The glue that binds us all:

Imaging matter below 10^{-15} m with an Electron-Ion Collider

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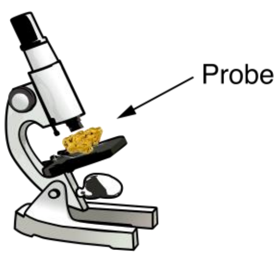
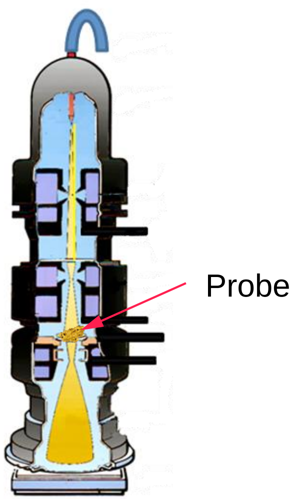
Ortvay Kollokvium, Eotvos Univ.
Budapest, December 10, 2015

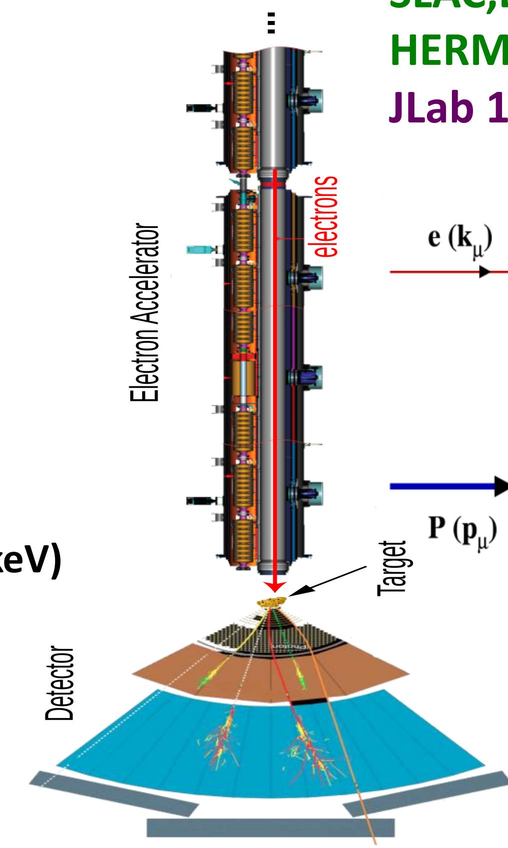
Structure of matter: Microscopes to Femtoscopes

Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm



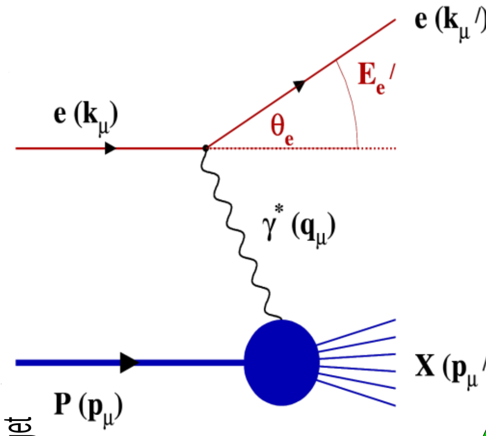
Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

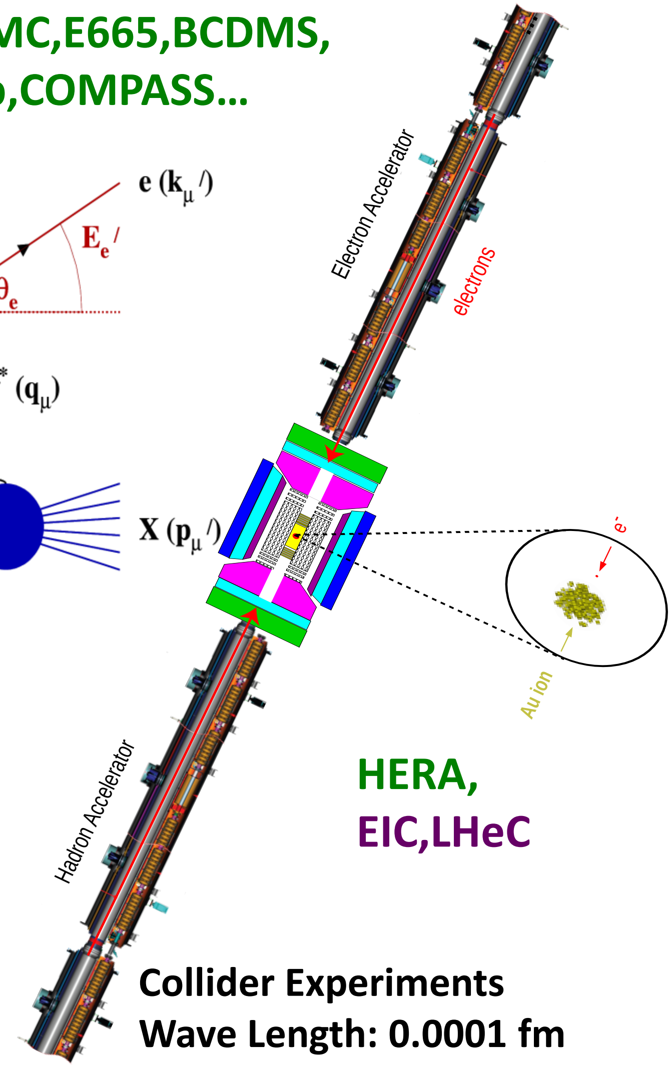




Fixed Target Particle Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm

SLAC,EMC,NMC,E665,BCDMS, HERMES,JLab,COMPASS…
JLab 12 GeV

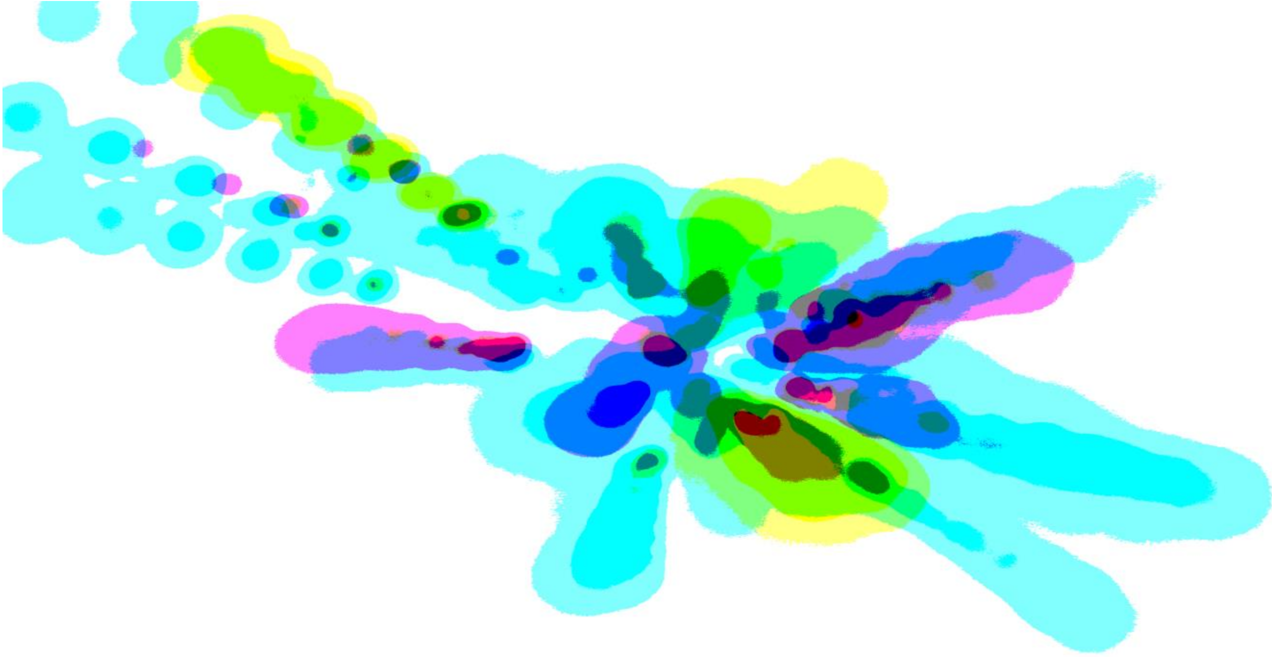




HERA,
EIC,LHeC

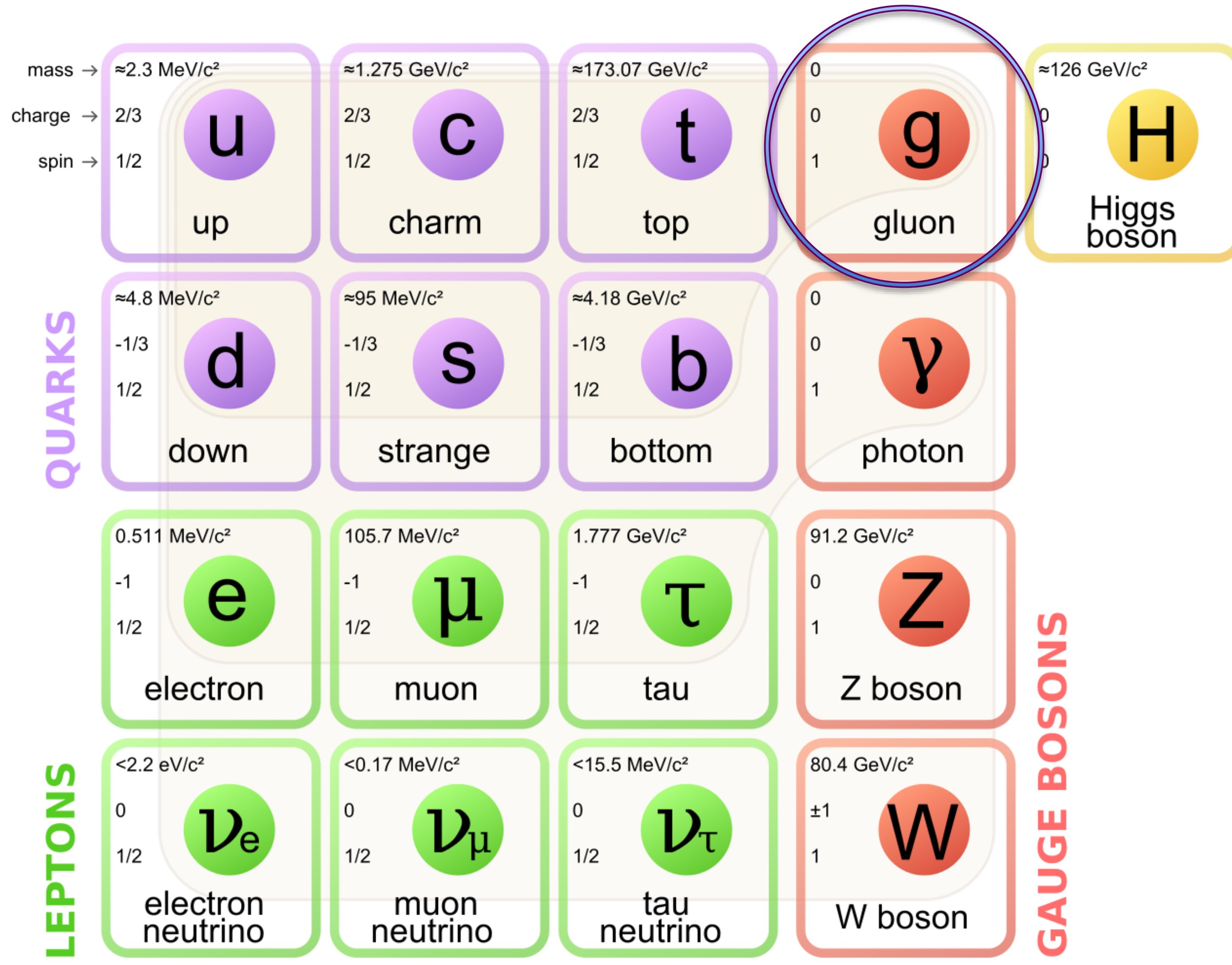
Collider Experiments
Wave Length: 0.0001 fm
(10 GeV + 100 GeV)
Resolution: 0.01-0.001 fm

Science case for an EIC



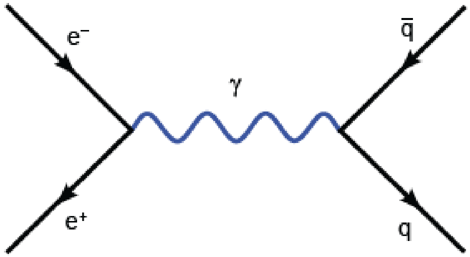
A study of origins in four acts:
the essential mystery, what we know,
what we would like to know, and…how to get there

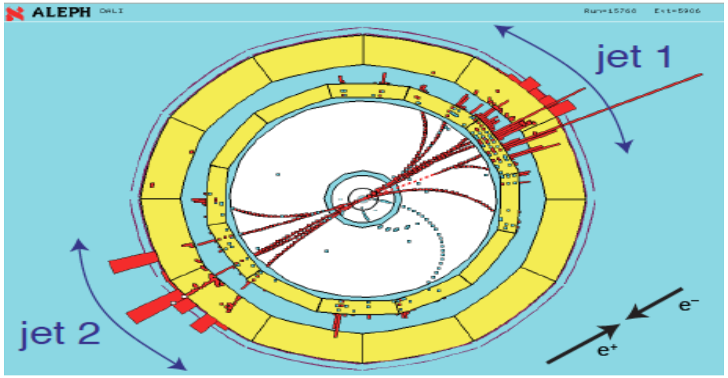
Act 1: The mysterious gluon

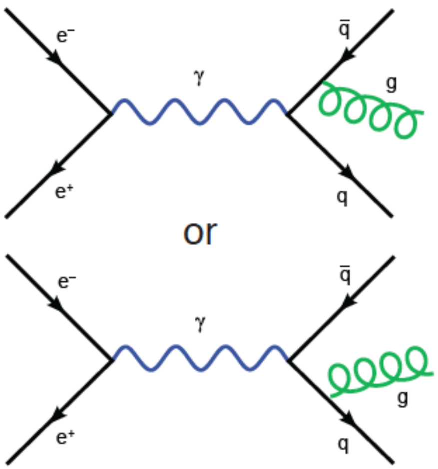


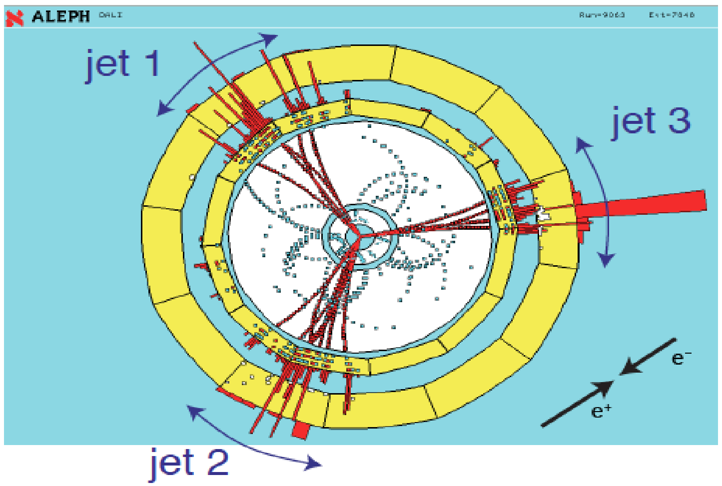
Gluons, the force carriers of the strong force,
are a fundamental building block of the standard model

Discovery of the gluon









EVIDENCE FOR A SPIN-1 GLUON IN THREE-JET EVENTS

High-energy e^+e^--annihilation events obtained in the TASSO detector at PETRA have been used to determine the spin of the gluon in the reaction $e^+e^- \rightarrow q\bar{q}g$. We analysed angular correlations between the three jet axes. While vector gluons are consistent with the data (55% confidence limit), scalar gluons are disfavoured by 3.8 standard deviations, corresponding to a confidence level of about 10^{-4}. Our conclusion is free of possible biases due to uncertainties in the fragmentation process or in determining the $q\bar{q}g$ kinematics from the observed hadrons.

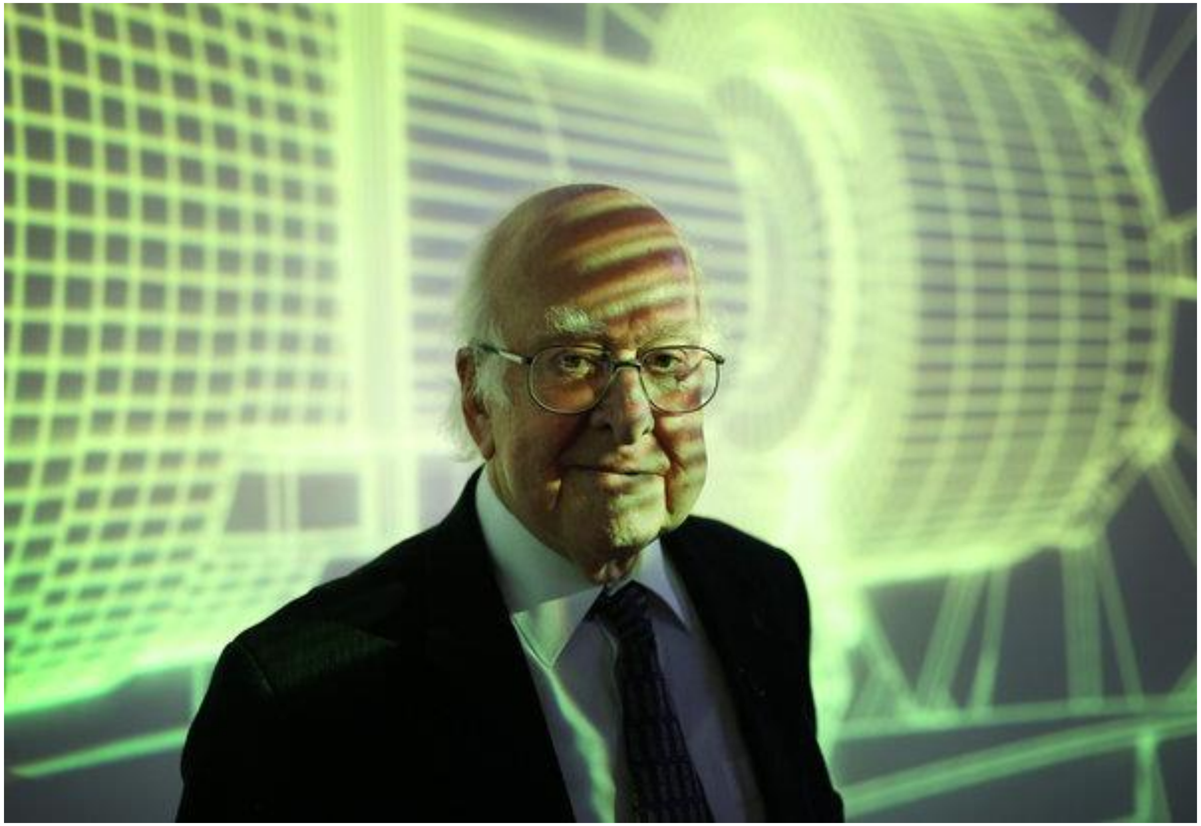
Physics Letters B, 15 December 1980

Gluons are massless…yet their dynamics is responsible for (nearly all) the mass of visible matter

The Higgs "God particle" is responsible for quark masses ~ 1-2% of the proton mass.


SAY "GOD PARTICLE" AGAIN!!!
memegenerator.net

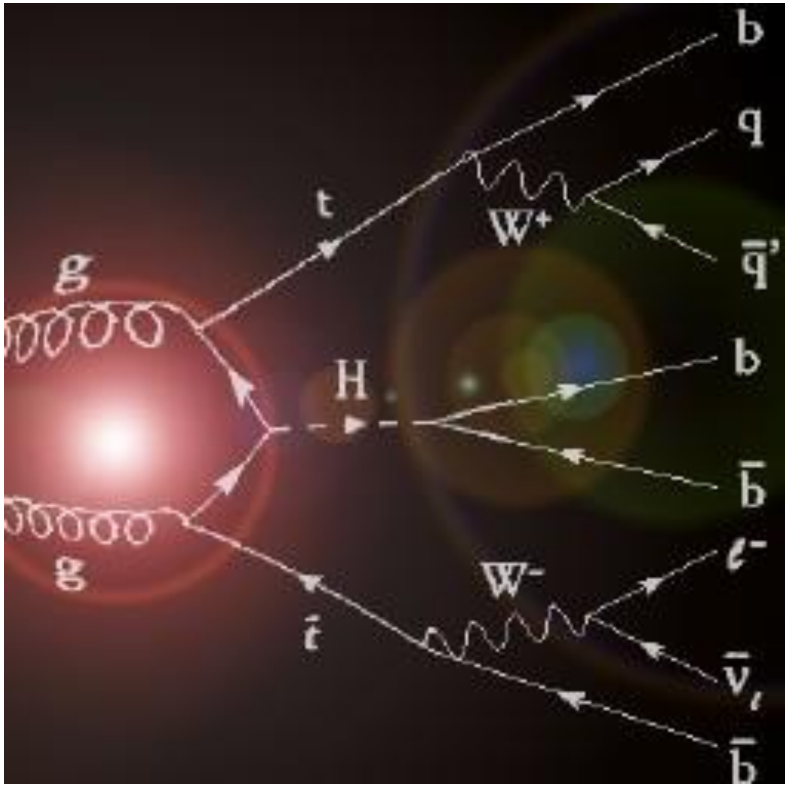
Higgs and the strong force



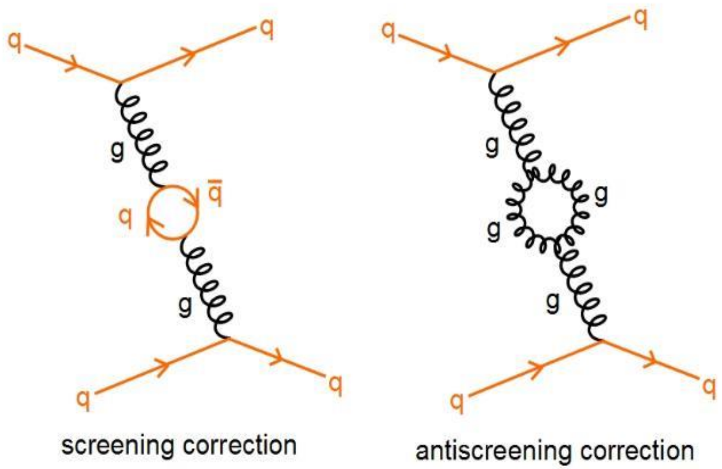
When he invented his boson in 1964, he said, "I wasn't sure it would be important."
He explained, "At the time the thought was to solve the strong force."

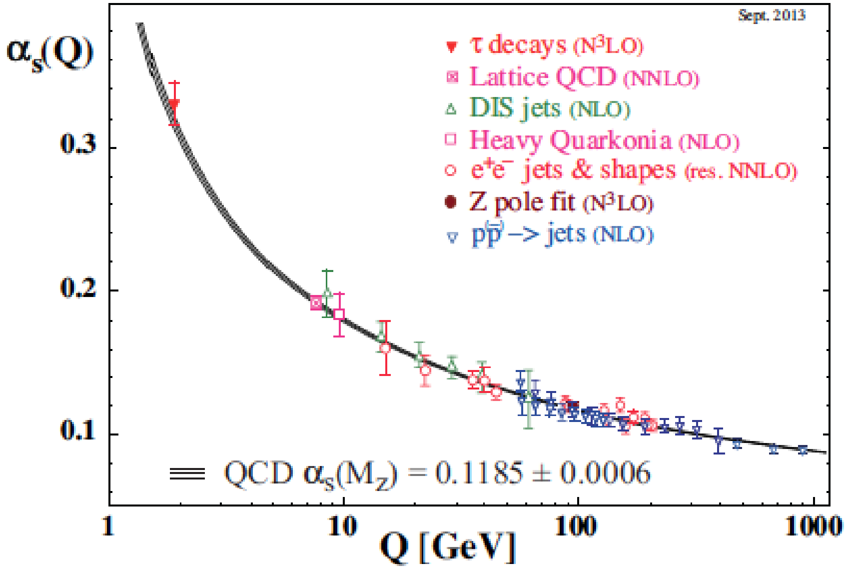
NY Times, Sept. 15, 2014

Higgs from Gluon fusion



Asymptotic freedom: the role of glue





David Gross

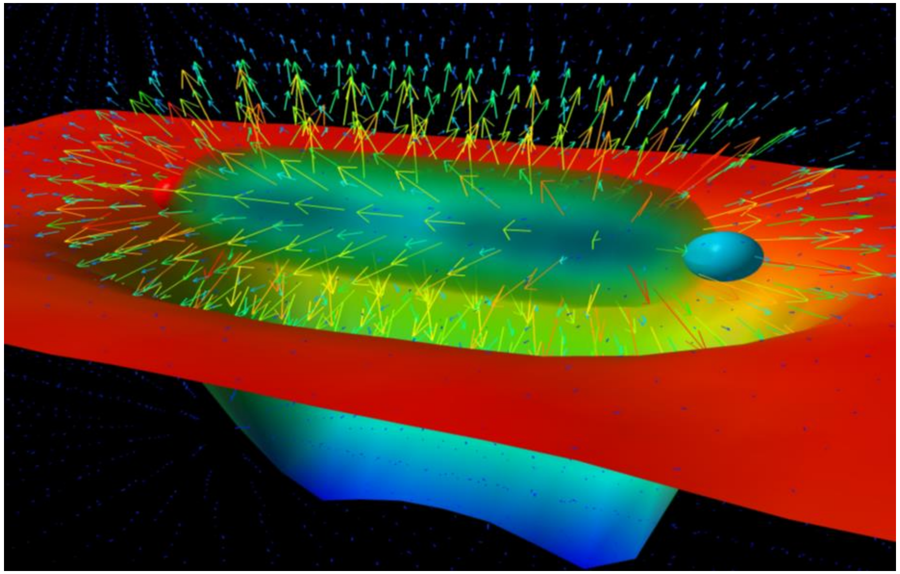
David Politzer

Frank Wilczek

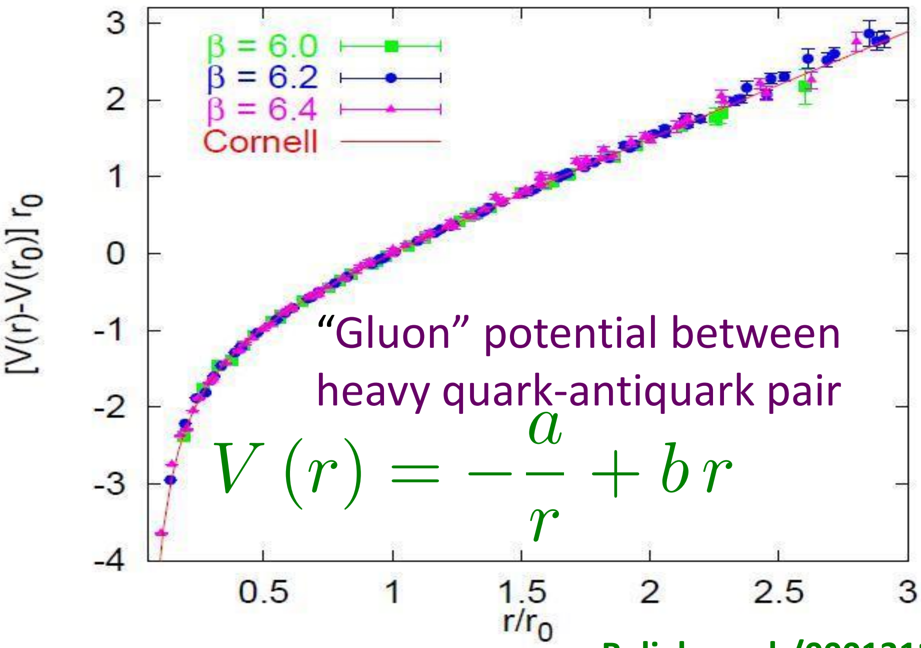
2004

The self-interaction (of color charged) gluons is fundamentally responsible for the asymptotic freedom of quarks and gluons in Quantum Chromodynamics (QCD)

Quark (and Gluon) confinement: the role of glue ?

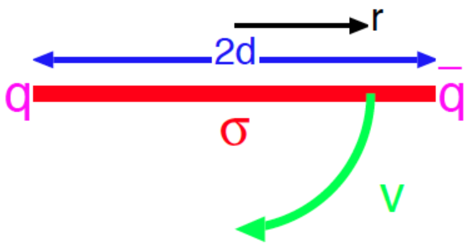


Quarks experience force of 16 tons at distances of ~ 1 Fermi (10^{-15} m)

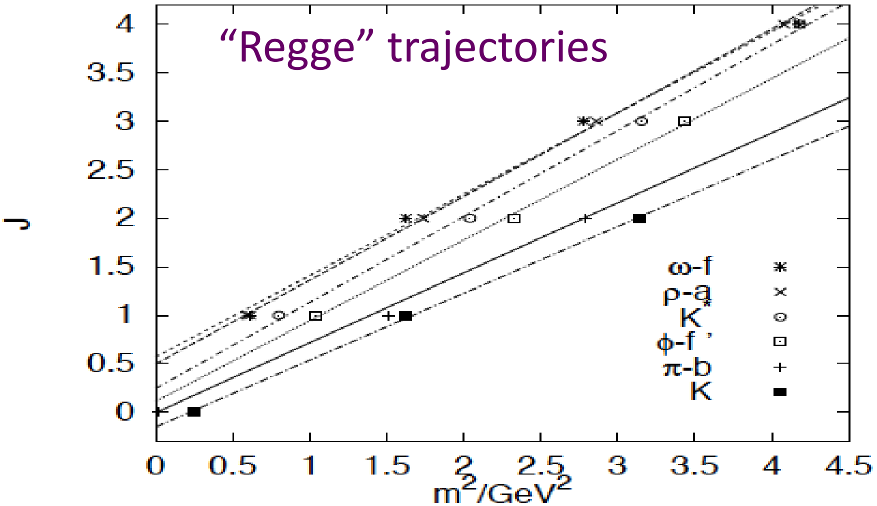


$$V(r) = -\frac{a}{r} + b\,r$$

Bali, hep-ph/0001312



Intuitive picture of quark confinement and stringy pictures of mesons



The essential mystery

- (Nearly) all visible matter is made up of quarks and gluons
- But quarks and gluons are not visible
- All strongly interacting matter is an emergent consequence of many-body quark-gluon dynamics.

  Example: Mass from massless gluons and (nearly) massless quarks
- There is an elegance and simplicity to nature’s strongest force we do not understand
- Understanding the origins of matter demands we develop a *deep and varied knowledge* of this emergent dynamics

Act 2. Quantum Chromodynamics: The Power and the Glory

New Quantum Numbers
The Eightfold Way / Unitary Symmetry
Mesons ~ 8 Baryons ~ 8 + 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 8
QCD the Theory of Strong Interactions

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

Jeffrey Mandula, Creutz-Fest 2014, BNL

Quantum Chromodynamics (QCD)

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

- Theory is rich in symmetries:

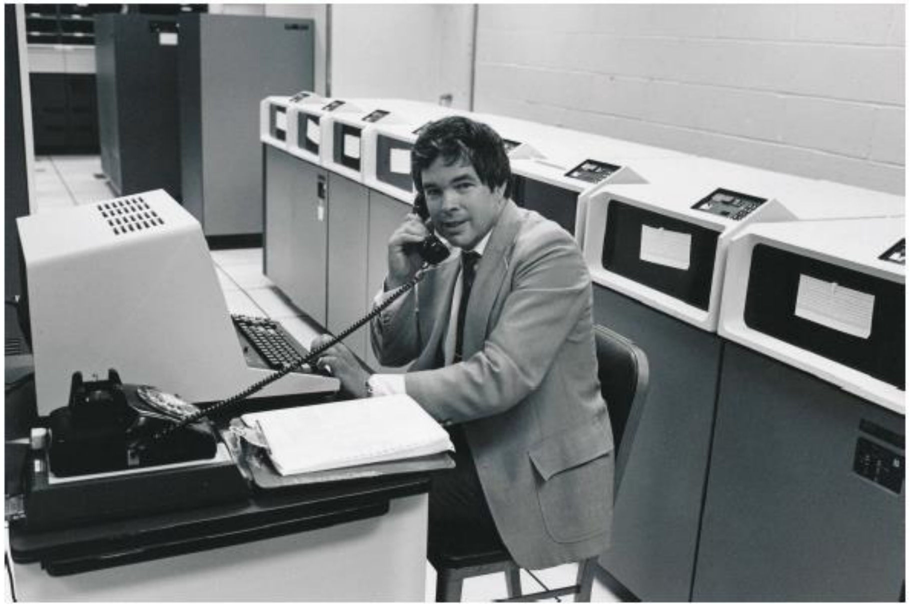
$$\underbrace{SU(3)_c}_{\text{i}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\text{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\text{iii}}$$

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) P &T broken by vacuum/quantum effects - ”emergent” phenomena

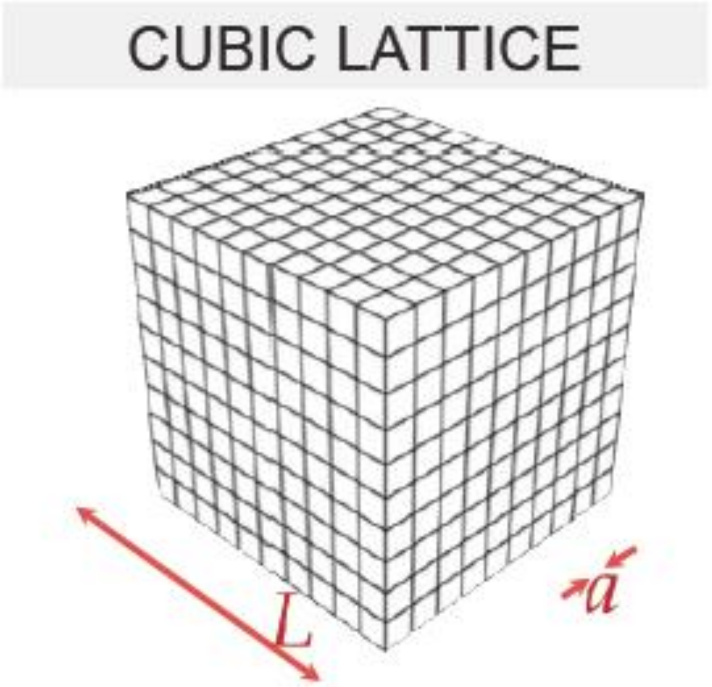
- Inherent in QCD are the deepest aspects of relativistic Quantum Field Theories (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry)

Numerical realization: Lattice QCD



Kenneth G. Wilson

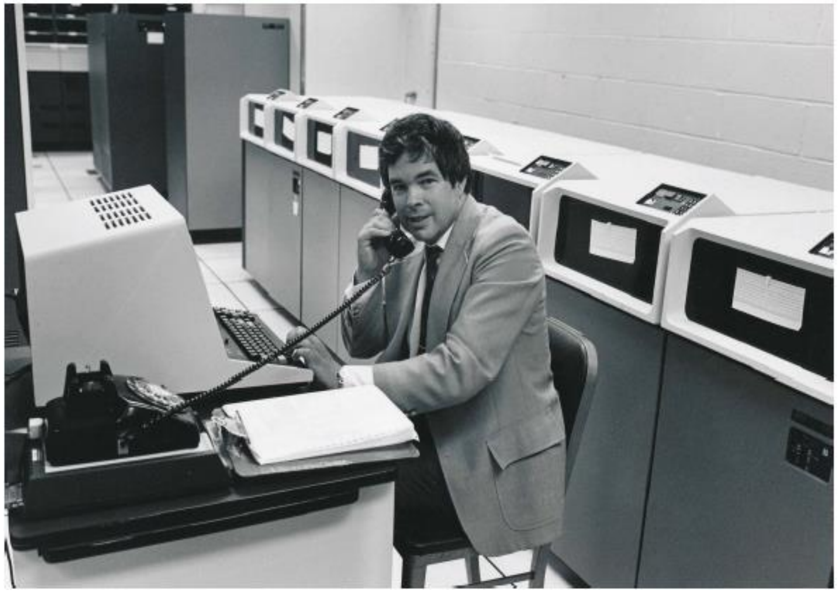
(1982)



Lattice regularization (UV&IR) of QCD

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

Numerical realization: Lattice QCD

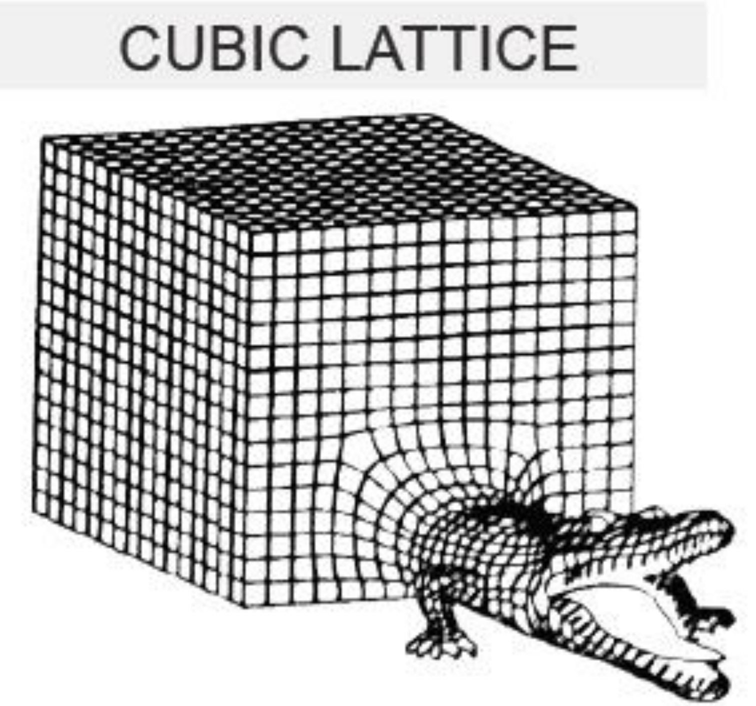


Kenneth G. Wilson

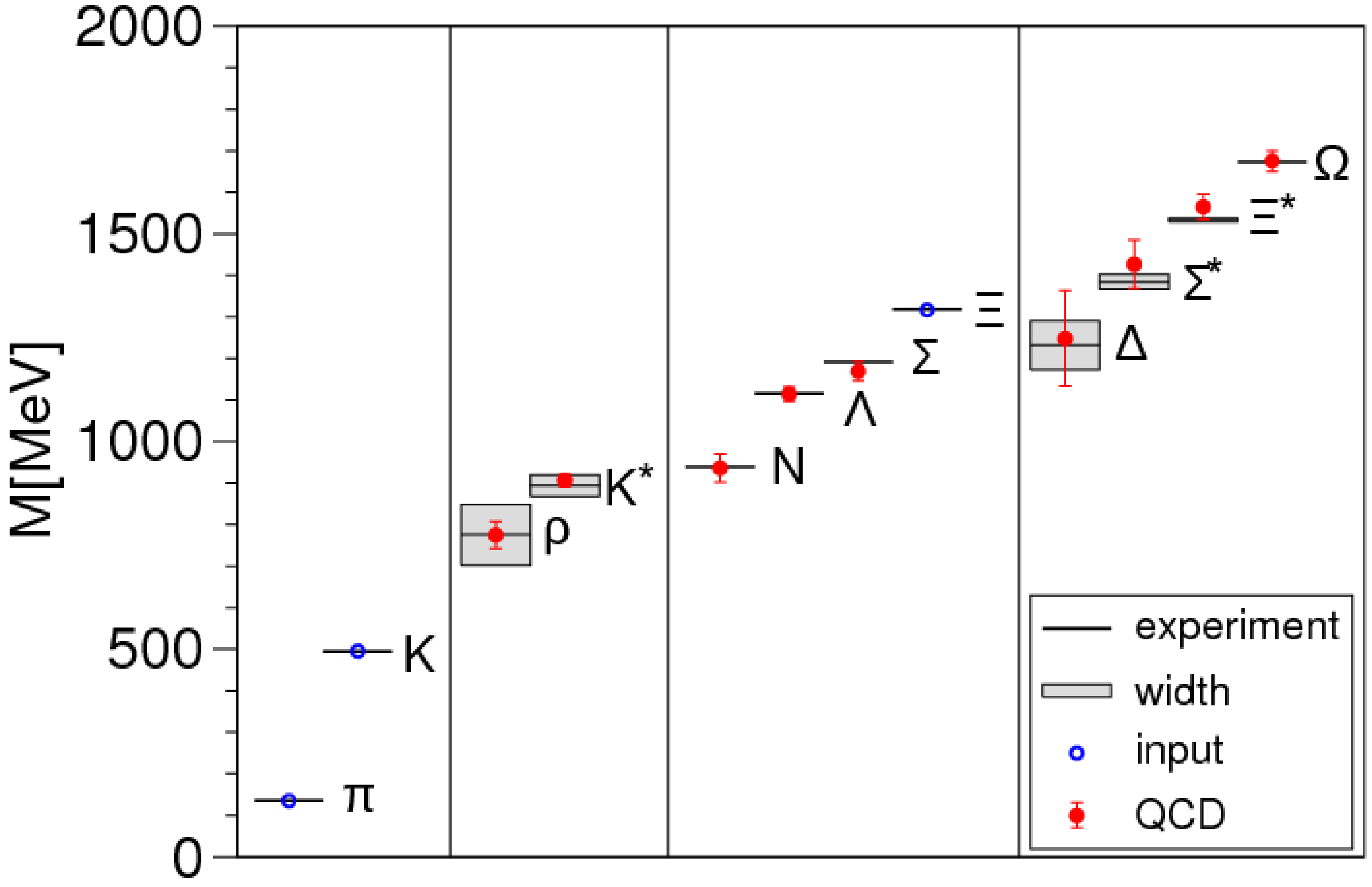
(1982)

Formidable computational problem

Very challenging for *dynamical processes*…

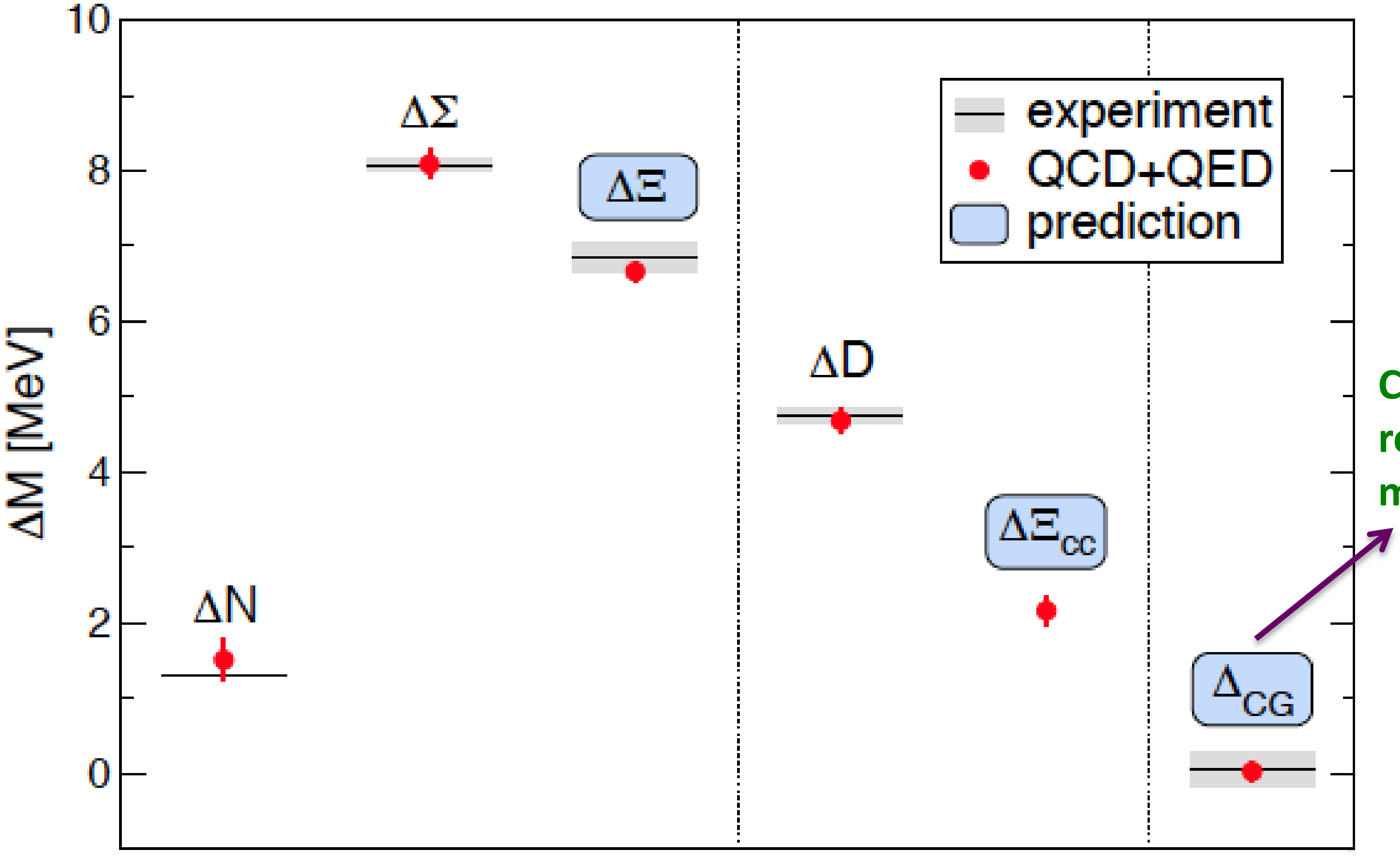


Precision QCD on the lattice



Durr et al., Science, 322 (2008)

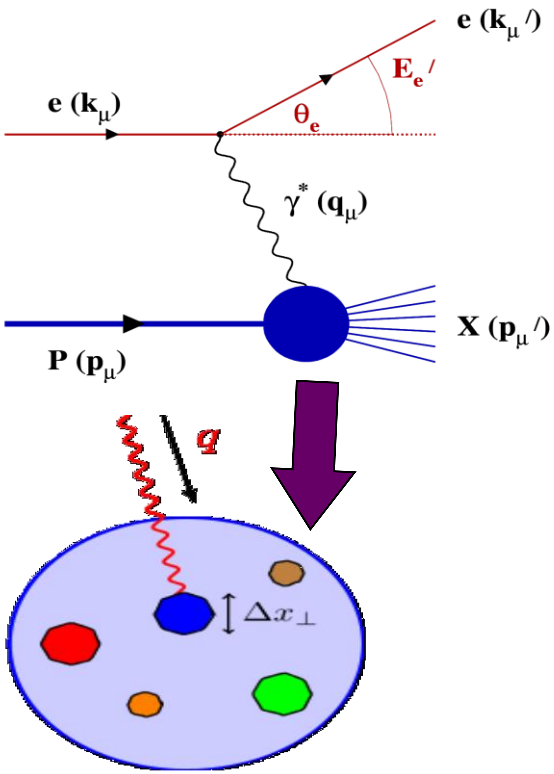
Precision QCD on the lattice



Coleman-Glashow relation among mass splittings

Budapest-Marseille-Wuppertal (BMW) Coll., arXiv:1406.4088

The deeply inelastic scattering (DIS) femtoscope



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4 E_e E'_e \sin^2\left(\frac{\theta'_e}{2}\right)$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

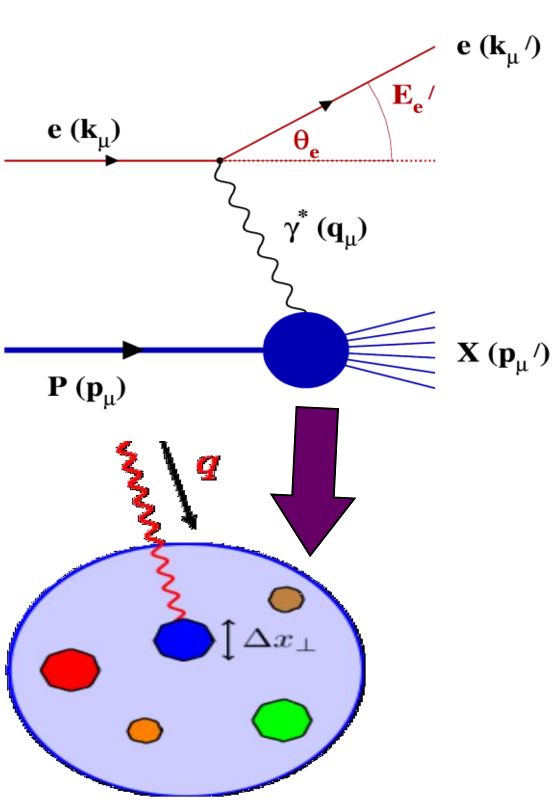
Bjorken variable: Measure of momentum fraction of struck quark

$$\frac{d^2\sigma^{eh\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{em}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions

gluon momentum distribution

The deeply inelastic scattering (DIS) femtoscope



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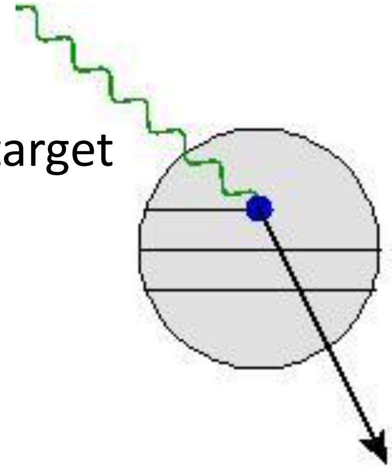
quark+anti-quark momentum distributions

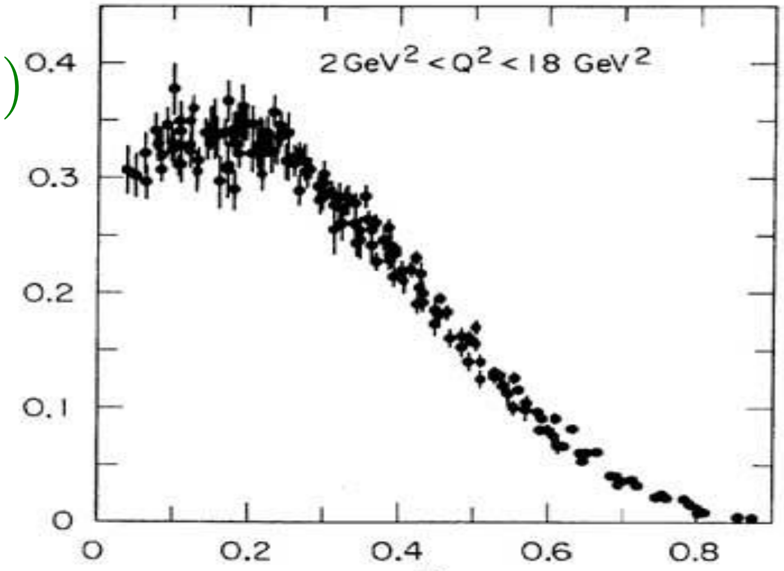
gluon momentum distribution

The deeply inelastic scattering (DIS) femtoscope

From SLAC fixed target DIS… (**late 1960s**)

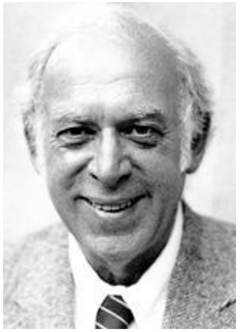


$F_2(x)$

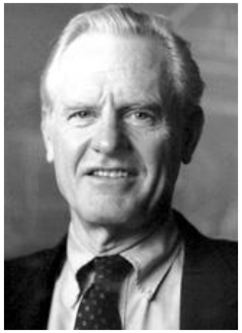


x

Discovery of quasi-free point-like quarks!



Friedman



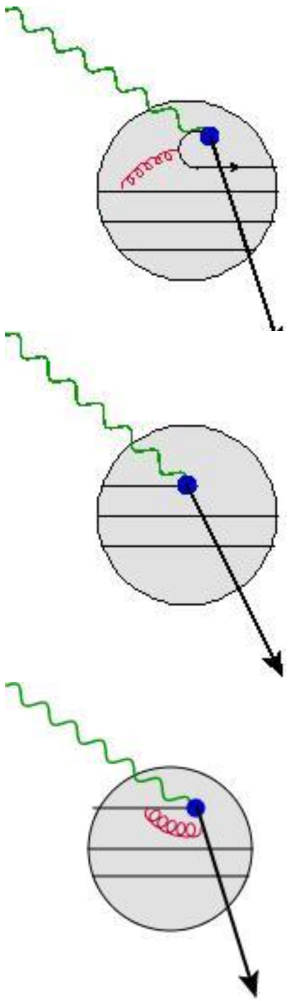
Kendall

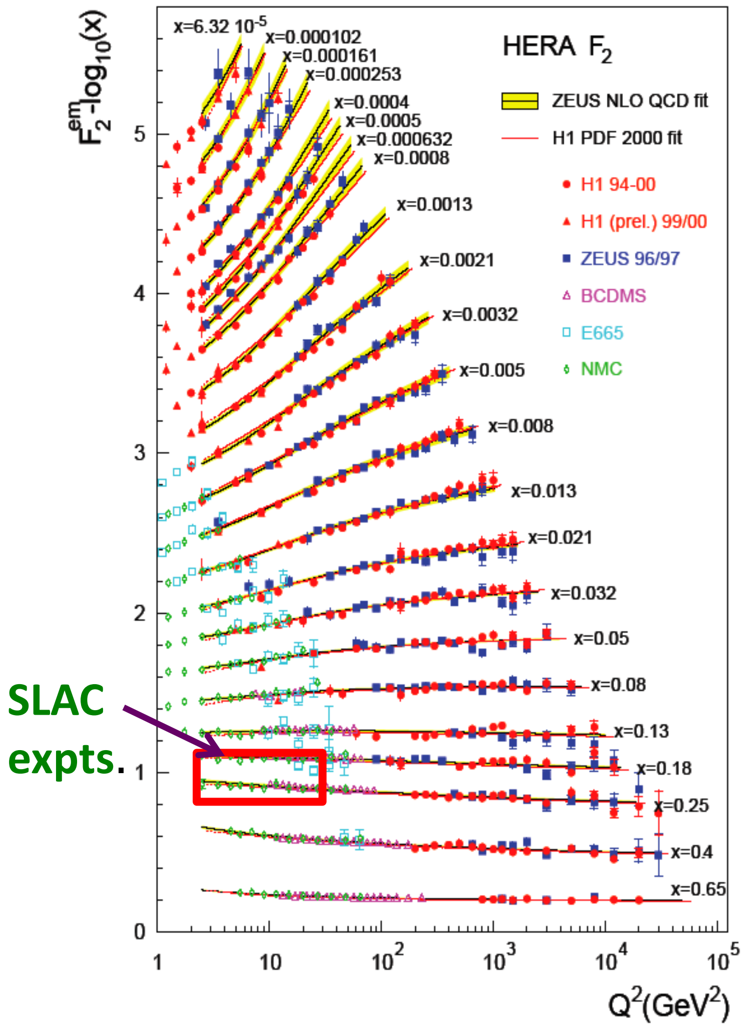
Taylor

(**1990**)

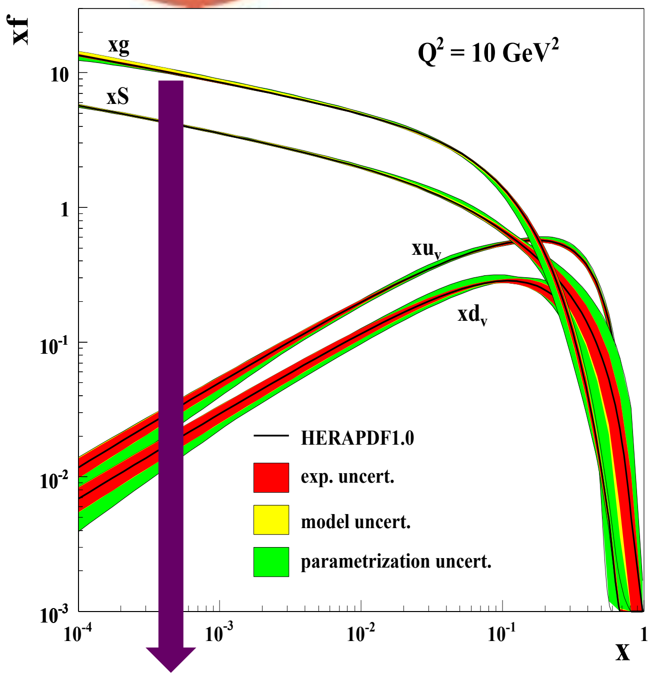
The deeply inelastic scattering (DIS) femtoscope

…to the HERA DIS collider (1990s)





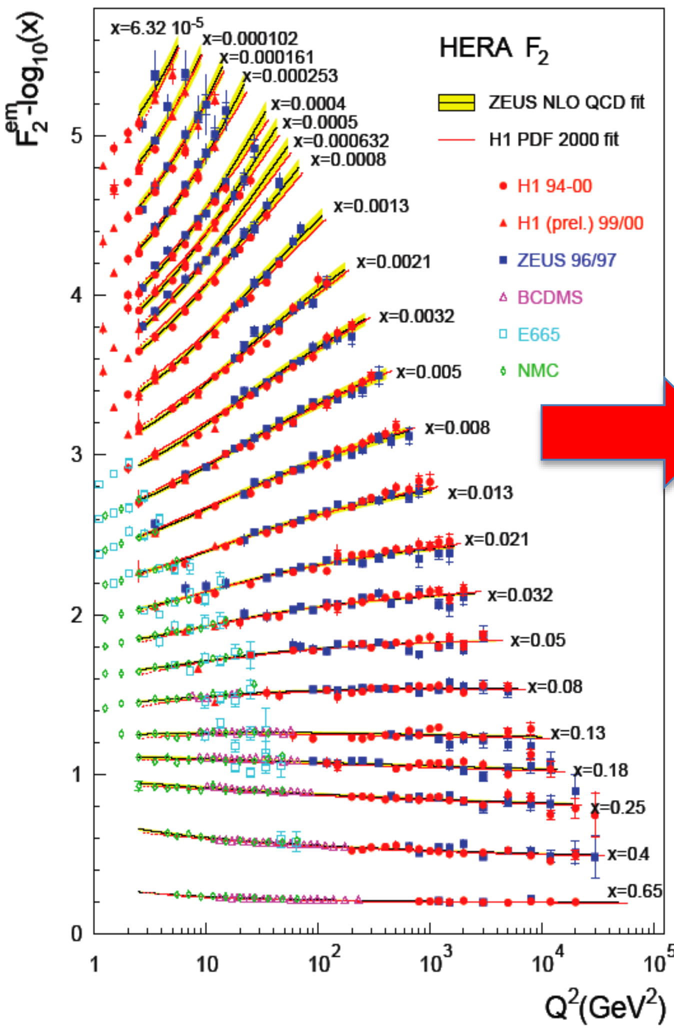
Gluons and "sea" quarks



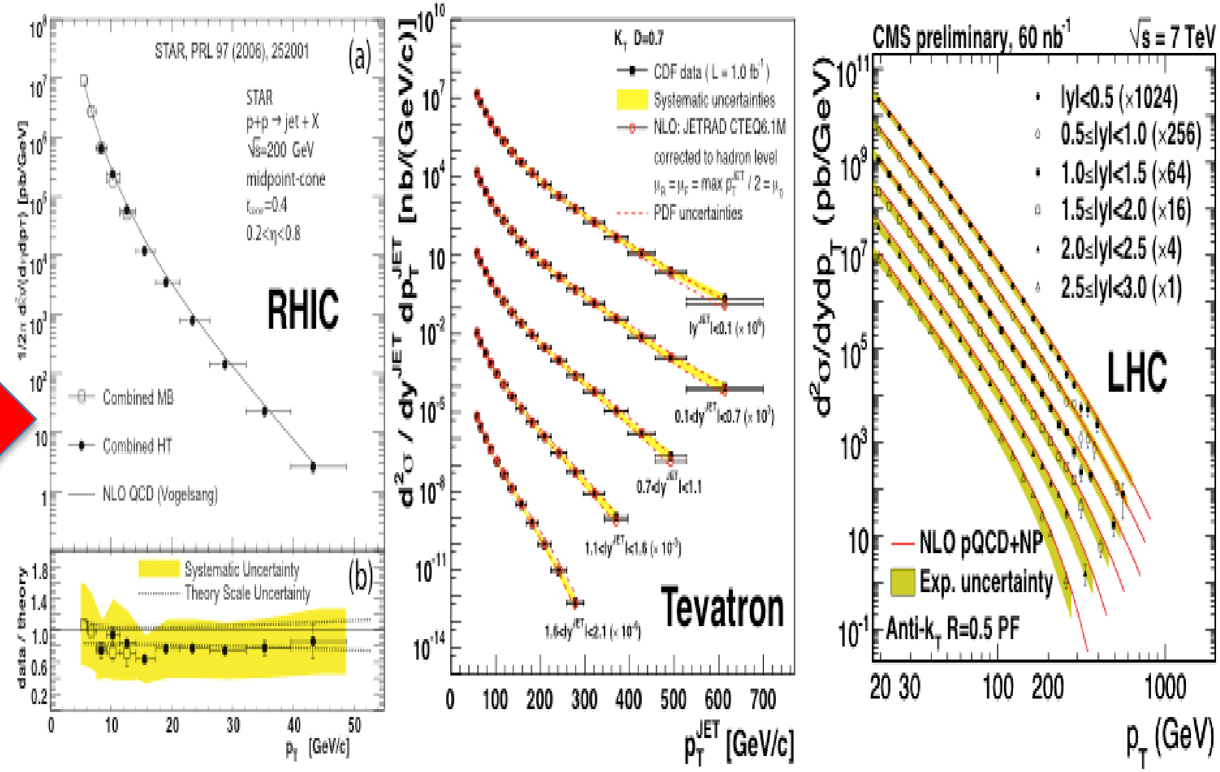
The proton at high energies (small x) is dominated by glue!

Perturbative QCD: now benchmark for new physics

Structure functions measured at HERA electron-proton collider



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

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

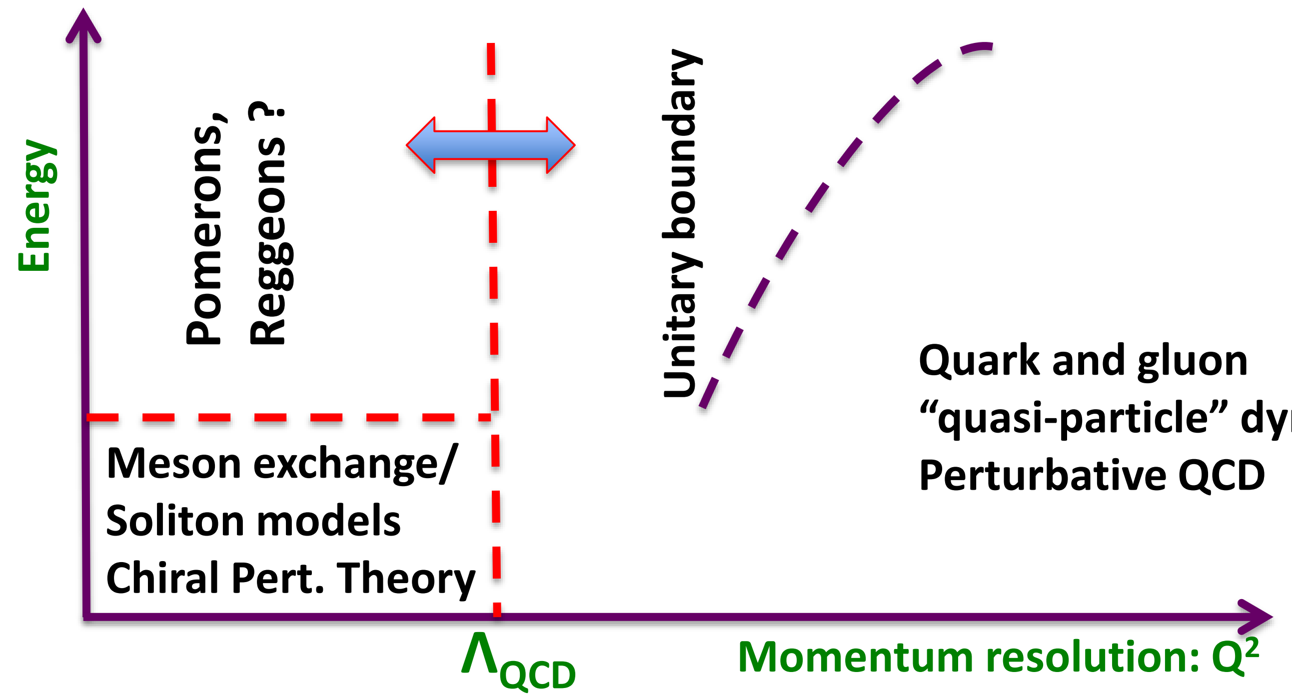
In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

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

Are we done ?

Act 3. Frontiers of our ignorance

Scattering in the strong interactions



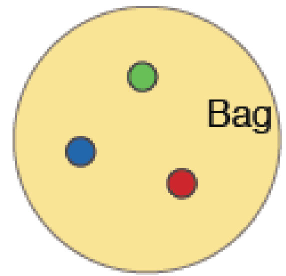
- Perturbative QCD describes only a small part of the total cross-section
- Lattice QCD is of very limited utility in describing scattering
- Effective theories: how do quark and gluon degrees organize themselves to describe the bulk of the cross-section ?

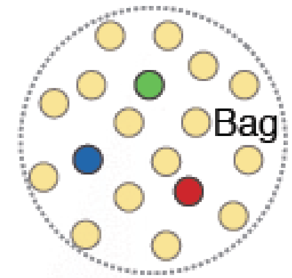
What does the proton look like ?

Static pictures | **Glue dominated boosted proton**

Bag model:

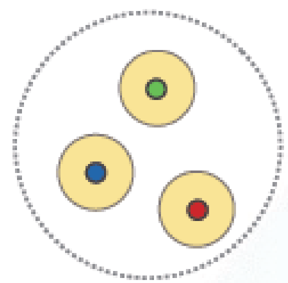
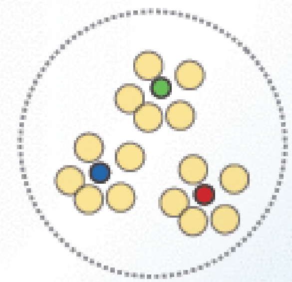
- Field energy distribution is wider than the distribution of fast moving light quarks





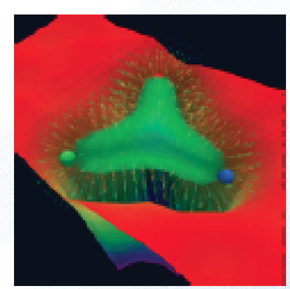
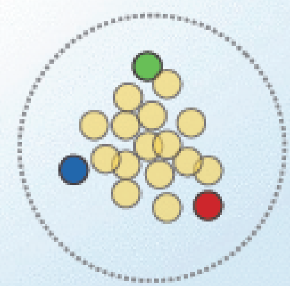
Constituent quark model:

- Gluons and sea quarks “hide” inside massive quarks
- Sea parton distribution similar to valence quark distribution

Lattice gauge theory:

- (with slow moving quarks)
- gluons are more concentrated than quarks

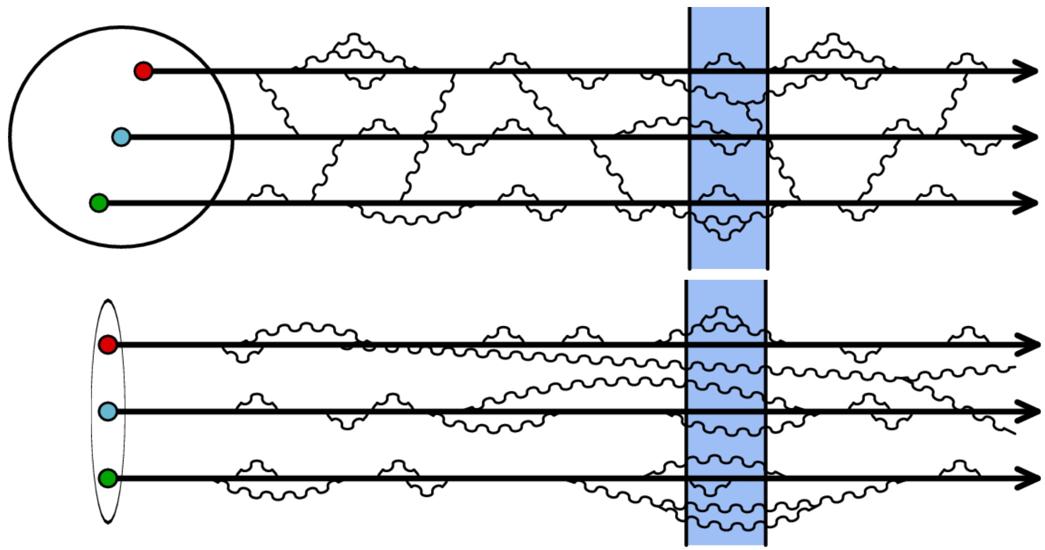



The boosted proton

In QCD, the proton is made up of quanta that fluctuate in and out of existence

Low Energy or large x

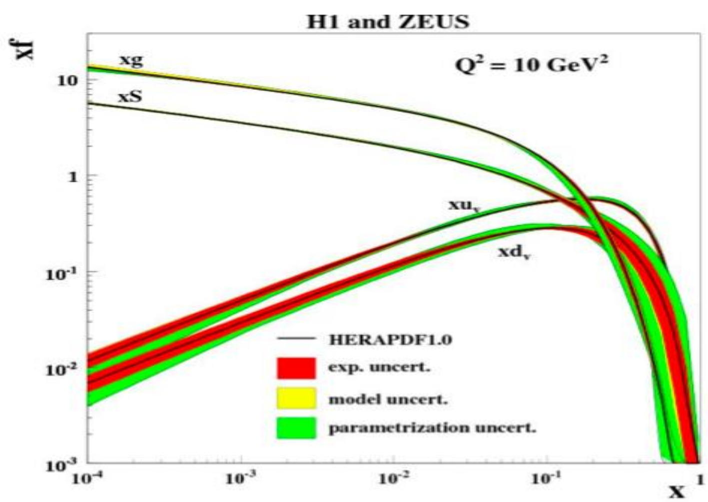
High Energy or small x



Wee parton fluctuations time dilated on strong interaction time scales

Long lived gluons can radiate further small x gluons…

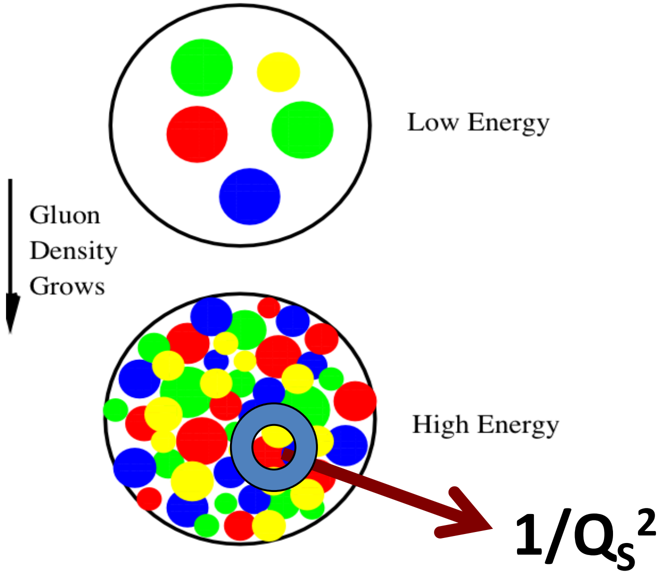
Is the proton a runaway popcorn machine at high energies ?



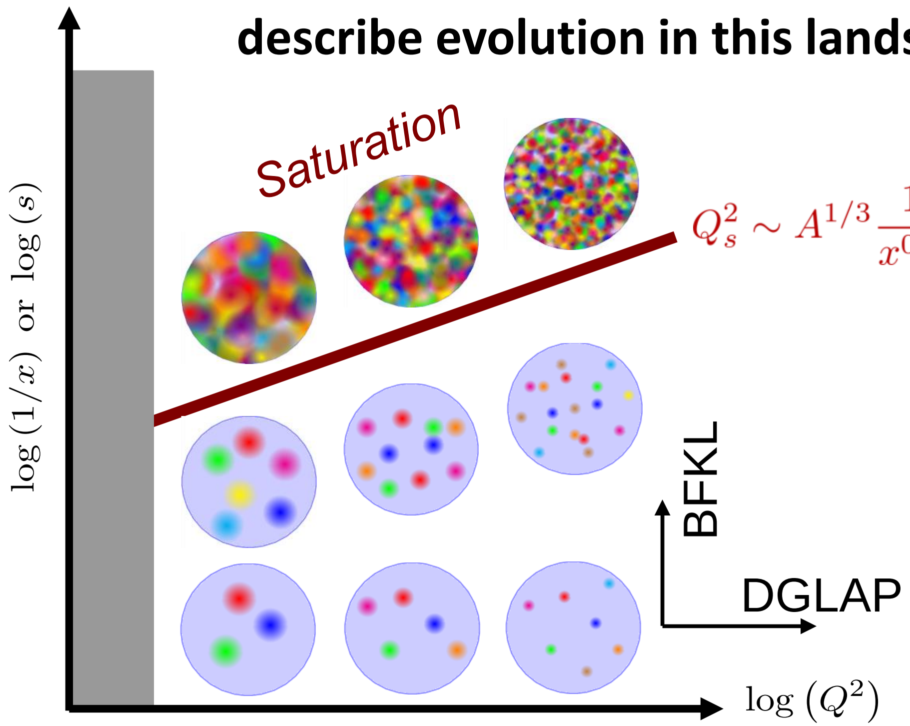
The boosted proton

Boosted protons: classical coherence from quantum fluctuations

Emergent dynamical saturation scale grows with energy

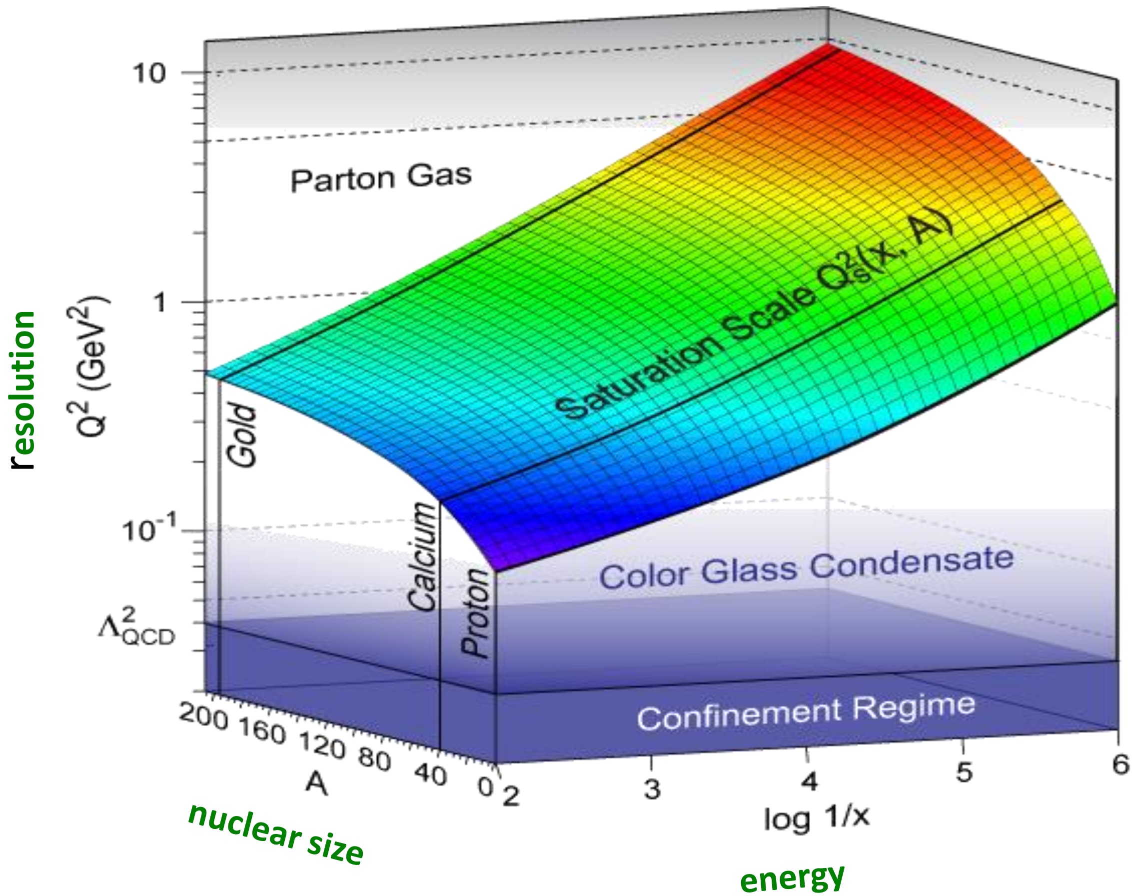


Powerful ``Wilsonian" RG equations describe evolution in this landscape

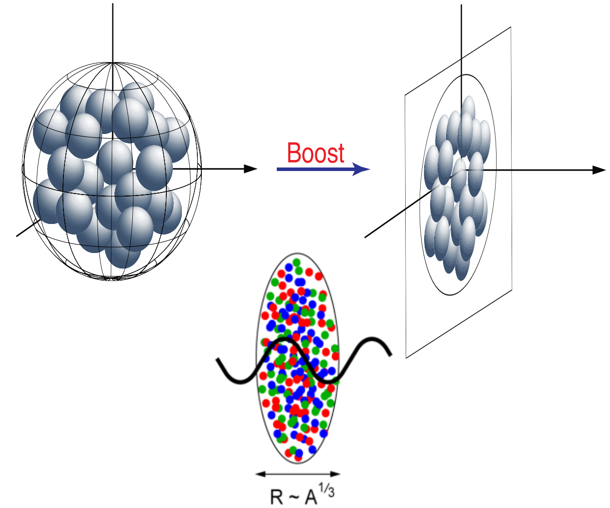


- How does this happen? What are the right degrees of freedom?
- How do correlation functions of these evolve?
- Is there a universal fixed point for RG evolution? Does the coupling run with Q_s^2?
- How does saturation transition to chiral symmetry breaking and confinement?

Many-body high energy QCD: a new frontier



A$^{1/3}$ enhancement of saturation scale in nuclei

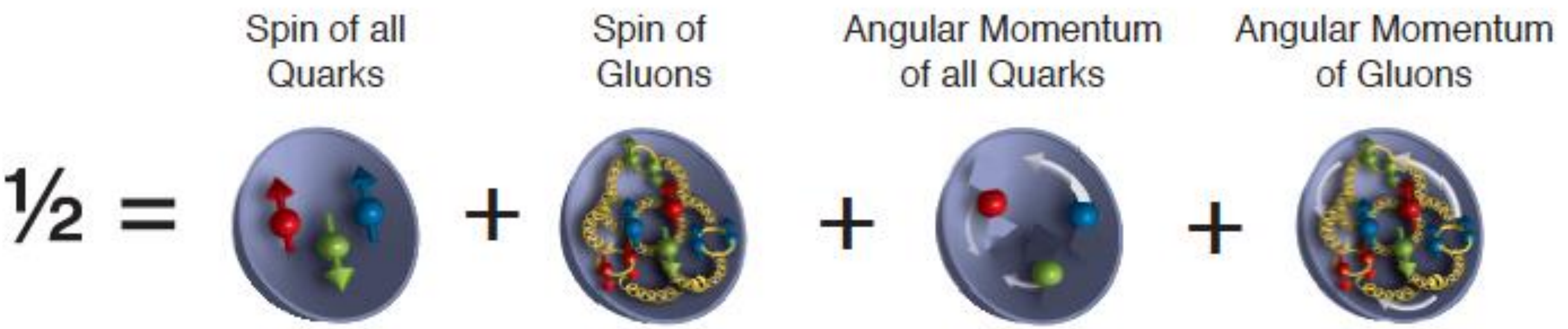


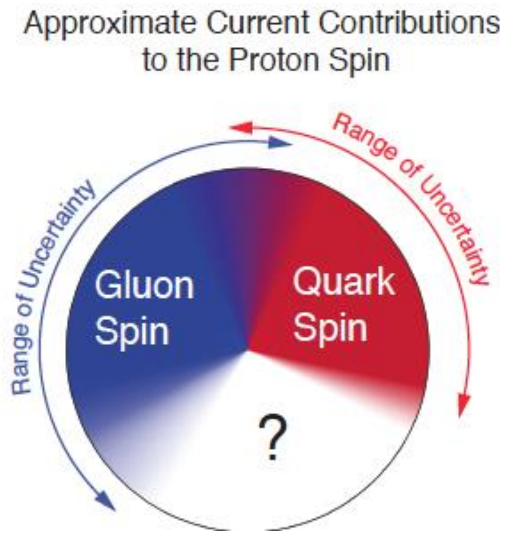
$$Q^2_{S,A} \approx A^{1/3} Q^2_{S,p}$$

Dynamically generated semi-hard "saturation scale" opens window for systematic weak coupling study of non-perturbative dynamics

Can we sneak up on confining dynamics "through the back door" ?

The proton's spin puzzle

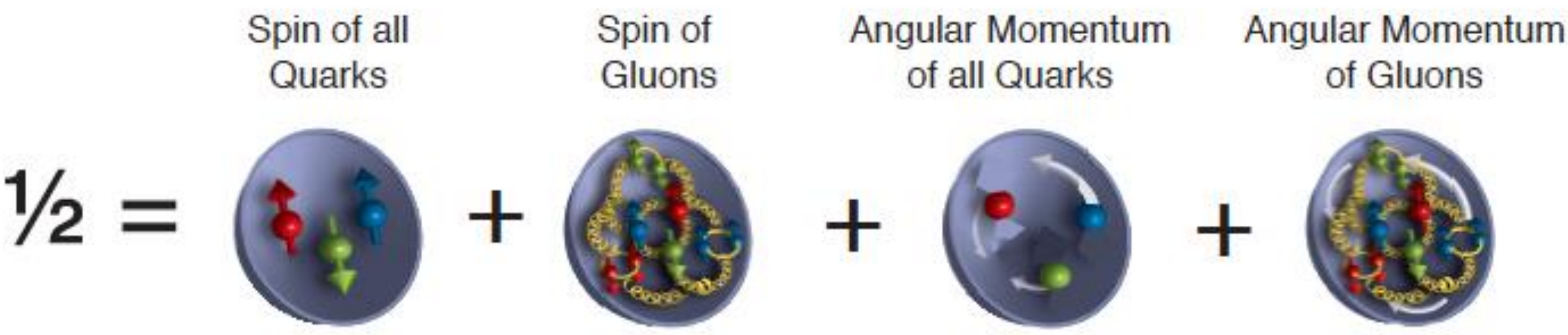


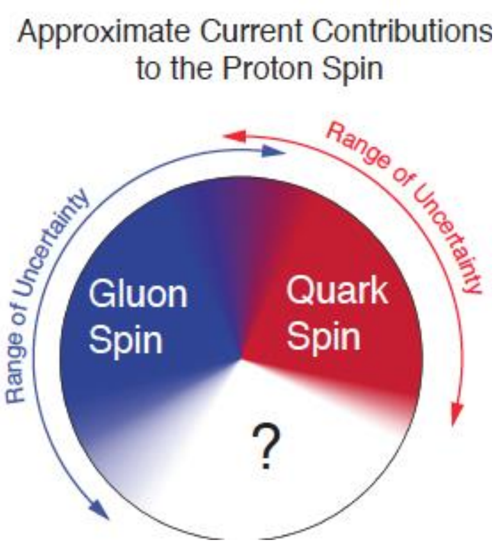


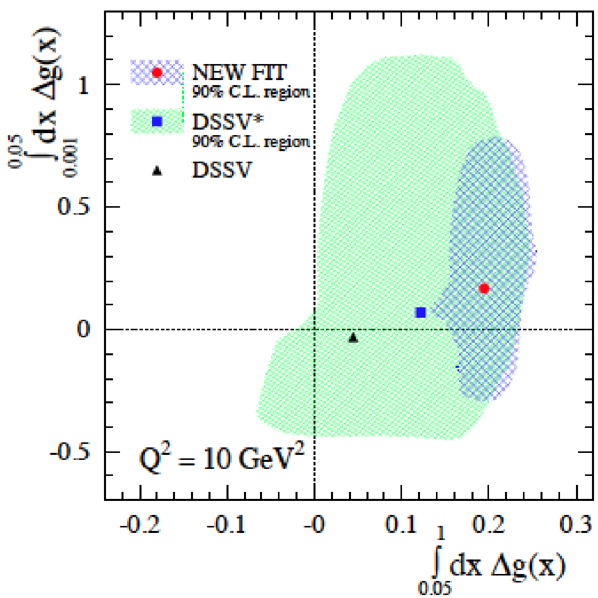
Fixed target deep inelastic scattering experiments showed that quarks carry only about
30% of the proton's spin

"Spin crisis" – a failure of the quark model picture of three relativistic "constituent" quarks

The proton's spin puzzle







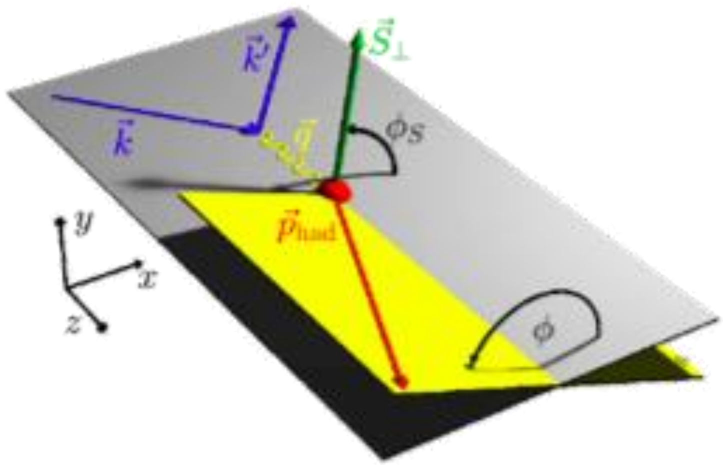
Clear evidence for gluon polarization from RHIC polarized proton-proton data

Gluons carry ~ 20-40 % of the Proton spin

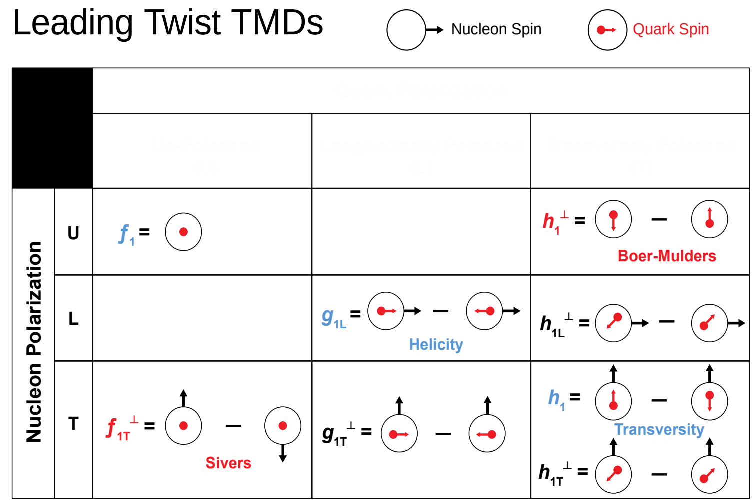
Where's the rest ?

D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRL 113 (2014)

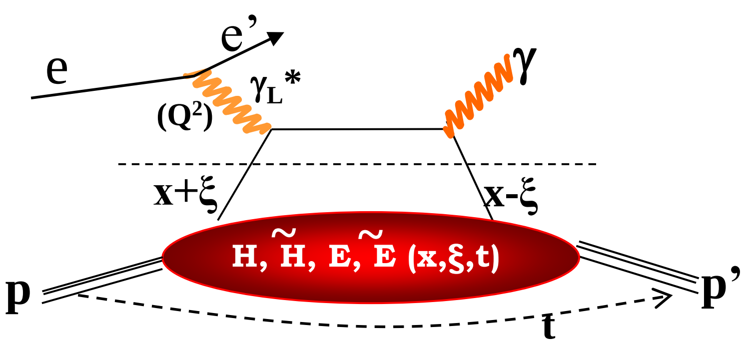
Imaging distributions of quarks and gluons ?



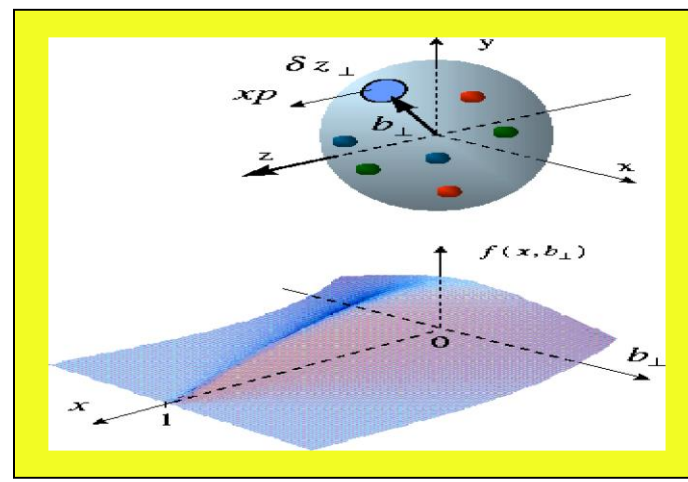
Transverse momentum dependent (TMD) distributions



Similar for gluons

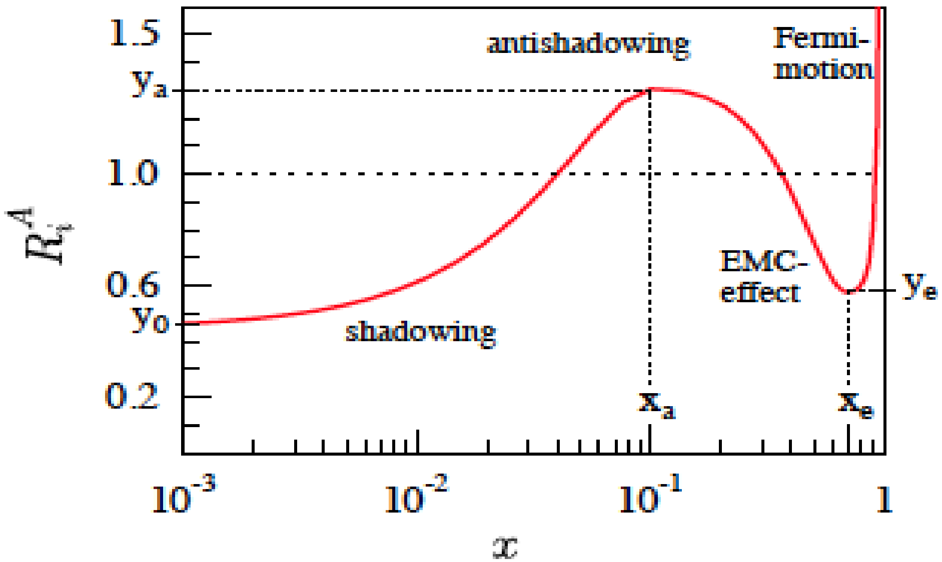


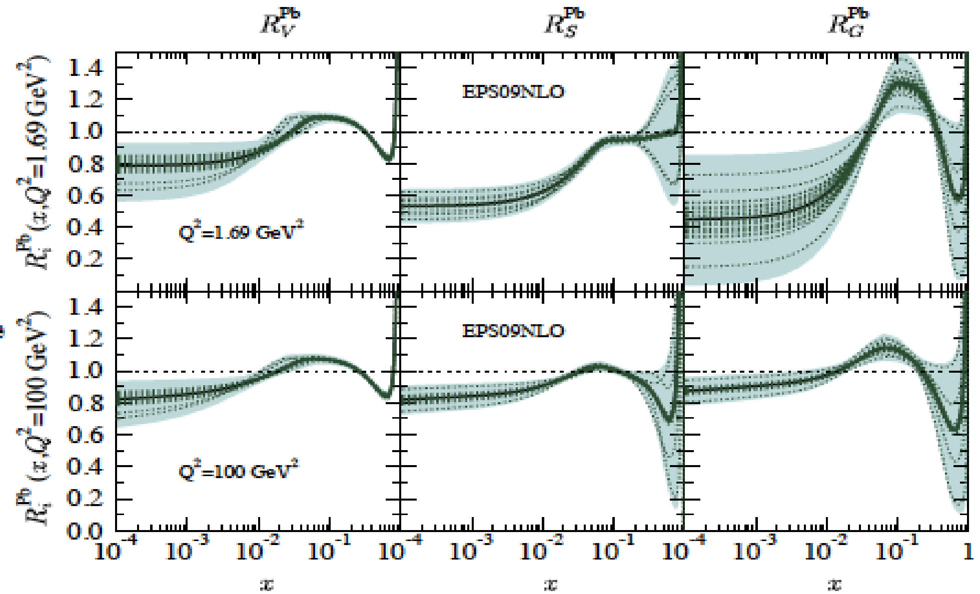
Generalized parton distributions (GPDs)



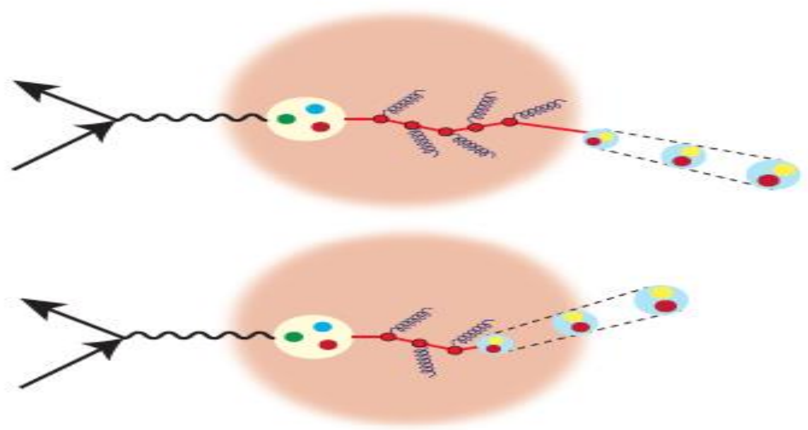
- Differential images correlating the spin, momentum and spatial distributions will provide fundamental insight into quark-gluon dynamics in nucleon structure

Nuclear glue: terra incognita





Quark (Gluon) distributions in nuclei- ***not simple superpositions*** **of nucleon Quark (Gluon) distributions**



The nucleus as a QCD laboratory :

Understand how quarks and gluons fragment and hadronize in and out of the medium

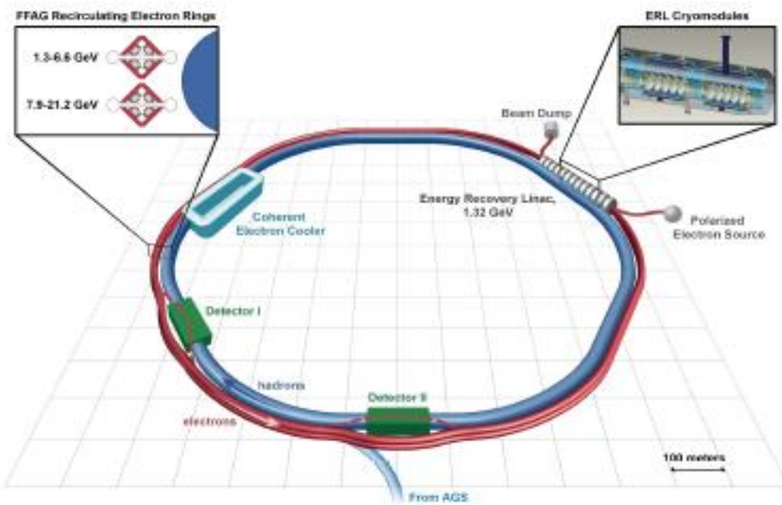
What is the quark-gluon nature of nuclear short-range correlations ?

Act 4. EIC: the ultimate QCD machine?

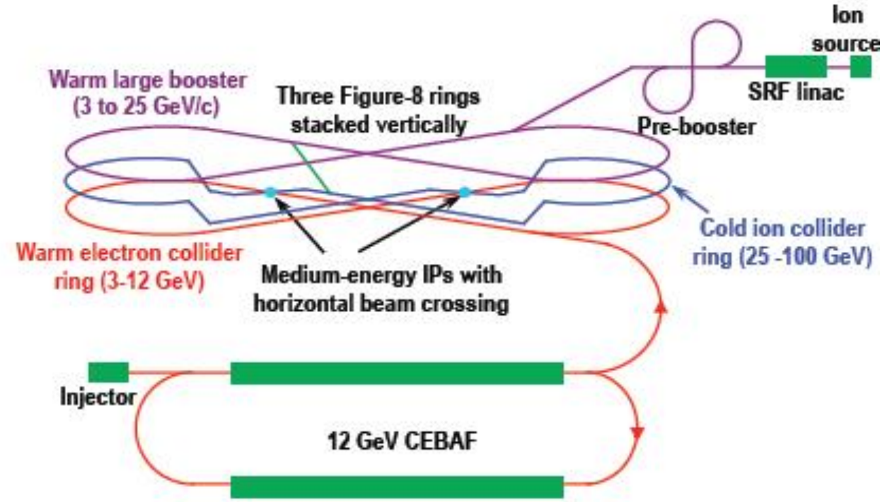
- The world's first polarized electron-polarized proton collider
- The world's first electron-heavy ion collider
- Luminosities: a hundred to up to a thousand times HERA
- Fine resolution inside proton down to 10^{-18} meters

US Electron-Ion Colliders: accelerator designs

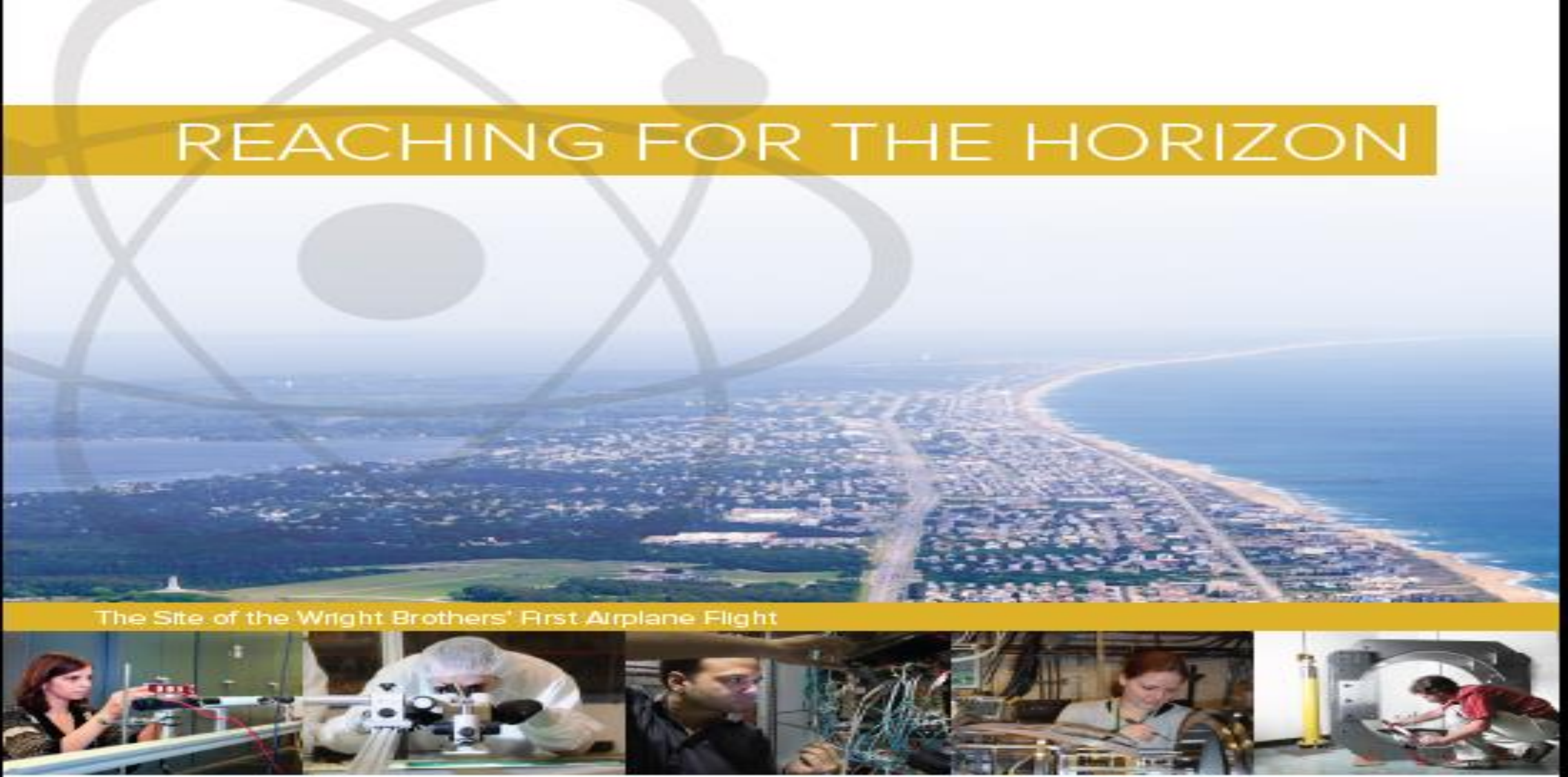
- **eRHIC (BNL)**
  - Add ERL+FFAG Recirculating e Rings to RHIC facility
  - Electrons 15.9 & 21.2 GeV
  - Ions (Au) up to 100 GeV/u
  - $\sqrt{s} \approx 18 - 93$ GeV
  - $L \approx 1.7\times10^{33}$ cm^{-2} s^{-1}/A at $\sqrt{s}=80$ GeV



- **MEIC (JLab)**
  - Figure-8 Ring-Ring Collider, use of CEBAF
  - Electrons 3-12 GeV
  - Ions 12-40 GeV/u
  - $\sqrt{s} \approx 11$-45 GeV
  - $L \approx 2.4\times10^{34}$ cm^{-2} s^{-1}/A at $\sqrt{s}=22$ GeV



◆ **LHeC at CERN – center-of-mass energies of 1.2 TeV (4 times HERA) electron-ion collisions; no polarized protons**



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

http://science.energy.gov/np/nsac/

RECOMMENDATION III

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

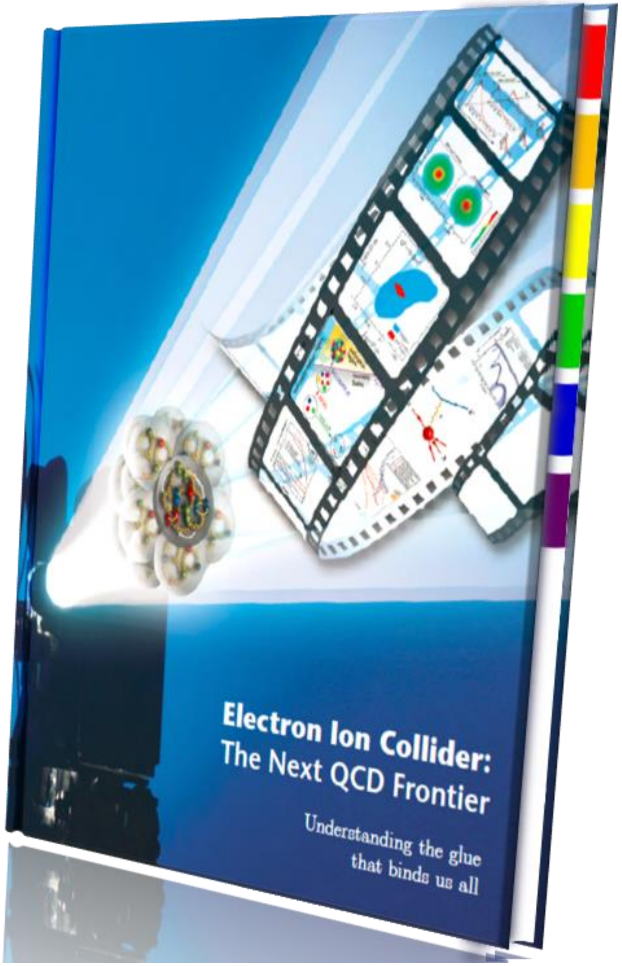
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier of ultra-dense gluon

fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

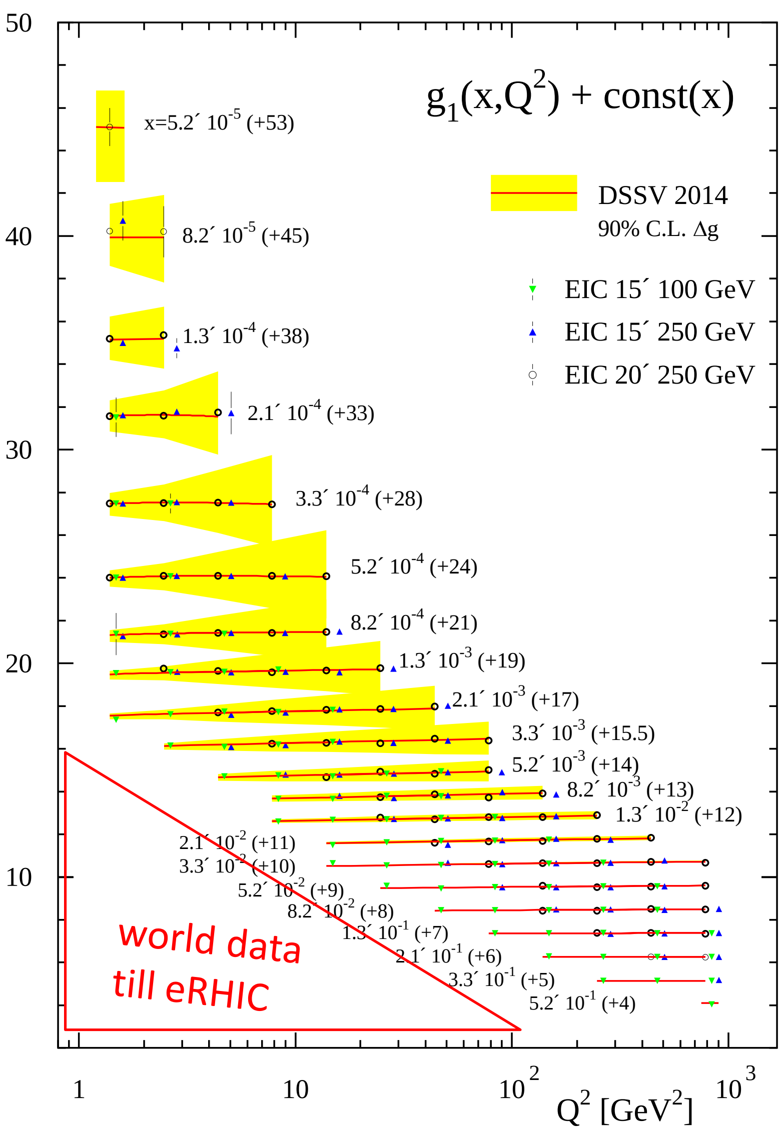
The vision of an EIC was already a powerful one in the 2007 Long Range Plan. The case is made even more compelling by recent discoveries. This facility can lead to the convergence of the present world-leading QCD programs at CEBAF and RHIC in a single facility. This vision for the future was expressed in the 2013 NSAC report on the implementation of the 2007 Long Range Plan with the field growing towards two major facilities, one to study the quarks and gluons in strongly interacting matter and a second, FRIB, primarily to study nuclei in their many forms. Realizing the EIC will keep the U.S. on the cutting edge of nuclear and accelerator science.

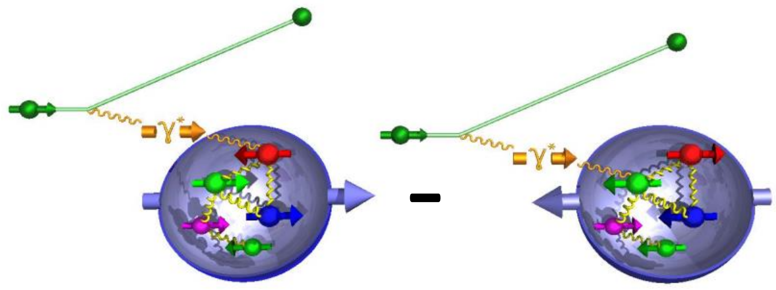
Select measurements



arXiv:1212.1701v3

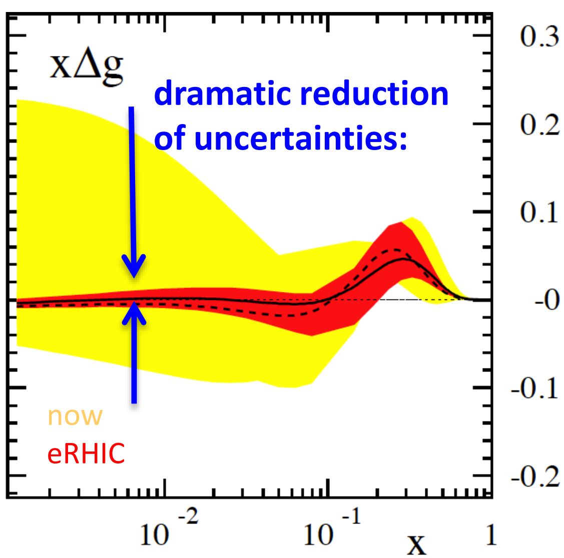
Resolving the proton's spin puzzle



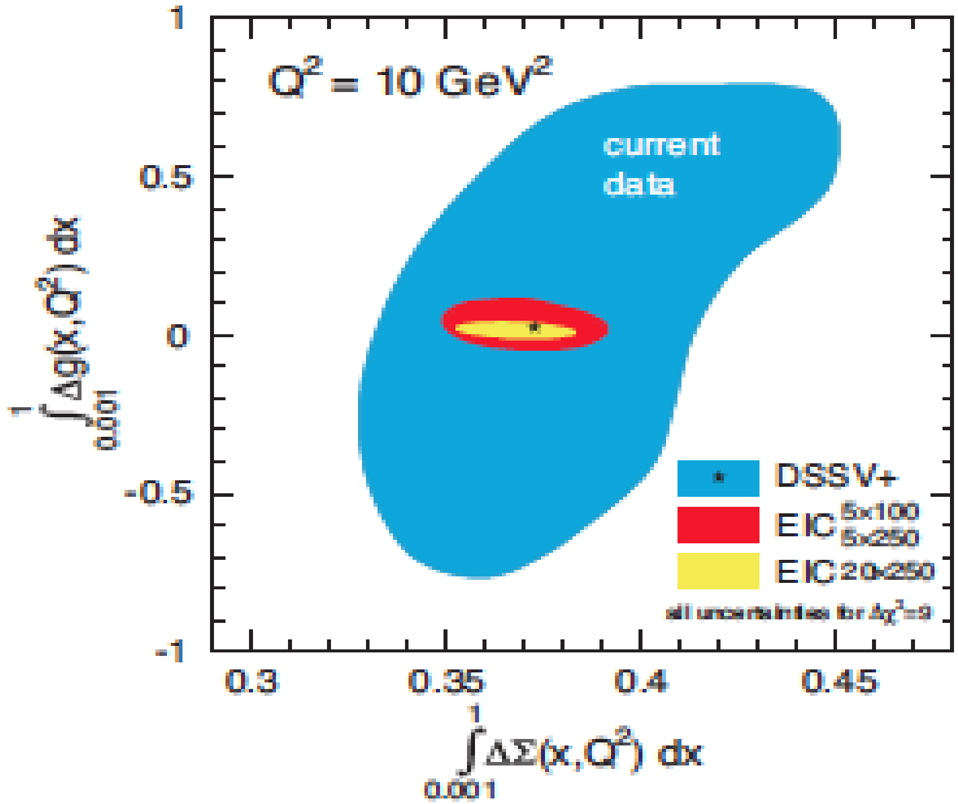


$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx \rightarrow \textbf{quark contr.}$$

$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2) \rightarrow \textbf{gluon contr.}$$

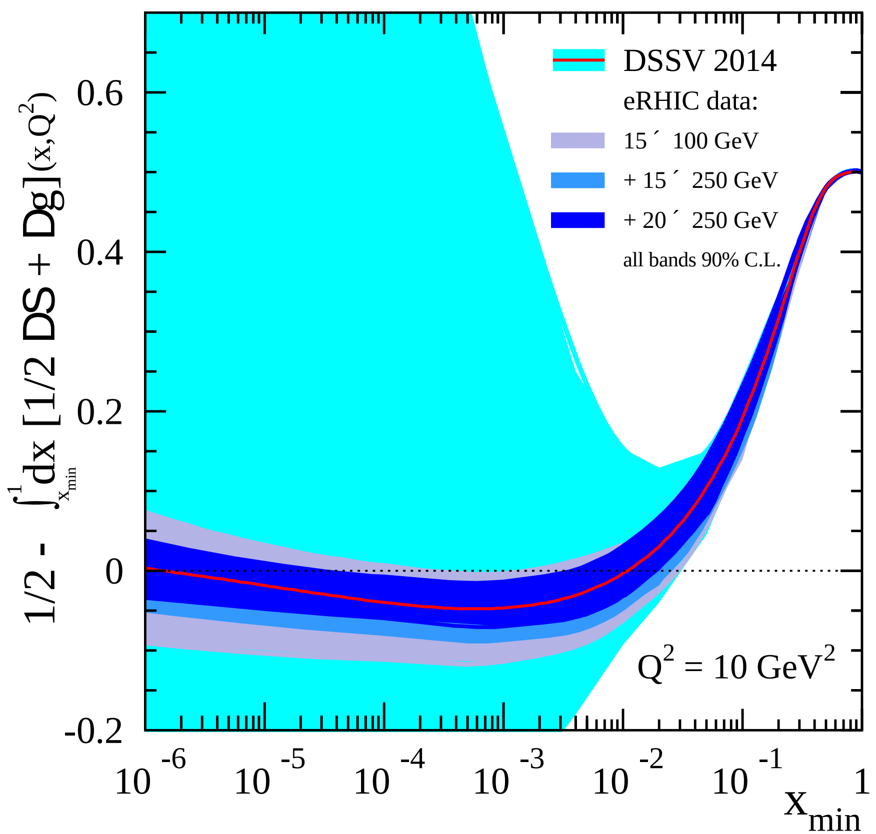


A money plot



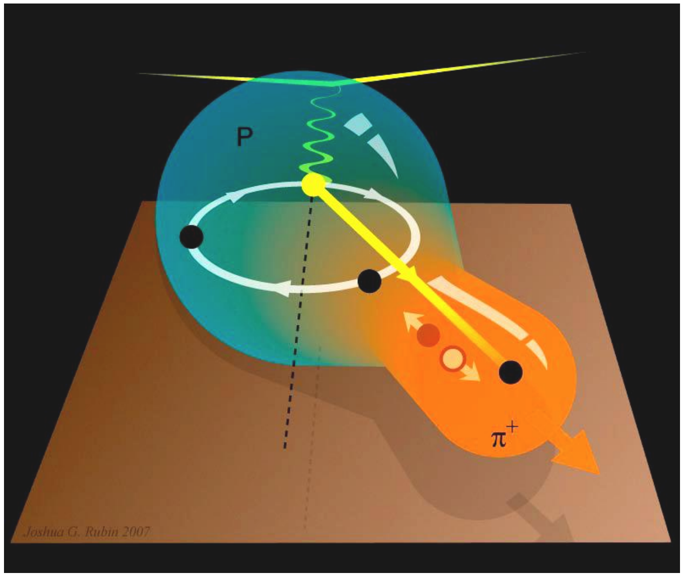
◆ Nail down the valence, sea quark and gluon contributions to the proton's spin

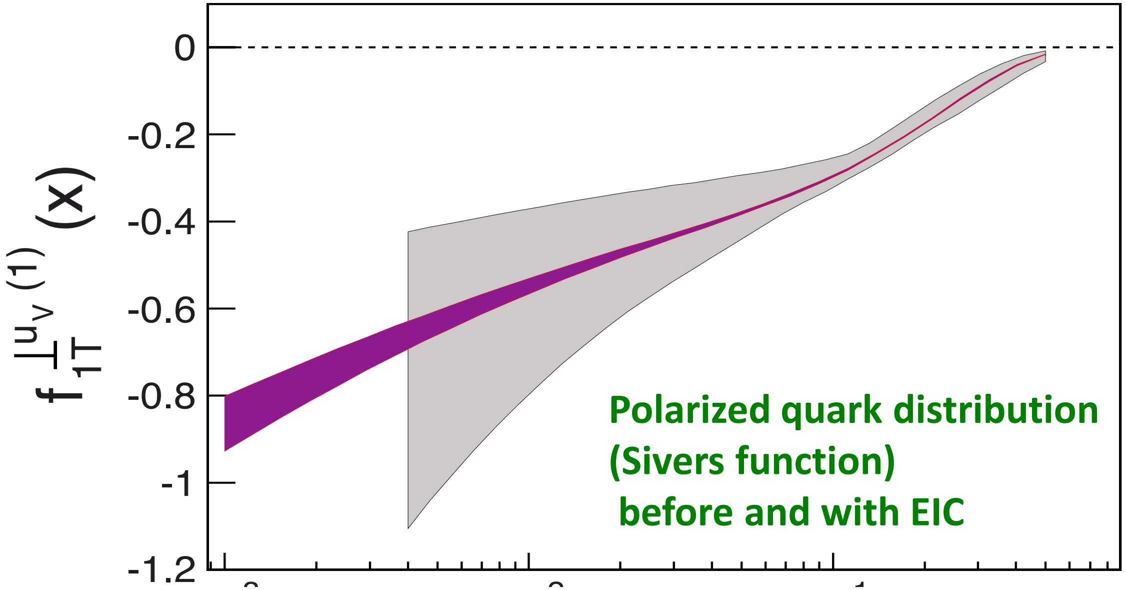
A money plot

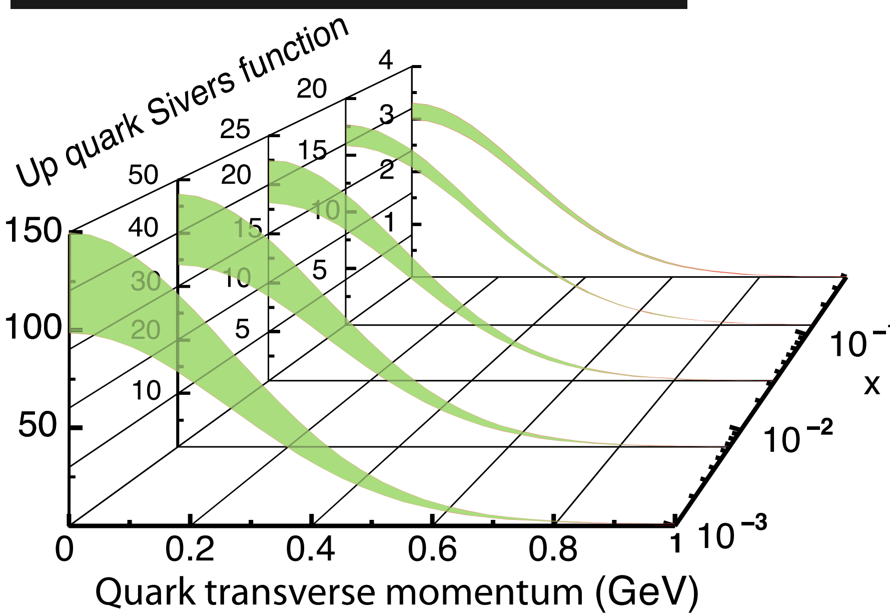


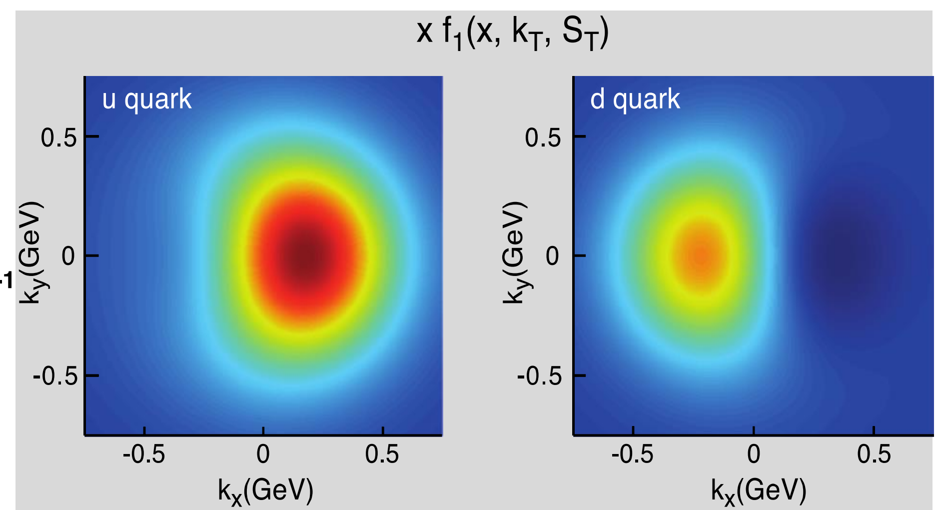
- Significantly quantify the remaining orbital contributions

3-D imaging in semi-inclusive reactions

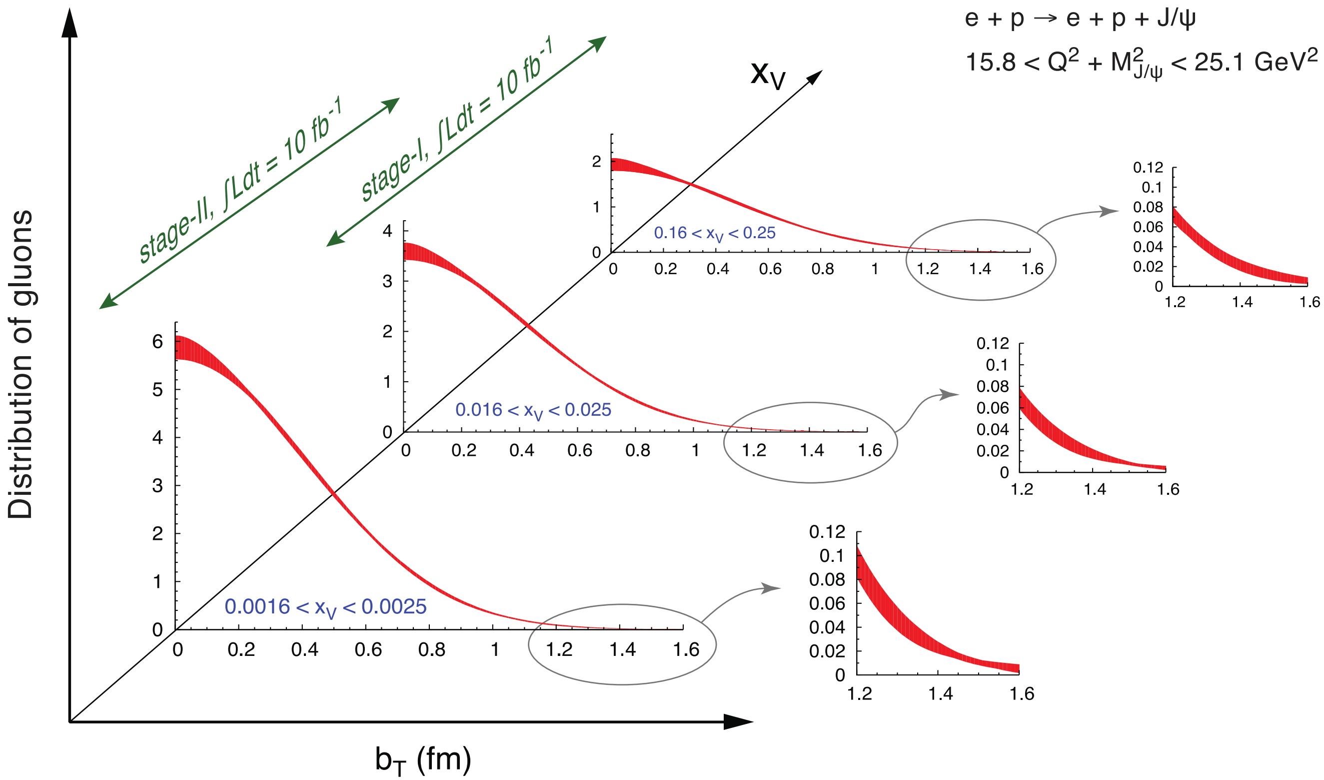






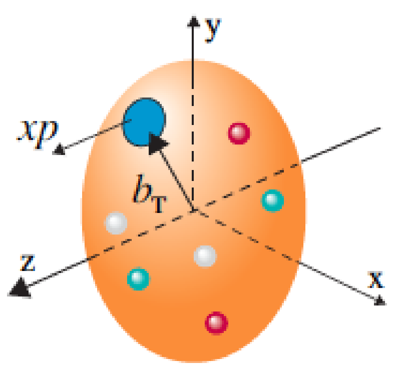


Projected images of spatial gluon distributions

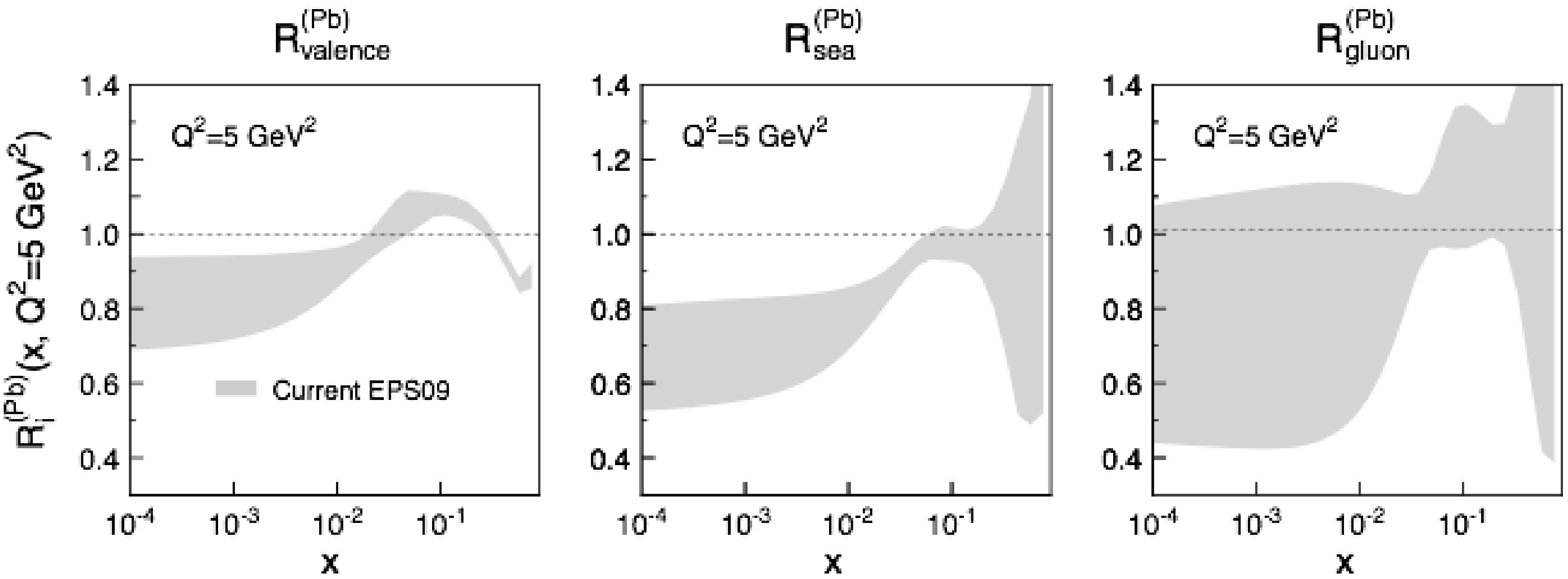


Generalized parton distributions (GPDs) uncover 3-D structure of matter below the Femto-scale:

- High precision spatial tomography gluon and sea quark distributions !

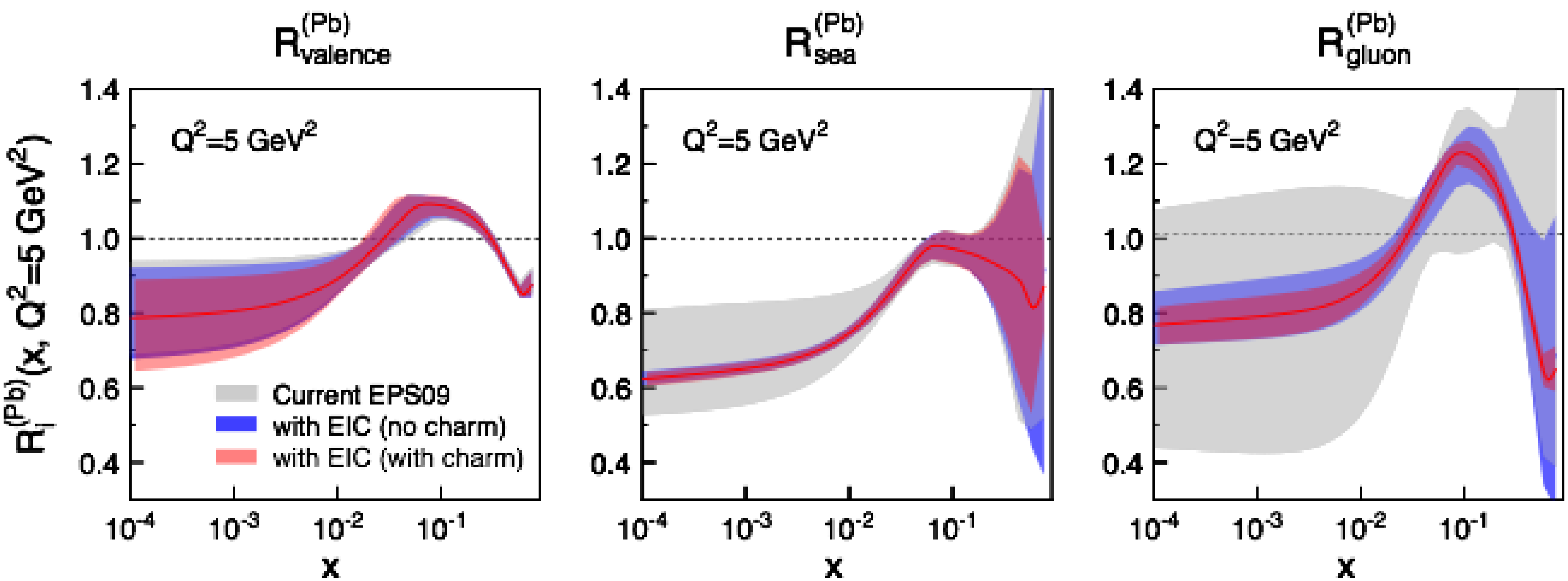


Entering terra-incognita in nuclei



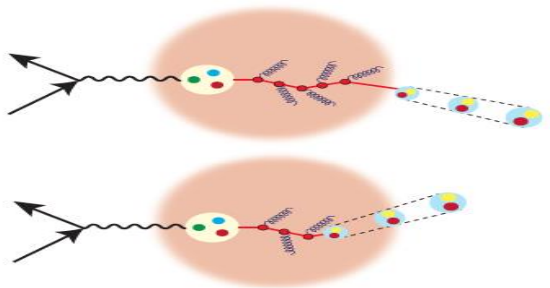
- **Current knowledge on distributions of quarks and gluons in nuclei**

Entering terra-incognita in nuclei

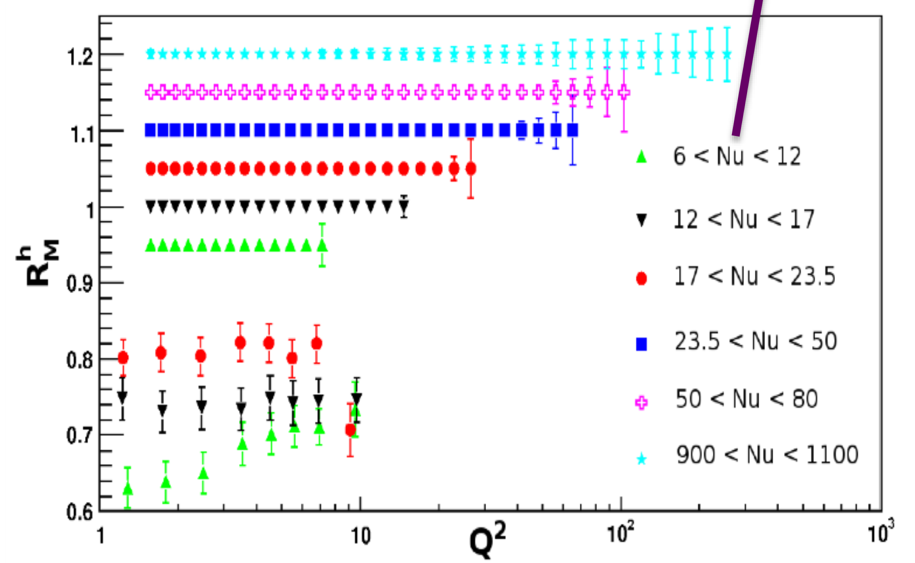


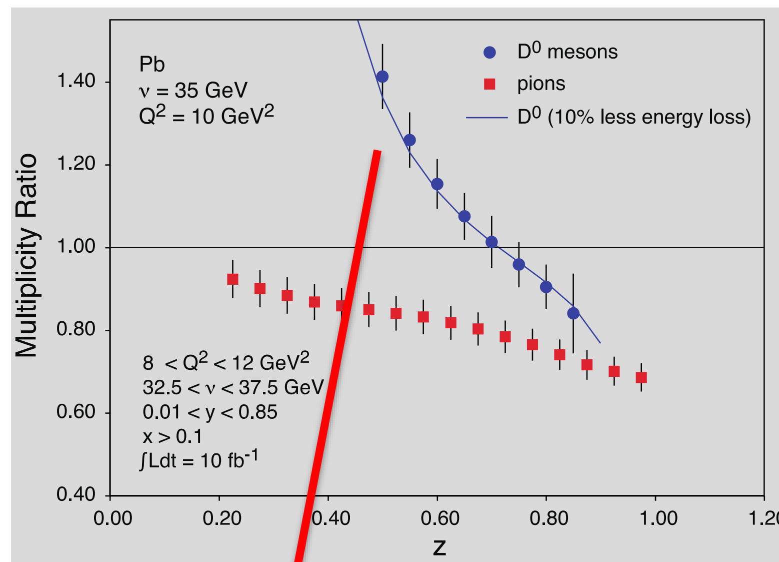
- **Dramatic improvement in precision extraction of nuclear gluons and sea quarks**

The Transubstantiation of Quarks and Glue into mesons and baryons



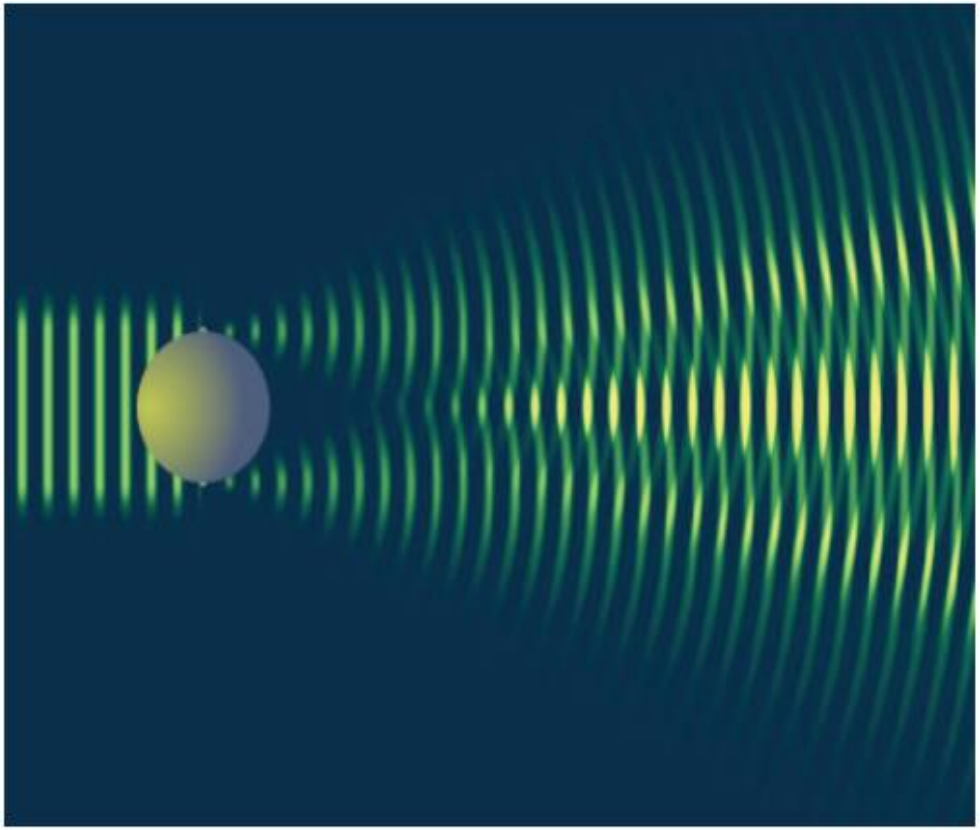
Nu is a coherence length. Dialing it determines whether quarks (gluons) fragment in or out of nucleus

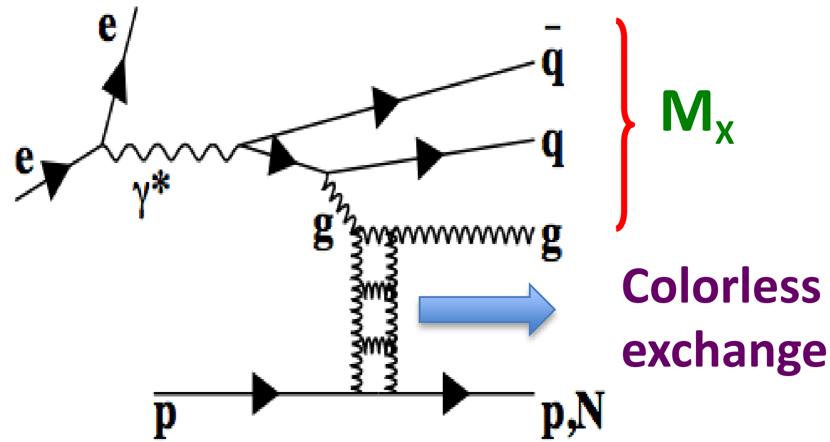




Novel sensitivity to heavy quark fragmentation

Diffraction for the 21st Century



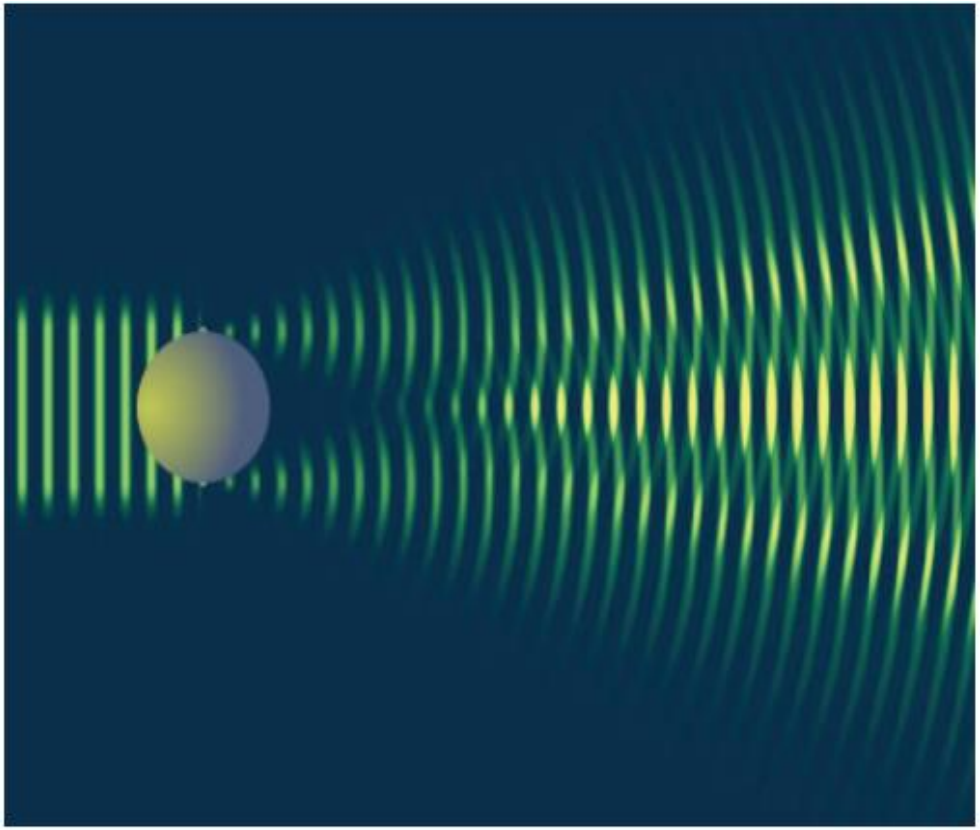


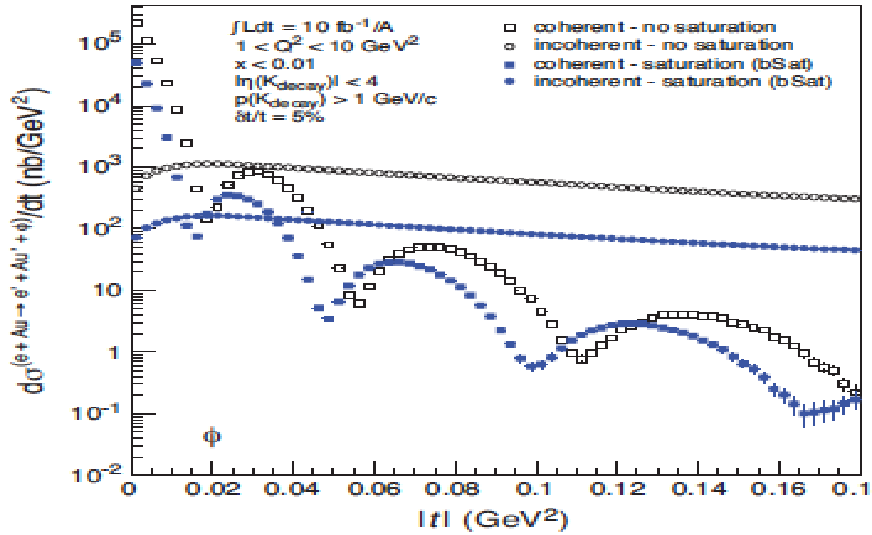
$$|e^-\rangle = |e_B\rangle + |e_B\,\gamma^*\rangle + |e_B\,\gamma^*\,q\bar{q}\rangle + |e_B\,\gamma^*\,q\bar{q}\,g\rangle + \cdots$$

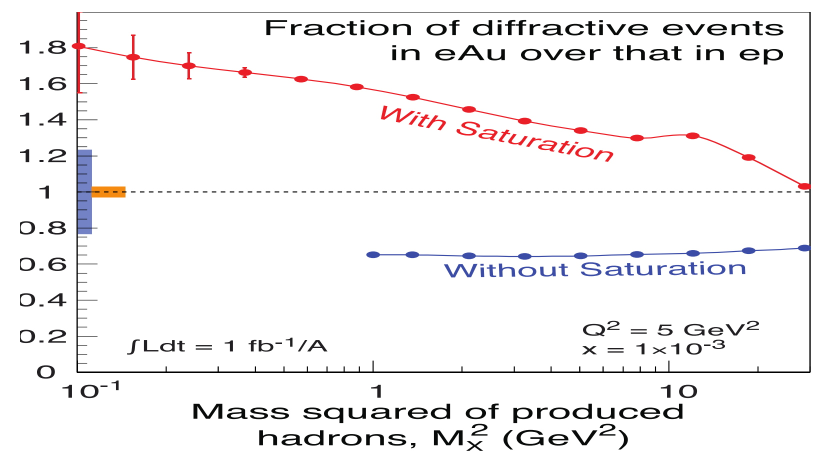
A TeV electron hits a nucleus (binding energy of 8 MeV/nucleon)

- **Day 1: prediction: nucleus remains intact in at least 1 in 5 events**

Diffraction for the 21st Century







A TeV electron hits a nucleus (binding energy of 8 MeV/nucleon)

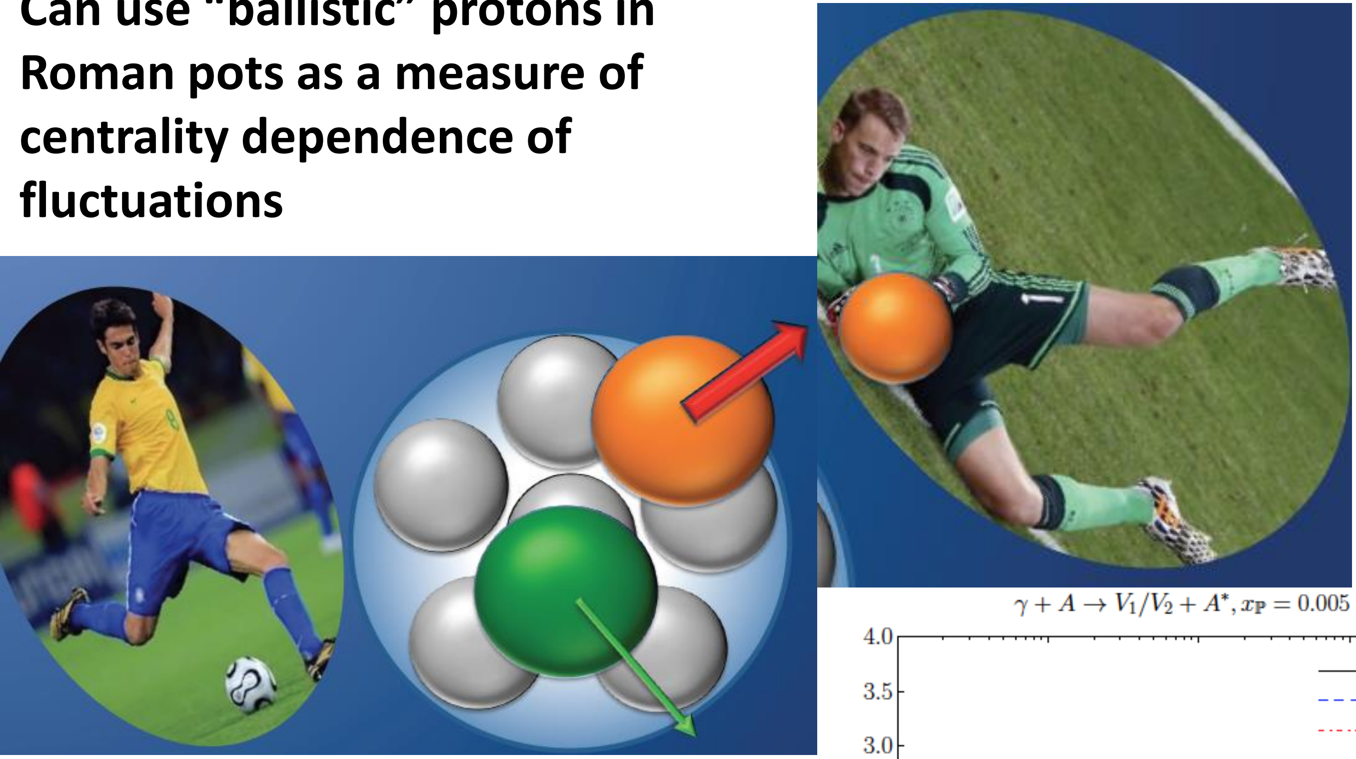
- **Day 1: prediction: nucleus remains intact in at least 1 in 5 events**

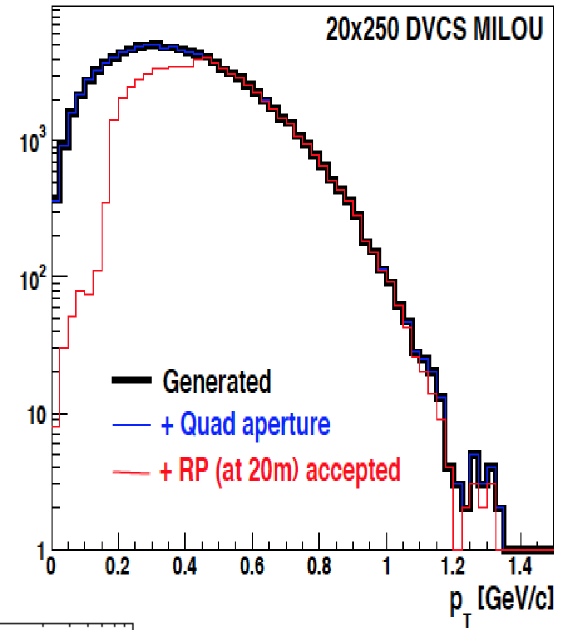

EIC whitepaper
New opportunities

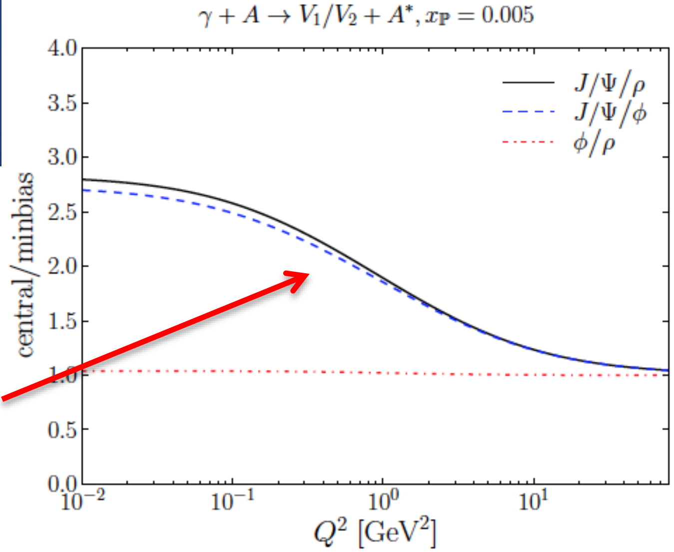
Probing rare glue fluctuations with ballistic protons

T. Lappi, H. Mantysaari, R. Venugopalan: PRL 114 (2015) 8, 082301

Can use "ballistic" protons in Roman pots as a measure of centrality dependence of fluctuations



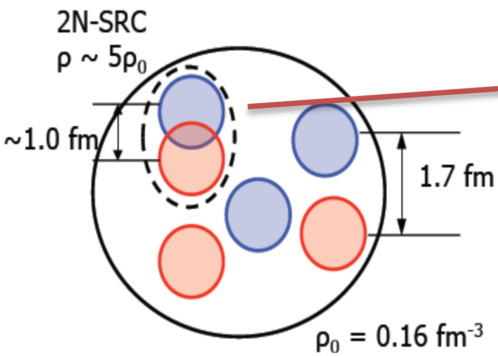


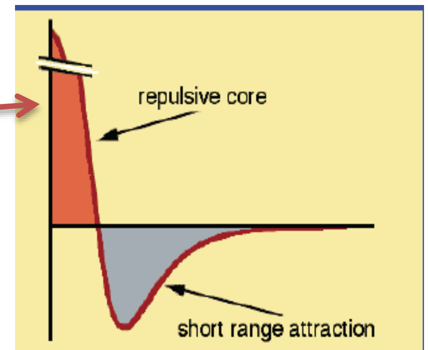


Central/min.bias double ratios very sensitive probe of fluctuations of strong gluon fields

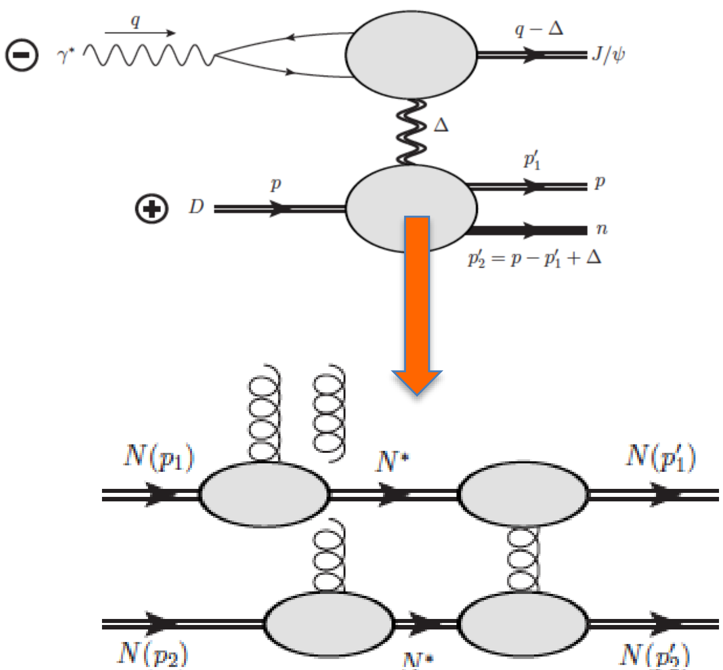
Probing short-range NN interactions with EIC

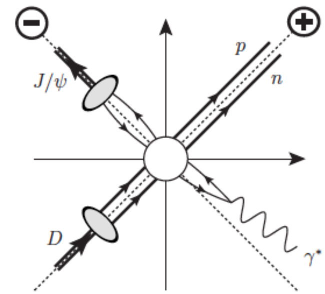
G.A. Miller, M. D. Sievert, R. Venugopalan, to appear tomorrow





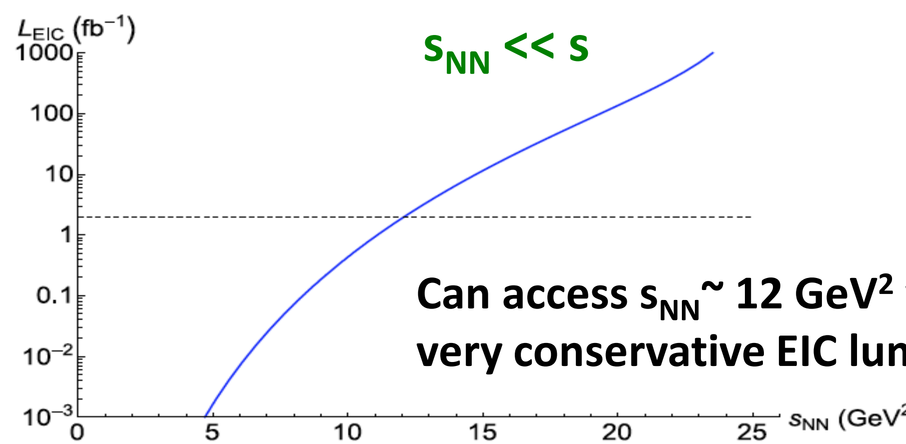
Use high energy DIS probes to probe short-range nuclear forces





Exclusive process

$$e + D \longrightarrow e + J/\Psi + n + p$$



$s_{NN} << s$

Can access s_{NN}~ 12 GeV^2 with very conservative EIC lumi.

Concluding Thoughts

- Our knowledge of the fundamental structure of matter is clouded by the vast fog of our ignorance
– though there are bright gems that shine through

- At the heart of the matter is the confining dynamics of QCD – this is many-body dynamics with gluons playing a lead role.

- Addressing this requires deep and varied knowledge
– an EIC enables unique and unprecedented measurements.
The history of DIS informs us that surprises may be anticipated

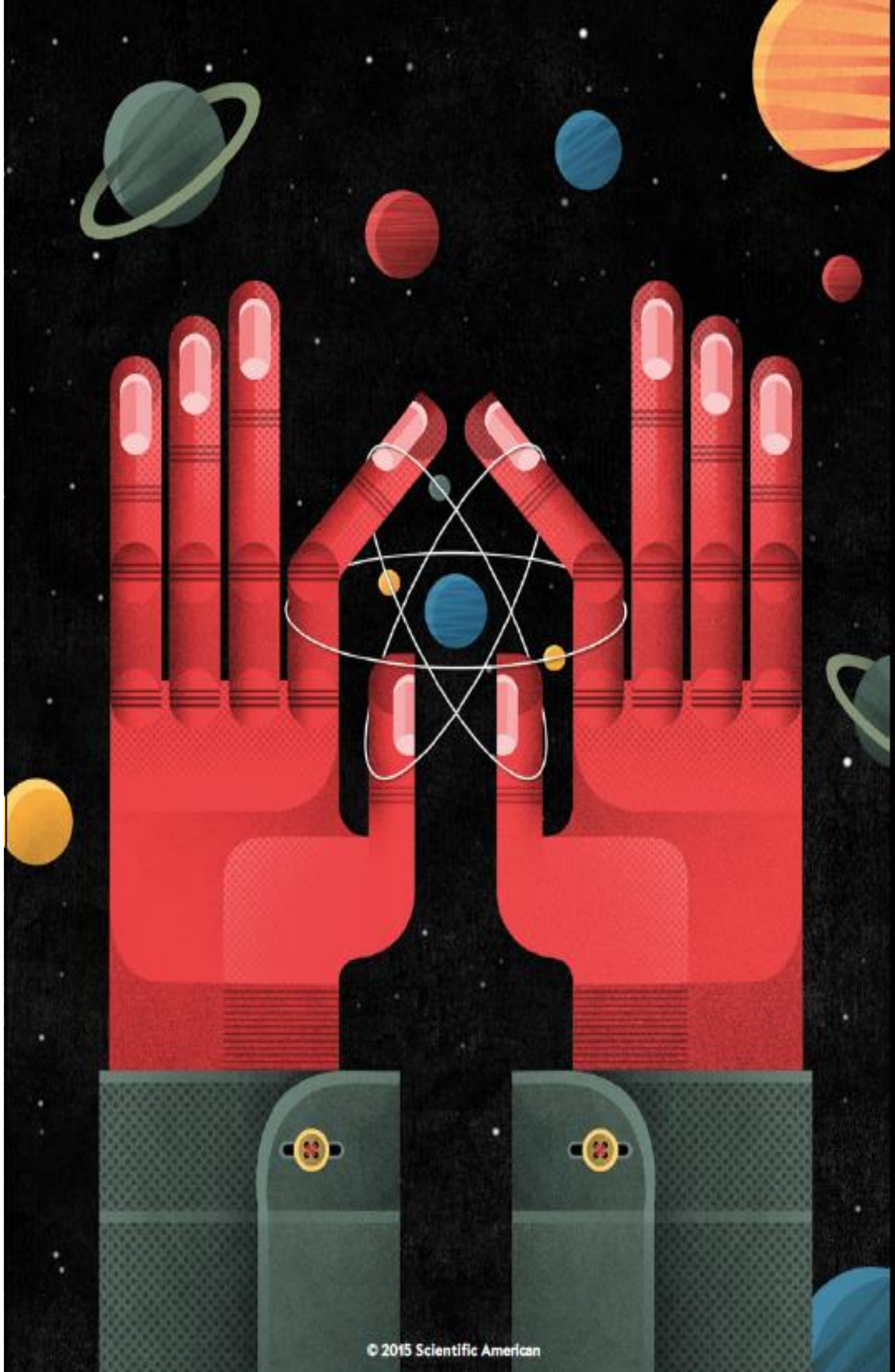
PARTICLE PHYSICS

the glue that binds us

Physicists have known for decades that particles called gluons keep protons and neutrons intact—and thereby hold the universe together. Yet the details of how gluons function remain surprisingly mysterious

By Rolf Ent, Thomas Ullrich and Raju Venugopalan

Illustration by Maria Corte



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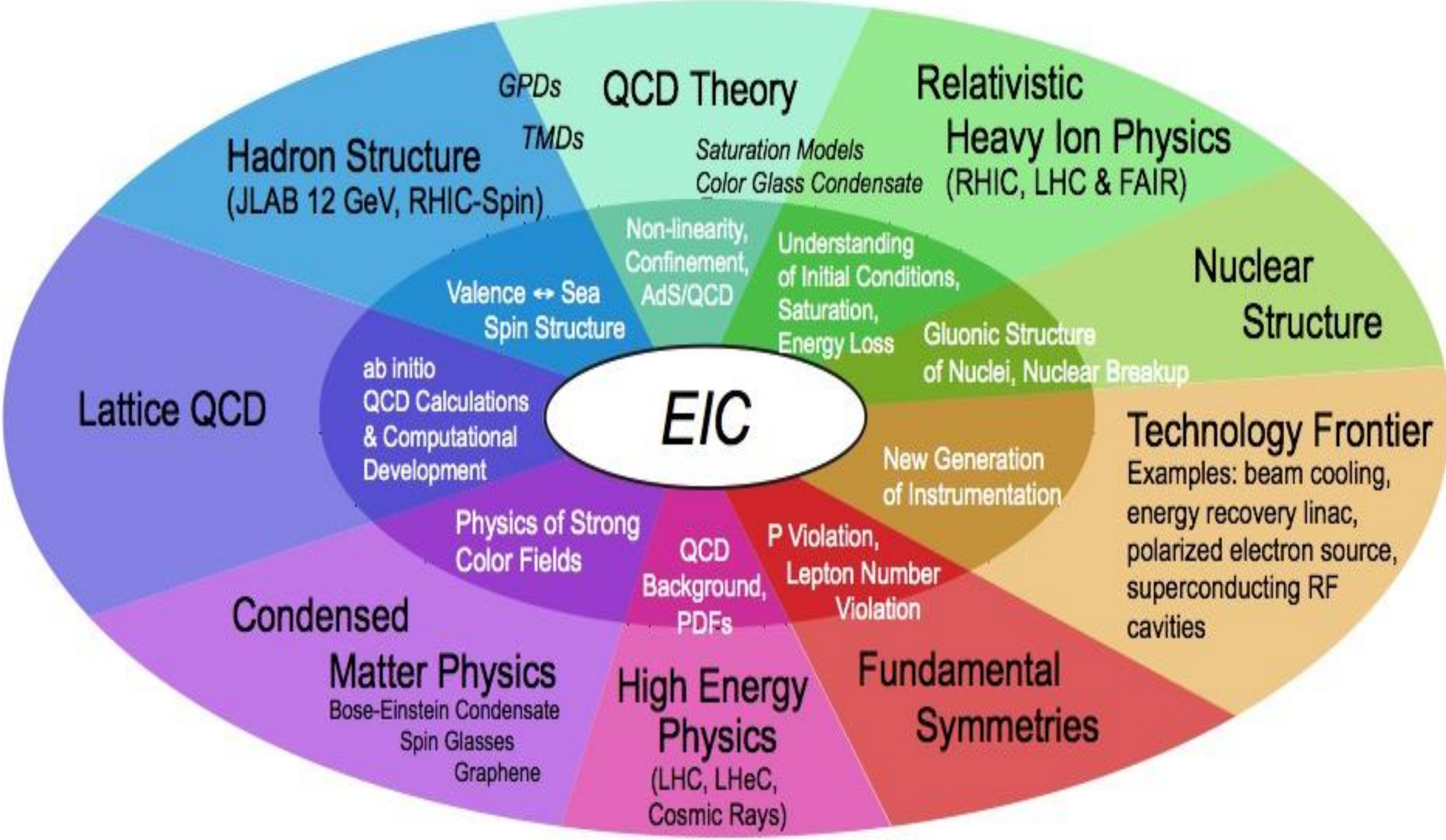
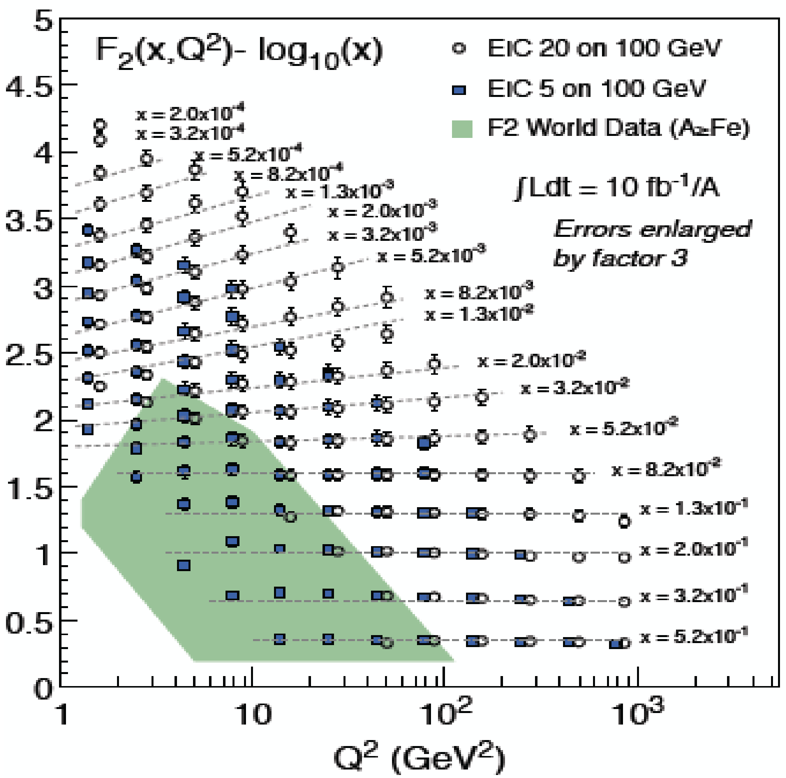
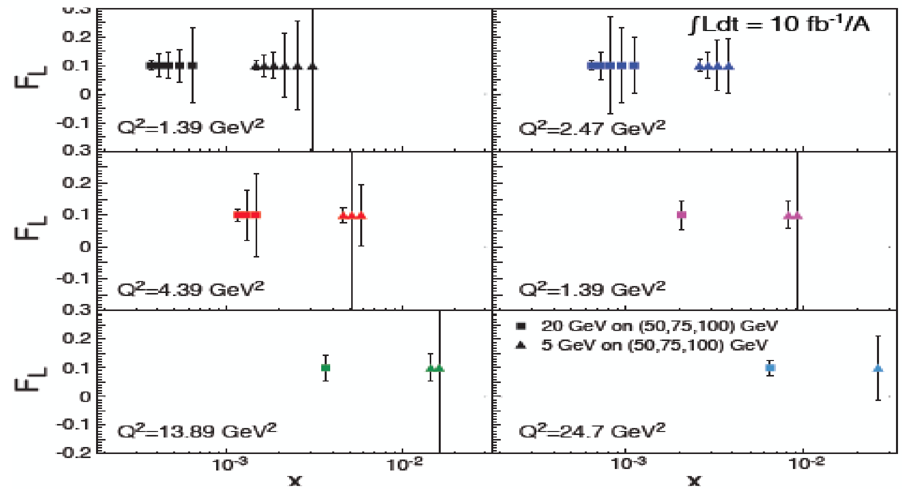


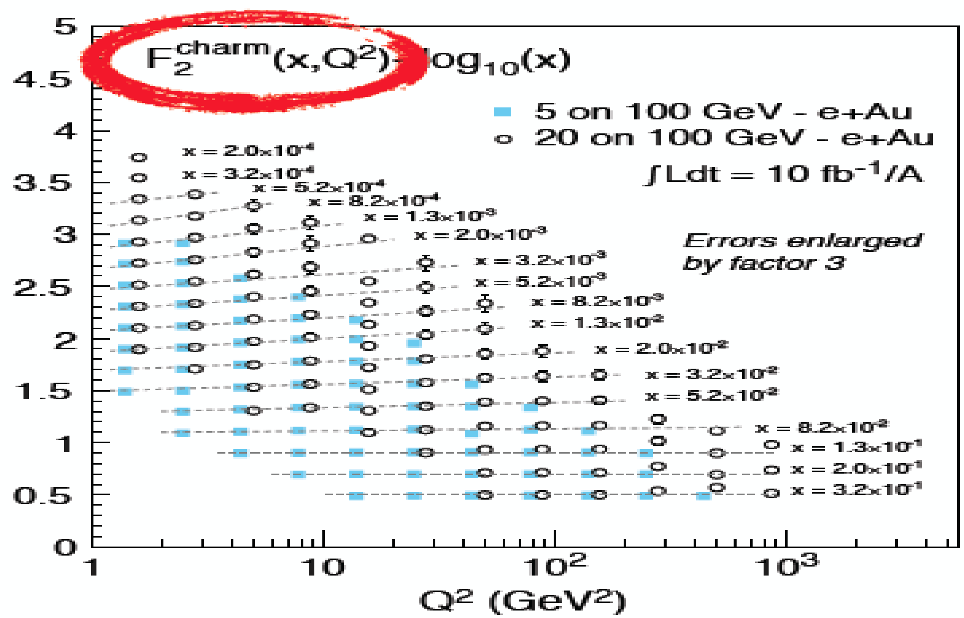
Slide by Thomas Ullrich

Entering terra-incognita in nuclei

$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

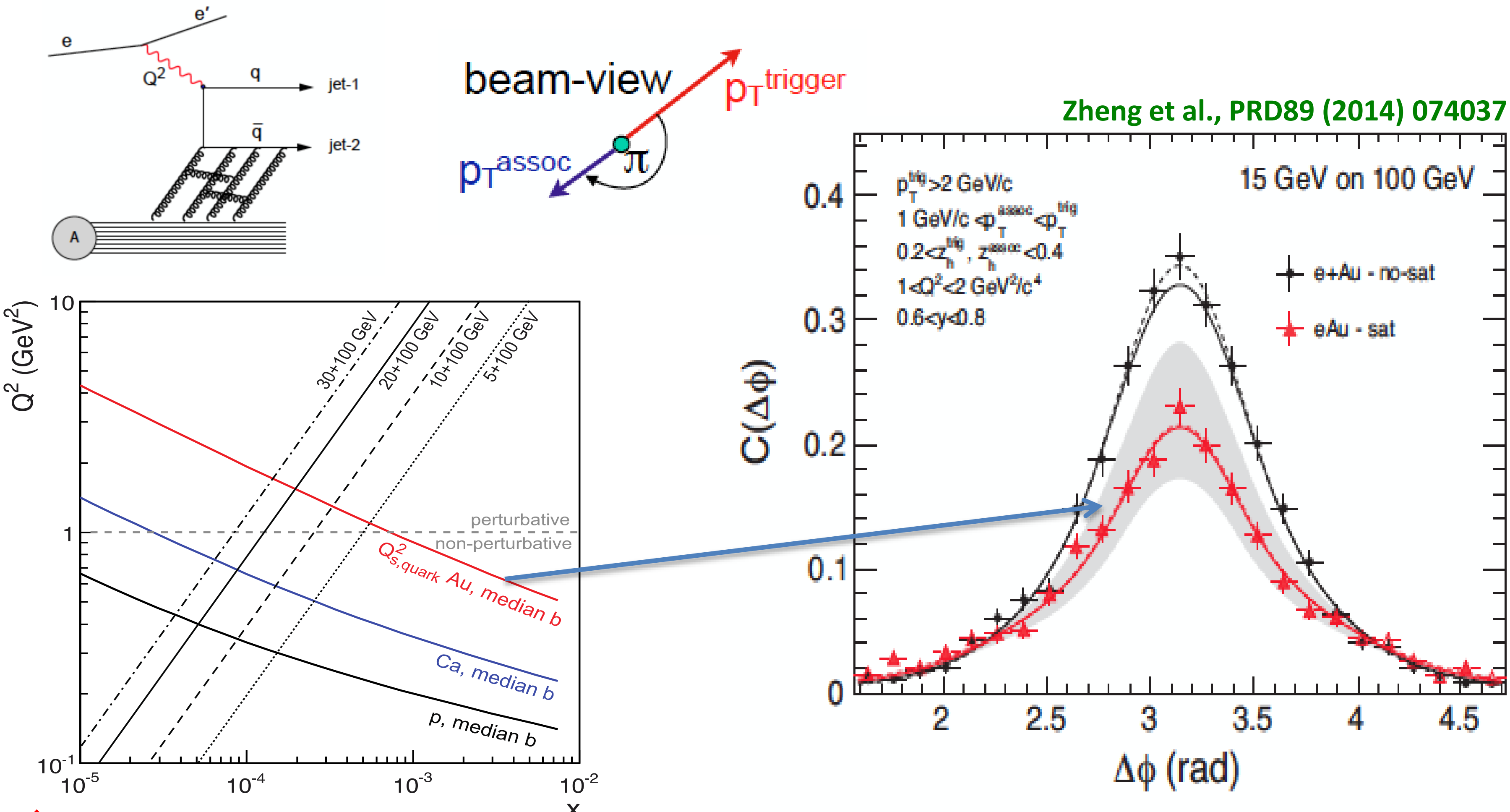






- First measurements of gluons and sea quarks in heavy nuclei

Differential probes of many-body correlations



- Di-hadron measurements are very sensitive to the evolution and dynamics of many body correlations—complementary suite of measurements to those in p+A collisions


PARTICLE PHYSICS
How Do Gluons Bind Matter?
MEDICINE
Lifting the Curse of Alzheimer's
COMPUTING
Innovating Beyond Moore's Law
SCIENTIFIC AMERICAN
ScientificAmerican.com
MAY 2015
RISE OF THE TYRANNOSAURS
20 finds—some bizarre—put T. rex in its place
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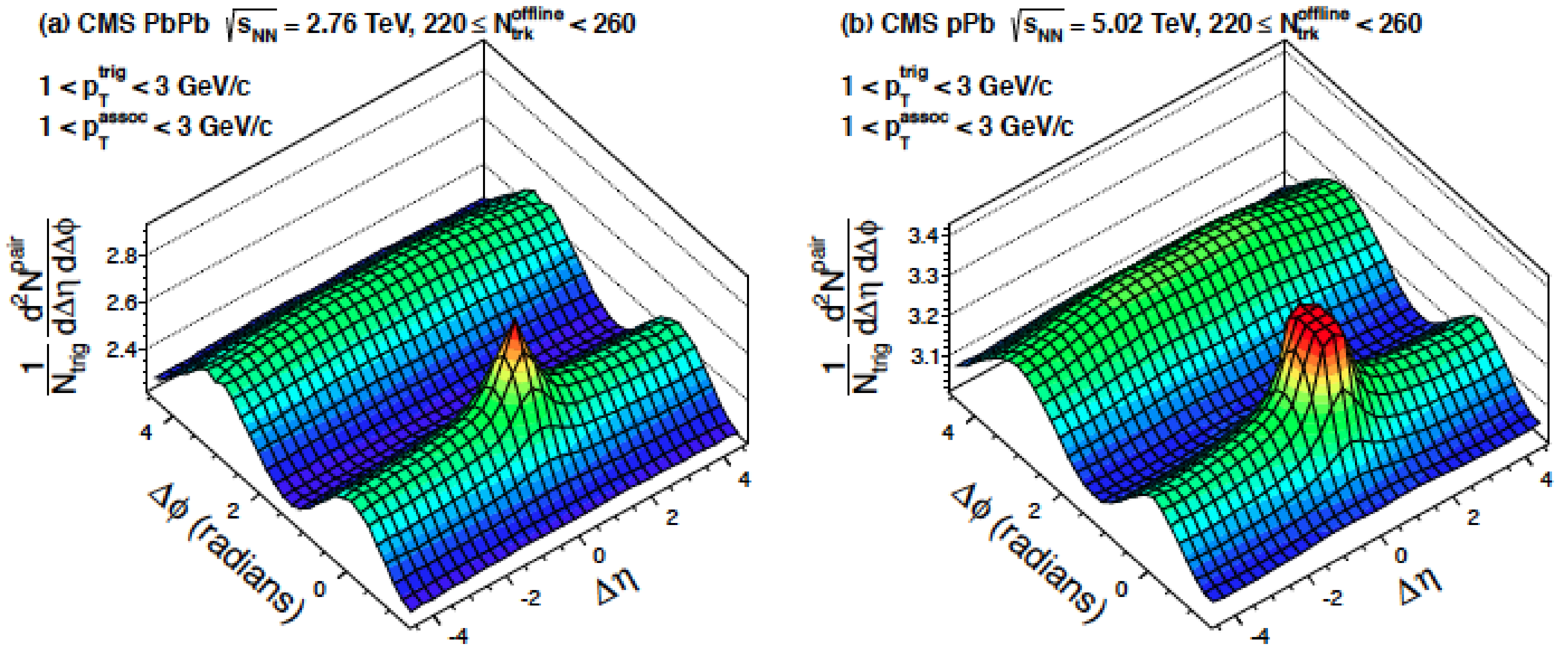
A final coda: definitive resolution of an LHC puzzle

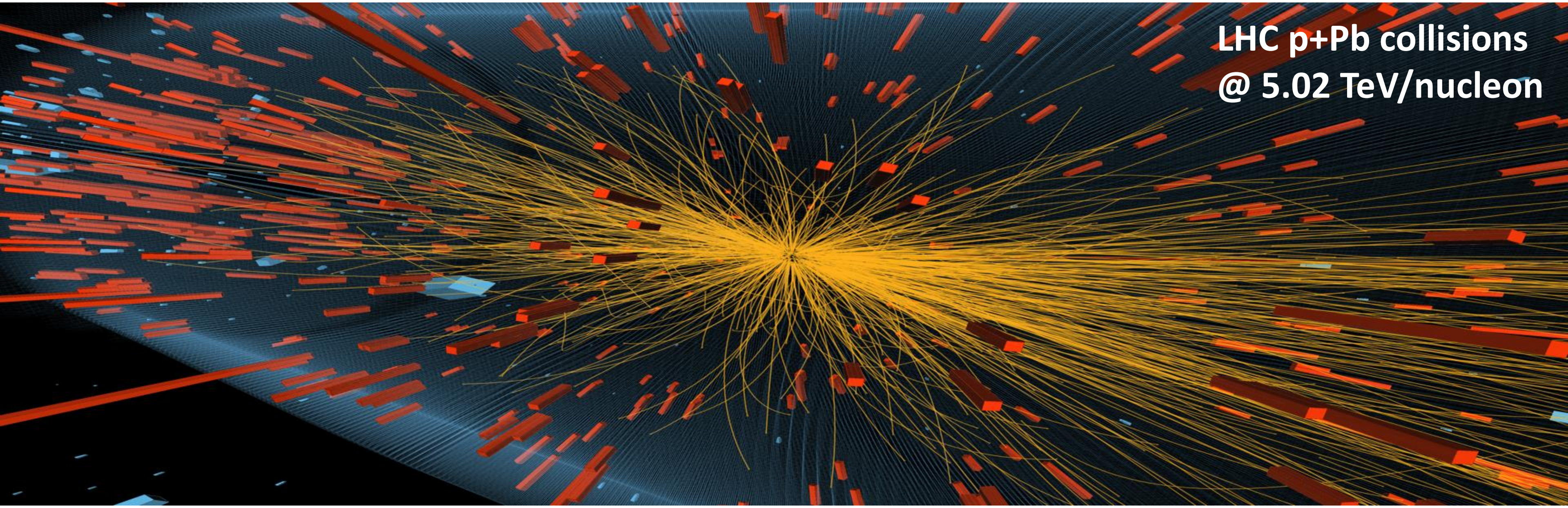


What EIC will contribute:

Photo-production in e+A very nearly like p+A –the photon fluctuates into a vector meson before hitting the nucleus
***– all p+A correlation measurements feasible*.**

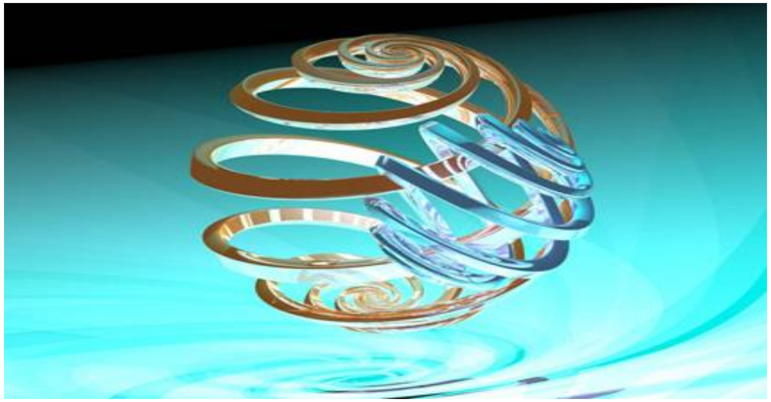
Varying momentum resolution Q^2 in e+A, one systematically dials away "final state" interactions…

A final coda: definitive resolution of an LHC puzzle



Is the matter created…

…the world's smallest droplet?



…or a novel form of gluon entanglement?