Form Factors and Moments of Nucleon PDFs From Lattice QCD

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Mapping Parton Distribution Amplitudes and Functions,
10th September 2018, ECT*, Trento

Credits

ETM Collaboration

Cyprus (Univ. of Cyprus, Cyprus Inst.), France (Orsay, Grenoble), Germany (Berlin/Zeuthen, Bonn, Frankfurt, Hamburg, Münster), Italy (Rome I, II, III, Trento), Netherlands (Groningen), Poland (Poznan), Spain (Valencia), Switzerland (Bern), UK (Liverpool), US (Temple, PA)

Collaborators, this work:

C. Alexandrou, S. Bacchio, K. Cichy, M. Constantinou, J. Finkenrath, K. Hadjiyiannakou, K. Jansen, Ch. Kallidonis, K. Ottnad, M. Petschlies, A. Scapellato, F. Steffens, A. Vaquero, C. Wiese

HPC–LEAP
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Outline

Lattice QCD short overview

- Landscape of simulations
- Extraction of nucleon observables
- Challenges at physical pion mass

Selected nucleon observable results from lattice QCD

- Spin decomposition of the nucleon
- Momentum decomposition of the nucleon
- Nucleon electromagnetic form factors

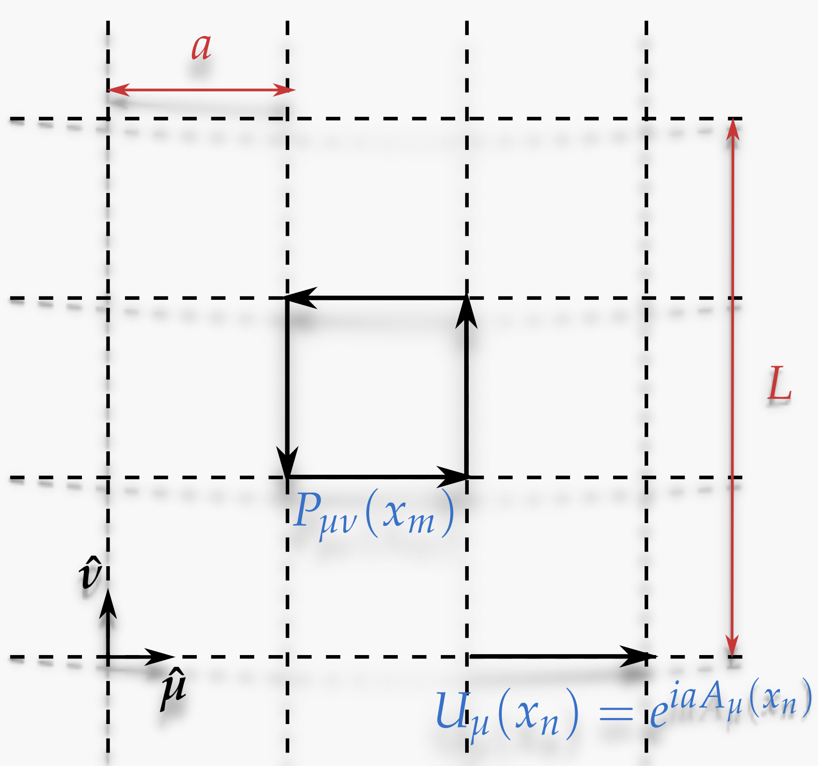
Lattice QCD – ab initio simulation of QCD

Free to choose

- quark masses (heavier is cheaper)
- lattice spacing *a* (coarser is cheaper)
- lattice volume $L^3 \times T$ (smaller is cheaper)

Choice of discretisation scheme

- e.g. Clover, Twisted Mass, Staggered, Overlap, Domain Wall, …
- Different trade-offs made for each choice



Eventually, all schemes must agree:

- At the continuum limit: $a \longrightarrow 0$
- At the infinite volume limit: $L \longrightarrow \infty$
- At physical quark mass

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Twisted Mass Lattice QCD

Formulation particularly attractive for nucleon structure

- Laborious tuning procedure during simulation to reach "maximal twist"
- $O(a)$ improved operators without requiring further operator improvement

R. Frezzotti, G. C. Rossi, JHEP 0408 (2004) 007

Ensembles at physical quark masses

- N_f=2,
  - a = 0.094 fm, $L^3 \times T = 48^3 \times 96$ (aL = 4.5 fm), $m_\pi L$ = 2.9
  - a = 0.094 fm, $L^3 \times T = 64^3 \times 128$ (aL = 5.9 fm), $m_\pi L$ = 3.9

(ETMC) A. Abdel-Rehim *et al.*, Phys. Rev. D95 094525 (2017)

- N_f=2+1+1,
  - a = 0.080 fm, $L^3 \times T = 64^3 \times 128$ (aL = 5.2 fm), $m_\pi L$ = 3.6

(ETMC) C. Alexandrou *et al.*, arXiv:1807.00495

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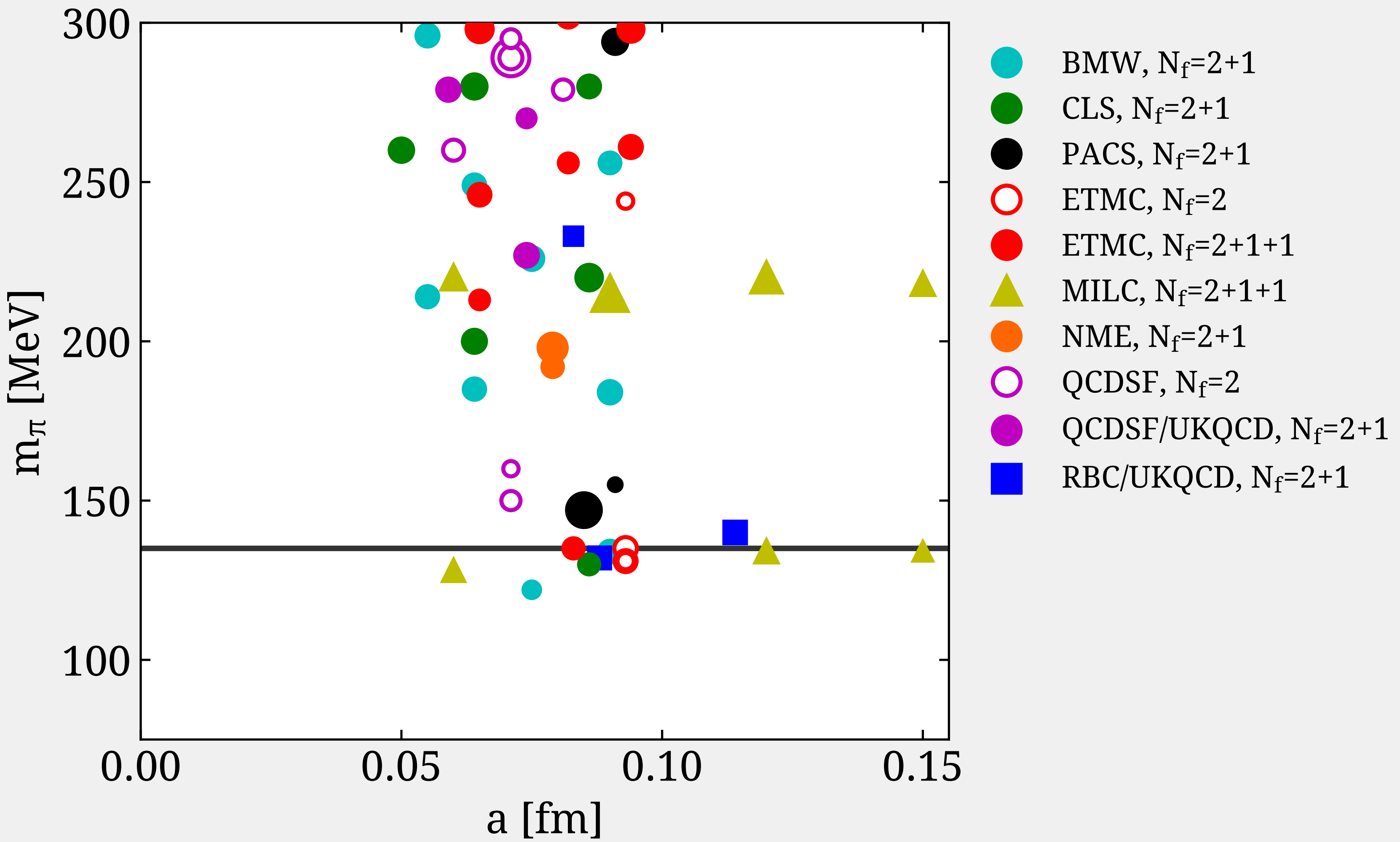
Simulation landscape



Selected presentation of lattice simulation points used for hadron structure

- Several collaborations at physical pion mass (horizontal line at $m_\pi \simeq 135$ MeV)
- Size of points indicates $m_\pi L$ (smallest: $m_\pi L = 2.3$ and largest $m_\pi L = 7$)

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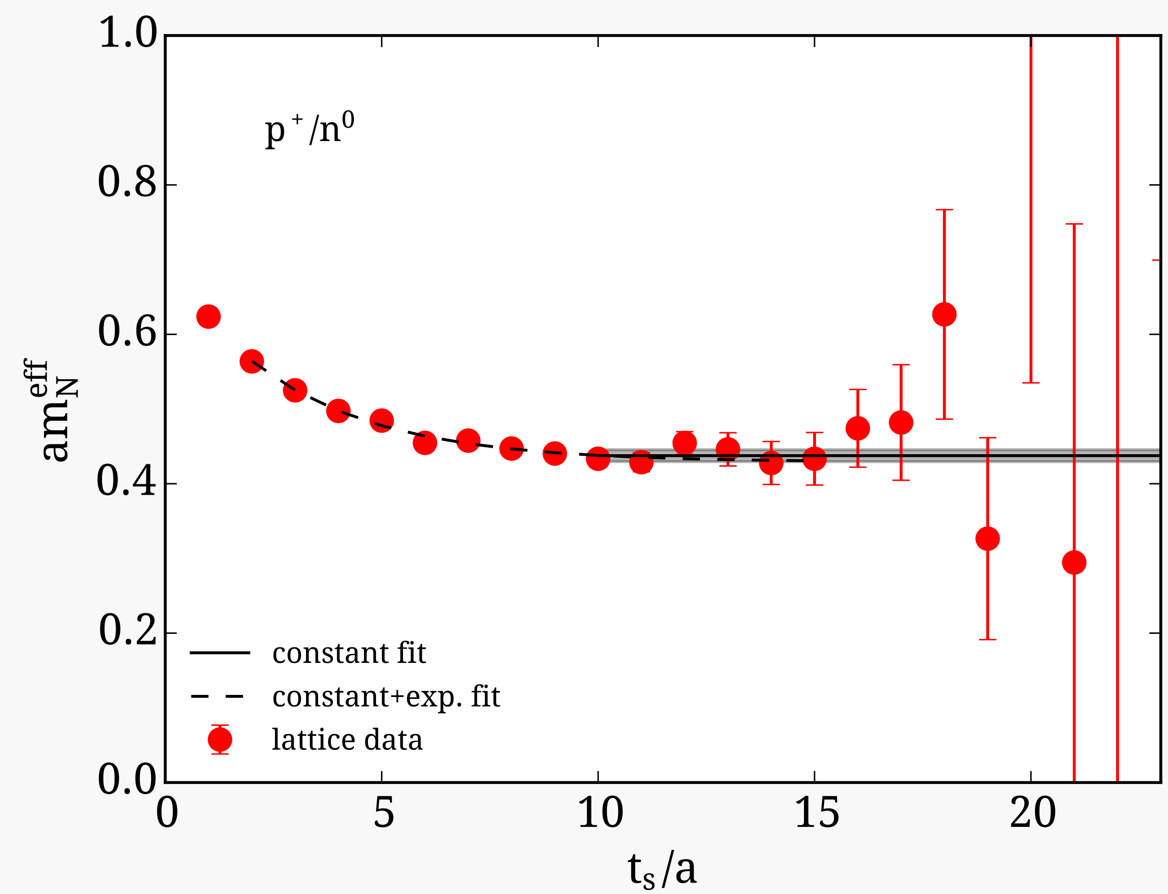
Nucleon structure on the lattice

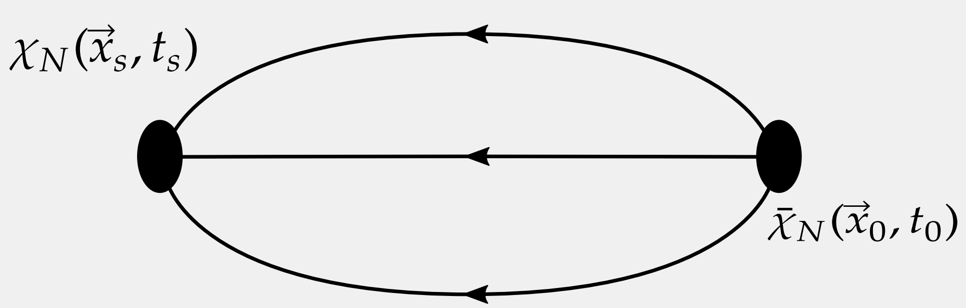
Two-point correlation functions

- **Statistical error:** $N^{-1/2}$ with Monte Carlo samples
- Correlation functions exponentially decay with time-separation

Systematic uncertainties

- Contamination from higher energy states





$$\sum_{\vec{x}_s} \Gamma^{\alpha\beta} \langle \bar{\chi}_N^{\beta}(x_s) | \chi_N^{\alpha}(0) \rangle = c_0 e^{-E_0 t_s} + c_1 e^{-E_1 t_s} + \ldots$$

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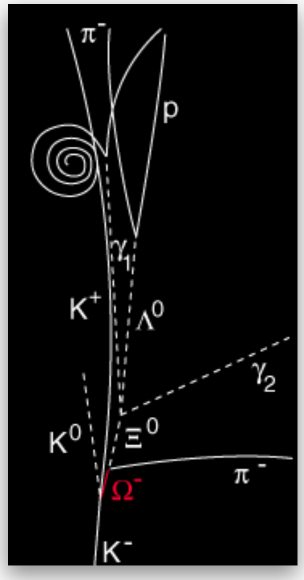
Nucleon structure on the lattice

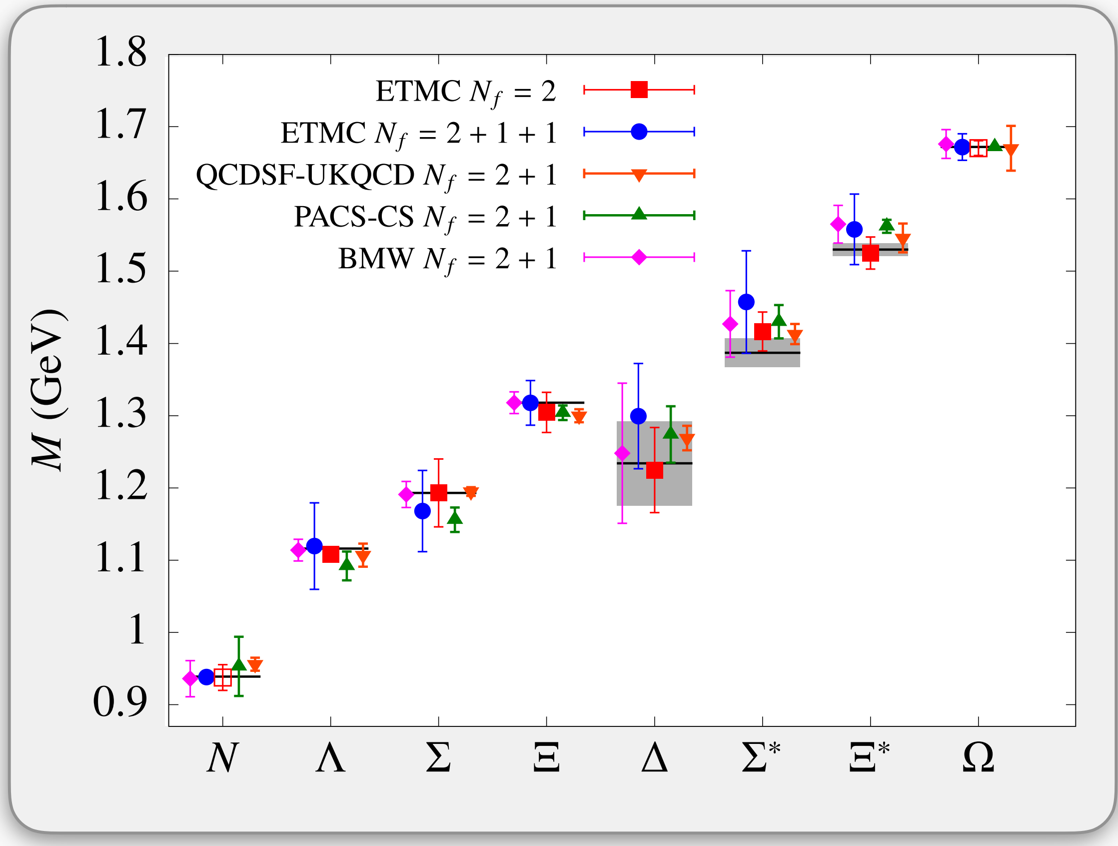
Reproduction of light baryon masses

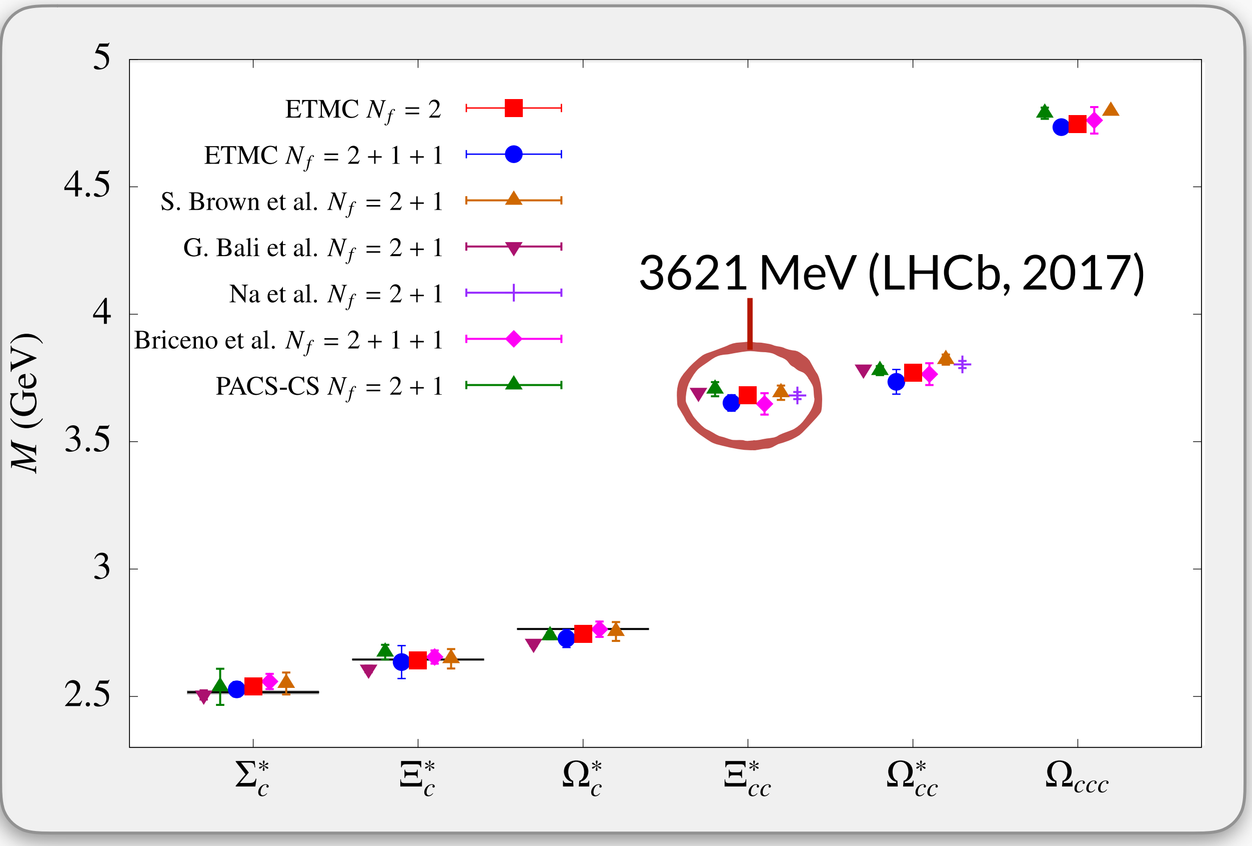
- Agreement between lattice discretisations
- Reproduction of experiment

Prediction of yet to be observed baryons

- Confidence through agreement between lattice schemes







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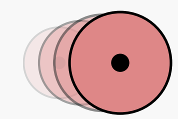
Phys. Rev. D96 (2017) no.3, 034511 [arXiv:1704.02647]

Nucleon structure on the lattice

Lattice Moments are readily accessible on the lattice

Unpolarised

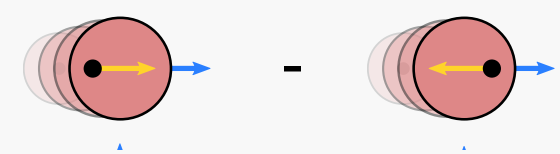
$$\mathcal{O}_{V}^{\mu\mu_1\mu_2\ldots\mu_n} = \bar{\psi}\gamma^{\{\mu}iD^{\mu_1}iD^{\mu_2}\ldots iD^{\mu_n\}}\psi$$



$$\langle 1\rangle_{u-d} = g_V\,,\;\; \langle x\rangle_{u-d},\;\; \ldots$$

Helicity

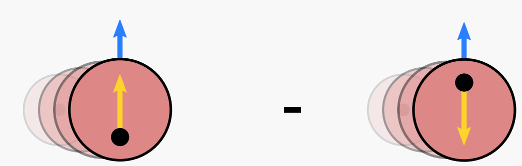
$$\mathcal{O}_{A}^{\mu\mu_1\mu_2\ldots\mu_n} = \bar{\psi}\gamma_5\gamma^{\{\mu}iD^{\mu_1}iD^{\mu_2}\ldots iD^{\mu_n\}}\psi$$



$$\langle 1\rangle_{\Delta u-\Delta d} = g_A,\;\; \langle x\rangle_{\Delta u-\Delta d},\;\; \ldots$$

Transverse

$$\mathcal{O}_{T}^{\nu\mu\mu_1\mu_2\ldots\mu_n} = \bar{\psi}\sigma^{\nu\{\mu}iD^{\mu_1}iD^{\mu_2}\ldots iD^{\mu_n\}}\psi$$



$$\langle 1\rangle_{\delta u-\delta d} = g_T,\;\; \langle x\rangle_{\delta u-\delta d},\;\; \ldots$$

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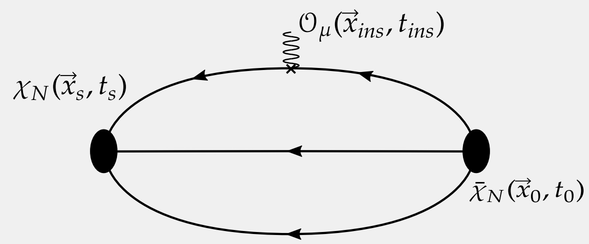
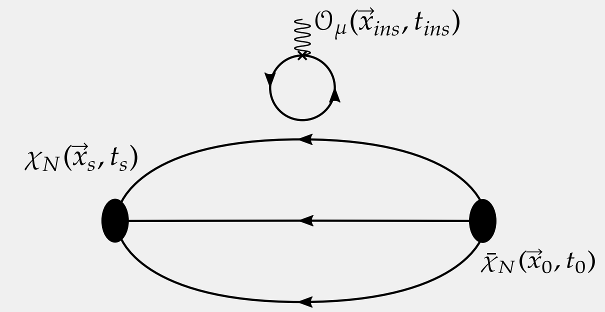
Lattice evaluation of matrix elements

$$G_\mu(\Gamma;\vec{q};t_s,t_{\rm ins}) = \sum_{\vec{x}_s \vec{x}_{\rm ins}} e^{-i\vec{q}.\vec{x}_{\rm ins}} \Gamma^{\alpha\beta} \langle \bar{\chi}^{\beta}_N(\vec{x}_s;t_s)|\mathcal{O}^\mu(\vec{x}_{\rm ins};t_{\rm ins})|\chi^\alpha_N(\vec{0};0)\rangle$$





Analyses for identifying excited state contributions

- Plateau:

$$R(t_s,t_{\rm ins},t_0) \xrightarrow[t_{\rm ins}-t_0\to\infty]{t_s-t_{\rm ins}\to\infty} \mathcal{M}[1+\mathcal{O}(e^{-\Delta(t_{\rm ins}-t_0)}, e^{-\Delta'(t_s-t_{\rm ins})})]$$

  fit to constant w.r.t. $t_{\rm ins}$ for multiple values of t_s

- Two-state fit: Fit, two- and three-point simultaneously, including first excited state
- Sum over $t_{\rm ins}$:

$$\sum_{t_{\rm ins}} R(t_s,t_{\rm ins},t_0) \xrightarrow{t_s-t_0\to\infty} \text{Const.} + \mathcal{M}(t_s-t_0) + \mathcal{O}(t_s e^{-\Delta t_s})$$

  fit to linear form, matrix element is the slope.

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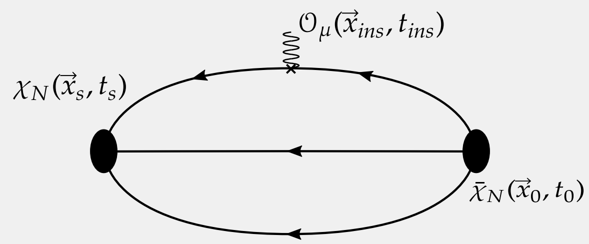
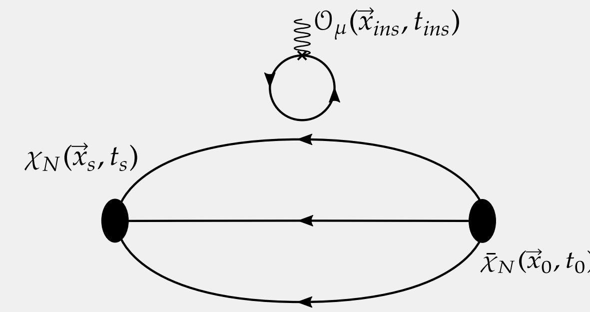
Lattice evaluation of matrix elements

$$G_\mu(\Gamma;\vec{q};t_s,t_{\rm ins}) = \sum_{\vec{x}_s\vec{x}_{\rm ins}} e^{-i\vec{q}.\vec{x}_{\rm ins}}\Gamma^{\alpha\beta}\langle\bar{\chi}_N^\beta(\vec{x}_s;t_s)|\mathcal{O}^\mu(\vec{x}_{\rm ins};t_{\rm ins})|\chi_N^\alpha(\vec{0};0)\rangle$$





Analyses for identifying excited state contributions

- Pla...

$$\ldots\mathcal{M}[1+\mathcal{O}(e^{-\Delta(t_{\rm ins}-t_0)}, e^{-\Delta'(t_s-t_{\rm ins})})]$$

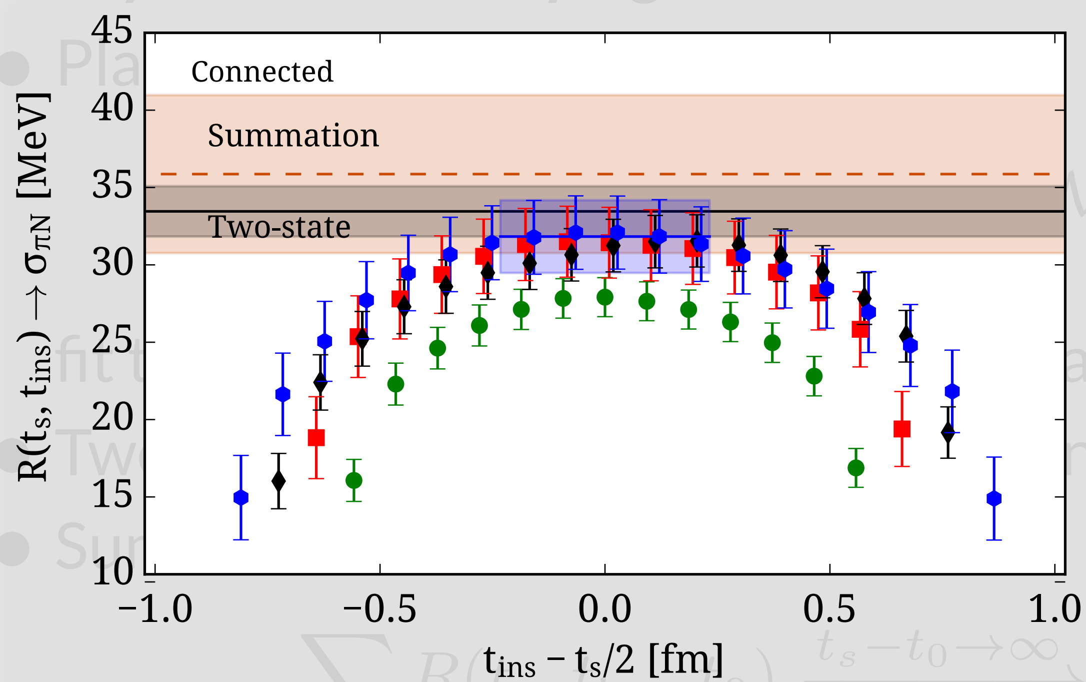
fit t... ...alues of t_s

- Tw... ...nt simultaneously, including first excited state

- Su...

$$\sum R(t_s,t_{\rm ins},t_0) \xrightarrow{t_s-t_0\to\infty} \text{Const.} + \mathcal{M}(t_s-t_0) + \mathcal{O}(t_s e^{-\Delta t_s})$$

fit to linear form, matrix element is the slope.



Connected, ~12,500 statistics

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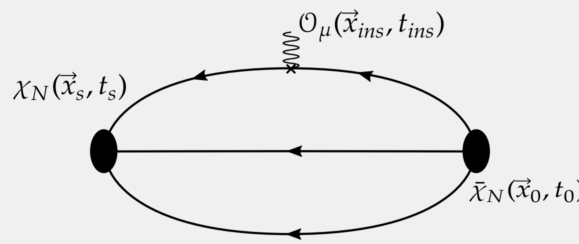
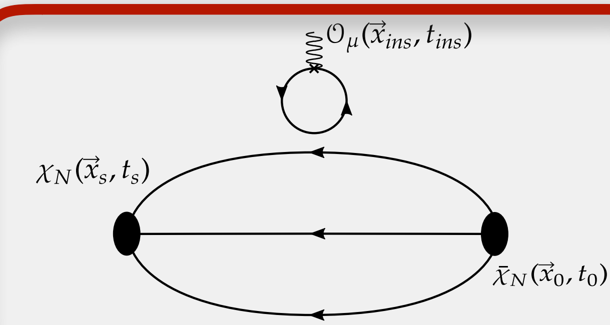
Lattice evaluation of matrix elements

$$G_\mu(\Gamma;\vec{q};t_s,t_{\rm ins}) = \sum_{\vec{x}_s\,\vec{x}_{\rm ins}} e^{-i\vec{q}.\vec{x}_{\rm ins}}\Gamma^{\alpha\beta}\langle\bar{\chi}^{\beta}_N(\vec{x}_s;t_s)|\mathcal{O}^\mu(\vec{x}_{\rm ins};t_{\rm ins})|\chi^{\alpha}_N(\vec{0};0)\rangle$$

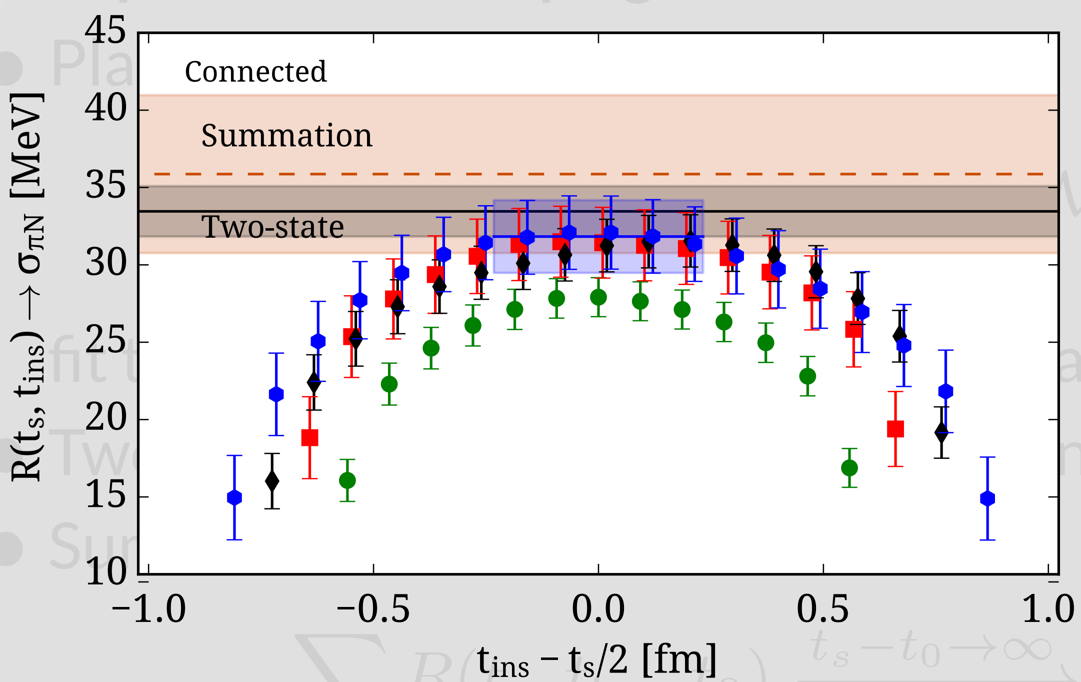




"Disconnected" contributions – estimate stochastically

Analyses for identifying excited state contributio

- Pla
  $\mathcal{M}[1+\mathcal{O}(e^{-\Delta(t_{\rm ins}-t_0)}, e^{-\Delta'(t_s-t_{\rm ins})})]$
  fit t ... alues of t_s
- Tw ... nt simultaneously, including first excited state
- Su
  $$\sum R(t_s,t_{\rm ins};t_0)\xrightarrow{t_s-t_0\to\infty}\text{Const.}+\mathcal{M}(t_s-t_0)+\mathcal{O}(t_s e^{-\Delta t_s})$$
  fit to linear form, matrix element is the slope.



Connected, ~12,500 statistics

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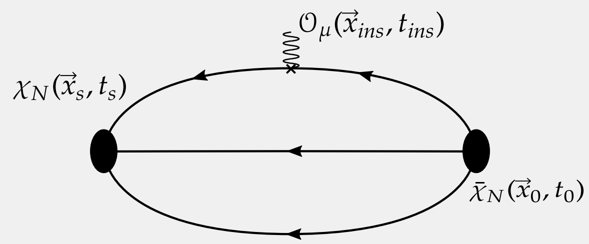
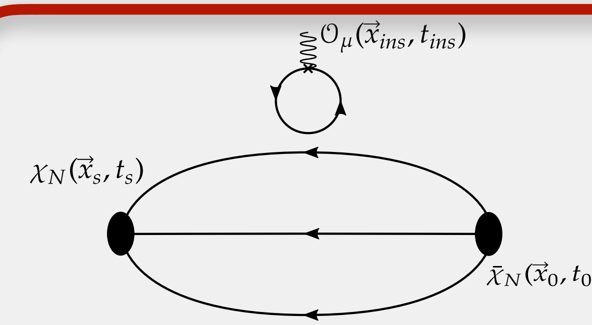
Lattice evaluation of matrix elements

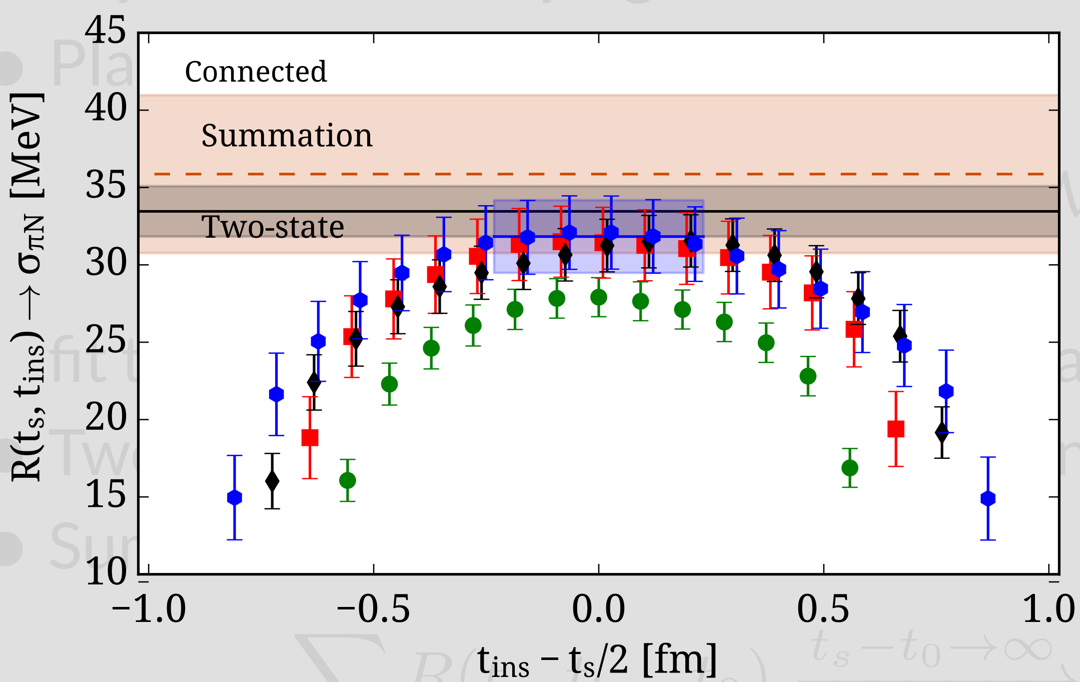
$$G_\mu(\Gamma;\vec{q};t_s,t_{\rm ins}) = \sum_{\vec{x}_s\,\vec{x}_{\rm ins}} e^{-i\vec{q}.\vec{x}_{\rm ins}}\Gamma^{\alpha\beta}\langle\bar{\chi}^\beta_N(\vec{x}_s;t_s)|\mathcal{O}^\mu(\vec{x}_{\rm ins};t_{\rm ins})|\chi^\alpha_N(\vec{0};0)\rangle$$



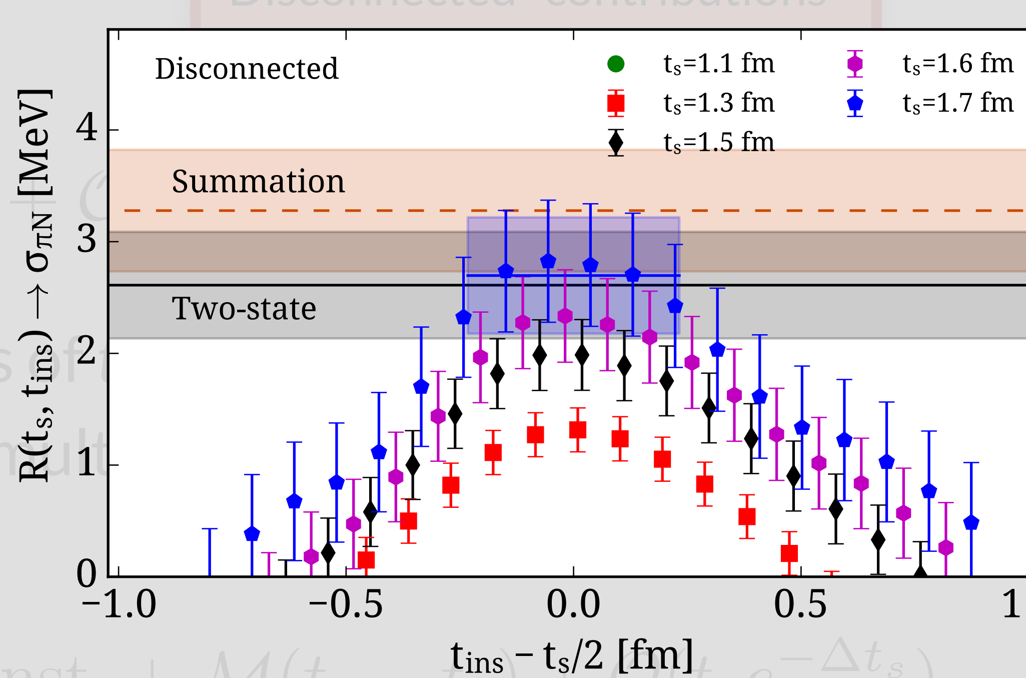


Analyses for identifying excited state contributio…

"Disconnected" contributions –



Connected, ~12,500 statistics



Disconnected, ~200,000 statistics

fit to linear form, matrix element is the slope.

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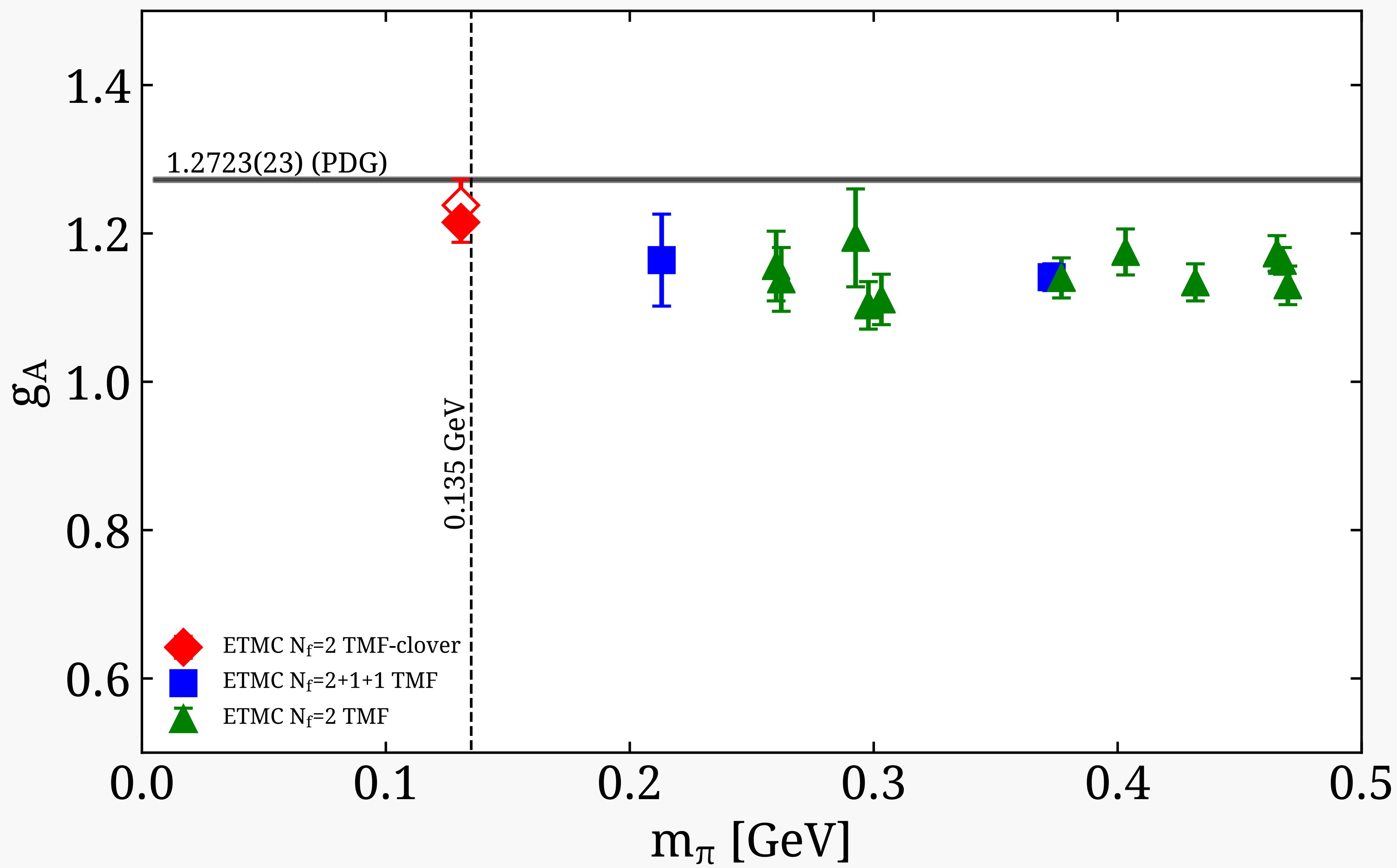
Axial matrix elements

Isovector axial charge

- Well known from β-decay
- Readily accessible on the lattice: $\mathcal{O}^A = \bar{u}\gamma_5\gamma_k u - \bar{d}\gamma_5\gamma_k d$
- Benchmark quantity in lattice QCD



Results at near physical pion mass only available recently

- Shown physical point: L=4.5 fm; N_f=2
- Under production: L=6 fm; N_f=2
  L=5.3 fm; N_f=2+1+1

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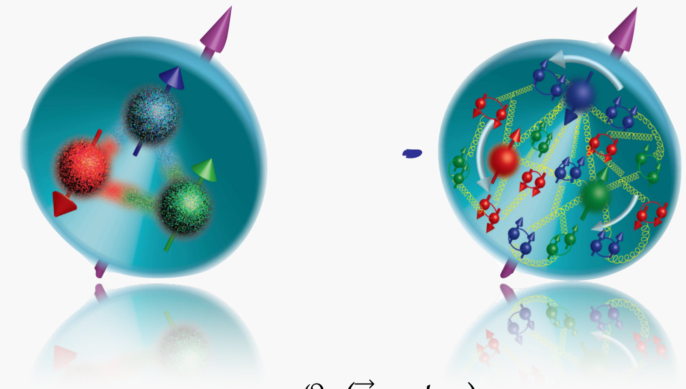
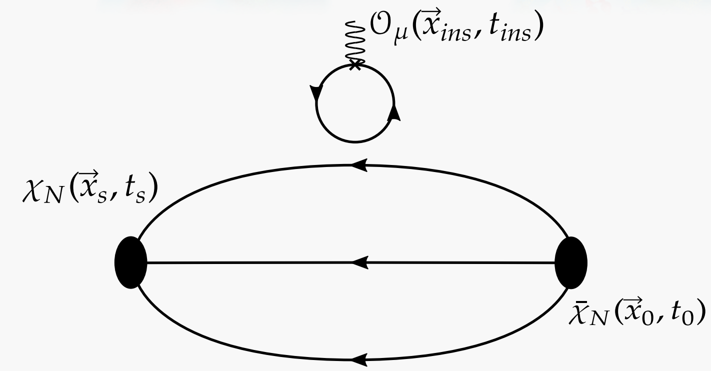
Nucleon Spin

Quark intrinsic spin contributions to nucleon spin



$$\frac{1}{2}\Delta\Sigma = \frac{1}{2}\sum_{q=u,d,s,\ldots} g_A^q$$



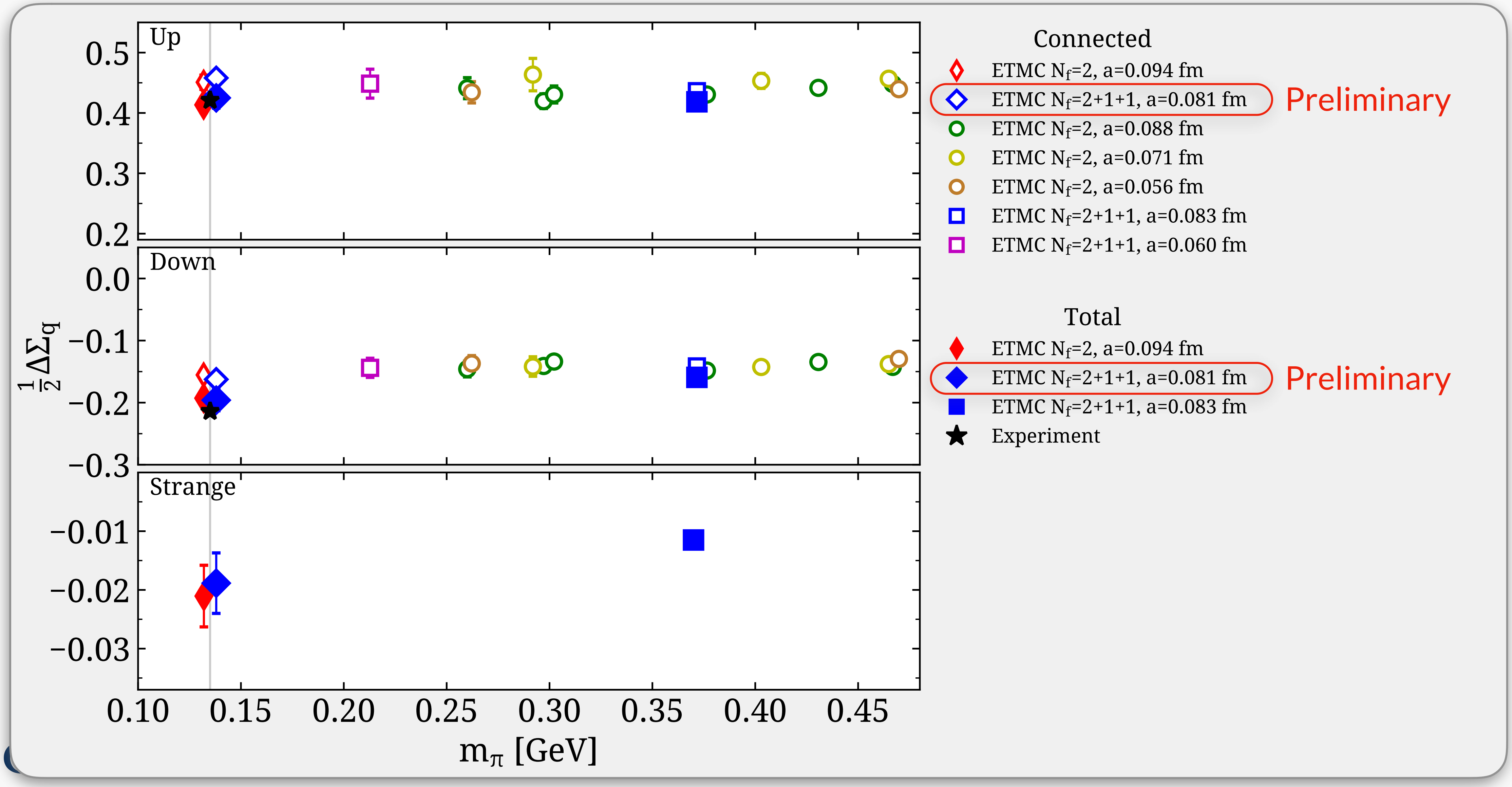
Quark intrinsic spin contributions to nucleon spin

- Need linear combination of isovector and isoscalar contributions for individual up- and down-quarks
- Strange quark contribution is sea-quark contribution only (disconnected diagrams)
- Very demanding on the lattice, need O(10) - O(100) times more statistics

Quark intrinsic spin contributions

Quark intrinsic spin contributions to nucleon spin

- Mild cut-off effects
- Strange and down-quark contributions negative



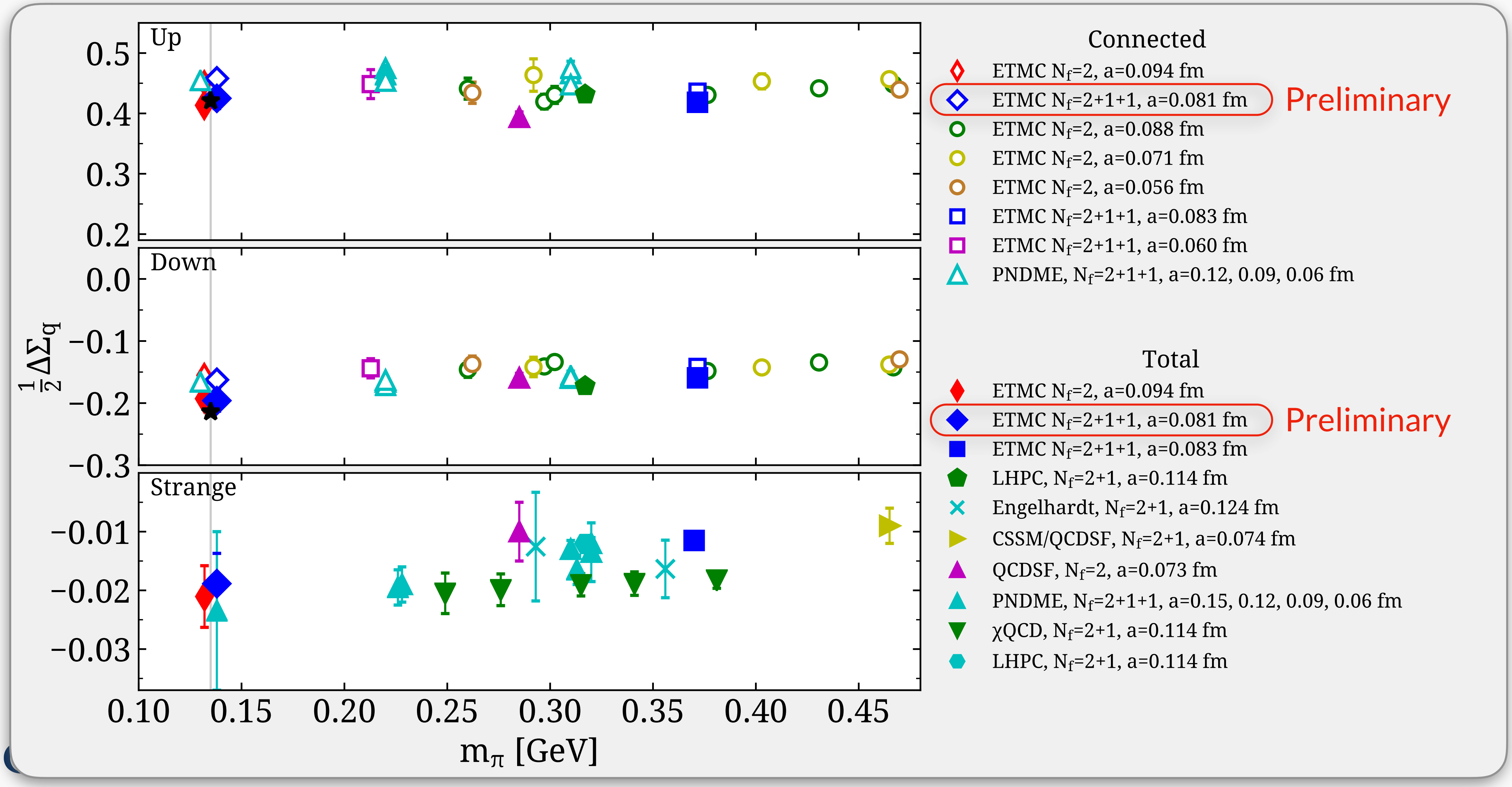
C. Alexandrou et al., PRL, arXiv:1706.02973

Quark intrinsic spin contributions

Quark intrinsic spin contributions to nucleon spin

- Mild cut-off effects
- Strange and down-quark contributions negative
- Overall agreement between formulations, and with experimental determinations

> u, d, and s intrinsic spin contributions at 40(4)% of ½, at physical pion mass



C. Alexandrou et al., PRL, arXiv:1706.02973

Quark Momentum Fraction

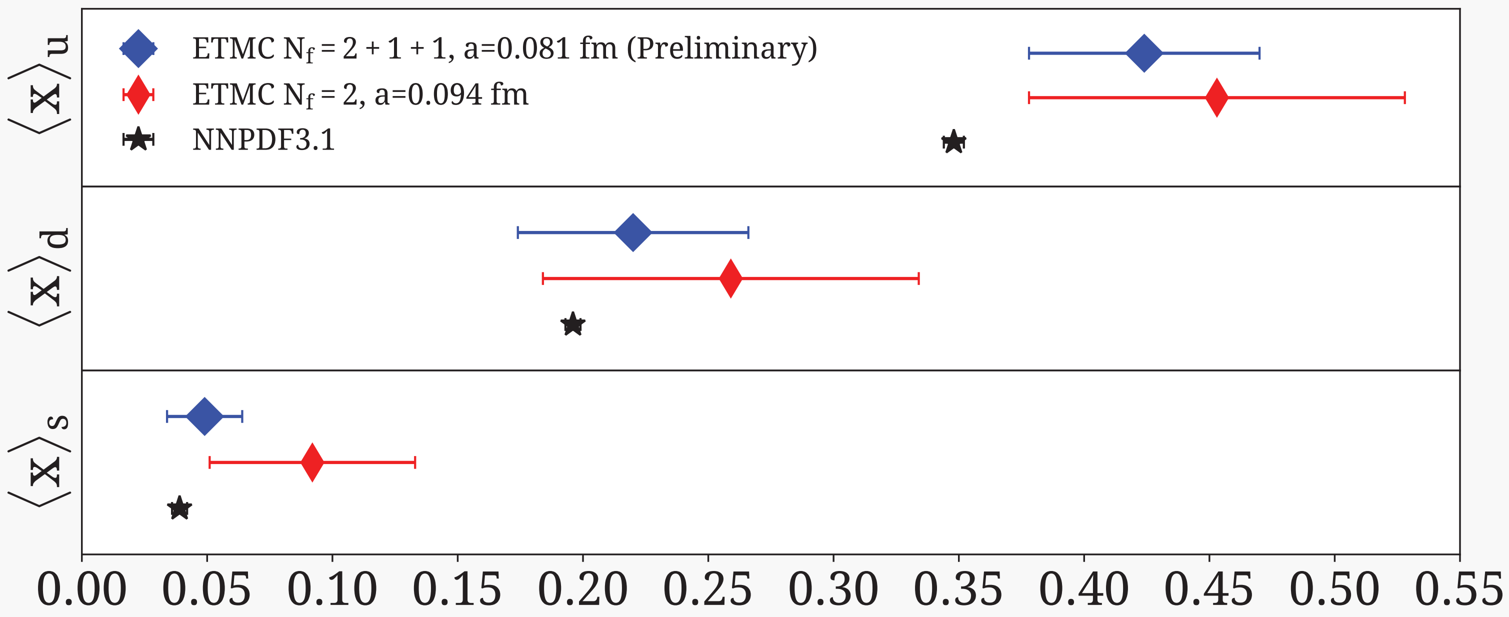
Quark momentum fraction from matrix element of vector first-derivative operator

$$\langle N(p',s')|\mathcal{O}_V^{\mu\mu_1}|N(p,s)\rangle = \bar{u}_N(p',s')[A_{20}(q^2)\gamma^{\{\mu}P^{\nu\}} + B_{20}(q^2)\frac{i\sigma^{\{\mu\alpha}q_\alpha P^{\nu\}}}{2M_N}$$

$$\mathcal{O}_V^{\mu\mu_1} = \bar{q}\gamma^{\{\mu}iD^{\mu_1\}}q \qquad + C_{20}(q^2)\frac{q^{\{\mu}q^{\nu\}}}{2M_N}]u_N(p,s)$$

Momentum fraction

- Physical point at two lattice spacings agrees within errors
- Individual quark contributions → disconnected diagrams



Momentum fraction:

$$\langle x \rangle_q = A_{20}^q(0)$$

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Quark Momentum Fraction

Quark momentum fraction from matrix element of vector first-derivative operator

$$\langle N(p',s')|\mathcal{O}_V^{\mu\mu_1}|N(p,s)\rangle = \bar{u}_N(p',s')[A_{20}(q^2)\gamma^{\{\mu}P^{\nu\}} + B_{20}(q^2)\frac{i\sigma^{\{\mu\alpha}q_\alpha P^{\nu\}}}{2M_N} + C_{20}(q^2)\frac{q^{\{\mu}q^{\nu\}}}{2M_N}]u_N(p,s)$$

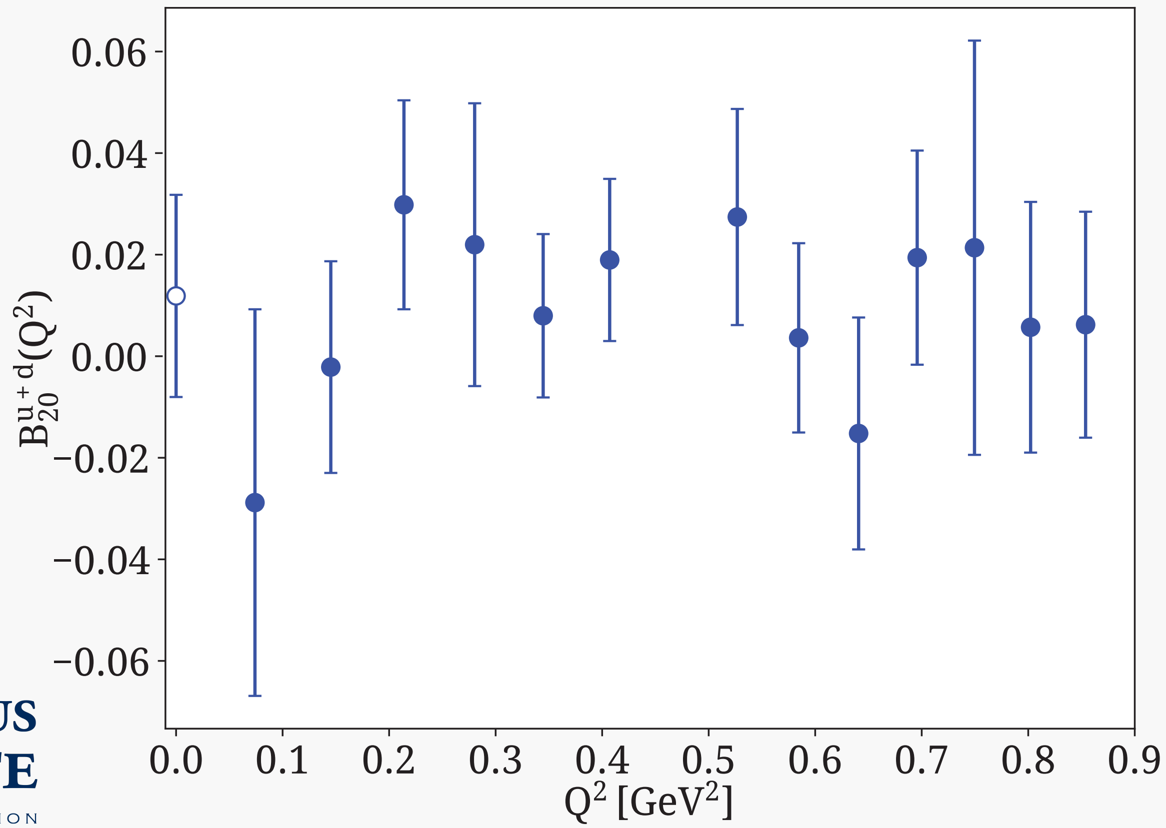
$$\mathcal{O}_V^{\mu\mu_1} = \bar{q}\gamma^{\{\mu}iD^{\mu_1\}}q$$

Nucleon spin:

$$J_q = \frac{1}{2}[A_{20}^q(0) + B_{20}^q(0)]$$

Nucleon total spin J_q

- Requires B_{20} at zero momentum transfer
- Isovector contribution small and consistent with 0



$$B_{20}^{u+d,\, s,\, c}(0)$$

All found small and consistent with zero

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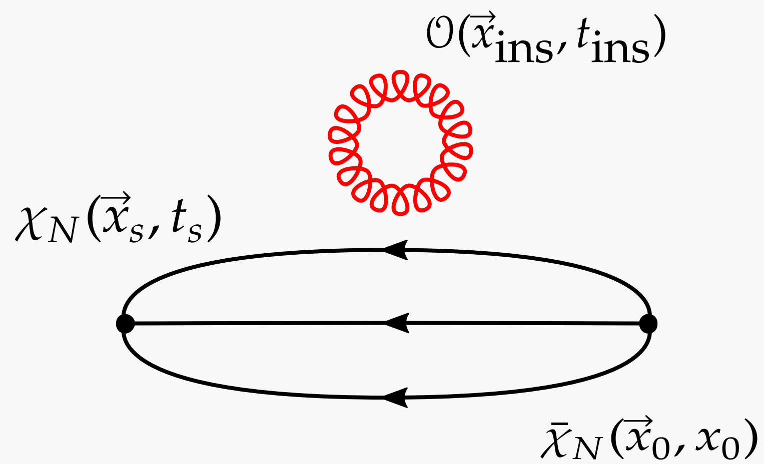
Gluon Momentum Fraction



Direct calculation from matrix element

Operator: $\mathcal{O}_g^{\mu\mu_1} = -\text{Tr}[G_{\mu\nu}G_{\nu\mu_1}]$

As in the case of quarks:

Gluon momentum fraction:

$$\langle x \rangle_g = A_{20}^g(0)$$

Gluon contribution to spin:

$$J_g = \frac{1}{2}[A_{20}^g(0) + B_{20}^g(0)]$$

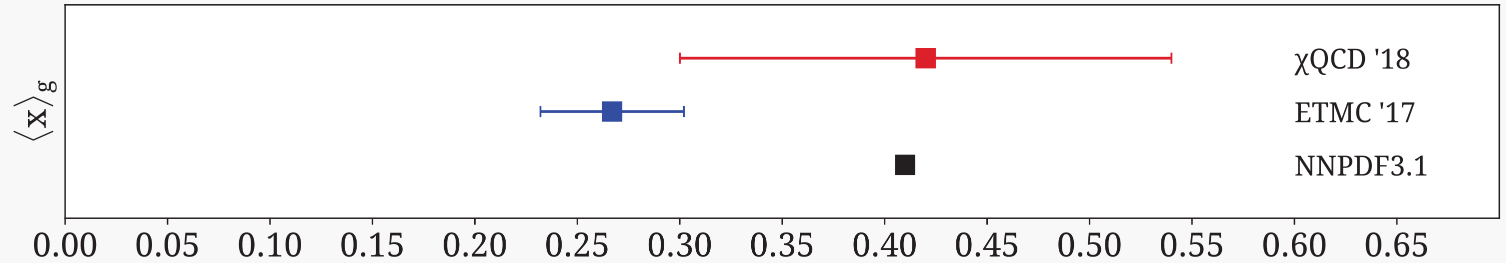
B_{20} not calculated here, but:

$$B_{20}^q(0) + B_{20}^g(0) = 0$$

Renormalization

- Mixes with quark operator
- Mixing determined purterbatively

$$\langle x \rangle_g = Z_{gg} \langle x \rangle_g^{\text{bare}} + Z_{gq} \sum_q \langle x \rangle_q^{\text{bare}}$$



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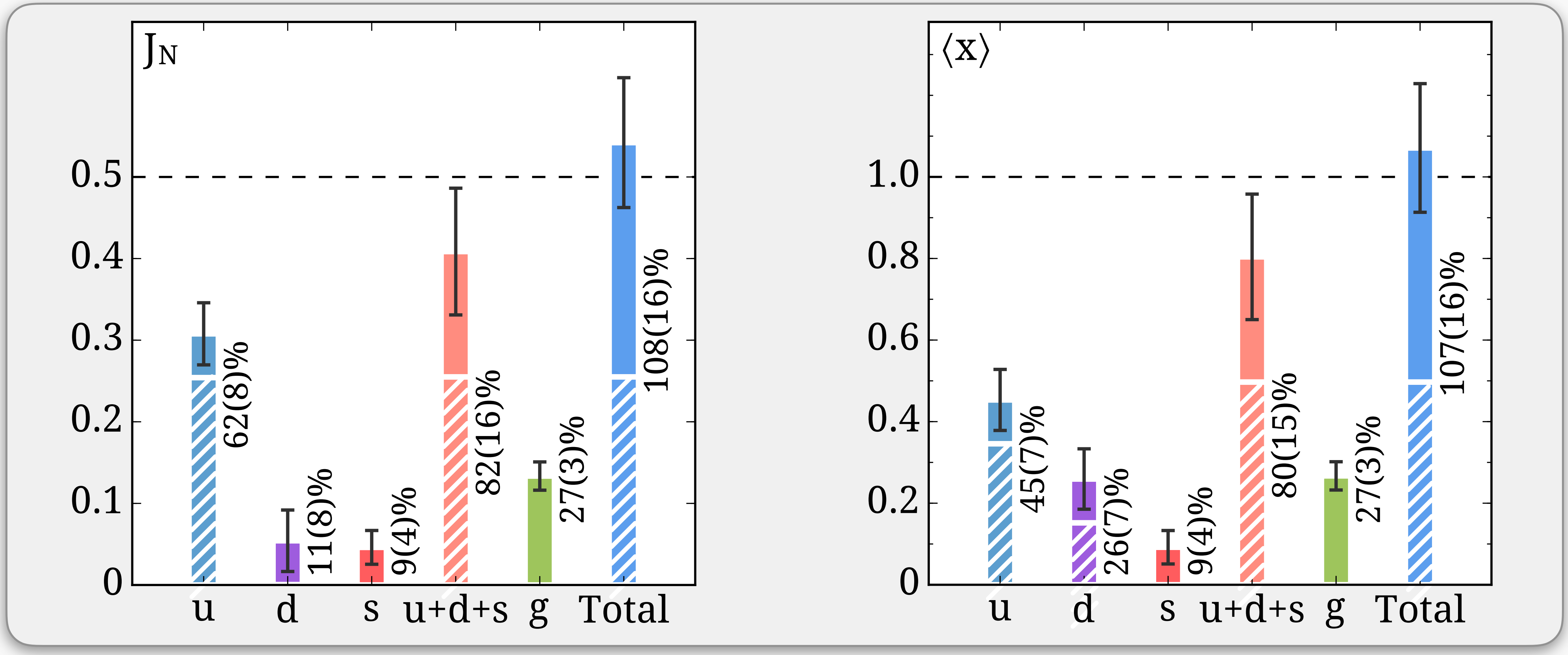
C. Alexandrou et al. (ETM collaboration), PRD, arXiv:1611.06901

Nucleon Spin

Parton spin and momentum contributions to nucleon spin

- Includes u, d, s, and gluons simulated at physical pion mass
- Spin and momentum sums satisfied within errors



$J^N_{u+d+s+g} = 0.541(62)(49)$

$\langle x \rangle_{u+d+s+g} = 1.07(12)(10)$

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C. Alexandrou et al., PRL, arXiv:1706.02973

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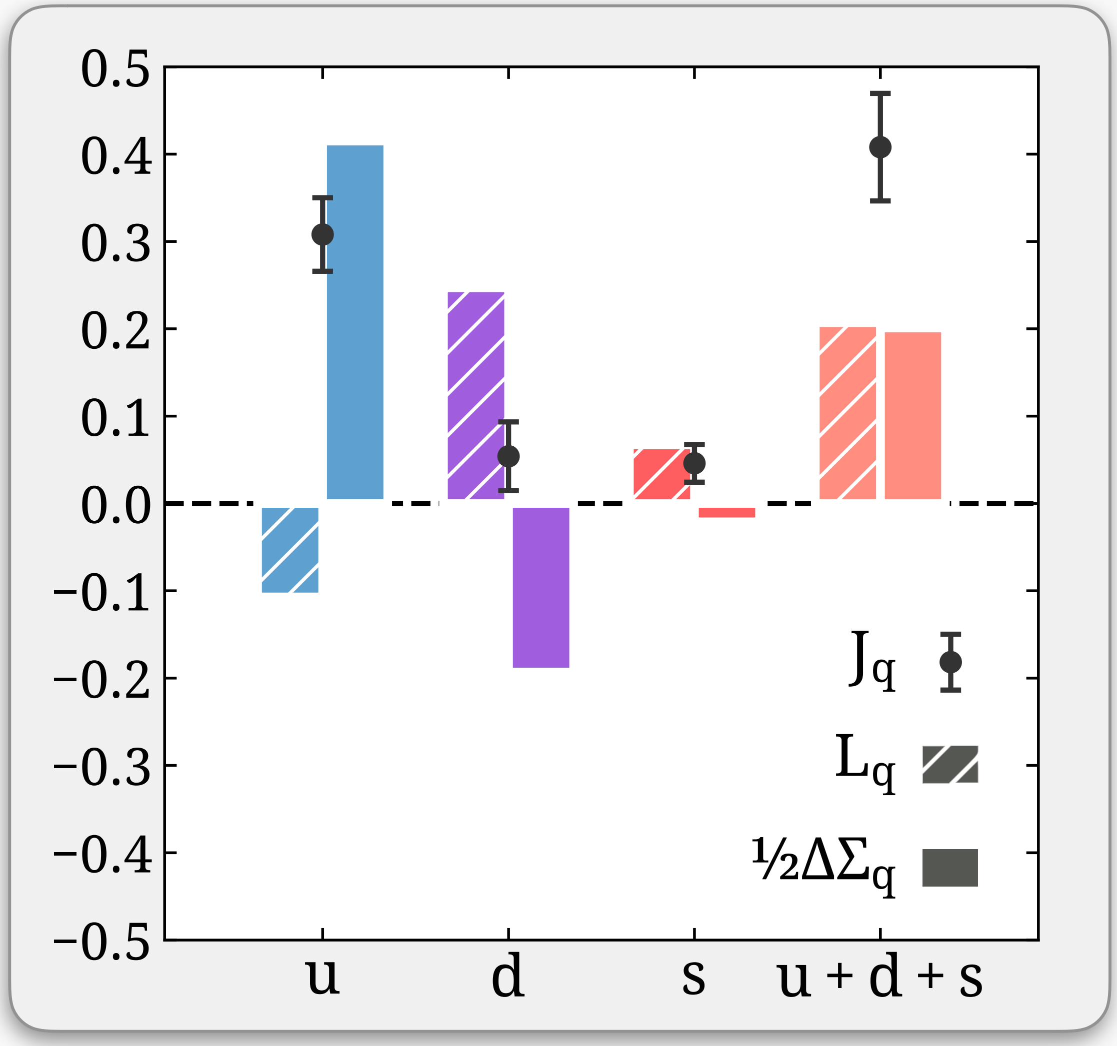

$$J^q = \frac{1}{2}\Delta\Sigma_q + L_q$$

- Angular momentum contribution deduced from Ji's spin sum
- Angular momentum: *hatches*
- Intrinsic spin: *solid*

	$\frac{1}{2}\Delta\Sigma$	J	L
u	0.415(13)(2)	0.308(30)(24)	-0.107(32)(24)
d	-0.193(8)(3)	0.054(29)(24)	0.247(30)(24)
s	-0.021(5)(1)	0.046(21)(0)	0.067(21)(1)
g	-	0.133(11)(14)	-
tot.	0.201(17)(5)	0.541(62)(49)	0.207(64)(45)

C. Alexandrou et al., PRL, arXiv:1706.02973

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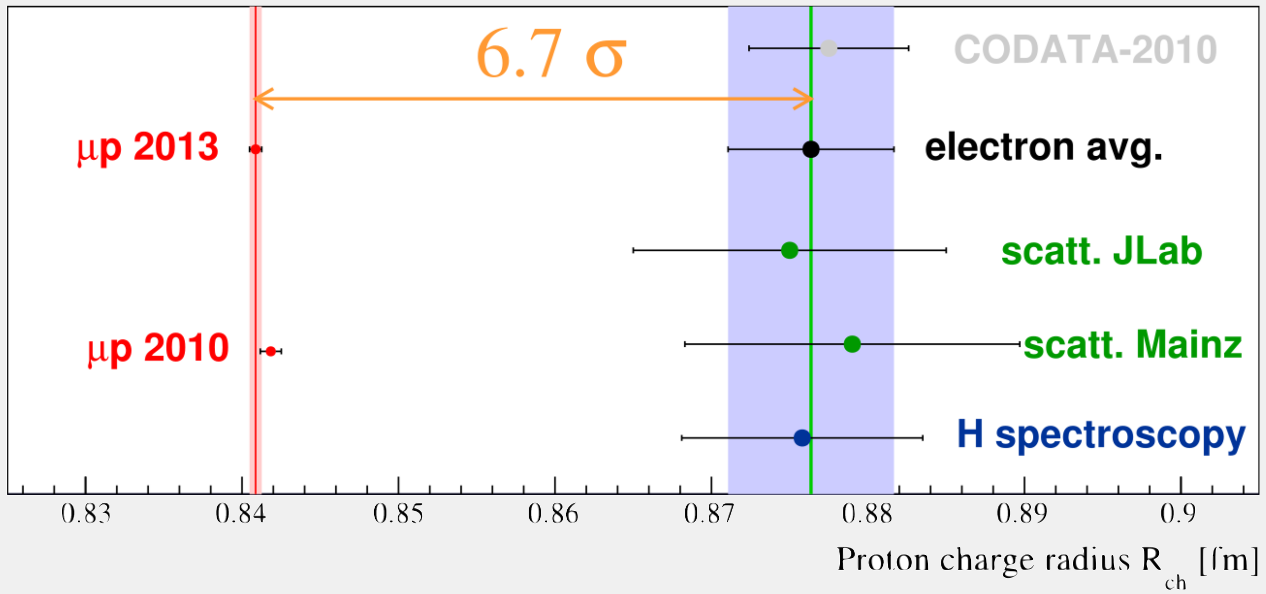
Nucleon Electromagnetic Form-Factors

Electromagnetic form-factors:

- Distribution of charges in proton
- Magnetic moment, electric and magnetic radii



- Discrepancy between proton radius measured using μH Lamb shifts vs e-p scattering
- R. Pohl *et al.*, Nature 466 (2010) 213, R. Pohl *et al.*, 353 (2016) 669-673 (muonic deuterium)
- vs. CODATA, Rev. Mod. Phys. 88 (2016) 035009

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Nucleon Electromagnetic Form-Factors

Matrix element:

$$\langle N(p',s')|j^\mu|N(p,s)\rangle = \sqrt{\frac{M_N^2}{E_N(\mathbf{p}')E_N(\mathbf{p})}}\bar{u}(p',s')\mathcal{O}^\mu u(p,s)$$

$$\mathcal{O}^\mu = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N}F_2(q^2), \quad q = p' - p$$

Sachs form-factors:

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{(2M_N)^2}F_2(q^2)$$

Isovector & Isoscalar combinations:

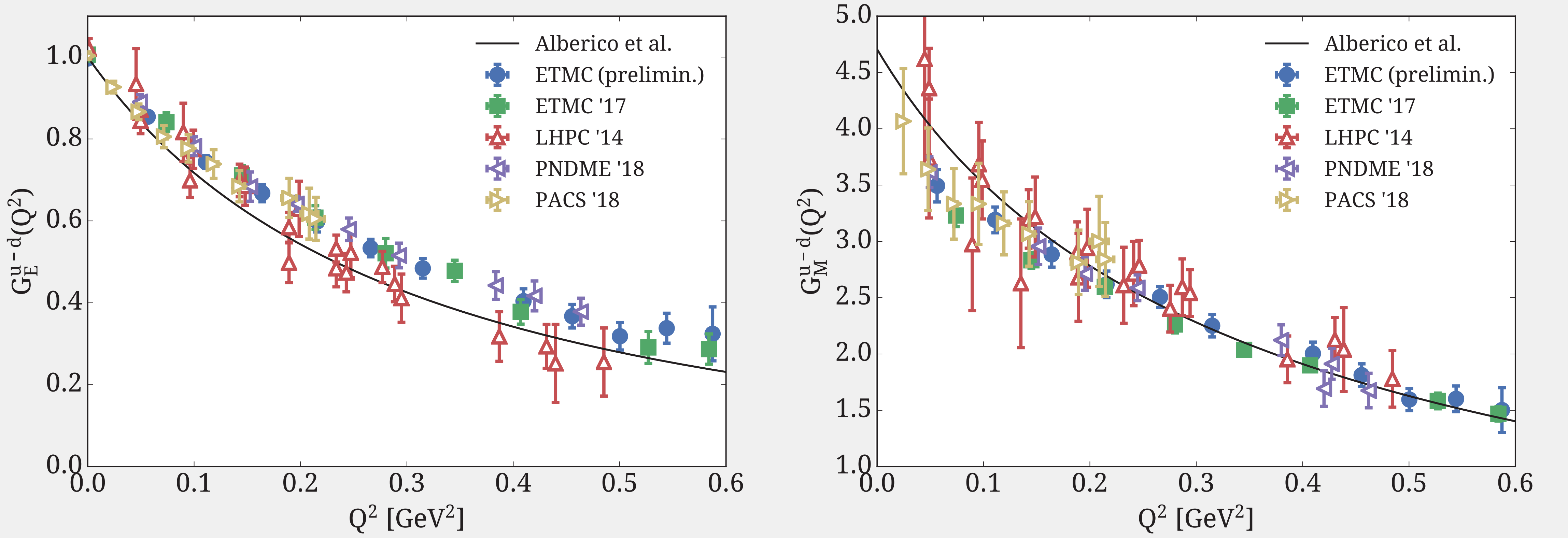
$$j_\mu^v = \bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d,\ j_\mu^s = \bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d$$

$$F^p - F^n = F^u - F^d$$

$$F^p + F^n = \frac{1}{3}(F^u + F^d)$$

Assuming flavour isospin symmetry

Nucleon Electromagnetic Form-Factors



- Multiple collaborations at near-physical pion mass for isovector (connected)
- Overall consistency between formulations
- Some discrepancy with experiment remains (e.g. G_M at low Q^2)

See: C. Alexandrou et al. arXiv:1706.00469 PRD

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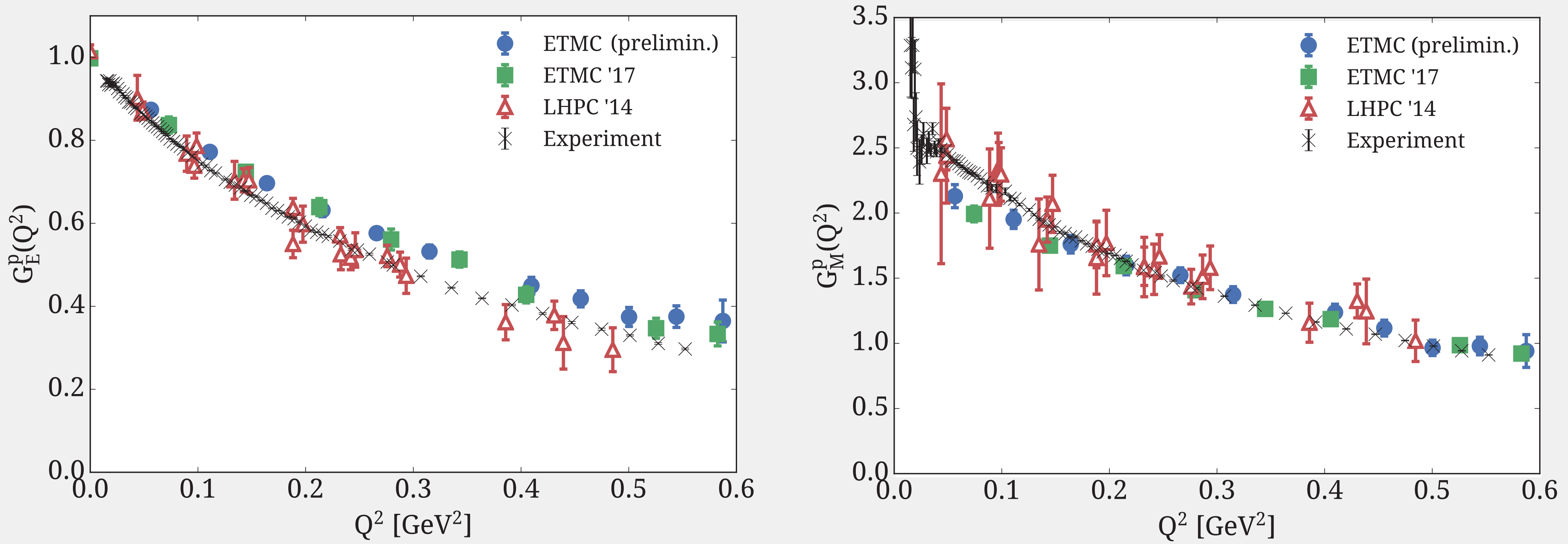
Nucleon Electromagnetic Form-Factors



Complete proton/neutron requires disconnected contributions

- Small in magnitude (few percent level)
- Only few studies on the lattice so far

See: C. Alexandrou et al. arXiv:1706.00469 PRD

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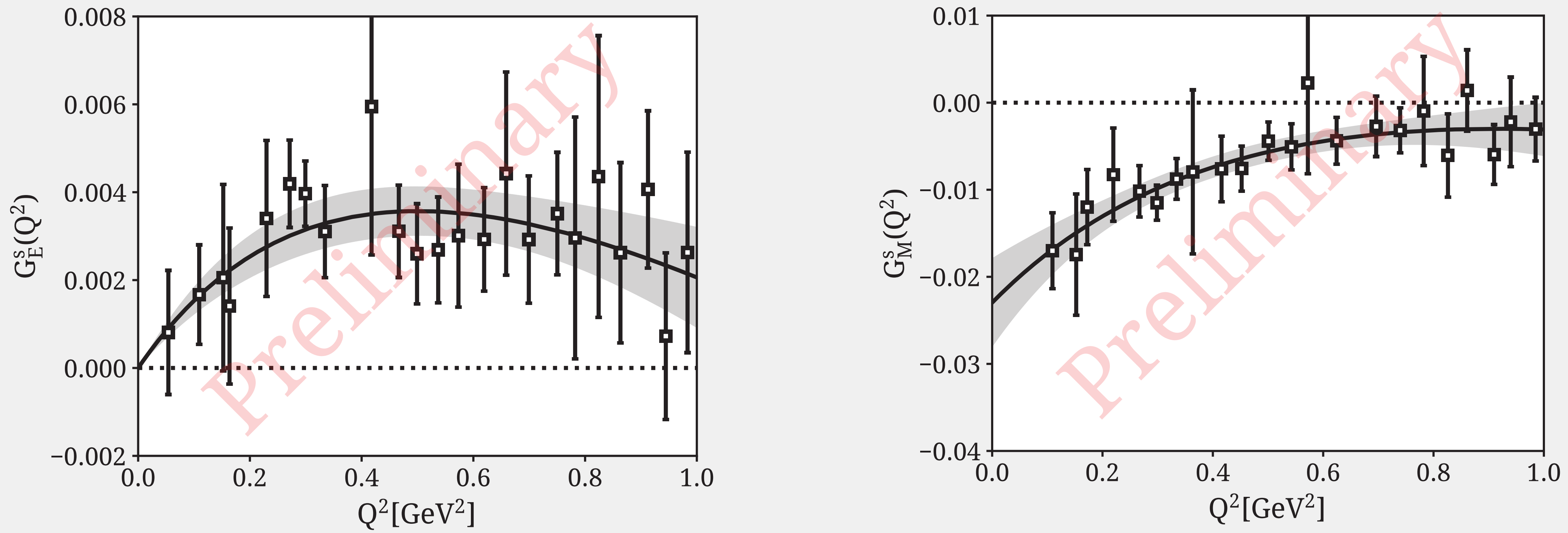
Nucleon Electromagnetic Form-Factors



Strange Electromagnetic form-factors are completely disconnected

- Quality of signal only possible with dedicated stochastic techniques (hierarchical probing)
- Preliminary result at physical pion mass

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Nucleon Electromagnetic Form-Factors

Extraction of radii

- Need slope at $Q^2 \longrightarrow 0$:

$$\frac{\partial}{\partial Q^2} G_E(Q^2)|_{Q^2=0} = -\frac{1}{6} G_E(0) \langle r_E^2 \rangle,$$

- Model Q^2 dependence:

– Dipole: $G_E(Q^2) = \frac{1}{(1+\frac{Q^2}{M_E^2})}$

– z-expansion: $G_E(Q^2) = \sum_{k=0}^{k_{\max}} a_k z^k \qquad z = \frac{\sqrt{t_{\rm cut}+Q^2} - \sqrt{t_{\rm cut}}}{\sqrt{t_{\rm cut}+Q^2} + \sqrt{t_{\rm cut}}}$

- Smallest momentum: $2\pi/L$

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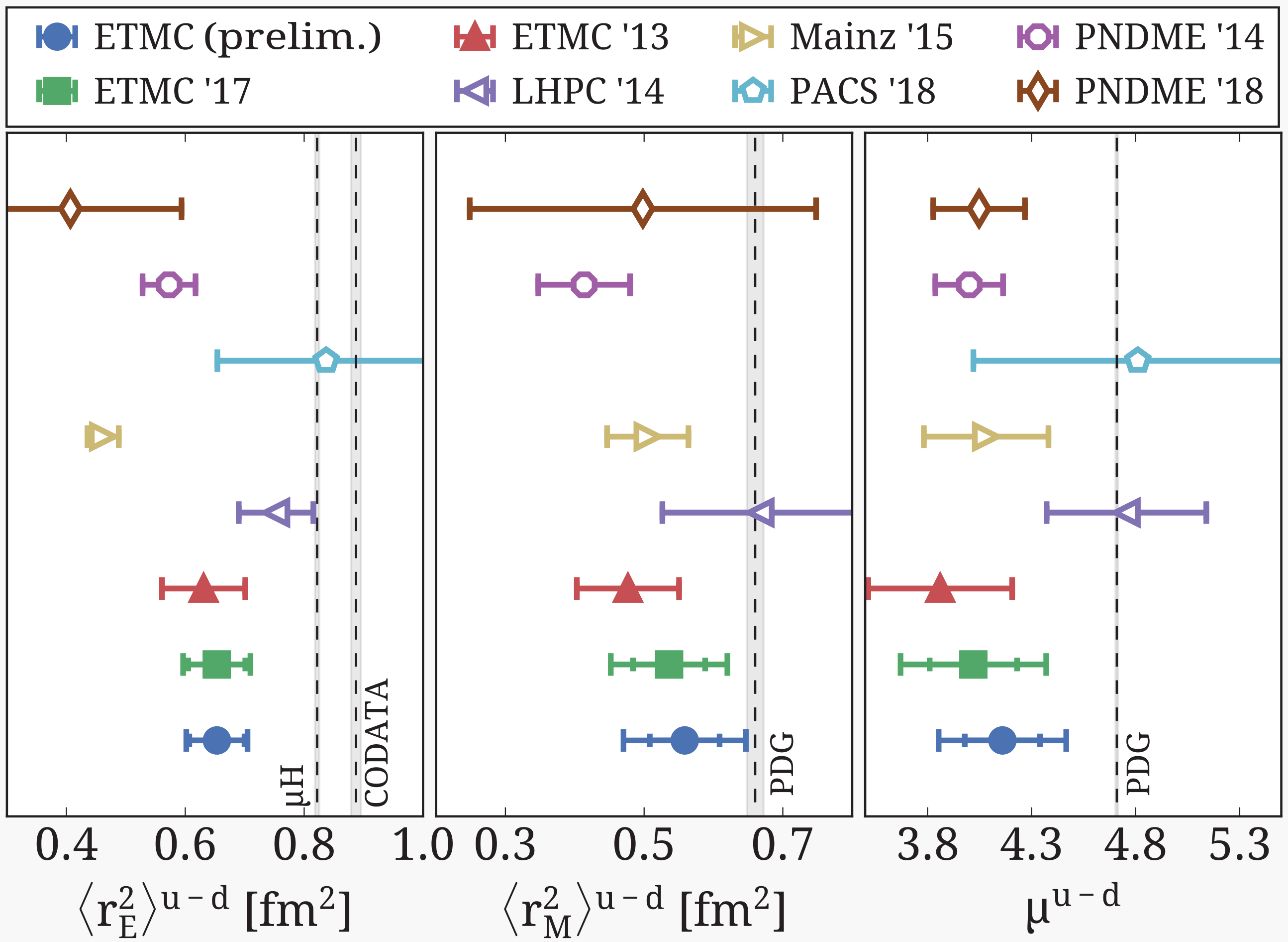
Nucleon Electromagnetic Form-Factors



Extraction of radii – isovector form-factors

- Reasonable agreement for magnetic quantities
- Agreement between collaborations/lattice schemes

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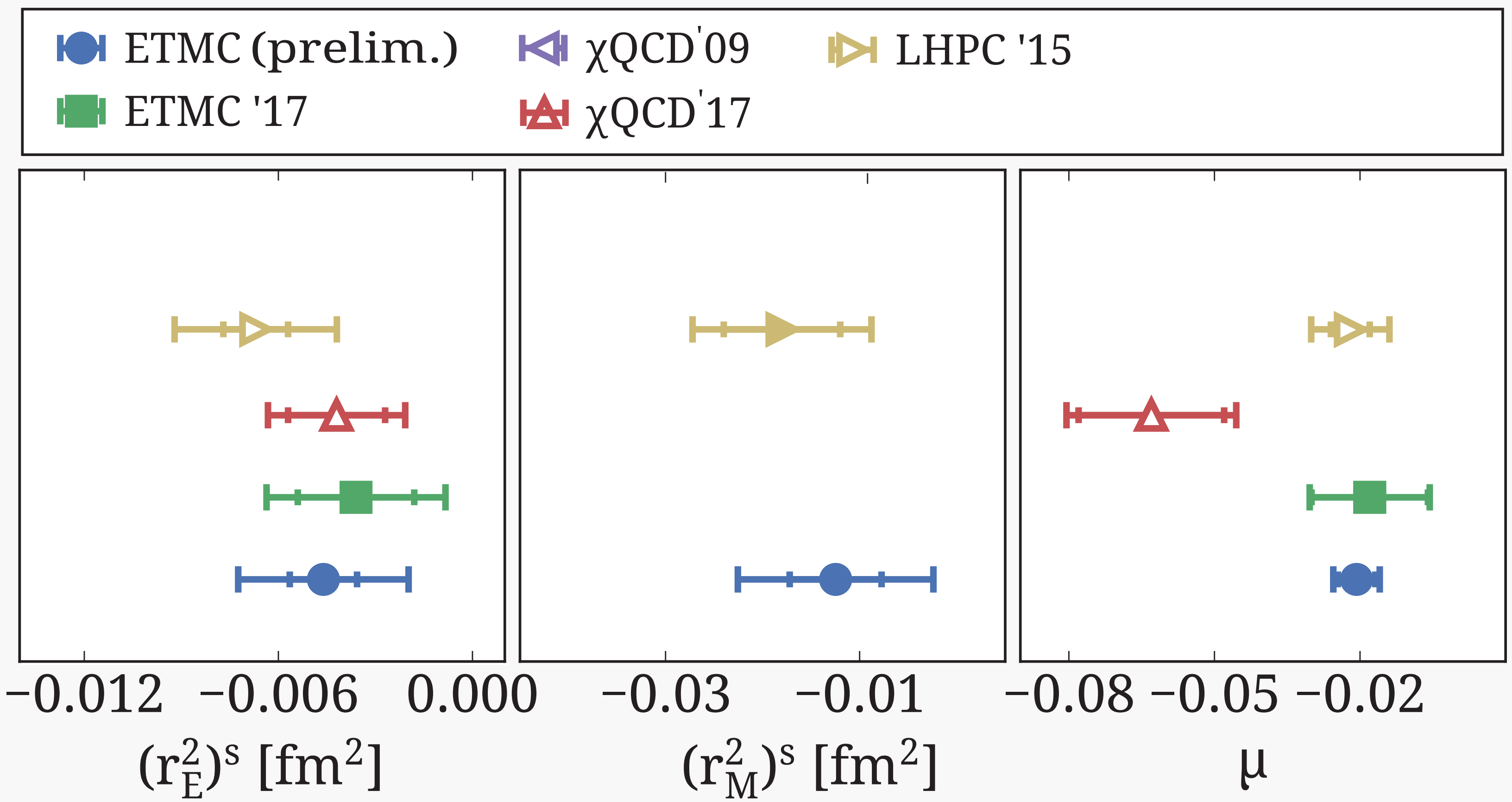
Nucleon Electromagnetic Form-Factors



Extraction of radii – strange form-factors

- ETMC results at physical pion mass
- Preliminary for N_f=2+1+1
- Agreement between collaborations/lattice schemes

Summary

Lattice QCD has entered a new era

- Physical pion mass simulations from a number of collaborations
- Other systematic uncertainties coming under control
- Techniques for disconnected diagrams make calculations of individual quark contributions feasible

Nucleon spin

- Spin decomposition of proton from lattice QCD with ~10% errors
- First results with all contributions, including gluon, at physical point
- Continuum limit and N_f=2+1+1 simulations ongoing

Electromagnetic form-factors

- Proton and neutron form-factors available thanks to accurate fermion loop calculation
- Results for strangeness at physical pion mass with statistical errors under control

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HPC-LEAP
EUROPEAN JOINT DOCTORATES

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Backup

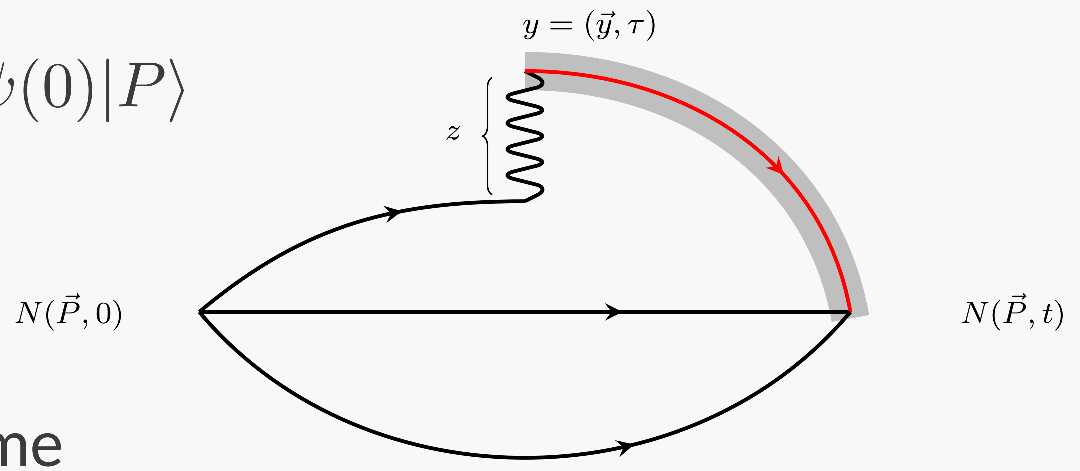
Parton Distribution Functions

$$q(x,\mu) = \int_{-\infty}^{\infty} \frac{d\xi^-}{4\pi} e^{-ixP^+\xi^-} \langle P|\bar{\psi}(\xi^-)\gamma^+ W(\xi^-,0)\psi(0)|P\rangle$$

Light-cone distributions

- Cannot be measured on a Euclidean lattice (ξ on light-cone)

$$\tilde{q}(x,P_3) = \int_{-\infty}^{\infty} \frac{dz}{4\pi} e^{-ixP_3 z} \langle P|\bar{\psi}(z)\gamma_3 W(z,0)\psi(0)|P\rangle$$



Quasi-PDF

- Spacial correlation function
- Connect to PDF at infinite momentum frame

Challenges

- Statistical error increases with momentum
- Renormalisation and matching at infinite momentum frame
- Continuum limit

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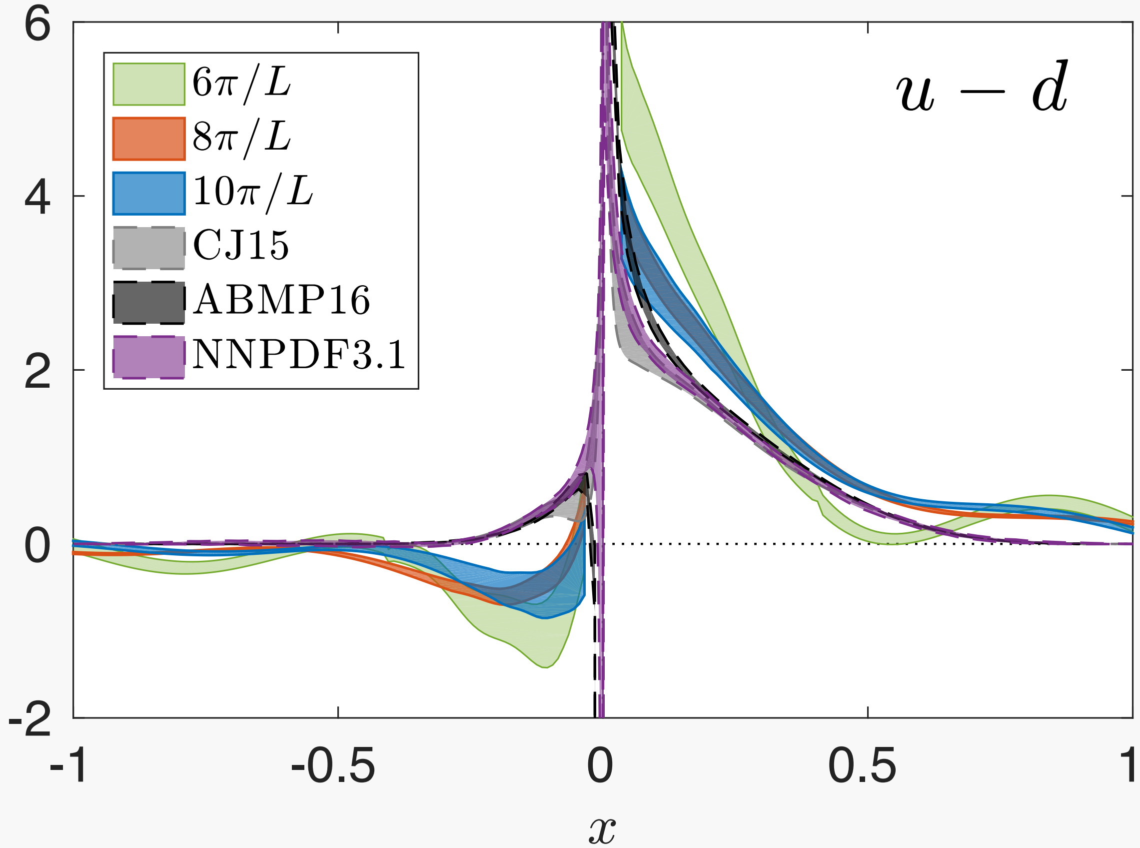
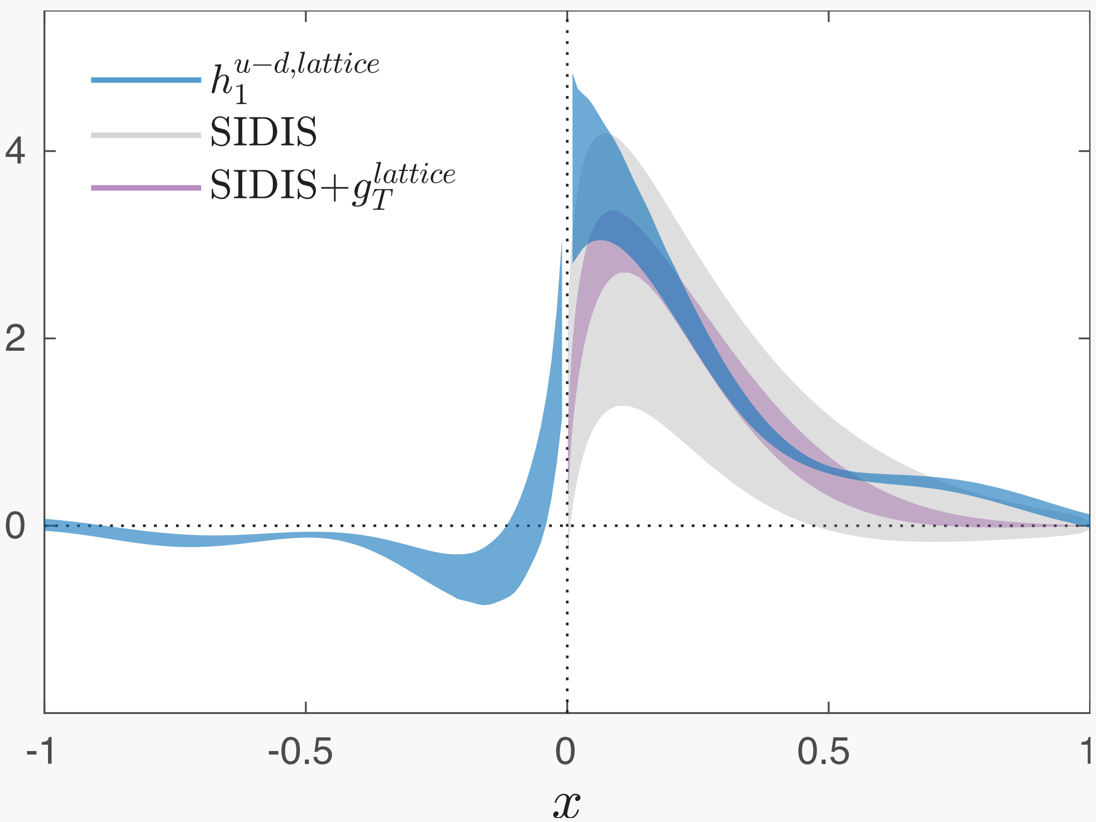
Parton Distribution Functions



C. Alexandrou *et al.*, arXiv:1803.02685



C. Alexandrou *et al.*, arXiv:1807.00232

PDFs on the lattice

- Available at physical pion mass
- Available at several momenta – reaching ~1.7 GeV

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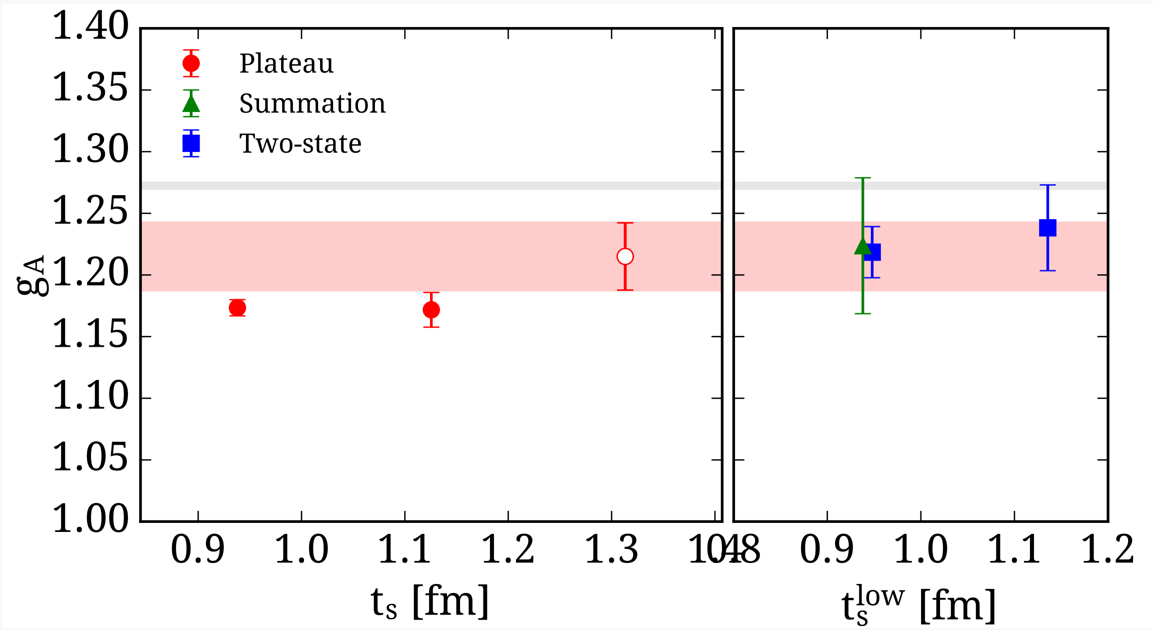
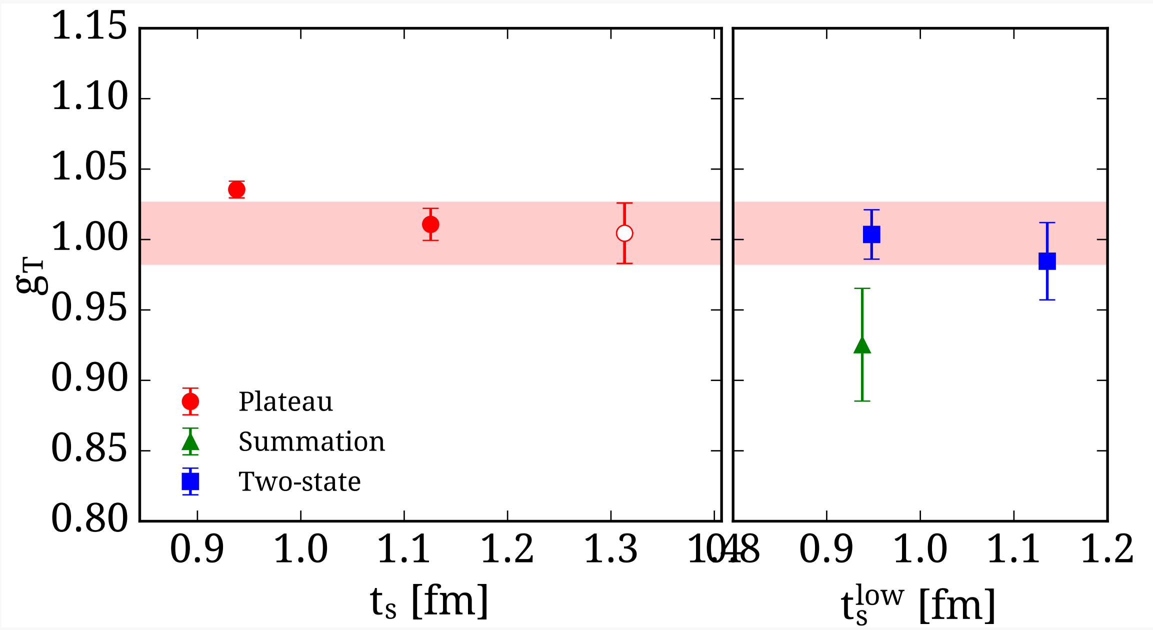
Excited States





Examples of analyses for identifying excited state effects

- Three methods
- Need multiple sink-source separations

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