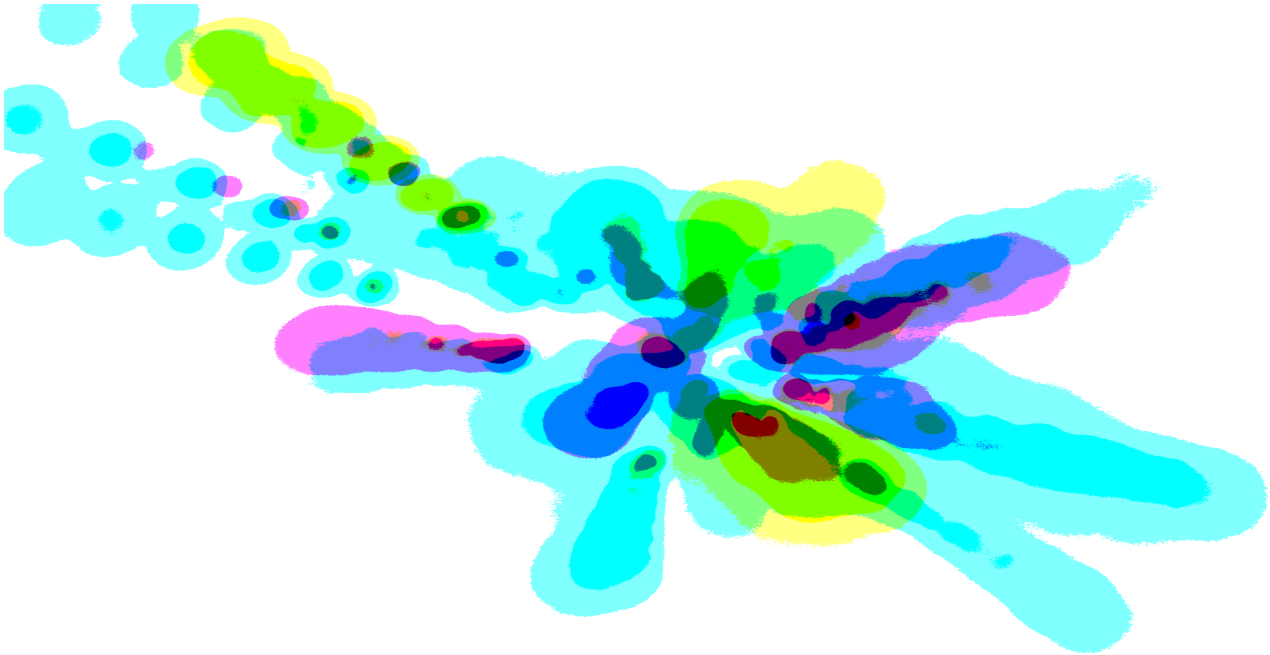
Why we need an Electron-Ion Collider



Raju Venugopalan
Brookhaven National Laboratory

RHIC future strategy, AGS users meeting, June 21-22, 2011

Preamble

- ✧ **What it is: a personal viewpoint**

- ✧ **What it is not: detailed discussion of final state measurements (see talks by Lamont and Sichtermann to follow)**

- ✧ **Does not contain: discussion of EW + BSM possibilities with EIC**

(active sub-group, several first studies: A. Deshpande, K. Kumar, M. Ramsey-Musolf, W. Marciano, Y. Li, M. Gonderinger, S. Taneja,…)

QCD: the "nearly" perfect theory

F. Wilczek, hep-ph/9907340

❖ Besides being a beautiful theory where nearly all phenomena are emergent, QCD also happens to explain ~ 99% of the mass of the visible universe

❖ A serious study of its many-body features is therefore of fundamental interest

❖ RHIC & LHC have blazed the trail, ushering in a new era of many-body QCD; Jet quenching, perfect fluidity, gluon saturation – unanticipated connections to other fields

❖ Nevertheless, little of concrete substance is known about the partonic structure of hadron and nuclear wavefunctions; *quantitative studies of the fundamental structure of visible matter demand precision probes*

Why we need an EIC

- **A suite of "gold" first measurements in QCD that in precision, reach and content will be unmatched by hadronic colliders.**

- **These measurements provide fundamental insight into the quark-gluon structure and dynamics of the vast bulk of visible matter in the universe**

- **Opens a novel regime of universal many-body QCD dynamics to precision study and discovery, complementing and corroborating in essential ways knowledge acquired at hadron colliders**

How is it different from HERA in collider mode ?

- **No polarization of protons at HERA**
- **No nuclear targets**
- **Limited rapidity coverage at HERA– focus was on BSM**
- **No particle ID at H1+ZEUS for "SIDIS"-flavor studies, correlations**
- **Extremely limited energy scan in last year of operation (~ 30 pb^{-1})**
- ***EIC luminosity 100-1000 that of HERA***

EIC: über femto-scope of parton structure

- World's first e+A collider

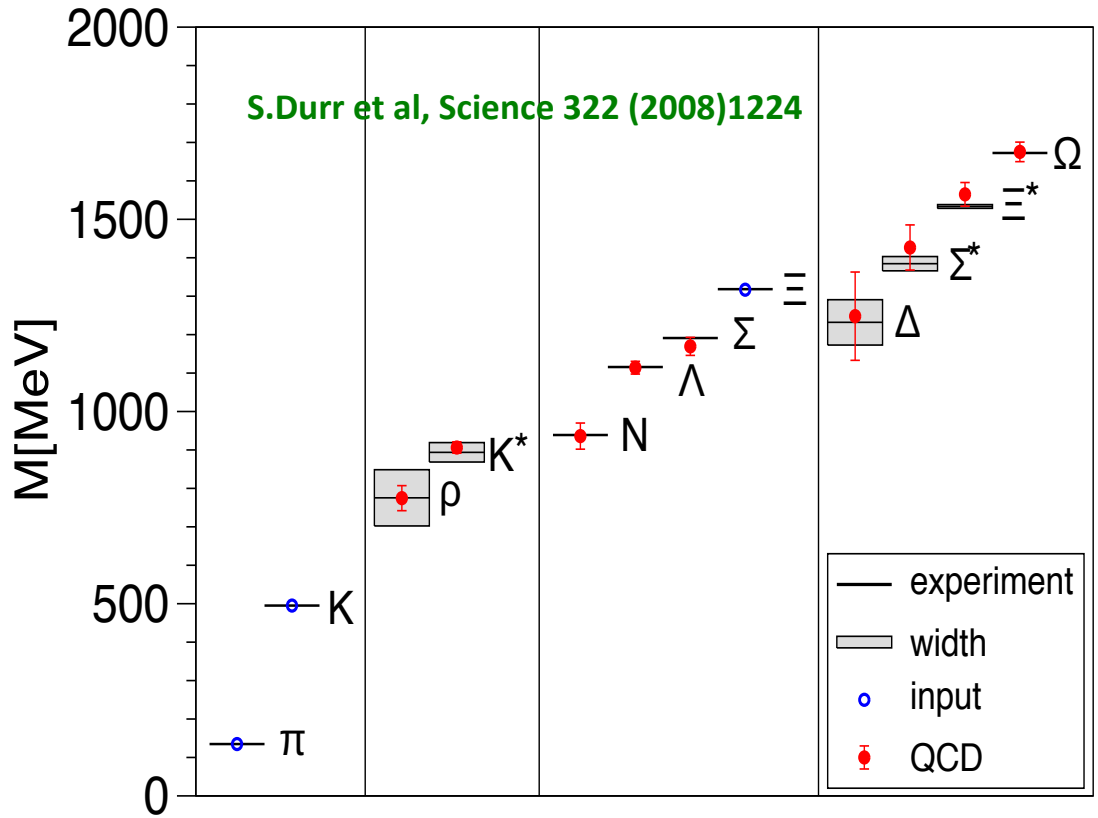
- World's first pol.e-pol.p collider

- What are the big questions that we can answer ?

The big picture

How do fundamental quarks and gluons make up visible matter ?

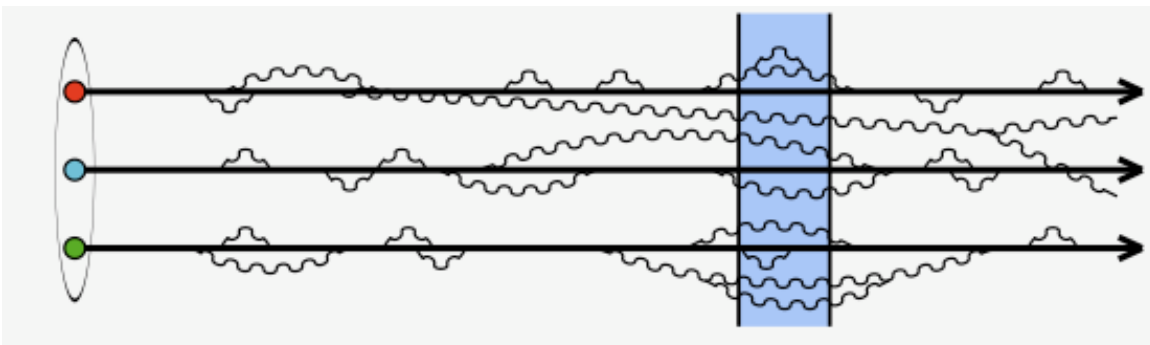
One answer: lattice QCD

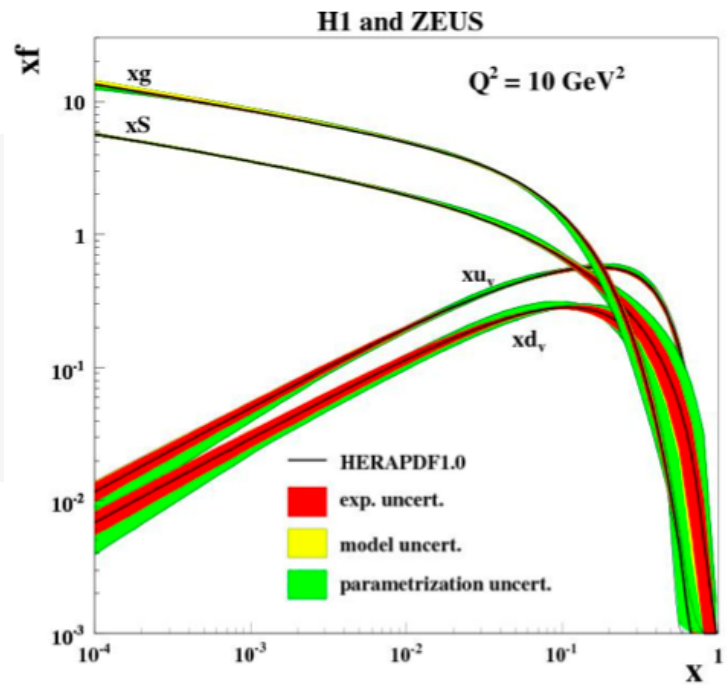


Absolutely essential but also far from the full story…

The big picture

Lattice QCD cannot explain the nature of the hadron when probed at short "time" scales

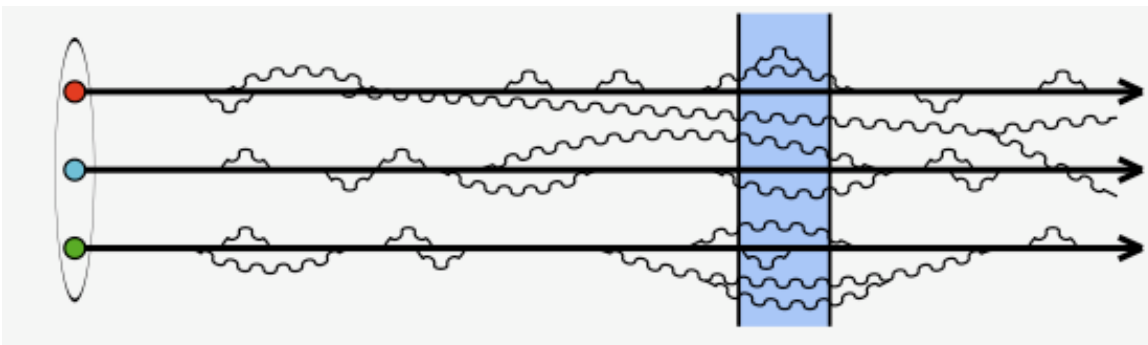


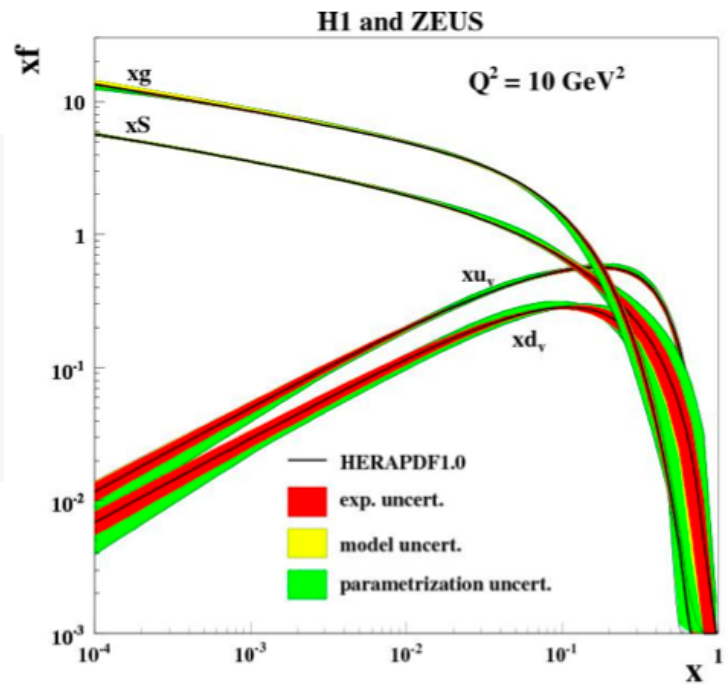


But these high resolution snapshots are also "the proton"…
- they are the relevant configurations for high energy hadron/nuclear scattering

The big picture

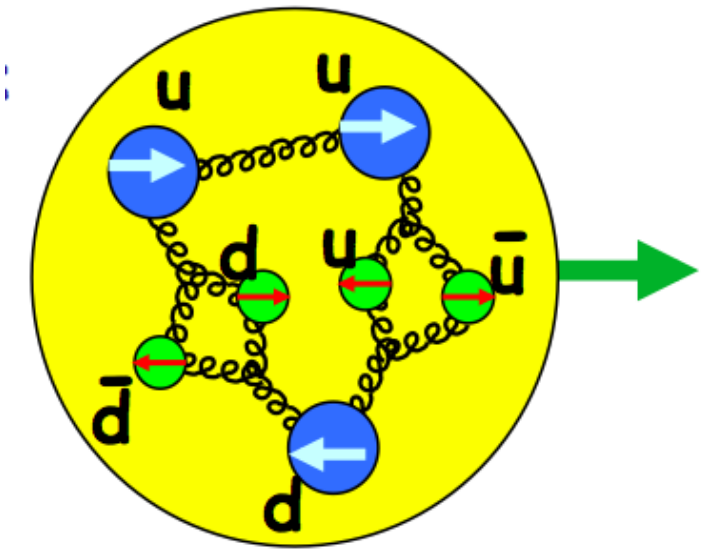
Lattice QCD cannot explain the nature of the hadron when probed at short "time" scales





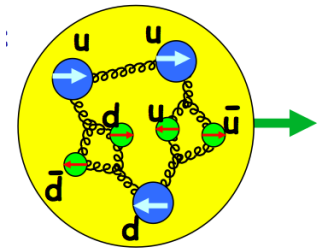
Understanding the fundamental structure of hadrons and nuclei requires detailed understanding of their dynamics

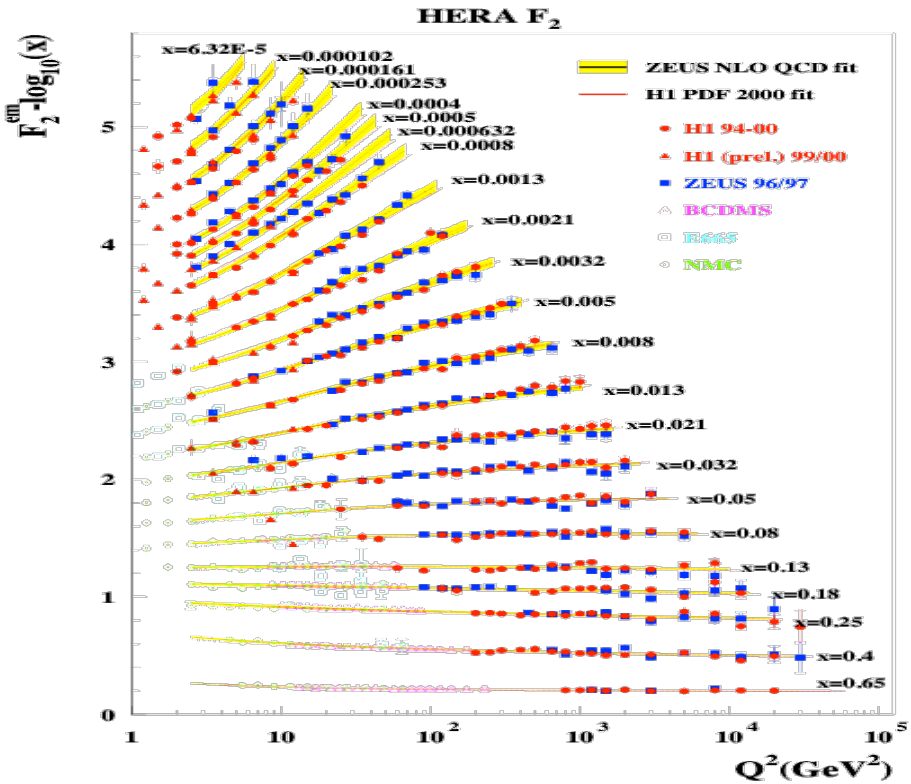
The hadron as a many-body system

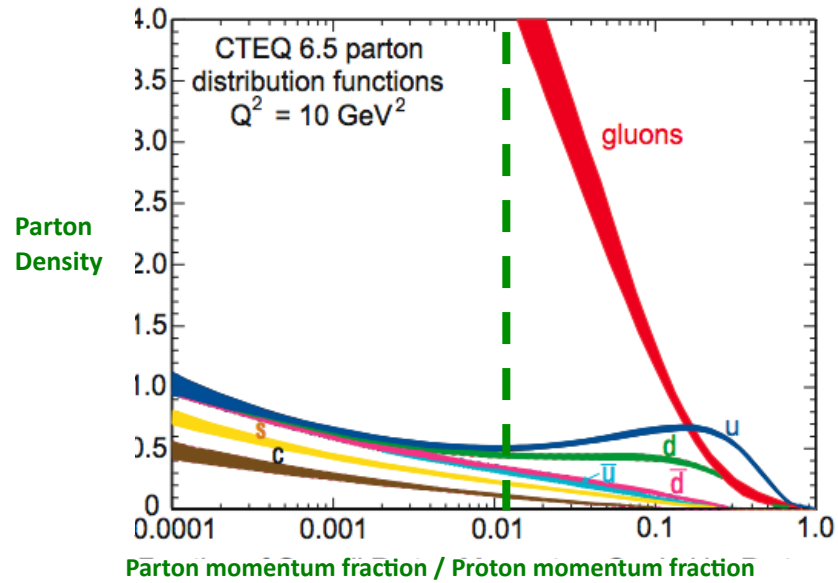


How do many-body quark and gluon fluctuations constitute the Mass, Motion, Spin, Flavor of hadrons and nuclei ?

The hadron as a many-body system



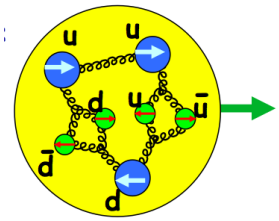




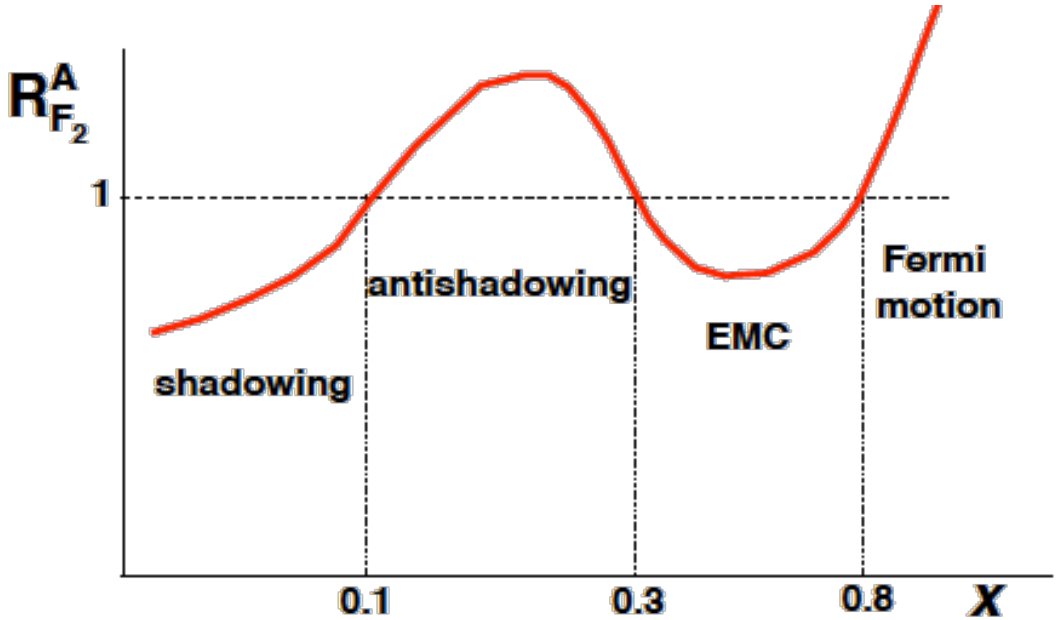
- How do quarks and gluons constitute the momentum of the hadron ?

✓ Pretty good idea for the proton from HERA (with massive impact on the LHC)

The hadron as a many-body system

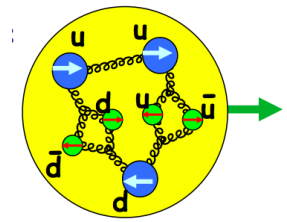


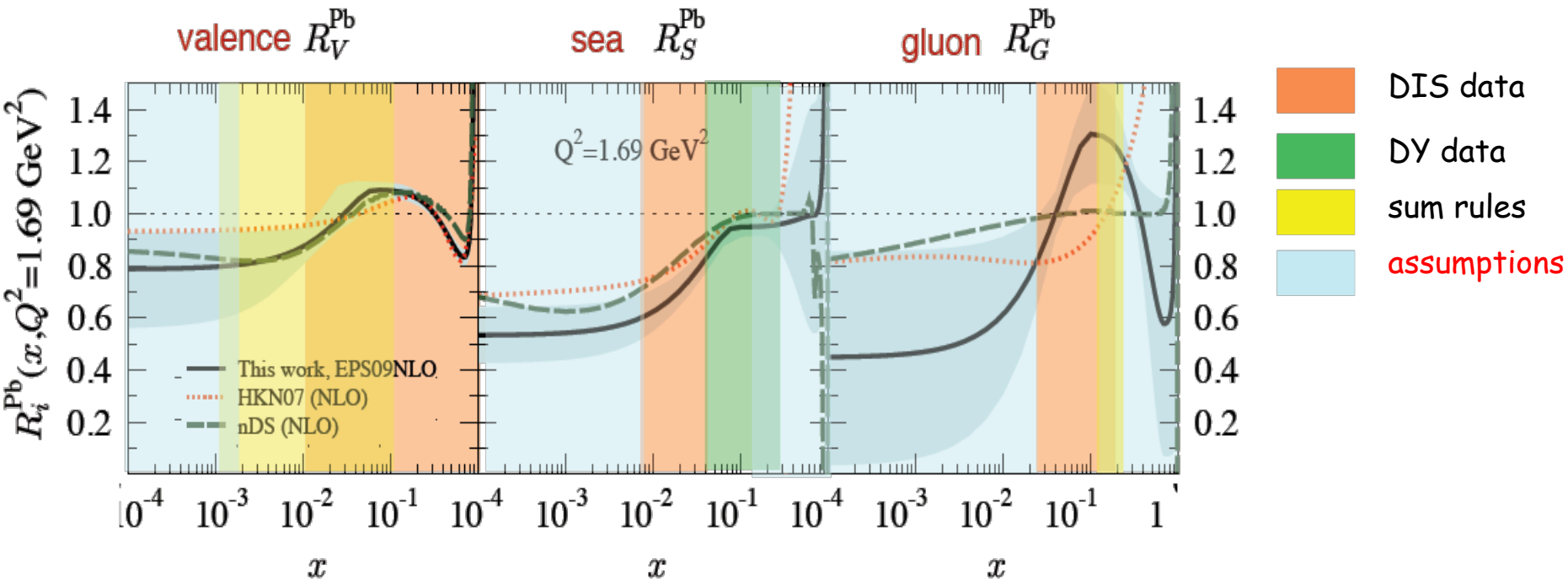
- How do quarks and gluons constitute the momentum of nuclei ?



Nuclei are not an incoherent superposition of nucleons

The hadron as a many-body system

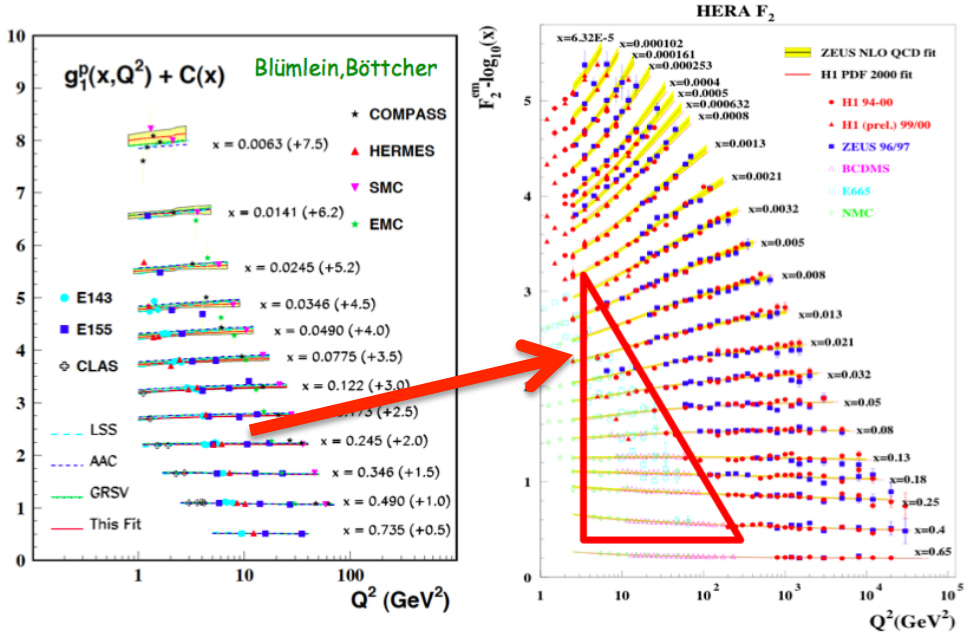




- How do quarks and gluons constitute the momentum of the nuclei ?

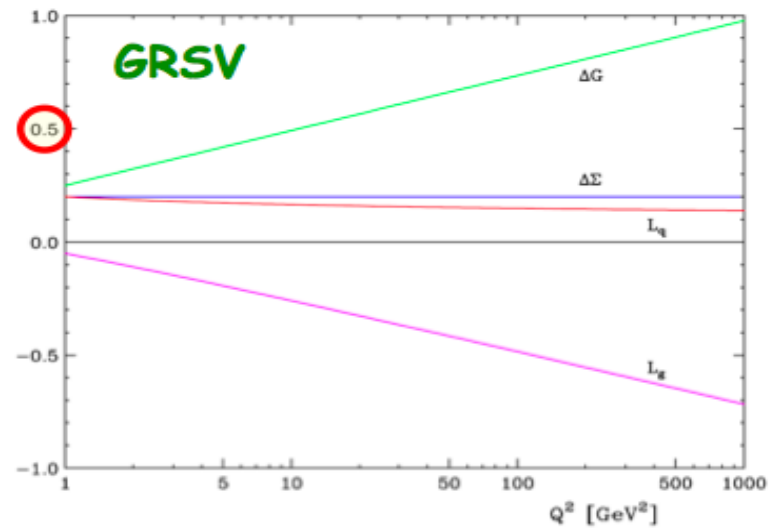
- We have virtually no knowledge of the Motion of gluons in a nucleus (some limited idea for sea quarks)

Spin from many-body dynamics



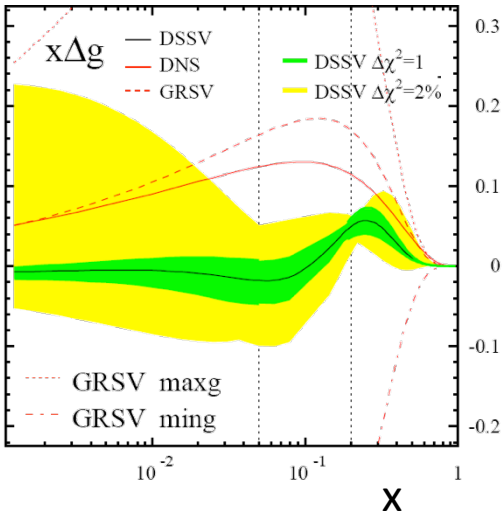
- How do quarks and gluons make up proton spin ?

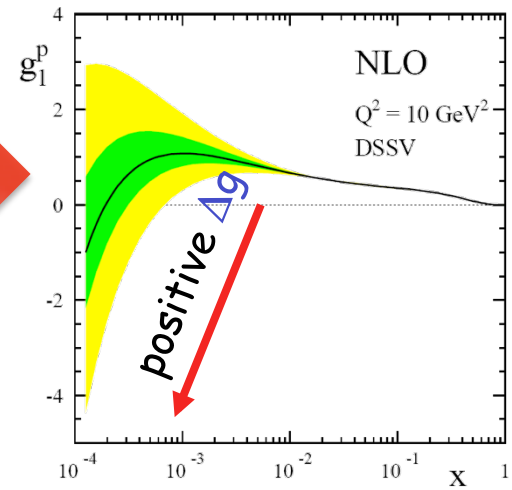
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$



Spin crisis: success of additive quark picture for spectroscopy not reproduced for spin (Bob Jaffe)

Spin from many-body dynamics

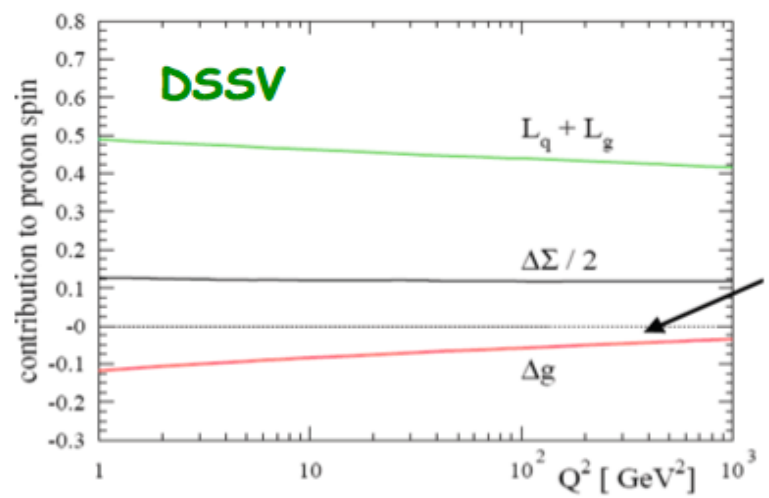




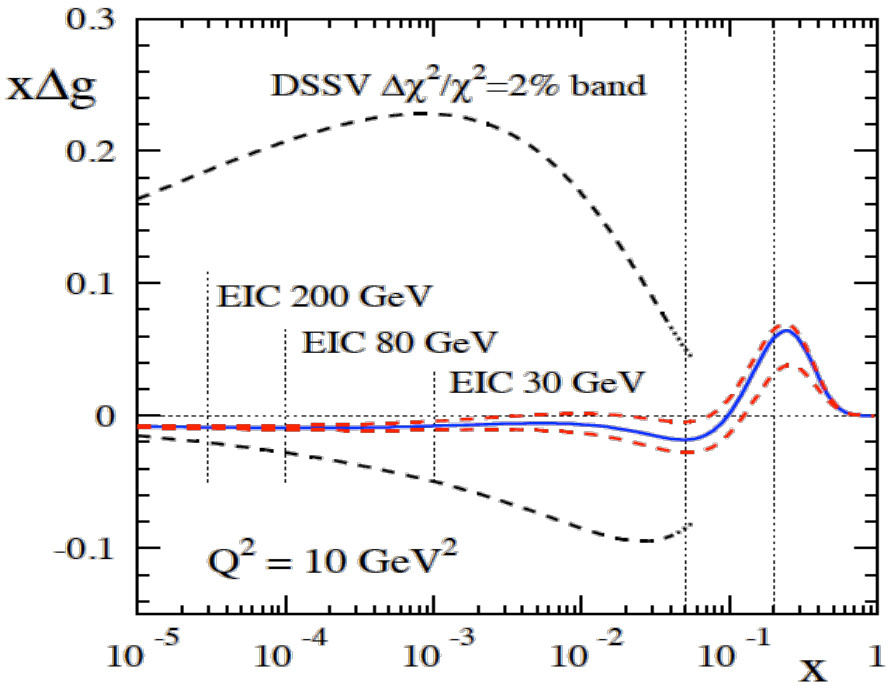
- **How do quarks and gluons make up proton spin ?**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- **Polarized protons from RHIC deepen the mystery**

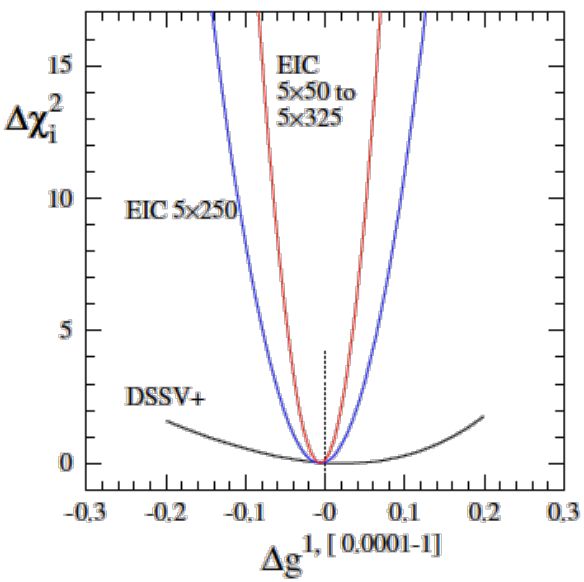


Spin from many-body dynamics

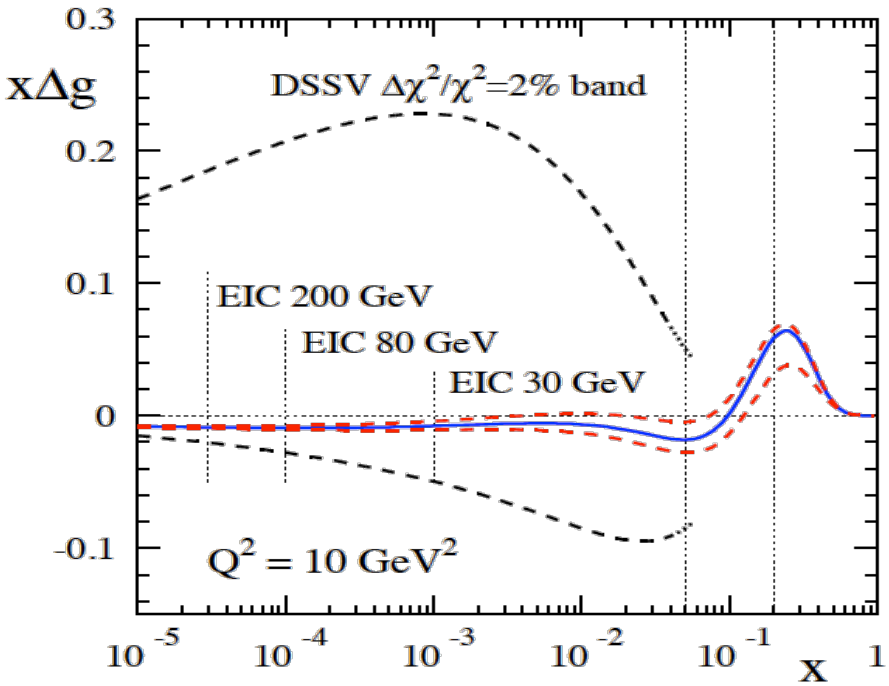


- **How do quarks and glue make up proton spin ?**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$



Spin from many-body dynamics



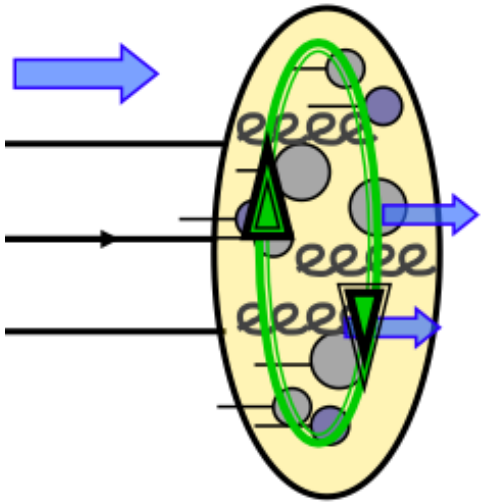
- **How do quarks and glue make up proton spin ?**

Small x (< 0.02) could in priniciple hide a unit of hbar in ΔG

χ^2 profile slims down significantly already for EIC stage-1 (one month of running)

Many-body dynamics of Orbital motion

Orbital momentum: correlation of spatial position of Quarks and Glue X Spin



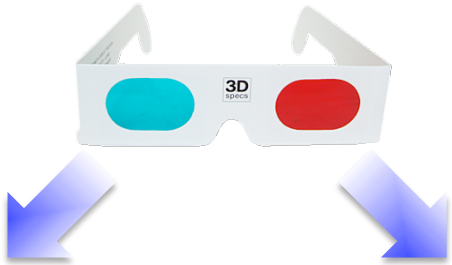
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

- **How do quarks and glue make up hadron spin ?**

❖ **The new frontier – tomography of Spin/Orbital landscape**

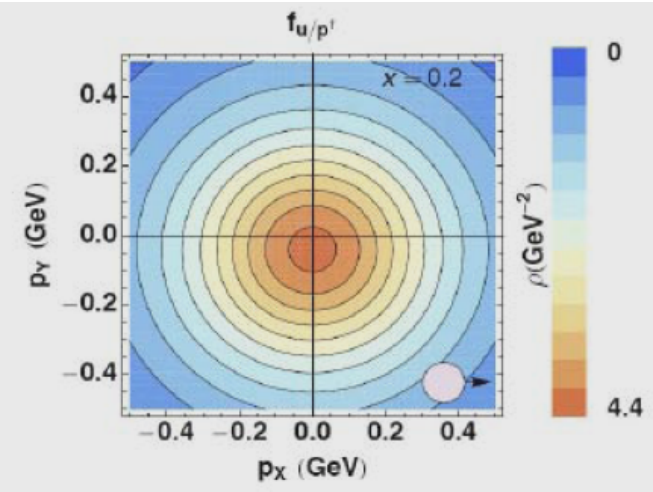
EIC will be unchallenged in tomography of gluons and sea quarks

A new frontier: Many-body tomography of nucleon and nuclei



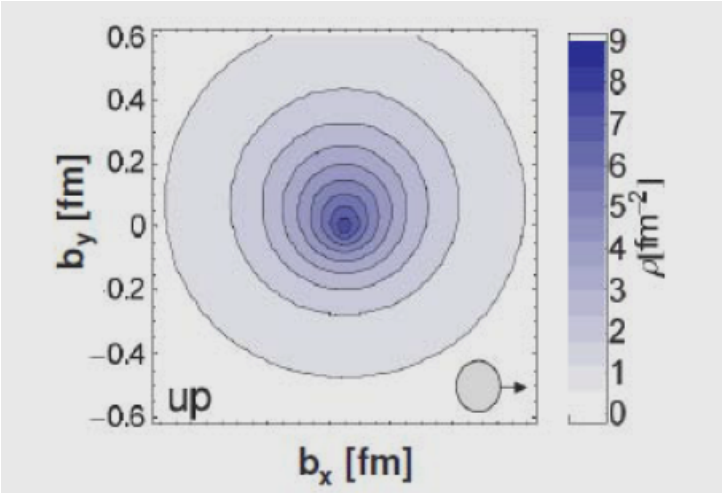
TMDs

(2+1 – D images in momentum space)



GPDs

(2+1 – D images in co-ordinate space)

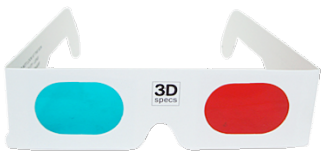


QCDSF collaboration

These are NOT Fourier conjugates:

High level connection through Wigner functions $W(x, k_T, b_T)$

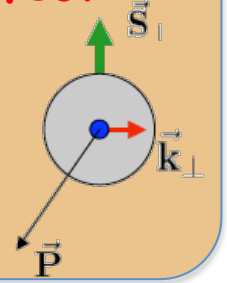
A new frontier: Many-body tomography of nucleon and nuclei

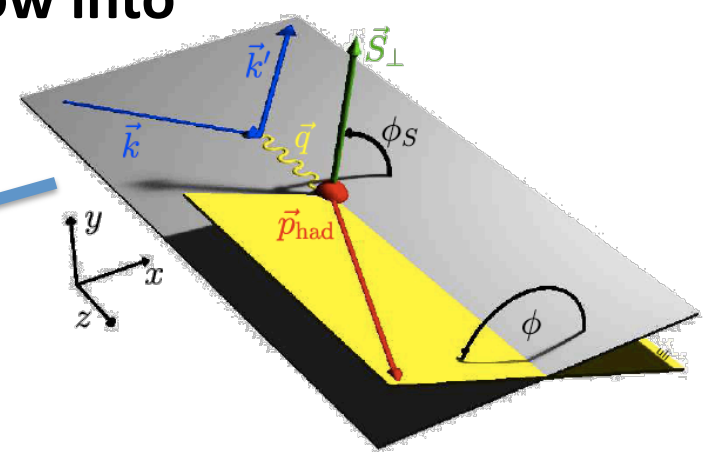


Semi-inclusive DIS opens new "TMD" window into Spin-momentum correlations in QCD

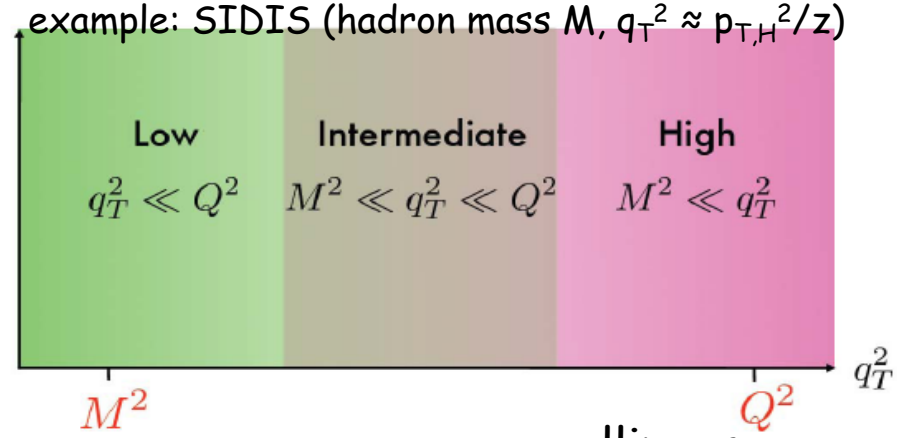
$f_{1T}^{\perp} \otimes D$ **"Sivers effect"**

correlation of transverse spin of proton with k_T of unpolarized quark



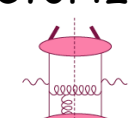


example: SIDIS (hadron mass M, $q_T^2 \approx p_{T,H}^2/z$)



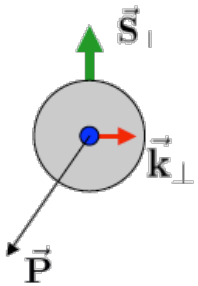
TMD factorization

collinear factorization



A new frontier: Many-body tomography of nucleon and nuclei

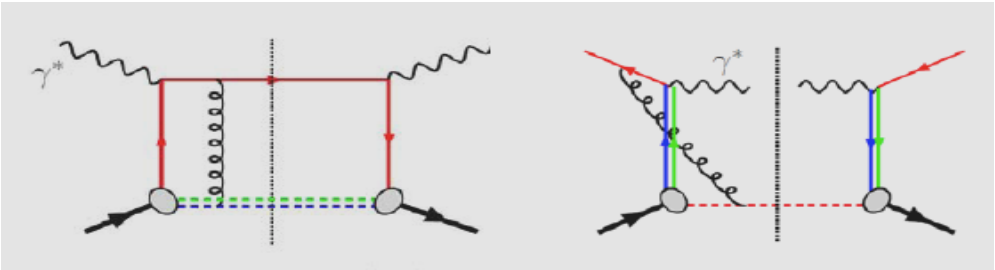
➢ **Semi-inclusive DIS opens new "TMD" window Into spin-momentum correlations in QCD**



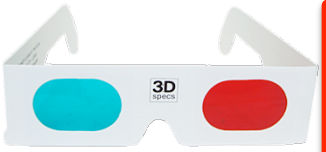
$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S}\cdot(\hat{\mathbf{P}}\times\mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

Same unintegrated distribution at small x as derived in CGC !

Opposite sign in DIS and Drell-Yan

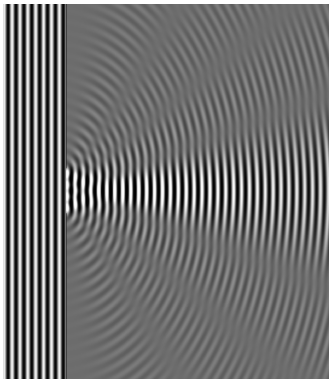


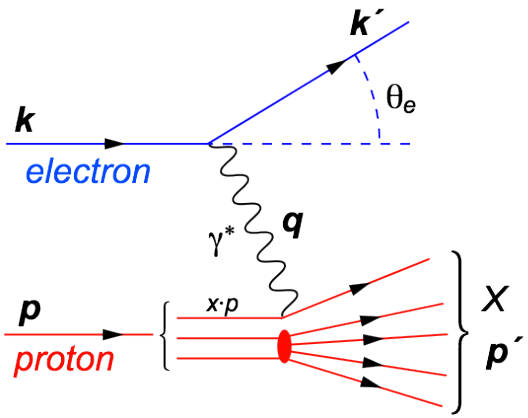
Attractive **Repulsive**

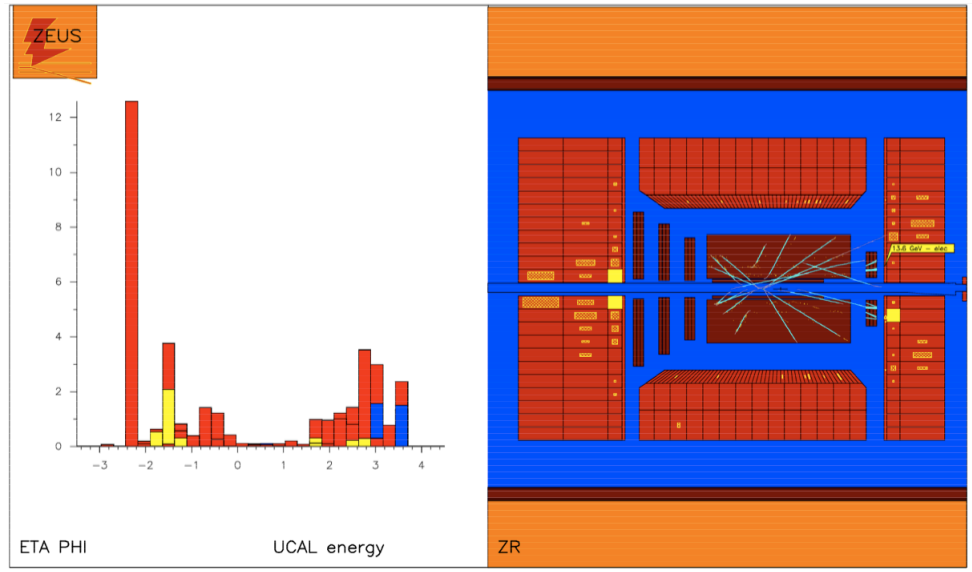


Correlation of spin and transverse momentum TMDs, a new window into how dynamics informs structure

Tomography: Hard Diffraction







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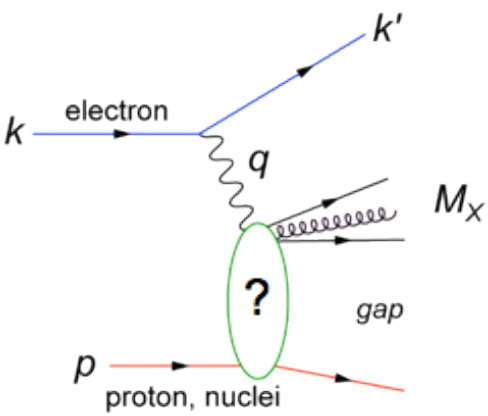
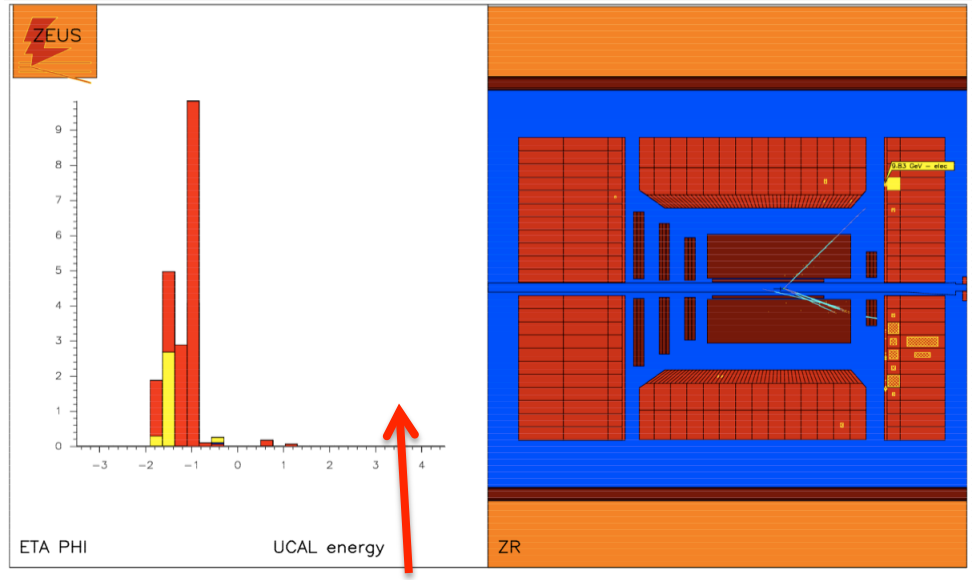
A typical ep event: No rapidity gap, partons radiate all through the available phase space

Tomography: Hard Diffraction



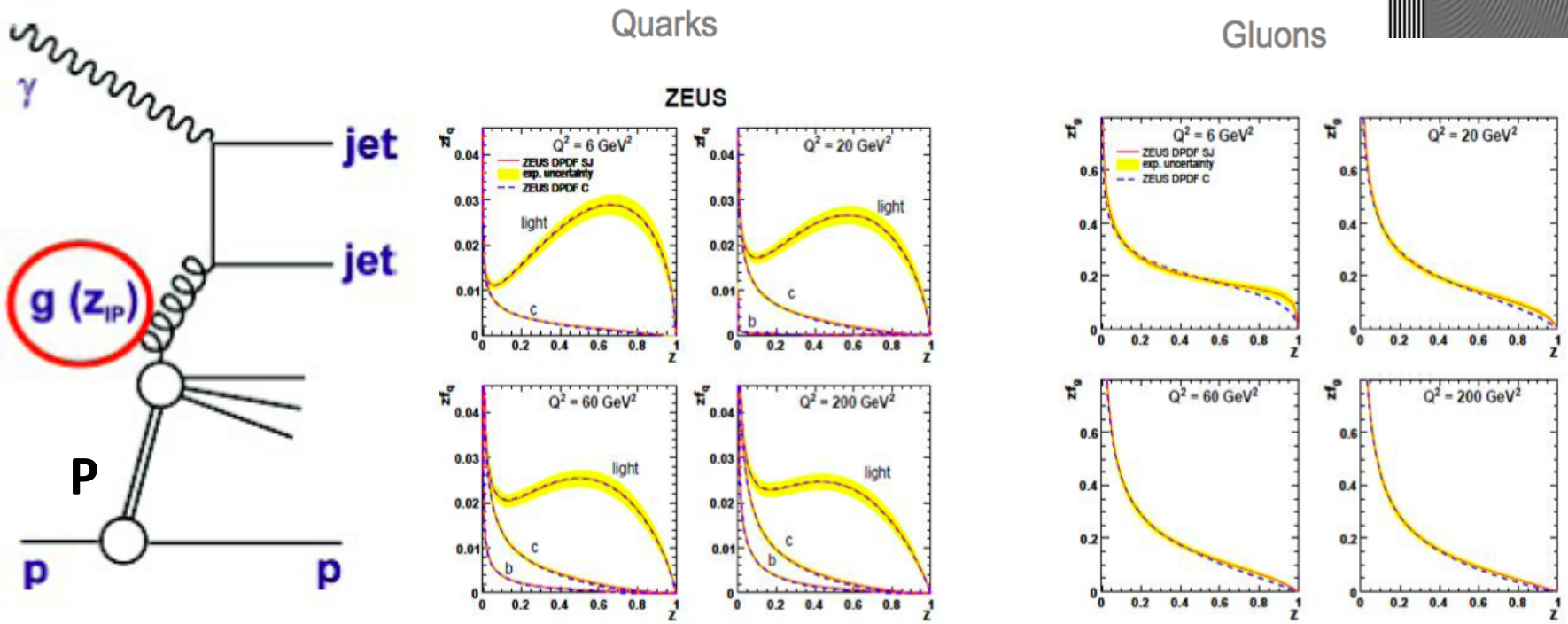


No activity in the p direction

- At HERA ~ 15% of all events - HARD diffractive events (M_X > 3 GeV)

In plain words: 1/7 events, a 50 TeV electron hits a proton at rest and… NOTHING happens to the proton!
The electron fragments into a hard final state…

Hard Diffraction: uncovering the many-body dynamics of color-singlet exchanges

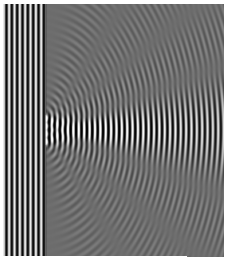


- What is the nature of such color singlet exchanges in nuclei ?

◆ **In large nuclei, saturation predicts 25-30 % Hard Diffractive events**

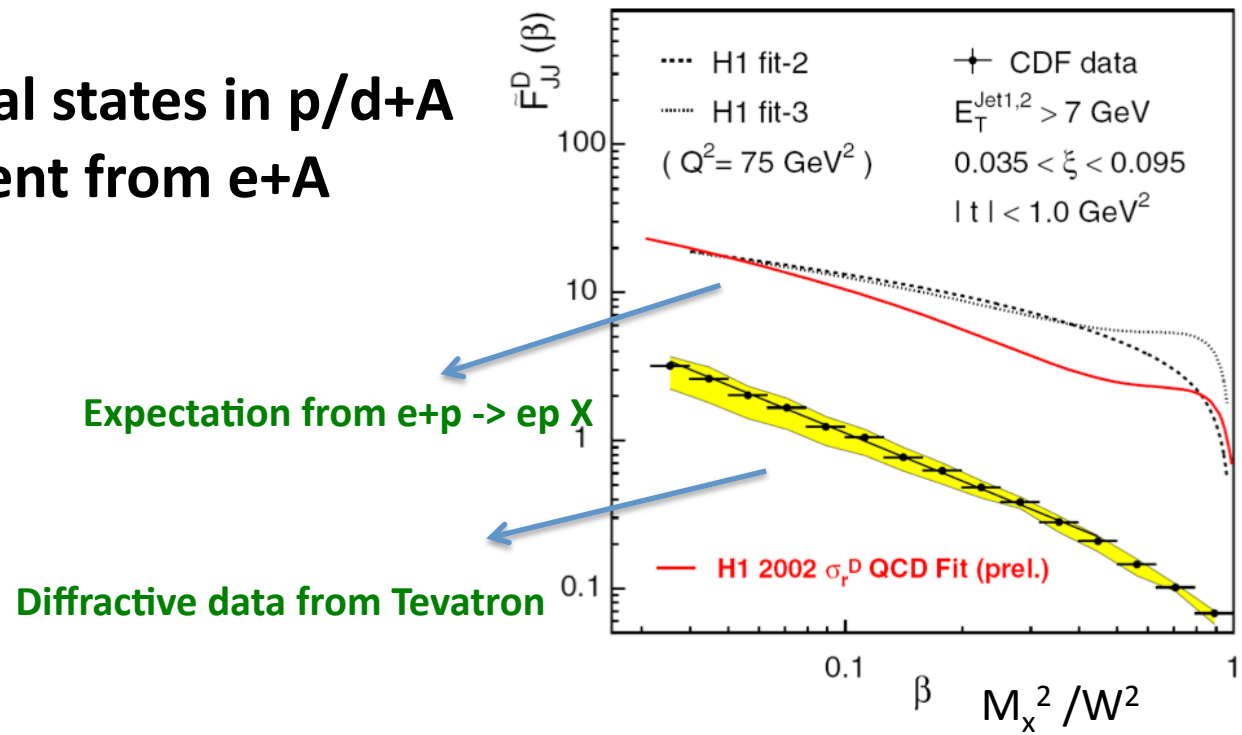
Natural number for "pQCD" is ≤ 10%

Hard Diffraction: uncovering the many-body dynamics of color-singlet exchanges



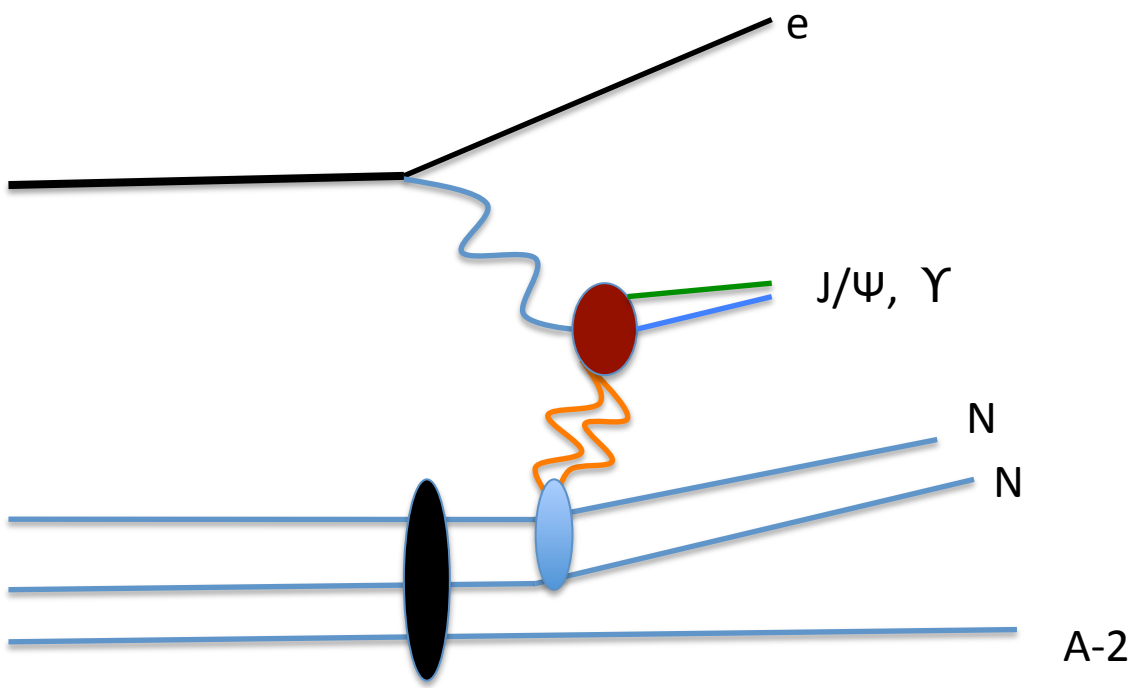
F. Schilling, hep-ex/0209001

Hard diffractive final states in p/d+A qualitatively different from e+A



- **What is the nature of such color singlet exchanges in nuclei ?**
  Again, dynamics and structure are intimately related

Exciting possible tie-in to short range nuclear forces in light nuclei

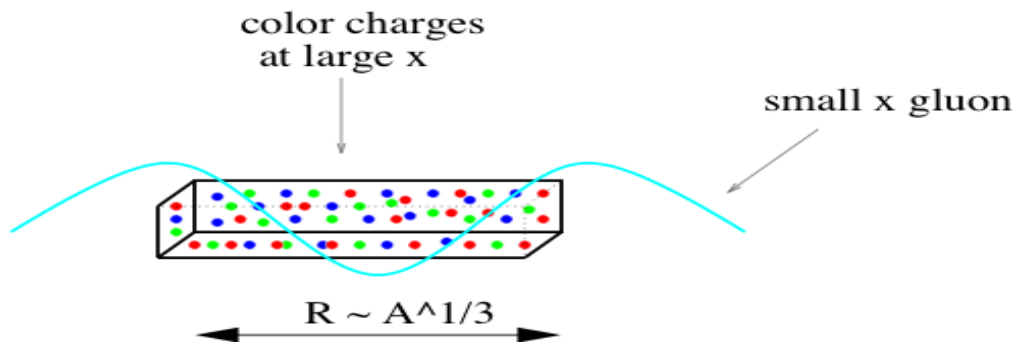


- **What is the glue and sea-quark description of short-range nuclear forces ?**

Significant extension of Jlab program on short-range nuclear forces and connections to FRIB – to be explored…

High precision hard probes of colored media

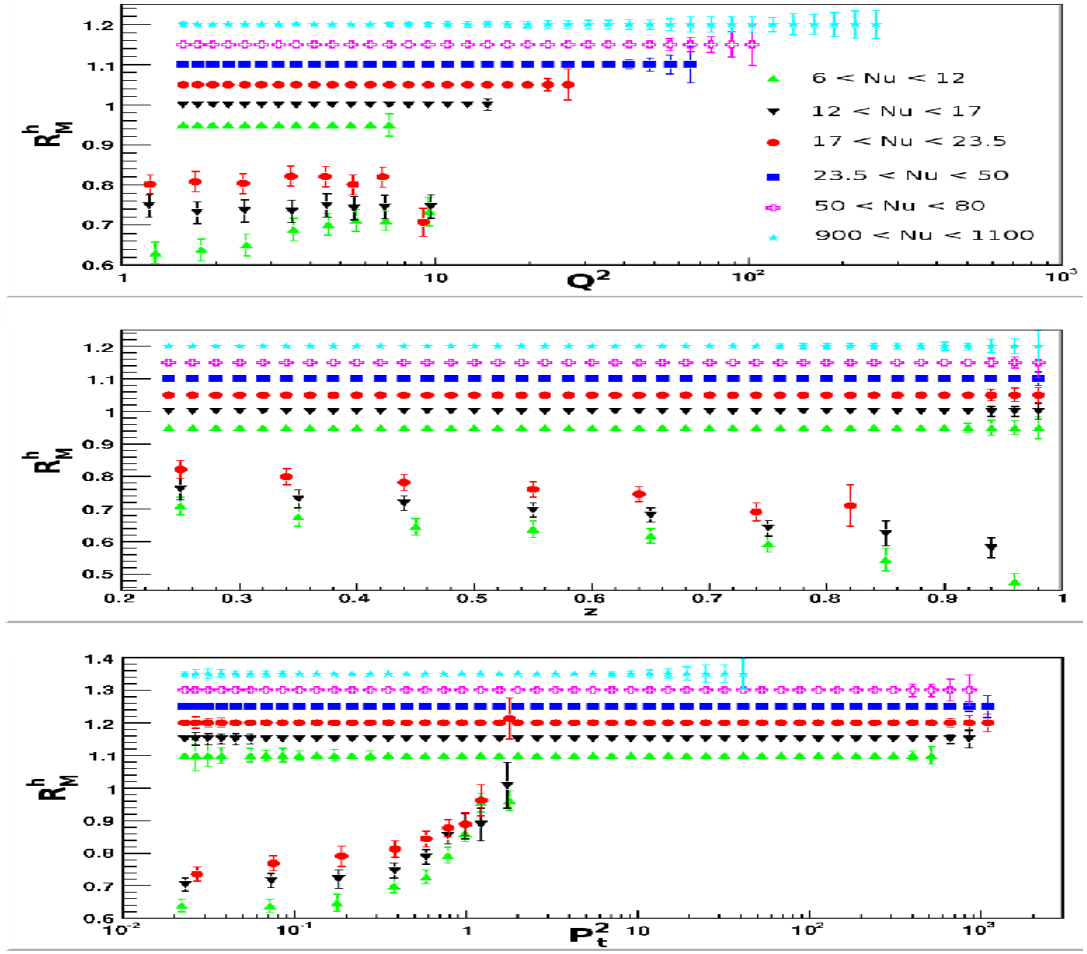
- **The e+A precision card:**



- **Can precisely tune life time of to control amount of partonic scattering with : $\nu = l_{coh} \sim 1/ 2\, m_N\, x$**
- **Precisely known fraction of parton momentum carried by probe helps tune fragmentation in and out of medium: $p_T^h / z = p_T^{\{q,g\}}$**
- **Vary independently size of probe ($\sim 2/Q^2$) from partonic to hadronic sizes**
- **Compute: $R_{eA}^{\{\pi,K,p,\phi,D,J/\Psi,\Upsilon)}$ to study multiple scattering, energy loss, extract energy and path length dependence of q_{hat}, medium modified fragmentation: IeA, JeA, to study correlations.**
- **Charm, Beauty studies in e+A for first time. Definitively settle intrinsic charm/strangeness question**
- **Exclusive final states to probe color singlet/octet interplay**

High precision hard probes of colored media

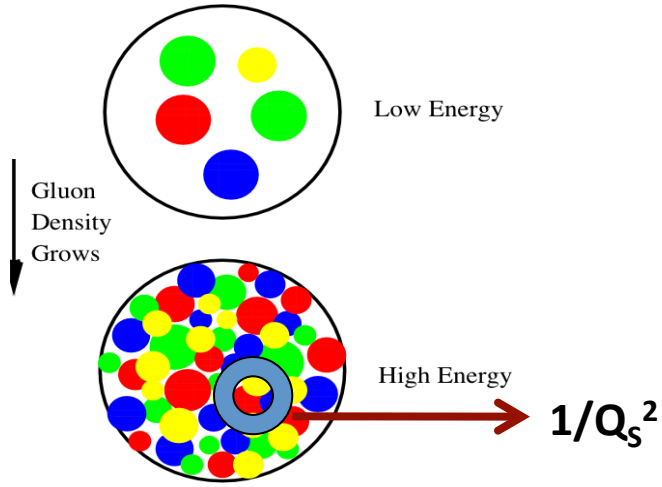
$$R_M^h = \frac{\frac{1}{N_A^{\rm DIS}}\frac{dN_A^h}{dz}}{\frac{1}{N_D^{\rm DIS}}\frac{dN_D^h}{dz}}$$



- **Reach much greater than previous e+A and Precision handles unmatched to uncover fundamental QCD dynamics of interactions of hard probes in media**

- **Complement and corroborate in essential ways results from hadron colliders**

Universal Gluodynamics in a novel QCD regime

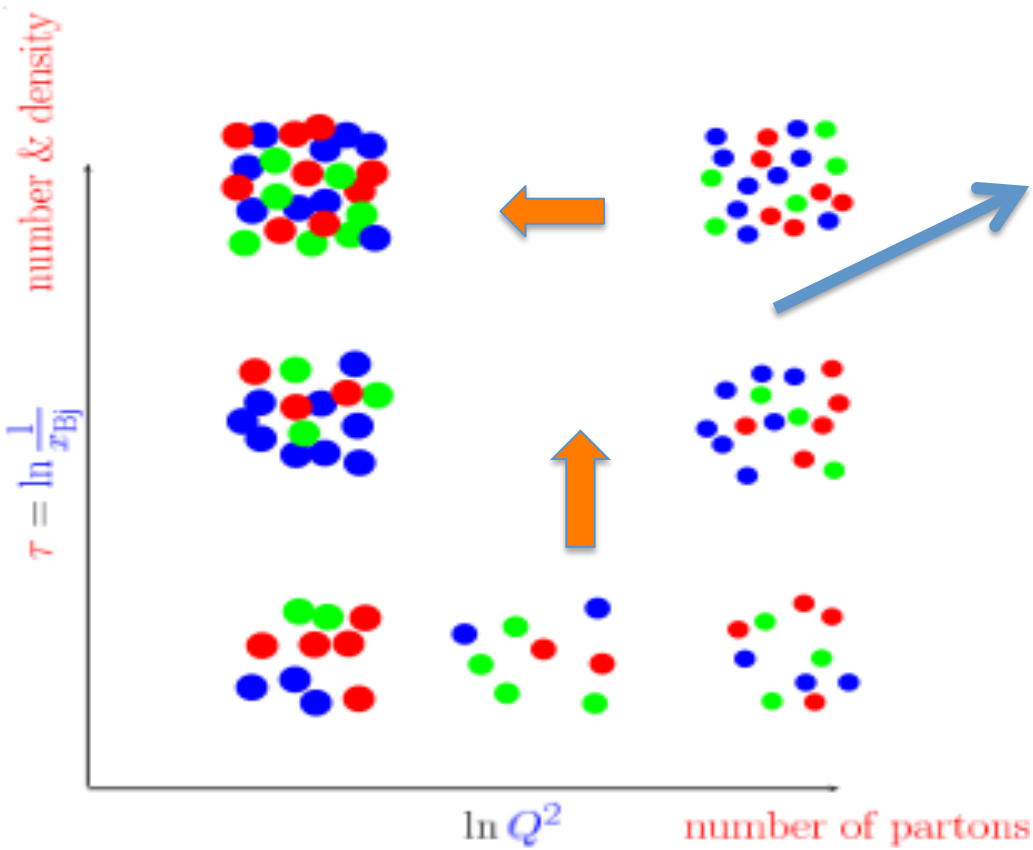


- **Are there universal many body states of saturated gluonic matter in hadrons and nuclei ?**

- **Evidence of saturation from d+A at x~ 10^{-2}-10^{-3} from recent PHENIX and STAR data is very strong but is the physics universal ?**

Bottom line: the $A^{1/3}$ "oomph" works and more precociously than naïve expectations. ***Excellent news for precision studies because of extended lever arm!***

Many-body dynamics of universal gluonic matter in QCD



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 the RG evolution of d.o.f

Does the coupling run with Q_s^2 ?

How does saturation transition to Chiral symmetry breaking and confinement

CGC Effective Theory:
B-JIMWLK hierarchy of n-point correlators

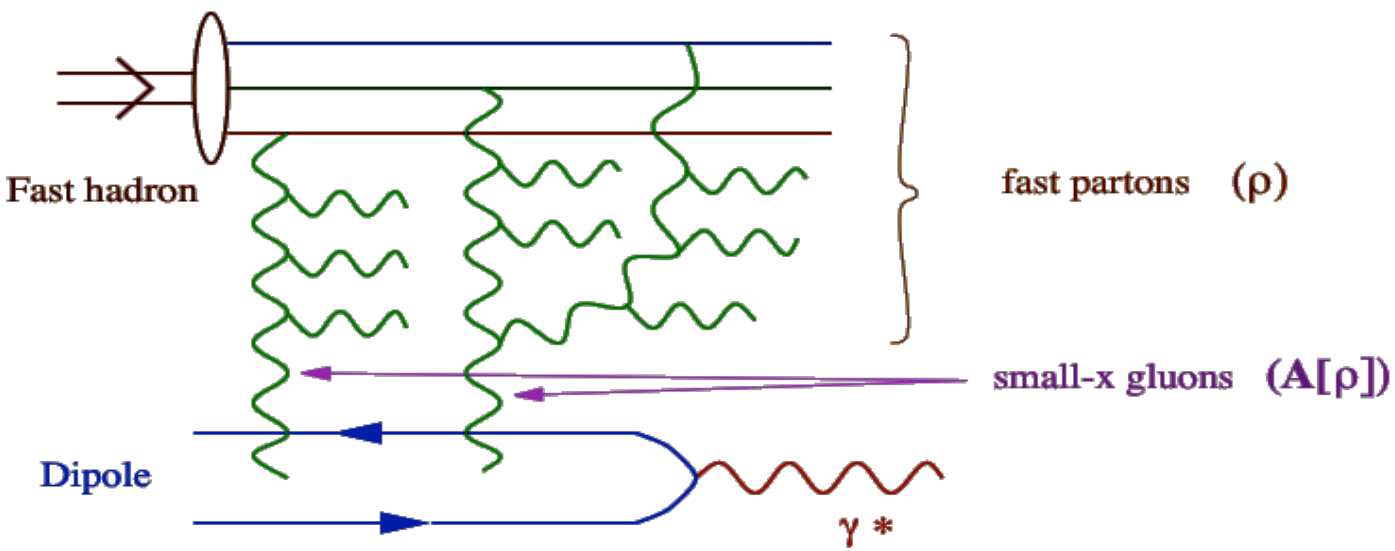
$$\langle O[\rho]\rangle_Y = \int [d\rho] O[\rho] W_Y[\rho]$$

JIMWLK Fokker Planck eqn: Brownian motion in functional space

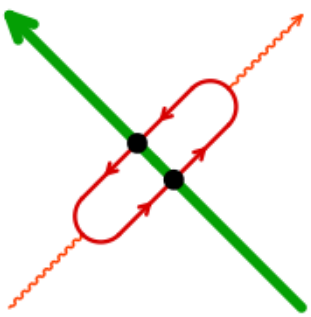
"diffusion coefficient"

$$\frac{\partial W[\tilde{\rho}]}{\partial Y} = \mathcal{H}\, W[\tilde{\rho}] \Rightarrow \frac{\partial}{\partial Y} < O[\alpha] >_Y = \underbrace{< \frac{1}{2}\int_{x,y} \frac{\delta}{\delta\alpha^a_Y(x)} \chi^{ab}_{x,y} \frac{\delta}{\delta\alpha^b_Y(y)} O[\alpha] >_Y}_{\mathcal{H}_{\mathrm{JIMWLK}}}$$

"time"



Inclusive DIS: dipole evolution

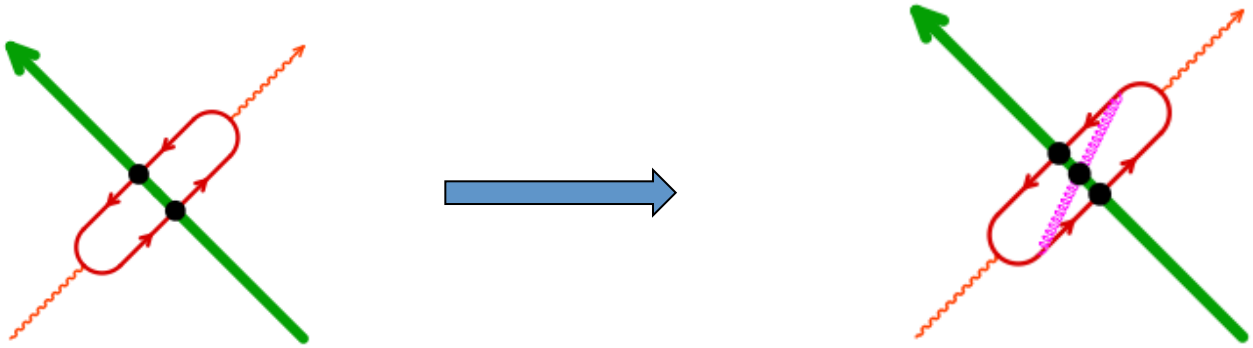


$$\sigma_{\gamma^* T} = \int_0^1 dz \int d^2 r_\perp \, |\psi(z, r_\perp)|^2 \sigma_{\rm dipole}(x, r_\perp)$$

$$\sigma_{\rm dipole}(x, r_\perp) = 2 \int d^2 b \int [D\rho] \, W_{\Lambda^+}[\rho] \, T(b + \frac{r_\perp}{2}, b - \frac{r_\perp}{2})$$

$$1 - \frac{1}{N_c} {\rm Tr} \left(V \left(b + \frac{r_\perp}{2} \right) V^\dagger \left(b - \frac{r_\perp}{2} \right) \right)$$

Inclusive DIS: dipole evolution



B-JIMWLK eqn. for dipole correlator

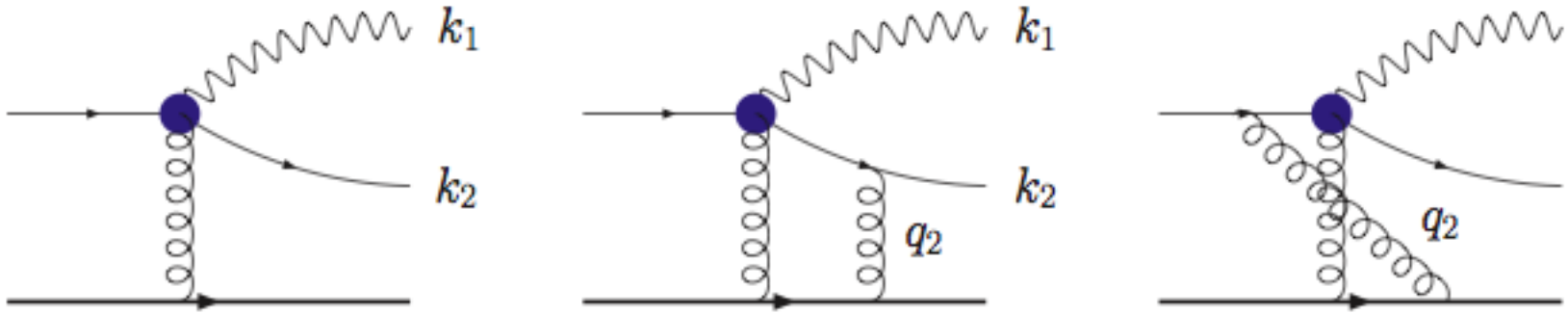
$$\frac{\partial}{\partial Y}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y = -\frac{\alpha_S N_c}{2\pi^2}\int_{z_\perp} \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2 (z_\perp - y_\perp)^2}\, \langle \mathrm{Tr}(V_x V_y^\dagger) - \frac{1}{N_c}\mathrm{Tr}(V_x V_z^\dagger)\, \mathrm{Tr}(V_z V_y^\dagger)\rangle_Y$$

Dipole factorization:

$$\langle \mathrm{Tr}(V_x V_z^\dagger)\, \mathrm{Tr}(V_z V_y^\dagger)\rangle_Y \longrightarrow \langle \mathrm{Tr}(V_x V_z^\dagger)\rangle_Y \langle \mathrm{Tr}(V_z V_y^\dagger)\rangle_Y \qquad N_c \rightarrow \infty$$

Resulting closed form eqn. is the Balitsky-Kovchegov eqn.
widely used in phenomenological applications

Universality: Di-jets in p/d-A collisions



Jalilian-Marian, Kovchegov (2004)
Marquet (2007)
Dominguez,Marquet,Xiao,Yuan (2011)

$$\frac{d\sigma^{qA\to qgX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[S_6(x,y,\bar{x},\bar{y}) - S_4(x,y,v) - \ldots\right]$$

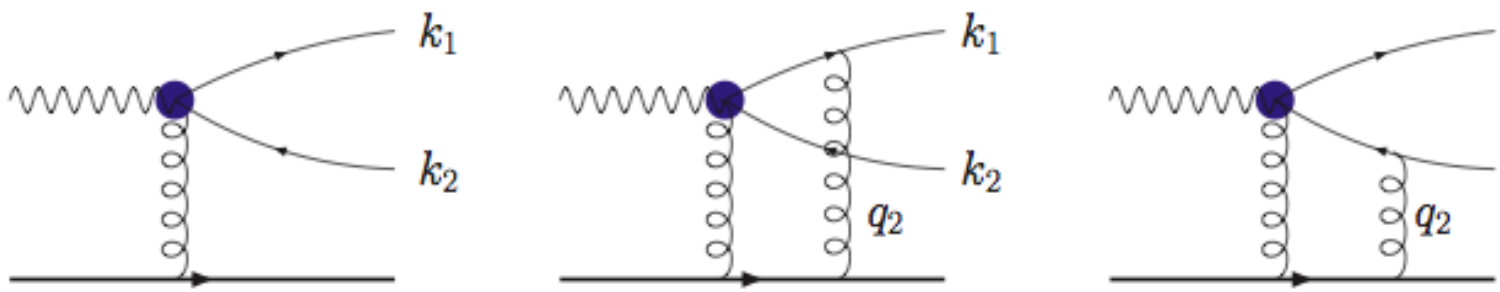
$$\frac{N_c}{2C_F}\left\langle Q(x,y\,\bar{y},\bar{x})D(y,\bar{y}) - \frac{D(x,\bar{x})}{N_c}\right\rangle \qquad \frac{N_c}{2C_F}\left\langle D(x,y)D(\bar{y},\bar{x}) - \frac{D(x,\bar{x})}{N_c}\right\rangle$$

Fundamental ingredients in CGC: universal dipoles, quadrupoles…

- **In p/d+A, background (pedestal) is large and varies with A, x-range: Convolution over proton wave.fn – further complication**

- **But p+A essential to uncover universal dynamics of high energy QCD!**

Semi-inclusive DIS: quadrupole evolution



Dominguez,Marquet,Xiao,Yuan (2011)

$$\frac{d\sigma^{\gamma^*_{\mathrm{T,L}} A \to q\bar{q}X}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x}\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[1 + Q(x,y;\bar{y},\bar{x}) - D(x,y) - D(\bar{y},\bar{x})\right]$$

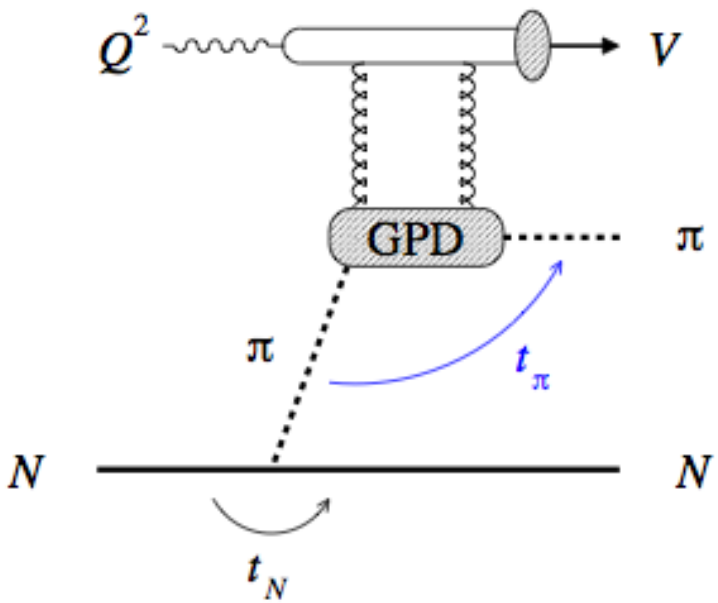
$$D(x,y) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y \qquad Q(x,y;\bar{y},\bar{x}) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_{\bar{x}}^\dagger V_{\bar{y}} V_y^\dagger)\rangle_Y$$

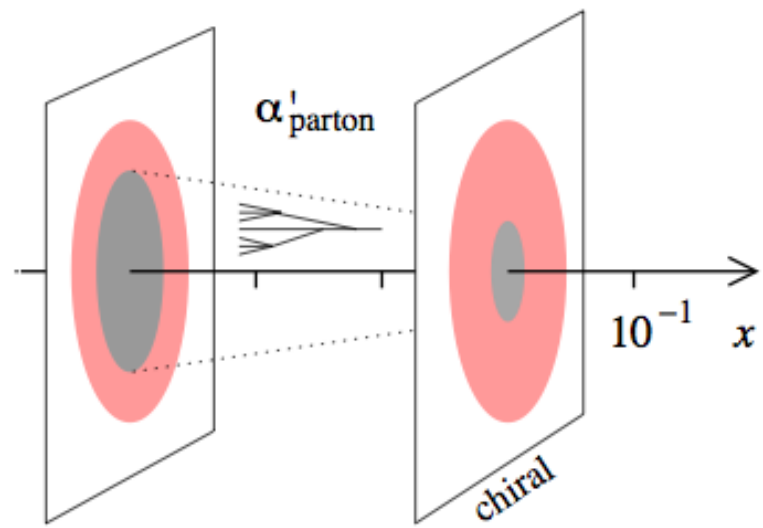
- **Chart with precision novel d.o.f in high energy QCD. Study their evolution with Energy through a multitude of final states – with far less background and systematic uncertainties than p/D-A**

- **Confirm universal nature of dynamics through same spirit of global analyses that established pQCD**

Space, the final frontier:saturation -> confinement

What is the role of chiral/confining dynamics at high energies ?

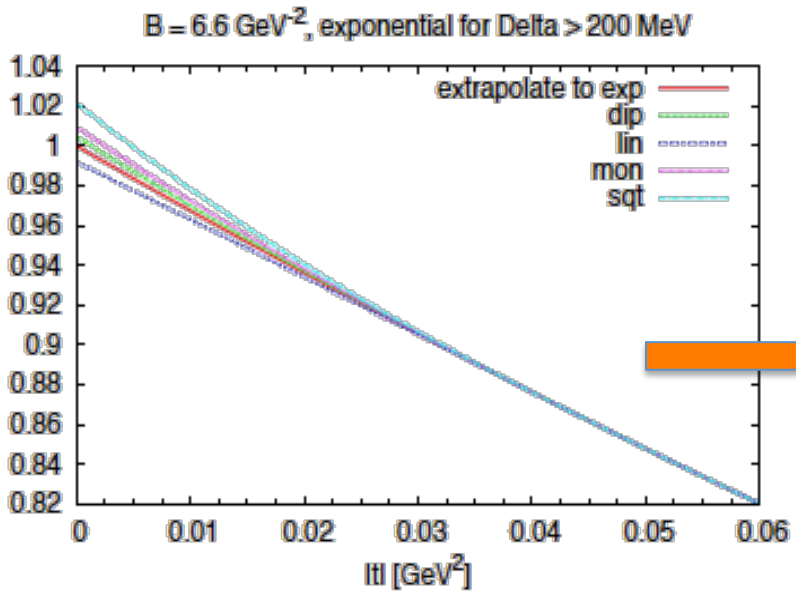


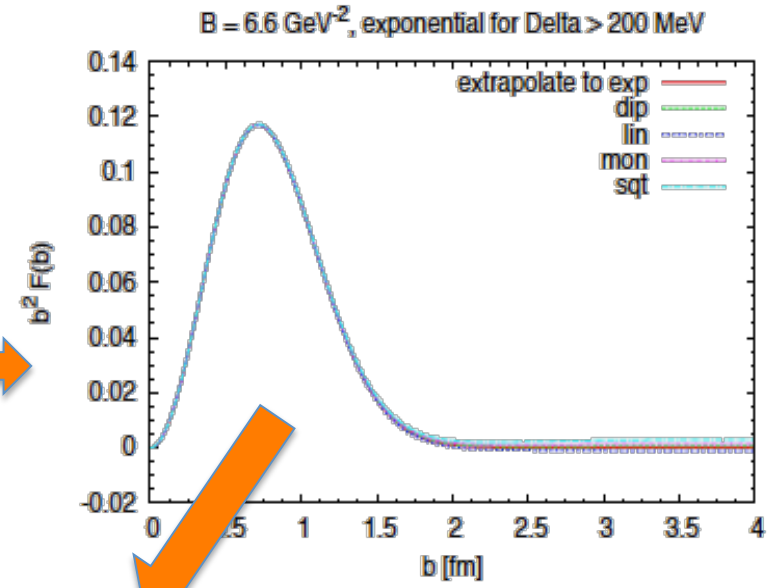


- **We know there is a profound connection: the Froissart bound. What is the underlying dynamics ?**

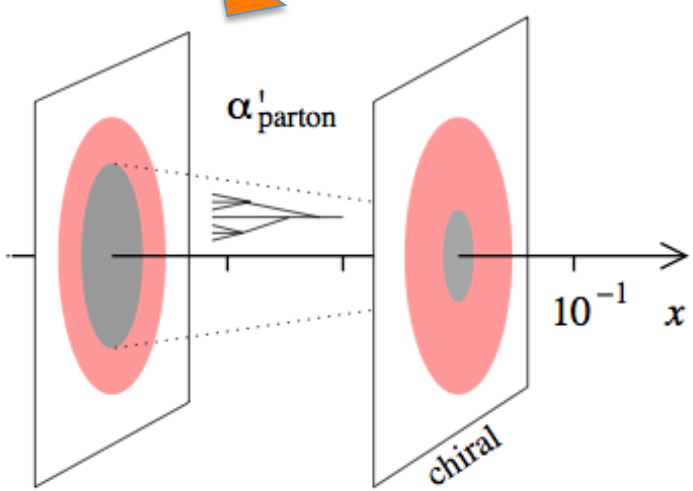
Space, the final frontier: saturation -> confinement

What is the role of chiral/confining dynamics at high energies ?





For the first time ever!
Unique controlled channels
to explore the transition



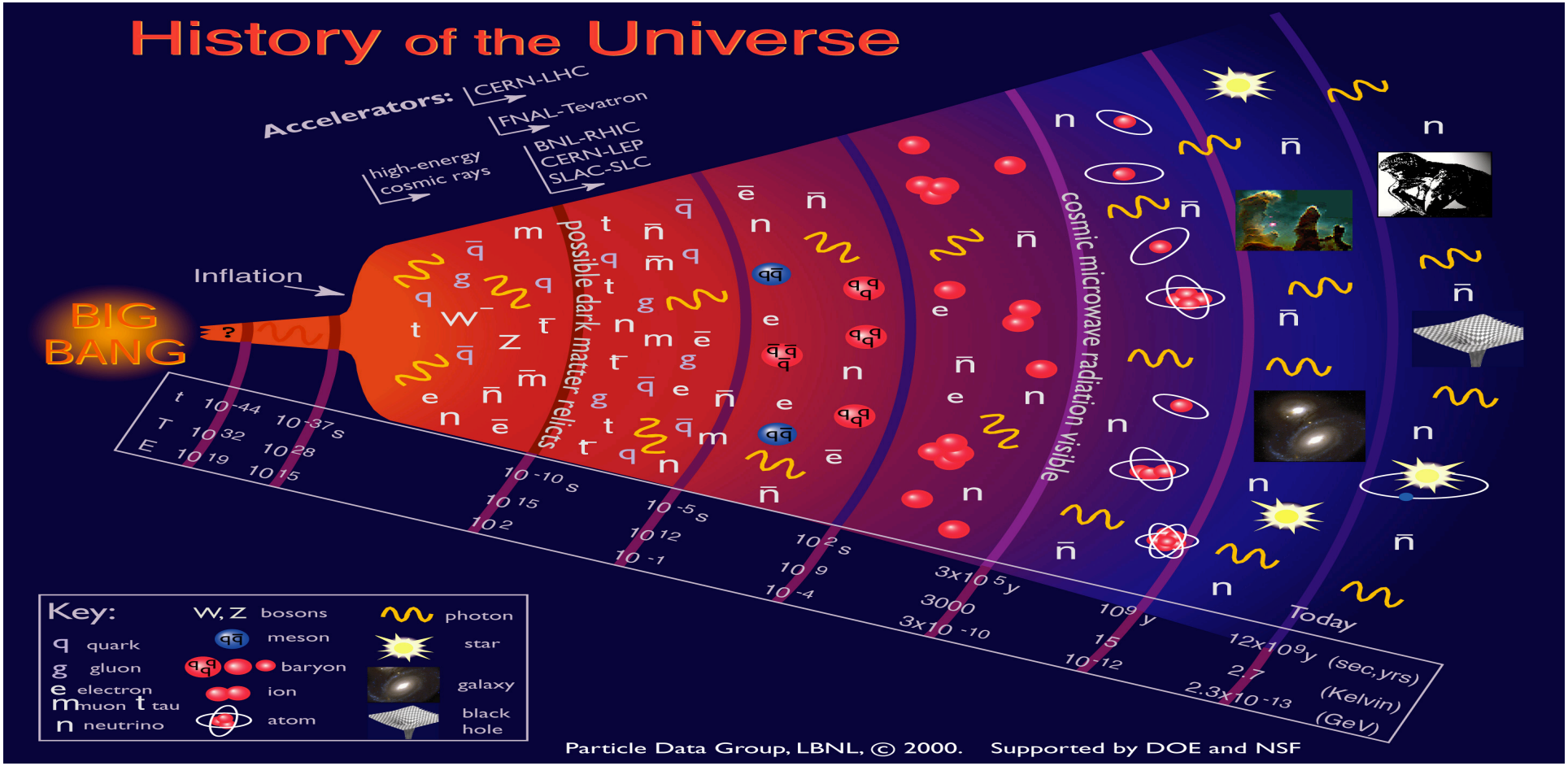
CGC-> Glasma: Initial dynamics in HI collisions

- For an order $1/\alpha_S$ contribution to the discussion, see our paper today

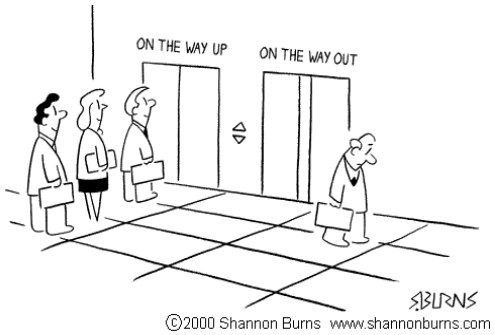
arXiv:1106.3927 (cross-list from nucl-th) [pdf, ps, other]
The initial spectrum of fluctuations in the little bang
Kevin Dusling, Francois Gelis, Raju Venugopalan

The elevator speech for RHIC

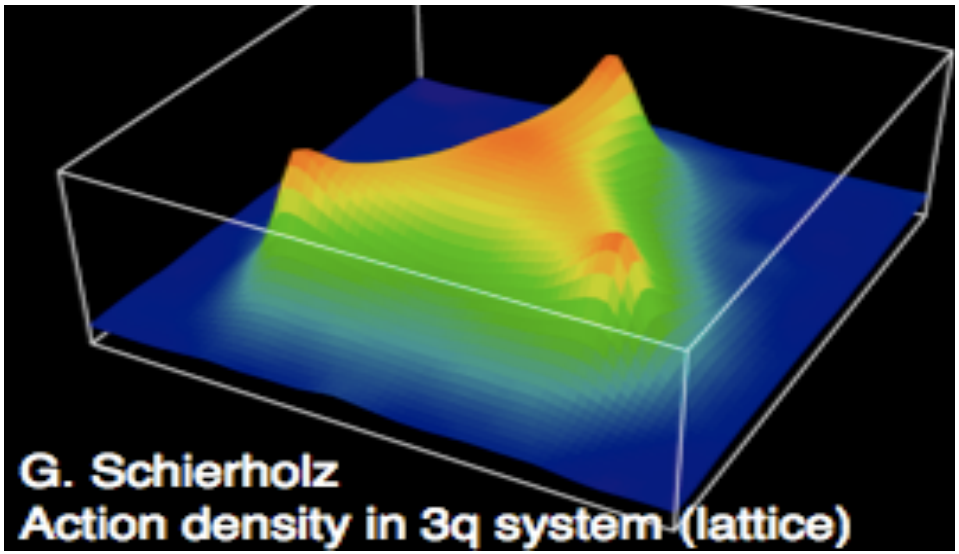
QGP -> hadron transition at ~10^{-5} secs after Big Bang

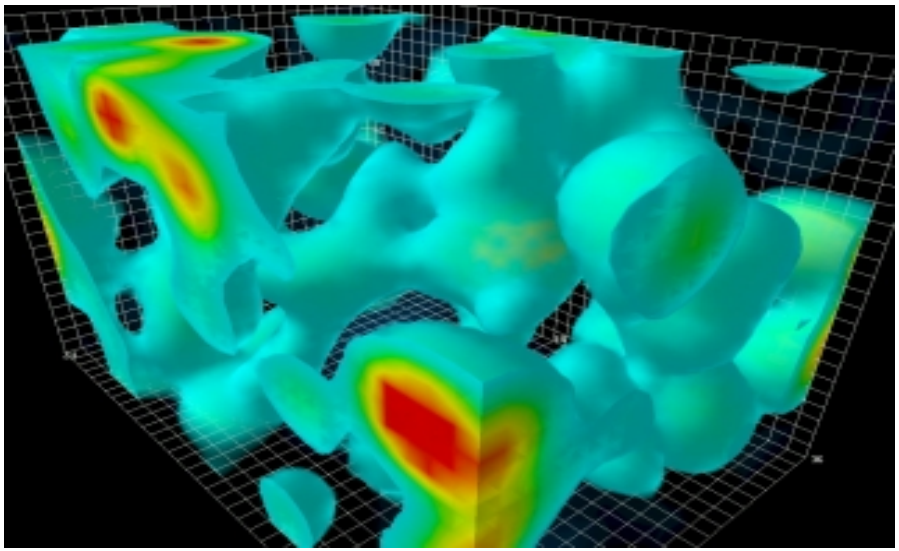


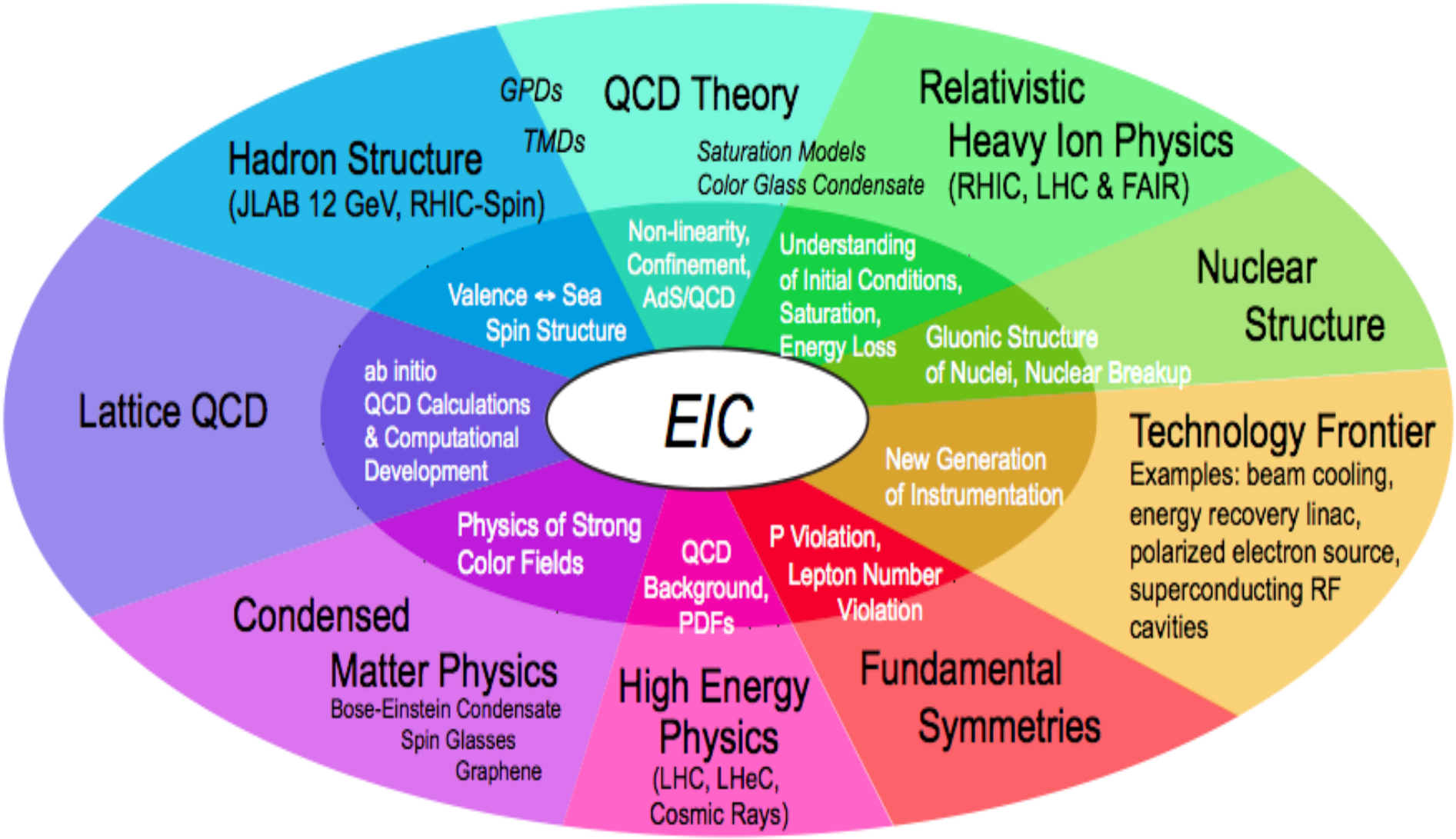
Elevator tweet for eRHIC



Investigate with powerful femtoscopes, elusive dynamics of gluons and "sea quarks" that fundamentally make up nearly all the mass of the visible universe






EIC
Hadron Structure
(JLAB 12 GeV, RHIC-Spin)
GPDs
TMDs
QCD Theory
Saturation Models
Color Glass Condensate
Relativistic
Heavy Ion Physics
(RHIC, LHC & FAIR)
Nuclear
Structure
Technology Frontier
Examples: beam cooling,
energy recovery linac,
polarized electron source,
superconducting RF
cavities
Fundamental
Symmetries
High Energy
Physics
(LHC, LHeC,
Cosmic Rays)
Condensed
Matter Physics
Bose-Einstein Condensate
Spin Glasses
Graphene
Lattice QCD
Valence ↔ Sea
Spin Structure
Non-linearity,
Confinement,
AdS/QCD
Understanding
of Initial Conditions,
Saturation,
Energy Loss
Gluonic Structure
of Nuclei, Nuclear Breakup
ab initio
QCD Calculations
& Computational
Development
New Generation
of Instrumentation
Physics of Strong
Color Fields
QCD
Background,
PDFs
P Violation,
Lepton Number
Violation