High-energy QCD and hadronization at the EIC

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JLab theory seminar
8 December 2010

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?

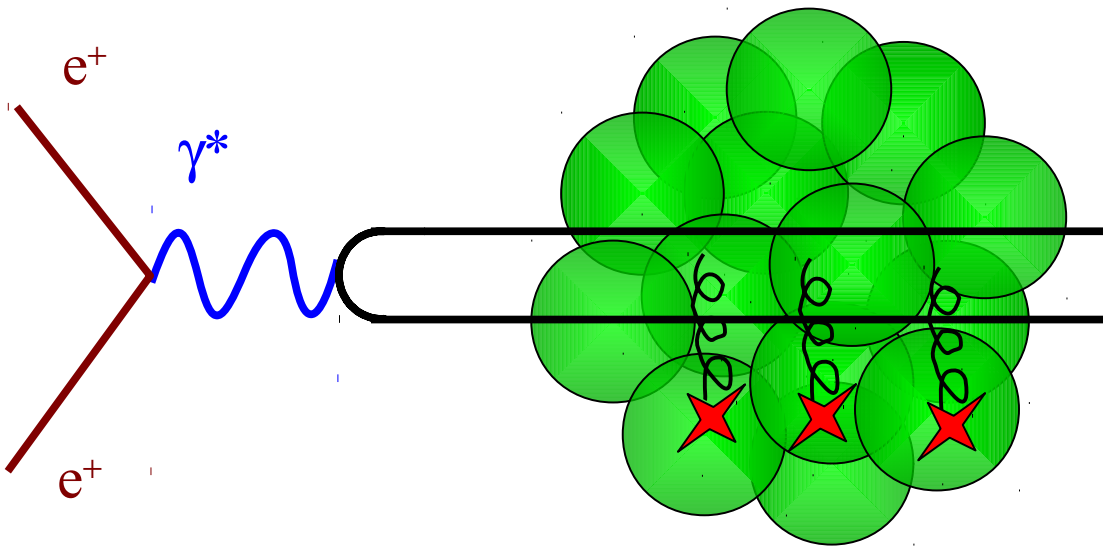
$$L_{QCD} = \bar{q}\left(i\gamma^{\mu}\partial_{\mu} - m\right)q - g\left(\bar{q}\gamma^{\mu}T_a q\right)A^a_{\mu} - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- The key to the answers is the Gluon:
  - Generates 99% of the hadron mass
  - Responsible for high-energy scattering
- Cannot "see" the glue in the low-energy world

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

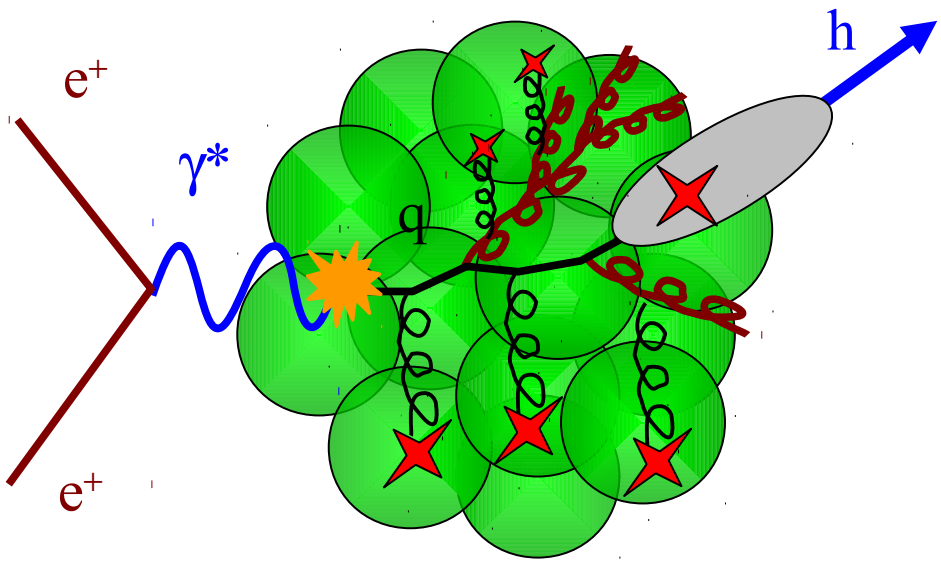
$\Rightarrow$ EXPERIMENTS $\Rightarrow$ EIC !

External (color neutral) probes



- **Small x:** high gluon density
  - non-linear dynamics, but small coupling
  - Perturbative tratment
    - High-energy scattering (LHC, cosmic rays, ...)
    - QGP initial consitions (RHIC, LHC)
- **Large x:** gluon antishadowing, EMC effect [Guzey]

Internally created (colored) probes



- **Hadrons/jets as probe of nuclear gluons**
  - Large-x probes of small x gluons
  - Complementary to previous methods
- **Nucleus as detector of propagating system**
  - How does confinement builds a hadron's color field around a colored parton?
  - How do parton showers evolve?

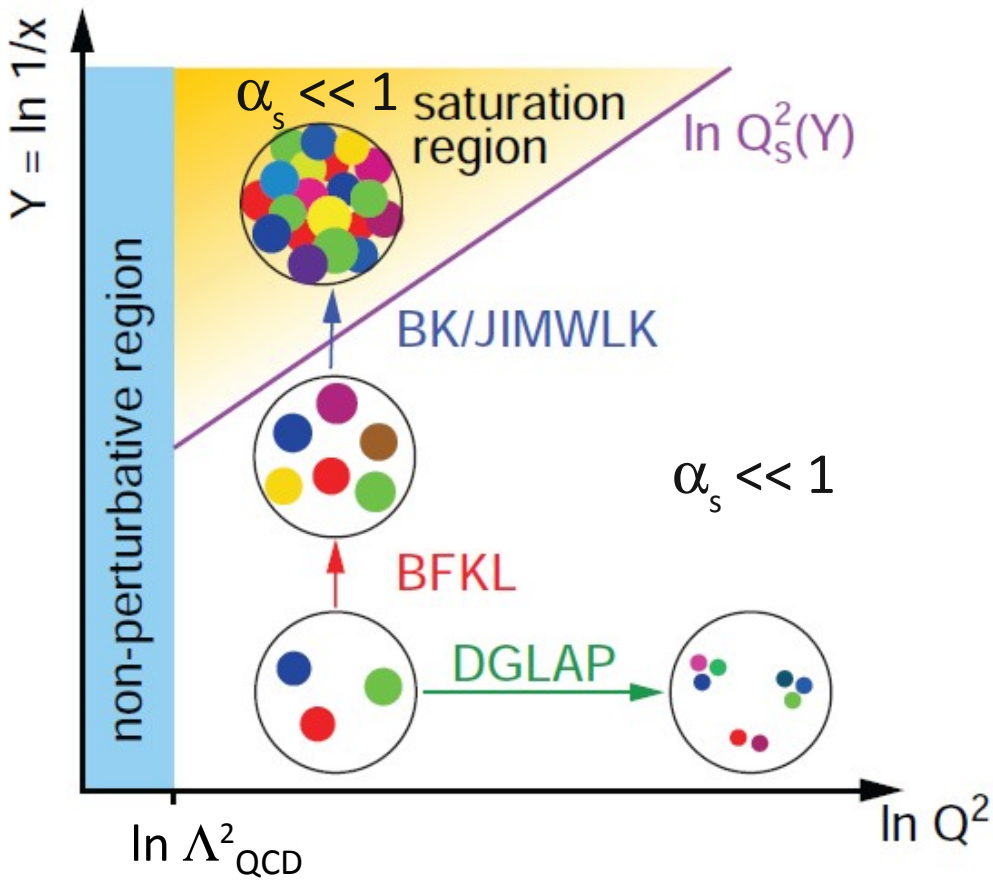
Saturation and Color Glass Condensate

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 ($x \sim 1/\sqrt{s}$)
- gluon dynamics in sat.region is non-linear but weakly couple

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



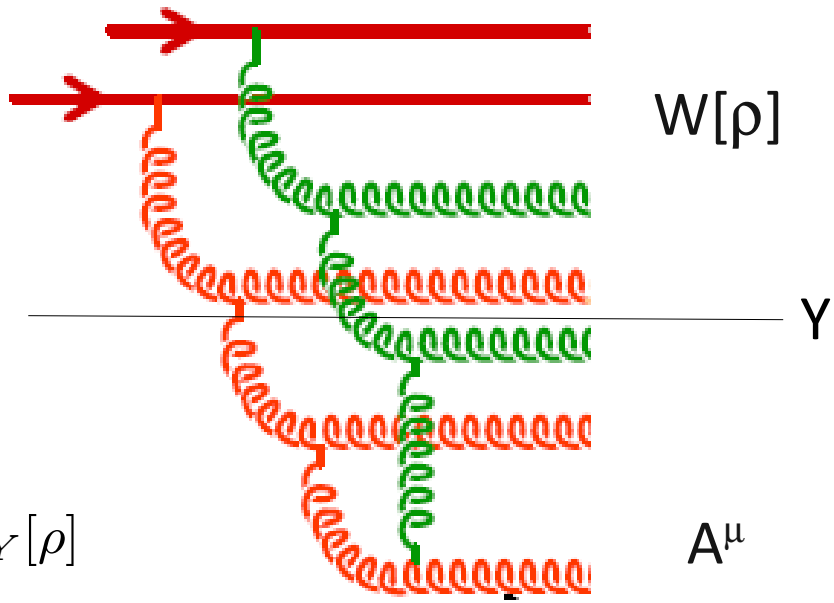
Saturation and Color Glass Condensate

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 at small x

- large-x color sources ρ
  - stochastic distribution W[ρ]
- small-x gluon fields A^μ



Renormalization group

- separation scale $Y = \ln(1/x)$
- evolution equation $\frac{\partial W_Y[\rho]}{\partial Y} = -\mathcal{H} W_Y[\rho]$

Universality

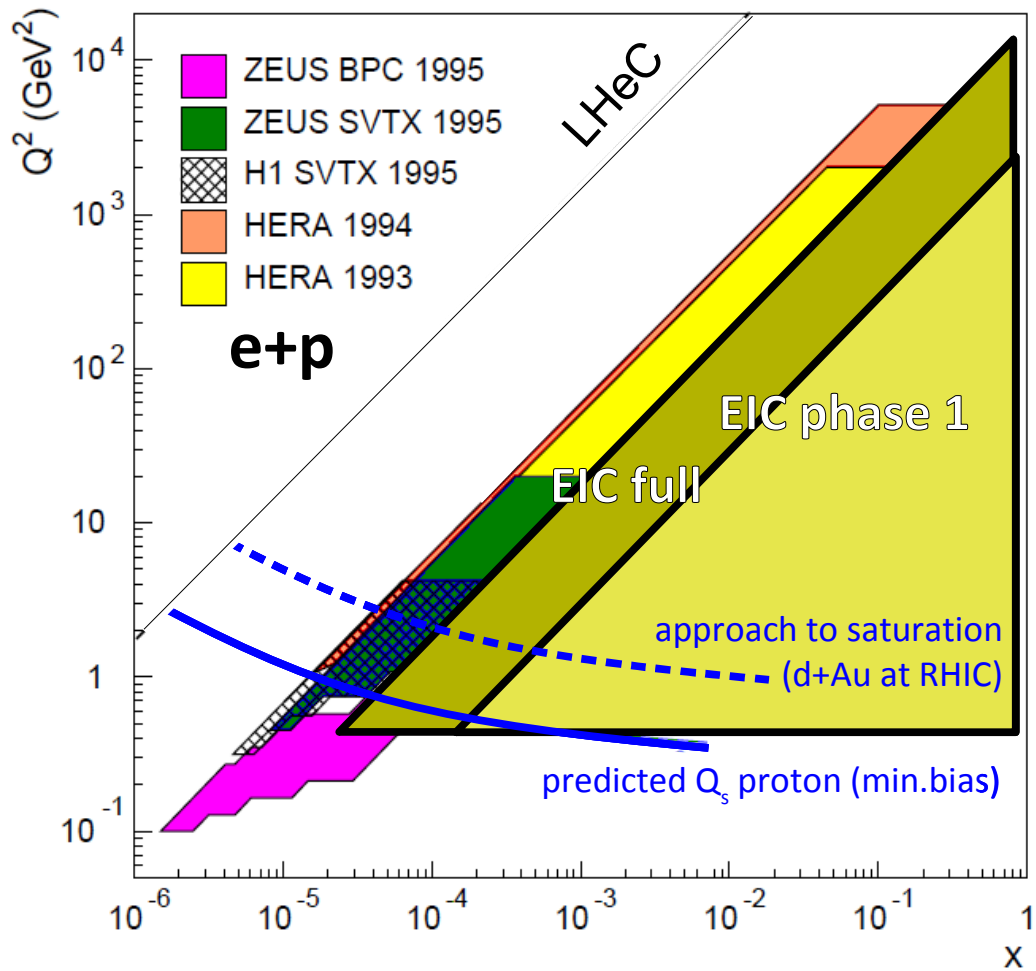
- Hadron / nucleus wave functions
- High-energy scattering: e+p, p+p, A+A, cosmic rays
- "Ridges" at RHIC and LHC !?

Where is saturation in e+p collision?

- HERA touches sat. region
- EIC
  - well outside "sat" region
  - might see approach
- Requiring Q^2 lever-arm, needs e+p with at least

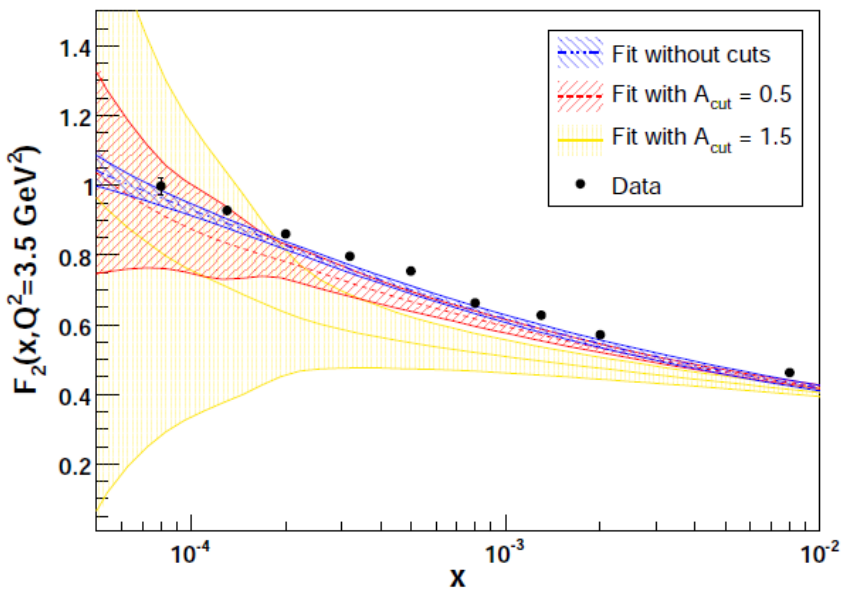
$$\sqrt{s} = 1 - 2 \text{ TeV}$$

  - unrealistic in the US
  - LHeC in Europe



Deviations from DGLAP evolution at HERA

- Predicted in CGC, but also small-x resummation
  - necessary but not sufficient condition
- Subtle signal, smooth onset: **needs global QCD fits**
  - **cut out** data in putative "saturation region" $Q^2 \leq A_{cut}\, x^{\lambda}$
  - **fit PDF** in "safe" region, **DGLAP evolve backwards**
  - **Compare to excluded data** [Caola,Forte,Rojo,2010]



Deviations from DGLAP evolution at HERA

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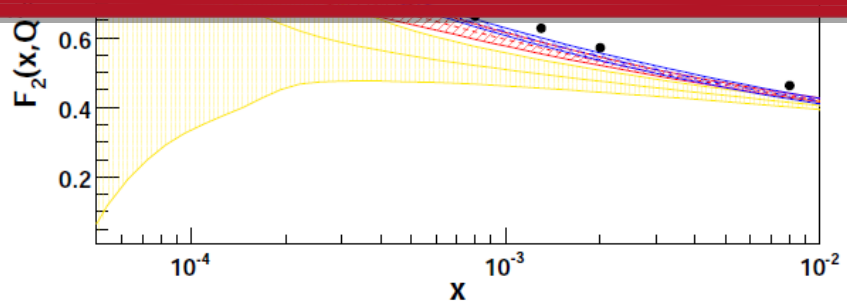
We do see deviations from DGLAP at HERA !!

...but cannot tell what causes them...
(CGC, small-x resum, ...)



Why using e+A at EIC?

Advantages:

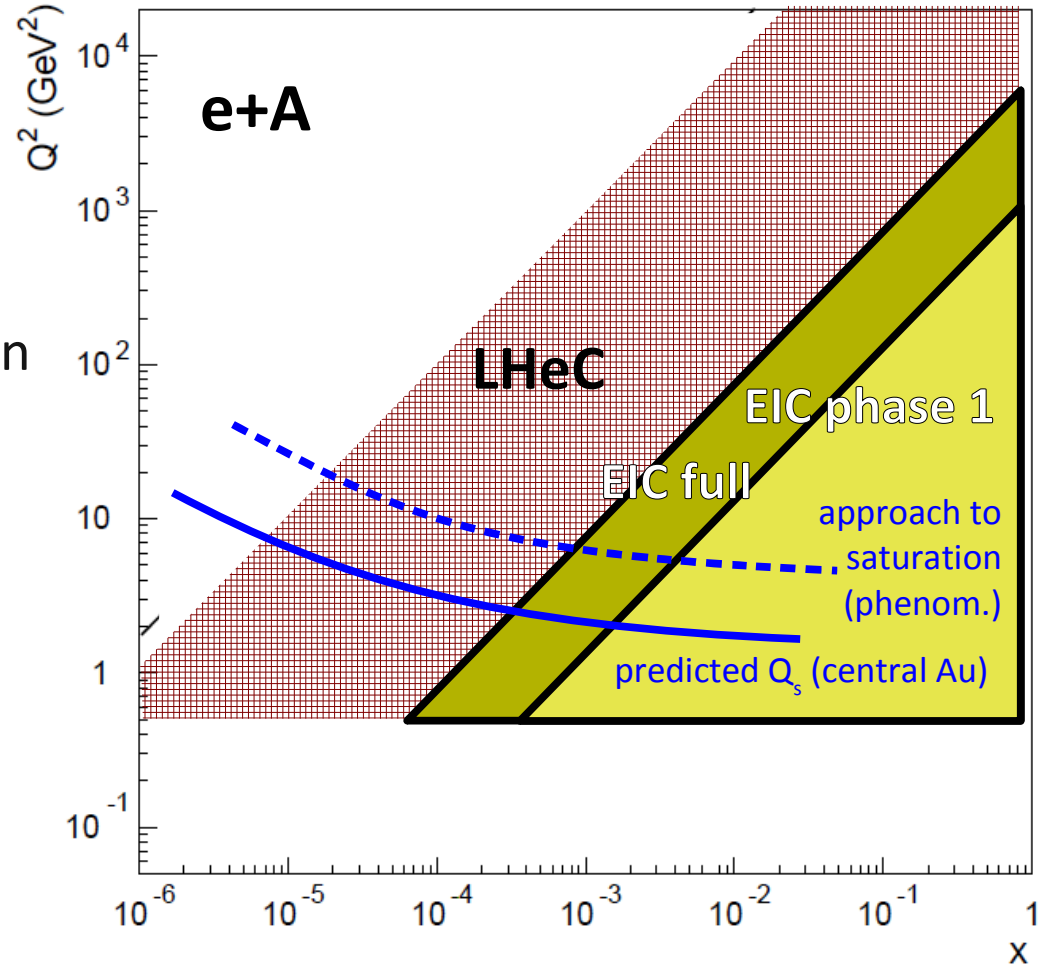
- Larger saturation scale

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

- Reduced small-x resummation effects ¬ **peculiar to EIC**

Disadvantages:

- Other nuclear effects:
  - LT shadowing
  - anti-shadowing
  - EMC



Can the EIC detect deviations from DGLAP in e+A ?

In which x region is CGC approach valid
(as opposed to other shadowing theories)?

Can we disentangle saturation from other nuclear effects ?

Is F_2 enough, or do we need F_L ?

Is medium energy enough,
or do we need the full EIC energy ?

Experimental tools

Accardi, Lamont, Marquet, summary talk, INT 2010

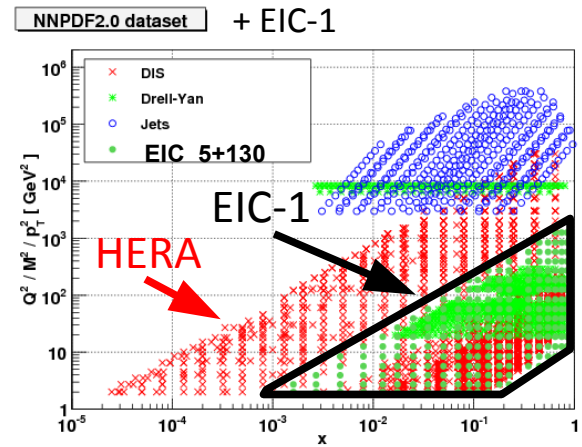
- **Inclusive nuclear structure functions: F_2, F_L, F_2^c, F_L^c**
  - integrated gluon $G_A(x)$
  - nuclear effects throughout (x,Q^2) plane
- **Dihadron p_T imbalance**
  - unintegrated gluon $G_A(x,p_T)$
  - non-linear QCD evolution, $Q_s(x)$
- **Diffractive vector mesons, and DVCS**
  - b-dependent nuclear gluons $G_A(x,b)$
  - interplay between small-x evolution and confinement

Deviations from DGLAP at EIC - preliminary

Accardi, Forte, Guzey, Rojo, Zhu, in prep.

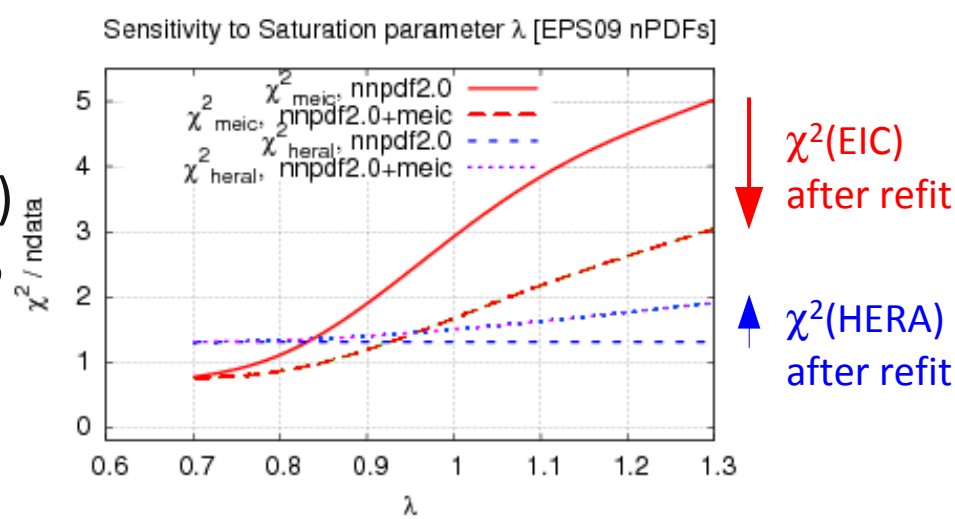
Pseudo-data

- sqrt(s) = 50 GeV (eRHIC 5+130 GeV)
- $\mathscr{L} = 10^{34}$ cm^{-2}s^{-1} for 1 month, 50% eff.
- $Q_s^2 = \lambda \times Q_s$(IP-sat model)



χ^2 analysis – with uncertainties

- Fit can make up for saturation effects, but only partly
- at $\lambda > 1.2$ ($Q_s^2 \approx 1$ GeV^2 at x=0.001) EIC data incompatible with DGLAP
- We are revisiting this, including energy scan (F2 *and* FL)



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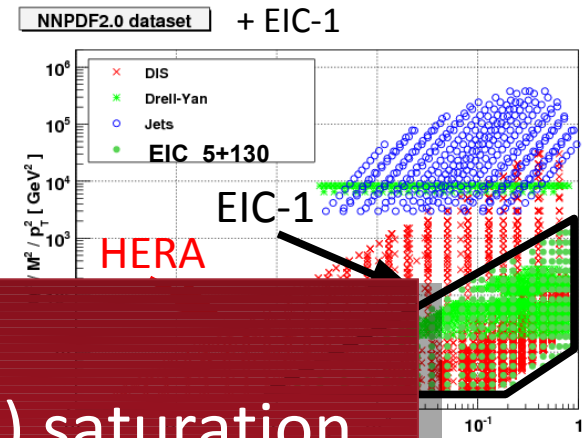

χ^2 anal

There is a chance to see (some) saturation at EIC phase 1

- Fit ca
  effec
- at $\lambda > 1.2$ ($Q_s^2 \approx 1$ GeV^2 at x=0.001)
  EIC data incompatible with DGLAP
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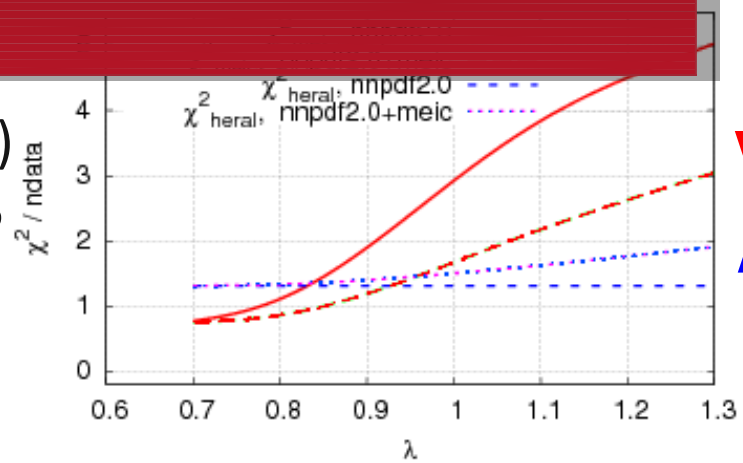
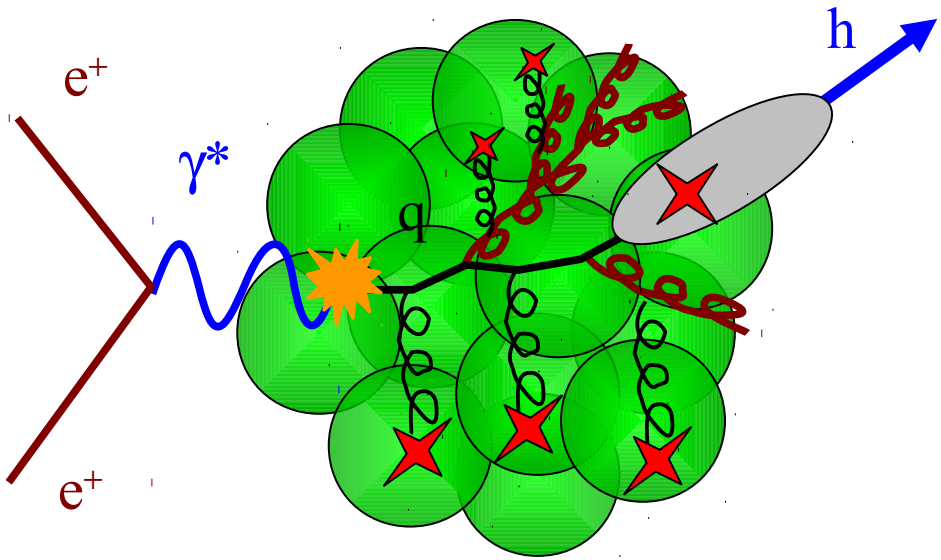


χ^2(EIC) after refit

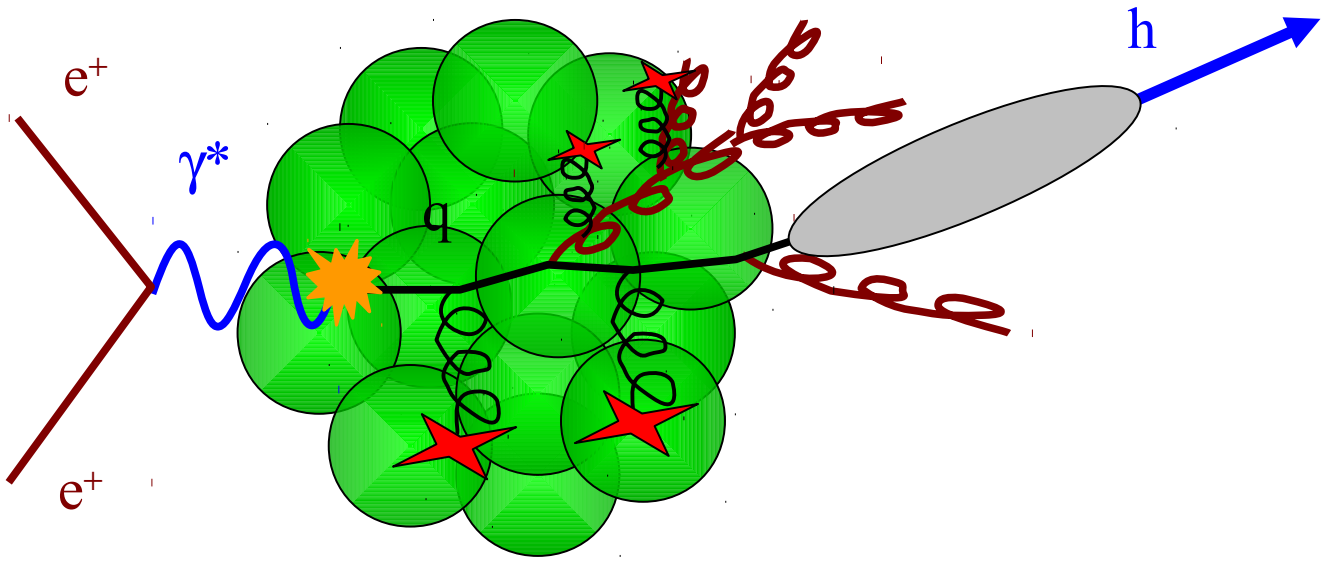
χ^2(HERA) after refit

Jets and hadronization



- **Use coloured probes to study soft nuclear glue**
  - → a "large-x" probe of small-x gluons
- **Use nuclei to study parton propagation and fragmentation**
  - → parton showers, energy loss, quark-to-hadron transition
  - → timescales controlled by ν
- **Ideal program for phase-1 EIC**

Jets and hadronization



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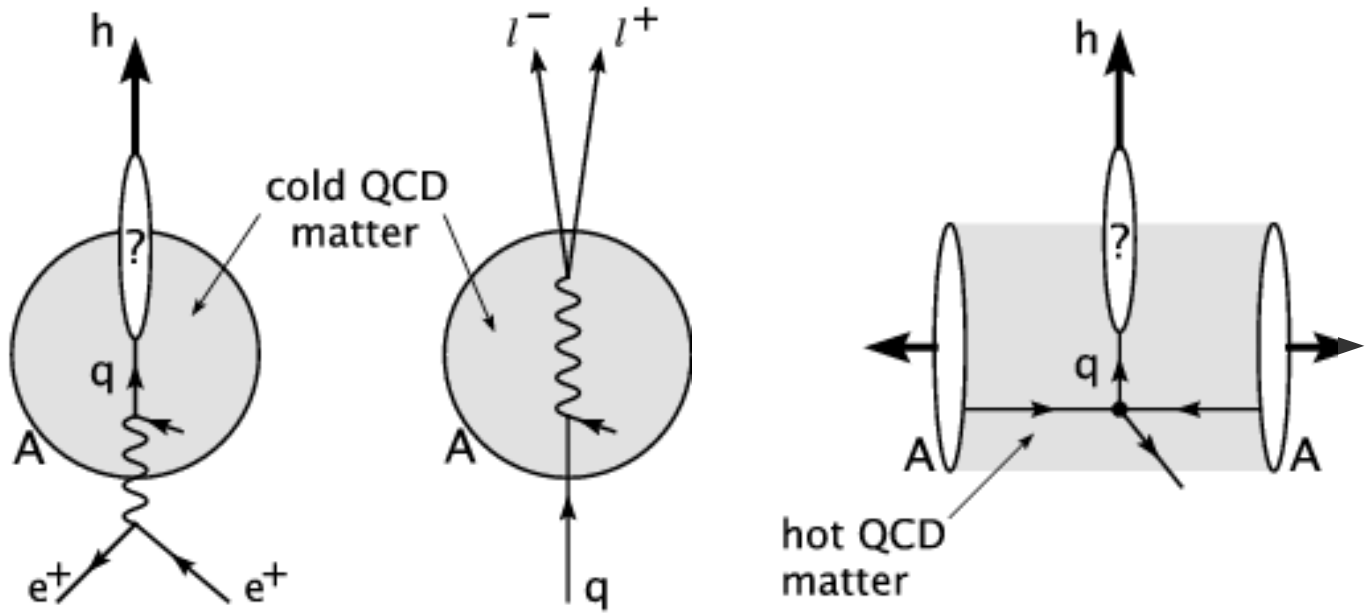
Cold vs. hot

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

Goals - 1

- Measure fundamental properties of cold QCD matter
  - ➡ Experimentally isolate pure energy loss regime (large nu)
  - ➡ Transport coefficients [Majumder, INT'10]
    - ▸ qhat $\leftrightarrow$ pT-broadening, bremsstrahlung
    - ▸ ehat $\leftrightarrow$ longitudinal energy loss
    - ▸ Calculable from first principles: lattice, CGC, ...

$$\hat{q} = \frac{2\pi\alpha_s C_R}{N_c^2 - 1} \int d\tau \langle A | U^\dagger(\tau, v) t^a F^{a\mu\rho} v_\rho U(\tau, v) t^b F_\mu^{b\sigma} v_\sigma | A \rangle$$

  - ➡ Saturation scale [Liang,Wang,Zhou '08; Kopeliovich et al. '10]

$$\hat{q}(\tau, y_\perp^2) = \frac{4\pi^2 \alpha_s C_A}{N_c^2 - 1} \rho_A(\tau) \left[x G(x, y_\perp^2) \right]_{x=0}$$

$$Q_s^2(y_\perp^2) = \int d\tau \hat{q}(\tau, y_\perp^2)$$

Goals - 2

- Fundamental tests of pQCD
  - ➡ Light and heavy quark energy loss
    - ▸ heavy quarks calculable due to large mass: theory benchmark
  - ➡ Parton shower evolution
    - ▸ kT vs rapidity ordering
    - ▸ space-time evolution [Sterman, INT fall 2009]

So in a sense, E "tells a series of stories", of all possible emissions that take time t:

$$E(\nu, Q) = 2 \int_0^\infty \frac{dt}{t} \Big[\int_{Q/t}^{1/t^2} \frac{dp_T^2}{p_T^2} A\left(\alpha_s(p_T)\right) \left(e^{-u\nu(p_T/Q)} - 1\right) + \frac{1}{2} B\left(\alpha_s(\sqrt{u}Q)\right) \left(e^{-u(\nu/2)} - 1\right) \Big]$$

Goals - 2

- Fundamental tests of pQCD
  - ➡ Light and heavy quark energy loss
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  - ➡ Parton shower evolution
    - ▶ kT vs rapidity ordering
    - ▶ space-time evolution [Sterman, INT fall 2009]
  - ➡ Important applications
    - ▶ MC generators, in all fields of High Energy Physics
    - ▶ QGP tomography

Goals - 3

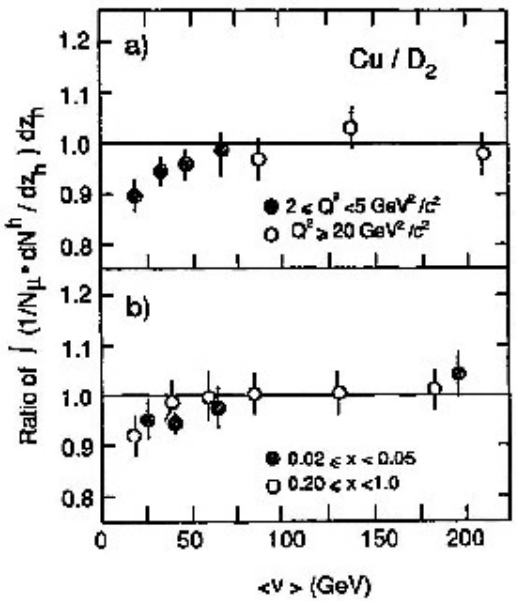
- Space-time evolution of hadronization
  - ➡ Dynamics of color confinement (small nu)
    - stages of hadronization: partons, prehadrons, hadrons
    - carachteristic production times, cross sections
    - new experimental data needed for
      - microscopic phenomenology
      - understanding in terms of color confinement
  - ➡ Production times important for
    - QGP tomography
    - neutrino oscillation experiments
    - ...

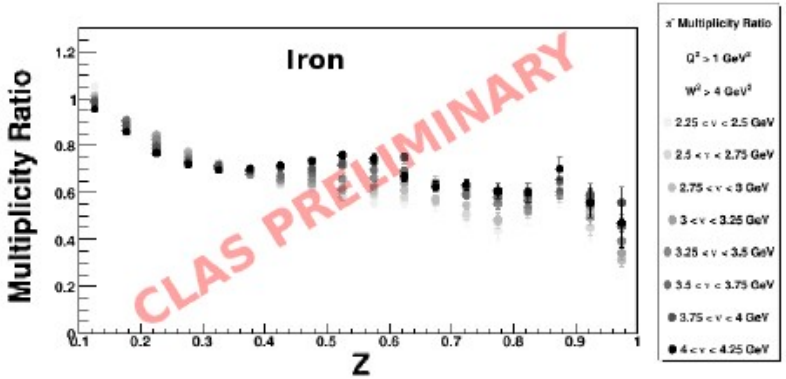
Tools - SIDIS

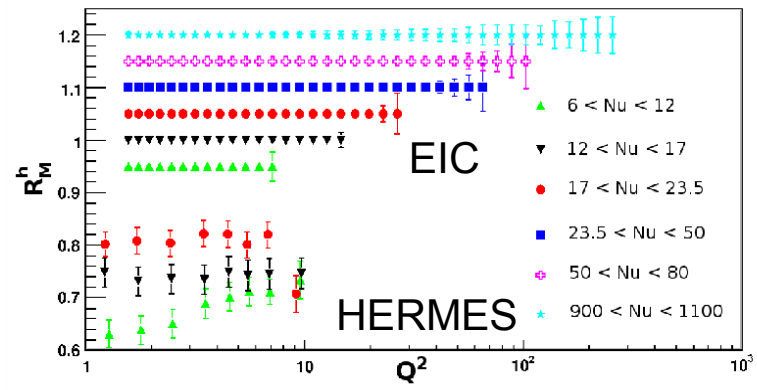
- Hadron production
  - ➡ "Leading hadrons",i.e., current fragmention
  - ➡ Correlation with target fragmentation [little discussed so far]
  - ➡ Main observables:
    - ▶ hadron attenuation R_M $$R_M^h(z_h) = \frac{1}{N_A^{DIS}} \frac{dN_A^h(z_h)}{dz_h} \Big/ \frac{1}{N_D^{DIS}} \frac{dN_D^h(z_h)}{dz_h}$$
    - ▶ P_T-broadening $$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$
    - ▶ 2-particle correlations
- **Unique at EIC:**
  - ➡ **heavy flavours (D, B)**
  - ➡ **multi-dimensional binning**
    (to be honest, CLAS and CLAS12 will have this, too – but ν, Q^2 very small)

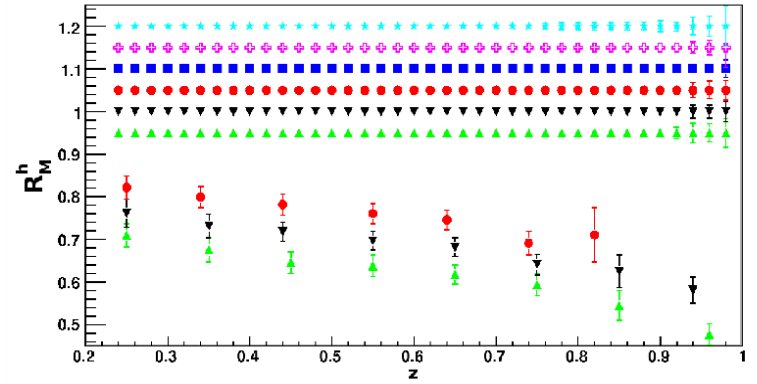
Tools - SIDIS

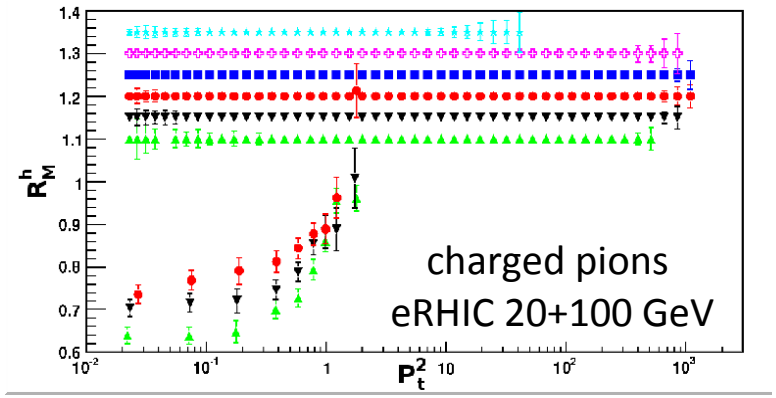
- Examples





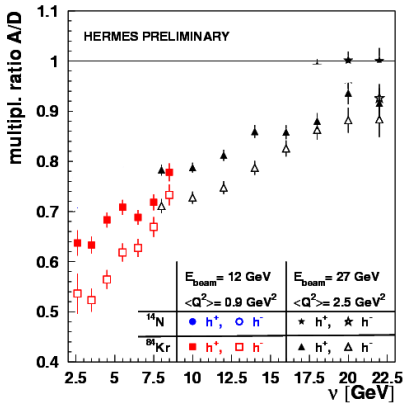


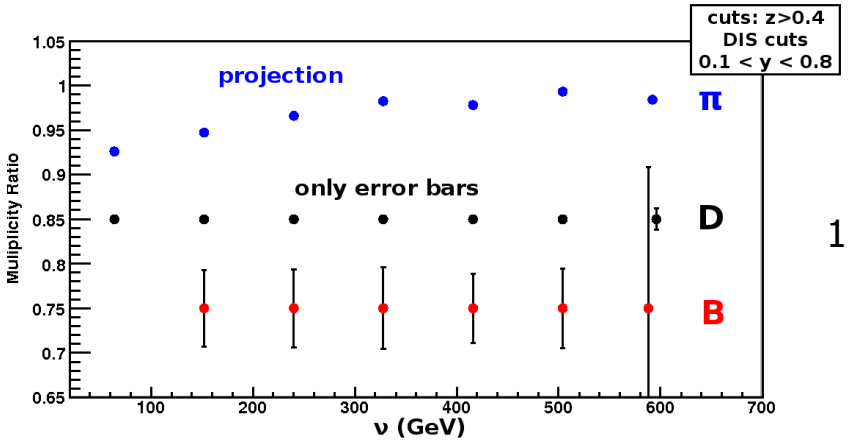




Tools - SIDIS

- Isolate, study pure energy loss



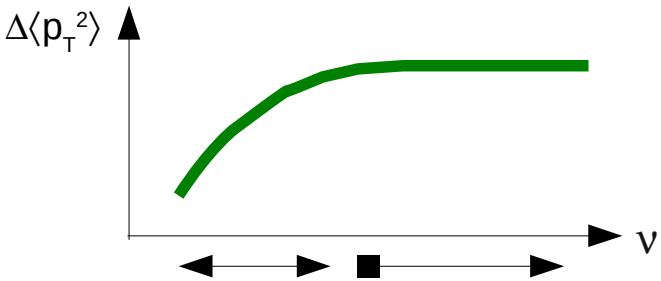


11+30 GeV/A Fe
L = 0.4 10^{33} cm^{-2} s^{-1}
1 month 100% running

[Dupré, Accardi]

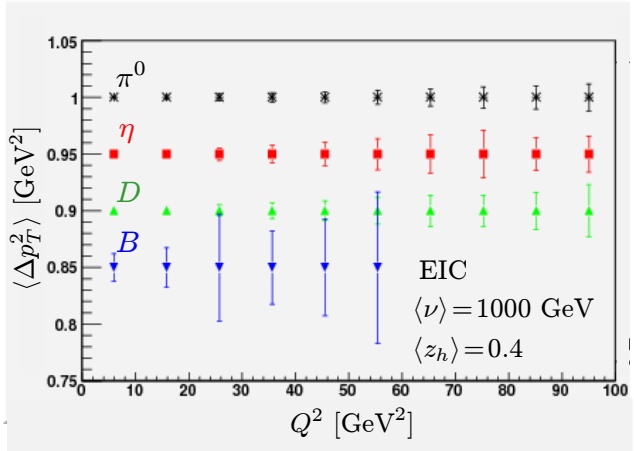
mixed phase

pure energy loss (?)



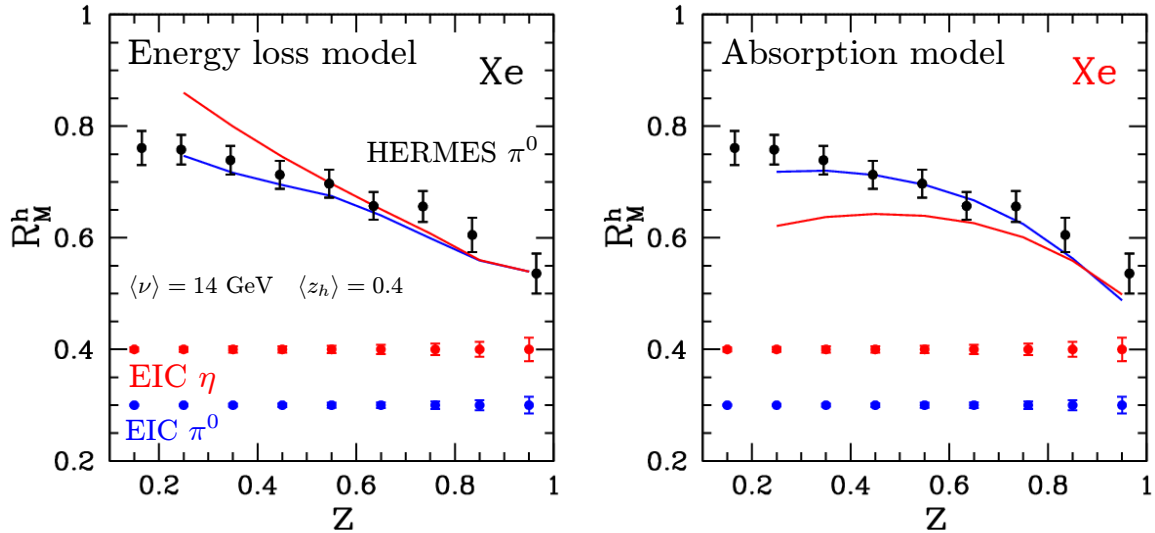
mixed phase

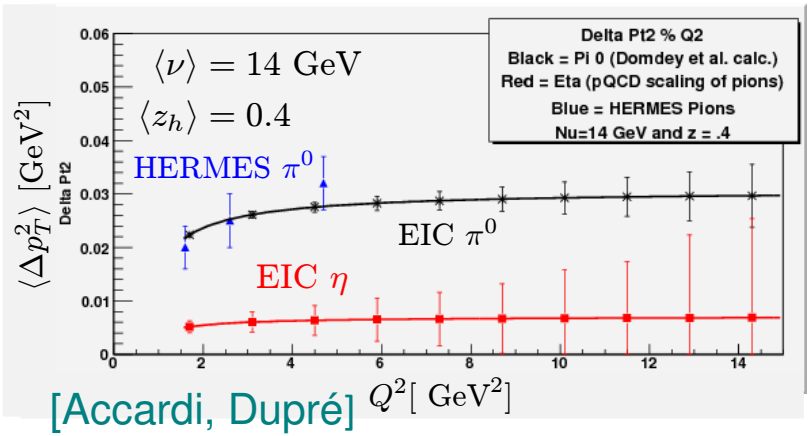
pure en. loss



Tools - SIDIS

- Study hadronization





[Accardi, Dupré]

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

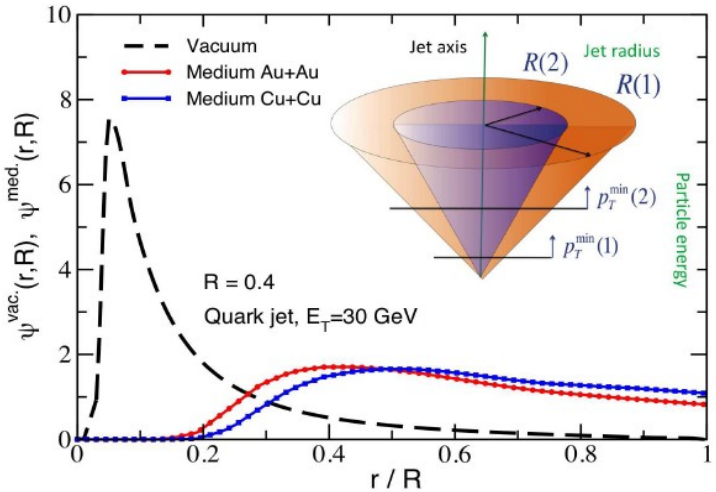
medium-modified DGLAP (Domdey et al.)

pQCD scaling of production time

Tools: jets

[I.Vitev]

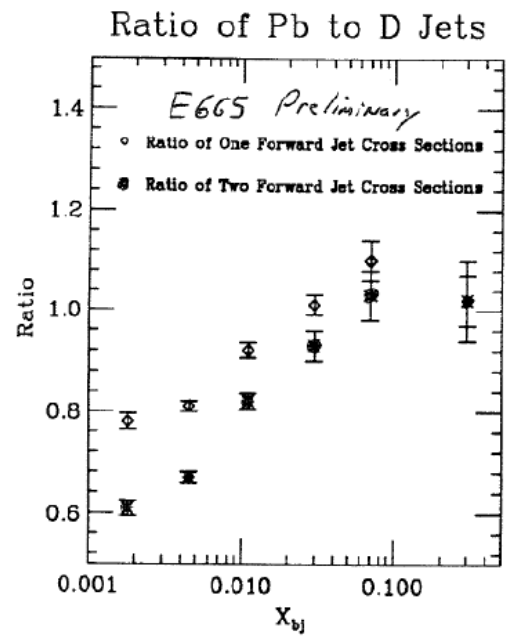
- Many more handles:
  - ➡ cone "radius"
  - ➡ minimum hadron energy
  - ➡ gluon, light-, and heavy-flavor jets

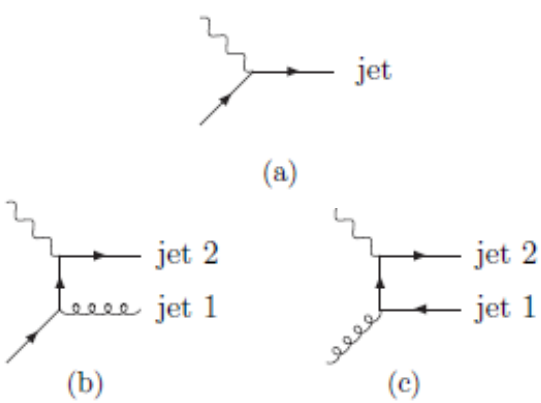


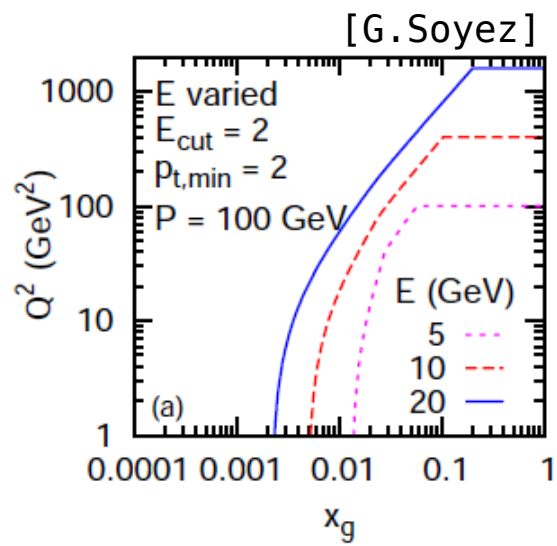
- 20 years of theoretical developments to be harvested
  - ➡ precise definitions of jets
    - ▶ IR and collinear safe
    - ▶ several algorithms, known advantages and disadvantages
  - ➡ large choice of "jet shapes"
    - ▶ characterization of energy flows inside the jet

Tools: jets

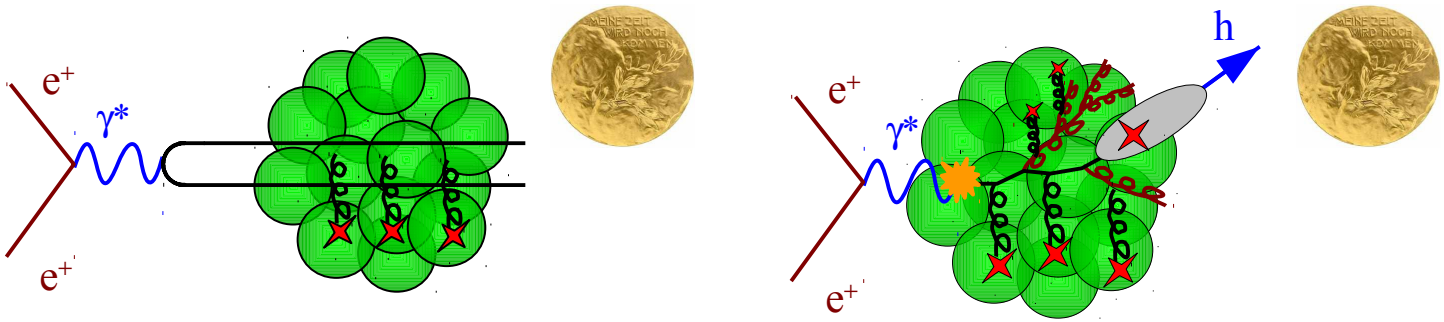
- **Jets: a unique opportunity at EIC**
  - ➡ E665: proof of principle
    - jets can be measured in e+A at s>1000 GeV^2
    - results unpublished
  - ➡ EIC, plenty to measure:
    - 1+1 jets: parton showers, transport coeff's
    - 2+1 jets: access to nuclear gluons
    - n+1 ???







Summary – my involvement



- Convener, INT Fall program, weeks 3-5
  - ➡ https://wiki.bnl.gov/eic/index.php/QCD_Matter_under_Extreme_Conditions
- Organizer, "*Nuclear Chromo-Dynamics at an EIC*", Argonne, April 2010
- Coordinator, "*Parton propagation and hadronization*" working group
  - ➡ R.Dupre' (energy loss, MC), J.Gilfoyle (Bose Einstein Correlations)
  - ➡ https://ic.jlab.org/wiki/index.php/EA_ppf
- Physics projects
  - ➡ Energy loss and hadronization, cold nucleus MC [w/ Dupre, Hafidi]
  - ➡ Saturation as DGLAP deviation [w/ Guzey et al.]
  - ➡ Proton structure functions and PDF fits [w/ Ent, Keppel]