Moriond 2021
Summary of the "Precision" session

- Personal selection of a quite short session + some digressions

Measurement of the fine structure constant
Pierre CLADÉ

Hadronic contributions to g-2
Gilberto COLANGELO

α_{QED}, a_e, a_μ. Progress in experiment and theory

CP violation in LR (K, B and neutron EDM)
Fabrizio NESTI

Recent results from NEDM
Stephanie ROCCIA

Neutron EDM and constraints on new physics

KOTO results
Satoshi SHINOHARA

Direct CP violation in K decays

Measurement of simplified template cross section in the H->WW channel with ATLAS
Ralf GUGEL

Recent measurement of α_{QED} (LKB)

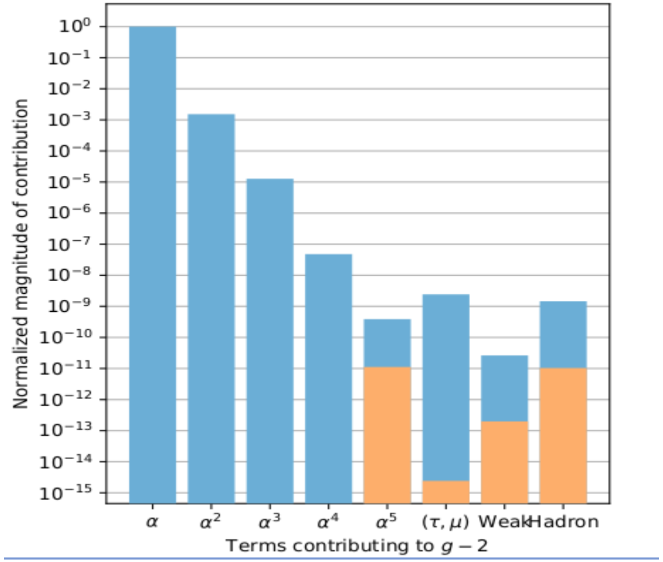
- Why?
  - Tests of QED exploit two phenomena : Lamb shift, and $(g\text{-}2)_e$ (or a_e)
  - In pure electron systems, the theoretical expressions are a function of α_{QED} and the lepton masses only, for example:

- QED calculation

$$a_e(QED) = \frac{g_e - 2}{2} = \sum_{n=1}^{\infty} A^{(2n)} \left(\frac{\alpha}{2\pi}\right)^n + \sum_{n=1}^{\infty} A^{(2n)}_{\mu,\tau} \left(\frac{m_e}{m_\mu}, \frac{m_e}{m_\tau}\right) \left(\frac{\alpha}{2\pi}\right)^n$$

- Other contributions

$$a_e\,(\text{theo}) = a_e\,(\text{QED}) + a_e\,(\text{Weak}) + a_e\,(\text{Hadron})$$

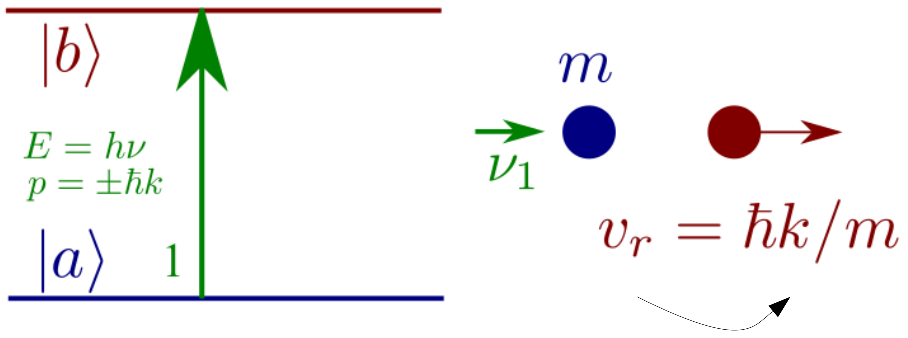


Recent measurement of α_{QED} (LKB)

- Experiment

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{Rb}}{m_e}\frac{h}{m_{Rb}}$$

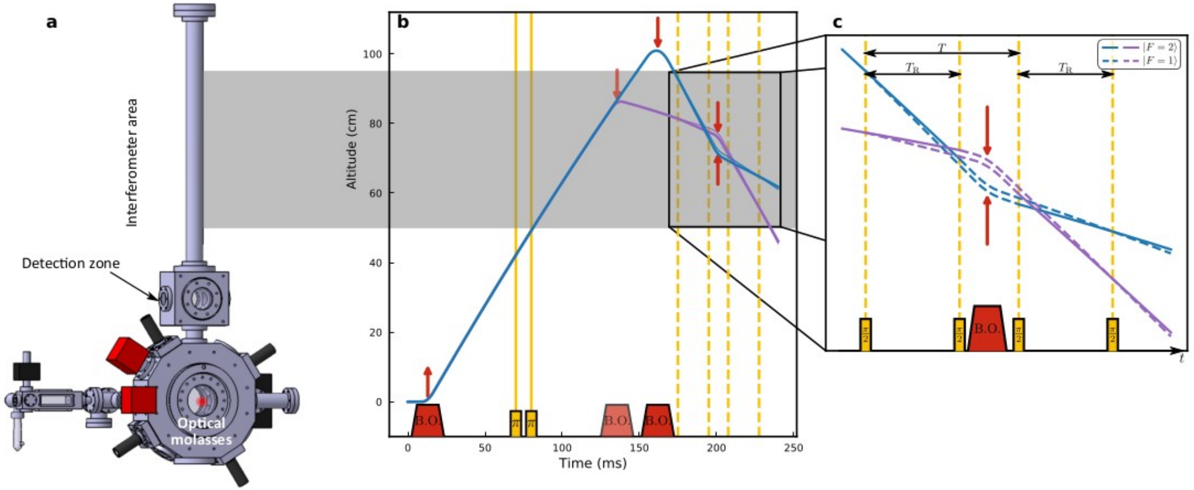
- Limitation : determination of $\frac{h}{m_{Rb}}$
- Recoil velocity :



Rubidium atoms : $v_r = 6\,\mathrm{mm\,s^{-1}}$

Recent measurement of α_{QED} (LKB)

- Experiment



- Laser cooled rubidium atoms (4 μK, about 10 cm s^{-1})
- Atom interferometer

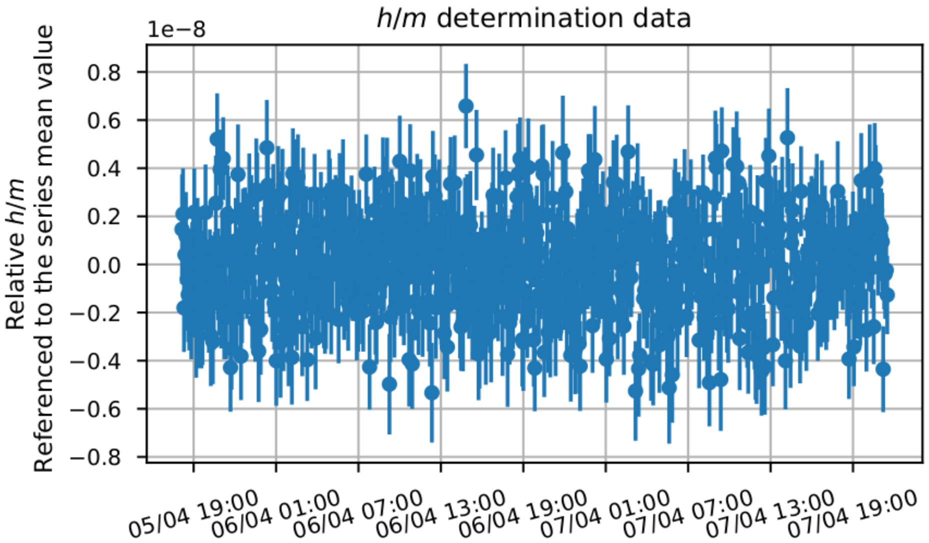
$^{87}R_b$ present in two states (excited / ground state), which interfere. The different velocities v_r induce a phase shift ϕ over the duration of the “flight”.

The interferometer measures ϕ, then $\phi \rightarrow v_r \rightarrow h/m_{Rb} \rightarrow \alpha_{QED}$

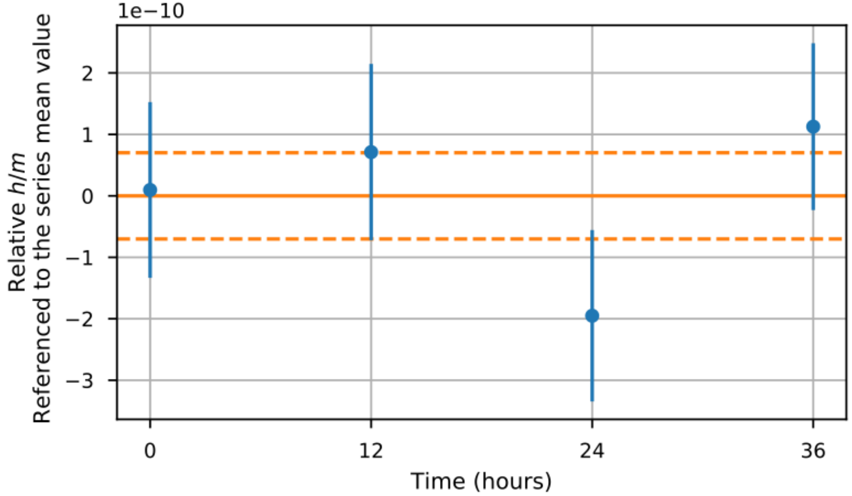
Recent measurement of α_{QED} (LKB)

- Result

Stable and reliable device ⇒ Long measurement periods



From Friday to . . . . Sunday



48h integration: $8.5 \cdot 10^{-11}$ on $\frac{h}{m}$

$\rightarrow 4.3 \cdot 10^{-11}$ on α

Recent measurement of α_{QED} (LKB)

- Result

Source	Correction $[10^{-11}]$	Relative uncertainty $[10^{-11}]$
Gravity gradient	-0.6	0.1
Alignment of the beams	0.5	0.5
Coriolis acceleration		1.2
Frequencies of the lasers		0.3
Wave front curvature	0.6	0.3
Wave front distortion	3.9	1.9
Gouy phase	108.2	5.4
Residual Raman phase shift	2.3	2.3
Index of refraction	0	< 0.1
Internal interaction	0	< 0.1
Light shift (two-photon transition)	-11.0	2.3
Second order Zeeman effect		0.1
Phase shifts in Raman phase lock loop	-39.8	0.6
Global systematic effects	64.2	6.8
Statistical uncertainty		2.4
Relative mass of ^{87}Rb [16] : $86.909\,180\,531\,0(60)$		3.5
Relative mass of the electron [14] : $5.485\,799\,090\,65(16) \cdot 10^{-4}$		1.5
Rydberg constant [14] : $10\,973\,731.568\,160(21)\mathrm{m}^{-1}$		0.1
Total: $\alpha^{-1} = 137.035\,999\,206(11)$		8.1

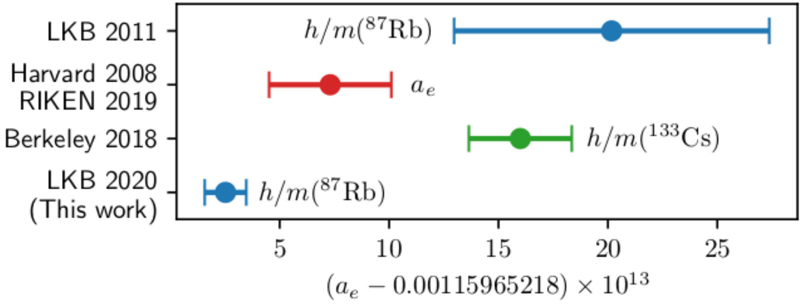
Improvement over previous result by a factor of 3.

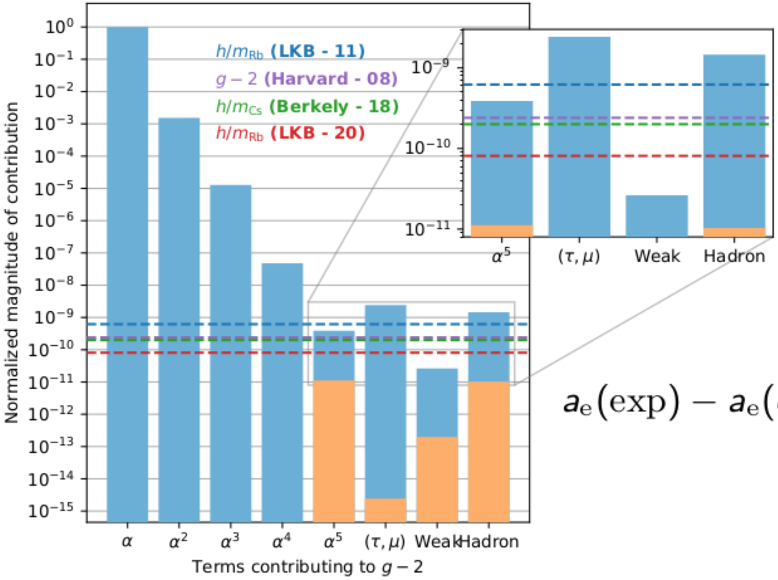
Systematics dominated measurement:

- knowledge of laser beam parameters (uncertainty in phase shift induced by beam small frequency dispersion)
- mass of $^{87}R_b$
- electron mass

Implications for a_e

- Recoil based measurement
- Direct measurement of a_e

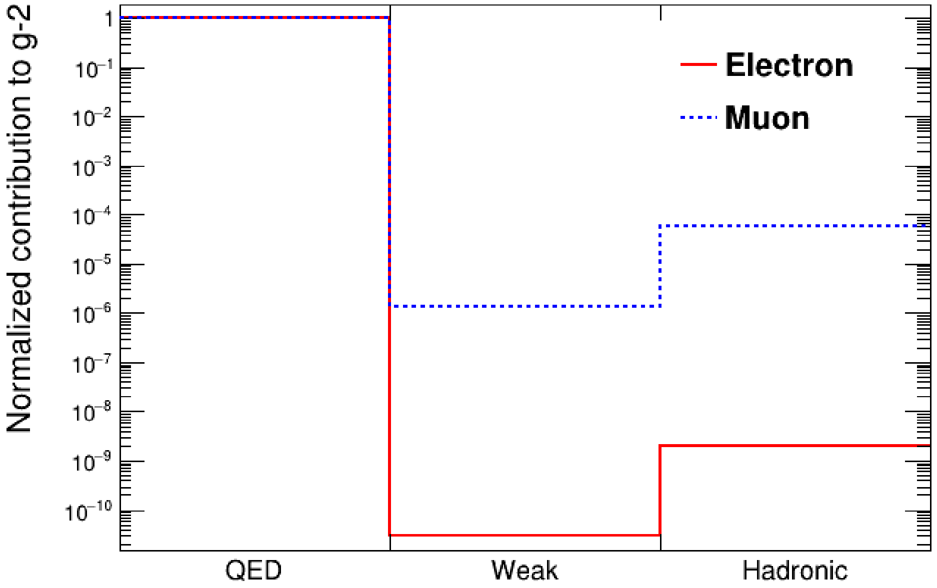




$$a_e(\mathrm{exp}) - a_e(\alpha) = (4.8 \pm 3.0) \times 10^{-13} (1.6\sigma)$$

a_μ

- a_e vs a_μ



τ lepton: $-0.052 < a_\tau < 0.013$ exp.
$a_\tau = 1.17721(5)\,10^{-3}$ SM

muon: $10^{11}\,a_\mu =$ $116592089\,(63)$ exp.
$116591803\,(49)$ SM
3.6 σ difference

electron: $10^{14}\,a_e =$ $115965218091\,(26)$ exp.
$115965218173\,(77)$ SM
➠ determine α_{QED}

Sensitivity to new physics: $a_\ell^{NP} \sim \frac{m_\ell^2}{\Lambda^2}$

$(m_\mu/m_e)^2 \sim 4 \times 10^4$

a_μ

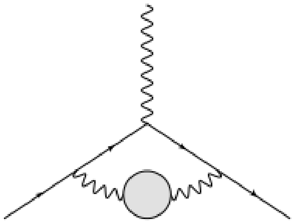
- Contributions to a_μ (as of 2018)

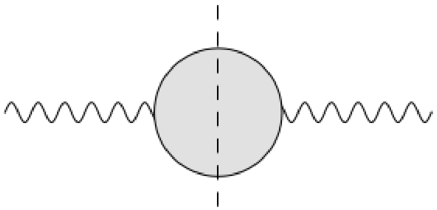
SM contribution	10^{11} × (value ± error)		Refs and notes
QED (5 loops)	116584718.951	± 0.080	[Ayoma et al, 2012, Laporta'17]
EW (2 loops)	153.6	± 1.0	[Gnendiger et al, 2013]
HVP (LO)	6923	± 42	[DHMZ'11, see also HLMNT'11,JS'11,...]
HVP (NLO)	-98.4	± 1.0	[Hagiwara et al, 2011]
HVP (NNLO)	12.4	± 0.1	[Kurz et al, 2014]
HLbL	105	± 26	[Prades et al, 2014] ``Glasgow consensus"
HLbL (NLO)	3	± 2	[Colangelo et al, 2014]
Total	116591803	± 49	[Davier et al, 2011]
Experiment	116592089	± 63	[Bennet at al, 2006]
Diff (Exp. - SM):	286	± 80	

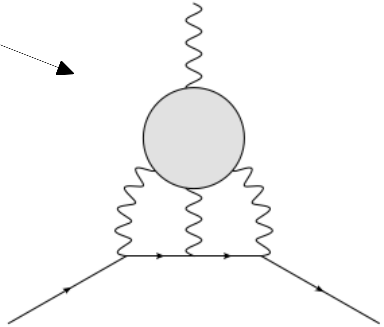
The difference is large: ~ 2 × (EW contribution)

a_μ

- Current evaluation : g-2 Theory Initiative, arXiv:2006:04844 (2020)
- Aim : full review of theoretical prediction for this parameter
  - QED, Weak : purely perturbative calculations, up to 5^{th} order and beyond
  - Hadronic contributions : “HVP” and “HLbL” combine perturbative calculations and input from data

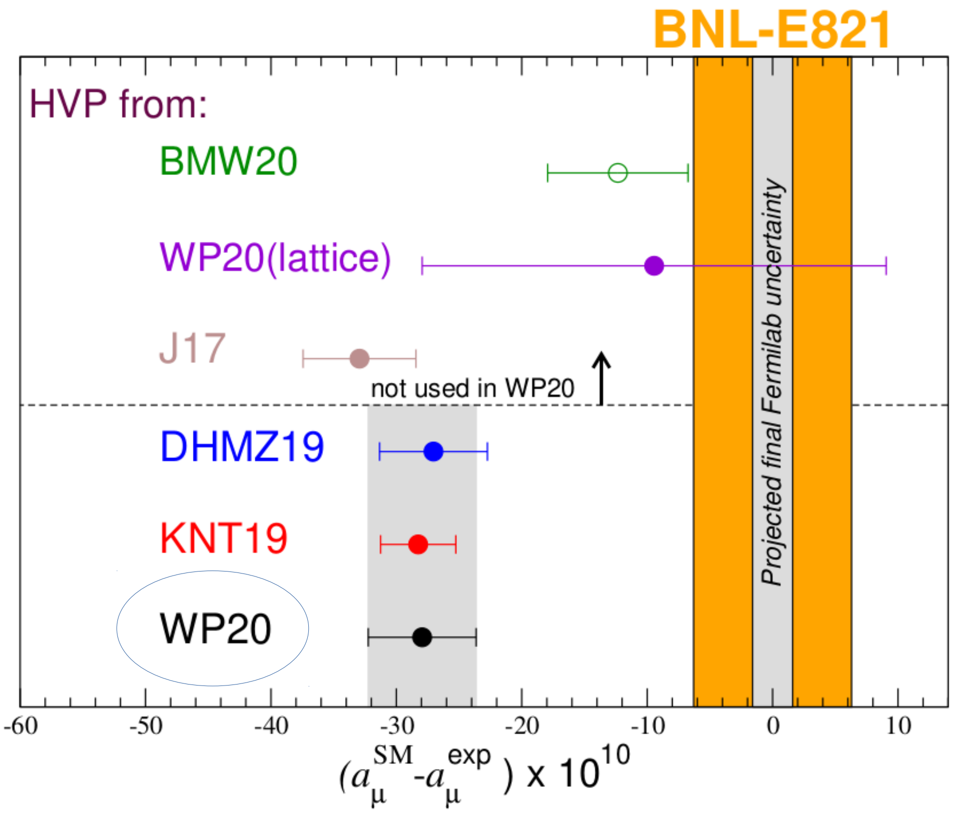






a_μ

- Current evaluation : g-2 Theory Initiative, arXiv:2006:04844 (2020)



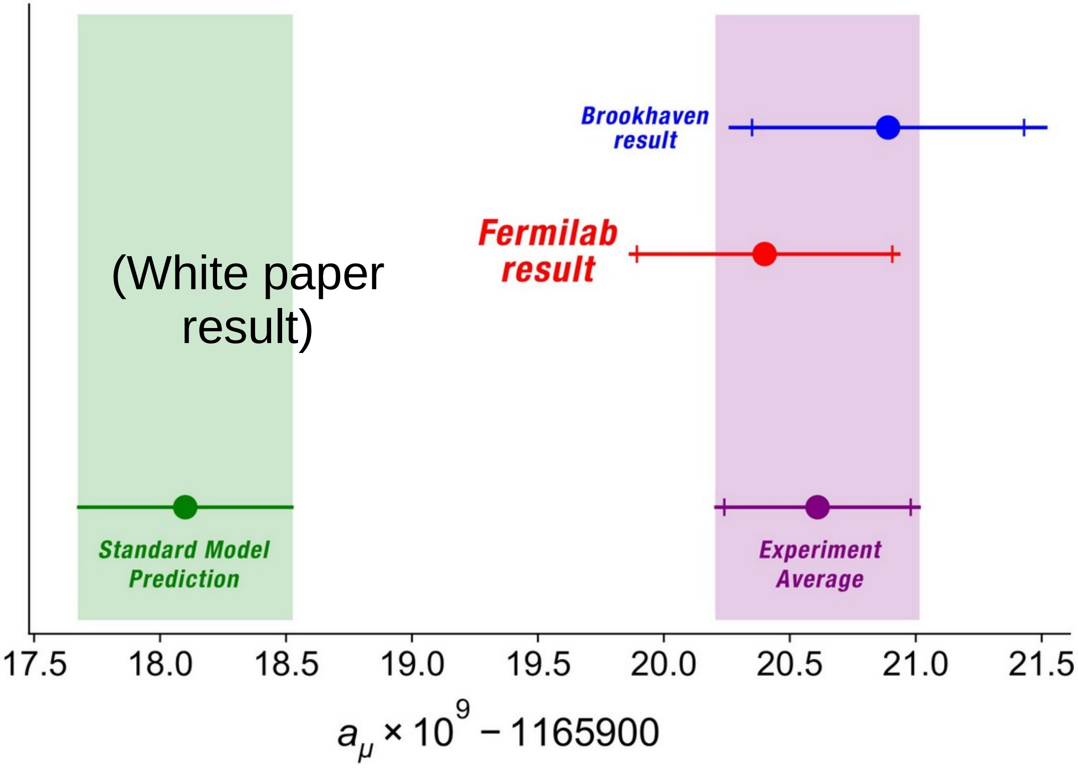
In depth evaluation of QED, Weak and Hadronic contributions. Dispersive results are still the baseline, and now also introduced for the LbL contributions

Lattice calculations gain momentum!

Moriond was just before the announcement of the last experimental result.

a_μ

- Experimental update : April 7, 2021, g-2 Collaboration (Fermilab)

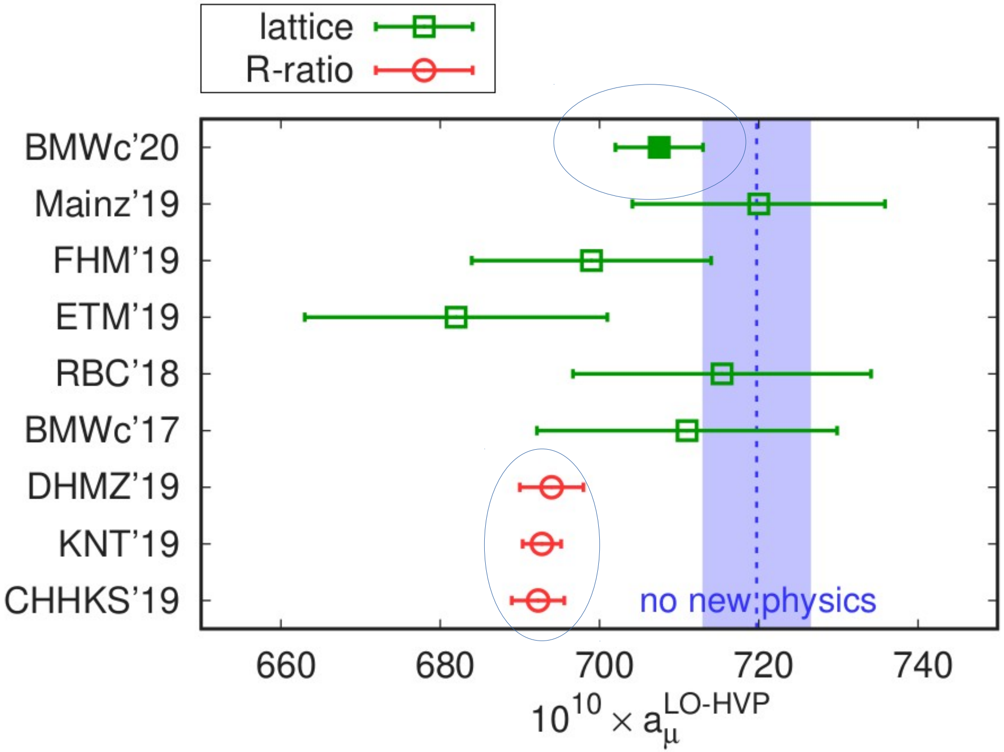


4.2 standard deviations!!

But..

a_μ

- Recent results in lattice QCD



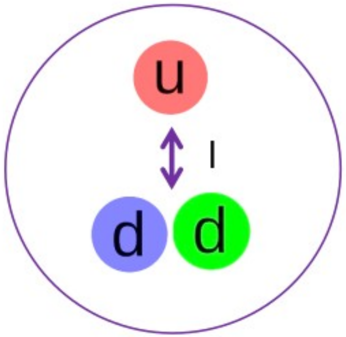
Latest lattice prediction ~as precise as the dispersive results, and in better agreement with measurement.

On arXiv since some time. Not used in White Paper as checks were still ongoing, and no independent result with same precision.

Finally published within a day from the experimental result.

Neutron EDM

- Motivation : test of CP violation



$d_n = 2/3\ e*l$

$l = 0.1 r_n \rightarrow d_n = 4.10^{-14}$ e.cm

But $d_n < 1.8\ 10^{-26}$ e.cm (90% C.L.)

A permanent asymmetry in the charge distribution
-> probe of P, T (CP) symmetries

Neutron EDM

- Motivation : test of CP violation

SM prediction d_n^{CKM}

Strong CP d_n^{θ}

New Physics at high scale d_n^{NP}

$$d_n = 10^{-32} e.cm + 10^{-16}\, e.cm\,(\theta) + \,10^{-24}\, e.cm \left(\frac{200\,GeV}{M}\right)^2 \sin(\varphi_{CP})$$

$$L_{eff} = L_{QCD} + \theta\, \frac{\alpha_S}{8\,\pi}\, \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.0039(2)(9)\theta\; e.fm$*

Experimental upper limit: $|d_n| \leq\, 2.10^{-13}\;\, e.fm$ → $\theta \lesssim 10^{-10}$

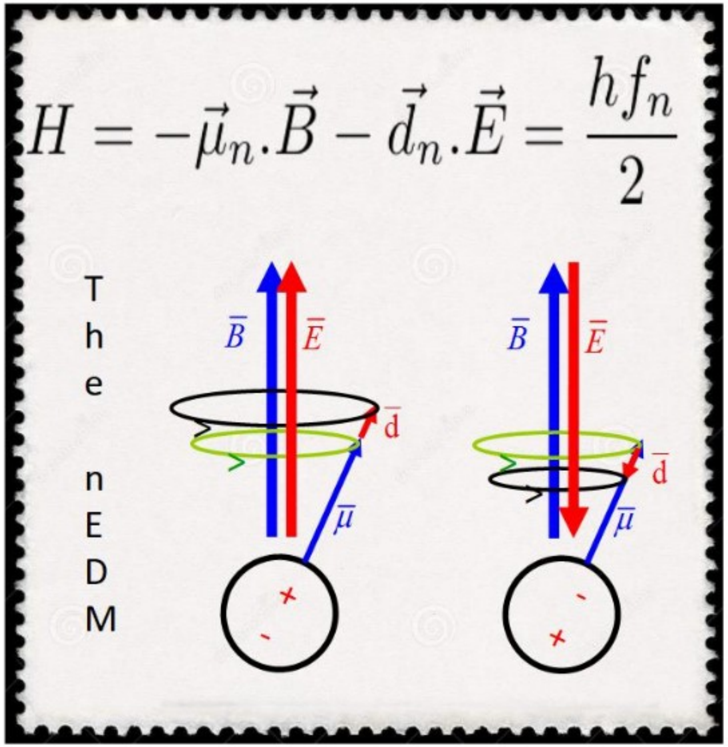
New CP violating phases
contributes to
* baryonic asymmetry of the universe
* neutron EDM

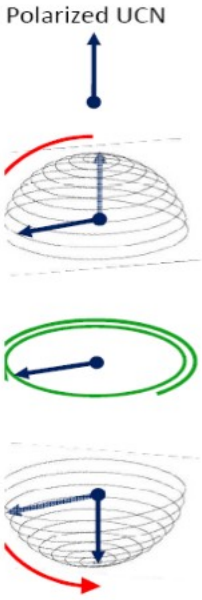
The nEDM is the probably most stringent test of electroweak baryogenesis

Another possibility is the leptogenesis

Neutron EDM

- Experiment : nEDM @ PSI. Principle, in a nutshell :





Ultra-cold, polarized neutrons. Measurement of the change of the Larmor precession frequency

$$f_n = \frac{1}{\pi\hbar}\left|\mu_n\vec{B}_0 + d_n\vec{E}\right|,$$

under change of polarity of the electric field :

|B| = 1036 nT
|E| = 11 kV / cm
T = 2 mK, v ~ 5m/s

Neutron EDM

- Result

The search for the neutron EDM

TABLE I. Summary of systematic effects in 10^{-28} e.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

Effect	Shift	Error	
Error on $\langle z \rangle$	...	7	(0 ± 68)
Higher-order gradients $\hat{G}$	69	10	(33 ± 14)
Transverse field correction $\langle B_T^2 \rangle$	0	5	
Hg EDM [8]	−0.1	0.1	
Local dipole fields	...	4	(-71 ± 81)
$v \times E$ UCN net motion	...	2	
Quadratic $v \times E$	...	0.1	
Uncompensated G drift	...	7.5	
Mercury light shift	...	0.4	
Inc. scattering ^{199}Hg	...	7	
TOTAL	69	18	(-38 ± 99)

Systematic error budget:

- Divided by a factor of 5
- Dominated by "new" effects
- Opens the door to a new generation of experiments

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}\ e.\text{cm}.$$

Compare to contribution from CKM : $d_n \sim 10^{-32}$ e.cm

Direct CP violation in K decays

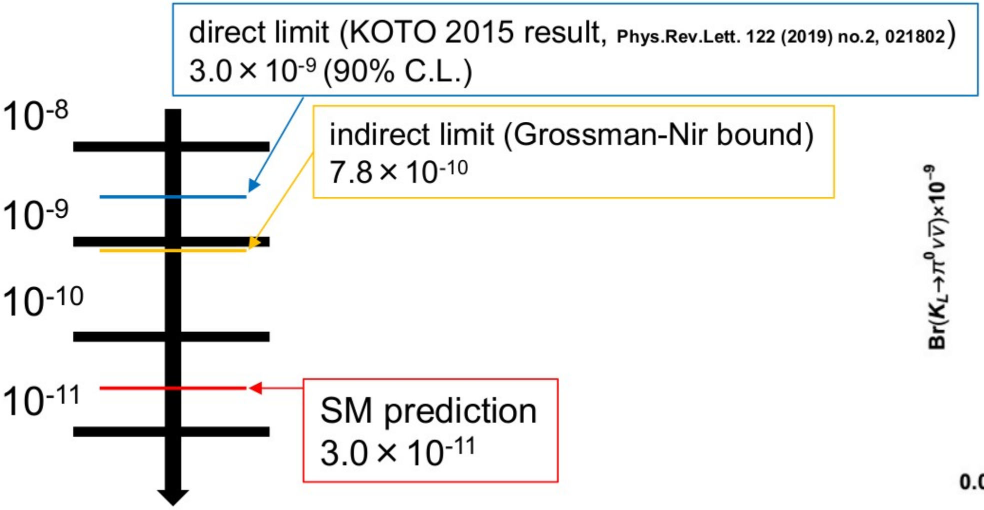
- Experimental program :

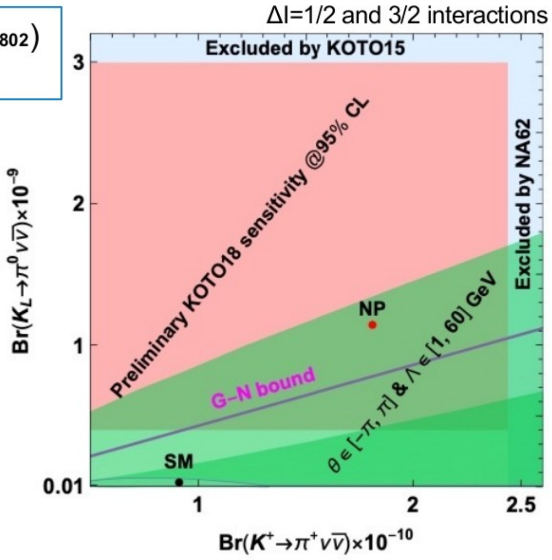
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

→ NA62 : $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\rm stat} \pm 0.9_{\rm syst}) \times 10^{-11}$

$$\mathcal{B}(K^0 \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{0.74} = (3.4 \pm 0.6) \times 10^{-11}$$

→ KOTO : BR < 3×10^{-9} (90% C.L.)



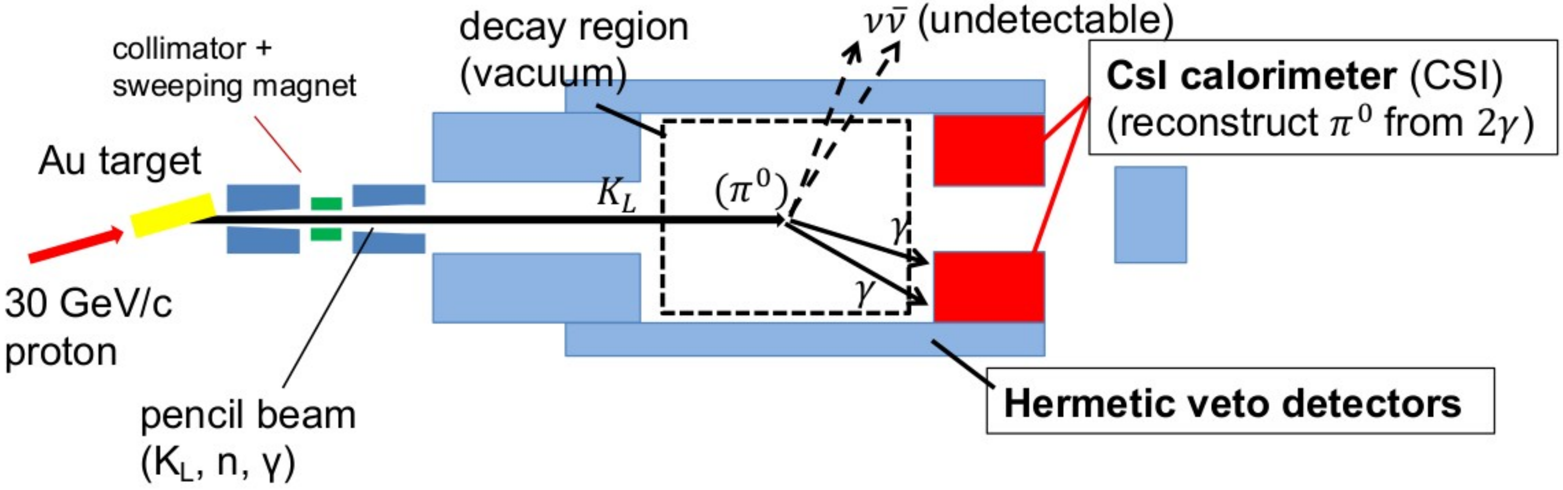


Direct CP violation in K decays

- The KOTO experiment

Signal

$$K_L \to \pi^0 \nu \bar{\nu} \ : (\pi^0 \to)\ 2\gamma + \text{nothing}$$

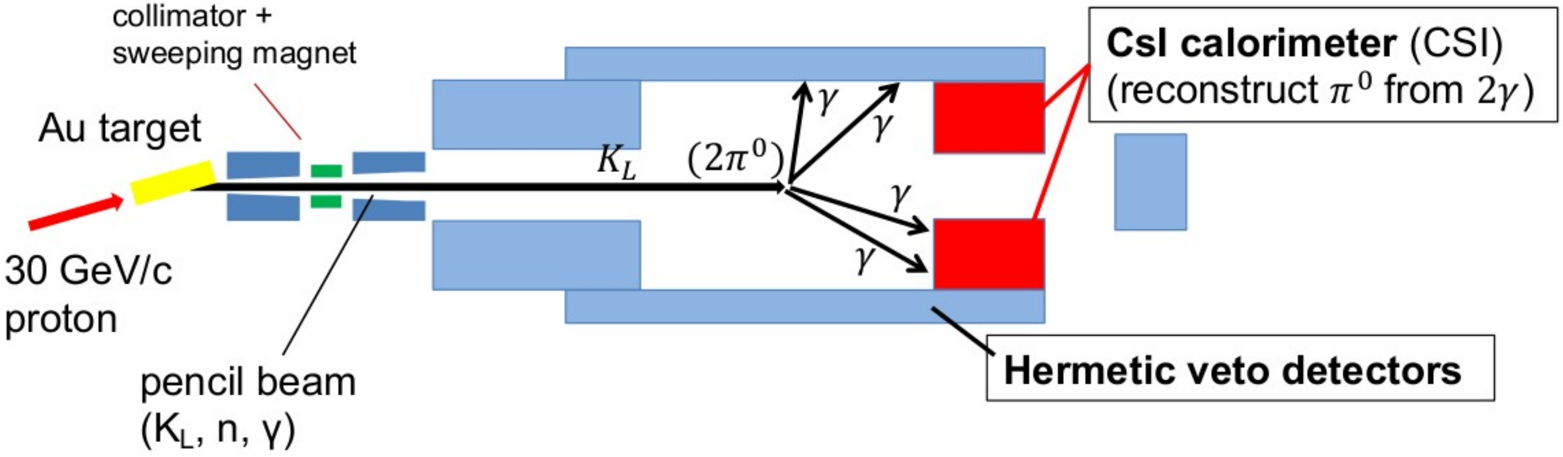


Direct CP violation in K decays

- The KOTO experiment

Background

ex.) $K_L \rightarrow 2\pi^0(\rightarrow 4\gamma)$ BR : 8.64×10^{-4}



Direct CP violation in K decays

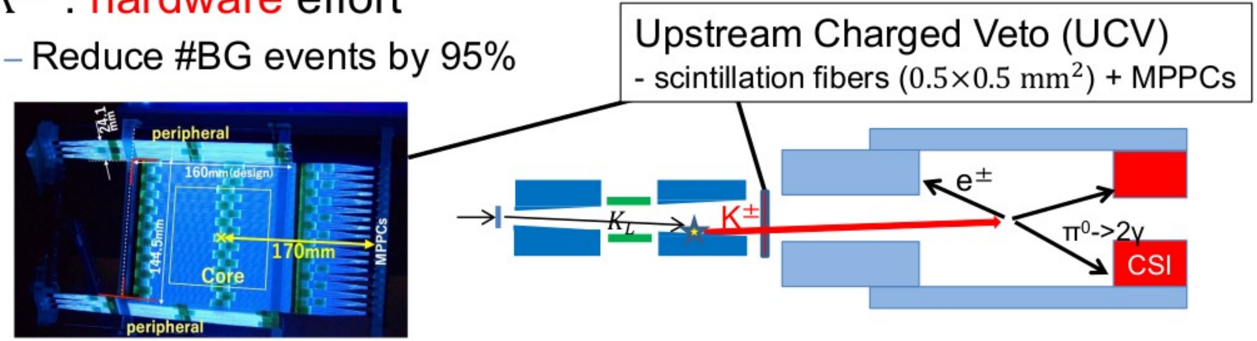
- The KOTO “anomaly” (as referred to by a flurry of “interpretation” papers)
  - 2015 data :
    - 2.2×10^{19} protons on target
    - 0.4 background events expected, <0.1 signal
    - None observed, limit BR < 3 10^{-9}
  - 2016 – 2018 :
    - 7×10^{19} protons on target
    - 1.2 background events expected, <0.1 signal
    - Three observed, limit BR < 4.9 10^{-9}

→ not an anomaly! But a drastic effort in background reduction is needed

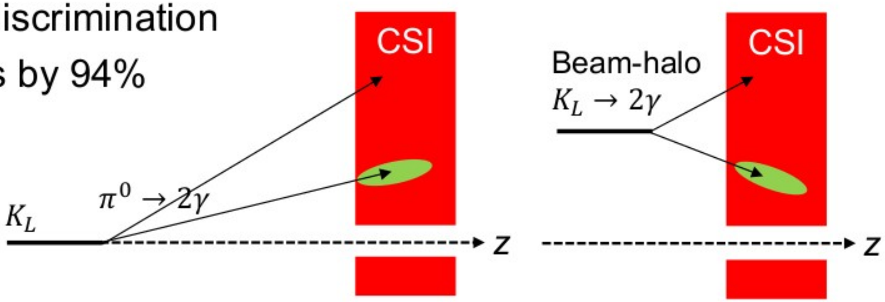
Direct CP violation in K decays

- Prospects

  - $K^{\pm}$: hardware effort
    - Reduce #BG events by 95%



  - Beam-halo $K_L \to 2\gamma$: software effort
    - EM shower shape discrimination
    - Reduce #BG events by 94%



Ultimately expect ~100 signal events, ~10% measurement precision

Sensitivity $O(10^{-11})$

Summary

- α_{QED} and $a_{e,\mu}$
  - α_{QED} : very precise new result at LKB, tension with main competitor (Berkeley). Upgrades ongoing to reach 10^{-11} uncertainty (a further factor of 8)
  - a_e : good agreement between direct measurement (spin precession) and calculation using α_{QED} as experimental input
  - a_μ : situation still unclear. Lots of momentum on the experimental and theory sides. Further updates from lattice QCD might change the picture.
- Neutron EDM
  - Test CP violation. Not yet sensitive, but new generation of experiments will push limits
- Direct CP violation in K decays
  - NA62 (charged current) in good agreement with SM.
  - KOTO (neutral current) : in progress; requires large increase in luminosity and background reduction to achieve advertised sensitivity.