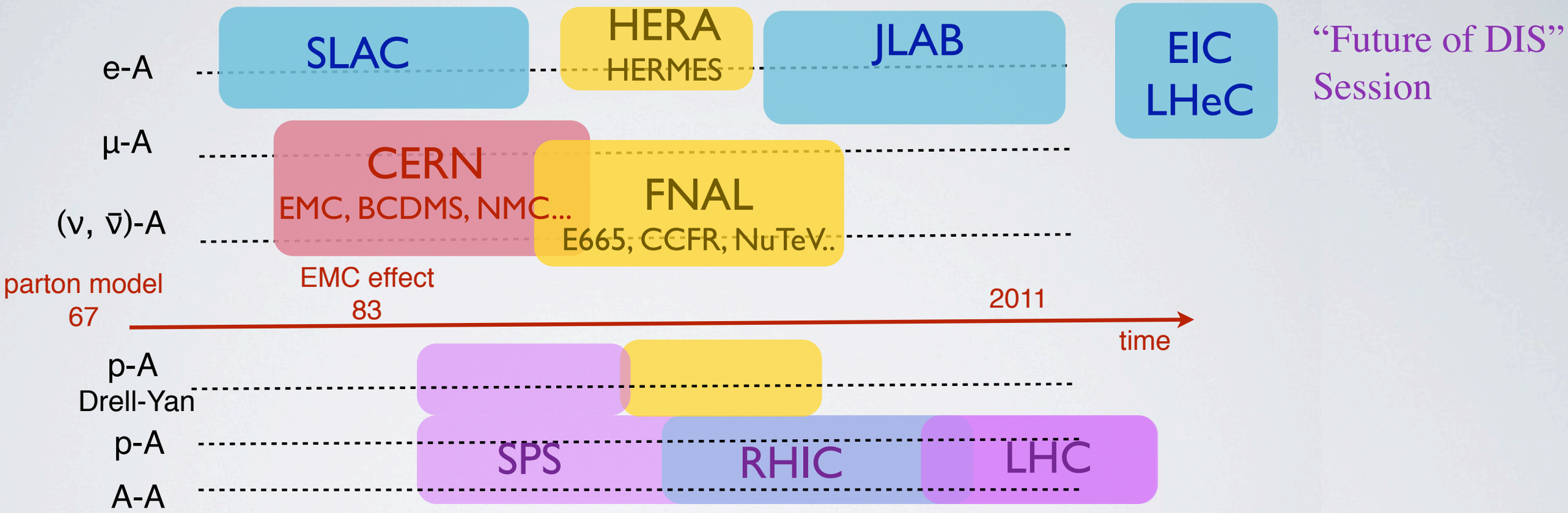
Quarks and Gluons in Nuclei

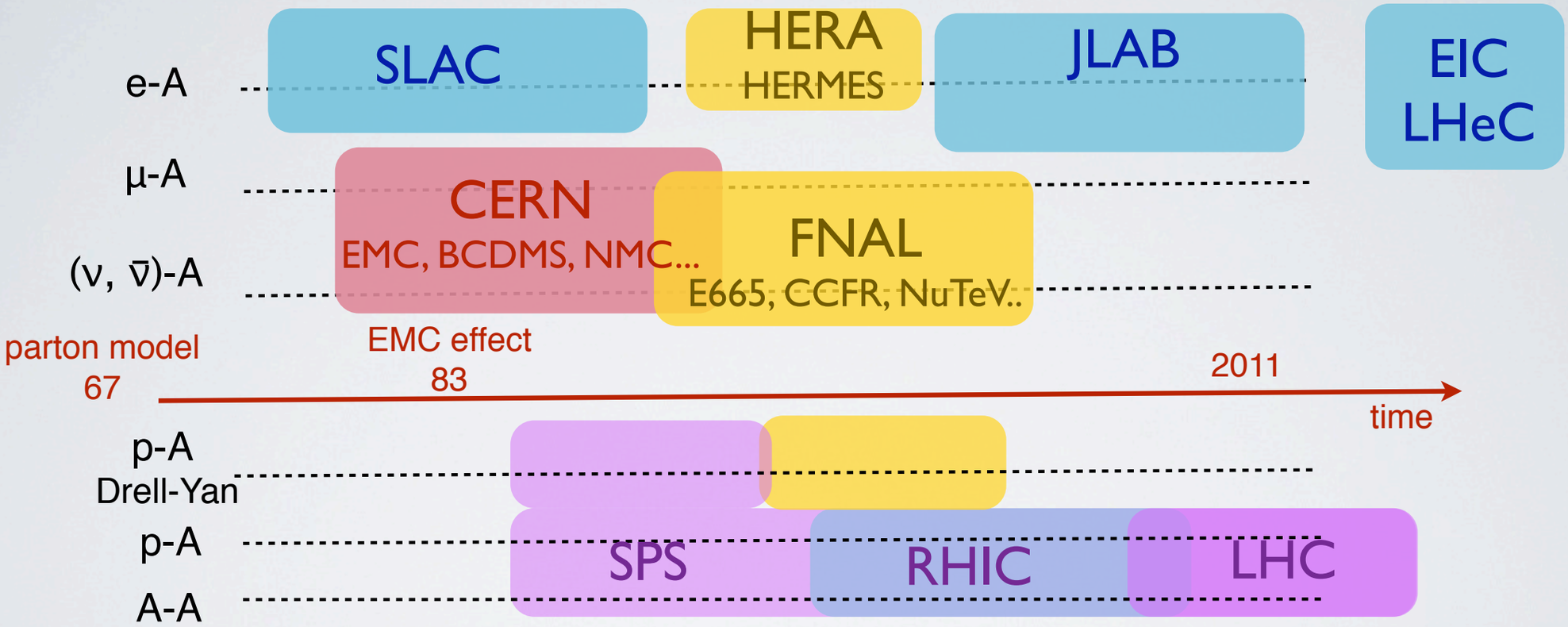
Javier L Albacete
IPhT CEA/Saclay

XIX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2011)
April 11-15, 2011
Newport News, VA USA

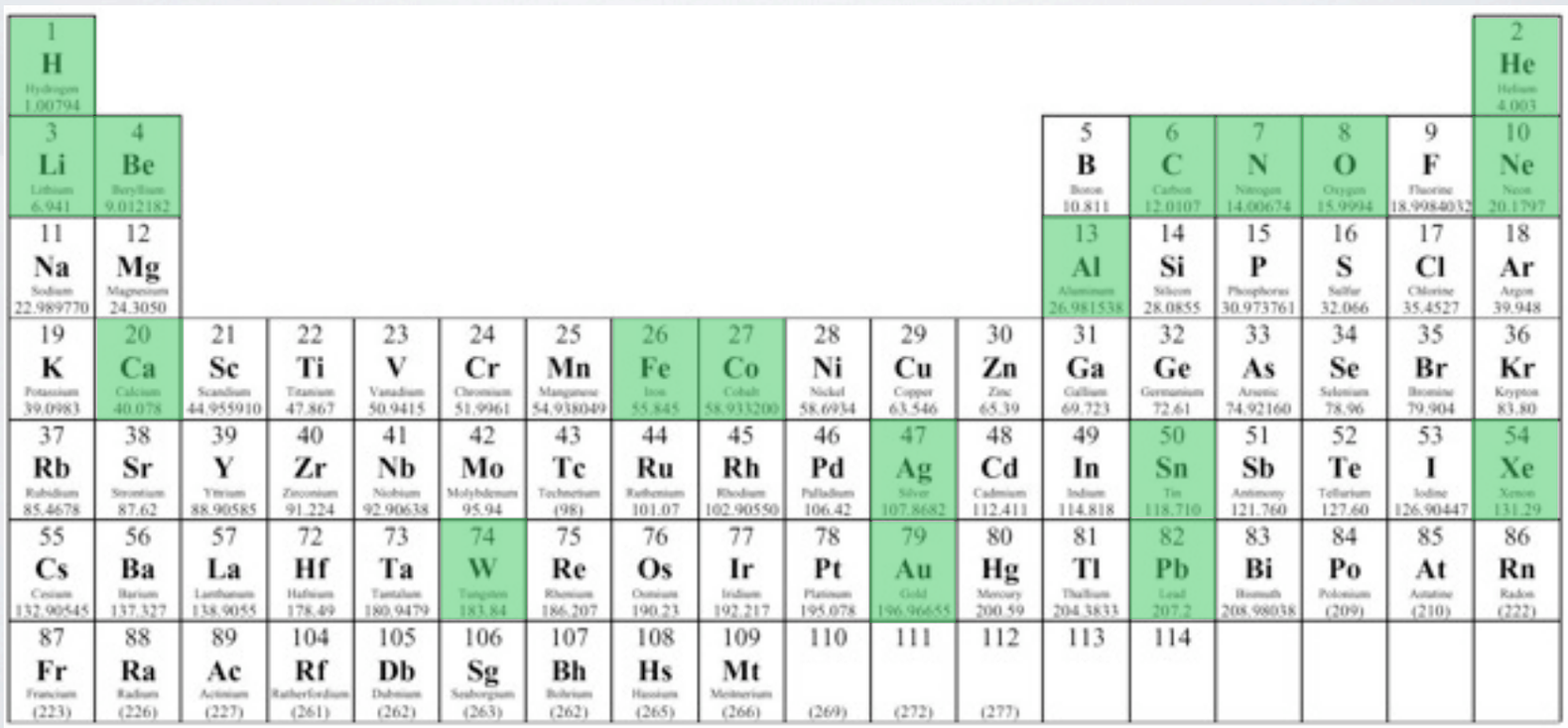
High energy nuclear experiments in the parton model era



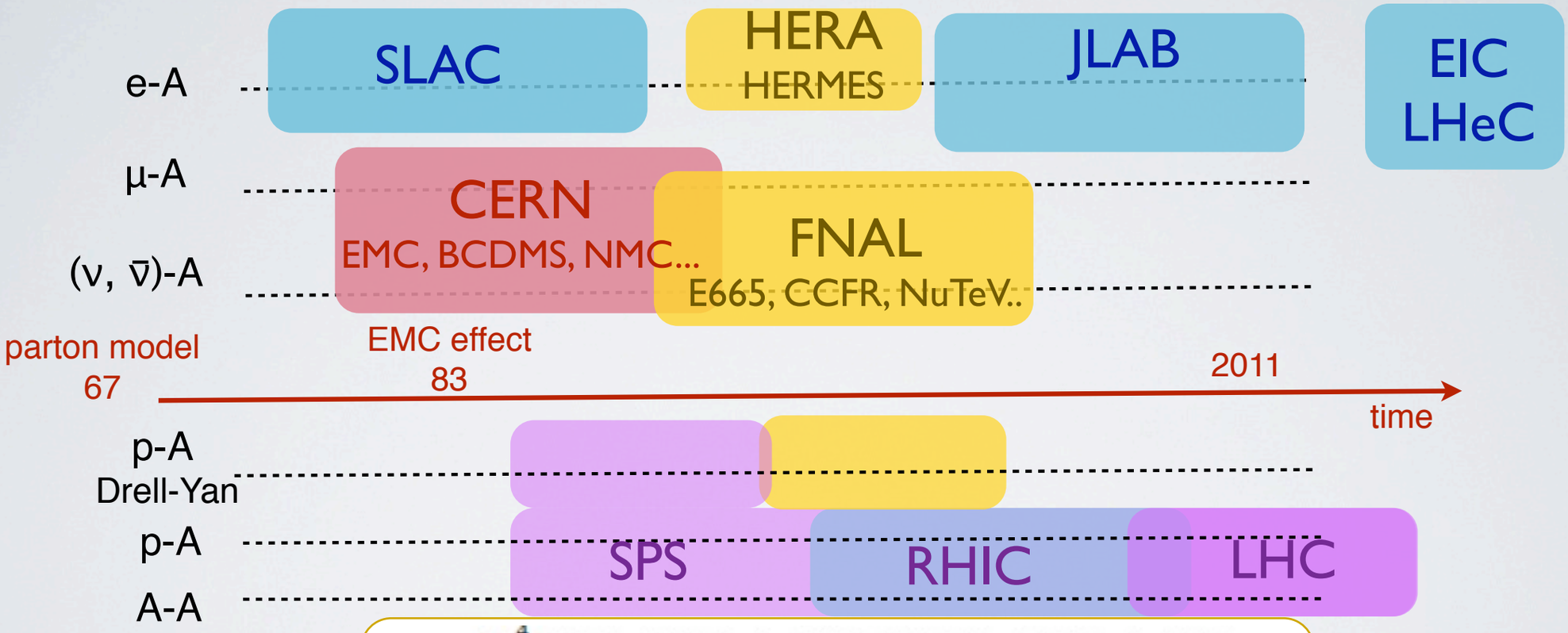
High energy nuclear experiments in the parton model era

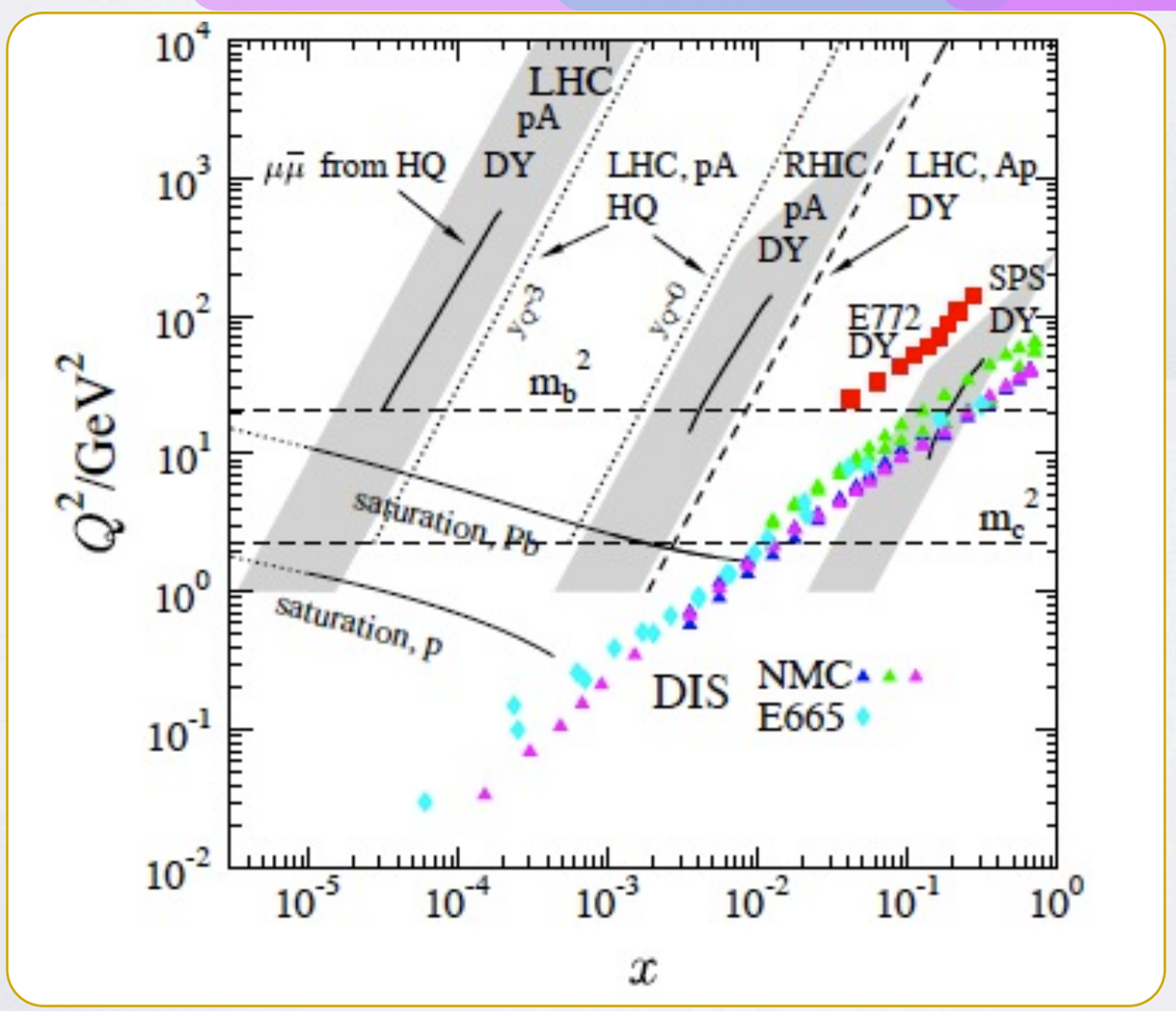


Many different nuclei tested over the years



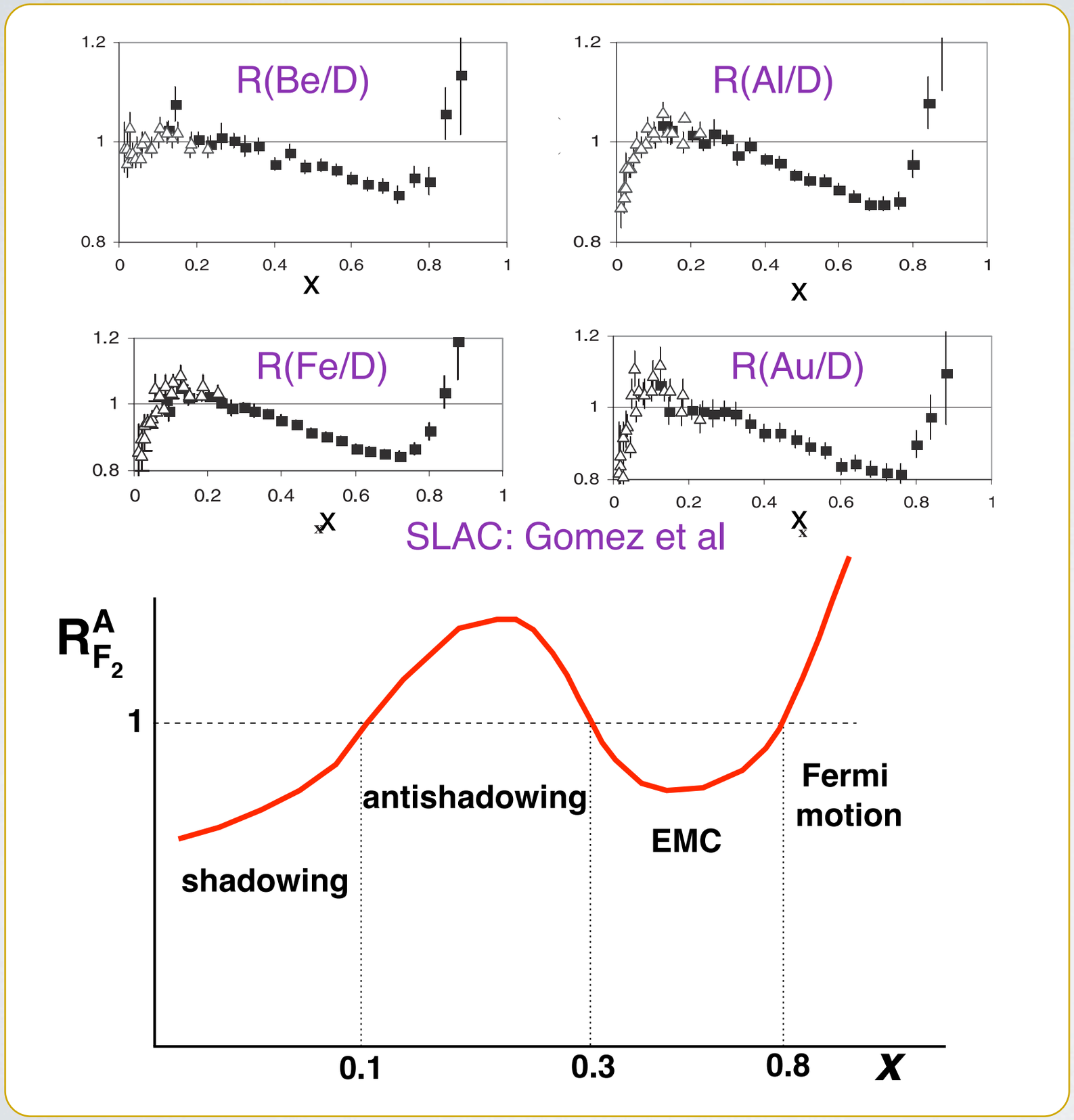
High energy nuclear experiments in the parton model era





Nuclei behave differently to a simple incoherent superposition of nucleons:

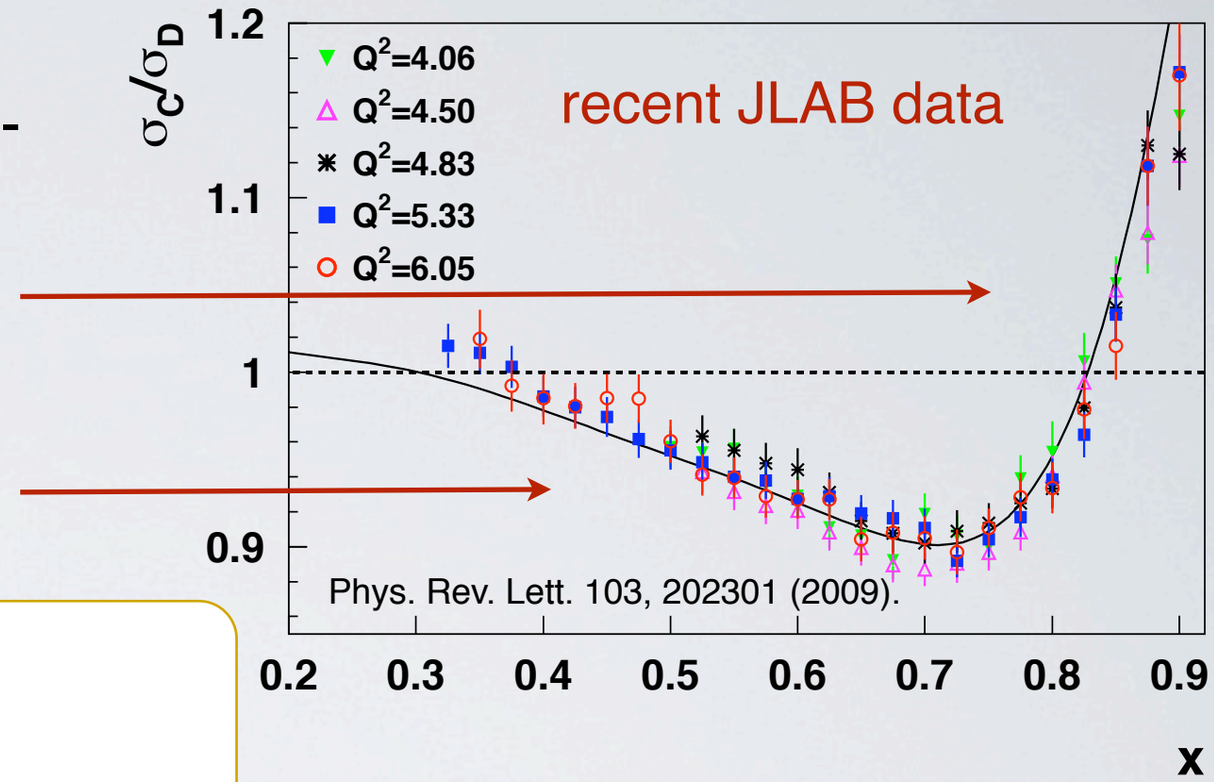
$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$



$x \gtrsim 0.3$: EMC effect and Fermi motion

Fermi motion (and other collective effects as short-range correlations) enhance scattering around (and beyond!) the kinematic limit in proton

EMC effect: "Valence quarks carry less momentum in a bound nucleon"



No universally accepted explanation yet...

* Nuclear structure effects:
  - Nuclear binding
  - Fermi motion and short range NN correlations

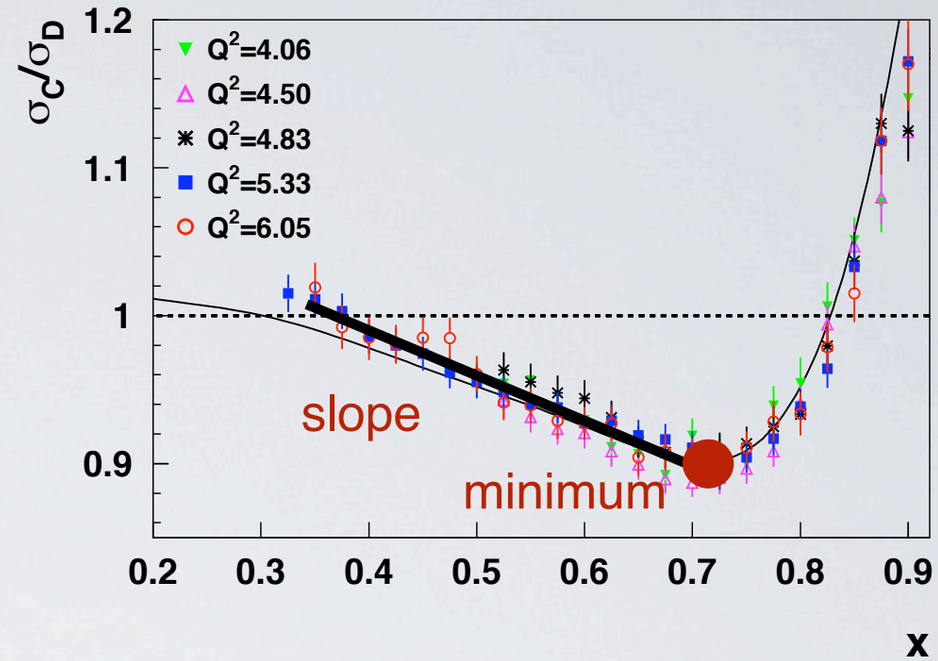
* Non-nucleonic d.o.f. in the nucleus wave function:
  - Mesons (pions...),
  - Coherent photon field ~ Z^2,
  - Multiquark (6q, 9q...) clusters

* Modification of the bound nucleon structure function
  - Change of QCD scale in nucleus (nucleon swelling)
  - Modified quark di-quark distributions inside nucleons
  - transparency
  - Quark-nucleon models: QSM, QCM....

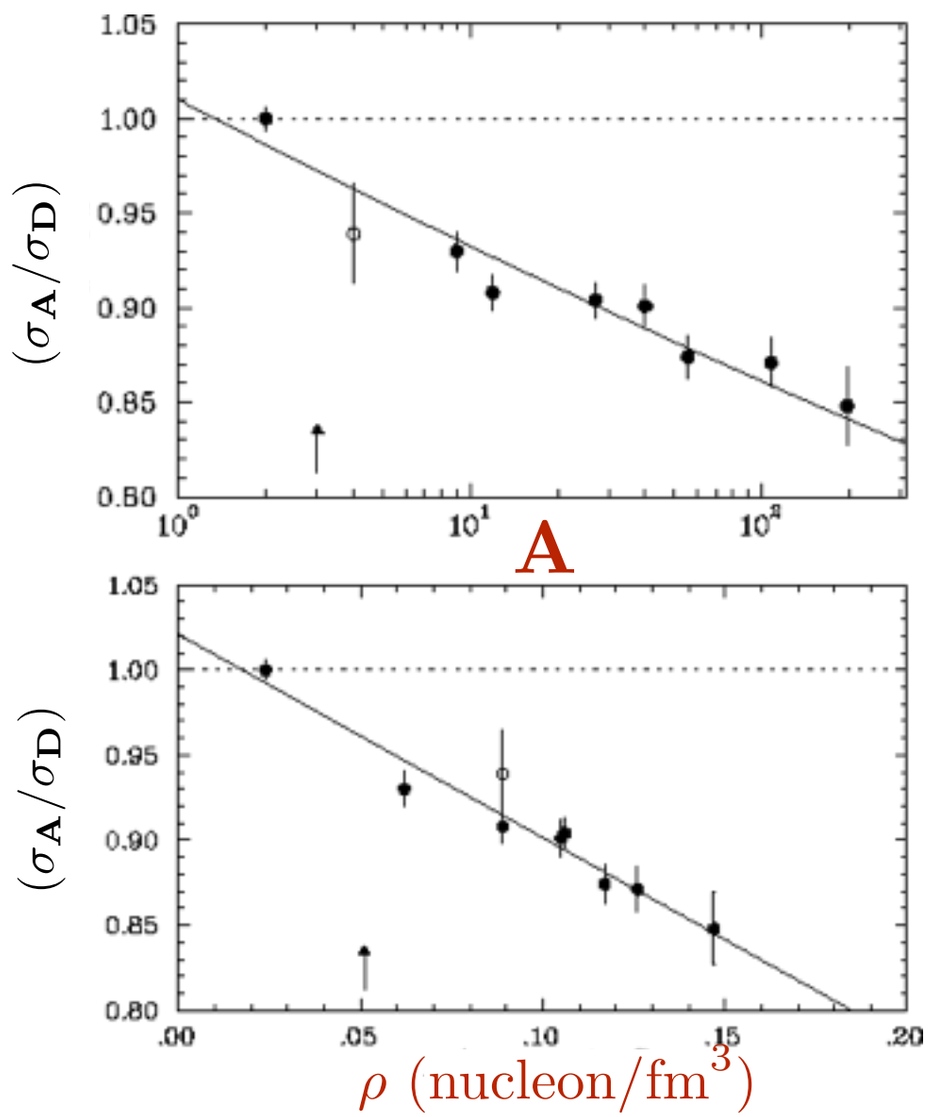
See talks by
Ian C. Cloet P.S III
Sergey Kulagin, Or Hen,
Ran Shneor P.S IX

EMC effect: (A, Q^2)-dependence

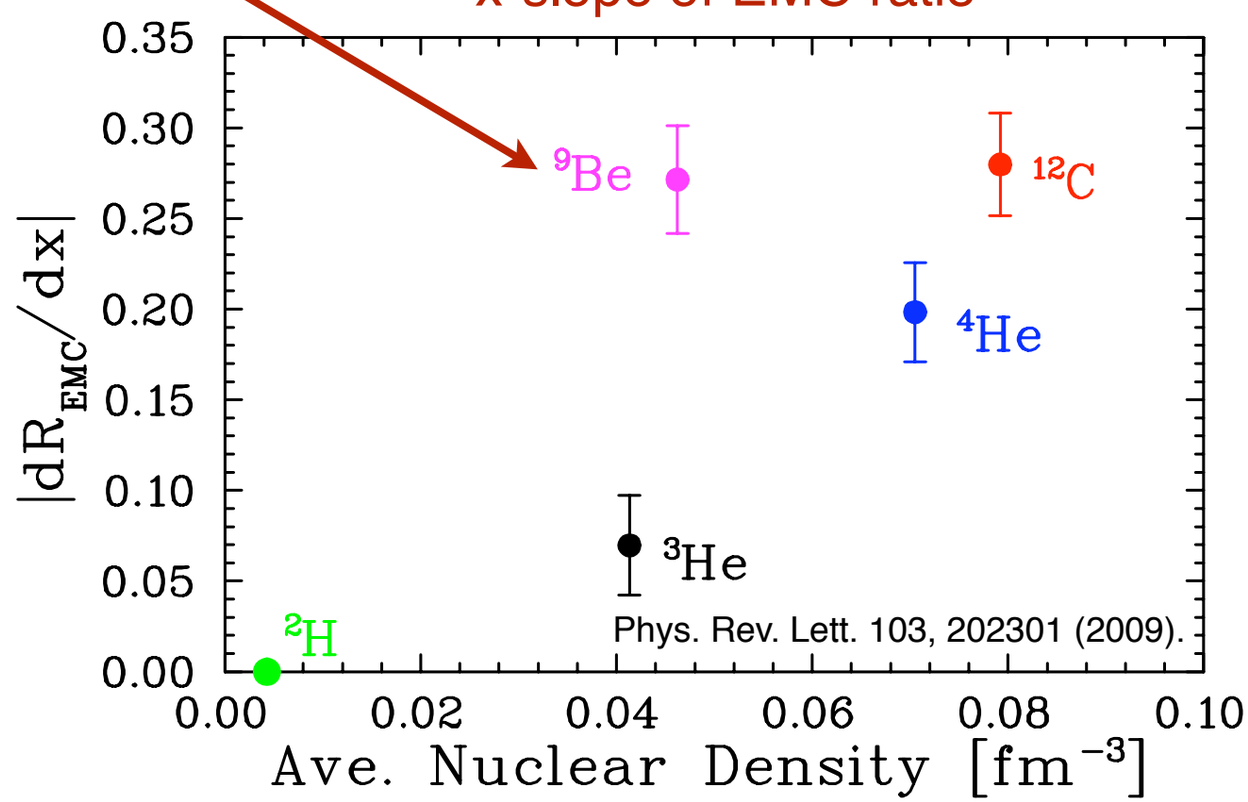
- Very mild Q^2-dependence
- Both ln(A) and linear ρ-dependence compatible with previous data
- However, recent JLAB data show strong dependence on local nuclear structure

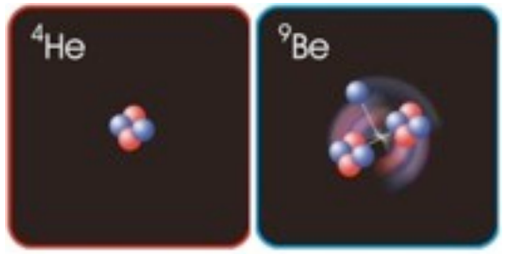


minimum of EMC ratio



x-slope of EMC ratio



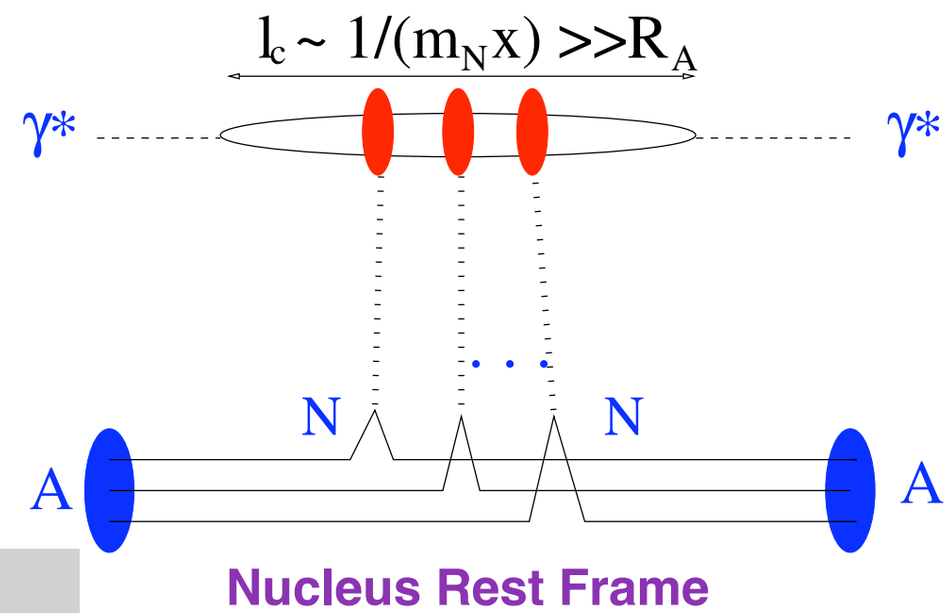


(Anti-)Shadowing

Shadowing is interpreted as due to coherent interaction with more than one nucleon:

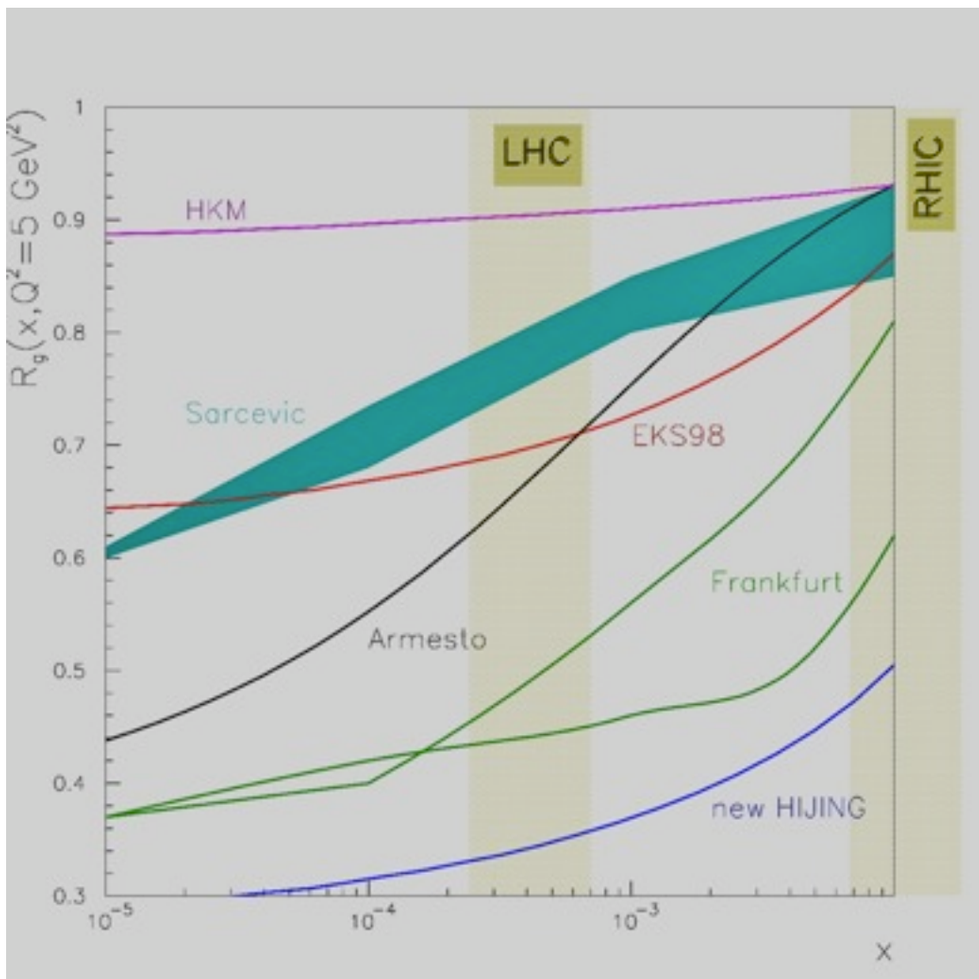
Different models vary in

* Resummation strategy: leading vs higher twists.
* Degree of coherence (eikonal vs finite coherence)
* Dynamic description of single scattering:
  meson / reggeon vs quarks/ gluons d.o.f
* Intermediate states:
  elastic (Glauber) vs inelastic (Gribov)



Below 10-2 different models diverge wildly!

Need of reliable extrapolation tools towards smaller x!



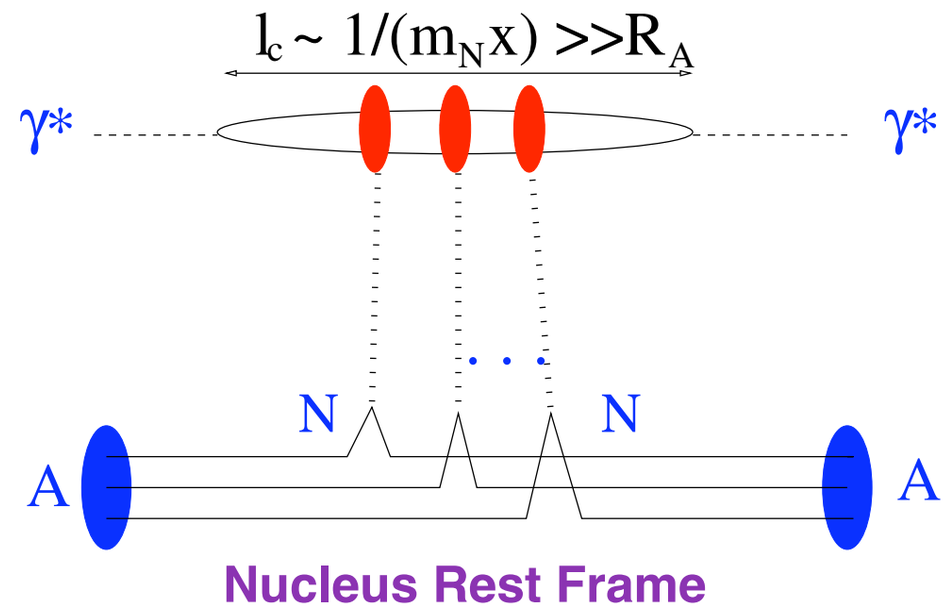
Antishadowing: Originates from baryon number / momentum sum rules

(Anti-)Shadowing

Shadowing is interpreted as due to coherent interaction with more than one nucleon:

Different models vary in

* Resummation strategy: leading vs higher twists.
* Degree of coherence (eikonal vs finite coherence)
* Dynamic description of single scattering:
  meson / reggeon vs quarks/ gluons d.o.f
* Intermediate states:
  elastic (Glauber) vs inelastic (Gribov)

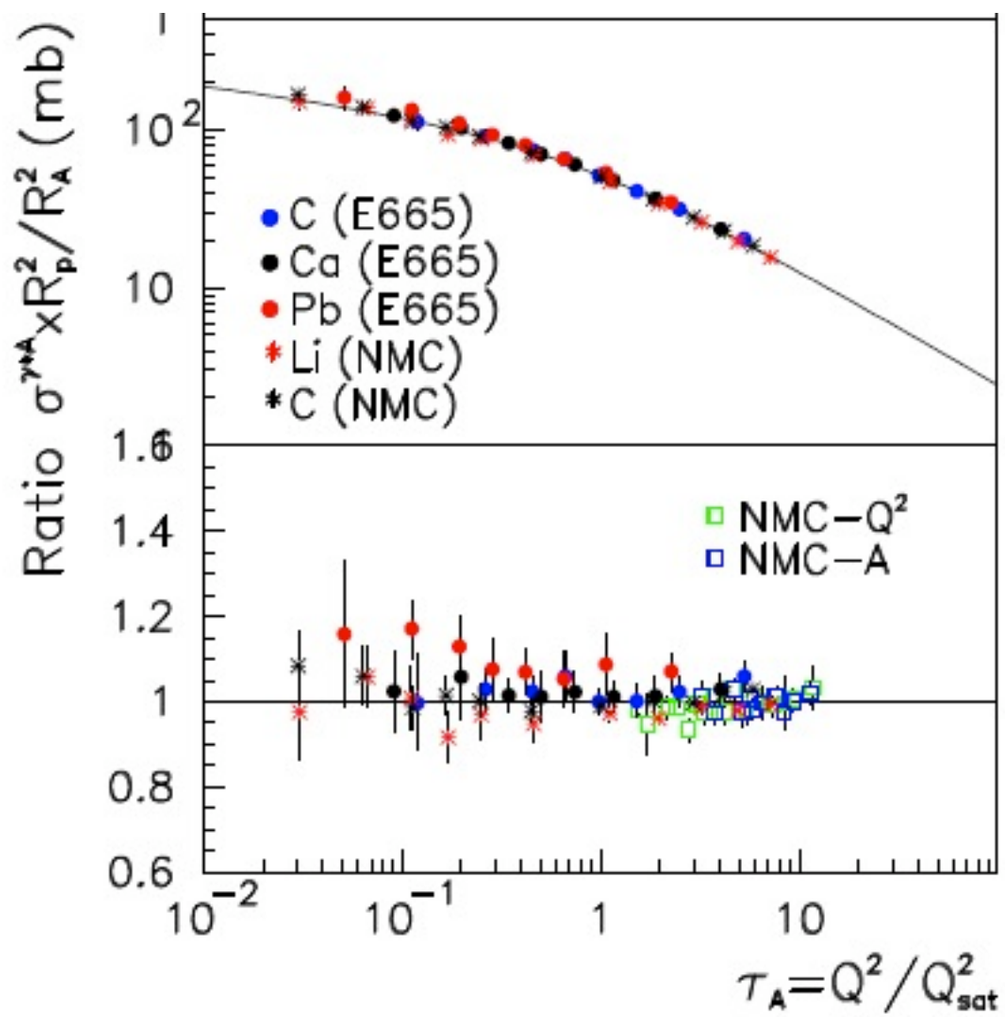


Geometric scaling of nuclear structure functions in the shadowing region

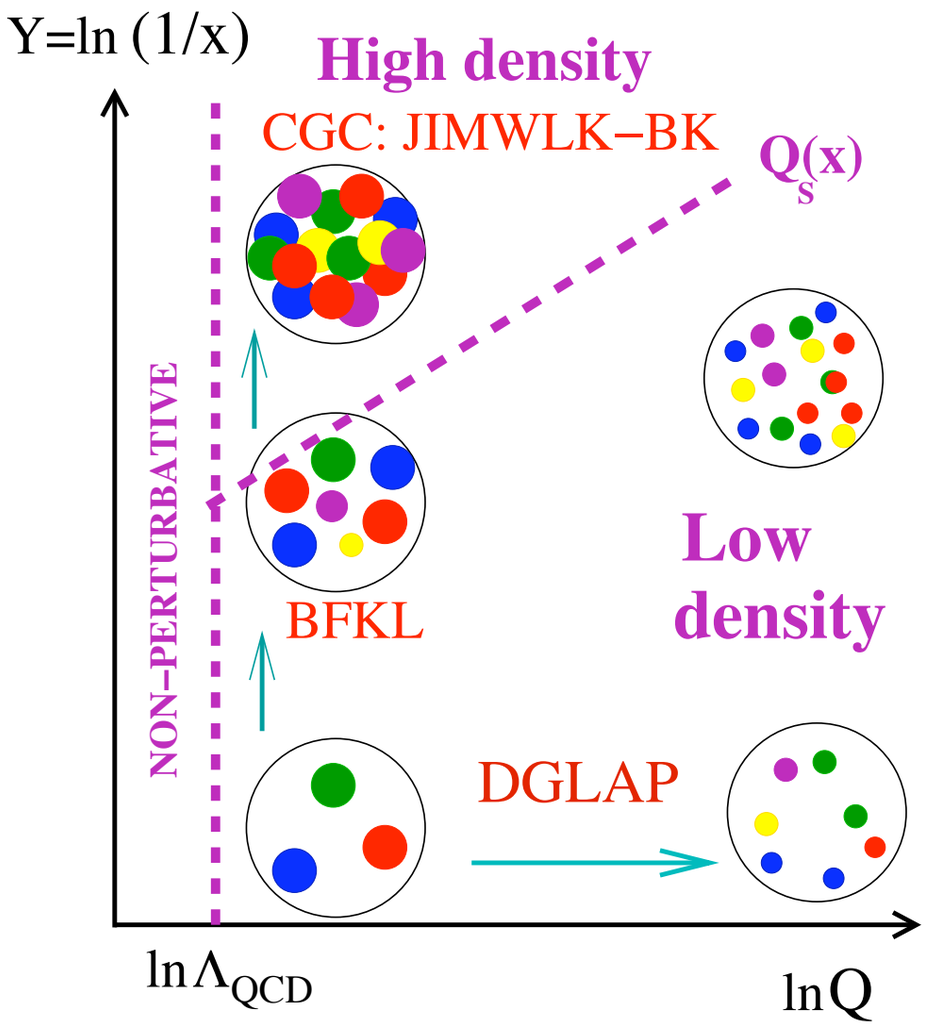
Armesto-Salgado-Wiedemann
Phys.Rev.Lett.94:022002,2005.

$$\sigma^{\gamma^* A}(x, Q^2) \to \sigma(\tau_A = Q^2/Q^2_{sA}(x))$$

$$Q^2_{sA}(x) \propto x^{-0.288} A^{\beta > 1/3}$$



Non-linear small-x evolution & Color Glass Condensate



"BK-JIMWLK"

$$\frac{\partial\phi(\mathbf{x},\mathbf{k_t})}{\partial\ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K}\otimes\phi(\mathbf{x},\mathbf{k_t}) - \phi(\mathbf{x},\mathbf{k_t})^2$$

radiation (BFKL) recombination

Non-linear *recombination* corrections in the high-density regime are demanded by UNITARITY

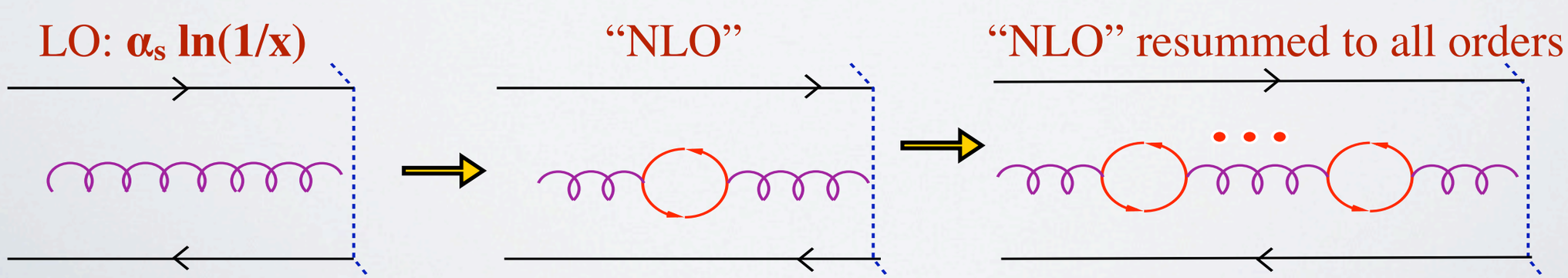
Nuclear enhancement: $Q^2_{sA} \approx A^{1/3} Q^2_{sp}$

Factorization only possible in certain cases

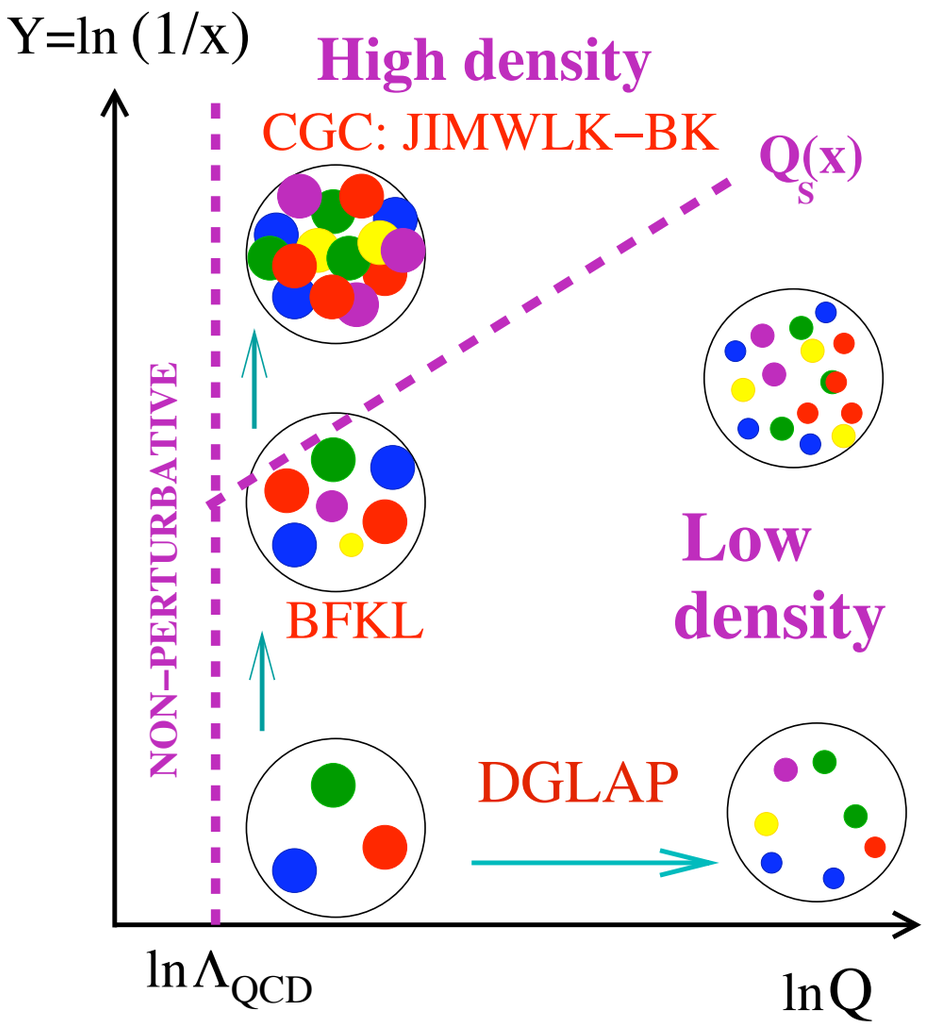
talk by F. Dominguez

Recent calculation of running coupling and full NLO corrections to the JIMWLK kernel

Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al.



Non-linear small-x evolution & Color Glass Condensate



"BK-JIMWLK"

$$\frac{\partial \phi(\mathbf{x},\mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x},\mathbf{k_t}) - \phi(\mathbf{x},\mathbf{k_t})^2$$

radiation (BFKL) recombination

Non-linear *recombination* corrections in the high-density regime are demanded by UNITARITY

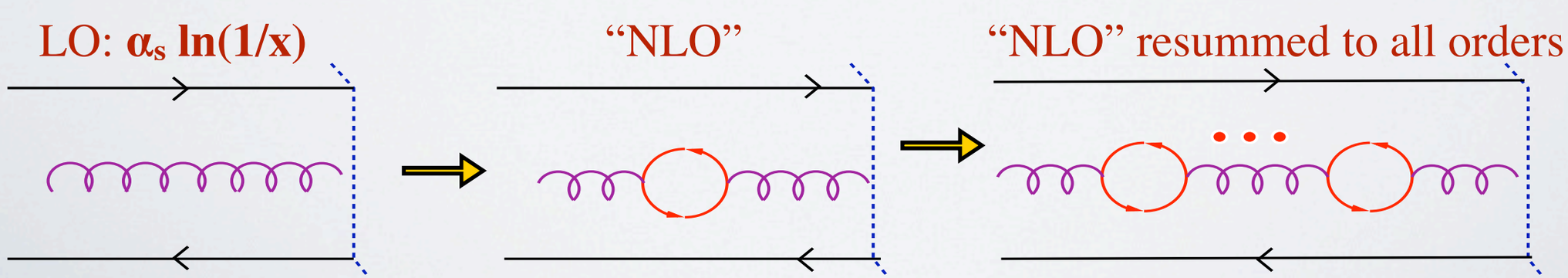
Nuclear enhancement: $Q^2_{sA} \approx A^{1/3} Q^2_{sp}$

Factorization only possible in certain cases

talk by F. Dominguez

Recent calculation of running coupling and full NLO corrections to the JIMWLK kernel

Balitsky-Chirilli; Kovchegov-Weigert, Gardi et al.



DGLAP dynamics: Global nuclear pdf (nPDF's) fits $0 < x < 1$

* Main assumptions:

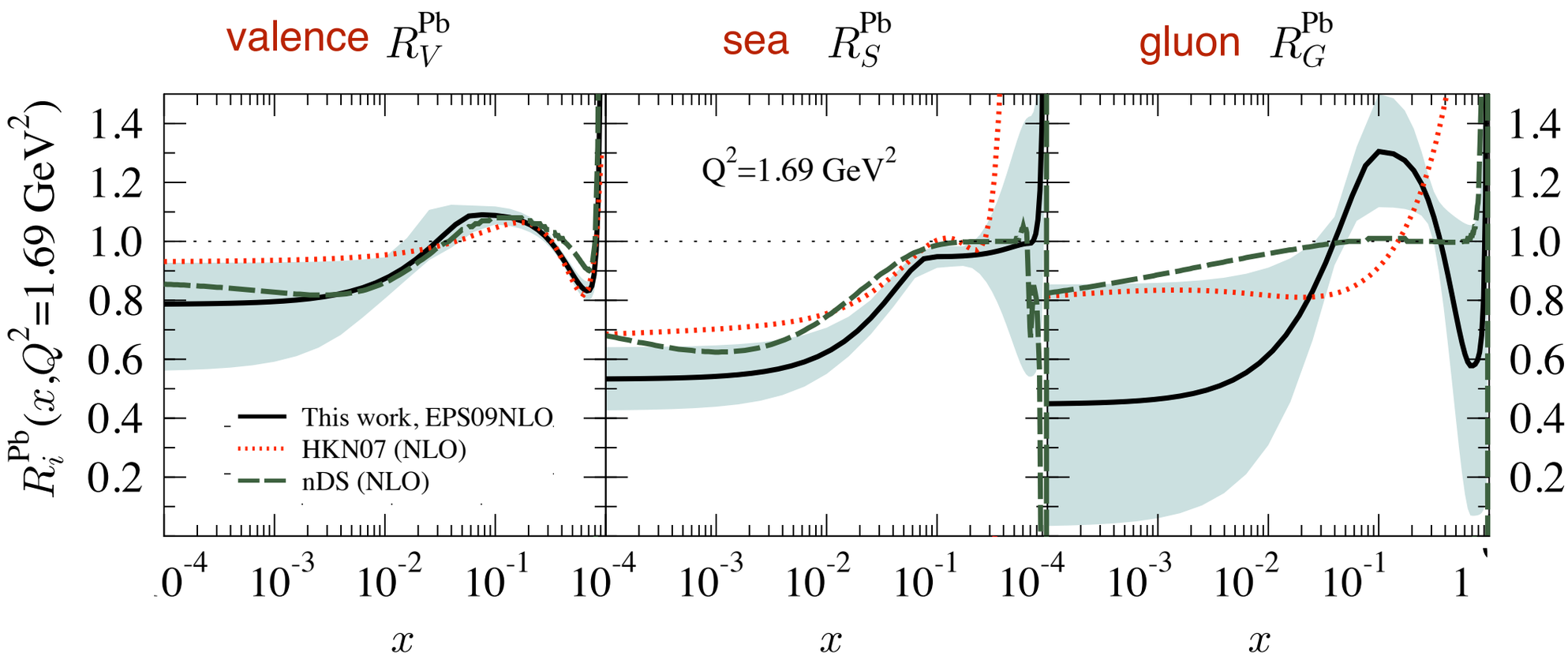
Collinear factorization holds in nuclear processes

ALL the nuclear effects are encoded in nuclear modification factors $R_A(x,Q^2)$

$$f_{i/A}(x,Q^2) = f_{i/N}(x,Q^2)\, R_{i/A}(x,Q^2)$$

Q^2-evolution calculated according to DGLAP. Some proton pdf set used as a baseline

x-dependence of nPDF's is parametrized at some initial scale Q^2~2-4 GeV^2



DGLAP dynamics: Global nuclear pdf (nPDF's) fits $0 < x < 1$

* Main assumptions:

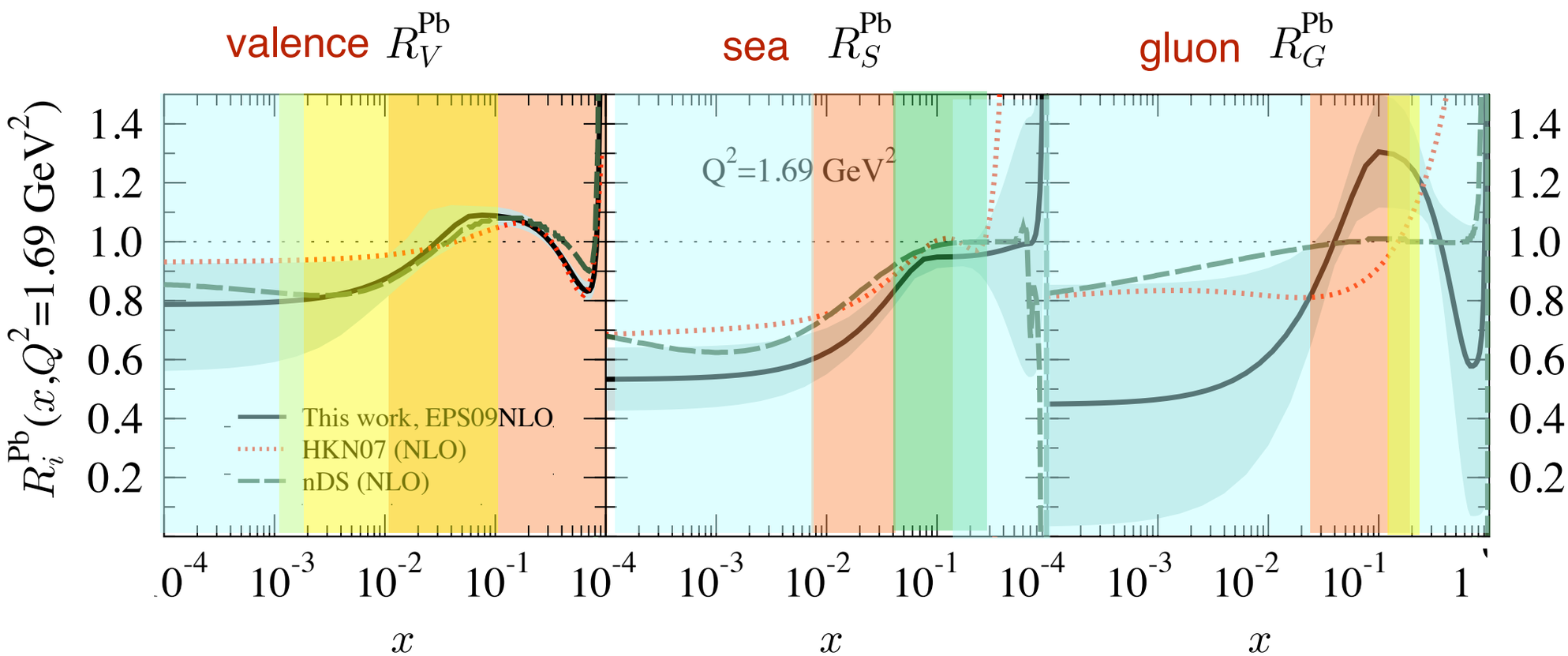
Collinear factorization holds in nuclear processes

ALL the nuclear effects are encoded in nuclear modification factors $R_A(x,Q^2)$

$$f_{i/A}(x,Q^2) = f_{i/N}(x,Q^2)\, R_{i/A}(x,Q^2)$$

Q^2-evolution calculated according to DGLAP. Some proton pdf set used as a baseline

x-dependence of nPDF's is parametrized at some initial scale Q^2~2-4 GeV^2



Constrained by DIS

Constrained by DY

Constrained by sum rules

Assumptions i.c.

DGLAP dynamics: Global nuclear pdf (nPDF's) fits $0 < x < 1$

* Main assumptions:

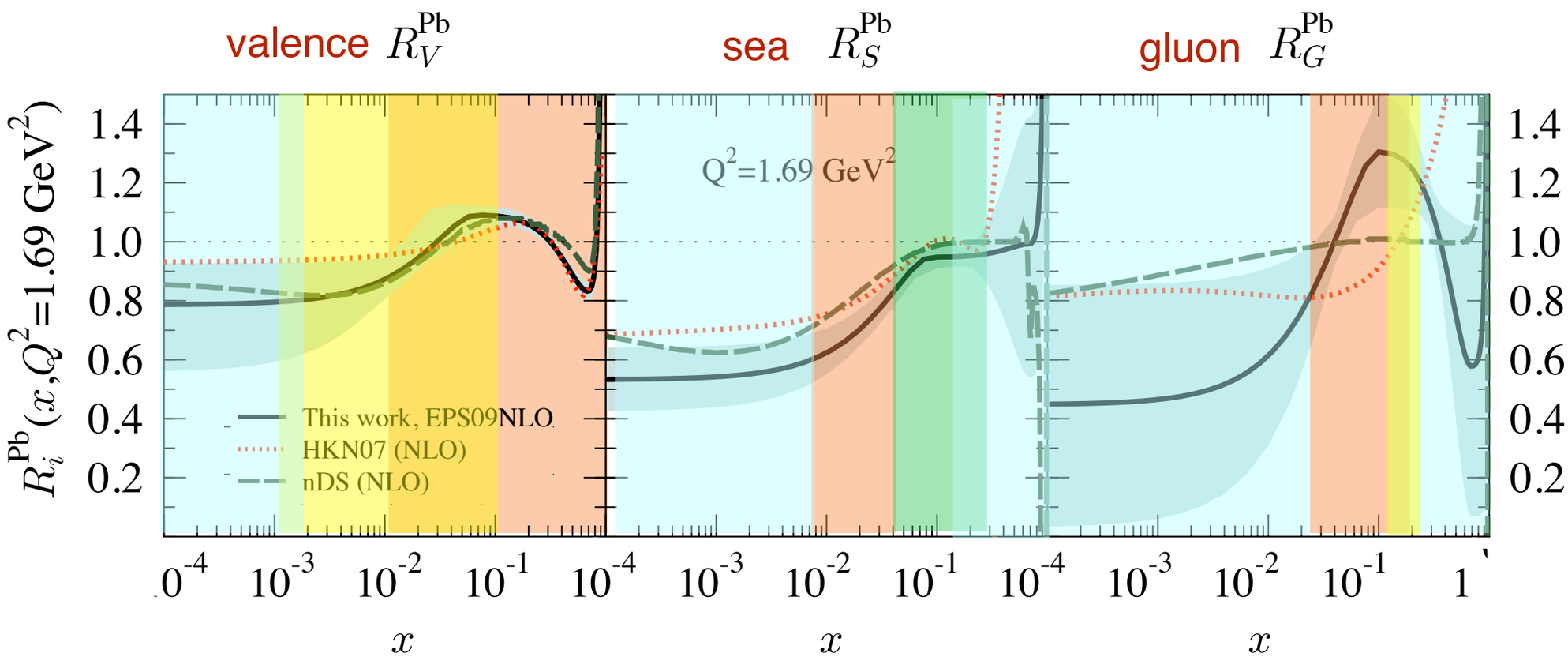
Collinear factorization holds in nuclear processes

ALL the nuclear effects are encoded in nuclear modification factors $R_A(x,Q^2)$

$$f_{i/A}(x,Q^2) = f_{i/N}(x,Q^2)\, R_{i/A}(x,Q^2)$$

Q^2-evolution calculated according to DGLAP. Some proton pdf set used as a baseline

x-dependence of nPDF's is parametrized at some initial scale Q^2~2-4 GeV^2



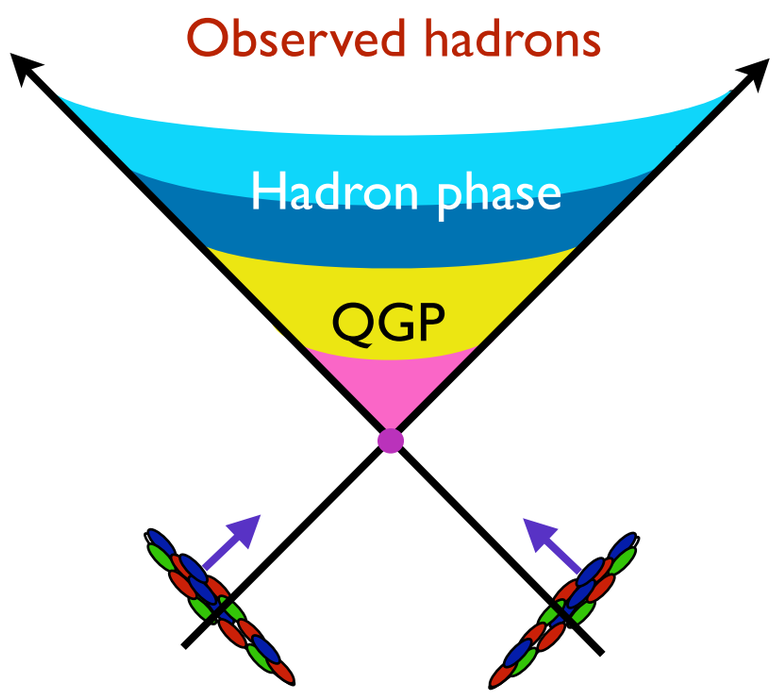
So far, the factorization assumption seems to work, with maybe two exceptions

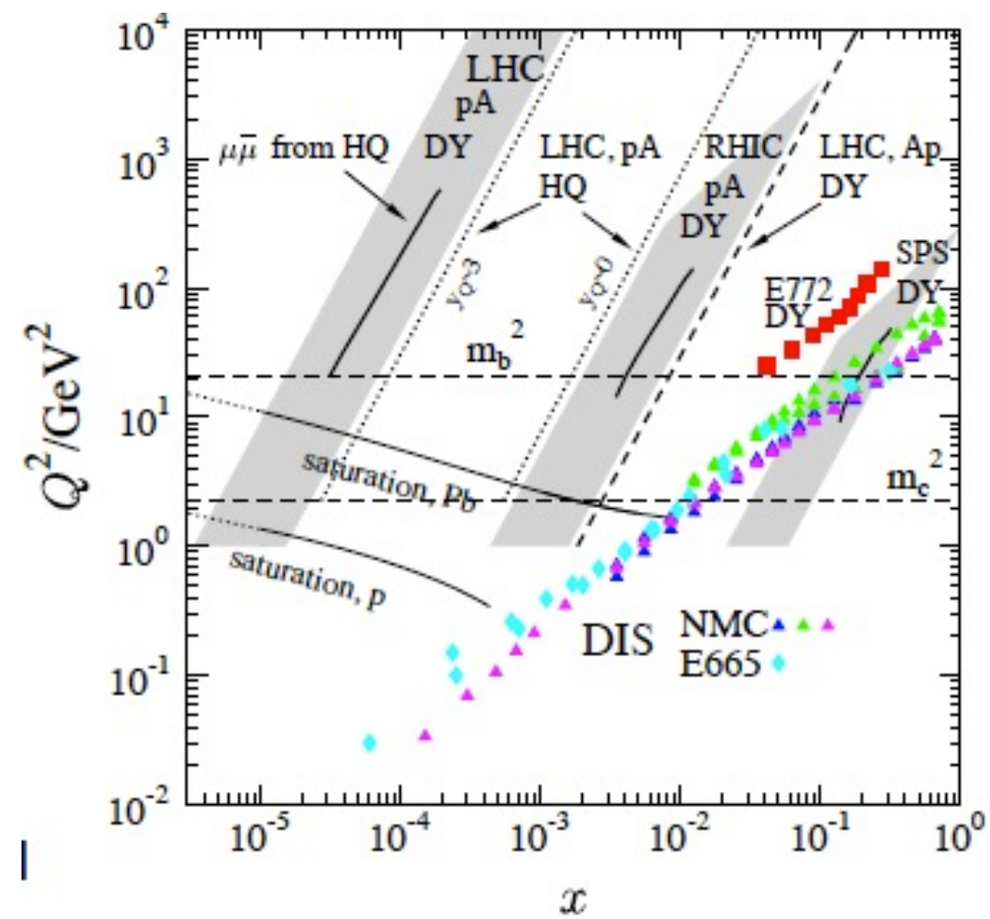
- Forward RHIC data (next)
- neutrino-A data (talk by Karol Kovarik)

Hadron colliders: p(d)+A and A+A

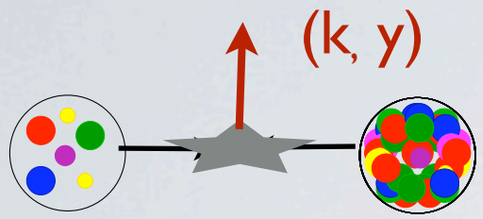
They provide access to a much larger kinematic region than available DIS nuclear data

p-A collisions (or “Cold Nuclear Matter” effects) provide a crucial baseline for the characterization of the “Quark Gluon Plasma” formed in A+A collisions





RHIC d+Au data at mid-rapidity: Moderate to high-x

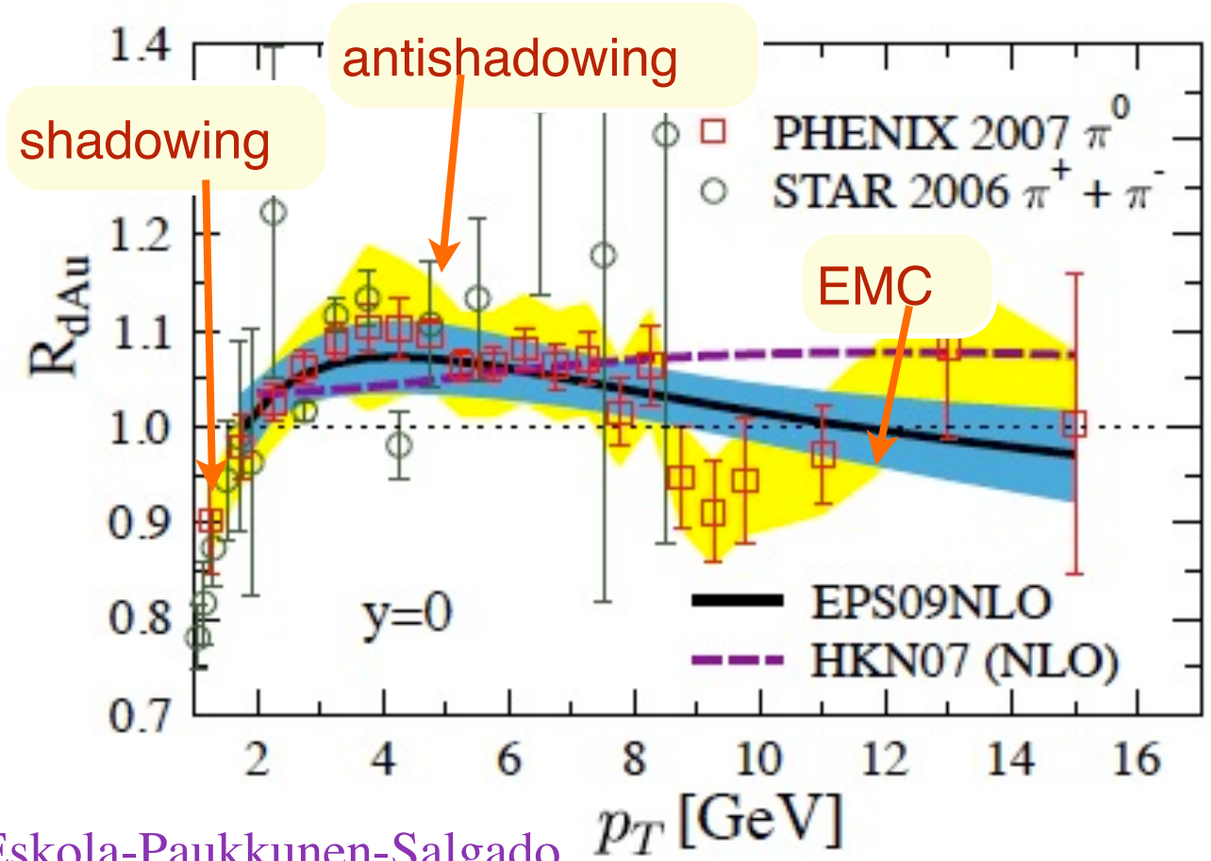


$$x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$$

Mid-rapidity data can be well described in terms of nPDF's + collinear factorization

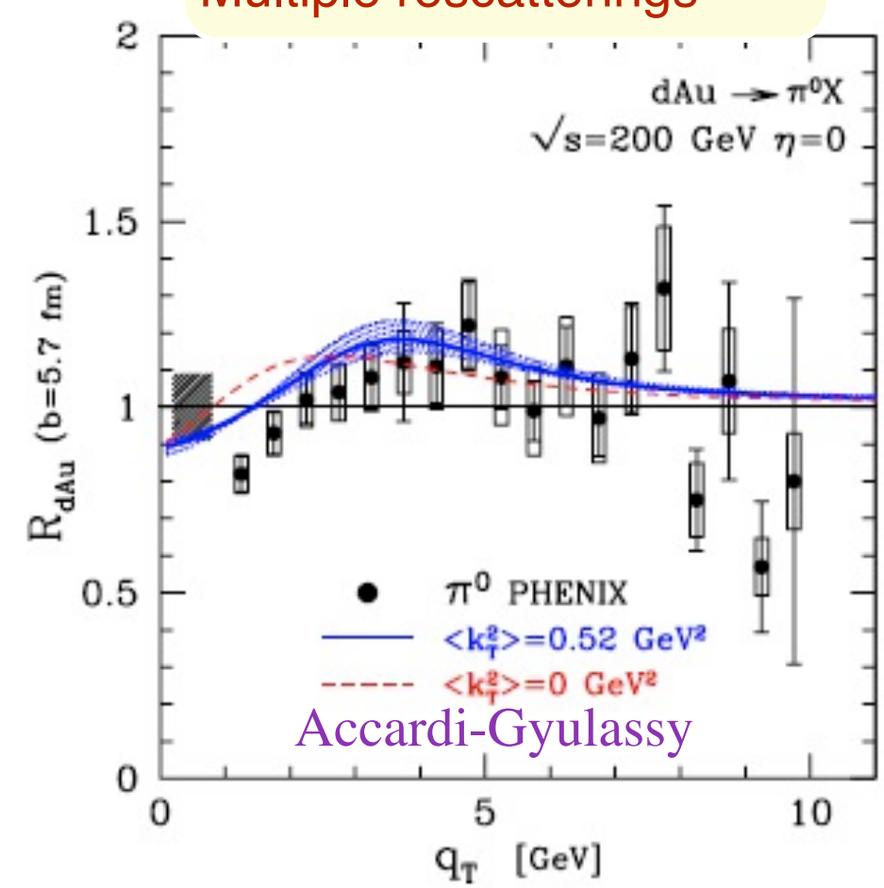
Other approaches based on resummation of multiple scatterings also work well

$$R_{dAu} = \frac{1}{N_{coll}} \frac{\text{Yield in dAu}}{\text{Yield in pp}}$$



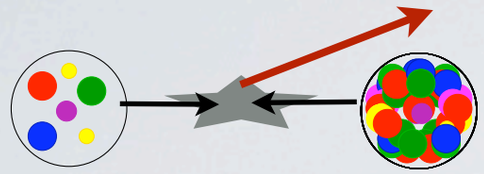
Eskola-Paukkunen-Salgado

Multiple rescatterings

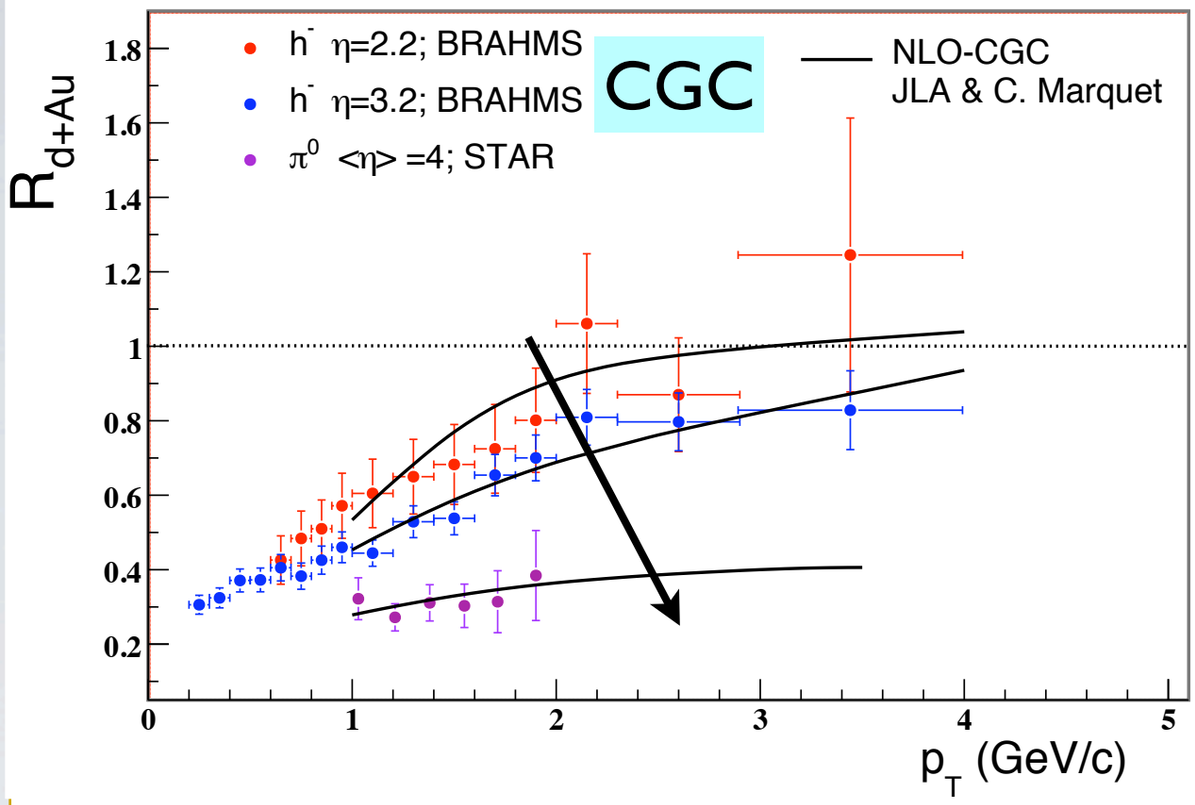


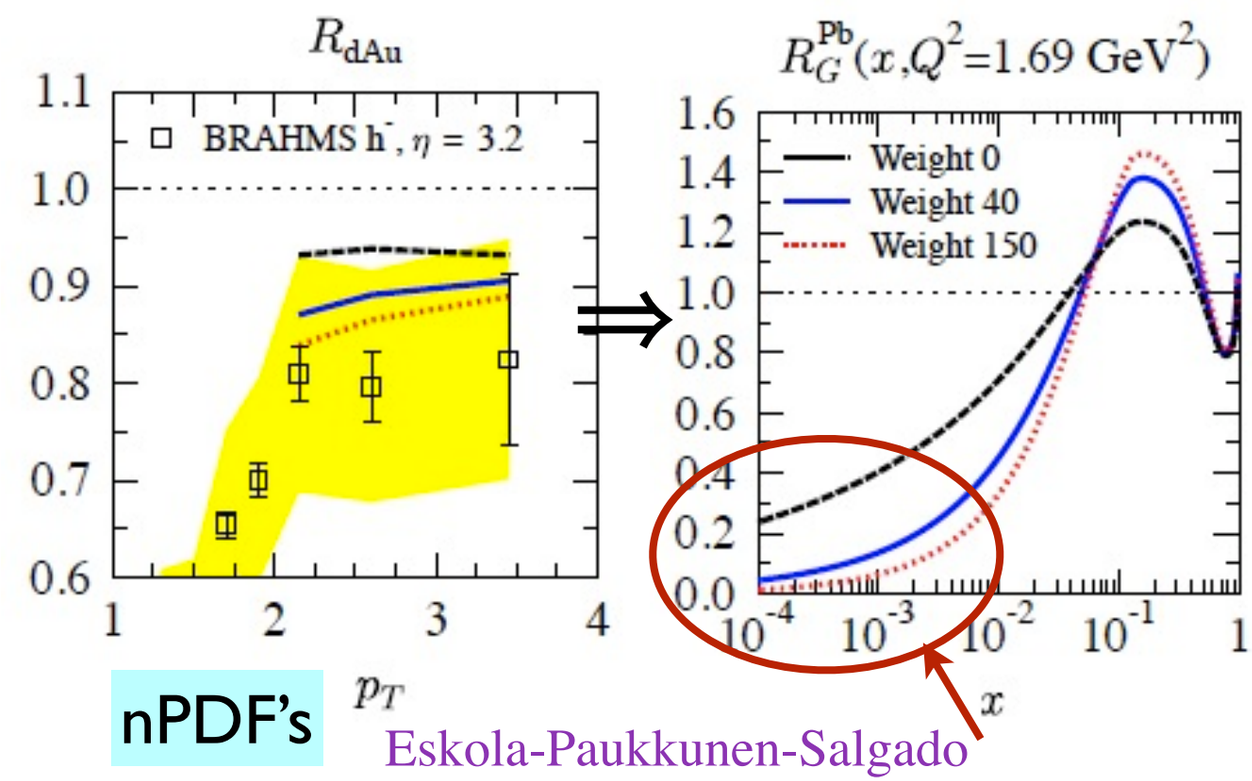
Accardi-Gyulassy

RHIC d+Au data at forward rapidity



$$x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$$

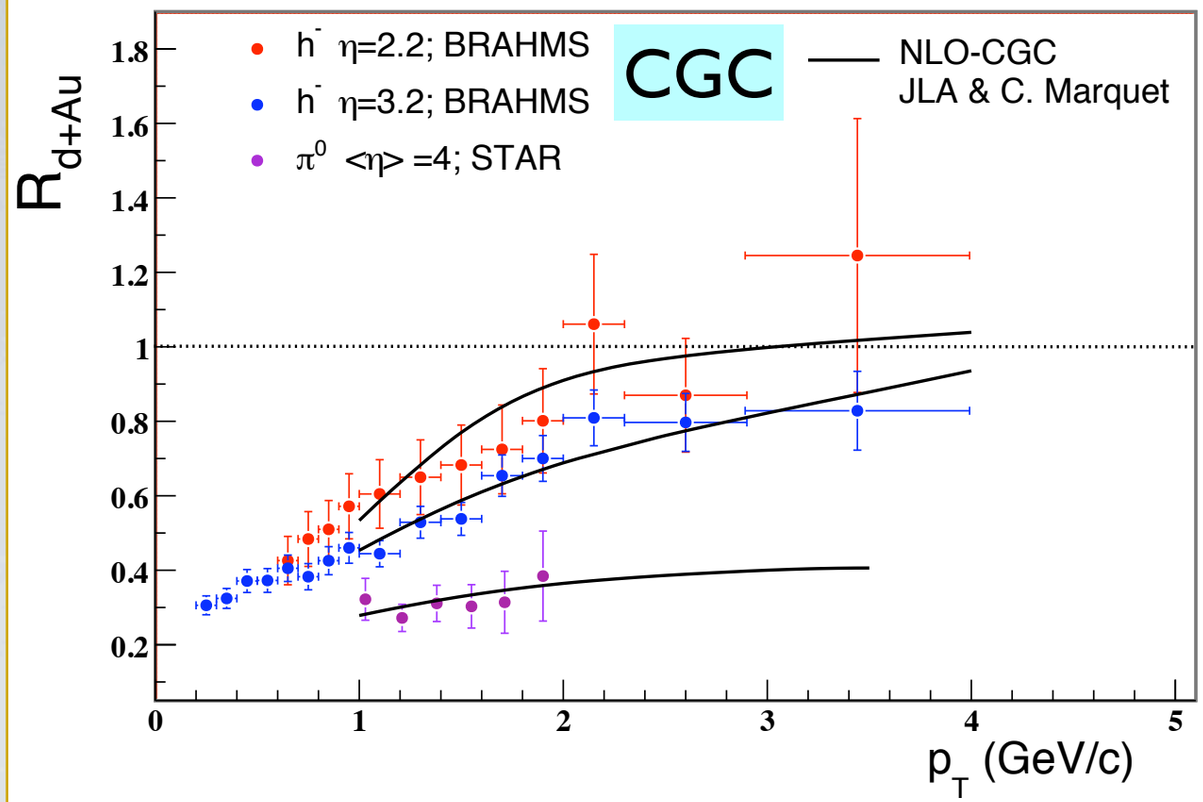


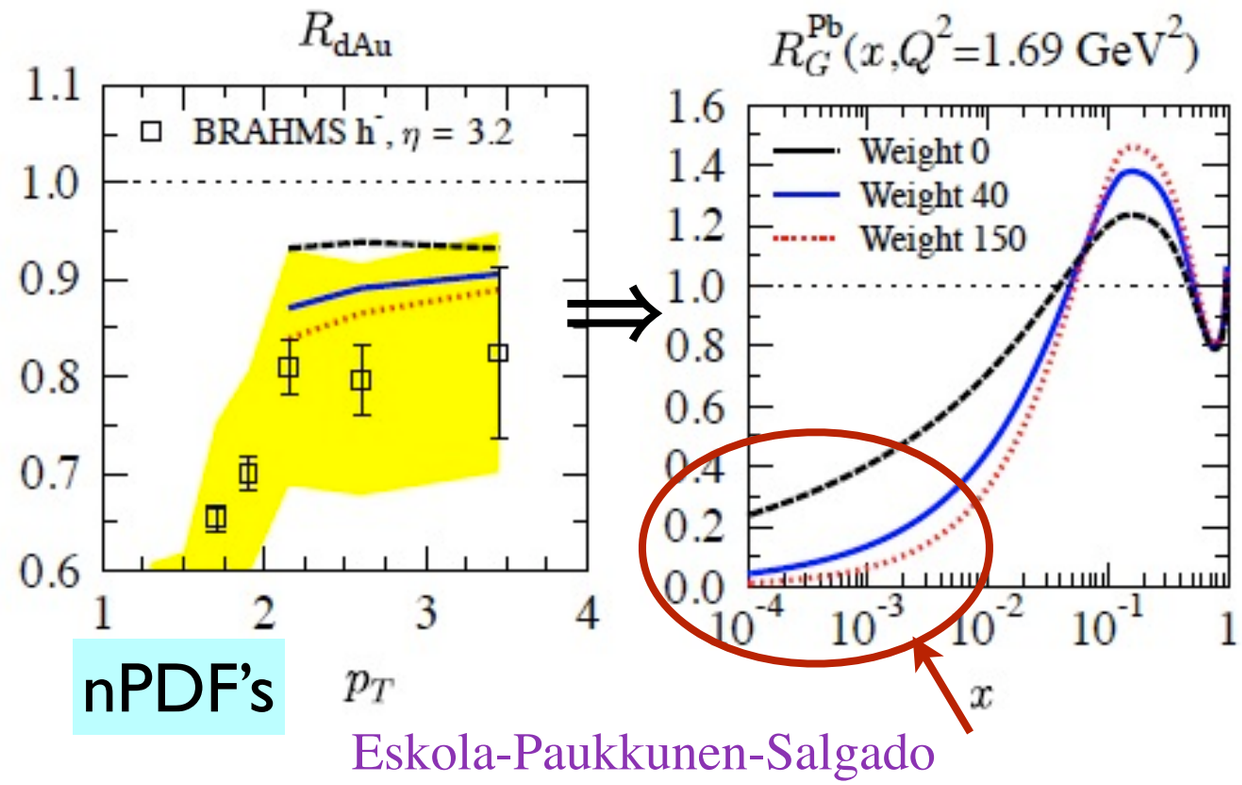


- Forward suppression predicted and well described in the CGC framework in terms of non-linear running coupling BK evolution

- nPDF's description of forward suppression involves a huge nuclear shadowing at small-x

RHIC d+Au data at forward rapidity





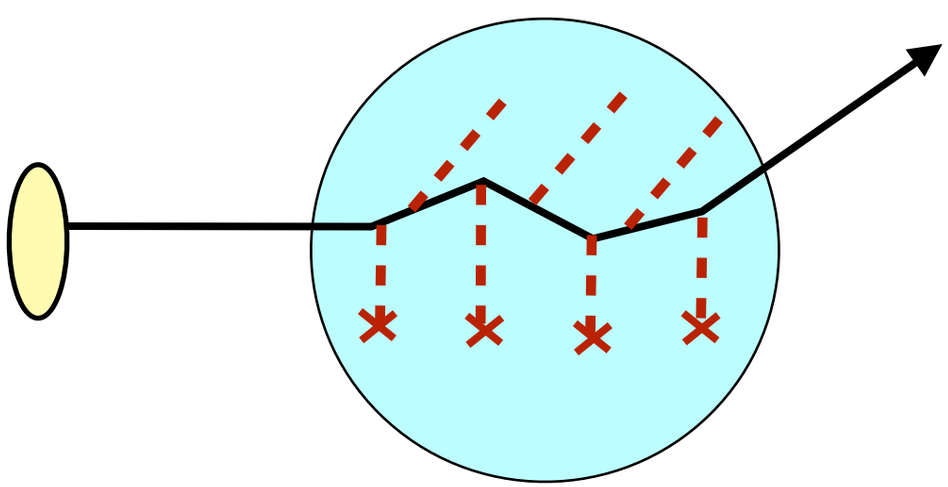
Eskola-Paukkunen-Salgado

Forward suppression well described in terms of non-linear rcBK evolution (CGC)

• nPDF's description of forward suppression involves a huge nuclear shadowing at small-x

Alternatively: Energy-loss (large-x effect). Target dependence -> breakdown of factorization

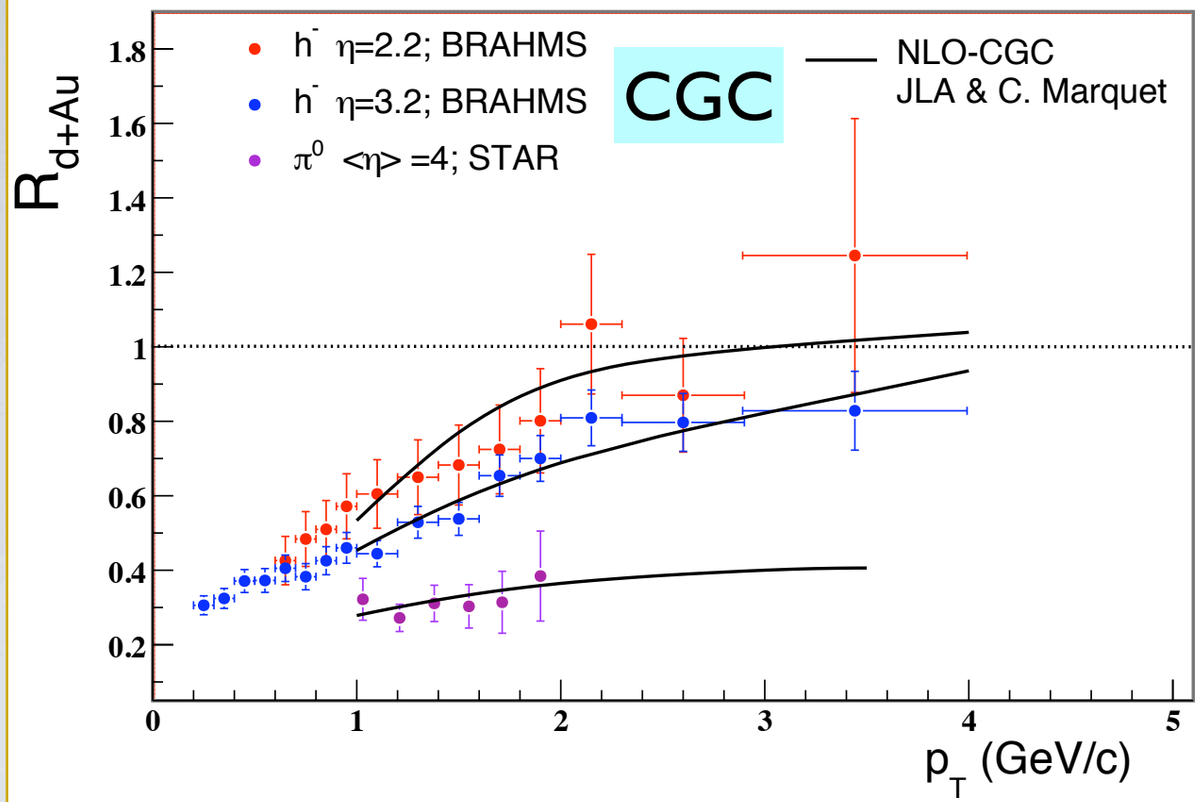
Frankfurt & Strickman, Kopeliovich et al

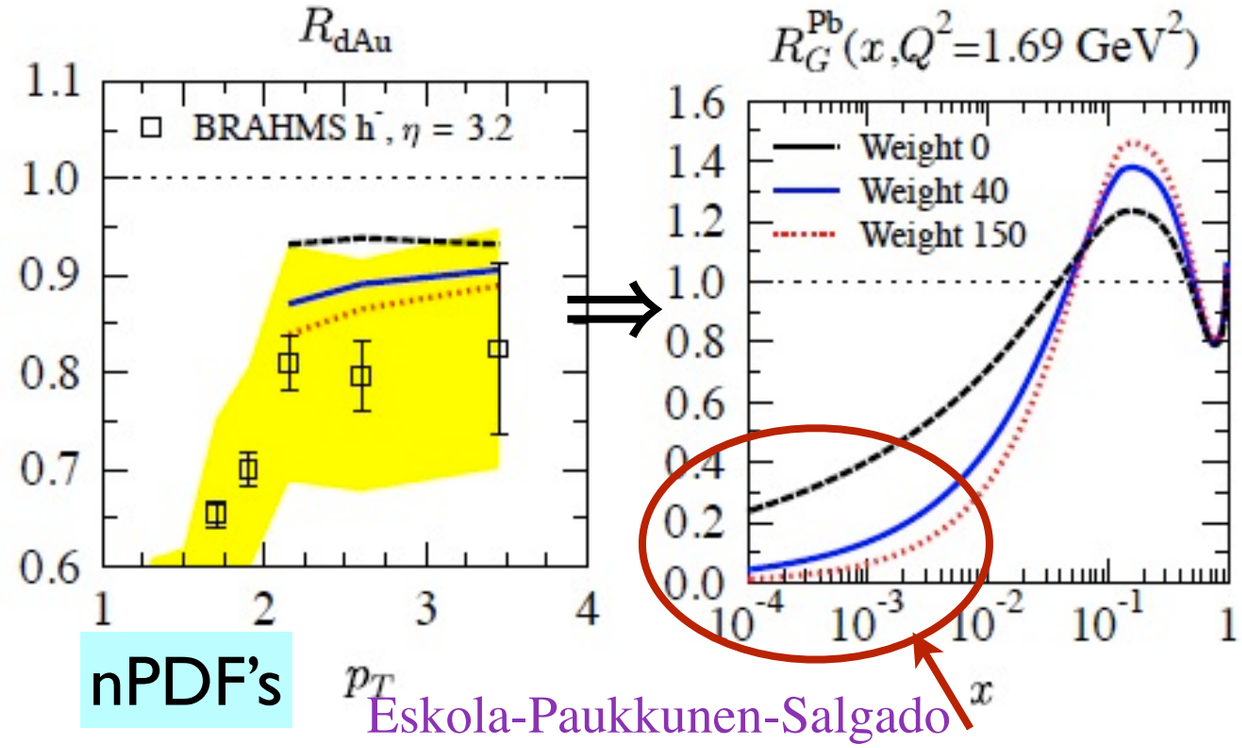


Probability of not losing energy:

$$P(\Delta y) \approx e^{-n_G(\Delta y)} \approx (1 - x_F)^{\#}$$

RHIC d+Au data at forward rapidity





- So, is RHIC forward suppression a small-x_2 (CGC) or a large-xF (energy conservation) effect??

- p-Pb collisions at the LHC probe both the target and the projectile at small-x already at mid-rapidity

- CGC calculations agree to predict a sizable suppression (~0.5) at y=0 in pPb at the LHC

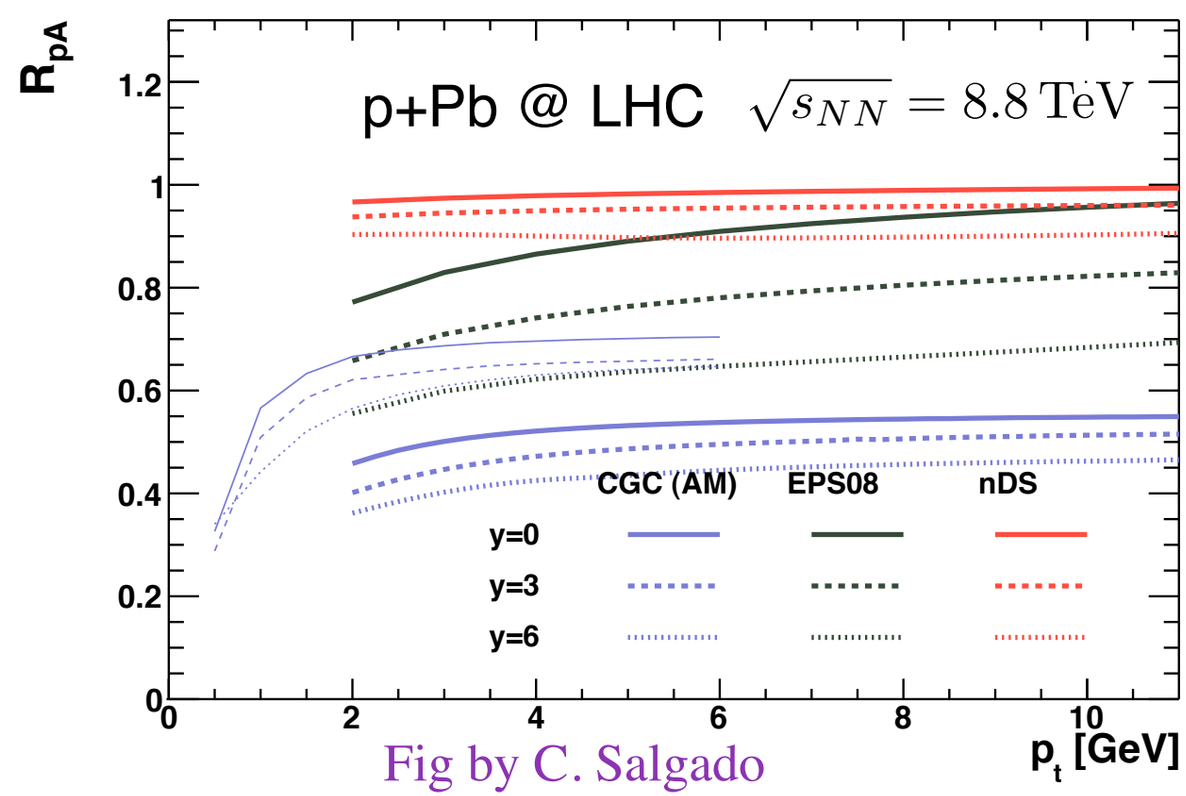
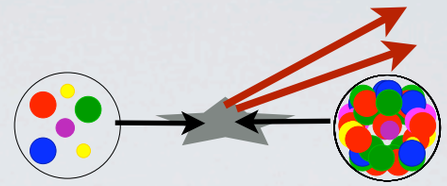


Fig by C. Salgado

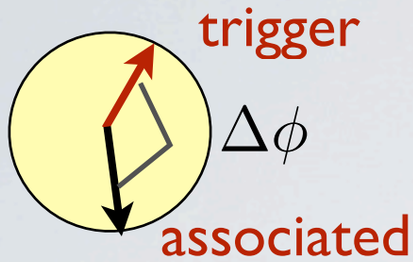
Forward di-hadron correlations in d+Au collisions at RHIC



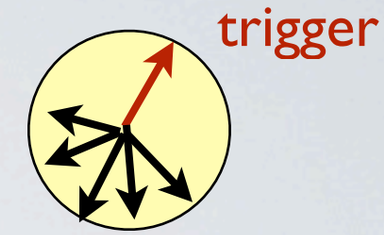
(k_1, y_1)
(k_2, y_2)

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

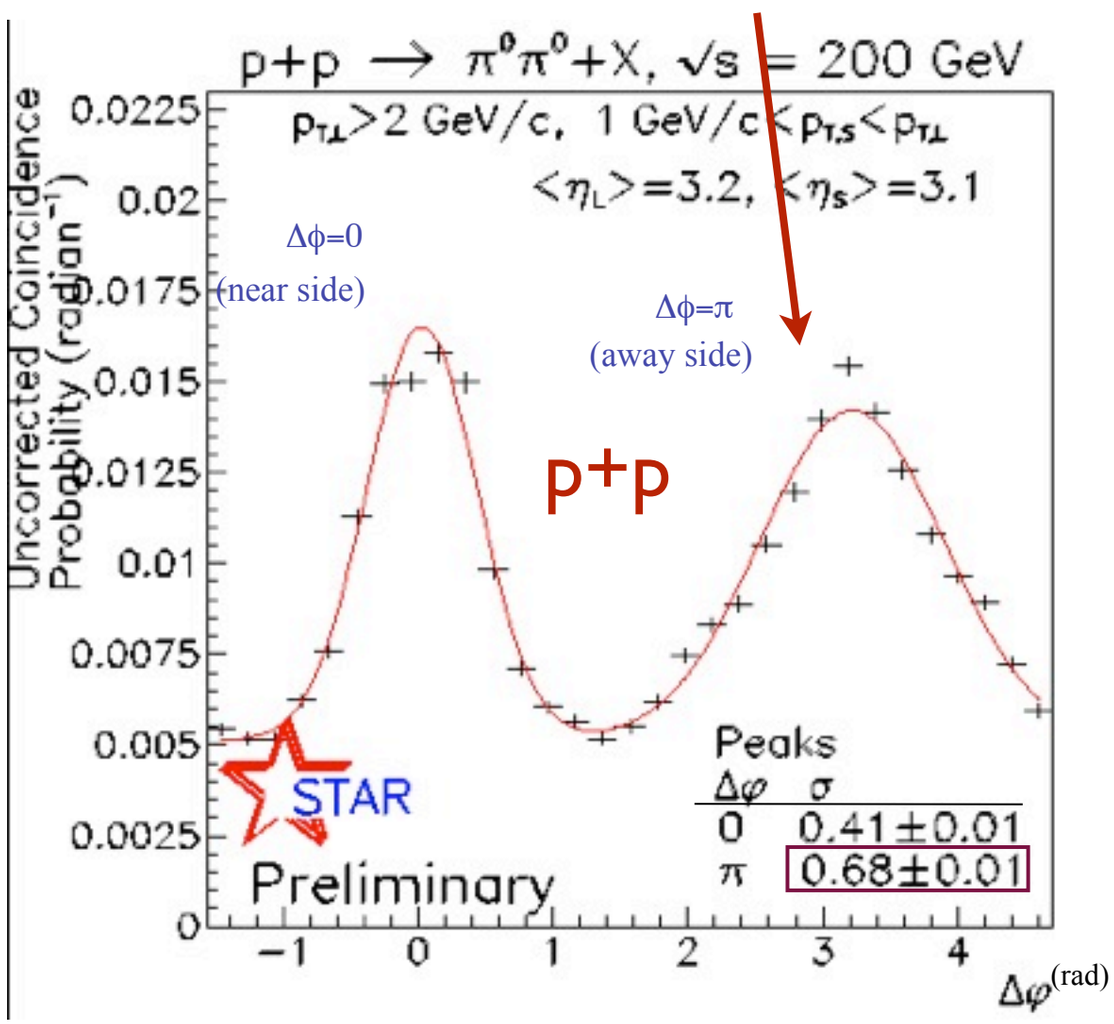
➡ "Coincidence probability" at measured by STAR Coll. at forward rapidities:



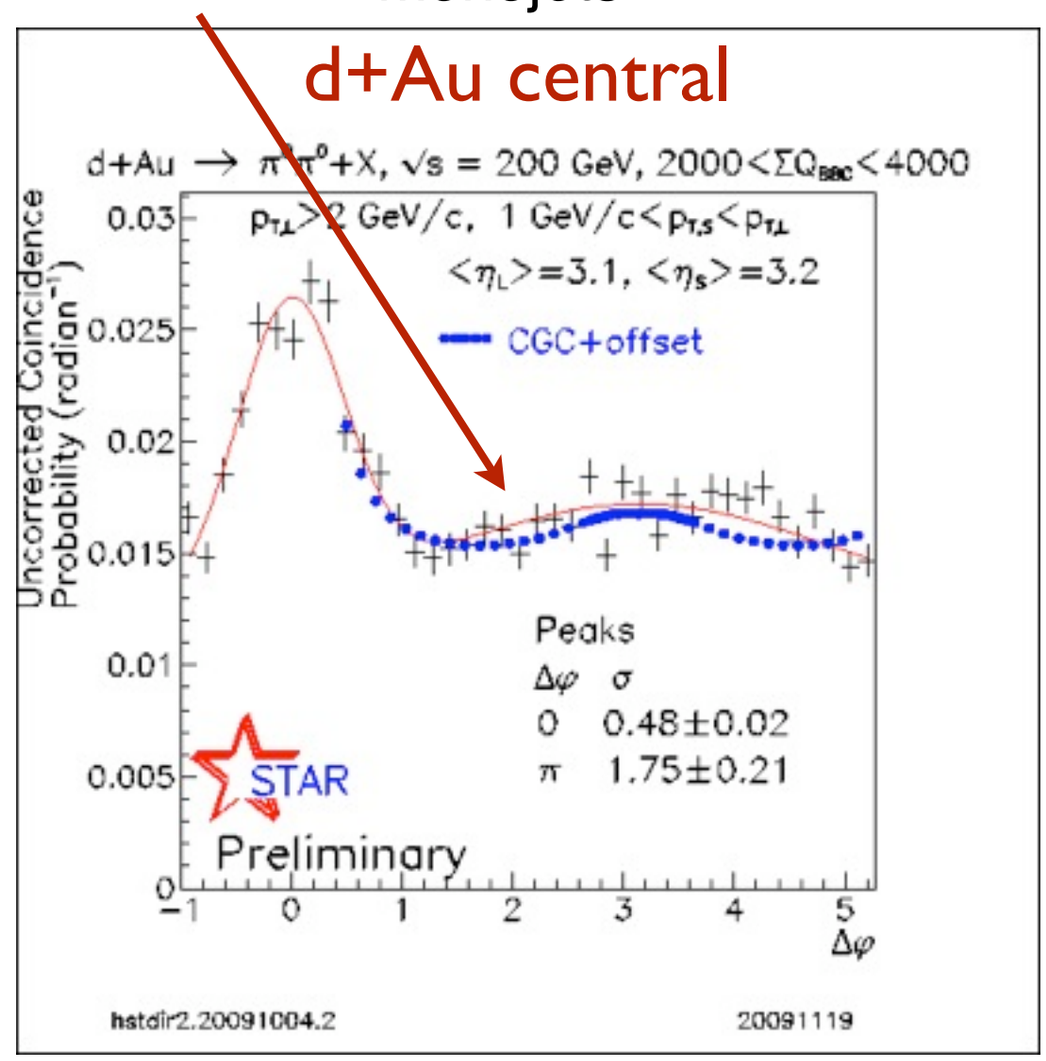
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$



➡ Away peak is present in p+p coll.

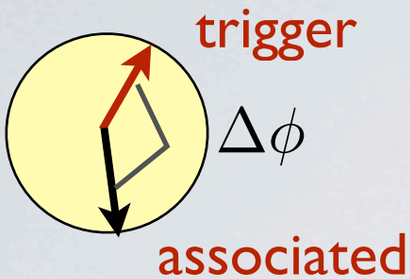


➡ Absence of away particle in d+Au coll. "monojets"

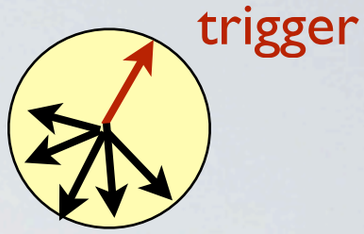


Forward di-hadron correlations in d+Au collisions at RHIC

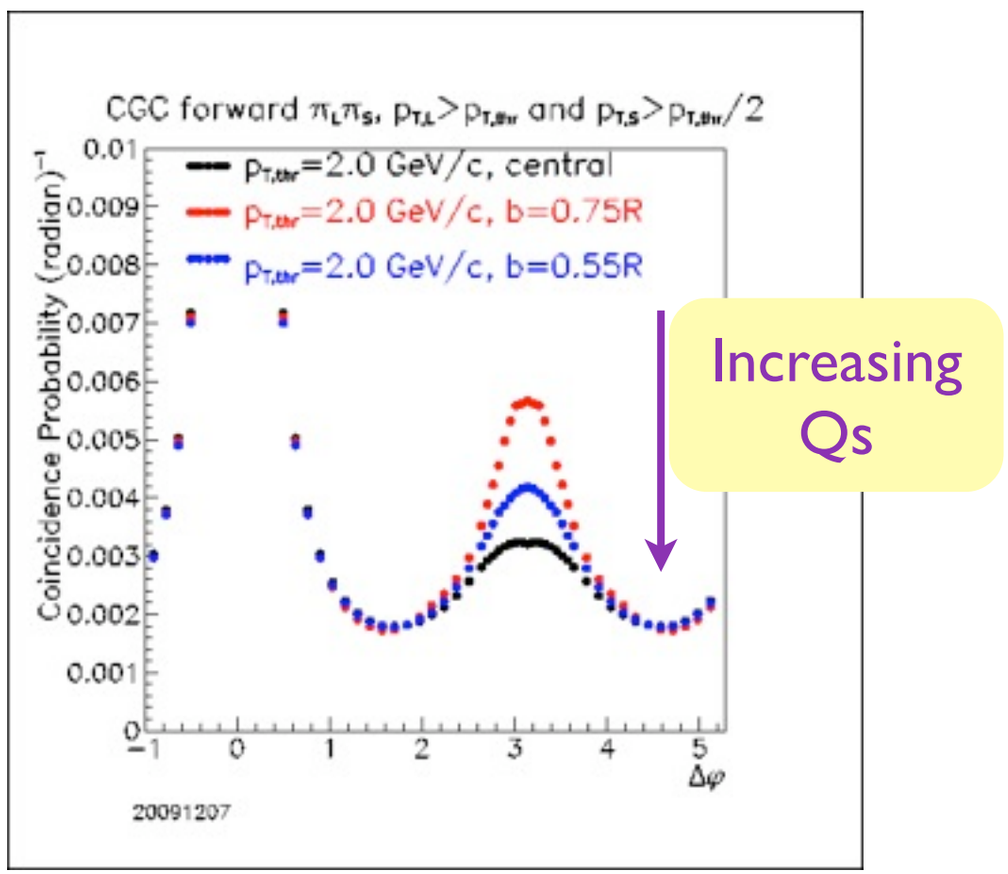
➡ "Coincidence probability" at measured by STAR Coll. at forward rapidities:

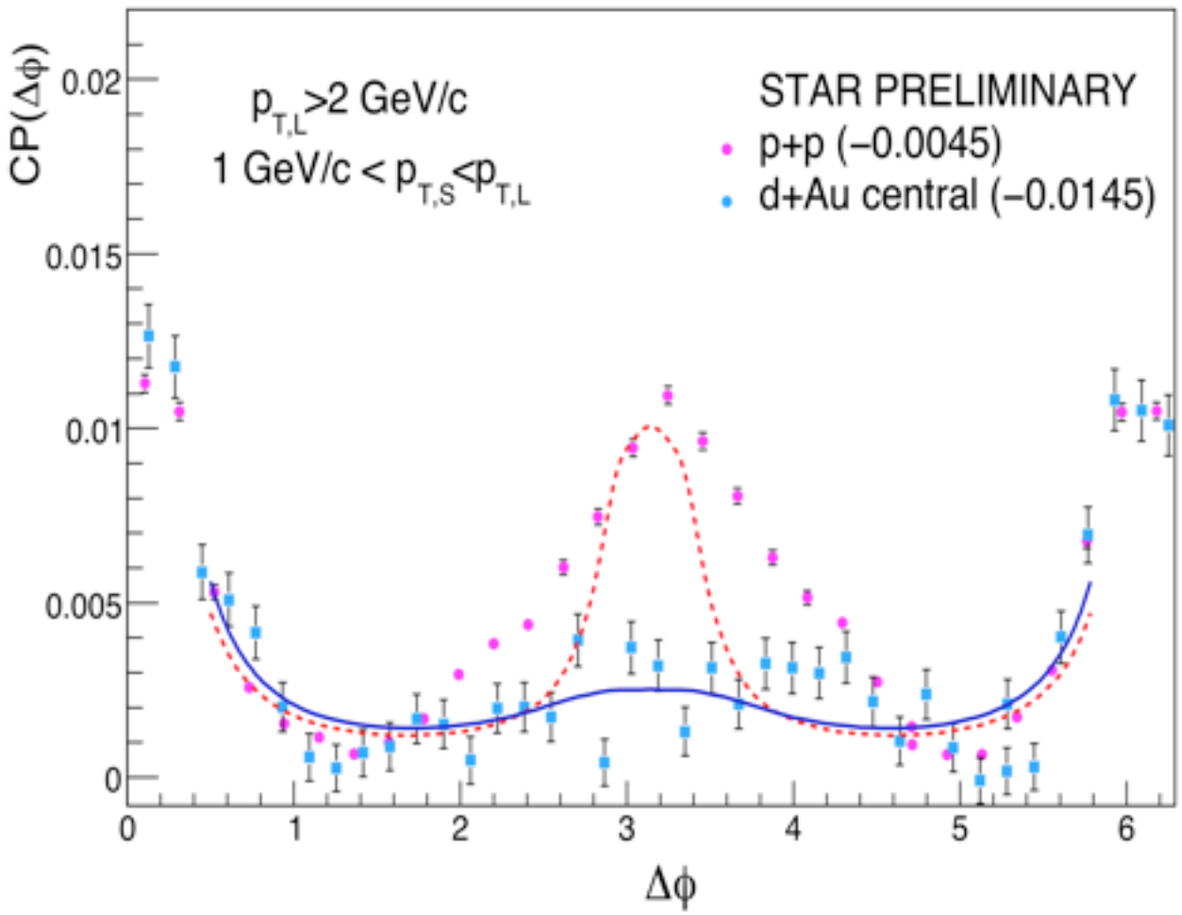


$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$



➡ This is well described in terms of CGC calculations. Higher twists (multiple rescatterings controlled by the saturation scale) induce the angular decorrelation

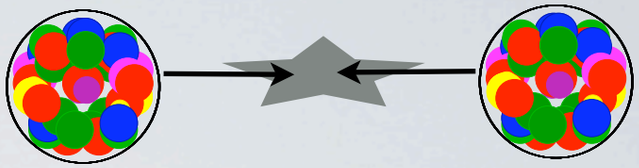




➡ Cannot be described in terms of standard DGLAP calculations

➡ Role of multiparton interactions may also be important

Multiplicities in A+A collisions



Both RHIC Au+Au and LHC Pb+Pb multiplicites indicate strong coherence or initial state effects: i.e they are very reduced w.r.t to a simple superposition of N+N collisions

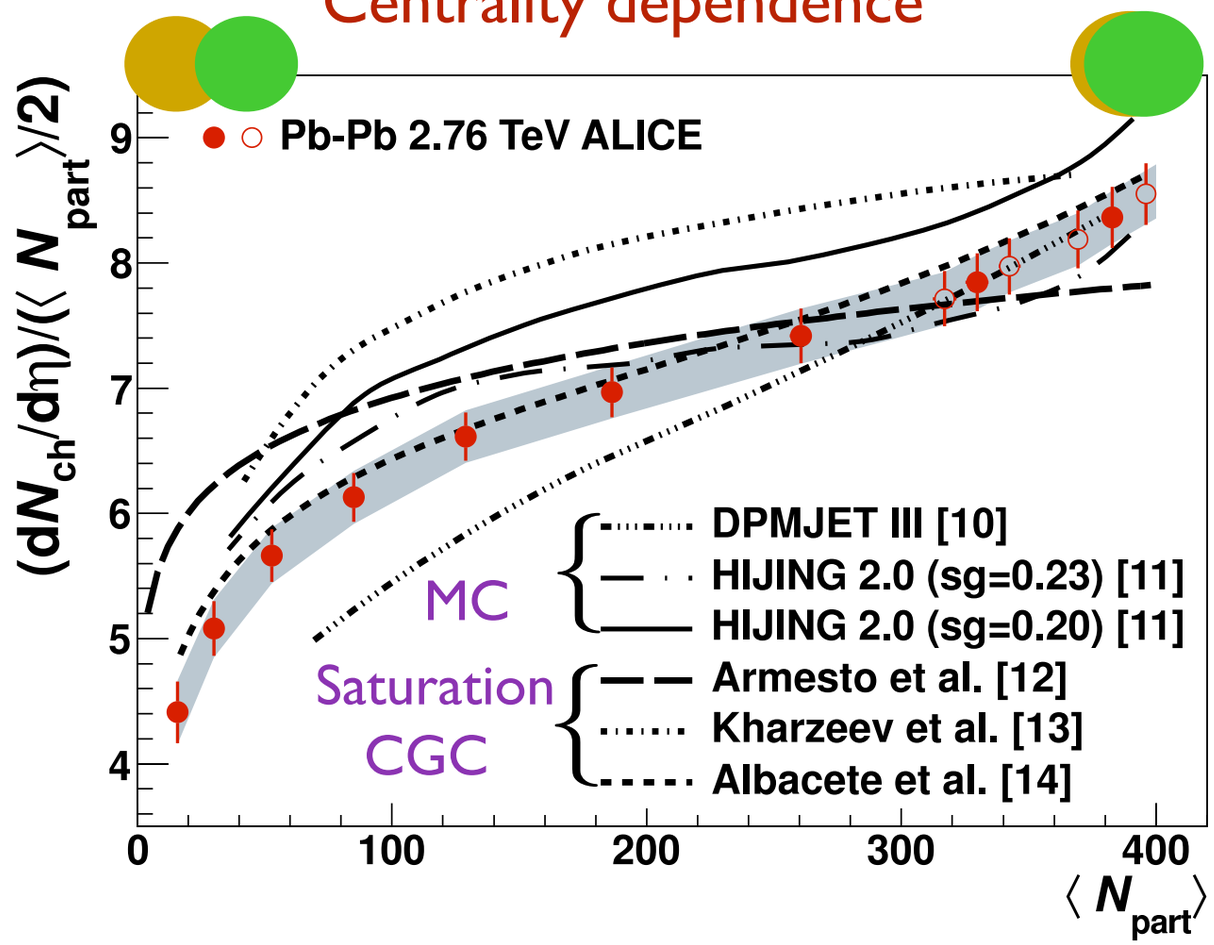
Empirically

$$\frac{1}{N_{part}} \left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \propto s^{0.15} f(N_{part})$$

KLN model: kt-factorization+CGC

$$\left.\frac{dN_{AA}}{d\eta}\right|_{\eta=0} \propto Q^2_{sA}(\sqrt{s}, b) \sim \sqrt{s}^{\lambda} N_{part}$$

Centrality dependence



Monte Carlo generators: Soft+Hard components.

- Strong energy dependence of the separation scale
- Large nuclear shadowing with strong b-dependence

CGC: Saturation effects strongly reduce the flux of incoming scattering centers (gluons)

Summary

- Data on DIS and DY on nuclei show a very rich structure, relating different phenomena from nuclear physics (EMC effect) to novel QCD phenomena as saturation (small-x)

- Forward RHIC data on single and double inclusive production (and ν-A data?) seem to indicate breakdown of collinear factorization in nuclear processes and is indicative (though not conclusive) of the onset of the CGC regime

- New JLAB 12 GeV run and LHC Pb+Pb (and p+Pb?) data will provide further constrains on nuclear structure.

- So, the field is open for progress both at the theoretical and experimental level and in all directions in the kinematic (x,Q^2)-plane

- EIC or LHeC needed to parallel the precision reached in proton studies

- My apologies for many interesting topics not covered in this talk...

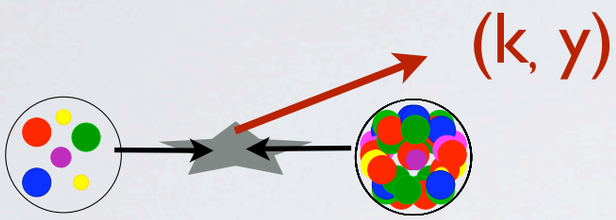
Thanks!!!

Back up slides

d+Au and p+p collisions at RHIC

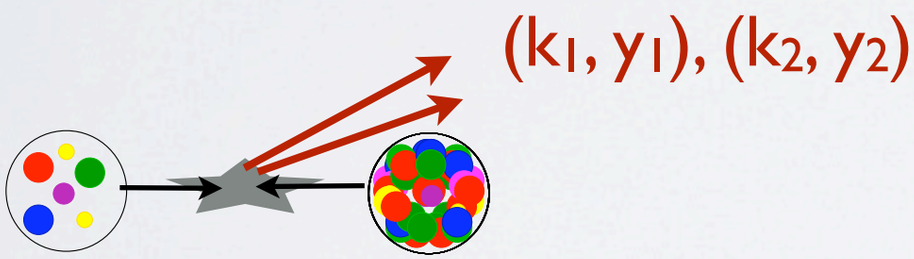
RHIC Kinematics:

- single particle production: Small-x ~ forward production



$$x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$$

- double inclusive production: Small-x ~ two particles in the forward region!



$$x_p = \frac{|k_1| e^{y_1} + |k_2| e^{y_2}}{\sqrt{s}}$$

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

At RHIC energies, forward measurements needed to isolate small-x (<0.01) effects

Back up slides