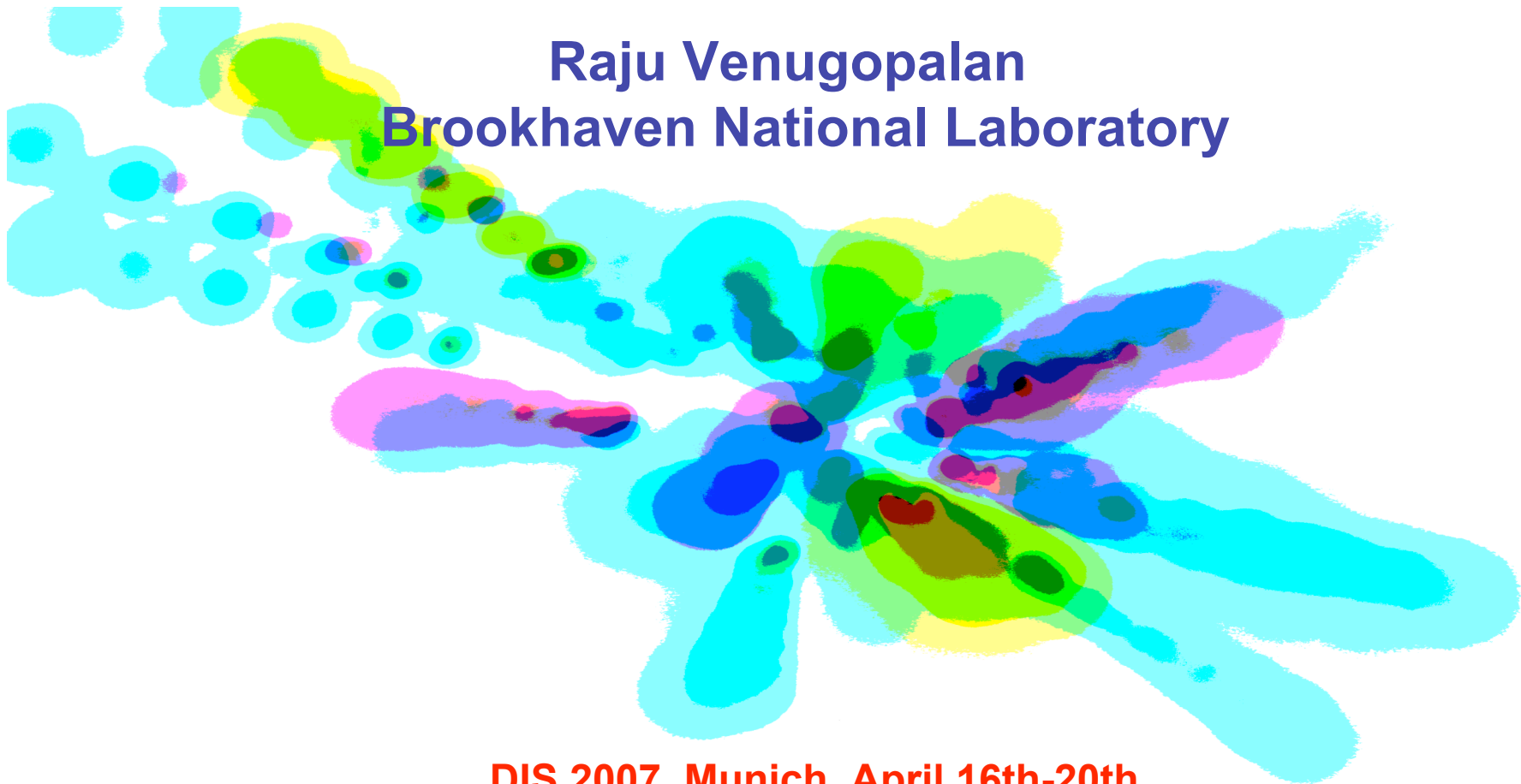


Universal features of QCD dynamics in hadrons & nuclei at high energies

Raju Venugopalan
Brookhaven National Laboratory



DIS 2007, Munich, April 16th-20th



Outline of talk

❖ Whither the “perfect” theory ?

- Bjorken-Feynman asymptotics
- Regge-Gribov asymptotics

❖ QCD coherence at small $x \Rightarrow$ Universality

- Saturation in hadrons & nuclei;
the Color Glass Condensate picture

❖ Multi-particle production in QCD at high energies

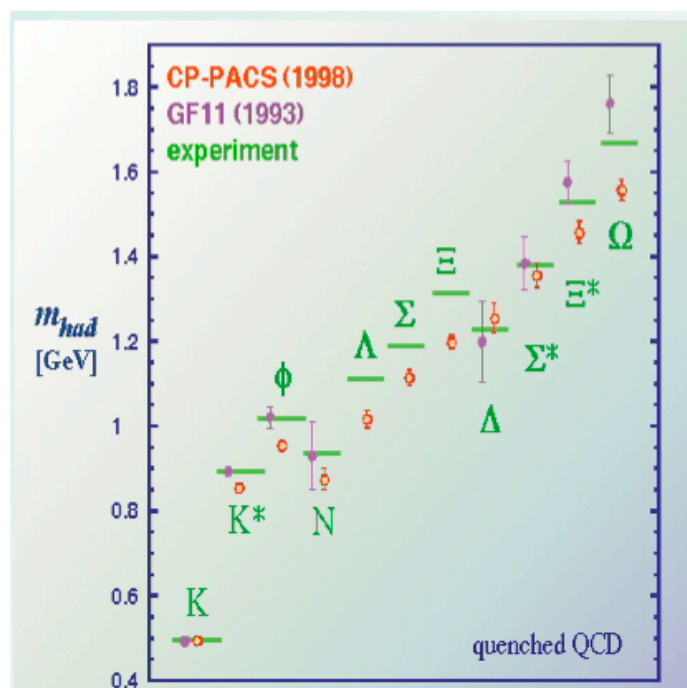
- Initial fluctuations & rapid thermalization in AA collisions

❖ Some open questions in QCD at high energies

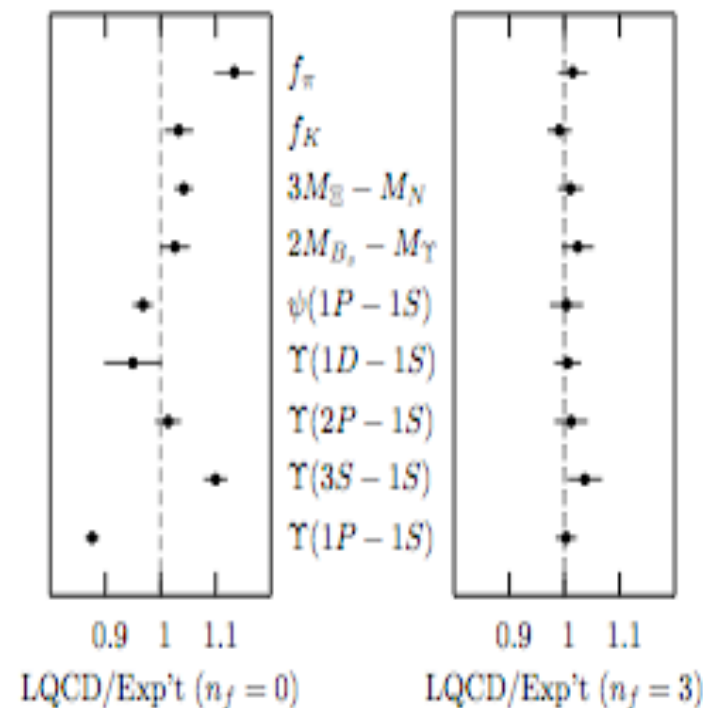
QCD - the perfect theory (F.Wilczek, hep-ph/9907340)

“Explains” ~ 99% of the mass of the visible universe

MILC:hep-lat/0304004



Hadron mass spectrum
vs quenched lattice results



Quenched QCD full QCD

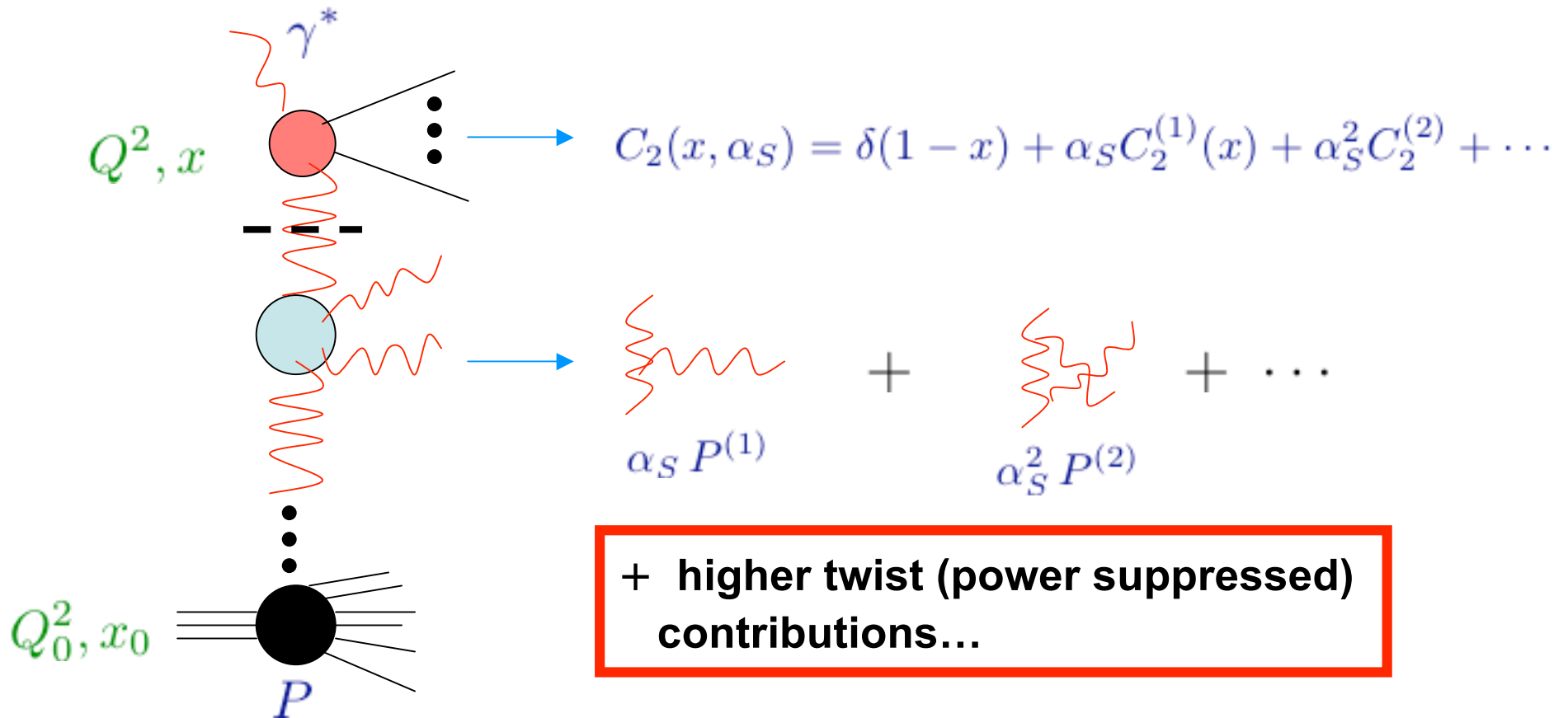
The dynamics of glue is central to our understanding of the structure of matter

Much of the discussion in pQCD has focused on the **Bjorken limit**:

$$Q^2 \rightarrow \infty ; s \rightarrow \infty ; x_{\text{Bj}} \approx \frac{Q^2}{s} = \text{fixed}$$

Asymptotic freedom,
the Operator Product Expansion (OPE)
& Factorization Theorems:
machinery of precision physics in QCD...

STRUCTURE OF HIGHER ORDER CONTRIBUTIONS IN DIS



- **Coefficient functions - C** - computed to NNLO for many processes, e.g., $gg \rightarrow H$

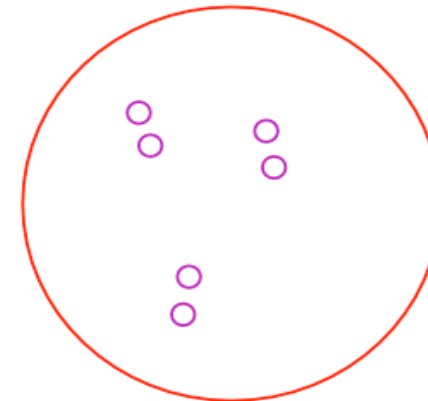
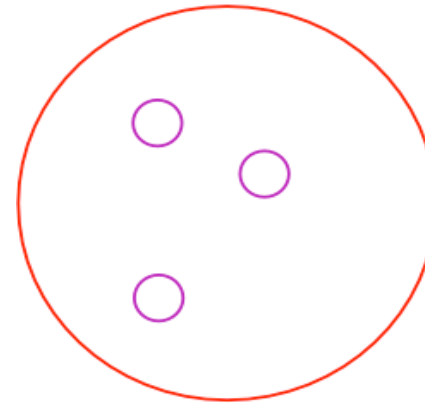
Harlander, Kilgore; Ravindran, Van Neerven, Smith; ...

- **Splitting functions - P** - computed to 3-loops

Moch, Vermaseren, Vogt (Vogt's talk)

Resolving the hadron -DGLAP evolution

increasing Q^2



But... the phase space density
decreases-the proton becomes
more dilute

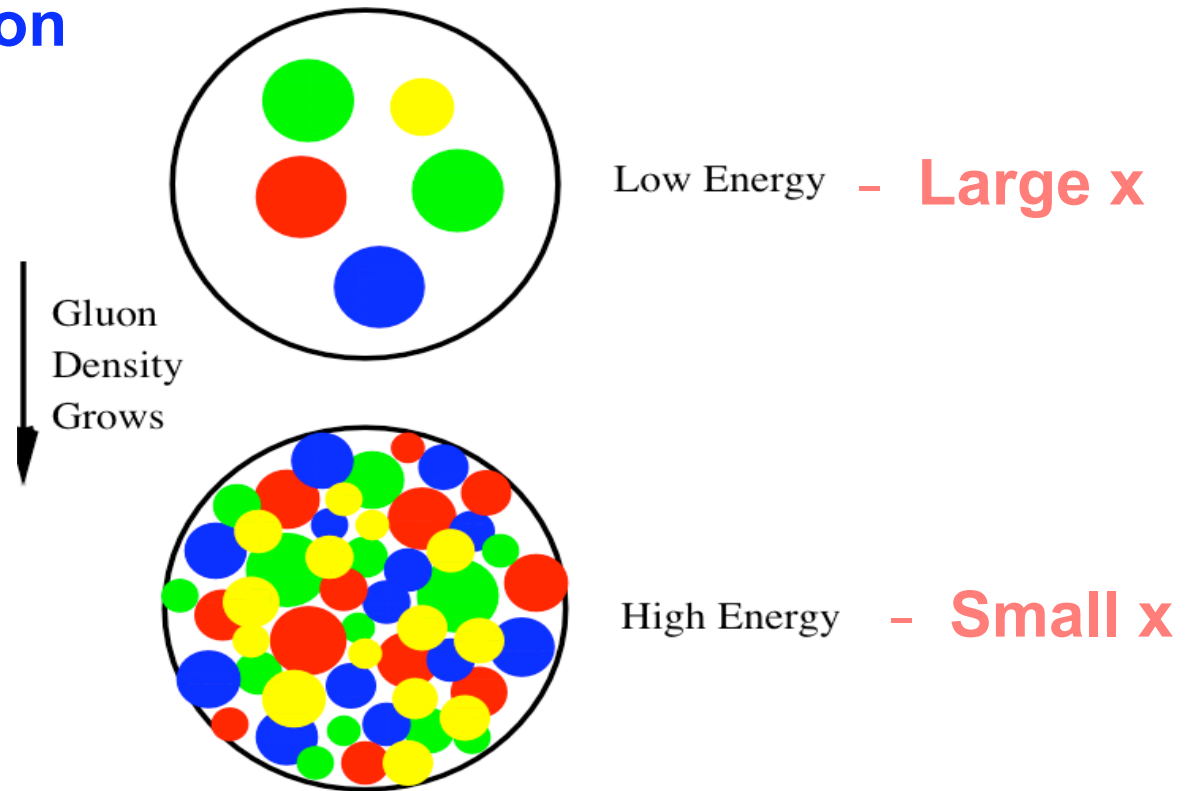
❖ The fundamental theory: “merely” background for
new physics ?

The other interesting limit-is the **Regge-Gribov limit** of QCD:

$$x_{Bj} \rightarrow 0; s \rightarrow \infty; Q^2 (\gg \Lambda_{\text{QCD}}^2) = \text{fixed}$$

**Physics of strong fields in QCD,
multi-particle production-
novel universal properties of theory in this limit ?**

Resolving the hadron -BFKL evolution

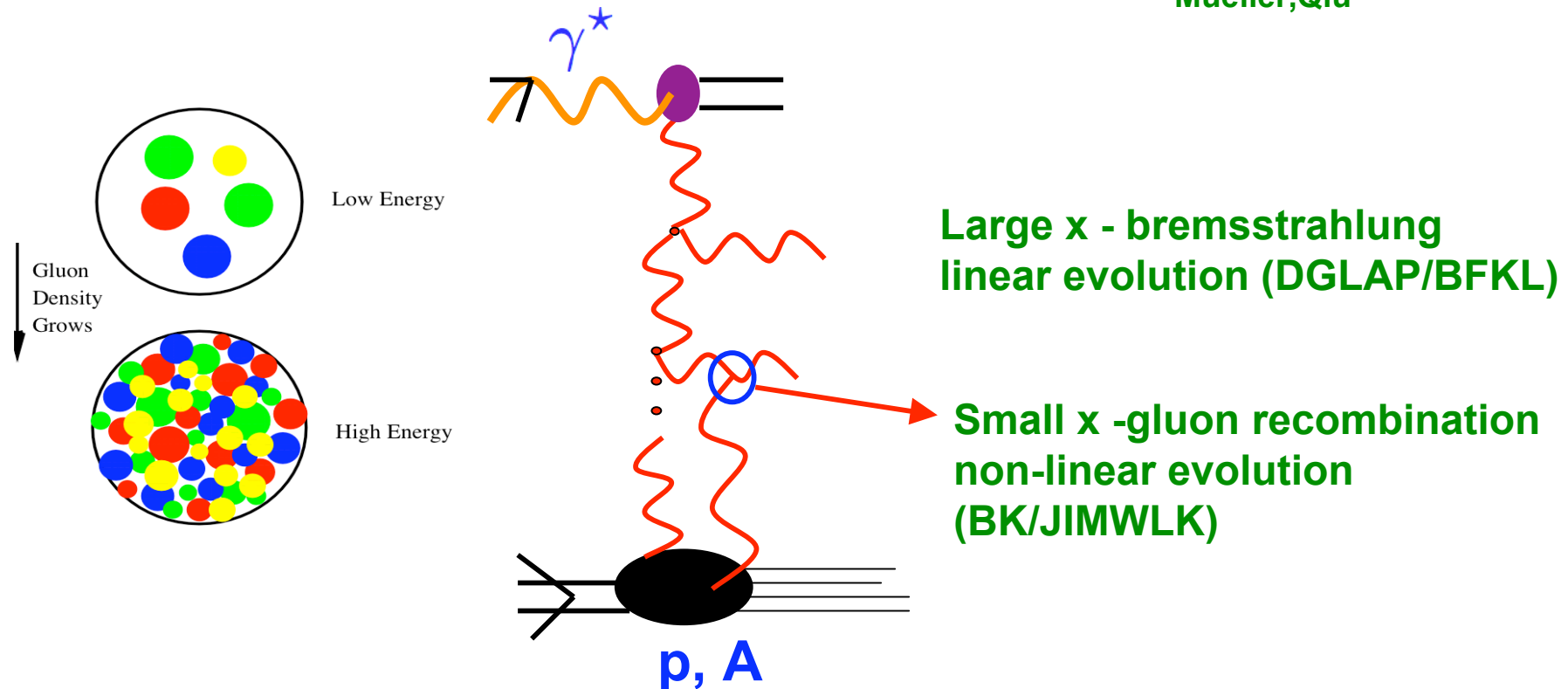


Gluon density saturates at

occupation # $f = \frac{1}{\alpha_S}$

Mechanism of gluon saturation in QCD

Gribov, Levin, Ryskin
Mueller, Qiu



Saturation scale $Q_s(x)$ - dynamical scale below which non-linear (“higher twist”) QCD dynamics is dominant

The Color Glass Condensate

McLerran, RV
Iancu, Leonidov, McLerran

In the saturation regime:

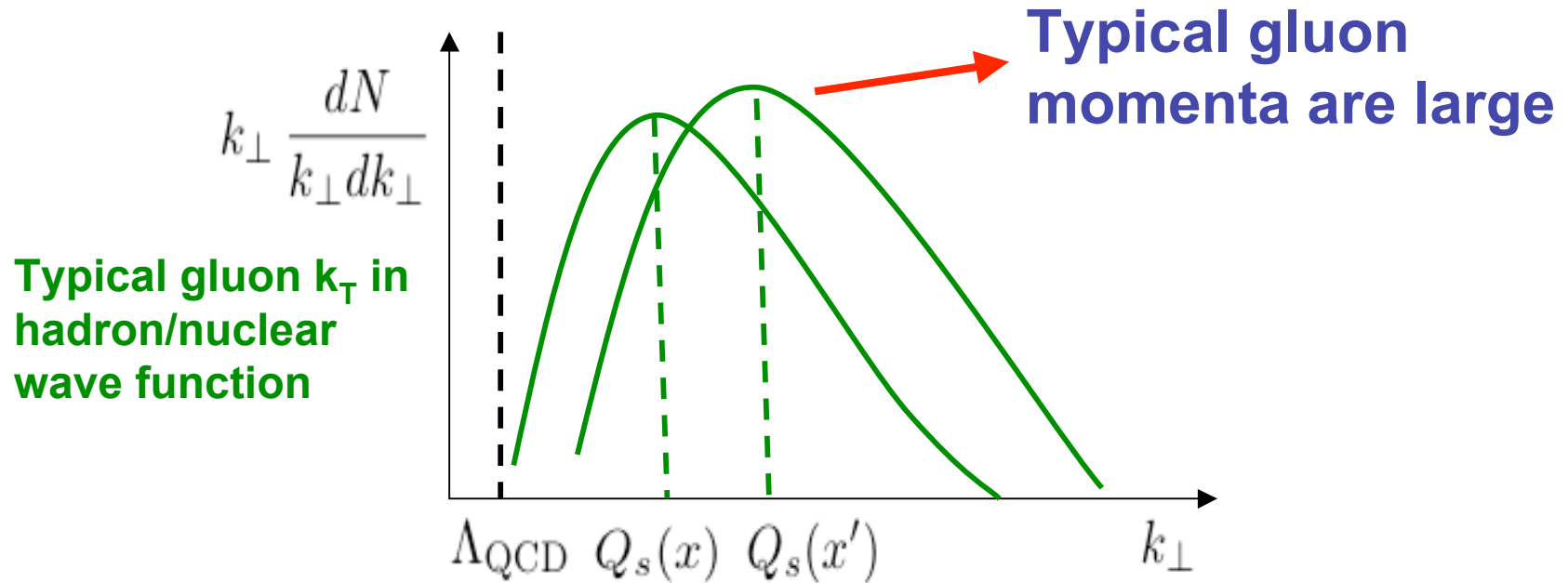
Strongest fields in nature!

$$E^2 \sim B^2 \sim \frac{1}{\alpha_S}$$

CGC: *Classical* effective theory of QCD describing dynamical gluon fields + static color sources in non-linear regime

- Novel renormalization group equations (JIMWLK/BK) describe how the QCD dynamics changes with energy
- A universal saturation scale Q_s arises naturally in the theory

Saturation scale grows with energy

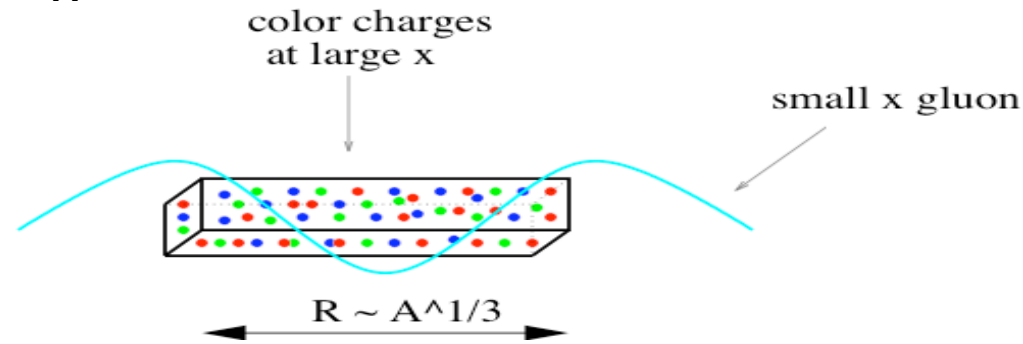


Bulk of high energy cross-sections:

- a) obey dynamics of novel non-linear QCD regime
- b) Can be **computed systematically** in weak coupling

Saturation scale grows with A

High energy compact ($1/Q < R_p$) probes interact coherently across nuclear size $2 R_A$ - experience large field strengths



Pocket formula:

$$Q_s^2 \propto \left(\frac{A}{x} \right)^{1/3}$$

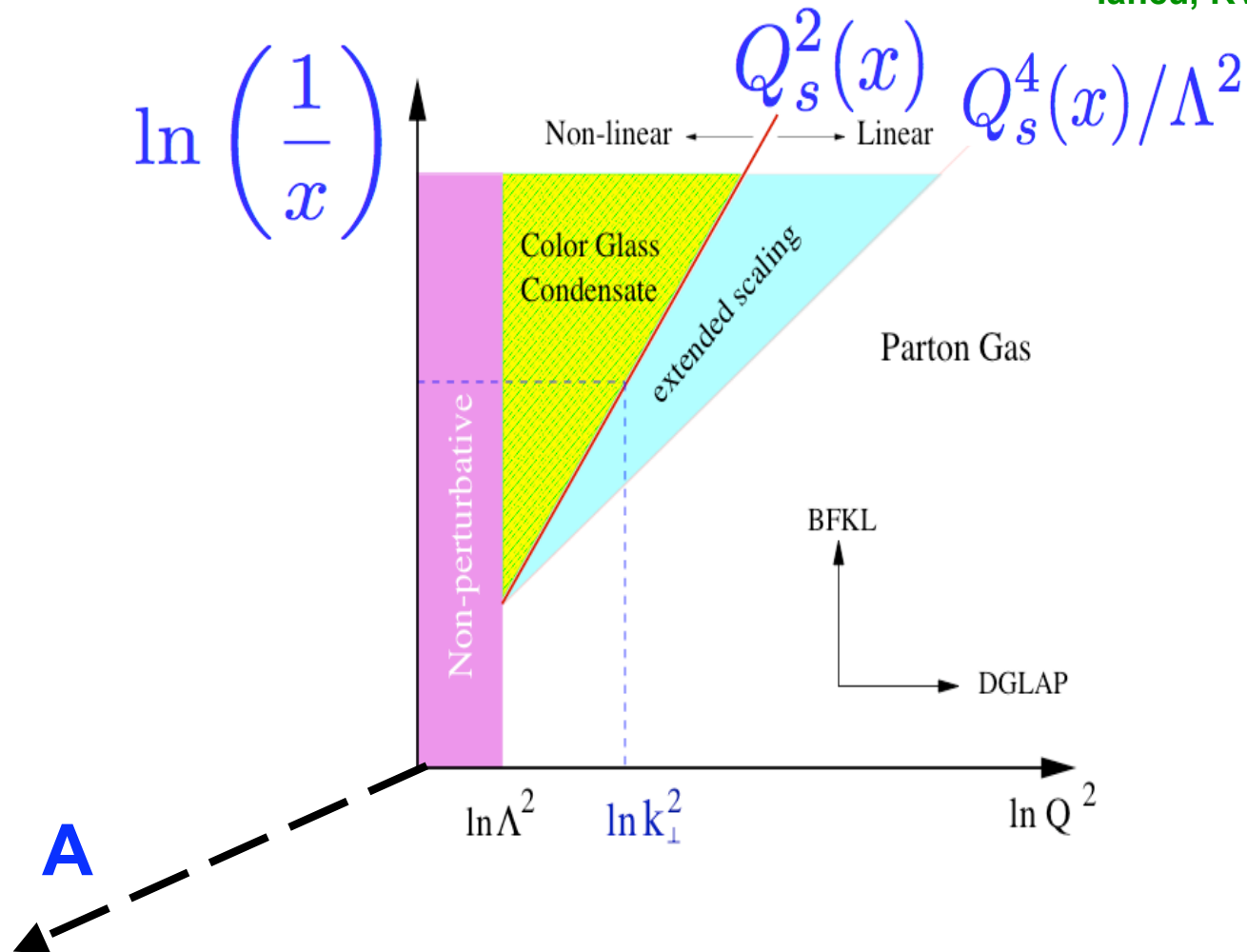
Enhancement of Q_s with $A \Rightarrow$ non-linear QCD regime reached at significantly lower energy in A than in proton

❖ Pocket formula holds up under detailed analysis

Kowalski, Lappi, RV

New window on universal properties of the matter in nuclear wavefunctions

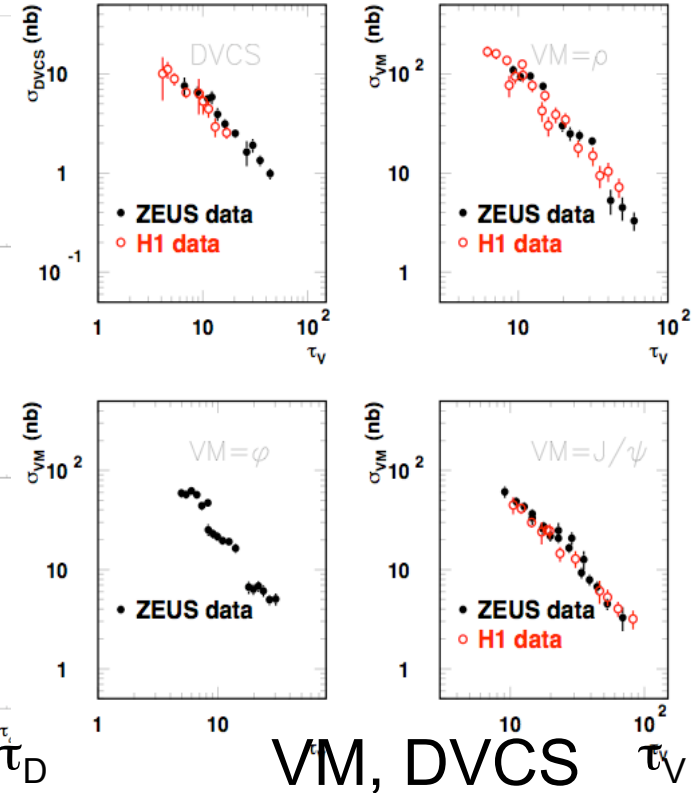
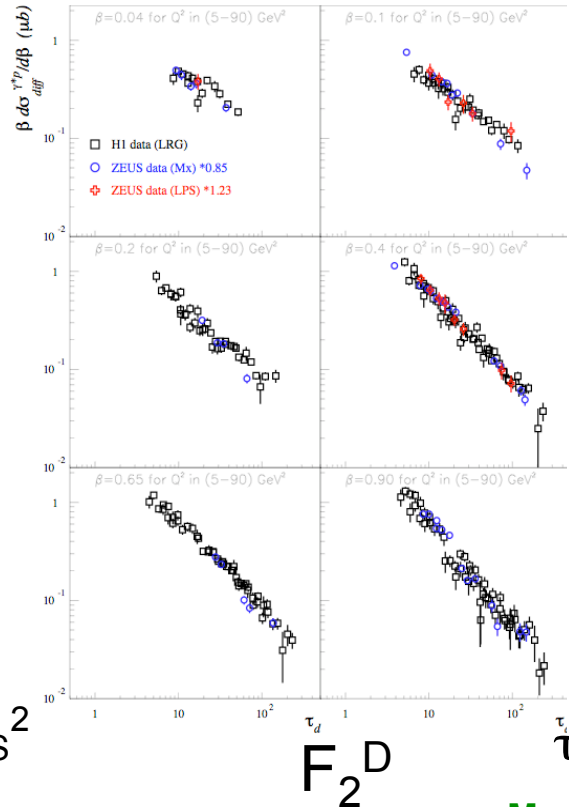
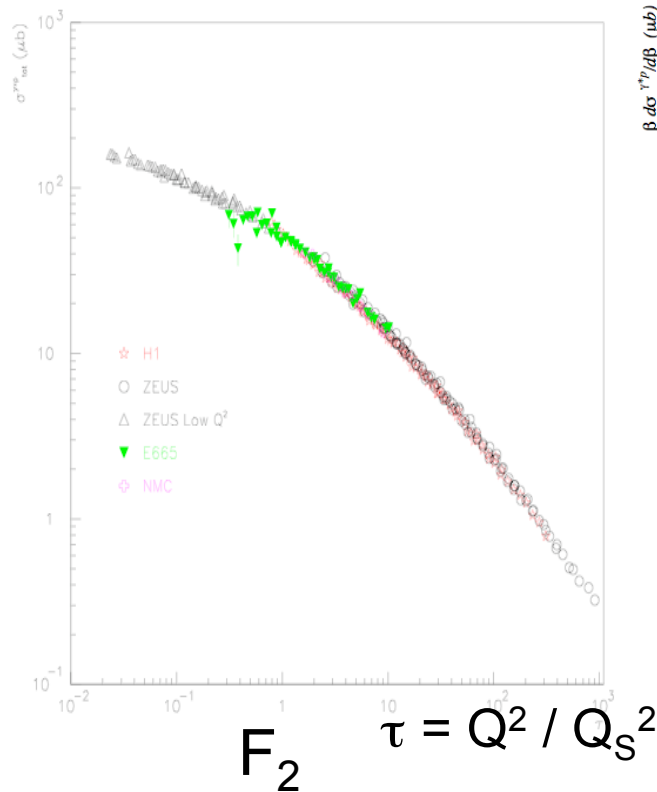
Iancu, RV, hep-ph/0303204



Can we quantify the various regimes ?

Evidence from HERA for geometrical scaling

Golec-Biernat, Stasto, Kwiecinski



Marquet, Schoeffel hep-ph/0606079

Gelis et al., hep-ph/0610435

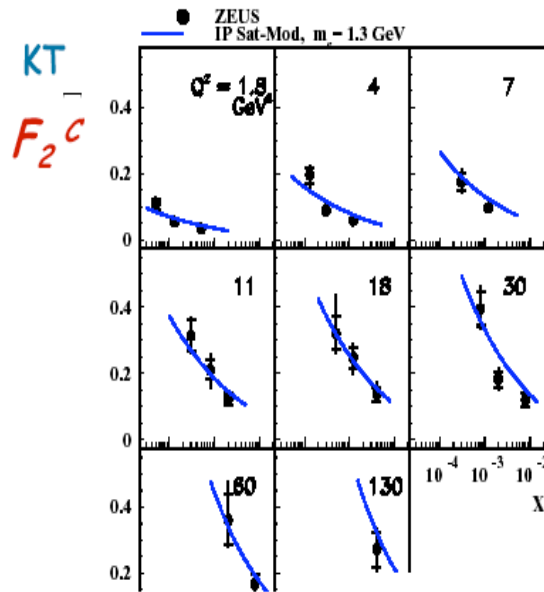
- ❖ Scaling seen for F_2^D and VM,DVCS for same Q_s as F_2

- ❖ Scaling confirmed by “Quality factor” analysis

- ❖ Recent NLO BK analysis: Albacete, Kovchegov, hep-ph-0704.0612

Recent caveats: Avsar, Gustafson, hep-ph/0702087

Saturation Models-excellent fits to HERA data

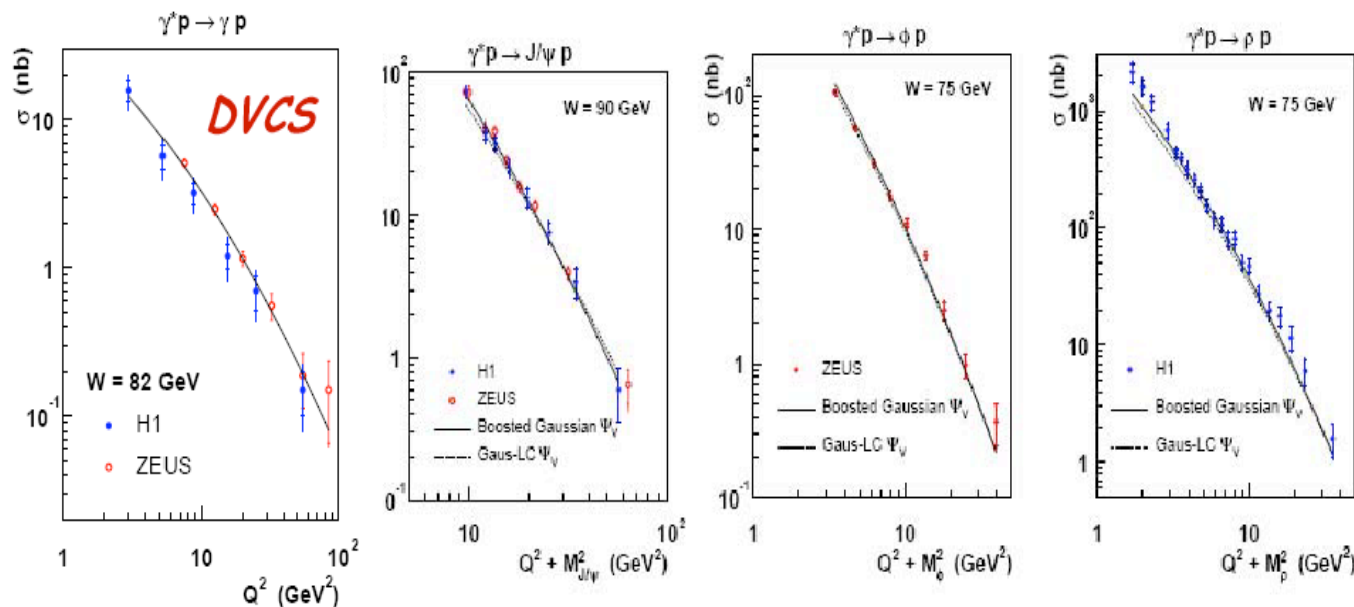


Dipole cross section determined
 by fit to F_2 \rightarrow
 Simultaneous description of many
 reactions

Kowalski et al.,
[hep-ph/0606272](https://arxiv.org/abs/hep-ph/0606272)

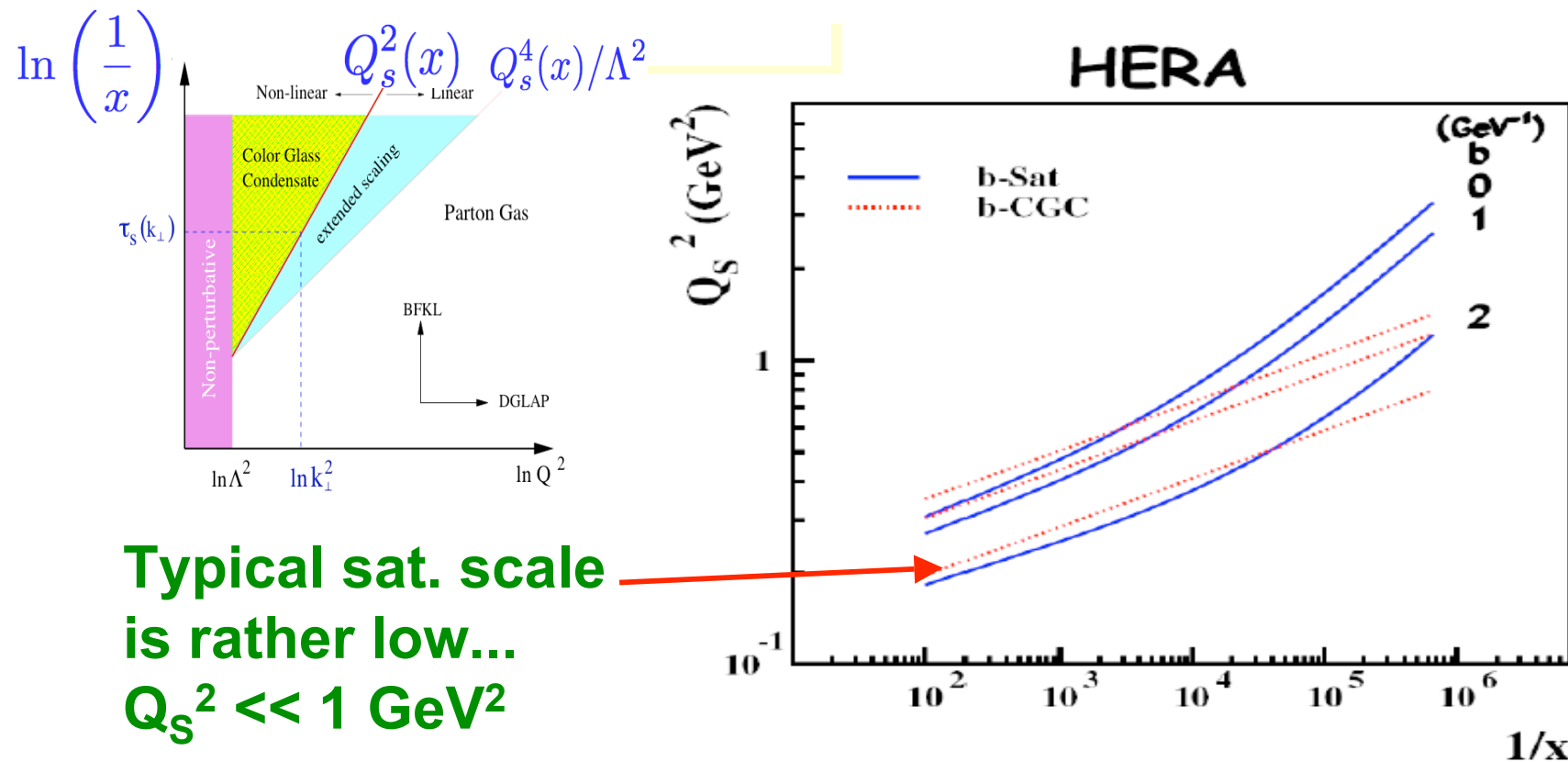
Vector Mesons

Also see Forshaw et al.
[hep-ph/0608161](https://arxiv.org/abs/hep-ph/0608161)



Caveat: Saturation scale extracted from HERA data inconsistent with model assumptions ?

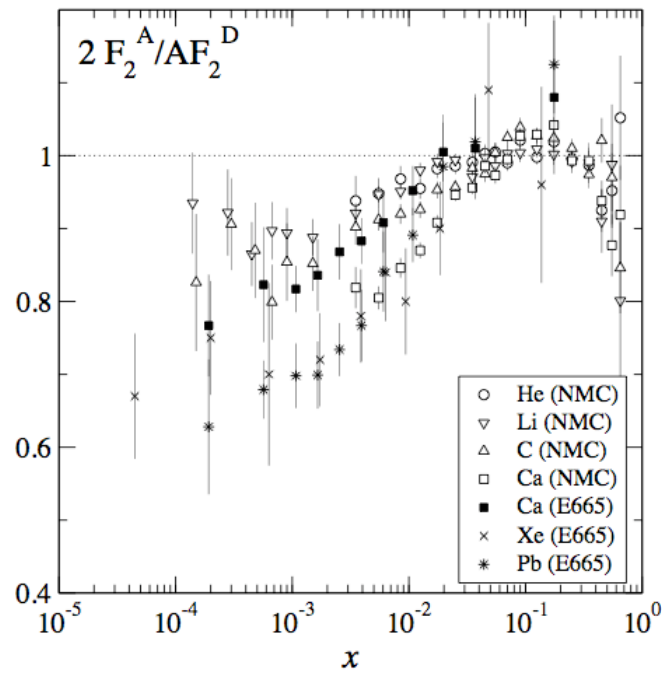
Model assumes $\alpha_S(Q_S) \ll 1$



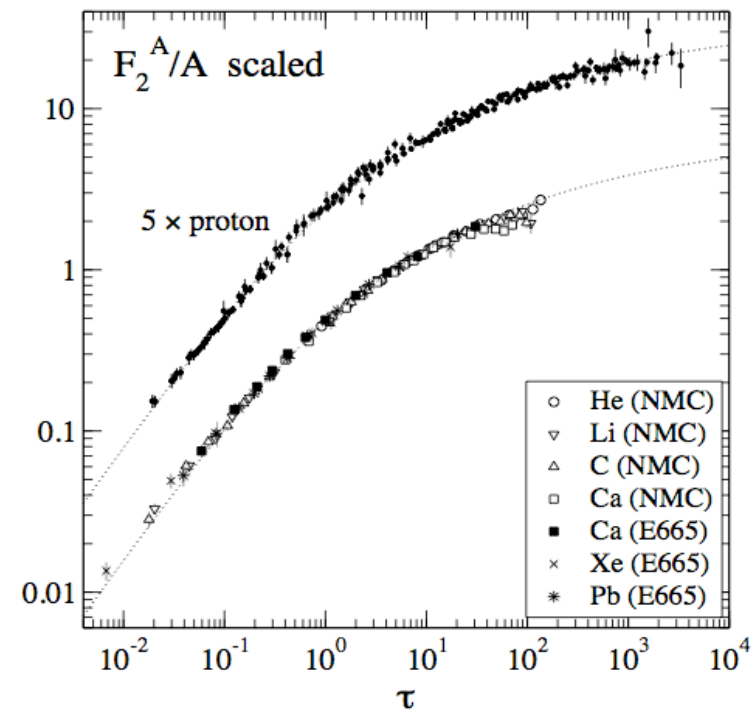
Evidence of geometrical scaling in nuclear DIS

Freund et al.,
hep-ph/0210139

Nuclear shadowing:



Geometrical scaling

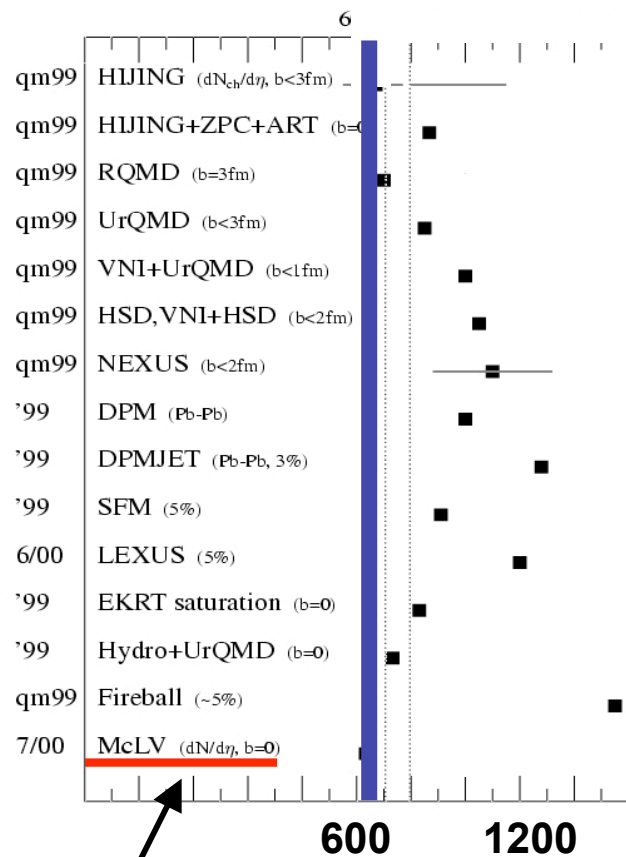


❖ Data scale as a function of $\tau = Q^2 / Q_s^2$

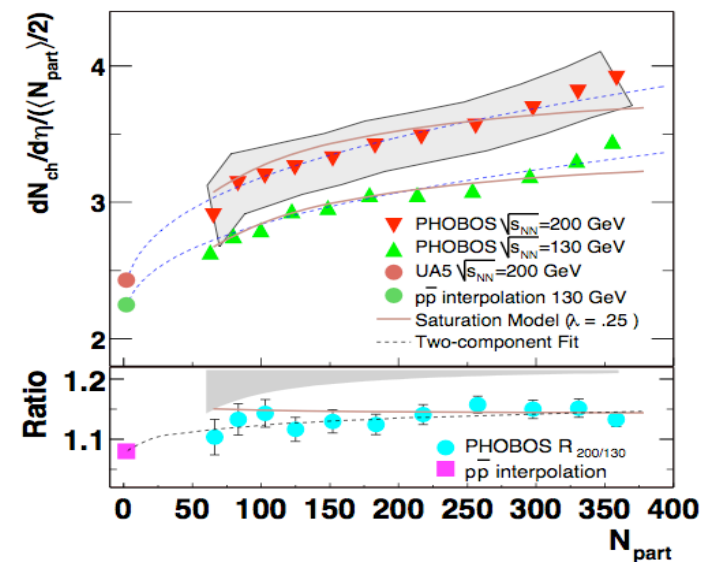
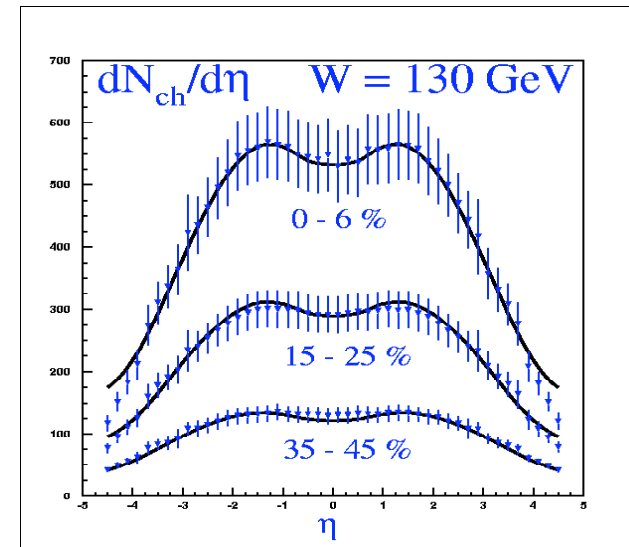
Evidence of non-linear saturation regime @ RHIC ?

Global multiplicity observables
in AA described in CGC models:

PHOBOS central Au+Au mult. vs models

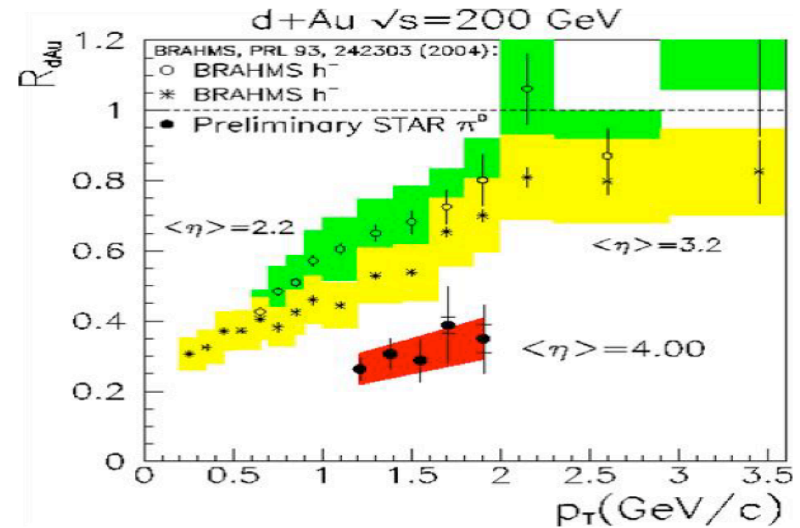
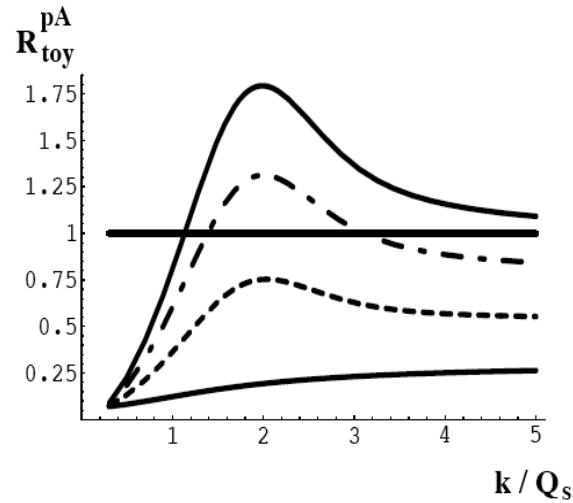


Krasnitz, RV



Kharzeev, Levin, Nardi

DA:



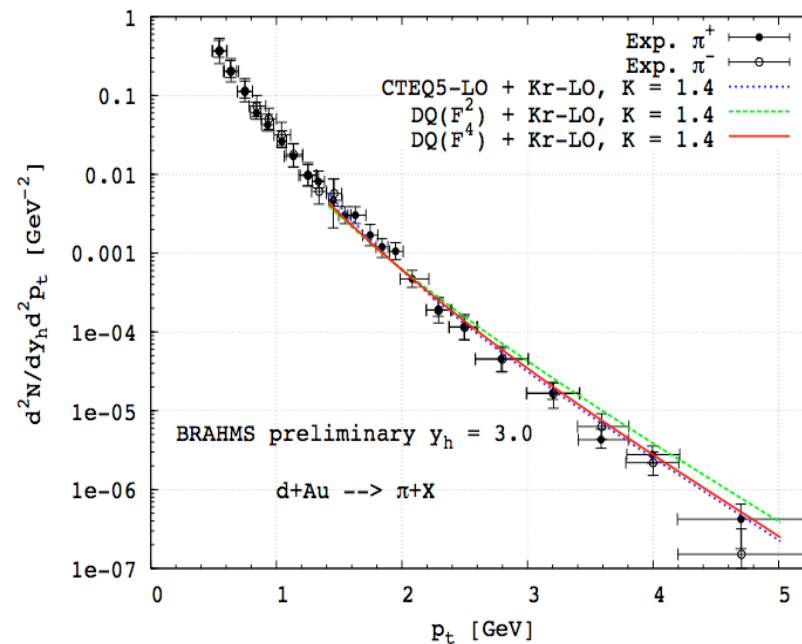
Kharzeev, Kovchegov, Tuchin
 Albacete, Armesto, Salgado, Kovner, Wiedemann
 Blaizot, Gelis, RV

D-Au pt spectra compared to
 CGC prediction

Hayashigaki, Dumitru, Jalilian-Marian

Forward pp @ RHIC as well

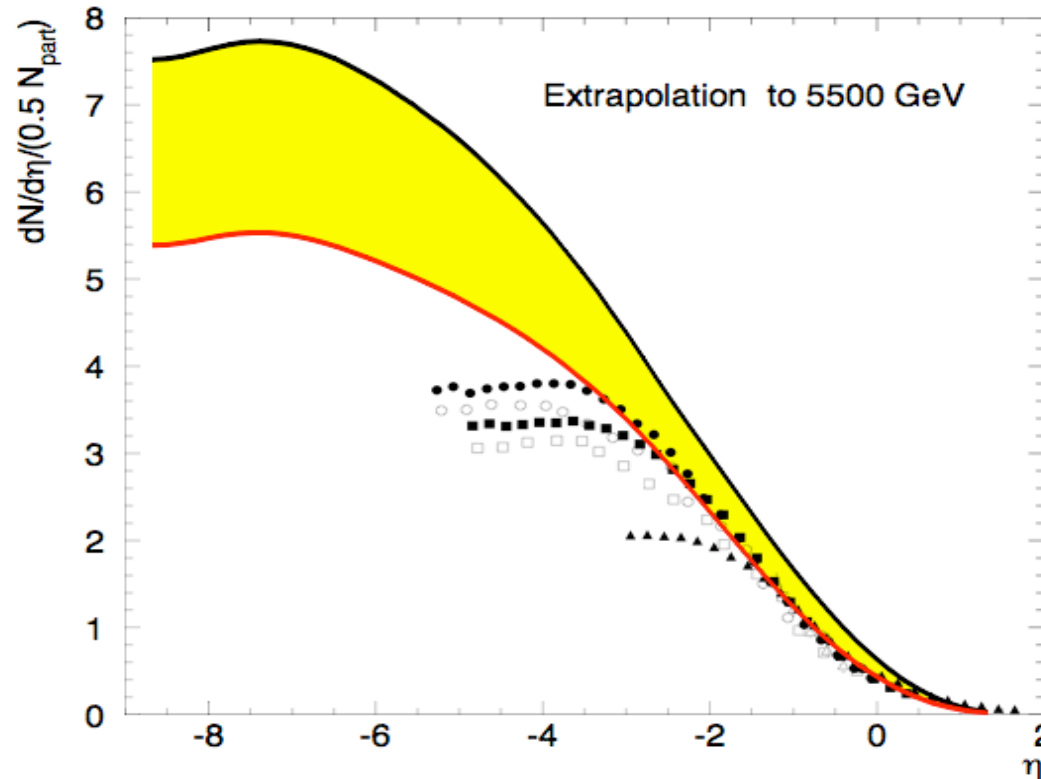
Boer, Dumitru, PRD 74, 074018 (2006)



Review: Jalilian-Marian, Kovchegov, hep-ph/0505052

Natural explanation for limiting fragmentation + deviations in CGC

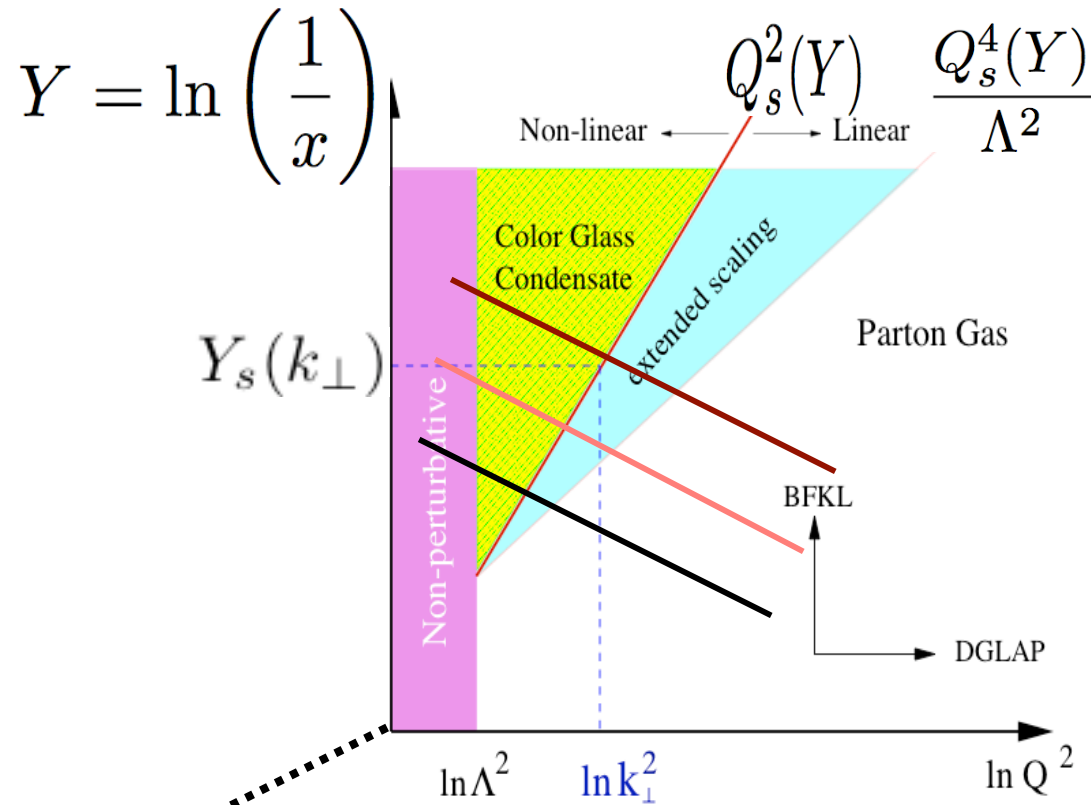
Jalilian-Marian



Extrapolation of BK-fit to RHIC LF data to LHC
 $dn/dy|_{y=0} = 1500-2250$ in A+A at LHC

Gelis,Stasto, RV, hep-ph/0605087

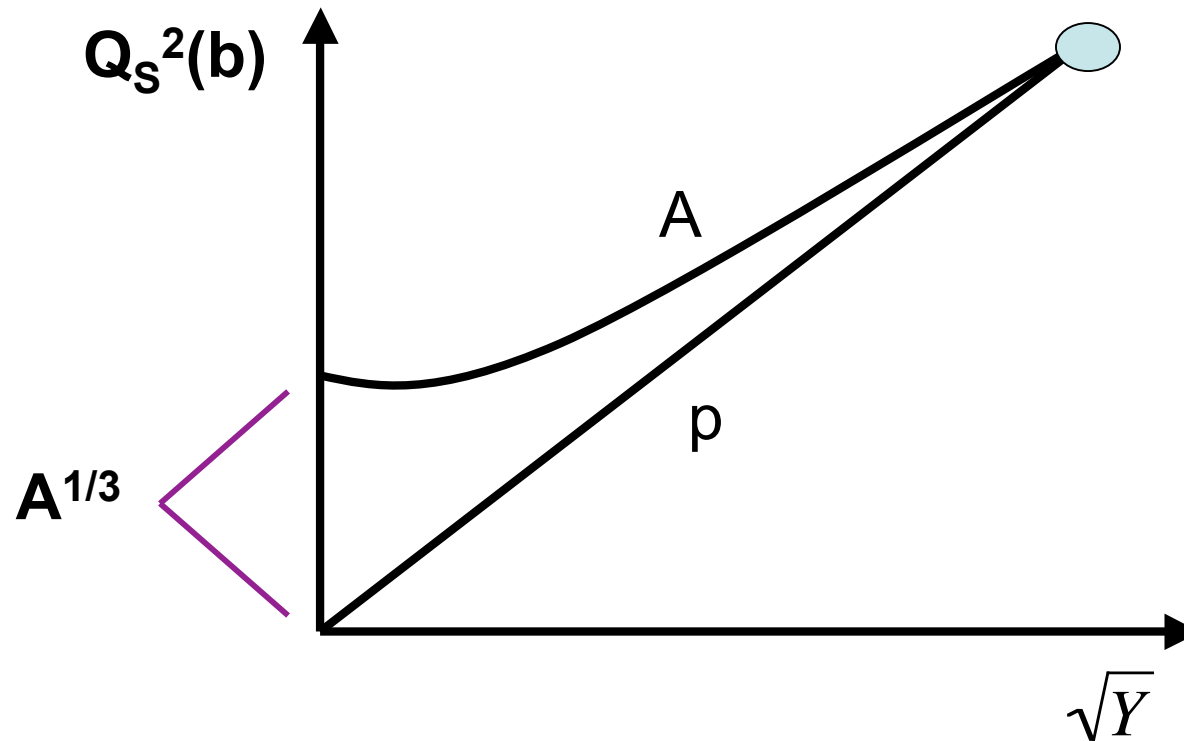
Estimates of the saturation scale from RHIC



- $Y_{\text{RHIC-central}} = 0 \ (x = 10^{-2}, Q_{s,\text{Au}}^2 = 1.3 \text{ GeV}^2)$
- $Y_{\text{RHIC}} = 3, Y_{\text{LHC-central}} = 0 \ (x = 5 \cdot 10^{-4}, Q_{s,\text{Au}}^2 = 3.2 \text{ GeV}^2)$
- $Y_{\text{LHC}} = 3 \ (x = 3 \cdot 10^{-5}, Q_{s,\text{Au}}^2 = 8.2 \text{ GeV}^2)$

Universal gluodynamics & energy dependence of Q_s

A.H. Mueller, hep-ph/0301109

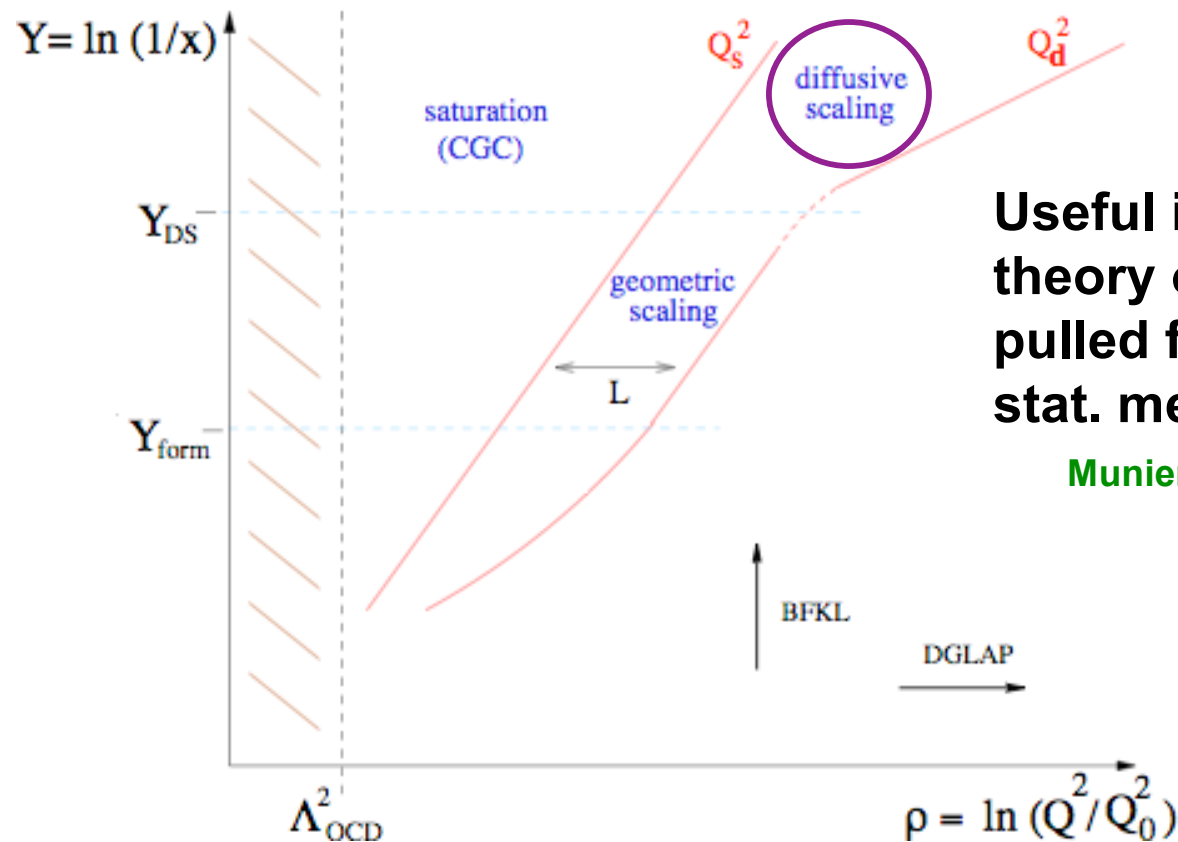


Small x QCD RG eqns. predict (fixed b) Q_s approaches universal behavior with increasing energy (Y) for **all hadrons and nuclei**

-can the approach to this behavior be tested ?

Pomeron loops and Diffusive scaling

Review: G.Soyez, hep-ph/0610436



Useful insights from
theory of unstable
pulled fronts in
stat. mech.

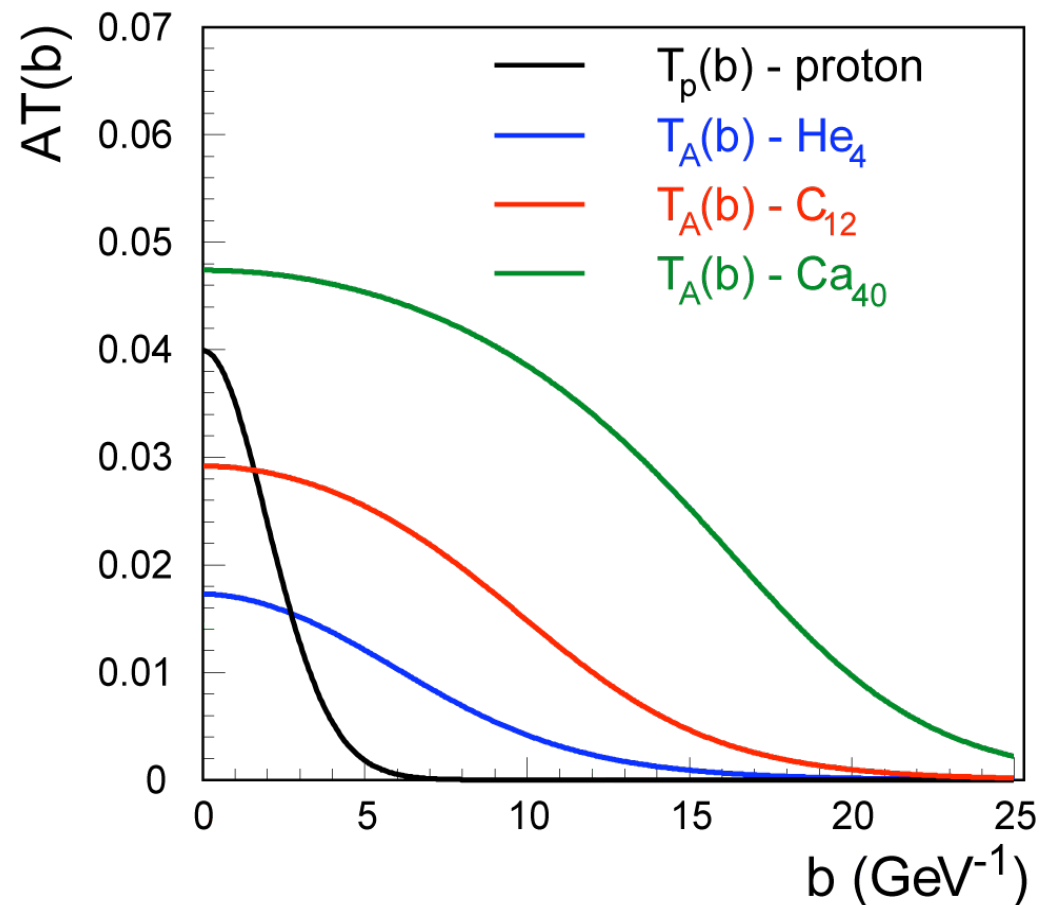
Munier, Peschanski;...

**Possible P-loop effects in forward gluon
production in p+p and p+A at the LHC**

Iancu, Marquet, Soyez, hep-ph/0605174,
Shoshi, Xiao, hep-ph/0612053

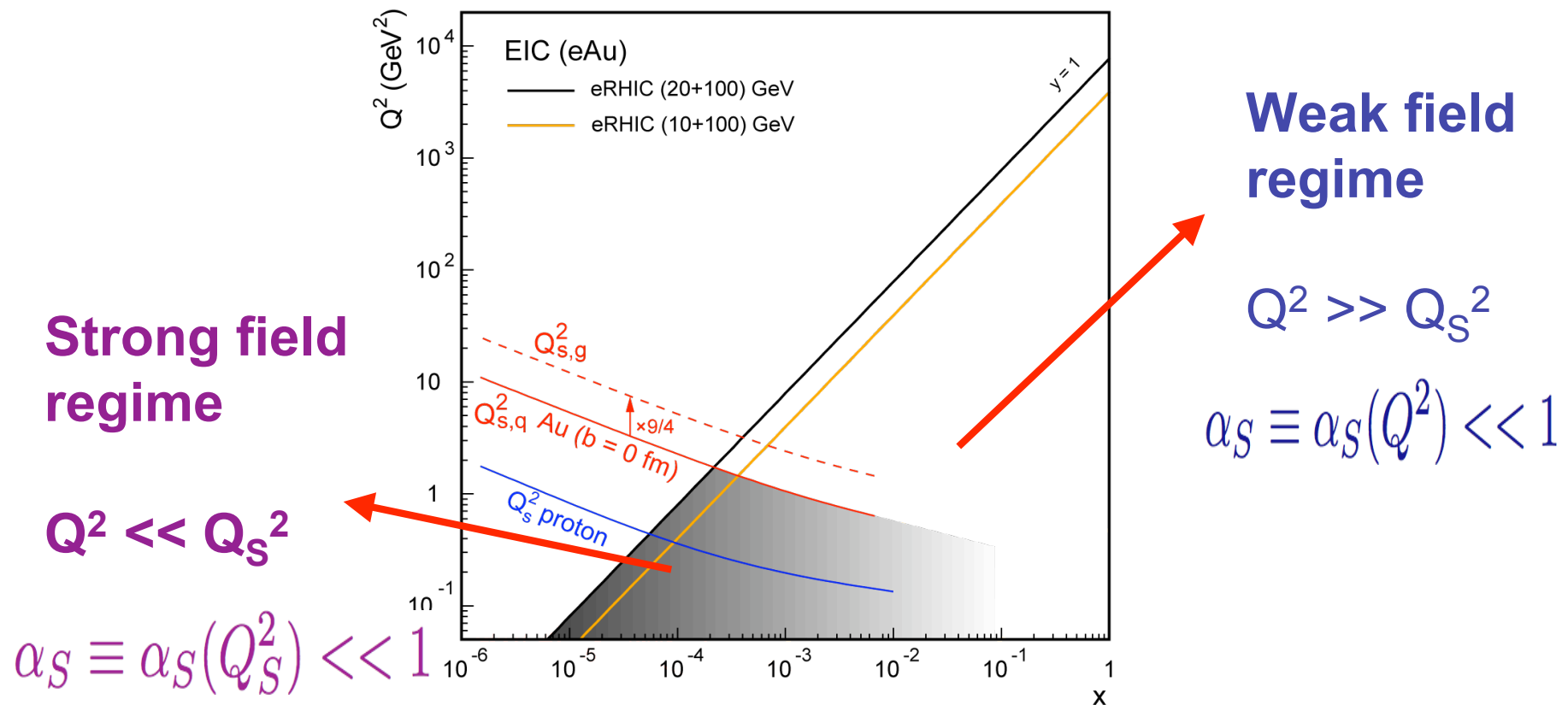
Strong color fields may be more accessible in eA collisions relative to ep

Nuclear profile more uniform-can study centrality dependence of distributions



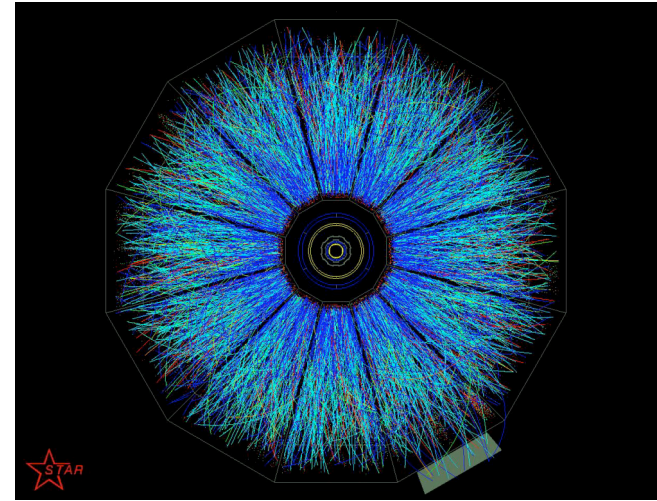
In eA DIS, cleanly access cross-over region from weak field to novel strong field QCD dynamics ?

(Talks by Surrow/Newman)



Qualitative change in final states: eg.,
 $1/Q^6 \rightarrow 1/Q^2$ change in elastic vector meson production

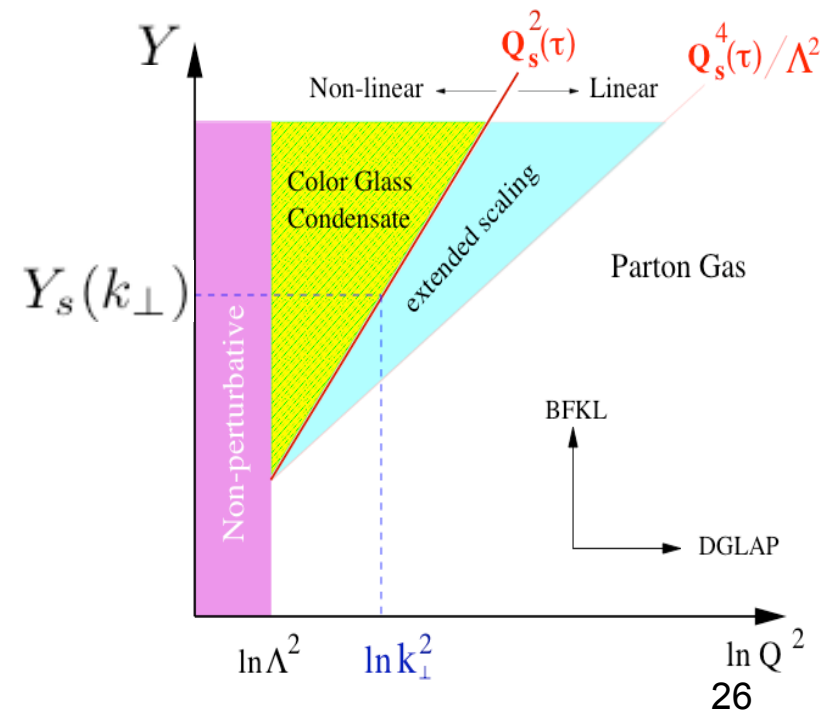
Can we compute
multiparticle production
ab initio in AA collisions ?



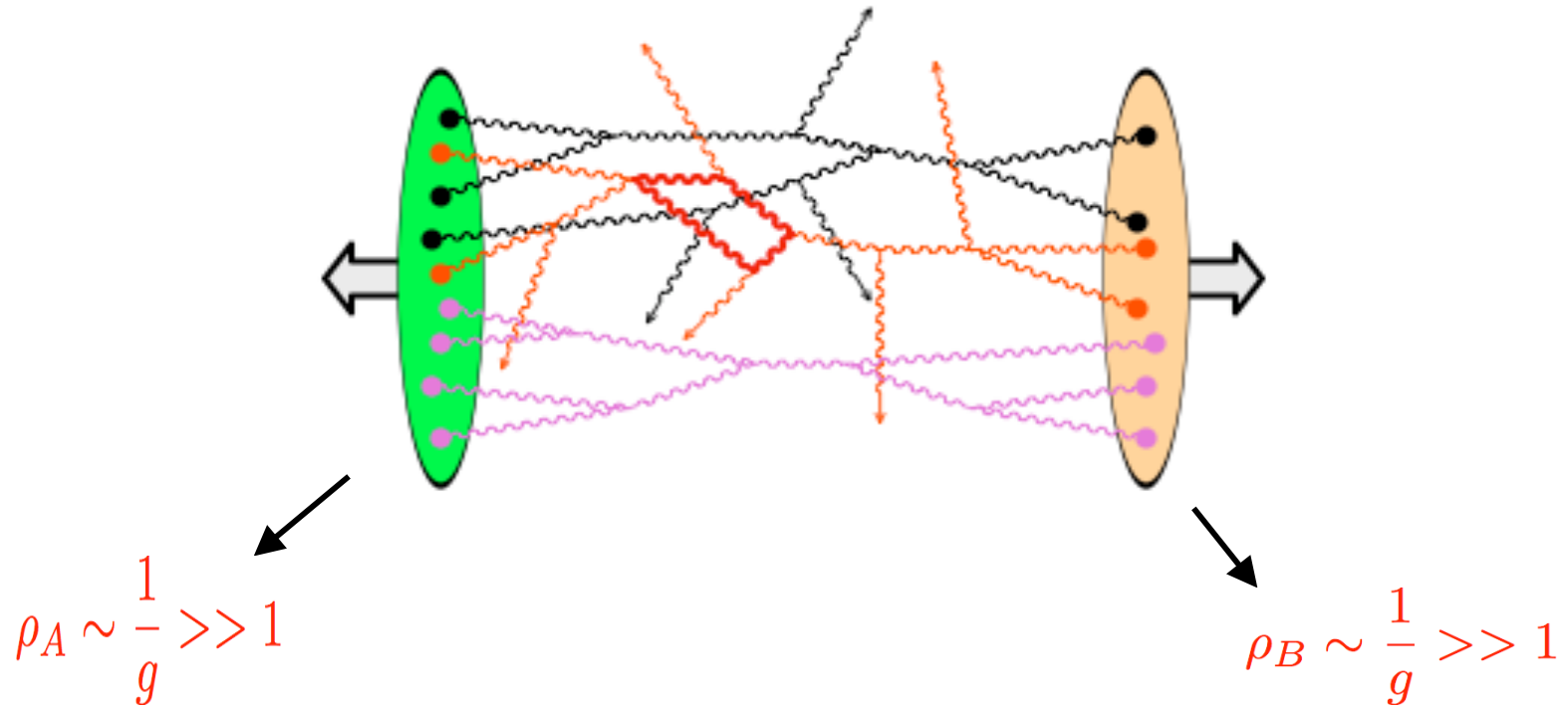
Framework:
CGC- classical fields
+ **strong** sources

$$\alpha_S(Q_s) \ll 1$$

$$\rho \sim \frac{1}{g} \left(\equiv \frac{1}{\sqrt{\alpha_S}} \right) \gg 1$$



Probability to produce $n \gg 1$ particles in HI collisions:



P_n obtained from cut **vacuum** graphs in field theories with strong sources.

General formula:

$$P_n = e^{-\frac{1}{g^2}} \sum_r b_r \sum_{p=1}^n \frac{1}{p!} \sum_{\alpha_1 + \dots + \alpha_p = n} \frac{b_{\alpha_1} \dots b_{\alpha_p}}{g^{2p}}$$

b_r - probability of vacuum-vacuum diagrams with r cuts

“cumulants” (Gyulassy-Kauffman)

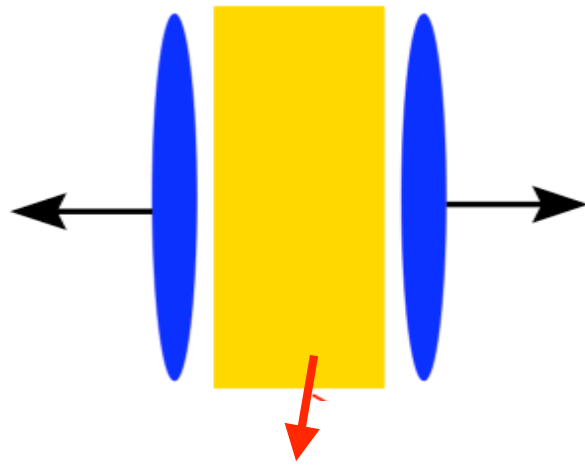
Observations:

- P_n is non-perturbative even for $g \ll 1$
- Even at tree level, P_n is *not a Poisson dist.*
- AGK rules understood as general properties of cut vacuum graphs in field theories with sources (CGC)

Straightforward power counting in g for inclusive multiplicity/energy dists.

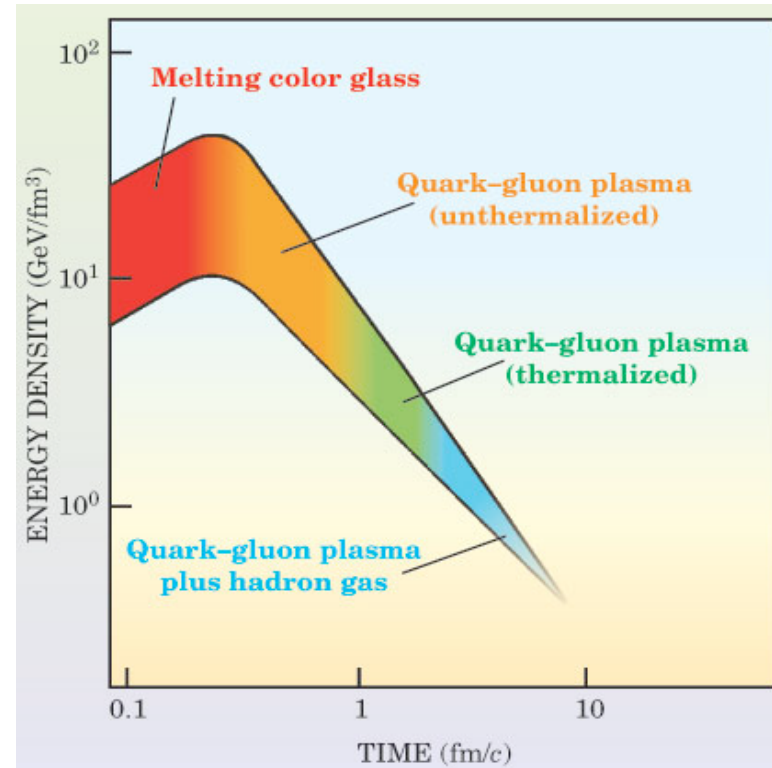
Glasma (\Glahs-maa\): non-equilibrium phase between CGC & QGP

T.Lappi & L. McLerran;
Kharzeev, Krasnitz, RV



Classical Fields with

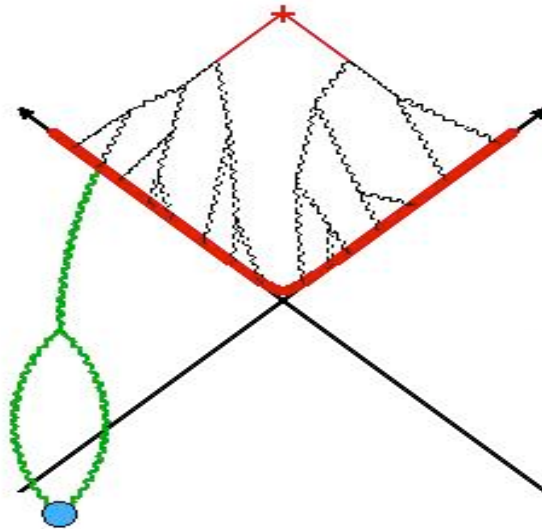
$$\text{occupation \# } f = \frac{1}{\alpha_S}$$



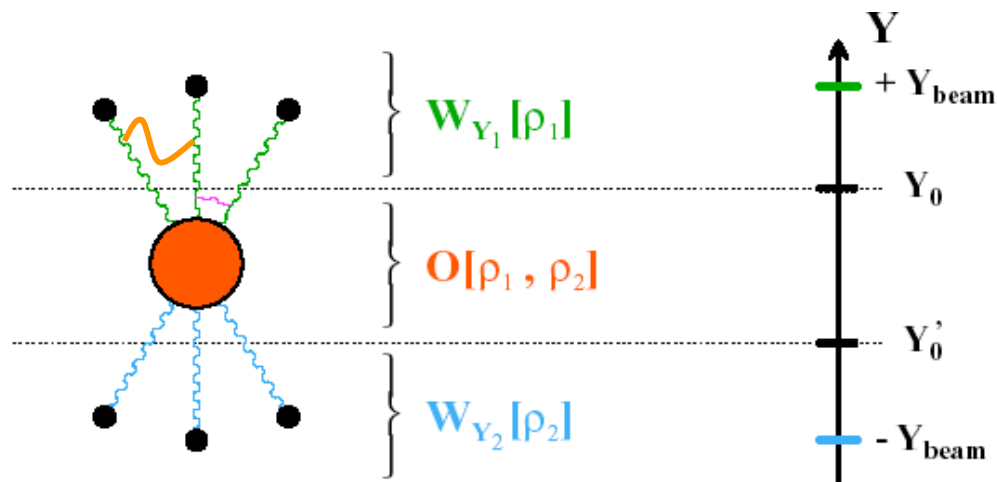
Given CGC initial conditions, can study space-time evolution of strong gluon fields

Small x quantum fluctuations on light cone
induce **(Weibel) instabilities** in classical fields
- may speed up thermalization

Romatschke, RV
Fukushima, Gelis, McLerran



High energy factorization important for NLO estimate



Gelis, Lappi, RV

Balitsky;
Fadin et al.

Outstanding questions in high energy QCD

(QCD Theory Workshop, DC, Dec. 15th-16th, 2006)

❖ What is the nature of glue at high density ?

❖ How do strong fields appear in hadronic or nuclear wavefunctions at high energies ?

(saturation/CGC/Reggeon Field Theory)

❖ How do they respond to external probes or scattering ?

(rapidity gaps, color transparency/opacity, energy loss)

❖ What are the appropriate degrees of freedom ?

(dipoles, pomerons, classical fields)

❖ Is this response universal ? (ep,pp,eA, pA, AA)

(collinear/ kT factorization)

Bright future for small x physics at the LHC and a future Electron Ion Collider (EIC, LHeC)