Nucleon & Nuclear Structure Inputs to Beyond-SM Searches

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SNOWMASS Rare Processes & Precision Frontier
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- Nucleon Charges & Form Factors
  - *Beyond-SM Contributions to neutron decays*
  - *Dark Matter searches*
  - *Lepton Flavor Violation*
- Nucleon/Nuclear Electric Dipole Moments
  - *nEDM from quark EDMs*
  - *Intrinsic nucleon moments from θ_{QCD}*
    and quark & gluon chromoEDMs
- Baryon number violation
  - *Proton decay*
  - *Neutron-antineutron oscillations*
- Neutrinoless double-beta decay
  - *Short- and Long-range Lepton Number Violation*
  - *Charged Pion Transition Amplitudes*
  - *Pion Annihilation Amplitudes*

Nucleon (q̄Γq) M.E's: Neutrinos & β-decay

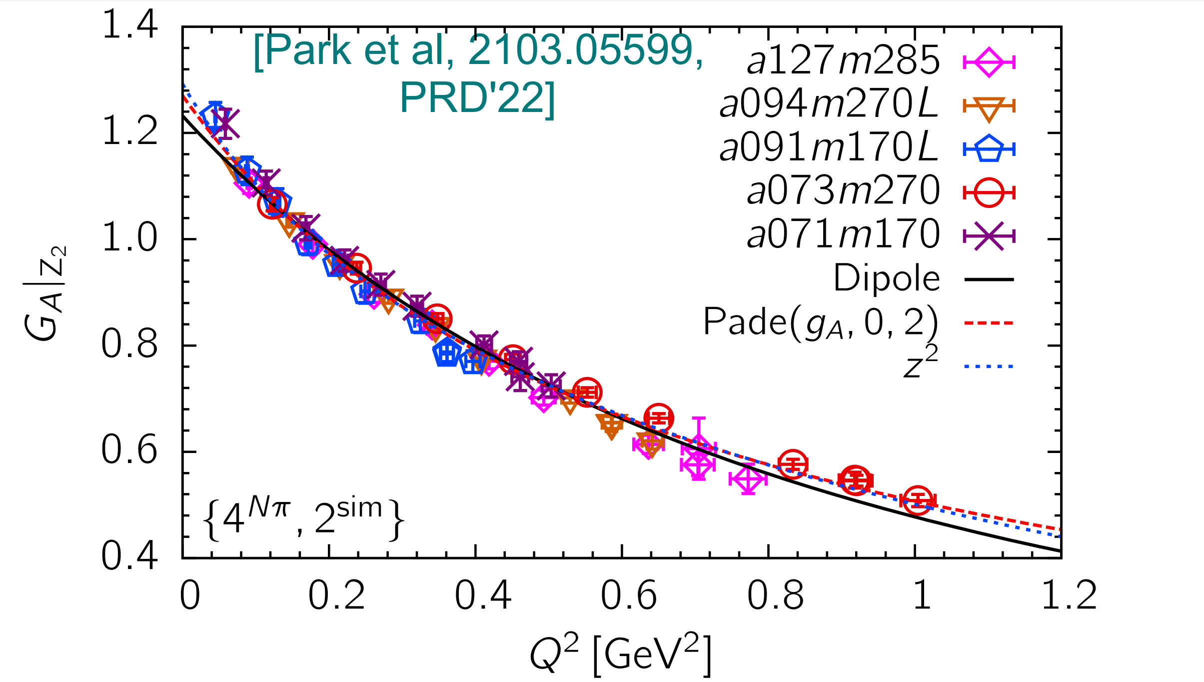
$$\langle p+q|\bar{q}\gamma_\mu\gamma_5 q|p\rangle = \bar{u}'\left[G_A\gamma_\mu + \tilde{G}_P\frac{q_\mu}{M}\right]\gamma_5 u$$

$$\langle p+q|\bar{q}\gamma_5 q|p\rangle = G_P\bar{u}'\gamma_5 u$$

$$\langle p|\bar{q}q|p\rangle = g_S\bar{u}'u$$

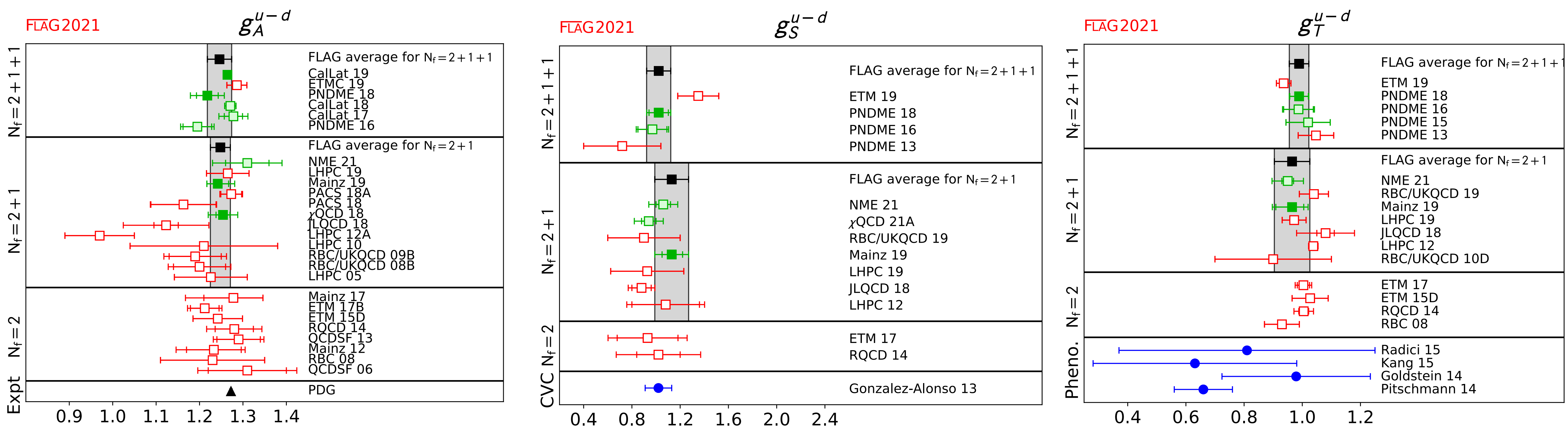
$$\langle p|\bar{q}\sigma_{\mu\nu}q|p\rangle = g_T\bar{u}'\sigma_{\mu\nu}u$$

- Axial form factors $G_A(Q^2)$: QE neutrino scattering
- isovector g_A : neutron β-decay
- g_S, g_T : sensitivity of β-decay to Beyond-SM physics



- ***Ongoing controversy on excited-state contamination in single-nucleon ME: e.g. Nπ states required for PCAC***
- ***Much harder problem in light nuclei***

[Y.Aoki et al, FLAG'21 2111.09849]



Nucleon ($\bar{q}\Gamma q$) M.E's: DM, LFV, CPv Sensitivity

- DM direct detection:
  scalar, fermion DM EFT couplings
  ~$g_{A,S,P,T}$, ⟨GG⟩, ⟨G$\tilde{G}$⟩

Example: scalar dark matter couplings
[Bishara et al 1707.06998]

$$\mathcal{Q}_{1,q}^{(6)} = (\varphi^* i\overset{\leftrightarrow}{\partial}_\mu \varphi)(\bar{q}\gamma^\mu q)\,, \qquad \mathcal{Q}_{2,q}^{(6)} = (\varphi^* i\overset{\leftrightarrow}{\partial}_\mu \varphi)(\bar{q}\gamma^\mu \gamma_5 q)\,,$$

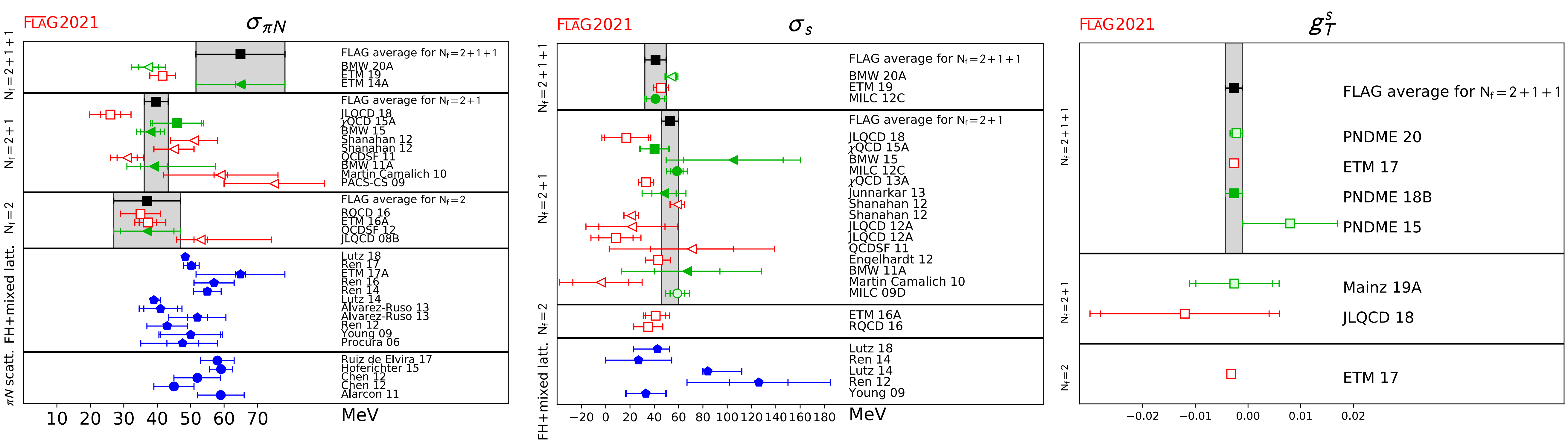
$$\mathcal{Q}_{3,q}^{(6)} = m_q(\varphi^*\varphi)(\bar{q}q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = m_q(\varphi^*\varphi)(\bar{q}i\gamma_5 q)\,,$$

$$\mathcal{Q}_{5}^{(6)} = \frac{\alpha_s}{12\pi}(\varphi^*\varphi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_{6}^{(6)} = \frac{\alpha_s}{8\pi}(\varphi^*\varphi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,.$$

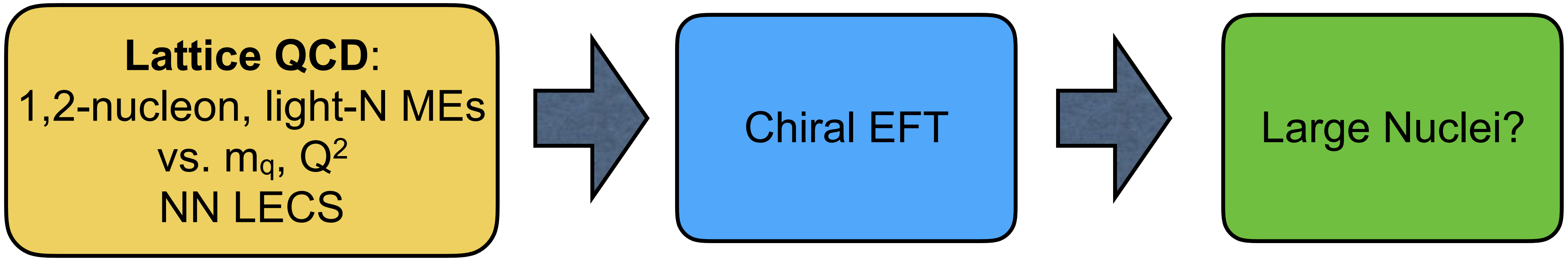
- Lepton Flavor violation
  μ→e conversion EFT couplings
  ~$G_{V,A,S,P,T}(Q^2 = -(m_\mu)^2)$, ⟨GG⟩

- g_T : CP violation in nucleon EDM from quark EDM

[Y.Aoki et al, FLAG'21 2111.09849]



Nuclear M.E's: Summary / Challenges



Single-nucleon matrix elements

- Quark matrix elements ($\bar{q}\Gamma q$) : ***precision results available***
  - persistent doubt about excited states
- Gluon matrix elements $\langle GG\rangle$, $\langle G\tilde{G}\rangle$ ~ ***straightforward (albeit expensive)***
  - Noise(Gluon observables) » Noise (Quark observables)
  - mixing with isoscalar quark densities
- Momentum dependence (form factors): ***straightforward***
  - large V_3 for small momentum transfer $Q^2 \lesssim 0.1\ \mathrm{GeV}^2$

Two-nucleon and light-nuclei MEs

- at the physical point: ***challenging***
  - dense spectrum of excitations
  - multiple-volume dependence needed

2-body amplitude of local interaction:

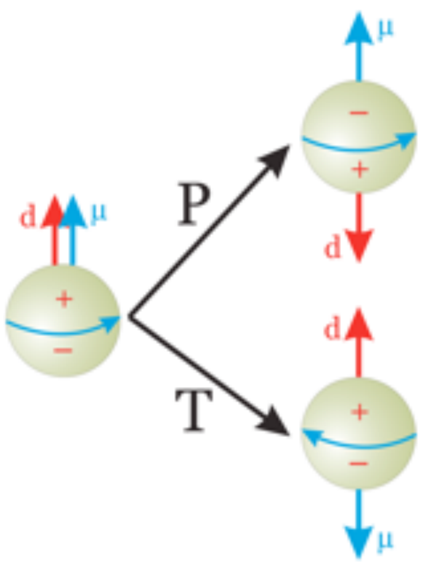
$$|\mathcal{A}_{V\to\infty}|^2 \propto \left(q\frac{\partial\phi(q)}{\partial q} + k\frac{\partial\delta(k)}{\partial k}\right)|\mathcal{A}_{V=L^3}|^2$$

δ(k) = scattering phase

ϕ(q) = lattice zeta fcn.

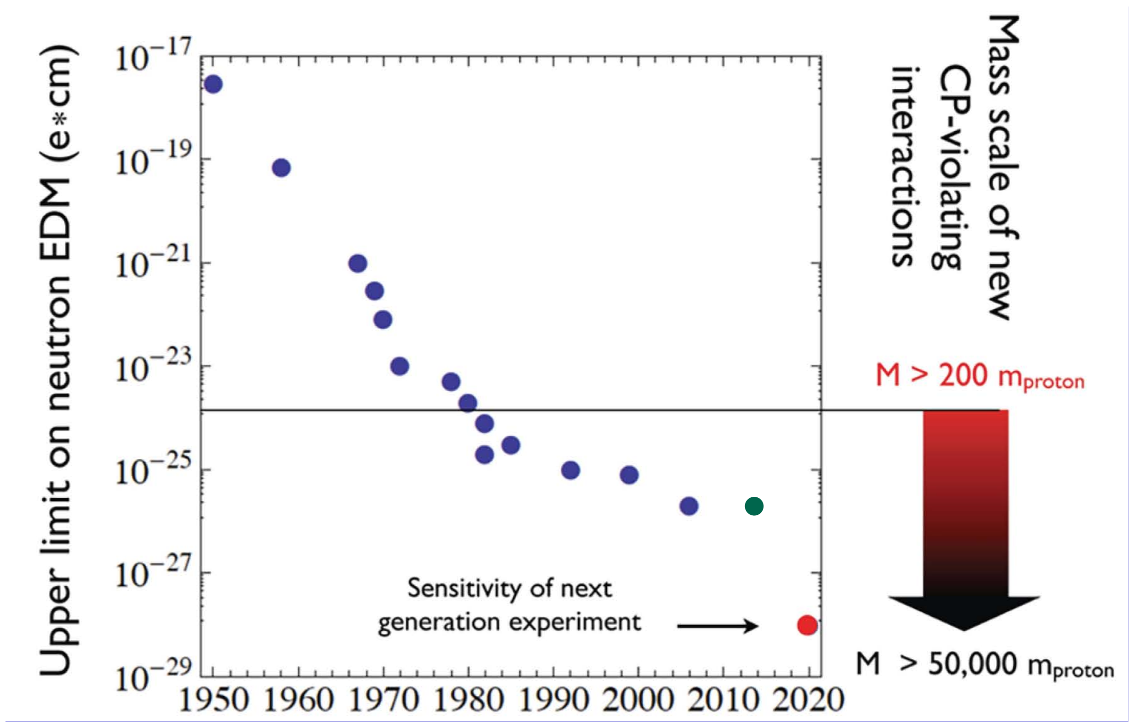
[Lellouch, Luscher, '01]

P, CP(T) Violation: Nucleon/Nuclear EDM



$$\vec{d}_N = d_N \frac{\vec{S}}{S}$$

$$\mathcal{L}_{int} = eA^{em}_\mu \mathcal{V}^\mu \qquad \text{(P,T-even)}$$
$$+ eA^{em}_\mu \mathcal{A}^\mu \qquad \text{(P,T-odd)}$$



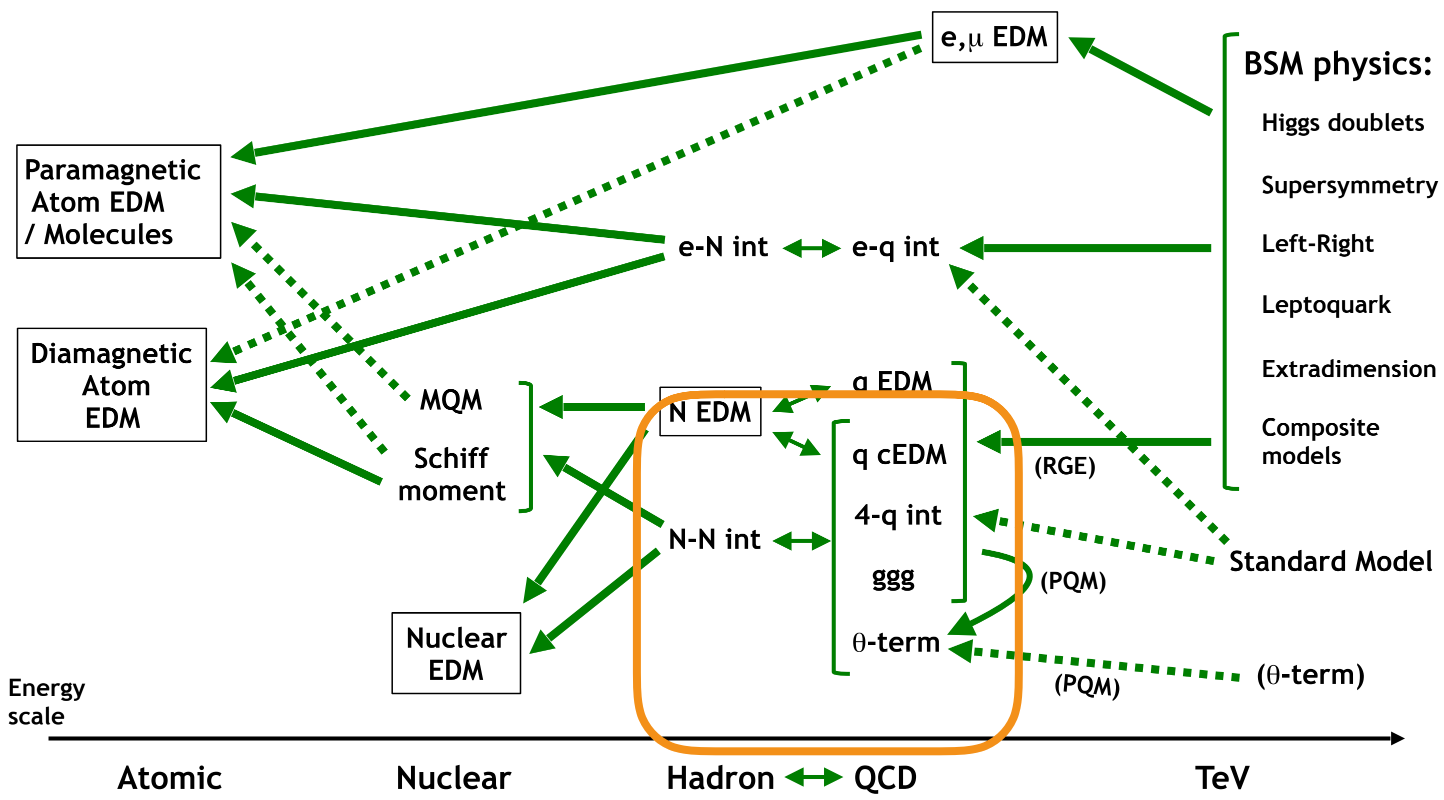
The most sensitive probe of non-CKM CPv:

- Any signal $>10^{-5}\cdot$(current bound)→discovery
- θ_{QCD}-induced EDM : Strong-CP problem
- Prerequisite for Baryogenesis (non-θ_{QCD} EDM)

	10^{-28} *e* cm
CURRENT LIMIT	<300
Spallation Source @ORNL	**< 5**
Ultracold Neutrons @LANL	~30
PSI EDM	<50 (I), **<5 (II)**
ILL PNPI	<10
Munich FRMII	**< 5**
RCMP TRIUMF	<50 (I), **<5 (II)**
JPARC	**< 5**
Standard Model (CKM)	< *0.001*

[B.Filippone '16]

Sources of Nucleon and Nuclei EDMs



[Yamanaka et al, EPJA53:54 (2017)]

- Effective quark-gluon CPv interactions organized by dimension [Engel, Ramsey-Musolf, van Kolck, Prog.Part.Nucl.Phys. 71:21 (2013)]

$$\mathcal{L}_{eff} = \sum_i \frac{c_i}{[\Lambda_{(i)}]^{d_i-4}} \mathcal{O}_i^{[d_i]}$$

d=4 : θ_{QCD}

d=5(6) : quark EDM, chromo-EDM

d=6 : 4-fermion CPv, 3-gluon (Weinberg)

- Lattice QCD: CPv at hadronic scale (Nucleon EDM and πN CPv interactions)

$$d_{n,p} = d_{n,p}^{\theta}\theta_{\rm QCD} + d_{n,p}^{cEDM} c_{cEDM} + \dots$$

Lattice methods for computing nEDM

- Background electric field

$$\mathcal{H} = -\vec{d}_N \cdot \vec{E}$$

- *CPv form factor* $F_3(Q^2 \to 0)$

$$\langle p+q | J^\mu | p \rangle_{\not{CP}} = \bar{u}_{p'} \left[F_1 \gamma^\mu + (F_2 + i F_3 \gamma_5) \frac{\sigma^{\mu\nu} q_\nu}{2 m_N} \right] u_p$$

Dirac — Pauli (anomalous magnetic dipole) — Electric dipole

Nucleon EDM from Quark EDMs

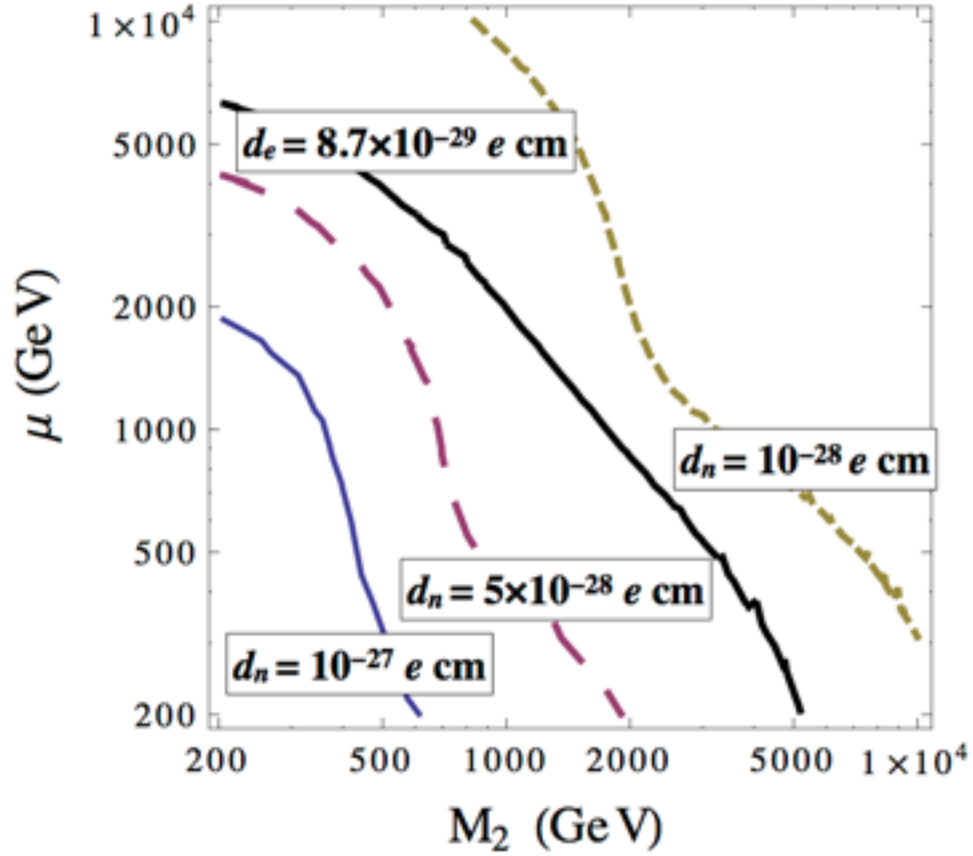
Quark EDM → nucleon EDM: "tensor charge"

$$\delta\mathcal{L}_{\rm CPV} \supset -\frac{ie}{2}\sum_{f=u,d,s,e} d_f\ \bar{f}\sigma_{\mu\nu}\gamma_5 F^{\mu\nu} f$$

$$d_N = g_T^u d_u + g_T^d d_d + g_T^s d_s$$

$$\langle N|\bar{q}\sigma^{\mu\nu}q|N\rangle = d_T^q\,\bar{u}\sigma^{\mu\nu}u$$

Constraints on split-SUSY model
[Bhattacharya et al, PRL115:212002 (2019)]



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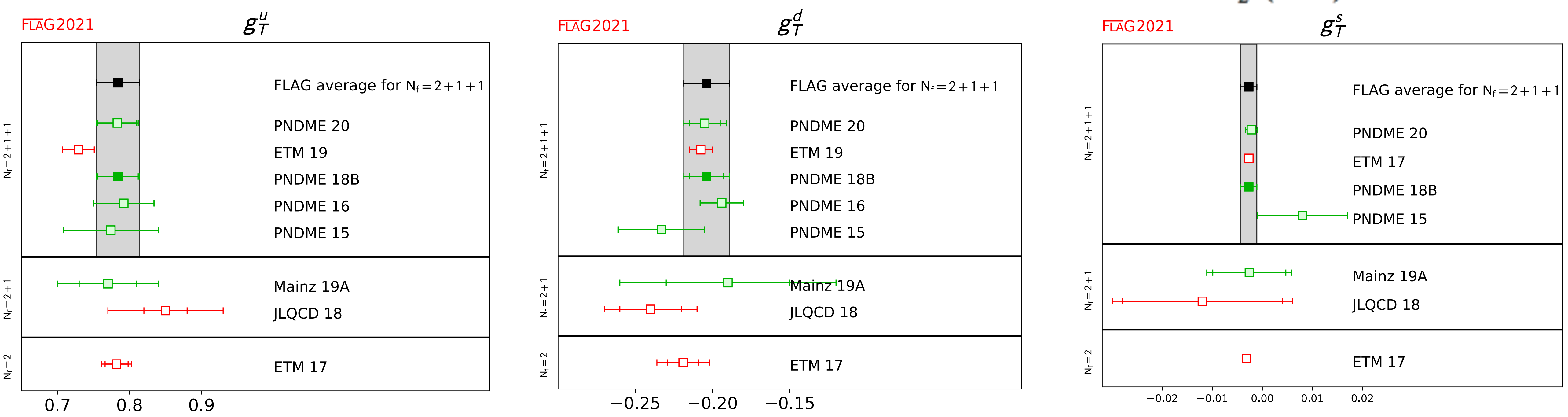
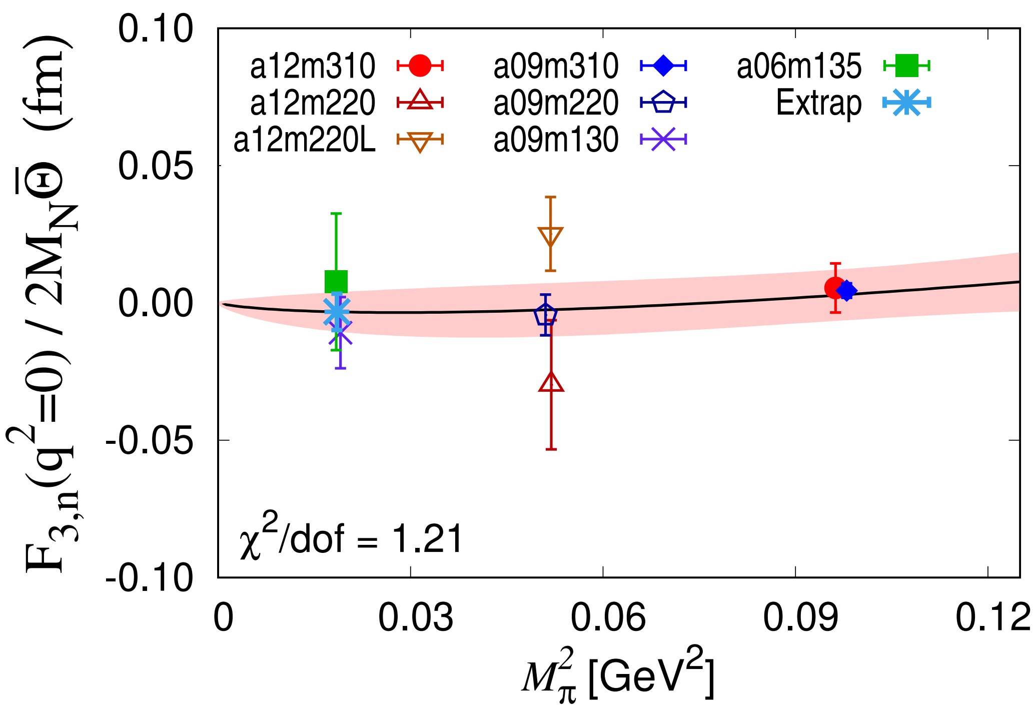
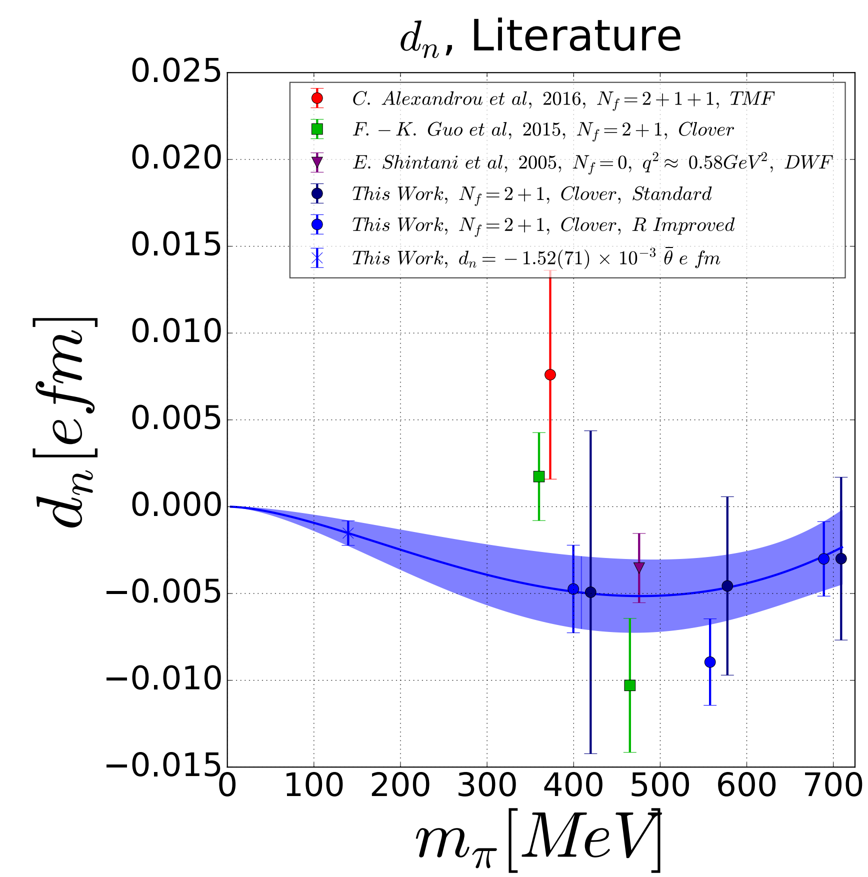


Nucleon EDM from θ_{QCD}-Term



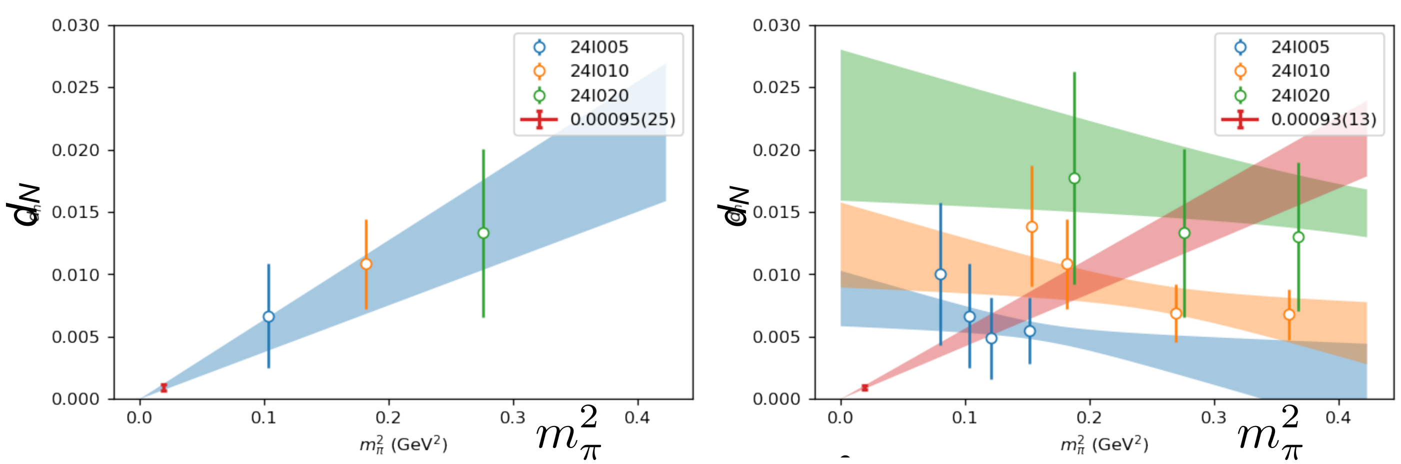
Wilson-Clover quarks

[T.Bhattacharya et al, Lattice'21]



Wilson-Clover quarks

[J.Dragos et al,1902.03254]



DW + Overlap quarks: [K.-F.Liu et al, PRELIMINARY]:

- partial-V_4 sampling of Q
- partial quenching to explore m_q dependence

Challenges:

- effect of θ_{QCD} vanishes at $m_q \to m_q^{phys;}$ chiral symmetry important
- noise in global $Q=\int F\tilde{F}$ grows with V_4
- $Q^2 \to 0$ extrapolation(*)

Topological Charge with Gradient Flow

[M.Luscher, JHEP08:071; 1006.4518]

Gradient flow: covariant *4D-diffusion* of quantum fields with "G.F." time t_{GF}:

$$\frac{d}{dt_{\rm GF}} B_\mu(t_{\rm GF}) = D_\mu G_{\mu\nu}(t_{\rm GF})\,, \quad B_\mu(0) = A_\mu$$

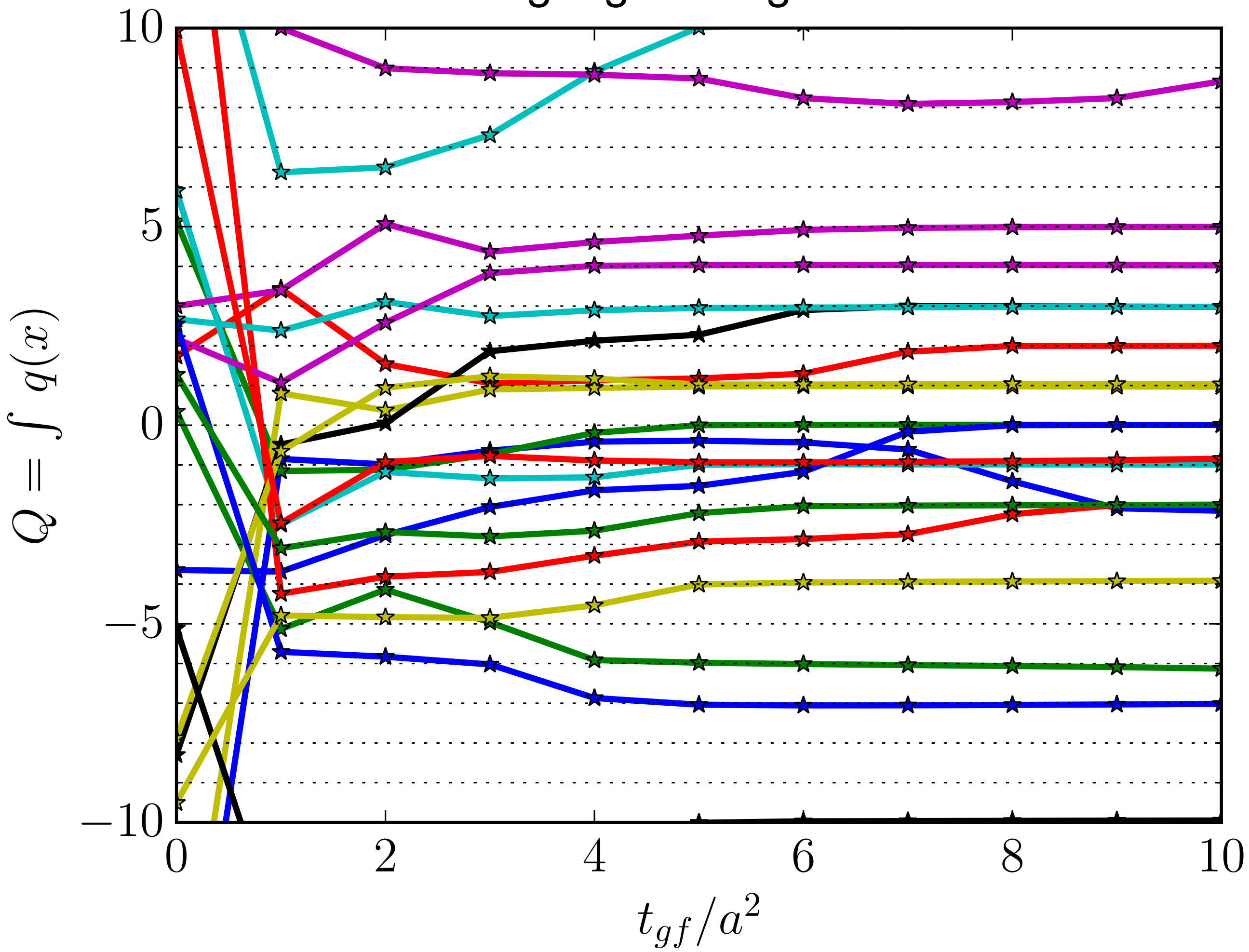
Tree-level:

$$B_\mu(x, t_{\rm GF}) \propto \int d^4y \, \exp\Big[-\frac{(x-y)^2}{4t_{\rm GF}}\Big] A_\mu(y)$$

Gradient-flowed topological charge:

$$\tilde{Q}(t_{\rm GF}) = \int d^4x \, \frac{g^2}{32\pi^2} \Big[G_{\mu\nu}\widetilde{G}_{\mu\nu}\Big]\Big|_{t_{\rm GF}}$$

total top. charge on 20 randomly chosen gauge configurations



- effective scale $\Lambda_{\rm UV} \to (t_{\rm GF})^{-1/2}$

  $\Longrightarrow$ renormalization prescription
- smooth fields (reduce $|G_{\mu\nu}|$)

  $\Longrightarrow$ continuous "cooling"
- remove $G_{\mu\nu}$ dislocations

  $\Longrightarrow$ separation of top. sectors

  [M.Luscher, JHEP08:071; 1006.4518]

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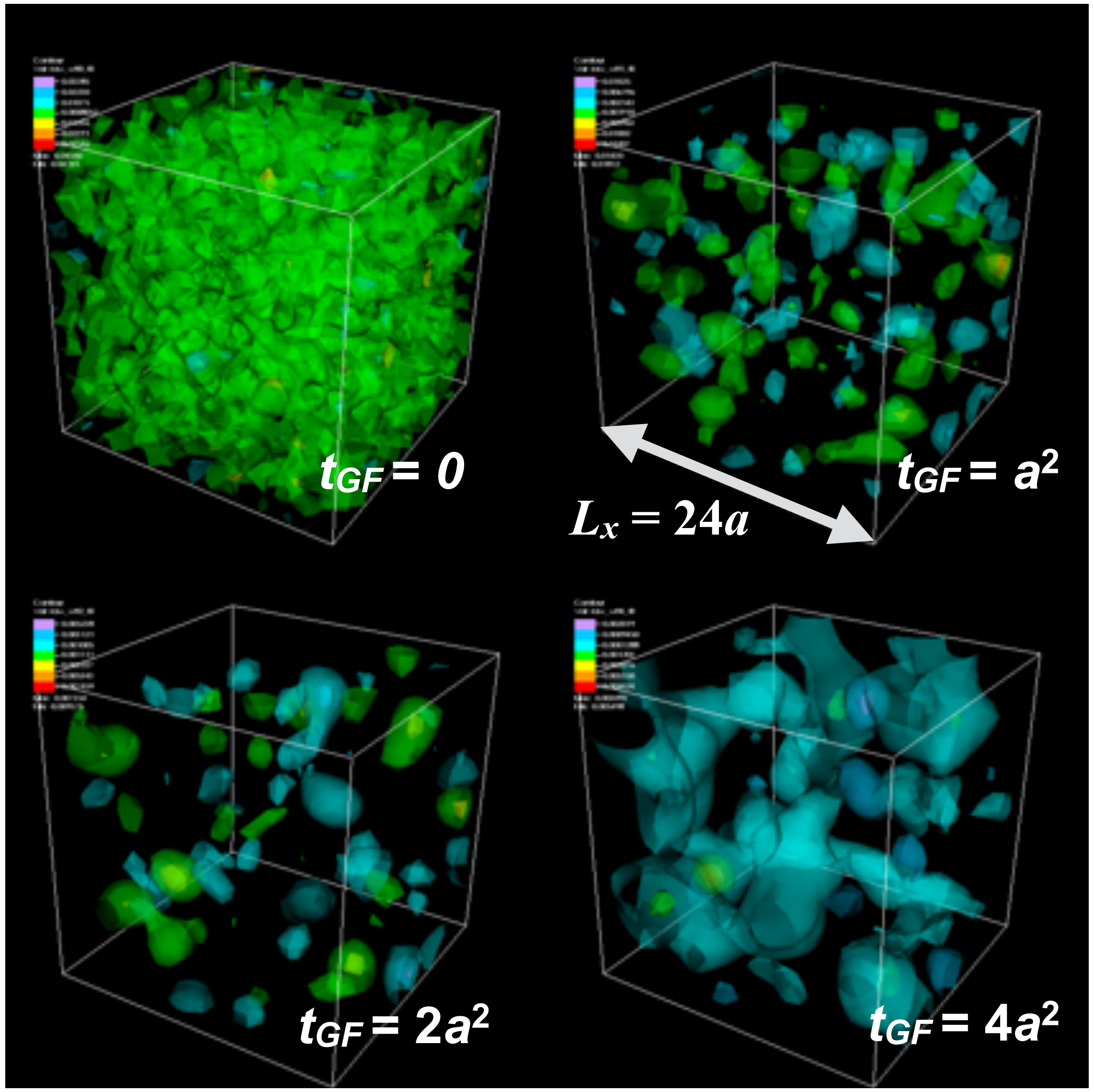

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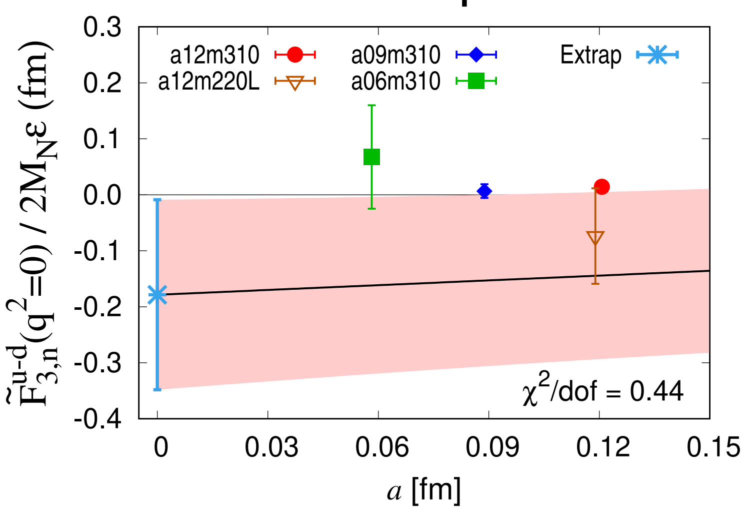
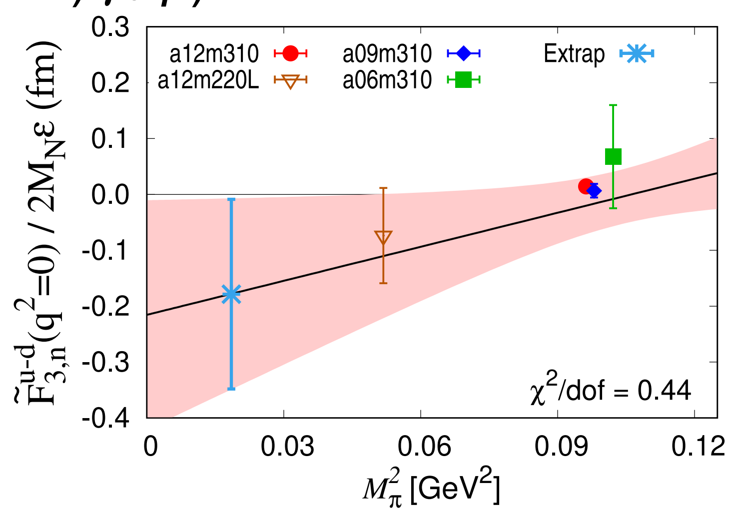
- remove $G_{\mu\nu}$ dislocations
  $\Longrightarrow$ separation of top. sectors
  [M.Luscher, JHEP08:071; 1006.4518]

$$\Leftarrow \quad \tilde{q}(t_{\rm GF}) = \frac{g^2}{32\pi^2} \Big[G_{\mu\nu}\widetilde{G}_{\mu\nu}\Big]\Big|_{t_{\rm GF}} \propto \tilde{\mathbf{E}} \cdot \tilde{\mathbf{H}}$$

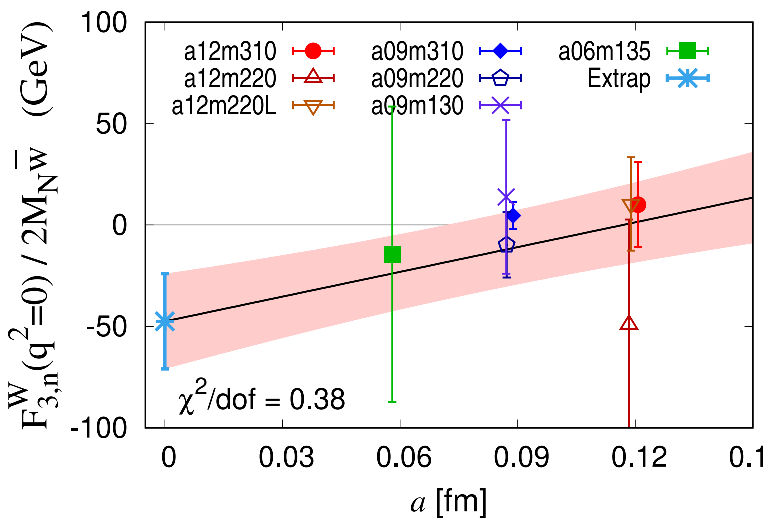
Nucleon EDM from Quark and Gluon cEDM

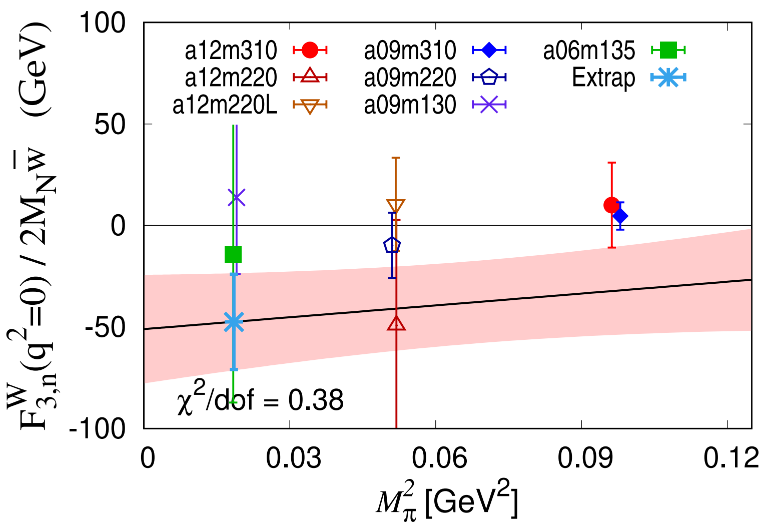
- dim-5 CPv: quark cEDM ($\bar{q}\,(\sigma\cdot F)\,\gamma_5 q$) :





- dim-6 CPv: Weinberg term ($\sim F\cdot F\cdot\tilde{F}$):





Wilson-Clover quarks
[T.Bhattacharya, Lattice 2021; 2203.03746]

Challenges:

- renormalization & mixing with lower-dim operators (e.g. dim-4 $F\tilde{F} \rightarrow \theta_{QCD}$-nEDM)
- quark cEDM (dim-5): quark-disconnected contractions for vector current and cEDM
- Weinberg term (dim-6): gluon noise

Renormalization & mixing with Gradient Flow:
[Mereghetti et al 2111.11449; J.Kim et al 2106.07633]

- novel nonperturbative scheme
- small t_{GF} expansion
  $\Longrightarrow$matching to pertrubative
- avoid power divergences

Nucleon&Nuclear EDMs: Summary/Challenges

Single-nucleon EDM

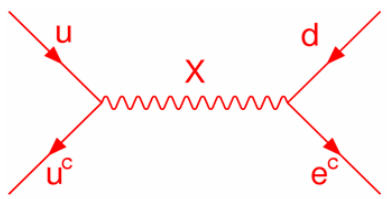
- θ_{QCD}-induced nEDM : ongoing work; some extrapolated results
  - potentially ***challenging*** at the physical point
- Higher-dim effective operators
  - quark/gluon cEDM mixing/renormalization tractable with Gradient flow
  - very noisy / weak "signal" -> ***straightforward*** with improved statistics
  - 4-quark CPv just starting; potentially ***challenging*** due to quark loops
  - depend on precision of θ_{QCD}-induced nEDM due to mixing

Multi-nucleon EDM and CPv NN interaction

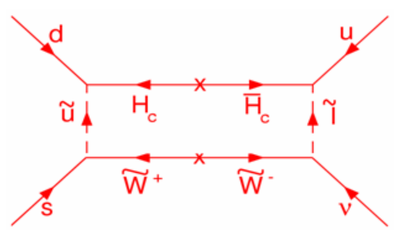
- **extremely challenging,** will need EFTs

Baryon Number Violation: Proton Decay

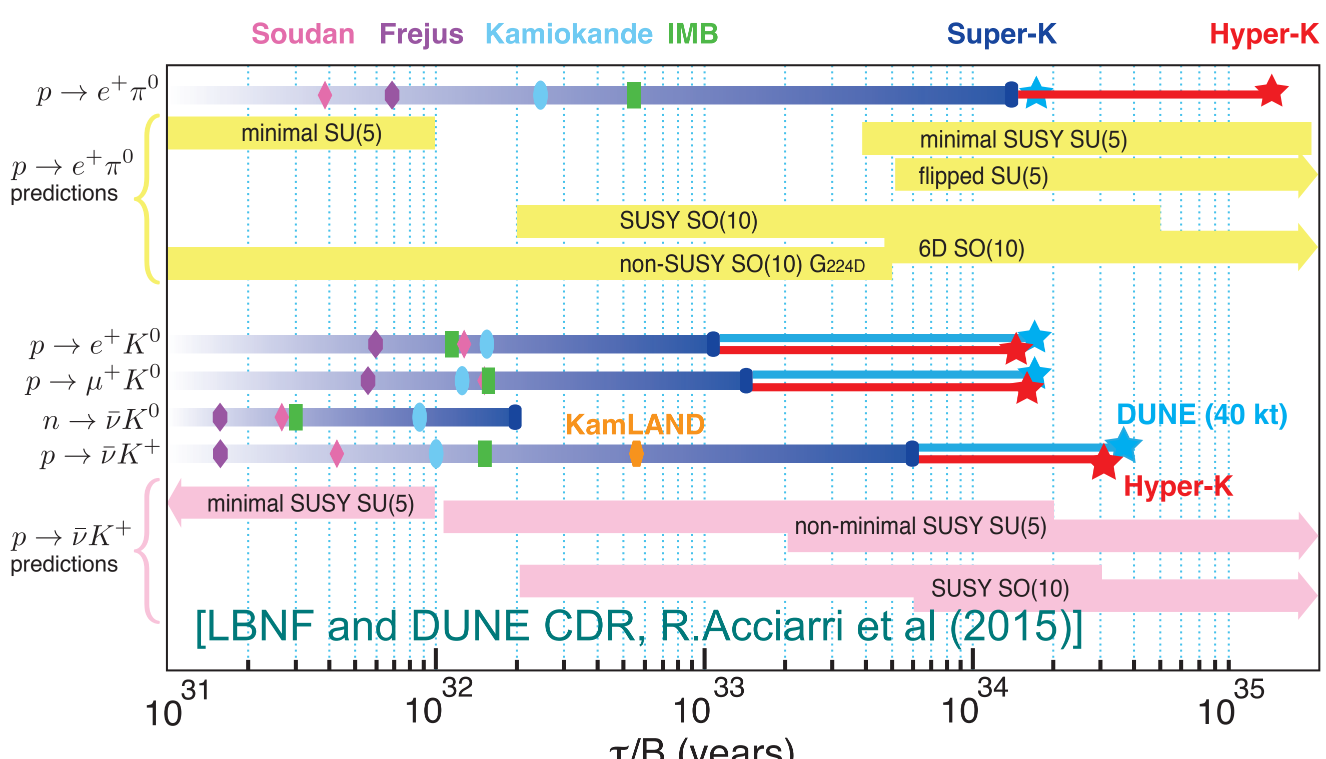
- **Proton decay: ΔB=1 violation**
  - Baryon number = accidental "symmetry" of SM; violated by sphalerons
  - Probe scales inaccessible to colliders: Limits on GUT, extra dim., etc
  - Limits on stability of nuclear matter



ordinary GUT
- min.$SU(5)$ ruled out by $\tau(p \rightarrow e^+\pi^0)$
- $SO(10)$ probed by next-gen exp.



SUSY GUT [Sakai,Yanagida '82; Weinberg '82]
- min.SUSY-$SU(5)$ ruled out by $\tau(p \rightarrow \bar{\nu}K^+)$
- SUSY-$SO(10)$ probed by next-gen exp.



- $\tau(p \rightarrow e^+\pi^0) \gtrsim 1.6\cdot10^{34}$,

  $\tau(p \rightarrow \bar{\nu}K^+) \gtrsim 5.9\cdot10^{33}$ [Super-K]
- Expect x10 limits from Hyper-K, DUNE
- DUNE: sensitive to $p \rightarrow \bar{\nu}K^+$ (SUSY GUT)

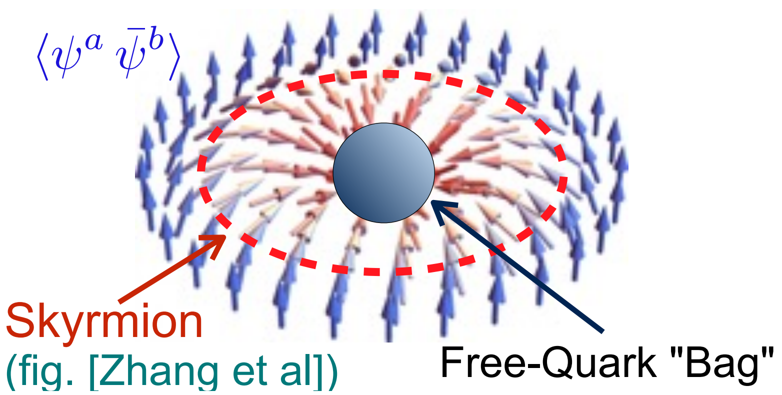
Alt. explanation of proton stability?

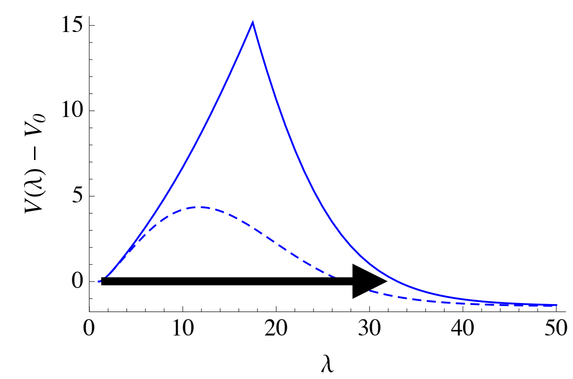
Multi-meson decay channels?

Proton Decay Matrix Elements

Is proton inherently stable?

Conjecture [A.Martin, G.Stavenga '12]
Topological stability of "Chiral Bag" proton :



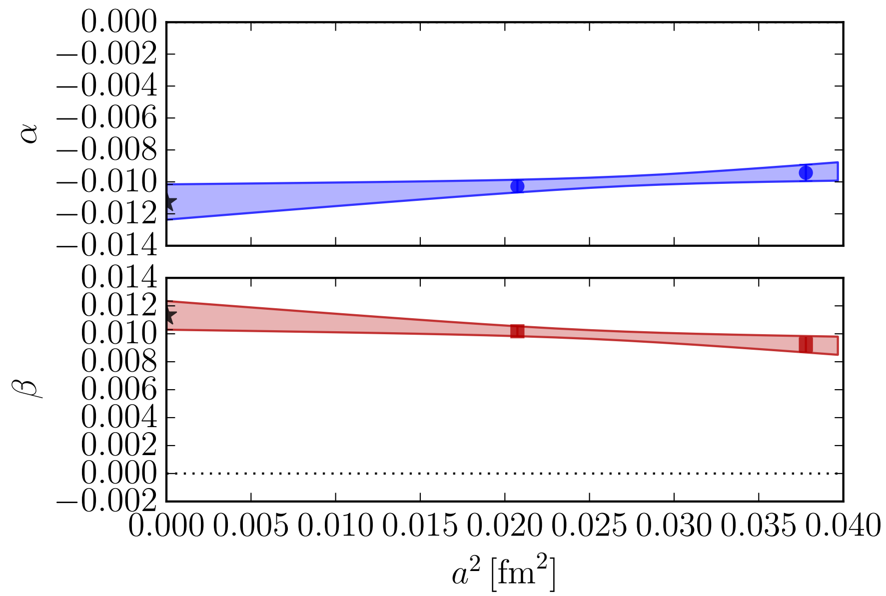


Lattice calculations with chirally-symmetric quarks:

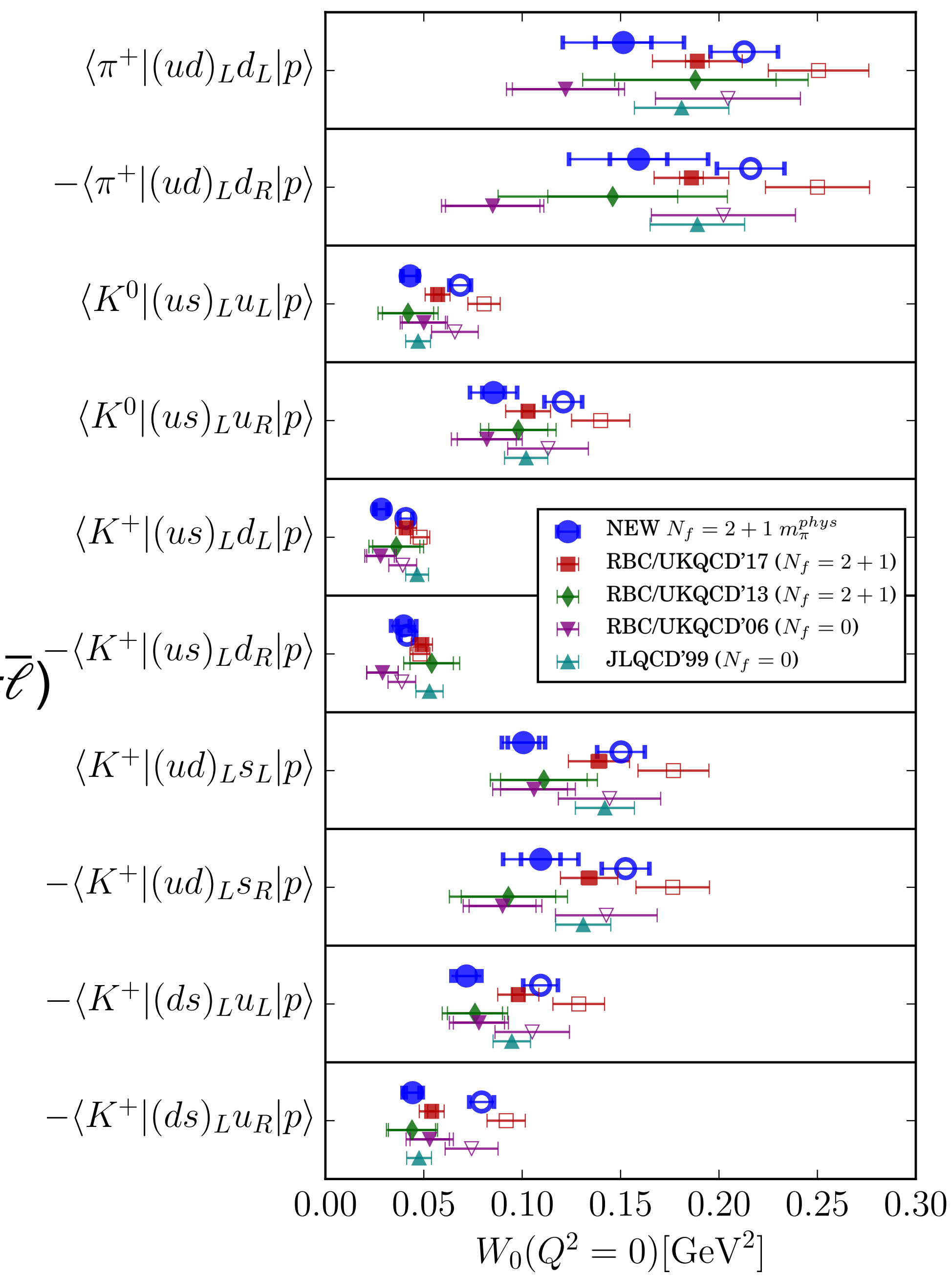
- Prev. at $m_\pi \gtrsim 300$ MeV
  [S.Aoki et al (2000)]
  [Y.Aoki et al (2006), (2013), (2017)]
- Physical quarks
  [J.Yoo, PRD'22]
- NEXT: $p\to\pi\pi$, $p\to\pi K$

Nucleon decay constants
($p\to 3\ell$ decays; LO ChPT $p\to K\bar\ell$, $\pi\bar\ell$)

$$\langle \mathrm{vac}|\epsilon^{abc}(\bar u^{aC} d^b)_R u^c_L|N\rangle = \alpha\, P_L U_N$$
$$\langle \mathrm{vac}|\epsilon^{abc}(\bar u^{aC} d^b)_L u^c_L|N\rangle = \beta\, P_L U_N$$



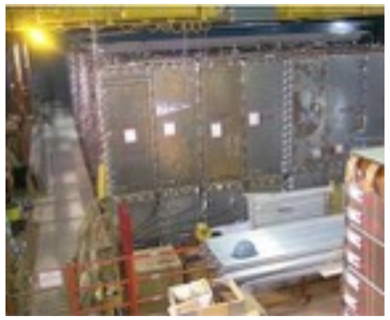
Nucleon-to-meson amplitudes
($p\to\pi\bar\ell, K\bar\ell$, decays)



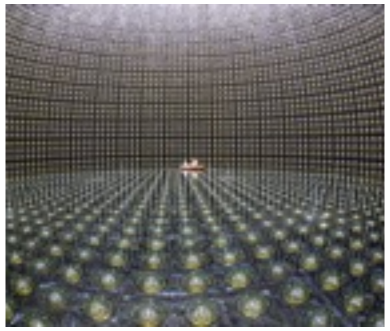
$\Longrightarrow$*NO SUPPRESSION at physical quark masses*

Baryon Number Violation : Neutron Oscillation

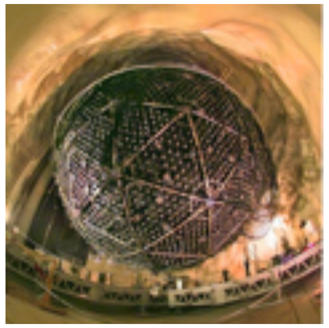
- **N$\bar{\text{N}}$ oscillation: ΔB = 2 = Δ(B–L) violation**
  - $\tau(^{56}Fe) \gtrsim 0.72 \cdot 10^{32}$ yr
    $\Longrightarrow \tau_{N\bar{N}} \gtrsim 1.4 \cdot 10^8$ s [Soudan]
  - $\tau(^{16}O) \gtrsim 1.77 \cdot 10^{32}$ yr
    $\Longrightarrow \tau_{N\bar{N}} \gtrsim 3.3 \cdot 10^8$ s [Super-K]
  - $\tau(^{2}H) \gtrsim 0.54 \cdot 10^{32}$ yr
    $\Longrightarrow \tau_{N\bar{N}} \gtrsim 1.96 \cdot 10^8$ s [SNO]
  - Quasi-free reactor neutrons
    $\tau_{N\bar{N}} \gtrsim 10^8$ s [ILL'94]



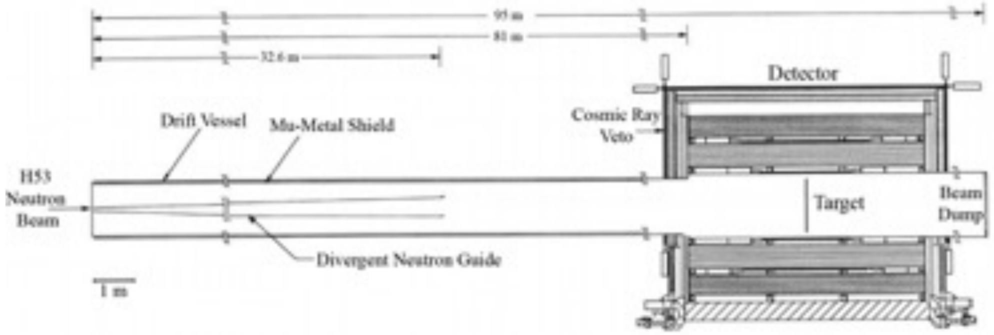
Soudan



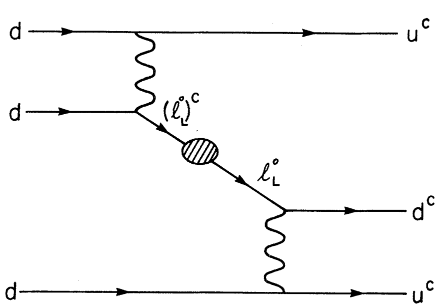
Super Kamiokande

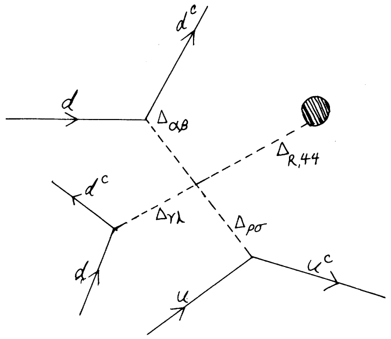


SNO



- GUT + massive Majorana lepton?
  [T.K.Kuo, S.T.Love, PRL45:93 (1980)]
- partial unification and (B–L) viol.?
  [R.N.Mohapatra, R.E.Marshak, PRL44:1316 (1980)]



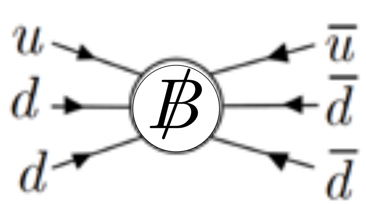


$$\delta m = -\langle \bar{n} | \int d^4x\, \mathcal{L}_{\text{eff}} \, | n \rangle = -\sum_i \frac{c_i}{M_X^5} \boxed{\langle \bar{n} | \mathcal{O}_i^{6q} | n \rangle}$$

oscillation time
$\tau_{n\bar{n}} = (2\delta m)^{-1}$

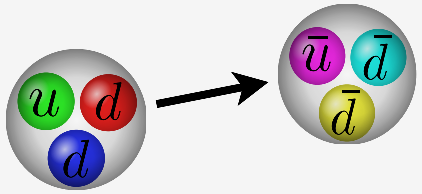
~ (BSM scale)$^{-5}$
$M_X \gtrsim$ (200–300) TeV

N-$\bar{\text{N}}$ amplitude

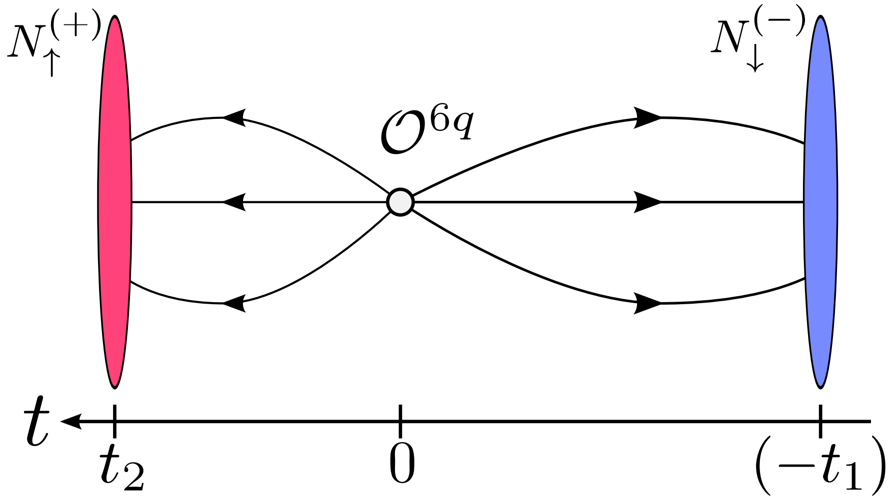


$$\mathcal{L}_{\text{eff}} = \sum_i \left[c_i \mathcal{O}_i^{6q} + \text{h.c.} \right]$$

Lattice QCD Result: Enhanced $N \Leftrightarrow \bar{N}$



Lattice QCD with physical-mass, chiral-symmetric quarks:
x(5-10) larger N-Nbar oscillation vs. nucleon Bag model
[E.Rinaldi, S.S., M.Wagman, et al, PRD99:074510 (2019)]
[E.Rinaldi, S.S., M.Wagman, et al, PRL122:162(2018)]



	$\mathcal{O}^{\overline{MS}}(2\text{ GeV})$	Bag "A"	$\frac{\text{LQCD}}{\text{Bag "A"}}$	Bag "B"	$\frac{\text{LQCD}}{\text{Bag "B"}}$
$[(RRR)_\mathbf{3}]$	0	0	–	0	–
$[(RRR)_\mathbf{1}]$	45.4(5.6)	8.190	5.5	6.660	6.8
$[R_\mathbf{1}(LL)_\mathbf{0}]$	44.0(4.1)	7.230	6.1	6.090	7.2
$[(RR)_\mathbf{1}L_\mathbf{0}]$	-66.6(7.7)	-9.540	7.0	-8.160	8.1
$[(RR)_\mathbf{2}L_\mathbf{1}]^{(1)}$	-2.12(26)	1.260	-1.7	-0.666	3.2
$[(RR)_\mathbf{2}L_\mathbf{1}]^{(2)}$	0.531(64)	-0.314	-1.7	0.167	3.2
$[(RR)_\mathbf{2}L_\mathbf{1}]^{(3)}$	-1.06(13)	0.630	-1.7	-0.330	3.2
	$[10^{-5}\text{ GeV}^{-6}]$	$[10^{-5}\text{ GeV}^{-6}]$		$[10^{-5}\text{ GeV}^{-6}]$	

MIT Bag model results from [S.Rao, R.Shrock, PLB116:238 (1982)]

Next steps: non-quasi-free oscillation

- full systematic UQ : finite volume, continuum limit
- "crossed" 2-neutron annihilation amplitudes $\langle \text{vac}|O^{6q}|nn\rangle$
- Nuclear medium effects

Neutrinoless Double-Beta Decay

$0\nu2\beta$: Experimental window into

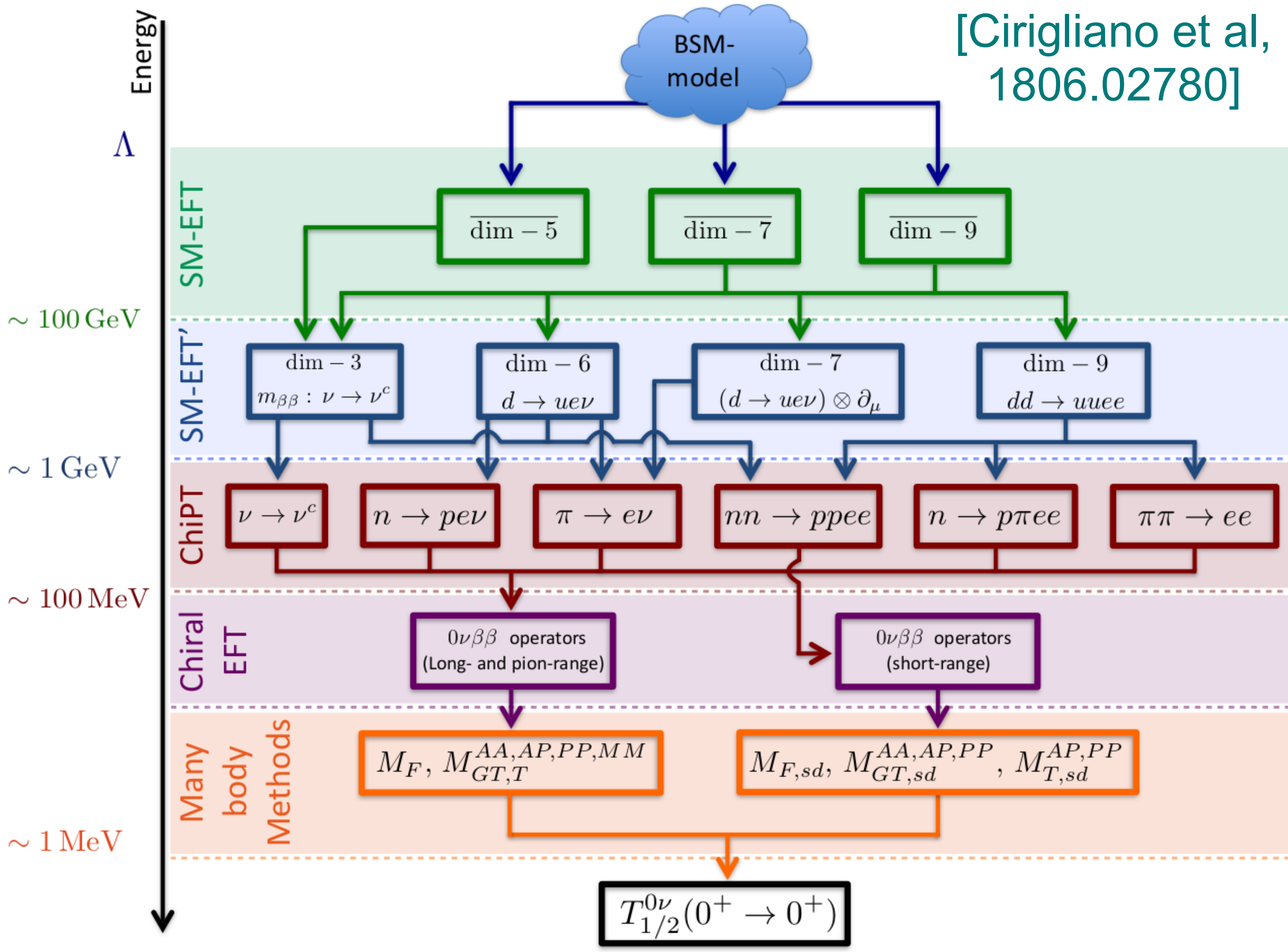
- Neutrino mass mechanism
- mass hierarchy
- leptogenesis (LNV $\Longrightarrow$ BNV thru spalerons)
- scale of BSM

Experiments

- current : NEMO3, KamLAND-Zen, EXO-200, Majorana, GERDA, CUORE, CUPID
- Next-gen: x100 lifetime constraints (e.g. ton-range nEXO (1t ^{136}Xe)

LNV mechanisms:

- light Majorana neutrino? – only in $0\nu2\beta$
- low-scale seesaw?
- BSM at TeV scale?
- neutrion flavor models



[Cirigliano et al, 1806.02780]

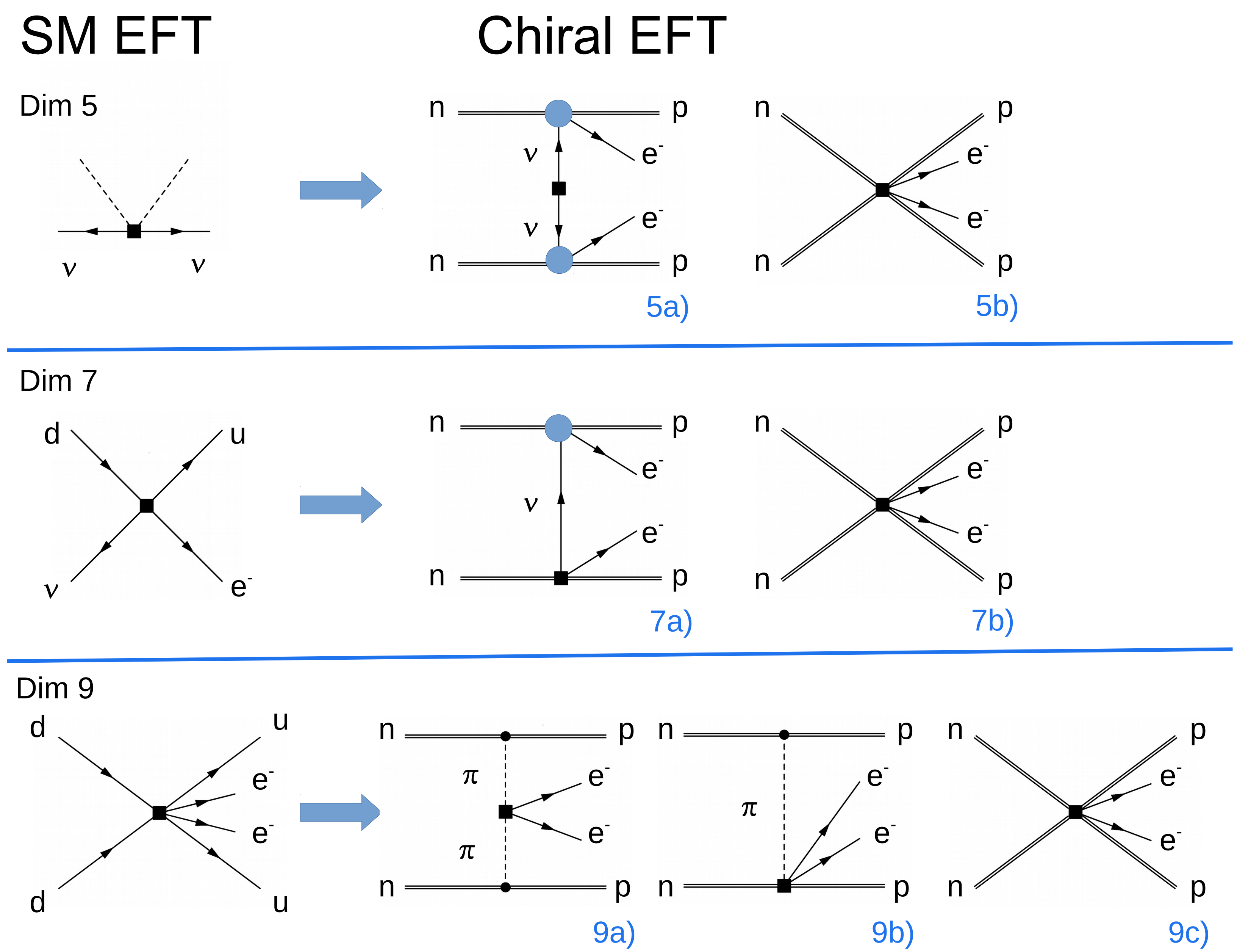
$$|m_{\beta\beta}| = |m_i U_{ei}^2| \leq 10^{-2} eV$$

$$\Gamma^{0\nu\beta\beta} \propto |m_{\beta\beta}|^2 \, |M^{0\nu}|^2$$

nuclear matrix elements
lattice QCD + EFT + many-body

EFTs for $0\nu 2\beta$

[2203.12169]

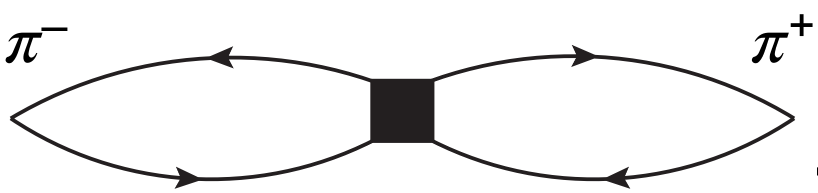


LNV operators in SM EFT: dim-5,7,9 [Prezeau et al, '03]

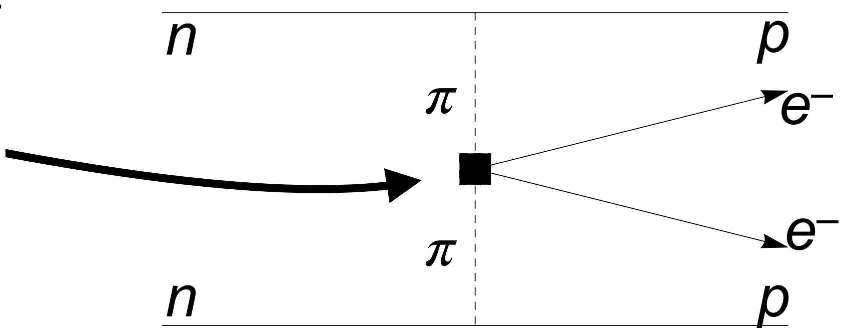
- dim-5, dim-7 $\Longrightarrow$ Long-range LNV
- dim-9 $\Longrightarrow$ Short-range, π-range LNV
- dim-5,7,9 $\Longrightarrow$ short-range contact conteractions in Chiral EFT

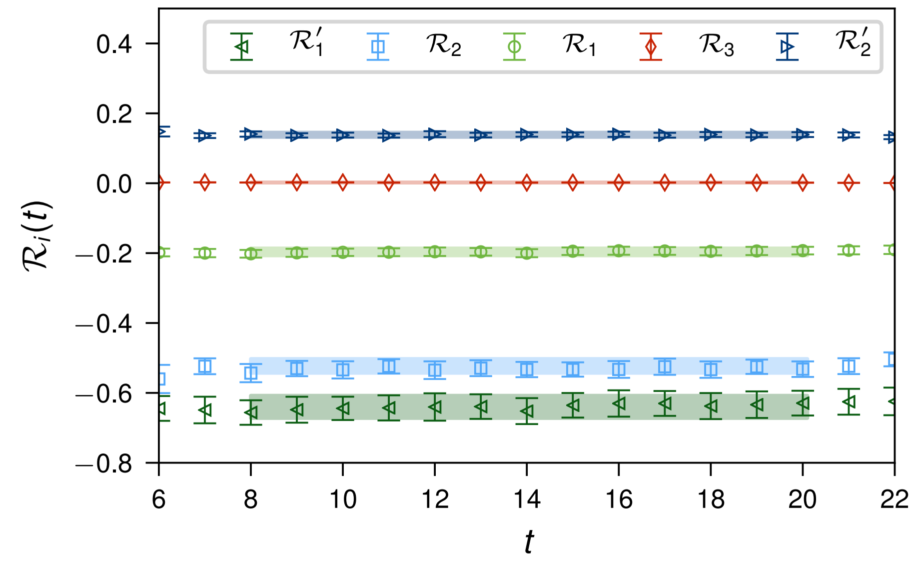
Short-Range LNV in $\pi^- \to \pi^+ ee$

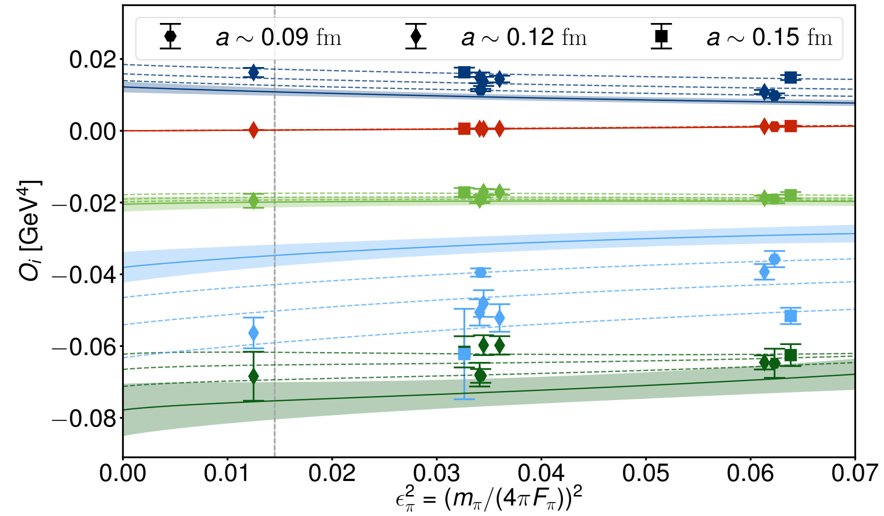
$\langle\pi^+|O^{4q}|\pi^-\rangle$ [Nicholson et al, PRL'18, 1805.02634]

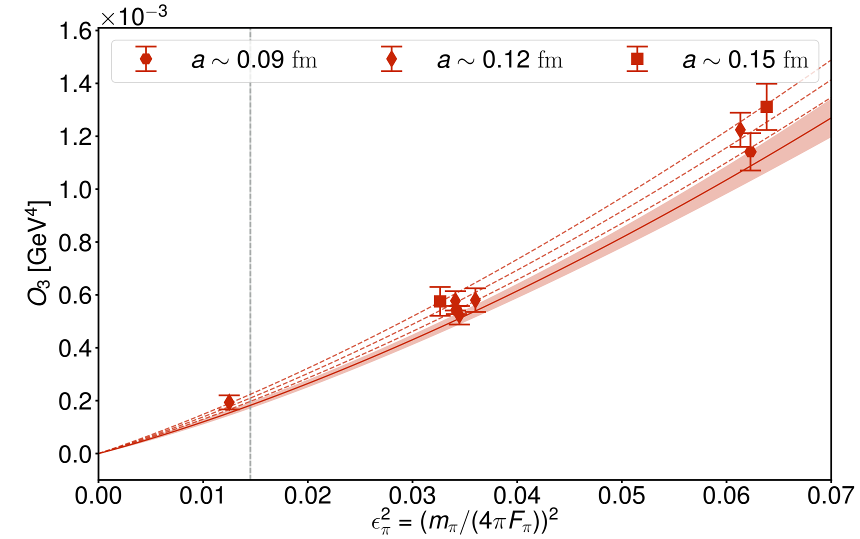


$$\langle\Omega|\Pi^+(t_f,\mathbf{p}_f)\mathcal{O}(0)\Pi^+(t_i,\mathbf{p}_i)|\Omega\rangle$$







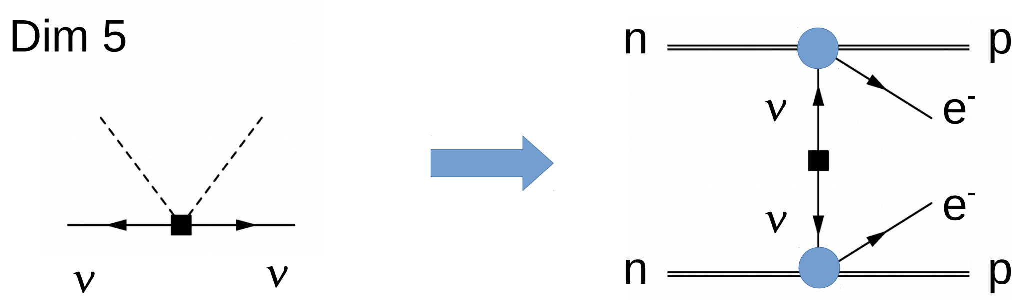


$$\mathcal{O}_{1+}^{++} = (\bar{q}_L\tau^+\gamma_\mu q_L)(\bar{q}_R\tau^+\gamma_\mu q_R)$$
$$\mathcal{O}_{2+}^{++} = (\bar{q}_L\tau^+ q_R)(\bar{q}_R\tau^+ q_L) + \{L \leftrightarrow R\}$$
$$\mathcal{O}_{3+}^{++} = (\bar{q}_L\tau^+\gamma_\mu q_L)(\bar{q}_L\tau^+\gamma_\mu q_L) + \{L \leftrightarrow R\}$$

&& color-mixed combinations O_1', O_2'

Short-Range LNV ~$(M_{BSM})^{-1}$
comparable in *See-Saw* models to
Long-Range LNV~ (chirality flip) ~ $m_{\beta\beta}$ ~ $(M_{BSM})^{-1}$

Long-Range LNV on a Lattice



$$\mathcal{L}_{\text{eff}} = 2\sqrt{2} G_F V_{ud} (\bar{u}_L \gamma_\mu d_L)(\bar{e}_L \gamma_\mu \nu_{eL})$$

+ light Majorana ν exchange

Challenges in $nn \to ppe^- e^-$

- nn, pp scattering / low-lying states on present lattices
- nonlocal operator in Euclidean time:
  light intermediate states E < $2m_N$ are exp. diverging with Euc.time

First step: $\pi^- \to \pi^+ e^- e^-$

- $1 \to 1$ amplitude, large exc. gap
- component of EFT matching

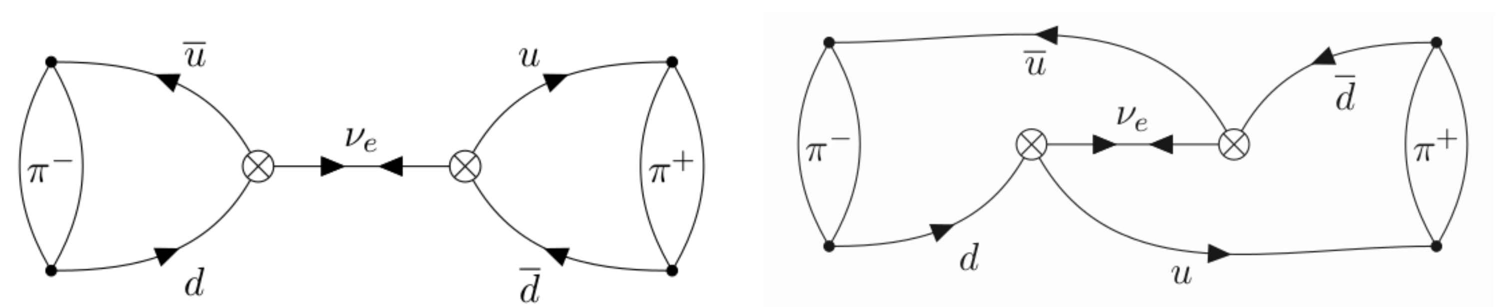


Fig. [Detmold, Murphy 2004.07404]

$$C_{\pi^- \to \pi^+ e^- e^-}(T, t_x, t_y) = \sum_{\vec{x}, \vec{y}} S_\nu(x - y) \left\langle \pi^+(T) \mathcal{T}\{ j_{L\alpha}(x) j_{L\beta}(y) \} (\pi^-)^\dagger \right\rangle$$

reg. at $|x-y| \sim O(a)$

Long-Range LNV: $\pi^- \to \pi^+ e^- e^-$ (1)

- $\langle \pi^+ e^- e^- | S_{NL} | \pi^- \rangle$ with reg. photon correlator [Detmold, Murphy; 1811.05554;2004.07404]

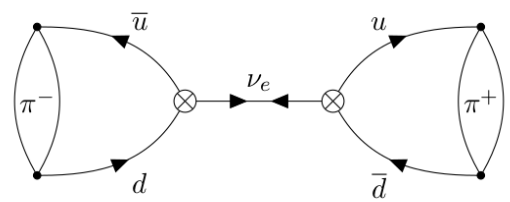
$$\sum_{\Delta \le t_{x,y} \le T-\Delta} \frac{C_{\pi^-\pi^+}(T, t_x, t_y)}{C_\pi(T)} \approx$$

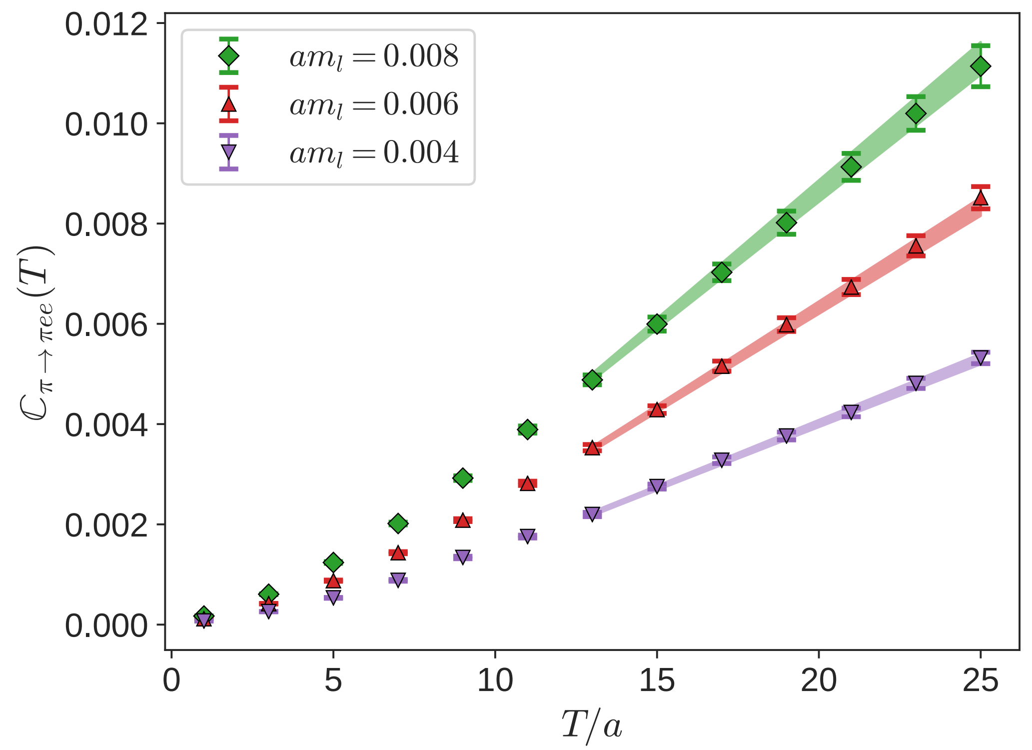
$$\approx (T - 2\Delta) \cdot \boxed{M^{0\nu}} + O\left(\frac{e^{-(|\vec{q}|+E_k-m_\pi)T} - 1}{|\vec{q}| + E_k - m_\pi}\right)$$

~ linear fit

E_k = energy of $\langle k | j_L | \pi \rangle$ state

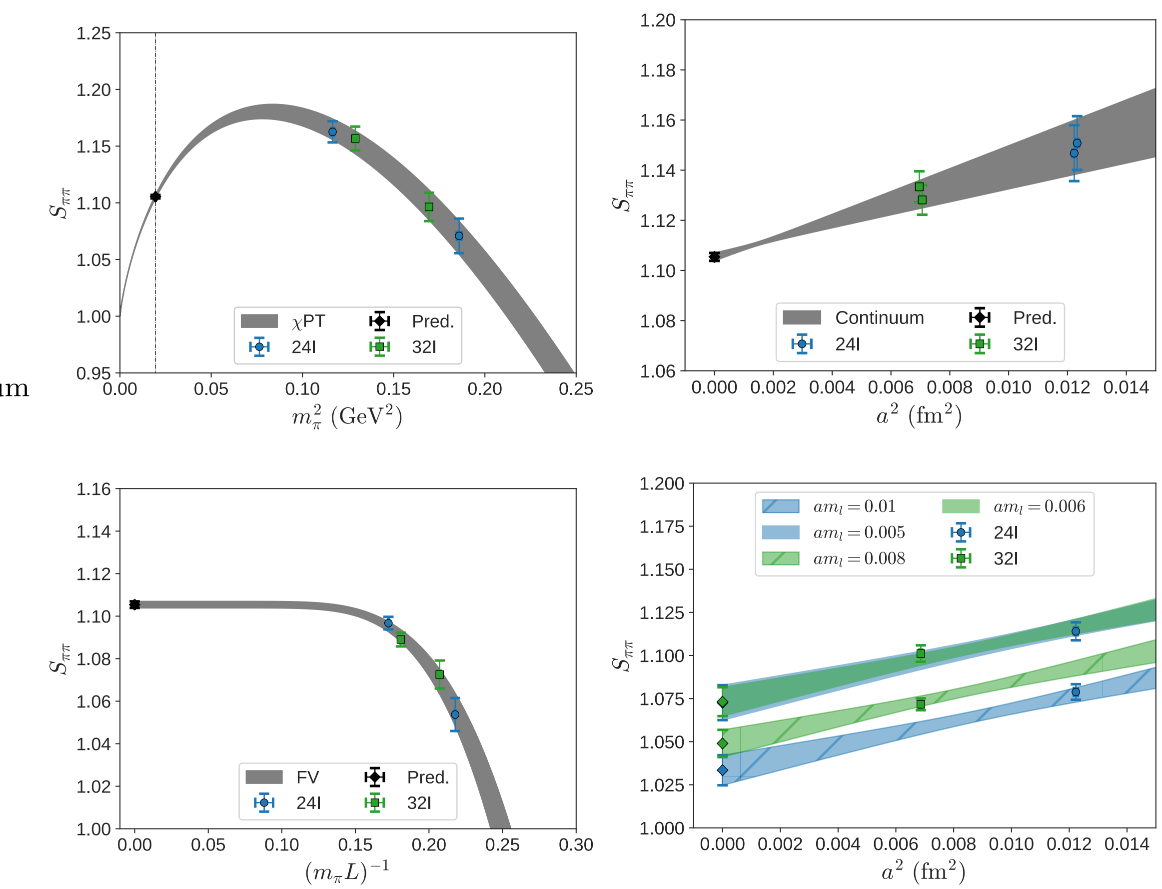
vac. E_k < mπ treated separately





- Chiral, FVE, continuum limit fit

$$\mathcal{S}_{\pi\pi} = \underbrace{1 + \frac{m_\pi^2}{8\pi^2 f_\pi^2}\left(3\log\left(\frac{\mu^2}{m_\pi^2}\right) + 6 + \frac{5}{6} g_\nu^{\pi\pi}(\mu)\right)}_{\text{NLO } \chi\text{PT}} + \underbrace{c_{FV}^{\text{NLO}} \frac{e^{-m_\pi L}}{(m_\pi L)^{3/2}}}_{\text{FV}} + \underbrace{c_a a^2}_{\text{Continuum}}$$



$$g_\nu^{\pi\pi}(770\text{ MeV}) = -10.78(12)_{\text{stat}}(4)_{\text{fit}}(50)_{\text{FV}}(9)_{\chi\text{PT}},$$
$$S_{\pi\pi} = 1.1054(14)_{\text{stat}}(6)_{\text{fit}}(61)_{\text{FV}}(10)_{\chi\text{PT}},$$
$$M^{0\nu} = 0.01880(6)_{\text{stat}}(2)_{\text{fit}}(10)_{\text{FV}}(2)_{\chi\text{PT}} \text{ GeV}^2$$

Long-Range LNV: $\pi^- \to \pi^+ e^- e^-$ (2)

- $\langle \pi^+ e^- e^- | S_{NL} | \pi^- \rangle$ with Infinite-Volume Reconstruction [Tuo, Feng, Jin, PRD, 1909.13525]

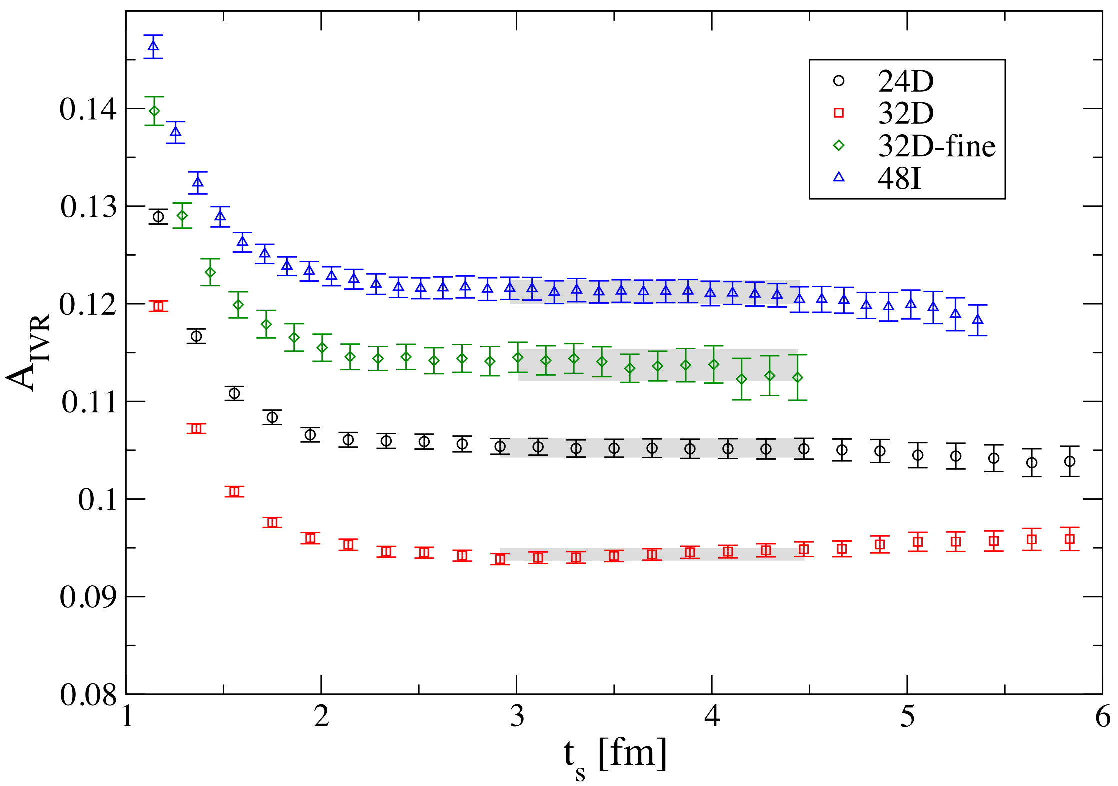
$$\sum_{t,\vec{x}} S(t,\vec{x}) H(t,\vec{x})$$

lattice hadronic tensor

$$\approx \sum_{|t|<t_s,\vec{x}} S(x) H(x)$$

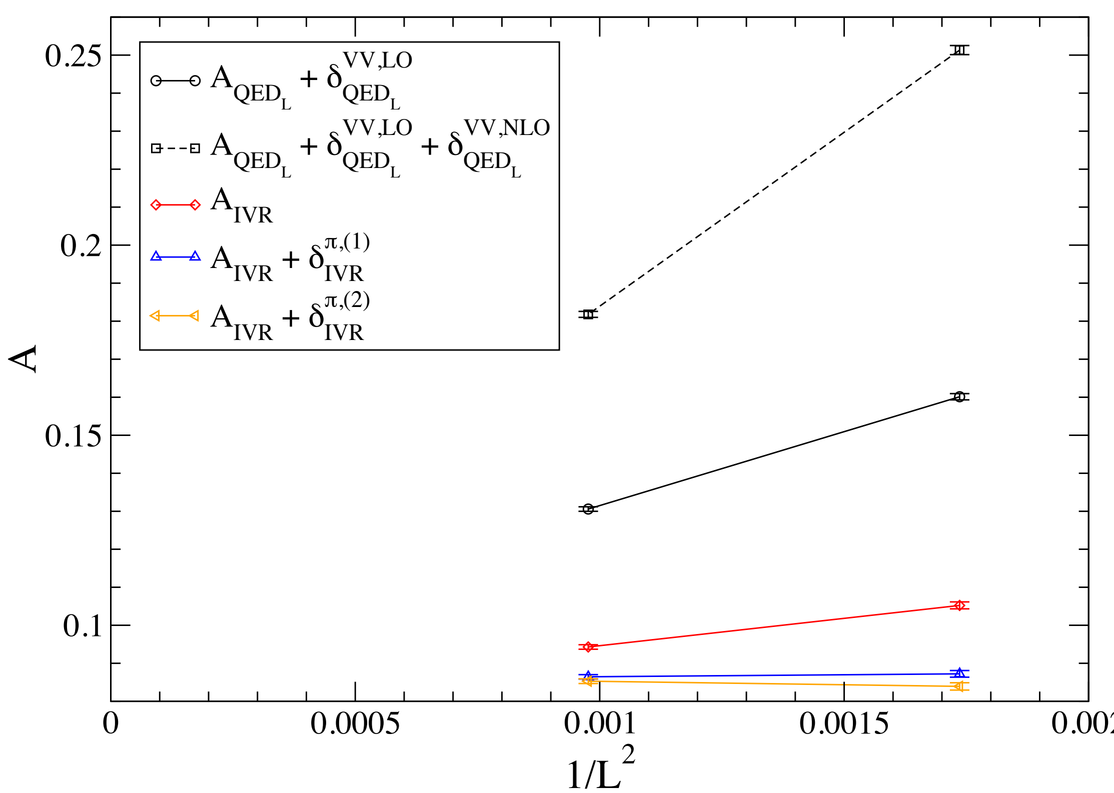
$$+\, 2 \sum_{\vec{x}} L(t_s,\vec{x}) H(t_s,\vec{x})$$

long-range extrap. based on 1-state dominance



- FVE, Long-range effects examined

$$g_\nu^{\pi\pi}(\mu)\Big|_{\mu=m_\rho} = -10.89(28)(33)_L(66)_a$$
$$\mathcal{S}_{\pi\pi} = 1.1045(34)_{\text{stat}}(74)_{\text{sys}}.$$

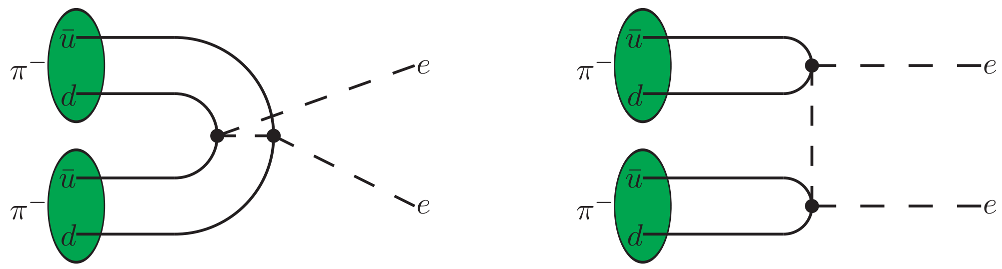


- in agreement with [Detmold, Murphy; 2004.07404]

$$g_\nu^{\pi\pi}(770\text{ MeV}) = -10.78(12)_{\text{stat}}(4)_{\text{fit}}(50)_{\text{FV}}(9)_{\chi\text{PT}},$$
$$S_{\pi\pi} = 1.1054(14)_{\text{stat}}(6)_{\text{fit}}(61)_{\text{FV}}(10)_{\chi\text{PT}},$$

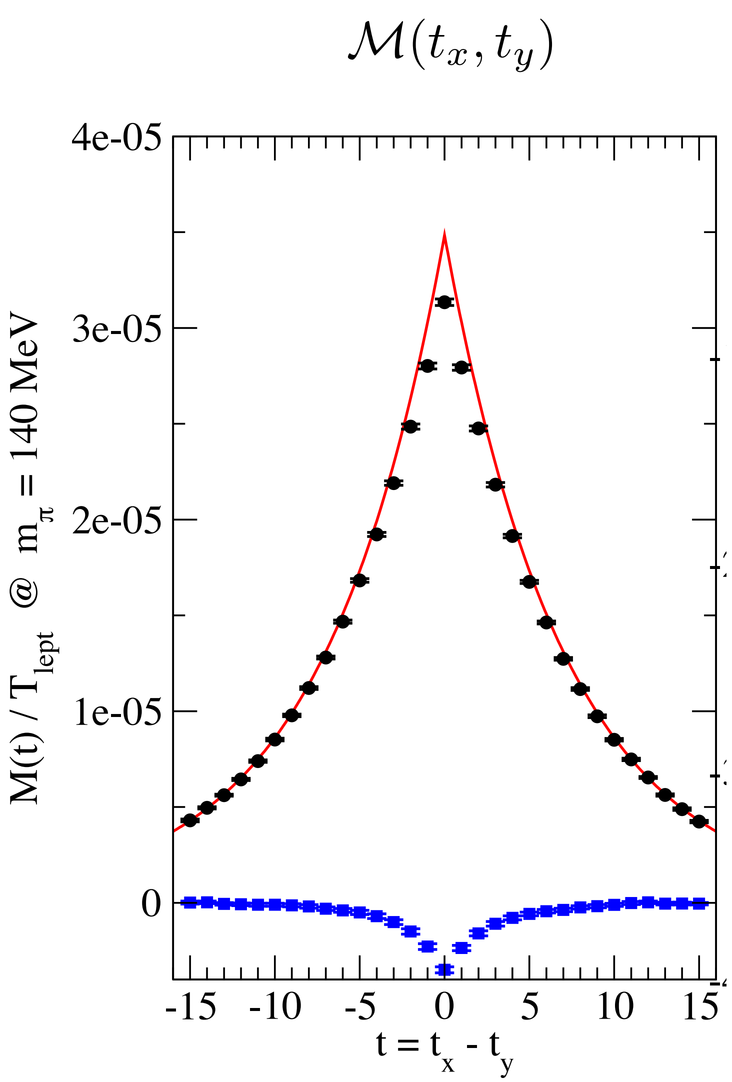
Long-Range LNV: $\pi^-\pi^- \to e^-e^-$

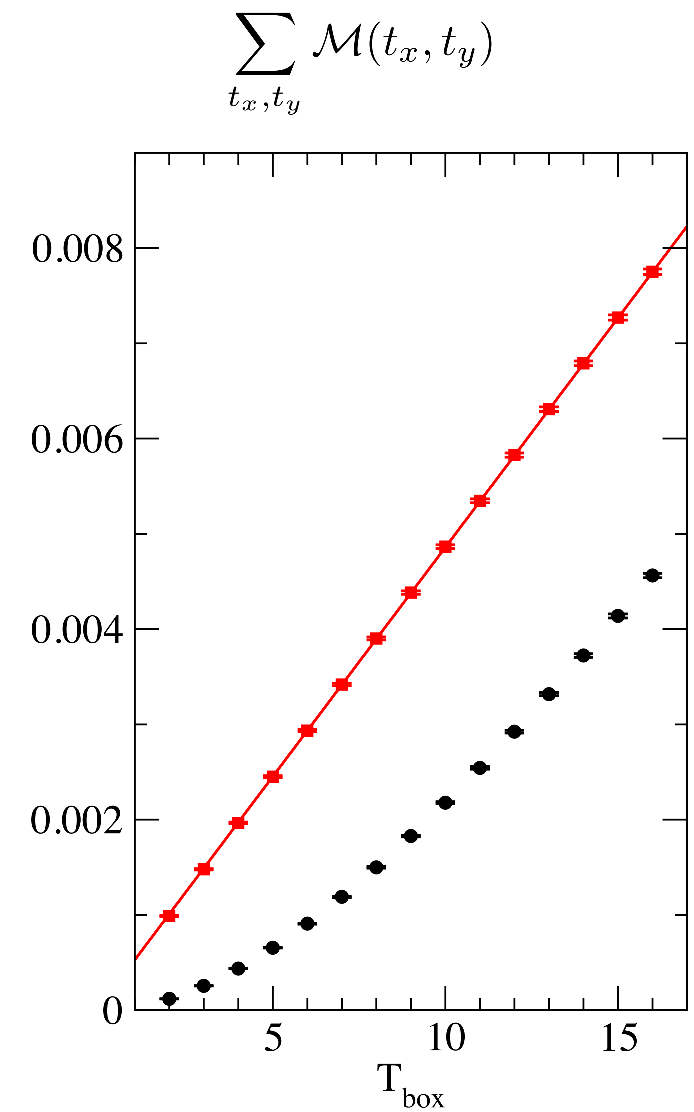
- $\langle ee|S_{NL}|\pi\pi\rangle$ [Feng et al, PRL, 1809.10511]



$$\mathcal{M}(T, t_x, t_y) = \frac{C_{\pi\pi\to ee}(T, t_x, t_y)}{C_{\pi\pi}(T)}$$

- (*) $\pi\bar{\nu}$ state treated analytically





$$\left.\frac{\mathcal{A}(\pi\pi\to ee)}{F_\pi^2\, T_{\text{lept}}}\right|_{m_\pi=420\text{ MeV}} = 1.517(13),$$

$$\left.\frac{\mathcal{A}(\pi\pi\to ee)}{F_\pi^2\, T_{\text{lept}}}\right|_{m_\pi=140\text{ MeV}} = 1.820(6).$$

NLO ChPT →

$$g_\nu^{\pi\pi}(m_\rho)\Big|_{m_\pi=420\text{ MeV}} = -8.50(9)_{\text{stat}}$$

$$g_\nu^{\pi\pi}(m_\rho)\Big|_{m_\pi=140\text{ MeV}} = -11.96(31)_{\text{stat}}$$

[Detmold, Murphy; 2004.07404]

Towards nn→ppe⁻e⁻ Amplitudes

Short-range LNV

- Methodology straightforward [R.Briceño, M.Hansen'15] analogous to NN Parity-vioation [CalLat]
- Main computing challenge: nn, pp spectroscopy & scattering states on a lattice with physical quarks

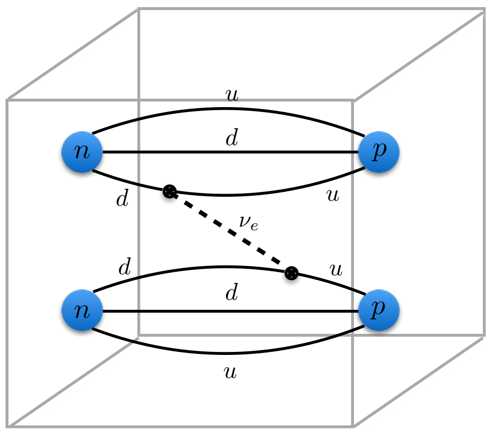
2-body amplitude of local interaction:

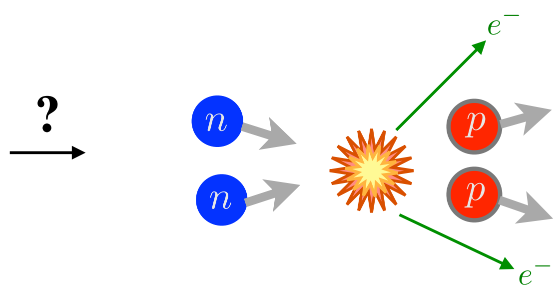
$$|\mathcal{A}_{V\to\infty}|^2 \propto \left(q\frac{\partial\phi(q)}{\partial q} + k\frac{\partial\delta(k)}{\partial k}\right)|\mathcal{A}_{V=L^3}|^2$$

δ(k) = scattering phase

ϕ(q) = lattice zeta fcn.

[Lellouch, Luscher, '01]





[Z.Davoudi, ECT* '19]

Long-range LNV : complicated by bi-locality of nn→pp

- Can be matched to pion-less EFT $\Longrightarrow$ short-range $(g_\nu)^{NN}$ [Z.Davoudi, S.V.Kadam, 2012.02083]
- On-shell intermediate states : may need addl. calculations to constrain (n)n→(n)pν amplitudes

Matching to EFTs beyond LO : combination of nn→pp, π+→π–, n→pπ LECs

SUMMARY

- Nucleon charges & Dark Matter scattering
  Remarkable progress sys/stat precision for single nucleons
- Nucleon/nuclear Electric Dipole Moments
  θ_{QCD} is challenging at the physical point
  Higher-dim operators: renormalization&mixing tractable
  Nuclear EDMs: CPv πN, NN coupling
- Baryon number violation operators
  Single-nucleon decay/oscillation straightforward
  Annihilation, in-medium effects challenging as 0nu2beta
- Neutrinoless double-beta decay
  Depend critically on
  - progress in NN spectrum & scattering
  - Effective many-body Theory