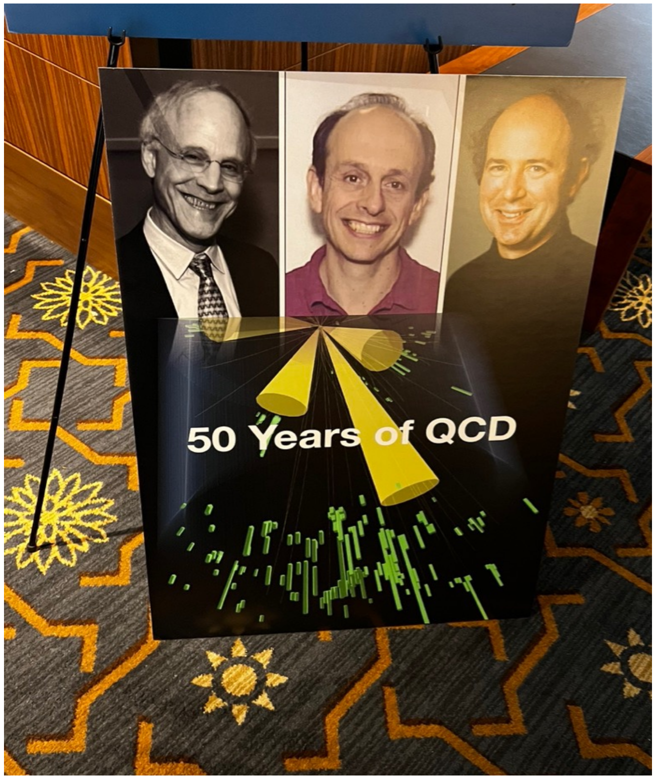
Quantum Chromodynamics at 50. The Power and the Glory

H.Fritsch,M. Gell-Mann, H. Leutwyler, PLB47 (1973) 365
D. Gross, F. Wilczek; PRL30 (1973) 1343; D. Politzer, PRL30 (1973) 1346



From Gell-Mann's 8-fold way to QCD: A lepidopteral metaphor

Jeffrey Mandula, Creutz-Fest 2014, BNL

New Quantum Numbers
The Eightfold Way / Unitary Symmetry
Mesons ~ $\underset{\sim}{8}$ Baryons ~ $\underset{\sim}{8} + \underset{\sim\sim}{10}$
Fundamental Representation Absent

The Quarks: Fractional Charge Triplets
Are They Real? (Constituents of Hadrons)
Are They Just a Mathematical Shorthand?
Relationship to Weak Currents?

Thinking About Real Quarks –
Spin/Statistics Problem → Parafermions
Color (New SU(3)!) – More Shorthand?
Still No Dynamics; Confinement a Mystery

Asymptotic Freedom → Quarks = Partons
Promotion of Color to the Essence of
Strong Dynamics; Gluons a Color $\underset{\sim}{8}$
QCD the Theory of Strong Interactions

Quantum Chromodynamics (QCD)

QCD - "nearly perfect" fundamental quantum theory of quark and gluon fields F.Wilczek, hep-ph/9907340

Theory is rich in symmetries: "Symmetries dictate interactions" – C.N Yang

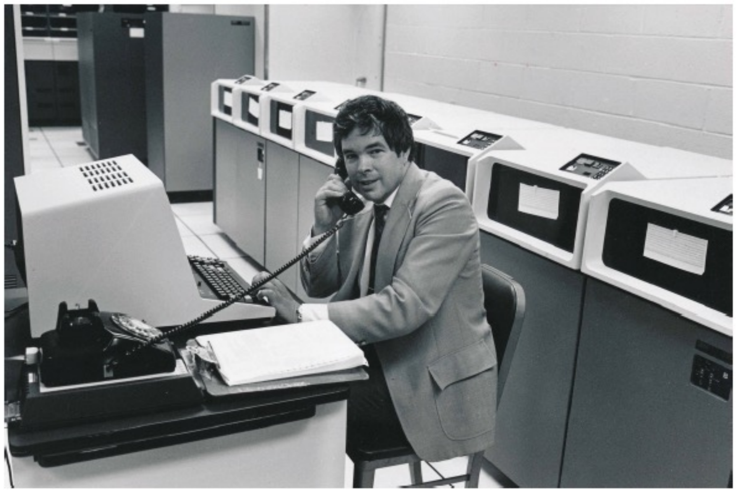
$$\underbrace{SU(3)_c}_{\text{i}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\text{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\text{iii}}$$

i) Gauge "color" symmetry: unbroken but confined
ii) Global "chiral" symmetry: exact for massless quarks
iii) Baryon number and axial charge (m=0) are conserved
iv) Scale invariance of quark (m=0) and gluon fields
v) Discrete C,P & T symmetries

Chiral, Axial, Scale and (in principle) C, P &T broken by vacuum/quantum effects - "emergent" phenomena

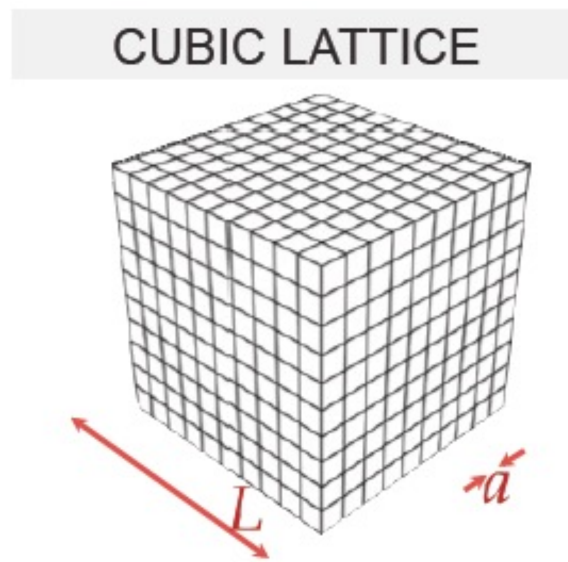
Inherent in QCD are the deepest aspects of relativistic Quantum Field Theories (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry)

Numerical realization: Lattice QCD



Kenneth G. Wilson

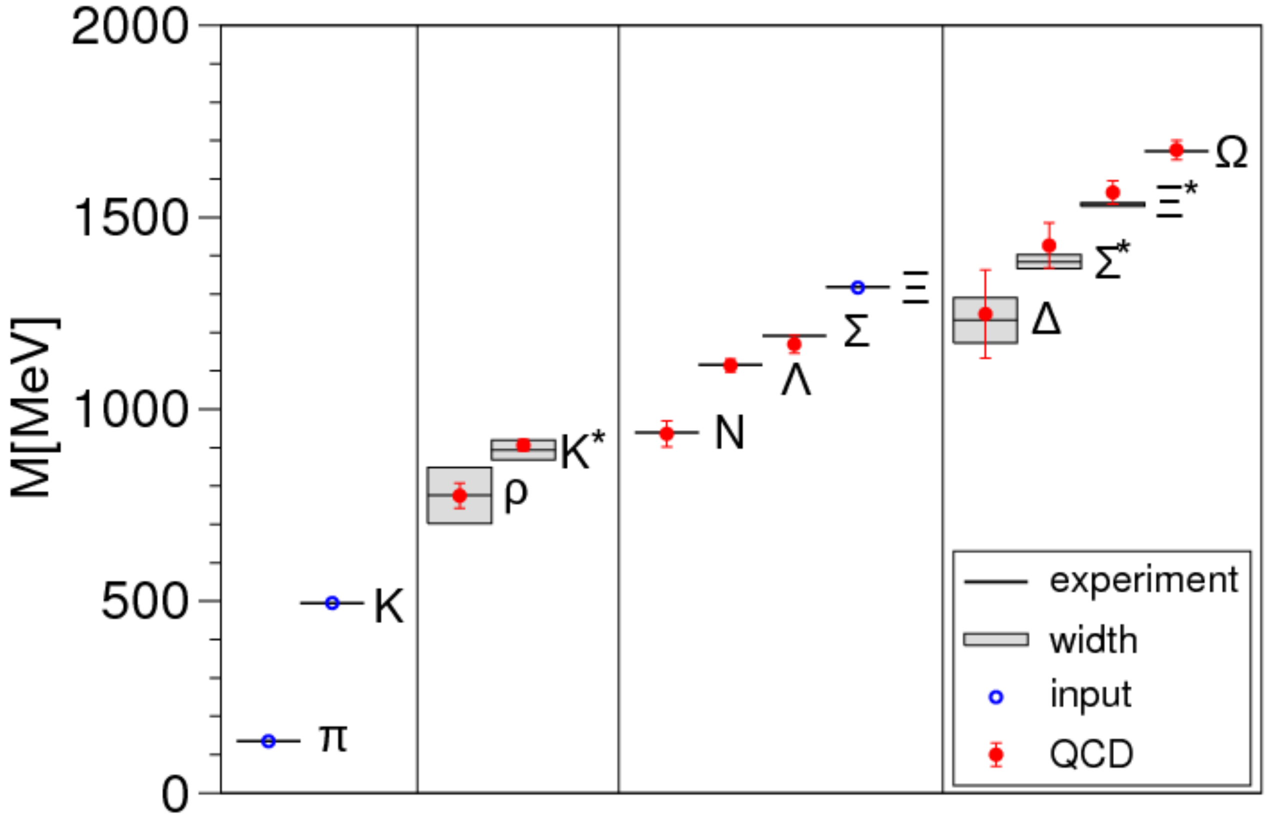
(1982)



Lattice regularization (UV&IR) of QCD

First principles treatment of static properties of QCD: masses, moments, thermodynamics at finite T (& μ_B ?)

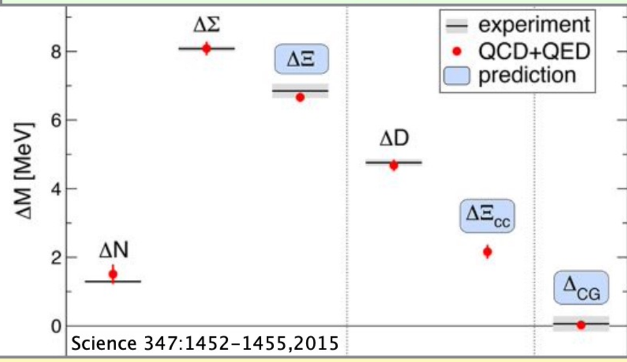
Precision QCD on the lattice



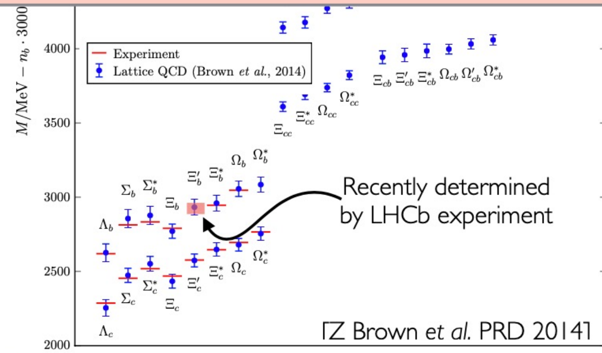
Durr et al., Science, 322 (2008)

The power of the lattice – unleashed!

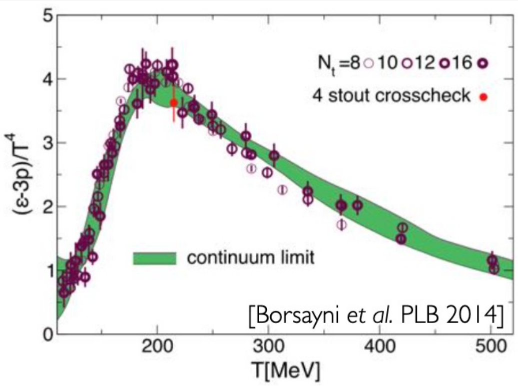
p-n mass splitting reproduced



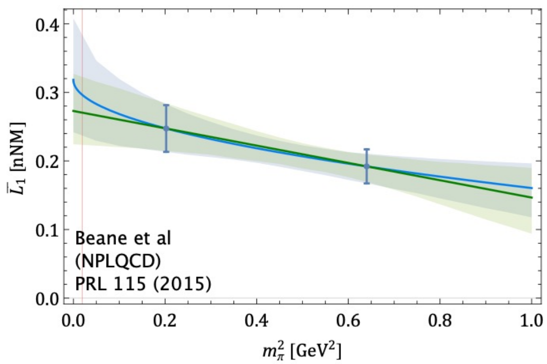
Predictions for new states



QCD Equation of state vs temperature



First studies of nuclear reactions



Slide courtesy of P. Shanahan

Noteworthy development: Constraining hadron matrix elements enabling discovery science with muon g-2

Muon g-2 Theory Initiative, R. Aliberti et al., Phys. Repts. 1143 (2025) 1

The power of the lattice – unleashed!

Quantity	Sec.	$N_f = 2+1+1$	Refs.	$N_f = 2+1$	Refs.	$N_f = 2$	Refs.
m_{ud}[MeV]	4.1.1	3.427(51)	[7–9]	3.387(39)	[10–16]		
m_s[MeV]	4.1.1	93.46(58)	[7–9, 17, 18]	92.4(1.0)	[11–15, 19]		
m_s/m_{ud}	4.1.2	27.227(81)	[7, 8, 20, 21]	27.42(12)	[12–14, 19, 22]		
m_u[MeV]	4.1.3	2.14(8)	[9, 23]	2.27(9)	[24]		
m_d[MeV]	4.1.3	4.70(5)	[9, 23]	4.67(9)	[24]		
m_u/m_d	4.1.3	0.465(24)	[23, 25]	0.485(19)	[24]		
$\overline{m}_c$(3 GeV)[GeV]	4.2.2	0.989(10)	[7–9, 18, 26, 27]	0.991(6)	[15, 28–32]		
m_c/m_s	4.2.3	11.766(30)	[7–9, 18]	11.82(16)	[29, 33]		
$\overline{m}_b(\overline{m}_b)$[GeV]	4.3	4.200(14)	[9, 34–37]	4.171(20)	[15]		
$f_+(0)$	5.3	0.9698(17)	[38, 39]	0.9677(27)	[40, 41]		
$f_{K^\pm}/f_{\pi^\pm}$	5.3	1.1934(19)	[20, 42–45]	1.1916(34)	[10, 12, 46–50]		
$f_{\pi^\pm}$[MeV]	5.6			130.2(8)	[10, 12, 46, 47]		
$f_{K^\pm}$[MeV]	5.6	155.7(3)	[21, 42, 43, 45]	155.7(7)	[10, 12, 46, 47]		

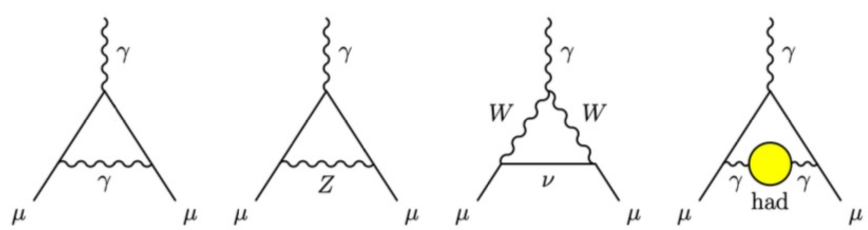
Quark masses, hadron decay constants

Quantity	Sec.	$N_f = 2+1+1$	Refs.	$N_f = 2+1$	Refs.
g_A^{u-d}	10.3.1	1.263(10)	[88–91]	1.265(20)	[92–96]
g_S^{u-d}	10.3.1	1.085(114)	[90]	1.083(69)	[93–97]
g_T^{u-d}	10.3.1	0.981(21)	[90, 98]	0.993(15)	[93–96]
g_A^u	10.4.1	0.777(25)(30)	[99]	0.847(18)(32)	[92]
g_A^d	10.4.1	−0.438(18)(30)	[99]	−0.407(16)(18)	[92]
g_A^s	10.4.1	−0.053(8)	[99]	−0.035(6)(7)	[92]
g_T^u	10.4.1	0.784(28)(10)	[100]		
g_T^d	10.4.1	−0.204(11)(10)	[100]		
g_T^s	10.4.1	−0.0027(16)	[100]		
$\sigma_{\pi N}$[MeV]	10.4.4	60.9(6.5)	[26, 101]	42.2(2.4)	[102–106]
σ_s[MeV]	10.4.4	41.0(8.8)	[107]	44.9(6.4)	[102–108]
$\langle x \rangle_{u-d}$	10.5.1	0.158(32)	[98, 109]	0.153(13)	[96, 110, 111]
$\langle x \rangle_{\Delta u-\Delta d}$	10.5.1	0.213(27)	[109]	0.200(13)	[96, 110]
$\langle x \rangle_{\delta u-\delta d}$	10.5.1	0.195(25)	[98, 109]	0.206(17)	[96, 110]

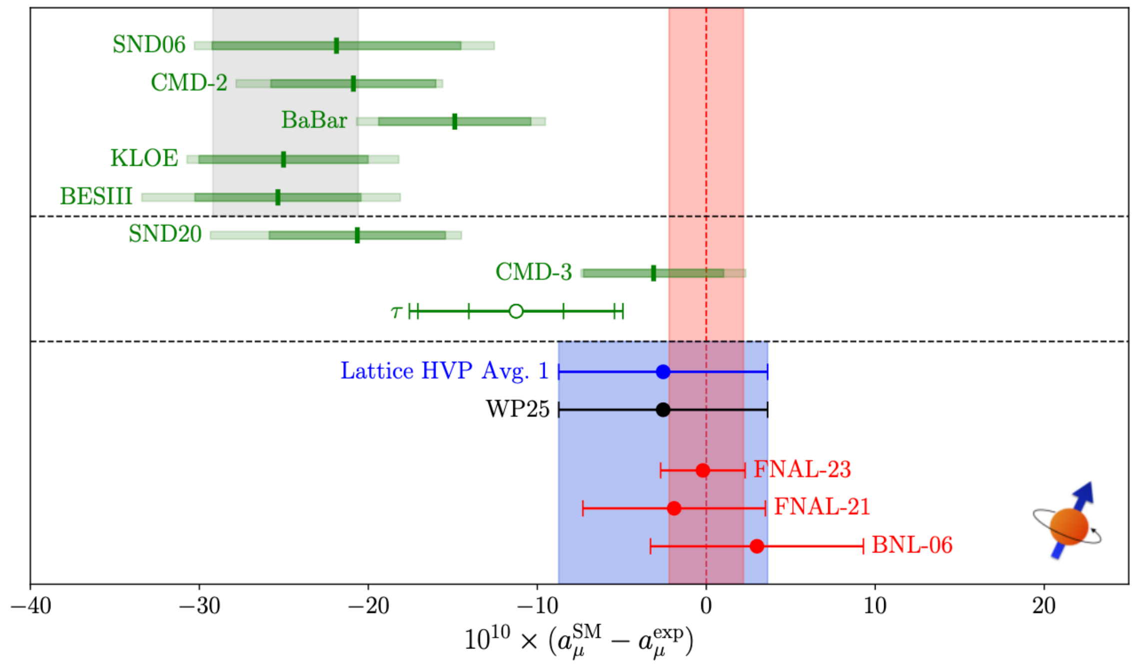
Nucleon matrix elements

FLAG review (Del Debbio, Portelli, et al., arXiv:2411.04268

QCD and BSM physics: Muon g-2



$$\boldsymbol{\mu} = g\frac{e}{2m}\boldsymbol{S}$$



The muon anomalous magnetic moment:

$$a_\mu = \frac{g_\mu - 2}{2} = F_2(0)$$

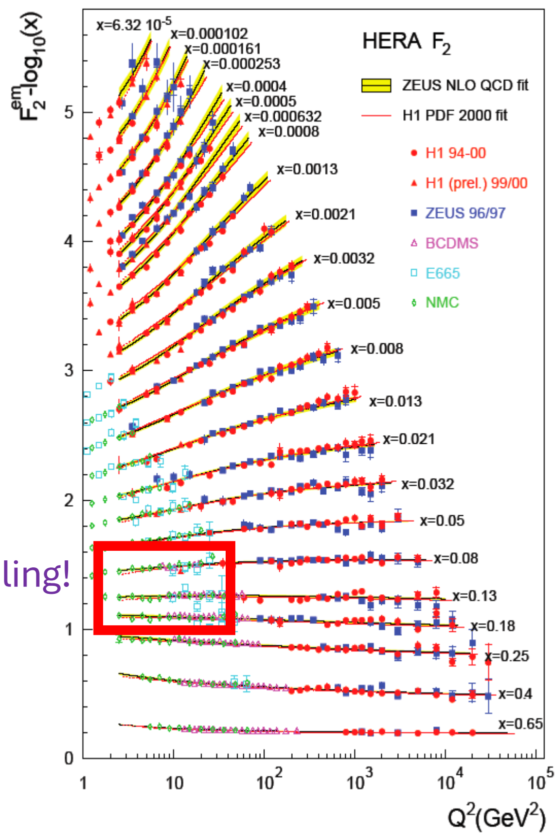
$$a_\mu^{\mathrm{SM}} = 116\,592\,033(62) \times 10^{-11}$$

$$a_\mu^{\mathrm{exp}} = 116\,592\,059(22) \times 10^{-11}$$

R. Aliberti et al., Phys. Repts. 1143 (2025) 1

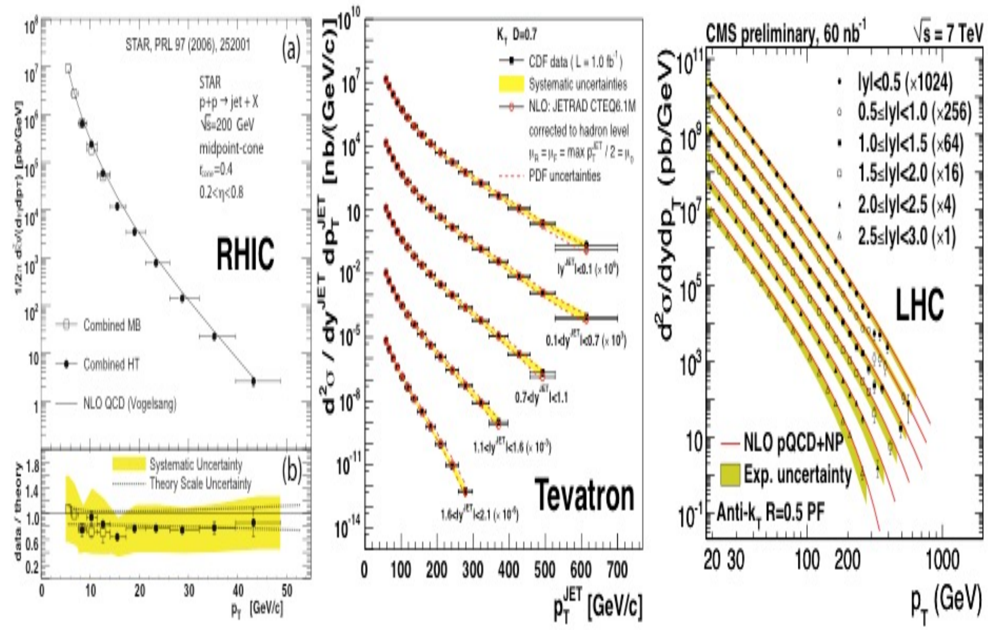
Perturbative QCD: Factorization = predictive power

Structure functions measured at
HERA electron-proton collider



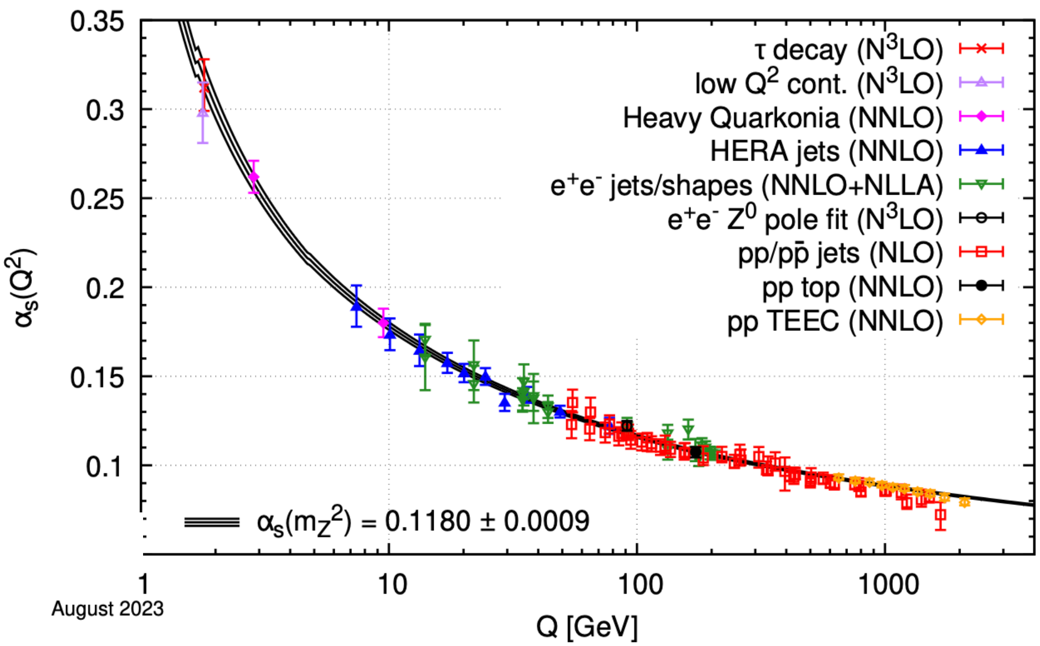
Bj scaling!

Jet cross-sections: proton-proton collisions (RHIC &LHC)
and proton-antiproton collisions at Fermilab

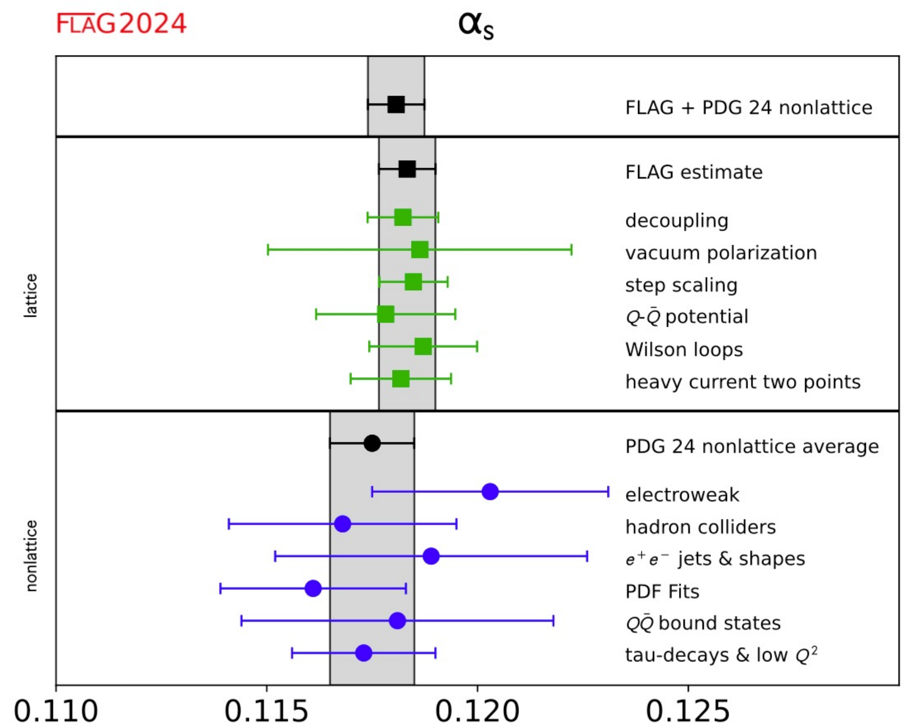


At large momenta, the weak QCD coupling
(asymptotic freedom!)
enables systematic computations

Precision extractions of the running coupling

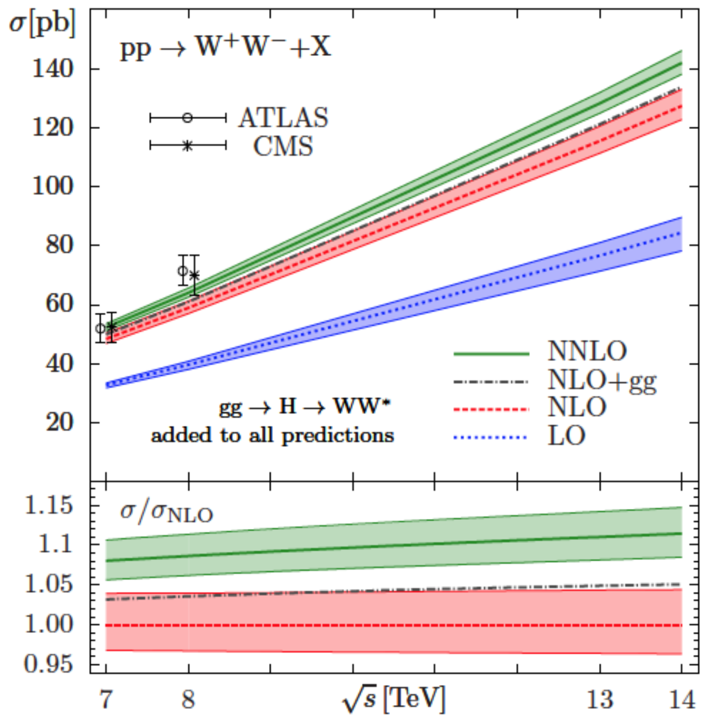


Particle Data Group (2024)



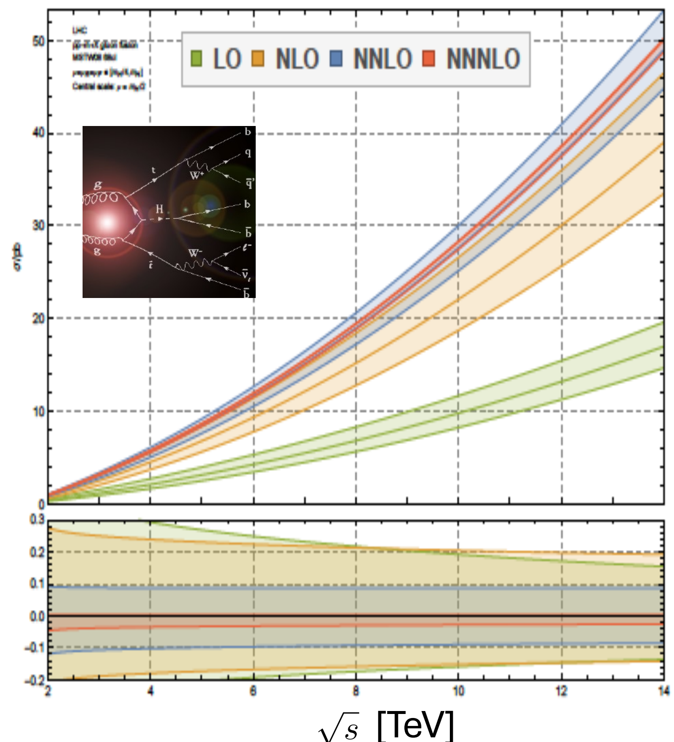
FLAG review (Del Debbio, Portelli, et al., arXiv:2411.04268)

Perturbative QCD: benchmark for new physics



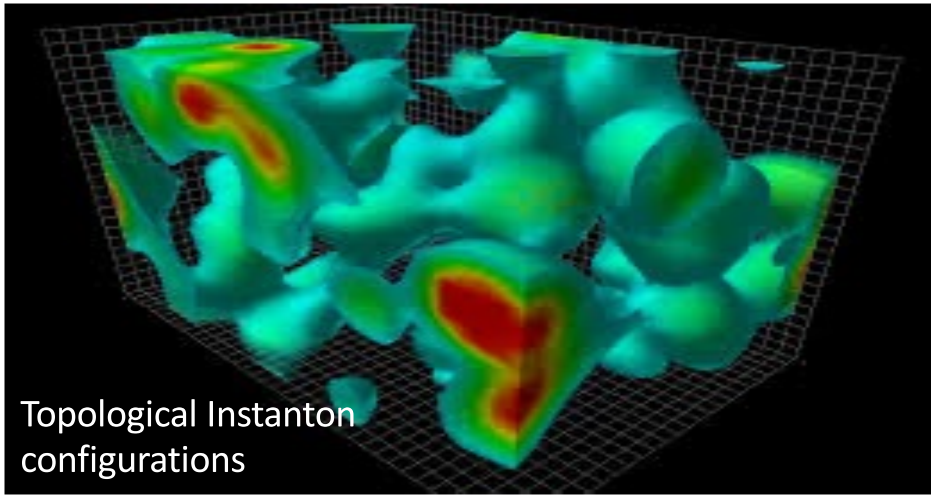
Gehrmann et al., arXiv:1408.5243

Gluon fusion to Higgs cross-section



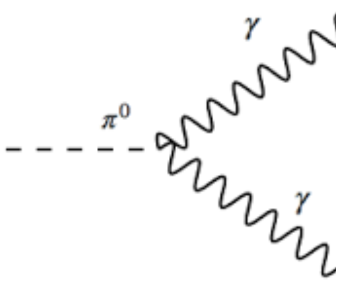
Anastasiou et al., arXiv:1503.06056

QCD vacuum exhibits non-trivial topology



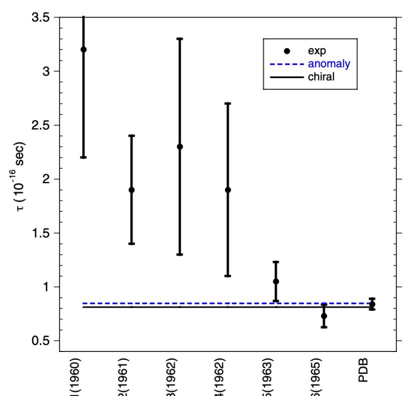
Lattice Gauge simulation
Derek Leinweber

Real-world manifestations:



The decay of $\pi^0 \rightarrow 2\gamma$

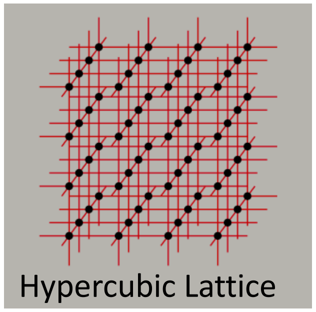
Adler; Bell-Jackiw (1969)



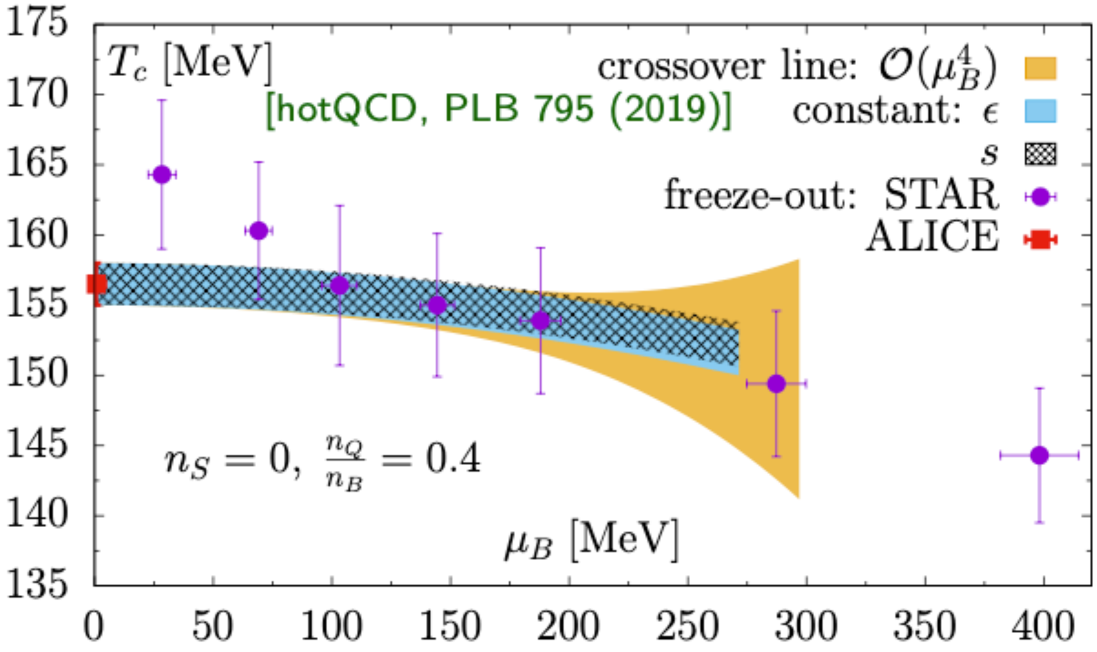
The mass of the $\eta^{'}$ meson (> the proton)
Is almost entirely generated by topology

t'Hooft (1976))
Witten; Veneziano (1979)

First principles Lattice QCD results



Critical (cross-over) Temperature from LQCD compared to Heavy-Ion collision results



Increasing baryon density/
Decreasing collision energy

Increasingly quantitative agreement of lattice computations with data fom heavy-ion collisions at RHIC & LHC

Are we done ?

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

F. Wilczek , "Quarks (and Glue) at the Frontiers of Knowledge", Talk at Quark Matter 2014