Sea (u, d, s) Quarks Contribution to Nucleon Electromagnetic Form Factors

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in collaboration with

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PRL 118, 042001 (2017)

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arXiv:1705.05849

QCD evolution

May 22-26, 2017
Jefferson Lab
Newport News, VA

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Strange Quark Contribution

- s - quark contribution arises from vacuum: sign and magnitude related to nonperturbative structure of nucleon

- Nonzero strange electric FF G^{s}_{E} at $Q^2 > 0$ implies different spatial distribution of s and $\bar{s}$ quarks

- Background in Q_{weak} experiment arises from magnetization of strange quark [strange magnetic FF G^{s}_{M}]

- $G^{s}_{E,M}(Q^2)$ *essential for determination of neutral weak FFs*

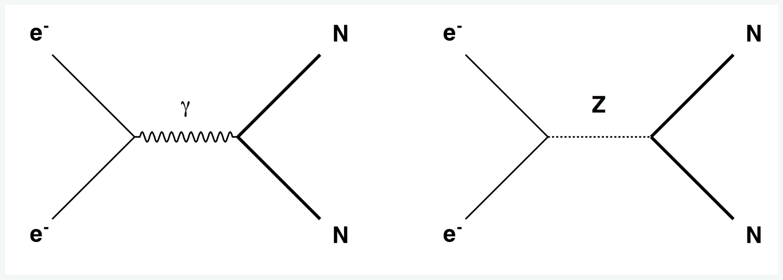
- Models results:

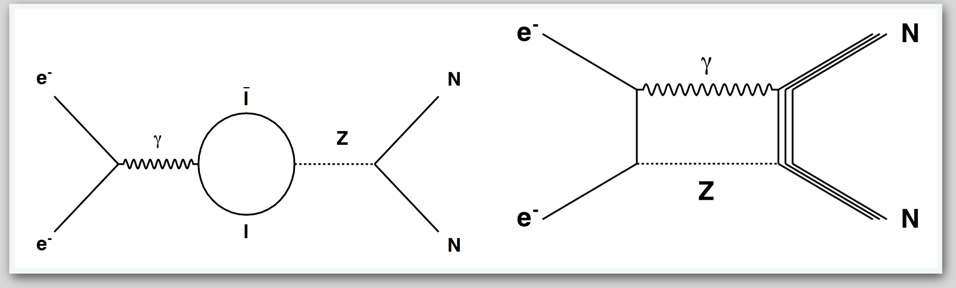
$$\boxed{\begin{array}{c} -0.5 < G^{s}M(0) < 0.3 \\ -0.25 < r_s < 0.4\ \mathrm{fm} \end{array}}$$

- Experimental results (G0, HAPPEX, A4, SAMPLE) of $G^{s}_{E,M}$ quite uncertain

Theory & Experiment: $G^s_{E,M}(Q^2)$

- Zel'dovich (1957): EM interaction with parity violation





$$\mathcal{M}_\gamma = -\frac{4\pi\alpha}{Q^2} e_i l^\mu J^\gamma_\mu$$

$$\mathcal{M}_Z = \frac{G_F}{2\sqrt{2}} \left(g^i_V l^\mu + g^i_A l^{\mu 5}\right)\left(J^Z_\mu + + J^Z_{\mu 5}\right)$$

- Kaplan, Manohar (88):

$$G^{Z,p(n)}_{E,M}(Q^2) = \frac{1}{4}\left[(1 - 4\sin^2\theta_W)(1 + R^{p(n)}_V) G^{\gamma,p(n)}_{E,M}(Q^2) - (1 + R^{n(p)}_V) G^{\gamma,n(p)}_{E,M}(Q^2) - (1 + R^{(0)}_V) G^s_{E,M}(Q^2)\right]$$

- Mckeown and Beck (89):

$$\begin{aligned} A^p_{PV} = & -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{1}{[\epsilon(G^p_E)^2 + \tau(G^p_M)^2]} \\ & \times \{(\epsilon(G^p_E)^2 + \tau(G^p_M)^2)(1 - 4\sin^2\theta_W)(1 + R^p_V) \\ & - (\epsilon G^p_E G^n_E + \tau G^p_M G^n_M)(1 + R^n_V) \\ & - (\epsilon G^p_E G^s_E + \tau G^p_M G^s_M)(1 + R^{(0)}_V) \\ & - \epsilon'(1 - 4\sin^2\theta_W) G^p_M G^e_A\} \end{aligned}$$

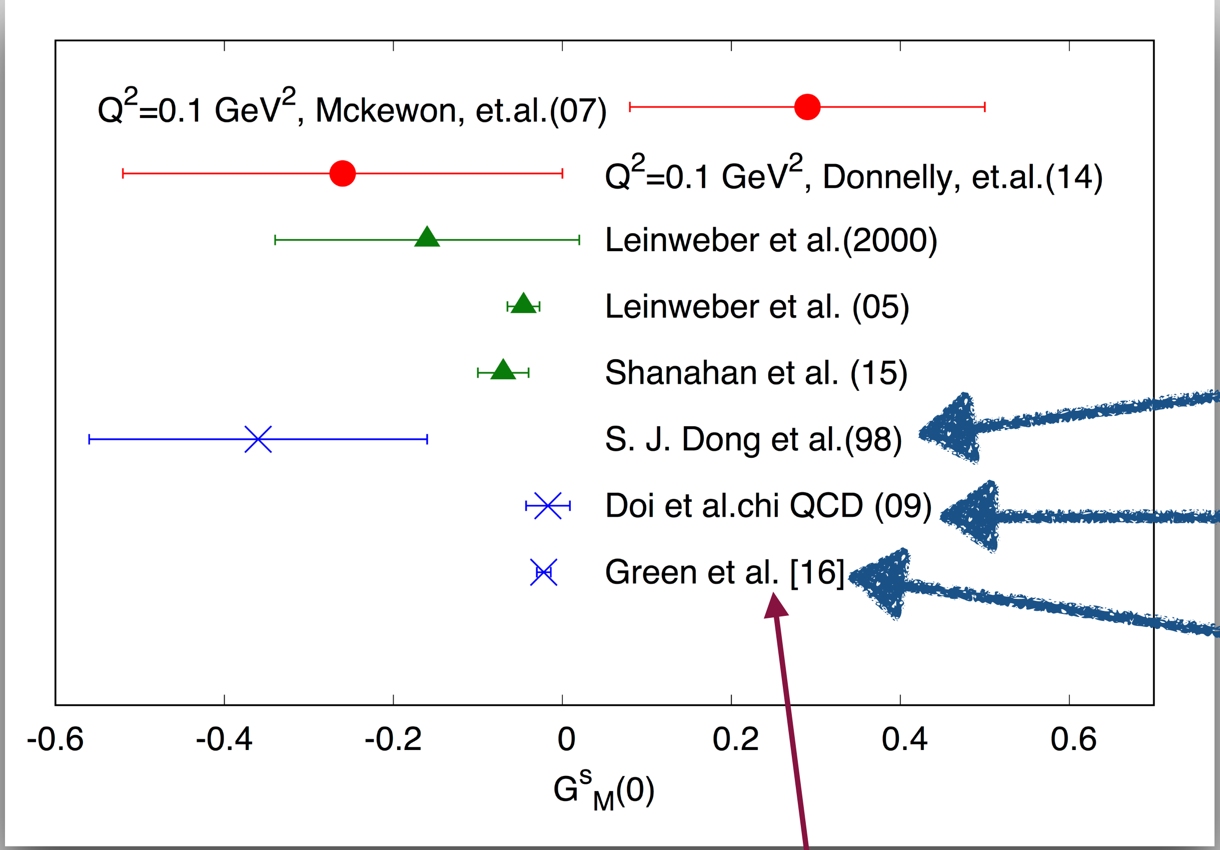
$\xleftarrow{}$ **Unknown**

Theory & Experiment: $G^{s}_{E,M}(Q^2)$

RED: Analysis of world expt. data

GREEN: Indirect calculation

BLUE: Lattice QCD



Quenched

Pion mass ~ 600 MeV

Pion mass ~ 315 MeV

For the first time obtained non-zero value of $G^{s}_{E}(Q^2)$

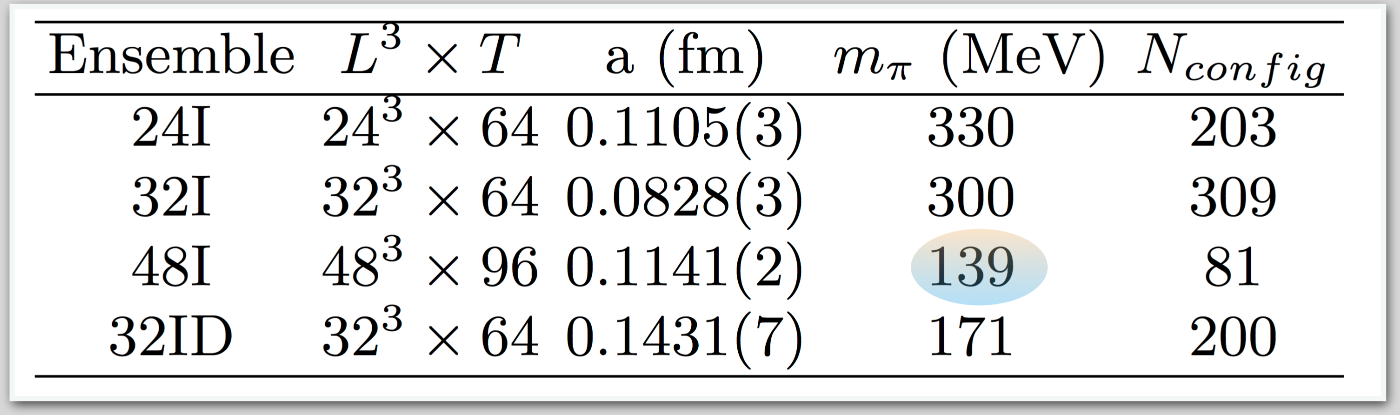
Light (u,d) Sea Quarks Contribution

- No calculation of sea *u, d* - quarks contribution to nucleon EMFF at physical point with controlled systematics

a) Negative contribution to proton charge radius - relevant to proton charge radius problem

b) Shifts neutron charge radius toward experimental value -lattice QCD estimate $<r_n>^2$ is much lower than 0.11 fm^2

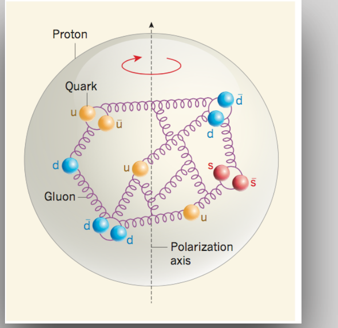
This work: Overlap fermion on RBC/UKQCD DWF gauge configurations

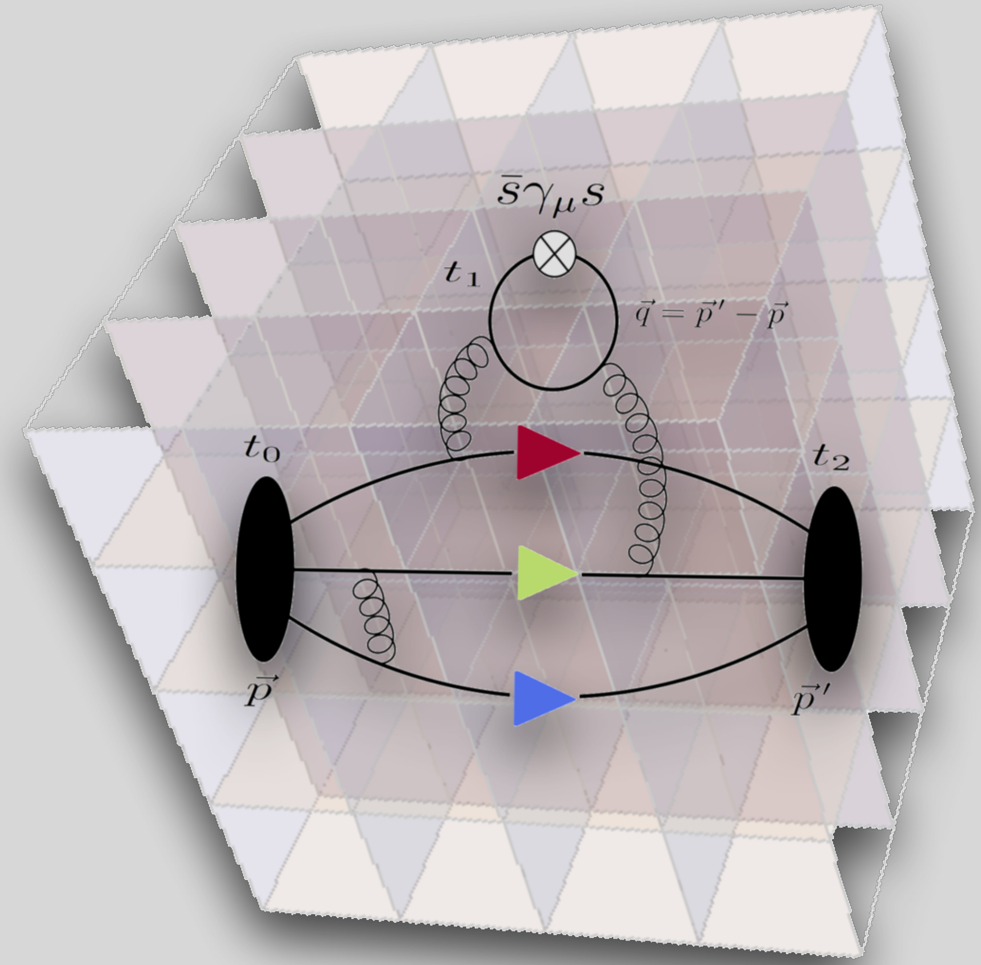


Ensemble	$L^3 \times T$	a (fm)	m_π (MeV)	N_{config}
24I	$24^3 \times 64$	0.1105(3)	330	203
32I	$32^3 \times 64$	0.0828(3)	300	309
48I	$48^3 \times 96$	0.1141(2)	139	81
32ID	$32^3 \times 64$	0.1431(7)	171	200

RSS, Yang, Alexandru, Draper, Liang, and Liu ,
PRL 118, 042001 (2017)

Reviewed by Ross Young
Nature 544, 419–420





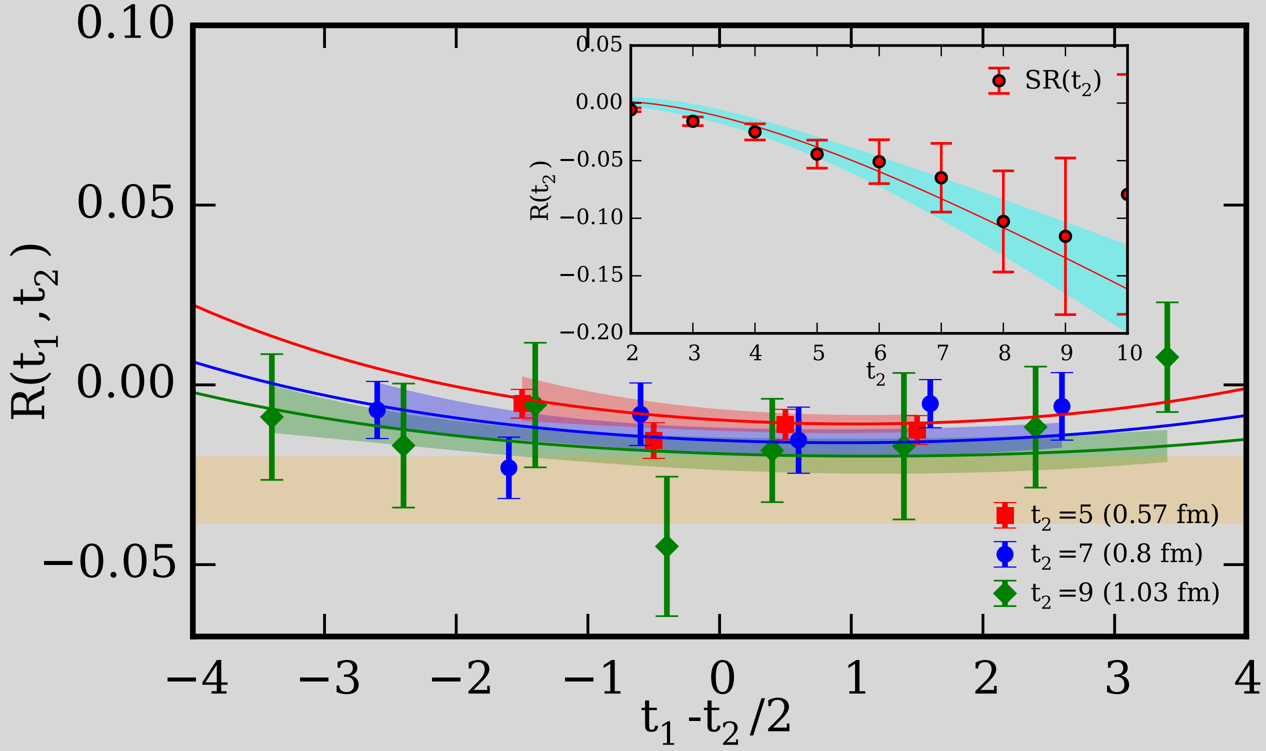
Ratio of nucleon 3pt/2pt correlation function

$$R_{\mu=i}(\Gamma_k) \xrightarrow{(t_2-t_1)\gg 1/\Delta m, t_1\gg 1/\Delta m} \frac{\epsilon_{ijk}q_j}{E_q+m_N} G_M^s(Q^2)$$

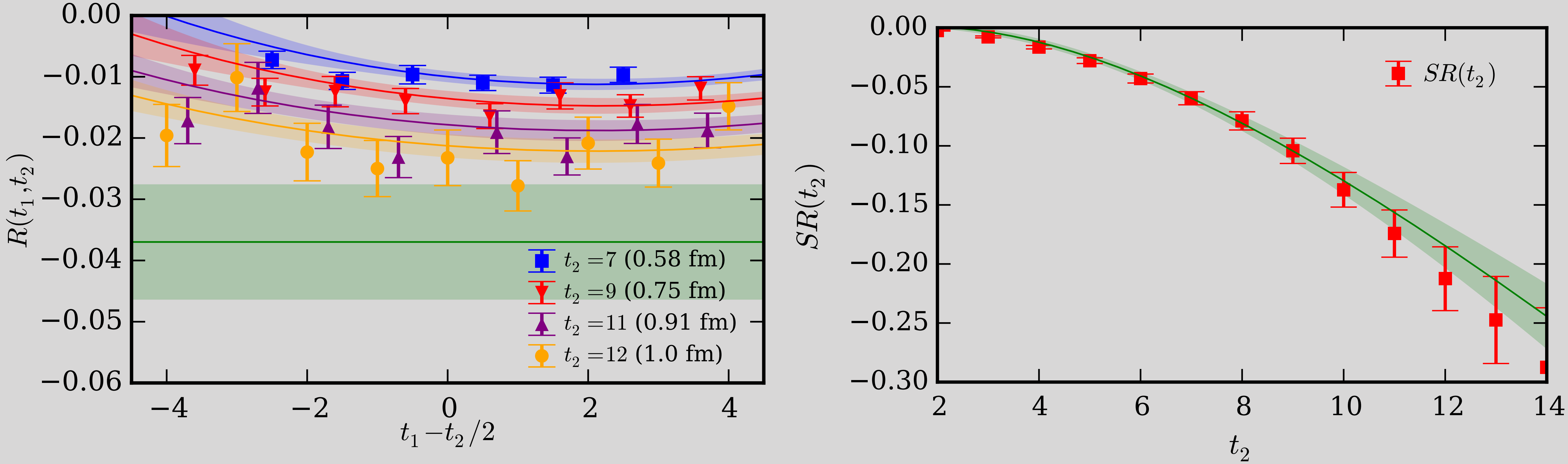
$$R_{\mu=4}(\Gamma_e) \xrightarrow{(t_2-t_1)\gg 1/\Delta m, t_1\gg 1/\Delta m} G_E^s(Q^2)$$

2-states combined correlated fit

48I, m_pi =207 MeV, $G^S_M(Q^2=0.05\ \mathrm{GeV}^2\ ) = -0.029(9)$

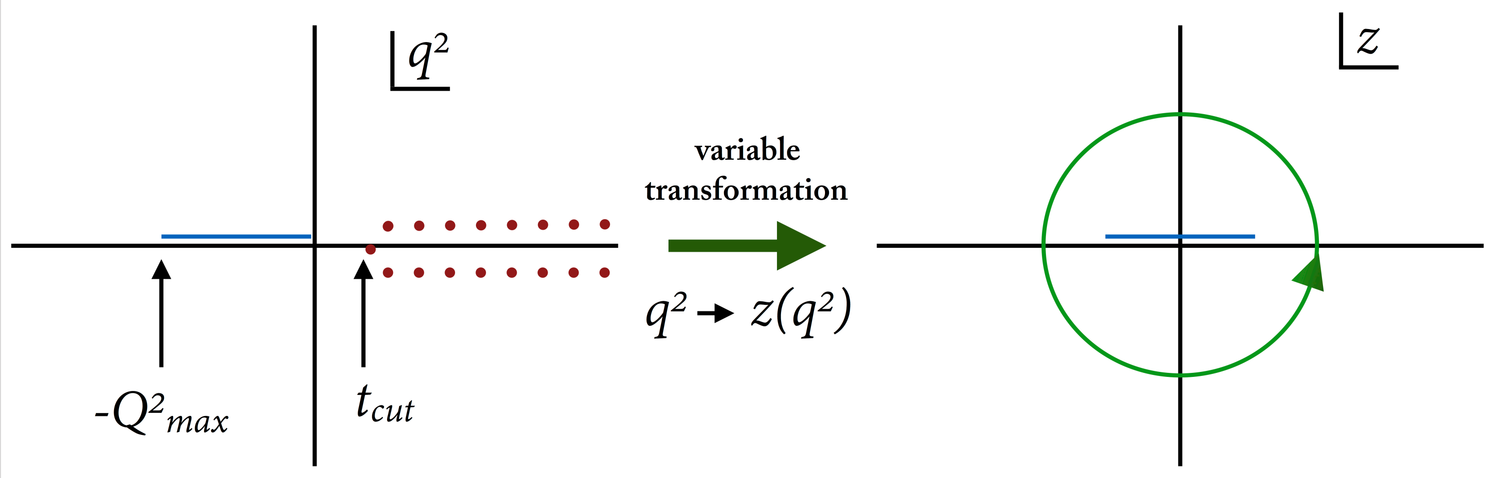


32I, m_pi =300 MeV, $G_M^{\textbf{light-sea}}\ (Q^2=0.22\ \mathrm{GeV}^2\ ) = -0.036(9)$



Q^2-Extrapolation

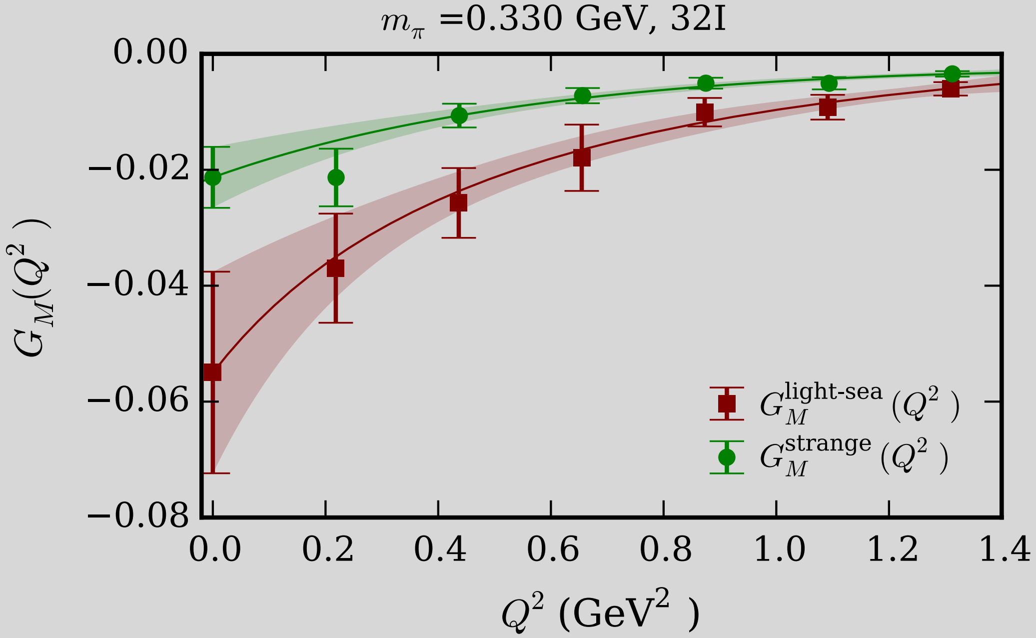
- z-expansion, R. Hill, *et al.* (2010)



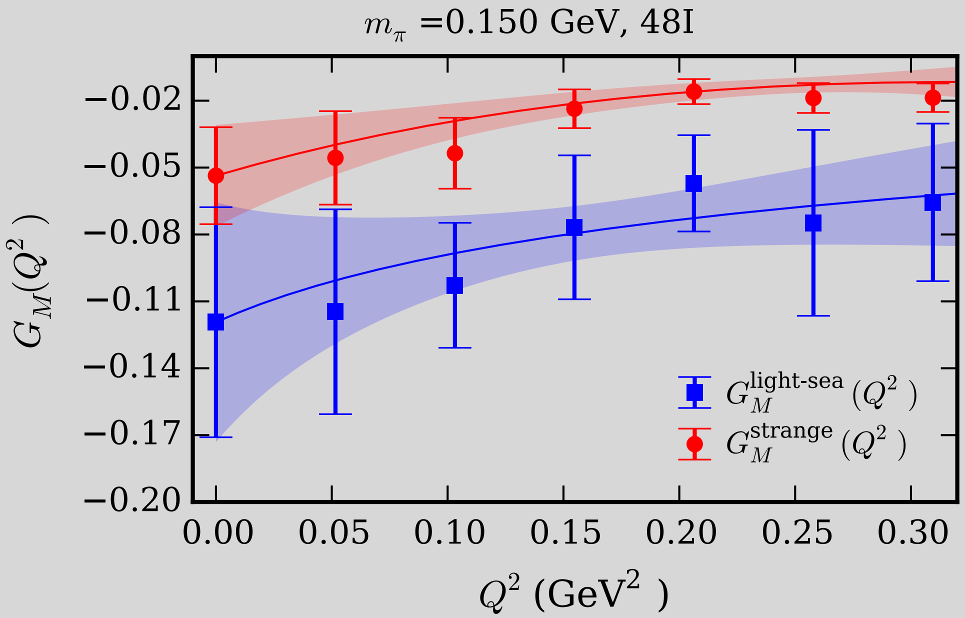
$$G_M^{s,z-exp}(Q^2) = \sum_{k=0}^{k_{max}} a_k z^k \;,\; z = \frac{\sqrt{t_{\rm cut}+Q^2}-\sqrt{t_{\rm cut}}}{\sqrt{t_{\rm cut}+Q^2}+\sqrt{t_{\rm cut}}}$$

*Keep first 3 terms and
include 4th term in systematics

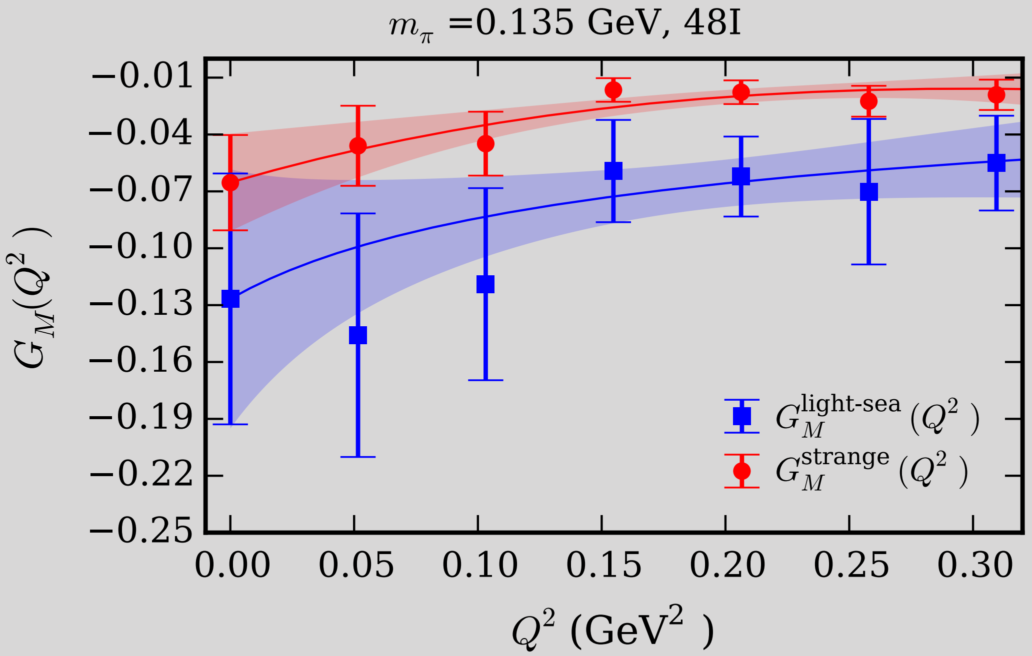
Q^2-Extrapolation



m_π =0.330 GeV, 32I



m_π =0.150 GeV, 48I



m_π =0.135 GeV, 48I

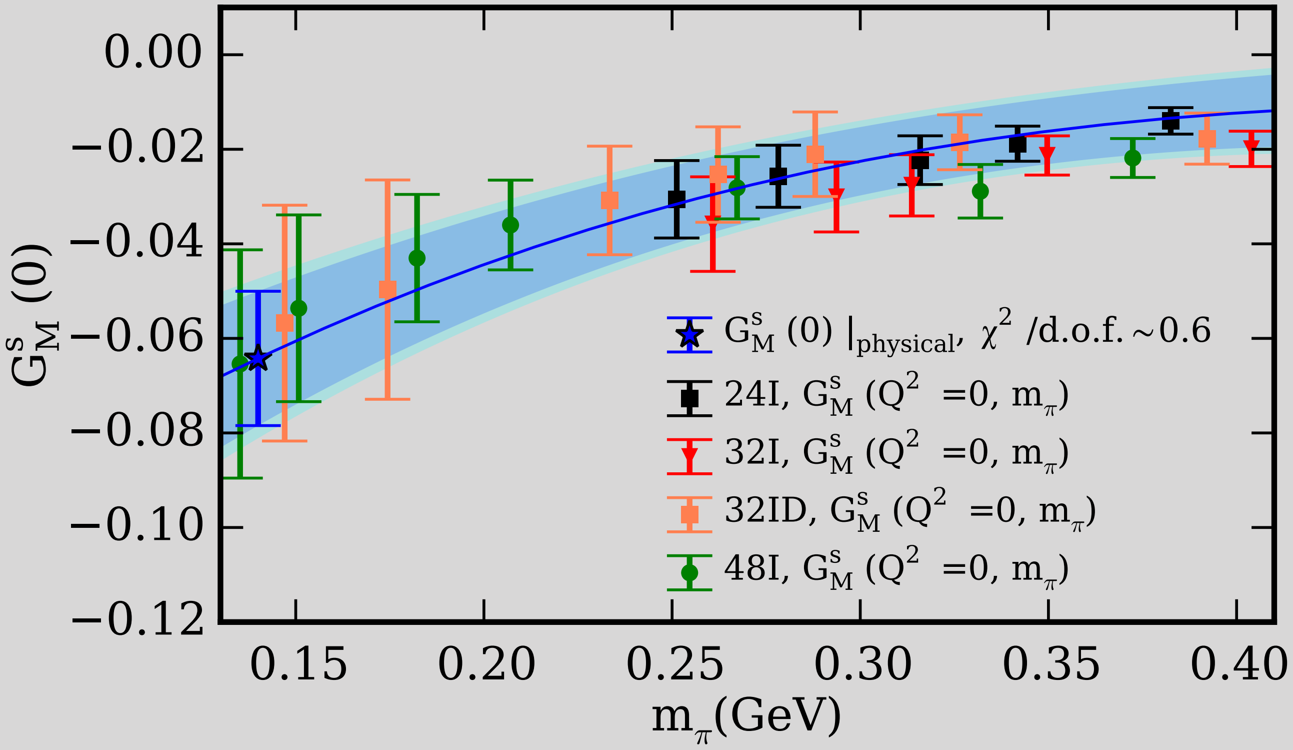
Continuum Extrapolation

*Global fit (s-quark magnetic moment)

$$G_M^s(0; m_\pi, m_{\pi,vs}, m_K, a, L) = A_0 + A_1 m_\pi + A_2 m_K$$
$$+ A_3 m_{\pi,vs}^2 + A_4 a^2 + A_5 m_\pi \left(1 - \frac{2}{m_\pi L}\right) e^{-m_\pi L}$$

Chiral interpolation - Musolf, et. al. (97);
Hemmert et. al (99).
Finite volume correction - S. Beane (04)

partially quenched pion mass



Correlated fit

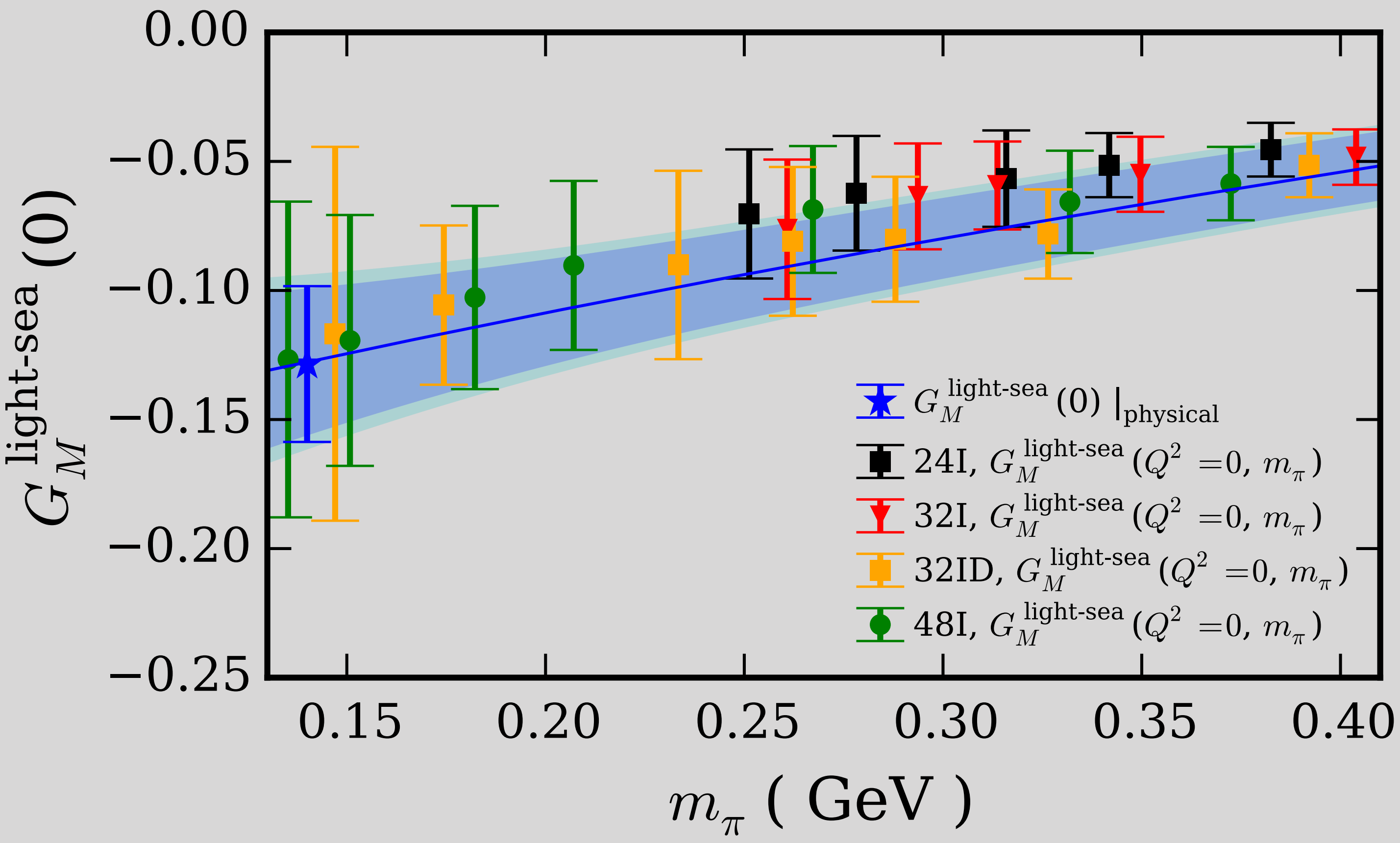
$G^s_M(0)$ |physical = - 0.064(14)(09)

A_1= 0.61(16)
A_2= -2.26(49)
A_3= 0.31(12)
A_4= 0.015(16)
A_5= -4.0(2.4)

*Global fit (light (u,d) quark magnetic moment)

$$G_M^{\text{light-sea}}(Q^2 = 0, m_\pi, m_K, m_{\pi,vs}, a, L) = A_0 + A_1\, m_\pi + A_2\, m_K$$
$$+ A_3\, a^2 + A_4\, m_\pi \left(1 - \frac{2}{m_\pi\, L}\right) e^{-m_\pi L}$$

Chiral extrapolation
Manohar, Savage, Jenkins, Luke
PL B 302:482-490, 1993



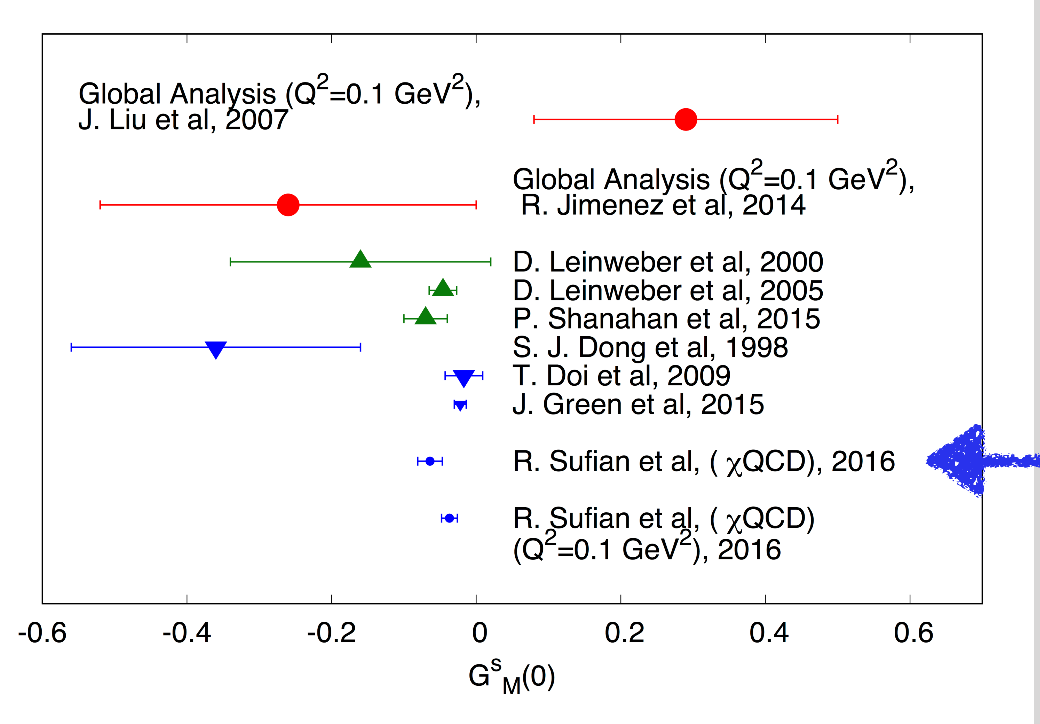
First calculation of
disconnected u,d - quarks
contribution at physical point

arXiv:1705.05849
RSS, Yang, Liang, Draper, Liu

Results : Light and strange $G_M(0)$

$G^S_M(0)$ Iphysical = - 0.064(14)(09)

$G_M^{\text{light-sea}}(0)$ Iphysical = - 0.129(30)(22)



Most precise and accurate estimates of G^S_M

(*include charge factors*)

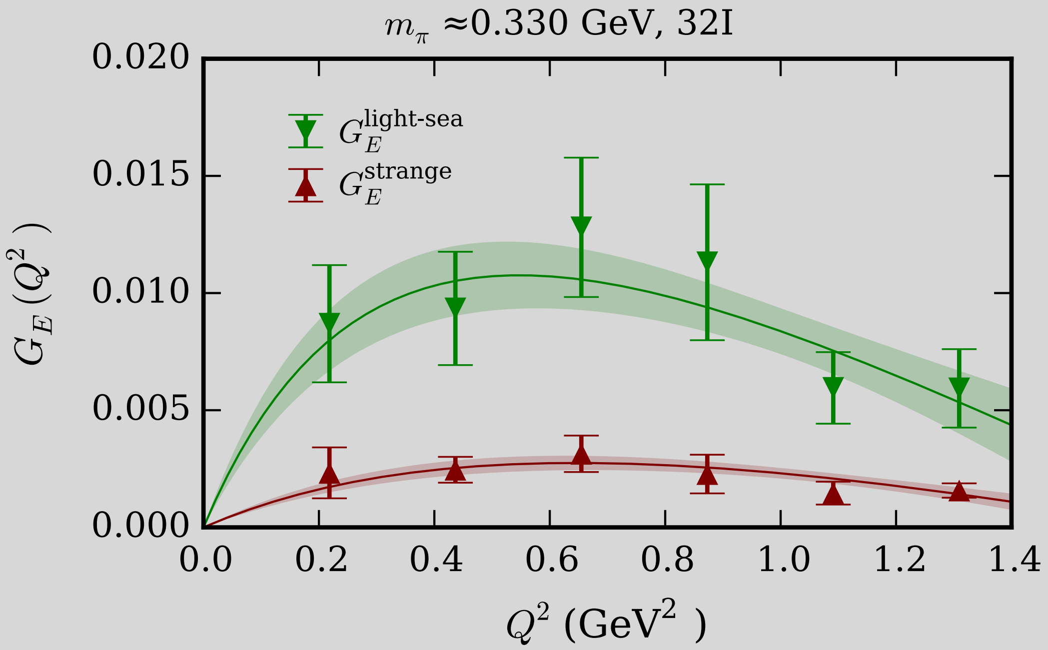
$$\boxed{\mu_M\,(\mathrm{DI}) = -0.022(11)(09)\,\mu_N}$$

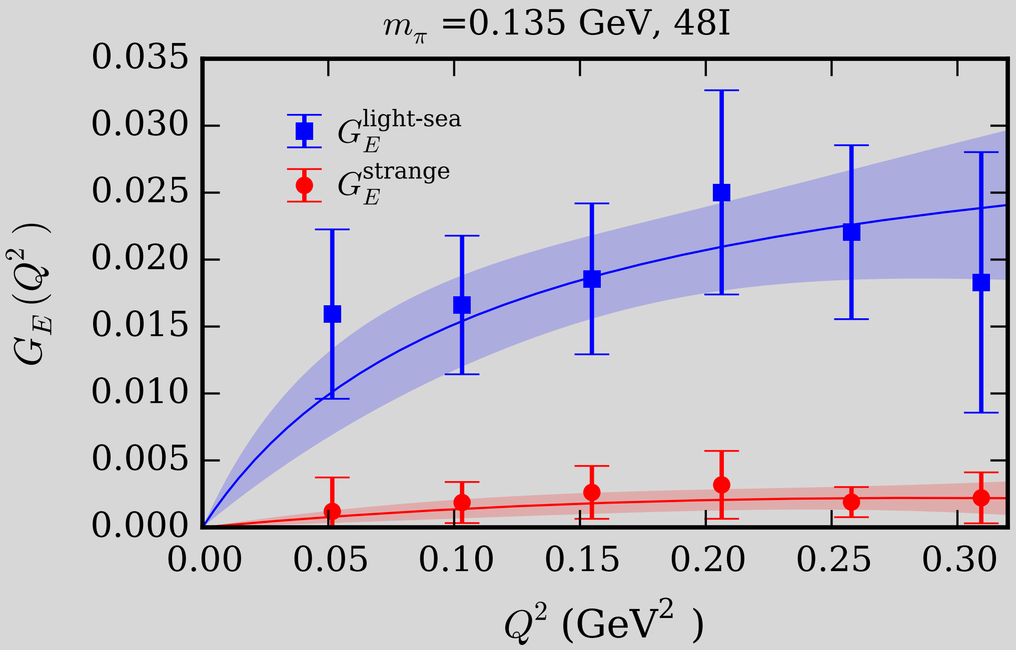
Strange & light-sea quarks electric form factor

- Electromagnetic current *C - odd*

- Sensitive to difference between contributions from *s* and $\bar{s}$

- Requires mechanisms beyond simple $g \longrightarrow s\bar{s}$ fluctuations





Charge Radii : Continuum Extrapolation

Charge radius

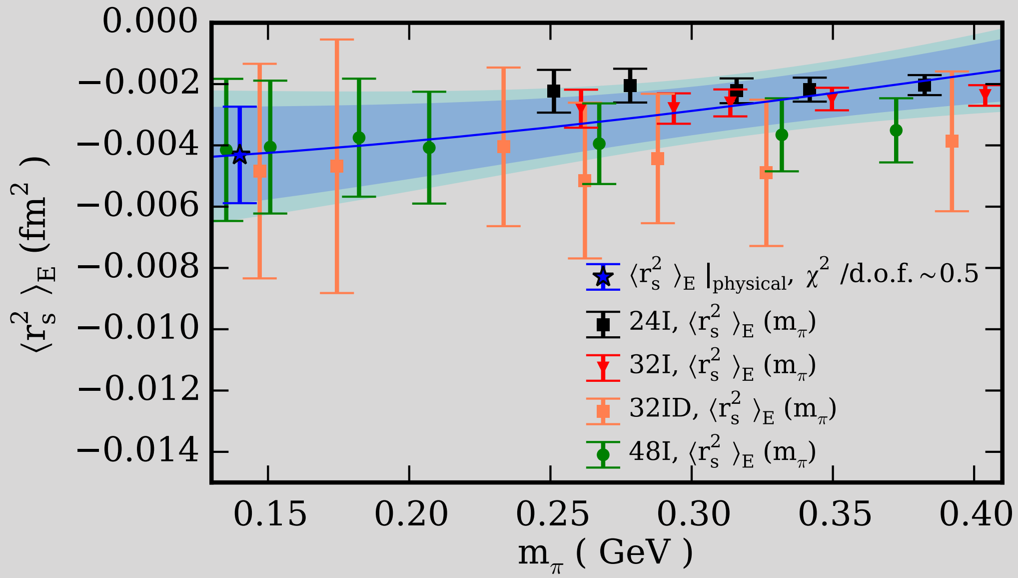
$$\langle r^2\rangle_E \equiv -6\frac{dG_E}{dQ^2}|_{Q^2=0}$$

Global fit formula

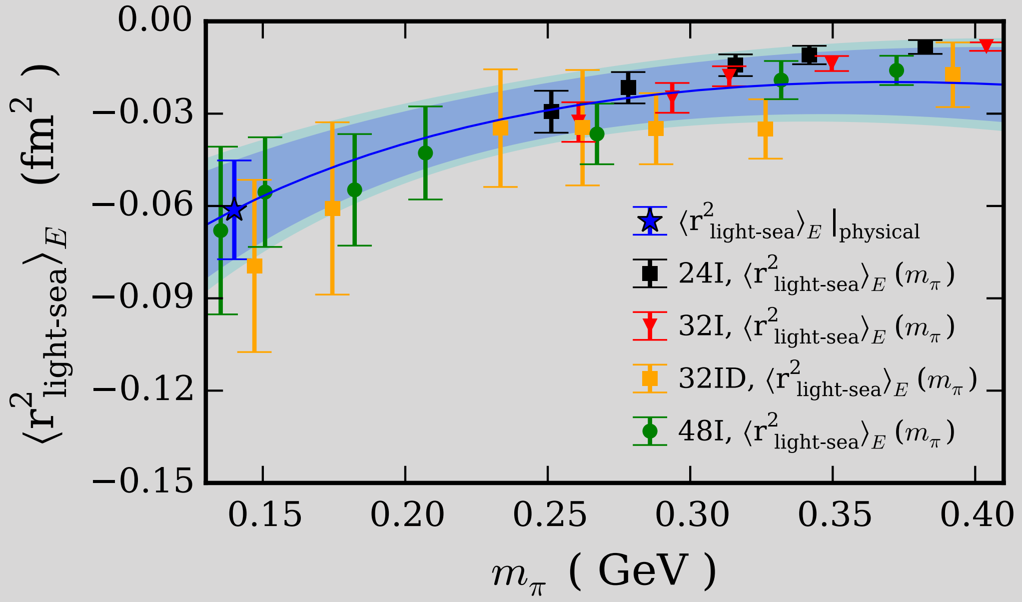
$$\langle r_s^2\rangle_E(m_\pi, m_{\pi,vs}, m_K, a, L) = A_0 + A_1\log(m_K)$$
$$+A_2 m_\pi^2 + A_3 m_{\pi,vs}^2 + A_4 a^2 + A_5\sqrt{L}e^{-m_\pi L}$$

*Chiral Extrapolation - Hemmert, et. al. (99); Hall (2012)

*Volume Correction - Tiburzi (14)



-0.0043(16)(14) fm²



-0.061(16)(15) fm²

An Estimate : Proton Charge Radii

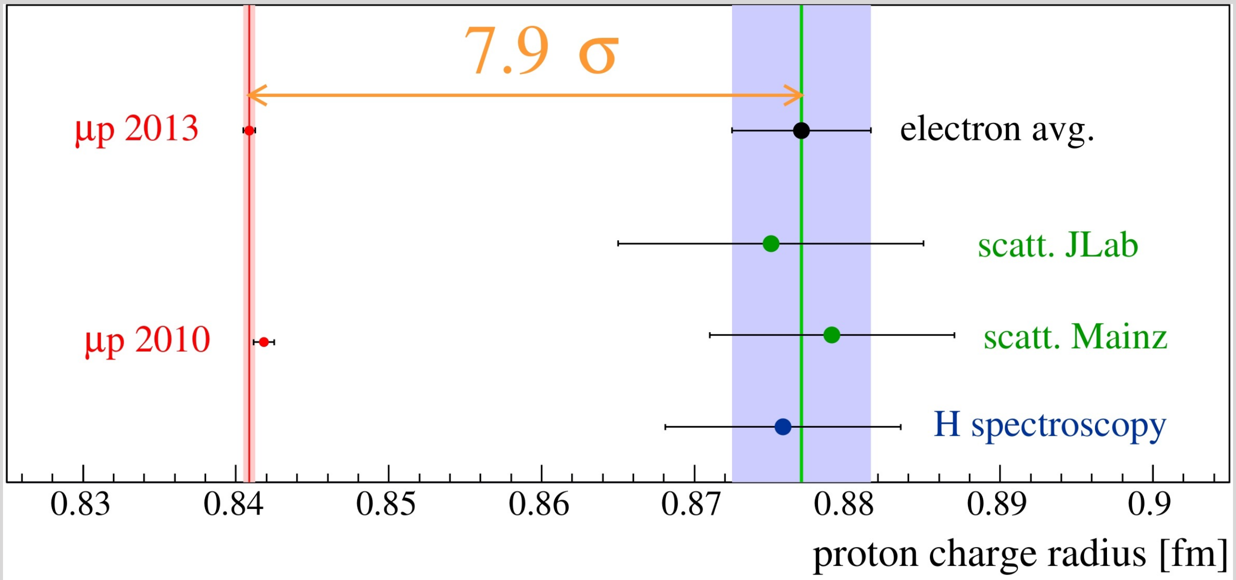
*Include charge factors of u,d,s quarks

$$\langle r_{\rm s}^2\rangle_E = 0.0014(05)(05)\,{\rm fm}^2,$$

$$\langle r^2_{\text{light-sea}}\rangle_E = -0.0203(53)(49)\,{\rm fm}^2.$$

Total

$$\xrightarrow{\quad} \boxed{\langle r^2\rangle_E\,({\rm DI}) = -0.019(05)(05)\,{\rm fm}^2}$$



Proton charge radius puzzle

2.5(9)% NEGATIVE contribution to $\langle r^p_E\rangle^2$

8% discrepancy

Nucleon radii	Experimental values
$\langle r_E^p\rangle^2$	$0.77\,{\rm fm}^2$ (ep CODATA)
$\langle r_E^p\rangle^2$	$0.707062\,{\rm fm}^2$ (μp Lamb shift)

An Estimate : Neutron Charge Radii

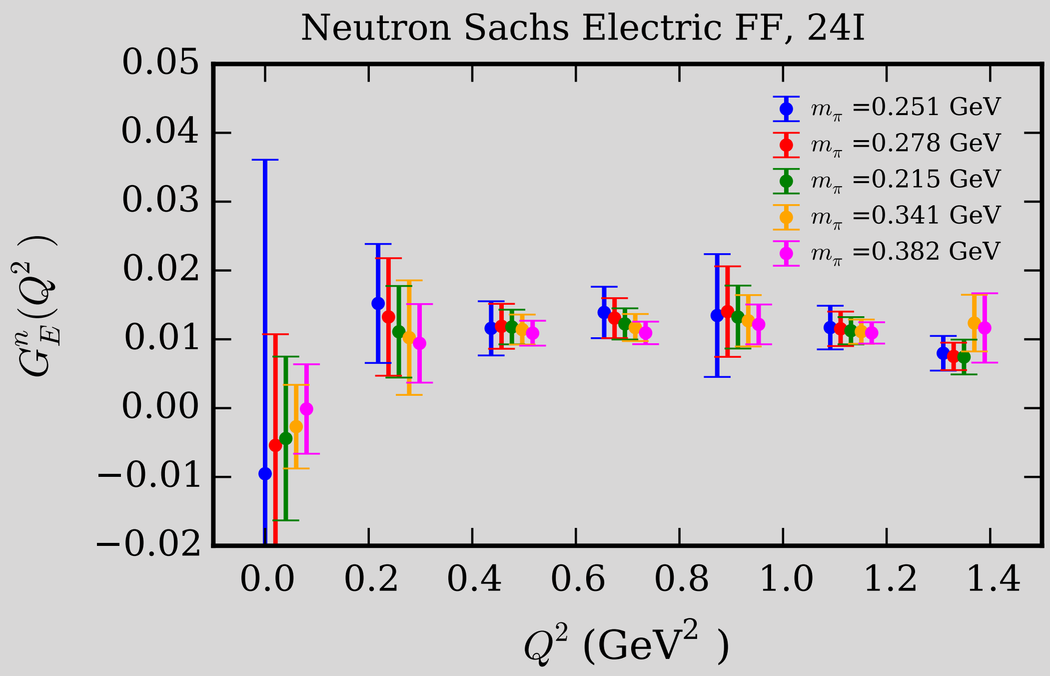
$\langle r^n_E \rangle^2$	-0.1161 fm^2

Experiment

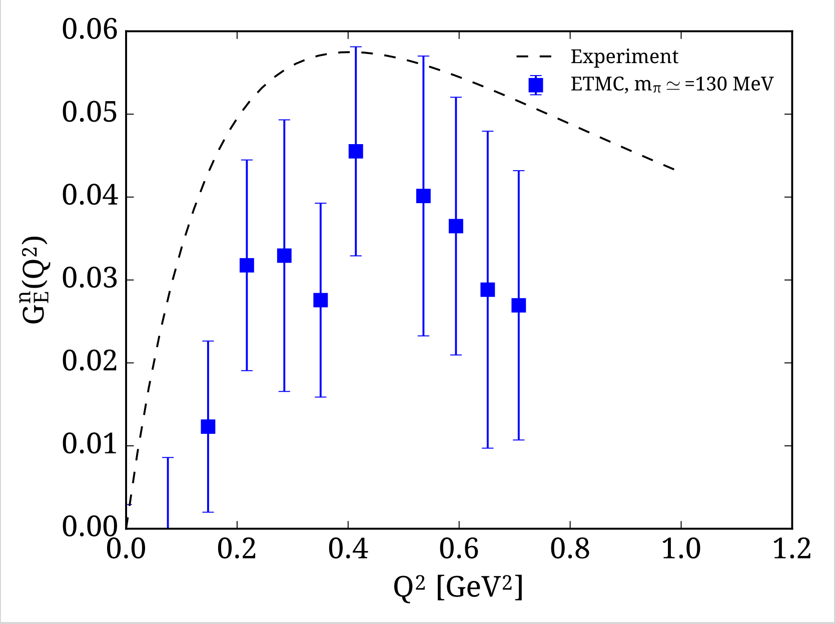
$$\langle r^2 \rangle_E\,(\text{DI}) = -0.019(05)(05)\ \text{fm}^2$$

Lattice QCD (DI)
16.3(6.1)% of
Experimental Value

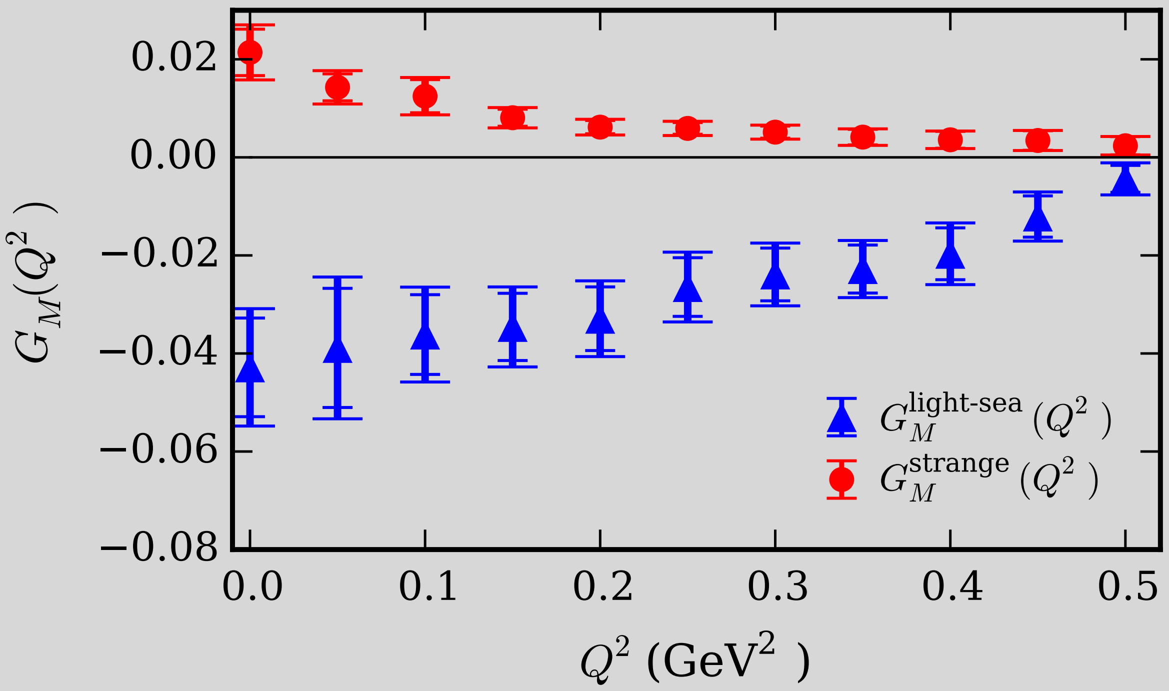
Connected Insertion Only

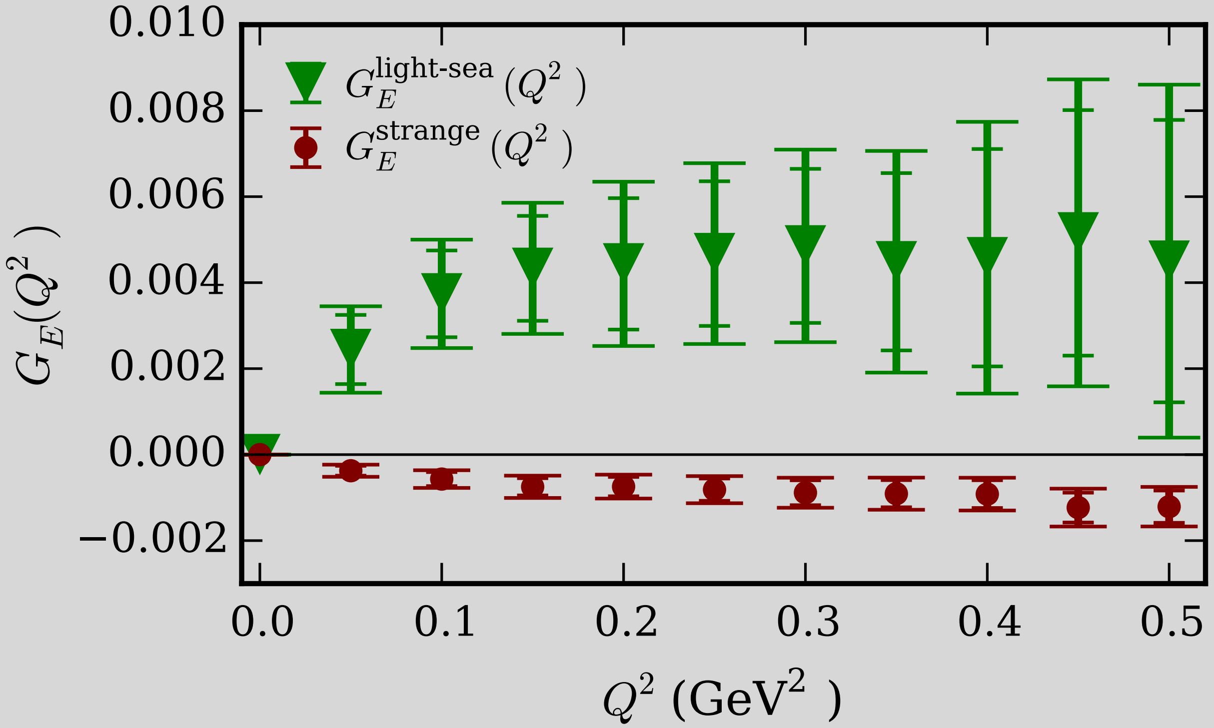


ETMC Collaboration
arXiv:1612.04644 [hep-lat]



Disconnected light and strange quarks contribution to nucleon EMFF





(*charge factors included*)

SUMMARY

*Most precise estimates of strange quark magnetic moment and charge radius

* Nonzero strange and light-sea quarks $G^{(DI)}_{E,M}(Q^2)$ up to 0.5 GeV^2

*Negative contribution from disconnected u,d,s quarks to nucleon mean square charge radius

*Disconnected quarks contribution cannot be ignored in Lattice QCD calculation of nucleon EMFF

Thank You

$$R(t_2, t_1) = C_0 + C_1 e^{-\Delta m(t_2 - t_1)} + C_2 e^{-\Delta m t_1} + C_3 e^{-\Delta m t_2},$$

$$SR(t_2) = \sum_{t_1 \geq t'}^{t_1 \leq (t_2 - t'')} R(t_2, t_1)$$

$$= (t_2 - t' - t^{''} + 1)C_0 + C_1 \frac{e^{-\Delta m t''} - e^{-\Delta m(t_2 - t' + 1)}}{1 - e^{-\Delta m}}$$

$$+ C_2 \frac{e^{-\Delta m t'} - e^{-\Delta m(t_2 - t'' + 1)}}{1 - e^{-\Delta m}} + C_3(t_2 - t' - t'' + 1)e^{-\Delta m t_2}.$$