Charged vs Neutral correlators
Isospin breaking in τ data for $(g-2)_\mu$

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for the RBC/UKQCD collaborations

Isospin-breaking effects on precision observables in Lattice QCD
University of Mainz, Germany, July 24th

Introduction

Hadronic spectral densities

- at low energies dominated by non-perturbative effects
- extracted from experiments
- extracted from lattice calculations, require solving inverse problems

Integrated hadronic densities relevant for SM phenomenology

- Hadronic-Vacuum-Polarization piece of $(g-2)_\mu$
  - directly in Euclidean space-time [Blum '02][Bernecker,Meyer '11]
  - neutral (EM current) spectral density
- inclusive τ decays
  - (mild) inverse problem [ETMC '23]
  - charged (weak current) spectral density

Goal: study relation charged vs neutral densities for $(g-2)_\mu$

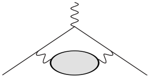
New York Times

Aug 10 2023

Compared with the traditional prediction, the latest g-2 measurement has a discrepancy of over 5-sigma, which corresponds to a one in 3.5 million chance that the result is a fluke, ...

A newer technique called a lattice calculation, which uses supercomputers to model the universe as a four-dimensional grid of space-time points, has also emerged. There's just one problem: It generates a g-2 prediction that differs from the traditional approach.

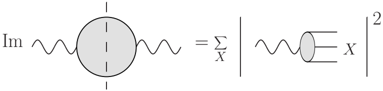
Rarely in physics does an experiment surpass the theory, but this is one of those times, Dr. Pitts said. "The attention is on the theoretical community," he added. "The limelight is now on them."



$$a_\mu = \frac{\alpha}{\pi} \int \frac{ds}{s} K(s, m_\mu) \frac{\mathrm{Im}\Pi(s)}{\pi}$$ [Brodsky, de Rafael '68]

analyticity $$\hat{\Pi}(k^2) = \Pi(k^2) - \Pi(0) = \frac{k^2}{\pi} \int_0^\infty ds \frac{\mathrm{Im}\Pi(s)}{s(s - k^2 - i\varepsilon)}$$

unitarity



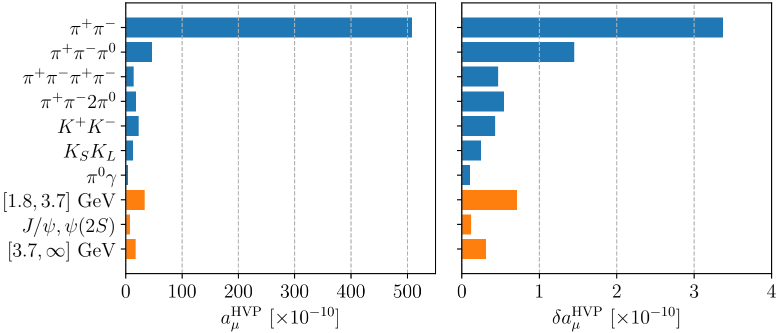
$$\frac{4\pi^2\alpha}{s} \frac{\mathrm{Im}\Pi(s)}{\pi} = \sigma_{e^+e^- \to \gamma^\star \to \mathrm{had}}$$

$$v_0(s) = \frac{\mathrm{Im}\Pi(s)}{\pi} = \frac{s}{4\pi\alpha^2} \sigma_{\mathrm{had}}(s)$$ spectral function

Dispersive approach

Breakdown

[White Paper '20, DHMZ19]



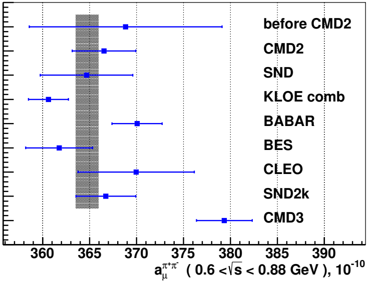
Combination of m_μ and ρ-meson physics $\rightarrow$ $\pi^+\pi^-$ dominant channel

Dispersive approach

Tensions in $\pi^+\pi^-$ channel

Large tensions among experiments: BaBar, KLOE, CMD3

[CMD3 2302.08834]



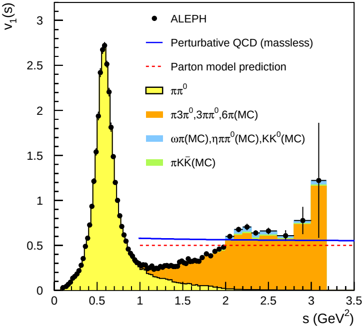
combination of different experiments?

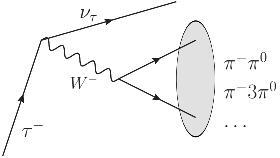
error of $\pi\pi$ contribution to a_μ?

τ decays: more consistent experimental picture
CLEO, OPAL, Aleph, Belle08 [Davier et al][Golterman et al]

MOTIVATIONS

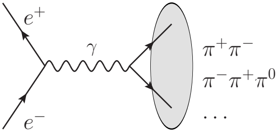
τ decays





$V - A$ current

Final states $I = 1$ charged



EM current

Final states $I = 0, 1$ neutral

τ data can improve $a_\mu[\pi\pi]$

→ 72% of total Hadronic LO

→ competitive precision on a_μ^W

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Isospin Corrections

Status

Restriction to $e^+e^- \to \pi^+\pi^-$ and $\tau^- \to \pi^-\pi^0\,\nu_\tau$

$$v_0(s) = \frac{s}{4\pi\alpha^2}\sigma_{\pi^+\pi^-(\gamma)}(s)$$

$$v_-(s) = \frac{m_\tau^2}{6|V_{ud}|^2}\frac{\mathcal{B}_{\pi\pi^0}}{\mathcal{B}_e}\frac{1}{N_{\pi\pi^0}}\frac{dN_{\pi\pi^0}}{ds}\left(1-\frac{s}{m_\tau^2}\right)^{-1}\left(1+\frac{2s}{m_\tau^2}\right)^{-1}\frac{1}{S_{\mathrm{EW}}}$$

Isospin correction $v_0 = R_{\mathrm{IB}} v_-$ $\quad R_{\mathrm{IB}} = \frac{\mathrm{FSR}}{G_{\mathrm{EM}}}\frac{\beta_0^3|F_\pi^0|^2}{\beta_-^3|F_\pi^-|^2}$ [Alemani et al. '98]

0. S_{EW} electro-weak radiative correct. [Marciano, Sirlin '88][Braaten, Li '90]

1. Final State Radiation of $\pi^+\pi^-$ system [Schwinger '89][Drees, Hikasa '90]

2. G_{EM} (long distance) radiative corrections in τ decays

Chiral Resonance Theory [Cirigliano et al. '01, '02]

Meson Dominance [Flores-Talpa et al. '06, '07]

3. Phase Space ($\beta_{0,-}$) due to $(m_{\pi^\pm} - m_{\pi^0})$

Radiative corrections

Long-distance effects

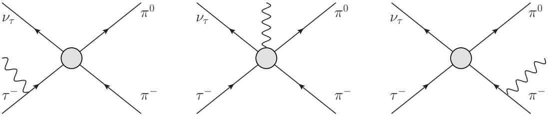
At low energies relevant degrees of freedom are mesons

Chiral Perturbation Theory [Cirigliano et al. '01, '02]

Meson dominance model [Flores-Talpa et al. '06, '07]

Corrections casted in one function $v_-(s) \to v_-(s) G_{\rm EM}(s)$

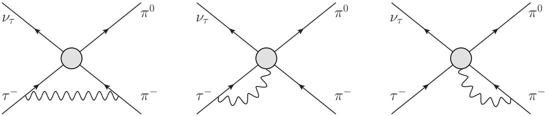
Real photon corrections



Real + virtual

$\to$ IR divergences cancel

Virtual photon corrections

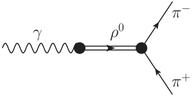


Form factors

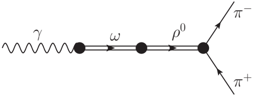
Pheno models

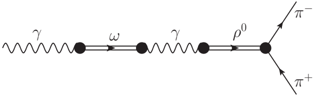
[Gounaris, Sakurai '68]
[Kühn, Santamaria '90]

$$F_\pi^0(s) \propto \frac{m_\rho^2}{D_\rho(s)}$$

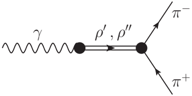


$$\times \left[1 + \delta_{\rho\omega} \frac{s}{D_\omega(s)}\right]$$

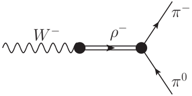




$$+ \frac{m_X^2}{D_X(s)} \qquad X = \rho' \,, \rho''$$



$$F_\pi^-(s) \propto \frac{m_{\rho^-}^2}{D_{\rho^-}(s)} + (\rho' \,, \rho'')$$



Sources of IB breaking in phenomenological models

$m_{\rho^0} \neq m_{\rho^\pm}$, $\Gamma_{\rho^0} \neq \Gamma_{\rho^\pm}$, $m_{\pi^0} \neq m_{\pi^\pm}$

$\rho - \omega$ mixing $\delta_{\rho\omega} \simeq O(m_u - m_d) + O(e^2)$

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Status

From the $(g-2)$ White Paper

" ... 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. "

"The ratio $|F_0(s)/F_-(s)|^2$ is the most difficult to estimate reliably, since a number of different IB effects may contribute."

Roadmap

1. EM corrections to hadronic τ decays
2. connect differential rates w/ Euclidean correlators
3. charged vs neutral correlators in Lattice QCD+QED

Definitions

Hadronic currents

$$\mathcal{J}^{\gamma}_{\mu} = Q_{\rm u}\overline{u}\gamma_\mu u + Q_{\rm d}\overline{d}\gamma_\mu d$$

$$\mathcal{J}^{-}_{\mu} = \overline{u}\gamma_\mu d\,, \qquad \mathcal{J}^{1}_{\mu} = \tfrac{Q_{\rm u}-Q_{\rm d}}{\sqrt{2}}\overline{u}\gamma_\mu d$$

Hadronic phase-space factor, i labels hadrons

$$d\Phi_f(p) \equiv (2\pi)^4\delta^4(p - \sum_i p_i)\, S_f \prod_i \frac{d^3 p_i}{(2\pi)^3 2\omega_i}$$

Charged spectral densities

$$\begin{aligned}\rho^{\rm w}_{\mu\nu}(p) &= \frac{1}{2\pi}\int d^4x\, e^{ipx}\,\langle 0|\mathcal{J}^{+}_{\mu}(x)\,\mathcal{J}^{-}_{\nu}(0)|0\rangle \\ &= \frac{1}{2\pi}\sum_f \int d\Phi_f\,\langle 0|\mathcal{J}^{+}_{\mu}(0)|p_1\cdots,{\rm out}\rangle\langle p_1\cdots,{\rm out}|\mathcal{J}^{-}_{\nu}(0)|0\rangle \\ &= (g_{\mu\nu} - p_\mu p_\nu)\,\rho^{\rm w}(s) \qquad [s = p^2]\end{aligned}$$

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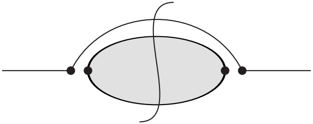
$$\mathcal{M}_f(P,q,p_1\cdots p_{n_f}) = \frac{G_F V_{ud}}{\sqrt{2}}\,\bar{u}_\nu(-q)\gamma^L_\mu u_\tau(P)\,\langle \text{out}, p_1\cdots p_{n_f}|\mathcal{J}^-_\mu(0)|0\rangle$$



$$d\Gamma = \frac{1}{4m}d\Phi_q \sum_f d\Phi_f \sum_{\text{spin}} |\mathcal{M}_f|^2$$

$$= \frac{1}{4m}d\Phi_q \frac{G_F^2|V_{ud}|^2}{2}\mathcal{L}_{\mu\nu}(P,q)\,\rho^{\mathsf{w}}_{\mu\nu}(p)$$

Charged spectral density isospin limit $= \rho^{\mathsf{w},0}$

$$\left[d\Phi_q = \frac{d^3q}{(2\pi)^3 2\omega_q}\right]$$

$$\frac{d\Gamma(s)}{ds} = G_F^2|V_{ud}|^2\frac{m^3}{16\pi^2}\left(1+\frac{2s}{m^2}\right)\left(1-\frac{s}{m^2}\right)^2\rho^{\mathsf{w},0}(s)$$

$$= G_F^2|V_{ud}|^2\,\frac{m^3}{16\pi^2}\,\kappa(s)\,\rho^{\mathsf{w},0}(s)$$

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$$\Gamma_e = \Gamma(\tau \to e\bar{\nu}\nu) = \frac{\mathcal{B}_e\Gamma}{\mathcal{B}} = \frac{G_\mathrm{F}^2 m_\tau^5}{192\pi^3}$$

conventionally $\rho^{\mathrm{w},0}(s) = \dfrac{m_\tau^2}{12\pi^2|V_\mathrm{ud}|^2\kappa(s)}\dfrac{\mathcal{B}}{\mathcal{B}_e}\dfrac{1}{\Gamma}\dfrac{d\Gamma}{ds}$

$O(\alpha)$ correction finite in Fermi theory [Kinoshita, Sirlin '59]

$$\Gamma_e = \frac{G_\mathrm{F}^2 m_\tau^5}{192\pi^3}\left[1 + \frac{\alpha}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right]\left[1 + O(m_W^2/m_\tau^2) + O(m_e^2/m_\tau^2)\right]$$

$\to$ 0.4% correction

W REGULARIZATION

Short-distance effects

[Sirlin '82][Marciano, Sirlin '88][Braaten, Li '90]

Effective Hamiltonian $H_W \propto G_\mathrm{F} O_{\mu\nu}$

G_F low-energy constant; 4-fermion operator $O_{\mu\nu}$

At $O(\alpha)$ new divergences in EFT $\rightarrow$ need regulator, Z factors

$$\frac{1}{k^2} = \frac{1}{k^2 - m_W^2} - \frac{m_W^2}{k^2(k^2 - m_W^2)}$$

[Sirlin '78]

1. universal UV divergences re-absorbed in G_F
2. process-specific corrections in S_{EW}, like a Z factor

Effective Hamiltonian at $O(\alpha)$: $H_W \propto G_\mathrm{F} S_{EW}^{1/2} O_{\mu\nu}$

matching required as noted by [Carrasco et al '15][Di Carlo et al '19]

Collect Feynman graphs in 3 classes which are individually IR safe:

- Factorizable leptonic corrections (initial state)
- Factorizable QCD corrections (final state)
- Non-factorizable corrections (initial-final state)

Isospin breaking

Initial state

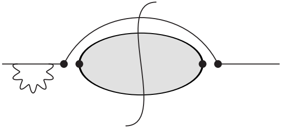
Wave-function renormalization

$$Z_\tau = 1 + \frac{\alpha}{2\pi}\left[\log\frac{m_\tau}{\mu} + 2\log\frac{m_\gamma}{m_\tau} + \cdots\right]$$

$$\frac{d\Gamma}{ds} \simeq 2 \times \tfrac{1}{2}[Z_\tau - 1]|\mathcal{M}|^2$$

$$\delta Z_\tau \equiv \frac{\alpha}{2\pi}\log(m_W/m_\tau)$$

[Sirlin '82]



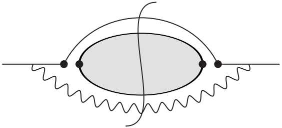
τ Bremsstrahlung

[Cirigliano et al '00, '01][MB et al, in prep]

$$\frac{d\Gamma}{ds}\ \frac{\alpha}{\pi}\left[G_{\log}(s,m_\gamma) + G_1(s) + G_2(s)\right]$$

$$G_{\log}(s,m_\gamma) = \log\frac{m_\gamma}{m_\tau} + \cdots$$

$$\delta\kappa(s) \equiv G_{\log}(s,m_\tau) + G_1(s) + G_2(s)$$



$$\frac{d\Gamma}{ds} \mathrel{+}= G_F^2 |V_{ud}|^2 \frac{m^3}{16\pi^2}\,\kappa(s)\,\rho^{w,0}(s)\left[\delta Z_\tau + \delta\kappa(s)\right]$$

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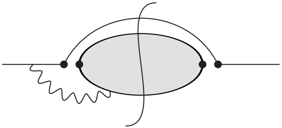
Virtual photon loop

[Sirlin '82]

$$\delta Z_{\kappa\rho} = \frac{2\alpha}{\pi}(1 + \tfrac{3}{2}\bar{Q}) \log(m_W/m_\tau)$$

[Cirigliano et al '01]

Finite parts EFT and 2π

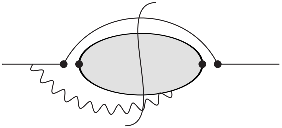


Lepton-Hadrons bremsstrahlung interfence

From EFT and 2π [Cirigliano et al' 00, '01]

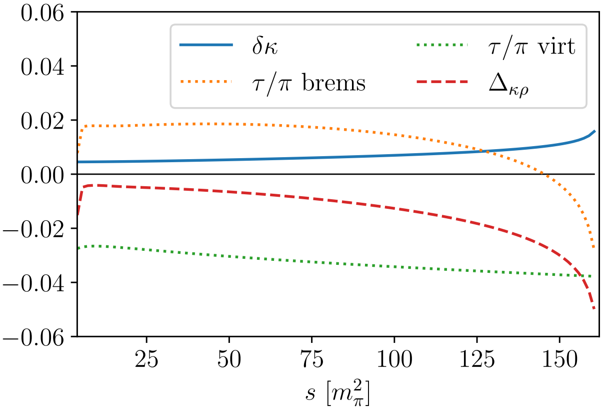
Structure-independent captured by EFT
Structure-dependent meson dominance

[Flores-Talpa et al. '06, '07]



$$\frac{d\Gamma}{ds} \mathrel{+}= G_F^2 |V_{\rm ud}|^2 \frac{m^3}{16\pi^2} \kappa(s)\, \rho^{\rm w,0}(s) \left[\delta Z_{\kappa\rho} + \Delta_{\kappa\rho}(s)\right]$$

Let's take a look



$\delta\kappa$ is channel and m_γ independent [MB et al, in prep]

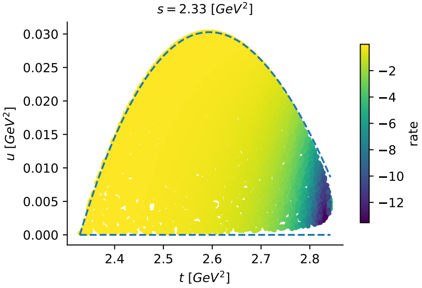
$\Delta_{\kappa\rho} \to 2\pi$, point-like, m_γ independent [Cirigliano et al '01, '02]

Intermezzo

Capitano

A numerical n-particle phase-space integrator

- Grid/GPT backend, support for several parallelization schemes
- partial support for 1-loop Passarino-Veltman functions
- no support for MCMC yet (needed for $>=6$ particles)
- currently private, soon public `github.com/mbruno46`



Used to cross-check analytic formulae

Example: Dalitz plot τ Bremsstrahlung
$\rightarrow$ wrong boundary: finite m_γ effects

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Hadronic Vacuum Polarization (HVP) contribution to a_μ

Time-momentum representation [Bernecker, Meyer, '11]

$$G^\gamma(t) = \frac{1}{3}\sum_k \int d\vec{x}\, \langle j_k^\gamma(x) j_k^\gamma(0)\rangle \quad \rightarrow \quad a_\mu = 4\alpha^2 \sum_t w_t G^\gamma(t)$$

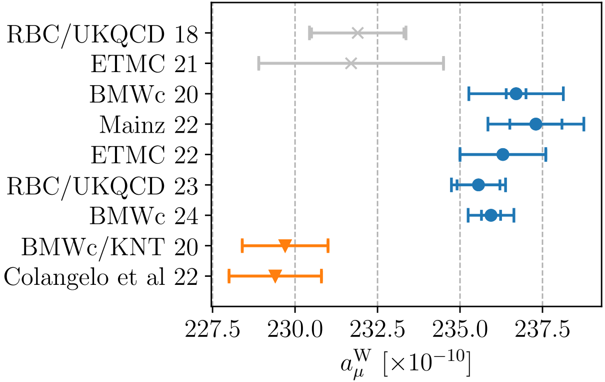
Windows in Euclidean time [RBC/UKQCD '18]

$$a_\mu^W = 4\alpha^2 \textstyle\sum_t w_t\, G^\gamma(t)\, [\Theta(t,t_0,\Delta) - \Theta(t,t_1,\Delta)]$$

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

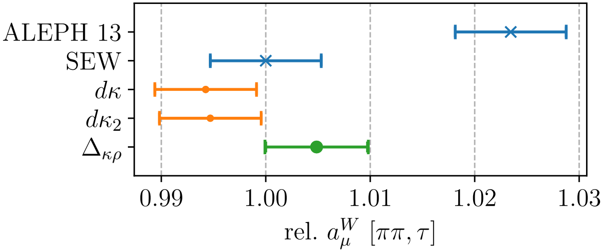
allow for in-depth cross-checks

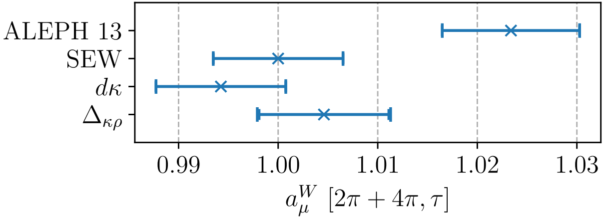
Tensions



RBC/UKQCD 18
ETMC 21
BMWc 20
Mainz 22
ETMC 22
RBC/UKQCD 23
BMWc 24
BMWc/KNT 20
Colangelo et al 22
227.5
230.0
232.5
235.0
237.5
a_μ^{W} [$\times 10^{-10}$]

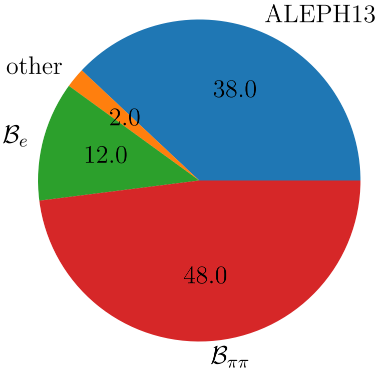
2π error breakdown





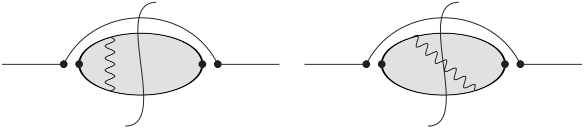
Towards a_μ^W

2π error breakdown



Isospin breaking

Final state



$+ \dots$

1. take experimental $d\Gamma/ds$ (e.g. Aleph13, Belle08)

2. $\delta\kappa$ initial state corrections: analytic, under control

3. $\Delta_{\kappa\rho}$ initial-finite mixed rad. corr:
   analytically known for intermediate two-pion channel
   effective field theory [Cirigliano et al '01, '02]
   meson dominance models [Flores-Talpa et al. '06, '07]
   new results from phenomenological models [Roig et al '23]

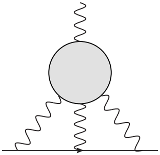
4. define $\delta\Gamma_{EM} \equiv \delta\kappa(s) + \Delta_{\kappa\rho}(s)$ and calculate:

$$\frac{m_\tau^2}{12\pi^2 G_{\mathrm{F}}^2 |V_{\mathrm{ud}}|^2 \kappa(s)} \frac{1}{S_{EW}} \frac{1}{1+\frac{\alpha}{\pi}\delta\Gamma_{EM}(s)} \left[\frac{\mathcal{B}_e}{\mathcal{B}} \frac{1}{\Gamma} \frac{d\Gamma}{ds}\right]_{\mathrm{exp}} = \rho^{\mathrm{w},0}(s) + \delta\rho(s)$$

5. Laplace transfrom to Euclidean time

6. add difference $ee - \tau$ evaluated from LQCD+QED

Synergy



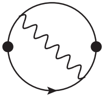
from QCD we need a 4-point function $f(x, y, z, t)$:

known kernel with details of photons and muon line

1 pair of point sources (x, y), sum over z, t exact at sink

stochastic sampling over (x, y) (based on $|x - y|$)

Successfull strategy: x10 error reduction [RBC '16]



from QCD we need a 4-point function $f(x, y, z, t)$:

$(g-2)_\mu$ kernel + photon propagator

Similar problem → re-use HLbL point sources!

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The RBC & UKQCD collaborations

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Raza Sufian
Tianle Wang

CERN
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Tobias Tsang

Columbia University
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Sarah Fields
Ceran Hu
Yikai Huo
Joseph Karpie (JLab)
Erik Lundstrum
Bob Mawhinney
Bigeng Wang (Kentucky)

University of Connecticut
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Luchang Jin (RBRC)
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Joshua Swaim
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Luigi Del Debbio
Felix Erben
Vera Gülpers
Maxwell T. Hansen
Tim Harris
Ryan Hill
Raoul Hodgson
Nelson Lachini
Zi Yan Li
Michael Marshall
Fionn Ó hÓgáin
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James Richings
Azusa Yamaguchi
Andrew Z.N. Yong

Liverpool Hope/Uni. of Liverpool
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LLNL
Aaron Meyer

University of Milano Bicocca
Mattia Bruno

Nara Women's University
Hiroshi Ohki

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Contribution to a_μ

Time-momentum representation [Bernecker, Meyer, '11]

$$G^\gamma(t) = \tfrac{1}{3}\sum_k \int d\vec{x}\, \langle j_k^\gamma(x) j_k^\gamma(0)\rangle \quad \rightarrow \quad a_\mu = 4\alpha^2 \sum_t w_t G^\gamma(t)$$

Isospin decomposition of u, d current

$$j_\mu^\gamma = \tfrac{i}{6}\left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right) + \tfrac{i}{2}\left(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right) = j_\mu^{(0)} + j_\mu^{(1)}$$

$$\tfrac{i}{2}\left(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right), \begin{bmatrix} I = 1 \\ I_3 = 0 \end{bmatrix} \quad \rightarrow \quad j_\mu^{(1,-)} = \tfrac{i}{\sqrt{2}}\left(\bar{u}\gamma_\mu d\right), \begin{bmatrix} I = 1 \\ I_3 = -1 \end{bmatrix}$$

Isospin 1 charged correlator $G_{11}^W = \tfrac{1}{3}\sum_k \int d\vec{x}\, \langle j_k^{(1,+)}(x) j_k^{(1,-)}(0)\rangle$

$$G_{II'}^\gamma \equiv \frac{1}{3}\sum_k \int d\vec{x} \langle j_k^{(I)}(x)\, j_k^{(I')}(0)\rangle\,, \quad \delta G^{11} \equiv G_{11}^\gamma - G_{11}^W$$

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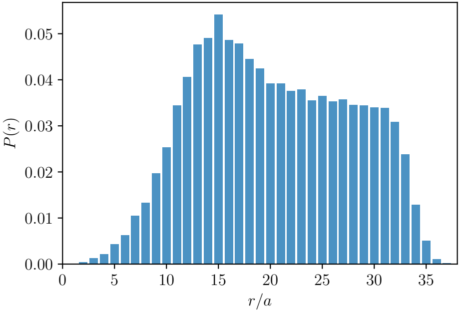
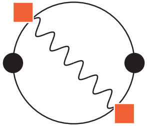
Sampling strategy

$$\tilde{V}_\Gamma(x_0, z_0, r) = \sum_{\vec{x},\vec{z}} \mathrm{tr}\Big[\Gamma D^{-1}(x,0)\gamma_\nu D^{-1}(0,z)\Gamma D^{-1}(z,r)\gamma^\nu D^{-1}(r,x)\Big]$$

$$V_\Gamma(|x_0 - z_0|) = \sum_r \Delta(r)\tilde{V}_\Gamma(x_0, z_0, r)$$

$O(10^3)$ points $\rightarrow$ $O(10^6)$ pairs



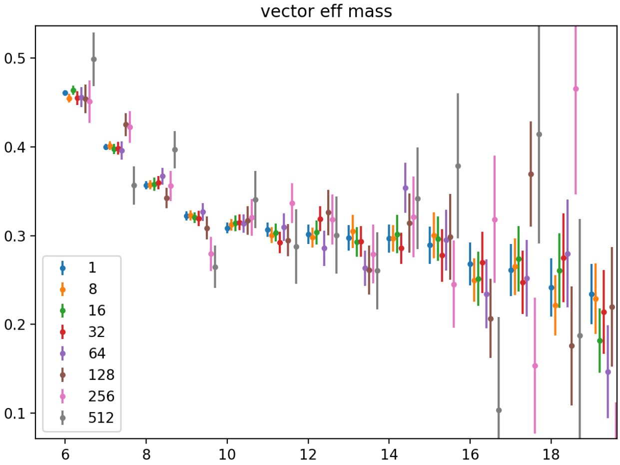


contract photon offline
$\rightarrow$ study QED_L vs QED_∞

Sparse propagators

Vector effective mass

observable dependent, low stat. but good guidance



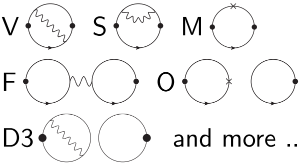
Example

Diagram V

IB corrections for charged (τ) and neutral (ee) [MB et al PoS'18]

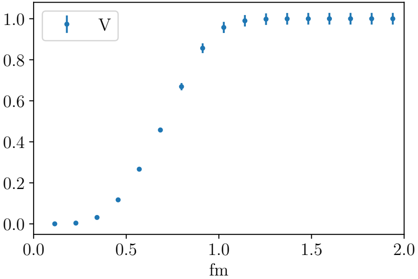
difference of τ and ee spectral densities in Euclidean time

many (quark) diagrams involved:



and more ...

[preliminary]



plot = cumsum[win $\times$ μ-kernel $\times V$]

64I phys.pion mass ensemble

first calculations of all diagrams [BMWc '20,'24]

ongoing RBC/UKQCD effort

- significant stat. improvement for leading-diagrams
- first results for sub-leading diagrams

Take $\Delta_{\kappa\rho}$ from EFT $\to$ restrict to two-pion channel

discard G^{γ}_{00}, keep G^{γ}_{01}

Lattice calculation fully inclusive in energy (cut at m_τ) and channels

G_{01} mostly dominated by $\pi\pi$. Is it correct?

simple estimate $a^W[3\pi] \leq 20\%$ of $a^W[2\pi]$ [MB Edinburgh '22]

Isospin-breaking in 2π and 3π from [Colangelo et al 22][Hofericther et al '23]

IB correction of $a^W[3\pi] \approx -1 \cdot 10^{-10}$

IB correction of $a^W[2\pi] \approx +1 \cdot 10^{-10}$

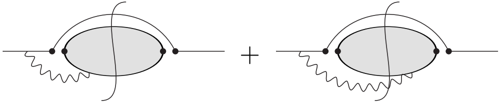
warning if precision from Lattice $\ll 2 \cdot 10^{-10}$

Long-distance

Final dream

Infrared divergences cancel out in total rate

cancellations occur in subset of diagrams



= IR safe

Intermediate two-pion channel

effective field theory [Cirigliano et al '01, '02]

meson dominance models [Flores-Talpa et al. '06, '07]

Full estimate in LQCD+QED

integral of inf.vol. kernel w/ 3-point QCD correlators

Conclusions

Windows very powerful quantities: intermediate window a_μ^W

hadronic τ-decays can shed light on tension lattice vs e^+e^-

τ data very competitive on intermediate window

historic tension w/ ee data and in IB τ effects

ongoing blinded analysis of Aleph $< 1\%$ accuracy on a_μ^W

Work in progress to finalize full formalism [MB et al, in prep]

W-regularization and short-distance corrections

(re-)calculation of initial state rad.cor.

numerical calculation of final state IB corrections

relevant also for QED correction to HVP

Thanks for your attention

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