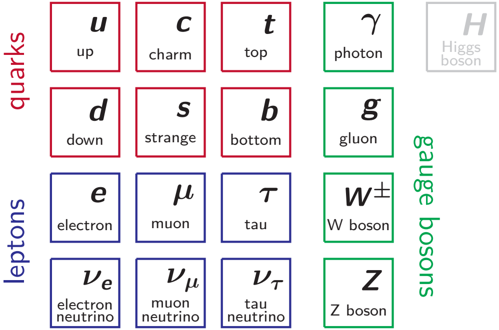

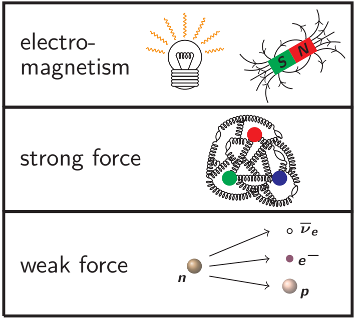

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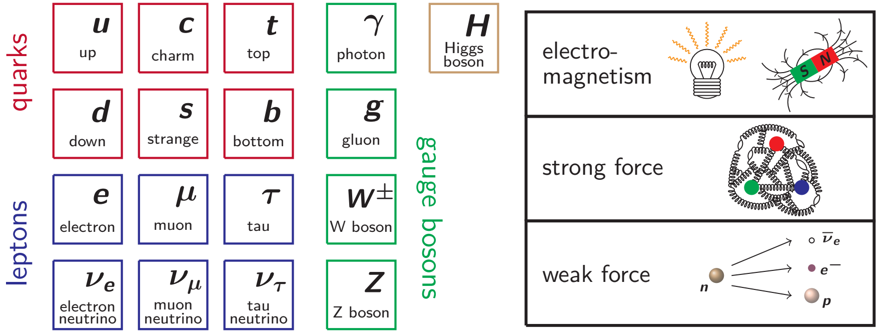


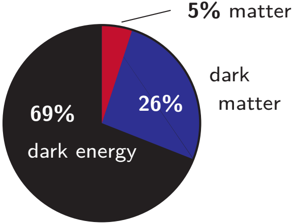
Higgs Boson discovered at LHC in 2012

→ Noble Prize 2013 for P. Higgs and F. Englert for prediction

The need for new physics

Many unsolved questions, for example:

- What is dark matter? Or dark energy?



- Why is there more matter than antimatter in the Universe?
- Why are there three generations of fermions?
- ...

New physics is out there!

Hunting for new physics

High-Energy Frontier:

Searches at particle colliders
such as the LHC at CERN

[https://cds.cern.ch/record/1295244]

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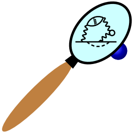
High-Precision Frontier:

New physics contributes via quantum effects



"The closer you look
the more there is to see"

[F. Jegerlehner, The Anomalous Magnetic Moment of the Muon]

- precision measurements of properties of known particles
- precise calculation within the Standard Model

→ find (potential) discrepancies

Lattice QCD

- Quantum Chromo Dynamics (QCD)
  $\rightarrow$ theory of the strong interaction
- strong coupling $\alpha_s \sim \mathcal{O}(1)$ at small energies
- quarks and gluons confined to hadrons

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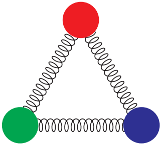

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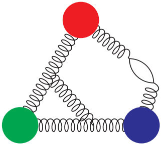

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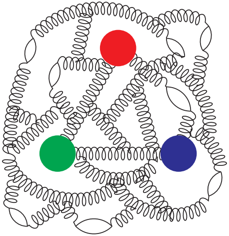

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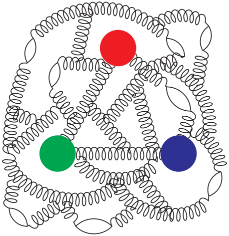

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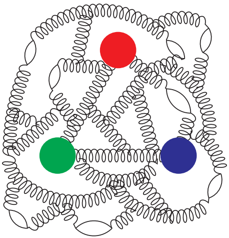
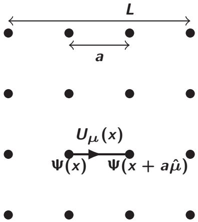


Lattice QCD in a nutshell

- Discretize (Euclidean) space-time by a 4d lattice
- Quantize QCD using Euclidean path integrals

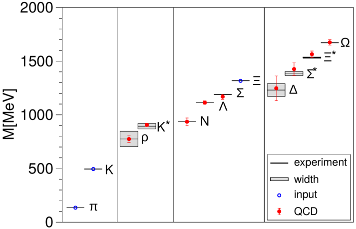
$$\langle A \rangle = \frac{1}{Z} \int \mathcal{D}[\Psi, \overline{\Psi}]\mathcal{D}[U]\, e^{-S_E[\Psi,\overline{\Psi},U]}\, A(U, \Psi, \bar{\Psi})$$



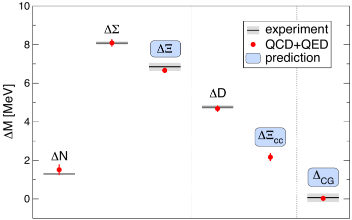
- gluonic expectation value: Monto Carlo techniques
- extrapolate to $a \rightarrow 0$ and $L \rightarrow \infty$

QCD on the lattice

- successfully used for hadronic observables, e.g. hadron spectrum



[S. Dürr *et al*, Science 322 (2008) 1224-1227]



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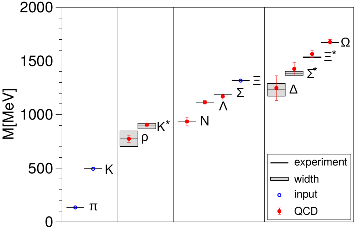

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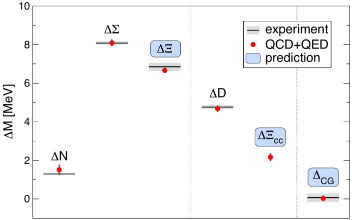

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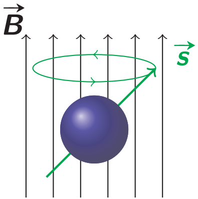
- Quantities studied in Lattice calculations include
  - Hadron Spectroscopy & interactions
  - weak decays of Hadrons & quark-mixing CKM matrix
  - Hadron Structure
  - QCD phase diagram
  - Beyond the Standard Model Physics
  - ...
- This talk: Lattice Calculations for Muon g-2

Magnetic Moment of the Muon

- magnetic moment $\vec{\mu}$ of the muon due to its spin $\vec{s}$ and electric charge e

$$\vec{\mu} = g\,\frac{e}{2m}\,\vec{s}$$

torque $\quad \vec{\tau} = \vec{\mu} \times \vec{B}$



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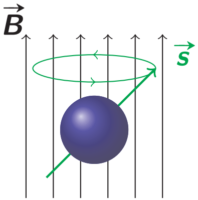

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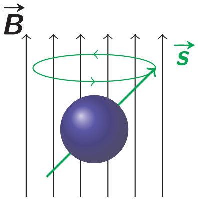
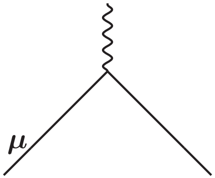


- gyromagnetic-factor (g-factor) of the muon

without quantum effects:

$$g = 2$$



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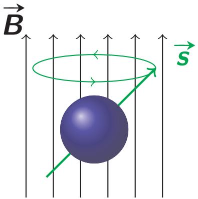

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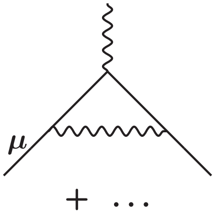
with quantum effects:

$$g = 2.00233\ldots$$

anomalous magnetic moment of the muon
"Muon g-2"

$$a_\mu = \frac{g-2}{2}$$



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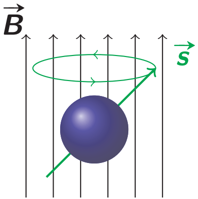

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anomalous magnetic moment of the muon "Muon g-2"

$$a_\mu = \frac{g-2}{2}$$

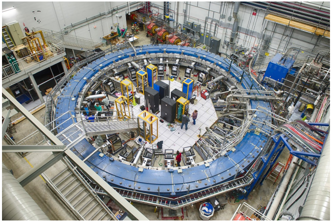
[https://upload.wikimedia.org/wikipedia/commons/a/aa/Julian_Schwinger_headstone.JPG]

Muon g-2: Experimental measurement

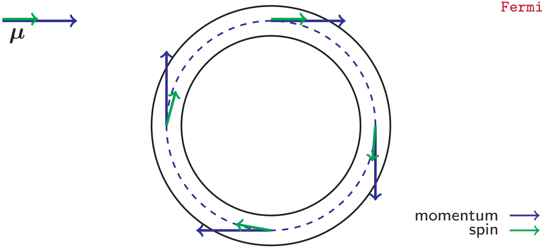
Previous: Muon g-2 @ BNL (2006)
[Phys.Rev. D73, 072003 (2006)]

New: Muon g-2 @ FNAL (2021)
[PhysRevLett.126.141801 (2021)]

measure precession frequency of muons in magnetic field:



[https://commons.wikimedia.org/wiki/File:Fermilab_g-2_(E989)_ring.jpg]



$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

$$a_\mu(\exp) = 11659206.1(4.1) \times 10^{-10}$$

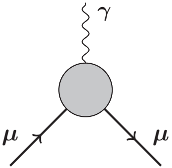
[PhysRevLett.126.141801 (2021)]

Muon g-2: Standard Model Prediction

White Paper (2020) of the Muon g-2 Theory initiative

[Phys.Rept. 887 (2020) 1-166]

[https://muon-gm2-theory.illinois.edu/]



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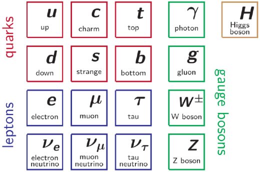

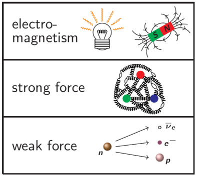

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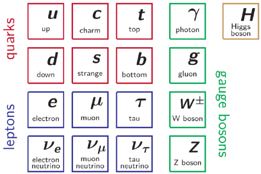
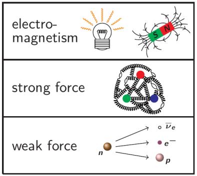
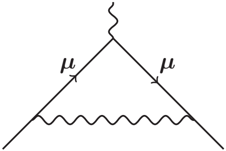




electro-magnetism $11658471.8931(104) \times 10^{-10}$



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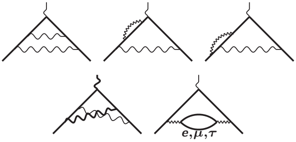

$+ \ \dots$

$O(10^4)$ diagrams at $O(\alpha^5)$

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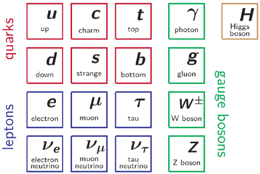

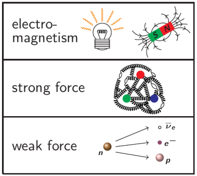

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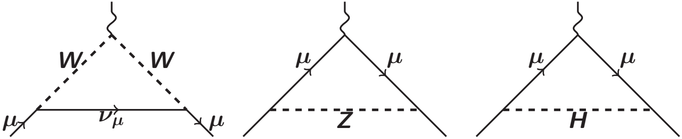

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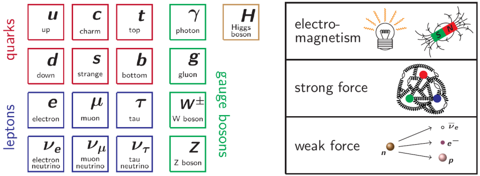

electro-magnetism	$\mathbf{11658471.8931(104)} \times \mathbf{10^{-10}}$
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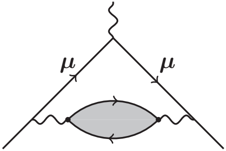

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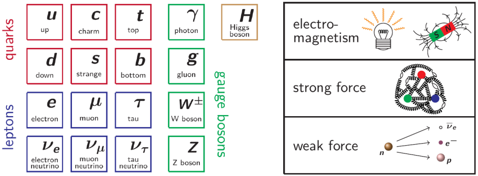

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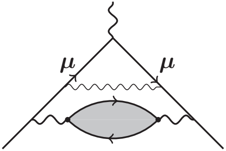

$+ \quad \ldots$

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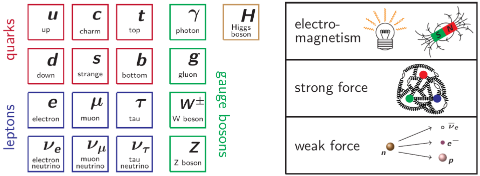

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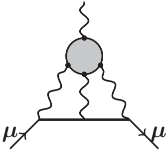


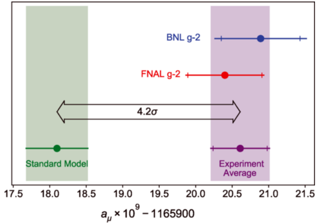
Experiment vs Standard Model prediction

Exp: $a_\mu = 0.00116592061(41)$

SM: $a_\mu = 0.00116591810(43)$

- This could be new physics!

Muon g−2 Coll., Phys. Rev. Lett. 126, 141801



Experiment vs Standard Model prediction

Exp: $a_\mu = \mathbf{0.00116592061(41)}$

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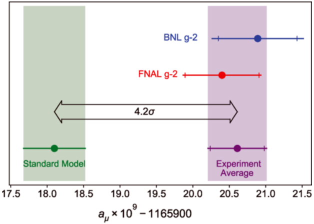

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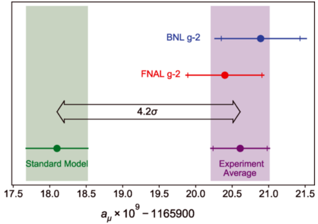
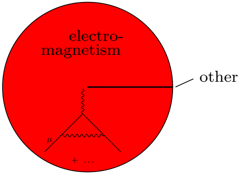


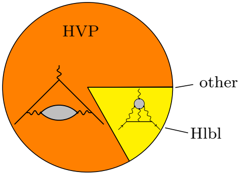
What's next?

- FNAL reduce error by factor $\sim$ **4**, new upcoming experiment @JPARC
- Breakdown of Standard Model Prediction

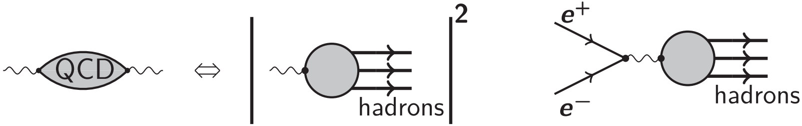
contribution to a_μ



contribution to variance $\Delta^2 a_\mu$

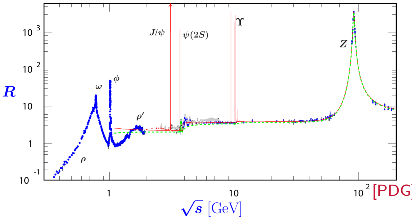


The HVP from R-ratio



$$R(s) = \frac{\sigma(e^+ e^- \to \text{hadrons}, s)}{\sigma(e^+ e^- \to \mu^+\mu^-, s)}$$

$$a_\mu^{\text{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \mathrm{d}s\, \frac{R(s)K(s)}{s^2}$$

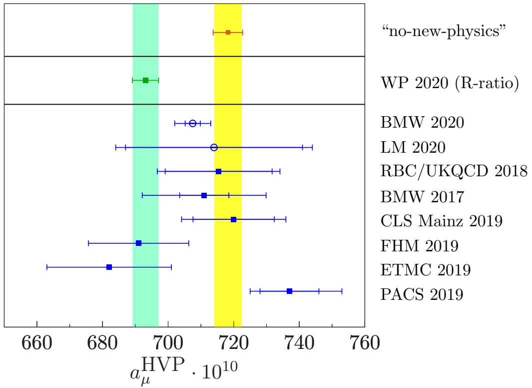


[PDG]

$a_\mu^{\text{hvp}} = 689.46(3.25)$	[Jegerlehner 18]
$a_\mu^{\text{hvp}} = 693.9(4.0)$	[DHMZ 19]
$a_\mu^{\text{hvp}} = 693.37(2.46)$	[KNT 18]
$a_\mu^{\text{hvp}} = 693.1(4.0)$	[white paper]

Lattice calculation of HVP

- Comparision of available lattice QCD calculations of HVP



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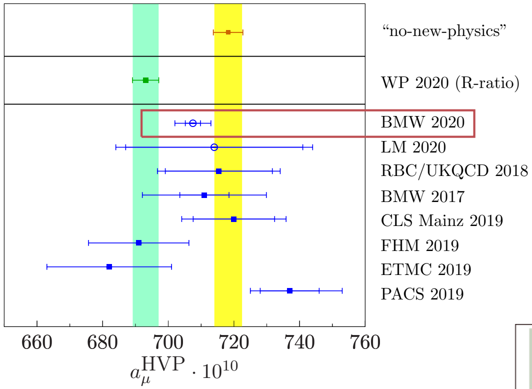
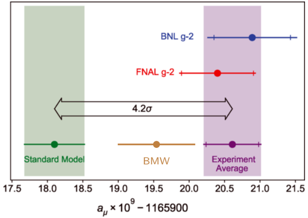


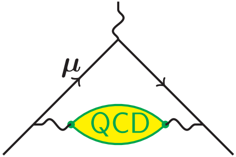


- recent lattice result by BMW

$$\boldsymbol{a_\mu^{\text{HVP}}(\text{BMW}) = 707.5(5.5) \times 10^{-10}}$$

Hadronic Vacuum Polarisation (HVP) from the lattice

- calculate hadronic part on the lattice



- vector two-point function

$$C_{\mu\nu}(t) = \sum_{\vec{x}} \langle J_\mu(t,\vec{x}) J_\nu(0) \rangle$$

- electromagnetic current

$$J_\mu = \frac{2}{3}\overline{u}\gamma_\mu u - \frac{1}{3}\overline{d}\gamma_\mu d - \frac{1}{3}\overline{s}\gamma_\mu s \; + \ldots$$

- a_μ from $C(t)$ [T. Blum, Phys.Rev.Lett.**91**, 052001 (2003); Bernecker and Meyer, Eur.Phys.J.**A47**, 148 (2011)]

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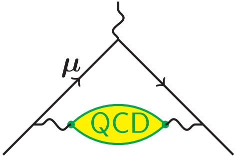

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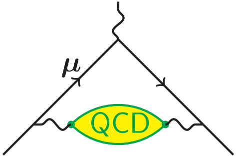

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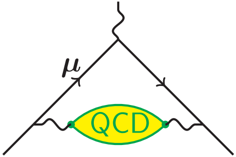

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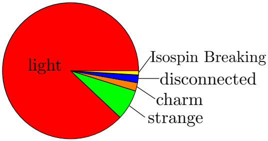
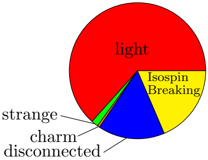
Precision Challenges for the HVP

- contributions to $a_\mu^{\mathrm{HVP}}(\mathrm{lat})$



contributions to $\Delta a_\mu^{\mathrm{HVP}}(\mathrm{lat})$



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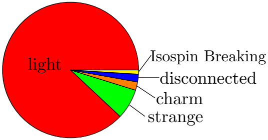

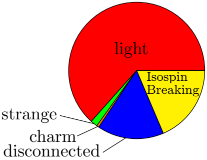

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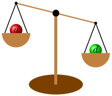

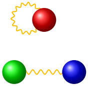

recent progress: [VG *et al*, PRL 121, 022003 (2018); D. Giusti *et al*, Phys. Rev. D 99, 114502 (2019); S. Borsanyi *et al*, Nature 593, 51 (2021); M. Cè *et al*, Phys. Rev. D 106, 114502 (2022)]

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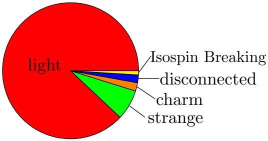

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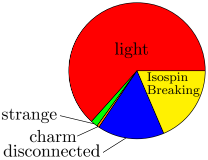

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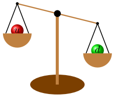

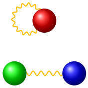

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- Disconnected contribution needs stochastic evaluation → noisy

recent progress: [V.G. et al, PoS LAT2014 (2014) 128], [T. Blum *et al*, Phys. Rev. Lett. 116, 232002 (2016)], [A. Stathopoulos et al, arXiv:1302.4018], [A. Gérardin *et al*, Phys. Rev. D 100, 014510 (2019)], [L. Giusti et al, Eur.Phys.J.C 79 (2019) 7, 586]

Light-quark contribution

- main challenges:
  - statistical noise at large t
  - finite volume effects (largest at large t)
  - discetisation effects at small t
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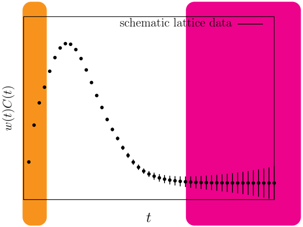

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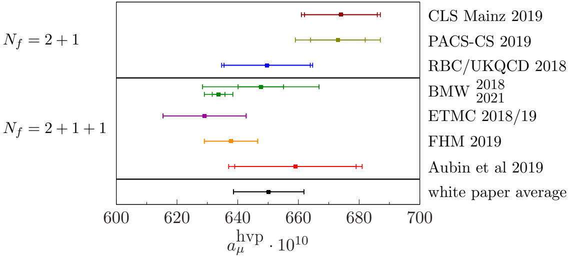

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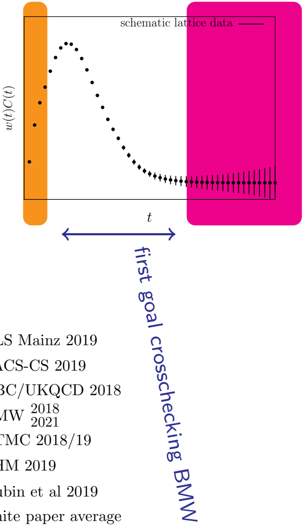

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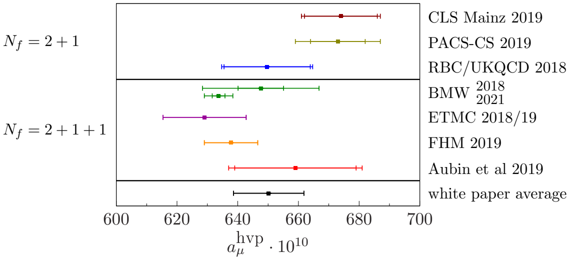


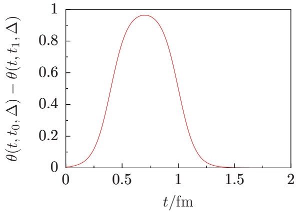
Lattice Cross Checks - Window method

- $a_\mu^{\rm HVP}$ from intermediate window $a_\mu = a_\mu^{\rm SD} + a_\mu^{\rm W} + a_\mu^{\rm LD}$

  [T. Blum, P. Boyle, VG *et al* Phys.Rev.Lett. 121 (2018) 022003]

$$a_\mu^{\rm W} = \sum_t w_t C(t)[\theta(t, t_0, \Delta) - \theta(t, t_1, \Delta)]$$

e.g. $t_0 = 0.4$ fm to $t_1 = 1.0$ fm



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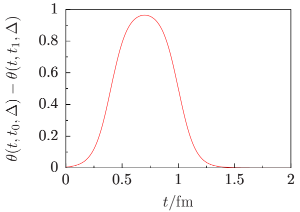
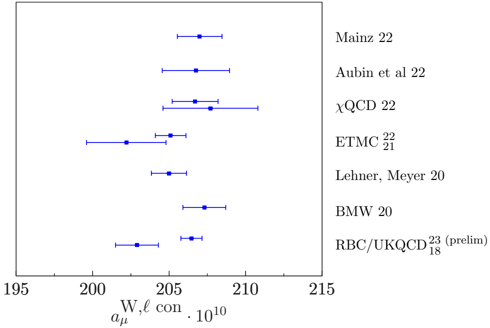
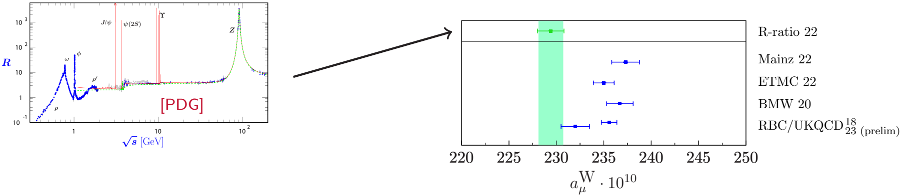




Window comparison with R-ratio

- compare ***R***-ratio with lattice using window quantity



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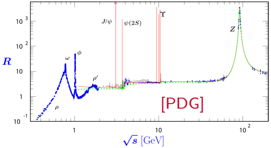

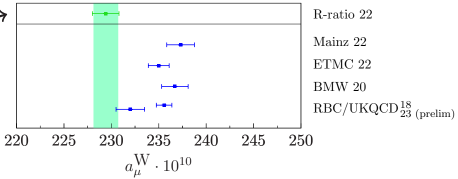

Quo Vadis g-2?

- "***R***-ratio Scenario": lattice consistent with ***R***-ratio (unlikely?)
- "BMW Scenario": Other (full) lattice calculations agree with BMW
  $\rightarrow$ tension between lattice and ***R***-ratio
- update of the Theory whitepaper in progress

Sep 22 @Higgs Centre

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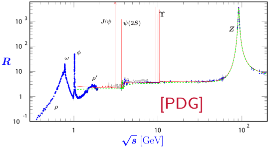

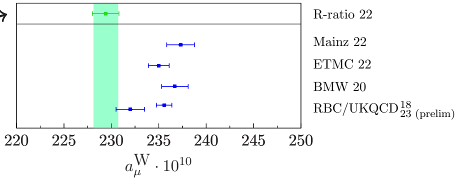

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Will we discover new physics with Muon g-2?

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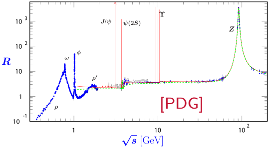

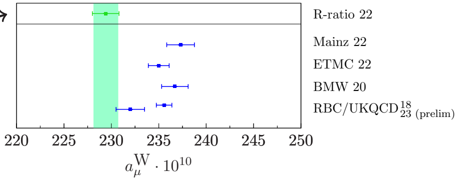

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Will we discover new physics with Muon g-2?

Maybe. Maybe not.

Summary

- Standard Model very successful, but leaves many open questions
- low-energy precision test of the Standard Model
  $\longrightarrow$ QCD: first principles calculations using Monte Carlo (Lattice QCD)
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