CP Violation and the Neutron Electric Dipole Moment from Lattice QCD

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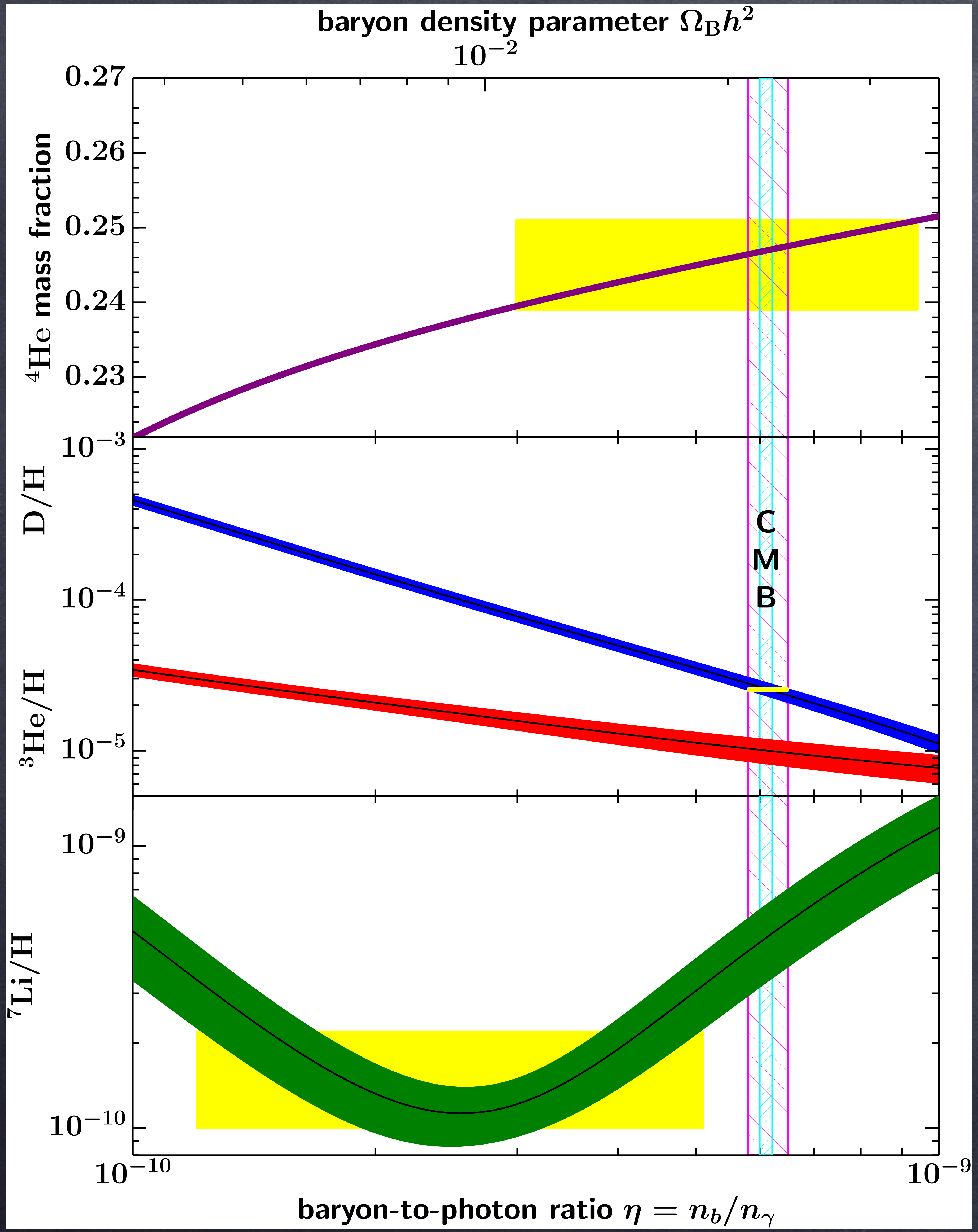
U.S. DEPARTMENT OF ENERGY Office of Science

EPS - HEP July, 7 2025

Matter antimatter asymmetry



PDG 2021

$$\eta = \frac{n_B}{n_\gamma} \qquad n_B = n_b - n_{\bar{b}} \qquad \eta = \frac{\text{(matter) - (antimatter)}}{\text{relic photons}}$$

$$\eta = (6.143 \pm 0.190) \times 10^{-10}$$ Concordance range

$$\Omega_b = \frac{\rho_b}{\rho_{\text{crit}}} \simeq \eta h^{-2}/274 \times 10^{10} = 0.02244 \pm 0.00069\ h^{-2}$$

$$\Omega_b h^2 = 0.02230 \pm 0.00021 \Rightarrow \eta = (6.104 \pm 0.058) \times 10^{-10}$$ PLANCK

Fields, Olive, Yeh, Young: 2020

$$\eta_{SM} \sim 10^{-26}$$

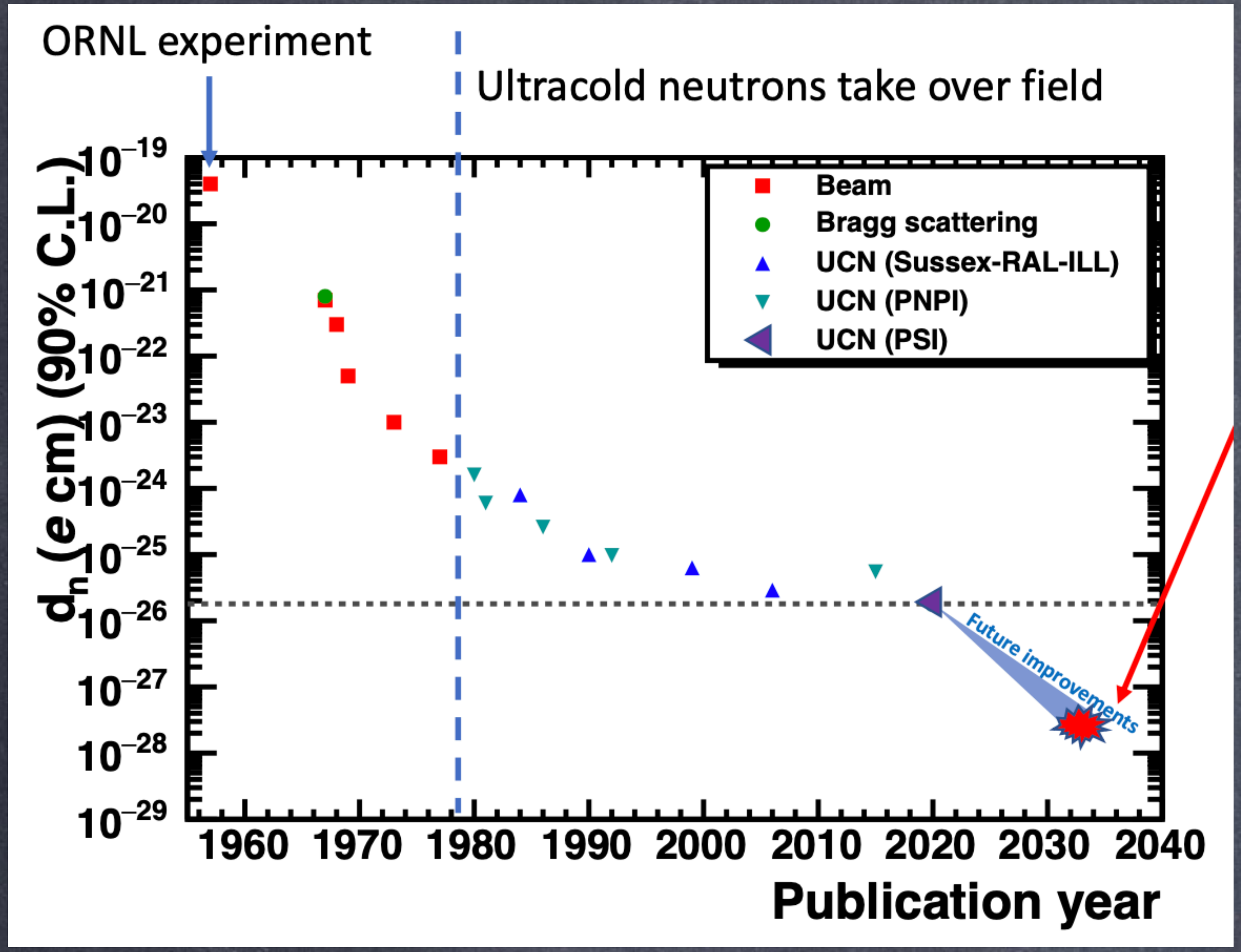
Gavela, Hernandez, Orloff, Pene: 1994

Huet, Sather: 1995

Rules out any mechanism of electroweak baryogenesis that does not make use of a new source of CP violation.

New source of CP violation

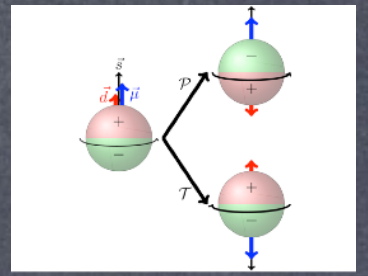
Neutron EDM

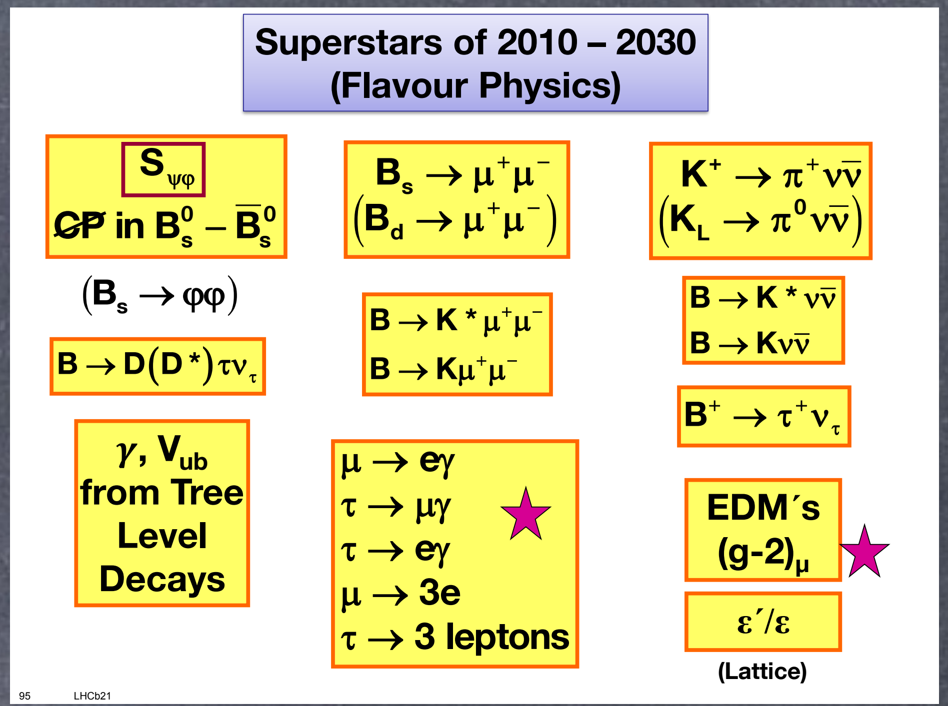


$$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}\ (90\%\ \mathrm{C.L.})$$

Abel et al.: 2020 (PSI)

$$H = -\mu\, \underline{B} \cdot \frac{S}{|S|} - d\, \underline{E} \cdot \frac{S}{|S|}$$





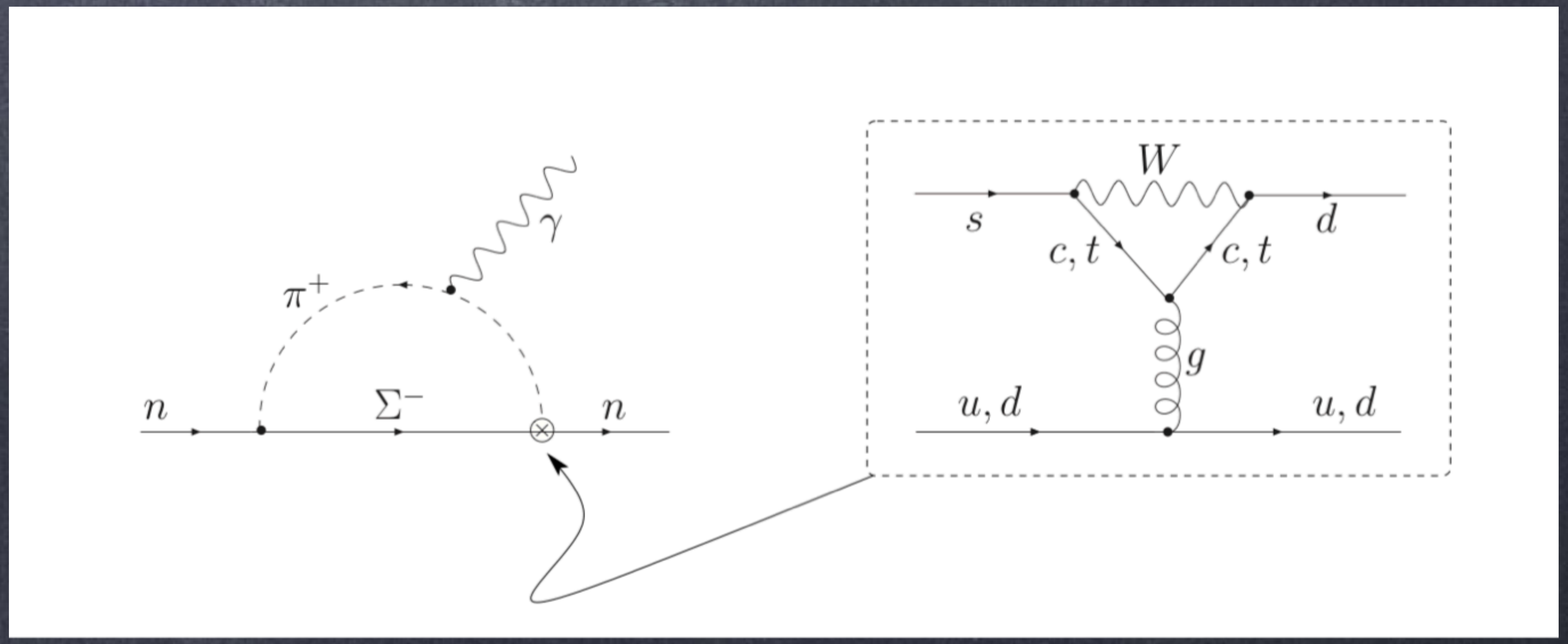
Alarcon et al.: 2022
Snowmass Summer Study Report

Buras: LHCb21

$$(d_n)_{\mathrm{SM}} = (1-6) \times 10^{-32} e\ \ \mathrm{cm}$$

Shabalin: 1978-1980 Khriplovich, Zhitnitsky: 1982
Gavela et al. : 1982 Seng: 2015

Experiment: Facility	Neutron Source	Measurement Cell	Measurement Techniques	90% C.L. (10^{-28} e-cm) With 300 Live Days	Year 90% C.L. Data Acquired
Crystal: JPARC	Cold Neutron Beam	Solid	Crystal Diffraction (High Internal $\vec{E}$)	< 100	Development
Beam: ESS	Cold Neutron Beam	Vacuum	Pulsed Beam	< 50	~ 2030
PNPI: ILL	ILL Turbine (UCN) PNPI/LHe (UCN)	Vacuum	Ramsey Technique, $\vec{E} = 0$ Cell for Magnetometry	Phase 1 < 100 < 10	Development Development
n2EDM: PSI	Solid D_2 (UCN)	Vacuum	Ramsey Technique, External Cs Magnetometers, Hg Co-Magnetometer	< 15	~ 2026
PanEDM ILL/Munich	Superfluid ^{4}He (UCN), Solid D_2 (UCN)	Vacuum	Ramsey Technique, Hg Co-External ^{3}He and Cs Magnetometers	< 30	~ 2026
TUCAN: TRIUMF	Superfluid ^{4}He (UCN)	Vacuum	Ramsey Technique, Hg Co-Magnetometer, External Cs Magnetometers	< 20	~ 2027
nEDM: LANL	Solid D_2 (UCN)	Vacuum	Ramsey Technique, Hg Co-Magnetometer, Hg External Magnetometer, OPM	< 30	~ 2026
nEDM@SNS: [illegible]	Superfluid ^{4}He (UCN)	^{4}He	Cryogenic High Voltage, ^{3}He [illegible] with SQUIDs, Dressed Spins, Superconducting Magnetic Shield	< 20 [illegible]	2029 [illegible]



CP-violating sources

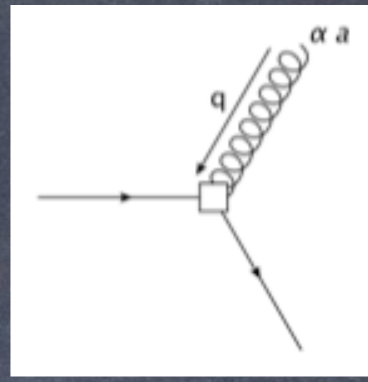
- Full list of dimension 5 and 6 operators is known

Buchmuller, Wyler: 1986
de Rujula et al.: 1991
Grzadkowski et al: 2010

$$O_{\mathrm{q}}^f(x) = \overline{\psi}_f(x)\gamma_5\sigma_{\mu\nu}\psi_f(x)F_{\mu\nu}$$

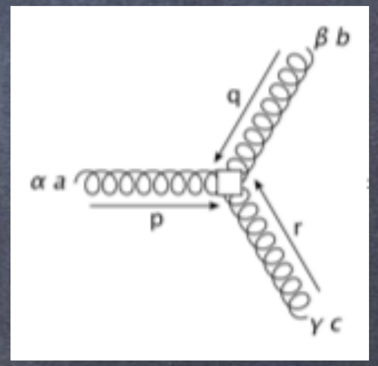
Quark EDM

$$O_{\mathrm{CE}}^f(x) = \overline{\psi}_f(x)\gamma_5\sigma_{\mu\nu}G^a_{\mu\nu}T^a\psi_f(x)$$



Quark-chromo EDM

$$O_{3\mathrm{g}}(x) = \frac{1}{6} i f^{abc} G^a_{\mu\rho}(x) G^b_{\nu\rho}(x) G^c_{\lambda\sigma}(x)\epsilon_{\mu\nu\lambda\sigma}$$



3-gluon CP-odd

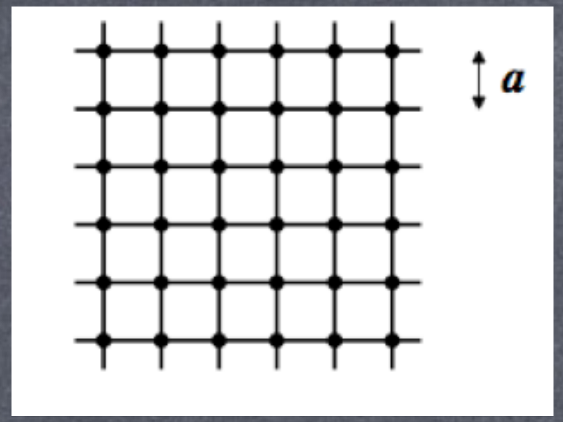
Weinberg: 1989

$$q(x) = \frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{tr}\left\{G_{\mu\nu}(x)G_{\rho\sigma}(x)\right\}$$

Topological charge density

$$\mathcal{L}_{\mathrm{QCD}+\theta} = \frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu} + \sum_{f=u,d,s,\ldots} \overline{\psi}_f(x)\left\{\gamma_\mu\left[\partial_\mu + gA^a_\mu T^a\right] + m_f\right\}\psi_f(x) - i\bar{\theta}q(x)$$

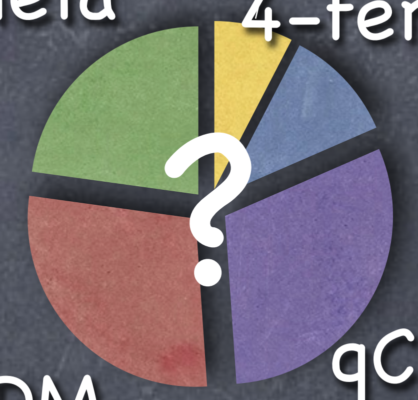
The role of lattice QCD



$$d_{\mathrm{N}} = M_{\mathrm{N}}^{\theta}\bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_i M_{\mathrm{N}}^{(i)}\tilde{d}_i \qquad \langle N|J_\mu \mathcal{O}_{\not{CP}}|N\rangle \to d\, \underline{E}\cdot\underline{S}$$

M_{N}^{θ} → Hadronic matrix element topological charge

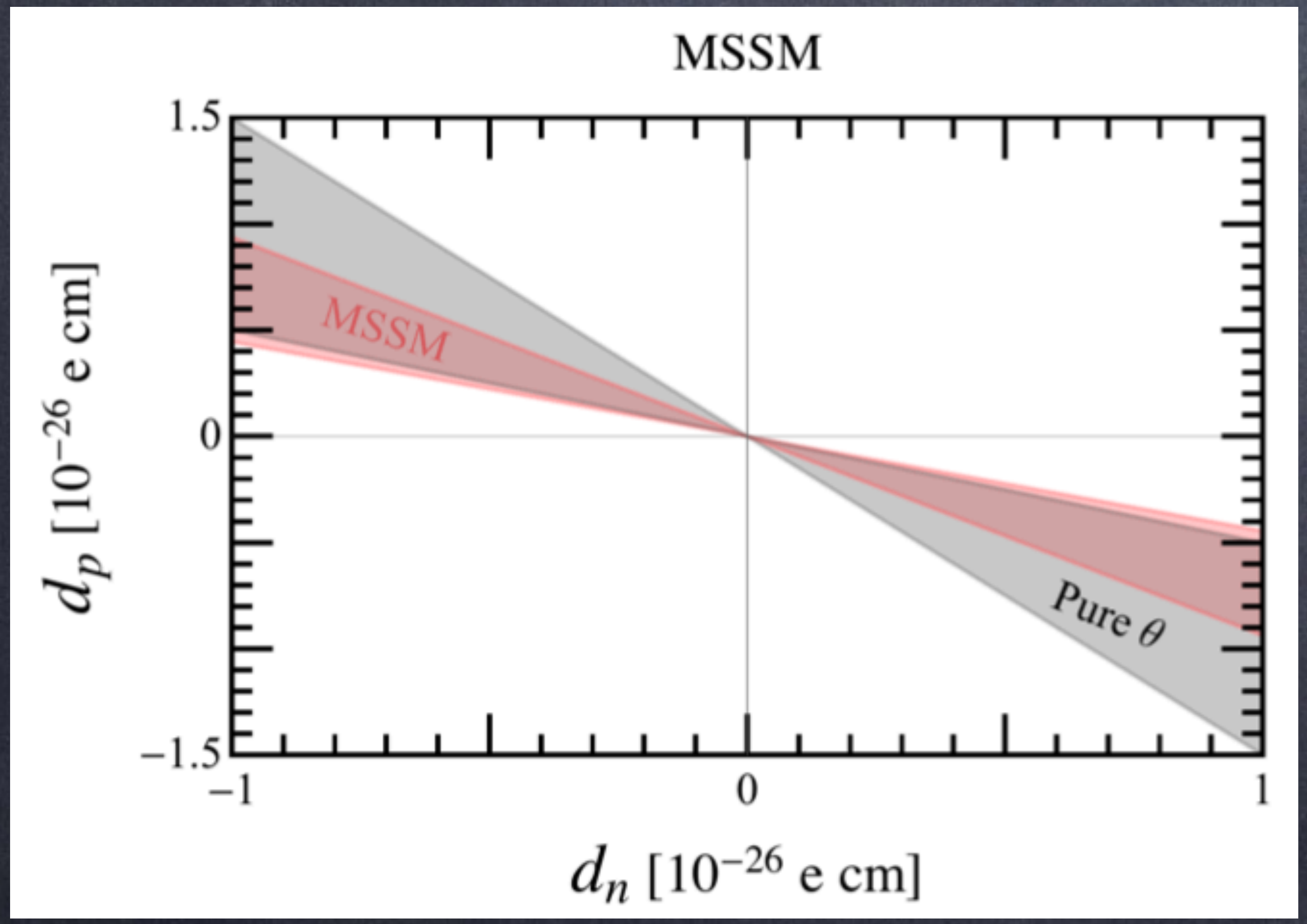
$M_{\mathrm{N}}^{(i)}$ → Hadronic matrix element CP odd operators



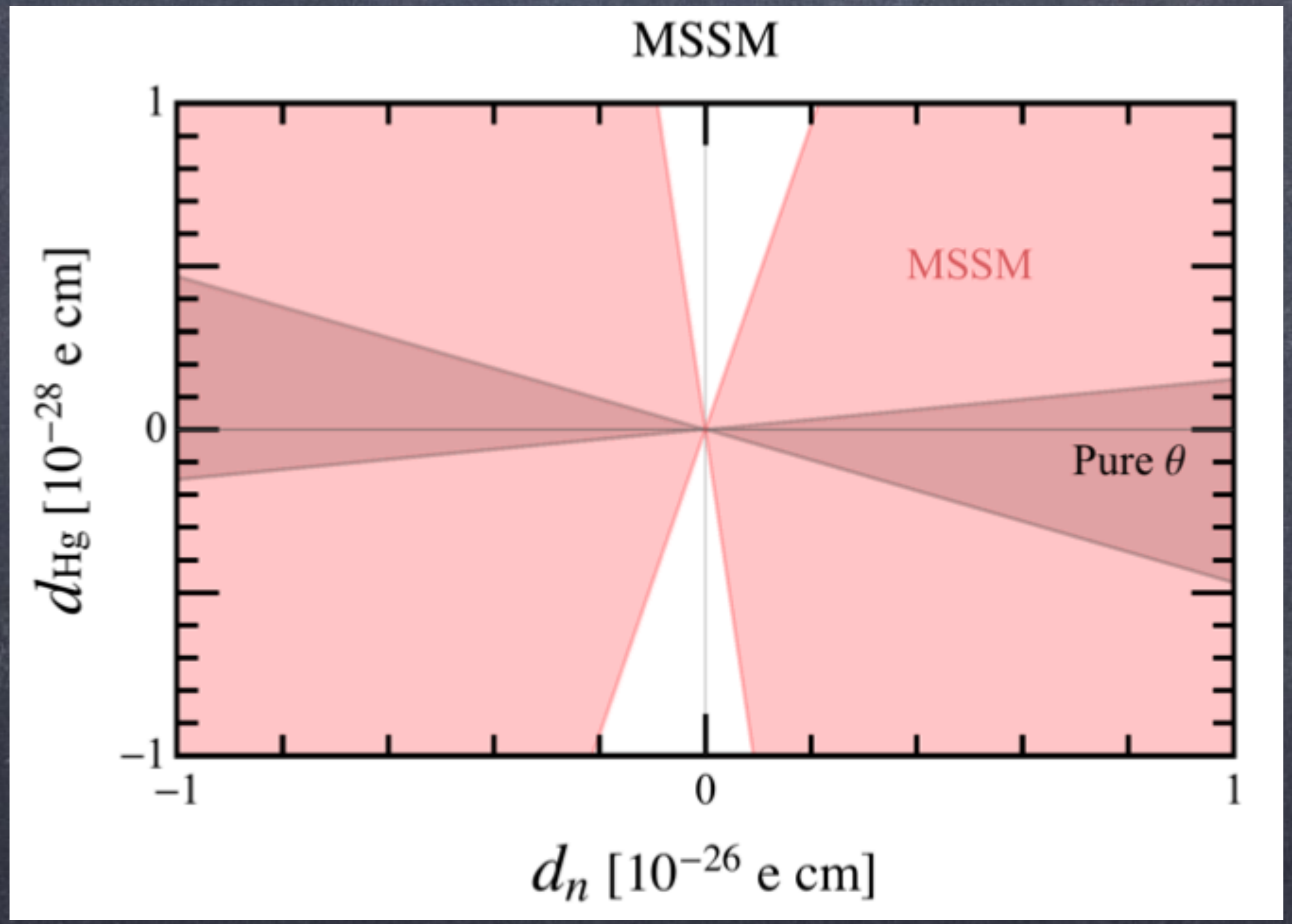
$$\begin{aligned} d_n = & -(1.5 \pm 0.7)\cdot 10^{-3}\bar{\theta} e\ \mathrm{fm} \\ & -(0.2 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) d_s \\ & -(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d + (50 \pm 40)\mathrm{MeV} e\tilde{d}_G \end{aligned}$$

Dragos, Luu, A.S., de Vries, Yousif: 2019

Shintani et al.: 2005
Berruto, Blum, Orginos, Soni 2006
A.S., Luu, de Vries: 2014-2015
Guo, Meißner, et al. : 2010-
Liang, Draper, Liu, Yang
Alexandrou et al. (ETMC): 2015-2020
Abramczyk et al. : 2017-
Dragos, Kim, Luu, Monahan, Rizik, A.S., de Vries, Yousif: 2015-2021
Yoon, Bhattacharya, Cirigliano, Gupta, Mereghetti: 2015-2021



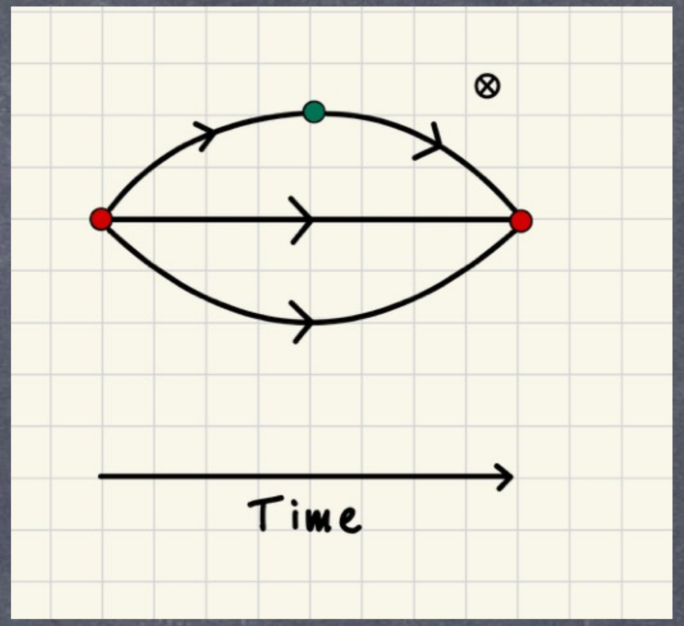
de Vries et al.: 2021

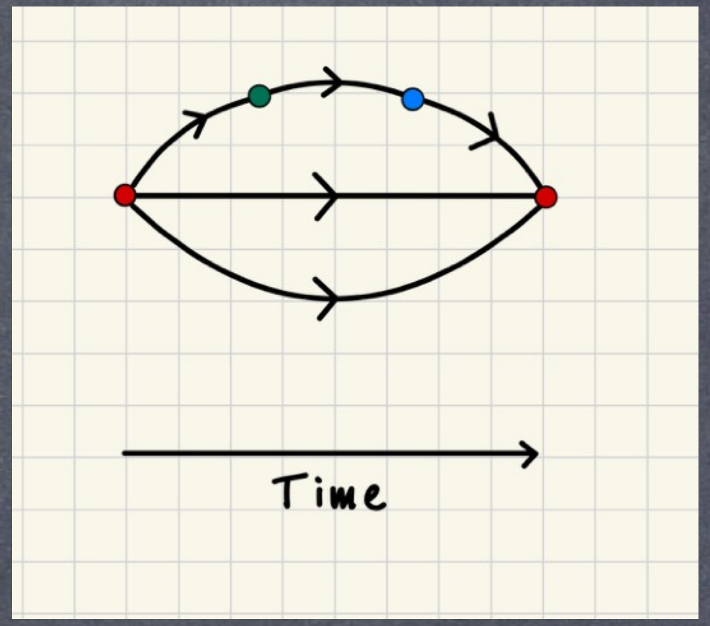


Alarcon et al.: 2022
Snowmass Summer Study Report

How to calculate nEDM

$$\langle N J_\mu^{\rm em} \overline{N} \rangle_{C\!\!\!/P\!\!\!/} \simeq \langle N J_\mu^{\rm em} O_{C\!\!\!/P\!\!\!/} \overline{N} \rangle_{\rm QCD} \quad \Rightarrow \quad \langle N(p_1) | J_\mu^{\rm em} | N(p_2) \rangle_{C\!\!\!/P\!\!\!/}$$





$$\langle N(p_1) | J_\mu^{\rm em} | N(p_2) \rangle_{C\!\!\!/P\!\!\!/} = \overline{u}_N(p_1) \Gamma_\mu^{C\!\!\!/P\!\!\!/}(Q^2) u_N(p_2)$$

$$\Gamma_\mu^{C\!\!\!/P\!\!\!/}(Q^2) \simeq F_1(q^2)\gamma_\mu + \frac{i}{2M_N} F_2(q^2)\sigma_{\mu\nu}q_\nu + i\bar{d}_{C\!\!\!/P\!\!\!/} \frac{1}{2M_N} F_3(q^2)\sigma_{\mu\nu}\gamma_5 q_\nu \qquad |d_N| = F_3(0)/2M_N \qquad q = p_1 - p_2$$

Challenges on the lattice

- Renormalization of $O_{C\!\!\!/P\!\!\!/}$ and continuum limit a -> 0
- Excited states contaminations $\sum_i a_i \, e^{-m_i x_4} \qquad E_0 < E_1 < \cdots$
- Signal-to-noise ratio

Gradient flow

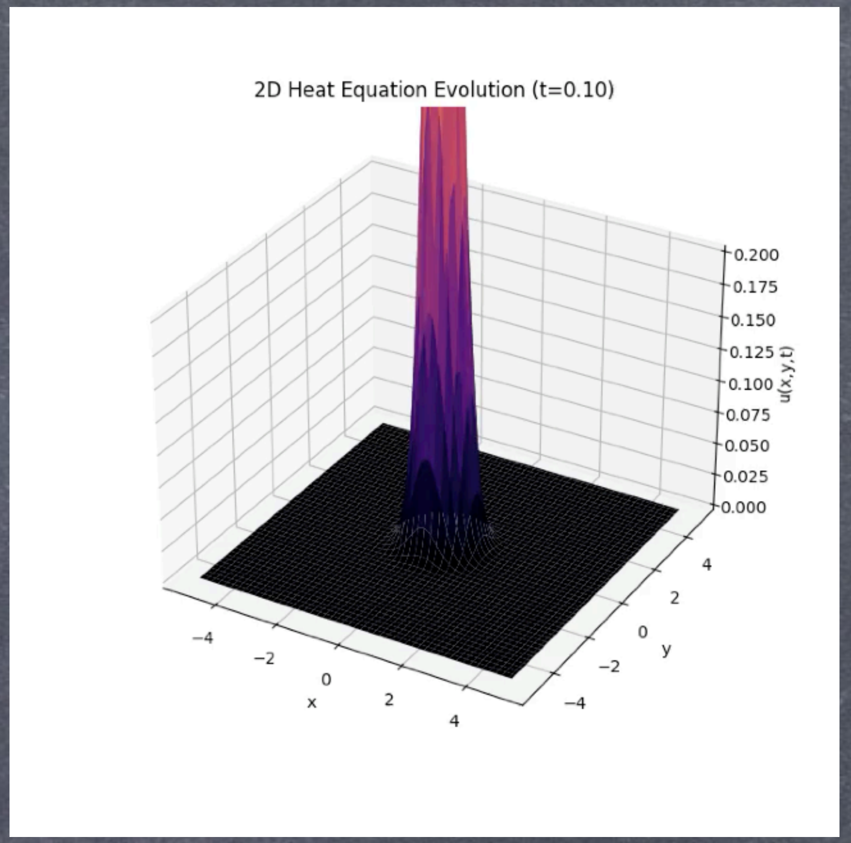
Narayanan, Neuberger:2006

Lüscher 2010
Lüscher, Weisz 2011

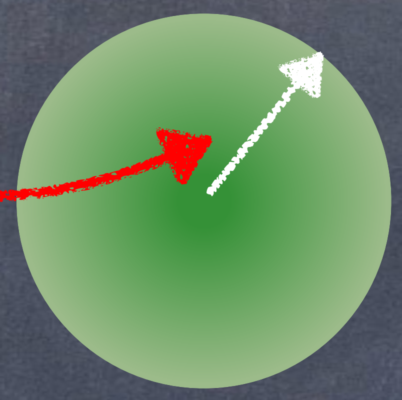
$x_\mu = (\mathbf{x}, x_4) \quad t \to \text{flow-time} \quad [t] = -2$

$A_\mu(x) \to B_\mu(t,x)$

$\psi(x) \to \chi(t,x)$



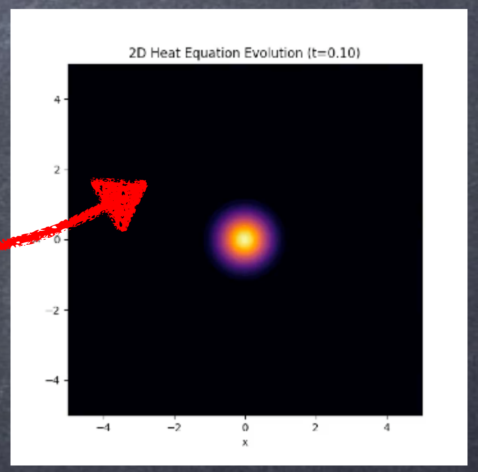
- Renormalizable smoothing for local fields
- Smoothing at short distance $\sqrt{8t}$



- Gaussian damping at large momenta
- Flowed gauge fields are finite

Lüscher: 2010
Lüscher, Weisz: 2011

$\sqrt{8t}$



- Renormalization of fermion operator multiplicative and "universal"

Lüscher: 2013

$$\mathring{\chi}(t,x) \propto \frac{\chi(t,x)}{\sqrt{t^2 \left\langle \overline{\chi}(t,x) \overleftrightarrow{\not{D}} \chi(t,x) \right\rangle}}$$

Makino, Suzuki: 2014

What is OpenLat

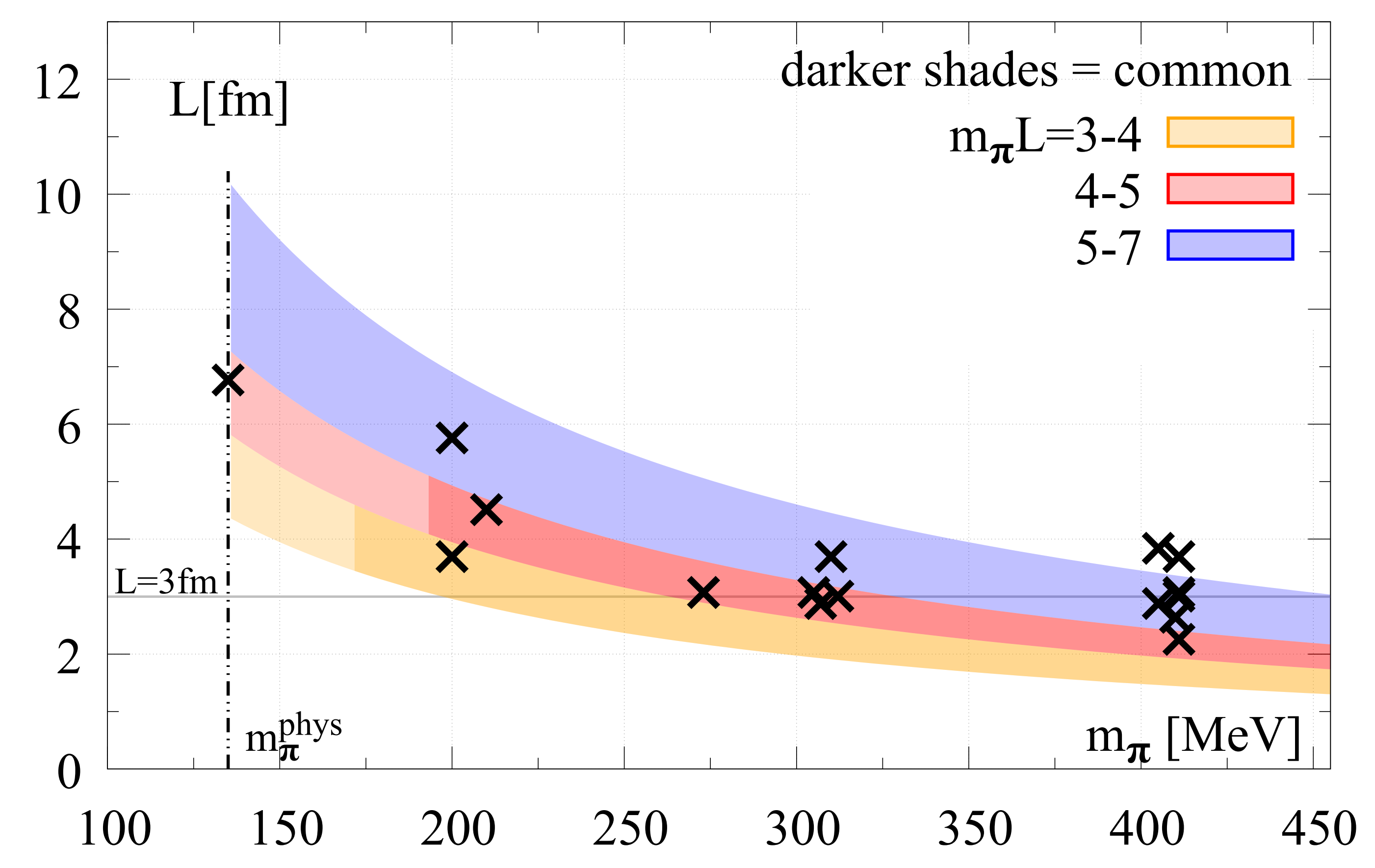
OPEN LATtice initiative

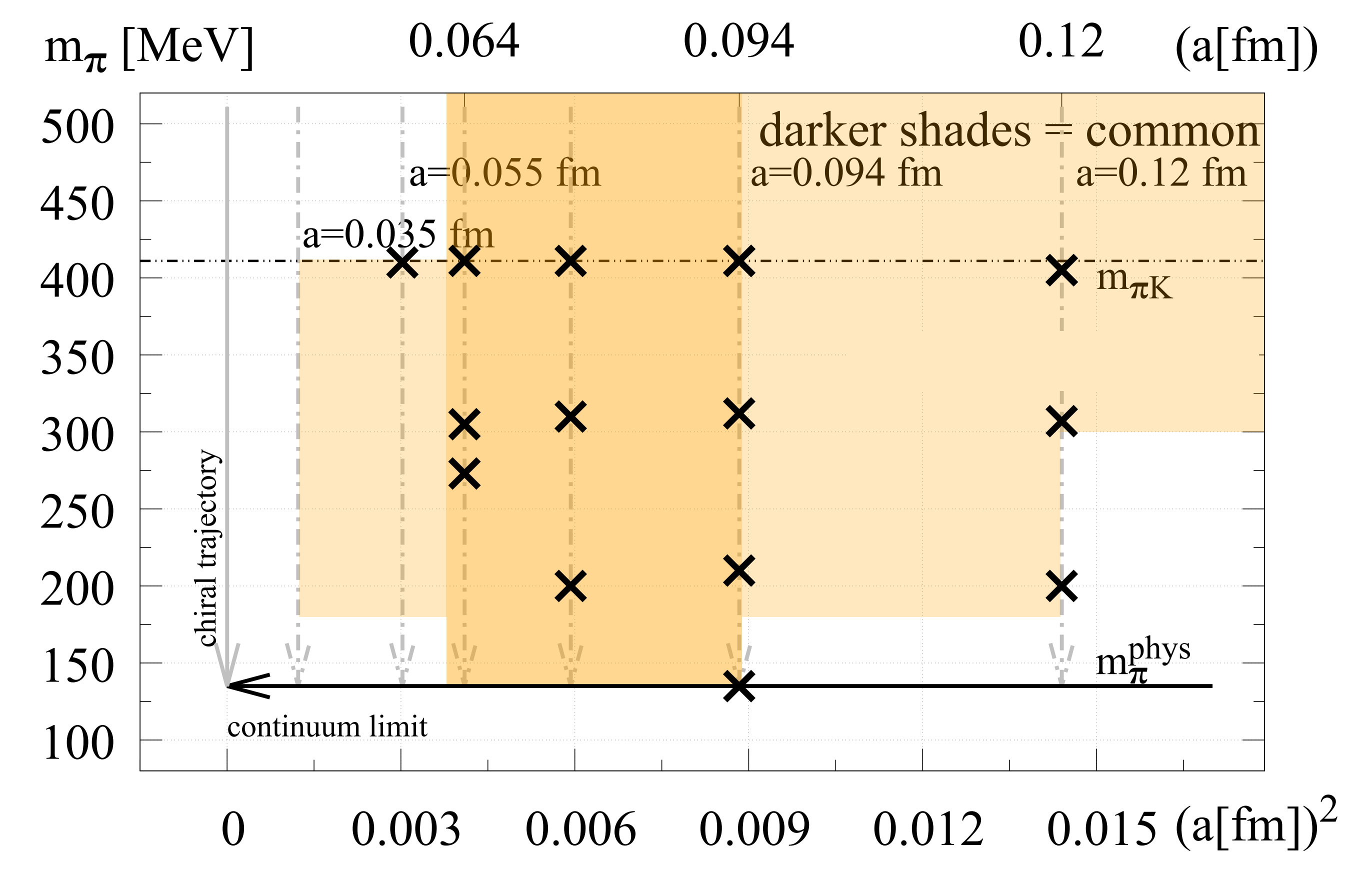
https://openlat1.gitlab.io

- OpenLat provides open access to cutting-edge (2+1)-flavor QCD gauge field ensembles, enabling the study of strong interaction phenomena with state-of-the-art simulations.
- The initiative bridges the gap for researchers without access to large-scale collaborations, fostering innovation and inclusivity in lattice QCD.
- Strategic choice of stabilized Wilson fermion framework for precision and stability in QCD simulations.

OpenLat: Current Status & Key Research Projects

OpenLat has made significant progress in producing and sharing high-quality lattice QCD ensembles.
Our two main research projects focus on precision studies of the thetaEDM parameter and advancements in lattice PDF calculations.





Project	Main Goal	Progress
EDM	Improve constraints on CP-violating effects in strong interactions (SM & BSM)	New lattice ensembles generated; analysis ongoing.
PDF	Develop new lattice techniques for parton distribution function (PDF) determination	Implementation of flowmom method; preliminary results obtained
Multi-hadron interactions		
Flavor physics		

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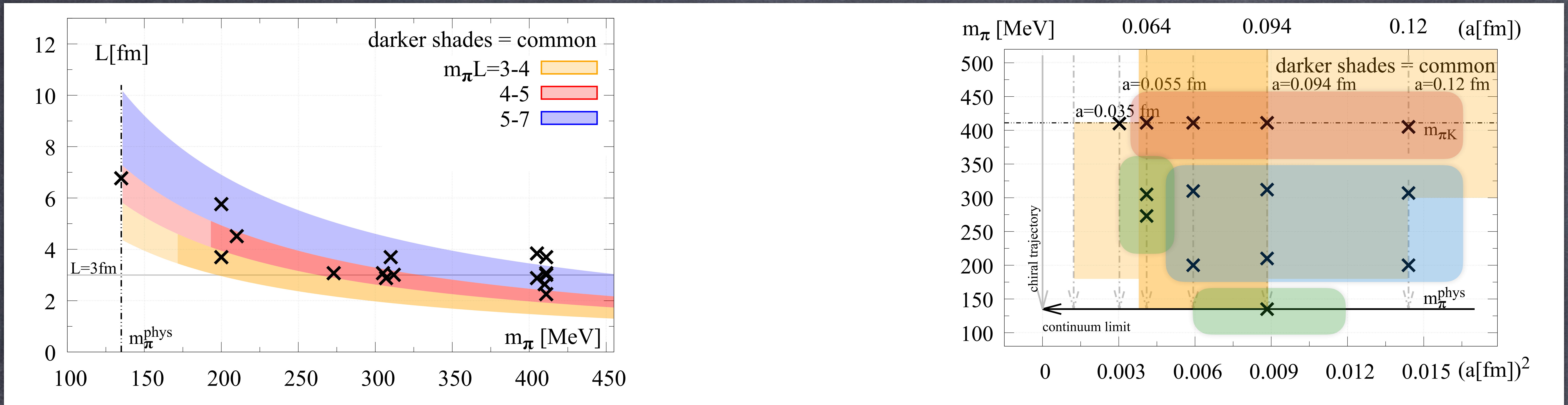

Stage 1

Stage 2 WORK IN PROGRESS

Stage 3 WORK IN PROGRESS

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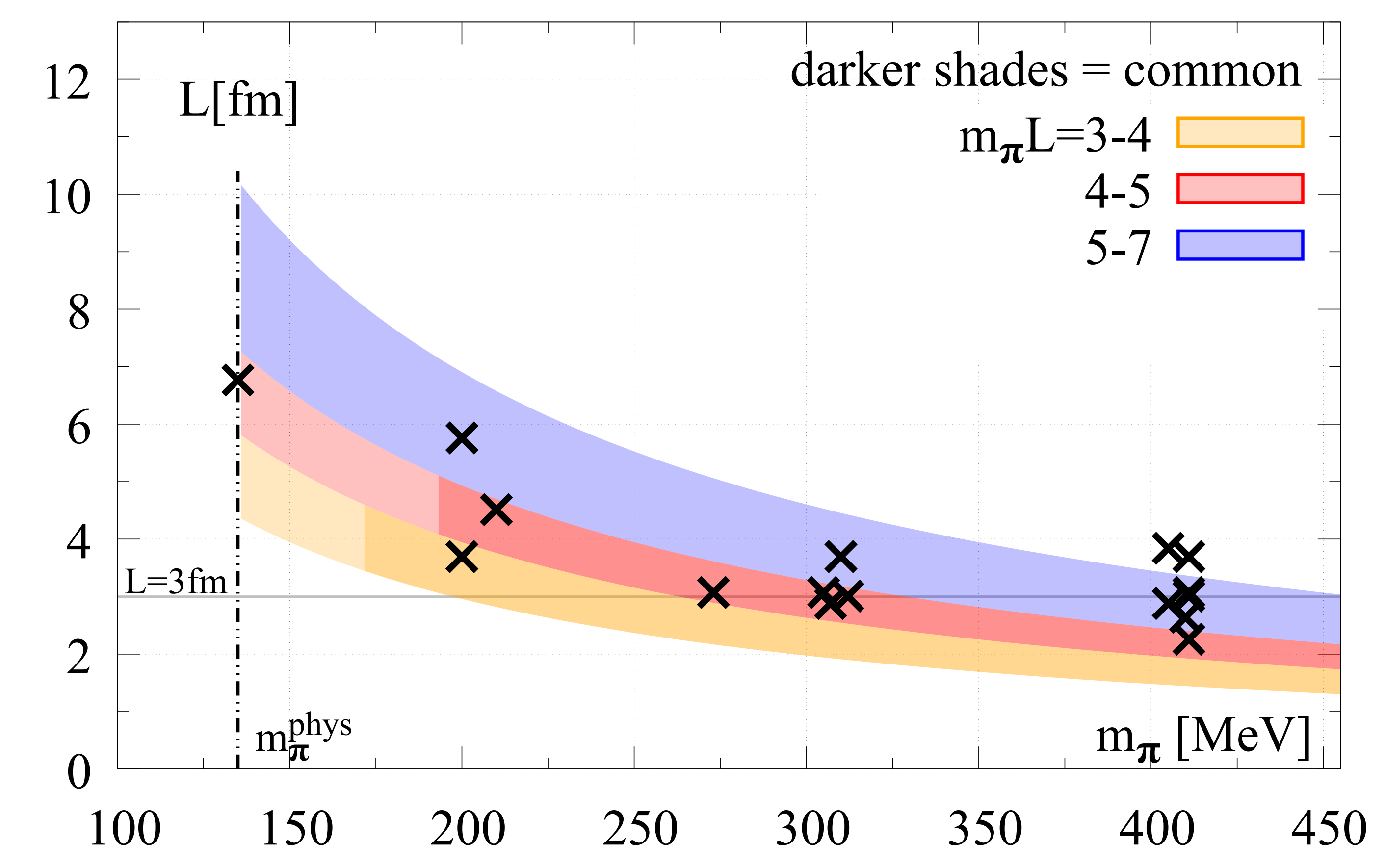
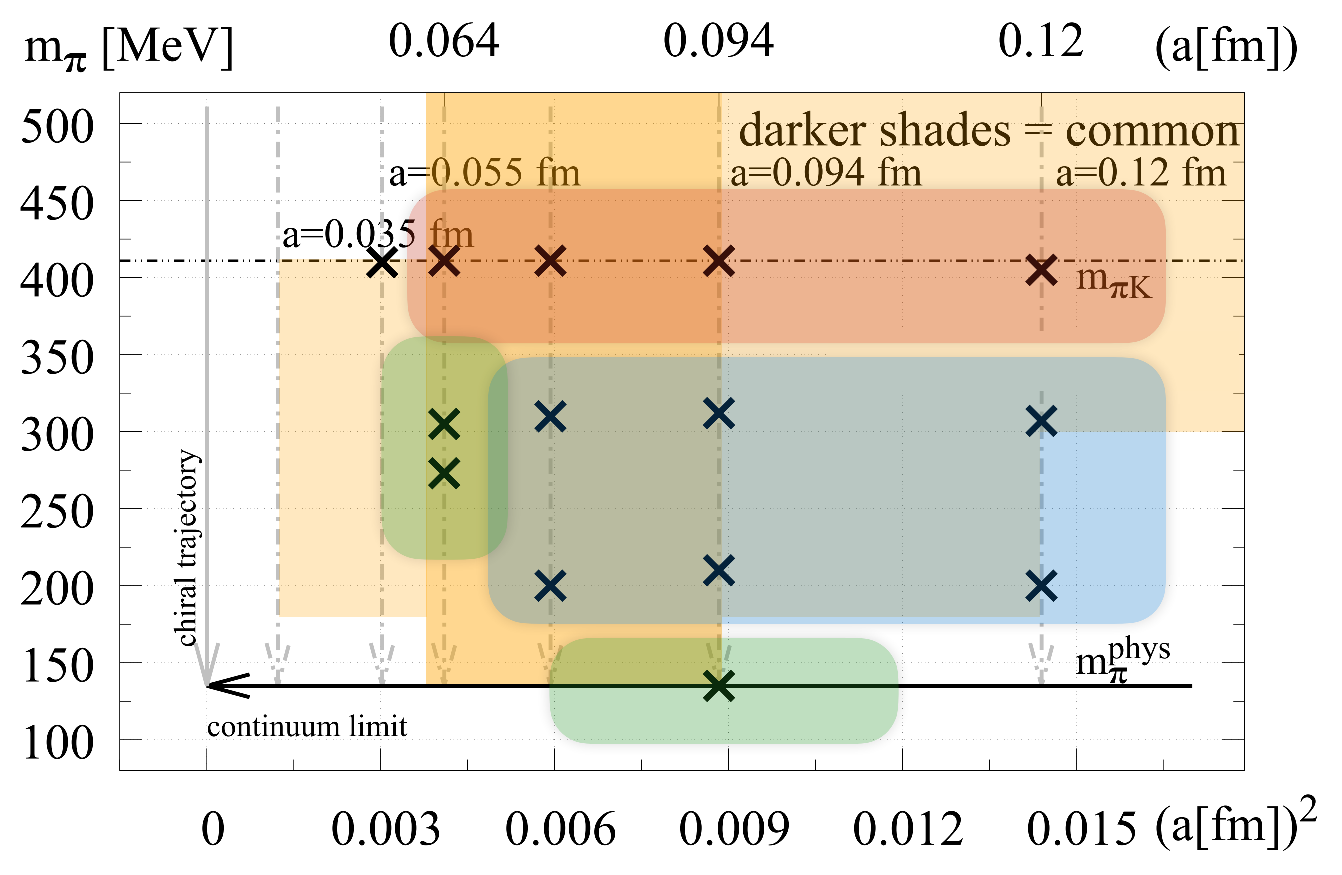




Stage 1 ✅

Stage 2 WORK IN PROGRESS

Stage 3 WORK IN PROGRESS

Perlmutter (NERSC)

JUWELS (FZJ)

Irene Joliot-Curie

PRACE
EuroHPC
Gauss

Gradient flow and topological charge

Lüscher: 2010

$$Q(t) = \int d^4x \; q(x,t) \qquad q(x,t) = \frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{Tr}\left\{G_{\mu\nu}(x,t)G_{\rho\sigma}(x,t)\right\}$$

$$\delta B_\mu(x,t) = \partial_t B_\mu \delta t$$

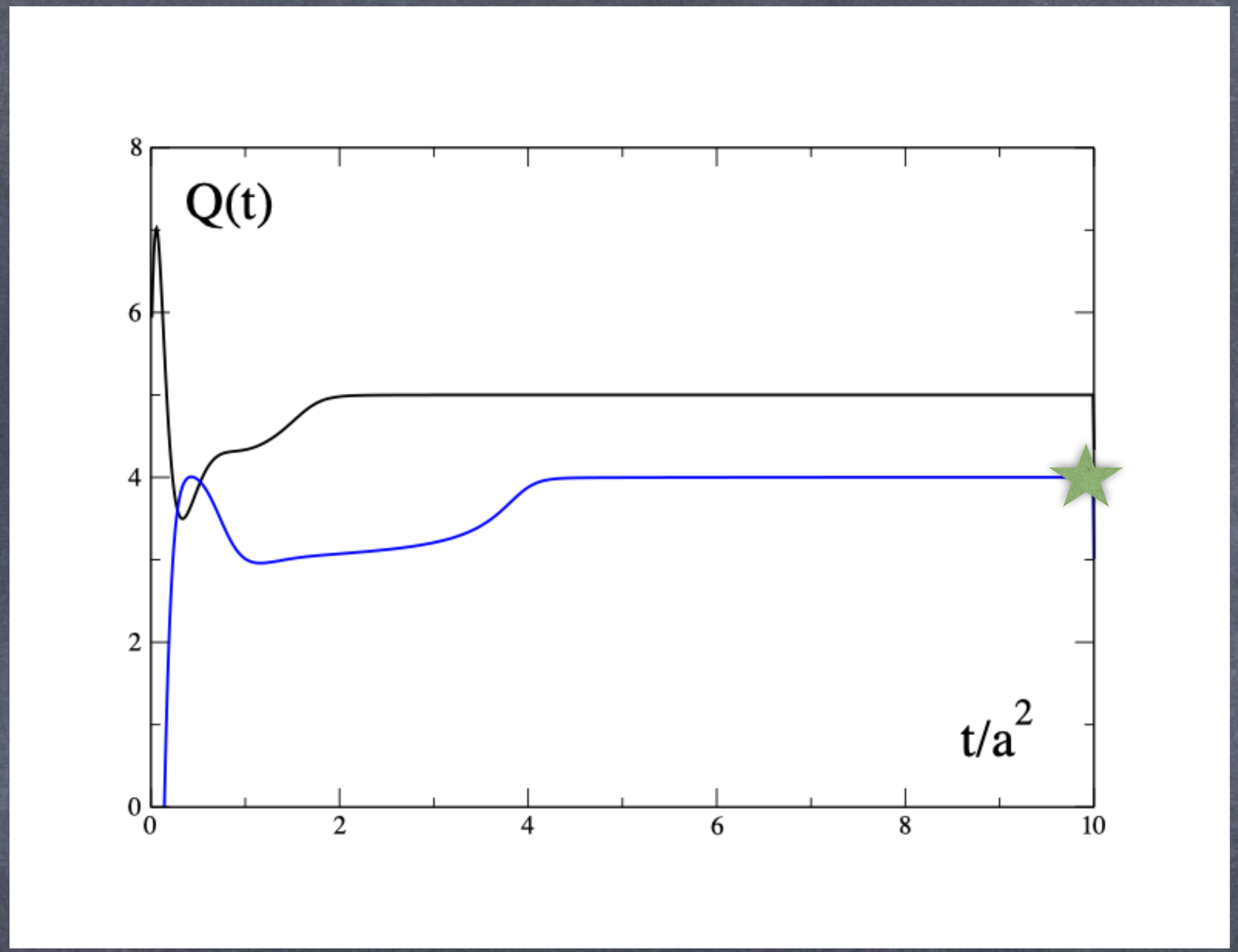
+

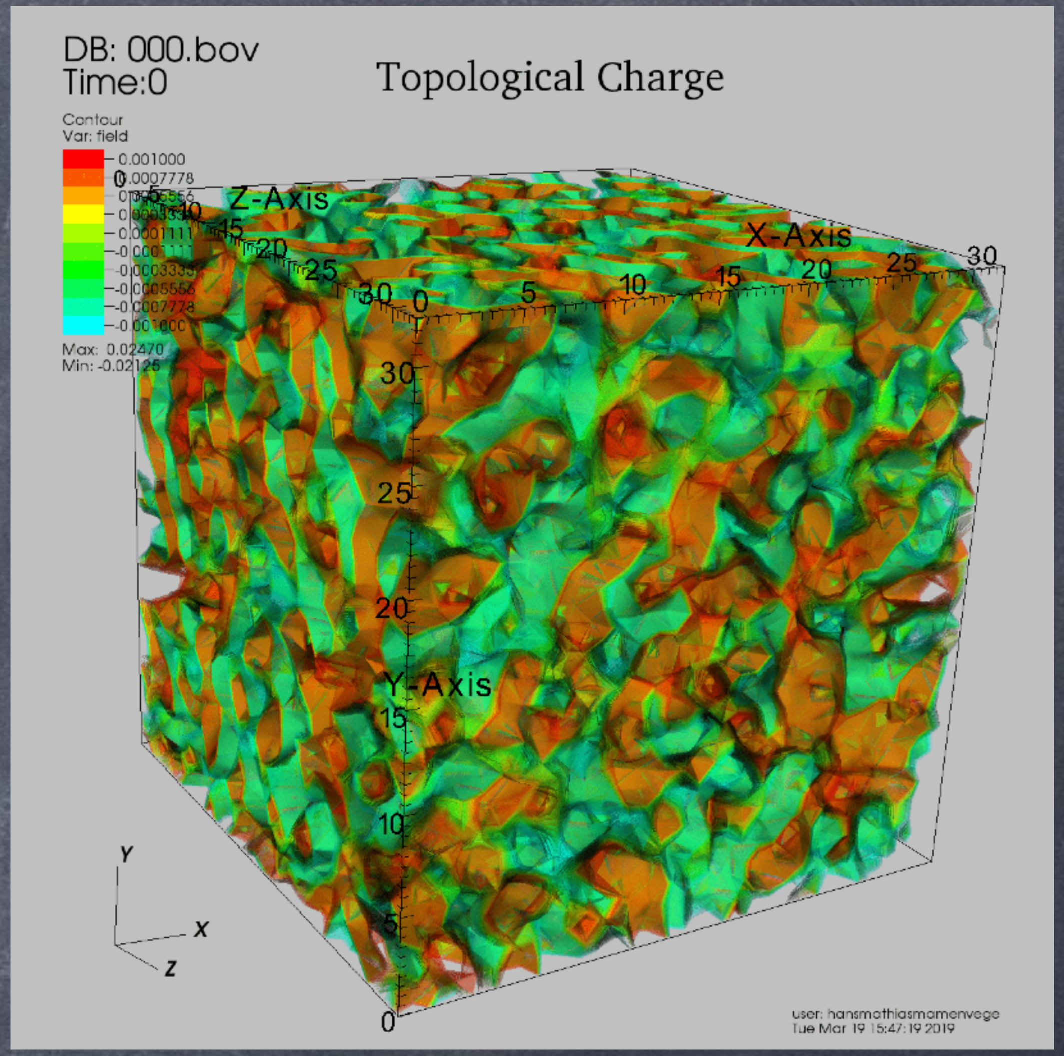
Bianchi identities

$$\partial_t q(x,t) = \partial_\mu \mathcal{K}_\mu(x,t)$$

$$\mathcal{K}_\mu(x,t) = \frac{1}{8\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{Tr}\left[G_{\nu\rho}(x,t)D_\alpha G_{\alpha\sigma}(x,t)\right]$$

$$\langle \cdots [Q(t)]_R \cdots \rangle = \langle \cdots Q(t) \cdots \rangle$$





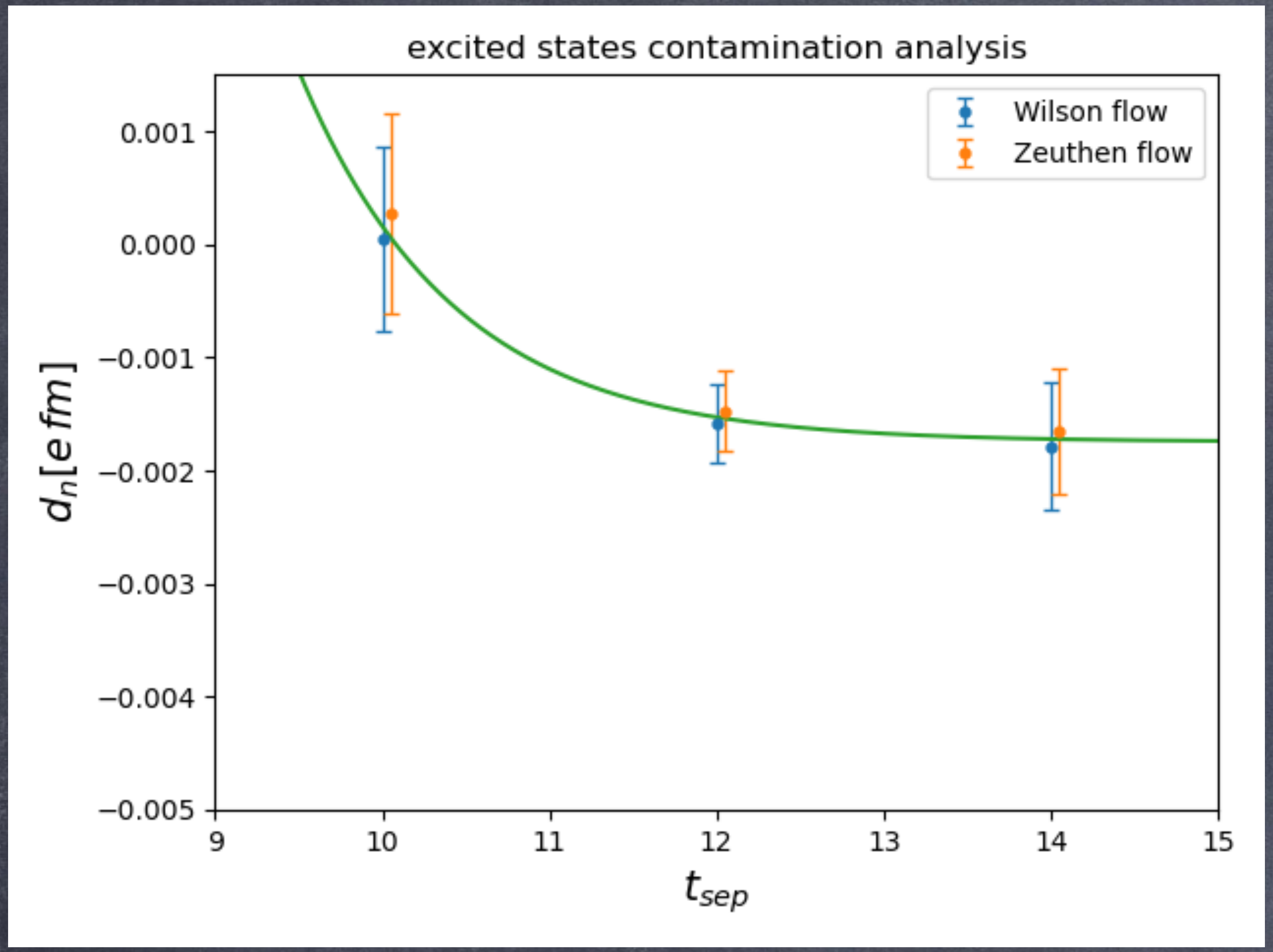
Pederiva, Vege: 2018
LatViz

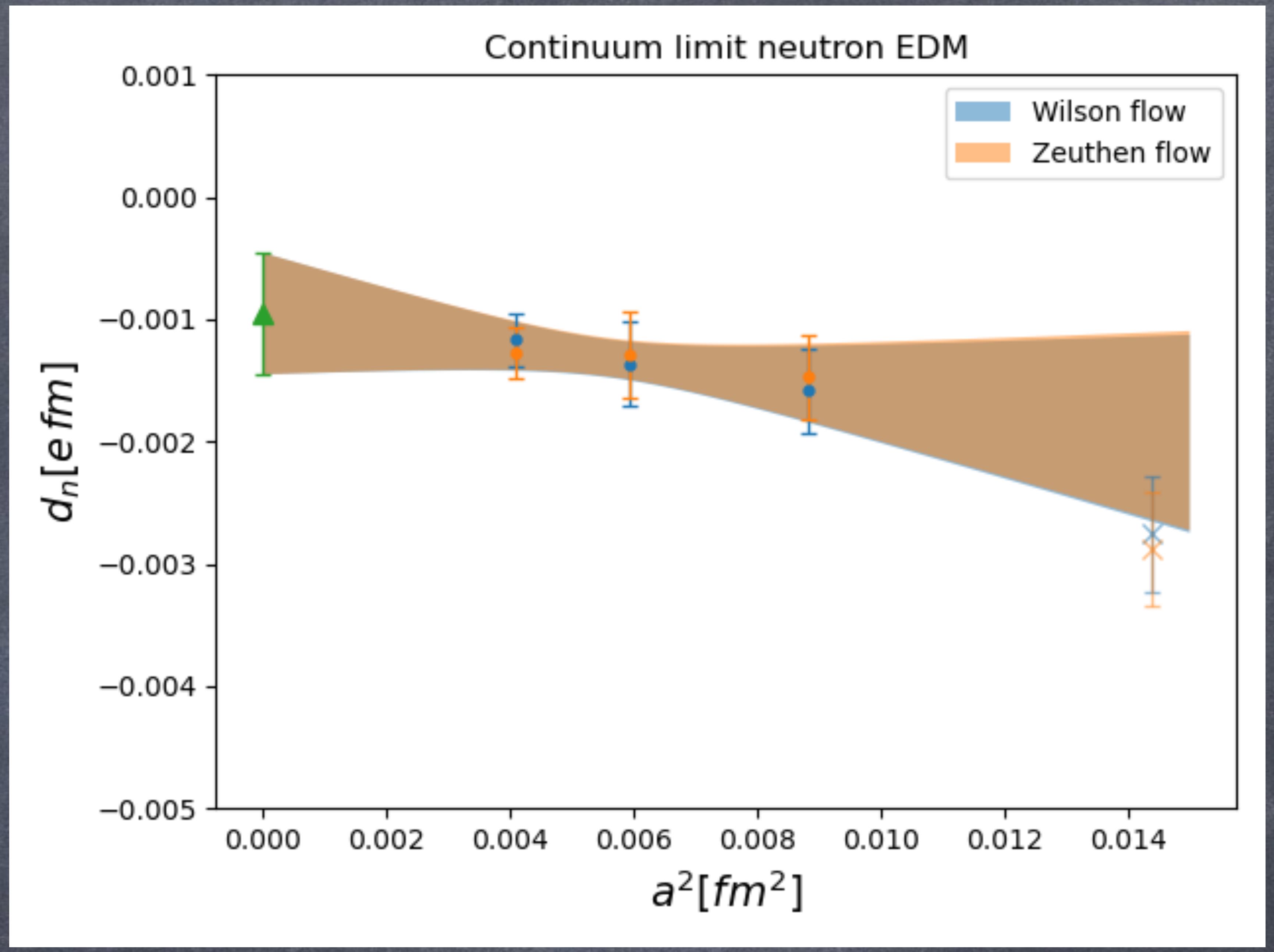
$$\partial_t Q(t) = 0 \qquad Q = \int d^4x \; q(x,t)$$

Equivalent to fermionic definition

Polyakov: 1987, Lüscher: 2010 Ce', Consonni, Engel, Giusti: 2015 Lüscher: 2021 Lüscher, Weisz: 2021

Systematics





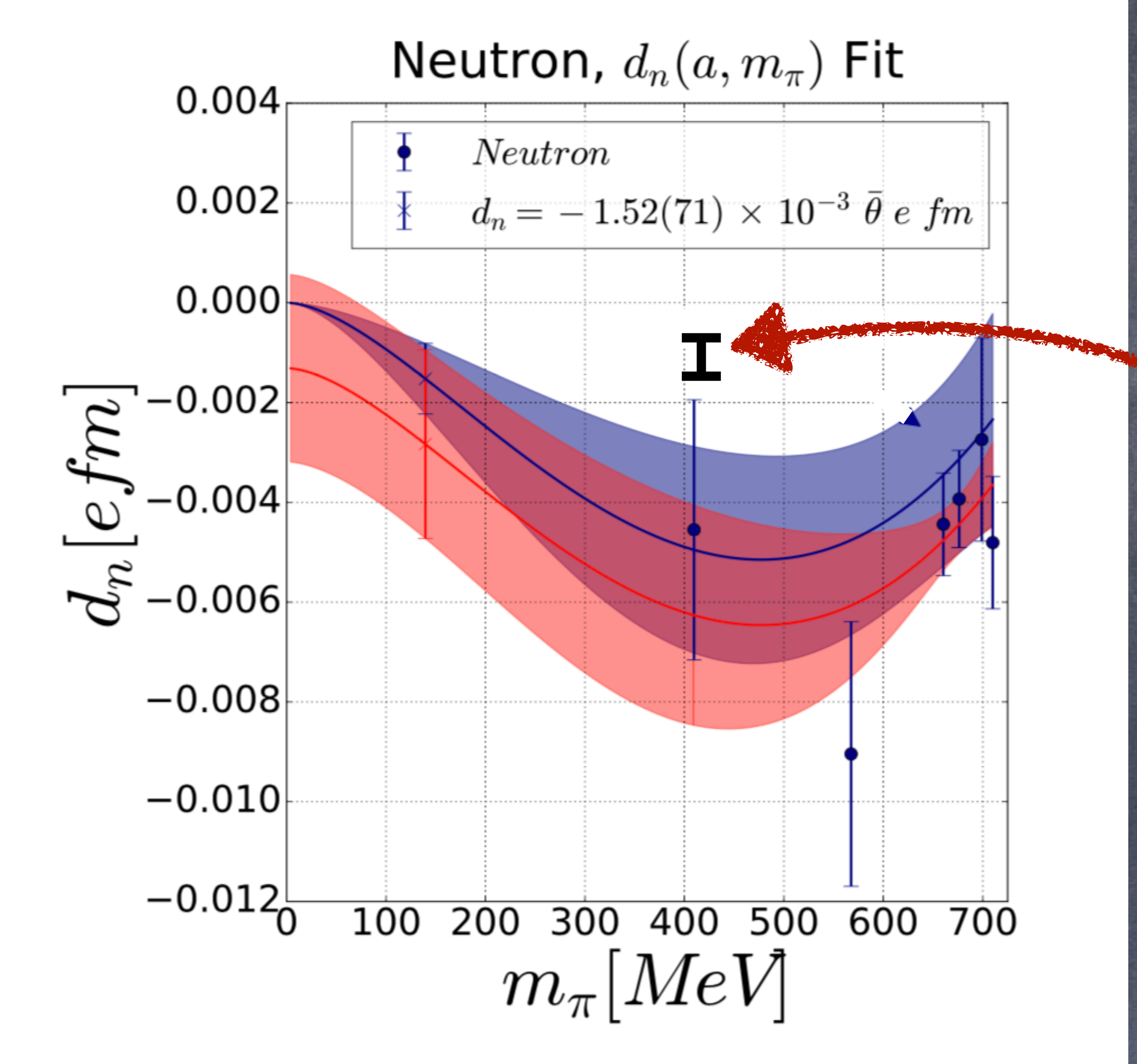
$$d_n(t_{\rm sep}) = d_n + A \cdot e^{-\delta t_{\rm sep}}$$

- ESC under control for $t_{\rm sep} \gtrsim 1.1~\rm fm$ for $m_\pi \simeq 410~\rm MeV$
- Compare with χPT predictions

- Topological charge computed $\sqrt{8t} \simeq 0.56~\rm fm$
- Results consistent with expected O(a) improvement
- Zeuthen flow Sint, Ramos: 2015

Neutron EDM from theta term

Dragos, Luu, A.S., de Vries, Yousif: 2019



$$d_n(\bar{\theta}) = \bar{d}_n - \frac{e g_A \bar{g}_0^{\bar{\theta}}}{8\pi^2 F_\pi} \ln \frac{m_\pi^2}{M_N^2}$$

Ottnad et al.: 2010
Mereghetti et al.: 2011

$$d_{n/p}(a, m_\pi) = C_1^{n/p} m_\pi^2 + C_2^{n/p} m_\pi^2 \ln \frac{m_\pi^2}{M_N^2} + C_3^{n/p} a^2$$

$$d_n(m_\pi = 412\ \text{MeV}) = -0.00095(50)\ \bar{\theta}\ e\ \text{fm}$$

Kim, A.S. (OpenLat): 2025

$$d_n^{\text{phys}} = -0.00152(71)\ \bar{\theta}\ e\ \text{fm}$$

$$|\bar{\theta}| < 1.98 \times 10^{-10} (90\%\text{CL})$$

$$\bar{g}_0^{\bar{\theta}} = -1.28(64) \cdot 10^{-2} \bar{\theta}$$

Ab-initio determination of $\bar{g}_0^{\theta}$

$$\bar{g}_0^{\bar{\theta}} = -1.47(23) \cdot 10^{-2} \bar{\theta}$$

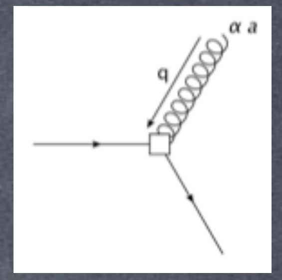
Crewther et al.: 1980
de Vries et al.: 2015

Quark-Chromo EDM
&
3-gluon CP-odd

Challenges with BSM operators

- Operators mix with lower dimensional operators

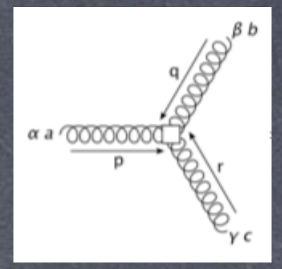
$$O^f_{\rm CE}(x) = \overline{\psi}_f(x)\gamma_5\sigma_{\mu\nu}G^a_{\mu\nu}T^a\psi_f(x)$$



- Power divergences need to be subtracted non-pertubatively

Maiani, Martinelli, Sachrajda: 1992

$$O_{3g}(x) = \frac{1}{6} i f^{abc} G^a_{\mu\rho}(x) G^b_{\nu\rho}(x) G^c_{\lambda\sigma}(x)\epsilon_{\mu\nu\lambda\sigma}$$



- Additional complicated mixing pattern

Bhattacharya, Cirigliano, Gupta, Mereghetti, Yoon: 2015

Cirigliano, Mereghetti, Stoffer: 2020

$$[O_{\rm CE}]_R = Z_{\rm CE}\left[O_{\rm CE} - \frac{C}{a^2}P\right] + \cdots$$

$$P^f(x) = \overline{\psi}_f(x)\gamma_5\psi_f(x)$$

$$[O_{3g}]_R = Z_{3g}\left[O_{3g} - \frac{C'}{a^2}q\right] + \cdots$$

$$q(x) = \frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{tr}\left\{G_{\mu\nu}(x)G_{\rho\sigma}(x)\right\}$$

qCEDM with RI-MOM Off-shell

$\frac{1}{a}$ d=4 —> 2 operators + 3 O(m)

$\log a$ d=5 —> 3 operators + (7 + 5) O(m,m²) + 4 “nuisance”

Strategy - Short flow-time expansion

$$\mathring{\mathcal{O}}_i(t) = \sum_j \zeta_{ij}(t,\mu)\,[O_j(t=0,\mu)]_{\mathrm{R}} + O(t)$$

Lüscher: 2013

A.S., Luu, de Vries: 2014-2015
Dragos, Luu, A.S. de Vries: 2018-2019
Rizik, Monahan, A.S.: 2018-2020
A.S.: 2020
Kim, Luu, Rizik, A.S.: 2020
Mereghetti, Monahan, Rizik, A.S., Stoffer: 2021
Crosas, Monahan, Rizik, A.S., Stoffer: 2023

Strategy - Short flow-time expansion

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LQCD

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- Calculation of matrix elements with flowed fields
    - Multiplicative renormalization (no power divergences and no mixing)

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$$\mathring{O}_i(t) = \sum_j \zeta_{ij}(t,\mu)\,[O_j(t=0,\mu)]_{\mathrm{R}} + O(t)$$

LQCD   PT - LQCD

- Calculation of matrix elements with flowed fields
  - Multiplicative renormalization (no power divergences and no mixing)
- Calculation of Wilson coefficients
  - Insert OPE in off-shell amputated 1PI Green's functions

$$\zeta_{ij}(t,\mu) = \delta_{ij} + \frac{\alpha_s(\mu)}{4\pi}\zeta_{ij}^{(1)}(t,\mu) + O(\alpha_s^2)$$

Strategy - Short flow-time expansion

$$\mathring{O}_i(t) = \sum_j \zeta_{ij}(t,\mu)\,[O_j(t=0,\mu)]_{\mathrm{R}} + O(t)$$

LQCD PT - LQCD

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Rizik, Monahan, A.S.: 2018-2020
A.S.: 2020
Kim, Luu, Rizik, A.S.: 2020
Mereghetti, Monahan, Rizik, A.S., Stoffer: 2021
Crosas, Monahan, Rizik, A.S., Stoffer: 2023

- Calculation of matrix elements with flowed fields
  - Multiplicative renormalization (no power divergences and no mixing)
- Calculation of Wilson coefficients
  - Insert OPE in off-shell amputated 1PI Green's functions

$$\zeta_{ij}(t,\mu) = \delta_{ij} + \frac{\alpha_s(\mu)}{4\pi}\zeta_{ij}^{(1)}(t,\mu) + O(\alpha_s^2)$$

- Power divergences subtracted non-perturbatively (LQCD)

Strategy - Short flow-time expansion

$$\mathring{\mathcal{O}}_i(t) = \sum_j \zeta_{ij}(t,\mu)\,[O_j(t=0,\mu)]_{\rm R} + O(t)$$

LQCD PT - LQCD

Lüscher: 2013

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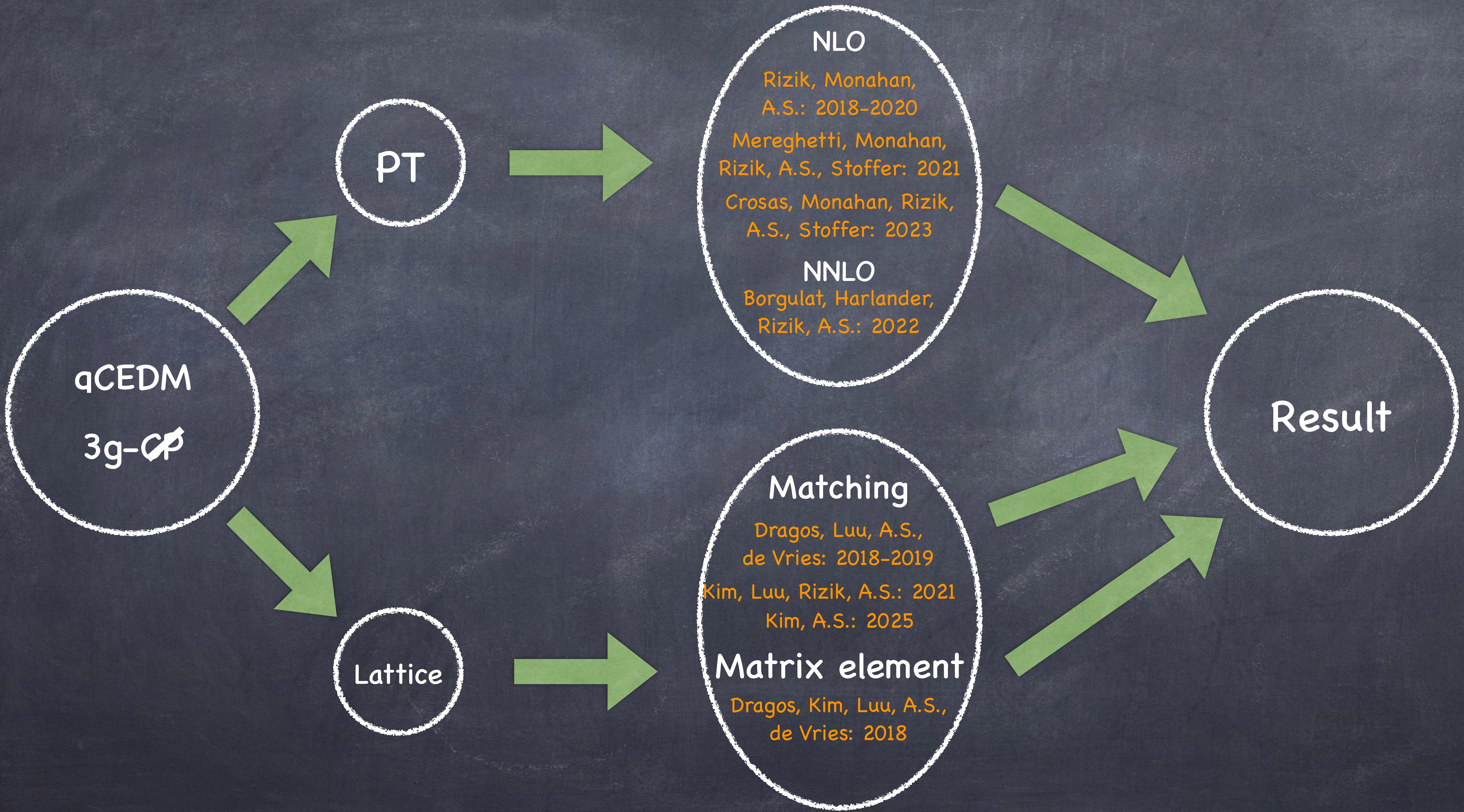
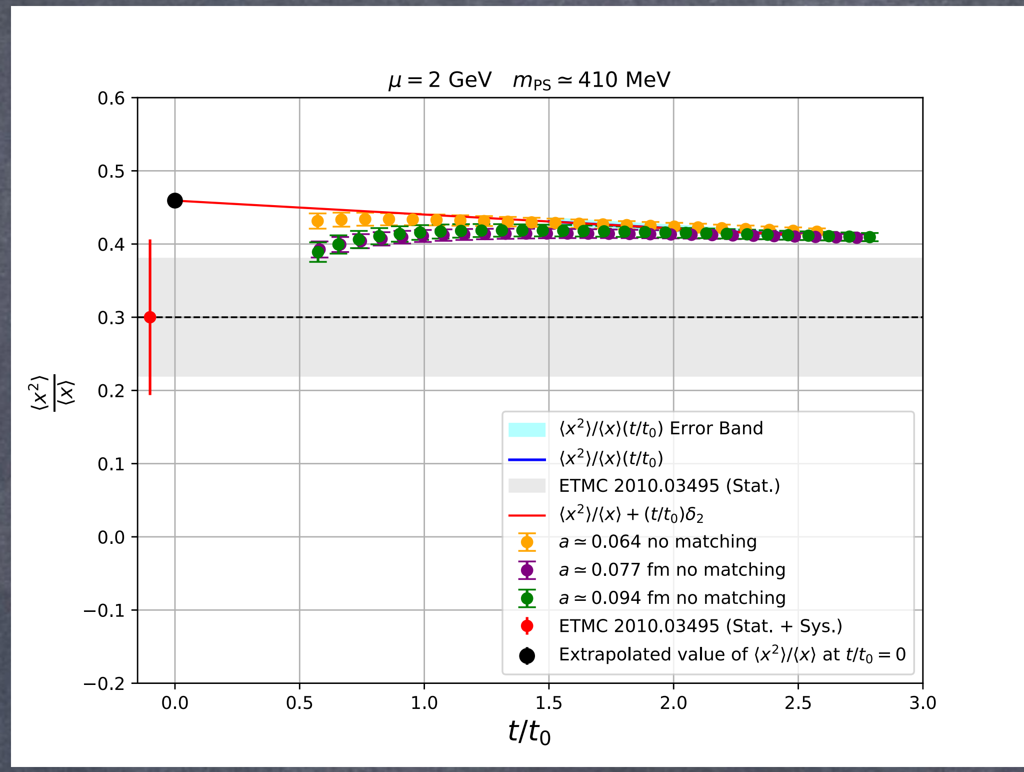
- Power divergences subtracted non-perturbatively (LQCD)
- Determination of the physical renormalized matrix element at zero flow-time

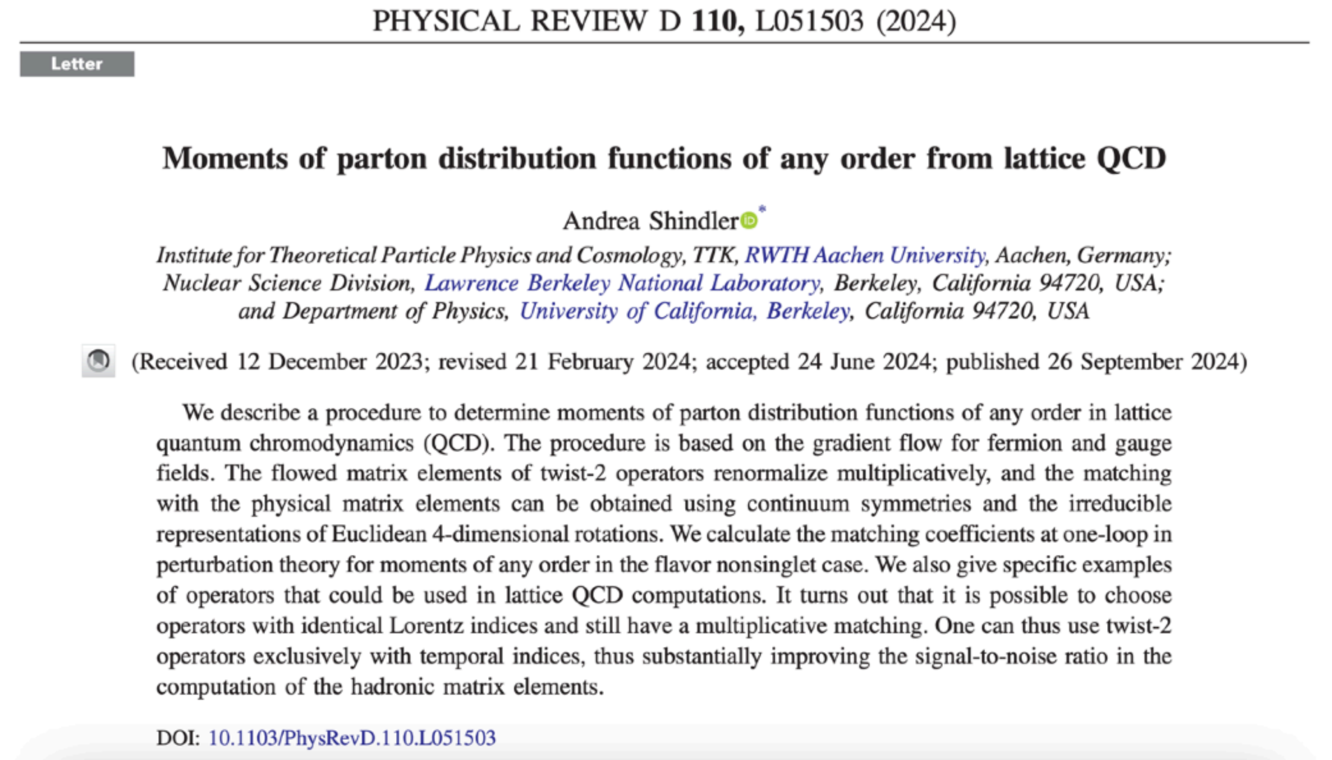
BSM contributions



Flowed moments – success

- PDFs describe quark and gluon structure of hadrons — essential for LHC predictions
- Large Bjorken-x remains poorly constrained due to limited experimental input
- New method to compute arbitrary PDF moments using gradient flow A.S.: 2023
- Enables reconstruction of PDFs from **first principles** with controlled uncertainties
- First lattice result for the pion valence PDF **competitive with global fits**.





PHYSICAL REVIEW D **110,** L051503 (2024)

Letter

Moments of parton distribution functions of any order from lattice QCD

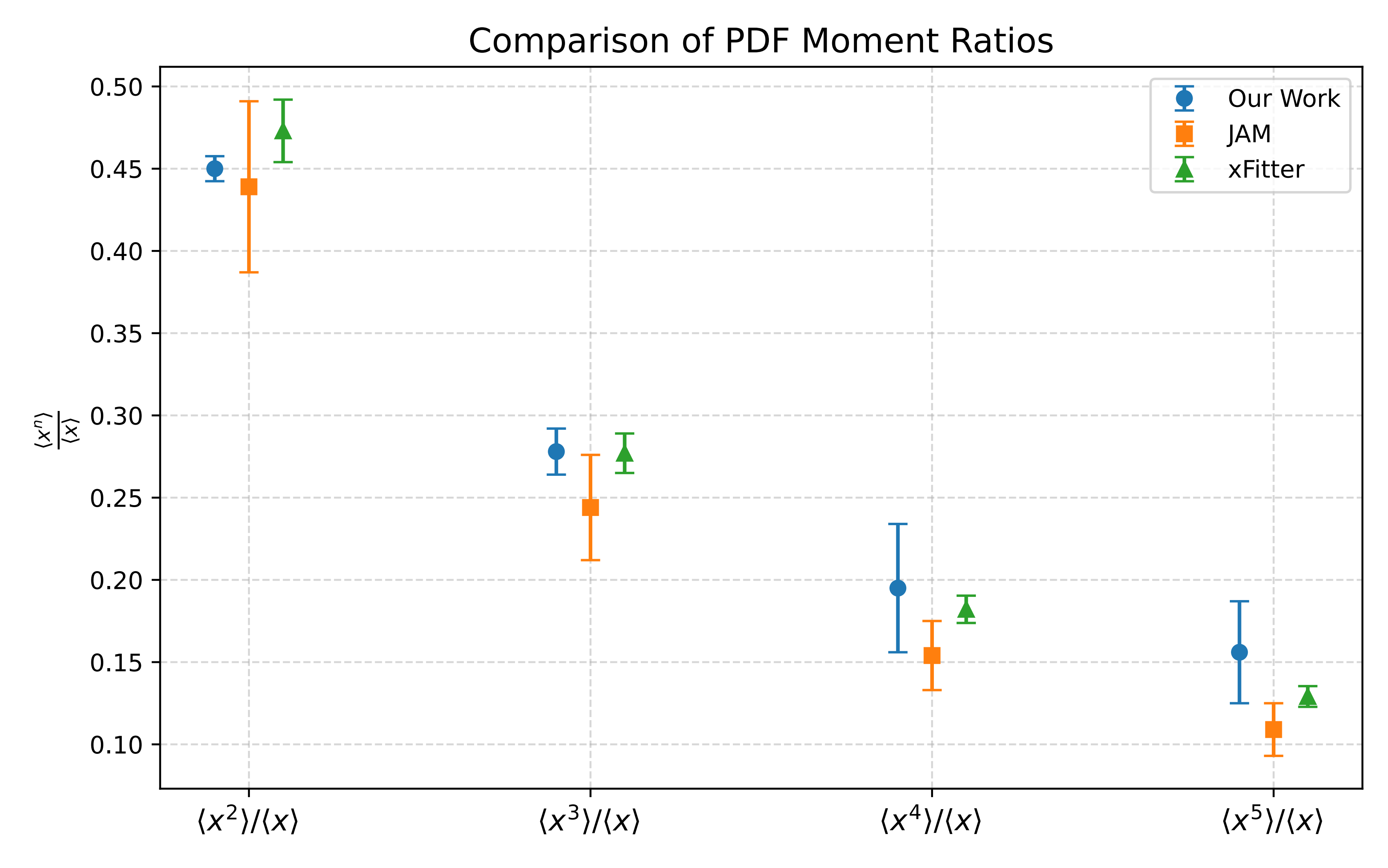
Andrea Shindler*

Institute for Theoretical Particle Physics and Cosmology, TTK, RWTH Aachen University, Aachen, Germany; Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA; and Department of Physics, University of California, Berkeley, California 94720, USA

(Received 12 December 2023; revised 21 February 2024; accepted 24 June 2024; published 26 September 2024)

We describe a procedure to determine moments of parton distribution functions of any order in lattice quantum chromodynamics (QCD). The procedure is based on the gradient flow for fermion and gauge fields. The flowed matrix elements of twist-2 operators renormalize multiplicatively, and the matching with the physical matrix elements can be obtained using continuum symmetries and the irreducible representations of Euclidean 4-dimensional rotations. We calculate the matching coefficients at one-loop in perturbation theory for moments of any order in the flavor nonsinglet case. We also give specific examples of operators that could be used in lattice QCD computations. It turns out that it is possible to choose operators with identical Lorentz indices and still have a multiplicative matching. One can thus use twist-2 operators exclusively with temporal indices, thus substantially improving the signal-to-noise ratio in the computation of the hadronic matrix elements.

DOI: 10.1103/PhysRevD.110.L051503

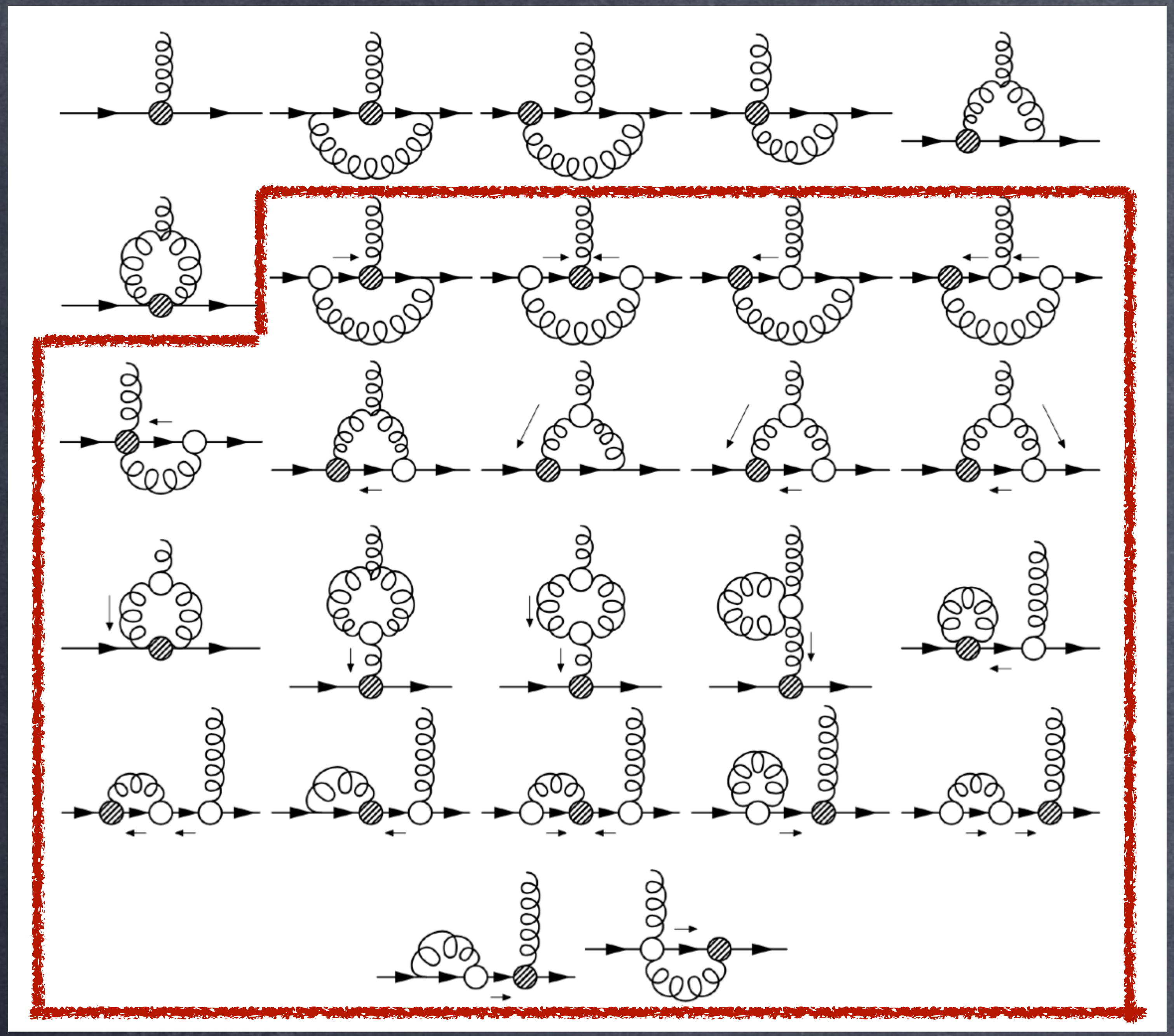


Karur, Kim, Pefkou, A.S., Walker-Loud (OpenLat): 2025

Quark-Chromo EDM

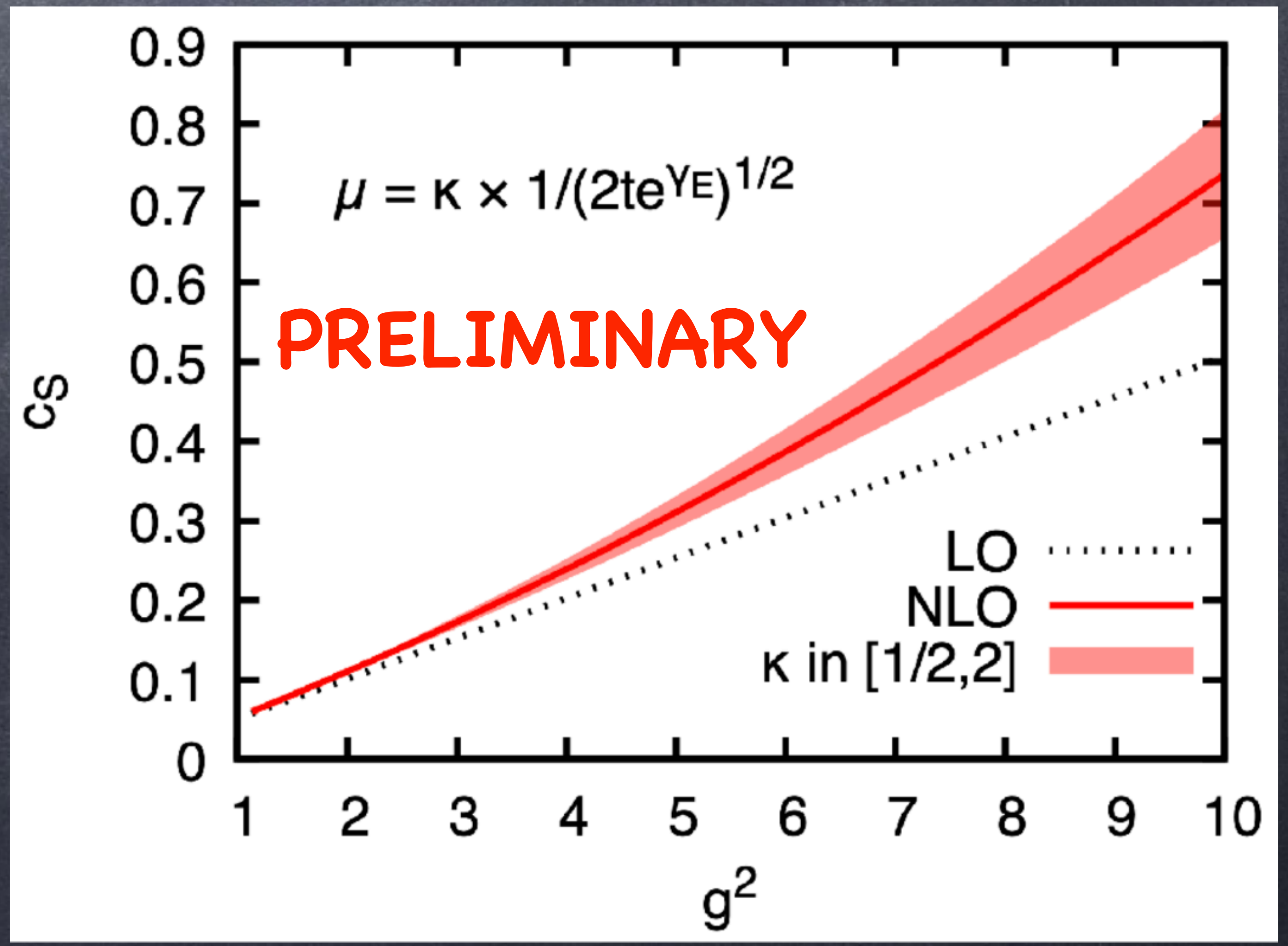
Rizik, Monahan, A.S.: 2020
Mereghetti, Monahan, Rizik, A.S., Stoffer : 2021

$\zeta_{\mathrm{CE,CE}}(t,\mu)$



- Expand integrands of loop integrals in all scales excluding t
  - Analytic structure altered —> distortion of IR structure
  - in matching equation the IR modification drops out in the difference
  - Expanding loop integrals in the RHS vanish in DR —> UV and IR are identical
  - The LHS is UV-finite, beside the renormalization of the bare parameters and flowed fermion fields
  - The IR singularities on the LHS exactly match the UV MS counterterms

Borgulat, Harlander, Rizik, A.S.: in progress



$$\zeta_{\mathrm{CE,CE}}(t,\mu) = \zeta_\chi^{-1} + \frac{\alpha_s}{4\pi}\left[2(C_F - C_A)\log(8\pi\mu^2 t) - \frac{1}{2}\Big((4+5\delta_{\mathrm{HV}})C_A + (3-4\delta_{\mathrm{HV}})C_F\Big)\right]$$

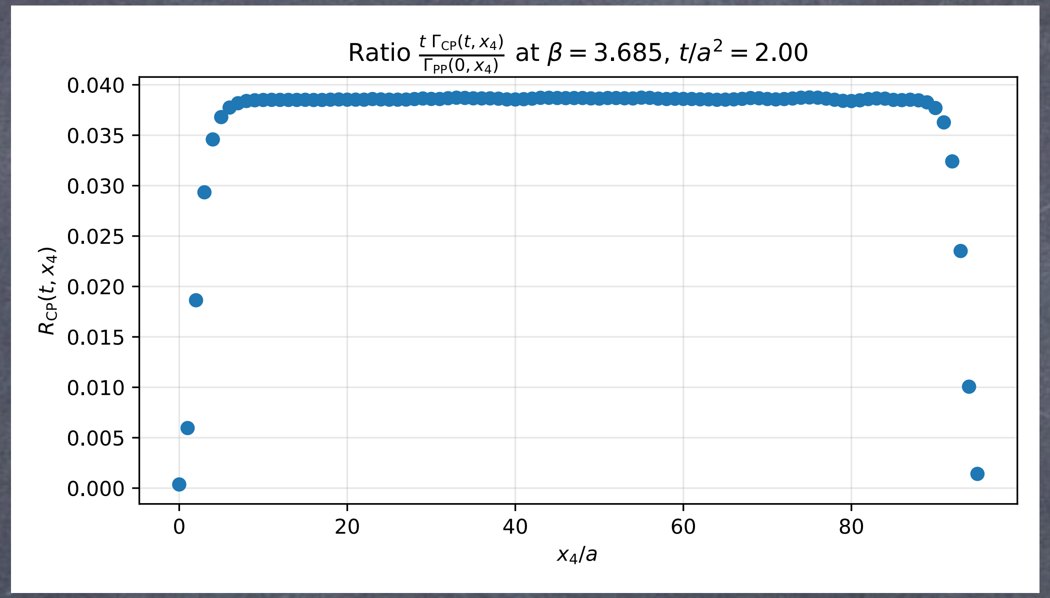
$$= 1 + \frac{\alpha_s}{4\pi}\Big[(5C_F - 2C_A)\log(8\pi\mu^2 t) - \frac{1}{2}\Big((4+5\delta_{\mathrm{HV}})C_A + (3-4\delta_{\mathrm{HV}})C_F\Big) - \log(432)C_F\Big]$$

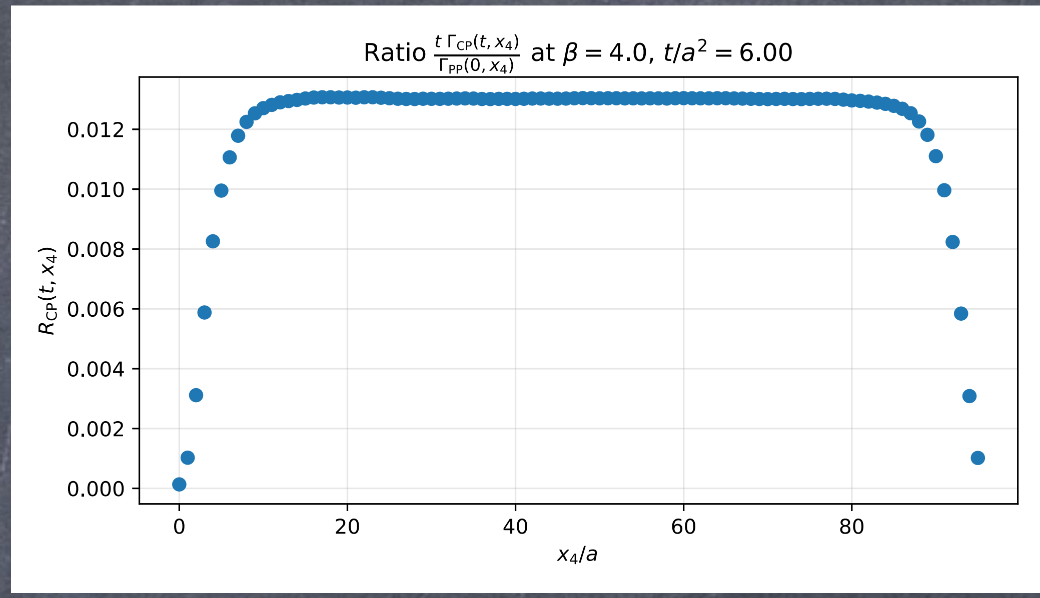
Warm-up MDM —> 2-loops (226 - 3375 FD)

Quark-Chromo EDM: power divergences

Kim, Luu, Rizik, A.S.:2020

$$\mathring{\mathcal{O}}_{\rm CE}(t) = \frac{\zeta_{\rm OP}(t,\mu)}{t} P_{\rm R}(0,\mu) + \sum_i \zeta_{{\rm CE},i}(t,\mu)\mathcal{O}_{i,{\rm R}}(0,\mu)$$





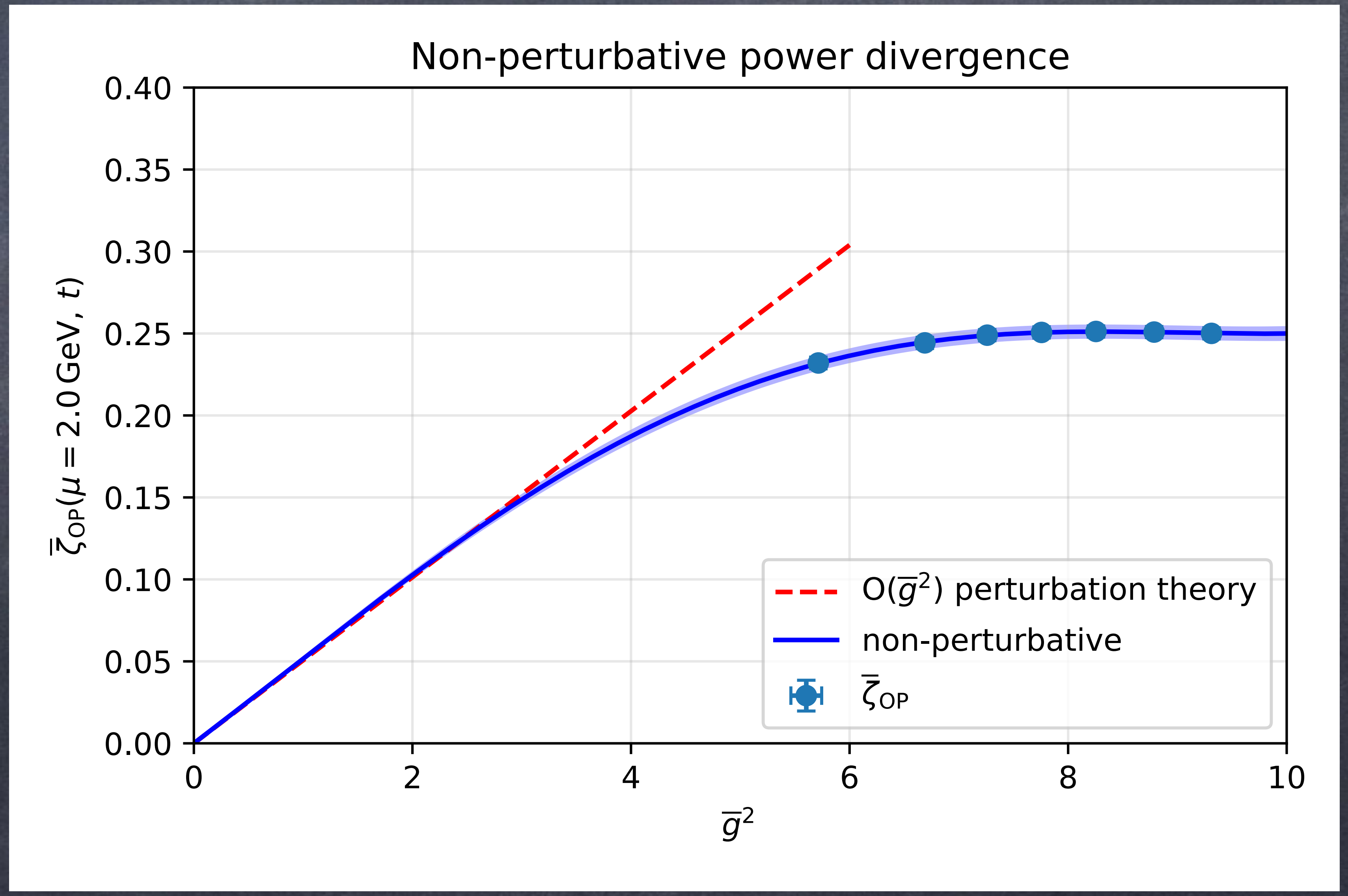
$$\Gamma_{CP}(t,x_4) = a^3 \sum_{\mathbf{x}} \left\langle \mathcal{O}^{ij}_{CE}(t,\mathbf{x},x_4) P^{ji}(0,\mathbf{0},0) \right\rangle$$

$$\Gamma_{PP}(x_4) = a^3 \sum_{\mathbf{x}} \langle P^{ij}(x_4,\mathbf{x}) P^{ji}(0,\mathbf{0}) \rangle$$

$$R_{\rm CP}(t,x_4) = t\,\frac{\langle 0|\mathcal{O}_{\rm CE}(t)|\pi\rangle}{\langle 0|P|\pi\rangle}$$

$$\bar{\zeta}_{\rm OP}(t,\mu) = t\,\frac{\left\langle 0|\mathring{\mathcal{O}}_{\rm CE}(t)|\pi\right\rangle}{\langle 0|P_{\rm R}(0,\mu)|\pi\rangle}$$

$$\bar{\zeta}_{\rm OP}(t,\mu) = \frac{1}{2\pi^2}\bar{g}^2 + \Delta^{(2)}\bar{g}^4 + \Delta^{(3)}\bar{g}^4 + \Delta^{(4)}\bar{g}^8$$



Rizik, Monahan, A.S.: 2018-2020

Kim, A.S. (OpenLat): 2025

3-gluon CP-odd

Crosas, Monahan, Rizik, A.S., Stoffer : 2023

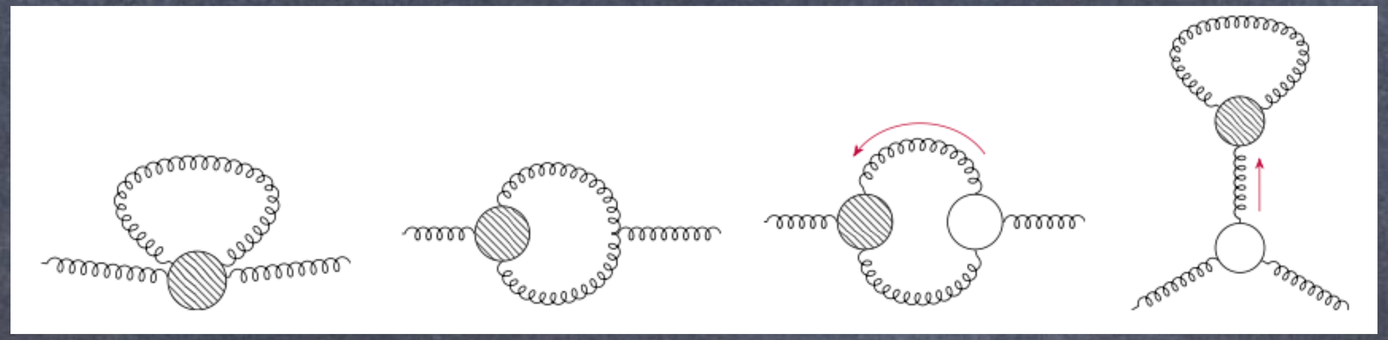
$$\mathcal{O}^R_{\widetilde{G}}(x,t) = \frac{1}{g^2}\mathrm{tr}[G_{\mu\nu}G_{\nu\lambda}\widetilde{G}_{\lambda\mu}] \qquad \zeta_{ij}(t,\mu) = \delta_{ij} + \frac{\alpha_s(\mu)}{4\pi}\zeta^{(1)}_{ij}(t,\mu) + O(\alpha_s^2)$$

$$\mathcal{O}^R_{\widetilde{G}}(x,t) = \sum_i \zeta_i(t,\mu)\mathcal{O}_i^{\mathrm{MS}}(x,\mu) + \sum_i \zeta_{\mathcal{N}_i}(t,\mu)\mathcal{N}_i^{\mathrm{MS}}(x,\mu) + \sum_i \zeta_{\mathcal{E}_i}(t,\mu)\mathcal{E}_i^{\mathrm{MS}}(x,\mu)$$

$$\mathcal{O}_\theta = \frac{1}{g_0^2}\mathrm{tr}[G_{\mu\nu}\widetilde{G}_{\mu\nu}]$$

$$\mathcal{O}_{CE} = (\bar{q}\tilde{\sigma}_{\mu\nu}\mathcal{M}t^a q)G^a_{\mu\nu}$$

$$\zeta^{(1)}_\theta = -\frac{9C_A}{4}\frac{1}{t}$$



$$\mathcal{O}_{\widetilde{G}} = \frac{1}{g_0^2}\mathrm{tr}[G_{\mu\nu}G_{\nu\lambda}\widetilde{G}_{\lambda\mu}]$$

$$\mathcal{O}_{\partial G} = \frac{1}{g_0^2}\partial_\nu \mathrm{tr}[(D_\mu G_{\mu\lambda})\widetilde{G}_{\nu\lambda}]$$

$$\zeta^{(1)}_{\widetilde{G}} = C_A\left[\frac{1}{3} + 6\log(8\pi\mu^2 t)\right] \qquad \zeta^{(1)}_{CE} = \frac{i\,C_A}{8}\left[\frac{31}{6} + 3\log(8\pi\mu^2 t)\right]$$

$$\zeta^{(1)}_{\partial G} = -\frac{179 C_A}{24} \qquad \zeta^{(1)}_{\Box\theta} = 0$$

$$\mathcal{O}_{\Box\theta} = \frac{1}{g_0^2}\Box\,\mathrm{tr}[G_{\mu\nu}\widetilde{G}_{\mu\nu}]$$

Neutron EDM from Lattice QCD

Quark EDM —>
simplest calculation with Lattice QCD. Precision 3%-5%. No Disc.

Theta-term nucleon EDM —> few calculations: 2 σ effect

—> new result have stronger signal

3 gluon operator —> Preliminary lattice QCD calculation on power divergence, 1-loop matching

4-fermion operators —> No Lattice QCD calculation, 1-loop matching

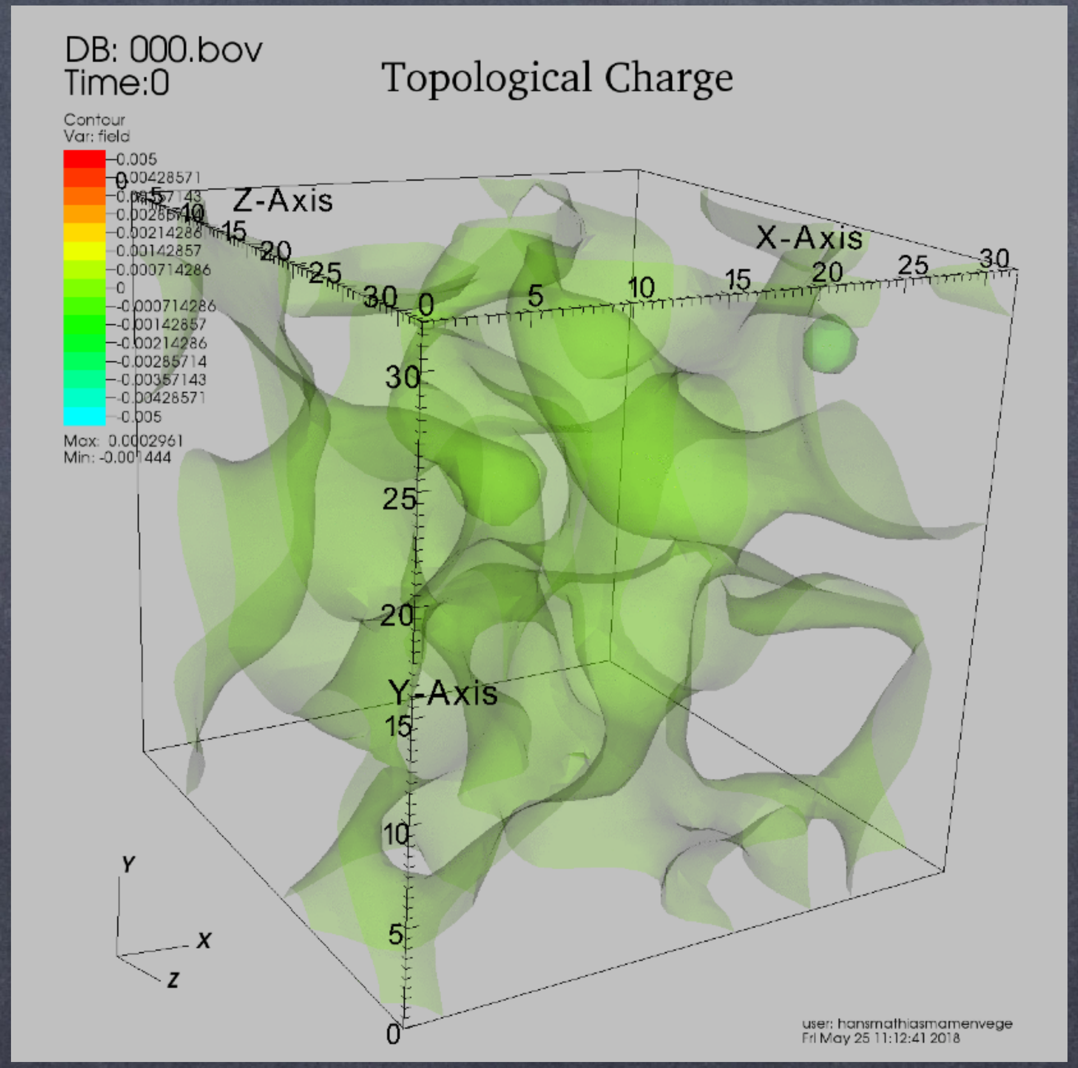
Quark-chromo EDM —>
First result with LO renormalization
New promising approach based on gradient flow —> 1-loop matching, NP power divergence, 2-loop in progress

	Renormalization	Continuum limit	Chiral extrapolation	Finite Volume	Excited States
θ - term	🟢	🟢	🟡	🟡	🟡
quark EDM	🟢	🟢	🟢	🟢	🟢
quark-chromo	🟢	🟡	🟡		
3-gluon	🟡				
4-fermion	🟡				

Summary

- Towards a new determination of nEDM from theta-term
  - Moving towards the physical point challenging (interpolation with χPT)
- Non-perturbative renormalization qCEDM matrix elements
  - Use of gradient flow is critical —> power divergences
- Perturbative matching of 3g-CP odd at NLO
  - Non-perturbative power divergence determination is in progress
- OpenLat: open science initiative. Gauges with SWF open to the whole community
- Results for parton distribution functions are very encouraging

Thank you!



Backup Slides

EDM experiments in the world

Chupp, Fierlinger, Ramsey-Musolf, Singh: 2019

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
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- Xe @ Heidelberg
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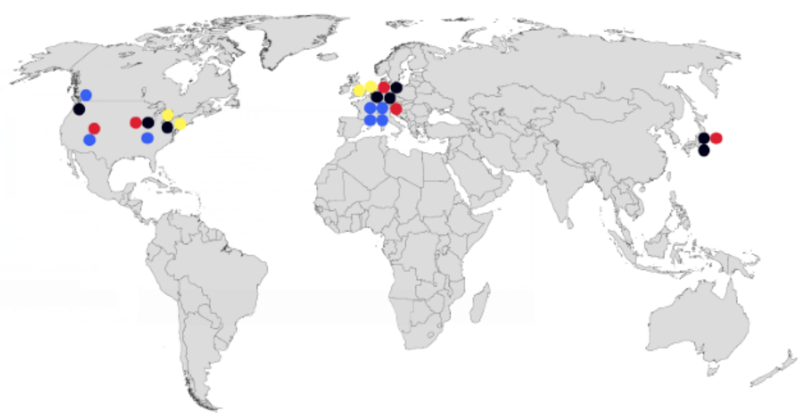
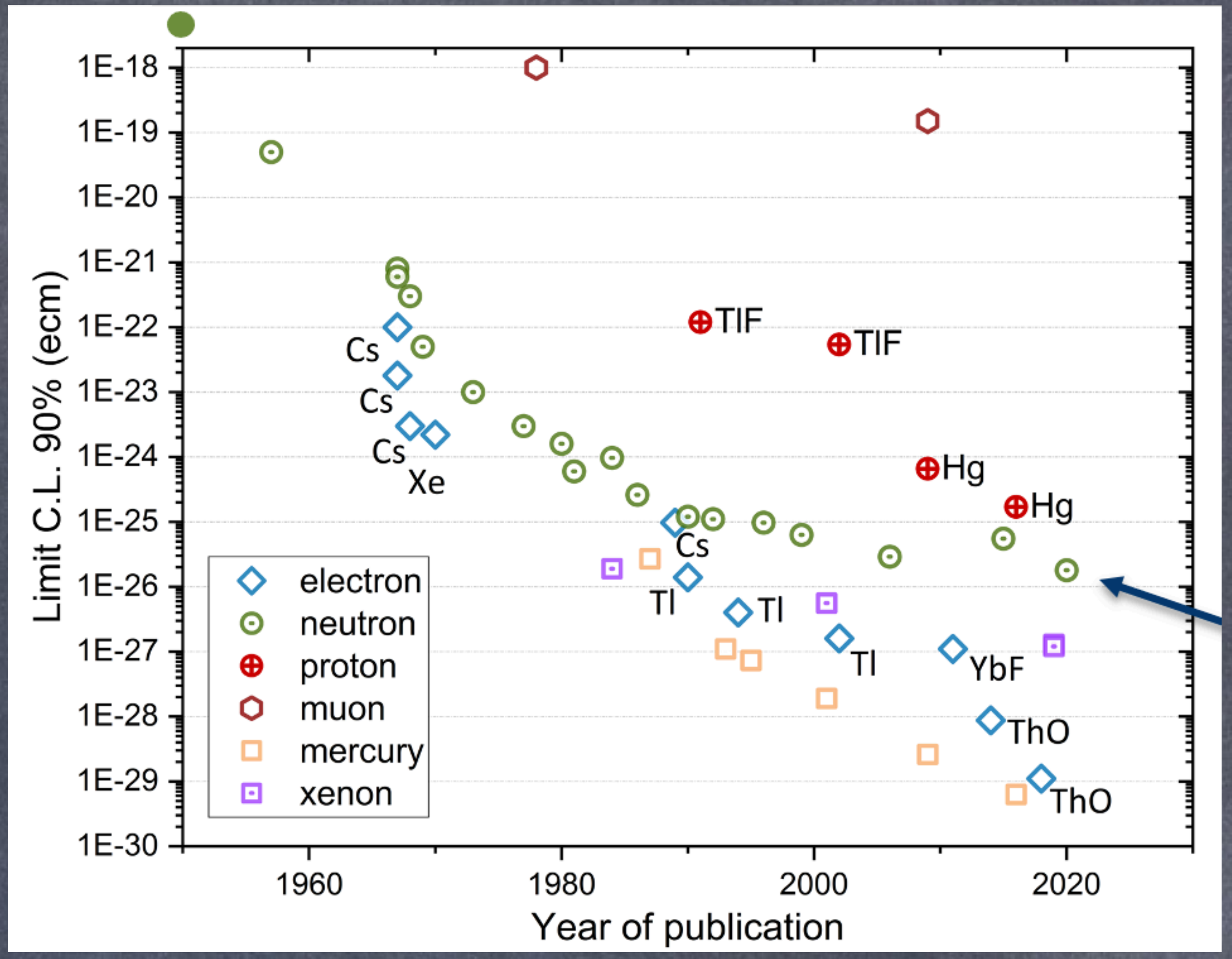


Molecules: (~ 55 ppl.)

- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhef
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial



	Result	95% u.l.	
	Paramagnetic systems		
Xe^m	$d_A = (\ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{\rm Cs}$
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm
	$d_e = (\ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm
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TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e cm
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e cm
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17}	e cm
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16}	e cm

$$|d_n| < 1.8 \times 10^{-26}\ e\ \text{cm}\ (90\%\ \text{C.L.})$$

Abel et al.: 2020
PSI

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Griffith et al.: 2009
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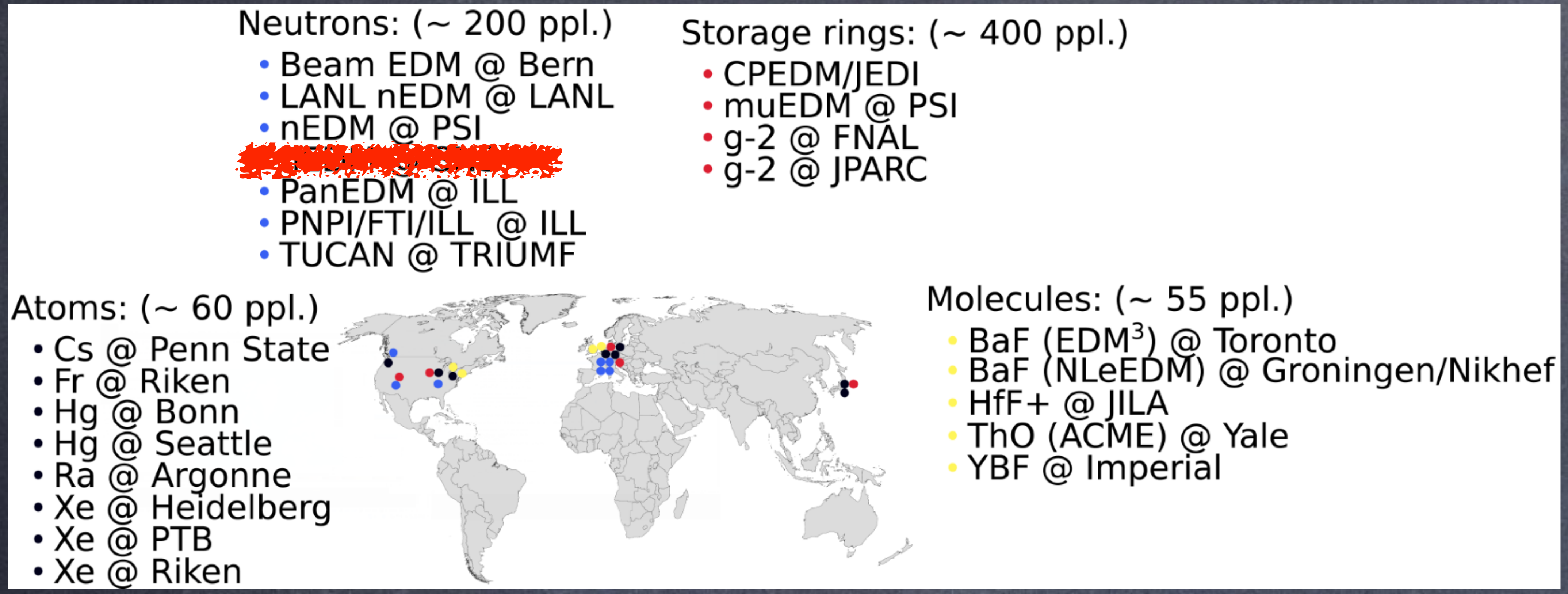

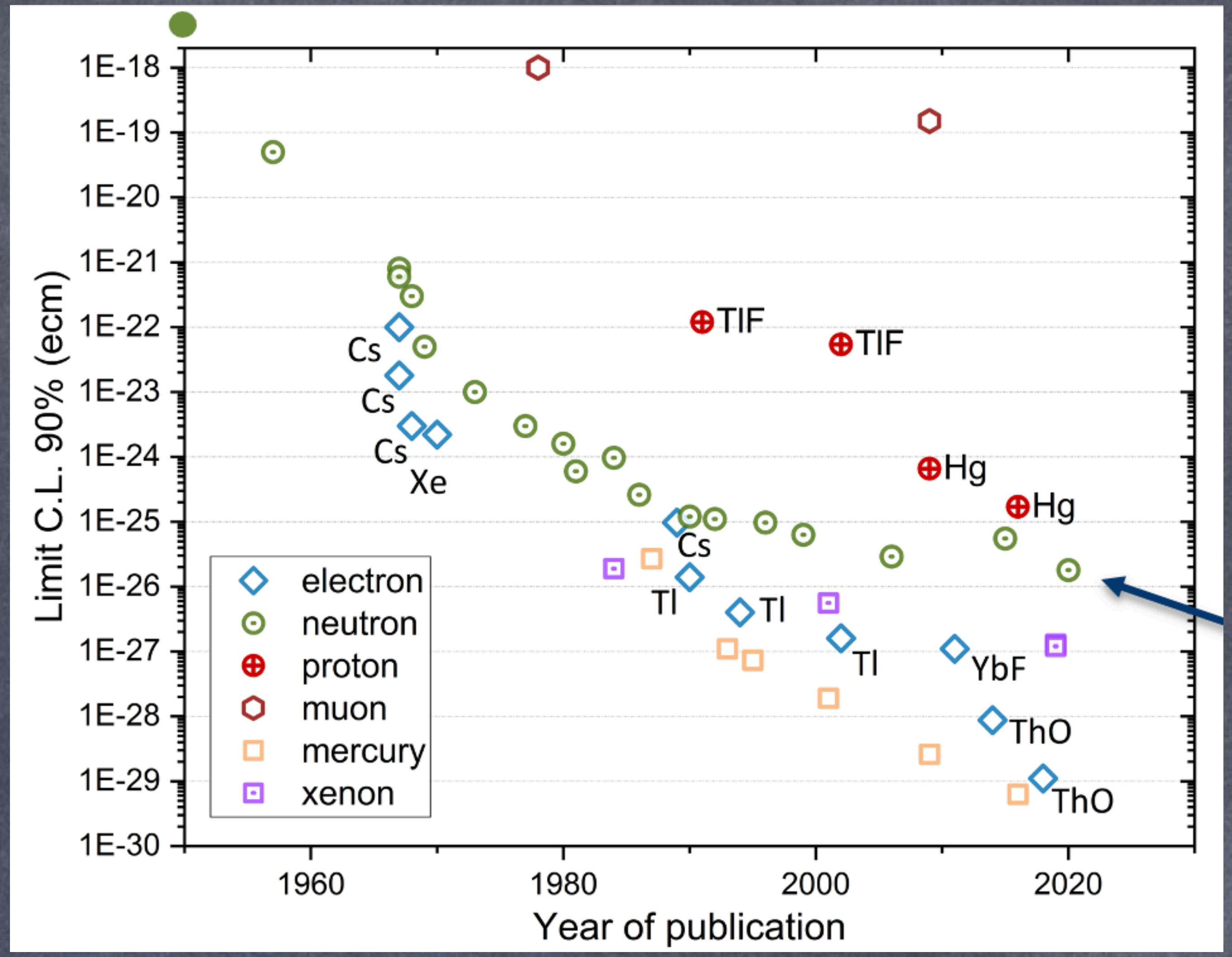

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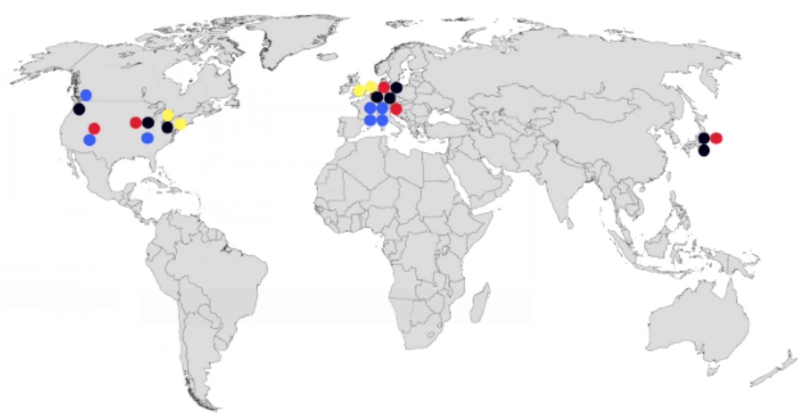

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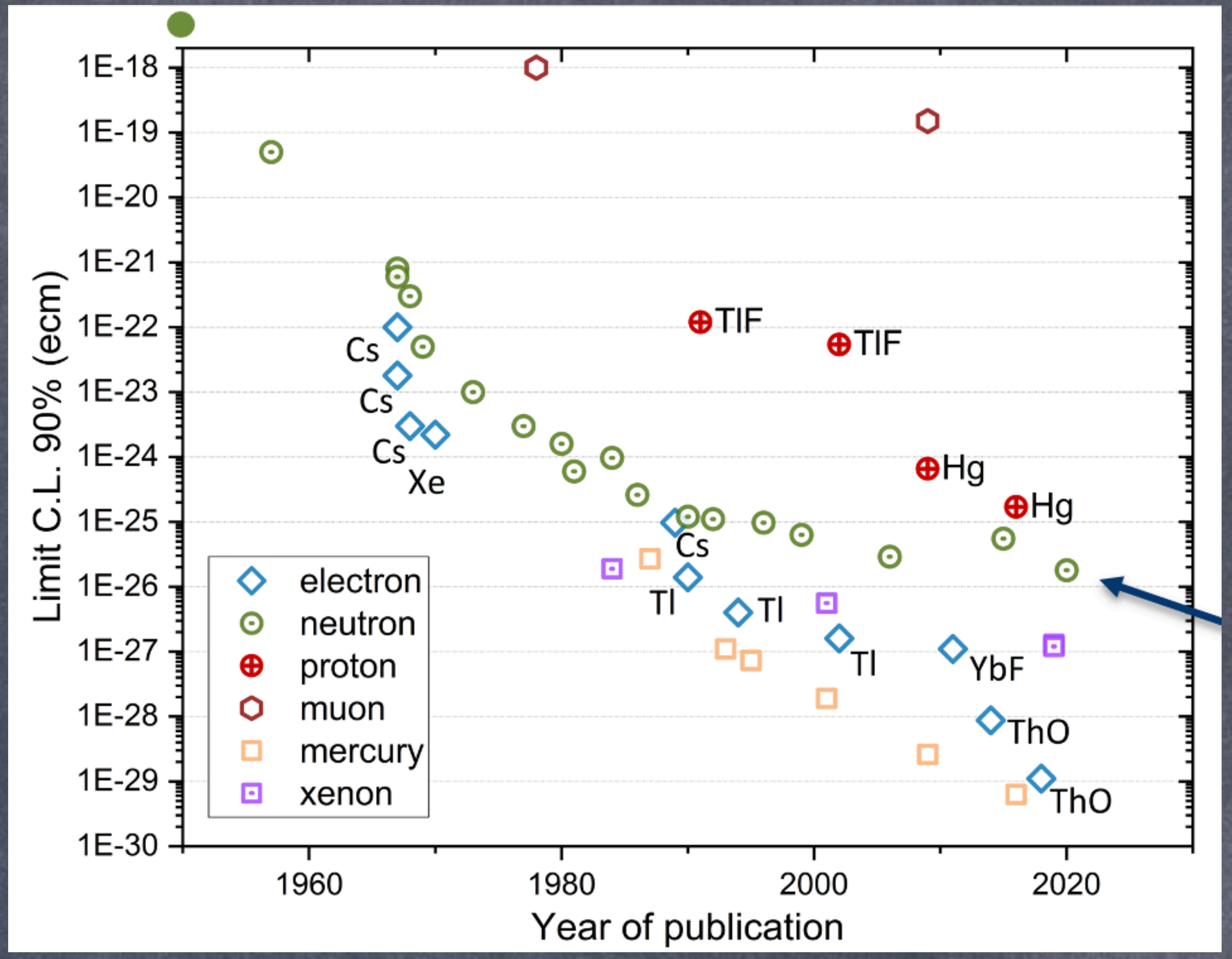

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Bishof et al: 2016

5 (10) yrs →

$$|d_n| \lesssim 3 \times 10^{-27}\ e\ \mathrm{cm}$$

PSI, LANL,...

$$|d_{^{199}Hg}| \lesssim 5 \times 10^{-31}\ e\ \mathrm{cm}\ (5 \times 10^{-32}\ e\ \mathrm{cm})$$

Bonn

$$|d_{^{225}Ra}| \lesssim 3 \times 10^{-27}\ e\ \mathrm{cm}$$

ANL

New physics scale

$$d_f \sim e q_f \sin(\delta_{\rm CPV}) \left(\frac{g^2}{16\pi^2}\right)^l \xi_{\rm FV} \frac{m_f}{M_{\rm NP}^2}$$

$$d_e \leq d_e^{\max}$$

$$M_{\rm NP} \gtrsim \sqrt{\frac{10^{29} e \text{ cm}}{d_e^{\max}}} \times \begin{cases} 50 \text{ TeV}, & \text{if } l = 1 \\ 2 \text{ TeV}, & \text{if } l = 2 \end{cases}$$

- The discovery potential in EDM searches can be roughly quantified by the reach in mass scale, assuming maximal CP violation.
- In all cases we see that the mass reach is very high - EDMs are exploring uncharted territory.
- if we insist that the scale of new physics is close to the electroweak scale, EDMs probe very small CP-violating couplings, still providing invaluable information for model building and understanding the nature of CP symmetry and its breaking.

Operator	Loop order	Mass reach
Electron EDM	1	$48\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_e^{\max}}$
	2	$2\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_e^{\max}}$
Up/down quark EDM	1	$130\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_q^{\max}}$
	2	$13\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_q^{\max}}$
Up-quark CEDM	1	$210\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_u^{\max}}$
	2	$20\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_u^{\max}}$
Down-quark CEDM	1	$290\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_d^{\max}}$
	2	$28\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_d^{\max}}$
Gluon CEDM	2 ($\propto m_t$)	$22\,\text{TeV}\sqrt[3]{10^{-29}\,\text{cm}/(100\,\text{MeV})/\tilde{d}_G^{\max}}$
	2	$260\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/(100\,\text{MeV})/\tilde{d}_G^{\max}}$

Alarcon et al.: 2022
Snowmass Summer Study Report

New physics scale

$$d_f \sim e q_f \sin(\delta_{\rm CPV}) \left(\frac{g^2}{16\pi^2}\right)^l \xi_{\rm FV} \frac{m_f}{M_{\rm NP}^2} \qquad d_e \le d_e^{\rm max} \quad \Rightarrow \quad M_{\rm NP} \gtrsim \sqrt{\frac{10^{29} e \text{ cm}}{d_e^{\rm max}}} \times \begin{cases} 50 \text{ TeV}, & \text{if } l = 1 \\ 2 \text{ TeV}, & \text{if } l = 2 \end{cases}$$

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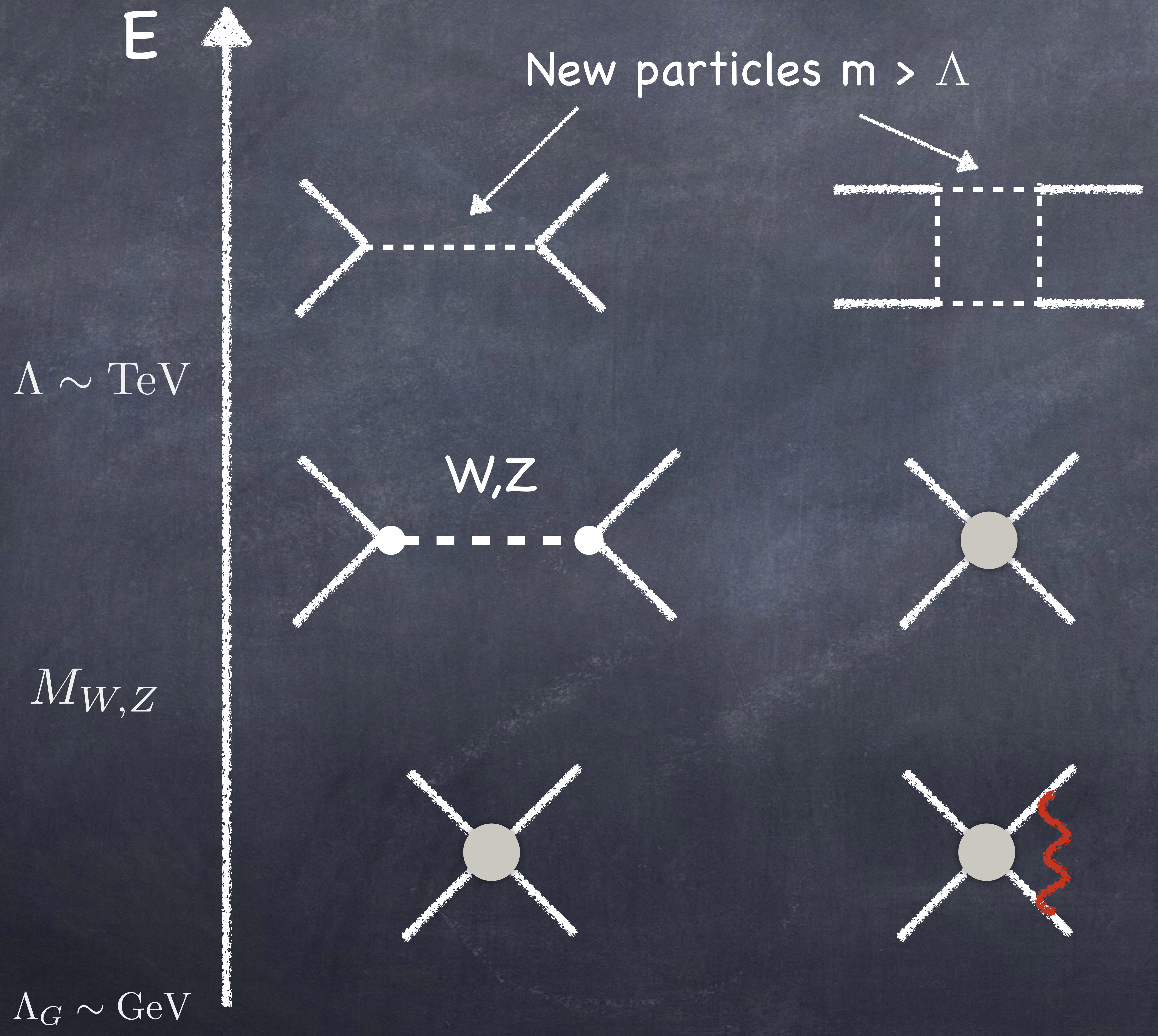
Alarcon et al.: 2022
Snowmass Summer Study Report

CP-violating effective operators

Cirigliano, Ramsey-Musolf: 2013

Engel, Ramsey-Musolf, Van Kolck: 2013



$$\mathcal{L}_{BSM}$$

$$\mathcal{L}_{SM} + \sum_{d\geq 5} \frac{\alpha_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}$$

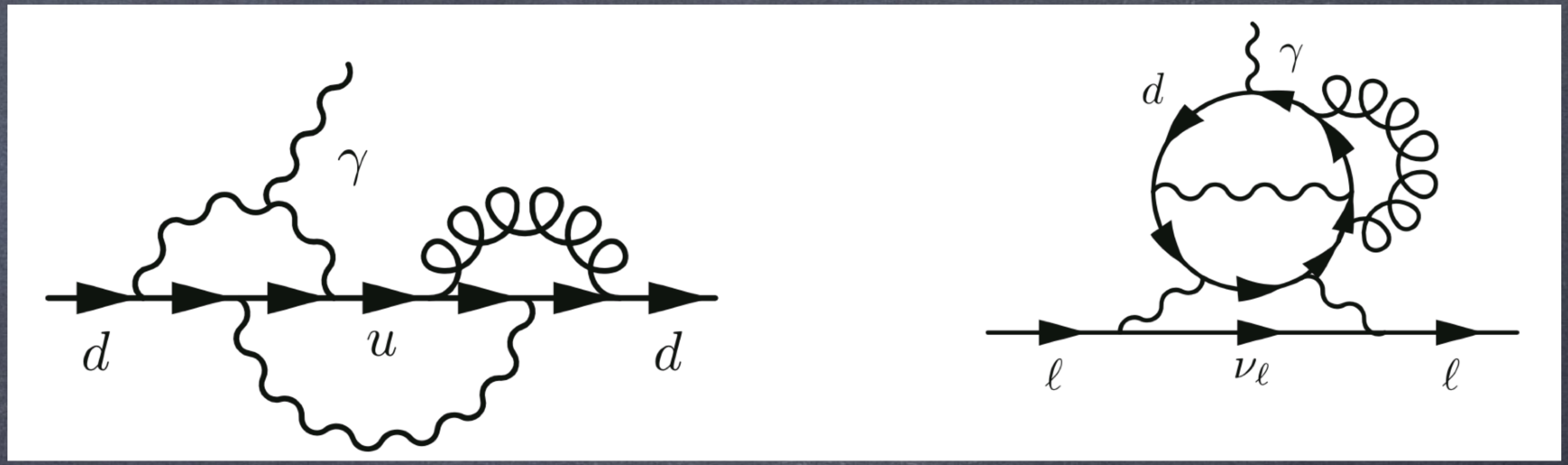
$$\mathcal{L}_{Fermi} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

$$+\mathcal{L}_{QCD} + \mathcal{L}_{QED}$$

EDM from the Standard Model

- No EDMs at 1-loop
- At 2-loops individual diagrams are non-zero, but the sum vanishes
- Quark EDM are induced at 3-loops
- Electron EDM are induced at 4-loops

Electron EDM can be larger due to hadronic loops
EDM of not elementary particles can be larger



Seng: 2015

EDM from the Standard Model

Shabalin: 1978-1980 Khriplovich, Zhitnitsky: 1982
Gavela et al. : 1982

- No EDMs at 1-loop
- At 2-loops individual diagrams are non-zero, but the sum vanishes
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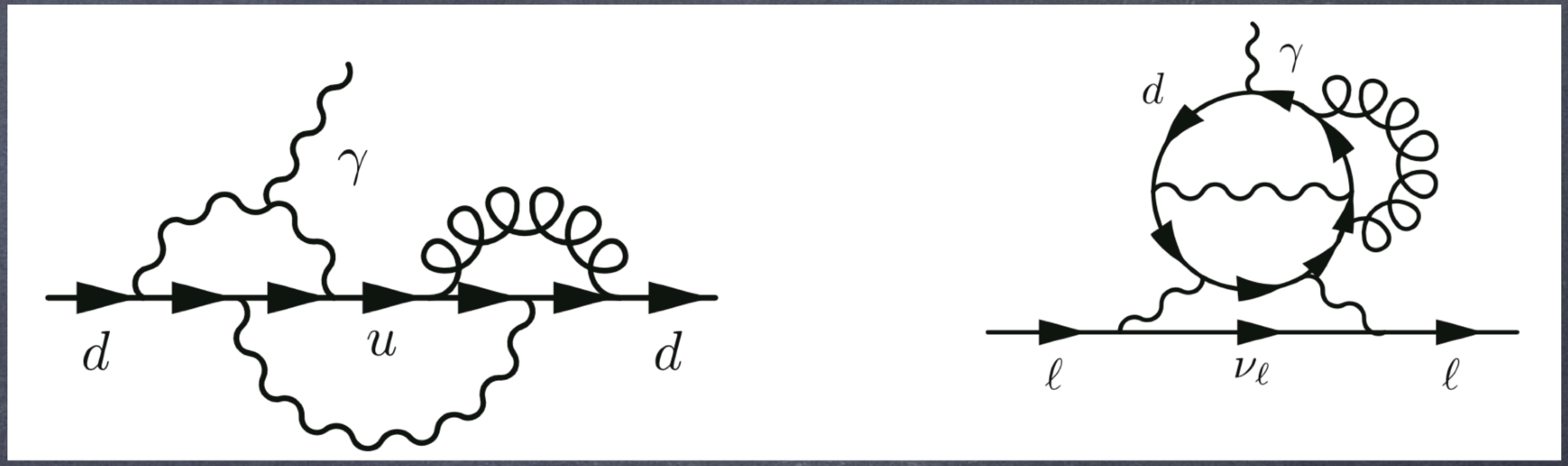
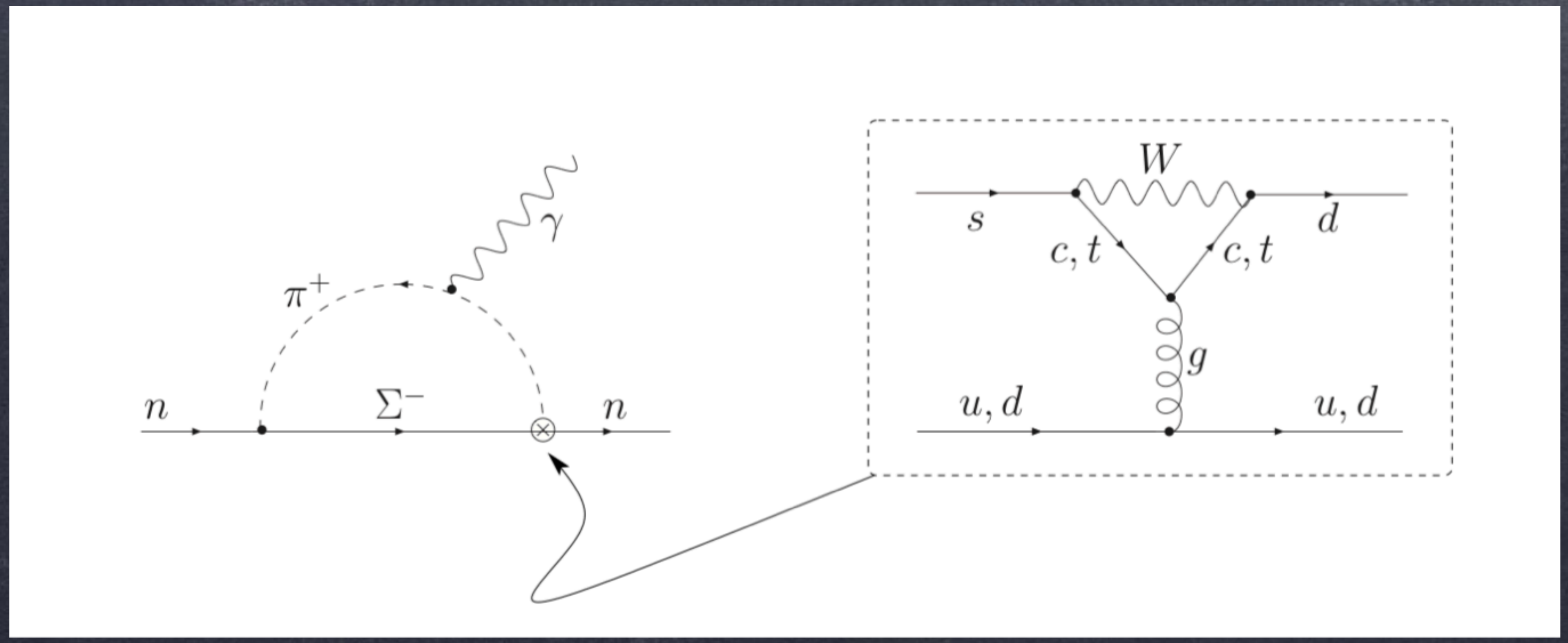


Electron EDM can be larger due to hadronic loops
EDM of not elementary particles can be larger

$$(d_n)_{\rm SM=(1-6)\times 10^{-32}} e \quad {\rm cm}$$

Seng: 2015

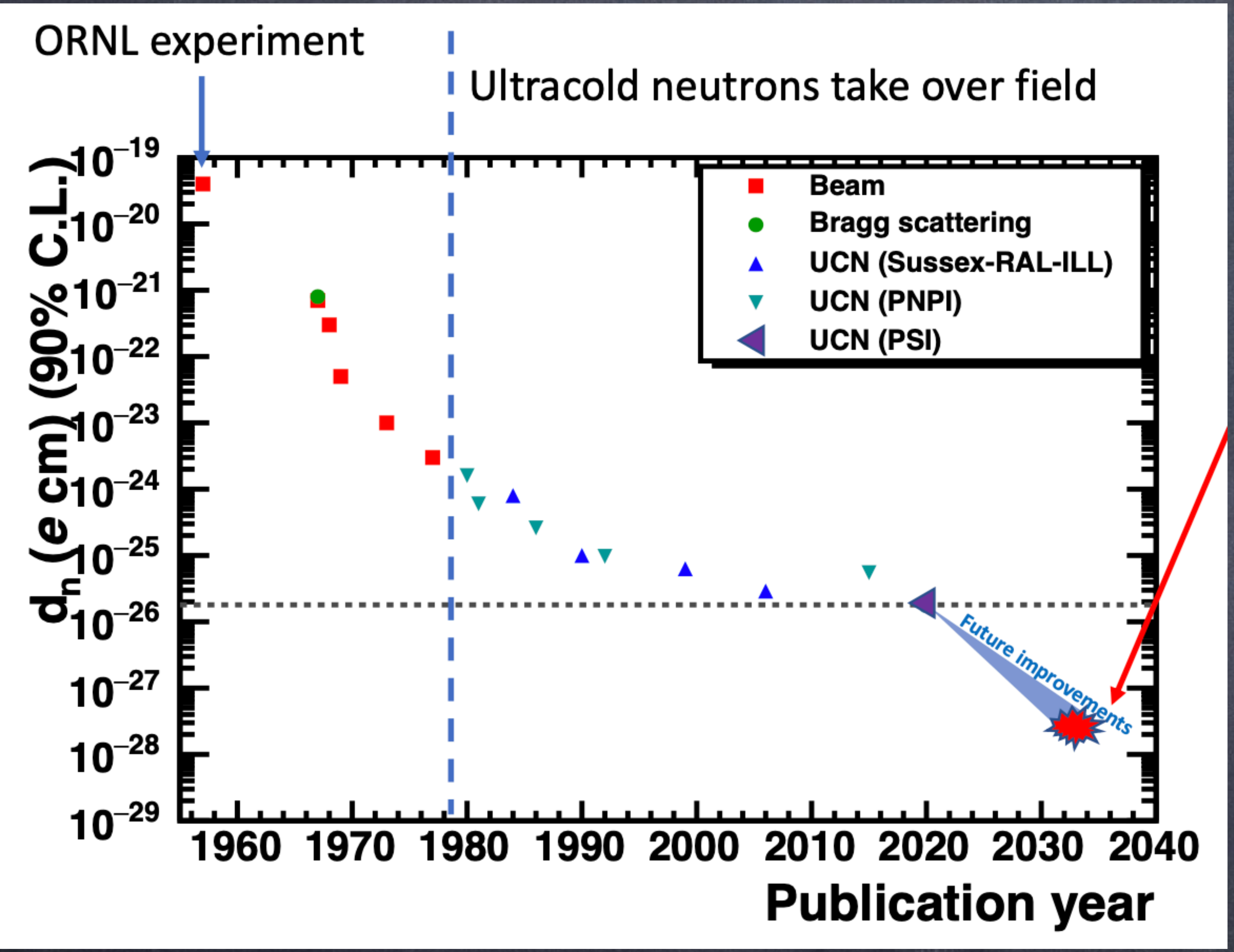


Neutron EDM

$|d_n| < 1.8 \times 10^{-26}$ e cm (90% C.L.)

Abel et al.: 2020 (PSI)

Alarcon et al.: 2022
Snowmass Summer Study Report



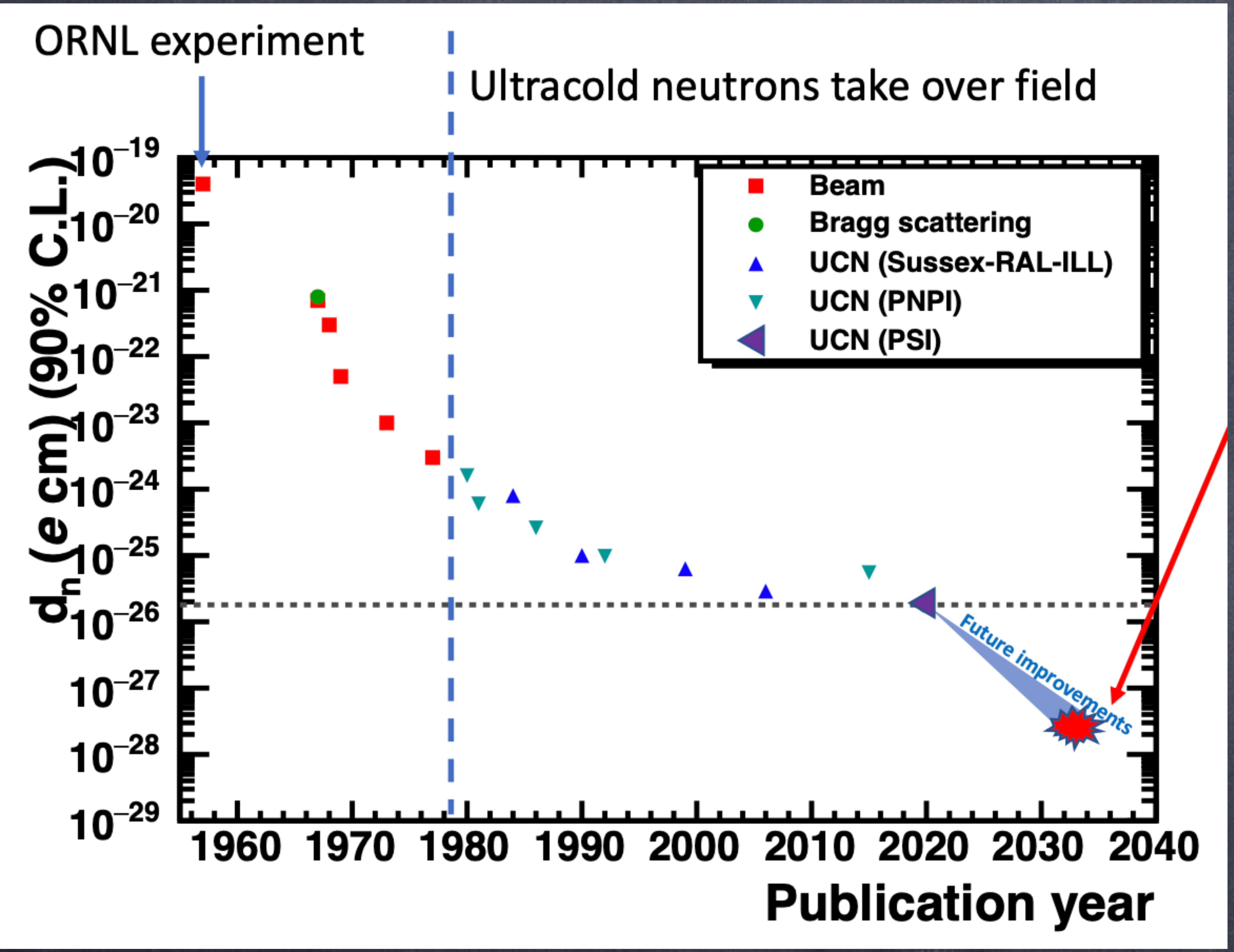
Experiment: Facility	Neutron Source	Measurement Cell	Measurement Techniques	90% C.L. (10^{-28} e-cm) With 300 Live Days	Year 90% C.L. Data Acquired
Crystal: JPARC	Cold Neutron Beam	Solid	Crystal Diffraction (High Internal $\vec{E}$)	< 100	Development
Beam: ESS	Cold Neutron Beam	Vacuum	Pulsed Beam	< 50	~ 2030
PNPI: ILL	ILL Turbine (UCN) PNPI/LHe (UCN)	Vacuum	Ramsey Technique, $\vec{E} = 0$ Cell for Magnetometry	Phase 1 < 100 < 10	Development Development
n2EDM: PSI	Solid D_2 (UCN)	Vacuum	Ramsey Technique, External Cs Magnetometers, Hg Co-Magnetometer	< 15	~ 2026
PanEDM ILL/Munich	Superfluid ^{4}He (UCN), Solid D_2 (UCN)	Vacuum	Ramsey Technique, Hg Co-External ^{3}He and Cs Magnetometers	< 30	~ 2026
TUCAN: TRIUMF	Superfluid ^{4}He (UCN)	Vacuum	Ramsey Technique, Hg Co-Magnetometer, External Cs Magnetometers	< 20	~ 2027
nEDM: LANL	Solid D_2 (UCN)	Vacuum	Ramsey Technique, Hg Co-Magnetometer, Hg External Magnetometer, OPM	< 30	~ 2026
nEDM@SNS: ORNL	Superfluid ^{4}He (UCN)	^{4}He	Cryogenic High Voltage, ^{3}He Capture for ω, ^{3}He Co-Magnetometer with SQUIDs, Dressed Spins, Superconducting Magnetic Shield	< 20 < 3	~ 2029 ~ 2031

Neutron EDM

$|d_n| < 1.8 \times 10^{-26}\ e\ \text{cm}\ (90\%\ \text{C.L.})$

Abel et al.: 2020 (PSI)

Alarcon et al.: 2022
Snowmass Summer Study Report



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nEDM@SNS: ORNL	Superfluid ^{4}He (UCN)	^{4}He	Cryogenic High Voltage, ^{3}He Capture for ω, ^{3}He Co-Magnetometer [illegible], Dressed Spins, Superconducting Magnetic Shield	< 20 < 3	~ 2029 ~ 2031

Quark-Chromo EDM: power divergences

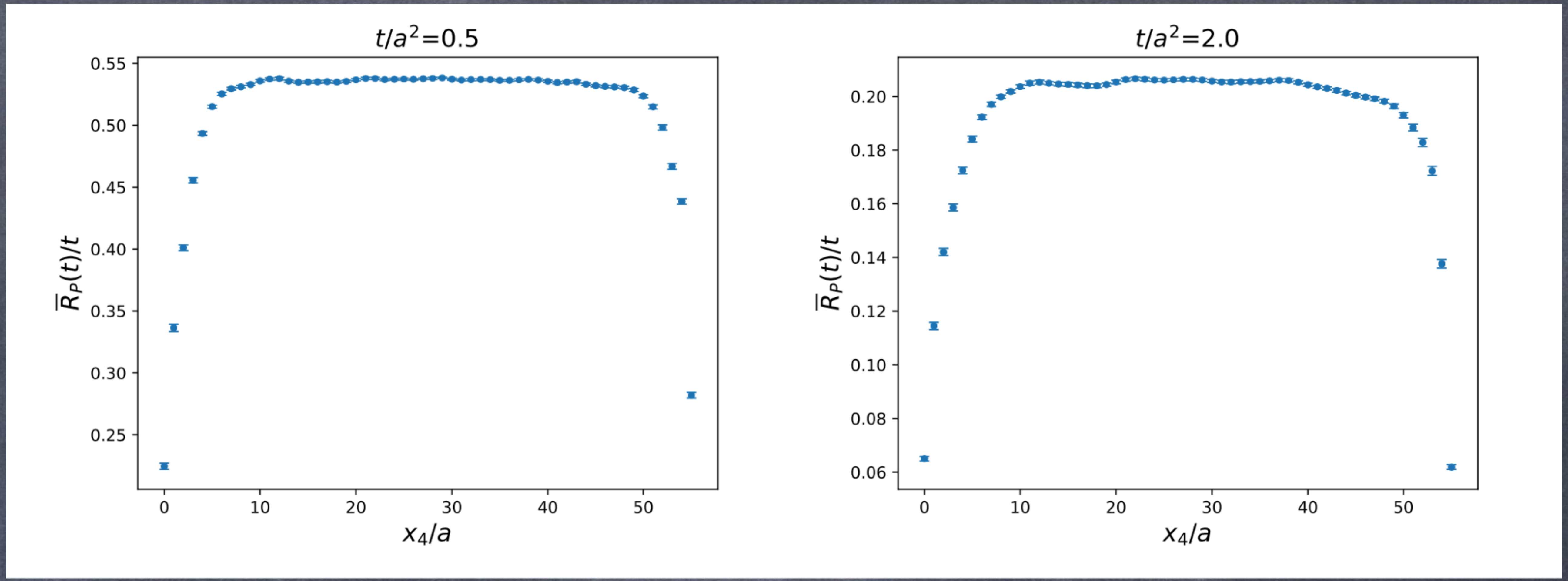
Kim, Luu, Rizik, A.S.:2020

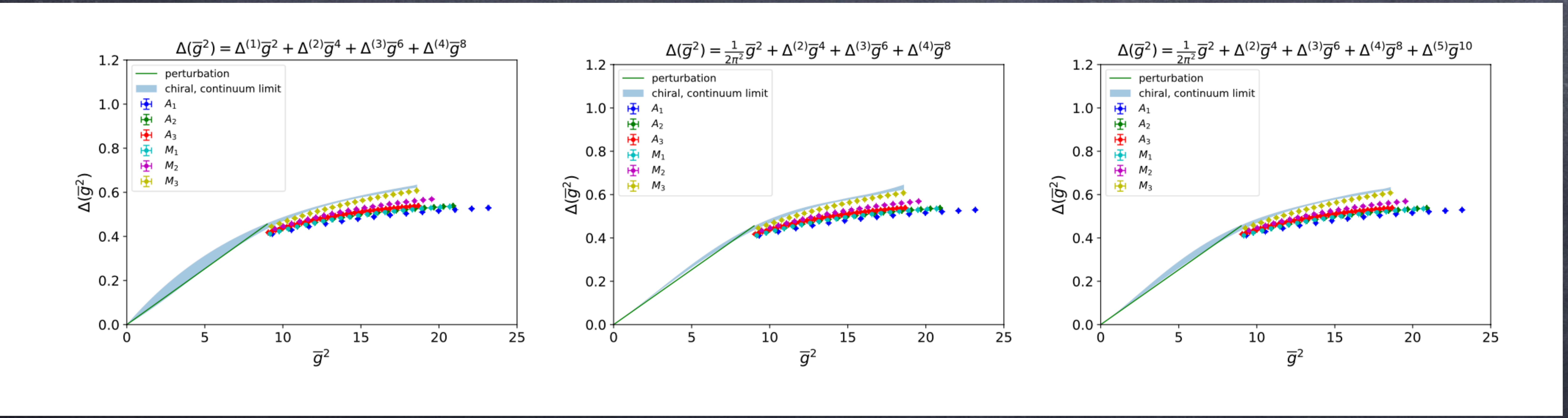
$$\mathcal{O}_{\mathrm{CE,R}}(t) = \frac{c_{\mathrm{OP}}(t,\mu)}{t} P_{\mathrm{R}}(0,\mu) + \sum_i c_{\mathrm{CE},i}(t,\mu)\mathcal{O}_{i,\mathrm{R}}(0,\mu)$$

$$\Gamma_{CP}(x_4;t) = a^3 \sum_{\mathbf{x}} \left\langle \mathcal{O}^{ij}_{CE}(x_4,\mathbf{x};t) P^{ji}(0,\mathbf{0};0) \right\rangle$$

$$\Gamma_{PP}(x_4;t) = a^3 \sum_{\mathbf{x}} \langle P^{ij}(x_4,\mathbf{x};t) P^{ji}(0,\mathbf{0}) \rangle$$

$$\overline{R}_{\mathrm{P}}(x_4;t) = t\frac{\Gamma_{\mathrm{CP}}(x_4;t)}{\Gamma_{\mathrm{PP}}(x_4,t)}$$





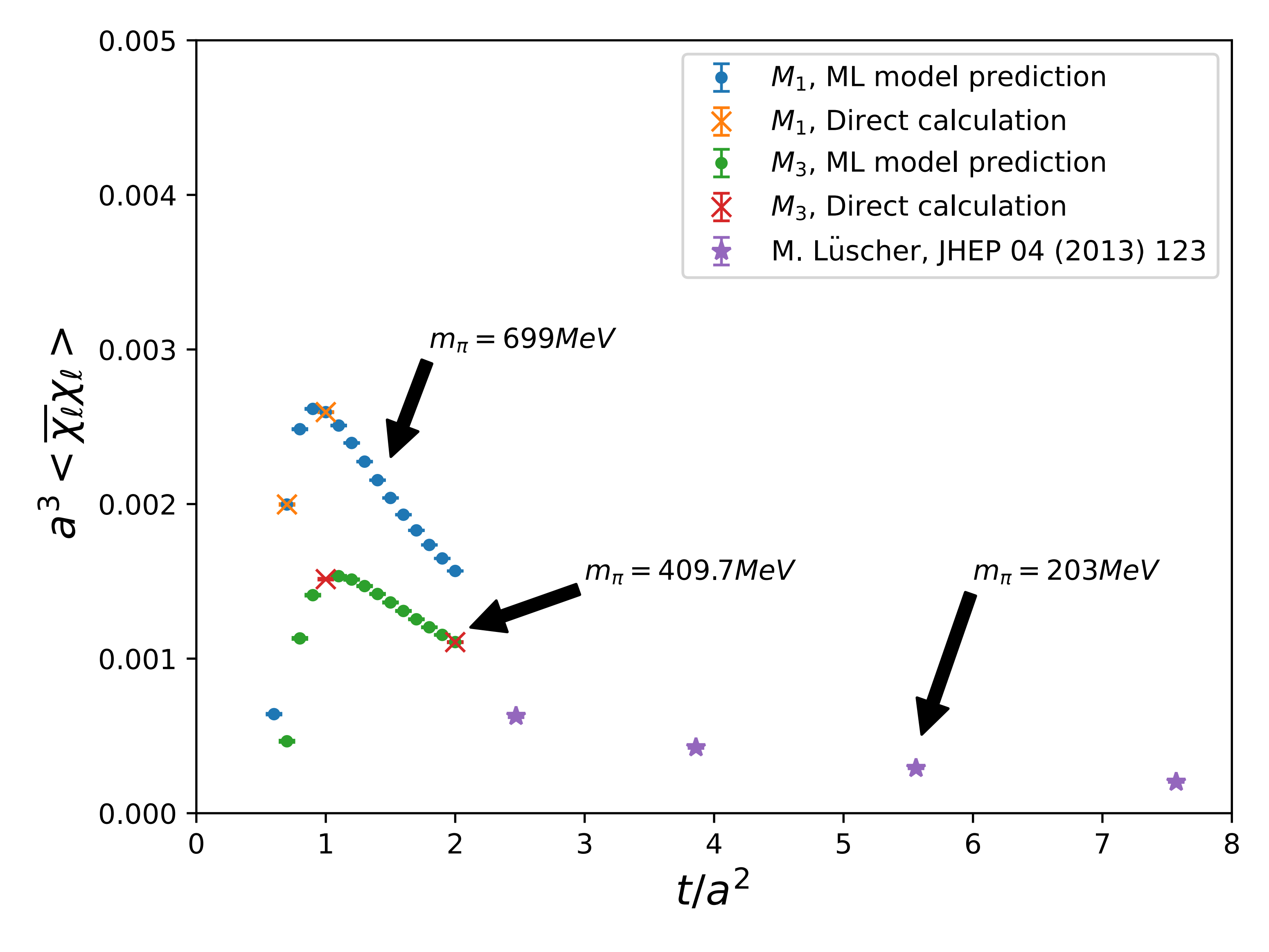
SYMLAT Status

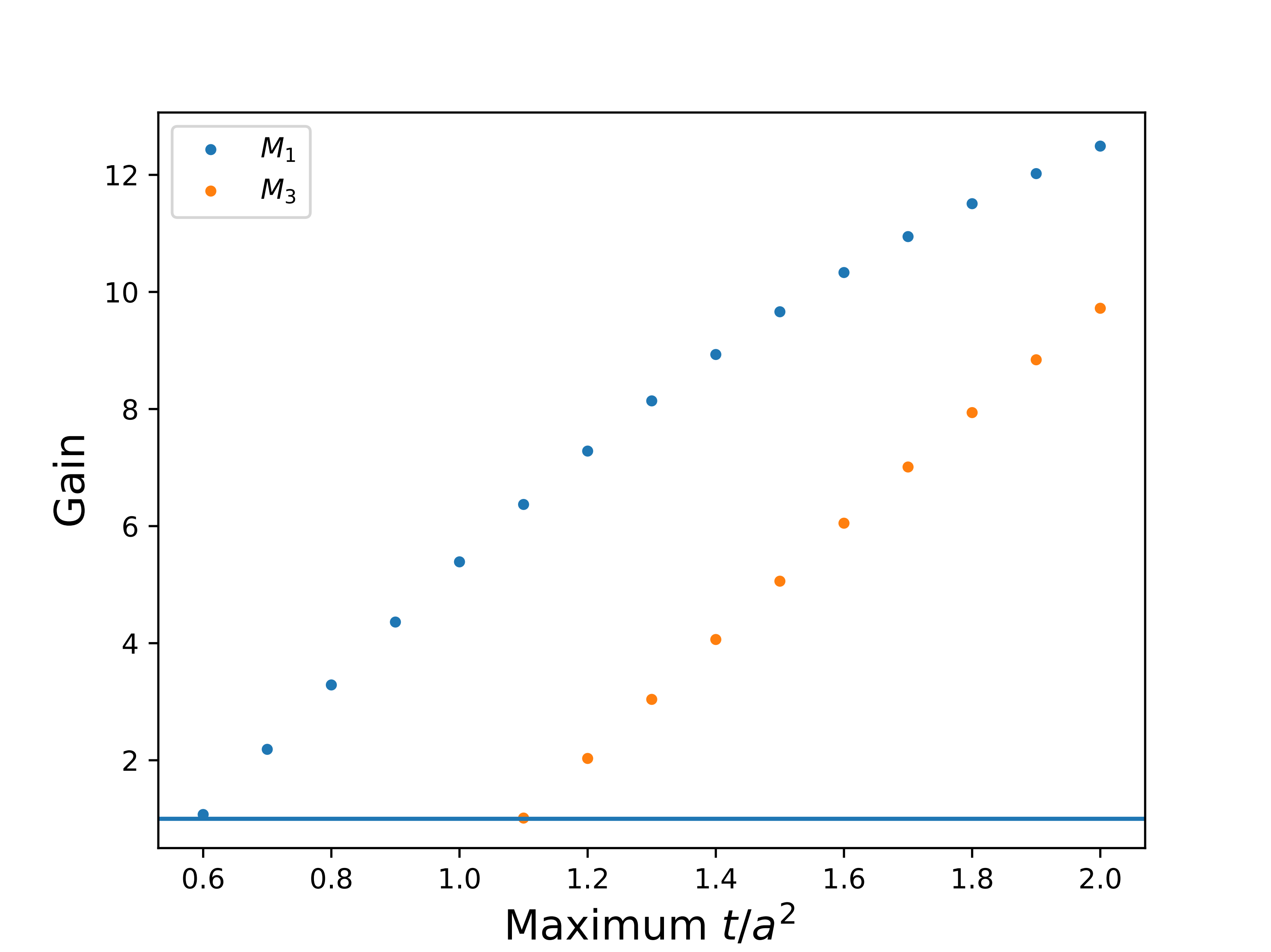
- Theta-term nucleon EDM —> first results 1409.2735 1507.02343 1809.03487 1902.03254
    - Renormalization, S/N
- Quark-chromo EDM —> renormalization
    - Power divergences —> PT 1810.05637 2005.04199 2111.1149
      Non-perturbative 1810.10301 2106.07633
    - Logs/mixing —> 2111.1149 2212.09824
- 3 gluon operator —> PT power divergences 2005.04199
  Preliminary studies for renormalization (power divergences) 1711.04730 1810.05637
  —> Logs/mixing 2308.16221

Scalar condensate

Kim, Pederiva, A.S.: 2024

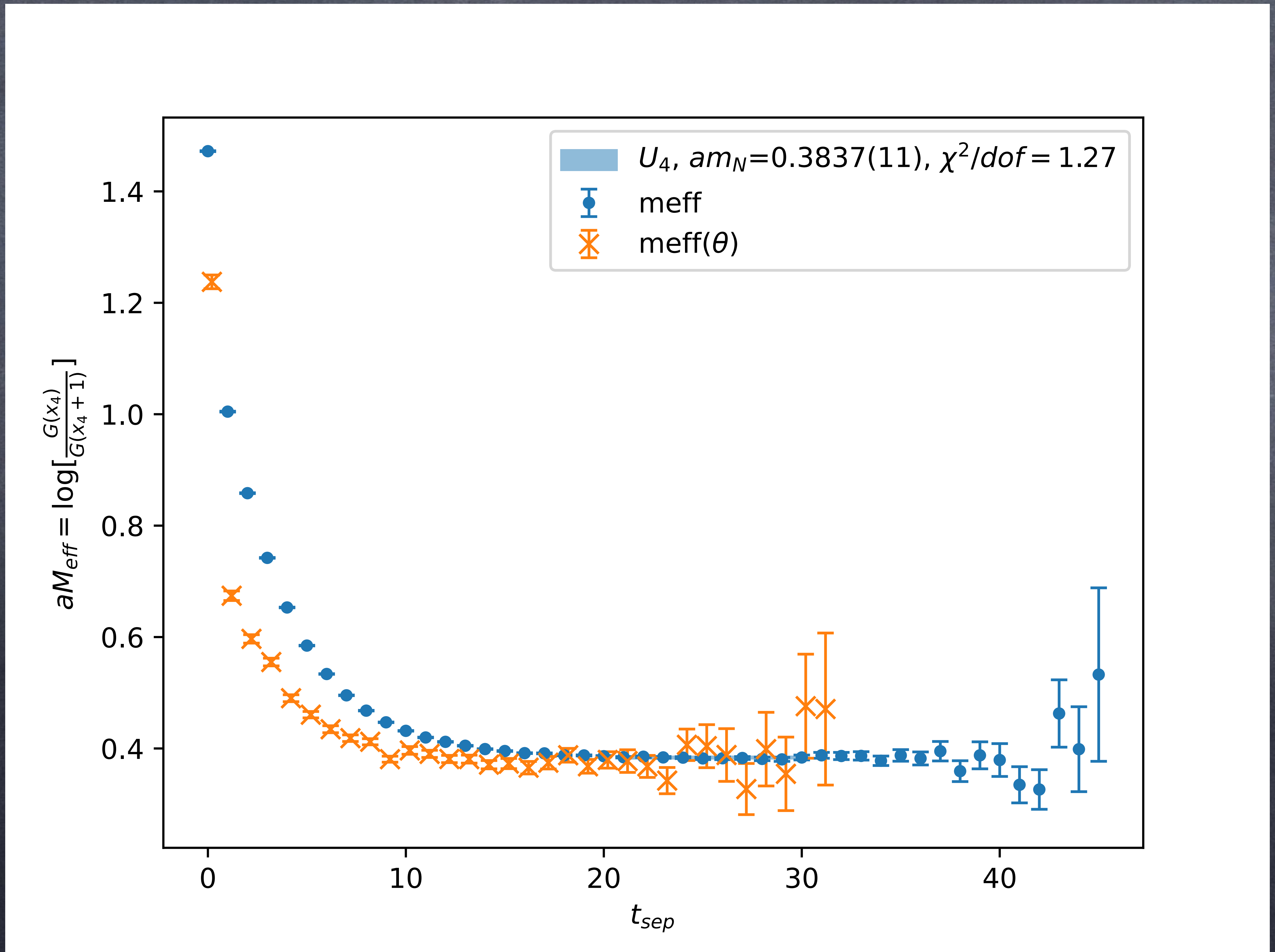
- Strong correlation between quark disconnected diagrams at different flow times
- Use of translation invariance beneficial
- Decision Tree algorithms reproduces correct distribution
- Results are compatible well below the statistical fluctuations of the lattice QCD direct calculation
- No need to large ensemble for training making use of time translation invariance





Theta-term dependence

$$\mathrm{tr}\left[P_+ G_{NN}\right] = 2|Z_N|^2 \mathrm{e}^{-M_N x_0} + \dots \qquad \mathrm{tr}\left[P_+ \gamma_5 G^Q_{NN}\right] = 2|Z_N|^2 \alpha_N \mathrm{e}^{-M_N x_0} + \dots$$



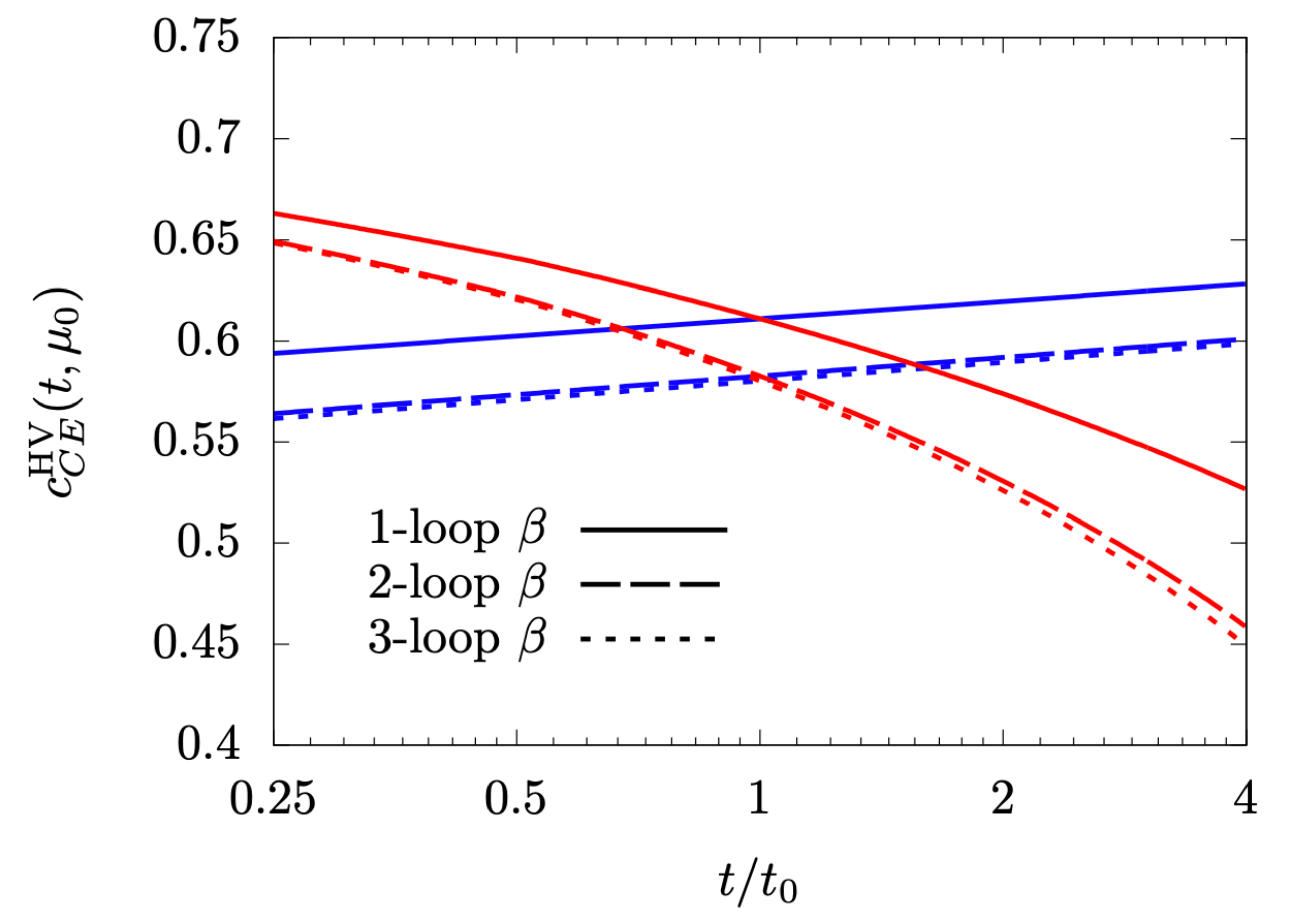
Scale dependence matching coefficients

$\bar{\mu}_0 = 3 \text{ GeV} \rightarrow \mu_0 = 1.13 \text{ GeV}$

$$t_0 = \frac{1}{8\pi\mu_0^2}$$

Red - Blue =

$$A_1 \alpha_s^2(\mu_0^2) \log^2(8\pi t \mu_0^2) + A_2 \alpha_s^2(\mu_0^2) \log(8\pi t \mu_0^2) + O(\alpha_s^3)$$

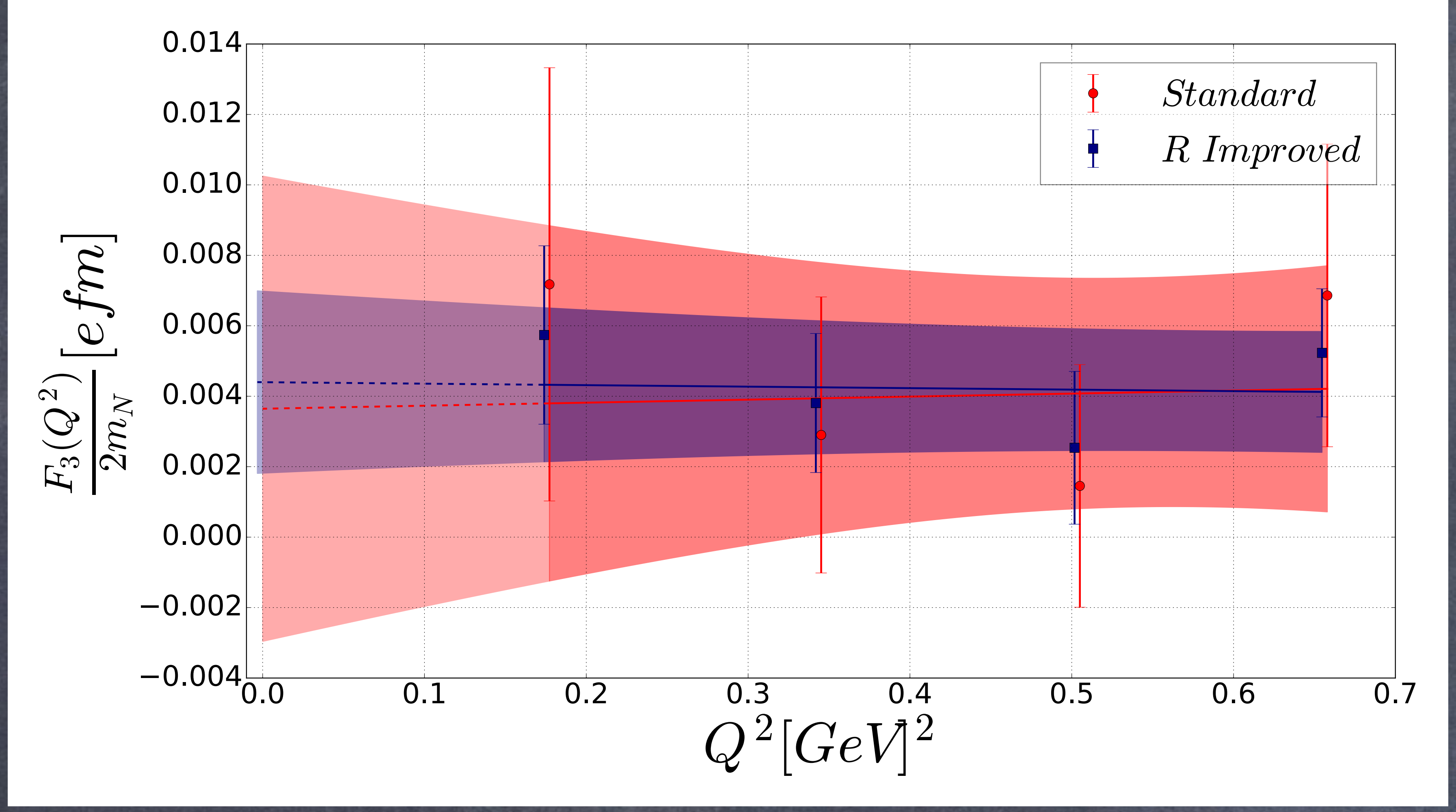


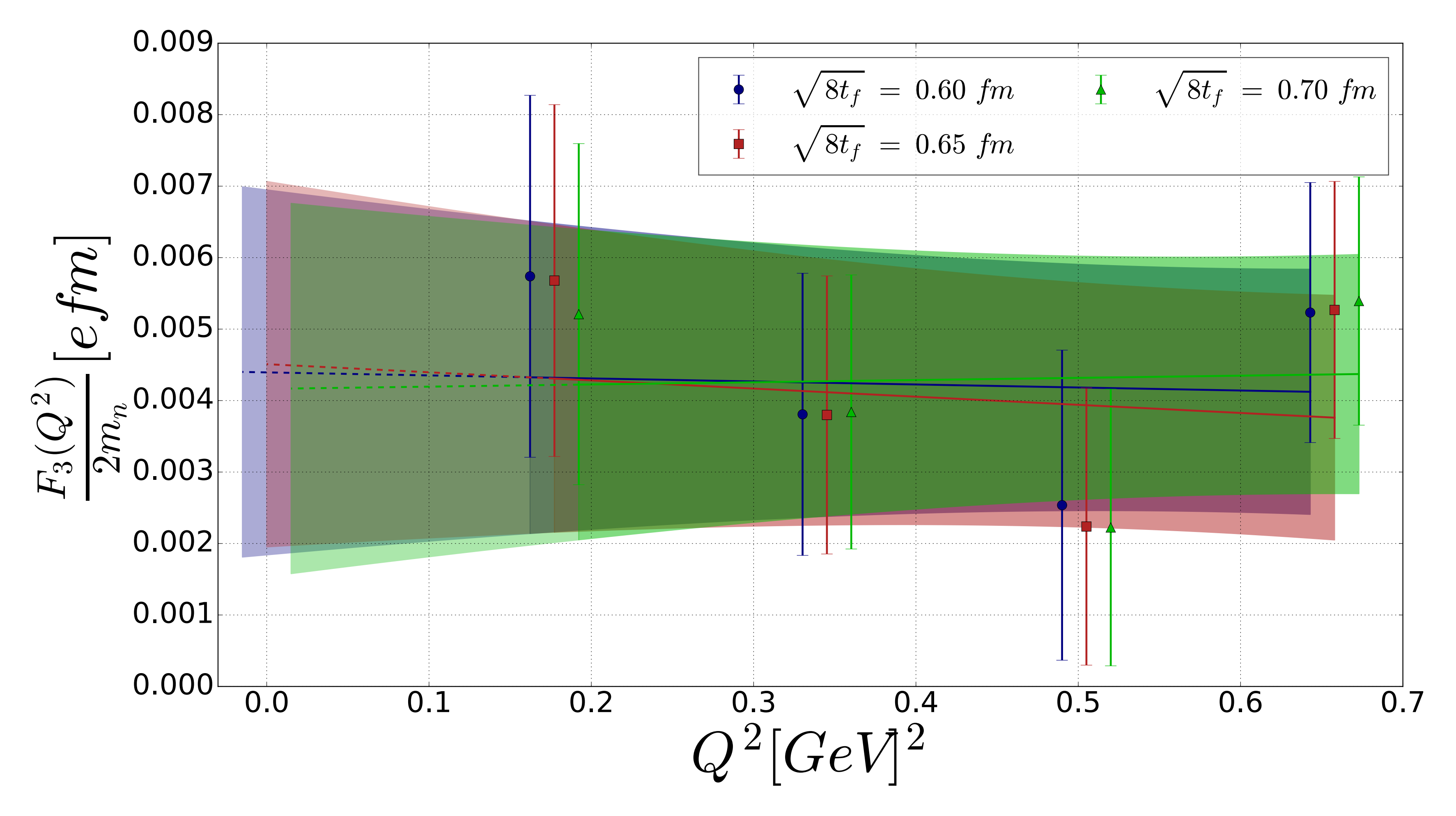
$t \in [t_0/4, 4t_0]$

10%-20% uncertainties from PT at 1-loop

CP-odd form factor

Dragos, Luu, A.S., de Vries, Yousif: 2019





$$\frac{F_3^{P/N}(Q^2)}{2M_N} = d_{P/N} + S_{P/N}Q^2 + H_{P/N}(Q^2)$$

$$\frac{d_P}{d_N} < 0 \qquad \frac{S_P}{S_N} < 0$$

Mereghetti et al.: 2011

Topological charge on the lattice

Discretize ⟶ $$q(x) = \frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\mathrm{tr}\left\{G_{\mu\nu}(x)G_{\rho\sigma}(x)\right\}$$

Continuity in space is lost
On the lattice it has no topological significance

Geometrical definition:

extend the lattice gauge field to a continuous one
Field between lattice points -> judicious interpolation
Smooth gauge fields (bound on field tensor)

Lüscher: 1982
Phillips, Stones: 1986

Fermionic definition:

Anomalous Ward Identity

Smit: 1980

$$\partial_\mu A_\mu = 2mP + \text{extra terms}$$

$$\partial_\mu A_\mu = 2mP + 2iN_f q_L$$

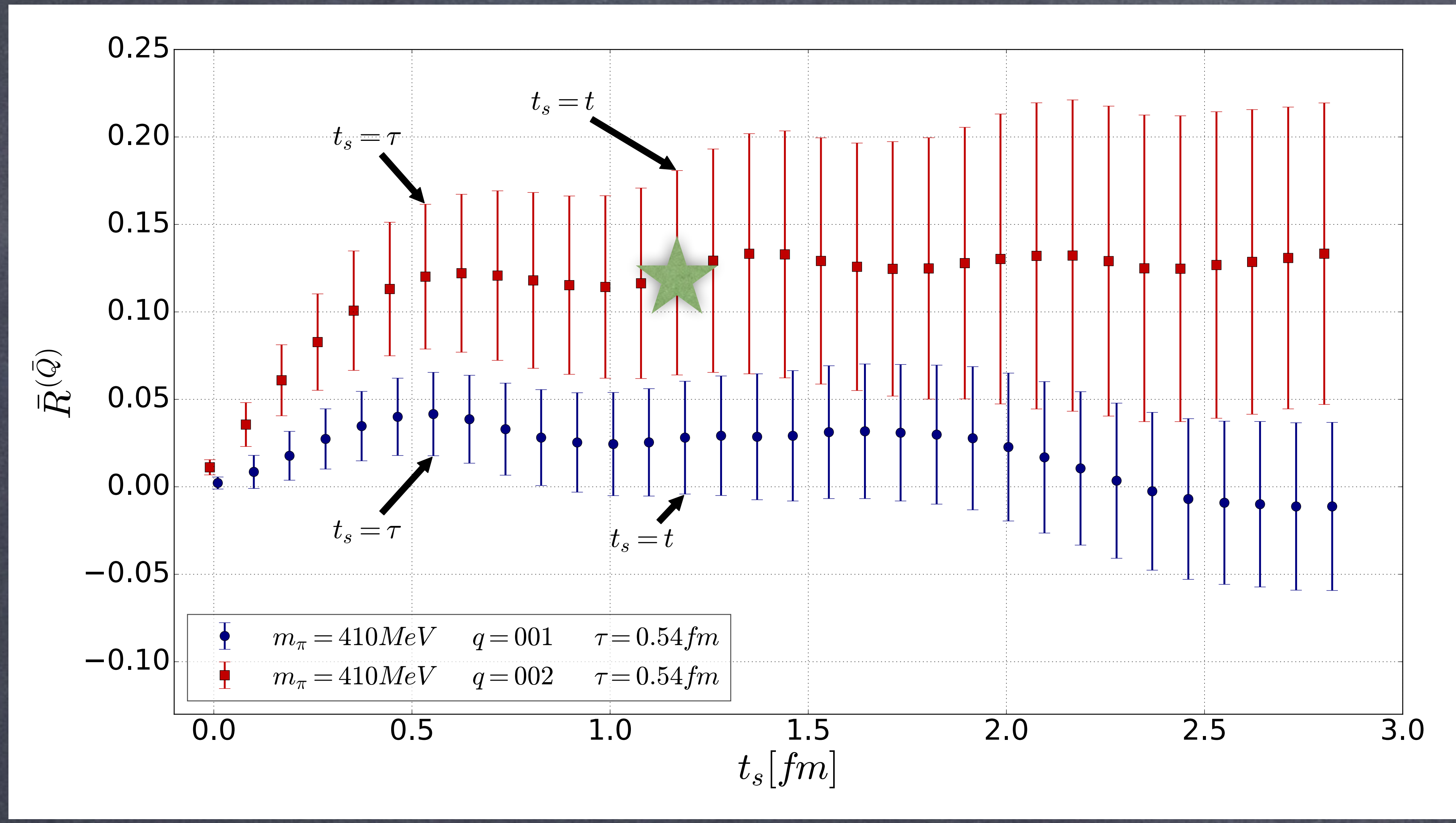
$$Q_L \propto m \sum_x \mathrm{Tr}\left(\gamma_5 S\right)$$

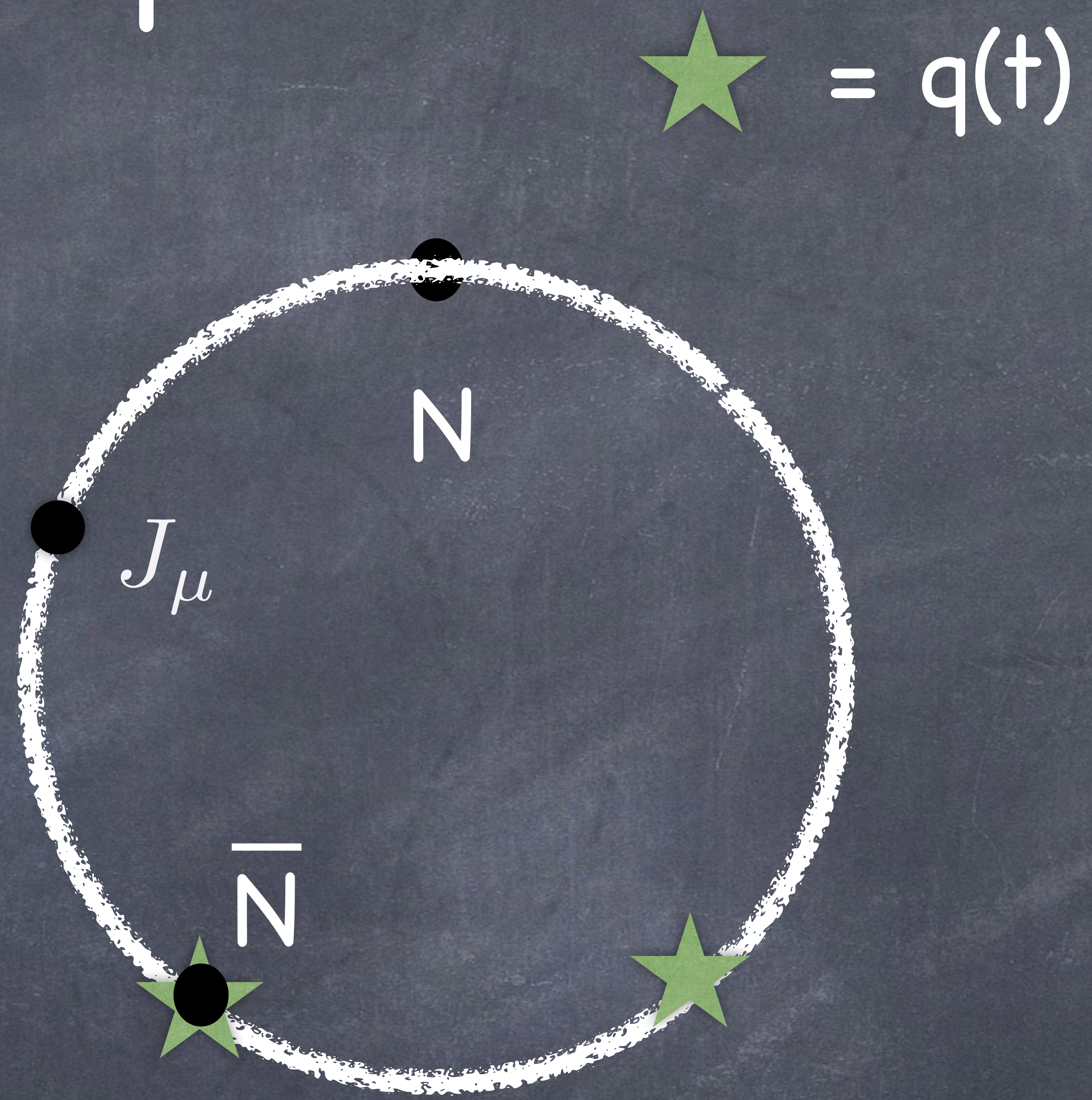
Atiyah, Singer: 1971

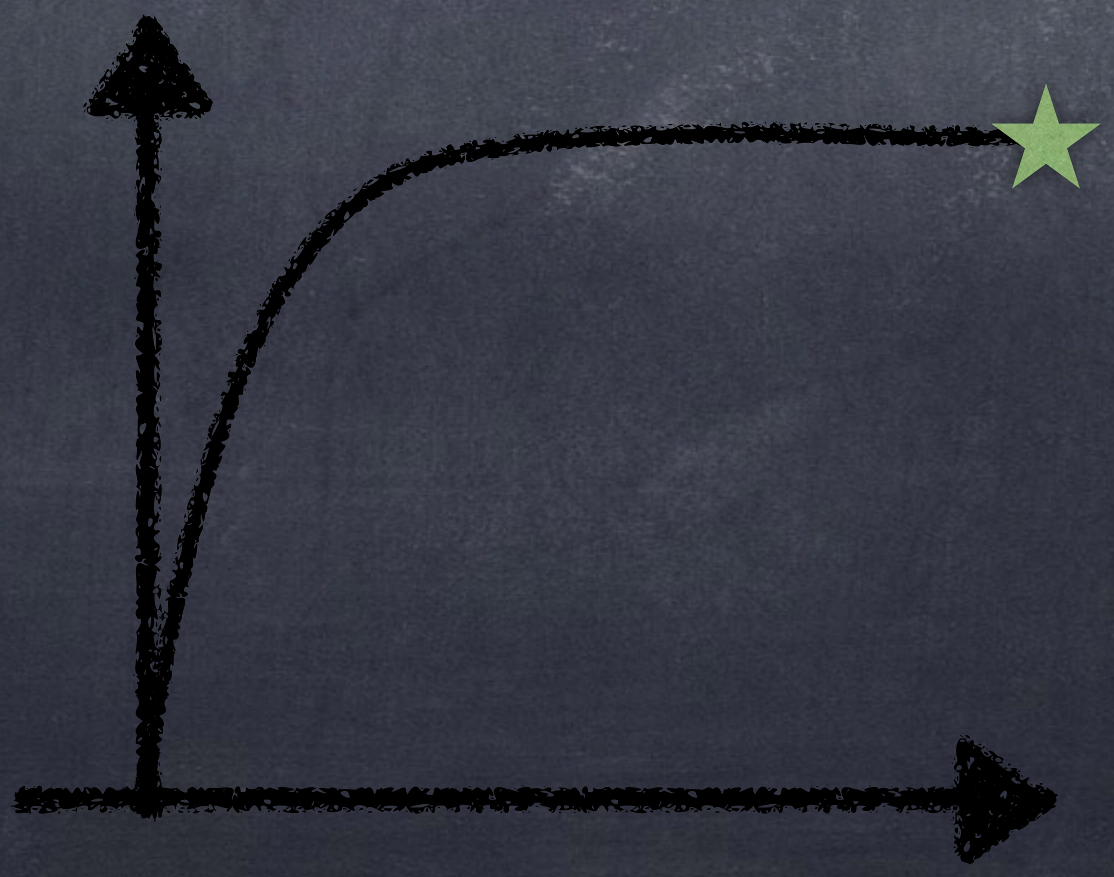
$$Q = n_+ - n_-$$

P. Hasenfratz: 1998
P. Hasenfratz, Laliena, Niedermeyer: 1998

Signal-to-noise improvement



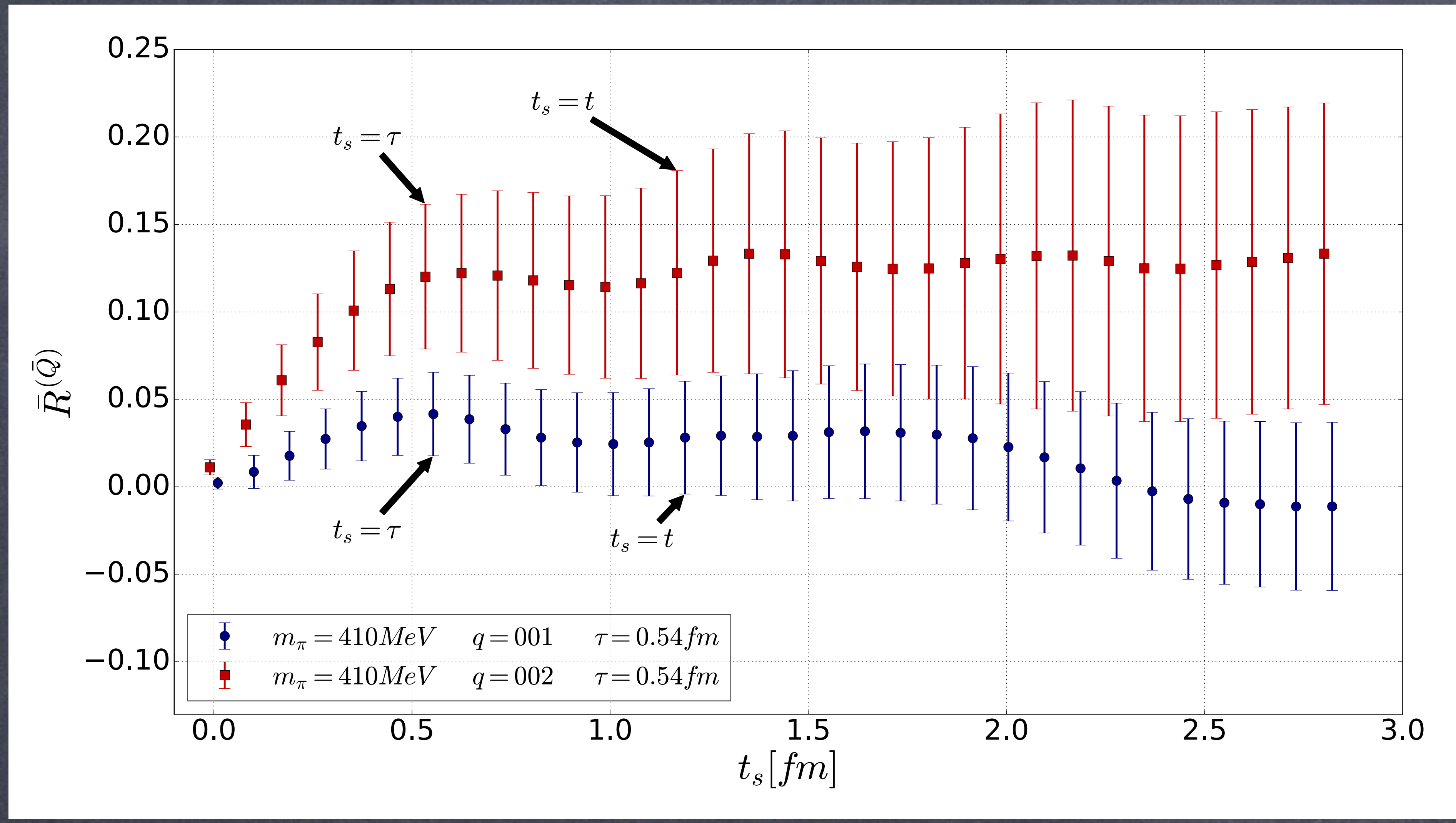


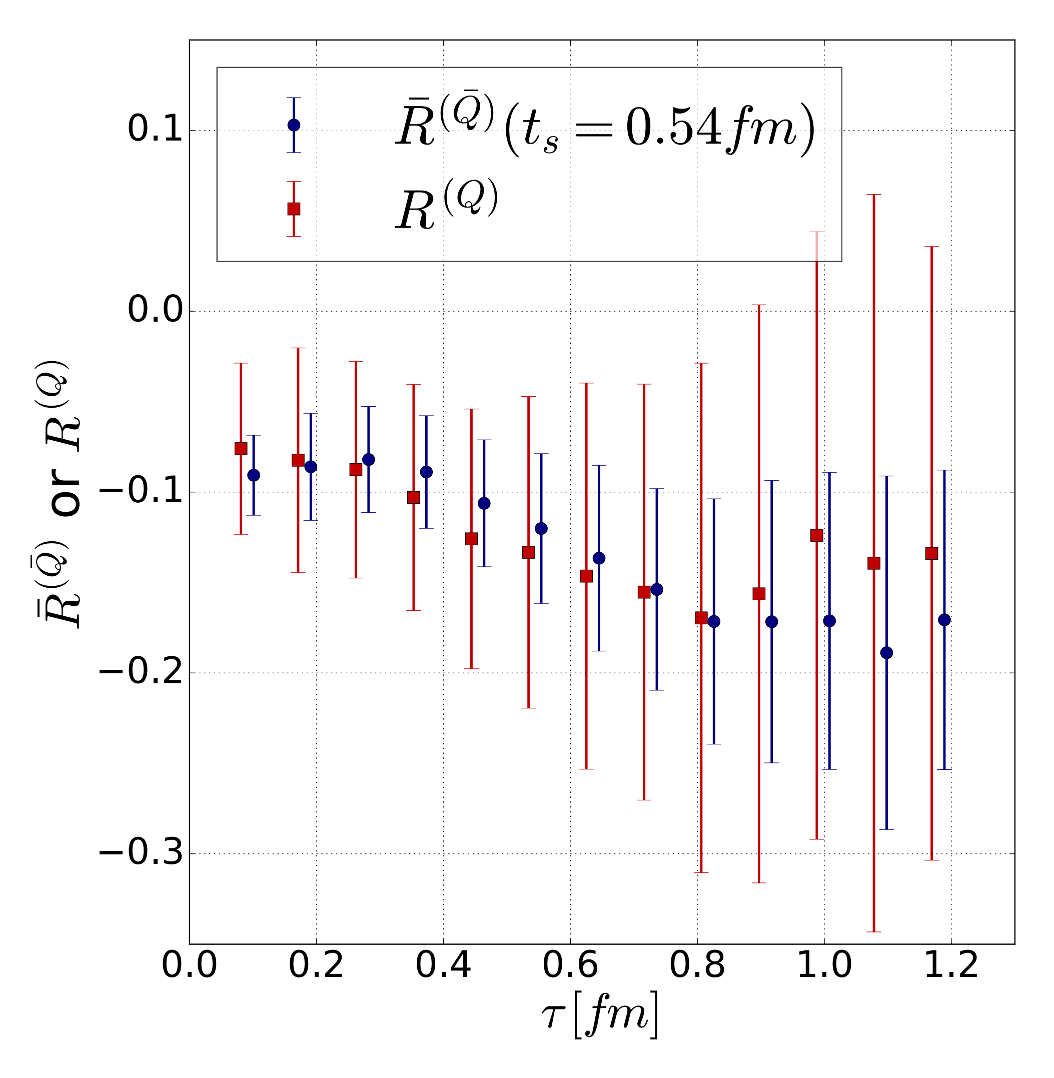


$$R^Q = \frac{G_3^Q(t, \tau, t_f; \underline{p}', \underline{q})}{G_2(\underline{p}', t)} \cdot K(t, \tau; \underline{p}', \underline{q})$$

Dragos, Luu, A.S.,
de Vries, Yousif: 2019

Signal-to-noise improvement





$$R^Q = \frac{G_3^Q(t,\tau,t_f;\underline{p}',\underline{q})}{G_2(\underline{p}',t)} \cdot K(t,\tau;\underline{p}',\underline{q})$$

Dragos, Luu, A.S.,
de Vries, Yousif: 2019