The glue that binds us all:

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

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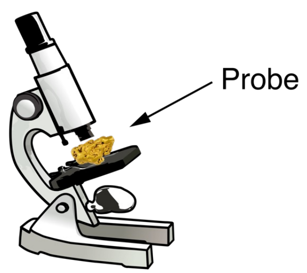
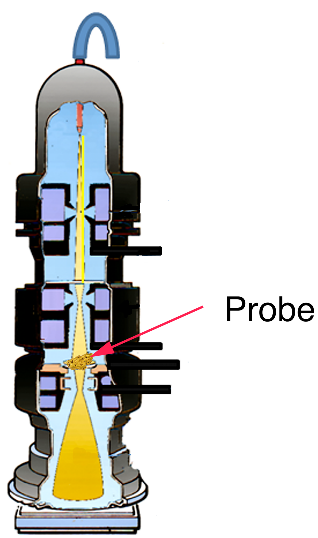
Structure of matter: Microscopes to Femtoscopes

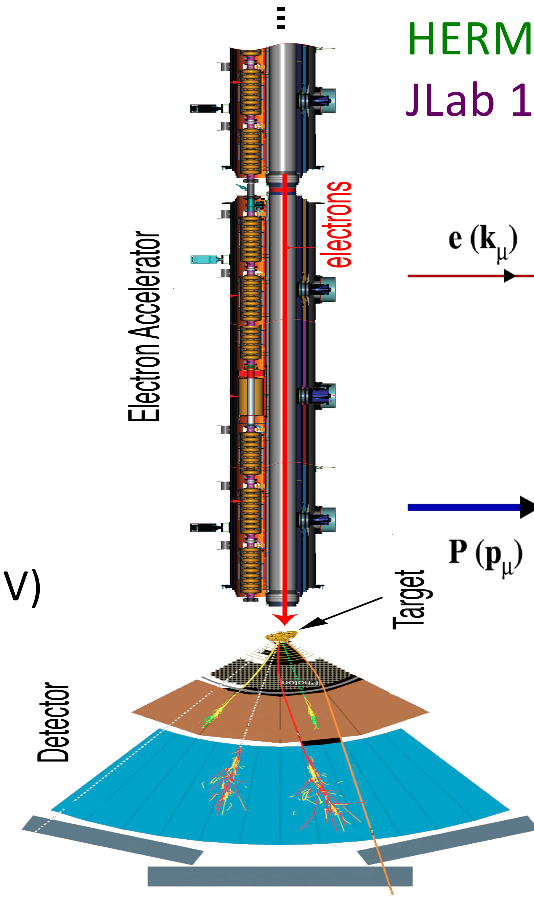
Light Microscope
Wave length: 380-740 nm
Resolution: > 200 nm

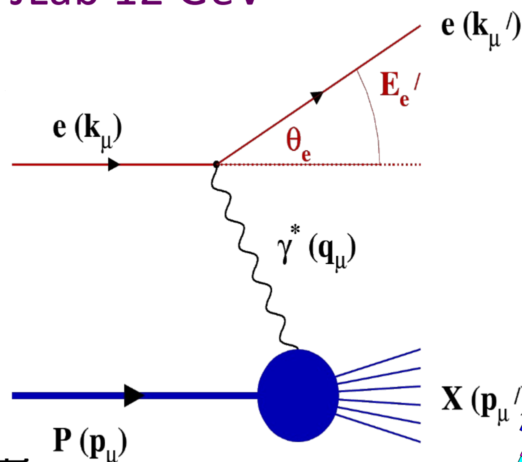


Electron Microscope
Wave length: 0.002 nm (100 keV)
Resolution: > 0.2 nm

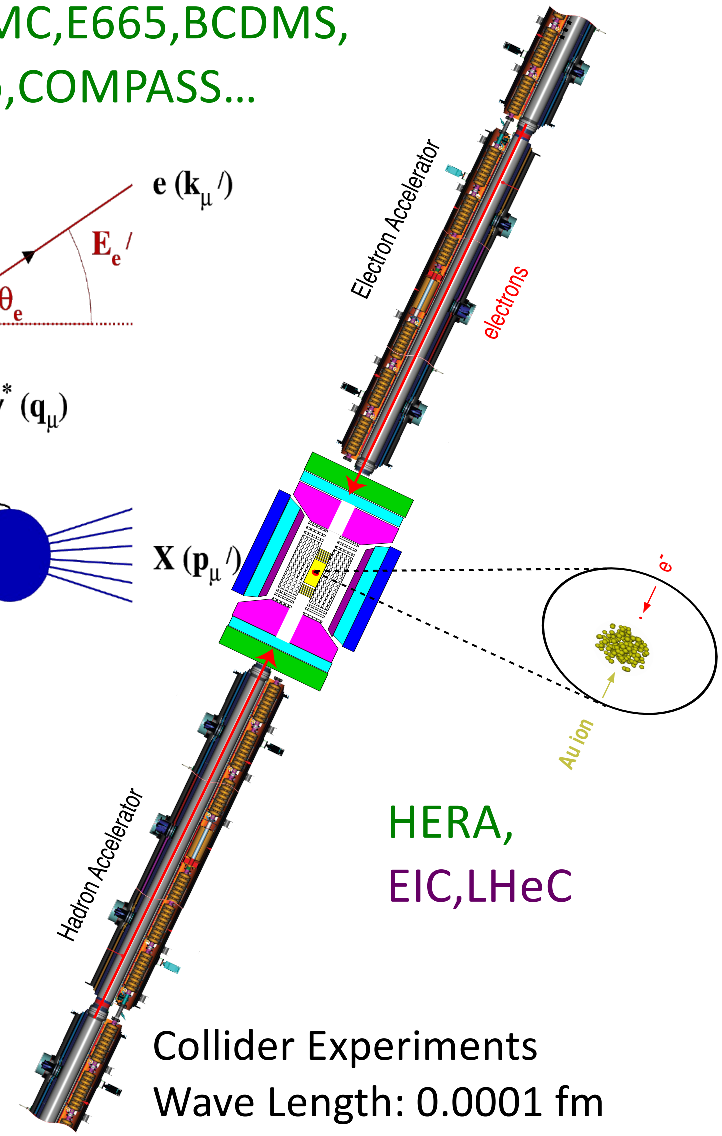


SLAC,EMC,NMC,E665,BCDMS,
HERMES,JLab,COMPASS…
JLab 12 GeV





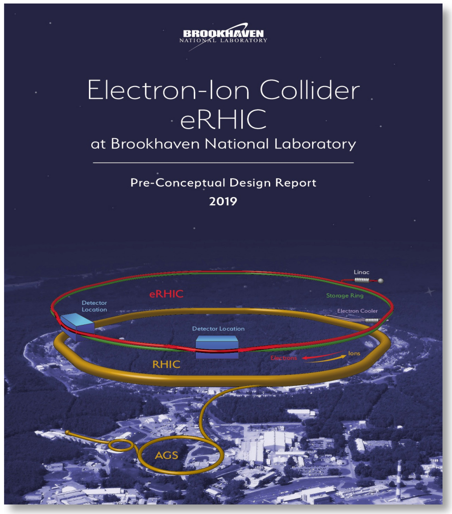
Fixed Target Particle
Accelerator Experiments
Wave length: 0.01 fm (20 GeV)
Resolution: ~ 0.1 fm

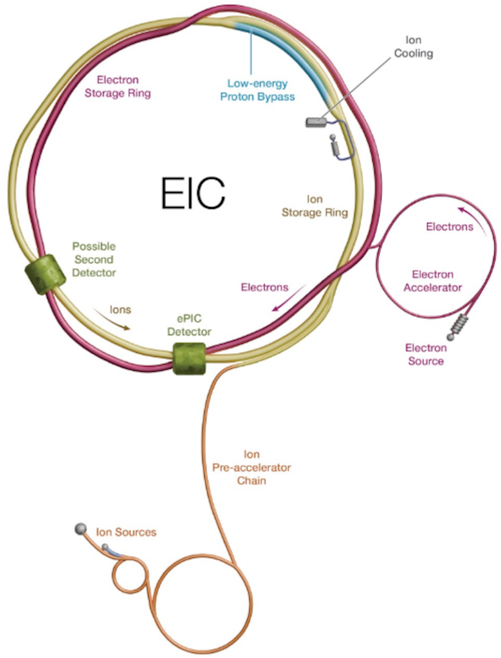


HERA,
EIC,LHeC

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

A powerful new femtoscope: The Electron-Ion Collider





$2-3 Bn Collider approved for construction at BNL – first collisions early 2030s

Polarized protons up to **275 GeV**; Nuclei up to ~ Z/A*275 GeV/n ~ **100 GeV/n**

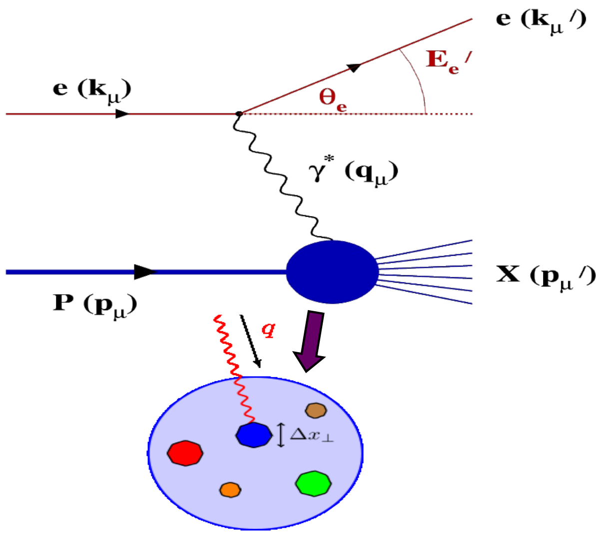
Electrons beams up to **18 GeV;** Center of mass collision energies: **20-140 GeV**

Design optimized to reach **10^{34} cm^{-2}sec^{-1}**

World's first electron-polarized proton and electron-nucleus collider

Luminosities a thousand times only previous collider (HERA)

The deeply inelastic scattering (DIS) femtoscope



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

Measure of resolution power

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

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

Measure of inelasticity

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

Bjorken variable: Measure of momentum fraction of struck quark

Inclusive DIS measurements: e+↑p/A → e'+X

Measure only the scattered lepton in the detector: structure functions (pdfs: F2,FL,**g1,g2**,…)

Semi-inclusive DIS (SIDIS) measurements: **e+↑p/A → e'+h(p,K,p,jet)+X**

Measure electrons in coincidence with identified hadrons/jets (Transverse momentum dependent dists. -TMDs)

Exclusive measurements (DVCS,…): e+↑p/A → e'+ photon/hadron + p/A

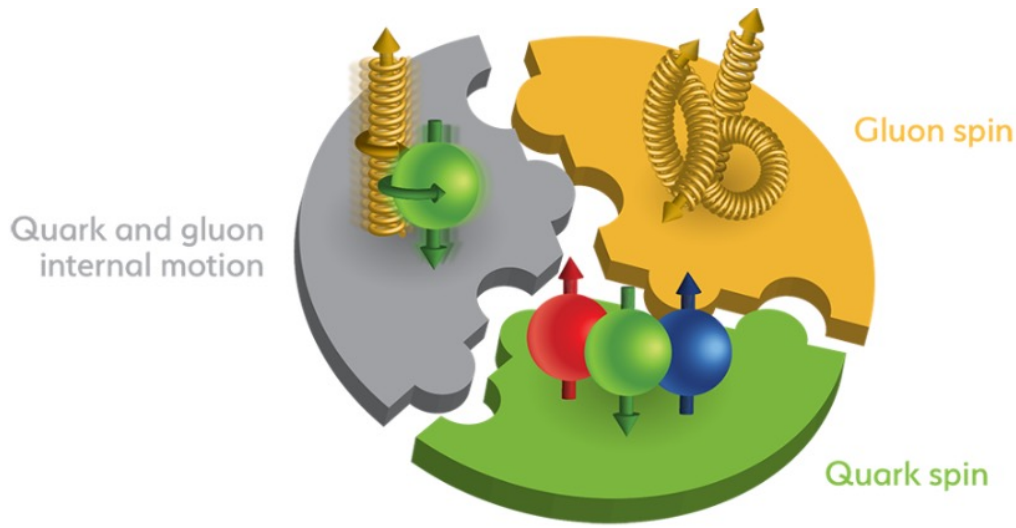
Measure electron, photon (or e.g., vector meson), intact proton/nucleus (Generalized parton dists. -GPDs)

Diffractive measurements: **e+↑p/A → e'+ hadrons/jets + rapidity gap (coherent diff.→ intact p/A)**

As for exclusive, but with rapidity veto on particle production (Diff. structure functions, F_2^D, F_L^D)

Also, measure nuclear fragments, multiparticle correlations, entanglement measures,…

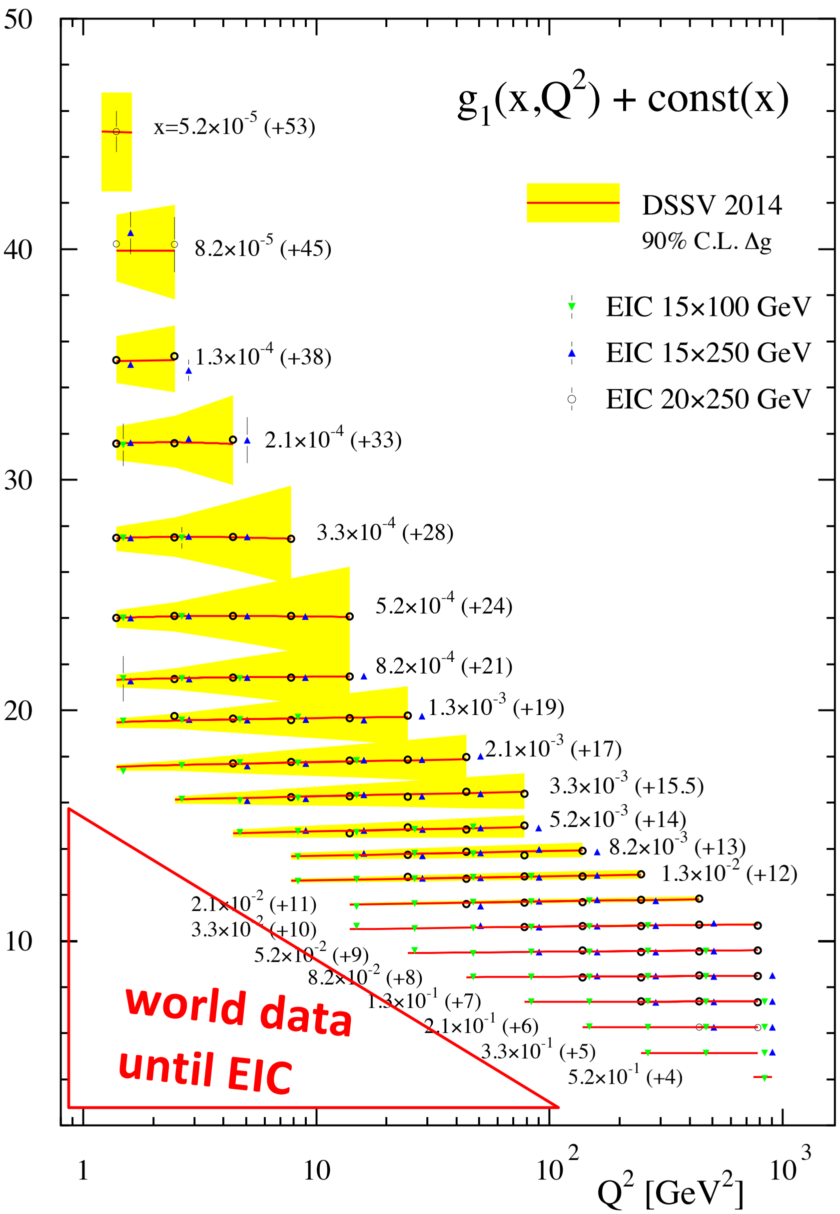
Resolving the proton's spin puzzle

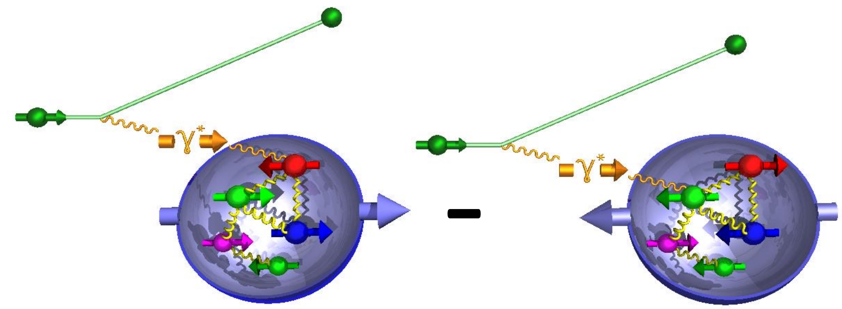


quark spin *gluon spin* *orbital angular momentum*

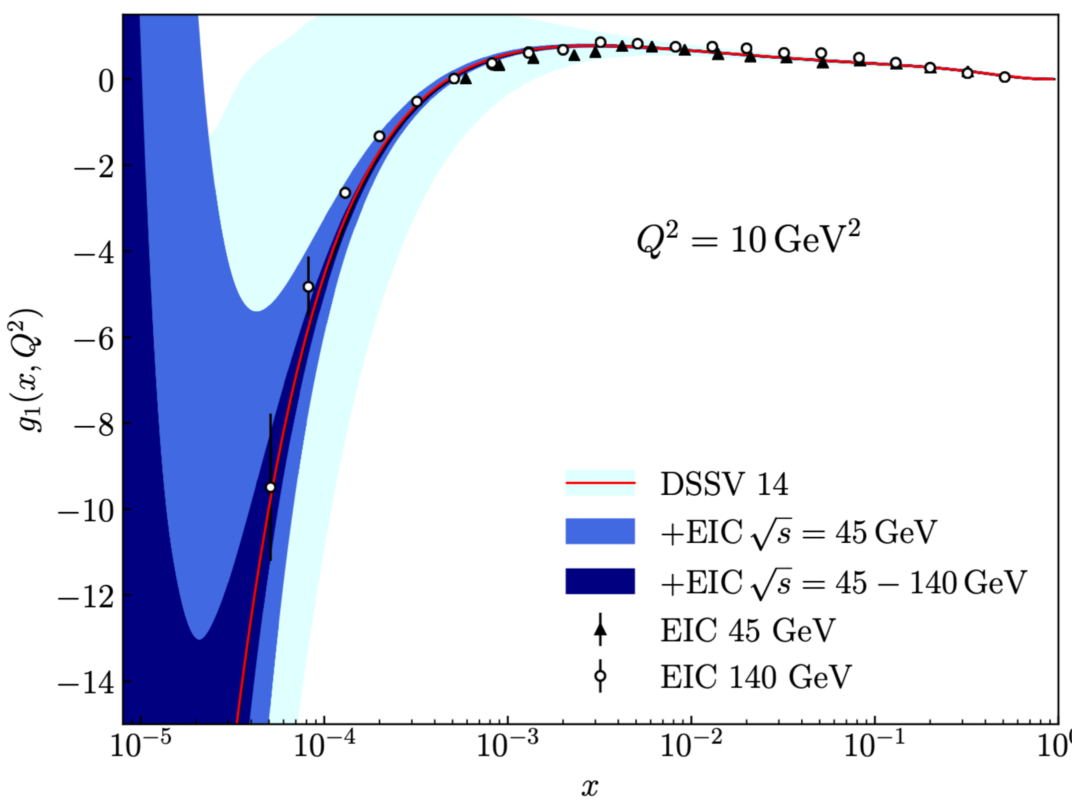
$$\frac{1}{2} = \frac{1}{2}\int_0^1 dx\, \Delta\Sigma(x, Q^2) + \int_0^1 dx\, \Delta G(x, Q^2) + \int_0^1 dx\, (\sum_q L_q + L_g)$$

Resolving the proton's spin puzzle

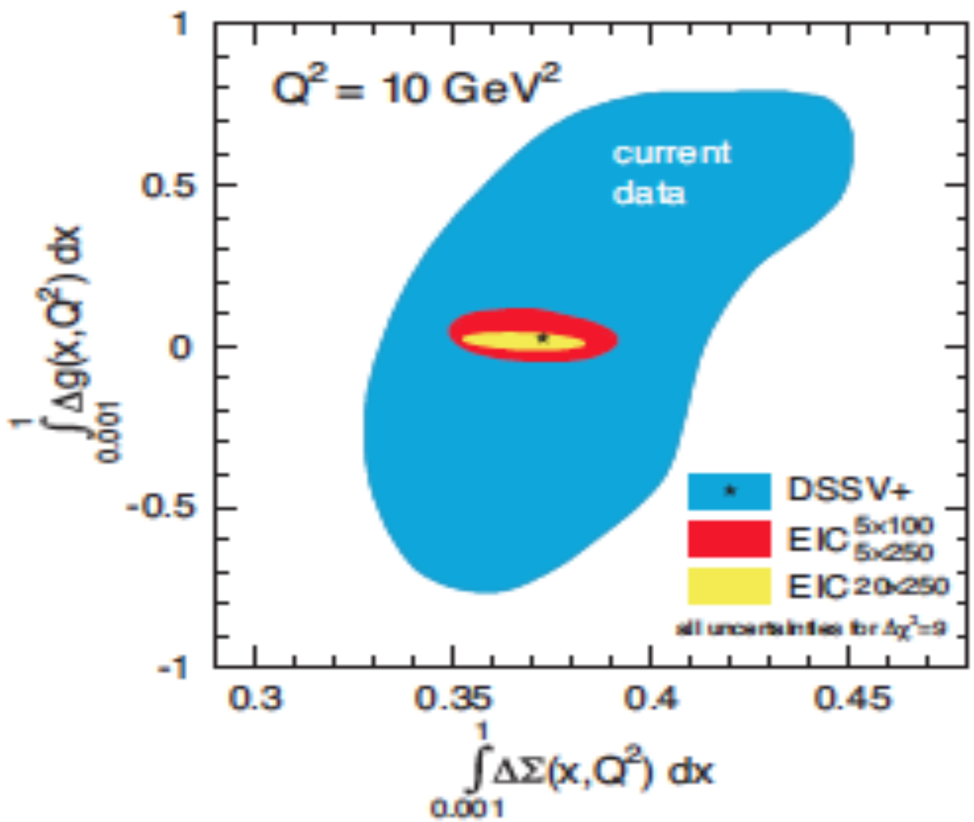


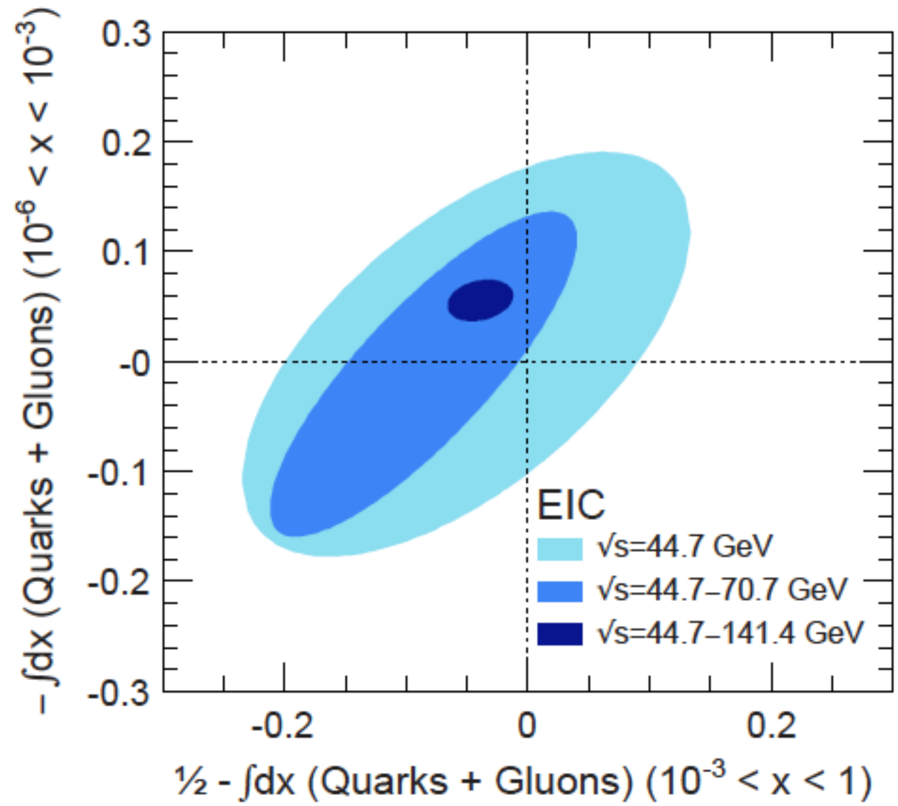


$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx \rightarrow \textbf{quark contr.}$$



Money plot





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

Such distributions can uncover first evidence for novel topological "sphaleron" transitions, that rapidly quench the proton's spin

Tarasov, Venugopalan, arXiv:2109.10370

From the parton model to QCD: role of the chiral anomaly

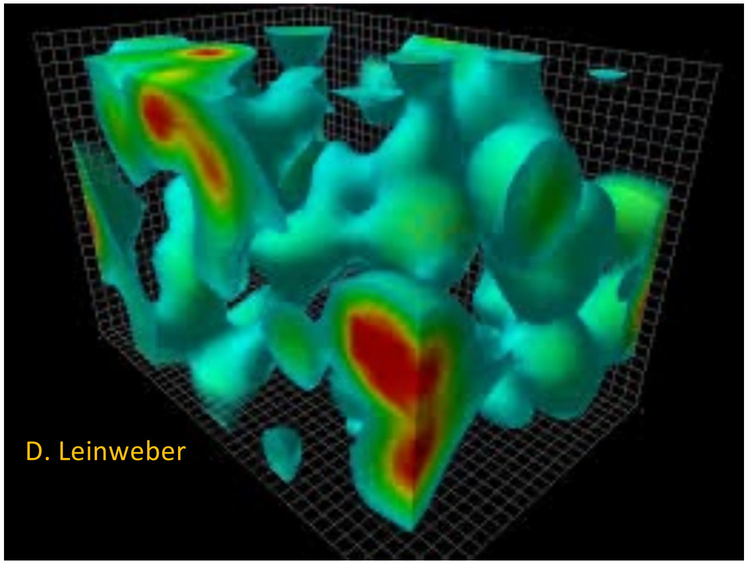
First moment $$\Delta\Sigma(Q^2) \propto \int_0^1 dx\, g_1(x,Q^2)$$

$$S^\mu\,\Delta\Sigma = \langle P,S\,|\,\bar\psi\,\gamma^\mu\gamma_5\,\psi\,|\,P,S\rangle \equiv \langle P,S\,|\,j_5^\mu\,|\,P,S\rangle$$

Isosinglet axial vector current in proton

$U_A(1)$ violation in QCD from the chiral anomaly: $$\partial_\mu J_5^\mu = 2n_f\partial_\mu K^\mu + \sum_{i=1}^{n_f} 2im_i\bar{q}_i\gamma_5 q_i$$

Chern-Simons current $$K_\mu = \frac{g^2}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\left[A_a^\nu\left(\partial^\rho A_a^\sigma - \frac{1}{3}g f_{abc}A_b^\rho A_c^\sigma\right)\right]$$



Polarized DIS is sensitive
to the topology of the QCD vacuum!

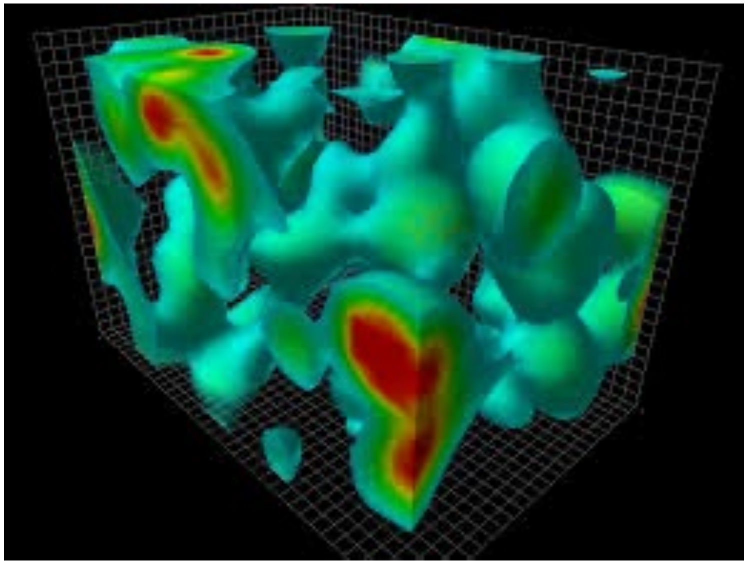
Topological mass generation and quark helicity

$$m_{\eta'}^2 \equiv -\frac{2\,n_f}{F_{\bar{\eta}}^2}\chi_{\rm YM}(0)$$ Witten-Veneziano formula

The mass of the η' meson in QCD (957 MeV) is topologically generated – proportional to the Yang-Mills topological susceptibility

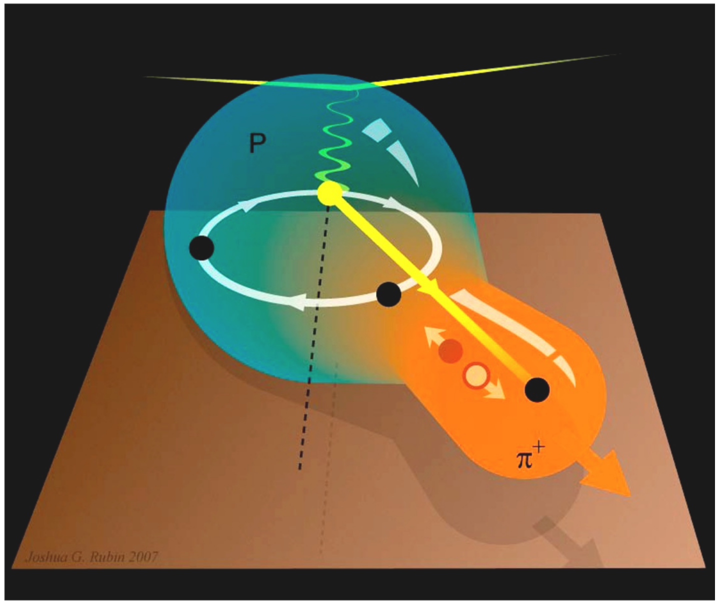
$$\Delta\Sigma(Q^2) = \sqrt{\frac{2}{3}}\,\frac{2n_f}{M_N}\,g_{\eta_0 NN}\,\sqrt{\chi'(0)}$$

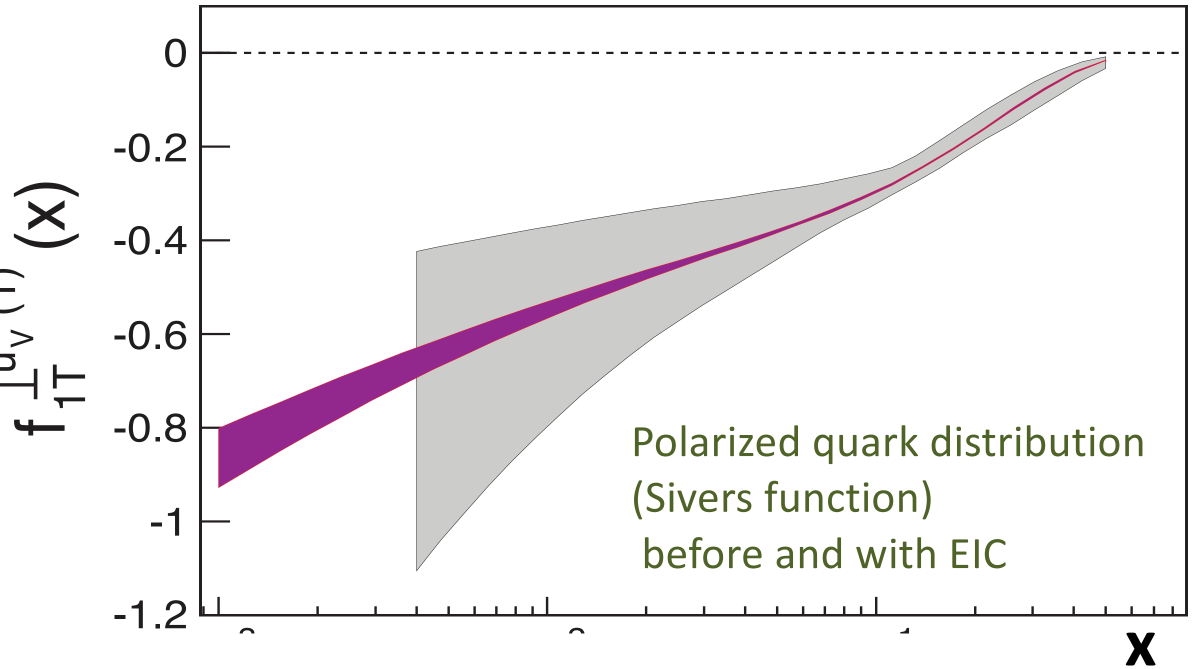
The same underlying physics tells us that the proton's quark helicity is proportional to the QCD topological susceptibility

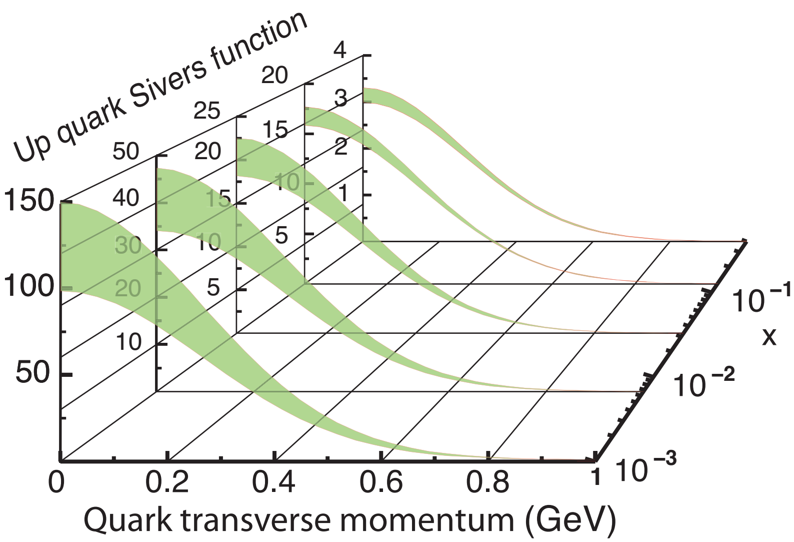


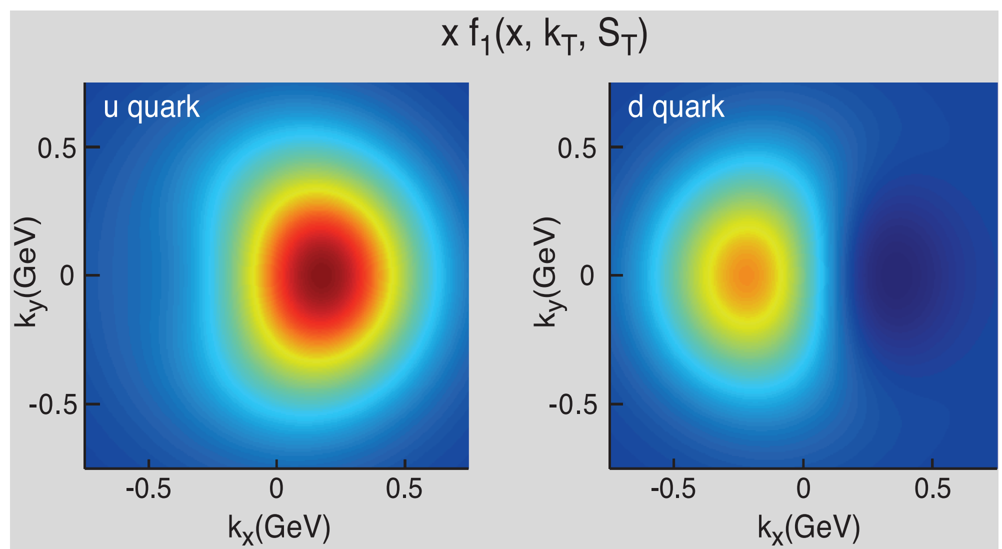
Shore, Veneziano (1990-1992)
Tarasov, RV, PRD (2022-2025)

3-D imaging of momenta in semi-inclusive reactions



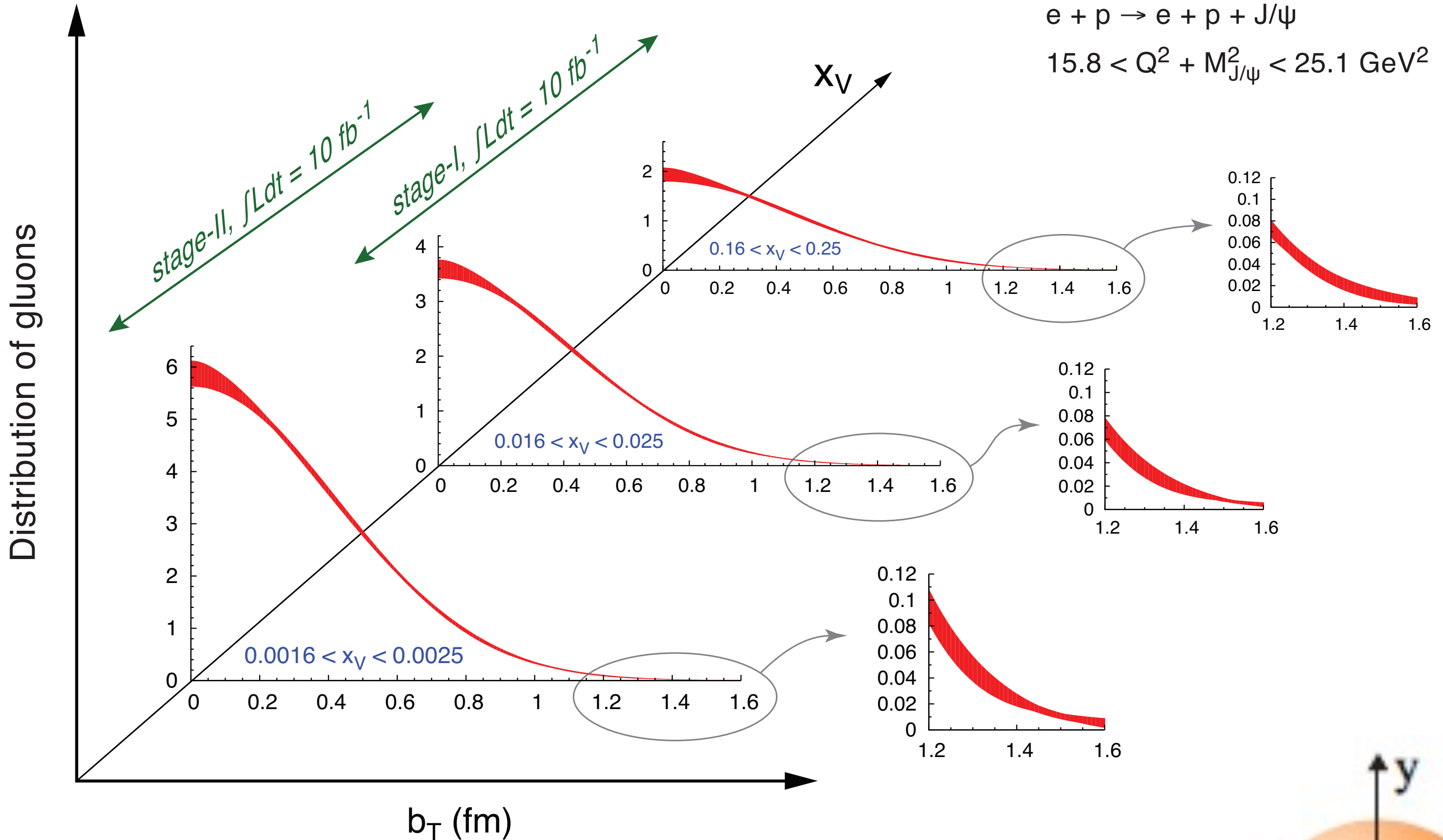


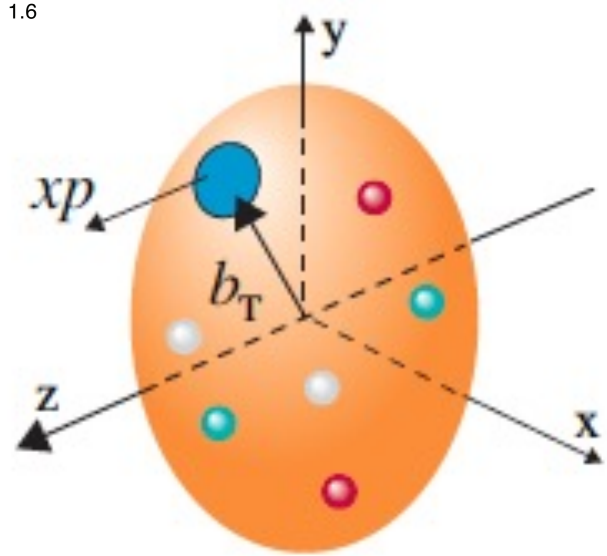




Sivers function: sensitive to "Aharanov-Bohm" type interferences in gluon exchanges

Projected images of spatial gluon distributions



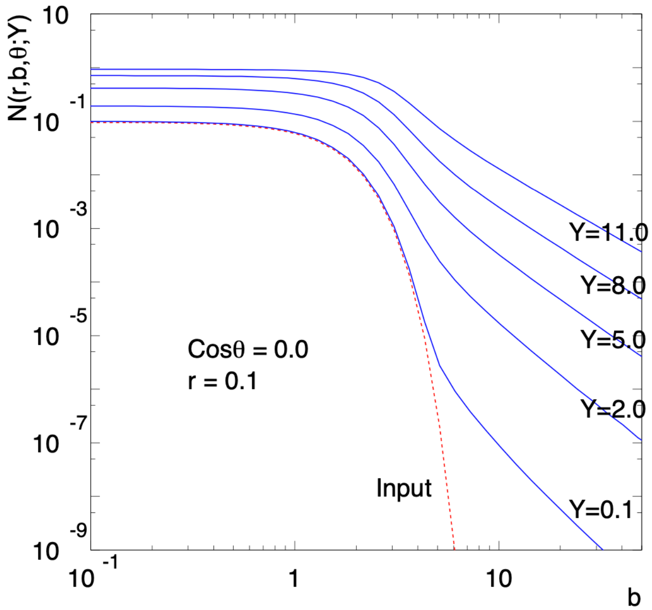


Generalized parton distributions (GPDs) uncover
3-D structure of matter below the Femto-scale:

High precision spatial tomography of gluon
and sea quark distributions

Spatial distributions inside the hadron

Dipole amplitude as function of impact parameter

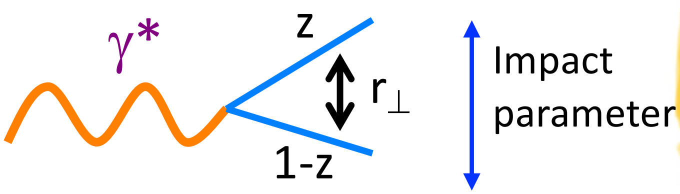


Golec-Biernat, Stasto, hep-ph/0306279

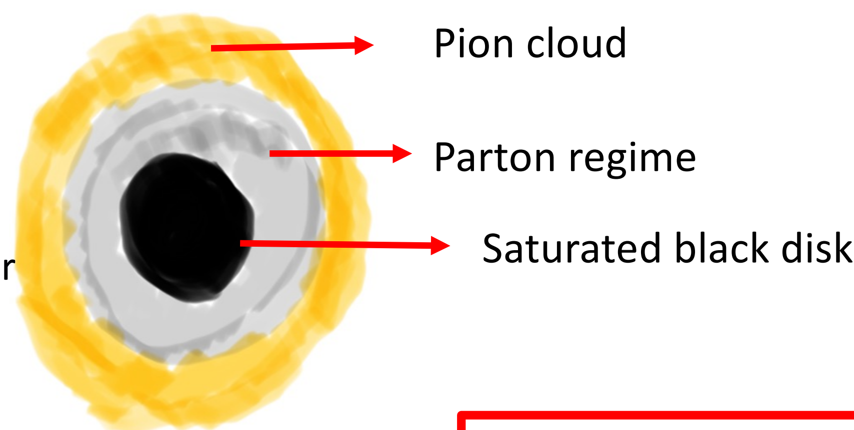
At fixed large b, exponential growth with rapidity

At small b, modest growth characteristic of gluon saturation

Even with sharp exponential suppression of initial dist. with b, Pert. Coulomb tail emerges quickly with rapidity evolution -reflective of missing physics of gluon/quark confinement

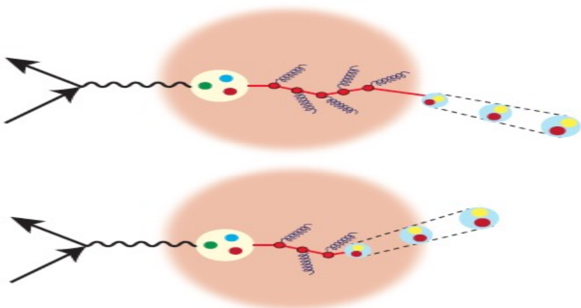


"Gribov" diffusion of the proton

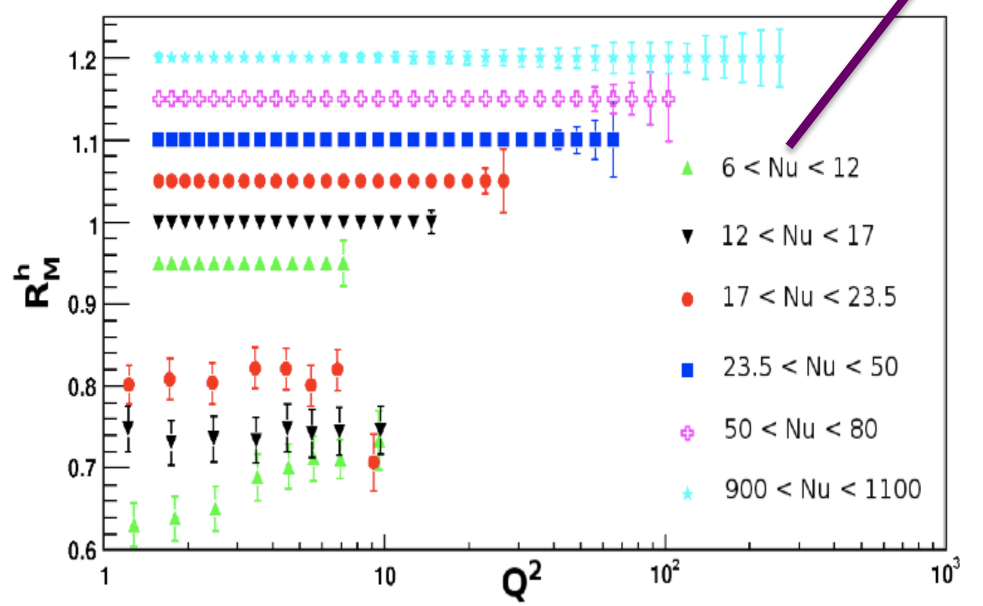


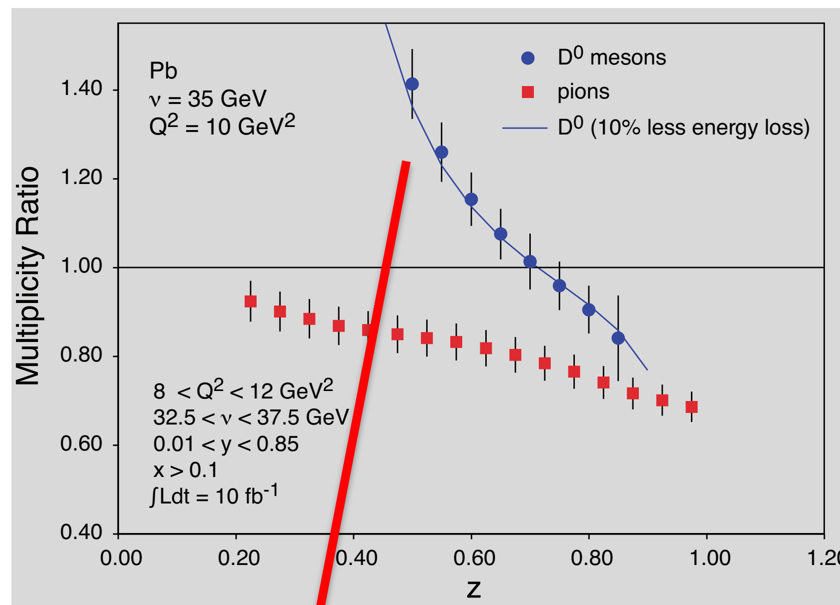
Fresh insight from diffractive/exclusive final states

Transubstantiation of quarks and glue into mesons and baryons



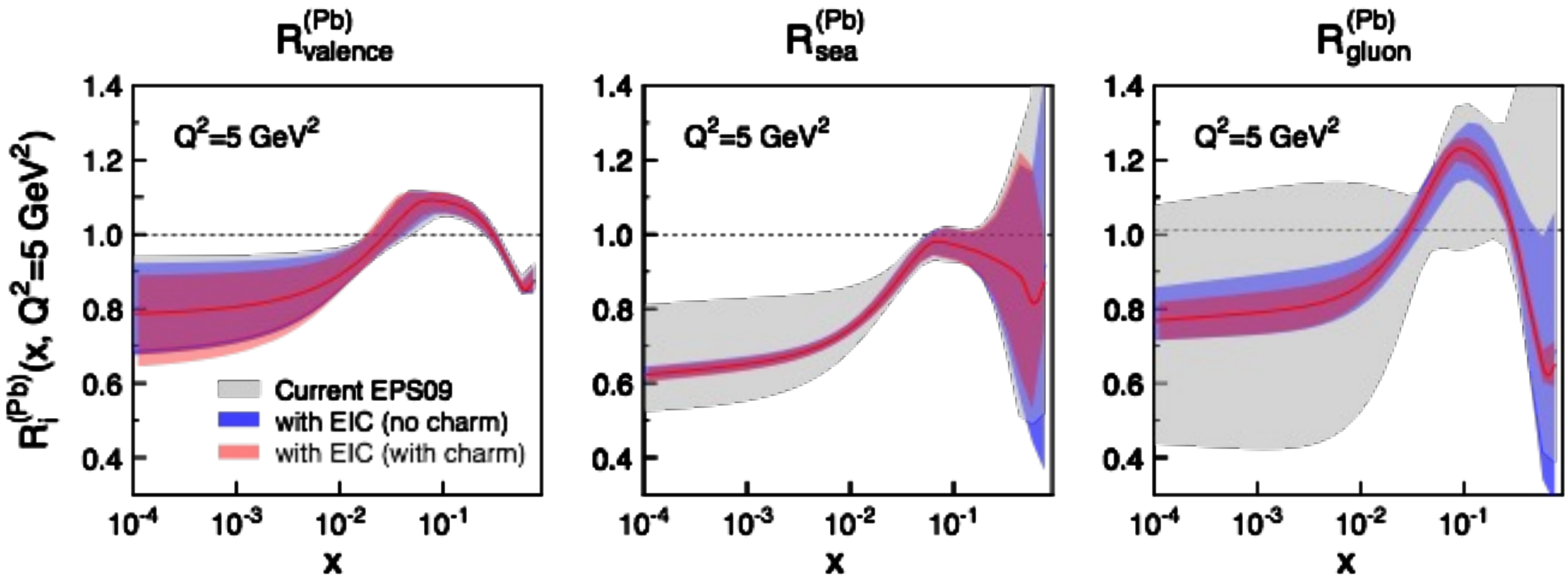
Nu is a coherence length. Dialing it determines whether quarks (gluons) fragment in or out of nucleus





Novel sensitivity to heavy quark fragmentation

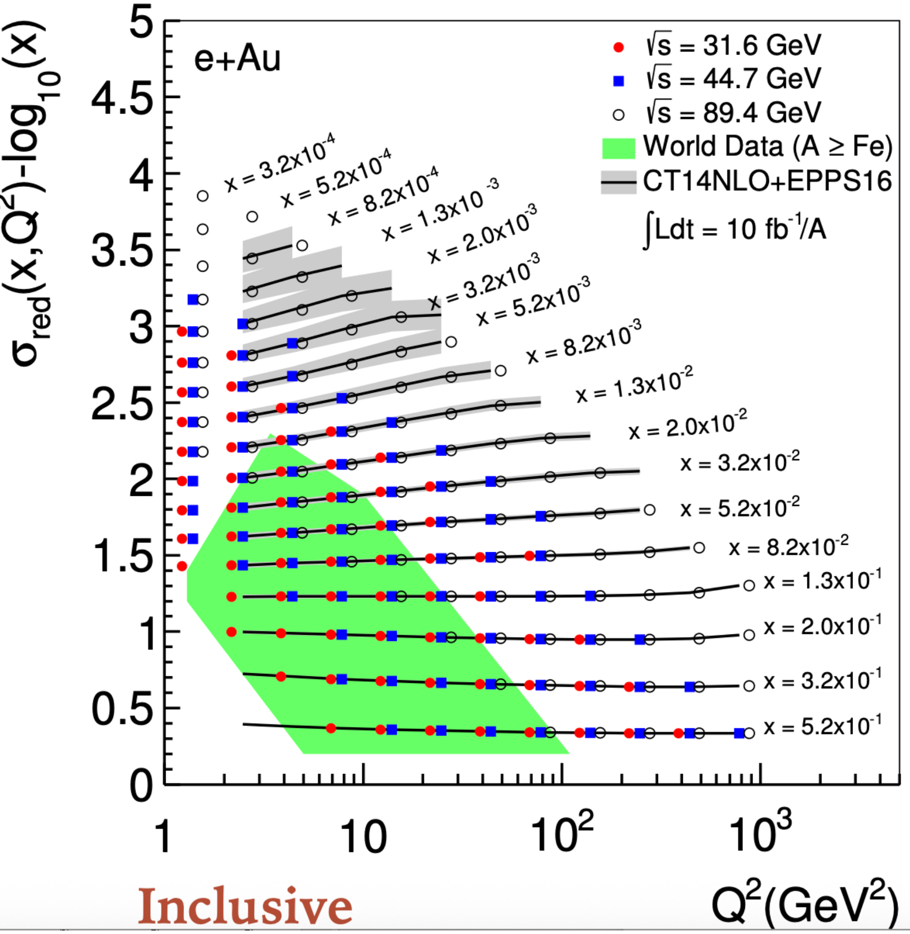
Entering terra-incognita in nuclei



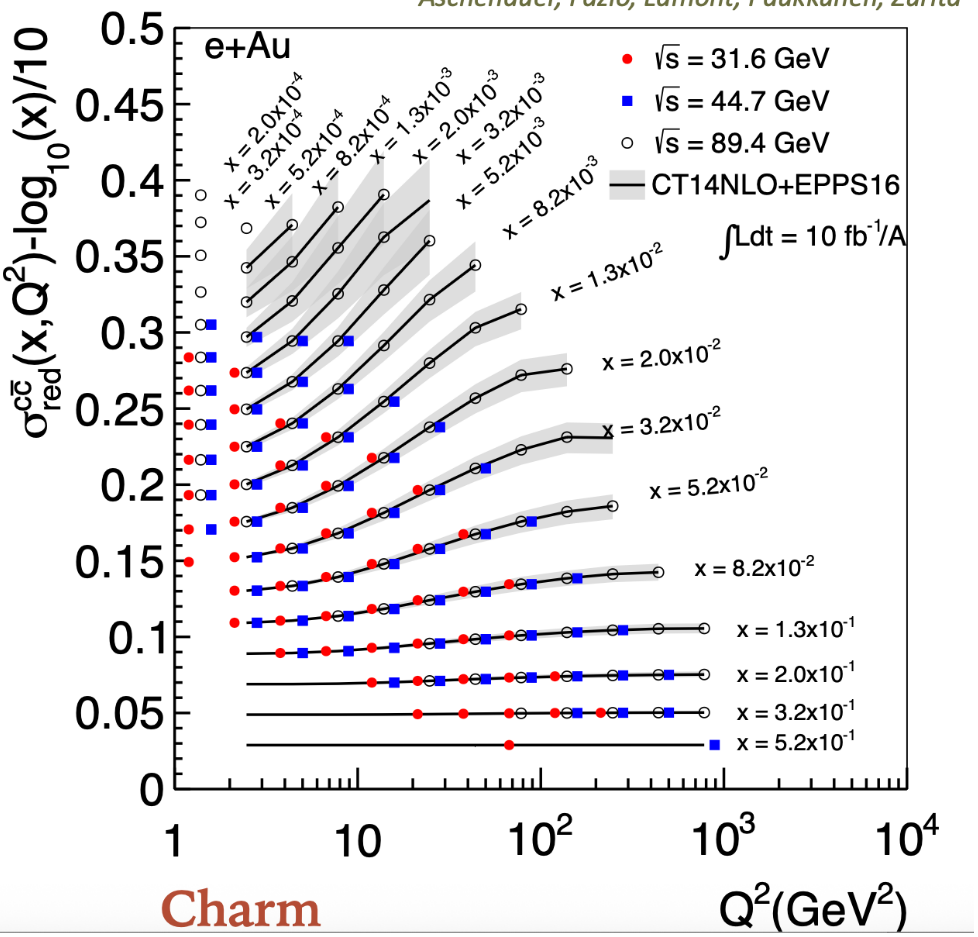
Dramatic improvement in precision extraction of nuclear gluons and sea quarks

Entering terra-incognita in nuclei

Aschenauer, Fazio, Lamont, Paukkunen, Zurita



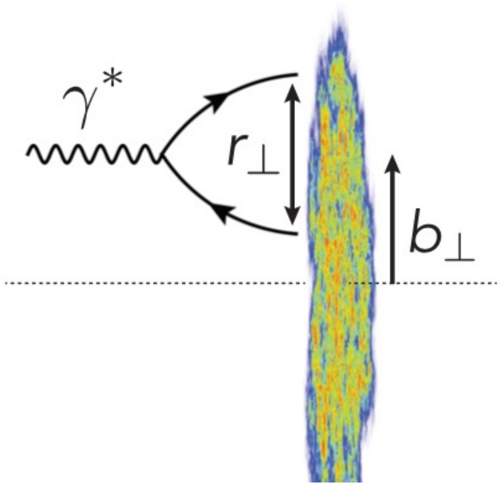
Inclusive



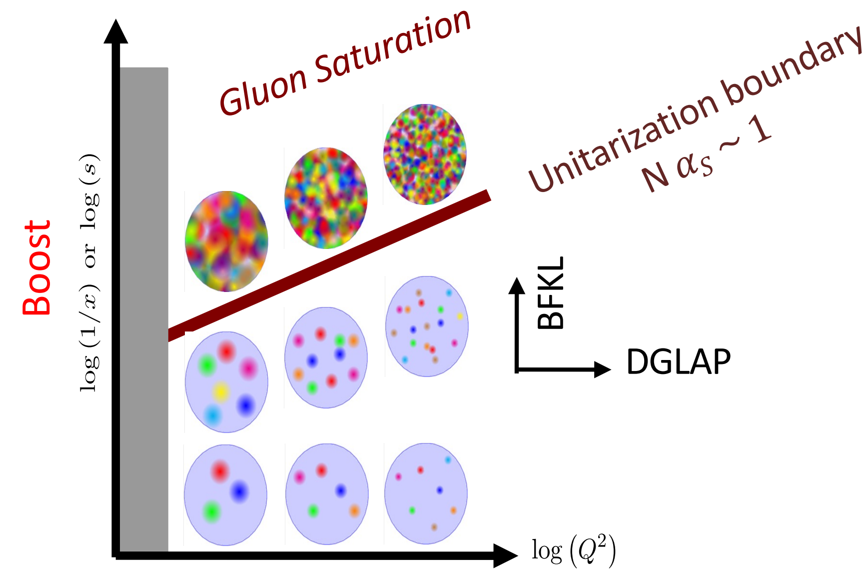
Charm

Dramatic improvement in precision extraction of nuclear gluons and sea quarks

Gluon saturation



Boosted target



$$\sigma_{q\bar{q}P}(r_\perp, x) = \sigma_0 \left[1 - \exp\left(-r_\perp^2\, Q_s^2(x)\right)\right]$$

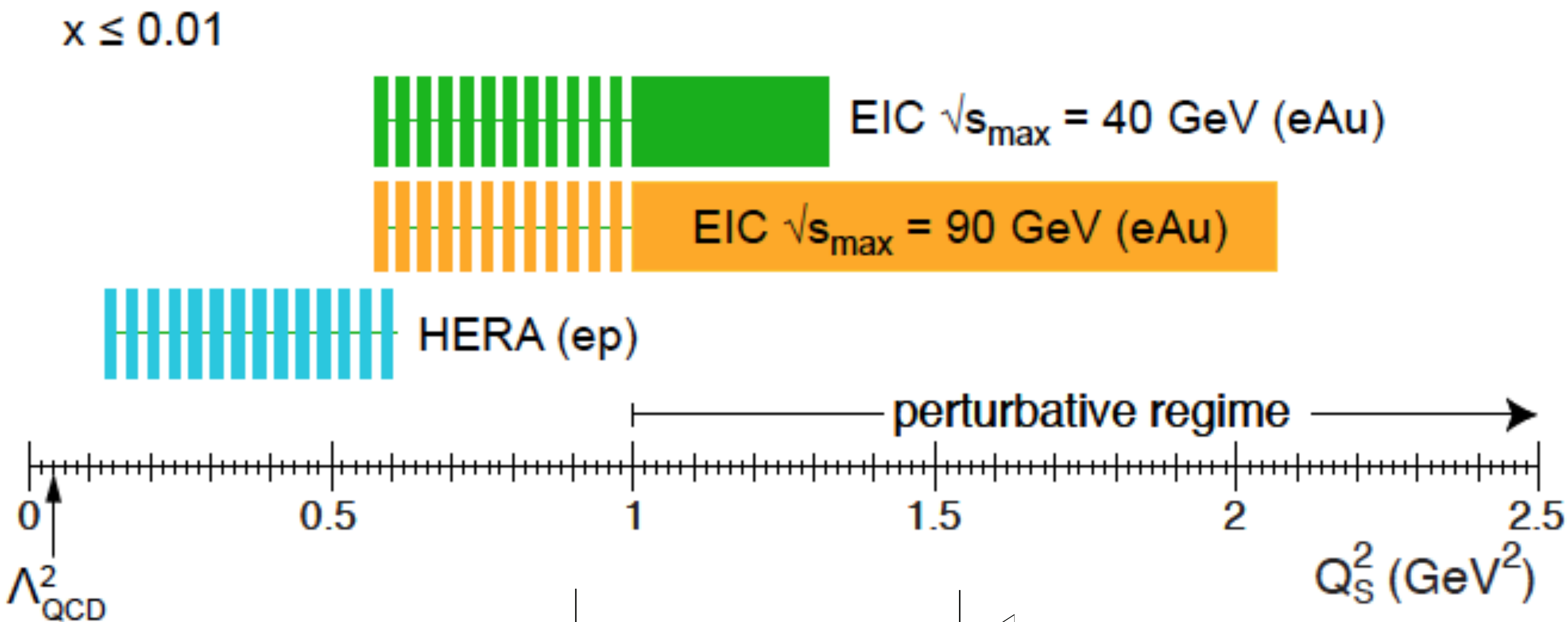
Emergent semi-hard scale $Q_s^2(x) = Q_0^2 \left(\frac{x_0}{x}\right)^\lambda$ → BFKL eigenvalue

Color transparency for $r_\perp^2 Q_S^2$ << 1 ($\sigma \propto A$)

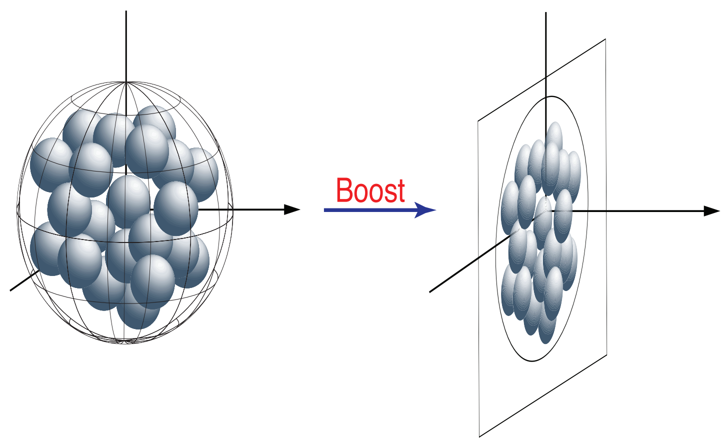
Color opacity ("black disk") for $r_\perp^2 Q_S^2$ >> 1 ($\sigma \propto A^{2/3}$)

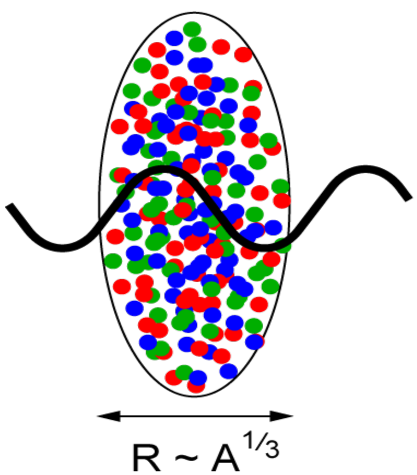
QCD picture of observed "shadowing" at small x

Saturation scale from dipole model fits to DIS data



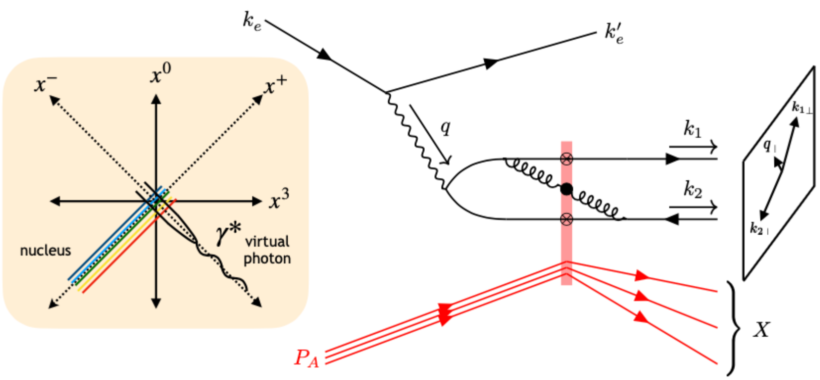
Big nuclear oomph:





dipole couples coherently with color charges in different nucleons in path of its scattering: $Q_S^2 \sim A^{1/3}$

Back-to-back dijets as a probe of gluon saturation



Back-to-back di-jets in DIS

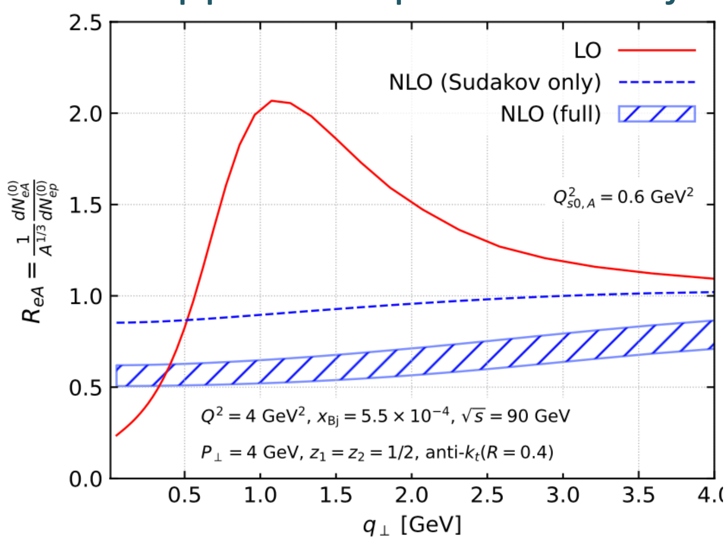
Factorization of small-x TMDs to NLO accuracy

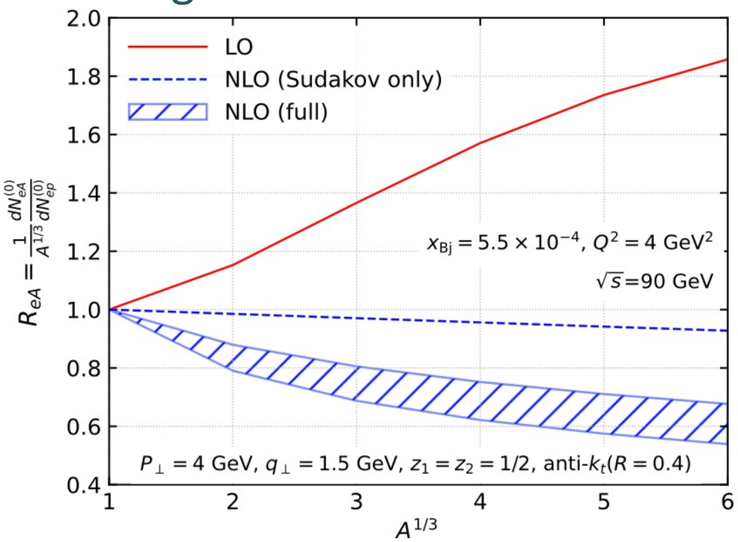
$$\mathrm{d}\sigma^{(0),\lambda=\mathrm{T}} = \mathcal{H}_{\mathrm{LO}}^{0,\lambda=\mathrm{T}} \int \frac{\mathrm{d}^2\boldsymbol{B}_\perp}{(2\pi)^2} \int \frac{\mathrm{d}^2\boldsymbol{r}_{bb'}}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{r}_{bb'}} \hat{G}^0_{\eta_c}(\boldsymbol{r}_{bb'},\mu_0)\mathcal{S}(\boldsymbol{P}_\perp^2,\mu_0^2)$$
$$\times\left\{1+\frac{\alpha_s(\mu_R)N_c}{2\pi}f_1^{\lambda=\mathrm{T}}(\chi,z_1,R)+\frac{\alpha_s(\mu_R)}{2\pi N_c}f_2^{\lambda=\mathrm{T}}(\chi,z_1,R)+\alpha_s(\mu_R)\beta_0\ln\left(\frac{\mu_R^2}{P_\perp^2}\right)\right\}$$
$$+\mathcal{H}_{\mathrm{LO}}^{0,\lambda=\mathrm{T}} \int \frac{\mathrm{d}^2\boldsymbol{B}_\perp}{(2\pi)^2} \int \frac{\mathrm{d}^2\boldsymbol{r}_{bb'}}{(2\pi)^2} e^{-i\boldsymbol{q}_\perp\cdot\boldsymbol{r}_{bb'}} \hat{h}^0_{\eta_c}(\boldsymbol{r}_{bb'},\mu_0)\mathcal{S}(\boldsymbol{P}_\perp^2,\mu_0^2)$$
$$\times\frac{-2\chi^2}{1+\chi^4}\left\{\frac{\alpha_s(\mu_R)N_c}{2\pi}\left[1+\ln(R^2)\right]+\frac{\alpha_s(\mu_R)}{2\pi N_c}\left[-\ln(z_1z_2R^2)\right]\right\}+\mathcal{O}\left(\frac{q_\perp}{P_\perp},\frac{Q_s}{P_\perp},\alpha_sR^2,\alpha_s^2\right)$$

$\hat{G}^0$ and $\hat{h}^0$ respectively are unpolarized and linearly polarized WW distributions,

$\mathcal{S}$ the Sudakov soft factor resumming double+single logs in P_T/q_T

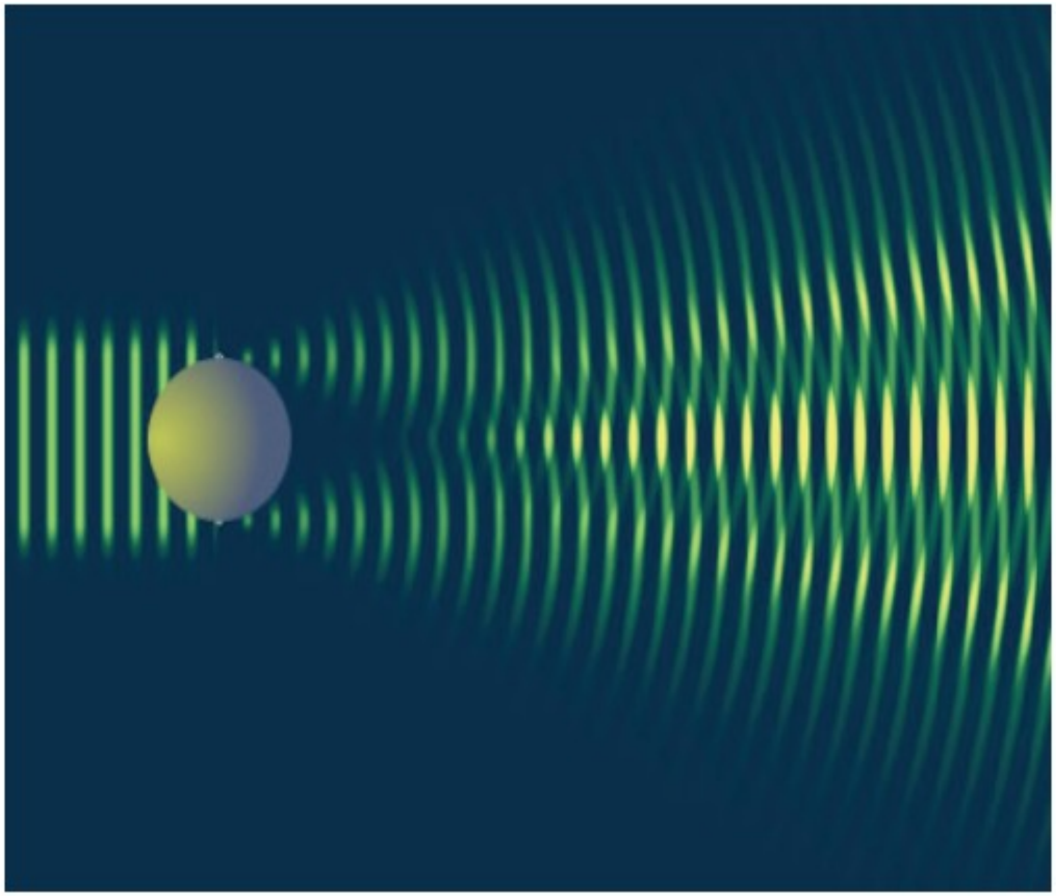
Suppression pattern in di-jets due to gluon saturation at the EIC

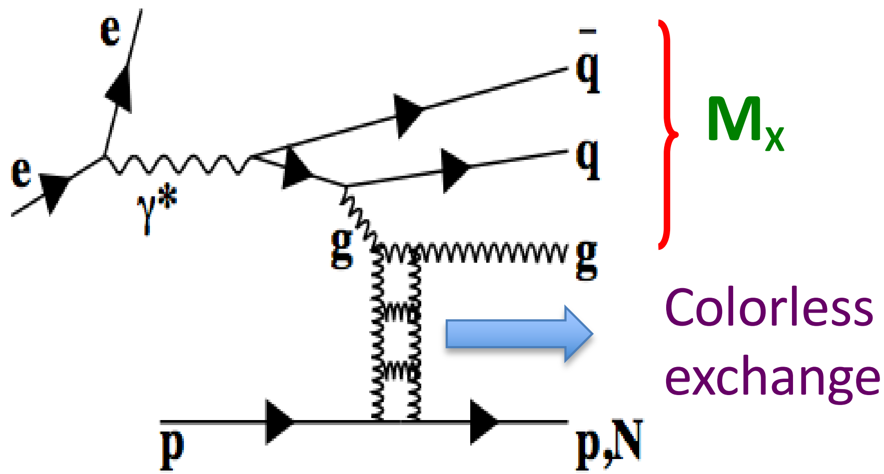




Caucal, Salazar, Schenke, Stebel, RV, arXiv:2308.00022, (PRL 2024)

Diffraction for the 21st Century



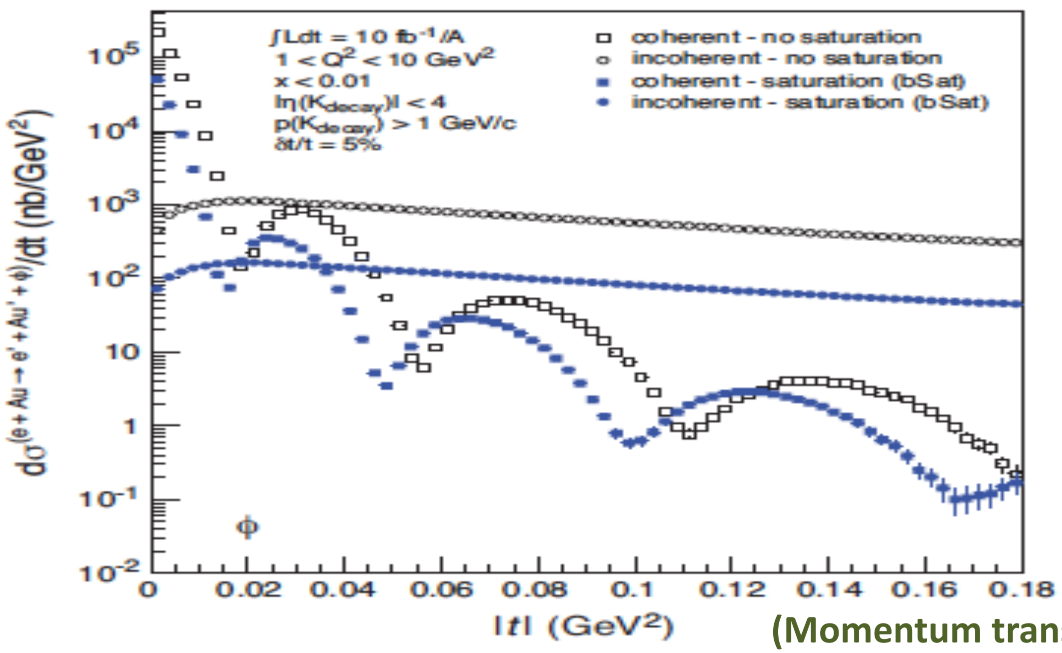


$$|e^-\rangle = |e_B\rangle + |e_B\,\gamma^*\rangle + |e_B\,\gamma^*\,q\bar{q}\rangle + |e_B\,\gamma^*\,q\bar{q}\,g\rangle + \cdots$$

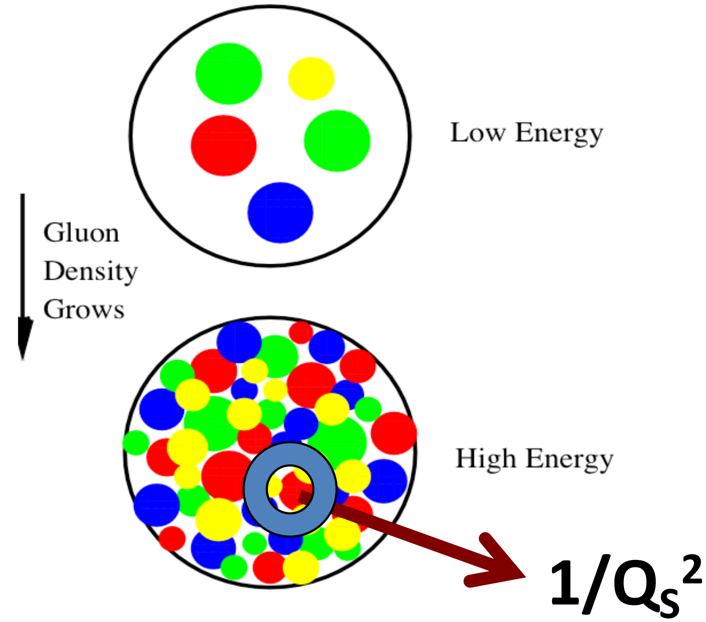
A TeV electron hits a nucleus (binding energy of 8 MeV/nucleon)

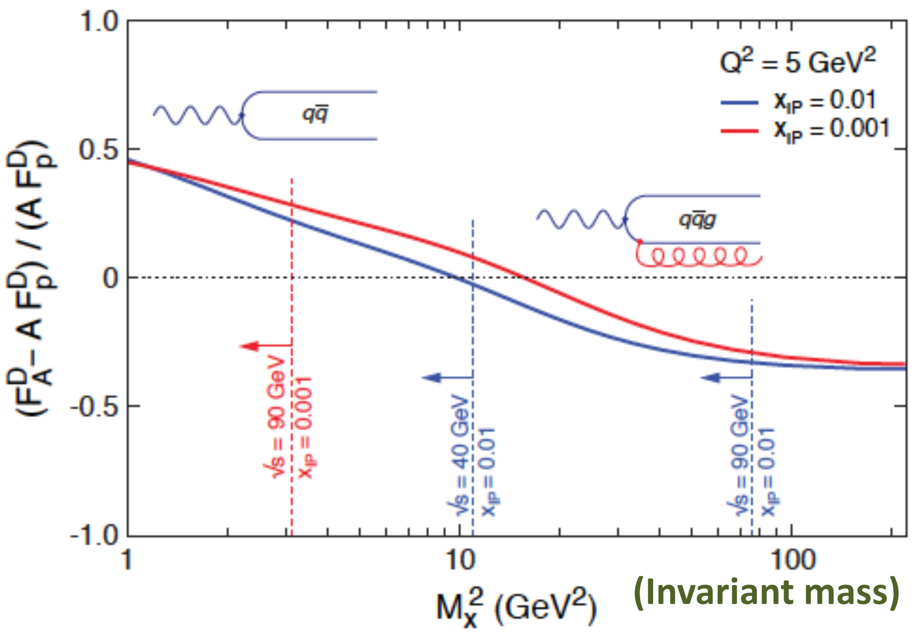
Day 1 prediction of gluon saturation: nucleus remains intact in 1 in 5 events

Diffraction for the 21st Century



(Momentum transfer)





(Invariant mass)

Such diffractive patterns are very sensitive to the wave-particle duality of overoccupied gluons

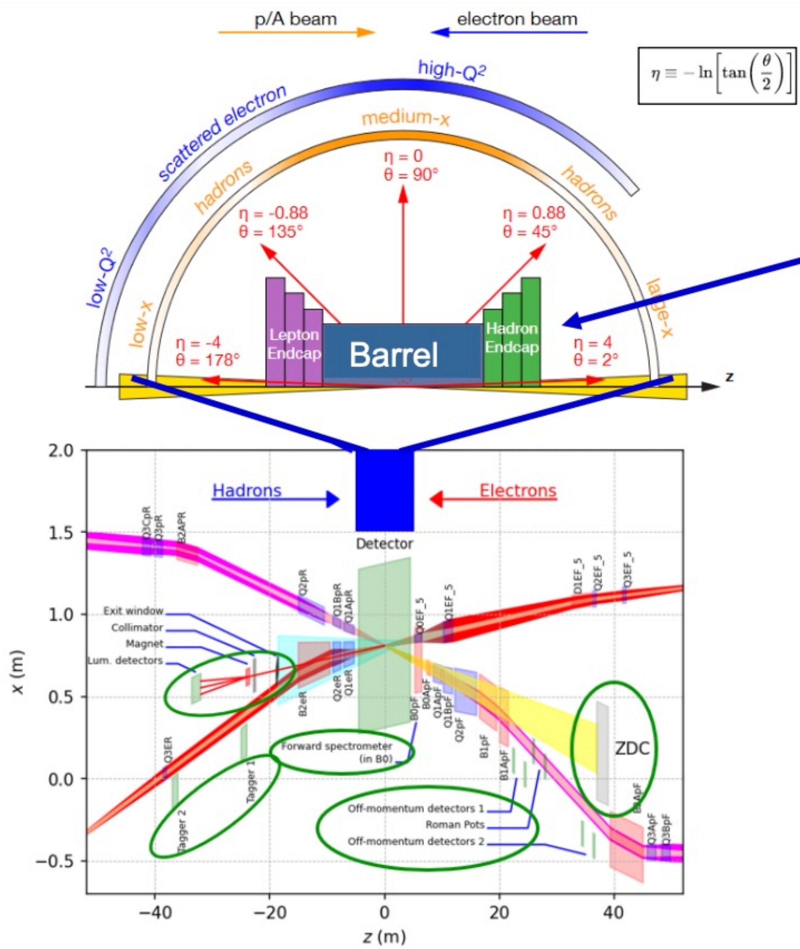
Can we understand such patterns in the language of quantum entanglement?

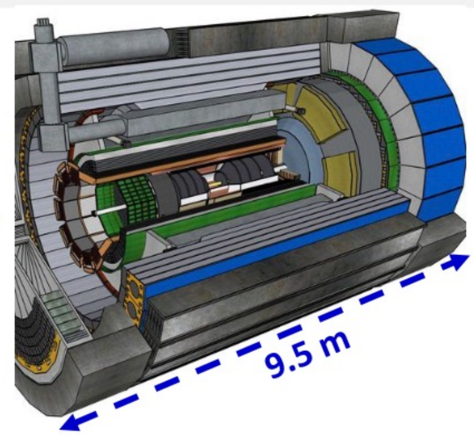
The EIC detector

Slide from S. Dalla Torre talk at EICUG

ePIC, an extended detector

ePIC





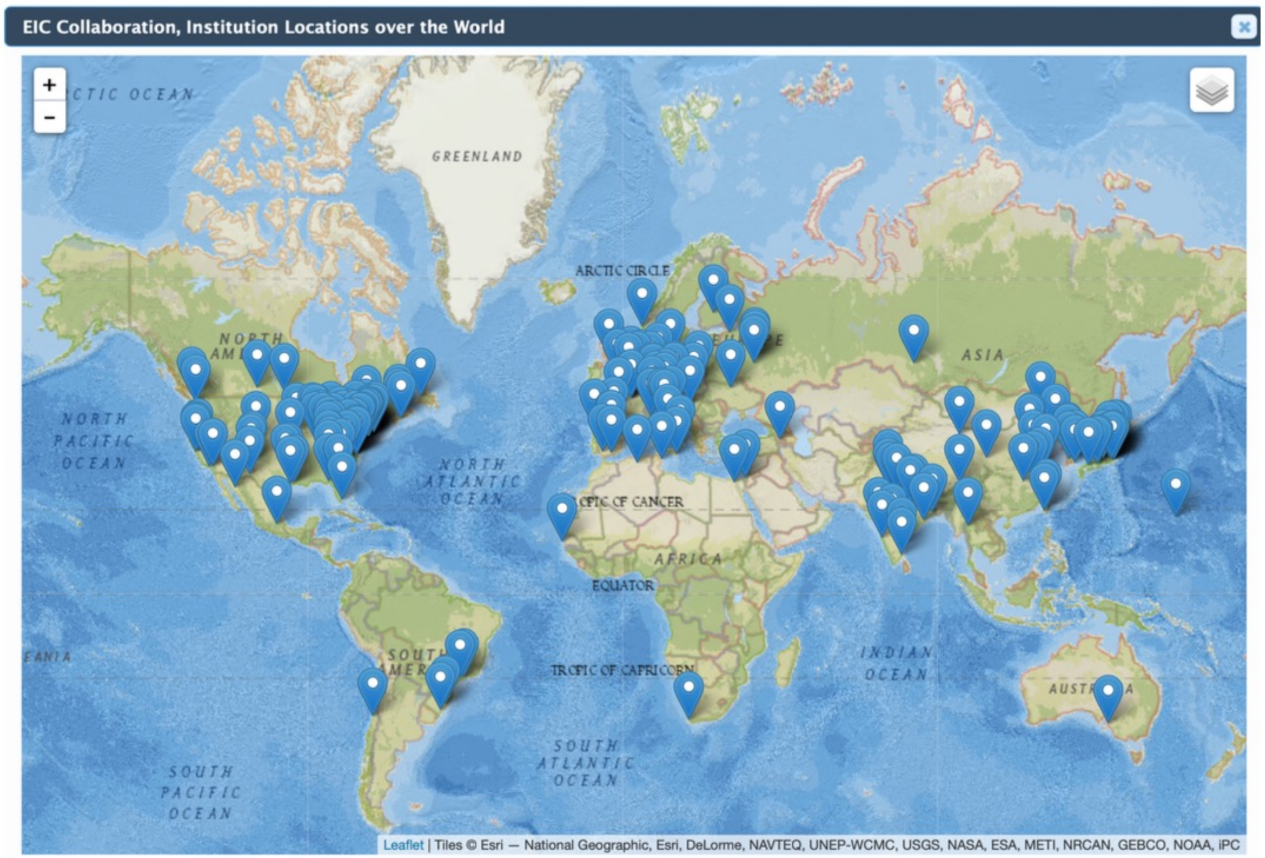
Central Detector (CD)

Total size detector: ~75m
Central detector: ~10m
Far Backward electron detection: ~35m
Far Forward hadron spectrometer: ~40m

Auxiliary detectors needed to tag particles with very small scattering angles both in the outgoing lepton and hadron beam direction (B0-Taggers, Off-momentum taggers, Roman Pots, Zero-degree Calorimeter and low Q2-tagger).

EIC Users Group

The **Electron-Ion Collider User Group (EICUG)** is an international affiliation of scientists dedicated to developing and promoting the scientific, technological, and educational goals and motivations for a new high energy **Electron-Ion Collider.**



1411 members

- 879 experimentalists
- 359 theorists
- 158 accelerator scientists
- 9 computer scientists
- 4 support
- 2 other

283 institutions

37 countries

https://www.eicug.org/index.html

Status as of September 3, 2023