(Nuclear physics at) the Electron-Ion Collider

Alberto Accardi
Hampton U. and Jefferson Lab

Quark Matter Italia

Rome, July 23rd, 2010

my gratitude for discussions, ideas, slides, to

J.Arrington, E.Aschenauer, W.Brooks,
F.Caola, I.Cloet, A.Daniel, R.Dupre, R.Ent,
S.Forte, V.Guzey, K.Hafidi, C.Keppel,
M.Lamont, V.Litvinenko, A.Majumder,
J.Rojo, T.Ullrich, Y.Zhang, ...

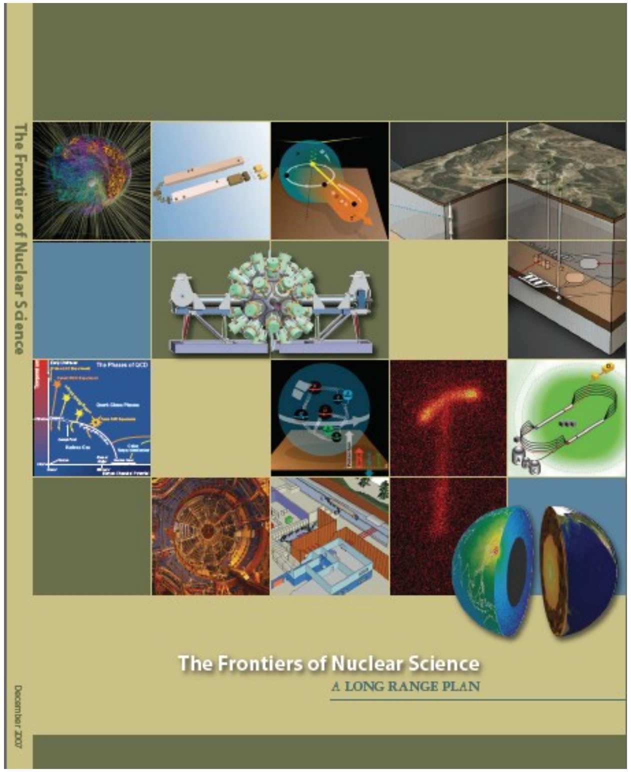
Overview

- The EIC project
- EIC science
- Basics of Deep-Inelastic Scattering
- Selected topics
  - Saturation and the Color Glass Condensate
  - Nuclear structure functions at medium-, large-x
  - Parton propagation and fragmentation in QCD matter
- Conclusion

- Appendices: useful links, additional observables

The EIC project

The EIC project



NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**.

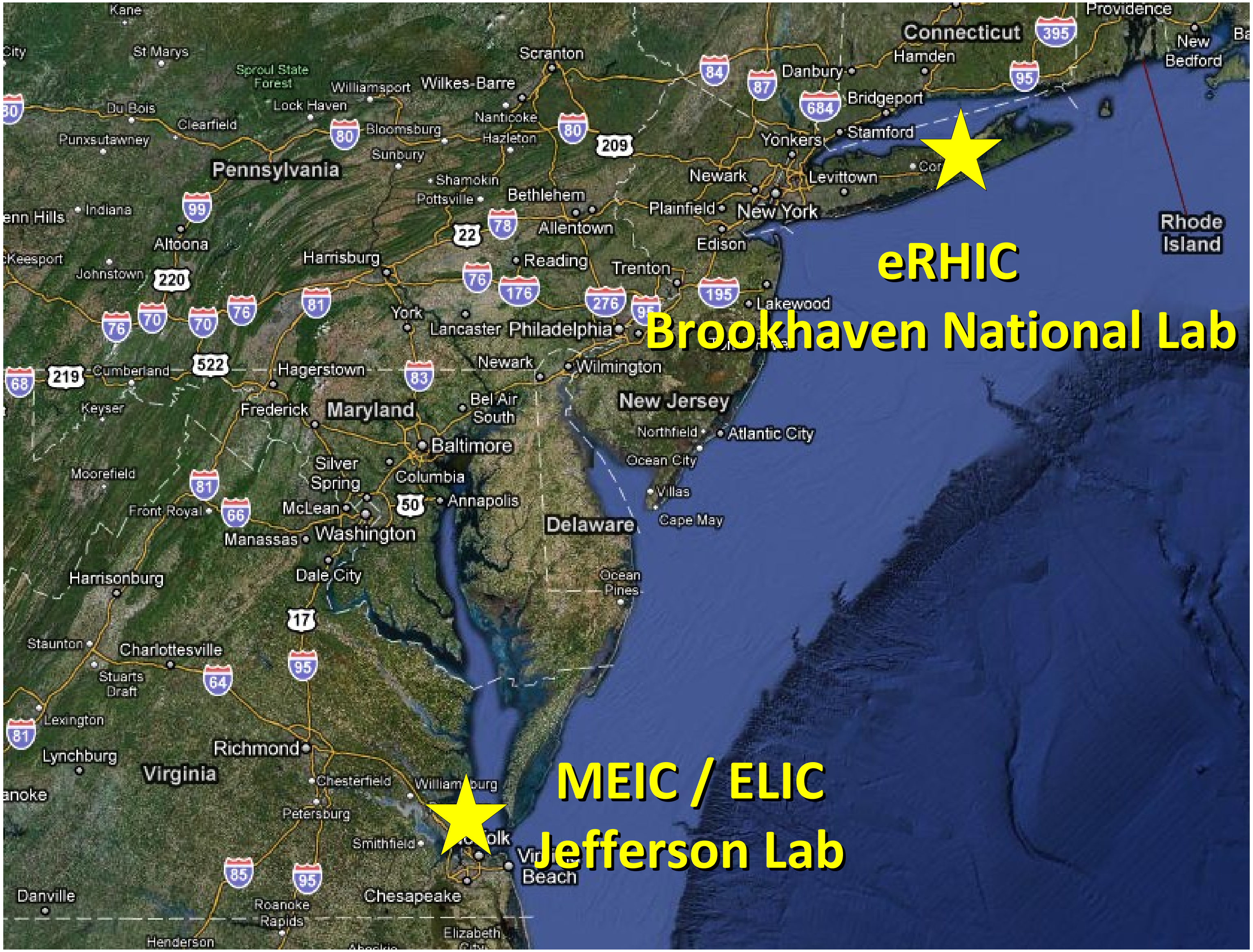
EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

The EIC project

US initiative driven by the QCD community in NP

- Colliding
  - (un)polarized electrons up to 20 (30) GeV
  - Hadrons
    - protons up to 250 GeV
    - ions up to Au/U at 100 GeV
  - with unprecedented luminosities (> 100x Hera)
- Unique
  - High energy eA collisions
  - Polarized beams:
    - e↑p↑
    - e↑ ^{3}He↑
- Timeline: ~ 2020

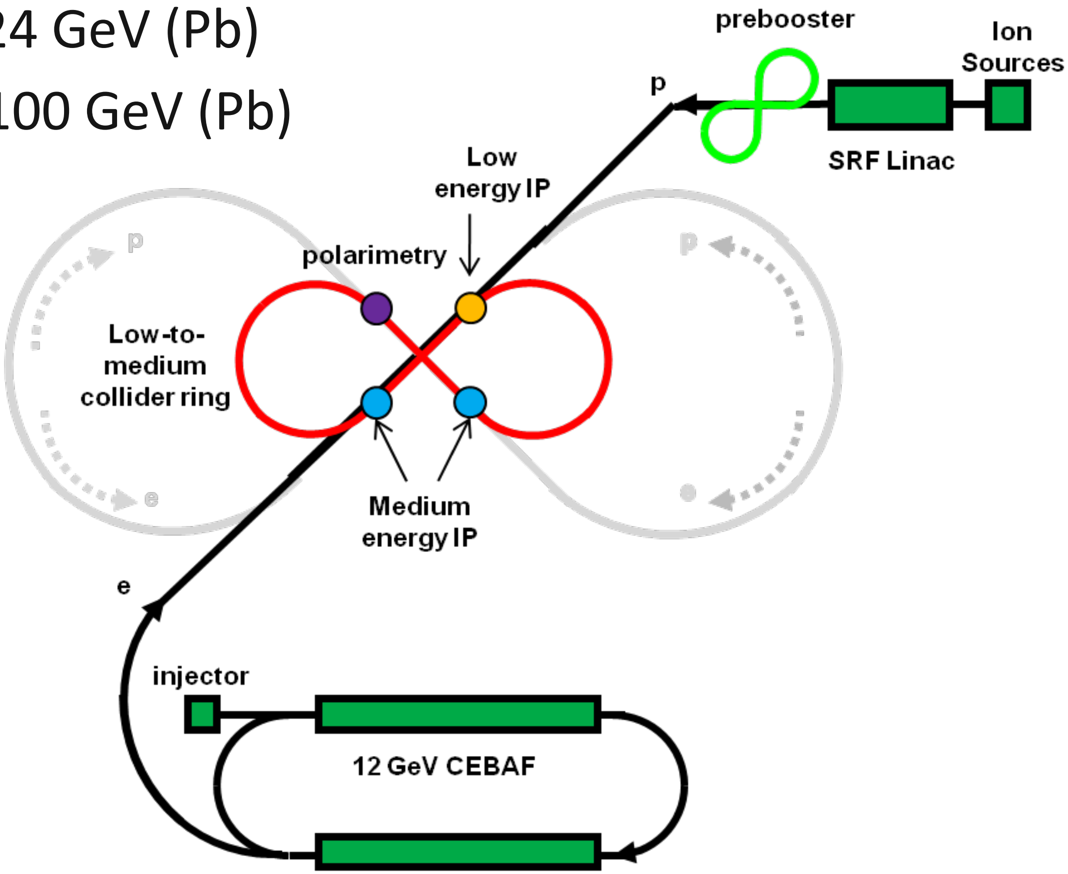
2 competing designs



2 competing designs

MEIC / ELIC at Jefferson Lab

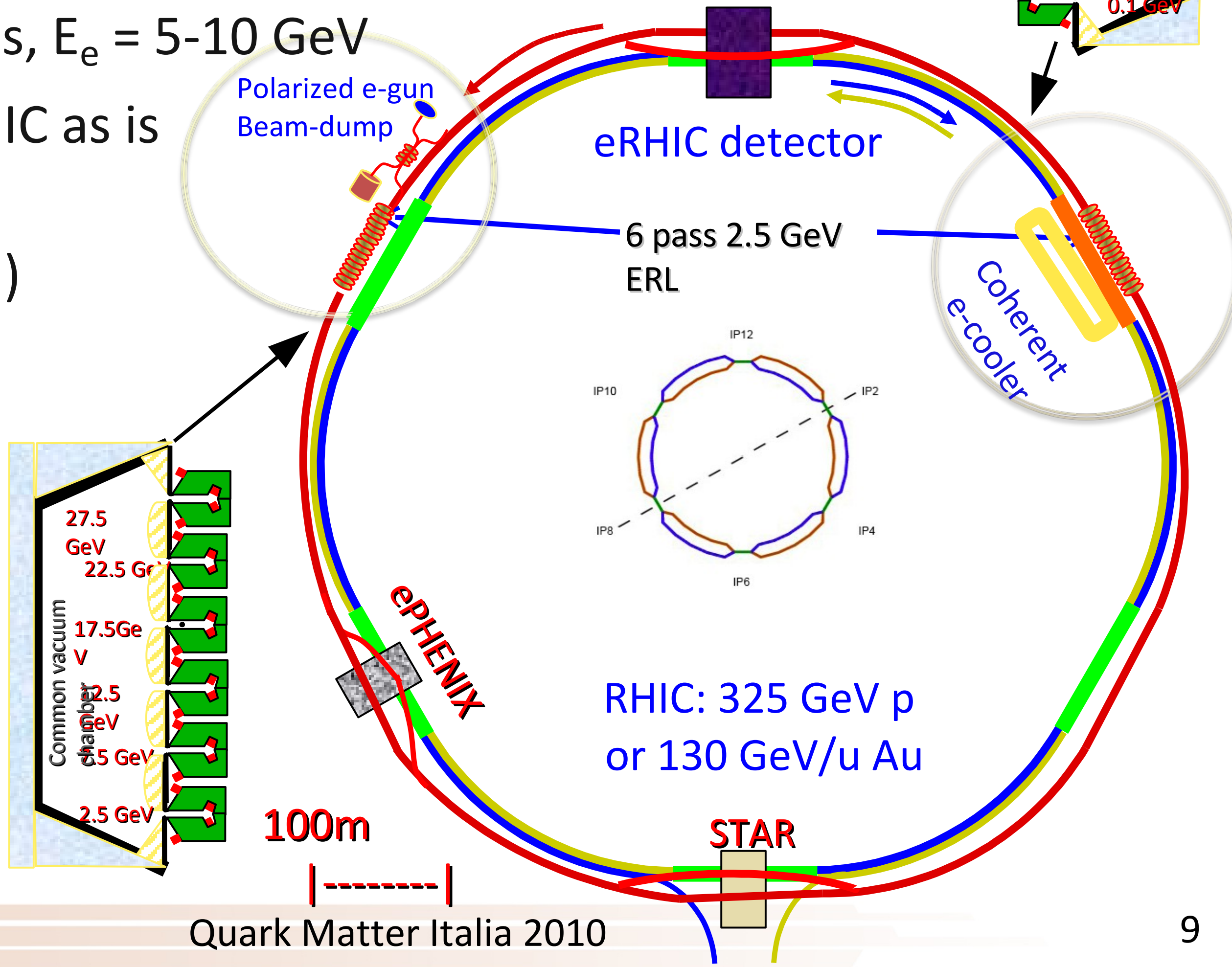
- **electrons:** use CEBAF as is after 12 GeV upgrade
- **protons/ions:** build 2 rings in stages
  - **MEIC:** up to 60 GeV (p), 24 GeV (Pb)
  - **ELIC:** up to 250 GeV (p), 100 GeV (Pb)
- **emphasizes luminosity**



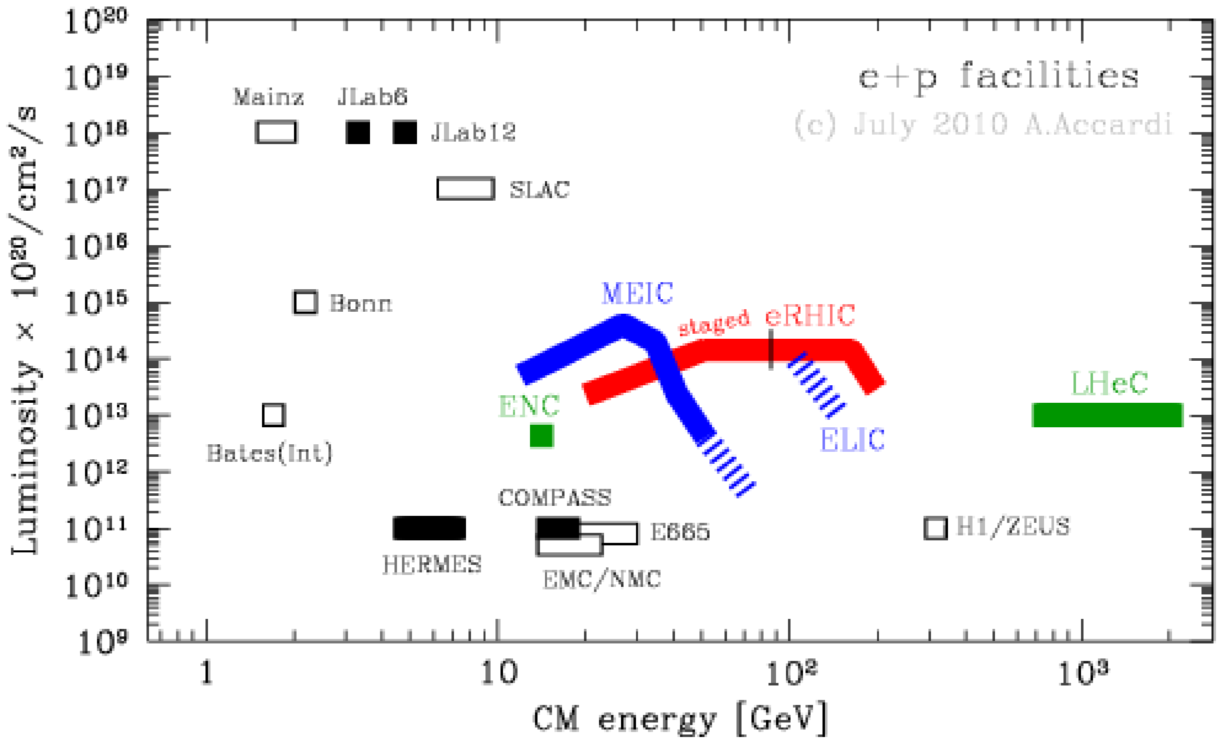
2 competing designs

eRHIC at Brookhaven National Lab

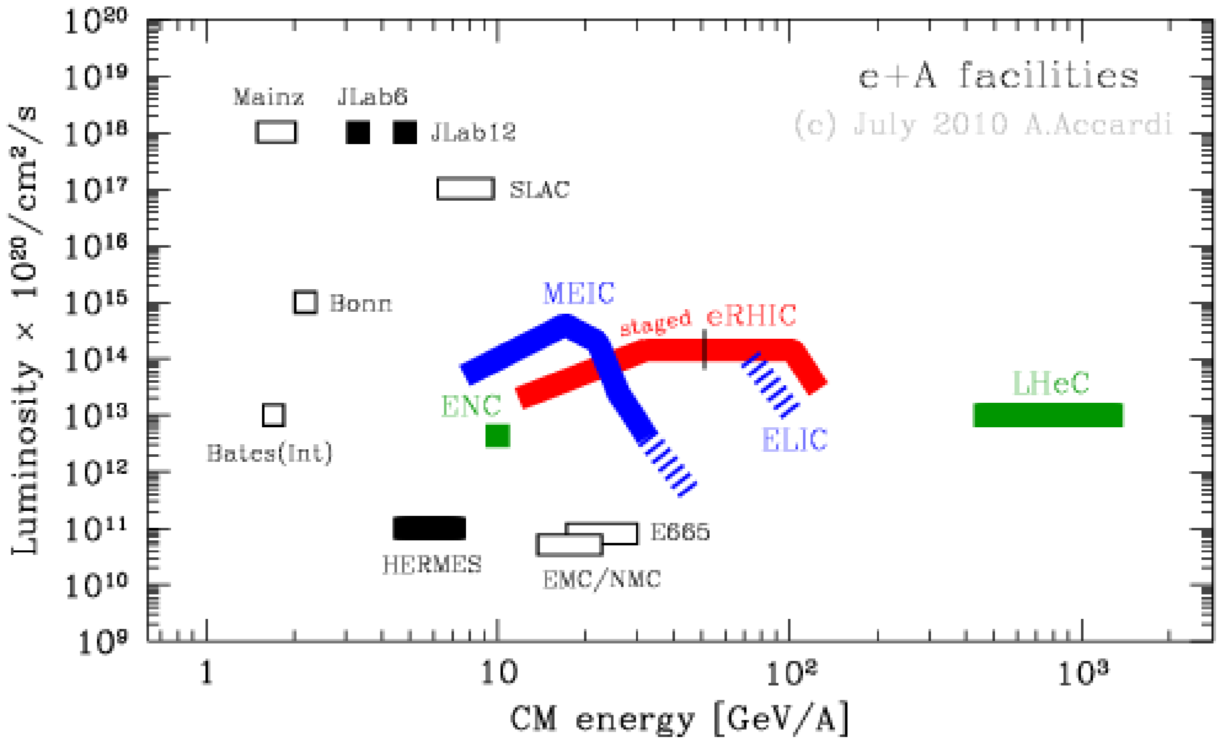
- **electrons:** build energy-recovery linac, in-tunnel e-ring, 6 passes
  - energy from 5 to 30 GeV
  - staging: 1-2 passes, E_e = 5-10 GeV
- **protons/ions:** use RHIC as is
  - up to 325 GeV (p)
    130 GeV(Au)
- **emphasizes energy**



2 competing designs: e+p



2 competing designs: e+A

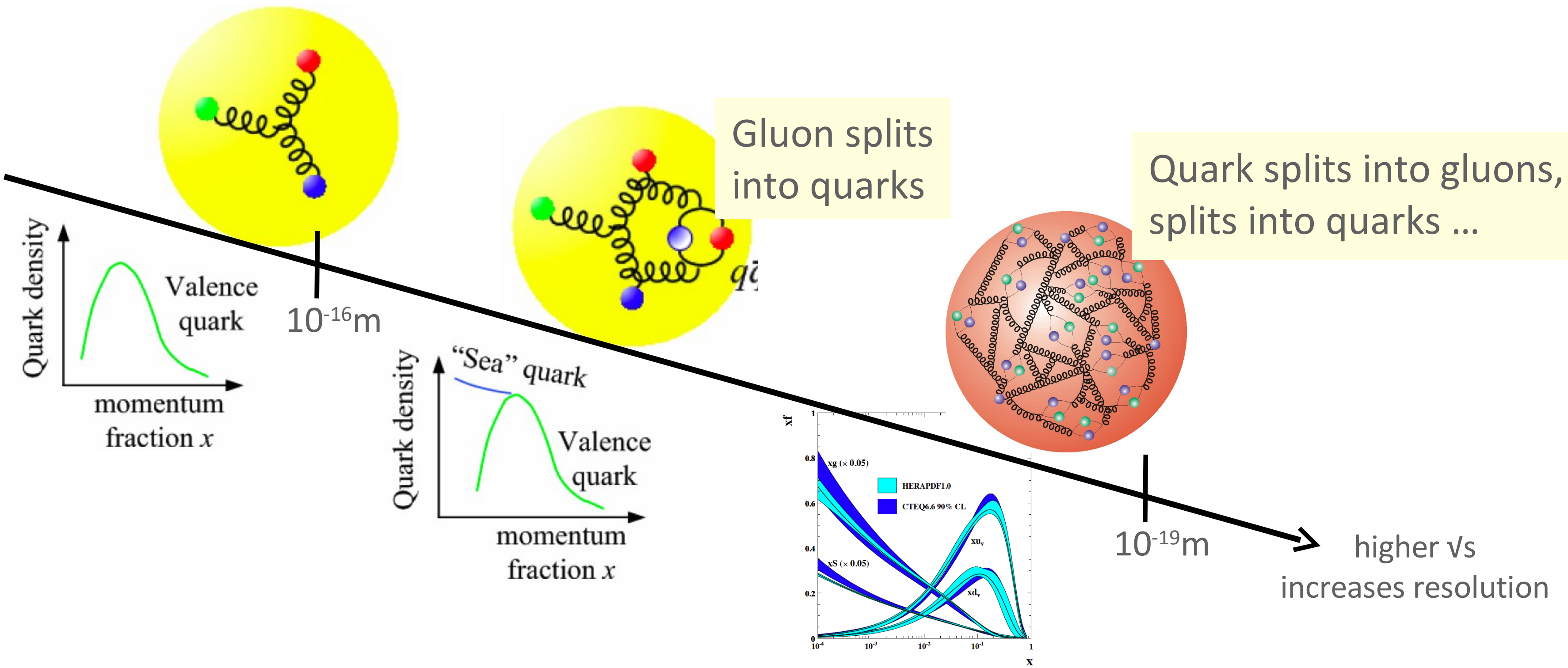


- Overlapping, but not identical, science programs
- **BNL and JLab are working in concert with DOE on strategy to downselect the design**

EIC science

Why electrons on protons / ions ?

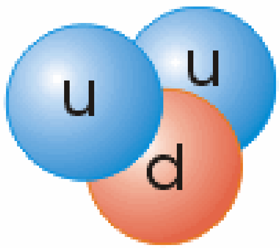
- ep/eA collisions are the perfect instrument for high precision studies. They are the ultimate microscope.



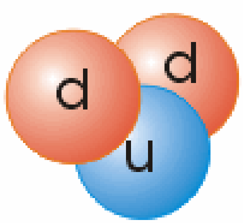
DIS is the master method to understand the quark and gluon structure of hadrons and nuclei

An early modern, popular and wrong view of the proton

The Proton



The Neutron



- Proton made of 2 up (*u*) quarks and 1 down (*d*) quark.
  - u-quark has charge +2/3
  - d-quark has charge –1/3
- The neutron is just the opposite: 2 d's and 1 u
  - hence it has charge 0
- The u and d quarks weigh the same, about 1/3 proton
  - That explains the fact that m(n) = m(p) to ~0.1%
- Every hadron in the Particle Zoo has its own quark composition

Not quite... as seen by a high-energy electron,
m_u, m_d ~ few MeV
So what's missing from this picture?

Slides modified from T.LeCompte – LHC talk at Argonne / J.Arrington, Argonne workshop, 2010

Energy is stored in field

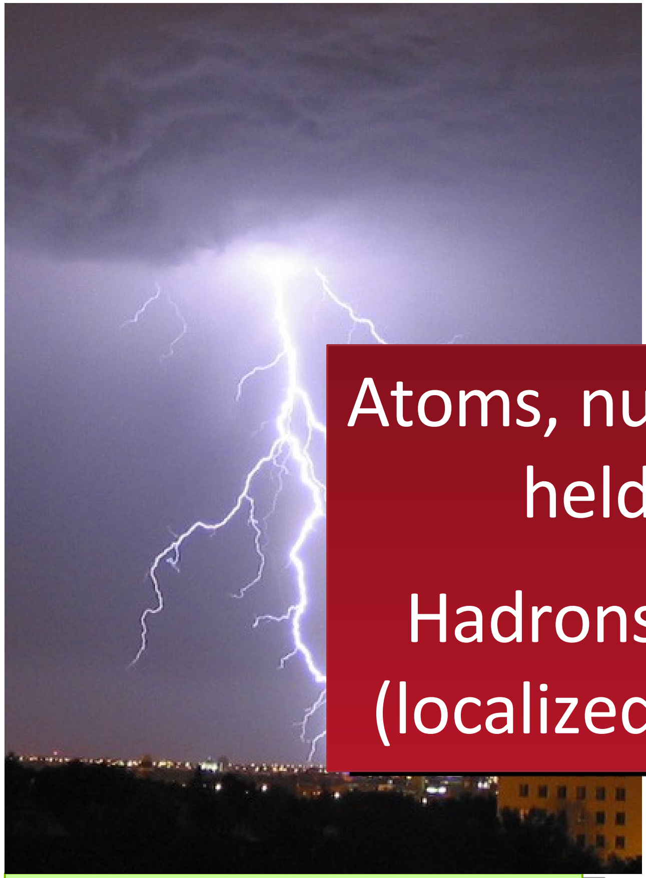
Thunder is good, thunder is impressive; but it is lightning that does the work.
(Mark Twain)

- Energy is stored in electric & magnetic fields
  - Energy density ~ $E^2 + B^2$
  - The picture shows what happens when the energy stored in earth's electric field is released
- Energy is also stored in the proton's gluon field
  - There is an analogous $E^2 + B^2$
  - Nothing unusual about the idea of energy stored there
    - What's unusual is the amount:

	Energy stored in the field
Atom	10^{-8}
Nucleus	1%
Proton	**99%**

Slides modified from T.LeCompte – LHC talk at Argonne / J.Arrington, Argonne workshop, 2010

Energy is stored in field



- Energy is stored in electric & magnetic fields
  - Energy density ~ $E^2 + B^2$
  - The picture shows what happens when the energy stored in earth's electric field is released

uon field

energy

Atoms, nuclei made up of constituents held together by some field

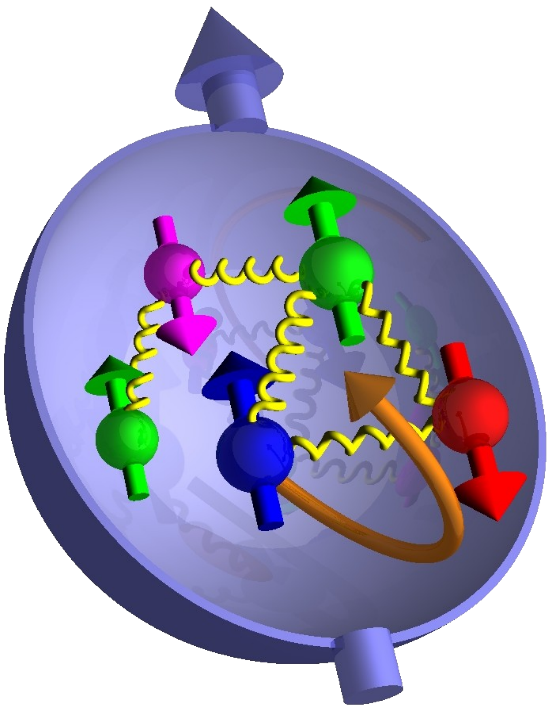
Hadrons made up of the field itself (localized around their 'constituents')

	Energy stored in the field
Atom	10^{-8}
Nucleus	1%
Proton	**99%**

Thunder is good, thunder is impressive; but it is lightning that does the work.
(Mark Twain)

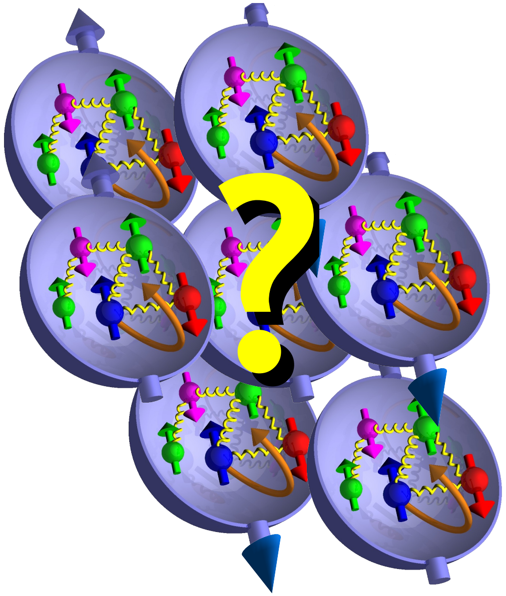
Slides modified from T.LeCompte – LHC talk at Argonne / J.Arrington, Argonne workshop, 2010

The modern proton



- 99% of proton’s mass/energy is due to this self-generating gluon field
- The “valence quarks” (uud)
  - act as boundary conditions on the field
  - determine the electromagnetic properties of the proton (gluons are electrically neutral)
- Proton and neutron mass are similar:
  - the gluon dynamics is the same
- Valence quarks don't even carry all of the proton's spin:
  - gluon / sea-quark spin?
  - orbital angular momentum?

The modern nucleus



- EMC effect discovered more than 30 years ago:
  - quarks / hadrons are modified inside a nucleus
  - $A \neq \Sigma$ p,n
  - still a theoretical mistery
- Nuclear gluons much less known
- Significant potential for
  - learning more about QCD
  - discovery of unexpected physics
- Use as filter / detector of propagating objects
  - hadronization, color confinement
  - color transparency

A common thread - a “glue” if you will…

- How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

$$L_{QCD} = \bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q - g\left(\bar{q}\gamma^{\mu}T_{a}q\right)A_{\mu}^{a} - \frac{1}{4}G_{\mu\nu}^{a}G_{a}^{\mu\nu}$$

- The key to the answers is the Gluon:
  - it represents the difference between QED and QCD
- Cannot “see” the glue in the low-energy world

Despite their preeminent role, properties of gluons in matter remain largely unexplored

$\Longrightarrow$ EXPERIMENTS

EIC science case

What is the nature and role of gluons, and their self-interactions?

- physics of Strong Color Fields `(saturation/non-linear QCD)`
- study the nature of color singlet excitations `(Pomerons)`
- role of gluons in atomic nuclei `(EMC/antishadowing, glue vs. qrks)`
- test and study the limits of universality `(eA vs. pA)`

EIC science case

What is the nature and role of gluons, and their self-interactions?

What is the spin and 3D quark-gluon structure of the nucleons?

- origin of proton's spin, role of angular momentum
- 3D spatial landscape of nucleons (GPDs, exclusive processes)
- 3D momentum landscape (TMDs, seminclusive processes)

EIC science case

What is the nature and role of gluons, and their self-interactions?

What is the spin and 3D quark-gluon structure of the nucleons?

Understand the transition of quarks and gluons into hadrons

- How do fast probes interact with the gluonic medium?

  `(energy-loss, color transparency)`

- How do gluons and color confinement turn a quark into a hadron?

  `(semi-inclusive on A vs. D)`

EIC science case

What is the nature and role of gluons, and their self-interactions?

What is the spin and 3D quark-gluon structure of the nucleons?

Understand the transition of quarks and gluons into hadrons

Electroweak physics (studies underway)

- Parity violating interactions as a tool `(PVDIS, charged currents)`
  - precision study of quark structure of the hadrons
- Beyond the standard model
  - Lepton Flavor and Number Violation

EIC science case

What is the nature and role of gluons, and their self-interactions?

(inclusive, diffraction, jets)

What is the spin and 3D quark-gluon structure of the nucleons?

(semi-inclusive, exclusive, jets)

Understand the transition of quarks and gluons into hadrons

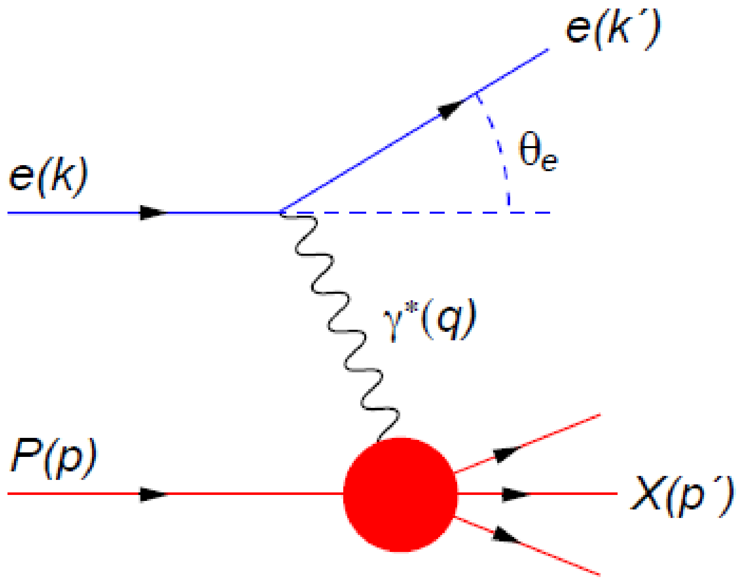
(semi-inclusive, jets)

Electroweak physics (studies underway)

(inclusive, missing mass)

Basics of DIS

DIS kinematics



Resolution power ("Virtuality"):

$$Q^2 = -q^2 = -(k - k')^2$$

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

Inelasticity:

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

Bjorken x:

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

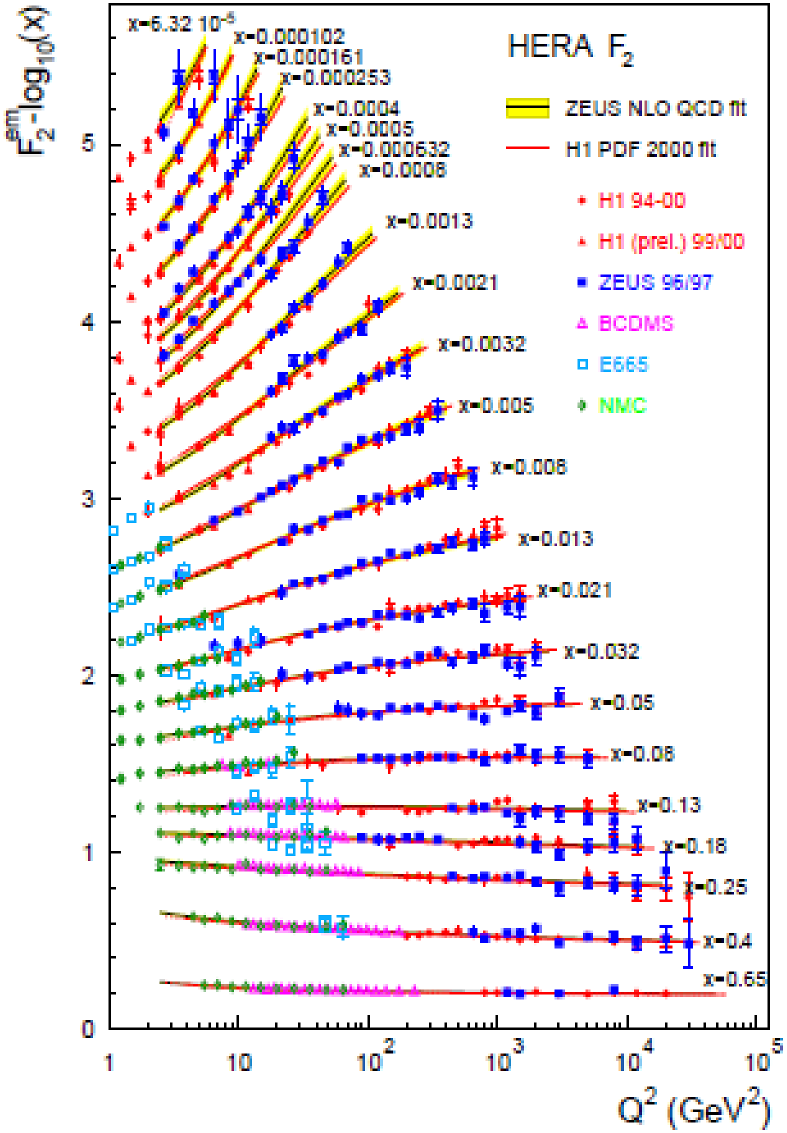
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions

gluon momentum distribution

8

Structure functions, quarks and gluons



Scaling violation:
role of gluons and pQCD evolution

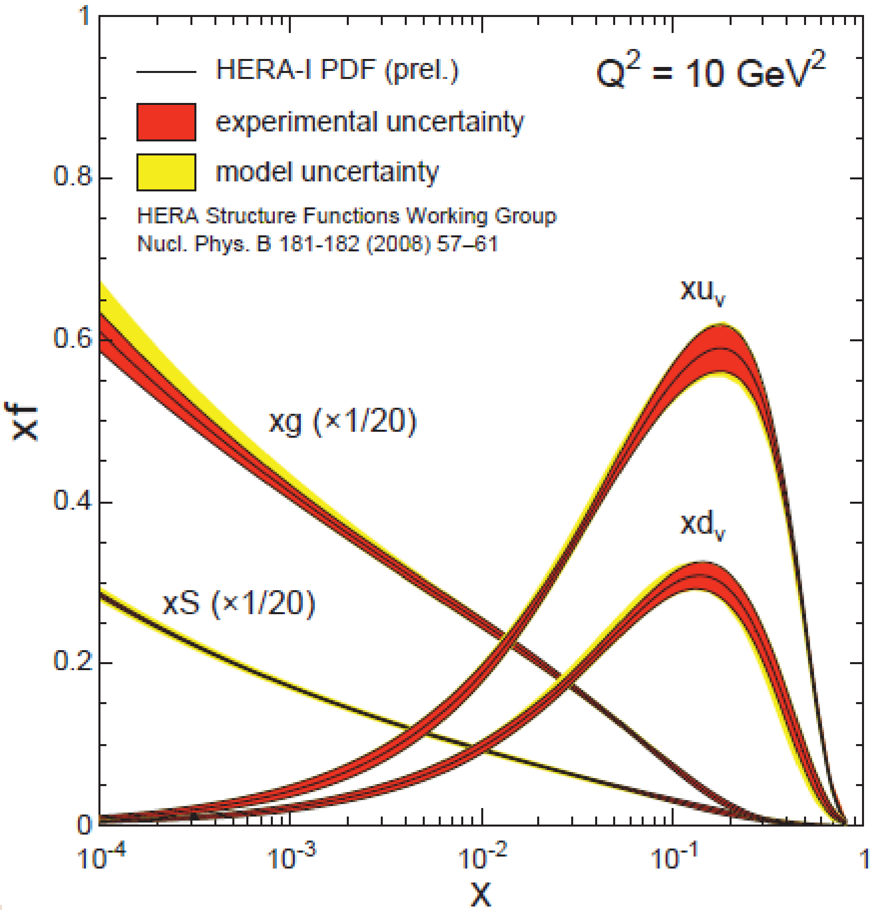
DGLAP evolution equation:

$F_2(x,Q_1^2) \to F_2(x,Q_2^2)$

Bjorken-scaling:
scattering on valence quarks

pQCD fits: from structure functions to partons

- pQCD analysis of structure functions (and other observables) allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions, with x = fractional momentum of the parton



- At LO, $x=x_B$

$$F_2(x,Q^2) = \sum_q e_q^2 x q(x,Q^2)$$

$$F_L(x,Q^2) = 0$$

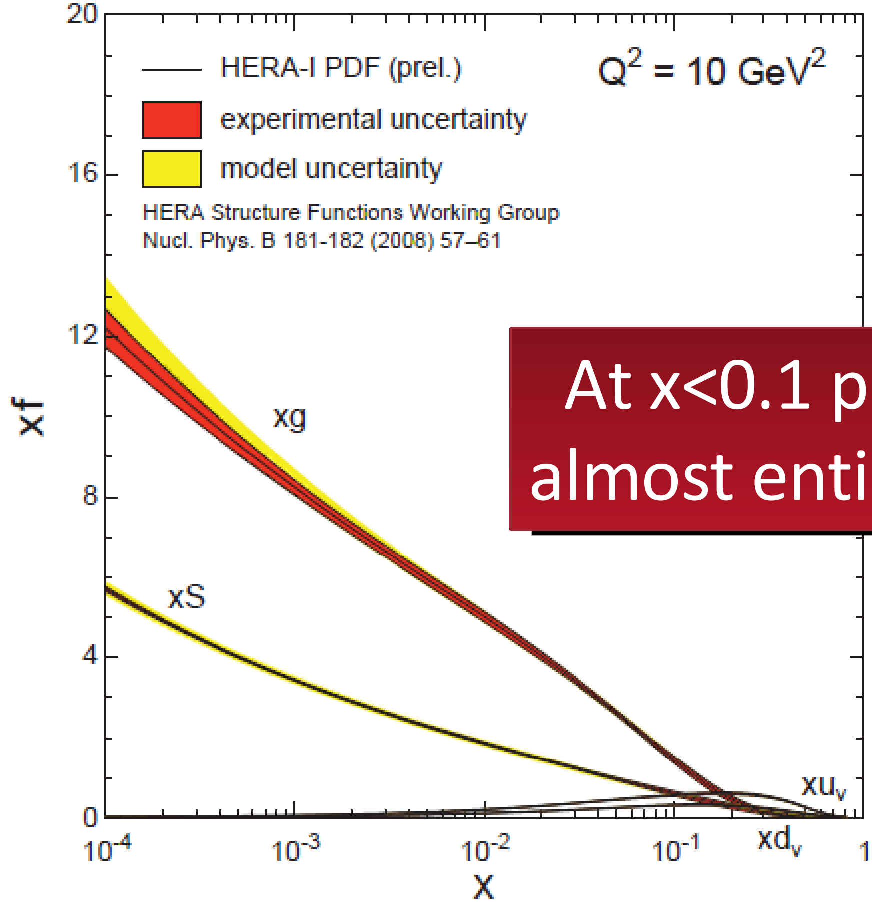
- At NLO

$$F_{2,L} = \sum_{i=q,g} H^i_{2,L} \otimes f_i$$

$$\frac{dF_2}{d\ln Q^2} \propto G$$

pQCD fits: from structure functions to partons

- pQCD analysis of structure functions (and other observables) allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions, with x = fractional momentum of the parton



- At LO, $x=x_B$

$$F_2(x,Q^2) = \sum_q e_q^2 x q(x,Q^2)$$

$$F_L(x,Q^2) = 0$$

At x<0.1 proton made almost entirely of gluons

$$F_{2,L} = \sum_{i=q,g} H^i_{2,L} \otimes f_i$$

$$\frac{dF_2}{d\ln Q^2} \propto G$$

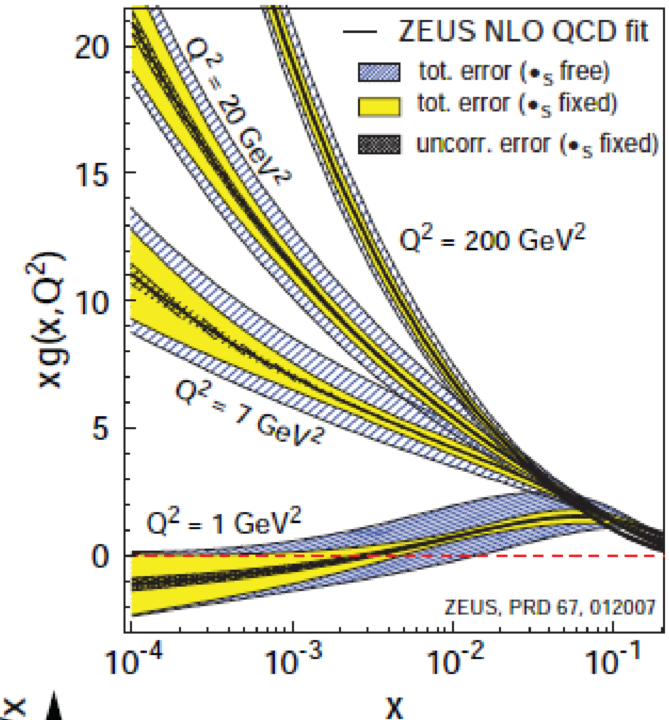
selected topics:

gluons at small x

Issues with our current understanding

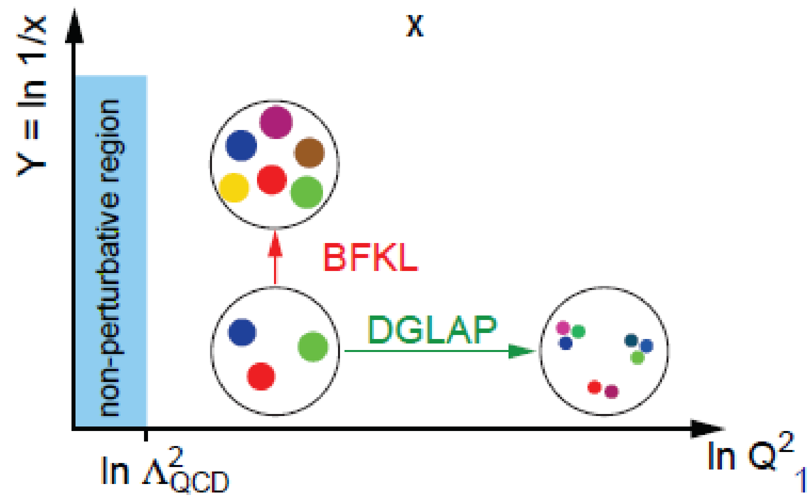
Linear DGLAP Evolution Scheme

- Low Q^2
  - $G(x, Q^2) < Q_{sea}(x, Q^2)$?
  - $G(x, Q^2) < 0$?
- Large Q^2
  - built in high energy "catastrophe"
  - G rapid rise violates unitary bound



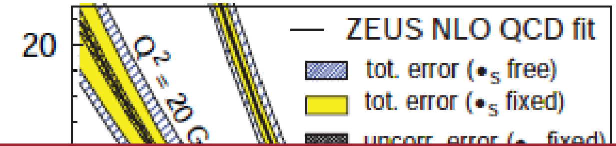
Linear BFKL Evolution Scheme

- Density along with σ grows as a power of energy
- Can densities & σ rise forever?
- Black disk limit: $\sigma_{total} \leq 2\,\pi\,R^2$



Issues with our current understanding

Linear DGLAP Evolution Scheme



Something's wrong:
gluon density is growing too fast

Gluons must saturate at some point

(gluon need to recombine, not only split)

What's the underlying dynamics?

Is our understanding of low-x hadrons adequate?

- Black disk limit: $\sigma_{total} \leq 2\pi R^2$

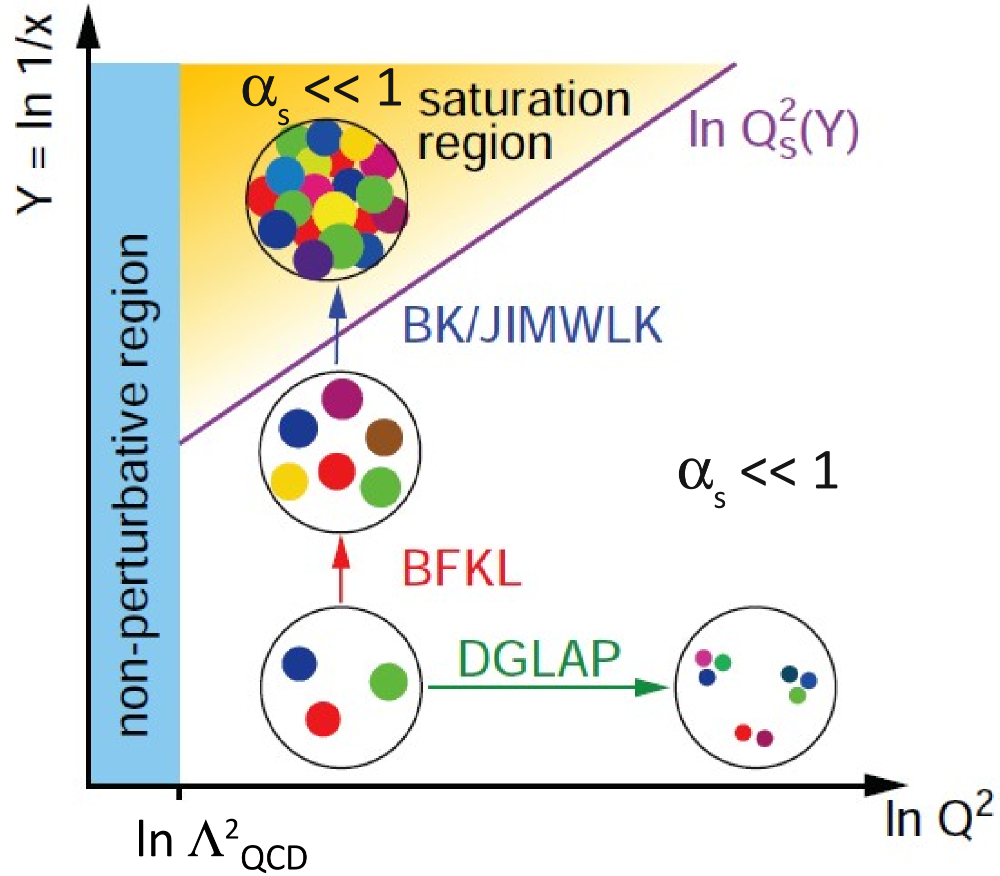
Saturation and Color Glass Condensate

Review: Gelis et al., arXiv:1002.0333

Stability of the theory requires maximum gluon occupation number $\sim 1/\alpha_s$ at which point further growth is damped

- gluons with $k_T < Q_s(x)$ saturate
- saturation scale grows as x decreases
- gluon dynamics is non-pert. but weakly coupled:

$$\alpha_s \sim \alpha_s(Q_s^2) \ll 1$$



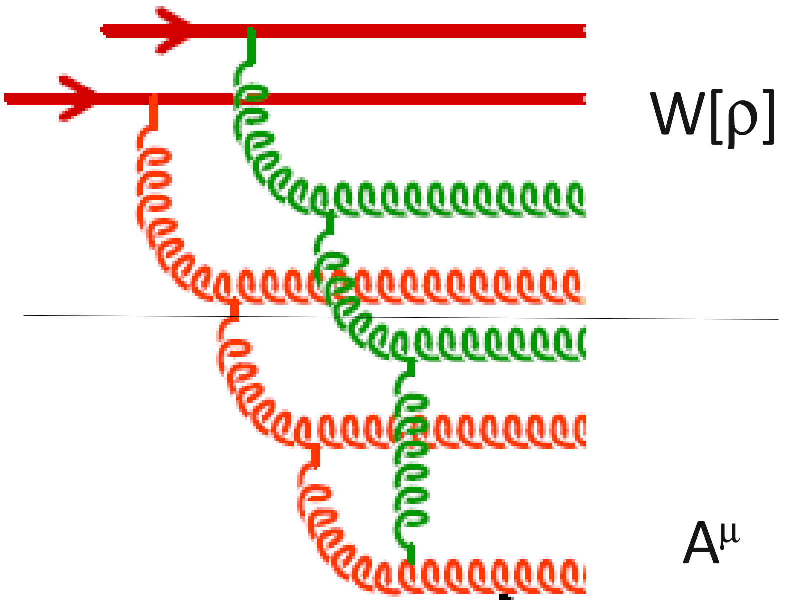
Saturation and Color Glass Condensate

Review: Gelis et al., arXiv:1002.0333

CGC is an effective theory of small-x gluons in the Infinite Momentum Frame, describing saturation and the approach to the saturation regime

Effective degrees of freedom

- large-x color sources ρ
  - stochastic distribution W[ρ]
- small-x gluon fields A^{μ}
- valid approximately at $x < 10^{-2}$



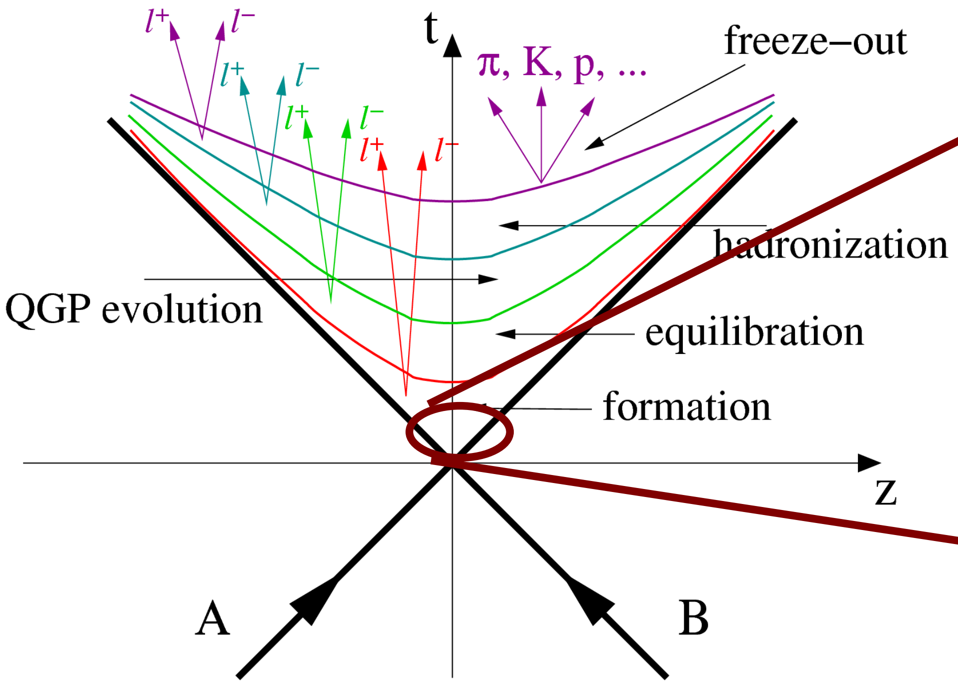
Renormalization group

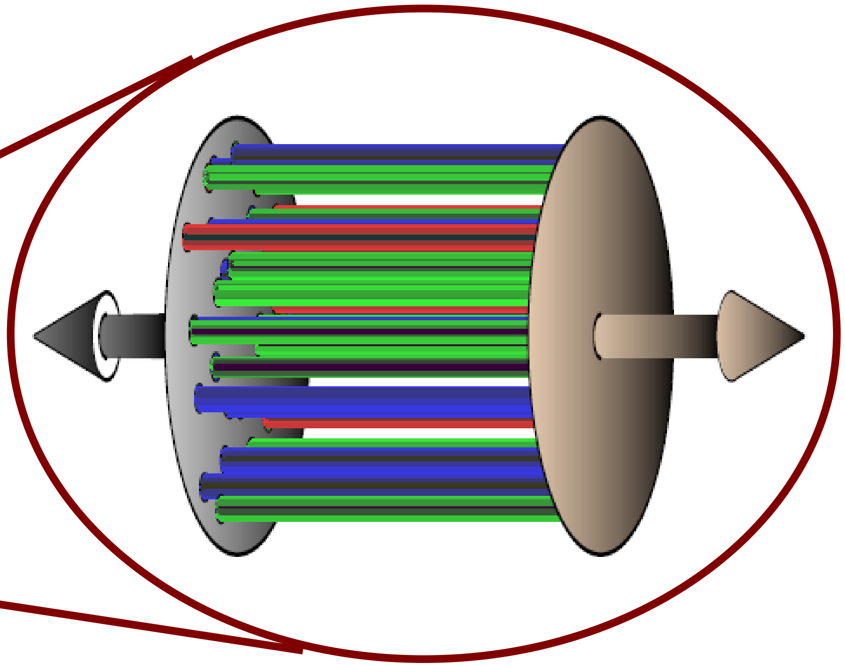
- separation scale $Y = \ln(1/x)$
- JIMWLK evolution equation $\frac{\partial W_Y[\rho]}{\partial Y} = -\mathcal{H} W_Y[\rho]$
- Universality
  - fixed RG point, similar to spin glasses

CGC and the Quark-Gluon Plasma

see J.Harris' lecture

Shattering 2 CGC sheets provides the initial conditions for QGP evolution: the "Glasma"

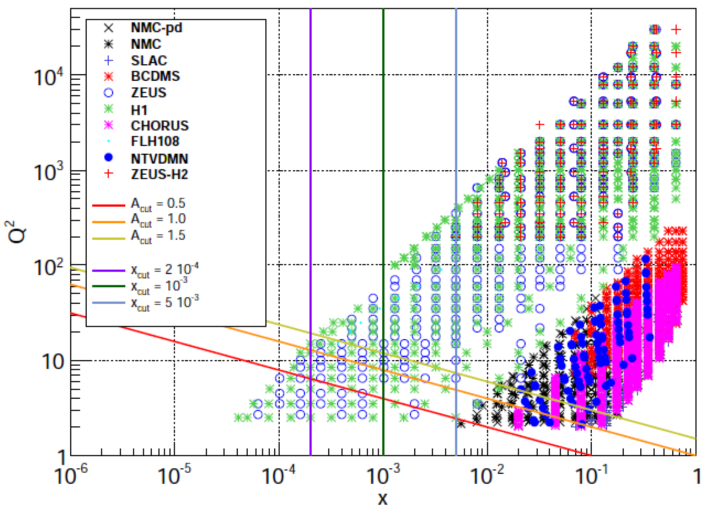




glasma flux tubes,
n-particle long-range correlations

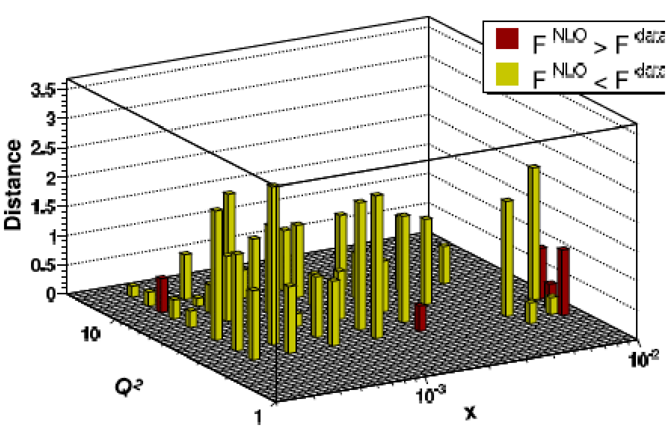
Experimental evidence: e+p at HERA

Deviation from DGLAP evolution [Gelis,2008; Caola,Forte,Rojo,2010]

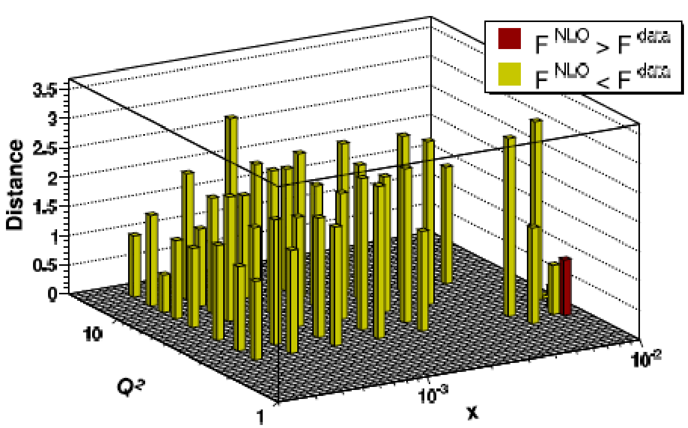


- **cut out** data in "saturation region" at low τ
- **fit PDF** in "safe" region
- **DGLAP evolve backwards**:
  - fit is systematically below data (too much DGLAP evolution)
  - full fit partly mimics saturation

DAT/TH DIST: NO CUT



DAT/TH DIST: CUT



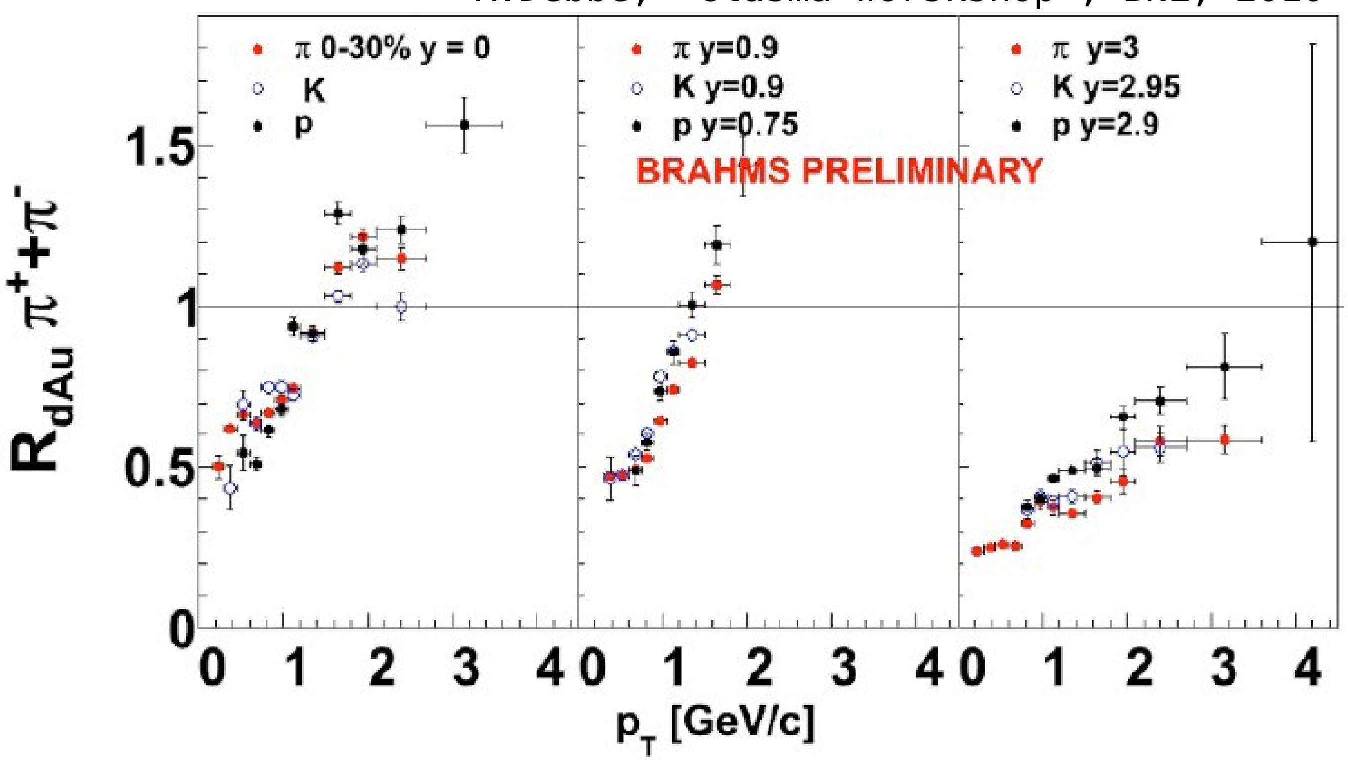
Using very precise combined HERA data

Experimental evidence: d+Au at RHIC

Large rapidity hadrons

- Suppression of Cronin effect at large y > 1
  - due to proximity to shadowing region
  - $x_{sat} \approx (p_T/\sqrt{s})e^{-y} \approx 0.001$

R.Debbe, "Glasma worskshop", BNL, 2010



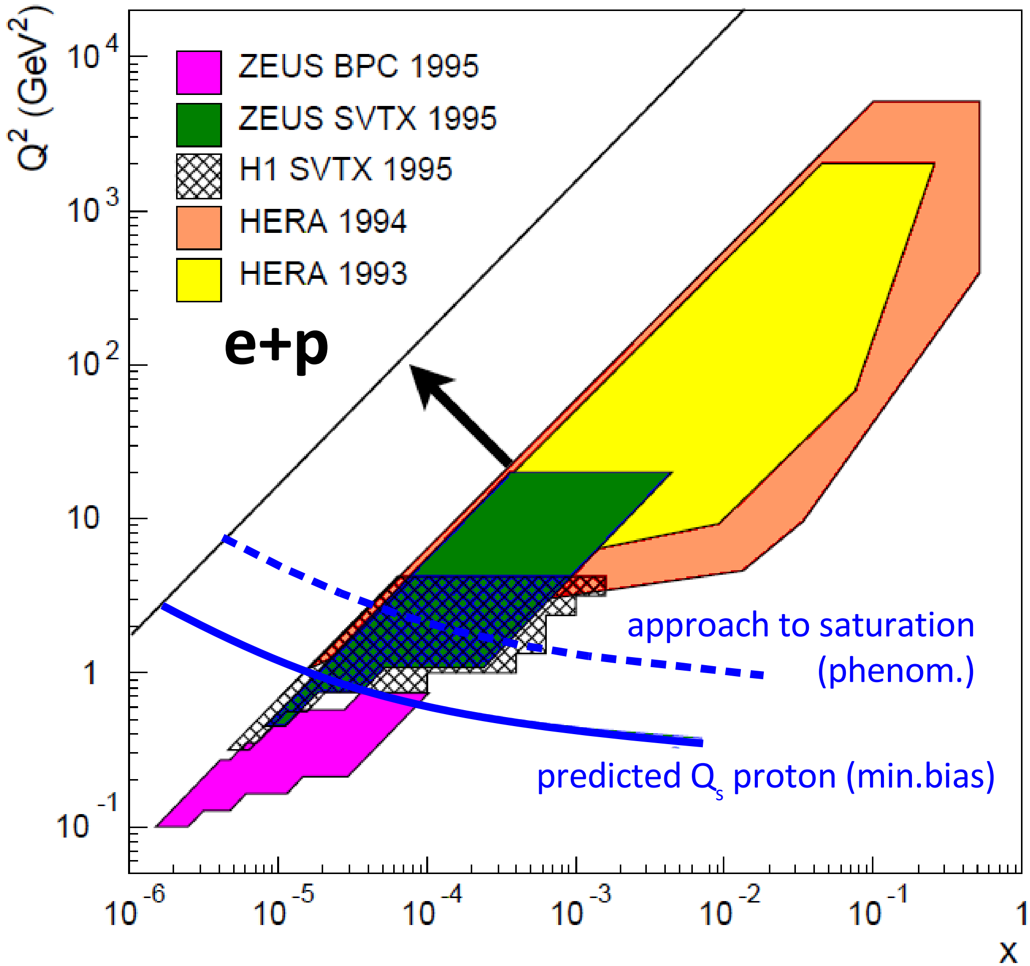
Why using e+A at EIC?

EIC cannot compete with HERA in e+p

- EIC well outside "sat" region
- Requiring Q^2 lever-arm, needs e+p with at least

$$\sqrt{s} = 1 - 2TeV$$

  - unrealistic in the US
  - LHeC in Europe



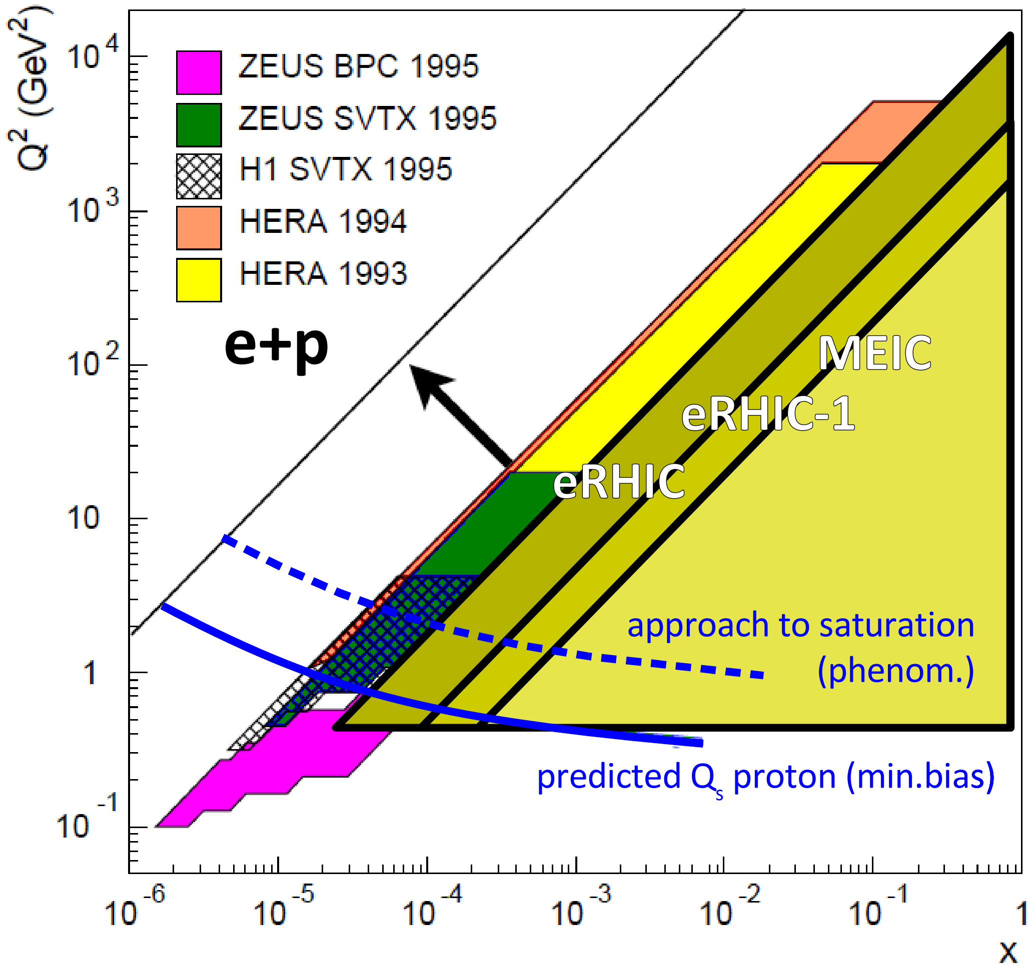
Why using e+A at EIC?

EIC cannot compete with HERA in e+p

- EIC well outside "sat" region
- Requiring Q^2 lever-arm, needs e+p with at least

$$\sqrt{s} = 1 - 2TeV$$

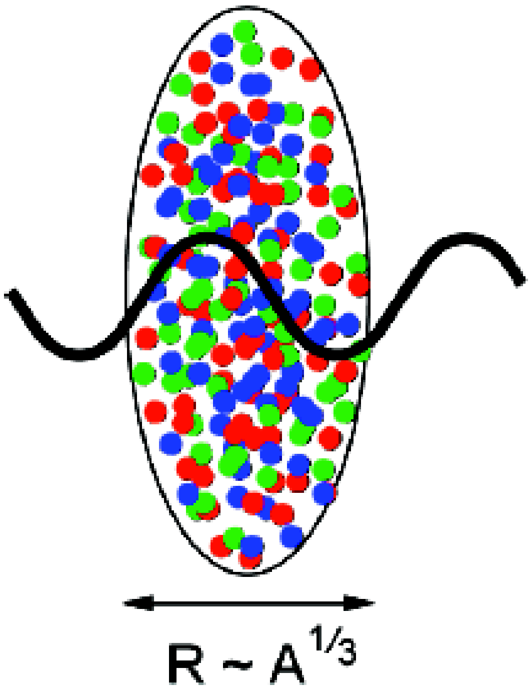
  - unrealistic in the US
  - LHeC in Europe



Why using e+A at EIC?

Use nuclei to boost Q_{sat}

- Probe interacts over distances $L \sim (2m_N x)^{-1}$
- For $L \gtrsim 2R_A \propto A^{1/3}$ interacts *coherently* with the whole nucleus



Pocket formula

$$Q_s^2 \sim \frac{\alpha_s x G(x, Q_s^2)}{\pi R}$$

$$\text{HERA, BFKL: } xG \sim 1/x^{1/3}$$

$$G_A \sim AG \qquad R_A \sim A^{1/3}$$

$$\left(Q_s^A\right)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{\frac{1}{3}}$$

Why using e+A at EIC?

Use nuclei to boost Q_{sat}

- Probe interacts over distances $L \sim (2m_N x)^{-1}$
- For $L \gtrsim 2R_A \propto A^{1/3}$ interacts *coherently* with the whole nucleus

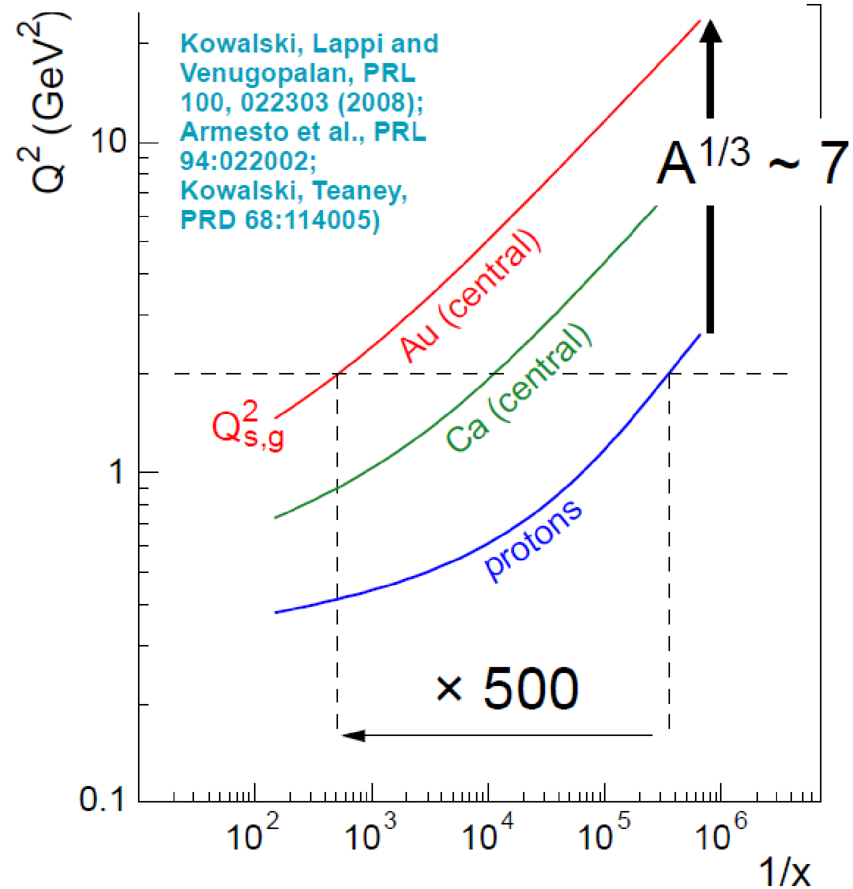
Pocket formula

$$Q_s^2 \sim \frac{\alpha_s xG(x, Q_s^2)}{\pi R}$$

$$\text{HERA, BFKL: } xG \sim 1/x^{1/3}$$

$$G_A \sim AG \qquad R_A \sim A^{1/3}$$

$$(Q_s^A)^2 \approx c\,Q_0^2 \left(\frac{A}{x}\right)^{\frac{1}{3}}$$



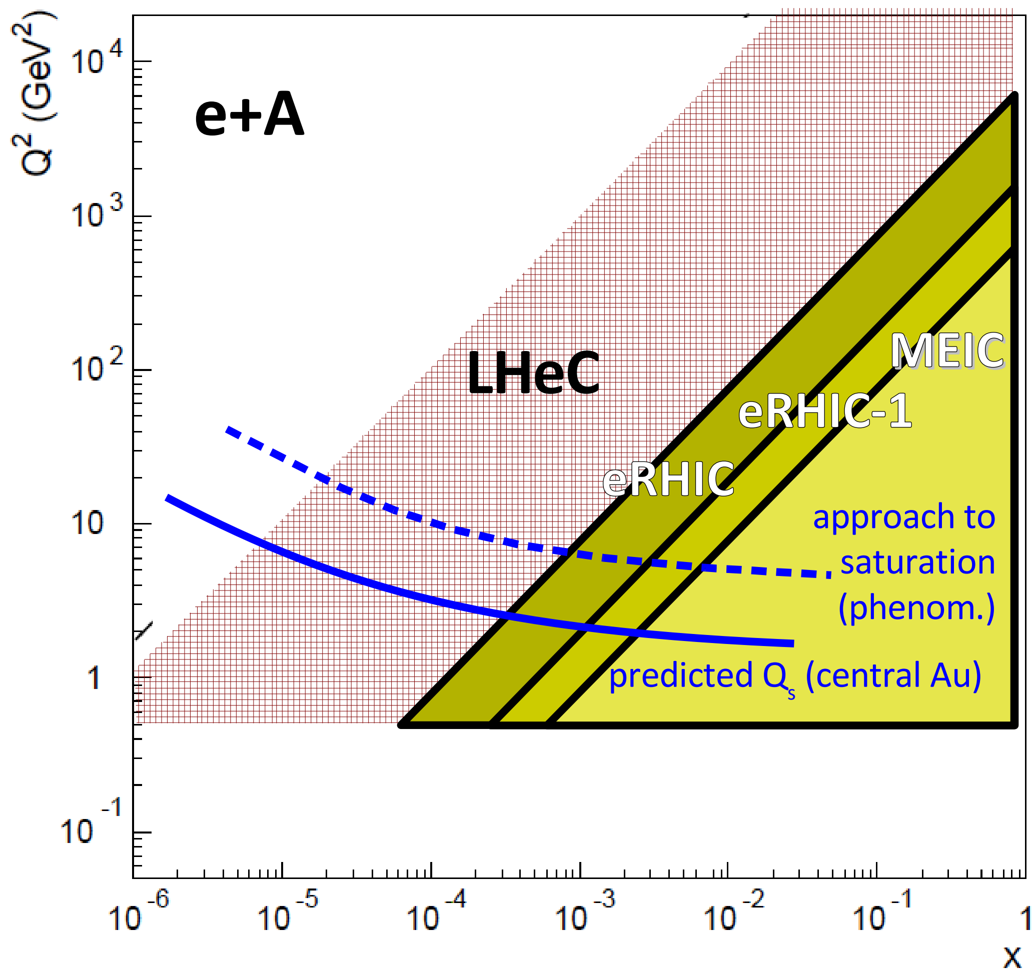
Why using e+A at EIC?

Use nuclei to boost Q_{sat}

- Nuclear targets:
  - gain factor 7 in Q_s
  - loose factor ~ 2 in √s
    [~ 0.4 in log(x)]

- **EIC will study the *approach to saturation***

- LHeC will go in the *deep saturation region*

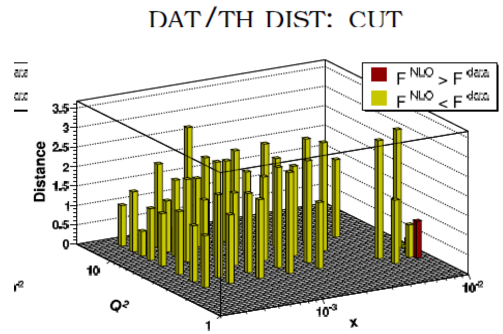


selected topics:

partons at larger x

Nuclear quark and gluon distributions

Parton distributions in nuclei are modified compared to free nucleons ***over the entire range of Bjorken x*** because of various nuclear effects.



From low to large x

- **Saturation**
- **Nuclear shadowing**
- **Anti-shadowing**
- **EMC effect**
- Fermi motion
- Short-Range Correlations, non nucleonic d.o.f.

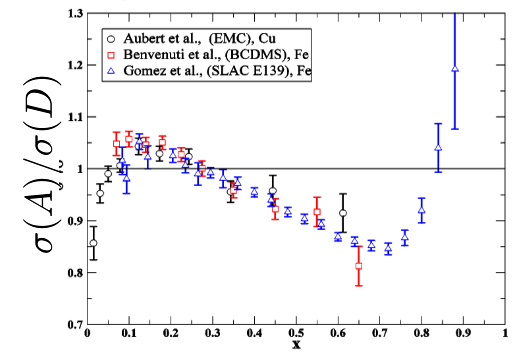
$x \sim 0.01$

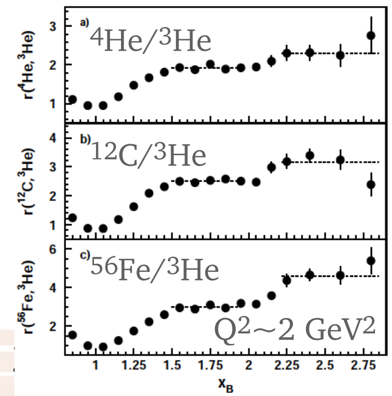
$x \sim 0.1$

$x \sim 0.7$

$x = 1$

$x > 1$





[CLAS, PRL96,2006]

Measurements and techniques

Quarks

- **Neutral current F_2**
  - day 1 measurement (inclusive)
  - proton and deuteron
  - spectator tagging
- **semi-inclusive mesons**
- **charged current F_2 , F_3**
  - requires high luminosity (studies underway)

(proton and deuteron, spectator tagging, semi-inclusive mesons, charged current: } flavor separation)

- **Proton vs. deuteron**
- **Spectator tagging** $e+D \to n+X$, $e+D \to n+X$
  - basic test of nuclear effects

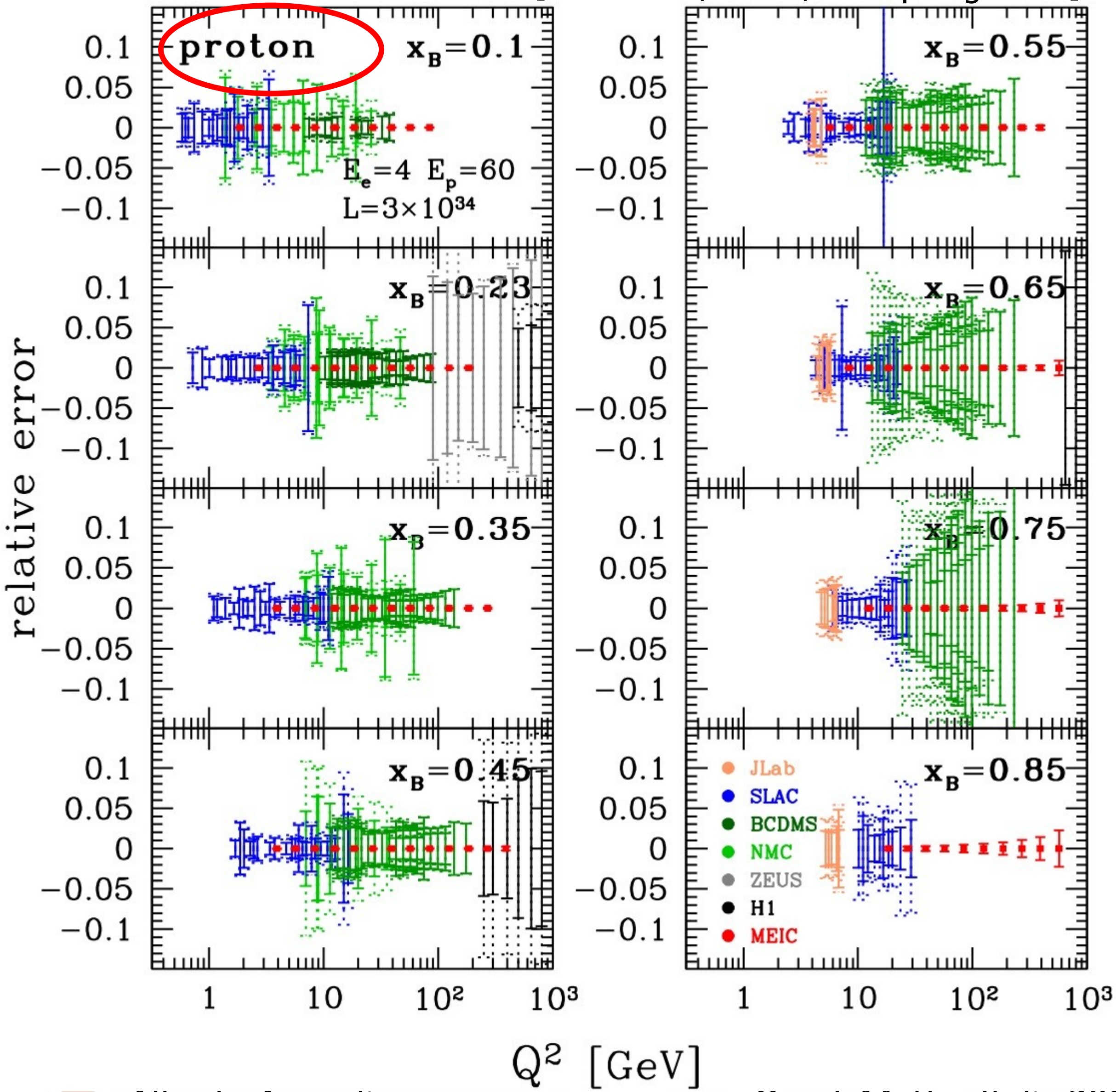
Measurements and techniques

Gluons

- **DGLAP evoultion / scaling violation of F2 $(\delta F_2 / \delta \ln Q^2)$**
  - day 1 measurement (inclusive)
- **$F_L \sim xG(x,Q^2)$**
  - requires running at more than one $\sqrt{s}$
- **2+1 jet rates**
  - sensitive to larger *x*
- **Diffractive vector meson production ~ $[xG(x,Q^2)]^2$**
  - most sensitive to saturation
  - challenging experimentally

Baseline - $F_2(p)$

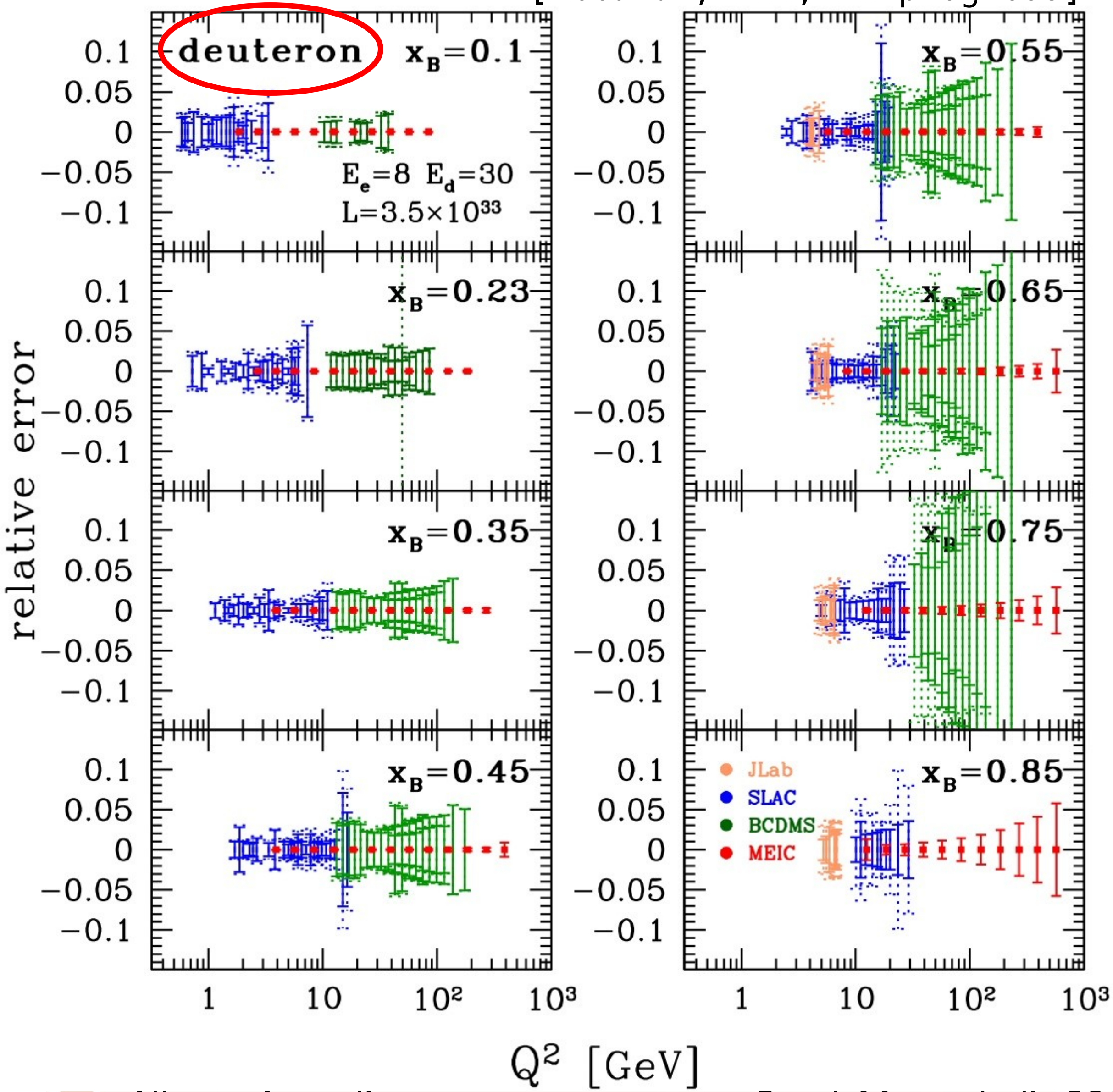
[Accardi, Ent, in progress]



- MEIC 4+60 GeV (s = 1000)
  - larger s (~4000 MeRHIC, or ~2500 MEIC) would cost luminosity
- $0.004 < y < 0.8$
- Luminosity ~ 3 x 10^{34}
- 1 year of running (26 weeks) at 50% efficiency, or **230 fb^{-1}**
- **Dominated by systematics ~ 1-2 %**
- **Larger luminosity useful at large x**

Baseline - F_2(D)

[Accardi, Ent, in progress]

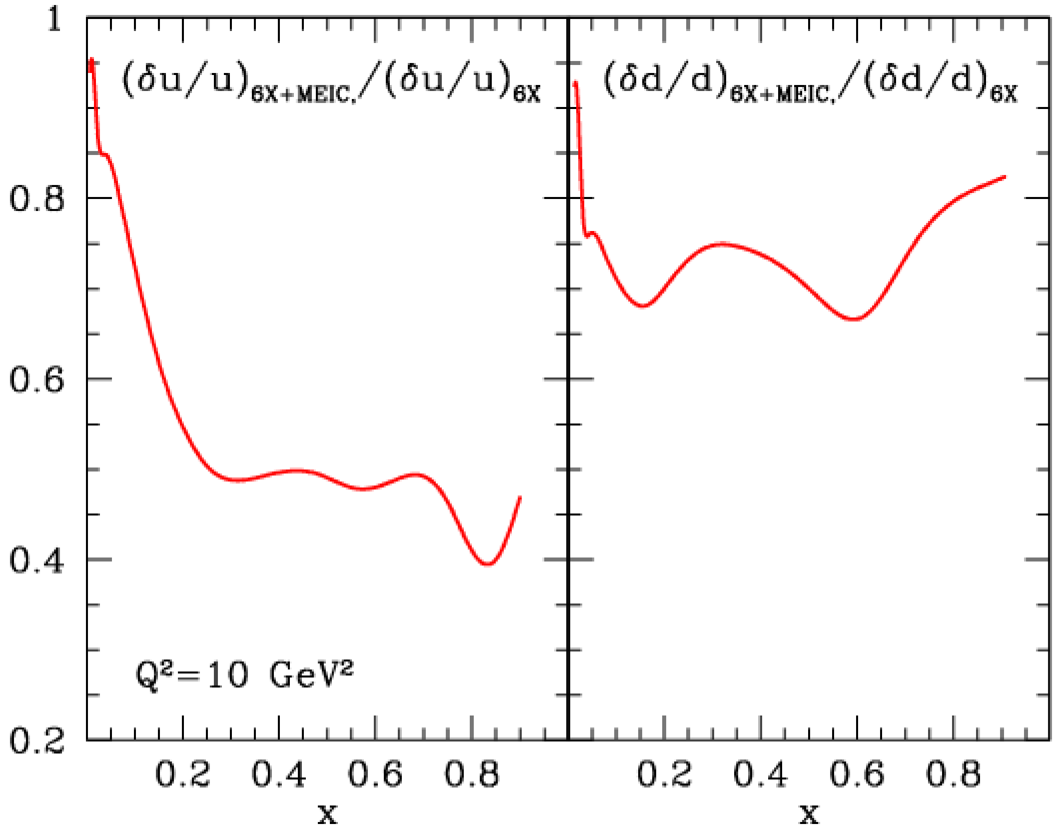


- MEIC 4+30
- 1 year of running (26 weeks) at 50% efficiency, or 35 **fb**$^{-1}$

Even with 1/10 statistics, improvement compared to past is impressive

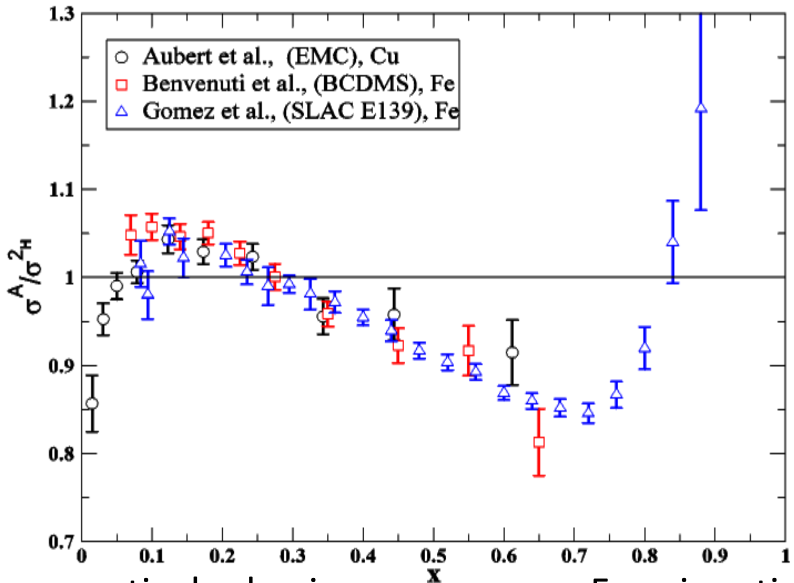
EIC will have excellent kinematic for n/p at large x!

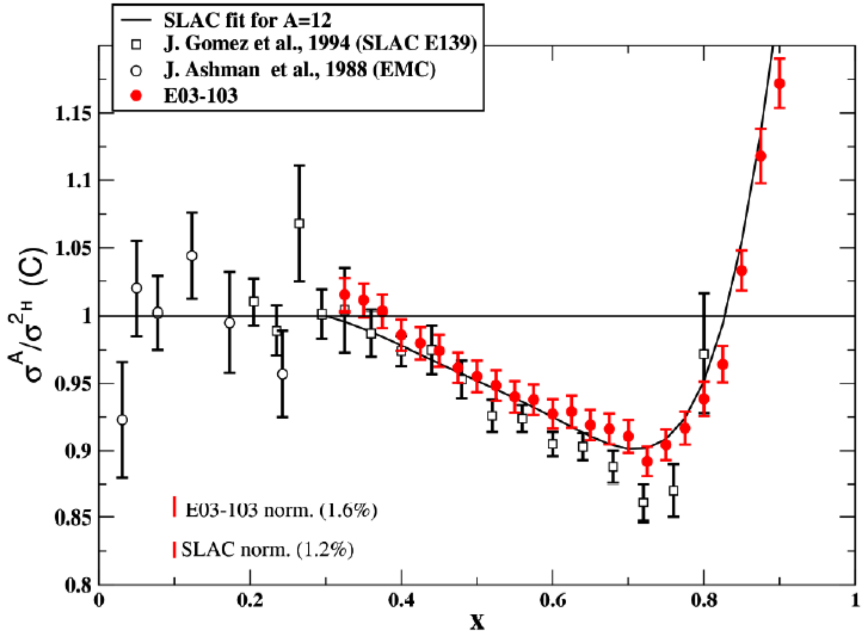
Baseline - projected impact on global fits



Sensible reduction in PDF error,
will be larger than shown if energy scan is performed

EMC effect - quarks





anti- shadowing Fermi motion

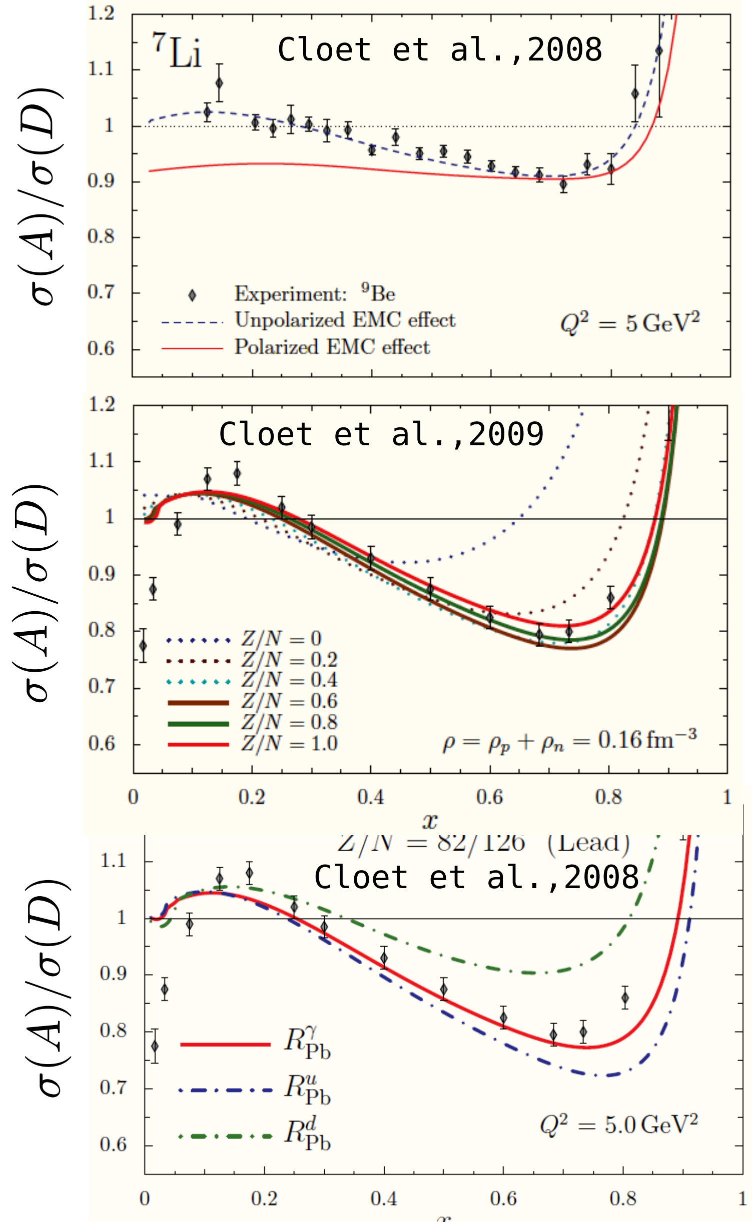
shadowing EMC region

After 30+ years, still a significant mistery:

- *Binding and Fermi motion:* not quite enough
- *Pion cloud:* disagrees with π+A Drell-Yan
- *Point-Like Configurations, Quark-Soliton coupling, ...*
- *Exotics:* partial deconfinement, 6 quark bags, ...

EMC effect - quarks

EIC measurements



- ❑ **Large Q^2 range**
  - really Q^2-independent?
- **polarized EMC effect**
  - candidate: ^{7}Li
- **isospin dependence**
  - needs large selection of light-to-heavy targets
- **flavor tagging** with semi-inclusive hadrons
  - but: hadron production is also modified on nuclei (see later)

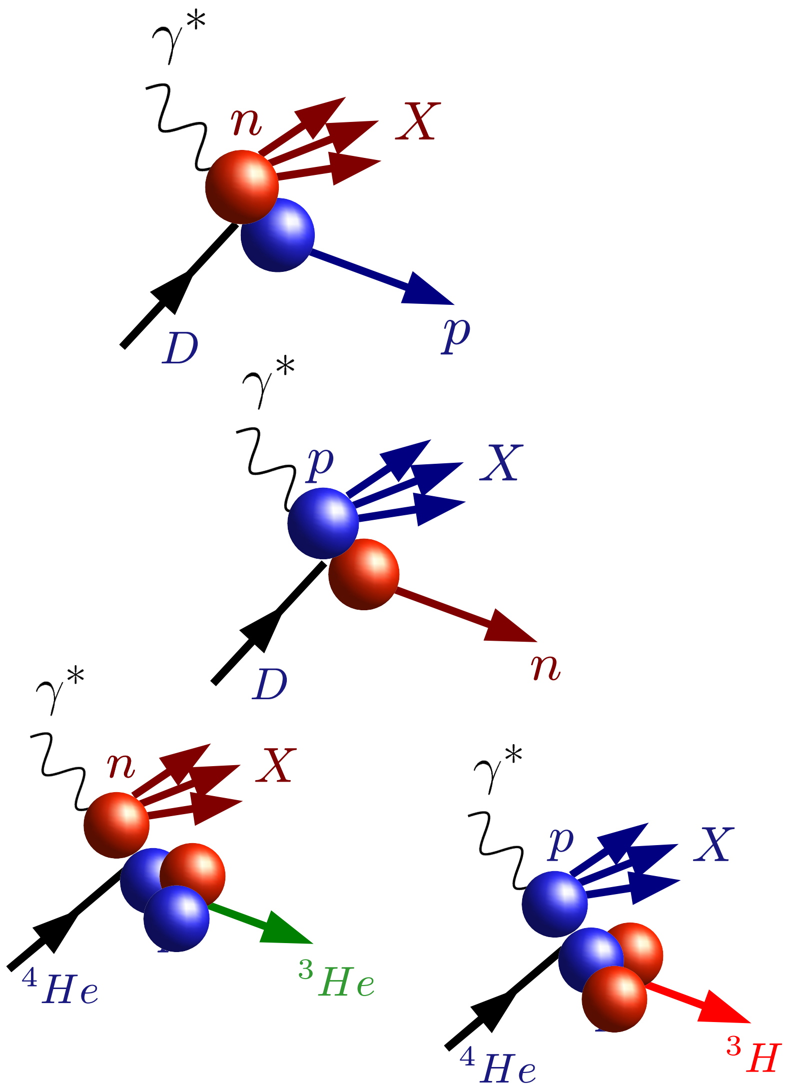
Bound nucleons

Spectator tagging

- measure **neutron F_2** in D target
  - flavor separation

- measure **proton F_2** in D target
  - **unique at colliders**
  - nuclear and off-shell effects **(a piece of the EMC puzzle)**

- **proton, neutron in light nuclei**
  - embedding in nuclear matter **(a piece of the EMC puzzle)**



Bound nucleons

Forward detection requirements

- Spectator neutron moves forward
  Light ions bent, but less than beam

- "straightforward" detectors
  - Zero Degree Calorimeter
  - wire chamber (e.g.) few meters away from IR
  - can do both D and He ?

- But... good performance required:
  - small to high spectator momentum, p_s, decent resolution
  - good angular resolution (challenging):
    backward spectators required to minimize Final State Int's

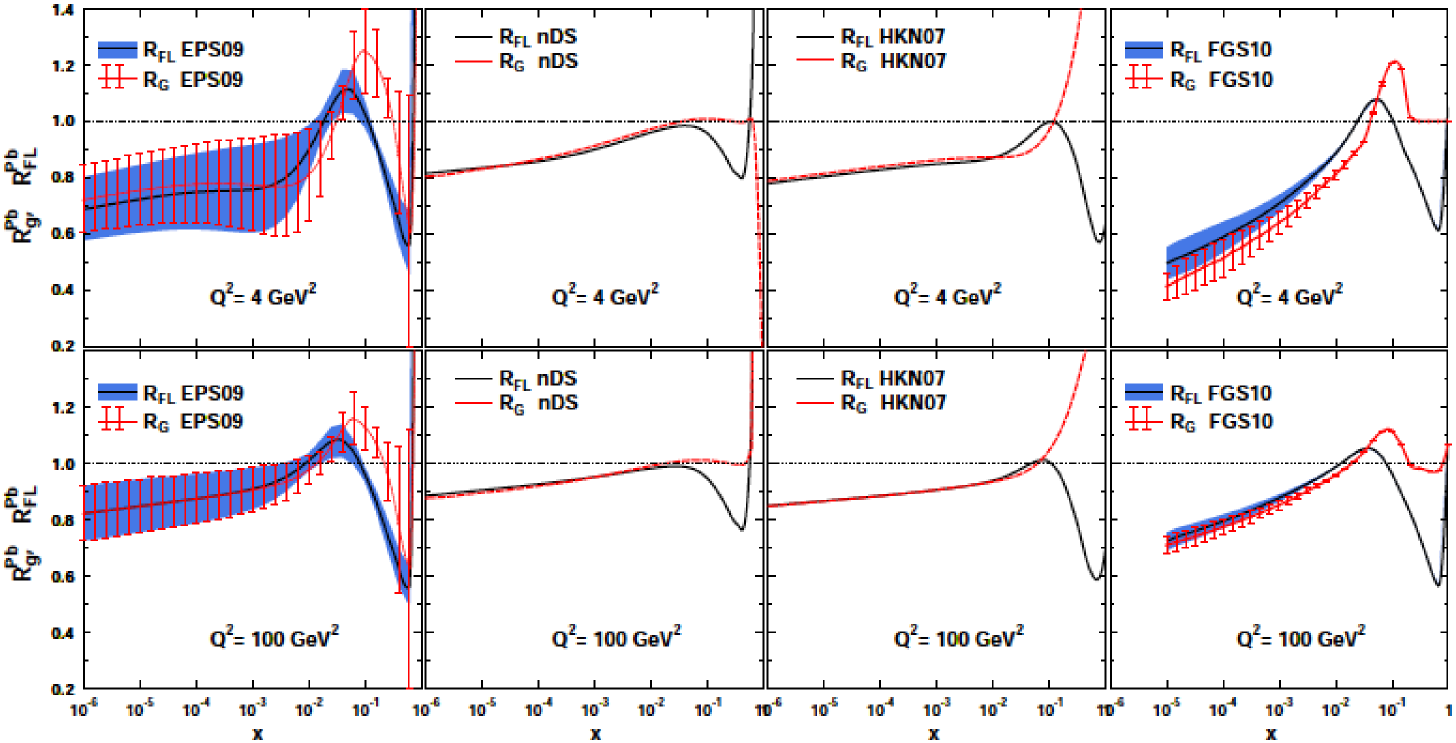
EMC effect - gluons

Nuclear gluons almost unknown

- only direct constrain is d+A -> π+X

EMC ratio for FL tracks nuclear gluons: $F_L^A / F_L^D \approx G_A / G_D$

Armesto et al., 1005.2035



EMC effect - gluons

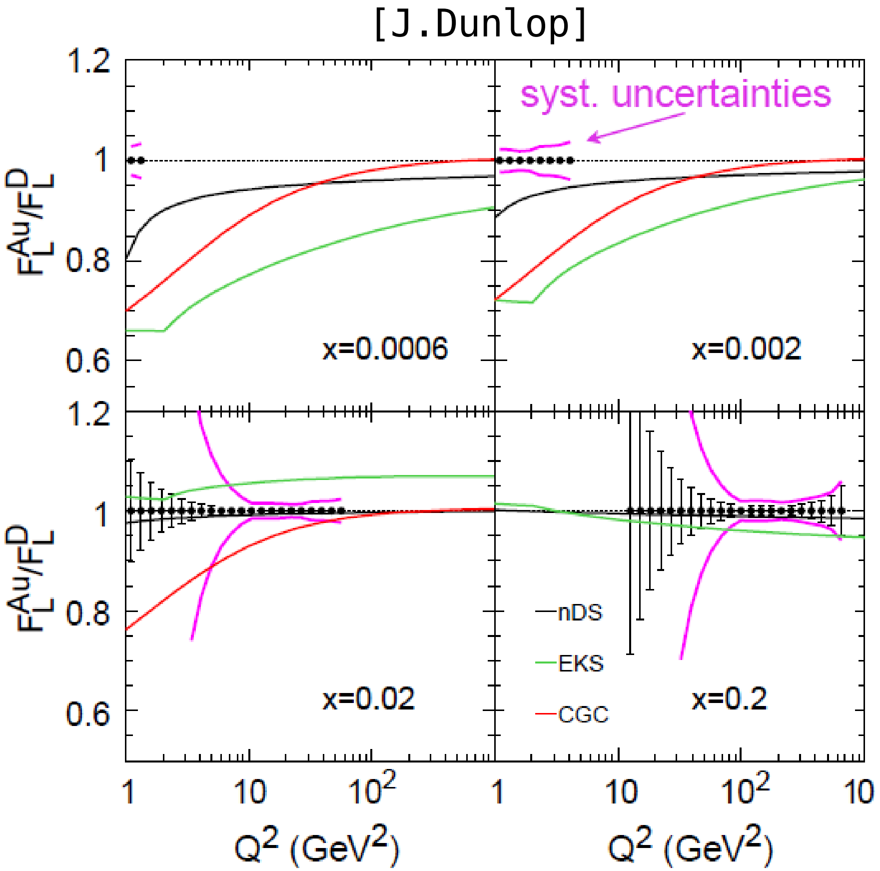
Measurement

- requires running at a few √s
- at least 100 times HERA luminosity

Example at eRHIC

- Run at 10+100, 5+100, 5+50 GeV
- Integrated lumi = 4, 4, 2 fb^{-1}
  (10 weeks, L=4x10^{33} $cm^{-2}s^{-1}$, 50% duty)
- 1% energy to energy normalization

dominated by systematic uncert.



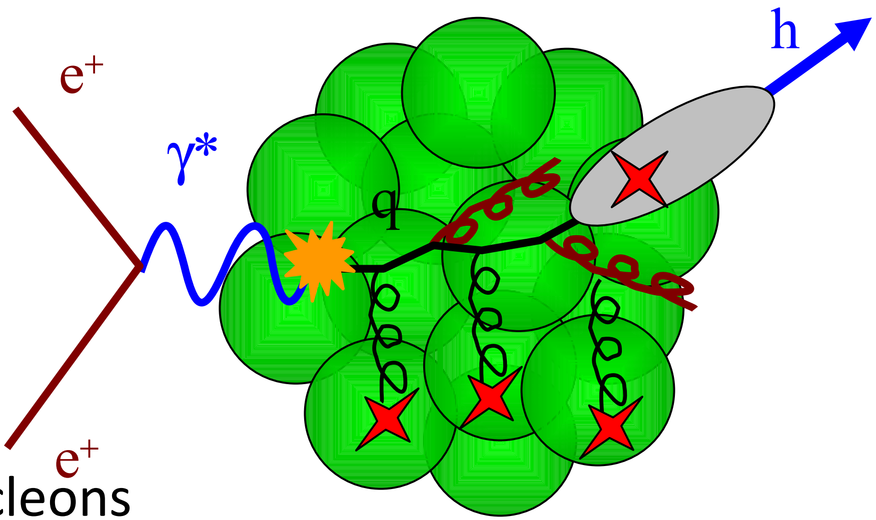
EIC can greatly contribute to measuring gluons nuclear modifications

selected topics:

hadronization in nuclei

Parton propagation and fragmentation

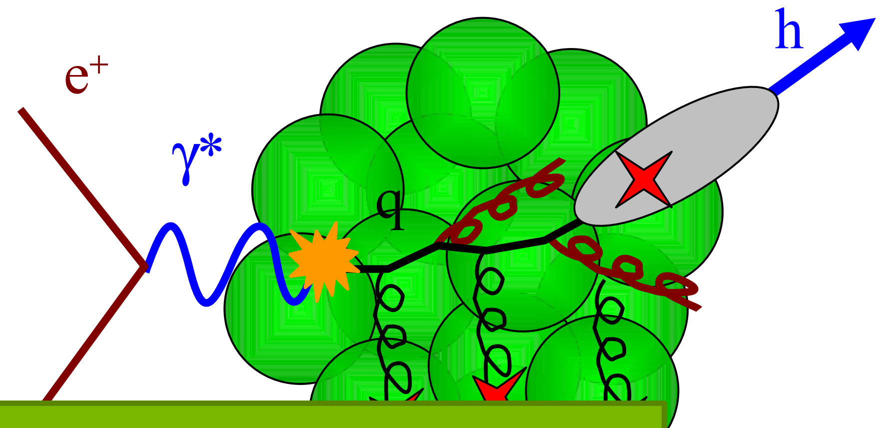
Review: Accardi et al., Riv.Nuovo Cim.032,2010



- **Nuclei as space-time analyzers**
- **Non perturbative aspects**
  - Color confinement dynamics
  - Probe nuclear gluons
  - new look at TMDs in “bound” nucleons
  - novel access to gluon GPDs
- **Perturbative QCD**
  - testing pQCD energy loss
  - DGLAP evolution, parton showers, jets

Parton propagation and fragmentation

Review: Accardi et al., Riv.Nuovo Cim.032,2010

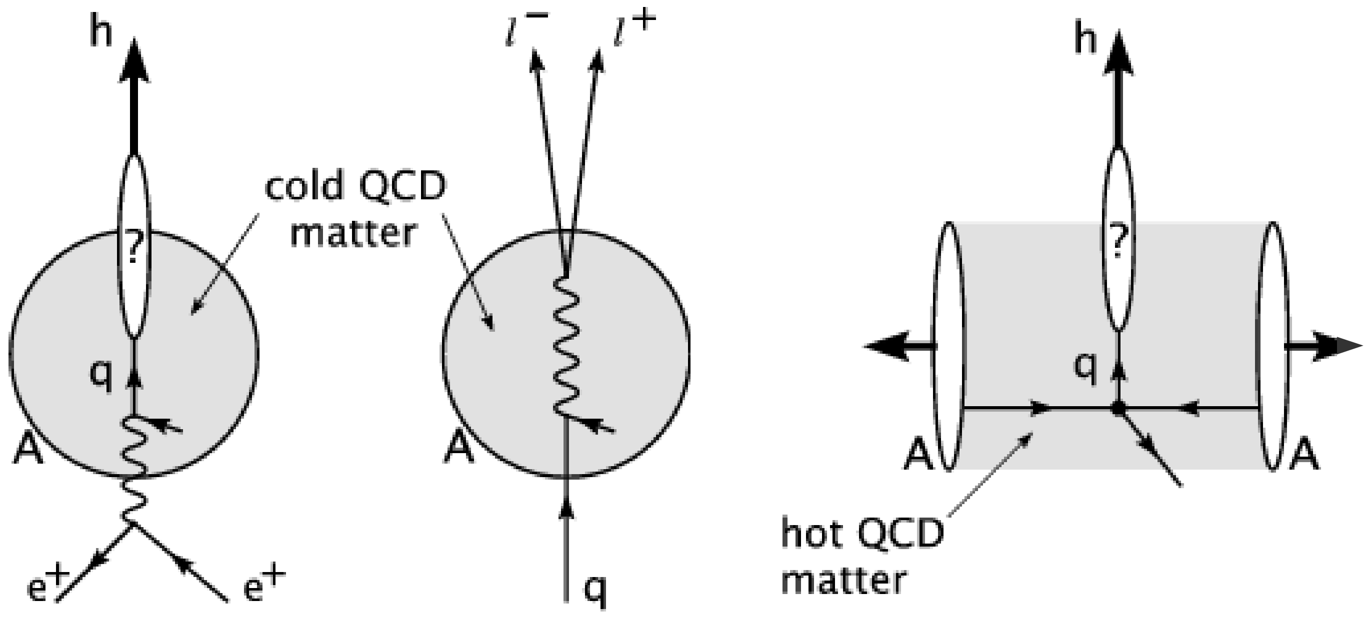


- **Nuclei as space-time analyzers**
- **Non perturbative aspects**
  - Color confinement dynamics
  - P
  - r
  - r
- **Pert**
  - testing pQCD energy loss
  - DGLAP evolution, parton showers, jets

Partons created in the medium can be used as color probes of nuclear gluons when parton lifetime and energy loss mechanisms are under theoretical control

Cold vs. hot

Review: Accardi et al., Riv.Nuovo Cim.032,2010



DIS
FS energy loss
+ hadronization

DY
IS energy loss
+ nuclear PDFs

properties of the QGP

DY vs. EMC effect

The EIC - large ν, Q^2, W^2, $\mathscr{L}$

Multi dimensional binning!

Large ν-range: $10 < \nu < 1600$ GeV

- large ν : can experimentally isolate pQCD energy loss
- small ν : detailed studies of (pre)hadronization

Large Q^2: role of virtuality in hadron attenuation

p_T-broadening

- strong constraints to theory models

Heavy flavors: B, D mesons ; J/psi "normal" absorption

Jets: "real" pQCD, IR safe jets, first time in e+A

- jet shape modifications
- measure nuclear gluons

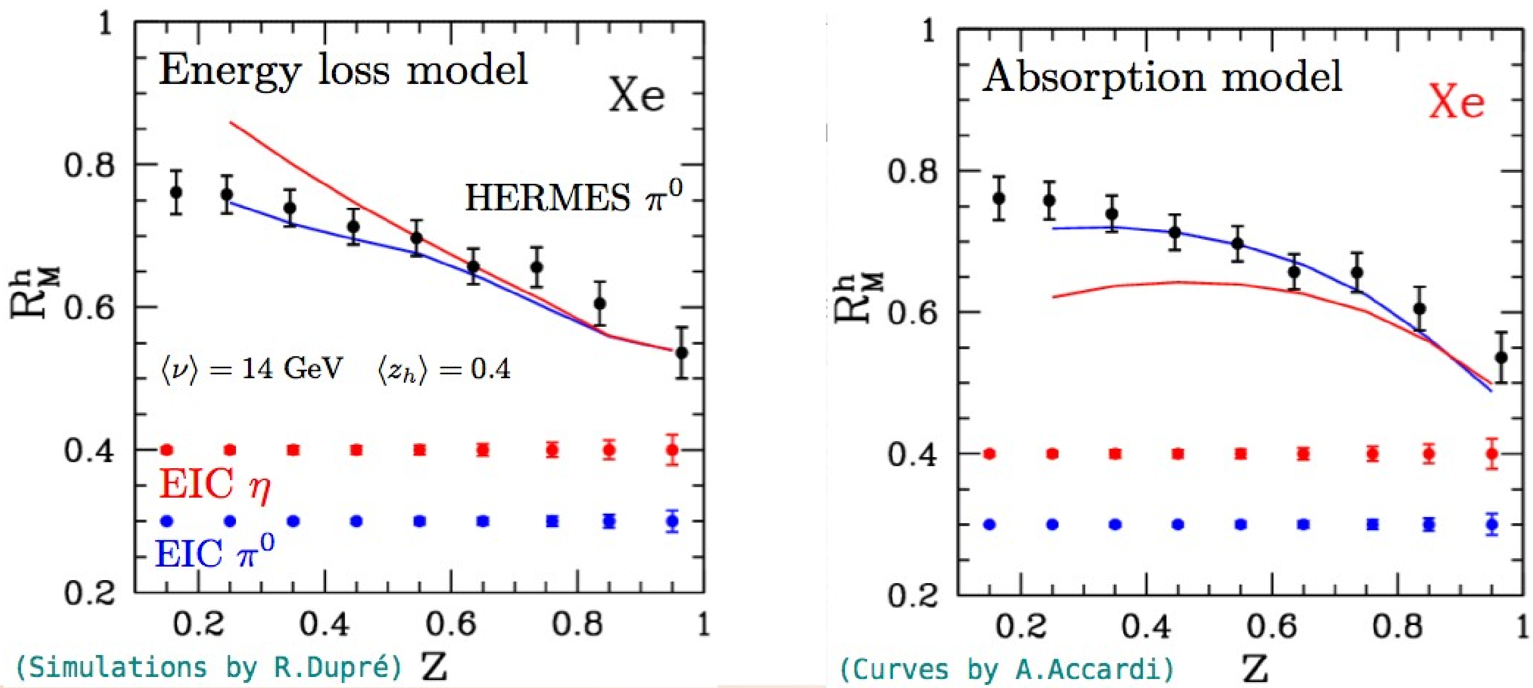
Photons: decouple from medium, tests parton propagation

Plus: dihadron correlations, baryon / target fragmentation, BEC, ..

Light quarks: π^0 vs. η

- can precisely test
  - dominance of energy loss over absorption mechanism
  - is π^0 as much suppressed as η as seen in QGP? Is K as much as Φ ?

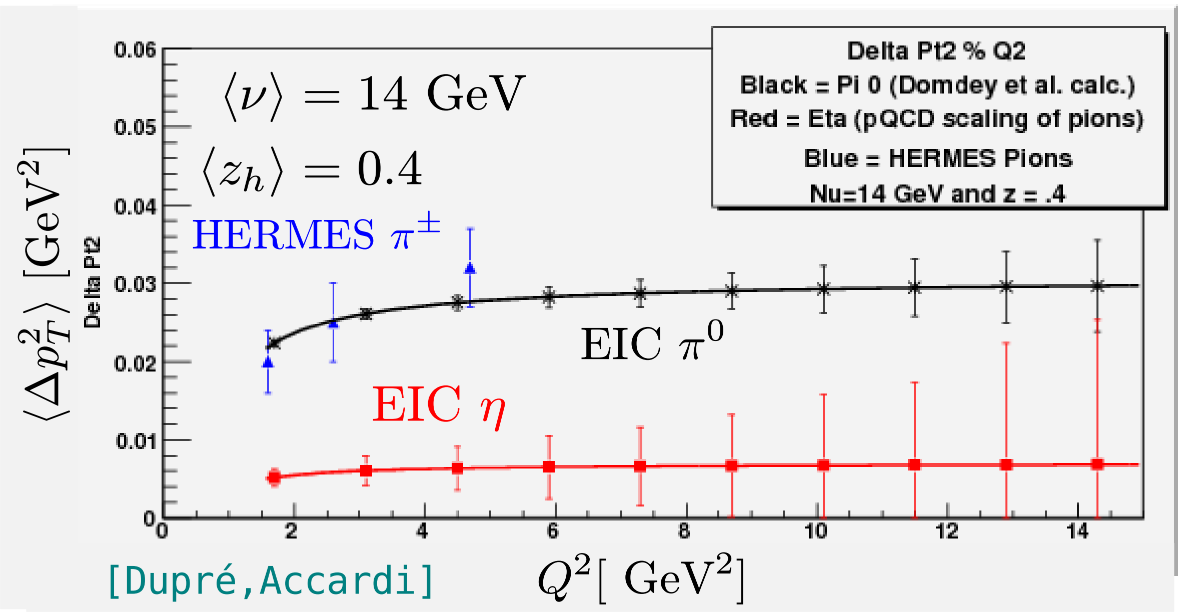
$$R_M^h(z_h) = \frac{1}{N_A^{DIS}} \frac{dN_A^h(z_h)}{dz_h} \Big/ \frac{1}{N_D^{DIS}} \frac{dN_D^h(z_h)}{dz_h}$$



Light quarks: π^0 vs. η

- can precisely test
  - dominance of energy loss over absorption mechanism
  - is π^0 as much suppressed as η as seen in QGP? Is K as much as Φ ?

$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$



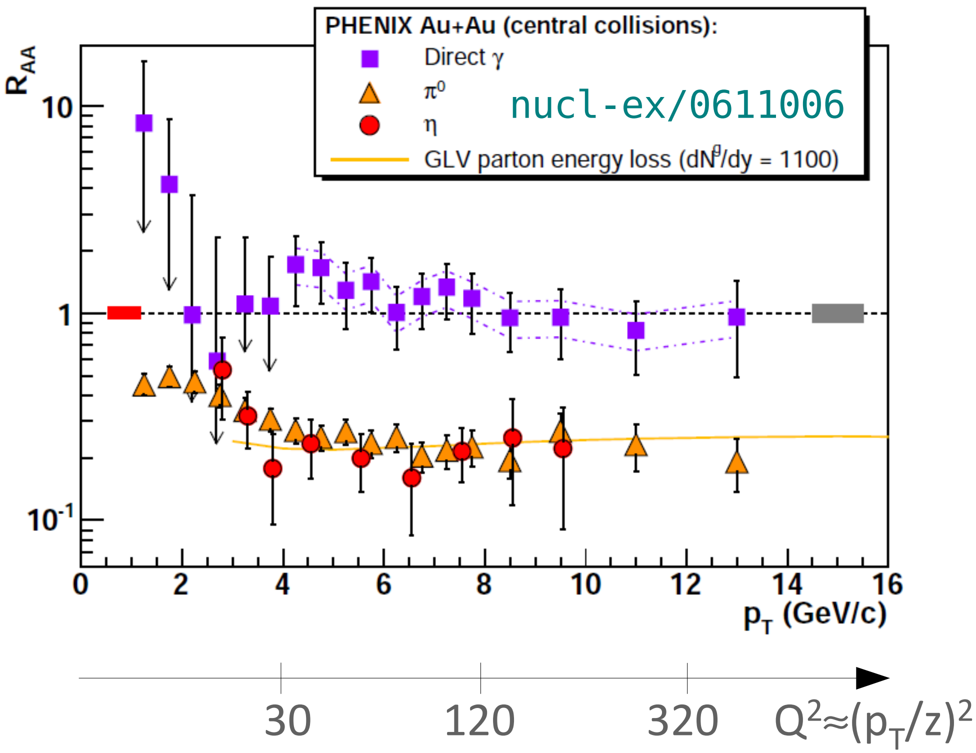
medium-modified DGLAP (Domdey et al.)

pQCD scaling of pions

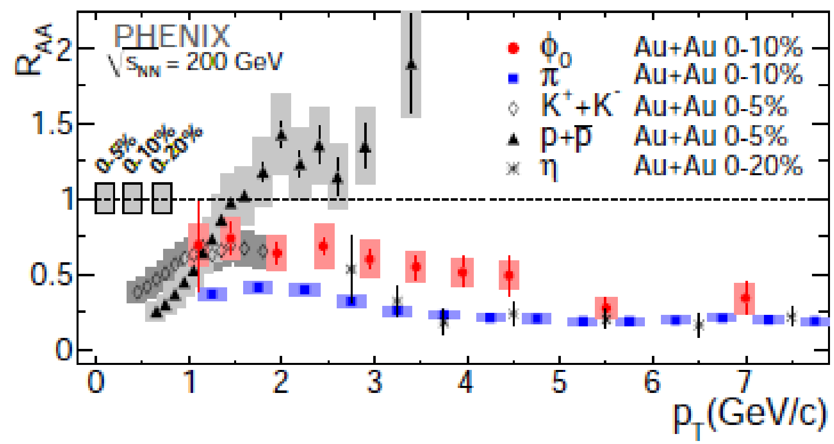
Light quarks: π^0 vs. η

- Compare with A+A at RHIC: $\pi^0 \approx \eta \;<\; K \approx \Phi$

$$R^h_{AA}(p_T) = \frac{\left(dN^h/d^2p_T\right)_{A+A}}{T_{AA}(b)\,\left(d\sigma^h/d^2p_T\right)_{p+p}}$$



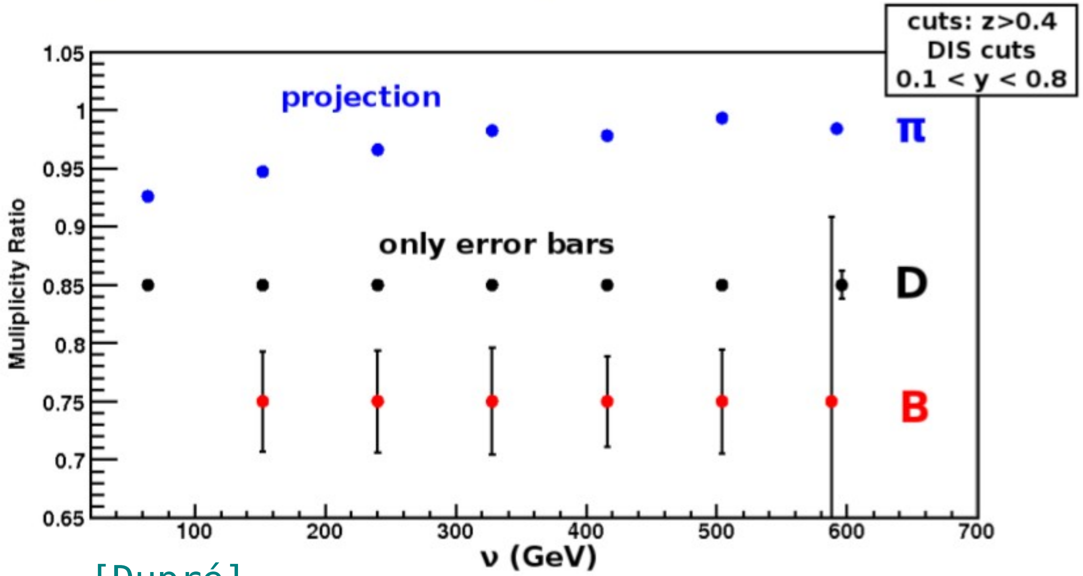
[PHENIX, arXiv:1004.3532]



see also: STAR, 0809.4737

Heavy quarks: D vs. B

- Large mass allows pQCD calculation of energy-loss, fragmentation
- Predicted to loose less energy than light quarks
  - not observed in the QGP at RHIC



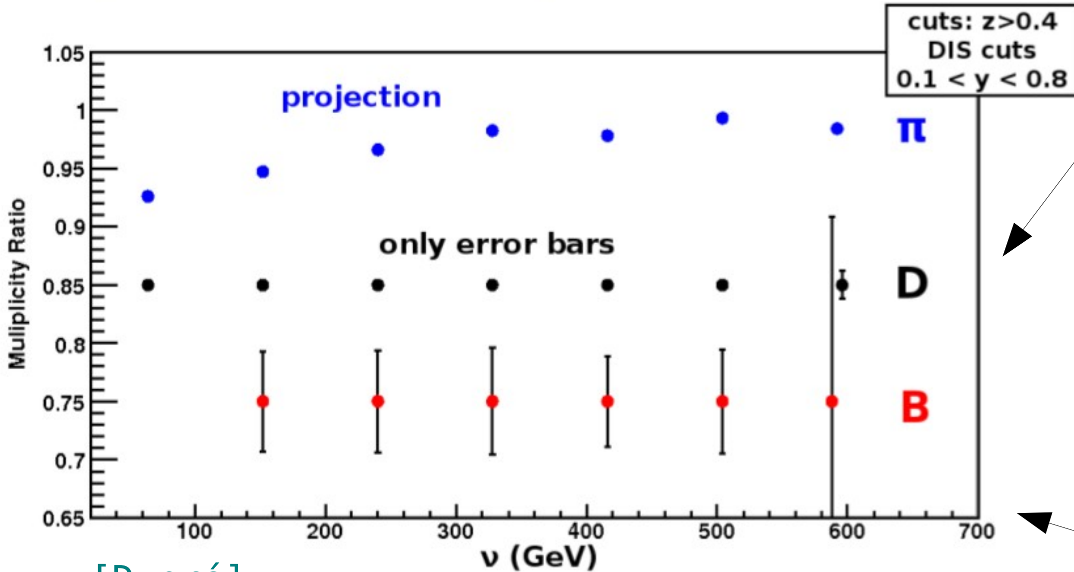
[Dupré]

11 + 30 GeV/A
L = 0.4 10^{33} cm^{-2} s^{-1}
1 month 100% running

- Requires
  - secondary vertex resolution < 100 μm
  - high luminosity, especially for B mesons

Heavy quarks: D vs. B

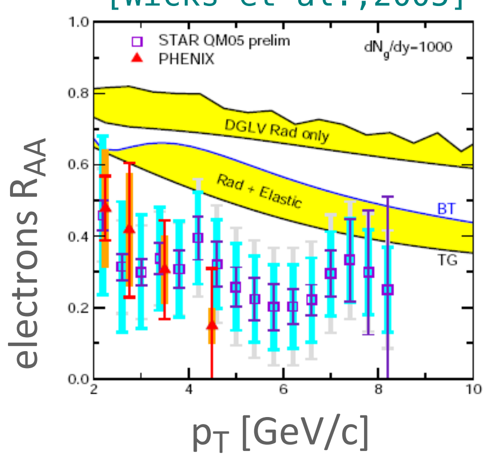
- Large mass allows pQCD calculation of energy-loss, fragmentation
- Predicted to loose less energy than light quarks
  - not observed in the QGP at RHIC



[Dupré]

Can solve RHIC's "heavy-flavor puzzle"

[Wicks et al.,2005]



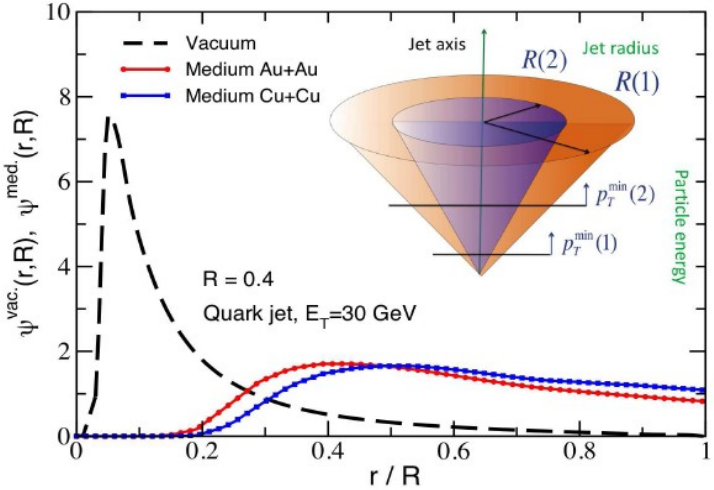
Q^2 range relevant to A+A

- Requires
  - secondary vertex resolution < 100 μm
  - high luminosity, especially for B mesons

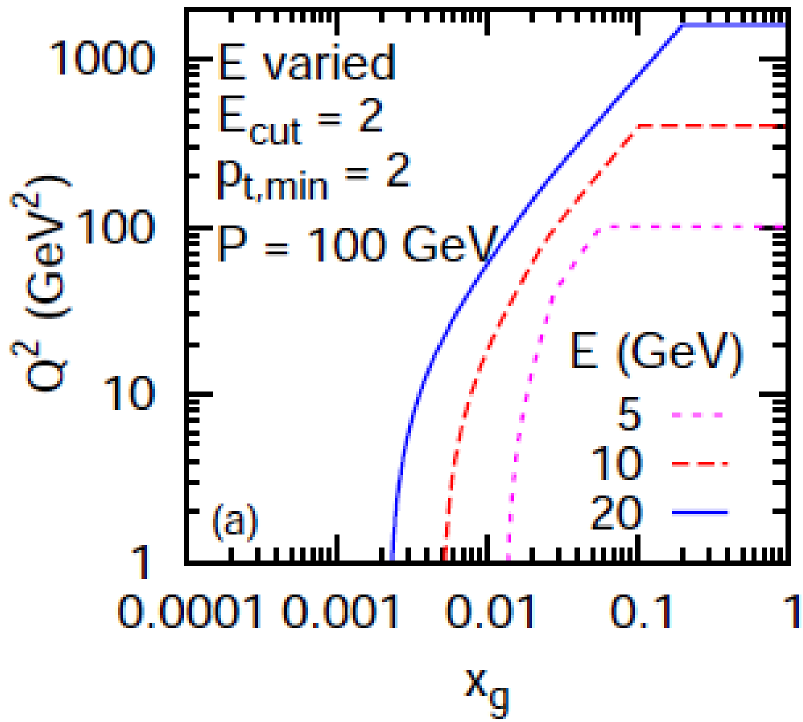
Jet production in e+A

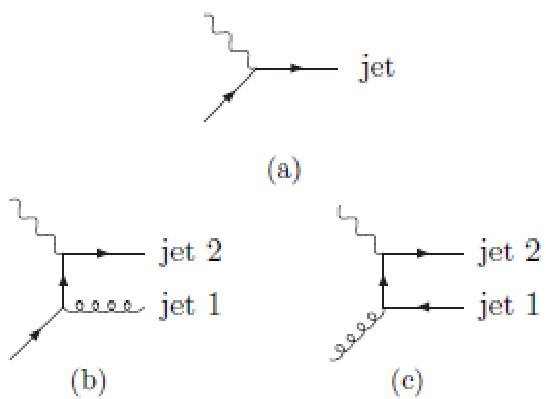
- **1+1 jets: study energy loss**
  - jet rates vs. cone:
    gluon radiation boradens the jets
  - rates vs. p_T^{min}, E^{min} :
    more handles on energy loss
- **2+1 jets: access to nuclear gluons**
  - after energy-loss under control
    from 1+1 studies

[I.Vitev]



[G.Soyez]



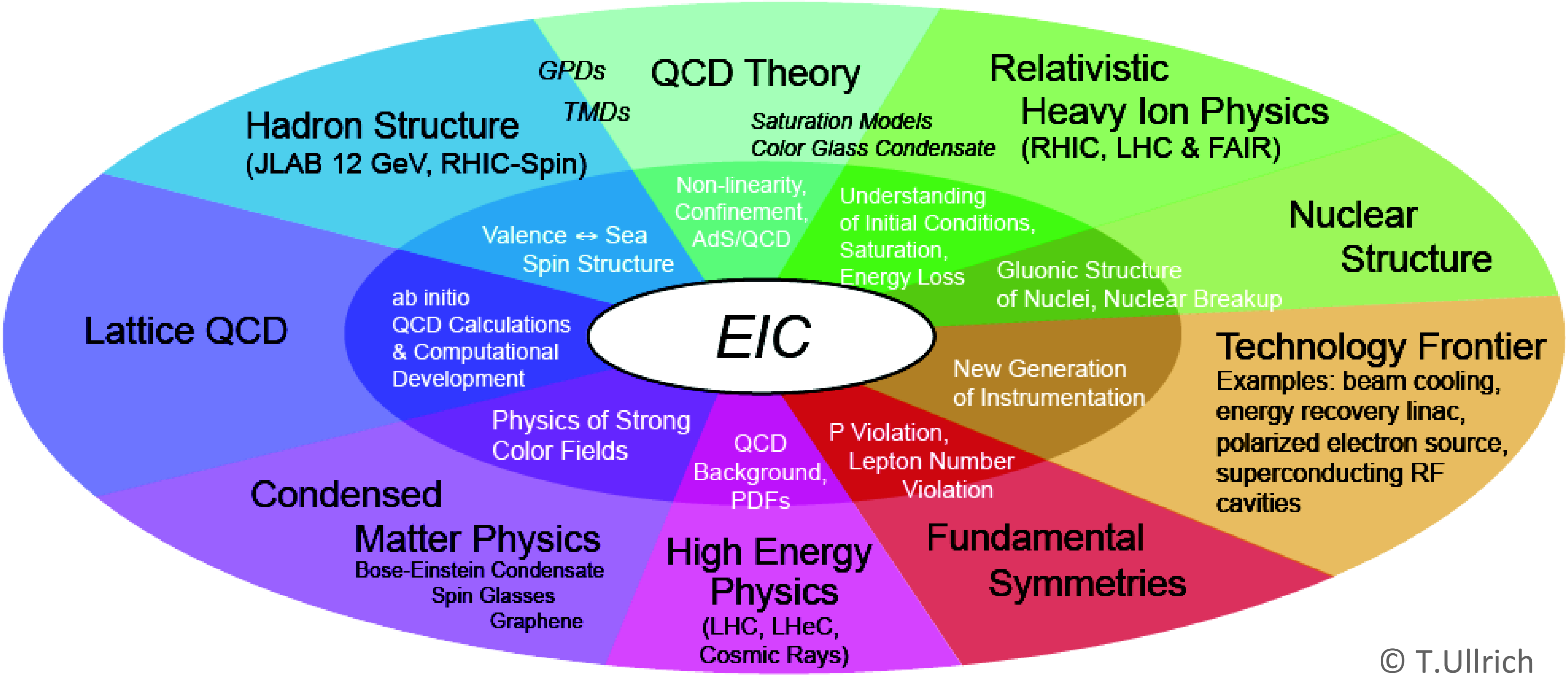


Other venues to explore

- **Target fragmentation**
  - observe particles that received energy from the scattered parton as opposed to observing particles that lost that energy
  - determine the centrality of photon-nucleus scattering
- **Bose-Einstein correlations** between produced hadrons
  - measure the source size of an excited color string, string tension
  - nuclear modification
- **Nuclear modification of Cahn effect**
  - more handles on quark energy loss
  - info on flavour dependence of nuclear modification of TMDs

The EIC

THE next generation QCD machine, a unique opportunity for fundamental physics



© T.Ullrich

appendix:

useful links

The JLab Nuclear Chromo-Dynamics (NCD) group

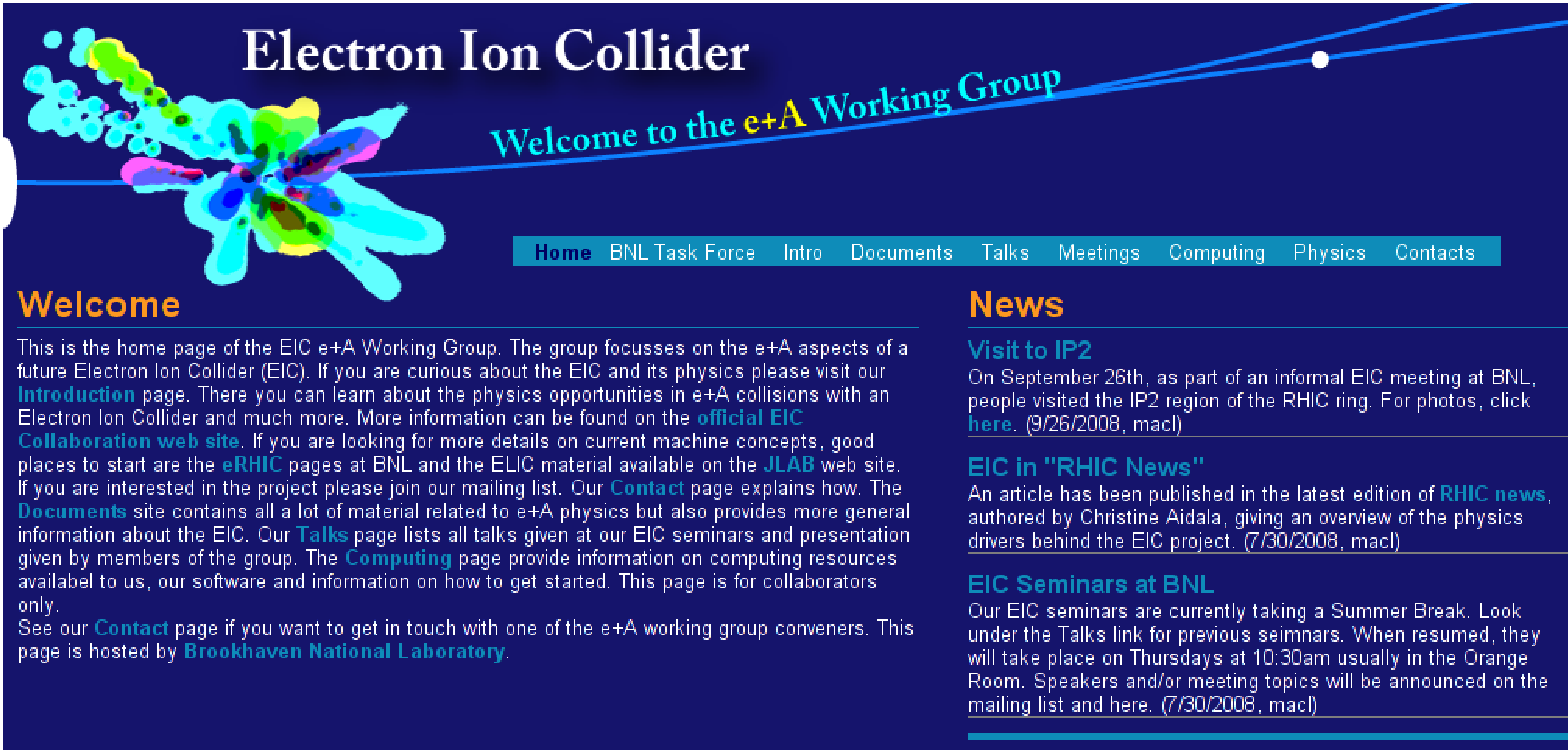
Co-chairs (W. Brooks, K. Hafidi)

D. Gaskell is the liaison between the NCD group and the detector group

Wiki: https://eic.jlab.org/wiki/index.php/E-A_Working_Group

- **Exclusive reactions** (DVCS, shadowing and anti-shadowing, nuclear form factors)
  V. Guzey (chair), S. Dhamija, R. Dupre, H. Egyian, A. El Alaoui, F-X. Girod, S. Gilad, G. Ron, D. Higinbotham, L. Zhu
- **Nuclear effects** (EMC effect, medium modification, shadowing and anti-shadowing)
  J. Arrington (chair), D. Dutta, D. Gaskell, S. Gilad, K. Joo, P. Reimer, P. Solvignon, R. Ent
- **Short range structure** (correlations, Bose-Einstein correlations)
  M. Sargsian (chair), J. Arrington, S. Gilad, D. Higinbotham, P. Solvignon, W. Brooks, J. Gilfoyle, K. Hafidi
- **Color in nuclei** (color transparency, color glass condensate, hidden color)
  D. Dutta (chair), L. El Fassi, M. Holtrop, R. Ent
- **Propagation in nuclei** (parton propagation, hadronization)
  A. Accardi (chair), W.Brooks, R.Dupre, L.El Fassi, J.Gilfoyle, H.Avakian, A.Majumder, T.Mineeva, J.Gilfoyle, A.Daniel

Strong support from theorists: C. Degli Atti, L. Frankfurt, K. Gallmeister, B. Kopeliovich, J. Miller, U. Mosel, J. Nemchik, I. Ryckebush, I. Schmidt, M. Strikman, S. Brodsky, , P. Hoyer, X-N. Wang, F. Arleo, S. Ahmad, S. Liuti, M. Siddikov



Electron Ion Collider

Welcome to the e+A Working Group

Home | BNL Task Force | Intro | Documents | Talks | Meetings | Computing | Physics | Contacts

Welcome

This is the home page of the EIC e+A Working Group. The group focusses on the e+A aspects of a future Electron Ion Collider (EIC). If you are curious about the EIC and its physics please visit our **Introduction** page. There you can learn about the physics opportunities in e+A collisions with an Electron Ion Collider and much more. More information can be found on the **official EIC Collaboration web site**. If you are looking for more details on current machine concepts, good places to start are the **eRHIC** pages at BNL and the ELIC material available on the **JLAB** web site. If you are interested in the project please join our mailing list. Our **Contact** page explains how. The **Documents** site contains all a lot of material related to e+A physics but also provides more general information about the EIC. Our **Talks** page lists all talks given at our EIC seminars and presentation given by members of the group. The **Computing** page provide information on computing resources availabel to us, our software and information on how to get started. This page is for collaborators only.

See our **Contact** page if you want to get in touch with one of the e+A working group conveners. This page is hosted by **Brookhaven National Laboratory**.

News

Visit to IP2

On September 26th, as part of an informal EIC meeting at BNL, people visited the IP2 region of the RHIC ring. For photos, click **here**. (9/26/2008, macl)

EIC in "RHIC News"

An article has been published in the latest edition of **RHIC news**, authored by Christine Aidala, giving an overview of the physics drivers behind the EIC project. (7/30/2008, macl)

EIC Seminars at BNL

Our EIC seminars are currently taking a Summer Break. Look under the Talks link for previous seimnars. When resumed, they will take place on Thursdays at 10:30am usually in the Orange Room. Speakers and/or meeting topics will be announced on the mailing list and here. (7/30/2008, macl)

http://www.eic.bnl.gov/

"Nuclear Chromo-Dynamic Studies with a Future EIC"
Argonne National Lab, April 7-9, 2010

A unifying theme or a glue if you will …

42 participants and 5 Physics sessions organized by the sub-groups chairs

- Nuclear effects (6 talks)
- Exclusive reactions (5 talks)
- Color in nuclei (5 talks)
- Propagation in nuclei (8 talks + colloquium)
- Short range structure (4 talks)

Talks available at **http://www.phy.anl.gov/mep/EIC-NUC2010/talks/**

“Gluons and quarks at high-energy”
INT, Seattle, Sep 13 - Nov 19

week	dates	topics
1	13–17 Sept	**Workshop** on "Perturbative and Non-Perturbative Aspects of QCD at Collider Energies"
2	20–24 Sept	open conceptual issues: factorization and universality, spin and flavor structure, distributions and correlations
3–5	27 Sept –15 Oct	small x, saturation, diffraction, nuclear effects; connections to p+A and A+A physics; fragmentation/hadronization in vacuum and in medium
6–7	18–29 Oct	parton densities (unpolarized and polarized), fragmentation functions, electroweak physics
8–9	1–12 Nov	longitudinal and transverse nucleon structure; spin and orbital effects (GPDs, TMDs, and all that)
10	15–19 Nov	**Workshop** on "The Science Case for an EIC"

http://www.int.washington.edu/PROGRAMS/10-3/

appendix:

additional material

Experimental evidence: e+p at HERA

Geometric scaling

- Data scale with $\tau = \frac{Q^2}{Q_0^2}\left(\frac{x}{x_0}\right)^\lambda$

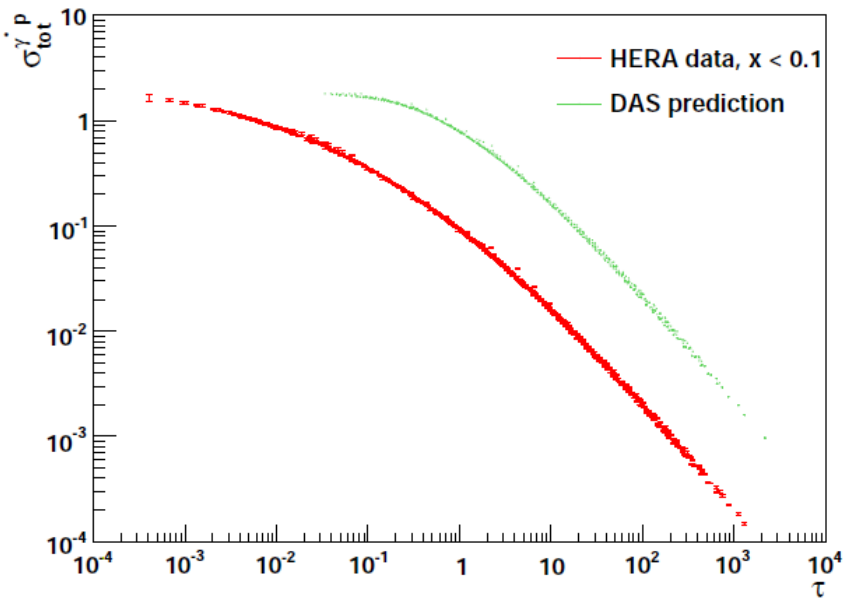
  [Stasto, Golec Biernat, Kwiecinsky, 2001]

- Evidence for saturation ?
  - CGC predicts $\lambda \approx 0.3$
  - agrees with data

  [Gelis et al., 2007]

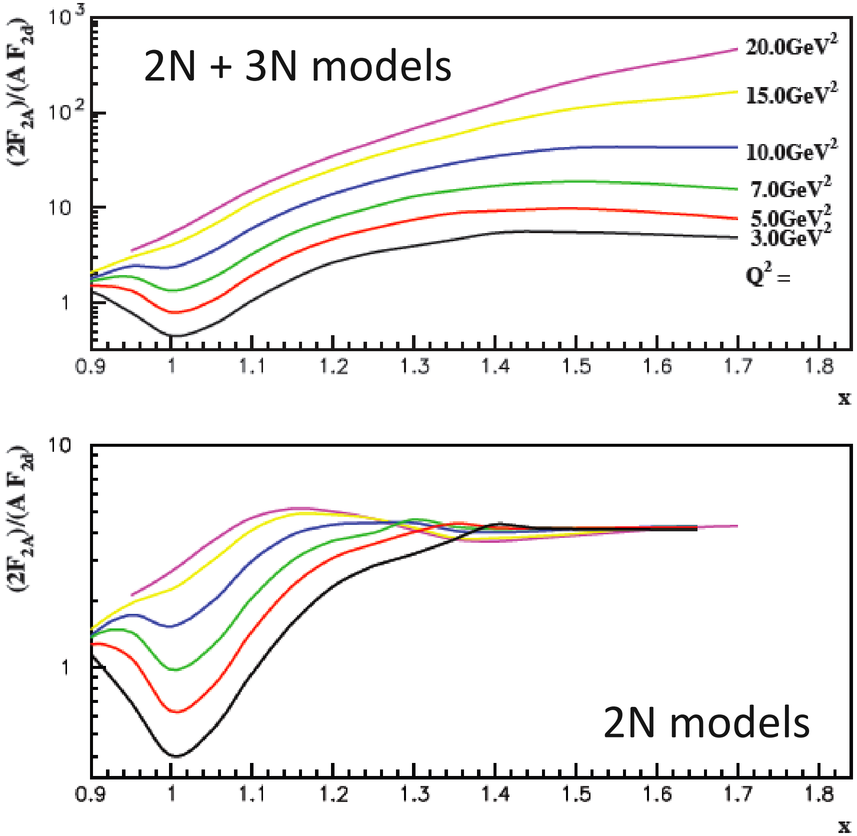
- But double-log solution to LO DGLAP also scales ("DAS")
  - similar λ

  [Caola, Forte, 2008]



Superfast quarks - Short range correlations @ larger Q^2 and smaller x

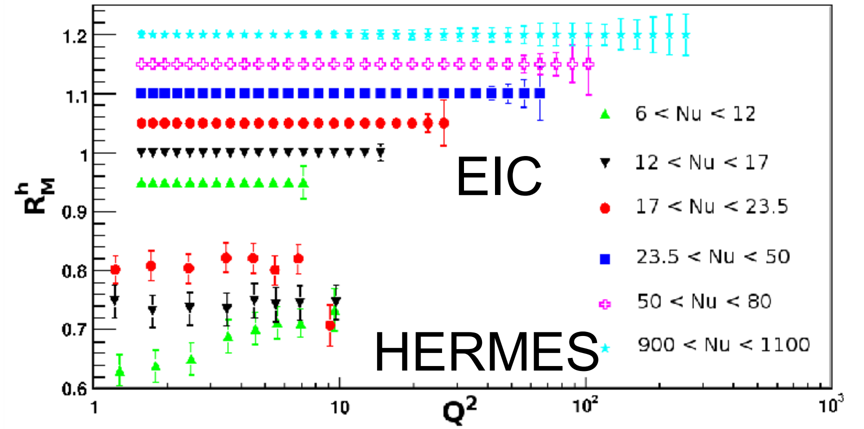
- x_B>1 possible with
  - high-momentum nucleons
  - exotics: 6q bags, ...
- For s=1000, L ≈ 10^{34}, statistics running out for x > 0.9 – 1
  - *Need to evaluate statistics for lower s, larger x*
  - *Not clear how high in x required to isolate short-range structure we are interested in*

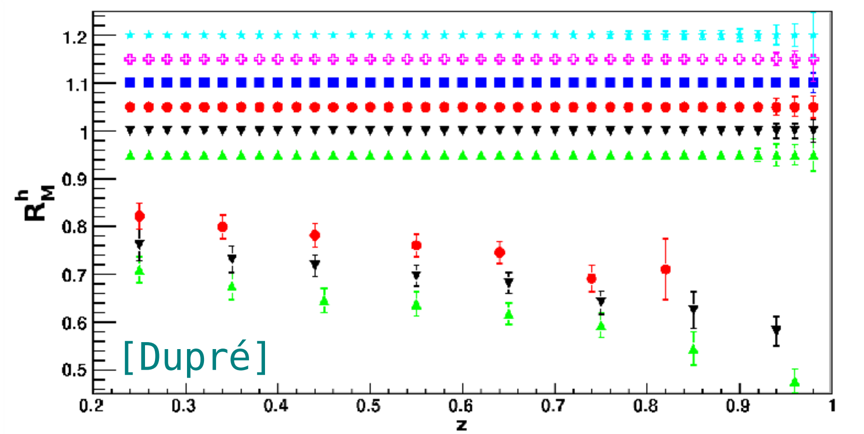


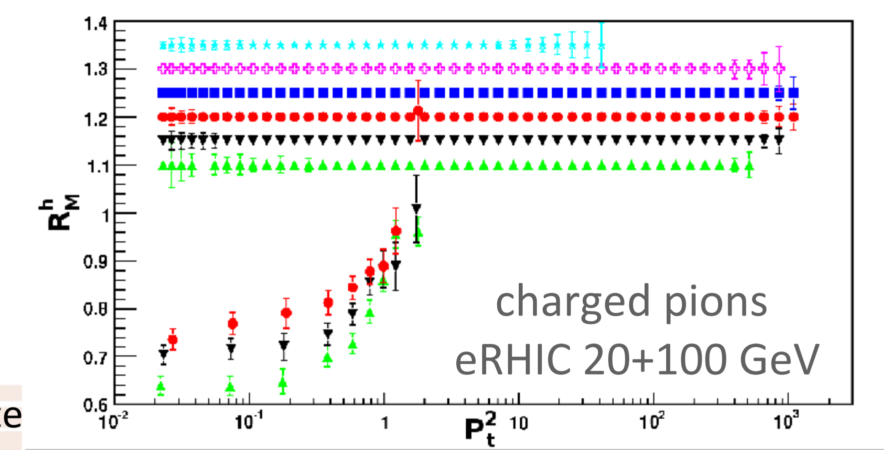
Plots by M.Sargsian

Multi-dimensional binning

- Simulation with PYTHIA 6.4.19
  - no nuclear effect yet
  - 10 weeks of beam at eRHIC
- High statistics: 5D distributions
- Large range in p_T , Q^2
- Small to large x_B: LO vs. NLO
- Large range in ν
  - small ν – hadronization inside A
  - large ν – precision tests
    - QCD en. loss
    - DGLAP evolution
    - parton showers

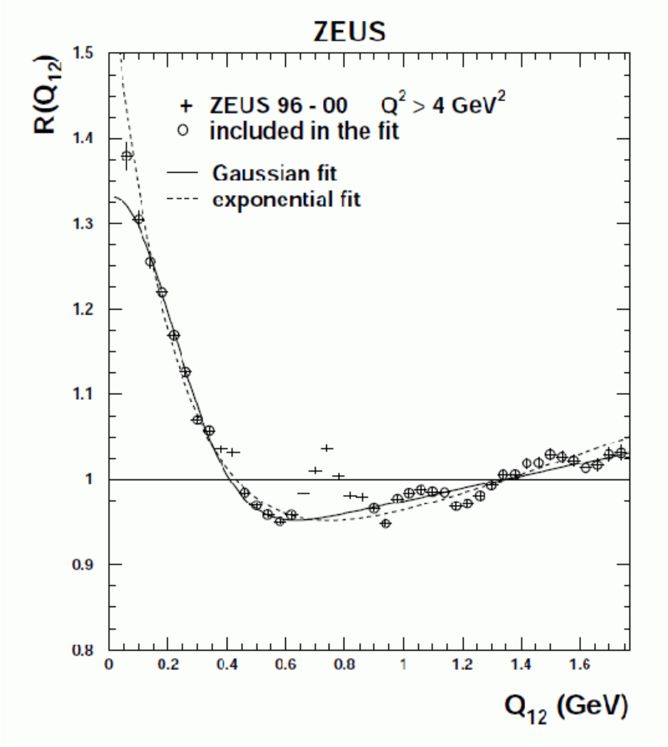


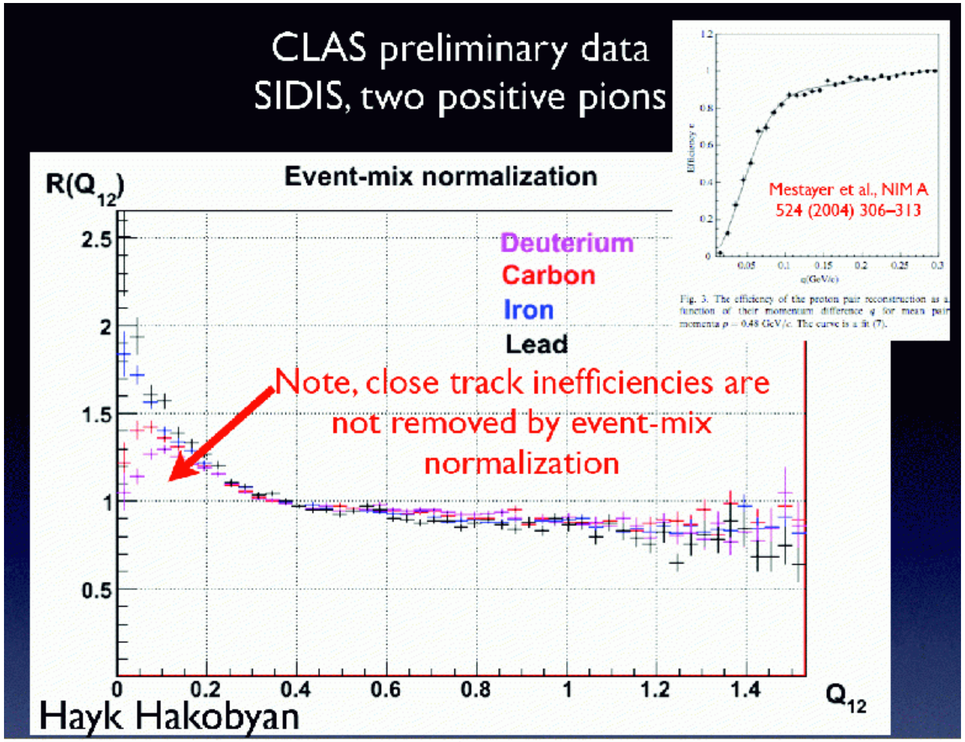




Bose-Einstein Correlations

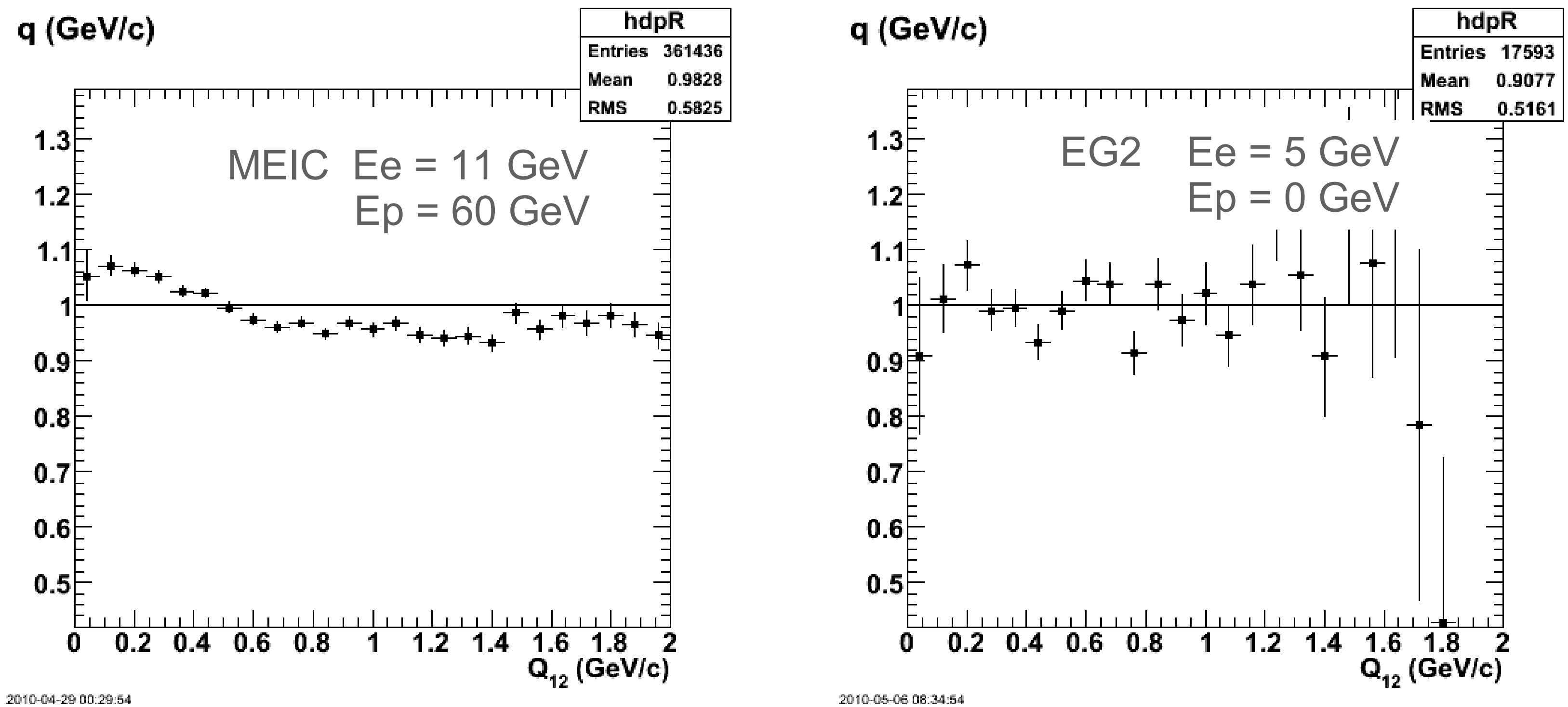
- HBT interferometry of identical particles
  - access to spatial size and temporal duration of hadronization
  - how is this modified in nuclei?
- In DIS, access to the string tension





Bose-Einstein Correlations

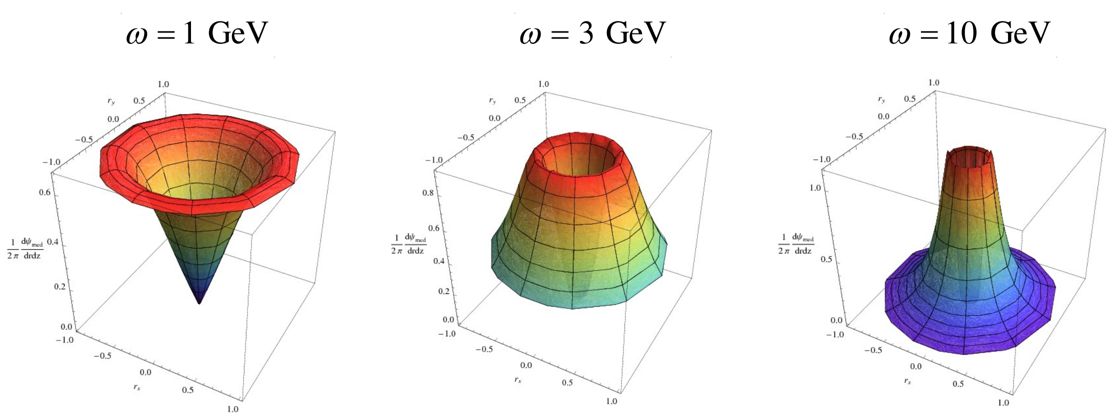
- HBT interferometry of identical particles
  - access to spatial size and temporal duration of hadronization
  - how is this modified in nuclei?
- In DIS, access to the string tension



G.Gilfoyle, PITHIA simulation (standard ZEUS params)

Photons

- Photon induced radiation, analogous to gluon bremsstrahlung
  - but photons do not self-interact, escape the medium
- Advantages over gluons
  - calculable angular pattern relative to hadron
  - different from fragmentation g, absorption g



[VITEV, PLB 2005]

N.B. The calculation is for coherent FS gluon emission. Expect similar pattern for γ

Photons

- Relax eikonal approximation: **access to nuclear gluon GPDs** [Majumder]