Hadron Structure from Lattice QCD

James Zanotti
The University of Adelaide

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Acknowledgements

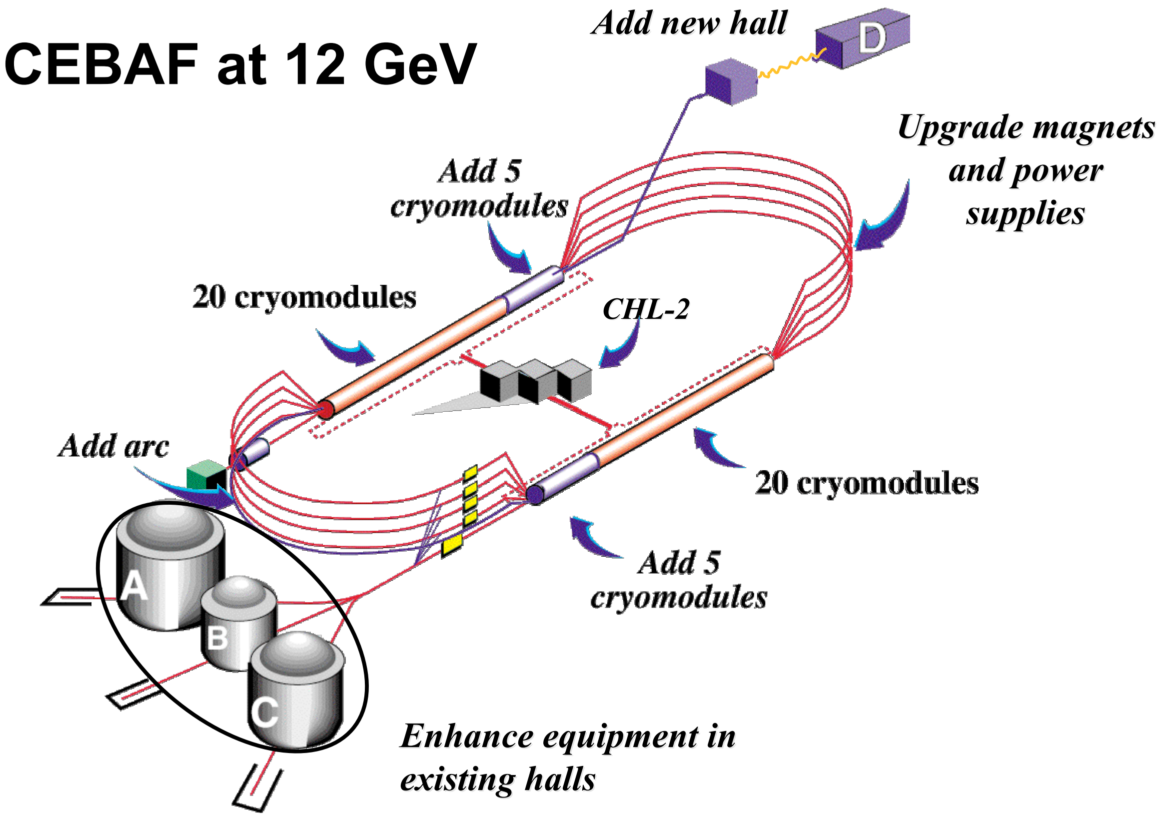
- **Thanks to everyone who sent data, plots, references**
    - **Special thanks to …..**
        - **Alex Chambers**
        - **Jack Dragos**
        - **Tim Harris**
        - **Huey-Wen Lin**
        - **Rudolf Rödl**
        - **Shoichi Sasaki**
- **Sorry if I don't cover your work, there are way too many topics to cover in 40mins**

Outline

- **Motivation - Experimental challenges & theoretical issues**
- **Nucleon charges (Axial, tensor, scalar)**
- **Momentum fraction**
- **Spin content, including** $\Delta s \quad \Delta G$
- **EM form factors (including strangeness, light nuclei, charge symmetry)**
- **Pion,** $\rho \to \pi\gamma$ **form factors**
- **Transverse Momentum Distributions & “quasi”-PDFs**
- **Summary & outlook**

Motivation

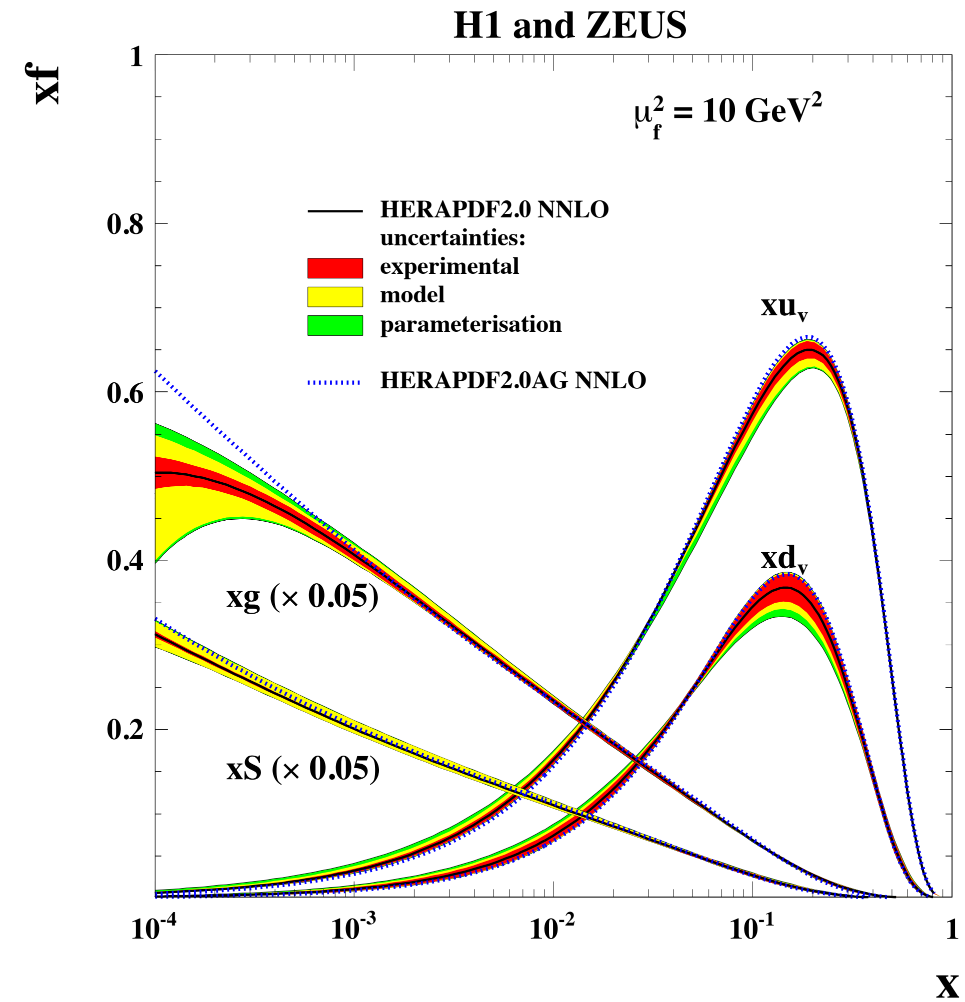
- **Major goal of nuclear physics community**
  - **understand the structure and behaviour of strongly interacting matter in terms of its basic constituents - quarks and gluons**
- **An important step towards this goal is the characterisation of the internal structure of the nucleon**
  - **Driving force behind several experimental programs, e.g. JLab 12 GeV upgrade**



Deep inelastic scattering (DIS) experiments

Parton distribution functions

[HERA, 1506.06042]



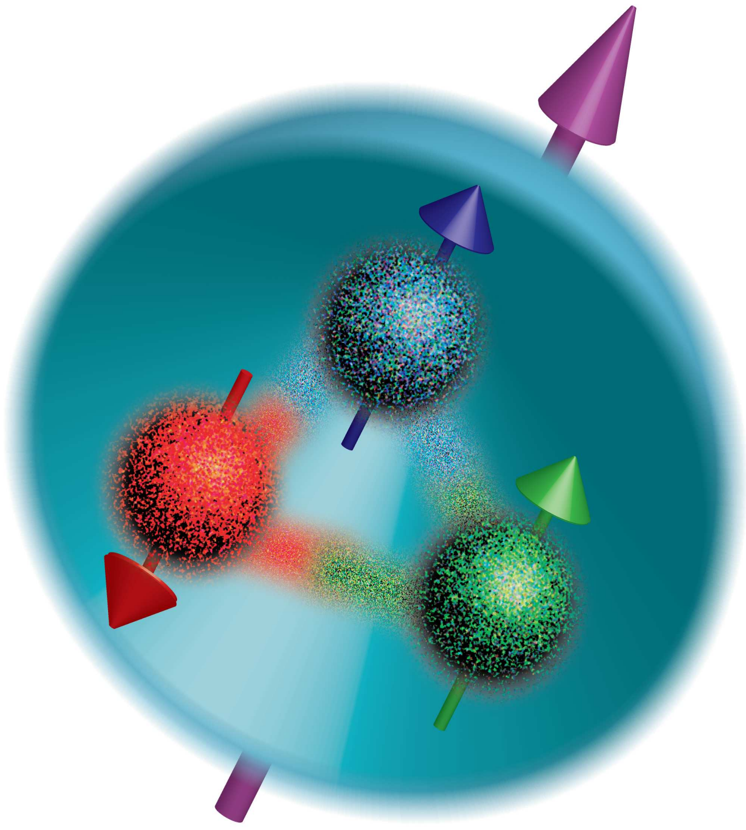
reveal the breakdown of the momentum of a (fast-moving) nucleon terms of its quark and gluon (parton) constituents

- The same cannot be said of our understanding of the nucleon spin, mass, magnetic moment, ….

Spin of the Proton

Proton has spin 1/2

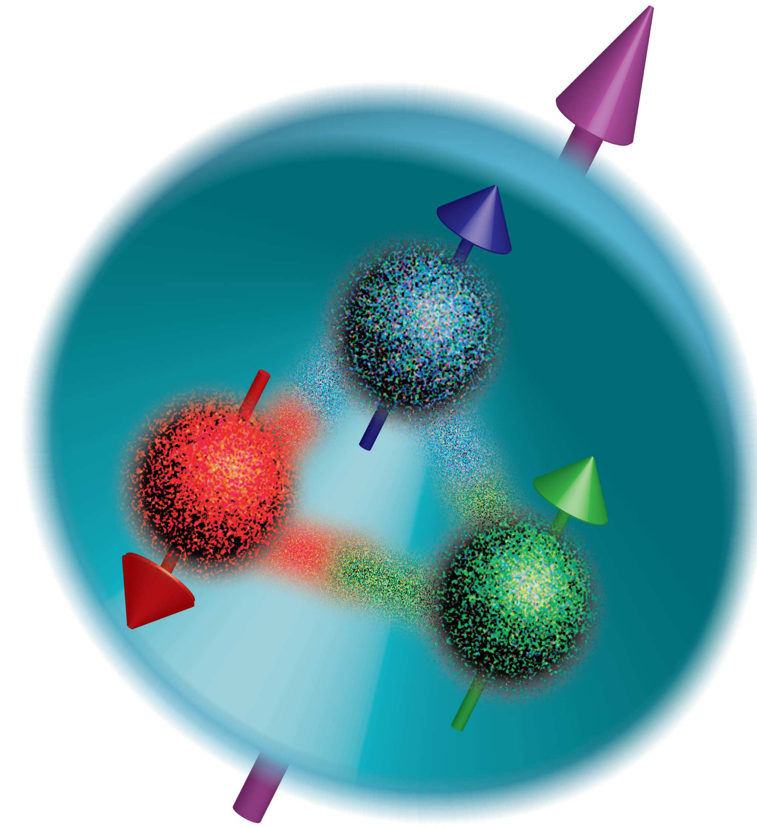
Spin of the Proton



Proton has spin 1/2

Quark Model predicts: only due to the spin of 3 valence quarks (also spin-1/2)

Spin of the Proton



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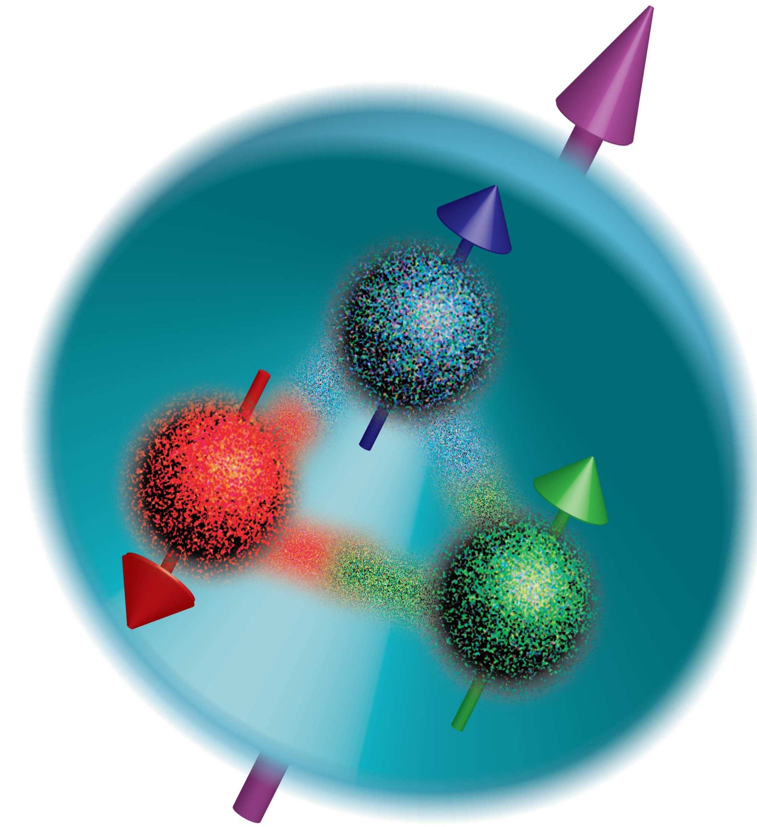
EMC (1988) found this only accounted for 1±12±24%

COMPASS (2007) improved this to 33±3±5%

"Spin crisis"?

Spin of the Proton



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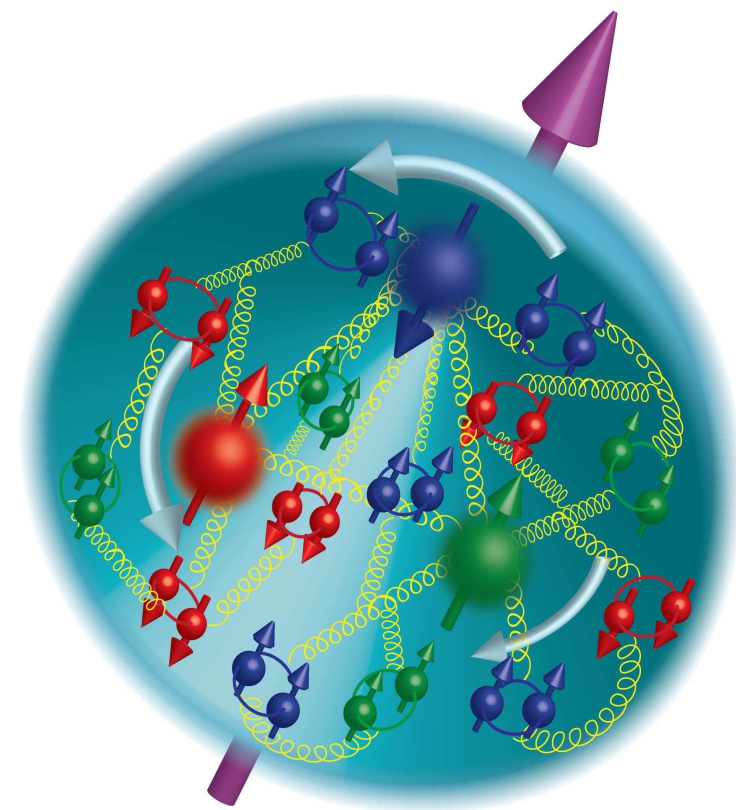

(EIC white paper [1212.1701])

⇒ **“Spin crisis”?**

No, only a “spin puzzle”

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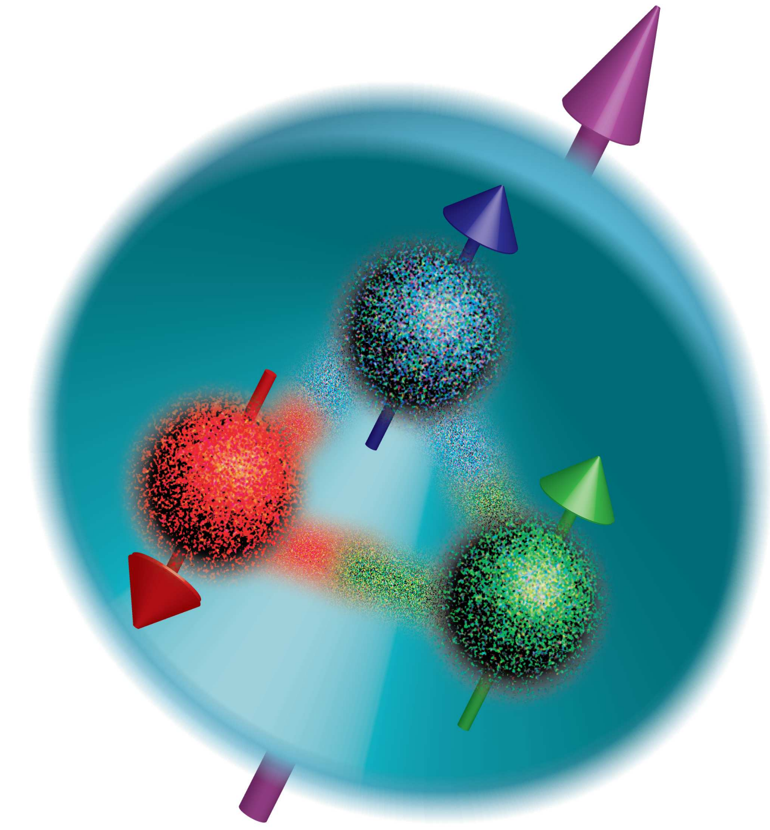

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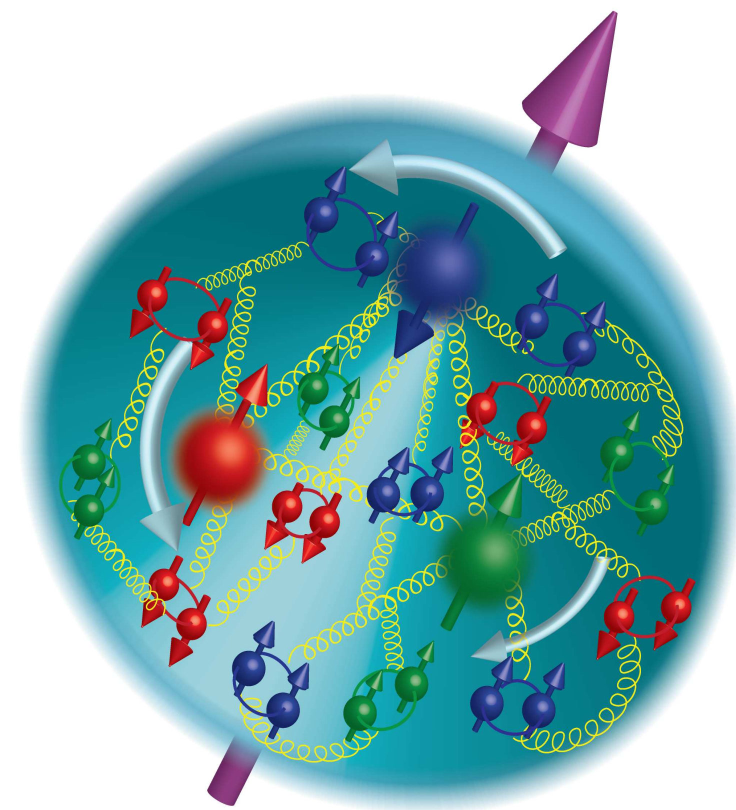


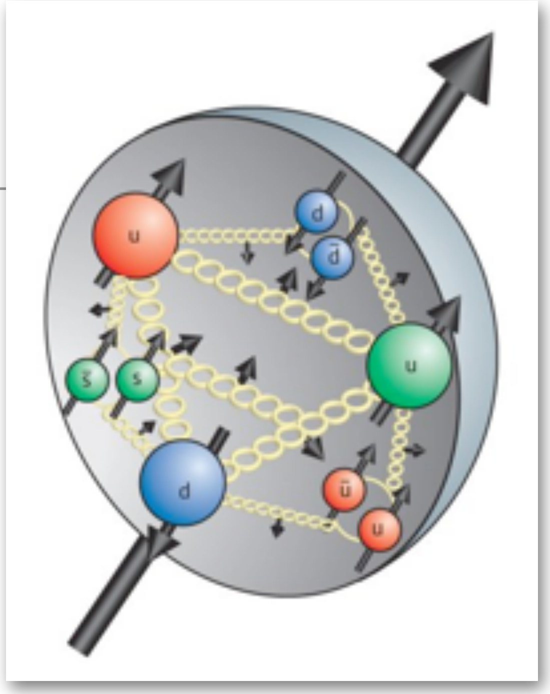
⇨ **"Spin crisis"?**

No, only a "spin puzzle"

(EIC white paper [1212.1701])

But how is the other 70% of the proton spin distributed between these components?

Spin of the Proton



How is the spin of the proton distributed between its constituents?

Jaffe & Manohar (1990): $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

X. Ji (1997): $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.33(3)(5)$$

Why so small?

Due to large negative Δs ?

Much effort to determine Δs experimentally $\int_0^1 g_1^p(x)\,dx = \frac{1}{36}(4a_0 + 3a_3 + a_8)$

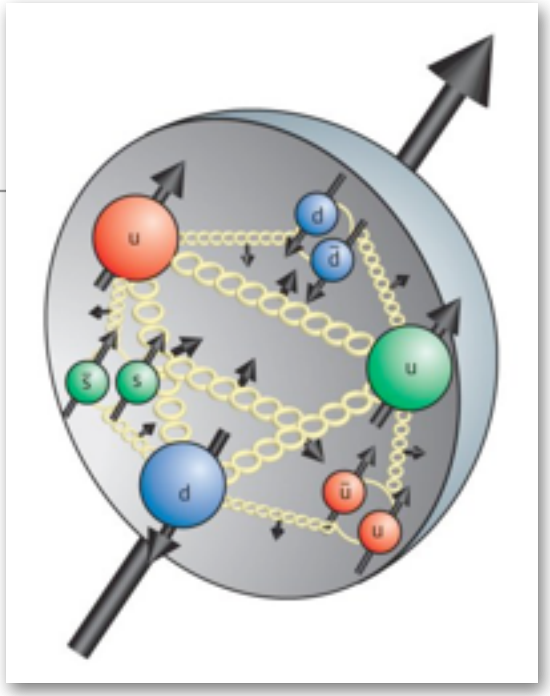
e.g. COMPASS, HERMES

$x \geq 0.004$ $\quad$ $x \geq 0.02$

Also g_A and semileptonic hyperon decays assuming SU(3) symmetry

→ $-0.15 \leq \Delta s \leq -0.03$

Spin of the Proton



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Why so small?

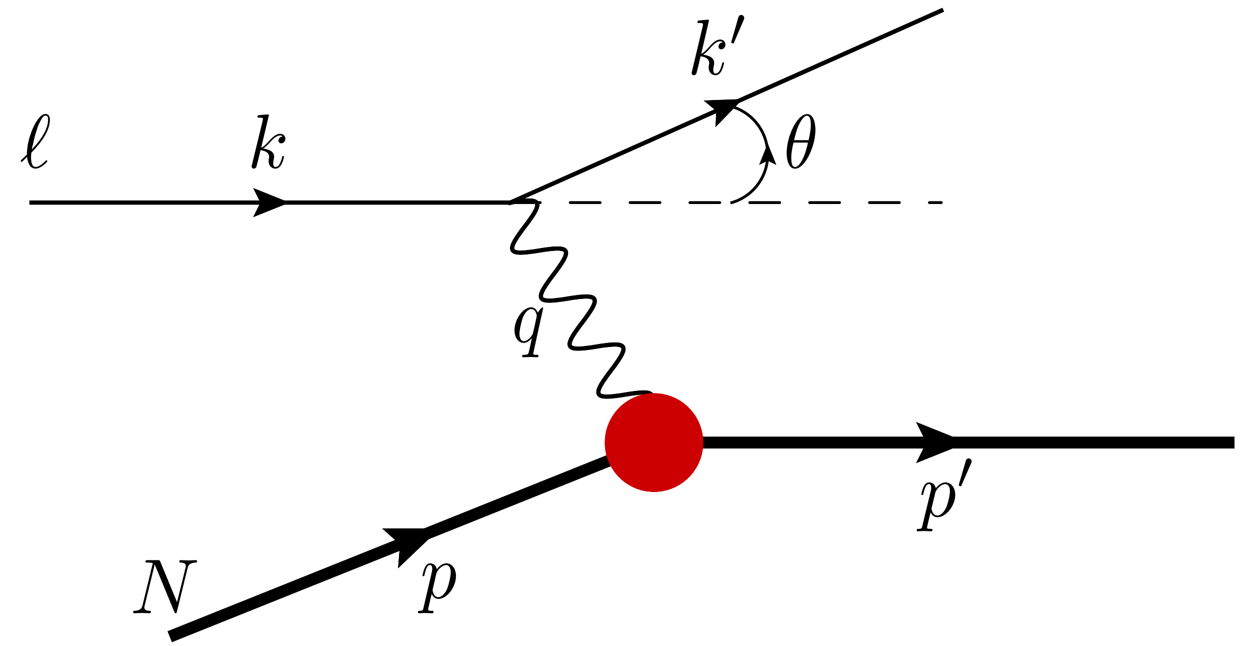
Large ΔG ?

Recent global analysis of RHIC (PHENIX & STAR) and COMPASS data

[de Florian et al., PRL113 012001((2014)]

$$\Delta G \approx \int_{0.005}^{0.2} \Delta g(x)\, dx = 0.1^{+0.06}_{-0.07}$$

(negligible contribution $x>0.2$, poorly constrained $0.001<x<0.05$)



Electromagnetic Form Factors

$$\langle p',\, s'|J^{\mu}(\vec{q})|p,\, s\rangle \;=\bar{u}(p',\, s')\left[\gamma^{\mu}F_1(q^2)+i\sigma^{\mu\nu}\frac{q_{\nu}}{2m}F_2(q^2)\right]u(p,\, s)$$

$$G_E(Q^2)=F_1(Q^2)-\tau F_2(Q^2)$$
$$G_M(Q^2)=F_1(Q^2)+F_2(Q^2)$$

Elastic Scattering - Polarisation Transfer

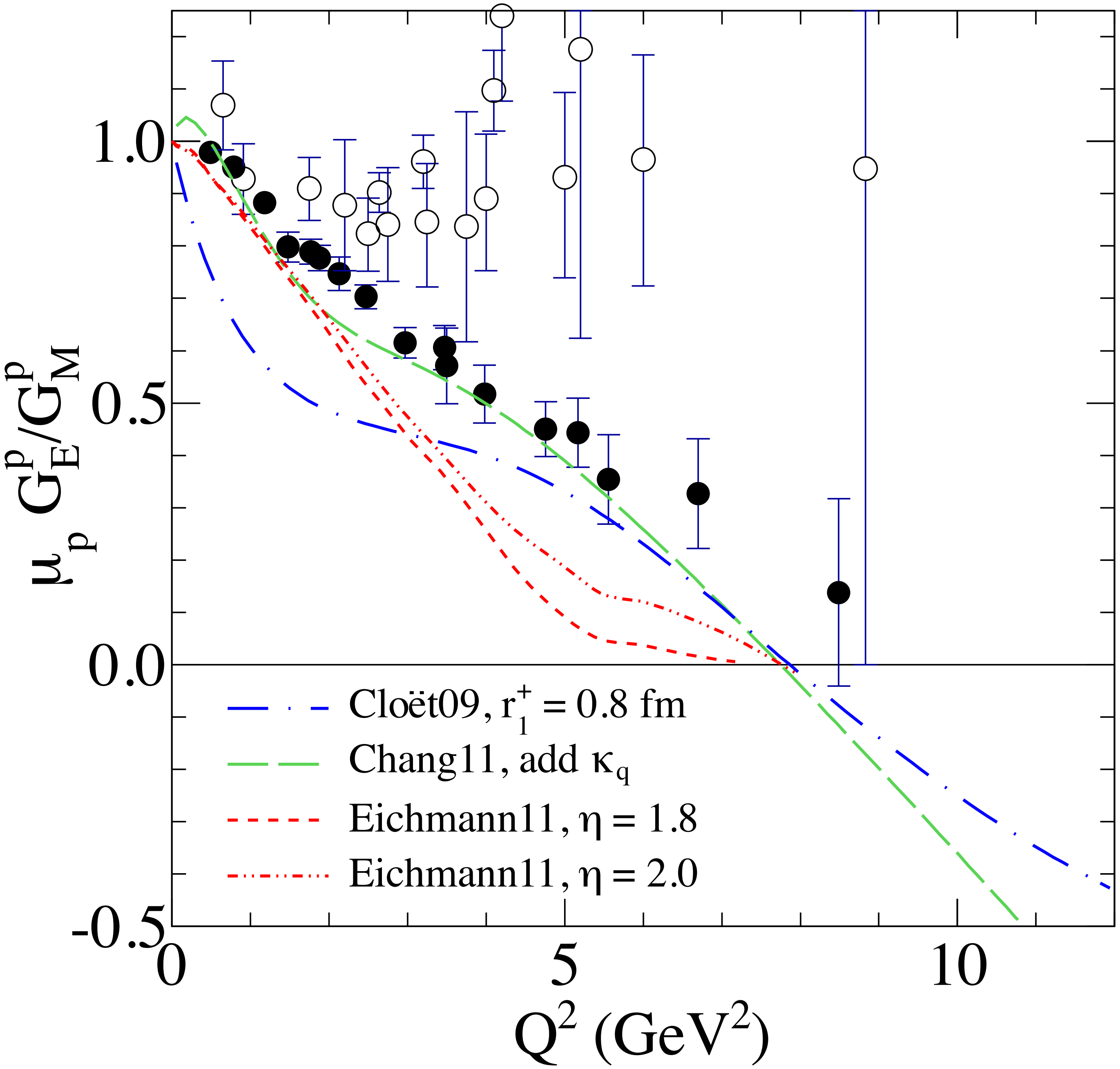
Polarisation transfer experiments at JLab revealed a surprising behaviour for *G_E/G_M*

Precise results now available up to 8-9 GeV^2

What is the origin of the linear fall-off?

Does G_E^p change sign?

[JLab, Hall A, PRC85 (2012) 045203]

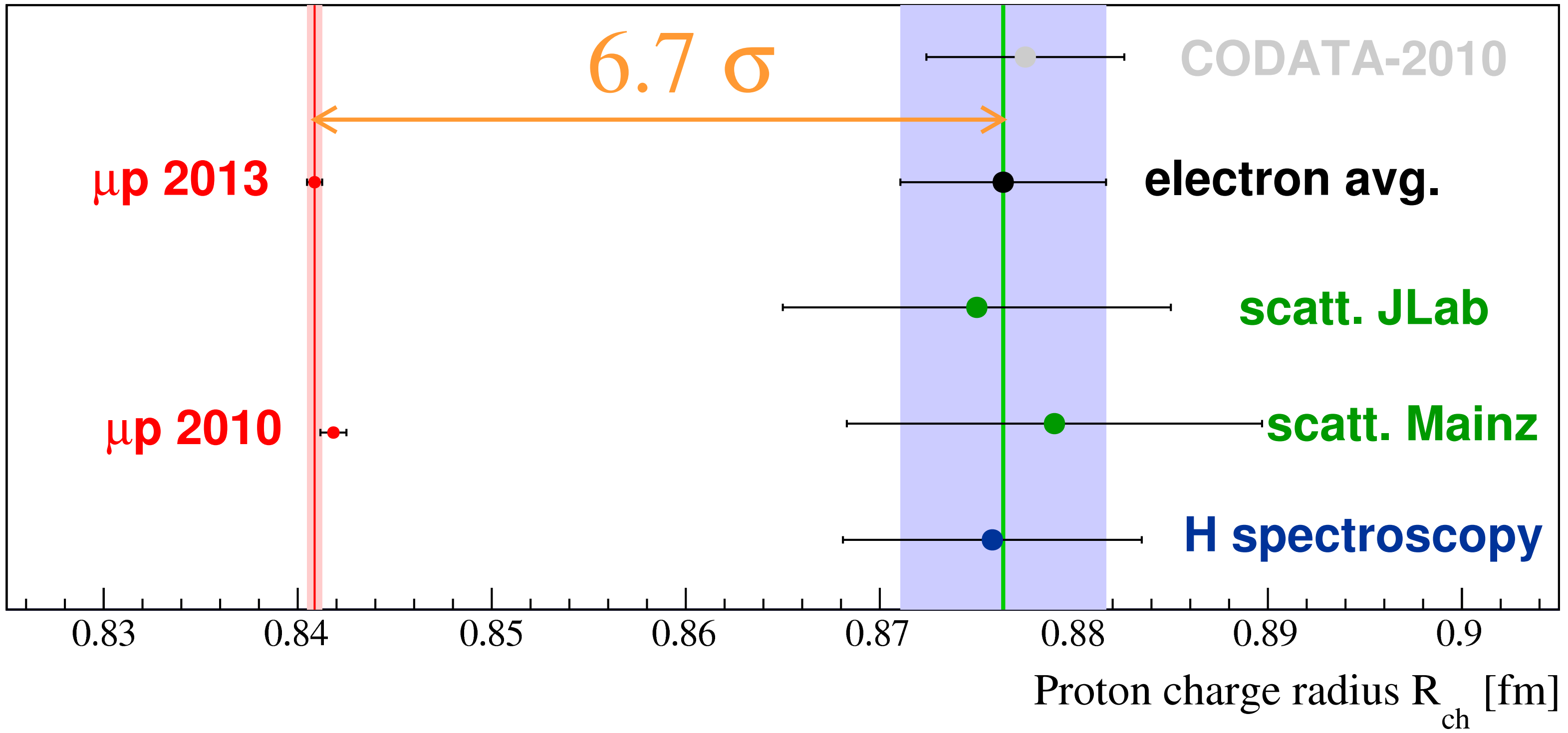


Size of the Proton

- **Charge radius of the nucleon**

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2 \rangle_E + p + \ldots$$

- $\sim 7\sigma$ **discrepancy between μH and H / *e-p* scattering**



[Arrington, arXiv:1506.00873]

Hadron Structure - new experiments

- **An understanding of nucleon spin is a major goal of many current and future experimental programs**

- **12 GeV JLab upgrade**

- **Origins of quark confinement**
- **Spin and flavour structure of the proton and neutron (PDF’s, GPD’s, TMD’s…)**
- **Quark structure of nuclei**
- **Probe potential new physics through high precision tests of the Standard Model**
- **Flavour separation of EM form factors**

Hadron Structure - new experiments

- **An understanding of nucleon spin is a major goal of many current and future experimental programs**

- 12 GeV JLab upgrade
- **COMPASS (II)**

- **Proton spin (GPDs, Gluon)**
- **TMDs**
- **Pi and K polarisabilities**

Hadron Structure - new experiments

- **An understanding of nucleon spin is a major goal of many current and future experimental programs**

- 12 GeV JLab upgrade

- COMPASS (II)

- **RHIC**

- **(PHENIX, STAR)**

  - **spin and orbital angular momentum of quarks and gluons**

  - **transverse spin structure of the proton**

Hadron Structure - new experiments

- **An understanding of nucleon spin is a major goal of many current and future experimental programs**
- 12 GeV JLab upgrade
- COMPASS (II)
- RHIC
- **MAMI (Mainz):**
  - **EM form factors, polarisabilities**
  - **Structure of nuclei**
  - **Parity violating - strange EM, axial form factor**

Hadron Structure - new experiments

- **An understanding of nucleon spin is a major goal of many current and future experimental programs**

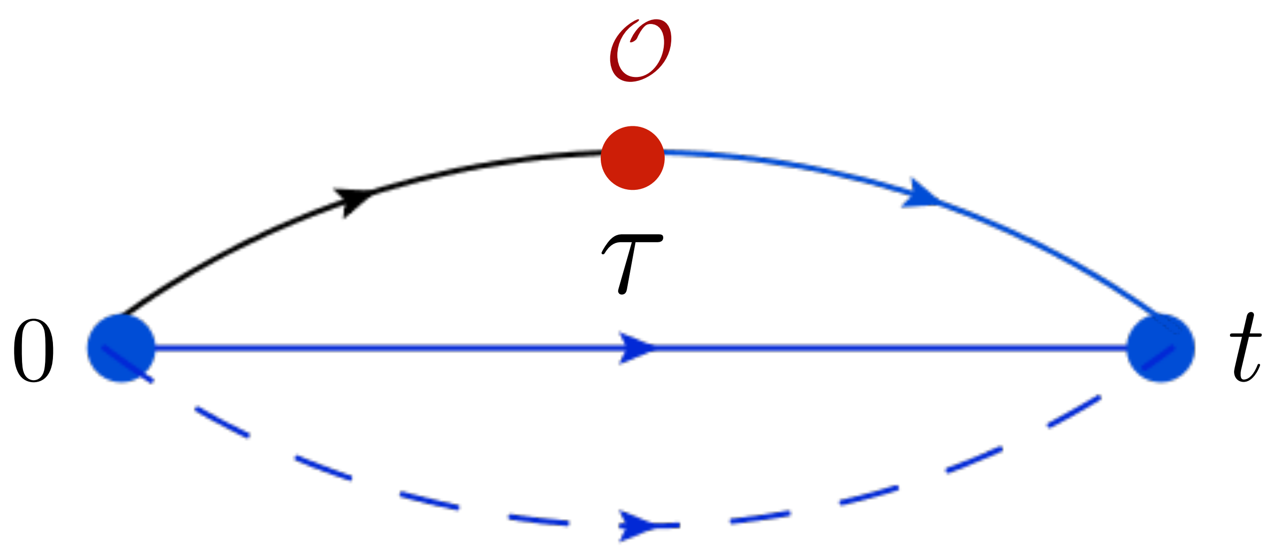
- 12 GeV JLab upgrade
- COMPASS (II)
- RHIC
- MAMI (Mainz)
- **Electron-Ion Collider (JLab or BNL)**

- **Dramatic improvement in understanding role of sea quarks and glue**
- **“Missing spin” provided by gluons**
- **High-energy probes of partons’ transverse momenta - contribution from orbital motion**

Lattice Hadron Structure

Lattice 3pt function

Most common method for determining matrix elements relevant for hadron structure calculations - 3pt function

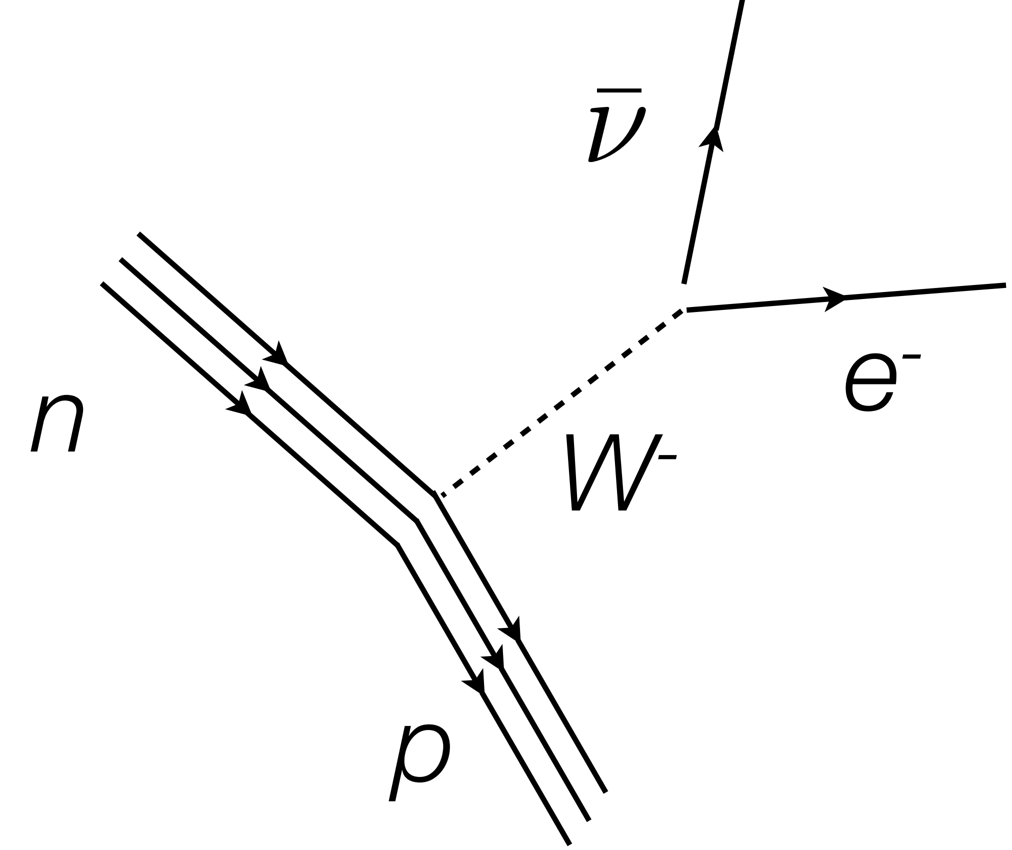


$$G(t,\tau,\vec{p},\vec{p}\,') = \sum_{s,s'} e^{-E_{\vec{p}\,'}(t-\tau)} e^{-E_{\vec{p}}\tau} \Gamma_{\beta\alpha} \langle \Omega | \chi_\alpha(0) | N(p',s') \rangle \langle N(p',s') | \mathcal{O}(\vec{q}) | N(p,s) \rangle \langle N p, s) | \overline{\chi}_\beta(0) | \Omega \rangle$$

For large times $1 \ll \tau \quad 1 \ll t-\tau$

⇨ **Extract matrix element**

⇨ **Determine form factors, charges, moments, …**



$$n \to p e^- \bar{\nu}_e$$

Nucleon axial charge

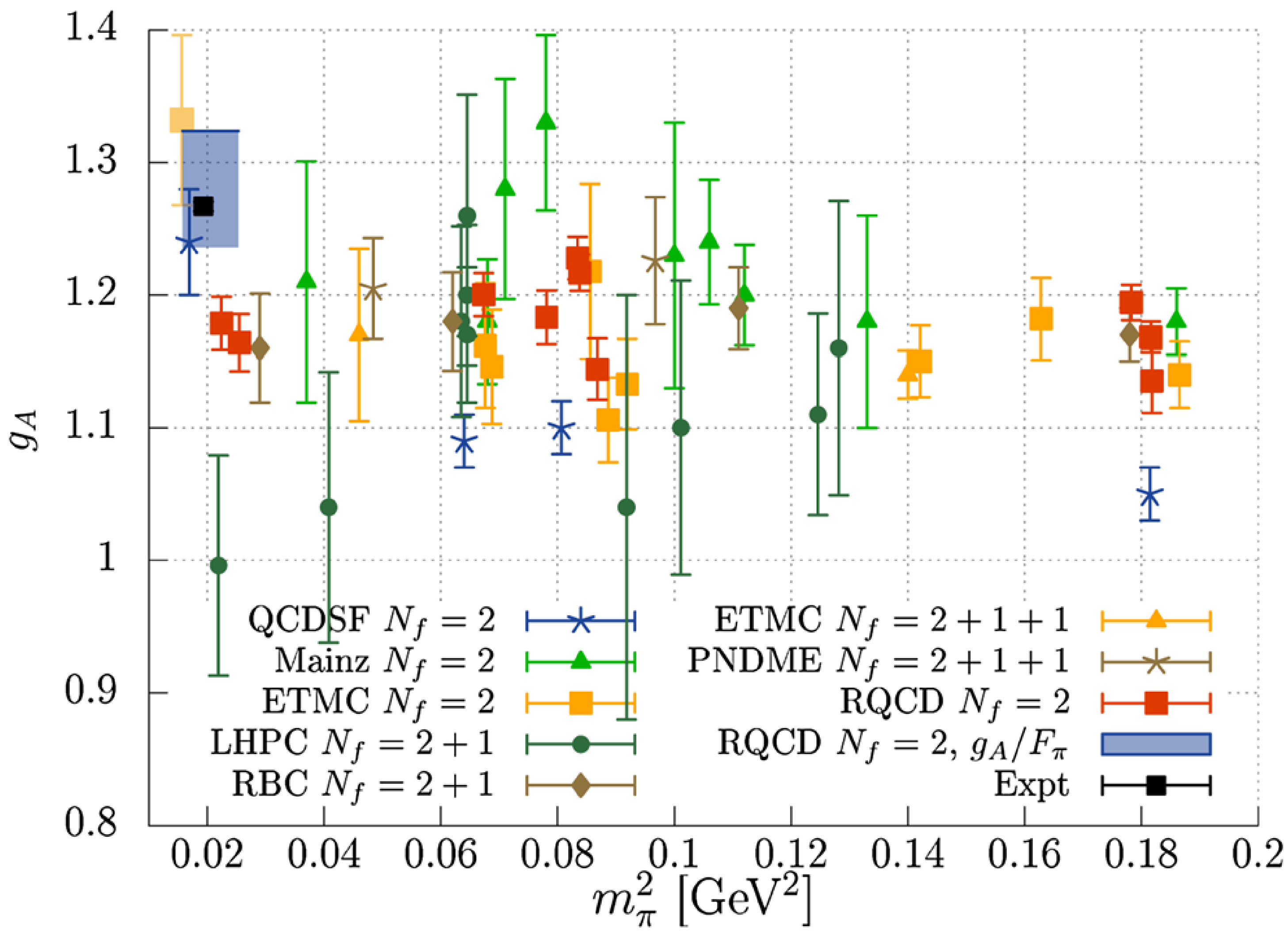
$$g_A^{\text{exp}} = 1.2701(25)$$

Relatively simple to compute on the lattice (p=q=0, isovector)

Good benchmark for hadron structure (understanding systematic errors)

Determination of g_A on the Lattice

Summary plot: RQCD PRD91 (2015) 054501



Results systematically 10-20% below experiment

Large scatter in the results

→ **interest in studying potential sources of systematic error**

Determination of g_A on the Lattice

Thorough investigations of

- **Lattice spacing**
- **Quark mass**
- **Finite volume**
- **Contamination from excited states**
- **Improved axial current**

[Dragos, Tue 17:30]
[Gupta, Thu 10:40]
[Harris, Sat 10am]
[Ohta, Wed 18:10]
[von Hippel, Sat 10:40]
[Yamanaka, Wed 17:10]
[Yamazaki, Wed 14:20 (Had Spec & Int)]

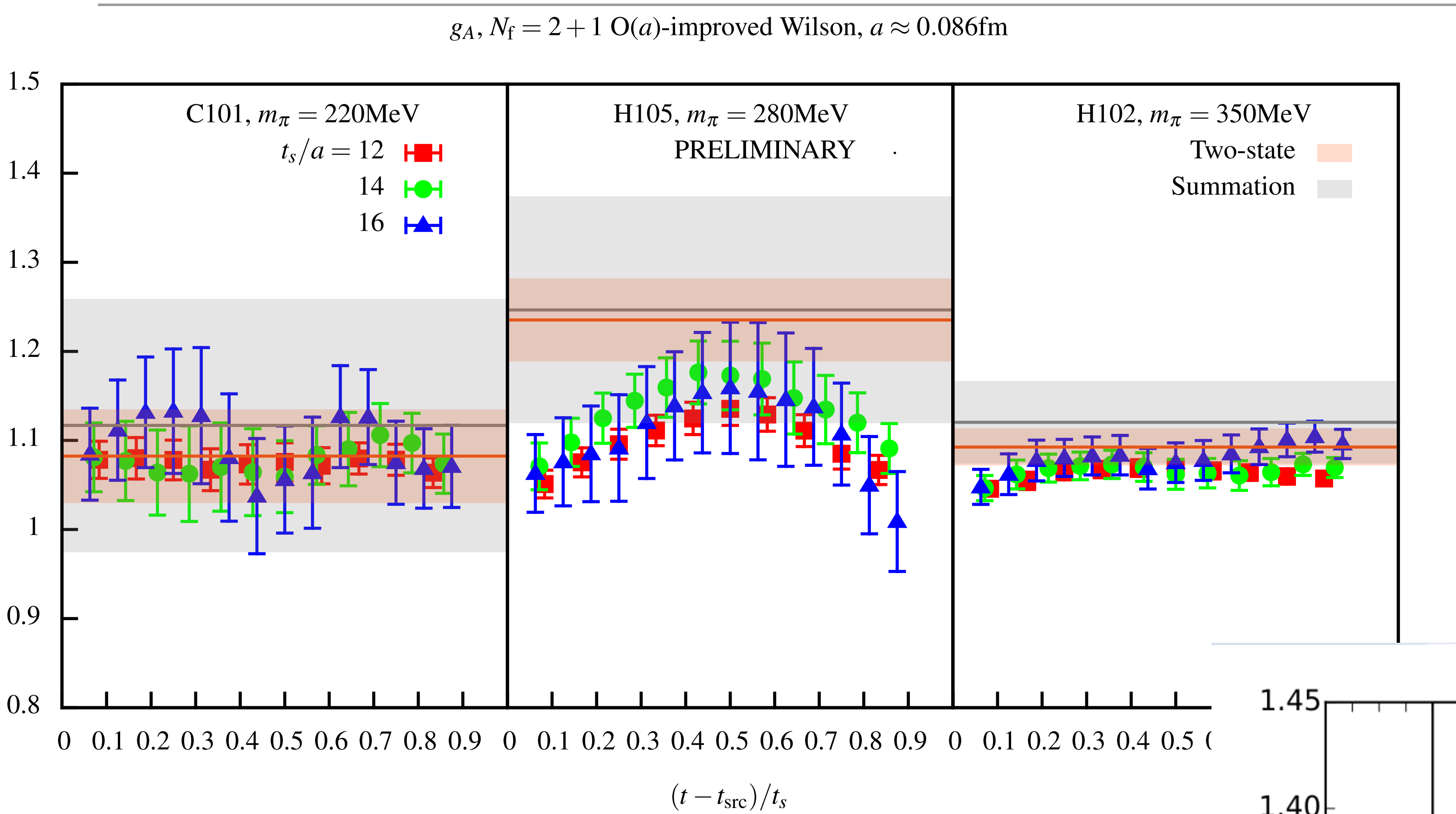
[Schiller, Sat 10:20]

g_A appears to be very sensitive to Lattice systematics

Lots of effort in reducing systematic errors ⇒ **flow on for other quantities**

Determination of g_A on the Lattice

Excited state contamination



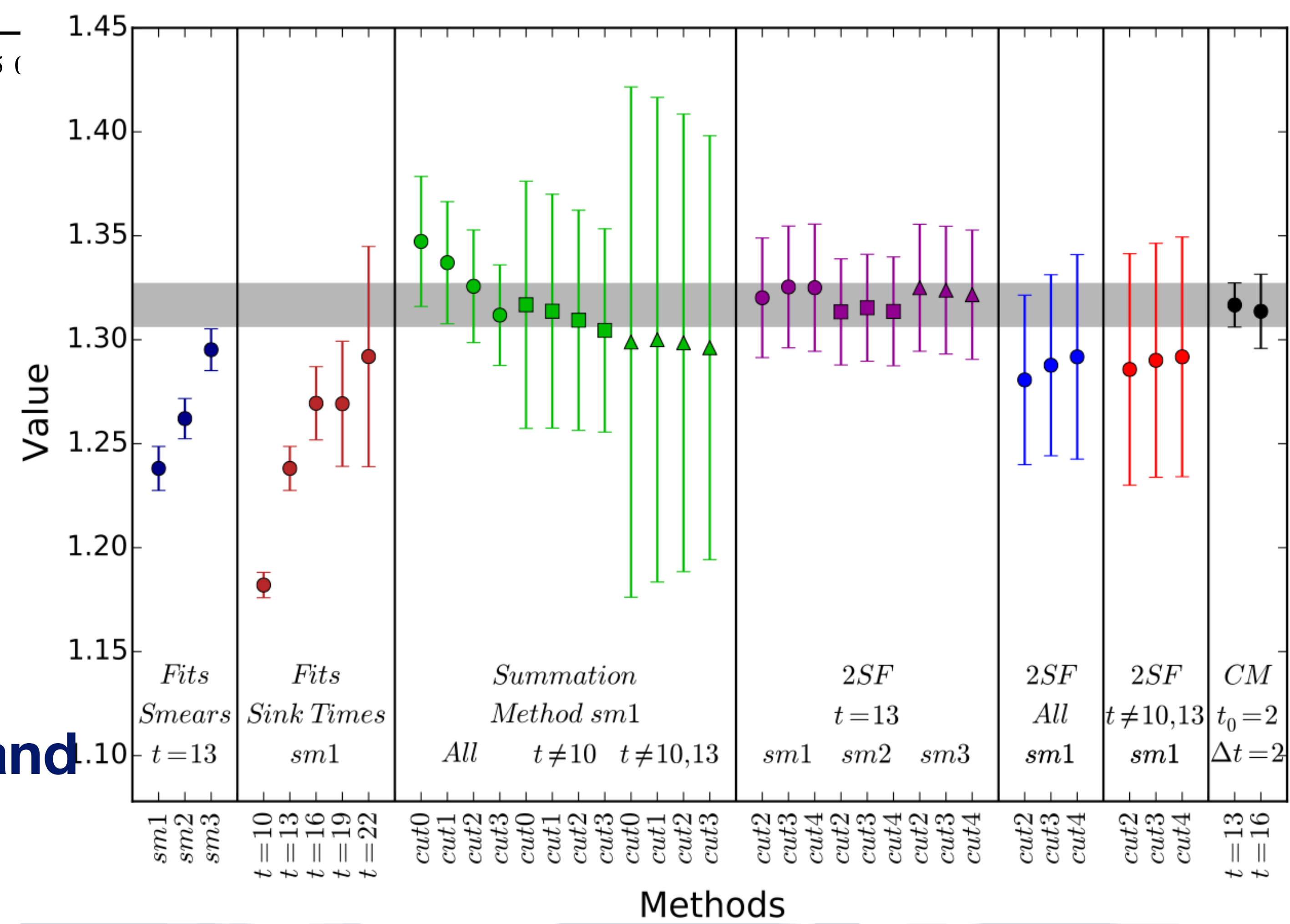
Mainz (Harris, Sat 10:00)

Multiple tsink

Summation and 2-exponential fits

CSSM/QCDSF (Dragos, Tue 17:30)

Comparison of various methods for suppressing excited states

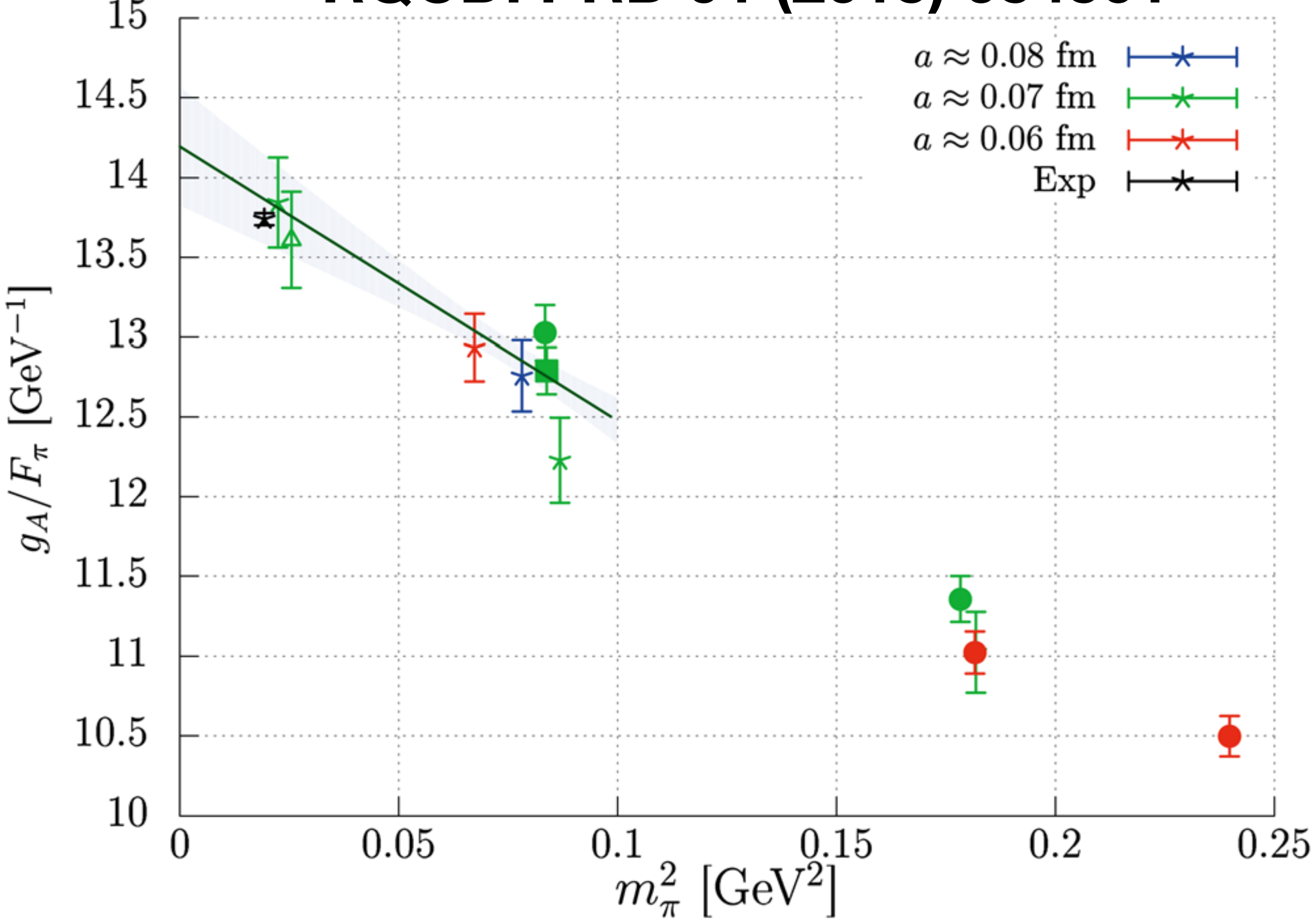


Small suppression of g_A for small times and poor operator choice

Determination of g_A on the Lattice

Renormalisation free ratio

RQCD: PRD 91 (2015) 054501

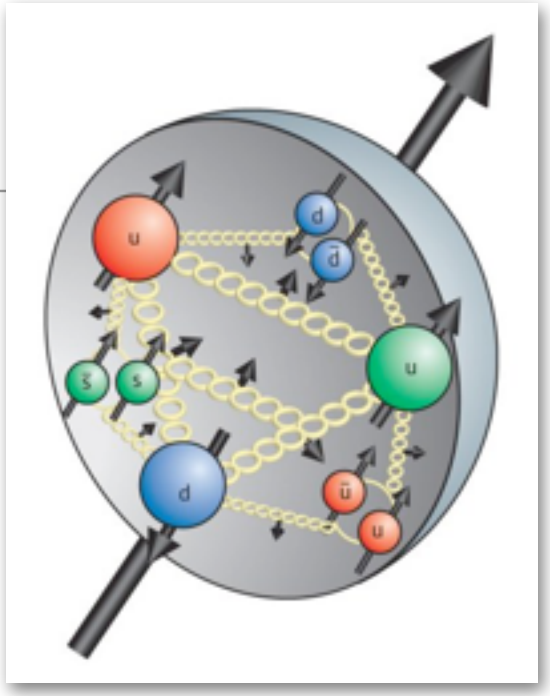


QCDSF: PLB 732 (2014) 41

g_A/f_π **Ratio extrapolation agrees with exp**

FV effects cancel in HBChPT

Spin of the Proton



How is the spin of the proton distributed between its constituents?

Recall Ji's sum rule: $$\frac{1}{2} = \sum_q J_q(\mu^2) + J_g(\mu^2)$$

Express in terms of moments of Generalised Parton Distributions

$$J_{q/g} = \frac{1}{2}\left[A_{20}^{q/g}(q^2=0) + B_{20}^{q/g}(q^2=0)\right]$$

which are obtained from the matrix elements of the energy momentum tensor

$$\langle P'|T^{\mu\nu}|P\rangle = \overline{U}(P')\left\{\gamma^\mu \overline{P}^\nu A_{20}(q^2) + \frac{i\sigma^{\mu\rho}q_\rho \overline{P}^\nu}{2m_N} B_{20}(q^2) + \frac{q^\mu q^\nu}{m_N} C_{20}(q^2)\right\} U(P)$$

Determine the quark orbital angular momentum

$$L_q = \frac{1}{2}\left[A_{20}^{q}(q^2=0) + B_{20}^{q}(q^2=0) - \Delta q\right]$$

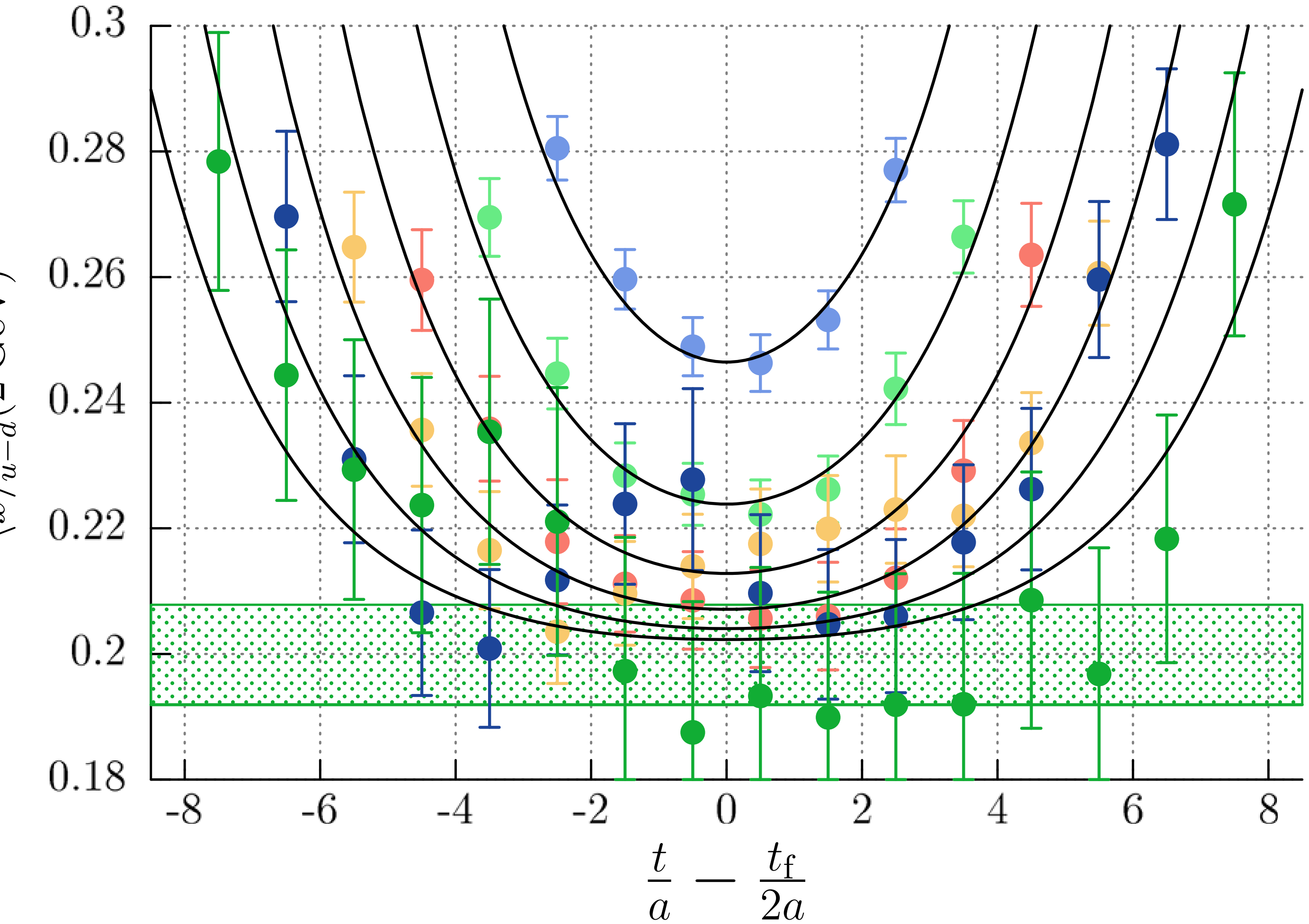
But $$\langle x\rangle^{q/g} = A_{20}^{q/g}(q^2=0)$$

Quark Momentum Fraction

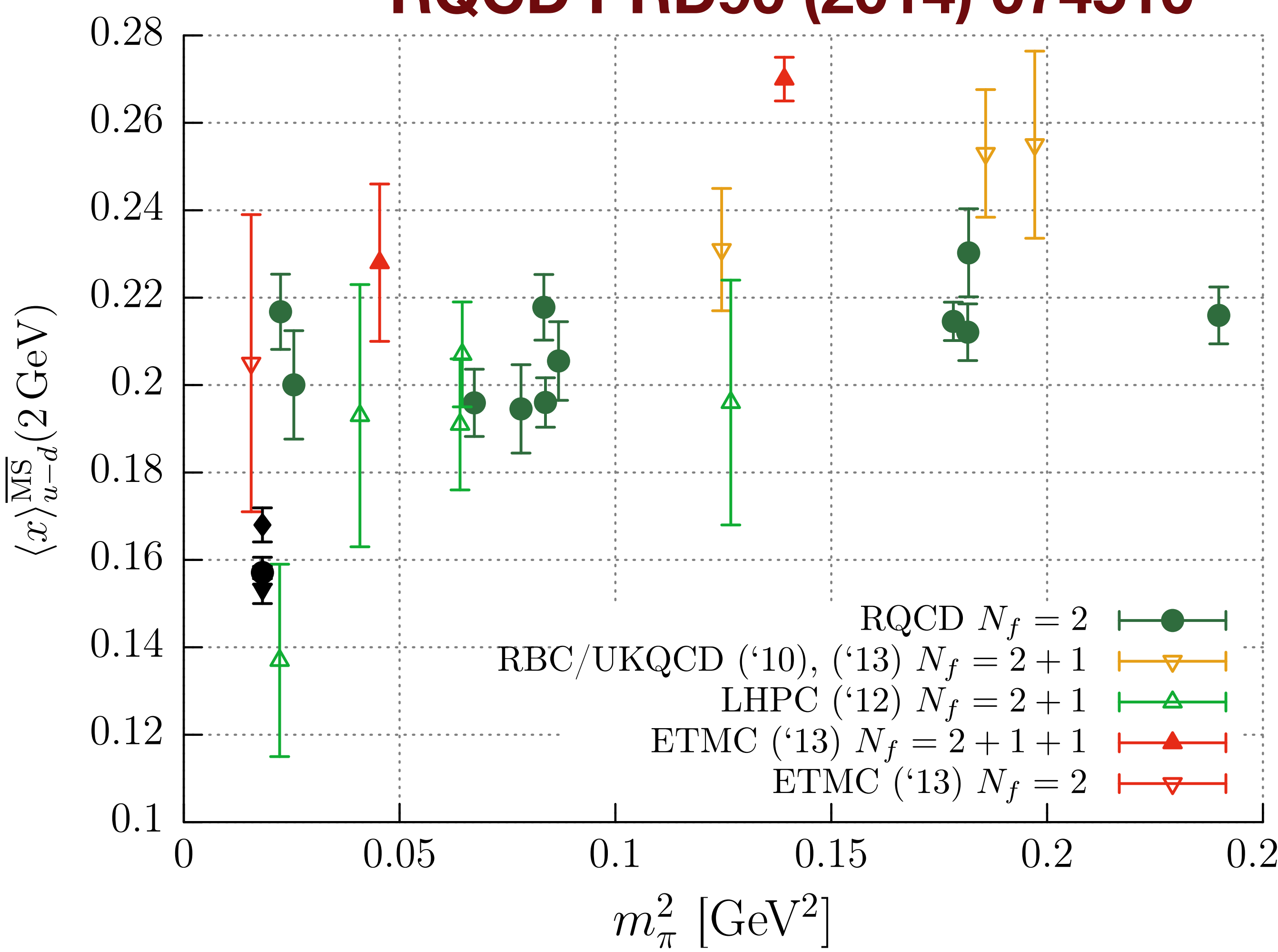
$$\langle x \rangle_q = \int_0^1 dx\, x\big(q(x) + \bar{q}(x)\big)$$

- **First moment of the (isovector) nucleon parton distribution function**
- **Notorious for producing lattice results ≈ 2x too large for isovector nucleon**
- **Known to be sensitive to excited state contamination**
- **Results near physical mass inconclusive**

IV, $a \sim 0.07$ fm, $m_\pi \sim 295$ MeV, $Lm_\pi = 3.42$



RQCD PRD90 (2014) 074510

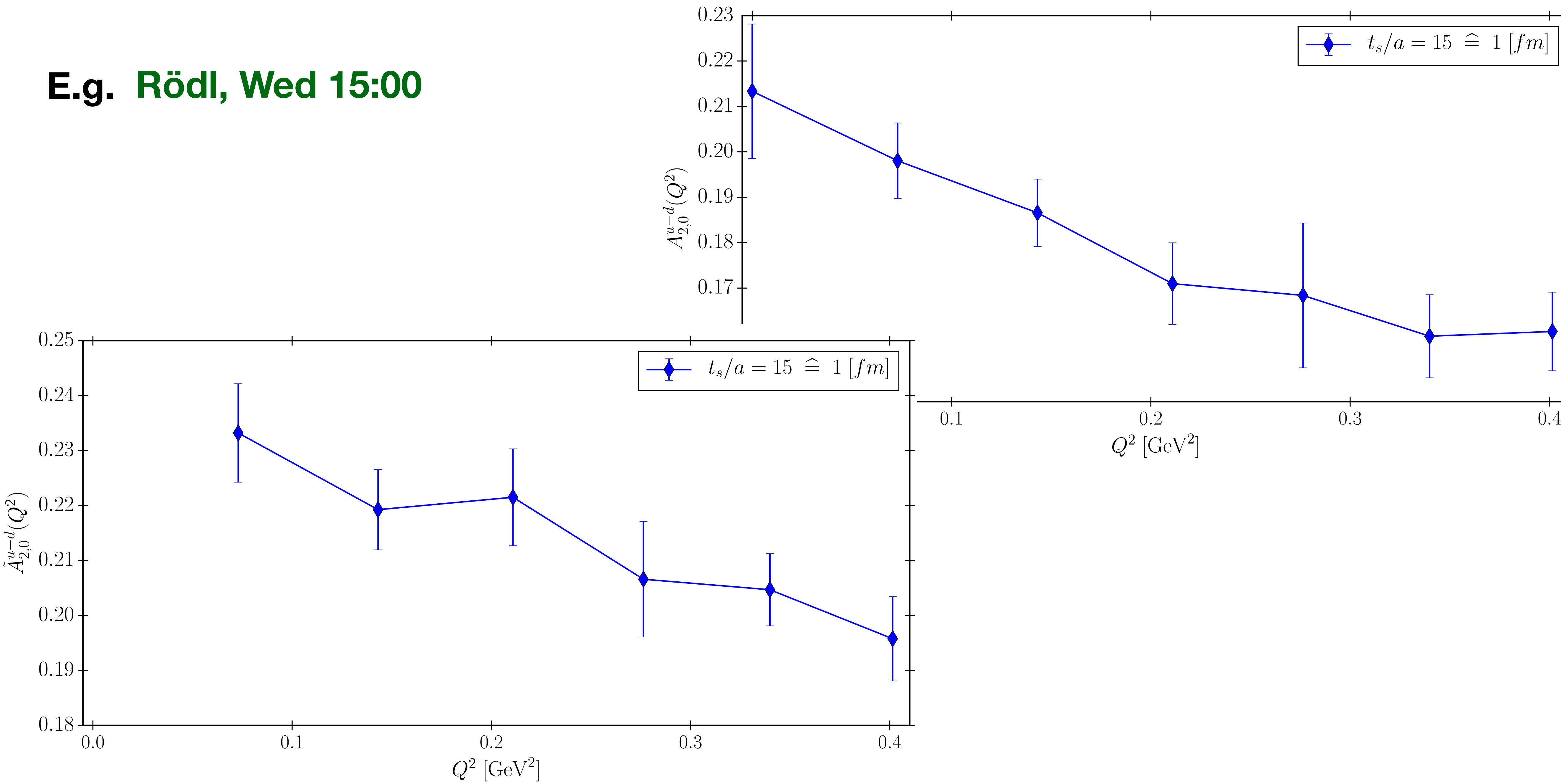


Spin of the Proton **Ji's sum rule**

Recall Ji's sum rule requires moments of Generalised Parton Distributions

$$J_{q/g} = \frac{1}{2}\left[\langle x\rangle^{q/g} + B_{20}^{q/g}(q^2=0)\right] \qquad \langle x\rangle^{q/g} = A_{20}^{q/g}(q^2=0)$$

E.g. Rödl, Wed 15:00



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$$\langle x\rangle^{q/g} = A_{20}^{q/g}(q^2=0)$$

$$\Rightarrow \quad L_q = \frac{1}{2}\left[\langle x\rangle^{q} + B_{20}^{q}(q^2=0) - \Delta q\right]$$

For reliable results for L_q

⇒ **need to control systematic errors for g_A and $\langle x\rangle^{u-d}$**

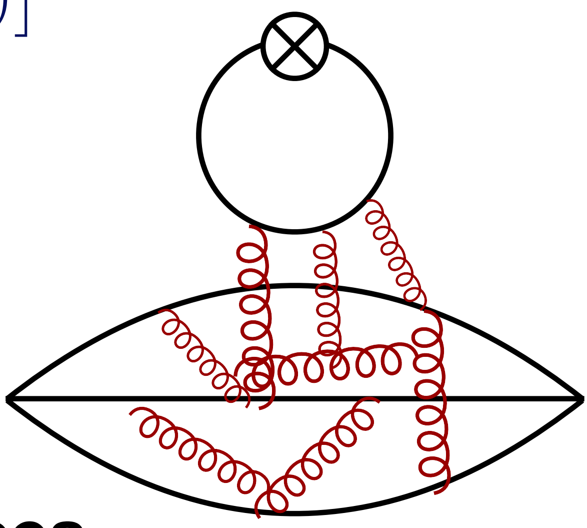
⇒ **disconnected contribitions for:**

$$\Delta q \qquad [g_A = \Delta u - \Delta d]$$

$$\langle x\rangle^{q}$$

Spin of the Proton

$$\Delta s = \int_0^1 dx \, [\Delta s(x) + \Delta \bar{s}(x)]$$



Δs **is a purely quark-line disconnected contribution**

A challenge on the lattice

Standard procedure: Use stochastic (random noise) sources

e.g. **[QCDSF/RQCD PRL108 (2012) 222001]**

$m_\pi = 285\,\mathrm{MeV}$

$\overline{\mathrm{MS}} \quad \mu = \sqrt{7.4}\,\mathrm{GeV}$

$$\Delta s = -0.020(10)(4)$$

Spin of the Proton

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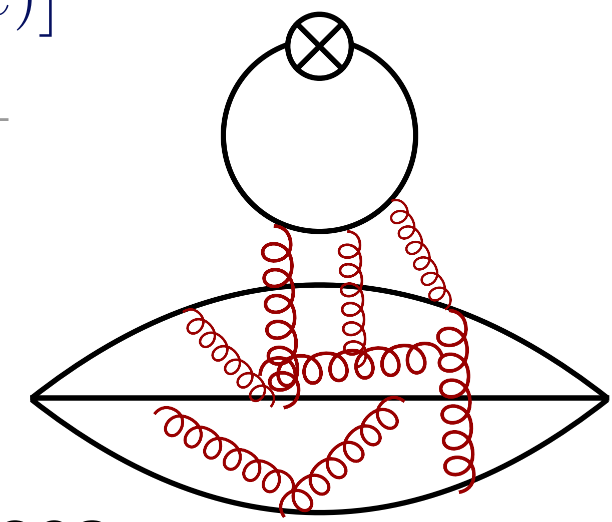

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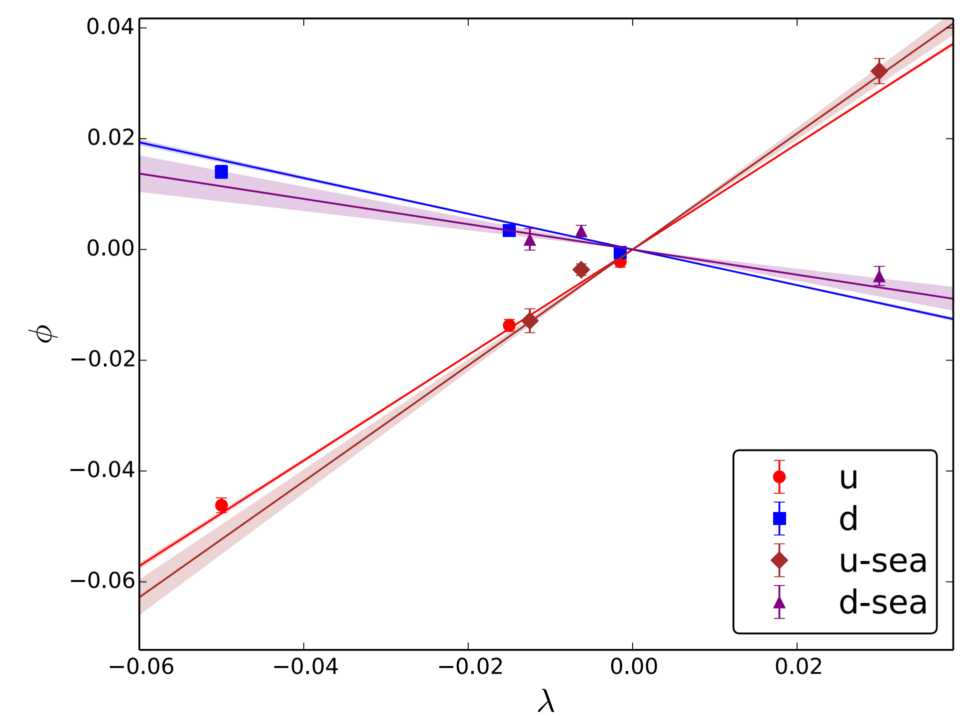
An alternative: Feynman-Hellmann method

[CSSM/QCDSF PRD90 (2014) 014510]

$$\frac{\partial E_H(\lambda)}{\partial \lambda} = \frac{1}{2E_H(\lambda)} \left\langle H \left| \frac{\partial S(\lambda)}{\partial \lambda} \right| H \right\rangle$$



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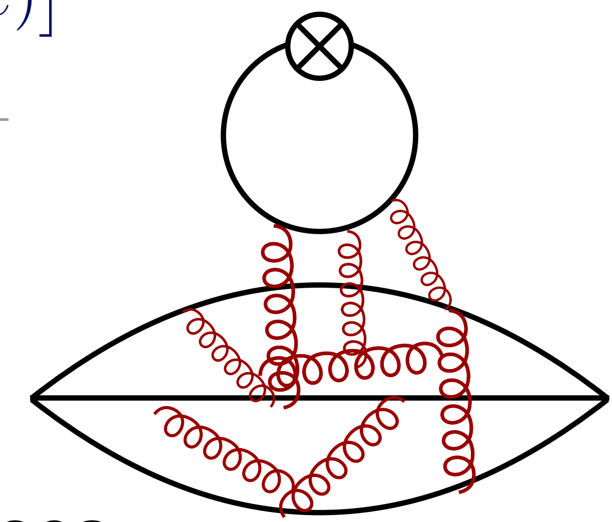

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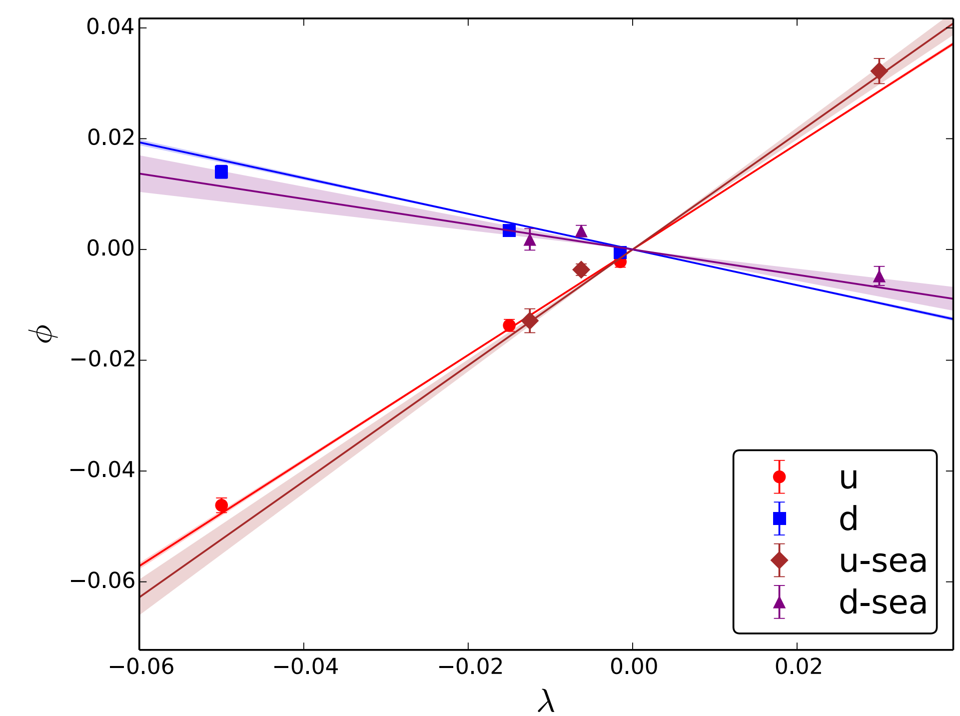


An alternative: Feynman-Hellmann method

[CSSM/QCDSF PRD90 (2014) 014510]

$$\frac{\partial E_H(\lambda)}{\partial \lambda} = \frac{1}{2E_H(\lambda)} \left\langle H \left| \frac{\partial S(\lambda)}{\partial \lambda} \right| H \right\rangle$$

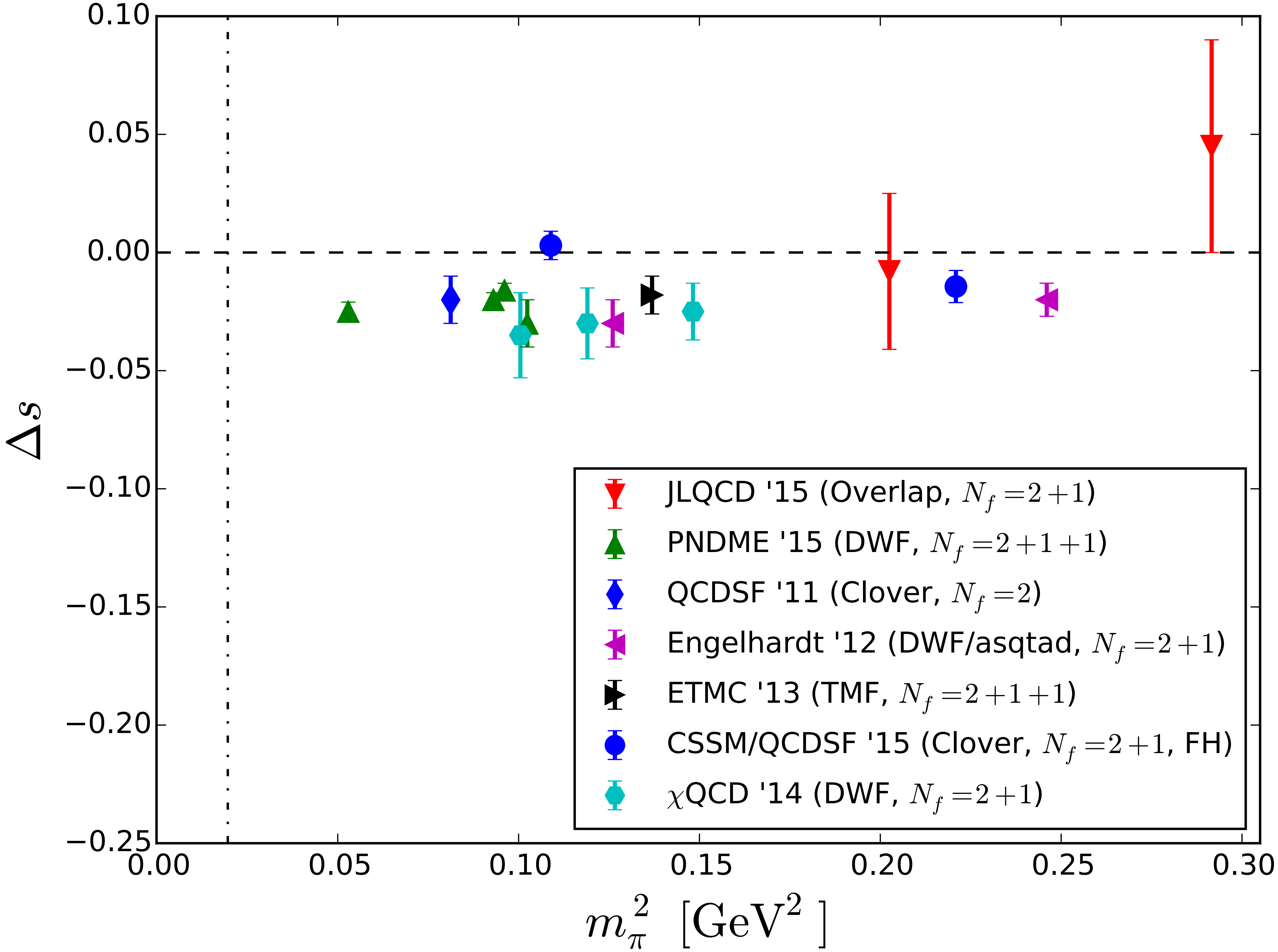
Also allows for full nonperturbative determination of singlet renormalisation constants

$$g_A = Z_A^{\text{NS}} g_A^{\text{latt}}$$

$$\Delta \Sigma = Z_A^{\text{S}} \Delta \Sigma^{\text{latt}}$$

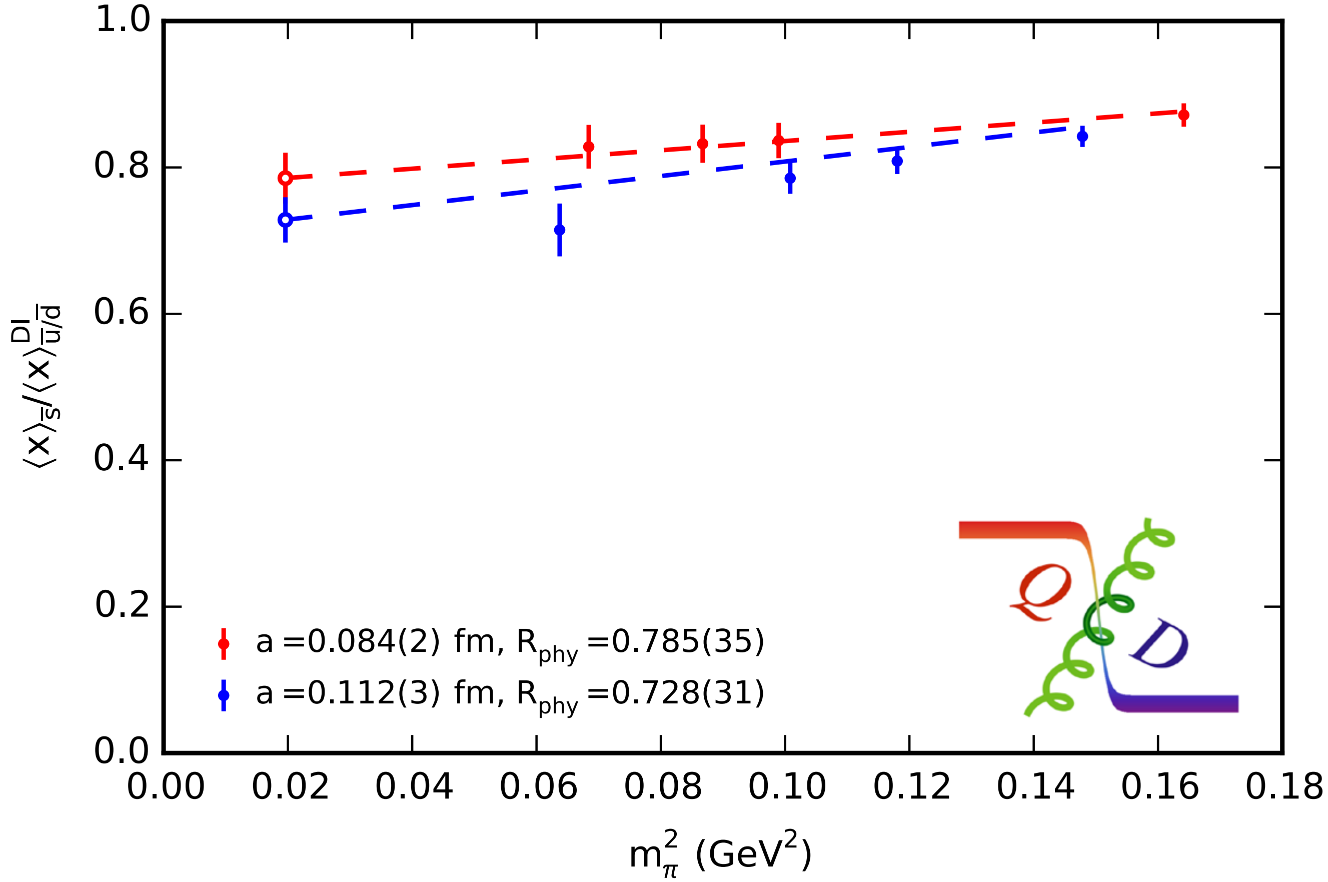
[CSSM/QCDSF, PLB740 (2015) 30]

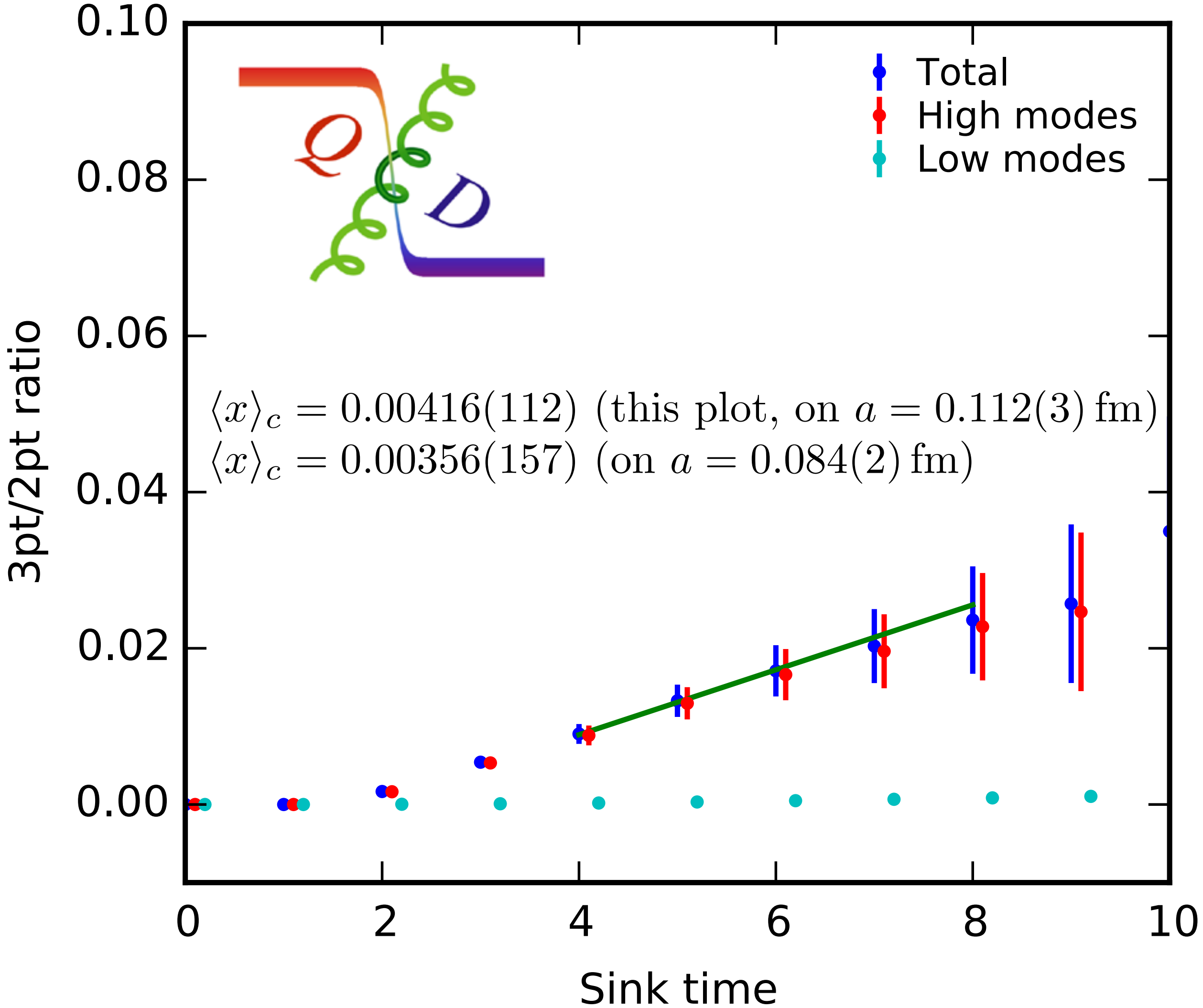
Disconnected Spin Contributions Δs



favours a small and negative Δs

Disconnected Contributions $\langle x \rangle^q$





non-zero charm contribution

Glue contribution to proton spin

Yang Thu 9:50am

Ji et al. [PRL 111 (2013) 112002] proposed a glue spin density operator

$$\vec{S}_G = \int d^3x \, \mathrm{Tr}[\vec{E}_C \times \vec{A}_C]$$ **(gauge-invariant)**

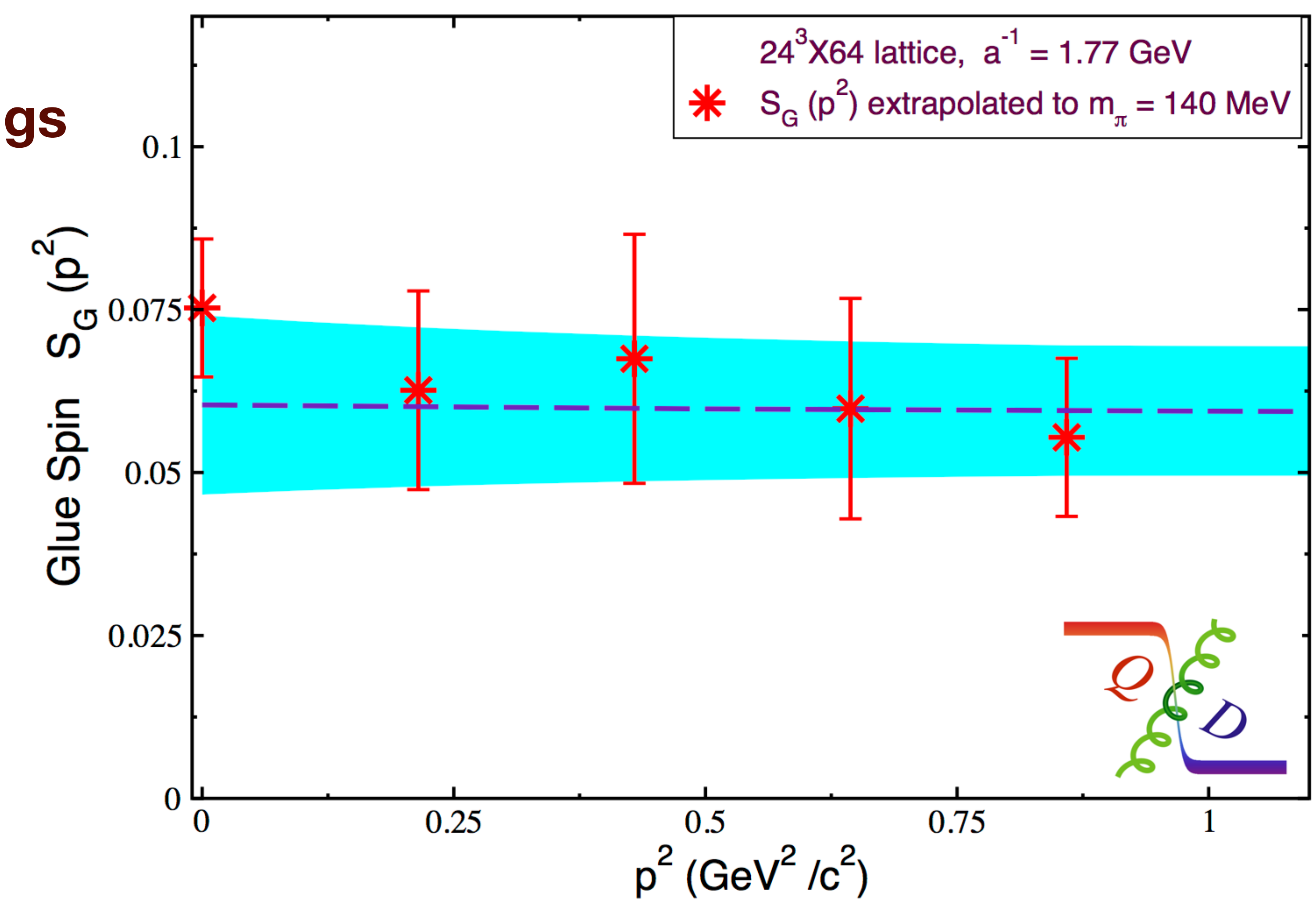
→ **Infinite momentum frame** → ΔG

RBC/UKQCD 2+1 24^3x48 DWF configs

Overlap definition of $F_{\mu\nu}$

Extrapolated to m_π^{phys}

Renormalisation soon!



Tensor Charge, $g_T = \int dx\, [\delta u(x) - \delta d(x)]$

Recent interest driven by

Phenomenological determinations now available using SIDIS data (HERMES, COMPASS)

Implications for new physics

Precision neutron β decay studies sensitive to possible BSM scalar and tensor interactions **[PNDME PRD85 (2012) 054512]**

⇒ **Require neutron matrix elements of appropriate low-energy operators**

$$\text{i.e. } g_T^{u-d},\ g_S^{u-d}$$ (to ~10%)

Quantify the contribution of the quark EDM to the nEDM and set bounds on new sources of CP violation **[PNDME 1506.04196, 1506.06411]**

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

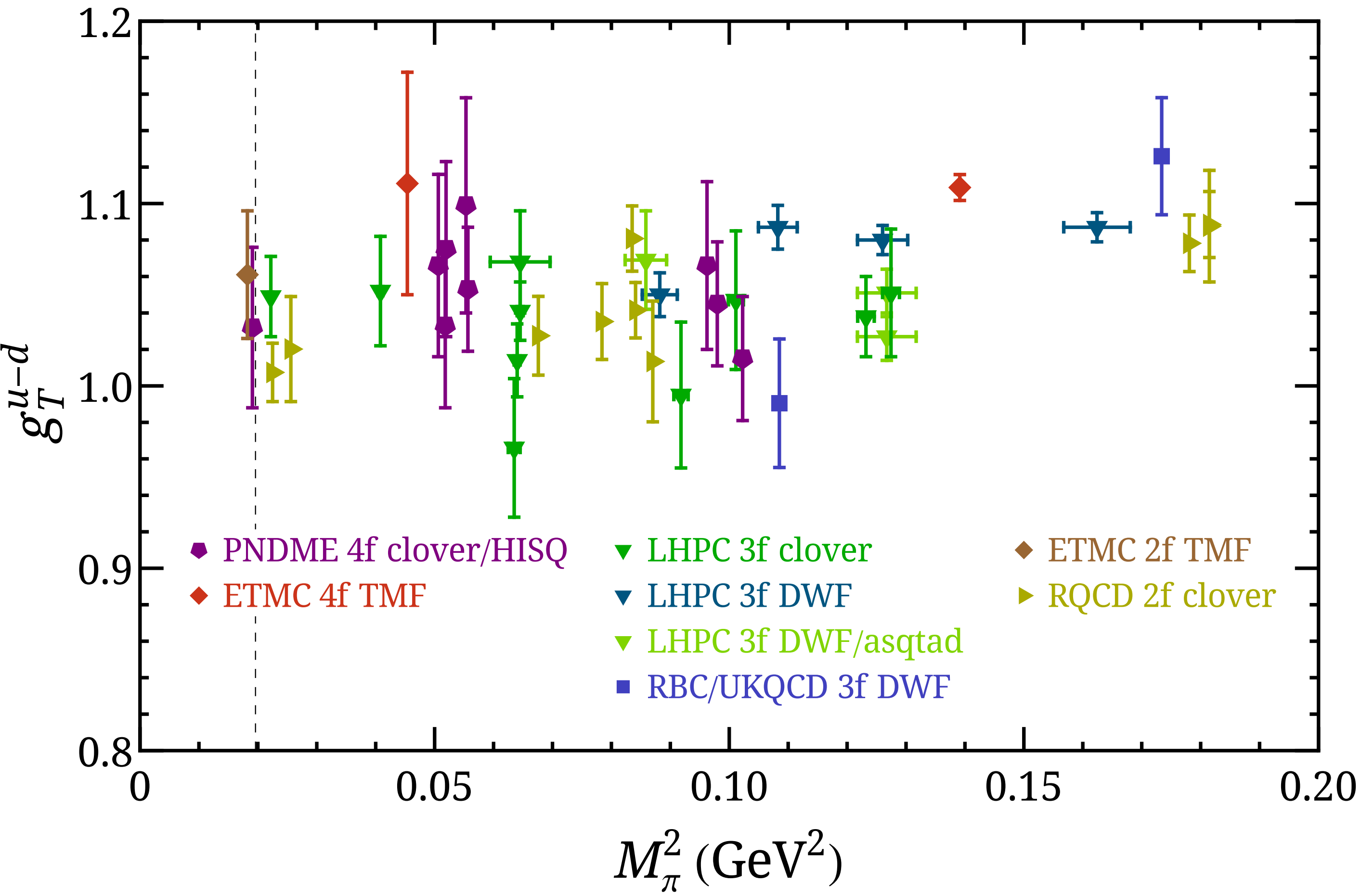
(including disconnected)

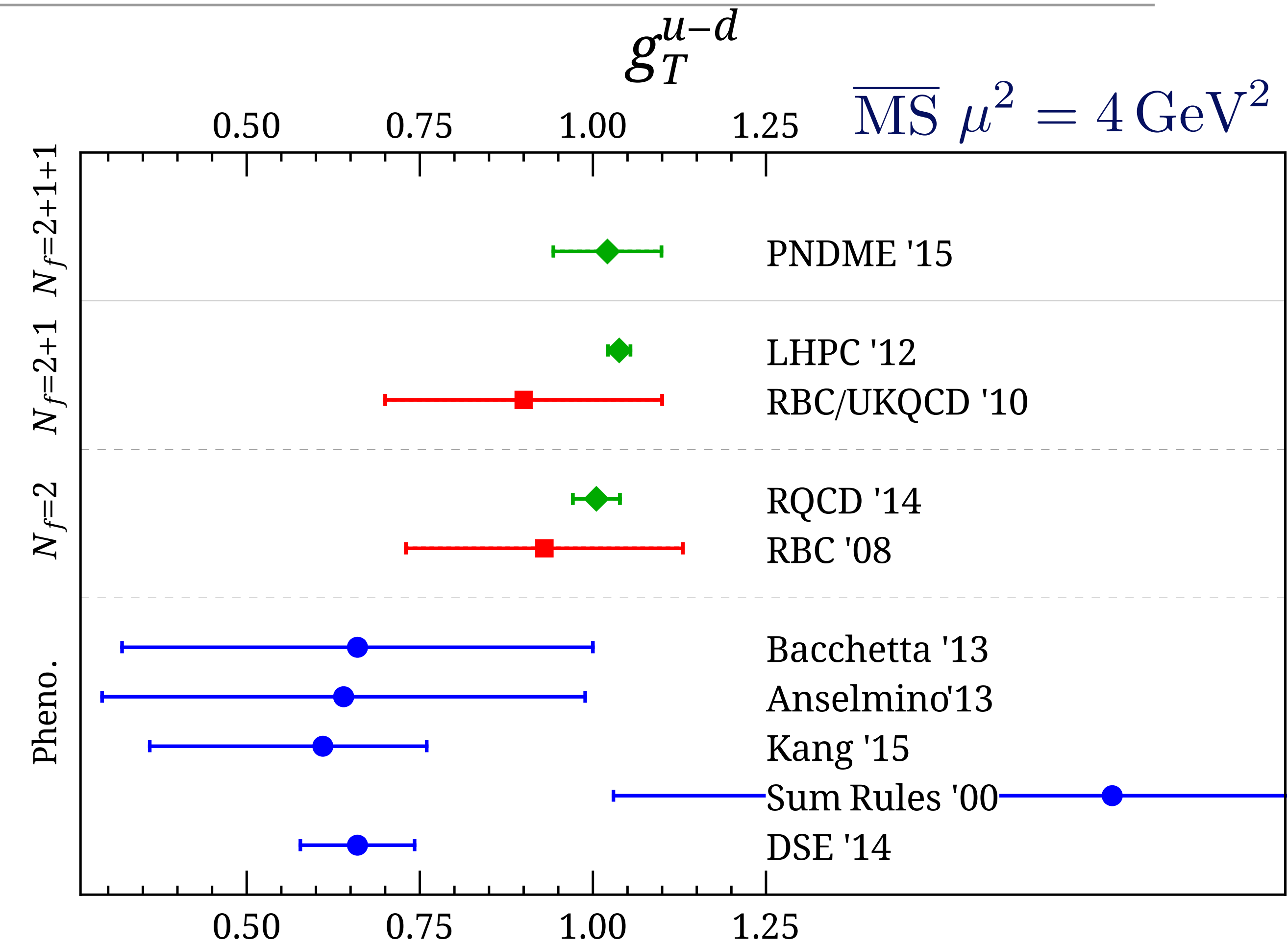
⇒ **See plenary talk by T. Izubuchi (Tue 11:45)**

Tensor Charge, $g_T = \int dx \, [\delta u(x) - \delta d(x)]$

[Gupta, Thu 10:40]

PNDME 1506.06411





Comprehensive study of systematics by PNDME

Introduced 'FLAG-like' colour-coding system for each systematic error

→ **10% uncertainty target achieved**

Scalar Charge, g_S

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

Commonly used for σ terms $\sigma_l^H = m_l\langle H|(\bar{u}u + \bar{d}d)|H\rangle \qquad \sigma_s^H = m_s\langle H|\bar{s}s|H\rangle$

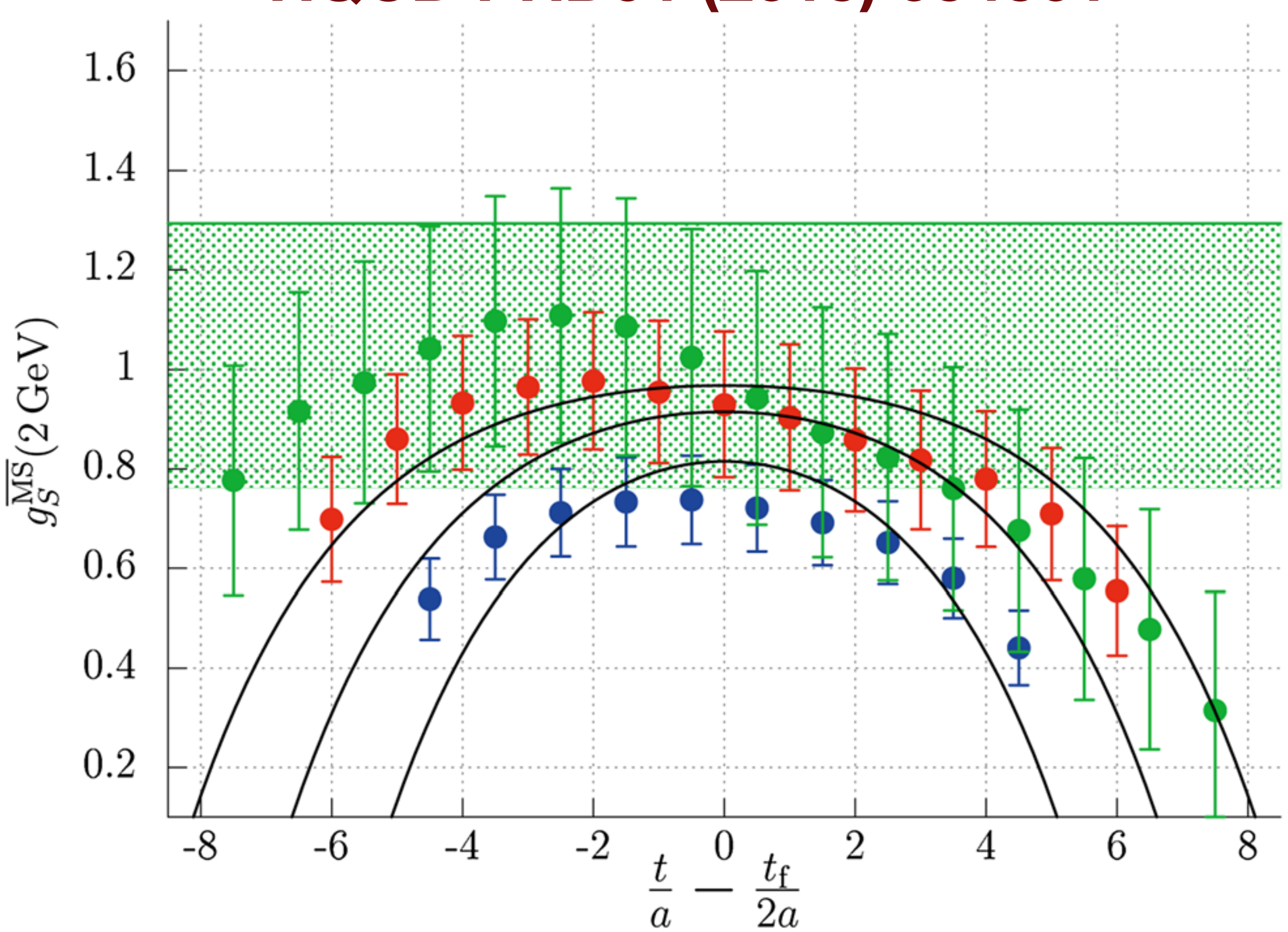
[R.Young, Latt'12 review]

Recent interest: new physics contributions to β decay: g_S^{u-d} **to 10%**

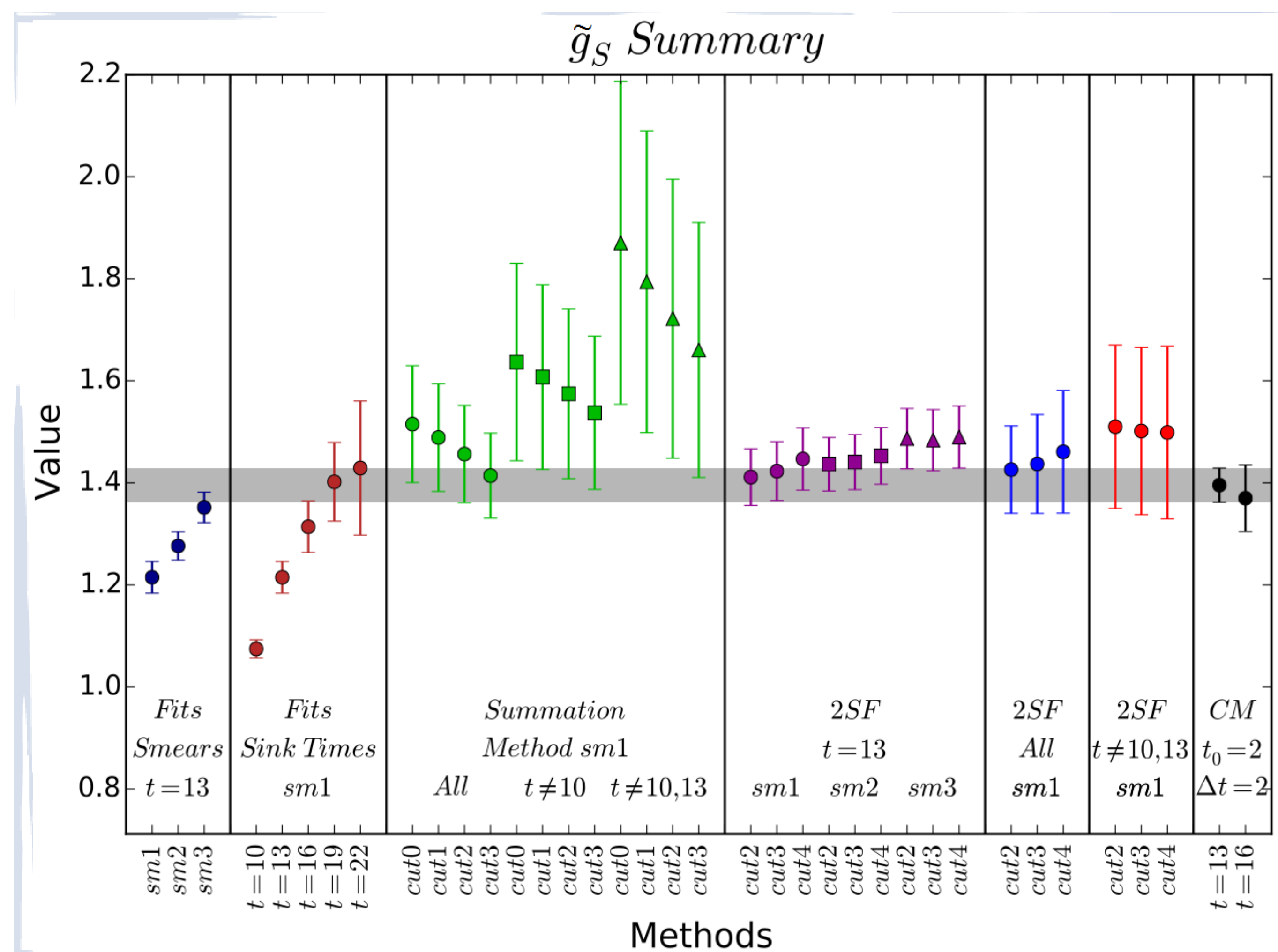
[PNDME PRD85 (2012) 054512]

Severe excited state contamination - take care!

RQCD PRD91 (2015) 054501



CSSM/QCDSF (Dragos, Tue 17:30)



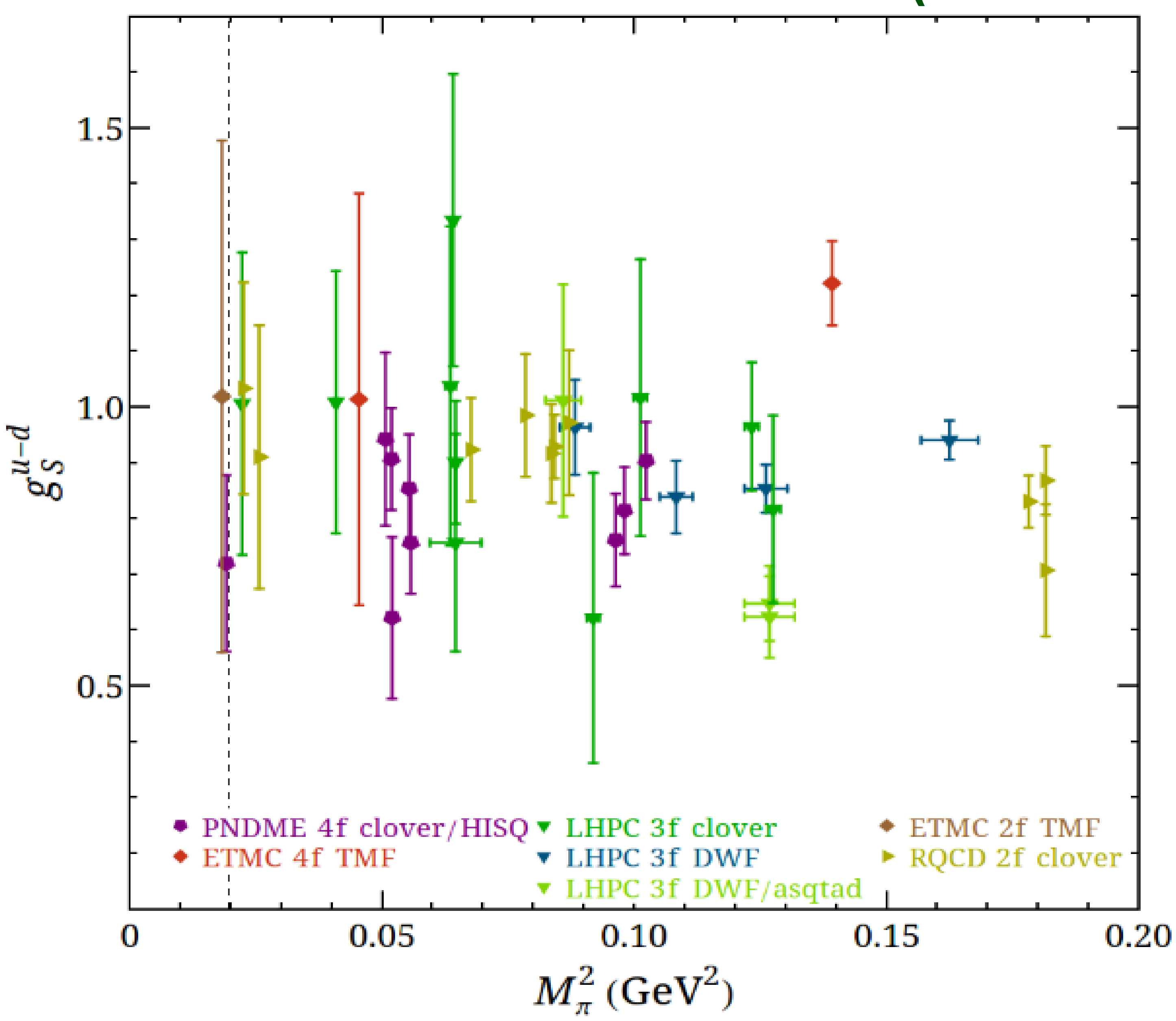
Scalar Charge, g_S

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

Large scatter in lattice determinations

Only determined to ~30%

(Plot from H-W Lin)



Electromagnetic Form Factors

Several new simulations with near-physical quark masses

LHPC [PRD90 (2014) 074507]	$m_\pi \approx 149\,\mathrm{MeV}$	
Mainz [arXiv:1504.04628]	$m_\pi \approx 193\,\mathrm{MeV}$	**Shintani, Wed 17:30**
PACS-CS	$m_\pi \approx 145\,\mathrm{MeV}$	**Yamazaki, Wed 14:20 (Had Spec & Int)**
PNDME	$m_\pi \approx 130\,\mathrm{MeV}$	**Gupta, Thu 10:40**

Progress in accounting for excited state contamination

Electromagnetic Form Factors

Shintani, Wed 17:30

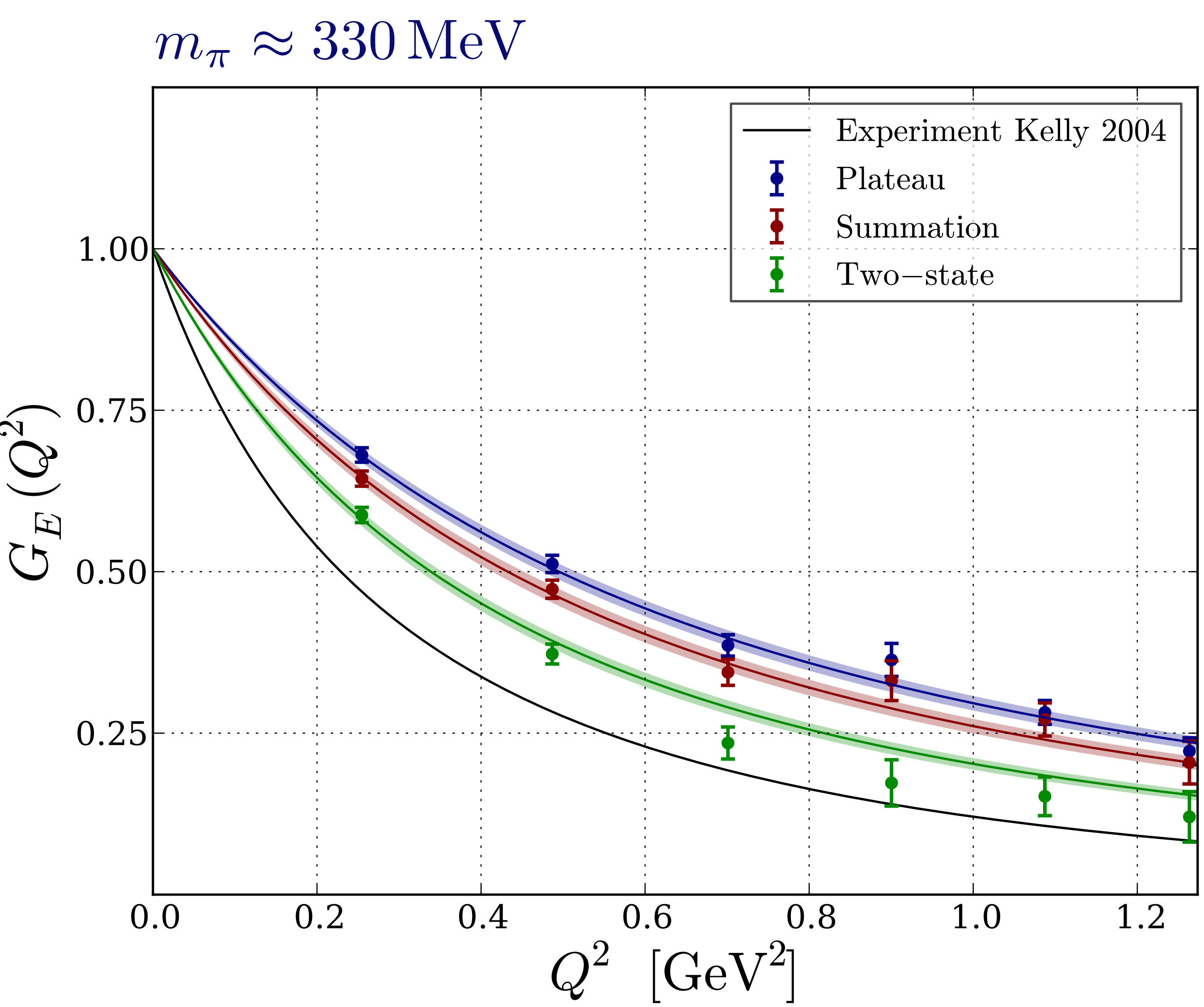
Mainz [arXiv:1504.04628]

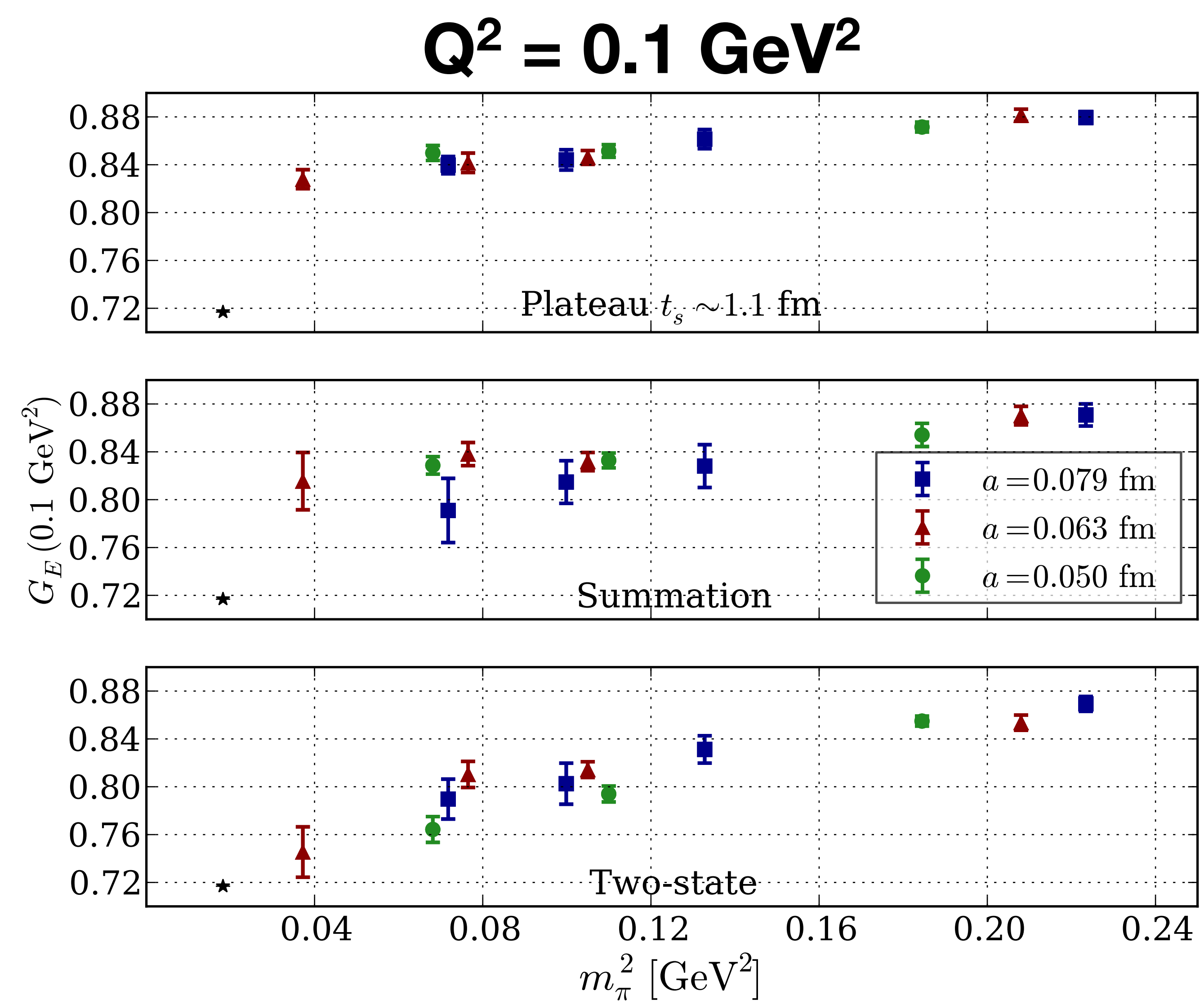
Evidence of excited state contamination in EM FFs

Effect becomes more problematic at light quark masses

Effect increases G_E at each Q^2

Improved approach to physical point

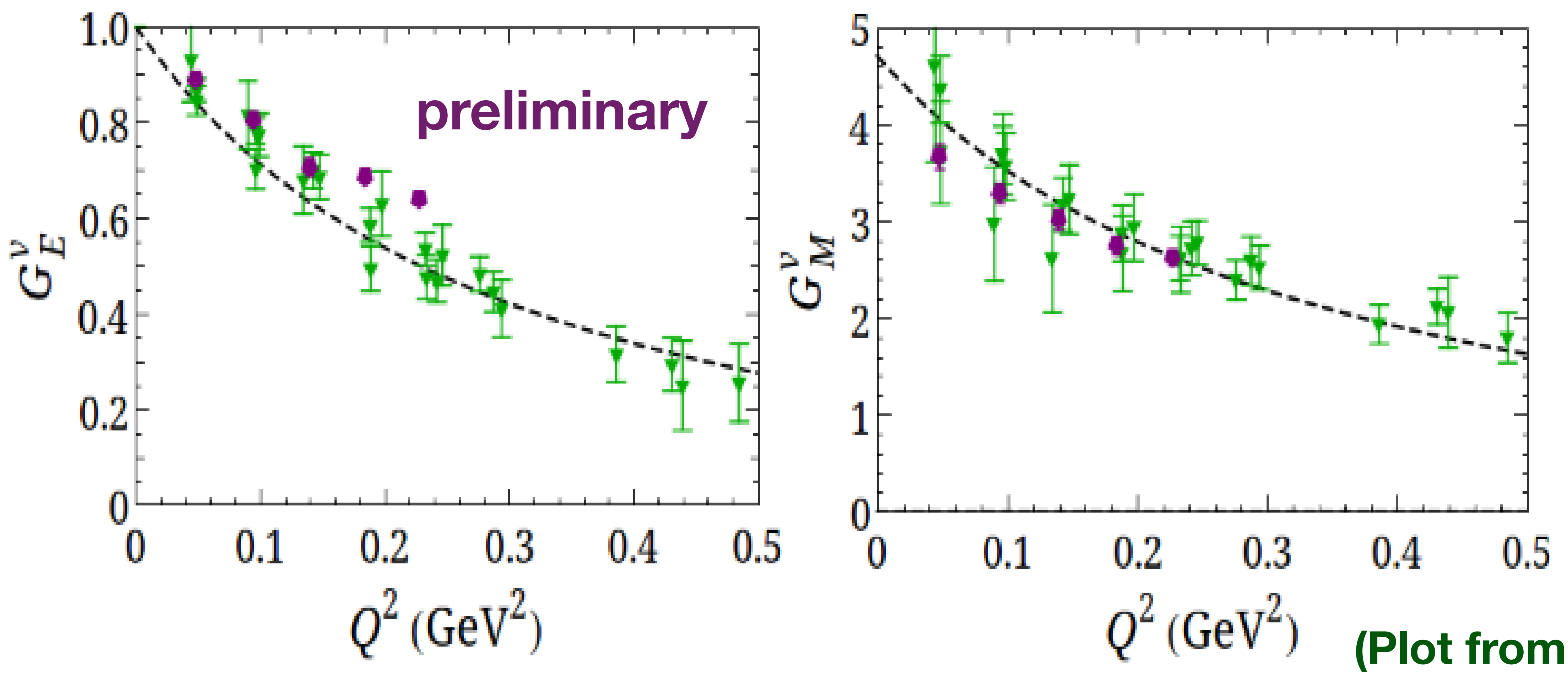




Electromagnetic Form Factors

Comparison of LHPC ($m_\pi \approx 149\,\mathrm{MeV}$) **PRD90 (2014) 074507**

PNDME ($m_\pi \approx 130\,\mathrm{MeV}$) **Gupta, Thu 10:40**



(Plot from H-W Lin)

Good agreement with parameterisation of experimental data

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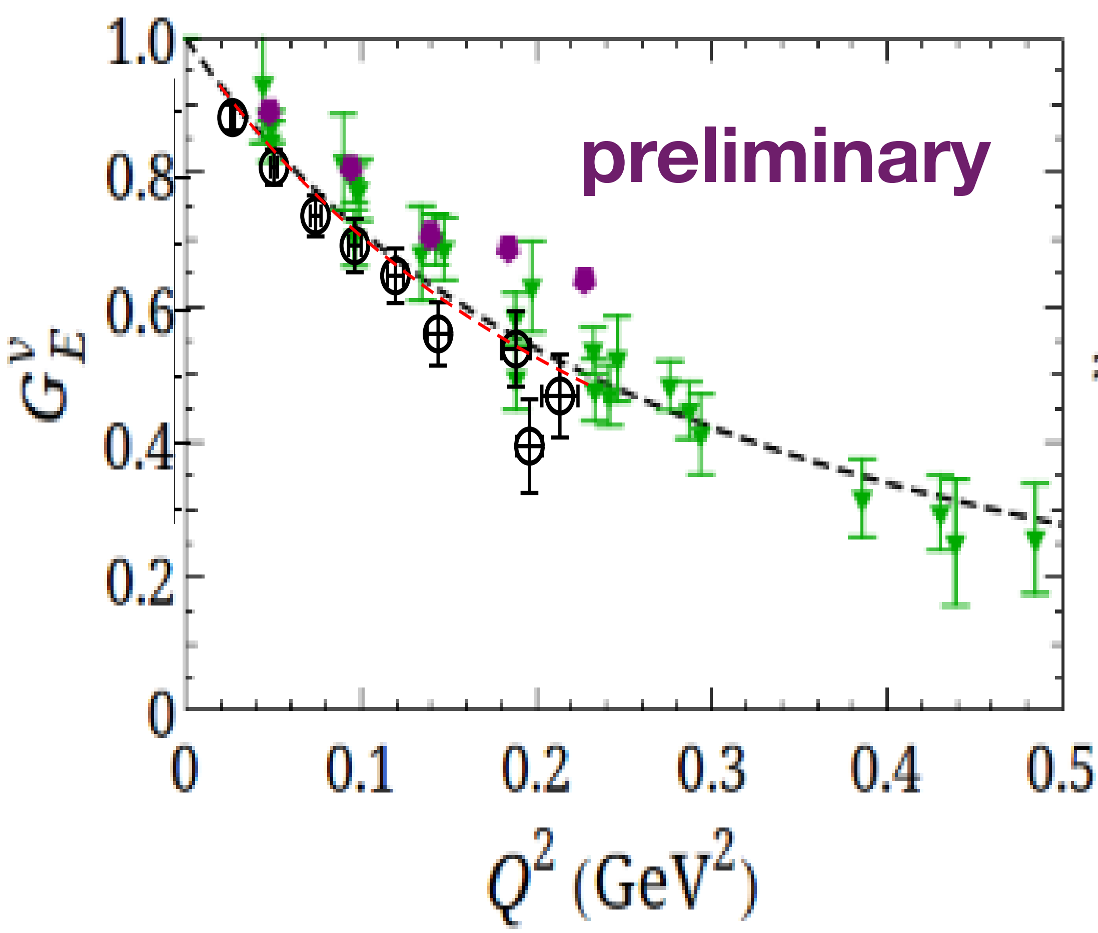

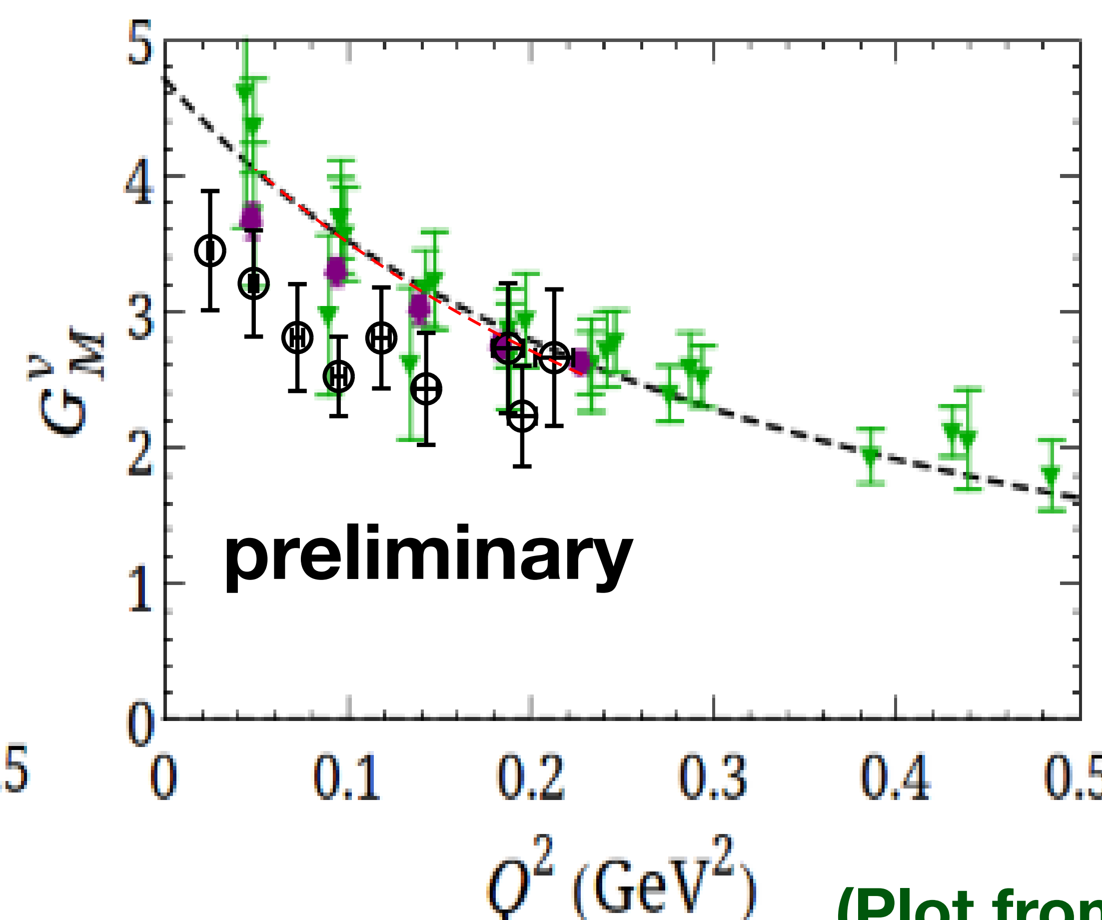

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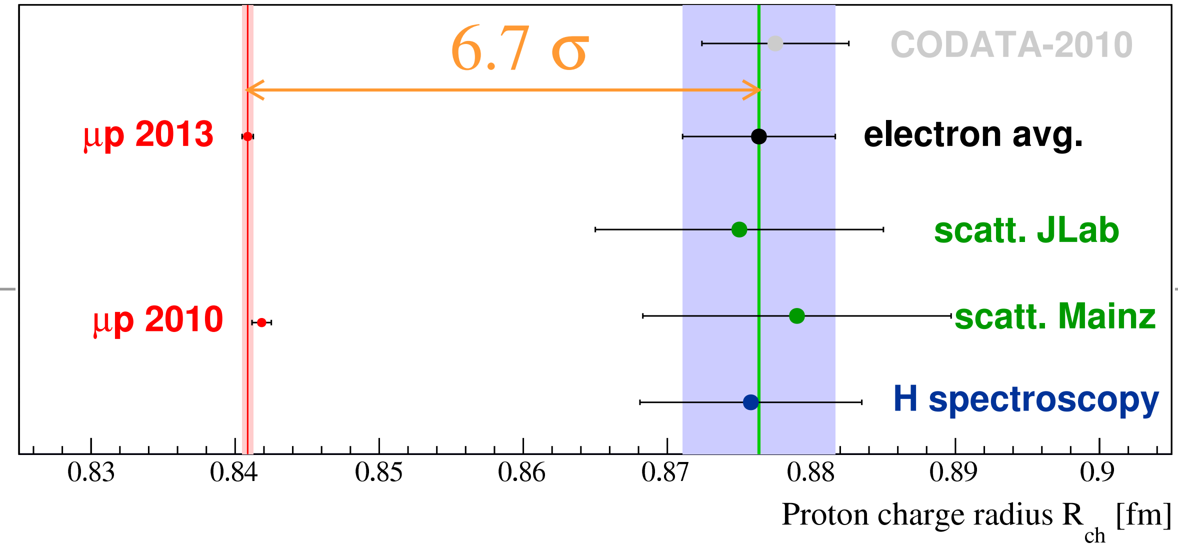
Good agreement with parameterisation of experimental data

Charge Radius



Lattice form factors now available with physical masses

(Direct or small chiral extrapolation)

Determine accurate radii @ $m_\pi \approx 140\,\mathrm{MeV}$:

Use finite-volume and excited-state corrected results

Need small $Q^2 < 4m_\pi^2 \sim 0.08\,\mathrm{GeV}^2$ (2π threshold)

dipole fit to large Q^2 data introduces unwanted model dependence

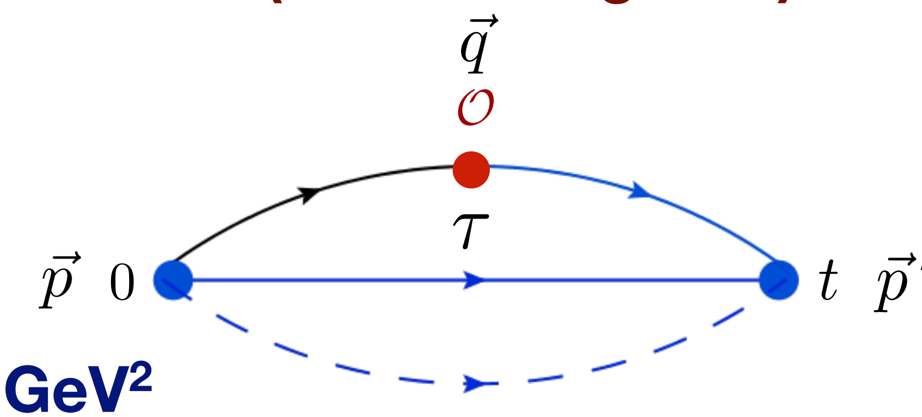
"z-fit" [Hill & Paz, PRD82 (2010) 113005] more reliable

Large Q^2

Lattice form factors difficult to determine at large Q^2 > 2-3 GeV^2 (even at large m_π)

Standard method:

fix $\vec{p}\,' = 0$ **vary** $\vec{q} = -\vec{p}$



⇒ **Large nucleon momenta required for Q^2 > 2-3 GeV^2**

Breit frame $\vec{p}\,' = -\vec{p}$ to maximise Q^2 at fixed $\vec{p}$?

New methods?

Large Q²

[R. Young, Thu 8:30am]

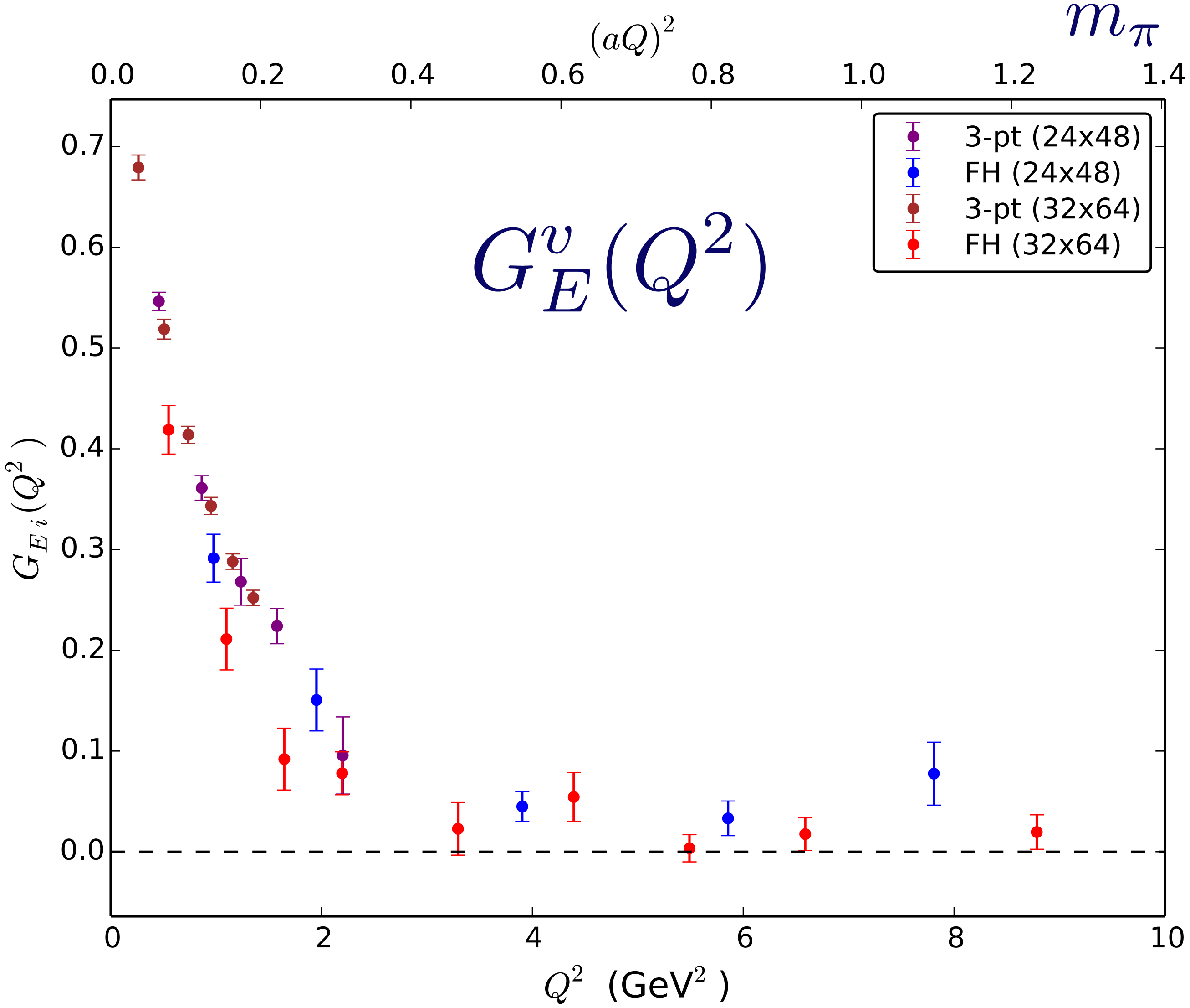
Application of Feynman-Hellmann to form factors

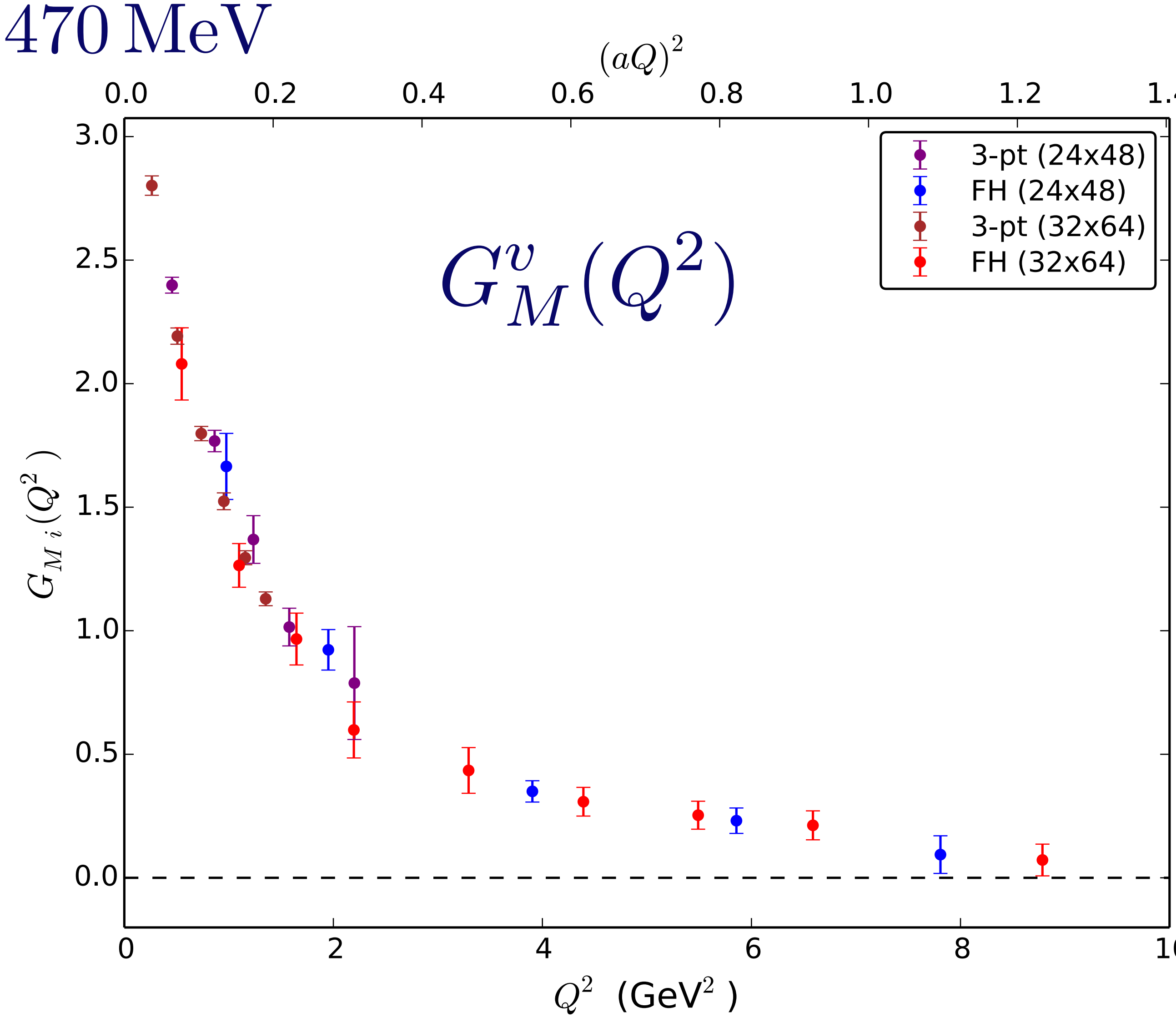
Only require 2-point functions → **simple excited state removal**

Choose Breit frame kinematics $|\vec{q}| = 2|\vec{p}| = 2|\vec{p}\,'|$

→ **single exponential** → **look for energy shifts**

$m_\pi \approx 470\,\mathrm{MeV}$





Large Q^2

[R. Young, Thu 8:30am]

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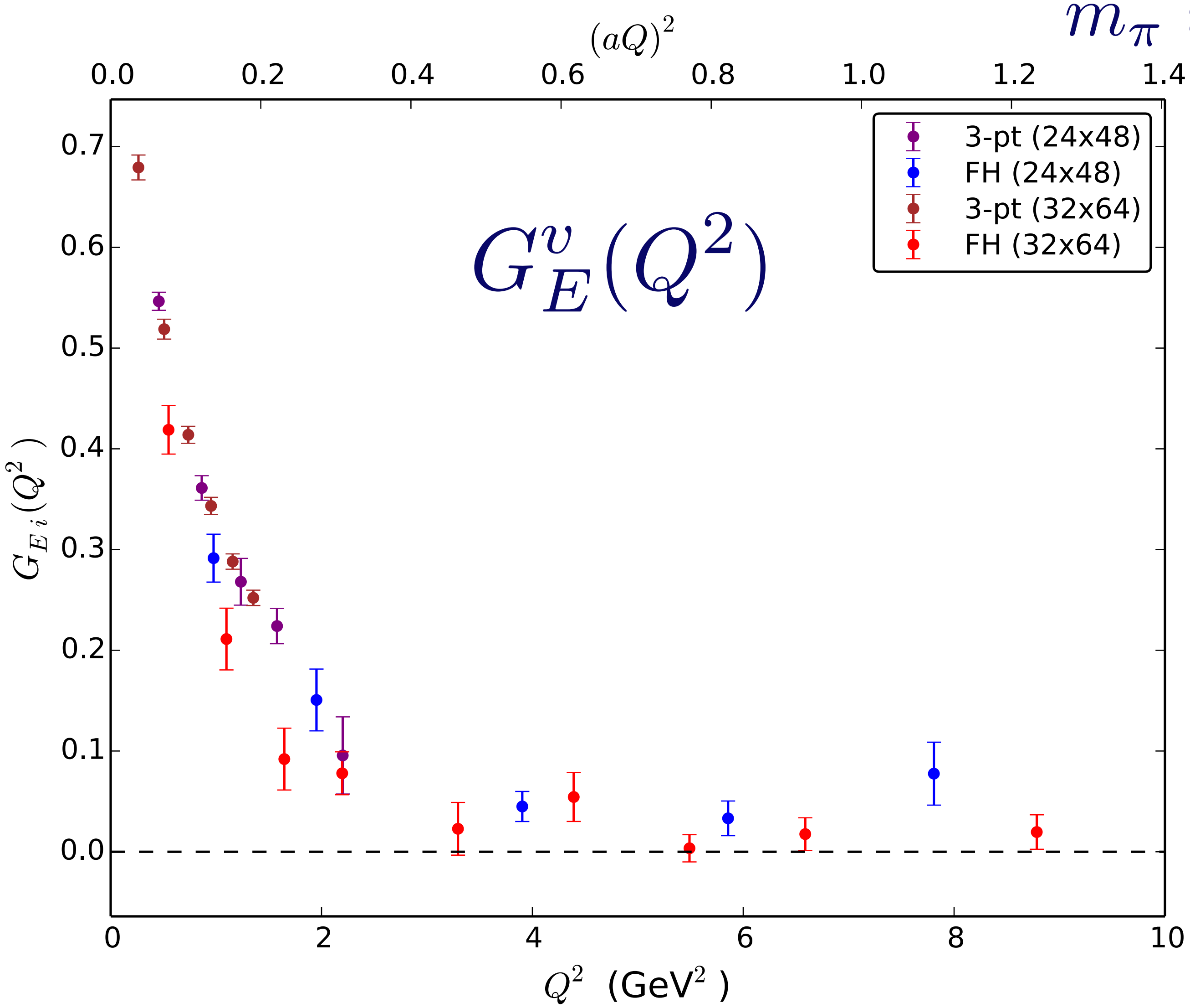
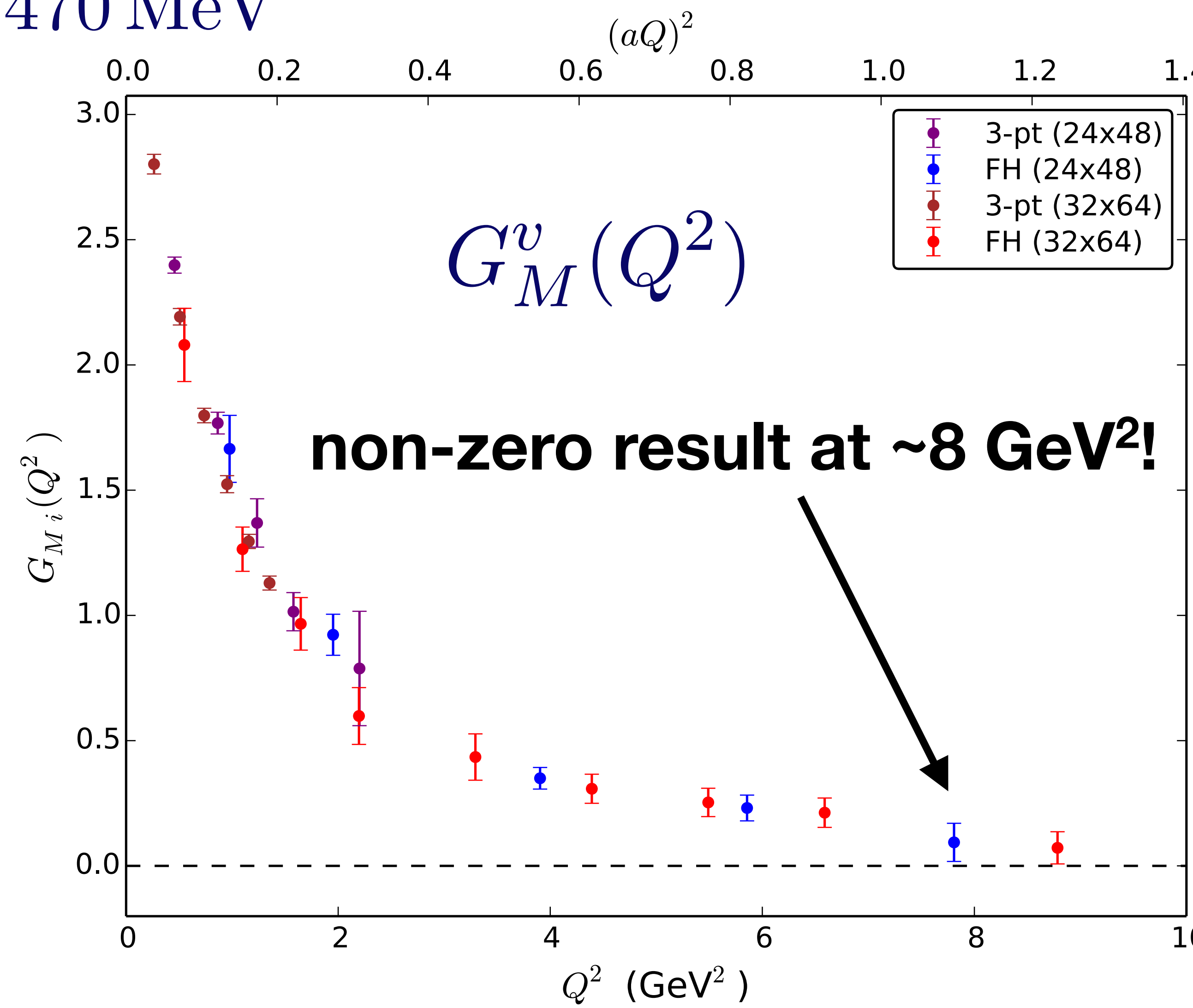




Neutron Form Factors

Experimental determination of neutron EM form factors difficult since

Neutron has no charge ⇒ G_E^n **naturally small**

Lack of free neutron target ⇒ **use** $^2\mathrm{H},\ ^3\mathrm{H},\ ^3\mathrm{He}$

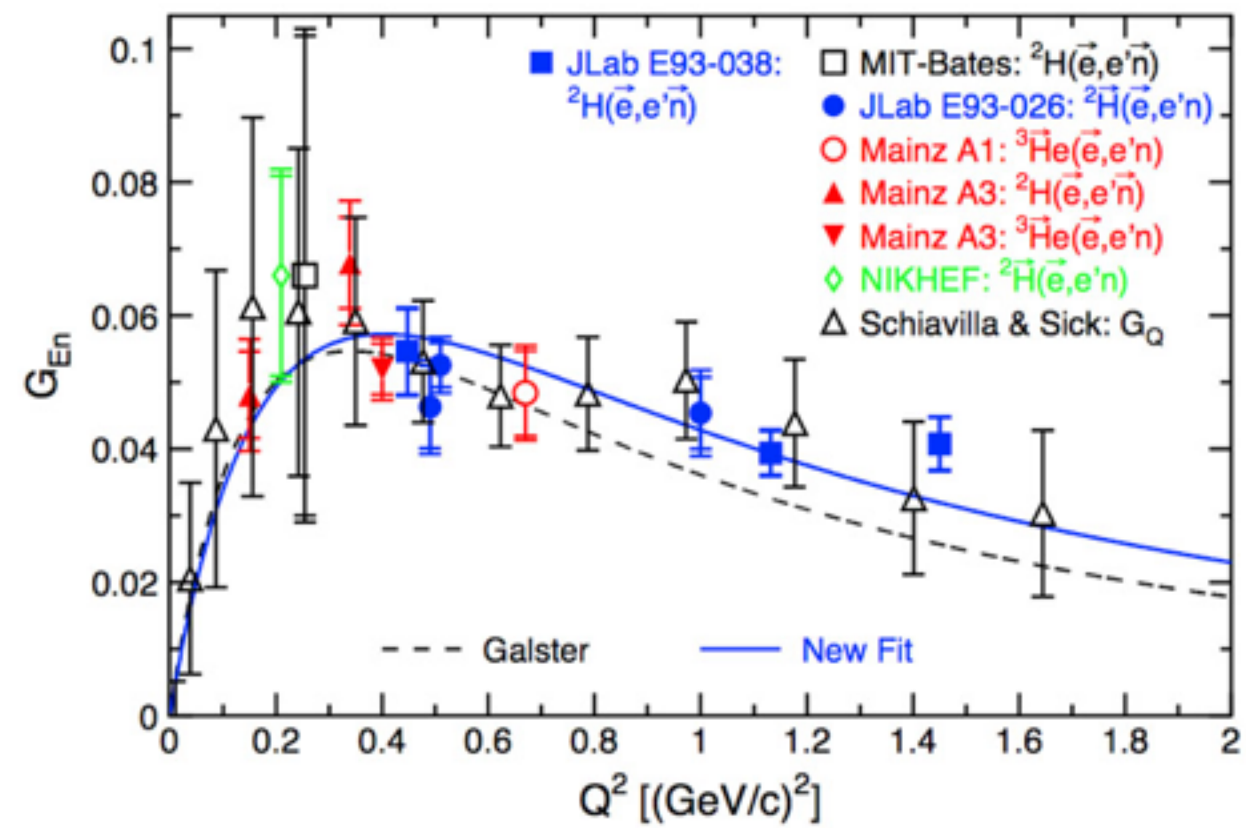
⇒ **requires corrections for nuclear effects (Fermi motion, Final State Interactions, Meson Exchange Currents) and proton contributions**

⇒ **Model dependence**

Opportunity for Lattice:

Direct $G^n_{E,M}(Q^2)$ **determination**

Determine $^2\mathrm{H},\ ^3\mathrm{H},\ ^3\mathrm{He}$ **form factors**



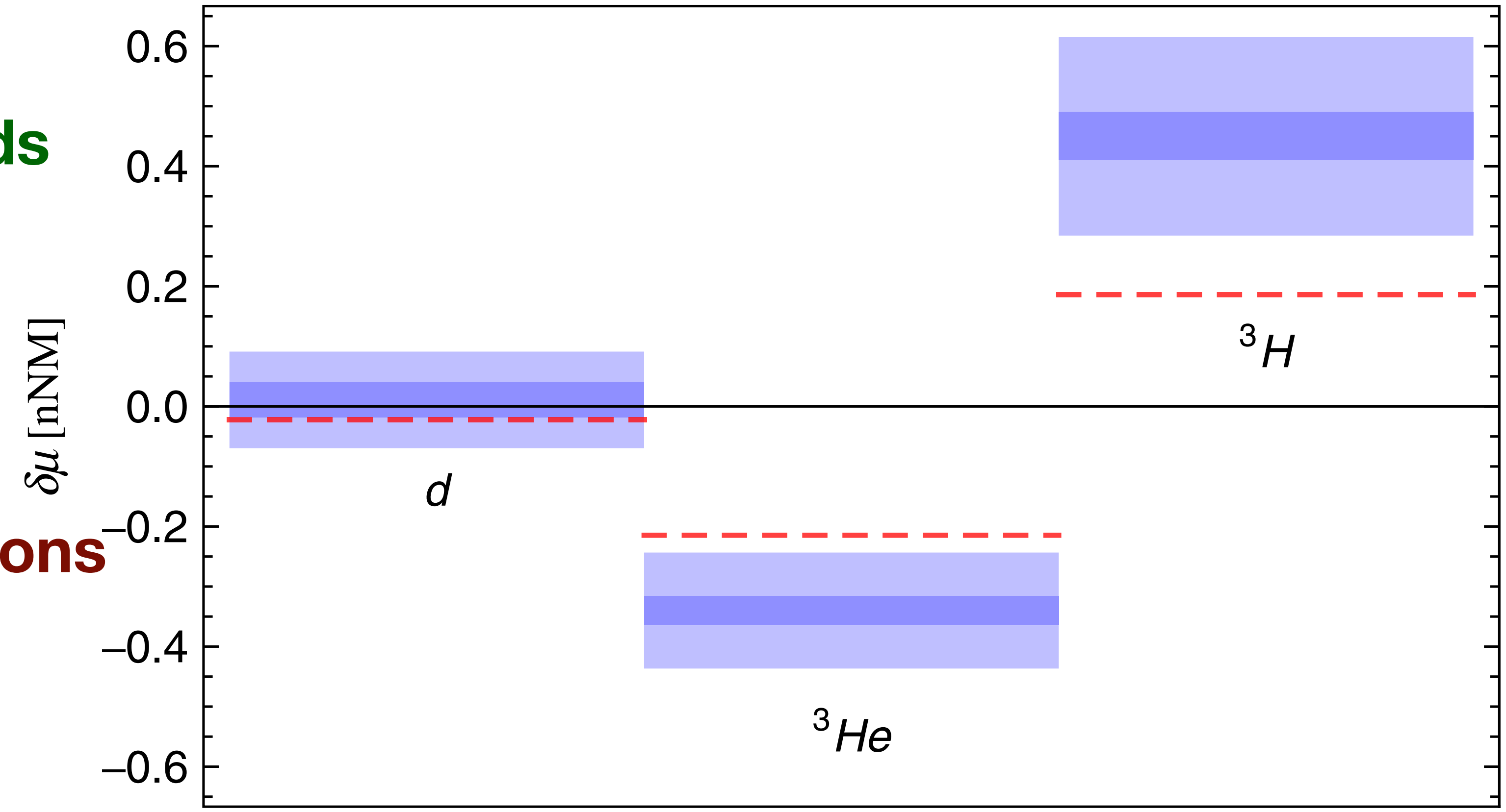
Magnetic Structure of Light Nuclei

[NPLQCD PRL 113 (2014) 252001 & 1506.05518]

Magnetic moments and polarizabilities of nucleons and light nuclei with A ≤ 4

Employ background magnetic fields

$$m_\pi \approx 800\,\mathrm{MeV}$$



Compare with shell model predictions

$$\mu_d^{\mathrm{SM}} = \mu_p + \mu_n$$

$$\mu_{^3H}^{\mathrm{SM}} = \mu_p$$

$$\mu_{^3He}^{\mathrm{SM}} = \mu_n$$

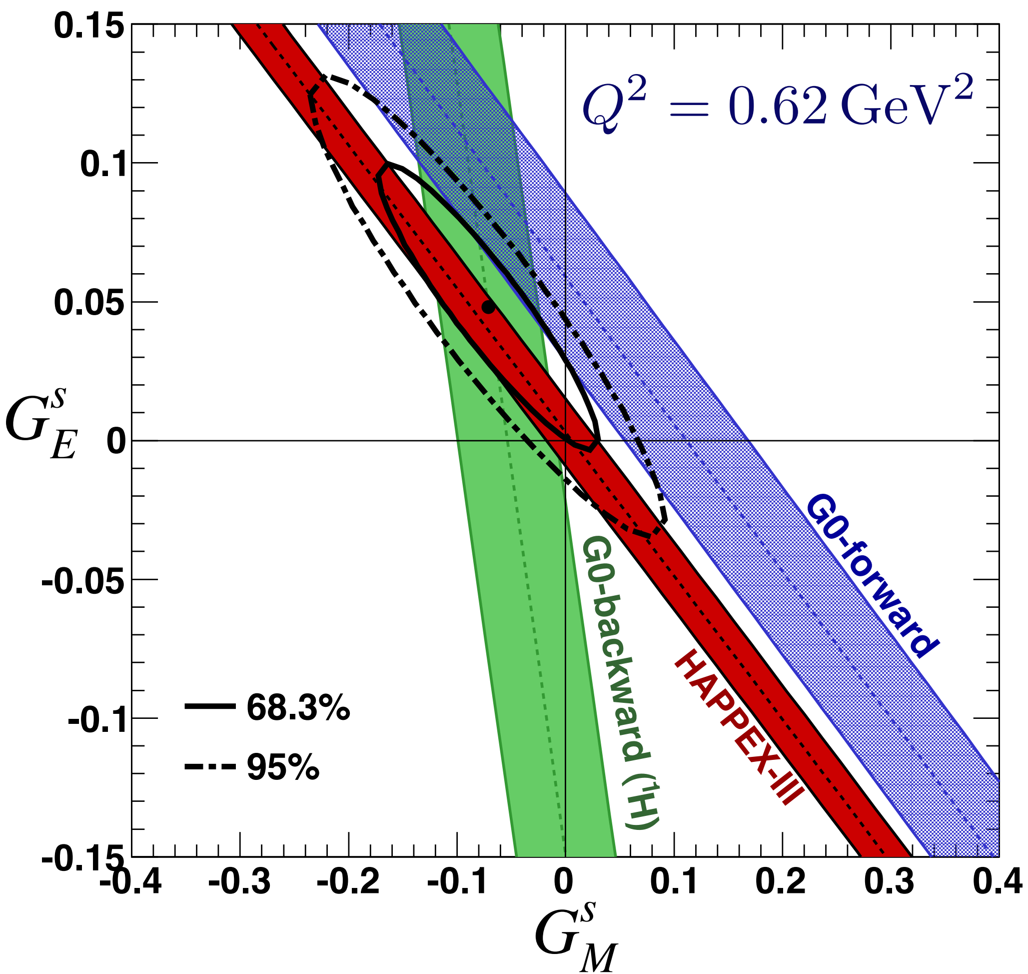
shell-model configuration captures their dominant structures

Deviations similar to experiment

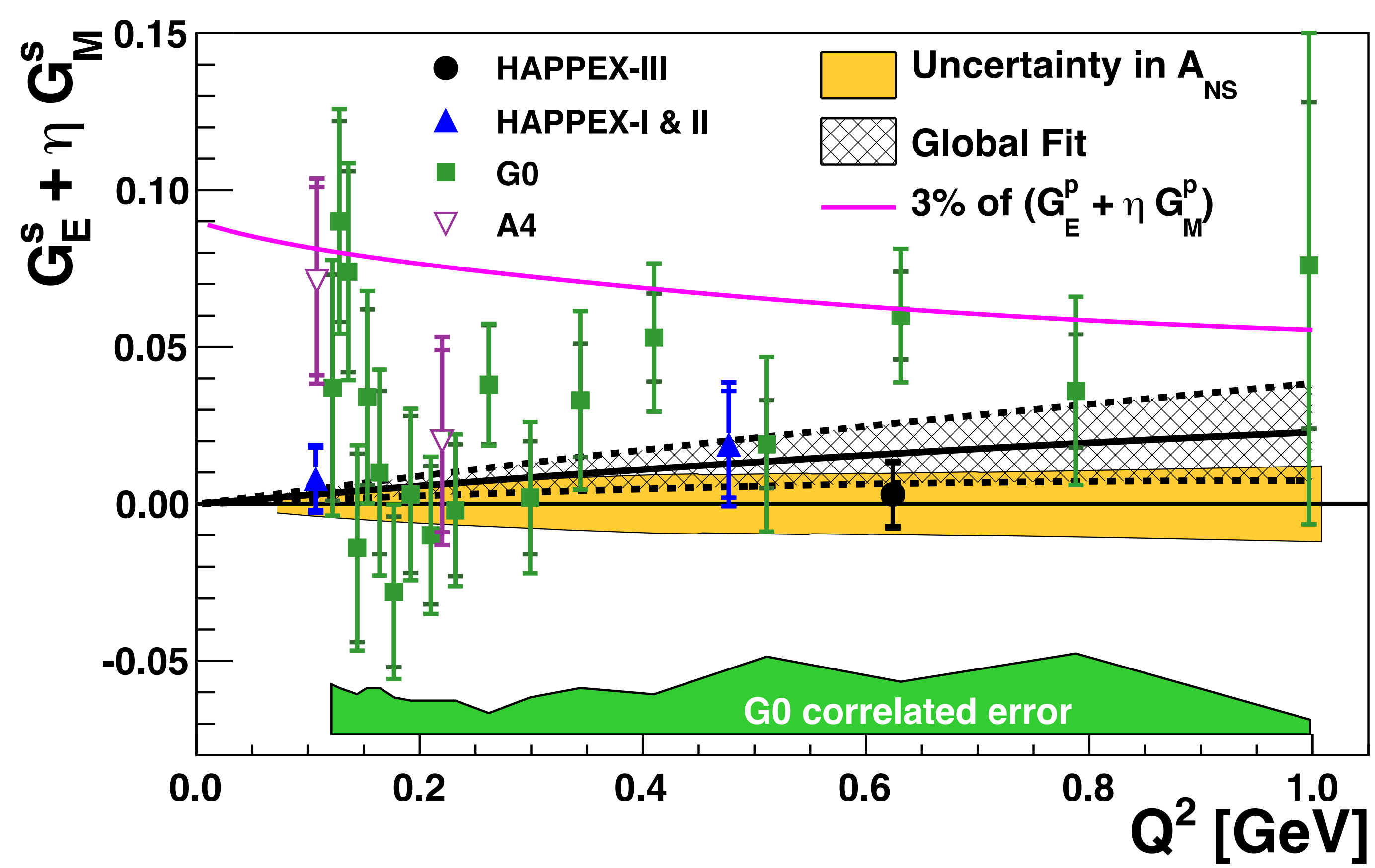
Implications for experiments using $^2\mathrm{H},\ ^3\mathrm{H},\ ^3\mathrm{He}$ for neutron properties

Strangeness Form Factors

- **Understanding hidden flavour - A fundamental challenge of hadronic physics**
- **Contributions arise entirely through interactions with QCD vacuum**
- **Extensive experimental searches**
  - **JLAB (G0, HAPPEX), MIT-Bates (SAMPLE), Mainz (A4)**



[HAPPEX-III PRL108 (2012) 102001]



Strangeness Form Factors

Qweak experiment (JLab)

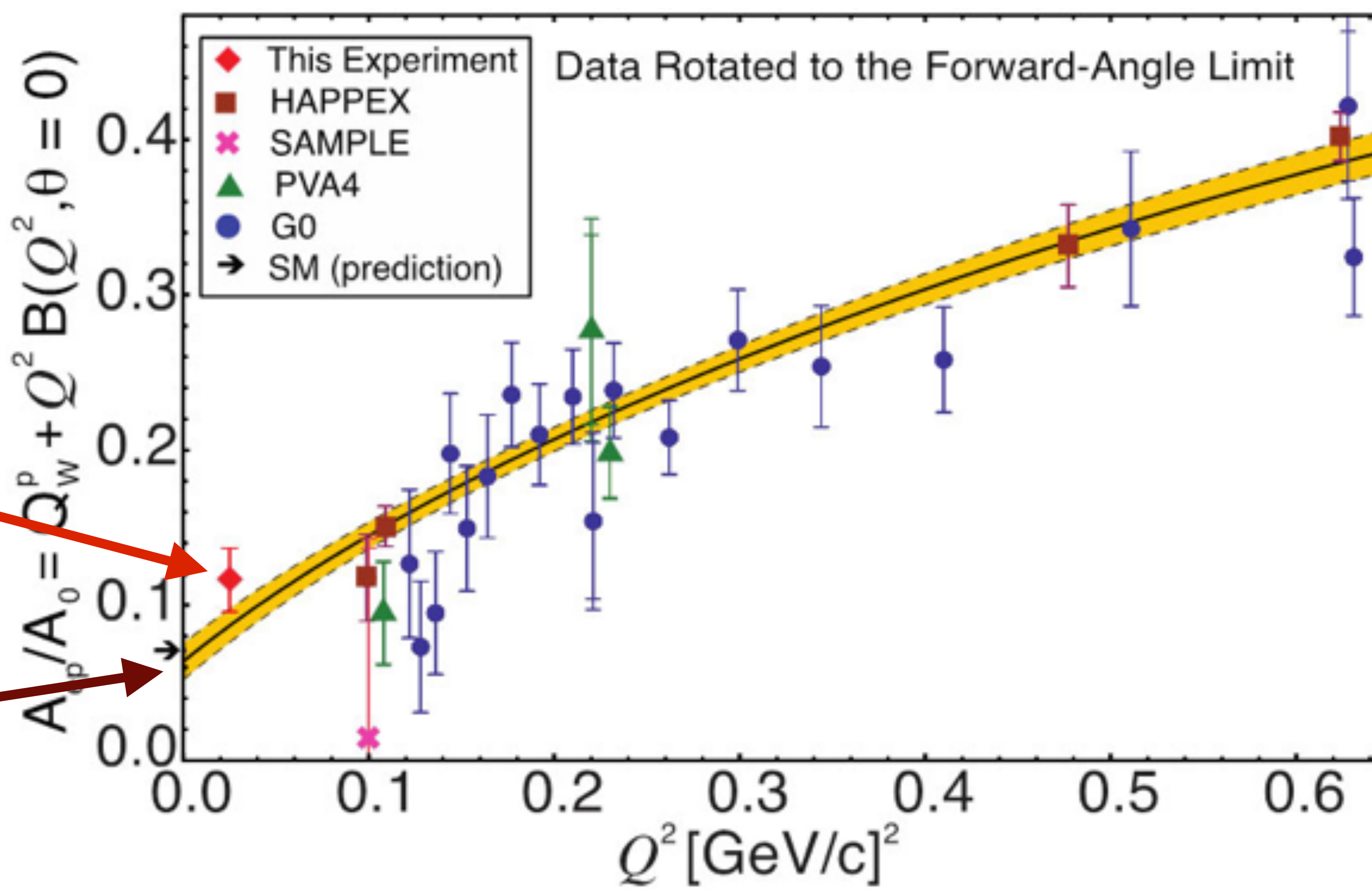
- **Implications for experimental determination of the proton's weak charge Q_W^p**
- Q_W^p **: neutral current analog to the proton's electric charge**
- **Precisely predicted to be small in the SM**

➡ **Constrain new parity-violating (PV) physics between electrons and light quarks**

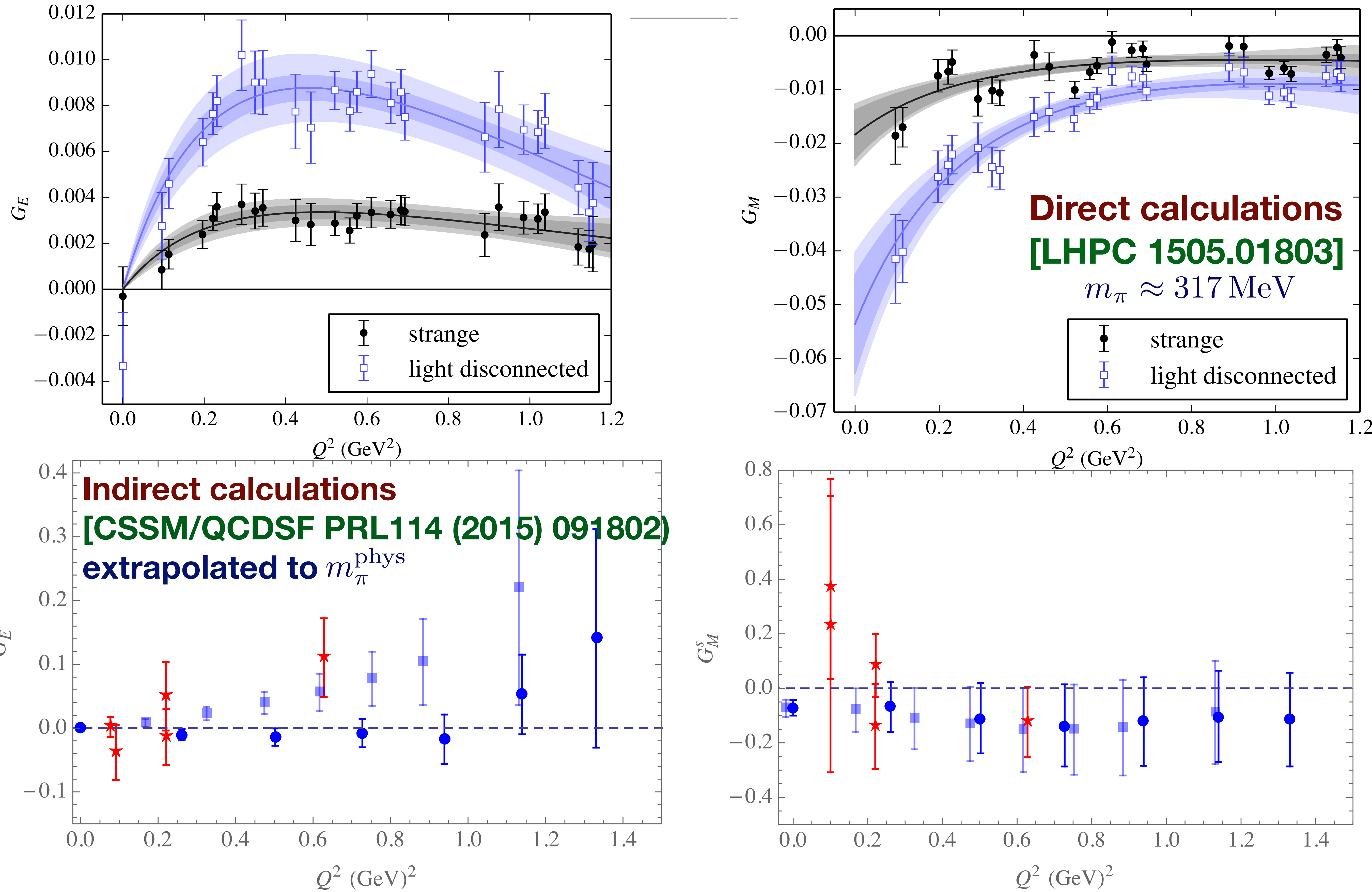
[Qweak PRL111 (2013) 141803]

4% data analysed

Q_W^p



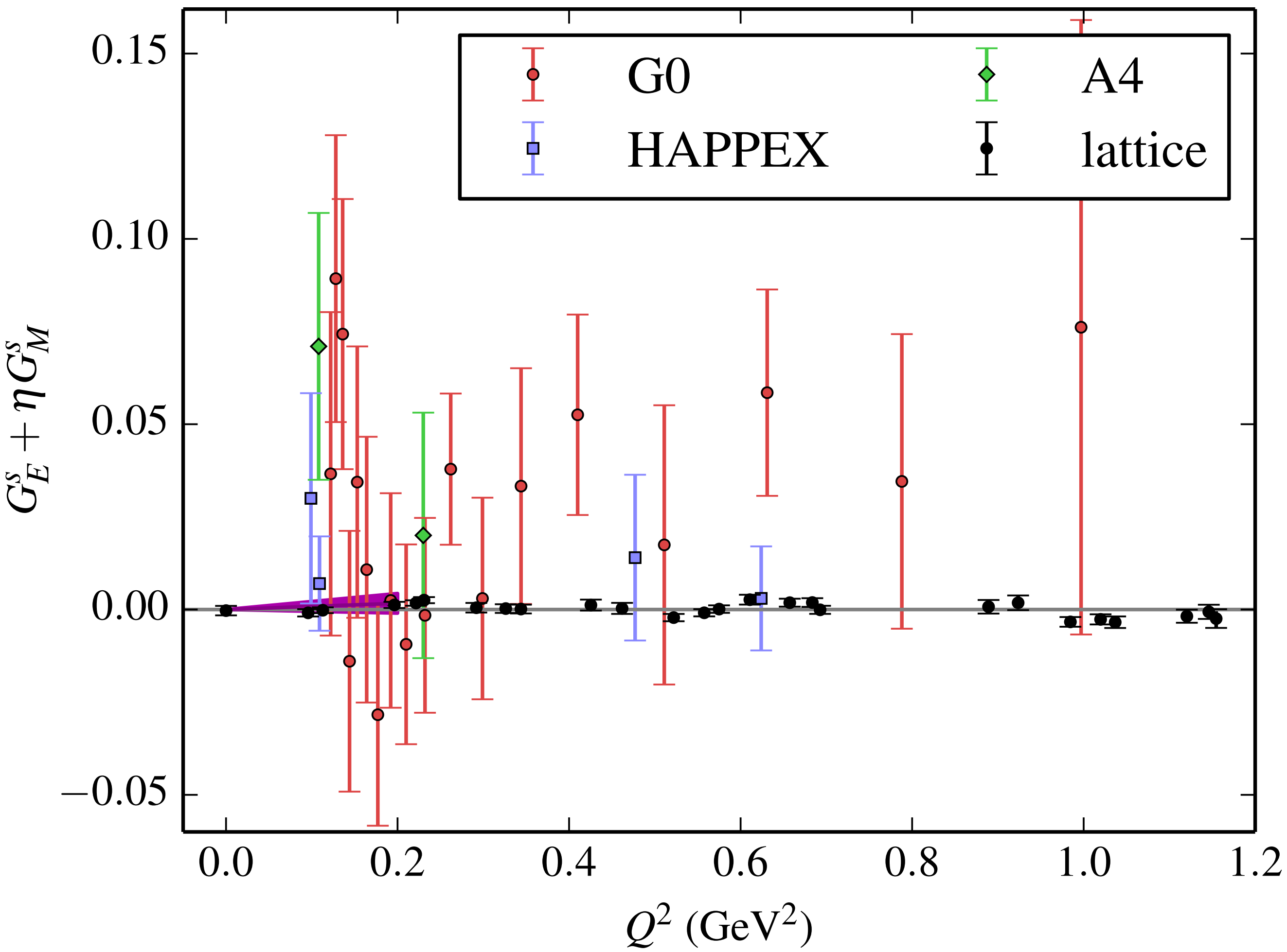
Strangeness Form Factor

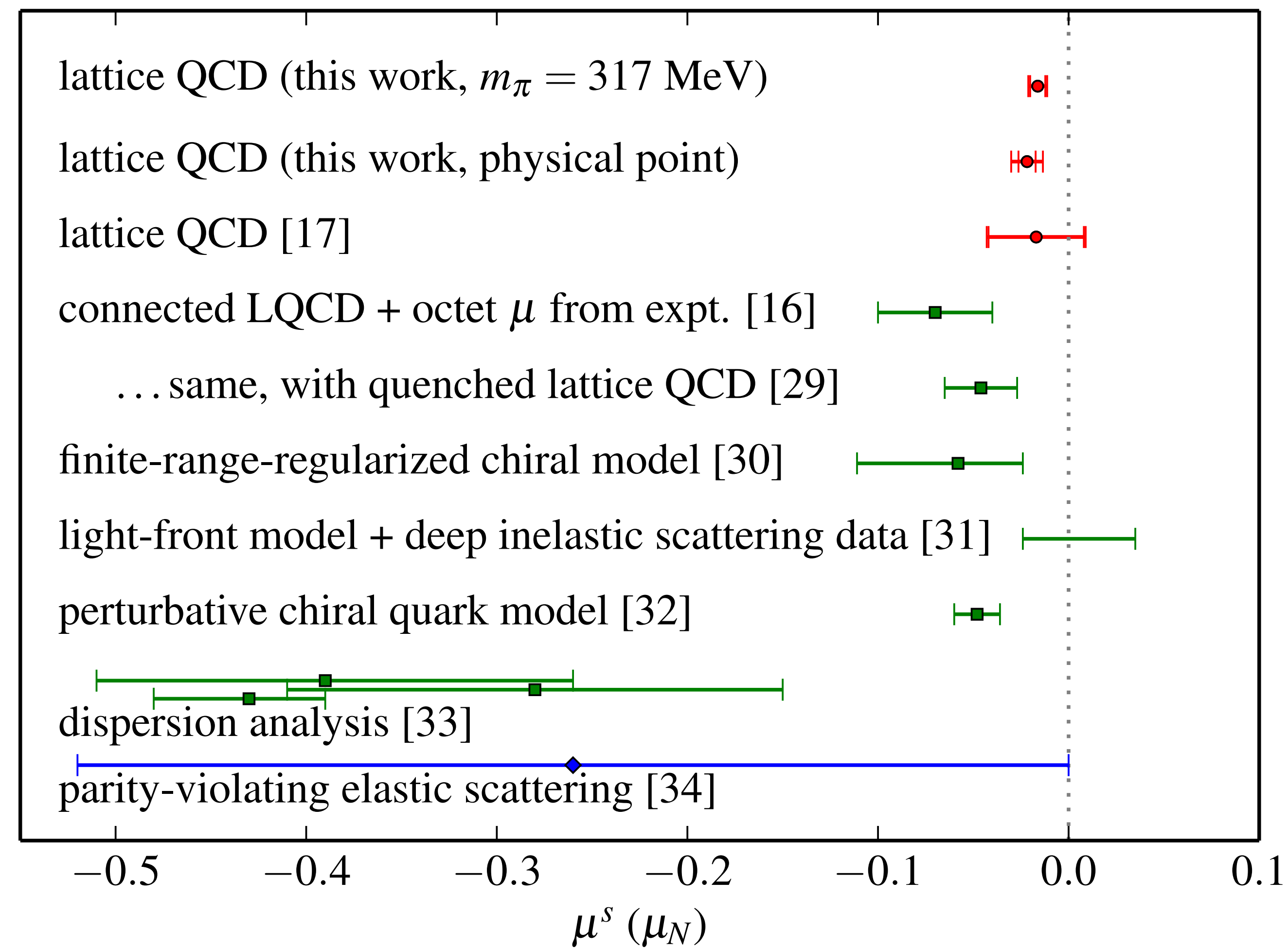


Strangeness Form Factor

[LHPC 1505.01803]

Comparison with experimental contraints





Presents a challenge for the next generation of experiments

Reached a precision where violations of charge symmetry will become important

Charge Symmetry

u quarks in the proton $\equiv$ *d* quarks in the neutron

Experimental determinations of $G^s_{E,M}(Q^2)$ rely on charge symmetry

(As does the inclusion of nuclear data for Qweak)

EM and weak interactions give access to different combinations of $G^{p,(u/d/s)}$

$$G^{p,\gamma} = \frac{2}{3}G^{p,u} - \frac{1}{3}\left(G^{p,d} + G^{p,s}\right)$$

$$G^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G^{p,u} - \left(1 - \frac{4}{3}\sin^2\theta_W\right)\left(G^{p,d} + G^{p,s}\right)$$

Assume charge symmetry $\left(G^{p,u} = G^{n,d}, \quad G^{p,d} = G^{n,u}, \quad G^{p,s} = G^{n,s}\right)$

$$\Rightarrow \left(G^{p,s}_{E/M} = \left(1 - 4\sin^2\theta_W\right)G^{p,\gamma}_{E/M} - G^{n,\gamma}_{E/M} - G^{p,Z}_{E/M}\right.$$

Charge Symmetry Violation

[CSSM/QCDSF PRD91 (2015) 113006]

Determine the degree to which charge symmetry is violated in EM form factors by

Combining chiral perturbation theory fits to isospin-averaged hyperon FFs

Input m_u/m_d from experiment (or FLAG)

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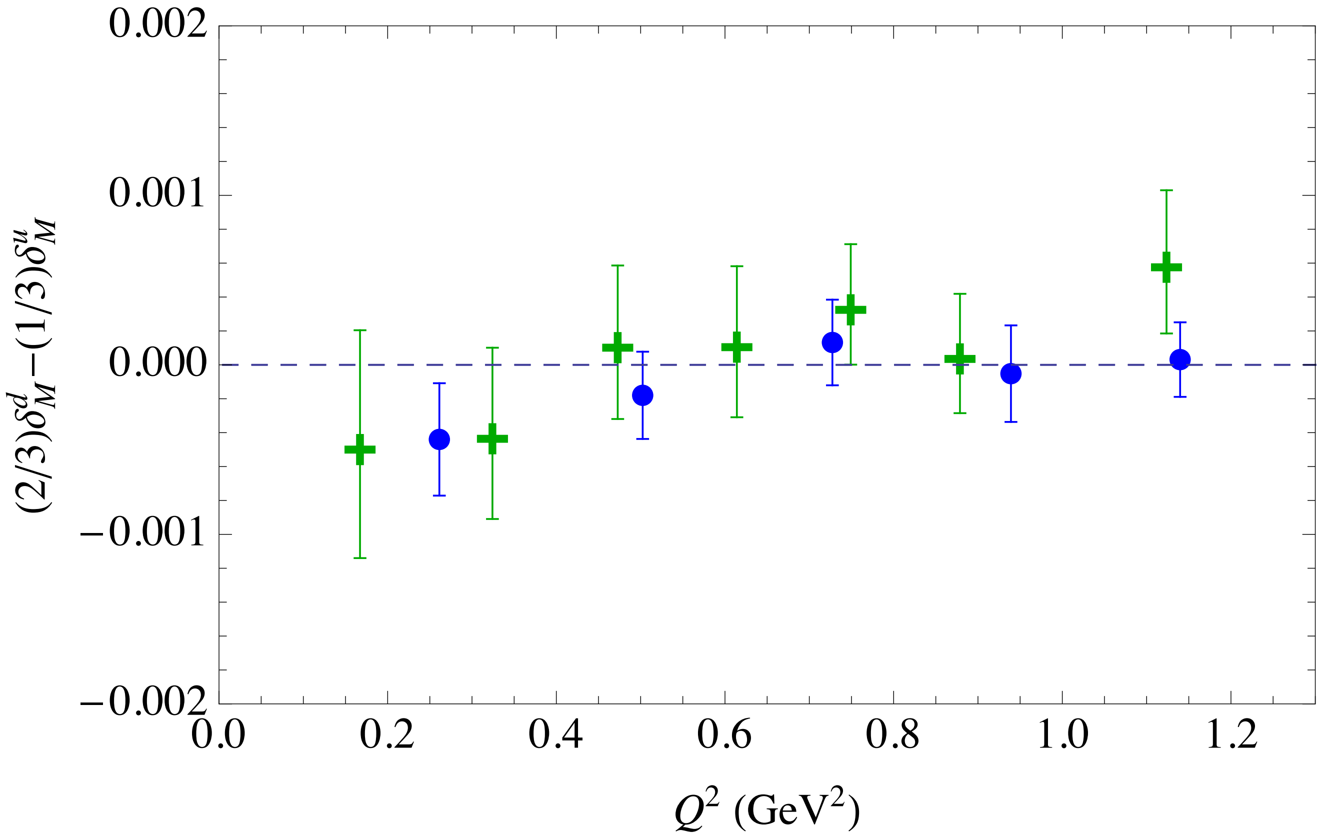

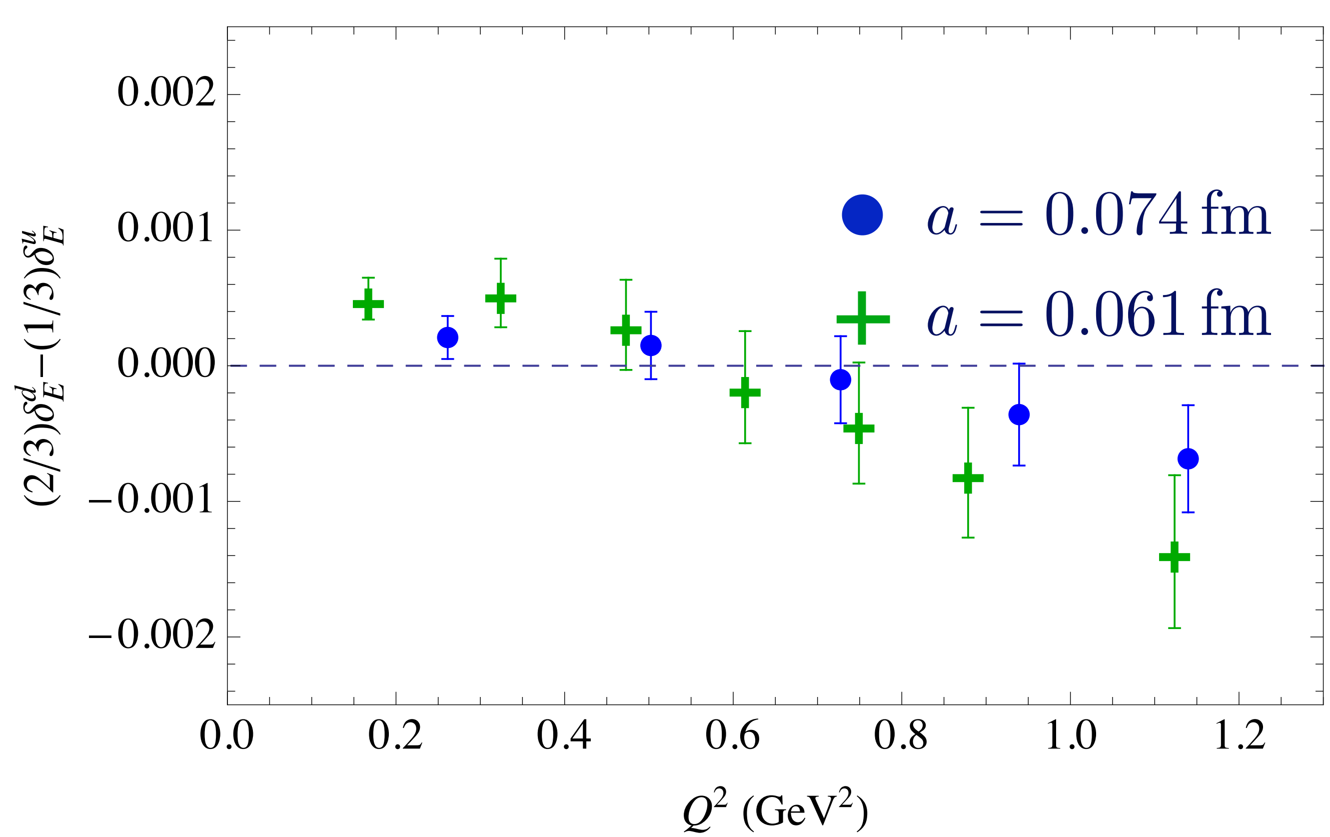

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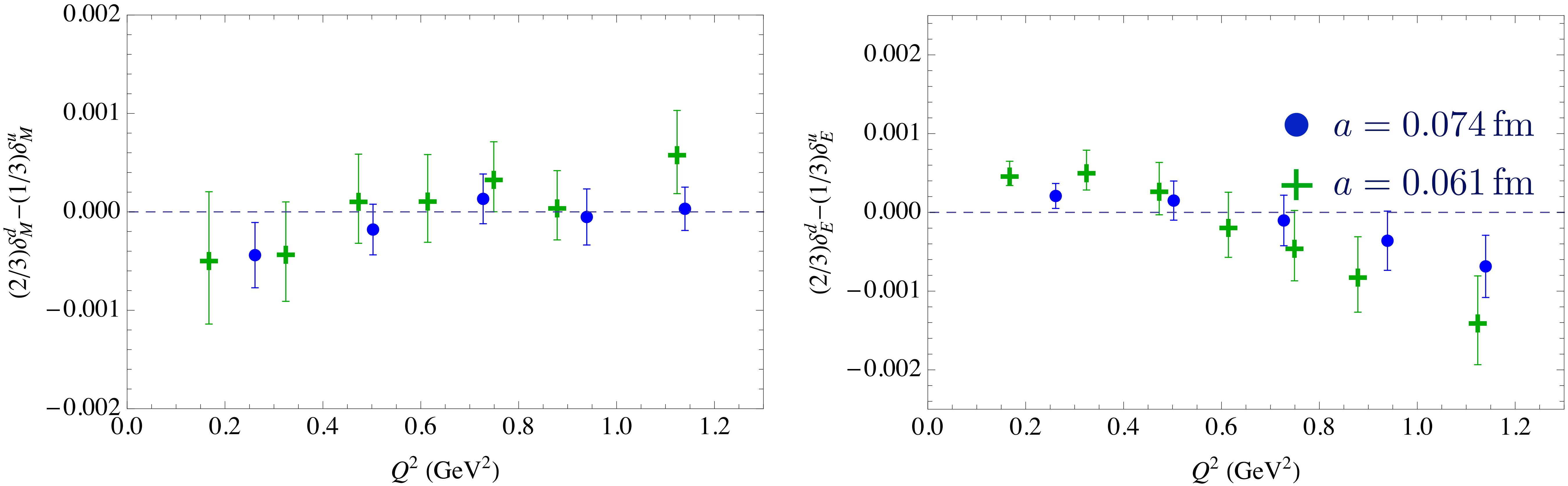


Charge symmetry satisfied to better than 0.2% (QCD)

Violations due to QED? Challenge for future QCD+QED simulations

Pion Form Factor

- **Asymptotic normalisation known from $\pi \rightarrow \mu + \nu$ decay**

$$F_\pi(Q^2 \rightarrow \infty) = \frac{16\pi\alpha_s(Q^2) f_\pi^2}{Q^2}$$

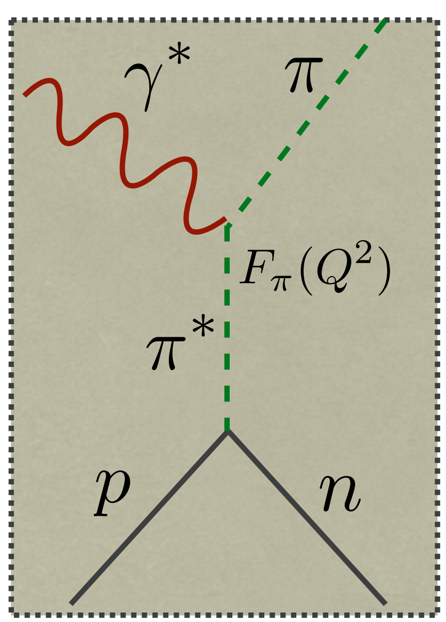
- **Allows to study the transition from the soft to hard regimes**

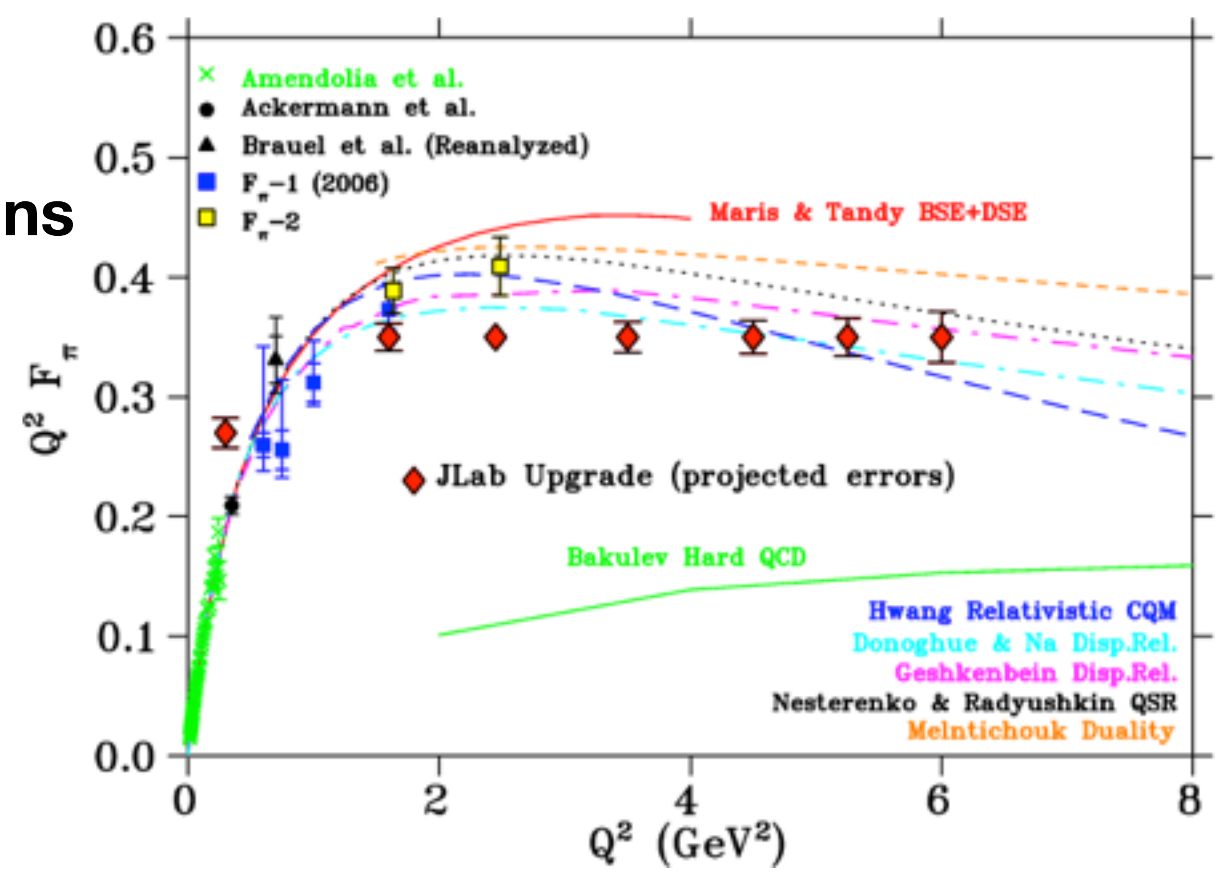
- **Low Q^2: measured directly by scattering high energy pions from atomic electrons**

→ **precise determination of $\langle r_\pi^2 \rangle$**

- **High Q^2: quasi-elastic scattering off virtual pions**

→ **Model dependence**





Pion Form Factor

[Bijnens-Ecker, 2014]

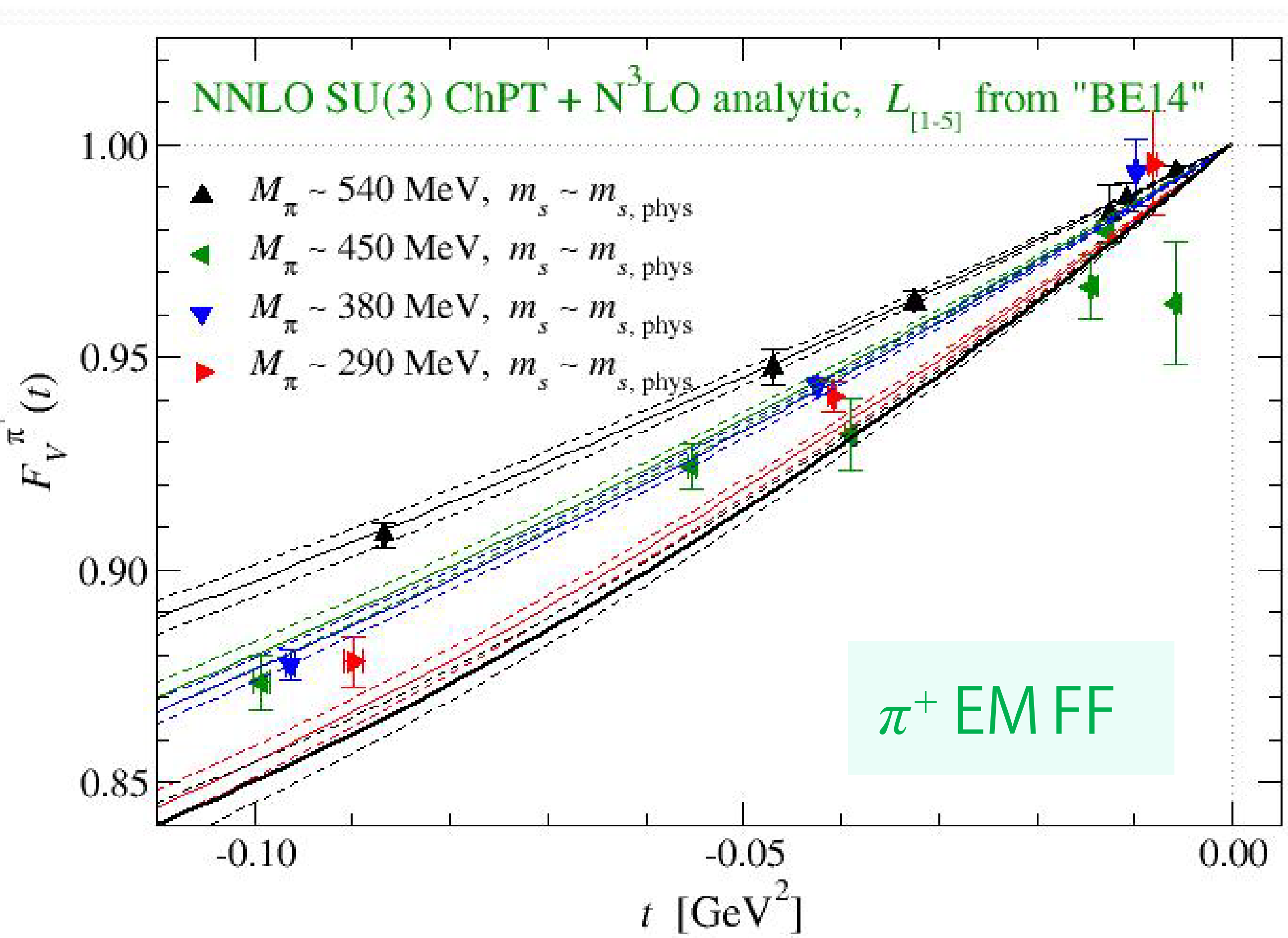
[T. Kaneko, Tue 16:30 (WD & ME)]

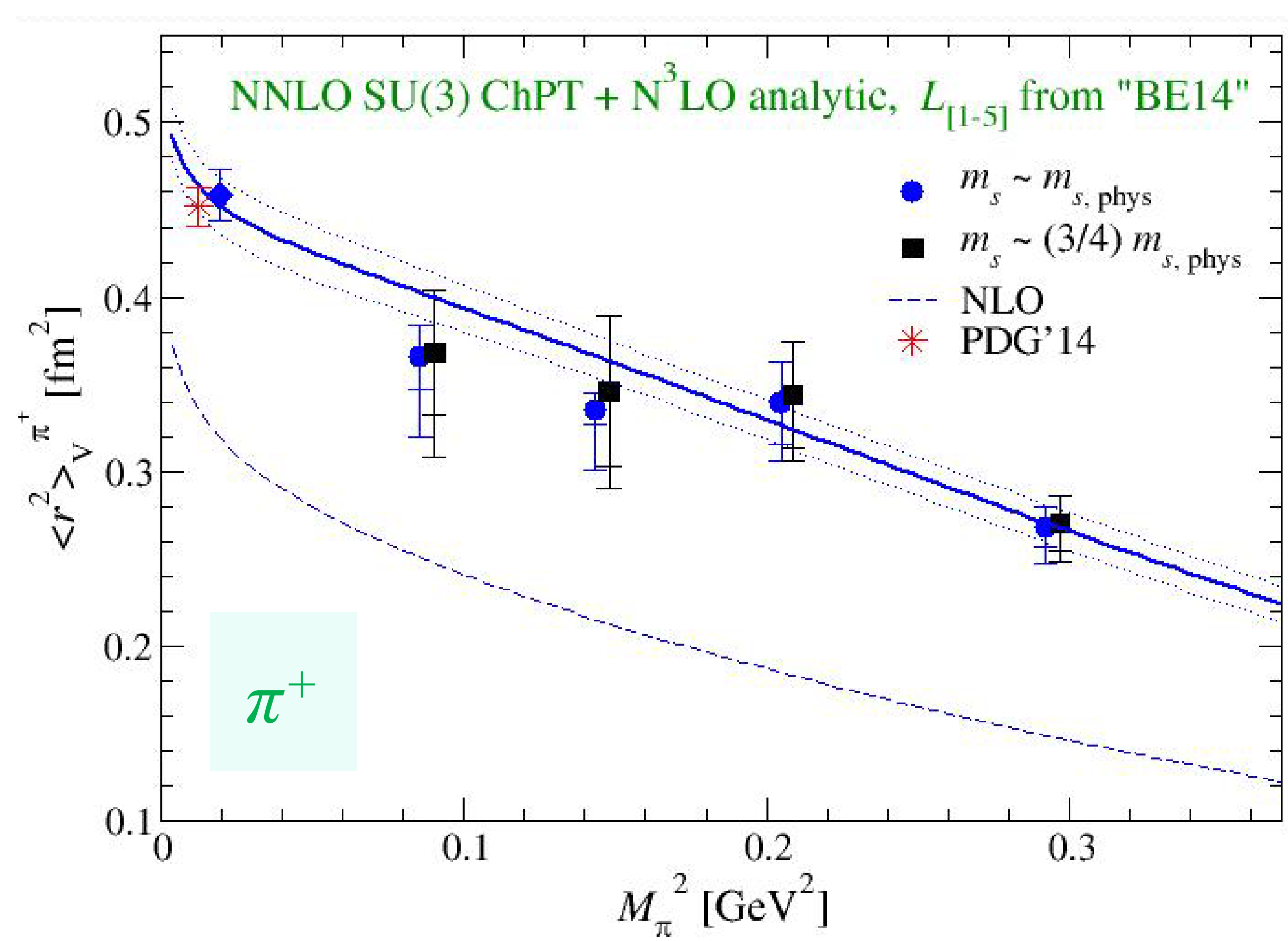
- **JLQCD: overlap quarks,** $290 \leq m_\pi \leq 540\,\mathrm{MeV}$ **(all-2-all propagators)**
- **NNLO SU(3) ChPT + N3LO analytic [Bijnens-Ecker, 2014] combined fit to**

$$F_{\pi^+}(q^2),\ F_{K^+}(q^2),\ F_{K^0}(q^2)$$

$$\langle r^2_{\pi^+}\rangle = 0.458(15)(38)\,\mathrm{fm}^2,\ \langle r^2_{K^+}\rangle = 0.380(12)(32)\,\mathrm{fm}^2,\ \langle r^2_{K^0}\rangle = -0.055(11)(45)\,\mathrm{fm}^2$$

PDG'14: $\langle r^2_{\pi^+}\rangle = 0.452(11)\,\mathrm{fm}^2,\ \langle r^2_{K^+}\rangle = 0.314(35)\,\mathrm{fm}^2,\ \langle r^2_{K^0}\rangle = -0.077(10)\,\mathrm{fm}^2$

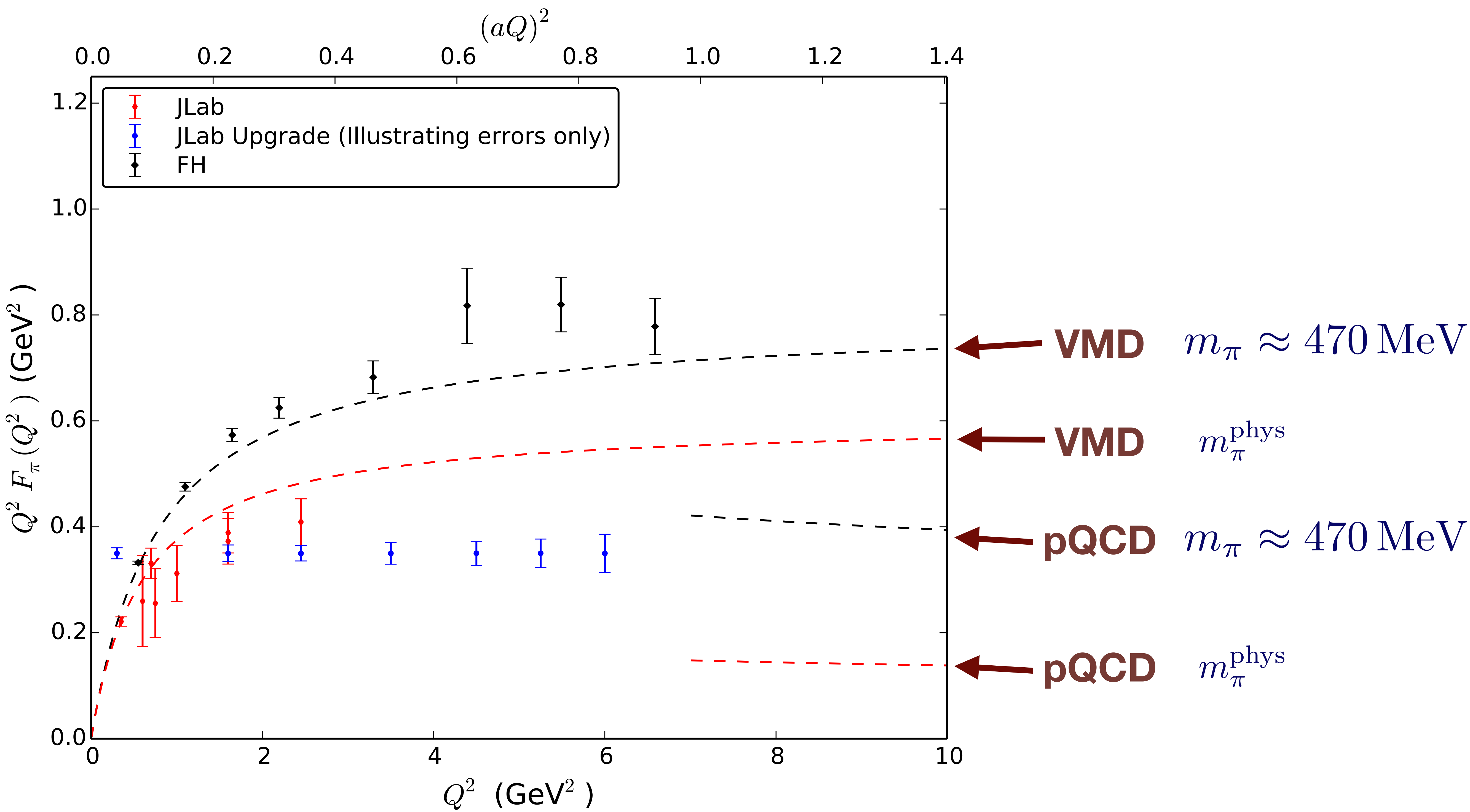




Pion Form Factor

[R. Young, Thu 8:30am]

Access large Q^2 via Feynman-Hellmann

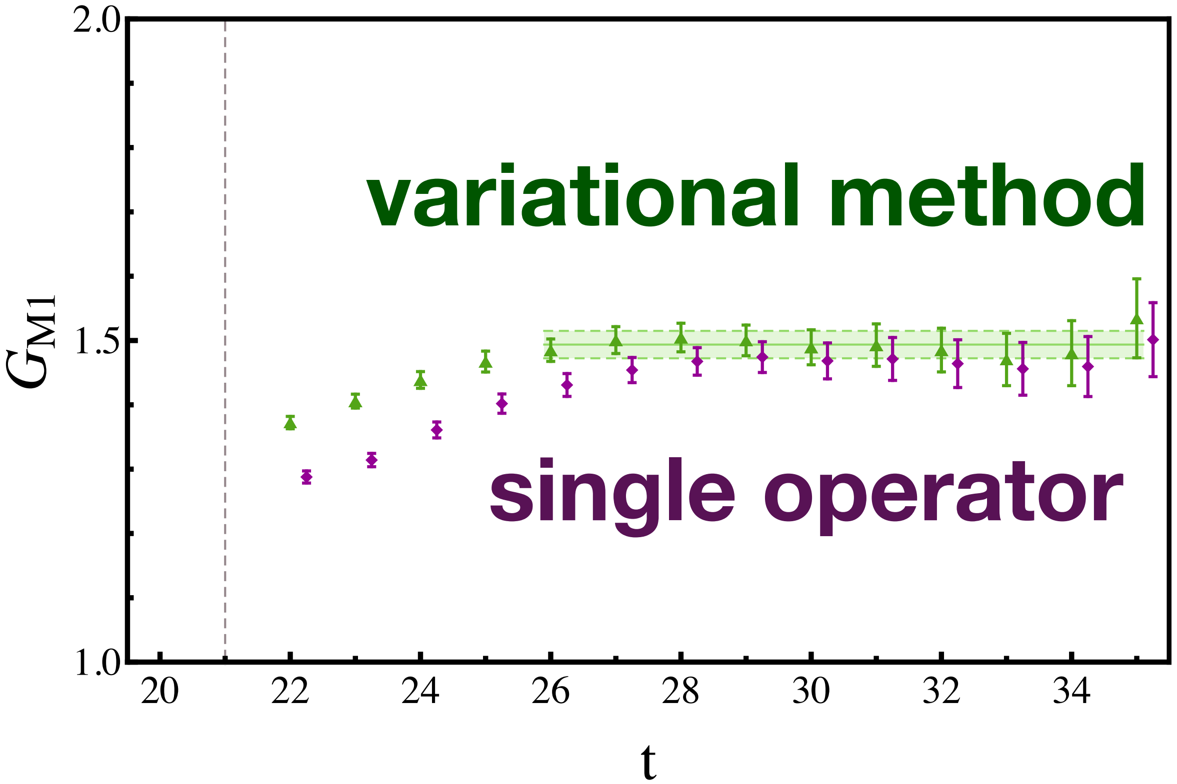


$\rho \to \pi\gamma$

[CSSM 1505.02876]

Relevant for experiments at JLab and Mainz studying hadronic excitations

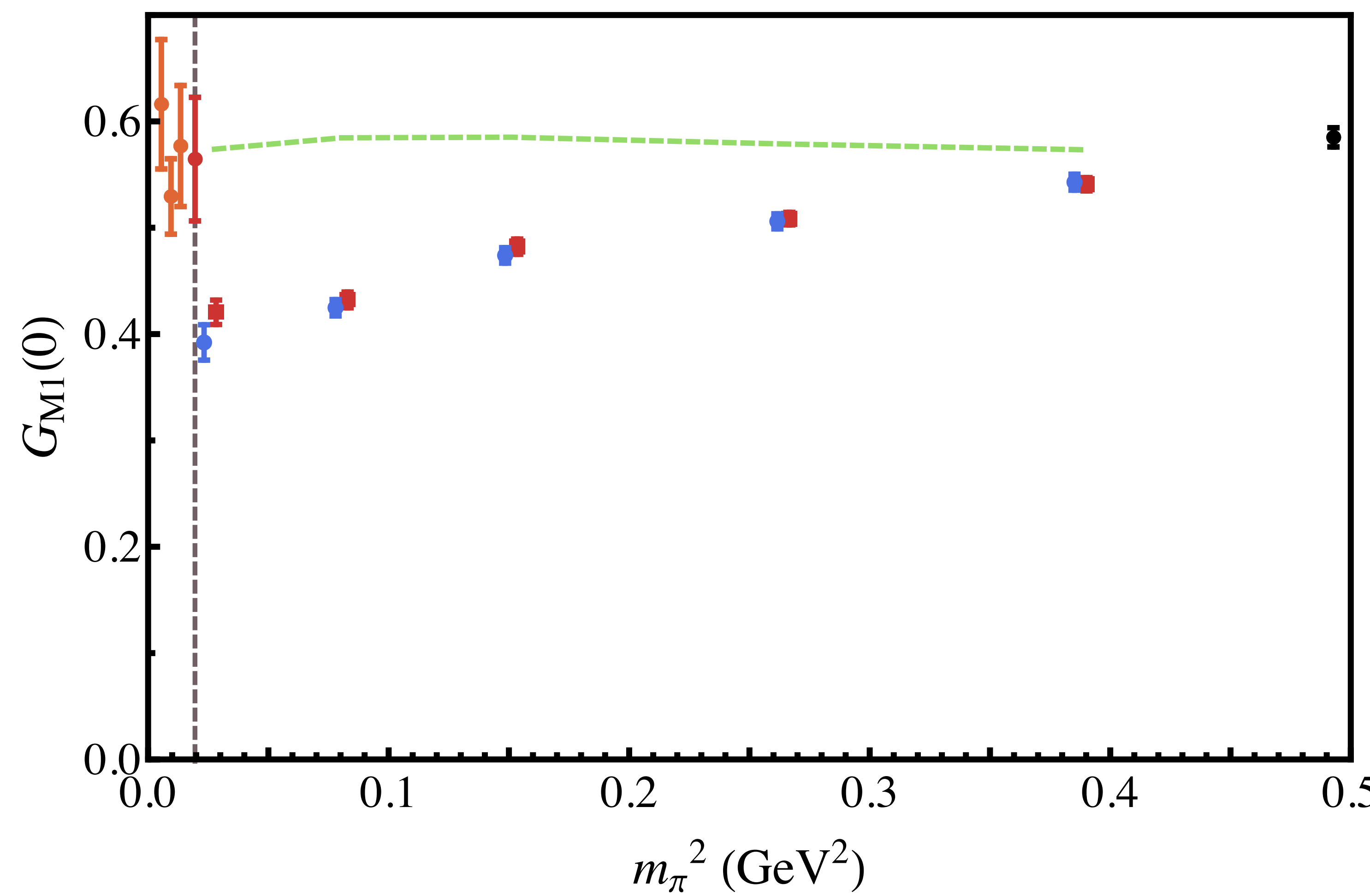
Develop framework for other radiative processes, e.g. $N^* \to N\gamma$



PACS-CS 2+1 Clover

$$156 \leq m_\pi \leq 700\,\text{MeV}$$

Variational method to remove excited states



Discrepancy due to

disconnected diagrams?

multiparticle operators?

finite volume?

Quark Distribution Functions

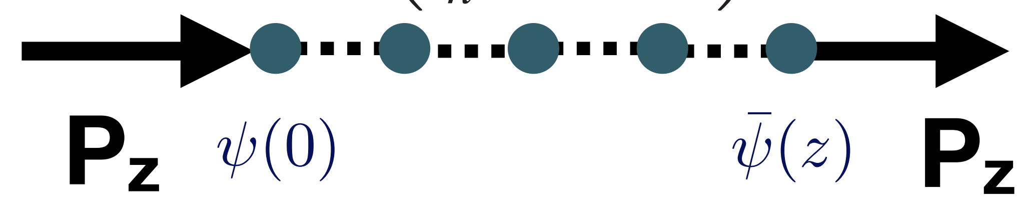
Recent proposal by Ji:

$$\tilde{q}_{\text{lat}}(x,\Lambda,P_z) = \int \frac{dz}{4\pi} e^{-izk} h(z,\Lambda,P_z),$$

“Quasi”-PDFs

$$h(z,\Lambda,P_z) = \langle \vec{P}|\bar{\psi}(z)\gamma_z\left(\prod_n U_z(n\hat{z})\right)\psi(0)|\vec{P}\rangle,$$

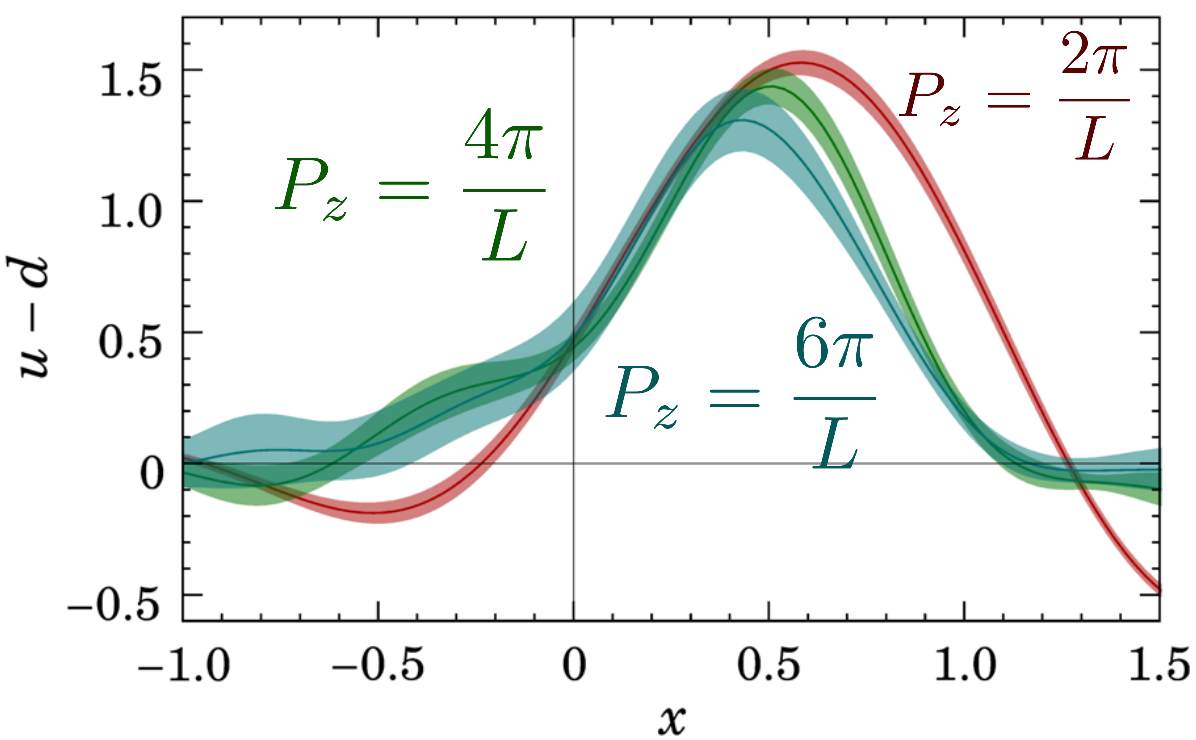
[PRL 110 (2013) 262002]



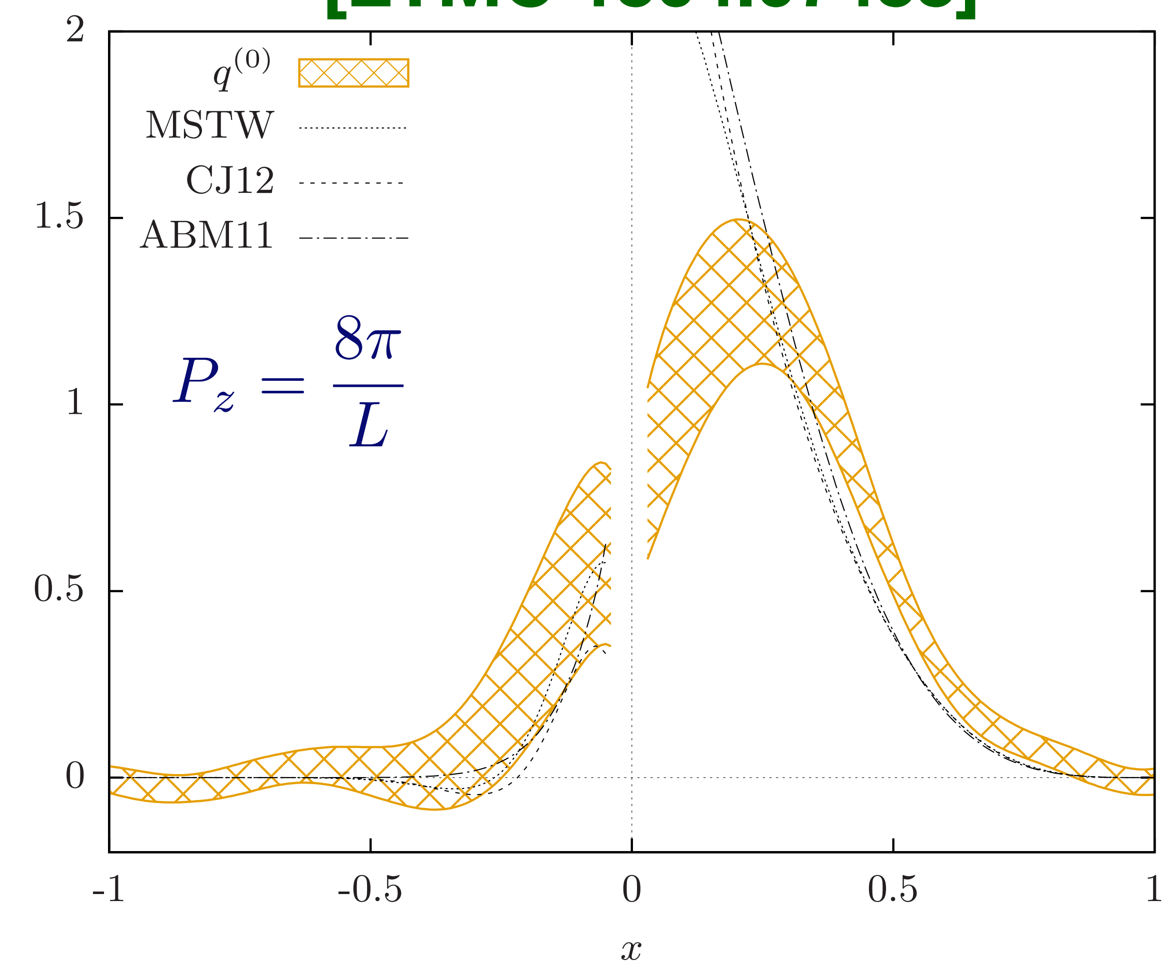
Connection to continuum through perturbative matching

2 lattice calculations

[H-W.Lin et al. PRD91 (2015) 054510]

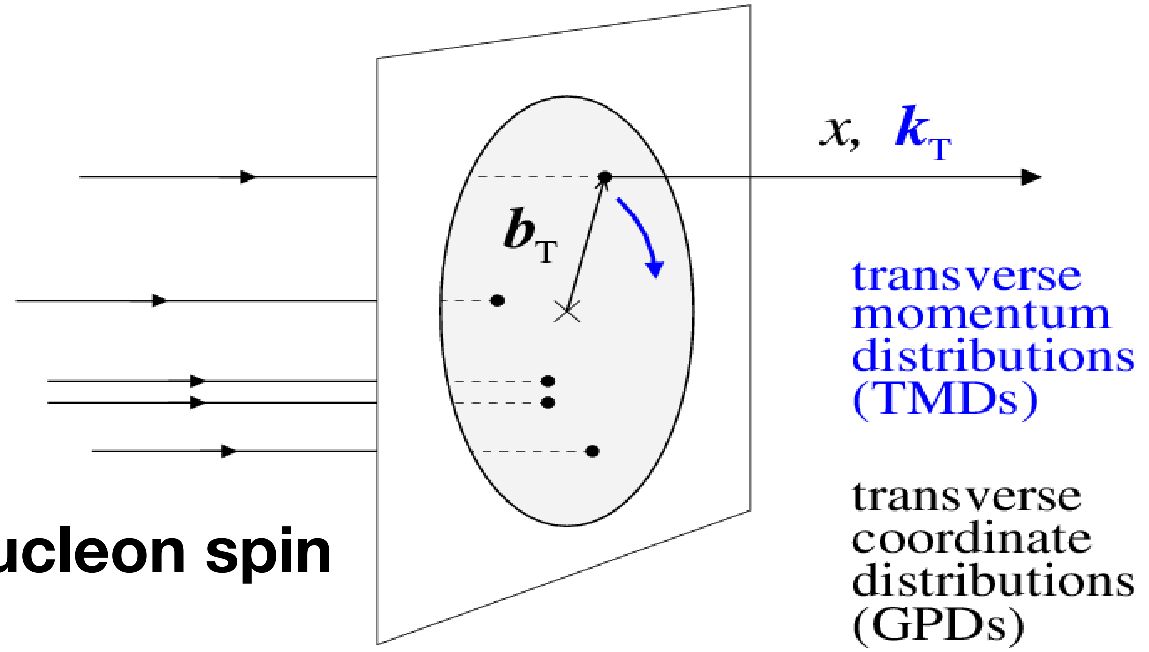


[ETMC 1504.07455]



Transverse Momentum Distributions

[Engelhardt, Wed 14:40]



3D imaging in momentum space

Relevant for:

- **orbital angular momentum contributions to nucleon spin**
- **spin-orbit correlations in hadrons**

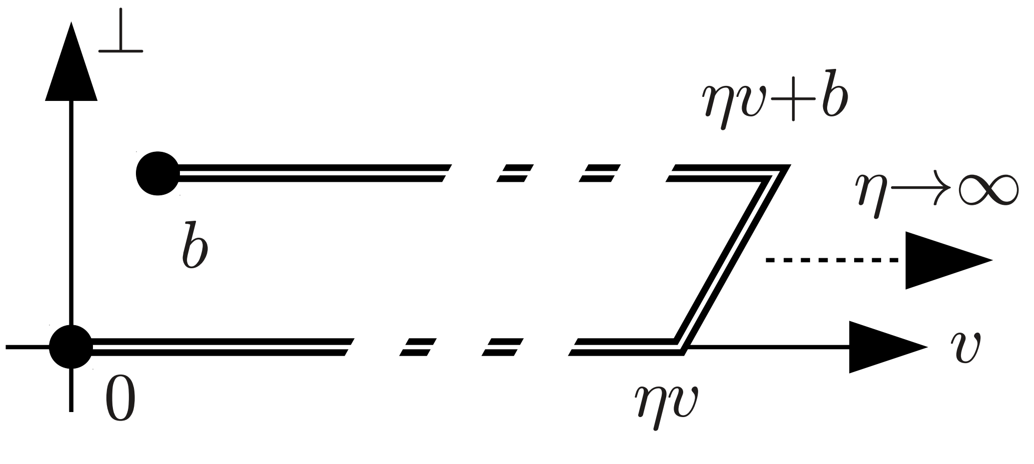
Accessed via Semi-Inclusive Deep Inelastic Scattering or Drell-Yan
[JLab, HERMES, COMPASS, RHIC]

Relevant matrix elements:

[LHPC: PRD85 (2012) 094510]

$$\langle P|\,\bar{q}(0)\,\Gamma\,\mathcal{U}[0,\,\eta v,\,\eta v+b,\,b]\,q(b)\,|P\rangle$$

Gauge link "along the light cone"

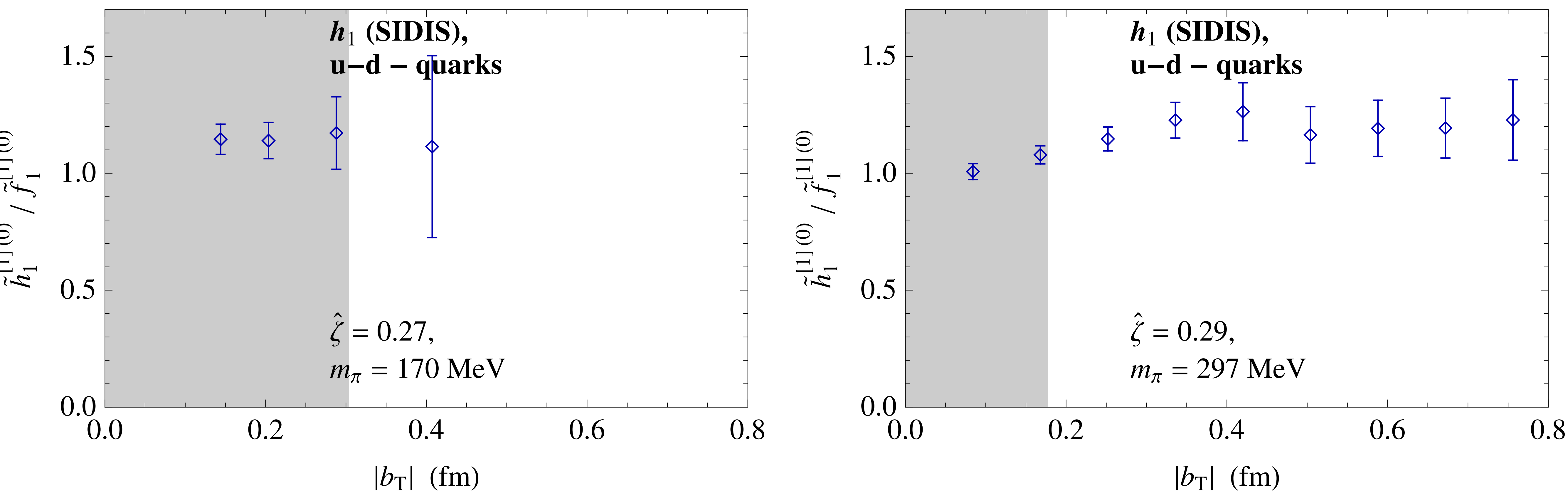


Transverse Momentum Distributions

[Engelhardt, Fri 15:40 (WD & ME)]

Nucleon update with $m_\pi \approx 170\,\mathrm{MeV}$ (2+1 DWF)

Dependence of SIDIS/DY limit on $|b_T|$



Recent investigated pion TMD **[LHPC 1506.07826]**

→ **understand approach to “light cone”**

Summary & Outlook

Excellent progress in understanding and controlling systematic errors

⇒ **Precise results at the physical point now achievable for**

- **isovector charges**
- **electromagnetic form factors**

With additional progress in computing disconnected contributions

Improved understanding of long term questions, e.g.

- **decomposition of proton spin**
- **role of hidden flavour**

Right time to tackle more “exotic” quantities relevant for upcoming experiments

quasi-PDFS, TMDs, nuclear effects, …

International Nuclear Physics Conference (INPC2016)



2004: Göteborg, Sweden

2007: Tokyo, Japan

2010: Vancouver, Canada

2013: Florence, Italy

2016: Adelaide, Australia

with dedicated lattice sessions on nuclear physics, hadron structure, finite density, …

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September 11-16, 2016

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