DESY Zeuthen - Theory Seminar 17th June 2021

$(g\text{-}2)_\mu$: Is the end of the Standard Model nigh?

UNIVERSITY OF LIVERPOOL

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- Introduction
- SM prediction from the Muon g-2 Theory Initiative:
  - Hadronic Vacuum Polarisation & Light-by-Light contributions
- Discussion, outlook & paths to further progress

Introduction

- **Muons** are like electrons, but about 200 times heavier,

  and they **decay**: $\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$

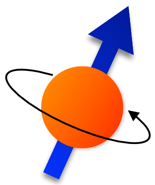
- Like other matter particles, they have intrinsic angular momentum, **spin = ½**

- As they are also **charged**, they have a magnetic moment: $\vec{\mu} = g \frac{Qe}{2m} \vec{s}$

- The **Dirac equation** (1928) not only implied antiparticles,

  but also tells us that the gyromagnetic factor **g = 2**

- If put in a magnetic field, muons precess (like a spinning top)



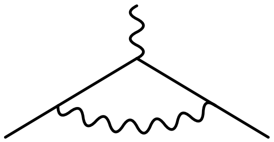
- This **g-2 precession** can be **measured very precisely** (Brendan Casey's seminar)

  and can be **calculated very precisely** (this talk)

Introduction

- 1947: small deviations from predictions in hydrogen and deuterium hyperfine structure; Kusch & Foley propose explanation with g = 2.00229 ± 0.00008

- 1948: Schwinger calculates the famous radiative correction:



➠ g = 2 (1+a), with the **anomaly**

$$a = \frac{g-2}{2} = \frac{\alpha}{2\pi} \approx 0.001161$$

``If you can't join 'em, beat 'em"

This explained the discrepancy and was a crucial step in the development of perturbative QFT and QED

- In terms of an effective Lagrangian, the anomaly is from the Pauli term:

$$\delta\mathcal{L}_{\rm off}^{\rm AMM} = -\frac{Qe}{4m}\, a\, \bar\psi_L \sigma^{\mu\nu}\psi_R F_{\mu\nu} \;+\; ({\rm L} \leftrightarrow {\rm R})$$

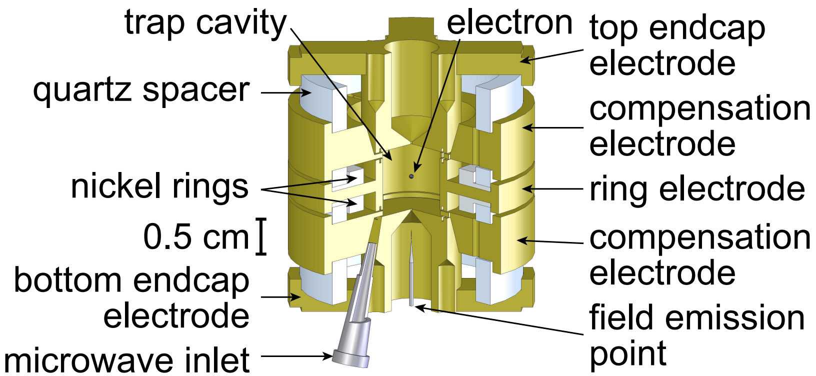
Note: This is a dimension 5 operator and NOT part of the fundamental (QED) Lagrangian, but occurs through radiative corrections and is **calculable in** (Standard Model) **theory**:

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm weak} + a_\mu^{\rm hadronic}$$

a_e vs. a_μ

a_e= 1 159 652 180.73 (0.28) 10^{-12} [0.24ppb]

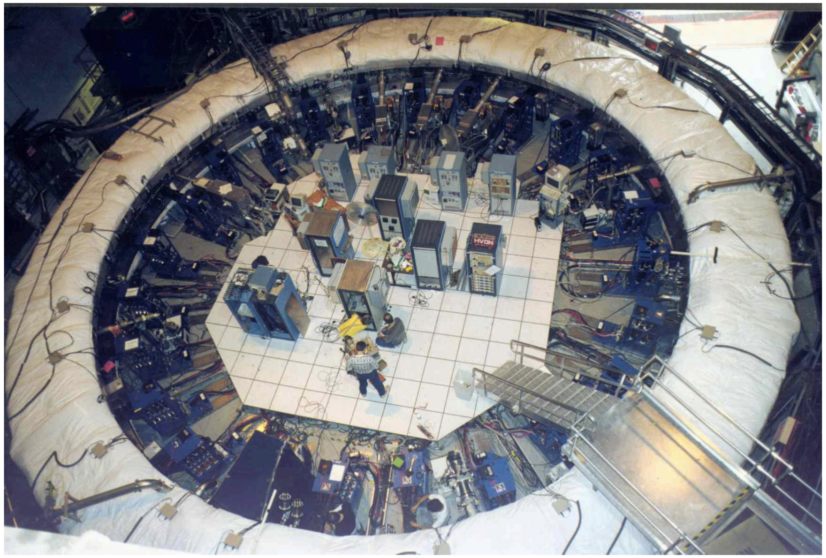
Hanneke, Fogwell, Gabrielse, PRL 100(2008)120801



one-electron quantum cyclotron

a_μ= 116 592 089(63) 10^{-11} [0.54ppm]

Bennet et al., PRD 73(2006)072003 BNL !



- a_e^{EXP} more than 2000 times more precise than a_μ^{EXP}, but for e^- loop contributions come from very small photon virtualities, whereas muon `tests' higher scales

- dimensional analysis: sensitivity to NP (at high scale Λ_{NP}): $a_\ell^{NP} \sim \mathcal{C}\, m_\ell^2 / \Lambda_{NP}^2$

→ μ wins by $m_\mu^2/m_e^2 \sim 43000$ for NP, but a_e determines α, tests QED & low scales

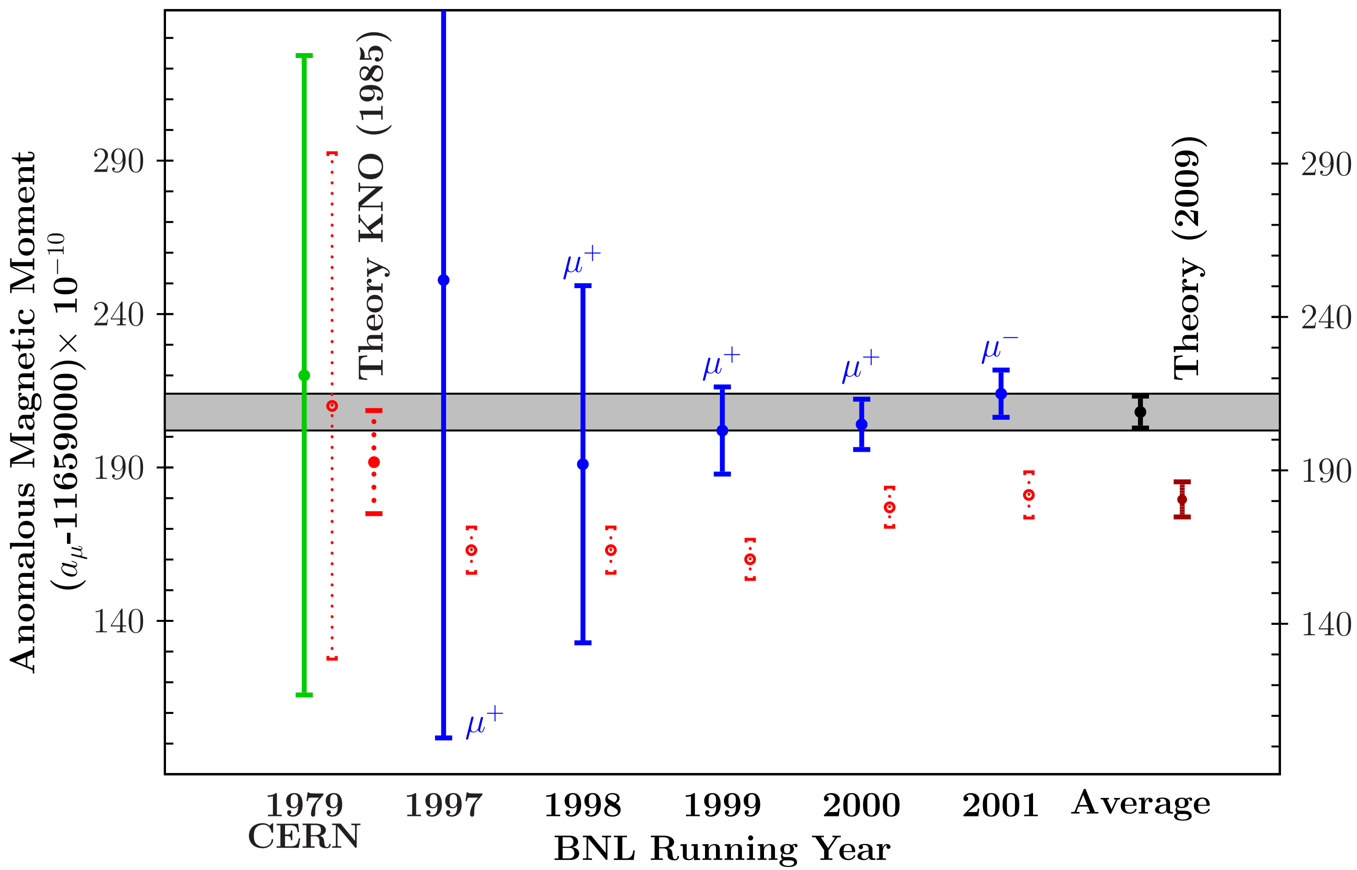
[Notes: τ too short-lived for storage-rings. Unclear exp situation with α from Cs vs Rb: 5.4σ]

a_μ: back to the future

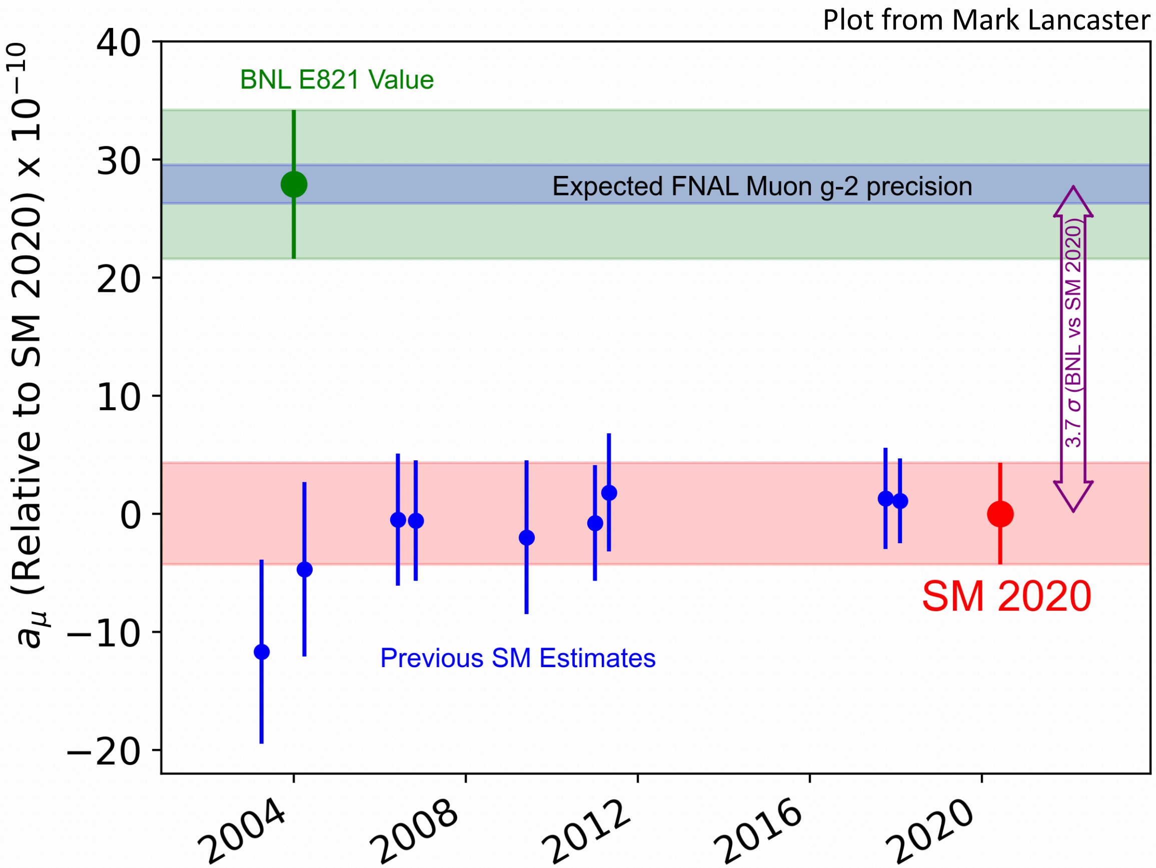
- CERN started it nearly 40 years ago
- Brookhaven delivered 0.5ppm precision
- E989 at FNAL and J-PARC's g-2/EDM experiments are happening and should give us certainty

g-2 history plot and
motto from Fred Jegerlehner's book:

`The closer you look the more there is to see'



SM theory vs. Experiment (before 7.4.2021)



- If the two don't match, something may be missing in the SM
- Precision measurements + precision theory

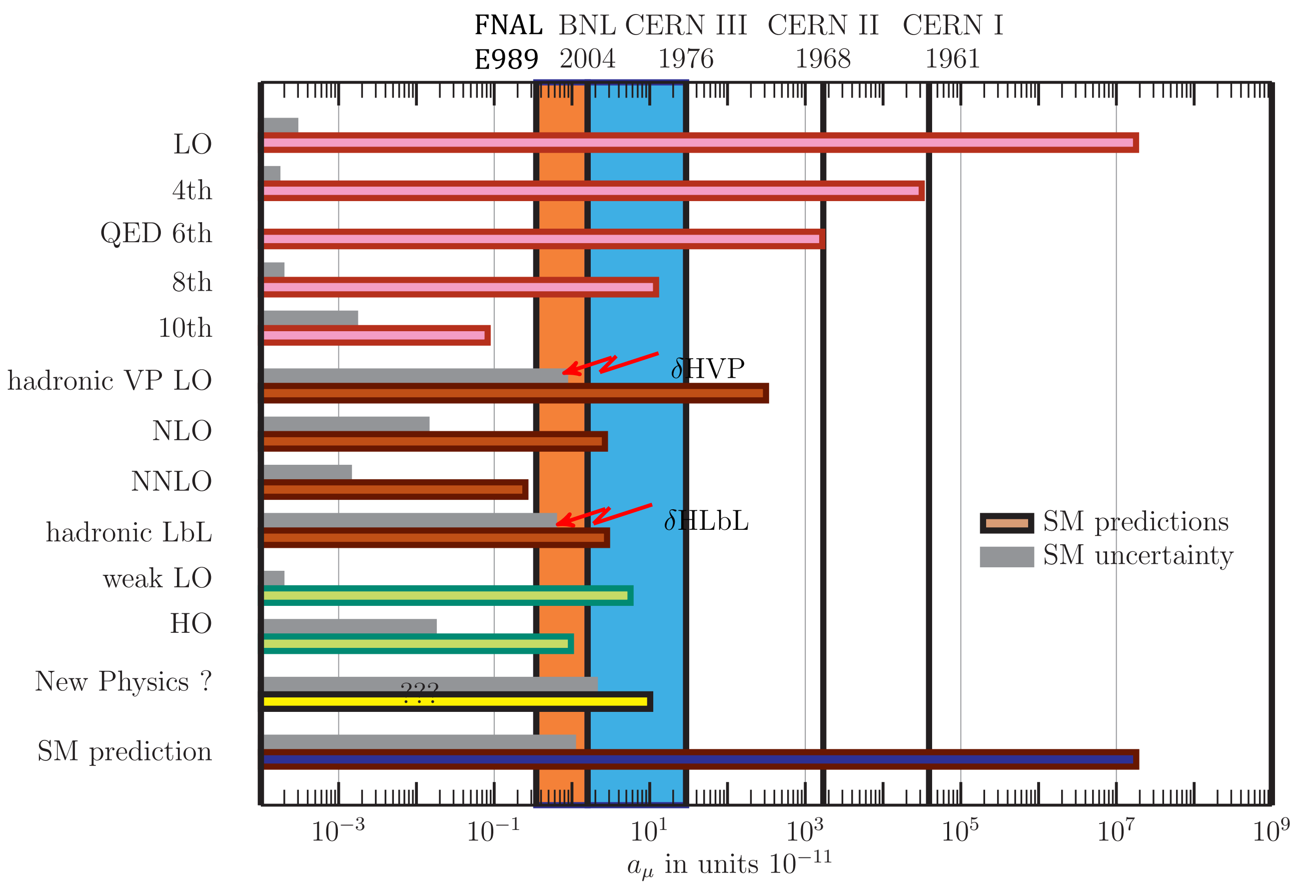
➡ discovery potential for **New Physics**

➤ need for consolidated & reliable SM prediction

$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}} + a_\mu^{\text{NP?}}$$

Theory vs. Experiment: sensitivity chart

Plot from Fred Jegerlehner

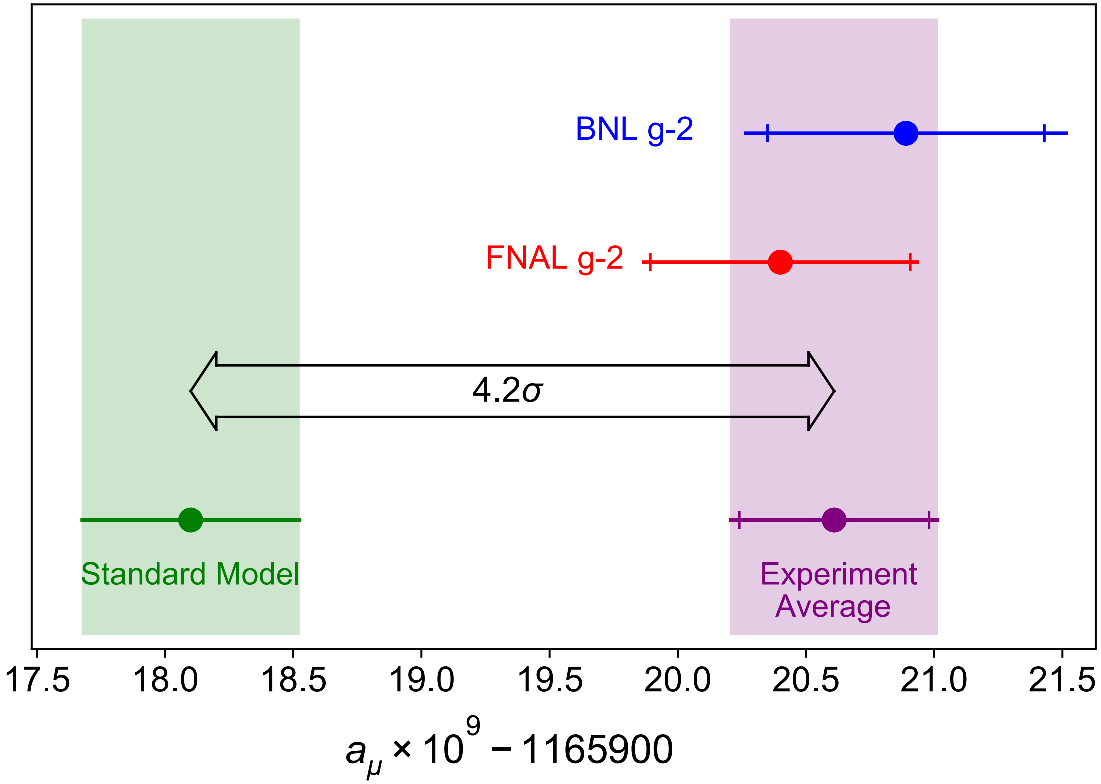


- Need to control the hadronic contributions

$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{hadronic}} + a_\mu^{\text{NP?}}$$

SM theory vs. Experiment (after FNAL on 7.4.2021)

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm
[Phys. Rev. Lett. 126 (2021) 14, 141801]



- Unblinding of Run 1 analyses: 25 February ’21
- FNAL confirms BNL
- Release of result: 7 April ’21
- As of today, PRL has 158 citations (most of them BSM)
- Run 1 is only 6% of total expected statistics

➤ But what about the Standard Model prediction?

Muon g-2 Theory Initiative est. 2017

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

``... map out strategies for obtaining the **best theoretical predictions for these hadronic corrections** in advance of the experimental result.''

- Organised 6 int. workshops in 2017-2020, (virtual) plenary workshop June 28 – July 2, 2021 hosted by KEK (Japan)
- **White Paper** posted 10 June 2020 (132 authors, from 82 institutions, in 21 countries)

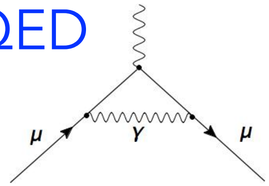
  ``**The anomalous magnetic moment of the muon in the Standard Model**''

  [T. Aoyama et al, arXiv:2006.04822, Phys. Rept. 887 (2020) 1-166] ➤ please follow citation recommendations

Group photo from the Seattle workshop in September 2019

SM WP20 prediction from the TI White Paper **(0.37 ppm)**

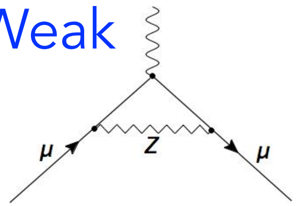
QED



+…

$116\,584\,718.9\,(1) \times 10^{-11}$ 0.001 ppm

Weak



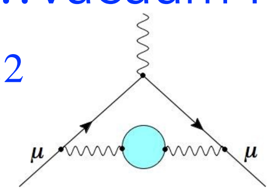
+…

$153.6\,(1.0) \times 10^{-11}$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

α^2

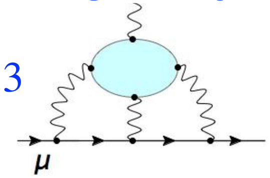


+…

$6845\,(40) \times 10^{-11}$ [0.6%] 0.34 ppm

…Light-by-Light (HLbL)

α^3



+…

$92\,(18) \times 10^{-11}$ [20%] 0.15 ppm

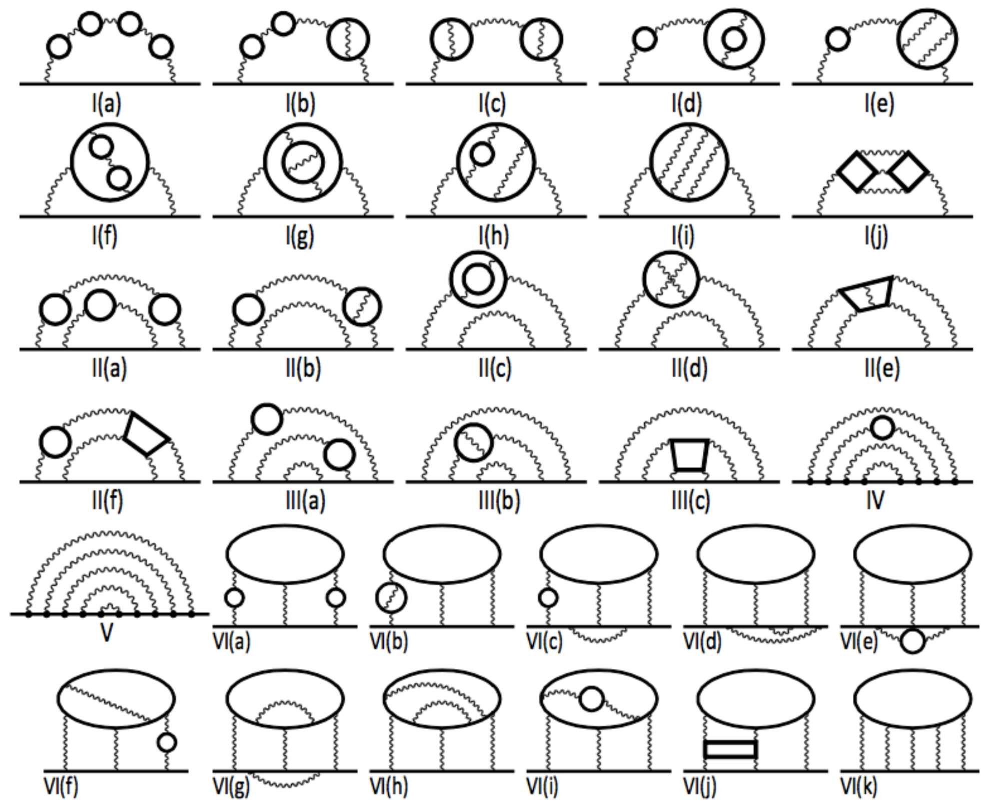
- Uncertainty dominated by hadronic contributions, now **δ HVP > δ HLbL**

a_μ^{QED} & a_μ^{weak} : a triumph for perturbative QFT

QED: Kinoshita et al. + many tests

- g-2 @ 1, 2, 3, 4 & 5 loops
- Subset of 12672 5-loop diagrams:
- code-generating code, including
- renormalisation
- multi-dim. numerical integrations

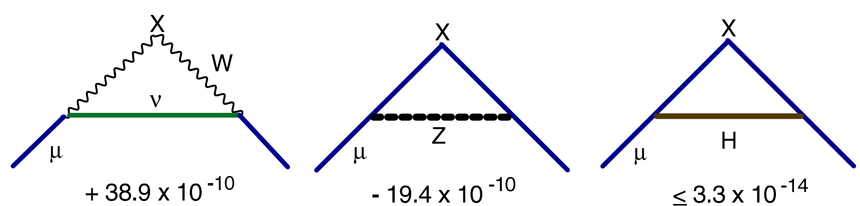
a_μ^{QED} **= 116 584 718.9 (1) × 10^{-11}** ✓



Weak: (several groups agree)

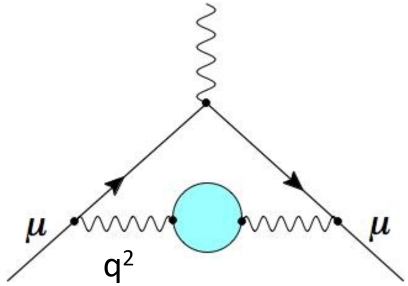
- done to 2-loop order, 1650 diagrams
- the first full 2-loop weak calculation

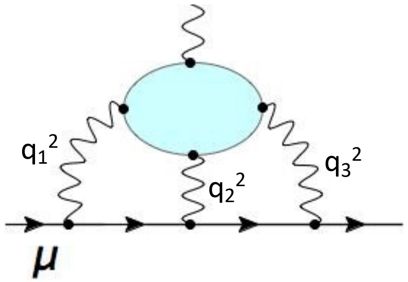
a_μ^{weak} **= 153.6 (1.0) × 10^{-11}** ✓



SM weak 1-loop diagrams

$a_\mu^{hadronic}$: non-perturbative, the limiting factor of the SM prediction





- **Q:** What's in the hadronic (**Vacuum Polarisation** & **Light-by-Light scattering**) blobs?

  A: Anything `**hadronic**' the virtual photons couple to, i.e. **quarks + gluons** + photons

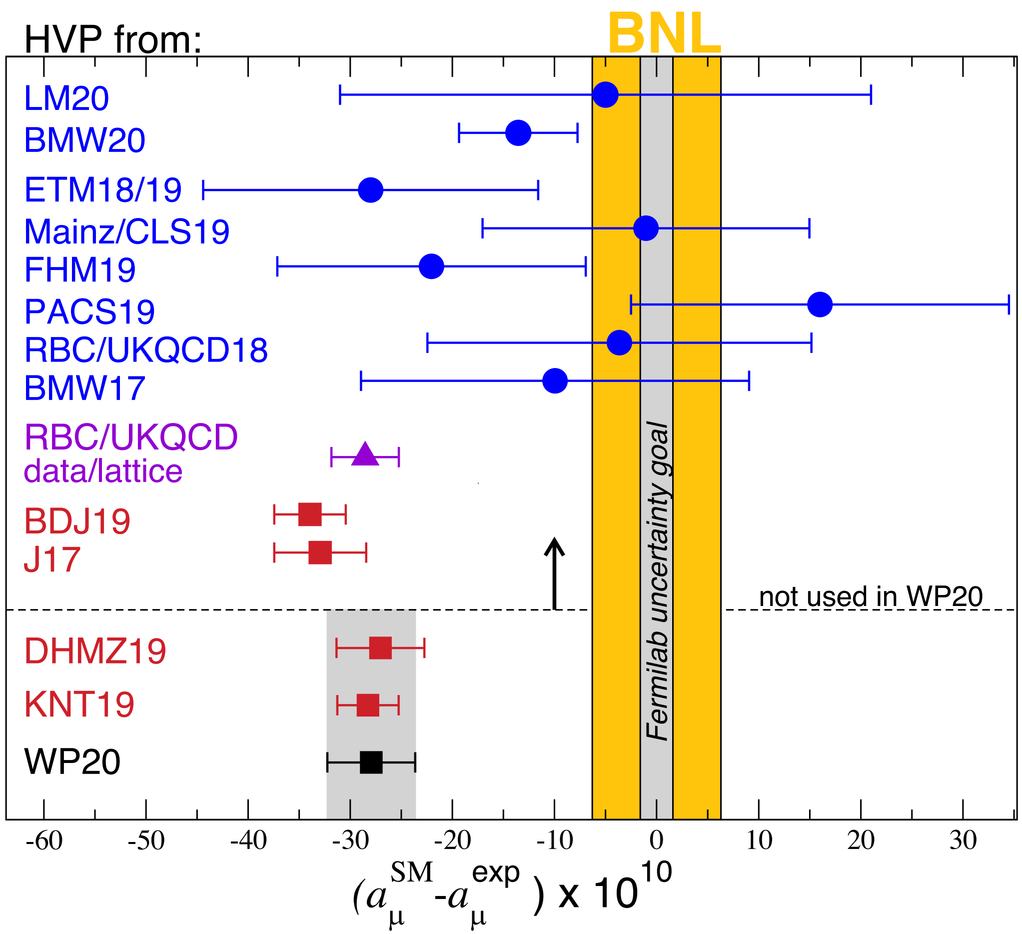
  But: low q^2 photons dominate loop integral(s) ➠ cannot calculate blobs with perturbation theory

- **Two very different strategies:**

  1. use wealth of hadronic data, `**data-driven dispersive methods**':
     - data combination from many experiments, radiative corrections required
  2. simulate the strong interaction (+photons) w. discretised Euclidean space-time, `**lattice QCD**':
     - finite size, finite lattice spacing, artifacts from lattice actions, QCD + QED needed
     - numerical Monte Carlo methods require large computer resources

  ➤ discussed in detail in Laurent Lellouch's recent talk

a_μ^{HVP} : WP20 Status/Summary of Hadronic VP contributions



Lattice QCD + QED

- impressive progress, but…
- large spread between results
- tensions when looking at `Euclidean time window' comparisons
- large systematic uncertainties (e.g. from non-trivial extrapolation to continuum limit, finite size)

Dispersive/lattice hybrid (`window' method)

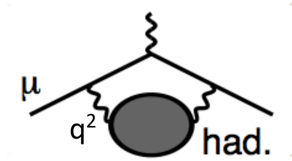
For WP20: Dispersive data-driven from **DHMZ** and **KNT**

TI White Paper 2020 value:

$$\mathbf{a_\mu^{HVP} = 6845\ (40) \times 10^{-11}}$$

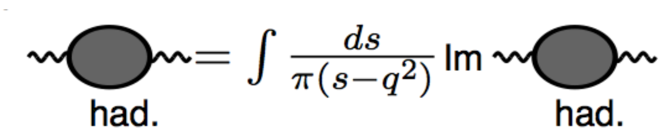
- **TI WP20** prediction uses dispersive data-driven evaluations with **minimal model dependence**
- a_μ^{HVP} **value and error** obtained **by merging** procedure ➠ accounts for tensions in input data and differences in data treatment & combination (going beyond usual χ^2_{min} inflation)

a_μ^{HVP} : Basic principles of dispersive method



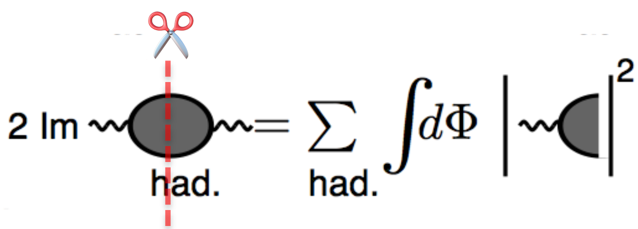
One-loop diagram with hadronic blob =

integral over q^2 of virtual photon, 1 HVP insertion



Causality ➠ analyticity ➠ dispersion integral:

obtain HVP from its imaginary part only



Unitarity ➠ Optical Theorem:

imaginary part (`cut diagram') =

sum over |cut diagram|^2, i.e.

∝ sum over all total hadronic cross sections

$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\mathrm{th}}}^{\infty} ds \, \frac{1}{s} \hat{K}(s) \sigma_{\mathrm{had}}(s)$$

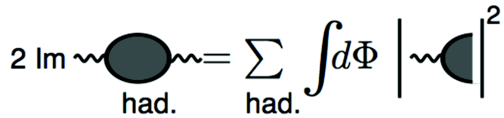
- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s$

$\Longrightarrow$ Lower energies more important

$\Longrightarrow$ $\pi^+\pi^-$ channel: 73% of total $a_\mu^{\mathrm{had,LO}}$

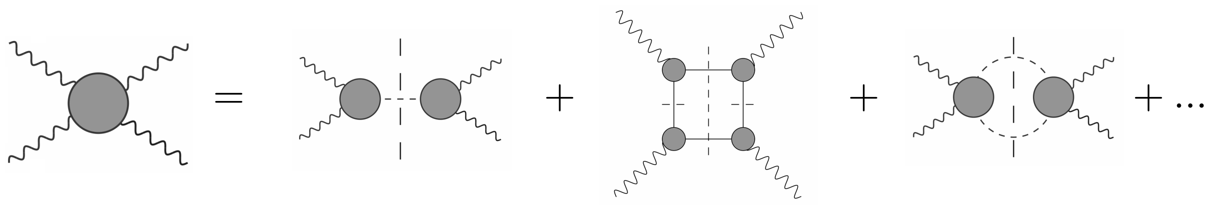
- Total hadronic cross section $\boldsymbol{\sigma_{\mathrm{had}}}$ from >100 data sets for **e^+e^- ➞ hadrons** in >35 final states
- Uncertainty of a_μ^{HVP} prediction from statistical & systematic uncertainties of input data
- Pert. QCD used only at large s, **no modelling** of $\sigma_{\mathrm{had}}(s)$ **required**, direct data integration

a_μ^{HLbL} : Hadronic Light-by-Light: Dispersive approach

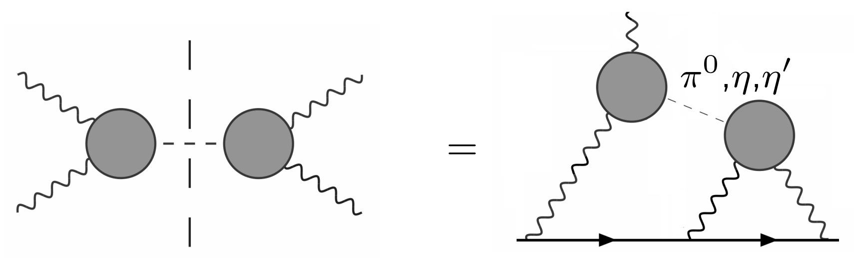
For HVP $\Rightarrow$ 

$\Rightarrow$ $\mathrm{Im}\Pi_{\mathrm{had}}(s) = \left(\frac{s}{4\pi\alpha}\right)\sigma_{\mathrm{had}}(s)$

For HLbL $\Rightarrow$ $\Pi_{\mu\nu\lambda\sigma} = \Pi^{\mathrm{pole}}_{\mu\nu\lambda\sigma} + \Pi^{\mathrm{box}}_{\mu\nu\lambda\sigma} + \bar{\Pi}_{\mu\nu\lambda\sigma} + \ldots$

$\Rightarrow$ 

$\Rightarrow$ Dominated by pole (pseudoscalar exchange) contributions

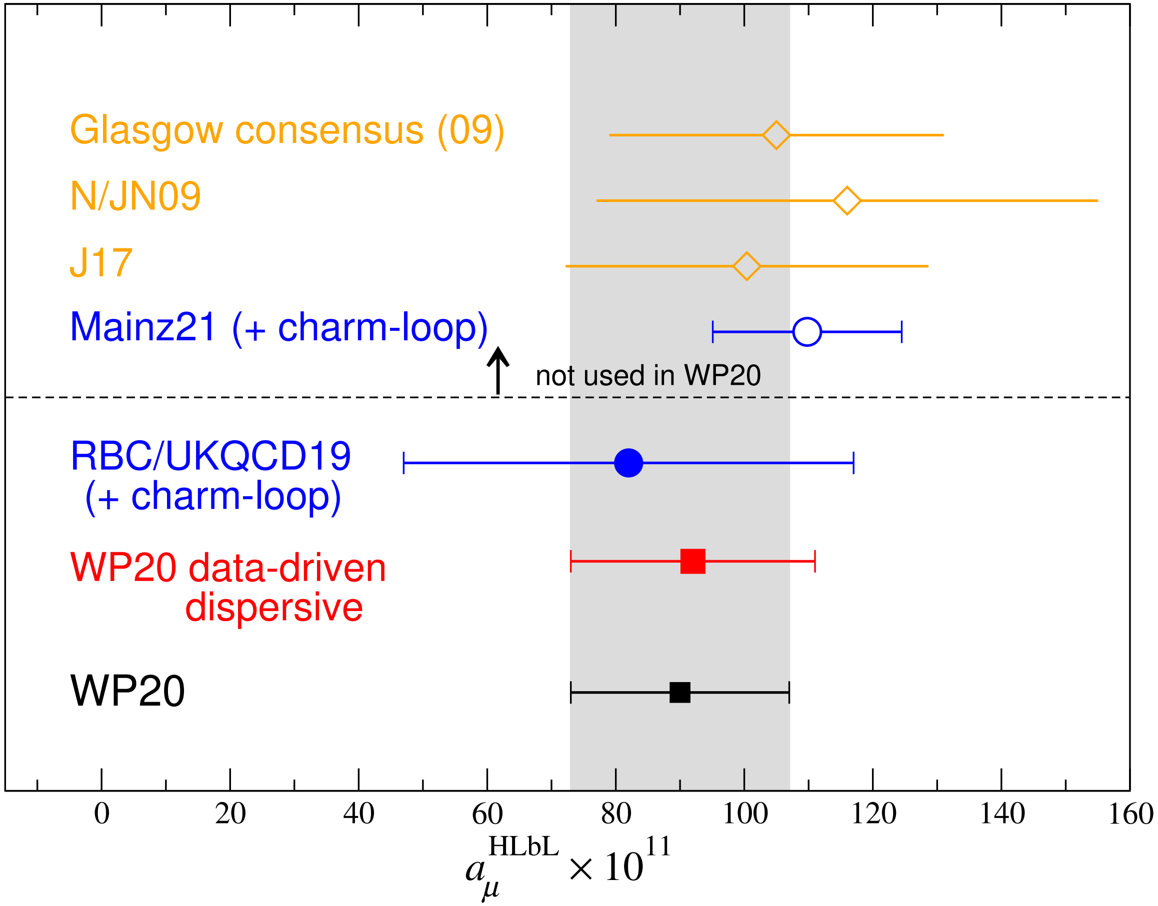
$\Pi^{\mathrm{pole}}_{\mu\nu\lambda\sigma} =$ 

$\Rightarrow$ Sum all possible diagrams to get a_μ^{HLbL}

- See also review by Danilkin+Redmer+Vanderhaeghen using dispersive techniques estimates $(8.7 \pm 1.3) \times 10^{-10}$ [Prog. Part. Nucl. Phys. 107 (2019) 20]

- With new results & progress, L-by-L can now be reliably predicted! ✓

a_μ^{HLbL} : WP Status/Summary of Hadronic Light-by-Light contributions



hadronic models + pQCD

very new lattice QCD + QED

lattice QCD + QED

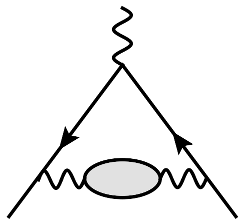
data-driven

TI White Paper 2020 value:

a_μ^{HLbL} **= 92 (18) × 10^{-11}** ✓

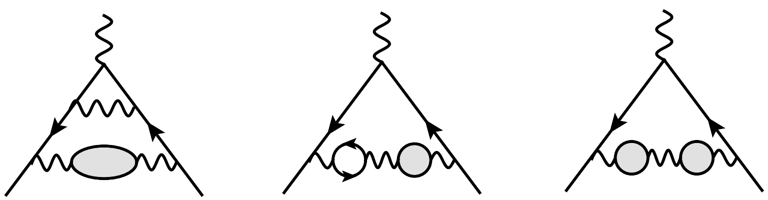
- data-driven dispersive & lattice results have confirmed the earlier model-based predictions
- **uncertainty much better under control** and at 0.15ppm already **sub-leading compared to HVP**
- lattice predictions now competitive, good prospects for combination and error reduction to ≤ 10%

a_μ^{HVP} : Higher orders & QED power counting; WP20 values in 10^{-11}



➤ All hadronic blobs also contain photons,
i.e. real + virtual corrections in $\sigma_{had}(s)$

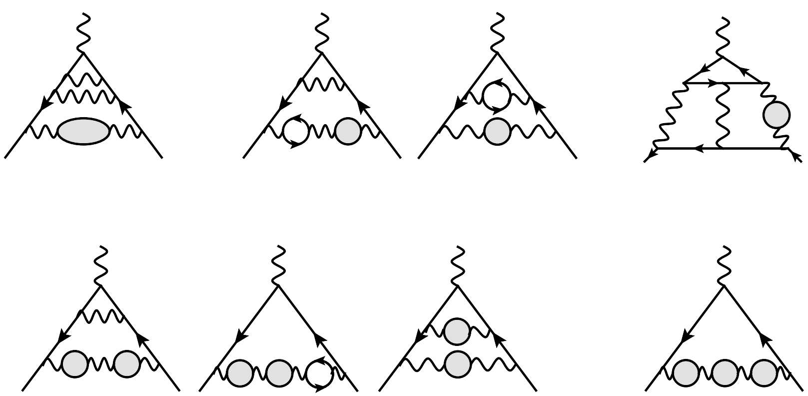
- LO: 6931(40)



- NLO: - 98.3(7)

  from three classes of graphs:
  - 207.7(7) + 105.9(4) + 3.4(1) [KNT19]

  (photonic, extra e-loop, 2 h-loops)



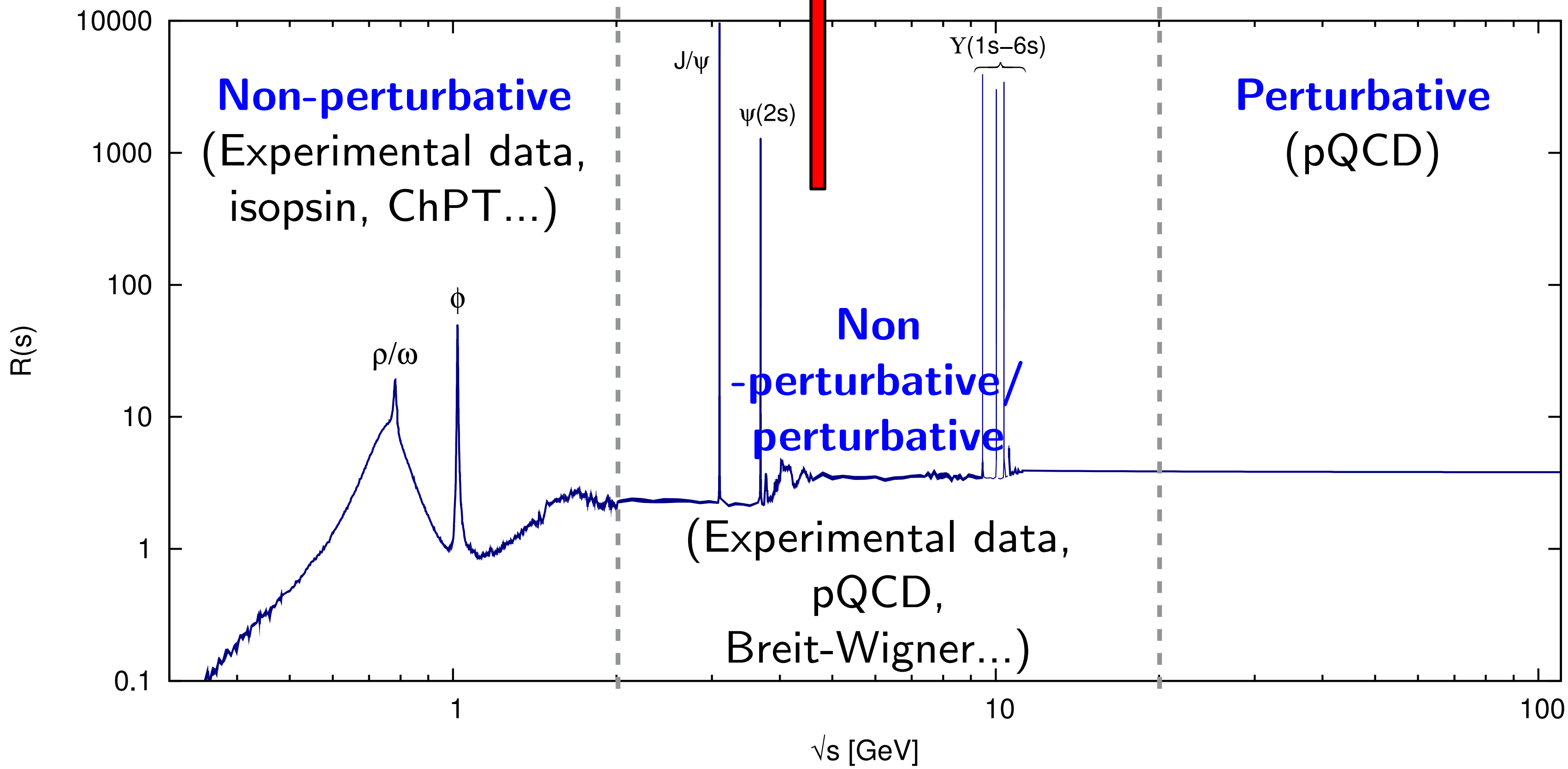
- NNLO: 12.4(1) [Kurz et al, PLB 734(2014)144, see also F Jegerlehner]

  from five classes of graphs:
  8.0 - 4.1 + 9.1 - 0.6 + 0.005

➥ good convergence,
iterations of hadronic blobs very small

HVP disp.: cross section (in terms of R-ratio) input

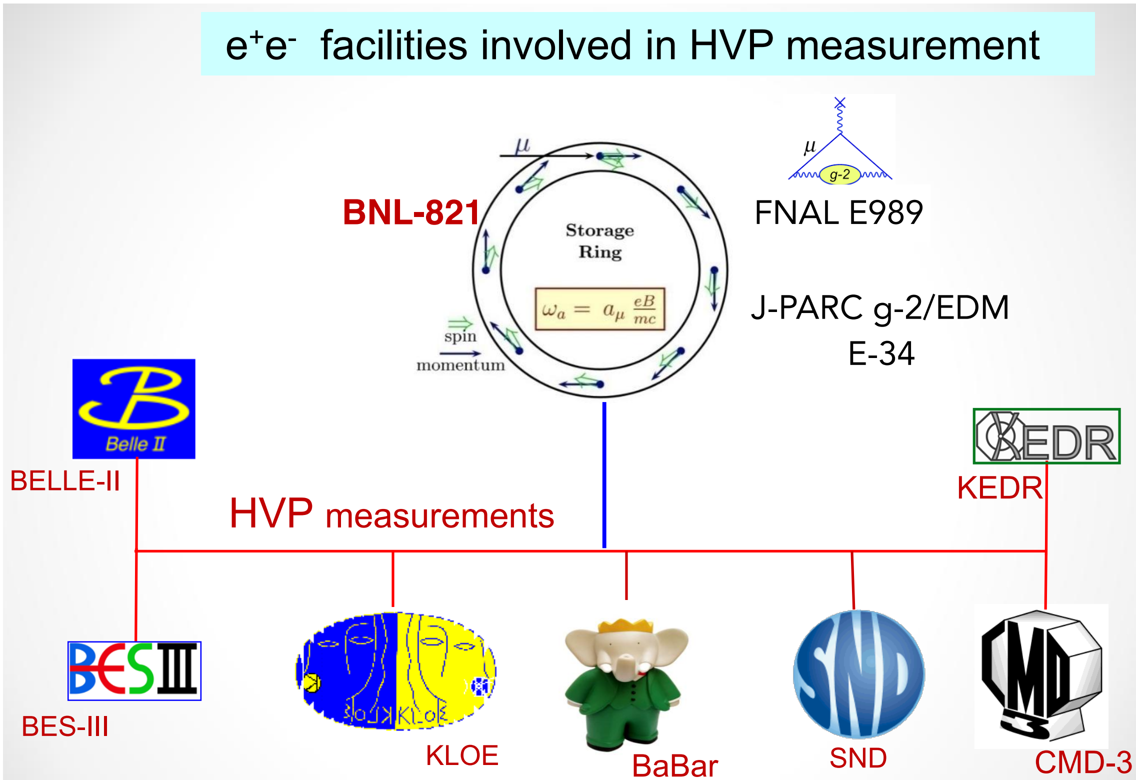
$$a_\mu^{\mathrm{had,\,LO\,VP}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{\mathrm{d}s}{s}R(s)K(s), \text{ where } R(s) = \frac{\sigma^0_{\mathrm{had},\gamma}(s)}{4\pi\alpha^2/3s}$$



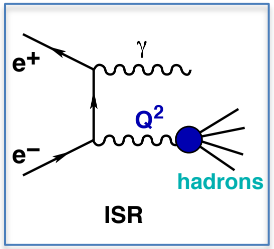
Must build full hadronic cross section/R-ratio…

a_μ^{HVP} : Recent (of 25+ years) experiments providing input $\sigma_{had}(s)$ data

S. Serednyakov (for SND) @ HVP KEK workshop



- Different methods: \`**Direct Scan**' (tunable e^+e^- beams) &
  \`**Radiative Return**' (Initial State Radiation scan at fixed cm energy) ↗



- Over last decades detailed studies of **radiative corrections** & **Monte Carlo Generators** for $\sigma_{had}(s)$
  - ➤ **RadioMonteCarLow** Working Group report: Eur. Phys. J. C66 (2010) 585-686
  - ➤ full NLO radiative corrections in ISR MC *Phokhara*: Campanario et al, PRD 100(2019)7,076004

HVP dispersive: cross section compilation

How to get the most precise σ^0_{had}? Use of $e^+e^- \rightarrow$ hadrons $(+\gamma)$ data:

- **Low energies:** sum ~35 exclusive channels, 2π, 3π, 4π, 5π, 6π, KK, KKπ, KKππ, ηπ, ..., [now very limited use iso-spin relations for missing channels]

- **Above ~1.8 GeV:** use of inclusive data or pQCD (away from flavour thresholds), supplemented by narrow resonances (J/Ψ, Υ)

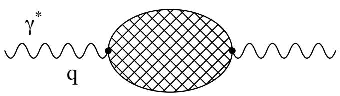
- Challenge of **data combination** (locally in √s, with **error inflation if tensions**):
  - many experiments, different energy ranges and bins,
  - statistical + systematic errors from many different sources,
  - use of correlations; must avoid inconsistencies, bias

  ➤ Significant differences between DHMZ and KNT in use of correlated errors:
    - KNT allow non-local correlations to influence mean values,
    - DHMZ restrict this but retain correlations for errors and also betw. channels

- σ^0_{had} means the `bare' cross section, i.e. excluding `running coupling' (VP) effects, but including Final State (γ) Radiation: data subject to Radiative Corrections

Rad. Corrs.: HVP for running $\alpha(q^2)$. Undressing

- Dyson summation of Real part of one-particle irreducible blobs $\mathbf{\Pi}$ into the effective, real running coupling $\boldsymbol{\alpha}_{\mathrm{QED}}$:

$\Pi \; =$ 

Full photon propagator $\sim \; 1 \; + \; \Pi \; + \; \Pi \cdot \Pi \; + \; \Pi \cdot \Pi \cdot \Pi \; + \; \ldots$

$$\rightsquigarrow \qquad \alpha(q^2) \; = \; \frac{\alpha}{1 - \mathrm{Re}\Pi(q^2)} \; = \; \alpha \, / \, \left(1 - \Delta\alpha_{\mathrm{lep}}(q^2) - \Delta\alpha_{\mathrm{had}}(q^2)\right)$$

- The Real part of the VP, $\mathrm{Re}\Pi$, is obtained from the Imaginary part, which via the *Optical Theorem* is directly related to the cross section, $\mathrm{Im}\Pi \sim \sigma(e^+e^- \to hadrons)$:

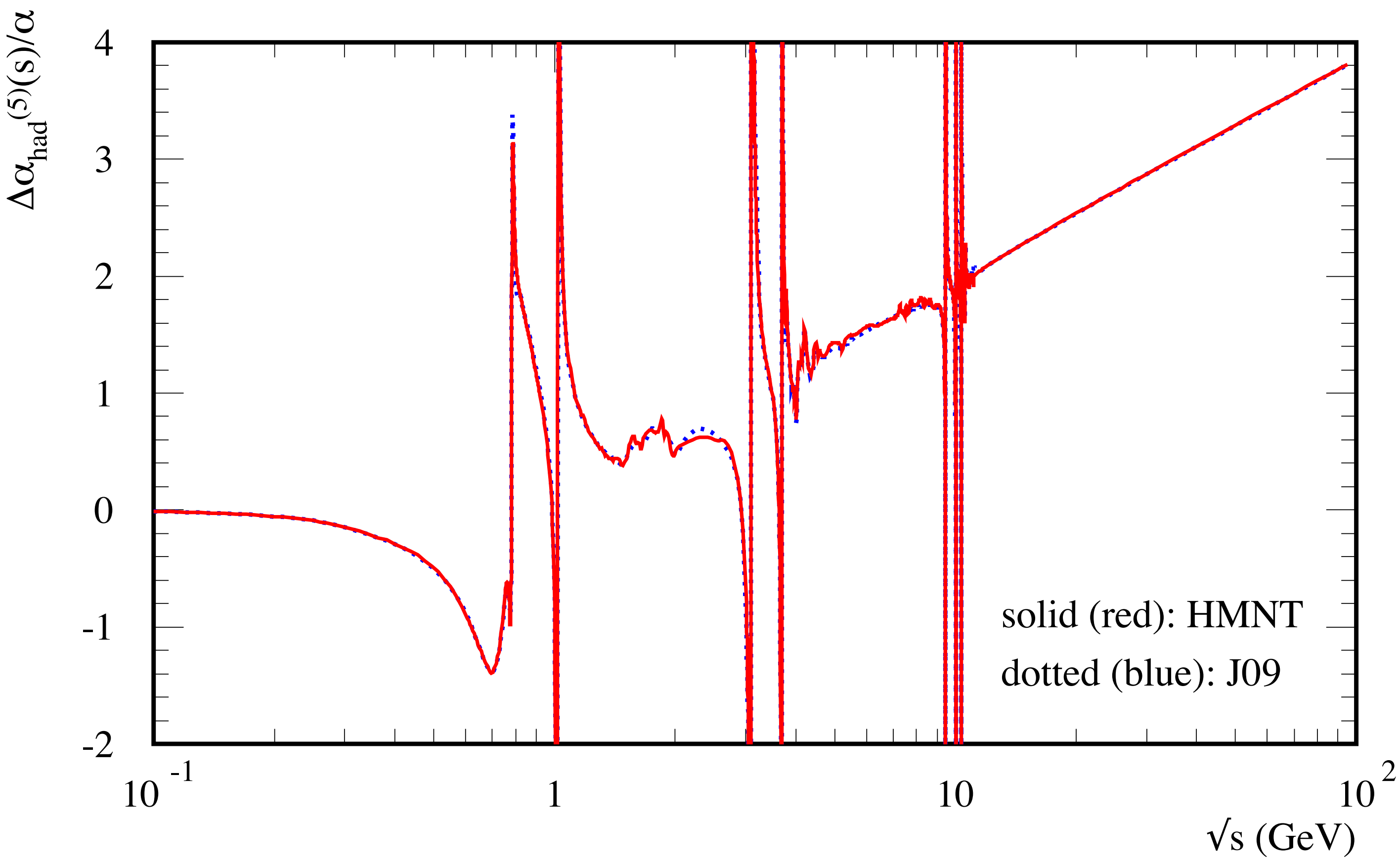
$$\Delta\alpha^{(5)}_{\mathrm{had}}(q^2) \; = \; -\frac{q^2}{4\pi^2\alpha} \, \mathrm{P} \int_{m_\pi^2}^{\infty} \frac{\sigma^0_{\mathrm{had}}(s) \, \mathrm{d}s}{s - q^2} \, , \quad \sigma_{\mathrm{had}}(s) = \frac{\sigma^0_{\mathrm{had}}(s)}{|1 - \Pi|^2}$$

[$\to \sigma^0$ requires 'undressing', e.g. via $\cdot(\alpha/\alpha(s))^2$ $\rightsquigarrow$ iteration needed]

- Observable cross sections σ_{had} contain the $|$full photon propagator$|^2$, i.e. $|$infinite sum$|^2$.
  $\to$ To include the subleading Imaginary part, use dressing factor $\frac{1}{|1-\Pi|^2}$.

Rad. Corrs.: HVP for running $\alpha(q^2)$. Undressing

- $\Delta\alpha(q^2)$ in the time-like: HLMNT compared to Fred Jegerlehner's new routines



For demonstration only, results >10 years old!

Different groups use their own HVP routines:

- Fred Jegerlehner,
- DHMZ,
- KNT,
- Novosibirsk (Fedor Ignatov)

→ with new version big differences (with 2003 version) gone

– smaller differences remain and reflect different choices, smoothing etc.

Rad. Corrs.: Final State γ Radiation

- Real + virtual , must be included in $\boldsymbol{\sigma^0_{had}}$ as part of the hadronic dynamics,
- but some events with real radiation will have been cut-off by experimental analyses
  (no problem if γ just missed but event counted. Possible problem of mis-identifies)
- Experiments (or compilations) account for this and add FSR back;
  - based on MC and **scalar QED** for pions (detailed studies, checked to work well)
  - contributes to systematic uncertainties
  - intrinsic part of Radiative Return analyses of many recent data sets
- Notes:
  - at low energies and at resonances, hard radiation is limited by phase space
  - different compilations apply **additional uncertainty** to cover possible problems of the **FSR (& VP**/undressing) treatment, e.g.

➤ KNT: $\boldsymbol{\delta a_\mu^{\mathrm{had,\,FSR}} = 7.0 \times 10^{-11}}$, and also $\boldsymbol{\delta a_\mu^{\mathrm{had,\,VP}} = 2.1 \times 10^{-11}}$

Channel	Energy range [GeV]	$a_\mu^{\text{had,LO VP}} \times 10^{10}$	$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) \times 10^4$	New data
		Chiral perturbation theory (ChPT) threshold contributions		
$\pi^0\gamma$	$m_\pi \le \sqrt{s} \le 0.600$	0.12 ± 0.01	0.00 ± 0.00	...
$\pi^+\pi^-$	$2m_\pi \le \sqrt{s} \le 0.305$	0.87 ± 0.02	0.01 ± 0.00	...
$\pi^+\pi^-\pi^0$	$3m_\pi \le \sqrt{s} \le 0.660$	0.01 ± 0.00	0.00 ± 0.00	...
$\eta\gamma$	$m_\eta \le \sqrt{s} \le 0.660$	0.00 ± 0.00	0.00 ± 0.00	...
		Data based channels ($\sqrt{s} \le 1.937$ GeV)		
$\pi^0\gamma$	$0.600 \le \sqrt{s} \le 1.350$	4.46 ± 0.10	0.36 ± 0.01	[65]
$\pi^+\pi^-$	$0.305 \le \sqrt{s} \le 1.937$	502.97 ± 1.97	34.26 ± 0.12	[34,35]
$\pi^+\pi^-\pi^0$	$0.660 \le \sqrt{s} \le 1.937$	47.79 ± 0.89	4.77 ± 0.08	[36]
$\pi^+\pi^-\pi^+\pi^-$	$0.613 \le \sqrt{s} \le 1.937$	14.87 ± 0.20	4.02 ± 0.05	[40,42]
$\pi^+\pi^-\pi^0\pi^0$	$0.850 \le \sqrt{s} \le 1.937$	19.39 ± 0.78	5.00 ± 0.20	[44]
$(2\pi^+2\pi^-\pi^0)_{\text{no}\eta}$	$1.013 \le \sqrt{s} \le 1.937$	0.99 ± 0.09	0.33 ± 0.03	...
$3\pi^+3\pi^-$	$1.313 \le \sqrt{s} \le 1.937$	0.23 ± 0.01	0.09 ± 0.01	[66]
$(2\pi^+2\pi^-2\pi^0)_{\text{no}\eta\omega}$	$1.322 \le \sqrt{s} \le 1.937$	1.35 ± 0.17	0.51 ± 0.06	...
K^+K^-	$0.988 \le \sqrt{s} \le 1.937$	23.03 ± 0.22	3.37 ± 0.03	[45,46,49]
$K_S^0K_L^0$	$1.004 \le \sqrt{s} \le 1.937$	13.04 ± 0.19	1.77 ± 0.03	[50,51]
$KK\pi$	$1.260 \le \sqrt{s} \le 1.937$	2.71 ± 0.12	0.89 ± 0.04	[53,54]
$KK2\pi$	$1.350 \le \sqrt{s} \le 1.937$	1.93 ± 0.08	0.75 ± 0.03	[50,53,55]
$\eta\gamma$	$0.660 \le \sqrt{s} \le 1.760$	0.70 ± 0.02	0.09 ± 0.00	[67]
$\eta\pi^+\pi^-$	$1.091 \le \sqrt{s} \le 1.937$	1.29 ± 0.06	0.39 ± 0.02	[68,69]
$(\eta\pi^+\pi^-\pi^0)_{\text{no}\omega}$	$1.333 \le \sqrt{s} \le 1.937$	0.60 ± 0.15	0.21 ± 0.05	[70]
$\eta 2\pi^+2\pi^-$	$1.338 \le \sqrt{s} \le 1.937$	0.08 ± 0.01	0.03 ± 0.00	...
$\eta\omega$	$1.333 \le \sqrt{s} \le 1.937$	0.31 ± 0.03	0.10 ± 0.01	[70,71]
$\omega(\to \pi^0\gamma)\pi^0$	$0.920 \le \sqrt{s} \le 1.937$	0.88 ± 0.02	0.19 ± 0.00	[72,73]
$\eta\phi$	$1.569 \le \sqrt{s} \le 1.937$	0.42 ± 0.03	0.15 ± 0.01	...
$\phi \to$ unaccounted	$0.988 \le \sqrt{s} \le 1.029$	0.04 ± 0.04	0.01 ± 0.01	...
$\eta\omega\pi^0$	$1.550 \le \sqrt{s} \le 1.937$	0.35 ± 0.09	0.14 ± 0.04	[74]
$\eta(\to \text{npp})K\bar{K}_{\text{no}\phi\to K\bar{K}}$	$1.569 \le \sqrt{s} \le 1.937$	0.01 ± 0.02	0.00 ± 0.01	[53,75]
$p\bar{p}$	$1.890 \le \sqrt{s} \le 1.937$	0.03 ± 0.00	0.01 ± 0.00	[76]
$n\bar{n}$	$1.912 \le \sqrt{s} \le 1.937$	0.03 ± 0.01	0.01 ± 0.00	[77]
		Estimated contributions ($\sqrt{s} \le 1.937$ GeV)		
$(\pi^+\pi^-3\pi^0)_{\text{no}\eta}$	$1.013 \le \sqrt{s} \le 1.937$	0.50 ± 0.04	0.16 ± 0.01	...
$(\pi^+\pi^-4\pi^0)_{\text{no}\eta}$	$1.313 \le \sqrt{s} \le 1.937$	0.21 ± 0.21	0.08 ± 0.08	...
$KK3\pi$	$1.569 \le \sqrt{s} \le 1.937$	0.03 ± 0.02	0.02 ± 0.01	...
$\omega(\to \text{npp})2\pi$	$1.285 \le \sqrt{s} \le 1.937$	0.10 ± 0.02	0.03 ± 0.01	...
$\omega(\to \text{npp})3\pi$	$1.322 \le \sqrt{s} \le 1.937$	0.17 ± 0.03	0.06 ± 0.01	...
$\omega(\to \text{npp})KK$	$1.569 \le \sqrt{s} \le 1.937$	0.00 ± 0.00	0.00 ± 0.00	...
$\eta\pi^+\pi^-2\pi^0$	$1.338 \le \sqrt{s} \le 1.937$	0.08 ± 0.04	0.03 ± 0.02	...
		Other contributions ($\sqrt{s} > 1.937$ GeV)		
Inclusive channel	$1.937 \le \sqrt{s} \le 11.199$	43.67 ± 0.67	82.82 ± 1.05	[56,62,63]
J/ψ	...	6.26 ± 0.19	7.07 ± 0.22	...
ψ'	...	1.58 ± 0.04	2.51 ± 0.06	...
$\Upsilon(1S-4S)$	...	0.09 ± 0.00	1.06 ± 0.02	...
pQCD	$11.199 \le \sqrt{s} \le \infty$	2.07 ± 0.00	124.79 ± 0.10	...
Total	$m_\pi \le \sqrt{s} \le \infty$	693.26 ± 2.46	276.11 ± 1.11	...

Table from KNT18,
PRD 97(2018)114025

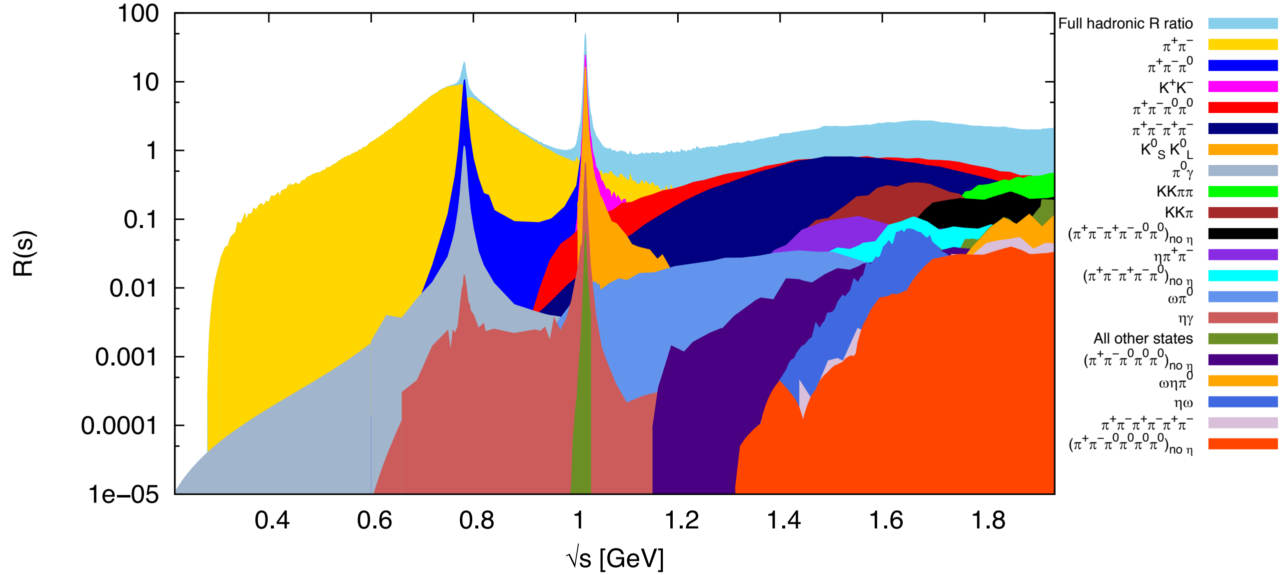
Update: KNT19
LO+NLO HVP for
$a_{e,\mu,\tau}$ & hyperfine splitting of muonium

PRD101(2020)014029

Breakdown of HVP contributions in ~35 hadronic channels

From 2-11 GeV, use of inclusive data, pQCD only beyond 11 GeV

a_μ^{HVP} : Landscape of $\sigma_{had}(s)$ data & most important $\pi^+\pi^-$ channel



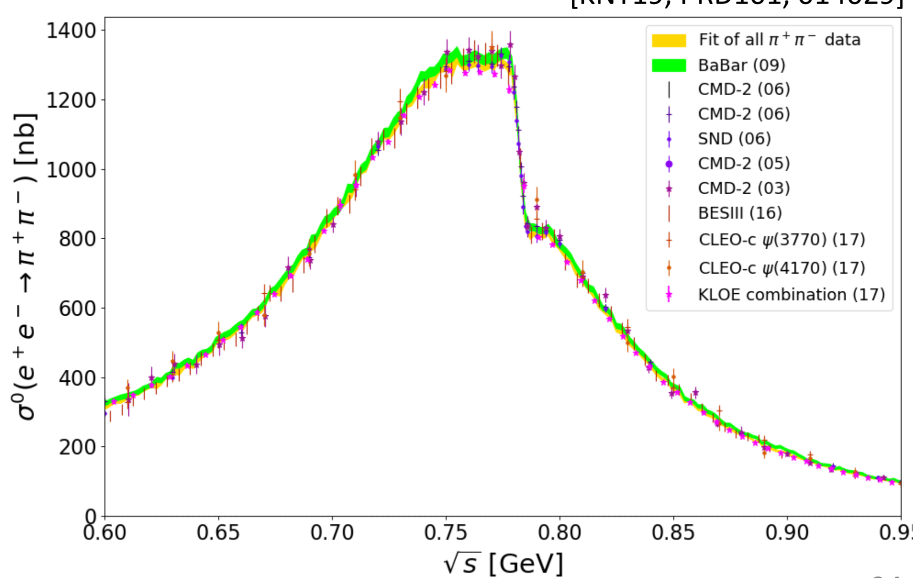
[KNT18, PRD97, 114025]

- hadronic channels for energies below 2 GeV
- dominance of 2π

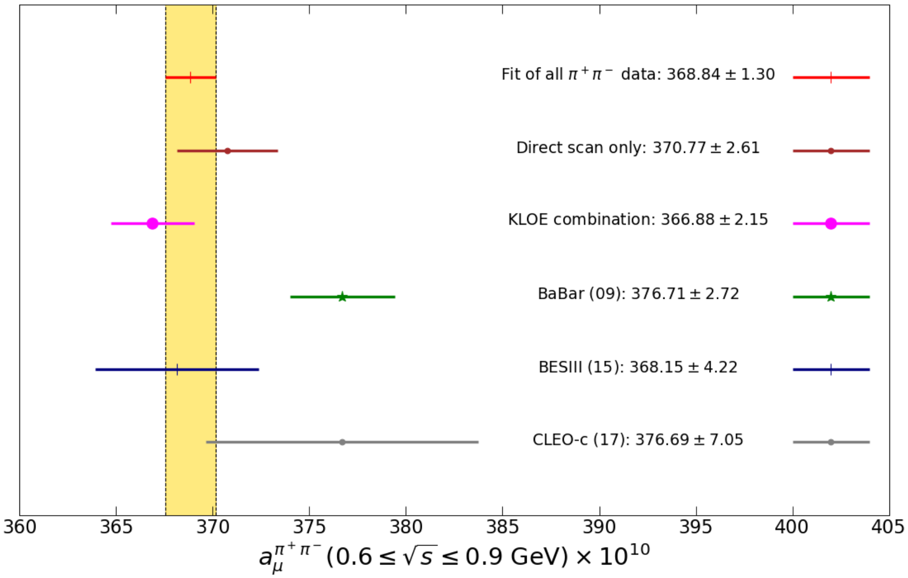
$\pi^+\pi^-$:

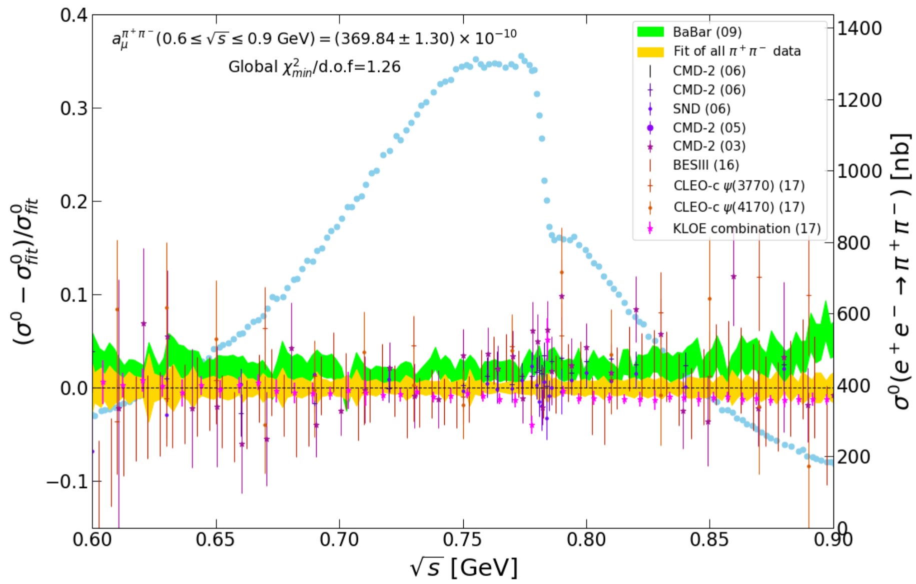
- Combination of >30 data sets, >1000 points, contributing >70% of total HVP
- Precise measurements from 6 independent experiments with different systematics and different radiative corrections
- Data sets from Radiative Return dominate
- Some tension in data accounted for by local χ^2_{min} inflation and via WP merging procedure

[KNT19, PRD101, 014029]



HVP: $\pi^+\pi^-$ channel [KNT19, Phys. Rev. D 101(2020)1, 014029]





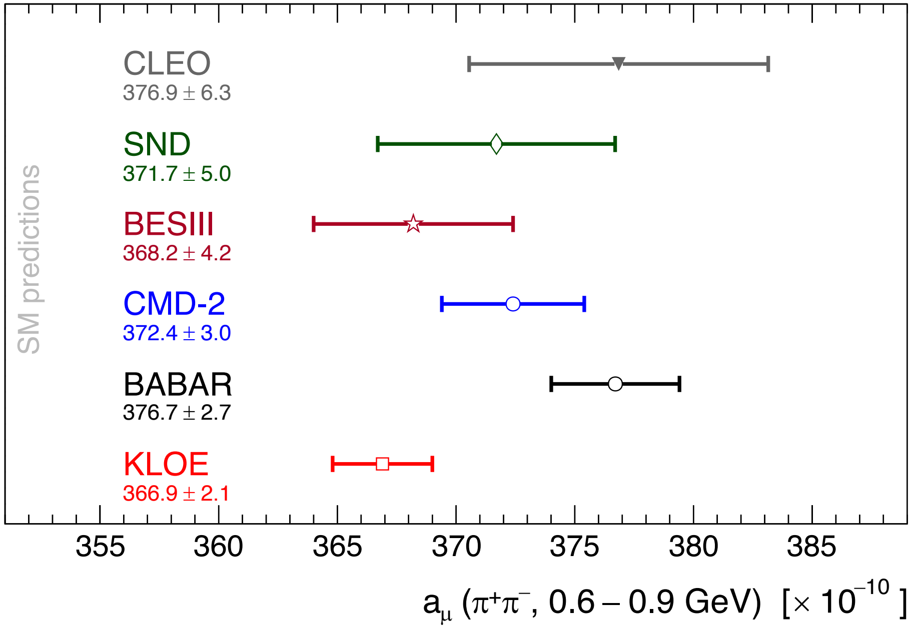
- Tension between different sets, especially between the most precise 4 sets from BaBar and KLOE
- Inflation of error with local χ^2_{min} accounts for tensions, leading to a ~15% error inflation
- Important role of correlations; their treatment in the data combination is crucial and can lead to significant differences between different combination methods

HVP: $\pi^+\pi^-$ channel [DHMZ, Eur. Phys. J. C 80(2020)3, 241]

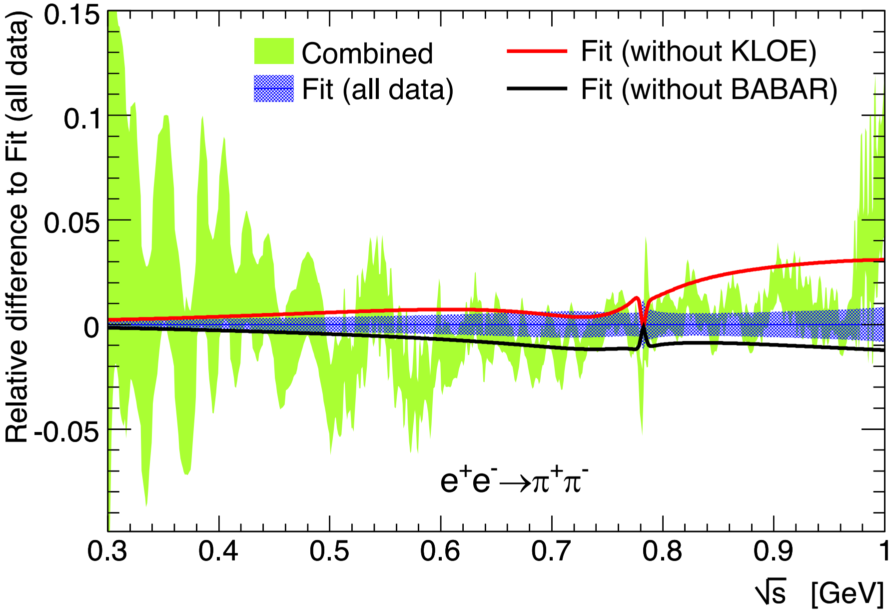
- In addition they employ a fit, based on **analyticity + unitarity + crossing symmetery,** similar to Colangelo et al. and Ananthanarayan+Caprini+Das, leading to stronger constraints/lower errors at low energies

- For 2π, based on difference between result for $a_\mu^{\pi\pi}$ w/out KLOE and BaBar, sizeable additional systematic error is applied and mean value adjusted

arXiv:1908.00921 Figure 5:

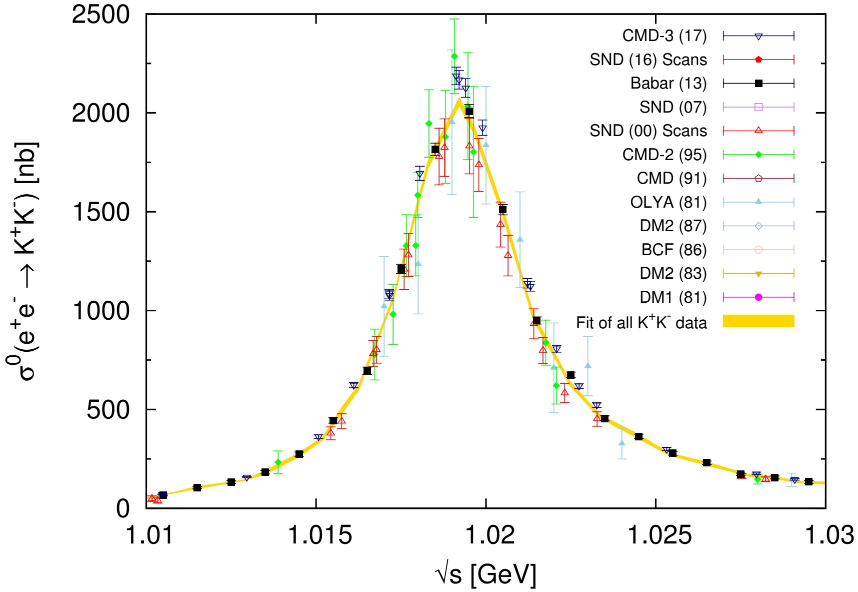


arXiv:1908.00921 Figure 6:



HVP: KK channels [KNT18, PRD97, 114025]

K^+K^-



New data:

BaBar: [Phys. Rev. D 88 (2013), 032013.]
SND: [Phys. Rev. D 94 (2016), 112006.]
CMD-3: [arXiv:1710.02989.]

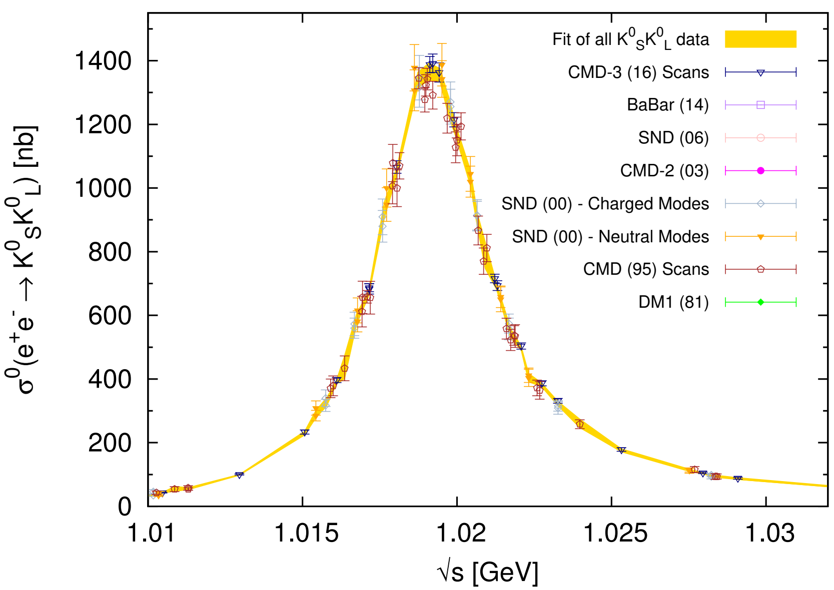
Note: CMD-2 data [Phys. Lett. B 669 (2008) 217.] omitted as waiting reanalysis.

$$a_\mu^{K^+K^-} = 23.03 \pm 0.22_{\text{tot}}$$

HLMNT11: $22.15 \pm 0.46_{\text{tot}}$

Large increase in mean value

$K^0_S K^0_L$



New data:

BaBar: [Phys. Rev. D 89 (2014), 092002.]
CMD-3: [Phys. Lett. B 760 (2016) 314.]

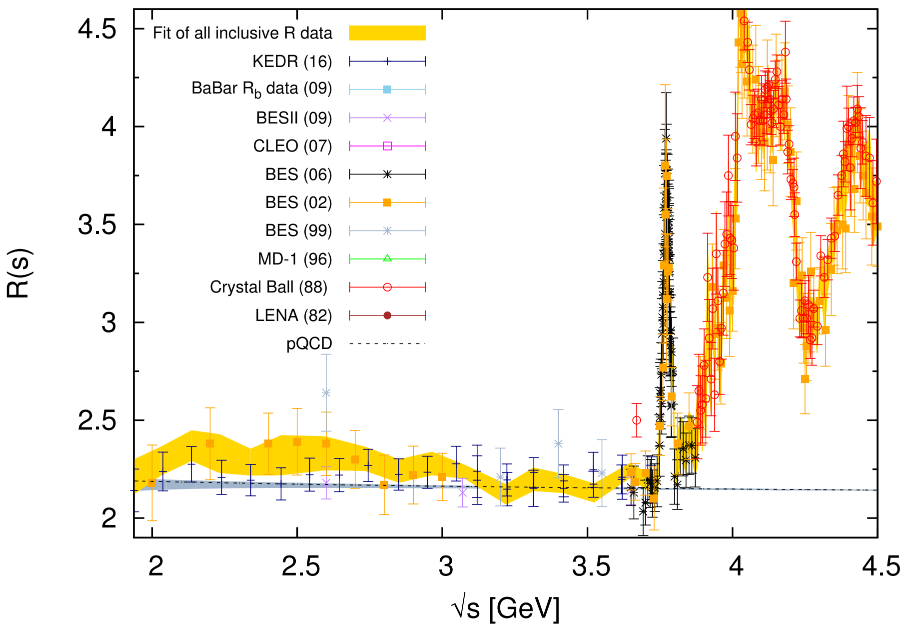
$$a_\mu^{K^0_S K^0_L} = 13.04 \pm 0.19_{\text{tot}}$$

HLMNT11: $13.33 \pm 0.16_{\text{tot}}$

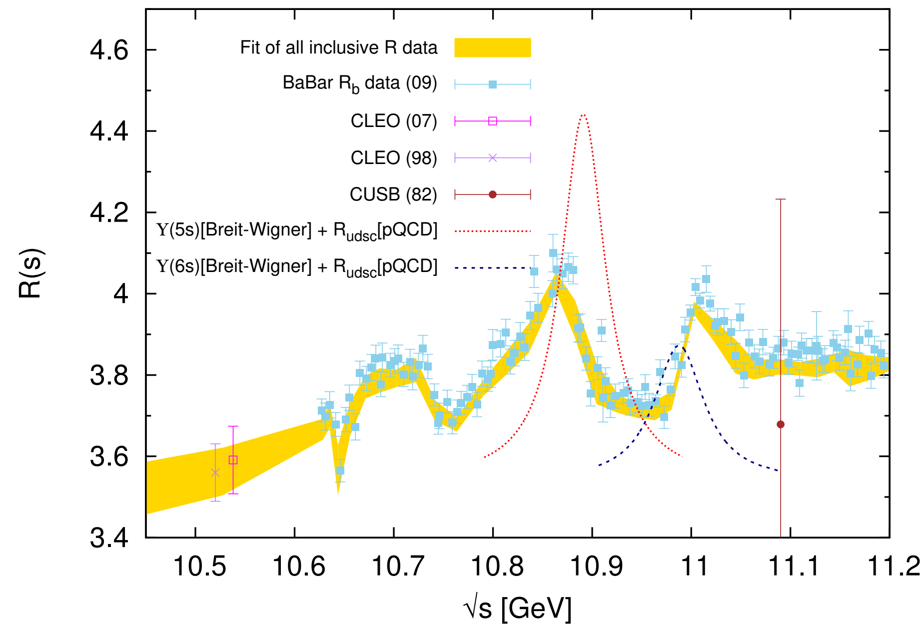
Large changes due to new precise measurements on ϕ

HVP: σ_{had} inclusive region [KNT18]

$\Rightarrow$ New KEDR inclusive R data [Phys.Lett. B770 (2017) 174-181, Phys.Lett. B753 (2016) 533-541] and BaBar R_b data [Phys. Rev. Lett. 102 (2009) 012001.].



KEDR data improves the inclusive data combination below $c\bar{c}$ threshold

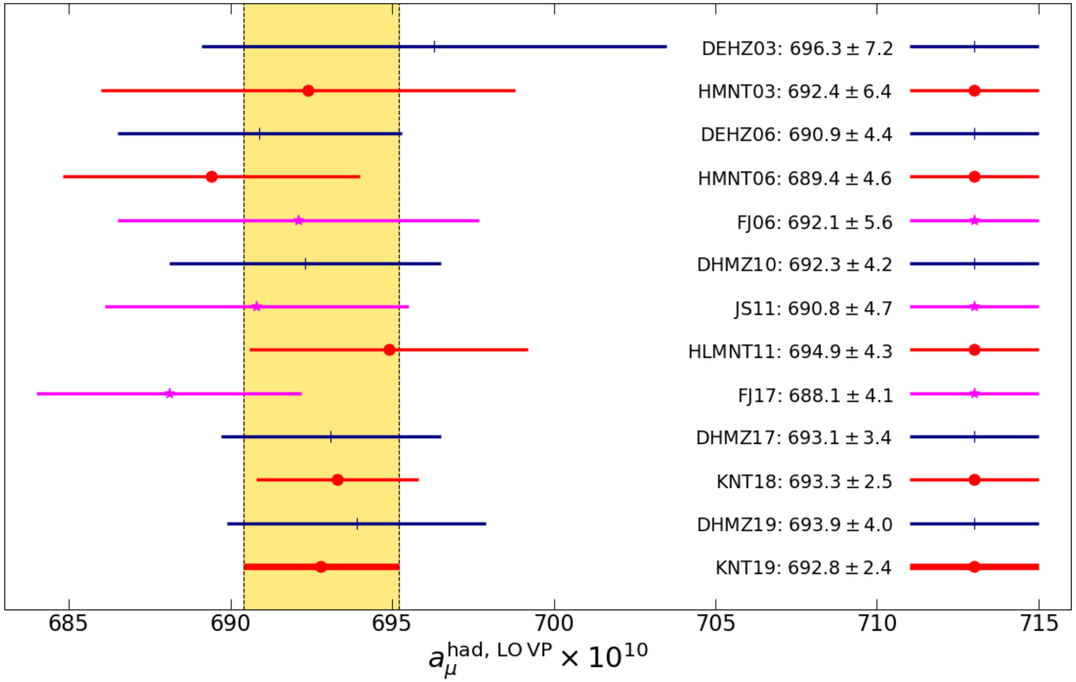


R_b resolves the resonances of the $\Upsilon(5S - 6S)$ states.

$\Longrightarrow$ **Choose to adopt entirely data driven estimate from threshold to 11.2 GeV**

$$a_\mu^{\text{Inclusive}} = 43.67 \pm 0.17_{\text{stat}} \pm 0.48_{\text{sys}} \pm 0.01_{\text{vp}} \pm 0.44_{\text{fsr}} = 43.67 \pm 0.67_{\text{tot}}$$

History plot of a_μ^{HVP} w. min. model dep. Pies.



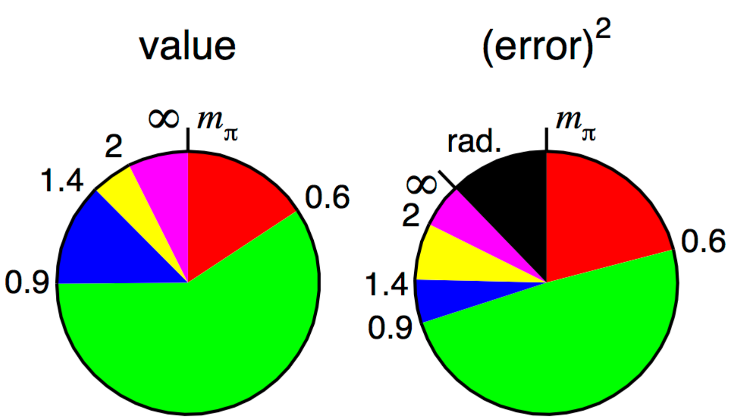
- Stability and consolidation over two decades thanks to more and better data input and improved compilation procedures

- Compare with `merged' DHMZ & KNT WP20 value:

$$\mathbf{a_\mu^{\text{had, LO VP}}(WP20) = 693.1(4.0)\times 10^{-10}}$$

Pie diagrams [KNT]:

- error still dominated by two pion channel
- significant contribution to error from additional uncertainty from radiative corrections



HVP: White Paper comparison & merging procedure

Detailed comparisons by-channel and energy range between direct integration results:

	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(0.83)(3.23)(0.55)	504.23(1.90)	3.62
$\pi^+\pi^-\pi^0$	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
K^+K^-	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
$K_S K_L$	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)(3.48)(1.47)	623.62(2.27)	2.46
$[1.8, 3.7]$ GeV (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
J/ψ, $\psi(2S)$	7.76(12)	7.84(19)	−0.08
$[3.7, \infty)$ GeV	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\text{HVP, LO}}$	$694.0(1.0)(3.5)(1.6)(0.1)_\psi(0.7)_{\text{DV+QCD}}$	692.8(2.4)	1.2

+ evaluations using unitarity & analyticity constraints for $\pi\pi$ and $\pi\pi\pi$ channels

[CHS 2018, HHKS 2019]

HVP: White Paper comparison & merging procedure

Conservative merging procedure developed during 2019 Seattle TI workshop:

- Accounts for the different results obtained by different groups based on the same or similar experimental input
- Includes correlations and their different treatment as much as possible
- Allows to give one recommended (merged) result, which is conservative w.r.t. the underlying (and possibly underestimated) uncertainties
- Note: Merging leads to a bigger error estimate compared to individual evaluations

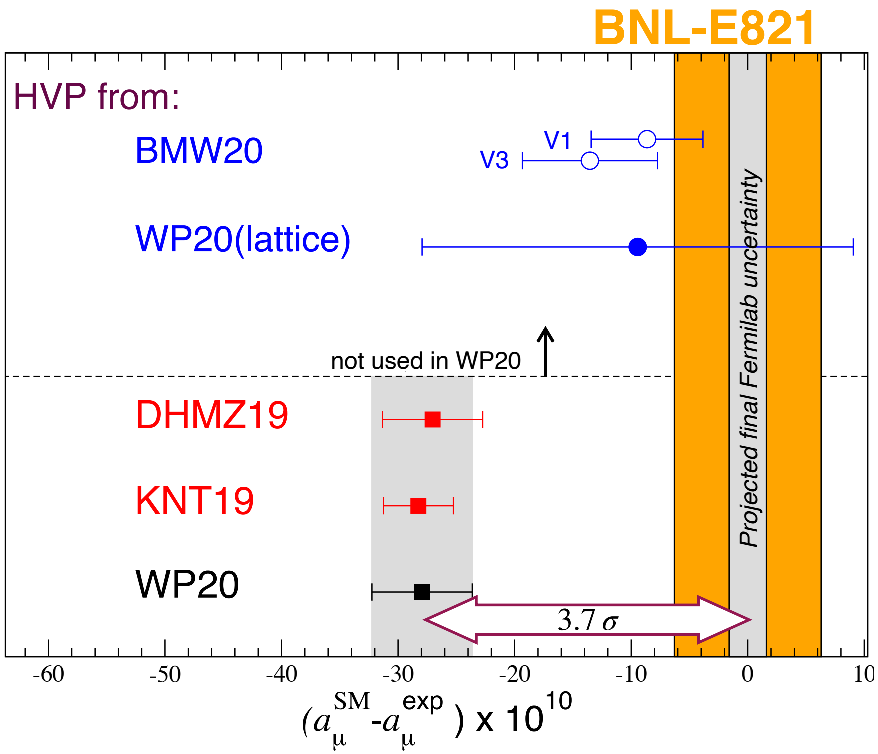
➠ $a_\mu^{\mathrm{HVP,\,LO}} = 693.1\,(4.0) \times 10^{-10}$ is the result used in the WP `SM2020' value

- This result does not include lattice, but is compatible with published lattice results apart from the BMW prediction:

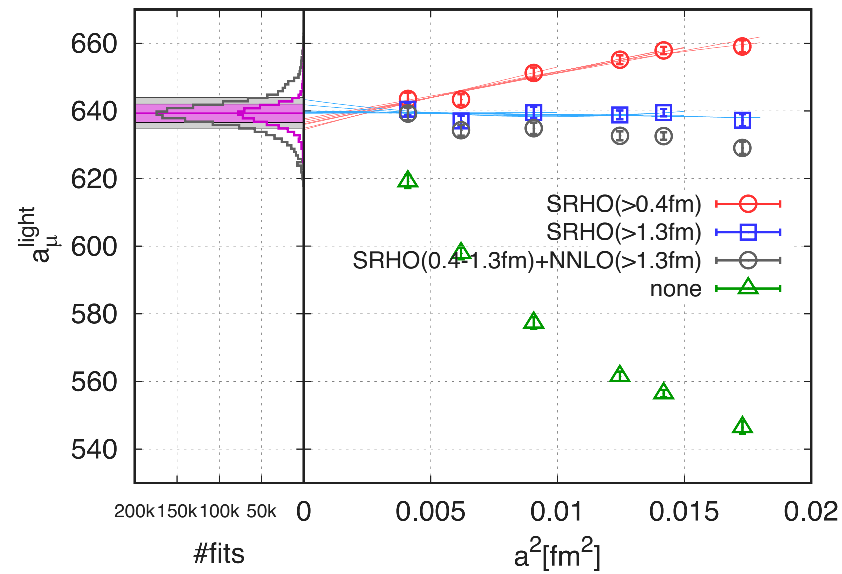
  $a_\mu^{\mathrm{HVP,\,LO}}\,(\mathrm{BMW}) = 707.5\,(5.5) \times 10^{-10}$ [Nature]

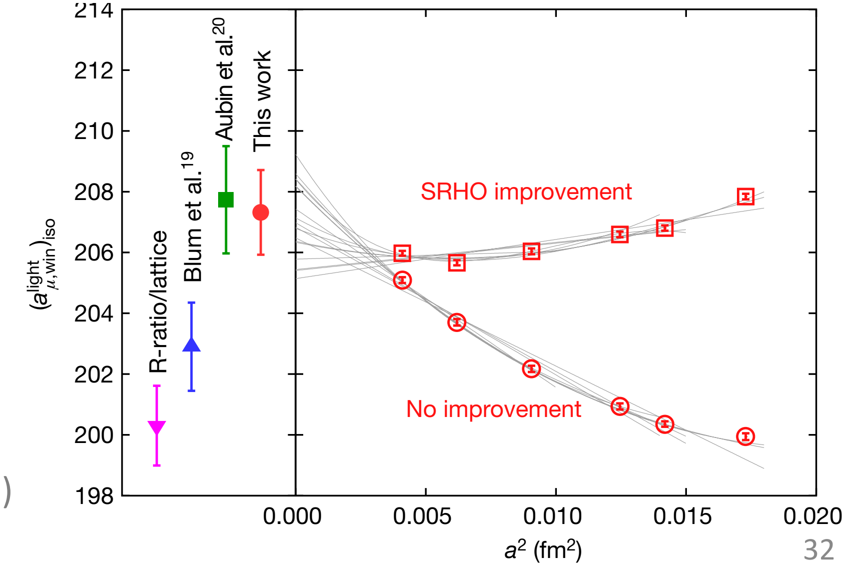
Efforts are ongoing in the community to check their result, with a topical online workshop from the g-2 Theory Initiative in November 2020 shedding first light.

Lattice HVP: Tension betw. BMW & data-driven. Systematics



BMW20 [Borsanyi et al, arXiv:2002.12347, 2021 Nature]

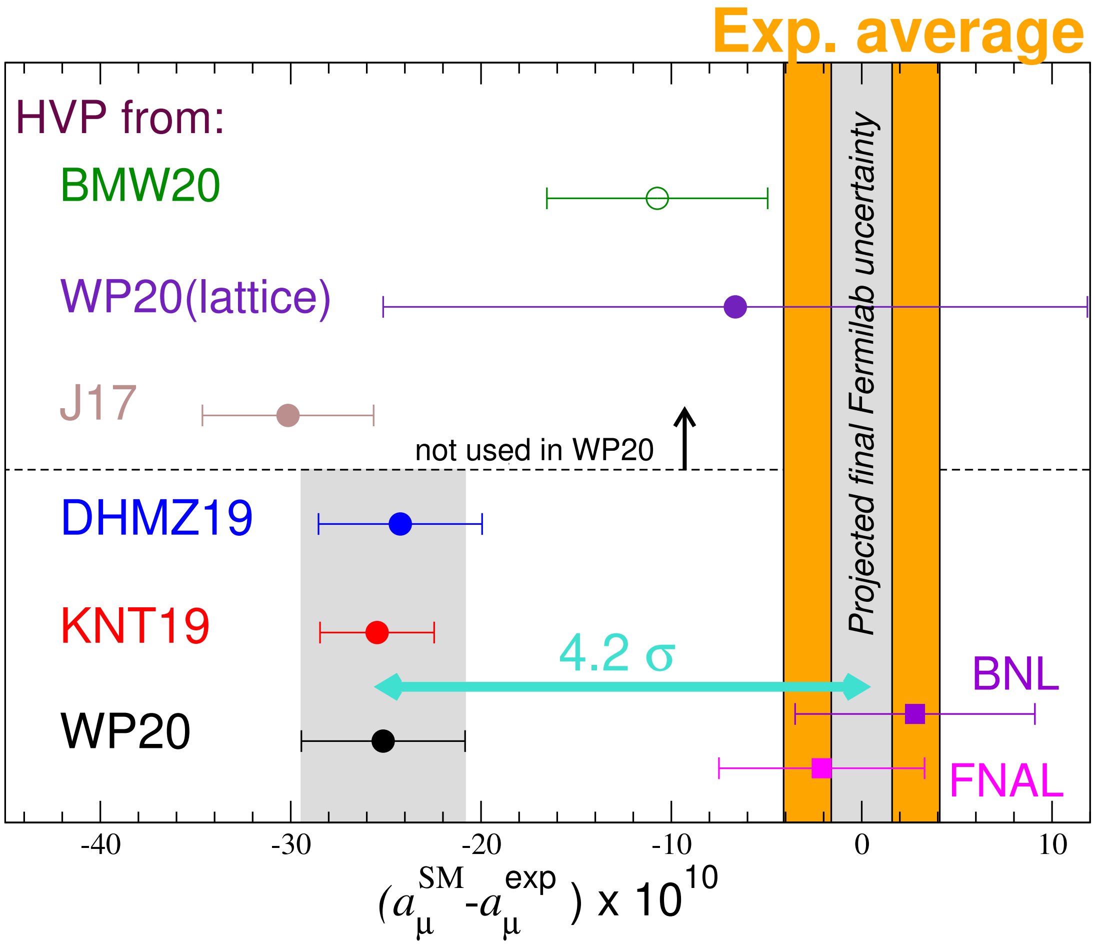




BMW20: large systematics from **continuum limit,** large taste-breaking corrections (`SRHO')

- upper right panel: limit and uncertainty estimation
- lower right panel: limit for central `window' compared to other lattice and data-driven results (3.7σ tension!)

Muon g-2 SM prediction from the TI WP vs. FNAL



SM prediction:

$$a_\mu^{SM} = 116\,591\,810(43) \times 10^{-11}$$

FNAL E989 (2021):

$$a_\mu^{E989} = 116\,592\,040(54) \times 10^{-11}$$

Combined with BNL E821 (2004):

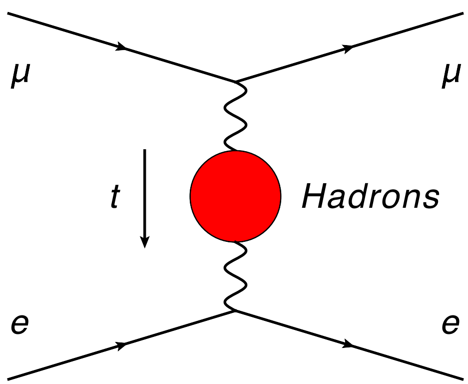
$$a_\mu^{exp} = 116\,592\,061(41) \times 10^{-11}$$

$$a_\mu^{SM} - a_\mu^{exp} = 251(59) \times 10^{-10} \quad (4.2\,\sigma)$$

This is experiment vs. theory **with** the new FNAL g-2 Run-1 result announced 7th April

HVP from electron-muon scattering in the space-like

M. Passera @ HVP KEK 2018 [A. Abbiendi et al, arXiv:1609.08987, EPJC 2017]



$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx\,(1-x)\,\Delta\alpha_{\mathrm{had}}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

$\Delta\alpha_{\mathrm{had}}(t)$ is the hadronic contribution to the running of α in the space-like region. It can be extracted from scattering data!

- use CERN M2 muon beam (150 GeV)
- Physics beyond colliders program @ CERN
- LOI June 2019
- Jan 2020: SPSC recommends pilot run in 2021
- goal: run with full apparatus in 2023-2024

Summary & Perspective

- The still **unresolved muon g-2 discrepancy** has triggered new experiments and a lot of theory activities, including and helped by the Muon g-2 Theory Initiative

- **Much progress** has been made for **HLbL** which previously was seen as the bottleneck.
  New data driven dispersive approaches & lattice have confirmed earlier model estimates and now allow a **reliable error estimate**, and **more work is in progress**
- For **HVP dispersive**, the **TI published a conservative & robust consensus**.
  Soon **new hadronic data for 2π** will come from **BaBar, CMD-3, BESIII and Belle-II**
- Longer term: direct HVP measurement planned with e-μ scattering: **MUonE** at CERN

- **Lattice** has started to deliver impressive results with **high precision**.
  Further work is needed and ongoing to scrutinize, check and improve different approaches, and lattice is expected to play an important role in the future

- The **Muon g-2 Theory Initiative** will continue to facilitate this work and to publish agreed & conservative SM predictions for g-2 prior to new experimental results
- With the **WP20 SM** prediction and the new first g-2 result from **FNAL**,

the discrepancy stands at 4.2σ and is more intriguing than ever.

Extras/discussion

Lattice HVP: Cross checks, window method (I)

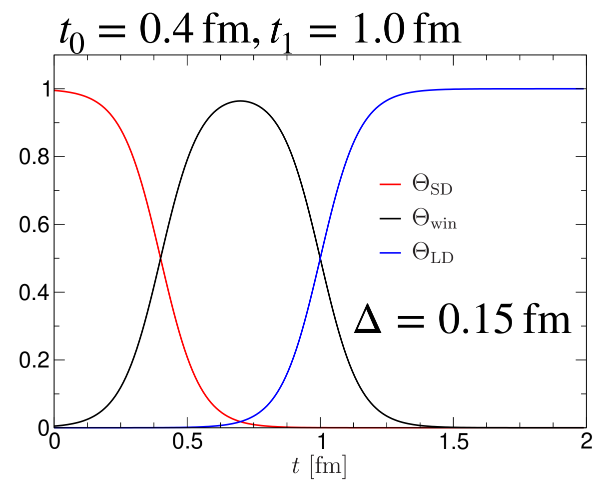
$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, \tilde{w}(t)\, C(t)$$

- Use windows in Euclidean time to consider the different time regions separately.

Short Distance (SD) $t : 0 \to t_0$

Intermediate (W) $t : t_0 \to t_1$

Long Distance (LD) $t : t_1 \to \infty$



- Compute each window separately (in continuum, infinite volume limits,…) and combine

$$a_\mu = a_\mu^{\mathrm{SD}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{LD}}$$

Lattice HVP: Cross checks, window method (II)

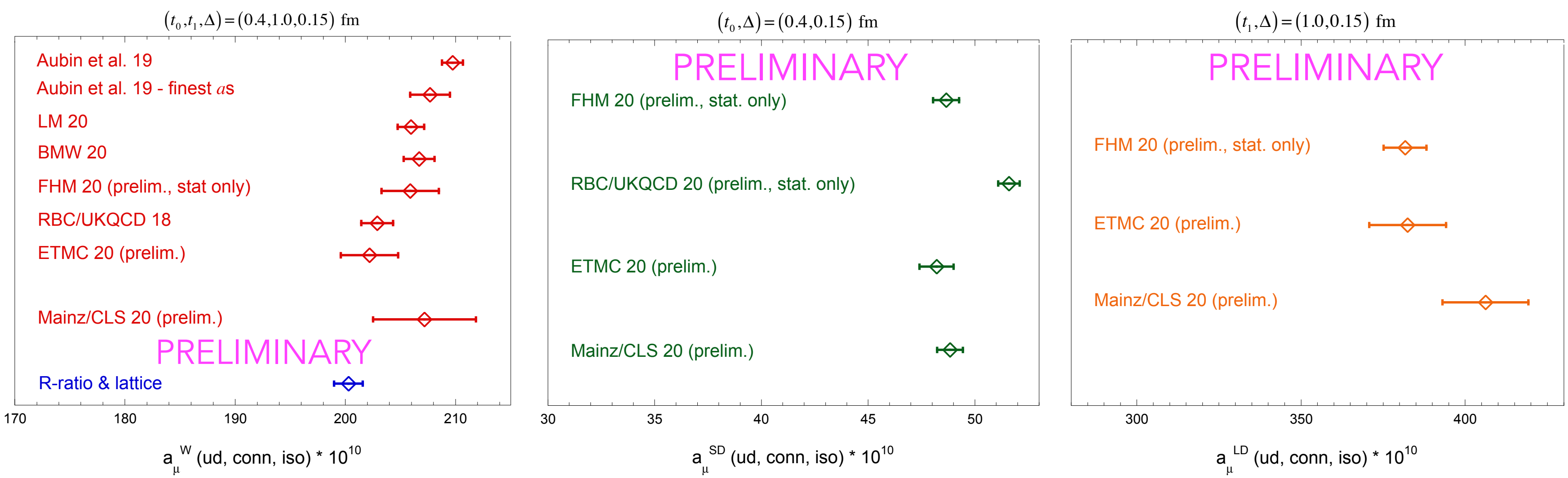
H. Wittig @ Lattice HVP workshop

$$t_0 = 0.4\,\text{fm}, t_1 = 1.0\,\text{fm}$$
$$\Delta = 0.15\,\text{fm}$$

$$a_\mu = a_\mu^{\rm SD} + a_\mu^{\rm W} + a_\mu^{\rm LD}$$

"Window" quantities

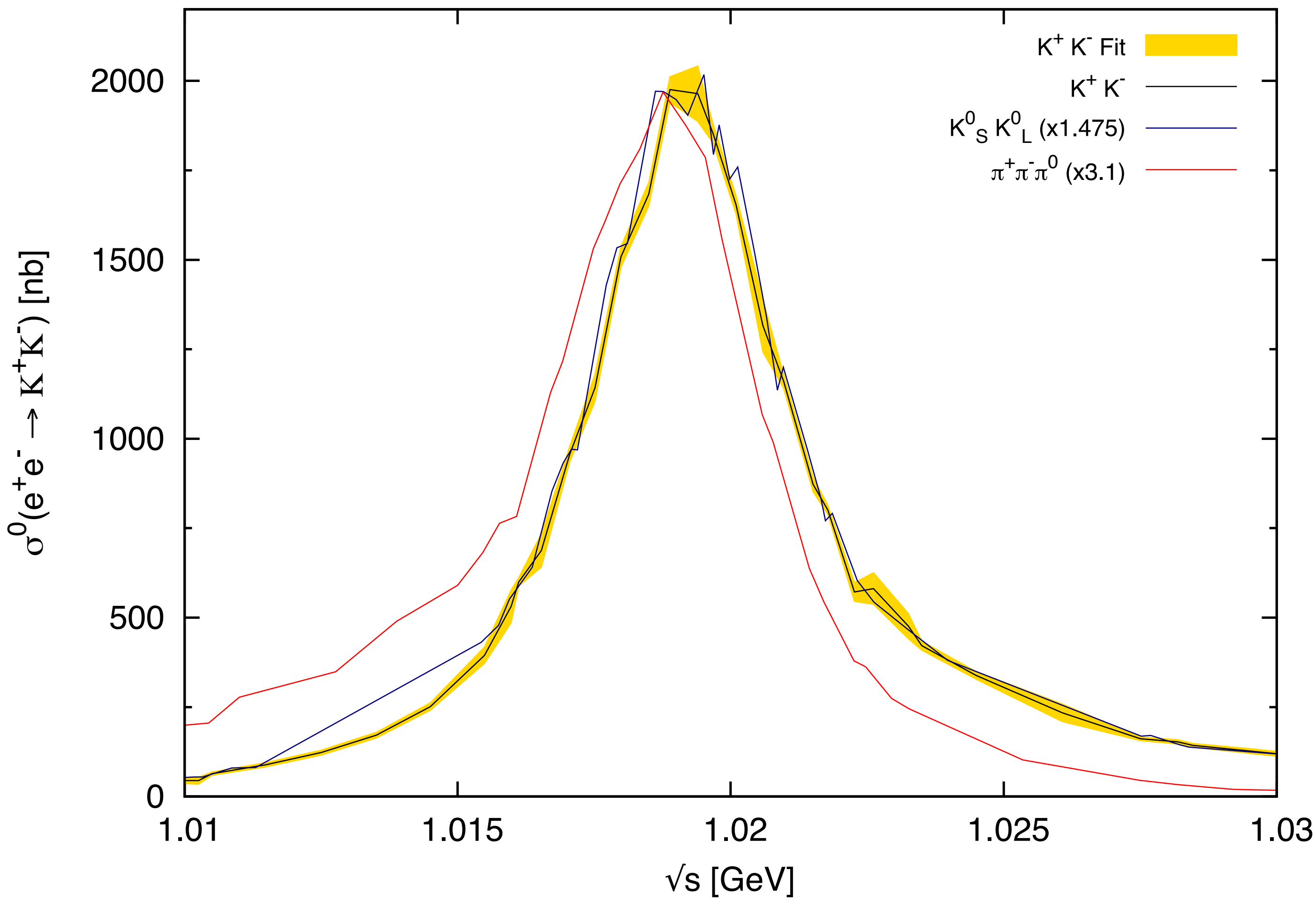
(Plots from Davide Giusti)



- Straightforward reference quantities
- Can be applied to individual contributions (light, strange, charm, disconnected,…)
- **Large discrepancies** between different results, also with data-driven: **BMW vs KNT: 3.7σ**
- Individual results **must sum up**, and different groups & discretisations **must agree** (universality)

HVP: Φ in different final states K^+K^-, $K_S^0K_L^0$, $\pi^+\pi^-\pi^0$

- Direct data integration automatically accounts for all hadronic dynamics, no resonance fits/parametrisations or estimates of mixing effects needed.



For demo. only, does not include latest data

a_μ^{HVP} : Hadronic tau decay data

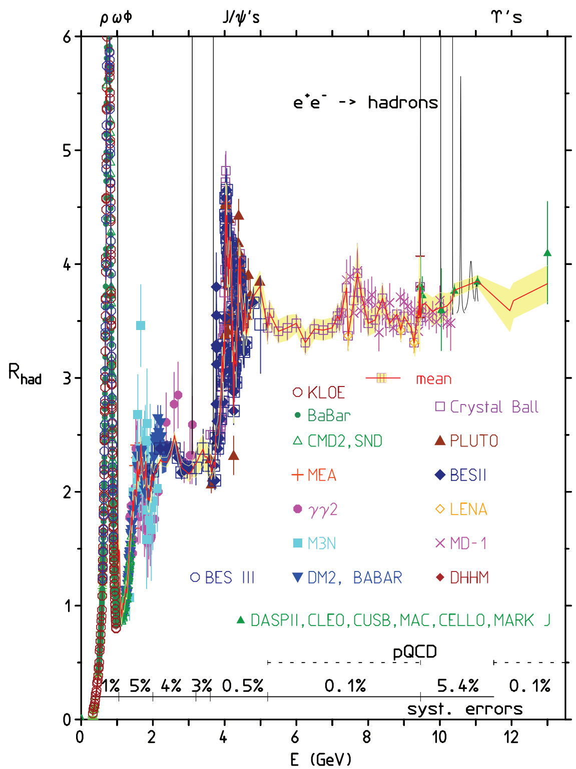
- Historically, hadronic tau decay data, e.g. $\tau^- \to \pi^0\pi^-\nu_\tau$, were used to improve precision of e^+e^- based evaluations
- However, with the increased precision of the e^+e^- data there is now limited merit in this (DHMZ have dropped it), and
- The required iso-spin breaking corrections re-introduce a model-dependence and connected systematic uncertainty (there is, e.g., no ρ–ω mixing in τ decays)
- Quote from the WP, where this approach is discussed in detail:

"Concluding this part, it appears that, at the required precision to match the e^+e^- data, the present understanding of the IB corrections to τ data is unfortunately not yet at a level allowing their use for the HVP dispersion integrals. It remains a possibility, however, that the alternate lattice approach, discussed in Sec. 3.4.2, may provide a solution to this problem."

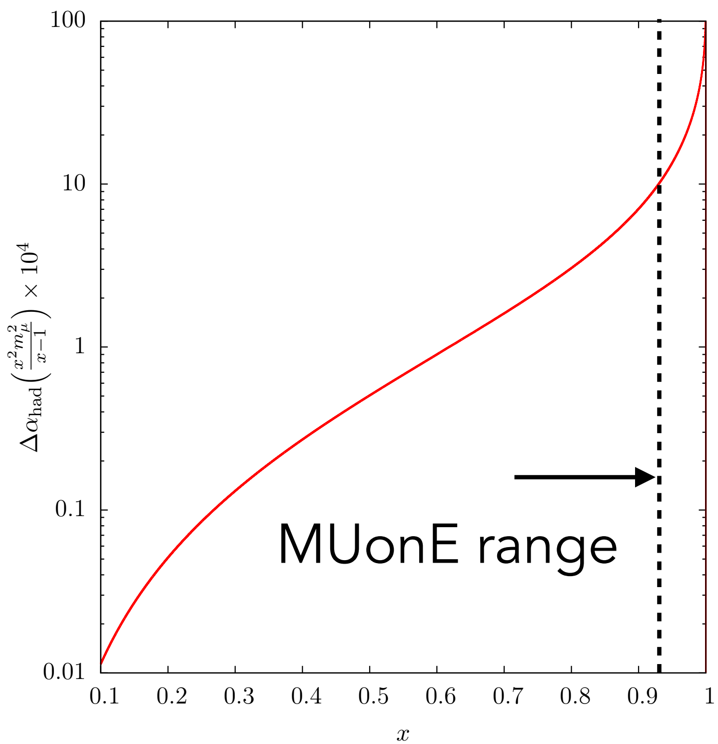
HVP from electron muon scattering in the space-like

C. Carloni @ g-2 INT workshop [A. Abbiendi et al, arXiv:1609.08987, EPJC 2017]

Time-like ↦ **Space-like**



F. Jegerlehner, EPJ Web Conf. 118



CC, Passera, Trentadue, Venanzoni PLB 746 (2015) 325

Smooth function

- requires calculations of radiative corrections [M. Fael @ g-2 INT workshop]
- complement region not accessible to experiment with LQCD calculation [M. Marinkovic @ g-2 INT workshop]

a_μ (SM): White Paper https://doi.org/10.1016/j.physrep.2020.07.006

White Paper [T. Aoyama et al, arXiv:2006.04822], 132 authors, 82 institutions, 21 countries

Contribution	Value $\times 10^{11}$	References
Experiment (E821)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	12.4(1)	Ref. [8]
HVP LO (lattice, $udsc$)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	2(1)	Ref. [31]
HLbL (lattice, uds)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	90(17)	Refs. [18–30, 32]
QED	116 584 718.931(104)	Refs. [33, 34]
Electroweak	153.6(1.0)	Refs. [35, 36]
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	92(18)	Refs. [18–32]
Total SM Value	116 591 810(43)	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	279(76)	

w.r.t. BNL

HVP: Connection between g-2 and $\Delta\alpha(M_Z^2)$

Precision observable $\alpha(M_Z^2) = \alpha/(1-\Delta\alpha(M_Z^2))$ as a sensitive test of HVP

Slide content by Massimo Passera

- Can Δa_μ be due to hypothetical mistakes in the hadronic $\sigma(s)$?
- An upward shift of $\sigma(s)$ also induces an increase of $\Delta\alpha_{had}^{(5)}(M_Z)$.
- Consider:

$$a_\mu^{HLO} \rightarrow \quad a = \int_{4m_\pi^2}^{s_u} ds\, f(s)\,\sigma(s), \qquad f(s) = \frac{K(s)}{4\pi^3}, \quad s_u < M_Z^2,$$

$$\Delta\alpha_{had}^{(5)} \rightarrow \quad b = \int_{4m_\pi^2}^{s_u} ds\, g(s)\,\sigma(s), \qquad g(s) = \frac{M_Z^2}{(M_Z^2 - s)(4\alpha\pi^2)},$$

and the increase

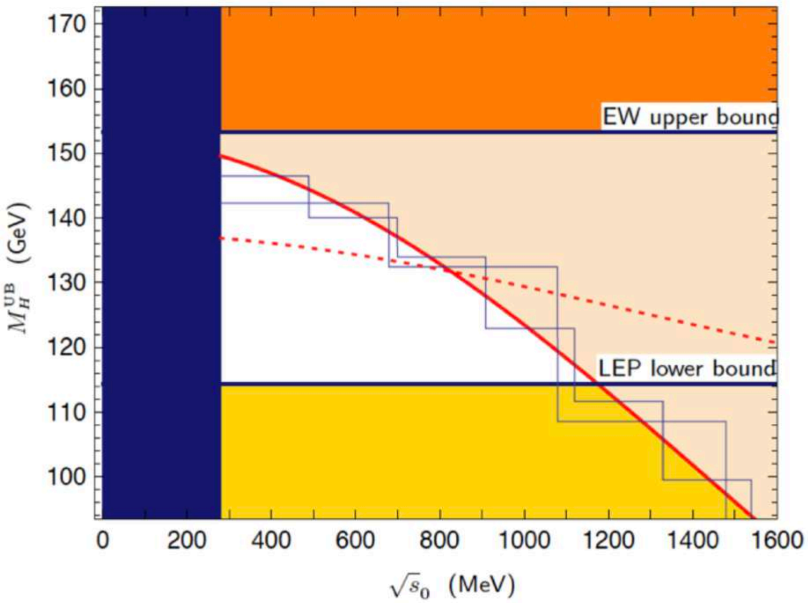
$$\Delta\sigma(s) = \epsilon\sigma(s)$$

$\epsilon>0$, in the range:

$$\sqrt{s} \in [\sqrt{s_0} - \delta/2, \sqrt{s_0} + \delta/2]$$

Note the very different energy-dependent weighting of the integrands…

HVP: Connection between g-2 and $\Delta\alpha(M_Z^2)$



Marciano, Passera, Sirlin (2008):

- changing the hadronic cross section at higher energies significantly upwards leads to tensions in EW precision fits of the SM.
- not easy to reconcile g-2 without running into problems with $\Delta\alpha(M_Z^2)$

Recent studies by several groups, e.g.

- Crivellin et al, PRL125(2020)9,091801: Shifts in HVP make fit based on HEPFitter worse, but they can not rule out shifts at low energies as obtained by the BMW lattice analysis
- Keshavarzi et al, PRD102(2020)3,033002: updating Marciano et al, again find significant tensions with Gfitter if shifts in HVP were to explain g-2, unless they are below ~0.7 GeV

- However, the low energies hadronic cross section measurements (mainly 2pi) are most precise there.