Challenges of QCD at the EIC

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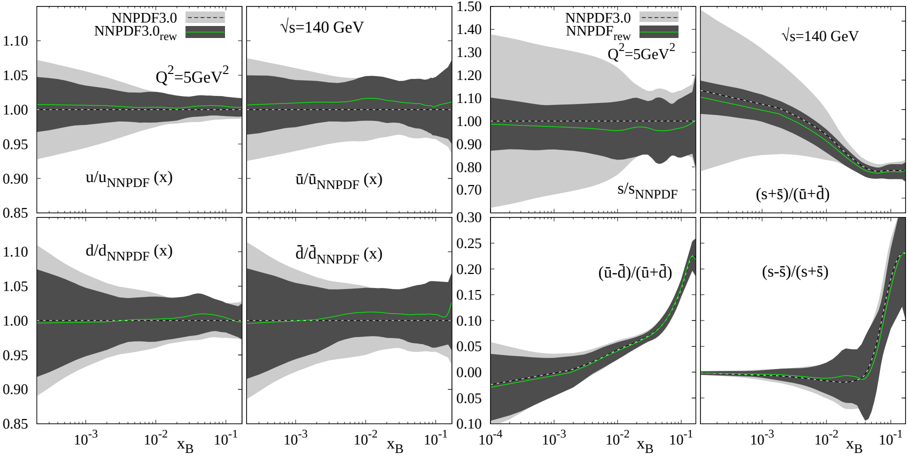
- The two EIC challenges: High precision and multitude of observables, a few topics from Yellow report 2103.05419
- Lattice QCD
- Power corrections, higher twist contributions
- models
- nucleon mass decomposition
- $e + A$: unifying hot and cold QCD

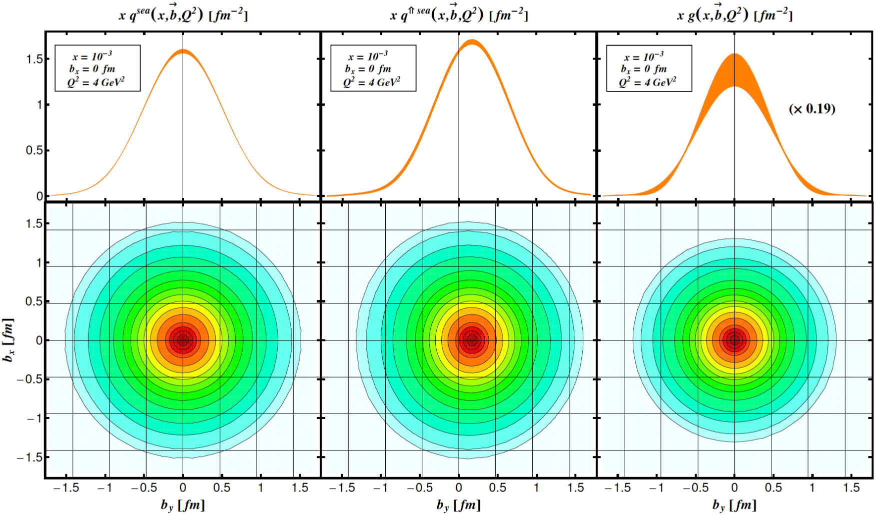
Impact plots from the Yellow Report I: PDFs and FFs



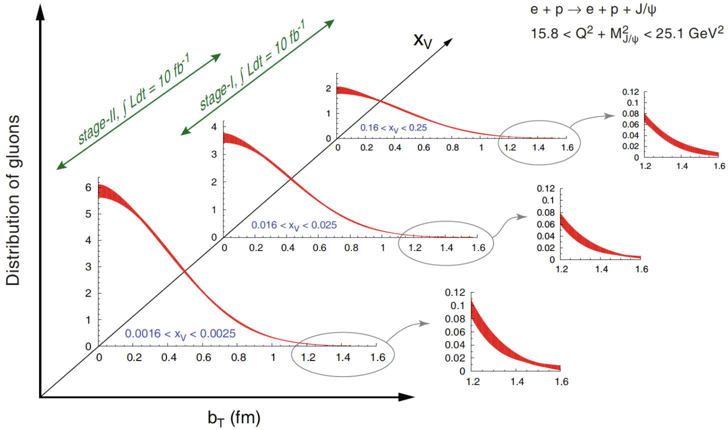
Results of a combined fit of PDFs and FFs for EIC pseudo data

Aschenauer, Borsa, Sassot, Van Hulsen, 1902.10663 by NNPDF

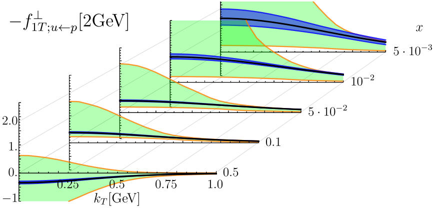
Impact plots from the Yellow Report II: quark GPDs

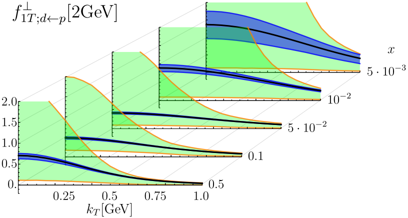


Impact plots from the Yellow Report III: Gluon GPDs



Impact plots from the Yellow Report IV: quark Sivers distributions





The big question: Can theory match this precision within one or two decades?

If not, you do not really know what you measure.

This is all about the contol of systematic uncertainties

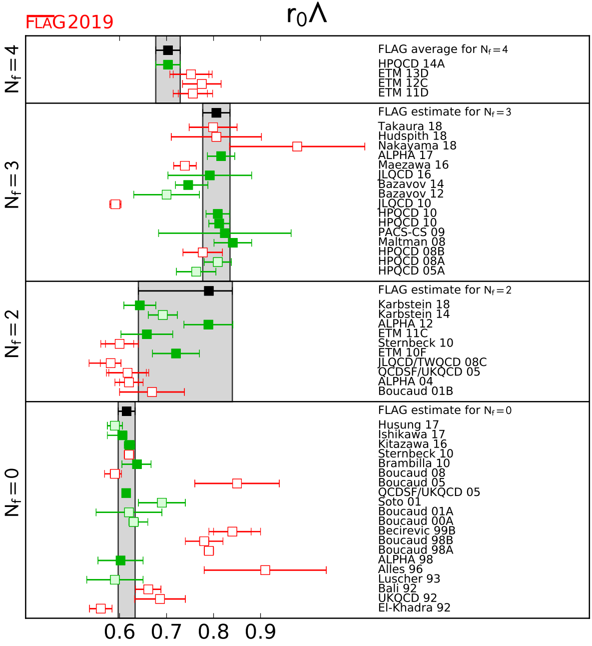
A paradigm: The FLAG Review

quality criteria:

- ● full control of systematic errors
- ○ partial control of systematic errors
- ● no control of systematic errors

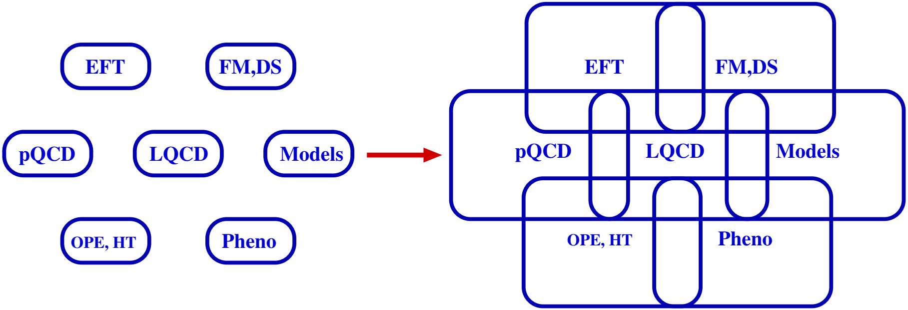
Sommer scale $r_0 = 0.472$ fm; $r_0^2 \frac{V_{Q\bar{Q}}(r_0)}{dr_0} = 1.65$; $\Lambda = \Lambda_{QCD,\overline{MS}}$

$r_0\Lambda$



FLAG2019
N_f = 4
N_f = 3
N_f = 2
N_f = 0
FLAG average for N_f = 4
HPQCD 14A
ETM 13D
ETM 12C
ETM 11D
FLAG estimate for N_f = 3
Takaura 18
Hudspith 18
Nakayama 18
ALPHA 17
Maezawa 16
JLQCD 16
Bazavov 14
Bazavov 12
JLQCD 10
HPQCD 10
HPQCD 10
PACS-CS 09
Maltman 08
HPQCD 08B
HPQCD 08A
HPQCD 05A
FLAG estimate for N_f = 2
Karbstein 18
Karbstein 14
ALPHA 12
ETM 11C
Sternbeck 10
ETM 10F
JLQCD/TWQCD 08C
QCDSF/UKQCD 05
ALPHA 04
Boucaud 01B
FLAG estimate for N_f = 0
Husung 17
Ishikawa 17
Kitazawa 16
Sternbeck 10
Brambilla 10
Boucaud 08
Boucaud 05
QCDSF/UKQCD 05
Soto 01
Boucaud 01A
Boucaud 00A
Becirevic 99B
Boucaud 98B
Boucaud 98A
ALPHA 98
Alles 96
Luscher 93
Bali 92
UKQCD 92
El-Khadra 92
0.6
0.7
0.8
0.9

The Changed Theory Landscape



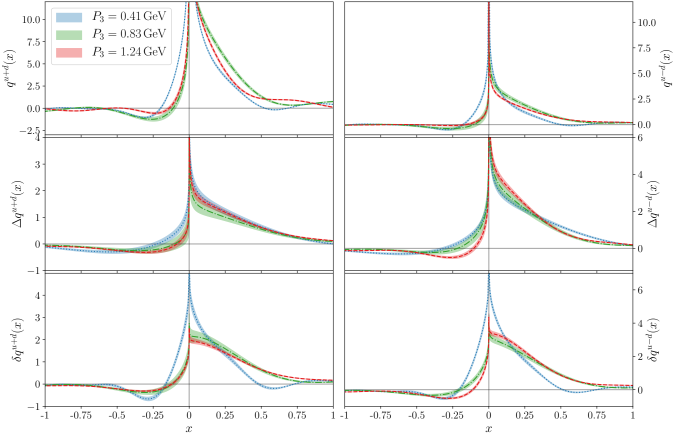
- Different theory subfields match in their regions of overlap
- The very broad EIC physics program needs consistent (!) input of all of them
- Only global collaboration can provide the needed qualified manpower and compute power

With novel lattice approaches formulated in recent years, lattice calculations can play a much more important role.

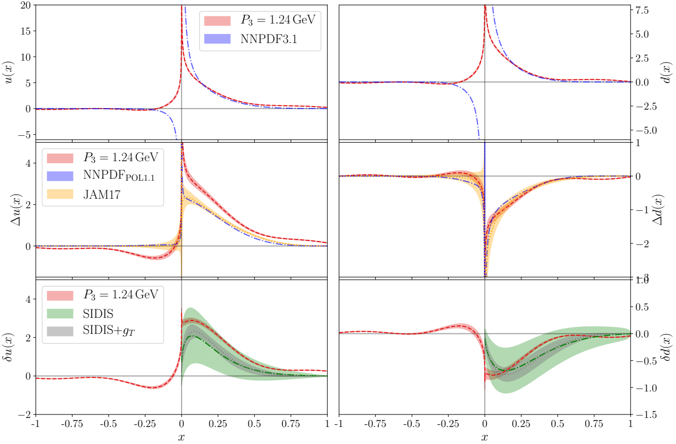
- X. Ji, PRL 110 (2013) 262002; arXiv:1305.1539
  quasi-PDFs etc.
- Y.Q. Ma and J.W. Qiu PRD 98 (2018) 074021; arXiv:1404.6860 lattice cross sections
- A. Radyushkin, PRD96 (2017) 034025; arXiv:1705.01488
  pseudo-PDFs etc.
- U. Aglietti et al. Phys.Lett. B441 (1998) 371; hep-ph/9806277
- V. Braun and D. Müller, EPJ C55 (2008) 349; arXiv:0709.1348
- A.J. Chambers et al., PRL 118 (2017) 242001; arXiv:1703.01153
- ...

I am a member of LPC (Y.B. Yang, X. Ji)

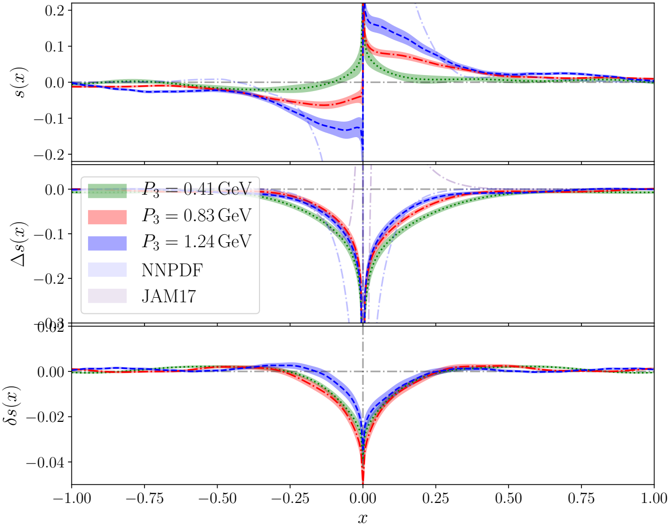
some new results of ETMC 2106.16065



light quark PDFs, quasi-PDFs

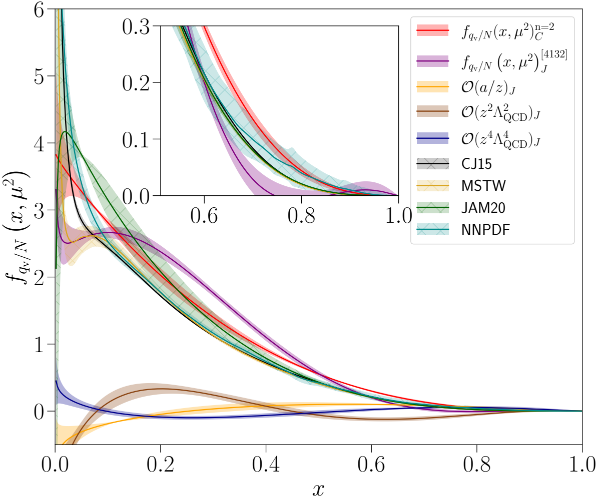


the light quark PDFs



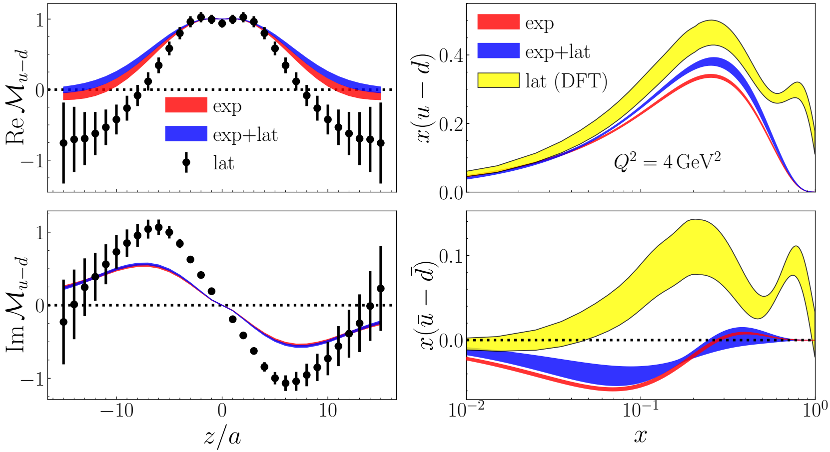
the strange quark PDFs

a new result from HadStruc Collaboration 2107.05199



leading twist PDFs plus corrections

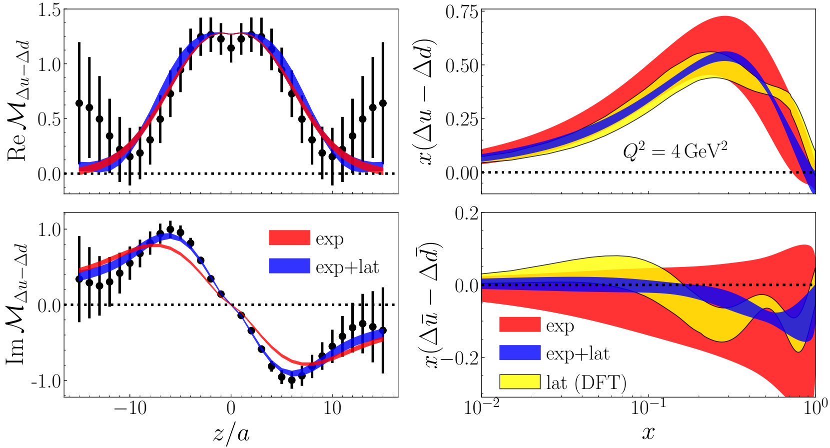
Ioffe-Time pseudo Distributions (pITD)



The future will see ever more Lattice augmented PDF fits

Real and imaginary parts of the isovector unpolarized matrix element M_{u-d}; quasi-PDFs; the resulting PDFs

Bringewatt et al. arXiv:2010.00548



Lattice augmented PDF fits

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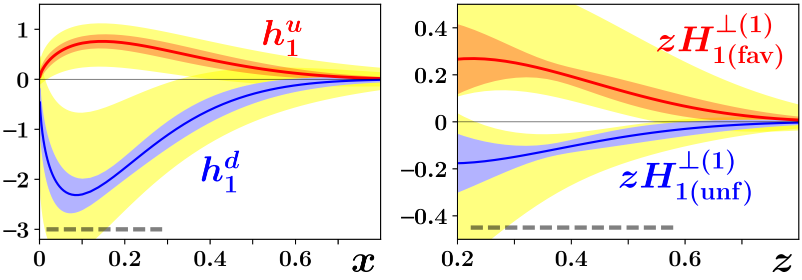
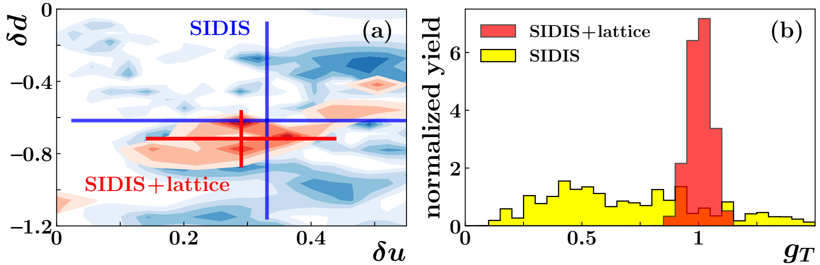


Lattice augmented transversity fits from JAM

Lin et al. arXiv:1710.09858

Transversity PDFs $h_1^{u,d}$ and favored $zH_{1(fav)}^{\perp(1)}$ and un-favored $zH_{1(unfav)}^{\perp(1)}$ Collins FFs



Lattice augmented transversity from fits from JAM

Lin et al. arXiv:1710.09858

Contour plot of δu and δd for the SIDIS only (blue) and SIDIS+lattice(red);

Normalized yields for the isovector tensor charge gT

The χQCD collaboration has very carefully investigated the continuum limit for quasi-PDF operators 2012.05448

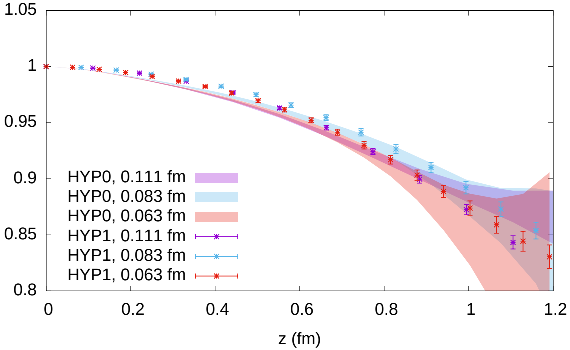
$$O_\Gamma(z) = \bar{\psi}(0)\Gamma U(0,z)\psi(z)$$

The bare $O_\Gamma(z)$ in lattice regularisation at 1-loop level contains an $1/a$ term

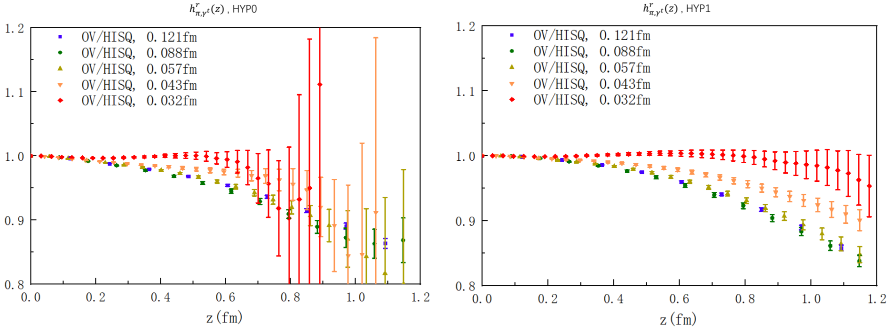
$$O_\Gamma(z) = \Gamma(1 + g^2(\gamma \log(p^2 a^2) - m_{-1}\tfrac{z}{a}) + ...)$$

$$h_{\pi,\Gamma}(z) = \langle \pi | O_\Gamma(z) | \pi \rangle$$

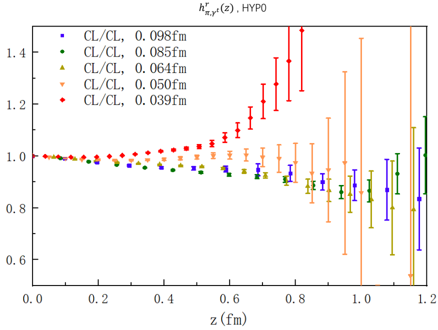
$$h_{\pi,\Gamma}(z) = \frac{\langle O_\pi(T/2) \sum_x (O_\Gamma(z;(\vec{x},t)) + O_\Gamma(z;(\vec{x},T-t))) O_\pi^\dagger(0) \rangle}{\langle O_\pi(T/2) O_\pi^\dagger(0) \rangle}$$

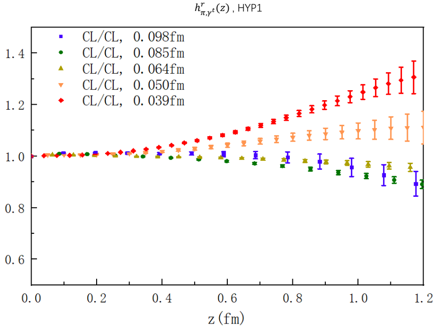


the RI/MOM renormalized pion matrix element for overlap valence on DWF sea



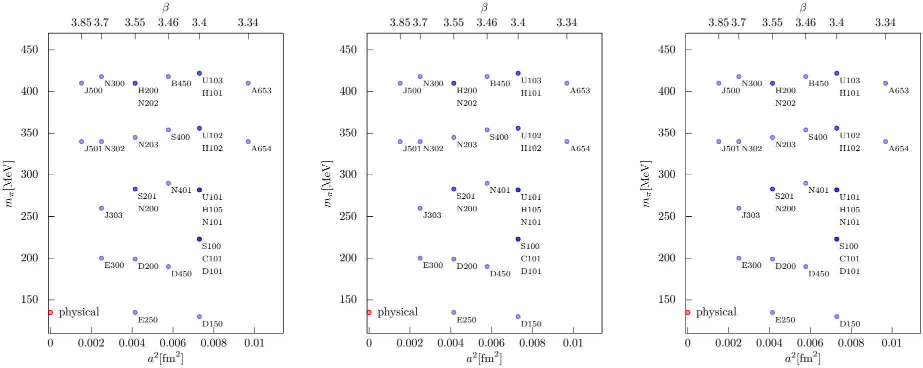
the RI/MOM renormalized pion matrix element for overlap valence on HISQ sea





the RI/MOM renormalized pion matrix element for clover fermions (CLS)

Bottom line: Taking the continuum limit is non-trivial

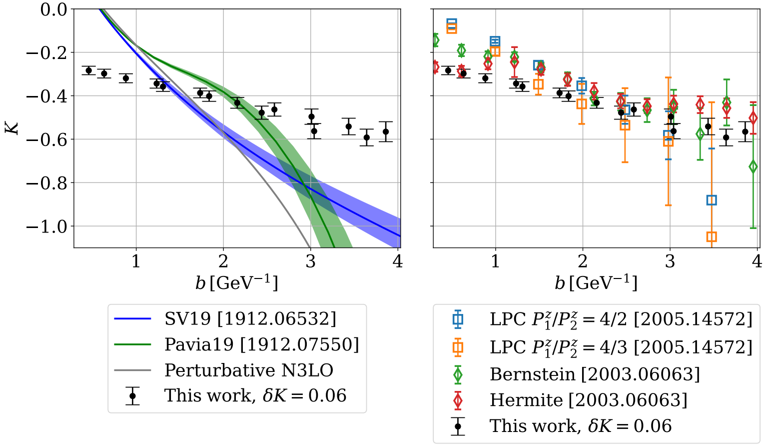


The CLS ensembles

A prime example for the speed of progress

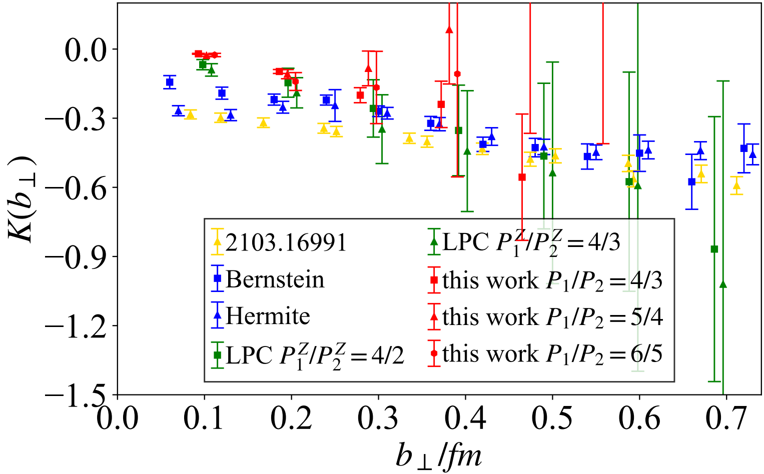
- MIT-Fermilab-BNL group P. Shanahan, M. Wagman, Y. Zhao 2003.06063 quasi-PDFs
- LPC: Q.-A. Zhang et al. 2005.14572 LaMET, soft function
- TMDC-RQCD, M. Schlemmer et al. 2103.16991 moment method 2002.07527
- Beijing-ETMC Y. Li et al. 2106.13027 LaMET, soft function

arXiv:2103.16991



Estimated higher twist uncertainty $\delta K = 0.06$

The newest result from Beijing-ETMC: arXiv:2106.13027



Four groups using three different lattice approaches get compatible results (most reliable way to estimate systematic uncertainties)

higher twist, power corrections

The task:

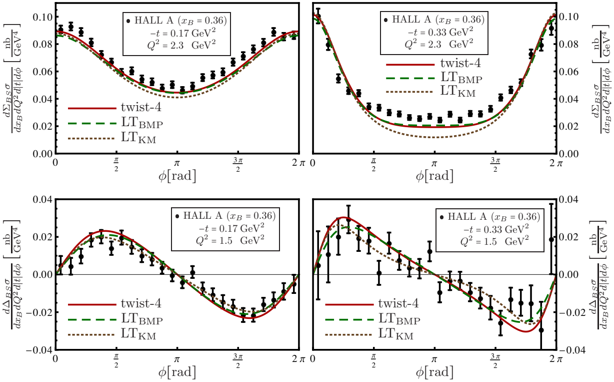
- disentangle all higher-twist distribution and fragmentation functions
- calculate all kinematic power corrections, e.g. $\sim \frac{m^2}{Q^2}$

One example: DVCS Braun, Manashov, Müller, Pirnay; 1401.7621

$$\frac{d\Sigma_{BS}\sigma}{dx_B dQ^2 d|t| d\phi} := \frac{1}{2}\left[\frac{d\sigma^{\rightarrow}}{dx_B dQ^2 d|t| d\phi} + \frac{d\sigma^{\leftarrow}}{dx_B dQ^2 d|t| d\phi}\right]$$

$$\frac{d\Delta_{BS}\sigma}{dx_B dQ^2 d|t| d\phi} := \frac{1}{2}\left[\frac{d\sigma^{\rightarrow}}{dx_B dQ^2 d|t| d\phi} - \frac{d\sigma^{\leftarrow}}{dx_B dQ^2 d|t| d\phi}\right]$$

and all kinematic corrections $\sim \frac{m^2}{Q^2}$ and $\sim \frac{t}{Q^2}$



The difference between LT_{KM} and LT_{BMP} illustrates the ambiguity in defining leading twist for DVCS.

Power corrections from a renormalon model for quasi-PDFs

Braun, Vladimirov, Zhang, 1810.00048

- power corrections for quasi-PDFs have the generic behavior

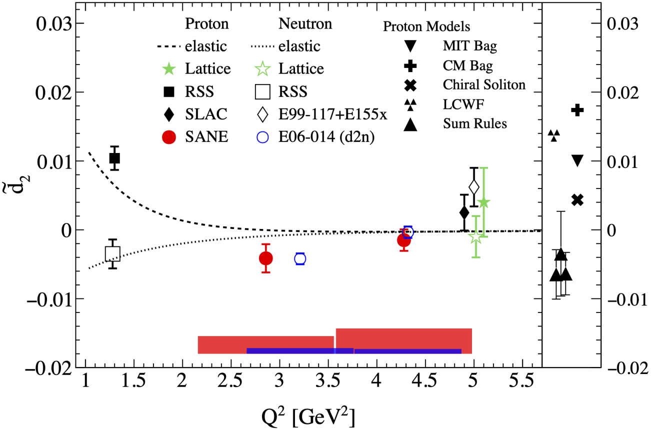
$$\mathcal{O} = q(x)\left\{1 + \mathcal{O}\left(\frac{\Lambda^2}{p^2}\,\frac{1}{x^2(1-x)}\right)\right\}$$

- power corrections for pseudo-PDFs have the generic behavior

$$\mathcal{O} = q(x)\left\{1 + \mathcal{O}\left(z^2\Lambda^2(1-x)\right)\right\}$$

bottom line: Interesting results, but you only know the size of power and higher-twist corrections after calculating them, which is possible on the lattice but extremely hard

the present status of $\tilde{d}_2$ SANE 1805.08835



Our 2005 lattice results look good, but they included no systematic errors.

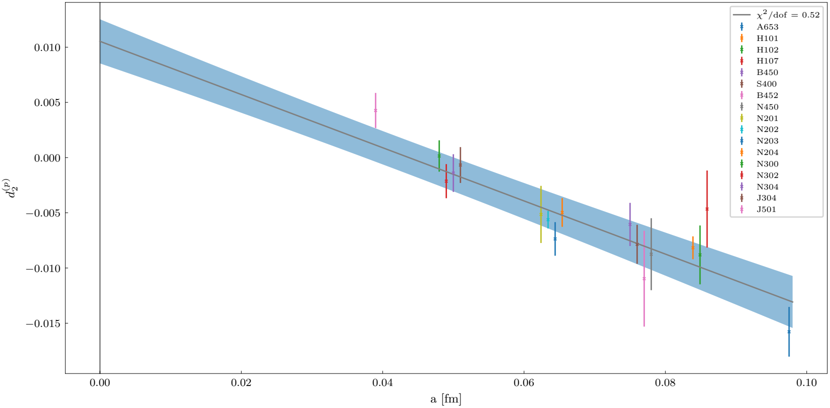
Experiments can only measure d_2^p and d_2^n. LQCD gives also d_2^u and d_2^d which can be translated into the colore force acting on a quark according to Burkhardt arXiv:0810.3589 (factor of 4 wrong)

$$\int_0^1 dx\ x^2 g_1^p(x,Q^2) = \frac{a_2^p}{2} + \mathcal{O}\left(\frac{m_N^2}{Q^2}\right)$$
$$\int_0^1 dx\ x^2 g_2^p(x,Q^2) = \frac{d_2^p - a_2^p}{3} + \mathcal{O}\left(\frac{m_N^2}{Q^2}\right)$$

$$d_2^q = -\frac{1}{2M(P^+)^2} \langle P_N, S_T|\bar{q}(0)\gamma^+ gG^{+y}(0)q(0)|P_N, S_T\rangle$$
$$F^u = -25 \pm 30\ \mathrm{MeV/fm} = -0.04 \pm 0.05\ (\Lambda_{QCD})^2$$
$$F^d = -14 \pm 13\ \mathrm{MeV/fm} = 0.02 \pm 0.02\ (\Lambda_{QCD})^2$$

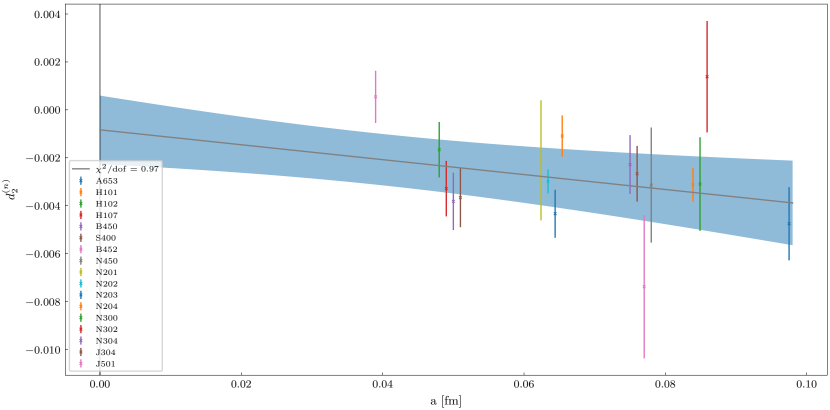
Can this be true?

d_2^p



$\chi^2/\text{dof} = 0.52$
A653
H101
H102
H107
B450
S400
B452
N450
N201
N202
N203
N204
N300
N302
N304
J304
J501
$d_2^{(p)}$
0.010
0.005
0.000
−0.005
−0.010
−0.015
0.00
0.02
0.04
0.06
0.08
0.10
a [fm]

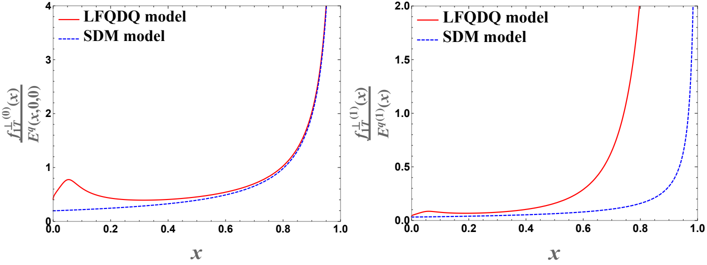
d_2^n



0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
−0.010
$d_2^{(n)}$
0.00
0.02
0.04
0.06
0.08
0.10
a [fm]
χ^2/dof = 0.97
A653
H101
H102
H107
B450
S400
B452
N450
N201
N202
N203
N204
N300
N302
N304
J304
J501

It will take quite some time before LQCD can match the experimental precision. Therefore, models will continue to be important.

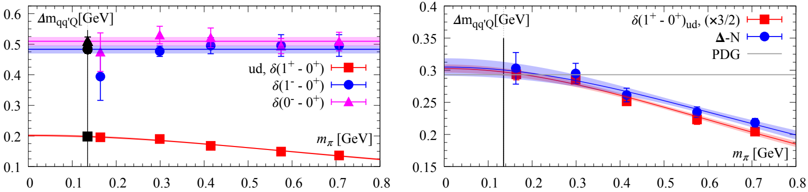
For example, one can relate GPDs to TMDs in quark diquark models, e.g. B. Pasquini et al. 1907.06960 B.Gujar et al. 2107.02216



Ratio of moments of the up quark Sivers function to the up quark GPD E^u

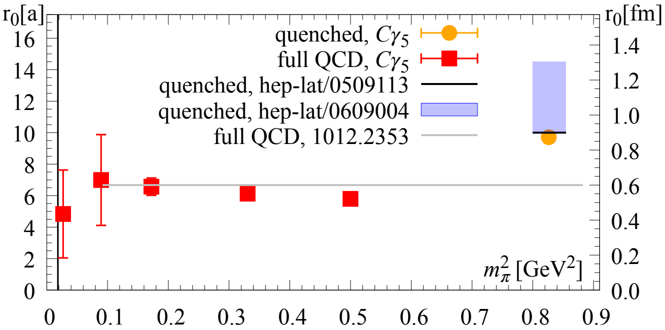
Diquarks from lattice QCD Francis, de Forcrand, Lewis, Maltmann 2106.09080 2+1 Clover fermions down to $m_\pi = 164$ MeV

A LQCD analysis of the $Q(q^c C\Gamma q)$ system.



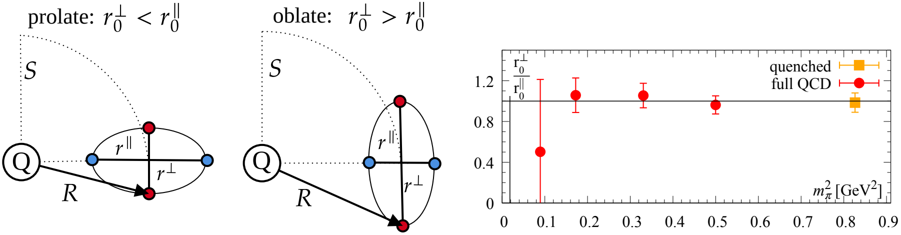
the 'good' diquark 0^+ dominates

One can study the geometry of the diquark

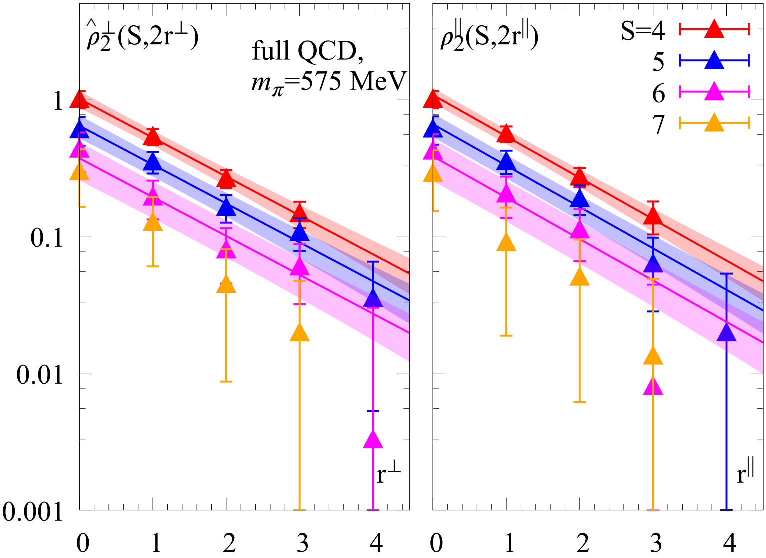


the diquark radius is roughly 0.6 fm

$$C_\Gamma(\vec{x}_1, \vec{x}_2, t) \;=\; \langle \mathcal{O}_\Gamma(\vec{0}, 2t)\rho(\vec{x}_1, t)\rho(\vec{x}_2, t)\langle \mathcal{O}_\Gamma(\vec{0}, 0)$$



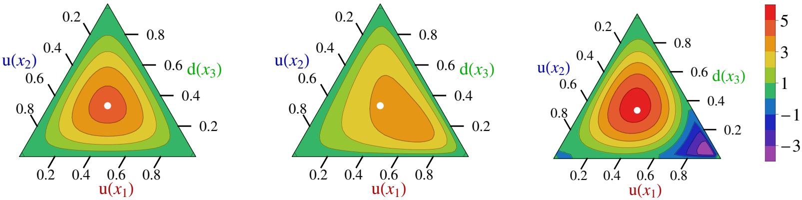
diquarks are roughly spherical



$\hat{\rho}_2^{\perp}(S,2r^{\perp})$
full QCD,
m_π=575 MeV
1
0.1
0.01
0.001
0
1
2
3
4
$r^{\perp}$
$\rho_2^{||}(S,2r^{||})$
S=4
5
6
7
$r^{||}$

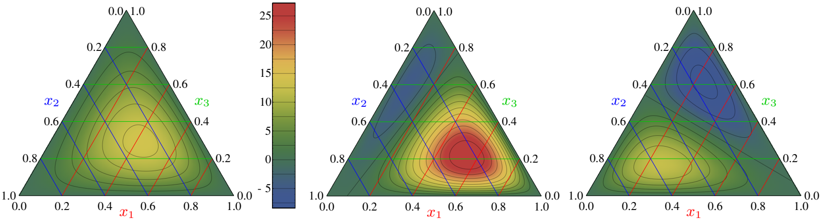
another example: Hadron distribution amplitudes

C. Mezrag, J. Segovia, L. Chang, C.D. Roberts; 1711.09101;
Fadeev-type 3 particle wave function



asymptotic, nucleon and roper wave function

V.Braun et al. 1403.4189 ; Lattice QCD



nucleon, $N^*(1650)$ and $N^*(1535)$

nucleon mass decomposition

The scale anomaly of QCD is of fundamental importance for the understanding of QFT.

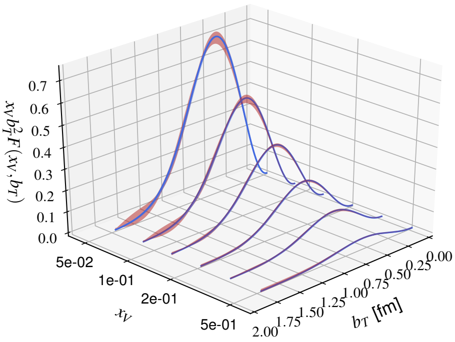
Q1: Does it contribute to m_N?
Ji hep-ph/9410274; Lorcé 1706.05853; Metz, Pasquini, Rodini 2006.11171; ...

Q2:If so, can it be isolated from experiment or Lattice QCD?
Kharzeev, Satz, Syamtomov, Zinovjev hep-ph/9901375, near threhold quarkonium photoproduction; He, Sub, Yang 2101.04942 LQCD

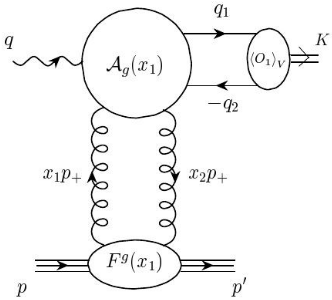
The answers to both questions are still open

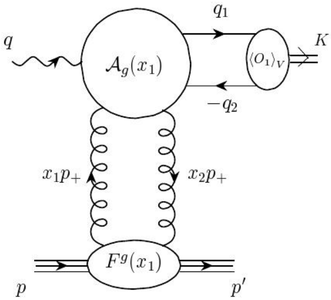
Experimentally, determining the gluon GPD from exclusive Υ production looks very promising

Yellow Report; Joosten and Meziani 1802.02616

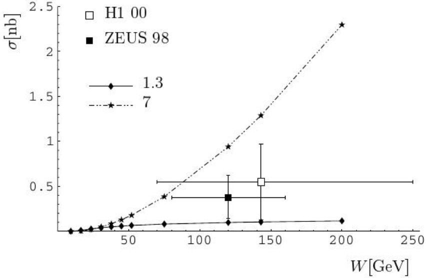


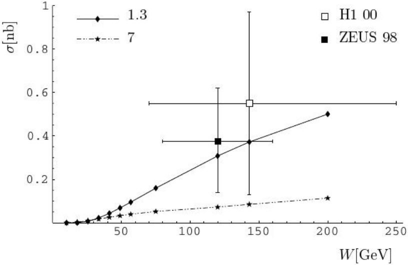
The problem is the control of systematic theoretical uncertainties:
A full NLO calculation of exclusive J/ψ and Y photoproduction
Ivanov, Schäfer, Szymanowski and Krasnikov, hep-ph/0401131



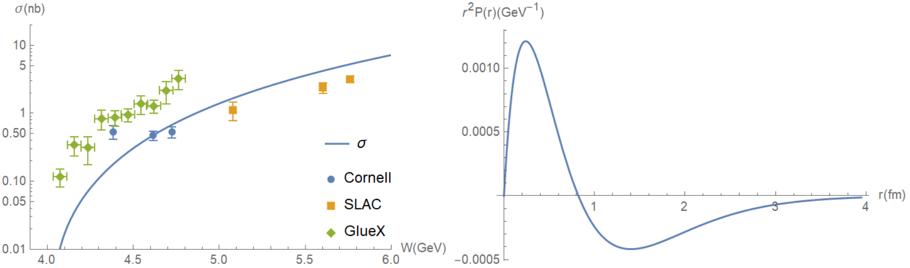


LO (left) and NLO (right) results for Υ photoproduction





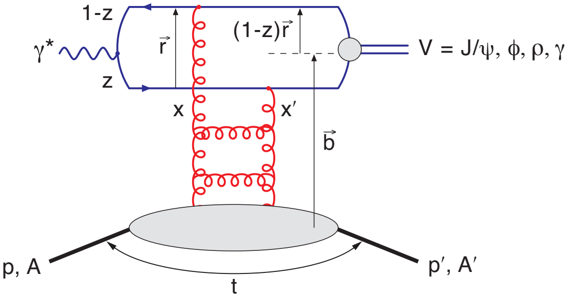
Guo, Ji, and Liu 2103.11506 argue that factorization should stay valid in the limit of threshold production and use lattice imput for the gravitational form factors from Shanahan and Detmold 1810.04626 to fit J/ψ GlueX data and extract the gluon pressure inside a proton.

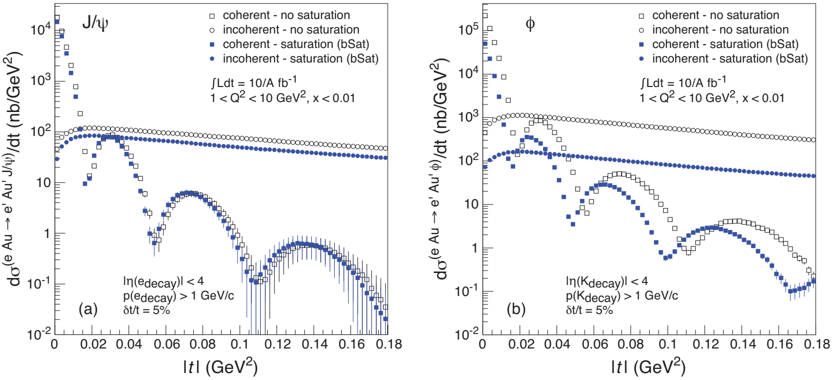


The J/ψ photoproduction cross-section; prediction using the gravitational formfactor from the lattice (line), and the gluon contribution to the pressure inside a proton and there is much more:

Hatta and Yang 1808.02163
Sun, Sun, and Zhou 2012.09443
Wang, Kou, Xie, and Chen 2102.01610
Zahed 2102.08191
Kou, Wang and Chen 2103.1001
Sun, Tong and Yuan 2103.12047
K.-F. Liu 2103.15768
Freese and Miller 2104.03213

Saturation is a key element of theoretical Heavy-ion physics.
At EIC it can be probed, e.g., in diffractive meson production
Toll and Ullrich, arXiv:1211.3048

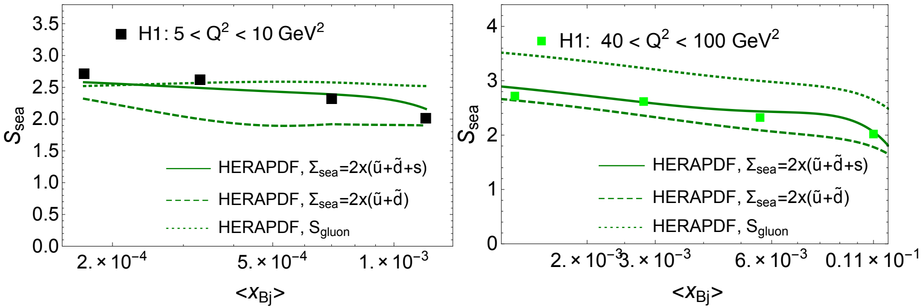




diffractive J/ψ and Φ production

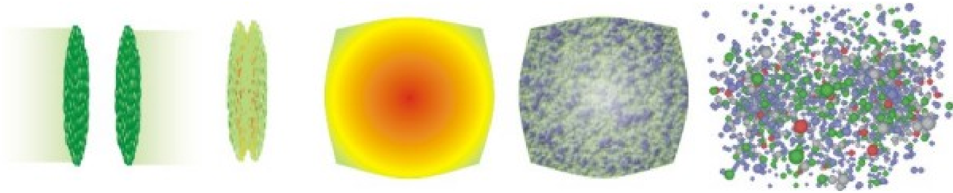
An information theoretical interpretation of DIS

Kharzeev and Levin arXiv:2102.09773

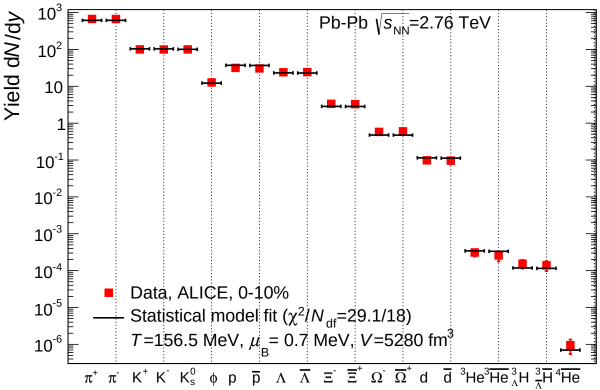


The entropy of partons resolved by DIS

QED and QCD, i.e. heavy-ion collisons and e+A are time reversal invariant no information loss, no entropy production, an entangled state

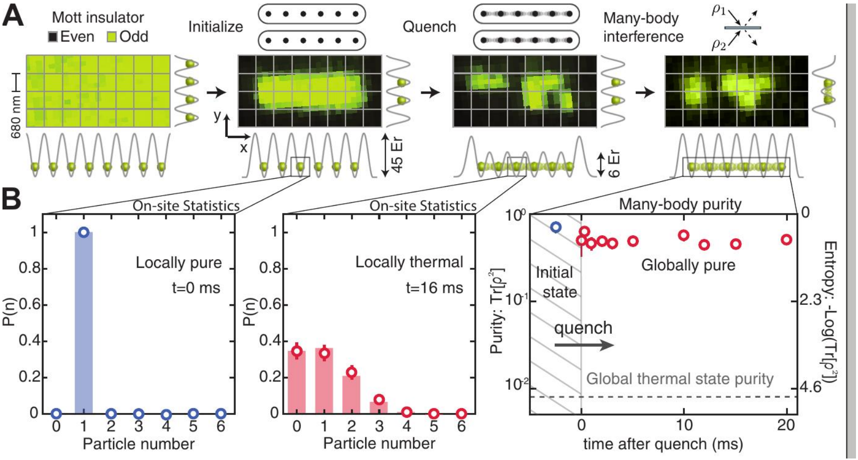


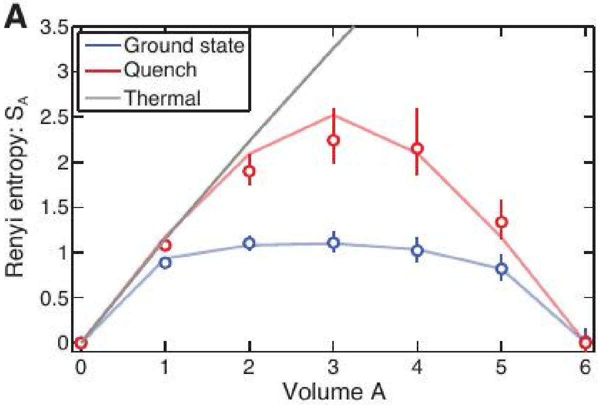
rapid thermalization and vorticity relaxation could be related to entanglement; EPR: Naive causality does not apply for entangled states; decoherence depends on the observable arXiv:1809.04681, ALICE, CERN



But: R(rms , $^{3}_{\Lambda}H$)=10.6 fm$\sim 2R_{\rm Pb}$; $E_B << 156$ MeV the yield should be suppressed

The experiment 1603.04409 “Quantum thermalization through entanglement in an isolated many-body system”





The message: Entanglement vs. statistics depends on the observable for all isolated quantum systems: e+p, e+A, p+A and A+A

a new field of research for the EIC ??

Conclusions

- At EIC accuracy the fine-print of theory calculations becomes crucial: LO vs. NLO vs. NNLO, w/o resumation, higher twist contributions, continuum extrapolation for Lattice calculations, solid all order proof for factorization or just plausibility arguments, ... there is no longer room for hand-waving arguments.
- On the other hand, the theory landscape has qualitatively changed over the last decade such that we can meet this challenge but only if all qualified manpower is combined. Even closer international collaboration is the key.
- Lattice QCD promises to play an ever more important role.