Calculation of nucleon electric dipole moments induced by quark chromo-electric dipole moments

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USQCD AHM, FNAL, May 1 2015

Motivation

- Fundamental Symmetry Exp <-> [QCD corrections] [Standard Mode & Beyond]

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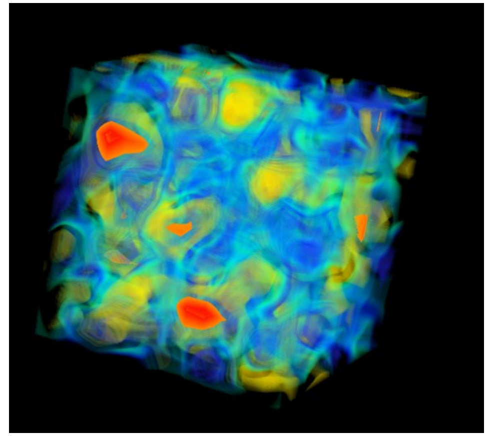

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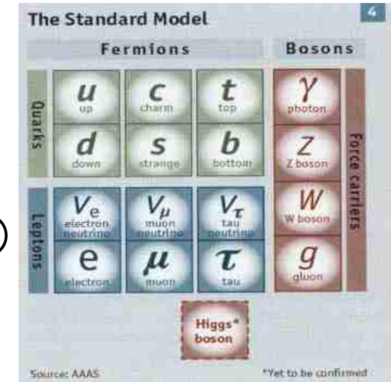


- Why is there more matter than antimatter in the present universe?

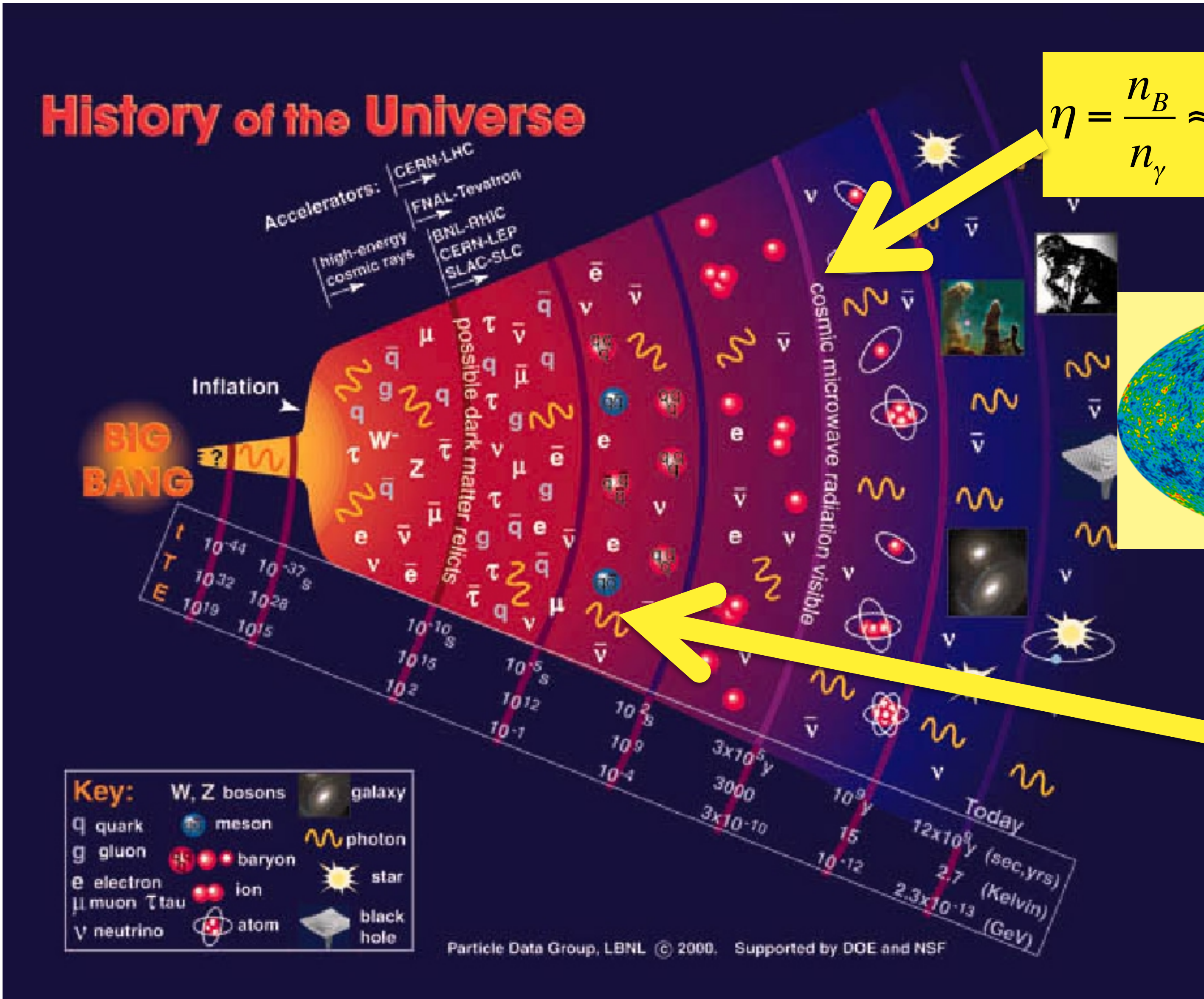
- USQCD 2013 White papers Fundamental Symmetries

"The main research thrusts during the next five years are: Electric Dipole Moments of the Neutron, Proton and Deuteron, Strong Interaction Contributions to the Muon Magnetic Moment,Nuclear Parity Violation, and Physics Beyond the standard model in Four-Fermi Operators. "

- P5 2014 Report Explore the Unknown Muon g-2, Baryon Num. V, Electric Dipole Moment

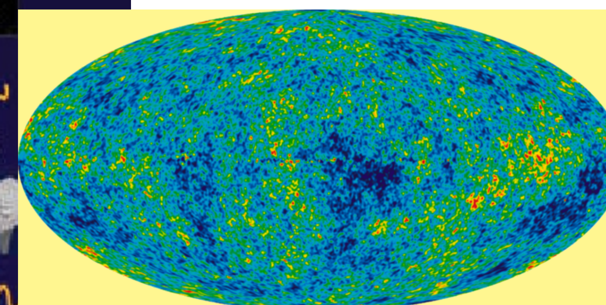
"Many extensions of the Standard Model, including Supersymmetry, have additional sources of CP non-conservation. Among the most powerful probes of new physics that does not conserve CP are the electric dipole moments (edm's) of the neutron, electron and proton. ... sensitive to new particle at the 10-100 TeV scale,... "

Matter dominant Universe



$$\eta = \frac{n_B}{n_\gamma} \approx (6.08 \pm 0.14) \times 10^{-10}$$

From CMB

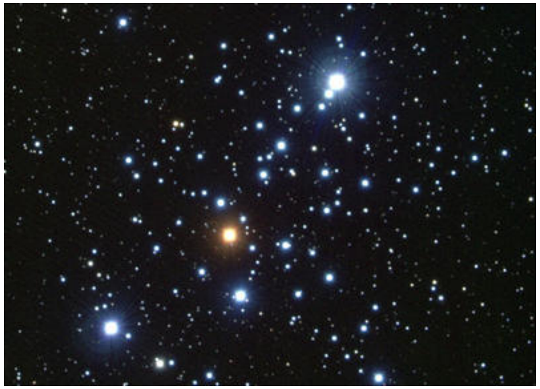


$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

SM, Without net baryon number

Sakharov's three conditions

- In 1967, Sakharov pointed out three concurrent conditions for a small non-zero η in early universe (T ~ O(10) TeV)



1. Baryon number (B) violation
   To produce net Baryon from initial B=0
2. Violation of C (charge conjugation symmetry) and **CP** (parity and C)

   <B> != 0 , B : C, CP odd
3. departure from thermal equilibrium
   <B> = 0 in equilibrium from CPT

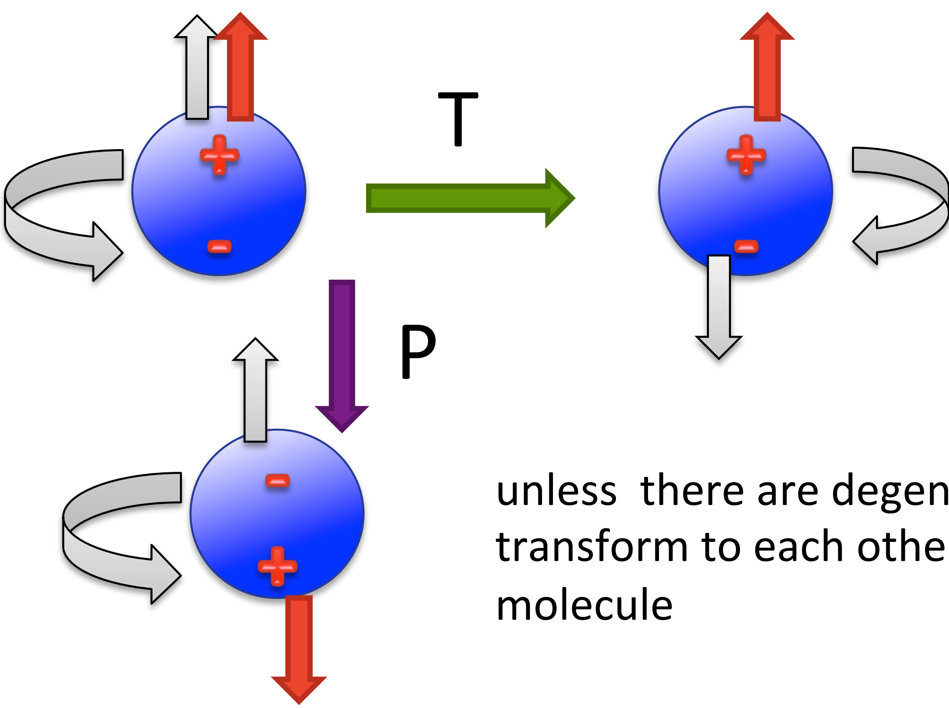
P & CP violation and Electric Dipole Moments (EDM)

- Electric Dipole Moment d

  energy shifts in an electric field E

$$\Delta H = \vec{d} \bullet \vec{E}$$

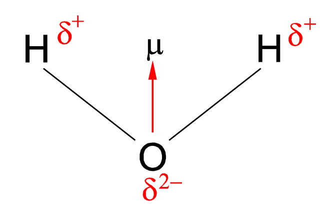
- A nonzero EDM is a signature of P and T (CP through CPT) violation



exp: $\Delta H \sim 10^{-6}$ Hz $\sim 10^{-21}$ eV
→ $|d| < \Delta H/E \sim 10^{-25}$ e cm

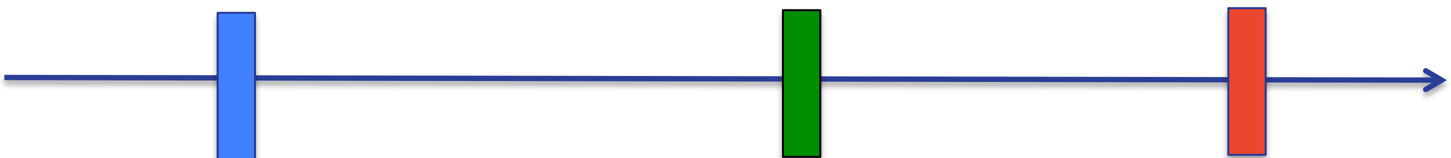
if theo: $d \sim 10^{-2} \times 1\ \mathrm{MeV} / \Lambda^2_{CP}$
→ Λ_{CP} >~ O(1) TeV

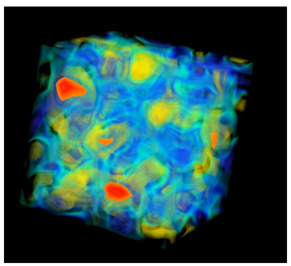
unless there are degenerate ground states transform to each other by Parity c.f. Water molecule



CP violation from BSM

- B

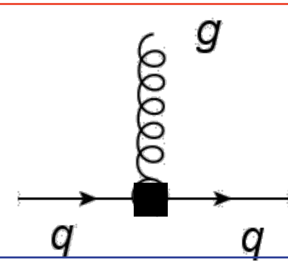




QCD Matrix Elements
dN, dP, gπNN, ...

EDM Experiments
Neutron, Proton, Deuteron,
Hg, electron, muon, ...

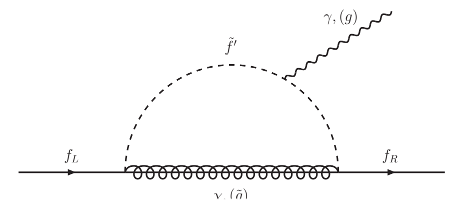
$$i\tilde{d}_q \bar{q}\sigma_{\mu\nu}\gamma_5 G_{\mu\nu} q$$

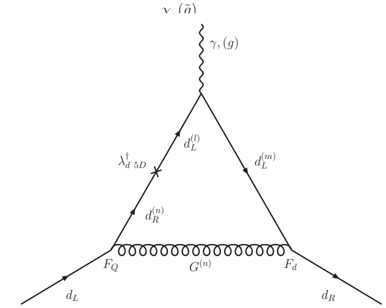


(d=6) CPV Effective Operators
Quark Chromo EDM,
Quark EDM, Weinberg, 4-fermi

$$i d_q \bar{q}\sigma_{\mu\nu}\gamma_5 F_{\mu\nu} q$$

$$d_W f^{abc} G^a G^b \tilde{G}^c$$





BSM CP Violations:
SUSY CKM, multi-Higgs
extra dimension, ...

CP violation from QCD

- QCD
  - θ term in the QCD Lagrangian:

$$\mathcal{L}_\theta = \bar{\theta}\frac{1}{64\pi^2}G\widetilde{G}, \quad \bar{\theta} = \theta + \arg\det M$$

renormalizable and CP-violation comes due to topological charge density.

  - EDM experiment provides very strong constraint on

    ⇒ θ and arg det M need to be unnaturally canceled !

    strong CP problem, unless massless quark(s)

$$|d_N^{\exp}| < 2.9 \times 10^{-26}\,\mathrm{e\cdot cm} \qquad \bar{\theta} < 10^{-9}$$

  - up quark mass less ?
  - Axion ?
  - contribution from CKM is very small < 1e-30 e cm

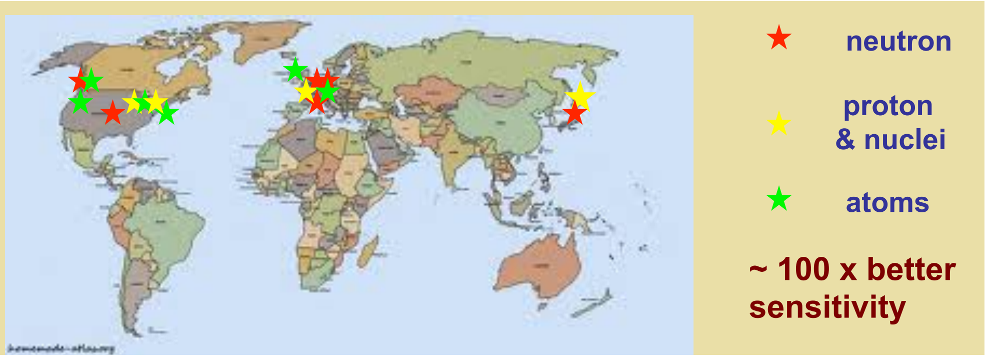
EDM Experiments

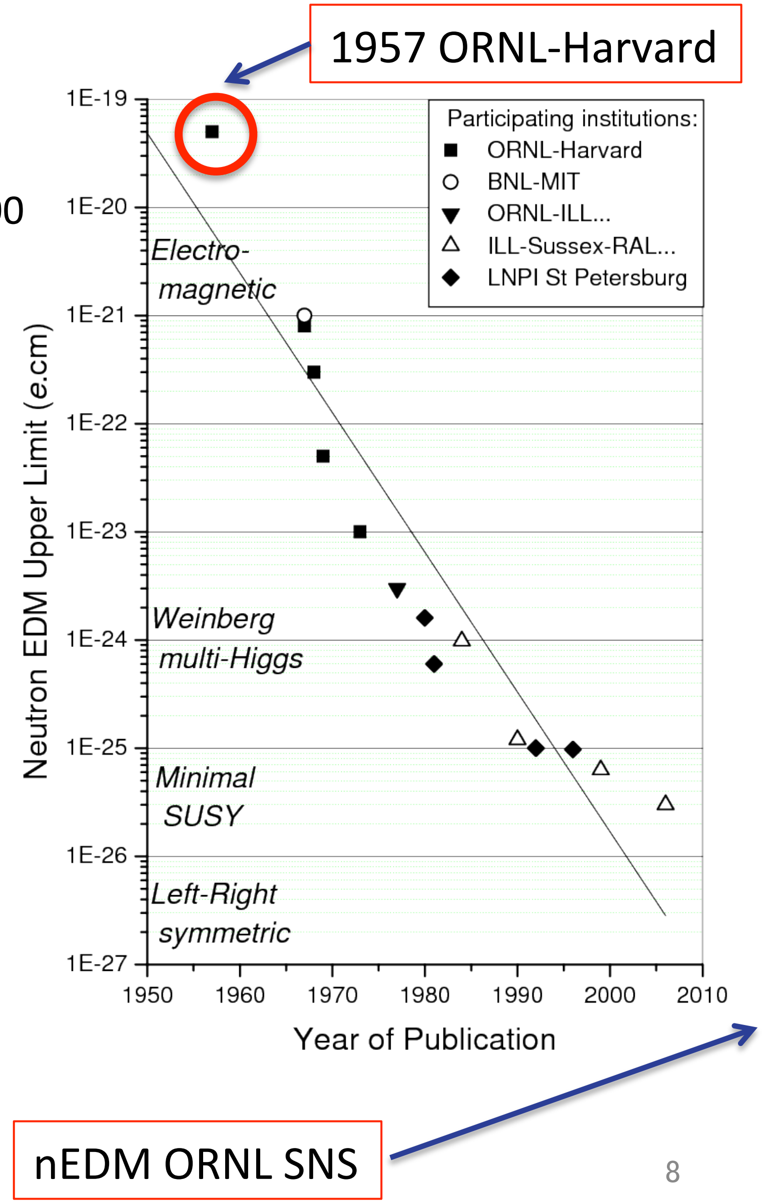
- The present and future experiments are aiming to check/exclude of MSSM

pEDM @ BNL
nEDM @ ORNL, PSI, ILL, J-PARC, TRIUMF ,FNAL, FRM2, …
charged hadrons @ COSY

Harris, 0709.3100

⇒ a sensitivity of $\underline{10^{-29}\ e\cdot cm}$!





- Current theoretical estimations are based on quark model, sum rules, …

non-perturbative computations of EDM $d_n(\theta, d_q, d_q^c, \ldots)$ are necessary

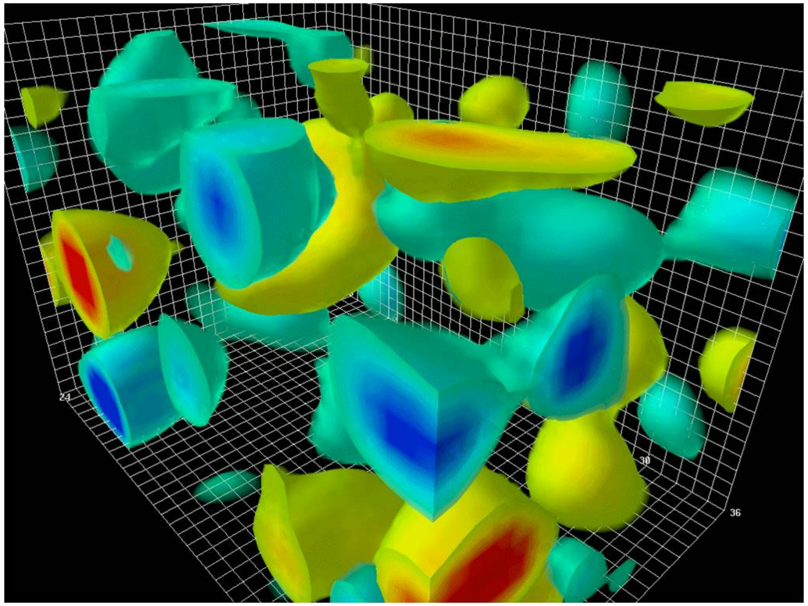
EDM from lattice QCD

- Three ingredients
  - QCD vacuum samples
  - source of CP violation
    - *Reweighting from CP symmetric vacuum*

      CPV source : Θ and/ or d_q
    - *Dynamical simulation*

      imaginary Θ, d_q

      [2007 Izubuchi et al, 2008, 2015 QCDSF]
  - Polarized Nucleons



[D. Leinweber]

- Two methods
  - Measure a spin splitting of energy
  - Form Factor F_3

CP violation on lattice : Reweighting

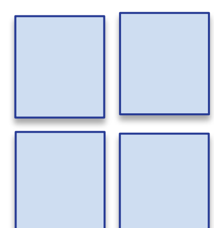
- Sources of CP violation (Θ , dq in our case)

$$S_{dq} = \int d^4x \sum_q i\tilde{d}_q \bar{q} \sigma_{\mu\nu} \gamma_5 G_{\mu\nu} q$$

$$S_\theta = i\frac{\theta}{32\pi^2} \int d^4x \ \mathrm{tr}[\epsilon_{\mu\nu\rho\sigma} G^{\rho\sigma} G^{\mu\nu}]$$
$$= i\theta \ Q_{\mathrm{top}}$$

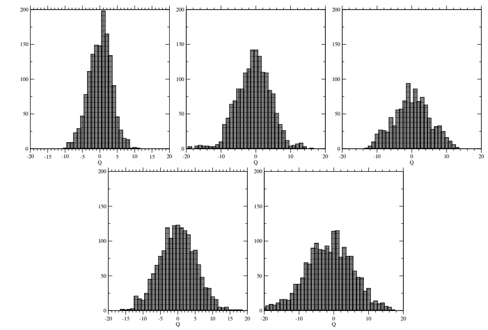
- Topological charge is measured either by gluonic observable GG^* or by counting zero mode of chiral fermions

$Q \rightarrow \Sigma \ G_{12} G_{34}, \quad G_{\mu\nu} = \mathrm{Im}$



- Θ =0, dq=0 lattice QCD ensemble is generated, then each sample of QCD vacuum are reweighted

Θ & dq reweighting

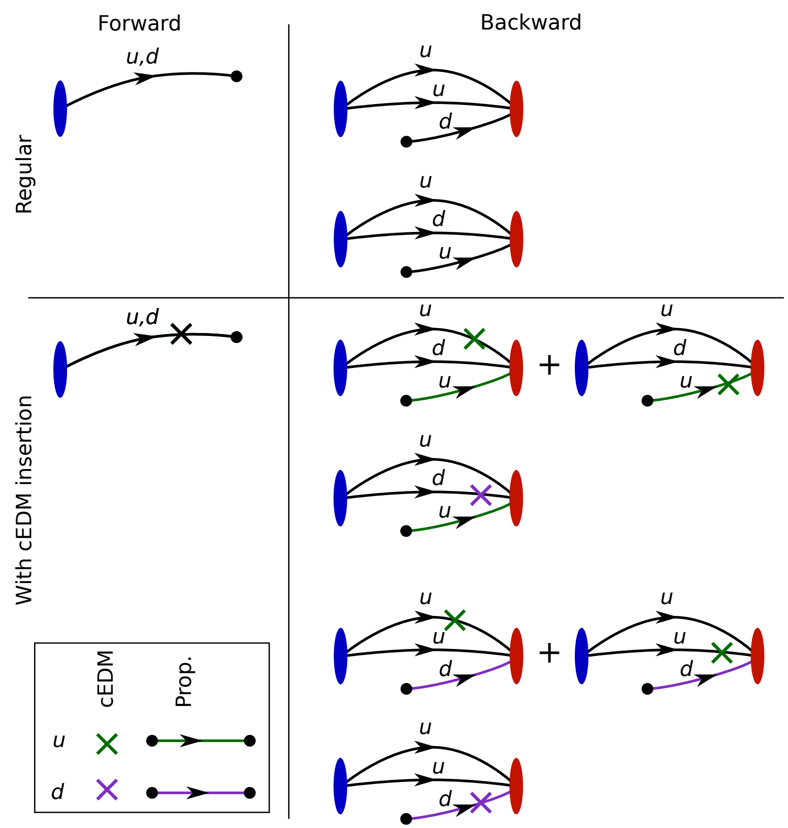


- Only LO in Θ and dq
- Θ reweighting factor via topological charge Q

$$\langle \mathcal{O} \rangle_{\theta} = \langle \mathcal{O} e^{i\theta Q} \rangle_{\theta=0}$$

- dq contribution needs 4pt function via sequential source and disconnected quark loop

$$\langle N_\beta(T) (\int d^4x \bar{q} G\sigma\gamma_5 q) [\bar{q}\gamma_\mu q]_\tau \bar{N}_\alpha(0) \rangle$$



- Signal of dq should be good due to the direct valence insertion in contrast to Θ's case
- Θ calculation and disconnected quark loop could be arranged as a by product of other connected calculations

Chiral symmetry & EDM

$$q(x) \to e^{i\gamma_5\theta} q(x)$$
$$\bar{q}(x) \to \bar{q}(x) e^{-i\gamma_5\theta}$$

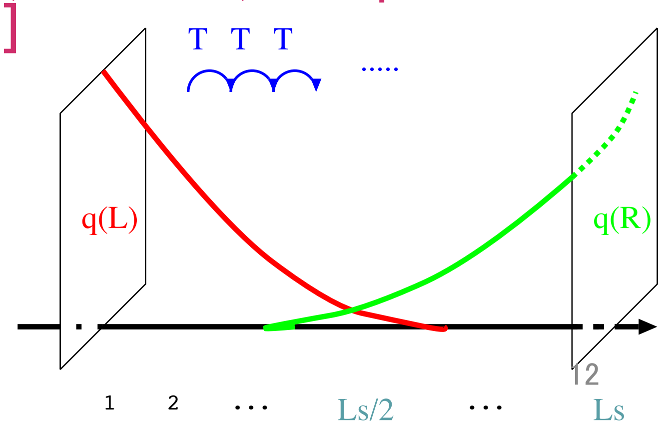
- Chiral symmetry is broken
  by lattice systematic error
  for Wilson-type quarks, which has "wrong" Pauli term by O(a)

$$\mathcal{L}_{\mathrm{Wilson}} = \mathcal{L}_{\mathrm{QCD}} + ca\bar{q}\sigma_{\mu\nu} \cdot F_{\mu\nu} q$$

- CP violation from θ or other BSM operators introduce extra artificial CP violation in simulation.

- In fact, chiral rotation of valence quark is not observable in continuum theory, and the EDM signal measured in Wilson quark due to valence quark's θ is unphysical, which should be carefully removed by taking continuum limit a → 0 [S. Aoki-Gockschu, Manohar, Sharpe et al. Phys.Rev.Lett. 65 (1990) 1092-1095 (1990)]

→ Our choice : chiral lattice quark called <u>domain-wall fermions (DWF)</u>

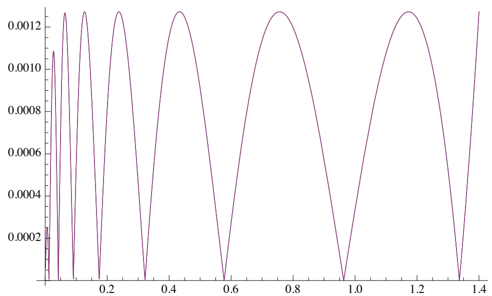


AMA+MADWF(fastPV)+zMobius accelerations

- We utilize complexified 5d hopping term of Mobius action [Brower, Neff, Orginos], zMobius, for a better approximation of the sign function.

$$\epsilon_L(h_M) = \frac{\prod_s^L(1+\omega_s^{-1}h_M) - \prod_s^L(1-\omega_s^{-1}h_M)}{\prod_s^L(1+\omega_s^{-1}h_M) + \prod_s^L(1-\omega_s^{-1}h_M)}, \qquad \omega_s^{-1} = b + c \in \mathbb{C}$$

- 1/a~2 GeV, Ls=48 Shamir ~ Ls=24 Mobius (b=1.5, c=0.5) ~ Ls=10 zMobius (b_s, c_s complex varying) ~5 times saving for cost AND memory



Ls	|eps(48cube) – eps(zMobius)|
6	0.0124
8	0.00127
10	0.000110
12	8.05e-6

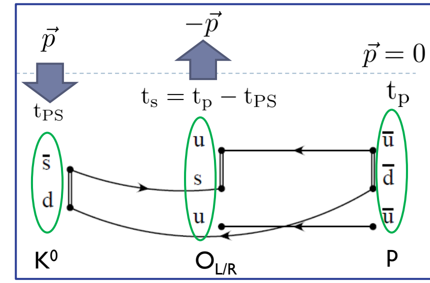
- The even/odd preconditioning is optimized (sym2 precondition) to suppress the growth of condition number due to order of magnitudes hierarchy of b_s, c_s [also Neff found this]

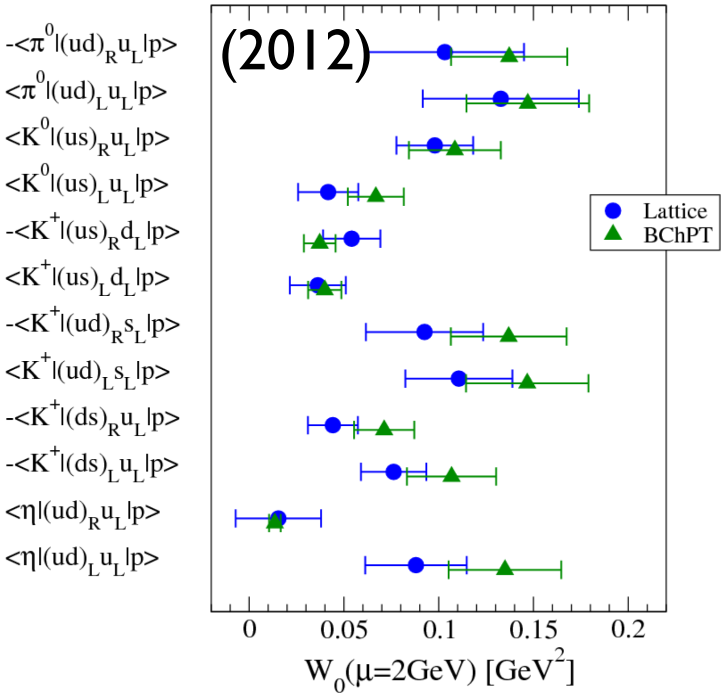
$$\texttt{sym2}: \quad 1 - \kappa_b M_4 M_5^{-1} \kappa_b M_4 M_5^{-1}$$

- Fast Pauli Villars (mf=1) solve, needed for the exact solve of AMA via MADWF (Yin, Mawhinney) is speed up by a factor of 4 or more by Fourier acceleration in 5D [Edward, Heller]
- All in all, sloppy solve compared to the traditional CG is 160 times faster on the physical point 48 cube case. And ~100 and 200 times for the 32 cube, Mpi=170 MeV, 140, in this proposal (1,200 eigenV for 32cube) .

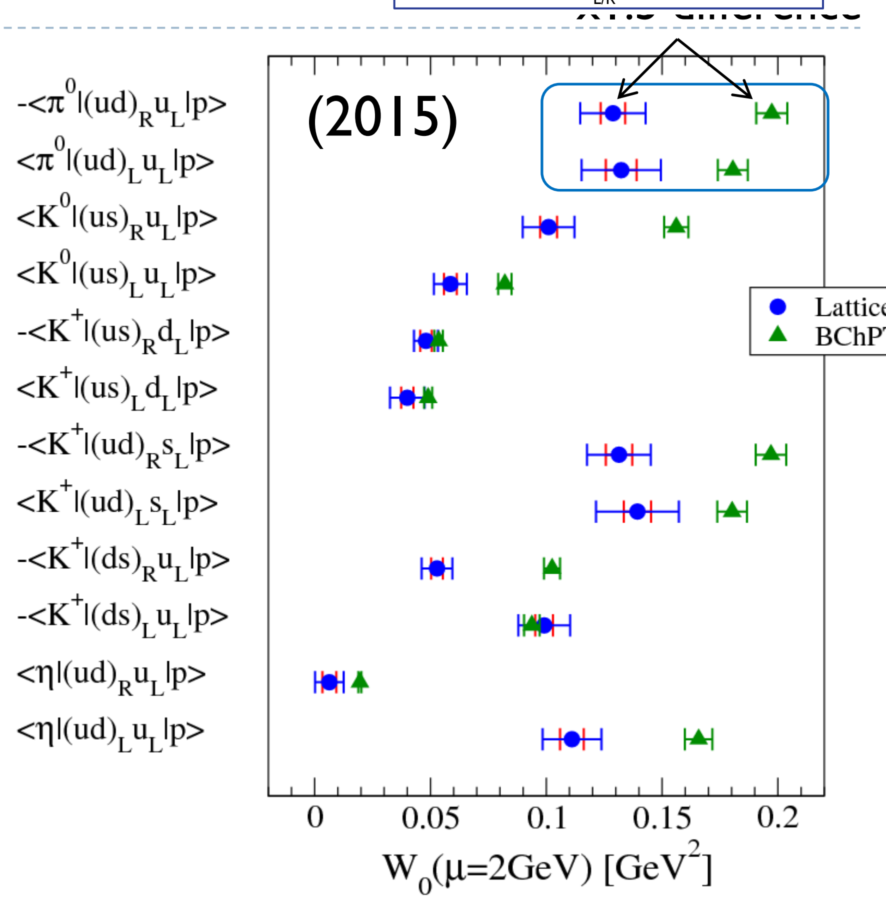
$$\underbrace{\frac{20,000}{600}}_{\text{MADWF+zMobius+deflation}} \times \underbrace{\frac{600*32/10}{300}}_{\text{AMA+zMobius}} = 33.3 \times 6.4 = \underline{210 \text{ times faster}}$$

proton decay example





Update



Summary

- To help open a new page on fundamental physics via C- and P- symmetry violation search, we propose neutron and proton EDM induced by BSM quark chromo EDM, and QCD Θ, terms.
- Nearly or On physical MDWF quark mass
  M(pi) ~ 170 MeV or 135 MeV (if available)
  Volume 32^3 ~ $(5\ \mathrm{fm})^3$
- 4 pt calculation
- 160 config, 1+32 AMA measurements (14+448 propagators) , signal is expected to be good.
- 2.2K + 72K propagators via AMA+zMobius+MADWF(fastPV) => 22.39 M Jps core hours
- Renormalization : perturbative analysis exists
  [Bhattacharya, Cirigliano, Gupta, Mereghetti, Yoon, arXiv: 1502.07325]
  Possibly Non-Perturbative Renormalizations via RI-SMOM or Gradient Flow. Chiral symmetry prevent unphysical mixings.

- 1) What precision is needed for the chromo-EDM induced matrix elements given the current (and projected) experimental uncertainties? How immediate are the experimental needs?

- From a recent review by Engel, Ramsey-Musolf, and Van Kolck (http://arxiv.org/pdf/1303.2371.pdf, Table 6) the range of allowed values of the hadronic matrix elements contributing to the neutron edm through the quark chromo-edm is an order of magnitude or more. These are model and sum-rule estimates. In short, very little is known and even rough (but reliable) lattice calculations will be enormously helpful. Robust, accurate, theoretical computations are crucial to support experimental proposals to measure the neutron and proton EDMS.

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Param	Coeff	Best Value[a]	Range	Coeff	Best Value[b,c]	Range[b,c]
$\bar{\theta}$	α_n	0.002	(0.0005-0.004)	$\lambda_{(0)}$	0.02	(0.005-0.04)
	α_p			$\lambda_{(1)}$	2×10^{-4}	$(0.5 - 4) \times 10^{-4}$
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1 - 10) \times 10^{-4}$	$\gamma_{(0)}^{+G}$	-0.01	(-0.03) – 0.03
	β_n^{dG}	8×10^{-4}	$(2 - 18) \times 10^{-4}$	$\gamma_{(1)}^{-G}$	-0.02	(-0.07) – (-0.01)
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09 - 0.9)$	$\tilde{\omega}_{(0)}$	8.8	(-25) – 25
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2 - 1.8)$	$\tilde{\omega}_{(1)}$	17.7	9 – 62
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$	$\tilde{\eta}_{(0)}$	-2×10^{-7}	$(-6 - 6) \times 10^{-7}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4 - 40) \times 10^{-9}$	$\tilde{\eta}_{(1)}$	-4×10^{-7}	$-(2 - 14) \times 10^{-7}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2 - 0.6) \times 10^{-3}$	$\gamma_{(0)}^{+\gamma}$	–	–
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8 - 2.4) \times 10^{-3}$	$\gamma_{(1)}^{-\gamma}$	–	–
d_q	ρ_n^u	-0.35	$(-0.17) - 0.52$	$\omega_{(0)}$	–	–
	ρ_n^d	1.4	0.7-2.1	$\omega_{(1)}$	–	–
δ_q	ζ_n^u	8.2×10^{-9}	$(4 - 12) \times 10^{-9}$	$\eta_{(0)}$	–	–
	ζ_n^d	-33×10^{-9}	$-(16 - 50) \times 10^{-9}$	$\eta_{(1)}$	–	–
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$	$\gamma_{(i)}^{\tilde{G}}$	2×10^{-6}	$(1 - 10) \times 10^{-6}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$	$\gamma_{(1)}^{\varphi ud}$	1×10^{-6}	$(5 - 150) \times 10^{-7}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$	$\gamma_{(i)}^{quqd}$	2×10^{-6}	$(1 - 10) \times 10^{-6}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11-14.5			
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6-1.2			

Table 6: Best values and reasonable ranges for hadronic matrix elements of CPV operators. First column indicates the coefficient of the operator in the CPV Lagrangian, while second column indicates the hadronic matrix element (sensitivity coefficient) governing its manifestation to the neutron EDM. Third and fourth columns give the best values and reasonable ranges for these hadronic coefficients. Firth to seventh columns give corresponding result for contributions to TVPV πNN couplings. [a] Units are e fm for all but the $\tilde{\rho}_n^q$ and ρ_n^q. [b] We do not list entries for $(\gamma_{(i)}^{\pm\gamma}, \omega_{(i)}, \eta_{(i)})$ as they are suppressed by α/π with respect to $(\tilde{\gamma}_{(i)}^{\pm\gamma}, \tilde{\omega}_{(i)}, \tilde{\eta}_{(i)})$. [c] The $\tilde{\omega}_{(0,1)}$ are in units of fm^{-1}.

- 2) Lattice nucleon matrix elements often have large contributions from excited states. How is your calculation dealing with excited-state contamination?

- We will calculate with multiple source-sink separations to detect excited state contamination. For this first calculation, we will focus on statistical errors. Systematic errors will be addressed fully once statistical control has been demonstrated.

- 3) Lattice nucleon matrix elements often have large finite-volume errors. What are your plans for studying finite-volume effects for these observables?

- FV effects will be addressed in future studies once control of statistical errors has been demonstrated. However, we recall that the DSDR+IDWF ensemble that is to be used has relatively large values of mpi L \approx 4 and L\approx 4.6 fm for precisely this reason.

- 4) Considering this is an exploratory study, and given the potential systematic issues, why use one of the most expensive ensembles with 170 MeV pions, rather than multiple less expensive ensembles to study systematics?

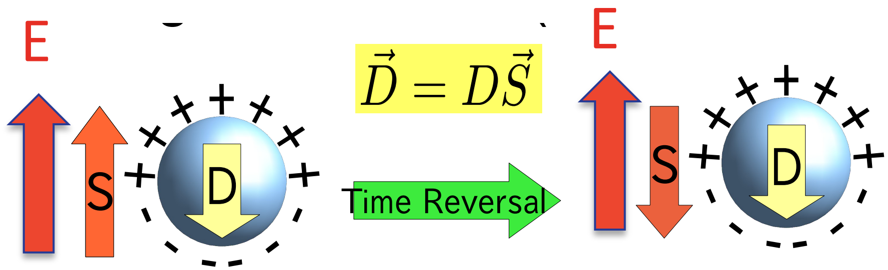
- As already mentioned, we expect statistical errors to dominate in these first calculations. With the development of AMA, computing with heavier quarks no longer represents a significant reduction in cost. We prefer to use lighter quarks, with masses closer to the physical point, for more realistic calculations and results (which already partially addresses significant systematics). Further, the added cost of the necessarily larger volume, is offset by the gain in statistics from volume averaging.

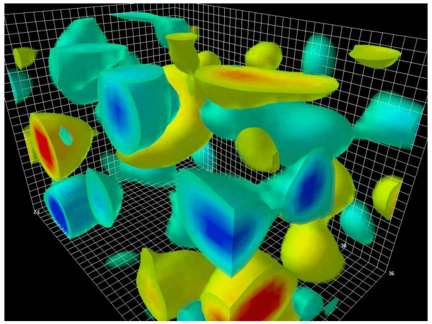
EDM Computations on Lattice

- Measure energies with external Electric field

$$\frac{\langle N_\uparrow(t)\bar{N}_\uparrow(t_0)\rangle}{\langle N_\downarrow(t)\bar{N}_\downarrow(t_0)\rangle} \to Ce^{\Delta M t}$$

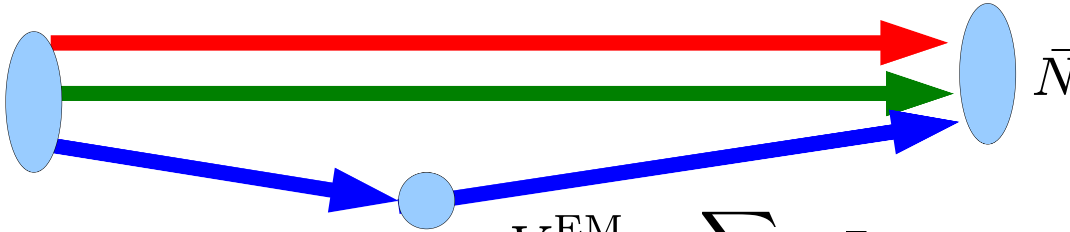
$$\begin{aligned}\Delta M &= M_N(E,\uparrow) - M_N(E,\downarrow)\\ &= -2D_N(\theta) S\cdot E\end{aligned}$$





- Form factors

$$\langle N(p')|V_\mu^{\mathrm{EM}}(q)|N(p)\rangle = F_1(q^2)\gamma_\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_N} + F_3(q^2)\frac{\sigma^{\mu\nu}q^\nu\gamma^5}{2m_N}$$

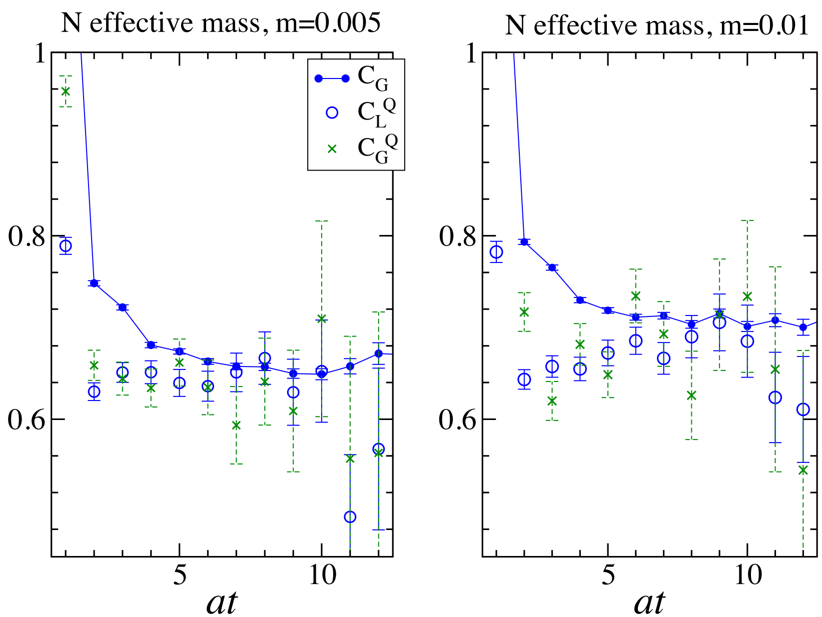


$$V_\mu^{\mathrm{EM}} = \sum_q e_q \bar{q}\gamma_\mu q$$

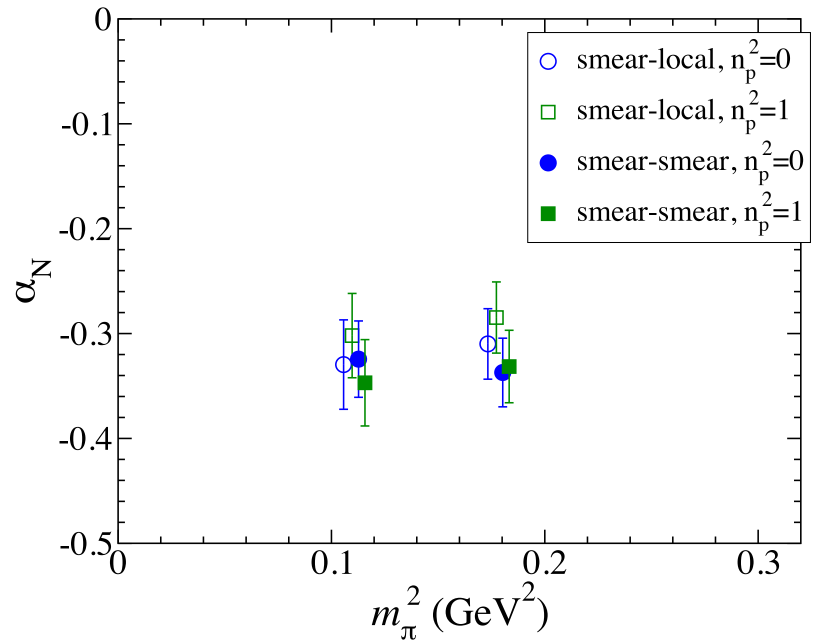
$$d_N = \lim_{Q^2\to 0} F_3(Q^2)/2m_N$$

CP even and odd 2point functions

effective nucleon mass



mixing coefficient



- need to take into account CP even/odd mixing α for Nucleon spinor, 2pt functions
- CP odd/even has a common mass

(Pospelov, Ritz 1998, S. Aoki *et al.* 2005)

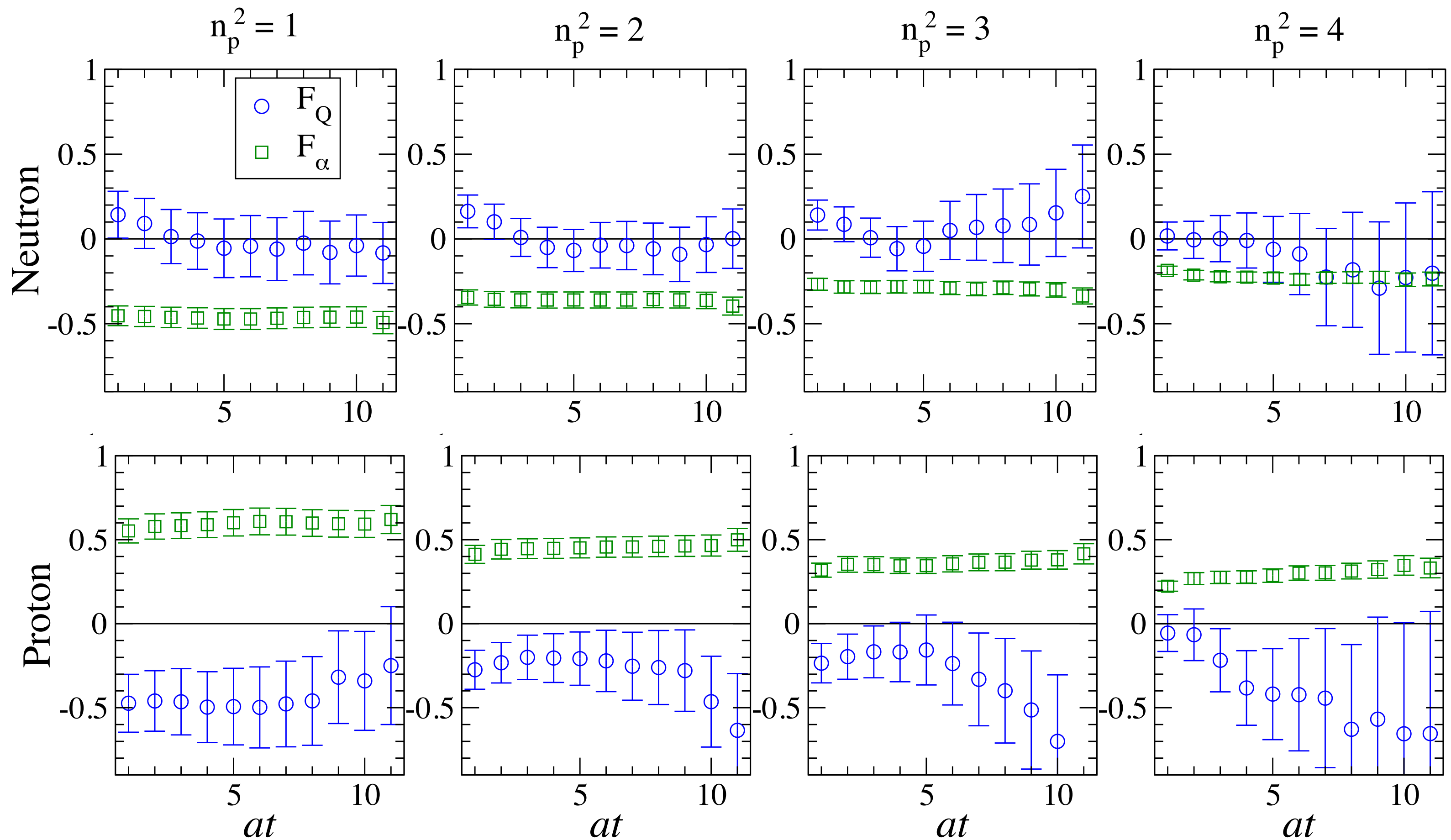
$$\sum_{s,s'} u_{s',\theta}(\vec{p})\bar{u}_{s,\theta}(\vec{p}) = E(\vec{p})\gamma_t - i\vec{\gamma}\cdot\vec{p} + me^{2i\alpha\gamma_5},$$

$$\approx E(\vec{p})\gamma_t - i\vec{\gamma}\cdot\vec{p} + m(1+2i\alpha\gamma_5)$$

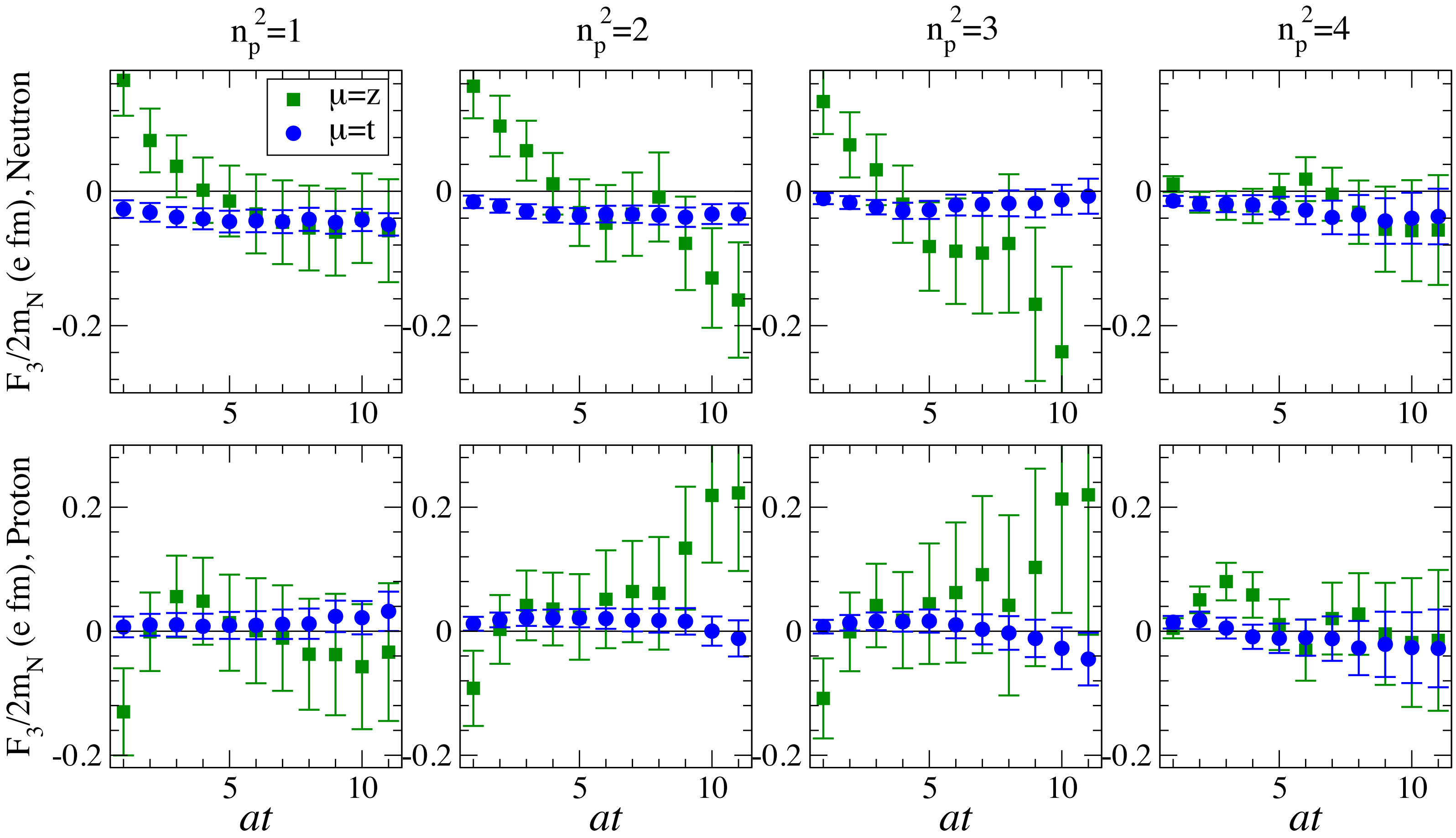
where $u_\theta = \exp i\alpha\gamma_5 u$.

F3 unsubtracted @ Mpi=300 MeV

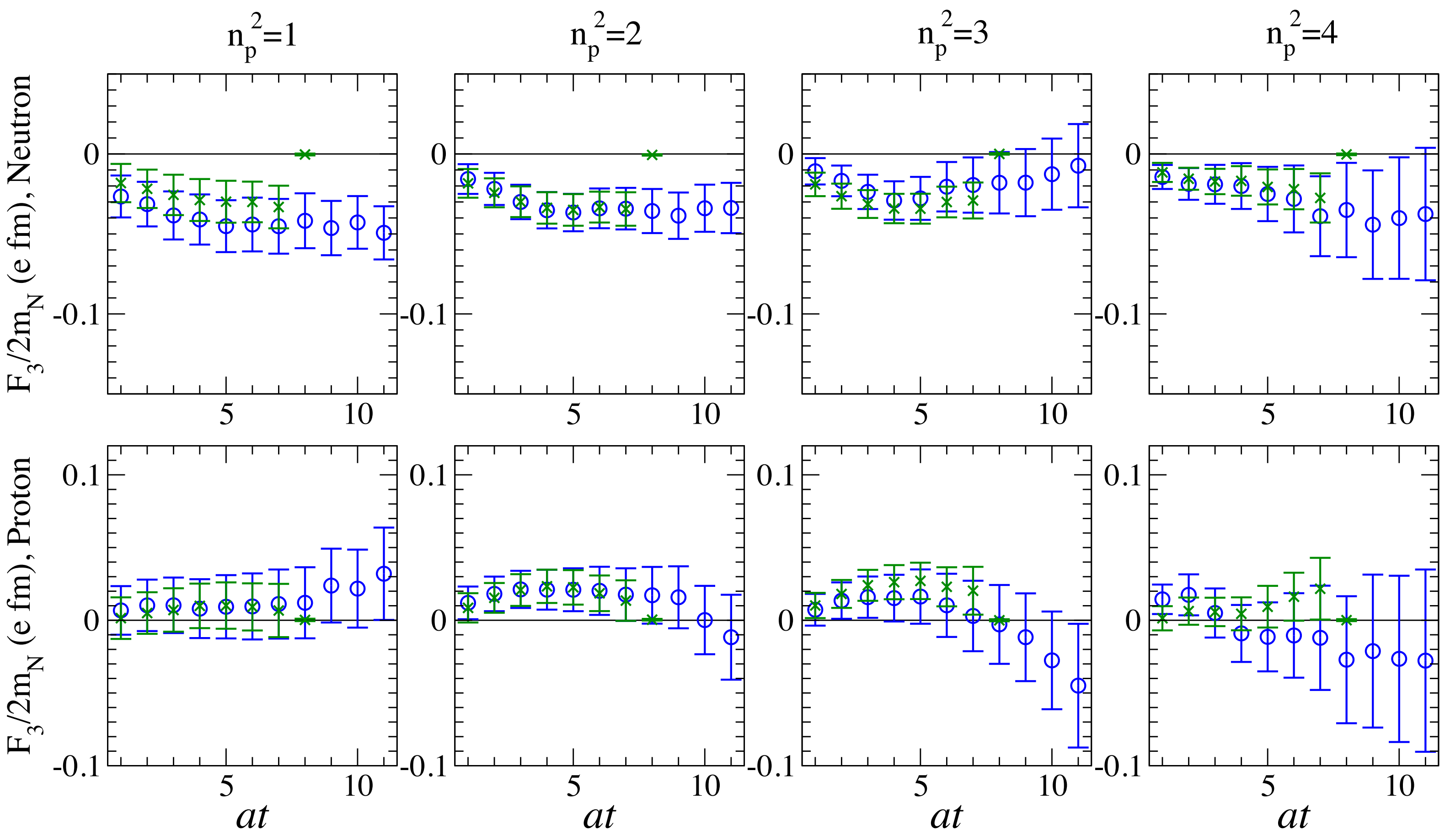
F3 = FQ + Fα
FQ : CP-odd 3pt function contribution
Fα : α x CP-even 3pt function (F1 and F2)



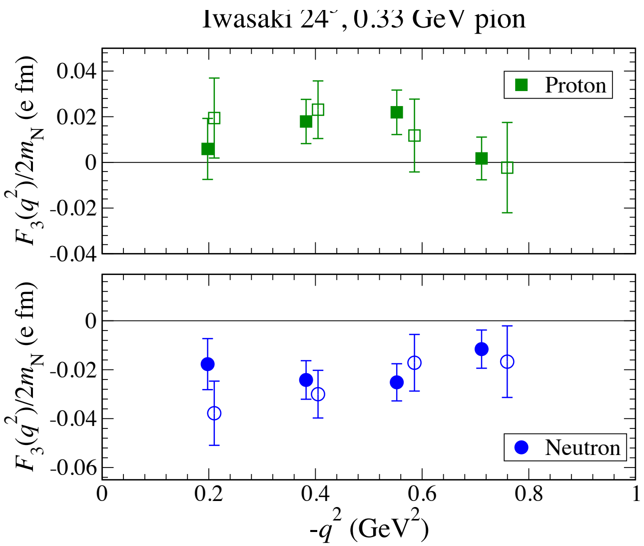
F3 subtracted @ Mpi=300 MeV

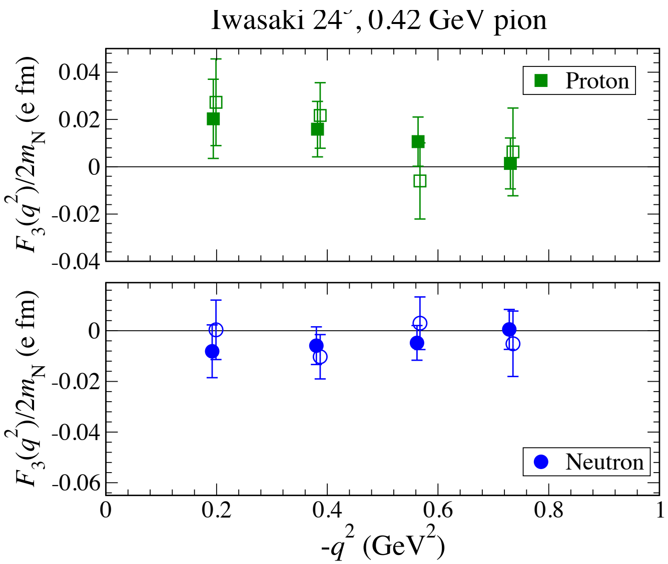


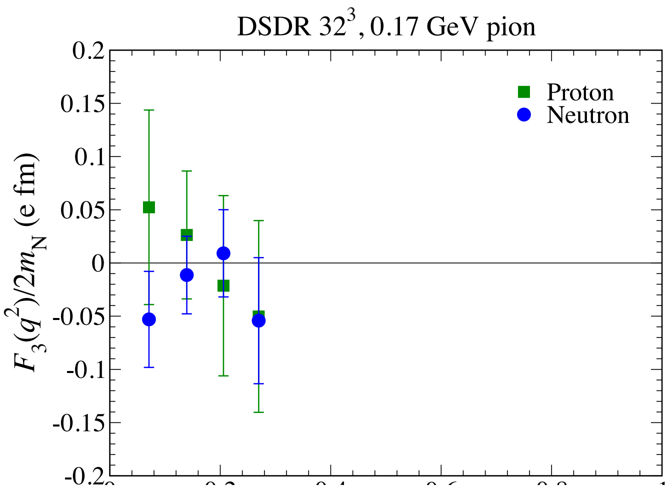
F3 form factor, excited state effect



F3 form factor, q2 dependence



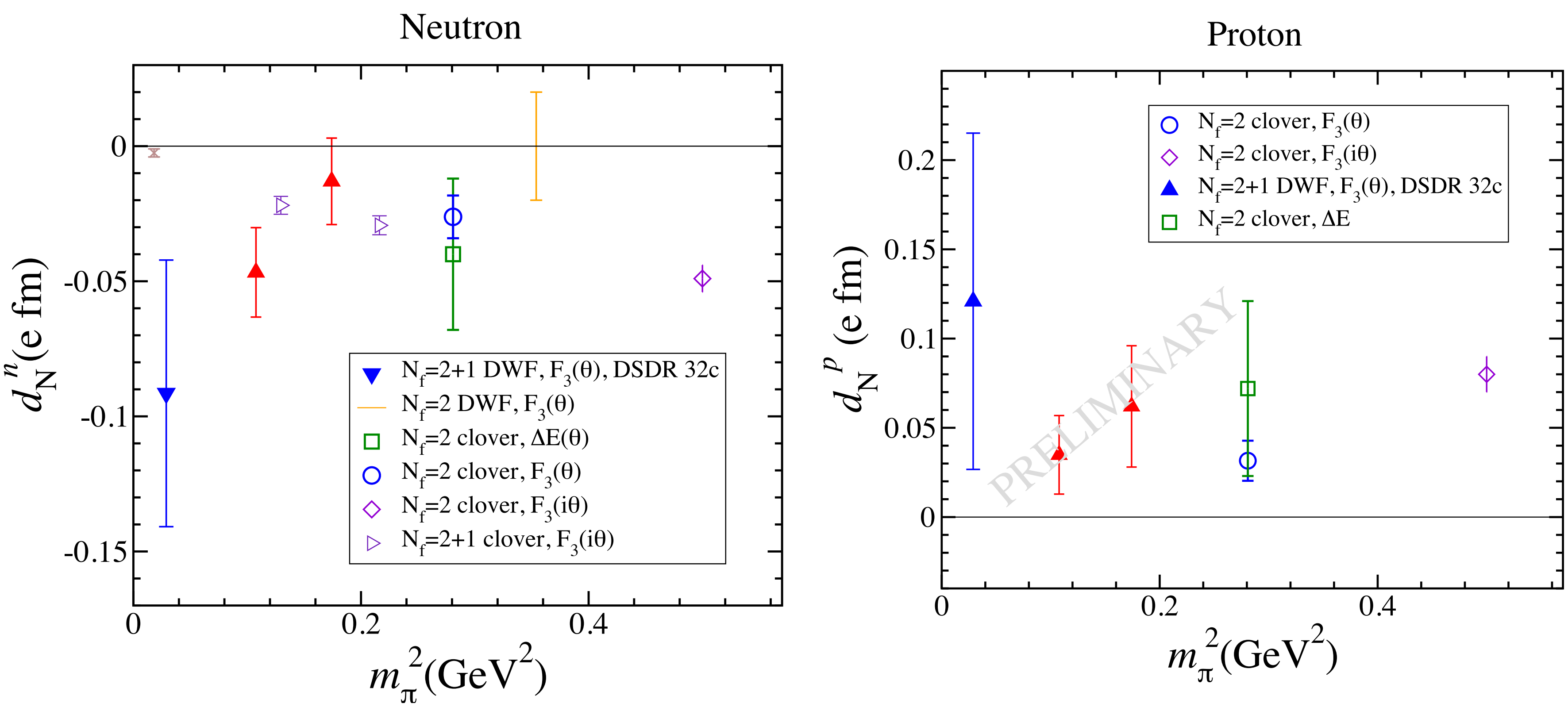




$$F_3(q^2)/2m_N = d_N + S'q^2 + \mathcal{O}(q^4)$$

Nculeon EDM

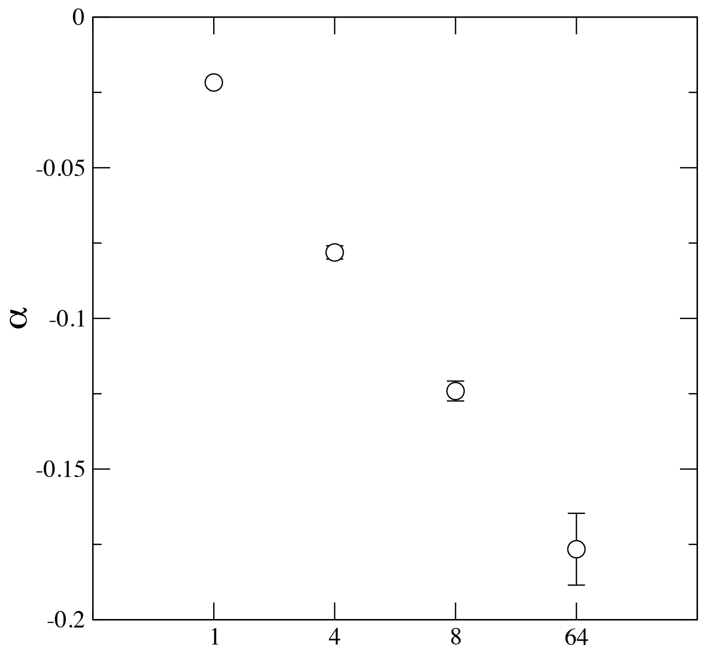
- dN should vanish in chiral limit → increase statistics

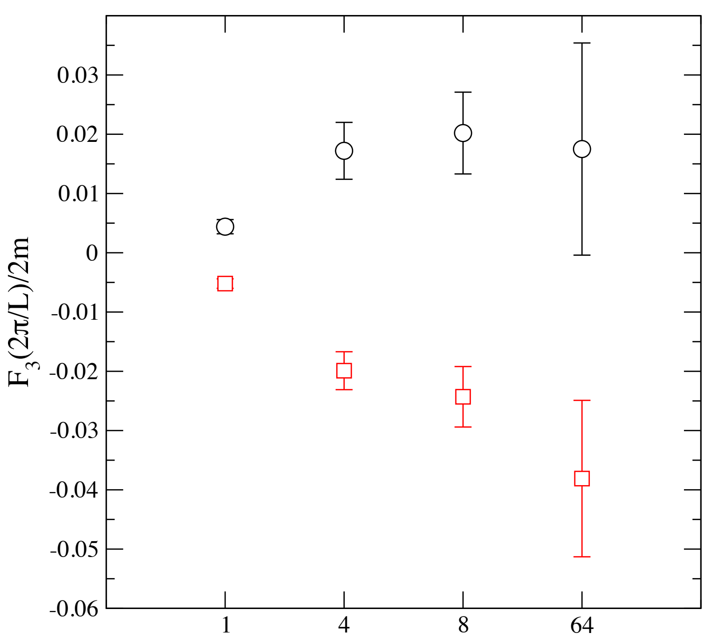


[purple symbols: clover fermion with dynamical imaginary theta, arXiv:1502.02295]

EDM local correlation

- Try on 24^3, $m_f = 0.005$ ensemble
- already summed over spatial location of operator (FT)
- Can sum up $Q(t)$ on time slices (1, 4, 8, 64)
- Correlate nucleon 2, 3 pt functions with $Q(t)$





Lattice literatures on EDM

- Spectrum method
  1. S. Aoki and A. Gocksch, Phys. Rev. Lett. 63, 1125 (1989).
  2. S. Aoki, A. Gocksch, A. V. Manohar, S. R. Sharpe, Phys. Rev. Lett. 65, 1092 (1990), in which they discussed about the possible lattice artifact in ref.1 results
  3. E. Shintani, et al., for CP-PACS collaboration, Phys. Rev. D75, 034507 (2007)
  4. E. Shintani, S. Aoki, Y. Kuramashi, Phys. Rev. D78, 014503 (2008)
- Form factor
  1. E. Shintani, et al., for CP-PACS collaboration, Phys. Rev. D72, 014504 (2005).
  2. Berruto, et al. for RBC collaboration, Phys. Rev. D73, 05409 (2006).
  3. E. Shintani et al., Lattice 2008.
- Imaginary θ
  1. T. Izubuchi, Lattice 2007.
  2. Horsley et al., arXiv:0808.1428 [hep-lat]

External Electric field method

[E.Shintani et al. (06, 07)]

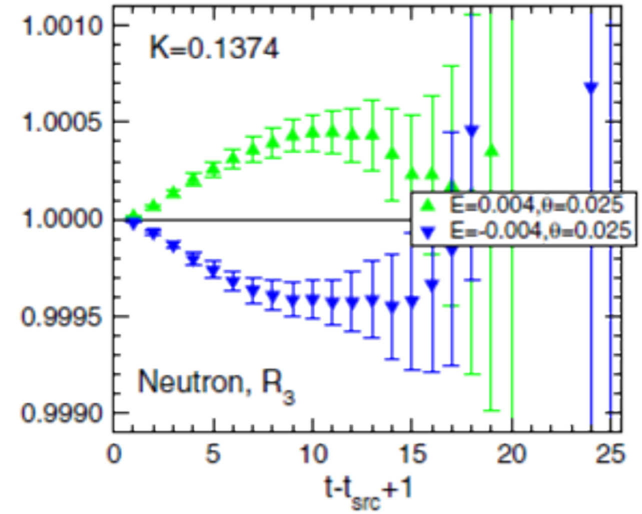
- Ratio of spin up and down

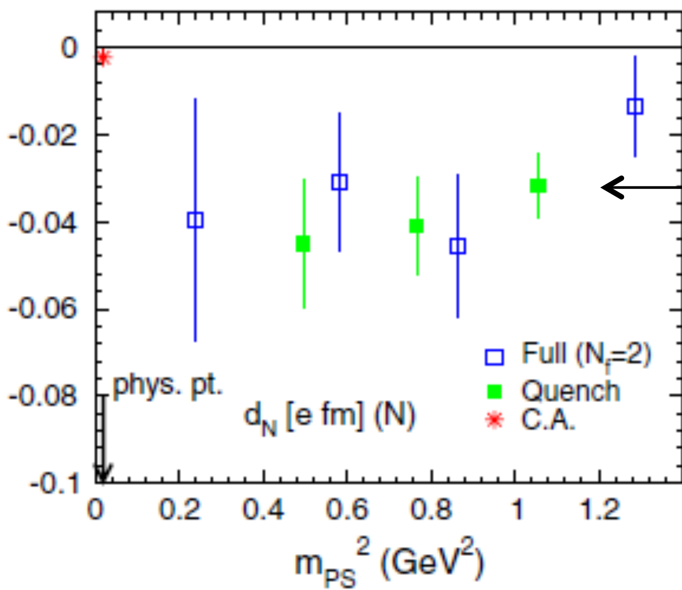
$$R_3 = \frac{\langle N(t)\bar{N}(0)\rangle^{\rm up}_{\theta,E}}{\langle N(t)\bar{N}(0)\rangle^{\rm down}_{\theta,E}} \simeq 1 + d_N E\theta t$$

Linear response, gradient is a signal of EDM.

- Reweighting works well for small real θ
- Temporal periodicity is broken by electric field.

  ⇒ additional systematic effects





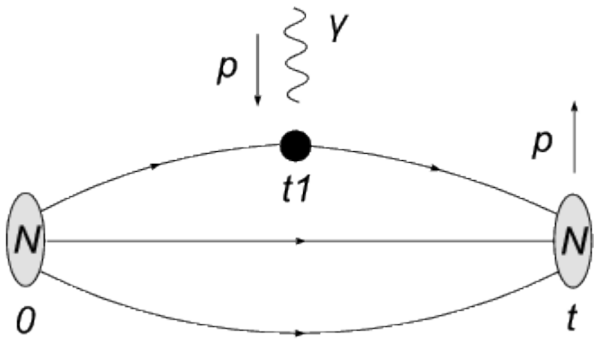
Full QCD with clover fermion:

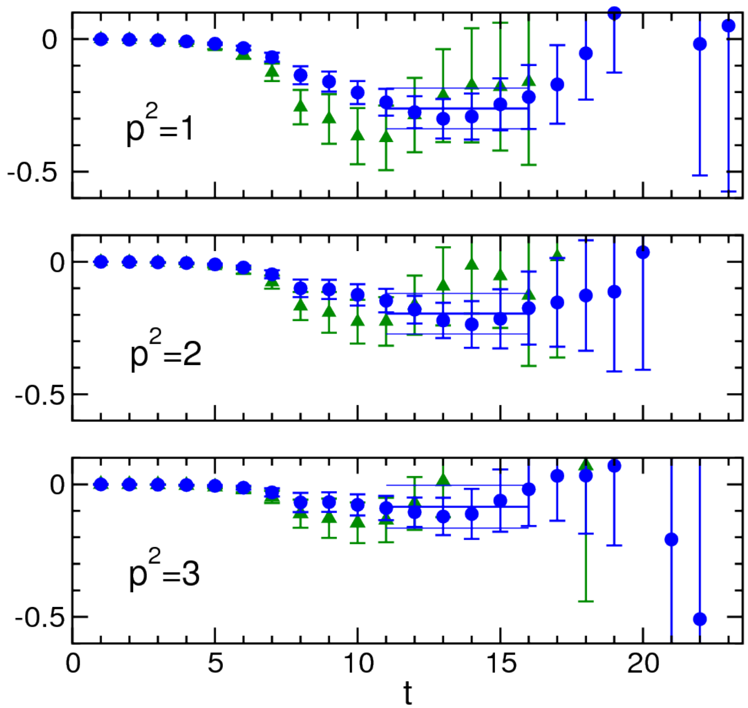
- There seems to be no significant difference between quench and full QCD for this heavy quark mass (pion mass >~ 500 MeV) .
- Statistical error is still large.
- Finite size effect from breaking of temporal periodicity is also significant

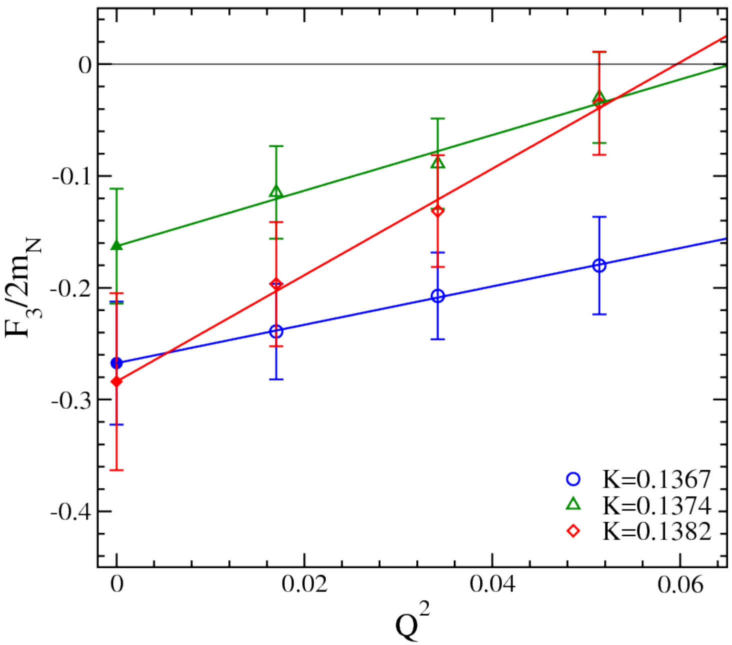
F. Berruto et al. (05)
E.Shintani et al. (05, 08)

Form factor $F_3(q^2)$

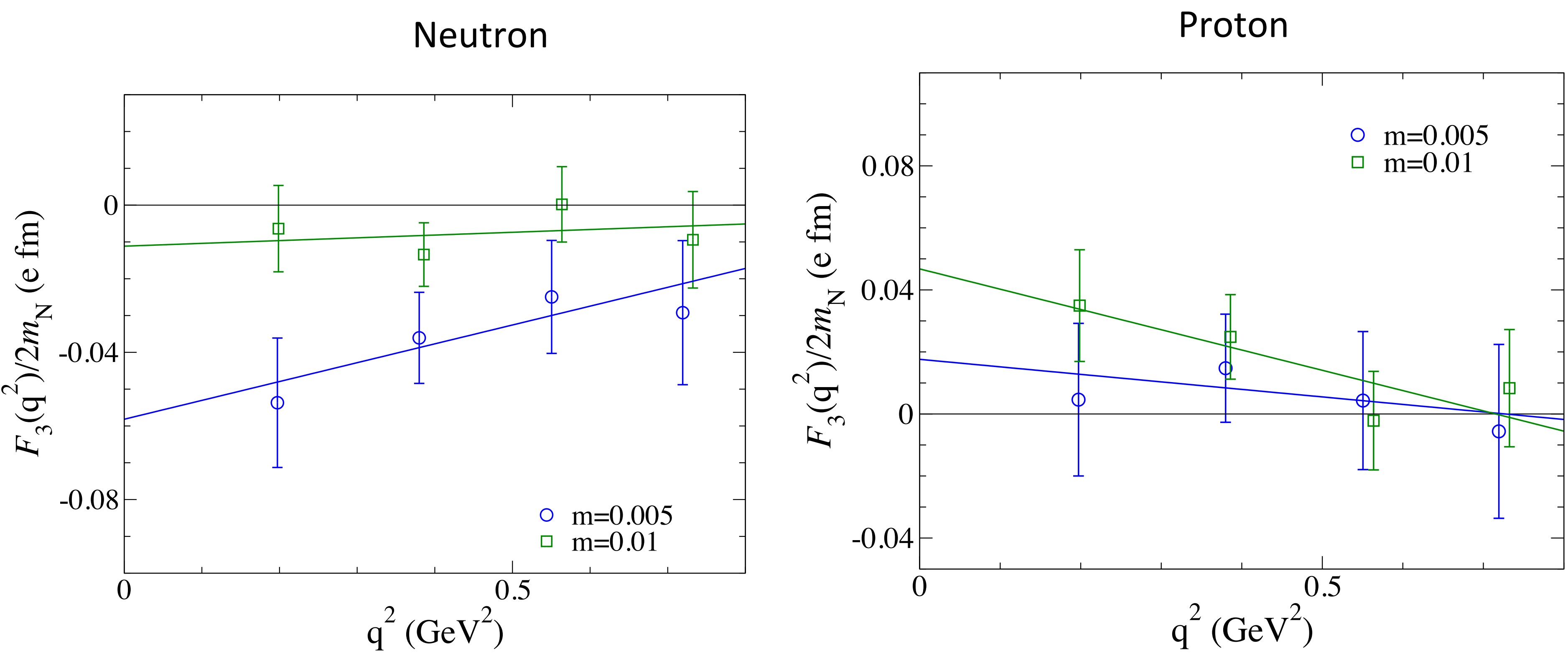
- Matrix element in θ vacuum
  - N_f=2 clover fermion
  - Size is 24^3×48 lattice (~2 fm^3)
  - Signal appears in 11 -- 16
  - $Q^2 \to 0$ limit with linear func.







$F_3(q^2)$ vs q^2



- Mpi=330 MeV (mf=0.005) 600 config x 32 AMA = 19.2 K measurements
- Mpi=420 MeV (mf=0.01) 400 config x 32 AMA = 12.8 K measurements
- (iso-vector) CP violating g(π-N-N) is related to the slope of F_3

[11 Vries, Timmermans, Mereghetti, van Kolck]

Comparison of results

- Full QCD

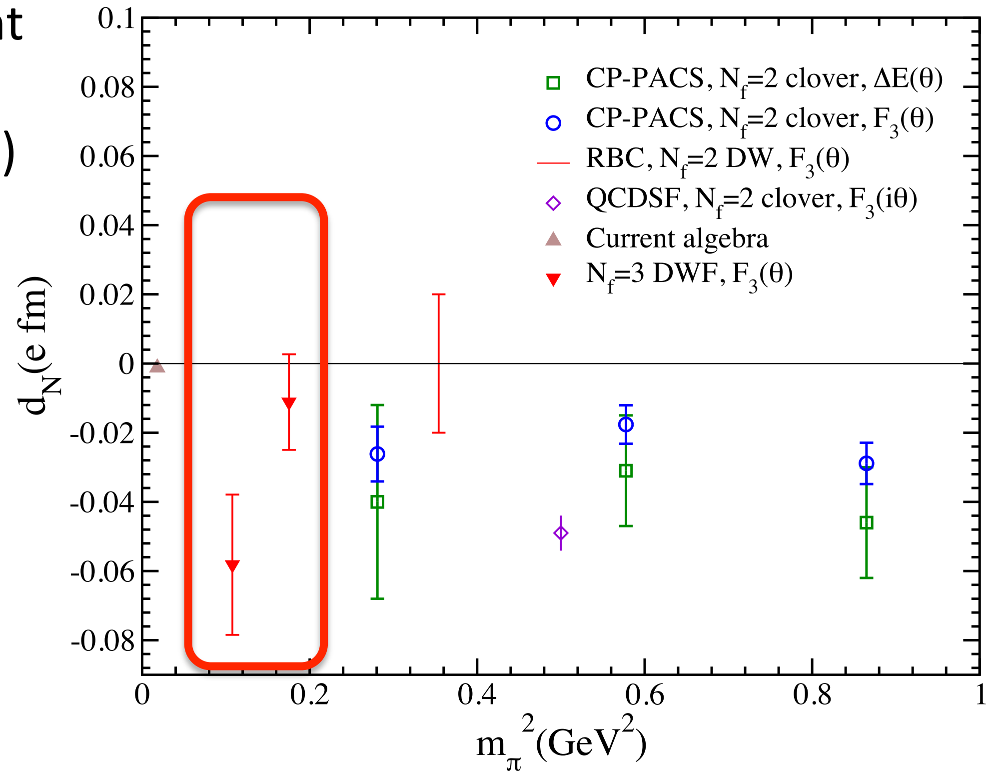
PRELIMINARY

$\Theta = 1$

• Lattice results are consistent within 1σ.
(not include systematic error)
• larger than the results of QCD Sum Rules or ChPT.

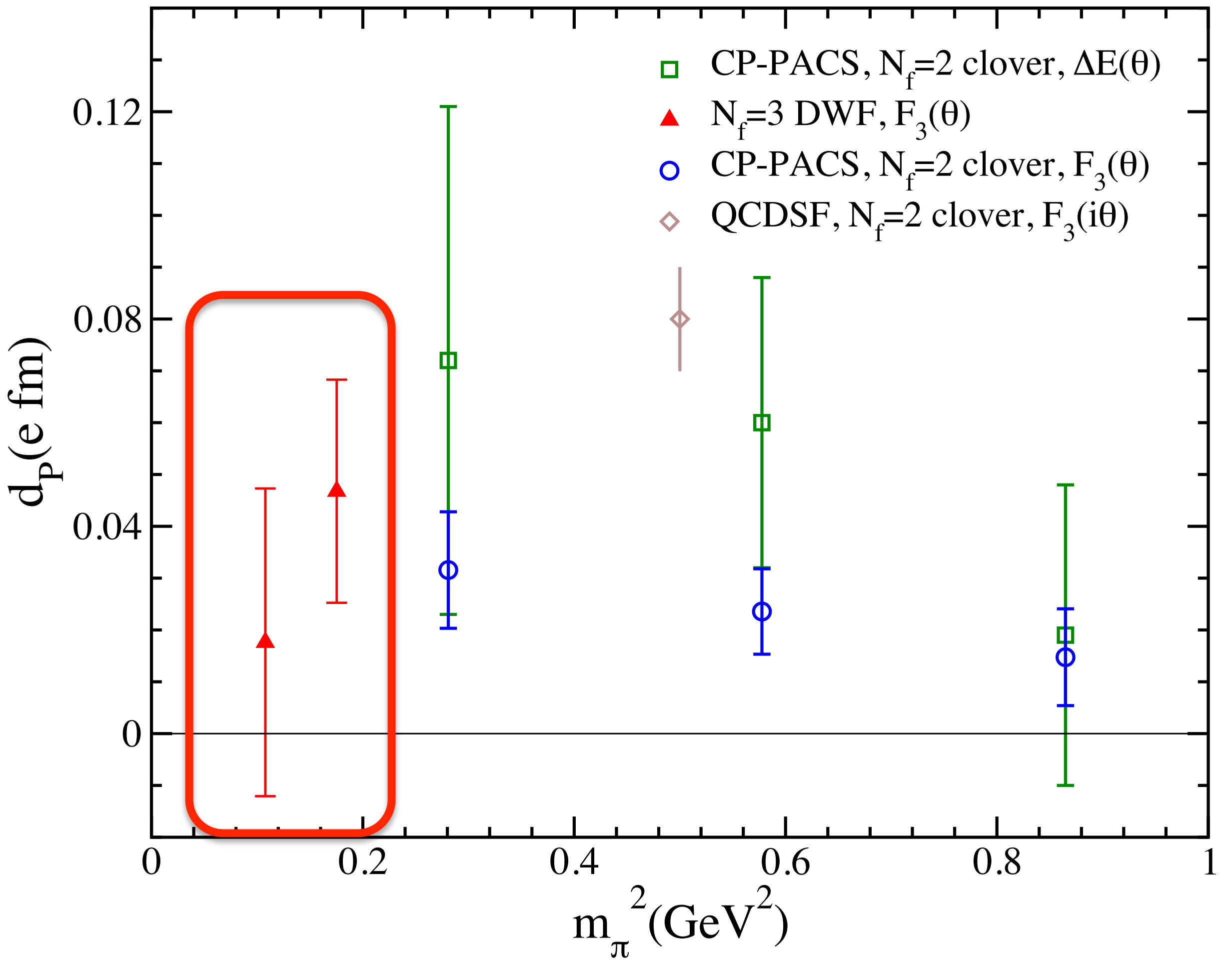
•no obvious quark mass dependence yet

statistics ?



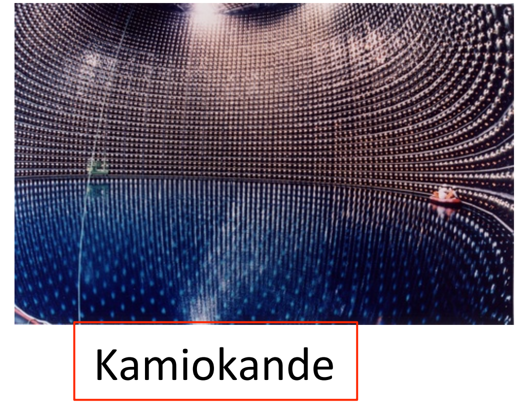
Proton EDM results

PRELIMINARY



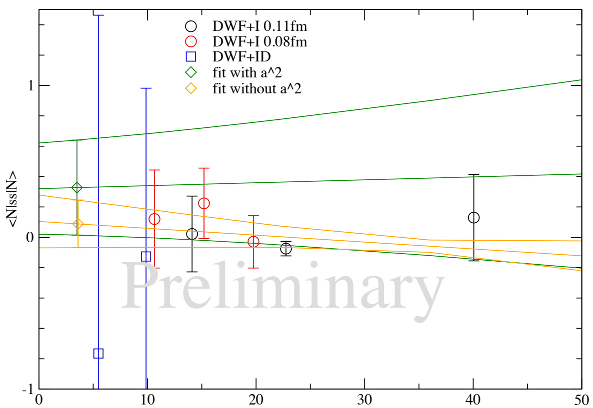
Nucleon calculations for High Energy Physics

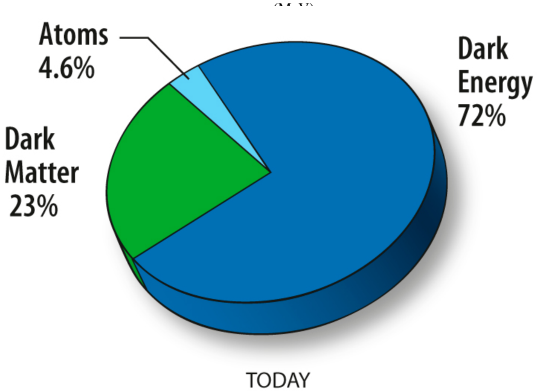
- Proton Decay Matrix Elements
  [Y. Aoki, E. Shintani, A. Soni]



- Strangeness contents in Nucleons for Direct Dirk Matter search
  [C. Jung]

$$\langle N|\bar{s}s|N\rangle$$





$$\Gamma_P \propto \left| \overline{v_e^c} \langle \pi|(ud)_{R/L} u_L|P\rangle \right|^2$$