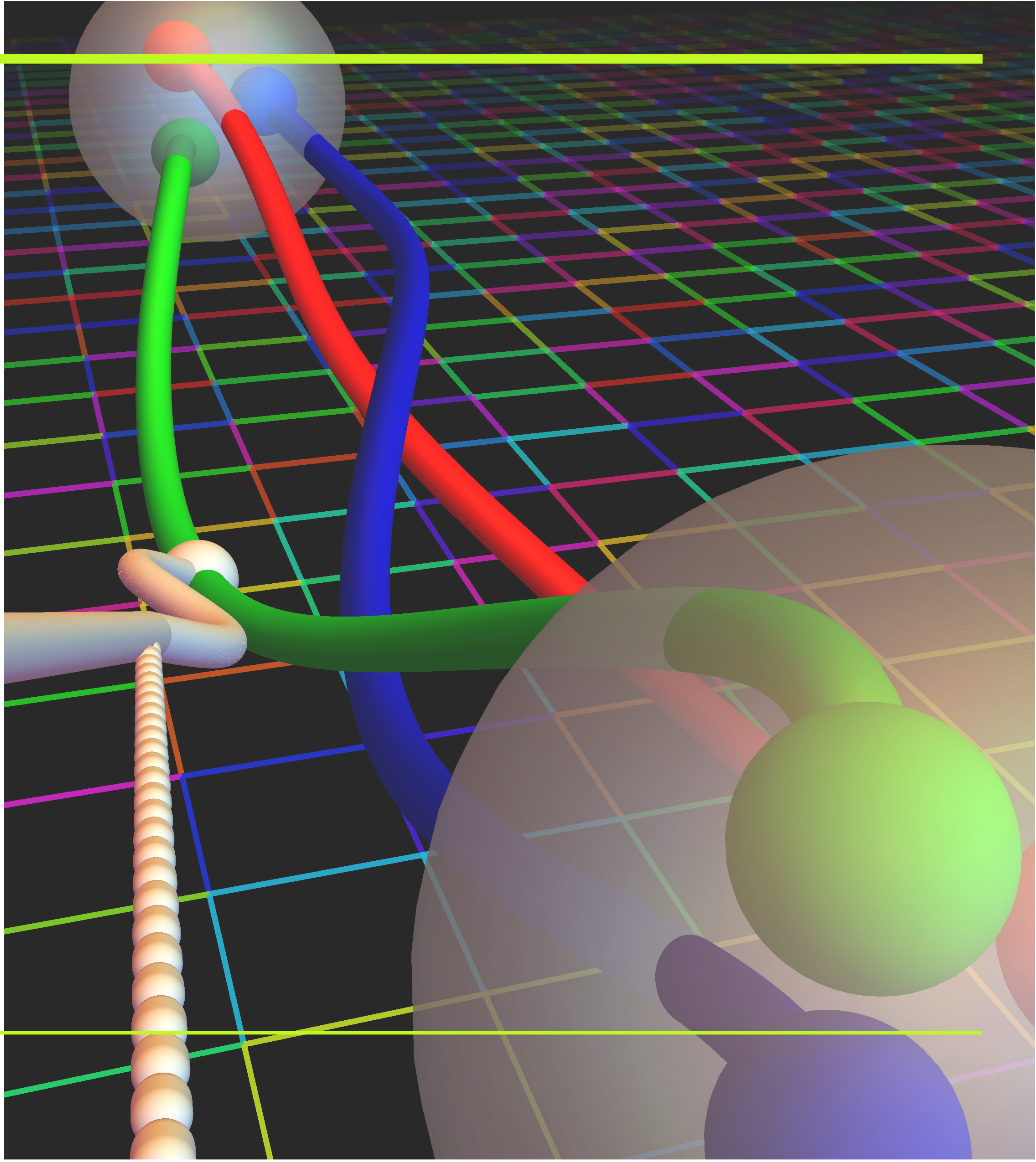
Adding QED to the lattice: *warming up to a non-perturbative calculation of neutron decay*



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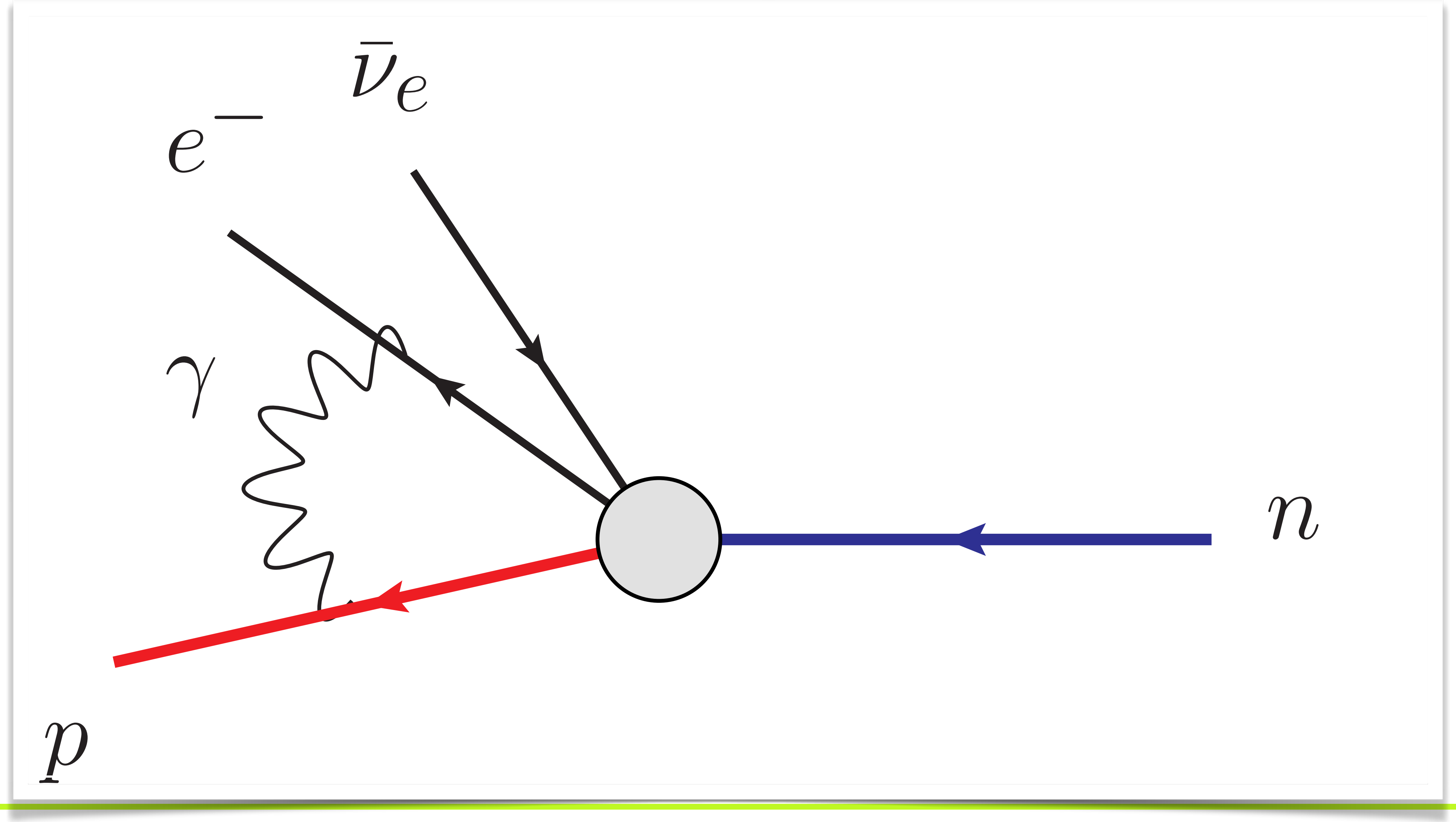
INT PROGRAM 23-1B: NEW PHYSICS SEARCHES AT THE PRECISION FRONTIER
MAY 24, 2023

Motivation

- β-decay is one of the most promising methods of testing the Standard Model
  - β-decay experiments are how we know the *weak*-interactions are V-A (left handed)
  - Precise measurements are used to search for small corrections to V-A structure
  - β-decay is used to determine elements of the quark mixing matrix (CKM)

- With current limits, our understanding of β-decay must be controlled with a precision of $O(10^{-4})$
  - The main challenge is understanding electromagnetic (QED) corrections often denoted *radiative* or *radiative QED* corrections
  - The challenge is that neutrons and protons are composite states of quarks and gluons, the degrees of freedom of QCD, which is a strongly coupled theory



Motivation

- The importance of neutron decays for obtaining a more (the most?) precise determination of V_{ud} places increased scrutiny on our ability to control the radiative QED corrections, Δ_R

$$|V_{ud}|^2 \tau_n \left(1 + 3\lambda^2\right) \left(1 + \Delta_R\right) = 5099.3(3) s$$

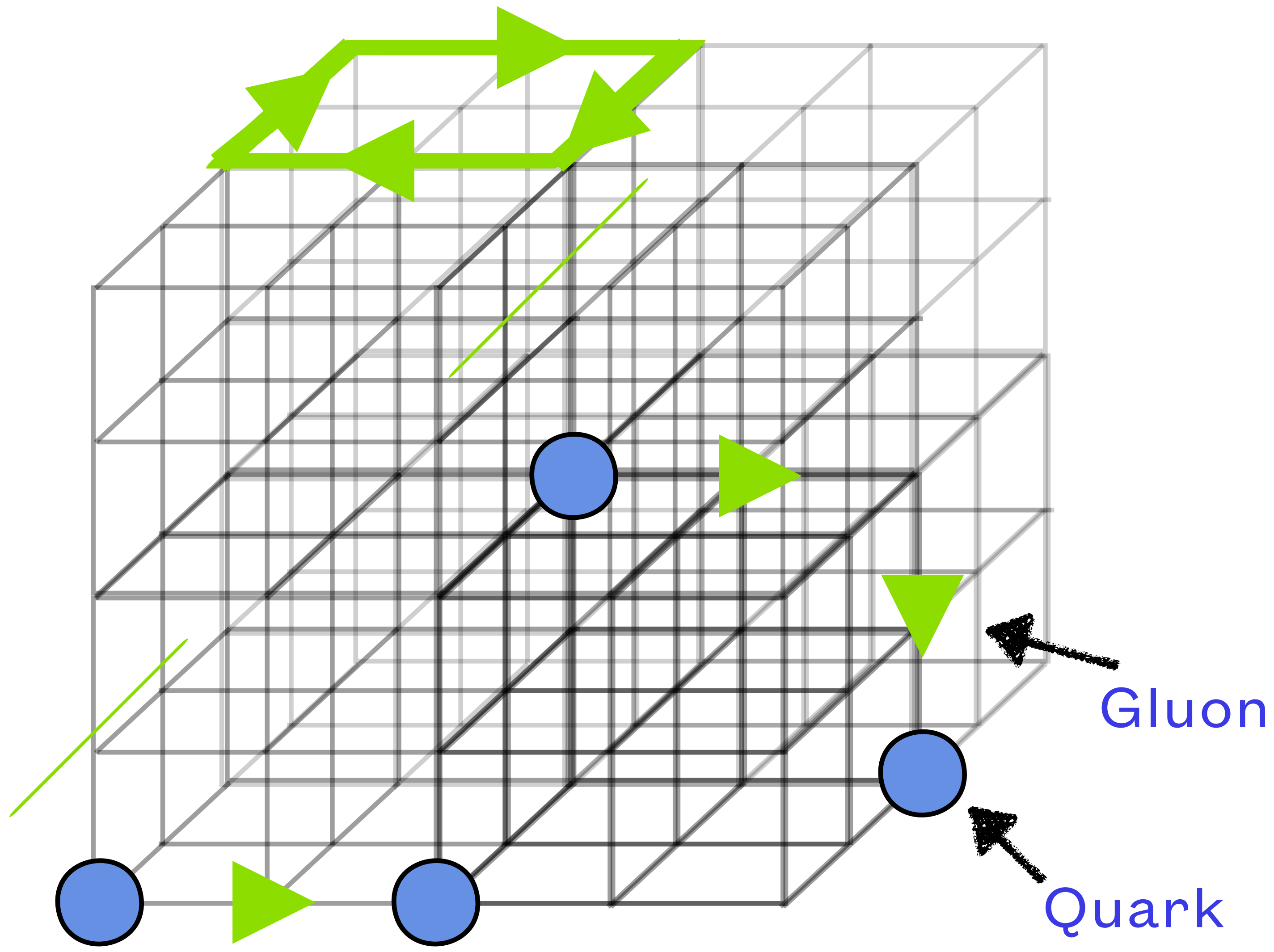
neutron lifetime nucleon axial charge

- We believe we know how to compute Δ_R, but it is required with a precision of 10^{-4}

- The dispersion theory methods that are used to determine Δ_R are well established (Cauchy contour integral of experimental data)
  - however, recently, it was uncovered that they missed an O(2%) correction to g_A
    (Δ_R can be thought of as a correction to g_V)
    Cirigliano, de Vries, Hayen, Mereghetti, Walker-Loud, Phys.Rev.Lett. 129 (2022) 2202.10439
- Could there be corrections to Δ_R that are missed by the dispersive methods relevant at the 10^{-4} level?
- The only viable method to cross check the determination of Δ_R is with lattice QCD + QED calculations
  - Lattice QCD offers a fully non-perturbative method to compute such corrections

Lattice QCD

- Introduce a finite lattice by discretizing 4D spacetime
  - Choose lattice action ~ $S[U, \overline{\psi}, \psi]$
  - Provides a momentum cutoff ~$1/a$
  - Wick rotate to imaginary time for Monte Carlo importance sampling of the gauge fields ~ e^{-S}
    - e^{-S} can be interpreted as a probability distribution and the quark determinant is real in Euclidean spacetime



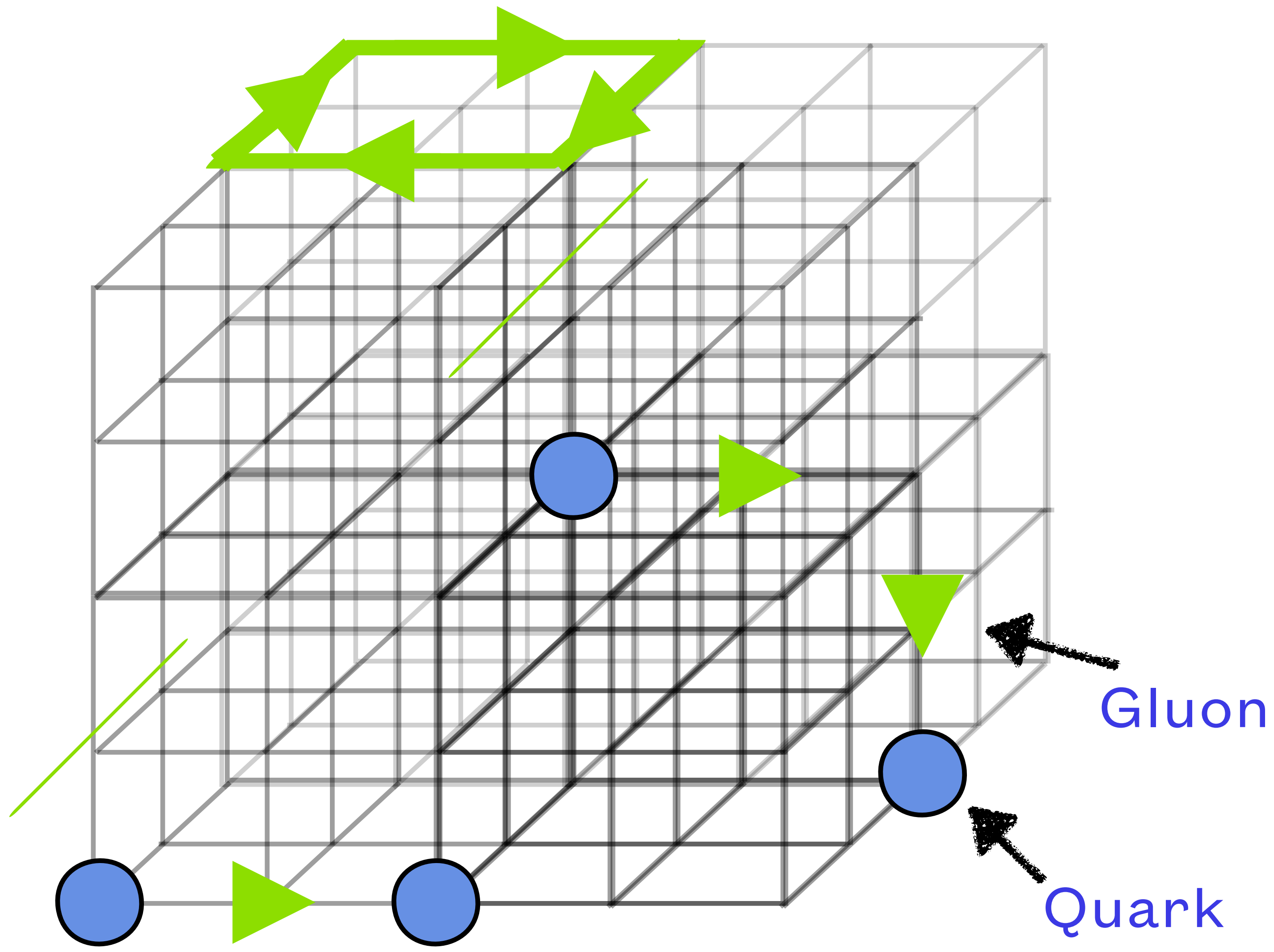
$$\langle O_2(t)\, O_1(0)\rangle = \frac{1}{Z}\int \mathscr{D}[U,\overline{\psi},\psi]\; e^{-S[U,\overline{\psi}\psi]}\, O_2[U,\overline{\psi},\psi]\; O_1[U,\overline{\psi},\psi]$$

$$C(t) = \langle O_2(t)\, O_1(0)\rangle = \sum_n Z_n^2 e^{-E_n t}$$

$$m_{eff} = -\frac{\ln C(t+1)}{\ln C(t)}$$

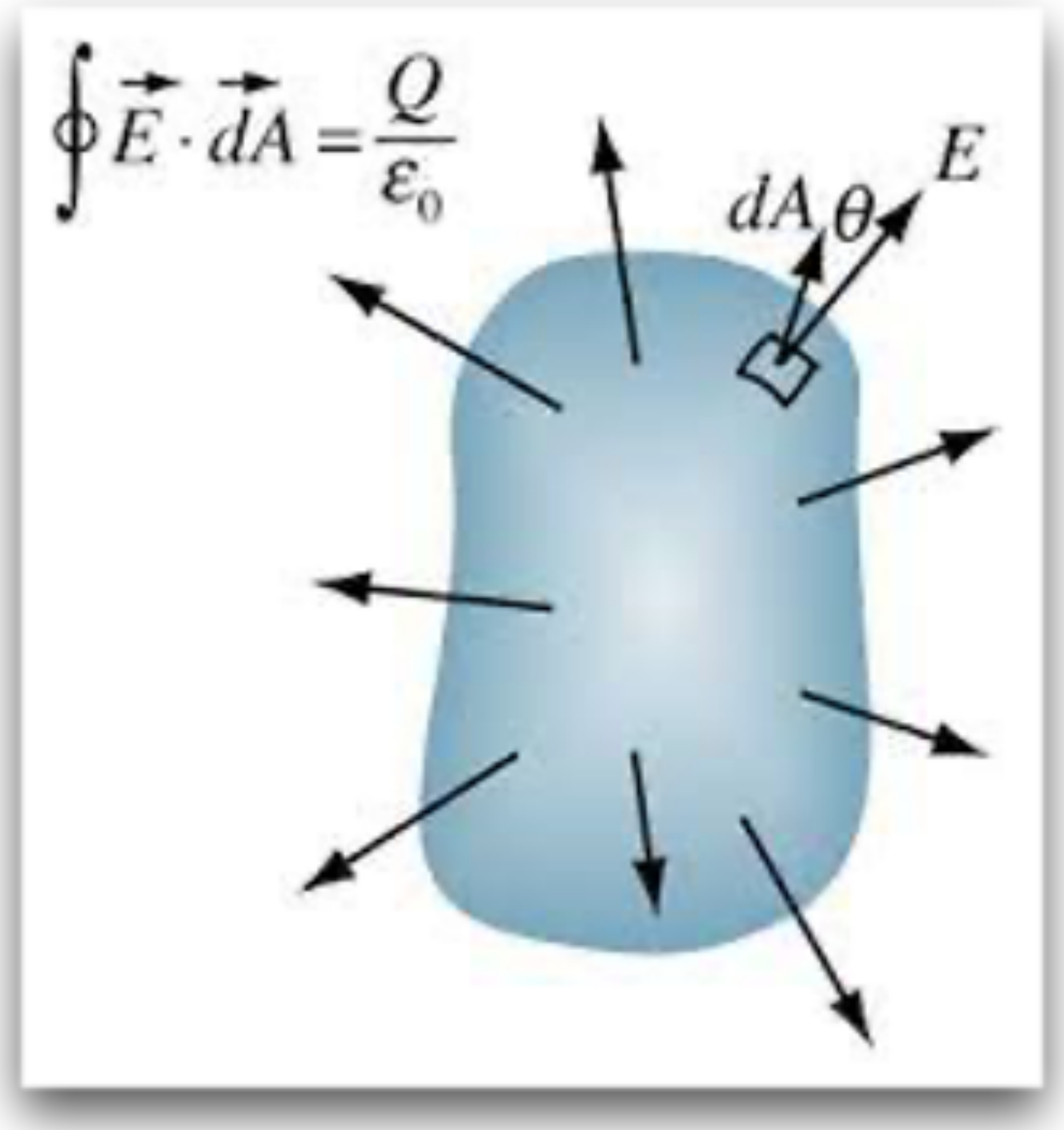
Lattice QED

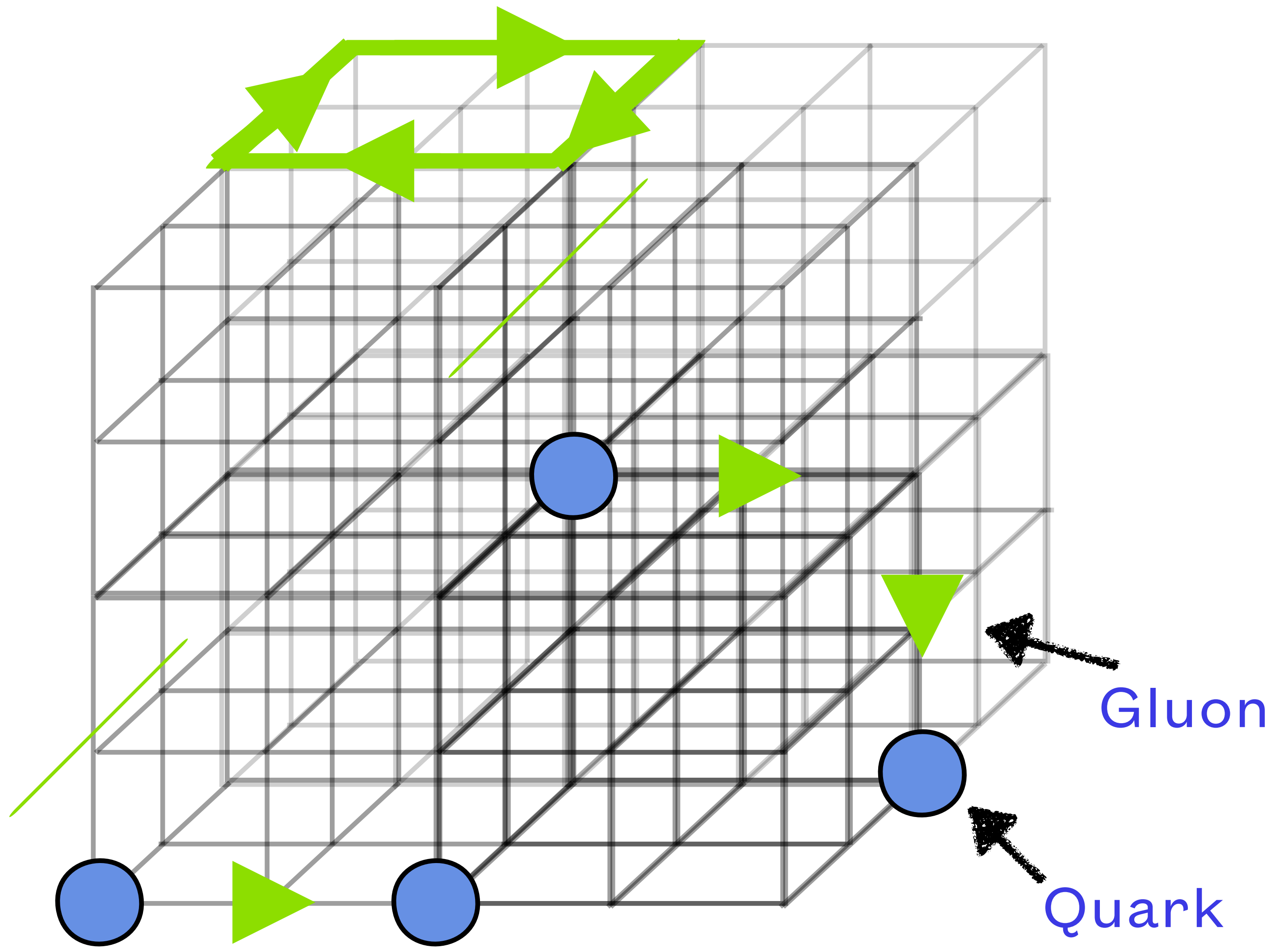
- How do charged states behave in a periodic finite volume?

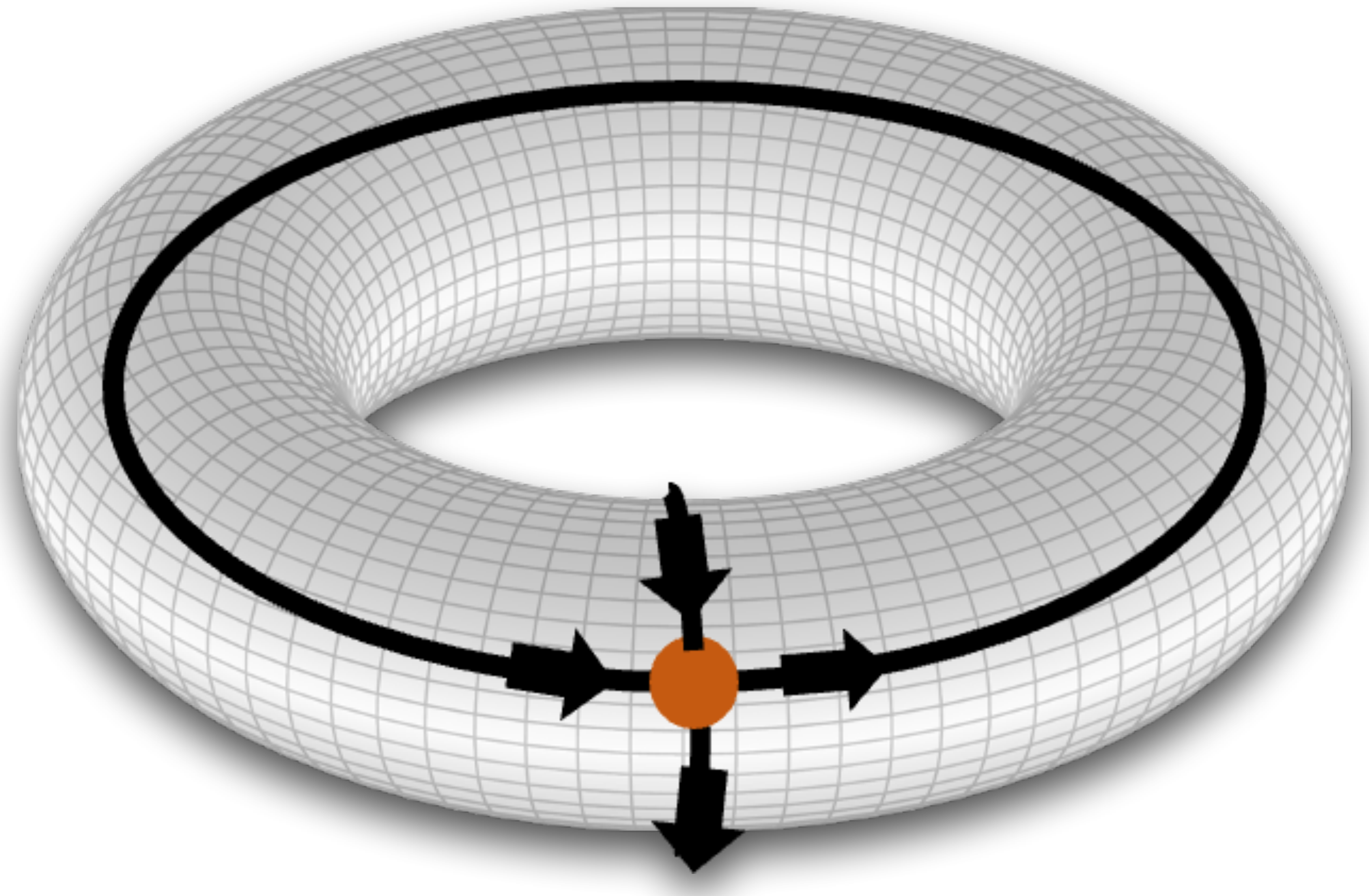


Lattice QED

- How do charged states behave in a periodic finite volume?
  - Consider Gauss' Law







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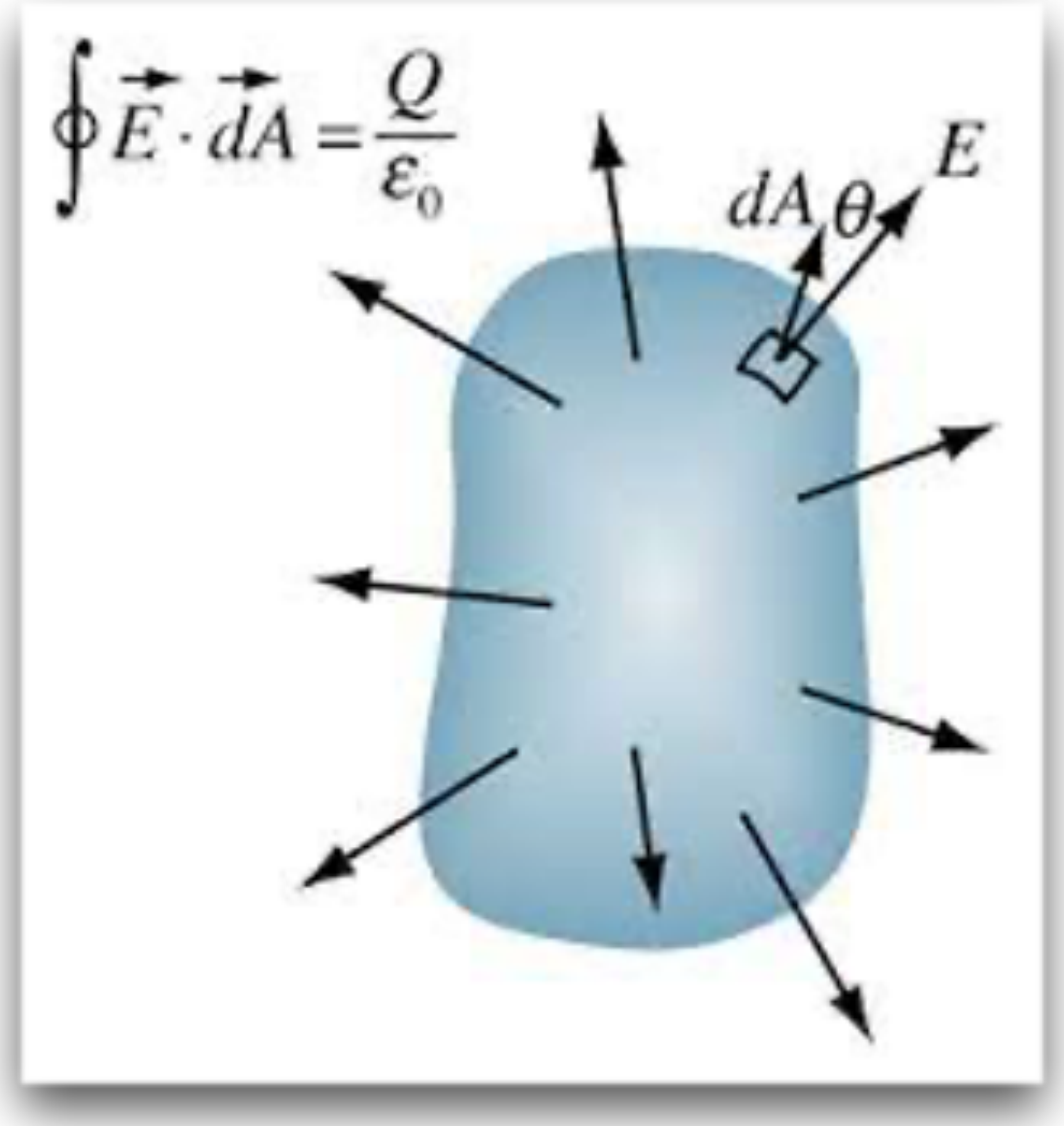
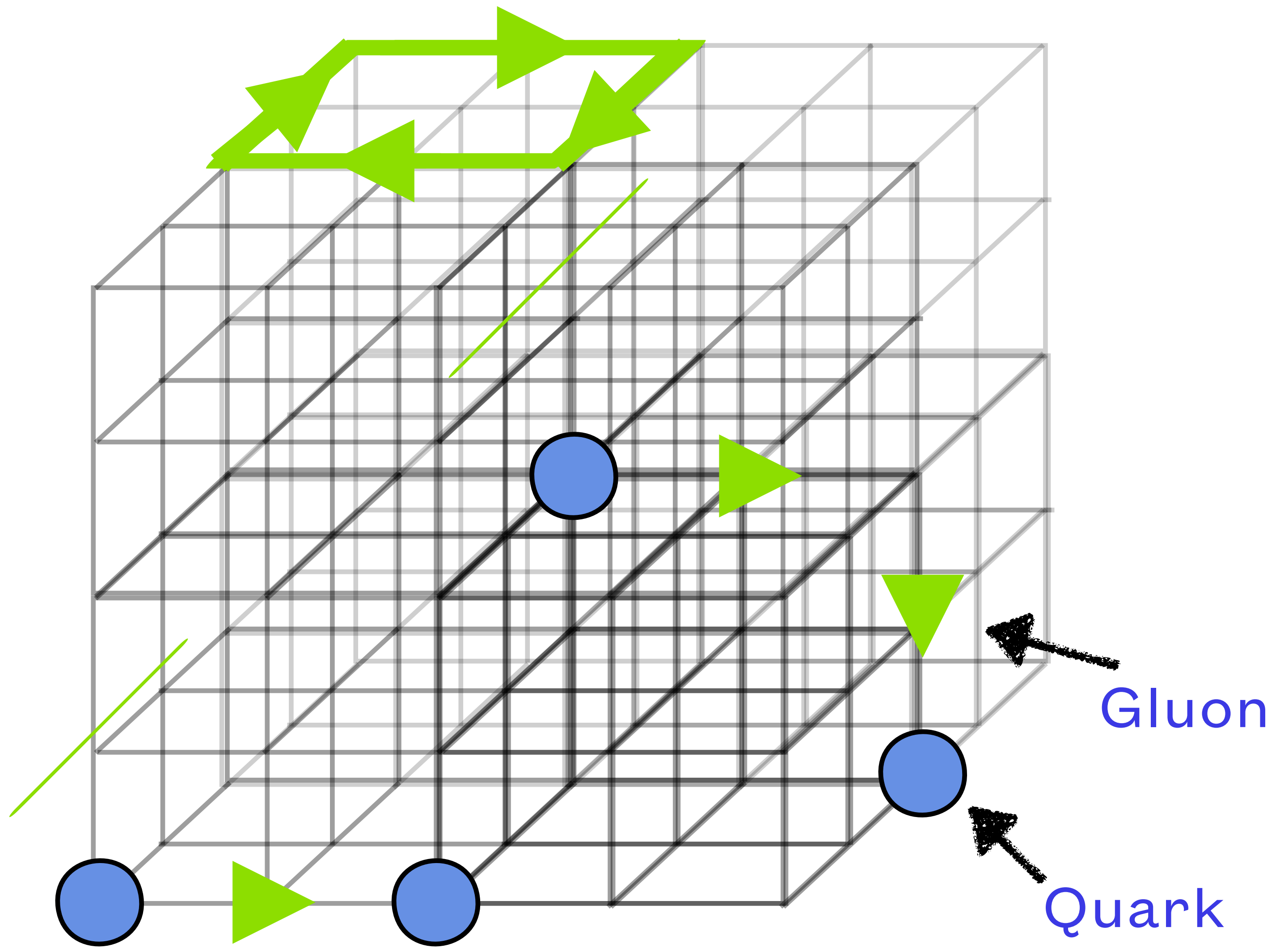
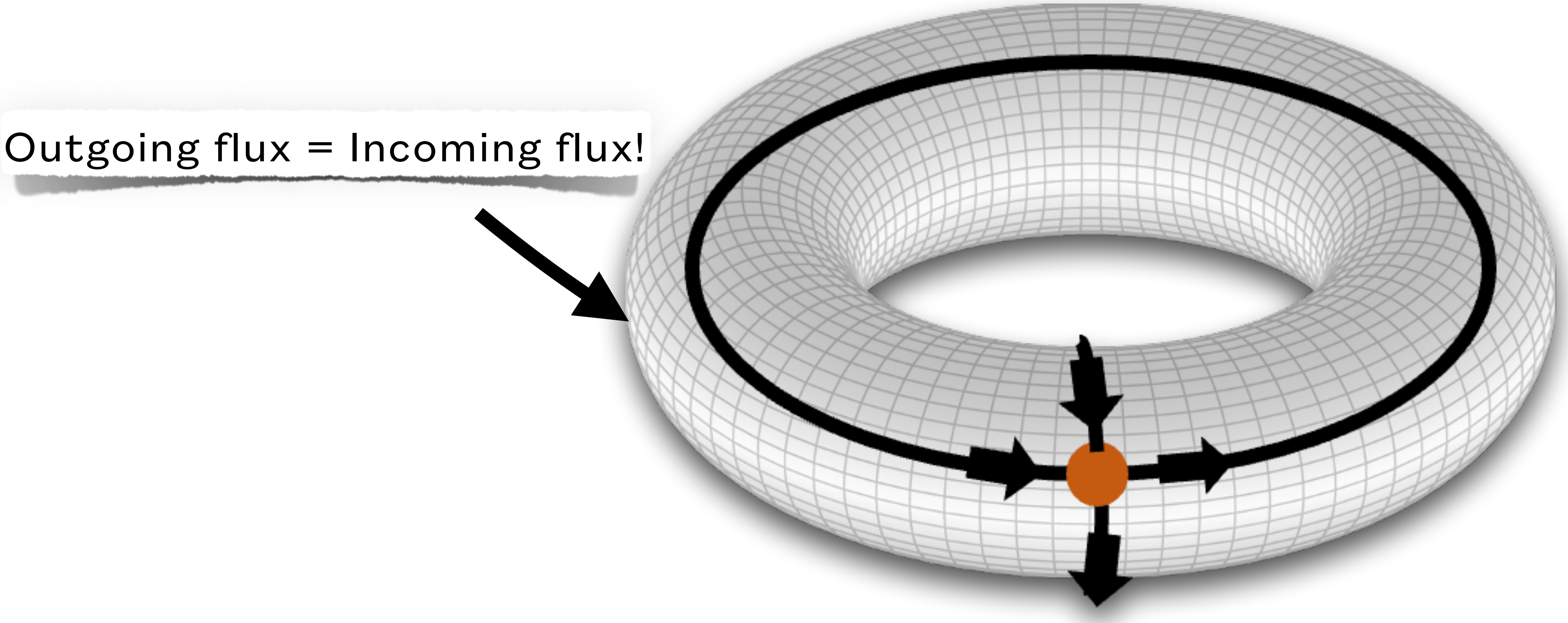
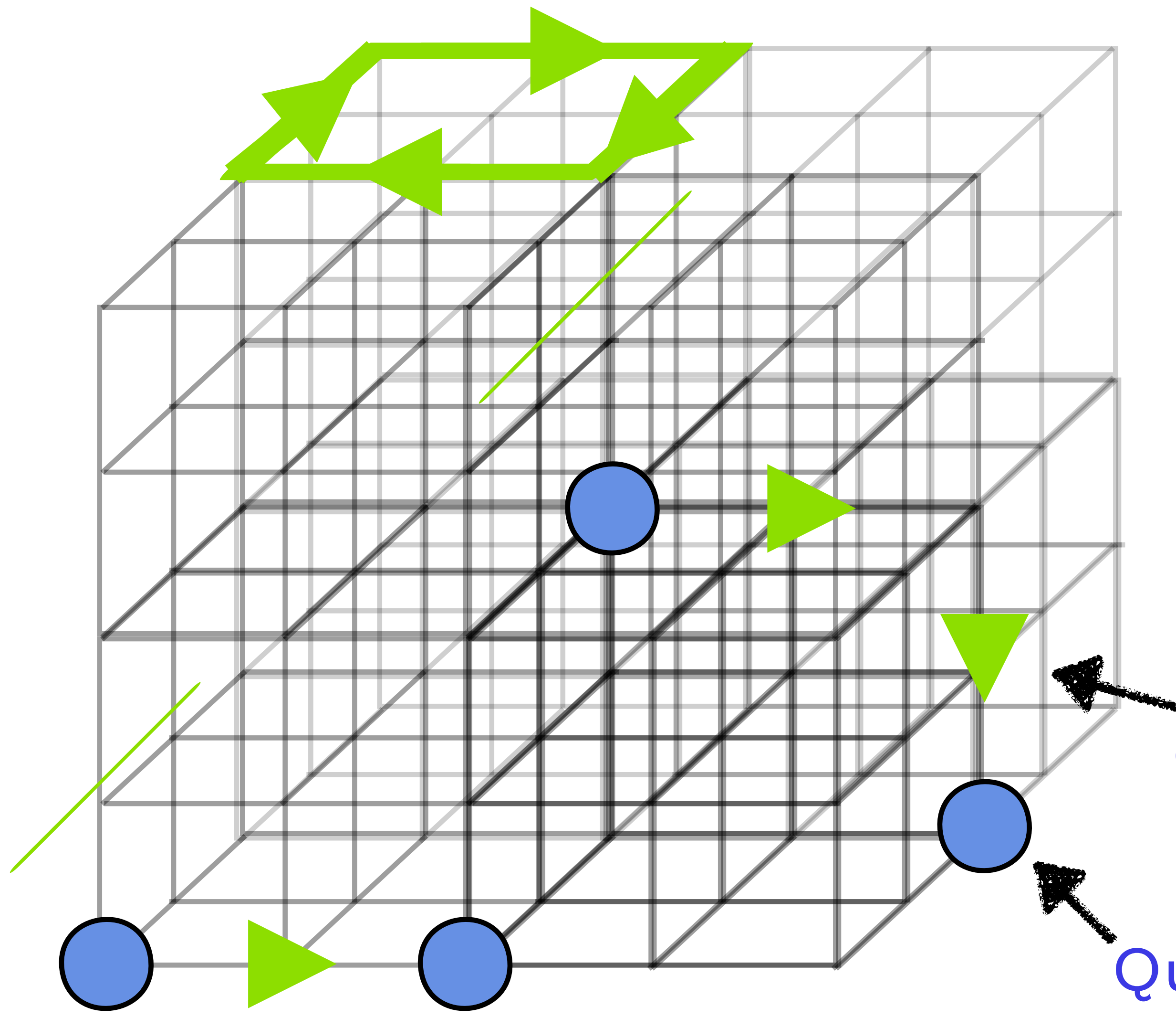






Lattice QED



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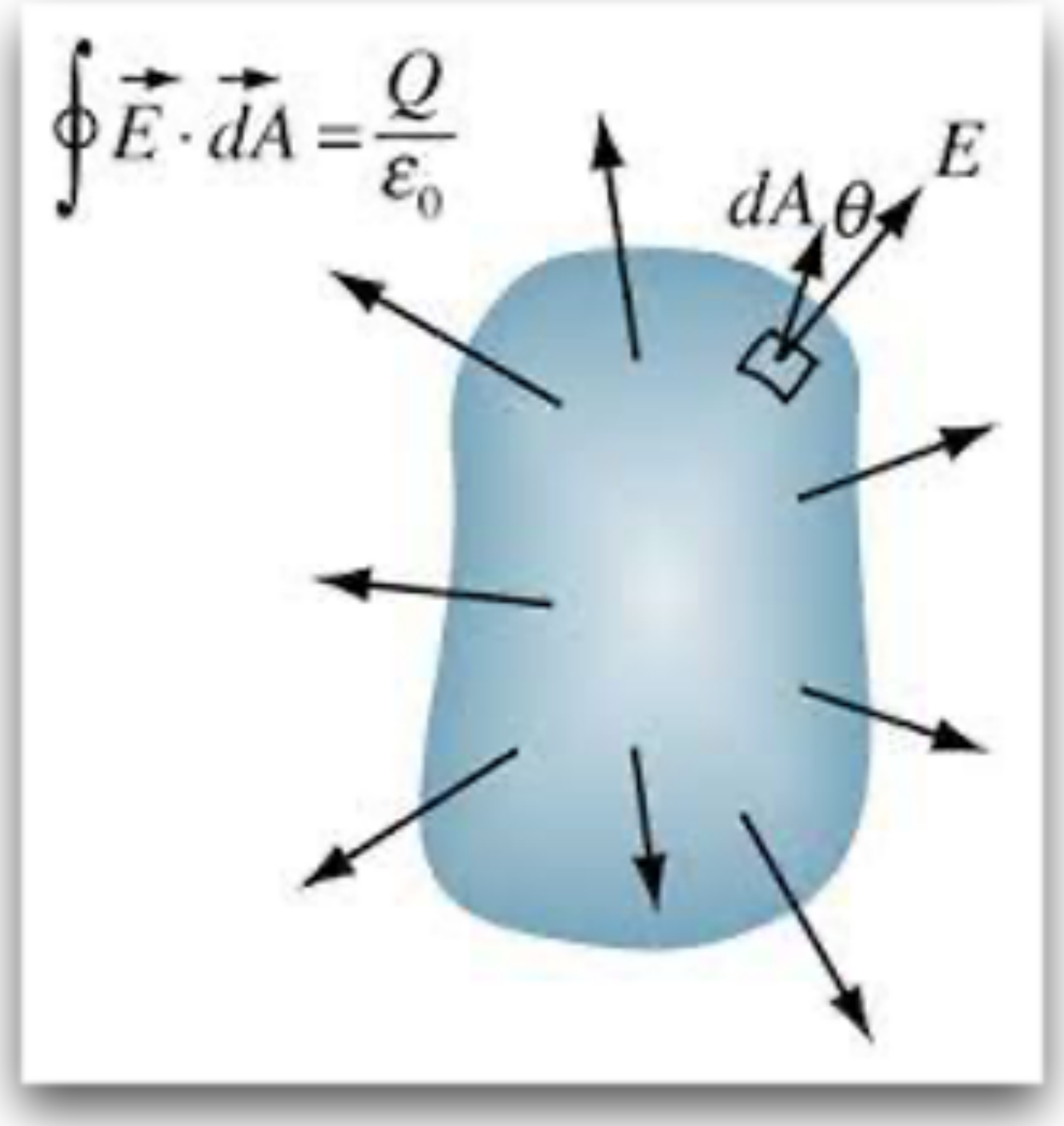
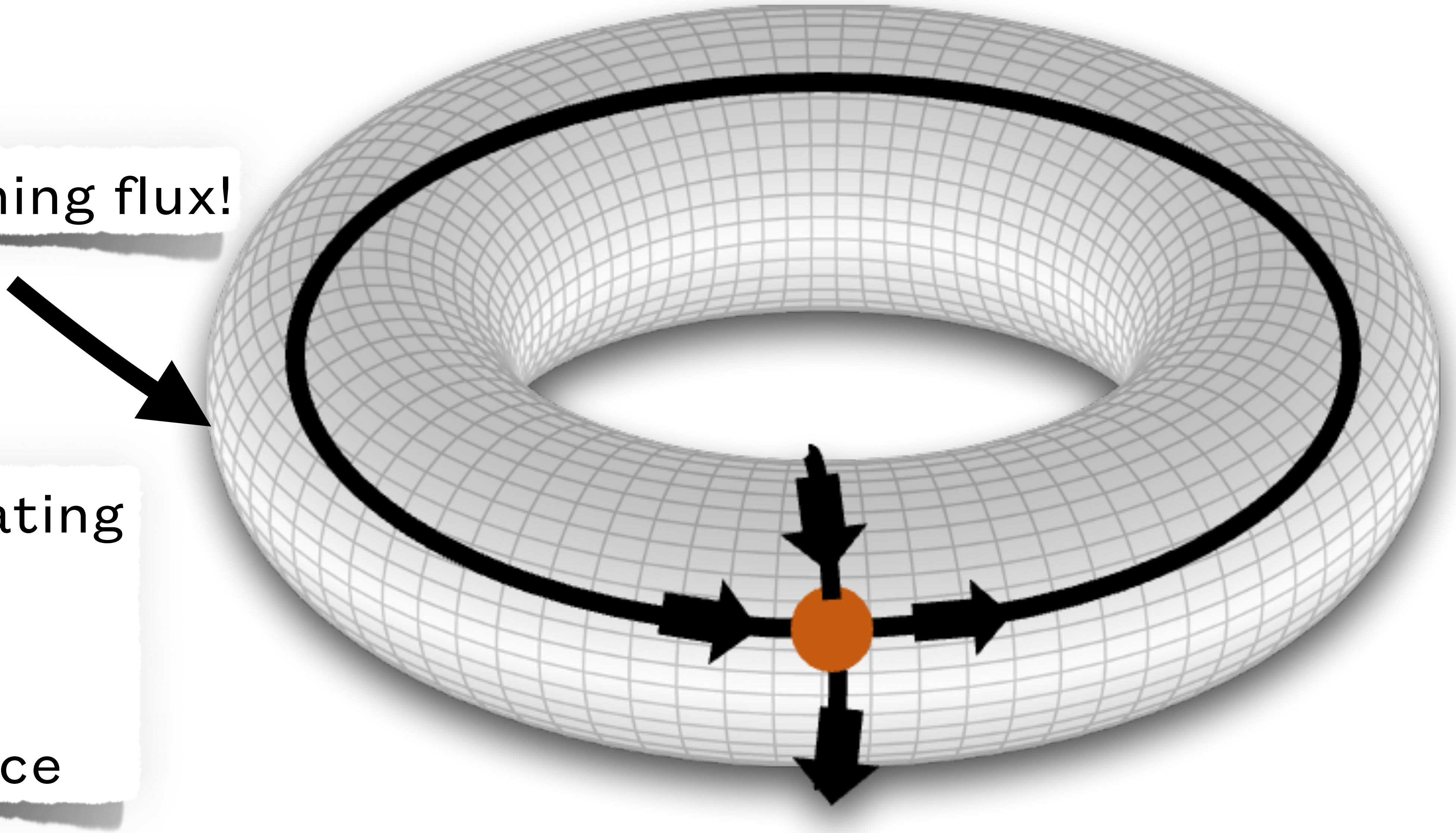


Outgoing flux = Incoming flux!

No charged propagating
states allowed
in the Hilbert space



Lattice QED

- How do charged states behave
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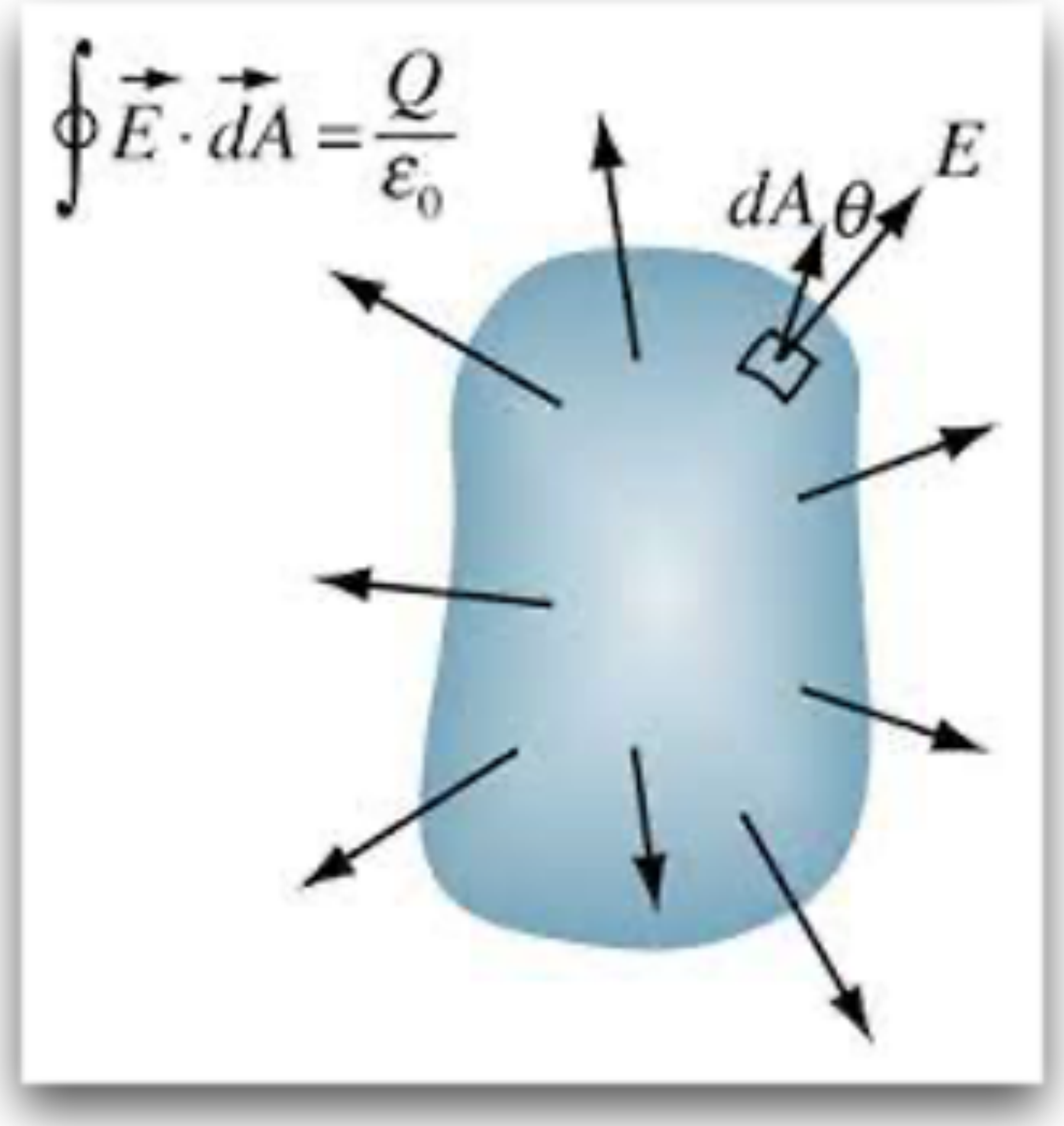
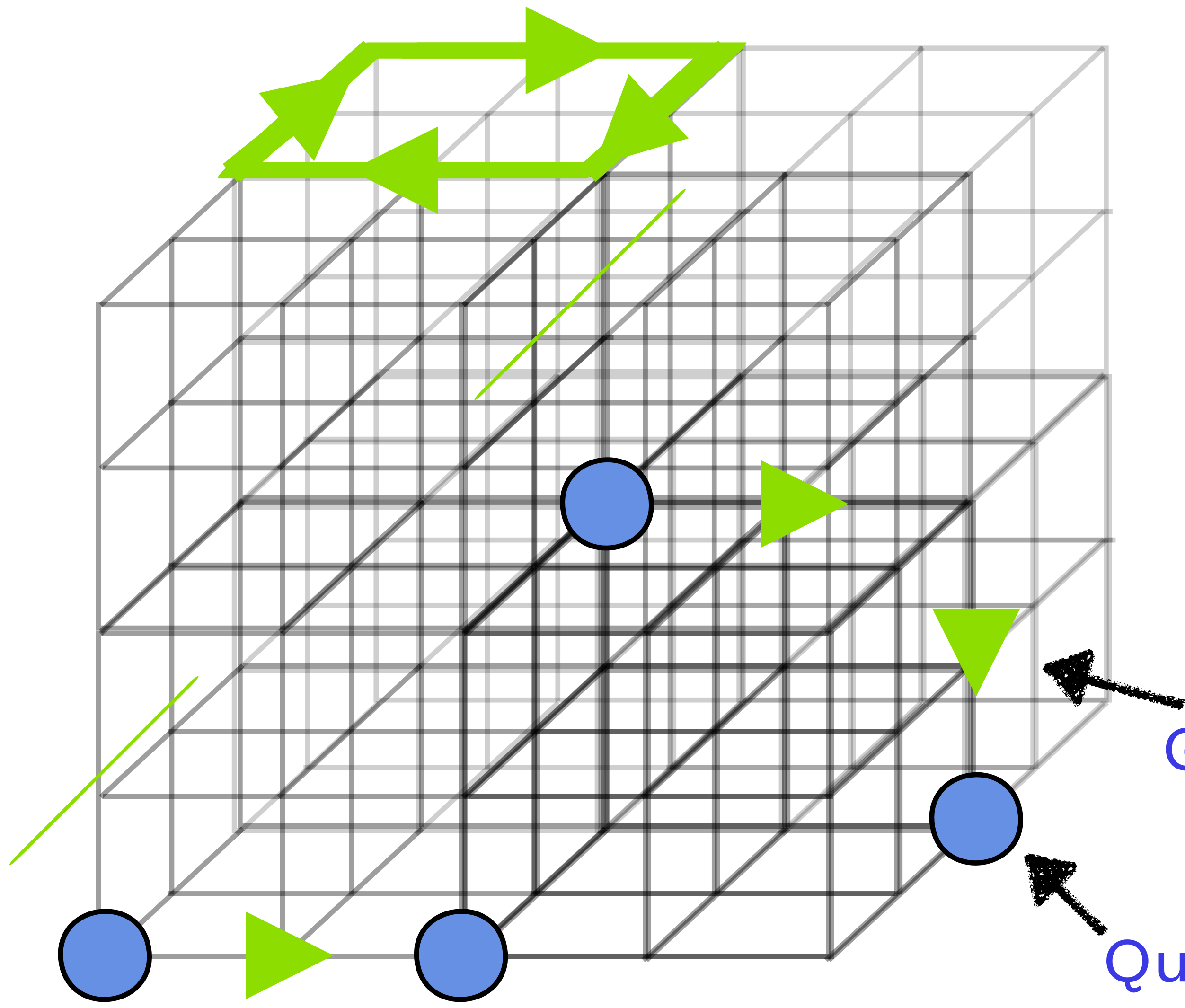
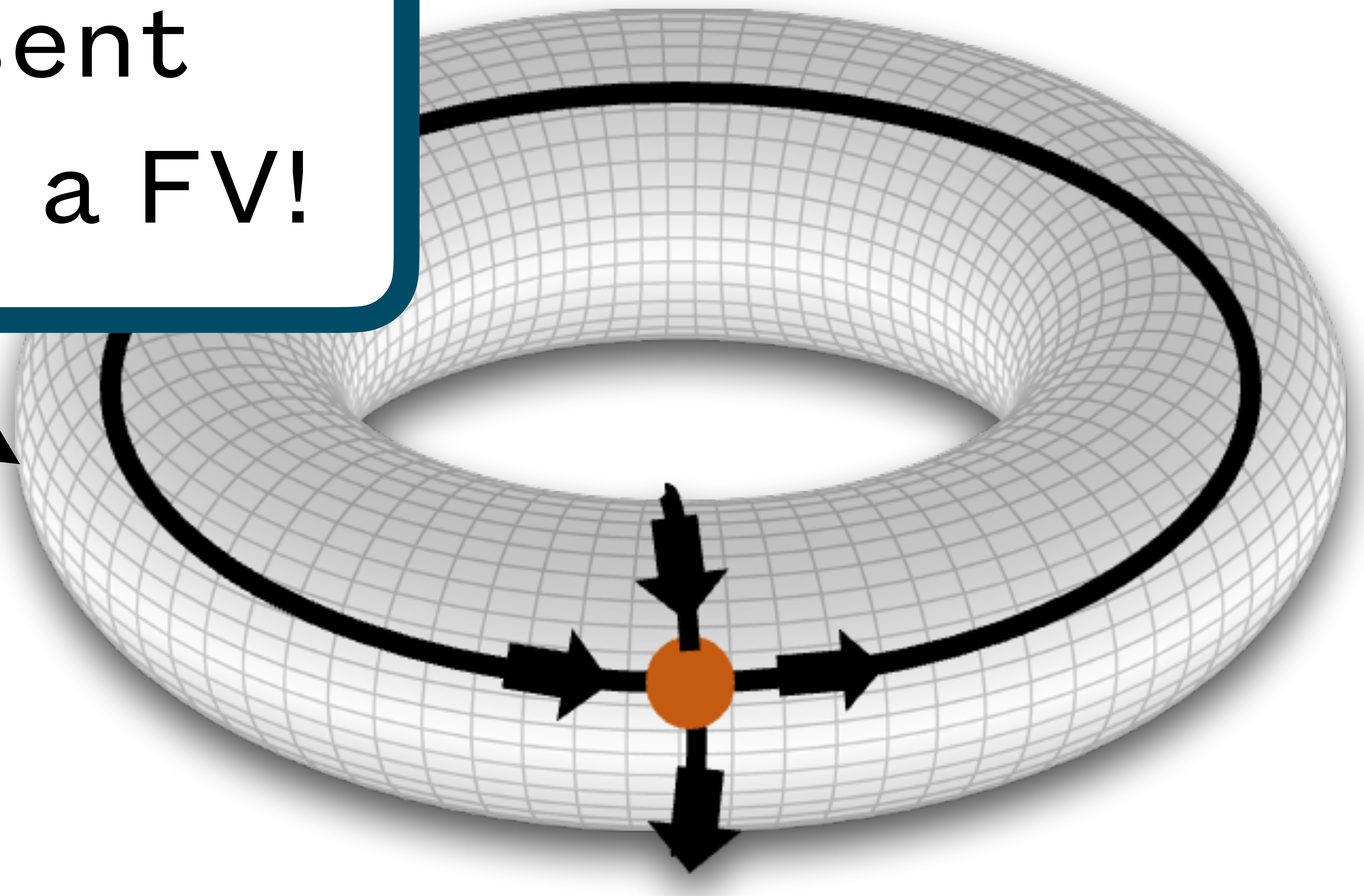


This is the first sign that we need to think more carefully about how to represent charge states in a FV!

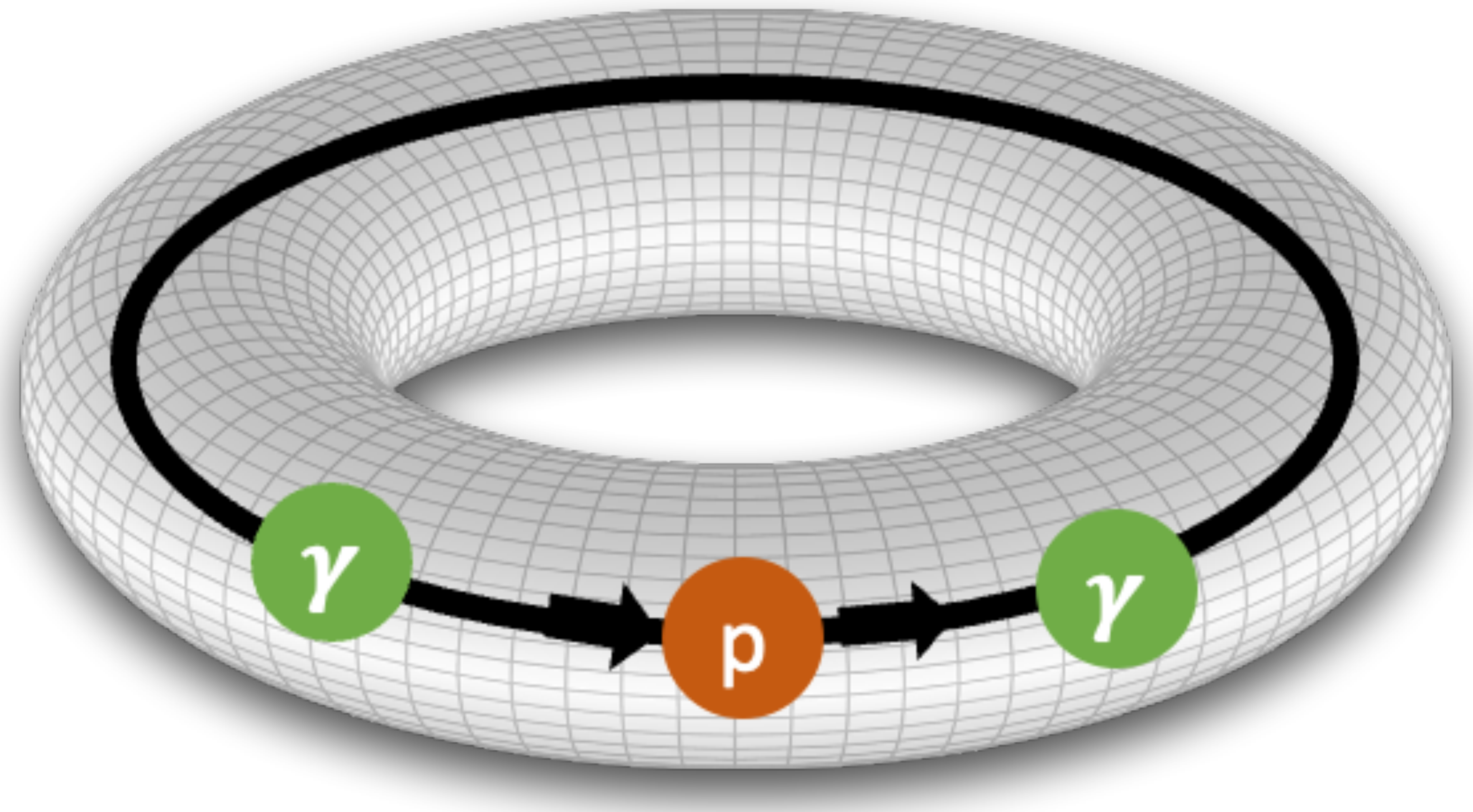




No charged propagating states allowed in the Hilbert space

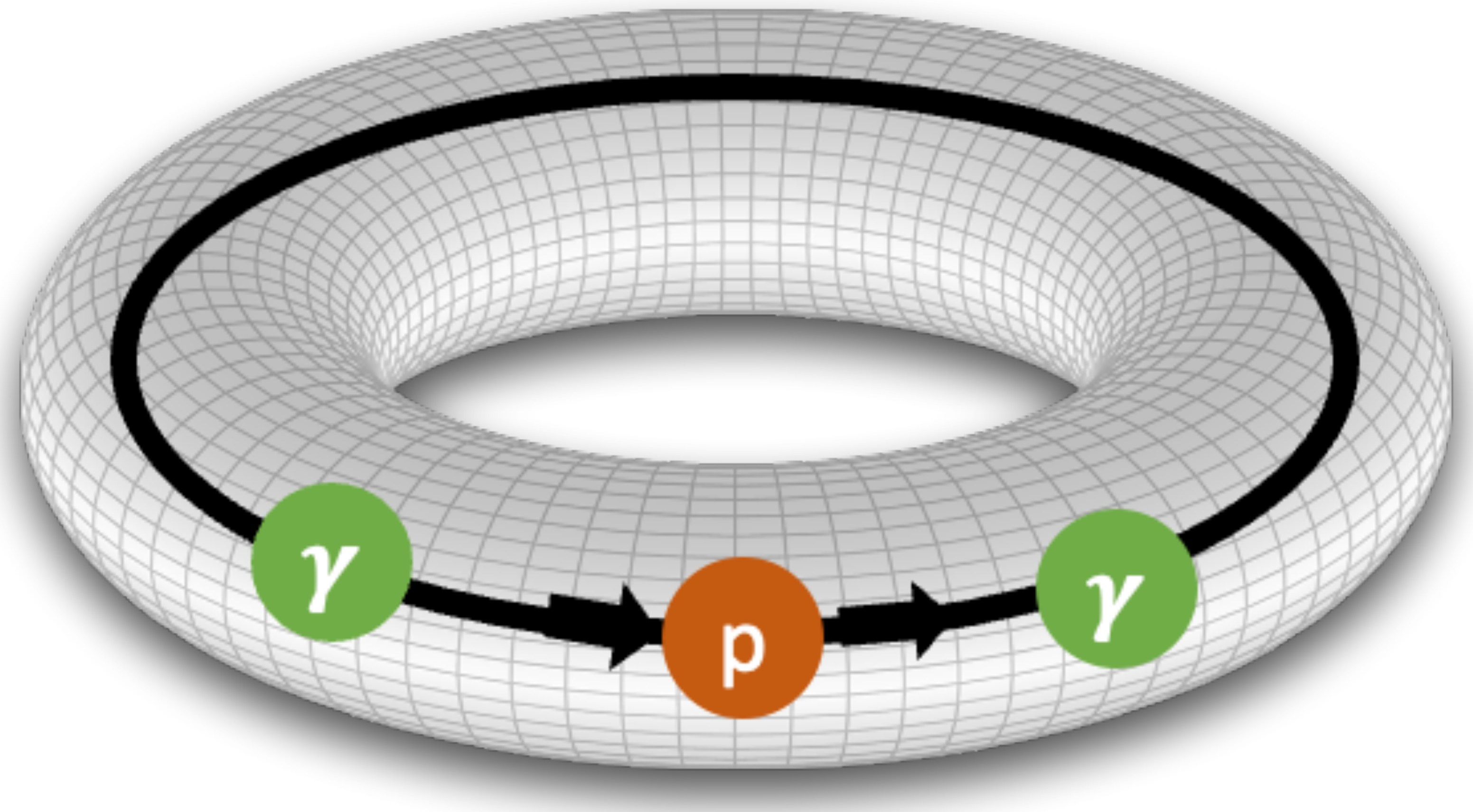
Lattice QED

- How do charged states behave in a periodic finite volume?
  - Consider the photon field decomposed into two modes, such that $A_\mu(x) = B_\mu / L + q_\mu(x)$, where B_μ is a constant, and $q_\mu(x)$ is a small fluctuation.



$$\mathscr{L} = \psi(i\gamma_\mu D_\mu + m_f)\overline{\psi} + \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2\xi}(\partial_\mu A_\mu)^2$$

Lattice QED



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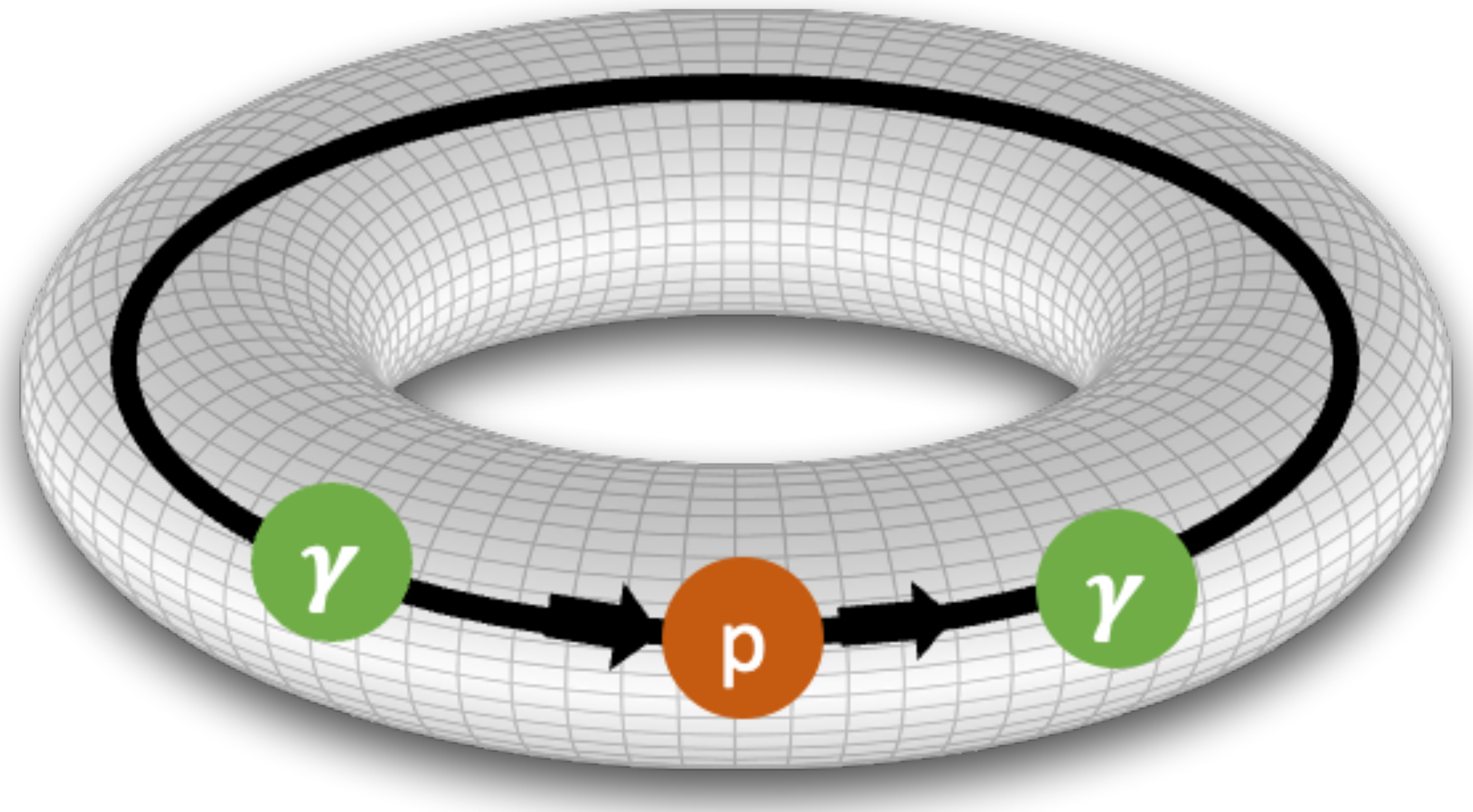
  - $A_\mu(x) = \frac{1}{V}\left[\tilde{A}_\mu(0) + \sum_{k_\mu \neq 0} \mathrm{e}^{ik\cdot x}\tilde{A}_\mu(k)\right]$

Lattice QED



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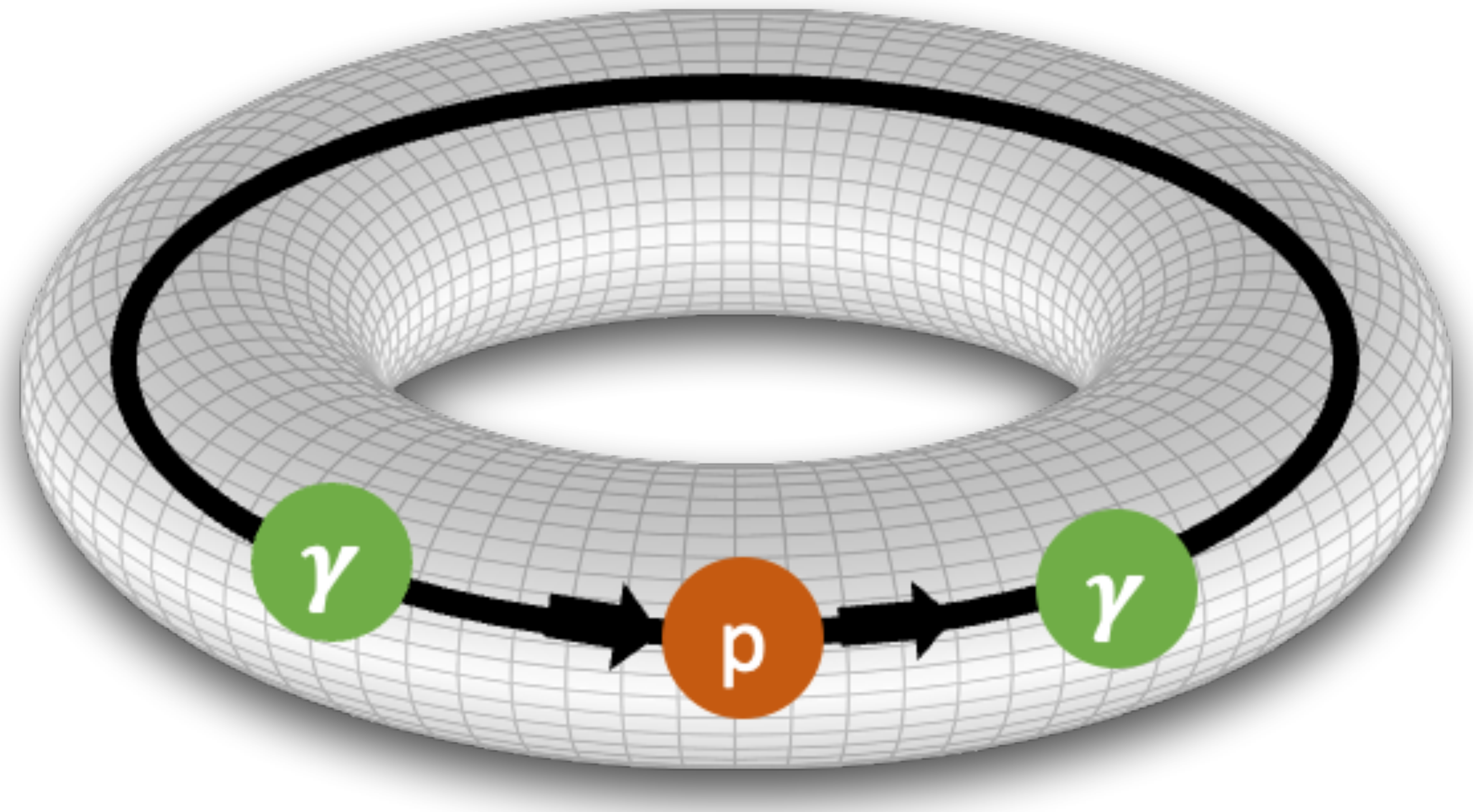
Lattice QED



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$$D_{\mu\nu}(x) = \frac{1}{V}\sum_{k_\mu} \mathrm{e}^{ik\cdot x}\left\{\frac{1}{k^2 + m_\gamma^2}\left[\delta_{\mu\nu} + \frac{k_\mu k_\nu(\xi - 1)}{k^2 + \xi m_\gamma^2}\right]\right\}$$

> In perturbation theory we often add an IR regulator so lets include it here as a photon mass

Lattice QED

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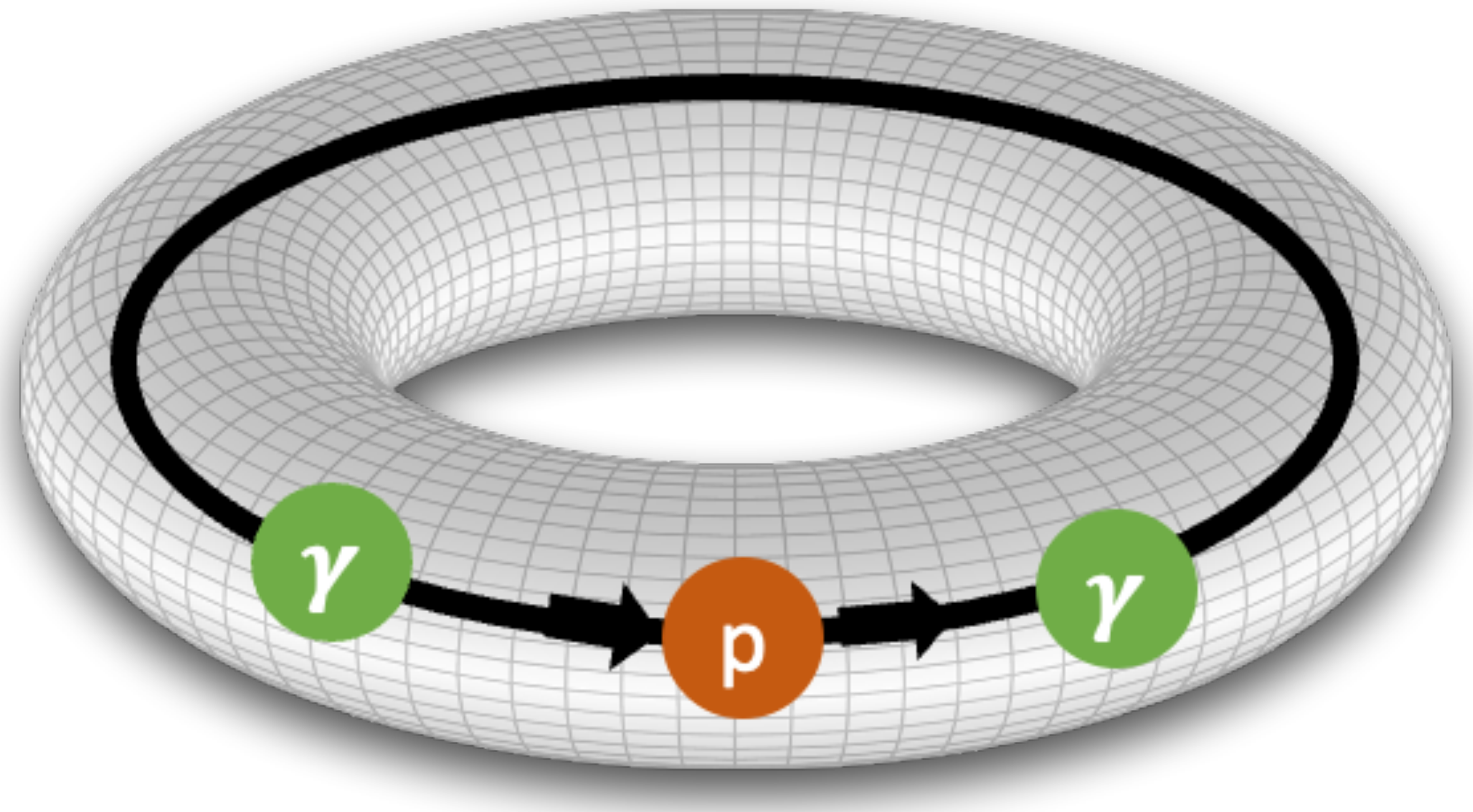

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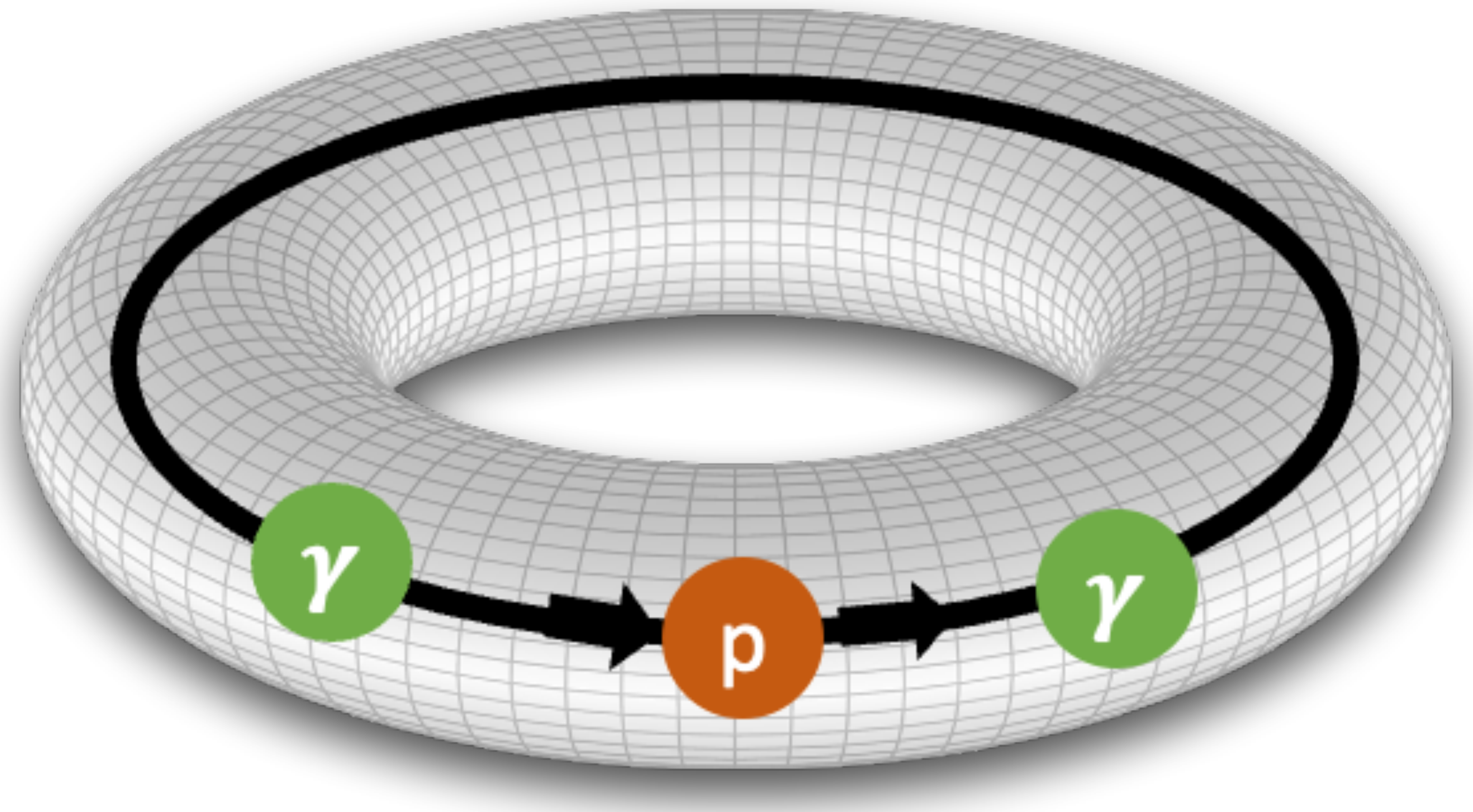
$$\rightarrow \frac{\delta_{\mu\nu}}{m_\gamma^2 V} + \frac{1}{V}\sum_{k_\mu \neq 0} \mathrm{e}^{ik\cdot x}\tilde{D}_{\mu\nu}(k)$$

Lattice QED



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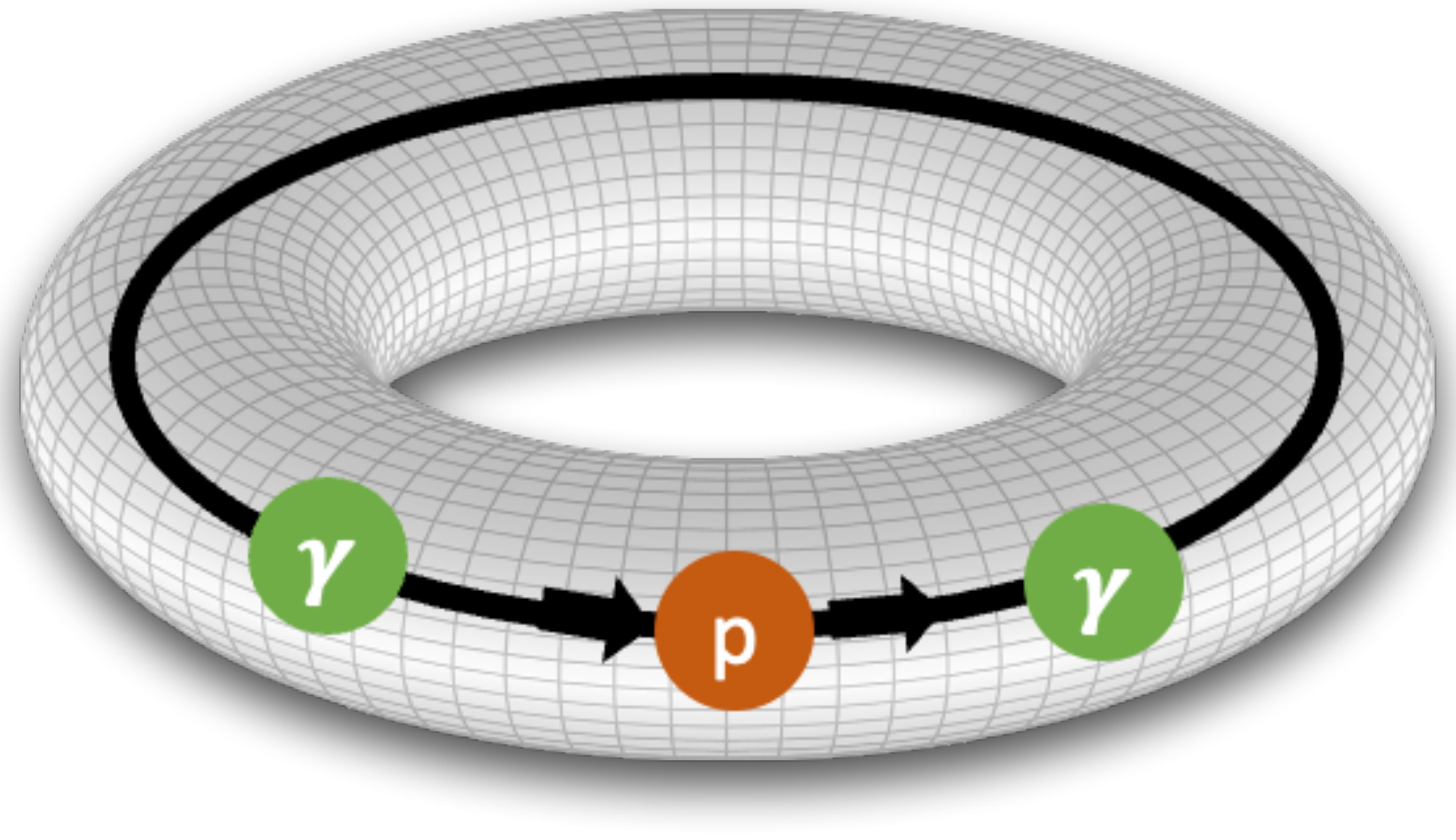
The zero mode necessarily modifies the IR physics, and must be treated carefully (non-perturbatively)

$$\frac{\delta_{\mu\nu}}{m_\gamma^2 V} + \frac{1}{V}\sum_{k_\mu \neq 0} \mathrm{e}^{ik\cdot x}\tilde{D}_{\mu\nu}(k)$$

Lattice QED



- Removing the zero modes:
  - $\text{QED}_{TL} \sim \tilde{A}_\mu(k_\mu = 0) = 0$
  - $\text{QED}_{L} \sim \tilde{A}_\mu(k_4, \vec{k} = 0) = 0$
  - $\text{QED}_{SF} \sim V^{-1} e \tilde{A}_\mu(0) \in \left(-\pi L_\mu^{-1}, \pi L_\mu^{-1}\right)$
  - $\text{QED}_{C} \sim A_\mu(x + \hat{L}_i) = -A_\mu(x)\,;\, \psi(x + \hat{L}_i) = C^{-1}\overline{\psi}^T(x)$
  - $\text{QED}_{M} \sim \mathscr{L}_{QED} + \frac{1}{2} m_\gamma^2 A_\mu^2$

Duncan et al. [hep-lat/9602005]

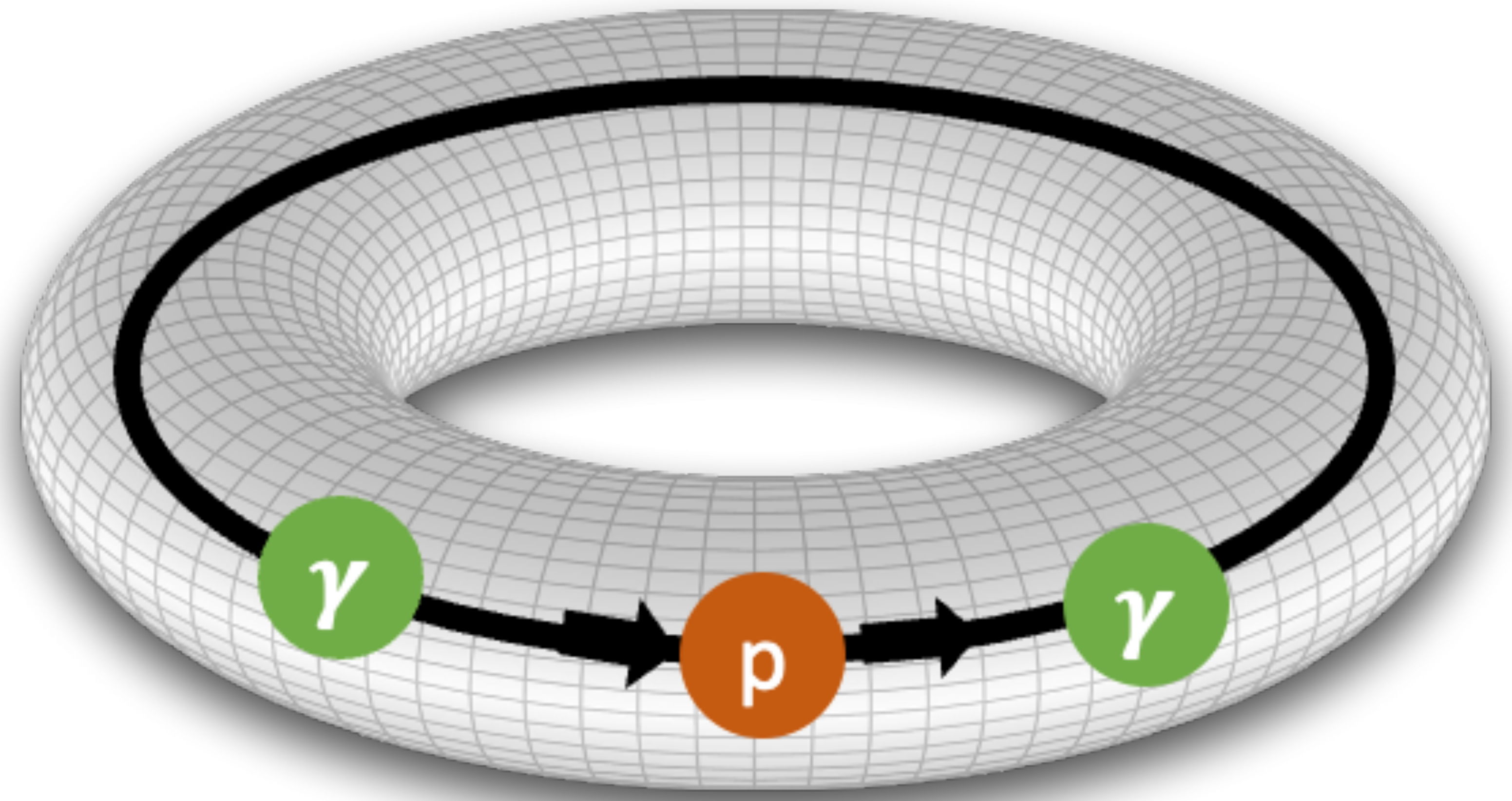
Hayakawa, Uno [0804.2044]

Gockeler et al. Nucl.Phys.B 334 (1990) 527-558

Lucini et al. [1509.01636]

Endres, Schindler, Tiburzi, Walker-Loud Phys.Rev.Lett 117 (2016) 072002

Lattice QED



- Removing the zero modes:
  - $\text{QED}_{TL} \sim \tilde{A}_\mu(k_\mu = 0) = 0$ — No transfer matrix
  - $\text{QED}_{L} \sim \tilde{A}_\mu(k_4, \vec{k} = 0) = 0$ — Non-local
  - $\text{QED}_{SF} \sim V^{-1} e\tilde{A}_\mu(0) \in \left(-\pi L_\mu^{-1}, \pi L_\mu^{-1}\right)$ — No transfer matrix?
  - $\text{QED}_{C} \sim A_\mu(x + \hat{L}_i) = -A_\mu(x)\,;\, \psi(x + \hat{L}_i) = C^{-1}\overline{\psi}^T(x)$ — Flavor-mixing
  - $\text{QED}_{M} \sim \mathscr{L}_{QED} + \frac{1}{2} m_\gamma^2 A_\mu^2$ — m_γ systematics

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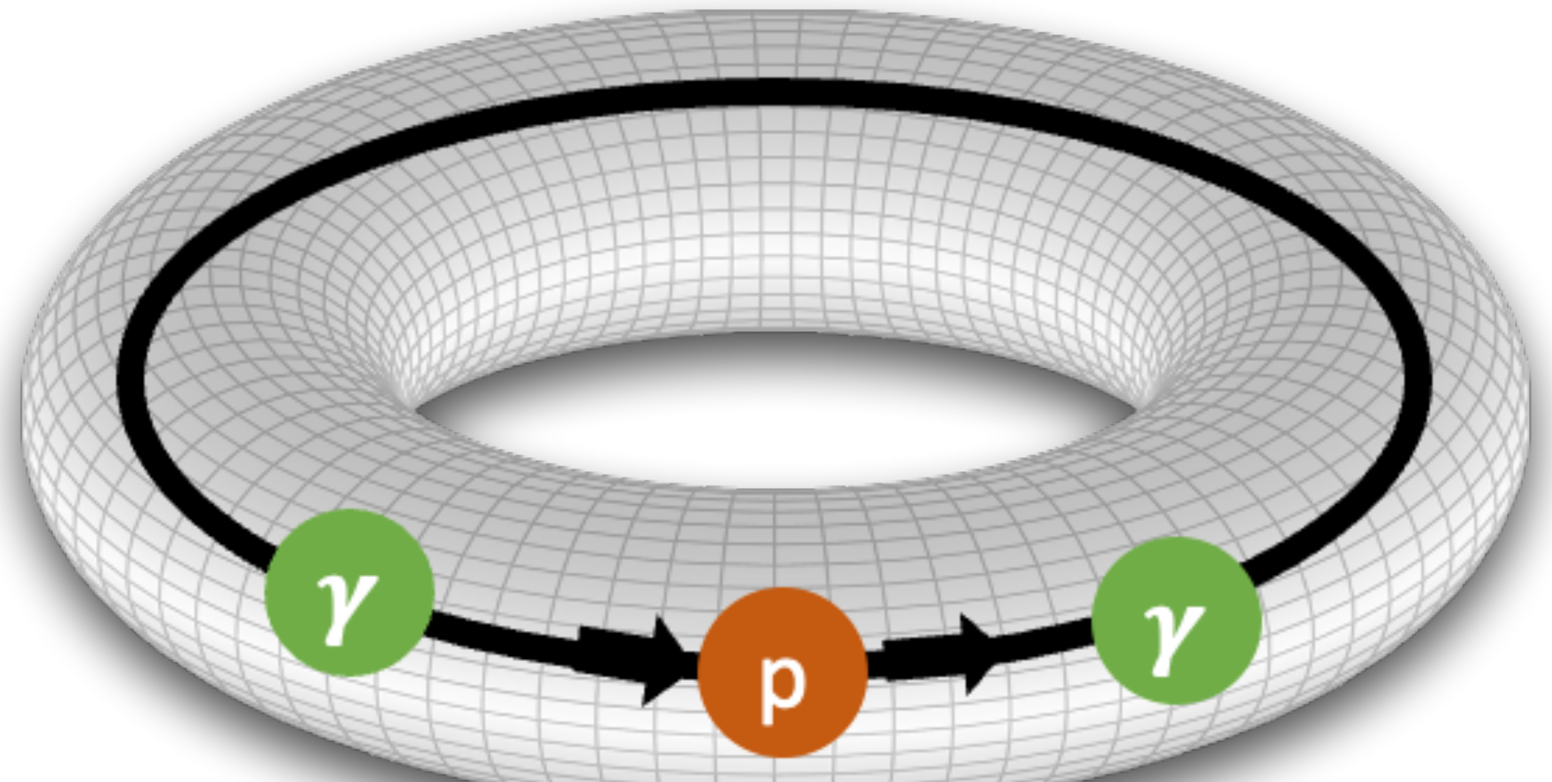

- Removing the zero modes:
  - QED_{TL} ~ $\tilde{A}_\mu(k_\mu = 0) = 0$ — *No transfer matrix*
  - QED_{L} ~ $\tilde{A}_\mu(k_4, \vec{k} = 0) = 0$ — *Non-local*
  - QED_{SF} ~ $V^{-1} e\tilde{A}_\mu(0) \in \left(-\pi L_\mu^{-1}, \pi L_\mu^{-1}\right)$ — *No transfer matrix?*
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  - QED_{M} ~ $\mathscr{L}_{QED} + \frac{1}{2} m_\gamma^2 A_\mu^2$ — *m_γ systematics*

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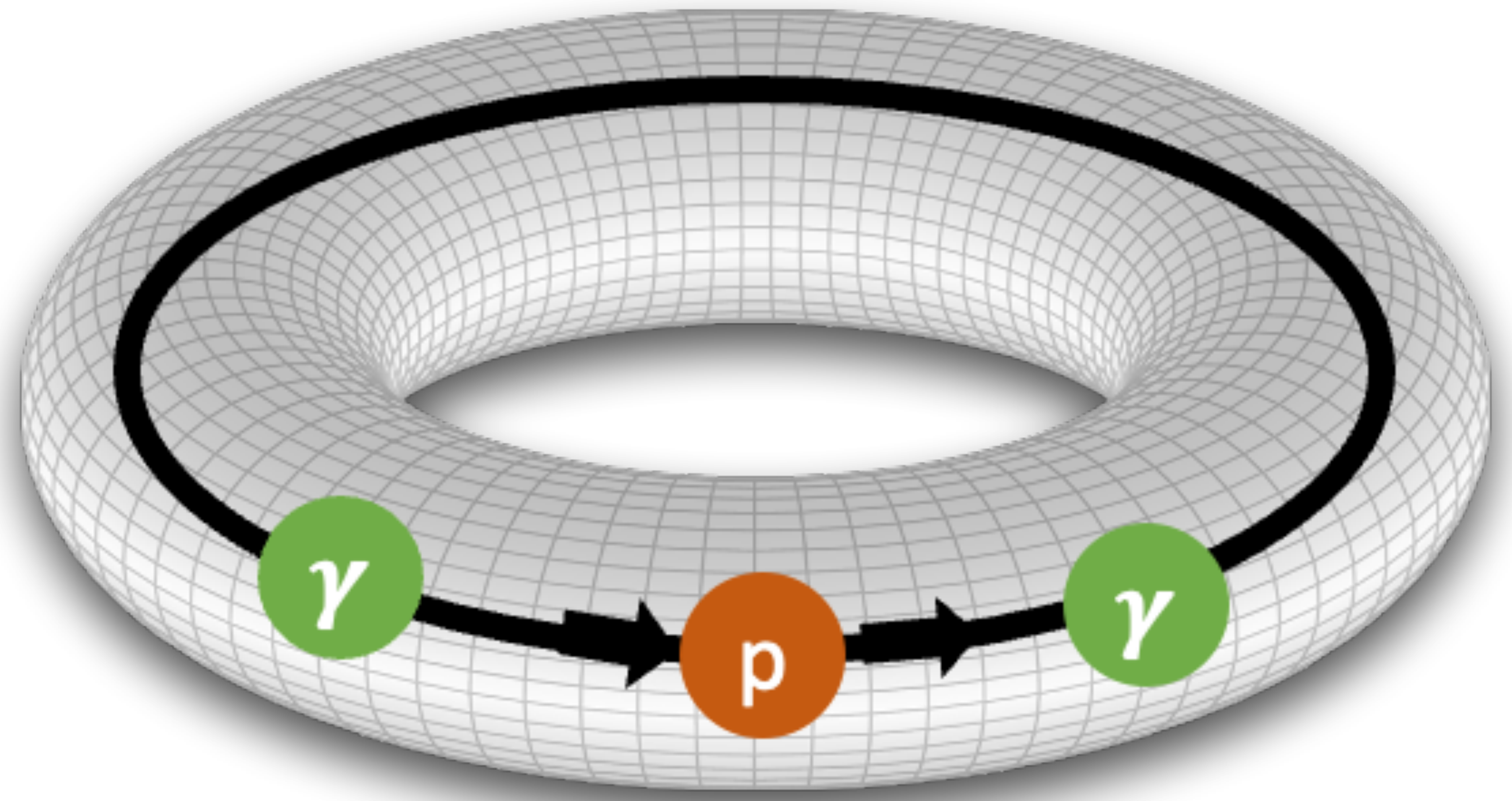
Lattice QCD+QED$_M$

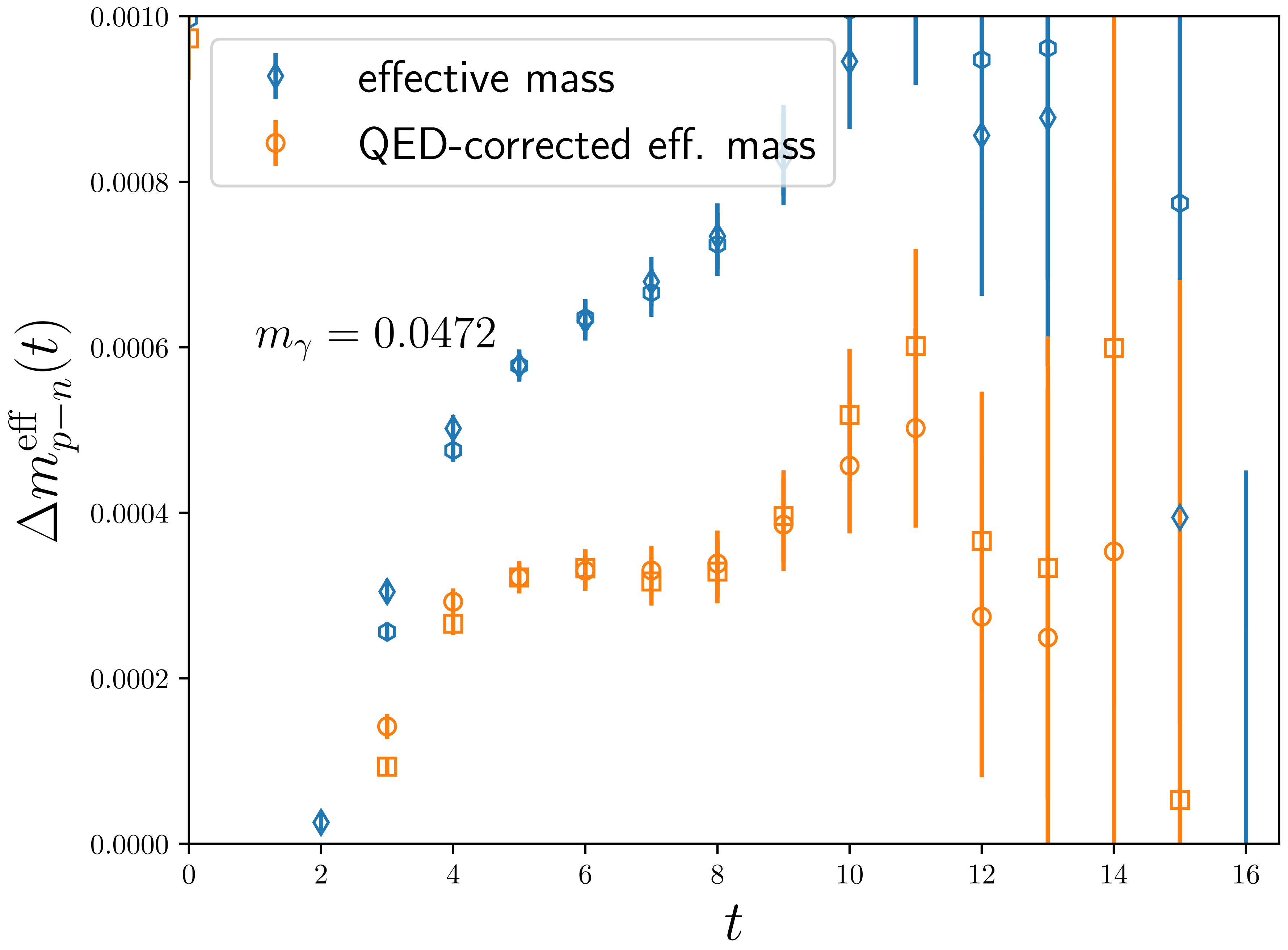


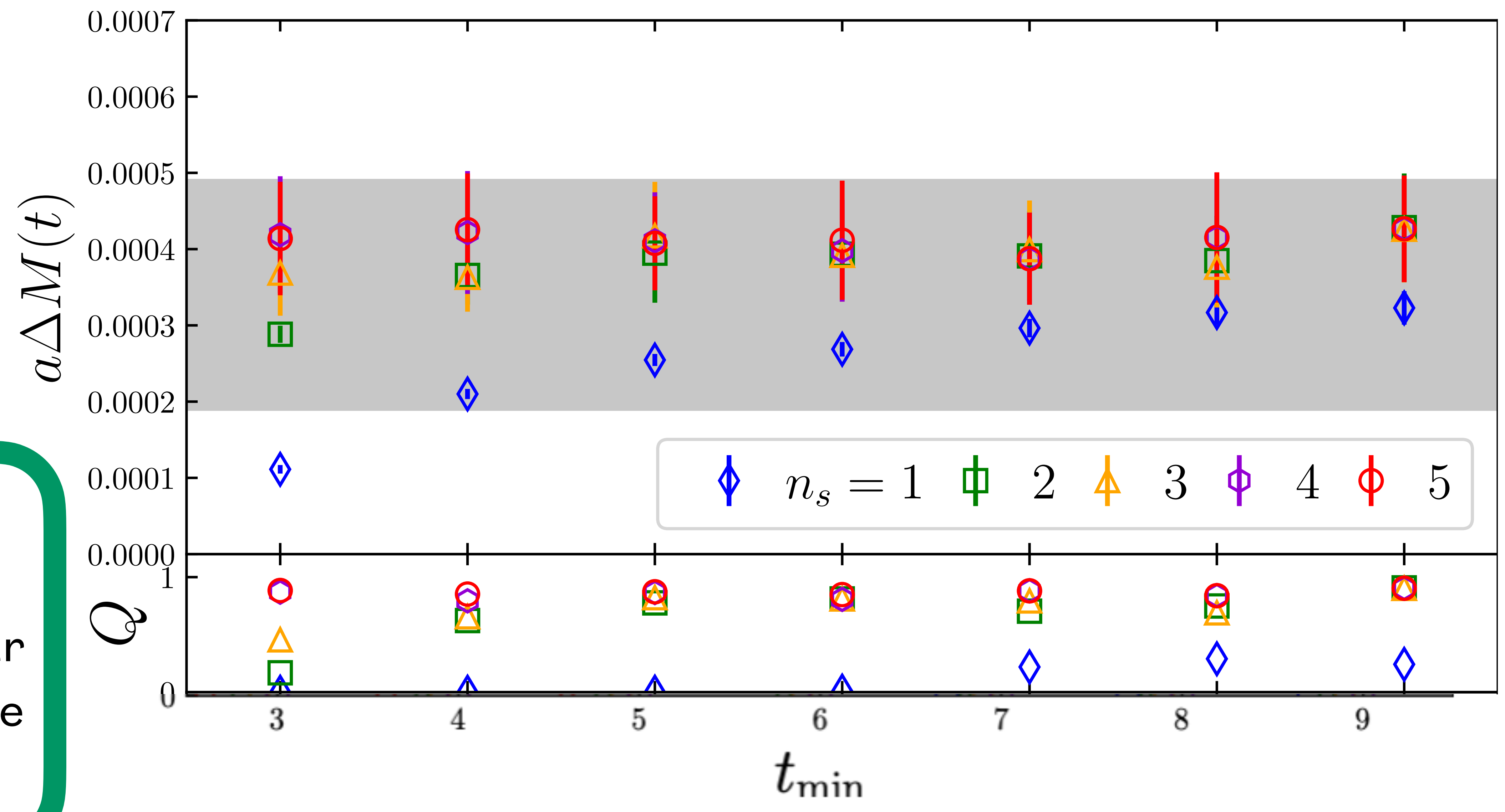
- Our program:
  - FV ~ $e^{-m_\gamma L}$
  - Correlation modified $C(t) = \sum_n A_n e^{-E_n(1+\frac{\zeta}{E_n^2})t-\zeta t^2}$ $\quad \zeta = \frac{e^2}{2m_\gamma^2 V}$
  - Two IR scales: m_γ, L
  - Determine range of validity for extrapolations
  - Lattice setup: $N_f = 2+1+1$ MDWF/HISQ
    - Preliminary results~
      - $a = 0.12$ fm, m_π~310 MeV
      - $L = 2.9, 3.8$ fm
      - $m_\gamma = \{1/8,1/4,1/3,5/12,1/2,2/3\} \times m_\pi$

$$D_{\mu\nu}(x) = \frac{1}{V}\sum_{k_\mu} e^{ik\cdot x}\left\{\frac{1}{k^2+m_\gamma^2}\left[\delta_{\mu\nu} + \frac{k_\mu k_\nu(\xi-1)}{k^2+\xi m_\gamma^2}\right]\right\}$$

$$\rightarrow \frac{\delta_{\mu\nu}}{m_\gamma^2 V} + \frac{1}{V}\sum_{k_\mu \neq 0} e^{ik\cdot x}\tilde{D}_{\mu\nu}(k)$$

Analysis - Correlator





Energy Splitting Stability Plot for $m_\gamma = 0.0472$

The presence of the zero mode is seen with the linear rise of the effective mass

$$R(t) = \sum_n A_n e^{-E_n(1+\frac{\zeta}{E_n^2})t - \zeta t^2}$$

Ratio of proton-neutron correlators

→ Subtract zero mode analytically to isolate QCD+QED, energy splitting

→ Bayesian fit to correlators using Peter Lepage's *lsqfit*

→ Extract energy splitting from the best fit:
$\delta E = 0.000395\,(65)$
Using the lattice spacing, this is roughly ~0.65(11)MeV
BUT, has not been extrapolated to phys. pt.

Analysis -Finite Volume

Endres, Schindler, Tiburzi, Walker-Loud Phys.Rev.Lett 117 (2016) 072002

Zohreh Davoudi and Martin J. Savage Phys. Rev. D **90**, 054503 (2014)

Z. Fodor, C. Hoelbling, S.D. Katz, L. Lellouch, A. Portelli, K.K. Szabo, B.C. Toth Phys. Lett. B755, 245 (2016),

$L \to \infty$

$$\frac{\delta_L M^{LO}}{M} = 2\pi\alpha Q^2 \frac{m_\gamma}{M}\left[I_1(m_\gamma L) - \frac{1}{(m_\gamma L)^3}\right]$$

$$\frac{\delta_L M^{NLO}}{M} = \pi\alpha Q^2 \frac{m_\gamma^2}{M^2}\left[2I_{1/2}(m_\gamma L) + I_{3/2}(m_\gamma L)\right]$$

$$I_n(z) = \frac{1}{2^{(n+1/2)}\pi^{3/2}\Gamma(n)} \sum_{\nu\neq 0} \frac{K_{3/2-n}(z|\nu|)}{(z\|\nu|)^{3/2-n}}$$

The extrapolation expressions are derived from NR EFT.
Note that these limits do not commute!

$m_\gamma \to 0$

$$M(m_\gamma) - M(0) = \Delta_\gamma M^{LO} + \Delta M_\gamma^{NLO} + \mathcal{O}\left(\frac{m_\gamma^3}{M^2}\right)$$

$$\frac{\Delta_\gamma M^{LO}}{M} = -\frac{\alpha}{2} Q^2 \frac{m_\gamma}{M}$$

$$\frac{\Delta_\gamma M^{NLO}}{M} = \left(C\alpha - \frac{\alpha}{4\pi}Q^2\right)\frac{m_\gamma^2}{M^2}$$

The mass shift from continuum QED_M has the LO term for both scalars and fermions

$$\frac{\Delta M_f}{M_0} = \frac{\alpha}{4\pi}\left\{ -2\pi\frac{m_\gamma}{M} + \mathcal{O}\left(\frac{m_\gamma^2}{M^2}\right)\right\}$$

$$\frac{\Delta M_s}{M_0} = \frac{\alpha}{4\pi}\left\{ -2\pi\frac{m_\gamma}{M} + \mathcal{O}\left(\frac{m_\gamma^2}{M^2}\right)\right\}$$

Analysis - Results

- Proton -Neutron mass difference
  - We removed the FV effects analytically and extrapolated to the $m_\gamma \to 0$ limit.

$$M_{p^+} - M_{n^0} \sim 0.947(62)\ \text{MeV}$$

PRELIMINARY

obs	ens	ΔQ	ΔaM	C	χ^2/dof	m_γ^{min}	m_γ^{max}
$\Omega^- - \Omega_{\text{QCD}}$	a12m310	-1	+0.001199(49)	−0.0059(50)	0.43	0.0472	0.1258
$\Omega^- - \Omega_{\text{QCD}}$	a12m310XL	-1	+0.000968(44)	+0.0154(47)	0.62	0.0472	0.1258
$\Omega^- - \Omega_{\text{QCD}}$	comb	-1	+0.001070(32)	+0.0057(34)	1.95		
$p^+ - n_{\text{QCD}}$	a12m310	1	+0.00097(14)	+0.0158(89)	2.08	0.0472	0.1258
$p^+ - n_{\text{QCD}}$	a12m310XL	1	+0.000786(96)	+0.0088(67)	1.03	0.0472	0.1258
$p^+ - n_{\text{QCD}}$	comb	1	+0.000825(78)	+0.0115(52)	1.86		
$n^0 - n_{\text{QCD}}$	a12m310	0	+0.000356(99)	+0.0038(57)	1.86	0.0472	0.1258
$n^0 - n_{\text{QCD}}$	a12m310XL	0	+0.000230(63)	+0.0011(44)	0.64	0.0472	0.1258
$n^0 - n_{\text{QCD}}$	comb	0	+0.000254(52)	+0.0022(33)	1.41		
$p^+ - n^0$	a12m310	1	+0.000634(77)	+0.0119(48)	1.53	0.0472	0.1258
$p^+ - n^0$	a12m310XL	1	+0.000556(42)	+0.0079(30)	1.41	0.0472	0.1258
$p^+ - n^0$	comb	1	+0.000568(37)	+0.0095(25)	1.87		

Endres, Schindler, Tiburzi, Walker-Loud Phys.Rev.Lett 117 (2016) 072002

André Walker-Loud, Carl E. Carlson, and Gerald A. Miller
Phys. Rev. Lett. **108**, 232301 (2012)

J. Gasser, M. Hoferichter, H. Leutwyler, A. Rusetsky, [1506.06747]

J. Gasser, H. Leutwyler, A. Rusetsky, Eur. Phys. J. C **80**, 1121 (2020)

Towards the Physical Point

- Our systematics:

$m_\pi \to m_\pi^{phys}$

$L \to \infty$

$a \to 0$

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- Our systematics:

$m_\pi \to m_\pi^{phys}$

$L \to \infty$

$a \to 0$

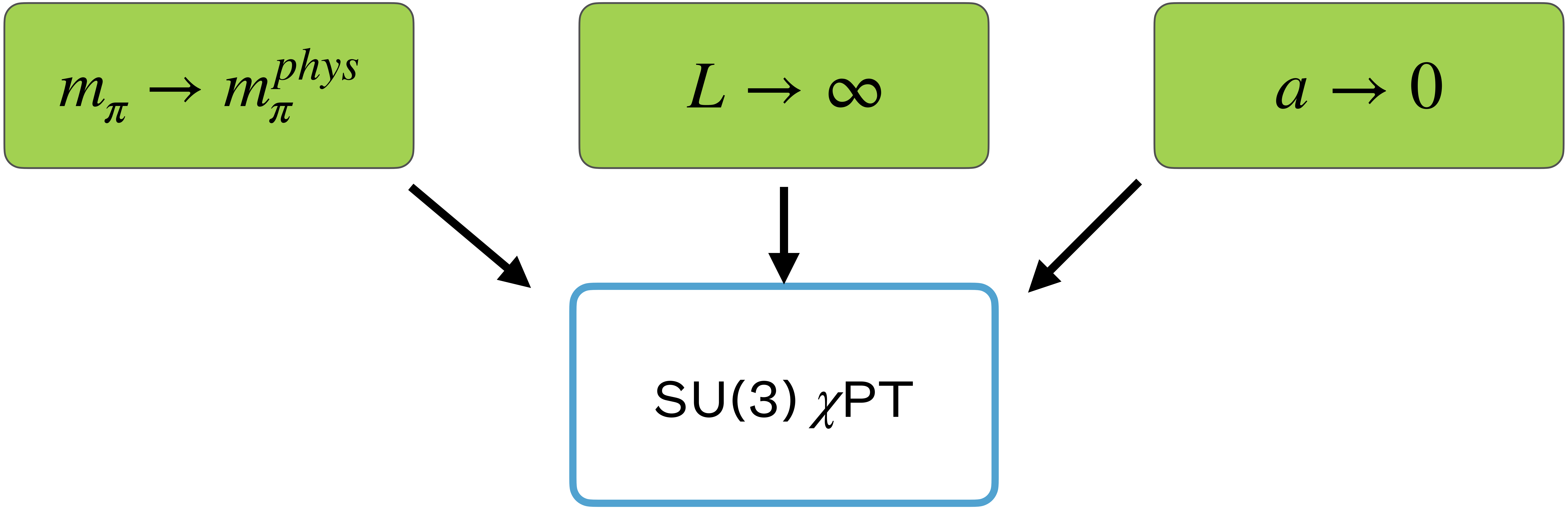
Lattice observables are necessarily calculated at unphysical m_π in, FV, with finite a

→

Need a tool that facilitates an extrapolation to the infinite volume continuum physics

Towards the Physical Point

- Our systematics:



Towards the Physical Point

- Our systematics:

$m_\pi \to m_\pi^{phys}$

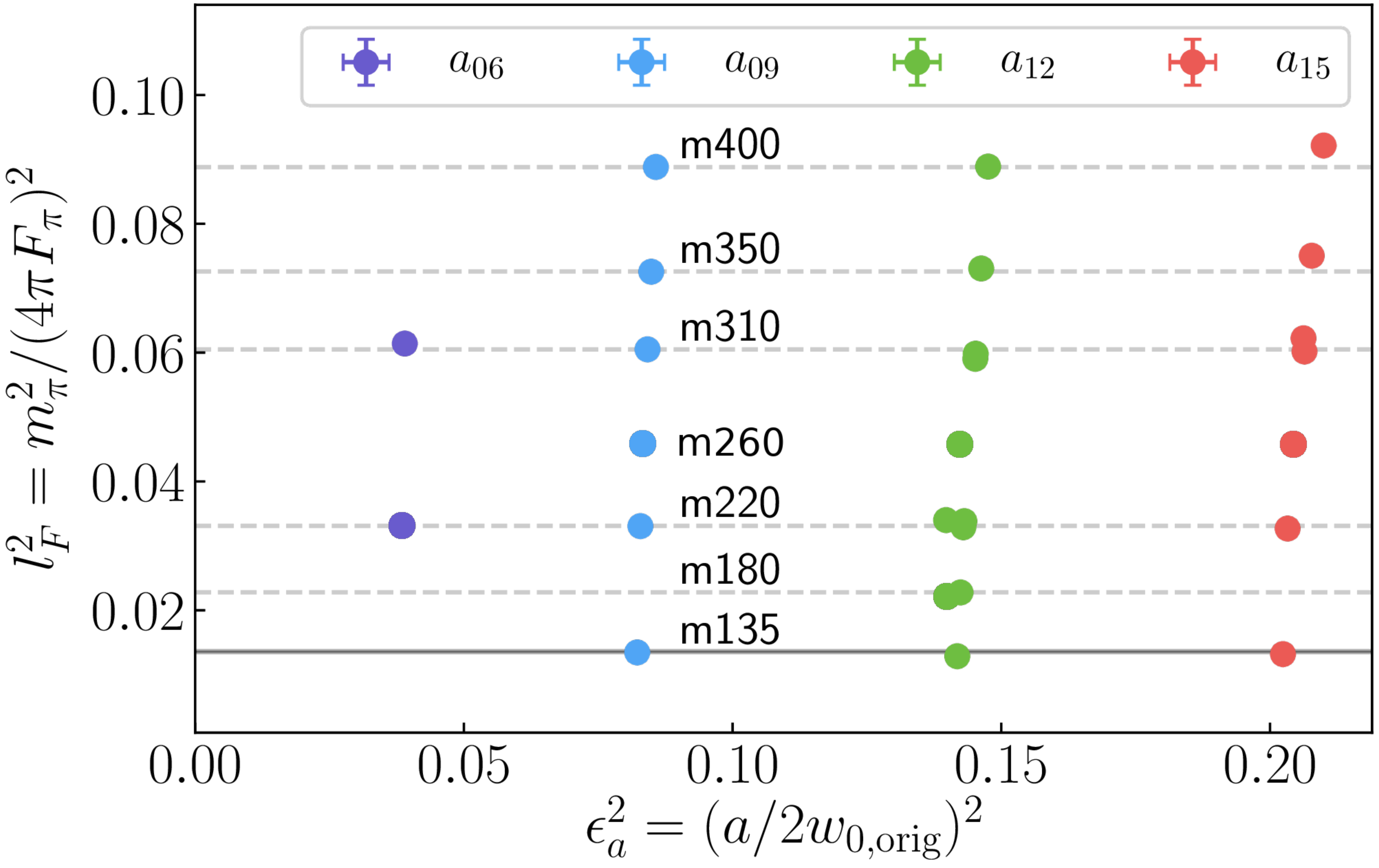
$L \to \infty$

$a \to 0$

SU(3) χPT

Must demonstrate control of QCD-only extrapolations

Towards the Physical Point



PHYSICAL REVIEW D **102,** 034507 (2020)

F_K/F_π from Möbius domain-wall fermions solved on gradient-flowed HISQ ensembles

Nolan Miller,[1] Henry Monge-Camacho,[1] Chia Cheng Chang (張家丞),[2,3,4] Ben Hörz,[3] Enrico Rinaldi,[5,2] Dean Howarth,[6,3] Evan Berkowitz,[7,8] David A. Brantley,[6] Arjun Singh Gambhir,[9,3] Christopher Körber,[4,3] Christopher J. Monahan,[10,11] M. A. Clark,[12] Bálint Joó,[13] Thorsten Kurth,[12] Amy Nicholson,[1] Kostas Orginos,[10,11] Pavlos Vranas,[6,3] and André Walker-Loud[3,6,4]

PHYSICAL REVIEW D **103,** 054511 (2021)

Scale setting the Möbius domain wall fermion on gradient-flowed HISQ action using the omega baryon mass and the gradient-flow scales t_0 and w_0

Nolan Miller,[1] Logan Carpenter,[2] Evan Berkowitz,[3,4] Chia Cheng Chang (張家丞),[5,6,7] Ben Hörz,[6] Dean Howarth,[8,6] Henry Monge-Camacho,[9,1] Enrico Rinaldi,[10,5] David A. Brantley,[8] Christopher Körber,[7,6] Chris Bouchard,[11] M. A. Clark,[12] Arjun Singh Gambhir,[13,6] Christopher J. Monahan,[14,15] Amy Nicholson,[1,6] Pavlos Vranas,[8,6] and André Walker-Loud[6,8,7]

PHYSICAL REVIEW D **75,** 054501 (2007)

Two meson systems with Ginsparg-Wilson valence quarks

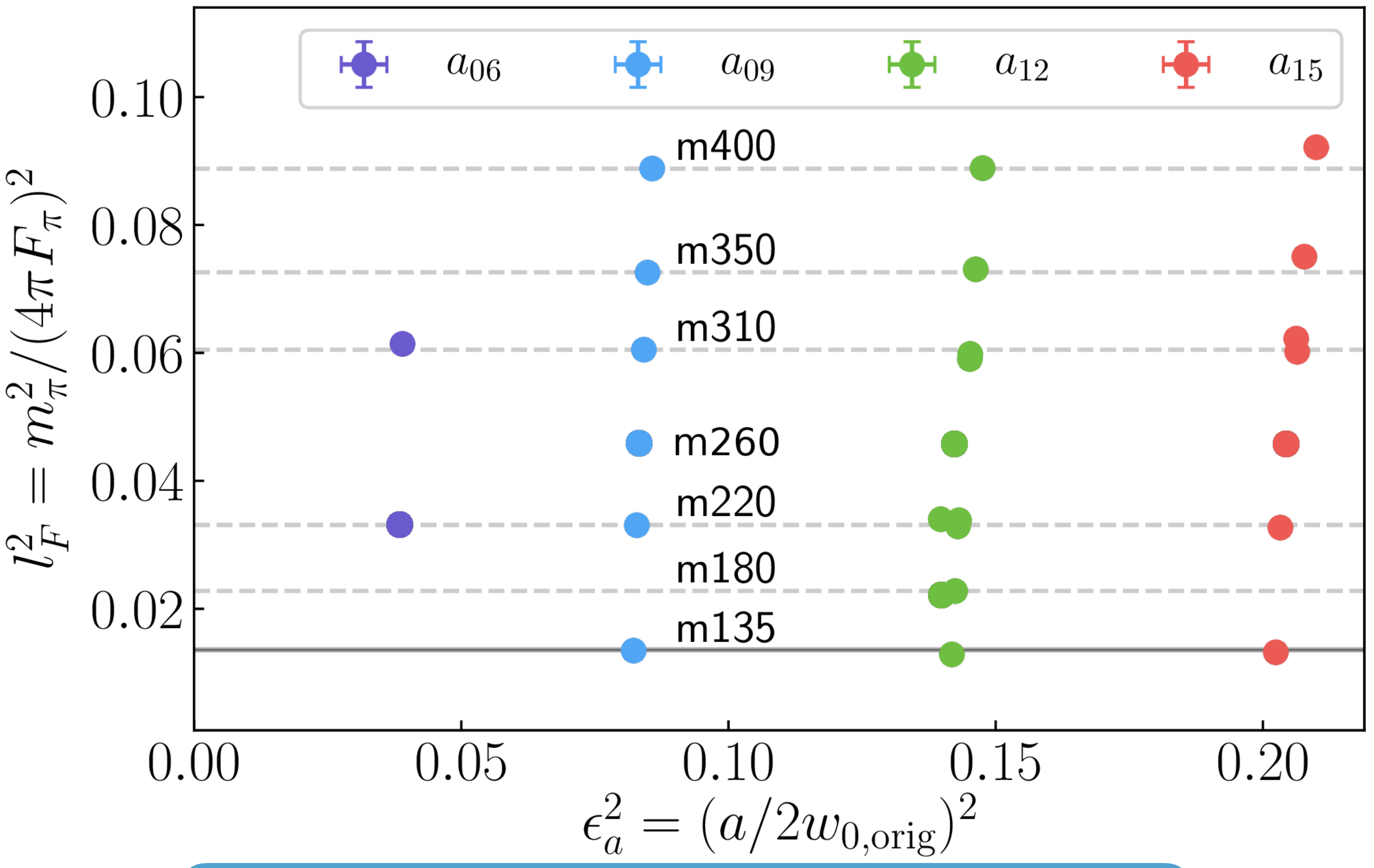
Jiunn-Wei Chen,[1,*] Donal O'Connell,[2,†] and André Walker-Loud[3,4,‡]

PHYSICAL REVIEW D **72,** 054502 (2005)

Chiral perturbation theory for staggered sea quarks and Ginsparg-Wilson valence quarks

Oliver Bär,[1,*] Claude Bernard,[2,†] Gautam Rupak,[3,‡] and Noam Shoresh[4,§]

Towards the Physical Point



Determine F_K, F_π m_π, m_K $\rightarrow m_q^l$, m_q^s

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Ensembles

EFT

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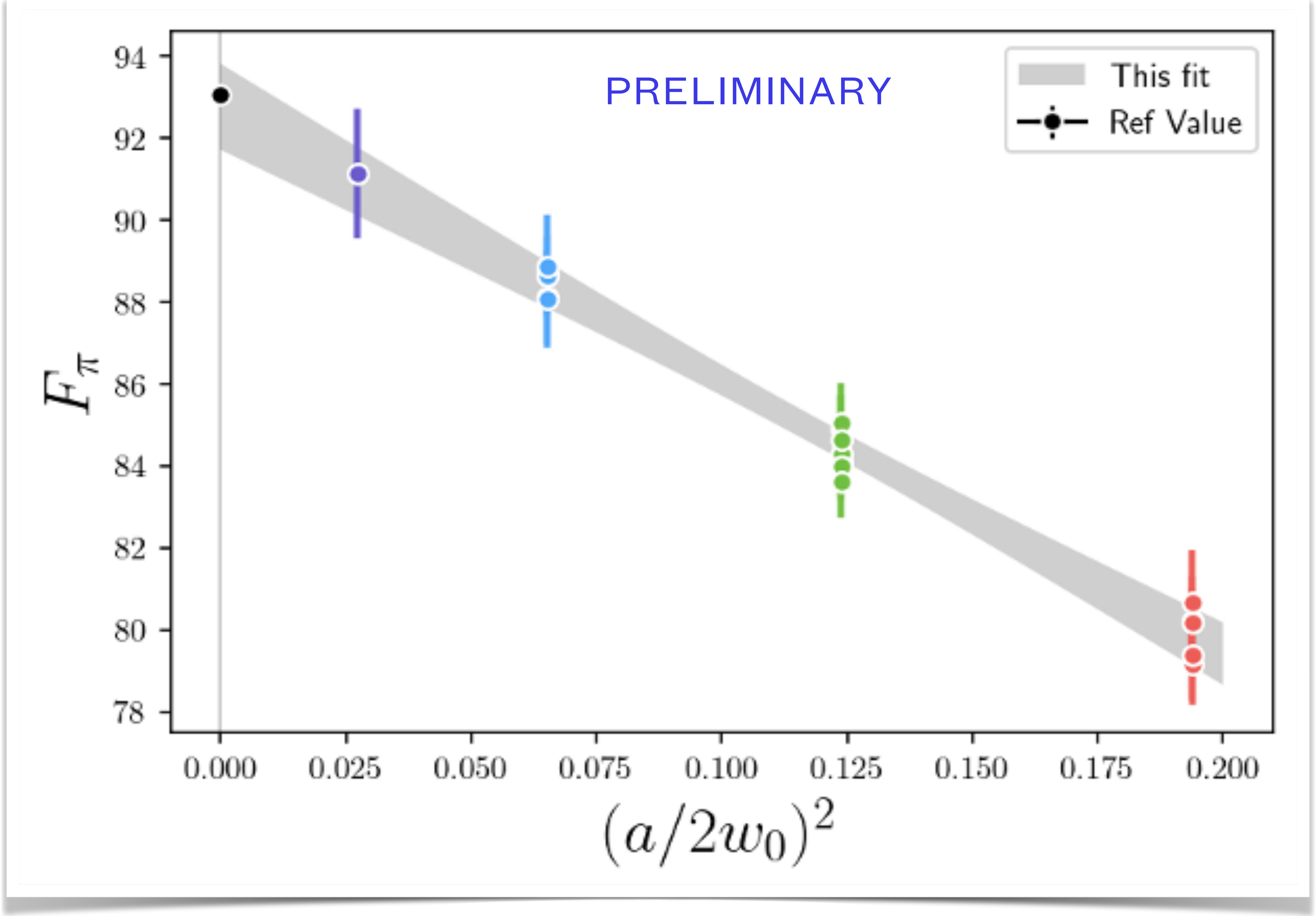
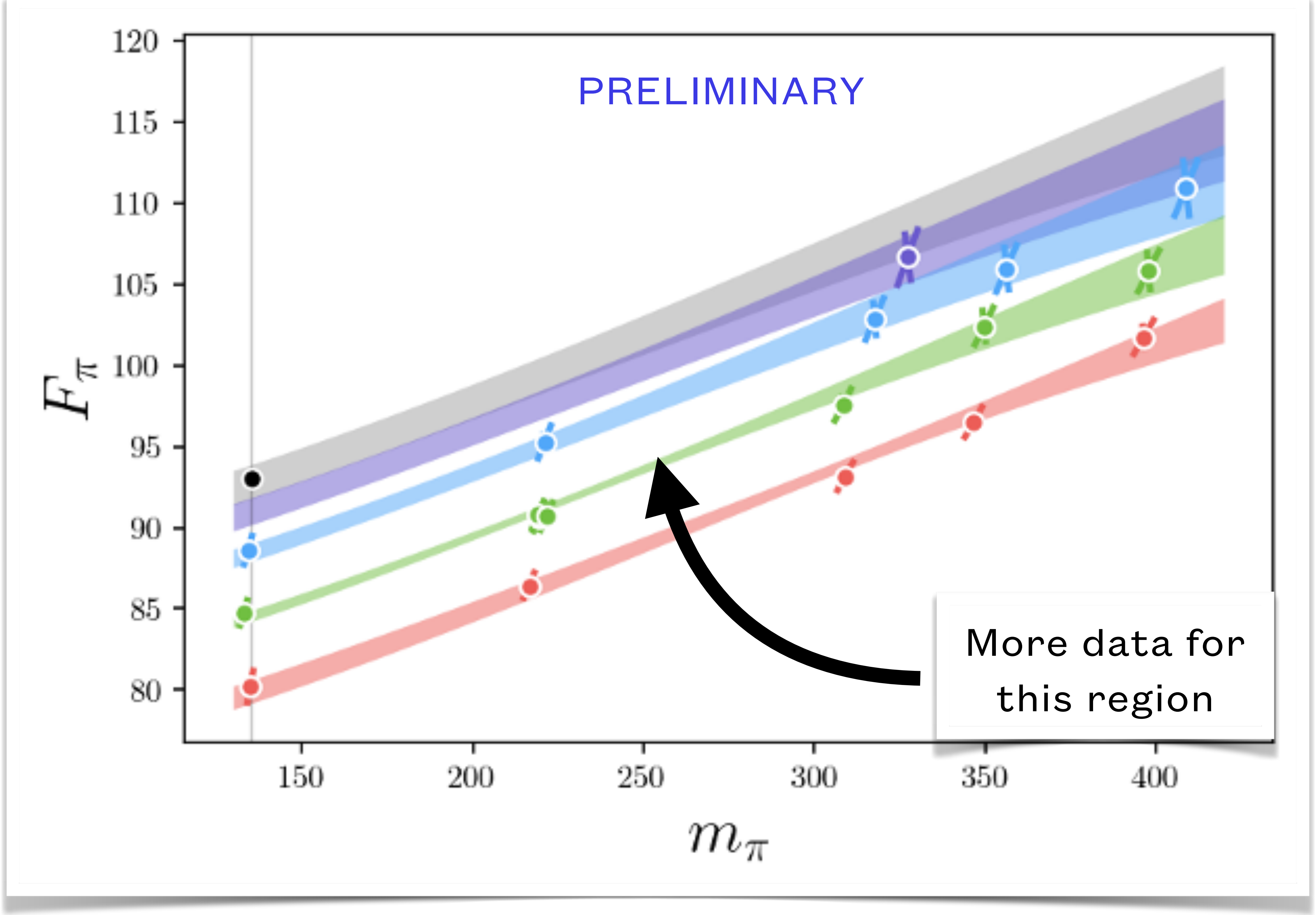
Towards the Physical Point

One point at .06, the new data will be at help to improve the precision of the continuum at mpi - 220





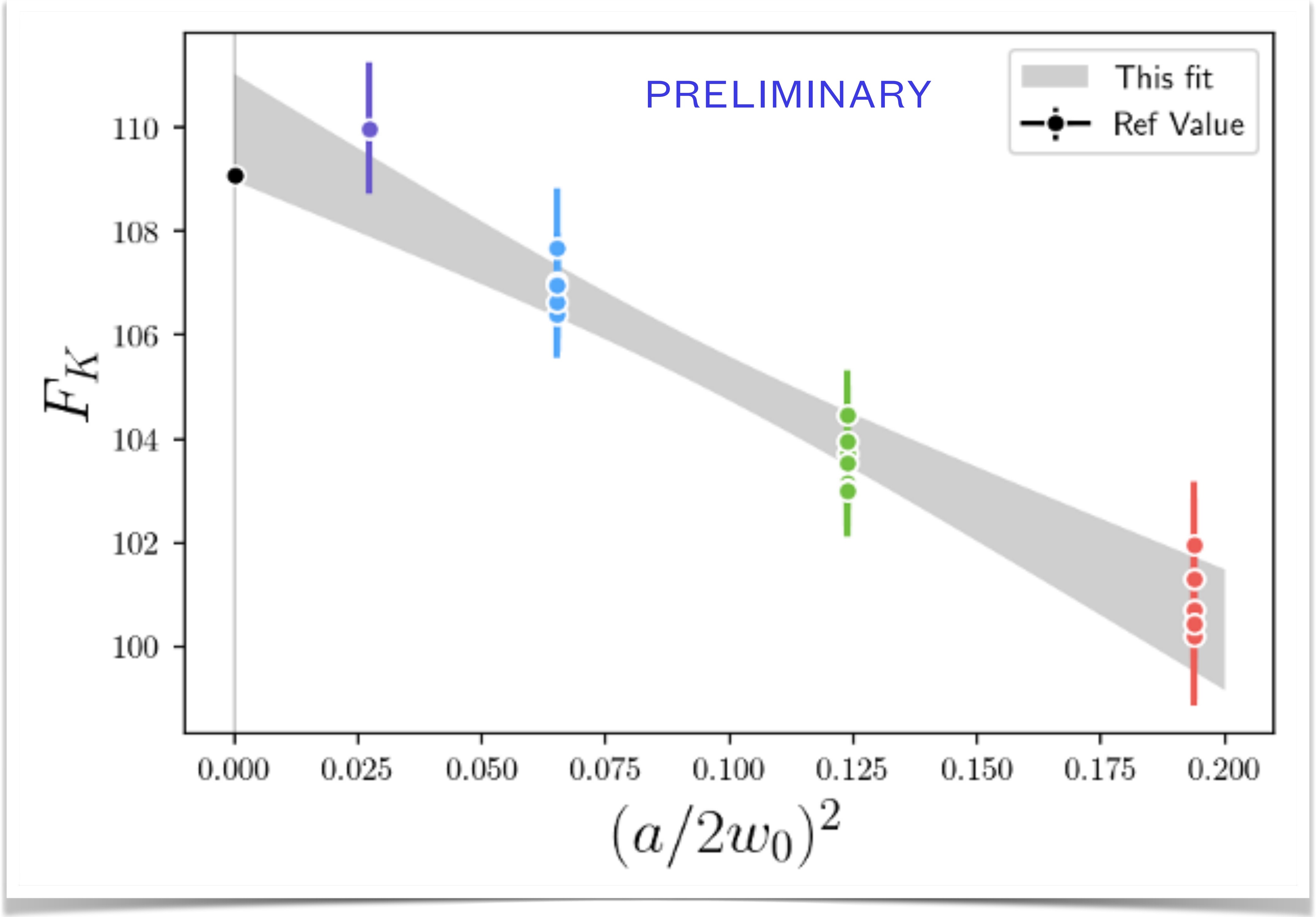
$$F_\pi = F\left\{1 + \delta(F_\pi)_{\chi\text{–logs}} + \delta(F_\pi)_{\text{CT}} + \delta(F_\pi)_{a^2} + \delta(F_\pi)_{\text{MA}}\right\}$$

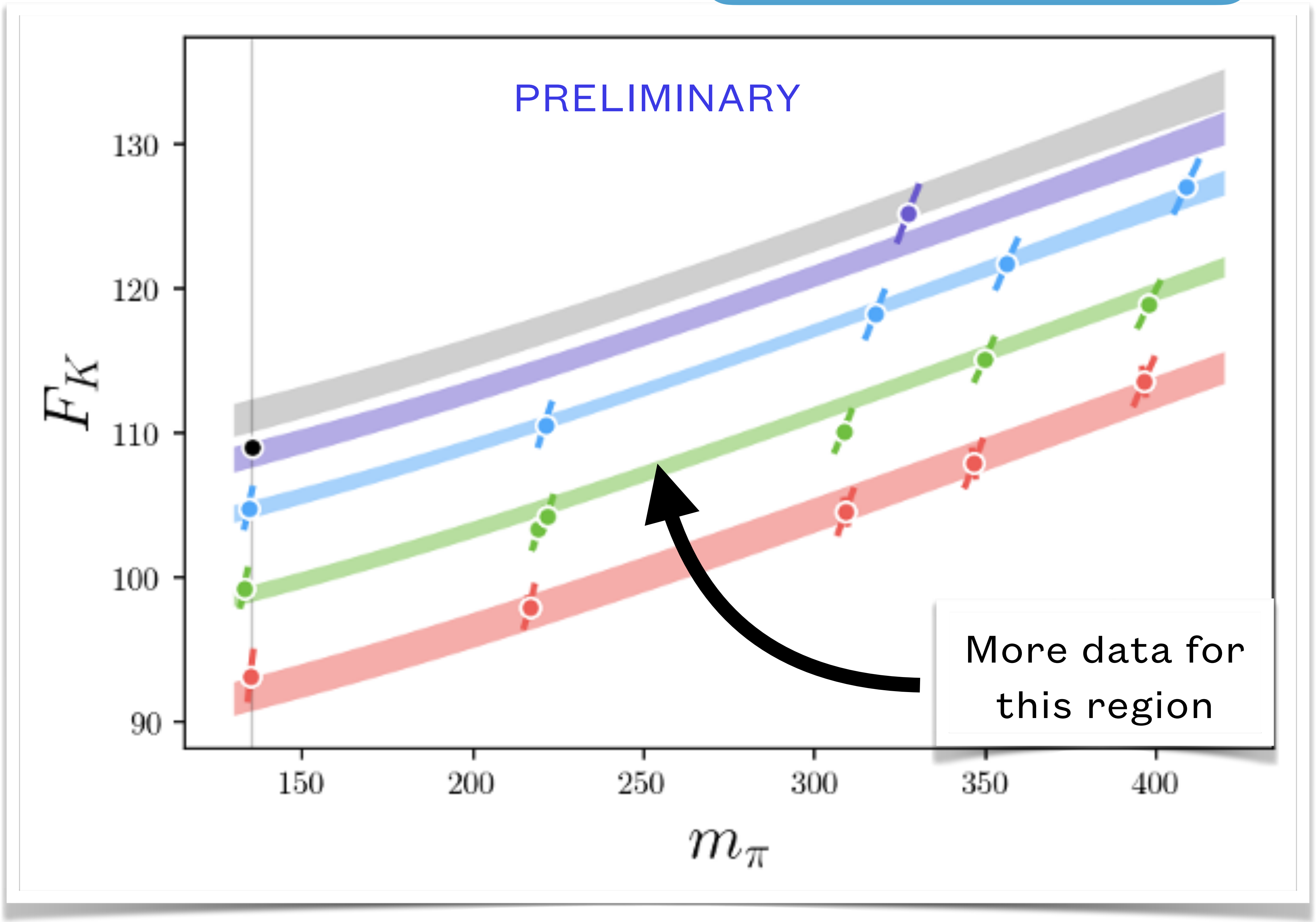
$$F_\pi = 92.8\ (1.0)\ \text{MeV}$$

$$F_\pi^{PDG} = 92.277\ (14)\ (21)\ (92)\ \text{MeV}$$

Towards the Physical Point

One point at .06, the new data will be at help to improve the precision of the continuum at mpi - 220





$$F_K = F\left\{1 + \delta(F_K)_{\chi\text{–logs}} + \delta(F_K)_{\text{CT}} + \delta(F_K)_{a^2} + \delta(F_K)_{\text{MA}}\right\}$$

$$F_K = 110.0\,(1.0)\ \text{MeV}$$

$$F_K^{PDG} = 110.08\,(19)(23)(19)\ \text{MeV}$$

Next Steps and Summary

- Once we have demonstrated control of the systematics, i.e. able to remove FV effects analytically, and m_γ range for smooth extrapolations, we can generate ensembles for a range of pion masses and lattice spacings.
  - It is necessary to compare our results to other formulations of LQED
- Lattice QCD calculations are challenging but previous the determination of g_A has shown a level of control at the sub-percent level.
  - Yet we need to understand how QED corrections impact g_A in a non-perturbative way in order to begin work on the $n \to pe\nu$ amplitude.
    - The goal is not to control the full calculation at 10^{-4} precision but to control the correlated correction at $10^{-4} / \alpha_{fs} \sim 10^{-2}$ level

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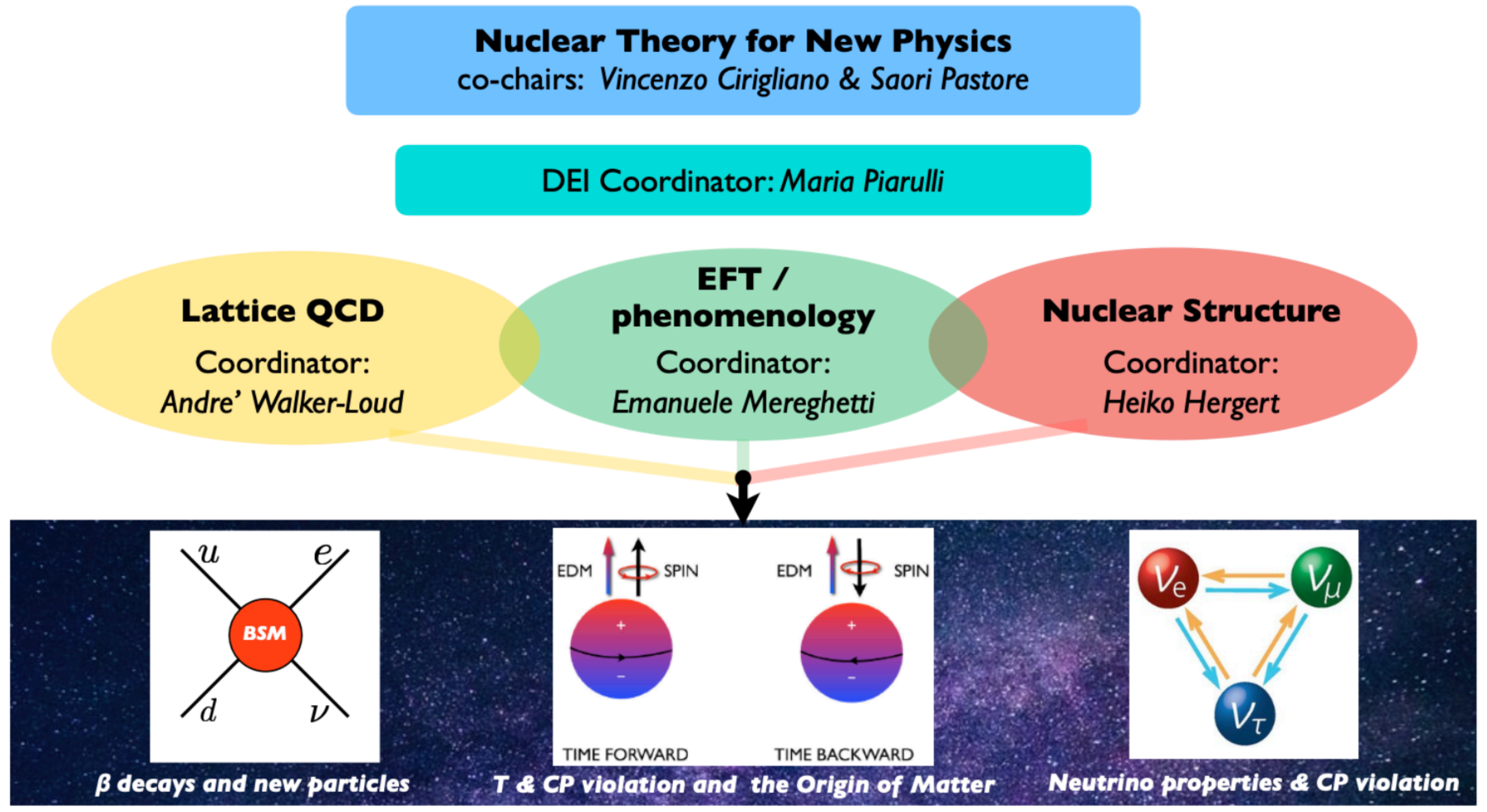
California Lattice Collaboration

QED_M Collaboration

André Walker-Loud	Henry Monge-Camacho
Amy Nicholson	Zack Hall
Andrea Schiller	Haobo Yan
Michele Della Morte	Ben Hoerz
Justus Tobias Tsang	Dean Howarth
Kate Clark	Pavlos Vranas



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