Electromagnetic Form Factors of the Nucleon at Large Momentum

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(Lattice Hadron Physics collaboration)

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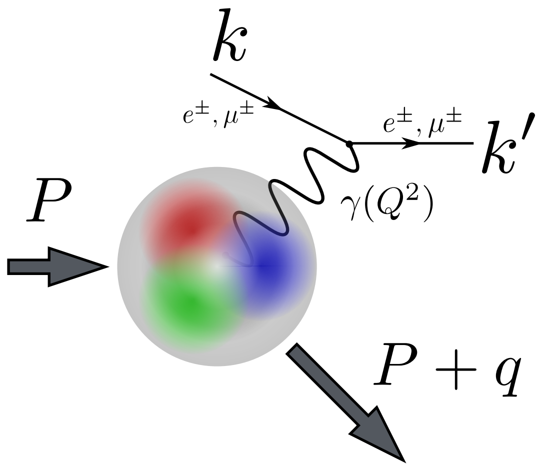
Outline

- Large-Q^2 Nucleon vector form factors
  - *Motivation*
  - *Methodology & challenges on a lattice*
- Preview of results
  - *Form factors and ratios*
  - *Light-Flavor contributions*
- Examining systematic effects
  - G_E/G_M *ratio*
  - *Disconnected diagrams*
- Summary & Outlook

Nucleon Elastic E&M Form Factors



$$Q^2 = -(k-k')^2 > 0$$

Elastic *e⁻p* amplitude

$$\langle P+q|\,\bar{q}\gamma^\mu q\,|P\rangle \;=\; \bar{U}_{P+q}\Big[\underbrace{F_1(Q^2)}_{\text{(Dirac)}}\gamma^\mu + \underbrace{F_2\,(Q^2)}_{\text{(Pauli)}}\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}\Big]U_P$$

Sachs Electric $\quad G_E(Q^2) = F_1(Q^2) - \dfrac{Q^2}{4M^2}F_2(Q^2)$

Magnetic $\quad G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$

Elastic *e⁻p* cross-section

- $G_{E,M}$ from ϵ-dep. at fixed $\tau(Q^2)$ (***"Rosenbluth separation"***)
- dominated by G_M at large Q^2
- 2γ corrections at $Q^2 \gtrsim 1$ GeV²

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\rm Mott}}{1+\tau}\Big[G_E^2 + \frac{\tau}{\epsilon}G_M^2\Big]$$

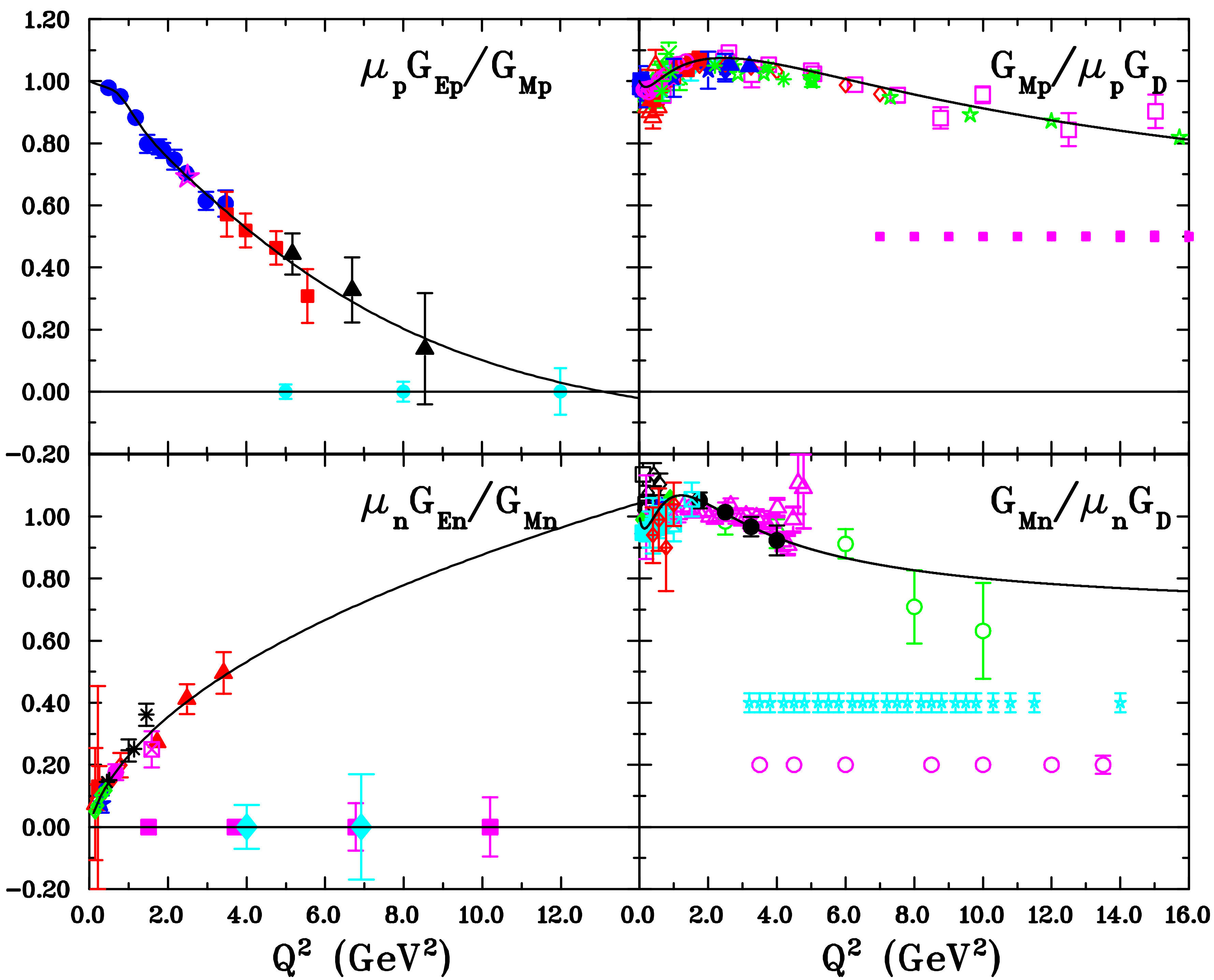
$$\tau = \frac{Q^2}{4M_N^2} \qquad \epsilon = \Big[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\Big]^{-1}$$

Polarization transfer: polarized *e⁻* beam
+ detect polarization of recoil nucleon
(alt.: transverse asymmetry on pol. target)

- *G_E/G_M ratio* (only small radiative corrections)

$$P_t/P_l \propto G_E/G_M$$

Recent Experiments @JLab : Projections

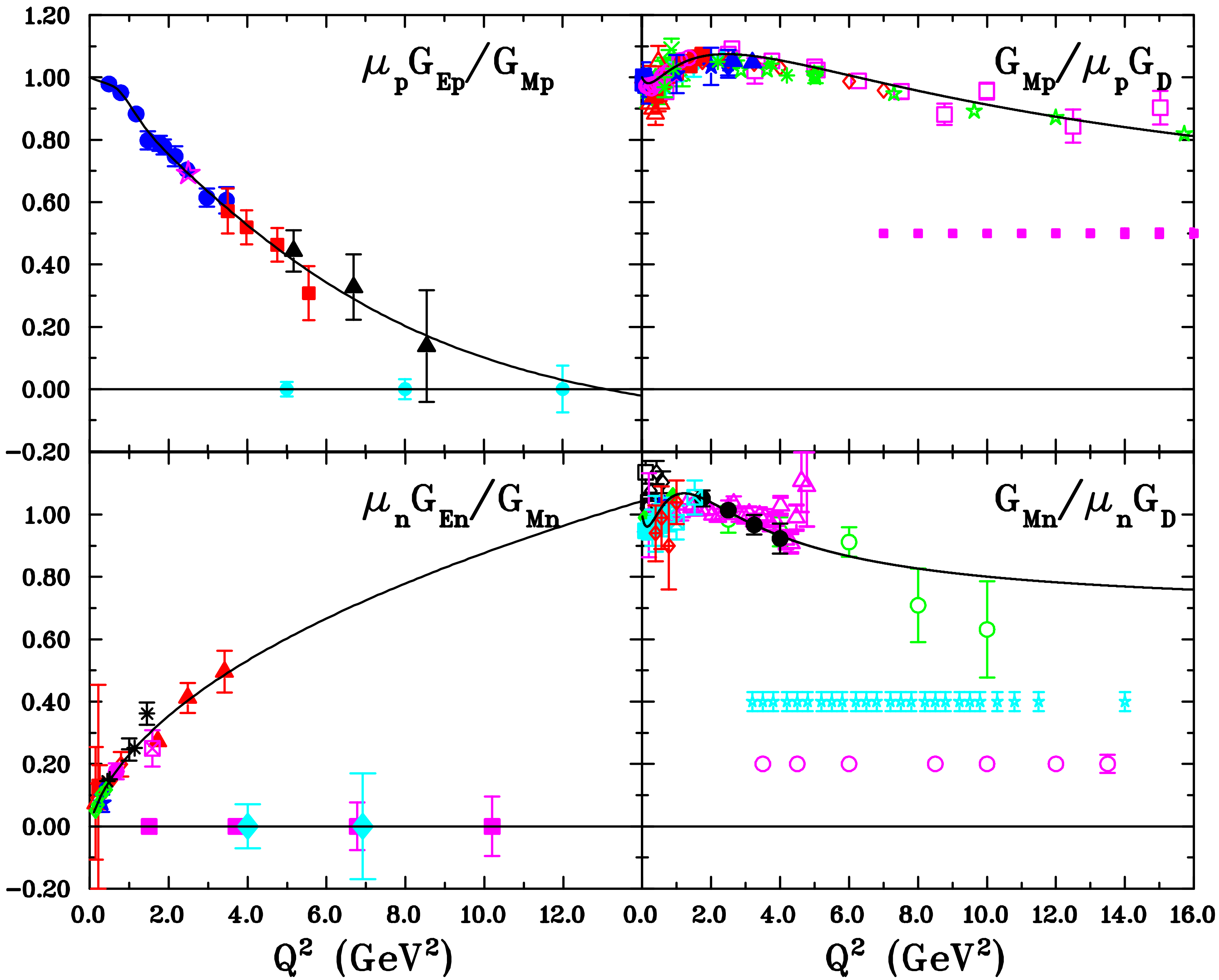


Projected new precision on proton & neutron form factors
[V. Punjabi et al, EPJ A51: 79 (2015); arXiv: 1503.01452]

Experiments at JLab@12GeV

- Hall A (HRS, SBS):
  - G_{Mp} @ $Q^2 \lesssim 17.5$ GeV^2
  - G_{Ep}/G_{Mp} @ $Q^2 \lesssim 15$ GeV^2 ;
  - G_{Mn} @ $Q^2 \lesssim 18$ GeV^2
  - G_{En}/G_{Mn} @ $Q^2 \lesssim 10.2$ GeV^2 ;
- Hall B (CLAS12):
  - G_{Mn} @ $Q^2 \lesssim 14$ GeV^2
- Hall C :
  - G_{En}/G_{Mn} @ $Q^2 \lesssim 6.9$ GeV^2

Recent Experiments: Projections + G_{Mp} Result



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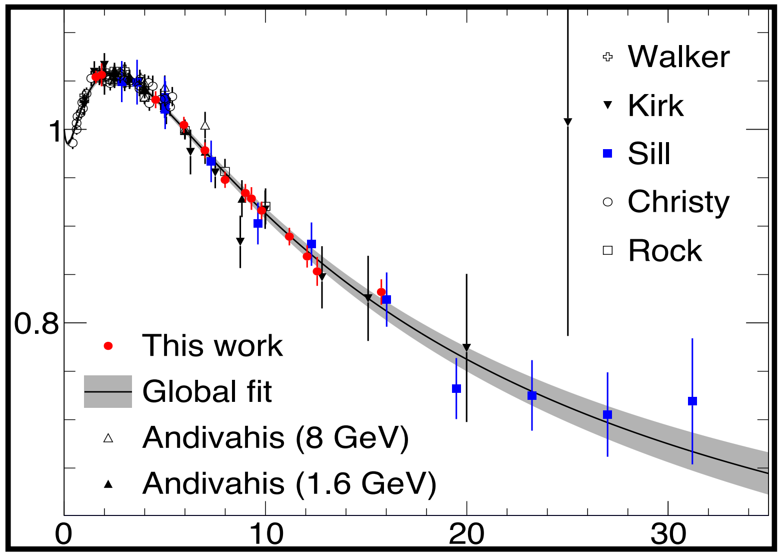
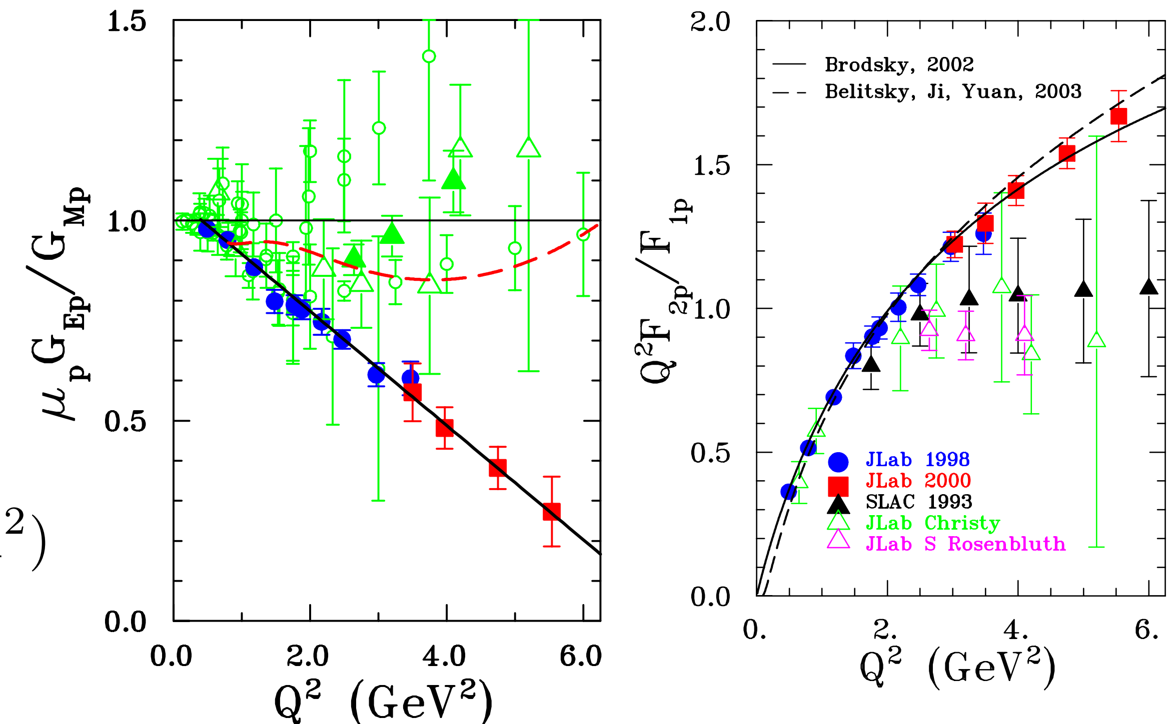


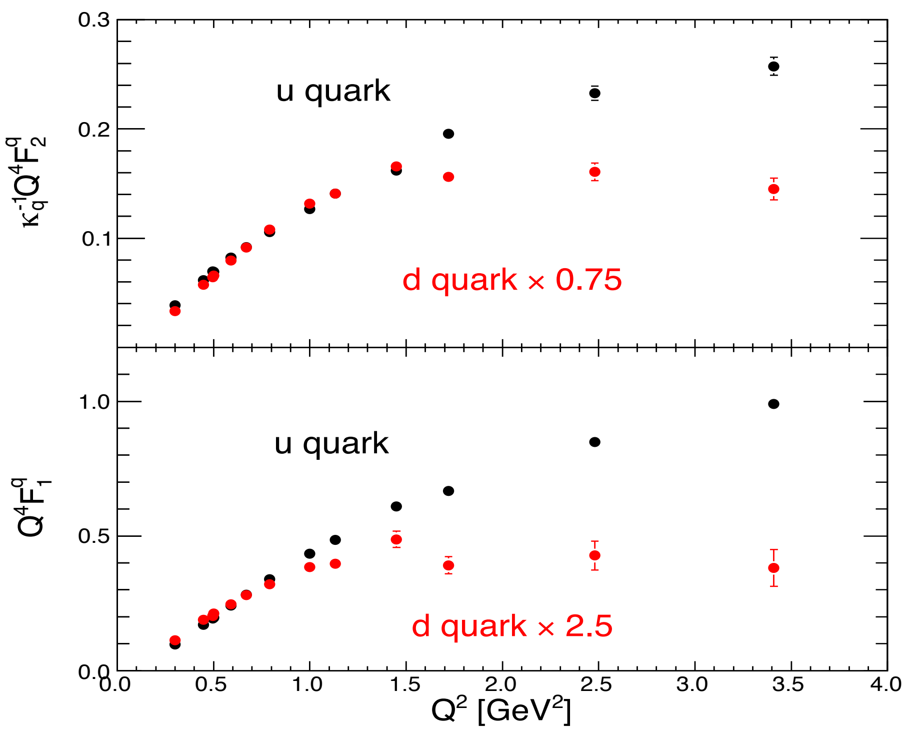
New G_{Mp} results (JLab Hall A)
[Christy et al, PRL'22]

Why Large-Q^2 Nucleon Form Factors?

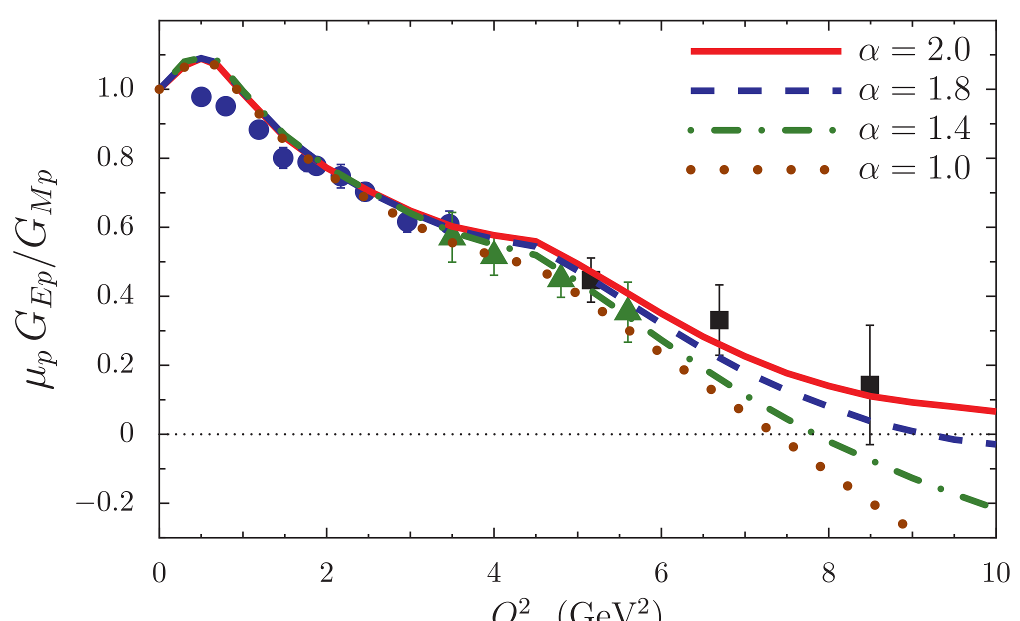
- *Rosenbluth / Pol.transfer discrepancy in G_E/G_M ?*
  Input from lattice QCD may help
- *Role of diquark correlations in elastic scattering ?*
  Neutron & proton G_E/G_M at/above Q^2 = 8 GeV²
- *Scale of transition to perturbative QCD ?*
  (F_2/F_1) scaling at large Q^2 : $Q^2 F_{2p}/F_{1p} \overset{?}{\propto} \log^2(Q^2/\Lambda^2)$
- *What are contributions from u and d flavors?*
  Proton <u>and</u> neutron data needed in wide Q^2 range



[Research Mgmt. Plan for SBS(JLab Hall A)]



[G.D.Cates, C.W.de Jager, S.Riordan, B.Wojtsekhovski, PRL106:252003, arXiv:1103.1808]



Dyson-Schwinger Eqns : quarks & 0⁺, 1⁺ diquarks
(α ≈ rate of transition const.quarks → pQCD with Q^2)
[Cloet, Roberts, Prog.Part.Nucl.Phys 77:1 (2014)]

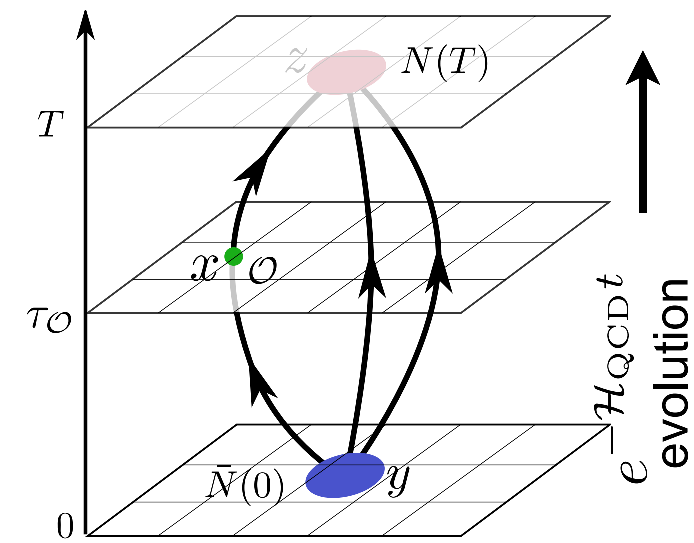
Nucleon Structure from Lattice QCD (in a Nutshell)

- Compute nucleon correlation functions

<u>Hadron Spectrum:</u>

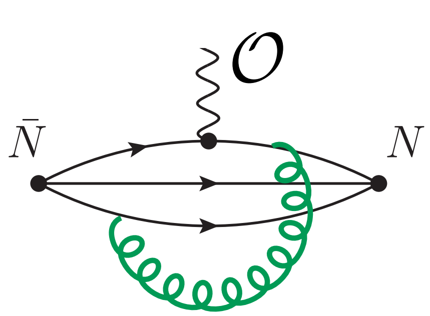
$$\langle N(\vec{p},T)\,\bar{N}(0)\rangle = \sum_{\vec{y}} \langle N(\vec{y},T)\,\bar{N}(0)\rangle$$

$$\sim |Z_0|^2 e^{-E_0 T}\left[1 + e^{-\Delta E_{10} T} + \dots\right]$$



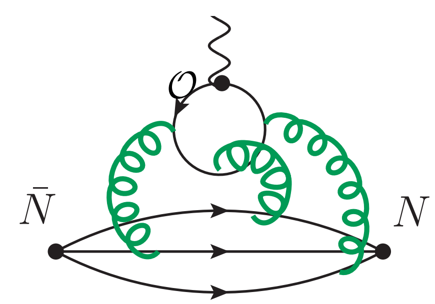
<u>Hadron Matrix Elements:</u>

$$\langle N(T)\mathcal{O}(\tau)\bar{N}(0)\rangle =$$



quark-connected

+



quark-disconnected

Quark lines = $(\not{D} + m)^{-1} \cdot \psi$

- Extract ground state matrix elements

$$\langle N(T)\mathcal{O}(\tau)N(0)\rangle = \sum_{n,m} Z_m e^{-E_n(T-\tau)} \langle n|\mathcal{O}|m\rangle e^{-E_m\tau} Z_n^*$$

$$\xrightarrow{T\to\infty} Z_0 Z_{0'}^* e^{-E_0\tau - E_{0'}(T-\tau)}\left[\langle 0'|\mathcal{O}|0\rangle + \underbrace{O\left(e^{-\Delta E\{T,\tau,(T-\tau)\}}\right)}_{\text{excited states}}\right]$$

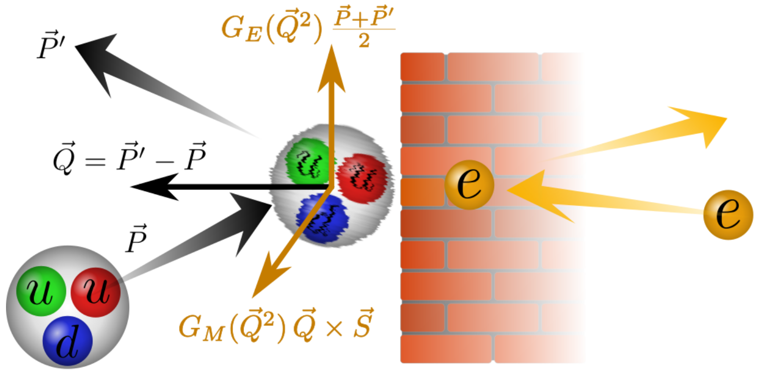
Ground state form factors

$$[\bar{u}'\gamma^\mu u]F_1 + [\bar{u}'\frac{i\sigma^{\mu\nu}q_\nu}{2m_N}u]F_2$$

Fit and discard

Systematic uncertainties
- discretization effects
- unphysical-heavy pion mass
- finite volume
- excited state contributions
- quark-disconnected diagrams

Challenges at Large Q²



- Excited-states gaps shrink
  - $E_1 - E_0 = \sqrt{M_1^2 + \vec{p}^2} - \sqrt{M_2^2 + \vec{p}^2} < M_1 - M_0$
  - N(~1500): $p_N \to 1.5$ GeV ⇒ ΔE = 500 → 300 MeV

- Stochastic noise grows faster with *T* [Lepage'89]:

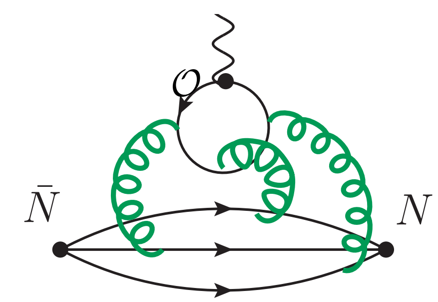
$$\begin{array}{lll} \text{Signal} & \langle N(T)\bar{N}(0)\rangle & \sim e^{-E_N T} \\ \text{Noise} & \langle |N(T)\bar{N}(0)|^2\rangle - |\langle N(T)\bar{N}(0)\rangle|^2 & \sim e^{-3m_\pi T} \\ \text{Signal/Noise} & & \sim e^{-(E_N - \frac{3}{2}m_\pi)T} \end{array}$$

SNR decay ~ O(10⁻⁴)
at T=1 fm/c
(phys.quarks, Q²≈12 GeV²)

- Discretization effects:
  O(a) Correction to current operator

$$(V_\mu)_I = [\bar{q}\gamma_\mu q] + c_V\, a\, \underbrace{\partial_\nu[\bar{q} i \sigma_{\mu\nu} q]}_{\propto Q}$$

- Quark-disconnected contributions:
  negligible (≲1%) at Q² ≤ 1 GeV², unknown at large Q²



- No reliable EFT/ChPT for m_π-, lattice-volume extrapolation at large-$p_{Nucleon}$

Many of the same challenges as for parton physics on a lattice
(LaMET , Quasi-/Pseudo- PDFs/DAs/TMDs)

Present QCD Calculation Parameters

QCD on lattice with $N_F = 2{+}1$ O(a²) dynamic quarks

Many thanks to [JLab , W&M , LANL , MIT] groups

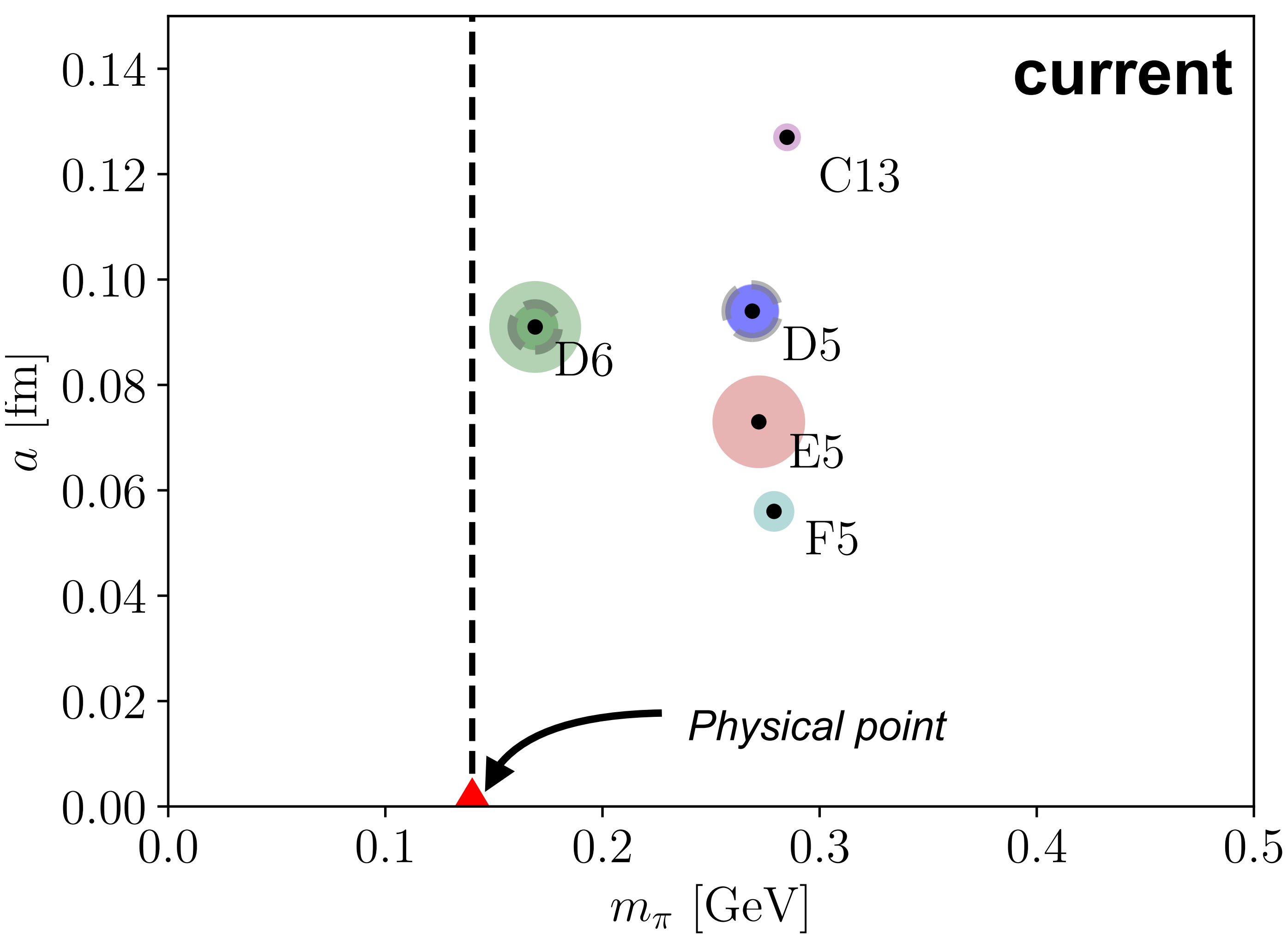
- Lattice spacing $a \approx 0.056 \div 0.091$ fm
- Nf=2+1 flavors ($SU(2)_f$ -symmetric + strange)
- Pion mass $m\pi = 170 \div 280$ MeV
- Physical volume $L \gtrsim 3.7\,(m\pi)^{-1}$
- Euclidean time t_{sep}= 0.5 ÷ 1.1 fm
  noise grows rapidly beyond 1fm

2022/25:

- Large Statistics (≳250k) on D6 ($m\pi$ =170 MeV), E5 ($m\pi$ =280 MeV, a=0.073 fm)
- Disconnected contractions on D5, D6

2026:

- initial Statistics ≳47k on F5, ($m\pi$ =280 MeV, a=0.056 fm)



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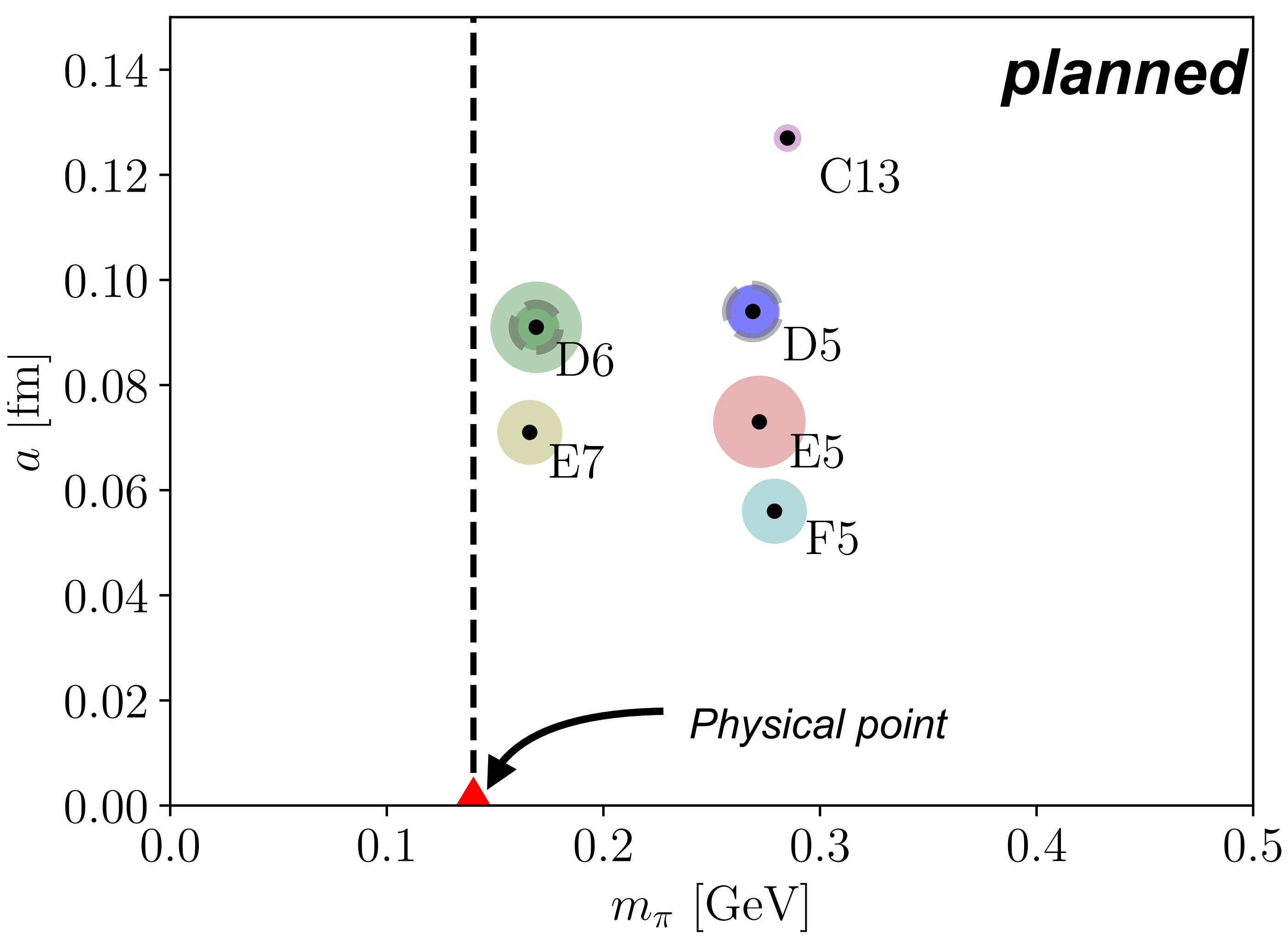
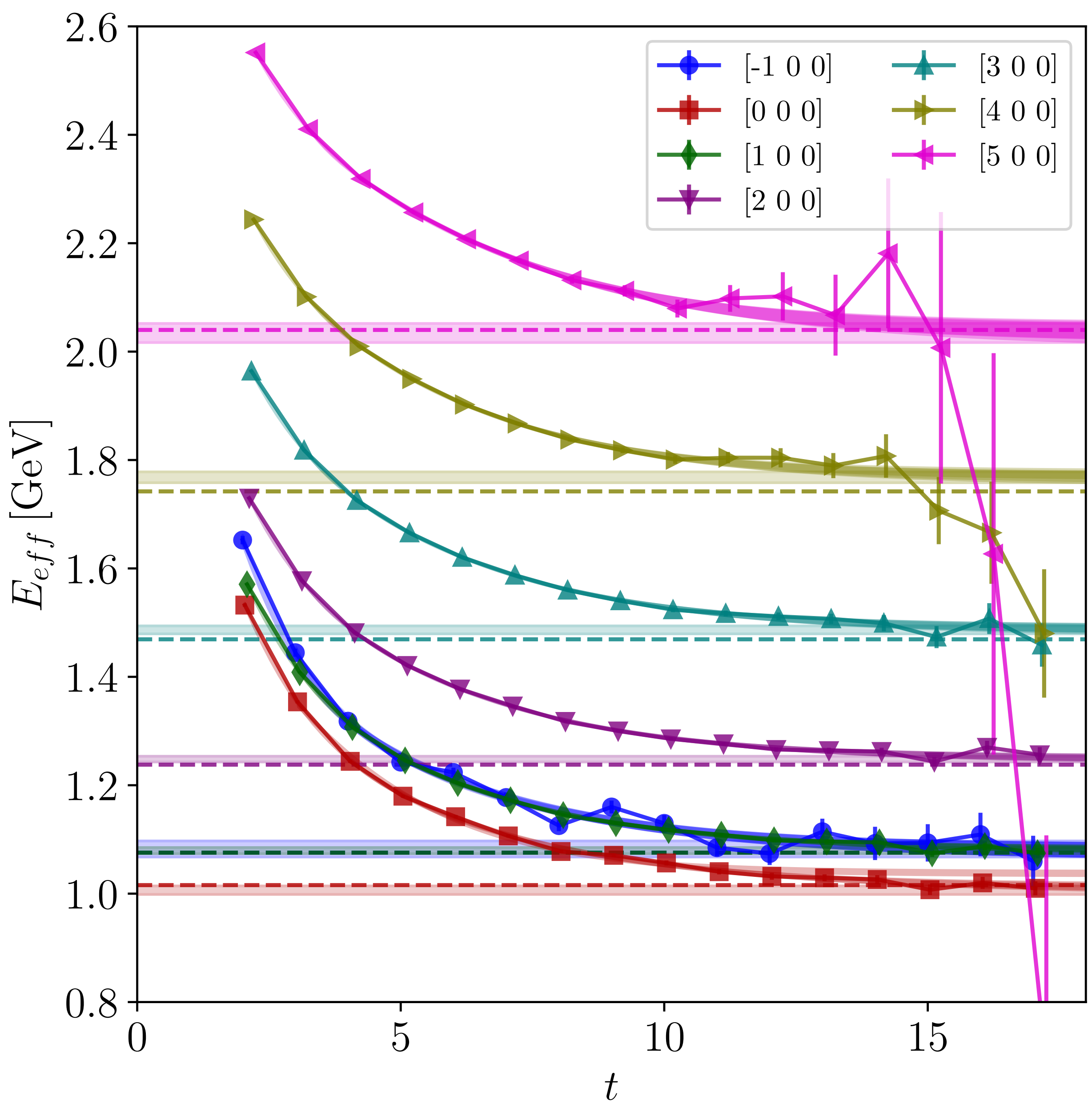
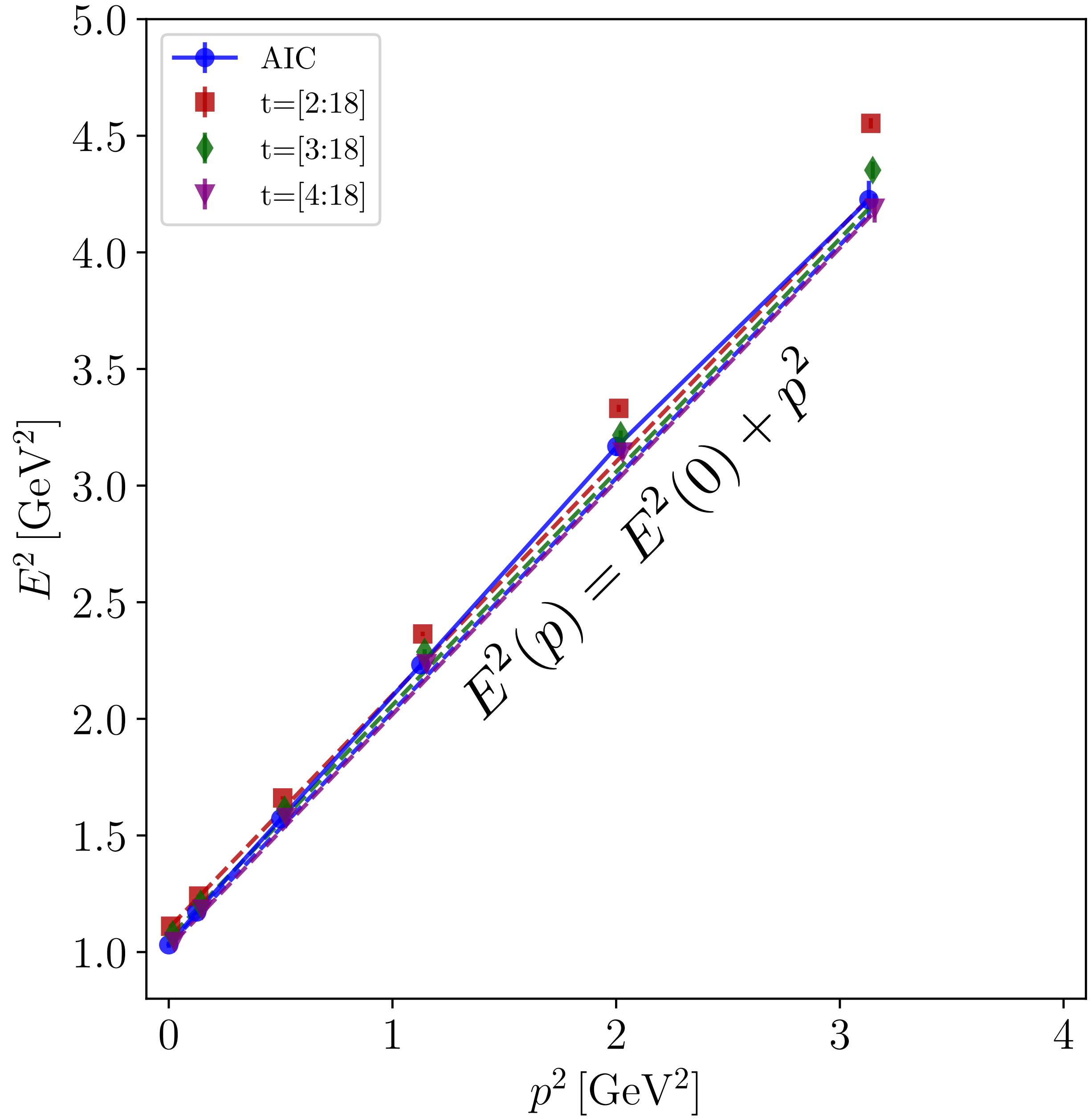


Lattice Nucleon Energy & Dispersion Relation (E5)

- E5 : $m\pi =$ 272 MeV , spacing $a = 0.073$ fm , 266k MC samples





- 2-state fits compared to Effective energy

$$E_{eff} = \frac{1}{a} \log \frac{C_{N\bar{N}}(t)}{C_{N\bar{N}}(t+a)}$$

- Lattice energies vs. continuum dispersion relation (dashed)

Analysis Minutiae

- Filter outliers: large deviation from median (~2% at a=0.09 fm, ~0.15% at a=0.07 fm)
  - *suppress noise in covariance estimates*

    [A.Agadjanov et al, Phys.Rev.Lett. 131 (2023) 261902]

$$|y - y_{median}| \geq 25 \cdot \underbrace{\Delta y}_{\text{(median abs. deviation)}}$$

- Varying fit windows

  Averaged wiith AIC

  [W.Jay, E.Neil PRD 103:114502(2021); E.Neil, J.W.Sitison, 109:014510(2024)].

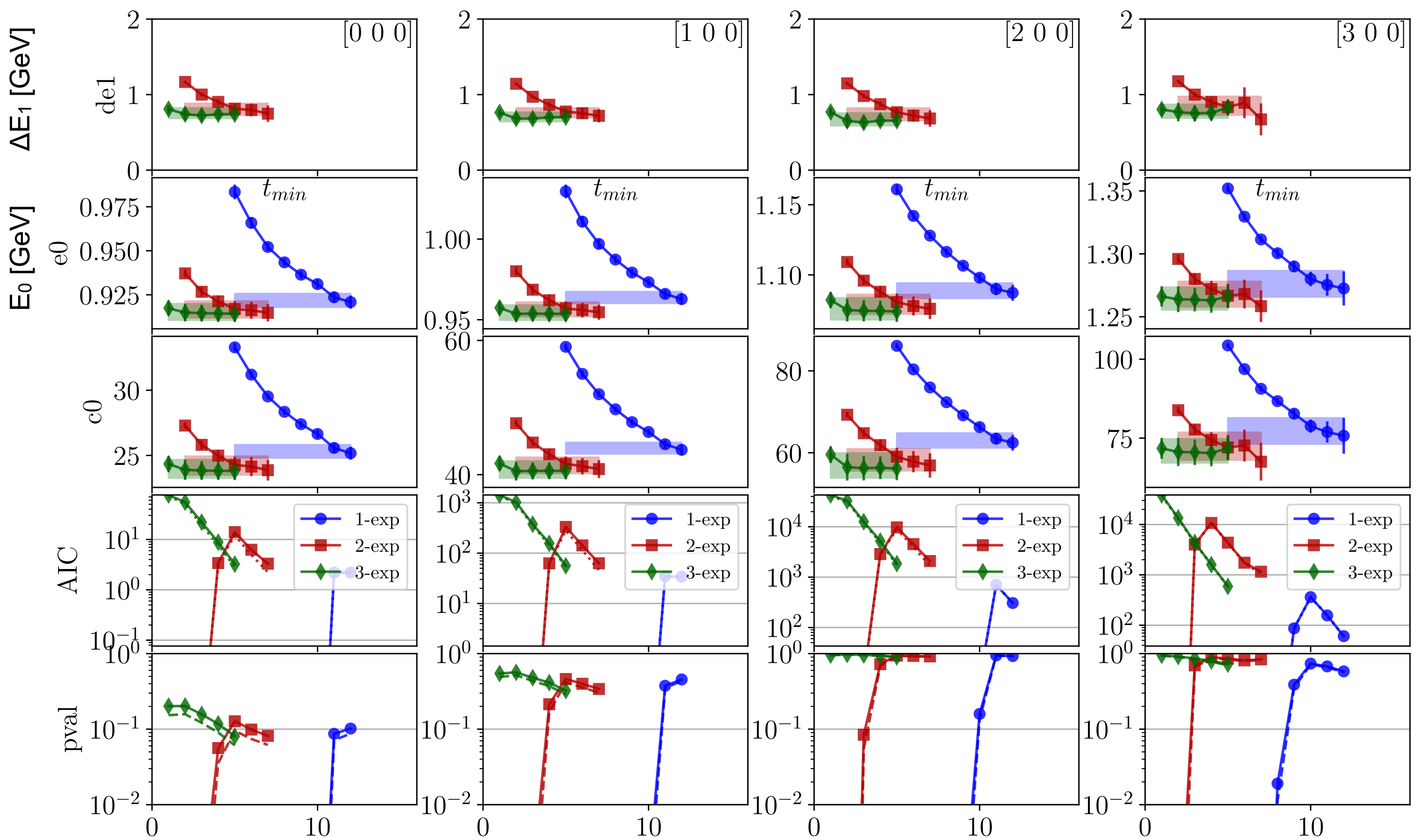
$$w_i \;\; \propto \exp\left(- \chi_i^2 + N_i^{\text{dof}} \right)$$

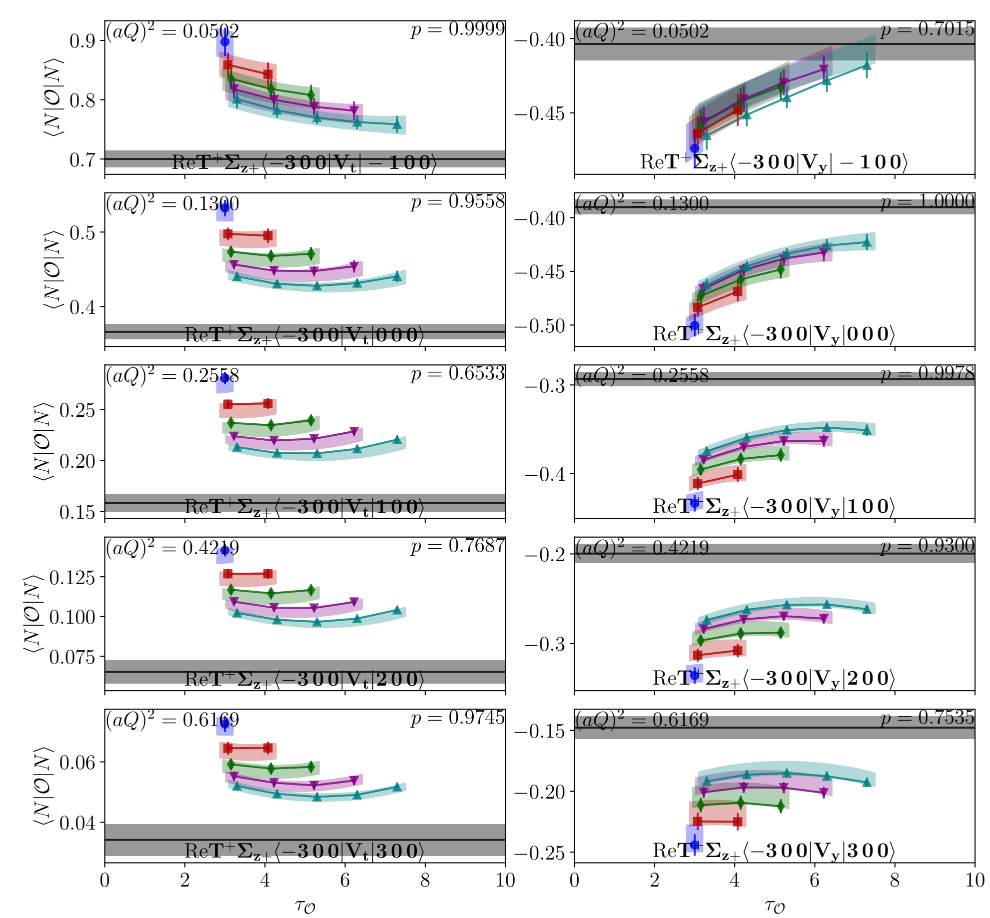
current matrix elements from $\langle N\, J\, \bar{N} \rangle$:
$$\begin{cases} \langle J_t \rangle & \propto G_E \\ \langle J_{\vec{q}\times\vec{S}} \rangle & \propto G_M \end{cases}$$

energies and ground-state amplitudes from $\langle N\, \bar{N} \rangle$:

$$\langle N(t)\, \bar{N}(0) \rangle \sim c_0 e^{-E_0 t} + c_1 e^{-(E_0 + \Delta E_1)t} + \ldots$$

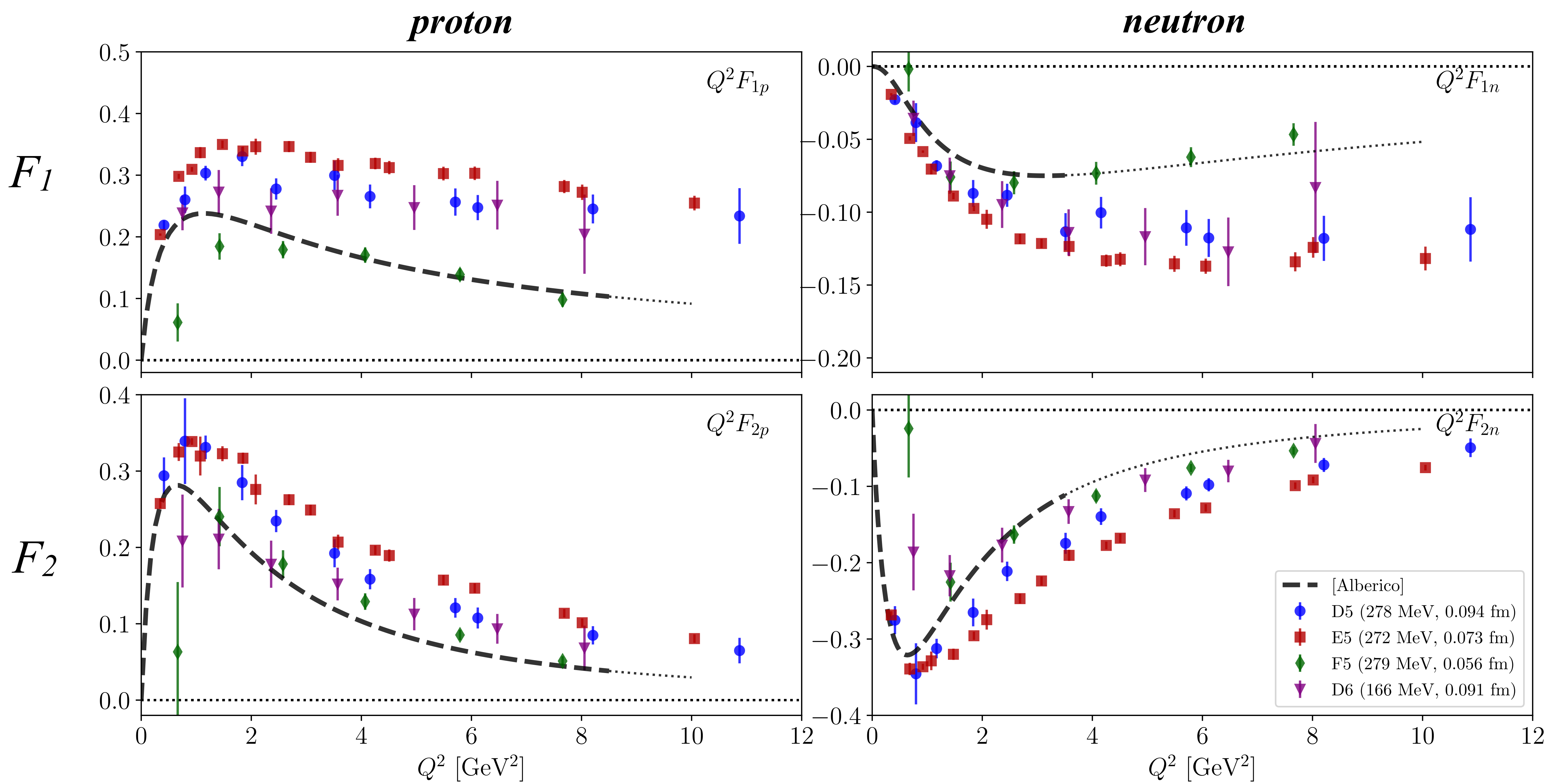
$$\langle N' |\, J(\tau)\, | N \rangle \sim \mathcal{A}_{00} \left[1 + O(e^{-\Delta E_1^{(\prime)} t} + \ldots)_{\text{exc}} \right]$$





Nucleon Form Factors: Dirac and Pauli

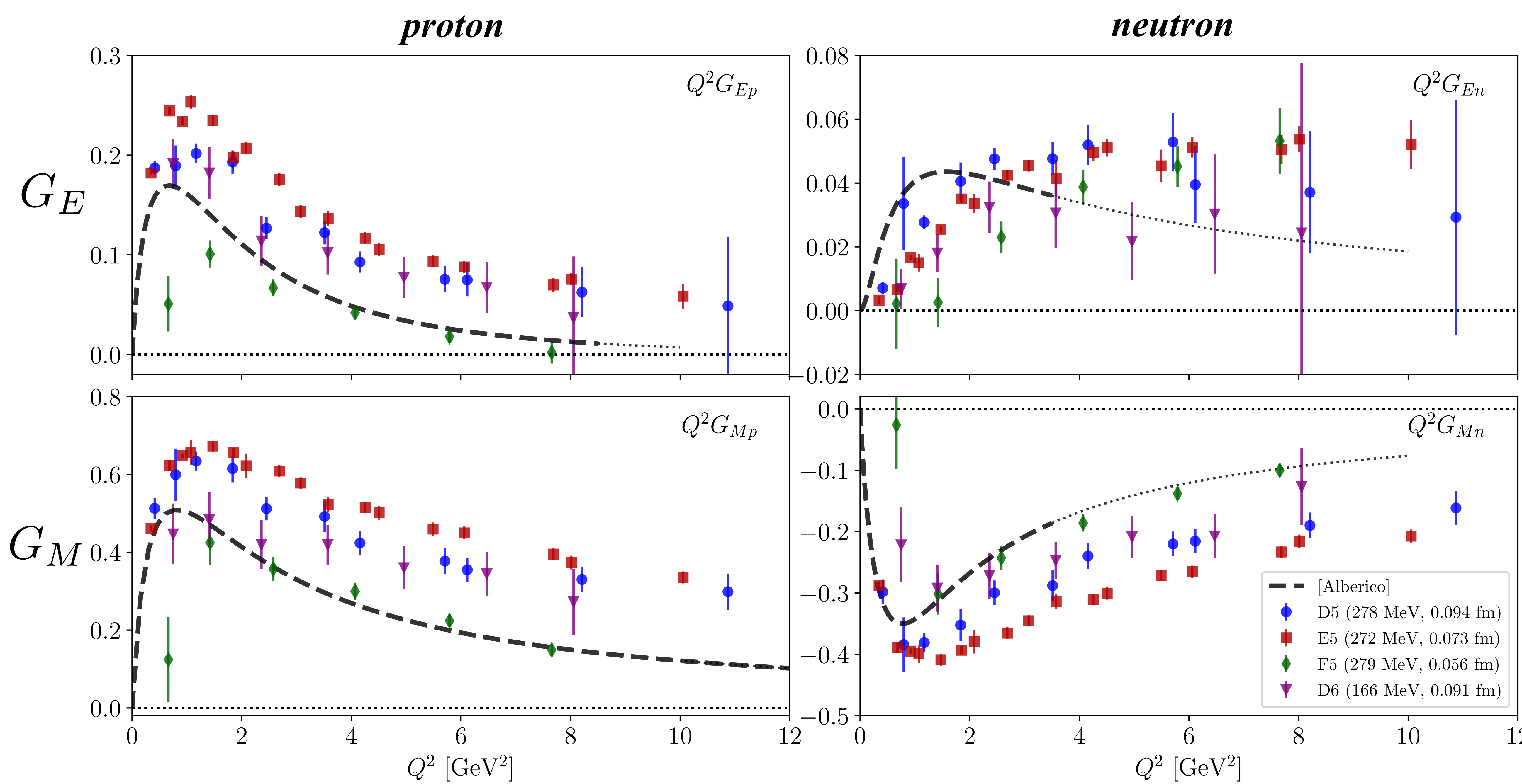
- Comparison of 4 ensembles (**D5** : 86k, **E5** : 266k, **F5** : 47k, **D6** : 261k)
- Lattice error bars: stat. + sys[high exc. states]
- *(dashed line)* Phenomenological fit [Alberico et al, PRC79:065204 (2008)]



- *No disconnected diagrams*

Nucleon Form Factors: Sachs Electric and Magn.

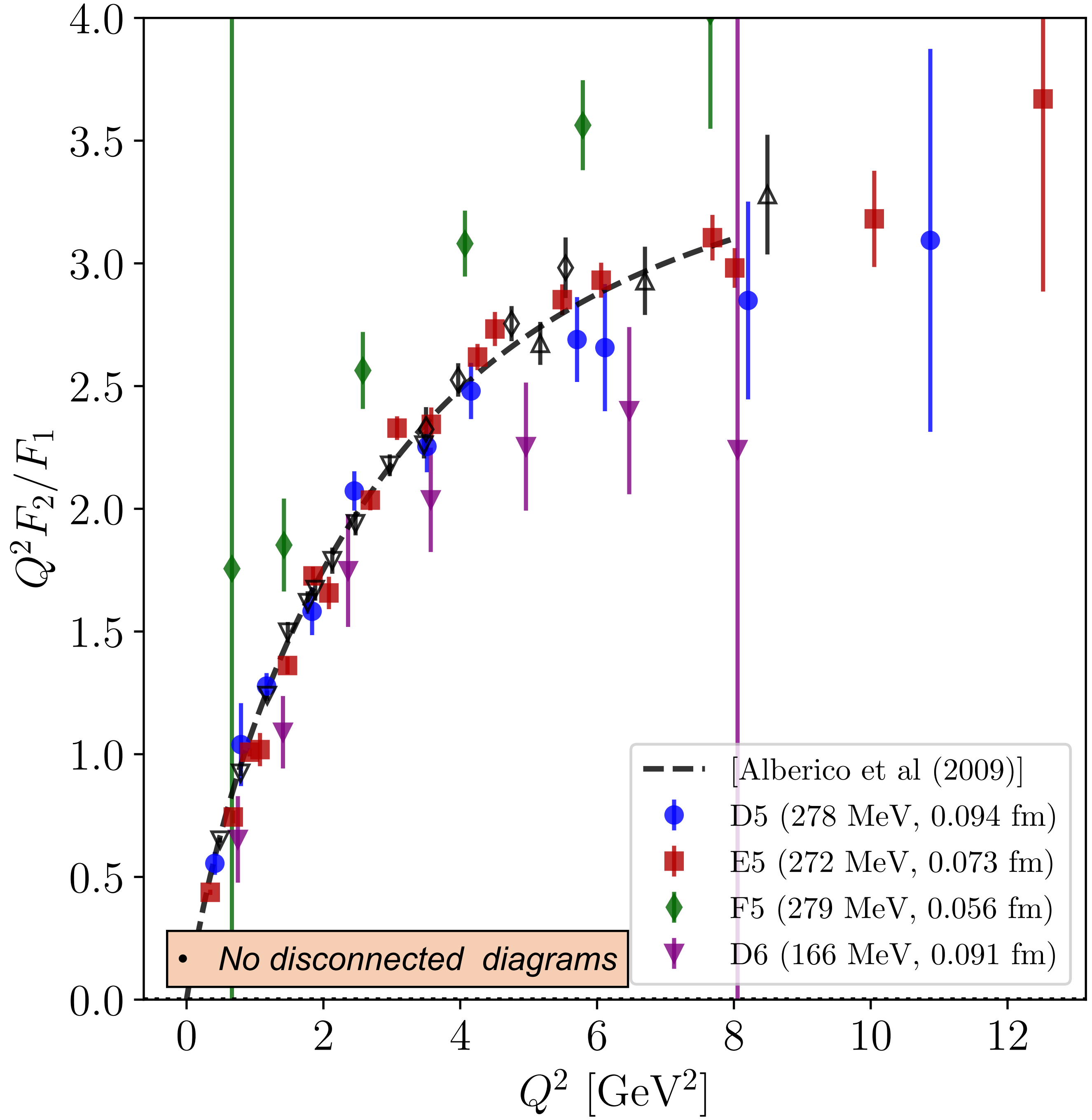
- Comparison of 4 ensembles (**D5** : 86k, **E5** : 266k, **F5** : 47k, **D6** : 261k)
- Lattice error bars: stat. + sys[high exc. states]
- *(dashed line)* Phenomenological fit [Alberico et al, PRC79:065204 (2008)]



- *No disconnected diagrams*

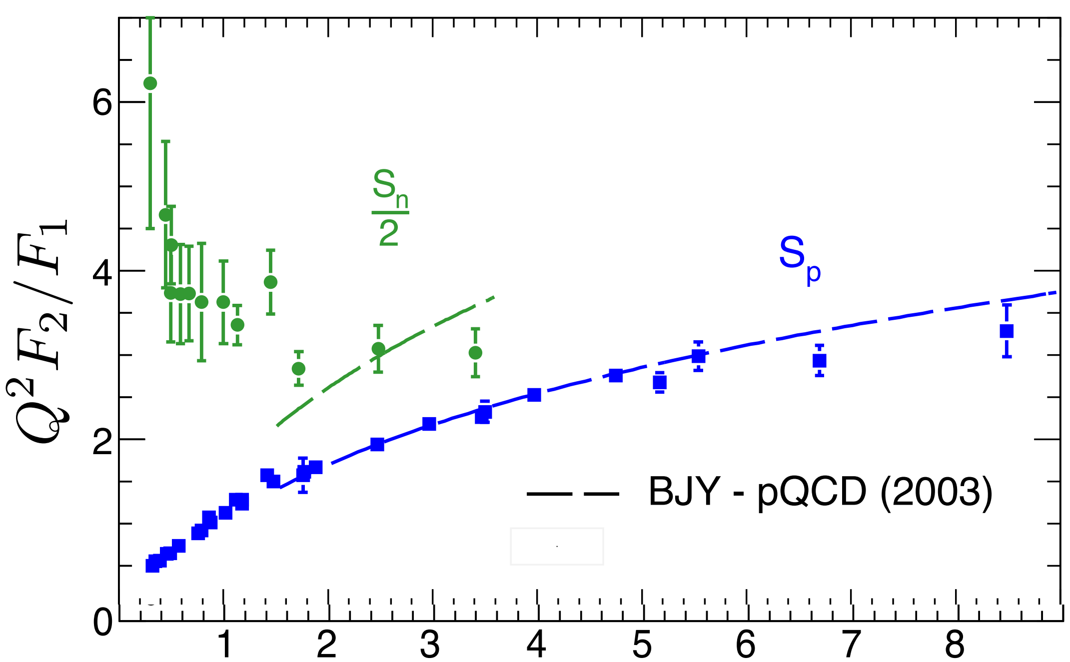
Proton F_2/F_1 Ratio

- Comparison of 4 ensembles (**D5** : 86k, **E5** : 266k, **F5** : 47k, **D6** : 261k)
- *(dashed line)* Phenomenological fit [Alberico et al, PRC79:065204 (2008)]
- (black points) Experimental data for proton ($Q^2 \lesssim 8.5$ GeV²)



- Prediction from pQCD + quark OAM [Balitsky, Ji, Yuan (2003)]

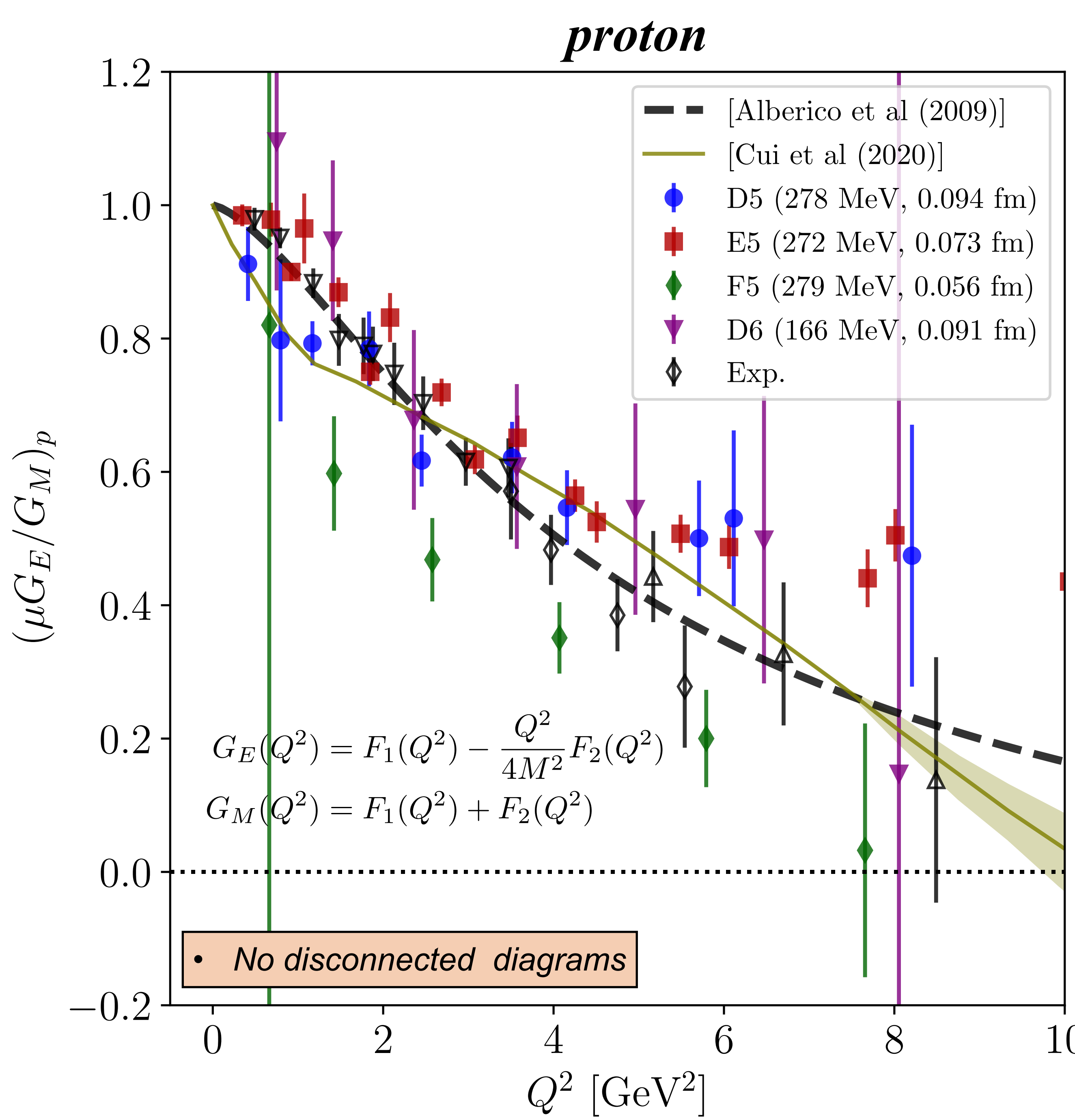
$$Q^2 F_{2p}/F_{1p} \overset{?}{\propto} \log^2(Q^2/\Lambda^2)$$

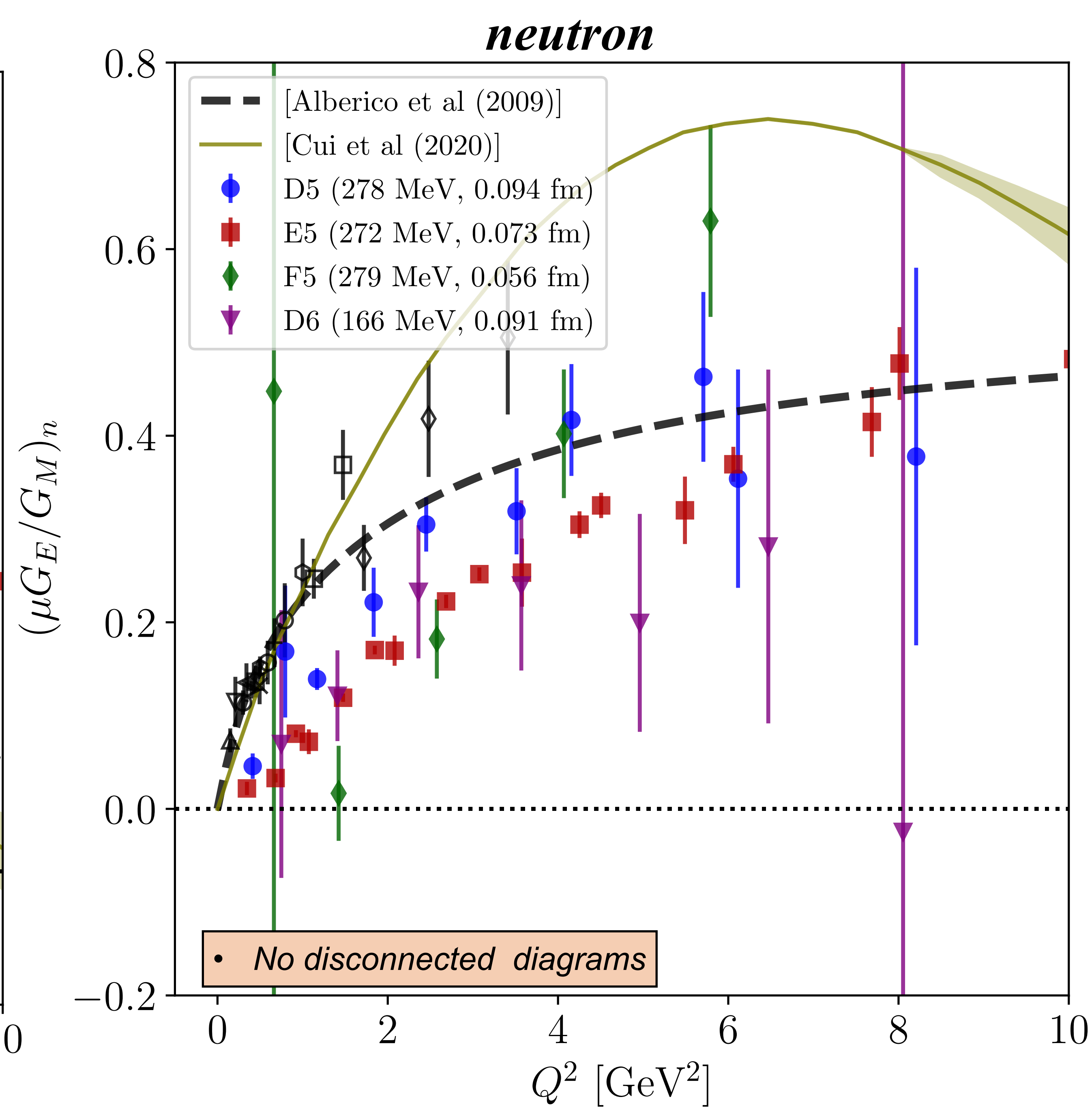


[G.D.Cates, et al, PRL106:252003 (2011)]

Proton & Neutron G_E/G_M Ratio

- Comparison of 4 ensembles (**D5** : 86k, **E5** : 266k, **F5** : 47k, **D6** : 261k)
- *(dashed line)* Phenomenological fit [Alberico et al, PRC79:065204 (2008)]
- *(black points)* Experimental data for proton ($Q^2 \lesssim 8.5$ GeV^2) and neutron ($Q^2 \lesssim 3.4$ GeV^2)





Proton&Neutron G_E/G_M from $\langle N J \bar{N}\rangle$ Correlators

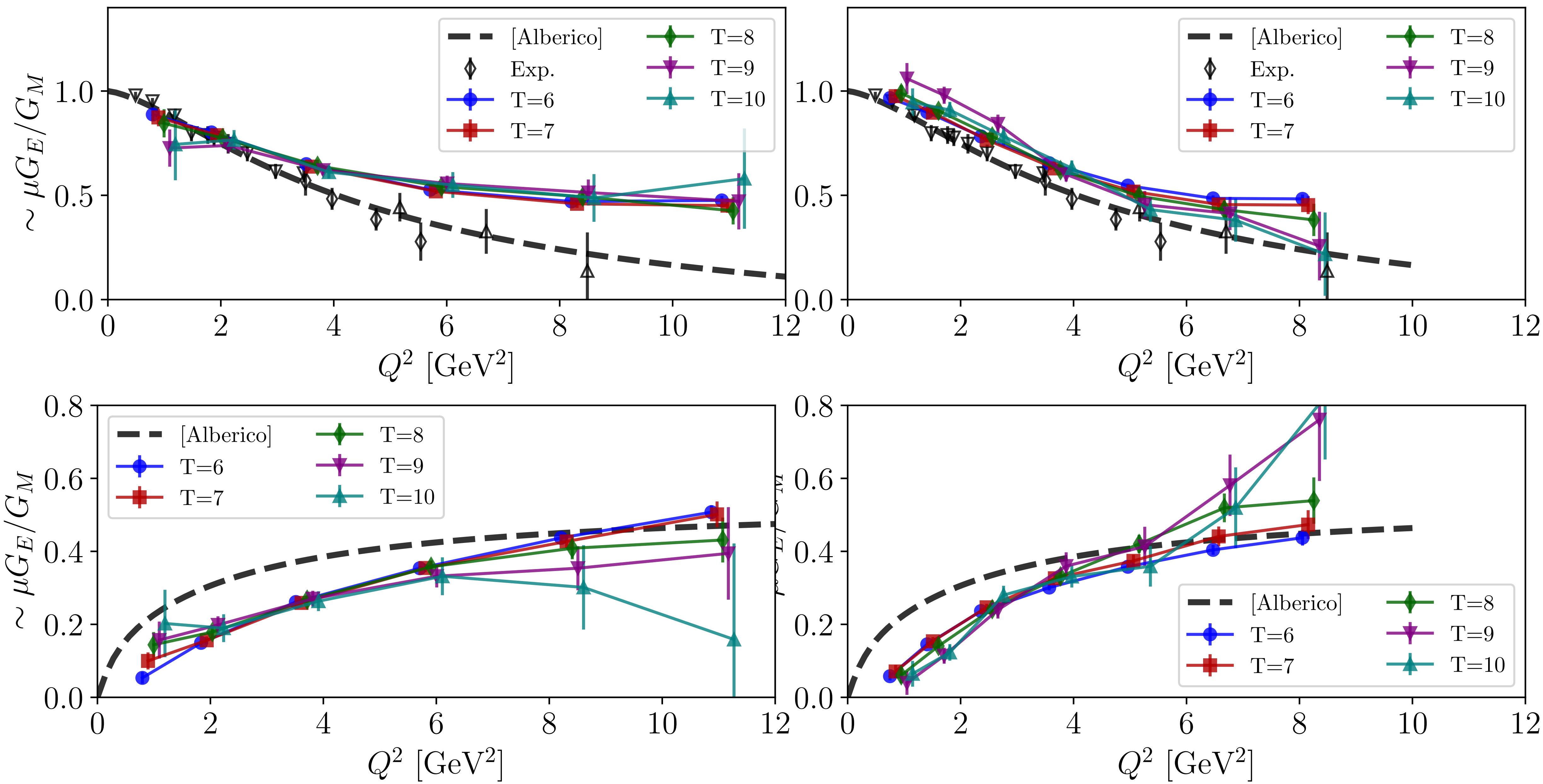
$$\left(\frac{\sinh\frac{\lambda'-\lambda}{2}}{\cosh\frac{\lambda'+\lambda}{2}}\right)\frac{\mathrm{Re}\langle N_\uparrow(p'_x,T)\,J_t(T/2)\,\bar{N}_\uparrow(p_x,0)\rangle}{\mathrm{Re}\langle N_\uparrow(p'_x,T)\,J_y(T/2)\,\bar{N}_\uparrow(p_x,0)\rangle}\overset{T\to\infty}{=}G_E/G_M$$

with $\begin{pmatrix} p^{(\prime)} & = m_N\sinh\lambda^{(\prime)} \\ E^{(\prime)} & = m_N\cosh\lambda^{(\prime)} \end{pmatrix}$

D5($m\pi$ =278 MeV, a = 0.094 fm) **D6($m\pi$ =170 MeV, a = 0.094 fm)**

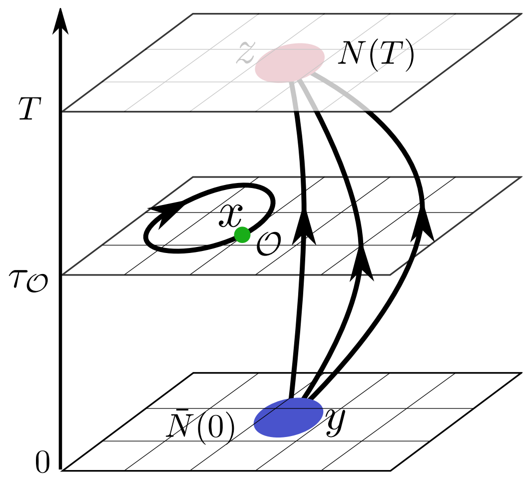
proton

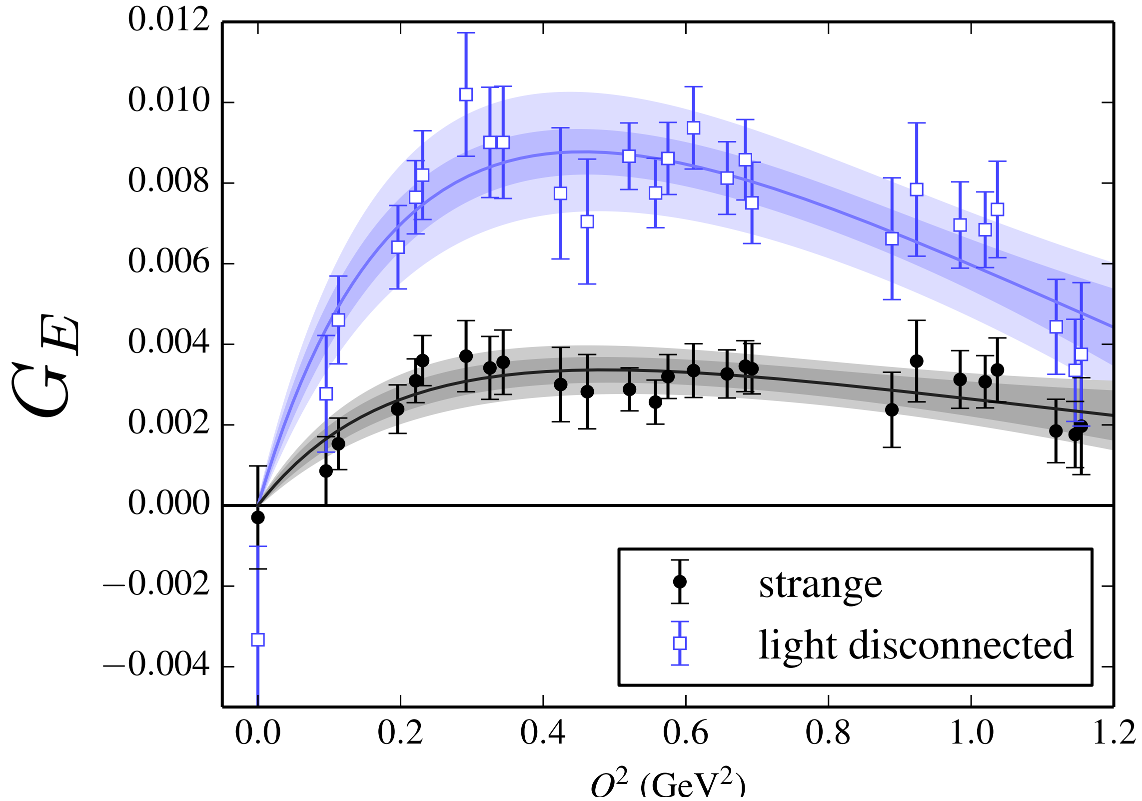
neutron



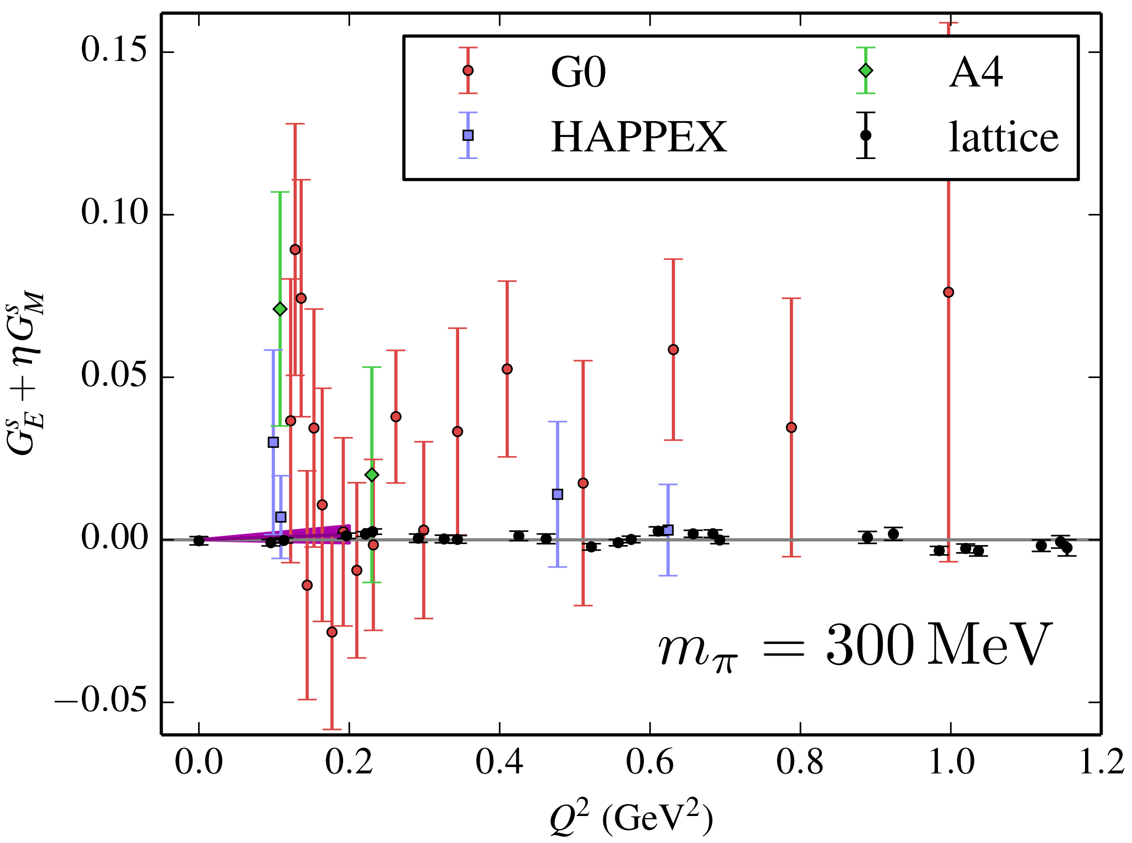
- Comparison of 4 ensembles (**D5** : 86k, **D6** : 261k); varying tsep = amount of exc.states
- *Nucleon excited state(s) have very similar GE/GM at large Q2?*

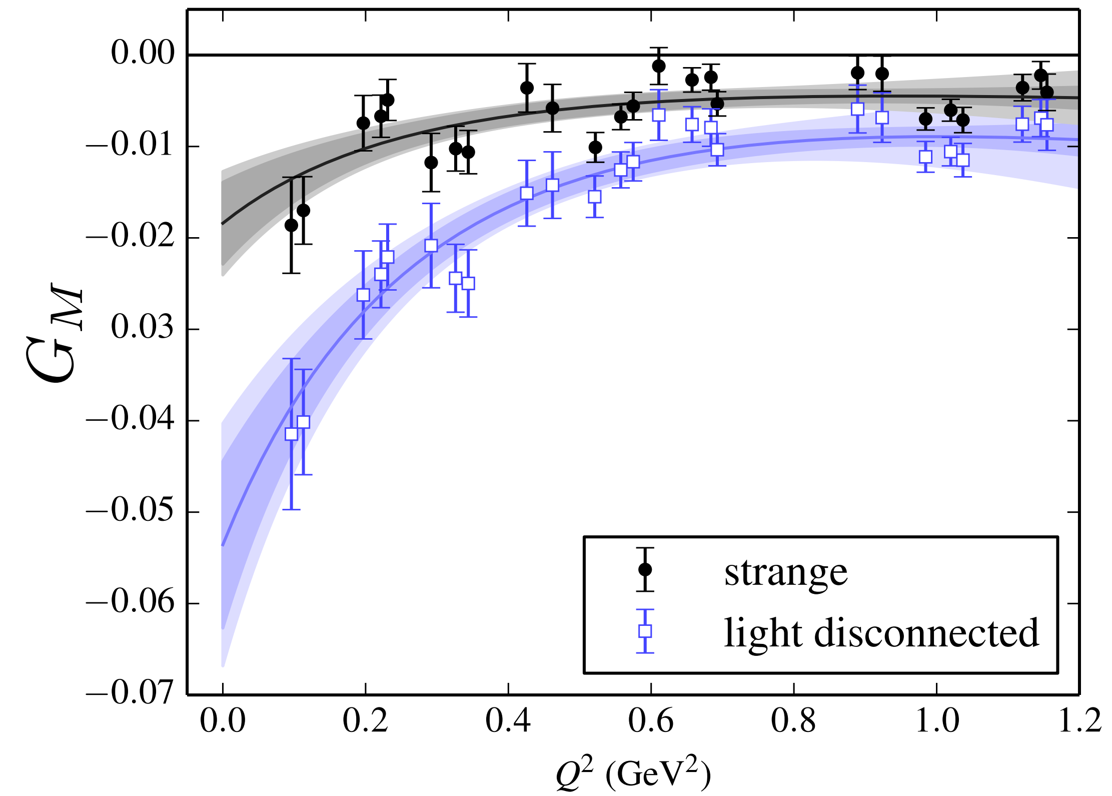
Disconnected Contributions to Vector FFs?





Disconnected-U,D and S:
≲ 1% of nucleon FFs at $Q^2 \lesssim 1$ GeV^2
[J. Green, S. Meinel, S.S. et al; PRD92:031501 (2015)]



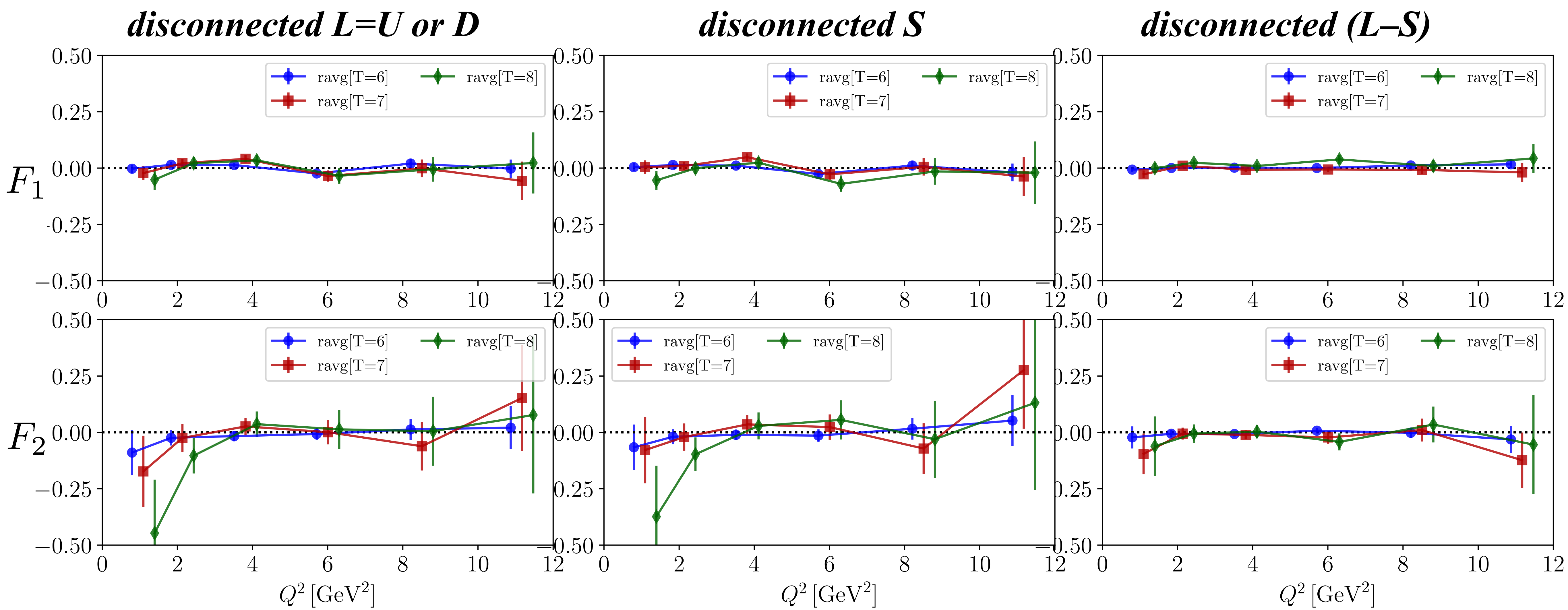


Disconnected-U,D & Strange vs. Connected (D5)

- *relative correction* $|\delta F_{1,2}^{disc} / F_{1,2}^{conn}| \lesssim 10\%$ *but quickly grows with Euclidean time*
- partial noise cancellation in (L–S) contributing to proton & neutron

$$P = \frac{1}{3}[2U - D]_{conn} + \frac{1}{3}[L - S]_{disc}$$

$$N = \frac{1}{3}[2D - U]_{conn} + \frac{1}{3}[L - S]_{disc}$$



D5 ensemble (m_π=280 MeV, a=0.094 fm), 86k samples of $\langle N\bar{N}\rangle$

G_E/G_M : Systematics from Disconnected U,D & S

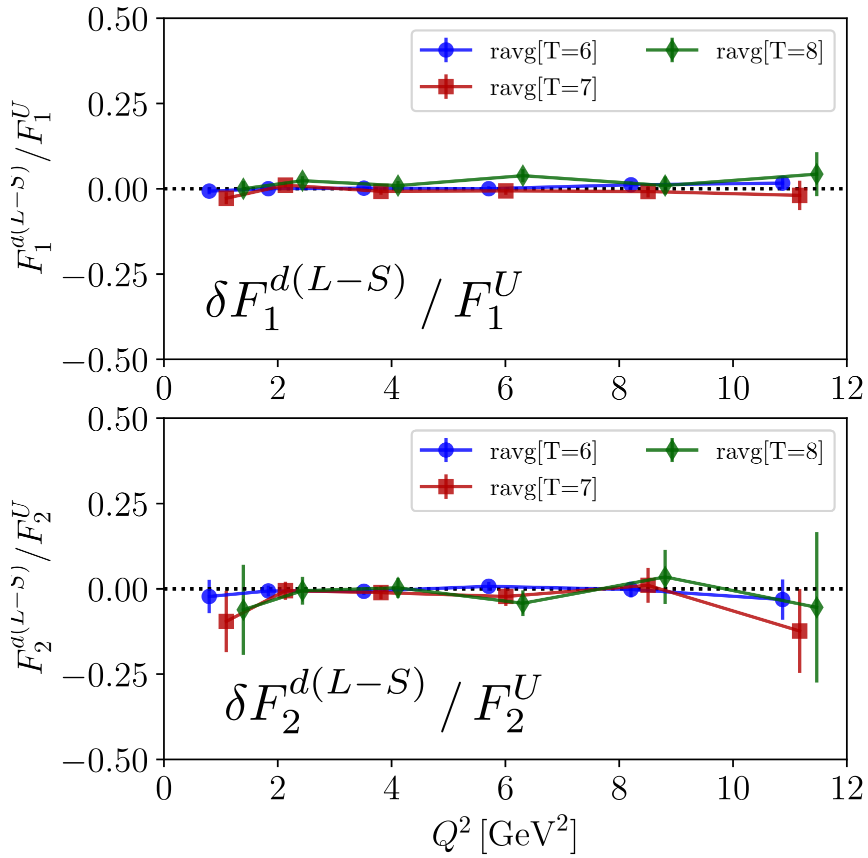
- partial noise cancellation in (L–S) contributing to proton & neutron

$$P = \frac{1}{3}\left[2U - D\right]_{conn} + \frac{1}{3}\left[L - S\right]_{disc}$$

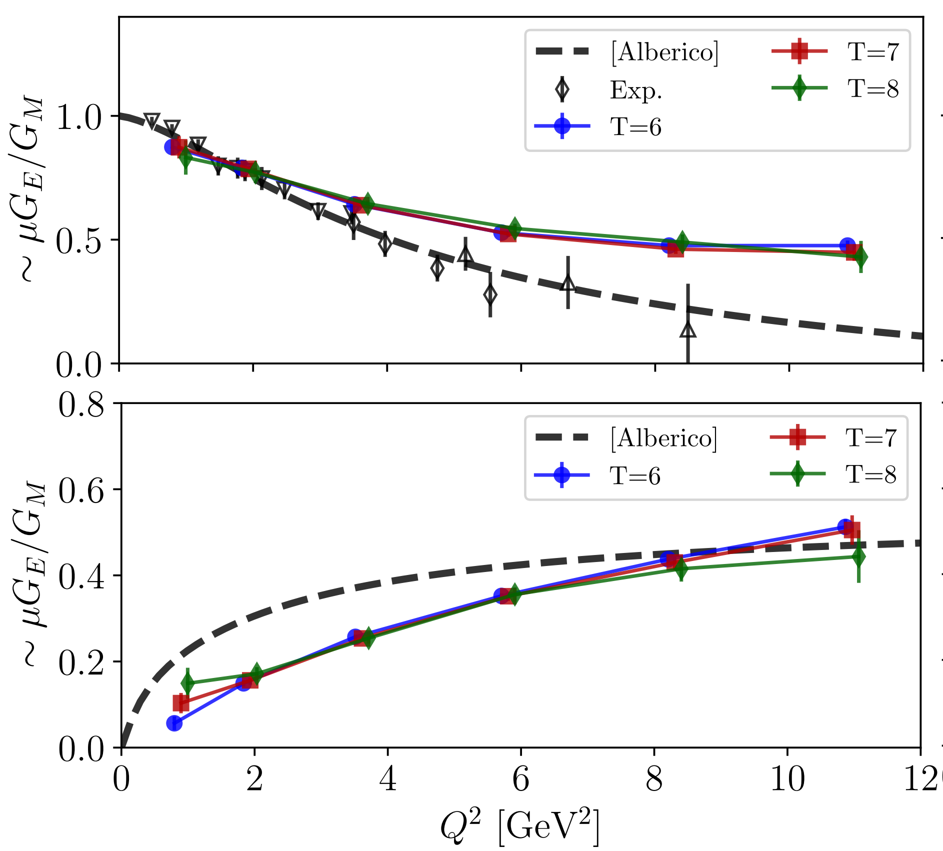
$$N = \frac{1}{3}\left[2D - U\right]_{conn} + \frac{1}{3}\left[L - S\right]_{disc}$$

- limited effect on G_E/G_M – *within stat. noise*
- larger effect on flavor-decomposition of $F_{1,2}$

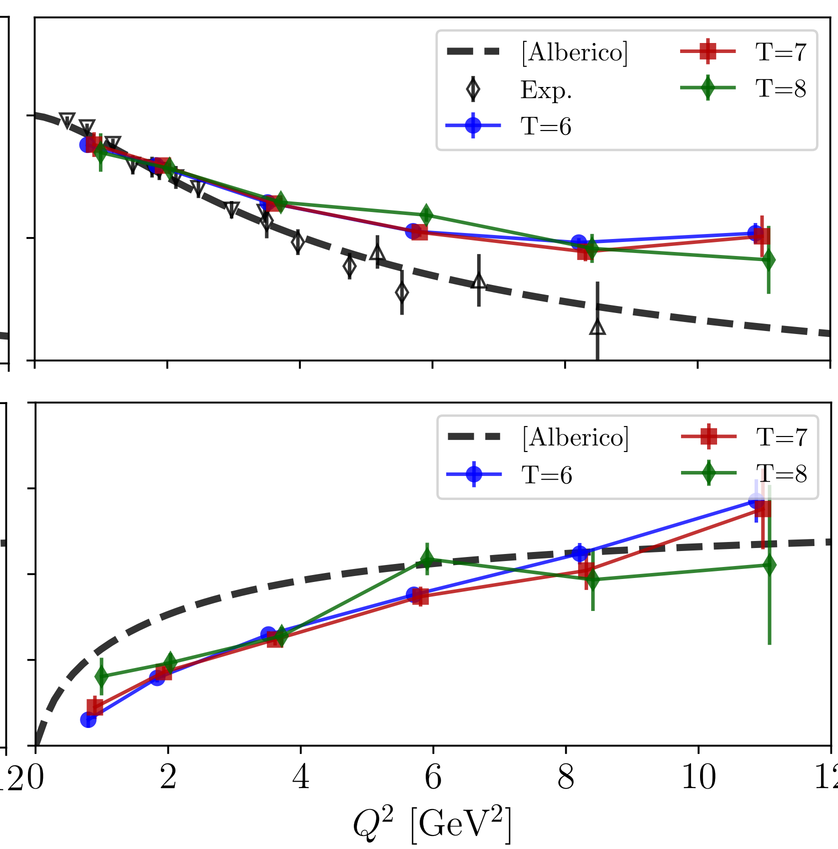
disconnected (L–S), relative to conn.



G_E/G_M, CONN. ONLY

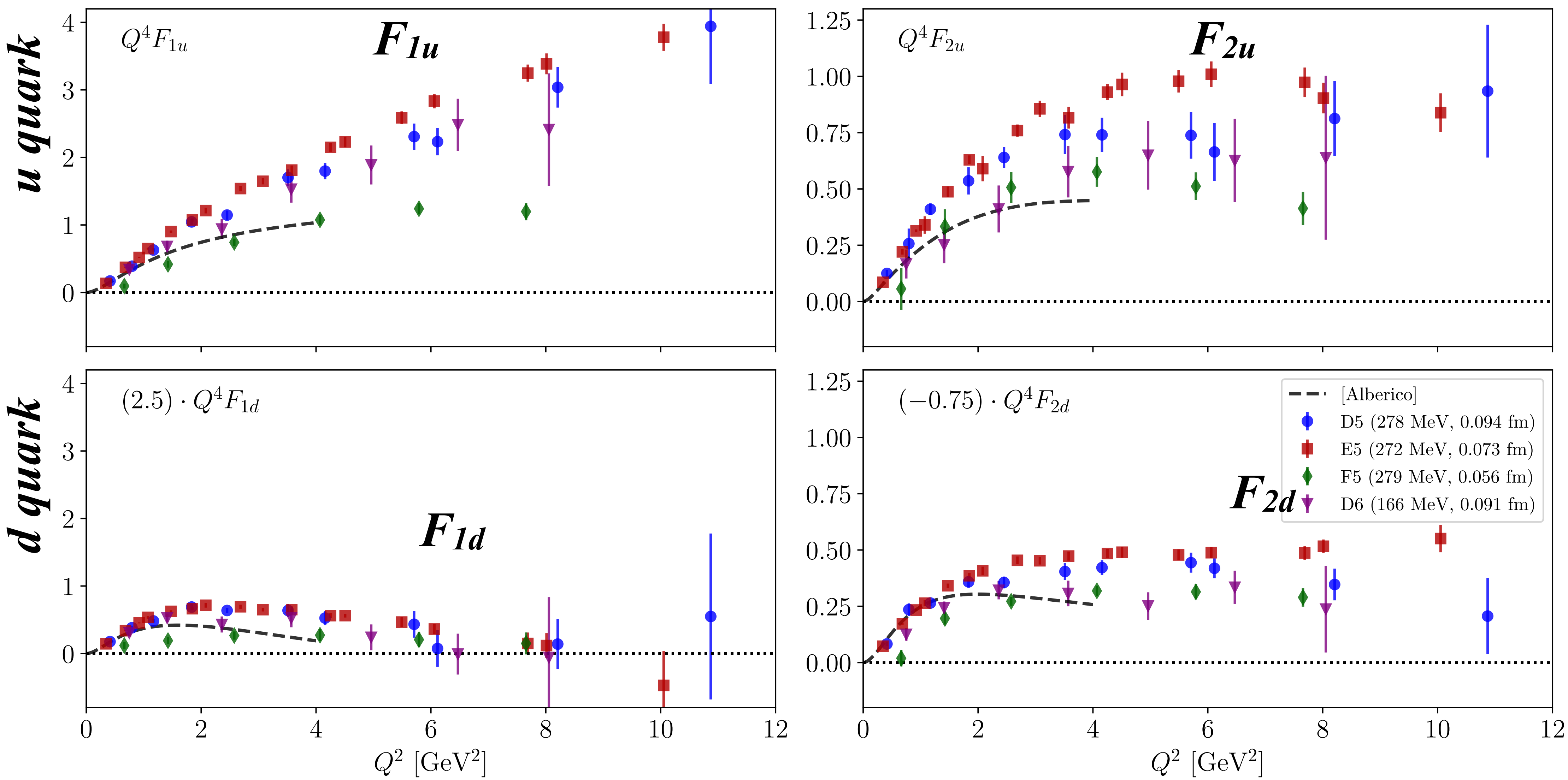


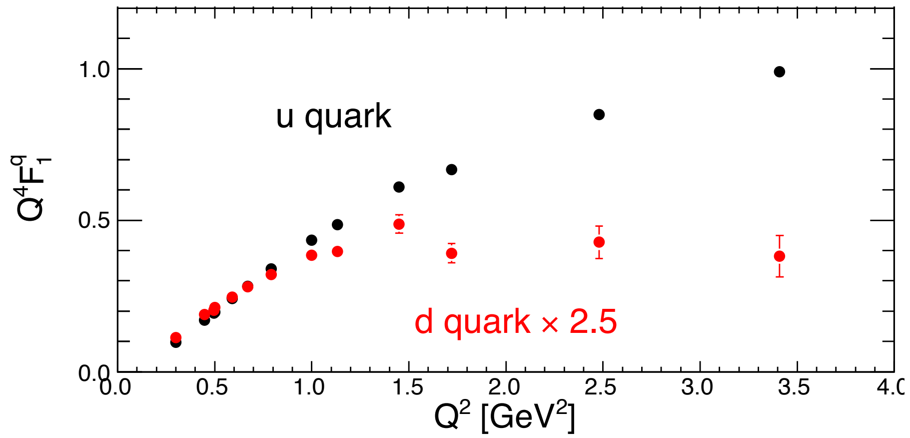
G_E/G_M, FULL

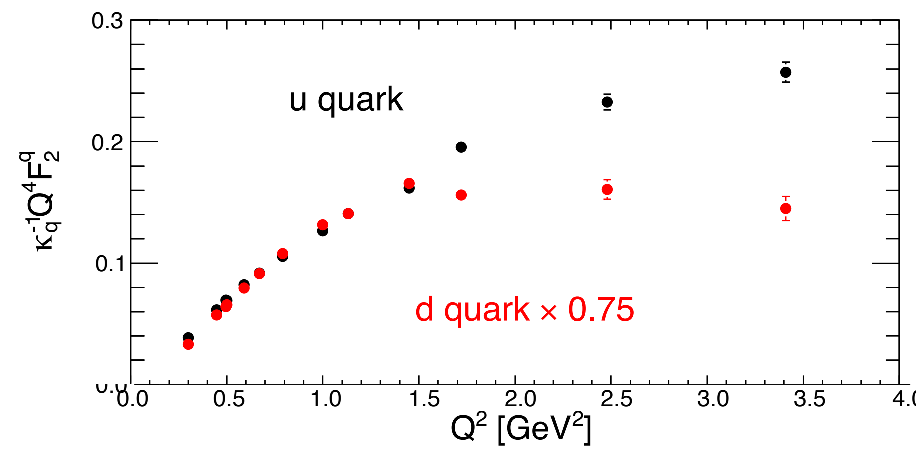


D5 ensemble ($m\pi$=280 MeV, a=0.094 fm), t_{sep}= 0.50÷0.75 fm

Light-flavor Contributions to Proton Form Factors

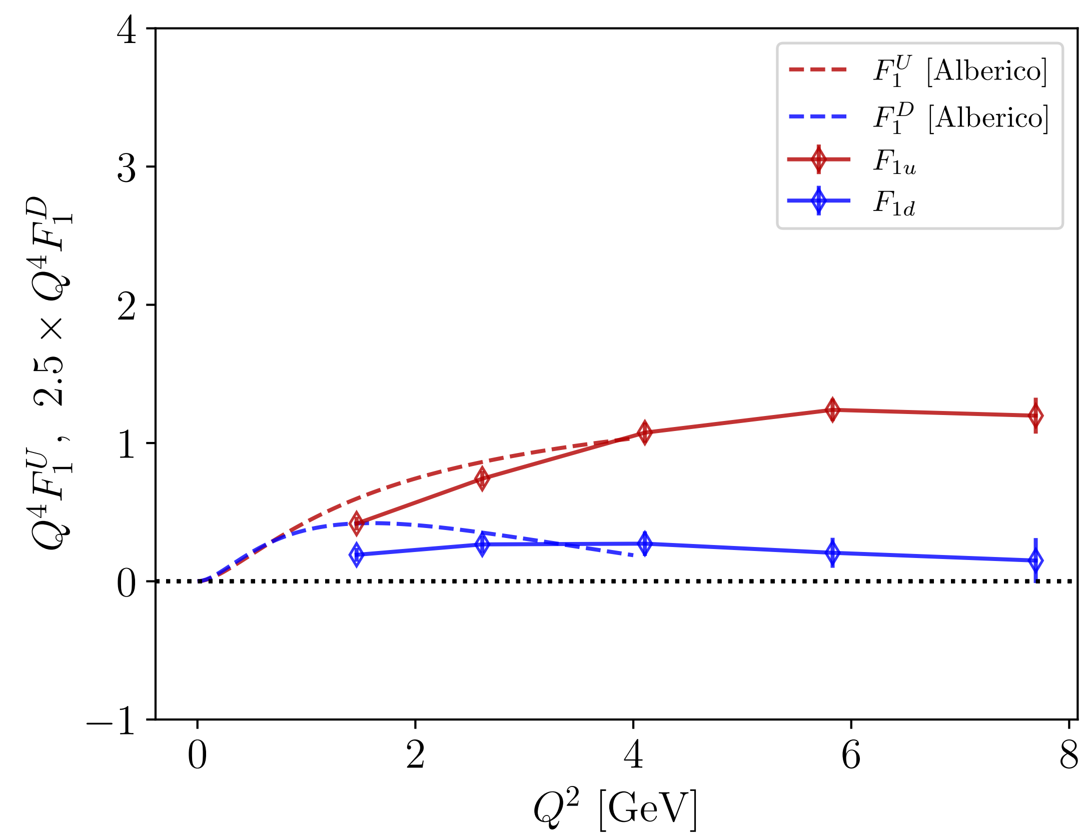


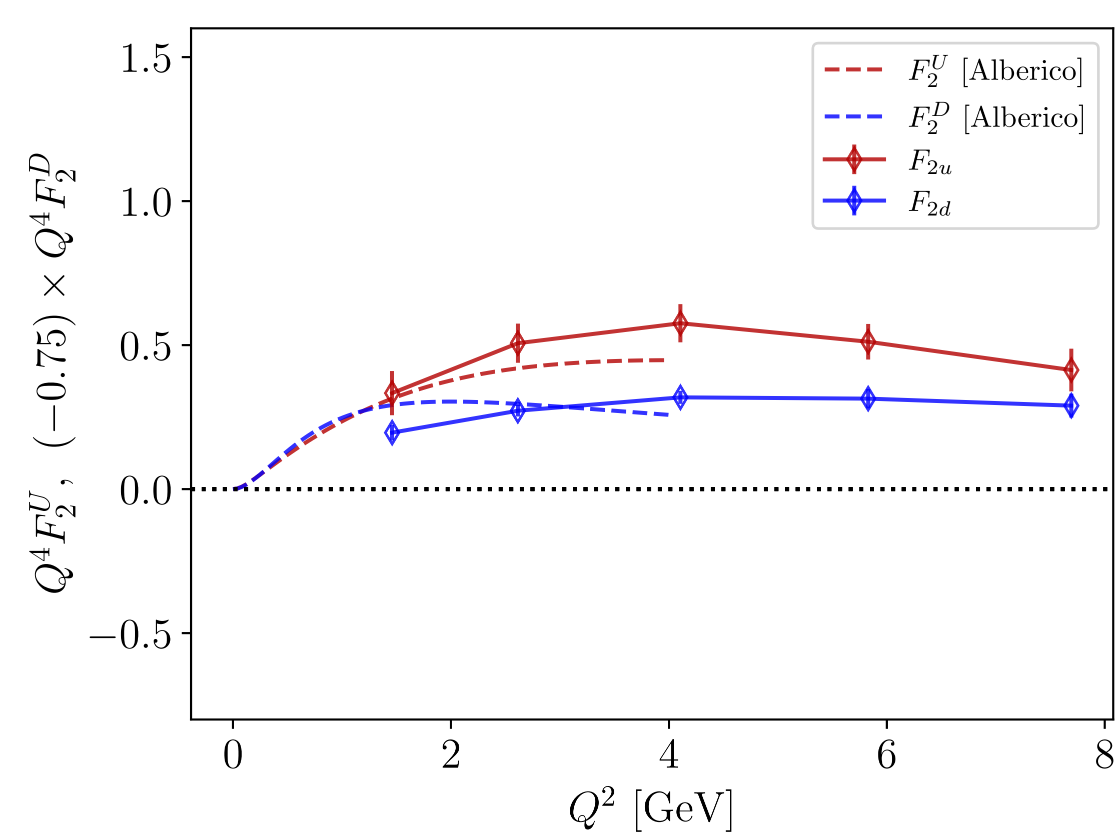


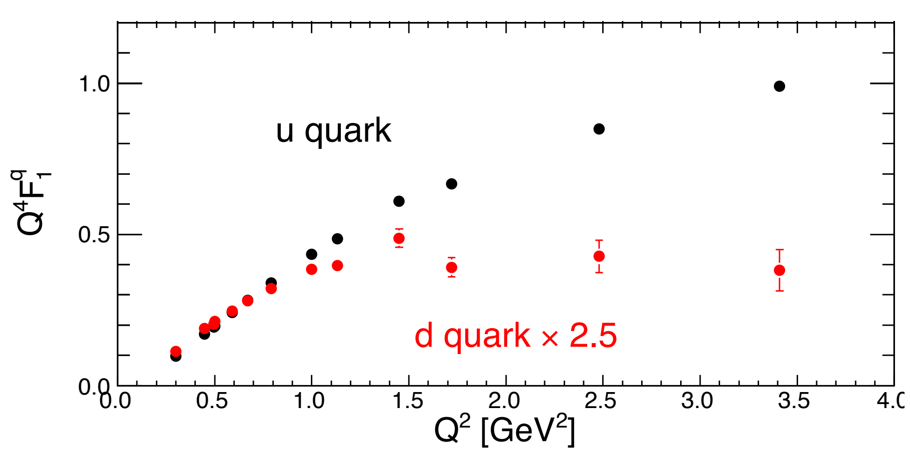


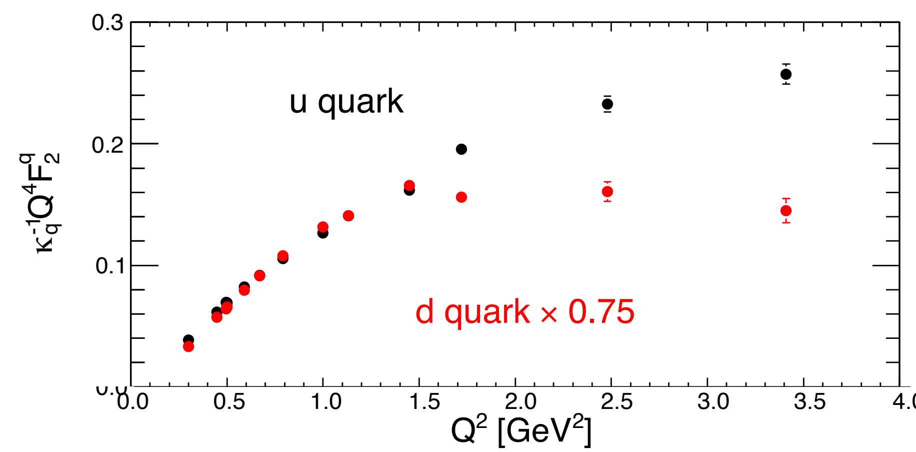
- Comparison of 4 ensembles (**D5** : 86k, **E5** : 266k, **F5** : 47k, **D6** : 261k)
- *(dashed lines)* flavor dependence [G.D.Cates, et al, PRL106:252003(2011)]

Light-flavor Contrib's to Proton FFs (a=0.056fm)









- Initial statistics on **F5** : (47k)
- *(dashed lines)* flavor dependence [G.D.Cates, et al, PRL106:252003(2011)]

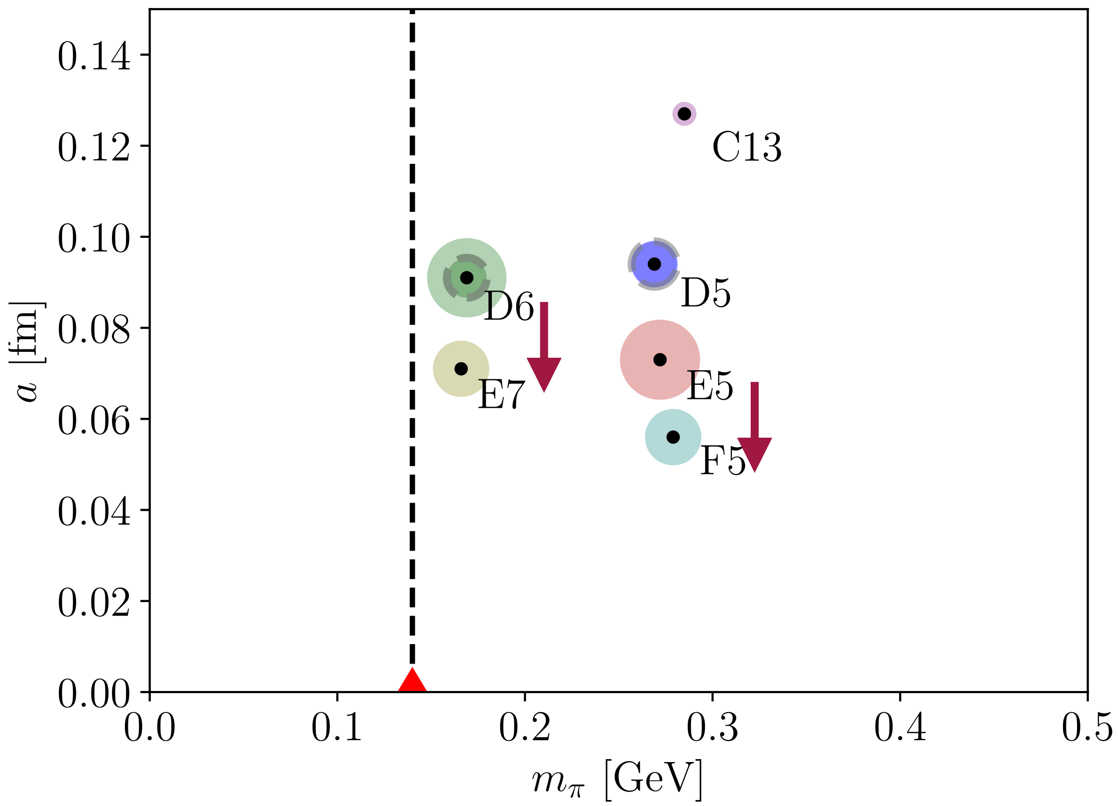
Summary

- High-statistics lattice calculations of nucleon form factors at high-momentum
  - up to $Q^2 \lesssim 10$ GeV^2
  - three lattice spacings $a \gtrsim 0.056$ fm
  - two pion masses $m\pi \gtrsim 170$ MeV

- Form factor results overshoot experimental data x(2 ... 2.5) ;
  G_E/G_M ratios in qualitative agreement
  - "quark-disconnected" contractions $\rightarrow$ little effect for $Q^2 \lesssim 6$ GeV^2 , uncertain for higher-Q^2
  - Non-physical quarks masses?
  - Discretization?
  - Excited states (most likely) — *need improved/variational nucleon operators*

Outlook

- Upcoming next-gen computing facilities (e.g. Jupiter at Julich SC)
  - More statistics (x10) to control excited state systematics
  - Smaller lattice spacings (0.09 ➞ 0.07 ➞ 0.05 fm); physical and 2x physical pion mass
  - Improved lattice vector-current operator



- *Effective theory for large-momentum form factors of nucleon-like states?*

- *Explanation for potential G_E/G_M universality – similar structure of excited N-like states?*