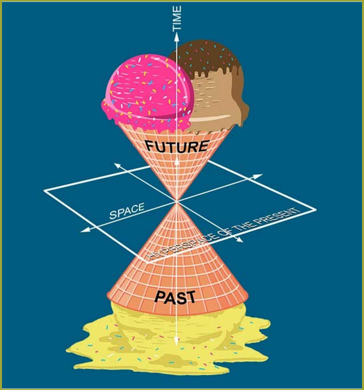
Overview of hadron structure from Lattice QCD

Martha Constantinou

Temple University



Light-Cone 2018
May 14, 2018

Material provided by

- ★ Utku Can
- ★ Christine Davies
- ★ Kyriakos Hadjiyiannakou
- ★ Jian Liang
- ★ Gerrit Schierholz
- ★ Yibo Yang

OUTLINE OF TALK

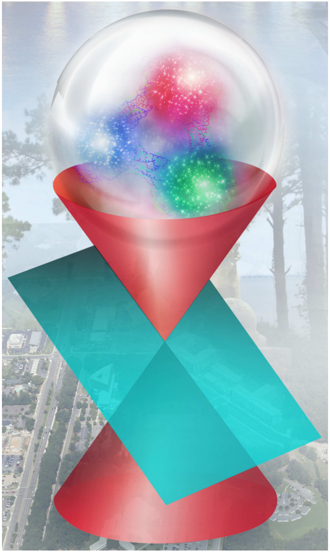
A. **Motivation**

B. **Introduction to Lattice QCD**

C. **Nucleon Charges**

D. **Hadron Form Factors**

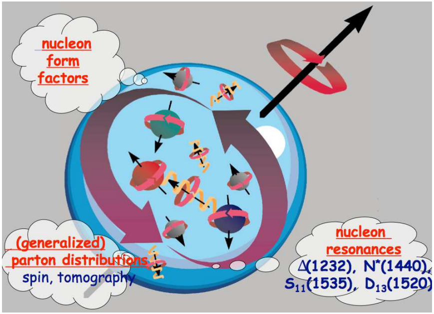
E. **Discussion**



A

Motivation

LQCD meets Nature

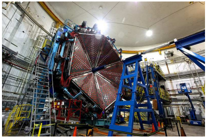


[M. Vanderhaeghen]

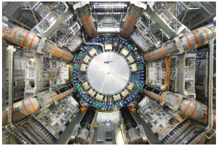
- 4-D discretization, ab initio formulation of QCD
- Make contact with well-known experimental data
- Provide input for quantities not easily accessible in experiments
- Guide New Physics searches

Rich experimental activities in major facilities

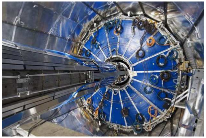
JLAB (12GeV Upgrade)



Argonne (ATLAS)



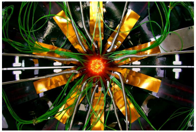
RHIC (BNL)



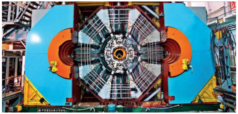
JPARC

- ★ Investigation of baryon & meson structure
- ★ Origin of mass and spin
- ★ New physics searches
- ★ proton radius puzzle
- ★ the list is long...

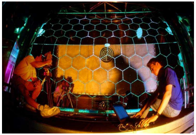
ALICE



BES III



COMPASS



PSI

MAMI

Lattice QCD receiving attention

Lattice-Related Talks @ Light-Cone 2018

- ★ This talk
- ★ “The Bjorken-x dependence of hadron structure from LQCD”, **C. Monahan**
- ★ “Pseudo-PDFs and quasi-PDFs structure”, **A. Radyushkin**
- ★ “An LQCD computation of quark PDFs at the physical point”, **F. Steffens**
- ★ “Full nucleon structure functions from the lattice”, **G. Schierholz**
- ★ “Lattice Field Theory in Real Time (and finite density)”, **P. Bedaque**
- ★ “Recent results in lattice QCD spectroscopy”, **B. Hoerz**
- ★ “Nucleon PDFs in small boxes”, **J. Guerrero**
- ★ “Pion Valence Distributions from Hadronic Lattice Cross Sections”, **R. Sufian**
- ★ “Pseudo Distributions from Lattice QCD”, **J. Karpie**
- ★ “Direct calculation of slope of form factors in lattice QCD”, **D. Richards**
- ★ “Excited-state contributions to nucleon charges in LQCD”, **C. Egerer**
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- ★ “Total decay and transition rates from lattice QCD”, **D. Robaina**

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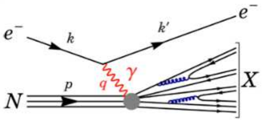
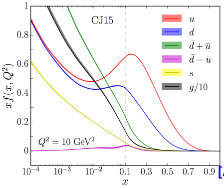
Lattice Talks @ Light-Cone 2013 - 2017: 14 total !

Probing Nucleon Structure





CJ15 PDFs

[A. Accardi et al., arXiv:1602.03154]

Parton Distribution Functions

★ Universal quantities for the description of the nucleon's structure (non-perturbative nature)

★ 1-dimensional picture of nucleon structure

★ Distribution functions are necessary for the analysis of Deep inelastic scattering data

★ Parametrized in terms of off-forward matrix of light-cone operators

★ Not directly accessible in a euclidean lattice

PDFs on the Lattice

★ **Moments of PDFs easily accessible in lattice QCD**

- **one relies on OPE to reconstruct the PDFs**
- **reconstruction difficult task:**

$\Rightarrow$ **signal-to-noise is bad for higher moments**
$\Rightarrow$ **n $>$ 3: operator mixing (unavoidable!)**

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★ **Alternative approaches to access PDFs**

Hadronic Tensor [K.F. Liu, Dong, PRL 72 (1994) 1790, K.F. Liu, PoS(LATTICE 2015) 115]

OPE without an OPE

- **the forward Compton amplitude**

$$T_{\mu\nu}(p,q)=\rho_{\lambda\lambda'}\int d^4x e^{iq\cdot x}\langle p,\lambda'|TJ_\mu(x)J_\nu(0)|p,\lambda\rangle$$

- **overcomes issues of renormalization and operator mixing**

see talk by G. Schierholz

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Direct access to PDFs

- quasi-PDFs [X. Ji, arXiv:1305.1539]
- pseudo-PDFs [A. Radyushkin, arXiv:1705.01488]
- good lattice cross-sections [Y-Q Ma&J. Qiu, arXiv:1709.03018]

see talks by C. Monahan, A. Radyushkin, F. Steffens, J. Guerrero, J. Karpie, R.Sufian

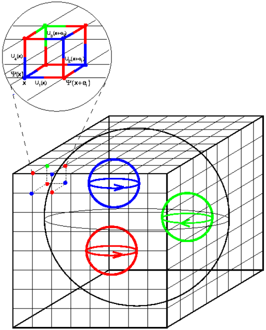
B

Introduction to Lattice QCD

Lattice formulation of QCD

★ **Space-time discretization on a finite-sized 4-D lattice**
- **Quark fields on lattice points**
- **Gluons on links**

★ **Serves as a regulator**
- **UV cut-off: inverse lat. spacing**
- **IR cut-off: inverse lattice size**



courtesy: USQCD

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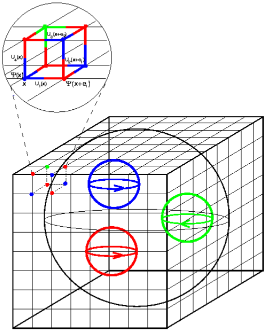


courtesy: USQCD

Technical Aspects

★ **Parameters (define cost of simulations):**

- **quark masses (aim at physical values)**
- **lattice spacing (ideally fine lattices)**
- **lattice size (need large volumes)**

★ **Discretization not unique:**

- **Wilson, Clover, Twisted Mass, Staggered, Overlap, Domain Wall**
- **Mixed actions**

Nucleon on the Lattice

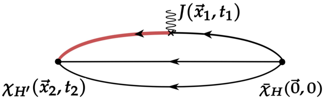
Multi-component task:

1. **Computation of 2pt- and 3pt-functions**

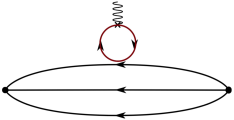
$$\text{2pt}: \quad G(\vec{q},t) = \sum_{\vec{x}_f} e^{-i\vec{x}_f\cdot\vec{q}}\, \boldsymbol{\Gamma}^{\mathbf{0}}_{\beta\alpha}\, \langle J_\alpha(\vec{x}_f,t_f)\overline{J}_\beta(0)\rangle$$

$$\text{3pt}: \quad G_{\mathcal{O}}(\boldsymbol{\Gamma}^{\kappa},\vec{q},t) =$$

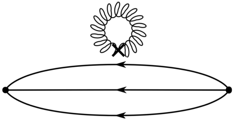
$$\sum_{\vec{x}_f,\vec{x}} e^{i\vec{x}\cdot\vec{q}} e^{-i\vec{x}_f\cdot\vec{p}'}\, \boldsymbol{\Gamma}^{\kappa}_{\beta\alpha}\, \langle J_\alpha(\vec{x}_f,t_f)\mathcal{O}(\vec{x},t)\overline{J}_\beta(0)\rangle$$



Connected



Disconnected Quark loop



Disconnected Gluon loop

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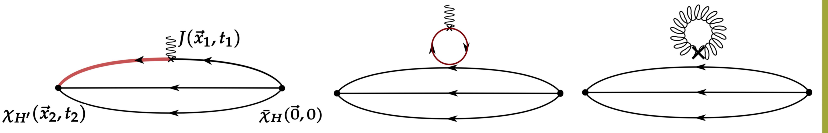


Connected | **Disconnected Quark loop** | **Disconnected Gluon loop**

2. **Construction of optimized ratio**

$$R^\mu_{\mathcal{O}}(\Gamma,\vec{q},t) = \frac{G_{\mathcal{O}}(\Gamma,\vec{q},t)}{G(\vec{0},t_f)} \times \sqrt{\frac{G(-\vec{q},t_f-t)G(\vec{0},t)G(\vec{0},t_f)}{G(\vec{0},t_f-t)G(-\vec{q},t)G(-\vec{q},t_f)}}$$

3. Computation of 2pt- and 3pt-functions

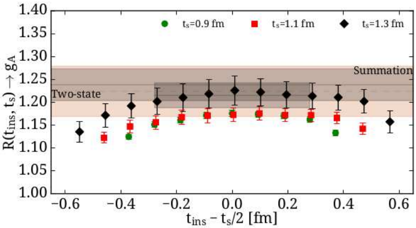
Plateau Method:

$$R_{\mathcal{O}}(\Gamma, \vec{q}, t) \underset{t-t_i \to \infty}{\overset{t_f - t \to \infty}{\longrightarrow}} \Pi^{\mu}(\Gamma, \vec{q})$$

2-state fits:

Summation Method:

$$\sum_t R_{\mathcal{O}}(\Gamma, \vec{q}, t) \underset{t_f \to \infty}{\longrightarrow} \mathcal{C} + \Pi^{\mu}(\Gamma, \vec{q}) * t_f$$



Nucleon on the Lattice

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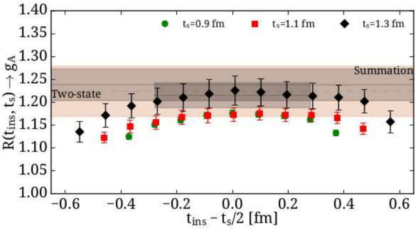

4. Renormalization:

connection to experiments

$$\Pi^R(\Gamma, \vec{q}) = Z_{\mathcal{O}}\, \Pi(\Gamma, \vec{q})$$

Simpler case!

Nucleon on the Lattice

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$$R_{\mathcal{O}}(\Gamma, \vec{q}, t) \xrightarrow[t - t_i \to \infty]{t_f - t \to \infty} \Pi^{\mu}(\Gamma, \vec{q})$$

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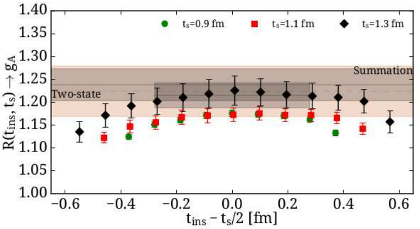

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connection to experiments

$$\Pi^{R}(\Gamma, \vec{q}) = Z_{\mathcal{O}}\, \Pi(\Gamma, \vec{q})$$

Simpler case!

5. Extraction of form factors

e.g. Axial current:

$$A^3_{\mu} \equiv \bar{\psi}\, \gamma_{\mu}\, \gamma_5\, \frac{\tau^3}{2}\, \psi \Rightarrow \bar{u}_N(p') \left[\mathbf{G_A}(\mathbf{q^2})\, \gamma_{\mu}\, \gamma_5 + \mathbf{G_p}(\mathbf{q^2})\, \frac{q_{\mu}\, \gamma_5}{2\, m_N} \right] u_N(p)$$

Inherited Uncertainties

Laborious effort to eliminate uncertainties

Statistical errors significantly increase with:

- ★ decrease of pion mass
- ★ increase of momentum transfer Q^2 between source-sink
- ★ increase of source-sink separation ($T_{\rm sink}$)

Systematic

- ★ Cut-off Effects due to finite lattice spacing
- ★ Finite Volume Effects
- ★ Contamination from other hadron states
- ★ Chiral extrapolation for unphysical pion mass
- ★ Renormalization and mixing

Also Talk by A. Walker-Loud, C. Egerer

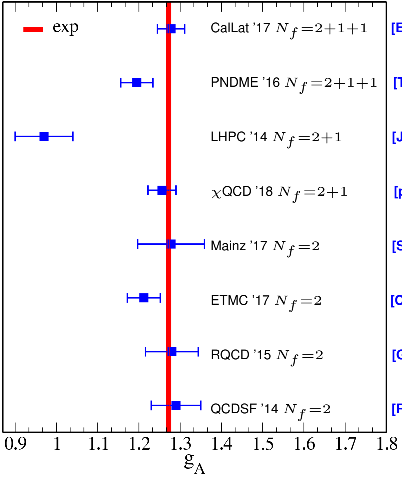
C

Nucleon

Structure

Nucleon Charges

Lattice community eager for g_A to agree with experiment



[E. Berkowitz et al., arXiv:1704.01114]

[T. Bhattacharya et al., Phys. Rev. D94 (2016) 054508, arXiv:1606.07049]

[J. Green et al., Phys. Lett. B734 (2014) 290, arXiv:1209.1687]

[preliminary]

[S. Capitani et al., arXiv:1705.06186]

[C. Alexandrou et al., Phys. Rev. D96 (2017) 054507, arXiv:1705.03399]

[G. Bali et al., Phys. Rev. D91 (2015) 054501, arXiv:1412.7336]

[R. Horsley et al., Phys. Lett. B732 (2014) 41, arXiv:1302.2233]

- ★ **Recent data at physical point agree with experiment**
- ★ **Challenge: Quantifying systematic uncertainties**

Systematic Uncertainties

Systematics must be addressed at the physical point

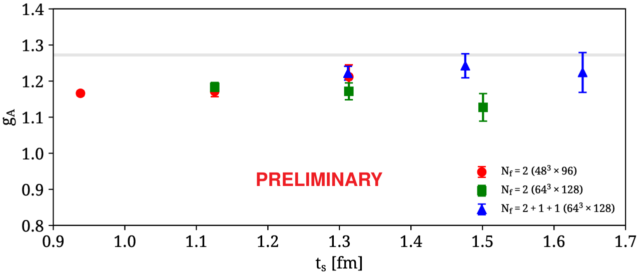
★ **ETM Collaboration: 3 ensembles at the physical point:**

N_f=2 $48^3 \times 64$ a=0.092fm

N_f=2 $64^3 \times 128$ a=0.082fm

N_f=2+1+1 $64^3 \times 128$ a=0.08fm

★ **Study of volume, quenching effects and excited states**



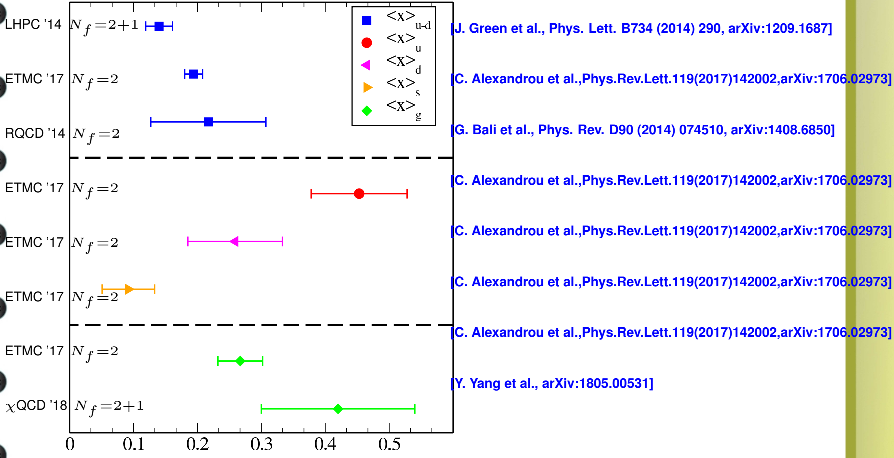
★ **Agreement with experiment at** $T_{\rm sink}$=1.5 − 1.65fm

★ **Volume effects are small**

★ **Combination of volume and quenching non-negligible**

Momentum Fraction

Quark momentum fraction: well-studied on the lattice



- ★ **Flavor decomposition: calculation of disconnected diagram**
- ★ **Gluon contributions accessible**

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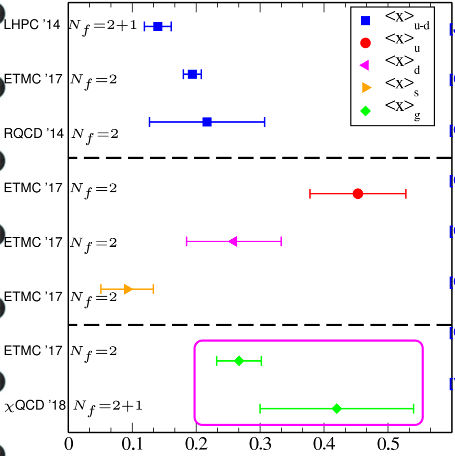

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[C. Alexandrou et al.,Phys.Rev.Lett.119(2017)142002,arXiv:1706.02973]

[G. Bali et al., Phys. Rev. D90 (2014) 074510, arXiv:1408.6850]

[C. Alexandrou et al.,Phys.Rev.Lett.119(2017)142002,arXiv:1706.02973]

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[Y. Yang et al., arXiv:1805.00531]

★ **Flavor decomposition: calculation of disconnected diagram**

★ **Gluon contributions accessible**

Parton Momentum Fraction

χQCD Collaboration:

Quark spin: overlap on RBC/UKQCD domain-wall ensembles, $m_\pi = 170,\ 300,\ 330\mathrm{MeV}$

Connected diagram: improved axial current [J. Liang et al., Phys. Rev. D 96 (2017) 034519]

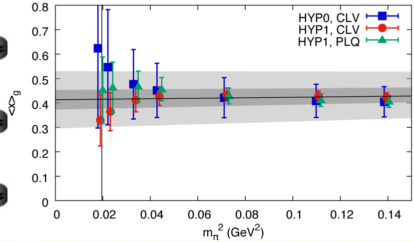
Disconnected diagram: check of anomalous Ward identity

Results (PRELIMINARY):

$$\Delta_u = 0.846(18)(32),\ \Delta_d = -0.410(16)(18),\ \Delta_s = -0.0353(83)(71)$$

Gluom momentum fraction: [Y. Yang et al., arXiv:1805.00531]

- ★ Various valence quarks - linear extrapolation
- ★ Non-perturbative renormalization
- ★ Various levels of HYP smearing and 2 definitions of operator



- ★ Renormalized results independent of the smearing
- ★ Systematic related to renormalization must be addressed
- ★ Mixing with quark operator must be eliminated

Spin Structure from First Principles

DIS experiment (1988) show 20-30$\%$ of spin carried by valence quarks

"... $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis-Jaffe sum rule. ... These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon."

[J. Ashman et al., Phys. Lett., vol. B206 (1988) 364]

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We need a theoretical formulation to address the proton spin puzzle

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Lattice QCD

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Lattice QCD

Spin Sum Rule (Ji):

$$\frac{1}{2} = \sum_q J^q + J^G = \sum_q \left(L^q + \frac{1}{2}\Delta\Sigma^q \right) + J^G$$

L_q: **Quark orbital angular momentum**
$\Delta\Sigma_q$: **intrinsic spin**
J^G: **Gluon part**

- **naive non-relativistic SU(6) quark model:** $\Delta\Sigma = 1,\ L_q = 0,\ J_g = 0$

Spin Structure from First Principles

DIS experiment (1988) show 20-30$\%$ of spin carried by valence quarks

"... $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis-Jaffe sum rule. ... These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon." **[J. Ashman et al., Phys. Lett., vol. B206 (1988) 364]**

We need a theoretical formulation to address the proton spin puzzle

Lattice QCD

Spin Sum Rule (Ji):

$$\frac{1}{2} = \sum_q J^q + J^G = \sum_q \left(L^q + \frac{1}{2}\Delta\Sigma^q \right) + J^G$$

L_q: **Quark orbital angular momentum**
$\Delta\Sigma_q$: **intrinsic spin**
J^G: **Gluon part**

- **naive non-relativistic SU(6) quark model:** $\Delta\Sigma = 1,\ L_q = 0,\ J_g = 0$

Extraction from LQCD:

$$\boxed{J^q = \frac{1}{2}\left(A_{20}^q + B_{20}^q\right)\ , \quad L^q = J^q - \Sigma^q\ , \quad \Sigma^q = g_A^q}$$

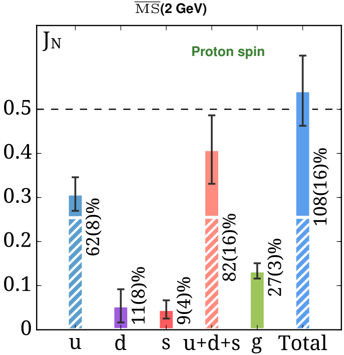
Necessary computations:

★ **Axial Charge**
★ **Quark Momentum Fraction**
★ **Gluon Momentum Fraction**

The proton spin puzzle from Lattice QCD

C. Alexandrou et al., Phys. Rev. Lett. 119, 142002 (2017), [arXiv:1706.02973]

- ★ **ETM Collaboration: simulations at the physical point**
- ★ $48^3 \times 96$, $a = 0.094\text{fm}$, $T_{\text{sink}} = 10a - 18a$



Striped segments: valence quark contributions (connected)
Solid segments: sea quark & gluon contributions (disconnected)

- ★ **Satisfaction of spin and momentum sum rule is not forced**

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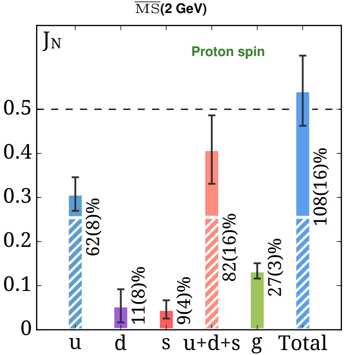
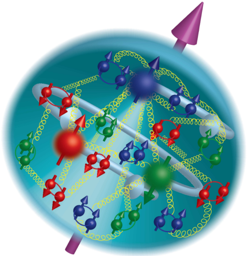


Better understanding of the spin distribution



Designed by Z.-E. Meziani

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D

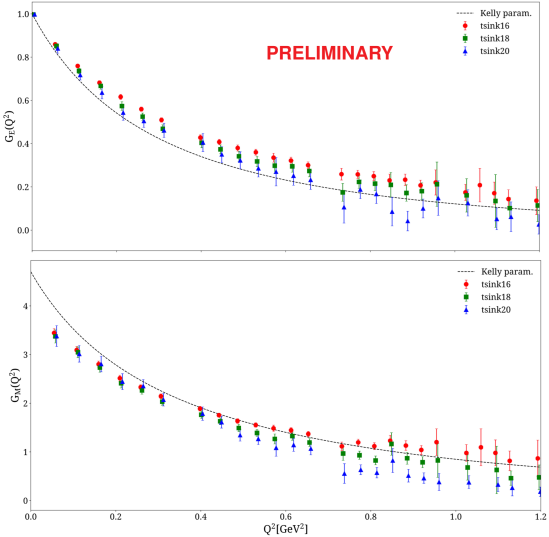
Hadron

Form Factors

Nucleon Electromagnetic Form Factors

ETM Collaboration: New ensembles at the physical point:

★ $N_f\!=\!2\!+\!1\!+\!1$ $\quad 64^3 \times 128 \quad a\!=\!0.08\mathrm{fm}$, **various** T_{sink} **up to** $1.6\mathrm{fm}$



Connected (isovector)

Excited states mostly affect $Q^2 > 0.4\mathrm{GeV}^2$

Talk by D. Richards: Direct access of slope fo Form Factors

Nucleon Electromagnetic Form Factors

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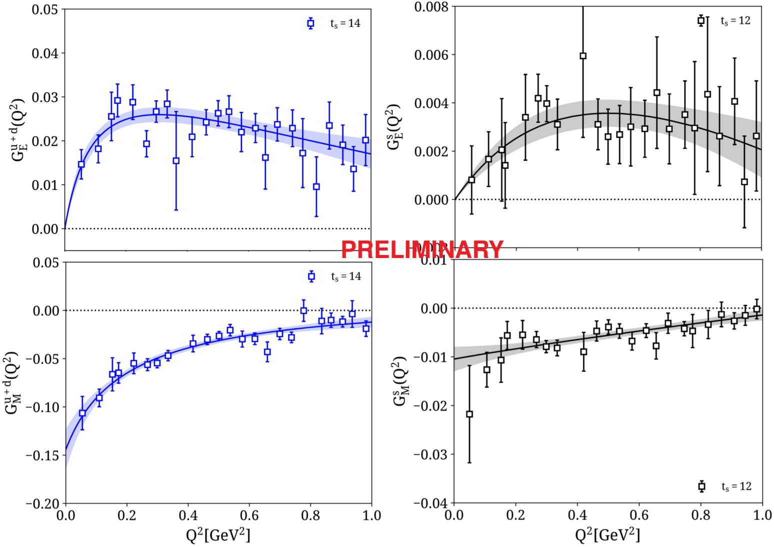
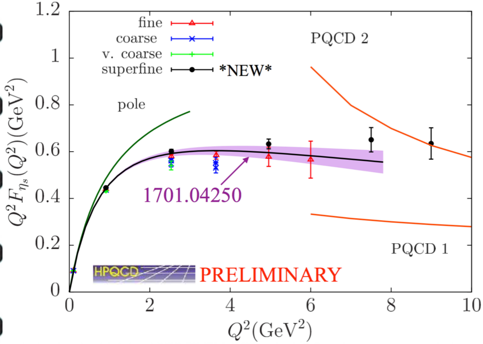


Meson Electromagnetic Form Factors

HPQCD Collaboration: [J. Koponen et al., Phys. Rev. D 96, 054501 (2017), arXiv:1701.04250]

- ★ $N_f{=}2{+}1{+}1$, $a{=}0.15,\ 0.12,\ 0.09,\ 0.06\mathrm{fm}$, **large** Q^2 **(Breit frame)**
- ★ **Comparison of pQCD to LQCD for pseudoscalar meson** $s\bar{s}$
- ★ **Qualitative picture also applies to** π **meson**
- ★ **Useful for new experiments** [G. M. Huber et al., JLAb, E12-06-101]



pole: simple pole with m_ϕ

PQCD 1: asymptotic pQCD form: $Q^2\,F(Q^2){=}8\pi\,\alpha_s f_\pi^2$

PQCD 2: corrections from non-asymptotic DA for η_s

- ★ **pole: works at low** $Q^2 < 1\mathrm{GeV}^2$
- ★ **no fall-off of LQCD data at large** Q^2 **as expected from pQCD**
- ★ **PQCD 2 larger values** $\&$ **stronger** Q^2 **dependence than LQCD data**

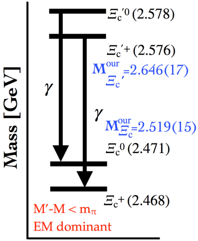
Electromagnetic Transition Form Factors

Ξ_c, $\Xi_c^{\prime}$: study heavy-quark dynamics - composed of different quarks (u, s, c)

Experiments (LHCb, PANDA, Belle II, BESIII, J-PARC) may provide information on spectroscopy, decays and structure of charmed baryons

Lattice Calculation:

[K. Can at al., Phy. Lett. B 772 (2017) 121, arXiv:1612.05722]: $N_f=2+1$, $m_\pi=156\text{MeV}$

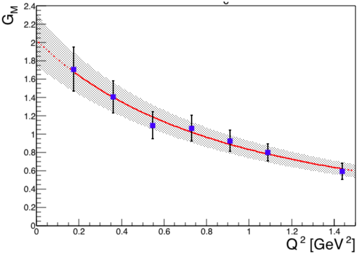


based on U-spin flavor symmetry:

$\Xi_c^+\gamma \to \Xi_c^{\prime +}$ **favorable**

$\Xi_c^0\gamma \to \Xi_c^{\prime 0}$ **suppressed**

$\Xi_c^+\gamma \to \Xi_c^{\prime +}$



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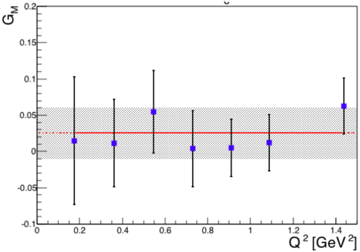

Lattice data confirm expectations from U-spin symmetry

E

Discussion

Discussion

Great progress over the last years:

- ★ **Simulations at the physical point**

  Talk by P.Bedaque on real time simulations

- ★ **Careful assessment of systematic uncertainties**
  - **Volume effects**
  - **quenching effect (strange and charm)**
  - **continuum limit**

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  - quasi-PDFs, pseudo-PDFs, good lattice cross sections, hadronic tensor
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★ **Beyond hadron structure**

- **Investigations to Nuclear Effects** (Talks by W. Detmold, D. Lee)

  [E. Chang et al. (NPLQCD), Phys. Rev. Lett. 120, 152002 (2018), arXiv:1712.03221]

- **Spectroscopy and exotic states** (Talks by B. Hoerz, A.Baroni)

THANK YOU

TMD Topical Collaboration

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BACKUP SLIDES