Lattice QCD for the LHC

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Physics at the LHC and beyond

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Outline

- Introduction
- Proton structure
- Λ_b decay
- Two topics of High Precision QCD
- Summary

Lattice QCD for non-LHC

- Fundamental quantum field theory questions: orbifold equivalence, SUSY QCD, Large N QCD, phase diagrams etc.
- Nonperturbative dynamics beyond the standard model: mostly technicolour. Recently axions: topological susceptibility $\chi_t = f_a^2 m_a^2$ at high temperatures of interest. [E Berkowitz et al, 1505.07455, R Kitano, N. Yamada, 1506.00370, S Borsanyi et al, 1508.06917]
- Low energy standard model tests: matrix elements relevant for (B)SM β-decay, $(g-2)_\mu$, dark matter couplings, K physics ($K \to \pi\pi$, ϵ'/ϵ [T Blum et al, 1502.00263; I Ishizuka et al, 1505.05289; C Lehner et al 1508.01801]), D physics.
- Fundamental parameters: connect experiment to m_u, m_d, m_s, m_c, V_{cs}, V_{cd}, running of α_{em}, weak charge.
- Hadron spectroscopy, decay constants and distribution amplitudes: BES III, JLAB, Belle 2, PANDA@FAIR etc.
- Generalized parton distributions (GPDs), transverse momentum distributions (TMDs) etc.: relevant for COMPASS 2, JLAB, BNL, MAMI etc.

Lattice QCD for LHC

Important for LHC physics but not for BSM searches

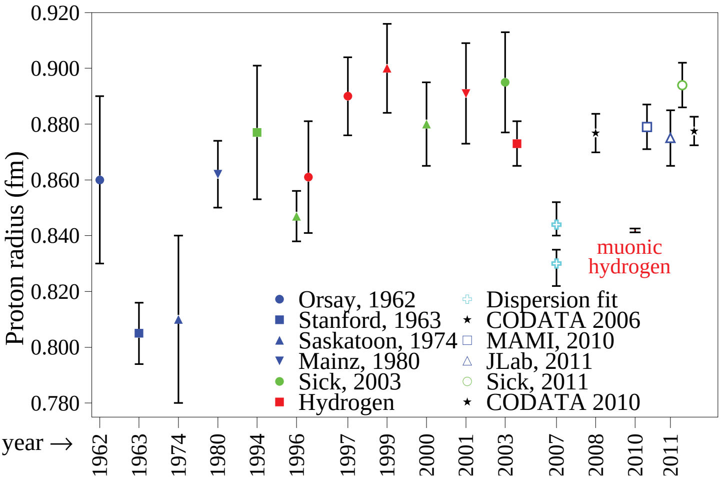
- ALICE (also ATLAS, CMS). QCD at high temperatures: transition temperature T_c to the QGP, hadron modifications at high T, Debye screening lengths, fluctuations of conserved charges, freezeout curve, equation of state, conductivity, role of magnetic fields etc.
- Spectroscopy of mesons and baryons with open and closed charm and bottom (LHC by-products) and some of their properties.

Important for SM tests at LHC

- Fundamental parameters: α_s, m_b.
- b-decays (LHC-b): f_B, f_{B_s}, electroweak decay form factors etc. to connect experiment to V_{cb}, V_{ub} etc.
- Hadron/proton structure: PDFs, DPDs (also distribution amplitudes for particle production).

Proton radius puzzle

We may not understand the probe used at LHC to discover new physics!

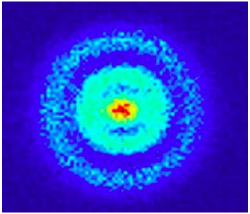


from R Pohl et al, arXiv 1301.0905

mass of the hydrogen atom:

$$\underbrace{938.29\,\mathrm{MeV}}_{\text{proton}} + \underbrace{0.51\,\mathrm{MeV}}_{\text{electron}} - \underbrace{0.0000136\,\mathrm{MeV}}_{\text{binding energy: }\frac{m_e\alpha_{em}^2}{2}}$$

RMS radius $\approx 0.92 \cdot 10^{-10}\mathrm{m} = 0.092$ nm

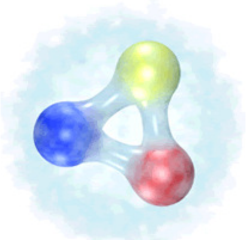


AS Stodolna et al, PRL (13) 213001

mass of the proton m_p:

$$\underbrace{2 \times 2.2\,\mathrm{MeV}}_{\text{up quarks}} + \underbrace{4.7\,\mathrm{MeV}}_{\text{down quark}} \underbrace{+}_{!!!} \underbrace{929.2\,\mathrm{MeV}}_{???}$$

RMS charge radius $\approx 0.84 \cdot 10^{-15}\mathrm{m} = 0.84$ fm



artist's impression

$$\text{Hydrogen:}\quad |E|\langle r_H^2\rangle^{1/2} = \sqrt{3}\underbrace{(m_e\alpha_{em})^{-1}}_{a_{\rm B}\approx 0.053\,{\rm fm}}|E| = \frac{\sqrt{3}}{2}\alpha_{em} \approx 0.006$$

$$\text{Proton:}\quad m_p\langle r_p^2\rangle^{1/2} \approx 4 = \mathcal{O}(1)$$

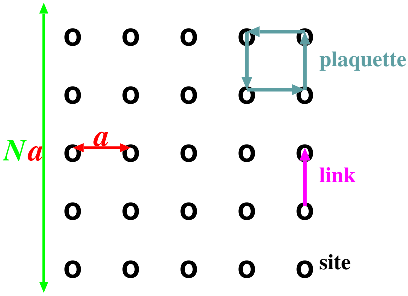
Solving a strongly coupled, non-linear, relativistic four-dimensional quantum system is not so easy
$\Longrightarrow$ numerical simulation.

Lattice spacing $a < 1/m_p$, i.e. $a\Lambda_{\rm QCD} \ll 1$, for polynomial cut-off effects.
$\Longrightarrow a^{-1} \gtrsim 2\,\text{GeV}$

Lattice extent $L \gg r_p$. Actually, finite size effects $\propto e^{-M_\pi L}$.
$\Longrightarrow L \gtrsim 4/M_\pi$
$\Longrightarrow L \gtrsim 5.8\,\text{fm}$ for physical pion mass.

This means $N = L/a > 5.8\,\text{fm} \cdot 2\,\text{GeV} \approx 60$.

We are lucky: $m_p/M_\pi \ll 60 \ll M_W/\Lambda_{\rm QCD} \ll M_{\rm Planck}/M_W$.



typical values:

$a^{-1} = 2\text{–}5$ GeV, $Na = 2\text{–}7$ fm

continuum limit: $a \to 0$, Na fixed

infinite volume: $Na \to \infty$

$$\langle O \rangle = \frac{1}{Z} \int [dU]\,[d\psi][d\bar{\psi}]\; O[U] e^{-S[U,\psi,\bar{\psi}]}$$

"Measurement": average over a representative ensemble of gluon configurations $\{U_i\}$ with probability $P(U_i) \propto \int [d\psi][d\bar{\psi}] e^{-S[U,\psi,\bar{\psi}]}$

$$\langle O \rangle = \frac{1}{n} \sum_{i=1}^{n} O(U_i) + \Delta O \qquad \Delta O \propto \frac{1}{\sqrt{n}} \xrightarrow{n\to\infty} 0$$

Input: discretized $\mathscr{L}_{QCD} = \frac{1}{16\pi\alpha_L(a)} FF + \bar{q}_f(\not{D} + m_f(a))q_f$

$$m_N^{\text{latt}} = m_N^{\text{phys}} \longrightarrow a$$
$$M_\pi^{\text{latt}}/m_N^{\text{latt}} = M_\pi^{\text{phys}}/m_N^{\text{phys}} \longrightarrow m_u(a) \approx m_d(a)$$
$$\ldots$$

Output: hadron masses, matrix elements, decay constants, etc...

Required:

1. $L = Na \to \infty$: FSE suppressed with $\exp(-LM_\pi) \Rightarrow LM_\pi \gtrsim 4$.
2. $m_q^{\text{latt}} \to m_q^{\text{phys}}$: chiral perturbation theory (χPT) helps for m_{ud} but m_{ud}^{latt} must be sufficiently small to start with ($M_\pi \lesssim 200\,\text{MeV}$?).
3. $a \to 0$: functional form known: $\mathcal{O}(a^2), \mathcal{O}(\alpha_s a) \Rightarrow \approx 4$ lattice spacings.

Only in very few calculations all the above is done as yet, e.g., light hadron spectrum, meson decay constants, α_s, $m_{u,d,s,c}$.

Computational challenges

Cost of simulation is proportional to

- number of points: $(L/a)^4$
- condition number of linear system: $1/M_\pi^2$
- $L^{1/2}/M_\pi$ in (Omelyan) time integration within hybrid Monte Carlo
- $1/a^{\geq 2}$ critical slowing down (autocorrelations)

Adjusting $L \propto 1/M_\pi$ this means:

$$\text{cost} \propto \frac{1}{a^{\geq 6}\, M_\pi^{7.5}}$$

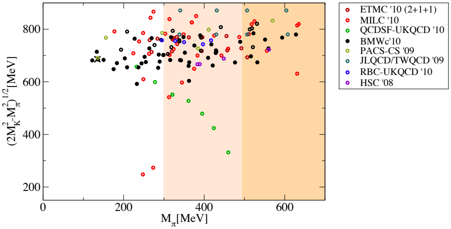
NB: for baryonic observables at small M_π additional noise/signal problems.

State of the art: $64^3 \times 128$ sites, corresponding to $\approx (4 \times 10^9)^2$ (sparse) complex matrices.

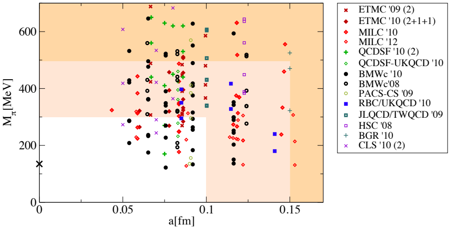
Tremendous progress in Hybrid Monte Carlo, solver, noise reduction.

Landscape of recent lattice simulations

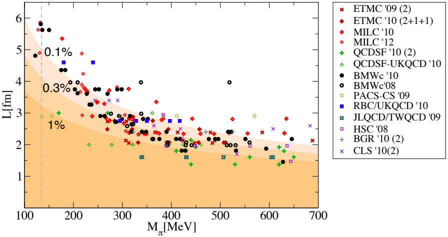
$M_{ss} \propto m_s$ vs. M_π



M_π vs. a

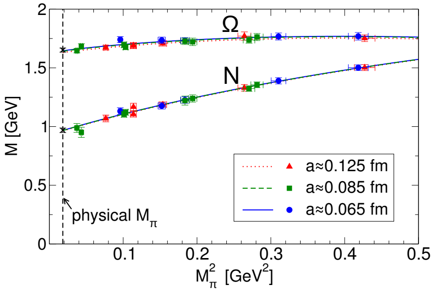


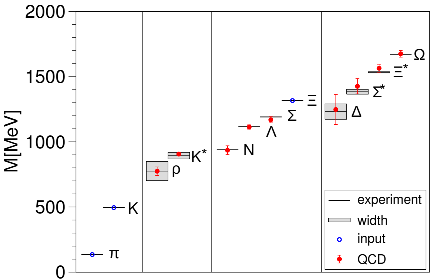
L vs. M_π



Figures taken from

[C Hoelbling, arXiv:1410.3403]

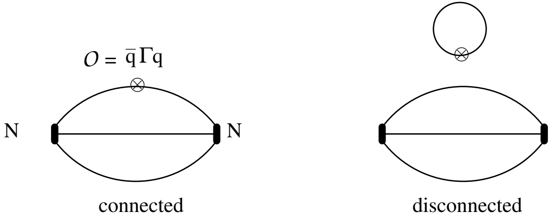




[BMW-c: S Dürr et al, arXiv:0906.3599]

Topic I: Proton structure. Three point functions

Evaluate $\langle N|\bar{q}\Gamma q|N\rangle$ (Lines: quark "propagators" M^{-1}_{xy}, $M = \not{D} + m_q$)



$q \in \{u, d\}$: both quark-line connected and disconnected terms.

$q = s$: only the disconnected term.

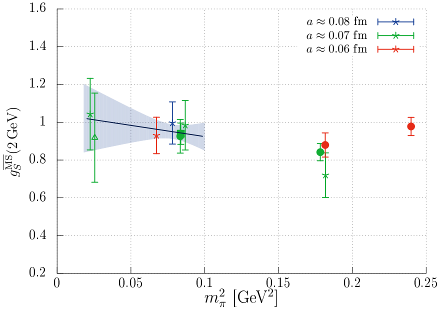
"Connected" requires only 12 rows (spin $\times$ colour) of M^{-1}.

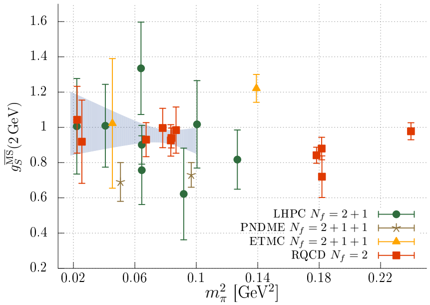
"Disconnected" $12N^3$ rows (timeslice): stochastic "all-to-all" methods.

"Disconnected" cancels ($m_u = m_d$, $\not{\text{QED}}$) from isovector combinations:
"proton minus neutron", i.e. $\langle p|(\bar{u}\Gamma u - \bar{d}\Gamma d)|p\rangle = \langle p|\bar{u}\Gamma d|n\rangle$.

Isovector scalar charge $g_S = G_S(0)$

$$\langle p|\bar{u}d|n\rangle = G_S(q^2)\bar{u}_p(\mathbf{p}_\mathrm{f})u_n(\mathbf{p}_\mathrm{i})$$



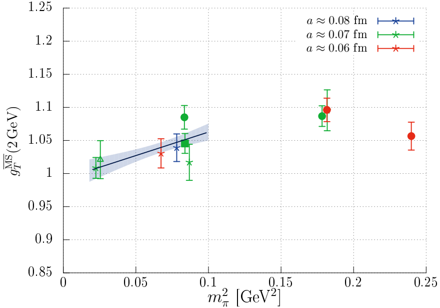


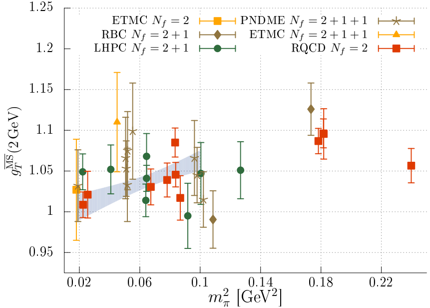
LHPC: 1206.4527, PNDME: 1306.5435, ETMC: 1411.3494, RQCD: 1412.7336

See also: ETMC: 1507.04936

Isovector tensor charge $g_T = G_T(0)$

$$\langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle = G_T(q^2)\bar{u}_p(\mathbf{p}_\mathrm{f})\sigma_{\mu\nu}u_n(\mathbf{p}_\mathrm{i})$$





ETMC: 1507.04936, RBC: 1003.3387, LHPC: 1206.4527,
PNDME: 1506.06411, RQCD: 1412.7336

General remark: we vary a^2 only by a factor 1.8 $\Rightarrow$ we cannot exclude lattice spacing effects of up to $0.071^2/(0.081^2 - 0.060^2) \cdot \Delta g \approx 1.7 \cdot \Delta g$.

Decomposition of the proton mass

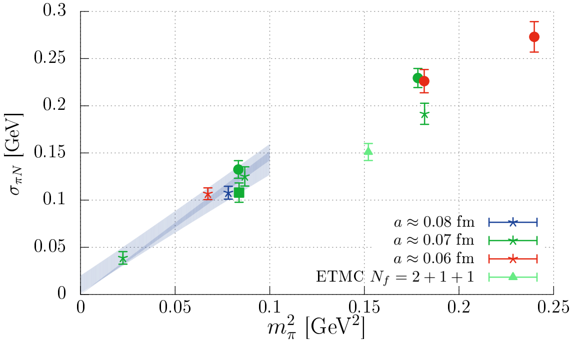
$$m_N = \underbrace{\sum_{q\in\{u,d,s,\dots\}} m_q \langle N|\bar{q}\,\mathbb{1}\,q|N\rangle}_{\text{quarks}} + \underbrace{\left\langle N\left|\frac{1}{8\pi\alpha_L}(\mathbf{E}^2-\mathbf{B}^2)+\sum_q \bar{q}\mathbf{D}\cdot\gamma q\right|N\right\rangle}_{\text{gluon interactions (Eucl. spacetime)}}$$
$$+\underbrace{\frac{1}{4}\left(m_N-\sum_q m_q\langle N|\bar{q}\,\mathbb{1}\,q|N\rangle\right)}_{\text{trace anomaly}}$$

VEV $\langle 0|\bar{q}q|0\rangle$ is understood to be subtracted from $\langle N|\bar{q}q|N\rangle$.

Pion-nucleon σ-term: $\sigma_{\pi N} = m_u\langle N|\bar{u}u|N\rangle + m_d\langle N|\bar{d}d|N\rangle = \sigma_u + \sigma_d$.

Requires computation of disconnected quark loops, unless obtained via derivative $\sigma_q = \partial m_N/\partial \ln m_q$.

Scalar particles (Higgs, neutralino etc.) couple $\propto$ quark matrix elements.



$LM_\pi \approx 6.7$: ■
$LM_\pi > 4.1$: ● ●
$LM_\pi > 3.4$: * * *

[RQCD: S Collins et al, in preparation]

The non-vanishing light quark masses are directly responsible for only ≈ 35 MeV of the nucleon mass but for 68 MeV of the pion mass!

This may not be too surprising since $m_N \not\to 0$ as $m_{ud} \to 0$: Most nucleon mass is from the glue.

The scalar matrix elements $m_q\langle N|\bar{q}q|N\rangle$ determine the coupling of the nucleon to scalar particles at zero recoil:

$$\frac{f_N}{m_N} \approx \sum_{q\in\{u,d,s\}} f_{T_q}\frac{\alpha_q}{m_q} + \frac{2}{27}f_{T_G}\frac{\alpha_c}{m_c} + \frac{2}{25}f_{T_G}\frac{\alpha_b}{m_b} + \frac{2}{23}f_{T_G}\frac{\alpha_t}{m_t}\,.$$

Cross section $\propto |f_N|^2$. Higgs example: $\alpha_q \propto m_q/m_W$.

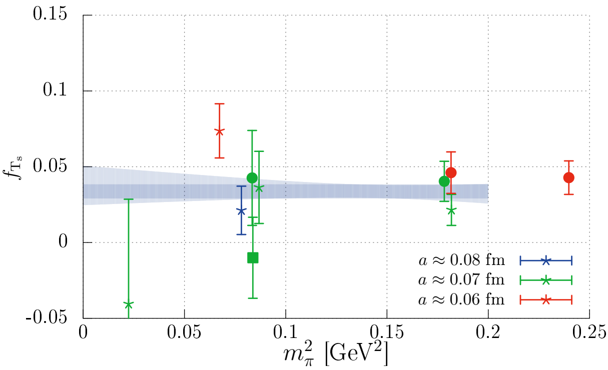
$$f_{T_q} \equiv \frac{m_q\langle N|\bar{q}q|N\rangle}{m_N}$$

are the contributions of the light quark masses to the proton mass and

$$f_{T_G} \approx 1 - \sum_{q\in\{u,d,s\}} f_{T_q}\,.$$

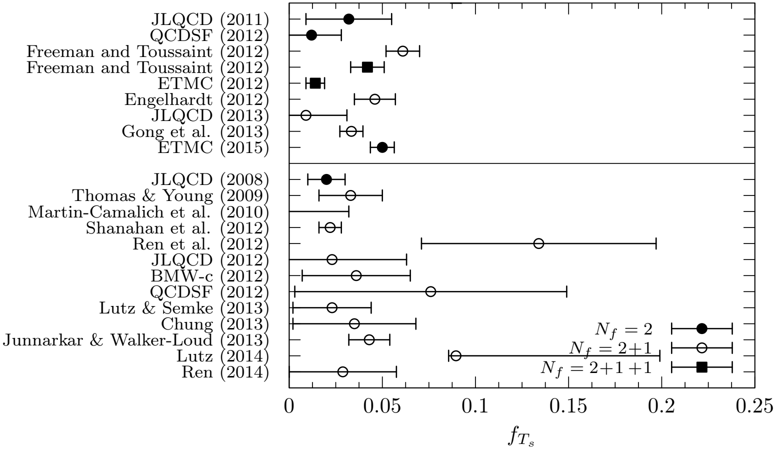
Little about f_{T_q} is known experimentally.

Scalar strangeness content



[QCDSF: GB et al, arXiv:1111.1600,
RQCD: S Collins et al, in preparation]

f_{T_s}: Other lattice results



direct method

from fit of $m_N(m_s)$

Spin of the nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \sum_{q,\bar{q}} L_q + J_g \ :$$

Ji decomposition into the contributions of the (longitudinal) quark spins

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \cdots ,$$

the (longitudinal) quark and antiquark orbital angular momenta $L_q = J_q - \frac{1}{2}\Delta q$ and the (longitudinal) gluon total angular momentum J_g.

Naïve non-relativistic SU(6) quark model: $\Delta\Sigma = 1$, $L_q = J_g = \Delta s = 0$.
Relativistic quark models: $\Delta\Sigma \sim 0.6$, $L_{\text{quarks}} \sim 0.2$.

I will say nothing about the Jaffe and Manohar decomposition:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathcal{L}_{\text{quarks}} + \Delta G + \mathcal{L}_g \quad \left(J_g \neq \Delta G + \mathcal{L}_g, J_q \neq \frac{1}{2}\Delta q + \mathcal{L}_q \right) .$$

Individual quark spin contributions ($q \in \{u, d, s\}$)

$$(\Delta q + \Delta\bar{q})\ s_\mu = \frac{1}{m_N} \langle N, s\,|\bar{q}\gamma_\mu\gamma_5 q|\,N, s\rangle = F_A^q(0) = \tilde{A}_{10}^q(0)$$

Axial charges:

$$a_3 = -s_\mu \frac{1}{m_N}\langle N, s|\bar{\psi}\gamma_\mu\gamma_5\lambda_3\psi|N, s\rangle = \Delta u - \Delta d = g_A$$

$$a_8 = -s_\mu \frac{\sqrt{3}}{m_N}\langle N, s|\bar{\psi}\gamma_\mu\gamma_5\lambda_8\psi|N, s\rangle$$

$$= \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2\Delta s - 2\Delta\bar{s}$$

$$a_0(Q^2) = -s_\mu \frac{1}{m_N}\langle N, s|\bar{\psi}\gamma_\mu\gamma_5\mathbb{1}\psi|N, s\rangle$$

$$= \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} = \Delta\Sigma(Q^2)\,.$$

$\psi = (u, d, s)^t$, λ_j are Gell-Mann flavour matrices.
$a_3 = g_A$ known from neutron β decay, assuming isospin symmetry.
a_8 usually estimated from hyperon β decay, assuming $\mathrm{SU}(3)_F$ symmetry.

Extraction of the Δq's from experiment

DIS gives spin structure functions of proton and neutron $g_1^{p,n}(x,Q^2)$.

First moment related to a_i's via OPE (leading twist):

$$\Gamma_1^{p,n}(Q^2) = \int_0^1 \mathrm{d}x\, g_1^{p,n}(x,Q^2) \quad = \quad \frac{1}{36}\left[(a_8 \pm 3a_3)C_{NS} + 4a_0 C_S\right]$$

Use models to extrapolate g_1 from experimental $x_{\min}$ to $x=0$!
$C_{S/NS} = C_{S/NS}(\alpha_s(Q^2))$.

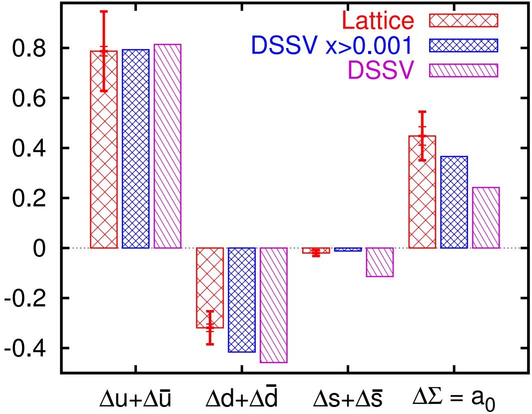
Combinations of a_i give Δq's, e.g., $(\Delta s + \Delta\bar{s})(Q^2) = \frac{1}{3}[a_0(Q^2) - a_8]$

SIDIS allows for direct measurements of the $\Delta q(x)$ but requires fragmentation functions.
[COMPASS, arXiv 1001.4654]

	Naive Extrap.	combined with DSSV
$(\Delta s + \Delta\bar{s})(5\,\mathrm{GeV}^2)$	$-0.02 \pm 0.02 \pm 0.02$	$-0.10 \pm 0.02 \pm 0.02$

DSSV: [de Florian et al, arXiv:0904.3821]

No continuum limit, $M_\pi \approx 290$ MeV $\Rightarrow$ add 20 % systematic error.

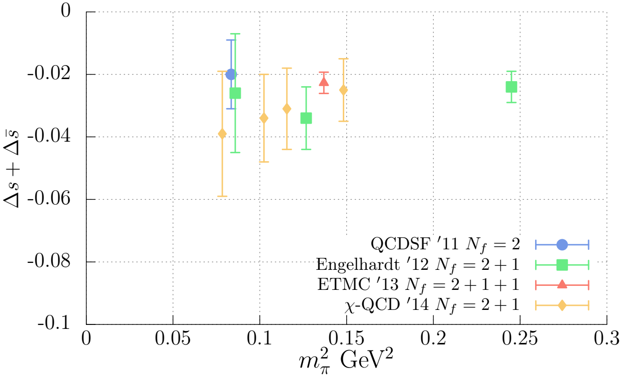


[QCDSF: GB et al, 1112.3354]

Result in the $\overline{\mathrm{MS}}$ scheme at $\mu^2 = 7.4$ GeV^2:

$$\begin{aligned} \Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} &= \quad 0.45(4)(9) \\ \Delta s + \Delta\bar{s} &= -0.020(10)(4) \end{aligned}$$

Comparison of recent lattice calculations



Consistency between different determinations: small $\Delta s + \Delta\bar{s}$.

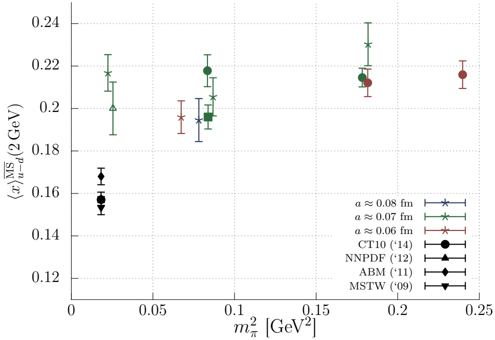
ETMC result shows statistical accuracy that is possible. Systematics!

[QCDSF: GB et al, 1112.3354; M Engelhardt, 1210.0025; ETMC: A Abdel-Rehim et al, 1310.6339; χQCD: Y Yang et al, unpublished.]

$\exists$ similar results by [UKQCD/CSSM: A Chambers et al, 1508.06856; T Bhattacharya et al, 1503.05975]

Isovector quark momentum fraction: $\langle x \rangle_{u-d}^{\overline{\rm MS}}(2\,{\rm GeV})$

[RQCD: GB et al, arXiv:1408.6850] $N_f = 2$



$LM_\pi \approx 6.7$: ■

$LM_\pi > 4.1$: ● ●

$LM_\pi > 3.4$: * * *

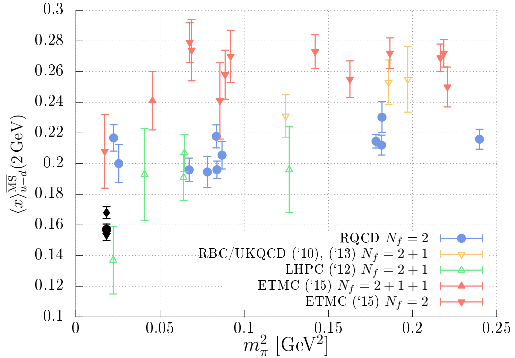
$LM_\pi \approx 2.8$: △

Mild dependence on V, M_π.
Renormalised non-perturbatively.
$\mathcal{O}(a)$ leading errors, a varied from 0.08 to 0.06 fm.

Improvement on earlier calculations which suffered from excited state contamination, obtaining $\langle x \rangle_{u-d}^{\overline{\rm MS}}(2\,{\rm GeV}) \sim 0.25$.

Near physical point but more work needs to be done — lattice spacing dependence? Lattice artefacts linear in a could exceed statistical errors by a factor of three.

$\langle x \rangle^{\overline{\text{MS}}}_{u-d}(2\,\text{GeV})$: summary of recent lattice results



RQCD: GB et al, 1408.6850; RBC/UKQCD: Y Aoki et al, arXiv:1003.3387; LHPC: J Green et al, arXiv:1209.1687; ETMC: A Abdel-Rehim et al, arXiv:1507.05068.

PDFs from

S Alekhin et al, 1310.3059; CT10: J Gao et al, 1302.6246; NNPDF: R Ball et al 1207.1303; A Martin et al 0905.3531.

Isosinglet $\langle x \rangle_q$

Huge uncertainties. Example $\langle x \rangle_s$:

NNPDF2.3 [R Ball et al, arXiv:1207.1303]:

$$\frac{\langle x \rangle_s}{\langle x \rangle_{u-d}} = 0.111(5)$$

CT10 [H-L Lai et al, arXiv:1007.2241]:

$$\frac{\langle x \rangle_s}{\langle x \rangle_{u-d}} \approx 0.17$$

MSTW2008 [A Martin et al, arXiv:0901.0002]:

$$\frac{\langle x \rangle_s}{\langle x \rangle_{u-d}} \approx 0.13$$

(I was too lazy to upload NNPDF3.0/CT14 etc. into LHAPDF)

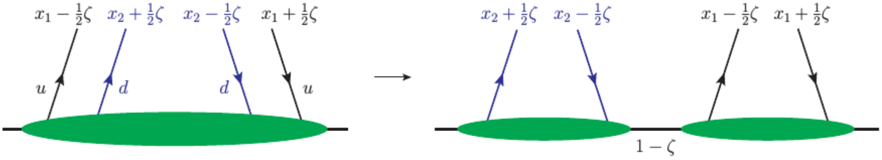
First lattice results on $\langle x \rangle_s / \langle x \rangle_{u,d}$ [χQCD: M Sun et al, 1502.05482; ETMC: C Alexandrou et al, 1410.8761]: Mixing of $\langle x \rangle_s$ with $\langle x \rangle_g$ and $\langle x \rangle_{u,d}$ ignored.

Double hard scattering: DPDs

Needed to describe background (underlying event, cf. Frank Krauss' talk)
Example W^+W^+ production. $qq \to qqW^+W^+$. Double parton scattering is important! [G Gaunt et al, arXiv:1003.3953]

Also (considering gluons) $c\bar{c}c\bar{c}$ over $c\bar{c}$ production ~ 100 times higher than theory predictions [LHCb, arXiv:1205.0975]!

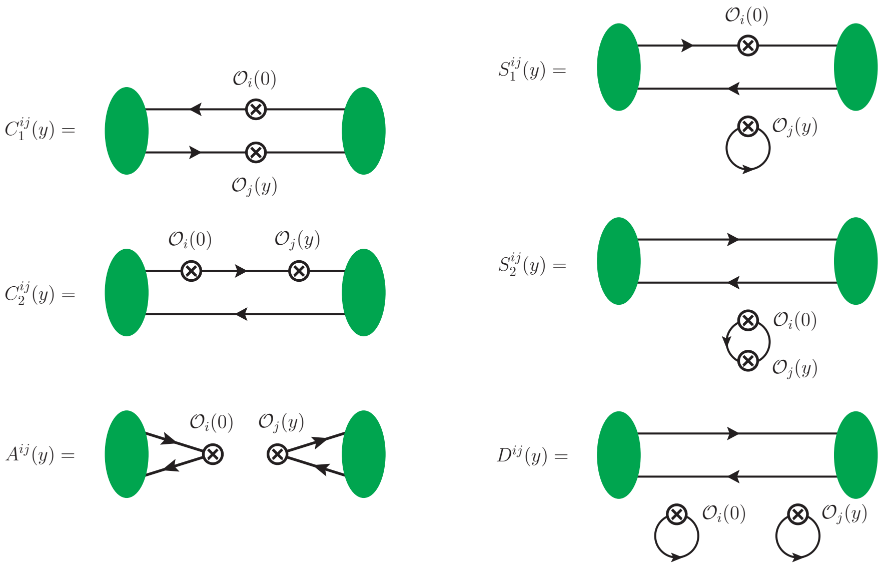
Typically convolution of DPD into two generalized form factors is assumed.



$$A^{ud}_{VV}(y^2, py = 0) = \int_{-1}^{1} d\zeta \int_{-1}^{1} dx_1 dx_2 \, F_{ud}(x_1, x_2, \zeta, \mathbf{y}^2)$$

can be extracted from four point functions on the lattice. For the pion:

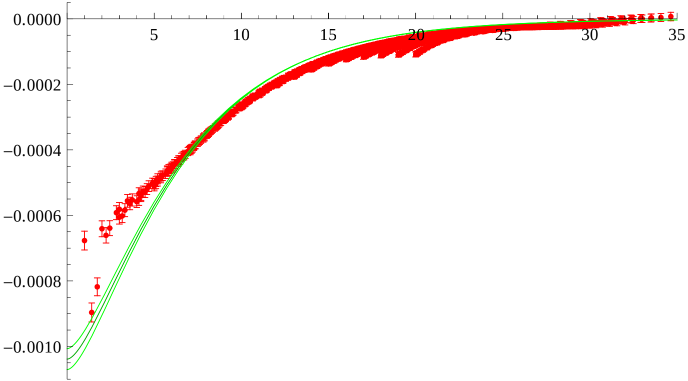
$$\langle \pi^- | [\bar{u}\gamma_{mu} d](\mathbf{y})[\bar{u}\gamma_\nu d(\mathbf{0})] | \pi^+ \rangle$$


$C_1^{ij}(y) =$
$\mathcal{O}_i(0)$
$\mathcal{O}_j(y)$
$C_2^{ij}(y) =$
$\mathcal{O}_i(0)$
$\mathcal{O}_j(y)$
$A^{ij}(y) =$
$\mathcal{O}_i(0)$
$\mathcal{O}_j(y)$
$S_1^{ij}(y) =$
$\mathcal{O}_i(0)$
$\mathcal{O}_j(y)$
$S_2^{ij}(y) =$
$\mathcal{O}_i(0)$
$\mathcal{O}_j(y)$
$D^{ij}(y) =$
$\mathcal{O}_i(0)$
$\mathcal{O}_j(y)$

Comparison of A_{VV} with convolution of EM formfactors

G Bali, L Castagnini, M Diehl, J Gaunt, B Gläßle, A Schäfer, C Zimmermann,.... very preliminary

$M_\pi \approx 290\,\text{MeV}$, lattice extent: $L = 40a$, $a \approx 0.071\,\text{fm}$.



Seems to work for $|\mathbf{y}| \gtrsim 0.4\,\text{fm}$

(Small $|\mathbf{y}|$: lattice artefacts. Large $|\mathbf{y}|$: finite size effects.)

[W Detmold, C Lehner, S Meinel, 1503.01421]

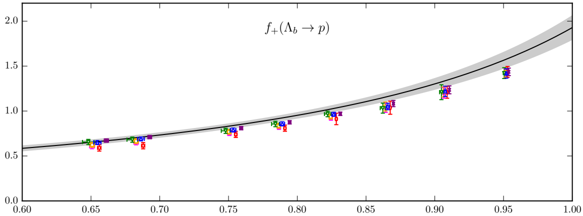
$q^2 \in [14, 22], [7, 15]$ GeV^2

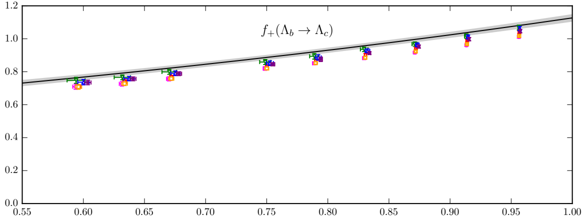
$a \approx 0.112, 0.085$ fm

$M_\pi \in [230, 350]$ MeV

FNAL heavy quark action tuned to give correct meson masses.

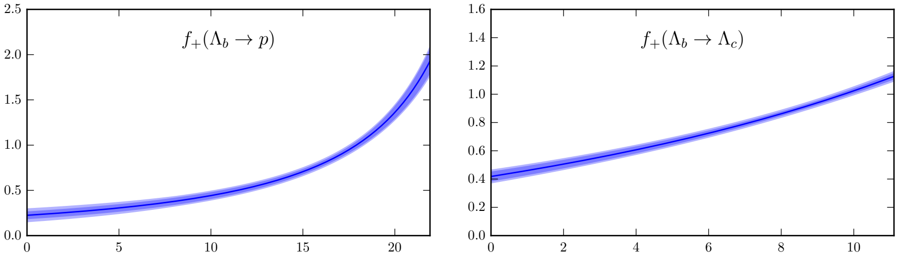
Curves: extrapolations to $a = 0$, $M_\pi = 135$ MeV.





Also $f_0, f_\perp, g_+, g_0, g_\perp$ have been computed.

Parametrization of the lattice data:

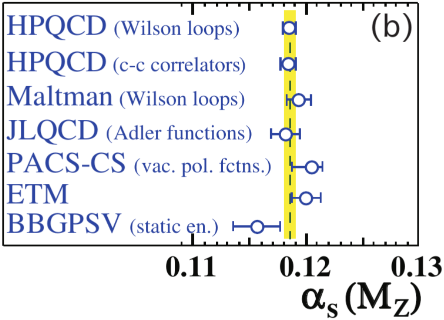


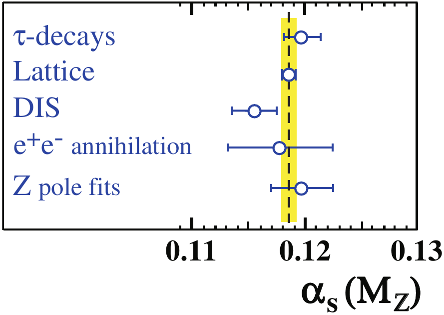
Note that lattice data covers $q^2 \in [14, 22]\,\mathrm{GeV}^2$ and $q^2 \in [7, 15]\,\mathrm{GeV}^2$

Authors claim, including all systematics and combining with data for smaller q^2, theory accuracy of 2.2% for $|V_{cb}|$ and 4.3% for $|V_{ub}|$ can be achieved.

Results used in [LHCb: R Aaij et al, 1504.01568].
(also talk by Marco Ciuchini).

Topic III: High precision QCD. Strong coupling parameter





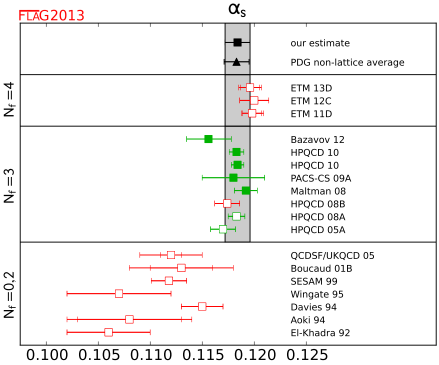
[PDG 2014]: Lattice average: $\alpha_s(M_Z) = 0.1185(5)$

World average: $\alpha_s(M_Z) = 0.1185(6)$
(cf. talk by Giulia Zanderighi)

World average without Lattice: $\alpha_s(M_Z) = 0.1183(12)$

Strong coupling parameter II

FLAG 2 report: [FLAG: S Aoki et al, 1310.8555]



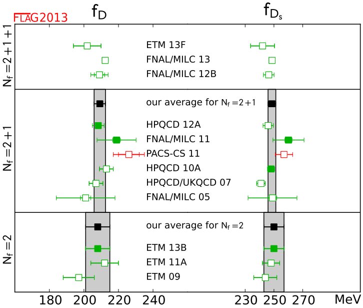
Lattice average: $\alpha_s(M_Z) = 0.1184(12)$

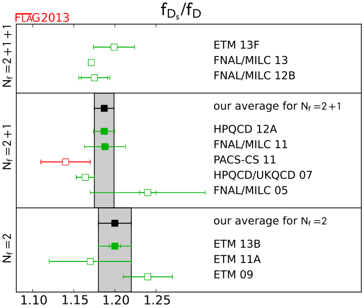
PDG world average without lattice: $\alpha_s(M_Z) = 0.1183(12)$

Lattice QCD will improve on this. Present limitation is scale μ of $\alpha(\mu)$ relative to the order of the perturbative matching to the $\overline{\text{MS}}$ scheme.

The precision frontier: D and D_s decay constants

FLAG 2 report: [FLAG: S Aoki et al, 1310.8555]





FLAG 2: $f_{D_s} = 248.6(2.7)$, $f_{D_s}/f_D = 1.187(12)$

Preliminary FLAG 3 analysis [FLAG: A Vladikas, 1509.01155]:

$N_f = 2+1$: $f_{D_s} = 249.8(2.3)$, $N_f = 2+1+1$: $f_{D_s} = 248.8(1.3)$

Latest CKMfitter `http://ckmfitter.in2p3.fr/` (did not check UTfit):

f_{D_s}

Reference	Article	N_f	Mean	Stat	Syst
ETMC09	[61]	2	244	3	9
HPQCD10	[71]	2+1	248.0	1.4	4.5
FNAL-MILC11	[70]	2+1	260.1	8.9	16.2
FNAL-MILC14	[69]	2+1+1	249.0	0.3	$^{+1.7}_{-2.1}$
ETMC14	[67]	2+1+1	247.2	3.9	2.2
Our average			248.2	0.3	1.9

f_{D_s}/f_D

Reference	Article	N_f	Mean	Stat	Syst
ETMC09	[61]	2	1.24	0.03	0.01
FNAL-MILC11	[70]	2+1	1.188	0.014	0.054
HPQCD12	[72]	2+1	1.187	0.004	0.023
FNAL-MILC14	[69]	2+1+1	1.1712	0.0010	$^{+0.0037}_{-0.0040}$
ETMC14	[67]	2+1+1	1.192	0.019	0.017
Our average			1.175	0.001	0.004

Potentially dangerous: [69] dominates.

Difference f_{D^+} vs f_{D^0}? Are f_{D^+}, f_{D_s} defined at all?

Electromagnetic corrections, e.g., [N Carrasco et al, 1502.00257]!

Summary

- Many quantities that are hard to constrain by experiment, e.g., $\sigma_{\pi N}$, f_{T_s}, g_S, g_T, are accessible in Lattice QCD.
- Lattice calculations are important to determine the spin content of the nucleon: Δq, $\Delta\Sigma$, J_q, $\langle x\rangle_{\Delta q}$, ...
  People should take $\Delta s + \Delta\bar{s} \approx -0.02$ result more seriously!
- In the past disconnected quark line diagrams were often omitted and differences quoted: g_A, $\langle x\rangle_{u-d}$, ..., but no Δs, $\Delta\Sigma$, J_q, $\langle x\rangle_q$ etc.
  Improved methods now allow for the calculation of these contributions.
- $\langle x\rangle_{u-d}$ comes out almost 20% bigger than expected.
  Lattice spacing effects? Renormalization?
- First studies of double hard parton scattering/quark correlations.
- High Mellin moments almost impossible to compute $\Rightarrow$ recent interest also in "quasi" parton distribution functions.
- Lattice QCD is major input in flavour physics.
  Reliable error estimates are very important!
- Electromagnetic corrections are now of major interest.