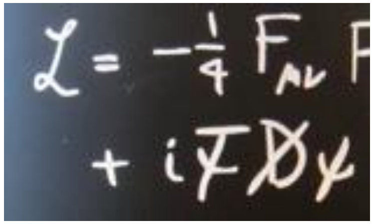
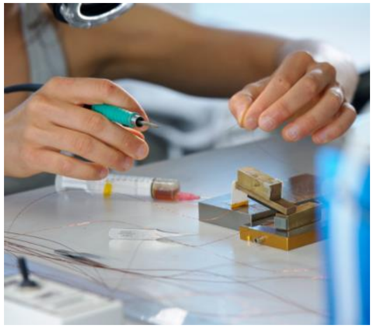
Precision QCD at low energies

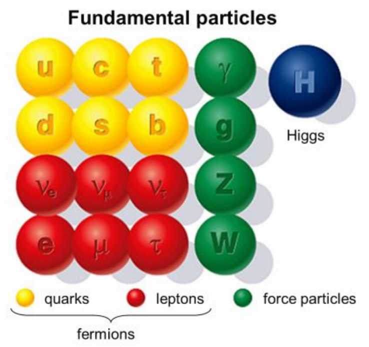


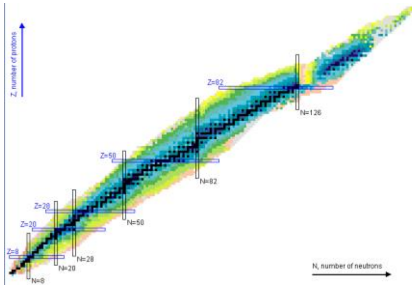
Gratefully acknowledge input from

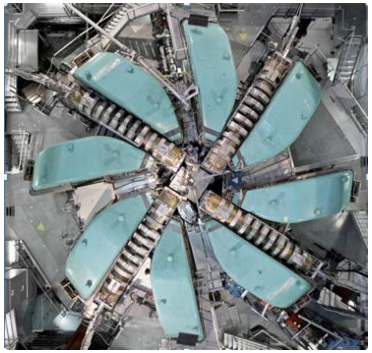
- A. Antognini
- C. Crawford
- C. Curceanu
- A. Denig
- E. Downie
- D. Gotta
- P. Kammel
- B. Märkisch
- G. Pignol
- J. Pretz
- M. Snow
- S. Ulmer

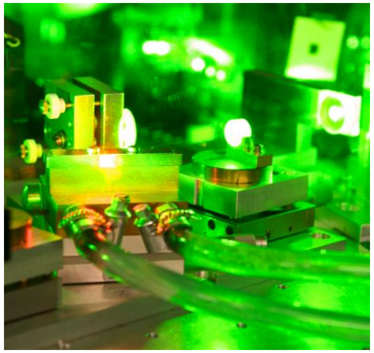


Klaus Kirch, ETH Zürich – PSI Villigen, Switzerland









Input to the ESPP Process

related in some way to low energy QCD

- ID6: Gamma factory for CERN
- ID18: EDM storage ring
- ID20: PBC Conventional Beams
- ID39: ISOLDE at CERN
- ID42: PBC at CERN
- ID76: J-PARC facilities and physics
- ID86: PIK reactor
- ID115: Hadron Physics Opportunities in Europe
- ID118: MUonE experiment
- ID121: PSI facilities and physics
- ID123: Electric dipole moment community input
- ID143: A New QCD Facility at the M2 beam line of the CERN SPS
- ID147: PERLE High Power Energy Recovery Facility
- ID148: NuPECC input
- ID163: QCD Theory Input
- ID164: ESS

QCD is a pillar of the Standard Model

- 19 param., masses, couplings, mixings, CP phases, θ_{QCD}, Higgs vev
- 7+ more with the inclusion of neutrino masses and mixings

- measure all parameters and fundamental interactions as accurately and precisely as possible!

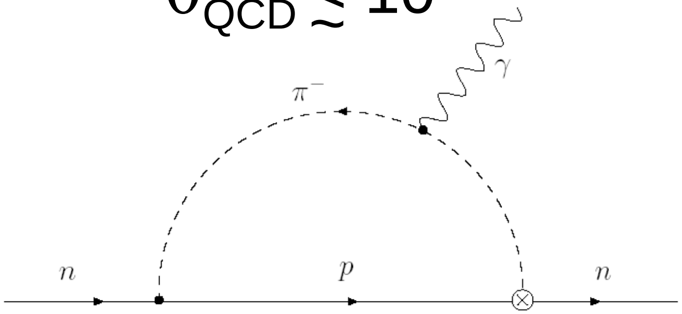
QCD and EDM

The strong CP problem

$$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + g^2/(32\pi^2)\ \theta_{QCD} G\tilde{G}$$

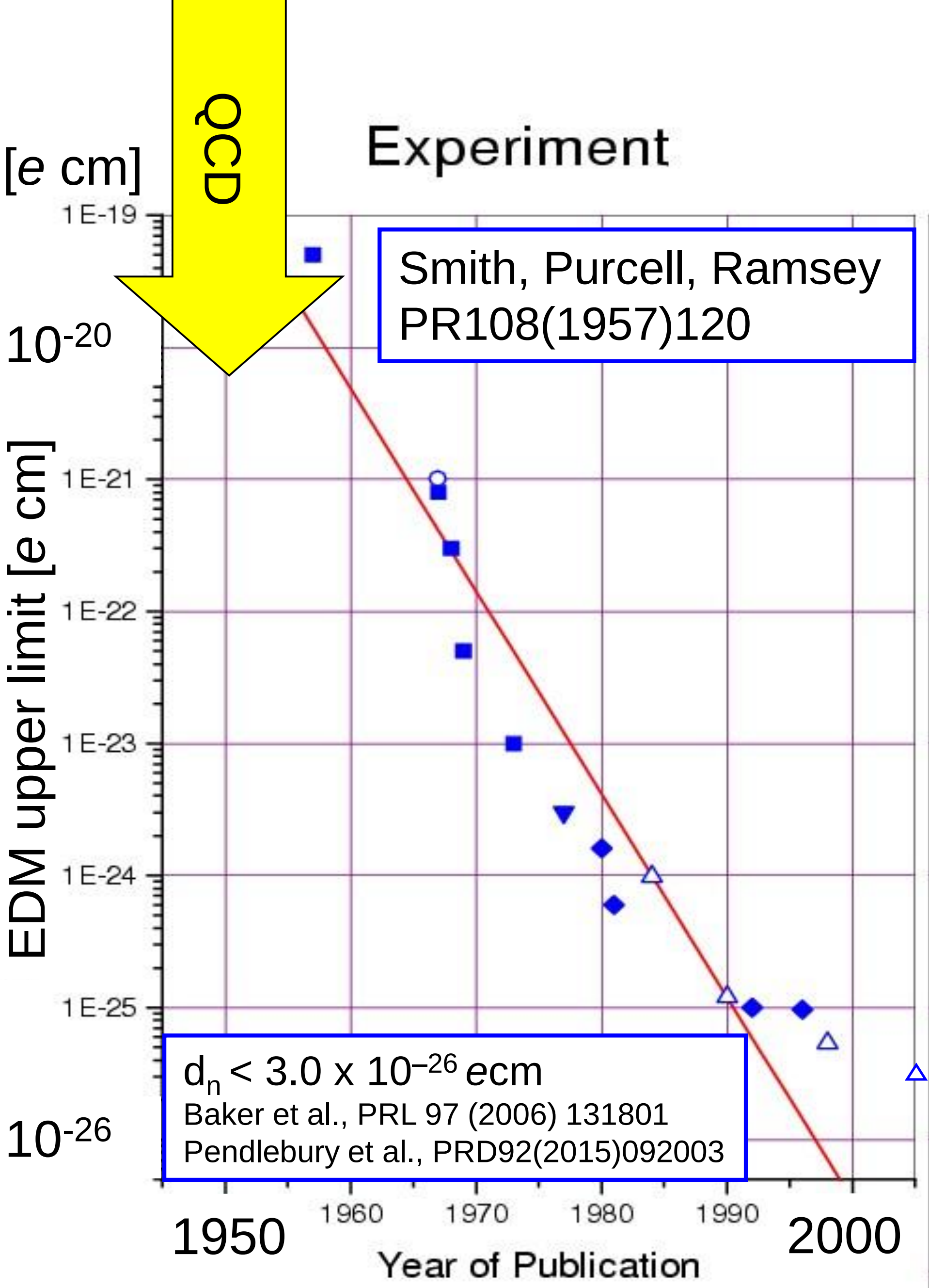
$$d_n \approx 10^{-16}\ e\ \mathrm{cm} \cdot \theta_{QCD}$$

$$\theta_{QCD} \lesssim 10^{-10}$$



Why is θ_{QCD} so small ?

Together, n and p EDM would test θ_{QCD} origin.
Lattice calculations progressing.



Smith, Purcell, Ramsey
PR108(1957)120

$d_n < 3.0 \times 10^{-26}$ ecm
Baker et al., PRL 97 (2006) 131801
Pendlebury et al., PRD92(2015)092003

See talk by S. Paul on EDM

QCD is responsible for

- the **hadron masses**
  - The description of the hadron spectrum is **not** topic of this talk.
  - The masses of the lightest mesons and baryons are being measured with much higher precision than calculable today.
  - Precision comparisons of theory and experiment remain dreams for the future
  - Precision data provide benchmark fundamental constants and allow for sensitive SM tests.

MASS of the CHARGED PION

simultanuous measurement with curved crystal spectrometer

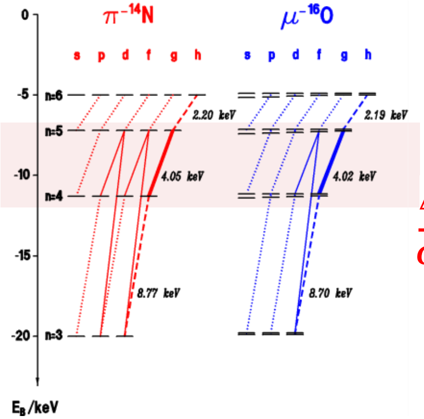
N_2 /O_2 mixture (10% / 90%) @ 1.4 bar

history

with exotic atoms

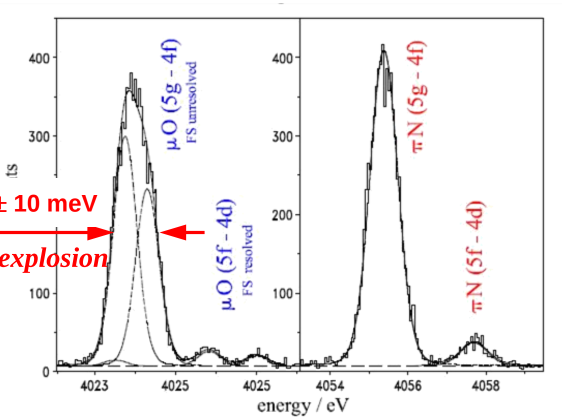
measurement ***calibration***

- **point like Coulomb potential**
- **no electron screening**
- **$E_{\mu O(5g-4f)}$ / $E_{\pi N(5g-4f)}$ = m_μ / m_π + ...**



ΔE = 750 ± 10 meV

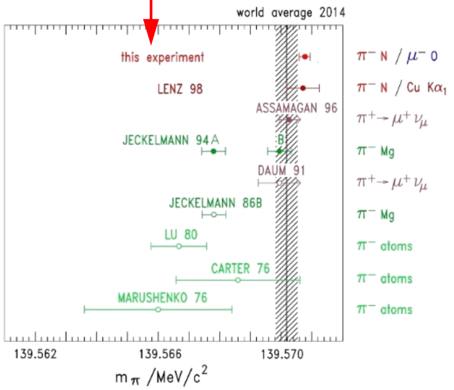
Coulomb explosion



m_π = *139.57077 ± 0.0018 eV*

(± *1.3ppm*)

M. Trassinelli et al., Phys. Lett. B 759 (2016) 583



Outlook

- ***π⁻Ne (no Coulomb explosion) and double flat crystal spectrometer*** ***Δm/m → 0.5ppm***
- ***Laser-induced excitation of metastable π⁻He⁺ states*** ***Δm/m → 0.1ppm***

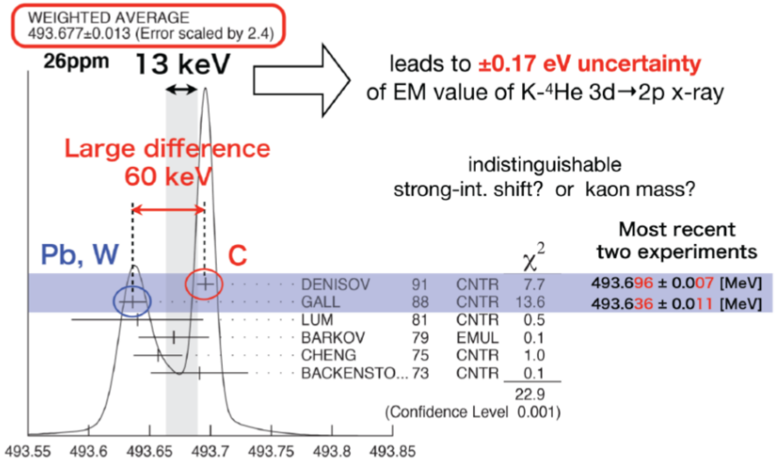
Courtesy: D. Gotta

Future programme and perspectives at DAΦNE and J-PARC

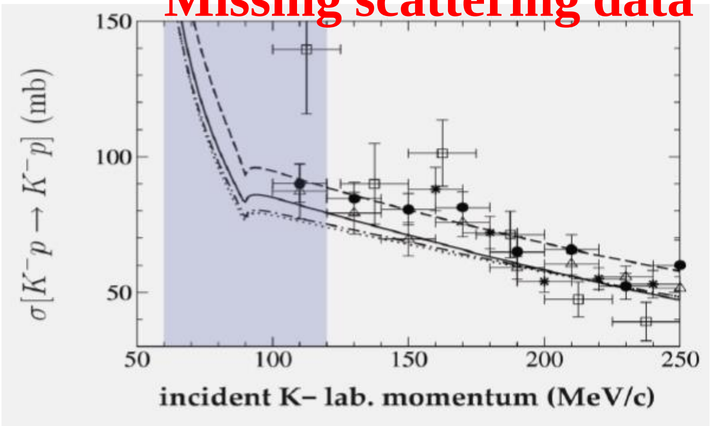
Courtesy: C. Curceanu

- Kaon mass - precision measurement at a level < 3-5 keV by low-Z kaonic atoms
- Kaonic helium transitions to the 1s level
- Other light kaonic atoms (K^-O, K^-C,…)
- Heavier kaonic atoms (K^-Si, K^-Pb…)
- Radiative kaon capture – Λ(1405) study
- Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)
- Studies of kaon-nuclei interactions at low-energies (E15 at J-PARC and AMADEUS at DAFNE)

Kaon mass problem

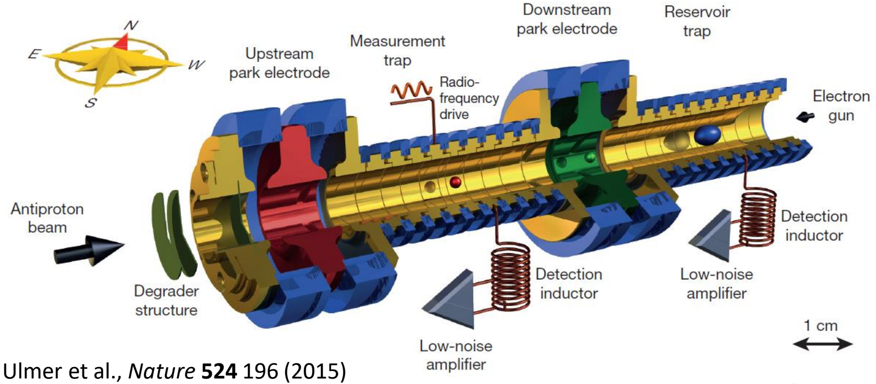


Missing scattering data



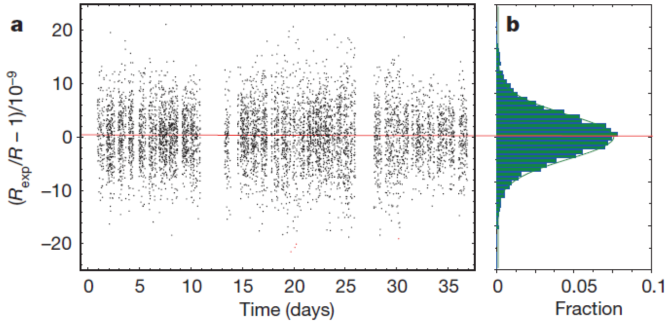
More infos: "The modern era of light kaonic atom experiments"
to appear (June 2019) in Reviews of Modern Physics
https://journals.aps.org/rmp/accepted/fb072Ed7Eb71590f30186b940e9d8107023ce0960

Antiproton/Proton Charge-to-Mass Ratio



S. Ulmer et al., *Nature* **524** 196 (2015)

$$m_{\mathrm{H}^-} = m_\mathrm{p}\left(1 + 2\frac{m_\mathrm{e}}{m_\mathrm{p}} - \frac{E_\mathrm{b}}{m_\mathrm{p}} - \frac{E_\mathrm{a}}{m_\mathrm{p}} + \frac{\alpha_{\mathrm{pol,H}^-} B_0^2}{m_\mathrm{p}}\right)$$



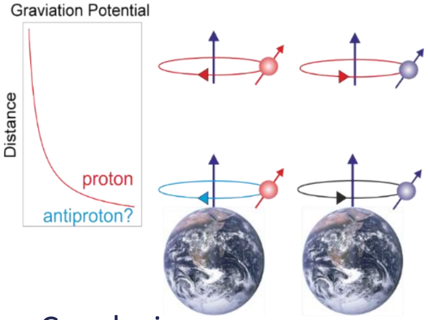
Inspired by work of TRAP collaboration (G. Gabrielse et al., PRL **82**, 3199(1999).)

- Applied two particle fast shuttling scheme to measure proton/antiproton q/m ratio using antiprotons and hydrogen ions (perfect proxies / low systematics)
- New method is 50 times faster than classical mass spectrometry techniques.

Result of 6500 proton/antiproton Q/M comparisons:

$$\boxed{\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}} - 1 = 1(69) \times 10^{-12}}$$

- Constrain of the gravitational anomaly for antiprotons:



$$\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\, U/c^2$$

Our 69ppt result sets a new upper limit of

$$|\alpha_g - 1| < 8.7 \times 10^{-7}$$

- Conclusion:

Matter and Antimatter clocks run at the same frequency

Courtesy: S. Ulmer

Measurements at the level of 10 ppt to 20 ppt in reach.

QCD and magnetic moments

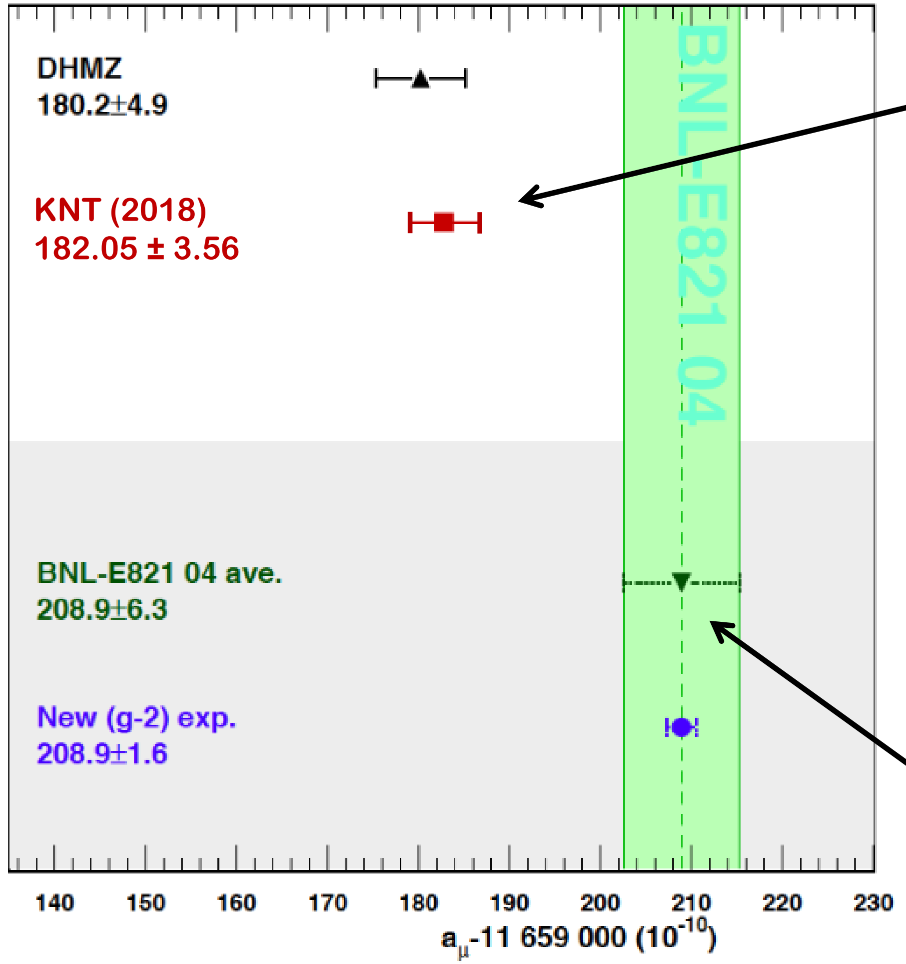
- Largest uncertainties in the muon anomalous magnetic moment (g-2)
  - thrilling SM - BSM result
  - huge challenge to calculations and experiments

See talk by G. Schnell covering MUonE

- Completely dominating baryon «anomalous magnetic moments»
  - high precision measurements far beyond QCD
  - benchmarks and BSM tests

Muon Anomalous Magnetic Moment $(g\text{-}2)_\mu$

Magnetic Moment: $\vec{\mu} = \mu_B \; g \; \vec{S}$



$a_\mu^{SM} = (g\text{-}2)_\mu / 2 =$

$(\ 11\ 659\ 182.05 \pm 3.56\ ) \cdot 10^{-10}$

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} =$

$(27.05 \pm 7.26) \cdot 10^{-10}$ $(3.7\ \sigma)$

BNL/E821 measurement

$a_\mu^{exp} = (\ 11\ 659\ 208.9 \pm 6.3\ ) \cdot 10^{-10}$

Courtesy: A. Denig

muon g-2 projects at FNAL (data taking) and J-PARC (constructing)

Standard Model Prediction of (g-2)$_\mu$

Hadronic contribution **non-perturbative,** the **limiting** contribution

$$a_\mu^{SM} \quad = \quad a_\mu^{QED} \quad + \quad a_\mu^{weak} \quad + \quad a_\mu^{had} \quad = \quad (\,11\,659\,180.05 \pm 3.56\,) \cdot 10^{-10}$$

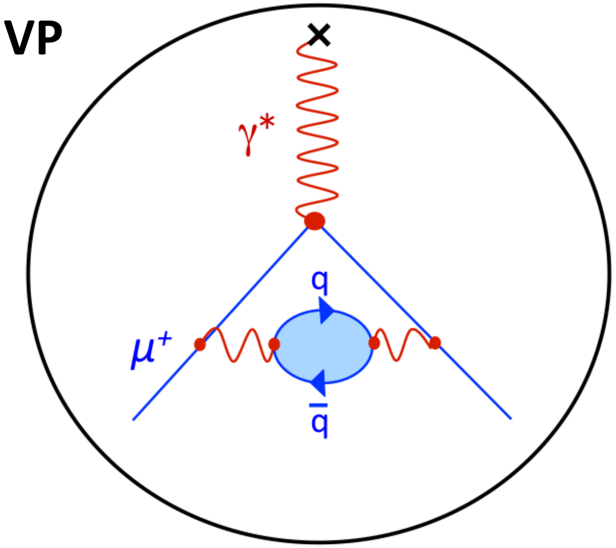
Teubner et al. '18

→ **HVP**: Hadronic Vacuum Polarization (693.27 ± **2.46**) · 10^{-10}

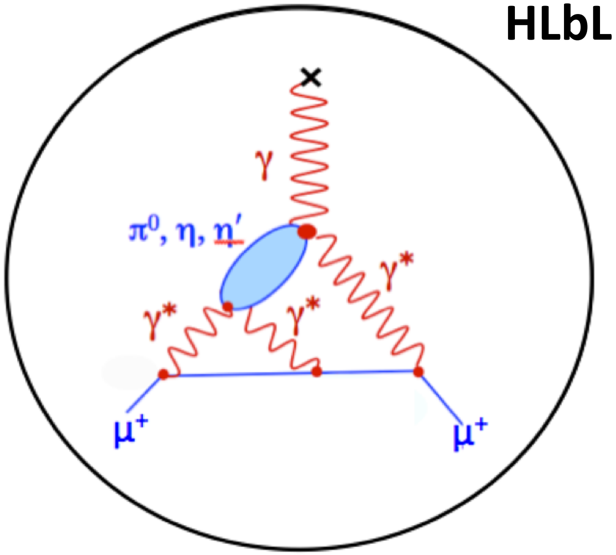
NLO (-9.82 ± **0.04**) · 10^{-10}

→ **HLbL**: Hadronic Light-by-Light (9.8 ± **2.6**) · 10^{-10}

HVP



HLbL



Courtesy: A. Denig

Related to exptl. hadronic cross section data

Related to exptl. hadronic transition form factor data

Hadronic Contributions to $(g\text{-}2)_\mu$

Goal: **Be ready for the interpretation of the upcoming FNAL $(g\text{-}2)_\mu$ experiment**

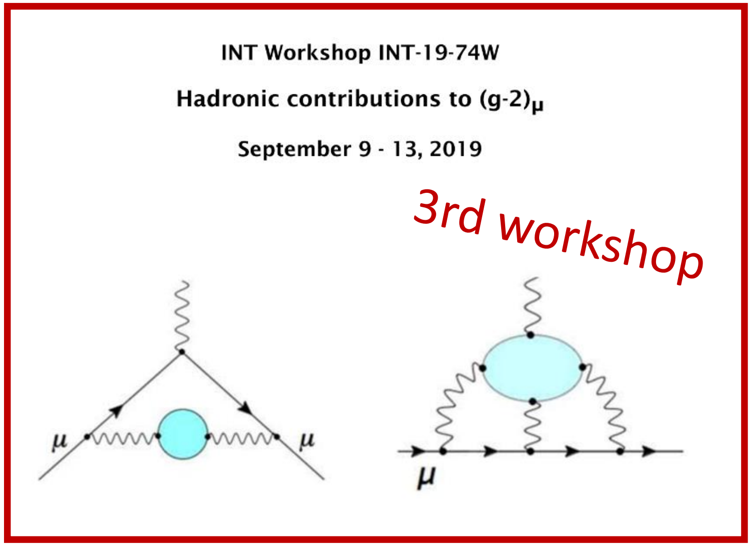
HVP: Leading contribution in dispersion integral e+e- → π+π- still not entirely understood, work in progress, measure relevant channels

HLbL: Huge experimental progress in measurement of TFFs

Lattice QCD: recent progress both for HVP and HLbL contributions
worldwide effort by various groups
accuracy still below phenomenological data-driven approaches
hybrid approach for HVP (combine lattice and data-driven calculations)

See talk by H. Wittig on lattice QCD

Muon (g-2) Theory Initiative: Coordinated effort (theory & expt.) to provide an updated theory Standard Model prediction of $(g\text{-}2)_\mu$



INT Workshop INT-19-74W

Hadronic contributions to $(g\text{-}2)_\mu$

September 9 - 13, 2019

3rd workshop

Courtesy: A. Denig

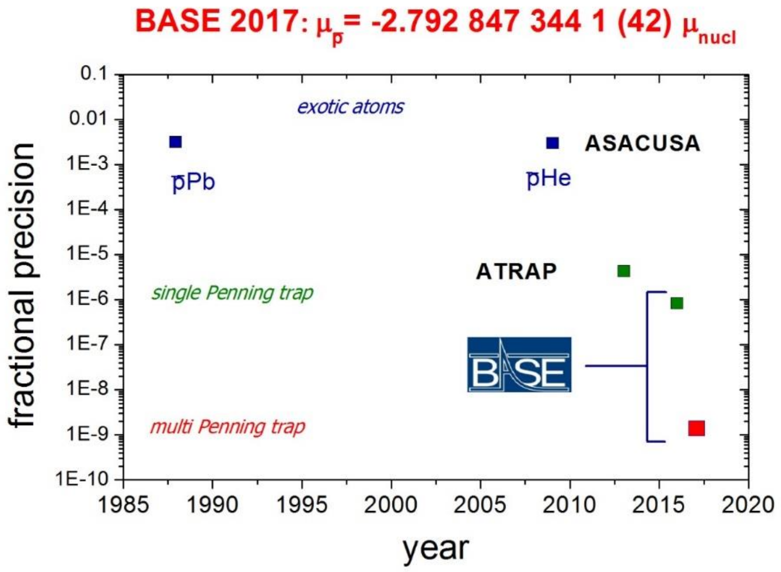
The Magnetic Moment of the Antiproton

Experiments on single protons and antiprotons in Penning traps

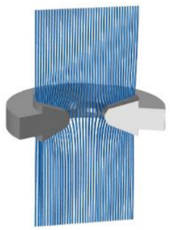
Using two particles in a mulit trap setup and

- a newly invented measurement scheme, the antiproton magnetic moment was determined with a precision on the ppb level.
- non-destructive spin quantum spectroscopy methods

Measurement improves previous best measurement by other collaborations by a factor of > 3000.



A. Mooser *et al.*, Nature **509**, 596 (2014)

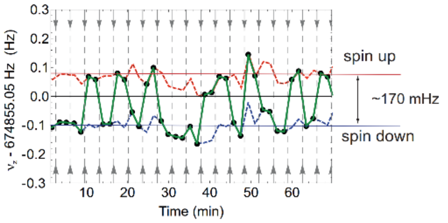


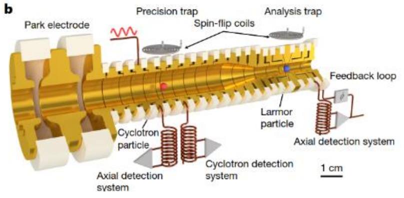
$$\frac{g_p}{2} = 2.792\,847\,350\,(9)$$

$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

C. Smorra *et al.*, Nature **550**, 371 (2017)

first measurement more precise for antimatter than for matter...

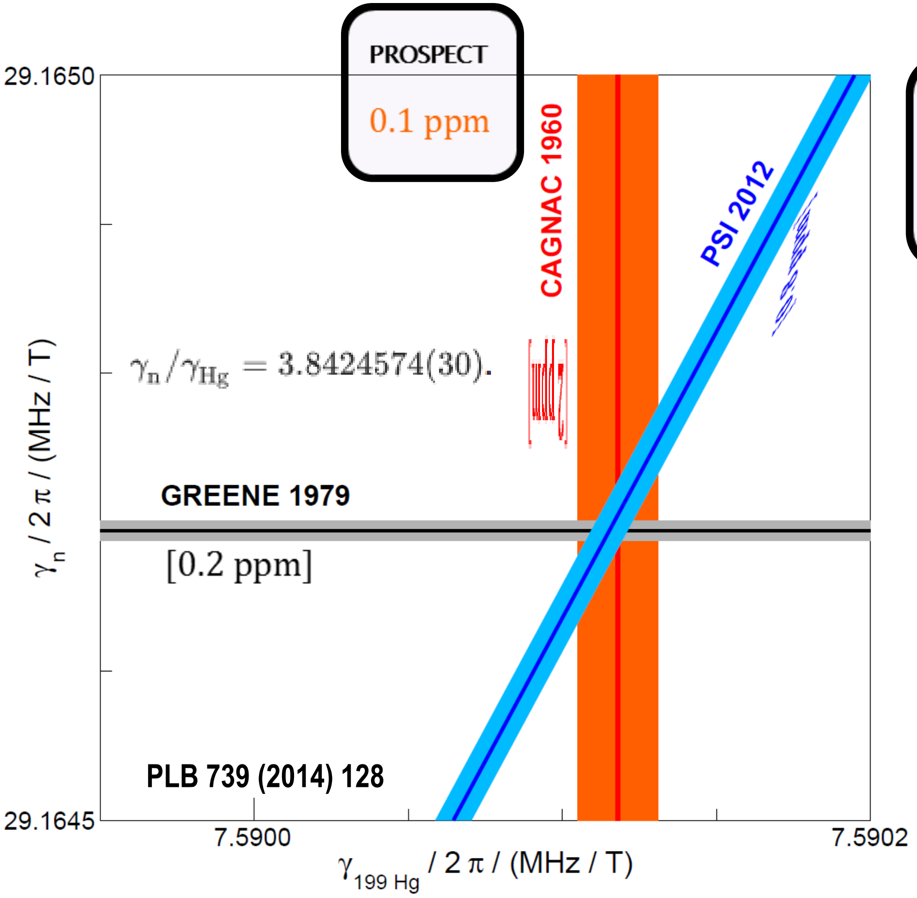




Further improvements: factor of 5 in reach, factor of 200 possible.

Courtesy: S. Ulmer

The neutron magnetic moment



PROSPECT
n/^{199}Hg
n2EDM
0.05 ppm

Courtesy: G. Pignol

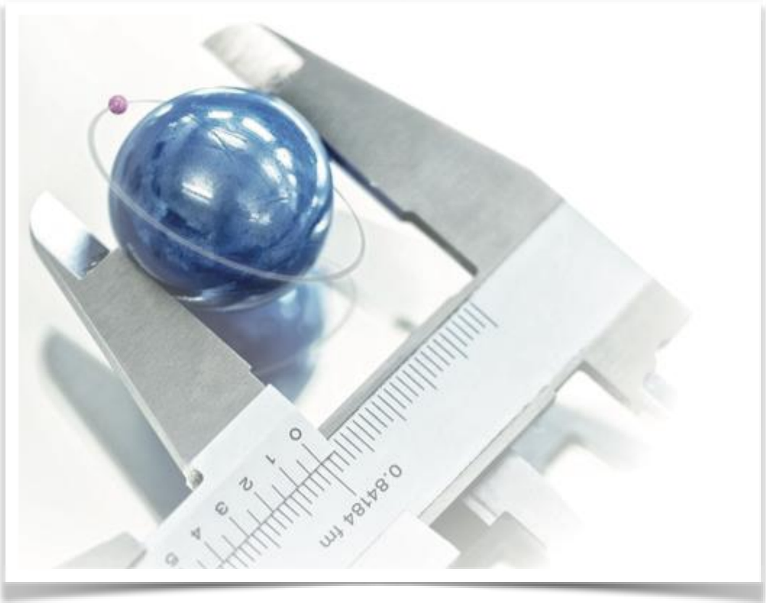
The neutron magnetic moment precision will be improved as a byproduct of the n2EDM experiment at PSI

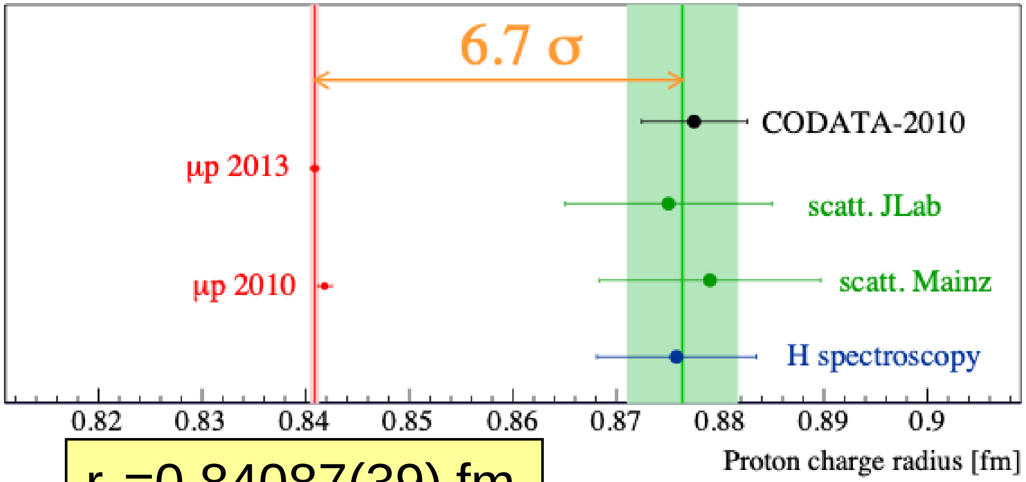
QCD and nucleon form factors

- electric and magnetic form factors at lowest momentum transfer:
  - proton charge radius
  - proton Zemach and magnetic radius
- weak nucleon form factors
  - axial coupling constant g_A
  - axial radius r_A

See talk by G. Schnell covering COMPASS++

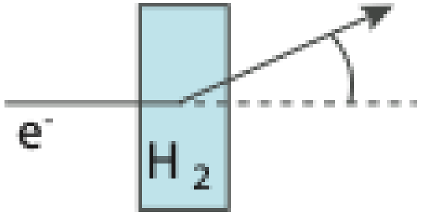
The proton radius puzzle



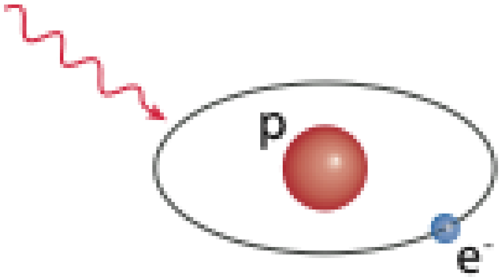


r_p=0.84087(39) fm

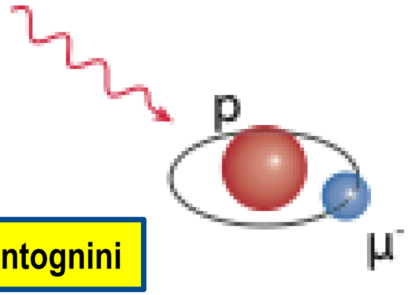
e-p scattering at low Q2



Laser spectroscopy in H



Laser spectroscopy in μp



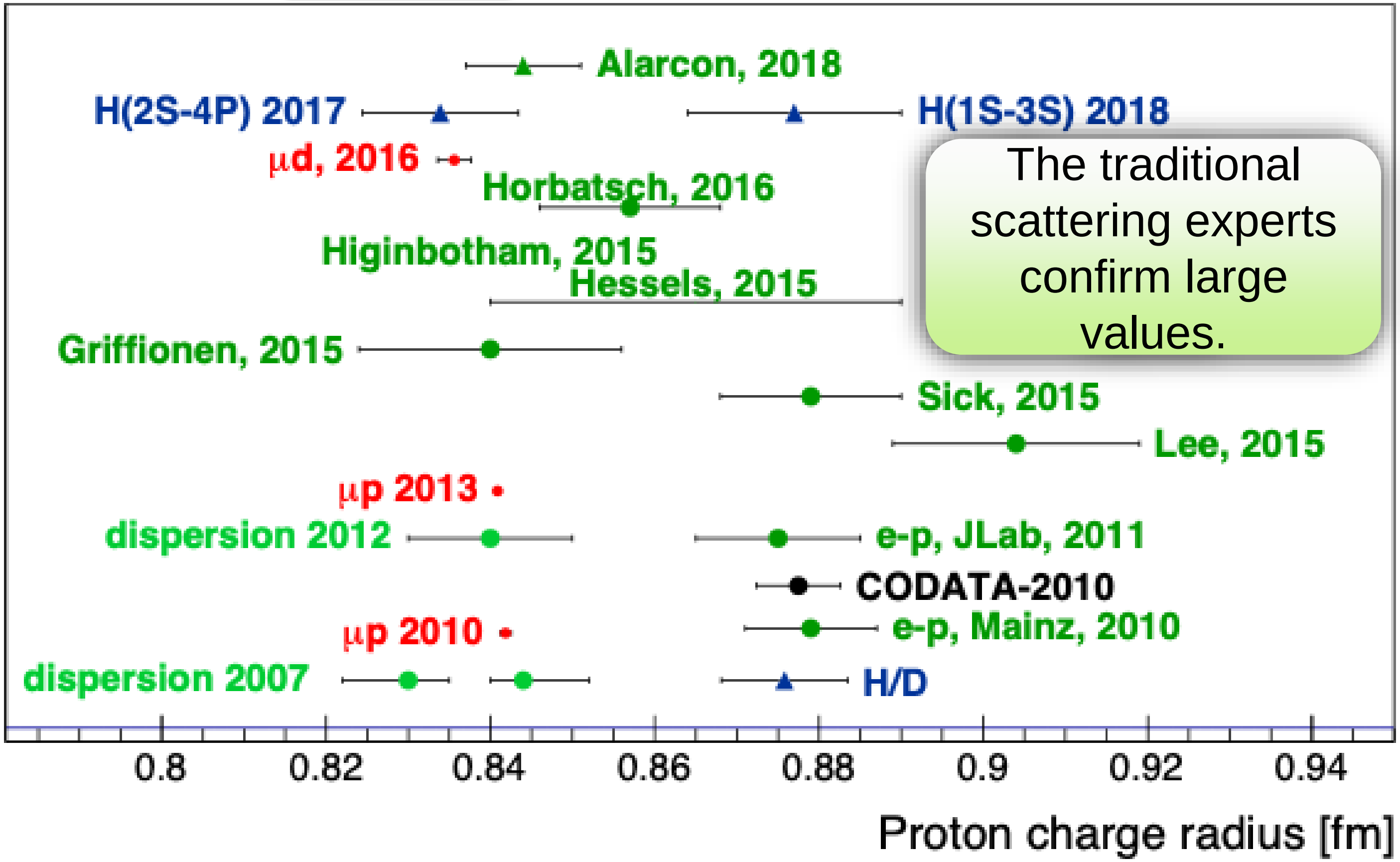
Courtesy: A. Antognini

Present status

e-p scattering
PRad 2018

H/D (1S-3S)
MPQ 2018

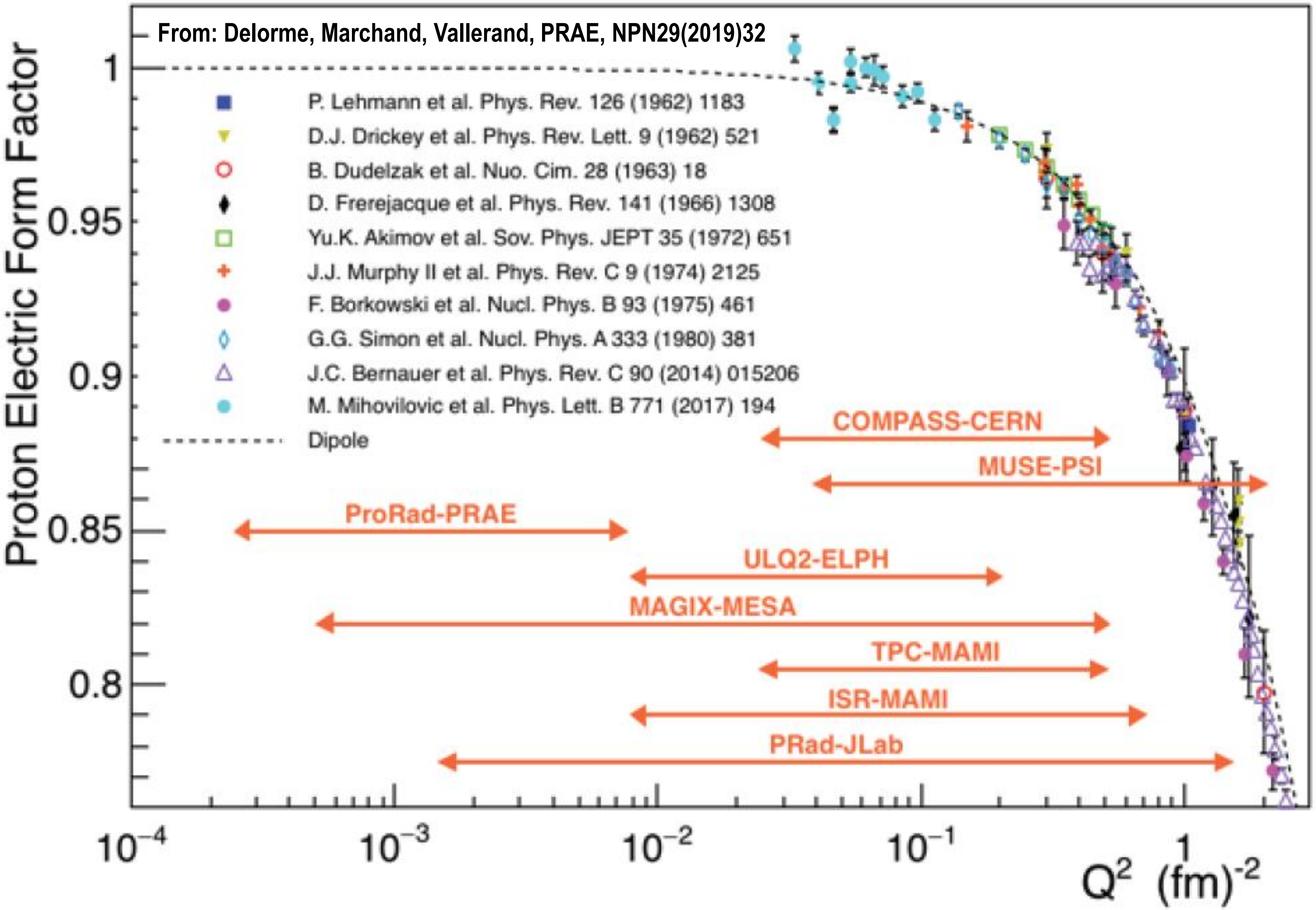
H(2S-2P)
Toronto 2018



The traditional scattering experts confirm large values.

Courtesy: A. Antognini

ep scattering experiments

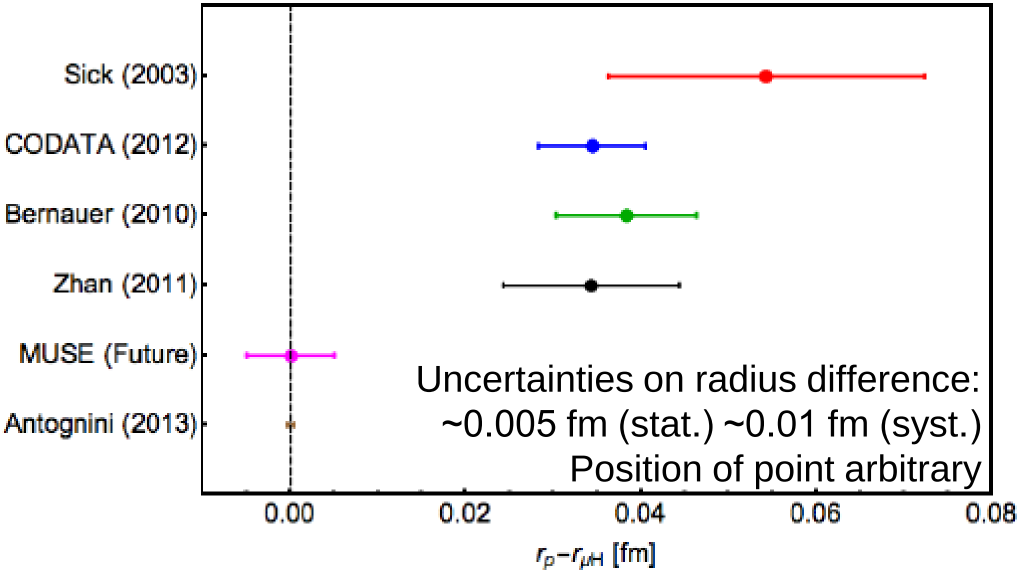


MUon Scattering Experiment at the Paul Scherrer Institute

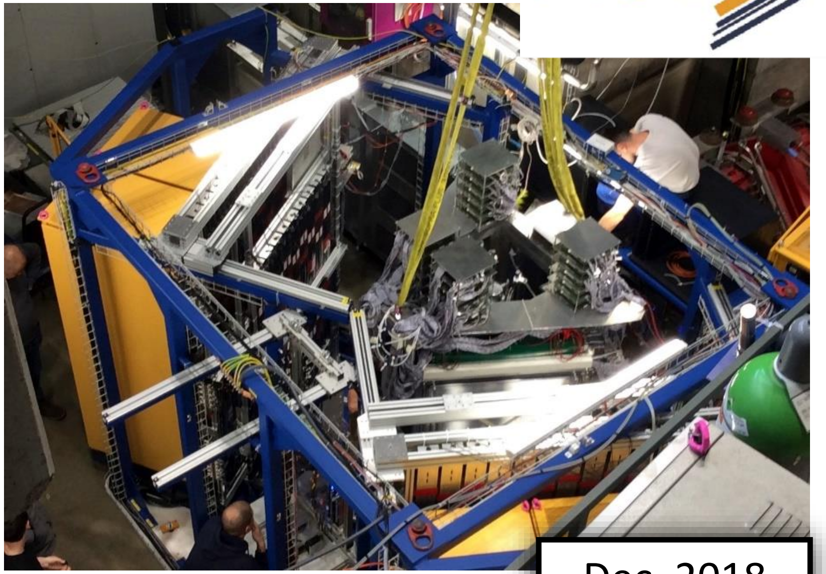
E Downie, G Ron, S Strauch, R Gilman et al.

MUSE

Courtesy: E. Downie



Uncertainties on radius difference:
~0.005 fm (stat.) ~0.01 fm (syst.)
Position of point arbitrary



Dec. 2018

- Simultaneous measurement of e and μ elastic scattering on proton
- Can access both polarities – determination of 2-photon effects
- Assembly of full system completed in Dec. 2018.
- Beam studies summer 2019; production data taking begins Dec 2019

NSF

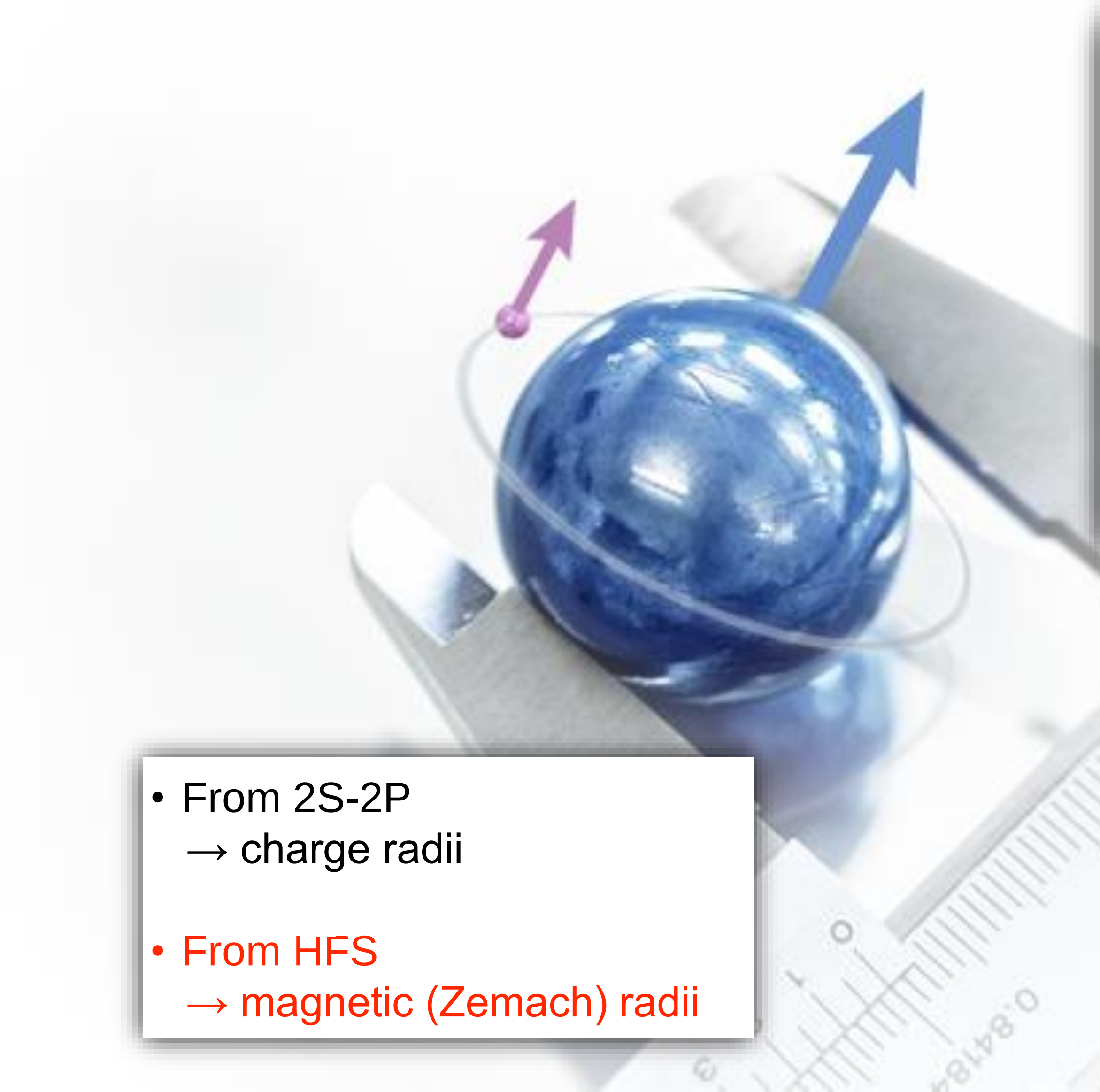
with
additional
support from

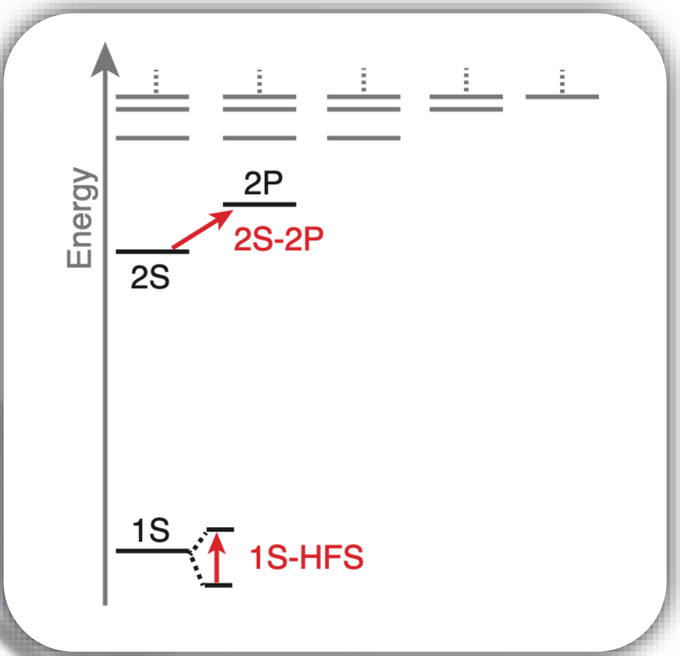
BSF
United States – Israel
Binational Science Foundation

PAUL SCHERRER INSTITUT
PSI

U.S. DEPARTMENT OF
ENERGY
Office of Science

The hyperfine splitting in μp





- 2S-2P μp
- 2S-2P μd
- 2S-2P μ^{3}He, μ^{4}He
- 1S-HFS μp

- From 2S-2P
  → charge radii

- From HFS
  → magnetic (Zemach) radii

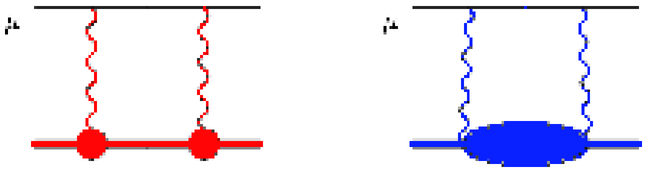
Courtesy: A. Antognini

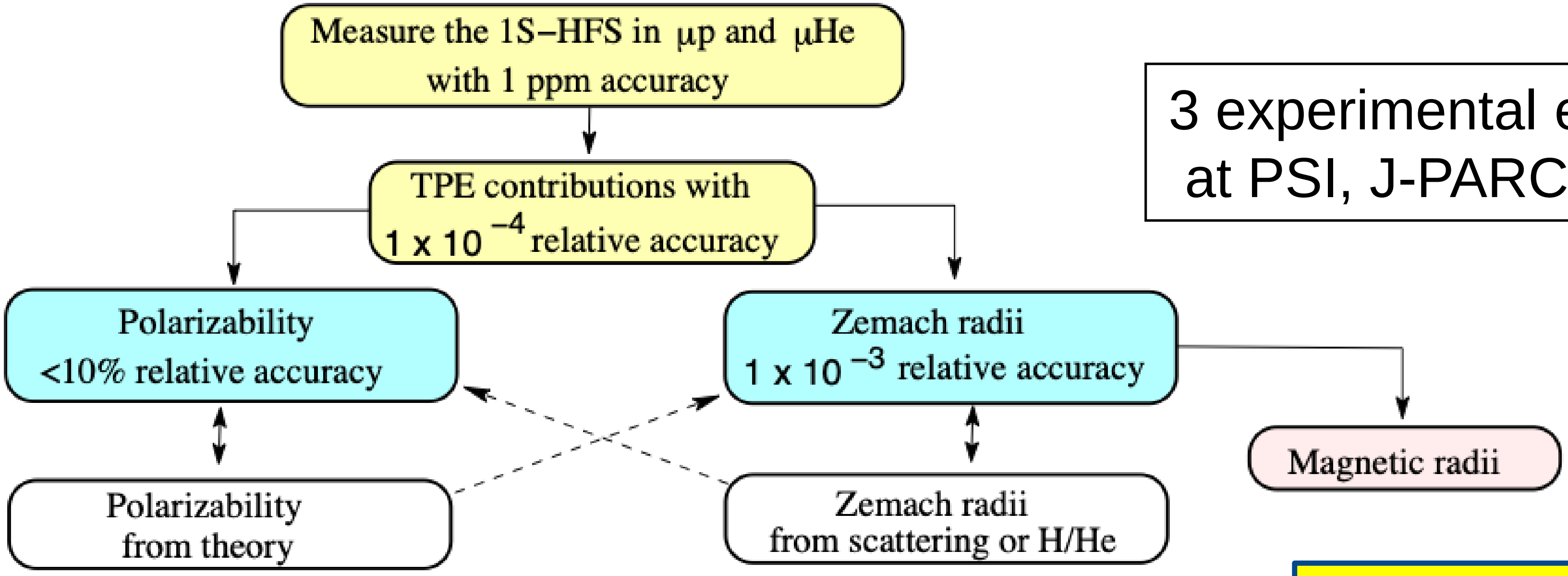
Hyperfine splitting theory and goals

Measure for the first time the 1S-HFS in μp and μHe+ and compare them with the theoretical predictions

$$\Delta E^{\rm th}_{\rm HFS} = 182.819(1) - \underbrace{1.301\,R_Z + 0.064(21)}_{\rm TPE}\ {\rm meV}$$

$$R_Z = \int d^3\vec{r}\,|\vec{r}| \int d^3\vec{r}'\,\rho_E(\vec{r}-\vec{r}')\,\rho_M(\vec{r}')$$





Measure the 1S–HFS in μp and μHe with 1 ppm accuracy

TPE contributions with 1×10^{-4} relative accuracy

Polarizability <10% relative accuracy

Zemach radii 1×10^{-3} relative accuracy

Polarizability from theory

Zemach radii from scattering or H/He

Magnetic radii

3 experimental efforts: at PSI, J-PARC, RAL

Courtesy: A. Antognini

New perspective on nucleon axial form factor

Nucleon axial radius and muonic hydrogen - a new analysis and review
R J Hill , P Kammel, W J Marciano and A Sirlin
Rep. Prog. Phys. **81** (2018) 096301

$$g_A(q^2) = g_A(0)(1 + \tfrac{1}{6} r_A^2 q^2 + \ldots)$$

2% for MuCap

- Nucleon axial radius r_A has surprisingly large uncertainty

$$r_A^2(z\ \mathrm{exp.}) = 0.46 \pm 0.22\ \mathrm{fm}^2 \qquad \nu_\mu d \to \mu^- pp$$

Phys.Rev. D93 113015, (2016)

  - basic nucleon property
  - doubles uncertainty in CCQE $\nu n \to p\mu$ cross section prediction (important for DUNE, T2HK)

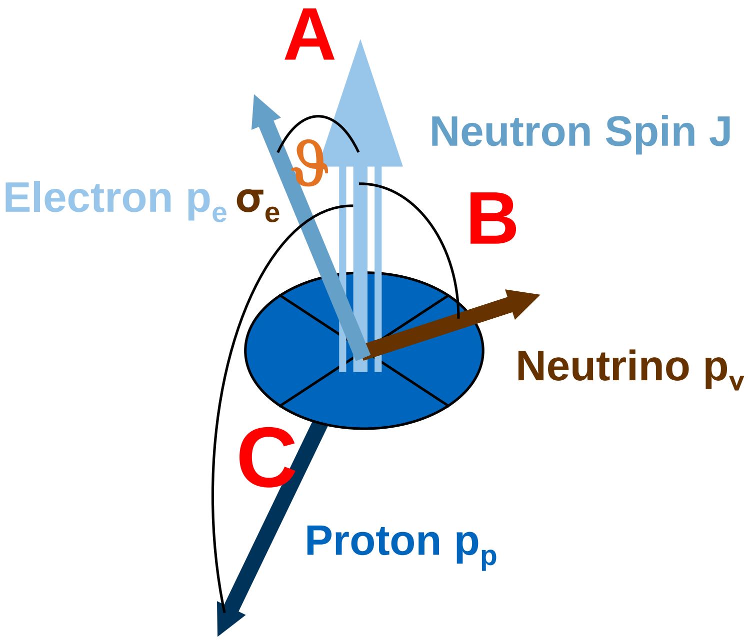
- Problem and opportunity for muon capture
  - Can g_P still be reliably extracted from MuCap?
  - Can one use MuCap to extract the axial radius?

Courtesy: P. Kammel

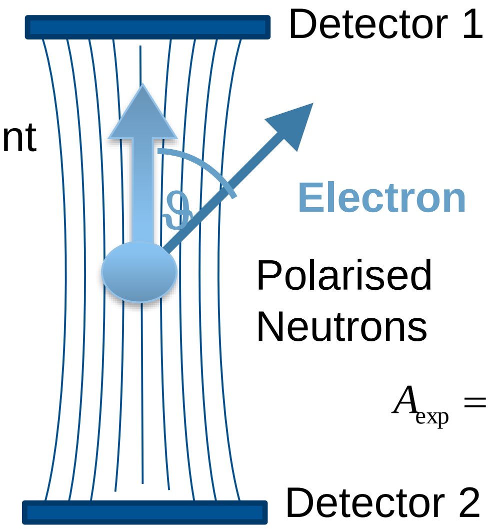
Axial Coupling from Neutron Decay

Determination of $\lambda = g_A/g_V$ from neutron decay via angular correlation coefficients: (typically) beta asymmetry *A*, or electron-neutrino correlation *a*

Beta Asymmetry: $A = -2\frac{\lambda^2+\lambda}{1-3\lambda^2}$



Very simple measurement principle:



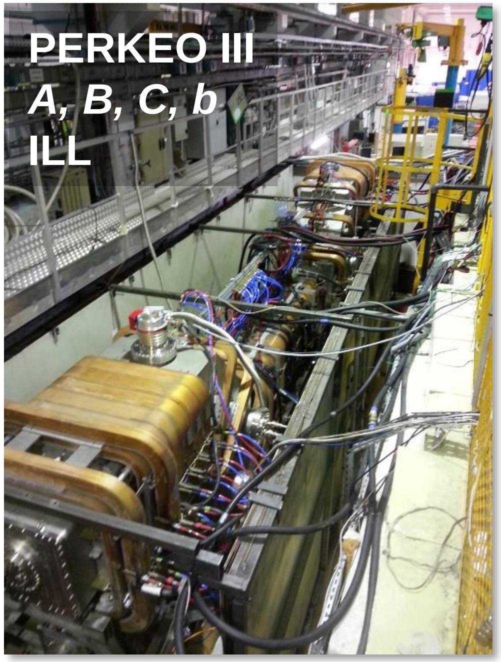
$$A_{\exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \tfrac{1}{2}\tfrac{v}{c} P A$$

Electron-Neutrino Correlation: $a = \frac{1-\lambda^2}{1-3\lambda^2}$

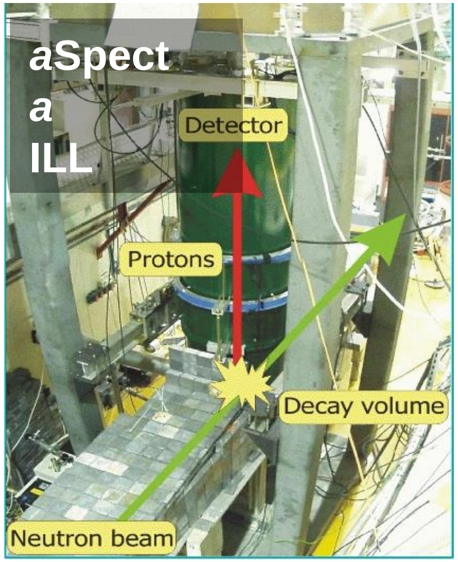
e.g. via proton spectrum

Courtesy: B. Märkisch

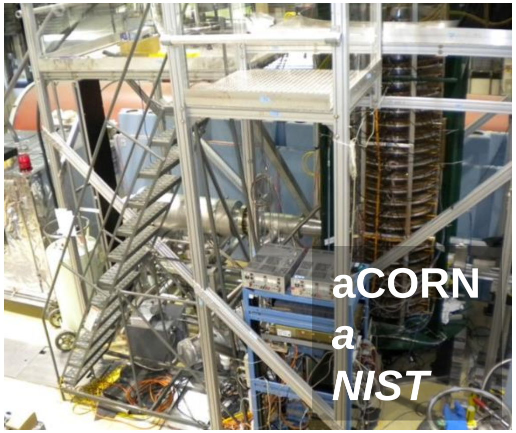
Neutron Decay Experiments



PERKEO III
A, B, C, b
ILL

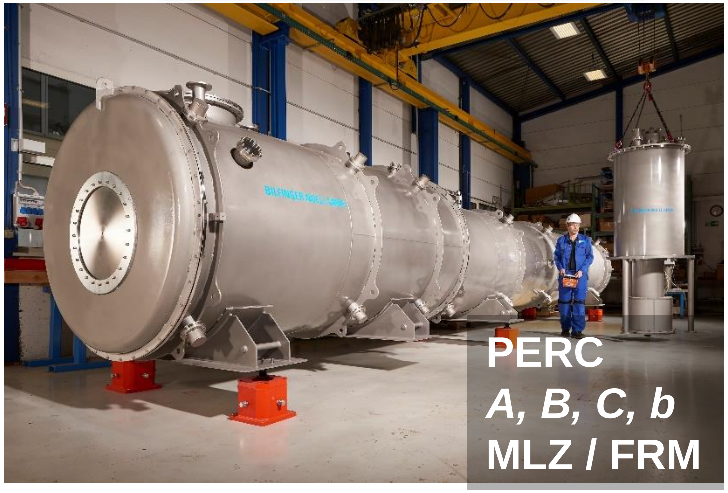


***a*Spect**
a
ILL



aCORN
a
NIST

Nab
a,b
SNS



PERC
A, B, C, b
MLZ / FRM

UCNA / UCNB
A, B, b
Los Alamos

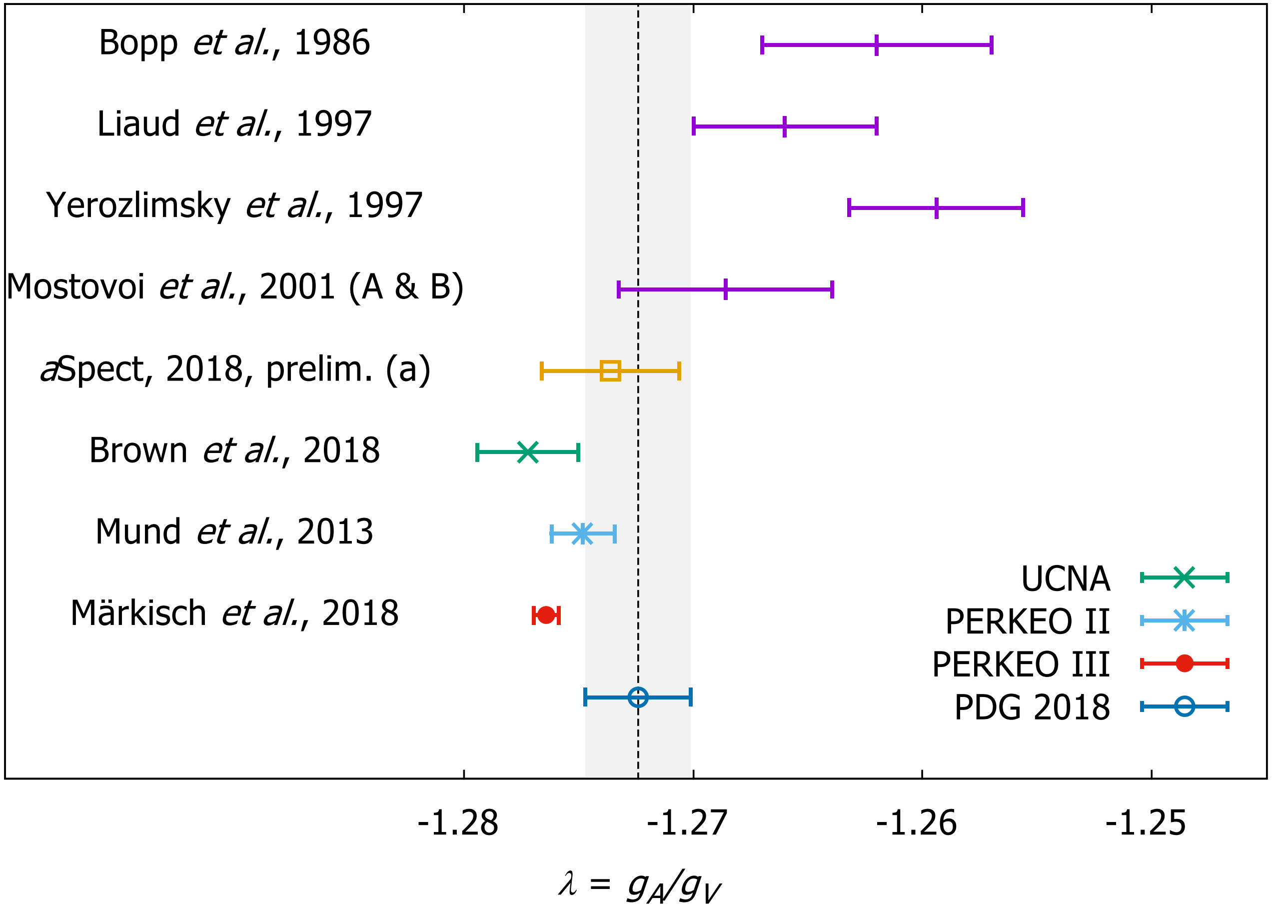
Courtesy: B. Märkisch

Axial Coupling: Status

New result by PERKEO III (arXiv:1812.04666): $\lambda = -1.27641(56)$, $\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$

UCNA and PERKEO III: blinded analysis.

All new measurements consistent.

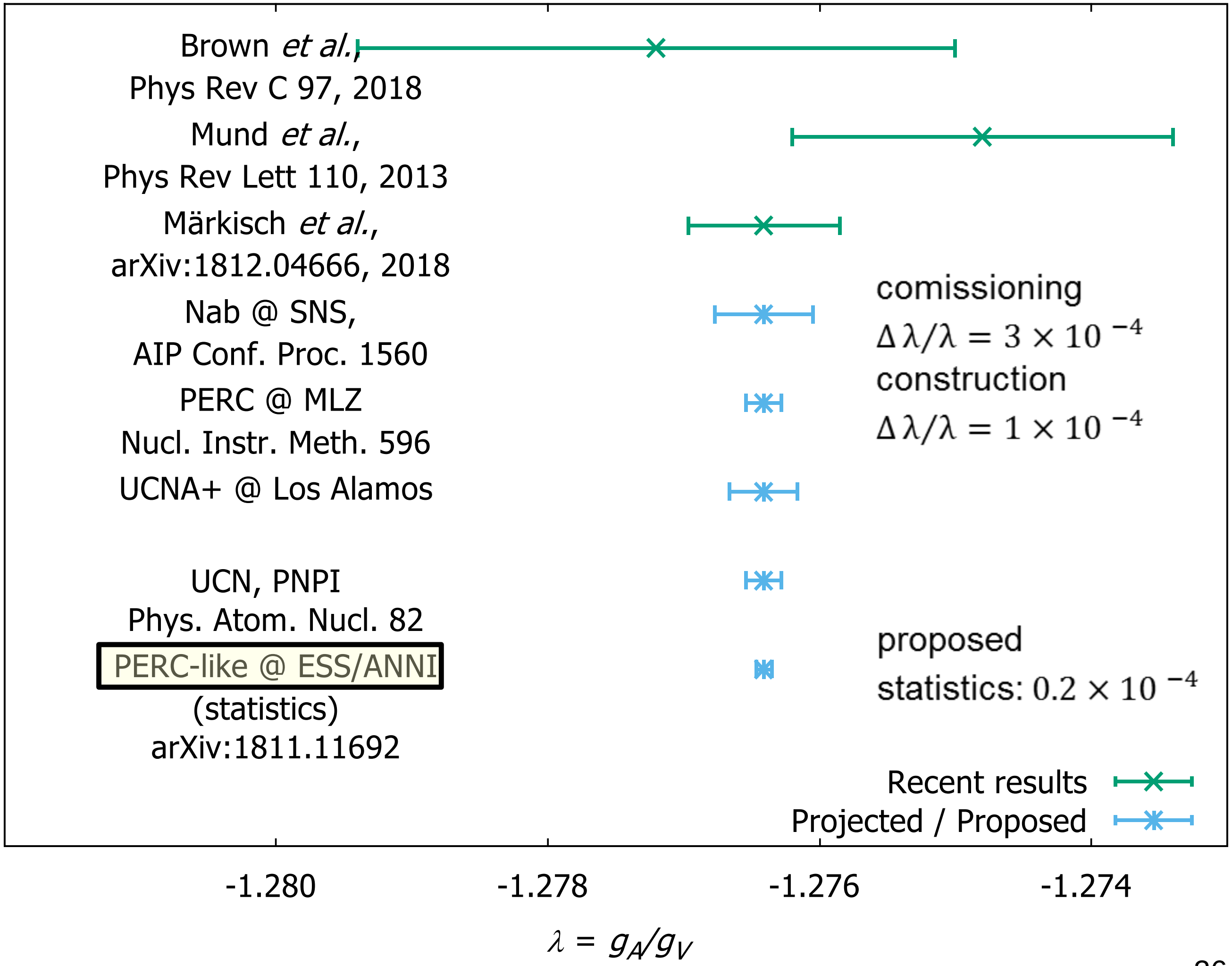


Courtesy: B. Märkisch

Axial Coupling: Prospects

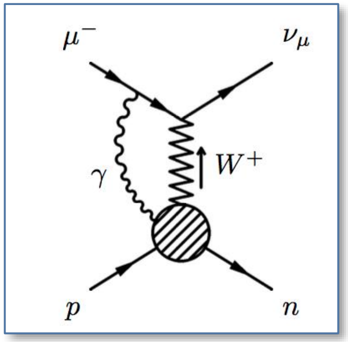
Strong efforts to improve: Goal $O(10^{-4})$ and below.

New beamlines and sources: FRM, Garching; SNS, Oak Ridge; ESS, Lund;



Courtesy: B. Märkisch

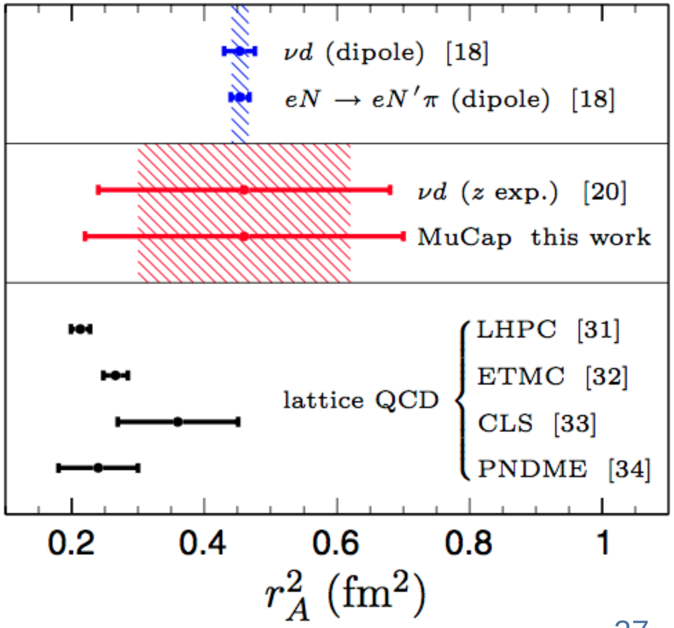
Axial Radius and Muon Capture Review



- Theory improvements
  - Theory uncertainties in Λ_S reduced to 0.2% level. (ignoring r_A^2 input uncertainty)
- g_P determination from muon capture
  - Δr_A^2 dominates uncertainty in g_A and g_P from theory.
  - MuCap still provides QCD test at 8% level: $g_P^{\text{theory}}/g_P^{\text{MuCap}} = 1.00(8)$
- r_A^2 determination from muon capture
  - Use EFT expression and $g_{\pi NN}$

$$\boxed{g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2)F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}g_a(0)m_\mu m_N r_A^2}$$

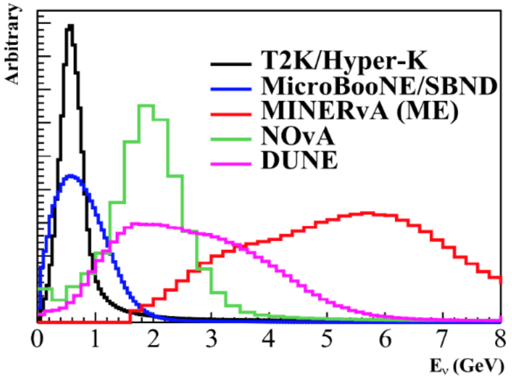
  - 0.3% future precision measurement of Λ_S would reduce
    - Δr_A^2 from 0.22 to 0.09 fm^2.
    - uncertainty in QE $\sigma(\nu d)$ by factor ~2.



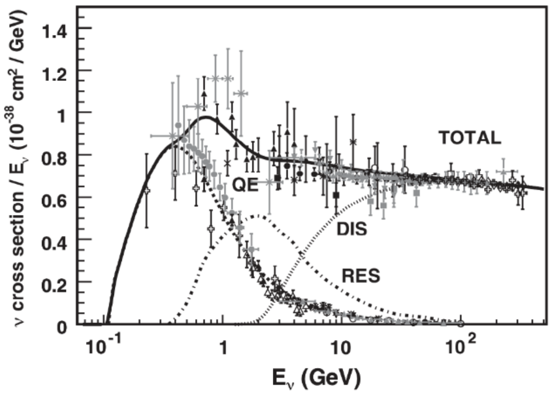
Courtesy: P. Kammel

Elementary targets for LBL experiments

- DUNE/T2HK

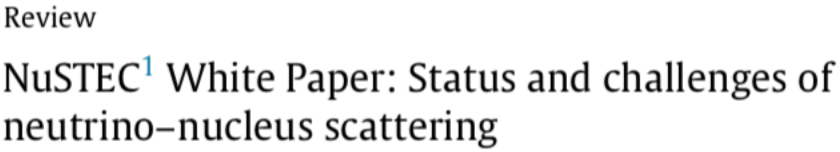


Katori and Martini, J. Phys. G: Nucl. Part. Phys. 45 (2018) 013001



Formaggio and Zeller, Rev.Mod.Phys. 84 (2012) 1307-1341

- Neutrino Scattering Theory Experiment Collaboration
  - http://nustec.fnal.gov


Review

NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

- INT Workshop INT-18-2a

  From nucleons to nuclei: enabling discovery for neutrinos, dark matter
  - Elementary neutrino-nucleon amplitudes
    - Study H_2/D_2 target option recommended by DUNE board

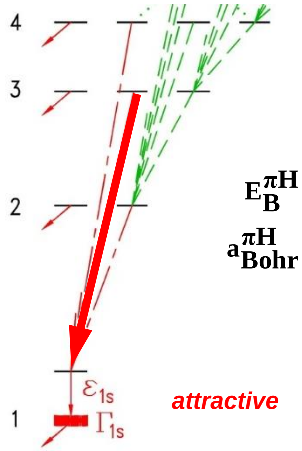
Courtesy: P. Kammel

QCD in basic hadronic interactions

- Scattering lengths, hadronic atoms
  - πp, πd
  - Kp, Kd
  - $\bar{p}p$ (→ backup)
- Hadronic weak interactions
  - The weak NN-potential is complementary to strong physics in hadronic and nuclear physics, and forms independent tests of both experimental nuclear reactions, and Lattice QCD calculations. (→ backup)

See talk by G. Schnell
covering DIRAC++

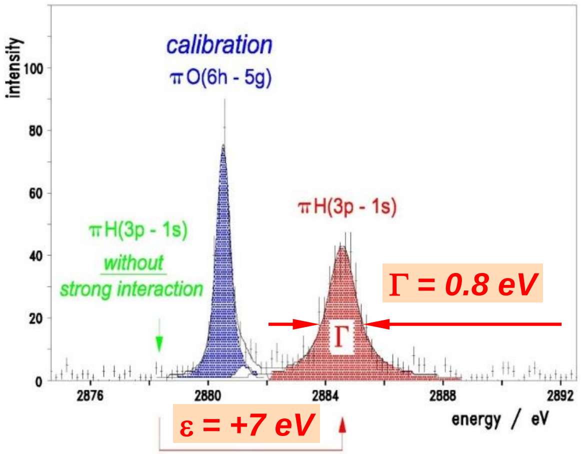
PIONIC HYDROGEN LEVEL SHIFT ε_{1S} and BROADENING Γ_{1S}



$E_B^{\pi H} = -3238$ eV

$a_{Bohr}^{\pi H} = 140$ fm

attractive



Γ = 0.8 eV

ε = +7 eV

measured X-ray lines

πH(2p-1s)

πH(3p-1s)

πH(4p-1s)

H_2 density 0.5% - 100% LH_2

only 2 independent scattering lengths a^+ *and* a^-

				Δ *experiment*	*Trueman correction*	χPT *
πH	*elastic scattering*	$\pi^- p \rightarrow \pi^- p$	$\varepsilon_{1s} \propto a^+ + a^-$ + …	± 0.2%	… ≈ 1%	+ (−9.0 ± 3.5)%
	charge exchange	$\pi^- p \rightarrow \pi^0 n$	$\Gamma_{1s} \propto (a^-)^2$ + …	± 2.6%	… ≈ 1%	+ (+0.5 ± 1.0)%
πD	*coherent sum*	$\pi^- p \rightarrow \pi^- p + \pi^- n$	$\varepsilon_{1s} \propto 2 \cdot a^+$ + …	± 1.3%	… ≈ 1%	+ ± 4%

* *J. Gasser et al., Phys. Rep. 456 (2008) 167*
M. Hoferichter et al., Phys. Lett. B 678 (2009) 65
V. Baru et al., Phys. Lett. B 694 (2011) 473

Courtesy: D. Gotta

πN ISOSPIN SCATTERING LENGTHS a^+ and a^-

Δ exp (*Coulomb de-excitation*) ≈ 3 × Δ theory

Δ exp << Δ theory

Δ exp << Δ theory

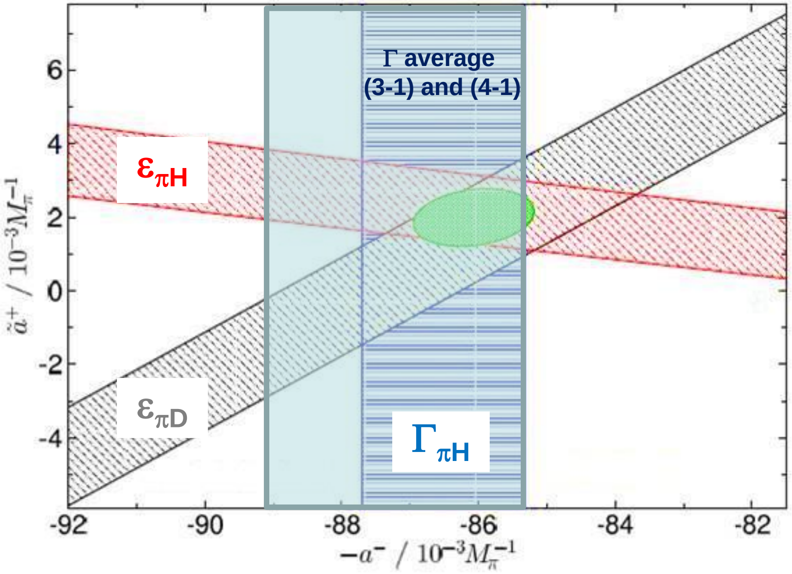


FIG. 2: Combined constraints in the $\tilde{a}^+ - a^-$ plane from data on the width and energy shift of πH, as well as the πD energy shift.

χPT: J. Gasser et al., Phys. Rep. 456 (2008) 167
M. Hoferichter et al., Phys. Lett. B 678 (2009) 65
V. Baru et al., Phys. Lett. B 694 (2011) 473
data: πH - R-98.01 : D. Gotta et al., Lect. Notes Phys. 745 (2008) 165
M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190
πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88

- consistency ✓
- $\varepsilon_{\pi D}$ decisive constraint
- $a^+ > 0$!

***large discrepancy* between**
pionic-atoms analysis
and
$a^+ = -15 \cdot 10^{-3} M_\pi^{-1}$ from lattice σ – term

Hoferichter et al. , arXiv: 1602.07688v2
Crivellin et al., Phys. Rev. D 89, 054021 (2014)
Ellis et al., Phys. Rev D,065026 (2008)
…

Outlook

- high statistics experiment of πH(4-1) and πH(5-1) lines:
less Coulomb de-excitation

ΔΓ/Γ 3% → 1%

Courtesy: D. Gotta

πN ISOSPIN SCATTERING LENGTHS a^+ and a^-

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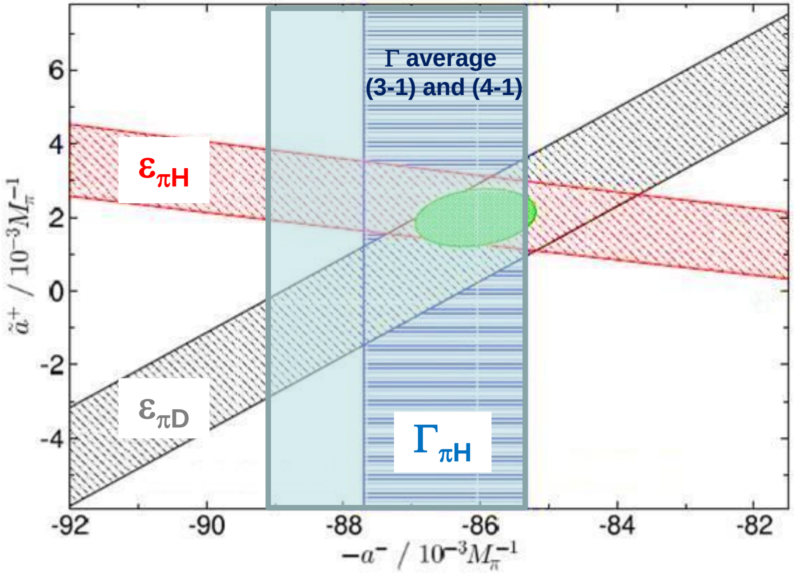

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Courtesy: D. Gotta

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Hoferichter et al. , arXiv: 1602.07688v2
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Ellis et al., Phys. Rev D,065026 (2008)
…

Outlook

- high statistics experiment of πH(4-1) and πH(5-1) lines:
less Coulomb de-excitation

$\Delta\Gamma/\Gamma$ 3% → 1%

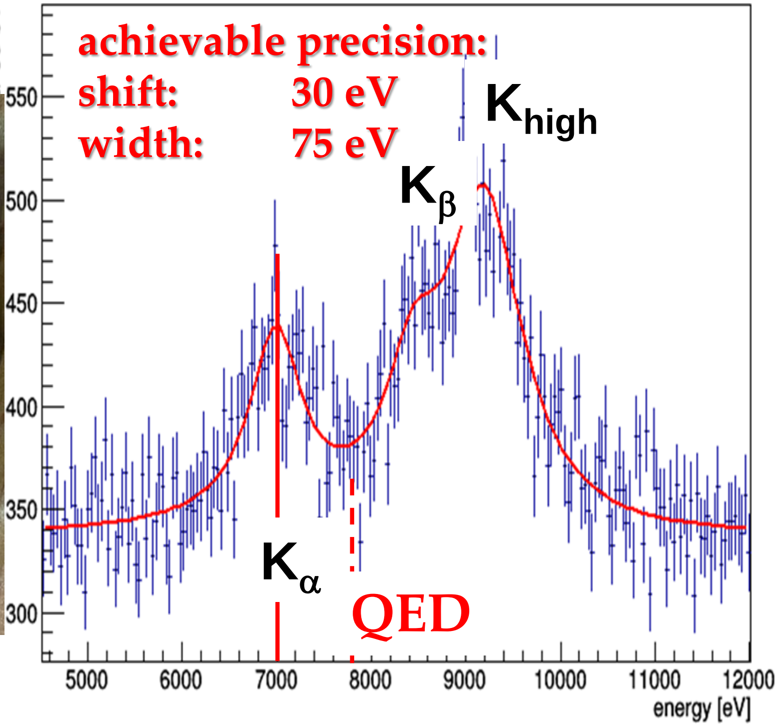
*precise knowledge of the πN σ-term is important for many experiments from DM direct detection to μ→e conversion

Exotic atoms at DAΦNE

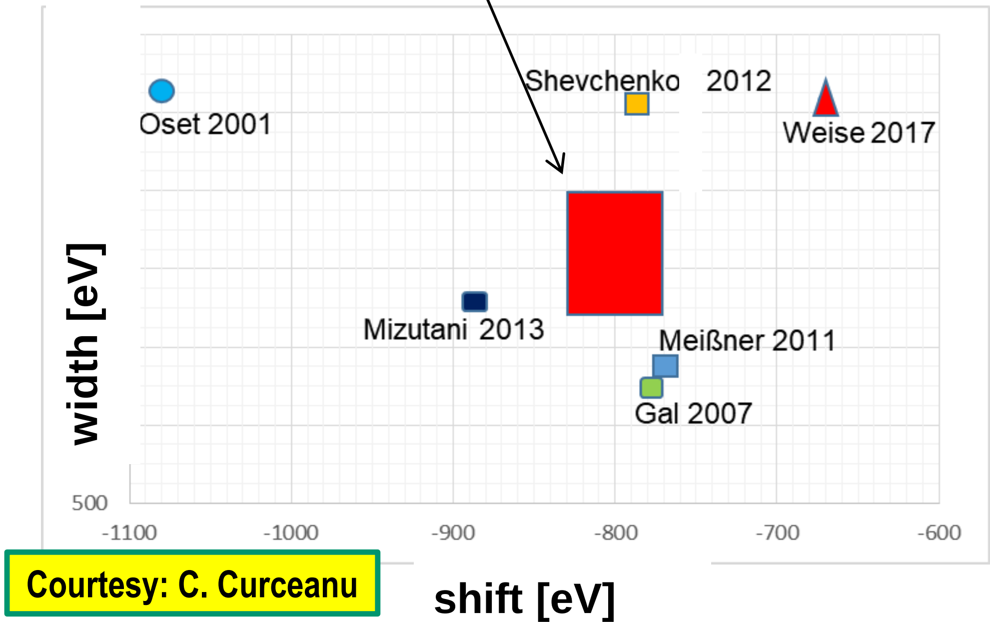
SIDDHARTA-2 experiment:

***Kaonic deuterium in 2019-2020*:**

800 pb^{-1} **to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as K$^-$p) with new SDD detectors**



Theories and SIDDHARTA-2 precision



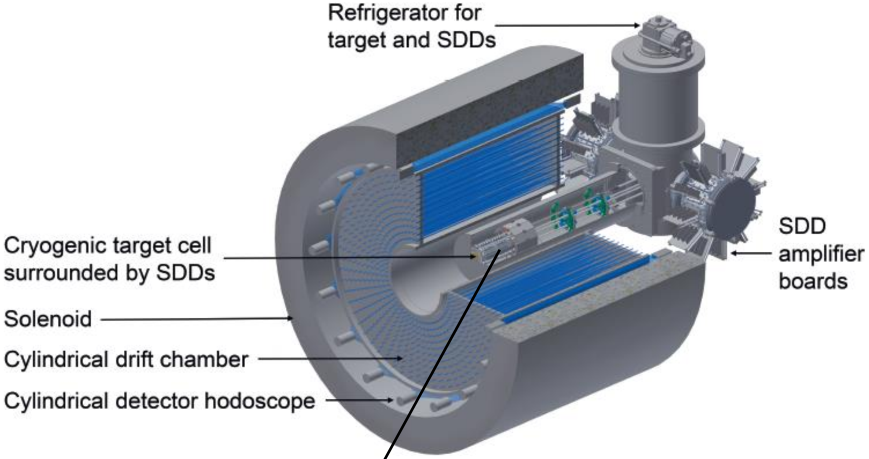
Courtesy: C. Curceanu

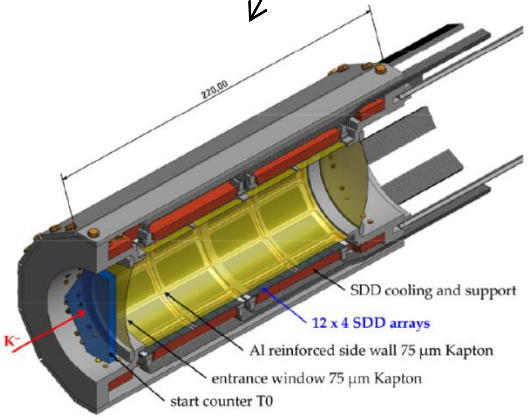
Exotic atoms at J-PARC

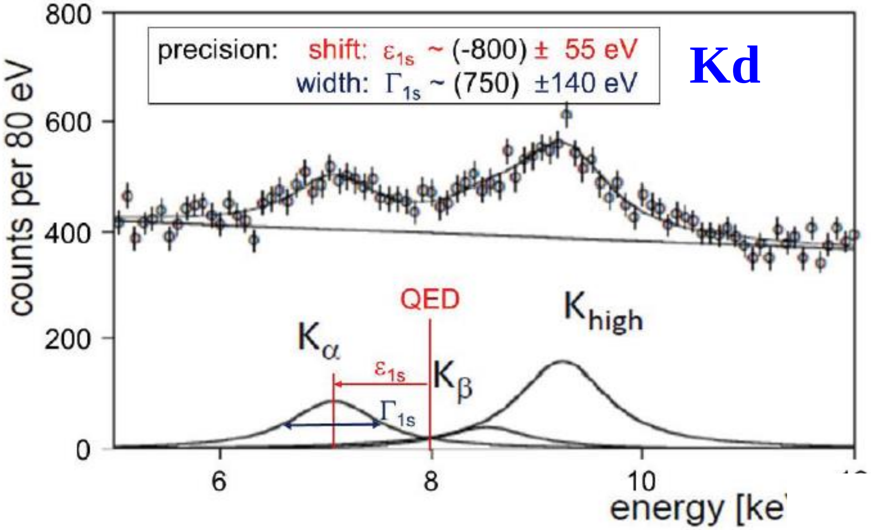
E57 experiment:

Kaonic deuterium in 2020:

to perform the measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state with new SDD detectors and different background sources than SIDDHARTA-2





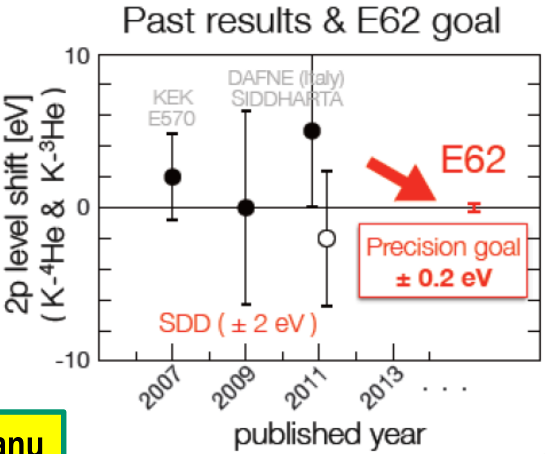


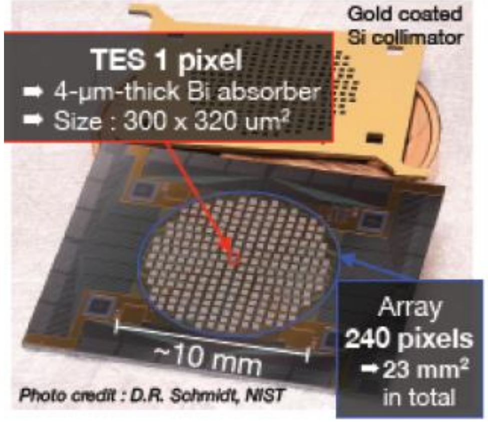
E62 experiment:

Kaonic helium3 and 4 in 2018:

the ultra-high precision measurement of the strong interaction induced energy shift and width of the kaonic helium3 and 4 2p –level with novel TES detectors (PTEP 2016, 091D01)

Courtesy: C. Curceanu





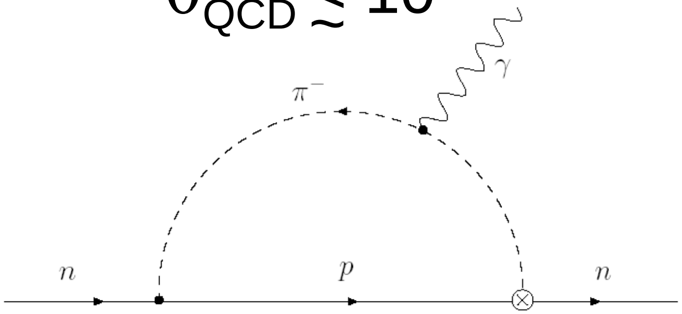
QCD and EDM

The strong CP problem

$$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + g^2/(32\pi^2)\ \theta_{QCD} G\tilde{G}$$

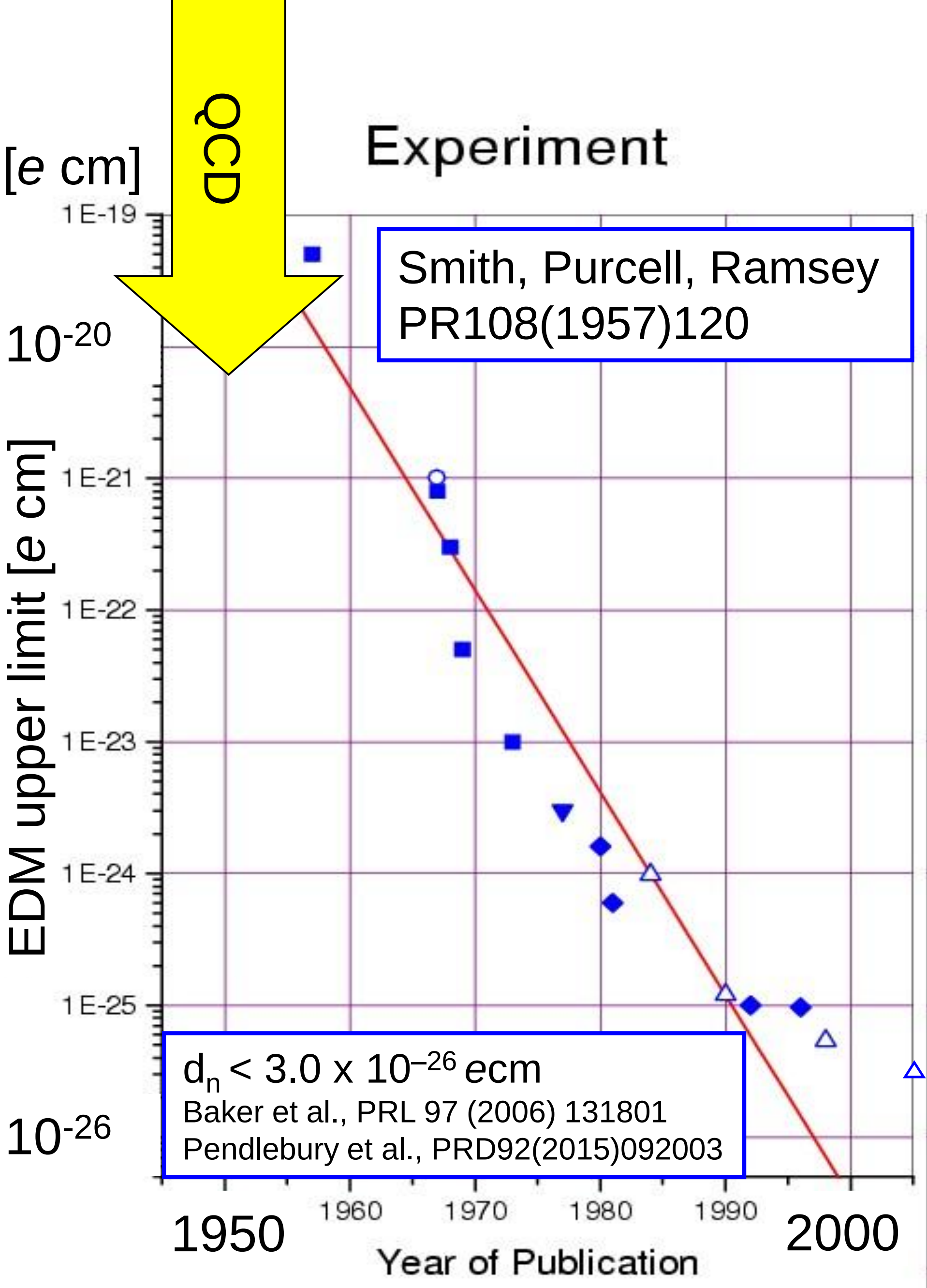
$$d_n \approx 10^{-16}\ e\ \mathrm{cm} \cdot \theta_{QCD}$$

$$\theta_{QCD} \lesssim 10^{-10}$$



Why is θ_{QCD} so small ?

Together, n and p EDM could test QCD origin. Lattice calculations progressing but difficult.



Smith, Purcell, Ramsey
PR108(1957)120

$d_n < 3.0 \times 10^{-26}$ ecm
Baker et al., PRL 97 (2006) 131801
Pendlebury et al., PRD92(2015)092003

Concluding remarks I

- Strong interaction between theory and low energy experiments needed
- Support next generation facilities (2022-30) in Europe, in particular
  - New high intensity e^- machines like PRAE and MESA
  - Cold neutron beam for particle physics at ESS
  - Higher intensity sources of UCN: ILL, PSI, FRM2, PNPI
  - Proton EDM demonstrator storage ring
  - Facilities with slow antiprotons, pions, kaons
  - New High intensity Muon Beam HiMB at PSI

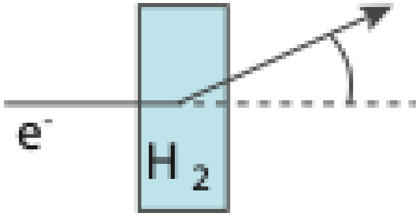
Concluding remarks II

- Diverse university/national/international facilities
- Multiple physics aspects involved in experimental project
- Tackling hot topics in particle physics with unique reach
- Small to mid-size collaborations in which young scientists can assume responsibility and excell
- Perfect environment for broad particle physics education
- Complementing huge multi-decade-long efforts
- Development of a variety of technologies
- Interfaces to other fields, especially nuclear, astroparticle and atomic physics

Backup

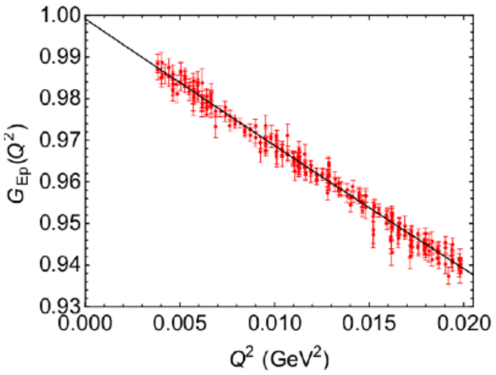
The proton radius puzzle

e-p scattering at low Q2

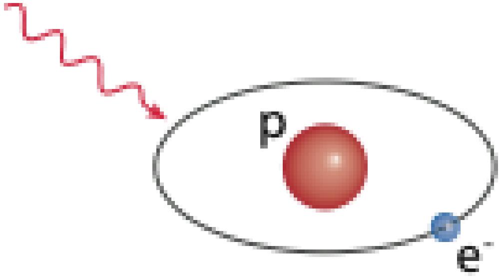


- measure elastic σ with 1% acc.
- Statistics: ok
- Challenge: small sensitivity
- Challenge: extrapolation to Q2=0

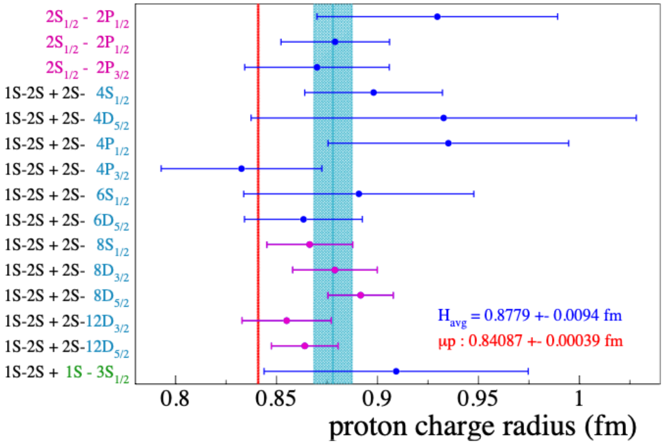
$$r_p^2 = -6\frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=}$$



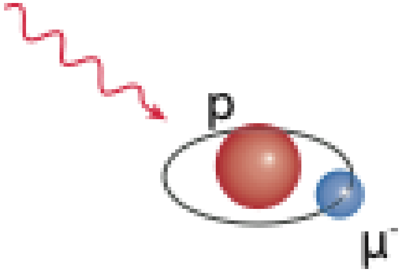
Laser spectroscopy in H



- 4σ discrepancy only with least square adjustment
- High-precision laser spectroscopy
- Challenge: systematic effects for large n-states



Laser spectroscopy in μp



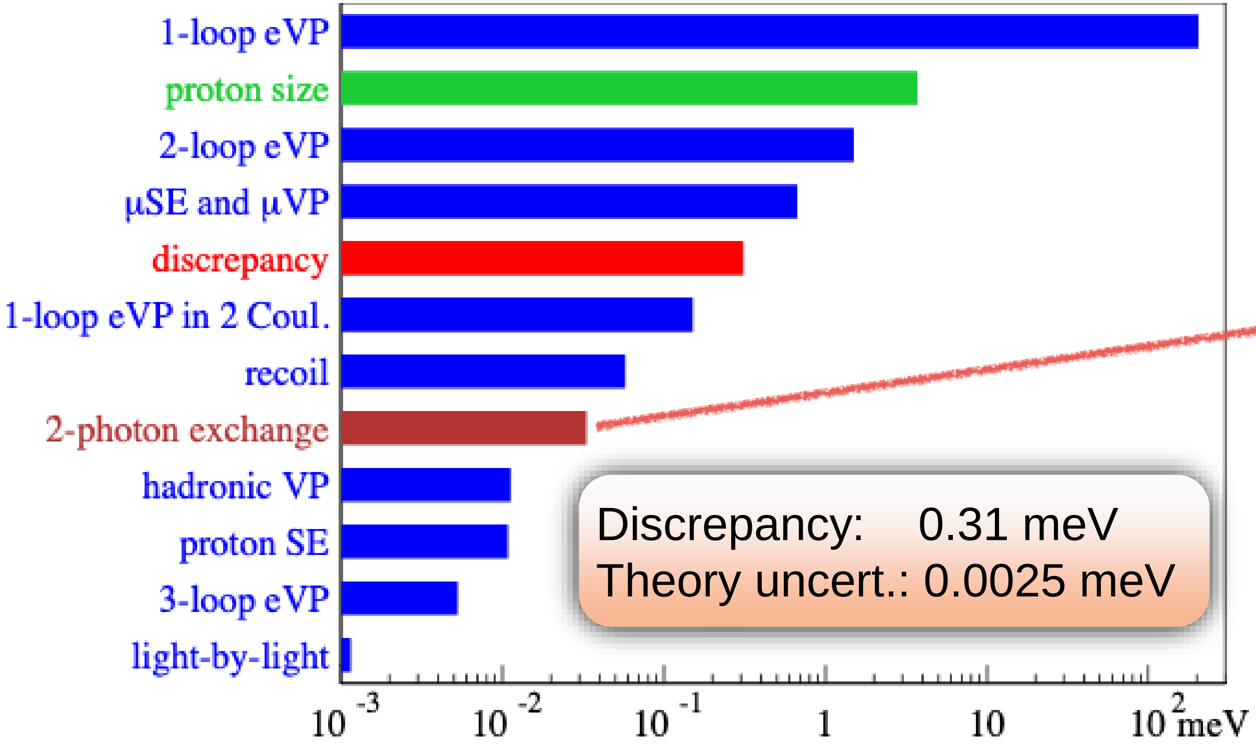
$$\Delta E_{\text{size}} = \frac{2\pi(Z\alpha)}{3}\, r_p^2\, |\Psi_{nl}(0)|^2 = \frac{2(Z\alpha)^4}{3n^3} m_r^3\, r_p^2\, \delta_{l0}$$

- High sensitivity to proton radius
- Challenge: statistics (laser power, muon rates)

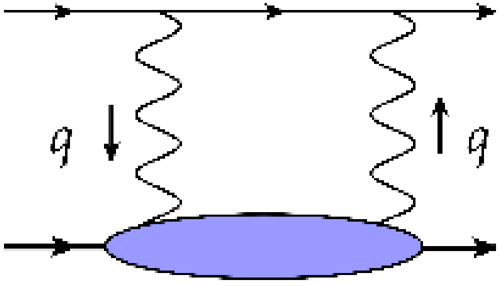
Courtesy: A. Antognini

Why is the μp theory reliable?

$$\Delta E^{\mathrm{th}}_{2P-2S} = 206.0336(15) - 5.2275(10)\, r_{\mathrm{p}}^2 + 0.0332(20) \quad [\mathrm{meV}]$$



Discrepancy: 0.31 meV
Theory uncert.: 0.0025 meV



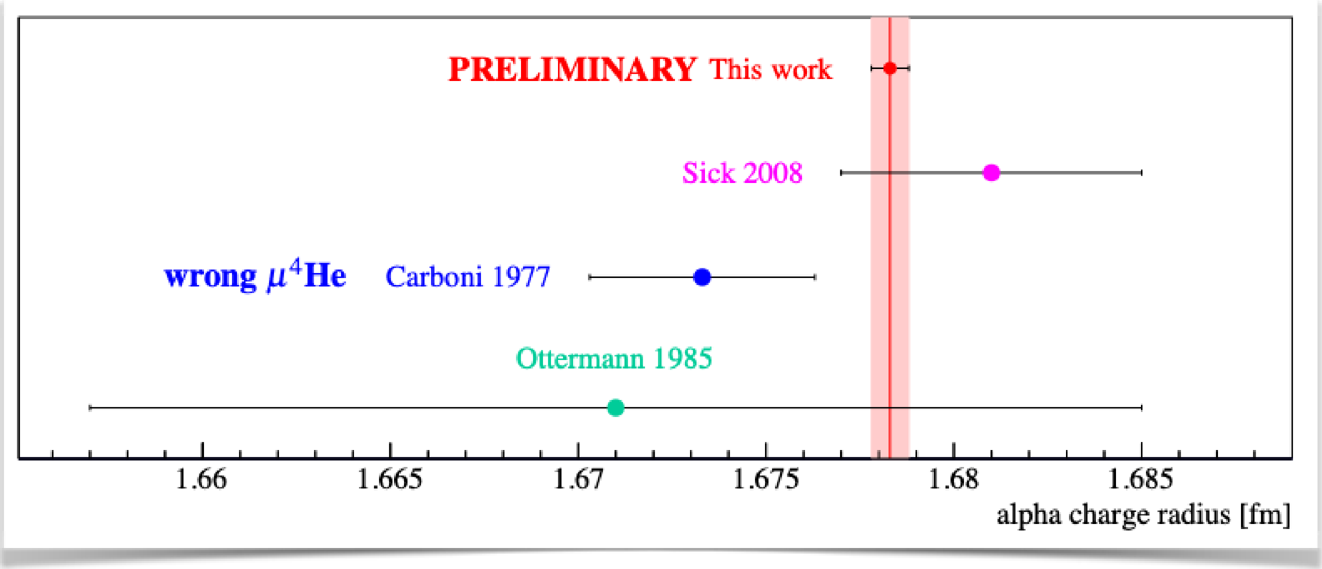
Pachucki, Carlson, Birse, McGovern, Pineda, Gorchtein, Pascalutsa, Vanderhaeghen, Alarcon, Miller, Paz, Hill…

Pachucki, Borie, Eides, Karschenboim, Jentschura, Martynenko, Indelicato Pineda, Miller, Karrol…

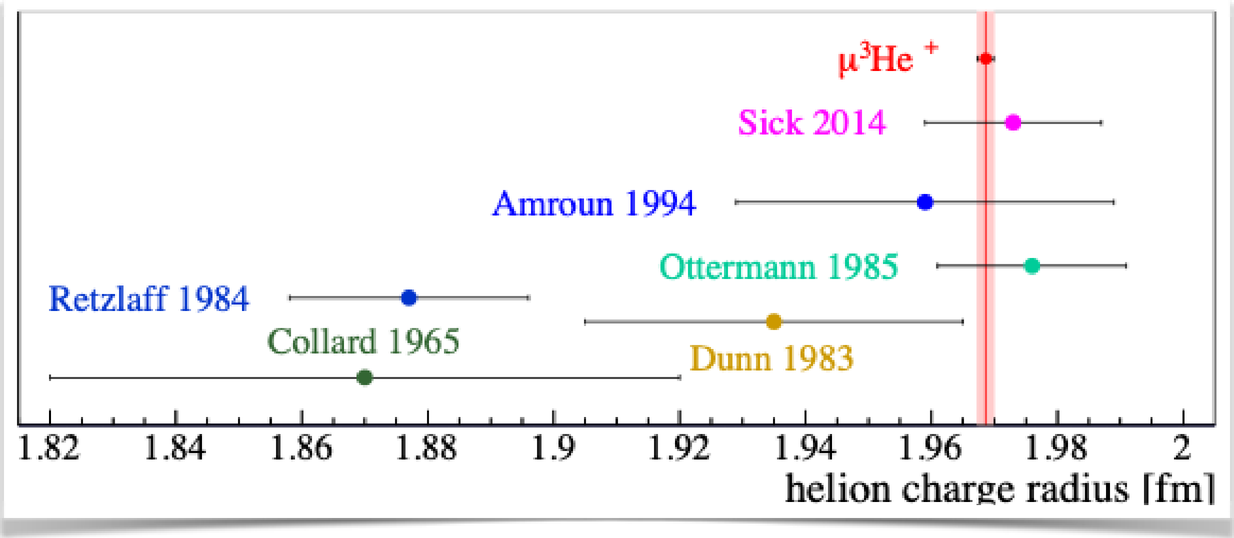
Hill, Paz, arXiv:1611.09917
Birse, McGovern, arXiv1206.3030
Hagelstein et al., arXiv:1512.03765
Peset and Pineda, arXiv:1406.4524

Courtesy: A. Antognini

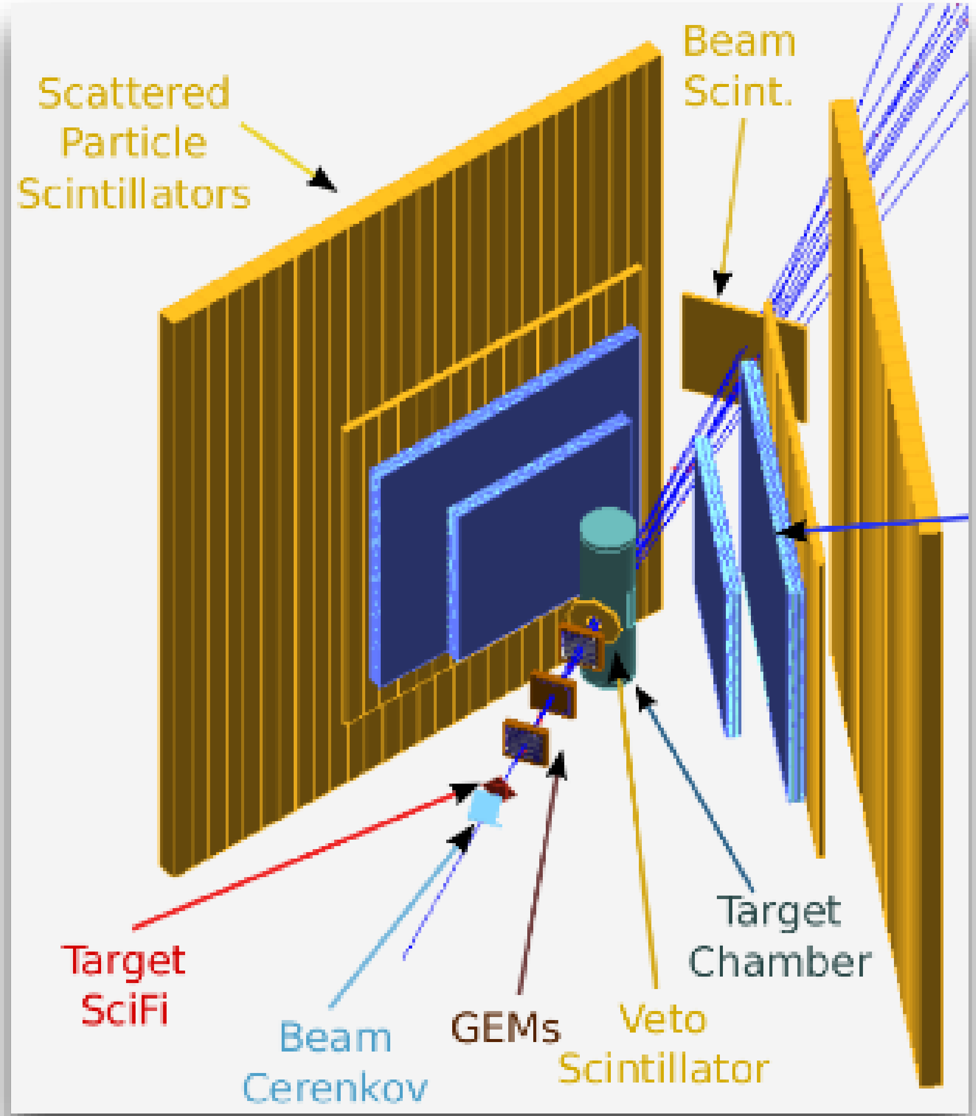
Alpha-particle and helion radii from μHe⁺ spectroscopy



Extraction of these charge radii from muonic helium is limited by the polarisability contributions.



MUSE: Muon scattering (ongoing at PSI)

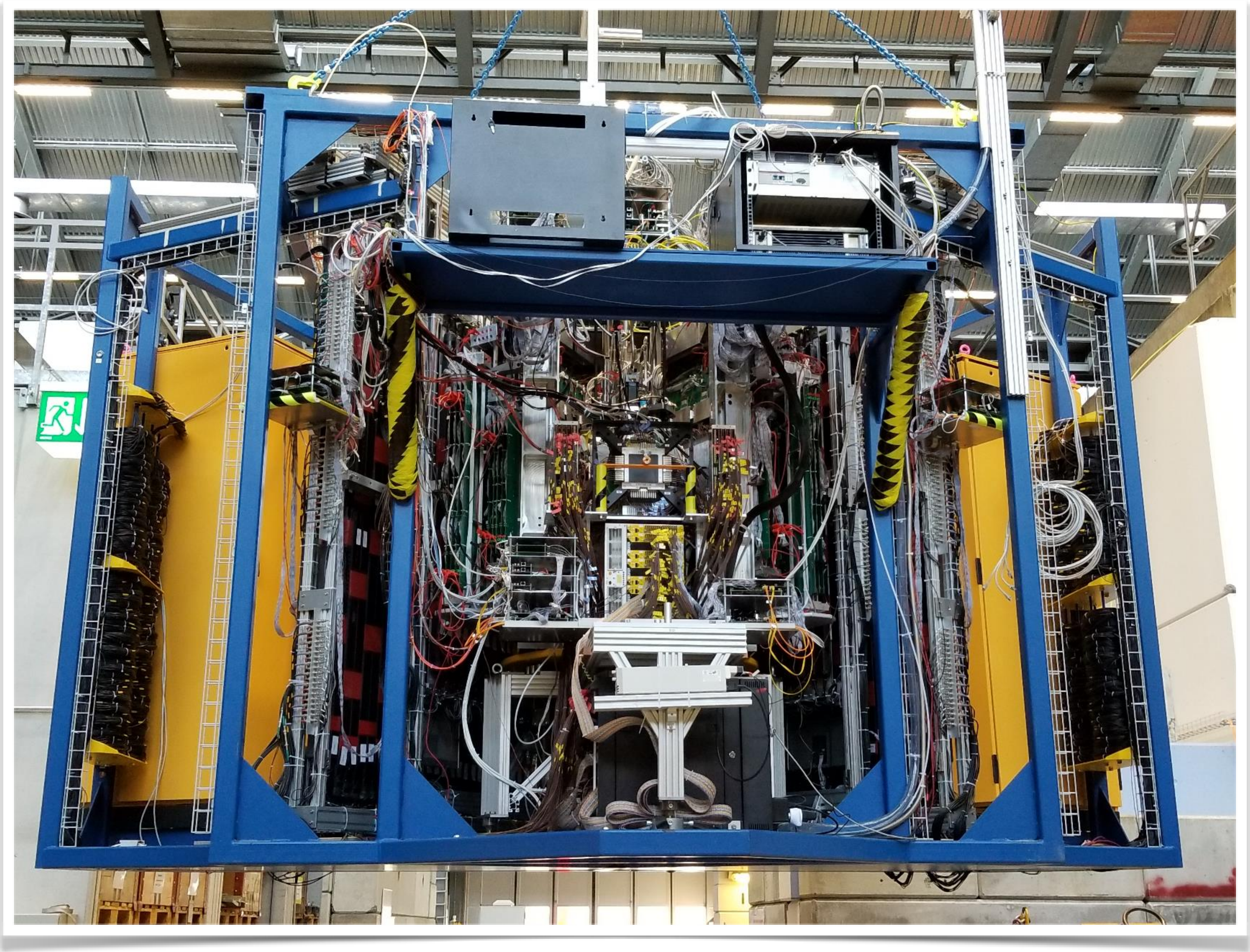


MUSE at PSI

- $\mu^{\pm}$-p, $e^{\pm}$-p scattering down to $Q^2_{min} = 2\times10^{-3}$ GeV^2
- Common uncertainties ⇨ precise $\Delta r = r_p^{\mu} - r_p^{e}$
- test μ-e universality
- measure TPE

arXiv:1709.09753

MUSE: an impressive setup ready to go

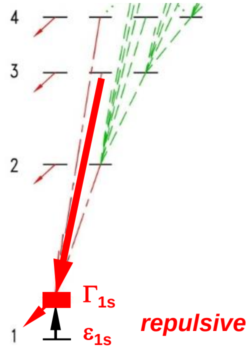


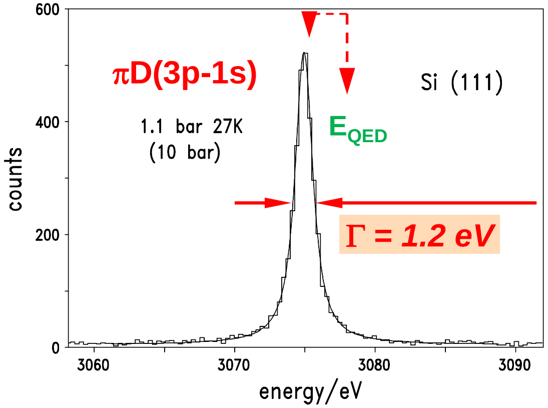
MUSE Notes

Courtesy: E. Downie

- All detector and DAQ components installed on experiment platform. All detector systems read out in < 100 µs.
- Five planes of the **beam hodoscope** to identify beam particle types. Time resolution up to 80 ps with ~ 99.8% efficiency.
- **GEM detectors** determine incident particle tracks with ~ 98% efficiency and < 100 µm resolution.
- **Cryotarget** fully operational. Hydrogen temperature stable to ~ ±0.01 K.
- **Straw-tube tracker** operated with low noise using PASTTREC cards for readout. Determines outgoing tracks with 99.9% tracking efficiency and ~ 150 µm position resolution.
- **Scattered Particle Scintillator walls** commissioned with average time resolutions ~ 45 ps and 55 ps for the rear and front walls, respectively.
- **Beam monitor** scintillators commissioned with up to 30 ps time resolution.

NN ⇔ πNN threshold parameter α



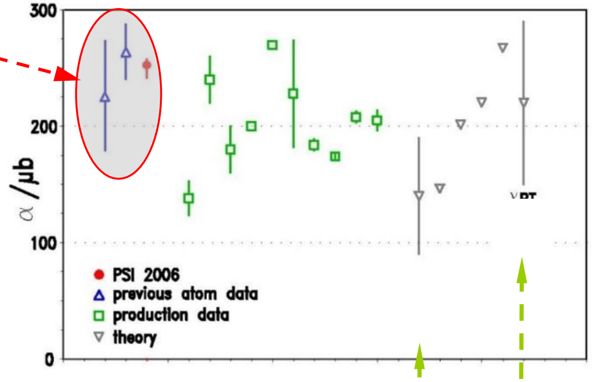


Th. Strauch et al.,
Phys.Rev.Lett.104 (2010)142503; Eur.J.Phys.47 (2011)88

exotic-atom results

earlier πD-atom results

new PSI result



charge symmety | *detailed balance (T invariance)*

$$\sigma_{\pi^- d \to nn} \leftrightarrow \sigma_{\pi^+ d \to pp} \leftrightarrow \sigma_{pp \to \pi^+ d}$$

<u>only</u> 1 parameter α

πD *„true" absorption* $\pi^- d \to nn$ $\Gamma_{1s} \propto \alpha + \ldots$

Δ experiment
+ 2%
– 4%

χPT

at present
Δα/α ≈ 30%

→ few % !?

χPT NLO

χPT LO

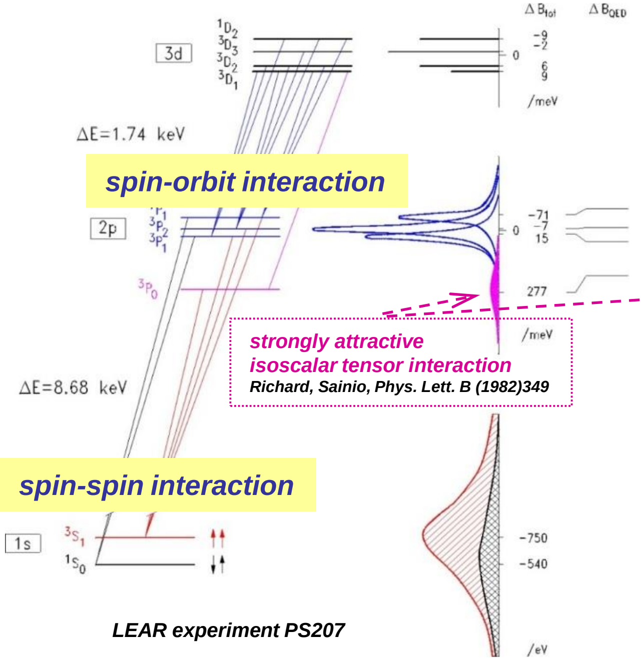
V. Lensky et al.,
Eur. Phys. J. A 27 (2006) 37

Outlook

- **high statistics experiment** $\Delta\Gamma/\Gamma \to 1\%$
- *theoretical progress needed*

Courtesy: D. Gotta

PROTONIUM - SEARCH for HFS



spin-orbit interaction

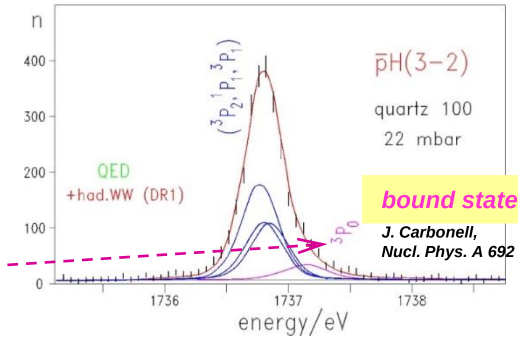
strongly attractive
isoscalar tensor interaction
Richard, Sainio, Phys. Lett. B (1982)349

spin-spin interaction

LEAR experiment PS207

M. Augsburger et al., Nucl. Phys. A 658 (1999) 149
D. Gotta et al., Nucl. Phys. A 660 (1999) 283

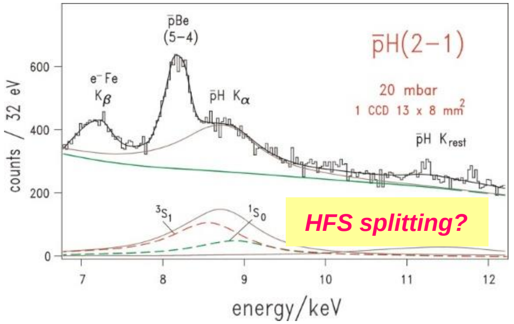
cyclotron trap + crystal spectrometer



bound states ?

J. Carbonell,
Nucl. Phys. A 692 (2001) 11

cyclotron trap + MOS CCD



HFS splitting?

Outlook

- **2p state:**
  better resolution
  factor of 2 possible

- **1s state:**
  much higher statisctics
  lower background
  fast read-out CCDs

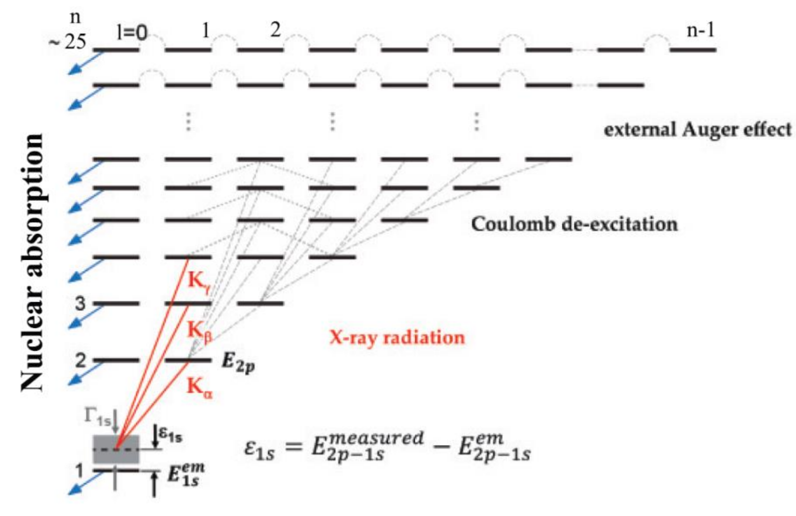
- ***mandatory:***
  ≥ LEAR-type beams

Courtesy: D. Gotta

Kaonic atoms spectroscopy: overview and perspectives

Kaonic atoms are fundamental tools for studying the QCD with strangeness in non-perturbative regime, to investigate:

- **Explicit and spontaneous chiral symmetry breaking**
- **Role of strangeness in Neutron Stars (EOS)**



Kaonic atom cascade to the fundamental level where the strong interaction shifts and broadens the level -> measured by X ray spectroscopy

Kaonic atoms research is being performed at:

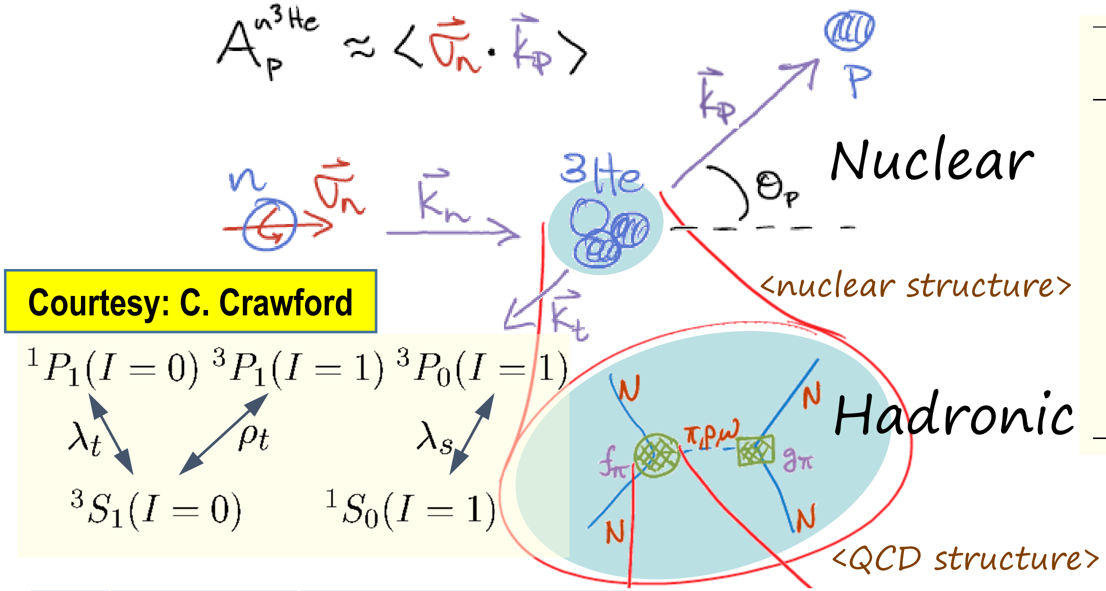
- **DAΦNE collider at LNF-INFN (Italy): SIDDHARTA, SIDDHARTA-2 experiments**
- **J-PARC in Japan: E57 and E62 experiments**

SIDDHARTA performed the most precise measurement of kaonic hydrogen: Phys. Lett. B704 (2011), 113; of kaonic helium-3 and -4, Phys. Lett. B 681 (2009), 310, Phys. Lett. B 697(2011) 19, Eur.Phys.J. A50 (2014) 91

Courtesy: C. Curceanu

Hadronic Weak Interaction

Courtesy: C. Crawford



$^1P_1(I=0)$ $^3P_1(I=1)$ $^3P_0(I=1)$

λ_t ρ_t λ_s

$^3S_1(I=0)$ $^1S_0(I=1)$

Coeff	DDH
$\Lambda_{0\ DDH}^{^1S_0-^3P_0}$	$-g_\rho h_\rho^0(2+\chi_V) - g_\omega h_\omega^0(2+\chi_S)$
$\Lambda_{0\ DDH}^{^3S_1-^1P_1}$	$g_\omega h_\omega^0 \chi_S - 3 g_\rho h_\rho^0 \chi_V$
$\Lambda_{1\ DDH}^{^1S_0-^3P_0}$	$-g_\rho h_\rho^1(2+\chi_V) - g_\omega h_\omega^1(2+\chi_S)$
$\Lambda_{1\ DDH}^{^3S_1-^3P_1}$	$\frac{1}{\sqrt{2}} g_{\pi NN} h_\pi^1 \left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$
$\Lambda_{2\ DDH}^{^1S_0-^3P_0}$	$-g_\rho h_\rho^2(2+\chi_V)$

C.-P. Liu, P.R.C. 75, 065501 (2007)
Haxton, Holstein, PPNP 7,1851(2013)

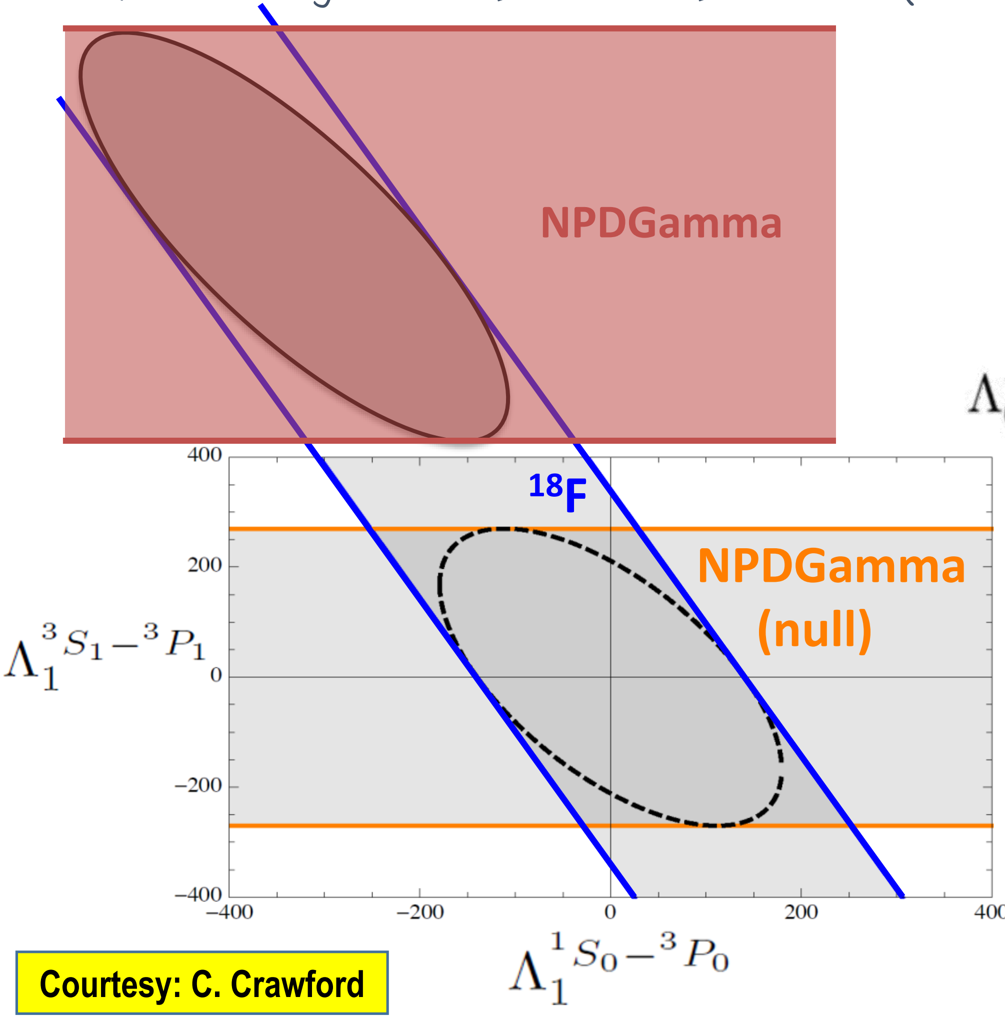
A	Obs	Result (10^{-7}) *		$\Lambda_0^{S_0^1-P_0^3}$	$\Lambda_1^{S_0^1-P_0^3}$	$\Lambda_2^{S_0^1-P_0^3}$	$\Lambda_0^{S_1^3-P_1^1}$	$\Lambda_1^{S_1^3-P_1^3}$	Improvement	
2	A_L^{pp}	419	± 43 *	1	1	0.4088			4	$\vec{p}$ ring
	A_γ^{np}	-0.3	± 0.14					-3.70E-04	**4**	**ESS**
	P_γ^{np}	1.8	± 1.8	-0.00012		0.00154	0.00105		**9**	**ILL/ESS**
	$d\phi/dz^{np}$	—	—	0.015		0.016		-0.011	∞	NG-C/**ESS**
3	A_L^{pd}	-0.35	± 0.85	-0.001	-0.0007	-0.0002	-0.0008		4	$\vec{p}$ ring
	A_γ^{nd}	78	± 34	0.0139	-0.0055	-0.0035	0.0037	0.0024	**22-35**	**ILL/ESS**
4	$A_p^{n^3He}$	0.117	± 0.093	7.18E-04	-2.25E-03	6.26E-05	-4.68E-04	-6.24E-04	**4**	**ESS**
5	$A_L^{p\alpha}$	-3.3	± 0.9	-0.00355	-0.00317		-0.00268	-0.00114	4	$\vec{p}$ ring
	$d\phi/dz^{n\alpha}$	1.7	± 9.1	0.0138	-0.0087		0.0033	-0.0033	**9-16**	NG-C/**ESS**
18	P_γ^{18F}	0	± 5100		36.3			15		
19	A_γ^{19F}	-740	± 190	-1.12	-0.75		-0.48	-0.32		

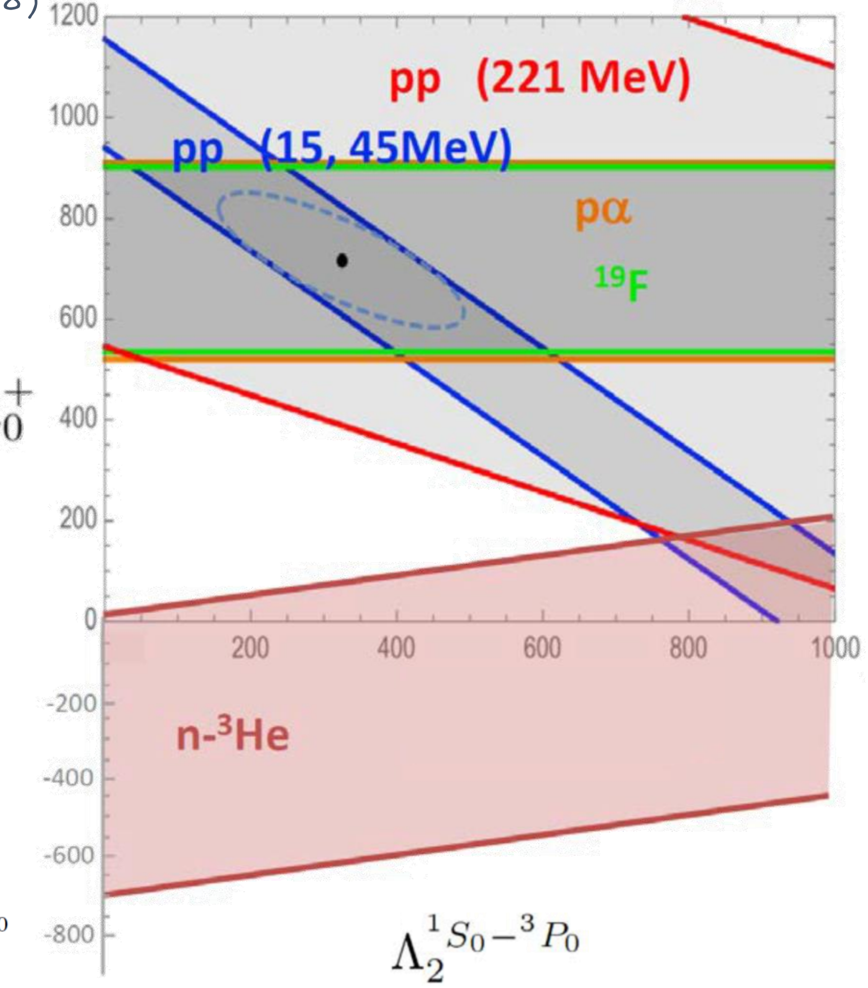
Recent neutron capture results

Suppressed by $1/N_c$, $\sin^2\theta_C$ Leading order ~ N_c

Large N_c expansion: Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

NPDGamma: Blythe et al, PRL 121, 242002 (2018)





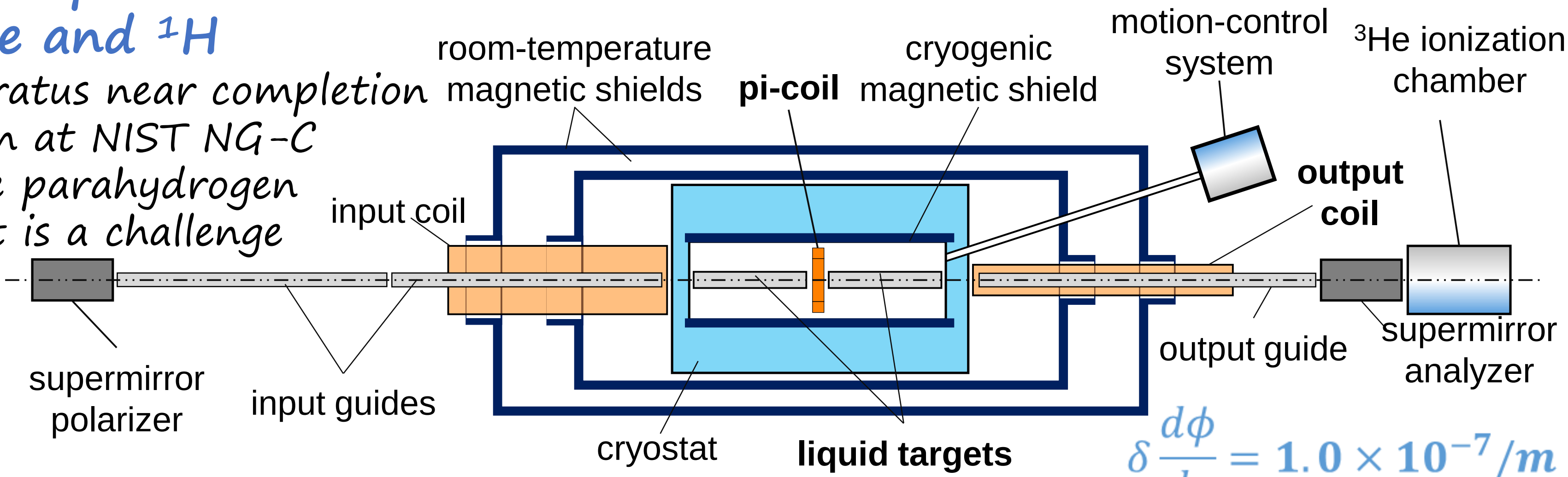
Courtesy: C. Crawford

$$A_\gamma^{np} = \left(-3.0 \pm 1.4_{stat} \pm 0.2_{sys}\right) \times 10^{-8} \quad A_\gamma^{n^3He} = \left(-1.2 \pm 0.9_{stat} \pm 0.1_{sys}\right) \times 10^{-8}$$

Tackling sub-leading couplings

Neutron spin rotation in ^{4}He and ^{1}H

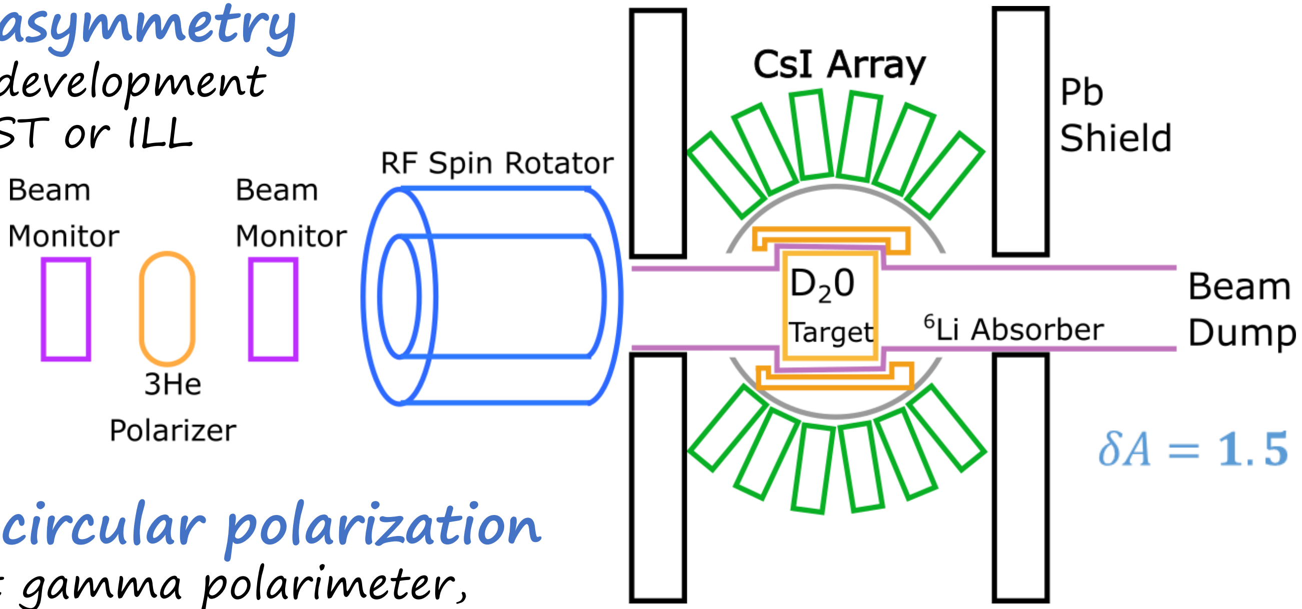
- Apparatus near completion
- To run at NIST NG-C
- Active parahydrogen target is a challenge



$$\delta \frac{d\phi}{dz} = 1.0 \times 10^{-7}/m$$

NDTG gamma asymmetry

- Initial stages of development
- Could run at NIST or ILL



$$\delta A = 1.5 \times 10^{-7}$$

NPDG gamma circular polarization

- Requires efficient gamma polarimeter, high flux neutron thermal beam

$$\delta P = 2.0 \times 10^{-8}$$

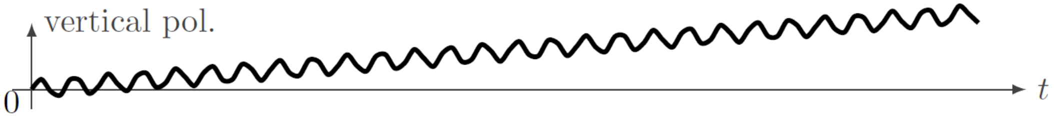
Courtesy: C. Crawford

Storage ring EDM precursor experiment at COSY

Courtesy: J. Pretz

- first step in staged approach
- performed at magnetic storage ring COSY at Forschungszentrum Jülich
- in a magnetic storage ring EDM just causes a tiny oscillation of the vertical polarization component (This effect was used in the muon $g-2$ experiment)

- The operation of a radio-frequency Wien filter at the spin precession frequency allows for a build-up of the vertical polarization due to an EDM



slope $\propto$ EDM

Current Status

- At this stage the observed build-up is mostly attributed to systematic effects (e.g. misalignment of magnets and beam position monitors causing deviations from the design orbit).
- Work is going on to minimize these effects using beam based alignment and quantify them with the help of simulations.
- The goal is to perform with COSY a first EDM measurement with a precision similar to the one of the muon, i.e. $10^{-19}\,e\,\mathrm{cm}$.
- It should also be clear that gaining further orders of magnitude in precision is only possible with a dedicated storage ring using counter rotating beams where many systematic effects mentioned above cancel.

Hadronic Vacuum Polarization Contribution

Dispersion Relation (exact):

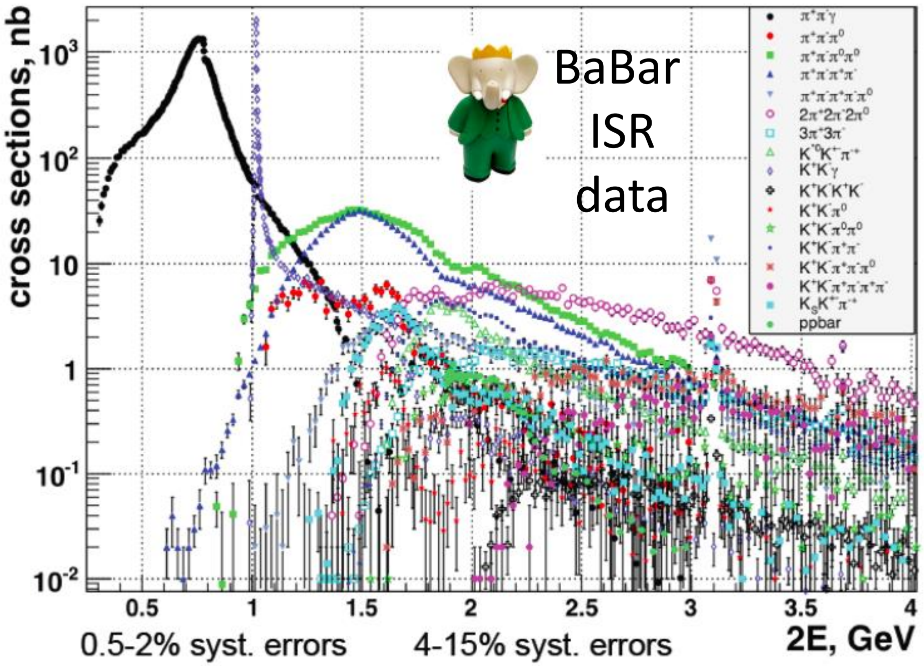
$$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\,\sigma_{had}$$

Intrinsic ~ 1 / s^2

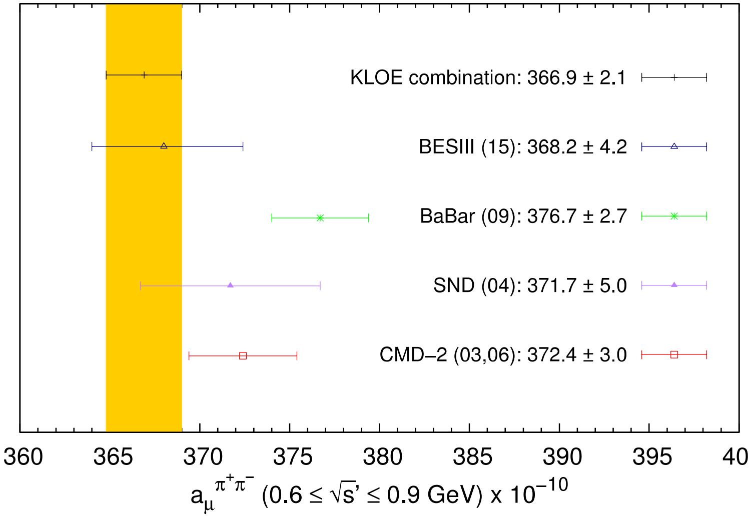
low energy contributions

especially important!

Courtesy: A. Denig



Unclear situation regarding dominating 2π contribution (~70% of total HVP)



Outlook:

- Reanalysis BABAR ISR 2π result
- New ISR analyses from BES III, BELLE II
- Energy scan data from Novosbirsk

--> Potential to further reduce HVP contrib., clarification of 2π puzzle

- New idea: determine HVP from eμ scattering (~10^{-5} accuracy required)

Hadronic Light-by-Light Contribution

Leading contribution is pole contribution from π^0

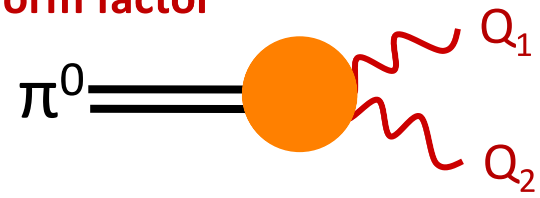
$$a_\mu^{\mathrm{HLbL};\pi^0(1)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\, w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$

3D integral representation

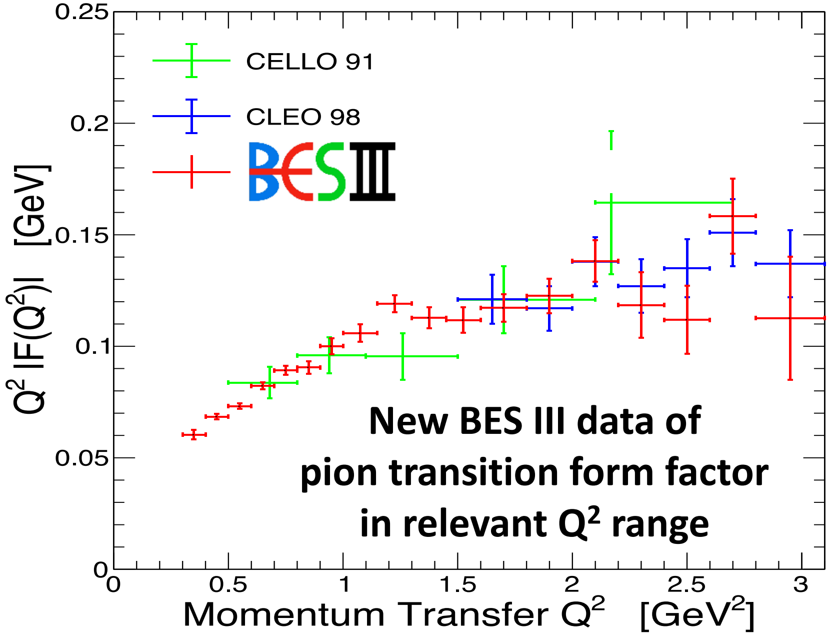
Weighting function

dominating Q^2 range below ~2 GeV^2

Transition form factor



- gamma-gamma reactions (e+e-)
- Meson Dalitz decays



New BES III data of pion transition form factor in relevant Q^2 range

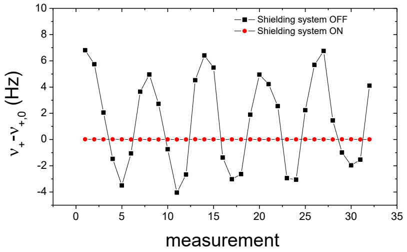
Outlook:

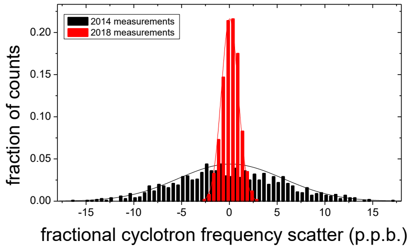
- Development of data-driven theory programme (Bern, Mainz)
- gamma-gamma TFF programme at BES III in relevant Q^2 range
- Huge expt. effort at meson factories (SPS-CERN, MAMI, BES III, ...)
- High-Q^2 data at BELLE-II
- Ultimate goal: double-tag measurements

Courtesy: A. Denig

Future Perspective

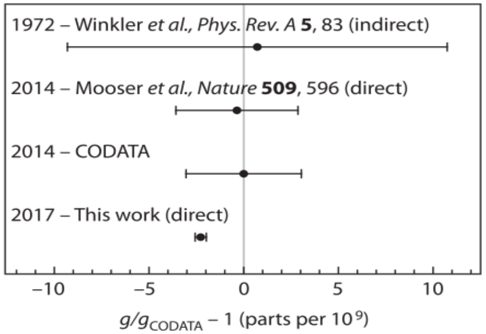
- Stability of charge-to-mass ratio measurements was improved by a factor of 3





- Measurements at the level of 10 ppt to 20 ppt in reach.

- Proton magnetic moment measurement methods reached sub ppb resolution

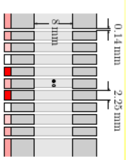


G. Schneider *et al.*, Science **358**, 1081 (2017)

$$\frac{g_p}{2} = 2.792\,847\,344\,62\,(82)$$

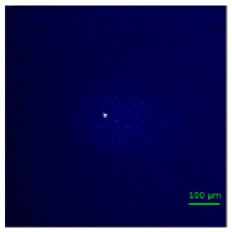
- Factor of 5 in reach, factor of 200 possible.

Future Developments for even higher precision



Sympathetic cooling of antiprotons

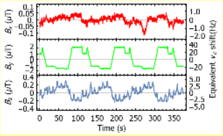
Detection of a single laser cooled $^9\mathrm{Be}^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN



M. Niemann, J. M. Cornejo, **C. Ospelkaus** et al.

Development of transportable antiproton traps

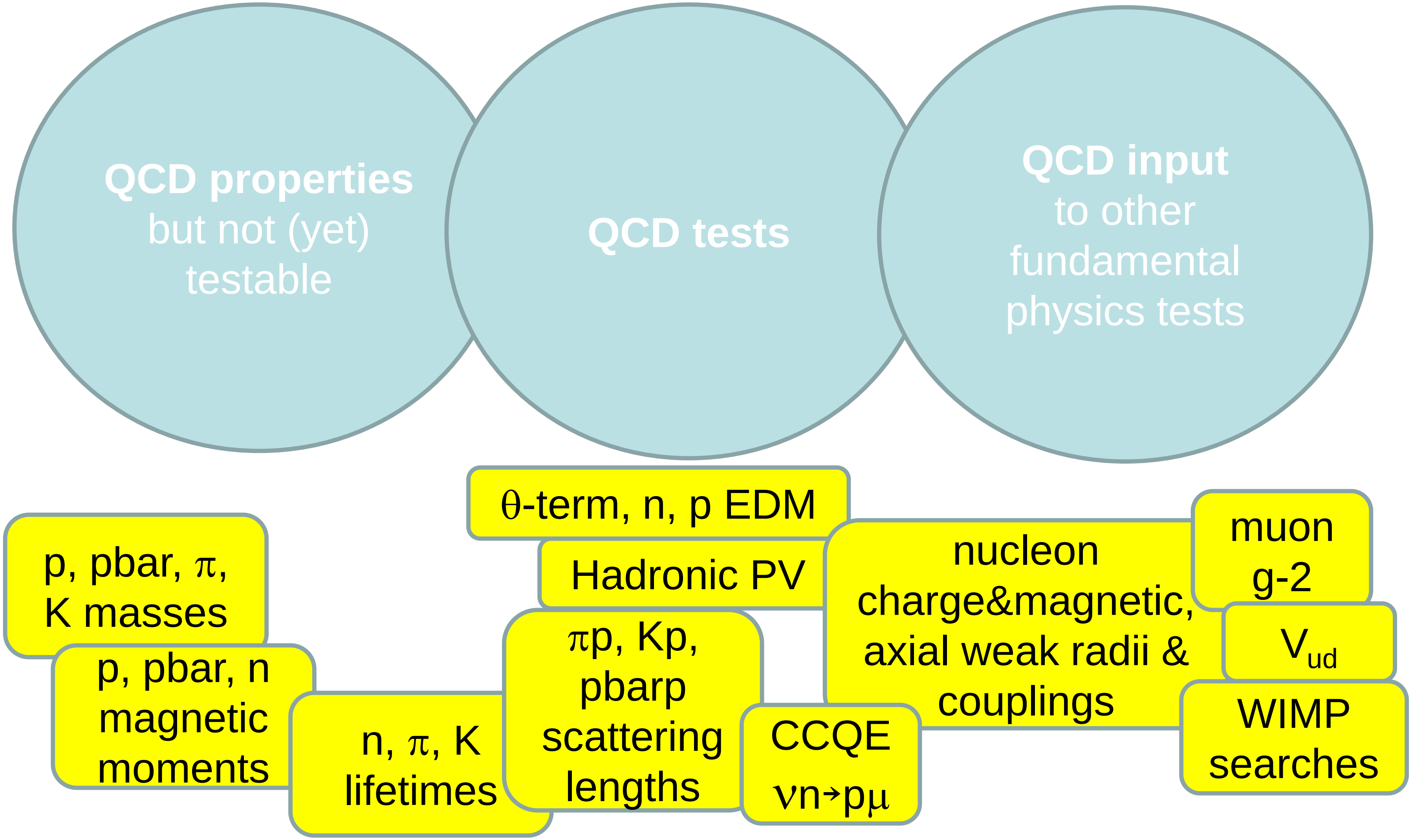
Effective noise reduction, parallel measurements in dedicated laboratories, higher statistics, etc.



C. Smorra,, **S. Ulmer** et al.

Courtesy: S. Ulmer

QCD at low energies



QCD properties
but not (yet)
testable

QCD tests

QCD input
to other
fundamental
physics tests

p, pbar, π, K masses

p, pbar, n magnetic moments

n, π, K lifetimes

θ-term, n, p EDM

Hadronic PV

πp, Kp, pbarp scattering lengths

CCQE
$\nu n \rightarrow p\mu$

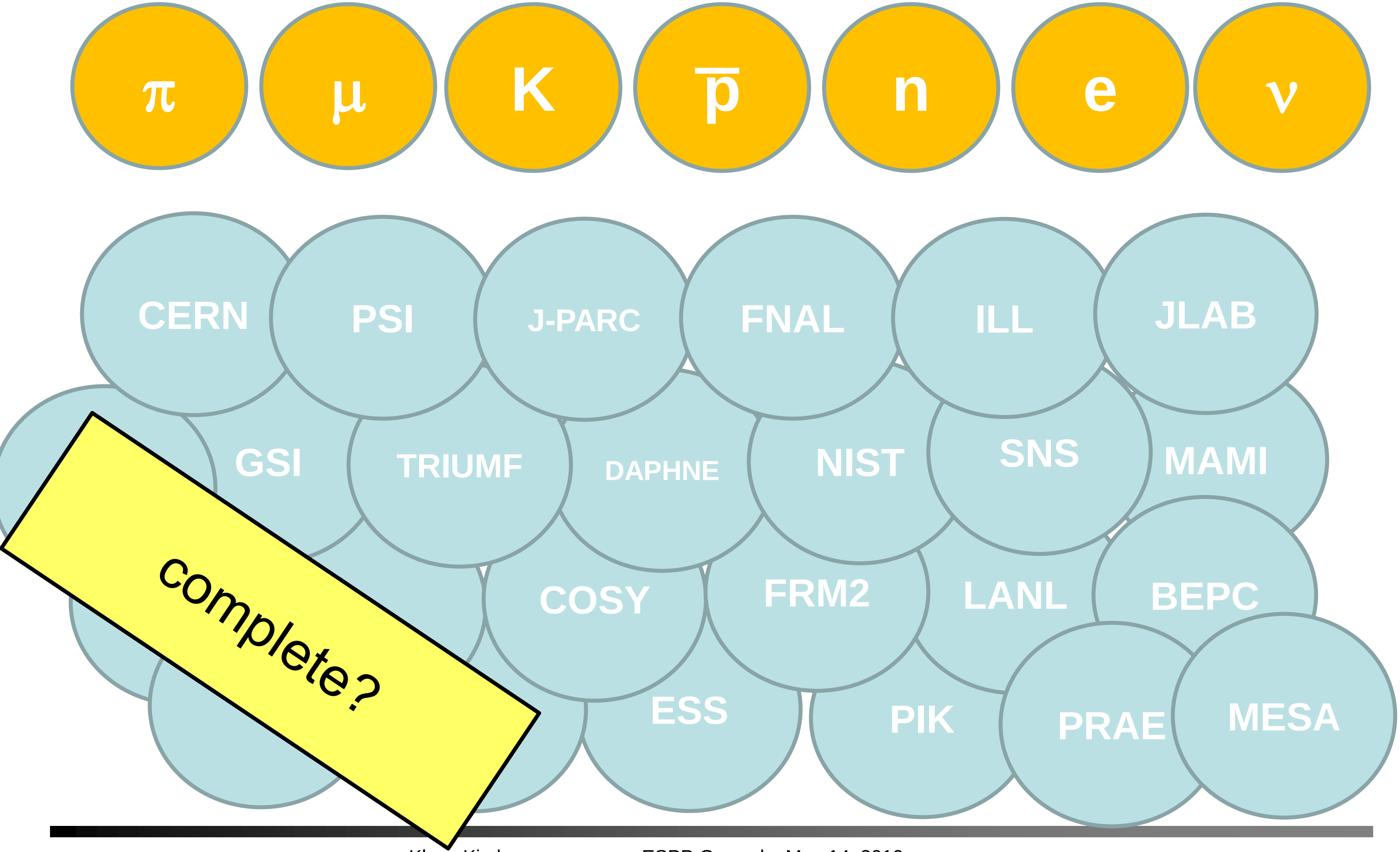
nucleon charge&magnetic, axial weak radii & couplings

muon g-2

V_{ud}

WIMP searches

Facilities impacting low-E QCD



π μ K $\bar{p}$ n e ν

CERN PSI J-PARC FNAL ILL JLAB

GSI TRIUMF DAPHNE NIST SNS MAMI

COSY FRM2 LANL BEPC

ESS PIK PRAE MESA

complete?