Baryogenesis, novel CP violation and the neutron electric dipole moment on the lattice

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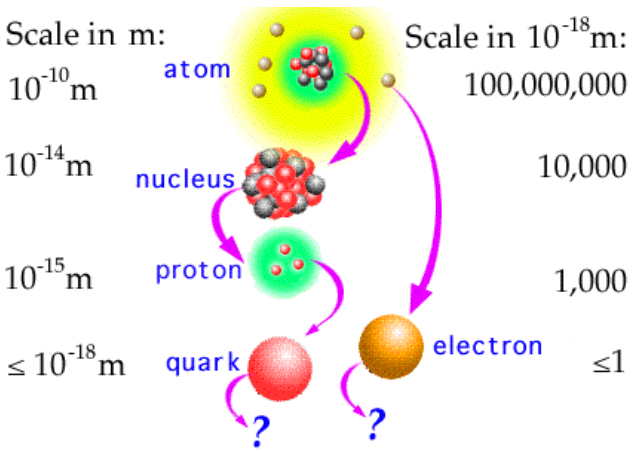

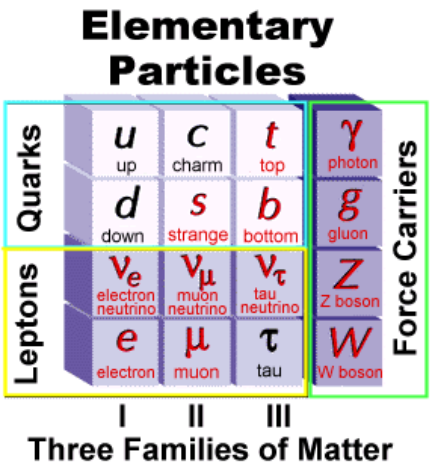

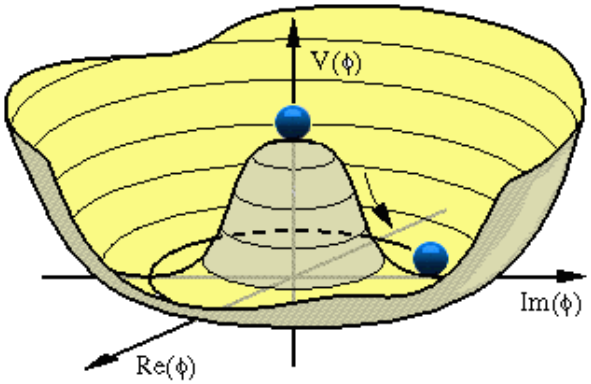

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Work done in collaboration with

PNDME collaboration
(Clover-on-HISQ)

- Tanmoy Bhattacharya
- Vincenzo Cirigliano
- Huey-Wen Lin
- Boram Yoon
- Yong-Chull Jang

Bhattacharya et al, PRD85 (2012) 054512
Bhattacharya et al, PRD89 (2014) 094502
Bhattacharya et al, PRD92 (2015) 114026
Bhattacharya et al, PRL 115 (2015) 212002
Bhattacharya et al, PRD92 (2015) 094511
Bhattacharya et al, arXiv:1606:07049

NME collaboration
(Clover-on-Clover)

- Tanmoy Bhattacharya
- Vincenzo Cirigliano
- Jeremy Green
- Yong-Chull Jang
- Bálint Joó
- Huey-Wen Lin
- Kostas Orginos
- David Richards
- Sergey Syritsyn
- Frank Winter
- Boram Yoon

Yoon et al, PRD D93 (2016) 114506

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Outline

- Physics Motivation
  - Baryogenesis, an open problem
  - Novel CP violation
  - Neutron EDM
- Matrix elements within nucleon states
- Status of control over systematic errors
- Results: g_A, g_S, g_T
- Quark EDM
- Quark Chromo EDM

Baryogenesis

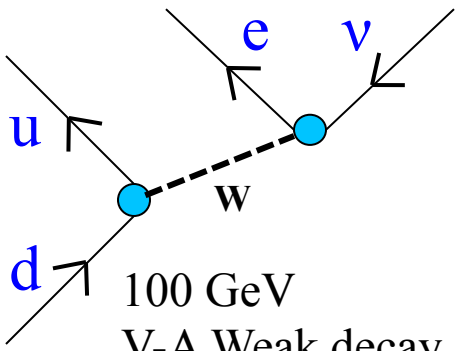
- Matter-antimatter asymmetry of the universe
  - The observed universe has $6.1_{-0.2}^{+0.3} \times 10^{-10}$ baryons for every black body photon rather than 10^{-20}
- Sakharov's three necessary conditions:
  - Baryon number violation
  - Evolution out of equilibrium
  - T-Violation (CP violation)
- Need CPV much larger than in the SM
  - CKM phase gives $d_n \sim 10^{-32}$ *e cm*
  - Θ determined from d_n *(=0 with Pecchi-Quinn)*

Novel CP violation

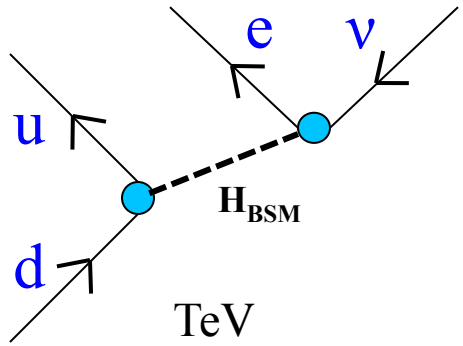
- Standard Model
  - CKM matrix of flavor mixing
    - $d_n \sim 10^{-32}$ e cm
  - Θ-term (Strong CP violation)
    - Pecchi-Quinn
    - Suppressed at high T
- Most BSM theories have new sources of CP violation
- Effective field theory: a model-independent tower of operators made of SM fields & ordered by dimension
- We are working with 2 leading operators
  - Quark EDM (contribution of each quark EDM to nEDM)
  - Quark chromo EDM (CPV contribution of each quark flavor's interaction with the color electric field)

Probing New Interactions: $M_{BSM} >> M_W >> 1$ GeV

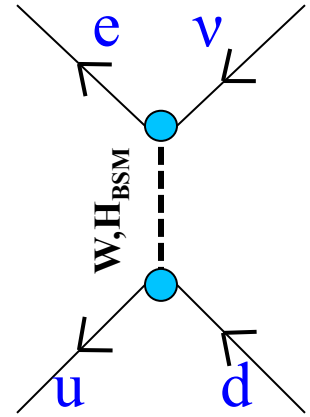
Many BSM possibilities for novel Scalar & Tensor interactions: Higgs-like, leptoquark, loop effects, …



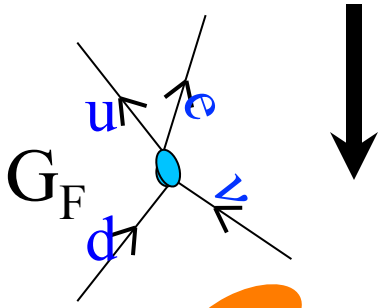
100 GeV
V-A Weak decay
e_L with a ν_L



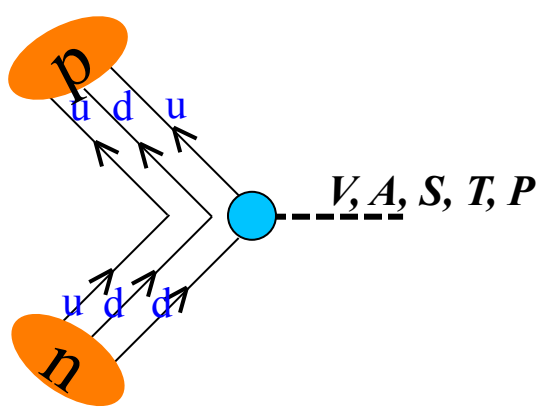
TeV
Novel S,T Interactions
e_R with a ν_L



LHC

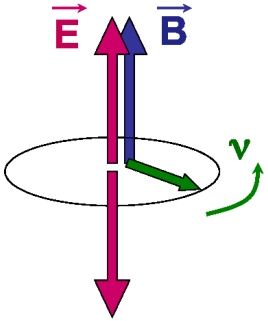


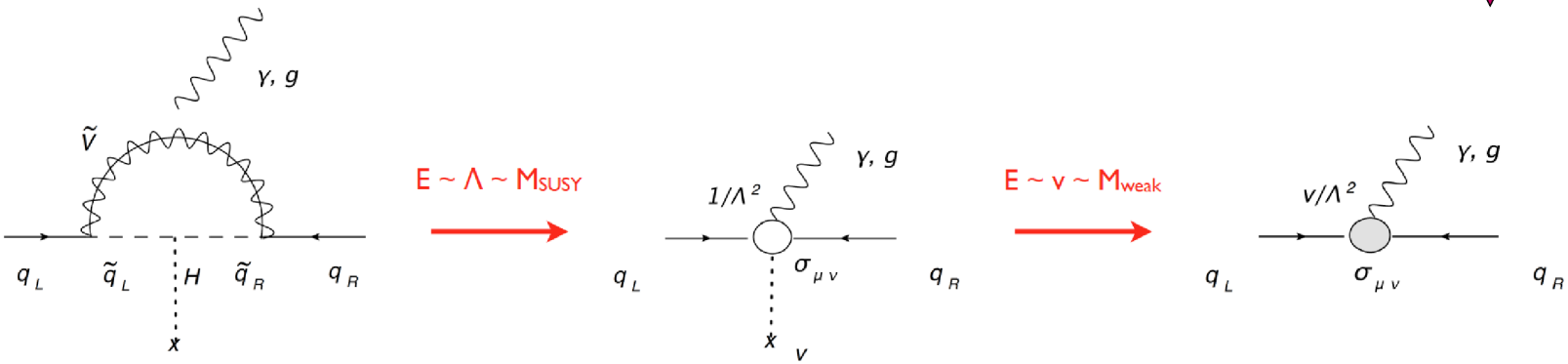
Neutron Decay

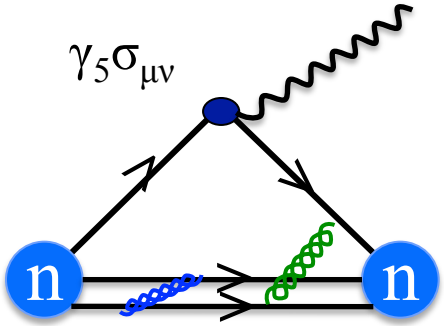


Effective Theory @ ~2 GeV
V-A (g_A, g_V) Weak interactions
S, T (g_S, g_T) New Interactions

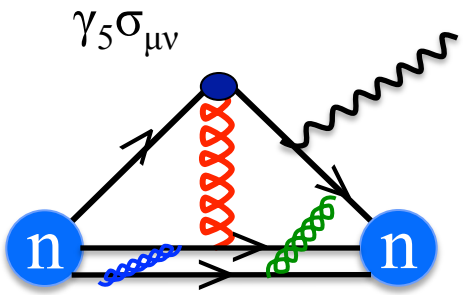
Novel CP violation: operators in EFT







γ attaches to the vertex



- 4-pt function as γ can attach to any quark line
- Gluon free end can attach to any quark line

Quark-EDM

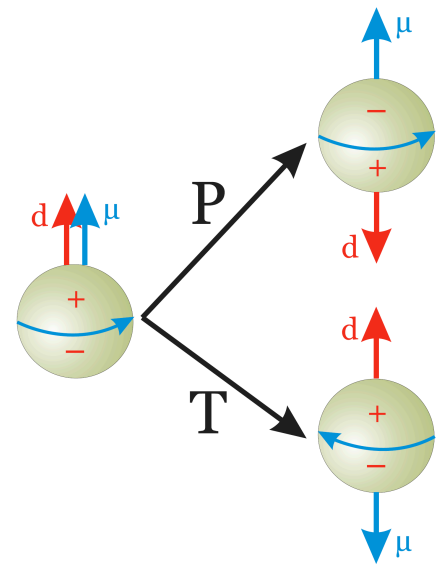
$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\, q\, F^{\mu\nu}$$

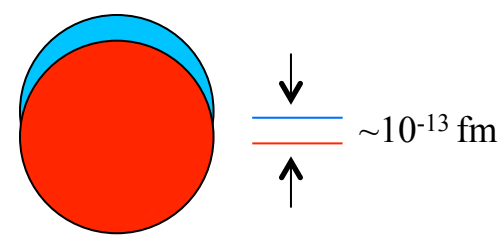
Chromo-EDM

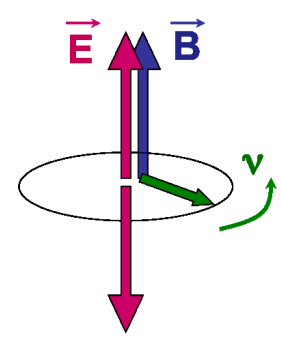
$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\, q\, \lambda^a G_a^{\mu\nu}$$

Neutron Electric Dipole Moment

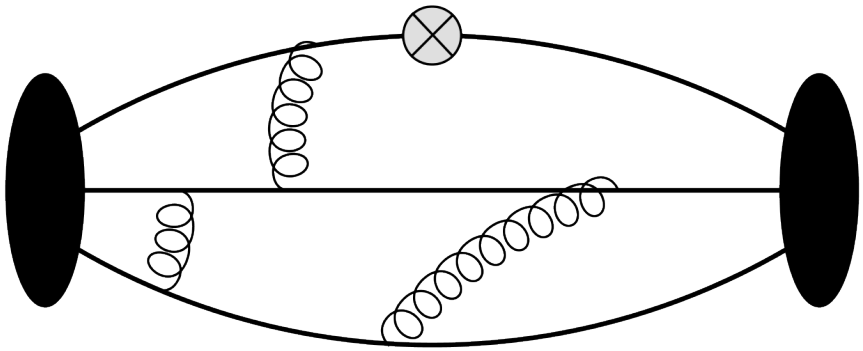
- New (larger) CP violation needed to explain weak scale Baryogenesis
- All CPV (T-violating) interactions contribute to the nEDM
- nEDM provides stringent constraints on BSM theories
- Need precise values of matrix elements of CP violating effective operators to convert bounds on nEDM into bounds on BSM parameters.
- Next gen experiments will reduce the bound $d_n < 2.9 \times 10^{-26}$ e cm **<u>to</u>** $\approx 10^{-28}$ e cm



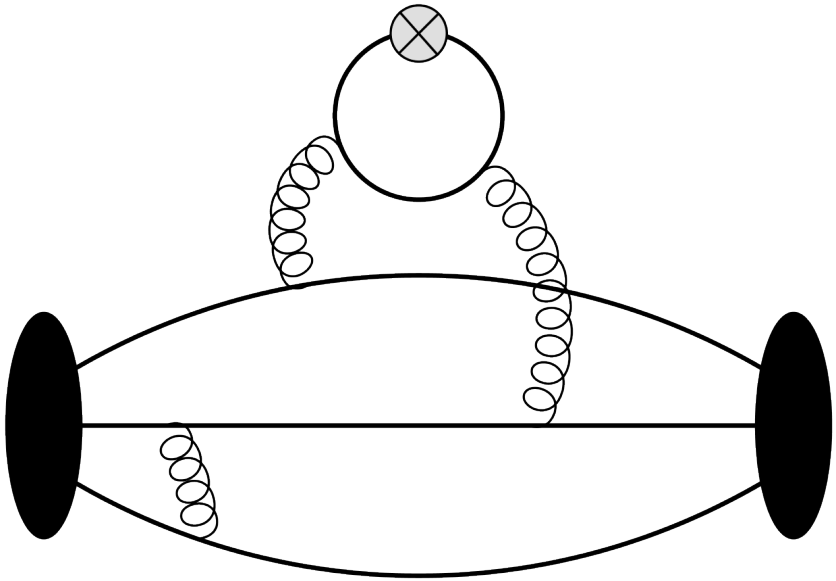




If we can extract the matrix elements of quark bilinear operators within the nucleon state by calculating the "connected" and "disconnected" correlation functions with high precision, we can address a number of physics questions.



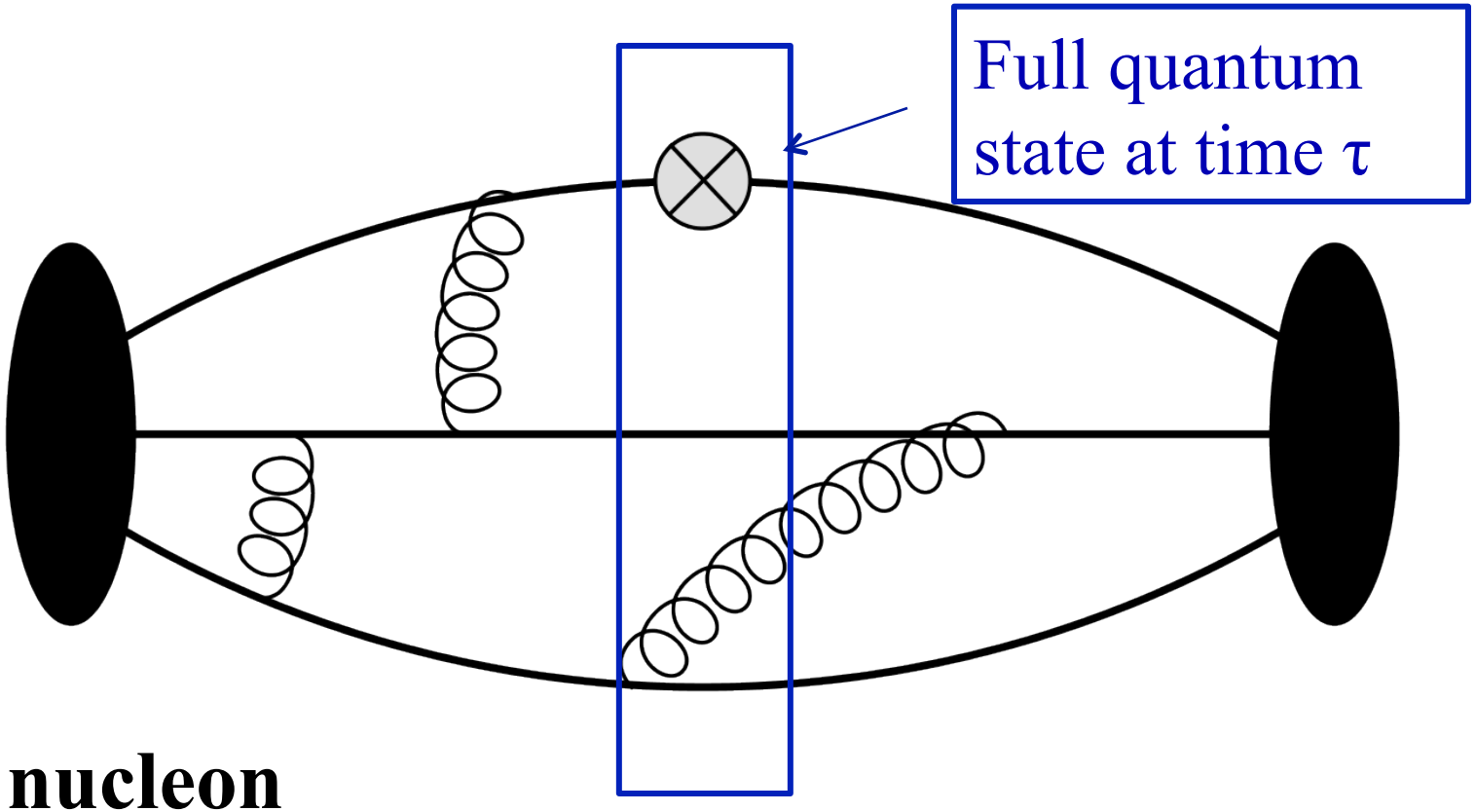
Connected



Disconnected

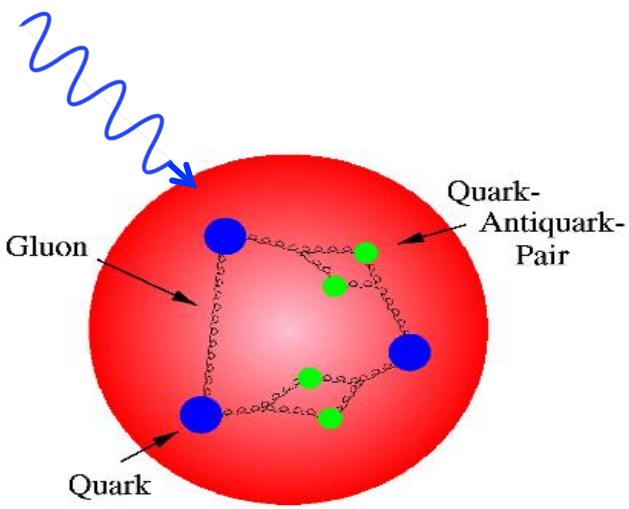
A number of matrix elements within nucleon states become accessible

- Iso-vector charges g_A, g_S, g_T $\langle p|\bar{u}\Gamma d|n\rangle$
- Axial vector form factors $\langle p(q)|\bar{u}\gamma_\mu\gamma_5 d(q)|n(0)\rangle$
- Vector form factors $\langle p(q)|\bar{u}\gamma_\mu d(q)|n(0)\rangle$
- Flavor diagonal matrix elements $\langle p|\bar{q}q|p\rangle$
- Quark EDM and quark chromo EDM
- Generalized Parton Distribution Functions



From nucleon 3-point function

matrix element of probe H_{int} in a nucleon state



Simplest quantities to calculate are the charges

g_A, g_S, g_T

Charges: What we know

- Experiment: Neutron decay
  - $g_A = 1.276(2)$

- CVC + Lattice QCD

Gonzalez-Alonso & Camalich
Phy. Rev. Lett. 112 (2014) 042501

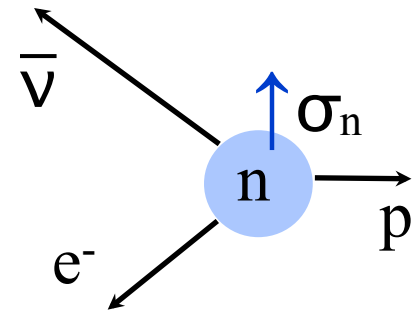
$$\frac{g_S}{g_V} = \frac{(M_N - M_P)^{QCD}}{(m_d - m_u)^{QCD}} = 1.02(8)(7)$$

Our result $g_S = 0.97(12) \oplus (m_d\text{-}m_u)^{FLAG} = 2.67(35)$ MeV

$$\boxed{(M_N\text{-}M_P)^{QCD} = 2.59(49) \text{ MeV}}$$

[Ultra]Cold Neutron Decay: Parameters sensitive to new physics

Neutron decay can be parameterized as



$$d\Gamma \propto F(E_e)\left[1 + b\frac{m_e}{E_e} + \left(B_0 + B_1\frac{m_e}{E_e}\right)\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \cdots\right]$$

b: Deviations from the leading order electron spectrum: Fierz interference term

B_1: Energy dependent part of correlation of antineutrino momentum with the neutron spin

Relating b, B_1 to $g_{S,T}$ & BSM couplings $\varepsilon_{S,T}$

$$H_{eff} \supset G_F \left[\varepsilon_S \boxed{\bar{u}d}\ \bar{e}(1-\gamma_5)\nu_e + \varepsilon_T \boxed{\bar{u}\sigma_{\mu\nu}d}\ \bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e \right]$$

$$g_S = Z_S \langle p | \bar{u} d | n \rangle \qquad g_T = Z_T \langle p | \bar{u} \sigma_{\mu\nu} d | n \rangle$$

Lattice QCD

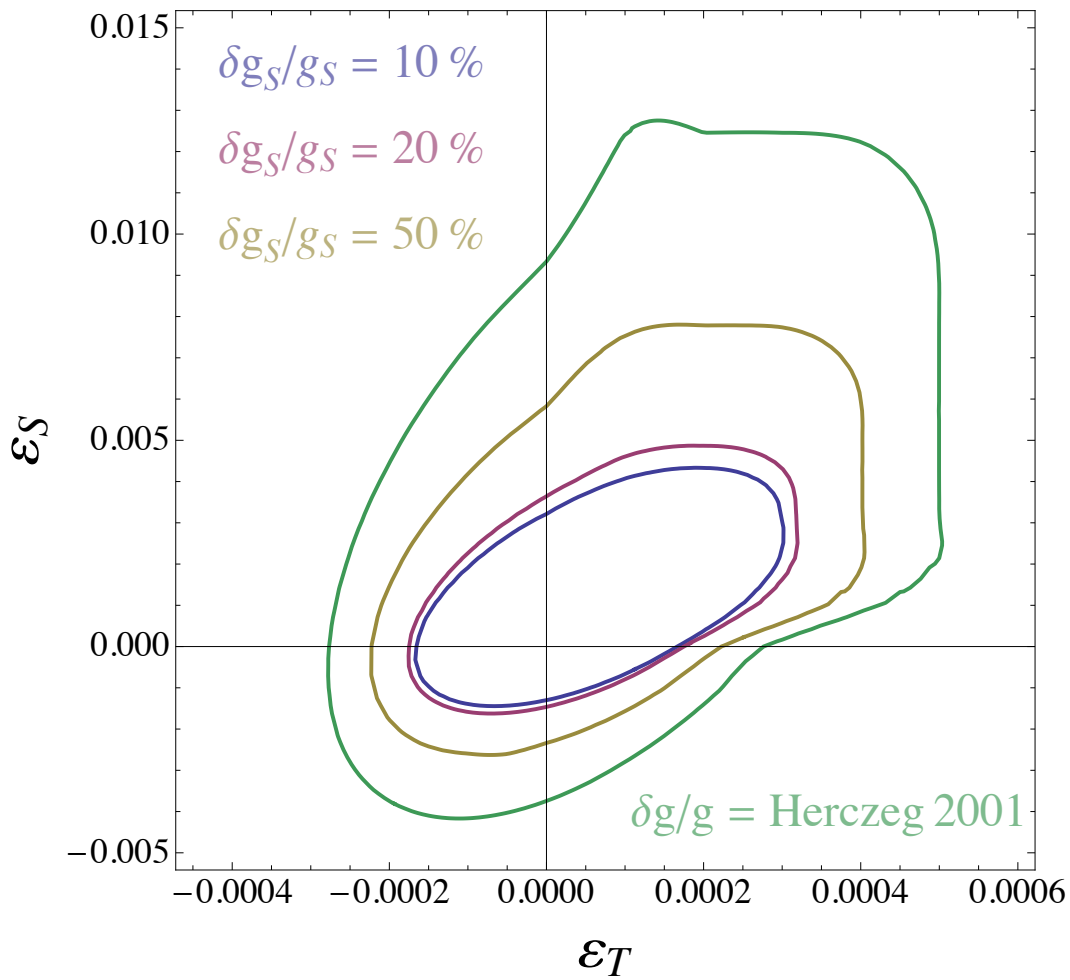
Linear order relations from $n \to p\, e\, \nu$ decay

$$b^{BSM} \approx 0.34 g_S \varepsilon_S - 5.22 g_T \varepsilon_T$$

$$b_\nu^{BSM} \equiv B_1^{BSM} = E_e \frac{\partial B^{BSM}(E_e)}{\partial m_e} \approx 0.44 g_S \varepsilon_S - 4.85 g_T \varepsilon_T$$

Impact of reducing errors in g_S and g_T from 50→10%

Allowed region in [ε_S , ε_T] (90% contours)



Experimental input

$|B_1 - b| < 10^{-3}$

$|b| < 10^{-3}$

$b_{0+} = 2.6\ (4.3) * 10^{-3}$

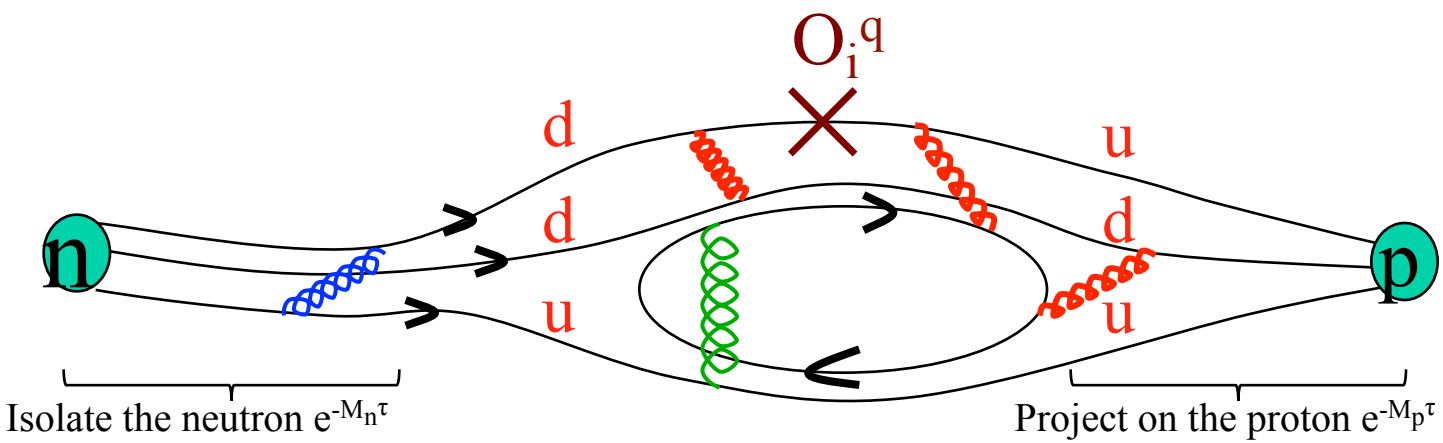
Impact limited by precision of ME from Lattice QCD

$$g_S \sim \langle p|\bar{u}d|n\rangle$$

$$g_T \sim \langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle$$

Goal: 10% accuracy in g_S and g_T

Achieving <10% uncertainty in nuclear charges $\langle p|\bar{u}\,\Gamma d|n\rangle$



- **Reached <10% uncertainty in nuclear charges. It required:**
  - High Statistics: O(1,000,000) measurements
  - Demonstrating control over all Systematic Errors:
    - Contamination from excited states
    - Non-perturbative renormalization of bilinear operators (RI_{smom} scheme)
    - ➢ Finite volume effects
    - ➢ Chiral extrapolation to physical m_u and m_d (simulate at physical point)
    - ➢ Extrapolation to the continuum limit (lattice spacing $a \rightarrow 0$)

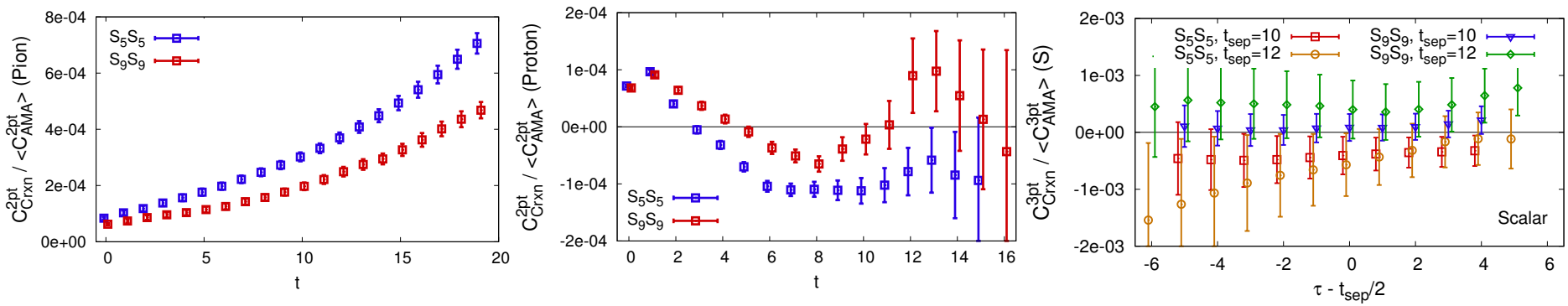
Toolkit

- Multigrid invertor
- Truncated solver method + bias correction (AMA)
- Coherent source sequential propagator
- 3-5 values of t_{sep} with smeared sources
- 2-state (3-state fit) to multiple values of t_{sep}
- Combined extrapolation in a, M_π, $M_\pi L$
- Variation of results with extrapolation Ansatz

Truncated solver + bias correction (AMA)

$$C^{AMA} = \frac{1}{N_{LP}} \sum_{i=1}^{N_{LP}} C_{LP}(x_i^{LP}) + \frac{1}{N_{HP}} \sum_{i=1}^{N_{HP}} \{C_{HP}(x_i^{HP}) - C_{LP}(x_i^{HP})\}$$

- Multigrid inverter with
  - $r_{LP} = 10^{-3}$
  - $r_{HP} = 10^{-7}$
  - $N_{LP} = 64-160$, $N_{HP} = 3\text{-}5$ per configuration
- The bias term is negligible (~1% of the error)
- The AMA error is <15% larger than LP



2+1+1 flavor HISQ lattices from MILC

M_s tuned to its physical value using $M_{s\bar{s}}$

a(fm)	m_l/m_s	Lattice Volume	M_π L	M_π (MeV)	# of Configs	HP lat. x Src.	AMA 64LP + 4(HP-LP)
0.12 □	0.2	$24^3 \times 64$	4.55	310	1013	8,104	64,832
0.12 △	0.1	$24^3 \times 64$	3.29	225	1000	24,000	
0.12 ◆	0.1	$32^3 \times 64$	4.38	228	958	7,664	
0.12 ▽	0.1	40^3 x 64	5.49	228	1010	8,080	68,680
0.09 □	0.2	$32^3 \times 96$	4.51	313	881	7,048	
0.09 ◆	0.1	$48^3 \times 96$	4.79	226	890	7,120	
0.09 ○	0.037	$64^3 \times 96$	3.90	138	883	7,064	84,768
0.06 □	0.2	$48^3 \times 144$	4.52	320	1000	8,000	64,000
0.06 ◆	0.1	$64^3 \times 144$	4.41	235	650	2,600	41,600

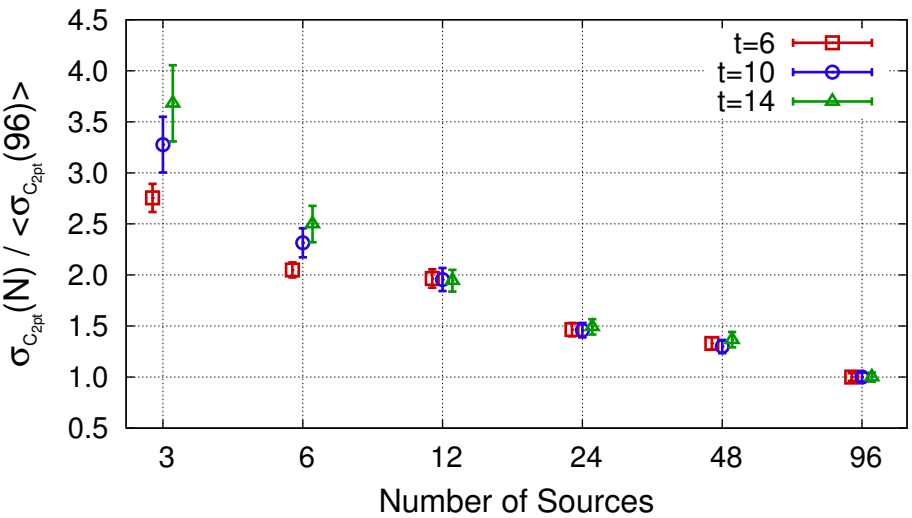
2+1 flavor Clover lattices (Jlab)

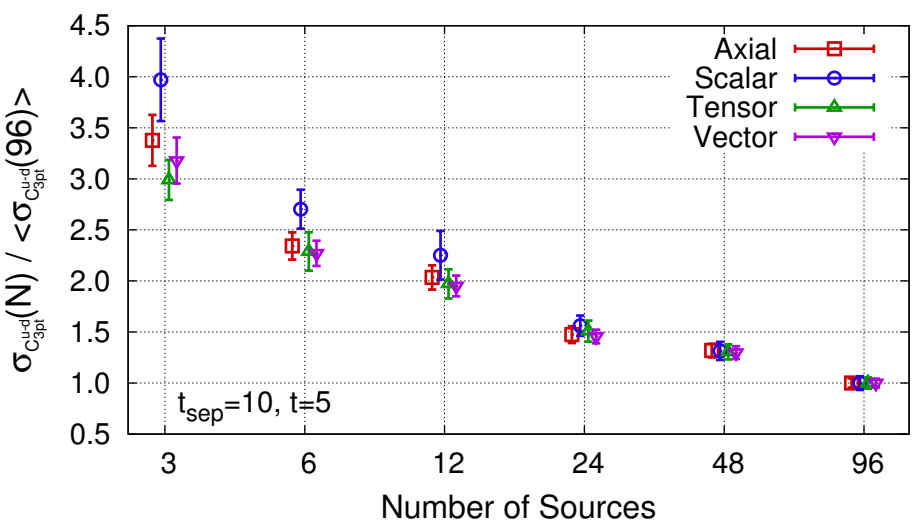
M_s tuned to its physical value using $(2M_{K^+}^2 - M_{\pi^0}^2)/M_{\Omega^-}^2$

a fm	M_π MeV	Lattice Volume	$M_\pi L$	t_{sep}	Smearing σ	# of Configs	HP Src.	LP Src
0.114	316	$32^3 \times 96$	5.85	8,10,12,14	5	1000	4000	128,480
0.081	312	$32^3 \times 64$	4.11	10,12,14,16,18	5	1005	3,015	96,480
0.081	312	$32^3 \times 64$	4.11	8,10,12,14,16	7	1005	3,015	96,480
0.081	312	$32^3 \times 64$	4.11	10,12,14,16,18	9	1005	3,015	96,480
0.081	312	$32^3 \times 64$	4.11	12	V357, V579	443	0,1329	42,528
0.079	192	$48^3 \times 96$	3.7	8,10,12,14,16	7	629	2,516	80,512
0.079	198	$64^3 \times 128$	5.08	8,10,12,14,16	7	467	2,335	74,720

Statistics

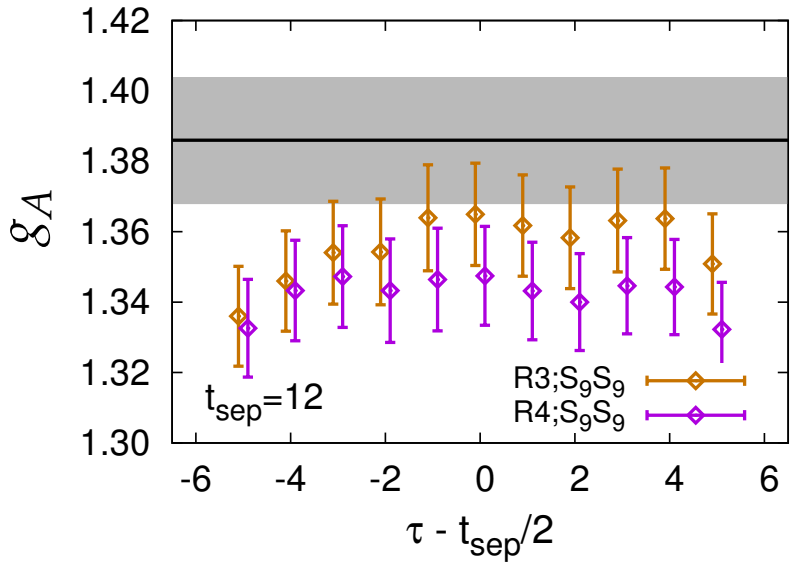
- Sample phase space adequately (ergodicity)
- Estimate of auto-correlation time





Tests of Statistics

- AIC: criteria for adding more parameters:
  - χ^2 decrease by 2 units for each parameter added
- 2-sample K-S test:
  - Divide data into bins/streams
  - Are data in different bins drawn from the same [unknown] distribution

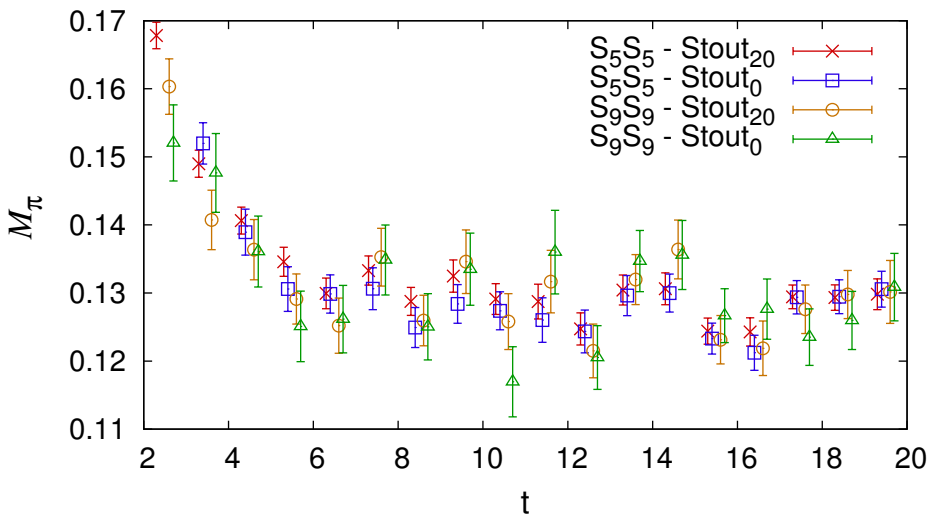


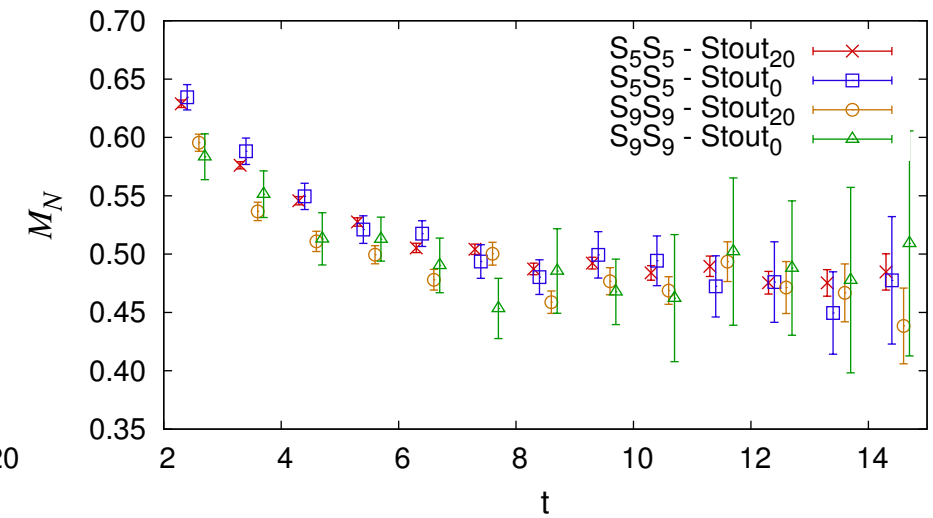
Smeared Sources

Gaussian Smearing

$$\left(1-\frac{\sigma^2\Delta^2}{4N_{GS}}\right)^{N_{GS}}$$

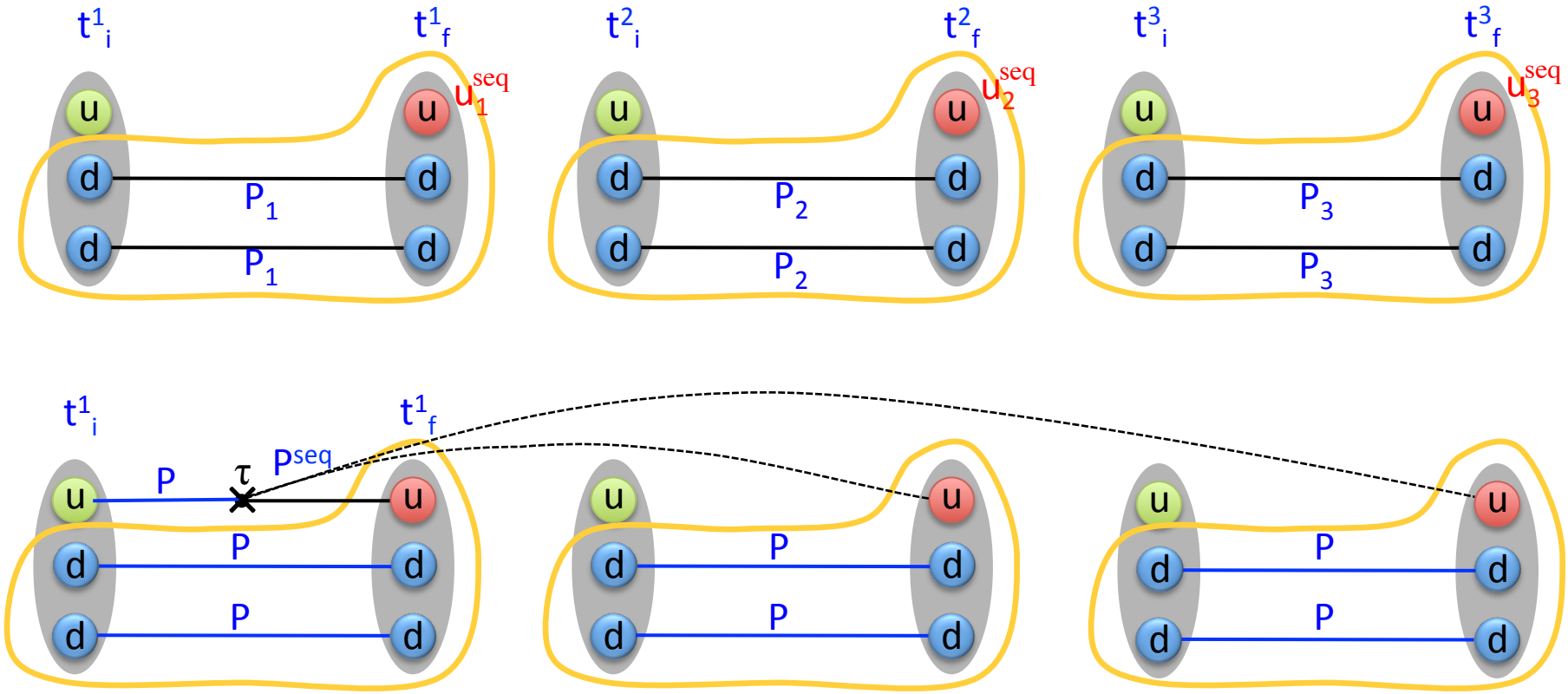
Smoothing links before smearing





ESC ↓ Variance ↑

Coherent source sequential propagator



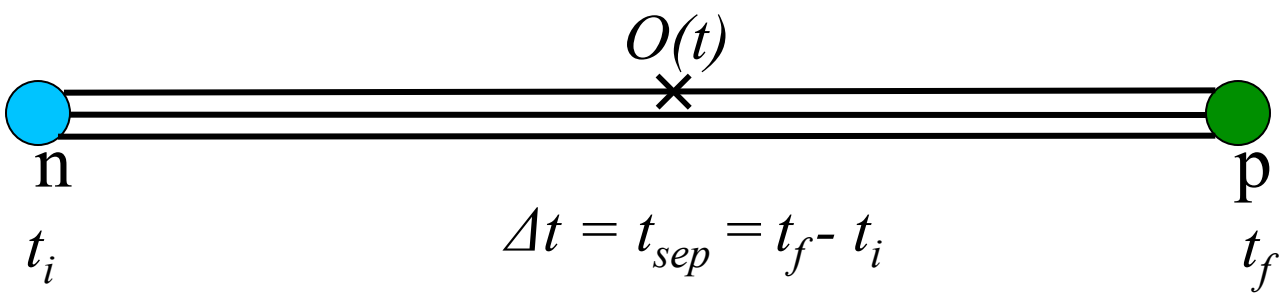
- Need only 1 sequential propagator instead of N_{meas}
- No significant increase in errors

Controlling excited-state contamination: 2-state fit

$$\Gamma^2(t) = |A_0|^2 e^{-M_0 t} + |A_1|^2 e^{-M_1 t} + \ldots$$

$$\Gamma^3(t, \Delta t) = |A_0|^2 \langle 0|O|0\rangle e^{-M_0 \Delta t} + |A_1|^2 \langle 1|O|1\rangle e^{-M_1 \Delta t} +$$
$$A_0 A_1^* \langle 0|O|1\rangle e^{-M_0 \Delta t} e^{-\Delta M(\Delta t - t)} + A_0^* A_1 \langle 1|O|0\rangle e^{-\Delta M t} e^{-M_0 \Delta t} + \ldots$$

M_0, M_1, … masses of the ground & excited states
A_0, A_1, … corresponding amplitudes



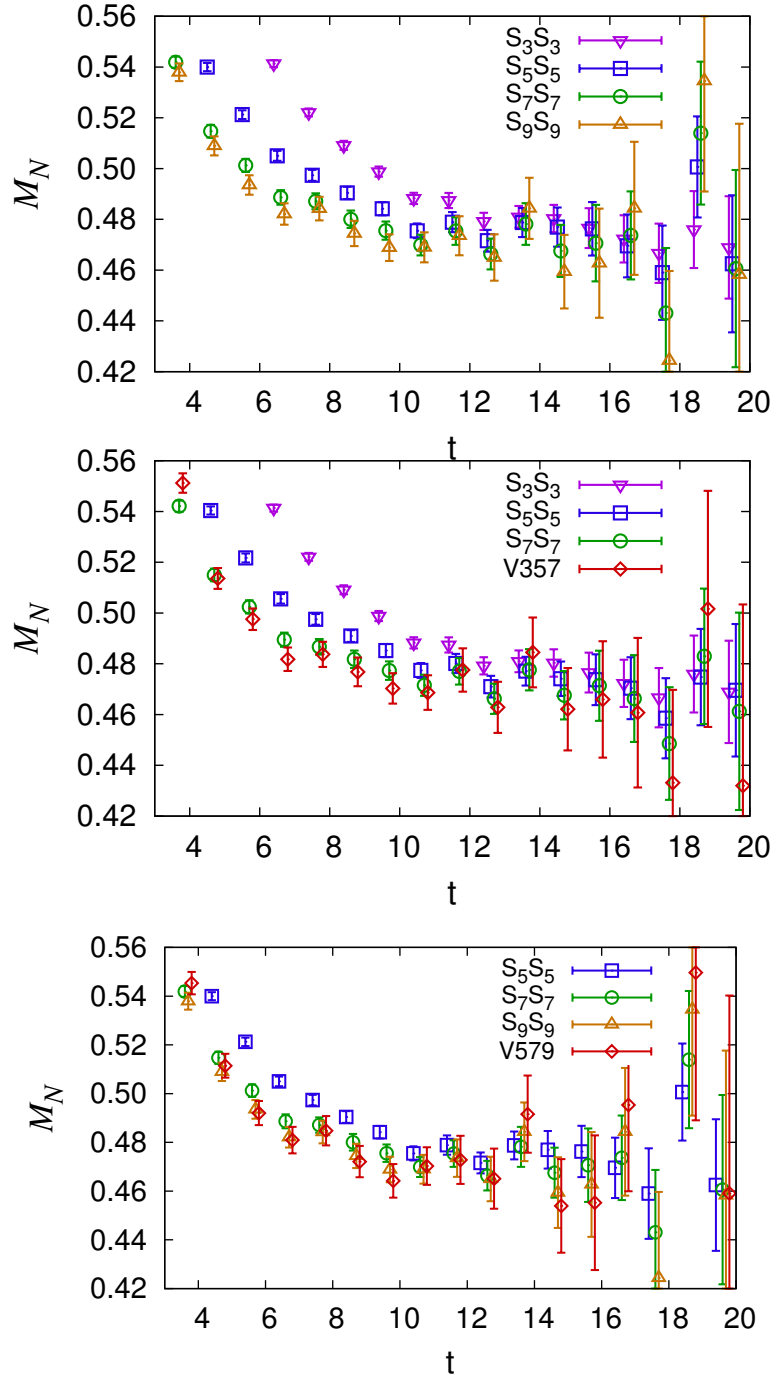
Make a simultaneous fit to data at multiple $\Delta t = t_{sep} = t_f - t_i$

Controlling excited-state contamination

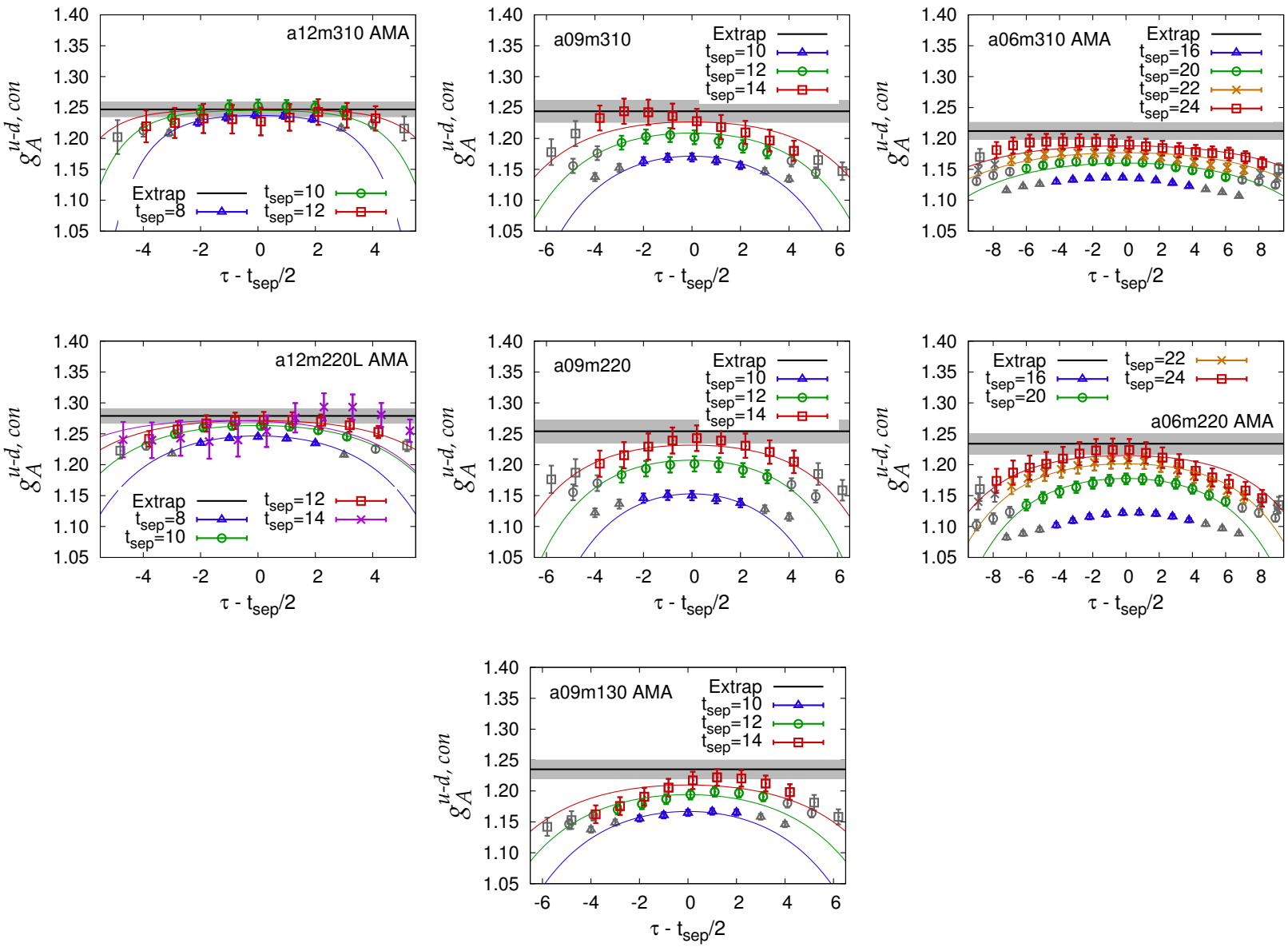
- Reduce A_n/A_0 in an n-state fit
  - Tune source smearing size σ
  - Tune the interpolating operator
- Variational method
- 2- versus 3-state fits to data at multiple values of t_{sep}

Efficacy of tuned smearing versus variational analysis

- Errors increase with larger smearing size σ
- Excited state contamination reduced with larger σ
- S_9S_9 "=" V579



g_A: Excited State Contamination



7 clover-on-HISQ ensembles: Bhattacharya et al, arXiv:1606:07049

Analyzing lattice data $\Omega(a, M_\pi, M_\pi L)$:
Extrapolations in $a, M_\pi^2, M_\pi L$

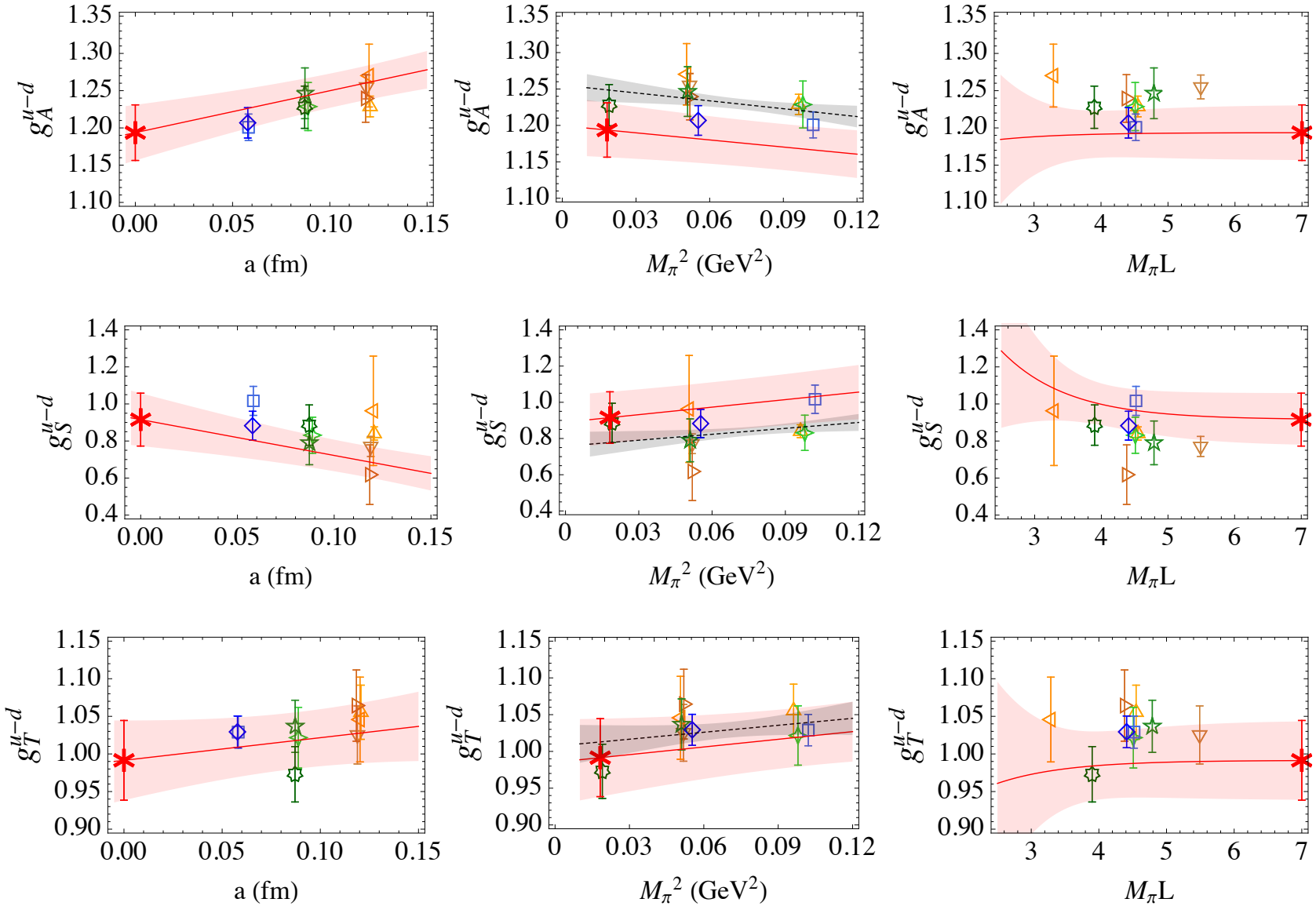
We use lowest order corrections when fitting lattice data w.r.t.

- Lattice spacing: a
- Dependence on light quark mass: $m_q \sim M_\pi^2$
- Finite volume: $M_\pi L$

$$g_{A,T}(a, M_\pi, L) = g + A\,a + B\,M_\pi^2 + C\,M_\pi^2 e^{-M_\pi L} + \ldots$$

$$g_S(a, M_\pi, L) = g + A\,a + B\,M_\pi + C\,M_\pi e^{-M_\pi L} + \ldots$$

Simultaneous extrapolation in a, M_π^2, $M_\pi L$



7 clover-on-HISQ ensembles: Bhattacharya et al, arXiv:1606:07049

Results on isovector charges of the proton (clover-on-HISQ)

(Bhattacharya et al, arXiv:1606:07049)

Isovector charges

*** $g_T = 0.987(51)$
** $g_A = 1.195(33)$
** $g_S = 0.97(12)$

Flavor diagonal charges

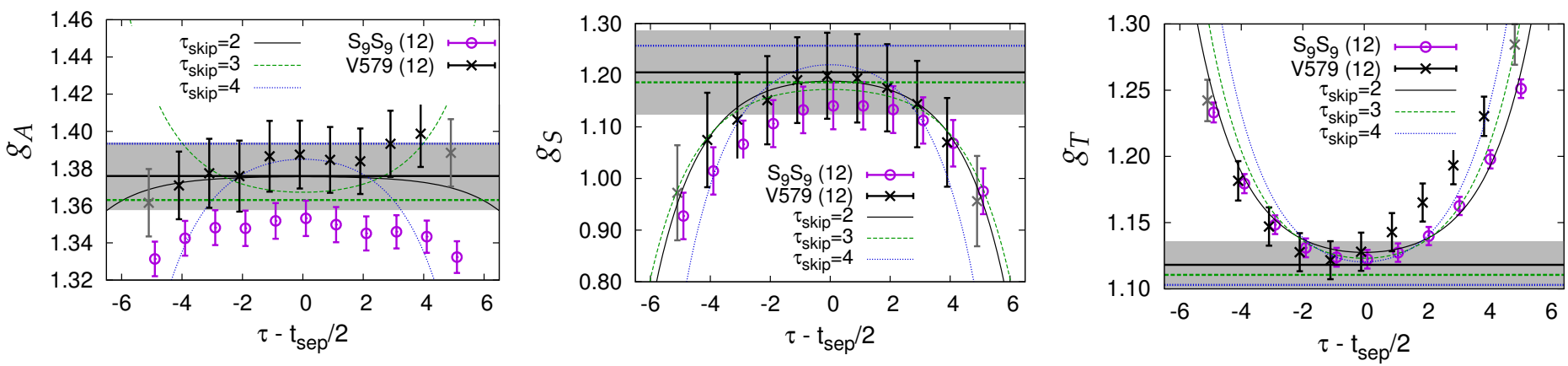
$g_T^u = 0.792(42)$
$g_T^d = -0.194(14)$

Taming excited state contamination

- For an n-state analysis reduce A_n/A_0
  → Tune smeared sources and/or operators

- Variational: construct matrix S_iS_j of correlators
- n-state fit to many t_{sep} with tuned sources

Anatomy of ESC: variational V579 versus S_9S_9



2+1f Clover-on-Clover t_{sep}=12 data on a=0.081fm, M_π=312 MeV, $32^3 \times 64$ lattices

What is needed for obtaining isovector charges with 2% total errors?

5000 lattices (30K trajectories) with

$M_\pi L \geq 4$

a = 0.1, 0.075, 0.05 fm

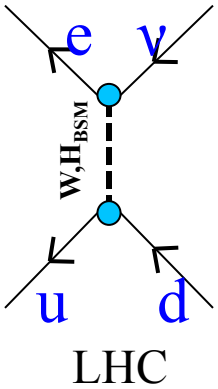
M_π = 300, 200, 140 MeV

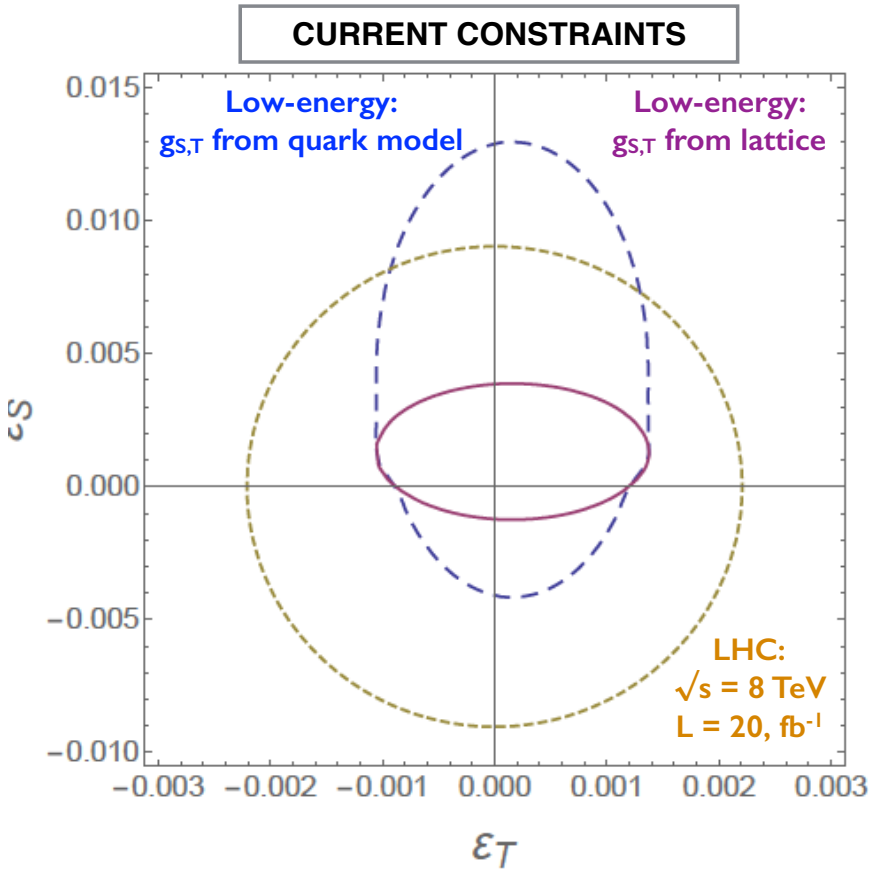
O(1,000,000) measurements

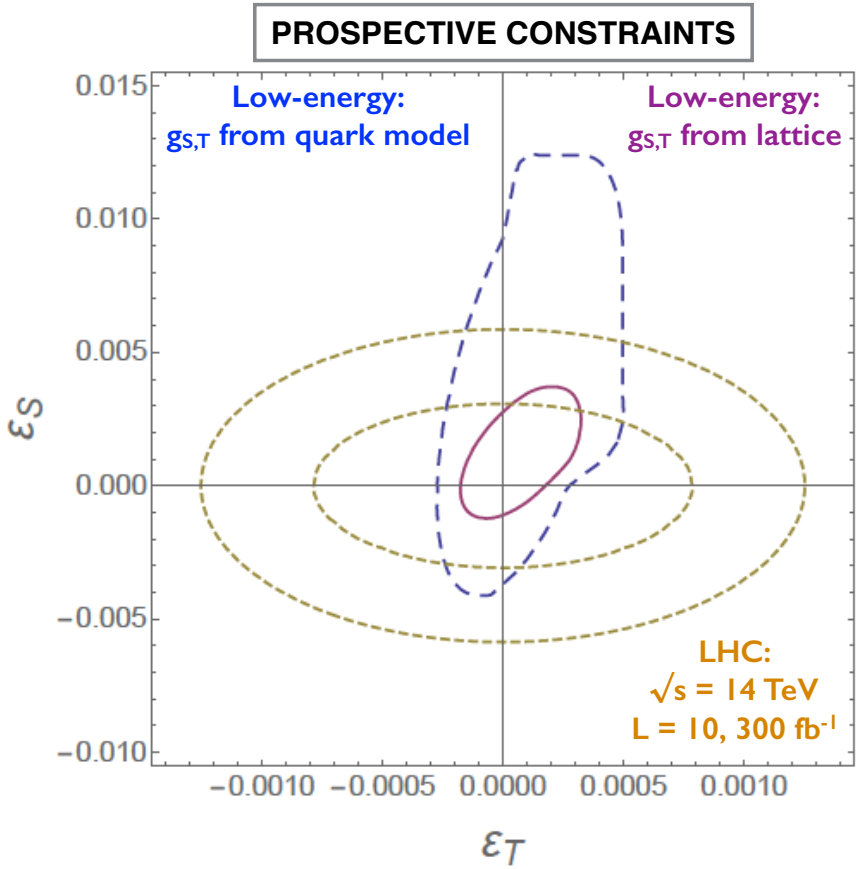
This is attainable by 2020

Constraints on [ε_S ,ε_T]: β-decay versus LHC

- LHC: (u+d → e+ν) look for events with an electron and missing energy at high transverse mass
- low-energy experiments + lattice with $\delta g_S/g_S$ ~10%

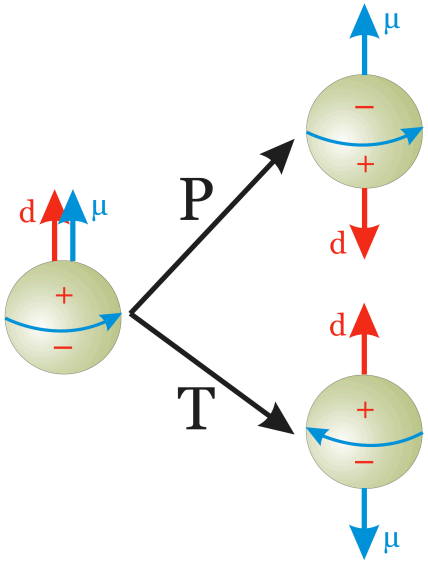


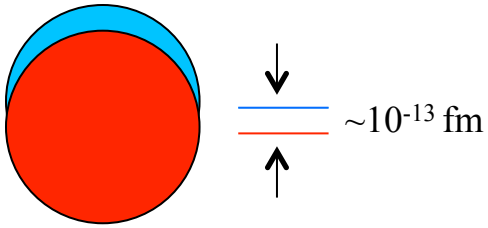


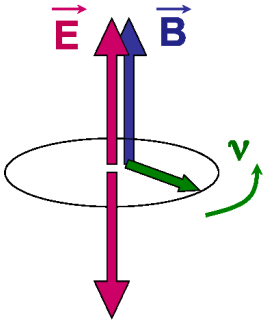


Neutron Electric Dipole Moment

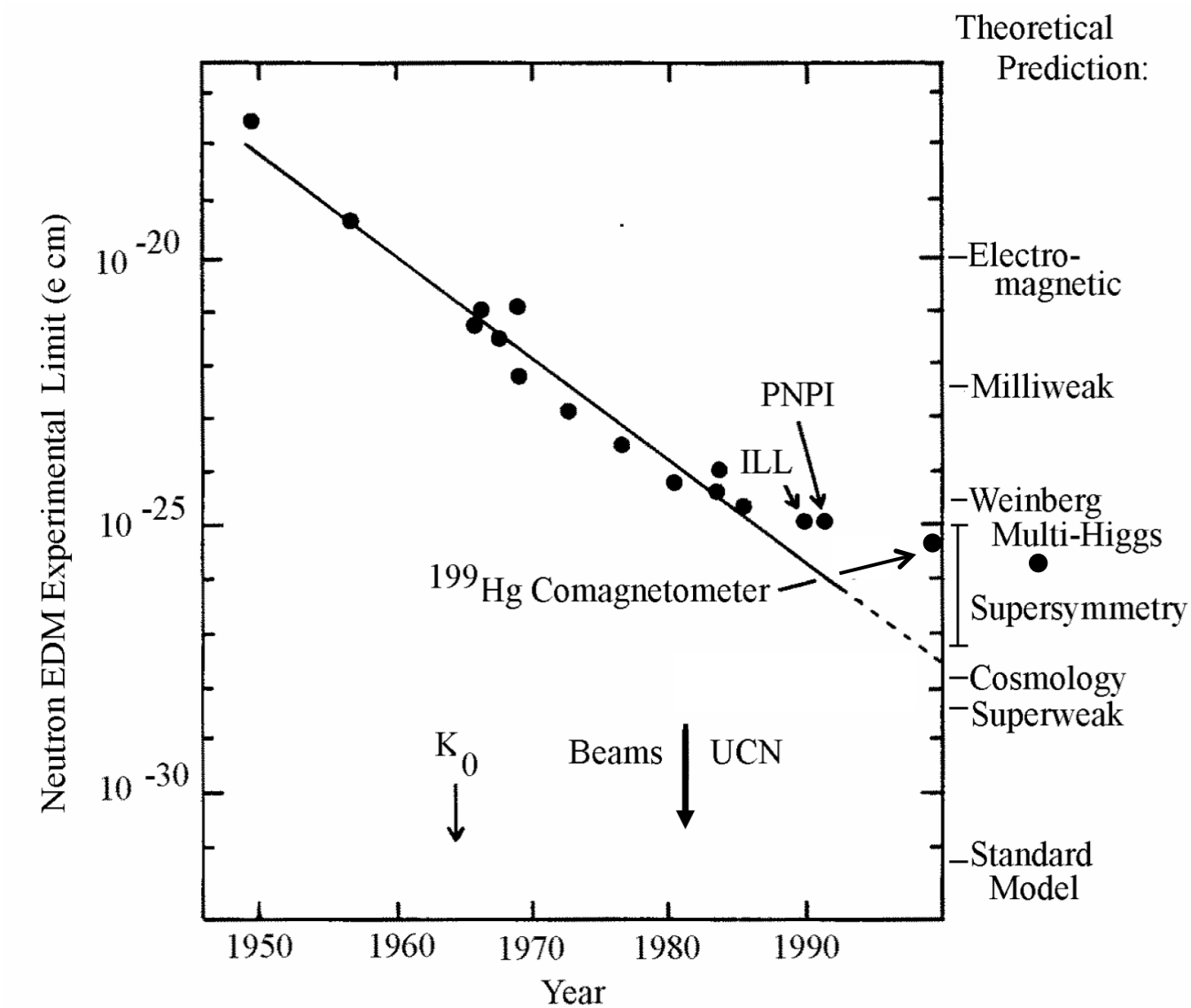
- Quark EDM: contribution of quark EDM to the NEDM
- Quark Chromo EDM: CPV contribution due to the interaction of quarks with the color electric field







Evolution of EDM Experiments



CP violating operators

- Dimension 3 and 4:
  - CP violating mass $\bar{\psi}\gamma_5\psi$
  - Toplogical charge $G_{\mu\nu}\tilde{G}^{\mu\nu}$.
- Suppressed by vEW/M2 : BSM
  - Electric Dipole Moment $\bar{\psi}\sigma_{\mu\nu}\tilde{F}^{\mu\nu}\psi$.
  - Chromo Dipole Moment $\bar{\psi}\sigma_{\mu\nu}\tilde{G}^{\mu\nu}\psi$.

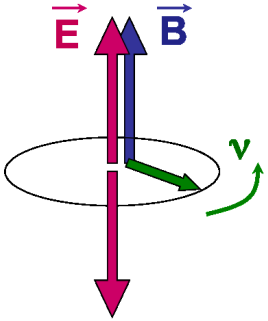
BSM:Suppressed by v/M^2

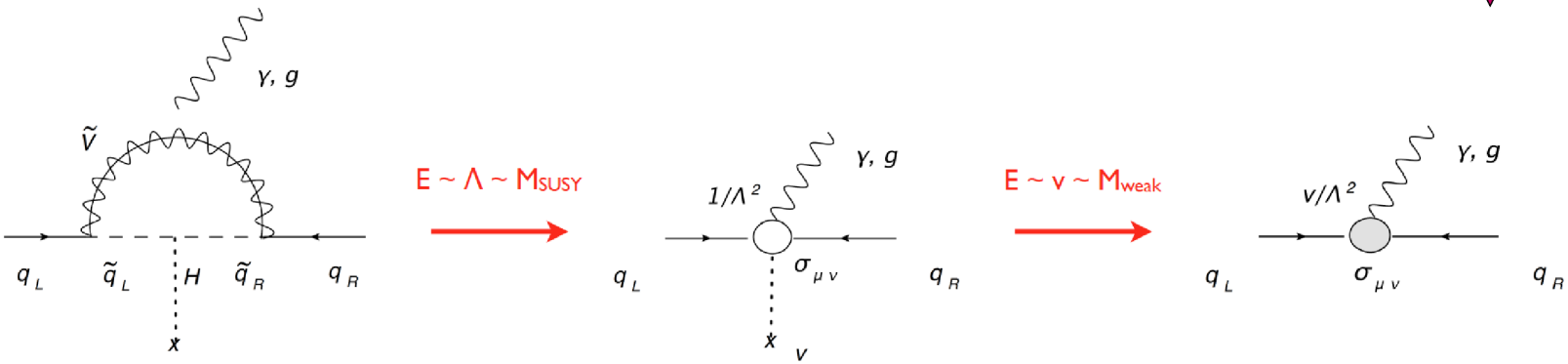
- Weinberg operator (Gluon chromo-electric moment):
  - $G_{\mu\nu}\, G_{\lambda\nu}\, \tilde{G}_{\mu\lambda}$

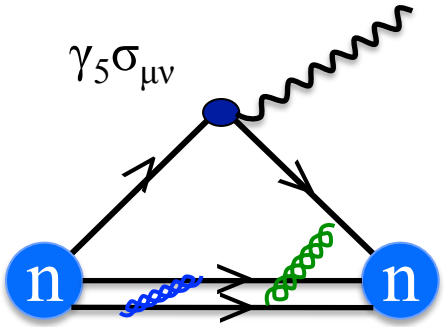
BSM:Suppressed by $1/M^2$

- Various four-fermi operators.

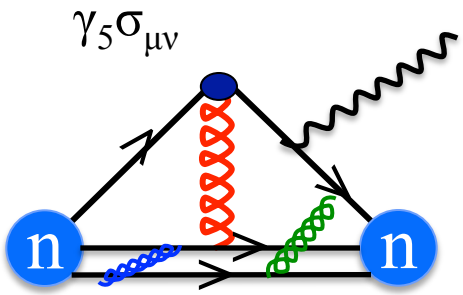
Novel CP violation: operators in EFT







γ attaches to the vertex



- 4-pt function as γ can attach to any quark line
- Gluon free end can attach to any quark line

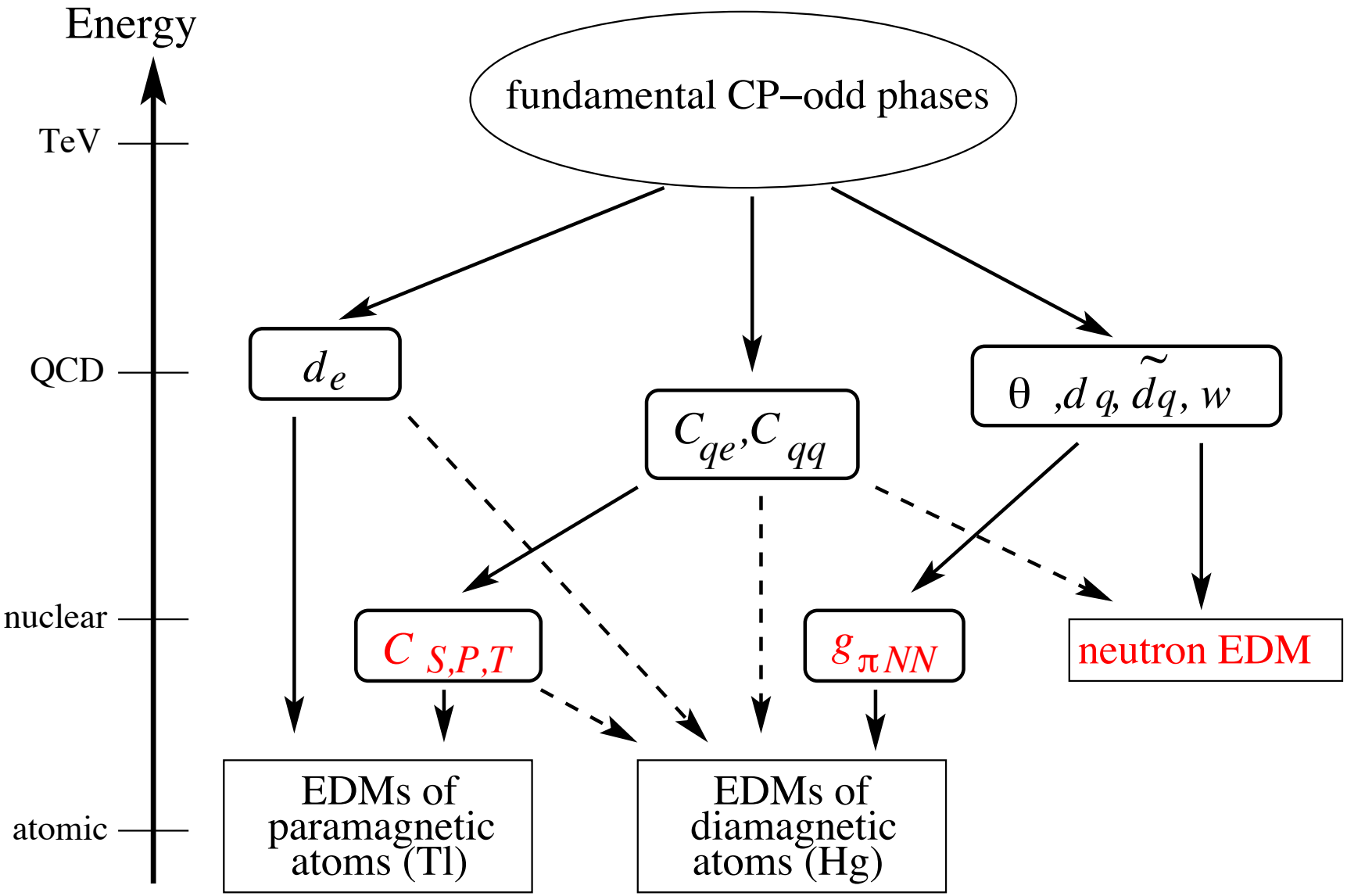
Quark-EDM

$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\, q\, F^{\mu\nu}$$

Chromo-EDM

$$\bar{q}\,\sigma_{\mu\nu}\gamma_5\, q\, \lambda^a G_a^{\mu\nu}$$

BSM → Couplings in EFT → EDM



Pospelov and Ritz, *Ann. Phys.* **318** (2005) 119

QCD + novel CPV Interactions

The low-energy effective Lagrangian is

$$L_{CPV} = L_{QCD} + i\Theta G_{\mu\nu}\tilde{G}^{\mu\nu} + i\sum_q d_q^{\gamma}\bar{q}\sigma^{\mu\nu}\tilde{F}_{\mu\nu}q + i\sum_q d_q^{G}\bar{q}\sigma^{\mu\nu}\tilde{G}_{\mu\nu}q + \cdots$$

The electromagnetic current, given by $\delta L/\delta A\mu$, becomes

$$j_F^{\mu} = j_{EM}^{\mu} + j_{CPV}^{\mu} = e\sum_q \bar{q}\gamma^{\mu}q + i\varepsilon^{\alpha\beta\mu\nu}p_{\nu}\sum_q d_q^{\gamma}\bar{q}\sigma^{\alpha\beta}q + \cdots$$

Need to calculate 3-point functions

$$\langle\Omega|N(t,p')j_F^{\mu}(\tau,p'-p)N(0,p)|\Omega\rangle =$$

$$\langle\Omega|N(p')|N_j\rangle e^{-\int dt\, H_F}\langle N_j|j_F^{\mu}(\tau,p'-p)|N_i\rangle e^{-\int dt\, H_F}\langle N_i|N(p)|\Omega\rangle \approx$$

$$\langle\Omega|N(p')|N_j\rangle e^{-\int dt\, H}(1-H_{CPV})\langle N_j|j_{EM}^{\mu}+j_{CPV}^{\mu}|N_i\rangle(1-H_{CPV})e^{-\int dt\, H}\langle N_i|N(p)|\Omega\rangle$$

$$\approx\langle\Omega|N(p')|N_j\rangle e^{-\int dt\, H}\langle N_j|j_{EM}^{\mu}+j_{CPV}^{\mu}+j_{EM}^{\mu}H_{CPV}+\ldots|N_i\rangle e^{-\int dt\, H}\langle N_i|N(p)|\Omega\rangle$$

Form-factors in the presence of *P, CP* violating interactions

$$\left\langle p_f, s_f \middle| J_F^\mu(q) \middle| p_i, s_i \right\rangle = \bar{u}(p_f, s_f)\Gamma^\mu(q)u(p_i, s_i)$$

$$\Gamma^\mu(q) = \gamma^\mu F_1(q^2)$$ Charge $F_1(0)=1$

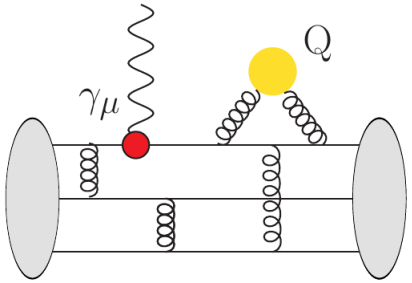
$$+ i\sigma^{\mu\nu} q_\nu \frac{F_2(q^2)}{2M}$$ Anomalous μ $(a_\mu = F_2(0))$

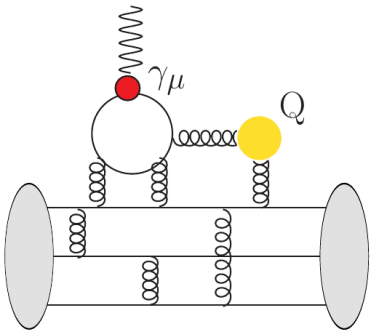
$$+ (\gamma^\mu \gamma^5 q^2 - 2M\gamma^5 q^\mu) F_A(q^2)$$ Anapole moment

$$+ \sigma^{\mu\nu} q_\nu \gamma^5 \frac{F_3(q^2)}{2M}$$ EDM $(d_n = F_3(0)/2M)$

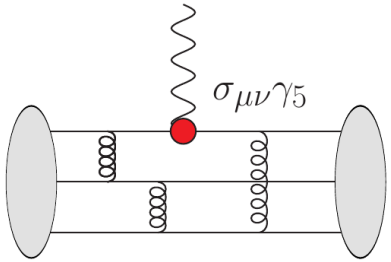
Diagrams to be calculated using Lattice QCD

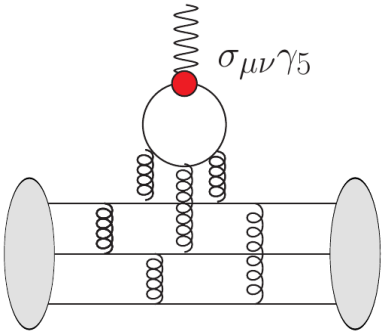
Θ-term



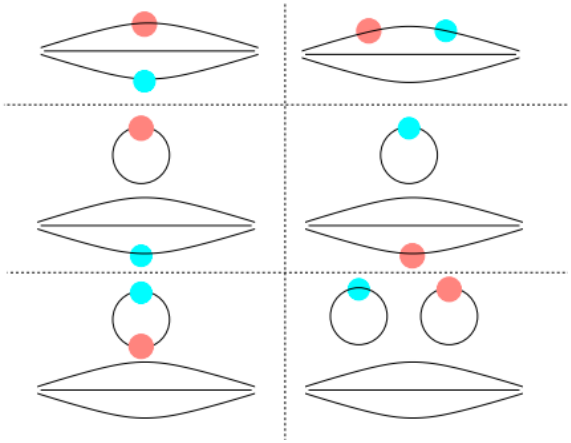


quark EDM



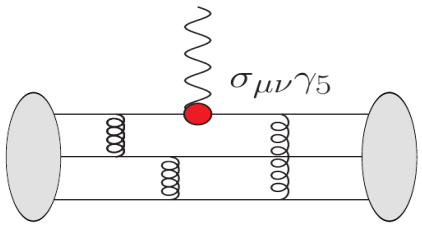


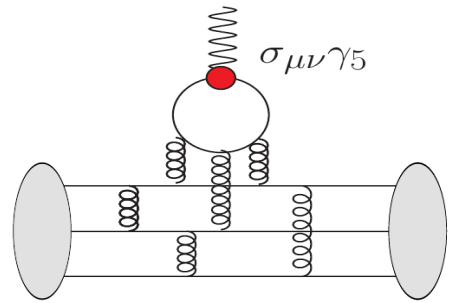
quark Chromo EDM
(4-pt function)

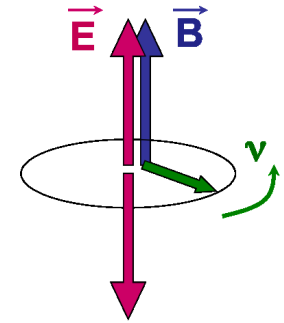


Constraining BSM using nEDM

quark EDM



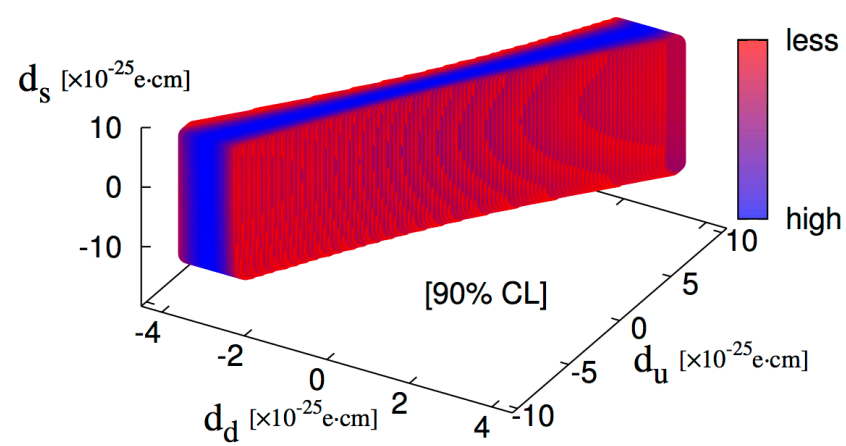




Assuming only quark EDM contribute to nEDM, then

$$d_n = d_u^\gamma g_T^u + d_d^\gamma g_T^d + d_s^\gamma g_T^s + \ldots$$

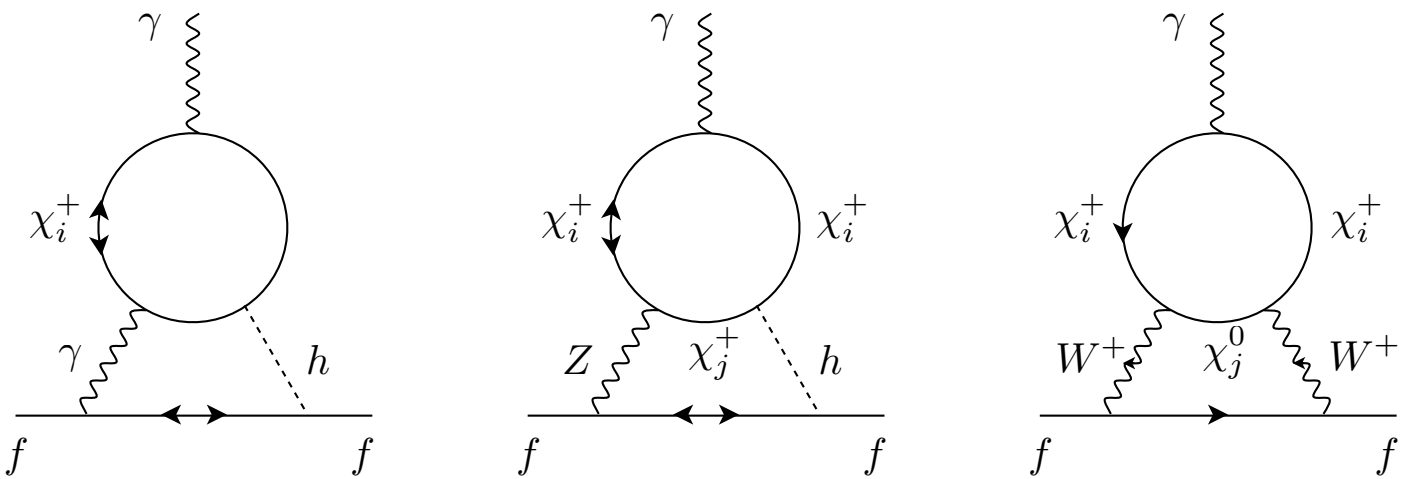
		New in 2016
$g_T^u =$	-0.232(28)	-0.192(12)
$g_T^d =$	0.774(68)	0.800(38)
$g_T^s =$	0.008(9)	



Bhattacharya et al, PRL 115 (2015) 212002
Bhattacharya et al, PRD92 (2015) 094511

Split Supersymmetry

- All scalars but one Higgs doublet are much heavier than Λ_{EW}
- Has gauge coupling unification, dark matter candidate
- Avoids flavor and CP constraints mediated by 1-loop terms with scalars
- Fermion EDMs arise at 2-loops: phases in gaugino-Higgsino sector communicated to SM fermions through *γh, Zh, WW* exchanges
- chromoEDM, Weinberg, …, operators do not arise at 2-loop

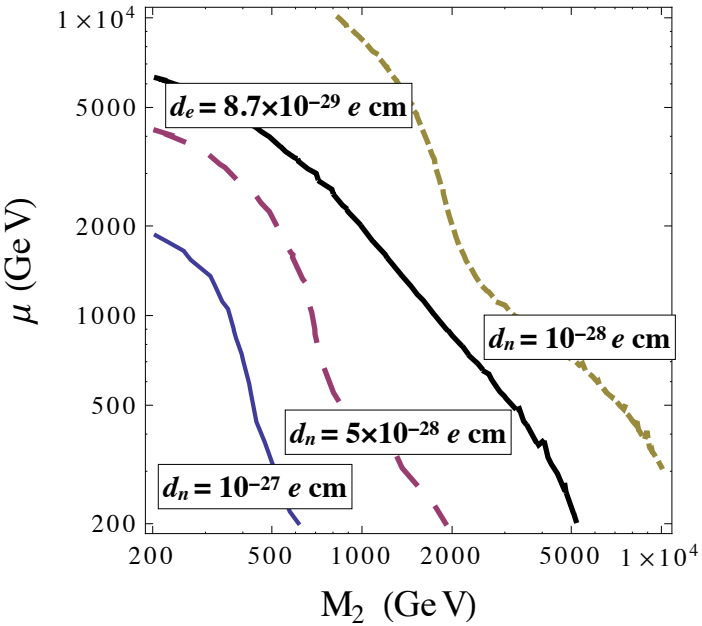


Our analysis followed the work of Giudice & Romanino, PL B634 (2006) 307

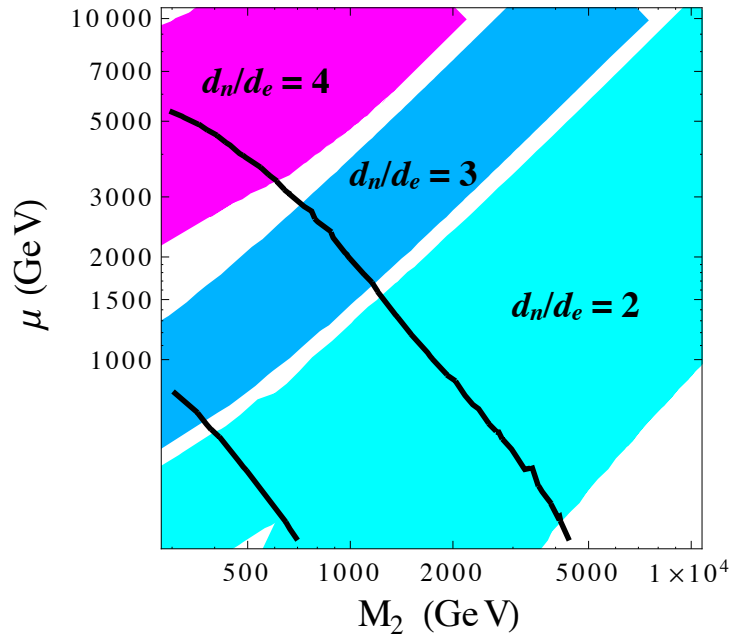
Constraint on Split Supersymmetry

- The correlation between d_n and d_e provides a constraint on Split SUSY.
- Using our estimates of $g_T(u,d,s)$ and $d_e = 8.7 \times 10^{-29}$ e cm gives a stringent upper bound:

$$d_n < 4 \times 10^{-28} \text{ e cm}$$



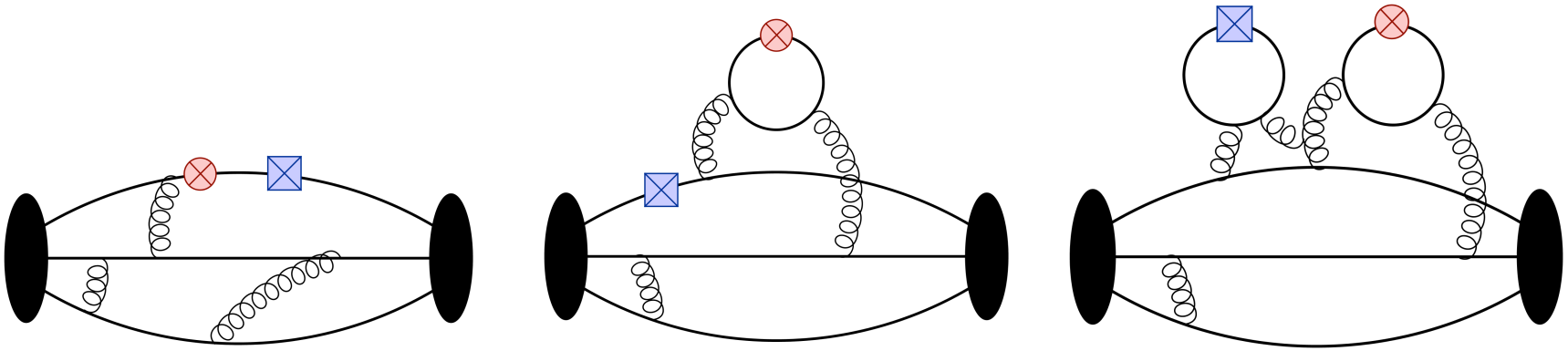
Contours of d_n , d_e versus gaugino (M_2) and Higgsino (μ) mass parameters setting tanβ=1 and sinϕ=1

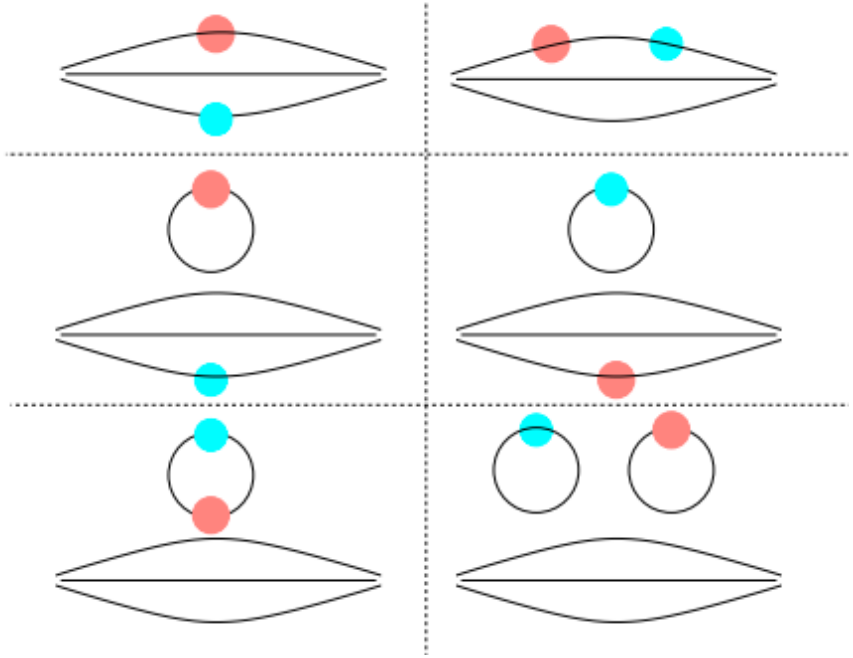


Correlation between d_n , d_e in split SUSY. Bands are for different d_n/d_e (ϕ independent) and solid lines are for $d_e = 8.7 \times 10^{-29}$ e cm & sinϕ=0.2 and 1.

Bhattacharya et al, PRL 115 (2015) 212002

Quark Chromo EDM: 4-pt functions





cEDM: Schwinger Source Method

The chromo EDM operator contribution arises due to the change in the Dirac action. The qEDM and cEDM terms are bilinear in the quark fields, so fermions can still be integrated out.

Change 1: Modify Dirac operator when calculating the inverse

$$\not{D} + m - \frac{r}{2}D^2 + c_{SW}\Sigma^{\mu\nu}G_{\mu\nu} \rightarrow \not{D} + m - \frac{r}{2}D^2 + \Sigma^{\mu\nu}(c_{SW}G_{\mu\nu} + i\varepsilon\tilde{G}_{\mu\nu})$$

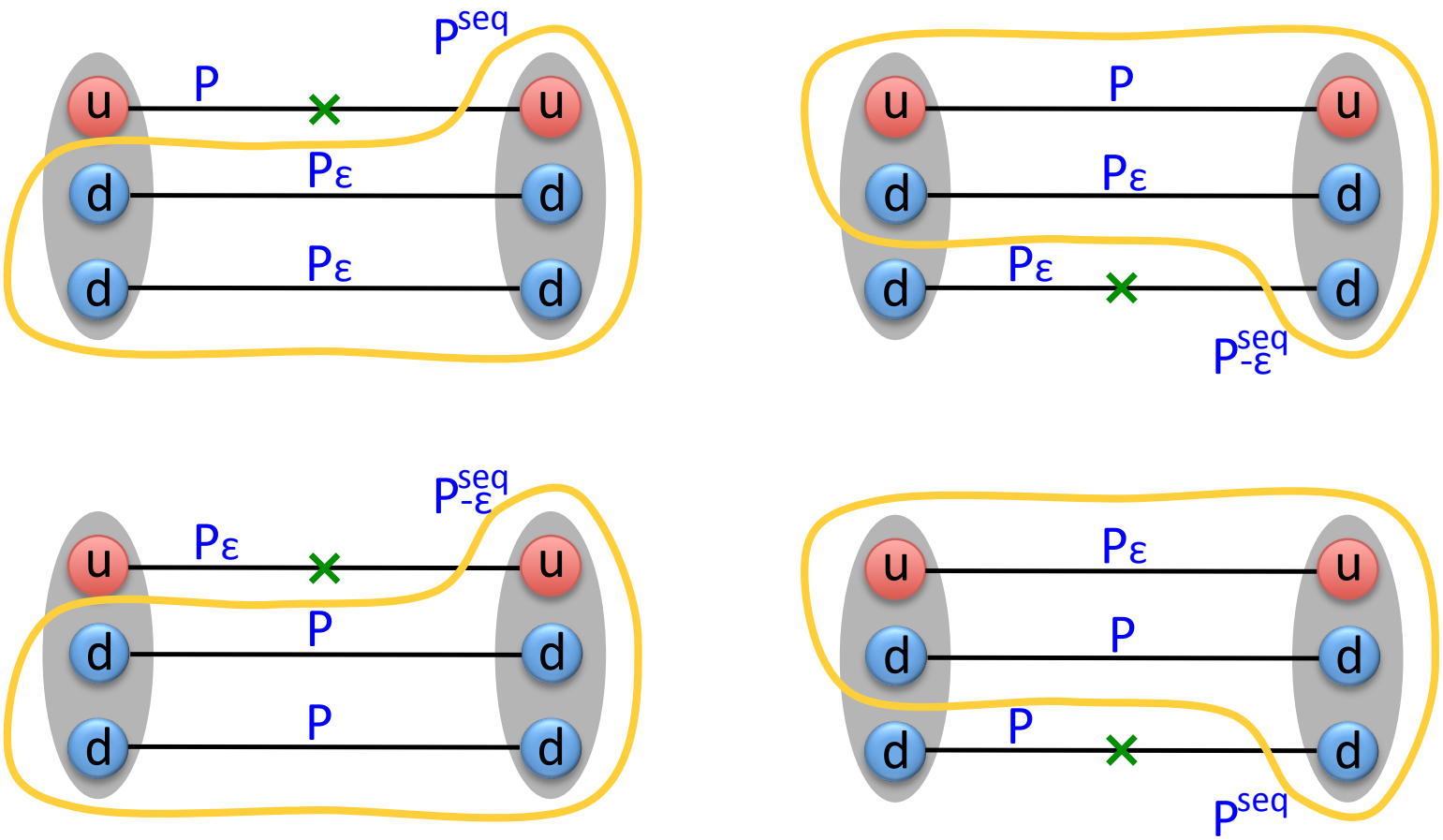
Change 2: Correct the Boltzmann weight of each gauge configuration. Reweight with the ratio of determinants:

$$\frac{Det[\not{D} + m - \frac{r}{2}D^2 + \Sigma^{\mu\nu}(c_{SW}G_{\mu\nu} + i\varepsilon\tilde{G}_{\mu\nu})]}{Det[\not{D} + m - \frac{r}{2}D^2 + c_{SW}\Sigma^{\mu\nu}G_{\mu\nu}]}$$

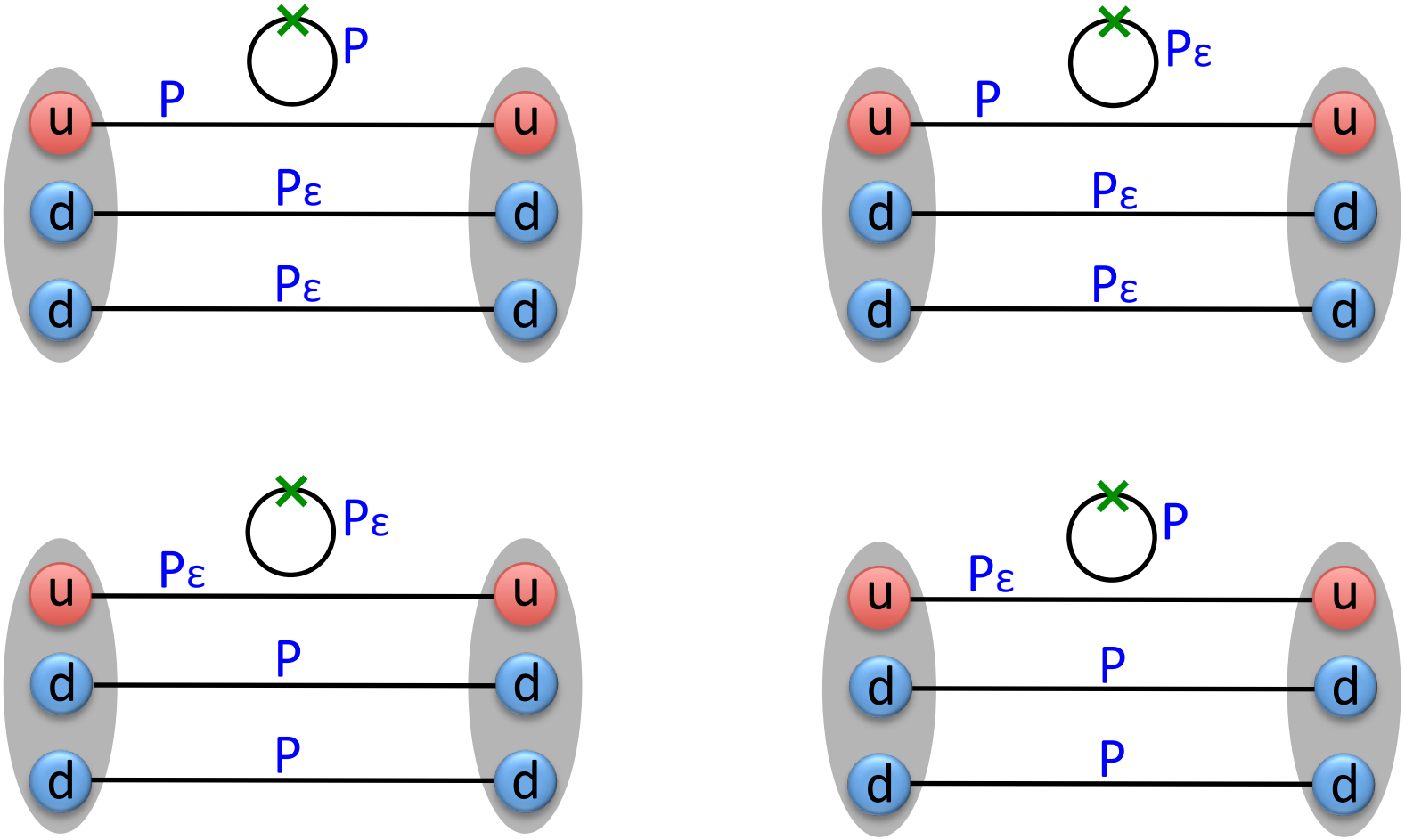
$$= \exp\{Tr\ Ln[1 + i\varepsilon\Sigma^{\mu\nu}\tilde{G}_{\mu\nu}(\not{D} + m - \frac{r}{2}D^2 + c_{SW}\Sigma^{\mu\nu}G_{\mu\nu})^{-1}]\}$$

$$\approx \exp\{Tr\ i\varepsilon\Sigma^{\mu\nu}\tilde{G}_{\mu\nu}(\not{D} + m - \frac{r}{2}D^2 + c_{SW}\Sigma^{\mu\nu}G_{\mu\nu})^{-1}\}$$

Connected Contribution



Disconnected Contribution

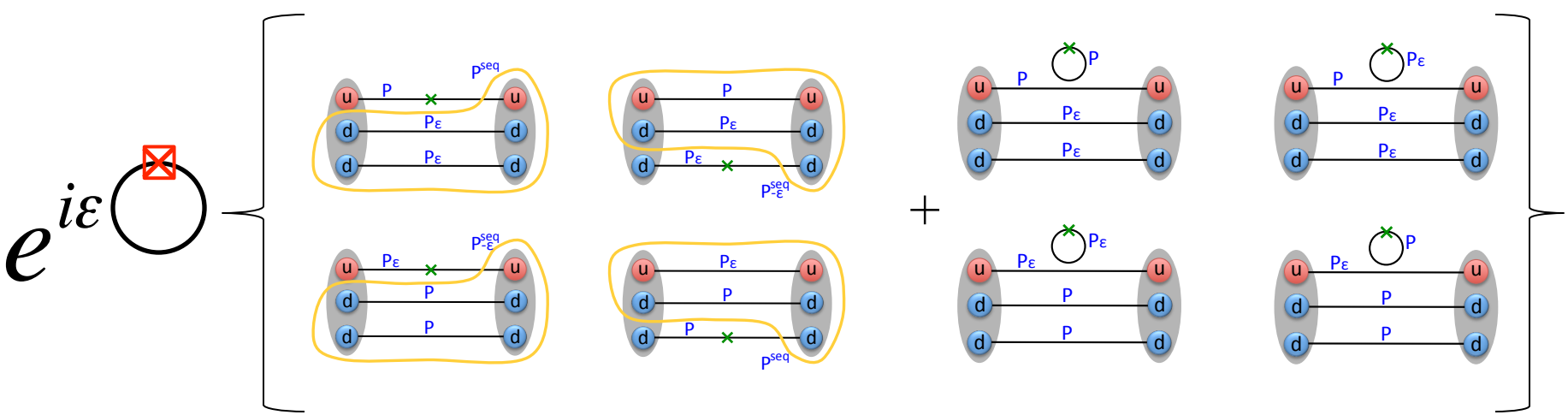


Reweight by the ratio of determinants

$$\frac{Det[\not{D} + m - \frac{r}{2}D^2 + \Sigma^{\mu\nu}(c_{SW}G_{\mu\nu} + i\varepsilon\tilde{G}_{\mu\nu})]}{Det[\not{D} + m - \frac{r}{2}D^2 + c_{SW}\Sigma^{\mu\nu}G_{\mu\nu}]}$$

$$= \exp\{Tr\ Ln[1 + i\varepsilon\Sigma^{\mu\nu}\tilde{G}_{\mu\nu}(\not{D} + m - \frac{r}{2}D^2 + c_{SW}\Sigma^{\mu\nu}G_{\mu\nu})^{-1}]\}$$

$$\approx \exp\{Tr\ i\varepsilon\Sigma^{\mu\nu}\tilde{G}_{\mu\nu}(\not{D} + m - \frac{r}{2}D^2 + c_{SW}\Sigma^{\mu\nu}G_{\mu\nu})^{-1}\}$$



Quark Chromoelectric Operator: Mixing

	C	$\partial^2 P$	E	$mF\tilde{F}$	$mG\tilde{G}$	$m\partial\cdot A$	$m^2 P$	P_{EE}	$\partial\cdot A_E$	A_∂	$A_{A(\gamma)}$
C	Z_C	X	X	X	X	X	X	X	X	X	X
$\partial^2 P$	0	Z_P	0	0	0	0	0	0	0	0	0
E	0	0	Z_T	0	0	0	0	0	0	0	0
$mF\tilde{F}$	0	0	0	$Z_m^{-1} Z_{F\tilde{F}}$	0	0	0	0	0	0	0
$m\,G\tilde{G}$	0	0	0	0	$Z_m^{-1} Z_{G\tilde{G}}$	X	0	0	0	0	0
$m\,\partial\cdot A$	0	0	0	0	0	$Z_m^{-1} Z_{\partial A}$	0	0	0	0	0
$m^2 P$	0	0	0	0	0	0	Z_m^{-1}	0	0	0	0
P_{EE}	0	0	0	0	0	0	0	X	X	X	0
$\partial\cdot A_E$	0	0	0	0	0	0	0	0	X	0	0
A_∂	0	0	0	0	0	0	0	X	X	X	0
$\partial\cdot A_E$	0	0	0	0	0	0	0	0	X	0	0
A_∂	0	0	0	0	0	0	0	X	X	X	0
$A_{A(\gamma)}$	0	0	0	0	0	0	0	0	0	0	X

Bhattacharya et al, PRD92 (2015) 114026 (arXiv:1502.07325 [hep-ph])

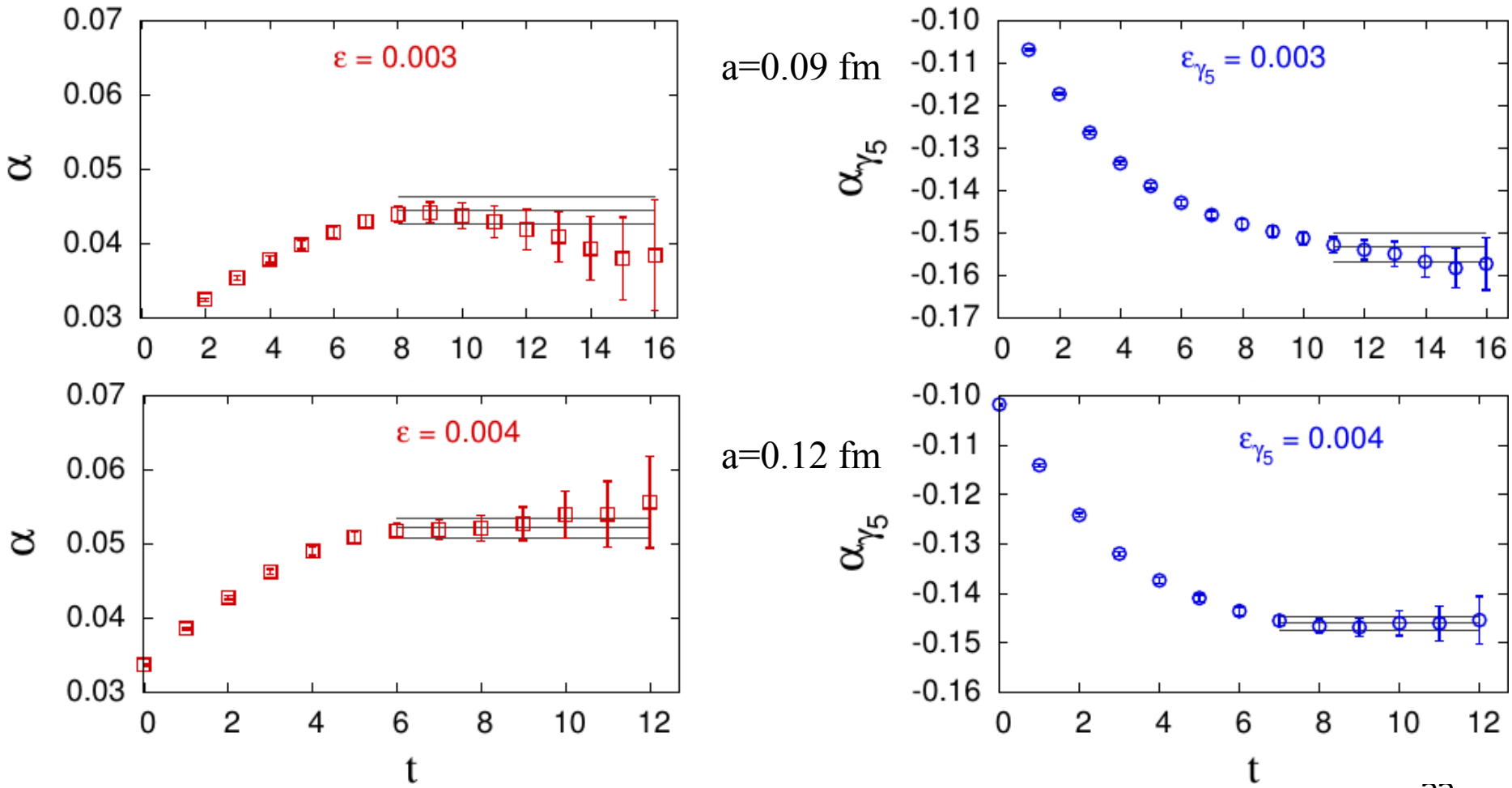
$$a^2\bar{\psi}\sigma\cdot\tilde{G}\psi \quad and \quad \bar{\psi}\gamma_5\psi$$

mix under renormalization

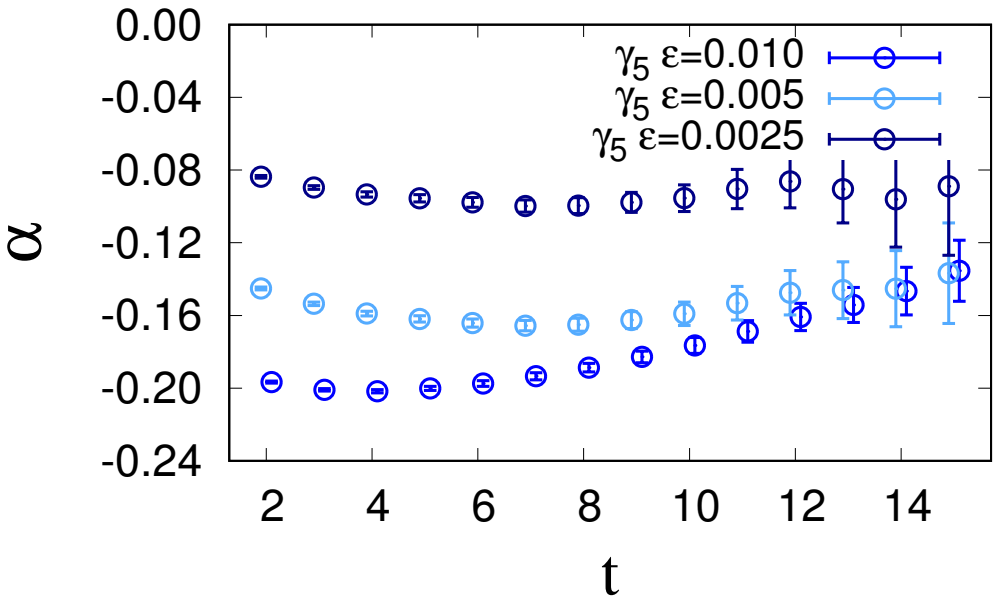
Need to do the same calculation as CEDM with insertion of $\bar{\psi}\gamma_5\psi$

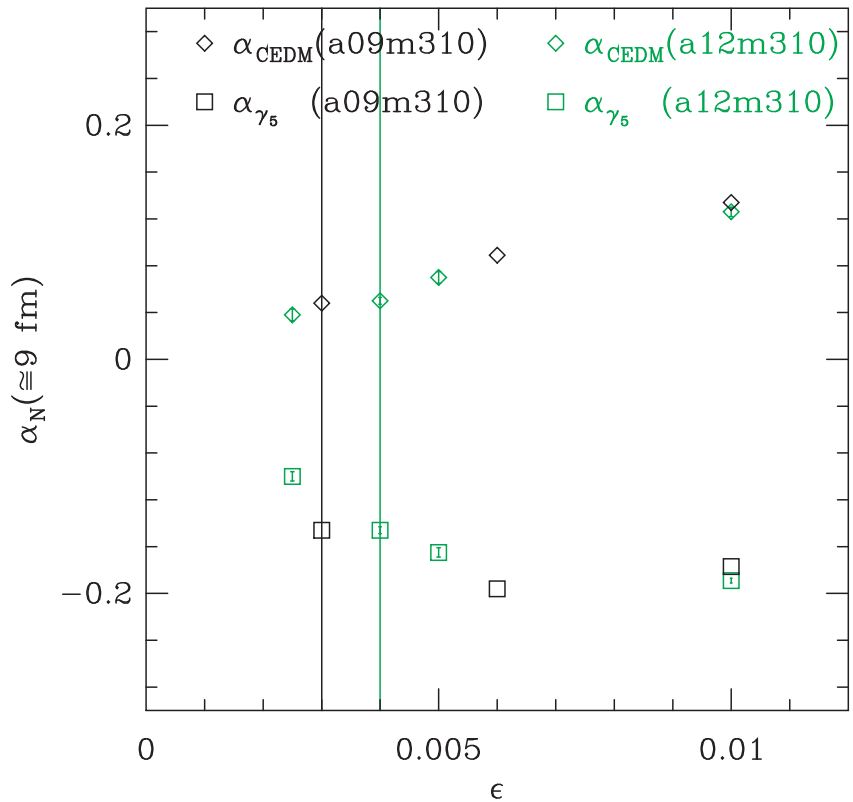
Does the method work?

With CP violation $$u_N(p)_N\bar{u}(p) = e^{i\alpha_N\gamma_5}(i\not{p} + M_N)e^{i\alpha_N\gamma_5}$$

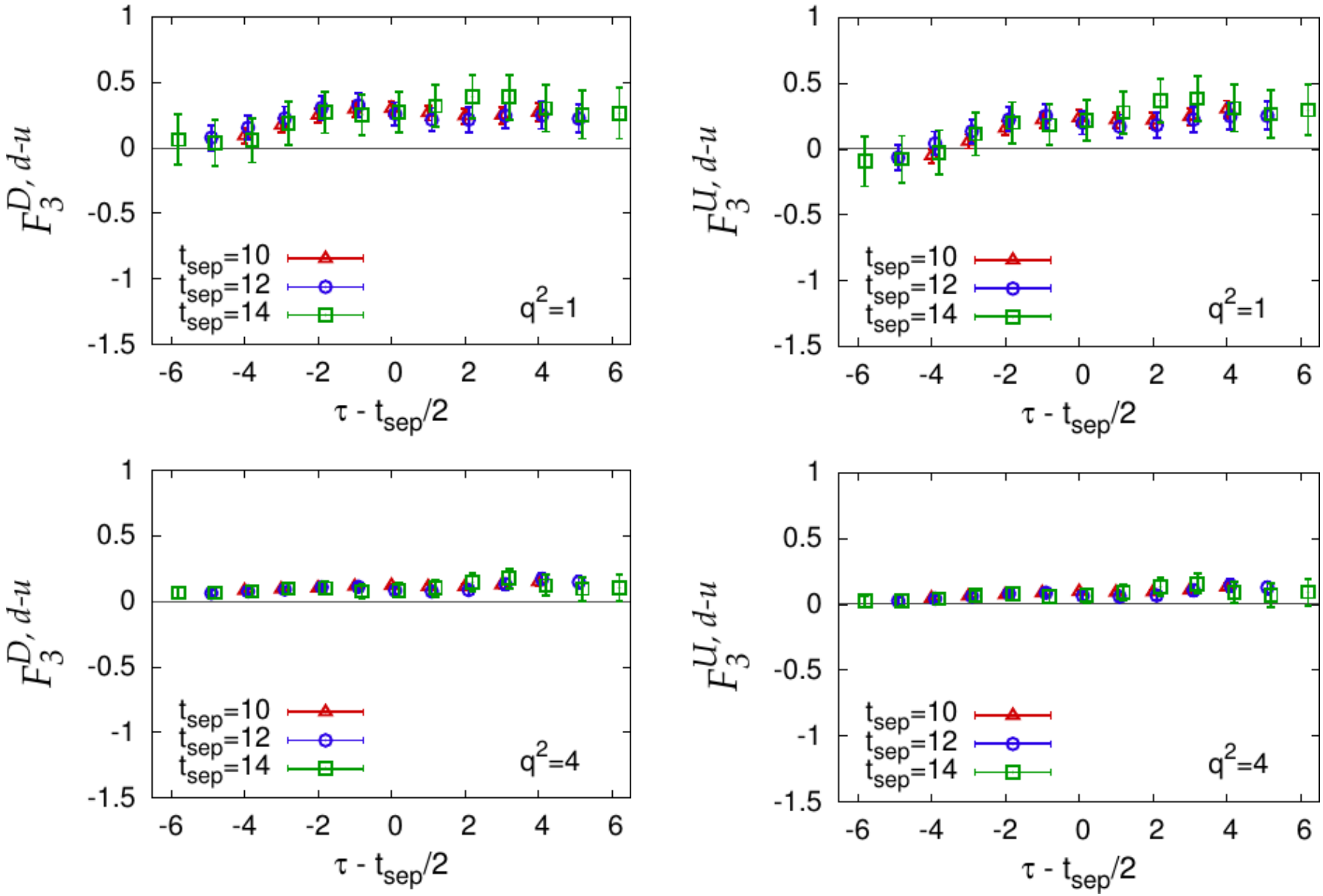


2-pt function: Phase α should be linear in ε for small ε

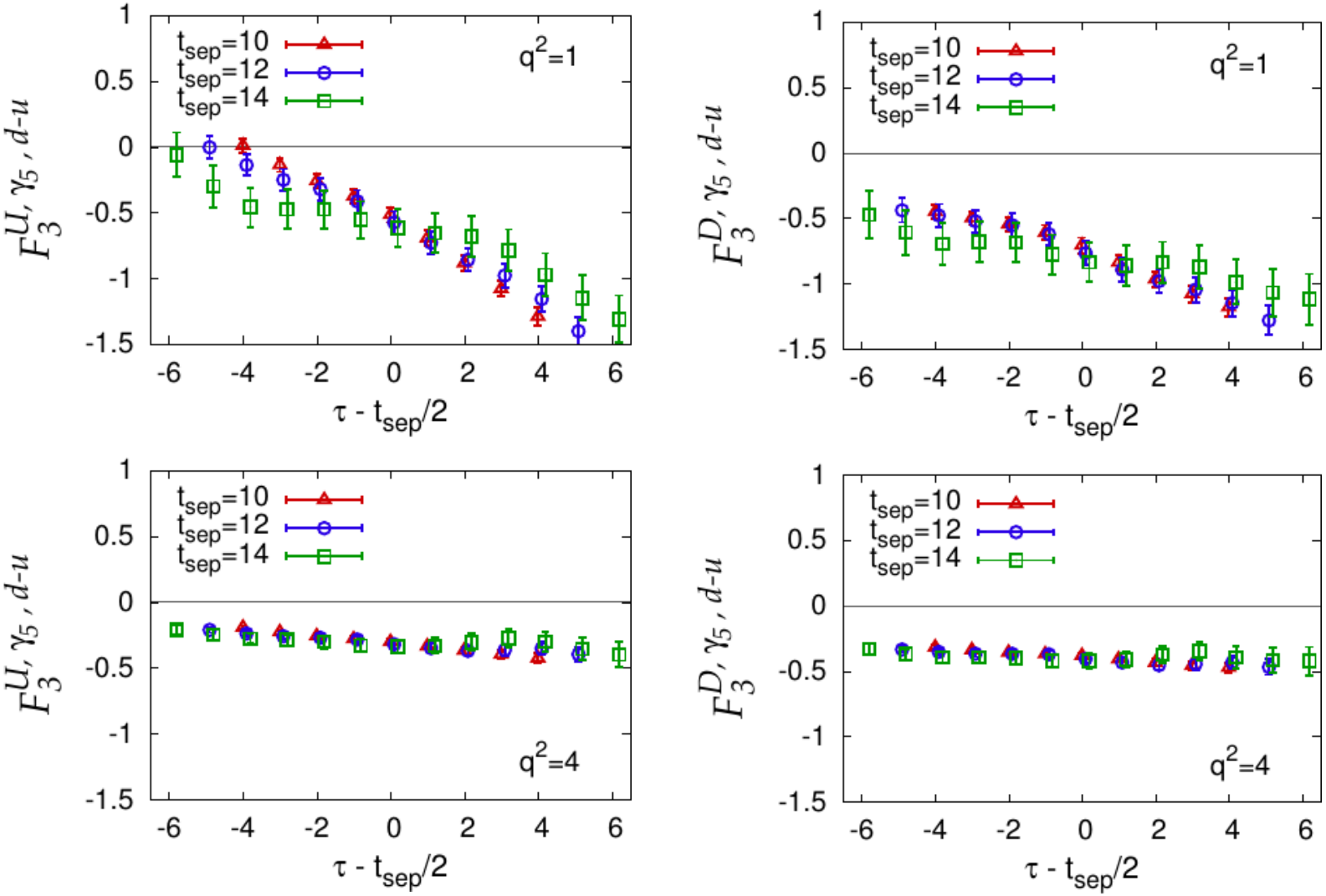




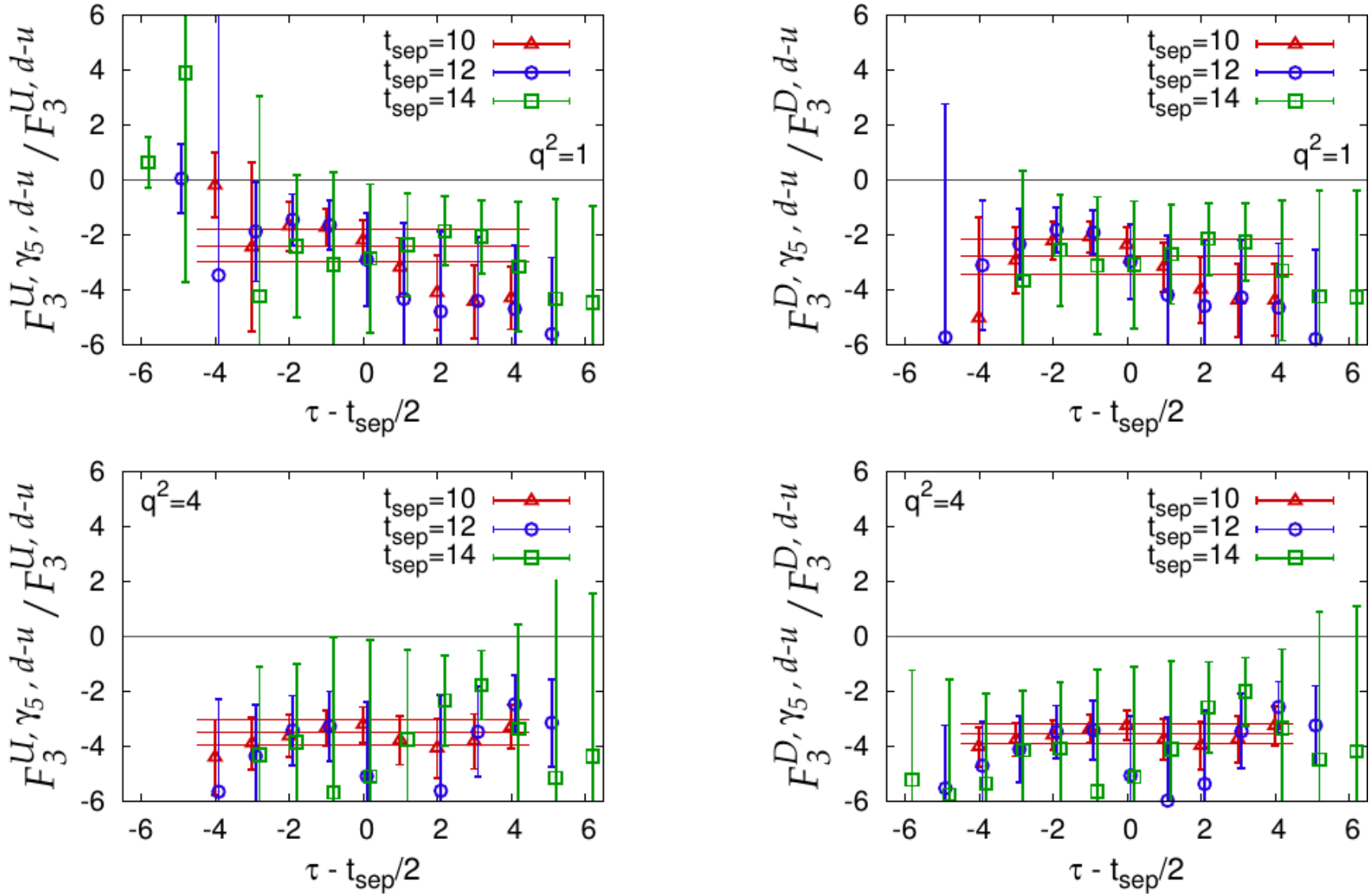
F3: Connected part of CEDM



F3: Connected part of γ_5



γ5 contribution is due to mixing with CEDM ➡ prop to it



Conclusions and Future

- Controlled excited state contamination to < 2%
- Renormalization Factors–Z: Parameterize and Control O(4) breaking to < 2%: g_A (3%), g_S (10%), g_T (3%)
- Higher Statistics: 9 ensembles; O(2000) configurations; O(100) measurements: g_A (1-2%), g_S (8%), g_T (2%)
- Improve the calculation of flavor-diagonal operators: qEDM– high precision *s,c* quark EDM g_T^s, g_T^c
- quark chromo EDM operator:
  - Signal in connected diagrams
  - Start calculations of disconnected diagram
  - Non-perturbation calculations of renormalization and mixing

Happy Birthday Martin