Lattice QCD for High-Energy Physics

Phiala Shanahan, MIT

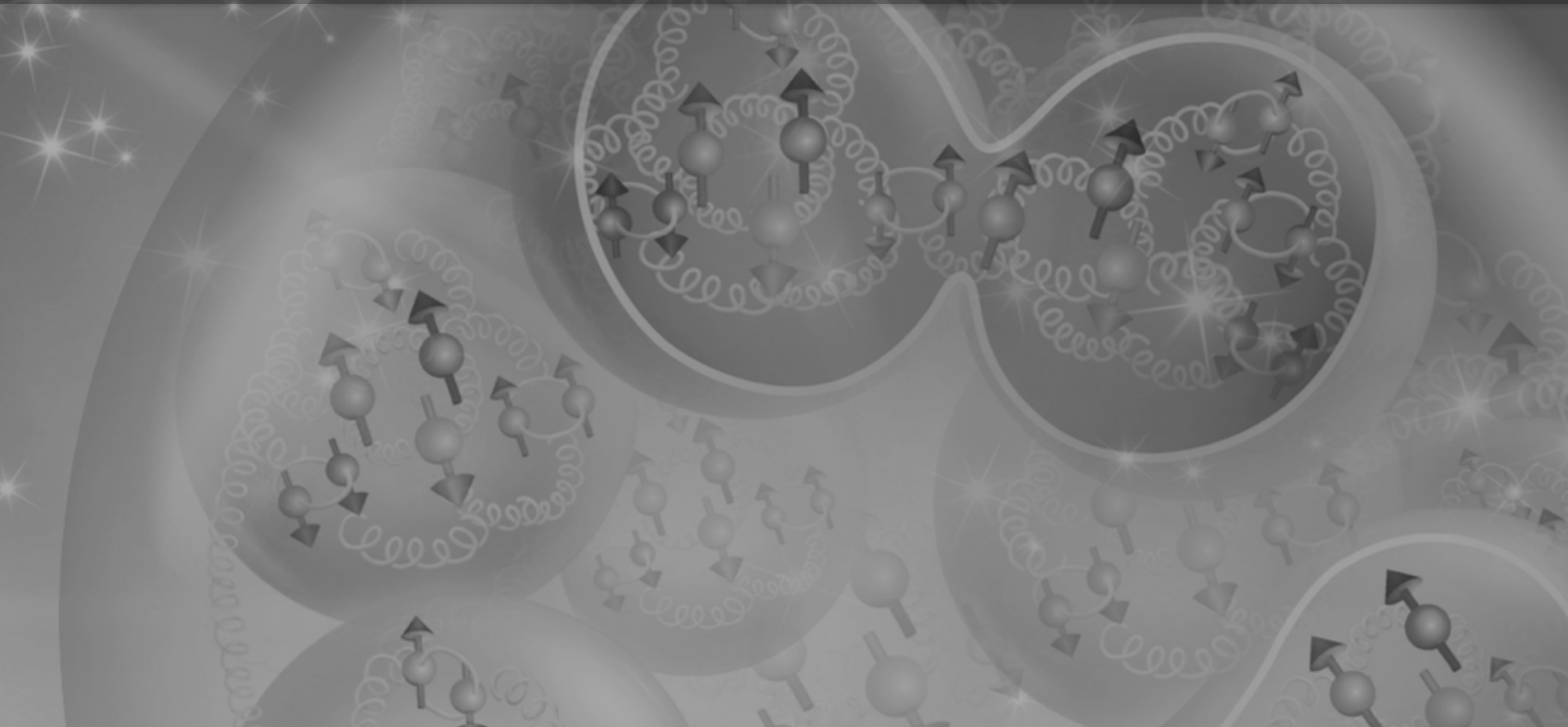

Image Credit: 2018 EIC User's Group Meeting

Lattice QCD for HEP

We are entering the

- Precision era of lattice QCD for simple systems
- Beginning of reliable lattice QCD results for nuclear matrix elements

I will highlight some new results in these areas since ICHEP2016

Lattice QCD can provide input for

Decay constants, form factors, mixing parameters

Hadronic vacuum polarisation and light-by-light scattering

Neutrino-nucleus interactions

Dark matter-nucleon and DM-nucleus interactions

Muon-nucleus cross-sections

Parton distribution functions

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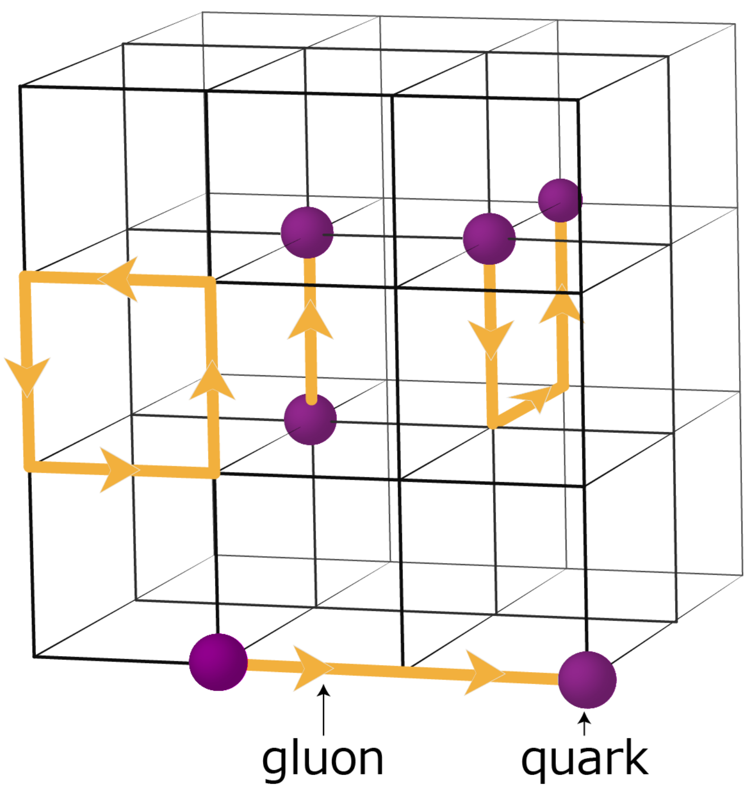
Lattice QCD

Numerical first-principles approach to
non-perturbative QCD

- Discretise QCD onto 4D space-time lattice
- Approximate QCD path integral using Monte-Carlo methods and importance sampling
- Run on supercomputers and dedicated clusters
- Take limit of vanishing discretisation, infinite volume, physical quark masses



Lattice QCD

Numerical first-principles approach to
non-perturbative QCD

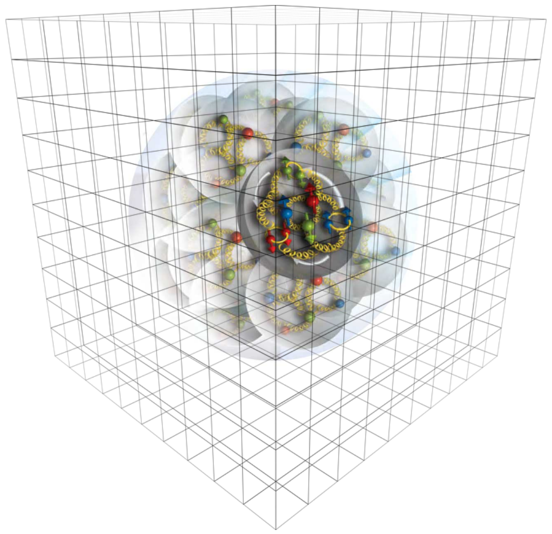
INPUT

Lattice QCD action has same free parameters as QCD: quark masses, α_S

- Fix quark masses by matching to measured hadron masses, e.g., π, K, D_s, B_s for u, d, s, c, b
- One experimental input to fix lattice spacing in GeV (and also α_S), e.g., $2S$-$1S$ splitting in Y, or f_π or Ω mass

OUTPUT

Calculations of all other quantities are QCD predictions



Highlights since ICHEP2016

- Quark masses and α_s
- Flavour physics
- $g-2$
- Parton distribution functions
- Neutrino physics
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Quark masses and α_s

The quark masses and α_s are the fundamental parameters of QCD
Their precise values are important for precision tests of the Standard Model

e.g., Next-generation of high-luminosity colliders will measure **Higgs partial widths to sub-percent precision** to look for deviations from Standard-Model expectations

→ Need **Standard Model calculations at same sub-percent precision**; largest uncertainties are currently in m_c, m_b, & α_s [LHCHXSWG-DRAFT-INT-2016-008]

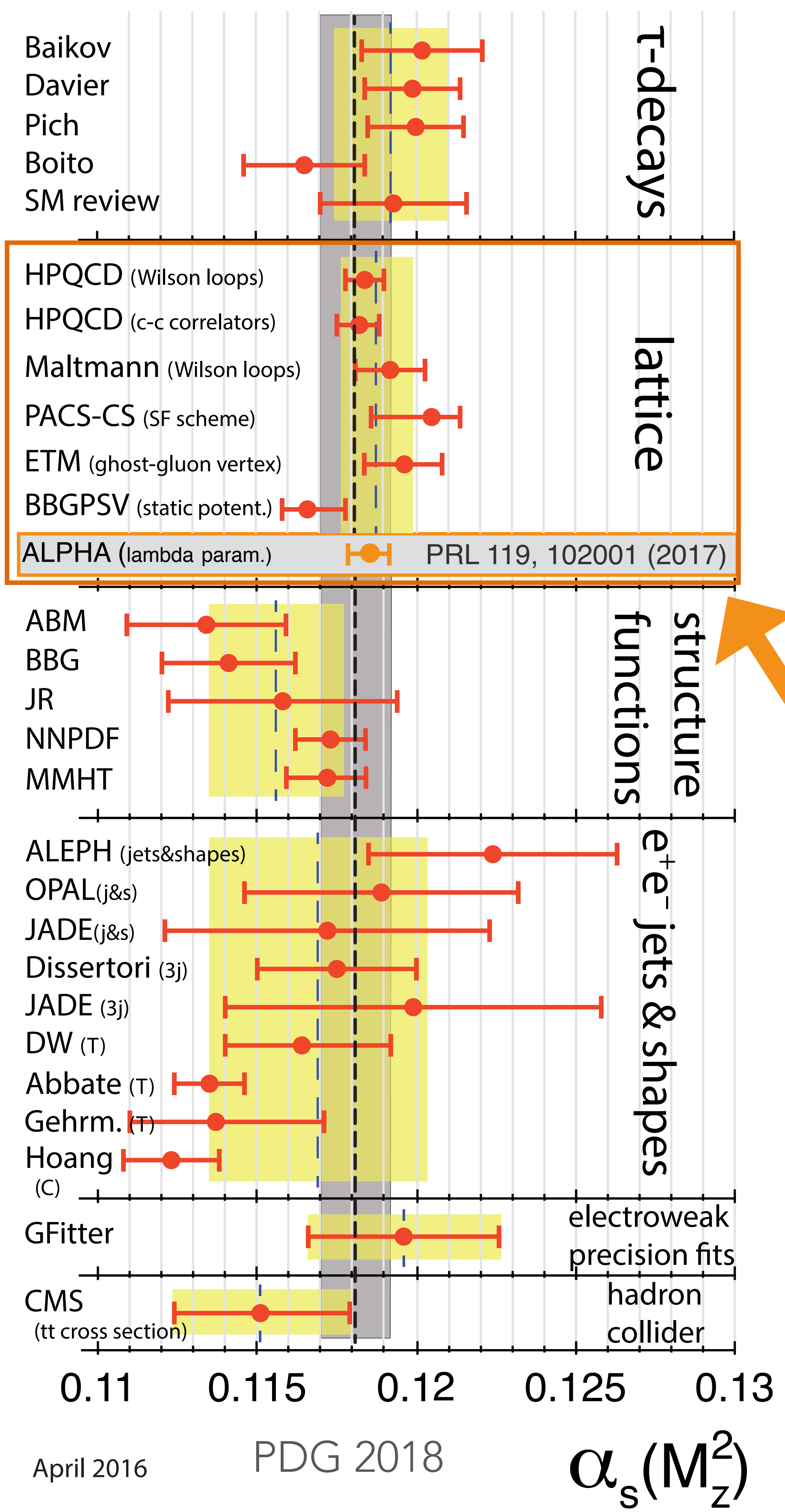
→ Lepage, Mackenzie, Peskin, [arXiv:1404.0319]

- Precision goals for m_c, m_b, & α_s needed by high-luminosity ILC
- Outlined timeline for lattice QCD progress

Continued progress towards precision goals since ICHEP2016

Next goals:

- Correlated determinations of m_c, m_b, and α_s
- Dynamical QED



α_s update

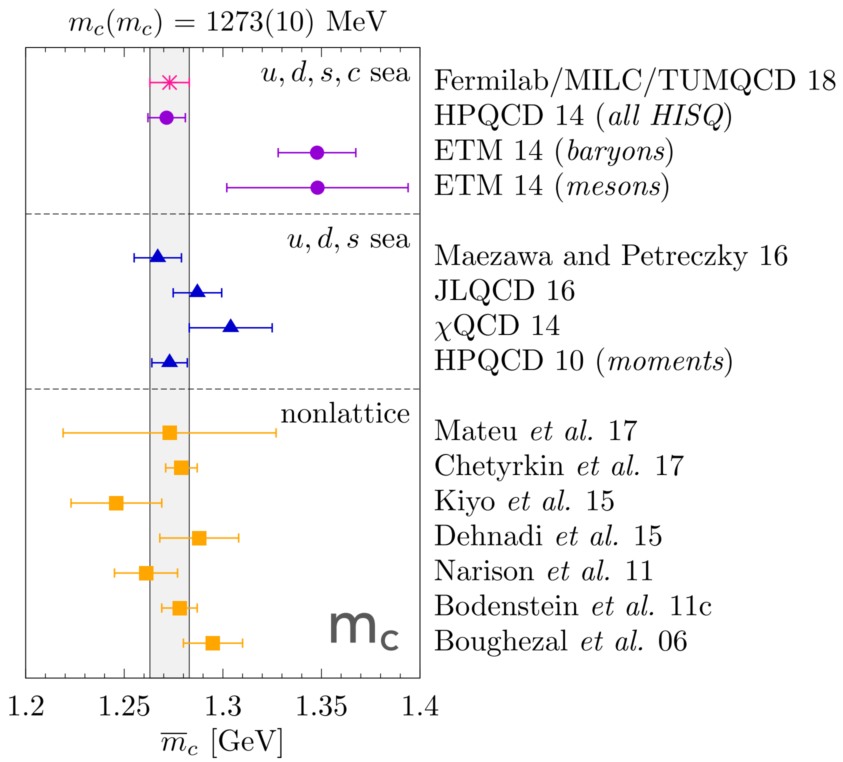
Best lattice QCD uncertainties ~0.6-0.7%, approaching ILC target: 0.6%.
Twice as precise as non-lattice world average

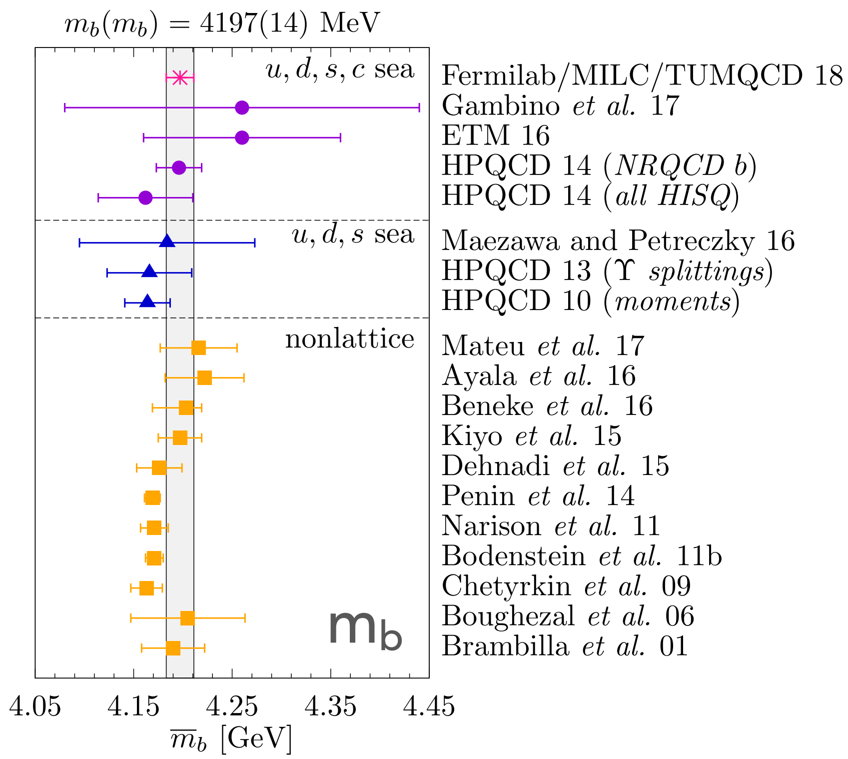
- Several independent lattice QCD methods available to obtain α_s
- Results consistent, despite significantly different sources of systematic uncertainty

2017 Highlight:

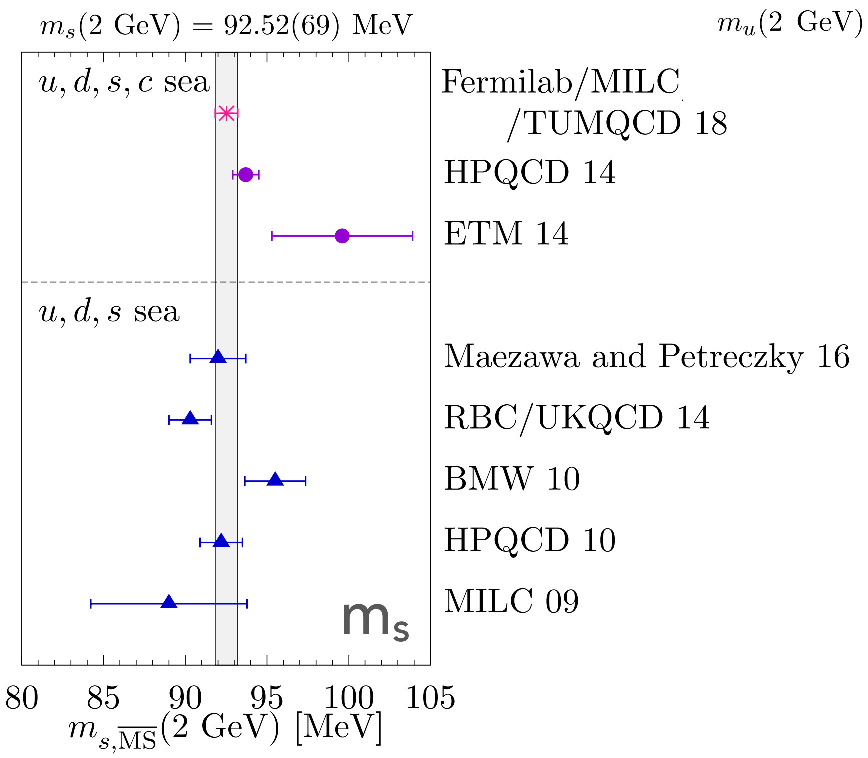
New lattice QCD determination based on finite size scaling (rather than Wilson Loops and quarkonia) consistent and precise: α_s =0.1185(8)(3) [PRL119, 102001]

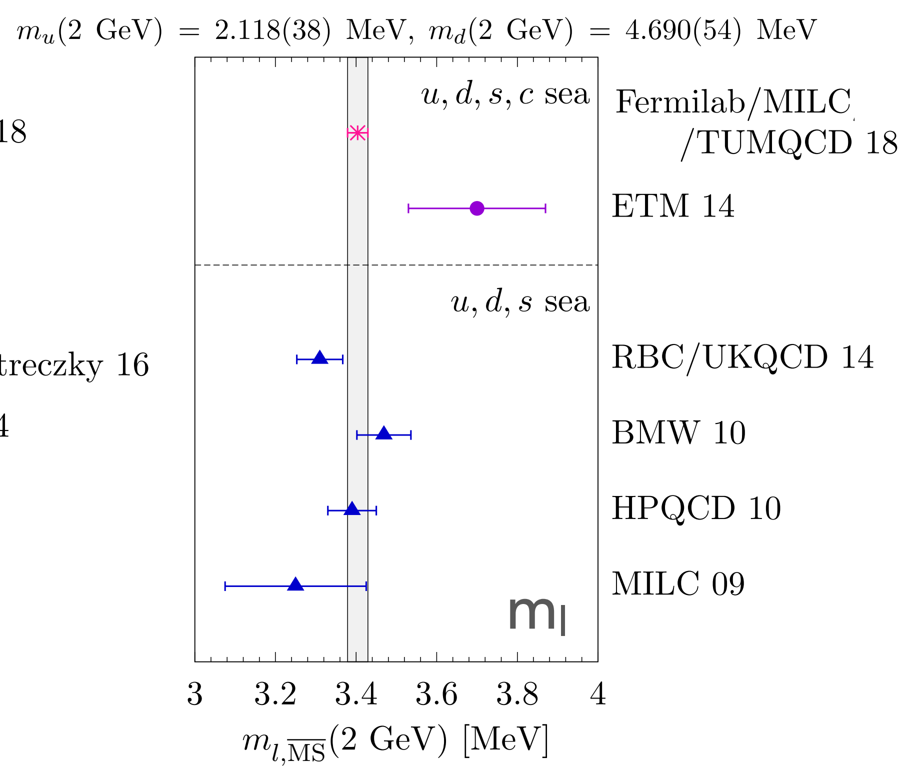
Quark masses update





MRS mass definition [arXiv:1712.04983]





2018 Highlight:
Significant improvement in heavy quark mass determinations using new method based on heavy-quark effective theory [arXiv:1802.04248]

Precision	**ILC goals**
$\delta m_b \sim 0.3$	0.3
$\delta m_c \sim 0.8$	0.7

Will improve further with inclusion of finer lattice spacings

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Flavour physics from lattice QCD

Lattice QCD can provide precise hadronic matrix elements for flavour physics:

[experiment] = [known] x [CKM] x [hadronic matrix element]

This leads to effort in two main directions:

1 **Lattice QCD + experiment**

➡ **CKM quark mixing matrix elements**

Simple tree-level processes in lattice QCD allow determination of all elements and phases other than V_{tb}

V_{ud} $\pi \to \mu\nu$	V_{us} $K \to \pi l\nu$ $K \to \mu\nu$	V_{ub} $B \to \pi l\nu$
V_{cd} $D \to \pi l\nu$ $D \to l\nu$	V_{cs} $D \to K l\nu$ $D_s \to l\nu$	V_{cb} $B \to D, D^* l\nu$
V_{td} $B^0 - \overline{B^0}$ mixing	V_{ts} $B_s - \overline{B_s}$	V_{tb}

2 **Lattice QCD + CKM**

➡ **Standard Model expectations for rare decays & mixing**

Target processes sensitive to beyond-SM physics

Flavour Lattice Averaging Group

Many lattice calculations of what are now "simple" flavour physics quantities

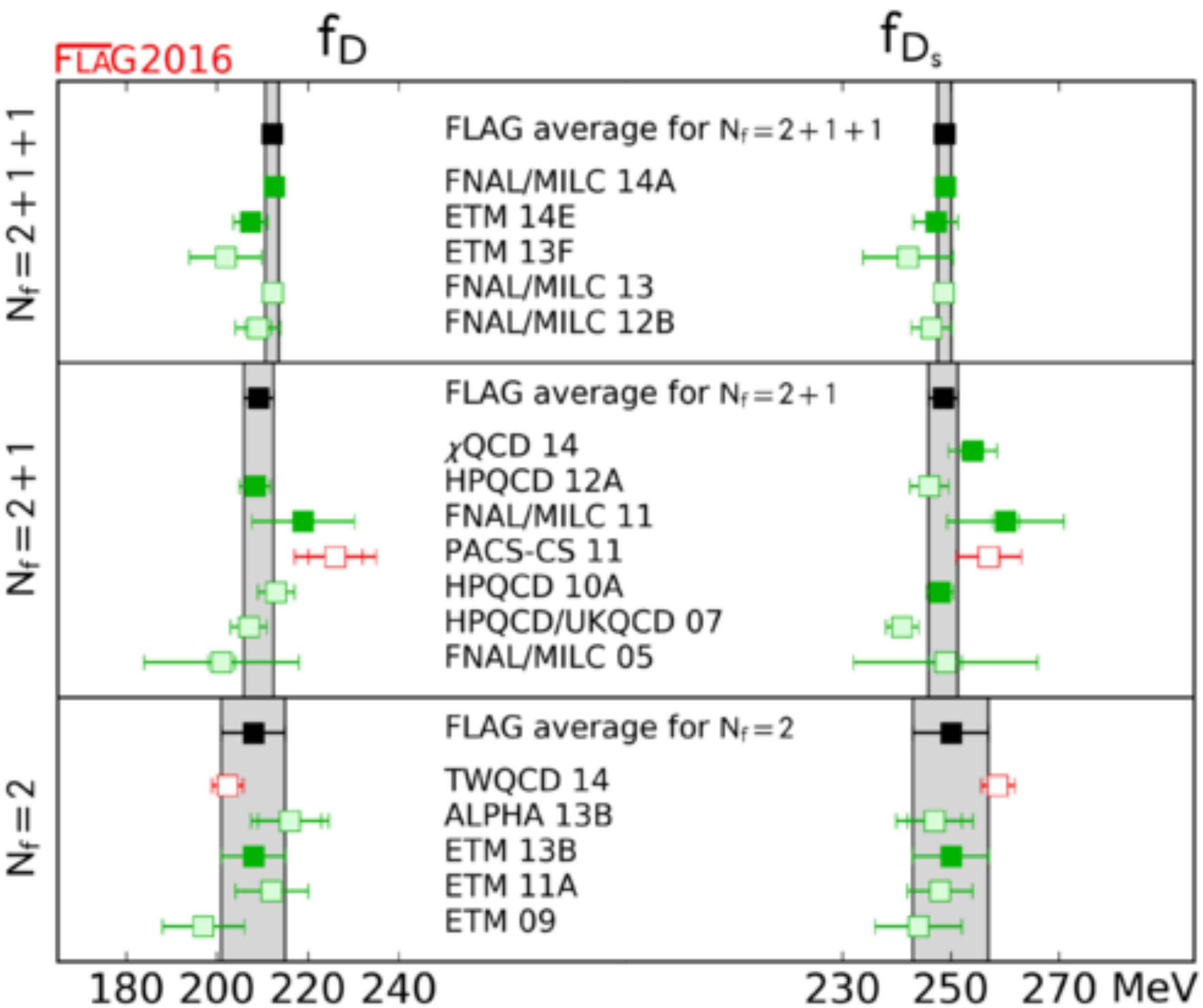
FLAG: Flavour Lattice Averaging Group
Similar effort to the PDG, for Lattice QCD

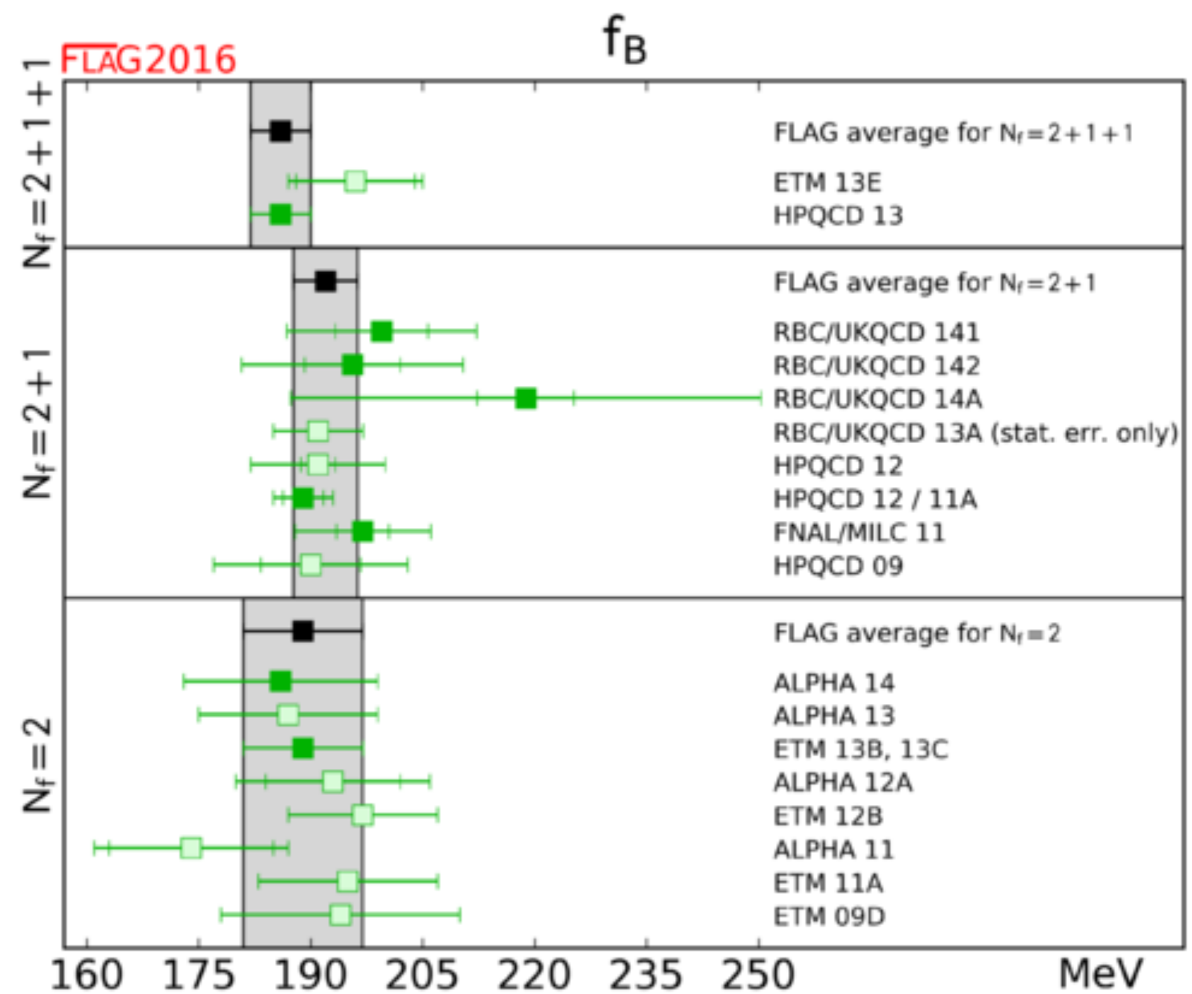
- Members from most major lattice QCD collaborations
- Evaluates and grades different aspects of each calculation ★ ○ ■
- Provides averages as the "Lattice QCD community consensus" value for a given quantity
- Includes lattice dictionary and summaries for non-experts
- Summary report every ~2 years: [arXiv:1105.3453] [1304.5422] [1607.00299]
  Dec 2017 update at http://flag.unibe.ch
- **New version planned for 2019:** coverage expanding to include simple baryon quantities e.g., g_A

FLAG 2016 example

Flavour Lattice Averaging Group

- Decay constants, form factors, kaon mixing, LECs…
- Colour coded for quality of calculation (# lattice spacings, volumes,…)





http://flag.unibe.ch

New results for $f_{B/D}$ from Fermilab lattice & MILC [arXiv:1712.09262] not yet in FLAG

B→Dℓν and B→D*ℓν

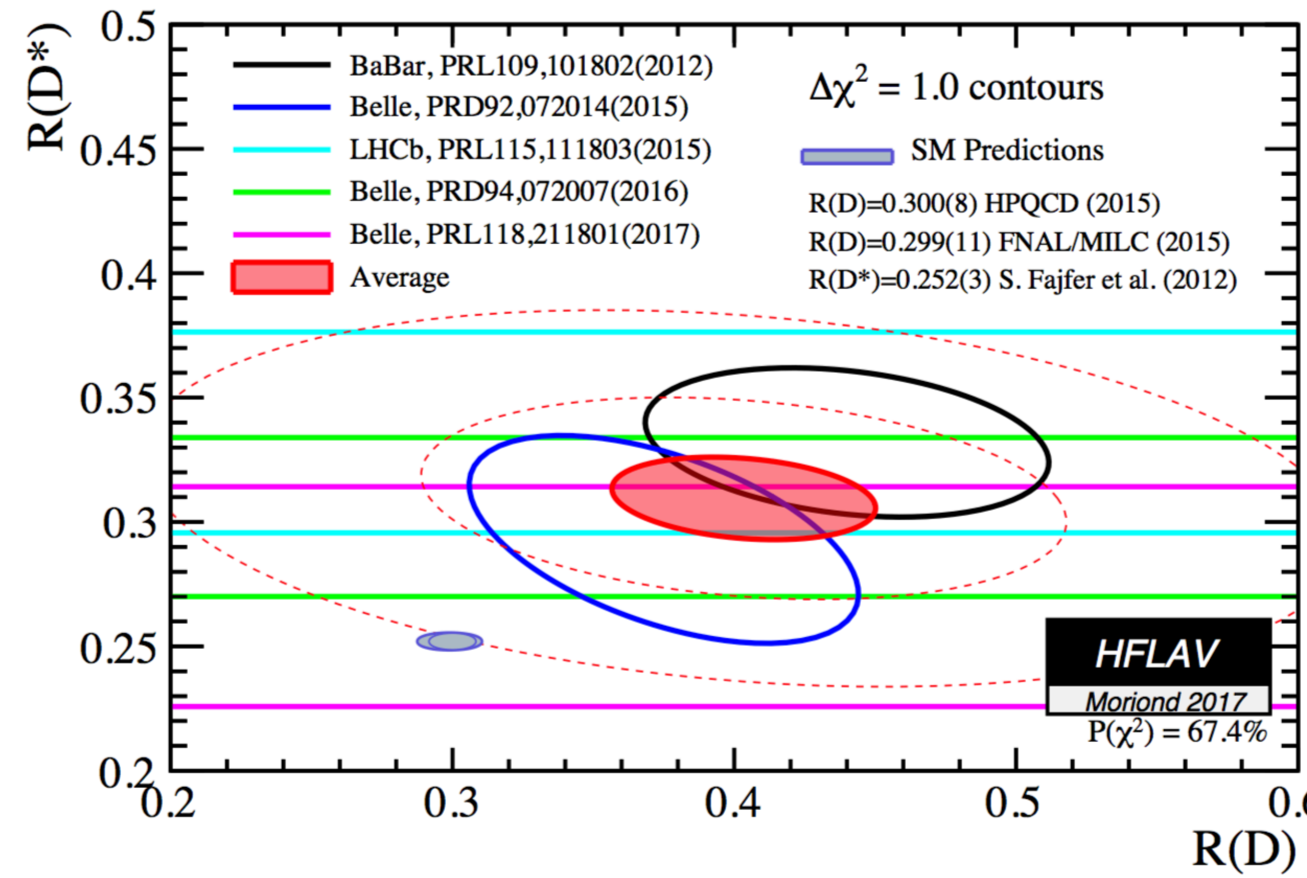
New lattice QCD results for B→Dℓν reveal **~4σ tension with experimental measurements** [HPQCD arXiv:1505.03925, MILC arXiv:1503.07237]

Belle 2 will provide further constraints

Standard Model predication for R(D*) uses experimental data plus HQET: uncertainties may be underestimated [arXiv:1203.2654]

Lattice determinations of $\bar{B} \to D^* \ell \bar{\nu}$ form factors at nonzero recoil (in progress) will provide independent constraints on R(D*) [arXiv:1710.09817]

$$R\left(D^{(*)}\right) = \Gamma\left(B \to D^{(*)}\tau\nu\right) \Big/ \Gamma\left(B \to D^{(*)} l\nu\right)$$



Heavy Flavour Averaging Group [arXiv:1612.07233]

$K^+ \to \pi^+ \nu \bar{\nu}$

$K^+ \to \pi^+ \bar{\nu} \nu$ decay is a rare process sensitive to many new physics scenarios
e.g., Custodial Randall-Sundrum, MSSM, Z, Z' models, Littlest Higgs with T-parity, LFU violation models

- **NA62 Experiment aims to test Standard Model at 10% precision with data to end 2018;**
  first dataset 2016, one event observed
- Short distance contribution to decay amplitude: perturbation theory + semileptonic kaon decay form factors
  Long-distance contribution O(5%) from phenomenological estimates.

2018 Lattice QCD highlight:
Exploratory calculation demonstrated feasibility of decay amplitude calculation, in particular long-distance component [Bai et al., arXiv:1806.11520]
Expectation that a fully controlled calculation will be possible within four years

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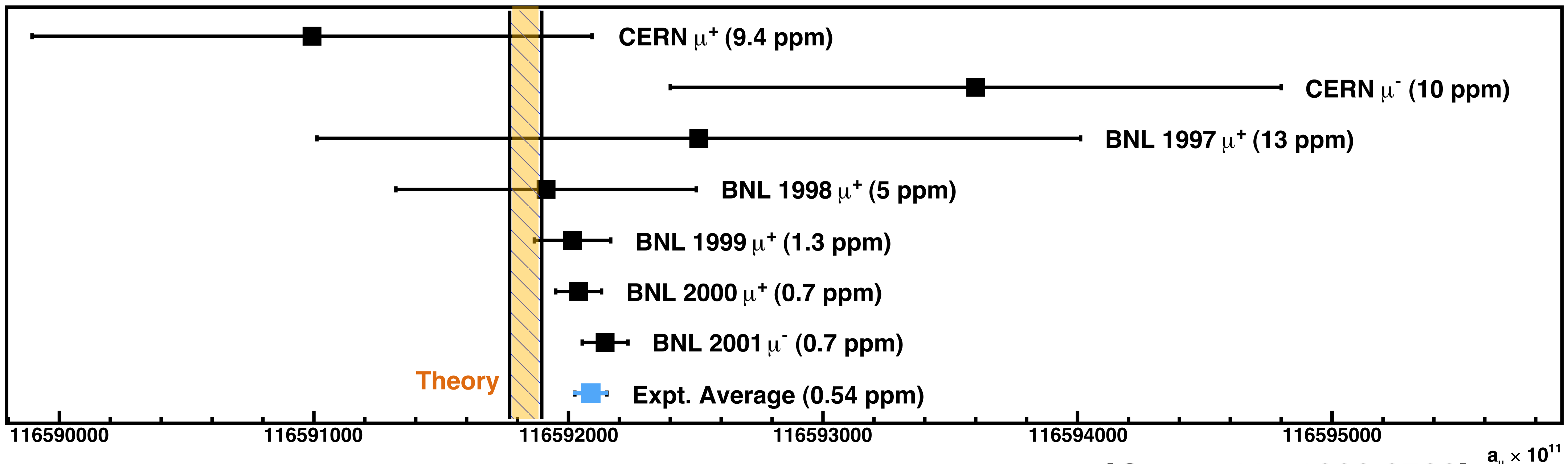
Muon g-2: status and challenges

Long standing discrepancy between measured value and SM estimate for muon anomalous magnetic moment (~3σ)



[Gray, arXiv:1009.0799]

Sign of new physics?

New experiments aiming at 4-fold uncertainty reduction (E989 @ Fermilab, E34 @ JPARC)

➡ if no shift in central values, tension will be ~7σ with projected theory improvements by 2020

Commensurate control of theory needed: **Muon g-2 Theory Initiative formed**
https://indico.fnal.gov/event/13795/

Standard Model muon g-2

Measured value

$$a_\mu^{\mathrm{E821}} = (116\,592\,089 \pm 63) \times 10^{-11}$$

Breakdown of SM contributions (2 evaluations of HVP)

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

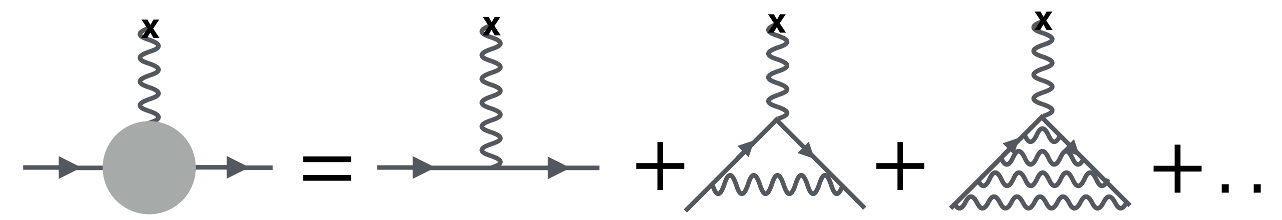
[T. Blum et al., arXiv:1311.2198]

Deviation

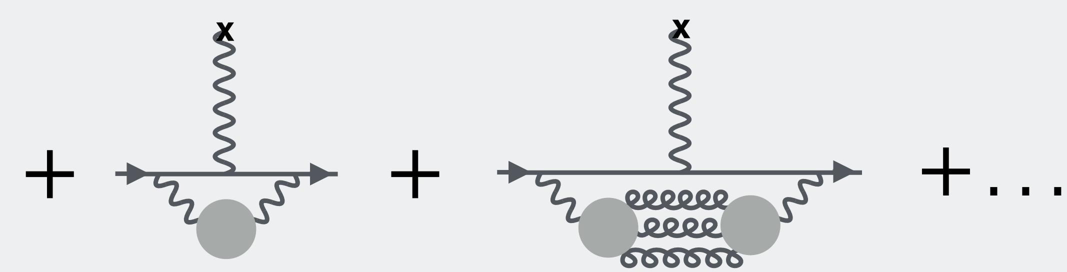
$$\begin{aligned}\Delta a_\mu(\mathrm{E821} - \mathrm{SM}) &= (287 \pm 80) \times 10^{-11}\ [20] \\ &= (261 \pm 78) \times 10^{-11}\ [21]\end{aligned}$$

Dominant uncertainties from hadronic corrections—calculable in lattice QCD

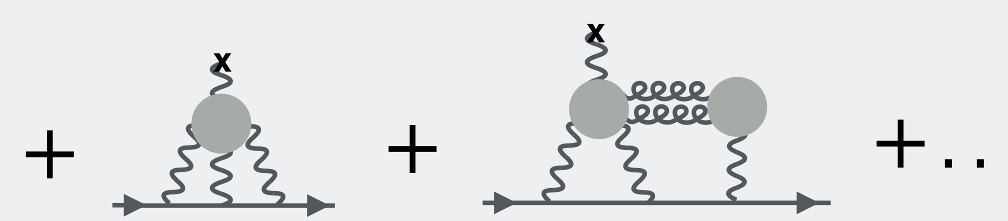
QED (5 loop) [Aoyama et al. 2012]



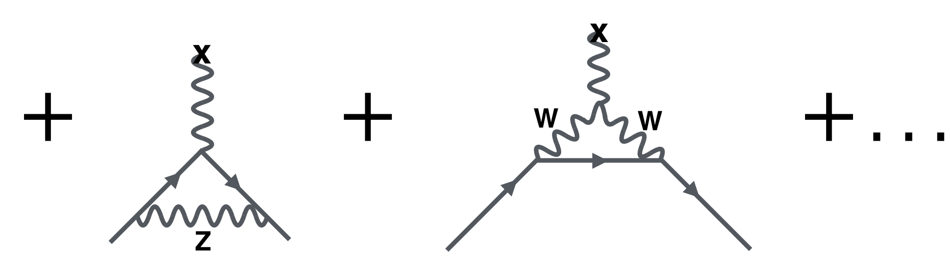
Hadronic vacuum polarisation



Hadronic light-by-light



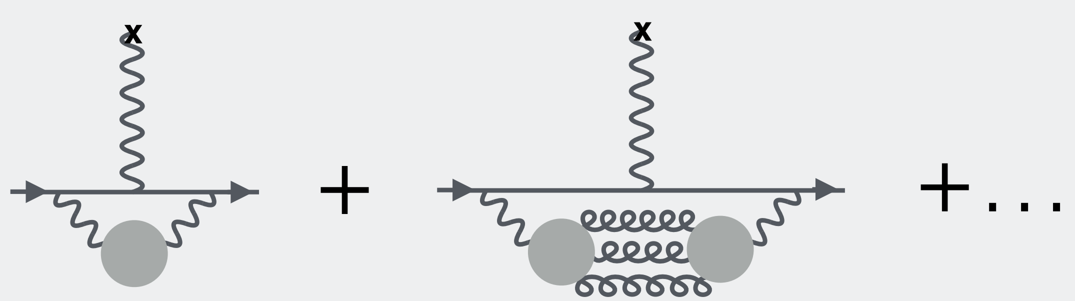
Electroweak (2 loop) [Czarnecki et al. 2006]



Standard Model muon g-2

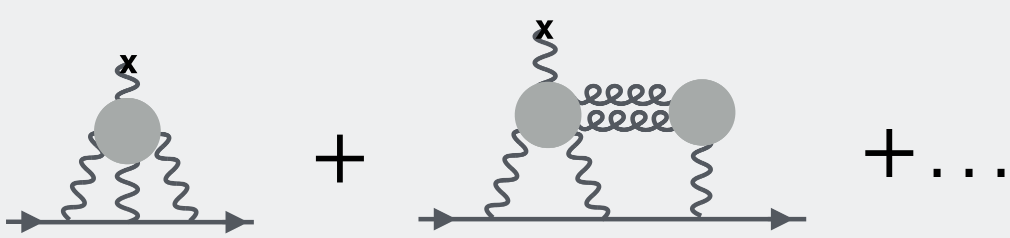
Dominant uncertainties in SM determination from hadronic corrections
Both calculable (in principle) from lattice QCD

Hadronic vacuum polarisation



Dispersion relation plus experimental data on "R-ratio" σ(e+e-→hadrons)

Hadronic light-by-light



Estimated from models including large-N_c, chiPT, vector meson dominance, etc.

2018: First lattice QCD calculation with QED and isospin breaking
[T. Blum et al., arXiv:1801.07224]

Since ICHEP2016: disconnected terms and lattice volume better controlled
[PRL118(2016)022005, PRD96(2017)034515]

Hadronic Vacuum Polarisation

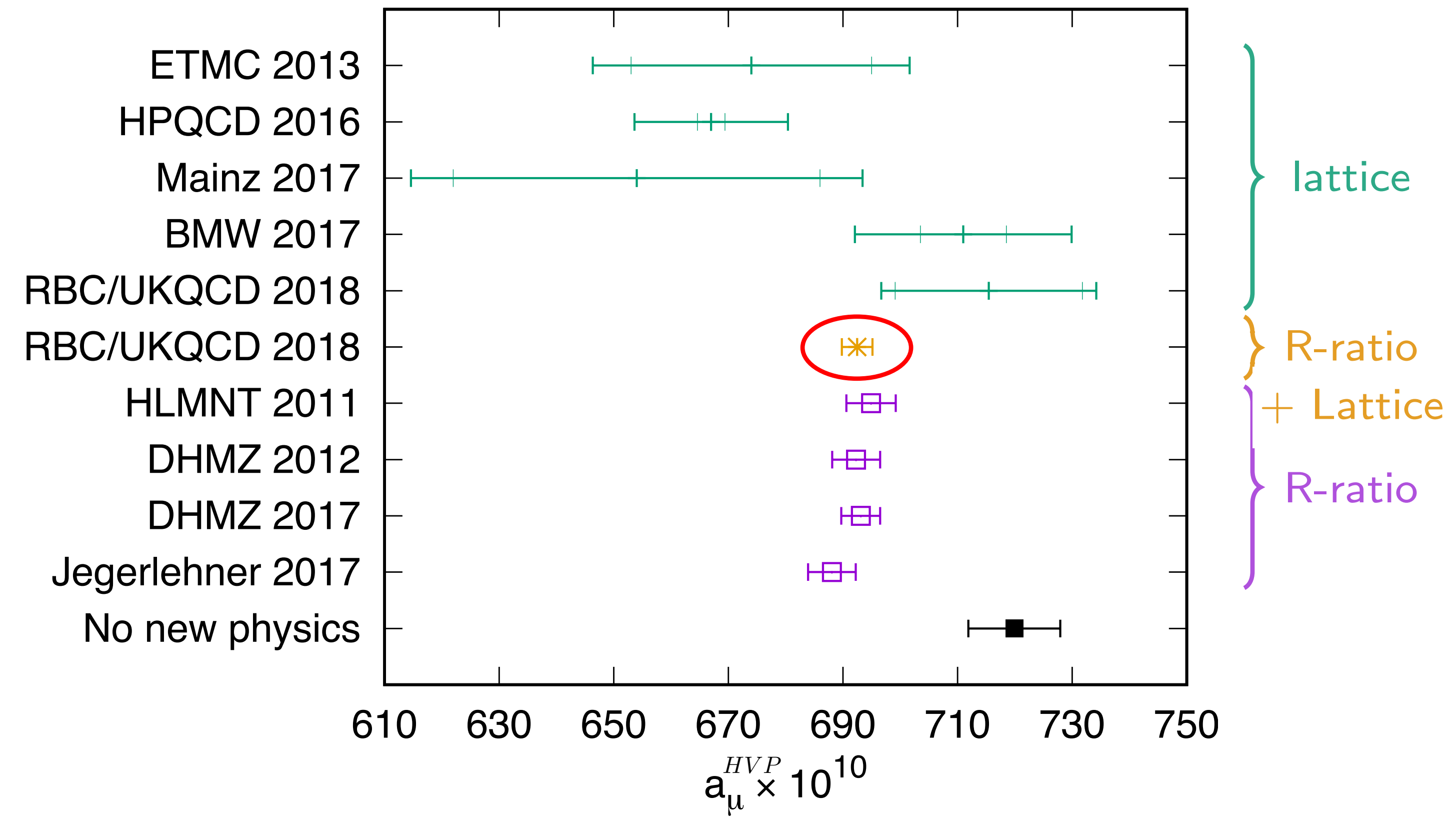
Combining lattice QCD and dispersion relations yields best current determination of HVP contribution
[T. Blum et al., arXiv:1801.07224]

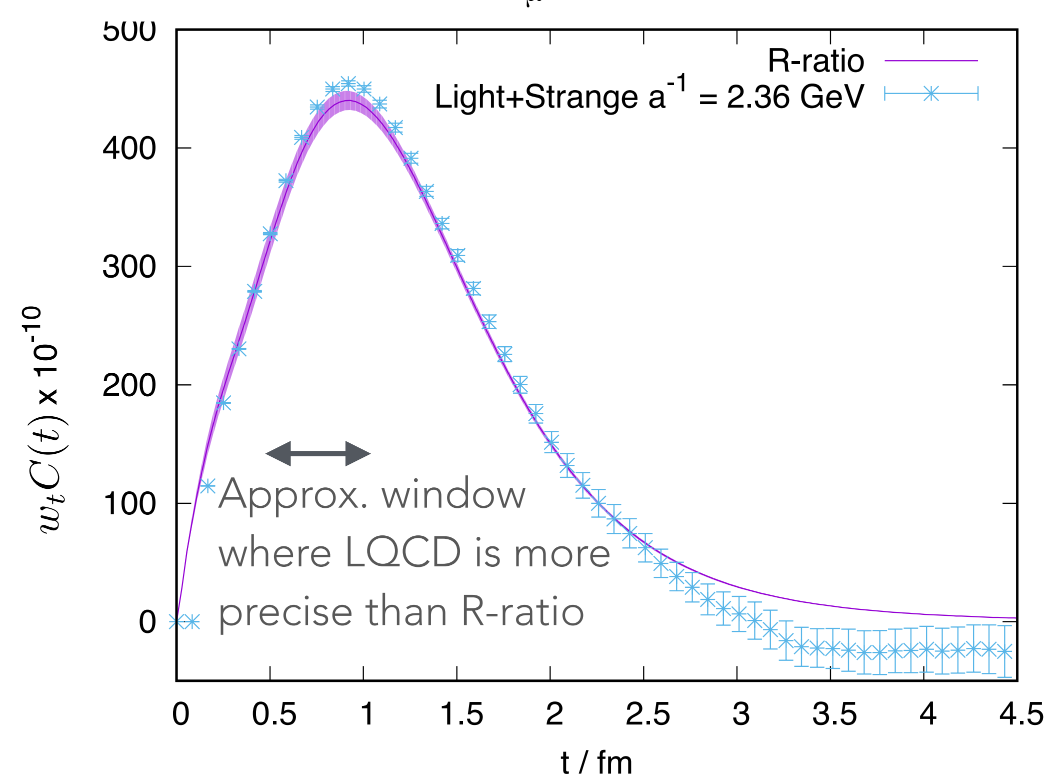
Use "R-ratio" experimental data on σ(e+e-→hadrons) at short and long distances *t*, lattice QCD in intermediate *t* region

$$a_\mu^{HVP} = \sum_t w_t C(t)$$

$$C(t) = \frac{1}{3} \sum_{\vec{x}} \sum_{j=0,1,2} \langle J_j(\vec{x}, t) J_j(0) \rangle$$

Flavour breakdown: light~90%, strange~8% and charm~2%





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Parton distribution functions

Parton distribution functions $f(x,\mu^2)$

Number densities of partons of type f with momentum fraction x at scale μ^2 in a given hadron

PDFs quantify fundamental aspects of hadron structure

Nucleon PDFs are needed for e.g., searches for new physics at the LHC through top-quark and Higgs-boson coupling measurements

Lattice QCD can provide

- Moments of PDFs with controlled uncertainties: $\int_0^1 x^n f(x,\mu^2) = \langle x^n \rangle_f(\mu^2)$

  → Inclusion in global PDF fits can reduce uncertainties
  see workshop slides http://www.physics.ox.ac.uk/confs/PDFlattice2017
  and community white paper [Prog.Part.Nucl.Phys.100 (2018) 107]

- First calculations of x-dependence of nucleon PDFs

Moments of PDFs

Lattice QCD can cleanly access low moments of PDFs (n ≲ 3)

[work to move beyond: Chambers et al., arXiv:1703.01153, Davoudi & Savage, arXiv:1204.4146]

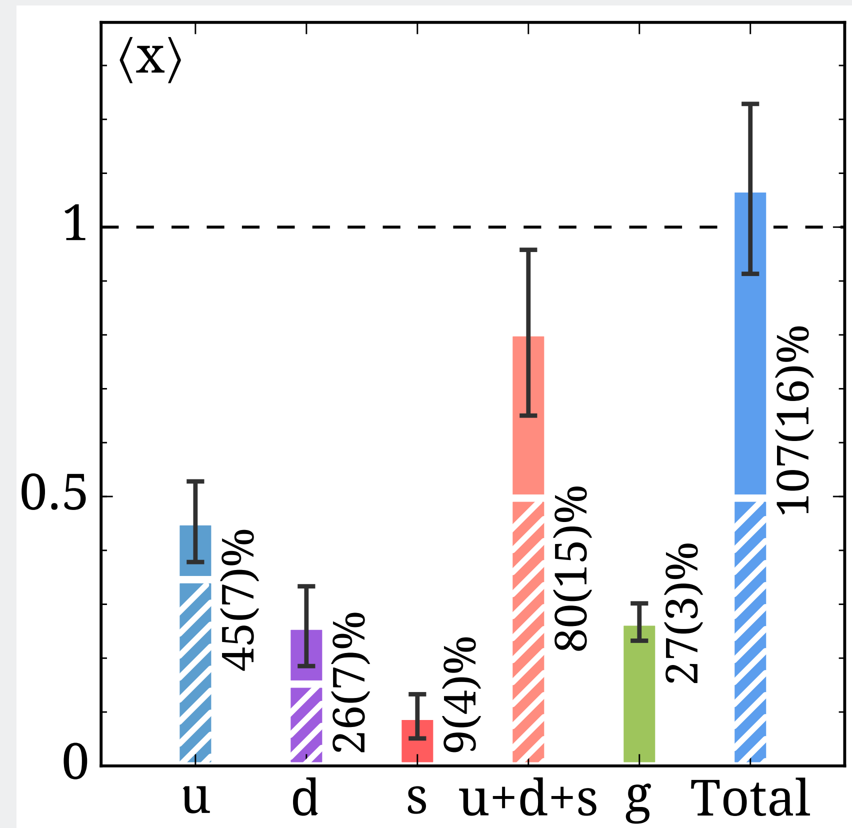
$$\int_0^1 x^n f(x,\mu^2) = \langle x^n \rangle_f(\mu^2)$$

State-of-the-art calculations have:

- Fully-controlled systematic uncertainties competitive with or better than experiment for some quantities
- Separate contributions from
  - Strangeness and light flavours
  - Charge symmetry violation
  - Gluons

2017 Highlight: All terms of nucleon momentum decomposition calculated with controlled uncertainties

$\overline{\text{MS}}$-scheme at 2 GeV

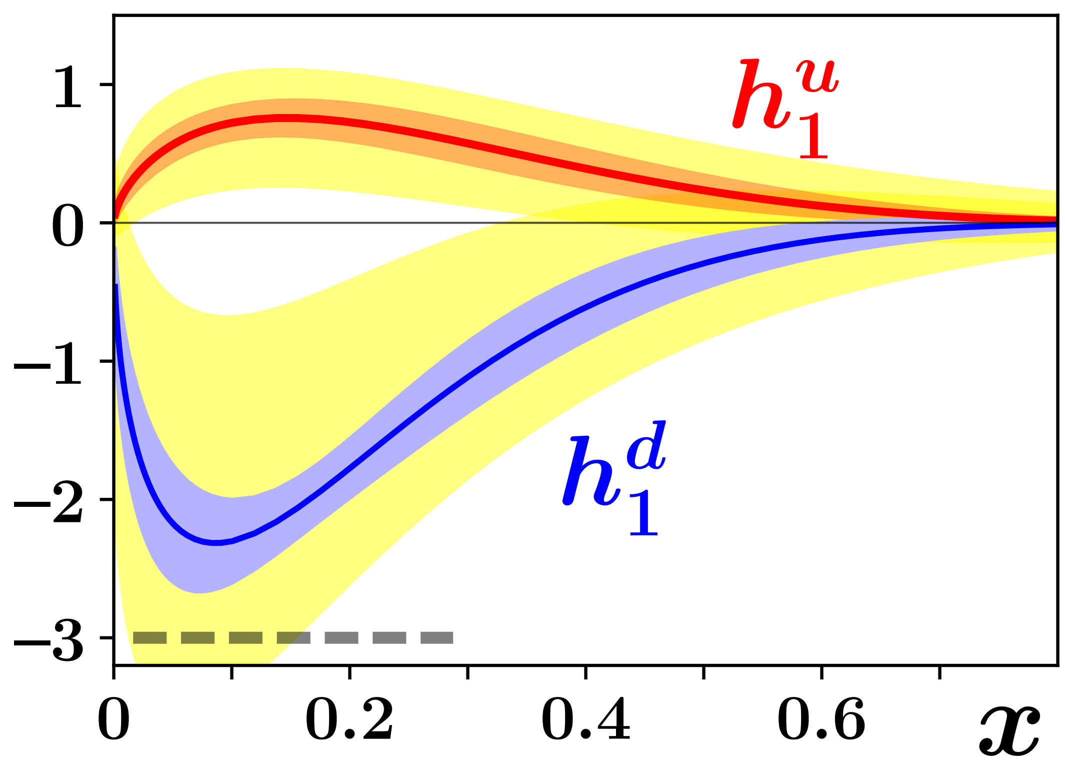


[C. Alexandrou et al., arXiv:1706.02973]

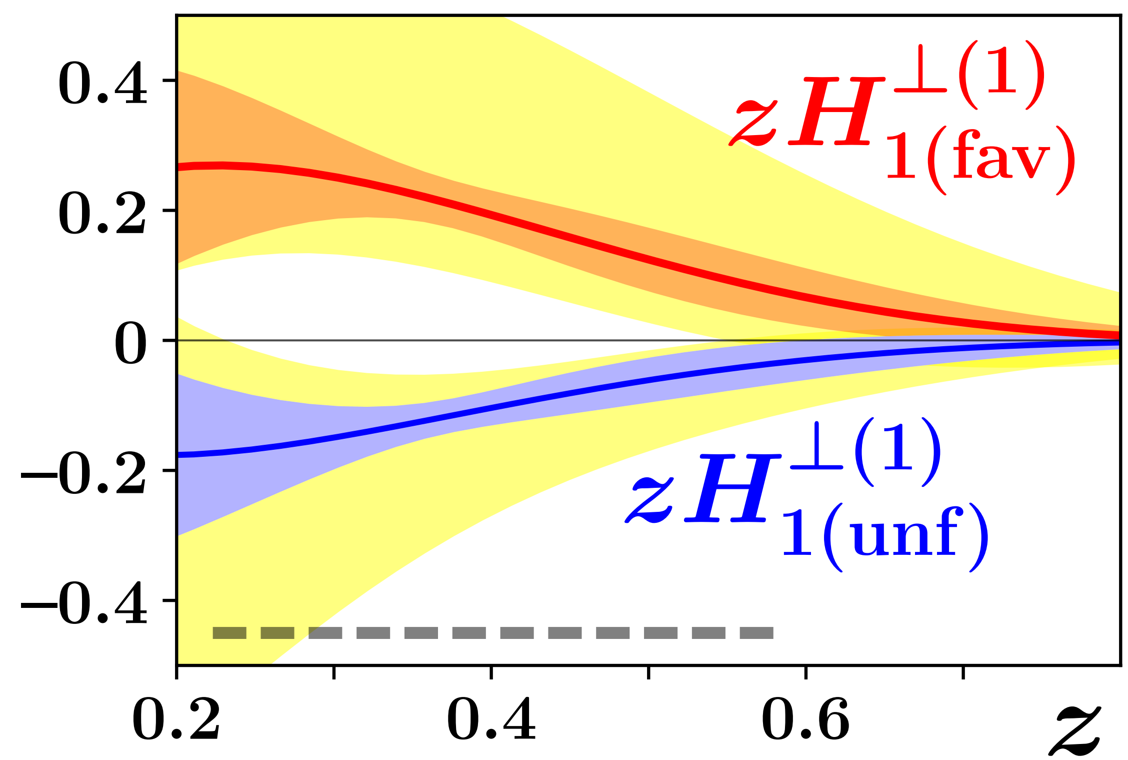
Constraints on global PDF fits

- Including lattice QCD results for moments in global PDF fits can yield significant improvements

Transversity PDFs



Collins fragmentation functions

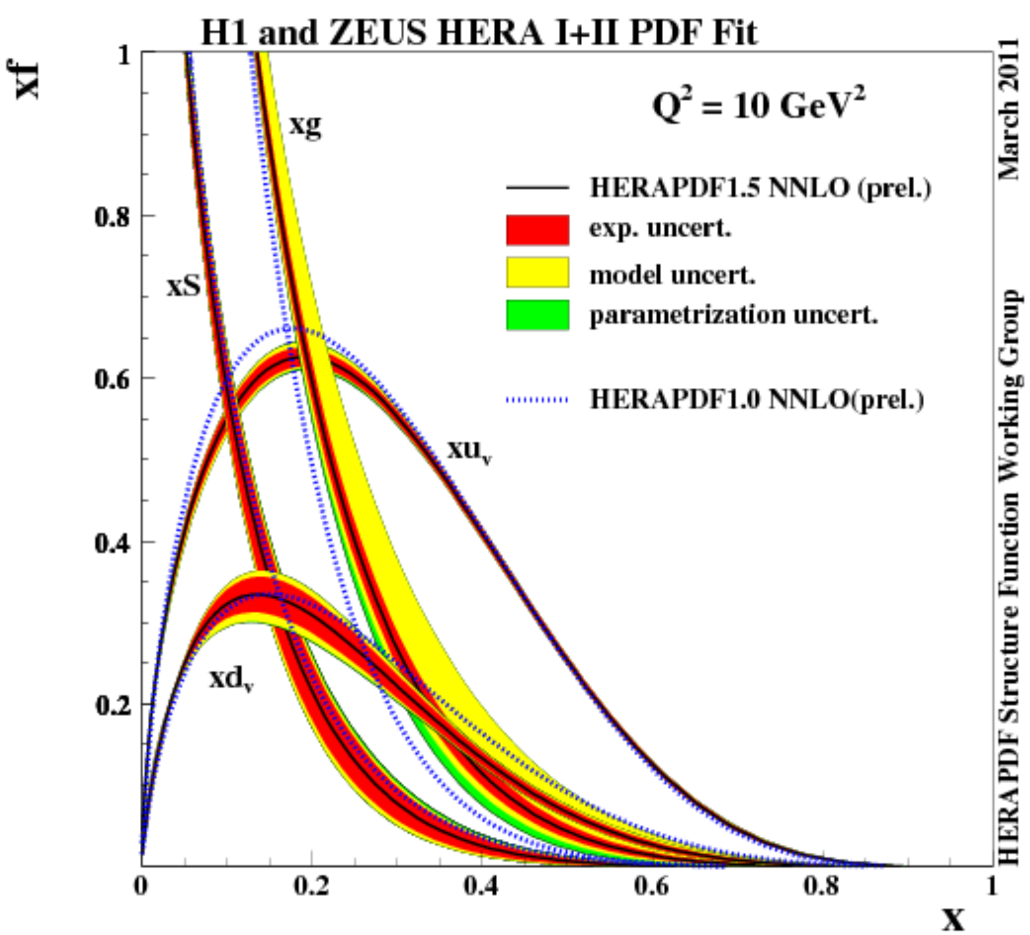


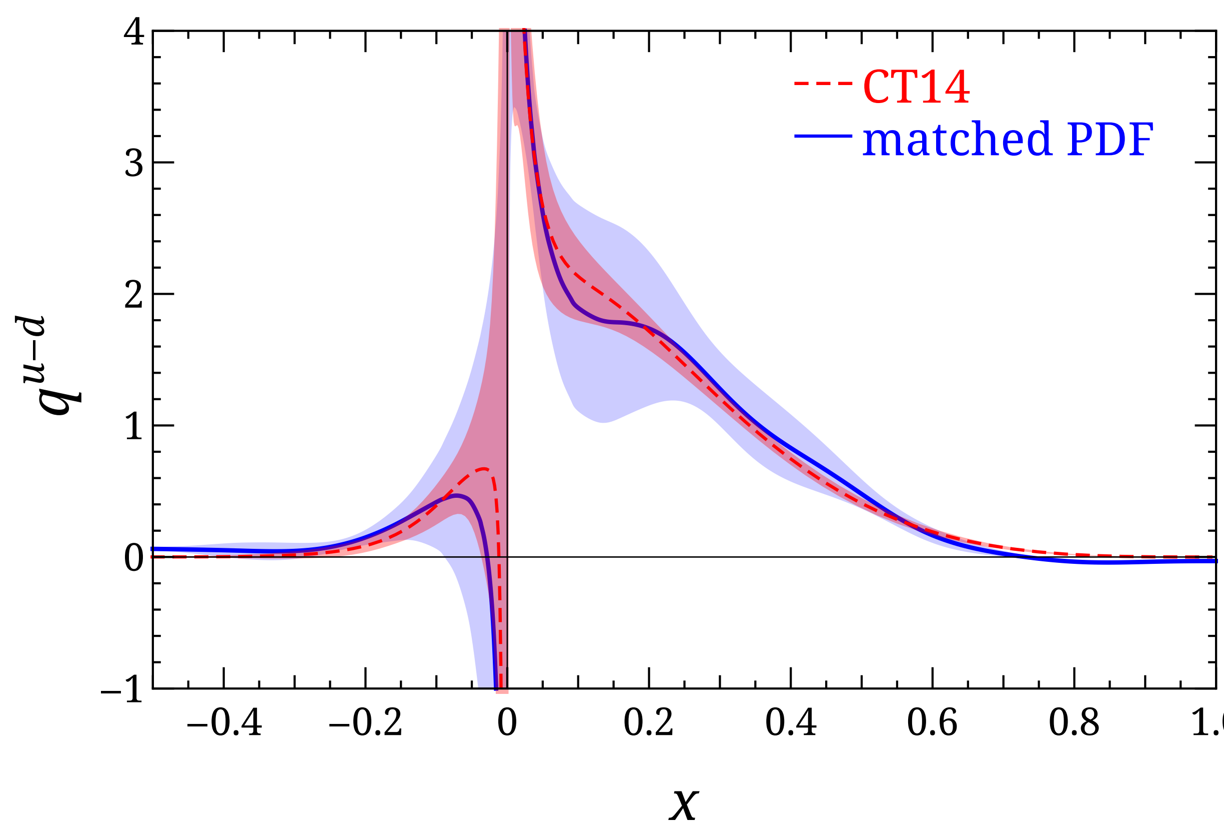
Yellow: SIDIS data only: direct constraints in region indicated by dashes
Blue/Red: SIDIS + lattice QCD for tensor charge (zeroth moment)

[H-W. Lin et al., arXiv:1710.09858]

x-dependence of PDFs

- First calculations of x-dependence of nucleon PDFs undertaken
  Quasi and pseudo-PDF calculations use non-local Euclidean correlators and perturbative QCD matching in high momentum limit [X. Ji, arXiv:1305.1539]
- Extremely rapid progress, but many systematics to be controlled
- Flavour separation is relatively straightforward





[J-W Chen et al., arXiv:1803.04393]

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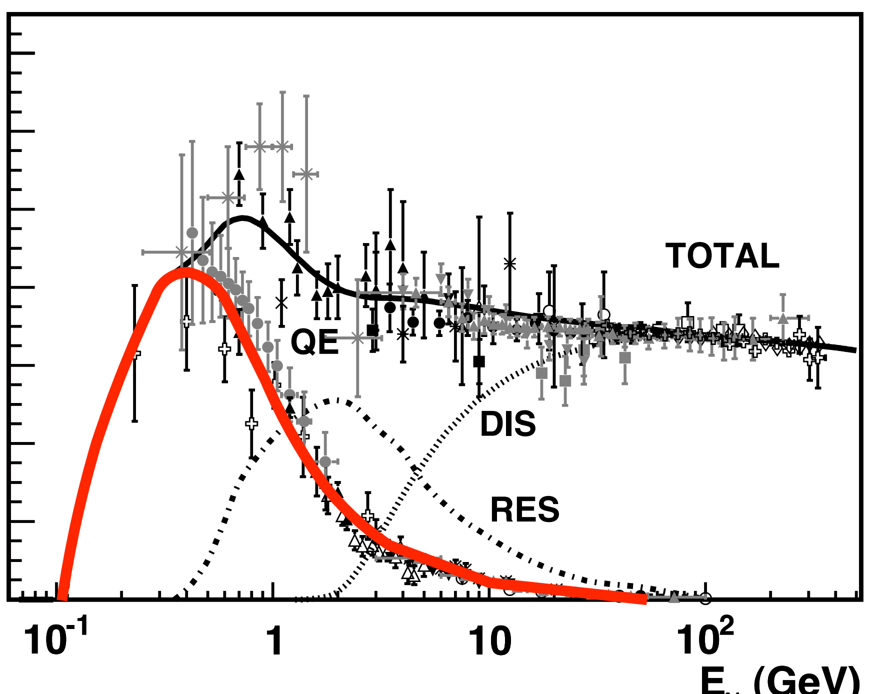
Long-baseline neutrino experiments

Seek to determine neutrino mass hierarchy, mixing parameters, CP violating phase

To differentiate between mixing & CP parameter scenarios → Need neutrino energy reconstruction from final state to better than 100 MeV

ν charged-current cross-section



[J.A. Formaggio, G.P. Zeller, RMP84 (2012) 1307]

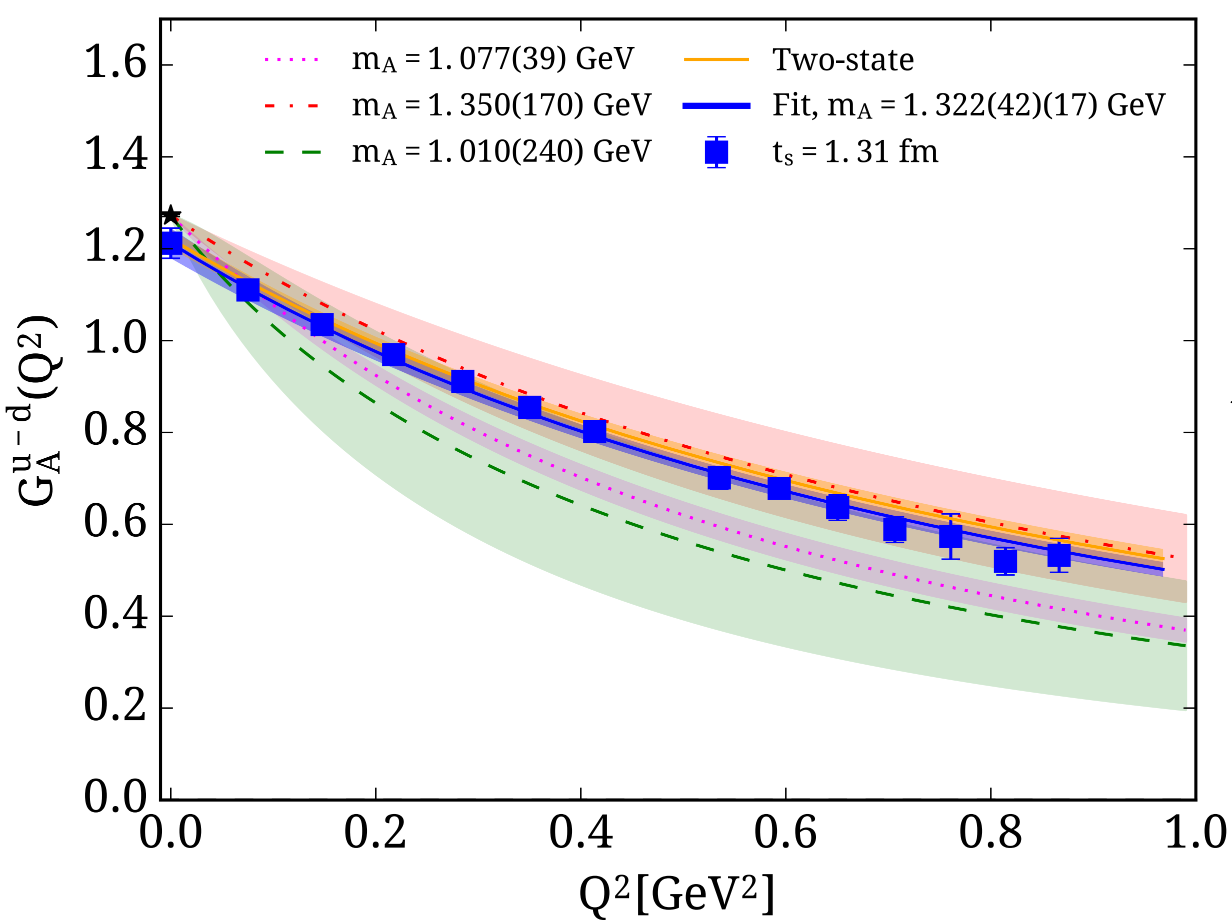
Lattice QCD: direct non-perturbative QCD predictions for nucleon and nuclear matrix elements

e.g., **axial** and **pseudo-scalar form factors** important in quasi-elastic region

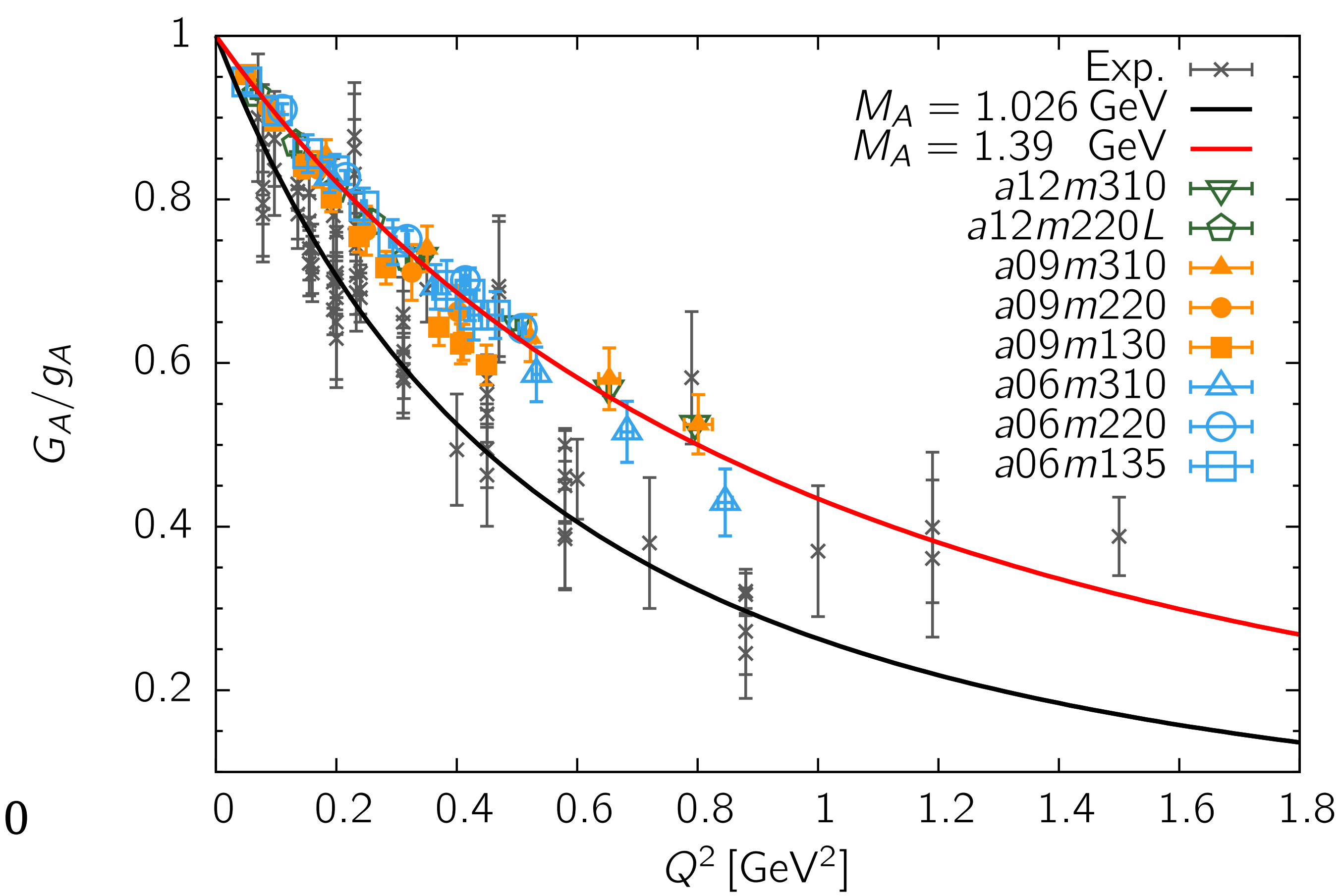
(Lattice QCD can also provide useful input in resonance and DIS regions, see appendix)

Nucleon axial form factors

- Nucleon properties are historically difficult calculations
- Recent calculations of nucleon form factors including axial in agreement with experiment with fully-controlled uncertainties
- Q^2-dependence well-determined in LQCD: competitive with experiment



[Alexandrou et al., PRD96 (2017), 054507]



[Gupta et al., PRD96 (2017), 114503]

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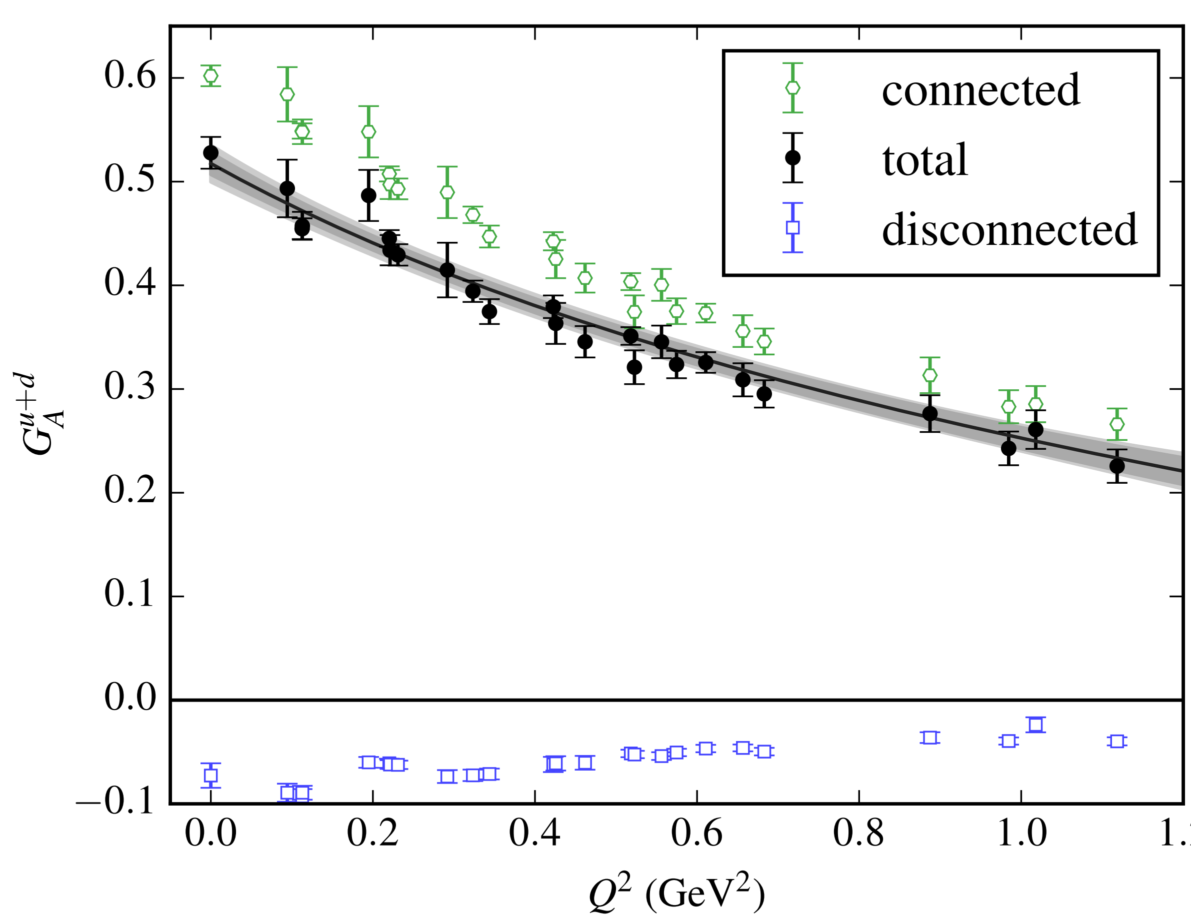


[Green et al., PRD 95, 114502 (2017)]

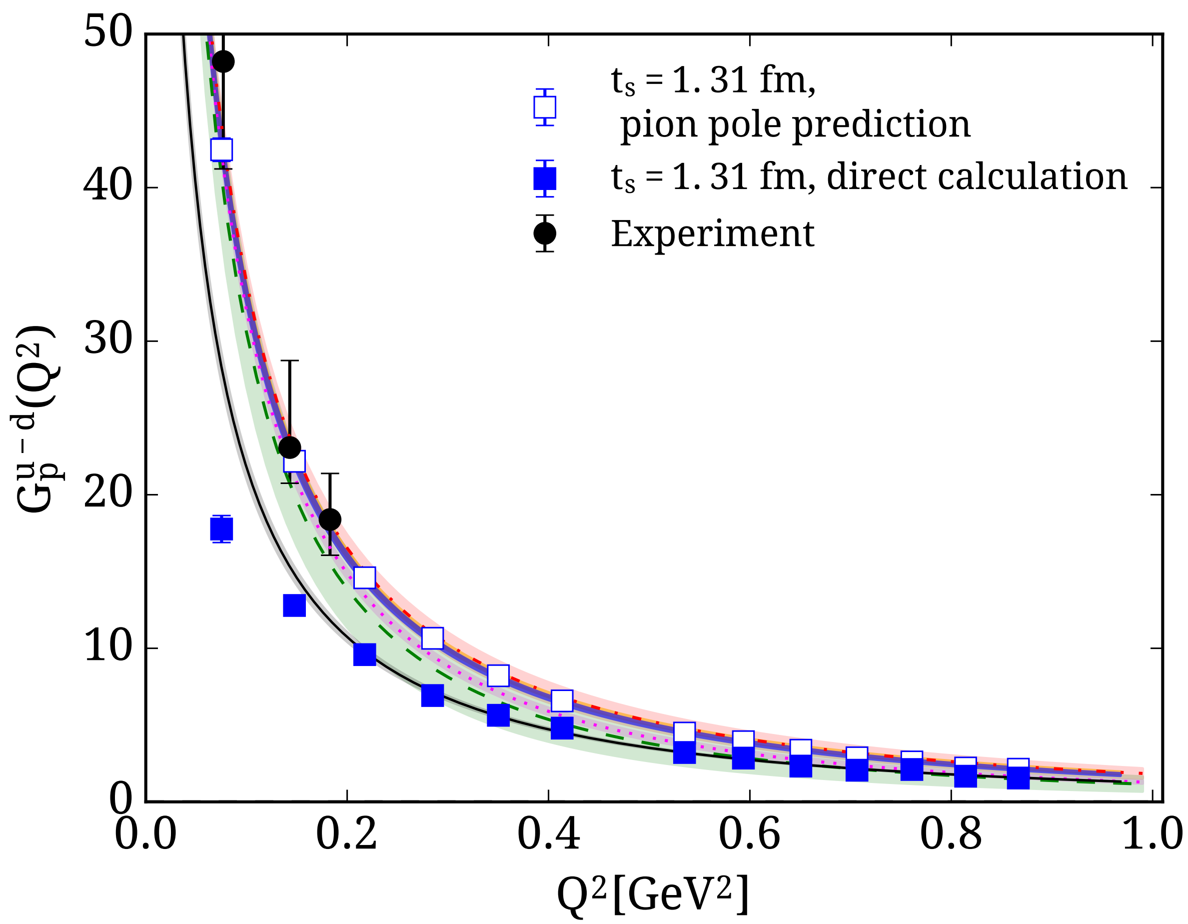
Strange quark contributions are determined separately and can be isolated

[Also Gupta et al., EPJ Web Conf. 175 (2018) 06029, Alexandrou et al., PRD96 (2017), 054507]

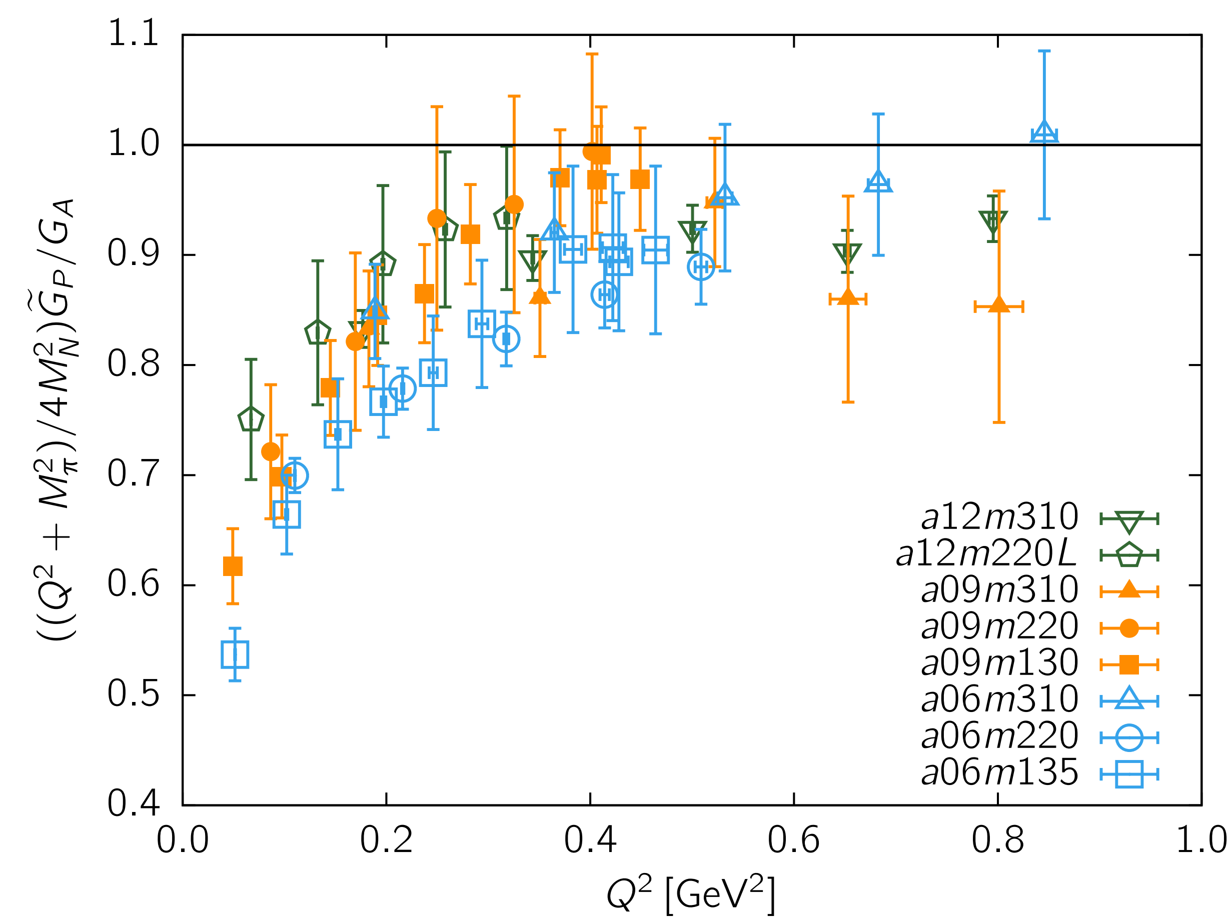
Nucleon pseudo-scalar form factors

- First calculations with controlled uncertainties
- Clear deviations from pion-pole dominants ansatz at low Q^2

$$\tilde{G}_P(Q^2) = G_A(Q^2)\left[\frac{4M_N^2}{Q^2 + M_\pi^2}\right]$$



[Alexandrou et al., PRD96 (2017), 054507]



[Gupta et al., PRD96 (2017), 114503]

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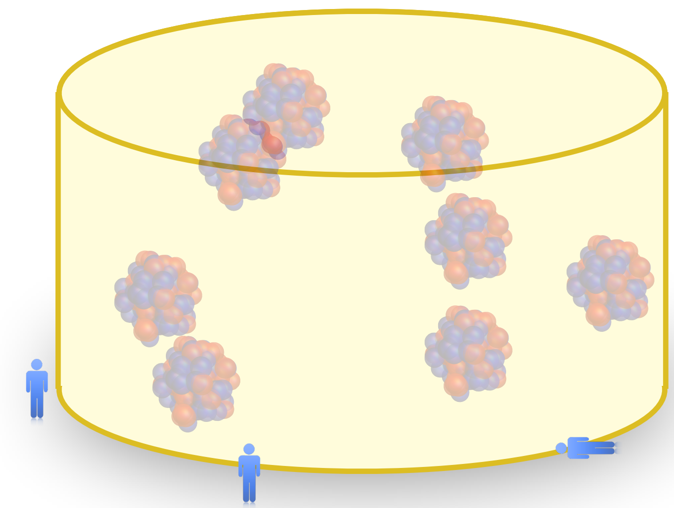
Dark matter direct detection

Look for scattering of WIMP dark matter on nuclear target

Detection rate depends on

- Dark matter properties
- Probability of interaction with nucleus
  i.e., *nuclear* effects are important



Low-energy limit of a generic spin-independent interaction is scalar → Determine **nucleon and nuclear scalar matrix elements** from lattice QCD

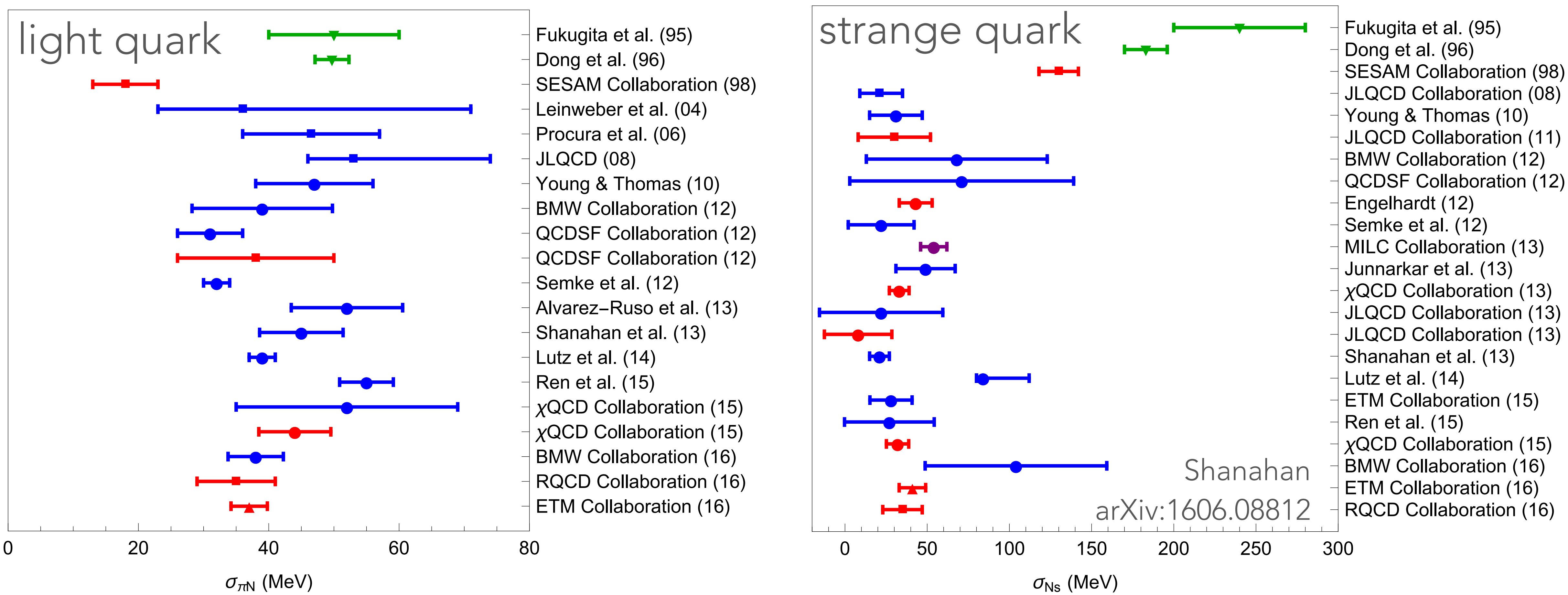
Other e.g., spin-dependent couplings can also be constrained

e.g., [Hoferichter et al., arXiv:1503.04811], [Hill et al., arXiv:1409.8290], [Fitzpatrick et al., arXiv:1203.3542]

Dark matter direct detection

Spin-independent scattering of many WIMP candidates governed by scalar matrix elements

Lattice QCD nucleon scalar matrix elements



Light quark: competitive with phenomenology

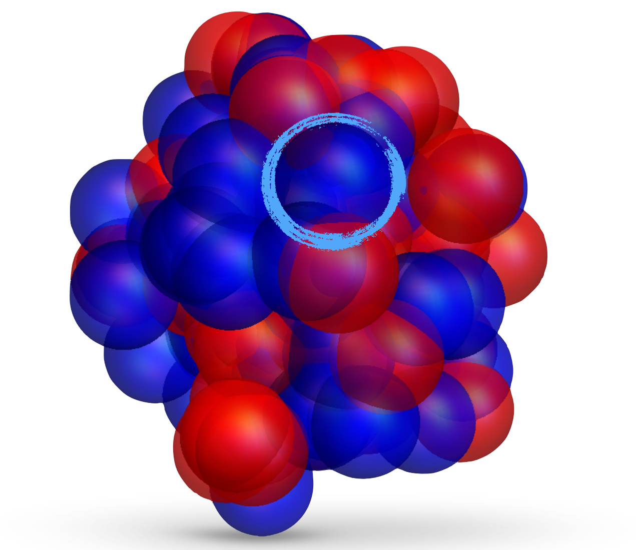
Note: tension with extraction using Roy–Steiner equations [Hoferichter arXiv:1506.04142]

Strange quark: much more precise than phenomenology

Dark matter direct detection

Direct detection experiments use nuclear targets e.g., Xenon

Determine interaction cross-section (with nucleus) for a given dark matter model

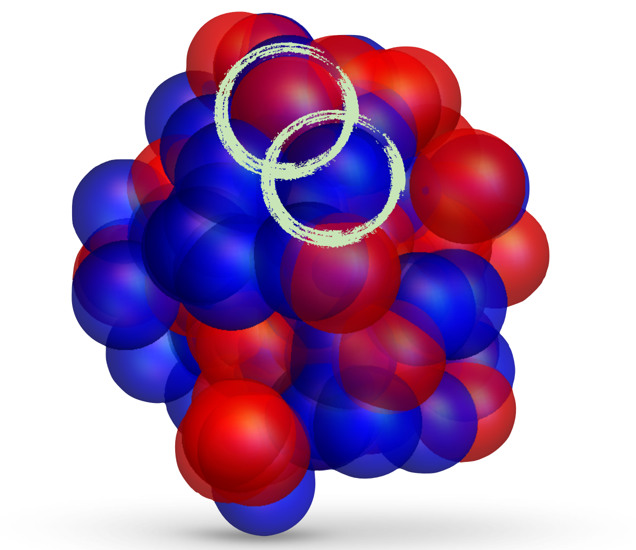


- Born approximation – interacts with a single nucleon

$$\sigma \sim |A \langle N|DM|N\rangle|^2$$

known from LQCD

- Interacts non-trivially with multiple nucleons



$$\sigma \sim |A \langle N|DM|N\rangle + \alpha \langle NN|DM|NN\rangle + \ldots|^2$$

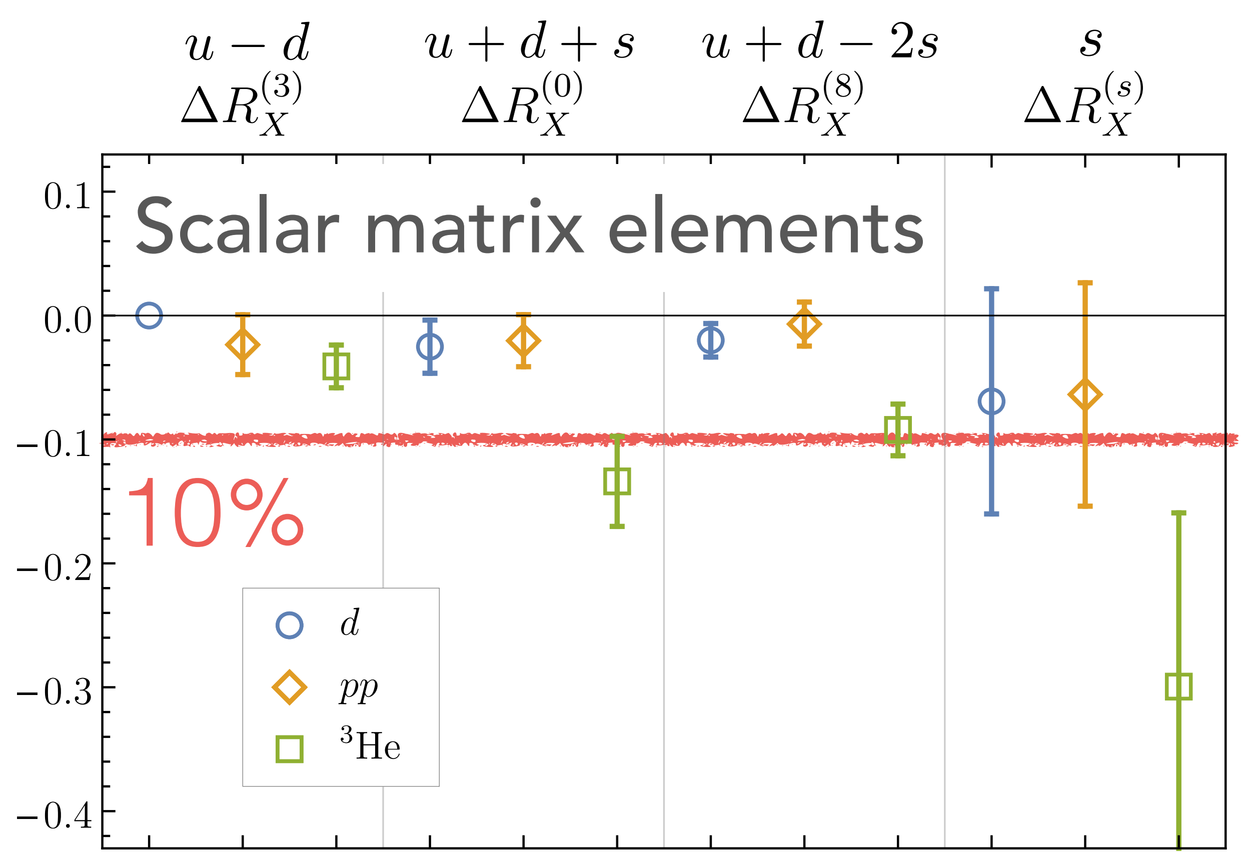
poorly known!

Second term may be significant!

Dark matter direct detection

Spin-independent scattering of WIMP candidates is governed by scalar matrix elements

- Lattice QCD calculation with m_π~800 MeV shows 10% nuclear effects in ^{3}He ➡ potentially very significant effects in e.g., Xenon
- Same calculation gives axial and tensor nuclear effects around ~1%



[NPLQCD PRL120 (2018), 152002]

$$\frac{\text{ME}}{\text{A(Nucleon ME)}} - 1$$

Older work: [NPLQCD PRD89 (2014) 074505]

Summary and outlook

Lattice QCD (+QED) is providing essential Standard Model input for high-energy physics experiments

- **Precision lattice QCD results for simple systems including hadrons**
  - ➡ FLAG lattice averaging to include hadron structure in 2019
  - ➡ Many more quantities will have fully-controlled systematic uncertainties by 2020
- **Beginning of reliable lattice QCD results for nuclear matrix elements**

Summary and outlook

Lattice QCD (+QED) is providing essential Standard Model input for high-energy physics experiments

… and also for many other topics not covered here

- Hadron spectroscopy
- Finite temperature and density
- Nuclear structure and reactions
- BSM physics (Technicolour theories, SUSY, …)

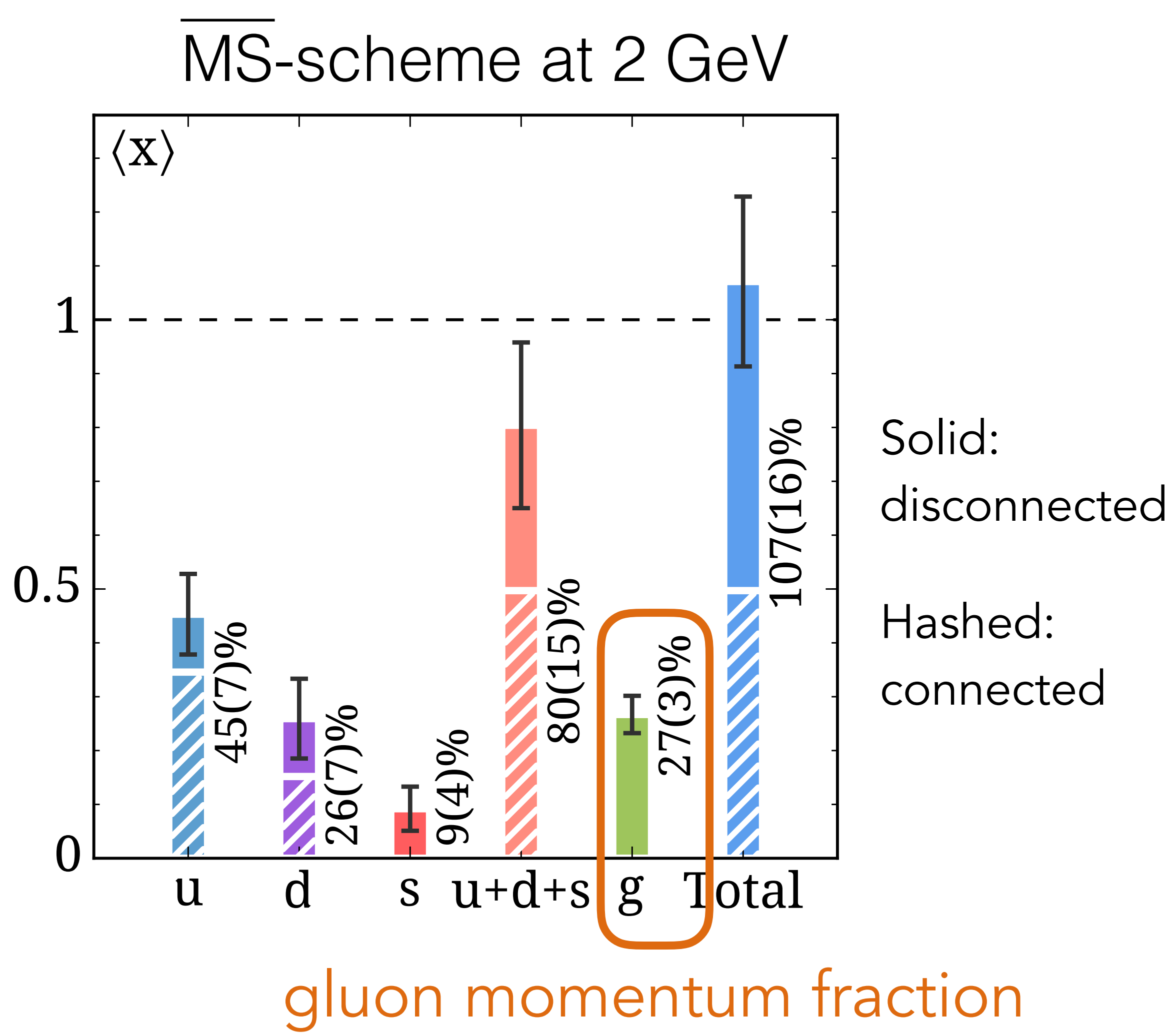
New results will be presented at Lattice conference July 22-28: see conference website and proceedings

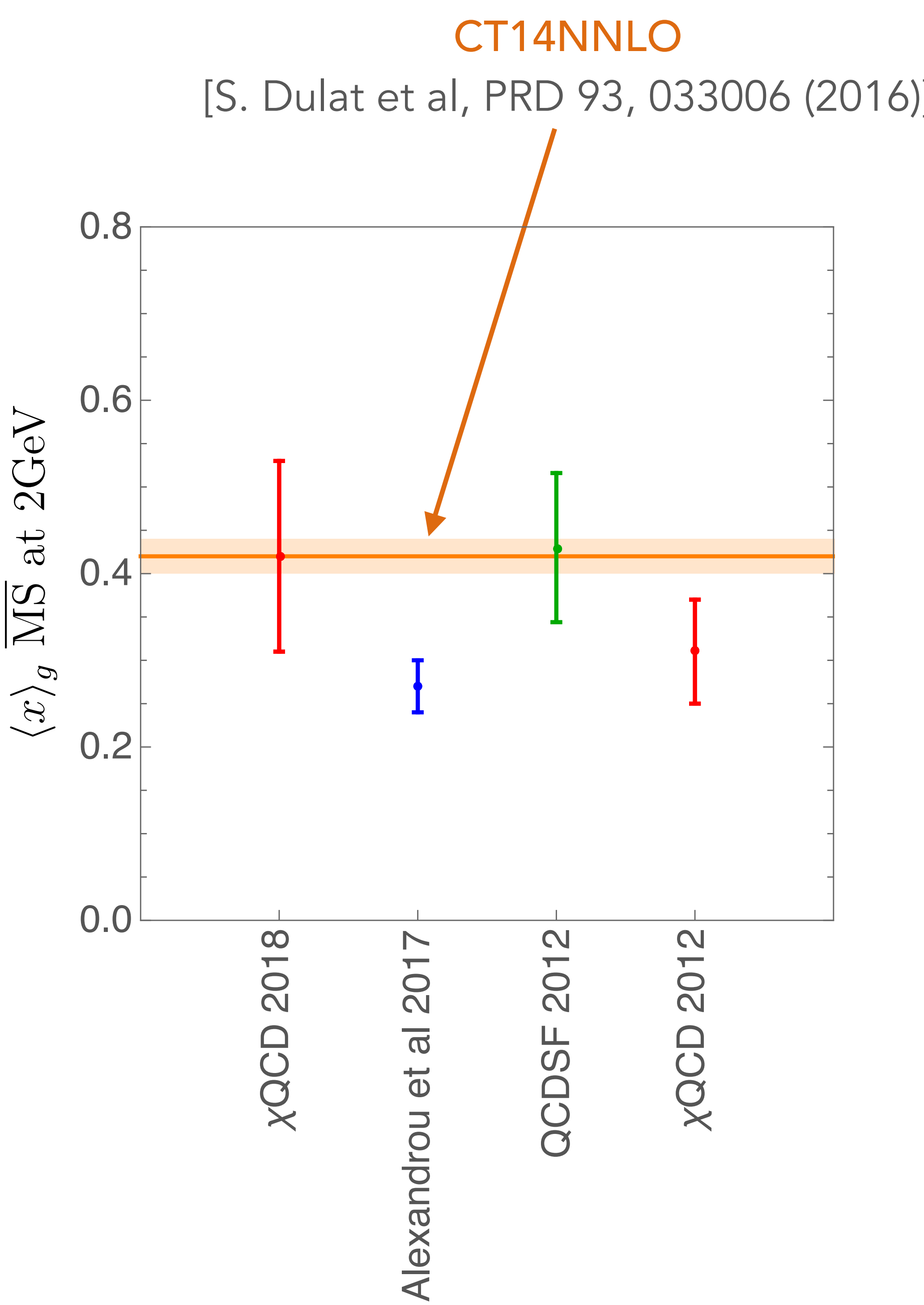
East Lansing, MI, USA

https://web.pa.msu.edu/conf/Lattice2018/

Nucleon gluon momentum fraction

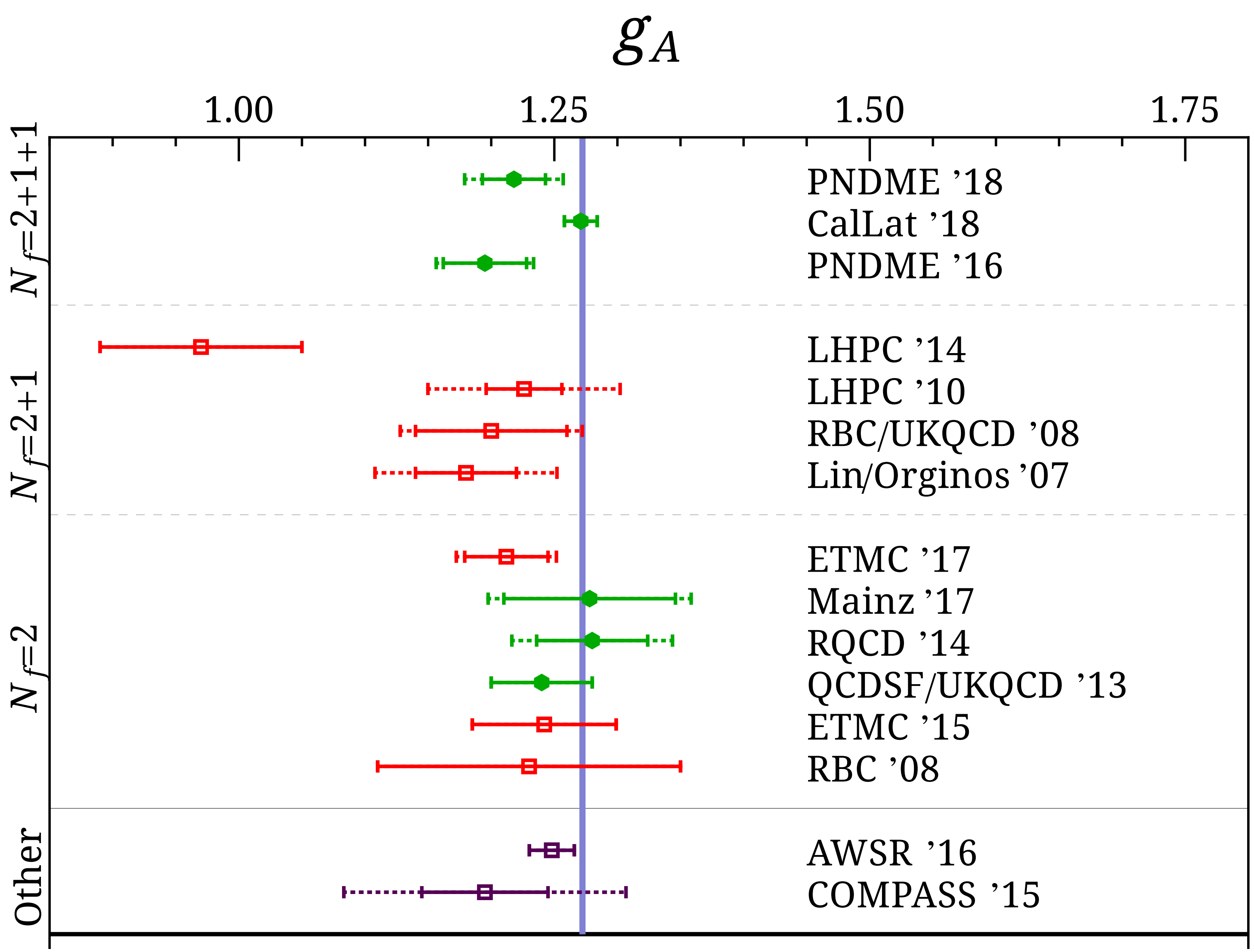
Two direct calculations at the physical point since last year
[C. Alexandrou et al., arXiv:1706.02973]
[Y-B. Yang et al., (χQCD) arXiv:1805.00531]





Nucleon axial charge

Complete calculations with controlled uncertainties from multiple collaborations in 2018



Blue vertical line:

$$g_A = 1.2671$$

determined with high precision from nuclear beta decay

[Gupta et al, arXiv:1806.09006]

Nucleon axial form factor

Traditionally assumed to have dipole form

$$G_A(Q^2) = \frac{g_A}{\left(1 + Q^2 / M_A^2\right)}$$

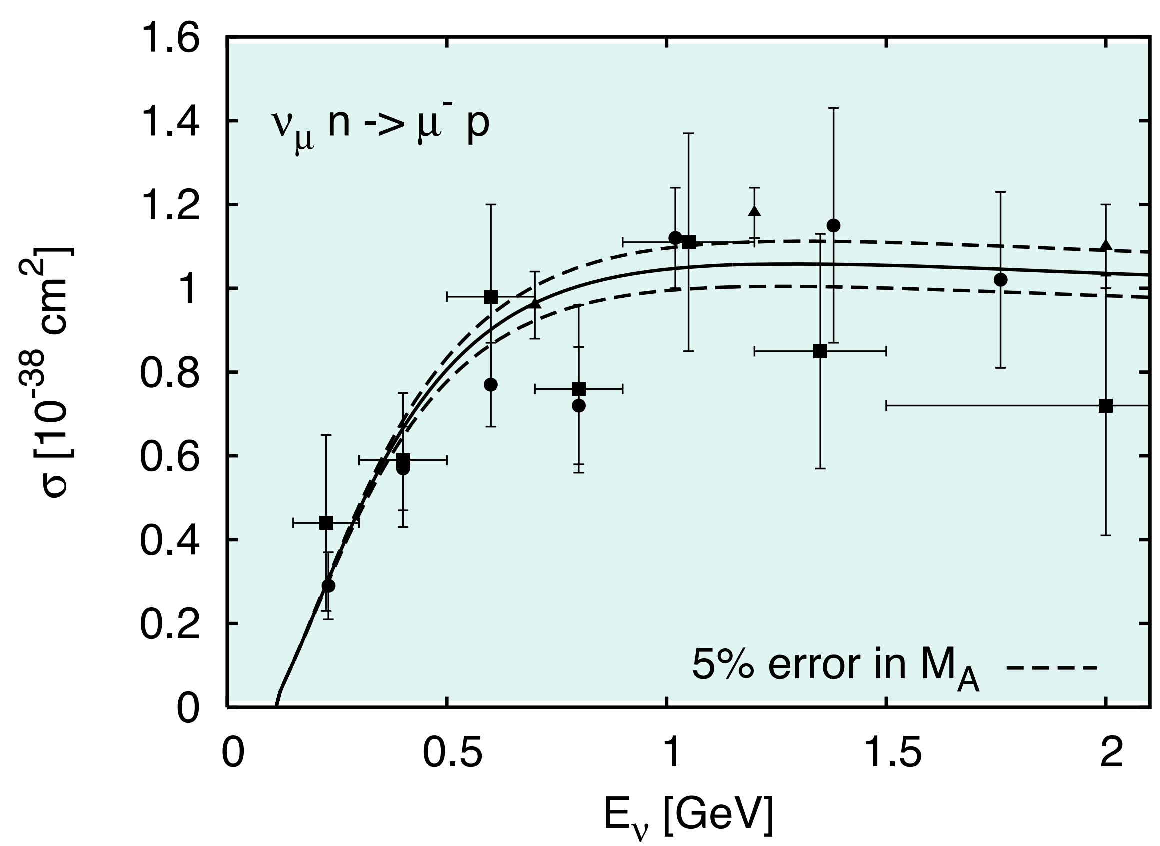
Axial charge determined with high precision from nuclear beta decay

Axial mass must be fit to data

Electromagnetic form factors show significant deviation from dipole parametrisation

→ **Model-indep. z-expansion commonly used to fit experimental or lattice QCD data** [Hill & Paz (2010), Bhattacharya (2011)]

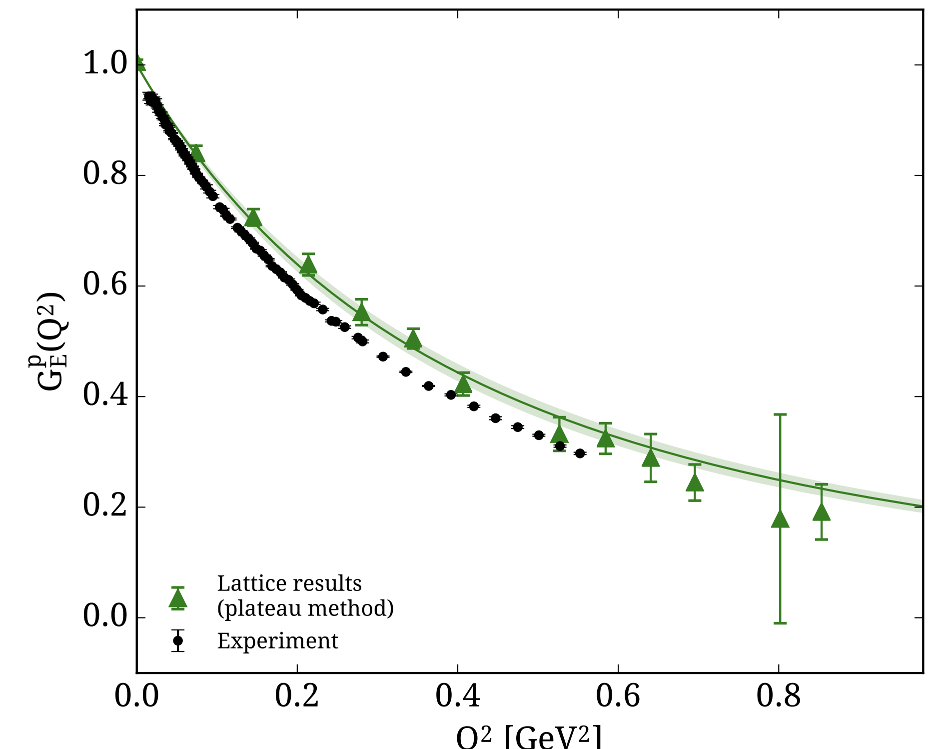
Total QE cross-section sensitive to the axial mass:

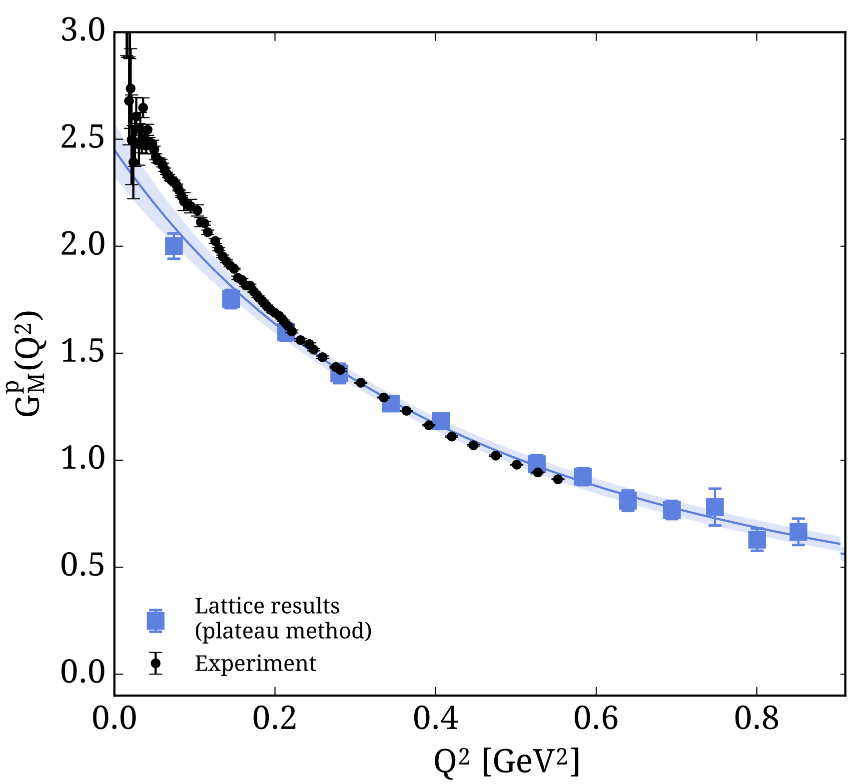


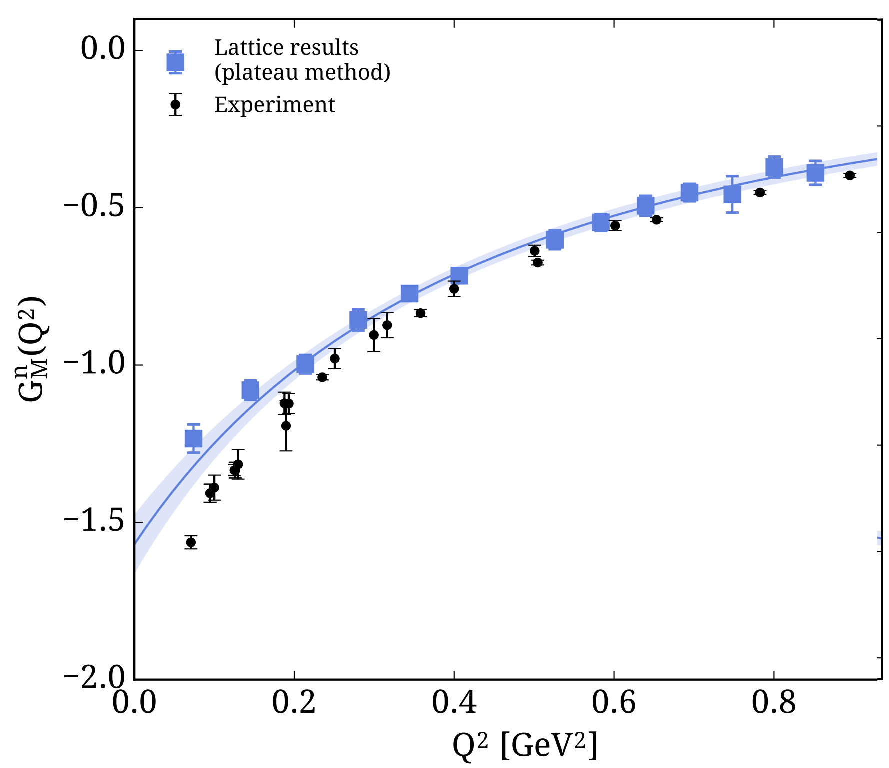
[Mosel, Ann. Rev. Nucl. Part. Sci. 66, 171 (2016)]

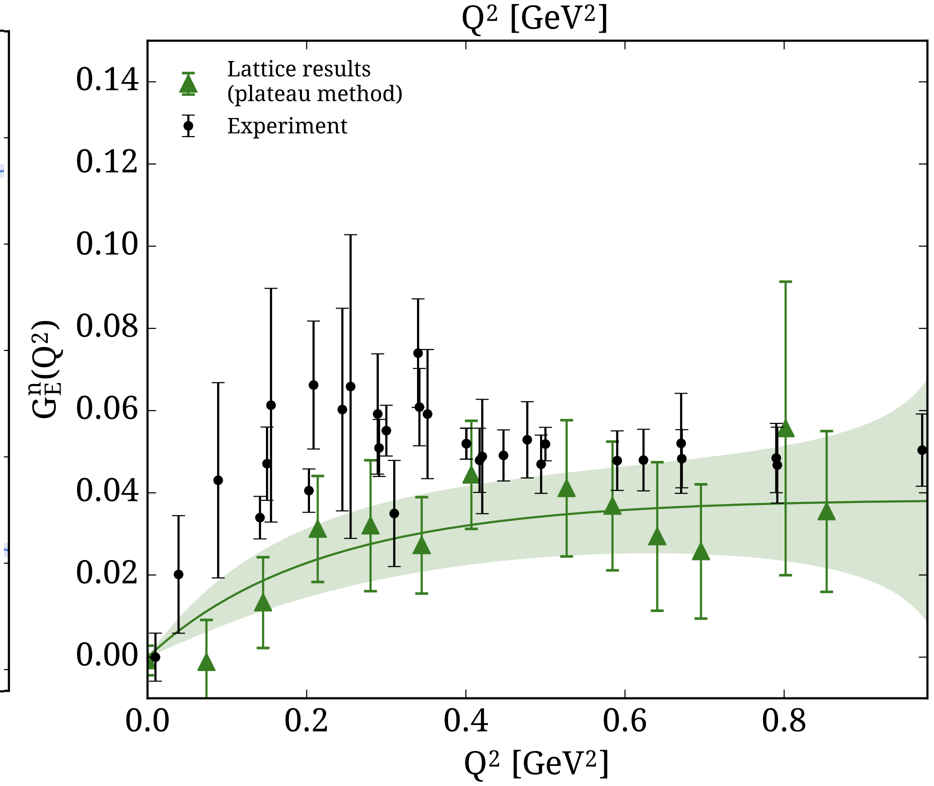
Nucleon electromagnetic form factors

State-of-the-art calculations have physical quark masses, large lattice volumes, and fine lattice spacings, but systematic uncertainties not yet controlled at a level comparable to flavour physics quantities









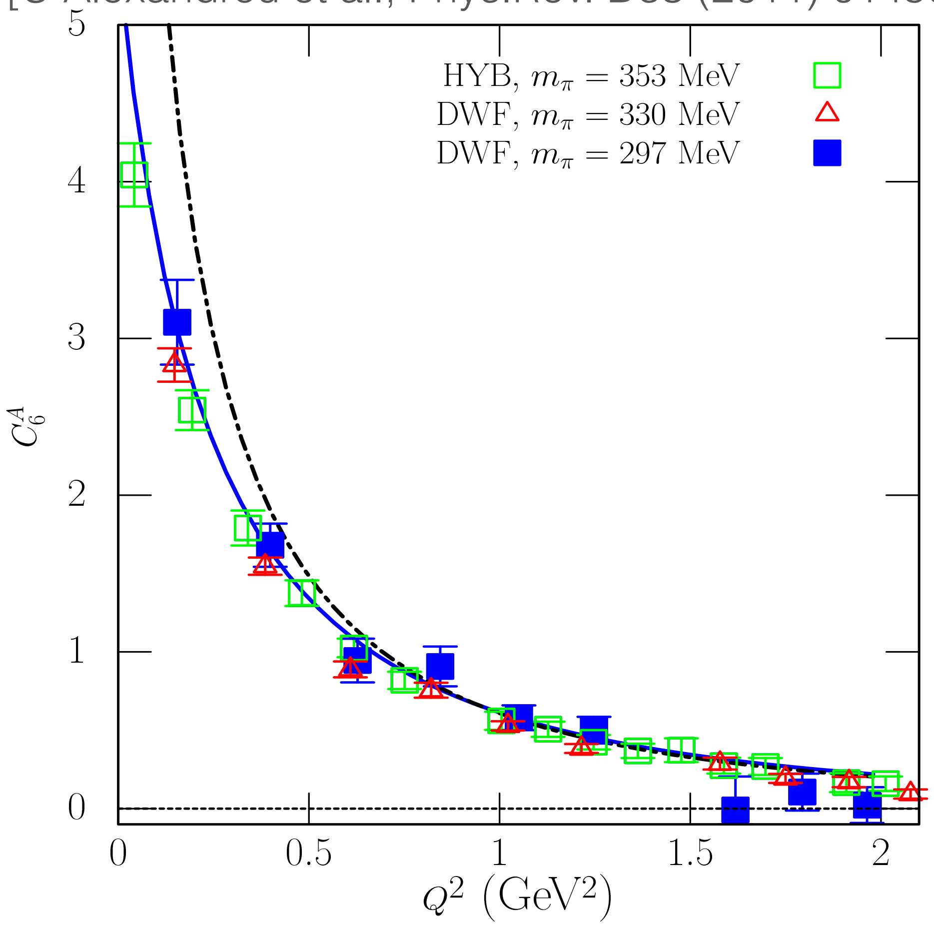
[Alexandrou et al., arXiv:1706.00469]

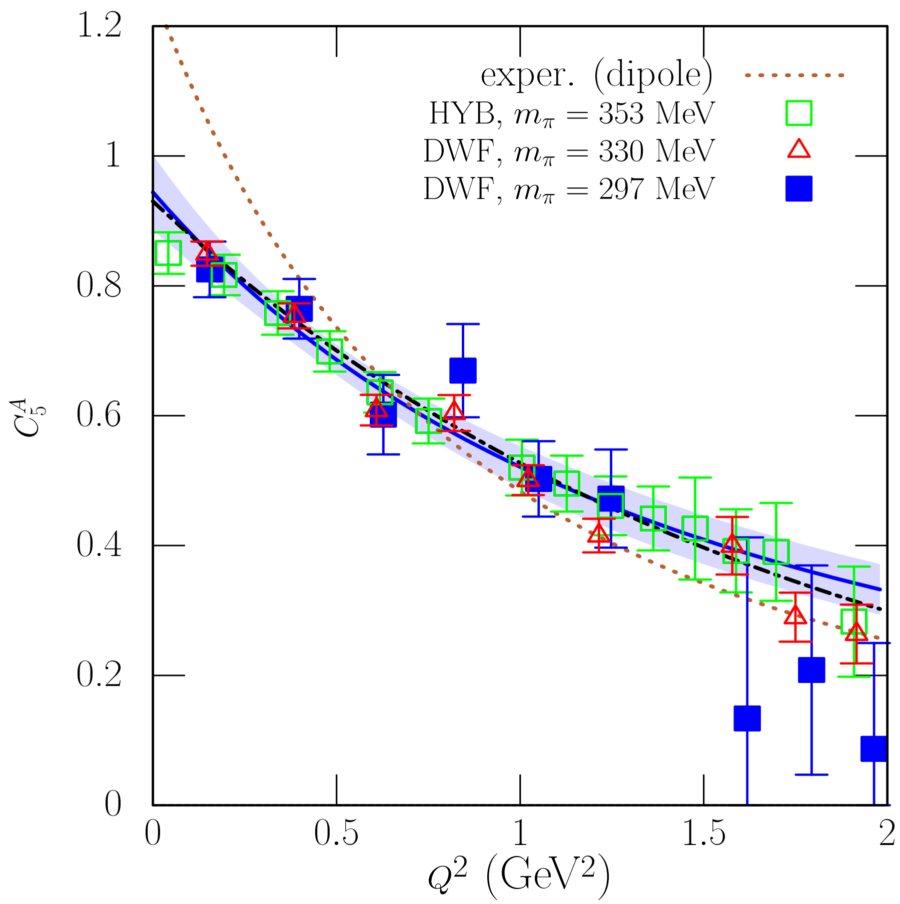
Transition form factors

Lattice QCD calculation of axial N Δ transition form factor:

$$\langle \Delta(p',s')|A^3_\mu|N(p,s)\rangle = i\sqrt{\frac{2}{3}}\left(\frac{m_\Delta m_N}{E_\Delta(\mathbf{p}')E_N(\mathbf{p})}\right)^{1/2} \bar{u}^\lambda_{\Delta^+}(p',s') \left[\left(\frac{C_3^A(q^2)}{m_N}\gamma^\nu + \frac{C_4^A(q^2)}{m_N^2}p'^\nu\right)(g_{\lambda\mu}g_{\rho\nu} - g_{\lambda\rho}g_{\mu\nu})\,q^\rho + C_5^A(q^2)g_{\lambda\mu} + \frac{C_6^A(q^2)}{m_N^2}q_\lambda q_\mu\right] u_P(p,s)$$

[C Alexandrou et al., Phys.Rev. D83 (2011) 014501]





CAVEAT: Complexities at physical point with unstable resonances, but formalism exists: [Lellouch-Lüscher hep-lat/0003023]

Muon g-2

Muon g-2: new lattice QCD results in last few years

Hadronic light-by-light

PRD93(2015)014503 (RBC)

PRL118(2016)022005 (RBC)

PRD96(2017)034515 (RBC)

Hadronic vacuum polarisation

PRL116(2015)232002 (RBC/UKQCD)

PRD93(2016)054508 (Aubin et al.)

JHEP04(2016)063 (RBC/UKQCD)

PRD96(2017)034516 (FNAL/HPQCD)

JHEP09(2017)153 (RBC/UKQCD)

PRL120(2017)152001 (FNAL/HPQCD/MILC)

arXiv:1801.07224 (RBC/UKQCD)