Probes of BSM physics using lattice QCD

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Extended Twisted Mass Collaboration

STIMULATE
European Joint Doctorates

Workshop on Standard Model and Beyond

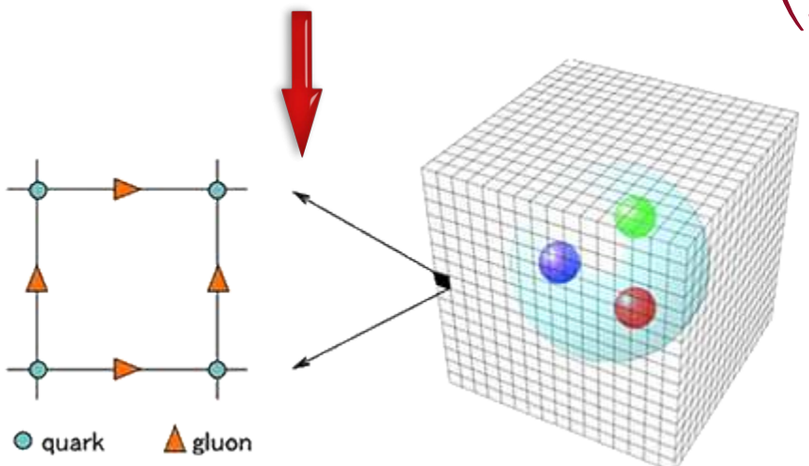
Κέρκυρα, 28 August - 8 September 2022

Outline

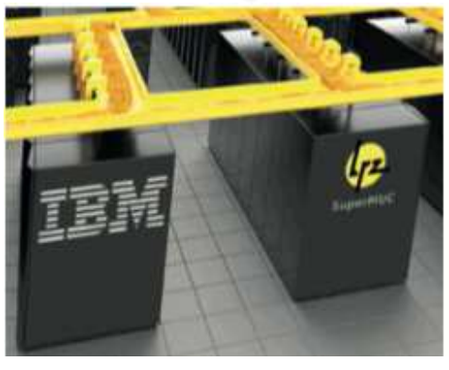
- Introduction
  - State-of-the-art lattice QCD simulations
- Probes of BSM physics
  - Scalar and tensor charges
  - Strangeness of the nucleon
  - Neutron electric dipole moment (nEDM)
  - Muon anomalous magnetic moment
- Conclusions

Extraction of matrix elements in lattice QCD

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}[U] \mathcal{O}(D^{-1}[U], U) \left(\prod_{f=u,d,s,c} \mathrm{Det}(D_f[U]) \right) e^{-S_{\mathrm{QCD}}[U]}$$



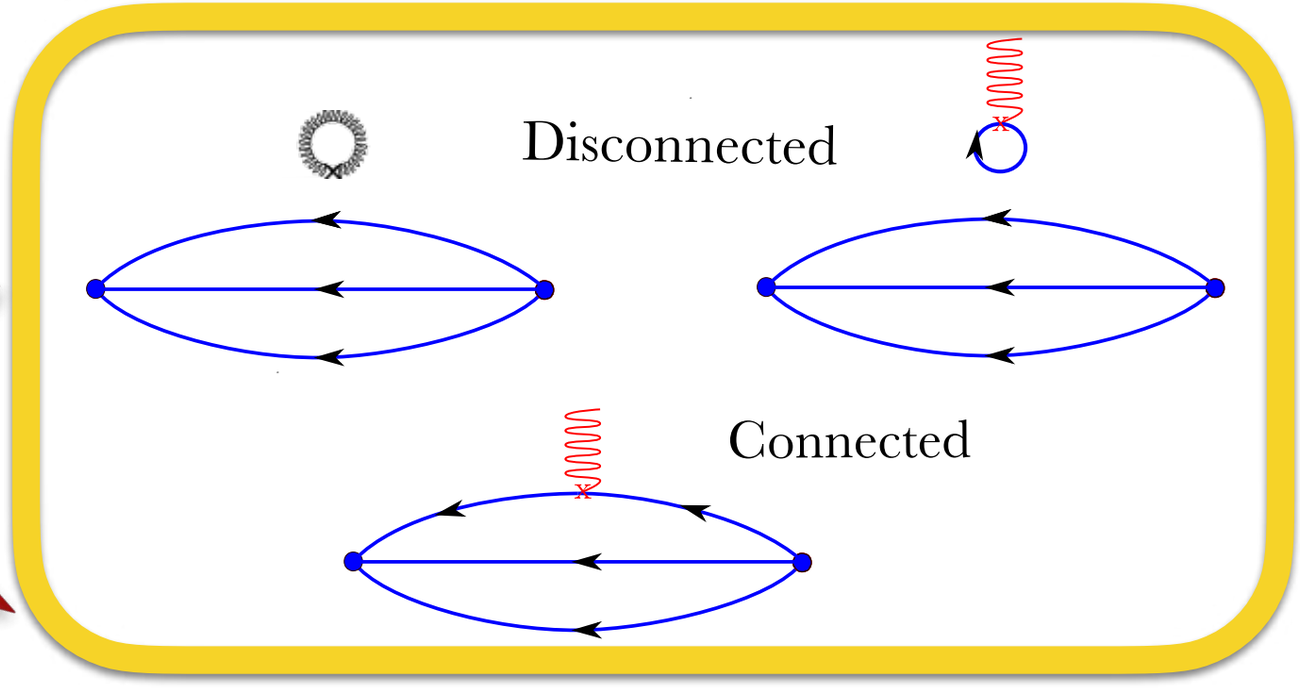
Simulation of gauge configurations U



Quark & gluon propagators

Data Analysis

contractions



Computational resources

Extended Twisted Mass Collaboration

PRACE

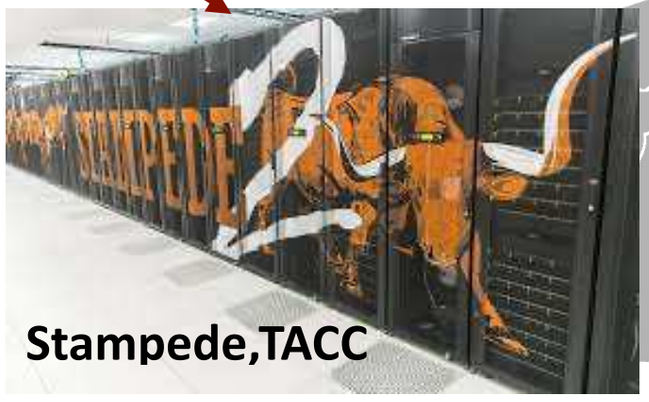
Piz Daint, CSCS

JSC

Summit, OLCF

HAWK, HLRS

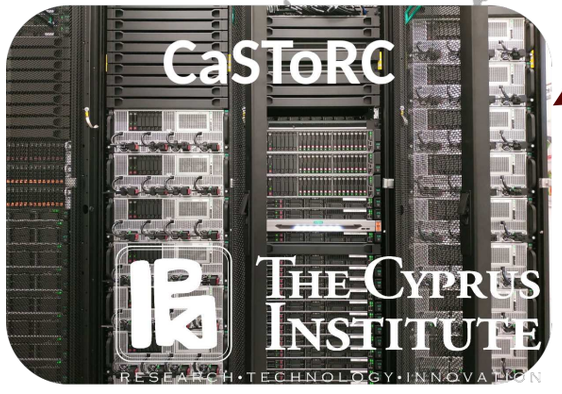
USA



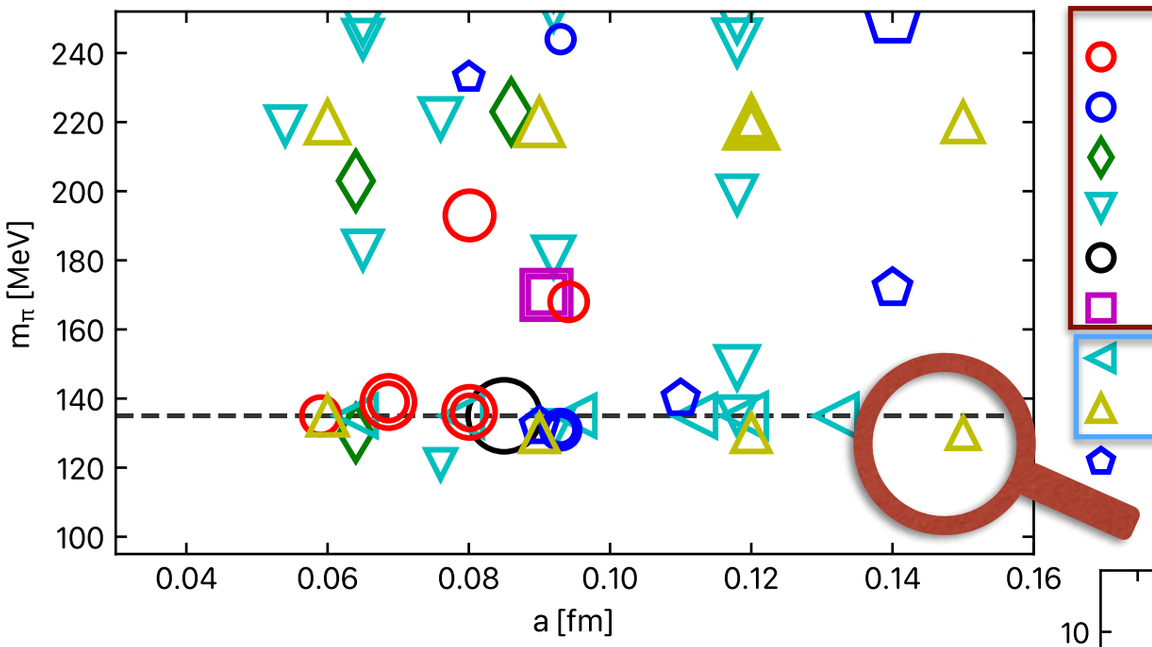
Stampede,TACC

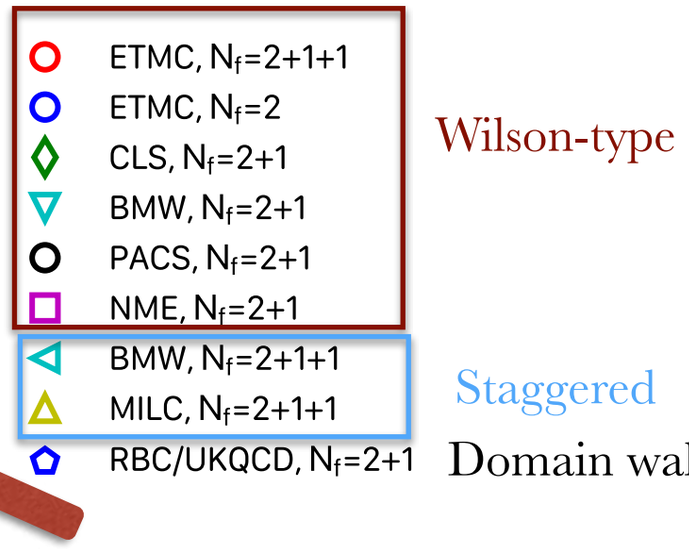
SuperMUC, LRZ

Marconi100, CINECA



Status of current simulations

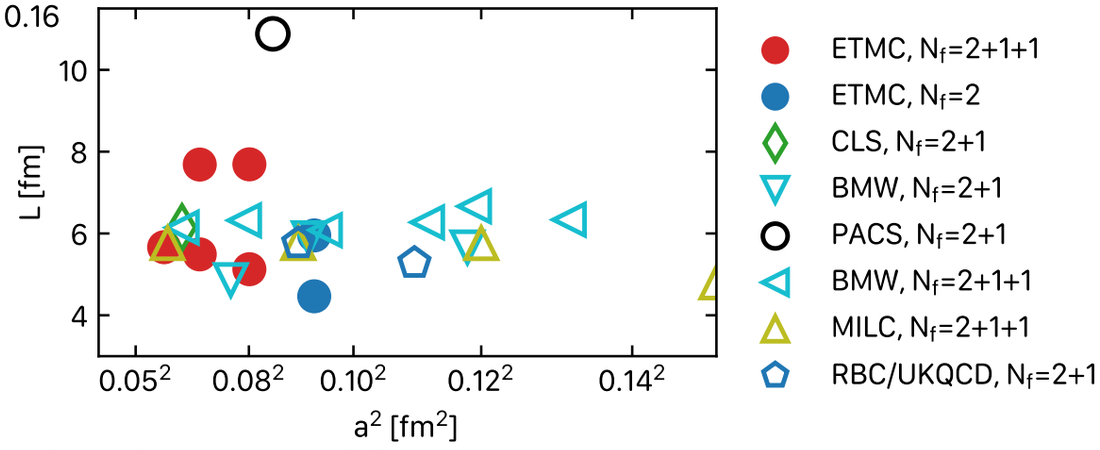




Wilson-type

Staggered

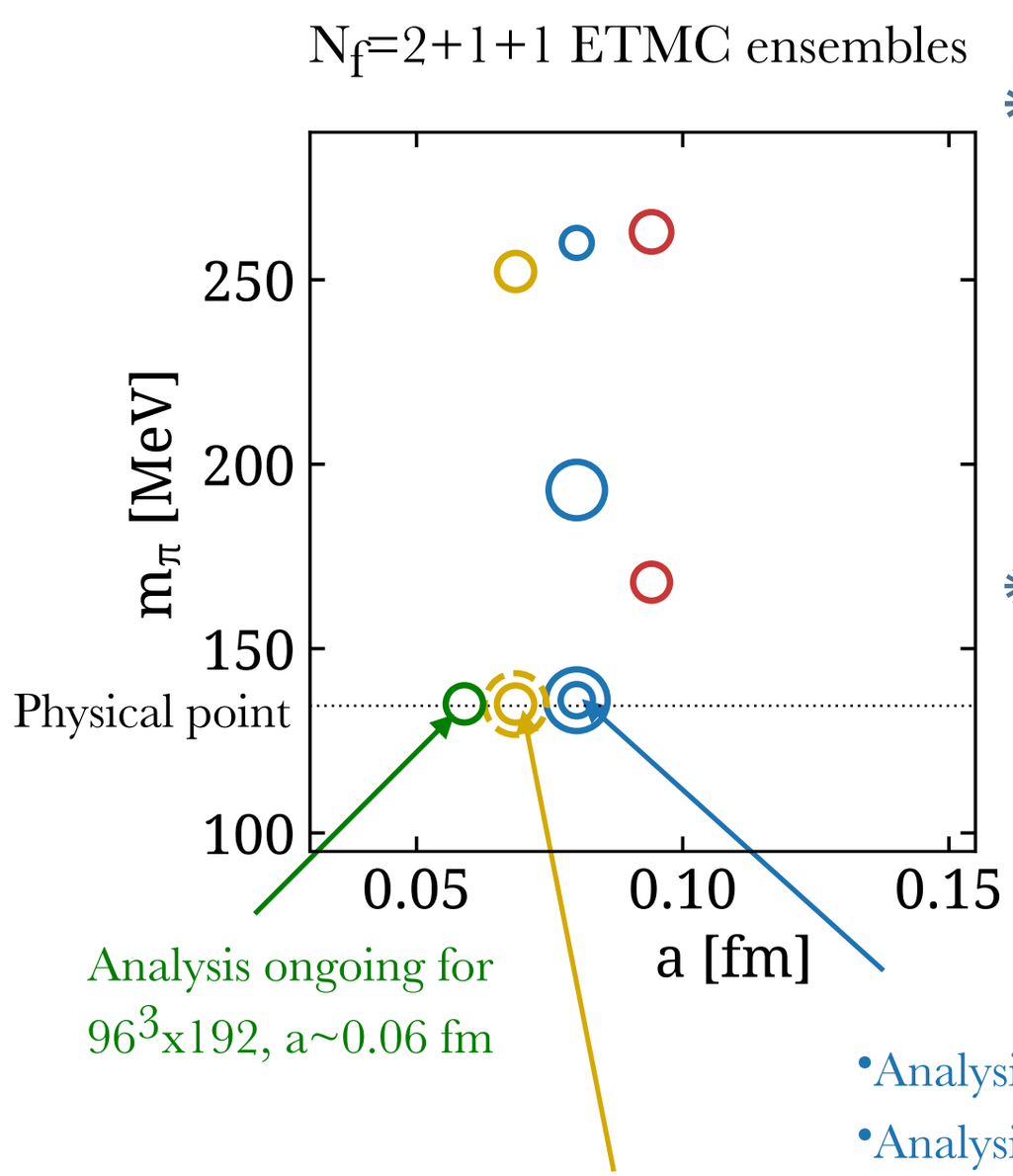
Domain wall



❋ A number of collaborations has physical point ensembles:

- Wilson-type: BMW, ETMC, CLS, PACS
  - BMW and ETMC have multiple lattice spacings 0.05<a<0.1 fm
  - PACS has a large volume ensemble at a single lattice spacing
- Staggered at physical point: MILC with 4 and BMW with 6 lattice spacings 0.05<a<0.15 fm
- Domain wall at physical point: RBC/UKQCD with 2 lattice spacings

Gauge ensembles generated by ETMC



- 5 ensembles at physical pion mass
  - 3 lattice spacings 0.05<a<0.1 fm —> take continuum limit **directly at the physical point** avoiding chiral extrapolation removing a major systematic error in the baryon sector
  - Two volumes at a=0.08 fm and 0.07 fm of Lm_π~3.6 (5.1 fm) and Lm_π ~5.4 (7.7 fm)

- Algorithmic improvements needed to go to a<0.05 fm due to critical slow down in HMC (long autocorrelations) —> new approaches e.g. Machine learning approaches using equivariant flows

G. Kanwar, et al., Phys. Rev. Lett. 125 (2020) 121601, arXiv:2003.06413; D. Boyda, et al., Phys.Rev.D 103 (2021) 074504, arXiv: 2008.05456; M. S. Albergo *et al.*, *Phys.Rev.D* 104 (2021) 114507, arXiv:2106.05934

C. A. *et al.* (ETMC), "Simulating twisted mass fermions at physical light, strange and charm quark masses" Phys. Rev. D98 (2018) 054518

Systematics & Challenges

- **Simulations directly at the physical point** ✓

  Systematic effects from chiral extrapolation are eliminated

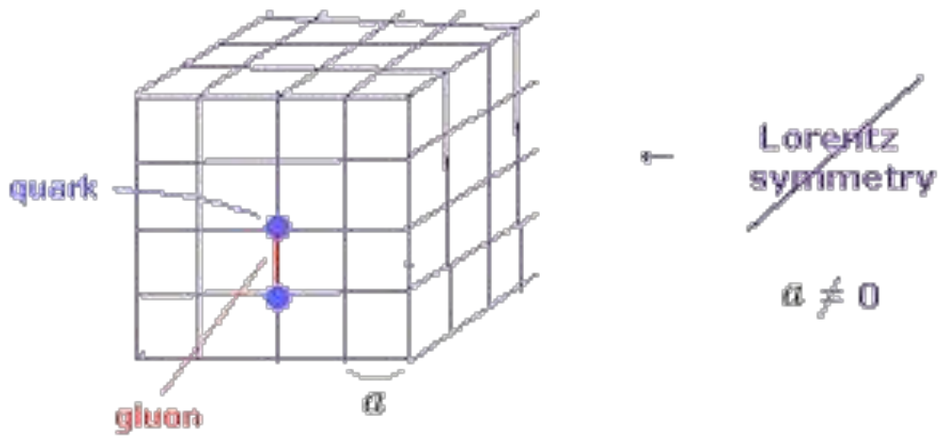
- **Discretisation effect:** Continuum limit

  —> need simulations for at least 3 lattice spacings

- **Finite volume effects:** Infinite volume limit

  —> need simulations for at least 3 volumes

Typically done using simulations for heavier than physical values of the pion mass



- **Ground-state identification**

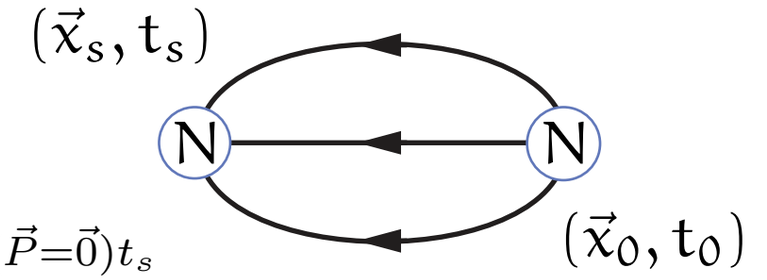
  Cross-check (one-, two- and three-state fits, summation), but two or more particle states create difficulties

- **Renormalisation**

  Non-perturbatively with improvements e.g using perturbative subtraction of lattice artefacts - more complicated for extended operators

- In what follows we assume **isospin symmetry** i.e. up and down quarks have equal mass, and **neglect EM effects**

Nucleon propagator

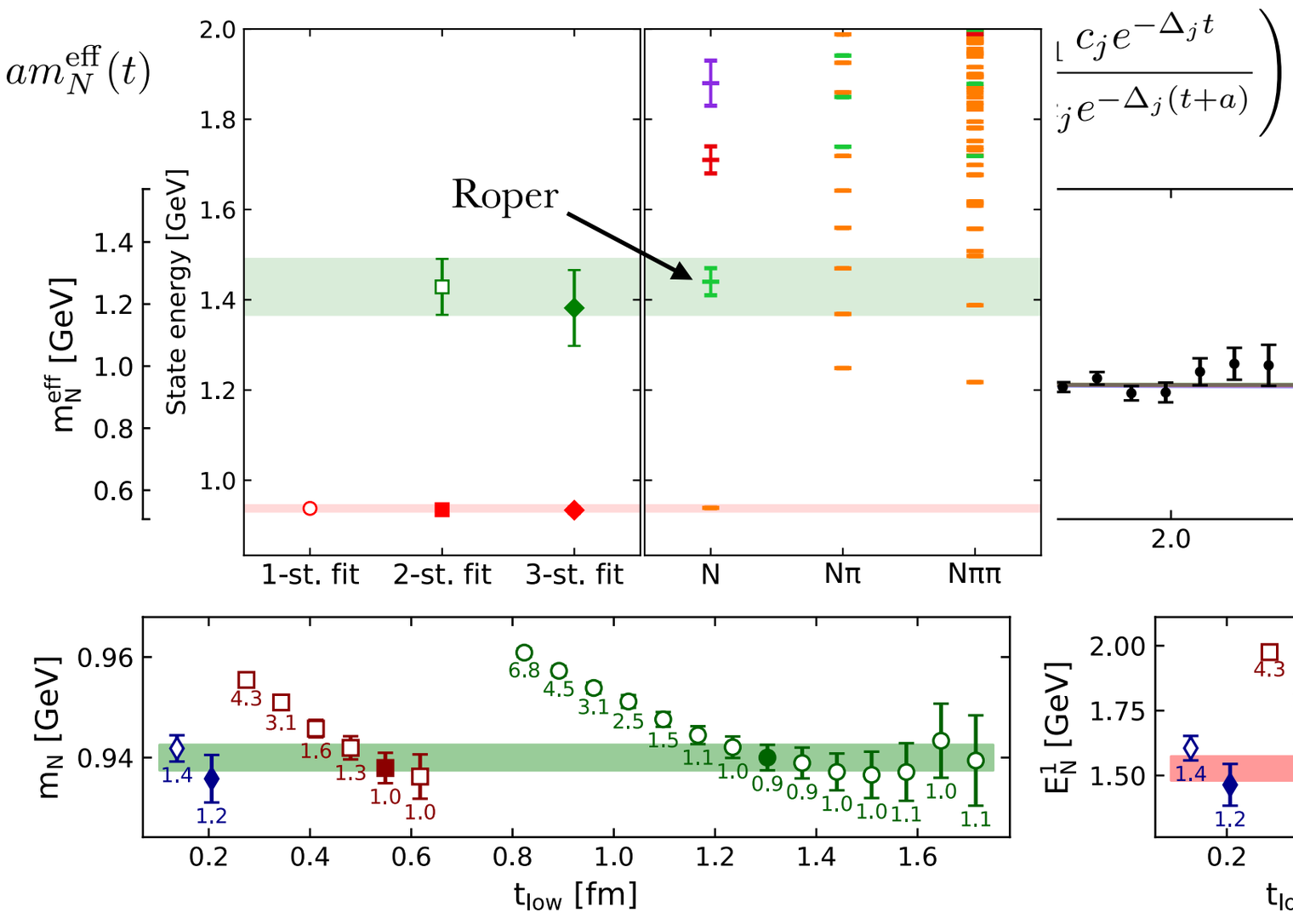


Analysis of two- and three-point functions C2pt and C3pt

$$C_{2\mathrm{pt}}(\Gamma_0;\vec{P}=\vec{0},t_s)=\sum_{\vec{x}_s}\mathrm{Tr}\left[\langle\Gamma_0 J_N(t_s,\vec{x}_s)\bar{J}_N(t_0,\vec{x}_0)\rangle\right]=\sum_{n=0}^{\infty}a_n e^{-E_n(\vec{P}=\vec{0})t_s}$$

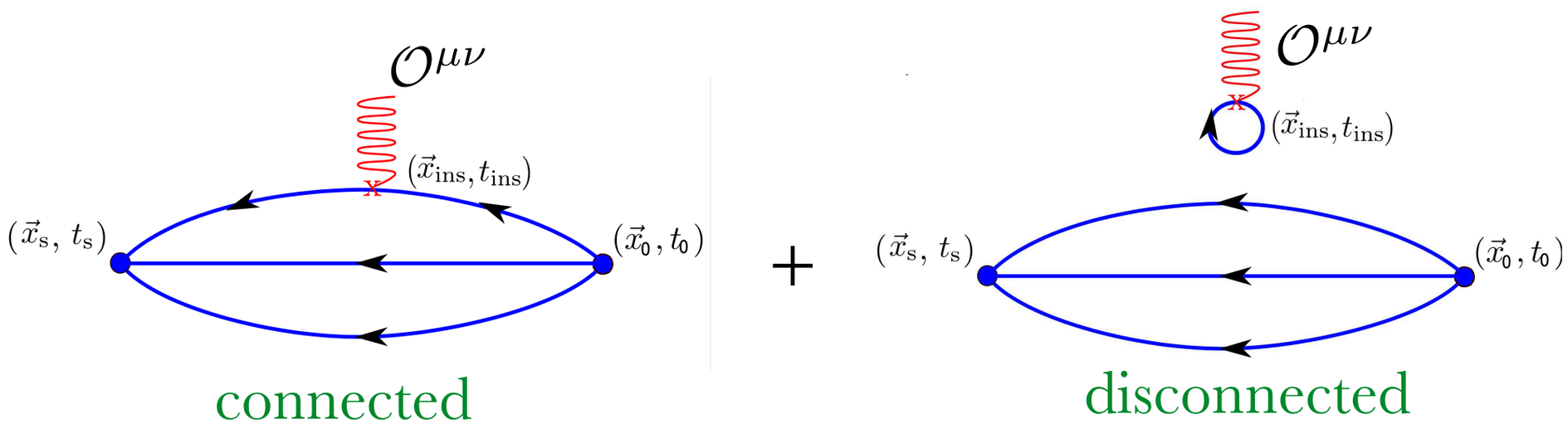
$$\xrightarrow{t_s\to\infty} a_0 e^{-m_N t_s}+\mathcal{O}\left(e^{-E_1(\vec{P}=\vec{0})t_s}\right)$$

Fit the nucleon two-point function or effective mass keeping up to two excited states



Nucleon matrix elements

$$C^{\mu\nu}_{\rm 3pt}(\Gamma;\vec{q}=0,t_s,t_{\rm ins}) = \sum_{\vec{x}_{\rm ins},\vec{x}_s} {\rm Tr}\left[\langle \Gamma J_N(t_s,\vec{x}_s)\mathcal{O}^{\mu\nu}(t_{\rm ins},\vec{x}_{\rm ins})\bar{J}_N(t_0,\vec{x}_0)\rangle\right]$$



connected

disconnected

✺ Identification of nucleon matrix element *M* (t_0=0)

Plateau and two-state fit:

$$R^{\mu\nu}(\Gamma;\vec{q}=\vec{0},t_s,t_{\rm ins}) = \frac{C^{\mu\nu}_{\rm 3pt}(t_s,t_{\rm ins})}{C_{\rm 2pt}(\Gamma_0,t_s)} \longrightarrow \boxed{\mathcal{M}} + \mathcal{O}(e^{-\Delta E(t_s-t_{\rm ins})}) + \mathcal{O}(e^{-\Delta E t_{\rm ins}})$$

Included in the two-state fit

Summation:

$$\sum_{t_{\rm ins}=a}^{t_s-a} R^{\mu\nu}(\Gamma;\vec{q}=\vec{0},t_s,t_{\rm ins}) \longrightarrow c + \boxed{\mathcal{M}} t_s + \mathcal{O}(e^{-\Delta E t_s})$$

L. Maiani, G. Martinelli, M. L. Paciello, and B. Taglienti, Nucl. Phys., B293: 420, 1987

Nucleon scalar and tensor charges

- The nucleon axial charge g_A is a fundamental quantity within the SM - well known experimentally and thus a benchmark quantity for lattice QCD

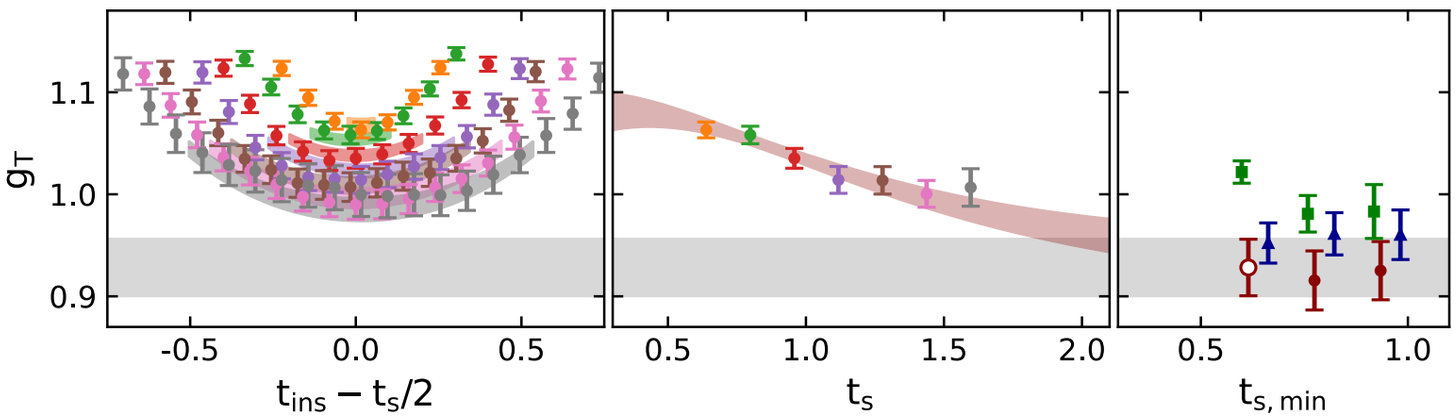
- Isovector tensor and scalar charges put limits on the existence of BSM interactions with scalar and tensor structure - relevant for ongoing neutrino experiments e.g. DUNE, IsoDAR, COHERENT, etc and less precisely known

Tanmoy Bhattacharya, et al., PRD 85 (2012) 054512, arXiv: 1110.6448

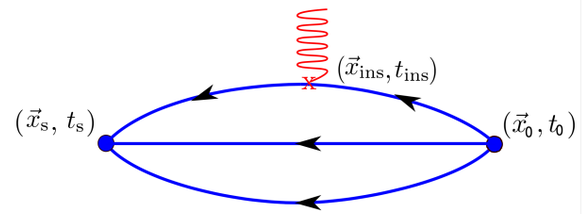
- The scalar charge determines the scattering cross-section of a scalar particle with the nucleon and are thus needed for direct dark matter searches

Extraction of isovector tensor charge

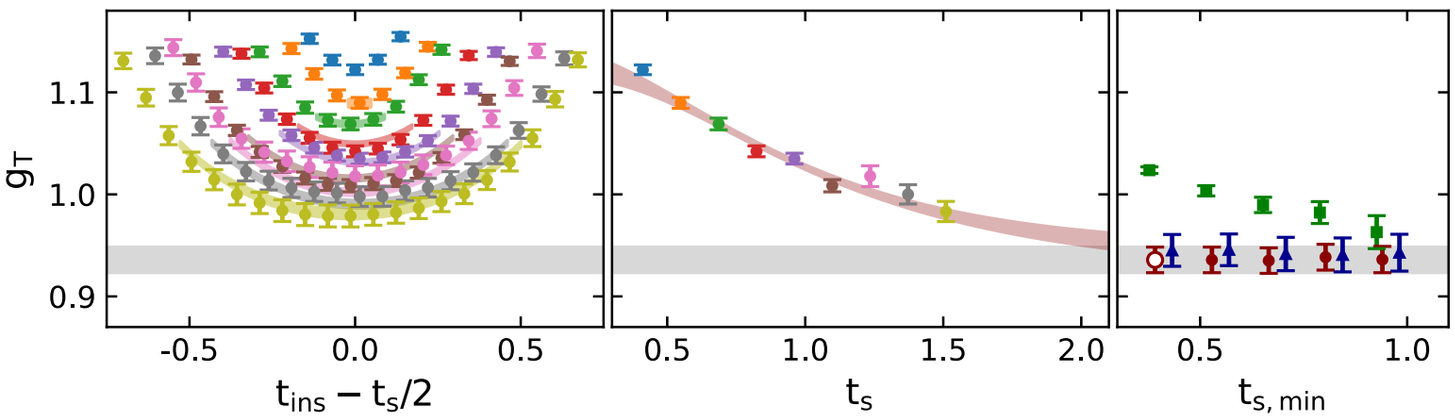
B-ensemble: 64^3 x 128, a~0.08 fm



t_s/a	t_s [fm]	n_{srcs}
8	0.64	1
10	0.80	2
12	0.96	4
14	1.12	6
16	1.28	16
18	1.44	48
20	1.60	64
2-point		264



C-ensemble: 80^3 x 160, a~0.07 fm

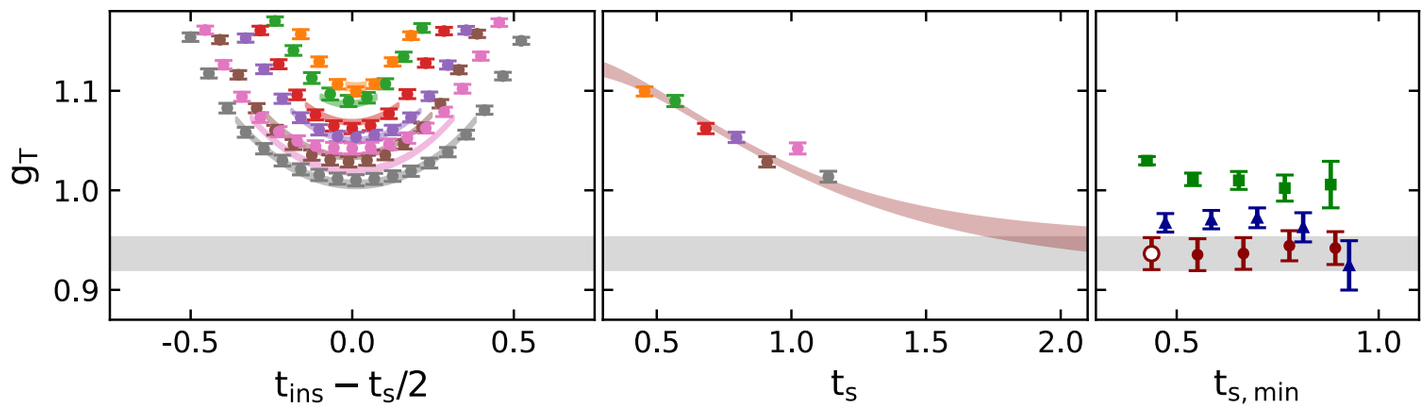


x 750 configurations =
15 M inversions!

t_s/a	t_s [fm]	n_{srcs}
8	0.549	1
10	0.686	2
12	0.823	5
14	0.961	11
16	1.098	24
18	1.235	45
20	1.372	116
22	1.509	246
2-point		650

x 401 configurations =
23.6 M inversions!

D-ensemble: 96^3 x 192, a~0.06 fm



t_s/a	t_s [fm]	n_{srcs}
8	0.456	1
10	0.570	2
12	0.684	4
14	0.798	8
16	0.912	16
18	1.026	32
20	1.140	64
22	1.254	16
24	1.368	32
26	1.482	64
2-point		368

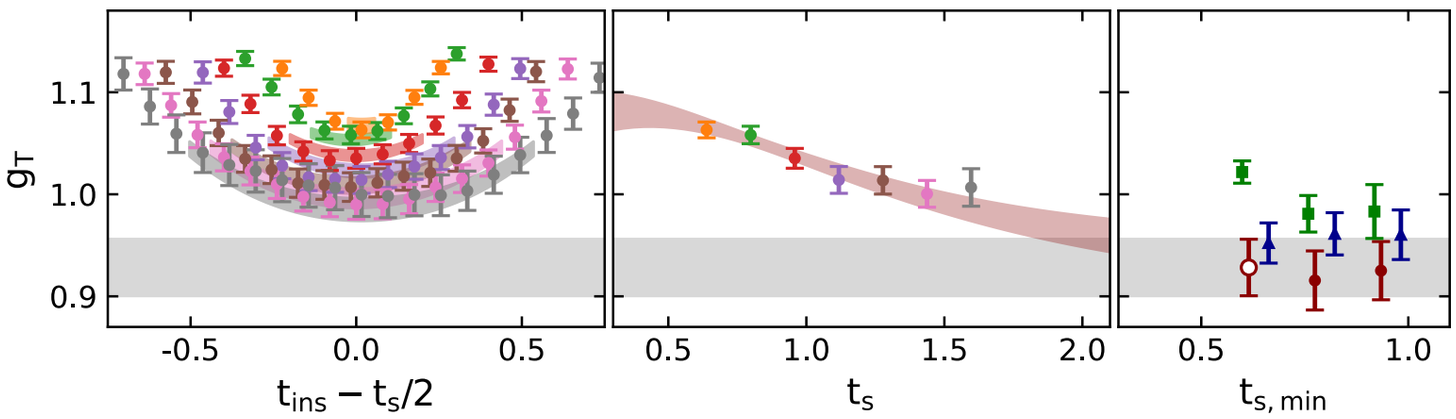
on-going

x 500 configurations =
15.9 M inversions!

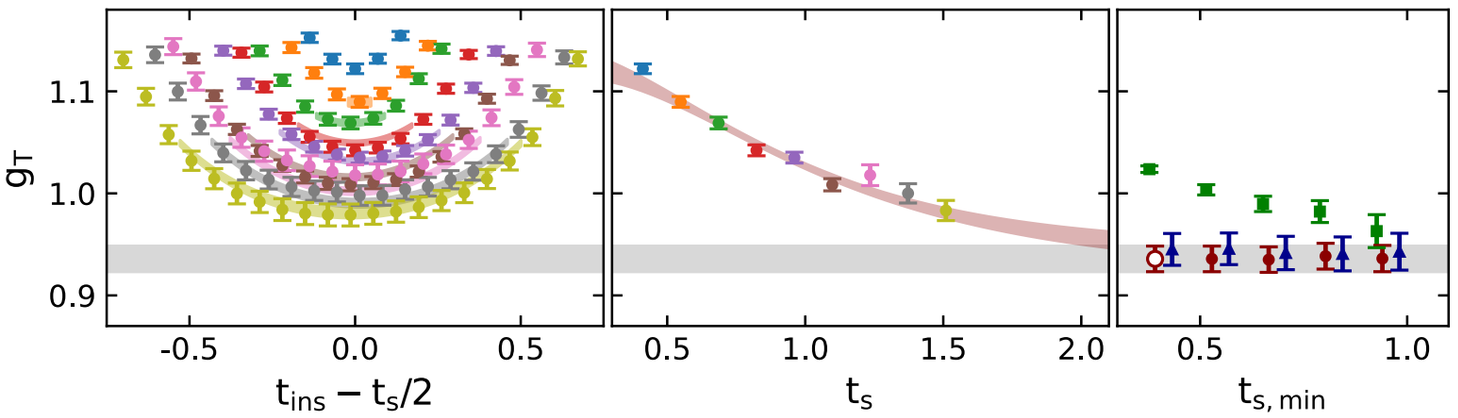
- Important to probe large t_s values keeping error approximately the same to reliably eliminate contributions from excited states

Isovector tensor charge

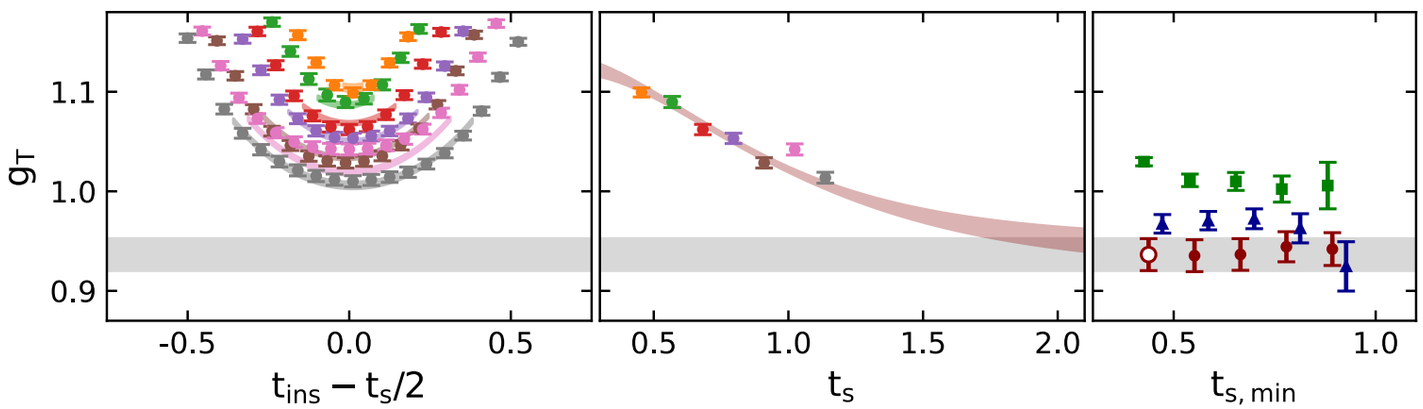
B-ensemble: 64^3 x 128, a~0.08 fm



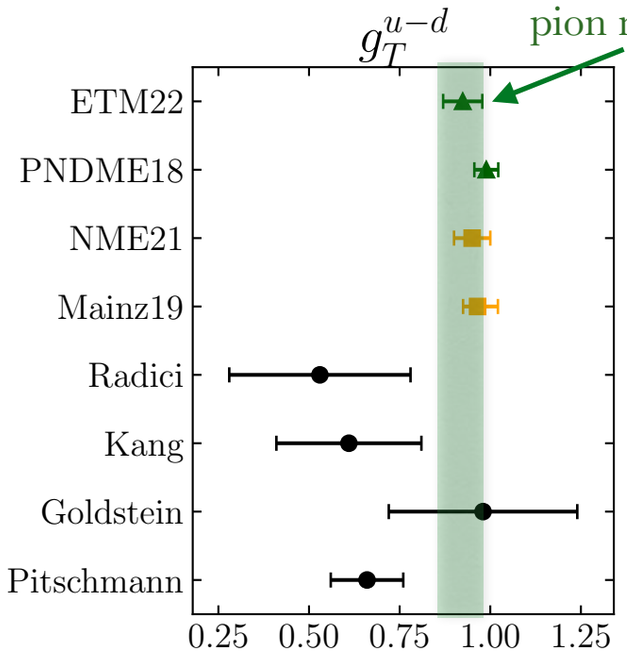
C-ensemble: 80^3 x 160, a~0.07 fm



D-ensemble: 96^3 x 192, a~0.06 fm



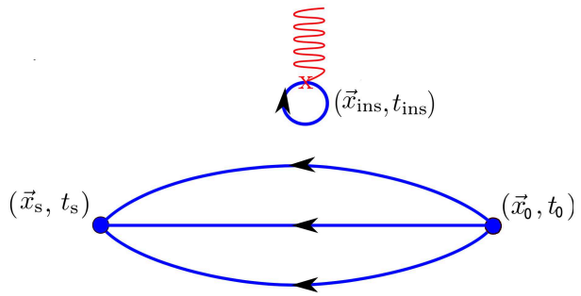
Continuum limit directly at physical pion mass



- Important to probe large t_s values keeping error approximately the same to reliably eliminate contributions from excited states

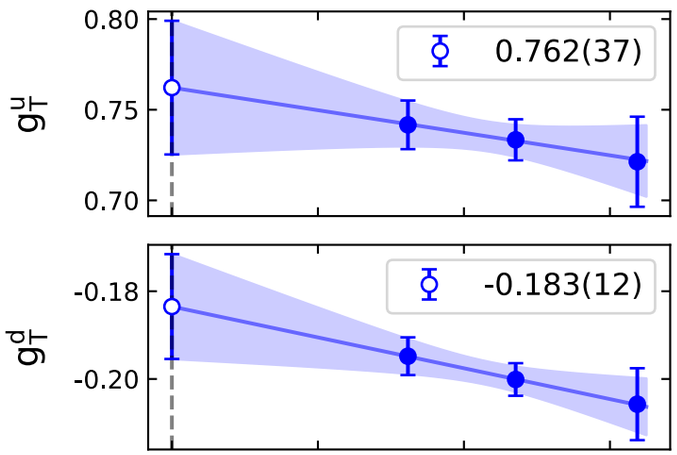
—> precision era of lattice QCD

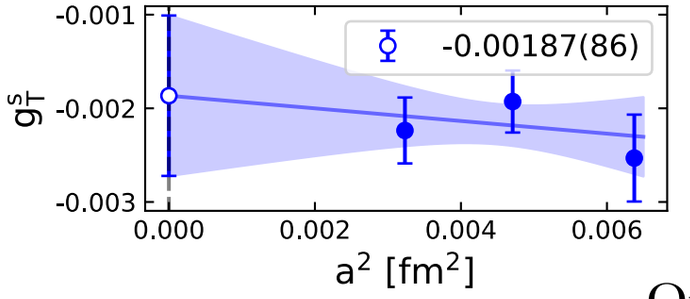
Flavor diagonal tensor charge



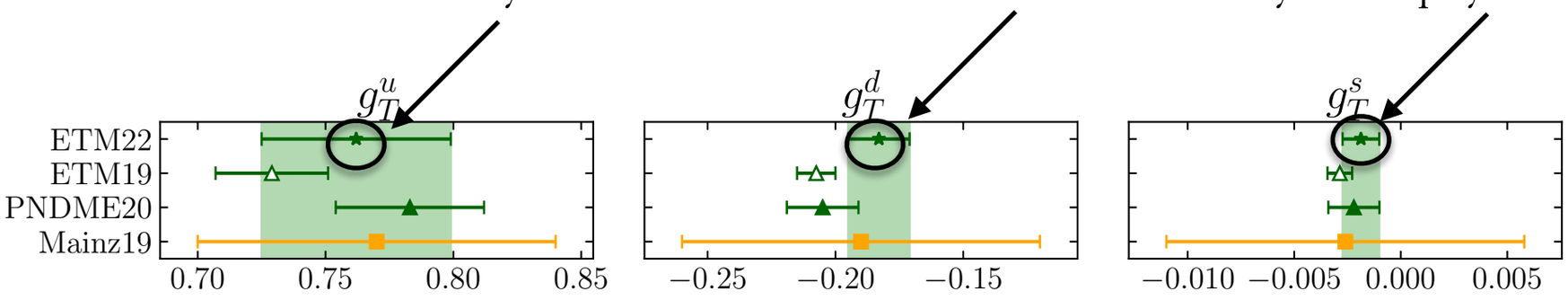
- Evaluate the disconnected contributions

- Obtain the tensor charge for the first time in the continuum using only physical point ensembles



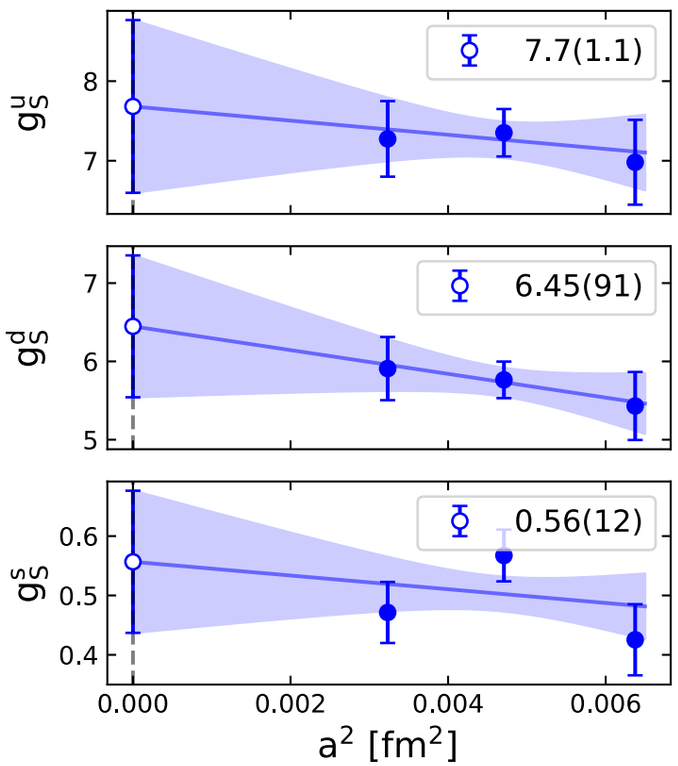


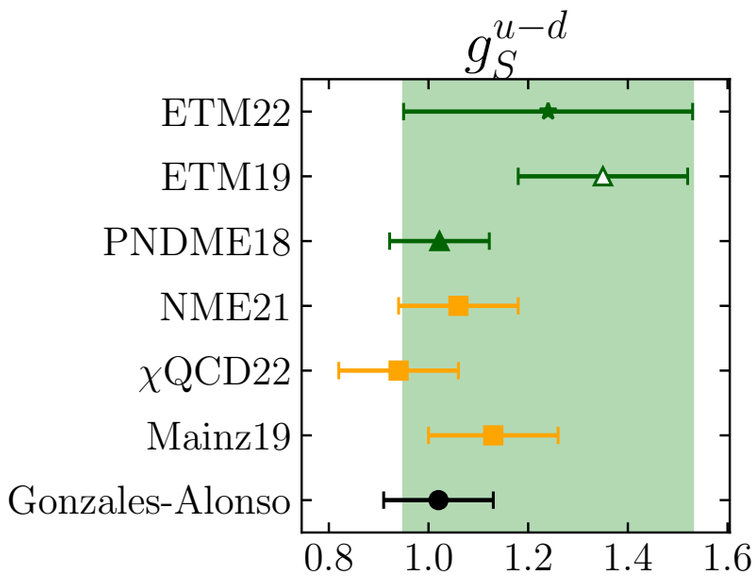
Only calculation in the continuum limit directly at the physical point



Nucleon scalar charge

- Perform a similar analysis for the scalar charge



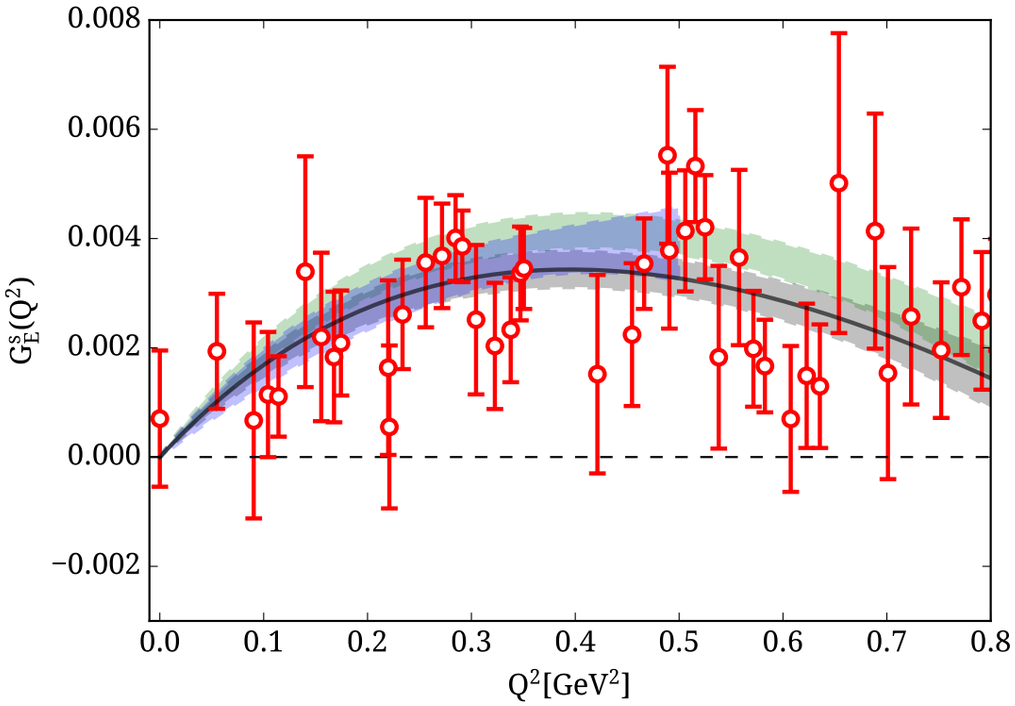


- Scalar charge is also directly related to the nucleon σ-terms or quark content $\sigma_q = m_q \langle N|\bar{q}q|N\rangle$

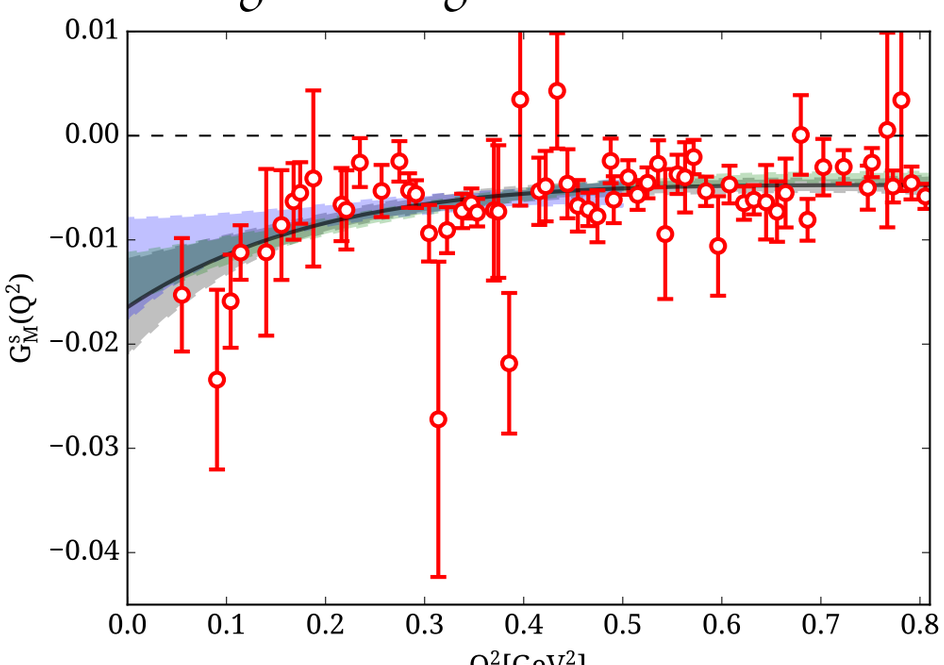
Strangeness of the nucleon

- Sea quark effects can be accurately determined —> provide precise input to experiments

B-ensemble: 64^3 x 128, a~0.08 fm

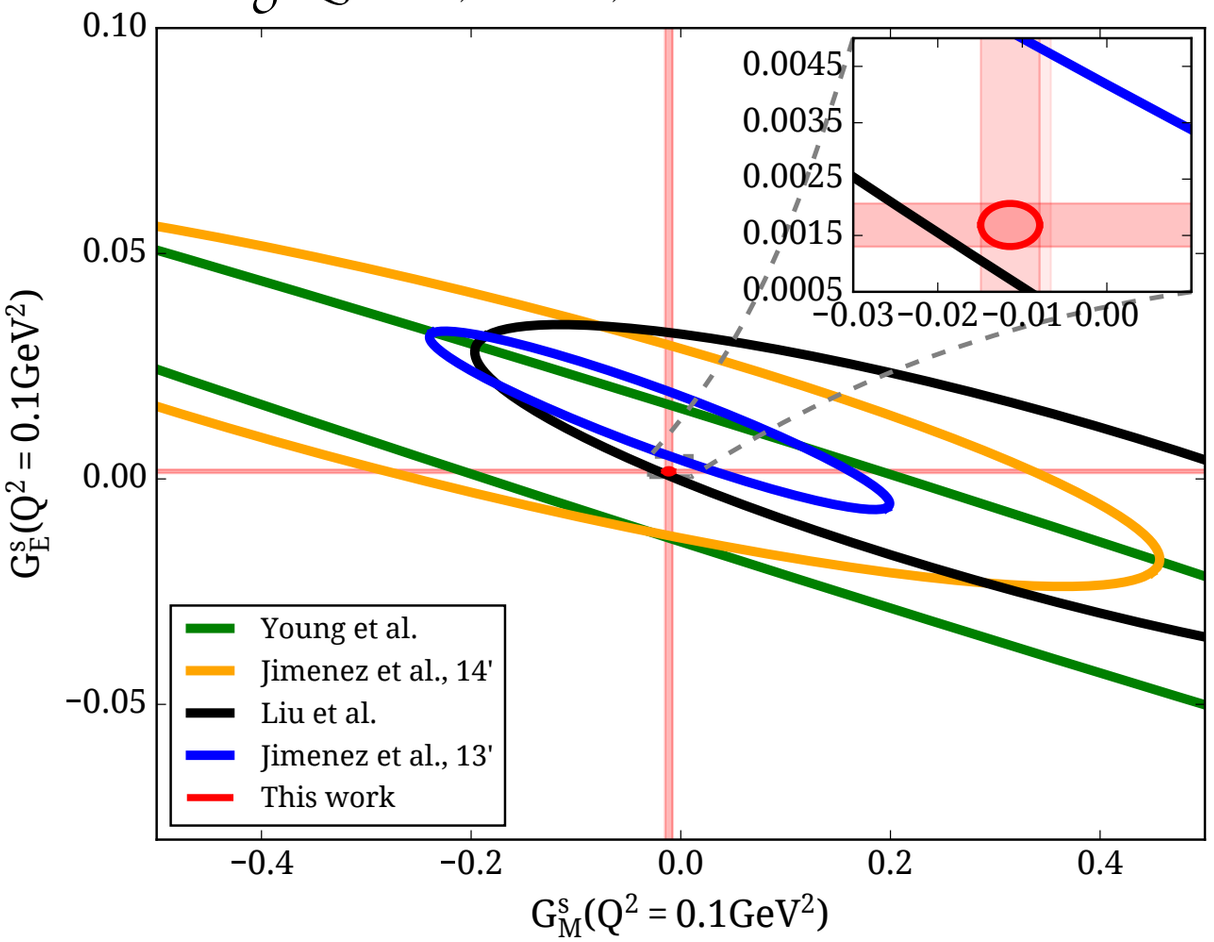


Negative magnetic moment



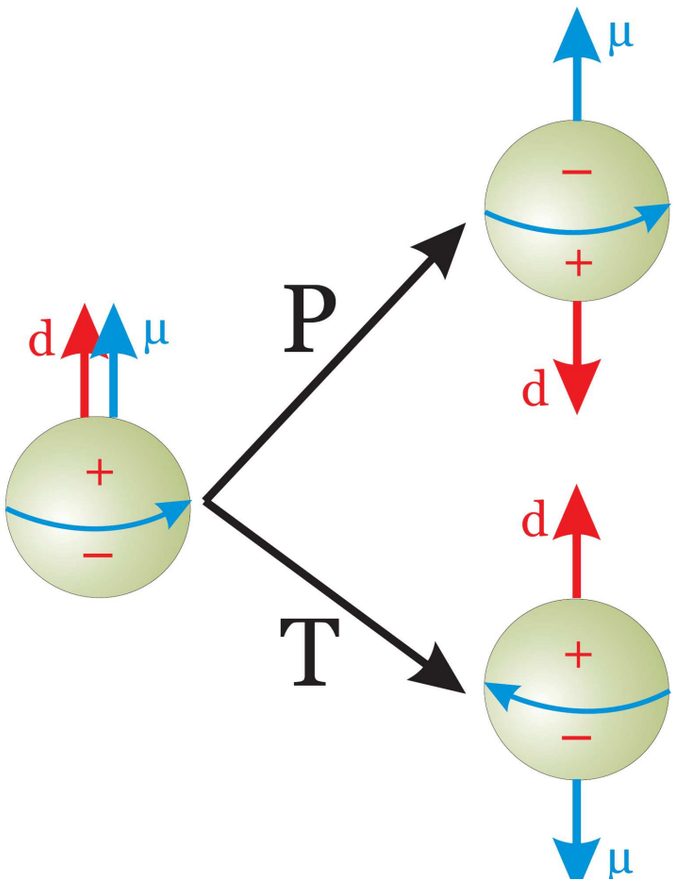
Significant input to experimental searches

e.g Q-Weak, SolID, etc



C. A. *et al.*, Phys. Rev. D 101 (2020) 031501, arXiv:1909.10744

Neutron electric dipole moment



- Possible detection of nEDM would break CP symmetry —> new source of CP violation within the Standard Model (SM)
- Despite experimental efforts over the last 70 years **no non-zero value has been measured**
- Best upper bound: $|d_N| < 1.8 \times 10^{-13}$ e fm

Abel *et al.*, Phys. Rev. Lett. 124, 081803 (2020)

New experiments are coming and plan to further improve current upper bound by 2 order of magnitude

Neutrons: (~ 200 ppl.)
- Beam EDM @ Bern
- LANL nEDM @ LANL
- nEDM @ PSI
- nEDM @ SNS
- PanEDM @ ILL
- PNPI/FTI/ILL @ ILL
- TUCAN @ TRIUMF

Storage rings: (~ 400 ppl.)
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

Atoms: (~ 60 ppl.)
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Hg @ Seattle
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken

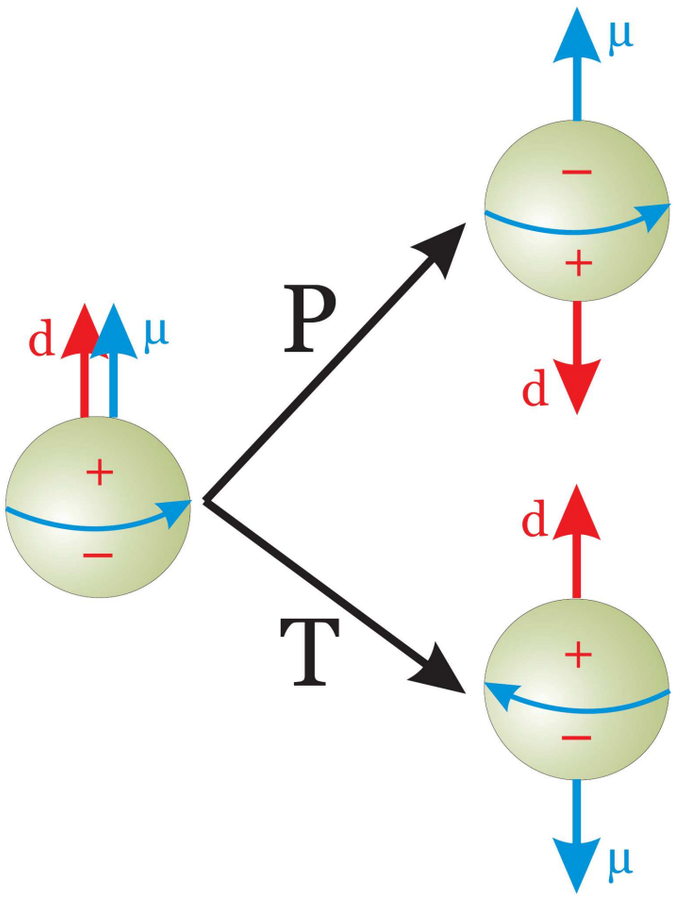
Molecules: (~ 55 ppl.)
- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhef
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial

source: https://www.psi.ch/en/nedm/edms-world-wide

Experiment	Features	Status
PSI	spallation so-D_2, magnetic fields	analysis/upgrading
PanEDM (ILL/Munich)	reactor He-II, 1st MSR	commissioning
ILL/PNPI/Gatchina	dual cell, 2nd best nEDM meast	upgrading source
LANL	spallation so-D_2 UCN source	2021-
TUCAN (Japan/Canada)	spallation He-II, MSR	upgrading, 2022-
SNS	fully cryogenic source/experiment	2022-
ILL/ESS n-beam	intense pulsed neutron beam	R&D, 2025-
J-PARC crystal	high E in crystal	R&D

source: [*J.W. Martin, J. Phys.: Conf. Ser. 1643 012002 (2020)*]

Motivation



- Possible detection of nEDM would break CP symmetry —> new source of CP violation within the Standard Model (SM)

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Abel *et al.*, Phys. Rev. Lett. 124, 081803 (2020)

Standard model prediction

- **Electroweak sector:** phase in quark mass from Yukawa coupling with Higgs field
  $|d_N| \sim O(10^{-19})$ e fm

- **Strong sector:** a QCD Lagrangian invariant under *C*, *P* and *T* transformations does not permit nEDM
  Include the *CP*-violating Cherns-Simons (CS) term:

$$\mathcal{L}_\theta(x) = -i\theta \frac{1}{32\pi^2} F^a_{\mu\nu}(x)\tilde{F}^{\mu\nu,a}(x) = -i\theta q(x)$$

$$\text{Topological charge: } \mathcal{Q} = \frac{1}{32\pi^2}\int d^4x F^a_{\mu\nu}(x)\tilde{F}^{\mu\nu,a}(x)$$

General approach

$$\mathcal{L}_{\mathrm{QCD}}(x) = \frac{1}{2g^2}\mathrm{Tr}\left[F_{\mu\nu}(x)\,F^{\mu\nu}(x)\right] + \sum_f \overline{\psi}_f(x)\,(i\gamma_\mu D^\mu + m_f)\psi_f(x)$$

❋ $\mathcal{L}_{\mathrm{QCD}}$ invariant under C, P and T transformations —> cannot induce a non-vanishing nEDM.

❋Insert the CP-violating Cherns-Simons (CS) term —> $\mathcal{L}(x) = \mathcal{L}_{\mathrm{QCD}}(x) + \underbrace{\mathcal{L}_\theta(x)}_{-i\theta q(x)}$

❋ Compute expectation values including CS-term: $\langle \mathcal{O}(x_1,...,x_n)\rangle_\theta = \frac{1}{Z_\theta}\int d[U]d[\psi_f]d[\bar{\psi}_f]\ \mathcal{O}(x_1,...,x_n)\ e^{-S_{\mathrm{QCD}}+i\theta\int q(x)d^4x}$

❋Sign problem: CS-term makes the action complex

- Measure the neutron energy in an external electric field
- Simulate with imaginary θ as done by e.g. QCDSF, Guo *et al.* 2015
- Since θ is small expand keeping only first order terms

Correlation with topological charge

$$\langle \mathcal{O}(x_1,...,x_n)\rangle_\theta = \langle \mathcal{O}(x_1,...,x_n)\rangle_{\theta=0} + \langle \mathcal{O}(x_1,...,x_n)(i\theta\mathcal{Q})\rangle_{\theta=0} + O(\theta^2)$$

❋ Measure the neutron CP-violating electromagnetic form factor $F_3(Q^2)$ and extract $F_3(0)$ —> $|d_N| = \frac{F_3(0)}{2m_N}$

❋We can only calculate $F_3(Q^2)$ and need to take Q^2 —>0

Nucleon matrix for nEDM

Form factor decomposition for the nucleon electromagnetic form factor:

$$\langle N^\theta(\vec{p_f},s)|J_\mu^{\rm EM}|N^\theta(\vec{p_i},s')\rangle = \bar{u}_N^\theta(\vec{p_f},s)\Gamma_\mu^\theta(q)u_N^\theta(\vec{p_i},s')$$

$$\Gamma^\theta(q) = F_1(Q^2)\gamma_\mu + \left(F_2(Q^2) + i\gamma_5 F_3^\theta(Q^2)\right)\frac{\sigma_{\mu\nu}q_\nu}{2m_N^\theta}\,; \qquad F_3^\theta = \theta F_3^{(1)} + O(\theta^3) \qquad m_N^\theta = m_N + O(\theta^2)$$

❋ Compute the 3-point function:

$$\langle J_N(\vec{p_f},t_s)J_\mu^{\rm EM}(\vec{q},t)\bar{J}_N(\vec{p_i},0)\rangle_\theta \sim |Z_N^\theta|^2 e^{-E_N^f(t_s-t)}e^{-E_N^i t}e^{i\alpha^\theta\gamma_5}\Lambda^\theta_{\frac{1}{2}}\Gamma^\theta_\mu\Lambda^\theta_{\frac{1}{2}}e^{i\alpha^\theta\gamma_5}$$

$$\alpha^\theta = \theta\alpha^{(1)} + O(\theta^3) \qquad Z_N^\theta = Z_N + O(\theta^2)$$

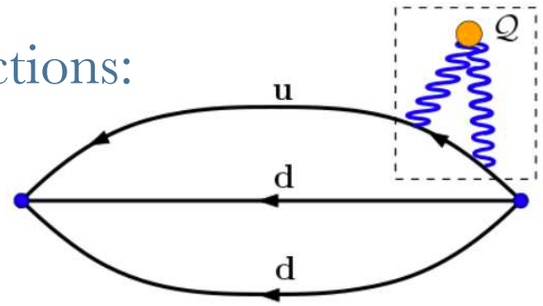
$$\langle J_N(\vec{p_f},t_s)J_\mu^{\rm EM}(\vec{q},t)\bar{J}_N(\vec{p_i},0)e^{i\theta\mathcal{Q}}\rangle = \langle J_N(\vec{p_f},t_s)J_\mu^{\rm EM}(\vec{q},t)\bar{J}_N(\vec{p_i},0)\rangle + i\theta\underbrace{\langle J_N(\vec{p_f},t_s)J_\mu^{\rm EM}(\vec{q},t)\bar{J}_N(\vec{p_i},0)\mathcal{Q}\rangle}_{\rm C_{3pt,\,Q}} + O(\theta^2)$$

$\rm C_{3pt}$

new element correlator with topological charge

❋ Need to determine $\alpha^{(1)}$ —> extracted from nucleon 2-point functions:

$$C_{2pt} = \langle J_N(\vec{p_f},t_f)\bar{J}(\vec{0},0)\rangle\,, \qquad C_{2pt,\mathcal{Q}} = \langle J_N(\vec{p_f},t_f)\mathcal{Q}\bar{J}(\vec{0},0)\rangle$$



$$\frac{C_{2\rm pt,\mathcal{Q}}}{C_{2\rm pt}} \to \alpha^1$$

❋ To extract matrix element take ratio of 3- and 2-point functions:

$$\Pi^{\mu k}_{3pt,\mathcal{Q}}(q) \equiv \lim_{t_f,t\to\infty}\frac{C_{3pt,\mathcal{Q}}}{C_{2pt,\mathcal{Q}}}R_{2pt} \qquad \text{e.g.} \qquad \Pi^{0k}_{3pt,\mathcal{Q}}(q) = \frac{iq_kC}{2m_N}\left(a^{(1)}G_E(Q^2) - \frac{F_3^{(1)}(Q^2)}{2m_N}(E_N+m_N)\right)$$

Topological charge

✺CP-odd EM form factor F_3 much less studied

✺Need topological charge for the computation of the matrix element - need an appropriate discretisation

- Field theoretic definition - Di Vecchia *et al.*, Nucl. Phys. B192, 392 (1981)
- Fermionic definition using spectral projectors - Giusti and Luescher, J. High Energy Phys. 03 (2009)

✺In the continuum the two definitions are equivalent

Field theoretic definition: $\mathcal{Q} = \frac{1}{32\pi^2} \int d^4x \, \epsilon_{\mu\nu\rho\sigma} \mathrm{Tr}\left[F_{\mu\nu}(x) F_{\rho\sigma}(x)\right]$

- Discretize $F_{\mu\nu}$ - use $O(a^2)$ improved definition by using Clover and rectangular Wilson loops
- Smooth out the ultraviolet fluctuations —> use gradient flow

$$\dot{V}_\mu(x,\tau) = -g_0^2 \left[\partial_{x,\mu} S_G(V(\tau))\right] V_\mu(x,\tau)$$
$$V_\mu(x,0) = U_\mu(x)$$

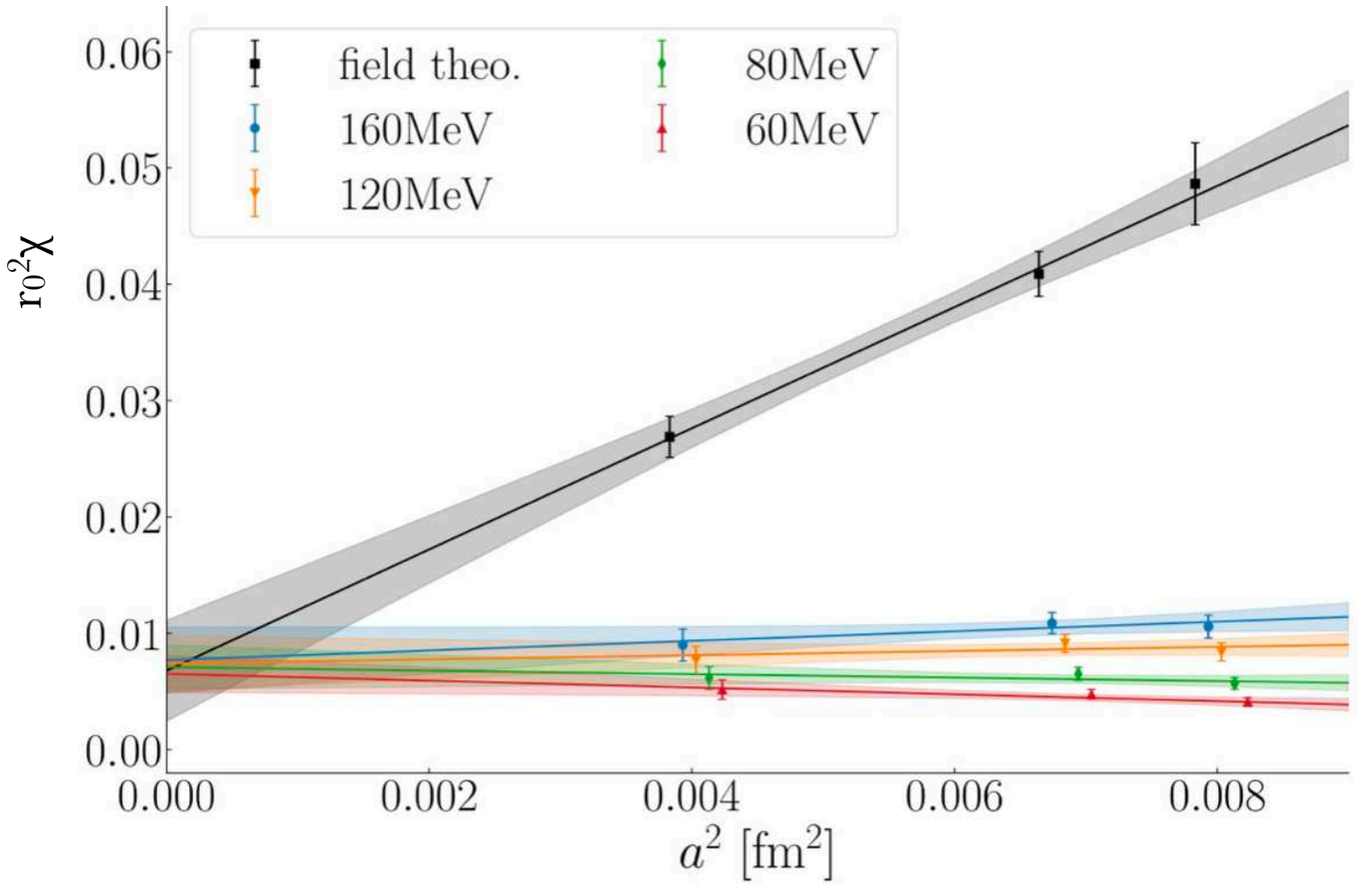
Spectral projector definition:

- Write in terms of the eigenmodes of the Wilson-Dirac operator

$$\mathcal{Q} = \frac{Z_S}{Z_P} \sum_i^{\lambda_i < M_{\mathrm{thr}}} u_i^\dagger \gamma_5 u_i \,, \qquad \left(D_W^\dagger D_W\right) u_i = \lambda_i u_i$$

Comparison of two definitions of topological charge (I)

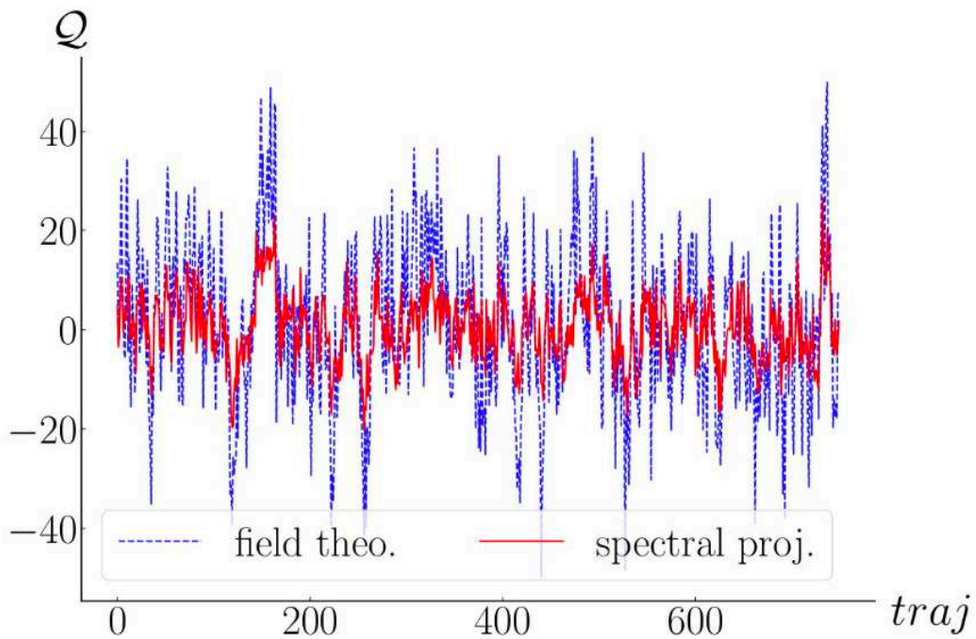
❋Topological susceptibility $\chi=\langle Q^2\rangle/V$

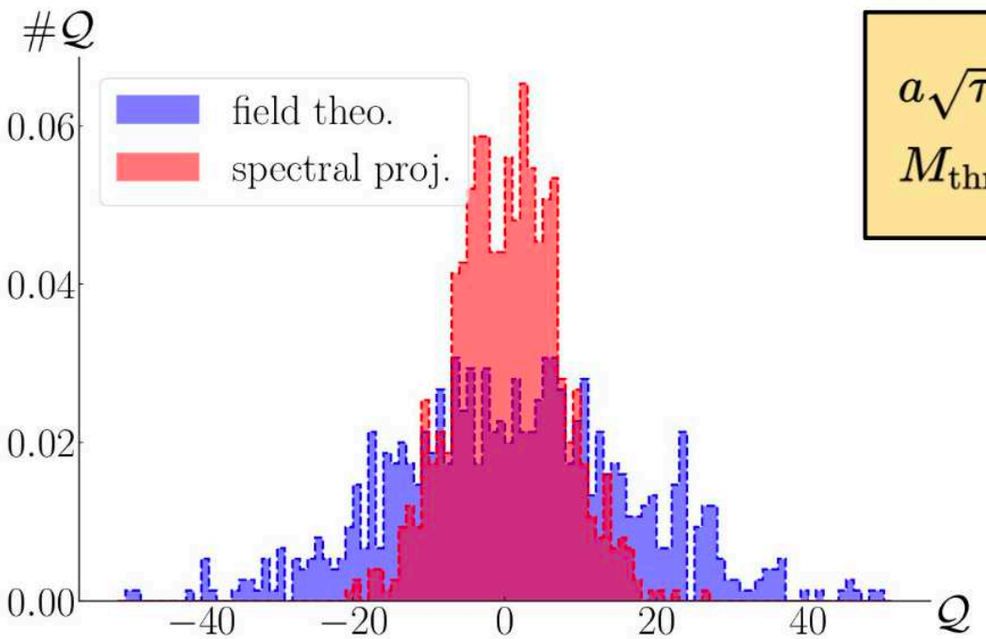


❋Topological susceptibility via spectral projectors shows milder cutoff effects as compared to the field theoretical definition

❋The choice oice of the threshold M_{thr} doesn't affect the continuum extrapolation

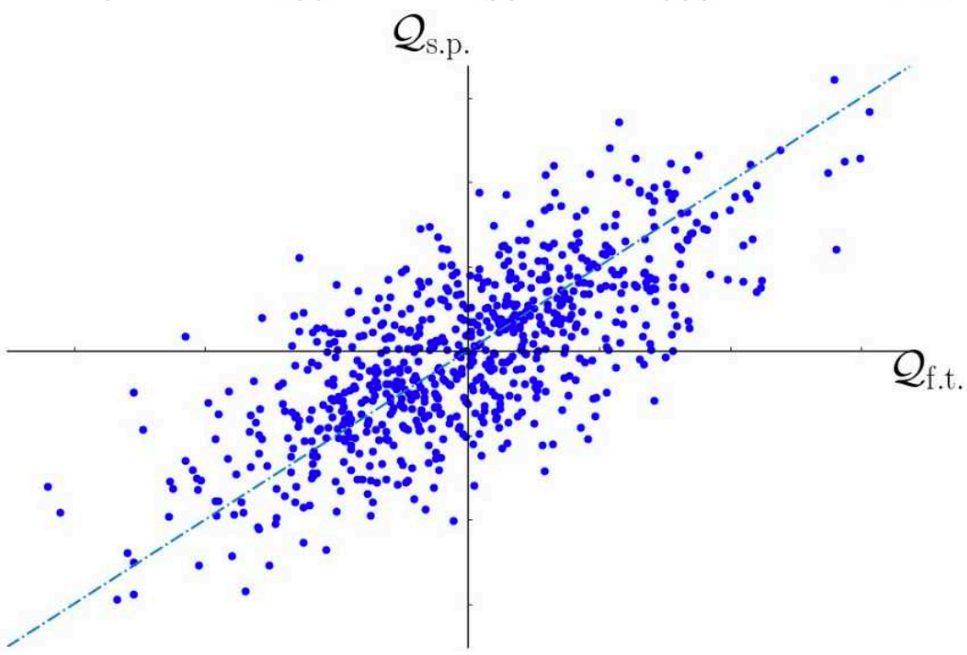
Comparison of two definitions of topological charge (II)





$a\sqrt{\tau_{\text{flow}}} = 0.15$ fm

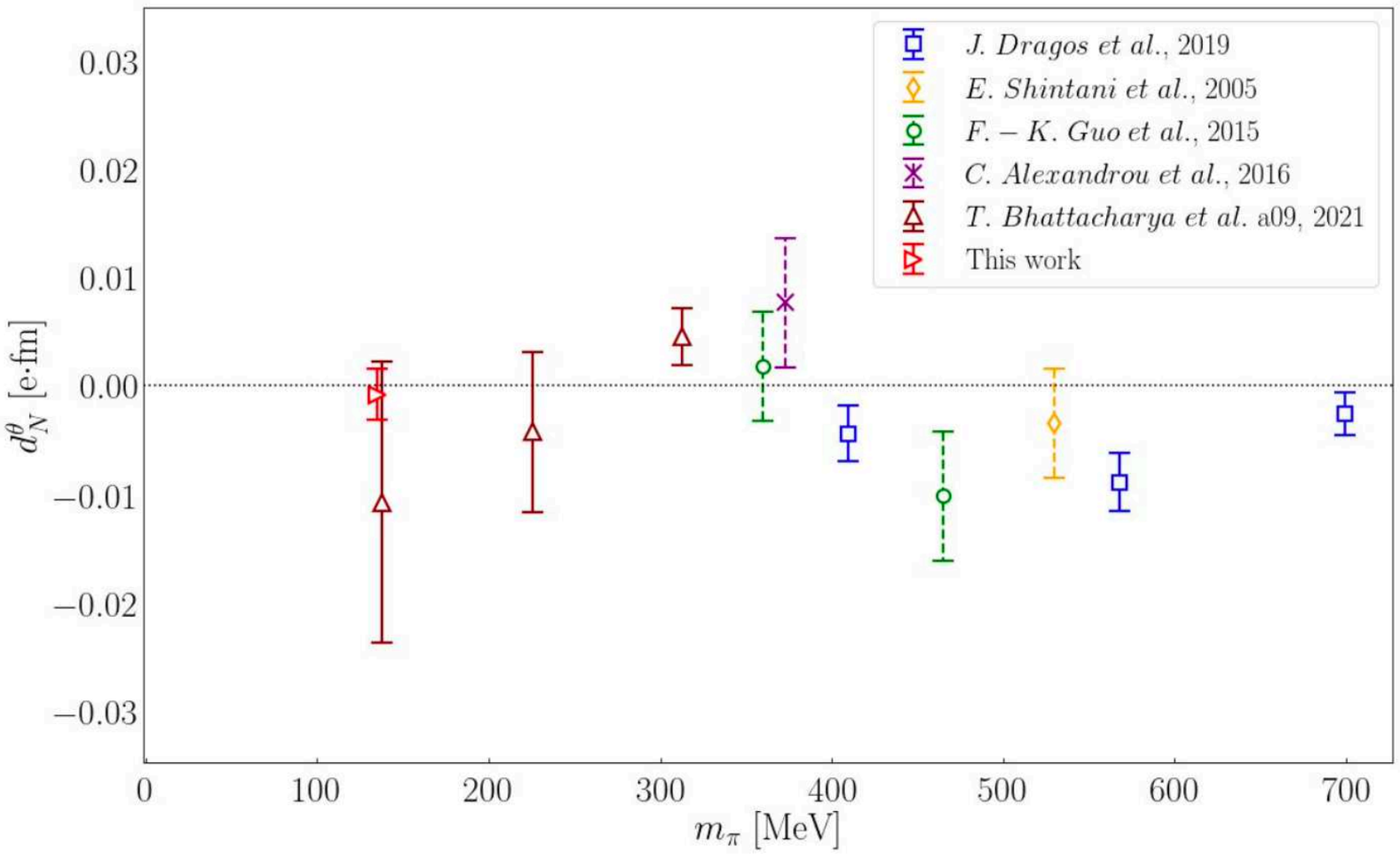
$M_{\text{thr}} = 65$ MeV



	Field Theoretical	Spectral Projectors
$< Q >$	1.2(1.4)	0.46(54)
$< Q^2 >$	254(22)	49.1(4.6)
Pearson Correlation Coefficient		72(2) %

C.A., A. Athenodorou, K. Hadjiyiannakou and A. Todaro, Phys. Rev. D 103, 054501 (2021), arXiv: 2011.01084

Results for nEDM



Chiral & continuum extrapolation

Paper	Neutron EDM
J.Dragos et al. (2019)	-0.00152(71)
T.Bhattacharya et al. (2021)	-0.003(7)(20)
T.Bhattacharya et al. (2021) with Nπ	-0.028(18)(54)
This work	-0.0009(24)

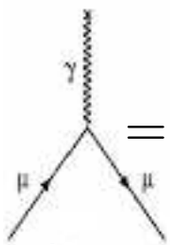
❋Results shown with dashed error bars are corrected by subtracting spurious contribution

Abramczyk et al., Phys. Rev. D 96, 014501 (2017)

❋Need at least two orders of magnitude better precision —> exascale problem

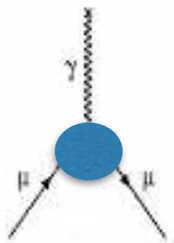
Muon anomalous magnetic moment

- Magnetic moment of e, μ, τ: $\vec{\mu} = g\frac{e}{2m}\vec{S}$
- Dirac equation predicts g=2



$$= -ie\,\bar{u}(p')\gamma_\mu u(p)$$

- Quantum fluctuations change this value:



$$= -ie\,\bar{u}(p')\left[\gamma_\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u(p)$$

$$F_1(0) = 1,\ g = 2 + 2F_2(0)$$

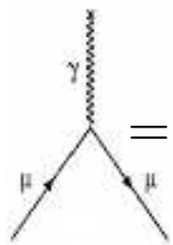
- Anomalous magnetic moment: $a \equiv \frac{g-2}{2} = F_2(0)$

FermiLab

- First measurement at CERN in the 60s and 70s
- 1997-2001 measurement at BNL
- Fermilab measurement 2021 (first run)
- J-PARC 2024+

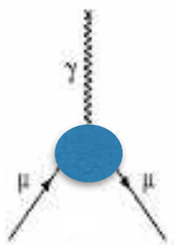
Muon anomalous magnetic moment

- Magnetic moment of e, μ, τ: $\vec{\mu} = g\frac{e}{2m}\vec{S}$
- Dirac equation predicts g=2



$$= -ie\,\bar{u}(p')\gamma_\mu u(p)$$

- Quantum fluctuations change this value:

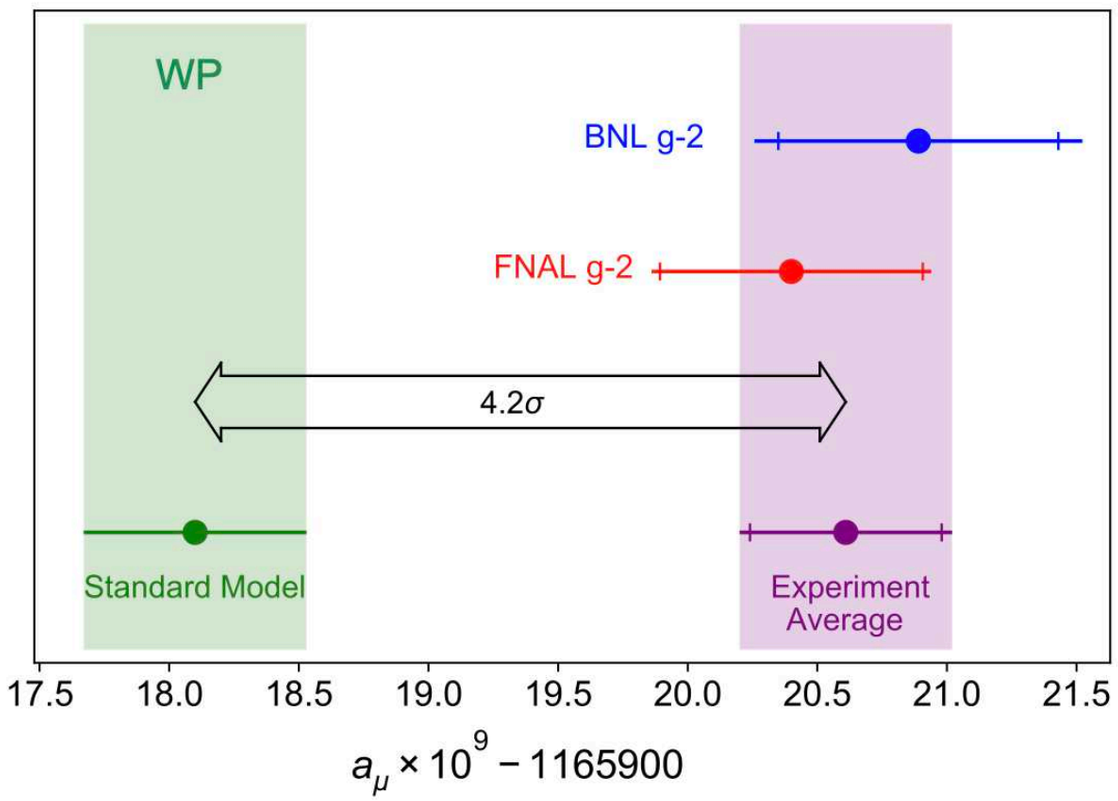


$$= -ie\,\bar{u}(p')\left[\gamma_\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right]u(p)$$

$$F_1(0) = 1,\ g = 2 + 2F_2(0)$$

- Anomalous magnetic moment: $a \equiv \frac{g-2}{2} = F_2(0)$

B. Abi *et al.*, Phys. Rev. Lett. 124, 141801 (2021)



SM contributions to muon g-2

$$a_\mu = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{EW}) + a_\mu(\mathrm{hadronic})$$

❋QED contribution: computed to α^5

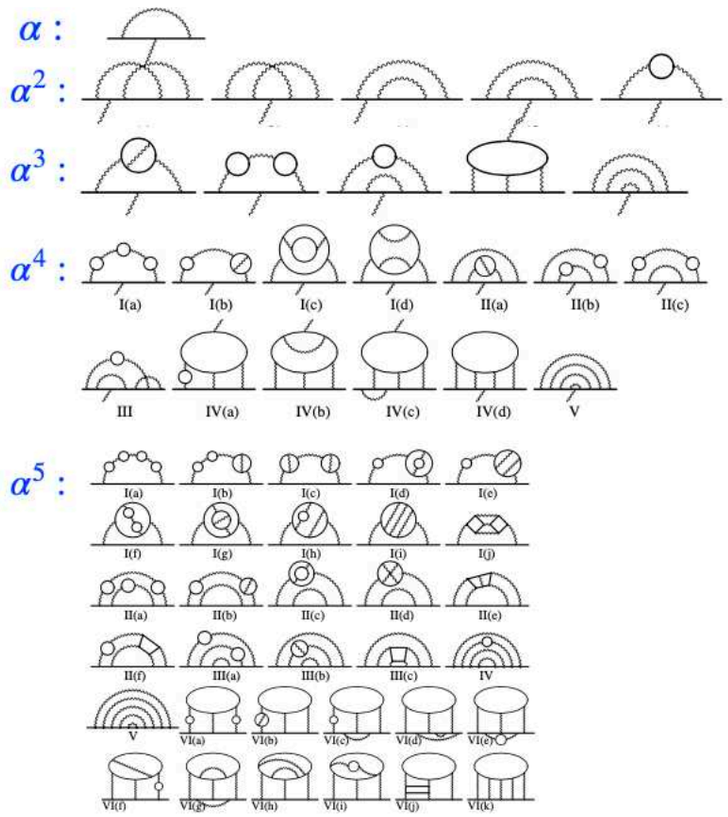
$$a_\mu(\mathrm{QED}) = 116584718.9(1) \times 10^{-11}$$

T. Aoyama et al, arXiv:1205.5370, PRL;
T. Aoyama, T. Kinoshita, M. Nio, Atoms 7 (1) (2019) 28

❋EW contribution: computed to two-loops

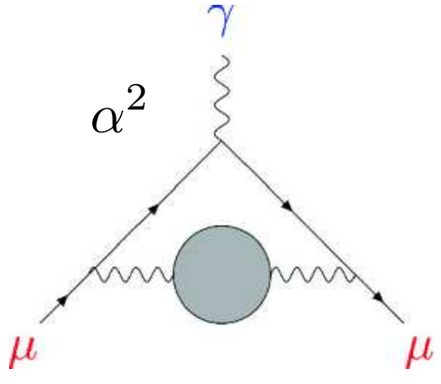
$$a_\mu(\mathrm{EW}) = 153.6(1.0) \times 10^{-11}$$

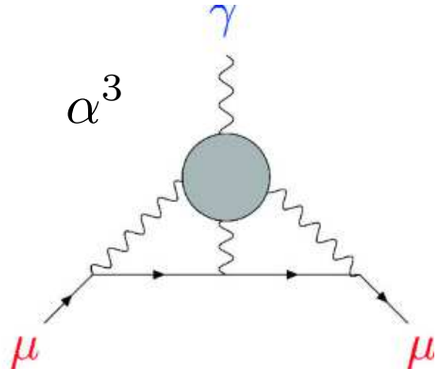
A. Czarnecki et al, hep-ph/0212229, PRD;
C. Gnendinger et al, arXiv:1306.5546, PRD



A. El-Khadra, Lattice 2021

❋Leading hadronic contributions: HVP and HLbL



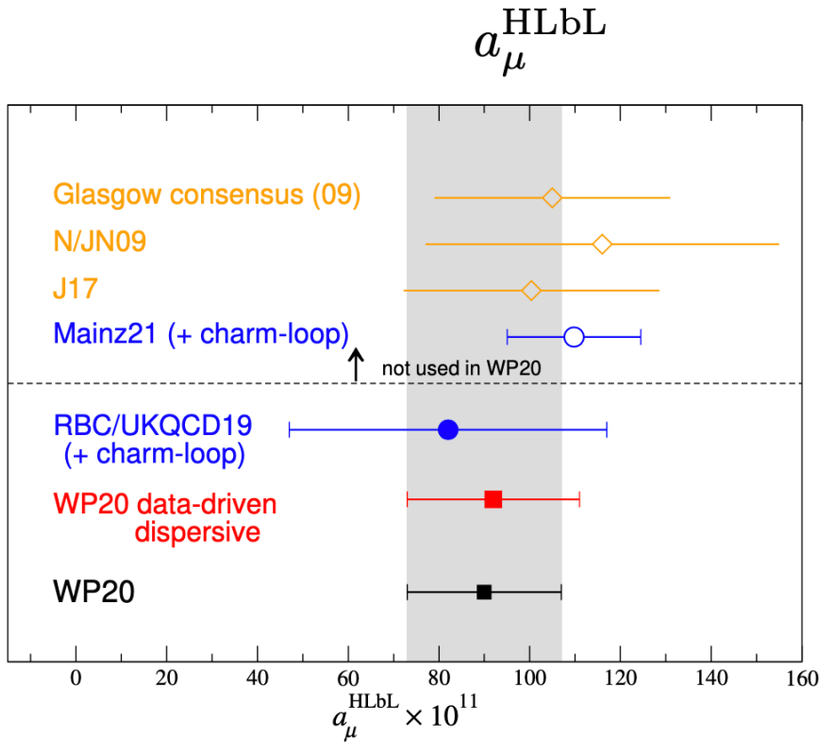


$$a_\mu^{\mathrm{HVP,LO}} = 6931(40) \times 10^{-11} \qquad a_\mu^{\mathrm{HLbL}} = 92(19) \times 10^{-11}$$

White paper, Theory g-2 initiative, Physics Reports 887 (2020)166, arXiv:2006.04822

Hadronic contributions using lattice QCD

✺HLbL computed by two lattice groups

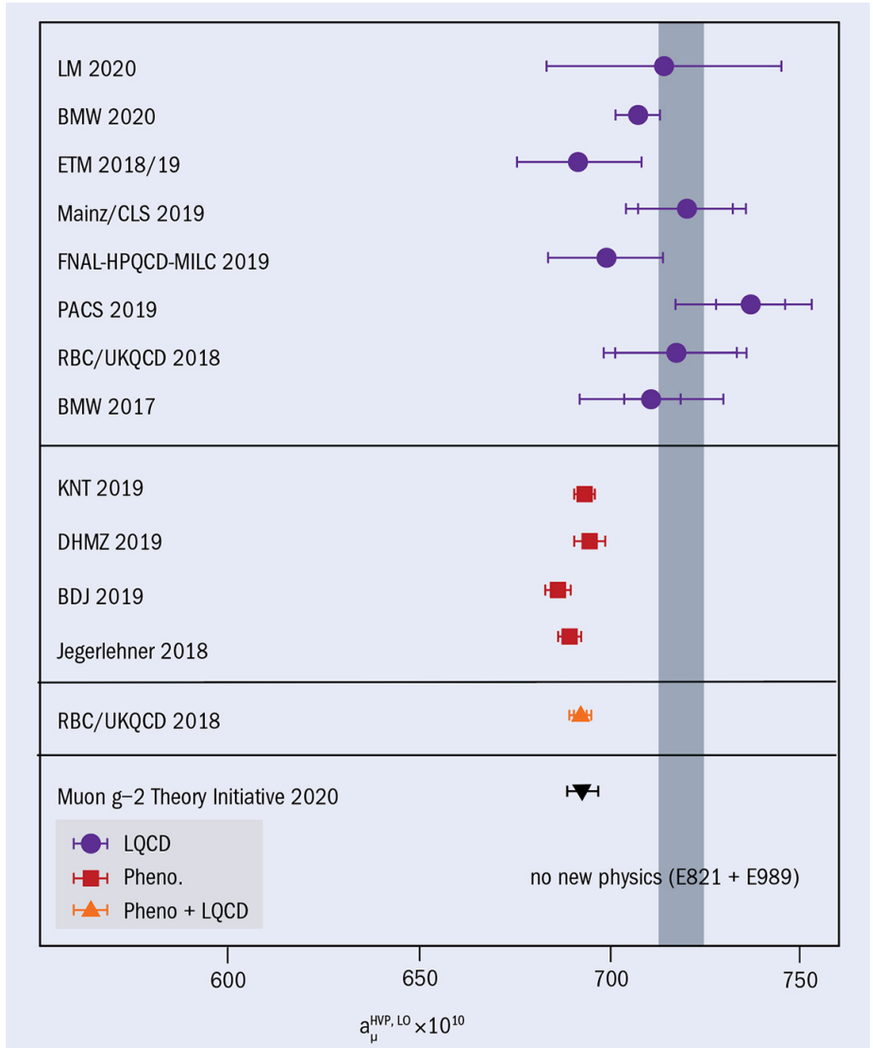


models of QCD +EFT, large N_c

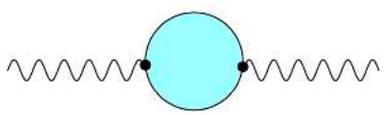
Lattice QCD + QED

data + dispersive approach

A. El-Khadra, Lattice 2021



✺New results on HVP by lattice groups



$$\hat{\Pi}(q^2) \equiv \Pi(q^2) - \Pi(0)$$

$$\Pi_{\mu\nu}(q^2) = \int d^4x\, e^{iqx} \langle j_\mu(x) j_\nu(0) \rangle = (q_\mu q_\nu - q^2 g_{\mu\nu}) \Pi(q^2)$$

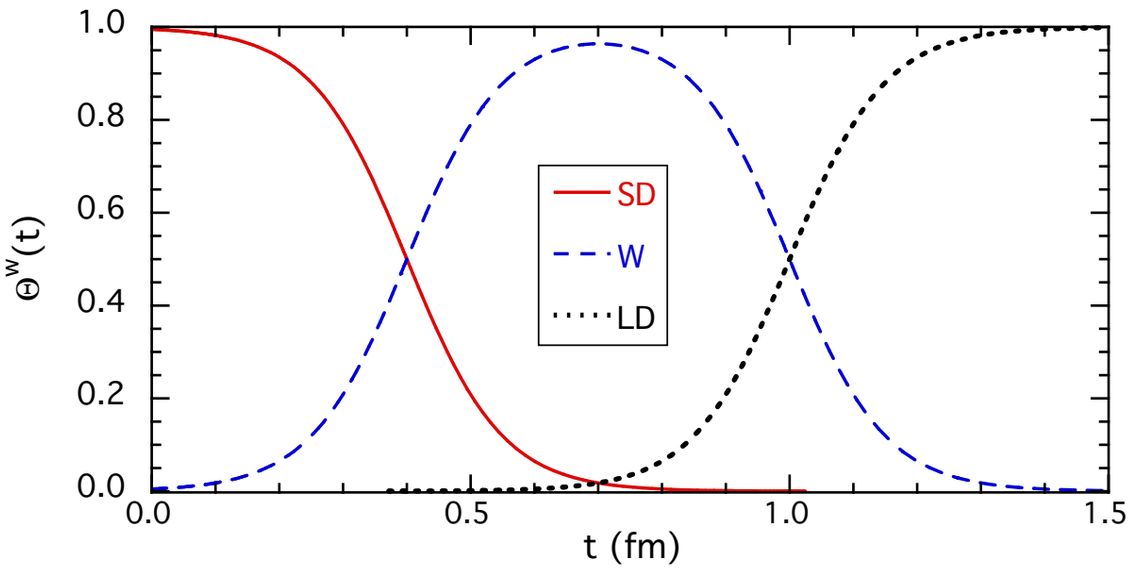
Compute two-point corrector $C(t) = \frac{1}{3} \sum_{i,x} \langle j_i(\vec{x}, t) j_i(\vec{0}, 0) \rangle$ and obtain $a_\mu^{\rm HVP,LO}$ by doing the Euclidean integral

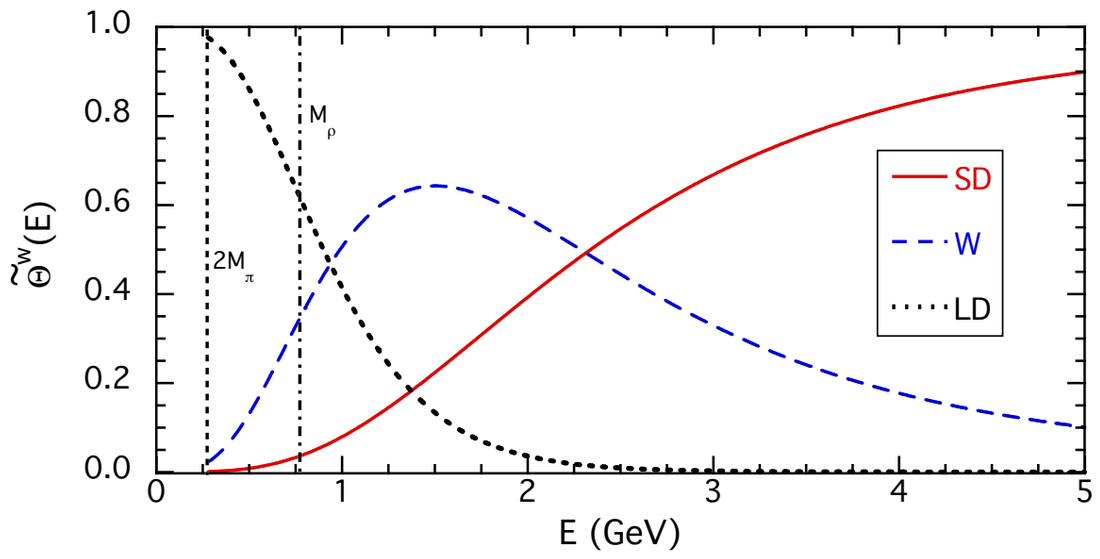
$$a_\mu^{\rm HVP,LO} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, t^2 K(m_\mu t) C(t)$$

Short- and intermediate-distance windows

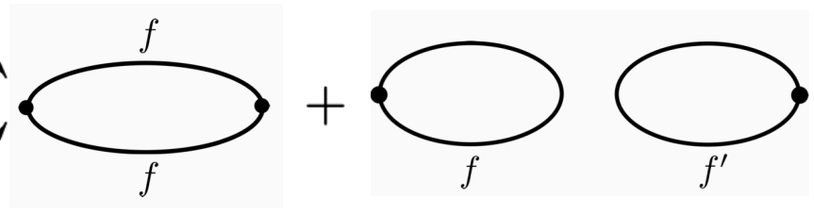
$$a_\mu^{\mathrm{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, t^2 K(m_\mu t) C(t)$$

❋ Consider three-windows as defined by RBC/UKQCD: $a_\mu^{\mathrm{HVP}} = a_\mu^{\mathrm{SD}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{LD}}$





$$a_\mu^{w} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt\, t^2 K(m_\mu t) C(t) \Theta_w(t)$$

$$\sum_f$$ 

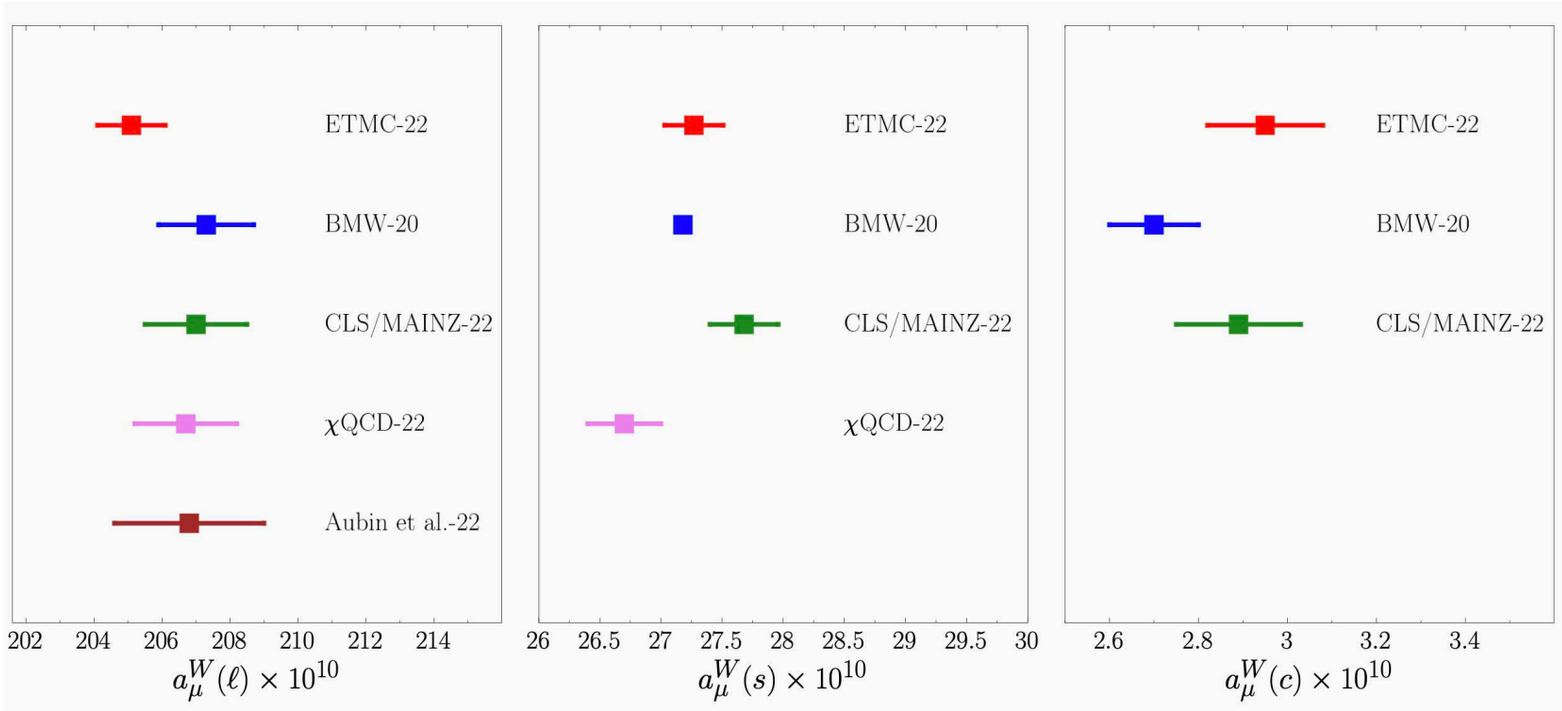
$$f = ud,\ s,\ c$$

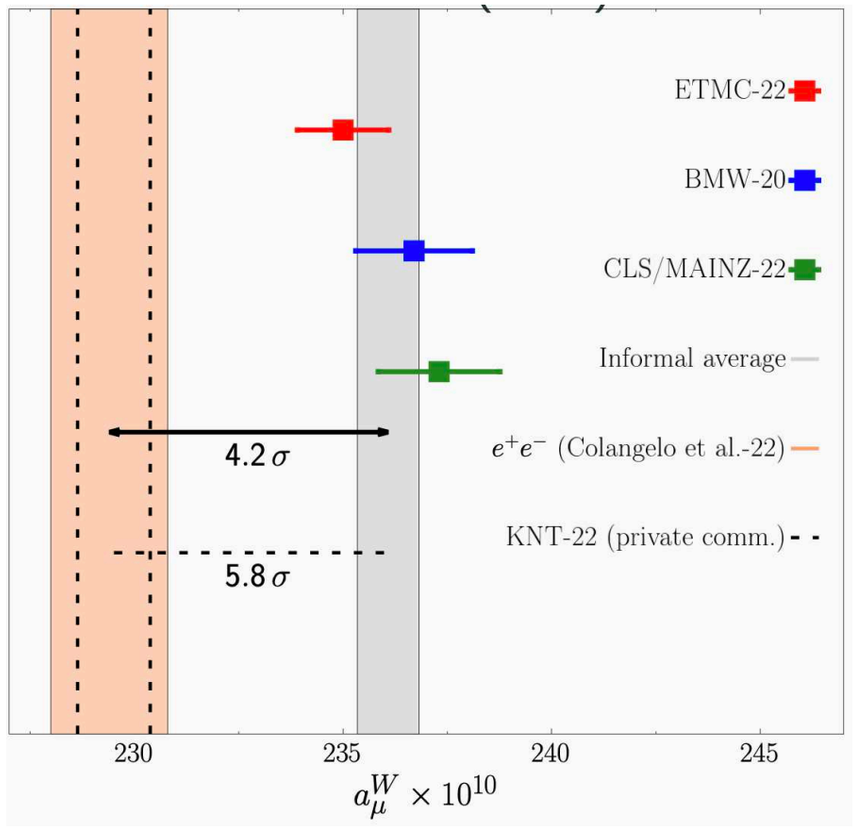
Lattice QCD results in the intermediate window

- ETMC result for $a_\mu^{\rm SD}$ in agreement with dispersive analysis

- All lattice results for $a_\mu^{\rm W}$ in very good agreement, but in tension with dispersive analysis to 4.2σ if we average ETMC, BMW and CLS/Mainz results

Giuseppe Gagliardi, Lattice 2022





—> Deviation of $e^+e^- \rightarrow$ hadrons data w.r.t. the SM in the low and (possibly) intermediate energy regions, but not in the high energy region

Conclusions

- Lattice QCD can yield accurate results with controlled systematics that provide valuable input for searches of new physics such as the nucleon scalar and tensor charges

- Lattice QCD results on the muon anomalous magnetic moment in the intermediate region are all in agreement but in tension with those from the dispersive analyses

- Lattice QCD is only producing results on Mellin moments, generalised parton distributions, transverse momentum distributions, semi-leptonic decays, etc.

Extended Twisted Mass Collaboration