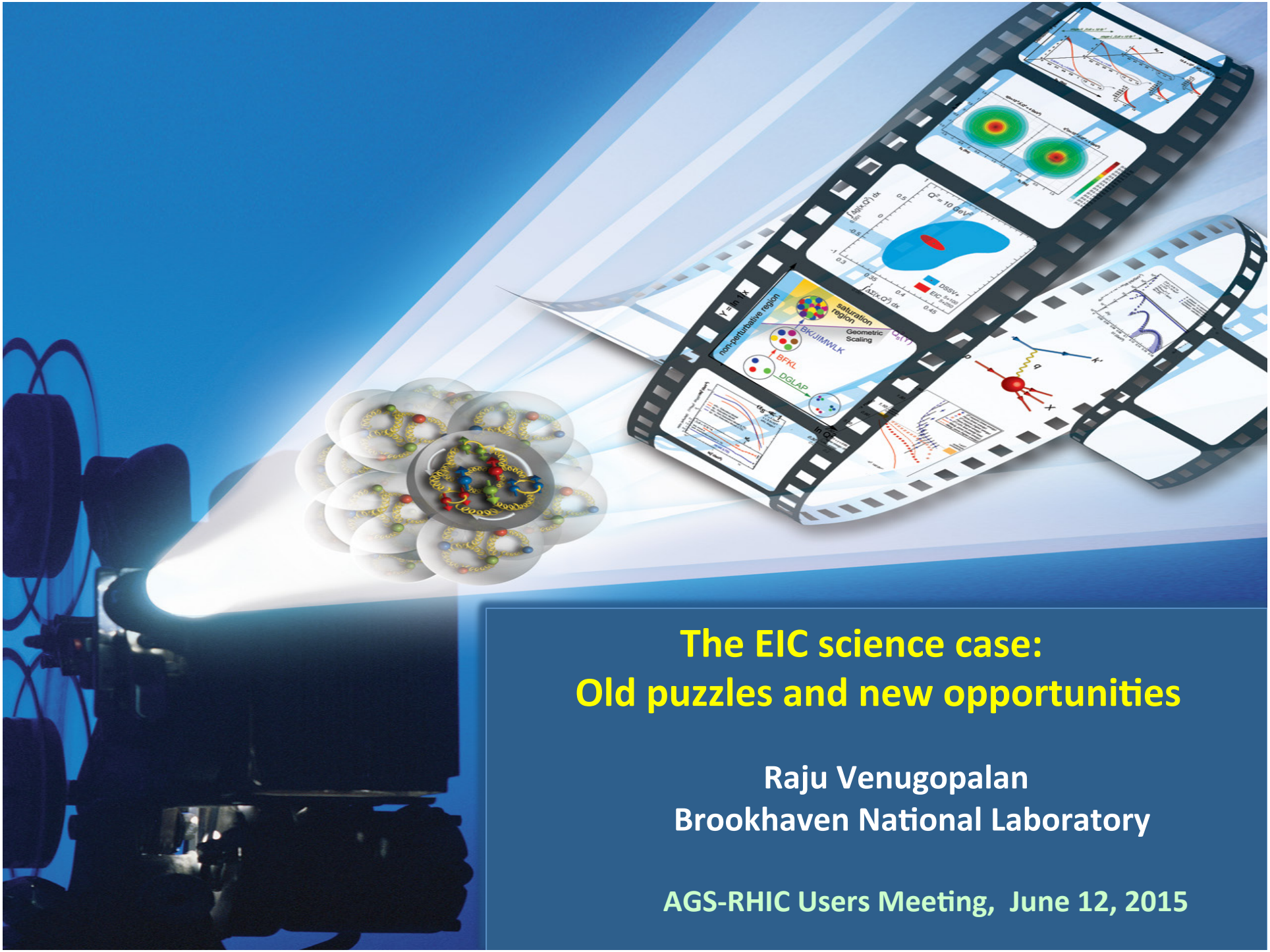

The EIC science case: Old puzzles and new opportunities

Raju Venugopalan
Brookhaven National Laboratory

AGS-RHIC Users Meeting, June 12, 2015

Talk Outline

- EIC science case: brief status report
- EIC science case: highlights
- Novel possibilities
  - the p+A limit of e+A
  - probing nuclear structure at short distances with EIC
  - hadron spectroscopy with EIC
- Outlook

INT program

10 Week INT program
In Fall 2010

Over 130 participants

INT Report on EIC Science

The EIC Science case:
a report on the joint
BNL/INT/JLab program

Gluons and the quark sea at high energies: distributions, polarization, tomography

Institute for Nuclear Theory • University of Washington, USA
September 13 to November 19, 2010

Editors:
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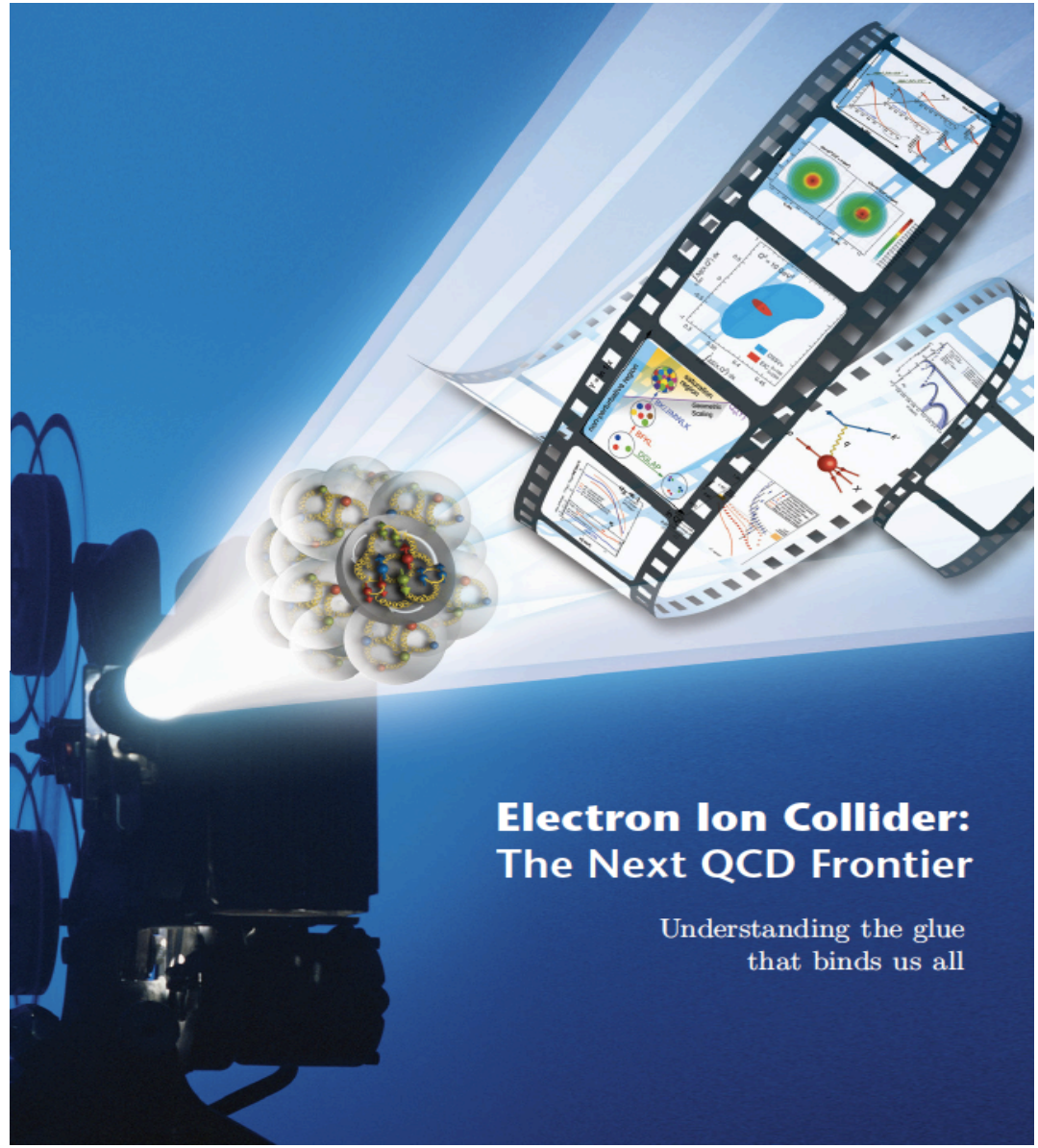
Brookhaven National Laboratory, USA
W. Vogelsang
Universität Tübingen, Germany

arXiv:1108.1713
cited 250 times to date

EIC white paper

Joint BNL/Jlab lead effort with large number of international collaborators

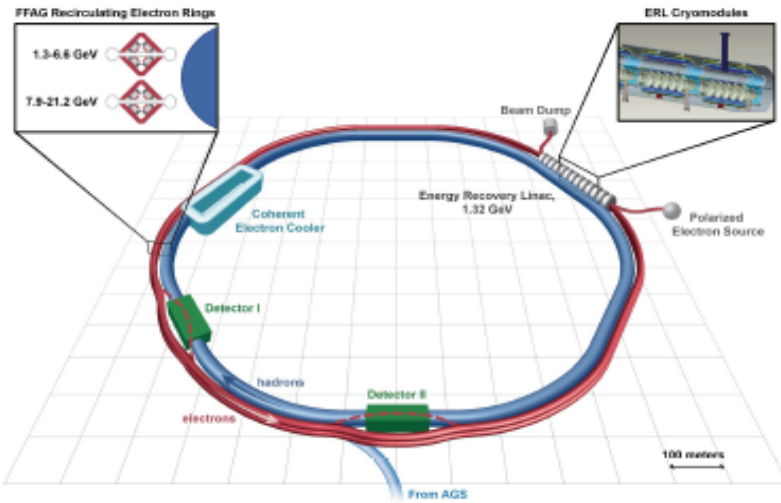
A. Accardi[14,28], J. L. Albacete[16], M. Anselmino[29], N. Armesto[37], E. C. Aschenauer[3,†], A. Bacchetta[36], D. Boer[33], W.K. Brooks[38,†], T. Burton[3], N.-B. Chang[23], W.-T. Deng[13,23], A. Deshpande[25,*,†], M. Diehl[11,†], A. Dumitru[2], R. Dupré[7], R. Ent[28,‡], S. Fazio[3], H. Gao[12,†], V. Guzey[28], H. Hakobyan[38], Y. Hao[3], D. Hasch[15], R. Holt[1,†], T. Horn[5,†], M. Huang[23], A. Hutton[28,†], C. Hyde[20], J. Jalilian-Marian[2], S. Klein[17], B. Kopeliovich[38], Y. Kovchegov[19,†], K. Kumar[25,†], K. Kumerički[40], M. A. C. Lamont[3], T. Lappi[34], J.-H. Lee[3], Y. Lee[3], E. M. Levin[26,38], F.-L. Lin[28], V. Litvinenko[3], T. W. Ludlam[3,‡], C. Marquet[8], Z.-E. Meziani[27,*,†], R. McKeown[28,‡], A. Metz[27], R. Milner[18], V. S. Morozov[28], A. H. Mueller[9,†], B. Müller[3,12,‡], D. Müller[22], P. Nadel-Turonski[28], H. Paukkunen[34], A. Prokudin[28], V. Ptitsyn,[3], X. Qian[4], J.-W. Qiu[3,*,†], M. Ramsey-Musolf[35,†], T. Roser[3,†], F. Sabatié[7,†], R. Sassot[31], G. Schnell[30], P. Schweitzer[32], E. Sichtermann[17,†], M. Stratmann[39], M. Strikman[21], M. Sullivan[24], S. Taneja[10,25], T. Toll[3], D. Trbojevic[3], T. Ullrich[3,†], R. Venugopalan[3], S. Vigdor[3,‡], W. Vogelsang[39,†], C. Weiss[28], B.-W. Xiao[6], F. Yuan[17,†], Y.-H. Zhang[28], L. Zheng[3,6]



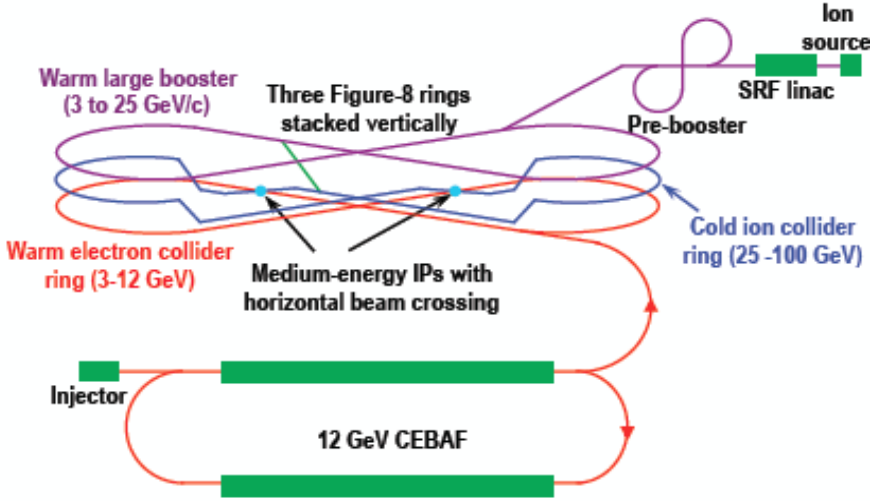
arXiv1212.1701v3
cited 158 times to date

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

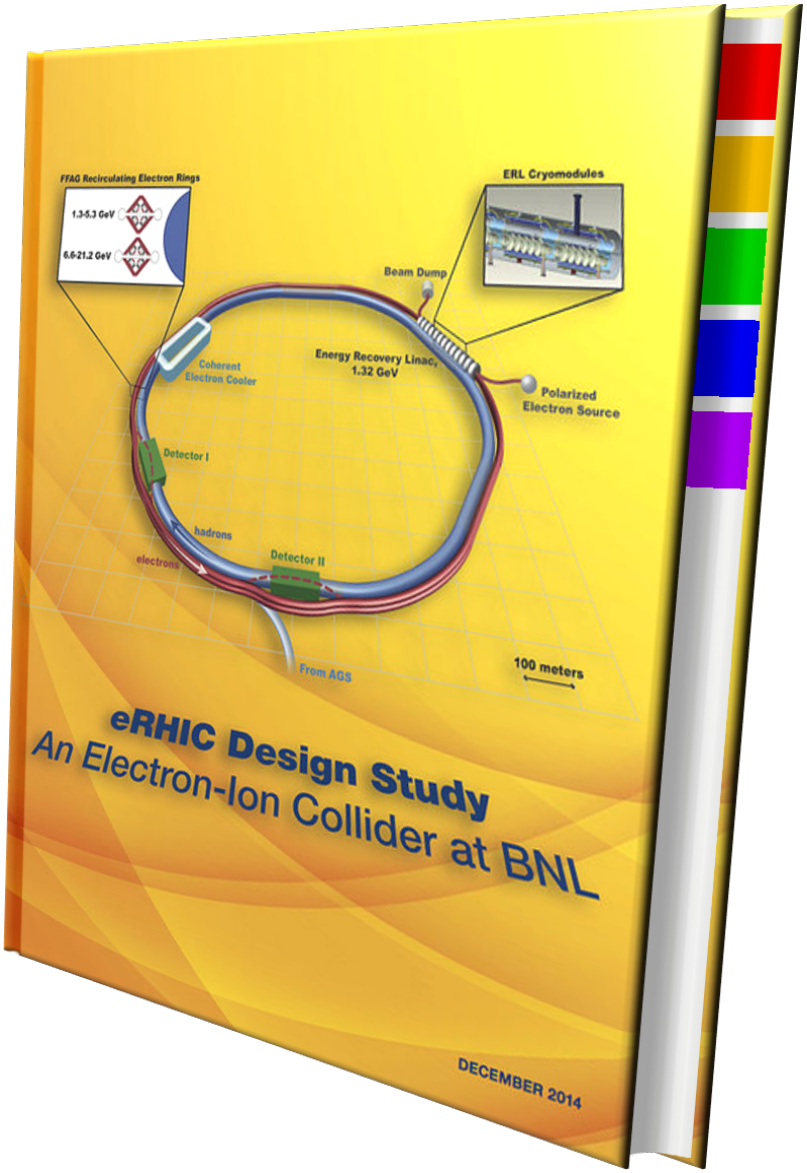


- **MEIC (JLab)**
  - Figure-8 Ring-Ring Collider, use of CEBAF
  - Electrons 3-12 GeV
  - Ions 12-40 GeV/u
  - $\sqrt{s} \approx 11$-45 GeV
  - $L \approx 2.4\times10^{34}$ cm^{-2} s^{-1}/A at $\sqrt{s}$=22 GeV



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

eRHIC design study



arXiv:1409.1633

Feature article, May 2015 issue of Scientific American

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

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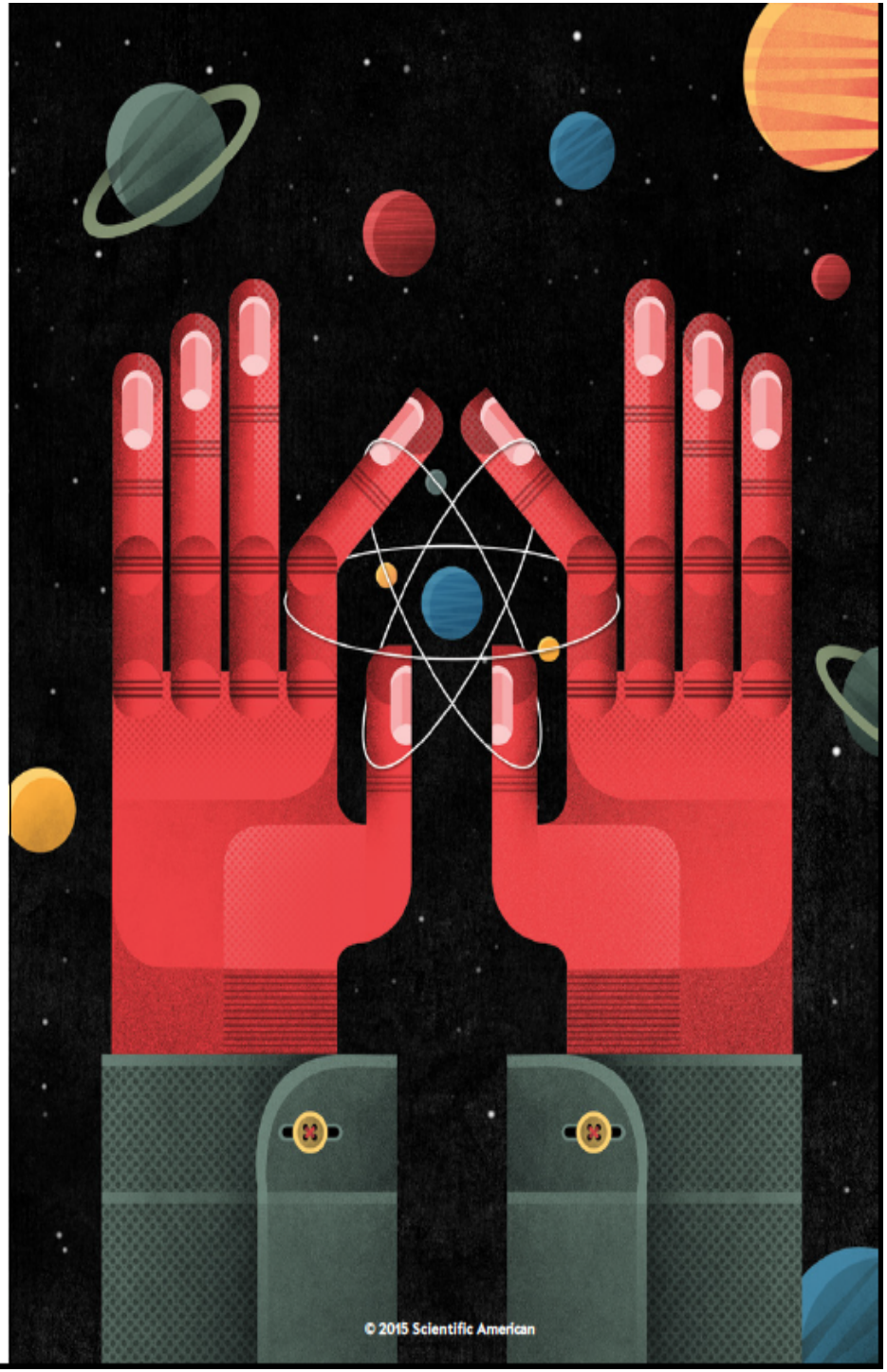
Illustration by Marta Cerar



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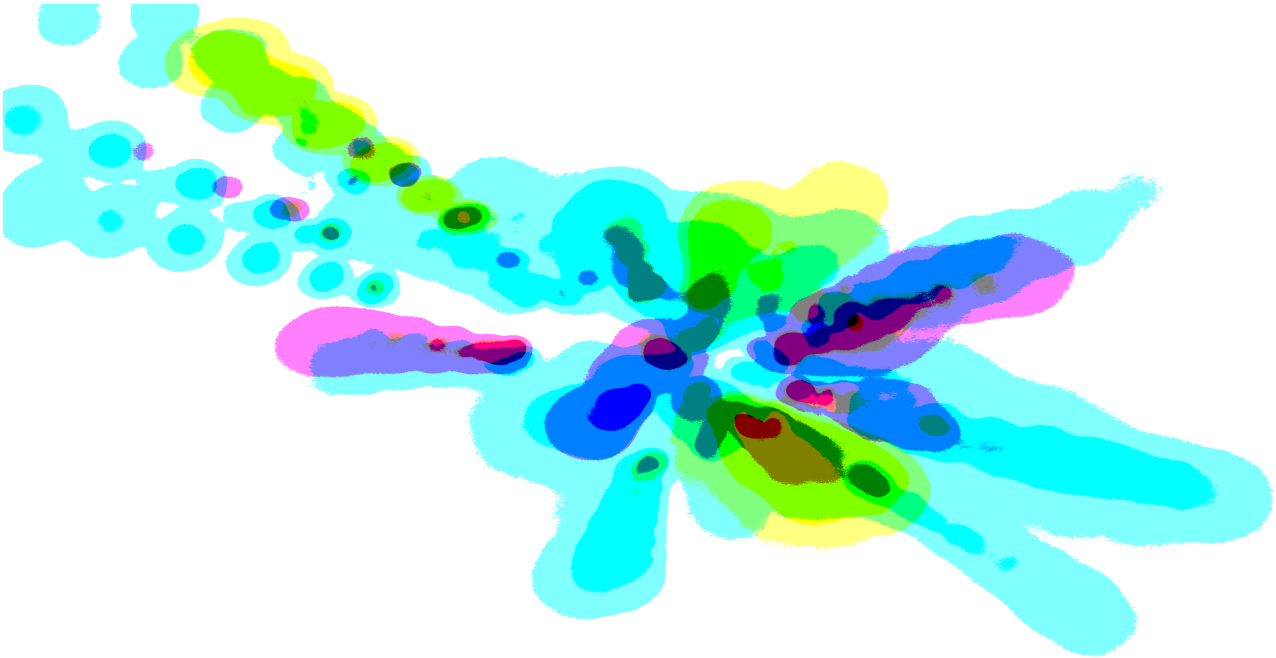
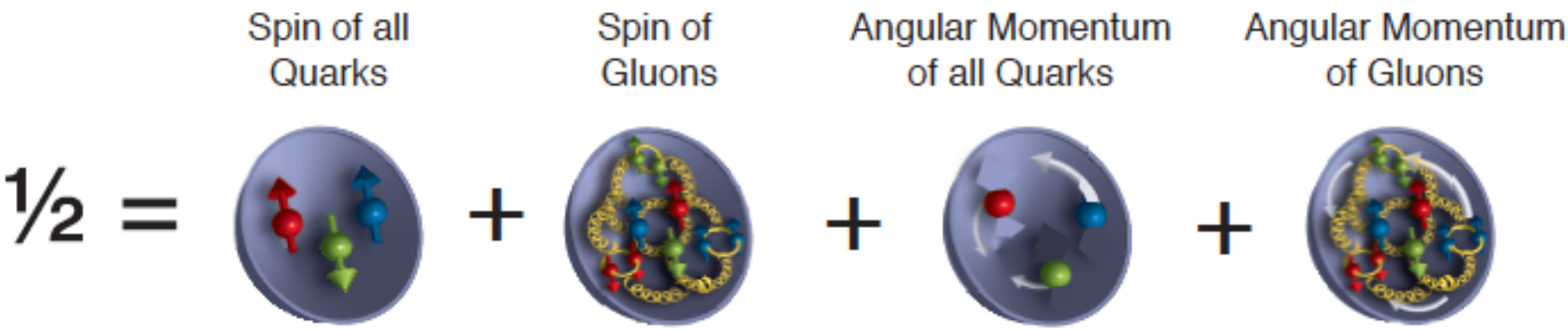
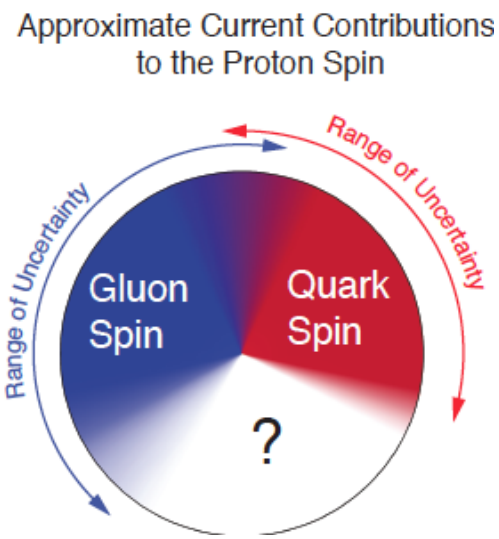
EIC whitepaper: science highlights



The proton's spin puzzle

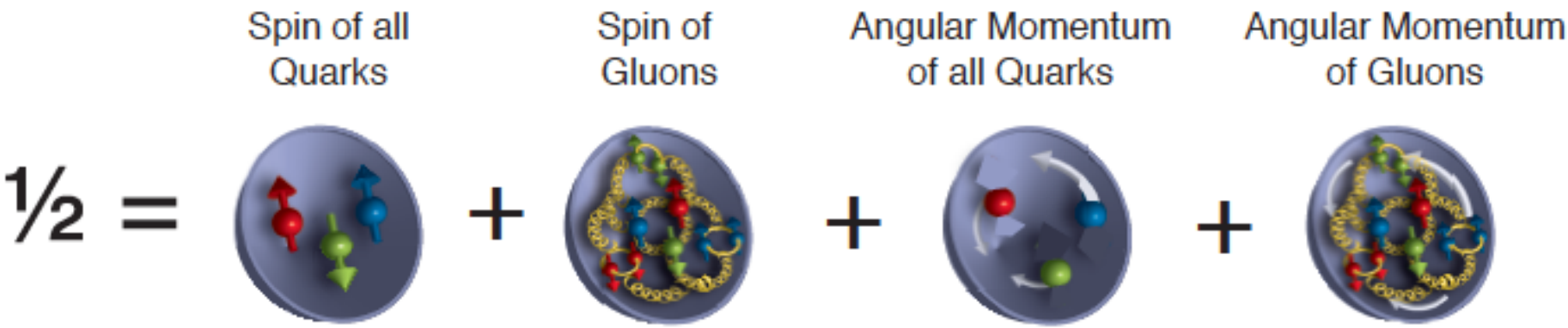


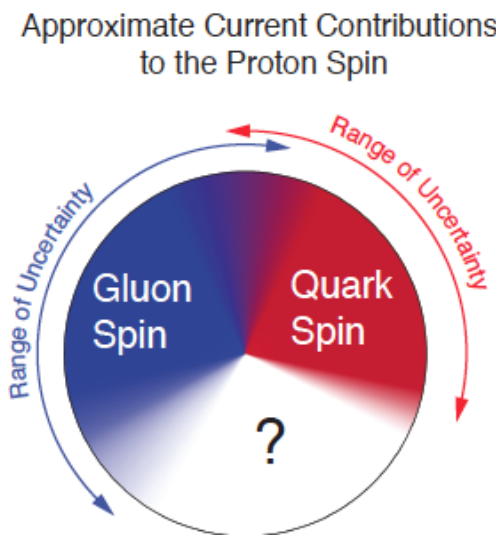


Fixed target deep inelastic scattering experiments showed that quarks carry only about 30% of the proton's spin

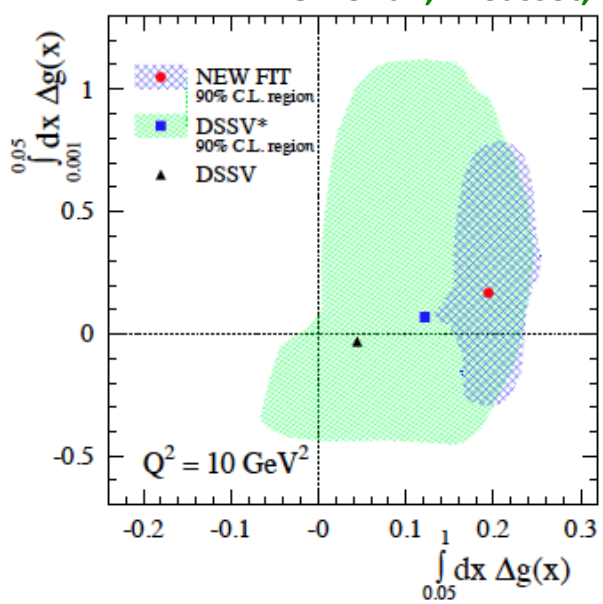
"Spin crisis" – a failure of the quark model picture of three relativistic "constituent" quarks

The proton's spin puzzle





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



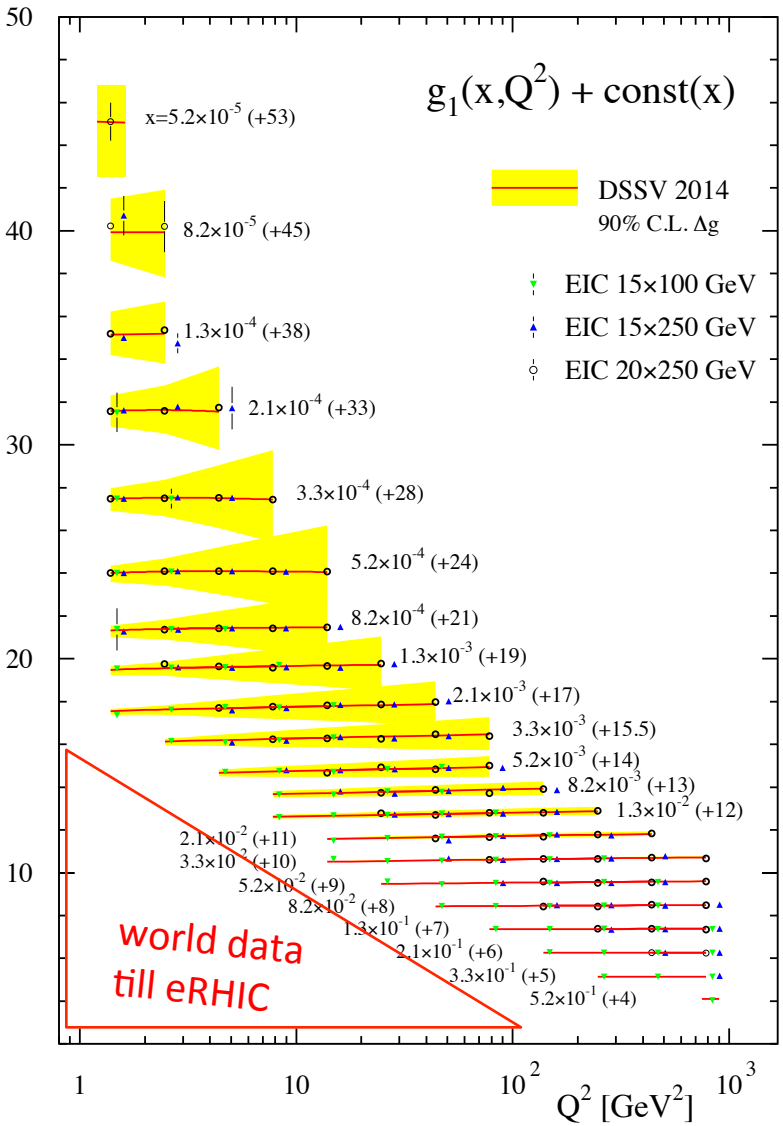
Clear evidence for gluon polarization from RHIC polarized proton-proton data

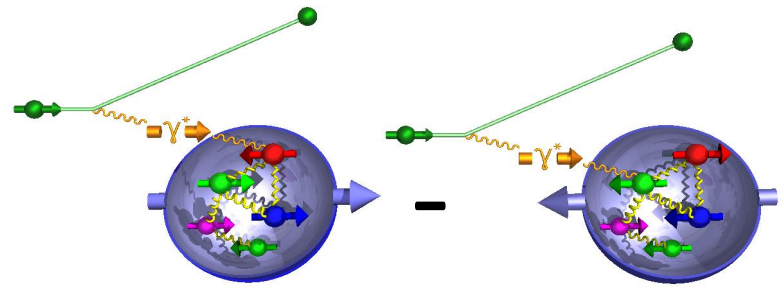
Gluons carry ~ 20-40 % of the proton spin

Where's the rest ?

See next talk by Elke

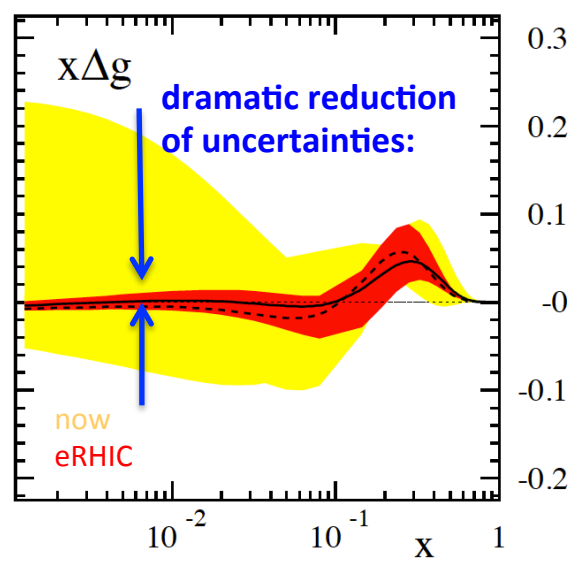
Resolving the proton's spin puzzle



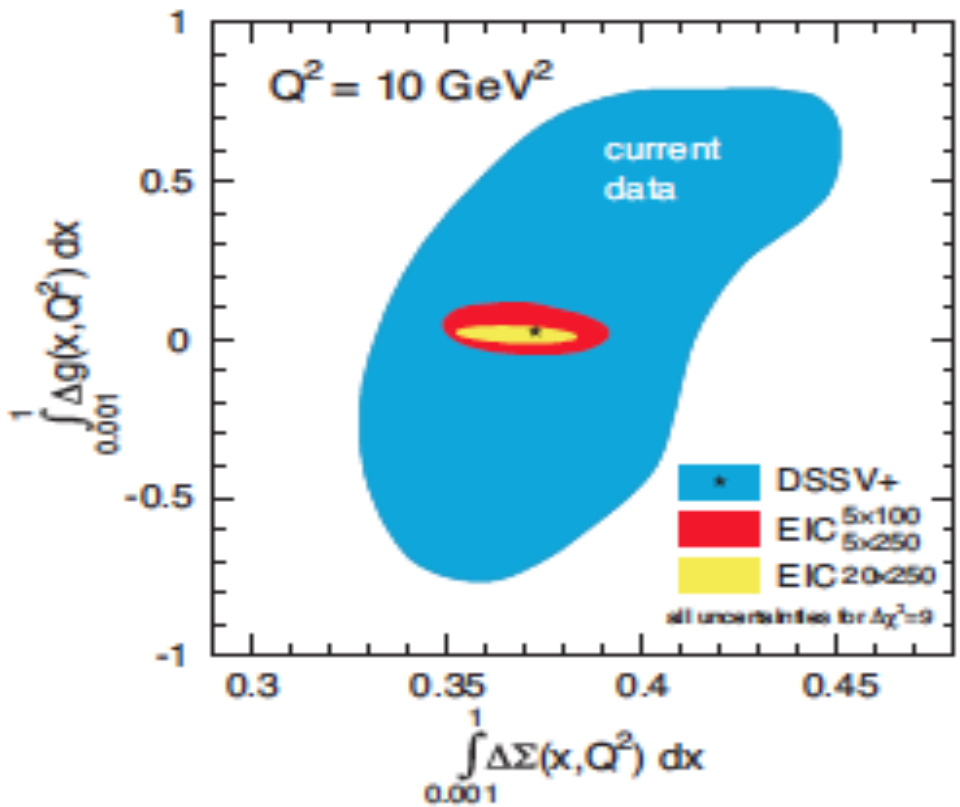


$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx \rightarrow \text{quark contr.}$$

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

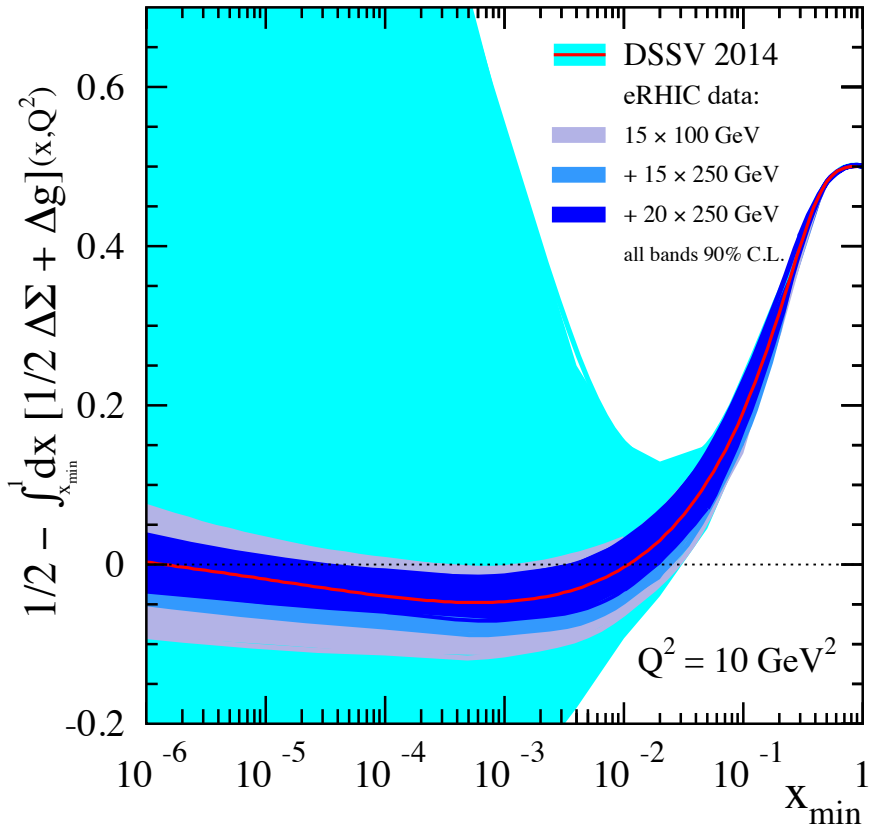


A money plot



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

A money plot



- Significantly quantify the remaining orbital contributions

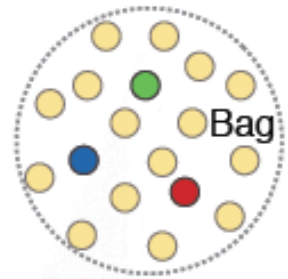
What does the proton look like ?

Static pictures

Glue dominated boosted proton

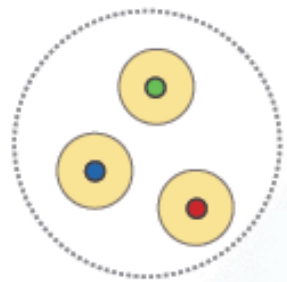
Bag model:

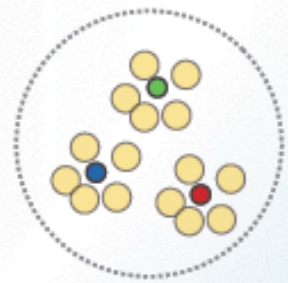
- Field energy distribution is wider than the distribution of fast moving light quarks



Constituent quark model:

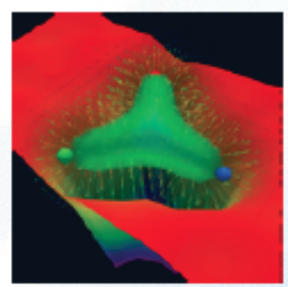
- Gluons and sea quarks "hide" inside massive quarks
- Sea parton distribution similar to valence quark distribution

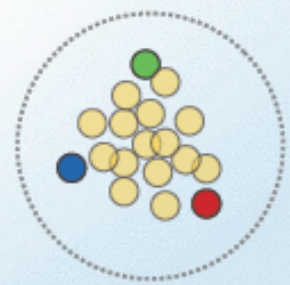




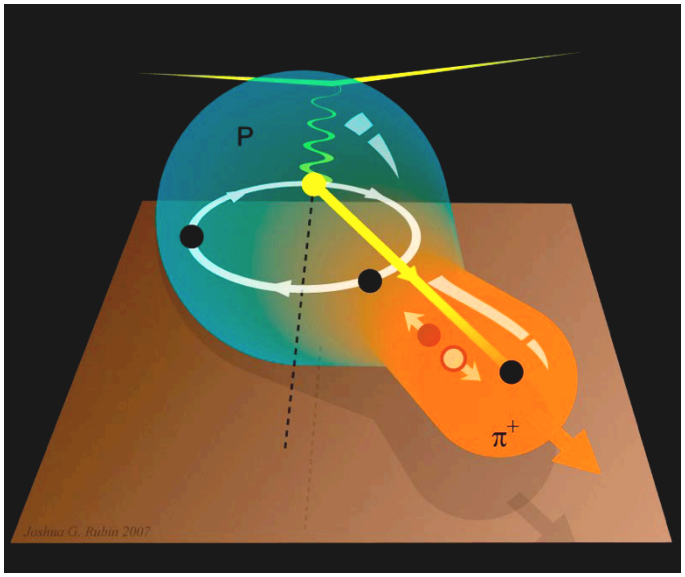
Lattice gauge theory:

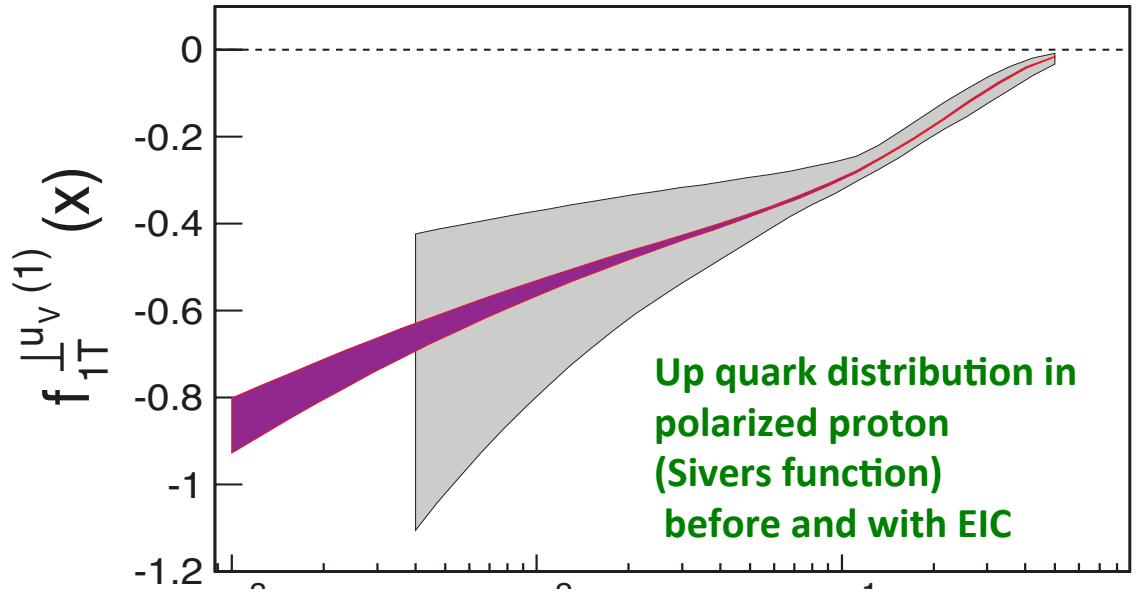
- (with slow moving quarks)
- gluons are more concentrated than quarks

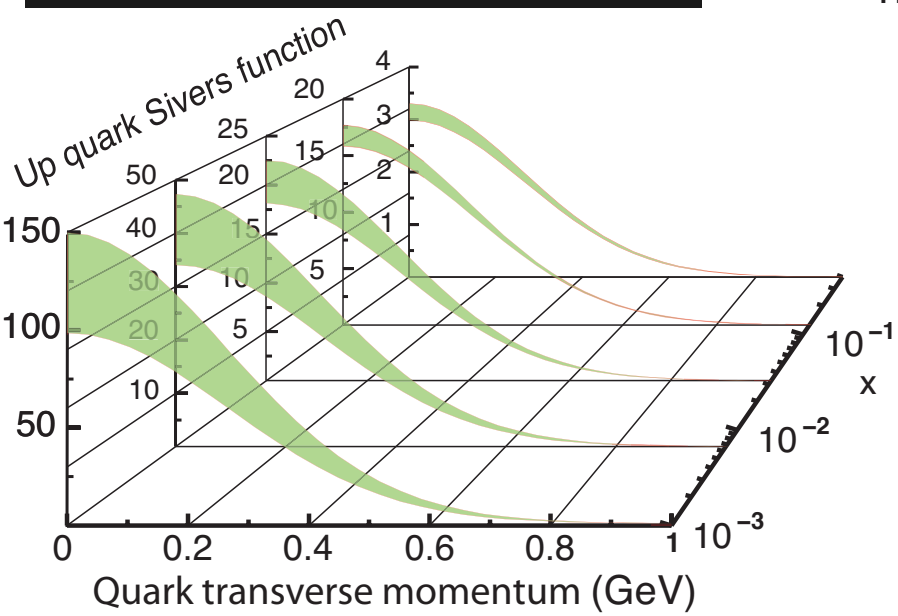


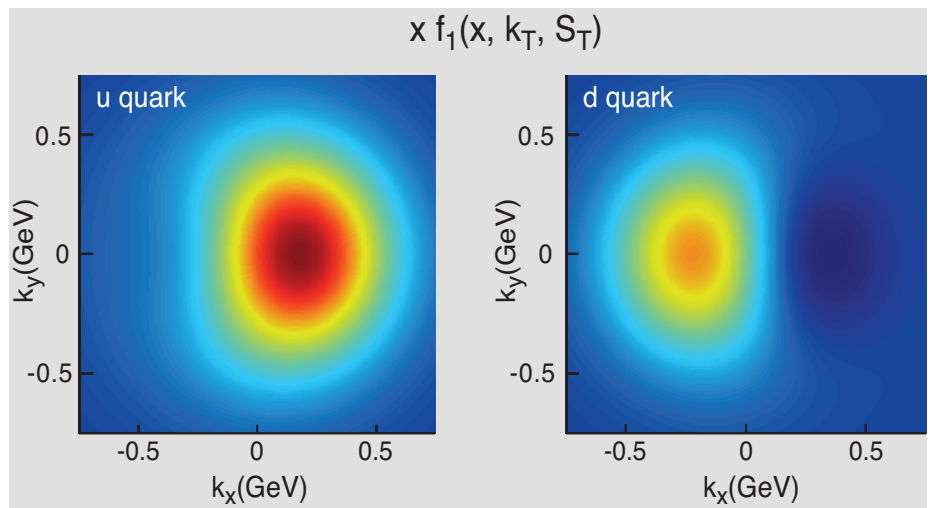


Quark and gluon tomography: 3-D momentum imaging in semi-inclusive reactions

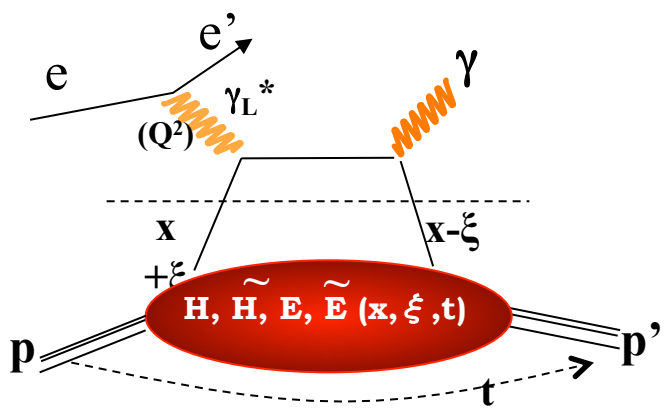


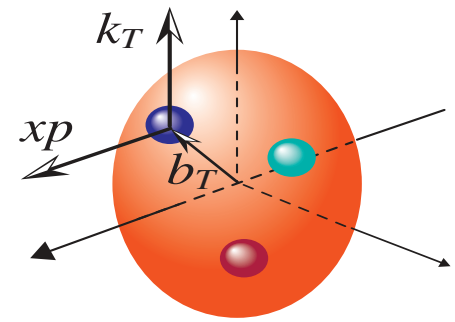


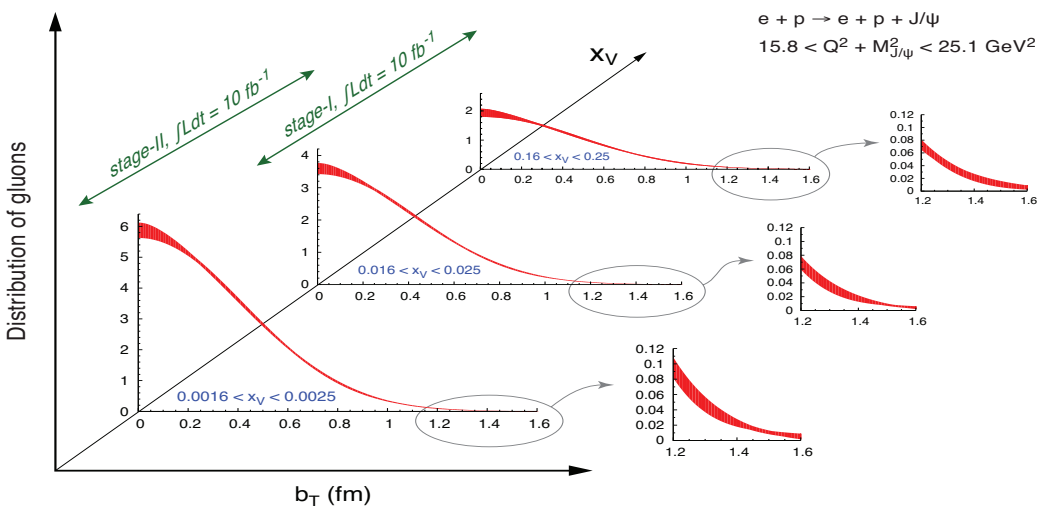


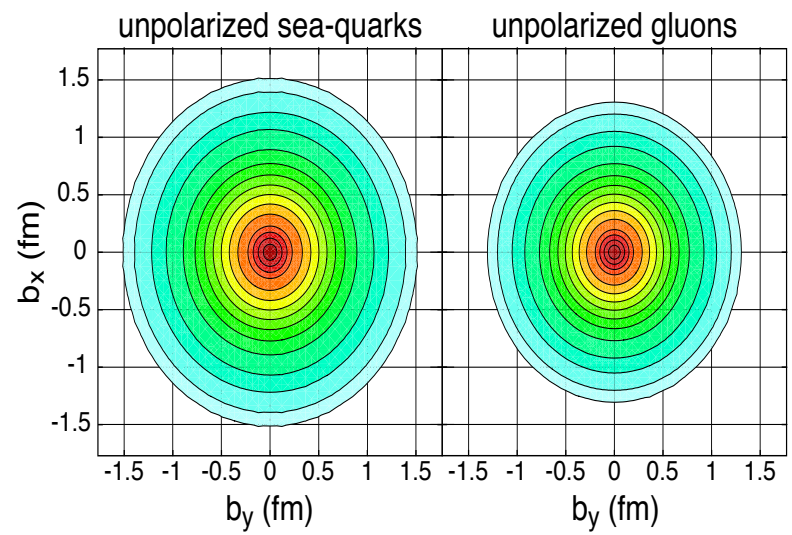


Quark and gluon tomography: 3-D spatial imaging in exclusive reactions



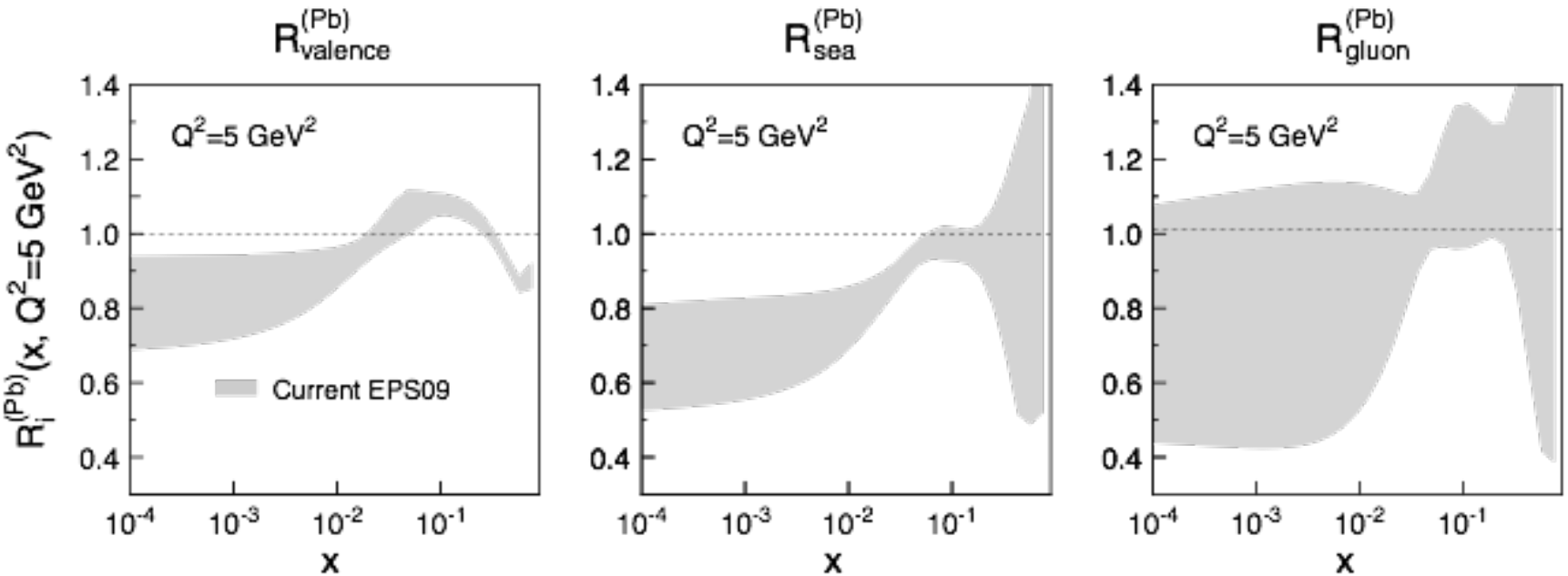






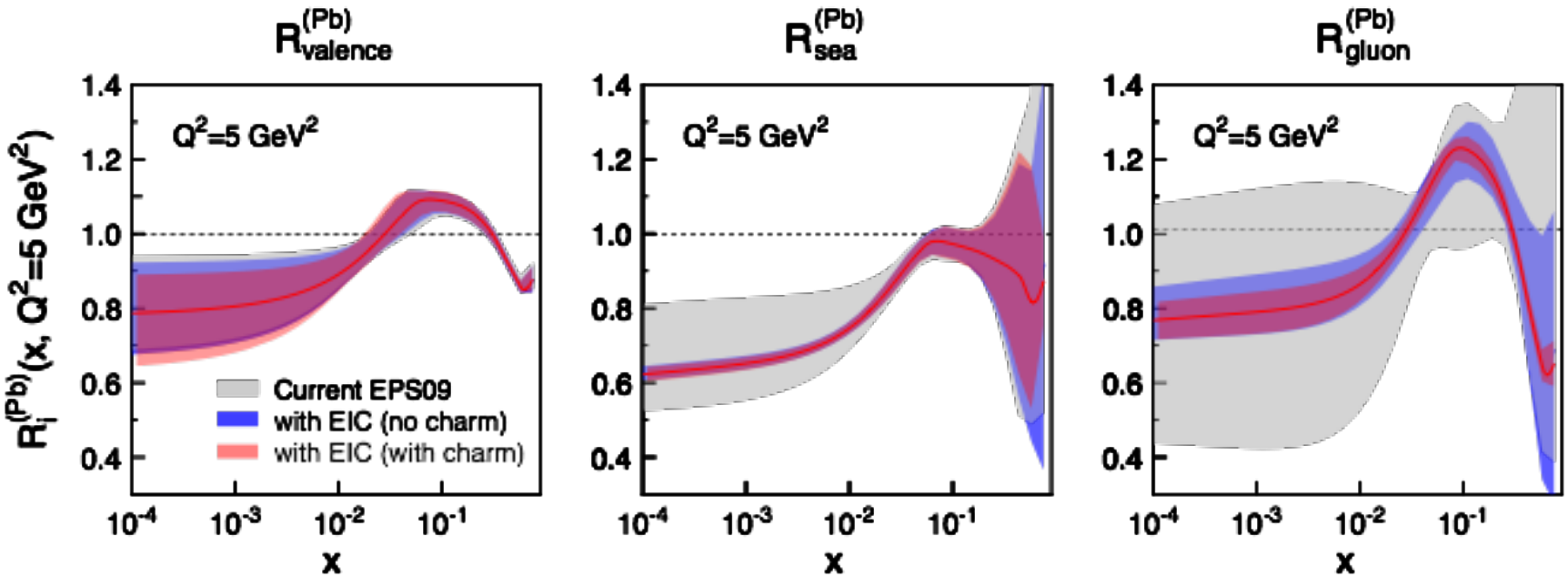
- **Such differential images correlating the spin, momentum and spatial distributions will provide fundamental insight into how quark-gluon dynamics generates the structure of the nucleon**

Entering terra-incognita in nuclei



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

Entering terra-incognita in nuclei

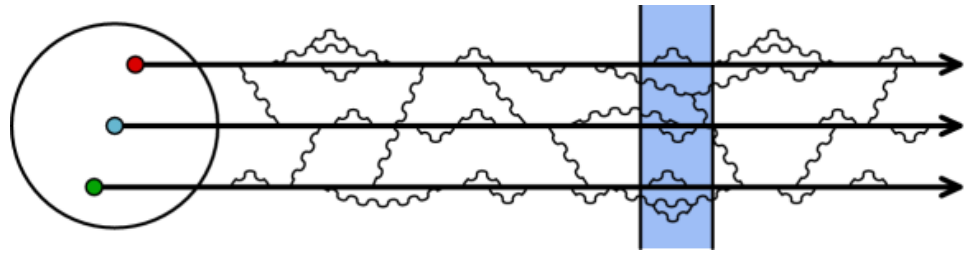


- Dramatic improvement in precision extraction of nuclear gluons and sea quarks

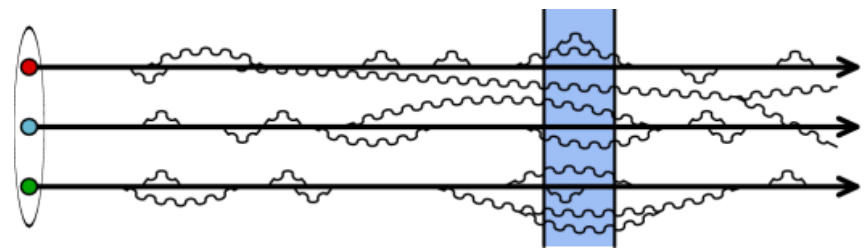
The proton's quantum foam & the stability of matter

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

Low Energy
"constituent picture"



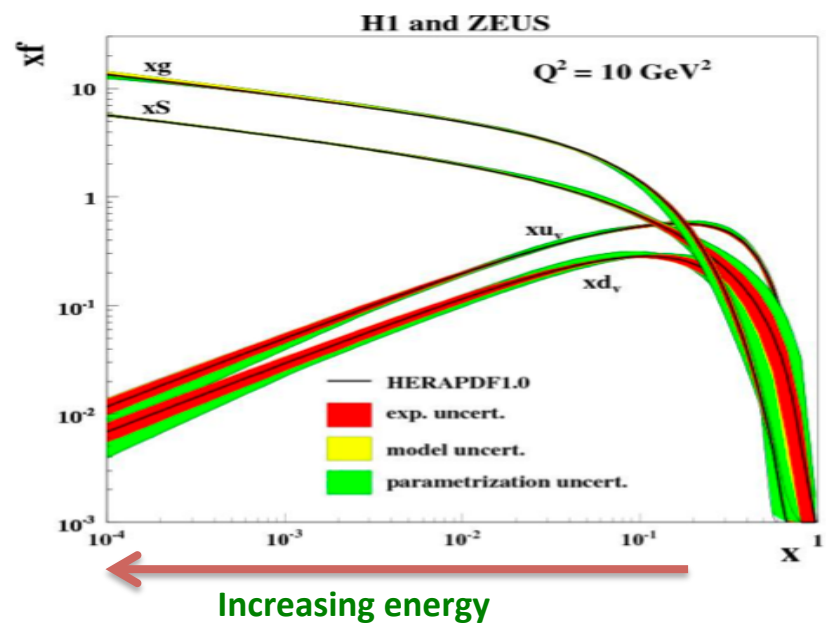
High Energy
"parton model picture"



Wee parton fluctuations (quantum foam) 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 ?

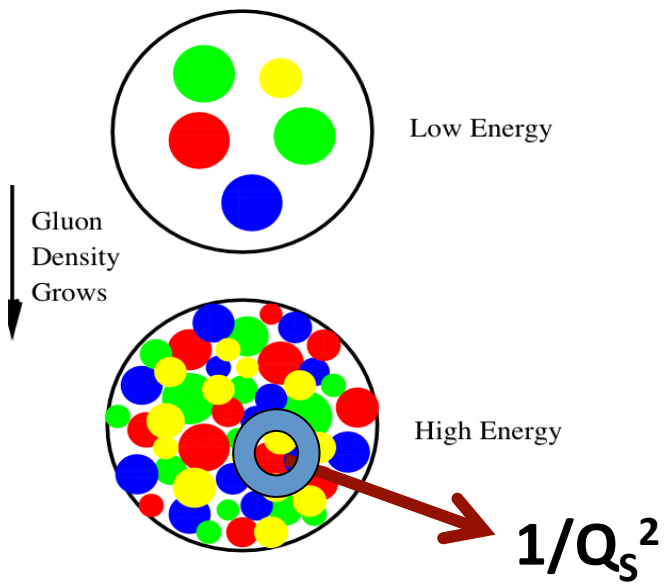


The runaway proton ?

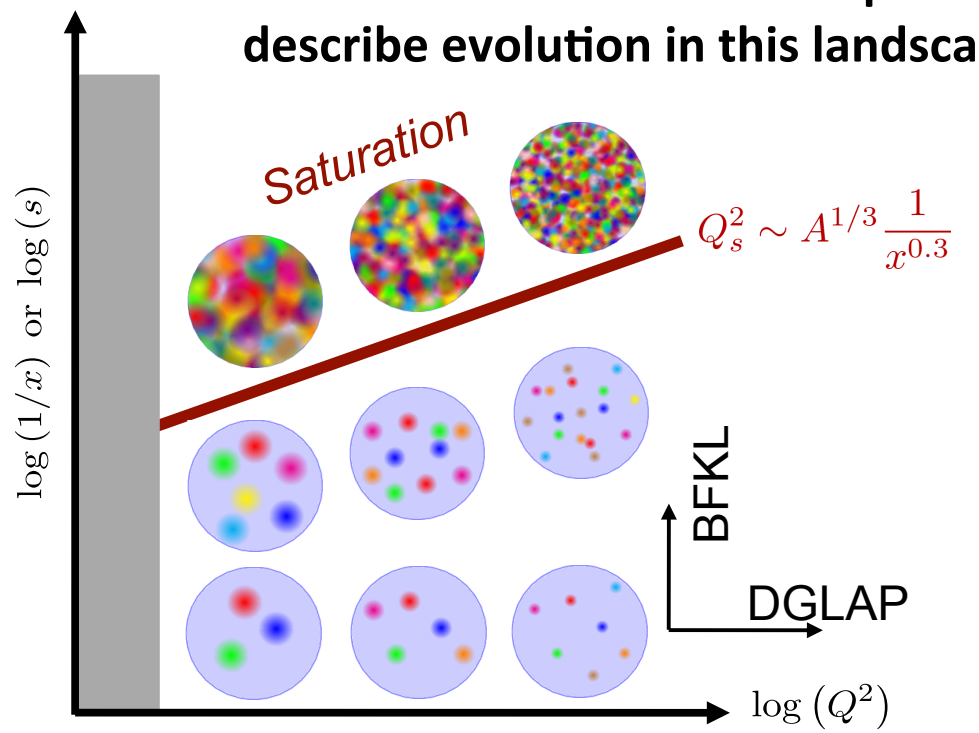
Matter is stable: how does nature keep the lid from blowing off?

Boosted protons: classical coherence from quantum fluctuations

Emergent dynamical saturation scale grows with energy



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

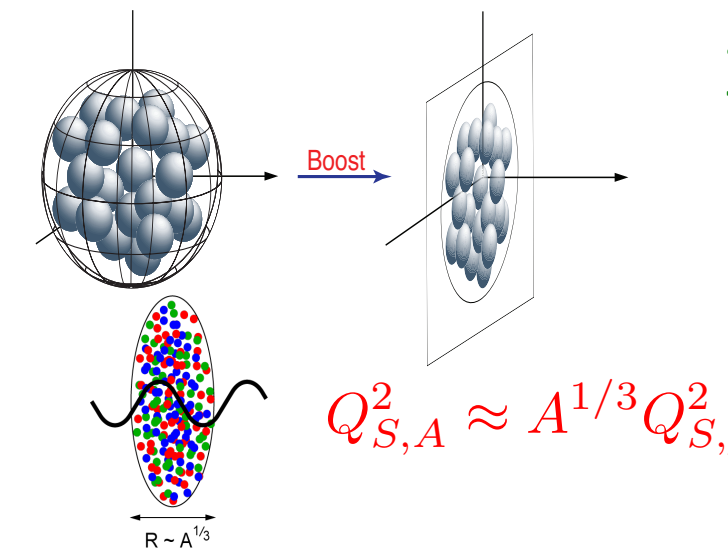


- **How does this happen? What are the right degrees of freedom?**
- **How do correlation functions of these evolve?**
- **Is there a universal fixed point for RG evolution? Does the coupling run with Q_s^2 ?**
- **How does saturation transition to chiral symmetry breaking and confinement?**

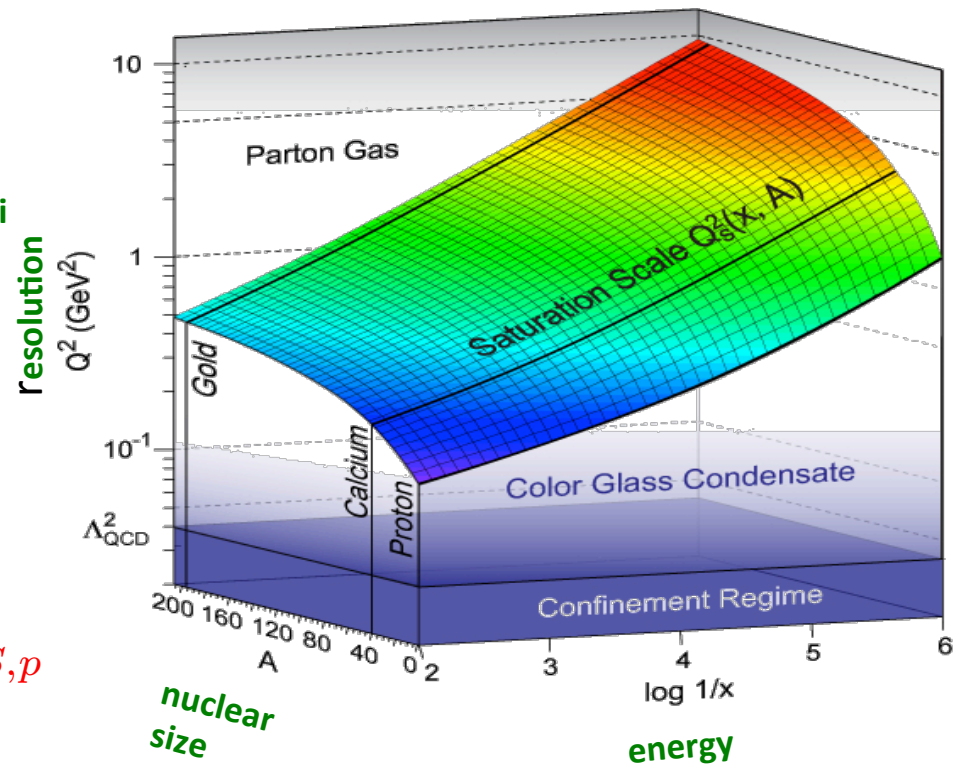
Boosted protons: classical coherence from quantum fluctuations

Emergent dynamical saturation scale grows with nuclear size

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



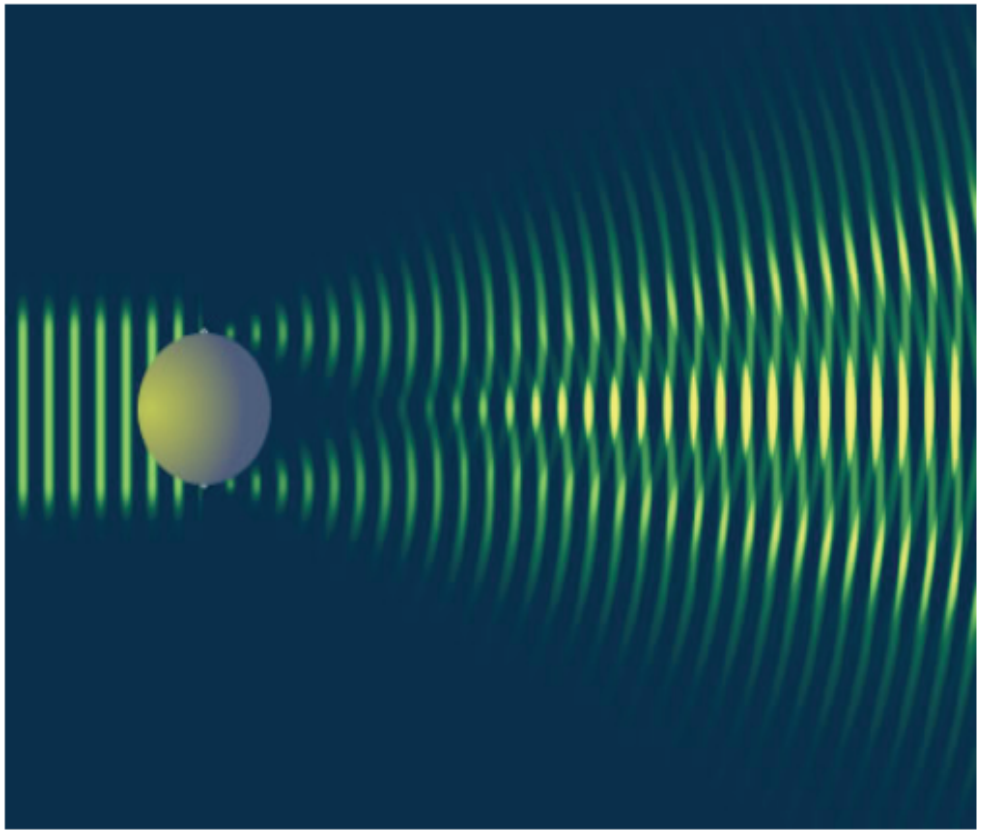
$$Q^2_{S,A} \approx A^{1/3} Q^2_{S,p}$$

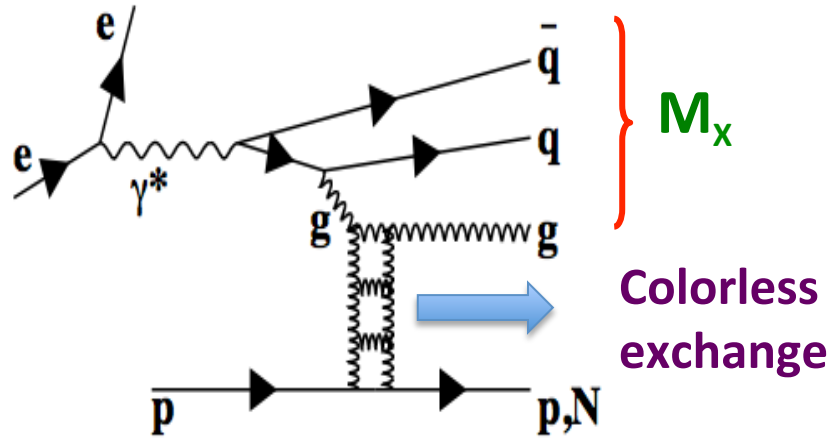


Dynamically generated semi-hard "saturation scale" opens window for systematic weak coupling study of non-perturbative dynamics

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

Diffraction for the 21st Century



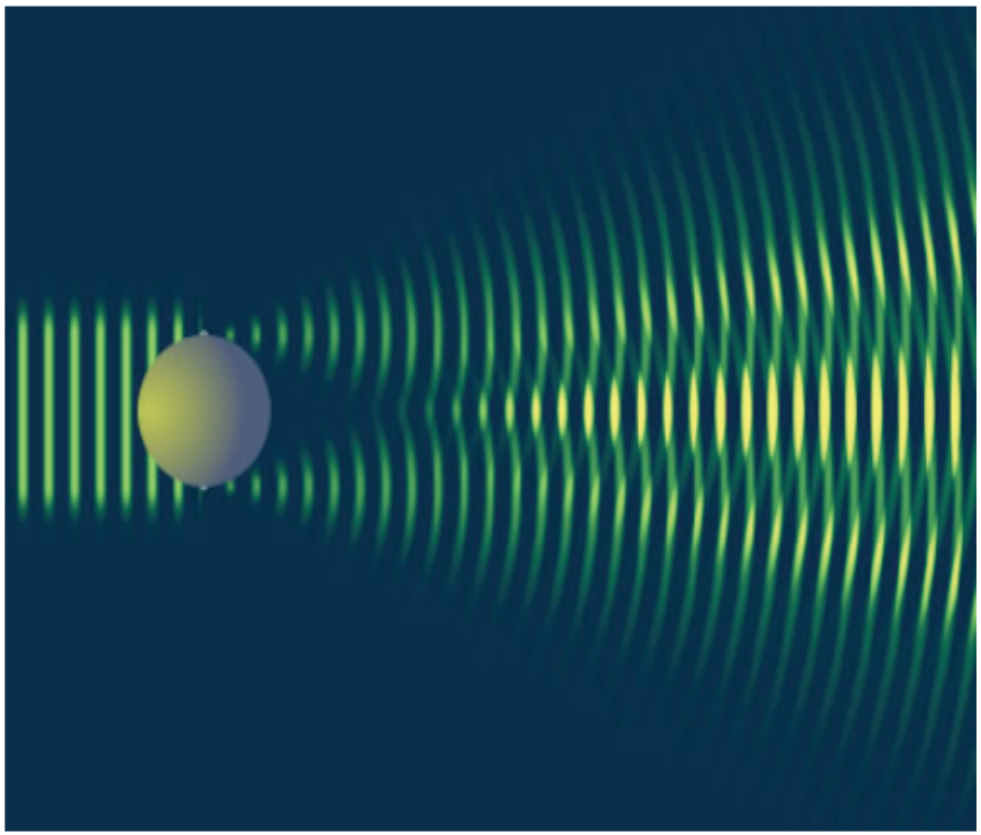


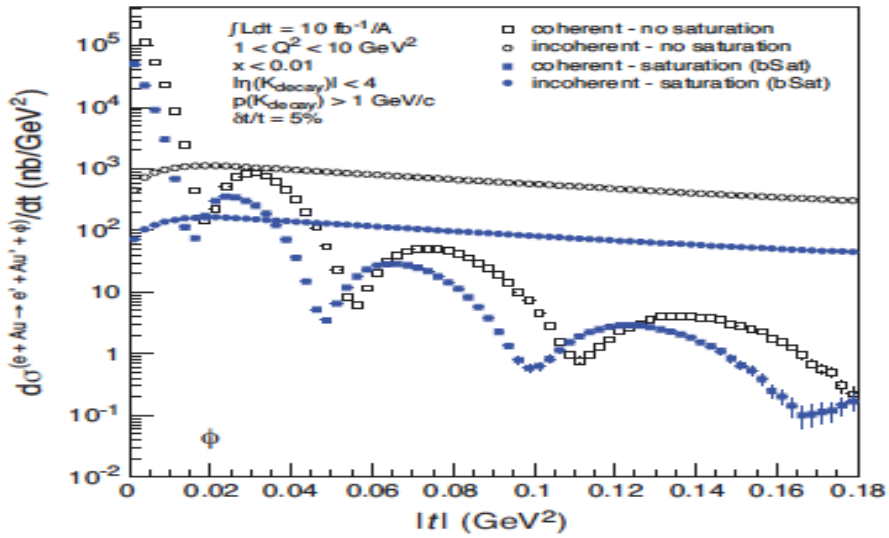
$$|e^-\rangle = |e_B\rangle + |e_B\,\gamma^*\rangle + |e_B\,\gamma^*\,q\bar{q}\rangle + |e_B\,\gamma^*\,q\bar{q}\,g\rangle + \cdots$$

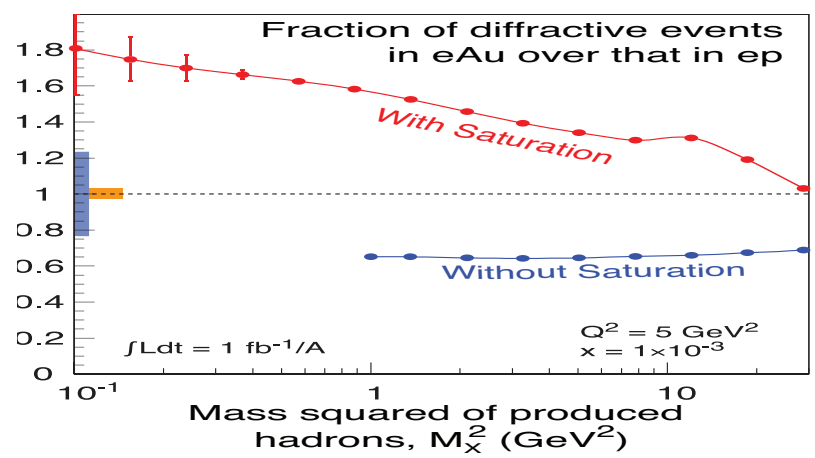
A TeV electron hits a nucleus (binding energy of 8 MeV/nucleon)

- **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)

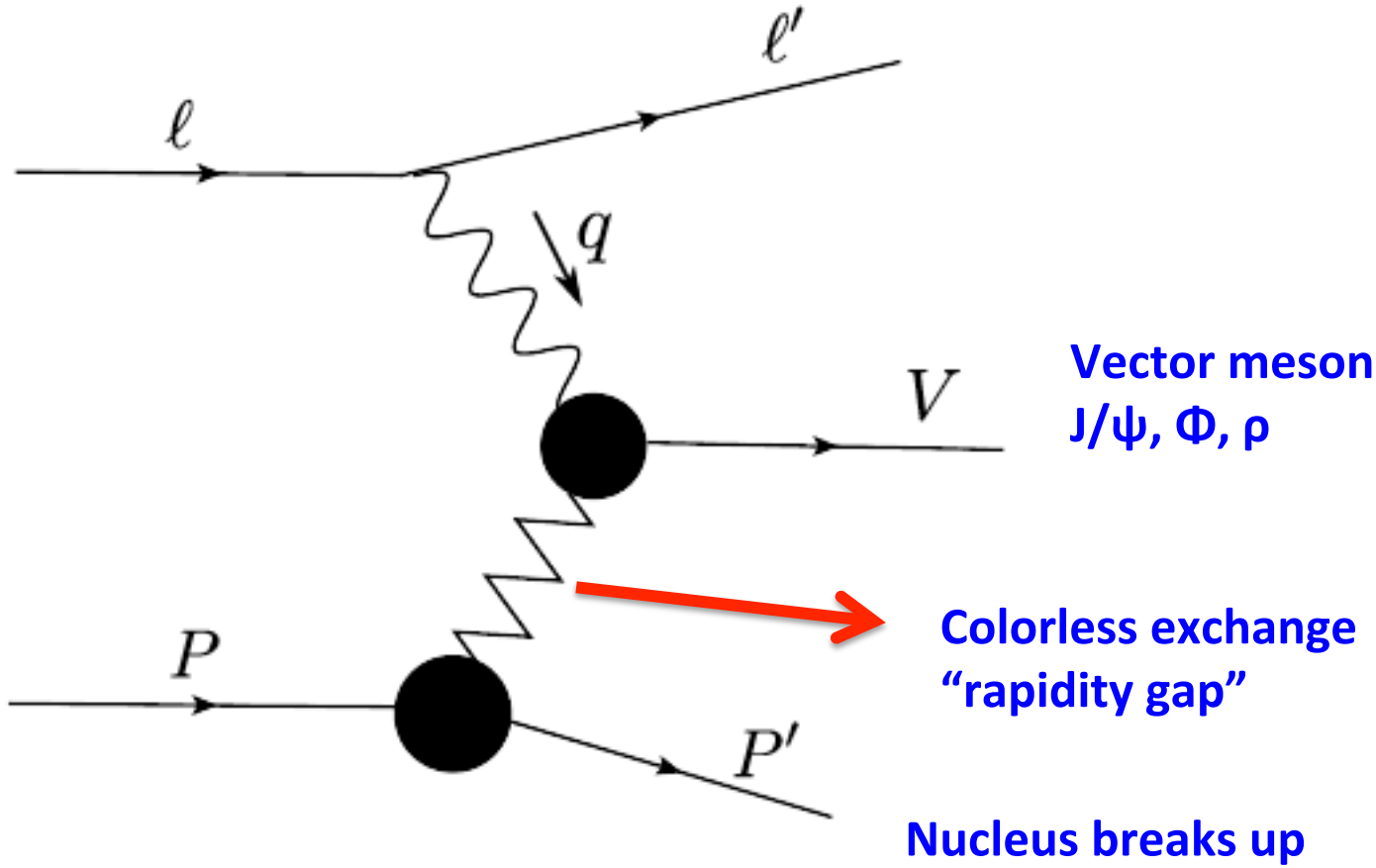
- **Day 1: prediction: nucleus remains intact in at least 1 in 5 events**

EIC whitepaper
New opportunities

Probing rare glue fluctuations with ballistic protons

Lappi,Mantysaari,RV: PRL 114 (2015) 8, 082301

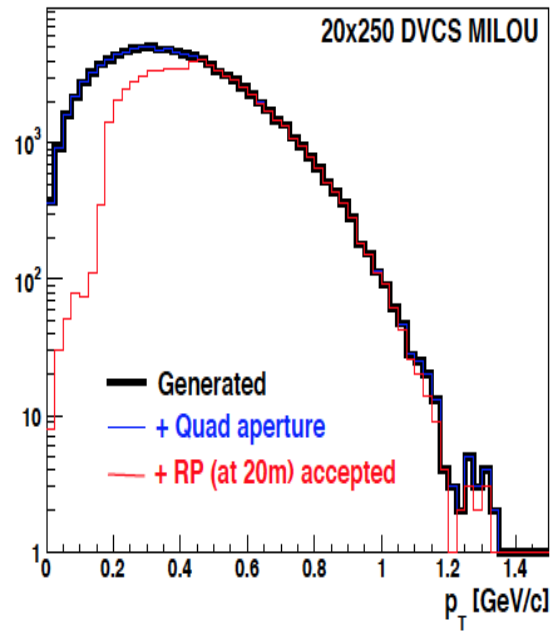
Incoherent diffraction (nucleus breaks up but no color is exchanged)
- directly sensitive to gluon field fluctuations



Probing rare glue fluctuations with ballistic protons

Lappi,Mantysaari,RV: PRL 114 (2015) 8, 082301

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



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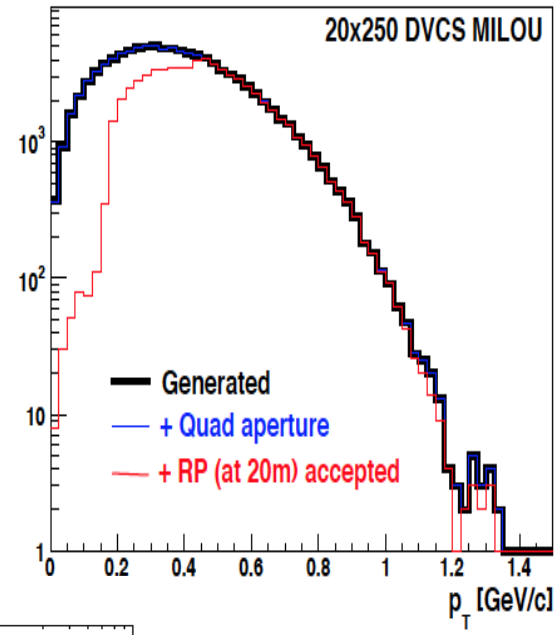
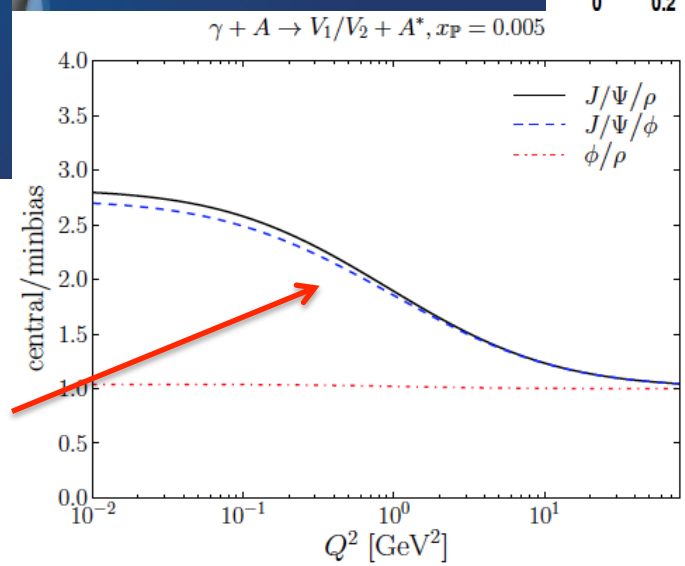
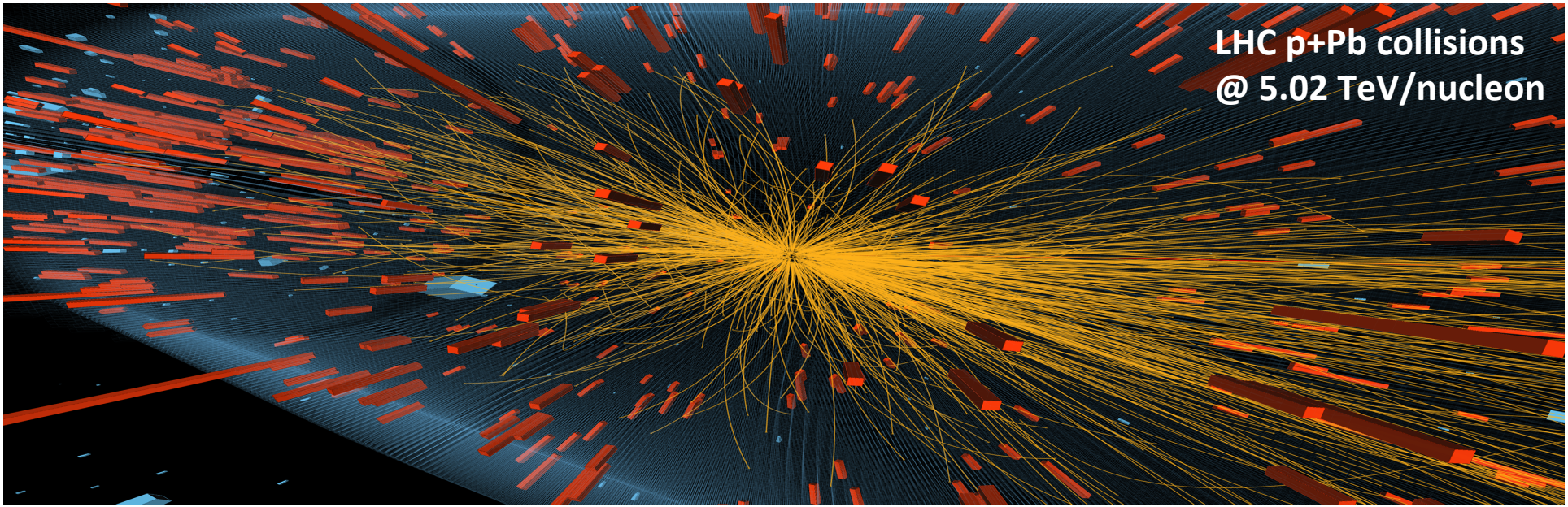




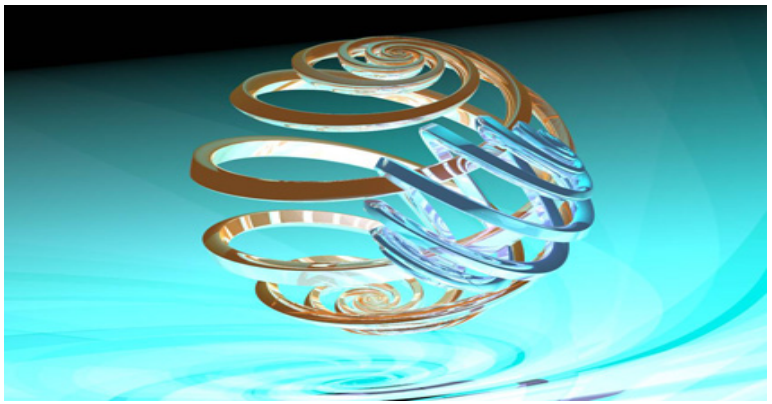
Central/min.bias double ratios very sensitive probe of fluctuations of strong gluon fields

Collectivity in small systems



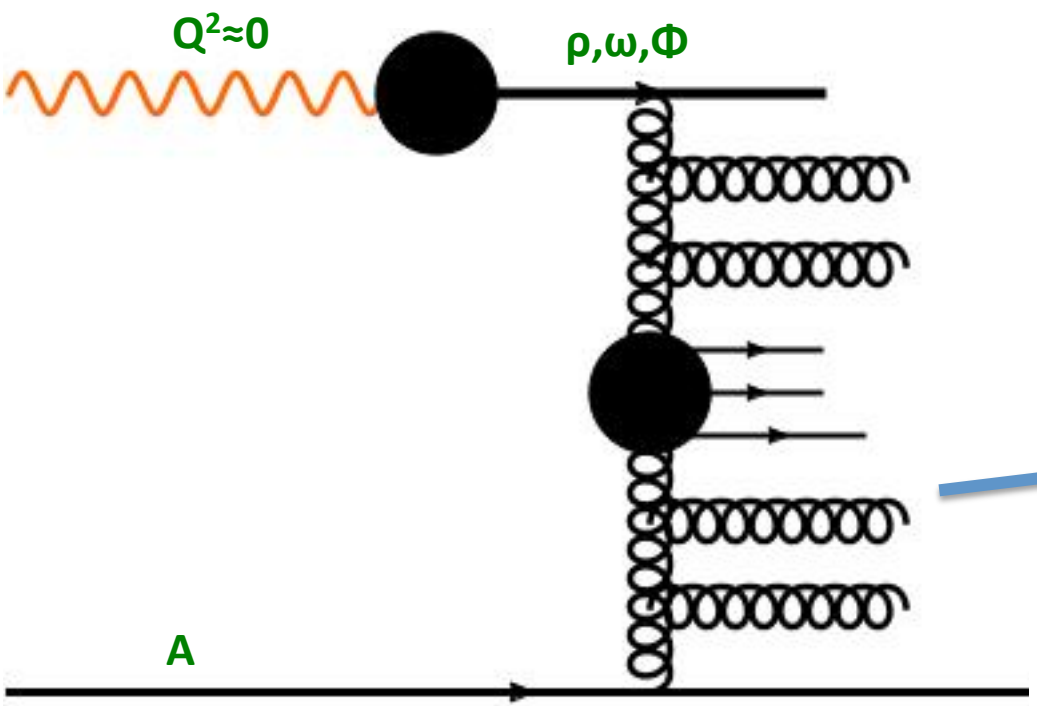
Is the matter created…

…the world's smallest droplet?



…or a novel form of gluon entanglement?

The p+A limit of e+A



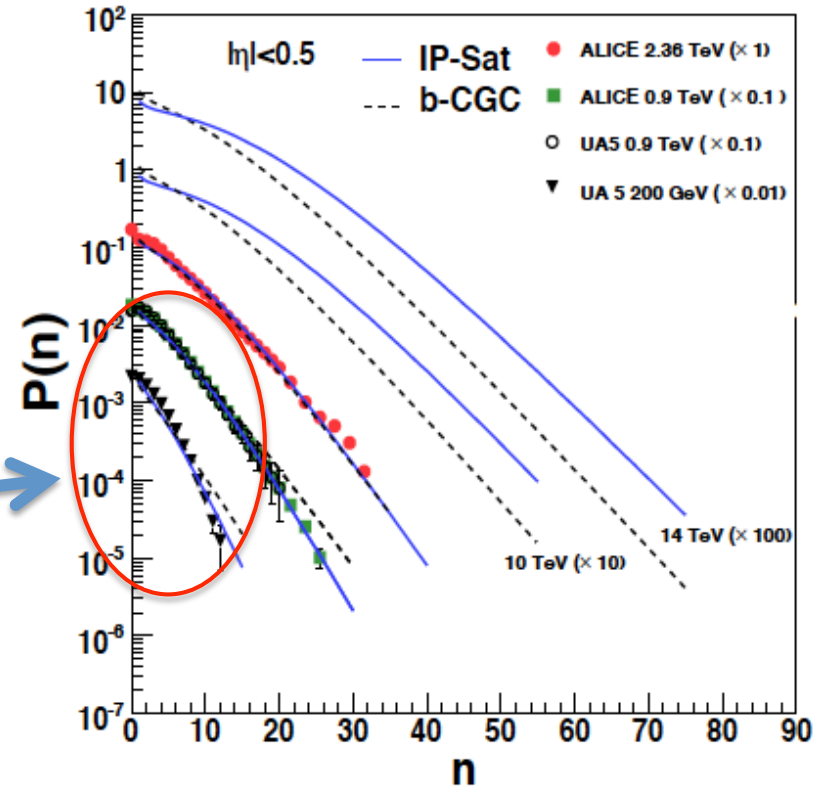
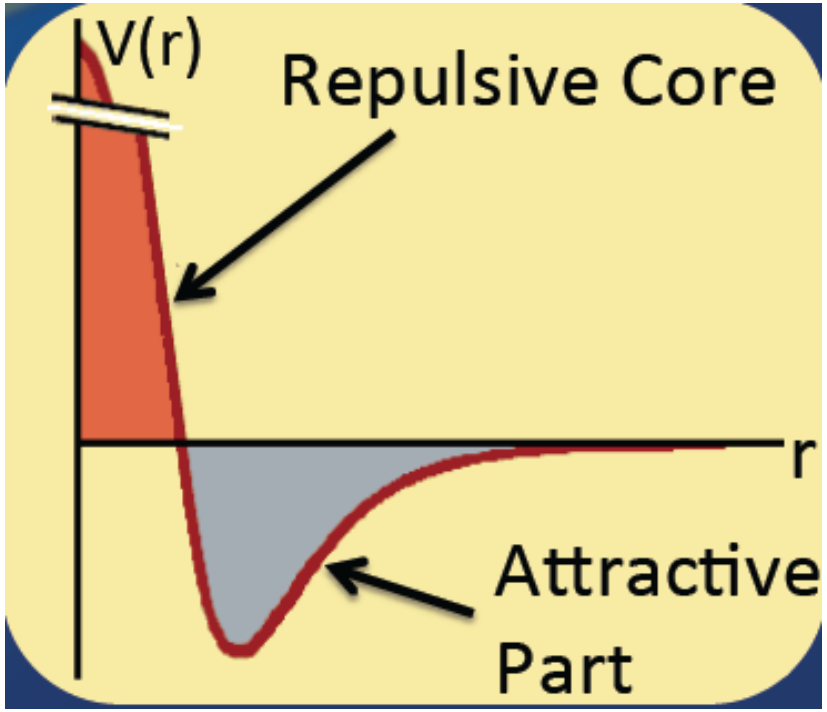
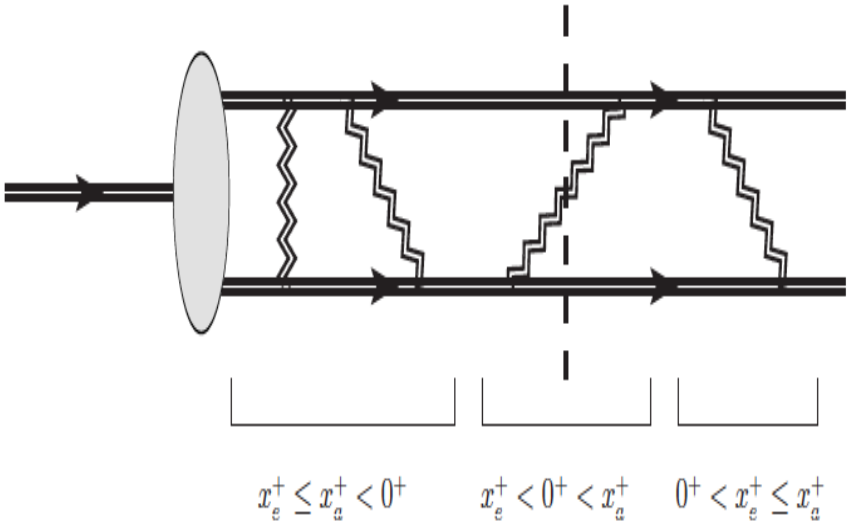


Photo-production in e+A is like p+A collisions – can perform all p+A-like correlation measurements in very rare e+A collisions – can one see the "ridge" in such events ?

Dial up Q^2 to see how these effects go away…

Short-range nucleon-nucleon interactions with EIC

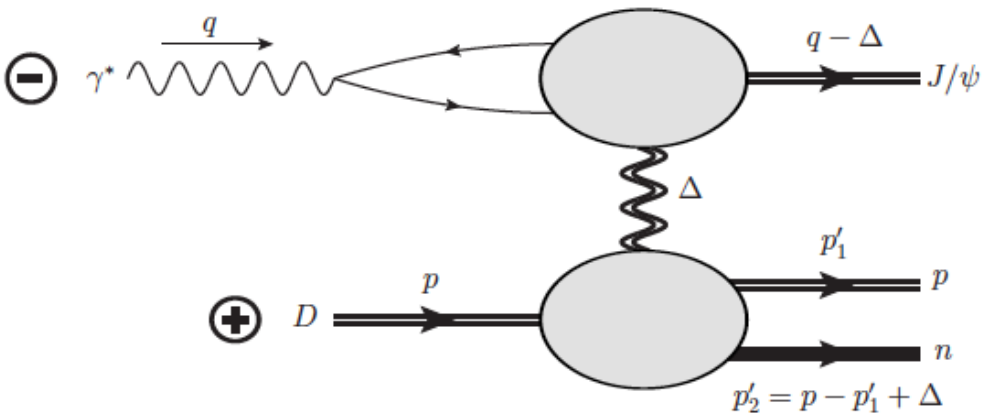


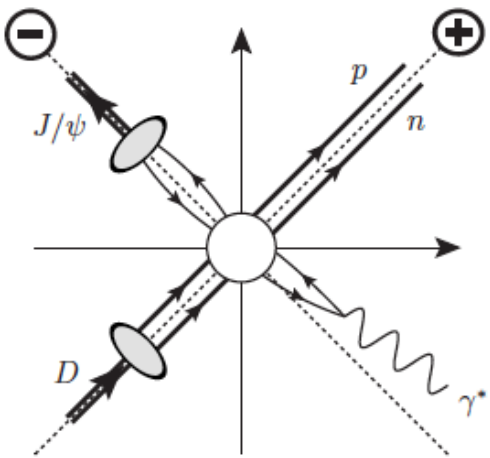


Can EIC provide insight into the short-range gluon contribution to the nucleon-nucleon potential ?

Short-range nucleon-nucleon interactions with EIC

Miller,Sievert,RV, in preparation





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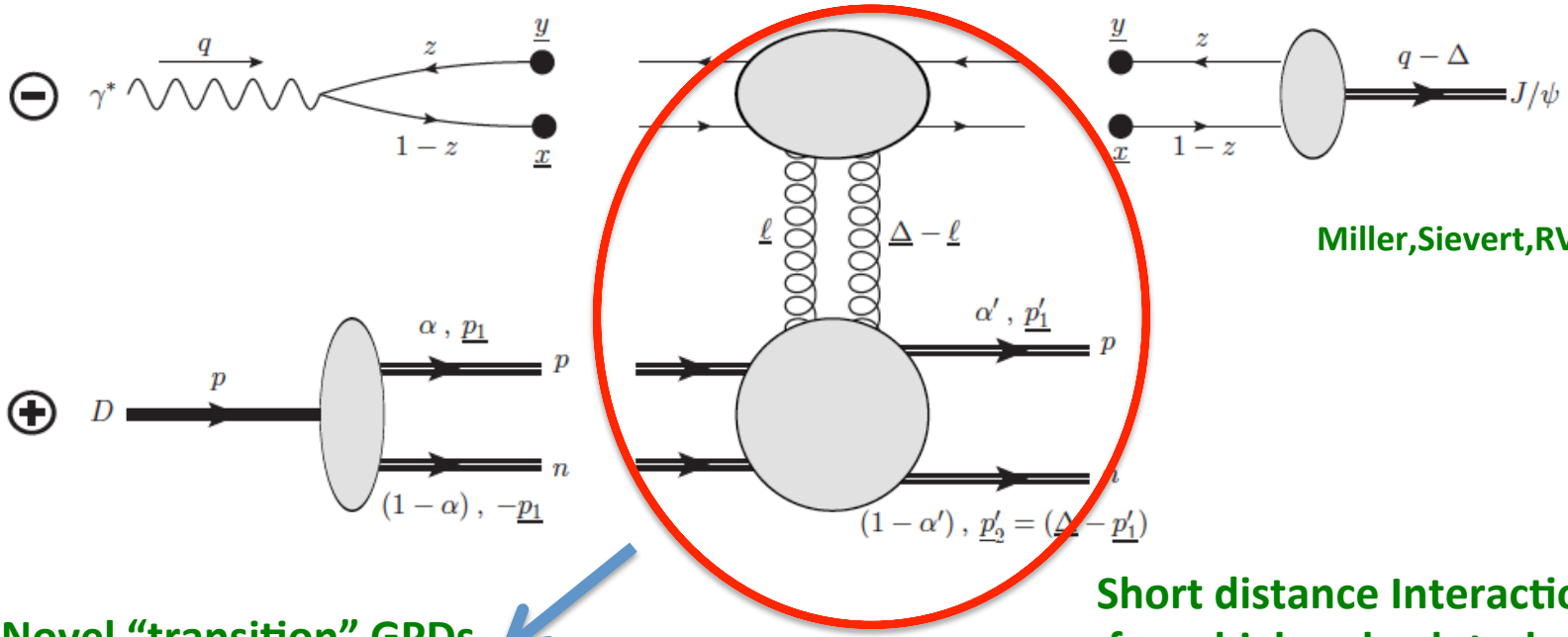
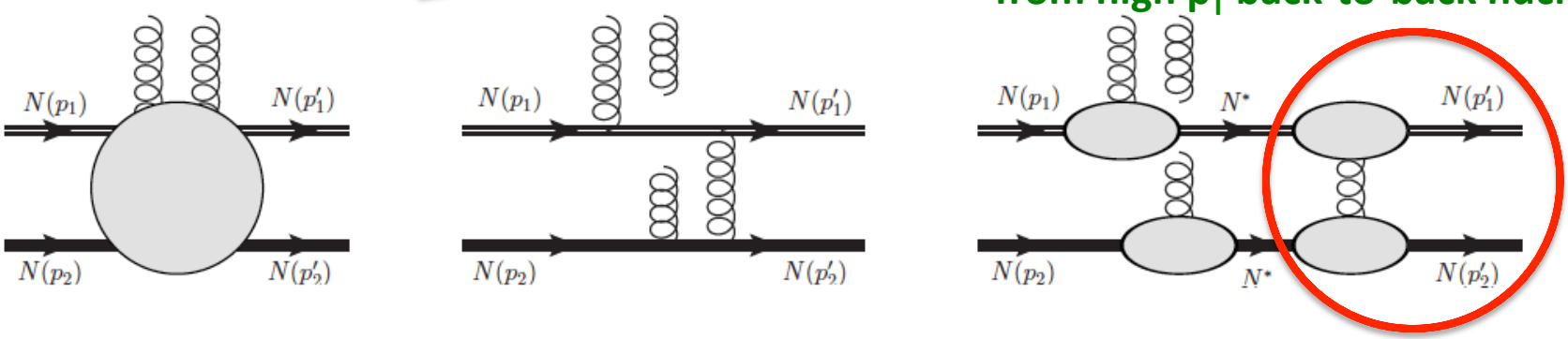


Miller,Sievert,RV,in preparation

Novel "transition" GPDs

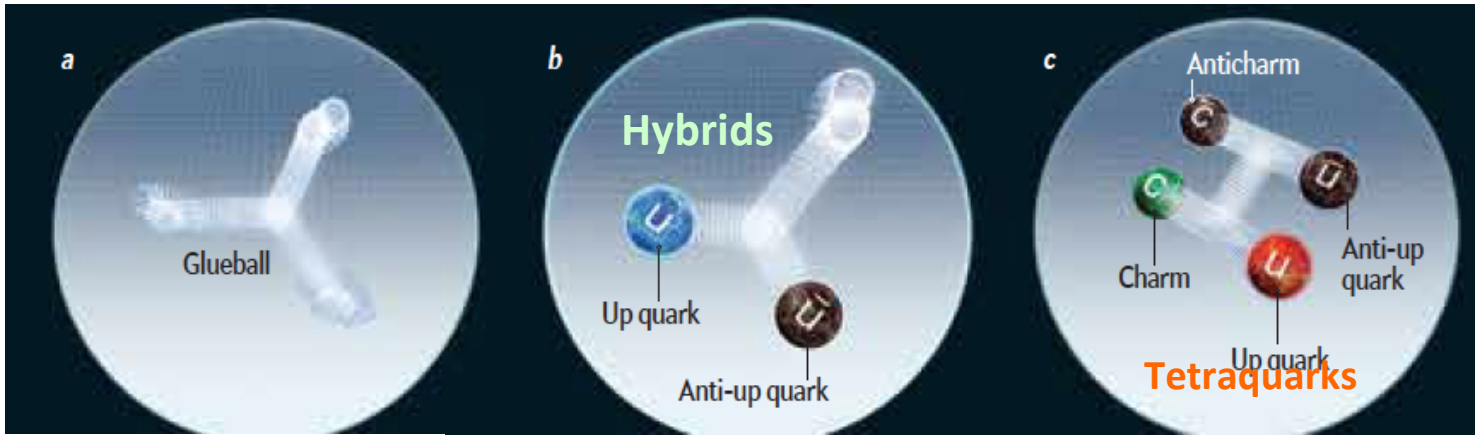
Short distance Interactions
from high p_T back-to-back nucleons

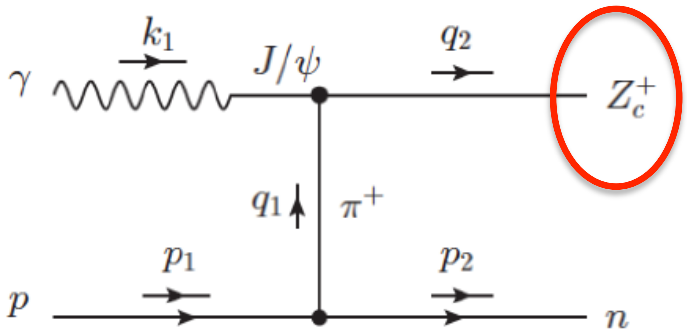


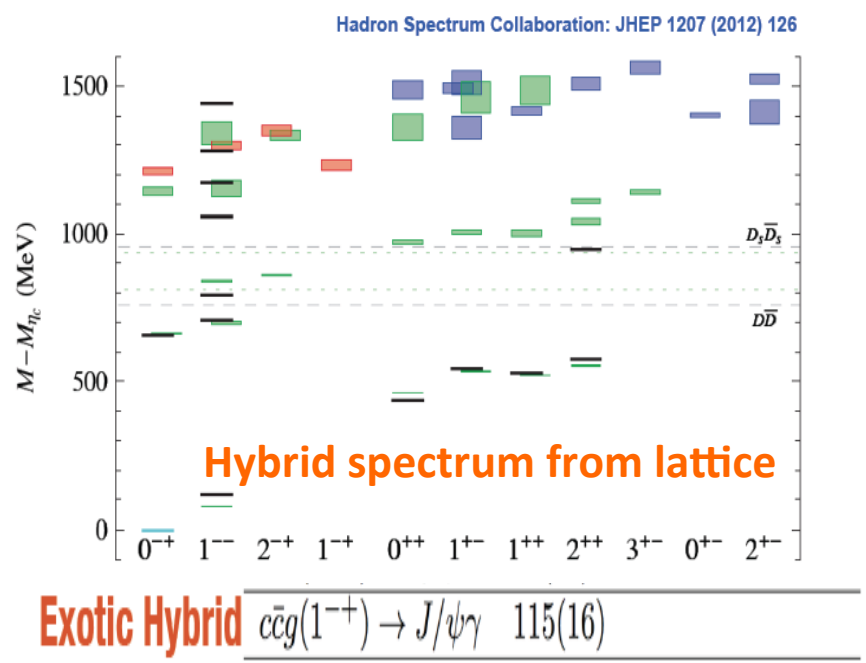
Preliminary estimate of rates suggest that these measurements are very feasible at EIC with p_T ~ several GeV range

Hadron spectroscopy at EIC

Exotic hadrons







Heavy quark tetra-quark and hybrid states are accessible in photoproduction

Preliminary studies for EIC (Justin Stevens at APS April meeting)

Outlook

- The EIC is the highest scientific priority of the US QCD community for new construction after FRIB

- The EIC whitepaper has demonstrated the potential of the EIC to provide definitive answers to outstanding questions regarding fundamental structure of matter

- The full range of scientific opportunities offered by such a versatile machine are only beginning to be realized…