Lattice Field Theory

Recent activities of the NIC group

Stefan Schaefer

88th PRC meeting, Hamburg, Nov 12, 2019

Strong coupling

The strong coupling of QCD has been target of lattice investigations for many years.

Non-perturbative Schrödinger Functional approach used by DESY group

- Coupling in SU(3) gauge theory `Lüscher et al, '94`
- $N_\mathrm{f} = 2$ `Della Morte et al '04` and `Fritzsch et al '12`
- $N_\mathrm{f} = 2 + 1$ `Bruno et al '17`

These are the final results. Long series of theoretical papers and partial results was needed to get there.

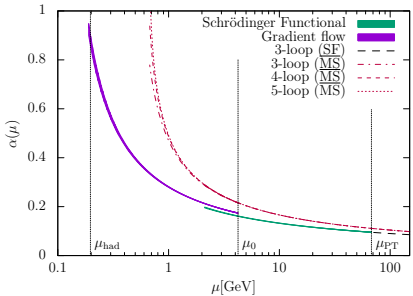
Ongoing work to improve precision.

Strong coupling: summary of strategy

- Finite size scaling
  Running from reaction of coupling to change of system size
- Use Schrödinger Functional for well-behaved finite size setup
- Combination of traditional SF coupling and newly developed gradient flow coupling for precision results
- Non-perturbative running from 0.2 GeV to 70 GeV $\rightarrow$ contact to perturbation theory
- Absolute scale from π and K decay constants $\rightarrow$ experimental input

$$\alpha^{(5)}_{\overline{\text{MS}}}(m_Z) = 0.11852(84)$$

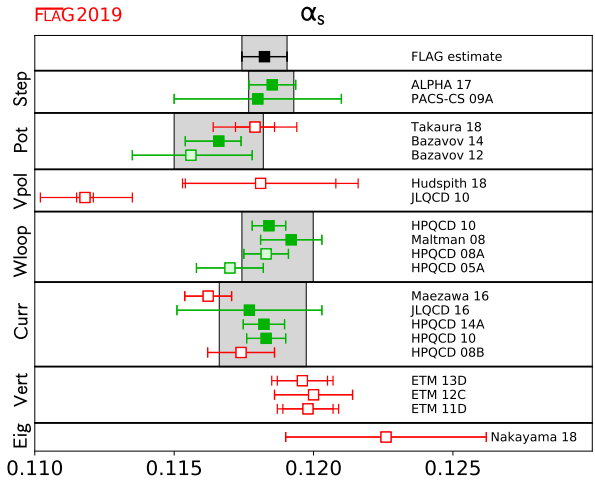
PRL 119 (2017) no. 10, 102001



Comparison to other lattice results

Regular collection and averaging of lattice results in FLAG report.

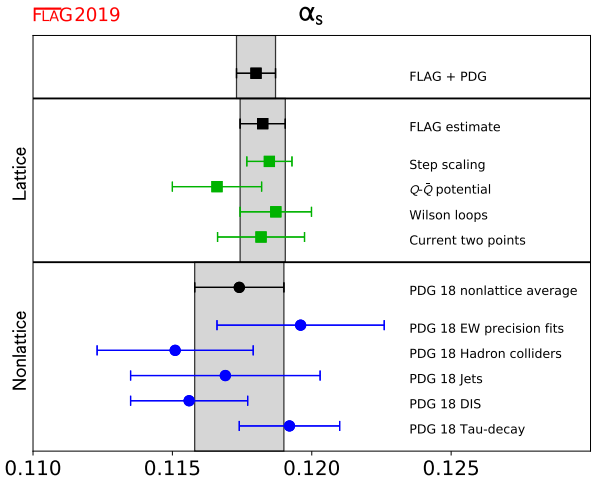
ALPHA result dominates final average.



Comparison to phenomenology

Unfortunately, no update of α_s in the PDG since 2016.

Lattice would dominate result.



Strong coupling: Present and Future

ALPHA collaboration is working on improving this result.

Current error roughly evenly split between running and scale setting.

Newly developed strategy for the running: surprising use of decoupling of heavy quarks.

Improved scale setting, leveraging the field configurations produced within CLS.

Parton distributions

Parton distribution functions (PDFs) encode the proton's structure

Needed to interpret high-energy collision data: LHC, Hera, …

Study of PDFs has long tradition at DESY, experimentally and theoretically.

Theory computation would make experiments more predictive.

$\rightarrow$ Need lattice QCD.

PDFs are a challenge for the lattice: light-cone quantities $\leftrightarrow$ Euclidean time

$$q(x,\mu) = \int_{-\infty}^{+\infty} d\xi^- \, e^{-ixP^+\xi^-} \, \langle N | \, \overline{\psi}(\xi^-) \, \Gamma W(\xi^-, 0) \, \psi(0) \, | N \rangle \, ,$$

with $W(\xi^-, 0)$ Wilson line between $\xi^- = \frac{1}{\sqrt{2}}(\xi^0 - \xi^3)$ and 0.

Parton distributions: standard approach

Strategy pursued since the ’80s: compute moments of PDFs

$$\langle x^n \rangle = \int_0^1 dx x^n q(x,\mu)$$

Local operators

$$\langle x \rangle \propto \langle N | \, \overline{\psi}(0) \, \gamma_\mu D_\mu \, \psi(0) \, | N \rangle$$

Feasible for low moments

Higher moments impractical due to operator mixing and large statistical uncertainties.

Parton distributions: new proposal

PDF: Wilson line $W((\xi^-, 0)$ on the light-cone

$$q(x,\mu) = \int_{-\infty}^{+\infty} d\xi^- \, e^{-ixP^+\xi^-} \, \langle N | \, \overline{\psi}(\xi^-) \, \Gamma W(\xi^-, 0) \, \psi(0) \, | N \rangle \, ,$$

New approach: quasi-PDF X. Ji,'13

$$\tilde{q}(x,\mu) = \int_{-z_{\text{max}}}^{+z_{\text{max}}} \frac{dz}{4\pi} \, e^{-ixP_3 z} \, \langle N | \, \overline{\psi}(0, z) \, \Gamma W(z, 0) \, \psi(0) \, | N \rangle \, ,$$

with z a space-like distance $\rightarrow$ feasible in Euclidean time.

Γ determines component: unpolarized, helicity or transversity

Parton distributions: Diagrams

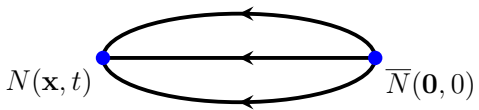
Use Large Momentum Effective Field Theory to connect the two

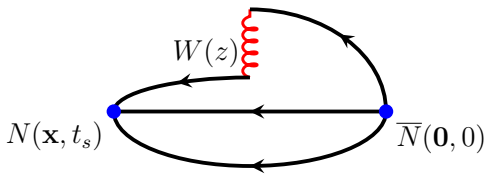
$$q(x,\mu) = \int_{-\infty}^{\infty} \frac{d\xi}{|\xi|} C\left(\xi, \frac{\mu}{P_3}\right) \tilde{q}\left(\frac{x}{\xi}, \mu, p_3\right) + O\left(\frac{m_N^2}{p_3^2}, \frac{\Lambda_{QCD}^2}{P_3^2}\right),$$

Recover PDF for $P_3 \to \infty$

Matching kernel $C\left(\xi, \frac{\mu}{p_3}\right)$ can be computed perturbation theory, currently 1-loop.

Need to compute two- and four-point functions on the lattice





Parton distributions

New approach a challenge for the lattice

- Renormalization needed to be devised
- Noisy signal: always a problem for baryons
  $P_3 \to \infty$ limit needs to be taken: Signal deteriorates even more
  Currently not possible to achieve $P_3 \gg m_n$.
- Potentially large discretization effects due to large momenta.
  Need multiple lattice spacings and $aP \ll 1$ in the future $\to$ under investigation

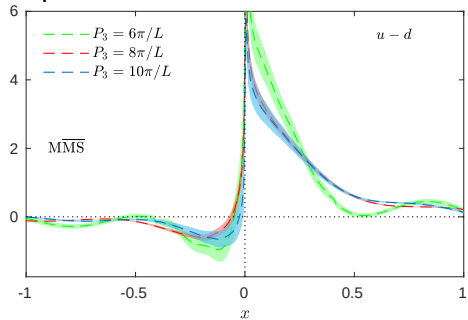
Extensive study led by K. Jansen and C. Alexandrou

`Phys.Rev. D99 (2019) no.11, 114504`

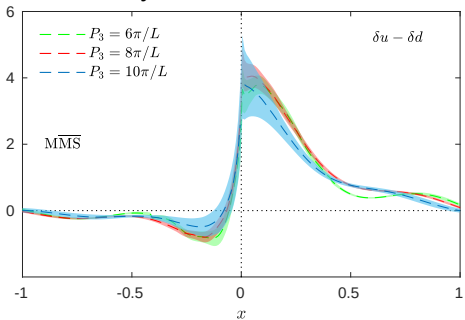
Examples

Approach to infinite momentum $P_3 \to \infty$

unpolarized $u - d$



transversity $\delta u - \delta d$



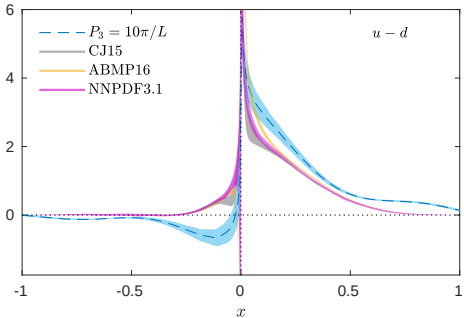
However, even largest momentum $P_3 \sim m_N$.

Signal deteriorates quickly for larger momenta.

Examples

Comparison to quasi-PDF computed from phenomenological determined PDFs.

unpolarized $u - d$



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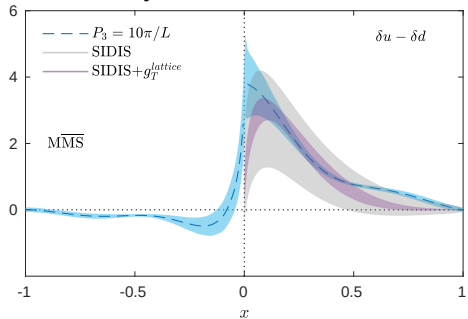

Summary: PDFs

Very promising approach to nucleon structure physics

Still need many more ideas to get precision results

Helmholtz International Fellow Award for Constantia Alexandrou

Intensification of successful Zeuthen-Cyprus collaboration
Already many common publications on this subject

Other projects: New paths

Quantum computing

- Quantum computers promise a new approach to field theoretical computations.
- Would make simulations at, e.g., finite chemical potential possible.
- Completely new algorithms and lattice setups need to be developed.
- Diverse hardware, still heavily evolving.
- Proof-of-principle in first toy model simulations of Schwinger model.
  Still a long way to go.
- Participation in European Flagship Programme QTFLAG.

Disclaimer: The list of further projects in not exhaustive.

Other projects: QCD

Theoretical analysis of the continuum limit

- Lattice quantities attain continuum limit $\propto a^n \left[\frac{1}{-\log a\Lambda_{\mathrm{QCD}}}\right]^{\hat{\gamma}}$
- Symanzik effective theory
  Analysis of $\hat{\gamma}$ for Yang–Mills and Wilson's QCD
  $\hat{\gamma} > 0 \Rightarrow$ acceleration of cont. limit
- Collaboration with Zeuthen TH group (P. Marquardt)

B-physics

- Development for $B \to \pi \ell \nu$ and $B_s \to K \ell \nu$.
- NP-HQET: Non-perturbative renormalization, well-defined cont. limit.
- Relevant for Belle-II.

Other projects: Gauge field generation

CLS

- European effort to generate large scale gauge field configurations.
- Crucial for many partners all over Germany and Europe, coordinated by NIC.
- Data management using DESY infrastructure (1M configs, 680TB)
  PaHN proposal to carry software to the future
- Monitoring, understanding and improving algorithmic setup.

ETMC

- Rich programme using twisted mass Wilson fermions.
- nucleon moments, charges and form factors, PDFs, ...

Summary

The NIC group is committed to making the Standard Model more predictive.

Road towards finding BSM effects.

Needs large scale simulations together with international partners.

Long term projects which overcome many technical and conceptual challenges.

High quality results recognized, see e.g. α_s.

Rich activities to explore and invent new apporaches.