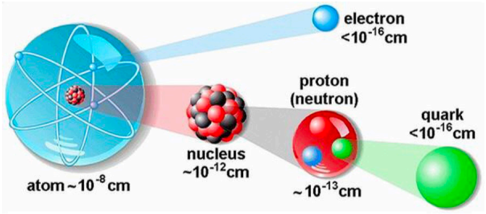
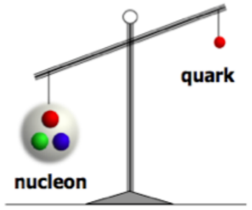
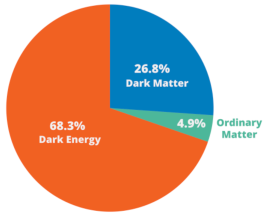
Simulating the Visible Universe



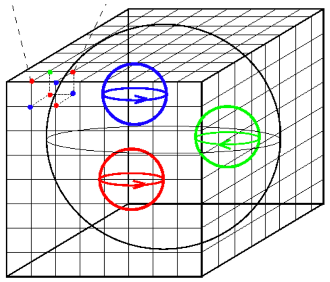




Martha Constantinou

Temple University

Summit Supercomputer, Oak Ridge National Lab



Blue Waters supercomputer, NCSA, UIUC (2013-21)

The ICASU Inaugural Conference

Physics Dept., University of Illinois in Urbana-Champaign

May 19, 2022

How can we study theoretically the core of the visible matter from **first principles**?

How can we study theoretically

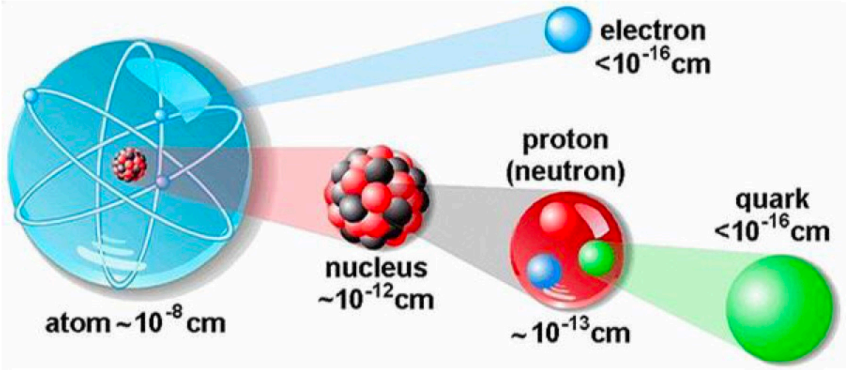
the core of the visible matter

from first principles?

How successful are

theoretical predictions ?

Structure of visible Matter



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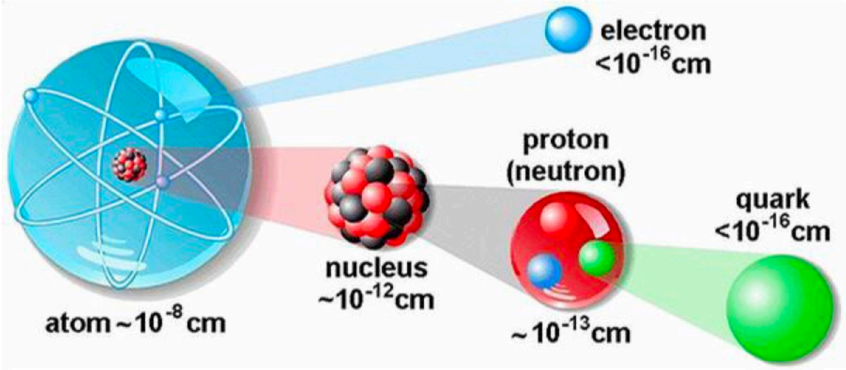
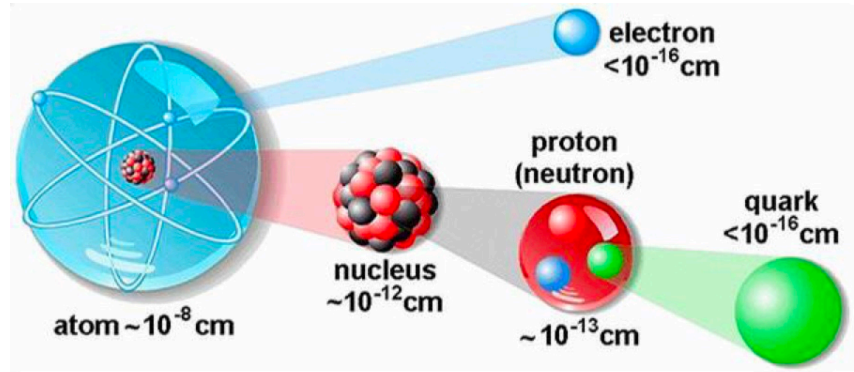
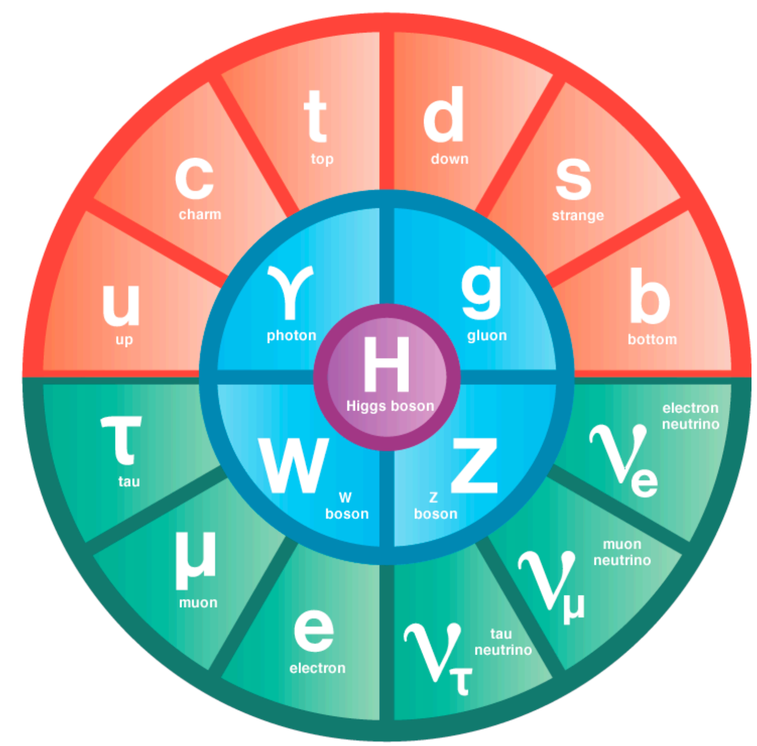


- ★ More than 99% of the mass of the visible matter comprises of hadrons (p, n, …)
- ★ structure of building blocks of matter governed by the strong force
- ★ The theory of the strong interactions is Quantum ChromoDynamics (QCD)

Structure of visible Matter



Standard model



QUARKS LEPTONS BOSONS HIGGS BOSON

Credit: Symmetry Magazine

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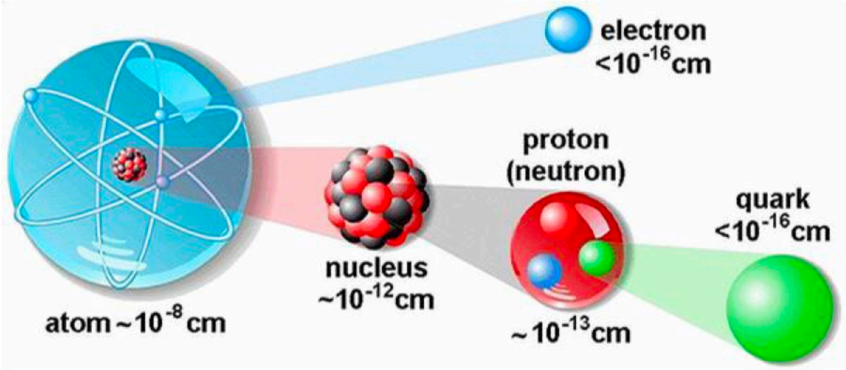

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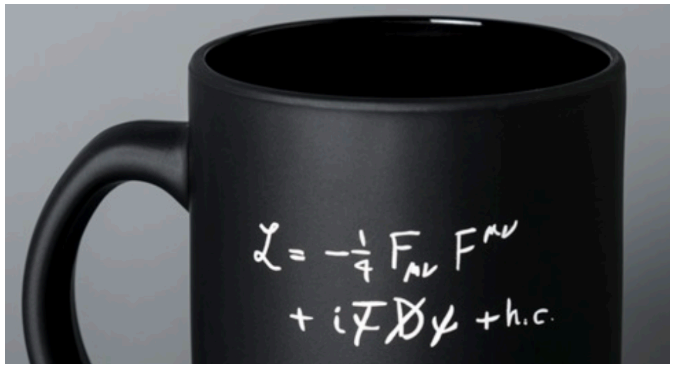
July 4, 2012 at CERN

Credit: Symmetry Magazine

Investigations of strongly interacting matter

Reproduces rich structure of all strongly interacting matter

Very elegant, highly non-linear: Cannot be solved analytically



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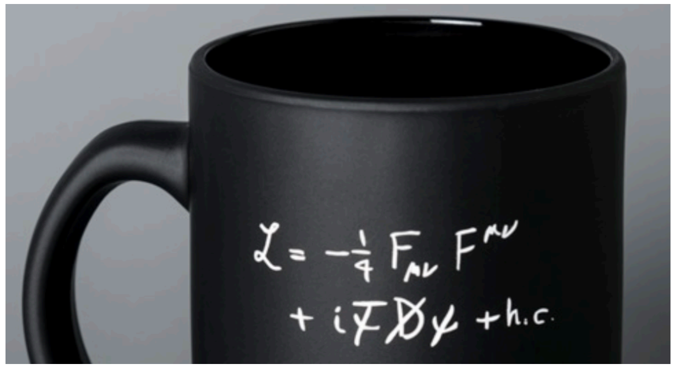

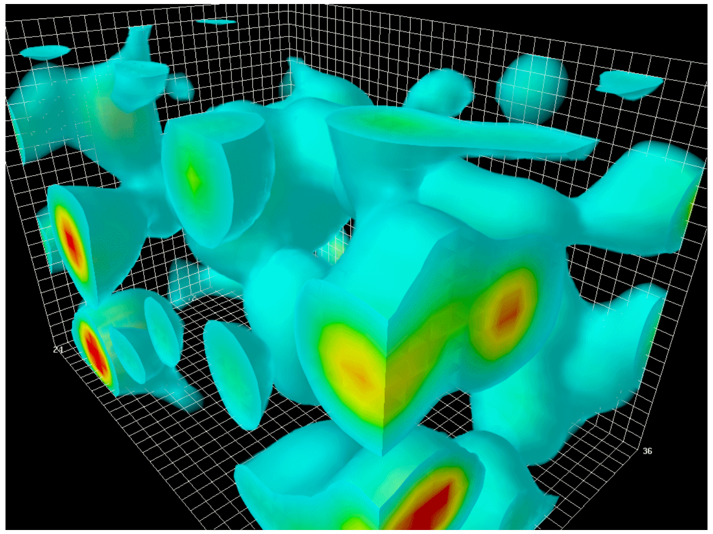

D. Leinweber: Quantum fluctuations of QCD vacuum

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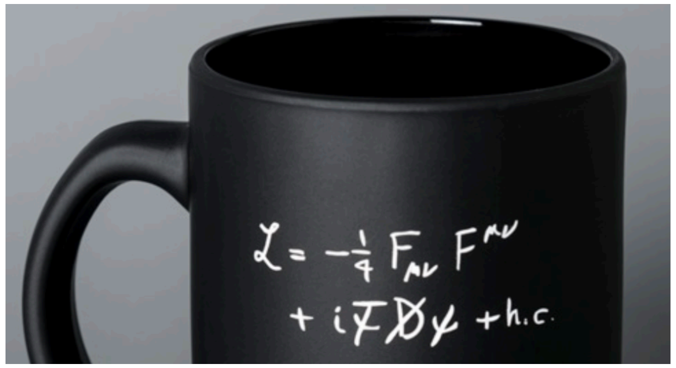

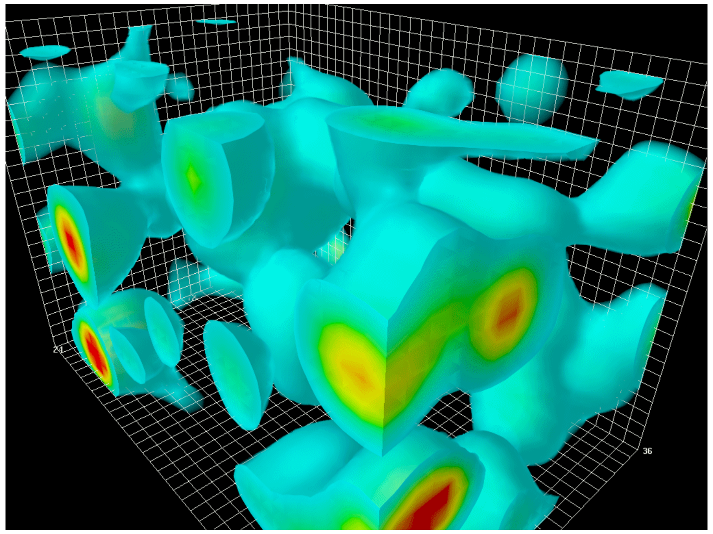

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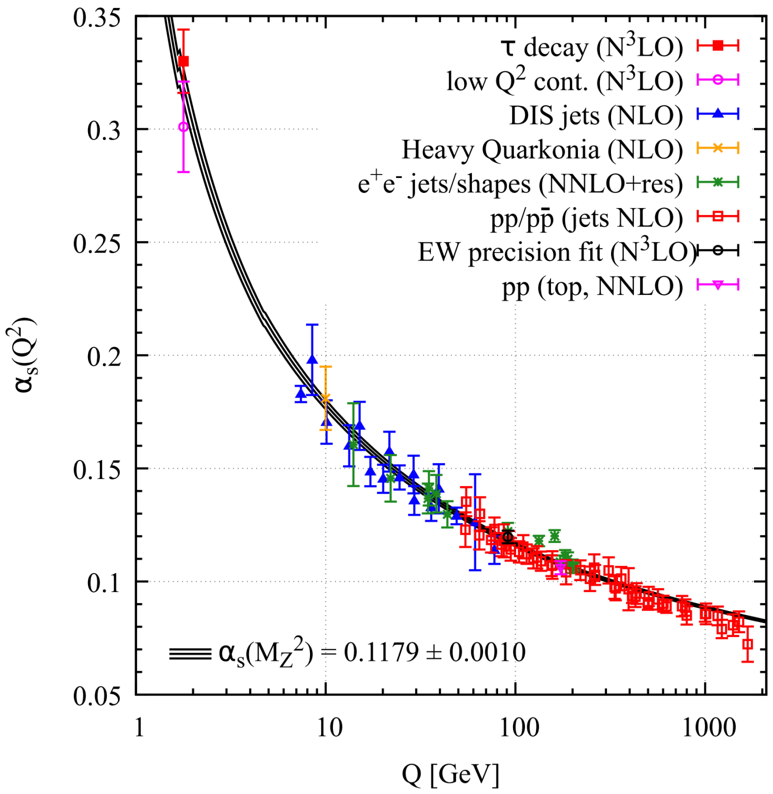
Confinement - Asymptotic freedom



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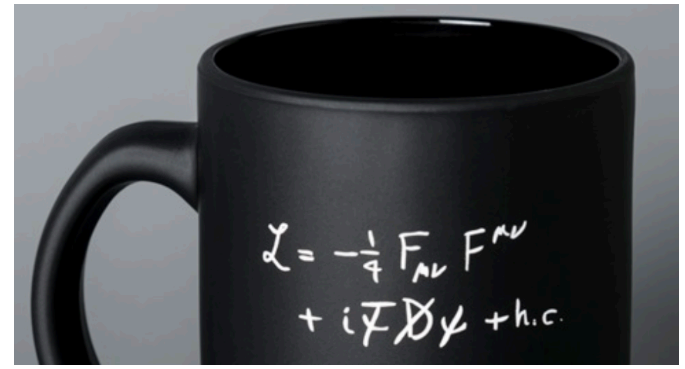

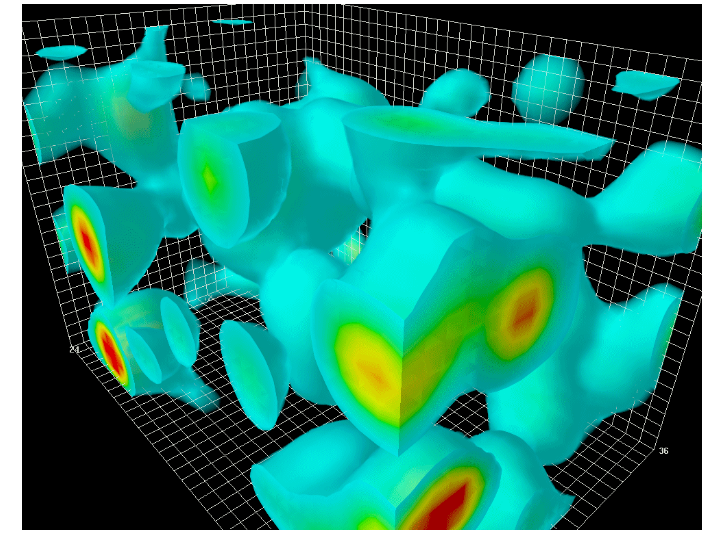

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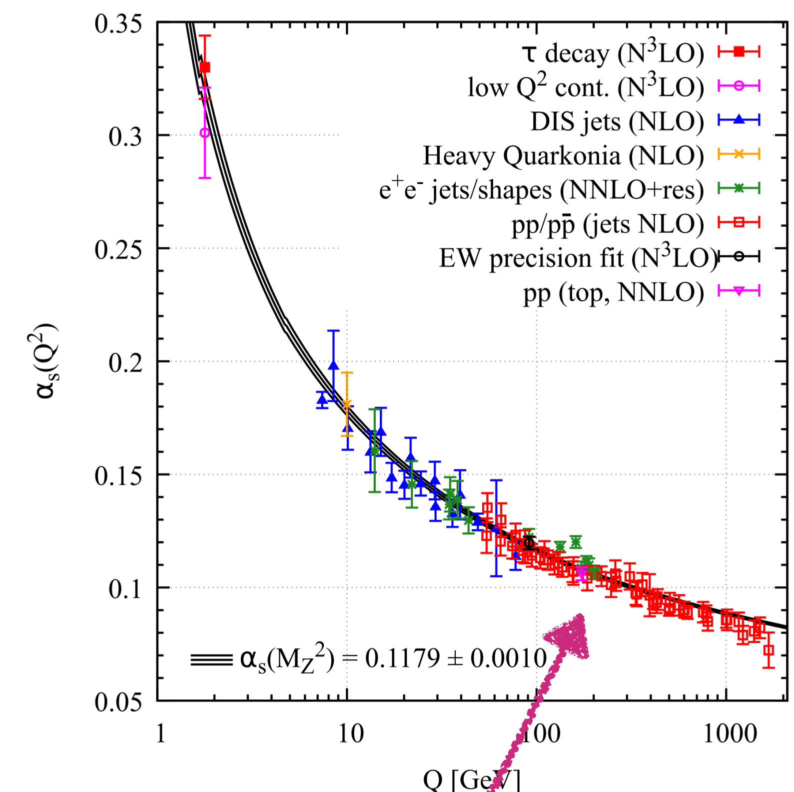

perturbation theory

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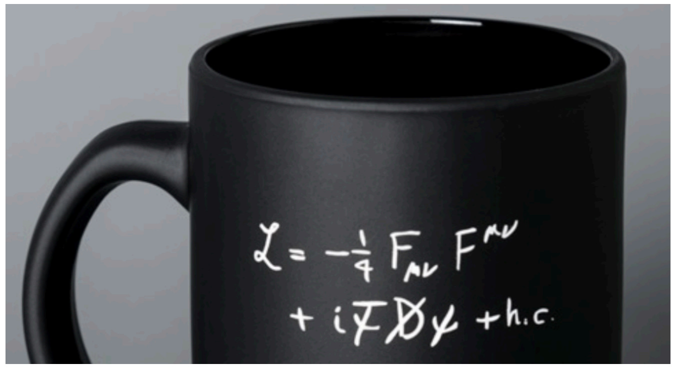

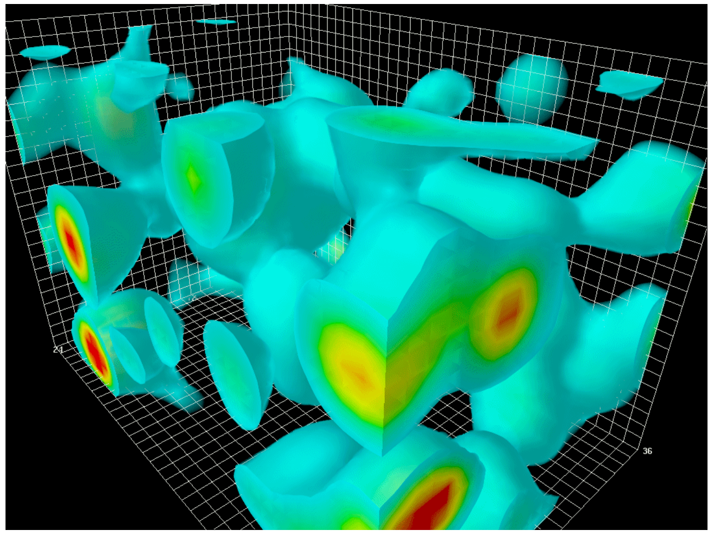

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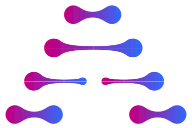
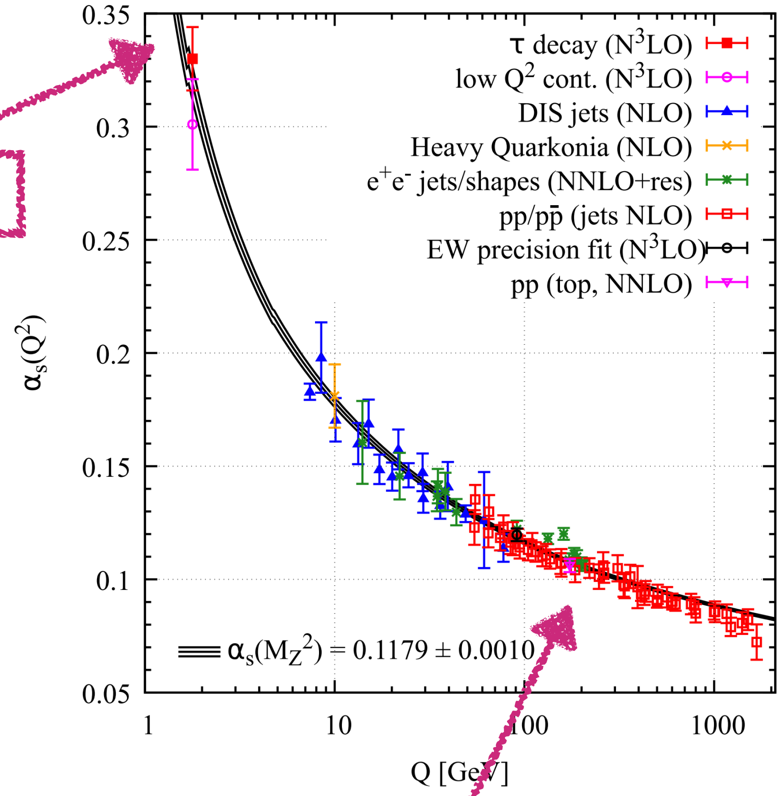
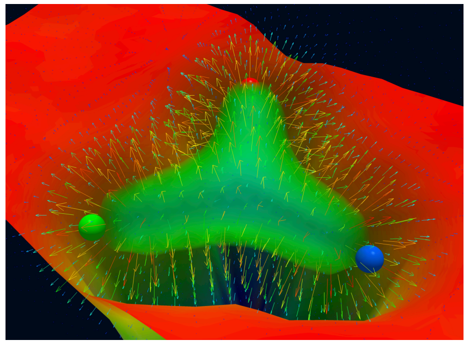


Quark confinement

Non-perturbative regime

Confinement - Asymptotic freedom





Flux tubes of QCD

Credit: D. Leinweber

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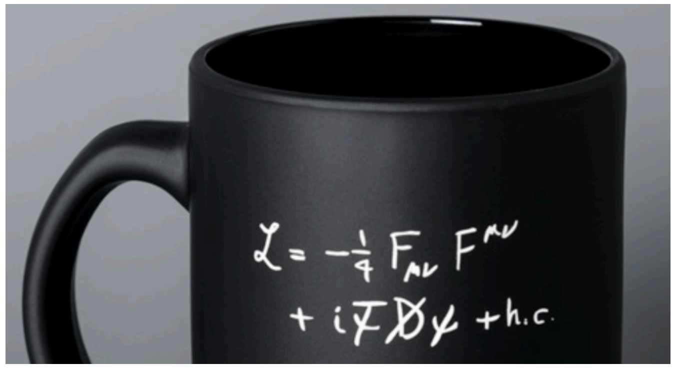

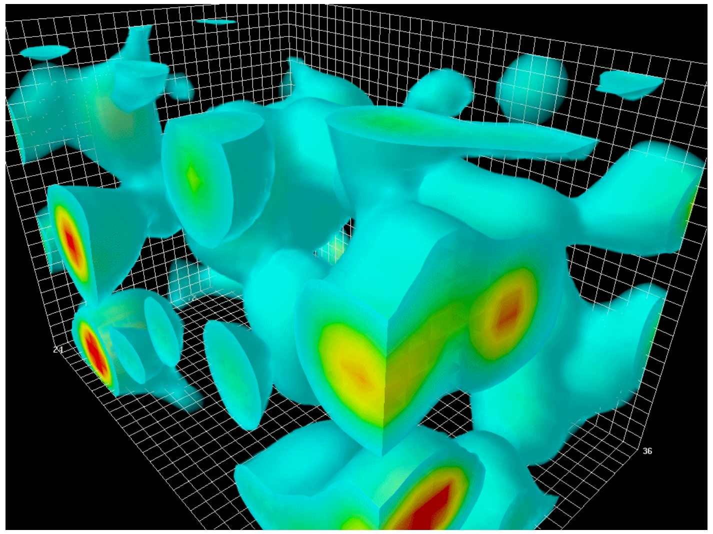

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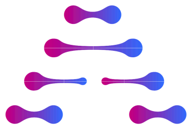
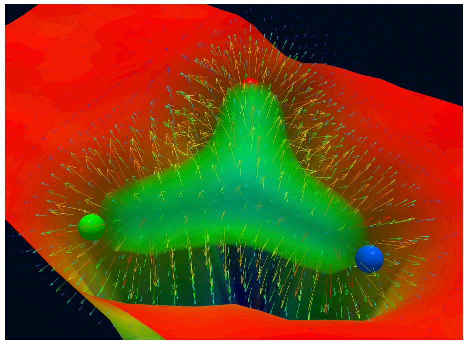


Quark confinement

Non-perturbative regime

Large-scale numerical simulations on supercomputers

Blue Waters supercomputer, NCSA, UIUC (2013 - 2021)
(Picture from Spin Symposium 2016)



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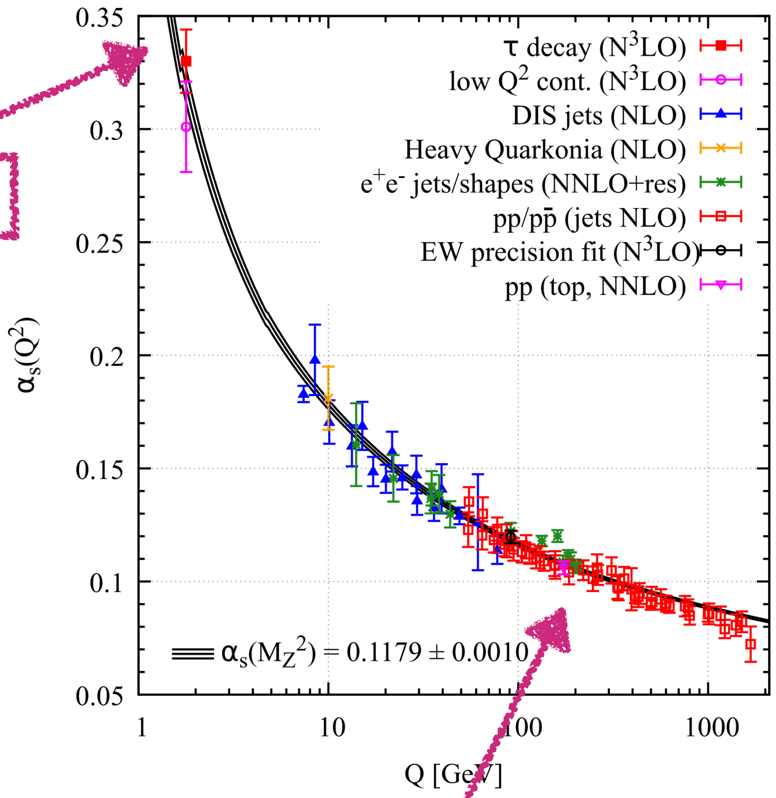

perturbation theory

Lattice formulation of QCD

K. Wilson

Lattice QCD formulation (1974)

Ideal first principle formulation of QCD
(simulations starting from original Lagrangian)

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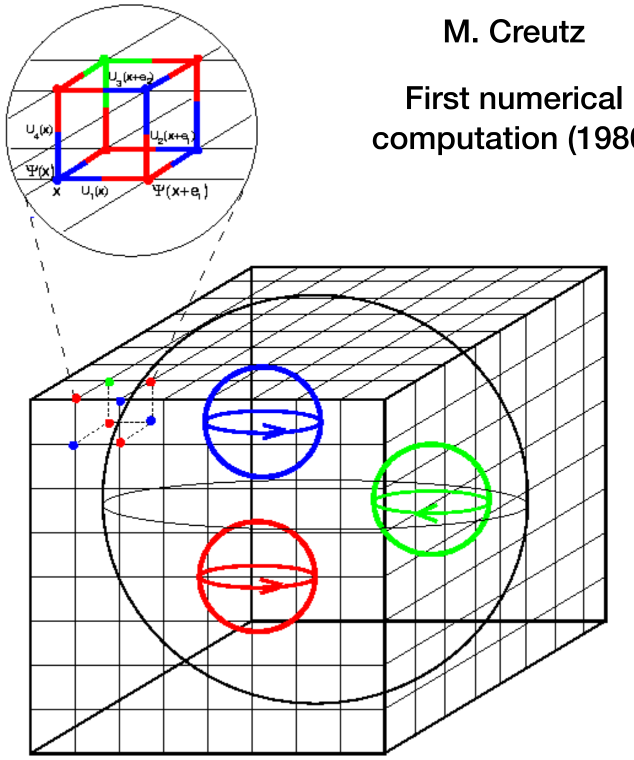
First numerical computation (1980)



courtesy: USQCD

★ Space-time discretization on a finite-size 4-D lattice

★ Serves as a regulator:

UV cut-off: inverse lattice spacing $$\int_{-\infty}^{\infty} dp \;\rightarrow\; \int_{-\pi/a}^{\pi/a} \frac{dp}{2\pi}$$

IR cut-off: inverse lattice size $$\int dpF(p) \;\rightarrow\; \sum_{n}^{N_{\max}} \frac{2\pi}{L} F(p_0 + \frac{2\pi n}{L})$$

★ Removal of regulator $$L \rightarrow \infty\,, \quad a \rightarrow 0$$

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★ Parameters (define cost of simulations):
quark masses (aim at physical values)
lattice spacing (ideally fine lattices)
lattice size (need large volumes)

★ Billions of degrees of freedom:
huge computational power
algorithmic improvements necessary

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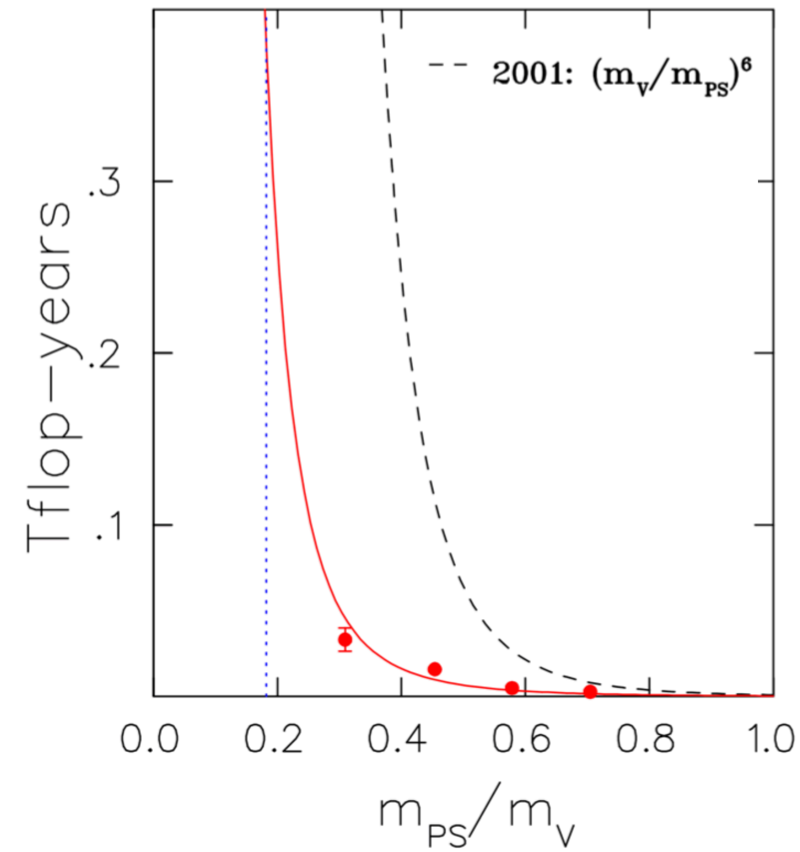

"Berlin" Wall plot, (Lattice Symposium 2001, Berlin Germany)

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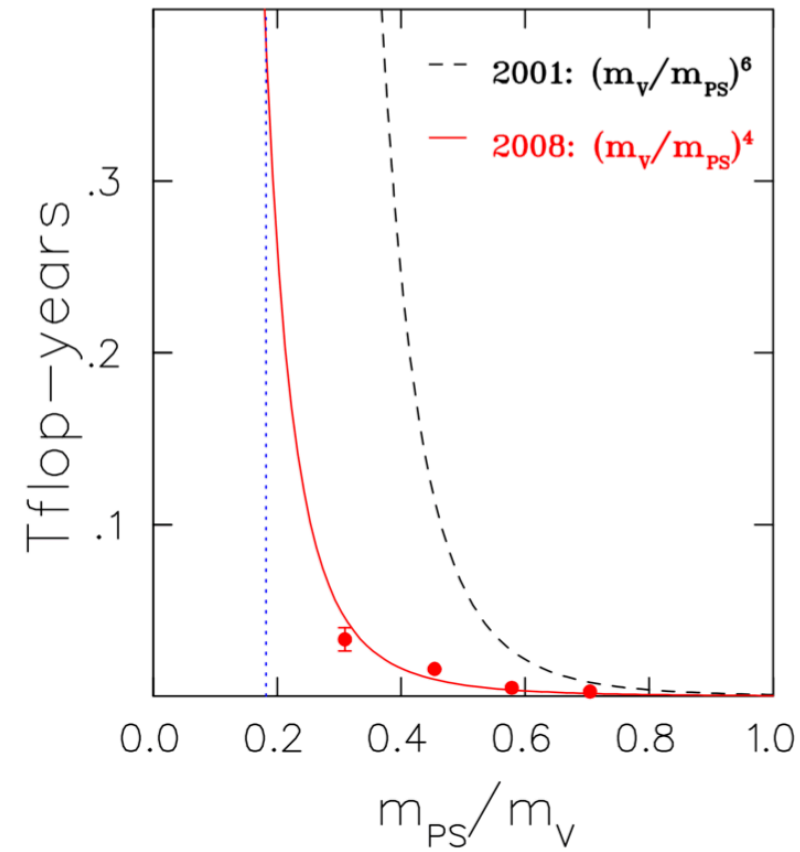

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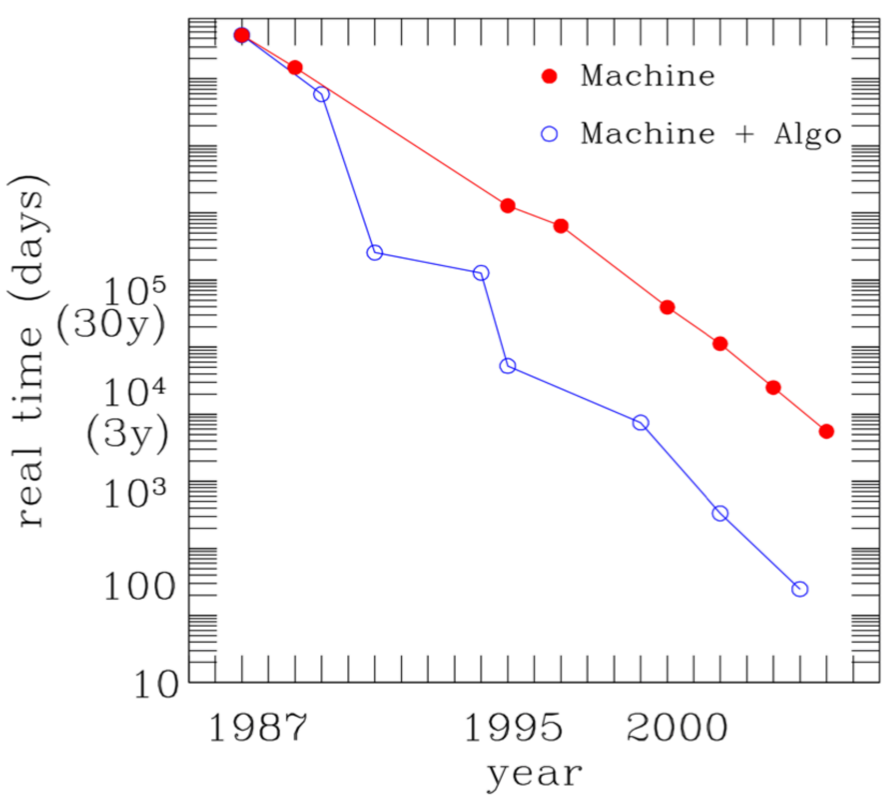

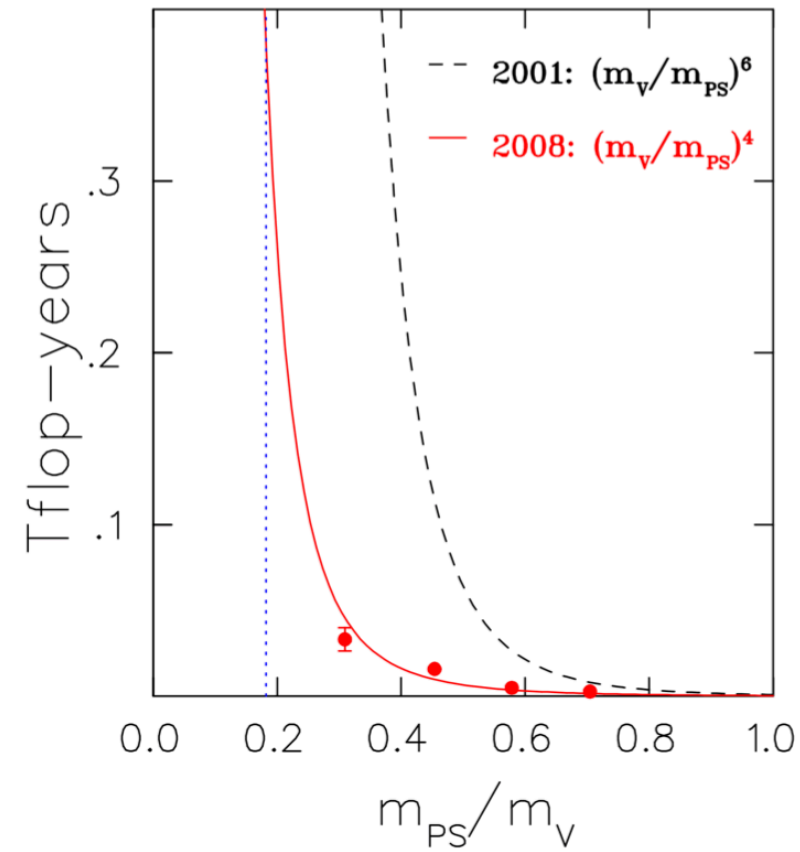

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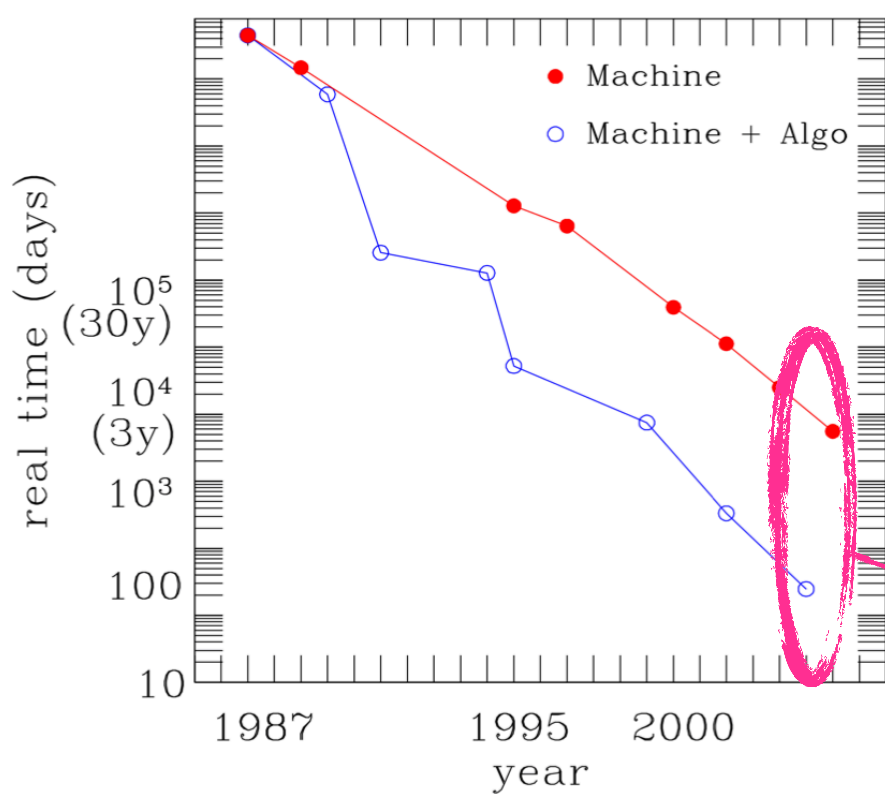
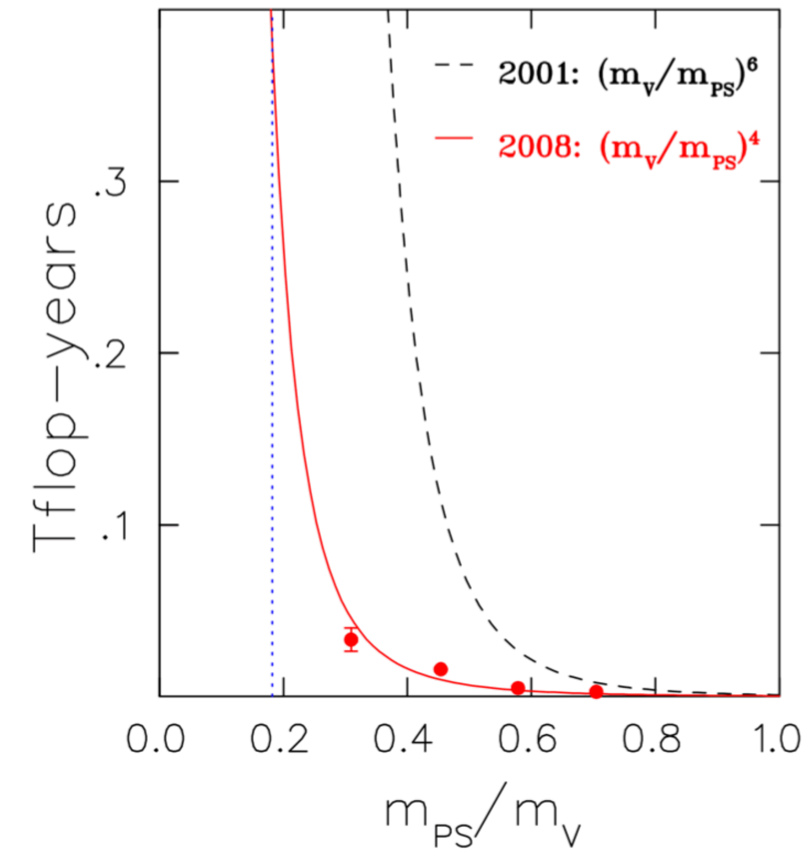


O(100) less cost



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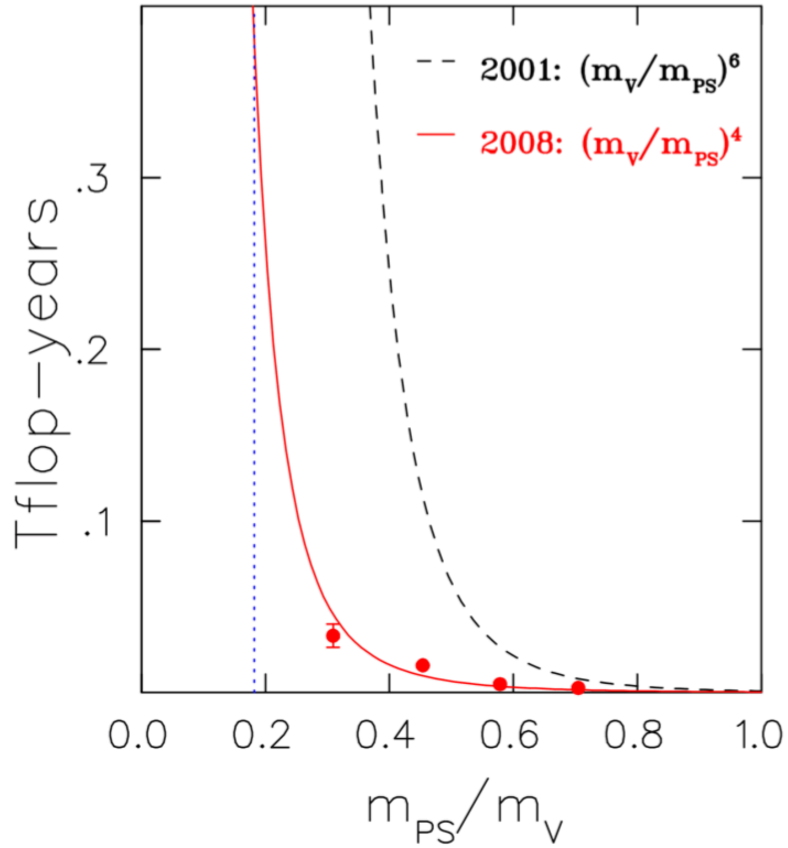

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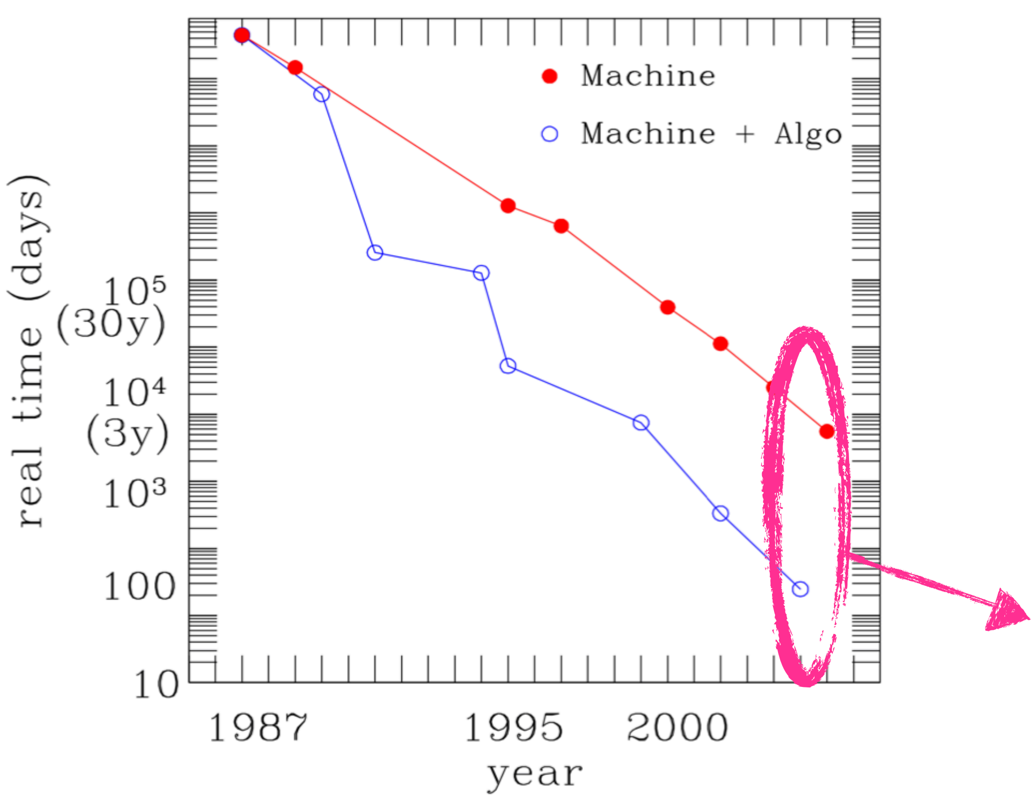
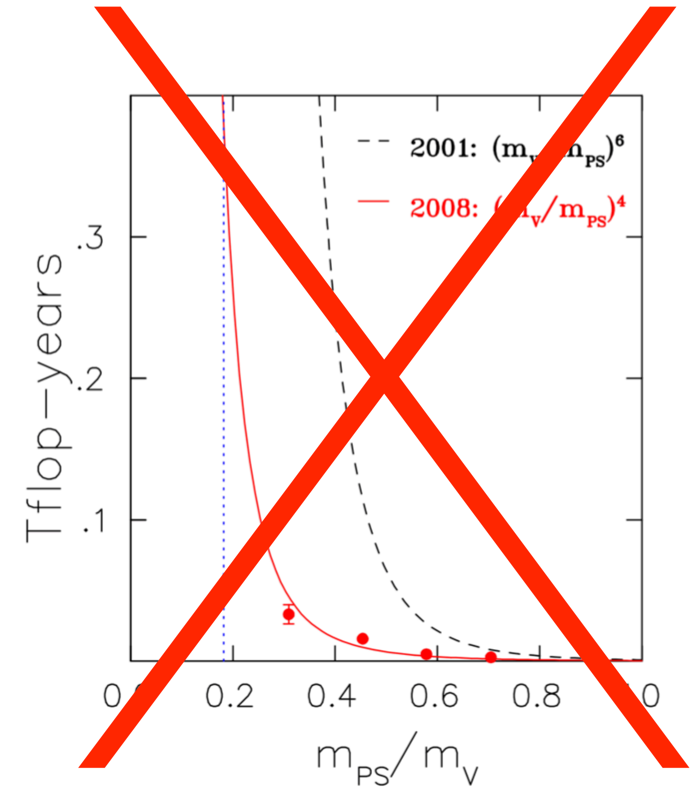


O(100) less cost

★ Critical to improve algorithms based on computer architecture

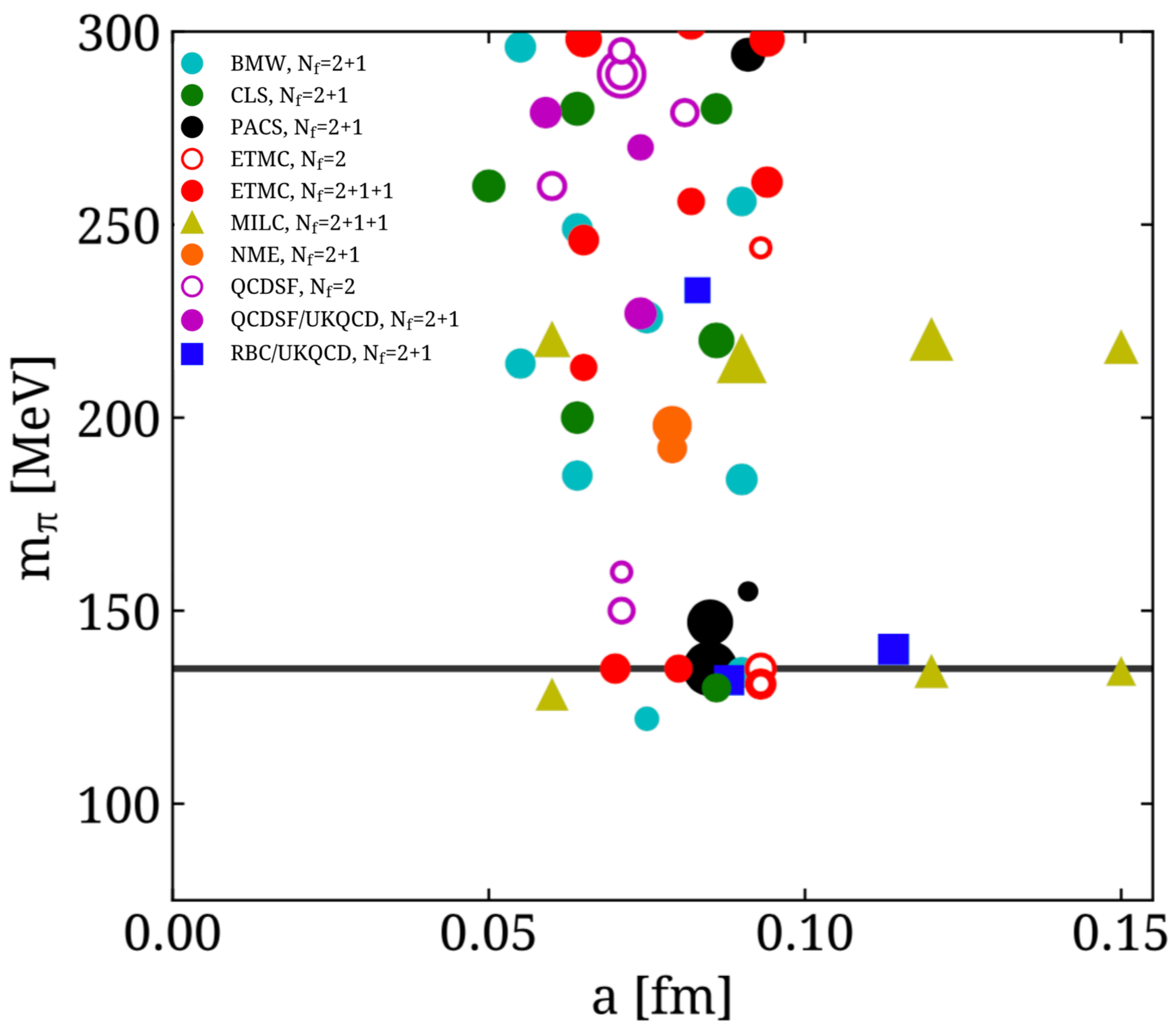
Landscape of numerical simulations

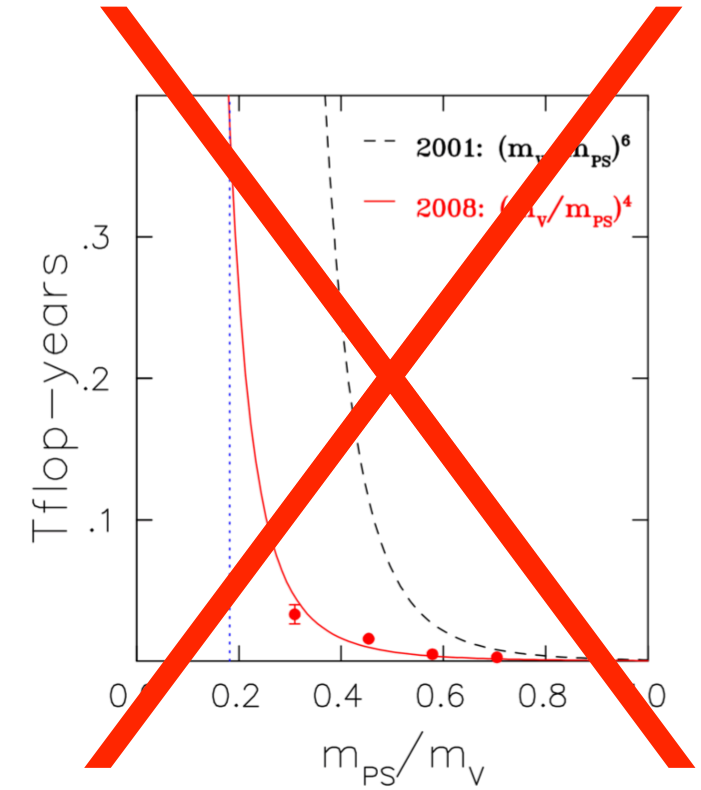


Landscape of numerical simulations

Lattice (fermion) formulations employed by various groups:

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





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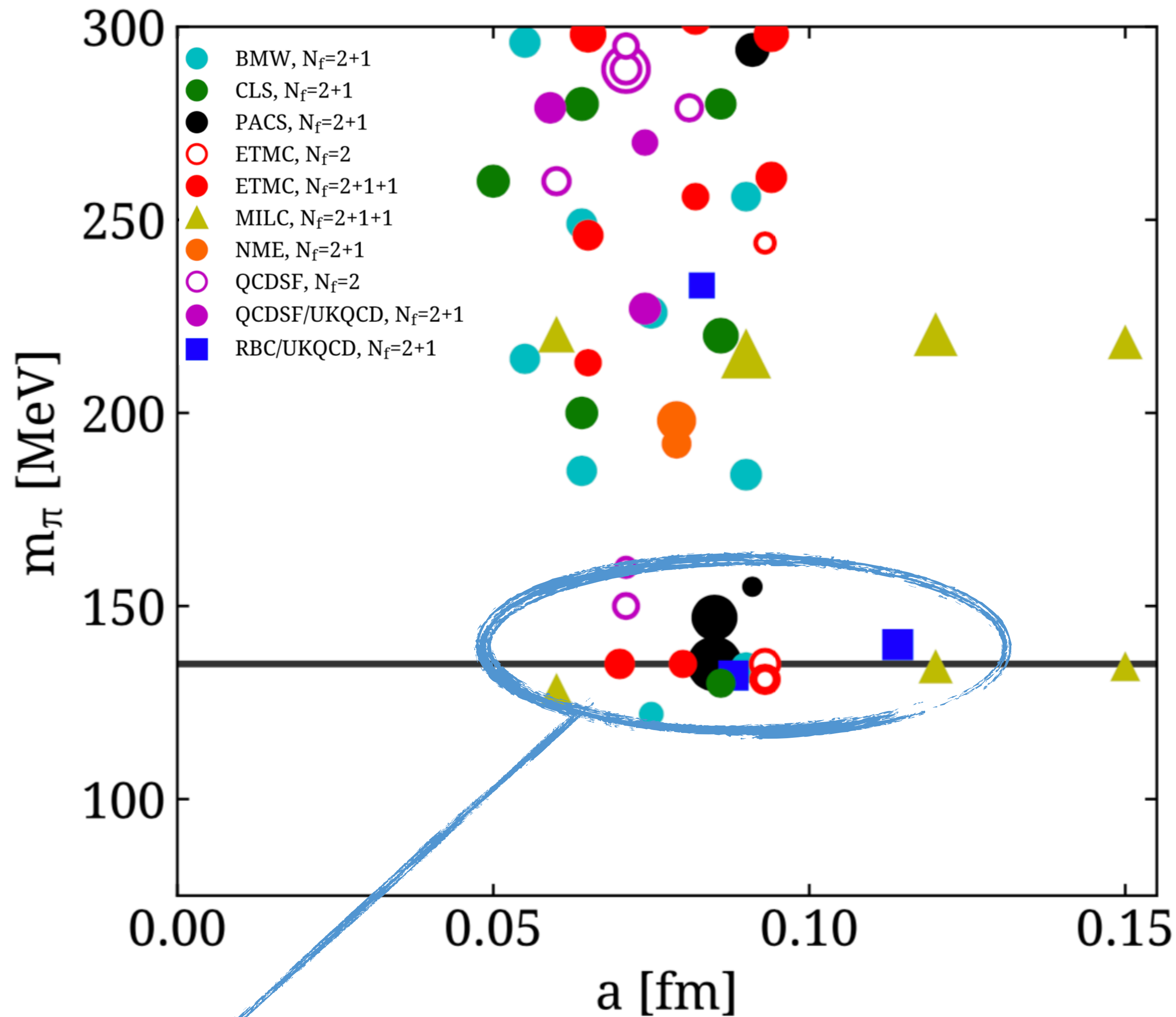

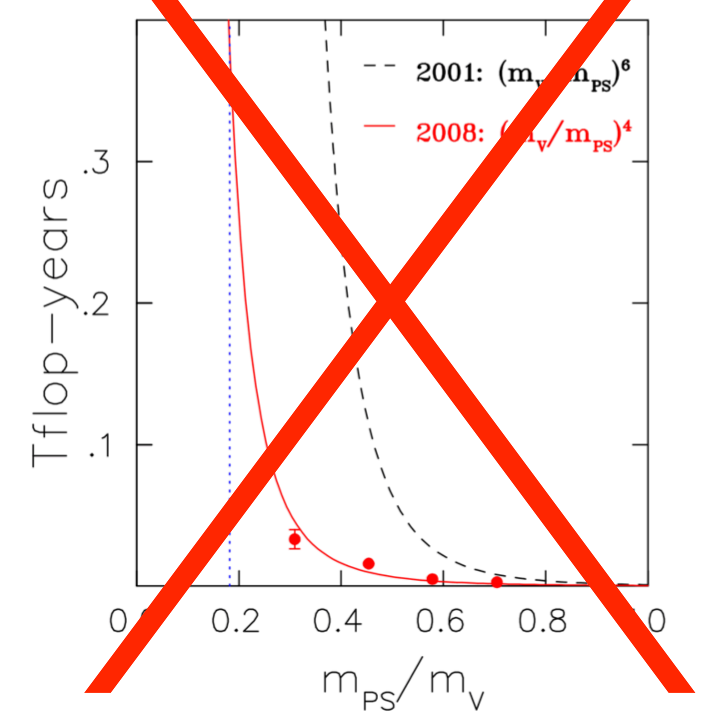

Ensembles with physical values for quark masses (physical point)

How is lattice QCD related to Nature?

High-Priority Scientific Questions

Numerical simulations of QCD address aspects of key questions

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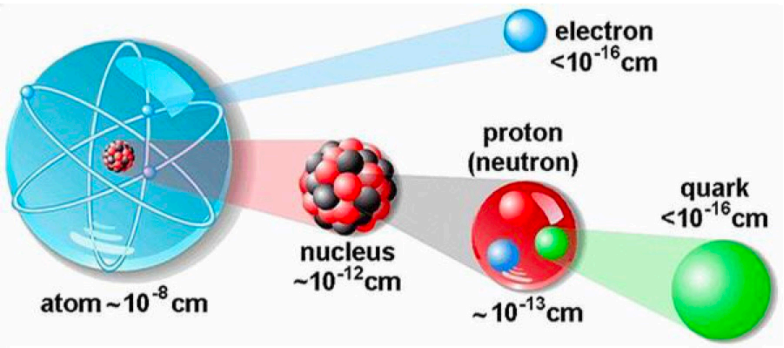
Numerical simulations of QCD address aspects of key questions

How do the properties of nucleons (p,n) emerge from the dynamics of their quark and gluon constituents?



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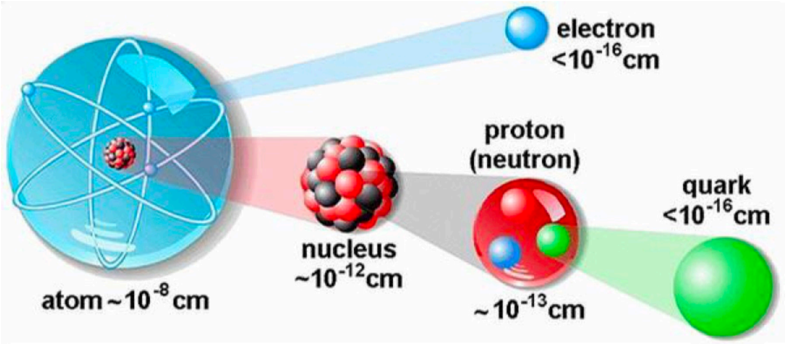
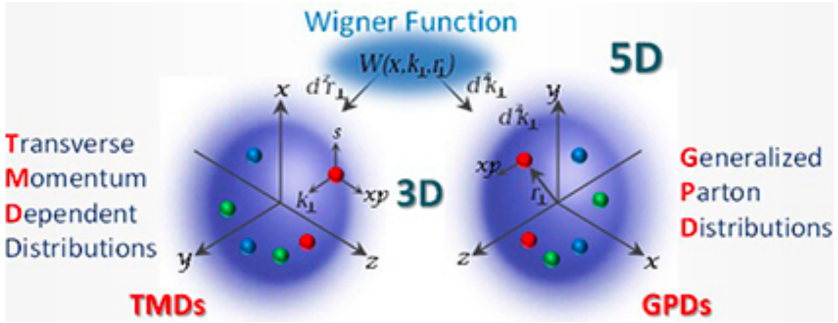


What is the 3-D tomographic mapping of nucleons (p,n)?



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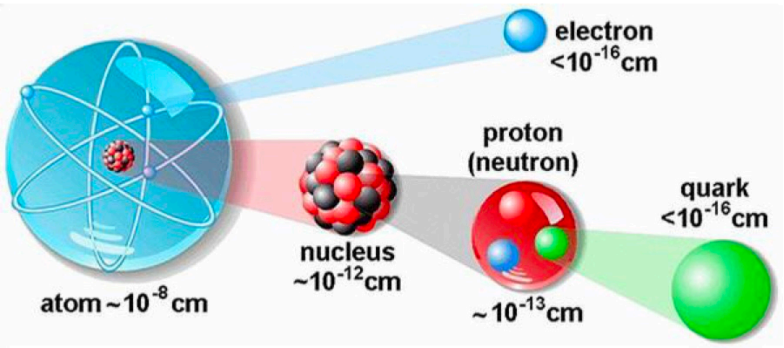

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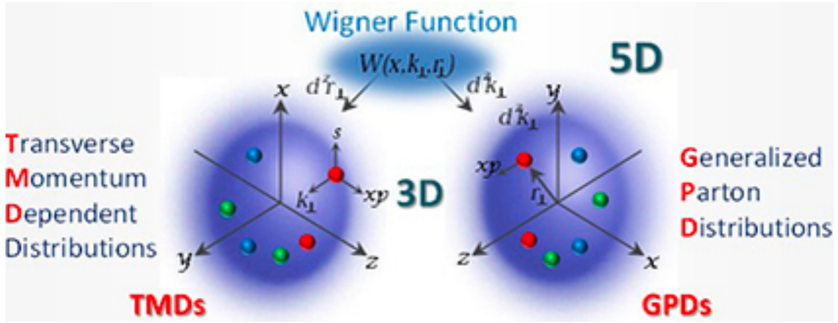
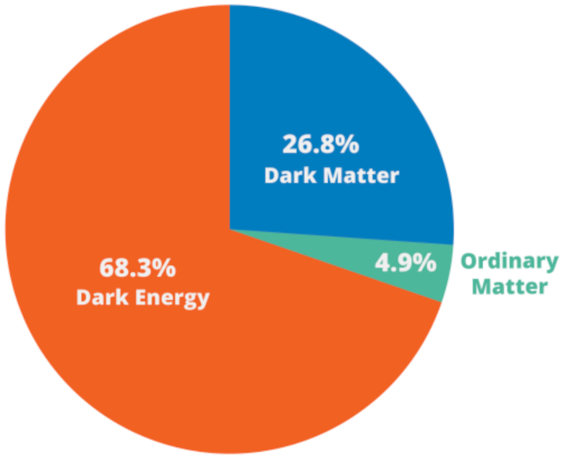
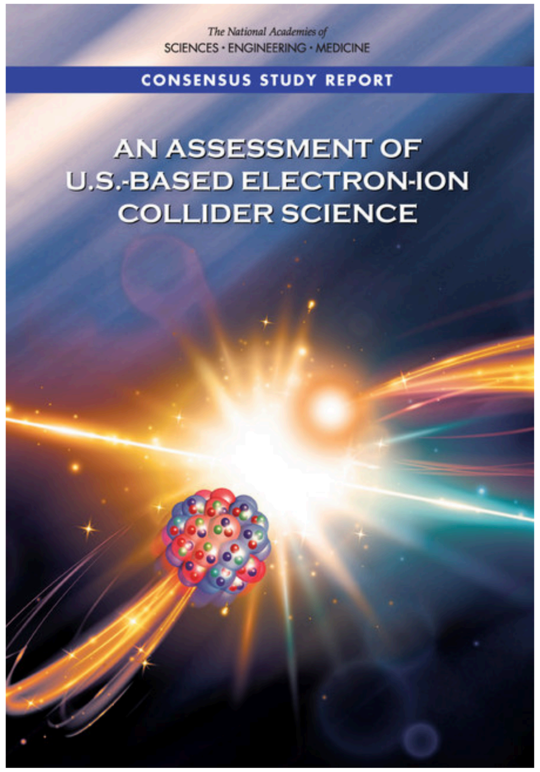


To what extent do we understand matter and energy? Is there New Physics to be discovered?



Advances of Lattice QCD are timely



Main Pillar of NAS
Assessment report for EIC

Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

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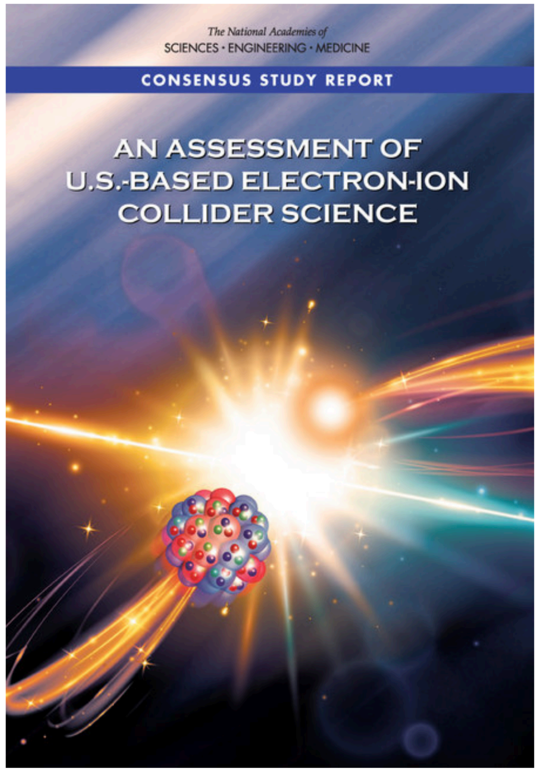

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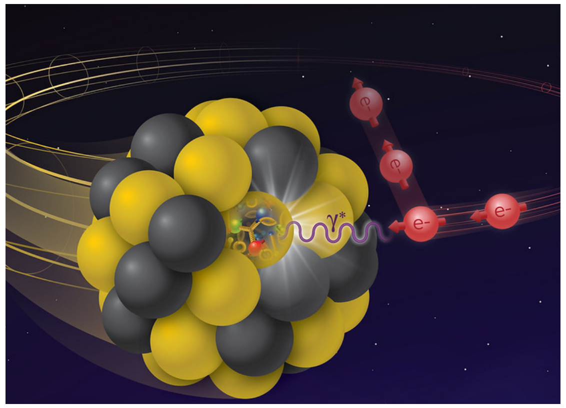
Lattice QCD is featured in the EIC Yellow Report
- 900-page document
- scientist from 151 Institutions

Lattice QCD can provide valuable input in understanding the proton mass and spin decomposition from *first principles*

How do we access information on the internal structure of hadrons?

Hadron Structure

★ **Structure of hadrons explored in high-energy scattering processes**



Artistic impression of collisions @ EIC

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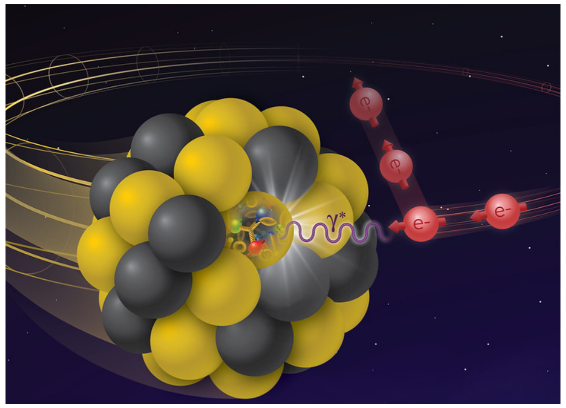
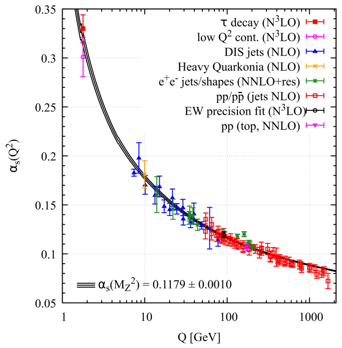


Artistic impression of collisions @ EIC

★ **Due to asymptotic freedom, e.g.**



$$\sigma_{\mathrm{DIS}}(x, Q^2) = \sum_i \left[H^i_{\mathrm{DIS}} \otimes f_i\right](x, Q^2)$$

$$[a \otimes b](x) \equiv \int_x^1 \frac{d\xi}{\xi}\, a\left(\frac{x}{\xi}\right)\, b(\xi)$$

Hadron Structure

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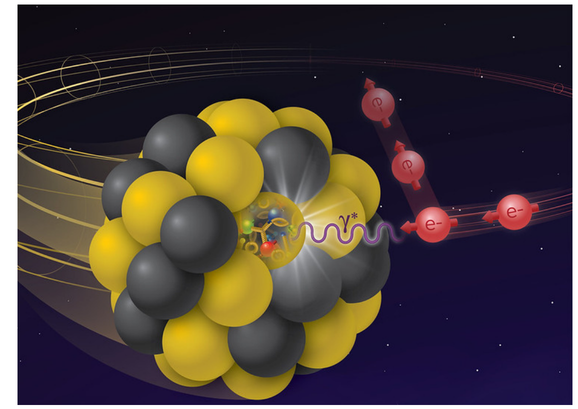
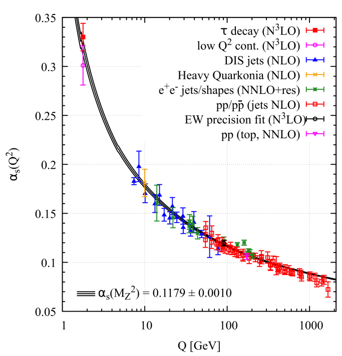


Artistic impression of collisions @ EIC

★ **Due to asymptotic freedom, e.g.**



$$\sigma_{\mathrm{DIS}}(x, Q^2) = \sum_i \left[H^i_{\mathrm{DIS}} \otimes \boxed{f_i}\right](x, Q^2)$$

$$[a \otimes b](x) \equiv \int_x^1 \frac{d\xi}{\xi}\, a\left(\frac{x}{\xi}\right) b(\xi)$$

Perturb. part (process dependent)

Non-Perturb. part (process "independent")

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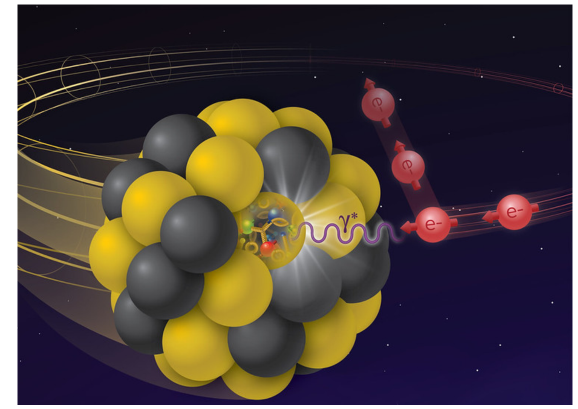

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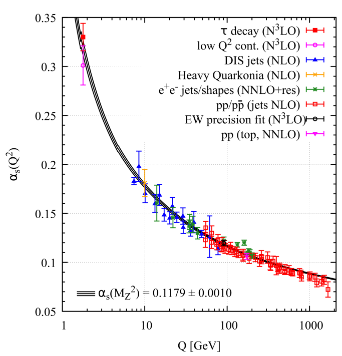

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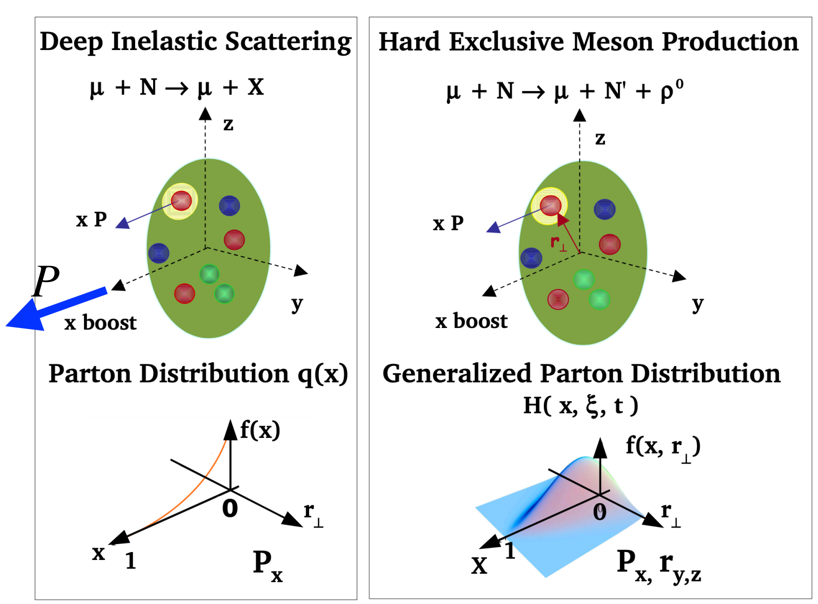
Perturb. part (process dependent)

Non-Perturb. part (process "independent")

★ Non perturb. part provides information on partonic structure of hadrons

★ Reveal correlations between the longitudinal parton momentum and their position in the transverse spatial plane within a hadron



What properties of the hadrons structure can Lattice QCD access?

(Some) open questions in proton structure

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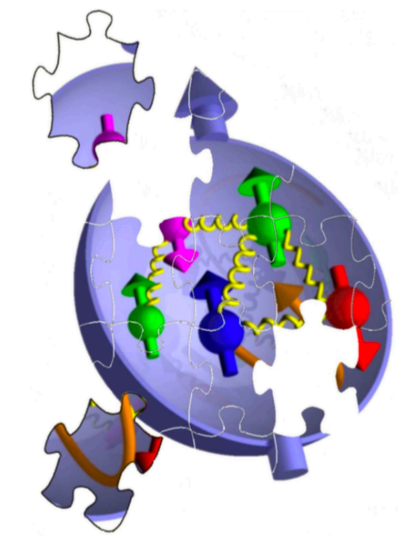
Where does the proton spin come from?

(Some) open questions in proton structure



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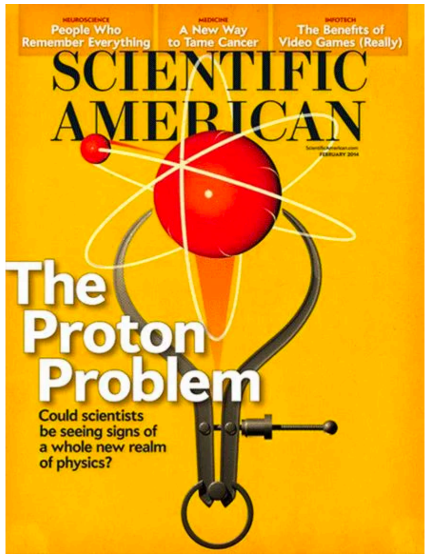

What is the size and shape of the proton and neutron?

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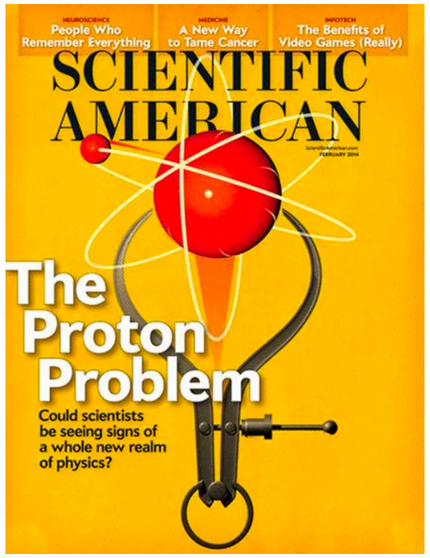
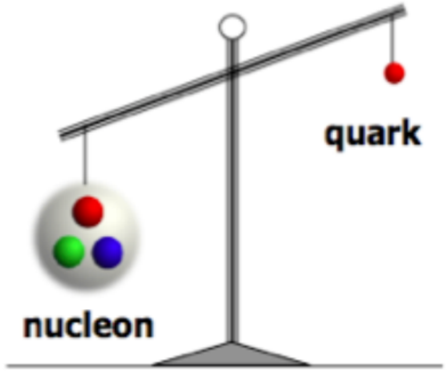
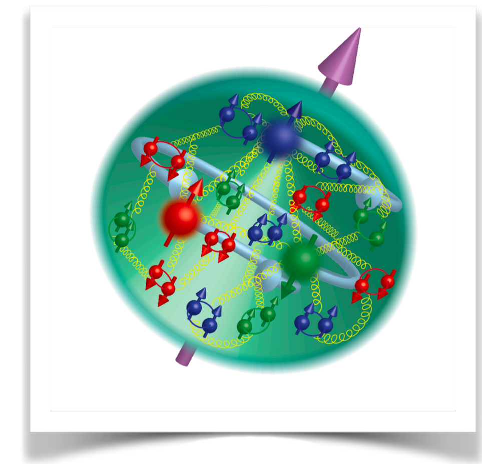


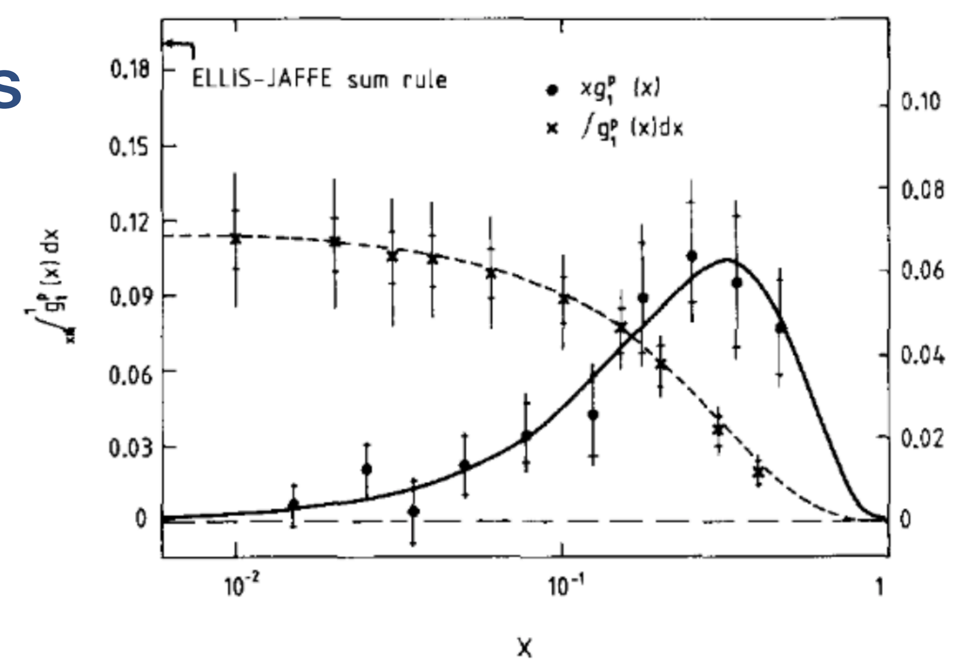
What is the mechanism giving mass to fundamental particles (p, n, etc)?



Proton spin "puzzle"



- ★ Fundamental degree of freedom (from space-time symmetry)
  (Proton spin:1/2)
- ★ Spin plays an important role in determining the structure of composite particles, like the proton
- ★ Simple models predict that the 3 quarks responsible for the proton's quantum numbers carry 1/3 of its spin
- ★ DIS experiments (1988) show surprising results for proton spin [J. Ashman et al., Phys. Lett., vol. B206 (1988) 364]



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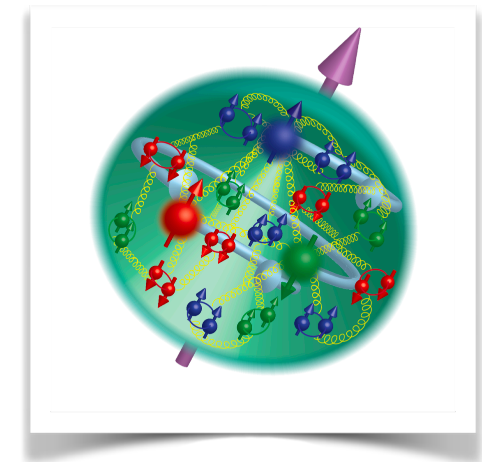

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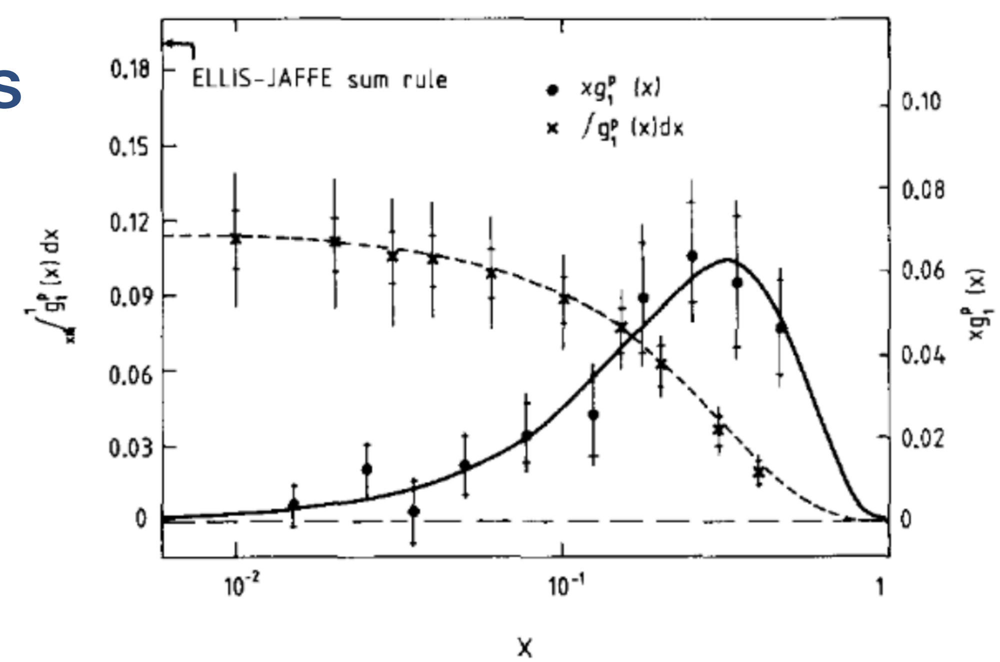
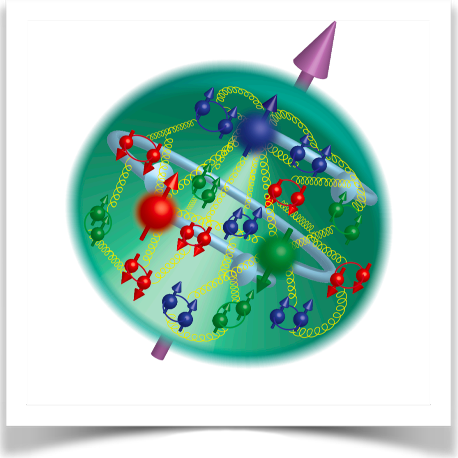


SPIN CRISIS !

Proton spin "puzzle"



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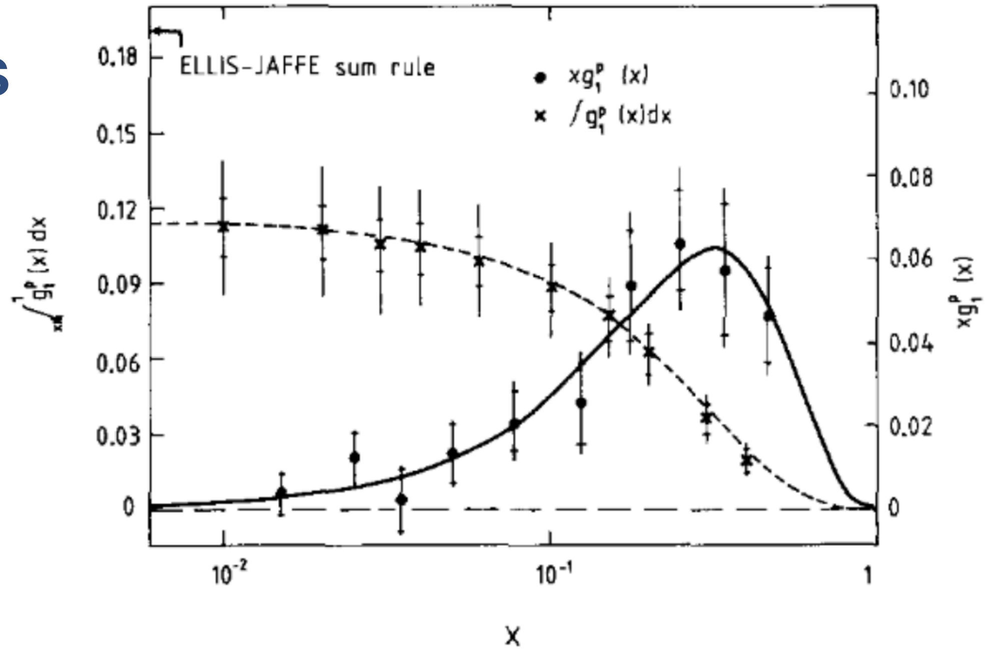
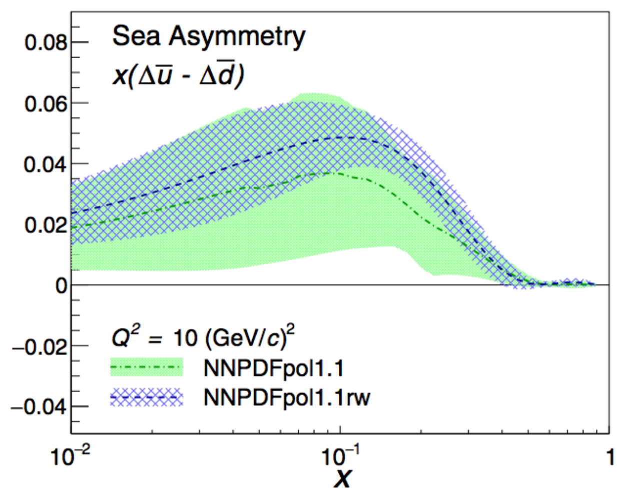


SPIN CRISIS !

We must quantify the proton spin decomposition

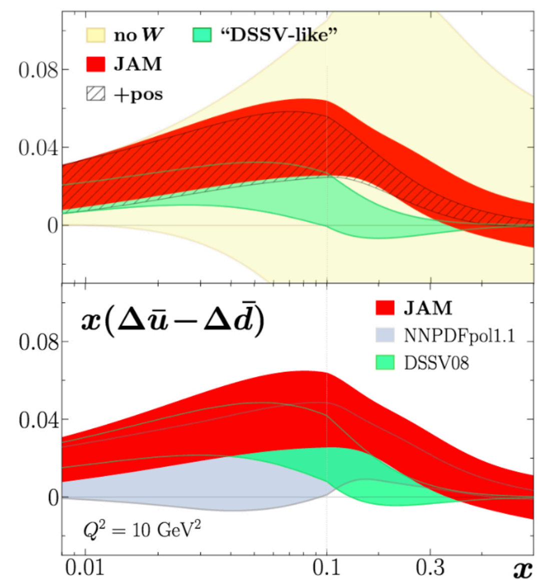
Understanding the proton spin

Experiment



[J. Adam et al. (STAR Collaboration), Phys. Rev. D 99, 051102(R)]

Global Analysis



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★ Significant progress from experiments and analysis of experimental data sets

- Recent RHIC results on flavor decomposition of antiquarks in spin

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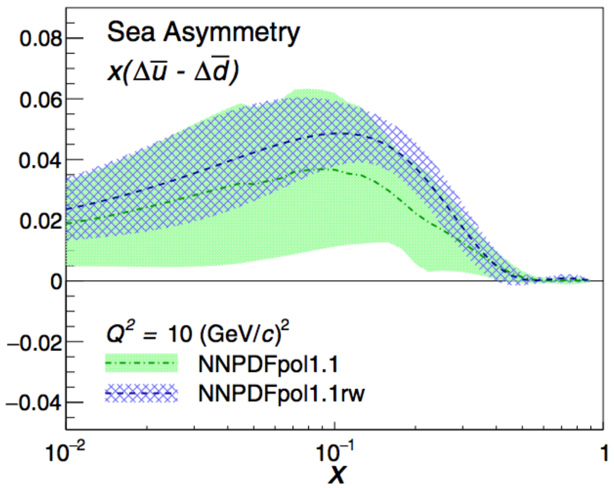

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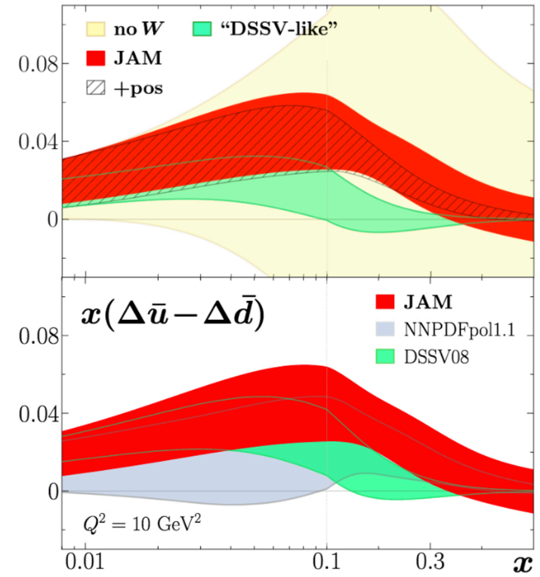

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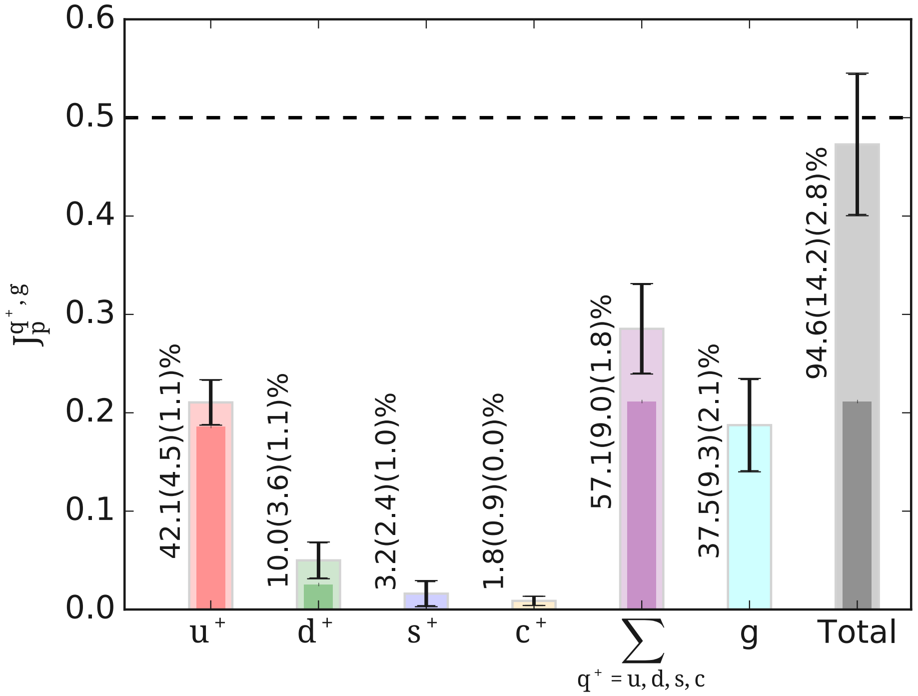
First-principles QCD



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Total spin fully decomposed from first principles

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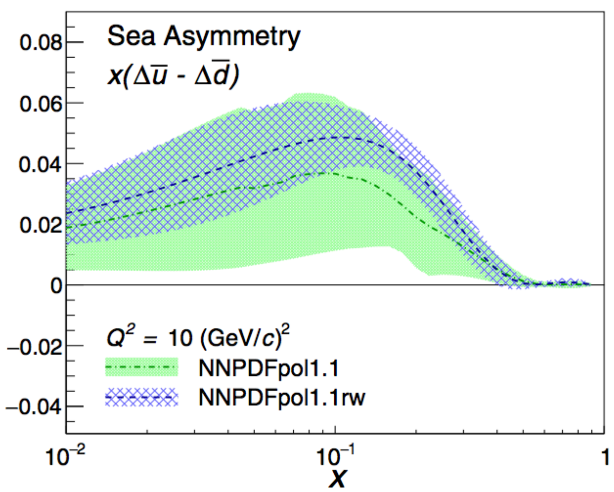

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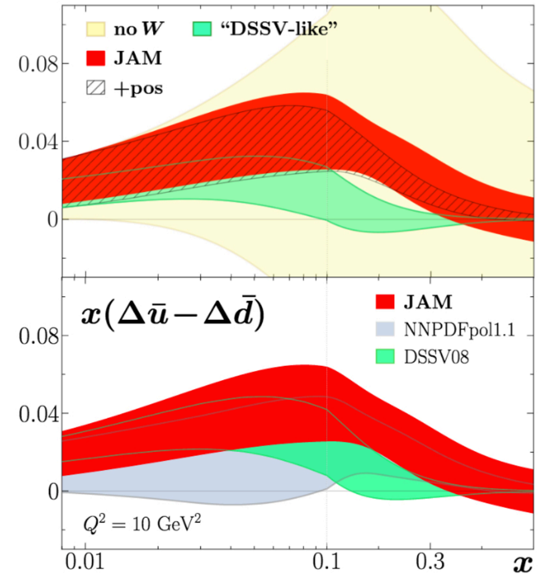

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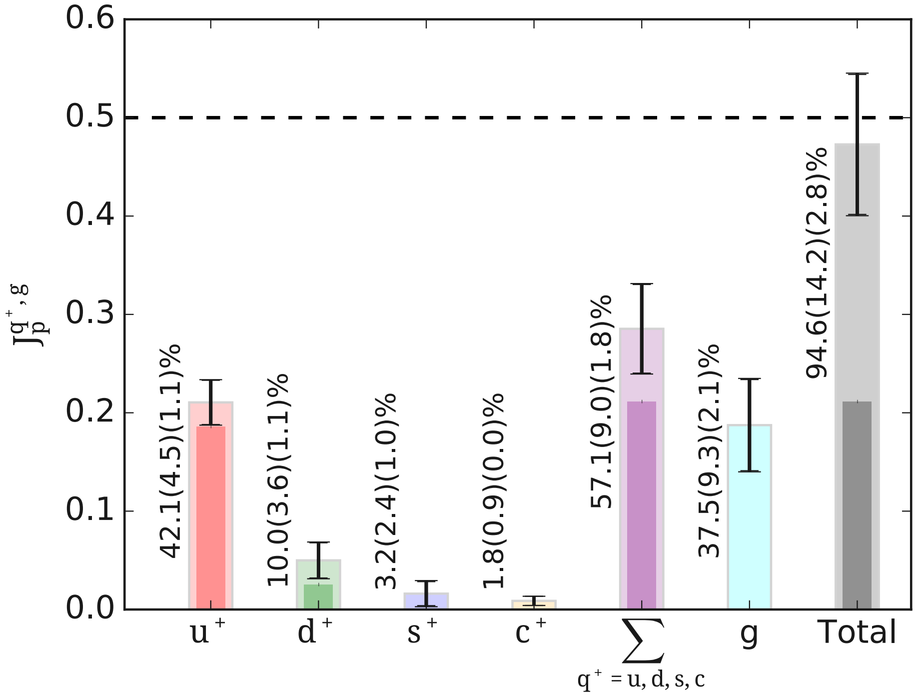

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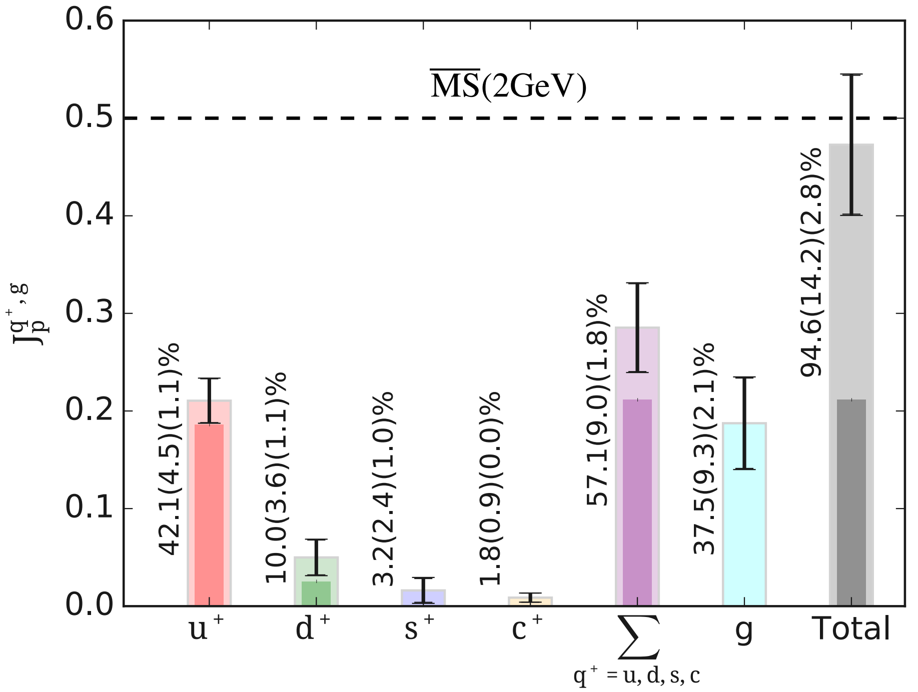
Resolution of a 35-year old puzzle

Impressive progress in the field leading to new opportunities

Spin decomposition



★ 2-years of intensive calculations with three distinct components to extract quark and gluon contributions

★ Individual quark spin identified

★ Large gluon contributions

★ Spin and momentum sum rules satisfied

★ Total spin contains:
- intrinsic spin
- orbital angular momentum

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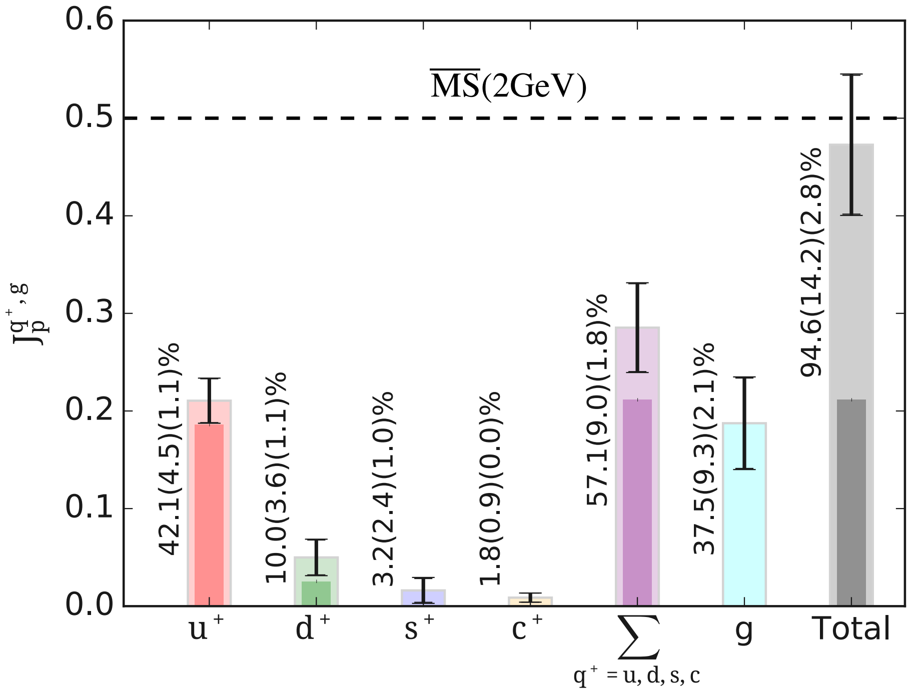

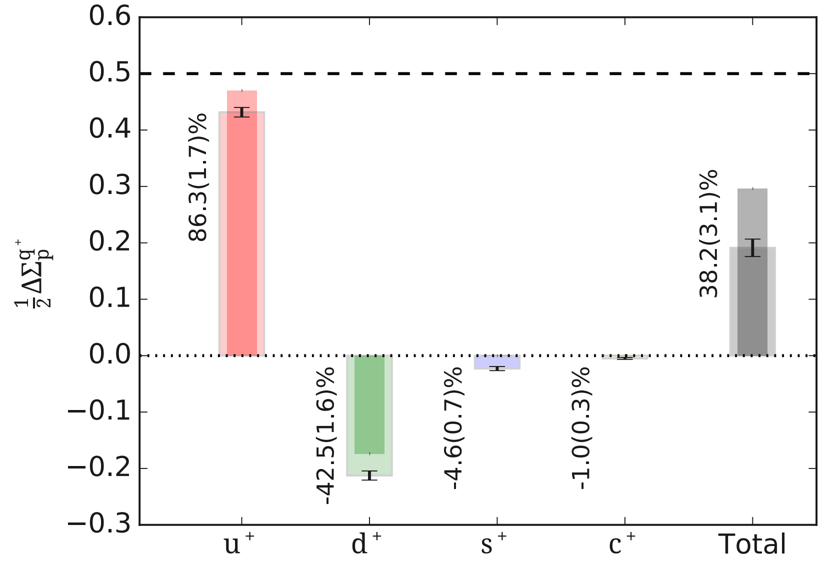

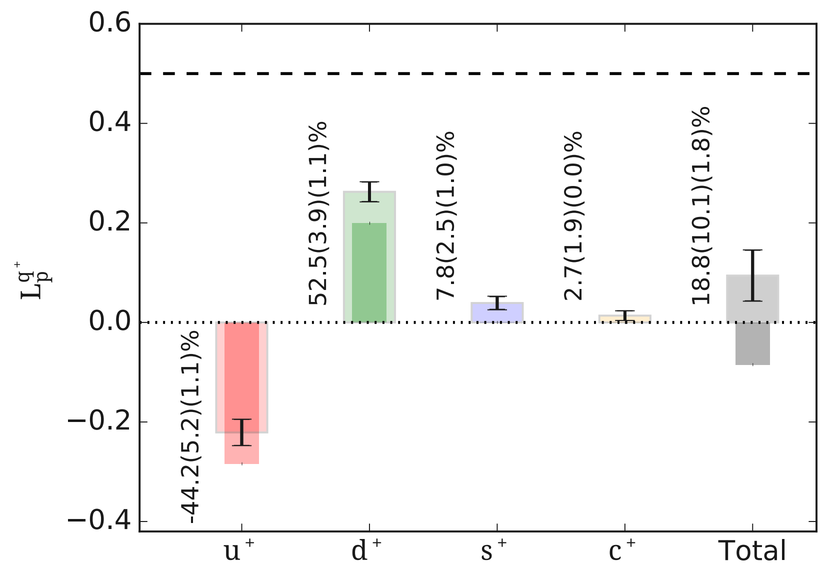

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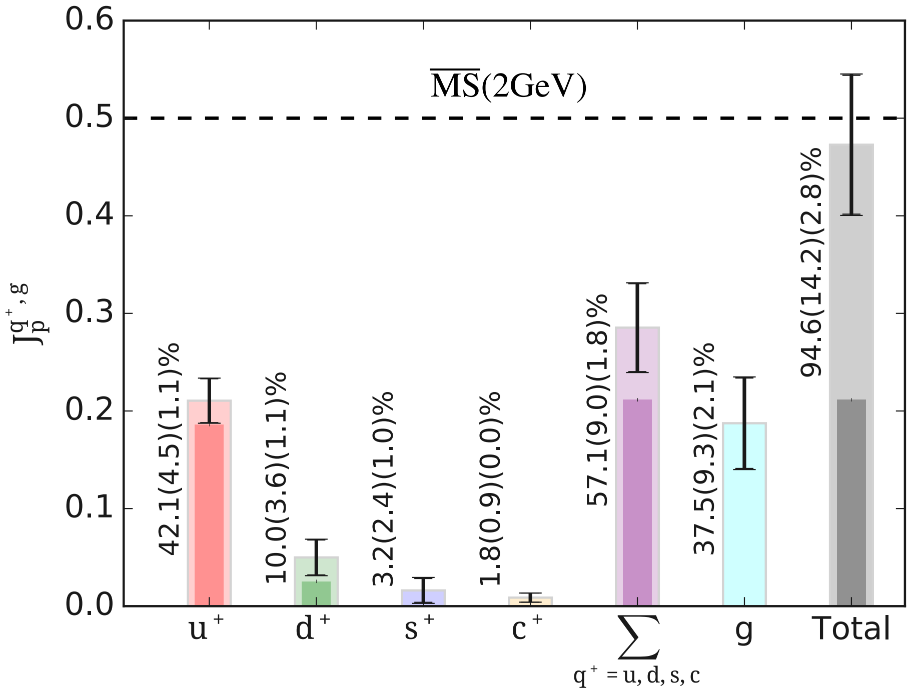

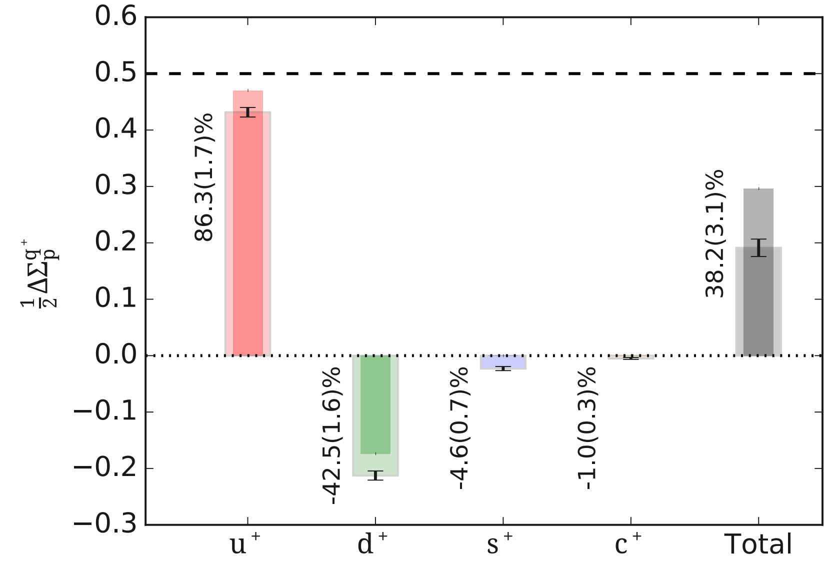

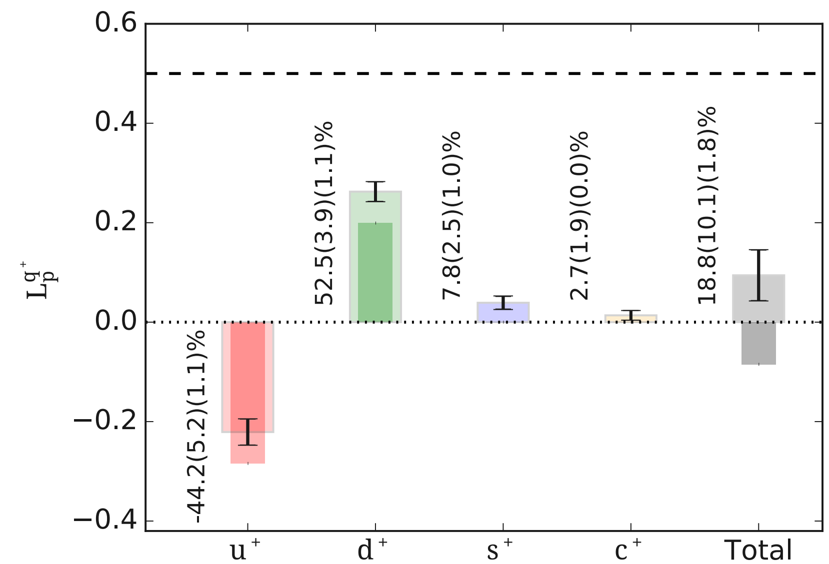

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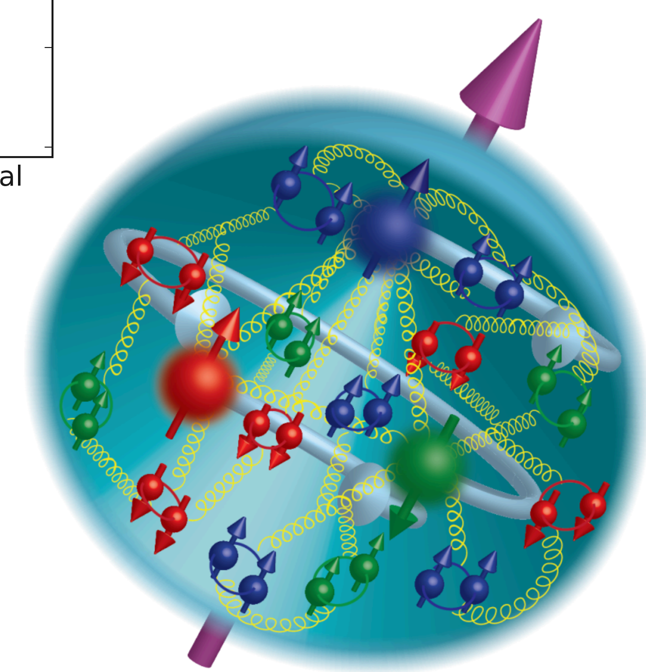
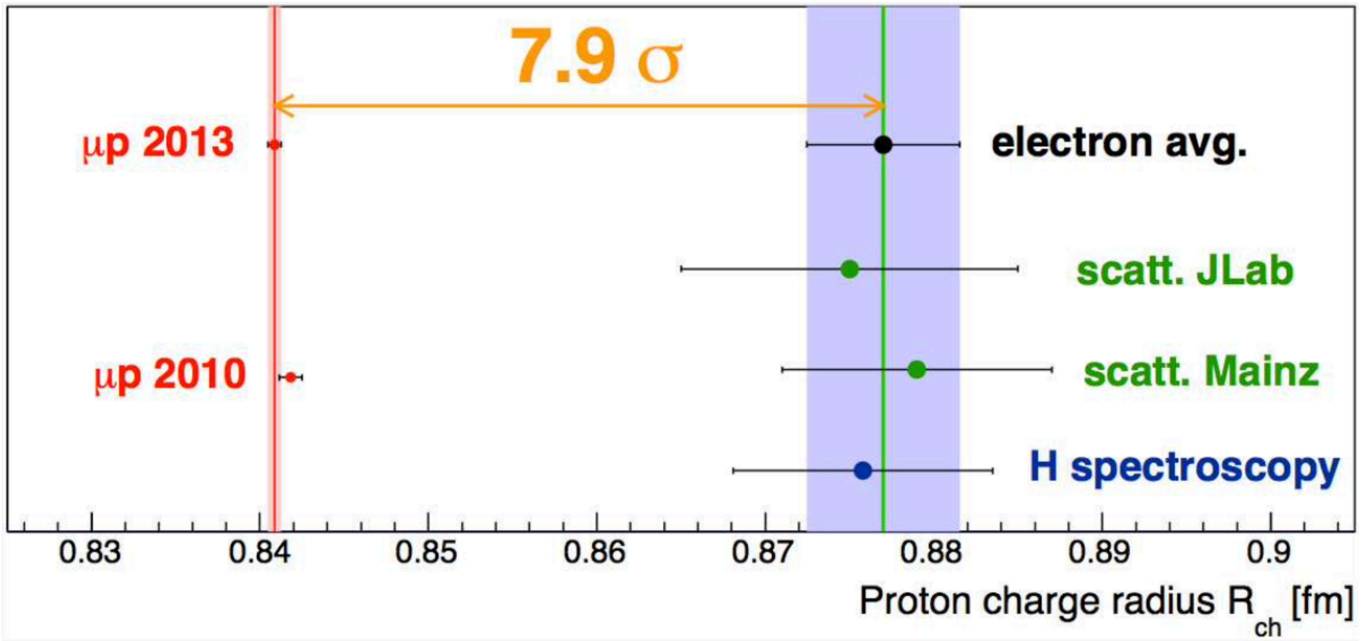
Better understanding of the spin distribution



Designed by Z.-E. Meziani

Proton radius crisis

[R. Pohl et al., Nature 466 (2010) 213]



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- ★ Muonic hydrogen experiment much more sensitive to proton size
- ★ Puzzling discrepancy between different methods
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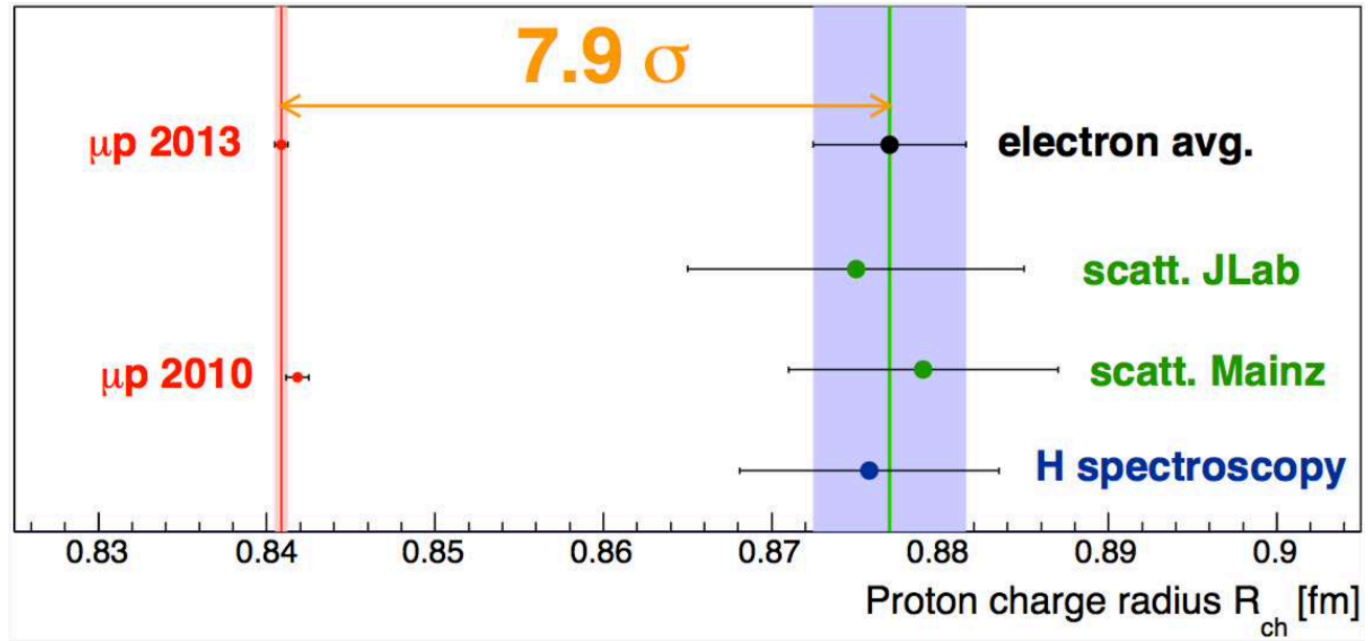

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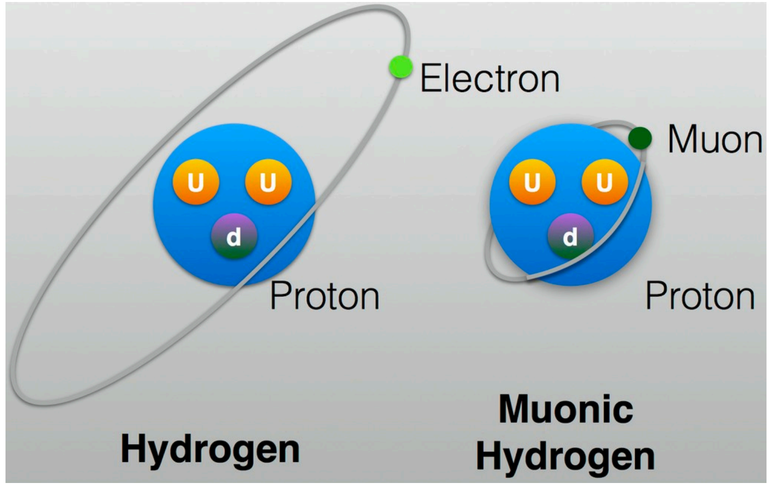
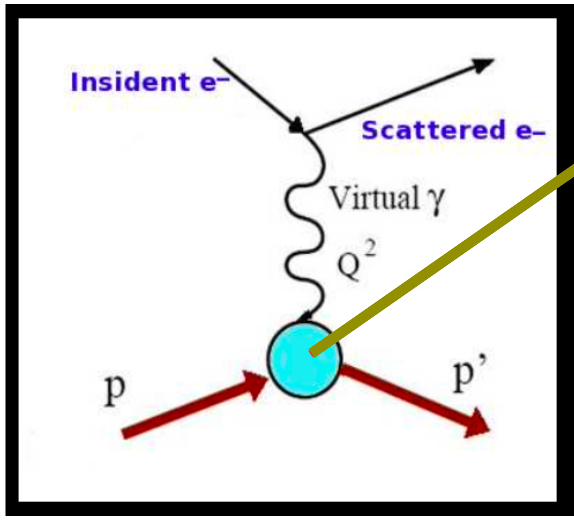


Credit: Taiwan News

Extracting the proton radius



Electromagnetic form factors

Electric charge and current distributions inside nucleon

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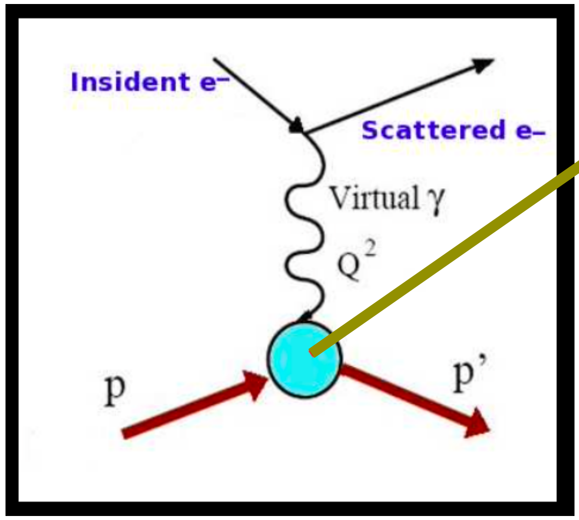

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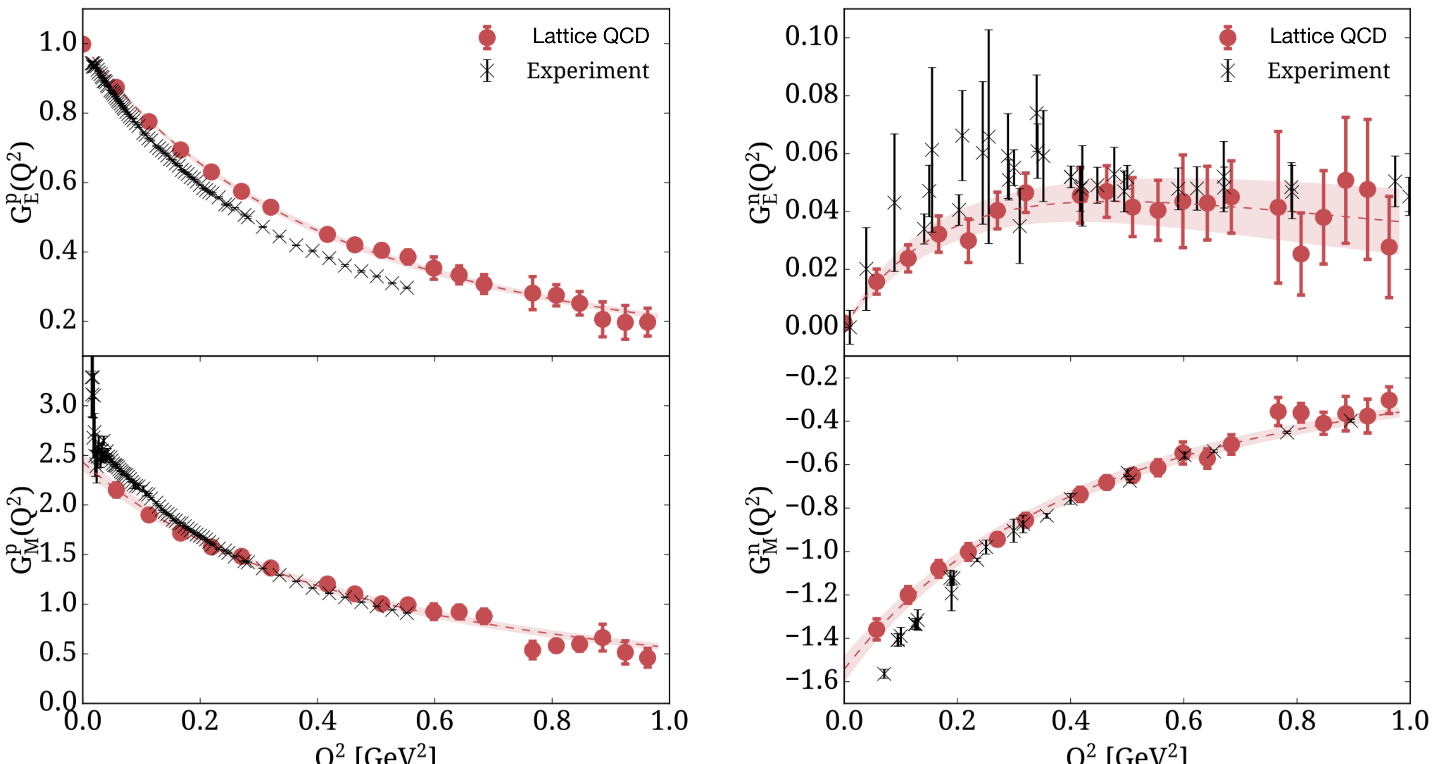

ETM Collaboration, PRD 100 (2019) 1, 014509

- ★ Extraction of p and n E/M FFs requires flavor decomposition (challenging!)
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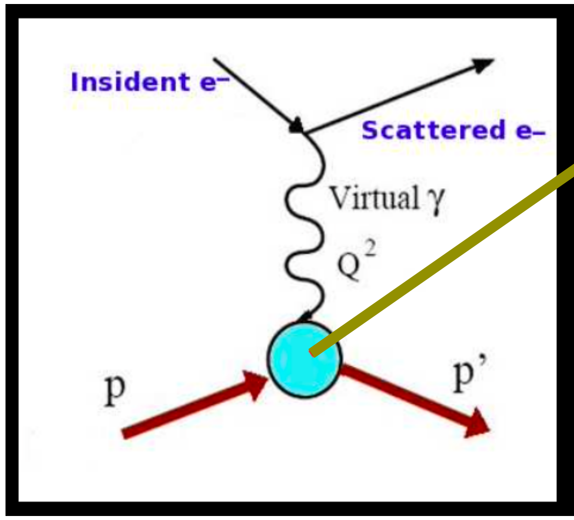

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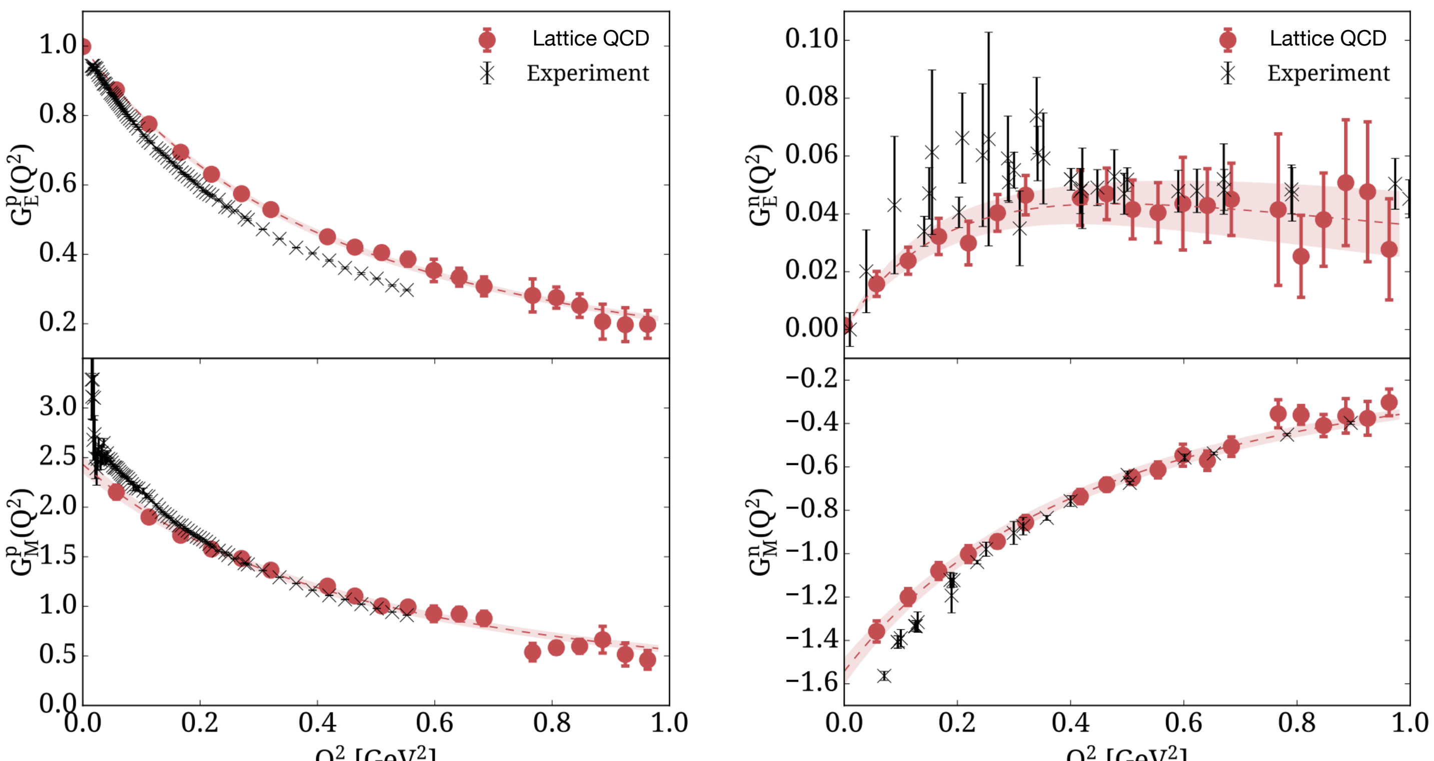
★ Charge radius: slope of FFs at $Q^2 = 0$

$$\langle r_i^2 \rangle = -\frac{6}{F_i(Q^2)} \frac{dF_i(Q^2)}{dQ^2}\Big|_{Q^2=0}$$



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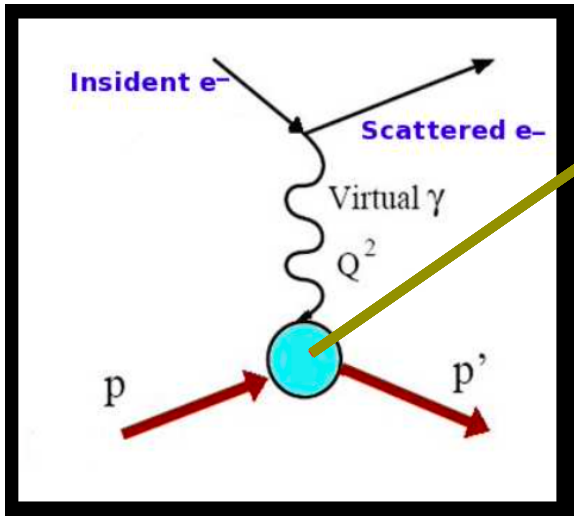

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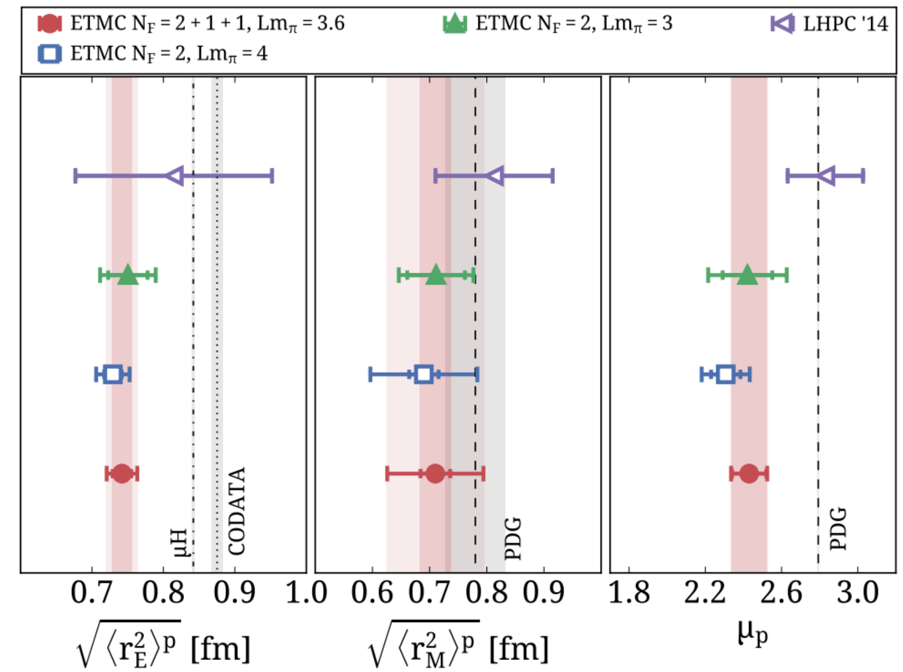

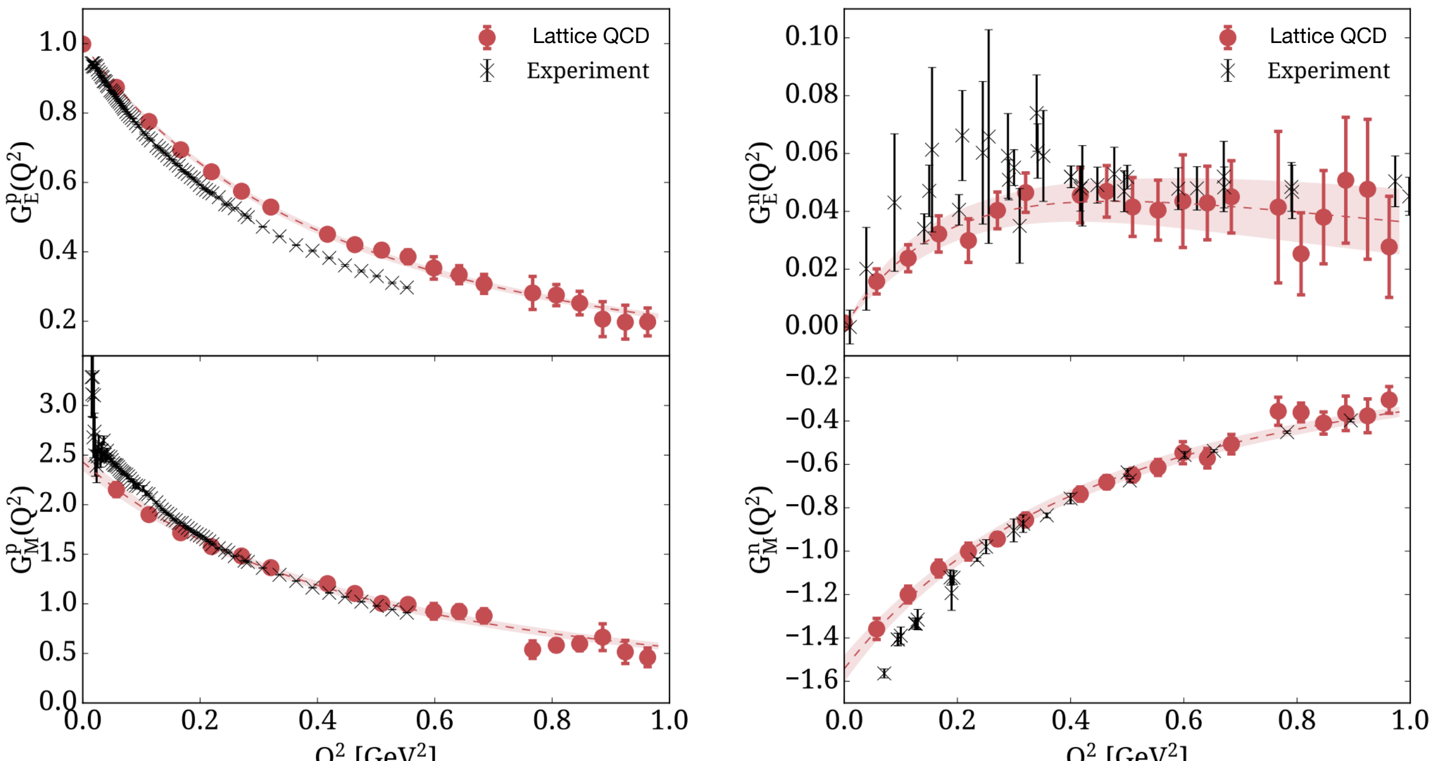

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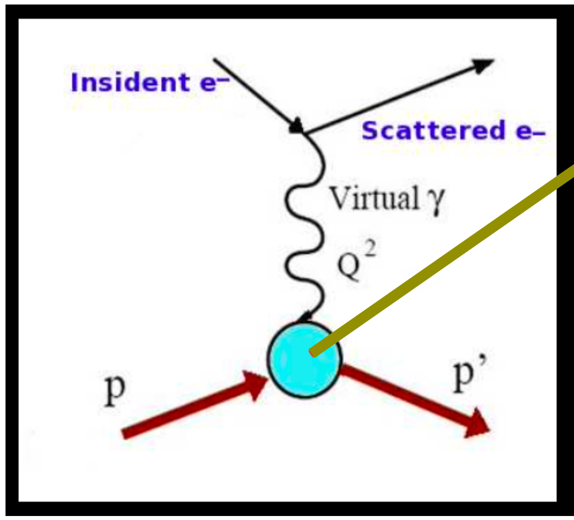

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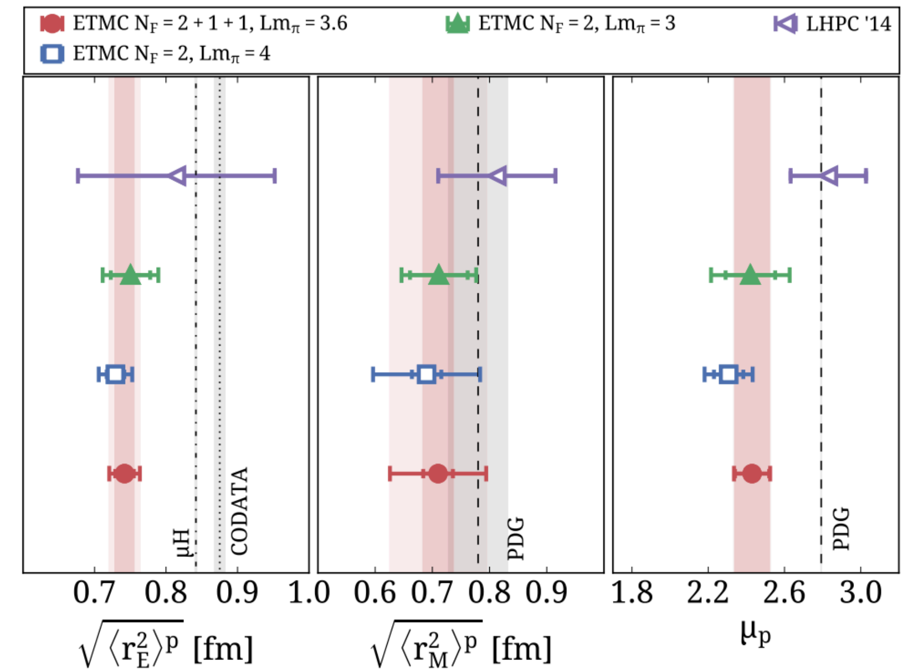

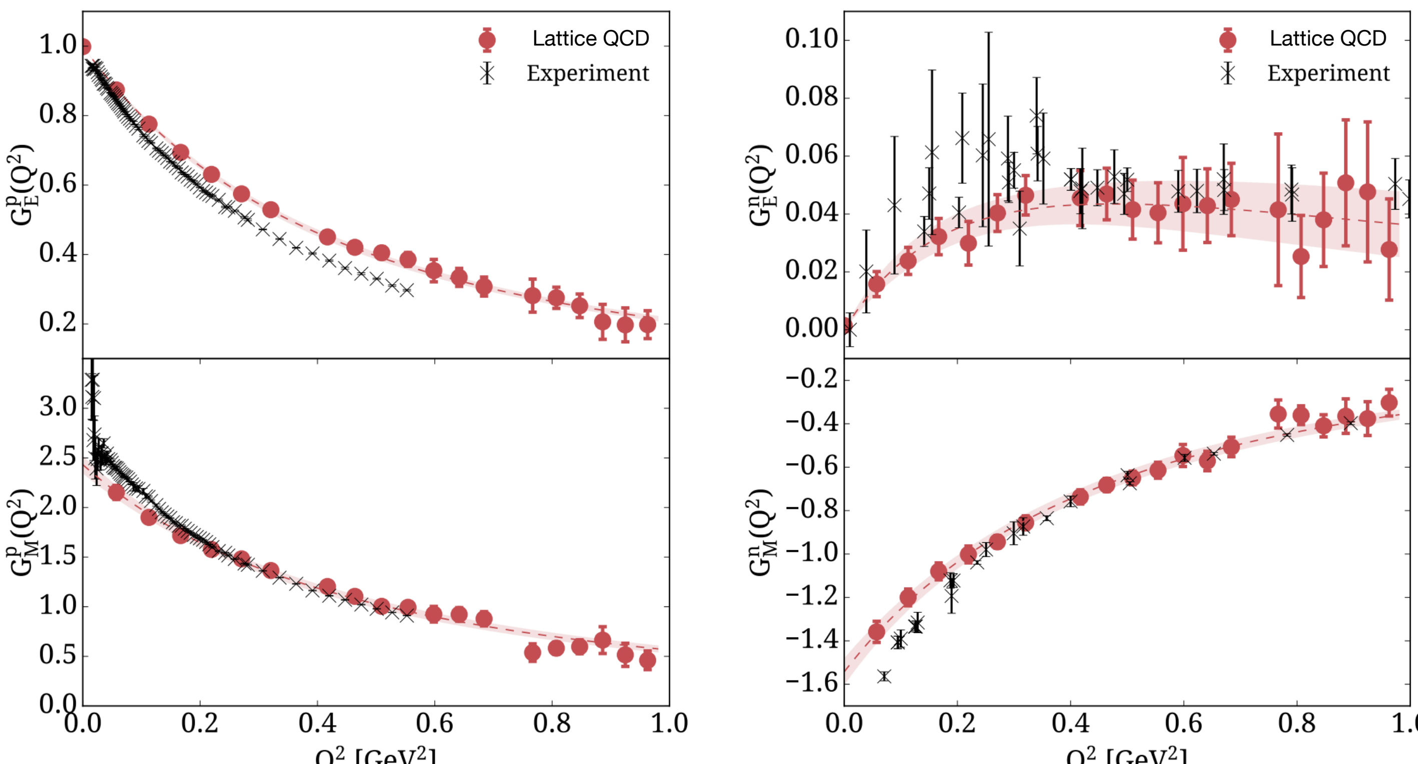

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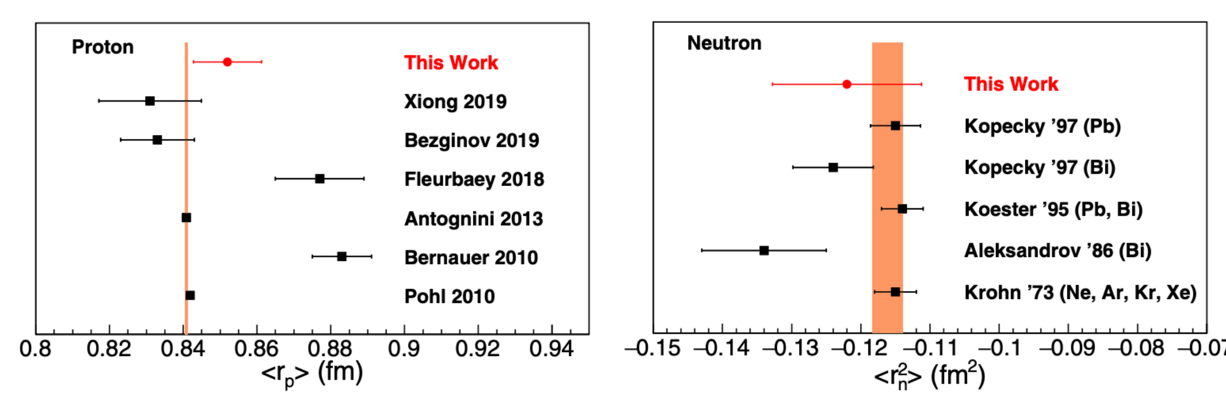
★ For the *first time* synergy between experimental data and lattice QCD results on radii



[H. Atac et al., Nature Comm. 12, 1759 (2021)]

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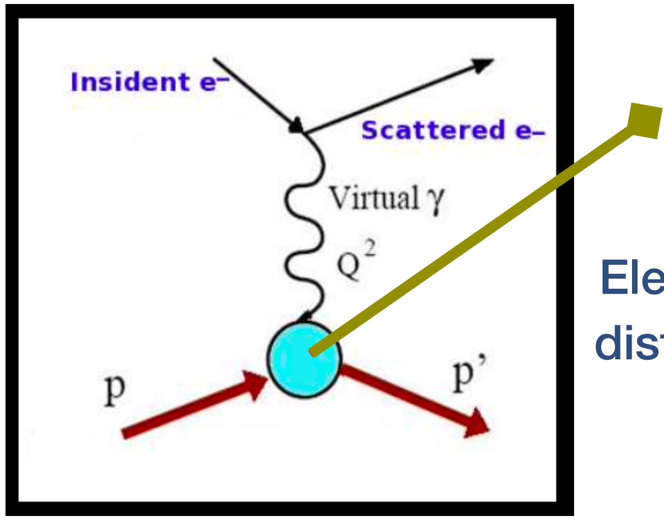

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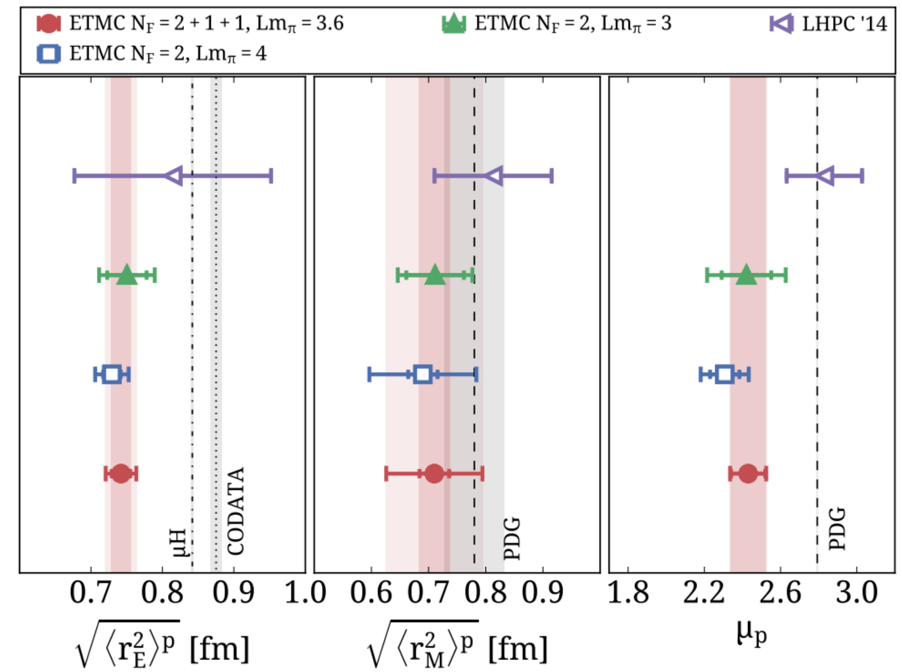

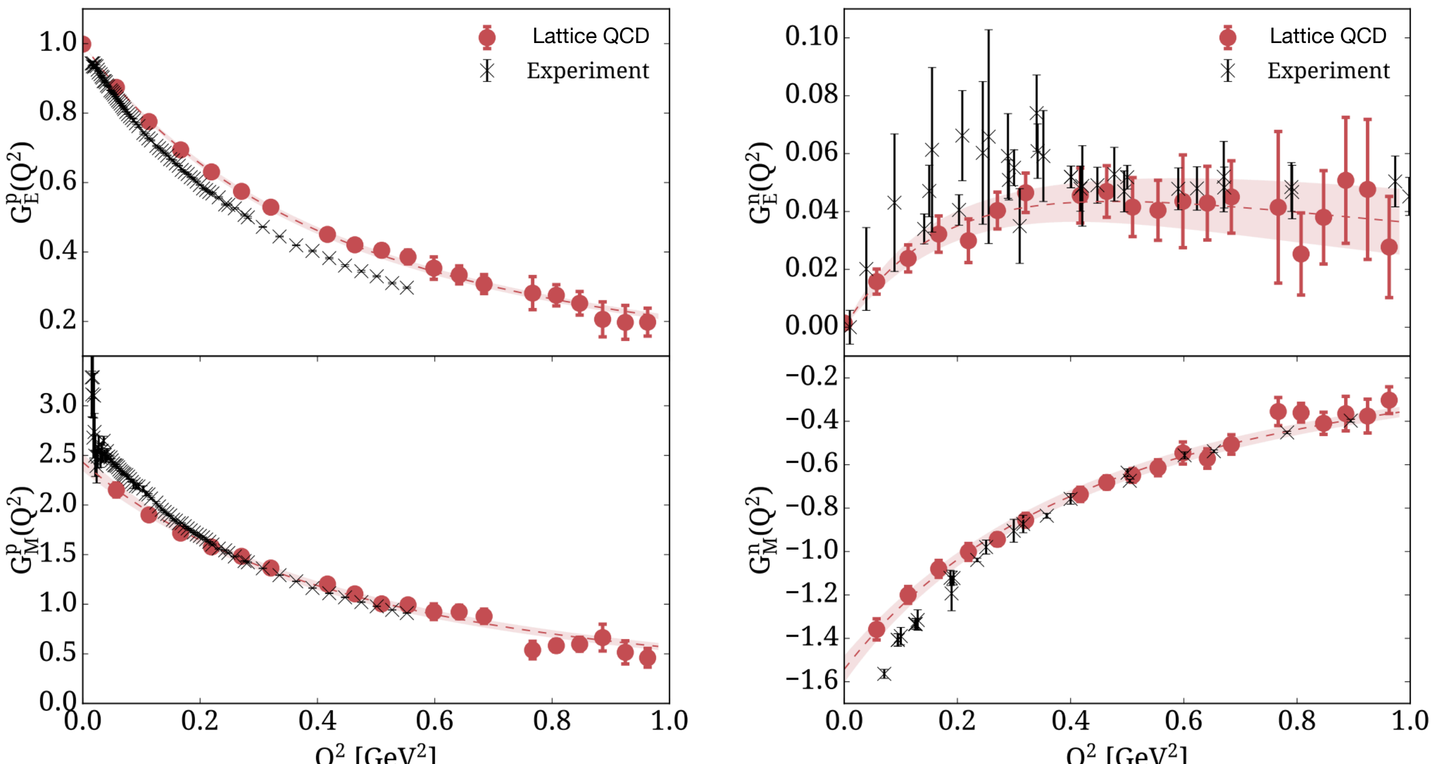

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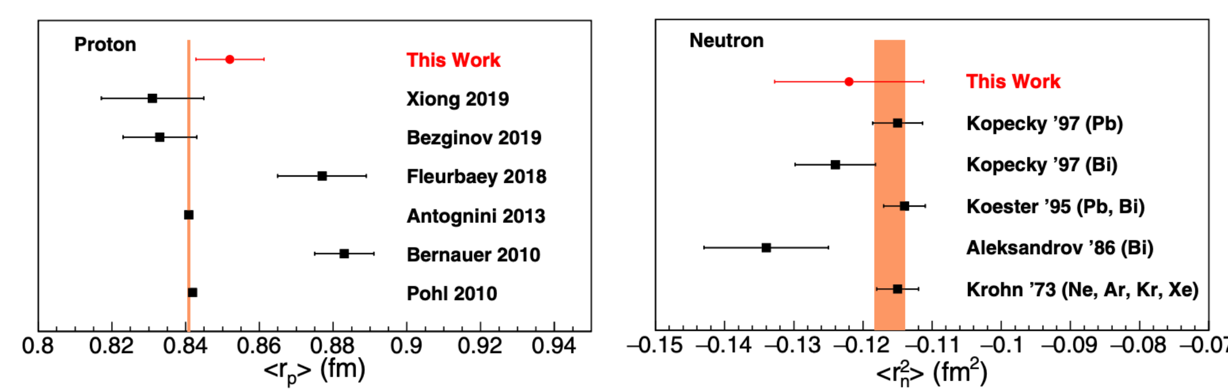

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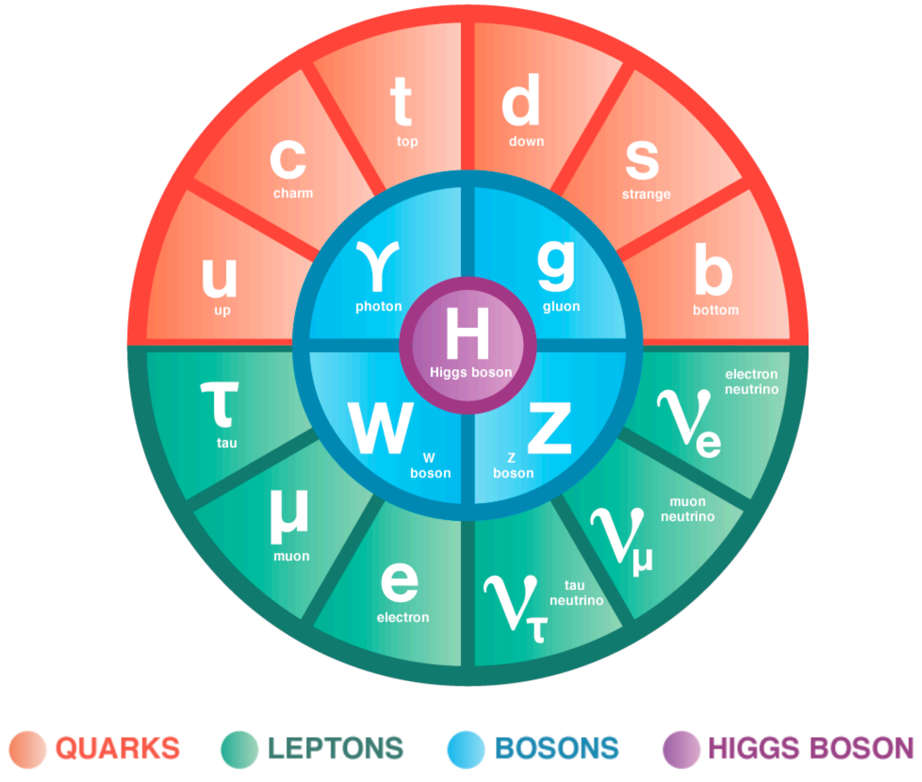
More work needed from theory and experiment

New Physics beyond the Standard Model of Particle Physics

Is the Standard Model sufficient to fully describe the building blocks of nature, or is there new physics to be discovered?



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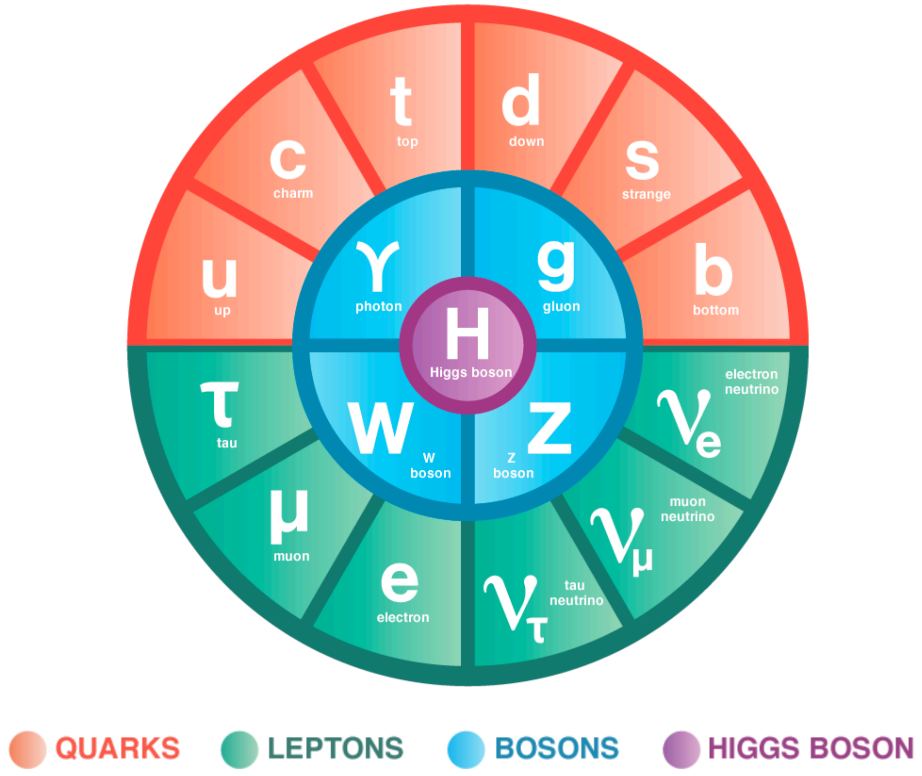

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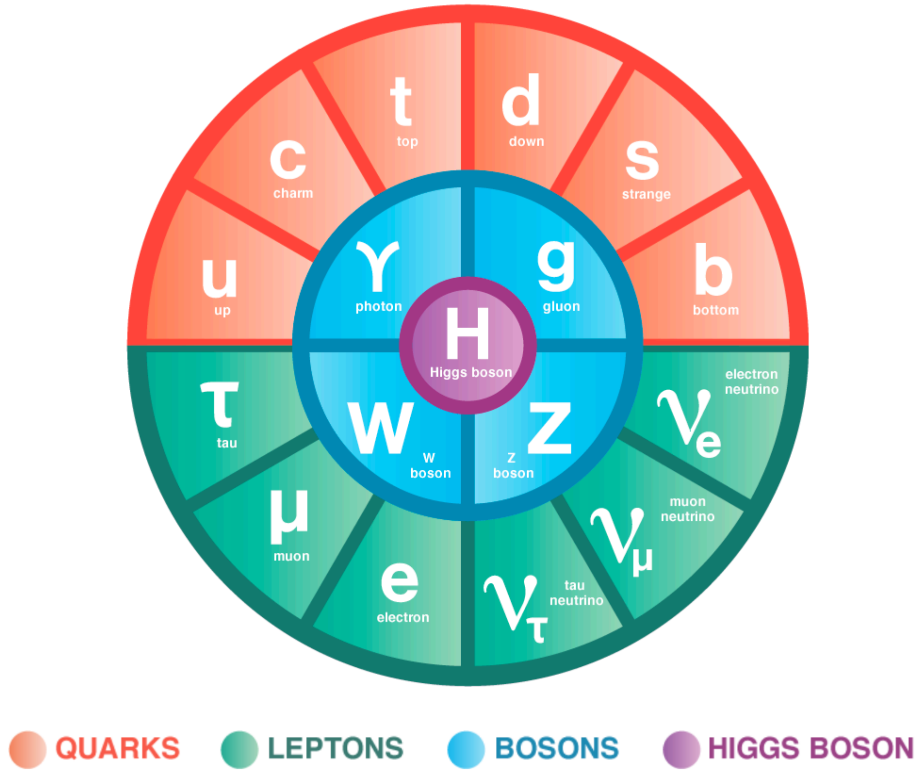
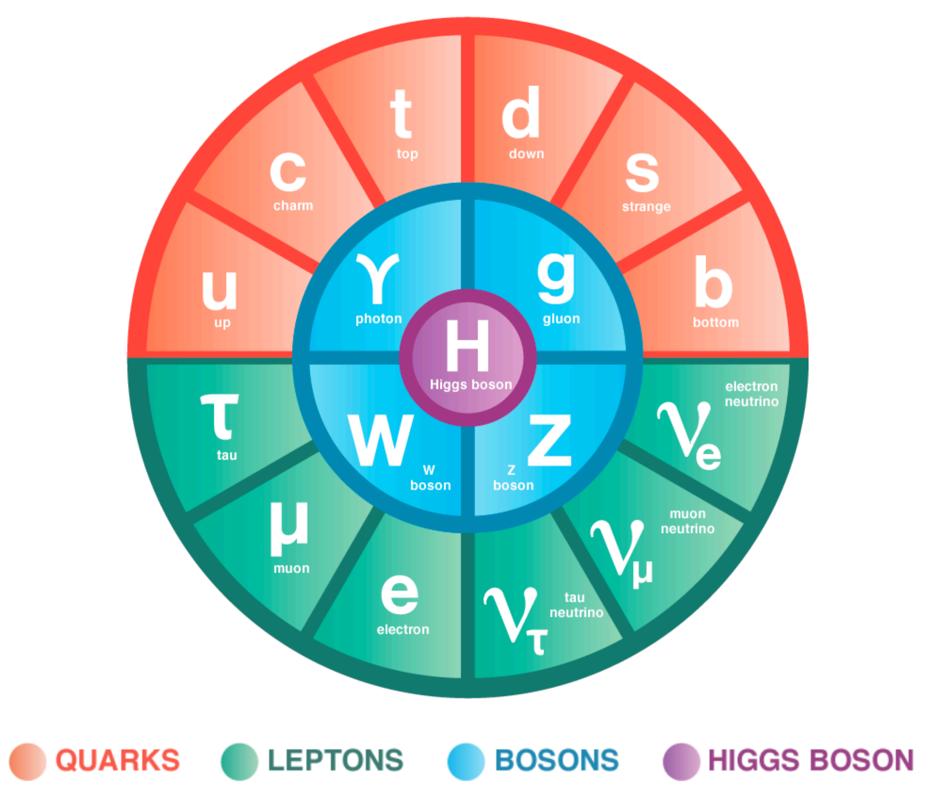
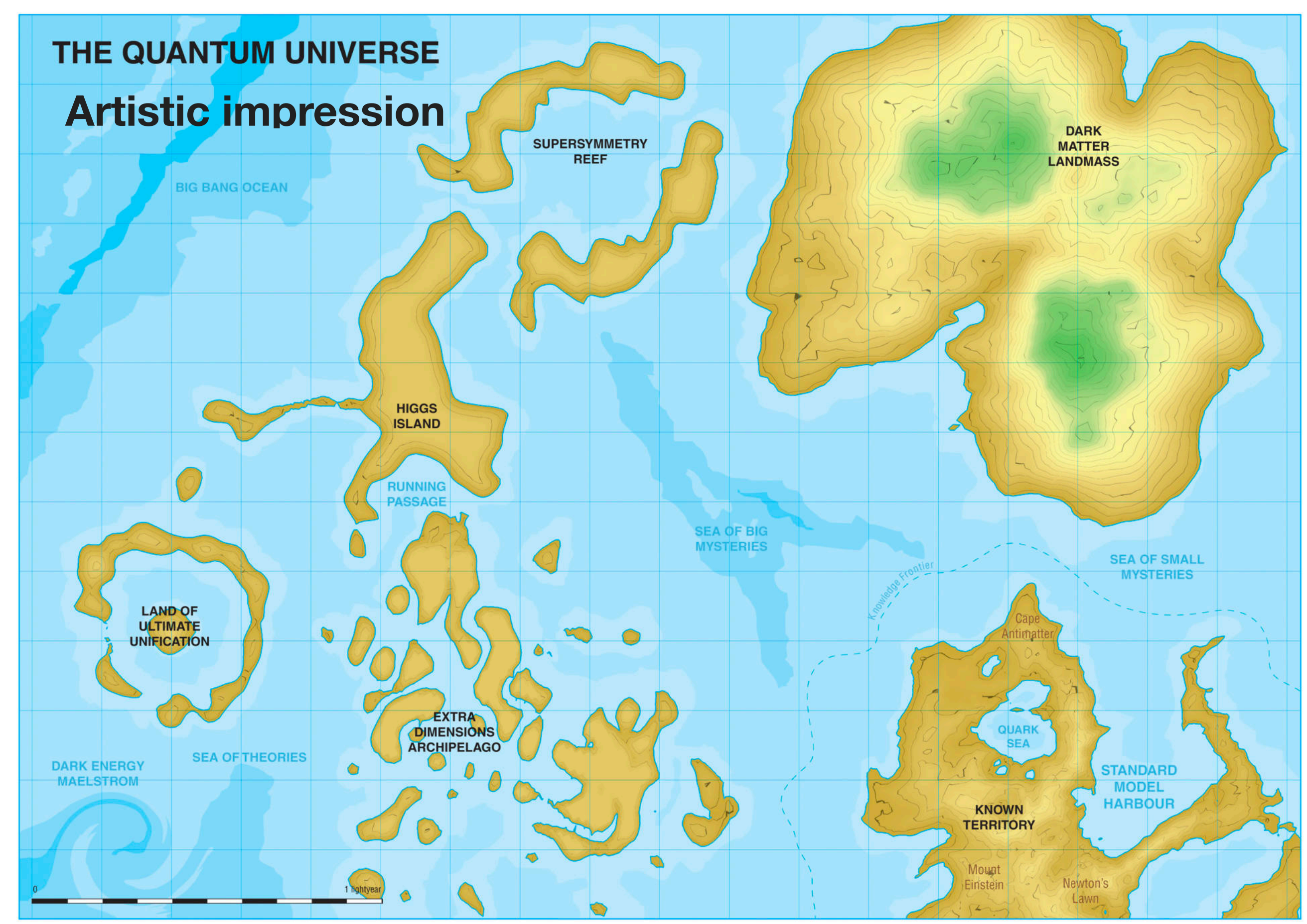
- ★ Standard model has deficiencies, e.g, inability to explain matter-antimatter asymmetry
- ★ Measurements from fundamental experiments can potentially challenge current theoretical picture indicating new physics



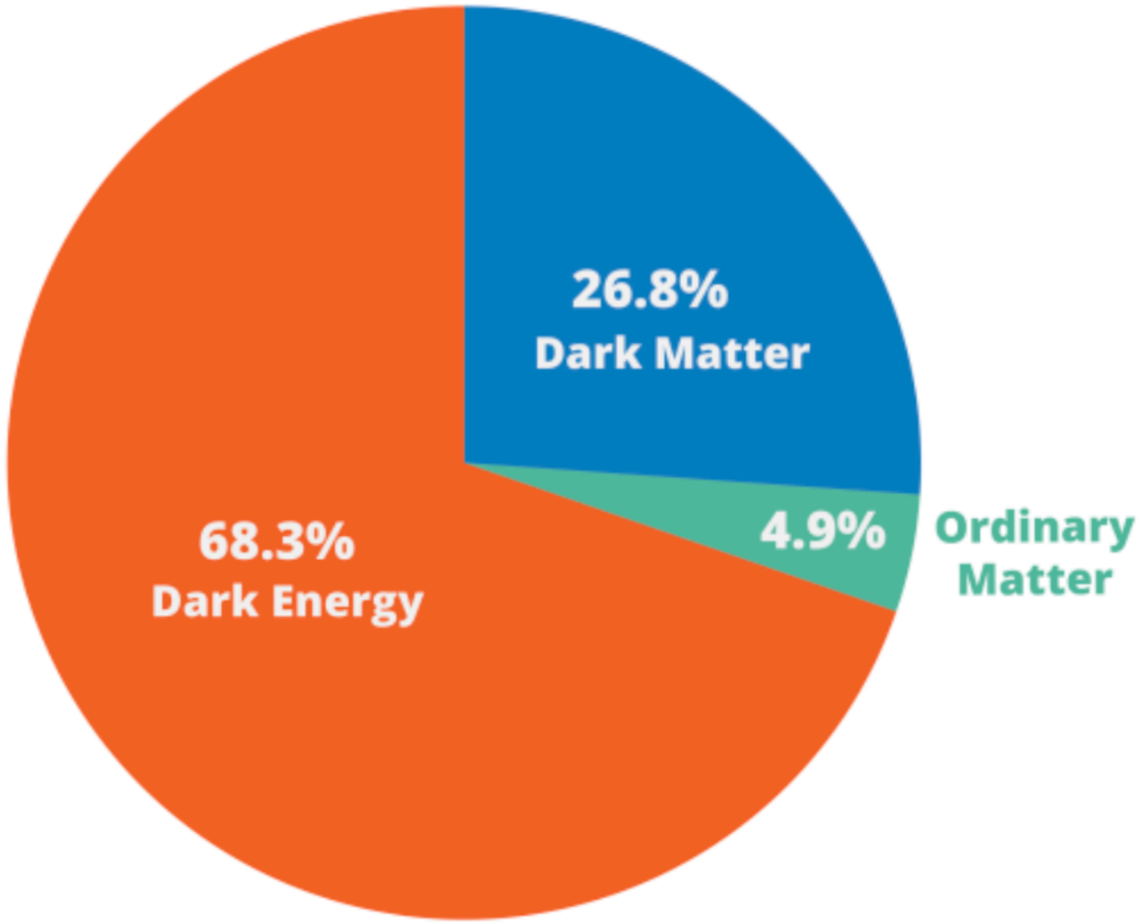
Is the Standard Model sufficient to fully describe the building blocks of nature, or is there new physics to be discovered?

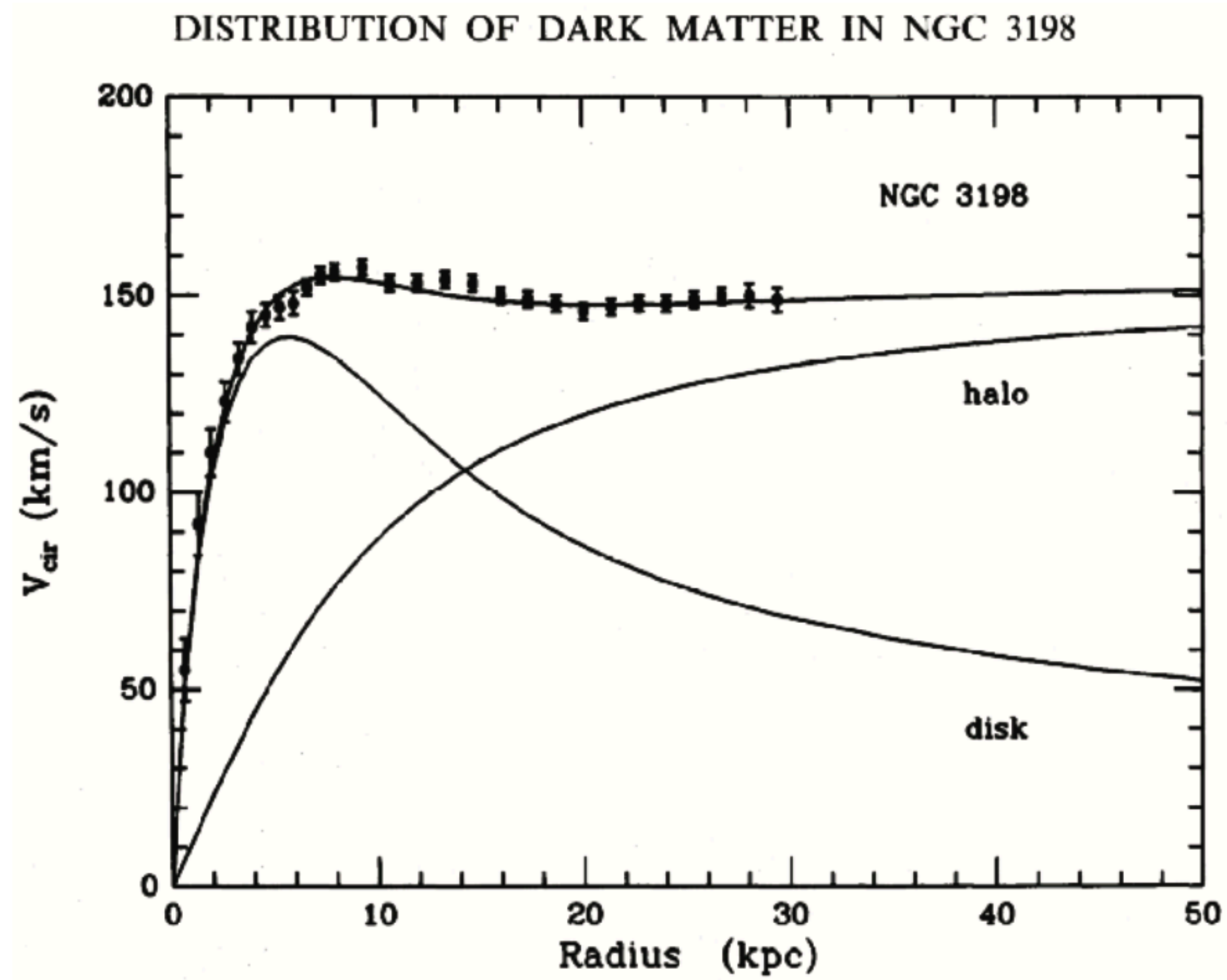
- ★ Standard model has deficiencies, e.g, inability to explain matter-antimatter asymmetry
- ★ Measurements from fundamental experiments can potentially challenge current theoretical picture indicating new physics





Dark Matter Searches





[T.S. van Albada et al., *Astrophys.J.* 295 (1985) 305]

- ★ Visible Universe consist a small amount of the energy-matter content of Universe
- ★ Evidence of Dark Matter
- ★ Rotation curve of galaxies (e.g., NGC 3198) require velocity contributions from dark matter to match observations besides the visible baryonic components

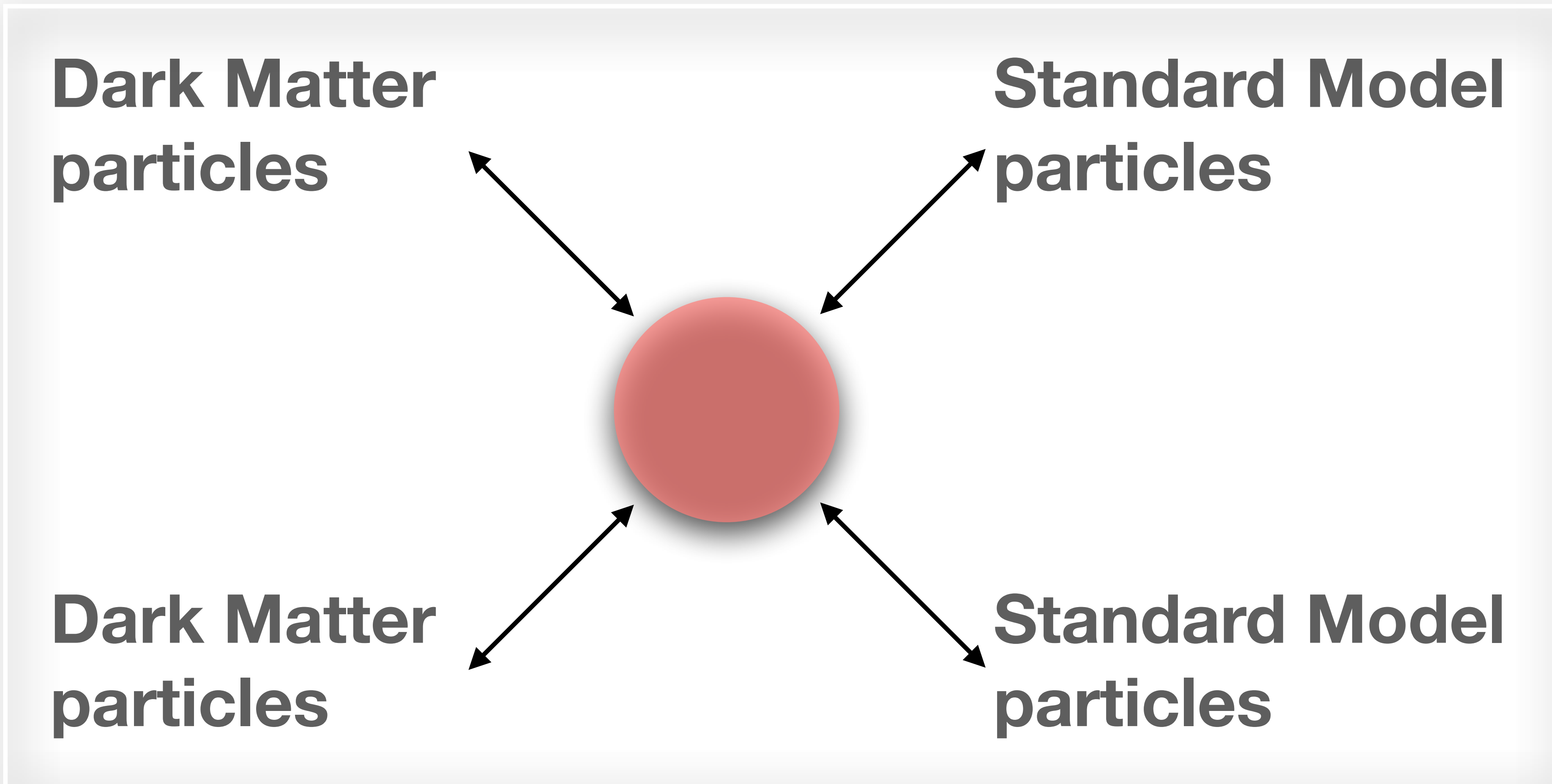
Searches for Dark Matter

Indirect Detection

Search for products of DM annihilation

Direct Detection

DM-SM scattering in detector



Colliders

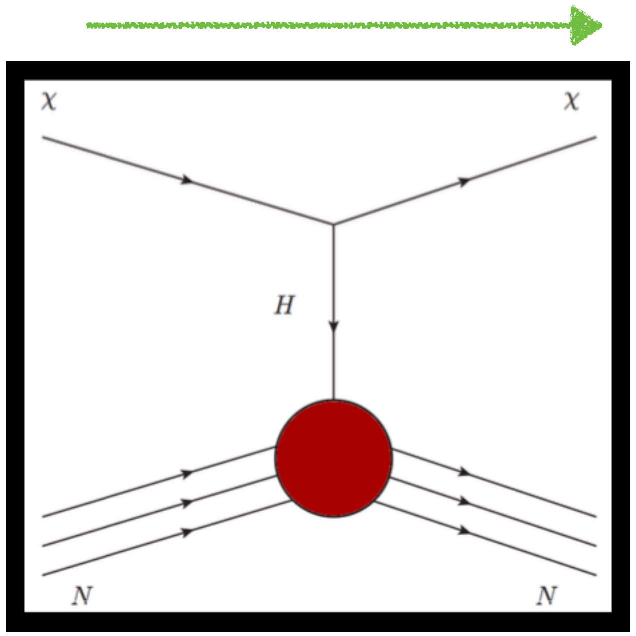
Production of DM (find anomalous missing energy)

Investigations are complementary

Direct searches of Dark Matter

★ Direct DM searches look for new scalar interactions (Higgs boson production)

★ Nucleon σ-terms enter the cross-section of the DM-nuclei elastic scattering



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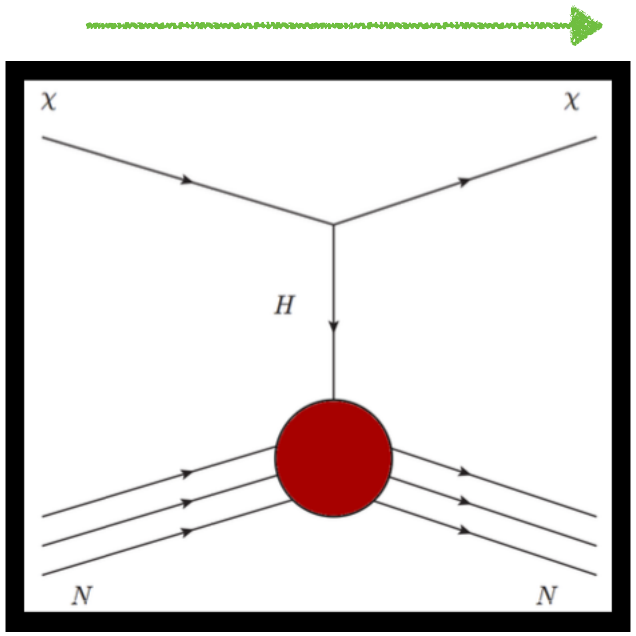

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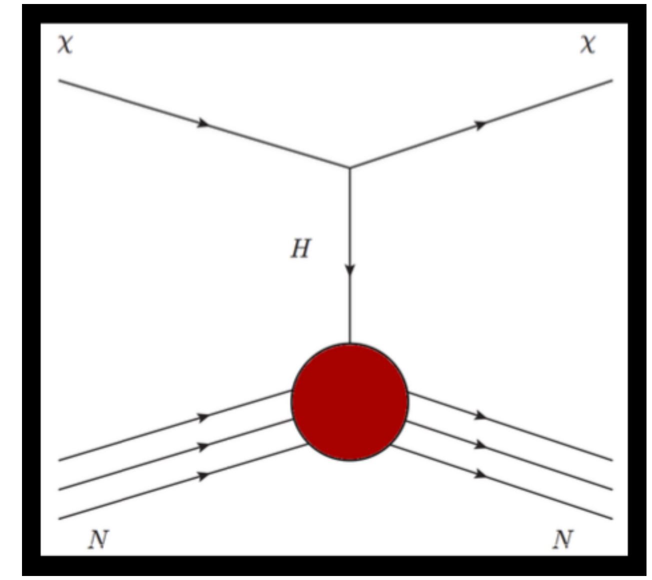

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σ-terms lead to large uncertainties in WIMP-nucleon cross-section

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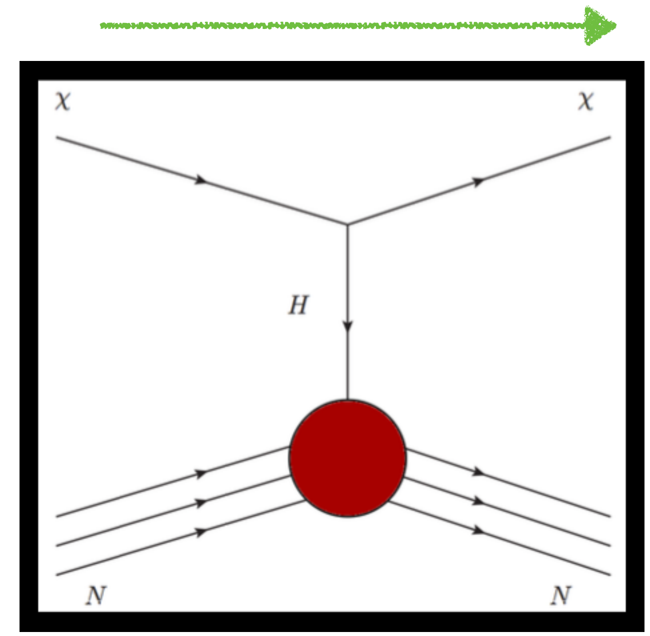

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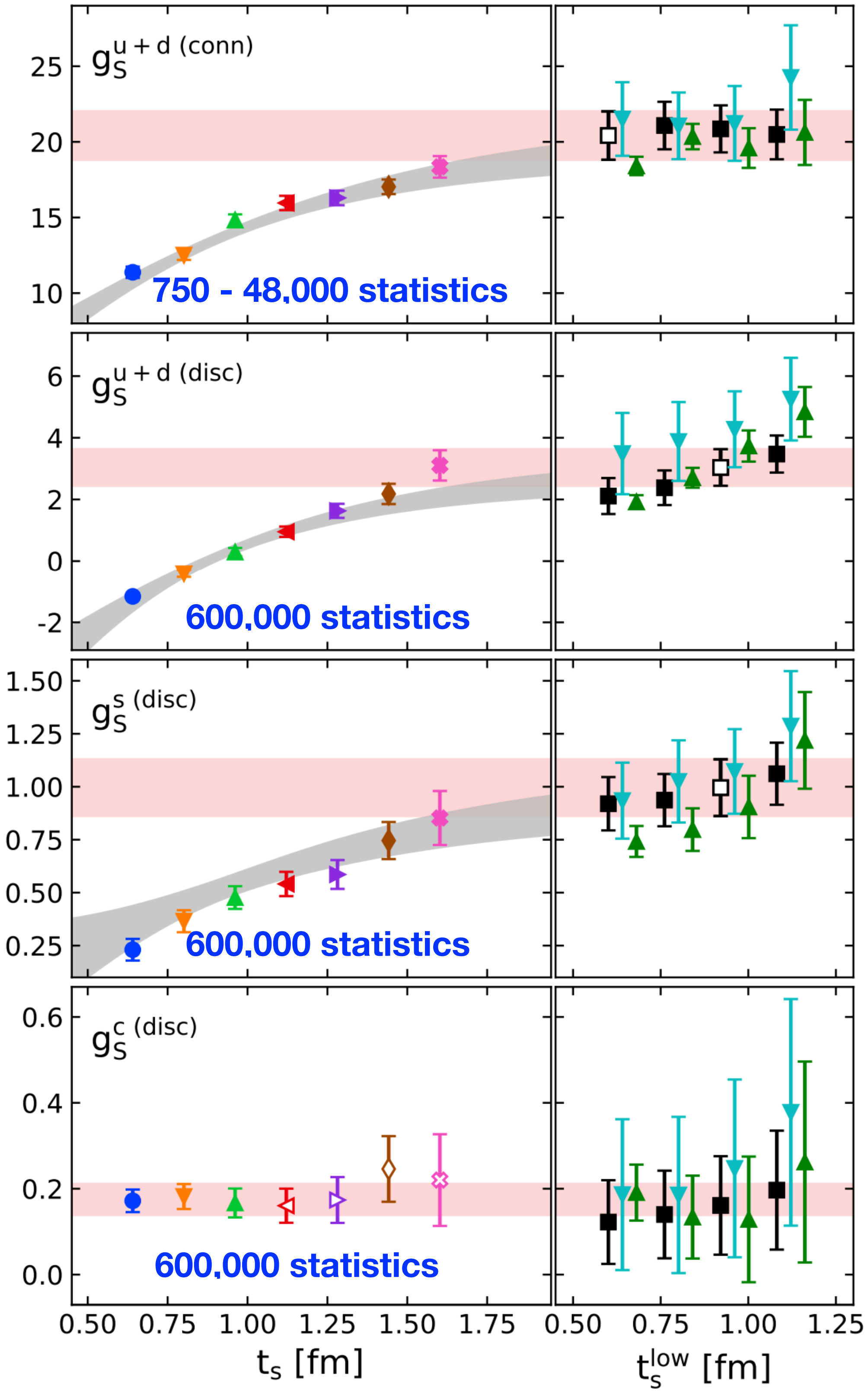
σ-terms lead to large uncertainties in WIMP-nucleon cross-section

★ Lattice QCD offers a great opportunity to extract the nucleon σ-terms

$$\sigma_f = m_{q_f}\langle N|\bar{q}_f q_f|N\rangle,\ \sigma_{\pi N} = m_{ud}\langle N|\bar{u}u + \bar{d}d|N\rangle$$

Direct searches of Dark Matter

★ Computationally challenging calculation



[C. Alexandrou et al., Phys. Rev. D 102 (2020) 5, 054517 arXiv:1909.00485]

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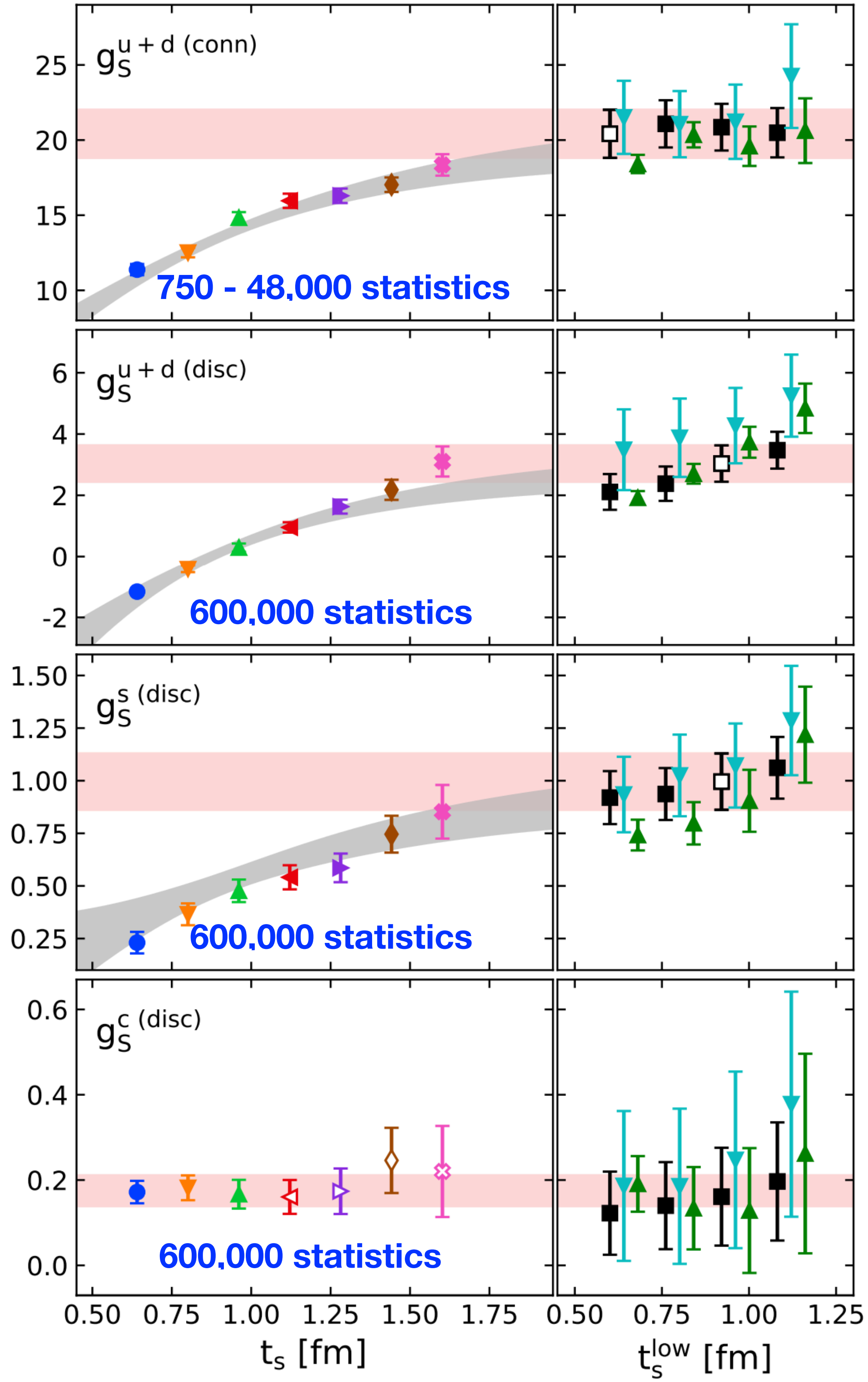

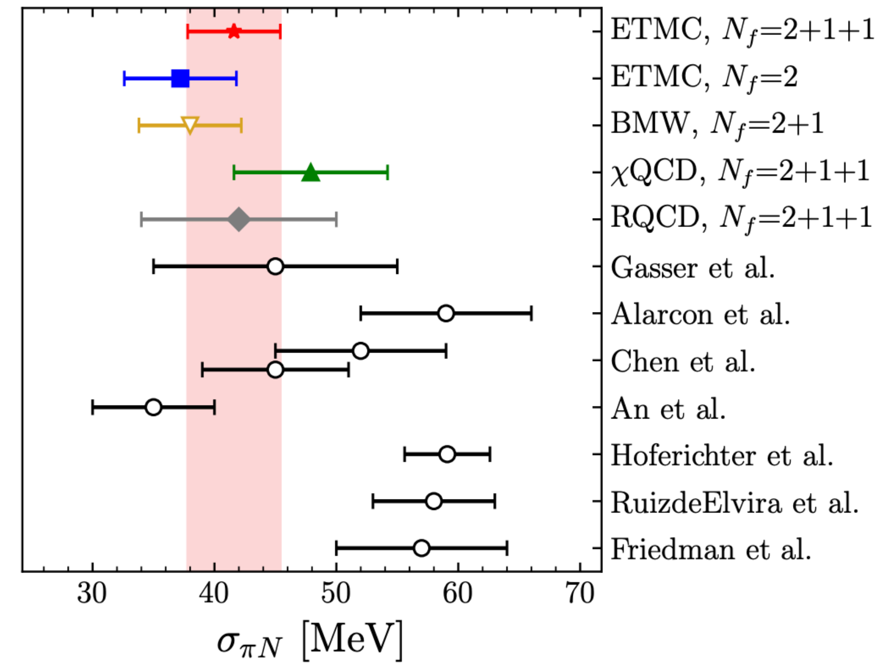

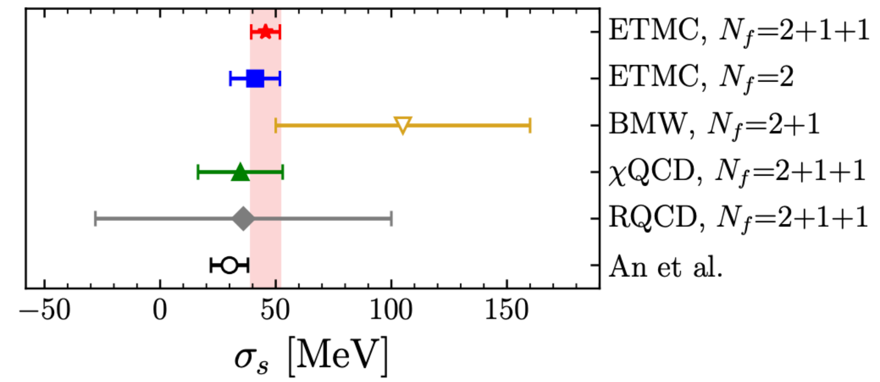

	$u+d$	s	c
σ [MeV]	41.6(3.8)	45.6(6.2)	107(22)
f^N	0.0444(43)	0.0487(68)	0.115(24)

$f^N_{ud} \equiv \sigma_{\pi N}/m_N$

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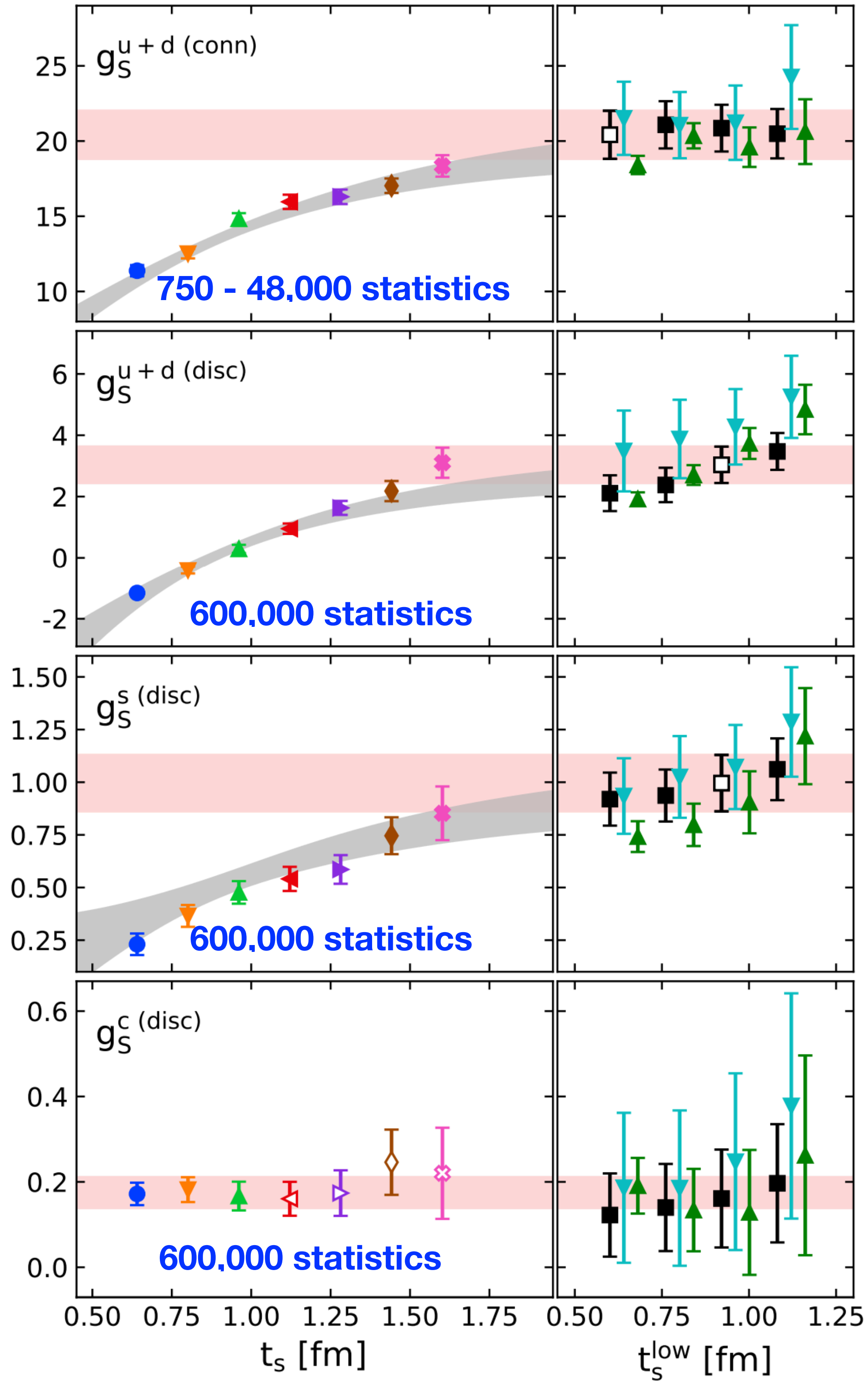

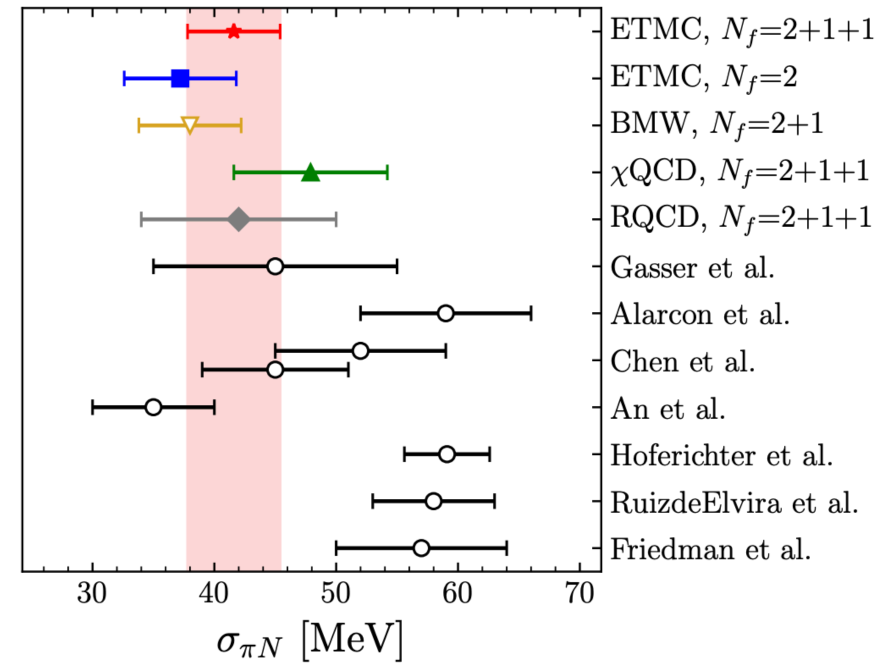

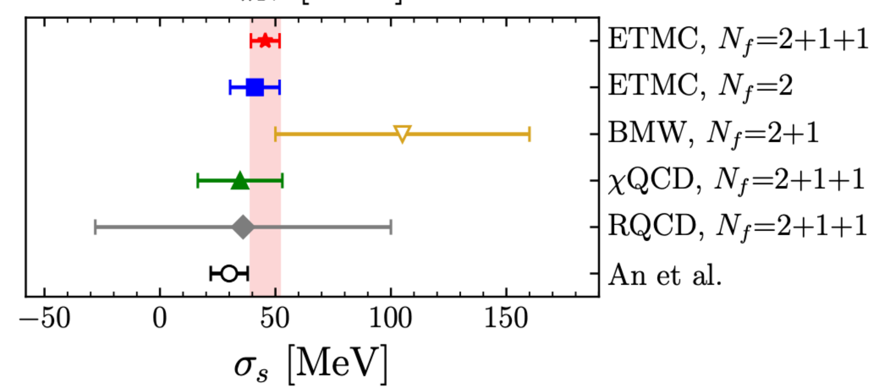

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Lattice results are high-accuracy

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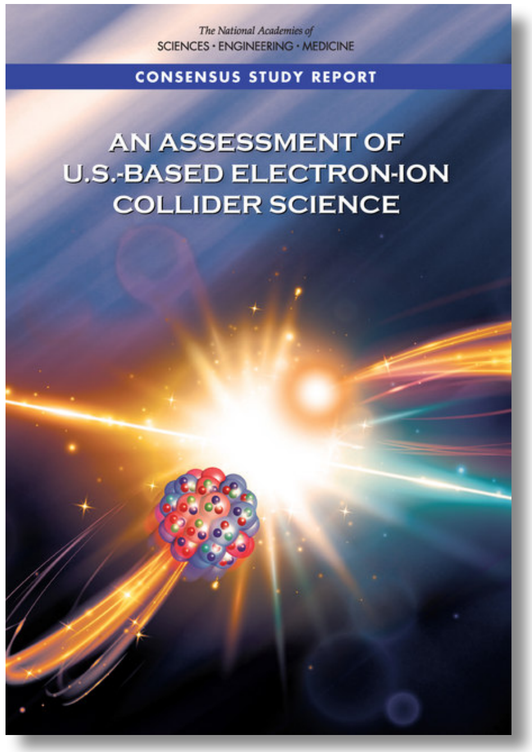
The Next Frontier:

Electron Ion Collider

Electron Ion Collider

A machine that will unlock the secrets of the strongest force in Nature



NAS report release:
07/24/2018

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Glowing report on a US-based EIC facility!

$2B investment of DOE
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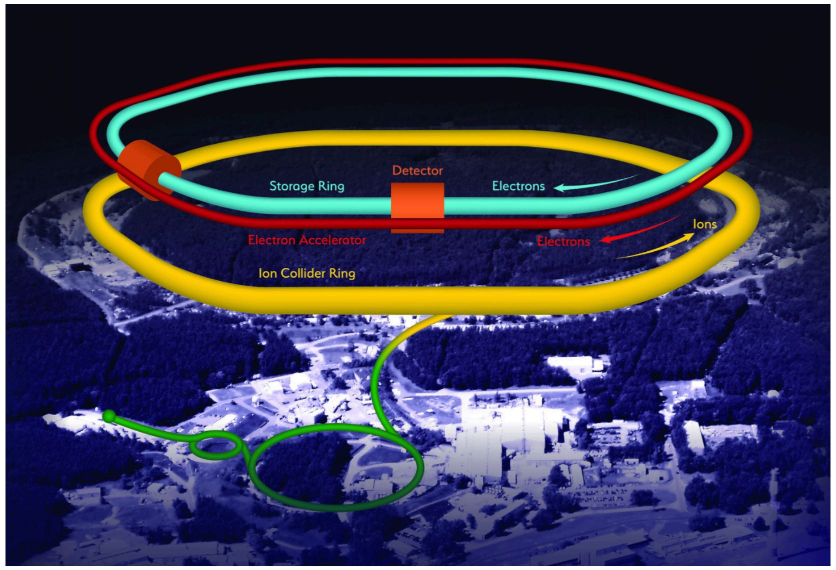

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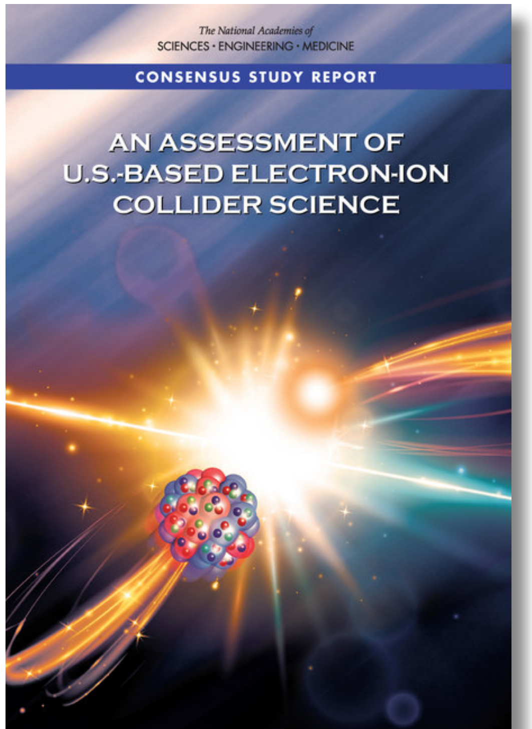

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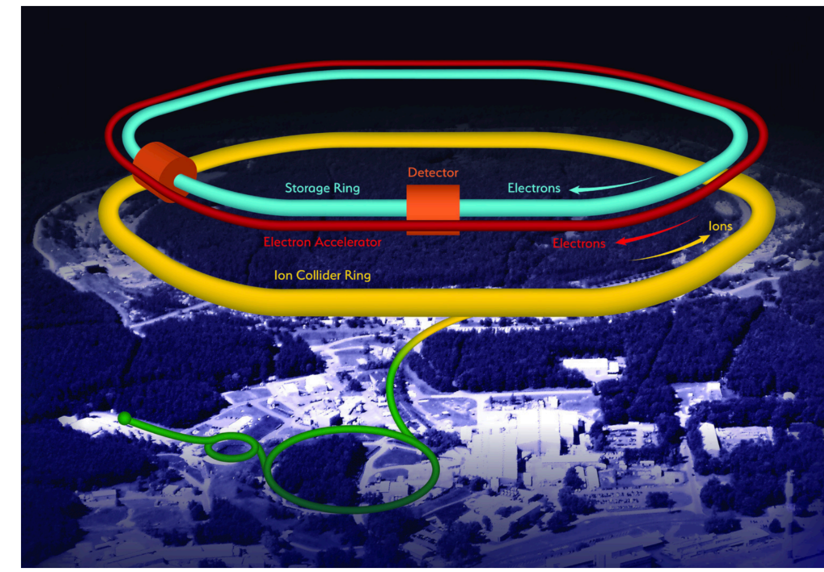
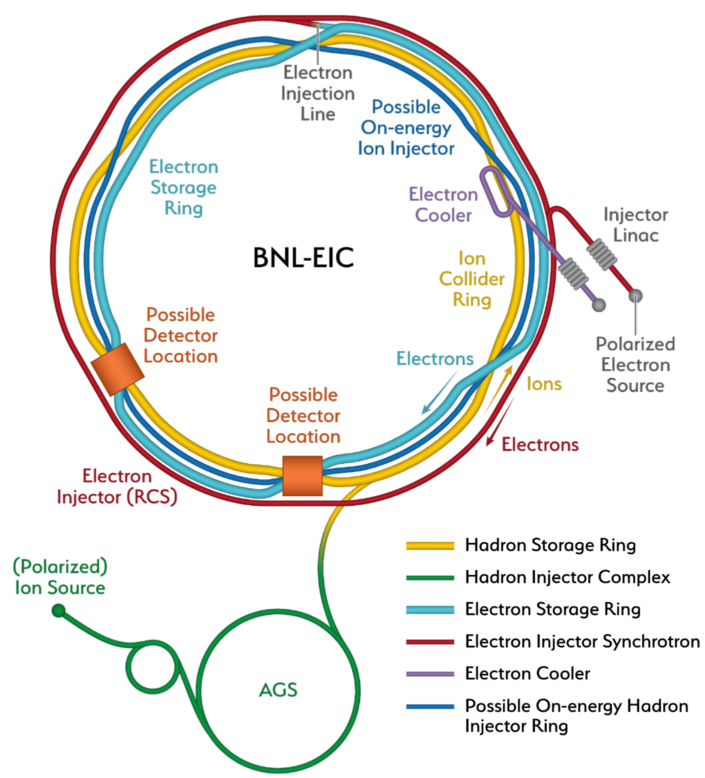
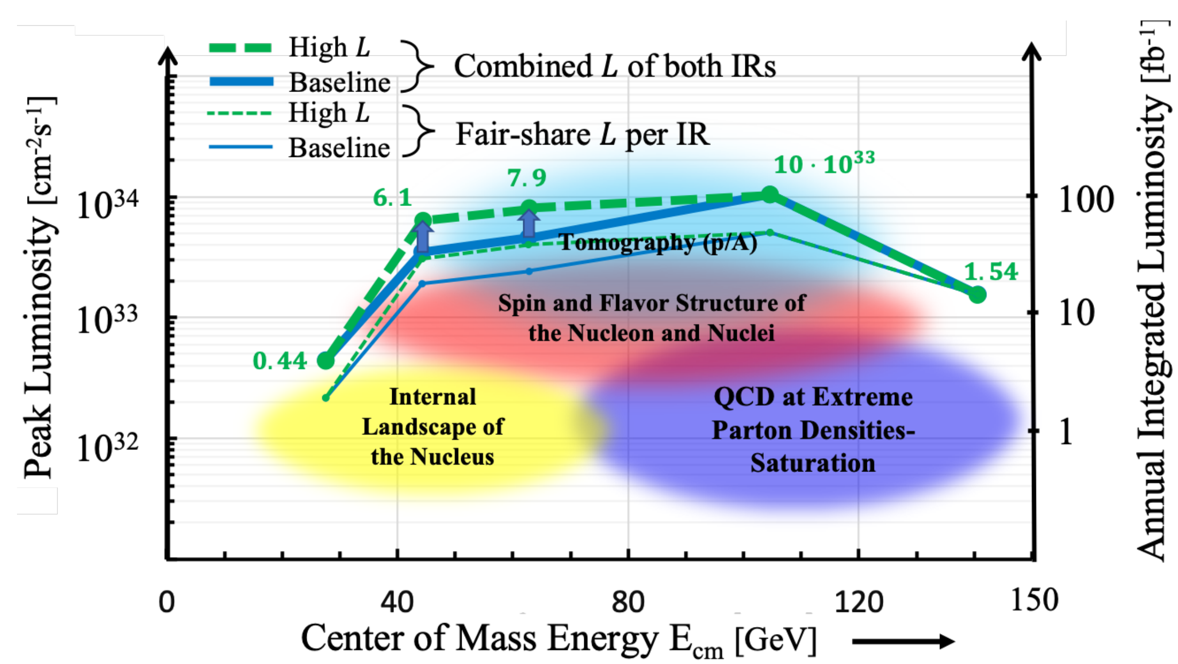


Accelerator Design





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U.S. DEPARTMENT OF ENERGY | Office of Science

DOE Early Career Award
Grant No. DE-SC0020405

Thank you

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TMD Topical Collaboration