8th International Workshop on Chiral Dynamics, Pisa, June 29 - July 3 2015

Electric Dipole Moments, New Physics, and Lattice QCD

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Outline

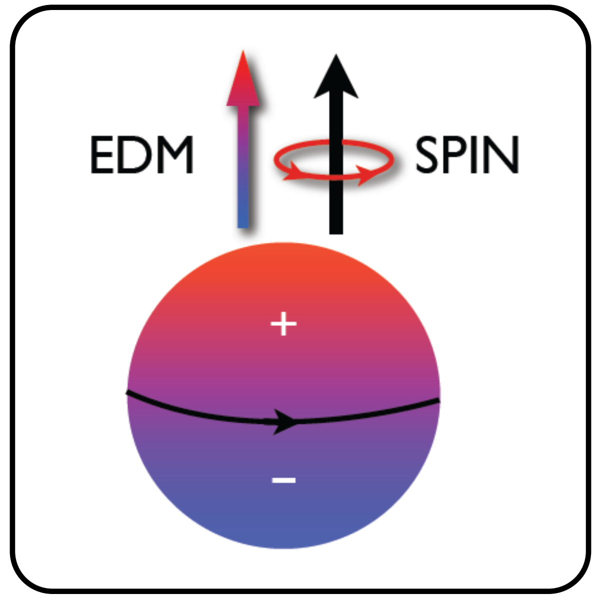
- Introduction: EDMs as probes of new physics
- Connecting hadronic EDMs to BSM physics
    - Chiral symmetry constraints
    - Matrix elements with Lattice QCD
    - Some phenomenological implications
- Conclusions

Why are EDMs interesting?

EDMs and symmetry breaking

- EDMs of non-degenerate systems violate P and T (CP): $\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$

Classical picture $\rightarrow$



Quantum level: Wigner-Eckart theorem $\vec{\mathbf{d}} \propto \vec{\mathbf{J}}$

- Ongoing and planned searches in several systems

★ n, p
★ Light nuclei: d, t, h
★ Atoms: diamagnetic (^{129}Xe, ^{199}Hg, ^{225}Ra, ...);
paramagnetic (^{205}Tl, ...)
★ Molecules: YbF, ThO, ...

EDMs and new physics

1. Essentially free of SM "background" (CKM)

ThO →

EDMs in $e \cdot cm$

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-29}	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29} **	$\sim 10^{-31}$
^{199}Hg	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
$\cdots$	$\cdots$		$\cdots$

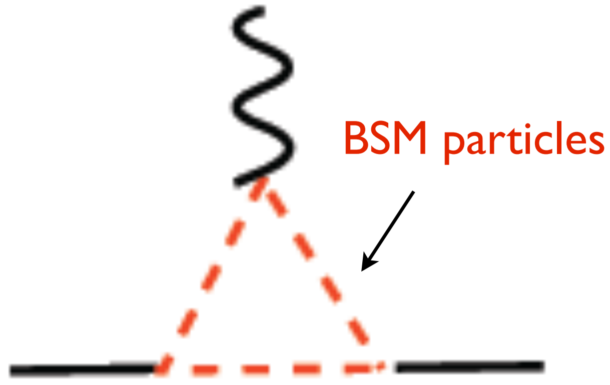
Observation would signal new physics or a tiny QCD θ-term ($< 10^{-10}$)

Multiple measurements can disentangle

2. EDMs probe high scale BSM physics

$$d_i \propto \frac{m_i}{\Lambda^2} \sin(\phi_{\mathrm{CP}})$$

- Current limits: $\Lambda \sim 100$ TeV, for $\phi_{CP} \sim O(1)$
- New particles with $M_{BSM} = \Lambda/\sqrt{c} \sim 1$ TeV



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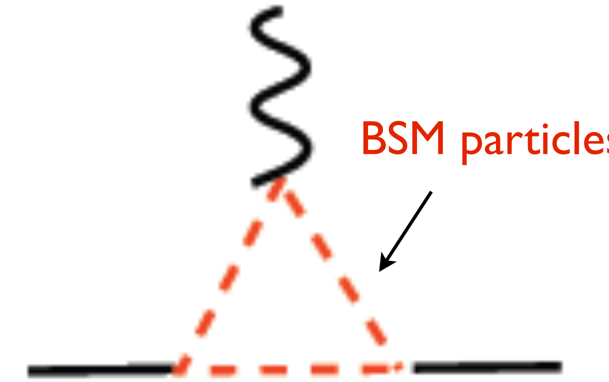
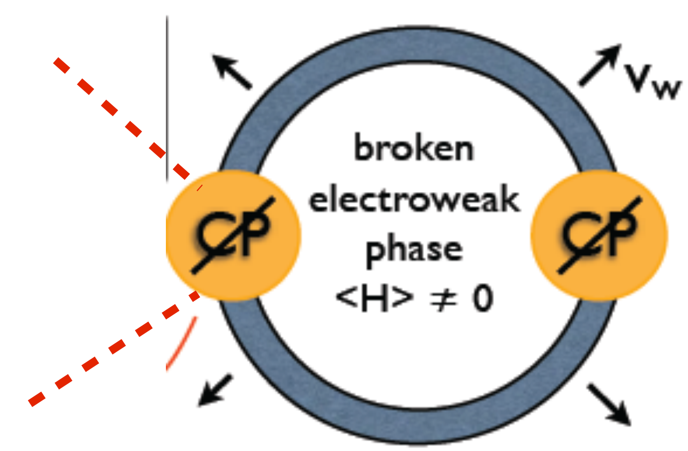


3. EDMs probe one of the three ingredients of baryogenesis

Sakharov '67

- B violation
- C and CP violation
- Departure from equilibrium

EDMs, K, B,...



Connecting EDMs to BSM physics

Connecting EDMs to BSM CPV

E

Λ
(~TeV)

Λ_{Had}
(~GeV)

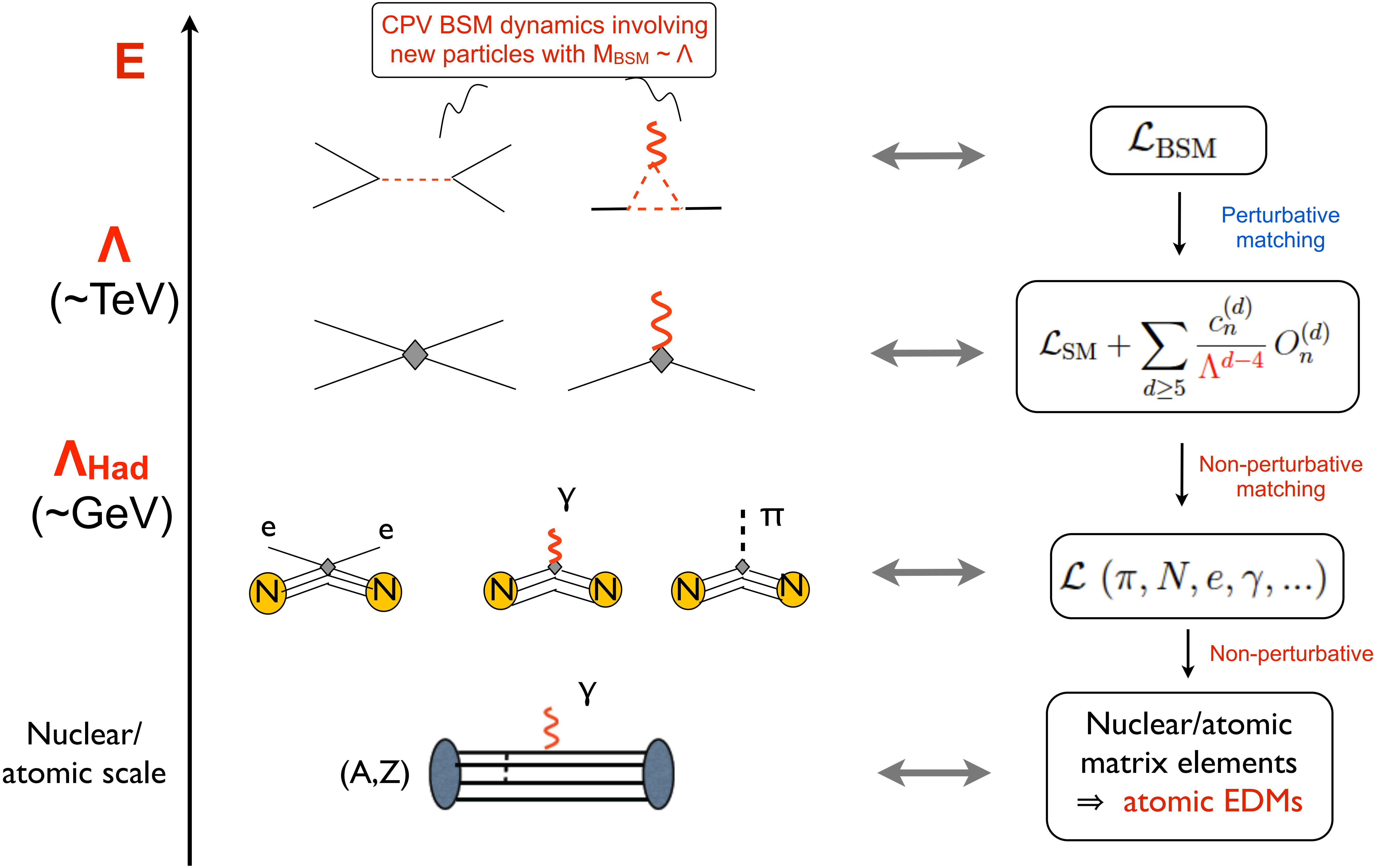
Nuclear/
atomic scale

Probing nature of BSM CP violation with EDMs requires robust theoretical tools to address multi-scale problem

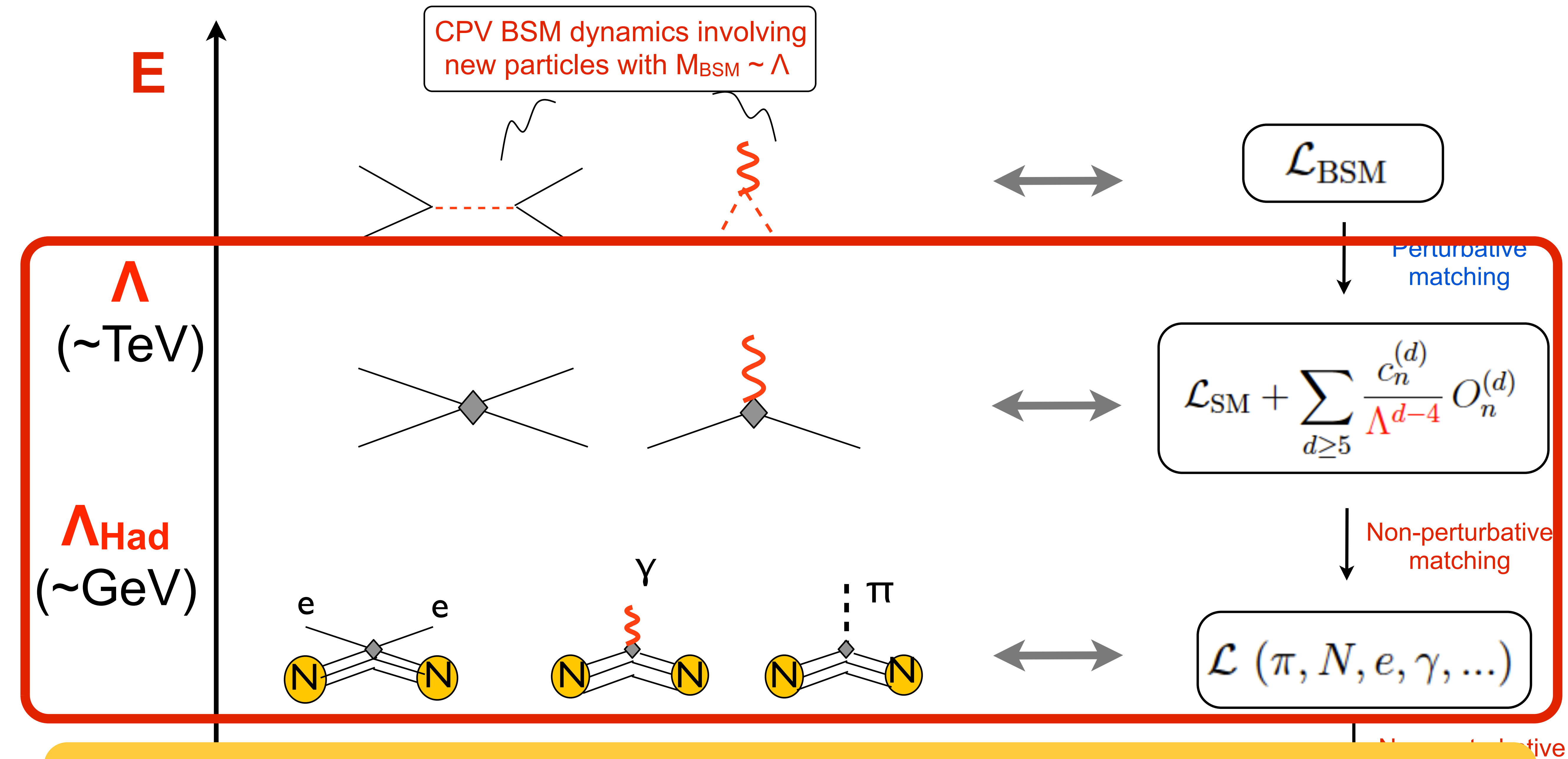
$(\Lambda > v_{ew} >> \Lambda_{Had} >> m_\pi >> m_e)$

Best tackled by a chain of EFTs linked by perturbative and non-perturbative matching

Connecting EDMs to BSM CPV



Connecting EDMs to BSM CPV



Focus of this talk is the matching from quarks/gluons → hadrons

Symmetry relations: chiral EFT

Non-perturbative calculation of "LECs": Lattice QCD

CPV at the quark-gluon level

- CPV $\mathcal{L}_{\text{eff}}$ at hadronic scale, induced by leading dim=4,6 operators

$$\mathcal{L}_{\text{CPV}} = -m_* \bar{\theta} \sum_{q=u,d,s} \bar{q}\, i\gamma_5 q$$

$$- \frac{i}{2} \sum_{q=u,d,s} d_q\, \bar{q}_i \sigma_{\mu\nu}\gamma_5 q\, F^{\mu\nu} - \frac{i}{2} g_s \sum_{q=u,d,s} \tilde{d}_q\, \bar{q}\sigma_{\mu\nu}\gamma_5 T^a q\, G^{\mu\nu,a}$$

$$+ c_w\, f^{abc} G^a_{\mu\nu} \tilde{G}^{\nu\beta,b} G^{\mu,c}_{\beta} + c_{4q}\, O_{4q} + c_{2q2\ell}\, O_{2q2\ell}$$

$$m_* = \frac{1}{\sum_i (1/m_i)}$$

$$d_q, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}$$

$$c_{w,4q,2q2\ell} \sim \frac{1}{\Lambda^2}$$

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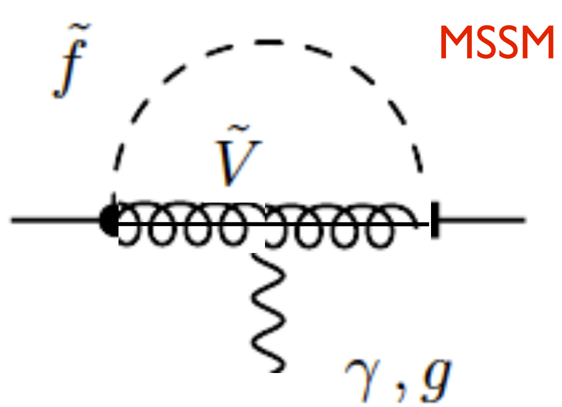
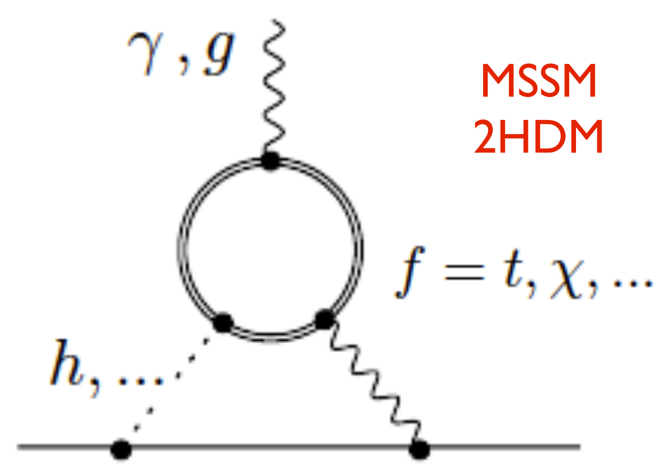
- Dim 6: induced by a variety of BSM scenarios





Quark EDM and chromo-EDM

CPV at the quark-gluon level

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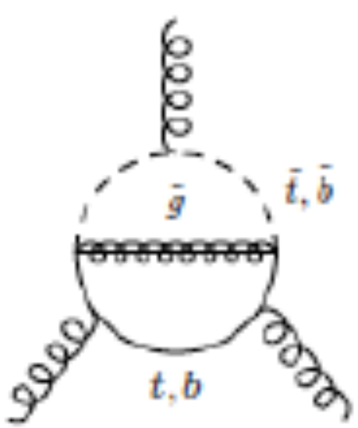
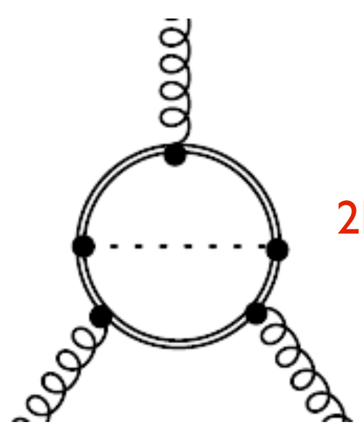


MSSM



2HDM

→ Gluon chromo-EDM

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- Dim 6: induced by a variety of BSM scenarios

Operator mixing $\Rightarrow$
EDM sensitivity to non-standard Higgs couplings (hVV, ...), heavy quark CPV, ...

See Dekens-deVries 1303.3156 for state-of-the art matching and running

CPV at the hadronic level

The above quark-gluon operators induce π,N CPV operators

Effective Lagrangian constructed according to chiral transformation properties of each quark-gluon operator

Great work on this by the Arizona-Groningen and Bonn-Julich groups: see 1505.06272 and 1412.5471 for recent reviews

CPV at the hadronic level

- Leading pion-nucleon CPV interactions characterized by few LECs

$$\mathcal{L}_{\mathrm{CPV}} = -\frac{i}{2}\,\bar{N}\,\bar{d}_N\,\sigma_{\mu\nu}\gamma_5\,N\,F^{\mu\nu} - \bar{N}\left[\bar{g}_0\,\vec{\tau}\cdot\vec{\pi} + \bar{g}_1\,\pi^0\right]N - \frac{\bar{\Delta}}{F_\pi}\,\pi^0\,\vec{\pi}\cdot\vec{\pi} + \ldots$$

Nucleon EDM $\bar{d}_N = \begin{pmatrix} \bar{d}_p & 0 \\ 0 & \bar{d}_n \end{pmatrix}$

T-odd P-odd pion-nucleon couplings

Short-range 4N and 2N2e coupling

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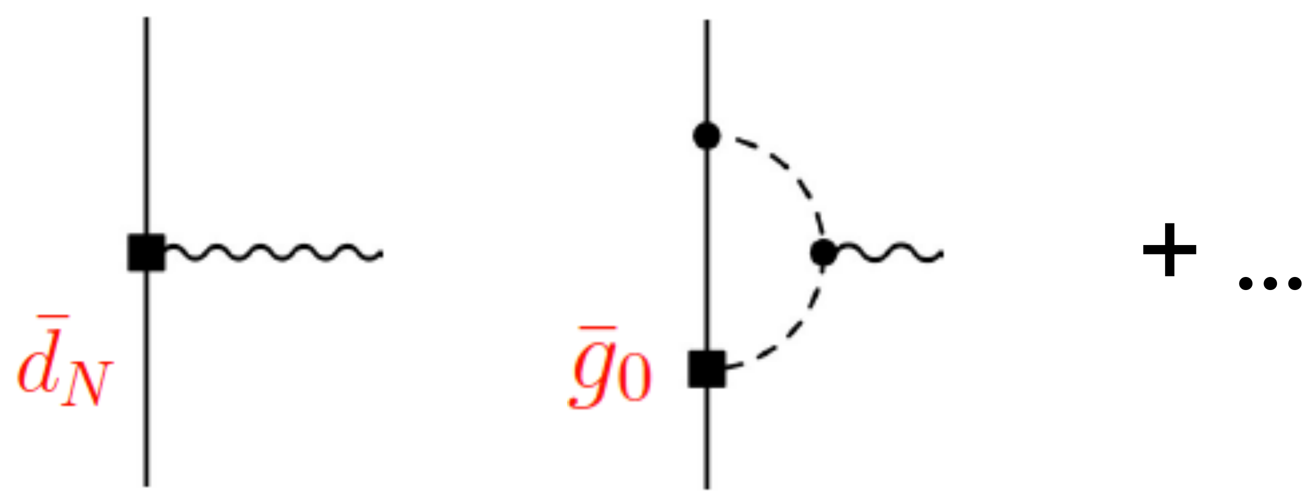
- At LO all hadronic EDMs are expressed in terms of these LECs:

Nucleon EDM



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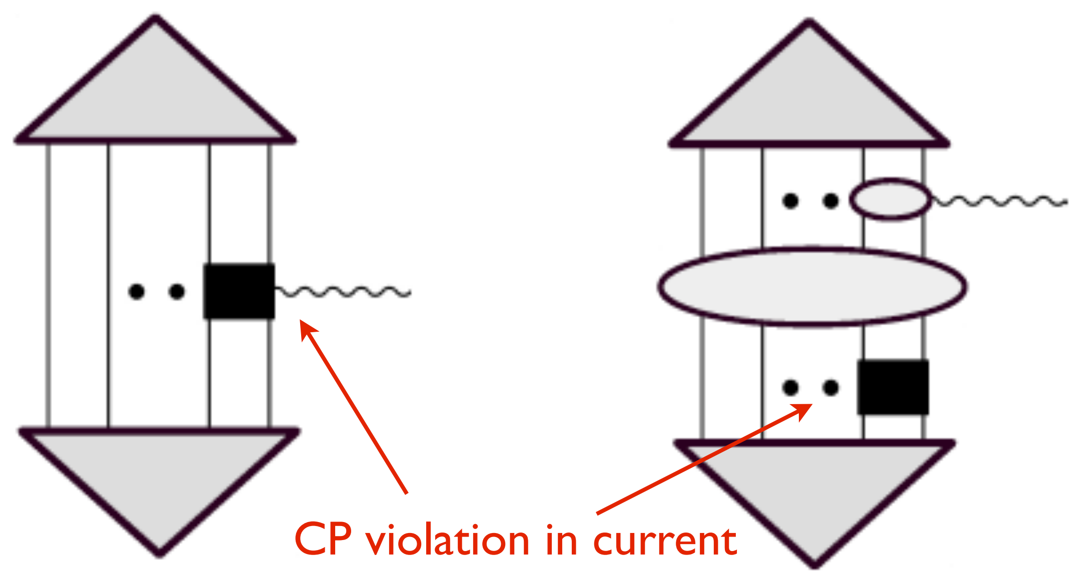
Nuclear EDMs



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$$d^A = c_n^A\,d_n + c_p^A\,d_p + c_0^A\,\bar{g}_0 + c_1^A\,\bar{g}_1 + c_\Delta^A\,\bar{\Delta} + \ldots$$

  - Light nuclei (d,t,h): chiral EFT calculations $\Rightarrow$ c_i^A at ~10% level
  - Diamagnetic atoms (^{199}Hg,...): O(1-10) uncertainties

Great work on this by the Arizona-Groningen and Bonn-Julich groups: see 1505.06272 and 1412.5471 for recent reviews

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Multiple measurements (n,p,d,t,h, ... ,^{199}Hg) ⇒
handle on CPV mechanism, provided we can reliably estimate
the LECs in terms of short-distance couplings

Great work on this by the Arizona-Groningen and Bonn-Julich groups: see 1505.06272 and 1412.5471 for recent reviews

LECs: symmetry relations

What do we know about CP-violating LECs?

A lot (but not everything) can be learned from chiral symmetry constraints

LECs: symmetry relations

- Prototype: theta term and mass splitting are chiral partners

$$\begin{pmatrix} \bar{q} i \gamma_5 q \\ \bar{q} \boldsymbol{\tau} q \end{pmatrix} \xrightarrow{SU_A(2)} \begin{pmatrix} -\bar{q} \boldsymbol{\alpha} \cdot \boldsymbol{\tau} q \\ \boldsymbol{\alpha}\, \bar{q} i \gamma_5 q \end{pmatrix}$$

- Nucleon matrix elements are related. At LO (soft pion theorem)

$$\langle N_f \pi^a | \bar{q} i \gamma_5 q | N_i \rangle \;\propto\; F_\pi^{-1} \, \langle N_f | \bar{q}\, \tau^a\, q | N_i \rangle$$

Crewther-DiVecchia-Veneziano-Witten 1979

$$\Downarrow$$

$$\boxed{\bar{g}_0 = \frac{\delta M_{n-p}^{m_d - m_u}}{m_d - m_u} \frac{2 m_d m_u}{m_d + m_u} \bar{\theta}}$$

- Corrections appear at NNLO

Mereghetti, van Kolck
1505.06272
and refs therein

LECs: symmetry relations

- Analysis of leading quark-gluon operators: summary

Mereghetti, & van Kolck 1505.06272, and references therein

$\bar{\theta}$	$\bar{g}_0$ from $\bar{\theta}$ determined by $(m_n - m_p)_{st}$
qCEDM	$\bar{g}_0$ and $\bar{g}_1$ determined by corrections to meson and baryon spectrum induced by CP-even qCMDM
4-quark	$\bar{g}_0, \bar{g}_1$ & $\bar{\Delta}$ determined by CP-even 4-q chiral partner

- No info from symmetry on 4-N
- No info from symmetry on d_n, d_p

To probe underlying CP violation,
need non-perturbative calculation of "CP-odd" quantities.
Large uncertainties from QCD/model estimates [O(1)→O(10)]
greatly dilute impact of experimental searches!

Beyond symmetry relations

- Lattice QCD can play a key role: systematically improvable calculations
  - Nucleon EDMs

$$d_{n,p}\ [\bar{\theta};\ d_{u,d,s};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

  - Pion-nucleon CP-odd couplings

$$\bar{g}_{0,1}\ [\bar{\theta};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

Beyond symmetry relations

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$$\bar g_{0,1}\,[\bar\theta;\ \tilde d_{u,d,s};\ c_w;\ c_{4q}]$$

RECENT PROGRESS

$$\frac{d_n}{\bar\theta} = -3.8(2)_{\rm stat}(9)_{\rm fit}\ 10^{-3}\,e\,{\rm fm}$$

Guo et al., 1502.02295

$$\frac{d_n}{\bar\theta} = -2.7(1.2)\ 10^{-3}\ e\,{\rm fm}$$

Akan et al., 1406.2882
Fit to Shintani et al, POS (Lat 2013) 298

$$\frac{\bar g_0}{F_\pi} = (15 \pm 2)\cdot 10^{-3}\sin\bar\theta$$

Mereghetti, van Kolck 1505.06272 with input from
A. Walker-Loud, '14; Borsanyi et al, '14.

Beyond symmetry relations

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  - Nucleon EDMs

$$d_{n,p}\ [\bar{\theta};\ d_{u,d,s};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

RECENT RESULTS
(LANL+ UW):
topic of the rest of this talk

  - Pion-nucleon CP-odd couplings

$$\bar{g}_{0,1}\ [\bar{\theta};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

Beyond symmetry relations

- Lattice QCD can play a key role: systematically improvable calculations

  - Nucleon EDMs

$$d_{n,p}\ [\bar{\theta};\ d_{u,d,s};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

WORK IN PROGRESS
(BNL, LANL, UConn)

  - Pion-nucleon CP-odd couplings

$$\bar{g}_{0,1}\ [\bar{\theta};\ \tilde{d}_{u,d,s}\ \ c_w;\ c_{4q}]$$

(A. Walker-Loud)

Exploit chiral symmetry constraint, relate to shifts in the mass and sigma term

Beyond symmetry relations

- Lattice QCD can play a key role: systematically improvable calculations
  - Nucleon EDMs

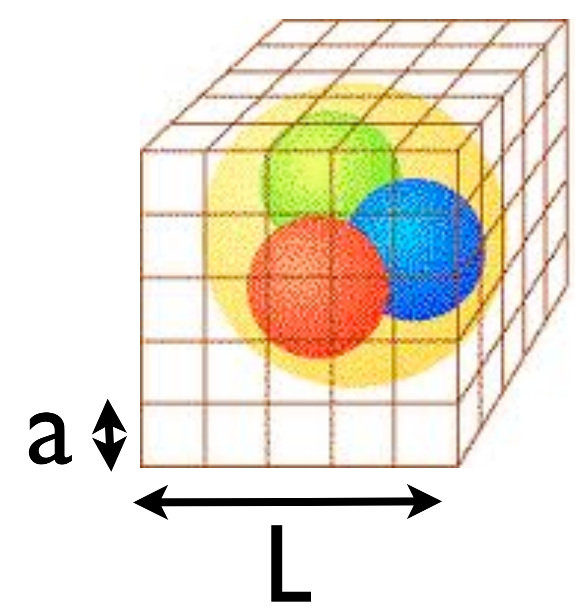
$$d_{n,p}\ [\bar{\theta};\ d_{u,d,s};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

FUTURE

  - Pion-nucleon CP-odd couplings

$$\bar{g}_{0,1}\ [\bar{\theta};\ \tilde{d}_{u,d,s};\ c_w;\ c_{4q}]$$

Matrix elements with lattice QCD



$d_{n,p}$ from quark EDMs

- Quarks directly couple to photon in CP-odd way

$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \, \bar{q} \sigma_{\mu\nu} \gamma_5 q \, F^{\mu\nu}$$

- Problem "factorizes": need tensor charge of the nucleon**

** Use $\sigma_{\mu\nu}\gamma_5 \propto \epsilon_{\mu\nu\alpha\beta}\,\sigma^{\alpha\beta}$

$$\boxed{d_N = d_u \, g_T^{(N,u)} + d_d \, g_T^{(N,d)} + d_s \, g_T^{(N,s)}}$$

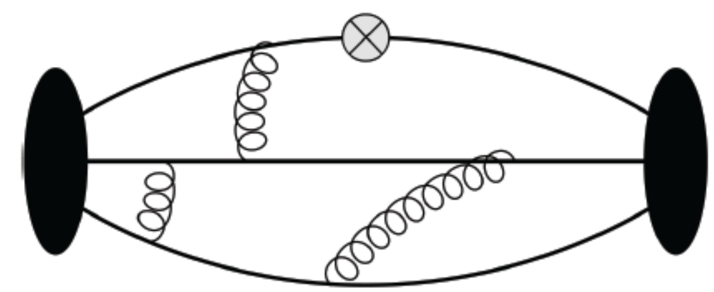
$$\langle N | \, \bar{q} \sigma_{\mu\nu} q \, | N \rangle \equiv g_T^{(N,q)} \; \bar{\psi}_N \sigma_{\mu\nu} \psi_N$$

Tensor charges from LQCD

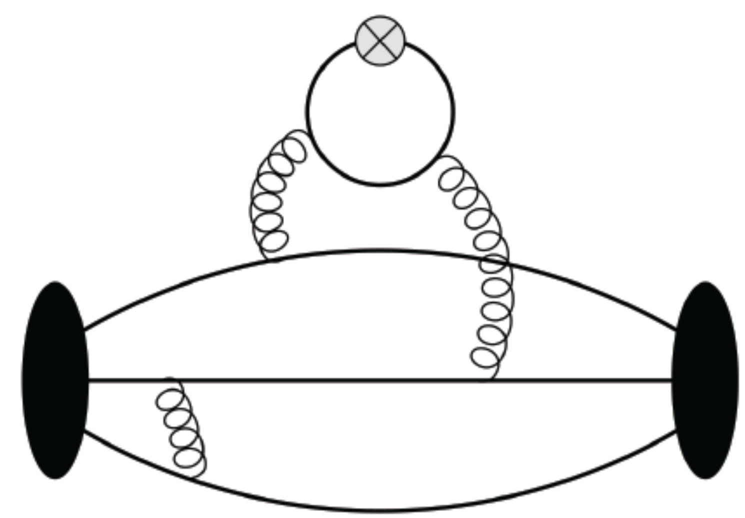
Bhattacharya, VC, Cohen, Gupta, Joseph, Lin, Yoon, 1506.04196, 1506.06411

- Calculation done with dynamical quarks (2+1+1)** on 9 ensembles: $a \in [0.06, 0.12]$ fm, $m_\pi \in [130, 310]$ MeV, $m_\pi L \in [3.3, 5.5]$

- Features:
  - Included connected and disconnected diagrams
  - Studied excited state contamination; performed non-perturbative renormalization (RI-SMOM)
  - Studied dependence on m_q, a, V



"Connected"

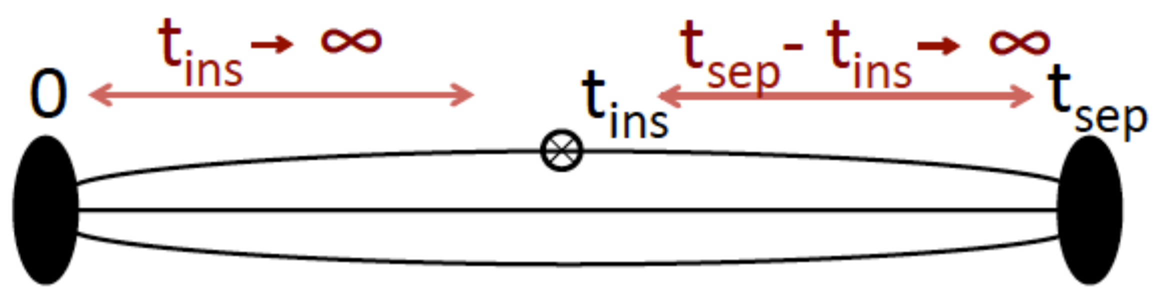


"Disconnected": smaller than statistical error of connected for q=u,d.
Only contribution for q=s

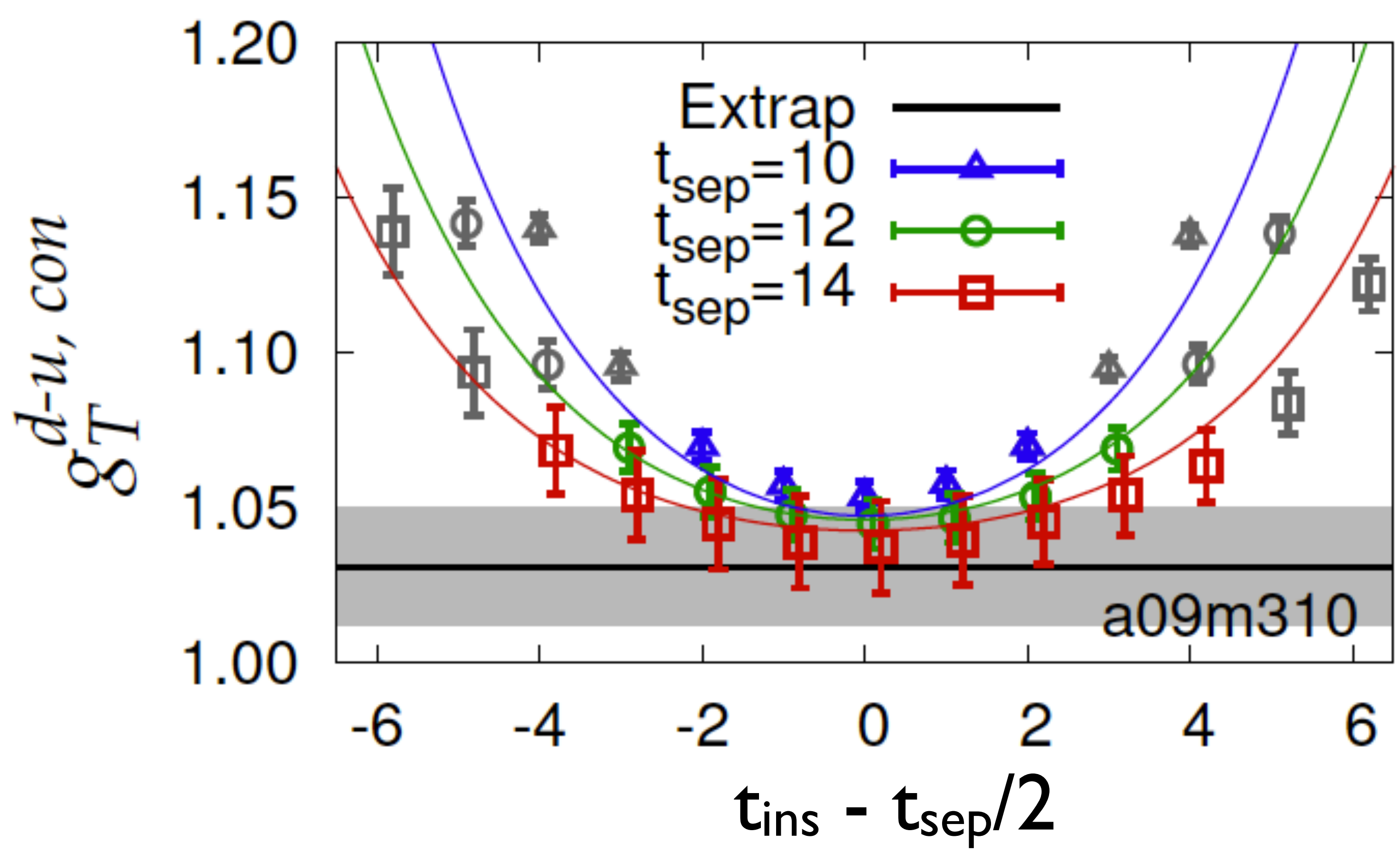
** Clover on staggered (MILC)

Excited states contamination

- Large t_{ins} and t_{sep} - t_{ins} would isolate neutron, but weak signal
- Calculate at different t_{sep}, t_{ins}, and keep one excited state in the fit

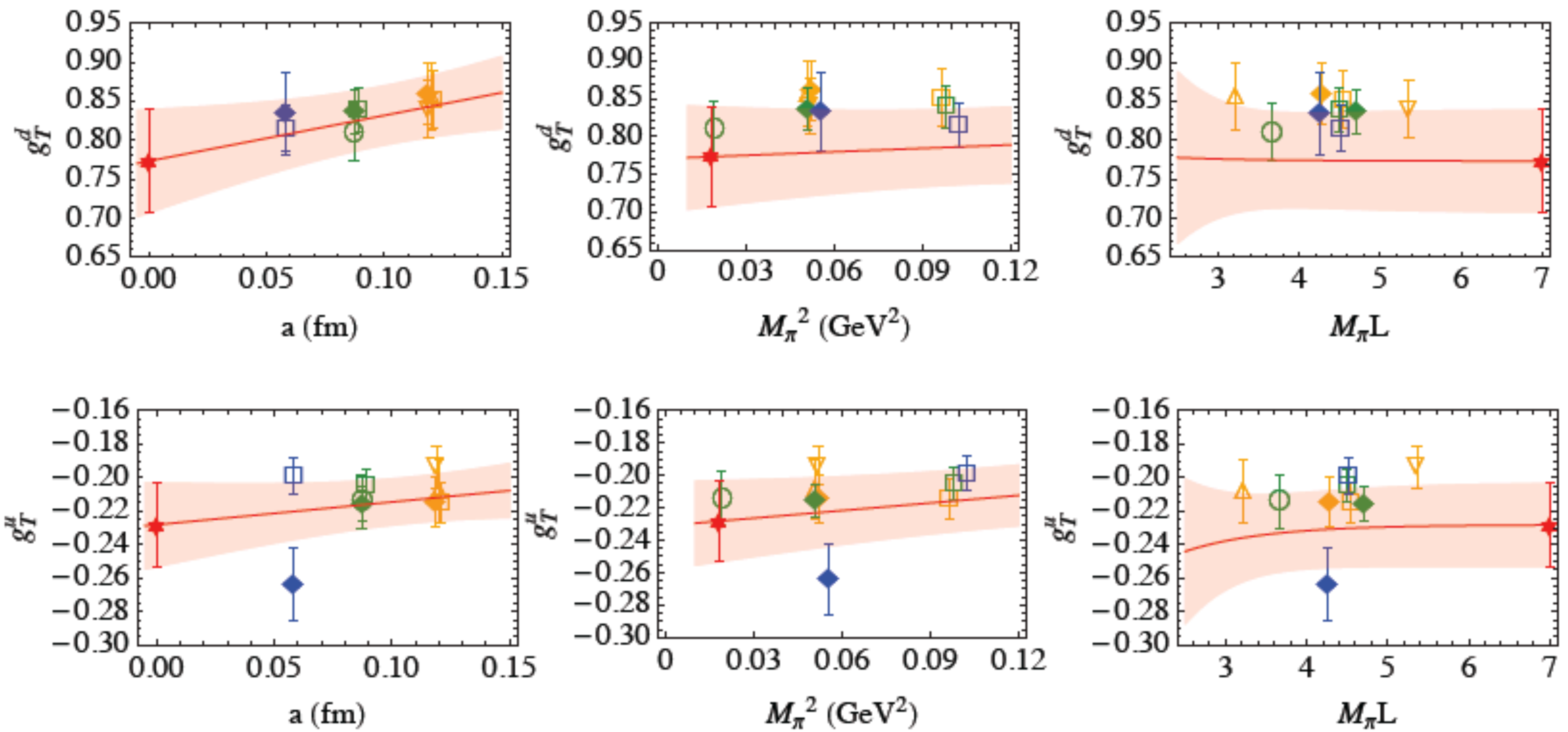


$$C^{3\mathrm{pt}}(t_{\mathrm{sep}}, t_{\mathrm{ins}}) = B_1 e^{-M_0 t_{\mathrm{sep}}} + B_2 e^{-M_1 t_{\mathrm{sep}}} + B_{12}\left[e^{-M_0 t_{\mathrm{ins}}} e^{-M_1(t_{\mathrm{sep}}-t_{\mathrm{ins}})} + e^{-M_1 t_{\mathrm{ins}}} e^{-M_0(t_{\mathrm{sep}}-t_{\mathrm{ins}})}\right]$$



Simultaneous fit in a, M_π, $M_\pi L$

$$g_T(a, M_\pi, L) = c_1 + c_2 a + c_3 M_\pi^2 + c_4 e^{-M_\pi L}$$

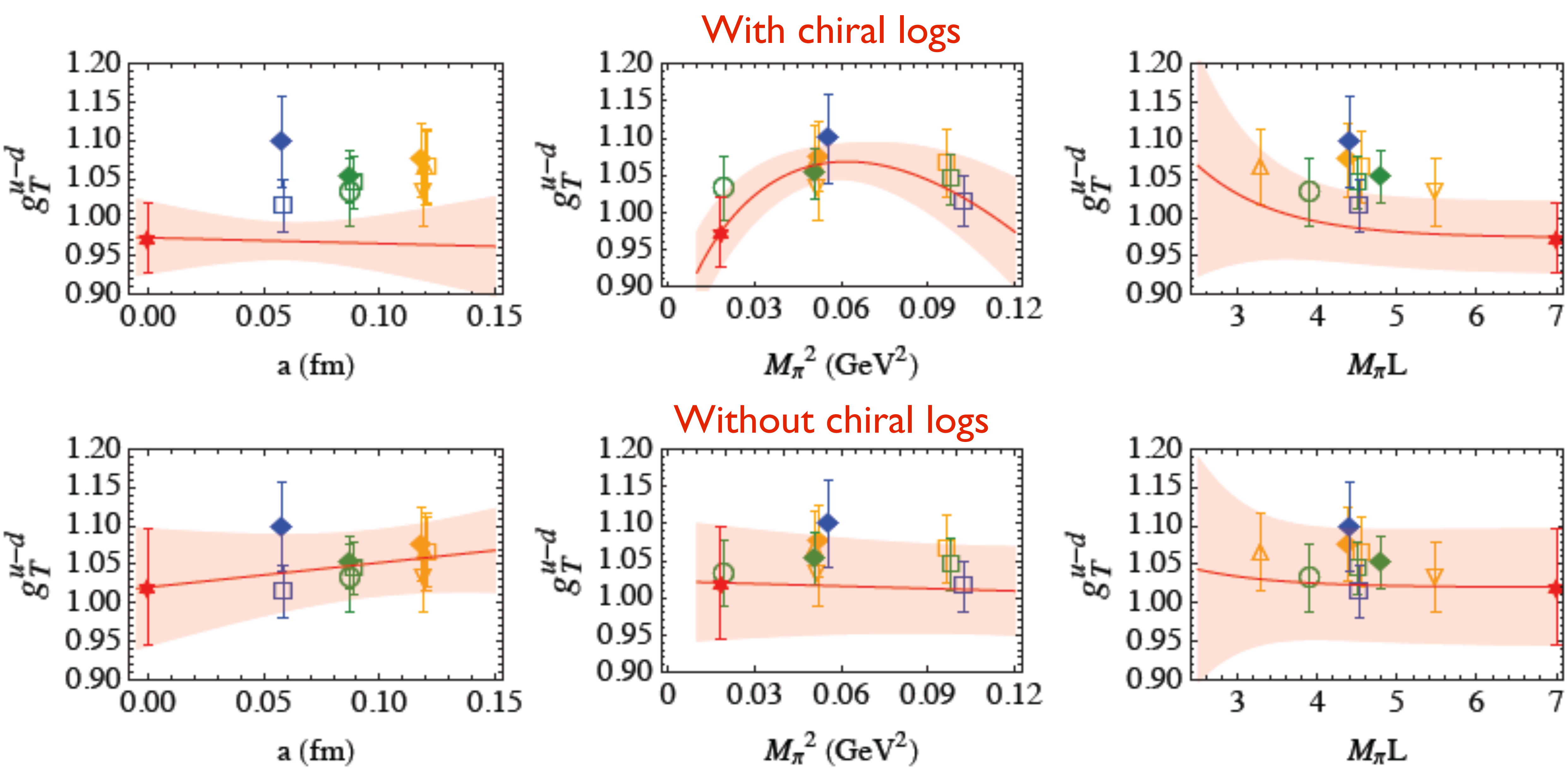


* Yellow (a=0.12 fm), green(a= 0.09 fm), blue (a=0.06 fm);
squares (M_π = 310 MeV), diamonds & triangles (M_π = 220 MeV), circles (M_π = 130 MeV)

- Including leading chiral logs, no significant difference in result

$$
g_T^i = c_1^i \left[1 + \frac{M_\pi^2}{(4\pi F_\pi)^2} f^i\left(\frac{M_\pi}{\mu}\right)\right] + c_2^i\, a + c_3^i(\mu)\, M_\pi^2 + c_4^i\, e^{-M_\pi L}
$$

de Vries et al, 1006.2304



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Results and impact on nEDM

- Flavor diagonal neutron tensor charges in $\overline{\text{MS}}$ @ 2 GeV

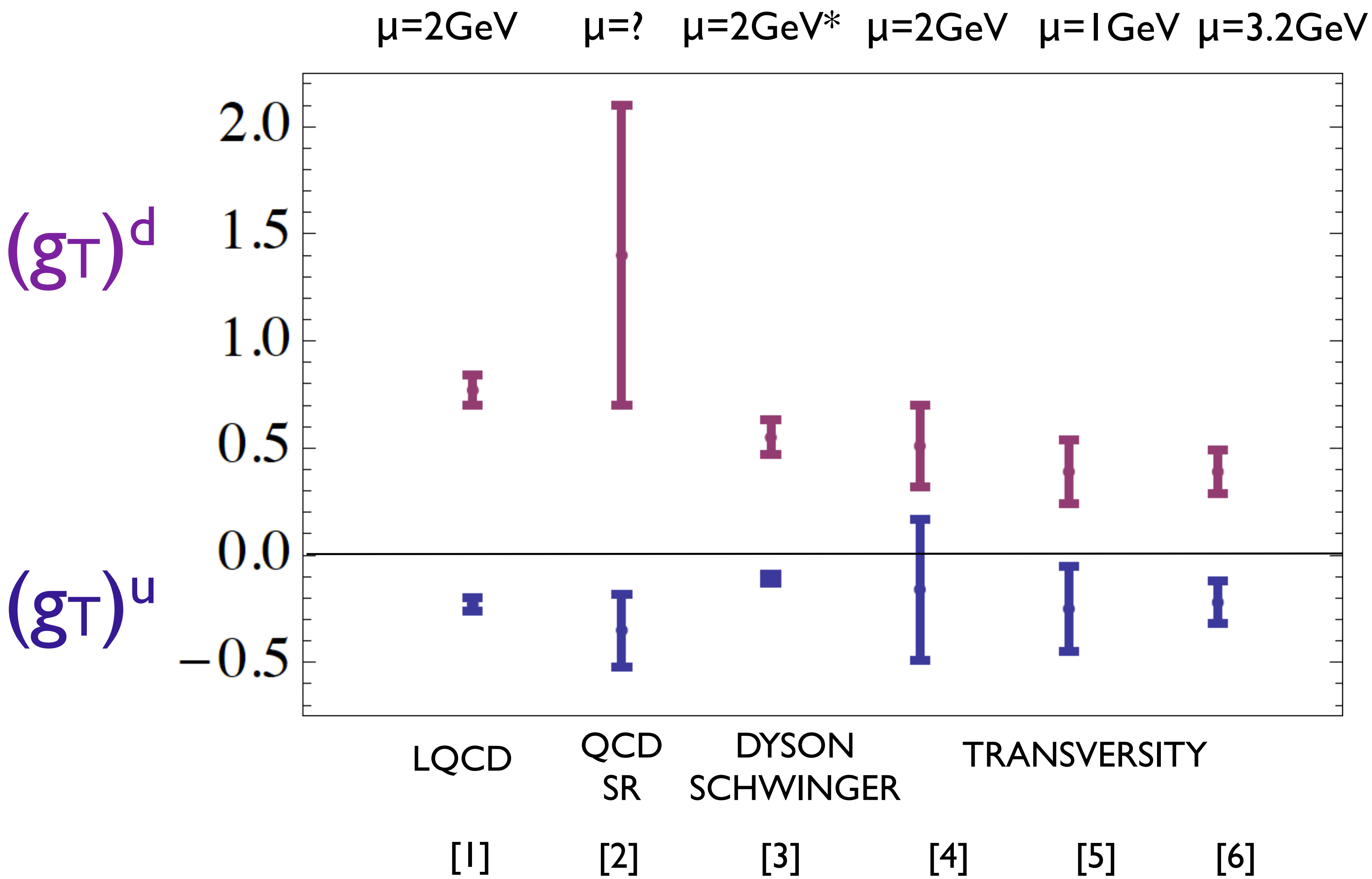
$$\boxed{d_n \;=\; d_u\, g_T^{(n,u)} \;+\; d_d\, g_T^{(n,d)} \;+\; d_s\, g_T^{(n,s)}}$$

$$g_T^{(n,u)} = -0.23(3)$$

$$g_T^{(n,d)} = 0.77(7)$$

$$g_T^{(s)} = 0.008(9)$$

- Comparison with non-lattice approaches and impact on nEDM



NOTE: no estimate of $(g_T)^s$ from other methods

[1] This work

[2] Pospelov-Ritz 2000

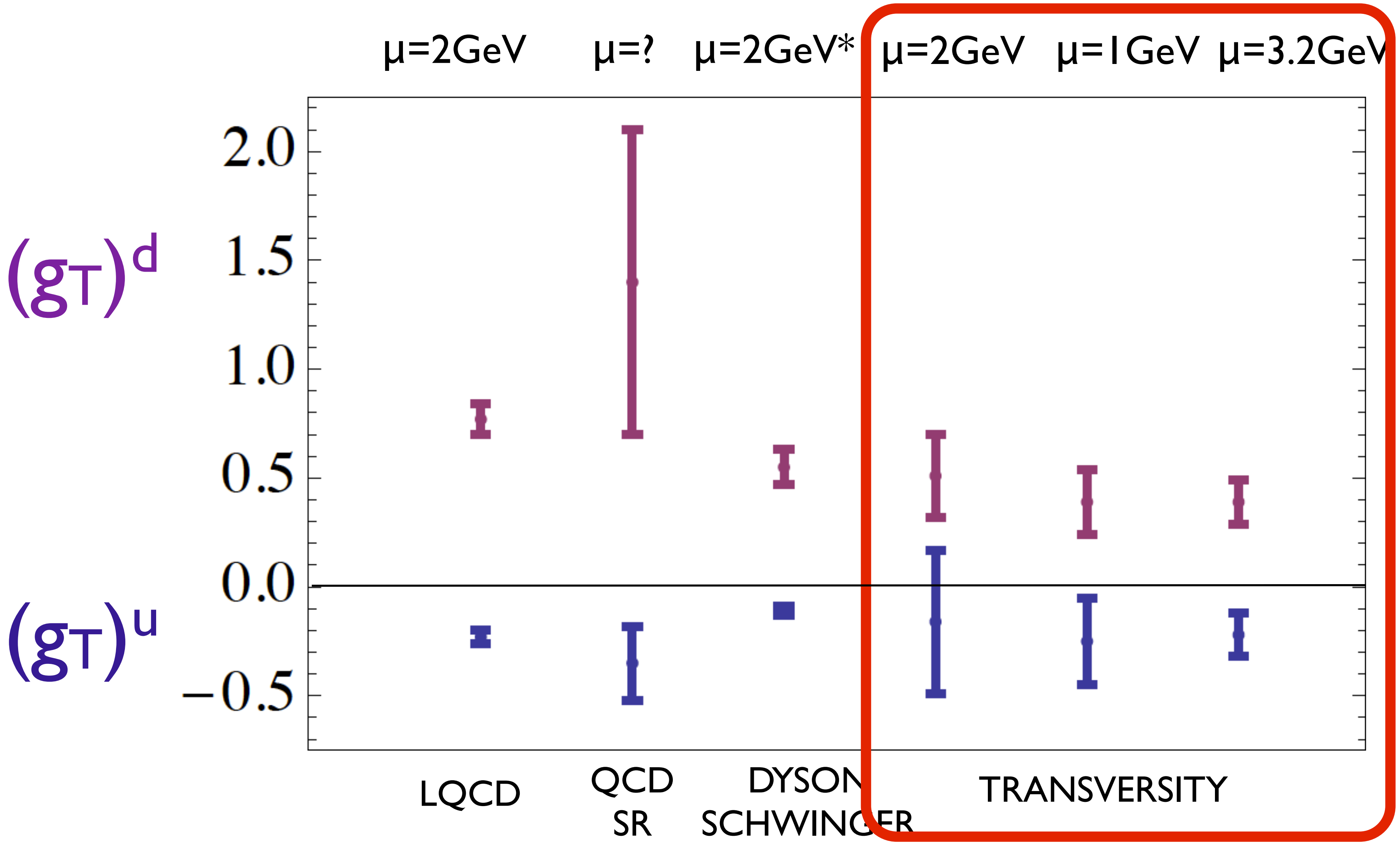
[3] Pitschmann et al 2014

[4] Bacchetta et al 2013

[5] Anselmino et al 2013

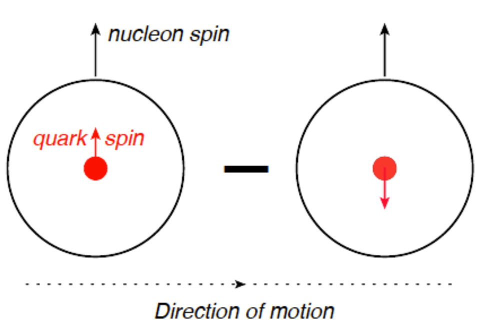
[6] Kang et al 2015

- Comparison with non-lattice approaches and impact on nEDM

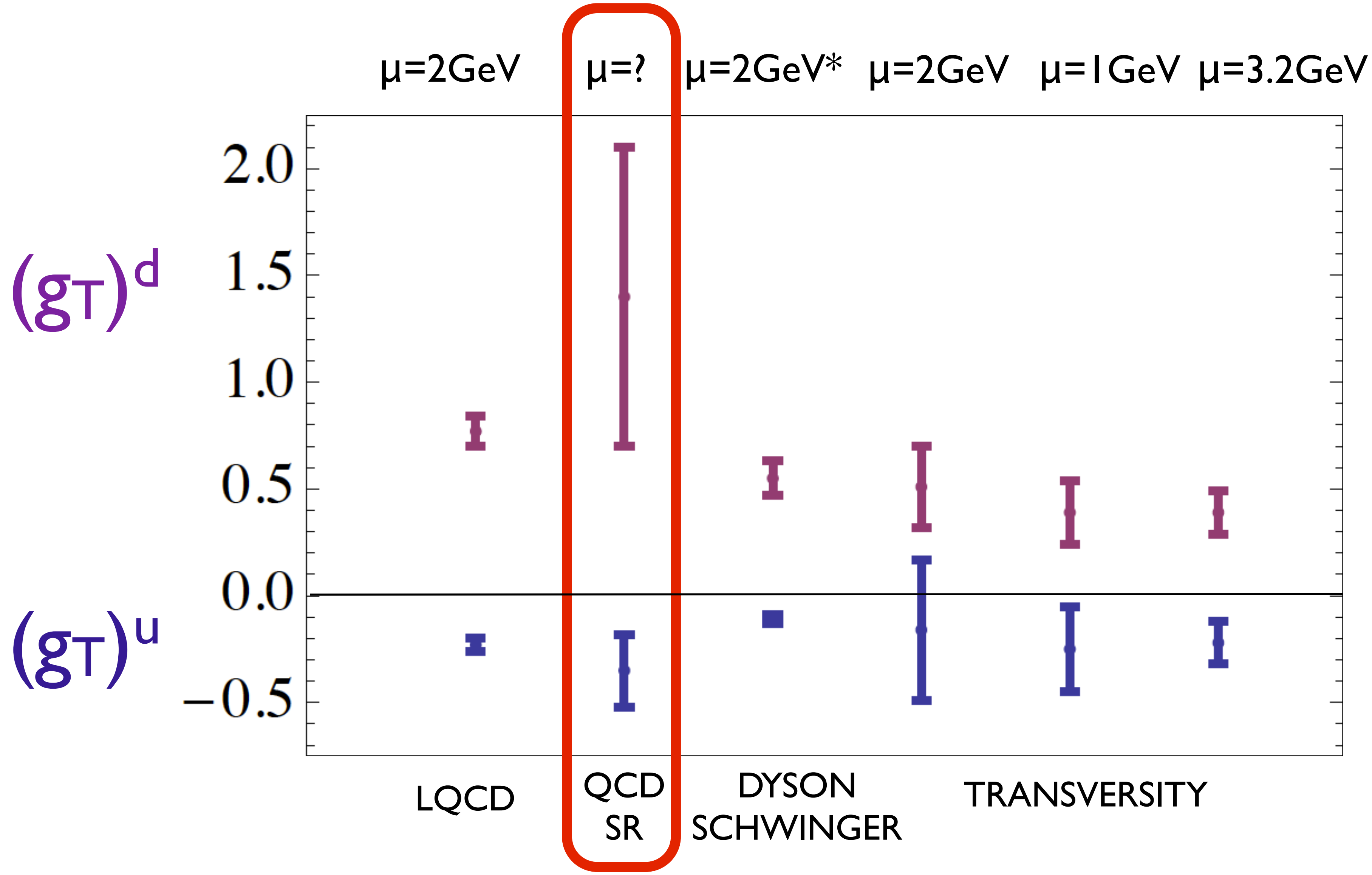


- Transversity analysis: currently large extrapolation uncertainty

$$g_T = \int_0^1 dx\,[h_{1T}^{q}(x) - h_{1T}^{\bar{q}}(x)]$$



- Comparison with non-lattice approaches and impact on nEDM

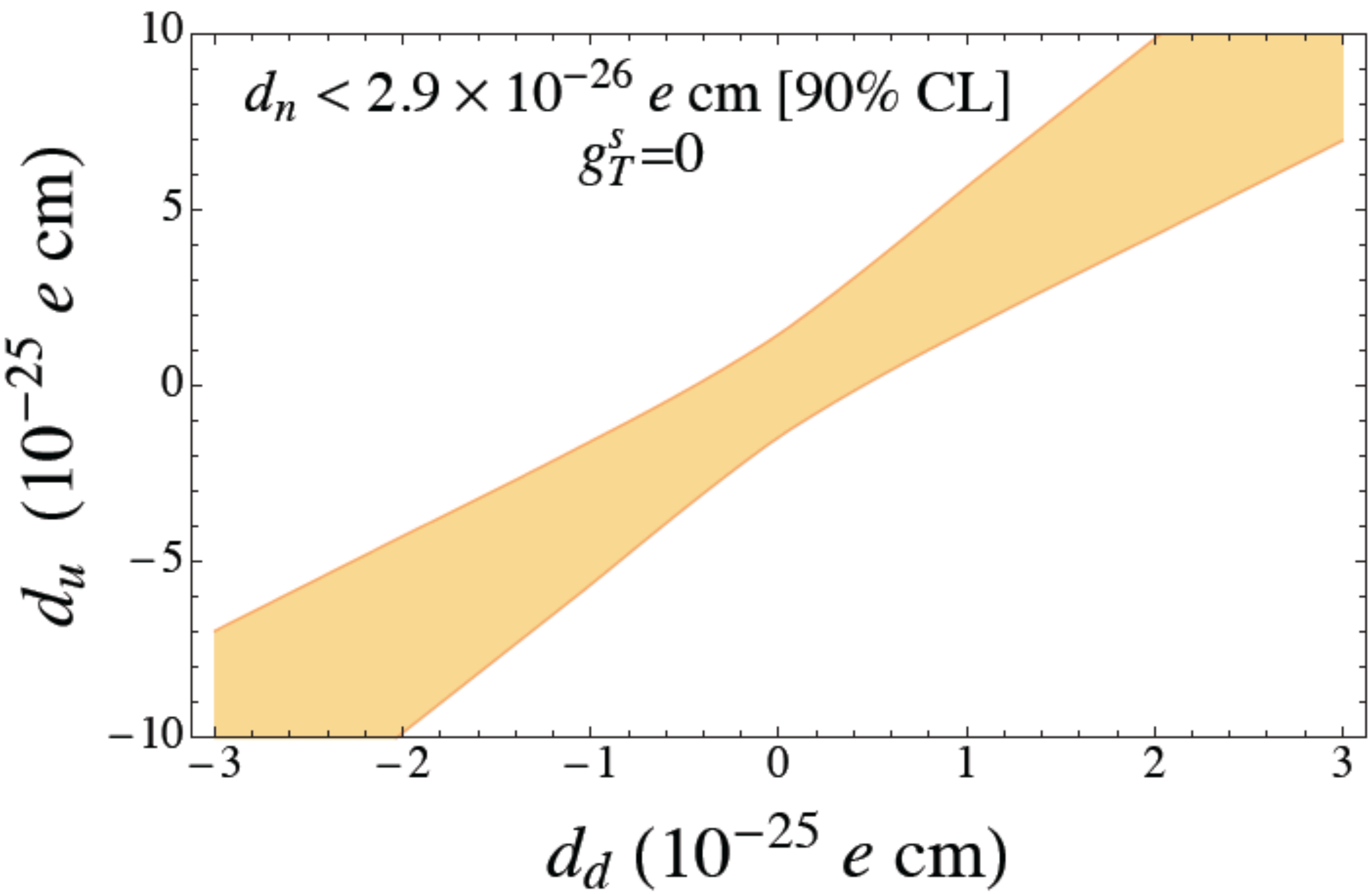


Widely used in BSM studies of neutron EDM

- $(g_T)^{u,d}$ uncertainty: 50% to 10% + scale/scheme dependence
- $(g_T)^{u,d}$ smaller central values: d_n "less sensitive" to new physics in d_q
- $(g_T)^s$: important for models in which $d_q \propto m_q$, since $m_s/m_d \sim 20$

Bounds on $d_{u,d}$

- Improved knowledge of $(g_T)^{u,d}$ enables more stringent tests of the pattern of CPV beyond the Standard Model



Assuming PQ mechanism and suppression of other CPV operators

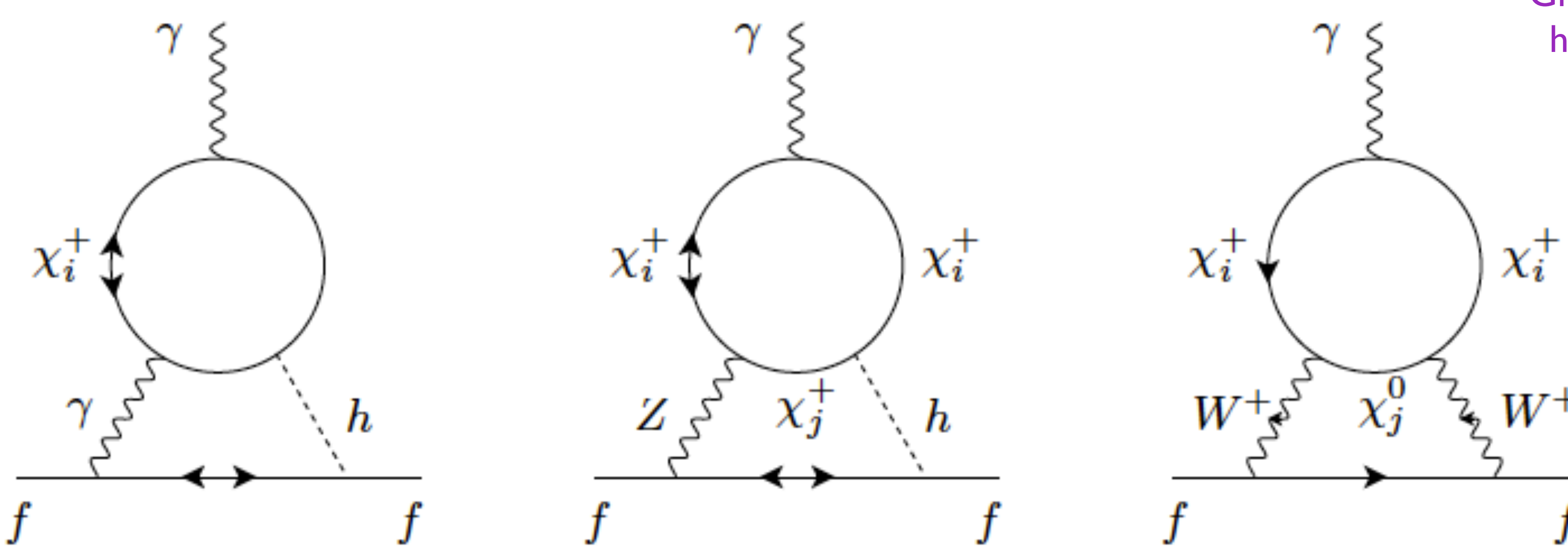
Implications for “split SUSY”

- All scalars except for one Higgs doublet are heavy. Good features: gauge coupling unification, DM candidate, no “flavor/CP problem”

Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004

- $d_{e,q}$ are the dominant CPV operators:

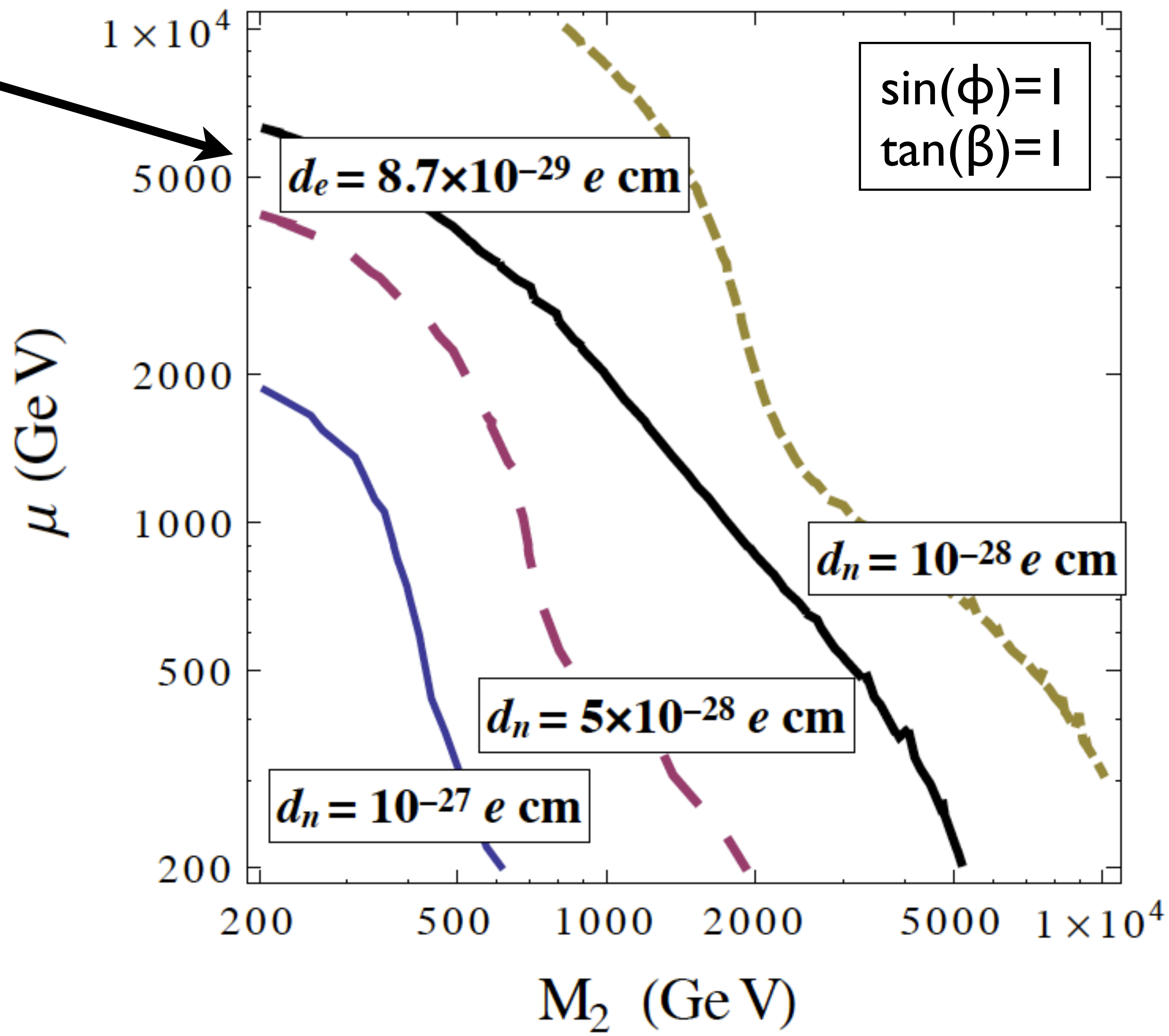
Giudice, Romanino
hep-ph/0510197



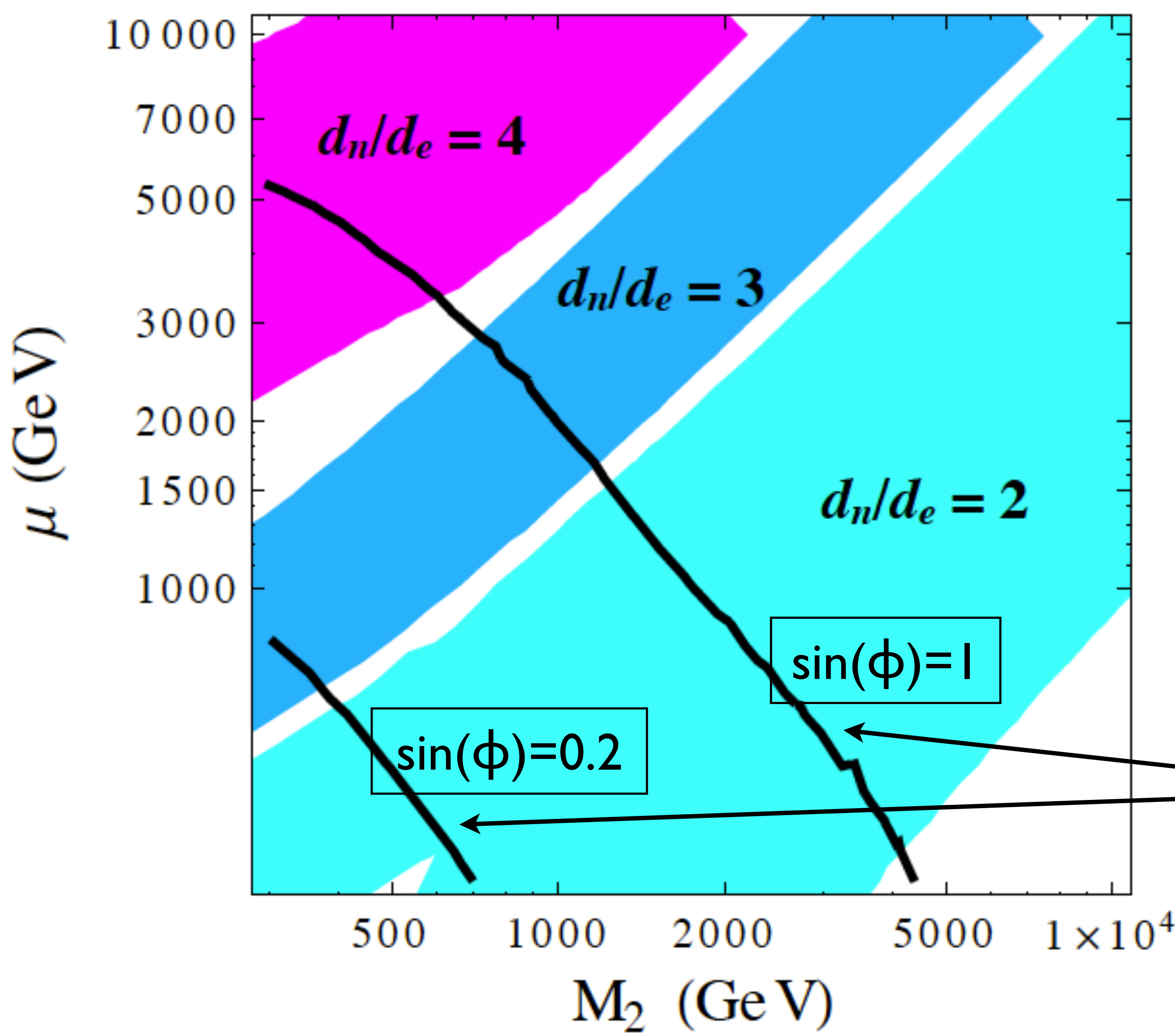
EDMs depend on gaugino (M_2) and Higgsino (μ) mass parameters, their relative phase (ϕ), and ratio of Higgs vevs $\tan(\beta)$ [$\sin(\phi)\sin(2\beta)$]

- Neutron and electron EDMs controlled by same parameters. They are both within reach of current searches for M_2, $\mu \sim O(10\ \mathrm{TeV})$

Current limit from ThO (ACME)



- The correlation between d_n and d_e provides an interesting experimental test for Split SUSY (Giudice-Romanino 2004)



The thickness of the bands reflects the uncertainty in $(g_T)^{u,d,s}$

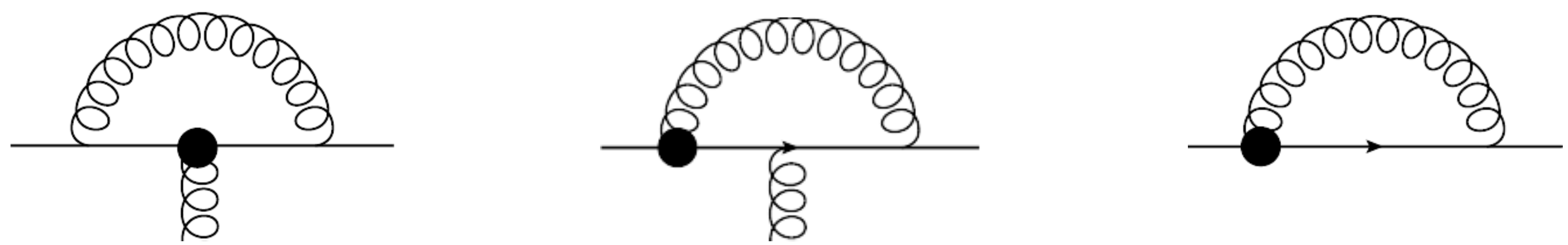
With old results each band would be as thick as the whole plot

$d_e = 8.7 \times 10^{-29}$ e cm

- Obtain the stringent upper bound $d_n < 4 \times 10^{-28}$ e cm: Split SUSY scenario can be falsified by current nEDM searches

$d_{n,p}$ from quark CEDMs

1. Renormalization in "RI-SMOM" scheme suitable for lattice

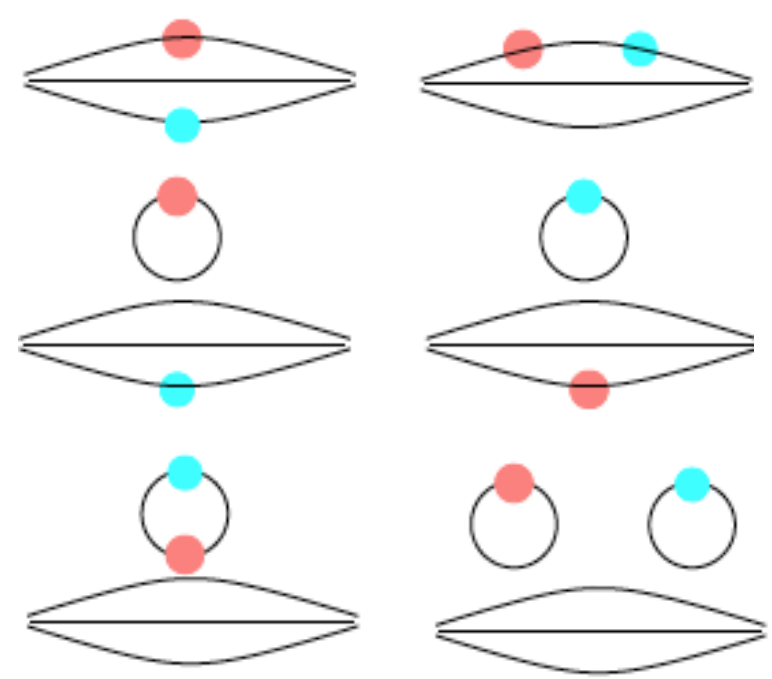


Bhattacharya, VC, Gupta, Mereghetti, Yoon, 1502.07325

2. Extraction of nucleon EDM from appropriate correlation functions

Requires 4-point function:

$$\boxed{\langle n | J_\mu^{\mathrm{EM}} \int d^4x \, O_i(x) \, | n \rangle}$$



Ongoing exploratory studies by RBC-UKQCD & LANL groups

Conclusions

- EDMs are a very powerful probe of new sources of CP violation
- Recent progress in hadronic / nuclear EDMs:
  - EDMs of light nuclei calculated in chiral EFT in terms of LECs
  - Identified powerful chiral symmetry constraints on LECs induced by BSM operators
  - Key role of lattice QCD in calculations of the LECs
    1. Nucleon EDM from quark EDMs at 10%, with all systematics
    2. Early steps towards nucleon EDM from quark chromo EDMs

Significant recent progress on the QCD side (EFT, Lattice)
Quite a bit left to do in the coming years

Backup

CP and chiral symmetry

- Chiral symmetry ($\Psi_{L,R} \rightarrow e^{\pm\chi}\,\Psi_{L,R}$) is spontaneously broken

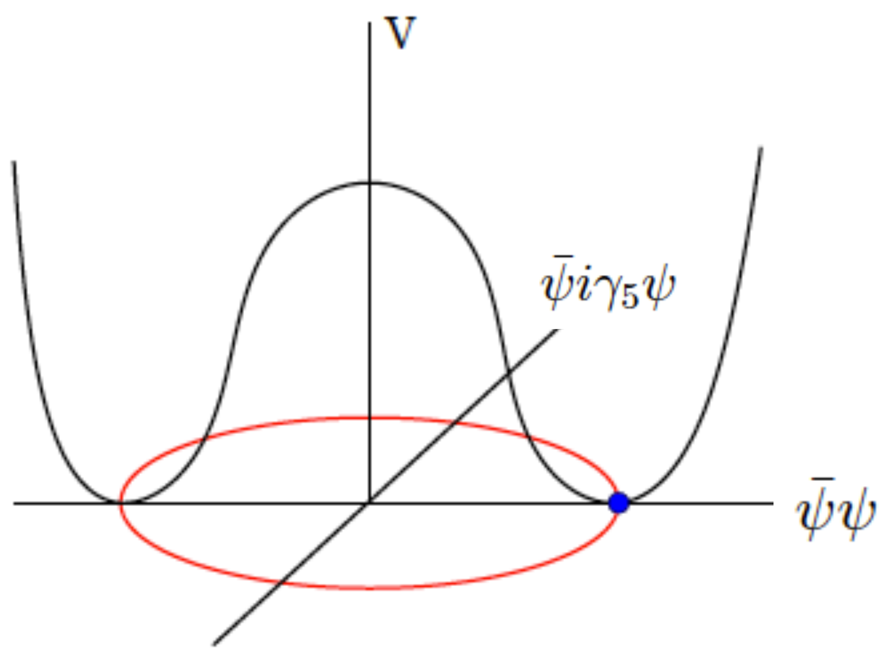


Figure from M. Creutz, 1103.3304

- Degenerate vacua. Each spontaneously breaks all but one $CP_\chi = \chi^{-1} CP \chi$

- Choice of fermion phases: CP_0 (standard CP) is preserved ($\langle \Omega | \, i\bar{\Psi}\gamma_5\Psi | \Omega \rangle = 0$)

  This defines a "reference vacuum" $|\Omega\rangle$

CP and chiral symmetry

- Chiral symmetry ($\Psi_{L,R} \to e^{\pm\chi}\,\Psi_{L,R}$) is spontaneously broken

- Chiral symmetry is explicitly broken by quark masses and BSM operators

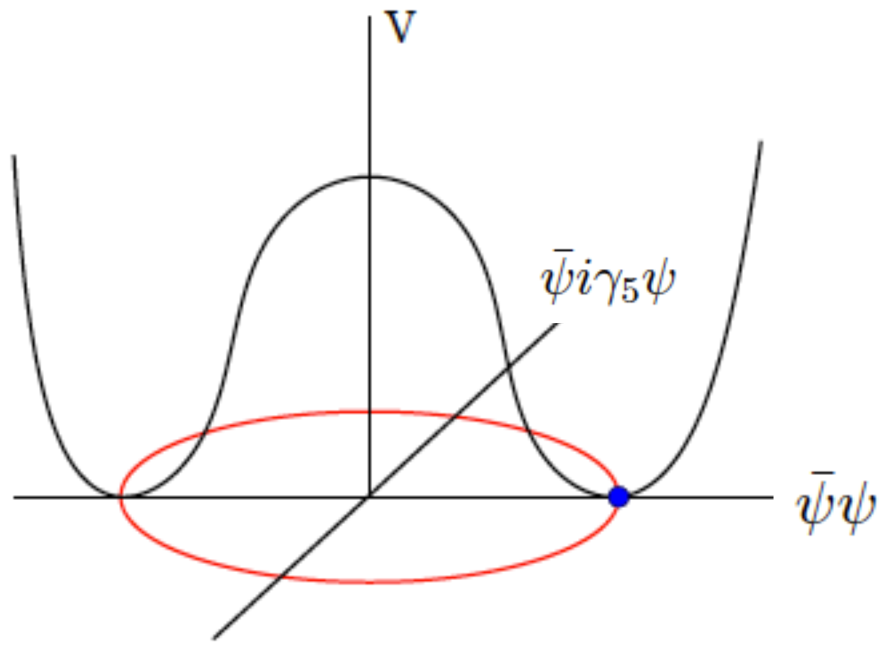
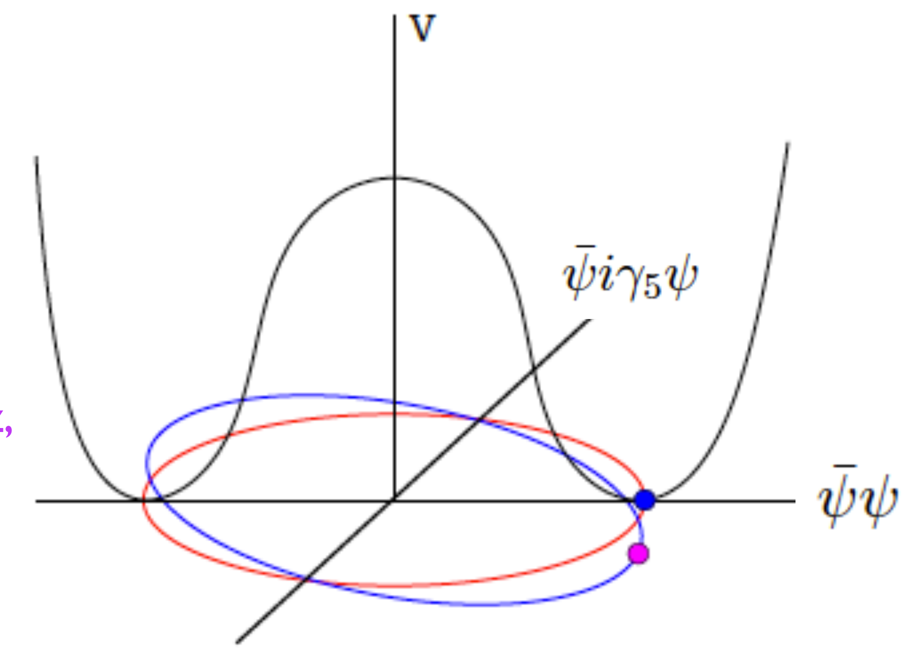


Figure from M. Creutz, 1103.3304



- Degenerate vacua. Each spontaneously breaks all but one $CP_\chi = \chi^{-1} CP \chi$

- Choice of fermion phases: CP_0 (standard CP) is preserved ($\langle\Omega|\, i\bar\Psi\gamma_5\Psi |\Omega\rangle = 0$)

  This defines a "reference vacuum" $|\Omega\rangle$

- Explicit chiral symmetry breaking $\delta\mathcal{L}$ lifts degeneracy, i.e. selects "true" vacuum and the associated unbroken CP

- If we want true vacuum to be $|\Omega\rangle$ then $\delta\mathcal{L}$ cannot be arbitrary. It satisfies

$$\langle\pi|\,\delta\mathcal{L}\,|\Omega\rangle = 0$$

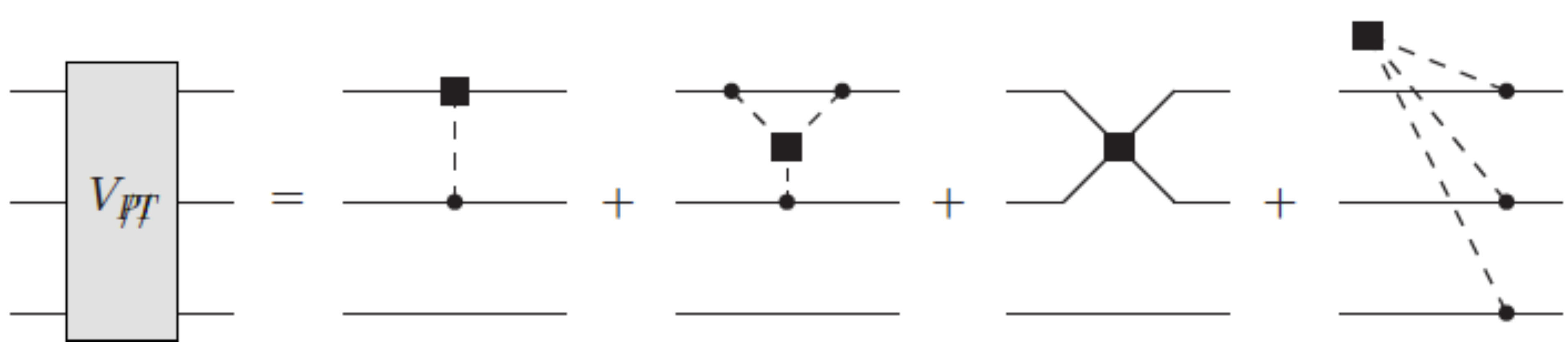
"Vacuum alignment"

EDMs of light nuclei

- Leading pion-nucleon CPV interactions characterized by few LECs

$$\mathcal{L}_{\mathrm{CPV}} = -\frac{i}{2}\,\bar{N}\,\bar{d}_N\,\sigma_{\mu\nu}\gamma_5\,N\,F^{\mu\nu} - \bar{N}\left[\bar{g}_0\,\vec{\tau}\cdot\vec{\pi} + \bar{g}_1\,\pi^0\right]N - \frac{\bar{\Delta}}{F_\pi}\,\pi^0\,\vec{\pi}\cdot\vec{\pi} + \ldots$$

- Leading PT violating potential



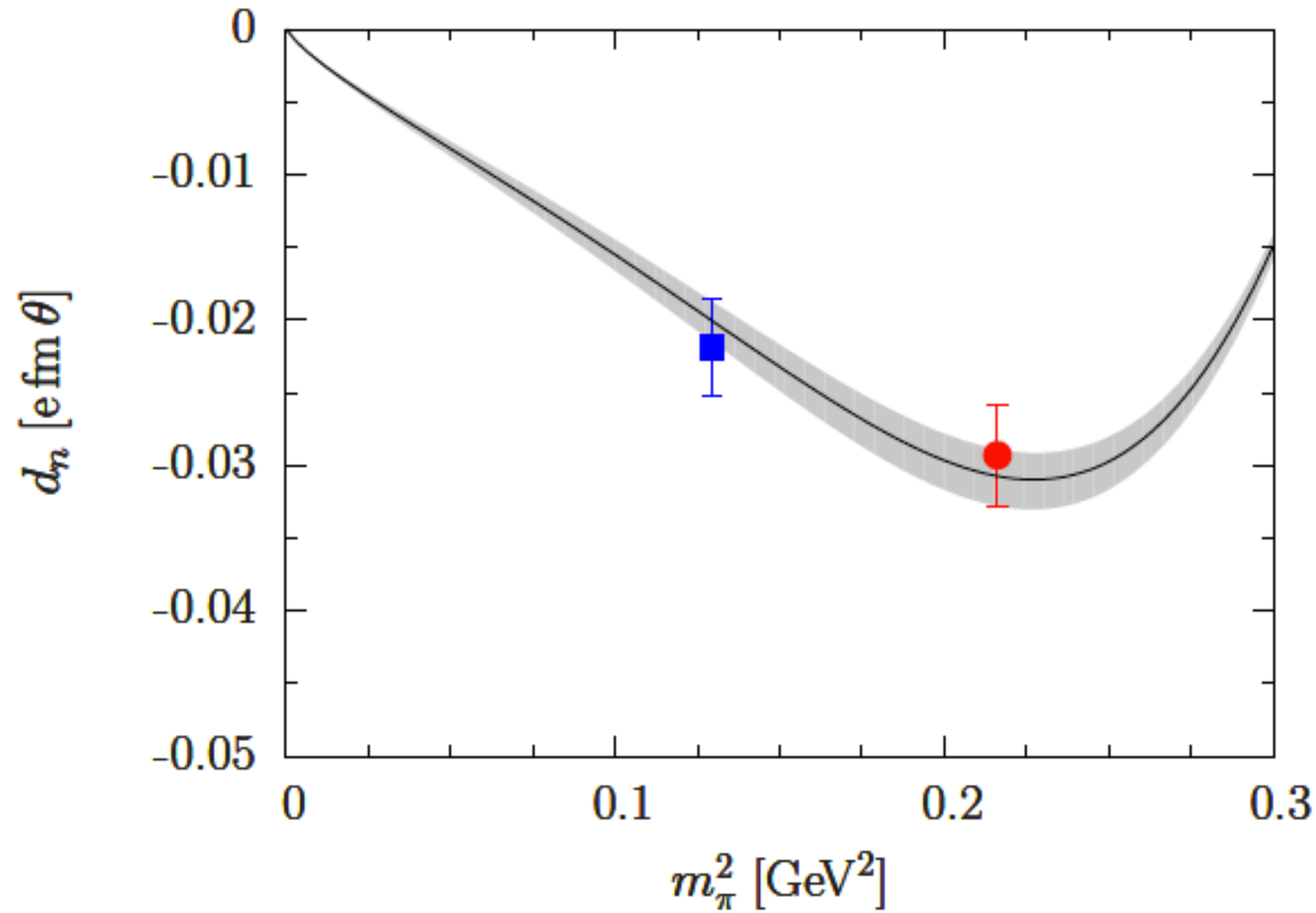
EDMs of light nuclei

	Potential (references)	d_n	d_p	$\bar{g}_0/F_\pi$	$\bar{g}_1/F_\pi$	$\bar{C}_1 F_\pi^3$	$\bar{C}_2 F_\pi^3$	$\bar{\Delta}/F_\pi m_N$
d_d	Perturbative pion [135, 147]	1	1	—	−0.23	—	—	—
	Av18 [87, 131, 136–138]	0.91	0.91	—	−0.19	—	—	—
	N^{2}LO [87, 137]	0.94	0.94	—	−0.18	—	—	—
d_t	Av18 [132, 136, 138]	−0.05	0.90	0.15	−0.28	0.01	−0.02	n/a
	Av18+UIX [87, 134]	−0.05	0.90	0.07	−0.14	0.002	−0.005	0.02
	N^{2}LO [87]	−0.03	0.92	0.11	−0.14	0.05	−0.10	0.02
d_h	Av18 [132, 136, 138]	0.88	−0.05	−0.15	−0.28	−0.01	0.02	n/a
	Av18+UIX [87, 134]	0.88	−0.05	−0.07	−0.14	−0.002	0.005	0.02
	N^{2}LO [87]	0.90	−0.03	−0.11	−0.14	−0.05	0.11	0.02

Table 3: Dependence of the deuteron, triton and helion EDMs on $\not{T}$ LECs for various PT potentials. Entries are dimensionless in the first two columns and in units of $e\,\mathrm{fm}$ in the remaining columns. "—" indicates very small numbers.

From Mereghetti & van Kolck, arXiv:1505.06272

d_n from theta term



From et al, 1502.02295

d_n from theta term

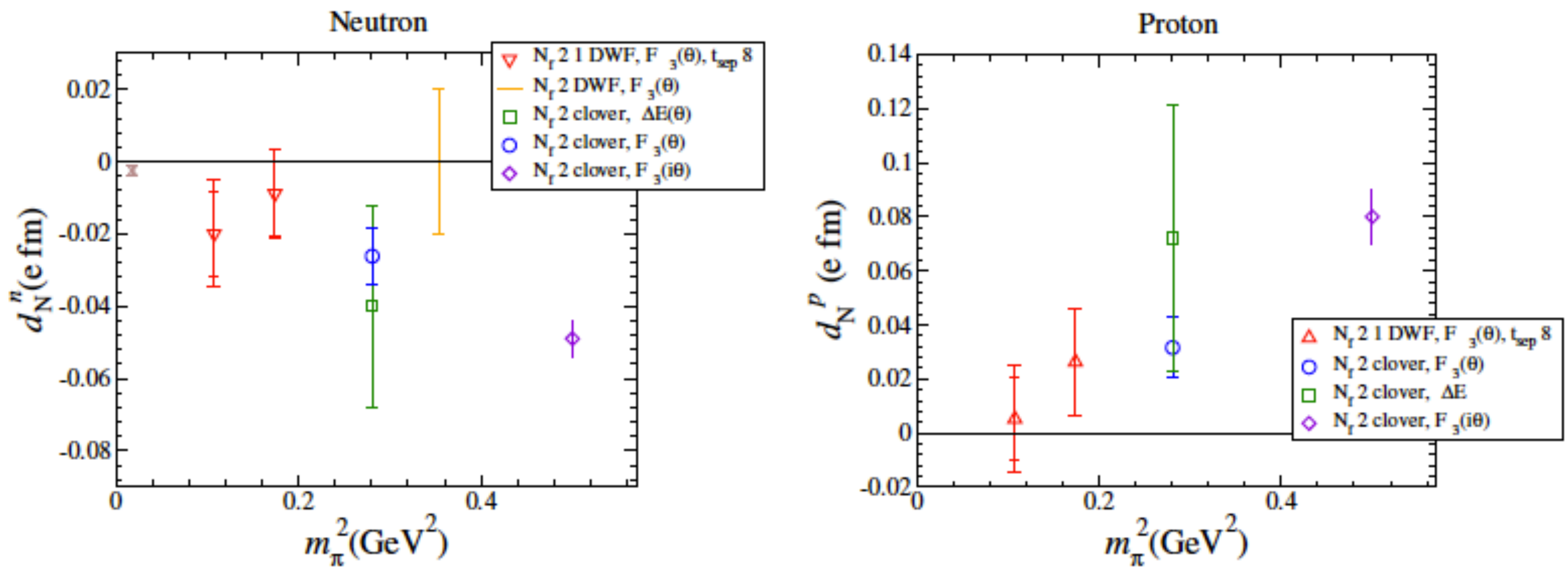


Figure 4: Summary plot of EDM for neutron (top) and proton (bottom) as a function of pion mass squared with full QCD calculation in the present analysis and other method and fermion action. Upper triangles shows our results including total error. The smaller error denotes the statistical error. The cross symbol denotes the range of model calculation based on the baryon chiral perturbation theory.

From Shintani et al, POS (Lattice 2013) 298 de Vries et al, 1006.2304

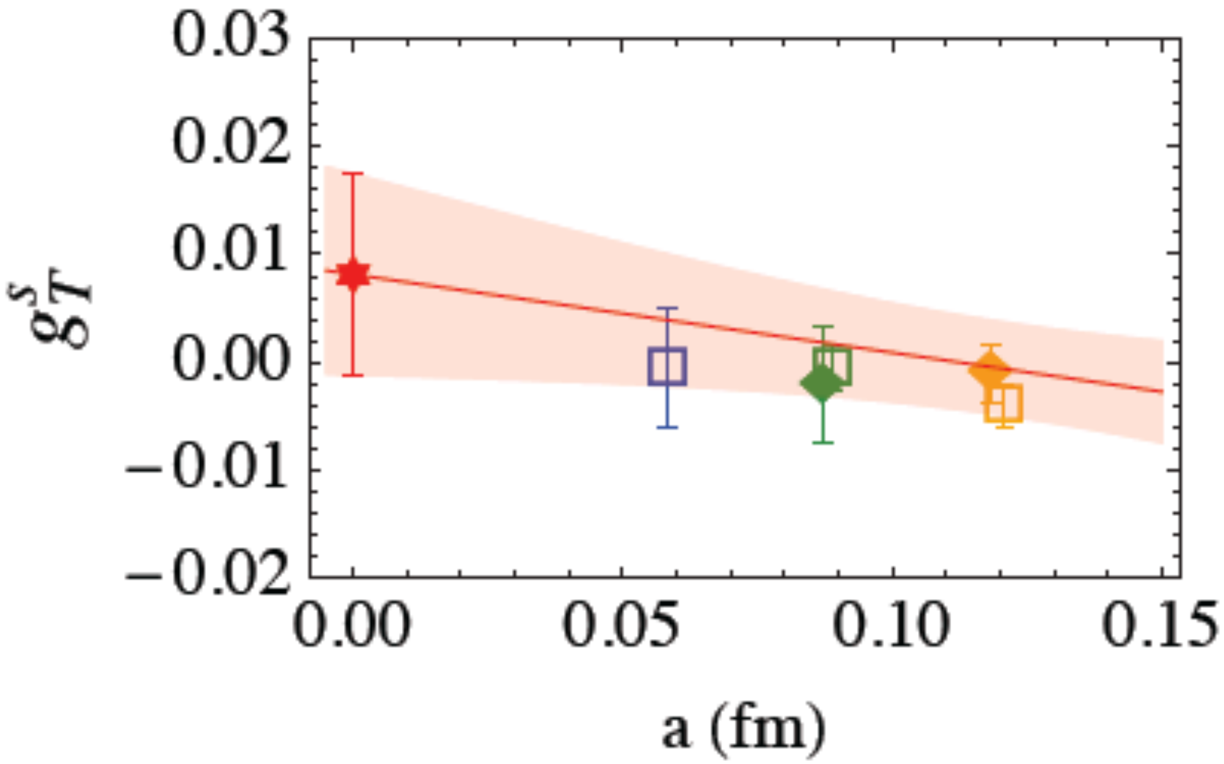
Chiral logs

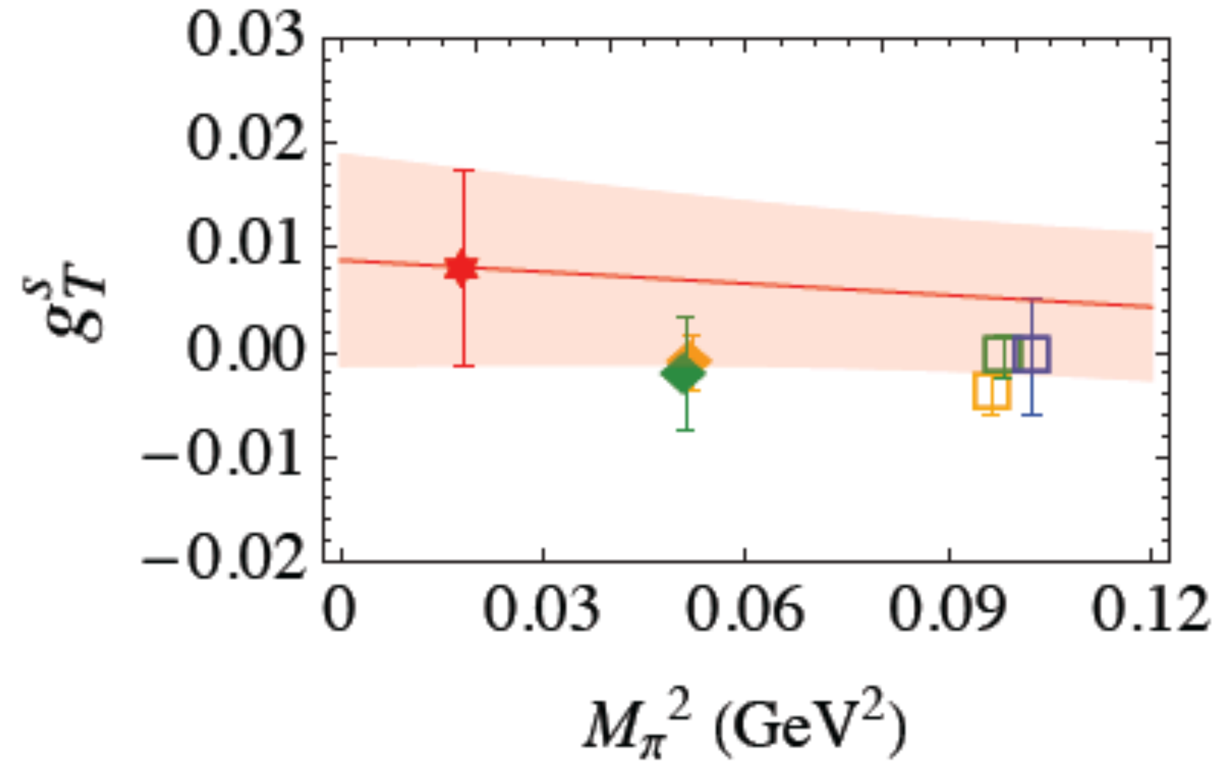
$$g_T^i = c_1^i \left[1 + \frac{M_\pi^2}{(4\pi F_\pi)^2}\, f^i\left(\frac{M_\pi}{\mu}\right)\right] + c_2^i\, a + c_3^i(\mu)\, M_\pi^2 + c_4^i\, e^{-M_\pi L} .$$

$$f^{u+d} = \frac{3}{4}\left[(2+4g_A^2)\log\frac{\mu^2}{M_\pi^2} + 2 + g_A^2\right]$$

$$f^{u-d} = \frac{1}{4}\left[(2+8g_A^2)\log\frac{\mu^2}{M_\pi^2} + 2 + 3g_A^2\right]$$

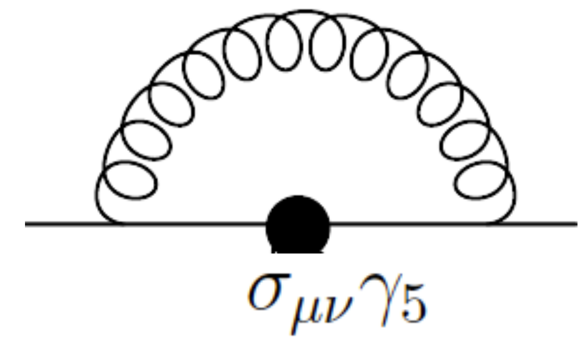
Strangeness tensor charge



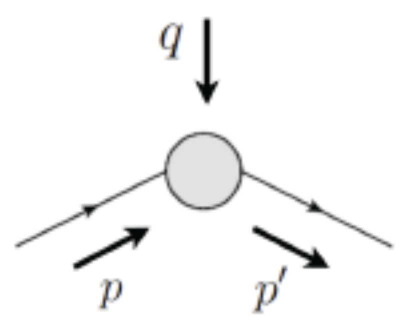


Quark EDM renormalization

- Tensor quark bilinear x EM field strength. Neglecting effects of O(α_{EM}), E renormalizes multiplicatively (as tensor density)



Non-perturbative renormalization method well known



$= \text{tree level}^*$

$p^2 = p'^2 = q^2 = - \Lambda^2$

Bochicchio et al, 1995

...

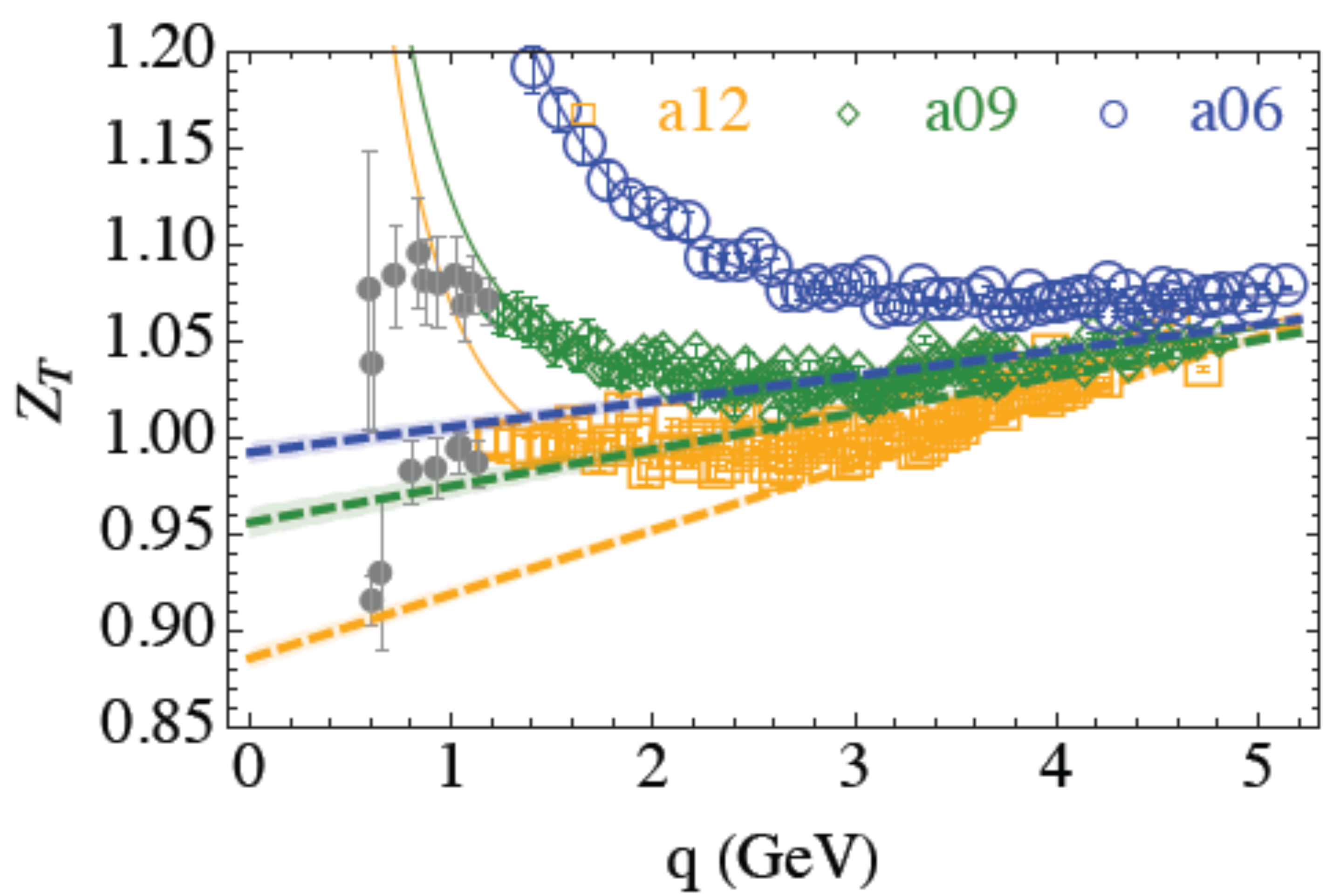
Aoki et al 2009

Fix renormalization constant by conditions on 2-quark amputated Green's functions in a given gauge, at non-exceptional momentum configurations

Non-perturbative renormalization

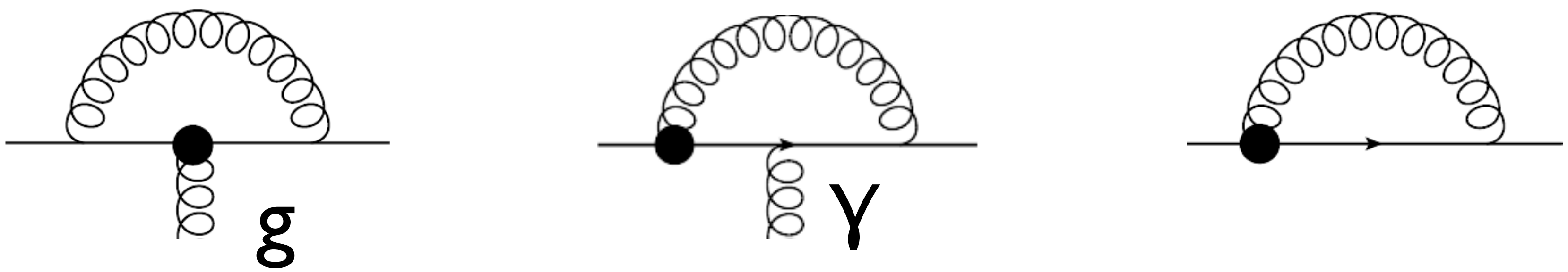
- Non-perturbative renormalization (RI-SMOM)
- The “window”: Λ_{QCD} << q << 1/a

Z_T in MS-bar at 2 GeV



Quark CEDM renormalization

- Renormalization of $C = ig_s\bar{\Psi}\sigma_{\mu\nu}\gamma_5 G^{\mu\nu}t^a\Psi$: diagonal + mixing with E, P



- C can mix with two classes of operators:

$$\begin{pmatrix} O \\ N \end{pmatrix}_{\mathrm{ren}} = \begin{pmatrix} Z_O & Z_{ON} \\ 0 & Z_N \end{pmatrix} \begin{pmatrix} O \\ N \end{pmatrix}_{\mathrm{bare}}$$

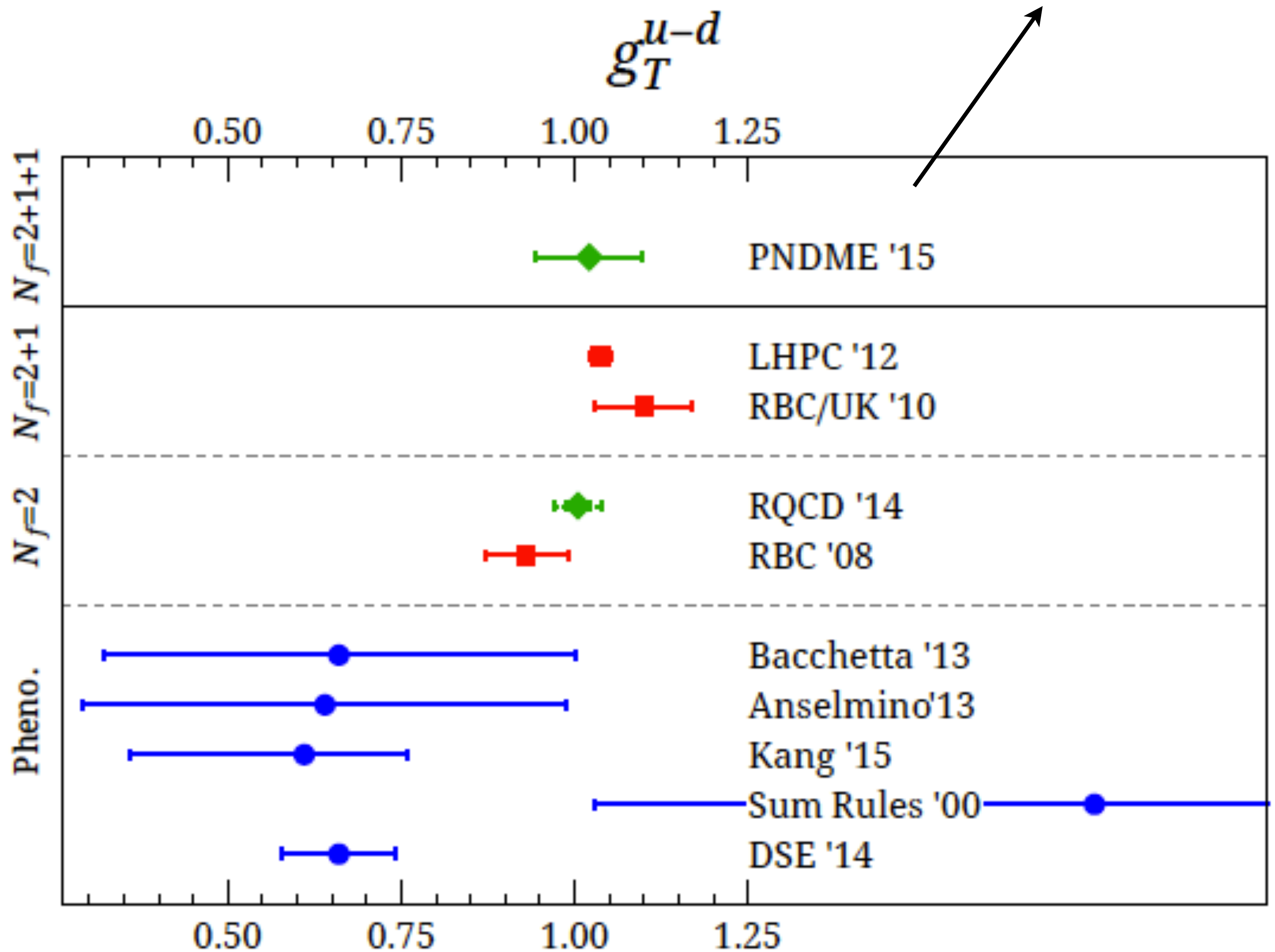
Kuger-Stern Zuber 1975
Joglekar and Lee 1976
Deans-Dixon 1978

- O: gauge-invariant operators with same symmetries of C, not vanishing by EOM
- N: Allowed by BRST Ward Identities. Vanish by EOM, need not be gauge invariant

Results on isovector tensor charge

- Isovector tensor charge in $\overline{\text{MS}}$ @ 2 GeV

$$g_T^{(n,d-u)} \equiv g_T^{u-d} = 1.02(8)$$



Quark CEDM renormalization

- Constructed basis [10 O's and 4 N's] and identified mixing structure
- Defined RI-MOM scheme for the O's
- Computed matching between MS-bar and RI-MOM scheme to $O(\alpha_s)$

Bhattacharya, VC, Gupta, Mereghetti, Yoon, 1502.07325

- C can mix with two classes of operators:

$$\begin{pmatrix} O \\ N \end{pmatrix}_{\rm ren} = \begin{pmatrix} Z_O & Z_{ON} \\ 0 & Z_N \end{pmatrix} \begin{pmatrix} O \\ N \end{pmatrix}_{\rm bare}$$

Kuger-Stern Zuber 1975
Joglekar and Lee 1976
Deans-Dixon 1978

- O: gauge-invariant operators with same symmetries of C, not vanishing by EOM
- N: Allowed by BRST Ward Identities. Vanish by EOM, need not be gauge invariant

Quark CEDM renormalization

- Operator basis

$O(\mathcal{M}^0)$

$$O_1^{(5)} \equiv C = ig\,\bar\psi\tilde\sigma^{\mu\nu}G_{\mu\nu}t^a\psi$$

$$O_2^{(5)} \equiv \partial^2 P = \partial^2\left(\bar\psi i\gamma_5 t^a\psi\right)$$

$$O_3^{(5)} \equiv E = \frac{ie}{2}\,\bar\psi\tilde\sigma^{\mu\nu}F_{\mu\nu}\{Q,t^a\}\psi$$

$O(\mathcal{M}^1)$

$$O_4^{(5)} \equiv (m\,F\tilde F) = \mathrm{Tr}\left[\mathcal{M}Q^2t^a\right]\,\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$$

$$O_5^{(5)} \equiv (m\,G\tilde G) = \mathrm{Tr}\left[\mathcal{M}t^a\right]\,\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}G^b_{\mu\nu}G^b_{\alpha\beta}$$

$$O_6^{(5)} \equiv (m\,\partial\cdot A)_1 = \mathrm{Tr}\left[\mathcal{M}t^a\right]\partial_\mu\left(\bar\psi\gamma^\mu\gamma_5\psi\right)$$

$$O_7^{(5)} \equiv (m\,\partial\cdot A)_2 = \frac{1}{2}\partial_\mu\left(\bar\psi\gamma^\mu\gamma_5\left\{\mathcal{M},t^a\right\}\psi\right) -$$

$O(\mathcal{M}^2)$

$$O_8^{(5)} \equiv (m^2P)_1 = \frac{1}{2}\,\bar\psi i\gamma_5\left\{\mathcal{M}^2,t^a\right\}\psi$$

$$O_9^{(5)} \equiv (m^2P)_2 = \mathrm{Tr}\left[\mathcal{M}^2\right]\;\bar\psi i\gamma_5 t^a\psi$$

$$O_{10}^{(5)} \equiv (m^2P)_3 = \mathrm{Tr}\left[\mathcal{M}t^a\right]\;\bar\psi i\gamma_5\mathcal{M}\psi$$

EOM

$$O_{11}^{(5)} \equiv P_{EE} = i\bar\psi_E\gamma_5 t^a\psi_E$$

$$O_{12}^{(5)} \equiv \partial\cdot A_E = \partial_\mu[\bar\psi_E\gamma^\mu\gamma_5 t^a\psi + \bar\psi\gamma^\mu\gamma_5 t^a\psi_E]$$

$$O_{13}^{(5)} \equiv A_\partial = \bar\psi\gamma_5\partial\!\!\!/\, t^a\psi_E \;-\bar\psi_E\overleftarrow{\partial\!\!\!/}\,\gamma_5 t^a\psi$$

$$O_{14}^{(5)} \equiv A_{A^{(\gamma)}} = \frac{ie}{2}\left(\bar\psi\{Q,t^a\}A\!\!\!/^{(\gamma)}\gamma_5\psi_E - \bar\psi_E\{Q,t^a\}A\!\!\!/^{(\gamma)}\gamma_5\psi\right)$$

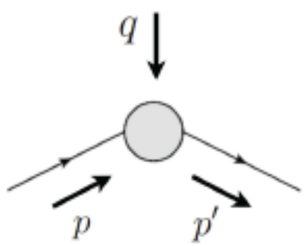
$$\psi_E \equiv (iD^\mu\gamma_\mu - \mathcal{M})\psi$$

- Keep powers of quark mass:
  - vacuum alignment
  - m_s/Λ_{QCD} effects

- Mixing structure

	C	$\partial^2 P$	E	$mF\tilde{F}$	$mG\tilde{G}$	$(m\partial\cdot A)_1$	$(m\partial\cdot A)_2$	$(m^2P)_1$	$(m^2P)_2$	$(m^2P)_3$	P_{EE}	$\partial\cdot A_E$	A_∂	$A_{A(\gamma)}$
C	X	X	X	X	X	X	X	X	X	X	X	X	X	X
$\partial^2 P$		X												
E			X											
$mF\tilde{F}$				X										
$mG\tilde{G}$					X	X								
$(m\partial\cdot A)_1$						X								
$(m\partial\cdot A)_2$							X							
$(m^2P)_1$								X						
$(m^2\hat{P})_2$									X					
$(m^2\hat{P})_3$										X				
P_{EE}											X	X	X	
$\partial\cdot A_E$												X		
A_∂											X	X	X	X
$A_{A(\gamma)}$														X

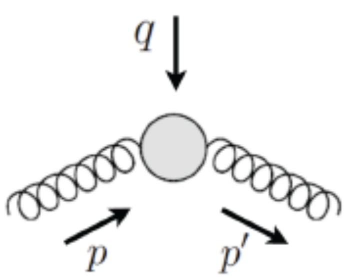
- RI-MOM scheme for CEDM operator:



$= \; 0^*$

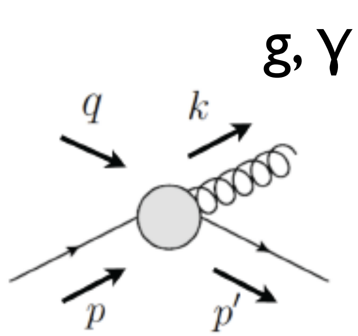
$p^2 = p'^2 = q^2 = - \Lambda^2$

* Coefficients of
7 spin-flavor structures



$= \; 0$

$p^2 = p'^2 = q^2 = - \Lambda^2$



$=$ tree-level**

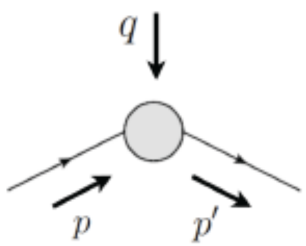
$p^2 = p'^2 = q^2 = k^2 = -\Lambda^2$

$s = u = t/2 = -\Lambda^2$

** 3 spin-flavor structures:
$\sigma_{\mu\nu}\gamma_5 k^\nu t^a$,
$\sigma_{\mu\nu}\gamma_5 (p-p')^\nu t^a$,
$\gamma_5 (p+p')_\mu \; t^a$

$s = (p+q)^2 \qquad u = (p-k)^2 \qquad t = (p-p')^2$

- RI-MOM scheme for CEDM operator:



$= 0^*$

$p^2 = p'^2 = q^2 = - \Lambda^2$

* Coefficients of
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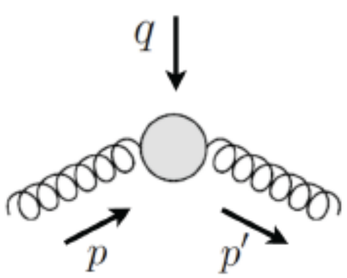
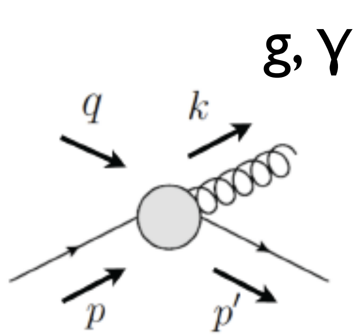


$= 0$

$p^2 = p'^2 = q^2 = - \Lambda^2$

Conditions are imposed in the chiral limit $m_q \to 0$



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$p^2 = p'^2 = q^2 = k^2 = - \Lambda^2$

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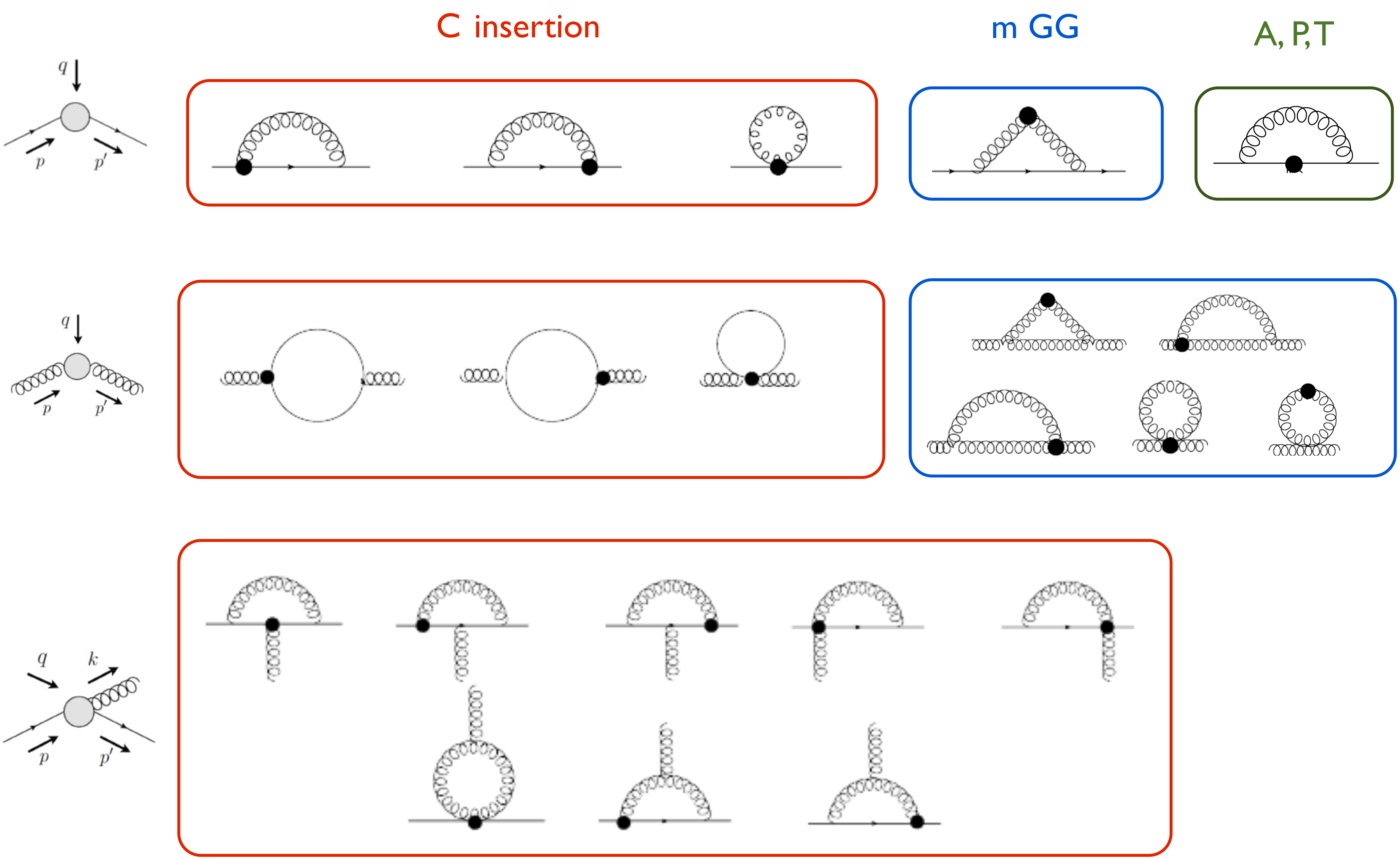
$\sigma_{\mu\nu}\gamma_5 k^\nu t^a$,
$\sigma_{\mu\nu}\gamma_5 (p-p')^\nu t^a$,
$\gamma_5 (p+p')_\mu \, t^a$

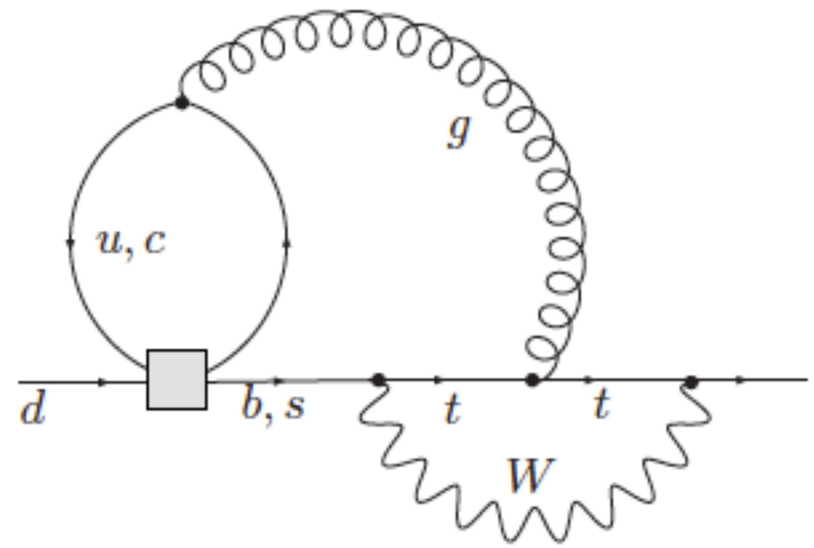
$s = (p+q)^2 \qquad u = (p-k)^2 \qquad t = (p-p')^2$

- Match RI-MOM to MS-bar: $\boxed{O_i^{\mathrm{RI-\tilde{S}MOM}} = C_{ij}\, O_j^{\overline{\mathrm{MS}}}}$

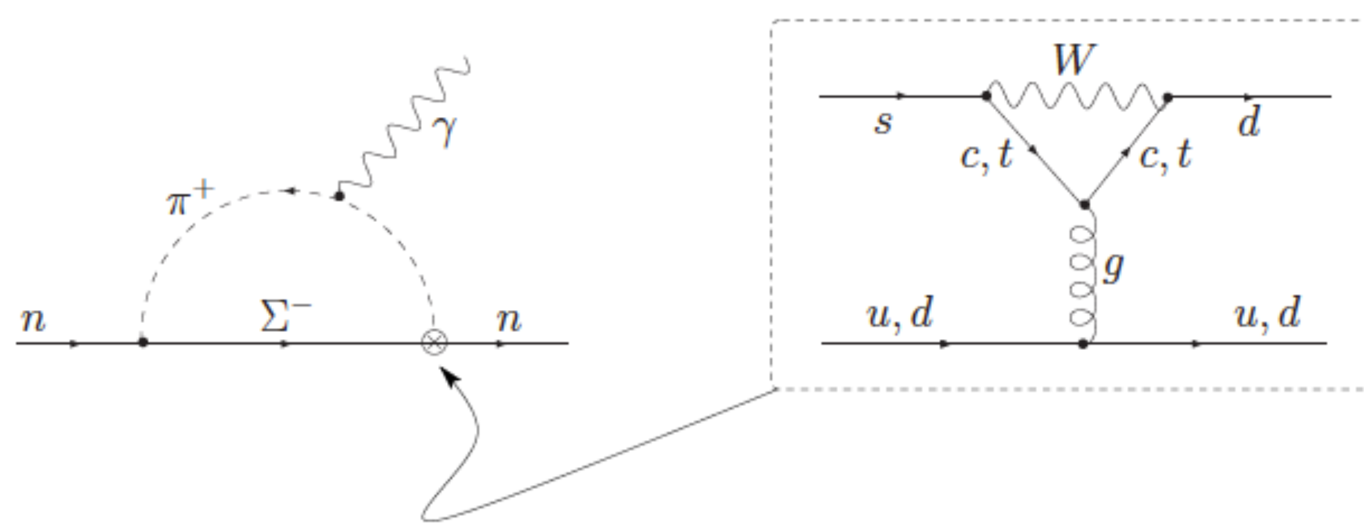


EDMs in the SM

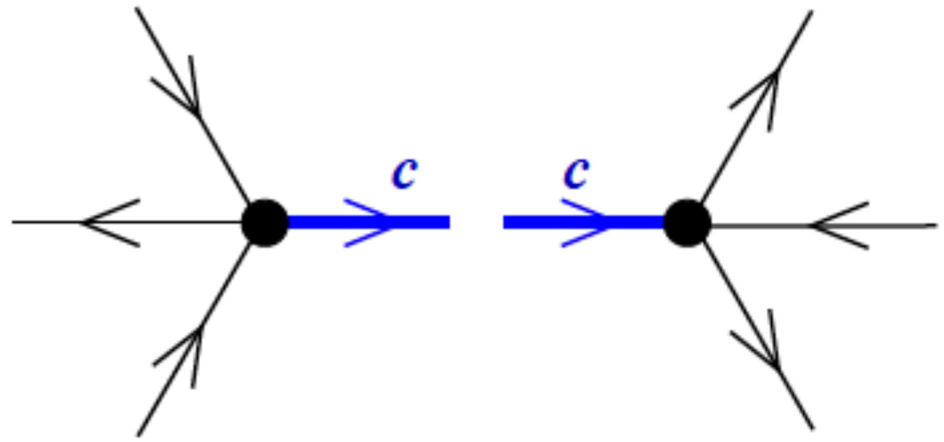
- Highly suppressed "short-distance" contributions (d_q) start at 3 loops



- Dominant "long-distance" contribution



- Mannel-Uraltsev mechanism in the SM: charm-mediated six-quark operators



- Dim-10 operator:

$$\Delta \equiv \mathrm{Im}\, U_4 = \mathrm{Im}\, V_{cs}^* V_{cd} V_{ud}^* V_{us}$$

$$\tilde{\mathcal{L}}_- = -i\frac{G_F^2}{2m_c^2}\Delta\left(\tilde{O}_{uds} - \tilde{O}_{uds}^\dagger\right),$$

$$\tilde{O}_{uds} = (\bar{u}\Gamma^\mu d)\,(\bar{d}\Gamma_\mu i\not{D}\Gamma_\nu s)\,(\bar{s}\Gamma^\nu u)$$

- $d_n \sim 10^{-31}$ e cm