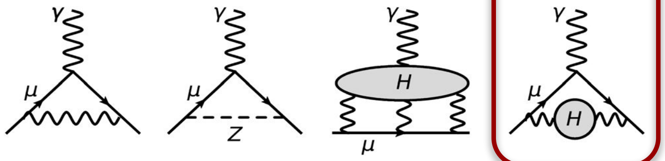
# Muon g-2: from Anomaly to Agreement

## The HVP contribution from Lattice QCD

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HLbL}} + \boxed{a_\mu^{\mathrm{HVP}}}$$




**Simone Bacchio**

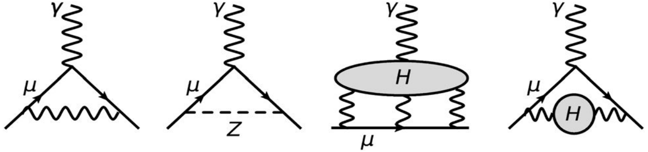
CaSToRC, The Cyprus Institute

Extended Twisted Mass Collaboration (ETMC)

**28/10/25 – Electromagnetic Interactions in Nucleon and Nuclei – Paphos**

# Why the HVP contribution? [WP25: arXiv:2505.21476]

$$a_\mu^{\mathrm{SM}} = \overset{\mathcal{O}(10^{-3})}{a_\mu^{\mathrm{QED}}} + \overset{\mathcal{O}(10^{-9})}{a_\mu^{\mathrm{EW}}} + \overset{\mathcal{O}(10^{-9})}{a_\mu^{\mathrm{HLbL}}} + \overset{\mathcal{O}(7\cdot 10^{-8})}{a_\mu^{\mathrm{HVP}}}$$

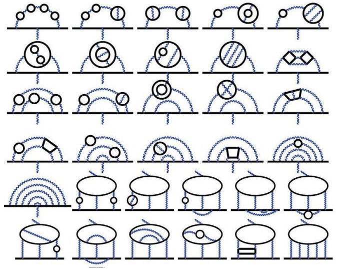



*Perturbative* *Non-perturbative*

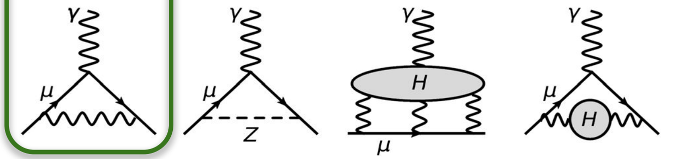
# Why the HVP contribution? [WP25: arXiv:2505.21476]

>99.99% of the value

Computed to $\alpha^5$, e.g.



$$a_\mu^{\rm SM} = \underbrace{\overset{\mathcal{O}(10^{-3})}{\boxed{a_\mu^{\rm QED}}} + \overset{\mathcal{O}(10^{-9})}{a_\mu^{\rm EW}}}_{\text{Perturbative}} + \underbrace{\overset{\mathcal{O}(10^{-9})}{a_\mu^{\rm HLbL}} + \overset{\mathcal{O}(7\cdot 10^{-8})}{a_\mu^{\rm HVP}}}_{\text{Non-perturbative}}$$




$\pm 10^{-12}$

$$\boxed{a_\mu^{\rm QED} = 116\,584\,718.931(104) \times 10^{-11}} \checkmark$$

[T. Aoyama *et al.* PRLs, 2012]

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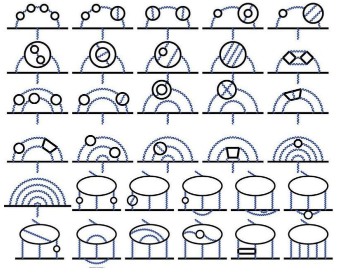

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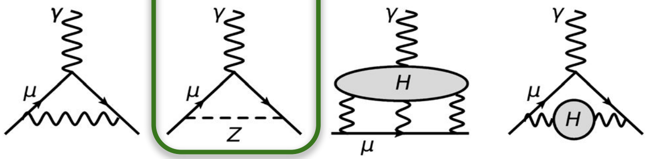


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[T. Aoyama *et al.* PRLs, 2012]

Computed at two loops $\pm 4\cdot 10^{-12}$

$$\boxed{a_\mu^{\mathrm{weak}} = 154.4\,(4) \times 10^{-11}} \checkmark$$

[Czarnecki *et al.* PRD (2006), Gnendiger *et al.* PRD (2013)]

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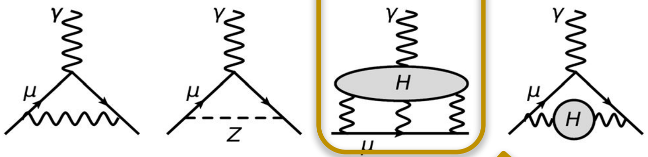


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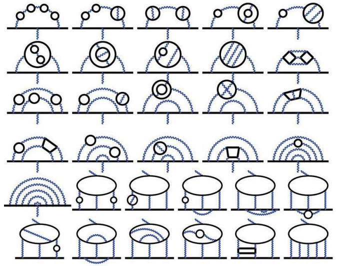

$\pm 10^{-12}$

$$a_\mu^{\text{QED}} = 116\,584\,718.931(104) \times 10^{-11} \checkmark$$

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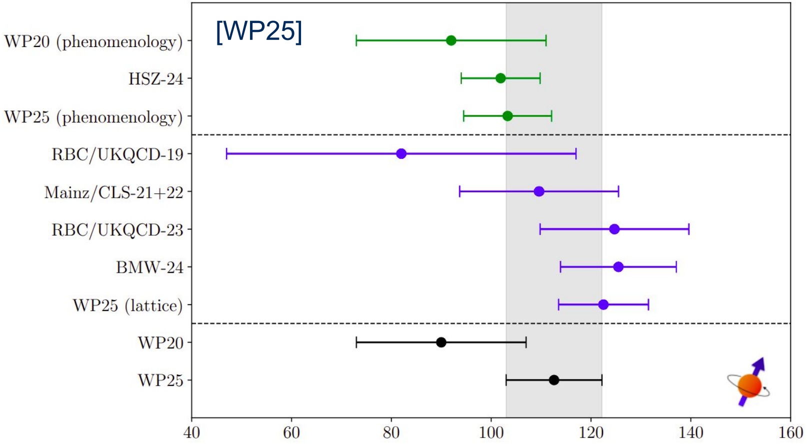
$\pm 10^{-10}$

$$a_\mu^{\text{HLbL}} = 112.6(9.6) \times 10^{-11}$$



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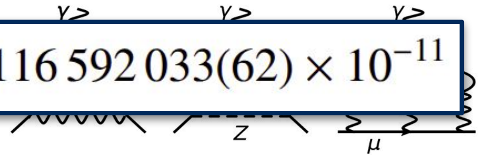
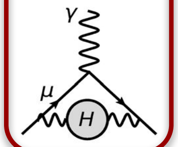


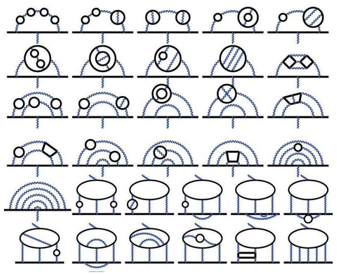

$$a_\mu^{\text{SM}} = 116\,592\,033(62) \times 10^{-11}$$

Perturbative

Non-perturbative

>99.99% of the value

Computed to $\alpha^5$, e.g.



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[Czarnecki *et al.* PRD (2006), Gnendiger *et al.* PRD (2013)]

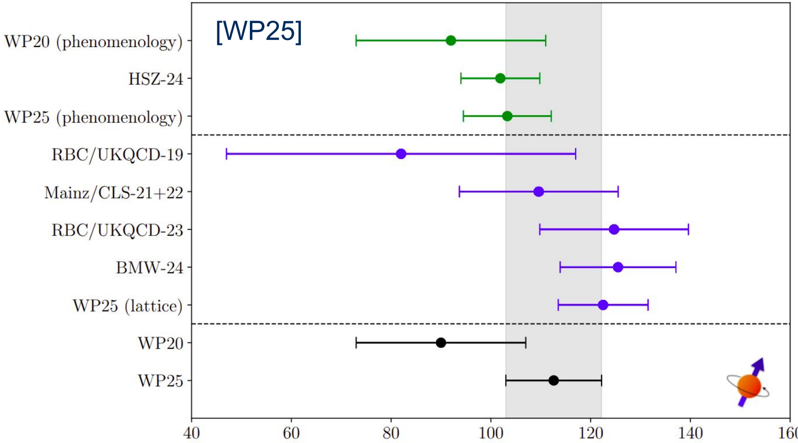
>98% of the error!

$\pm 6\cdot 10^{-10}$

$$a_\mu^{\text{HVP}} = 7045(61) \times 10^{-11}$$

$\pm 10^{-10}$

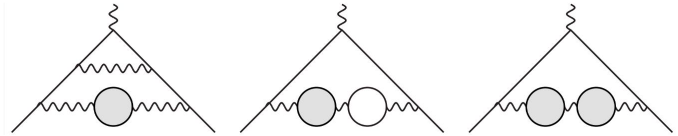
$$a_\mu^{\text{HLbL}} = 112.6(9.6) \times 10^{-11}$$



# The Hadronic Vacuum Polarization

$$a_\mu^{\mathrm{HVP}} = \underbrace{a_\mu^{\mathrm{HVP,LO}}}_{\mathcal{O}(7\cdot 10^{-8})} + \underbrace{a_\mu^{\mathrm{HVP,NLO}}}_{\mathcal{O}(10^{-9})} + \underbrace{a_\mu^{\mathrm{HVP,NNLO}}}_{\mathcal{O}(10^{-10})}$$

Relevant diagrams at NLO and NNLO:



The key ingredient is the spectral density of the HVP:


$\rho^{\mathrm{HVP}}(\omega) \Rightarrow$

*Dispersive approach* *Lattice TMR approach*

$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty d\omega\, \rho^{\mathrm{HVP}}(\omega)\, \hat{K}_{a_\mu}(\omega) = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, G^{\mathrm{HVP}}(t)\, \tilde{K}_{a_\mu}(t)$$

with
$$G^{\mathrm{HVP}}(t) = \int_0^\infty d\omega\, e^{-\omega t}\, \rho^{\mathrm{HVP}}(\omega)$$
$$\tilde{K}_{a_\mu}(t) = \int_0^\infty d\omega\, e^{-\omega t}\, \hat{K}_{a_\mu}(\omega)$$

Currently, two theoretical approaches to compute it:

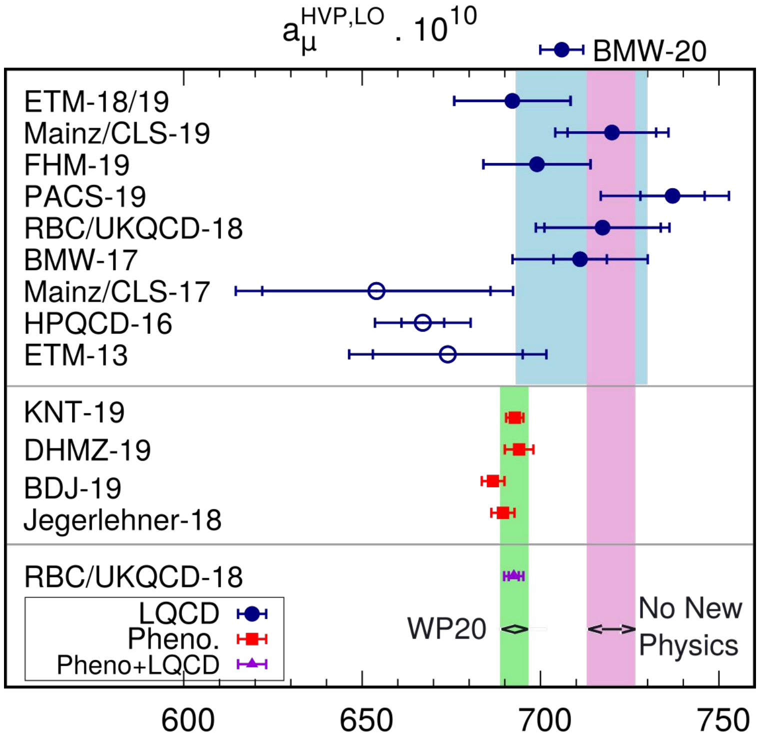
- **Dispersive approach:**

  Relates $a_\mu^{\mathrm{HVP}}$ to $e^+e^- \to \text{hadrons}$ cross-sections via optical theorem (or to hadronic $\tau$ decay)

- **Lattice TMR approach:**

  Relates $a_\mu^{\mathrm{HVP}}$ to vector-vector Euclidean correlation functions

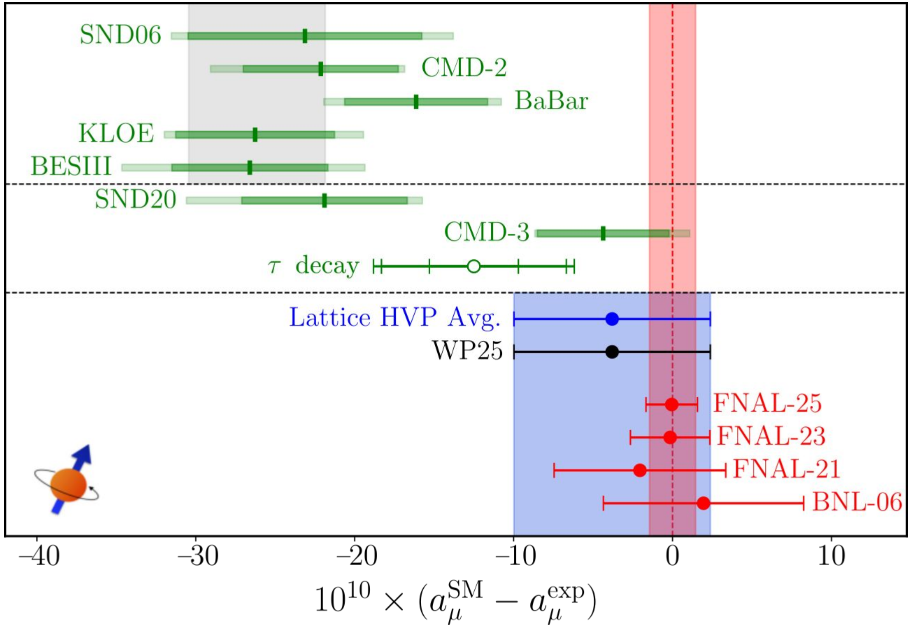
# From Anomaly to Agreement




Results in WP20

- **BMW20:** first precise lattice QCD calculation
  [Sz. Borsanyi *et al.*, 2020]

## Results in WP25



# Ingredients for high-precision Lattice QCD results

- **(Pre-)Exascale computing:** EuroHPC-JU is the largest pan-European initiative dedicated to funding HPC resources.

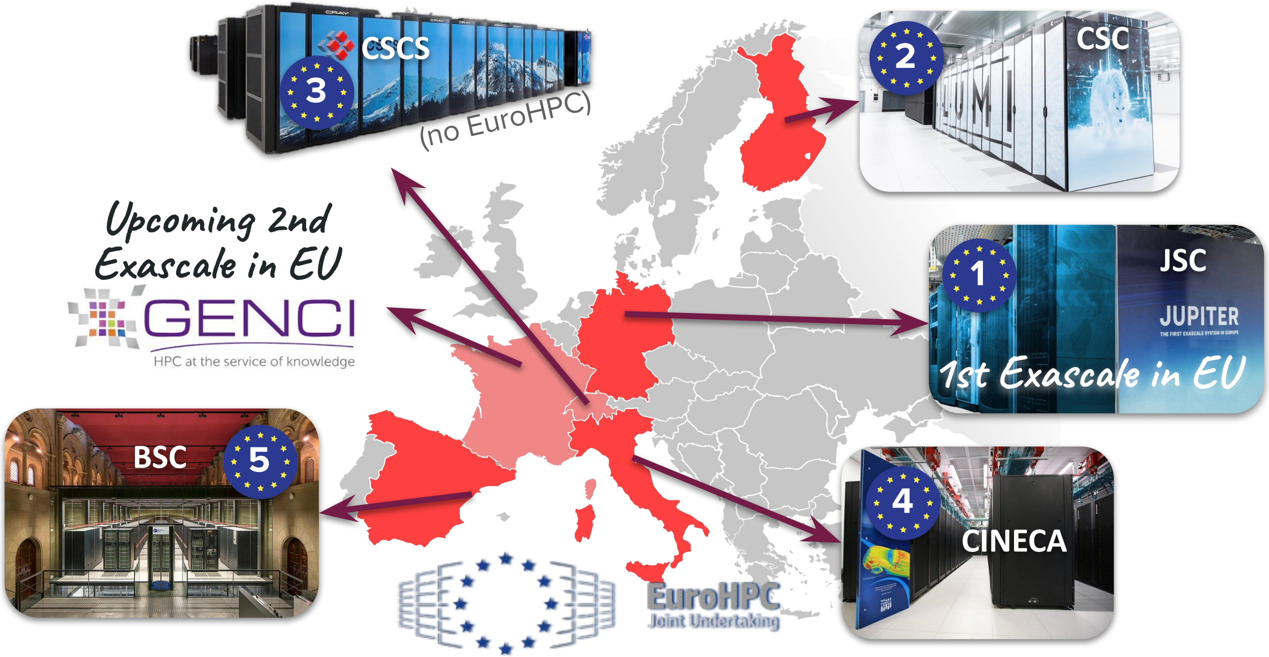
*1 ExaFLOP/s*
*=*
*"1 million PC performance"*

FLOP/s=Floating Operations per second

TOP 500 The List.

| | | |
|---|---|---|
| 1 | **El Capitan** | HPE Cray EX255a, AMD 4th Gen EPYC (24C 1.8GHz), AM |
| 2 | **Frontier** | HPE Cray EX235a, AMD Opt 3rd Gen EPYC (64C 2GHz), |
| 3 | **Aurora** | HPE Cray EX Intel Exascale Compute Blade, Xeon CPU M |
| 4 | **Jupiter Booster** | BullSequana XH3000, GH Superchip (72C 3GHz), NVIDI |
| 5 | **Eagle** | Microsoft NDv5, Xeon Platinum 8480C (48C 2GHz), NV |

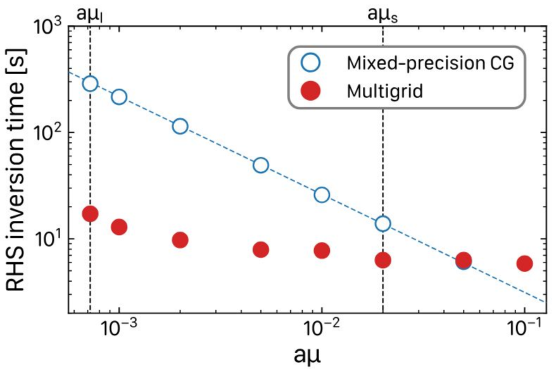
*Exascale Systems*



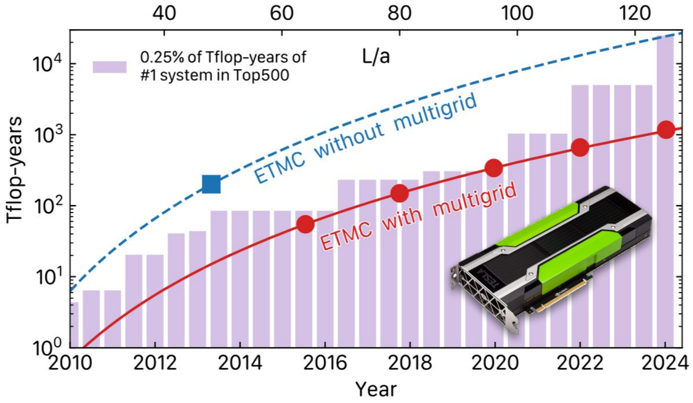
# Ingredients for high-precision Lattice QCD results

- **(Pre-)Exascale computing:** EuroHPC-JU is the largest pan-European initiative dedicated to funding HPC resources.
- **Reach sub-percent precision:** through the combination of cutting-edge HPC infrastructure and novel algorithms.

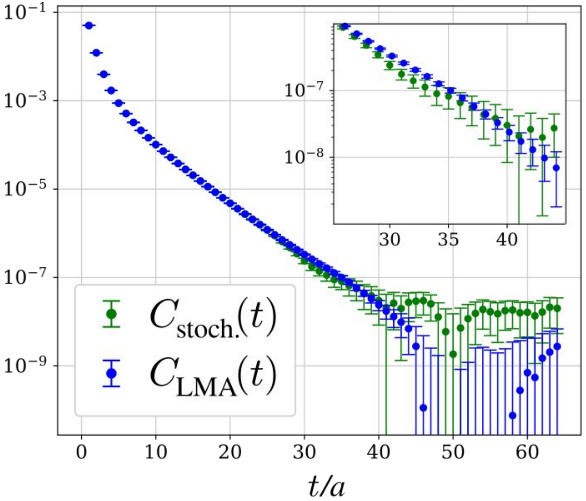
*Gain 1: Multigrid methods employed for computing quark propagators achieved up to 100× speed-up for light quarks.*




*Gain 2: Increased computational resources allow to simulate larger ensembles and higher statistics*




*Gain 3: Deflation of low-modes allows to reach larger distance*



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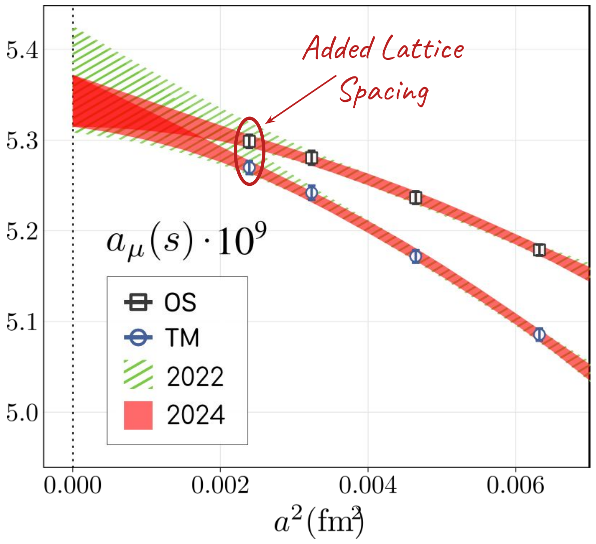
- **Reach sub-percent accuracy:** comprehensive set of ensembles enables full control of systematic effects.

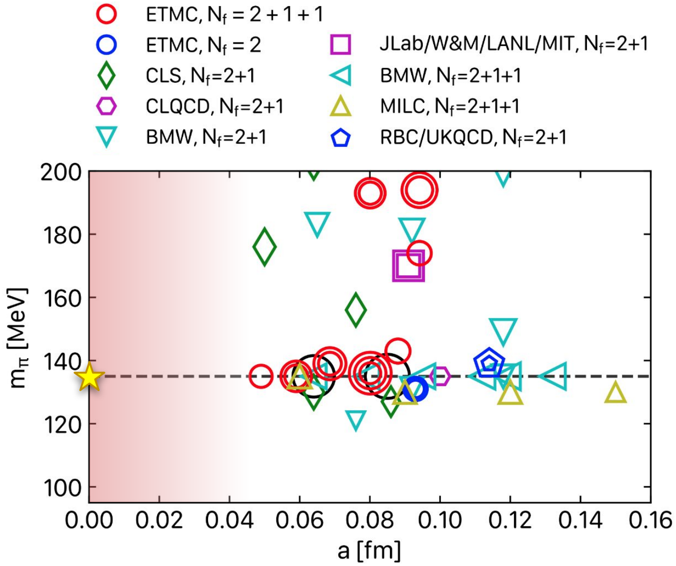
$$\langle \mathcal{O} \rangle = \lim_{\substack{\vec{\mu}_f \to \vec{m}_f \\ V \to \infty \\ a \to 0}} \langle \mathcal{O} \rangle_{a,V,\vec{\mu}_f}$$

✔ $\vec{\mu}_f \to \vec{m}_f$ : Simulations directly at physical parameters

! $V \to \infty$ : Finite-size effects exponentially suppressed

!! $a \to 0$ : Inevitable extrapolation!



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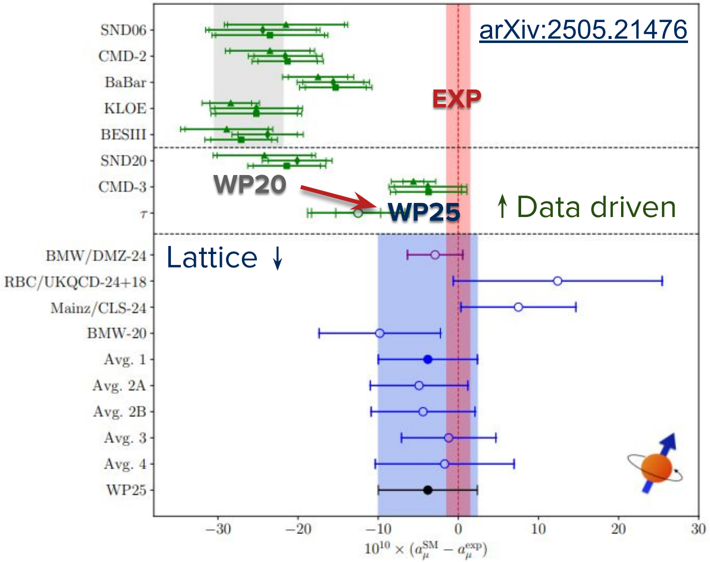
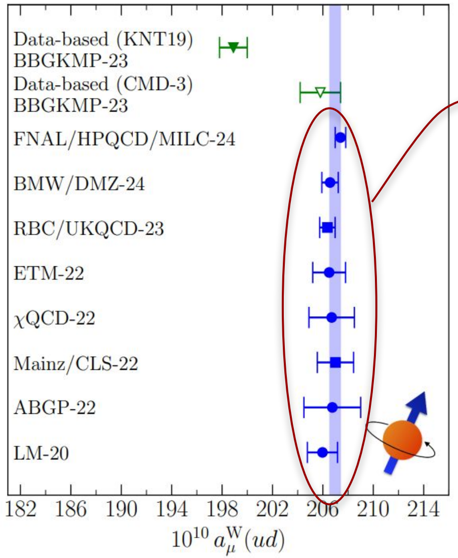
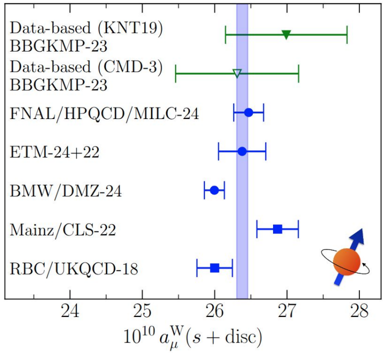
- **(Pre-)Exascale computing:** EuroHPC-JU is the largest pan-European initiative dedicated to funding HPC resources.
- **Reach sub-percent precision:** through the combination of cutting-edge HPC infrastructure and novel algorithms.
- **Reach sub-percent accuracy:** comprehensive set of ensembles enables full control of systematic effects.
- **Independent calculations for robust final results:** thanks to the collective effort of many collaborations.

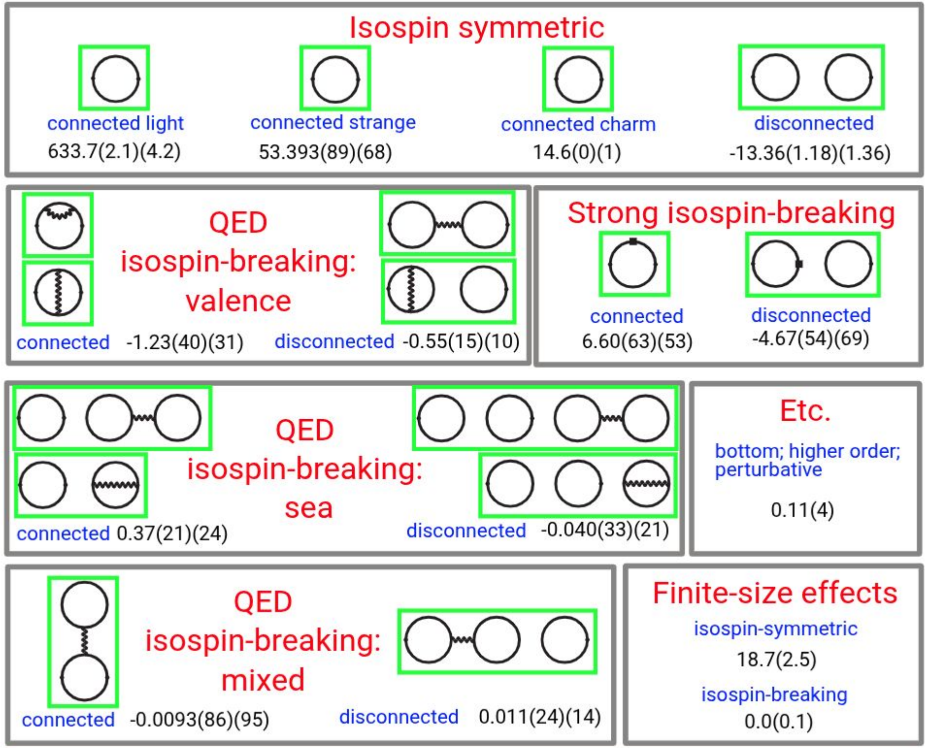



All statistically independent results, but with over-estimated / conservative systematic uncertainties!



# The anatomy for the Lattice QCD calculation




$$10^{10}\times a_\mu^{\text{LO-HVP}} = 707.5(2.3)_{\text{stat}}(5.0)_{\text{sys}}[5.5]_{\text{tot}}$$

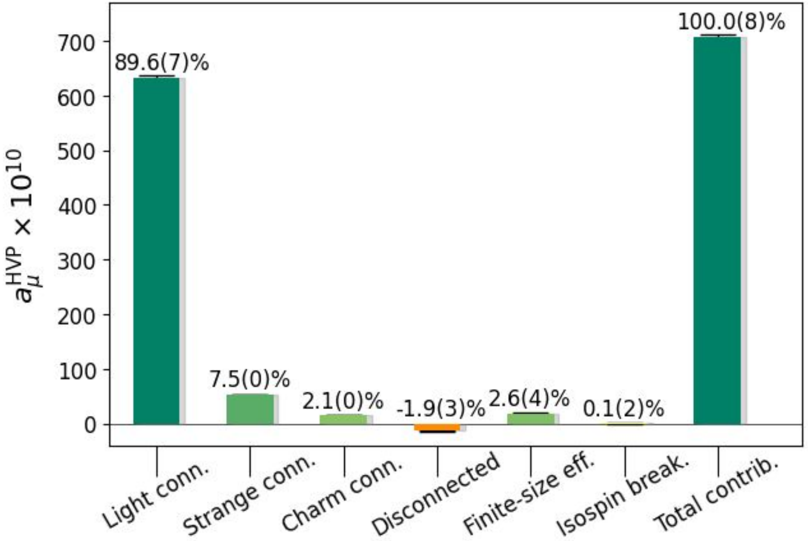
Article | Published: 07 April 2021

**Leading hadronic contribution to the muon magnetic moment from lattice QCD**

Sz. Borsanyi, Z. Fodor, J. N. Guenther, C. Hoelbling, S. D. Katz, L. Lellouch, T. Lippert, K. Miura, L. Parato, K. K. Szabo, F. Stokes, B. C. Toth, Cs. Torok & L. Varnhorst

*Nature* **593**, 51–55 (2021) | Cite this article

**24k** Accesses | **684** Citations | **957** Altmetric | Metrics



# Key tool: Euclidean correlation functions

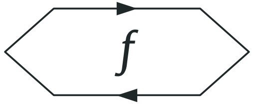
The correlation function between two electromagnetic currents:

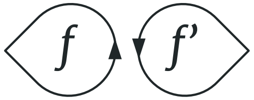
$$C_{2pt}(t) \equiv \langle J_{em}(t) J_{em}(0) \rangle = \langle J_{em} | T^t | J_{em} \rangle = \sum_n \underbrace{\langle J_{em} | n \rangle \langle n | J_{em} \rangle}_{\rho^{\mathrm{HVP}}(\omega)} e^{-E_n t} \longrightarrow$$

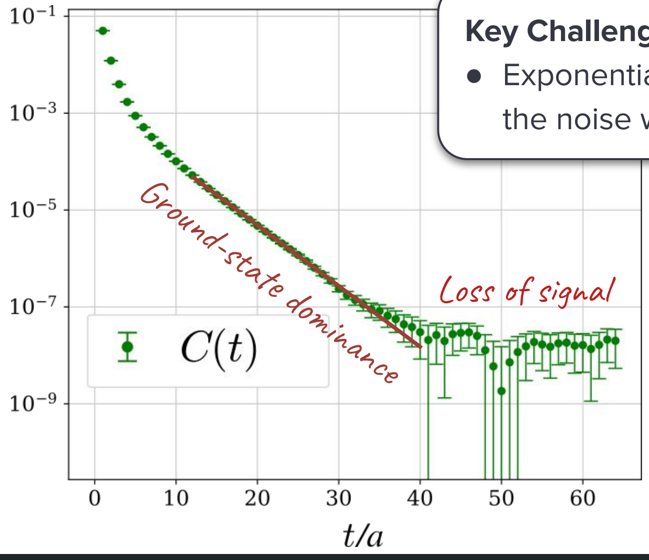
Exponential suppression!

$$e^{-H}$$


$$J^i_{\text{em}} = \frac{2}{3}\bar{u}\gamma^i u - \frac{1}{3}\bar{d}\gamma^i d - \frac{1}{3}\bar{s}\gamma^i s + \frac{2}{3}\bar{c}\gamma^i c$$

$J_{em}(t)$  $J_{em}(0)$ Connected


$J_{em}(t)$  $J_{em}(0)$ Disconnected


**Key Challenge:**
- Exponential growth of the noise with distance

# Key technique: Low-Mode Averaging (LMA)

**Concept:** Low-modes dominate at large distance in correlation functions!

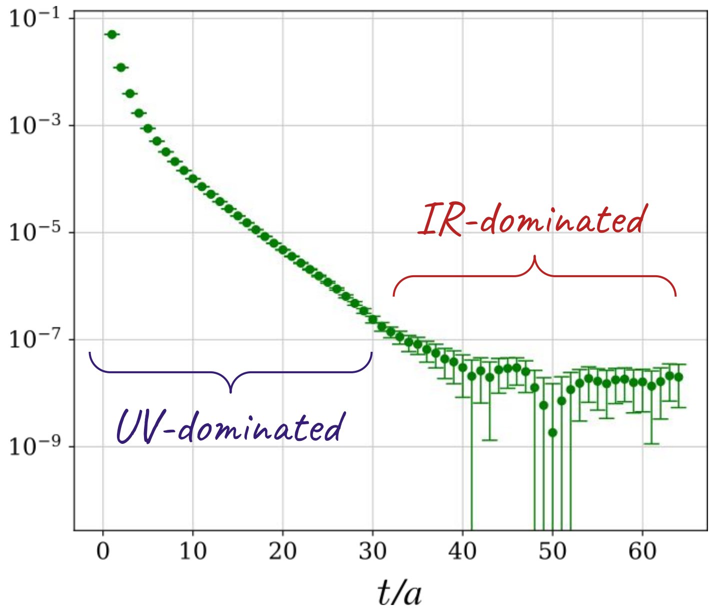
$$S_r(x,y) = \overbrace{|P_{\mathrm{IR}} Q_r^{-1} P_{\mathrm{IR}} \eta(x)\rangle \langle \eta(y)| \gamma_5}^{\text{IR contribution}} + \overbrace{|P_{\mathrm{UV}} Q_r^{-1} P_{\mathrm{UV}} \eta(x)\rangle \langle \eta(y)| \gamma_5}^{\text{UV contribution}}$$

Quark Propagator

$$= \underbrace{\sum_{j=1}^{K} \frac{|v_j(x)\rangle \langle v_j(y)| \gamma_5}{\lambda_j + ir\mu}}_{\text{Computed Exactly}} + \underbrace{\frac{1}{N} \sum_{\eta} |\widetilde{\phi}_r^{\eta}(x)\rangle \langle \eta(y)| \gamma_5 \Big|_{N \gg 1}}_{\text{Computed Stochastically}},$$

- In the correlation function computed stochastically, we replace the IR part with an **exact** knowledge of it

$$C_{\mathrm{LMA}}(t) = C_{\mathrm{stoch.}}(t) - C^{\mathrm{IR}}_{\mathrm{stoch.}}(t) + C^{\mathrm{IR}}_{\mathrm{exact.}}(t)$$



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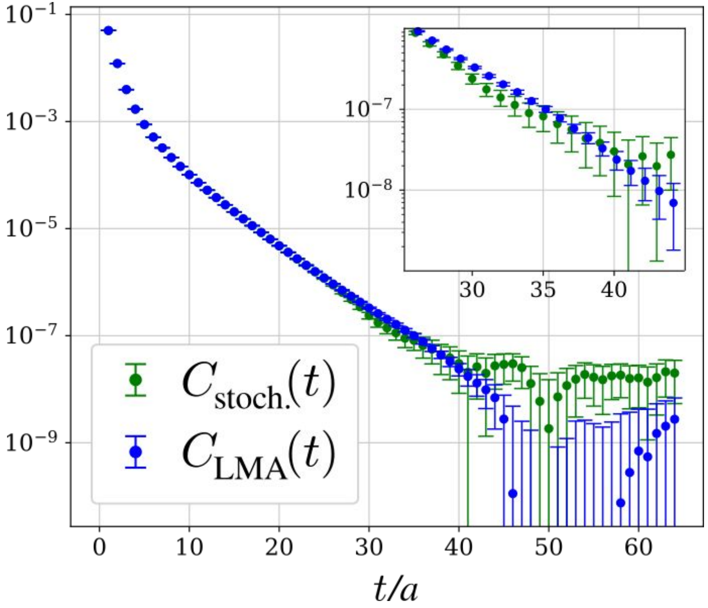

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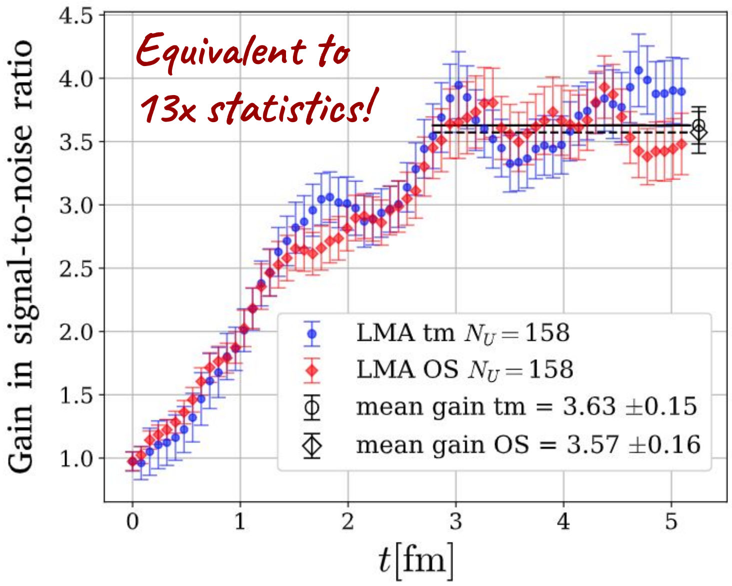
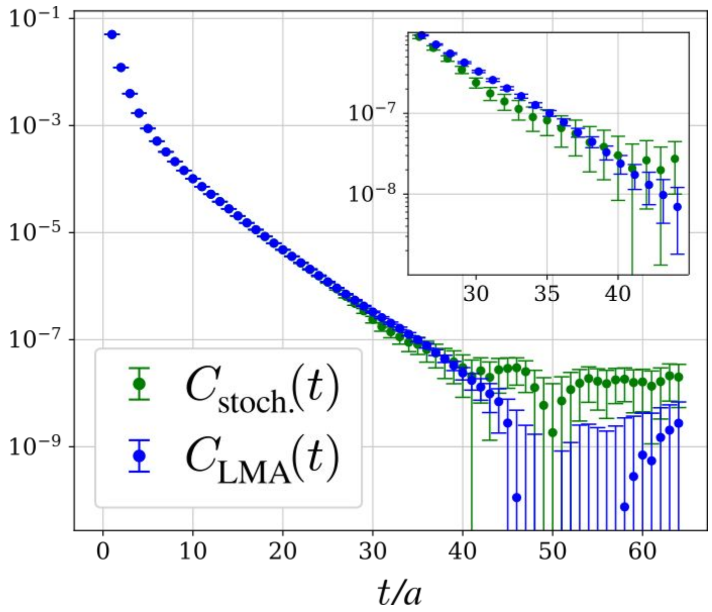
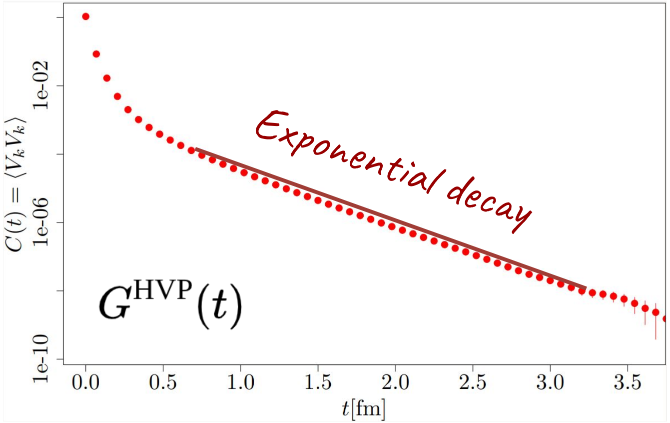
[Poster by C. Schneider, Tue. eve.]

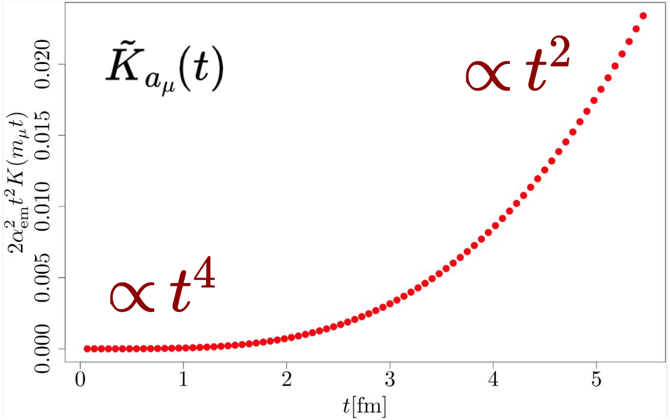


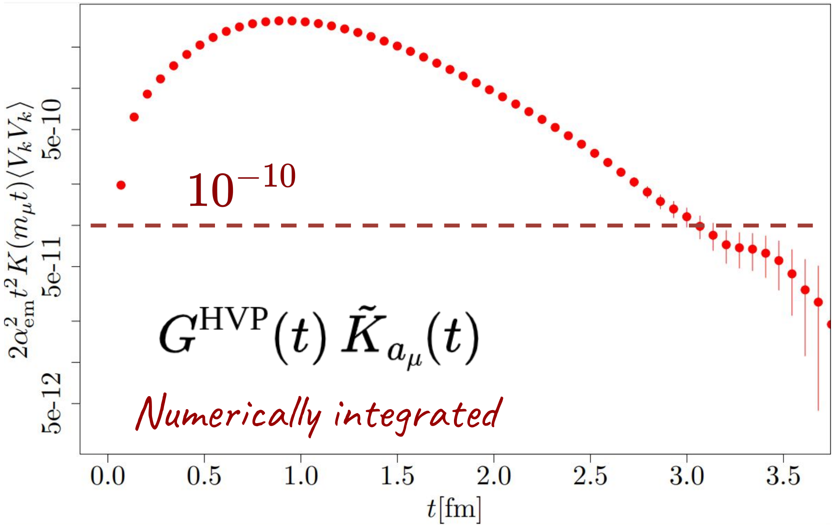



# From correlator to HVP contribution

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



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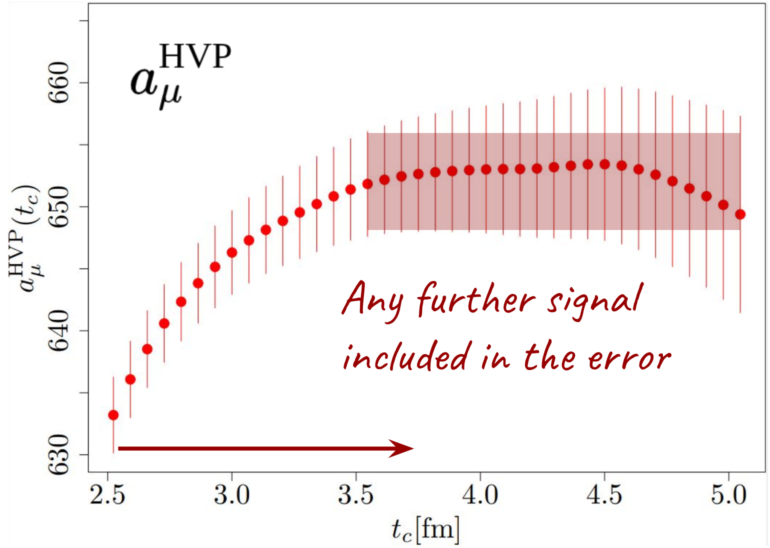
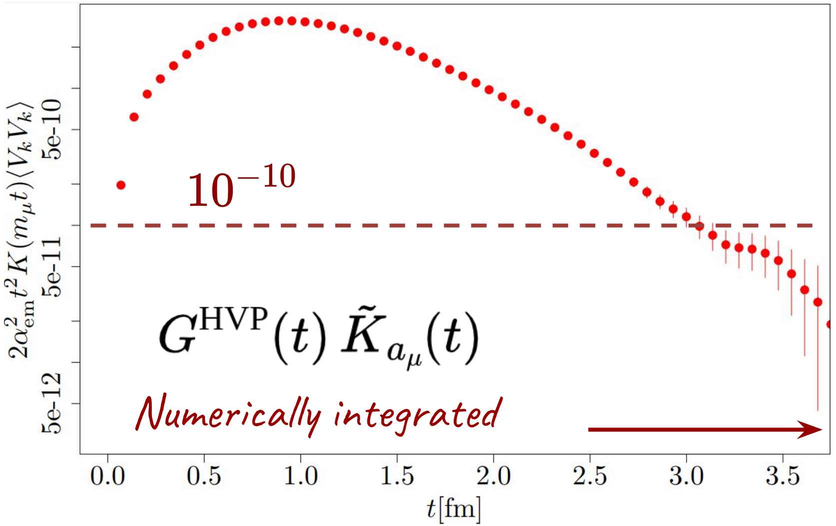



*Taking the continuum limit reduces the parametrization systematic below other uncertainties.*

# Beyond Muon g-2: Windows observables [RBC/UKQCD]

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

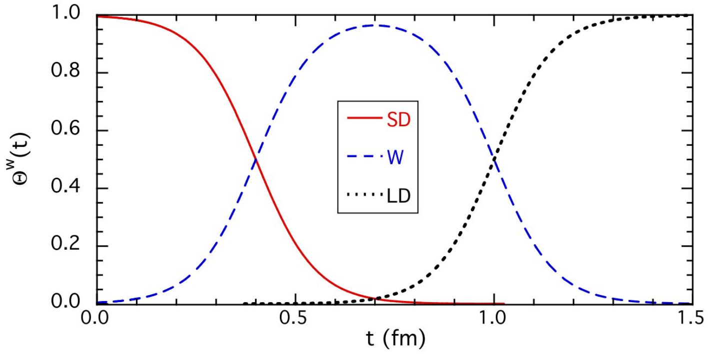
➢ Each window observable can be compared directly between lattice QCD and data-driven

Lattice QCD ⟺ Data-driven

$$\boxed{a_\mu^{\mathrm{HVP,\,LO}} = 2\alpha^2 \int_0^\infty dt\, t^2\, K(m_\mu t)\, \Theta^w(t)\, V(t)}$$

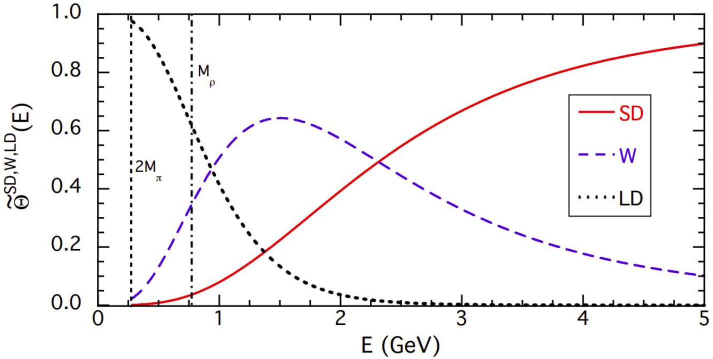
$$\Theta^{\mathrm{W}}(t) \equiv \underbrace{\frac{1}{1+e^{-2(t-t_0)/\Delta}}}_{1-\,\Theta^{\mathrm{SD}}(t)} - \underbrace{\frac{1}{1+e^{-2(t-t_1)/\Delta}}}_{\Theta^{\mathrm{LD}}(t)}$$

$t_0 = 0.4$ fm
$t_1 = 1$ fm
$\Delta = 0.15$ fm




$$\boxed{a_\mu^{\mathrm{HVP,\,LO}} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^\infty ds\, \frac{\tilde{K}(s)}{s}\, \tilde{\Theta}(s)\, R(s)}$$

$$\tilde{\Theta}^w(E) = \frac{\int_0^\infty dt\; t^2\; e^{-E\,t}\; K(m_\mu t)\; \Theta^w(t)}{\int_0^\infty dt\; t^2\; e^{-E\,t}\; K(m_\mu t)}$$

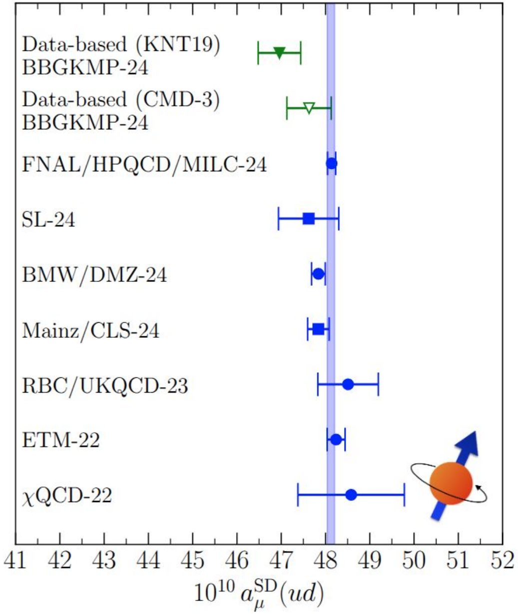


# Beyond Muon g-2: Windows observables [RBC/UKQCD]

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

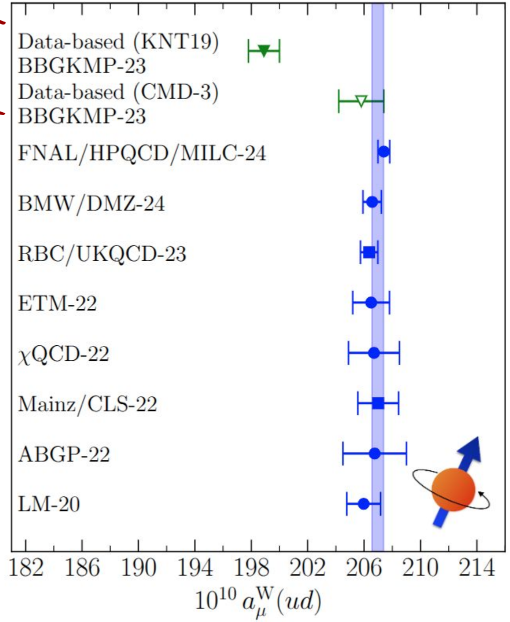
- ➢ Each window observable can be compared directly between lattice QCD and data-driven

$a_\mu^{\mathrm{SD}} = 69.10(26) \times 10^{-10}$



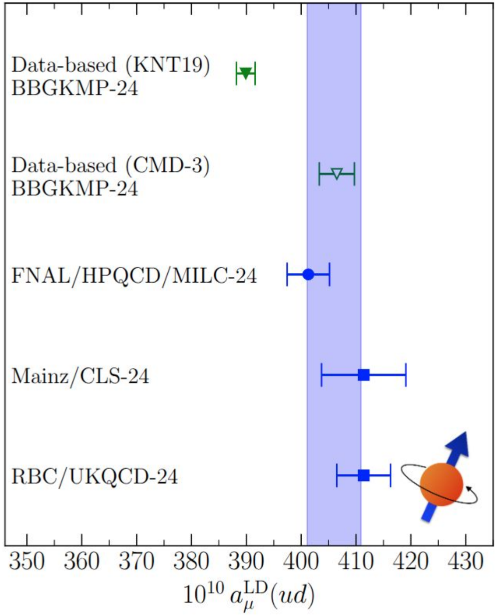

*Main discrepancy*

$a_\mu^{\mathrm{W}} = 236.58(43) \times 10^{-10}$




*Main uncertainty*

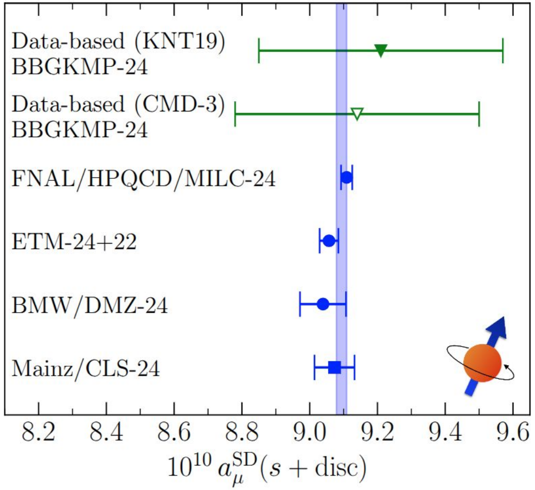
$a_\mu^{\mathrm{LD}}(ud) = 406.0(4.9) \times 10^{-10}$

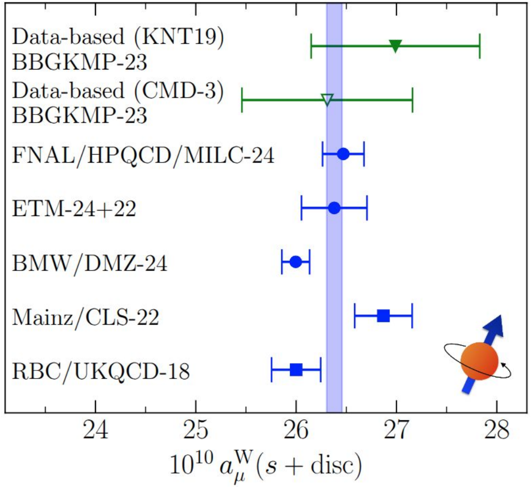


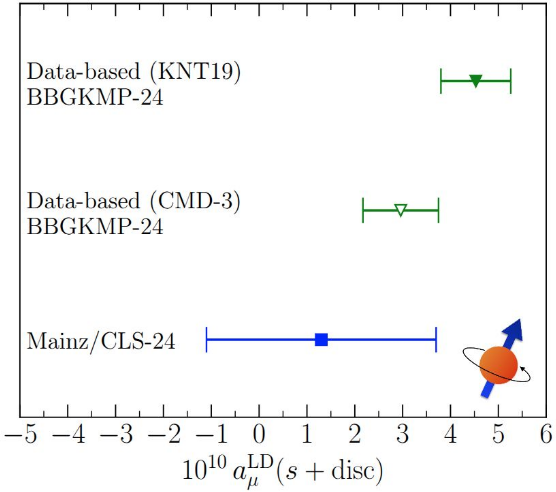
# Beyond Muon g-2: ... with isoscalar (I=0) and isovector (I=1)

$$a_\mu^{\mathrm{HVP}} = \underset{3\pi,\ldots}{a_\mu^{I=0}} + \underset{\pi^+\pi^-,\ldots}{a_\mu^{I=1}} \Rightarrow a_\mu(ud) = \frac{10}{9} a_\mu^{I=1} \qquad a_\mu(s+\mathrm{disc}) = a_\mu^{I=1} - \frac{1}{9} a_\mu^{I=1}$$

*Confirmation that the two-pion channel is the main source of discrepancy*



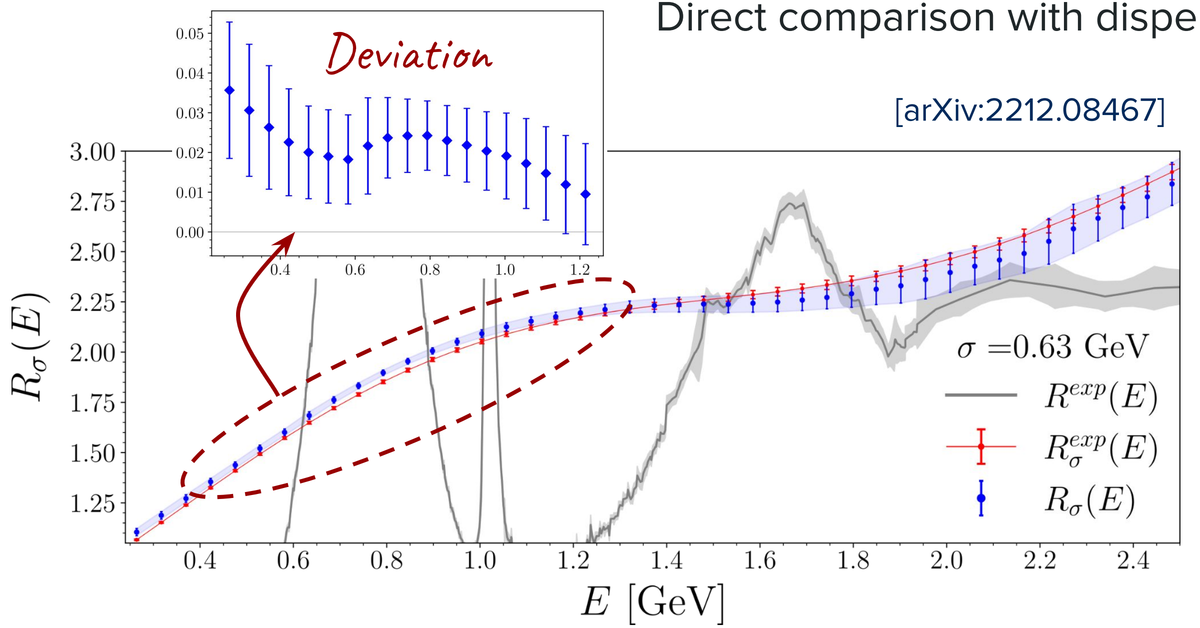



# Beyond Muon g-2: Energy-smeared R-ratio

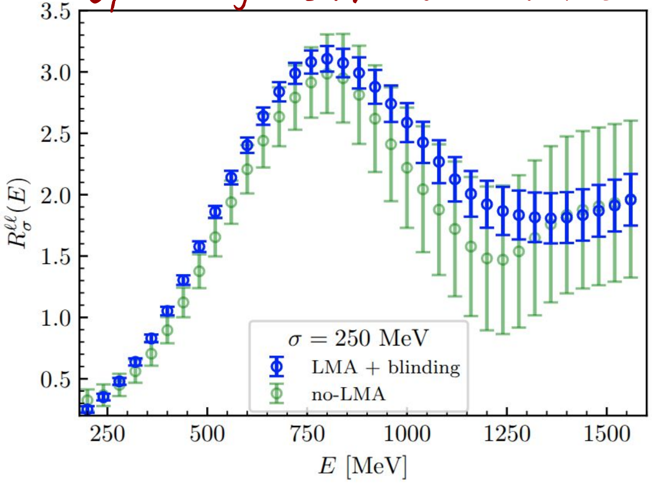
$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty d\omega\, \rho^{\mathrm{HVP}}(\omega)\, \hat{K}_{a_\mu}(\omega) \quad \Rightarrow \quad R_\sigma(E) = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty d\omega\, \rho^{\mathrm{HVP}}(\omega)\, N_\sigma(E-\omega)$$

Direct comparison with dispersive approaches energy-by-energy

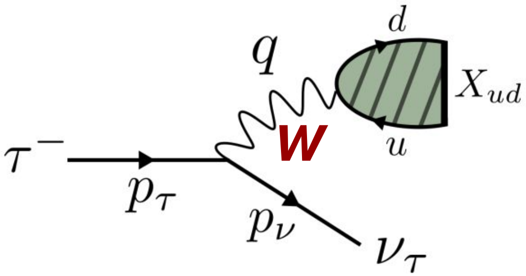
[arXiv:2212.08467]




Upcoming result with new data



# Other opportunities with current-current correlators




Inclusive semileptonic τ decay and determination of $|V_{us}|$

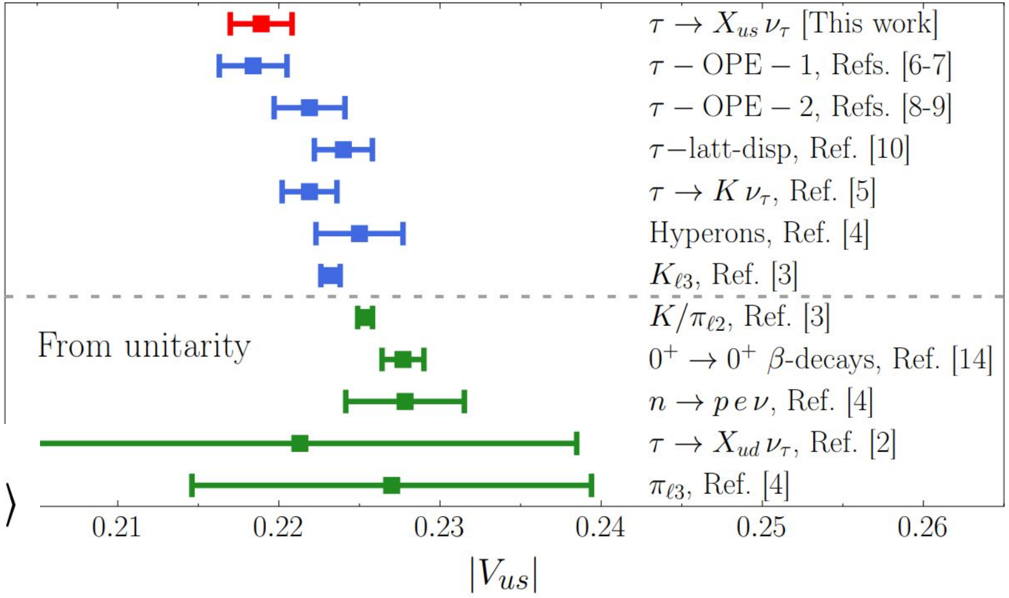
[arXiv:2308.03125, arXiv:2403.05404]

$$|\mathcal{A}|^2 = \sum_X |\mathcal{A}(\tau \to X_{ud}\,\nu_\tau)|^2 =$$

$$\left(\frac{G_F}{\sqrt{2}}\right)^2 |V_{ud}|^2 L^{\alpha\beta}(p_\tau, p_\nu) \times$$

$$\sum_X \langle 0 | J^\alpha_{ud}(0) | X_{ud}(q) \rangle \langle X_{ud}(q) | J^\beta_{ud}(0)^\dagger | 0 \rangle$$

Hadronic tensor



# Conclusions

**Resolving the $(g\text{-}2)_\mu$ puzzle was on of the recent greatest achievement of Lattice QCD, coming with many opportunities.**

**Credits:**

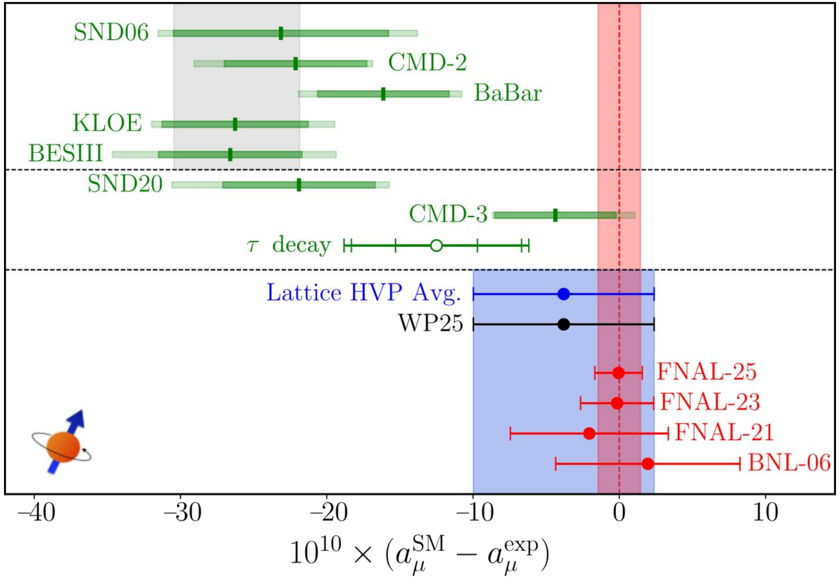
- BMW: First high-precision calculation
- RBC/UKQCD: Windows observables

**From $(g\text{-}2)_\mu$ to dispersive vs lattice results:**

- Windows comparisons
- Isovector vs isoscalar
- Energy smeared R-ratio

And many other opportunities on the same data

**Results in WP25**



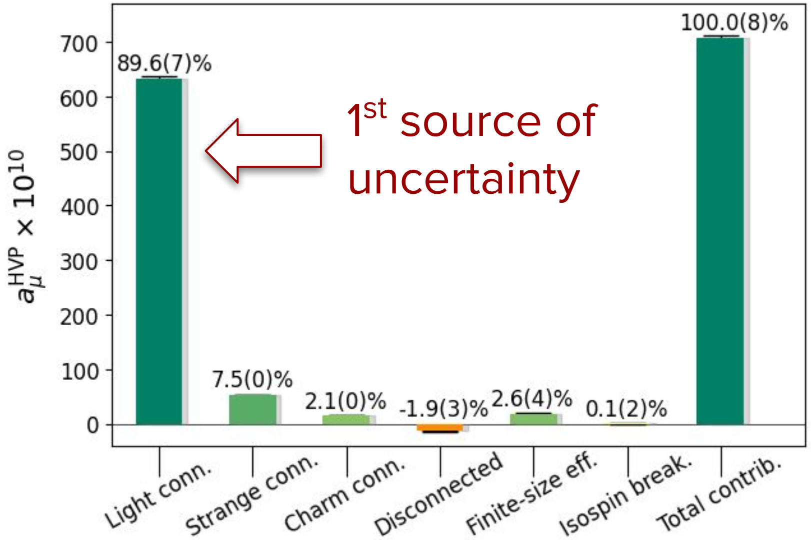
# Question: *Can we do better?*

$$\pm 10^{-12} \quad \pm 4\cdot 10^{-12} \quad \pm 10^{-10} \quad \pm 6\cdot 10^{-10}$$

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HLbL} + a_\mu^{\rm HVP}$$

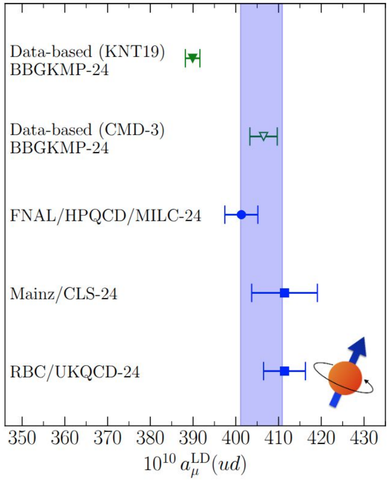
*Can we bring it to $\pm 10^{-10}$ ?*

*5x reduction of the error...*

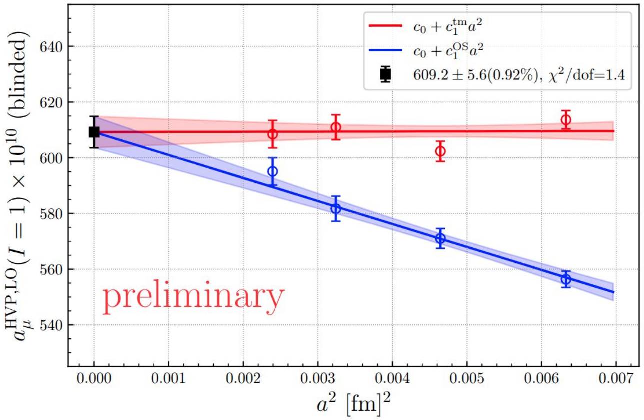



1st source of uncertainty

$$a_\mu^{\rm LD}(ud) = 406.0(4.9) \times 10^{-10}$$

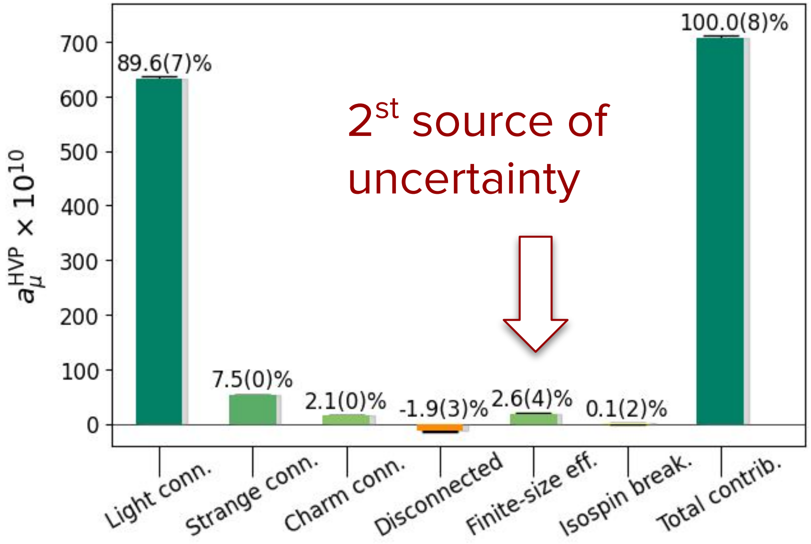



*One more results coming*



# Question: *Can we do better?*

$$\begin{array}{ccccc} & \pm 10^{-12} & \pm 4{\cdot}10^{-12} & \pm 10^{-10} & \pm 6{\cdot}10^{-10} \\ a_\mu^{\mathrm{SM}} = & a_\mu^{\mathrm{QED}} & + a_\mu^{\mathrm{EW}} & + a_\mu^{\mathrm{HLbL}} & + a_\mu^{\mathrm{HVP}} \end{array}$$

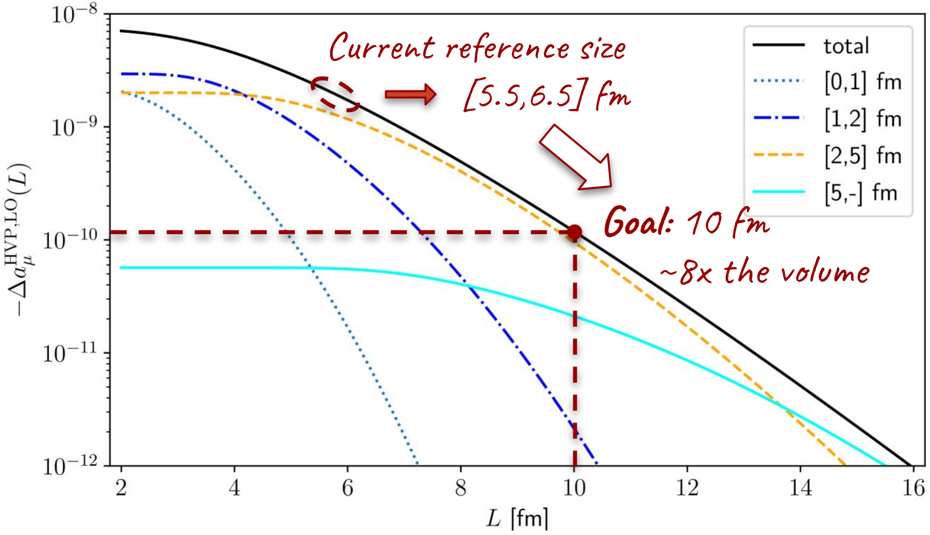



**Anatomy of finite-volume effect on hadronic vacuum polarization contribution to muon $g-2$**

Sakura Itatani [1,*] Hidenori Fukaya [2,†] and Shoji Hashimoto [1,3,‡]

[arXiv:2411.05413]

$$\Delta a_\mu^{\mathrm{HVP,LO}}(L) \equiv a_\mu^{\mathrm{HVP,LO}}(L) - a_\mu^{\mathrm{HVP,LO}}(\infty)$$

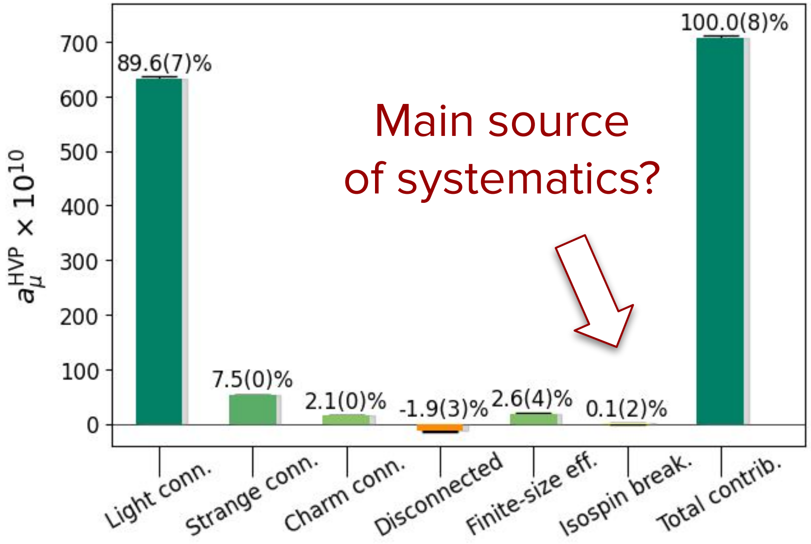


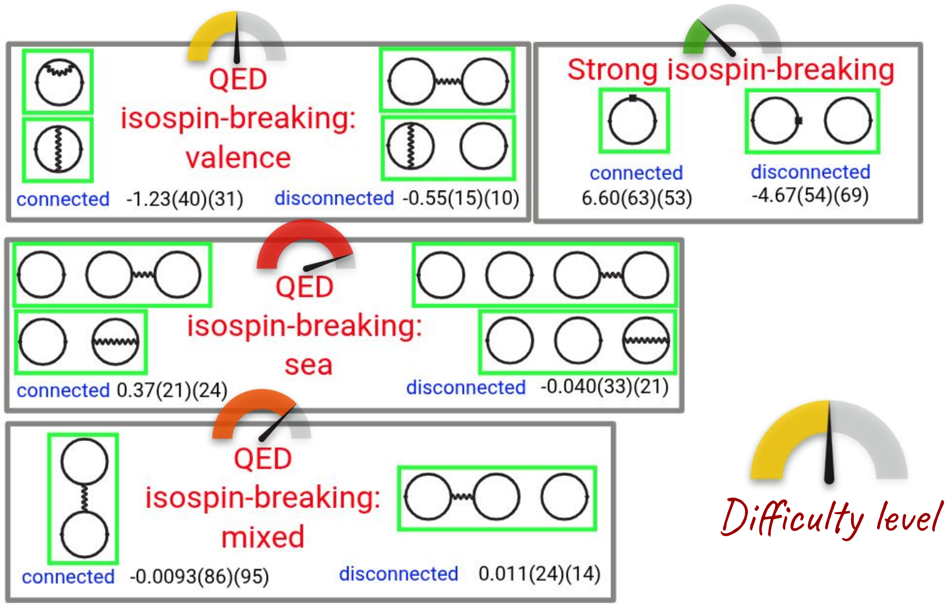
# Question: *Can we do better?*

$$\overset{\pm 10^{-12}}{} \quad \overset{\pm 4\cdot 10^{-12}}{} \quad \overset{\pm 10^{-10}}{} \quad \overset{\pm 6\cdot 10^{-10}}{}$$

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HLbL}} + a_\mu^{\mathrm{HVP}}$$

BMW is currently the only collaboration to have computed all contributions within the same framework. Remarkably, they cancel—but what if they didn't?



# Answer: *Yes, we can!*

$$\overset{\pm 10^{-12}}{} \quad \overset{\pm 4\cdot 10^{-12}}{} \quad \overset{\pm 10^{-10}}{} \quad \overset{\pm 6\cdot 10^{-10}}{}$$

$$a_\mu^{\rm SM} = \underset{}{\overset{\pm 10^{-12}}{a_\mu^{\rm QED}}} + \overset{\pm 4\cdot 10^{-12}}{a_\mu^{\rm EW}} + \overset{\pm 10^{-10}}{a_\mu^{\rm HLbL}} + \overset{\pm 6\cdot 10^{-10}}{a_\mu^{\rm HVP}}$$

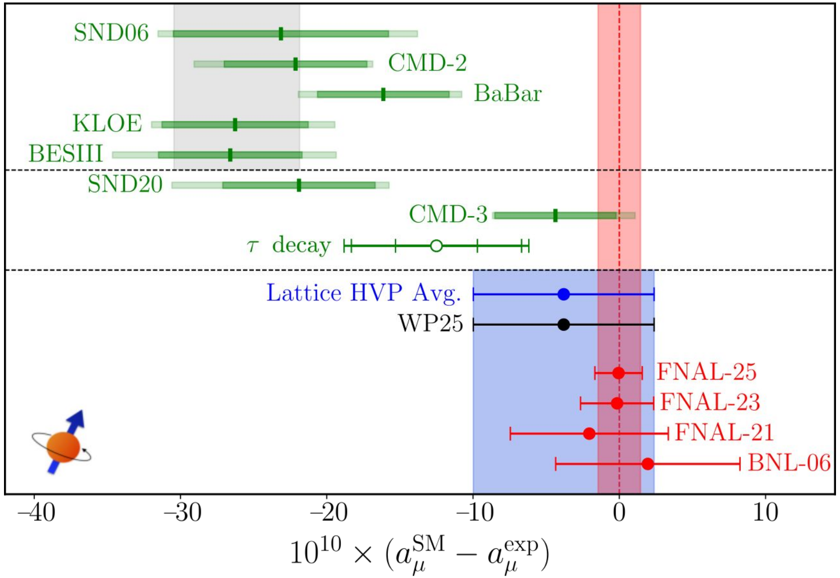
*Can we bring it to* $\pm 10^{-10}$ *?*

Nothing prevents Lattice QCD from reaching experimental precision.

It's only a matter of **time**, **resources**, and **interest**.

<u>Lattice QCD is a systematically improvable framework!</u>

**Results in WP25**



# Answer: *Yes, we can!*

$$\underset{\phantom{x}}{a_\mu^{\rm SM}} = \overset{\pm 10^{-12}}{a_\mu^{\rm QED}} + \overset{\pm 4{\cdot}10^{-12}}{a_\mu^{\rm EW}} + \overset{\pm 10^{-10}}{a_\mu^{\rm HLbL}} + \overset{\pm 6{\cdot}10^{-10}}{a_\mu^{\rm HVP}}$$

$\longrightarrow$ *Can we bring it to* $\pm 10^{-10}$ *?*

Nothing prevents Lattice QCD from reaching experimental precision.

It's only a matter of **time**, **resources**, and **interest**.

<u>Lattice QCD is a systematically improvable framework!</u>

*Thank you for your attention!*

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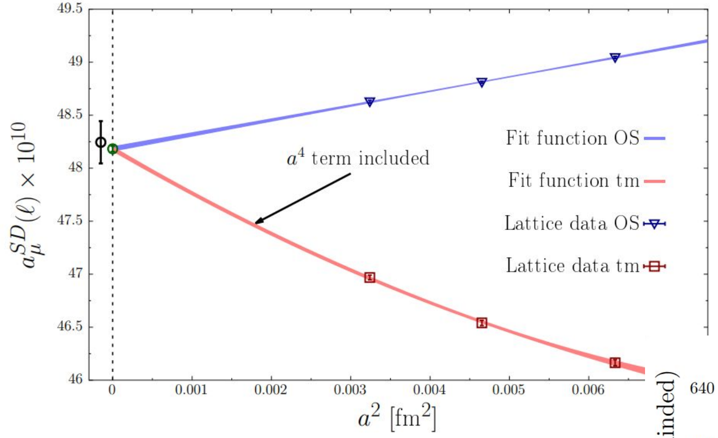
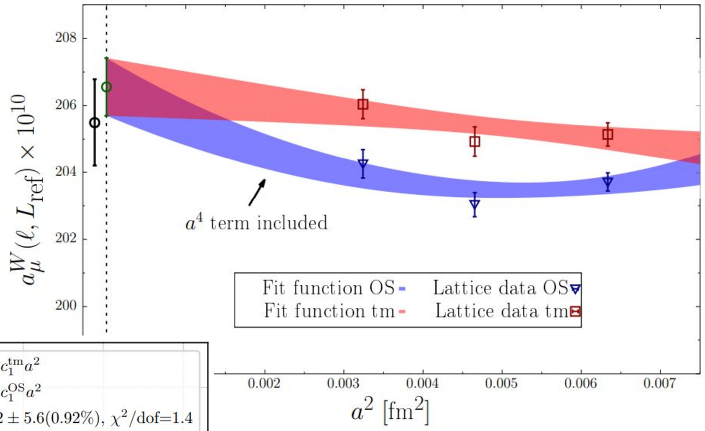
**POSTDOC/0524/0001 VISION-ERC/0524/0001 EXCELLENCE/0524/0017**

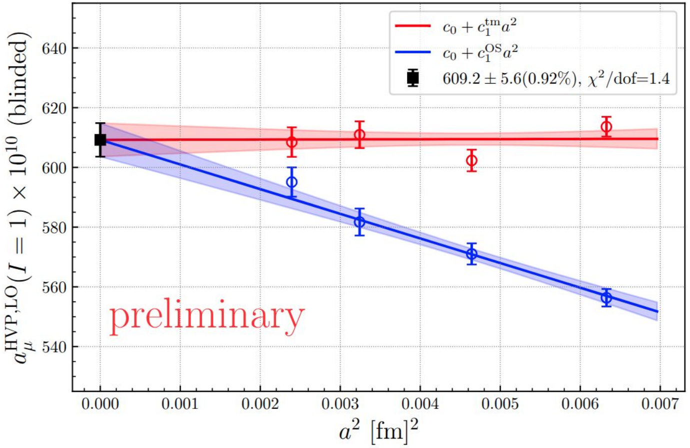
# Backup



$a_\mu^{SD}(\ell) \times 10^{10}$
$a^4$ term included
Fit function OS
Fit function tm
Lattice data OS
Lattice data tm
$a^2$ [fm$^2$]

$a_\mu^{W}(\ell, L_{\rm ref}) \times 10^{10}$
$a^4$ term included
Fit function OS
Lattice data OS
Fit function tm
Lattice data tm
$a^2$ [fm$^2$]

$a_\mu^{\rm HVP,LO}(I=1) \times 10^{10}$ (blinded)
$c_0 + c_1^{\rm tm} a^2$
$c_0 + c_1^{\rm OS} a^2$
$609.2 \pm 5.6 (0.92\%)$, $\chi^2$/dof=1.4
preliminary
$a^2$ [fm]$^2$