QCD Matter under Extreme Conditions - a summary of weeks 3-5

Alberto Accardi (JLAB)
Matt Lamont (BNL)
Cyrille Marquet (CERN)

Organisational Matters

- Wiki page exists:

https://wiki.bnl.gov/eic/index.php/QCD_Matter_under_Extreme_Conditions

Contents [hide]

Discussion page on golden candidates

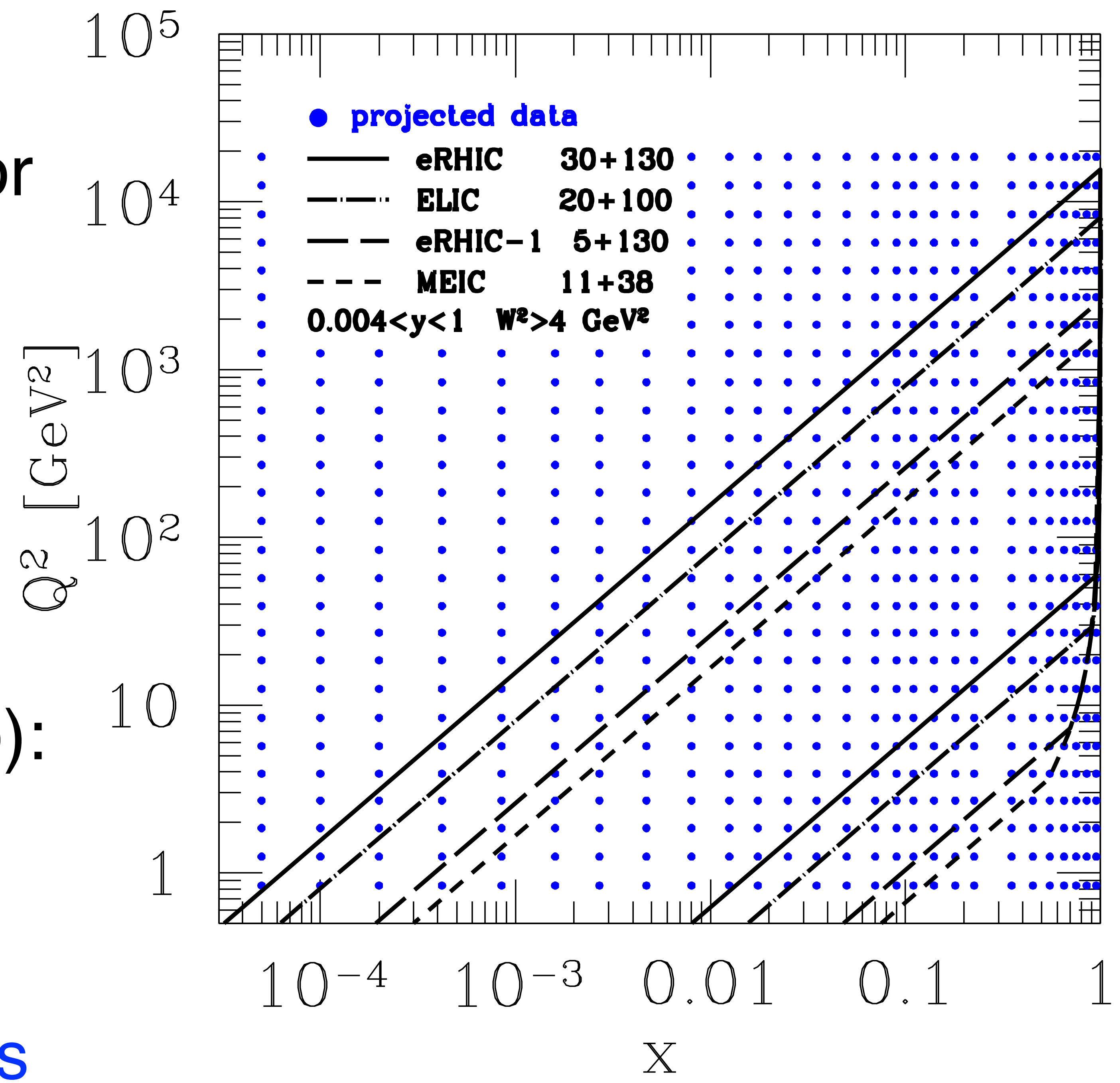
Detailed minutes of the weeks can be found on the wiki page

Golden Measurement Candidates

- Important measurements in e+A fall into 3 categories:
  - ➡ Nuclear gluons at small-x
    - Inclusive structure functions (F_2, F_L, F_2^c, F_L^c)
    - di-hadrons (and di-jet) imbalance
    - Exclusive production (especially J/ψ and DVCS)
  - ➡ Nuclear gluons at larger-x
    - Gluon anti-shadowing / EMC effect
  - ➡ Jets and hadronization
    - Use hadrons and jets as probes of nuclear gluons
    - Use nuclei to test in-medium fragmentation, pQCD energy loss and parton showers
- Whilst we deem all measurements as important, not all can be called “golden” measurements of the whole programme….

Kinematics Grid

- We would like to compare different theoretical models for physics at both small- and large-x.
- A kinematic grid has been provided to theorists for studies of the following variables for D, Ca, Au (or Pb):
  - ➡ inclusive structure functions (small- and large-x)
  - ➡ diffractive structure functions (small-x)
  - ➡ exclusive production (small-x)



https://wiki.bnl.gov/eic/index.php/X,Q_grids

Disclaimer

this is not a summary of all the interesting physics of e+A collisions,
it rather reflects what was talked about during the program

this is not a summary of the presentations, but rather a summary of
the discussions we had during the program and of the subsequent work

we shall not mention all the topics discussed either,
instead we focus on the golden measurements (candidates)

Inclusive structure functions

Nuclear gluons throughout the x-Q^2-A plane

from the gluon EMC effect to saturation physics

this is fundamental knowledge about the
nuclear wave function that is still lacking

$$F_2 \;, F_L \;, F_2^c \;, F_L^c$$

the most basic observables from the theory side
discussed from the beginning as golden measurement

we should aim, for all of these, to get the same precision
that was reached at HERA with the F_2 combined data

also, the heavy-ion program at the LHC would benefit a lot from a
precise determination of nuclear pdfs in e+A over a large x-Q^2 range
(the impact of HERA on the LHC p+p program cannot be overestimated)

during the program, the main focus was small x:
what can one learn about non-linear QCD from the structure functions ?

Saturation and inclusive SFs ?

there is a large higher-twist cancelation in F_2 (from summing F_T and F_L)

this is presumably why the leading-twist approximation is able to describe F_2 down to 2 GeV^2 at HERA

Bartels

if we had as precise F_L data, we might see the collinear approach fail already at 5-10 GeV^2 ? DGLAP fits for the diffractive structure function F_2^D (for which there is no such cancellation) become problematic at a much higher Q^2 around 8 GeV^2

precise F_L may already change the DGLAP picture for protons at $Q^2 \sim 2\text{-}5\ GeV^2$

for a Pb nucleus, deviations from DGLAP would be unambiguously identified within the x range of the full-energy EIC (if Qs reaches about 1 GeV, the precise value is model-dependent)

Accardi

TO DO: update dipole models with new combined H1/ZEUS data on F2 (this may already eliminate some of them, or at least slightly modify parameters)

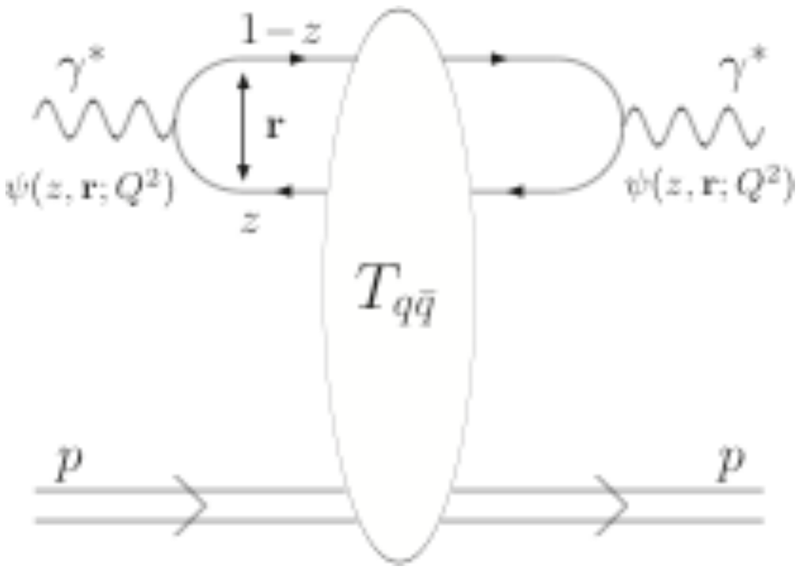
saturation models and others: Kopeliovich, Pirner, Strikman

DIS at small x

- the cross section at small x

Mueller (1990), Nikolaev and Zakharov (1991)

$$\sigma_{T,L}^{\gamma^* p \to X} = 2 \int d^2r \, dz \, |\psi_{T,L}(z, \mathbf{r}; Q^2)|^2 \underbrace{\int d^2b \, T_{q\bar{q}}(\mathbf{r}, \mathbf{b}, x_B)}$$



overlap of $\gamma^* \to q\bar{q}$ splitting functions

dipole-hadron cross-section computed in the CGC or with dipole models

Chirilli

the existing CGC phenomenology is still based on the leading log approximation, F_2 and F_L will be the first observables where NLL will be available for practical analysis

- estimating the importance of saturation

Diehl and Lappi

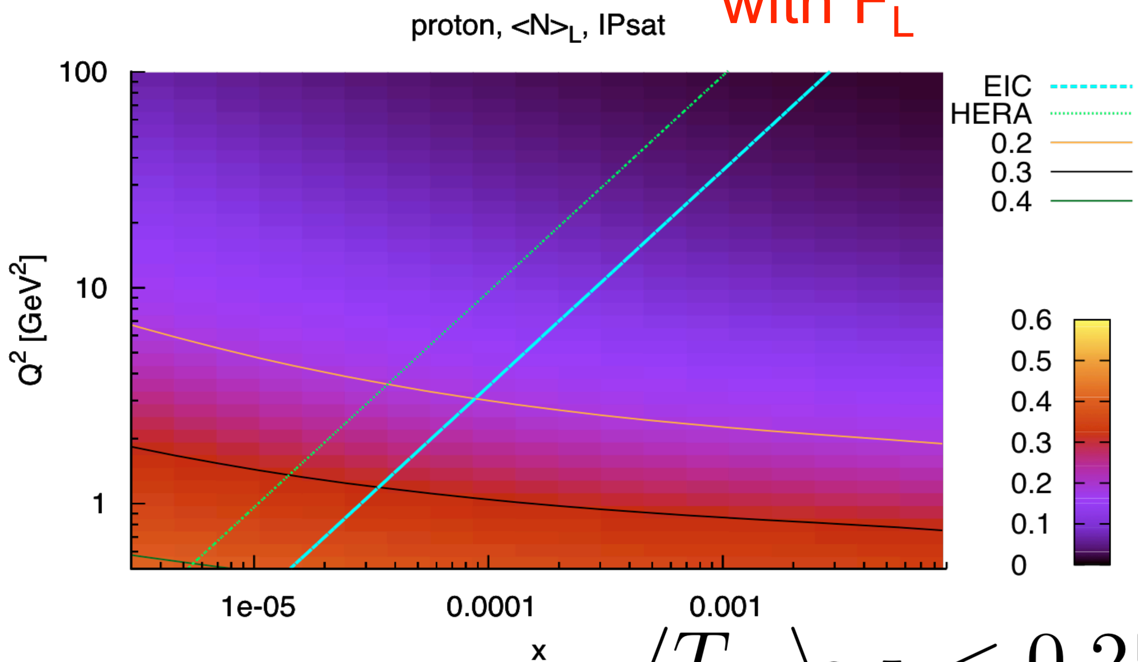
$$\langle T_{q\bar{q}} \rangle_{2,L}(x, Q^2) = \frac{\int d^2r dz \; |\psi_{2,L}(z, \mathbf{r}; Q^2)| \int d^2b \; T^2_{q\bar{q}}(\mathbf{r}, \mathbf{b}; x)}{\int d^2r dz \; |\psi_{2,L}(z, \mathbf{r}; Q^2)| \int d^2b \; T_{q\bar{q}}(\mathbf{r}, \mathbf{b}; x)}$$

average dipole scattering amplitude $\langle T_{q\bar{q}} \rangle_{T,L} < 0.6 - 0.7$ and not 1 because of b int

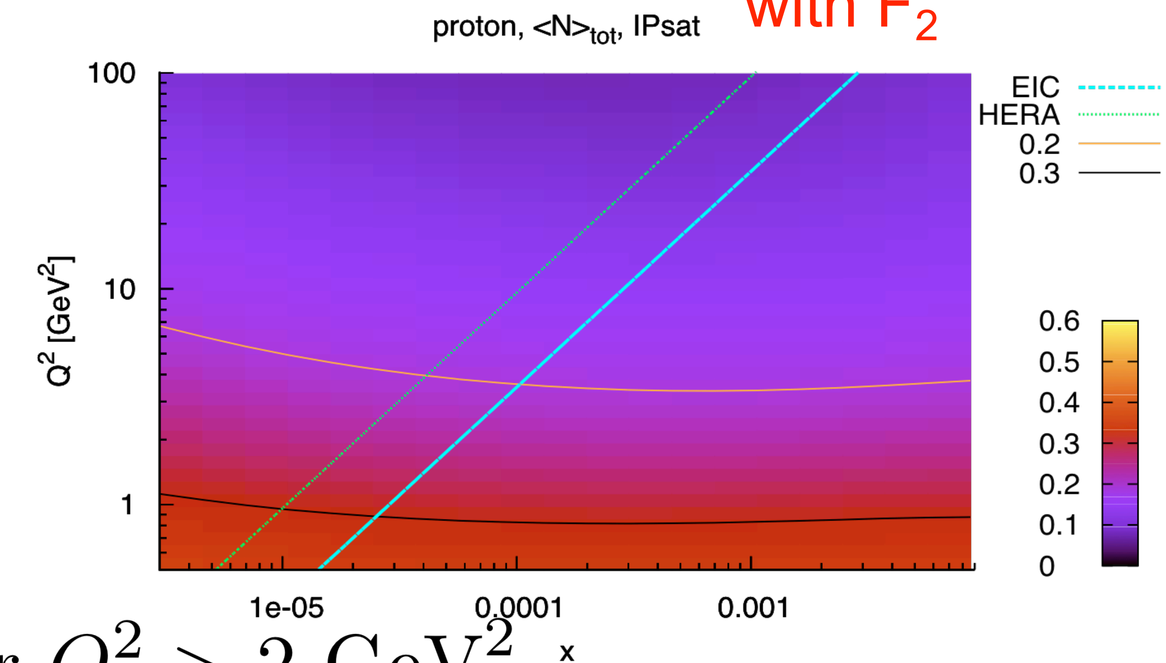
Average strength of scattering

- off the proton

with F_L



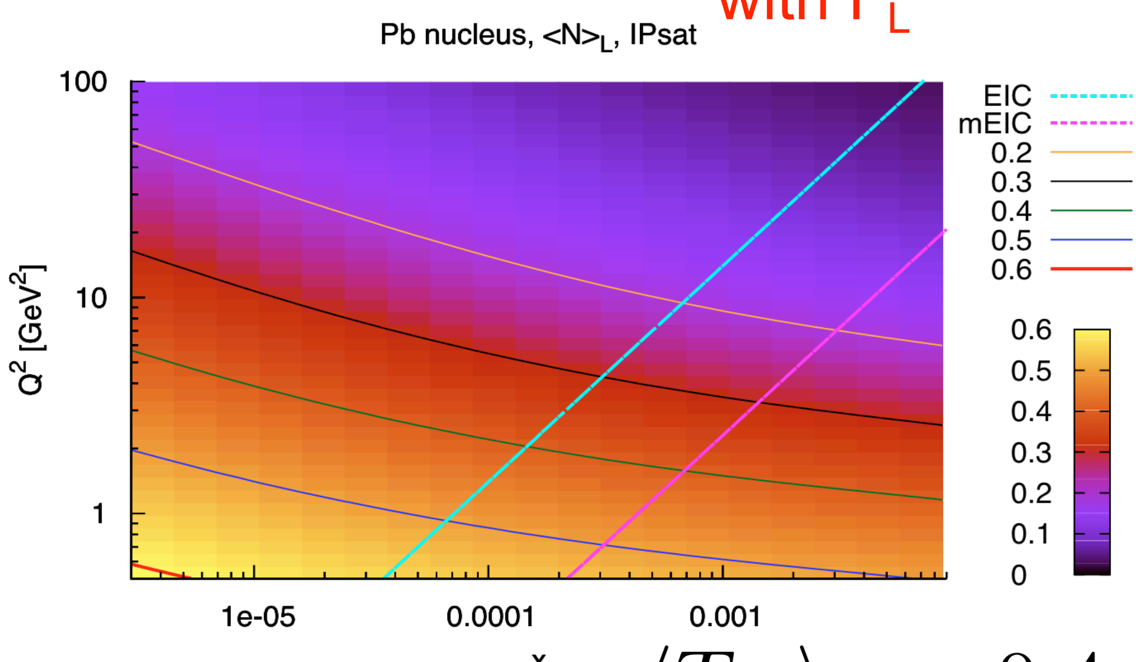
with F_2



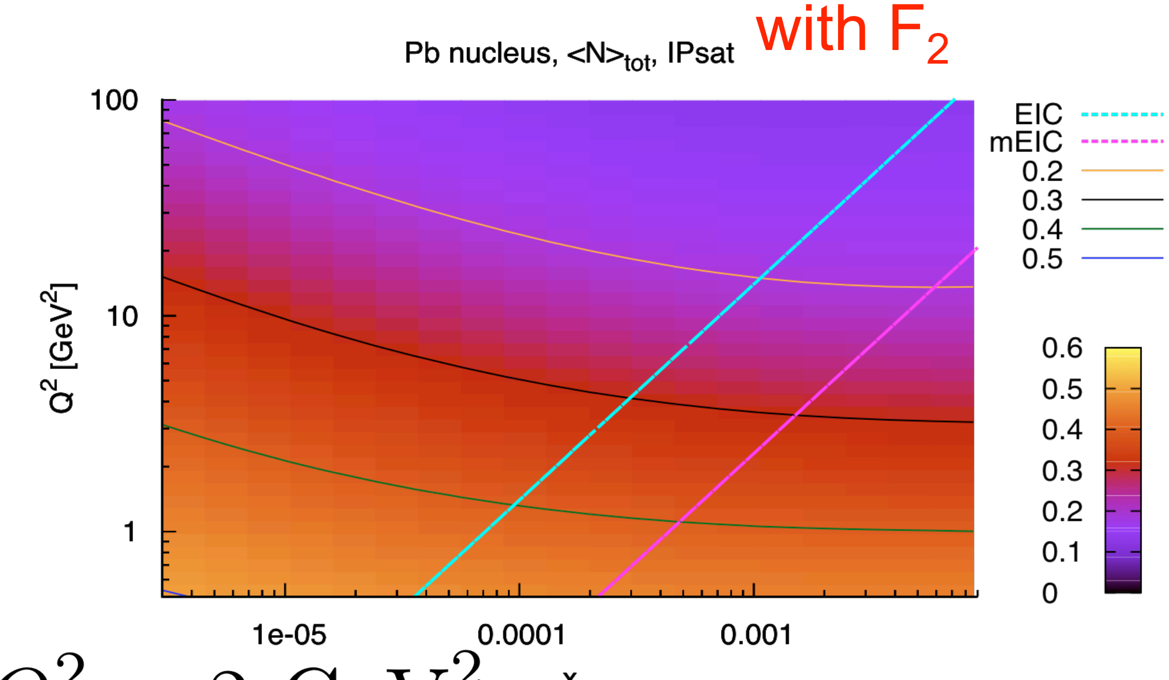
$$\langle T_{q\bar{q}}\rangle_{2,L} < 0.25 \text{ for } Q^2 > 2 \text{ GeV}^2$$

- off the nucleus

with F_L



with F_2

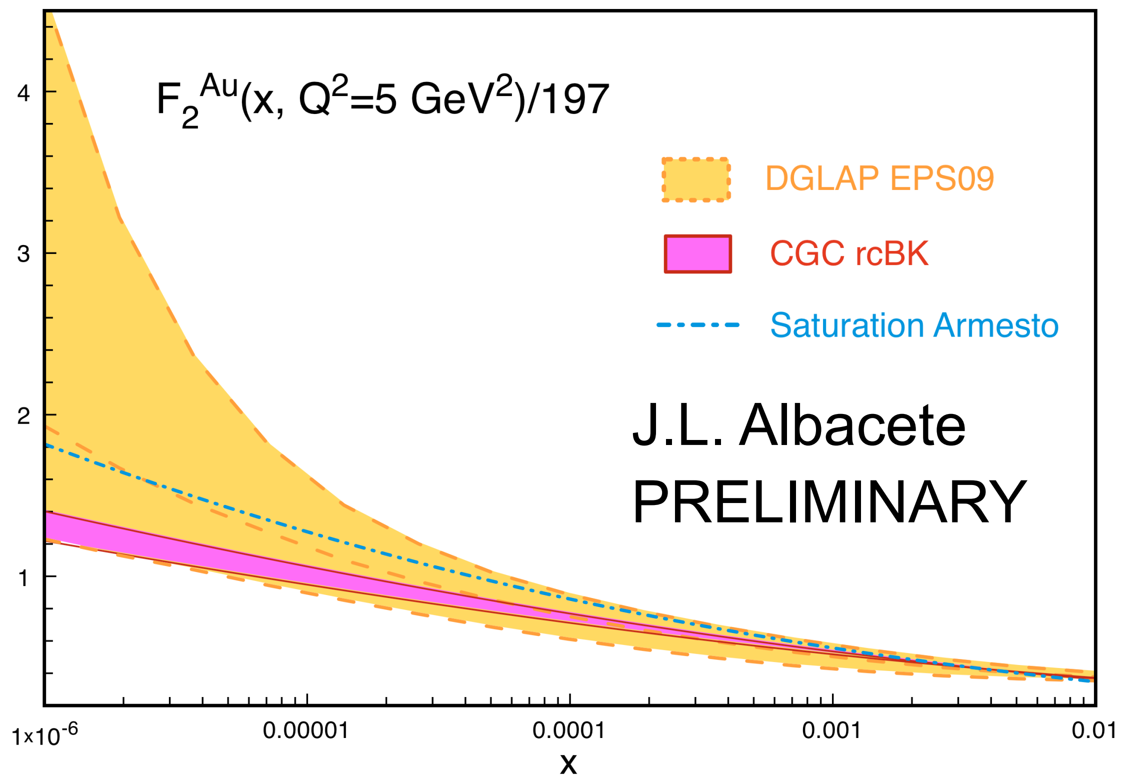


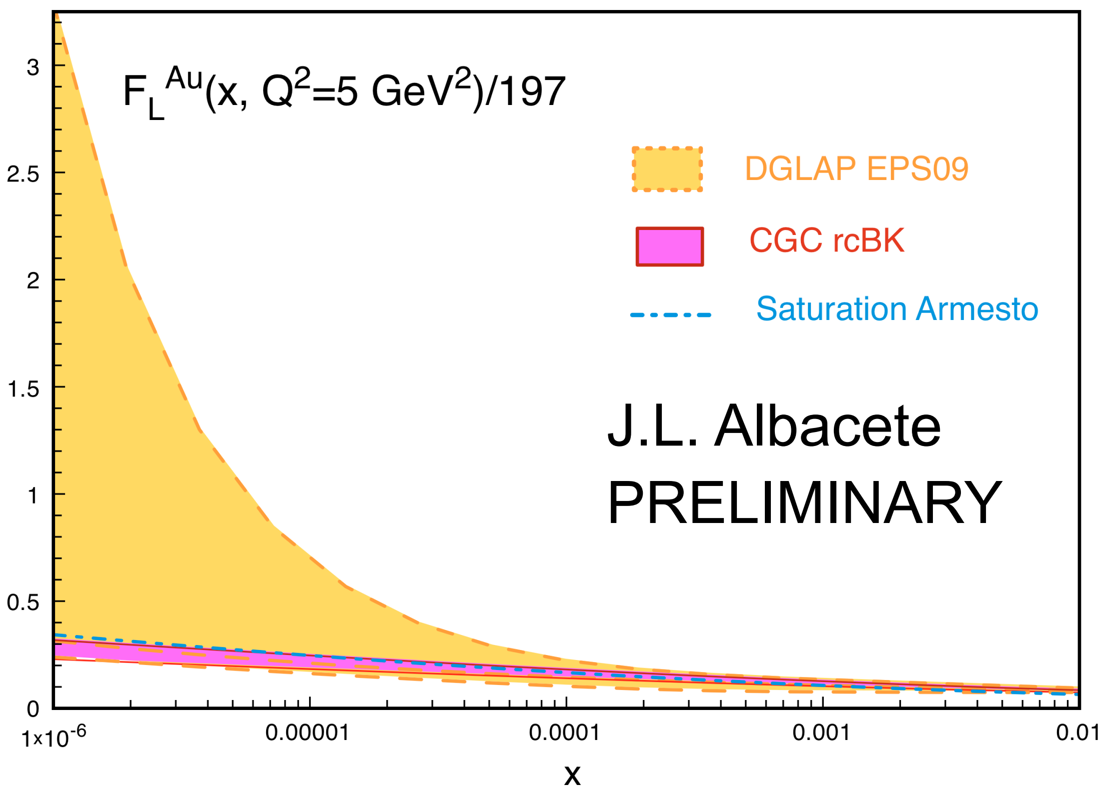
$$\langle T_{q\bar{q}}\rangle_{L} \simeq 0.4 \text{ for } Q^2 = 2 \text{ GeV}^2$$

Expectations for e+A

- using the small-x QCD evolution

extrapolating from relatively large-x data, the non-linear QCD evolution can predict the structure functions



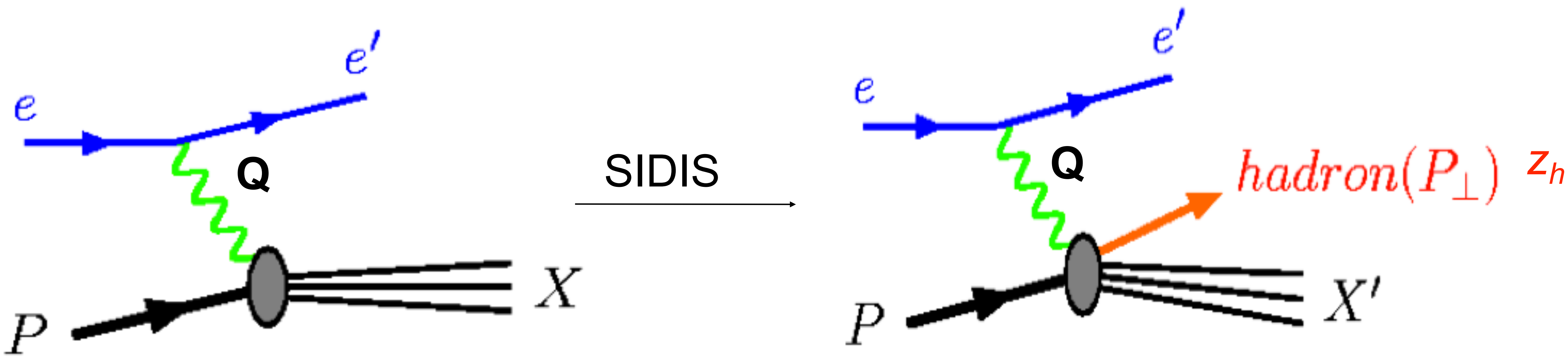


still this need to be checked with data, it is not absolutely clear that the CGC is already applicable in the x range where one starts the evolution

the CGC initial conditions for heavy-ion collisions are based on such extrapolations too

Semi-inclusive DIS
and
di-hadron azimuthal correlations

k_T-dependent small-x gluons



- at small x and large Q[2]

the cross section is proportional to the TMD quark distribution

$$xq(x,k_\perp)=\frac{N_c}{4\pi^4}\int d^2b\,d^2q_\perp F(q_\perp,x)\left[1-\frac{k_\perp\cdot(k_\perp-q_\perp)}{k_\perp^2-(k_\perp-q_\perp)^2}\ln\left(\frac{k_\perp^2}{(k_\perp-q_\perp)^2}\right)\right]$$

TMD-pdf

u-pdf

$$F(q_\perp,x_B)=\int\frac{d^2r}{(2\pi)^2}\,e^{-iq_\perp\cdot\mathbf{r}}[1-T_{q\bar{q}}(\mathbf{r},x_B)]$$

CM, Xiao and Yuan (2009)

obtained from non-linear QCD evolution

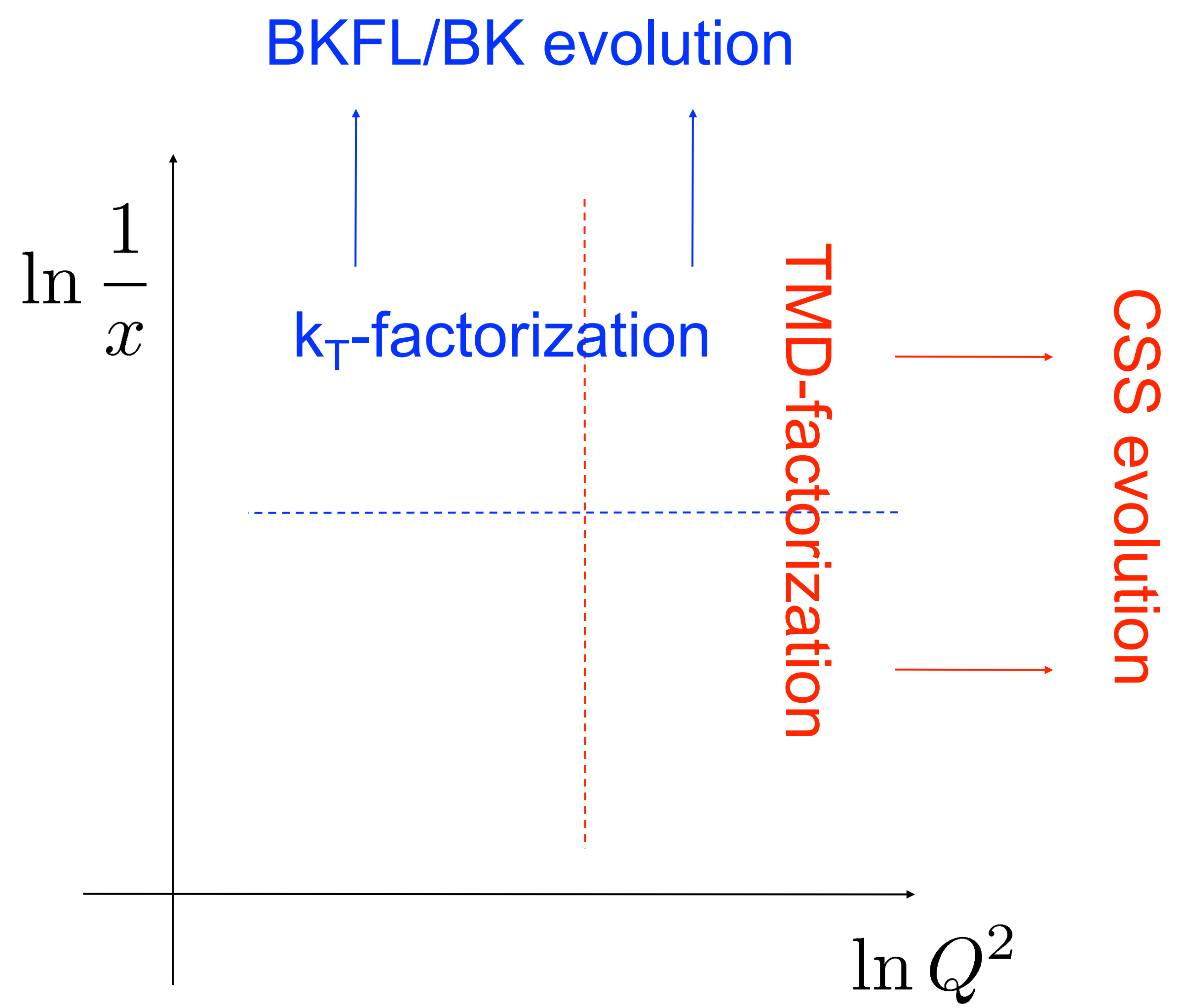
for saturation physics the relevant regime is low P_T (~ Qs)

the transition with collinear factorization at large P_T is interesting also

TMD-pdf / u-pdf relation

- at small x and large Q^2

in the overlaping domain of validity, TMD & k_T factorization are consistent



- the saturation regime

the TMD factorization can be used in the saturation regime, when $P_\perp^2 \sim Q_s^2$

this will be new already for protons

even if Q^2 is much bigger than Q_s^2, the saturation regime will be important when $P_\perp^2 \sim Q_s^2$

in fact, thanks to the existence of Q_s, the $|P_\perp| \to 0$ limit is finite, and computable with weak-coupling techniques ($Q_s \gg \Lambda_{QCD}$)

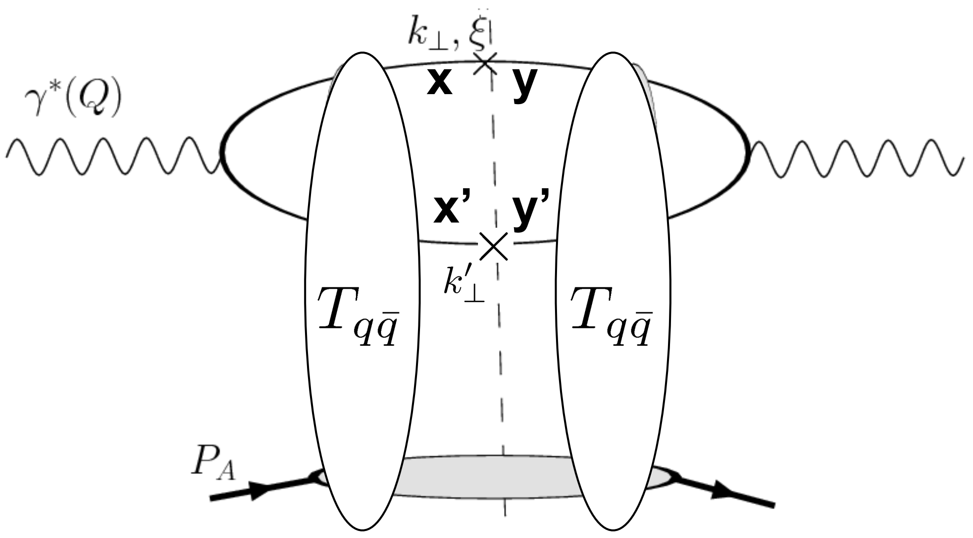
eventually true at small x

Di-hadron correlations

- the di-jet cross section in the dipole picture

$$\frac{d\sigma_{T,L}^{\gamma^* p\to q\bar{q}X}}{d^2k_\perp d^2k'_\perp} = \int \frac{d^2x}{2\pi}\frac{d^2y}{2\pi}\frac{d^2x'}{2\pi}\frac{d^2y'}{2\pi}\, e^{-ik_\perp\cdot(\mathbf{x}-\mathbf{y})}e^{-ik'_\perp\cdot(\mathbf{x}'-\mathbf{y}')}\int d\xi\, \Phi_{T,L}(\xi,\mathbf{x}-\mathbf{x}',\mathbf{y}-\mathbf{y}';Q^2)$$
$$\times[T_{q\bar{q}}(\mathbf{x}-\mathbf{x}',x_B)+T_{q\bar{q}}(\mathbf{y}-\mathbf{y}',x_B)-T_{q\bar{q}\bar{q}q}(\mathbf{x},\mathbf{x}',\mathbf{y}',\mathbf{y},x_B)]$$

because of the 4-point function $T_{q\bar{q}\bar{q}q}$, there is no k_T factorization (unless saturation and multiple scatterings can be safely neglected)



- SIDIS was a special case

in SIDIS, the $k'_\perp$ integration sets **x'=y'**, and then $T_{q\bar{q}\bar{q}q}(\mathbf{x},\mathbf{x}',\mathbf{x}',\mathbf{y},x_B) = T_{q\bar{q}}(\mathbf{x}-\mathbf{y},x_B)$

this cancellation of the interactions involving the spectator antiquark in SIDIS is what led to k_T factorization

with dijets, this does not happen, and as expected, the cross section is a non-linear function of the u-pdf

Constraining the 4-point function

unlike most observables considered in DIS, di-hadrons probe more than the dipole scattering amplitude, it probes the 4-point function

$$T_{q\bar{q}\bar{q}q}(\mathbf{x},\mathbf{x}',\mathbf{y}',\mathbf{y},x_B)$$

only in special limits it can be simplified, such as $|k_\perp + k'_\perp| \ll |k_\perp|\ ,|k'_\perp|$

Dominguez, Xiao and Yuan (2010)

we expect to see the same effect in e+A vs e+p than the one discovered in d+Au vs p+p collisions at RHIC

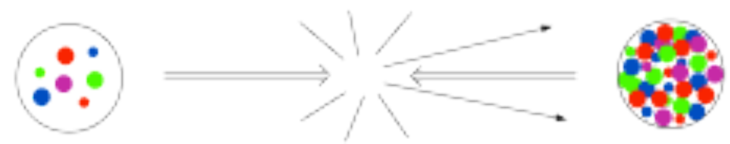
the same 4-point function is involved in the d+Au case
but the e+A measurement could help constrain it better
the background will be much smaller than in d+Au for instance

the evolution of higher point functions (~ multi-gluon distribution)
is different from that of the 2-point function (single gluon distribution)
it is equally important to understand it

Dumitru and Jalilian-Marian (2010)

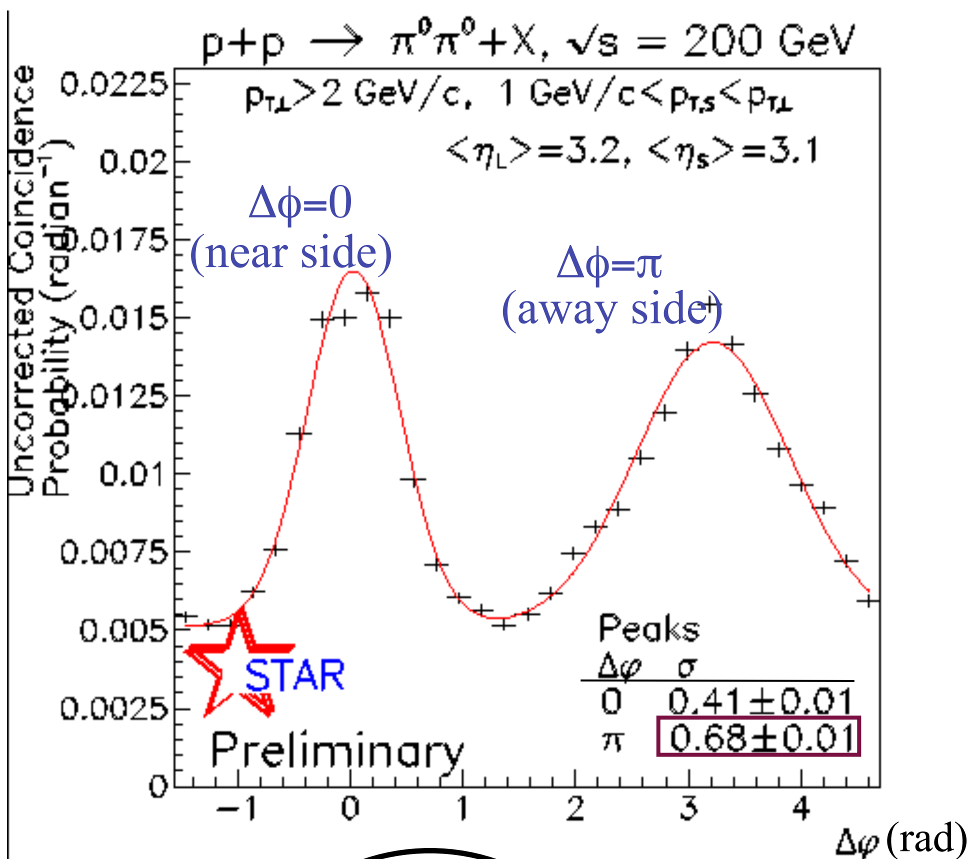
Di-hadron p_T imbalance in d+Au

$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$

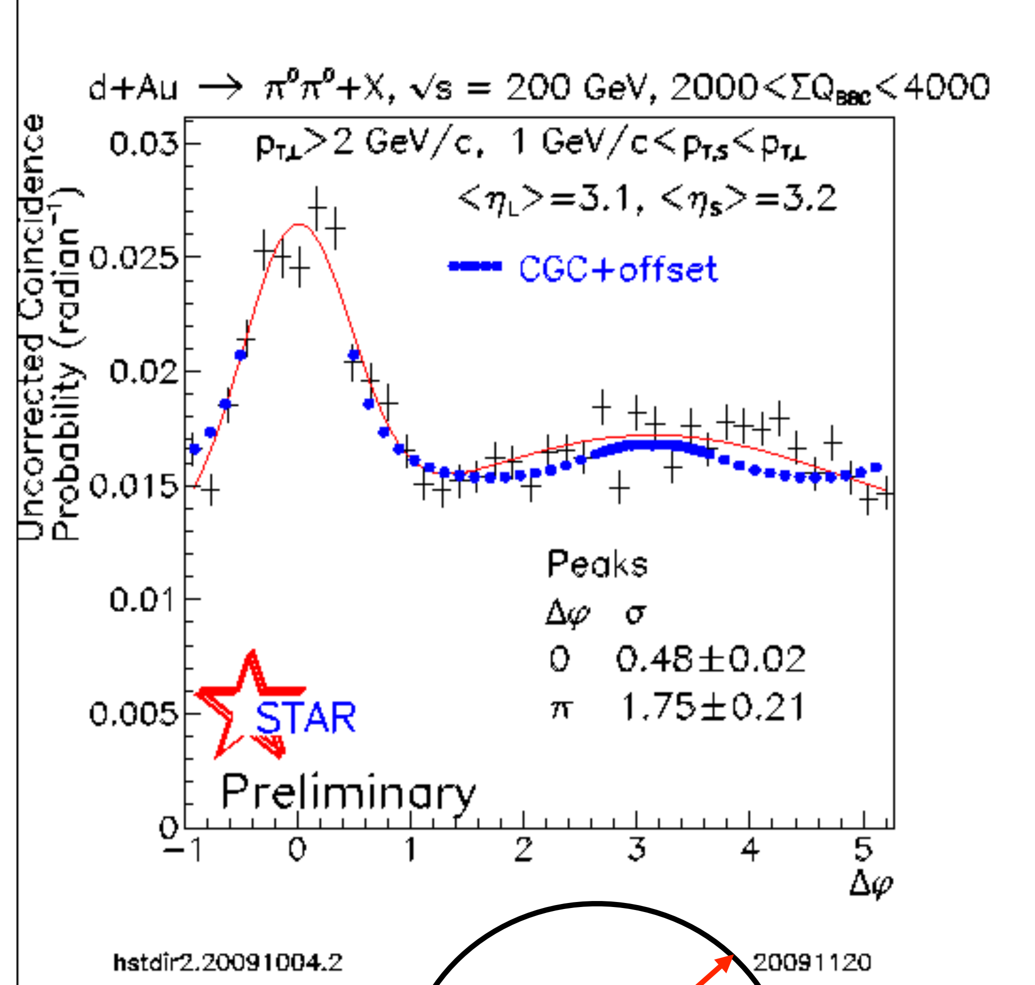


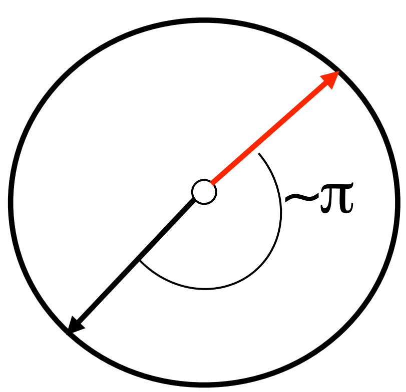
Albacete and CM (2010)

p+p

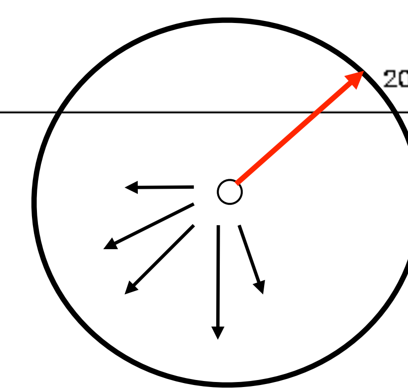


d+Au central





this happens at forward rapidities,
but at central rapidities, the p+p and
d+Au signal are almost identical

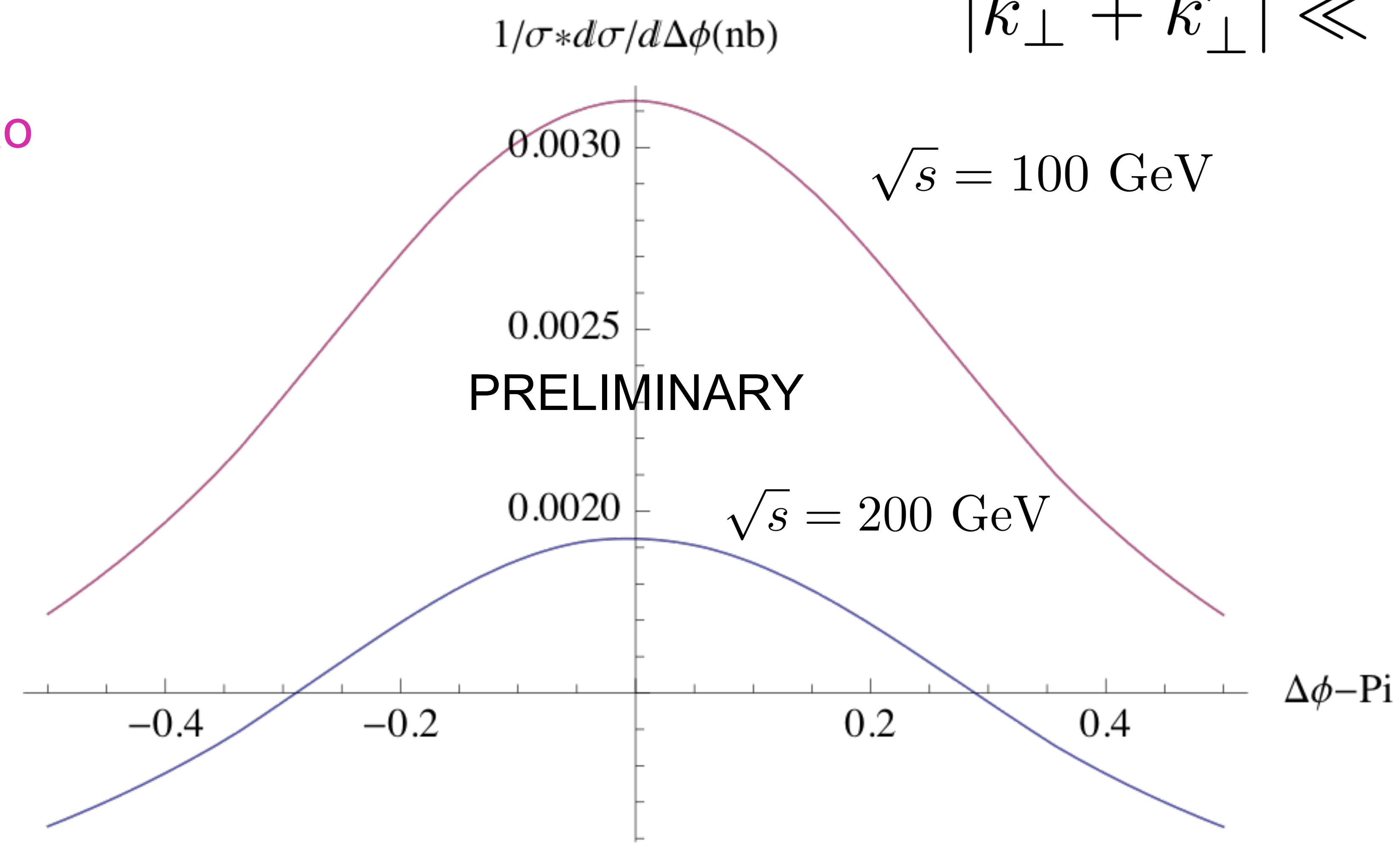


Di-hadron p_T imbalance in e+A

- the di-hadron cross section in the small momentum imbalance limit

$$|k_\perp + k'_\perp| \ll |k_\perp|\ ,|k'_\perp|$$

Xiao



not e+A vs e+p but rather e+A at two different energies

z and k_T dependent fragmentation included

in-medium energy loss and p_T broadening neglected

Diffractive VM production and DVCS

b-dependent gluons

need exclusive measurements to pin down the transverse distribution of small-x gluons/the impact-parameter dependence of the dipole cross section

this is crucial knowledge for heavy-ion collisions, both the average impact-parameter distribution and its fluctuations need to be understood

Gelis

the fluctuations, accessible with incoherent diffraction, represent the main uncertainty in v_2 (elliptic flow) calculations for instance

on the theory side, understanding high-energy QCD evolution as a function of b remains a challenge ⇒ interplay between small-x evolution and confinement

TO DO: compare different meson channels (rho, phi) as well as DVCS
so far J/Psi is used for studies (see next slides)

TO DO: learn about how (light and heavy) nuclei break-up due to a momentum transfer, as very little is known
perhaps the p+A program at RHIC could contribute on this in the next years

VM production off the CGC

- the diffractive cross section

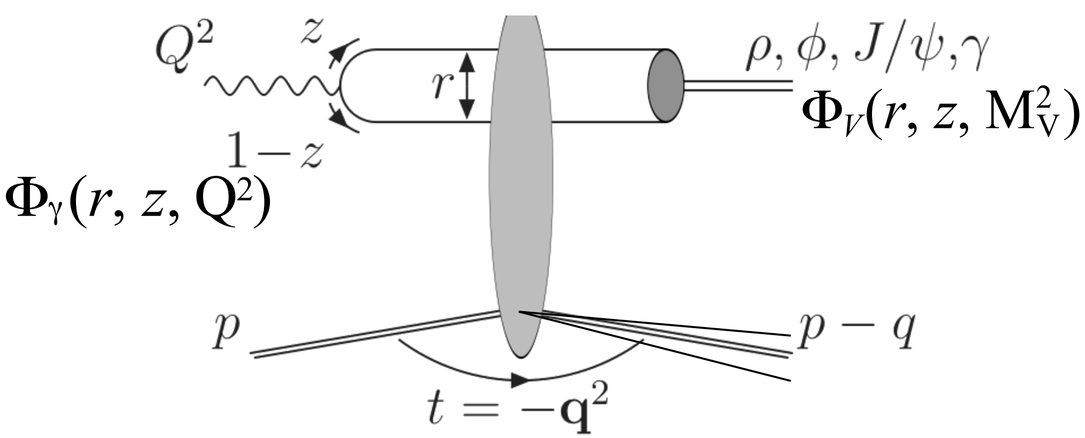
amplitude conjugate amplitude

$$\frac{d\sigma^{\gamma^* p \text{®} VY}}{dt} = \frac{1}{4\pi}\int d^2r\, d^2r' \underbrace{\varphi(\mathbf{r}, Q^2, M_V^2)\varphi^*(\mathbf{r}', Q^2, M_V^2)}_{\text{overlap functions}} \int d^2b\, d^2b'\, e^{iq_\perp.(\mathbf{b}-\mathbf{b}')} \left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b}) T_{q\bar{q}}(\mathbf{r}',\mathbf{b}') \right\rangle_x$$

overlap functions

r : dipole size in the amplitude

r' : dipole size in the conjugate amplitude



target average at the cross-section level: contains both broken-up and intact events

one needs to compute a 4-point function, that gives access to gluon correlations

- the exclusive part

obtained by averaging at the level of the amplitude:

$$\left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b}) T_{q\bar{q}}(\mathbf{r}',\mathbf{b}') \right\rangle_x \Rightarrow \left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b}) \right\rangle_x \left\langle T_{q\bar{q}}(\mathbf{r}',\mathbf{b}') \right\rangle_x$$

probes b dependence:

$$\frac{d\sigma^{\gamma^* p \text{®} Vp}}{dt} = \frac{1}{4\pi}\left| \int d^2r\, \varphi(\mathbf{r}, Q^2, M_V^2) \int d^2b\, e^{iq_\perp.\mathbf{b}} \left\langle T_{q\bar{q}}(\mathbf{r},\mathbf{b}) \right\rangle_x \right|^2$$

Coherent diffraction

Stage 1: precise transverse imaging of the gluons, from light to heavy nuclei
Stage 2: how the small-x evolution modifies the transverse distribution of gluons

- the dipole-nucleus cross-section

Kowalski and Teaney (2003)

$$T^p_{q\bar{q}}(r,b,x) = 1 - e^{-f(r,x,b)}$$

$$\Downarrow$$

$$T^A_{q\bar{q}}(r,b,x) = 1 - e^{-\sum_i f(r,x,b-b_i)}$$

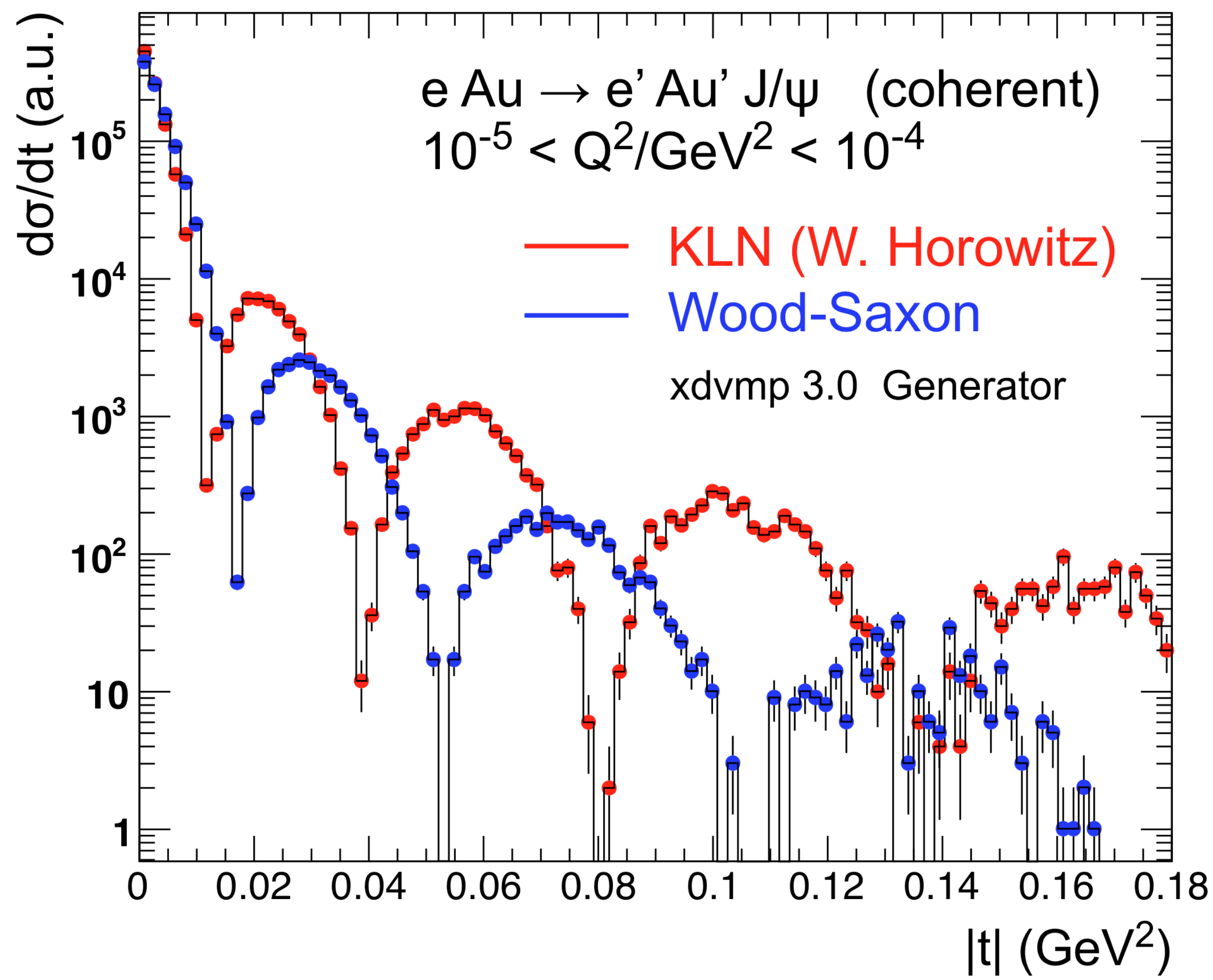
$T_A(\{b_i\})$ ← position of the nucleons

averaged with the Wood-Saxon distribution

assumption of independent nucleons not compatible with QCD non-linear evolution

Horowitz, Toll and Ullrich

large incoherent contribution not shown



compared with CGC-inspired gluon distribution (KLN): differences are seen and are big enough to be tested (need 50 MeV resolution on momentum transfer)

Incoherent diffraction (proton case)

Dominguez, C.M. and Wu (2009)

- as a function of t

exclusive production:

the proton undergoes elastic scattering dominates at small |t|

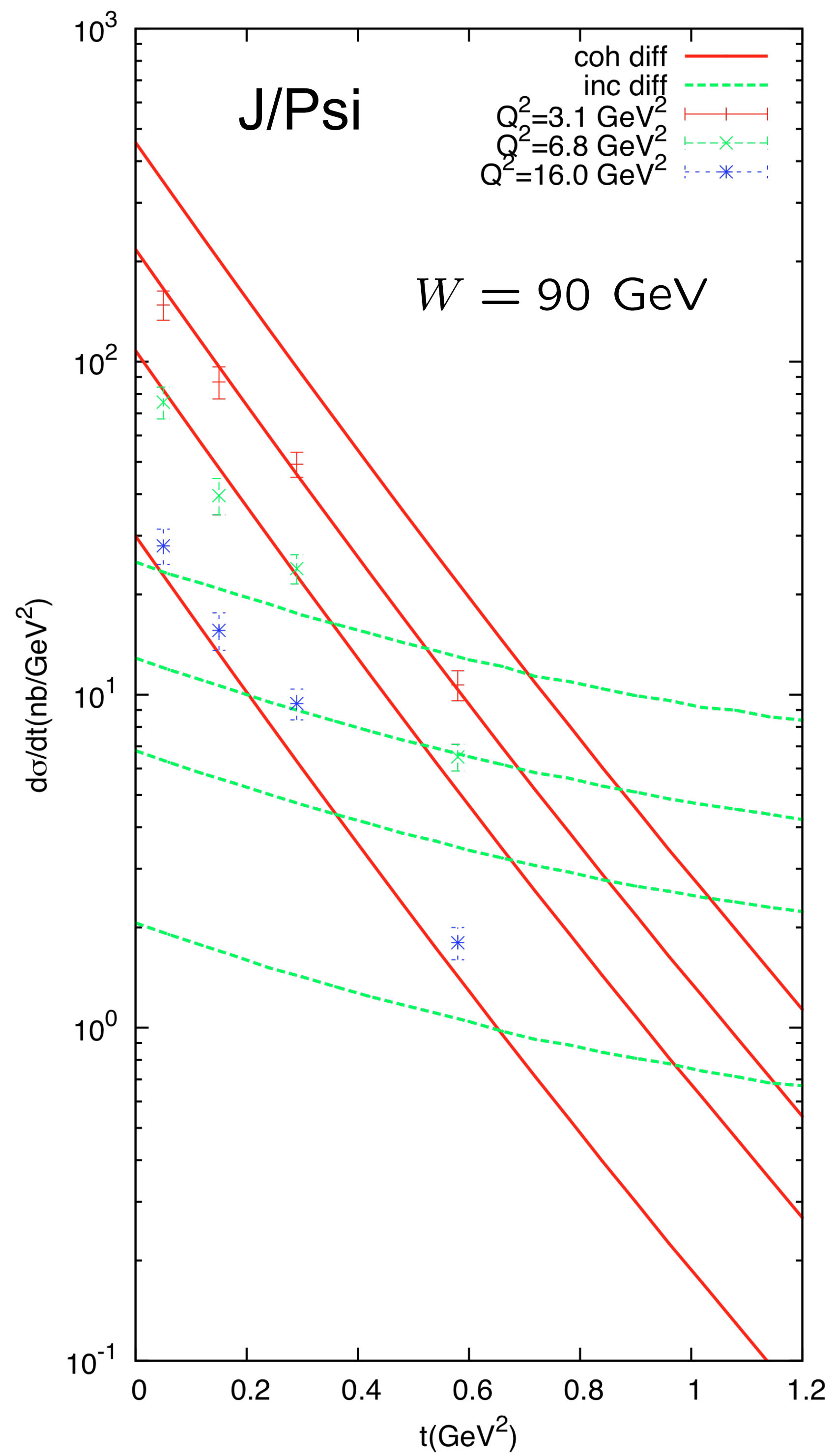
diffractive production :

the proton undergoes inelastic scattering dominates at large |t|

- two distinct regimes

exclusive
→ exp. fall at $-t < 0.7$ GeV^2
diffractive
→ power-law tail at large |t|

the transition point is where the data on exclusive production stop



From protons to nuclei

- qualitatively, one expects three contributions

exclusive production is called coherent diffraction

the nucleus undergoes elastic scattering, dominates at small |t|

intermediate regime (absent with protons)

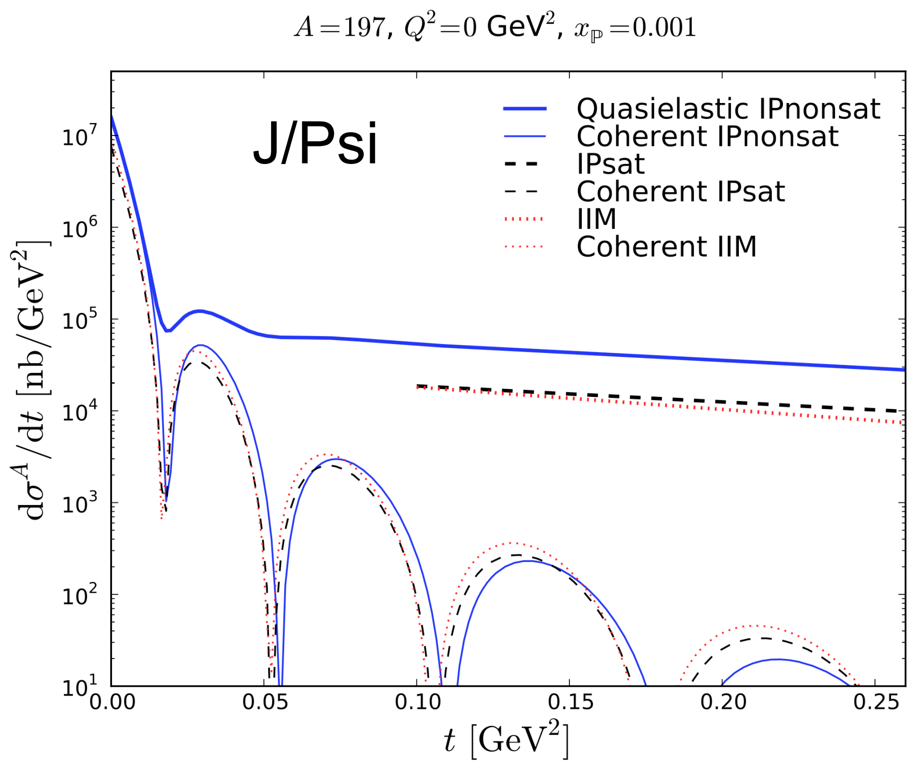
the nucleus breaks up into its constituents nucleons, intermediate |t|

then there is fully incoherent diffraction

the nucleons undergo inelastic scattering, dominates at large |t|

- three regimes as a function of t:

coherent diffraction
→ steep exp. fall at small |t|
breakup into nucleons
→ slower exp. fall at $0.02 < -t < 0.7$ GeV^2
incoherent diffraction
→ power-law tail at large |t|

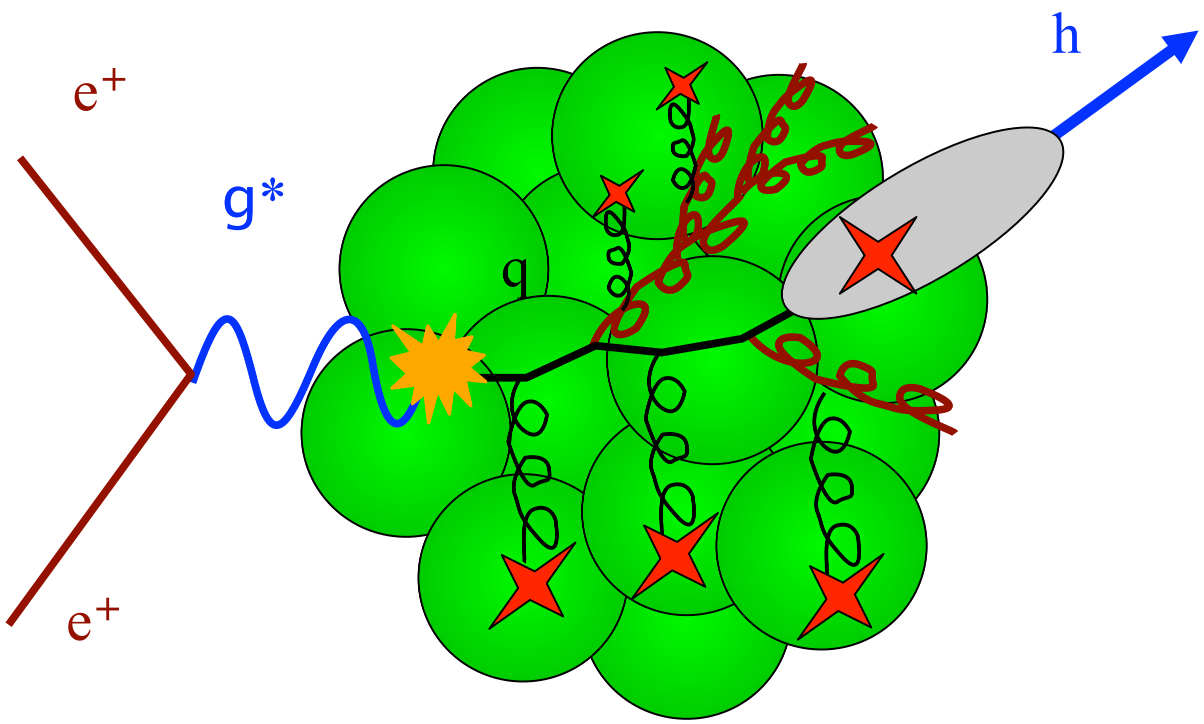


Lappi and Mantysaari (2010)

e+A Golden Science Matrix

Primary new science deliverables	What we hope to fundamentally learn	Basic measurements	Typical required precision	Special requirements on accelerator/ detector	What can be done in phase I	Alternatives in absence of an EIC	Gain/Loss compared with other relevant facilities	Comments
integrated nuclear gluon distribution	The nuclear wave function throughout x-Q^2 plane	F_L, F_2, F_L^c, F_2^c	What HERA reached for F2 with combined data	displaced vertex detector for charm	stage I: large-x & large-Q^2 need full EIC, for F_L and F_2^c	p+A at LHC (not as precise though) & LHeC	First experiment with good x, Q^2 & A range	This is fundamental input for A+A collisions
k_T dependence of gluon distribution and correlations	The non-linear QCD evolution - Qs	SIDIS & di-hadron correlations with light and heavy flavours		Need low-pt particle ID	SIDIS for sure TBD: saturation signal in di-hadron p_T imbalance	1) p+A at RHIC/LHC, although e+A needed to check universality 2) LHeC	Cleaner than p+A: reduced background	
b dependence of gluon distribution and correlations	Interplay between small-x evolution and confinement	Diffractive VM production and DVCS, coherent and incoherent parts	50 MeV resolution on momentum transfer	hermetic detector with 4pi coverage low-t: need to detect nuclear break-up	Moderate x with light and heavy nuclei	LHeC	Never been measured before	Initial conditions for HI collisions – eccentricity fluctuations

Jets and hadronization

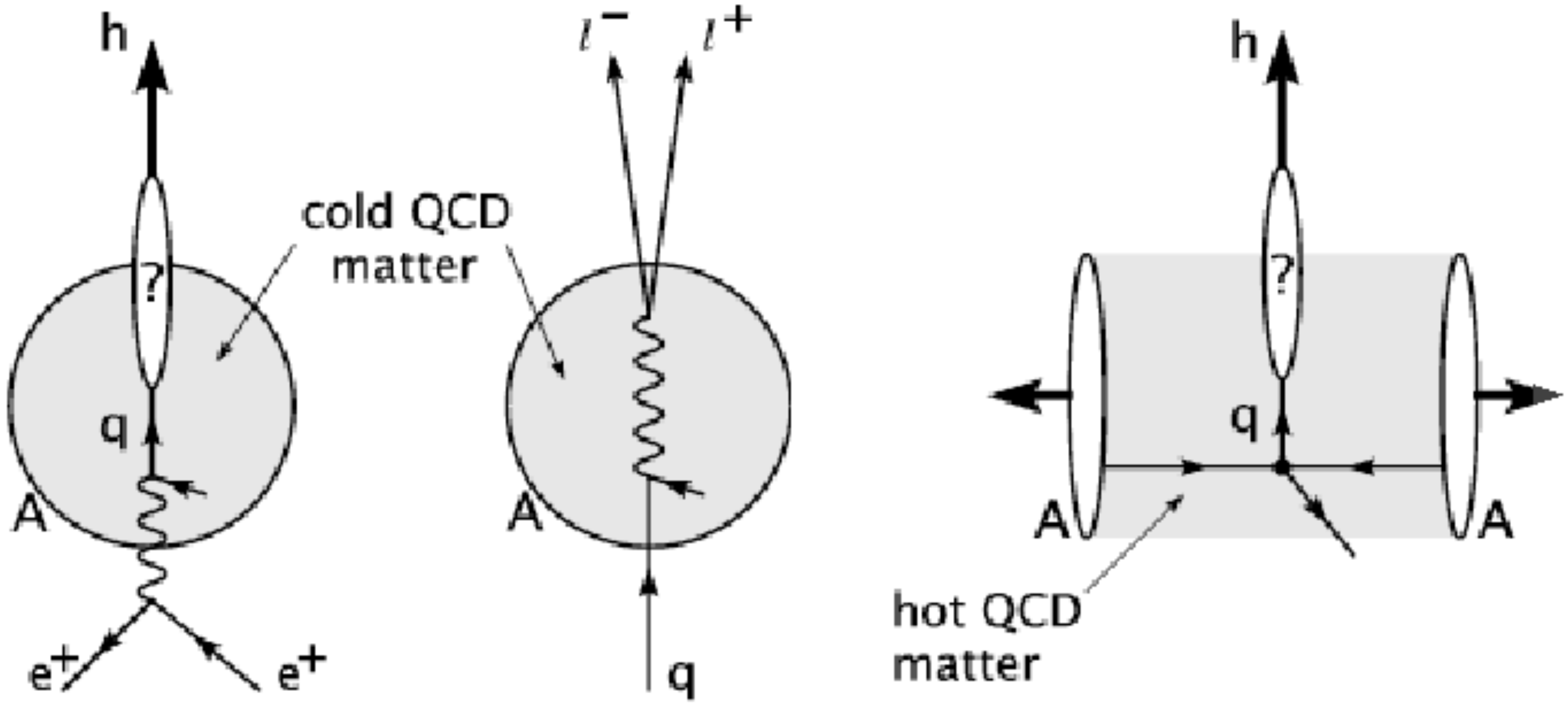


- **Use coloured probes to study soft nuclear glue**
  - ➡ a “large-x” probe of small-x gluons
- **Use nuclei to study parton propagation and fragmentation**
  - ➡ parton showers, quark-to-hadron transition
- **Ideal program for phase-1 EIC**

Jets and hadronization

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 - I

- Measure fundamental properties of cold QCD matter
  - Experimentally isolate pure energy loss regime (large nu)
  - Transport coefficients [Majumder]
    - qhat ↔ pT-broadening, bremsstrahlung
    - ehat ↔ 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]

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

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

Goals - 2

- Fundamental tests of pQCD [any idea for a catchier header?]
  - 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 [any idea for a catchier header?]
  - 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]
  - 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
    - p_T-broadening
  - **Unique at EIC:**
    - heavy flavours (D, B)
    - multi-dimensional binning

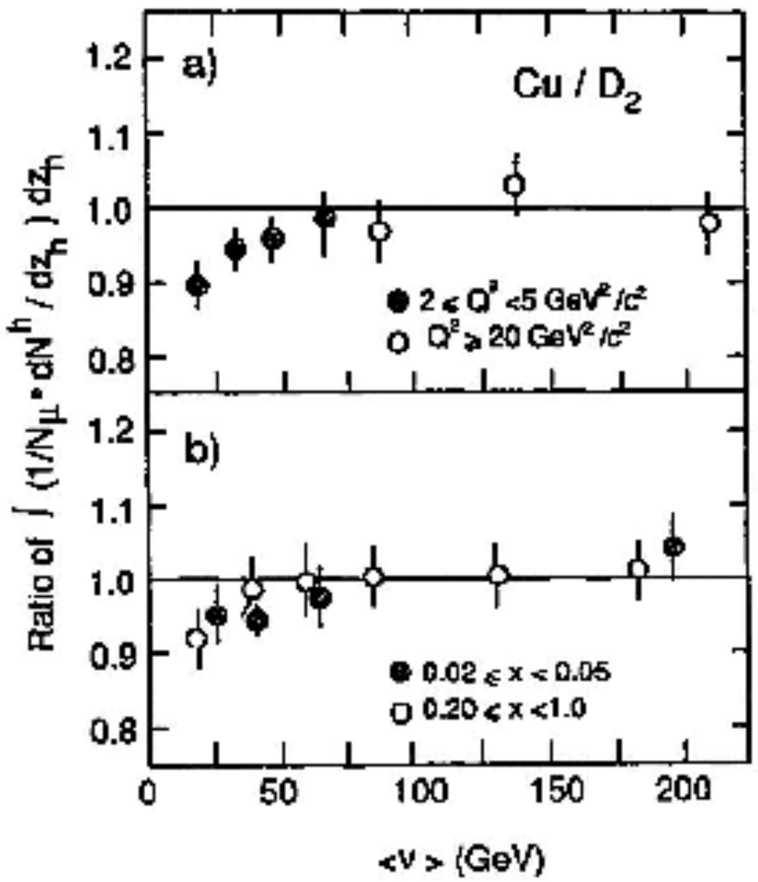
$$R_M^h(z_h) = \frac{1}{N_A^{DIS}} \frac{dN_A^h(z_h)}{dz_h} \Big/ \frac{1}{N_D^{DIS}} \frac{dN_D^h(z_h)}{dz_h}$$

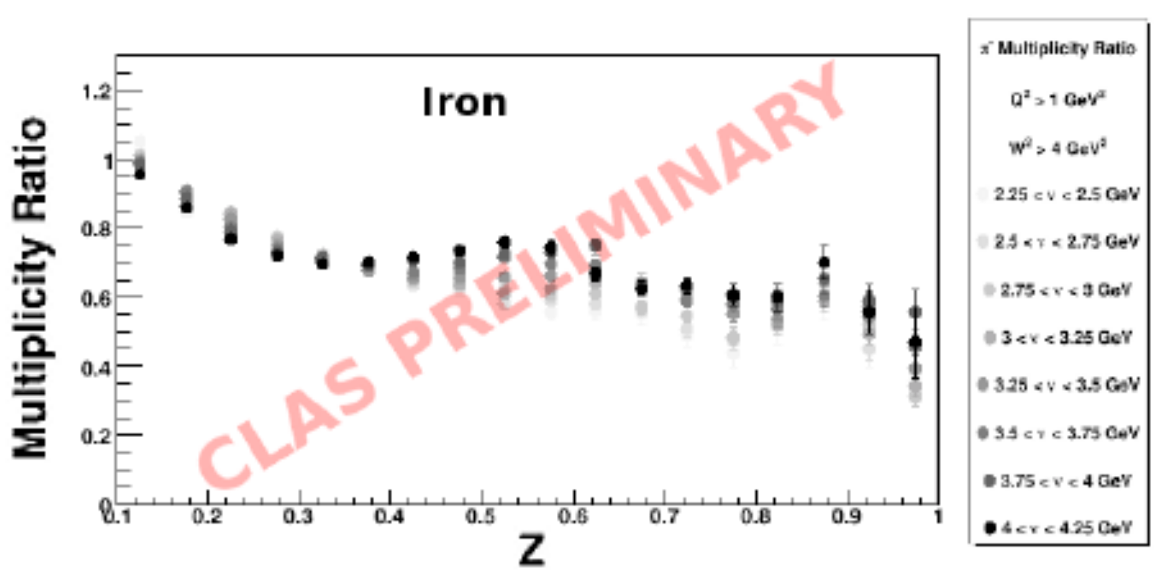
$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$

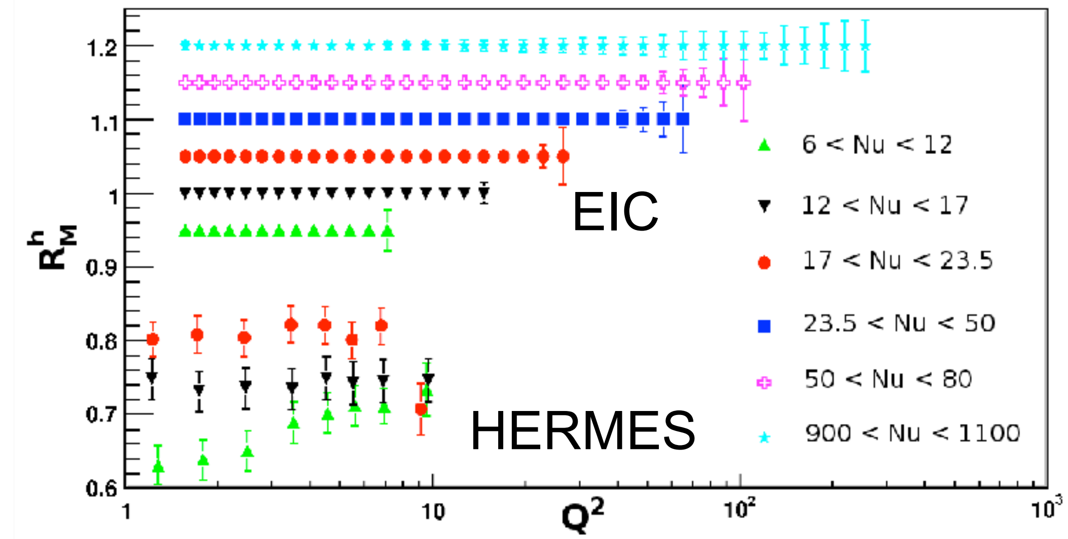
Tools - SIDIS

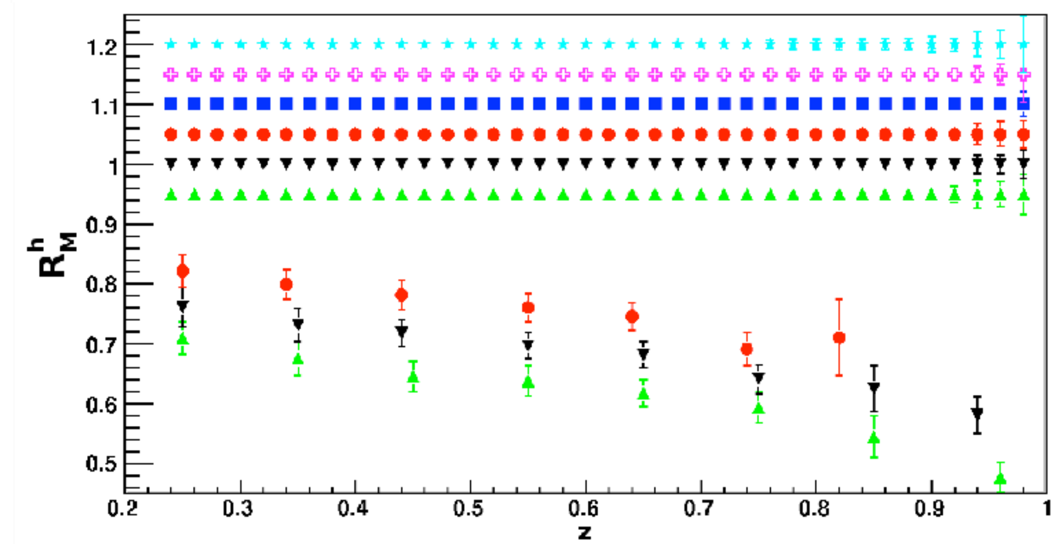
➡ Examples:

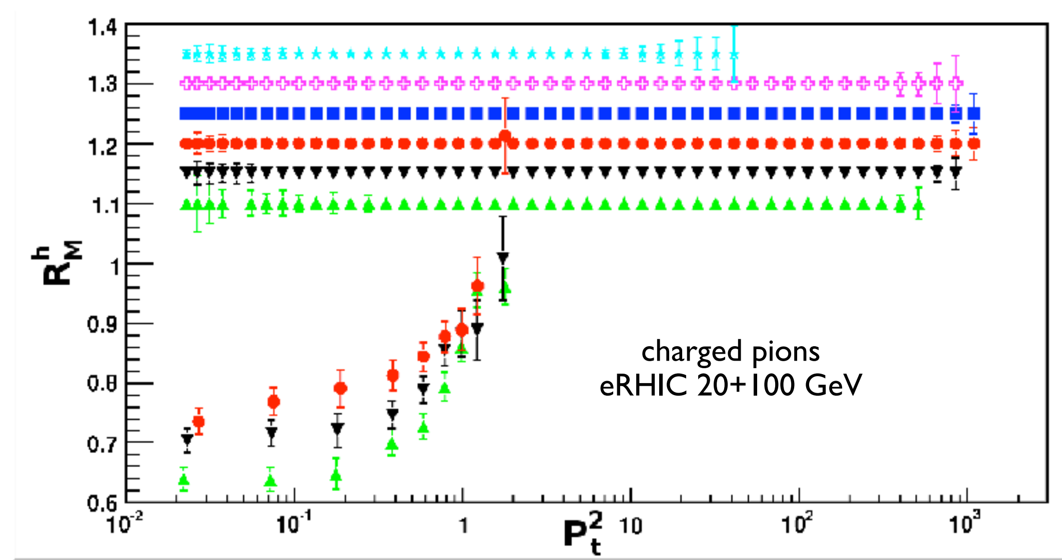
EMC





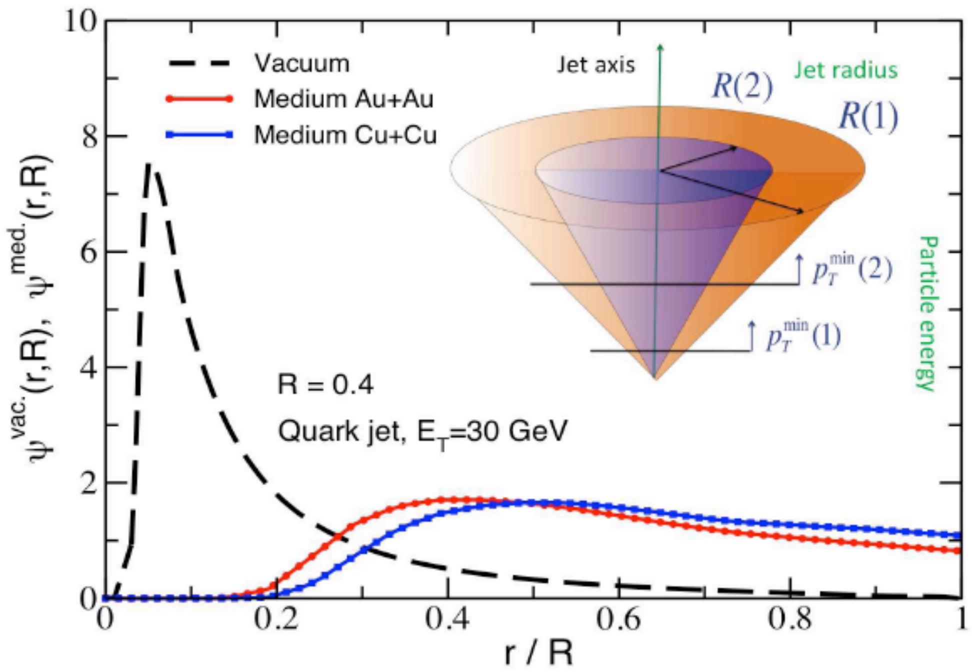






Tools - jets

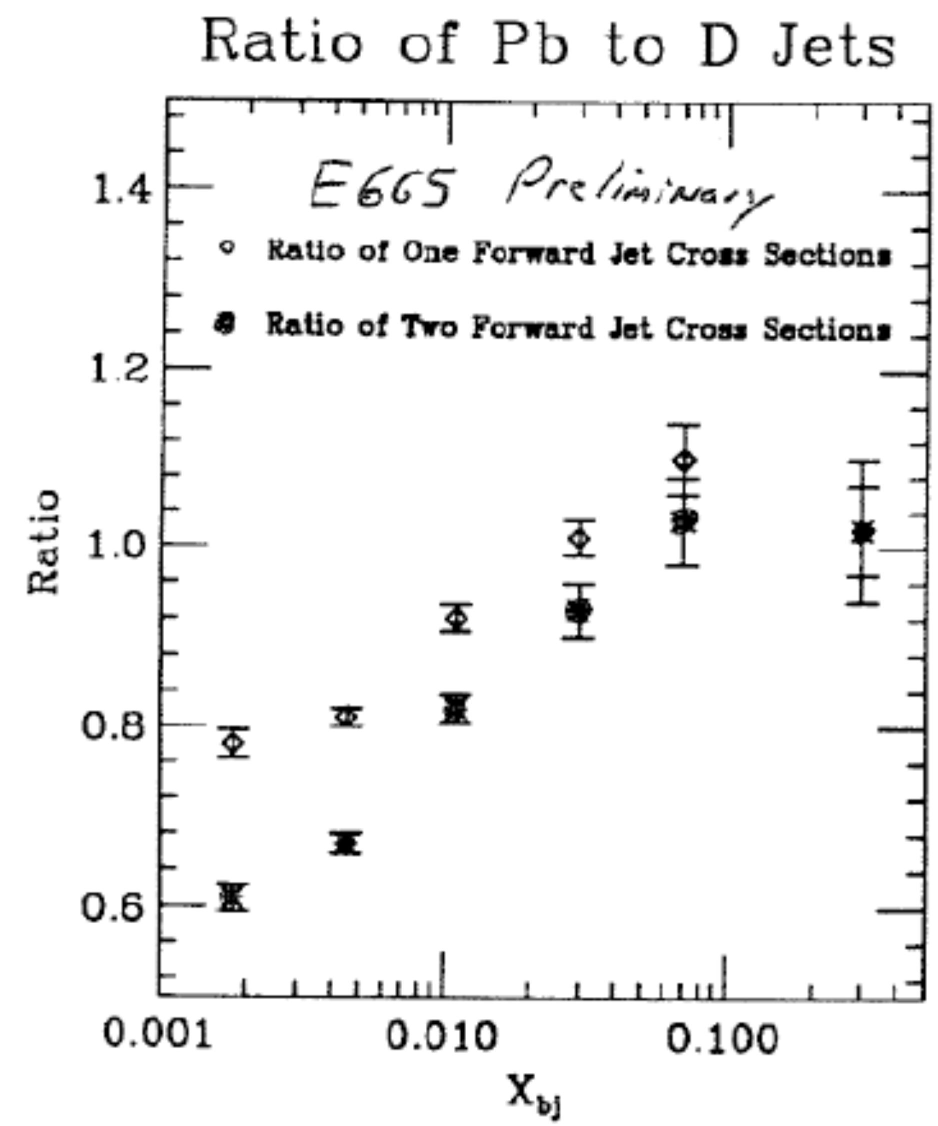
[I.Vitev]



- ➡ Jets
  - 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

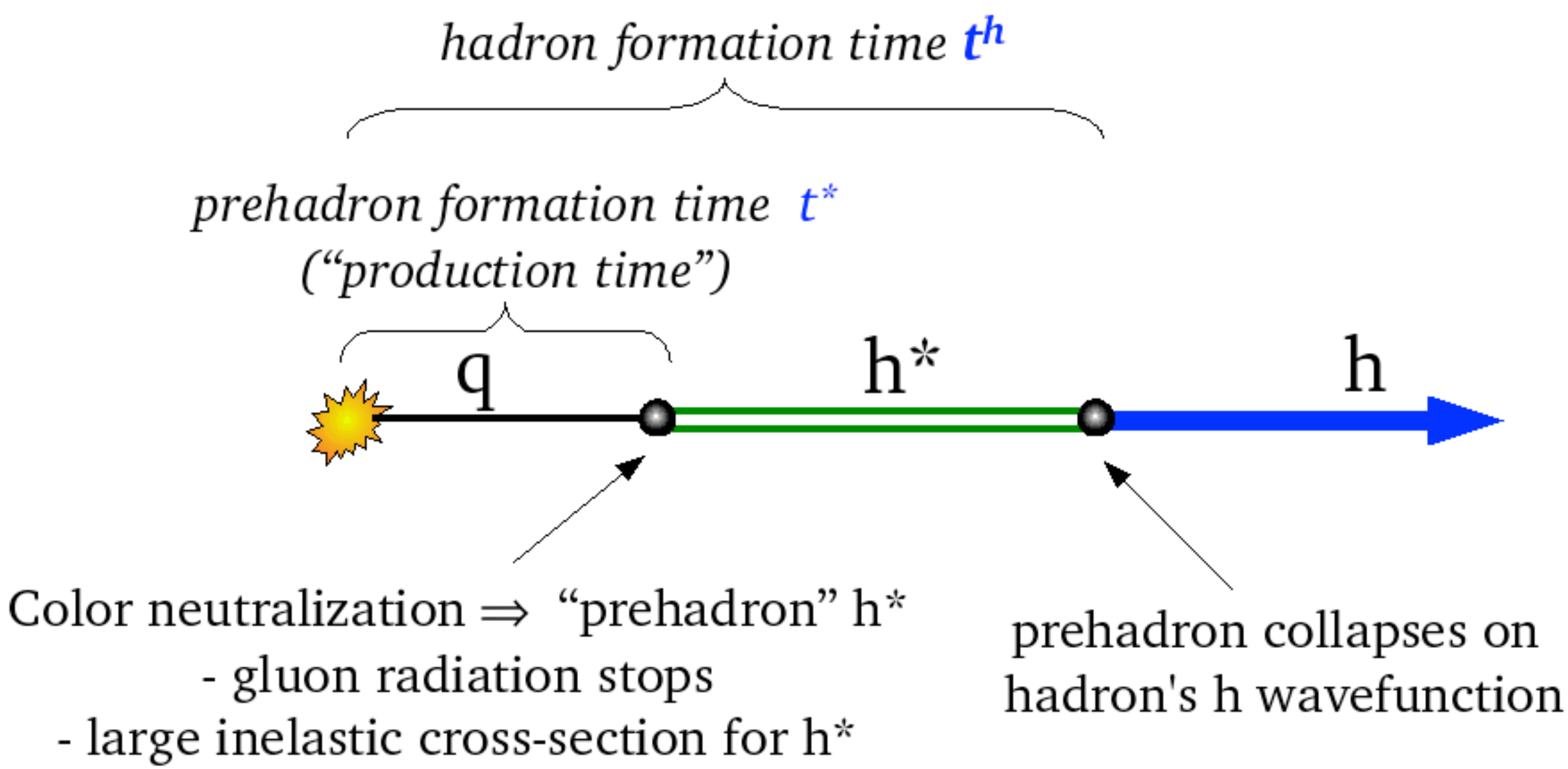
➡ **Jets: a unique opportunity at EIC**



- 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: control over in-medium parton showers
  - 2+1 jets: access to nuclear gluons
  - n+1 ???

Step 1 – pure energy loss regime

➡ Characteristic times controlled by ν (at LO, $\nu = E_{quark}$)



Step 1 – pure energy loss regime

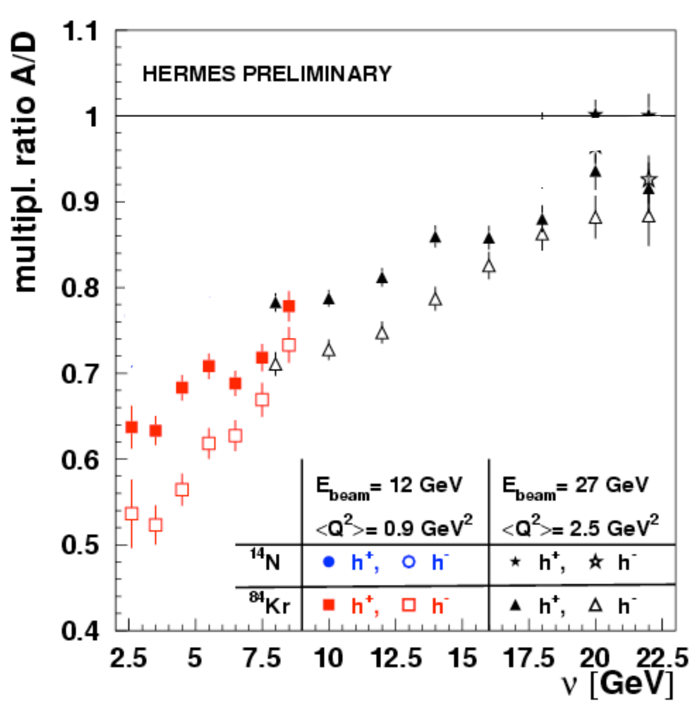
- Processes
  - low ν
    - short production times
    - mix of energy loss and prehadron absorption
  - large ν
    - long production times
    - pure energy loss

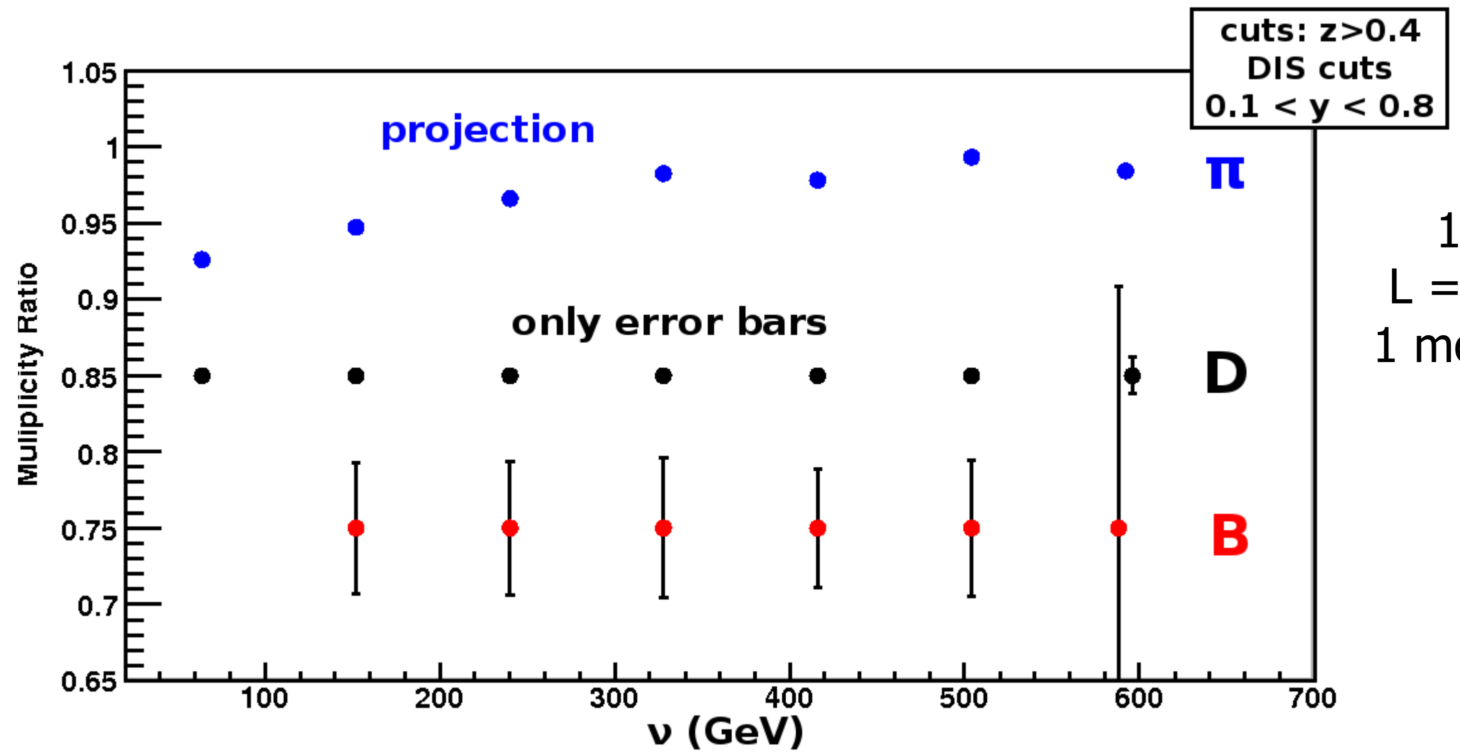
- Observables
  - low ν : hadron observables
    - R_M^h, $\Delta\langle p_T^2\rangle$ and their interplay (important!!)
  - large ν : attenuation disappears
    - p_T broadening
    - jet observables

Step 1 – pure energy loss regime

➡ How to experimentally isolate energy loss processes

- Check how $R_M \to 1$ as $\nu \to \infty$
  - start with "light" mesons: π, η, K, ϕ, ...
  - repeat for heavy flavors: D, B, ...





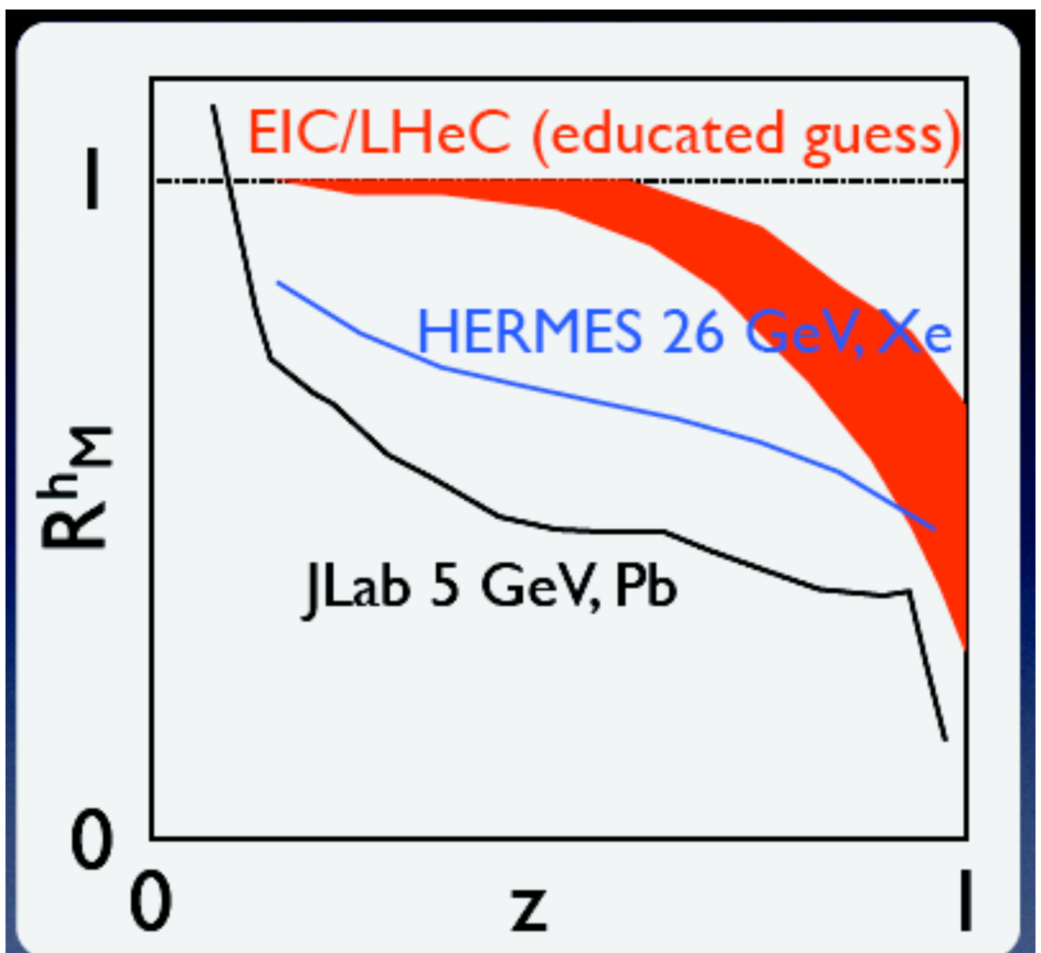
11+30 GeV/A Fe
L = 0.4 10^{33} cm^{-2} s^{-1}
1 month 100% running

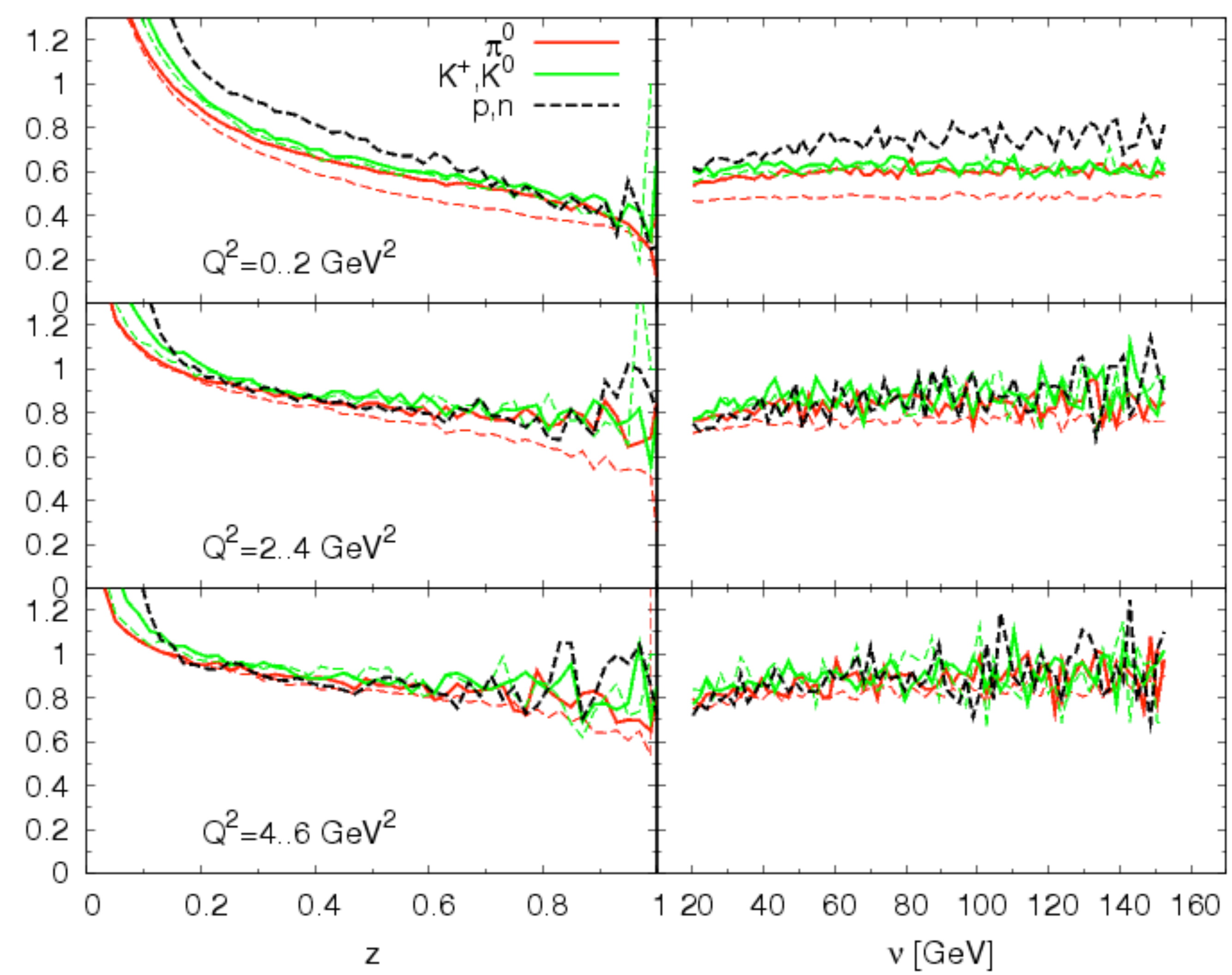
[Dupré]

mixed phase | pure energy loss (?)

Step 1 – pure energy loss regime

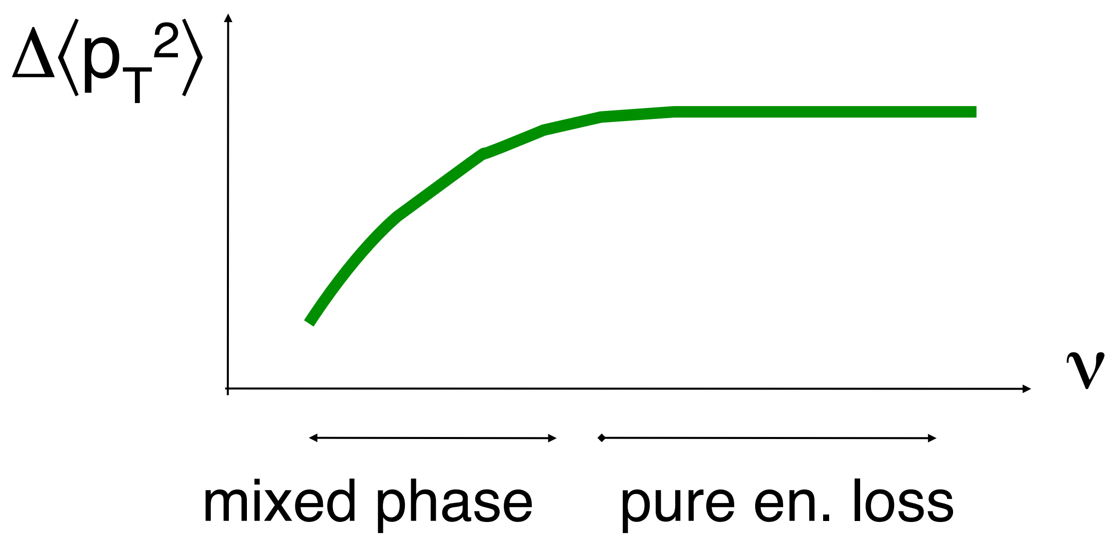
- How to experimentally isolate energy loss processes
  - Check how $R_M \to 1$ as $\nu \to \infty$
    - Does attenuation disappear at high-energy?
      - ✓ breakdown of unversality at large x_F (large z) [Kopeliovich et al. '05]
      - ✓ GiBUU model [Gallmeister et al., INT talk 2010]



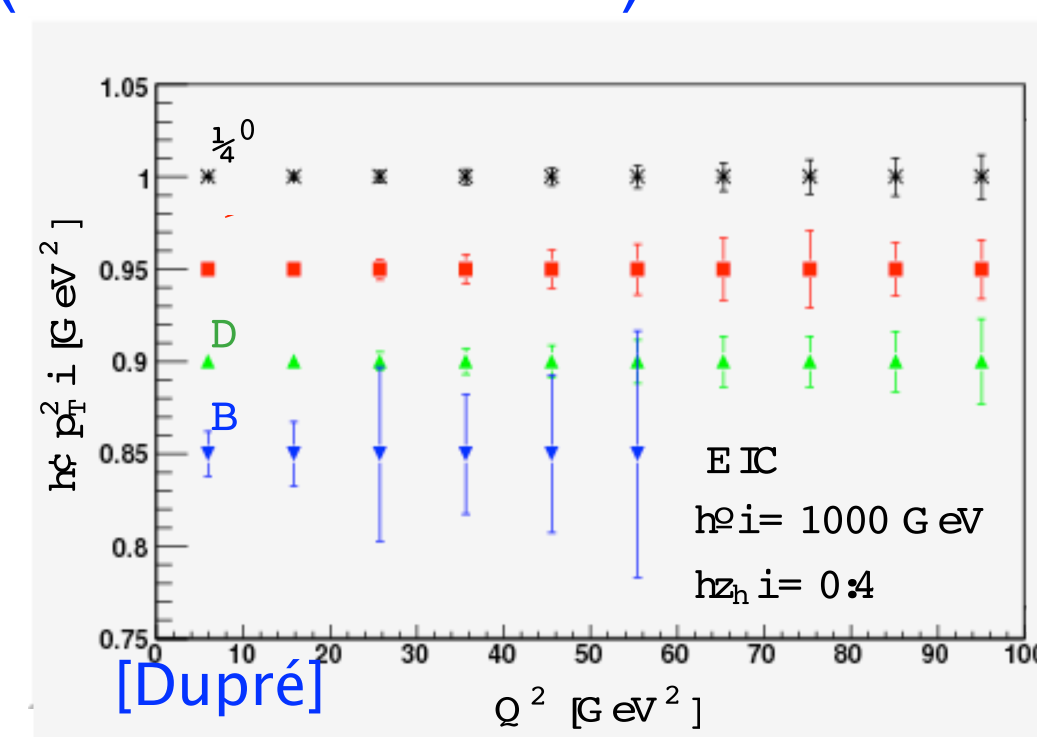


Step 1 – pure energy loss regime

- cross-check with p_T-broadening:
  - Expectation: plateau at large ν, in energy loss regime

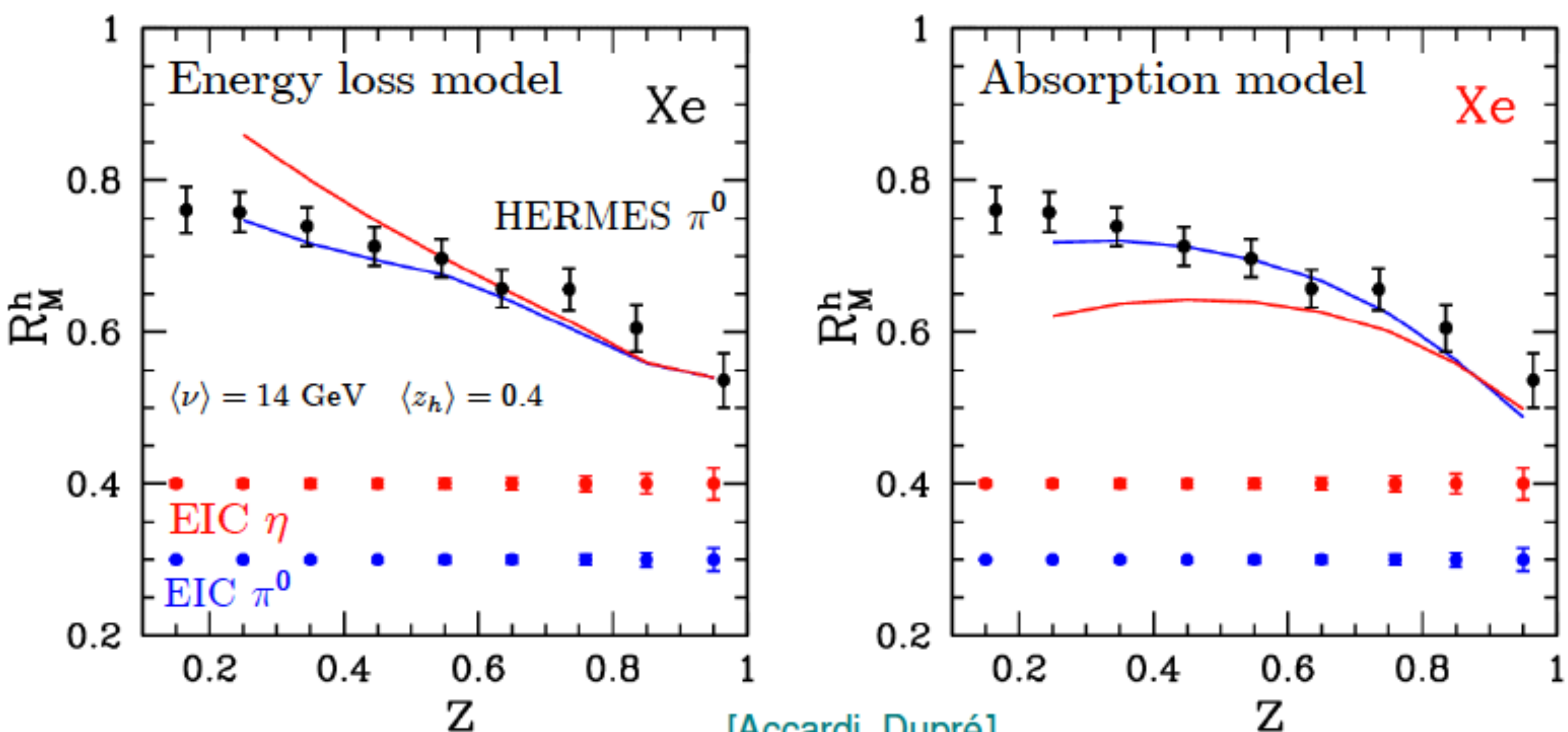


- Choose kinematics with RM~1 (a bit of an overkill)
- Extract qhat ($\leftrightarrow Q_{sat}$)
  - from p_T-broadening vs. z
- Study DGLAP evolution
  - from p_T-broadening vs. Q^2



Step 2 – hadronization

- Study space-time evolution of fragmentation
  - Fix energy loss theory from large ν
  - Go to low ν
  - Extract production times, prehadron cross sections
    - from R_M, p_T-broadening vs. z



[Accardi, Dupré]

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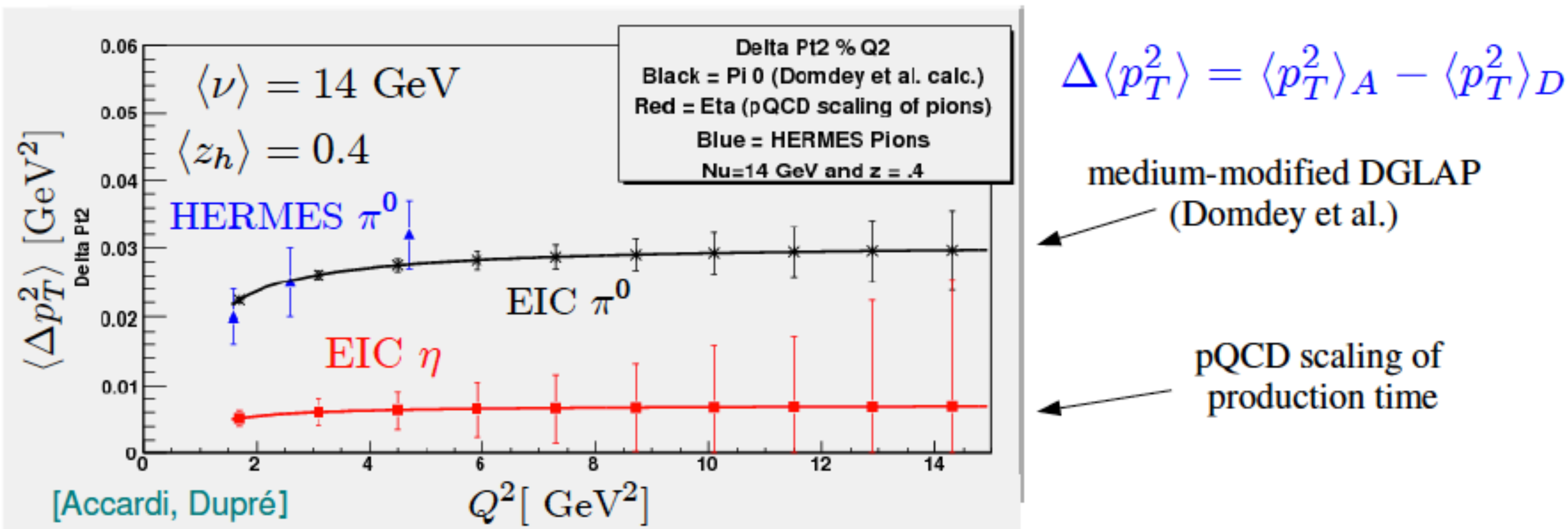
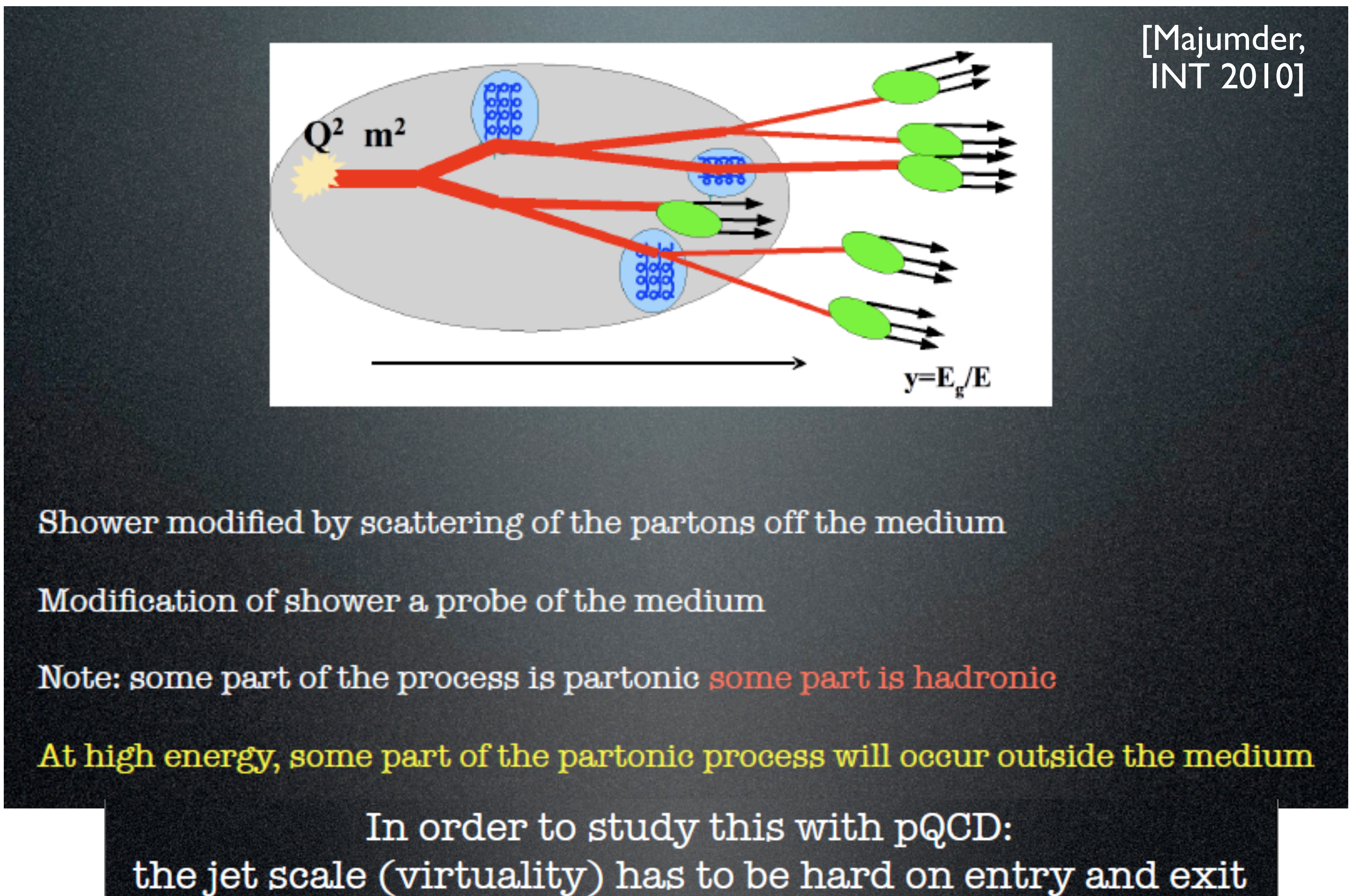


Step 2 – hadronization

- TO DO
  - Summary plots, simulations at standard kinematics
    - e.g., fixed integrated luminosity
    - $x>0.05$
    - for the discussed observables
    - ...
  - Compare different theory predictions
    - Absorption models [Kopeliovich,GiBUU,Accardi...]
    - Energy loss models [Salgado-Wiedemann, DGLV, ...]
    - different flavors: π, η, K, ϕ, D, B
    - ...

Step 3 – jets

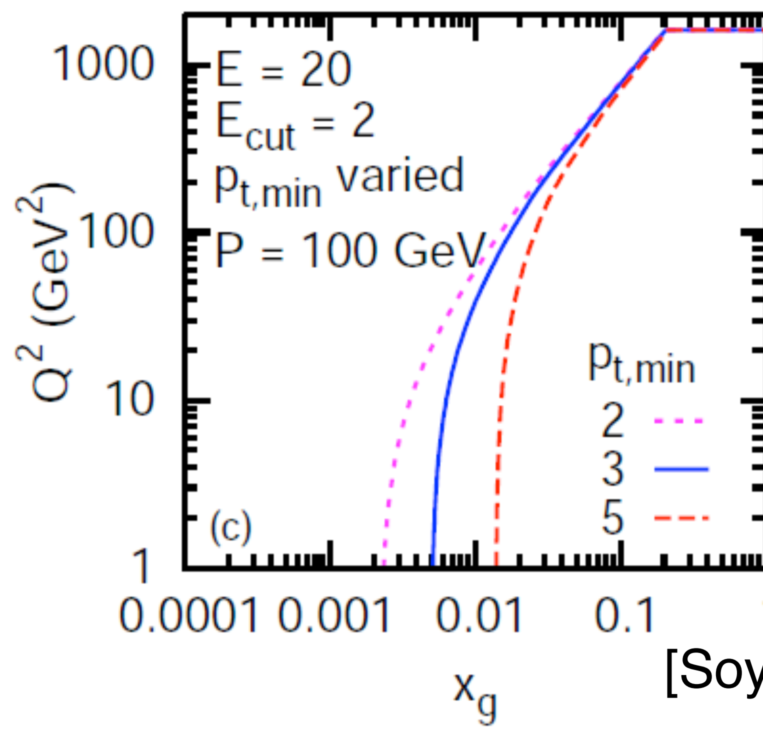
- 1+1 jets
  - to cross check transport coefficients
    - qhat from broadening, ehat from redistribution of long. momentum
  - to study evolution of parton shower



Step 3 – jets

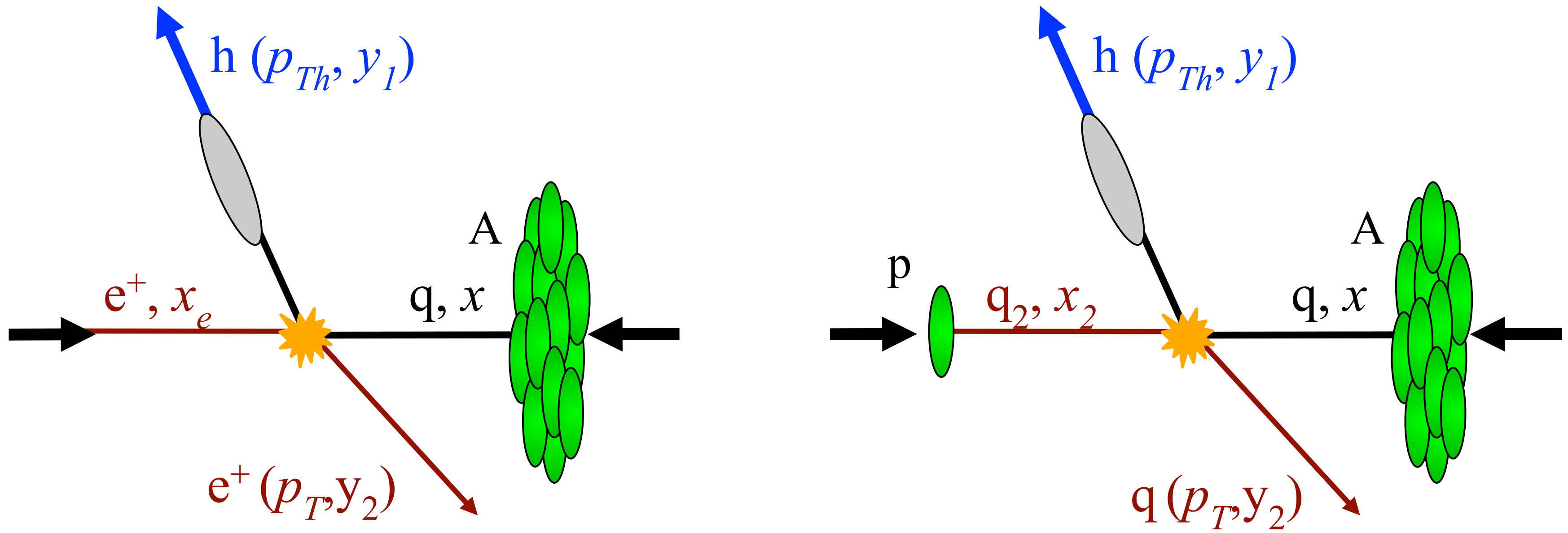
➡ TO DO – need manpower, please help out, big rewards!!

- Identify most promising jet observables
  - (draw on 20+ years of jet phsyics on proton targets!)
- Develop suitable energy-loss Monte Carlos
  - PyQM [Dupre, Accardi] - a bit too simplistic for jets
  - Q-Pythia / Q-Herwig - very well suited
  - Majumder's medium-modified shower MC
    - ✓ only 1 month old, parton-level only, but very promising
- Simulations, simulations, simulations
  - 1+1 jets: many observables
  - 2+1 jets: minimum p_{jet}, (x,Q) reach
  - ...



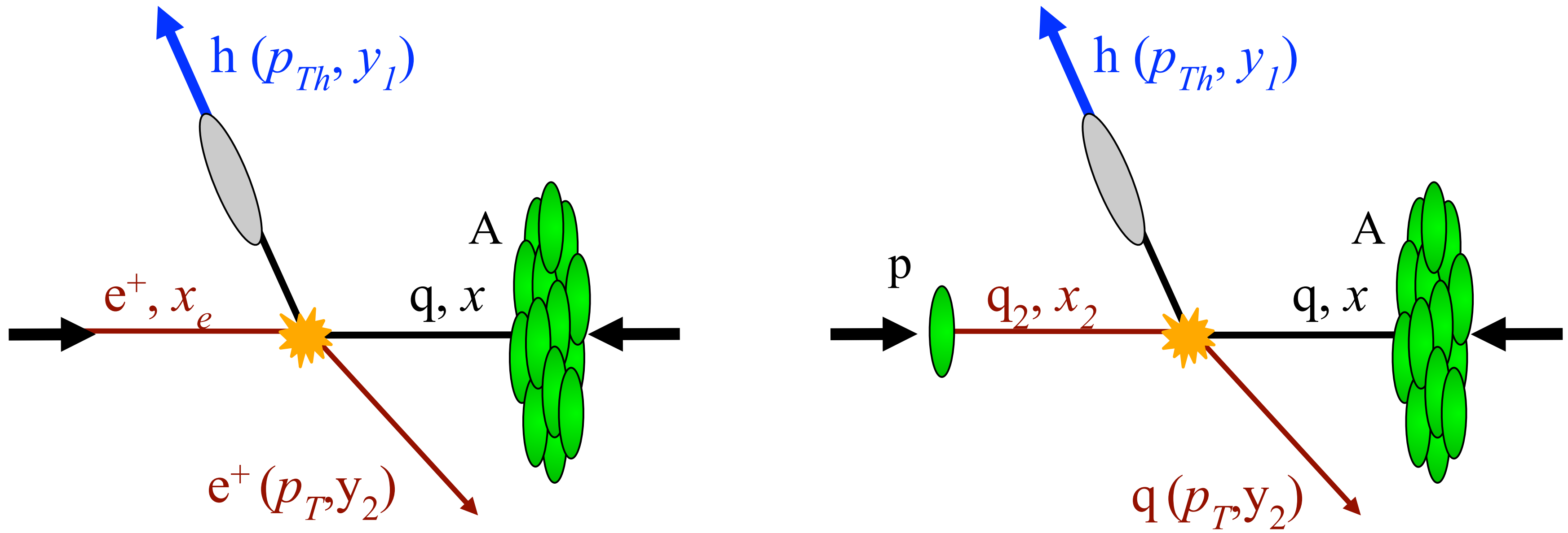
[Soyez]

Advantages over p+A



- Initial-state nuclear modifications can be factored out experimentally
  - e.g. $R_M^h(z_h) = \frac{1}{N_A^{DIS}} \frac{dN_A^h(z_h)}{dz_h} \Big/ \frac{1}{N_D^{DIS}} \frac{dN_D^h(z_h)}{dz_h}$
- No initial-state energy-loss
- Precise control on initial state kinematics (x,Q²), and F.S. quark energy
- Only t-channel contributions
- Reduced soft background for jet reconstruction
- $p + A \rightarrow \gamma + h + X$ is closest analog, but suffers from most other drawback

Advantages over p+A



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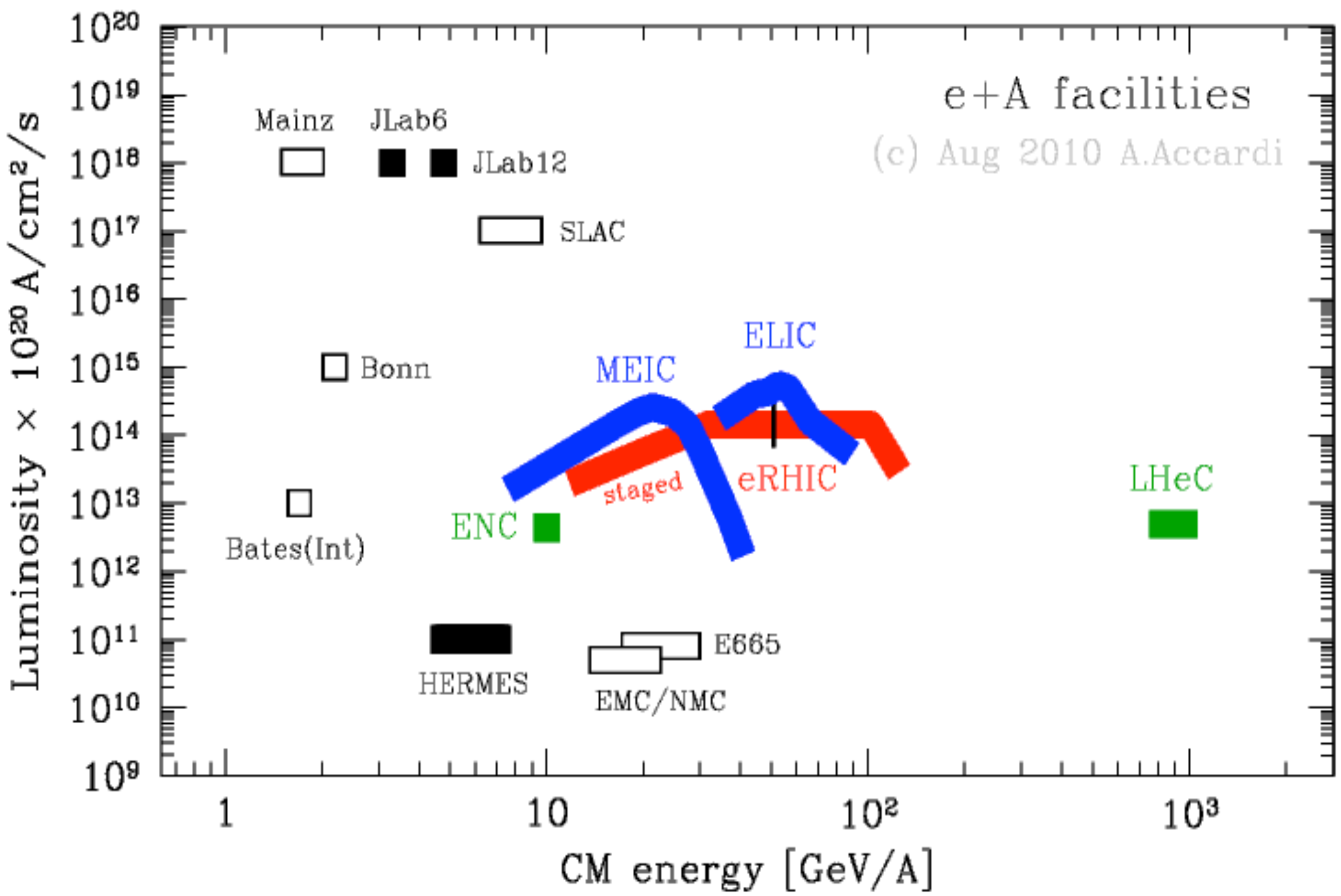
  - e.g
- No i
- Pred … uark energy
- Only
- Reduced soft background for jet reconstruction
- $p + A \to \gamma + h + X$ is closest analog, but suffers from most other drawback

p+A is NOT a substitute for e+A

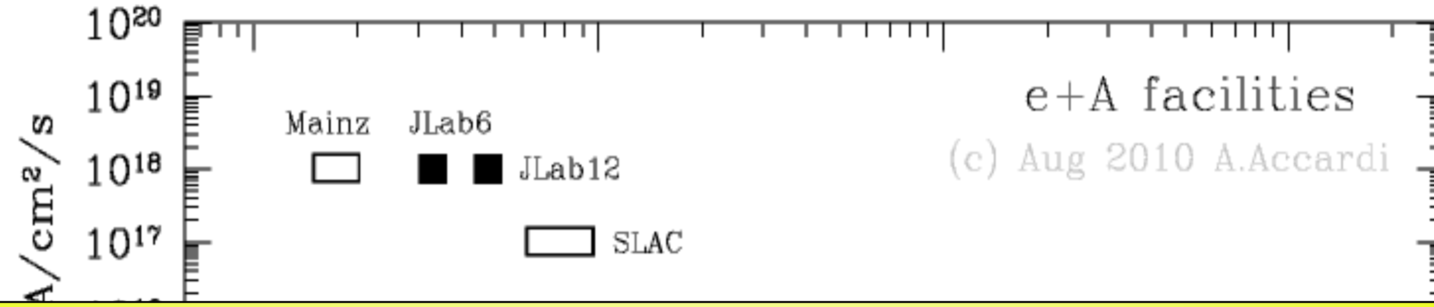
just a stand-in
if EIC or LHeC not built

Other e+A competitors



	$x \gtrsim 0.05$	low ν	high ν	heavy q	jets	multi-D bins
LHeC	enough statistics?	$\nu_{min} =?$	YES	YES	YES	maybe
ENC	YES	YES	NO	NO	NO	maybe
Compass $\mu + A$???	YES	YES	at least π	?	?	maybe

Other e+A competitors



without an EIC:

either LHeC, or push for nuclear targets at Compass

ENC likely not in pure energy loss regime: can only partially complete the J&H program

						multi-D bins
LHeC						maybe
ENC						maybe
Compass $\mu + A$???	YES	YES	at least π	?	?	maybe

Summary, jets & hadronization

- **EIC unique in several respects**
  - high luminosity
    - multi-dimensional binning
    - reduction in theoretical uncertainties
  - wide nu range
    - isolate pure energy loss regime
    - cold matter transport coefficients
    - unambiguous study of prehadronic phase at low nu
  - Heavy quarks
  - Jets

Summary, jets & hadronization

	unique at EIC	interpret-ability	needs further work?	suggested rating
cold transp. coeff. and Q_s	√	√		
space-time hadronization		√		
heavy quarks, heavy flavors	√	open for surprises	√	
jets (parton showers)	√	√	√	

➡ All scientific goals attainable in phase 1

➡ Phase 2 will offer more leverage, but not qualitatively new insights, for jets and heavy flavors

Experimental considerations

- Experimental considerations for e+A fall into 2 main topics:
- IR/Detector designs
  - ➡ For details, see talks from this Tuesday
    - V. Litvinenko, A. Hutton
    - T. Horn, E. Aschenauer
- MC Tools/availability
  - ➡ MC codes in general
    - plenty of e+p/A+A codes, not a lot for e+A
  - ➡ Radiative corrections (lots of work by E. Aschenauer)
    - need a handle on magnitude of effect
      - codes exist for e+p, need work for e+A
    - feeds into the IR/Detector design

Not enough time to go through things in detail - see slides on web for more details

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1

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- XDVMP - eXclusive Diffractive Vector Meson Production
  - ➡ authored by T. Toll and T. Ullrich
  - ➡ see talk by T. Toll in e+A focus weeks
  - ➡ still under development but significant progress has been made

http://rhig.physics.yale.edu/~ullrich/xdvmp/

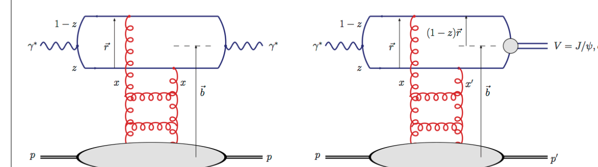
2

eXclusive Diffractive Vector Meson Production

- What we need:
  - ➡ Multi-purpose e+A generator
    - low and high x, Q^2
    - exclusive final states
    - diffraction
    - ...
  - ➡ Will probably need to be a collection of many programmes built into one package

3

eXclusive Diffractive Vector Meson Production



$$\mathcal{A}_{T,L}^{\gamma^* p \to V p}(x,Q,\Delta) =$$

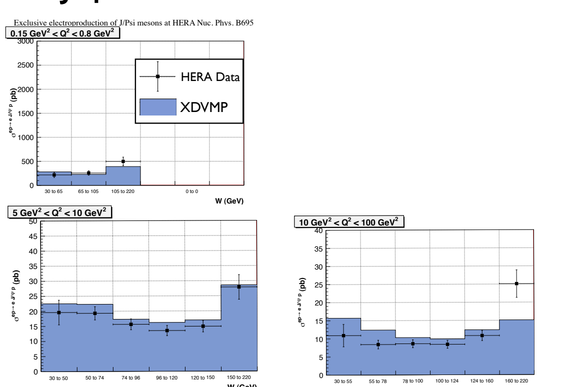
$$i\int \mathrm{d}r \int_0^1 \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2\mathbf{b} (\Psi_V^*\Psi)_{T,L} (2\pi r) J_0([1-z]r\Delta)(2\pi b) J_0(b\Delta) \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}$$

Known from QED — Needs to be modelled

Exclusive diffractive processes at HERA within the dipole picture, H. Kowalski, L. Motyka, G. Watt, Phys. Rev. D74, 074016, arXiv:hep-ph/0606272v2

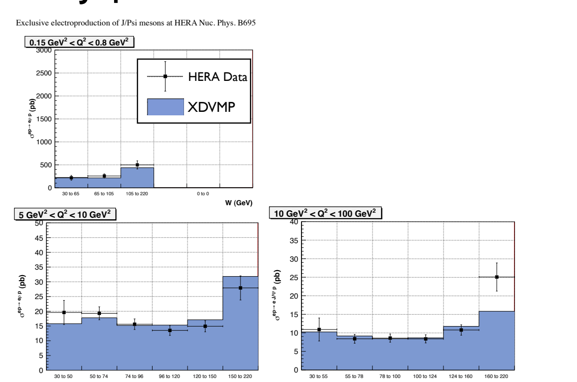
4

J/ψ at HERA vs b-CGC model



5

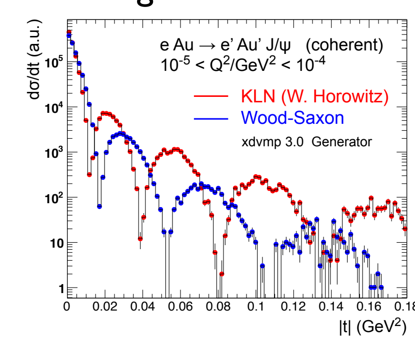
J/ψ at HERA vs b-Sat model



Plots produced by M. Savastio

6

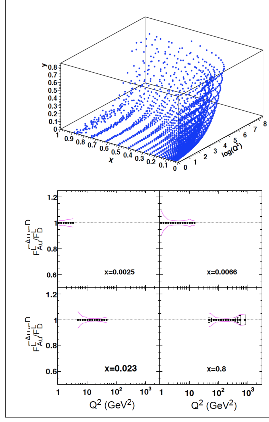
Using XDVMP: dσ/dt



A definitive measurement requires excellent momentum (t) resolution and large range in t

7

Precision measurements of F_L



- $F_L \sim \alpha_s G(x,Q^2)$: the most direct way to access $G(x,Q^2)$
- F_L measurement requires running at several $\sqrt{s}$
- In order to extract F_L, need at least two measurements of the inclusive cross-section with a wide span in inelasticity, y ($Q^2 = sxy$)
- Study of systematic errors shows that they dominate the statistical errors (for 4 fb^{-1}/A)
  - ➡ F_L for 4 GeV electrons on 50, 70, 100 and 250 GeV proton energies

8

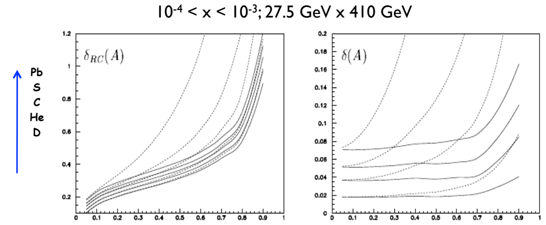
Radiative Corrections (RC) and why they are important

- RC modify the kinematics → Q^2
  - ➡ initial state: $E'_{beam} = E_{beam} - E_\gamma$
    - photon goes along the beam line
  - ➡ final state: $E'_{out} = E_{out} - E_\gamma$
    - photon goes somewhere in the calorimeter
- RC and detector smearing effects do not factorize
  - ➡ need to have RC effects implemented in the MC code to unfold the effects in the kinematics
- A lot of RC codes exist for e+p (e.g. RADGEN), not the case for e+A

9

Radiative Corrections: What do we know?

$10^{-4} < x < 10^{-3}$; 27.5 GeV x 410 GeV

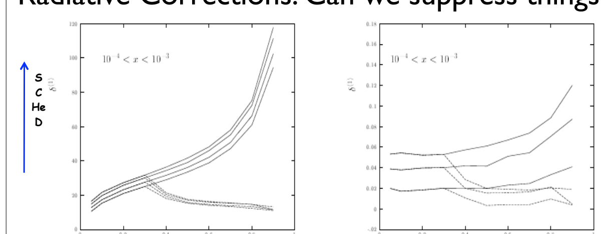


$$\delta_{RC}(A) = \frac{d\sigma^A/dy}{d\sigma_B^A/dy} - 1 \qquad \delta_{RC}(A) = \frac{1+\delta_{RC}(A)}{1+\delta_{RC}(D)} - 1$$

- Solid: inelastic radiative corrections
- Dashed: inelastic, quasi-elastic and elastic radiative corrections
  - ➡ Huge effect at large y!!

10

Radiative Corrections: Can we suppress things?



- Elastic/quasi-elastic part:
  - ➡ require some hadrons in the detector
- Inelastic part (solid line):
  - ➡ dashed line: after cuts $E_\gamma > 10$ GeV → E-p_z from hadronic state is smaller

11

Radiative Corrections: Outlook in e+A

- Djangoh:
  - ➡ http://wwwthep.physik.uni-mainz.de/~hspiesb/djangoh/djangoh.html is compiled at BNL and running
  - ➡ e+A part is included but need to do more studies
  - ➡ HERACLES can be interfaced with other MC codes
- HERMES code (RADGEN + e+A version of LEPTO) installed at BNL but no nuclear effects are included
- Can compare results between eA-RADGEN and HERACLES
  - ➡ can nPDFs be included?

12

Outlook

- Firstly, would like to thank Markus and Elke for their hard work and contributions during the 3 weeks of the e+A programme (and presumably much more!!)
- We'd also like to thank all of the participants for their contributions to the e+A weeks

BUT

The work is not yet finished!!!

- A write-up of the work will be published.
  - ➡ Contributors have been contacted and asked to provide small contributions and calculations for the document

Need to receive everything before Christmas

Experimental Part

Experimental considerations

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    - ▸ …
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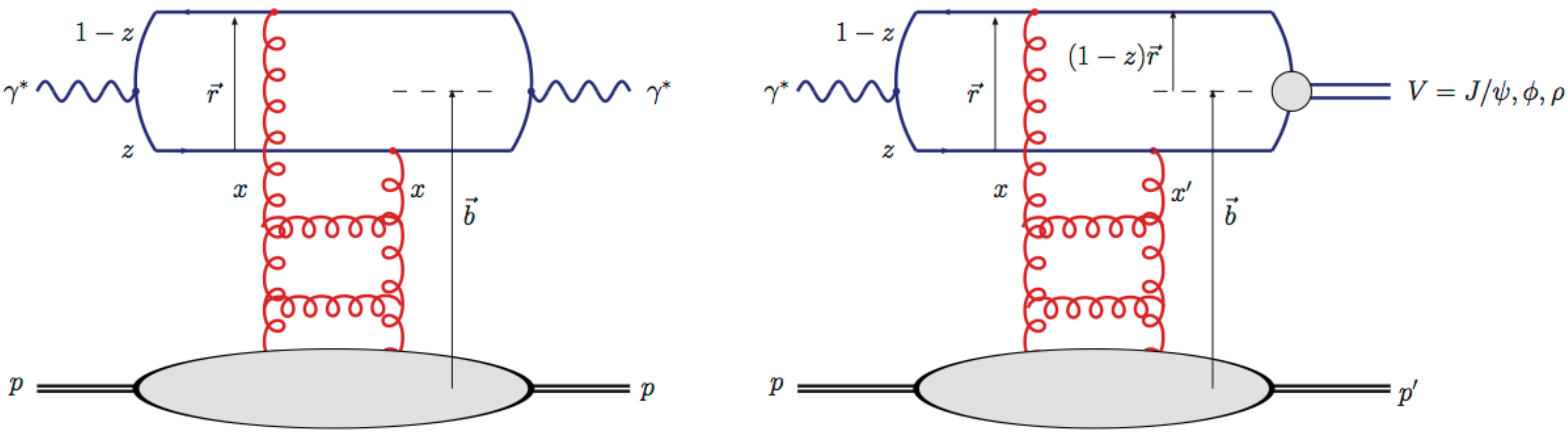
eXclusive Diffractive Vector Meson Production



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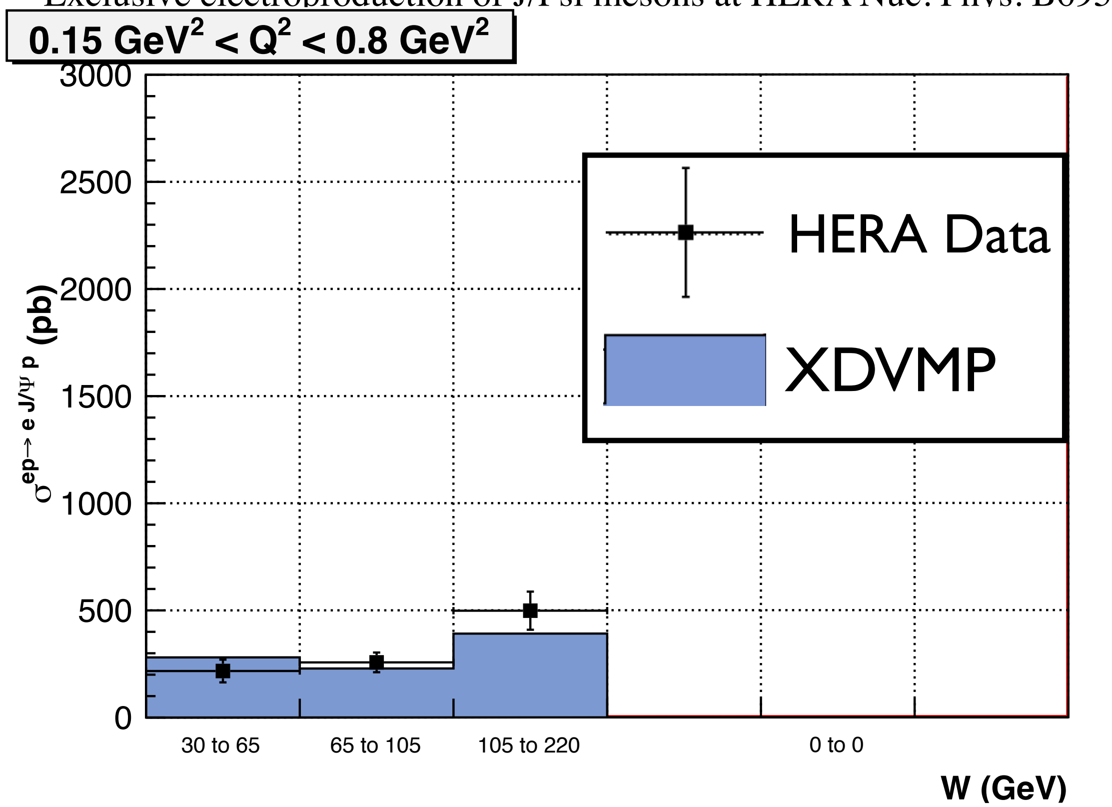
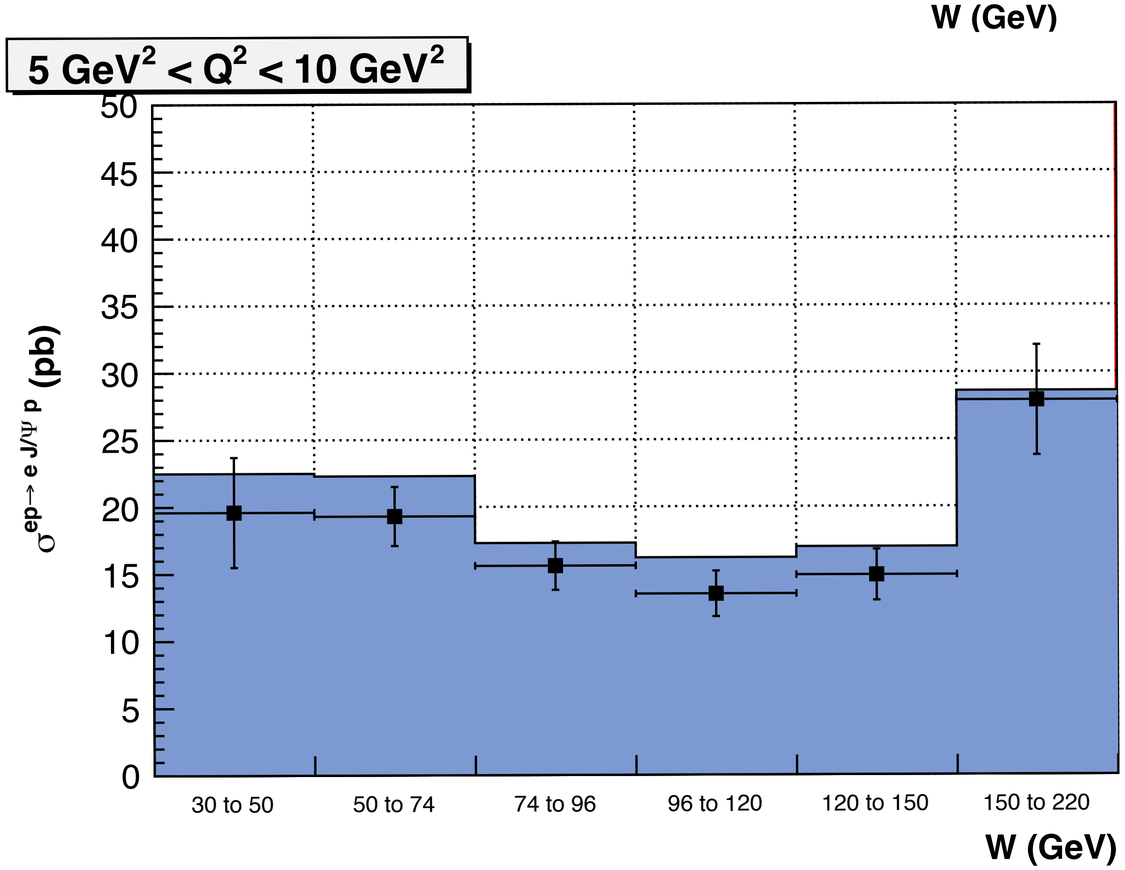
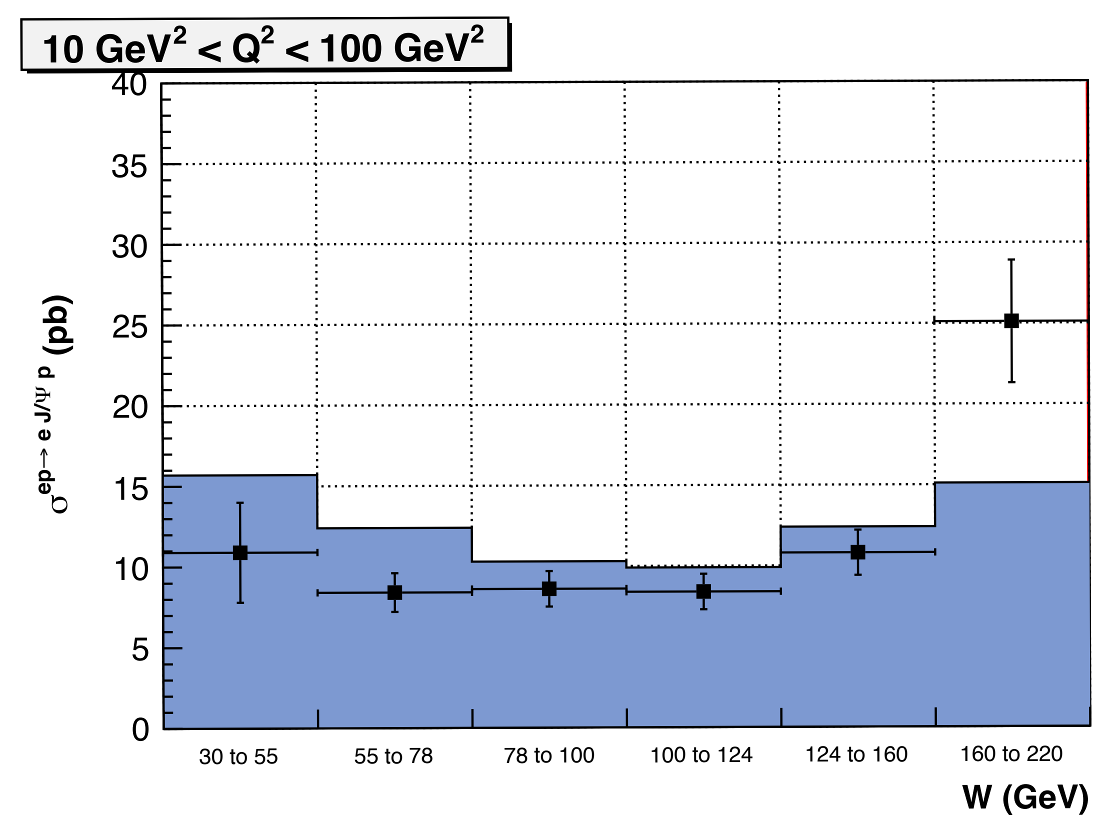
J/ψ at HERA vs b-CGC model

Exclusive electroproduction of J/Psi mesons at HERA Nuc. Phys. B695







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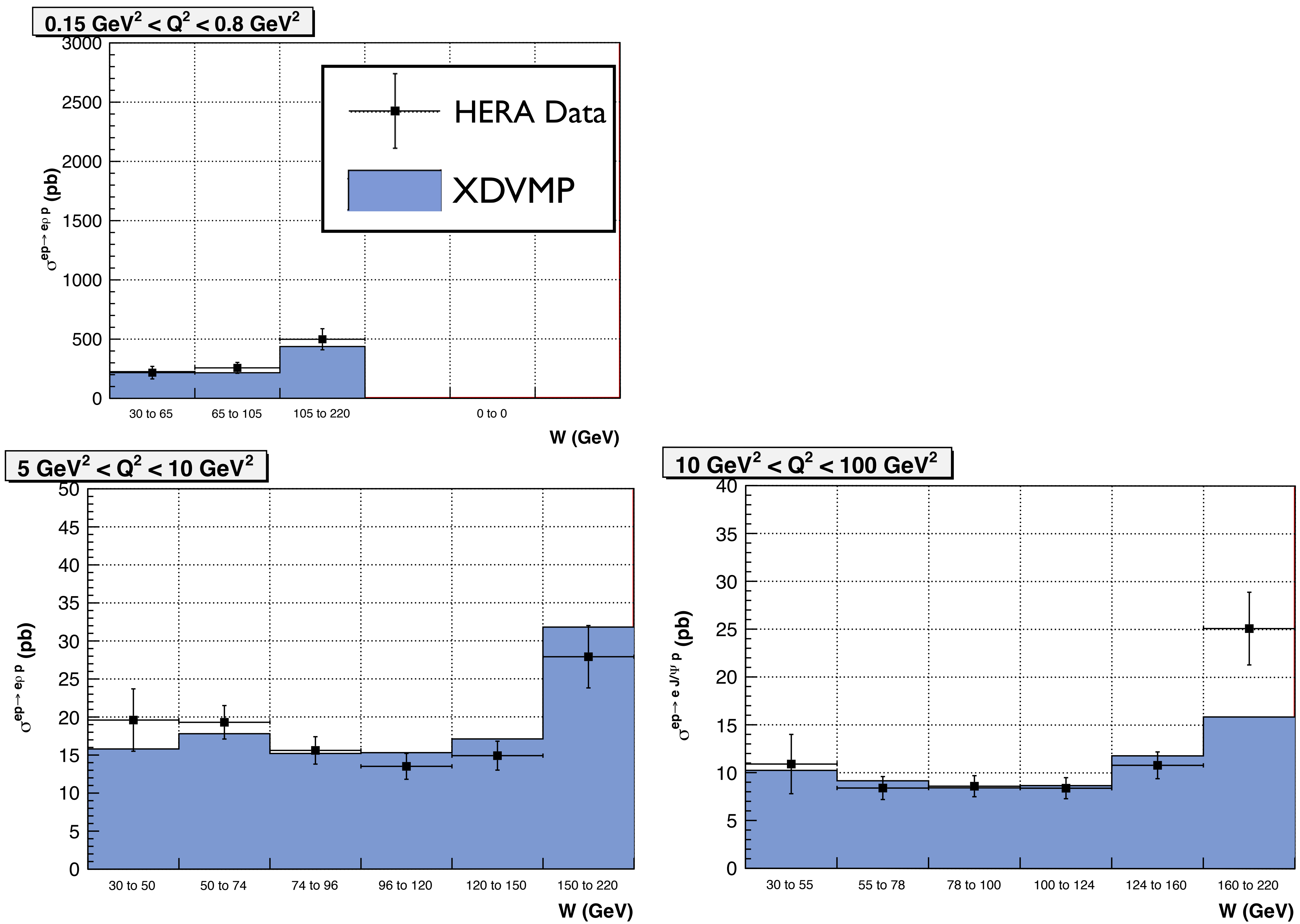
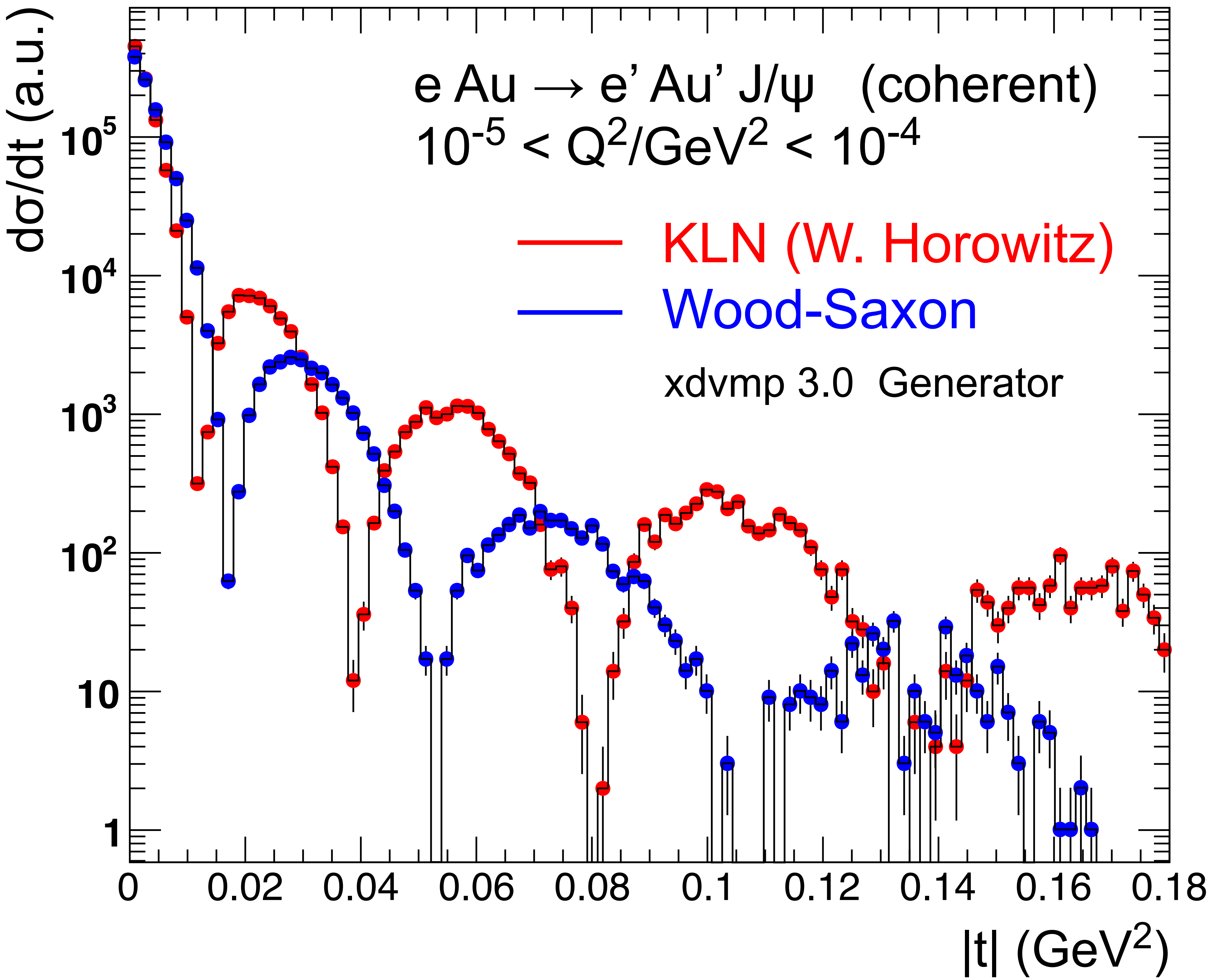


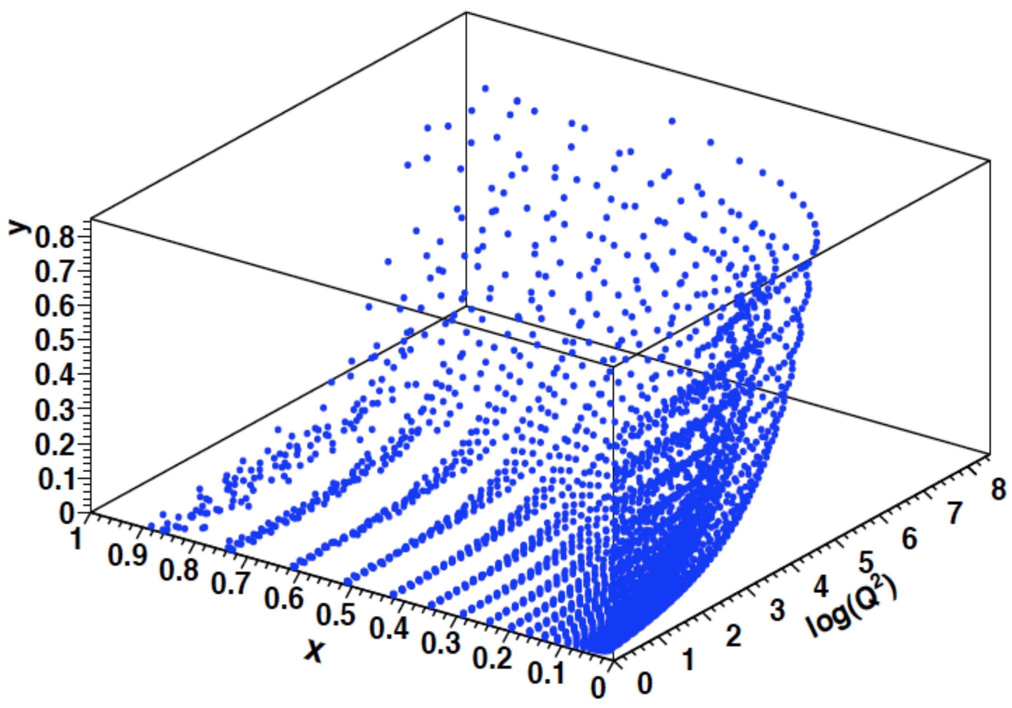
Plots produced by M. Savastio

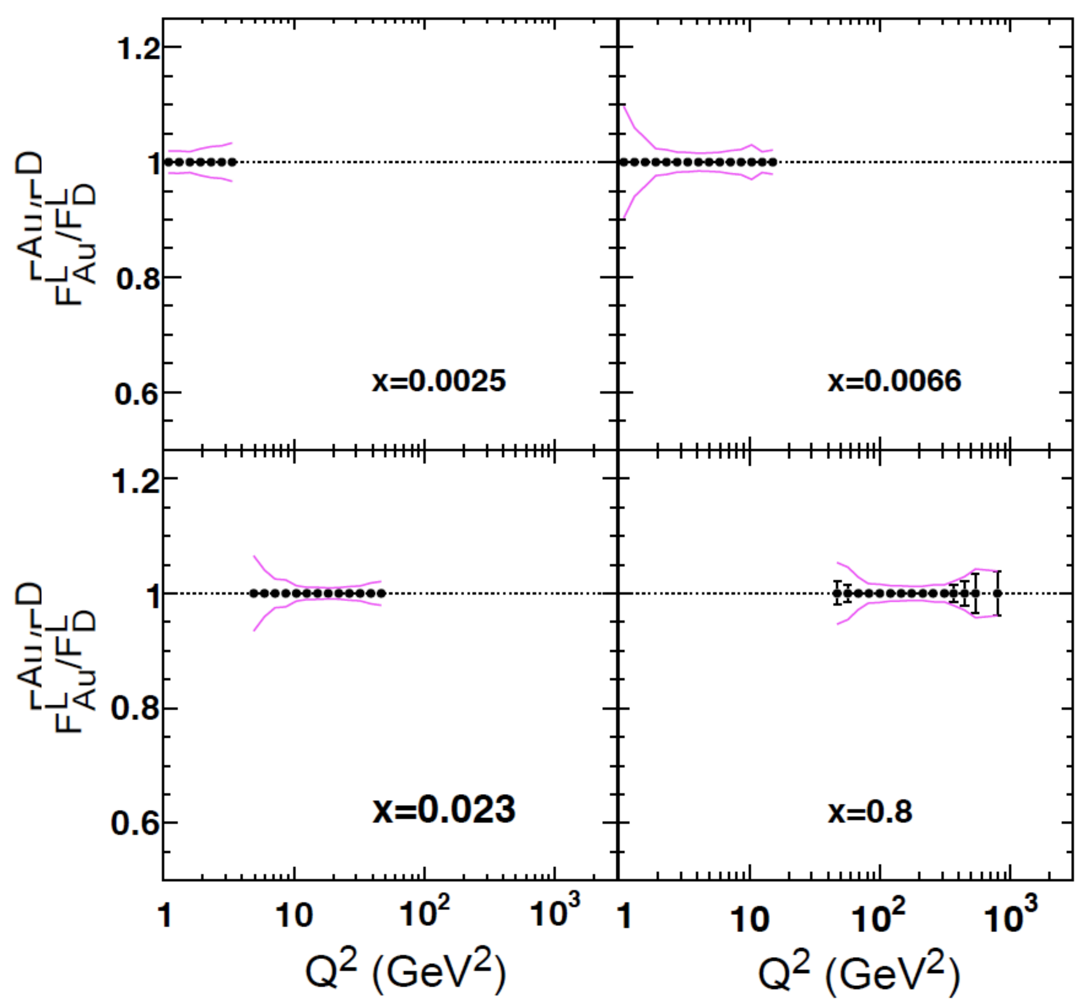
Using XDVMP: dσ/dt



A definitive measurement requires excellent momentum (t) resolution and large range in t

Precision measurements of F_L





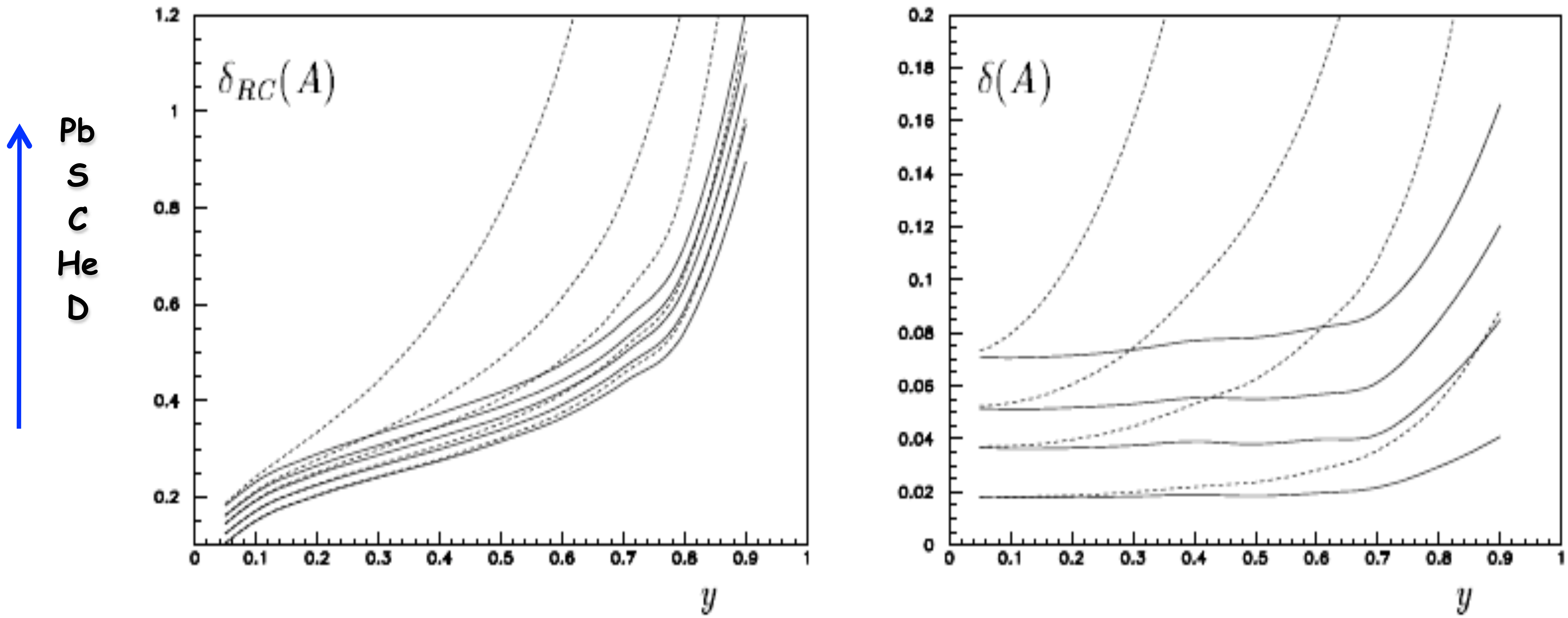
- $F_L \sim \alpha_s G(x,Q^2)$: the most direct way to access $G(x,Q^2)$
- F_L measurement requires running at several $\sqrt{s}$
- In order to extract F_L, need at least two measurements of the inclusive cross-section with a wide span in inelasticity, y ($Q^2 = sxy$)
- Study of systematic errors shows that they dominate the statistical errors (for 4 fb^{-1}/A)
  - ➡ F_L for 4 GeV electrons on 50, 70, 100 and 250 GeV proton energies

Radiative Corrections (RC) and why they are important

- RC modify the kinematics → Q^2
  - ➡ initial state: $E'_{beam} = E_{beam} - E_{\gamma}$
    - ‣ photon goes along the beam line
  - ➡ final state: $E'_{out} = E_{out} - E_{\gamma}$
    - ‣ photon goes somewhere in the calorimeter
- RC and detector smearing effects do not factorize
  - ➡ need to have RC effects implemented in the MC code to unfold the effects in the kinematics
- A lot of RC codes exist for e+p (e.g. RADGEN), not the case for e+A

Radiative Corrections: What do we know?

$10^{-4} < x < 10^{-3}$; 27.5 GeV x 410 GeV

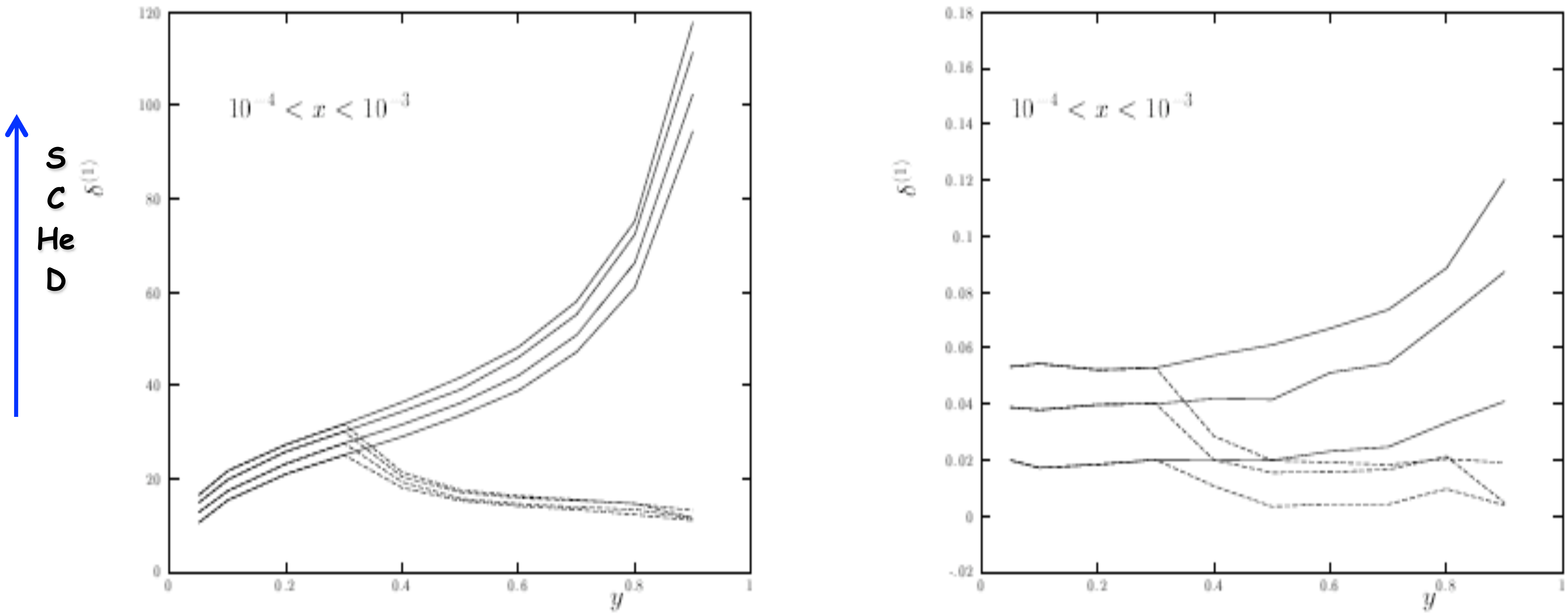


$$\delta_{RC}(A) = \frac{d\sigma^{A}/dy}{d\sigma^{A}_{B}/dy} - 1$$

$$\delta_{RC}(A) = \frac{1+\delta_{RC}(A)}{1+\delta_{RC}(D)} - 1$$

- Solid: inelastic radiative corrections
- Dashed: inelastic, quasi-elastic and elastic radiative corrections
  - ➡ Huge effect at large y!!

Radiative Corrections: Can we suppress things?



- Elastic/quasi-elastic part:
  - ➡ require some hadrons in the detector
- Inelastic part (solid line):
  - ➡ dashed line: after cuts $E_\gamma > 10$ GeV → $E-p_z$ from hadronic state is smaller

Radiative Corrections: Outlook in e+A

- Djangoh:
  - ➡ http://wwwthep.physik.uni-mainz.de/~hspiesb/djangoh/djangoh.html is compiled at BNL and running
  - ➡ e+A part is included but need to do more studies
  - ➡ HERACLES can be interfaced with other MC codes
- HERMES code (RADGEN + e+A version of LEPTO) installed at BNL but no nuclear effects are included
- Can compare results between eA-RADGEN and HERACLES
  - ➡ nPDFs are included!!