Initial Stages

(pA, initial state, approach to equilibrium: Observables and Concepts)

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Quark Matter 2014 - Students day - Darmstadt - May 2014

@CASSalgado @HotLHC

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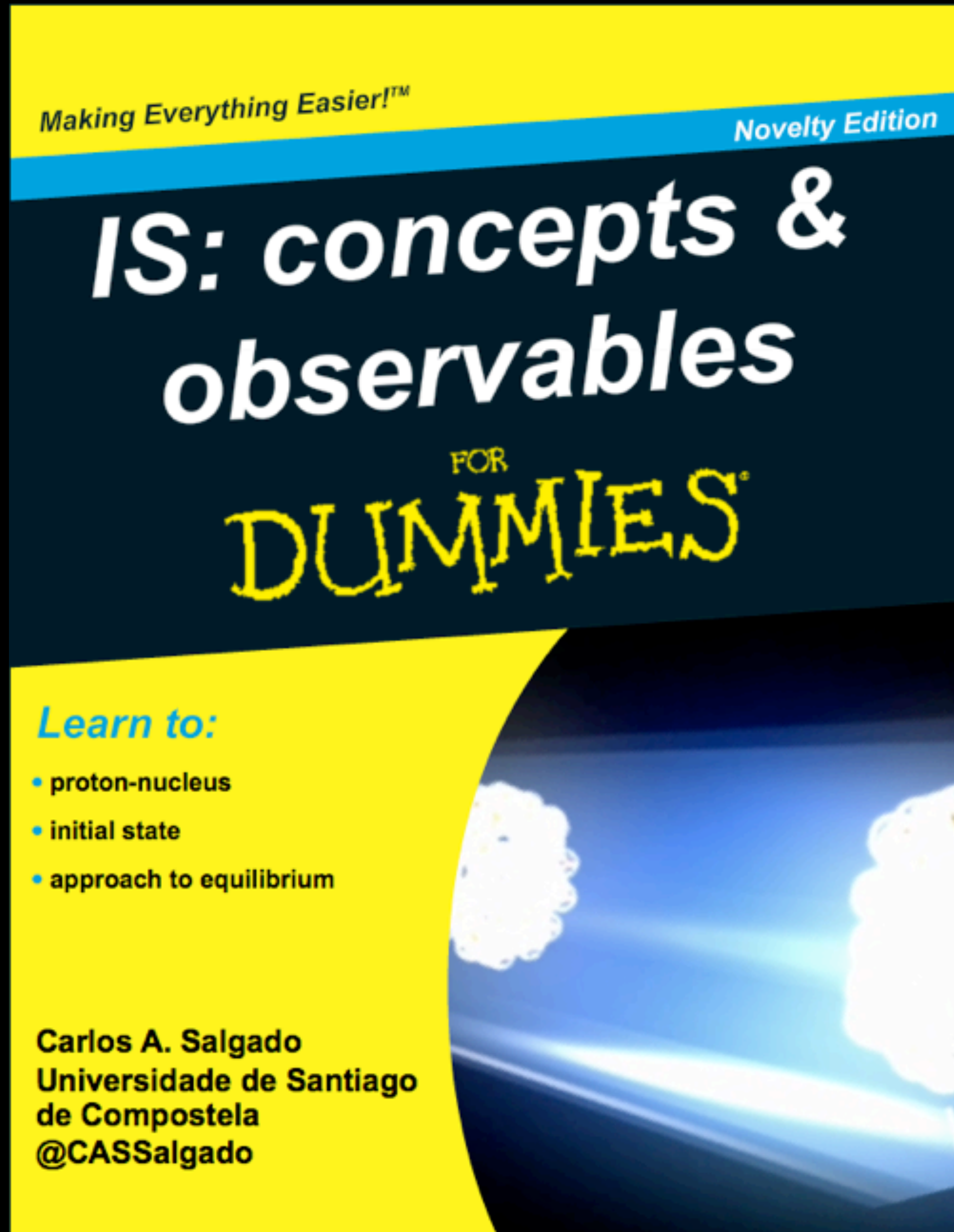
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Learn to:
• proton-nucleus
• initial state
• approach to equilibrium
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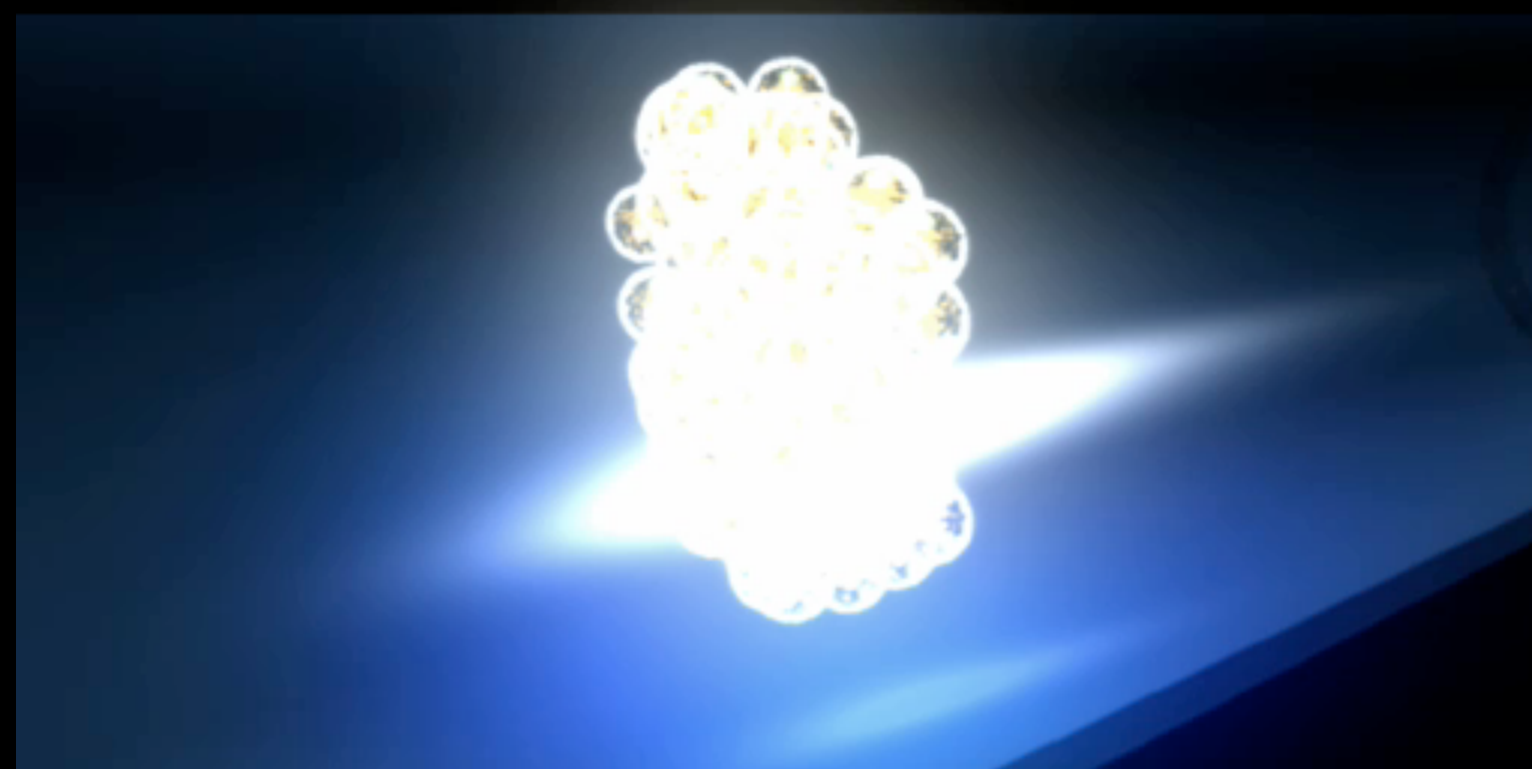
INITIAL STAGES

↳ Structure of the colliding objects

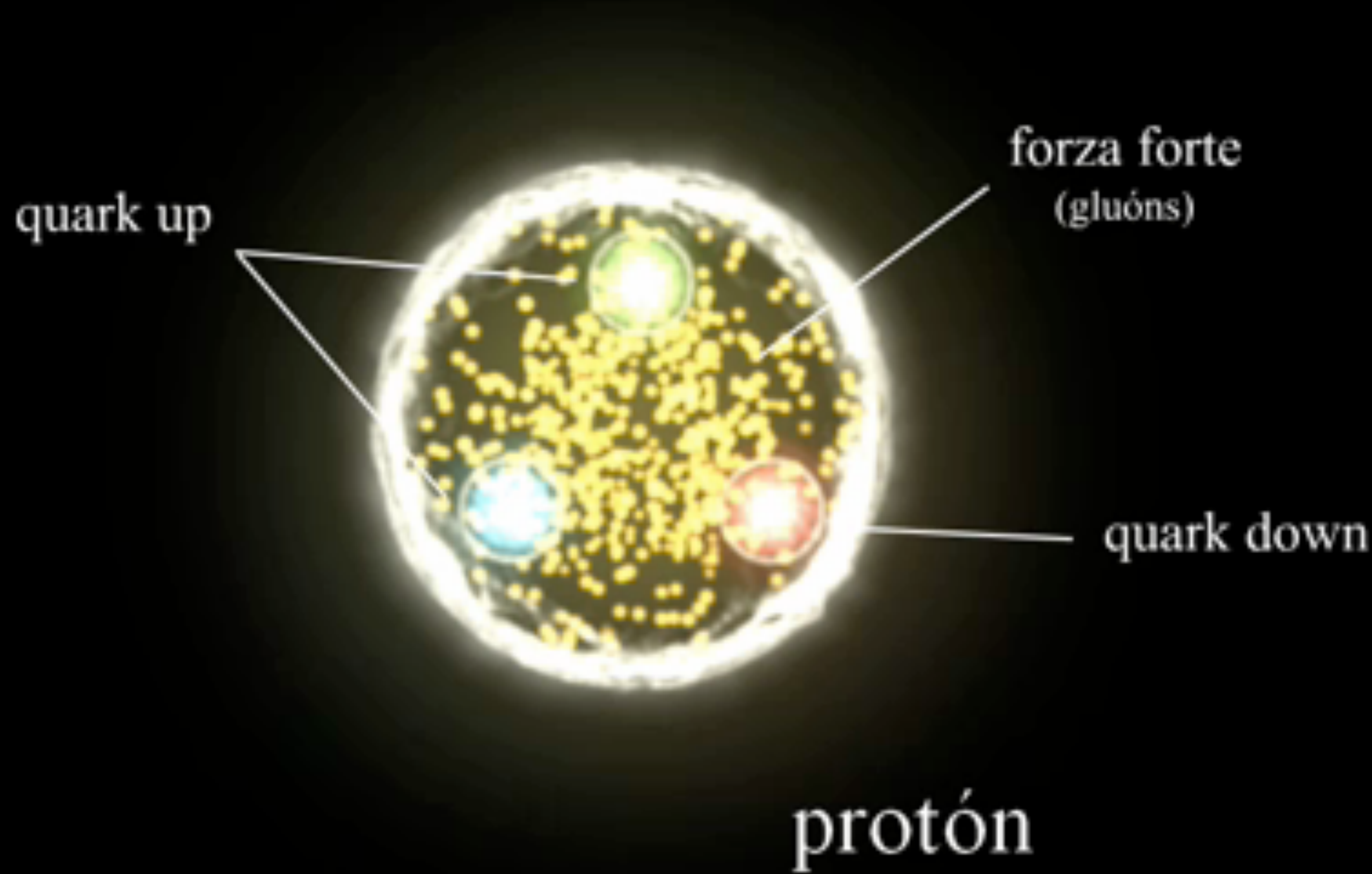
↳ Built of collective behavior



Structure of the colliding objects

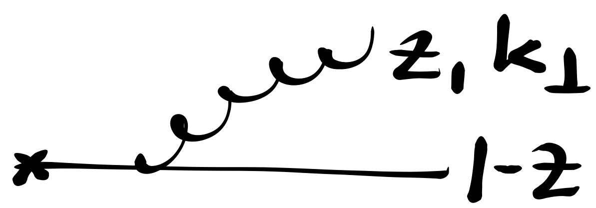
QCD is a Quantum Field Theory

↳ Quantum fluctuations ↔ virtual particles



Splitting probability: the building block

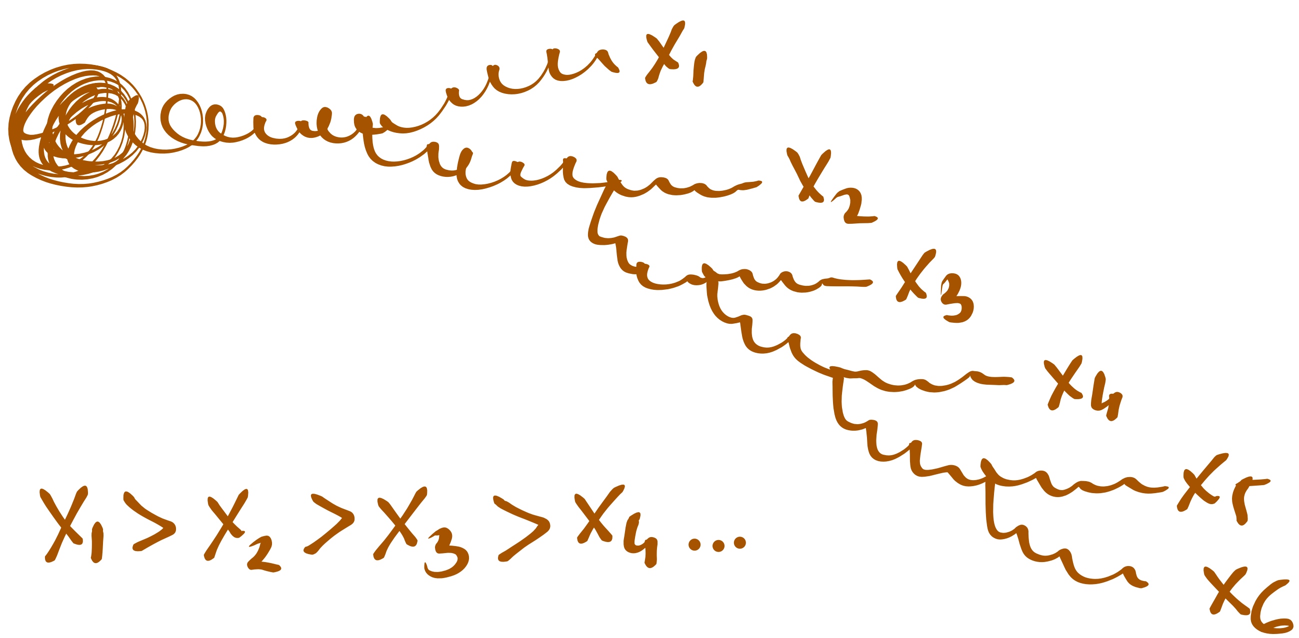
The splitting probability of an off-shell parton computed in pQCD



$$dP(z,\theta) \sim \alpha_s \frac{dz}{z}\frac{d\theta}{\theta}$$

Soft and collinear divergent

- Large probability to emit soft and collinear gluons
- Divergencies need to be resumed (renormalization techniques)



$$x_1 > x_2 > x_3 > x_4 \dots$$

The picture is a shower of partons produced by subsequent splittings

Heuristic: Collision "counts" partons

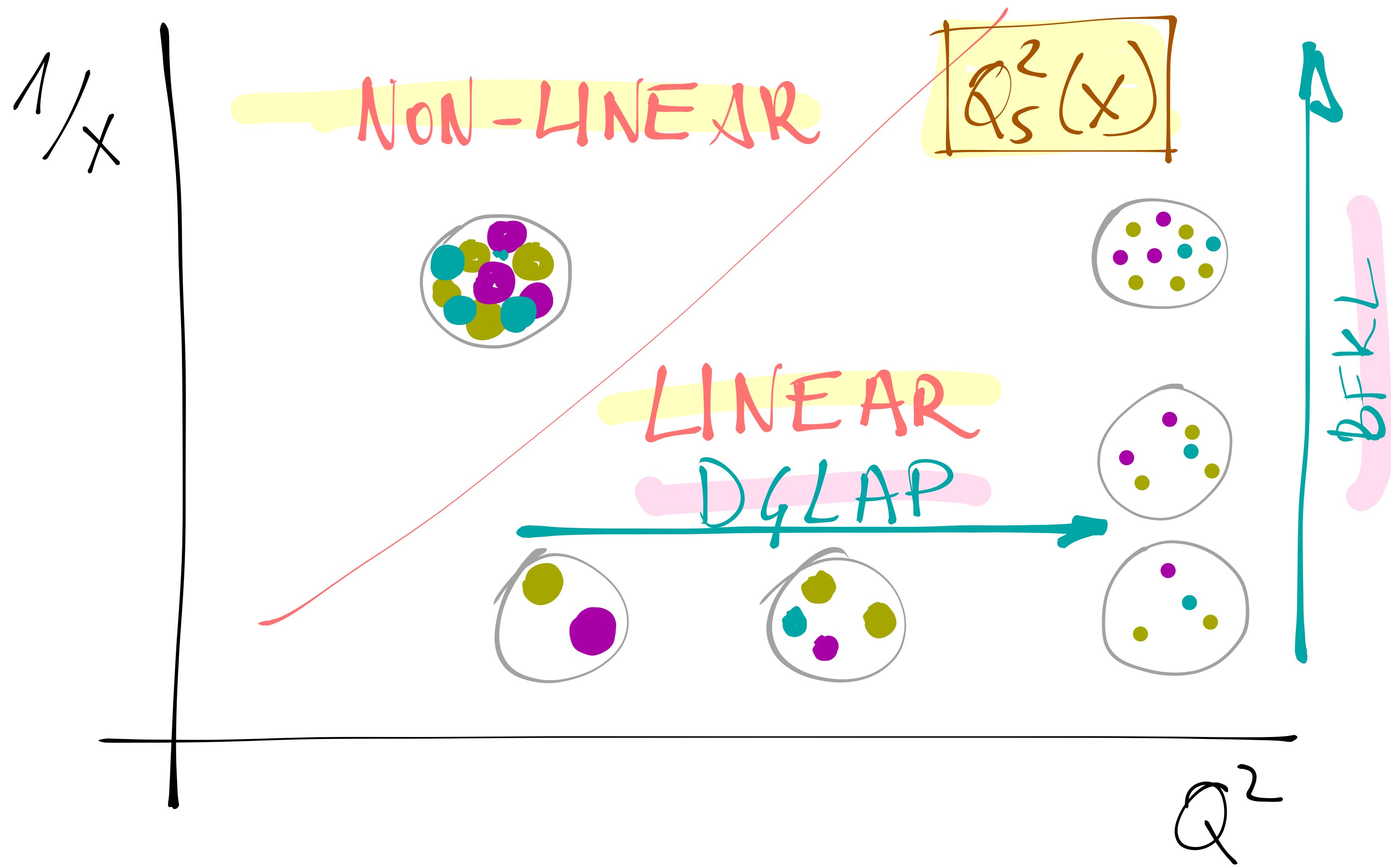
(Incoherent) cross section proportional to the number of partons in hadron

- Quantum fluctuations put on-shell by the probe

Lifetime of the fluctuation of the order of the size of the probe

- The probe cannot resolve smaller fluctuations (stay virtual)
- Harder probes resolve smaller components (basic idea of pQCD factorization)

Quantum fluctuations: Linear/non-linear dynamics



Different kinematical regions: dominated by different dynamics

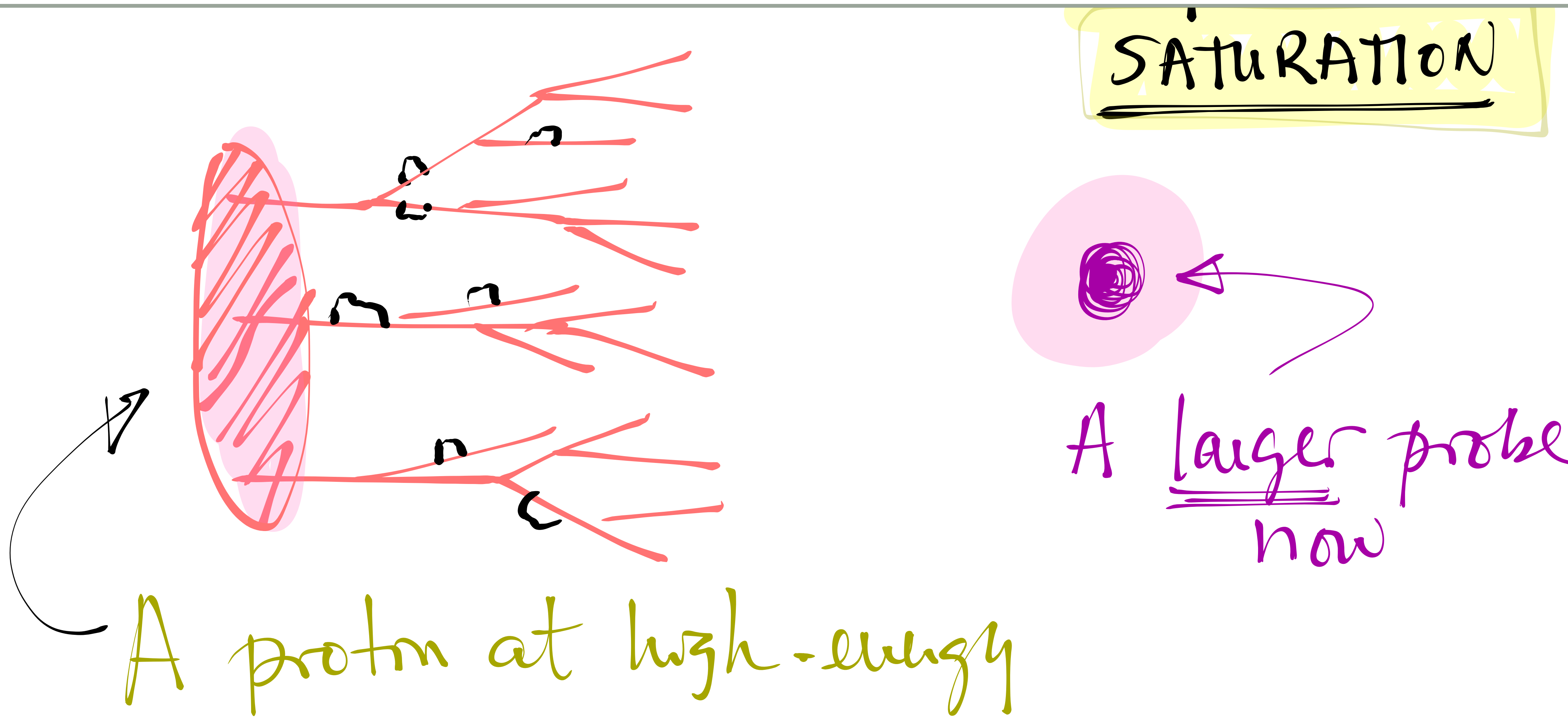
- Large-Q : Linear
- Small-x : Non-linear (eventually)

Where is the boundary? (Information from experiment needed)

Heuristic: Collision “counts” partons II

Coherent cross section: the probe can interact with more than one parton

- TAMES the cross section



Saturation of partonic densities (gluon fusion) - aka Color Glass Condensate

- **<u>Color correlations</u> among different partons in the proton/nucleus** linear

DGLAP equations [Dokshitzer, Gribov, Lipatov, Altarelli, Parisi, 70's]

Parton Distribution Functions (PDFs)

$$f_i(x, Q^2)$$

- "Number" of partons of type *i* inside the proton/nucleus with a fraction of momentum *x*

DGLAP eqs

$$\frac{\partial f(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z} P(z) f\left(\frac{x}{z}, Q^2\right)$$

$$= \frac{\alpha_s}{2\pi}\int dz \int dy\, \delta(zy-x)\, P(z)\, f(y,Q^2)$$

Clear probabilistic interpretation

- Larger scale probe smaller distances where more splittings are resolved - number increases

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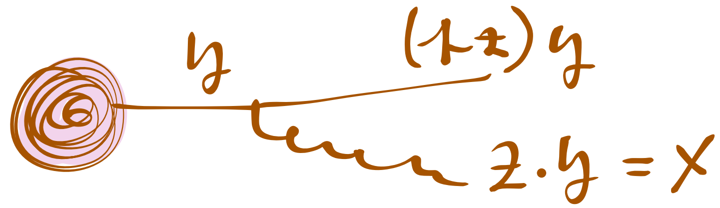
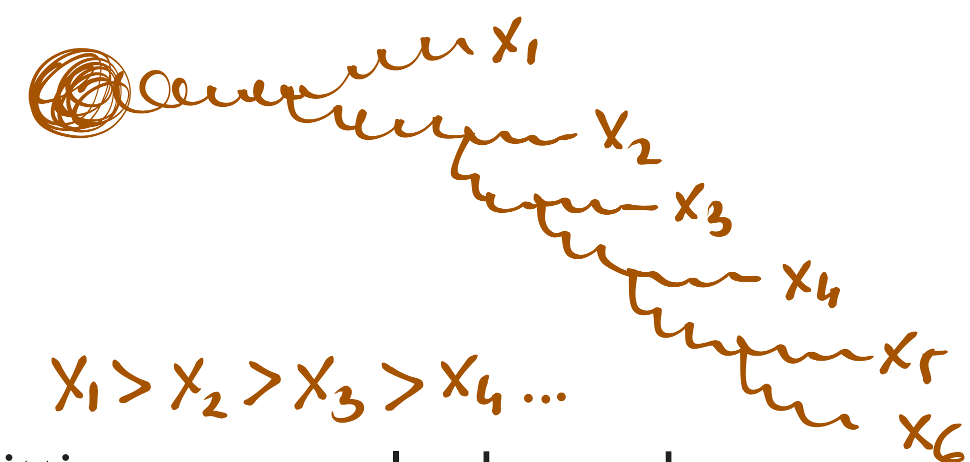




Clear probabilistic interpretation

- Larger scale probe smaller distances where more splittings are resolved - number increases

DGLAP and global fits

Full DGLAP are a set of coupled differential equations

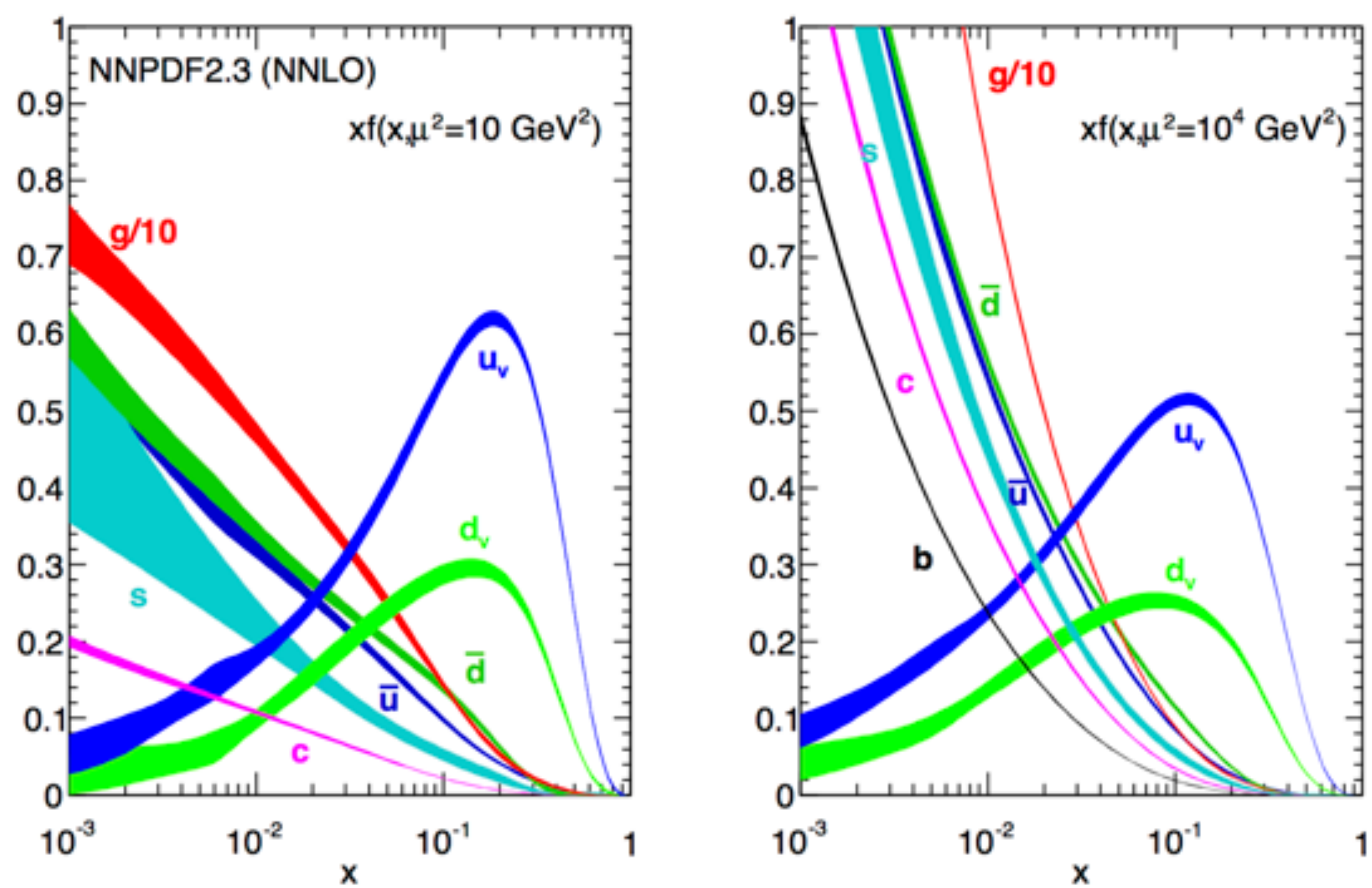
- Different parton content during evolution

$$\frac{\partial q_i}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\sum_j P_{q_i q_j} \otimes q_j + P_{q_i g} \otimes g\right]$$

$$\frac{\partial g}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\left[\sum_j P_{g q_j} \otimes q_j + P_{gg} \otimes g\right]$$

Global fits

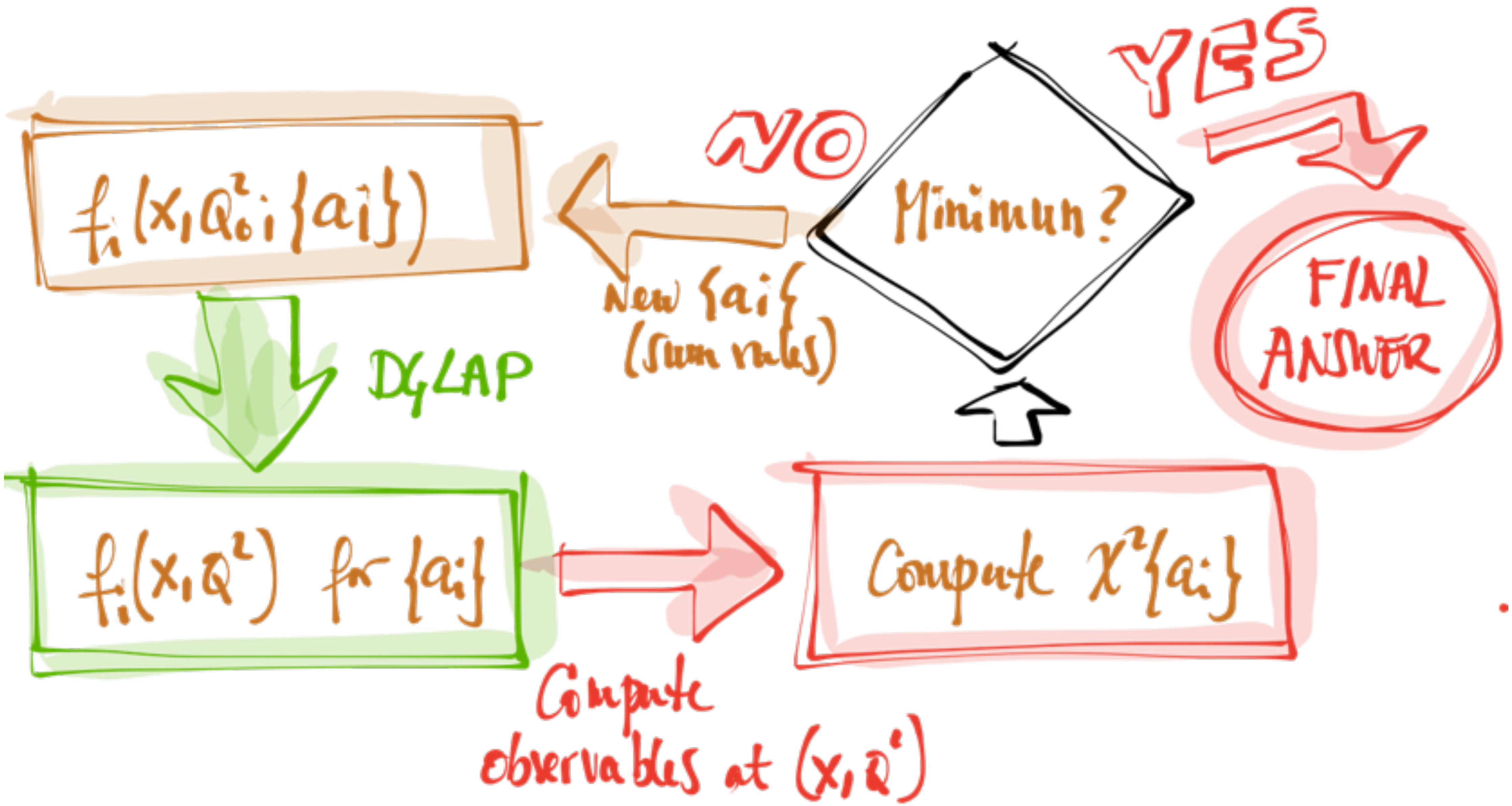
- Initial conditions for the evolution obtained from data



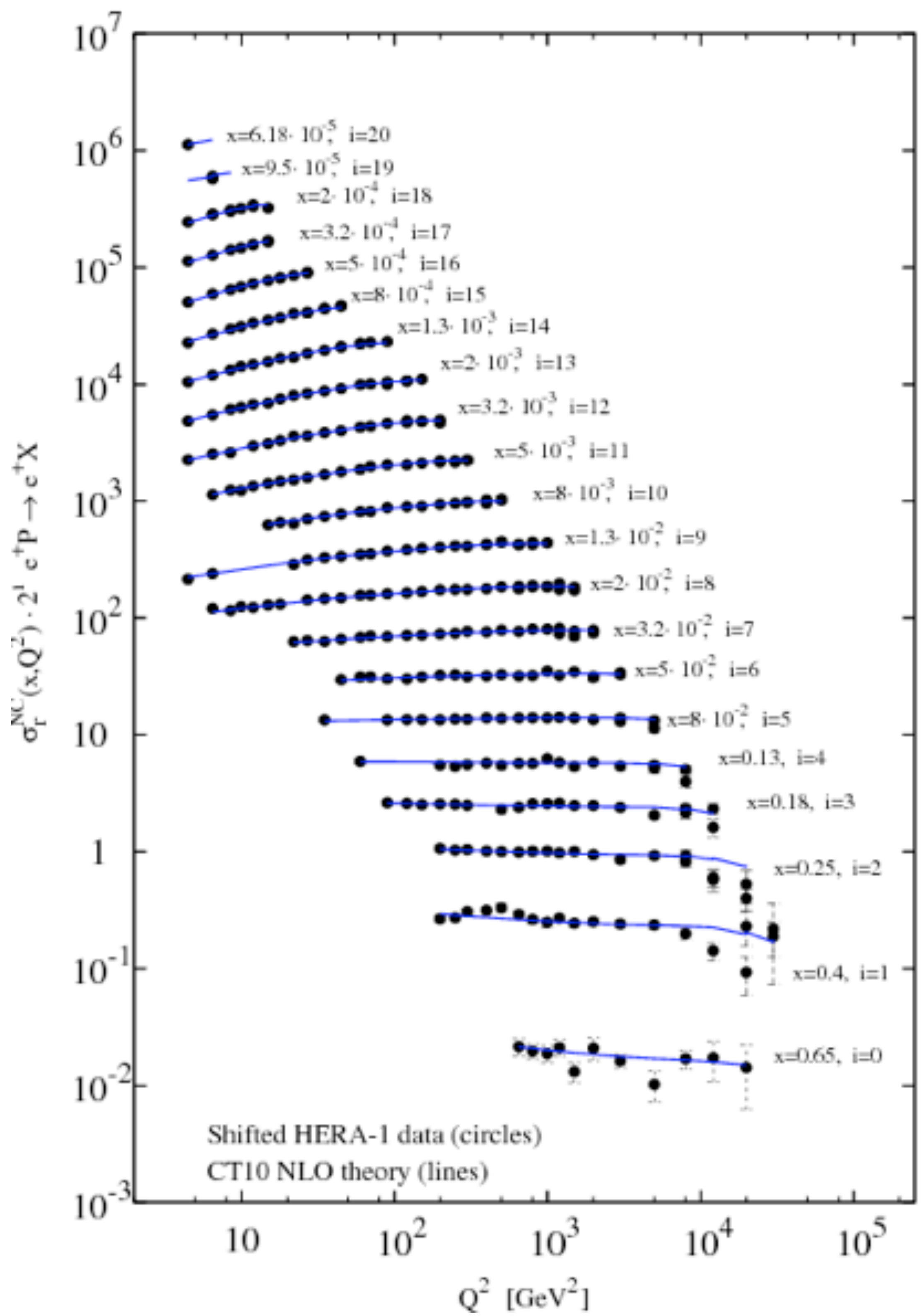
Plot from http://nnpdf.hepforge.org

DGLAP approach: Global fits

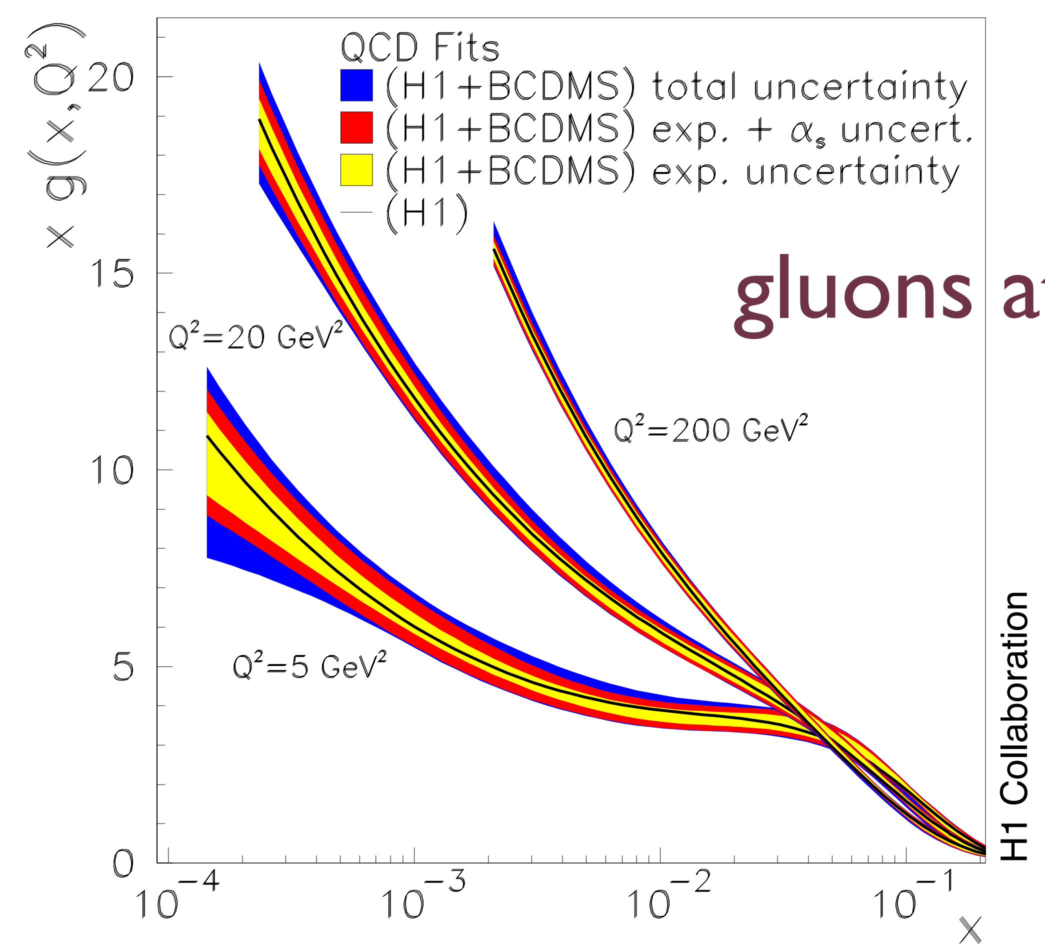
- **One of the most standardized procedures in High-Energy Physics.**
- Main goal: provide a set of Parton Distribution Functions (PDFs)



Proton PDFs and DIS data



- The initial conditions for evolution (non-perturbative) extracted from data in global fits - using different observables and systems



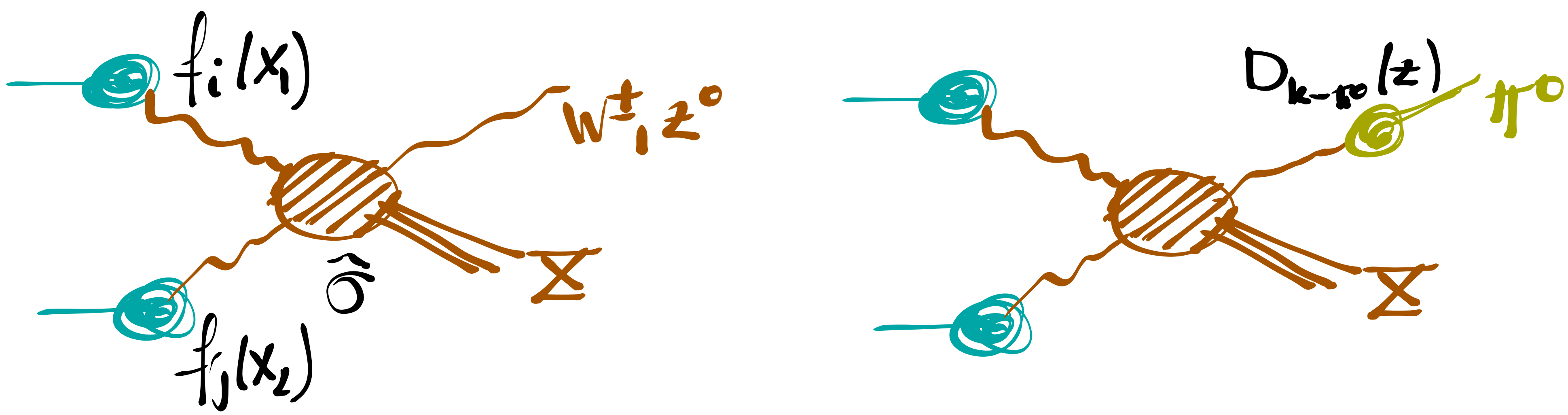
gluons at NLO

Collinear factorization

Collinear factorization

$$\sigma^{AB\to h} = f_i^A(x_1,Q^2) \otimes f_j^B(x_2,Q^2) \otimes \hat{\sigma}^{ij\to h}$$

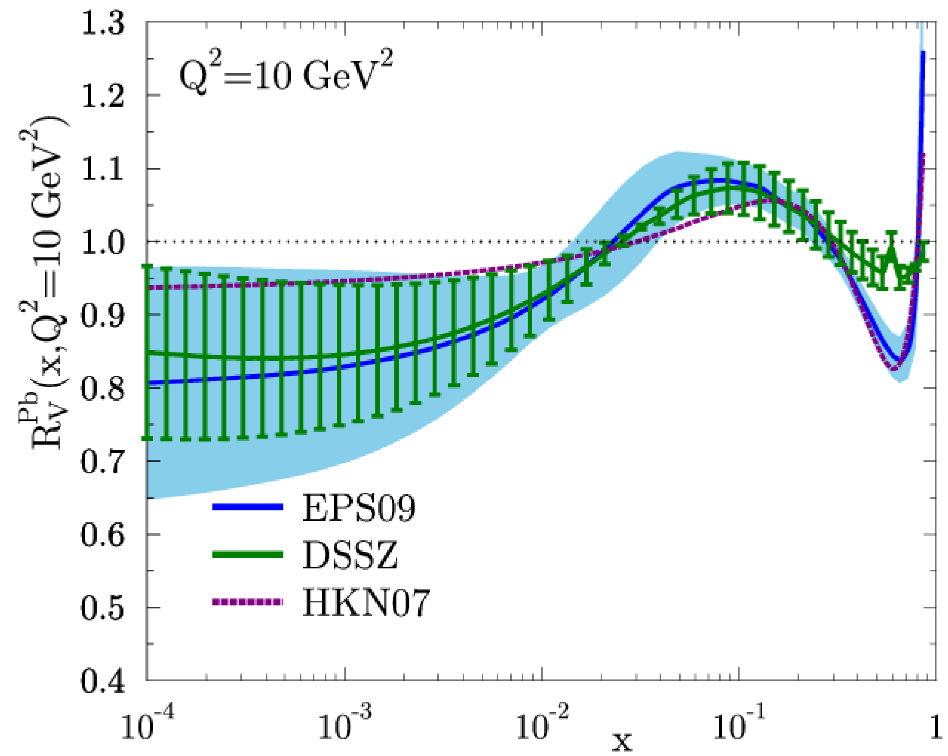
- A hard cross section is the convolution of **universal** PDFs and partonic cross sections

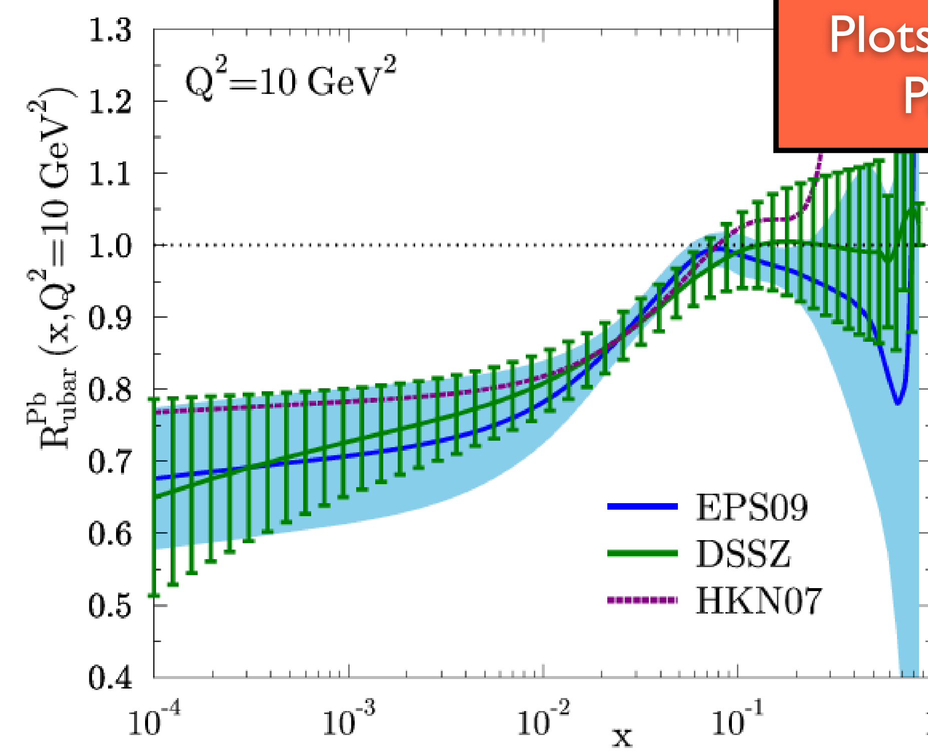


Factorization of long-distance and short distance terms in the cross section

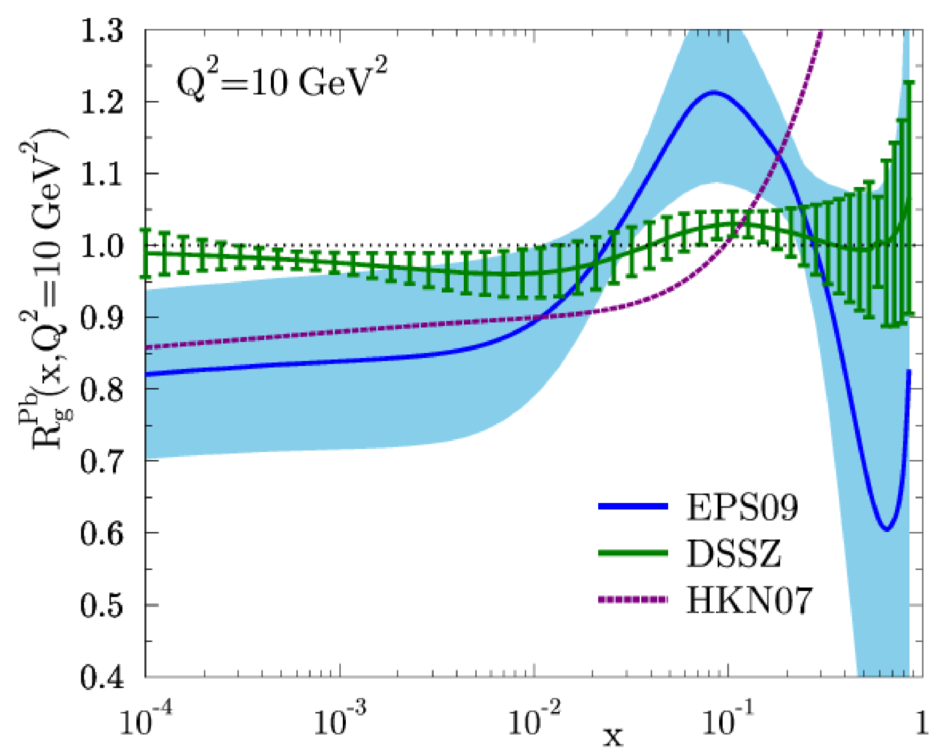
- Short-distance (perturbative) in the partonic cross section
- Long-distance (non-perturbative) in the PDFs and Fragmentation Functions (FF)

Global fits for nucleus





Plots from Hannu Paukkunen



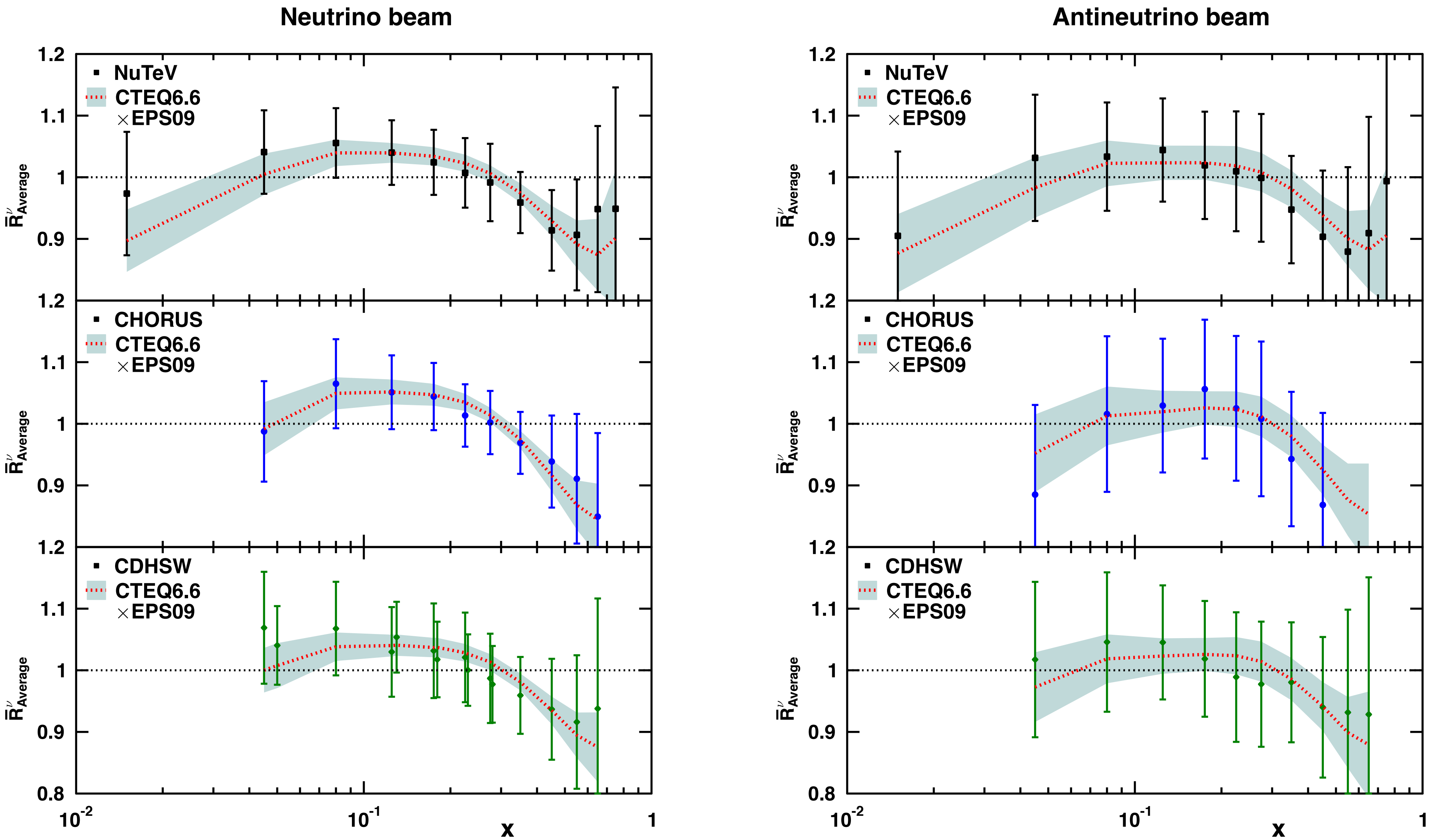
Ratios of the PDF of a proton inside a nucleus over that in a free proton

- Isospin effects may be important (e.g. W production in pPb@LHC)

$$R_i^A(x,Q^2) = \frac{f_i^{p/A}(x,Q^2)}{f_i^p(x,Q^2)}$$

DGLAP approach - Some recent results I

- **Agreement of EPS09 with neutrino DIS data**



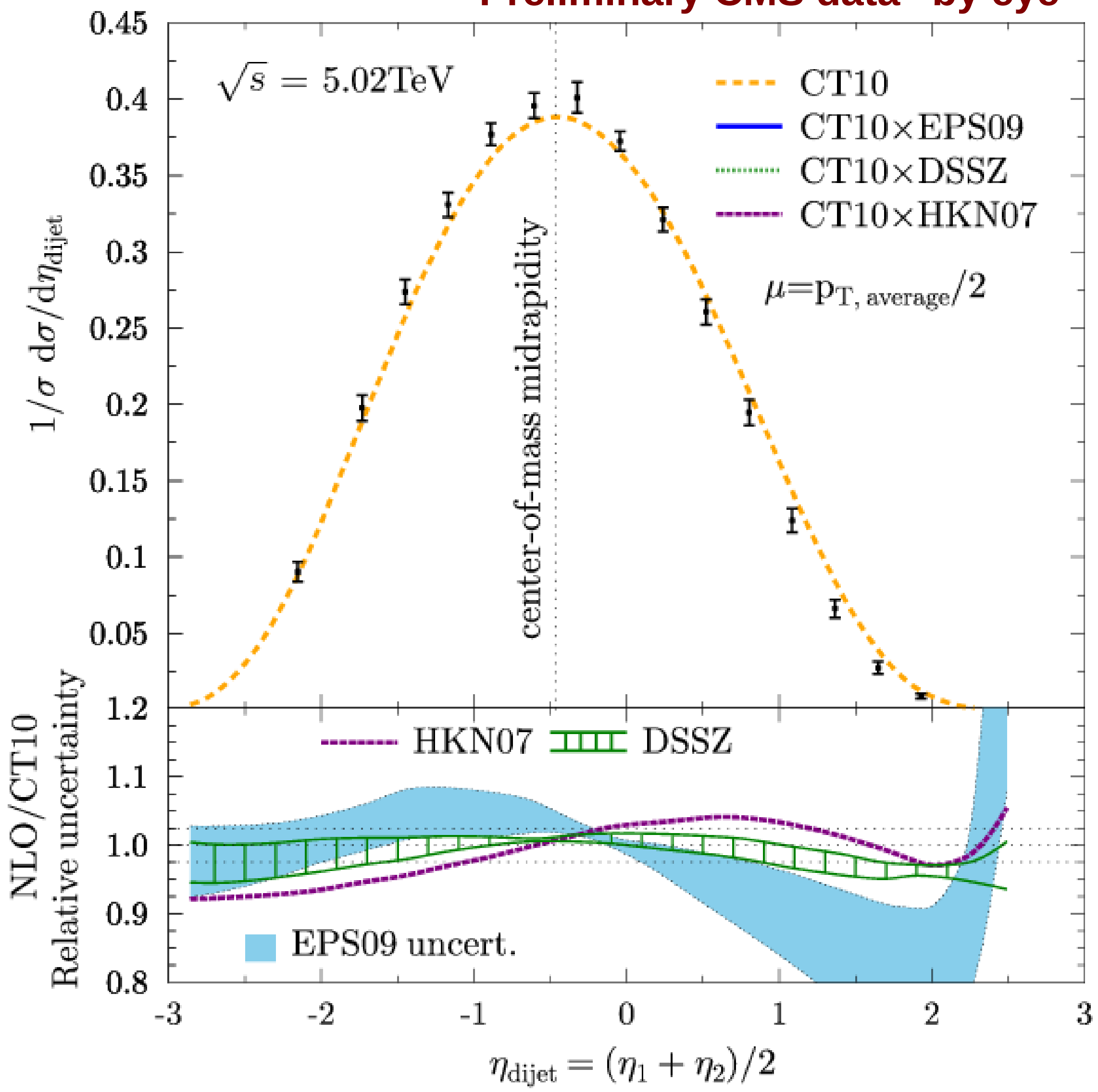
[Paukkunen, Salgado, 2013]

- **Collinear factorization works - universal set of nPDFs**
- Neutrino data important for proton global fits

DGLAP approach - Some recent results II

- **Dijet data in proton-nucleus collisions at LHC - CMS**

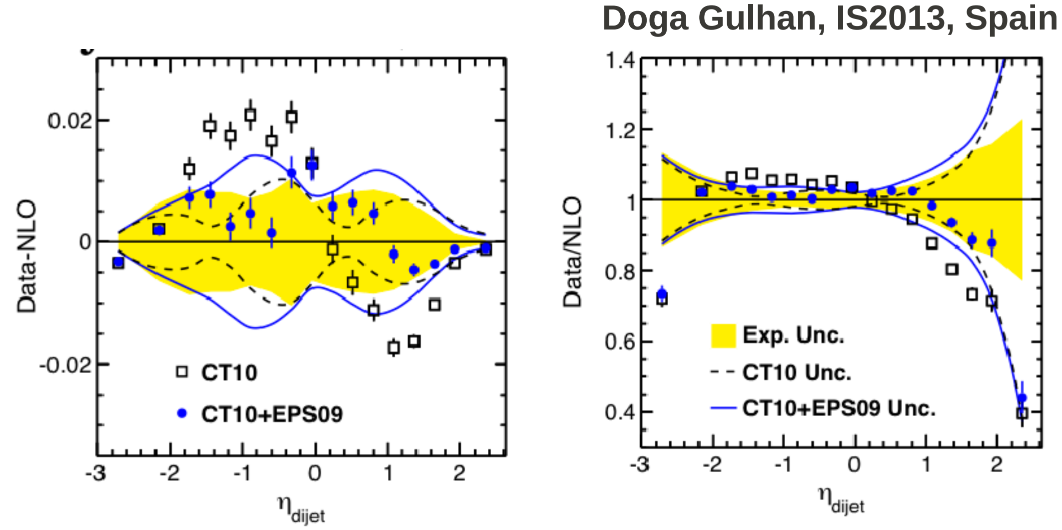
Preliminary CMS data "by eye"



[Eskola, Paukkunen, Salgado, 2013]

[Plots from Paukkunen - LHeC workshop - Jan 2014]

Doga Gulhan, IS2013, Spain



Much more at this Quark Matter

DGLAP approach - Some recent results II

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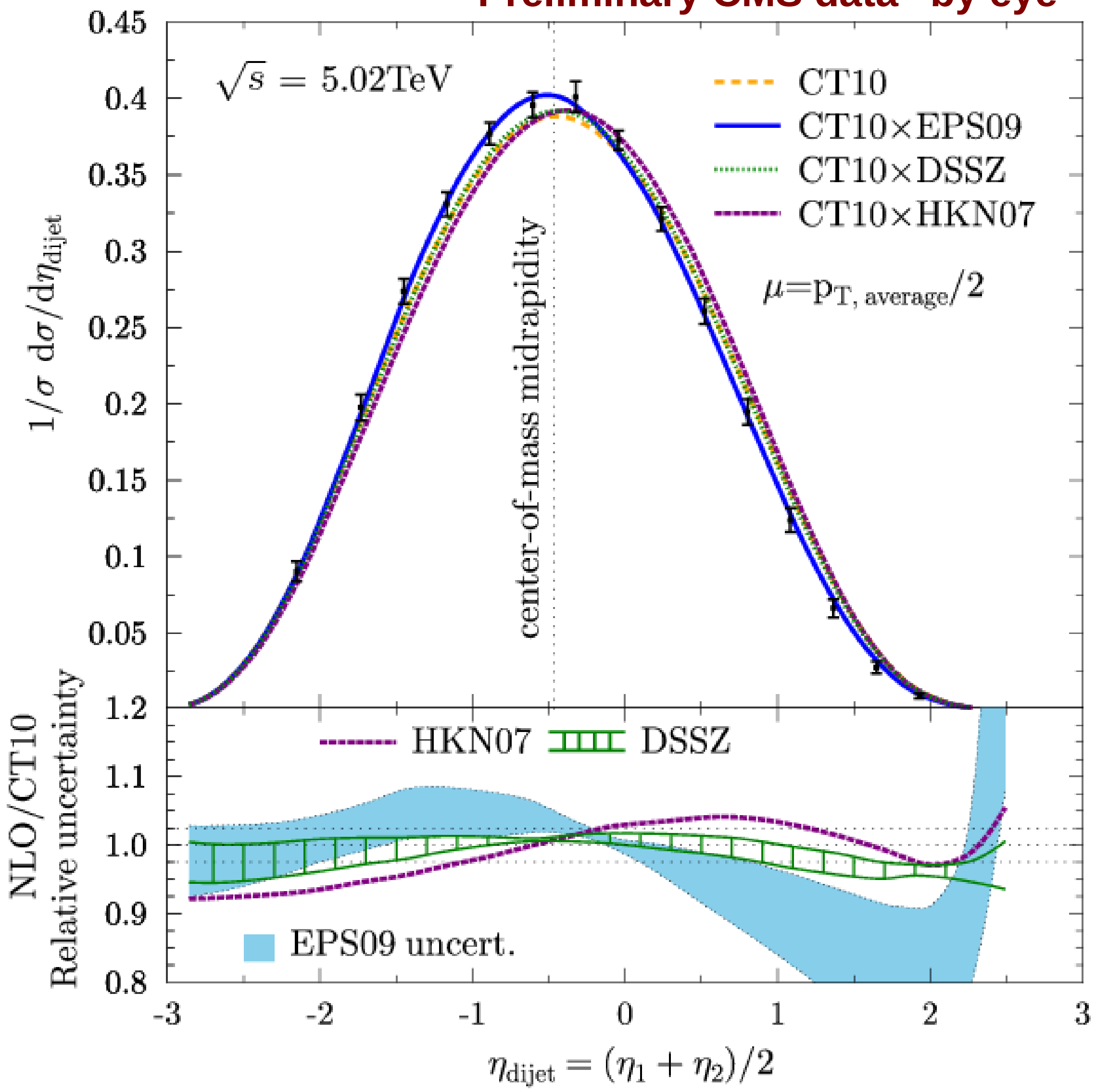

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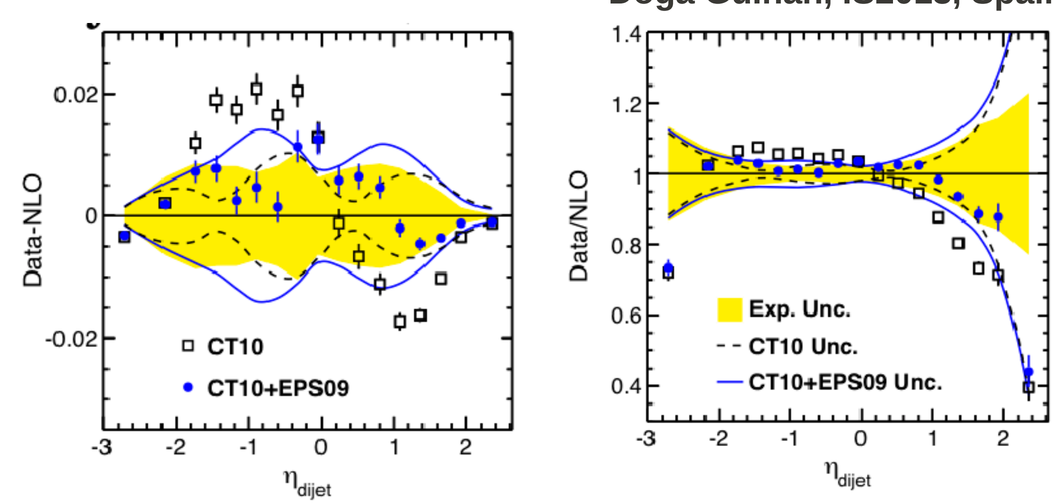


Much more at this Quark Matter

Linear evolution — DGLAP

Concepts

- * Gluon multiplication
- * Dilute regime
- * Universal PDFs
  - ↳ Factorization

Observables

- * DIS ep/eA
- * hard processes
- * R_{pA}
- * New EW observables

ALSO: Cold nuclear matter effects on hadronization
↳ Energy loss
↳ Quarkonia suppression...

From Dilute to Dense

Parton Saturation

Color Correlation in the transverse plane → $1/Q_{sat}$

Color Glass Condensate → General framework

From Dilute to Dense

Parton Saturation

Color Correlation in the transverse plane → $1/Q_{sat}$

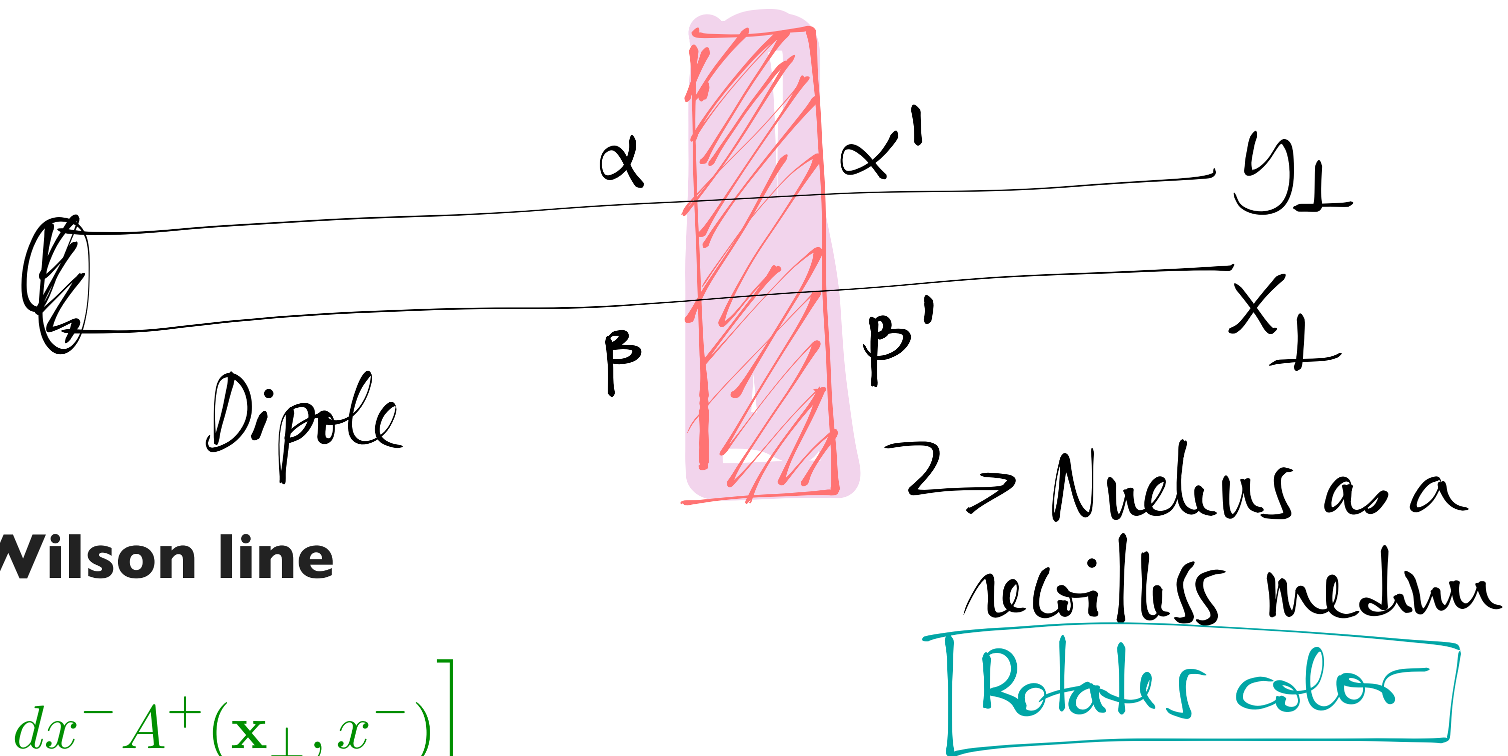
Color Glass Condensate → General framework

$$Q_{sat}^2 \sim \frac{xg(x,Q_{sat}^2)}{\pi R^2} \sim \frac{A^{1/3}}{x^{\lambda}}$$

Saturation in the dipole picture

A convenient way of discussing the problem is the dipole picture

- A dipole measures the **color correlations** in transverse plane



Propagator of the quark - Wilson line

$$W(\mathbf{x}) = \mathcal{P} \exp \left[i \int dx^- A^+(\mathbf{x}_\perp, x^-) \right]$$

So that the S-matrix is $|\alpha'; \beta'\rangle \equiv S_{\alpha'\beta'\alpha\beta} |\alpha; \beta\rangle = W_{\alpha'\alpha}(\mathbf{x}_\perp) W^\dagger_{\beta'\beta}(\bar{\mathbf{x}}_\perp) |\alpha; \beta\rangle$

and the total interaction probability (cross section w/ needed factors)

$$P^{q\bar{q}}_{\rm tot} = \left\langle 2 - \frac{2}{N_C} {\rm Tr} \left[W(\mathbf{x}_\perp) W^\dagger(\bar{\mathbf{x}}_\perp) \right] \right\rangle$$

Medium averages

All the medium properties are encoded in the averages of Wilson lines

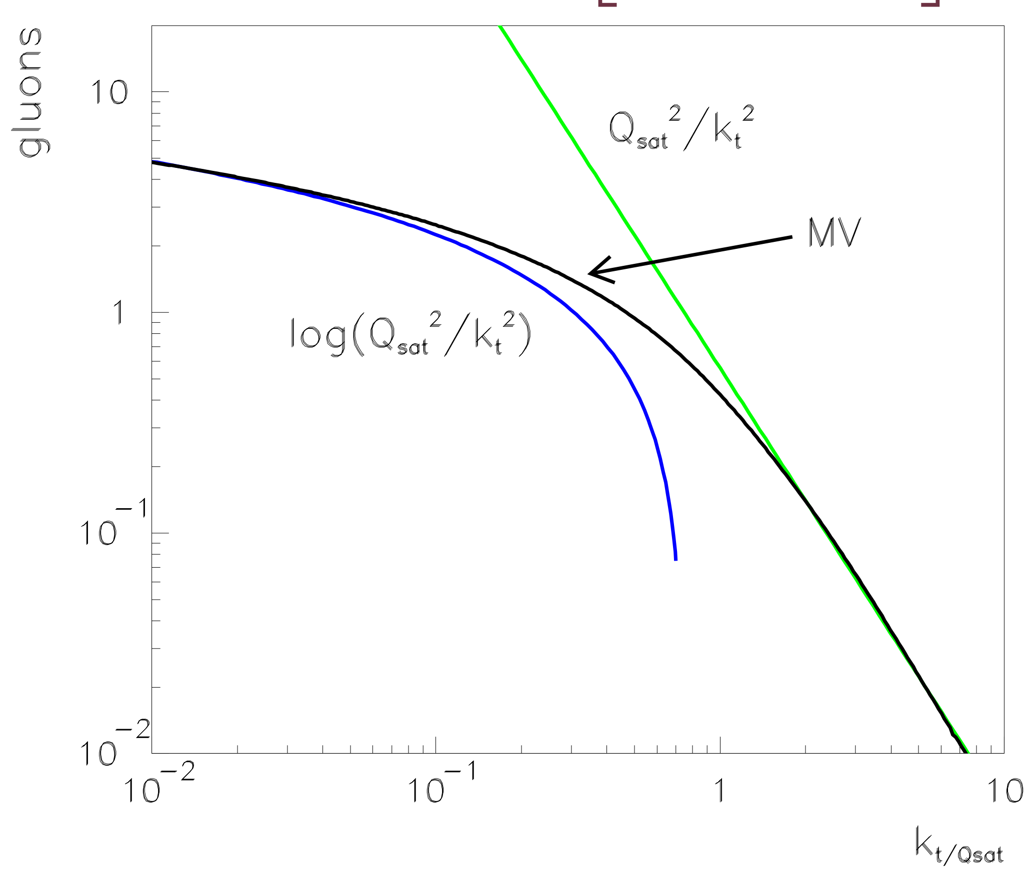
- Several prescriptions used. Here, just focus on a simple one

$$\frac{1}{N}\mathrm{Tr}\left\langle W(\mathbf{x}_\perp)W^\dagger(\bar{\mathbf{x}}_\perp)\right\rangle \approx \exp\left\{-\frac{1}{8}Q^2_{\mathrm{sat}}(\mathbf{x}_\perp-\bar{\mathbf{x}}_\perp)^2\right\}$$

The dipole "counts" the number of gluons, the unintegrated gluon distribution

$$N(r) = 1-\exp\left[-\frac{1}{8}Q^2_{\mathrm{sat}}r^2\right] \quad \Longrightarrow \quad \phi(k) = \int \frac{d^2r}{2\pi r^2}\mathrm{e}^{i\mathbf{r}.\mathbf{k}}N(r)$$

[up to logs: McLerran, Venugopalan 1994]



Two important consequences

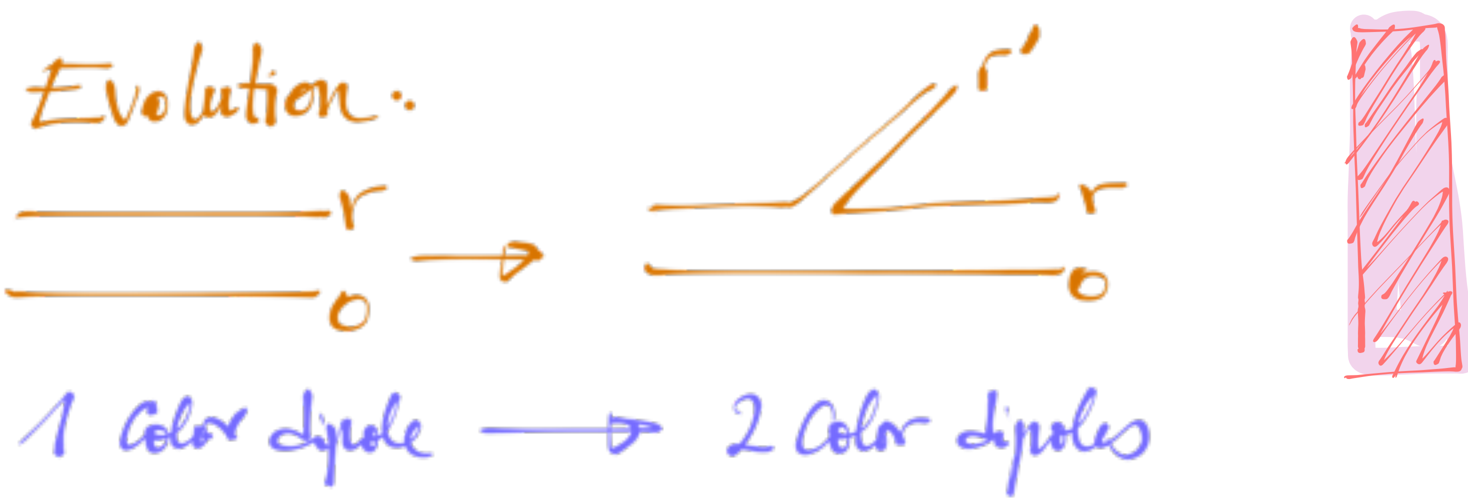
- Qsat cuts-off the low momentum
- Geometric scaling

$$\phi = \phi(k^2/Q^2_{\mathrm{sat}})$$

QCD evolution

A way of including QCD evolution in the dipole picture (in *x*)

- Boost the dipole: the splitting probability can be computed
- Use the large-N limit



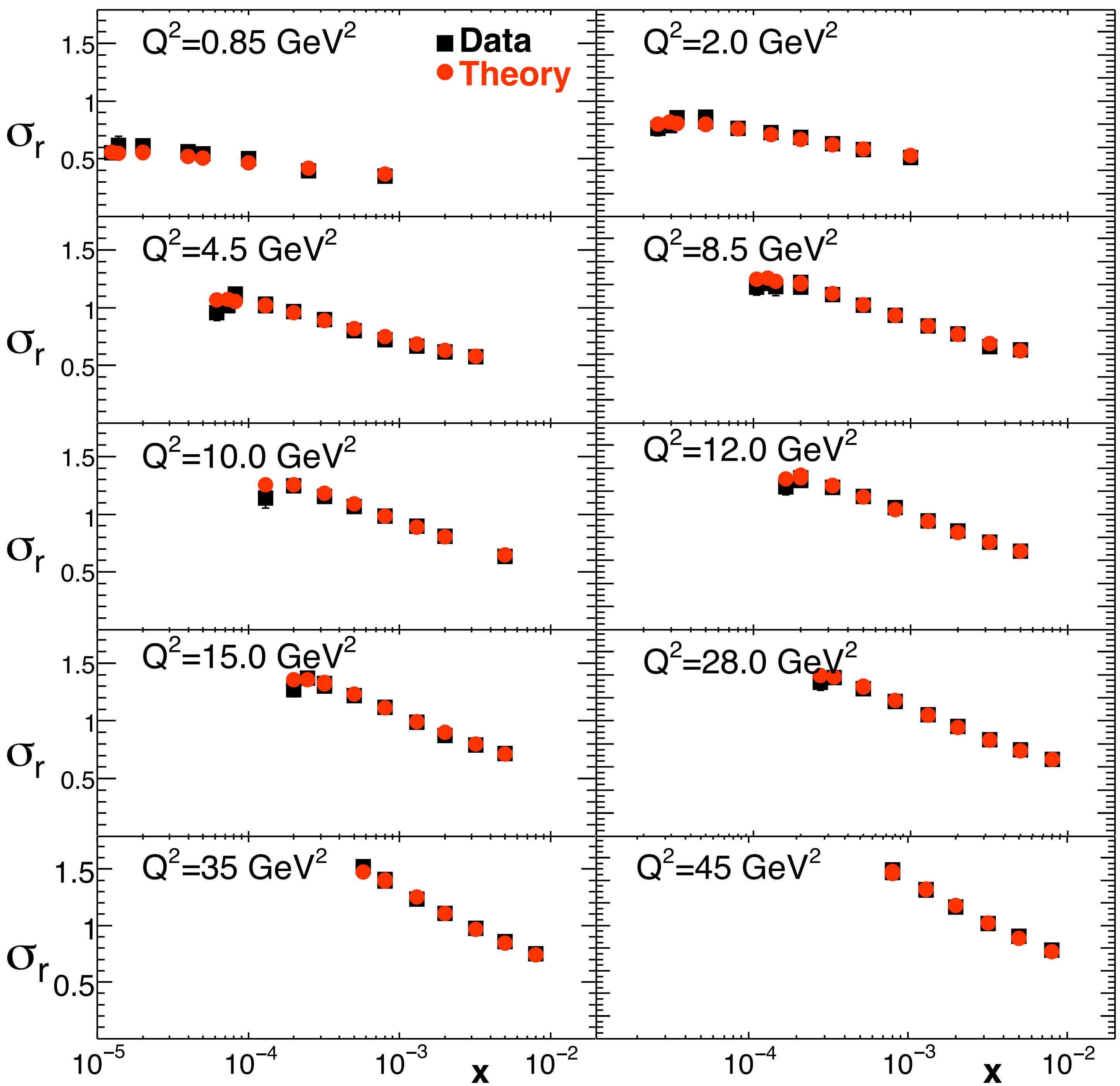
BFKL

$$\frac{\partial N(r,y)}{\partial y} = \int d^2r' \, K(r,r') \left[N(r') + N(r-r') - N(r) - N(r')N(r-r') \right]$$

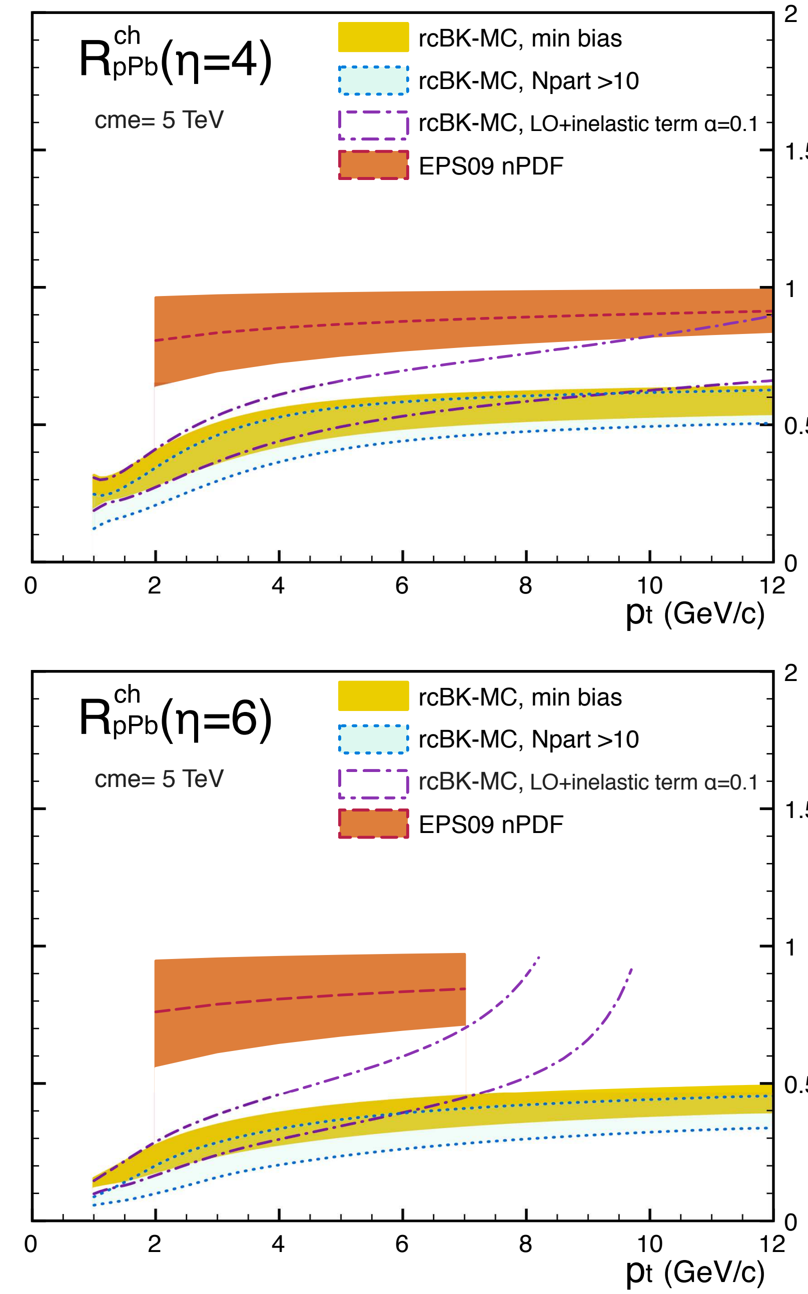
[Balitsky-Kovchegov eqs]

Fits using BK evolution

[AAMQs - 2010]



[Albacete, Dumitru, Marquet 2013]

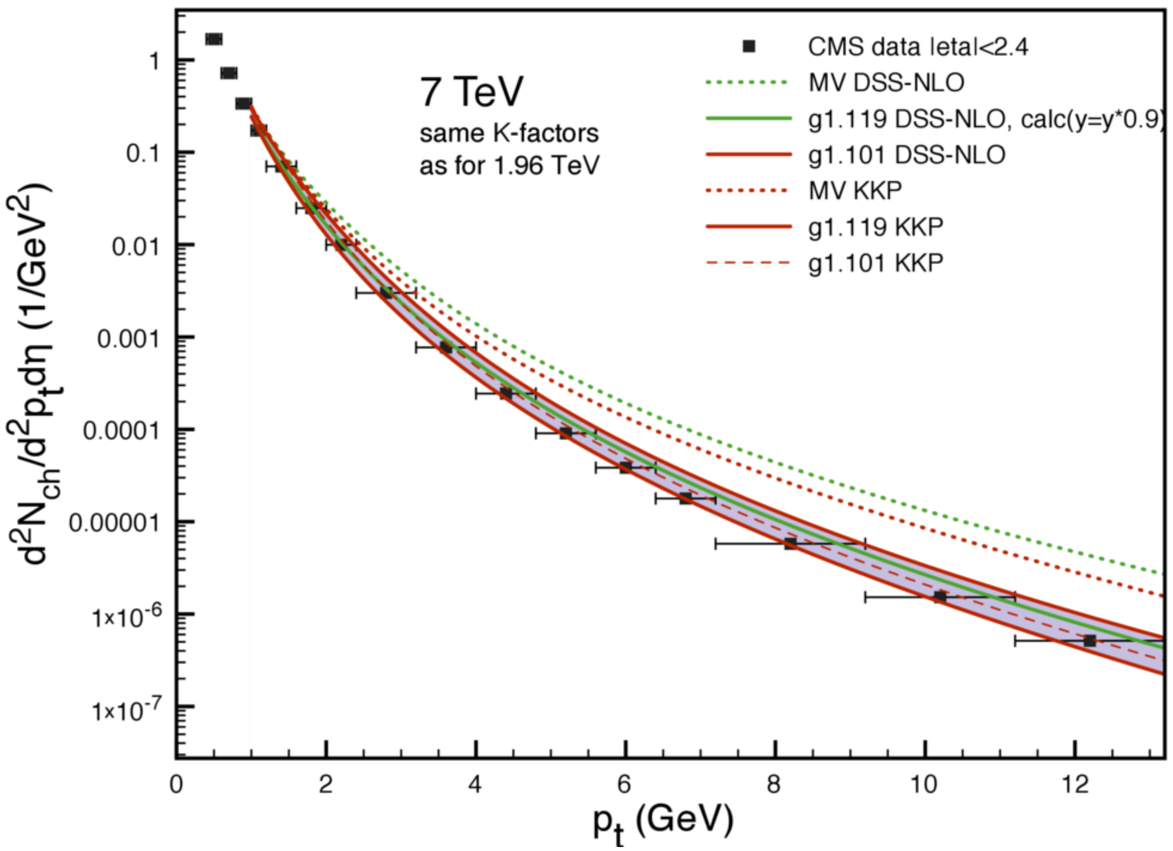


- **Checks of validity of the formalism with proton-nucleus data**

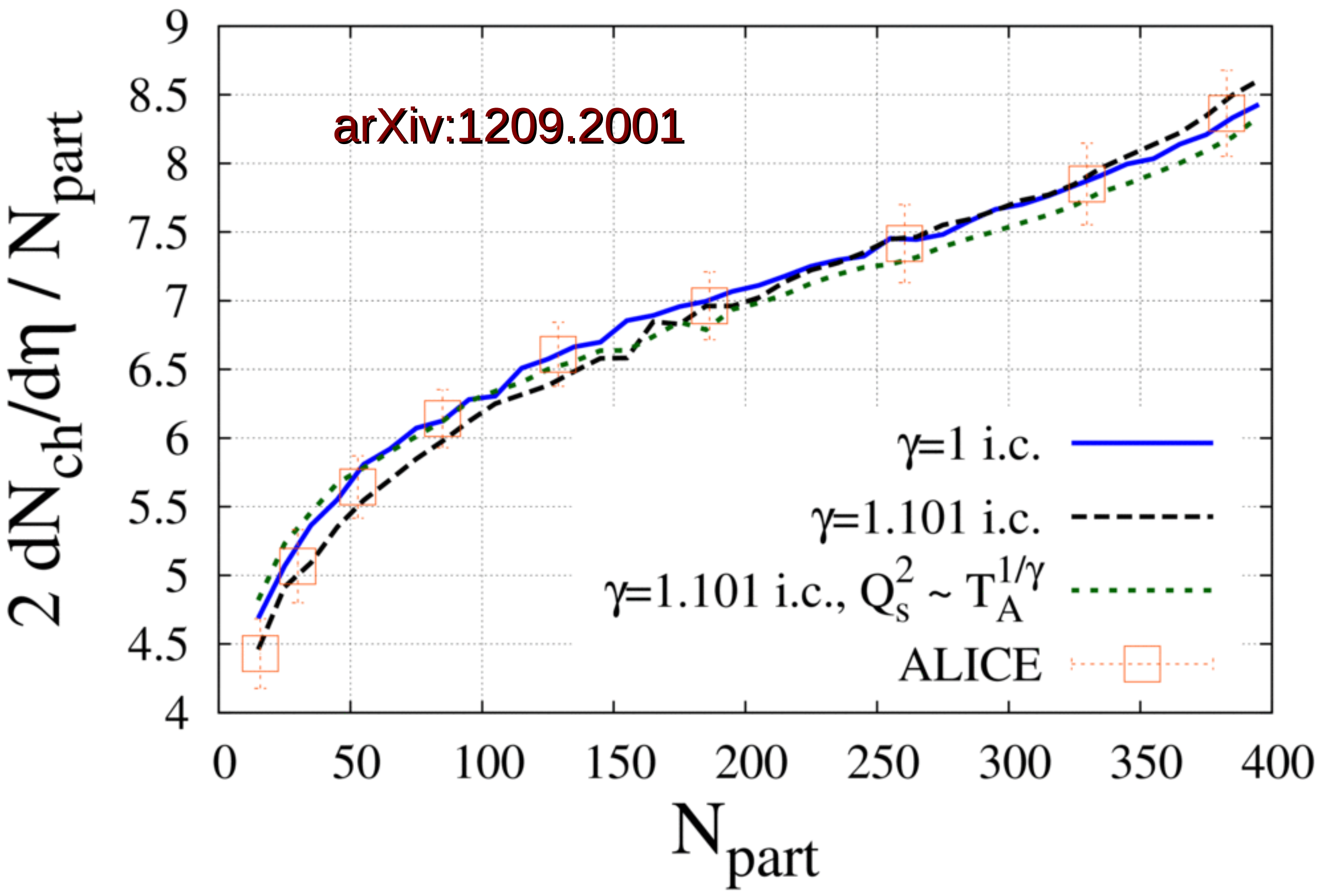
Multiparticle production and the CGC

Gluon distributions obtained in the fits with BK reproduce multiplicities

[From Dumitru at IS2014]



[Albacete, Dumitru, Fujii, Nara 2013]



Multiplicities are reproduced in a QCD-based approach

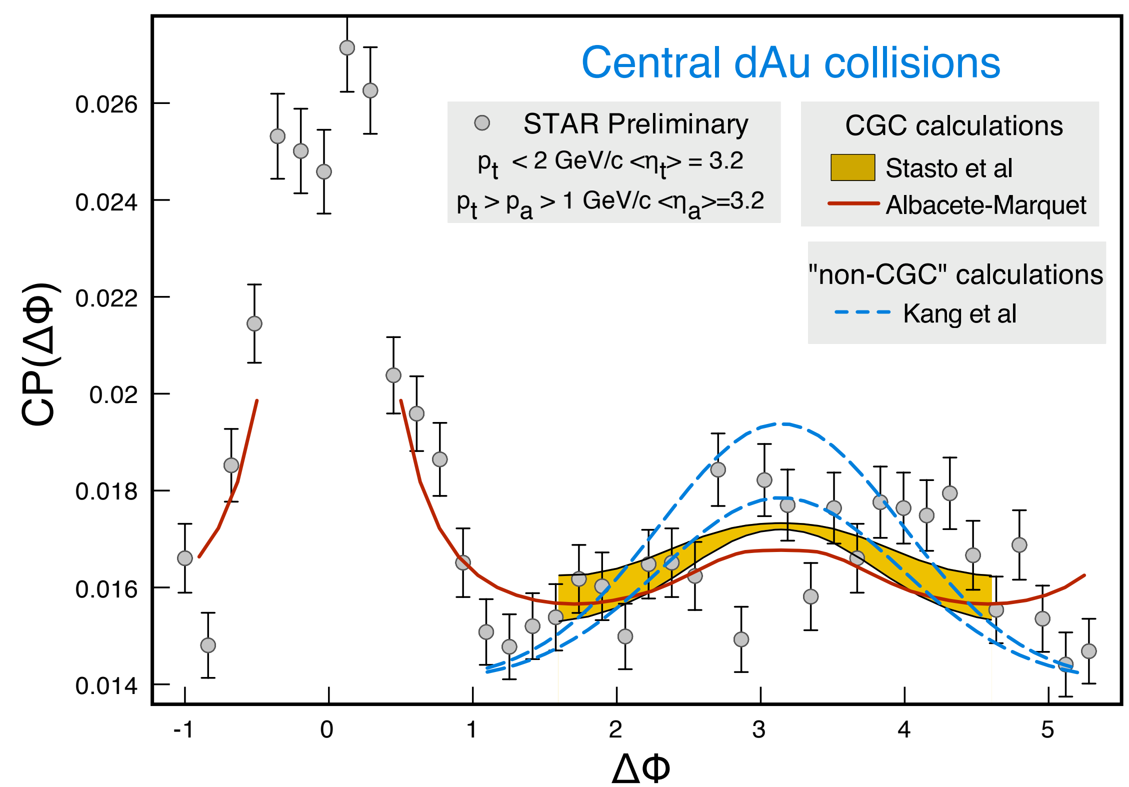
- QCD evolution equations with initial conditions from DIS experiments
- Uncertainties in geometry, kinematics, etc
- First results at NLO available [Chirilli, Xiao, Yuan 2012; Stasto, Xiao, Zaslavsky 2013]

Multiparticle correlations

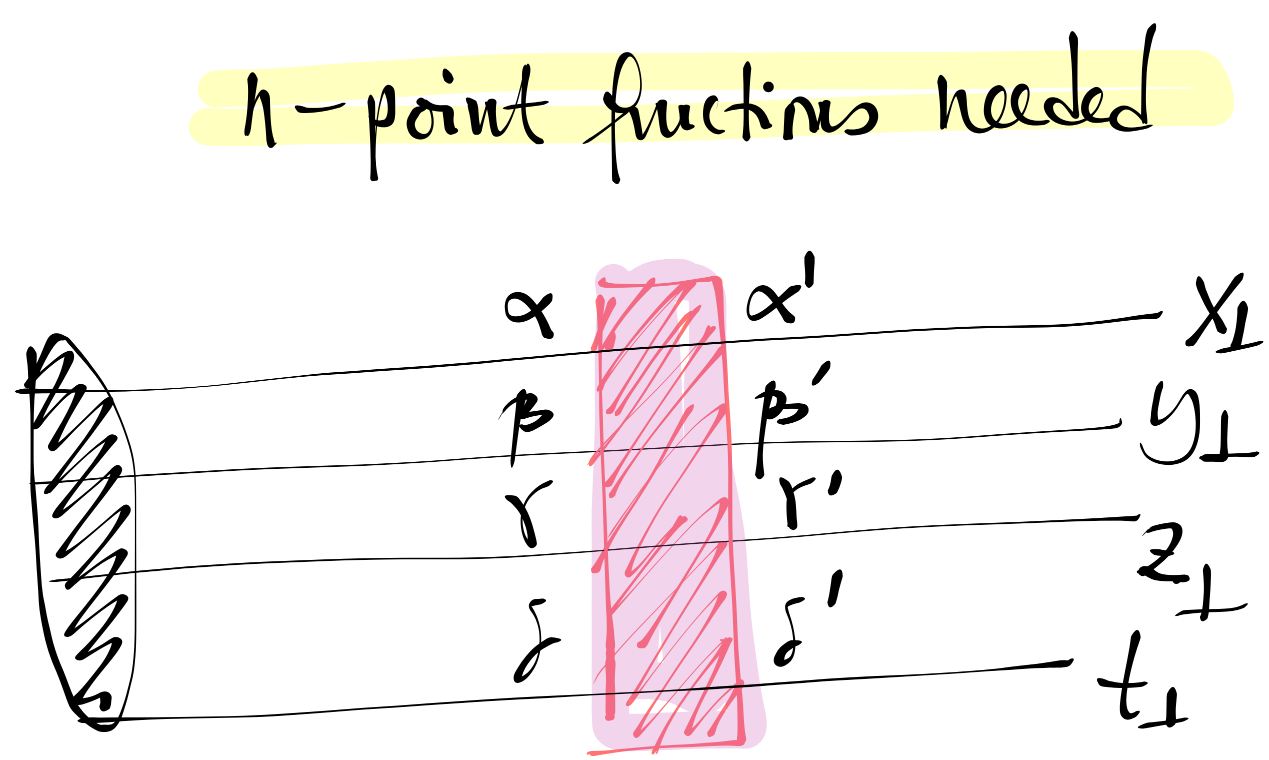
Single particle production - dipole cross section

More differential (e.g. 2-particle inclusive)

- Measure different color correlation functions - n-point functions
- Promising but still a lot of work ahead in theory and experiment
- Improved description of medium properties
- One of the hot topics in last years



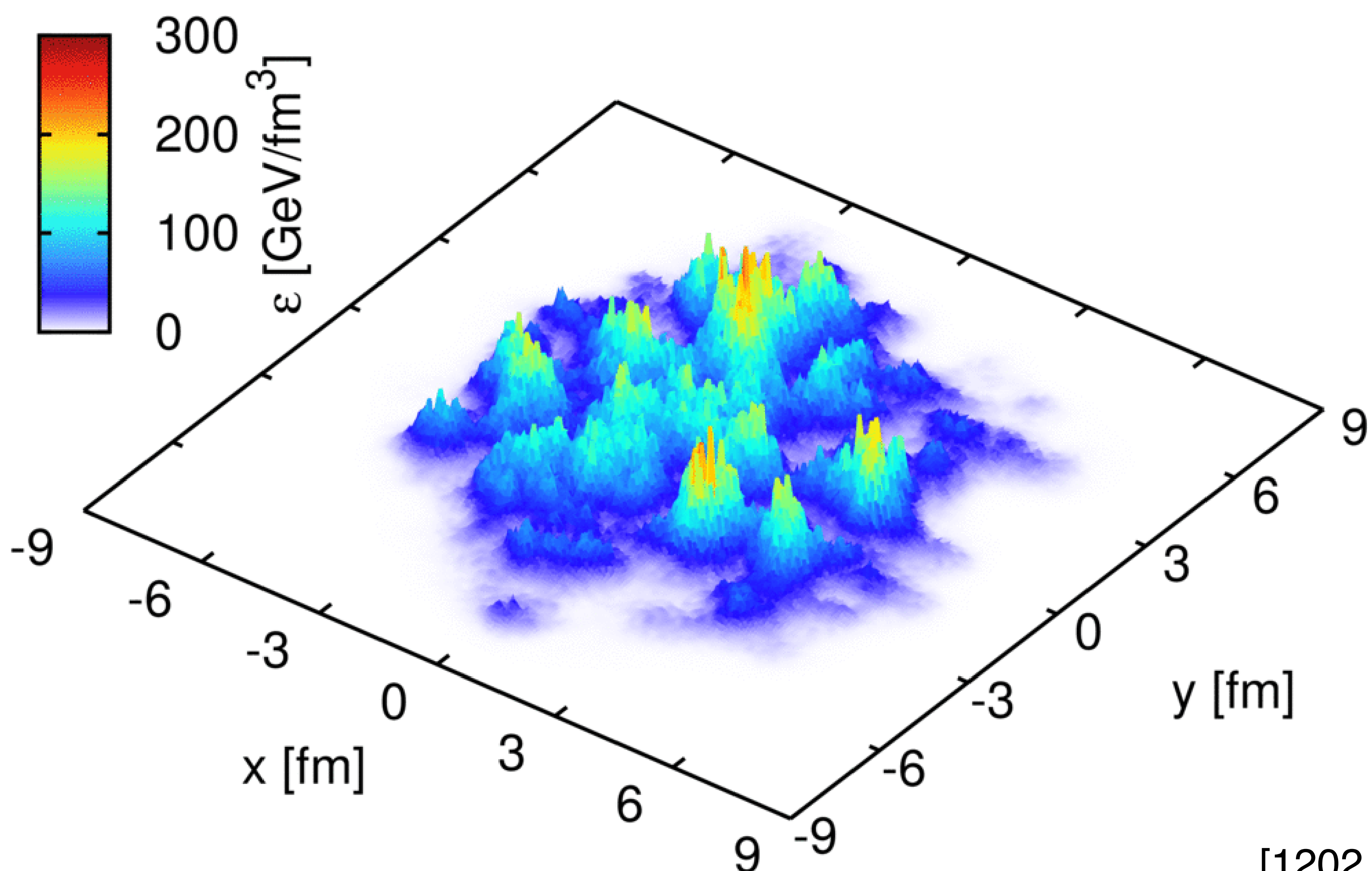
[Plot from Albacete, Dumitru, Marquet, 2013]



Fluctuations...

Fluctuations

- Physical quantities (e.g. energy density) computed event-by-event



[1202.6646]

Undo the medium averages...

- Will not affect averaged quantities unless other mechanism appears, e.g. hydro

Non-linear evolution - CGC

Concepts

* Gluon fusions
  Saturation
  tames the growth
* Color correlation
  lenght ~ $1/Q_{sat}$
  ↳ Dipole
* Wilson line
  → S-matrix

Observables

* ep/eA scattering
* Multiplicities
* R_{pA}
* Correlations

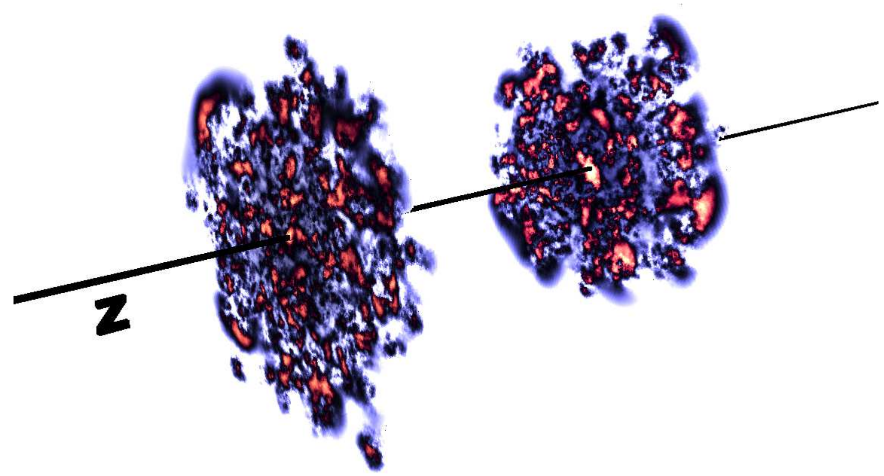
↓

harmonics, v_n..

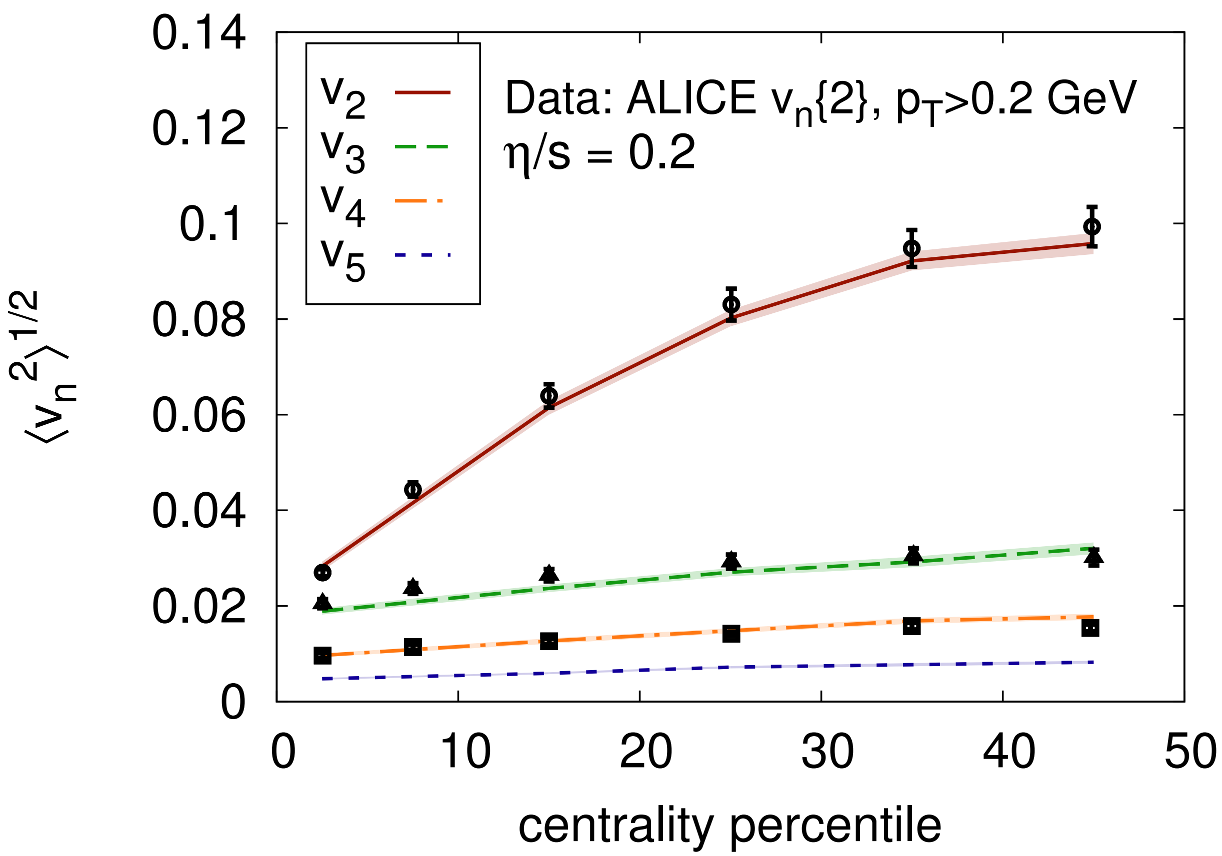
the Ridge

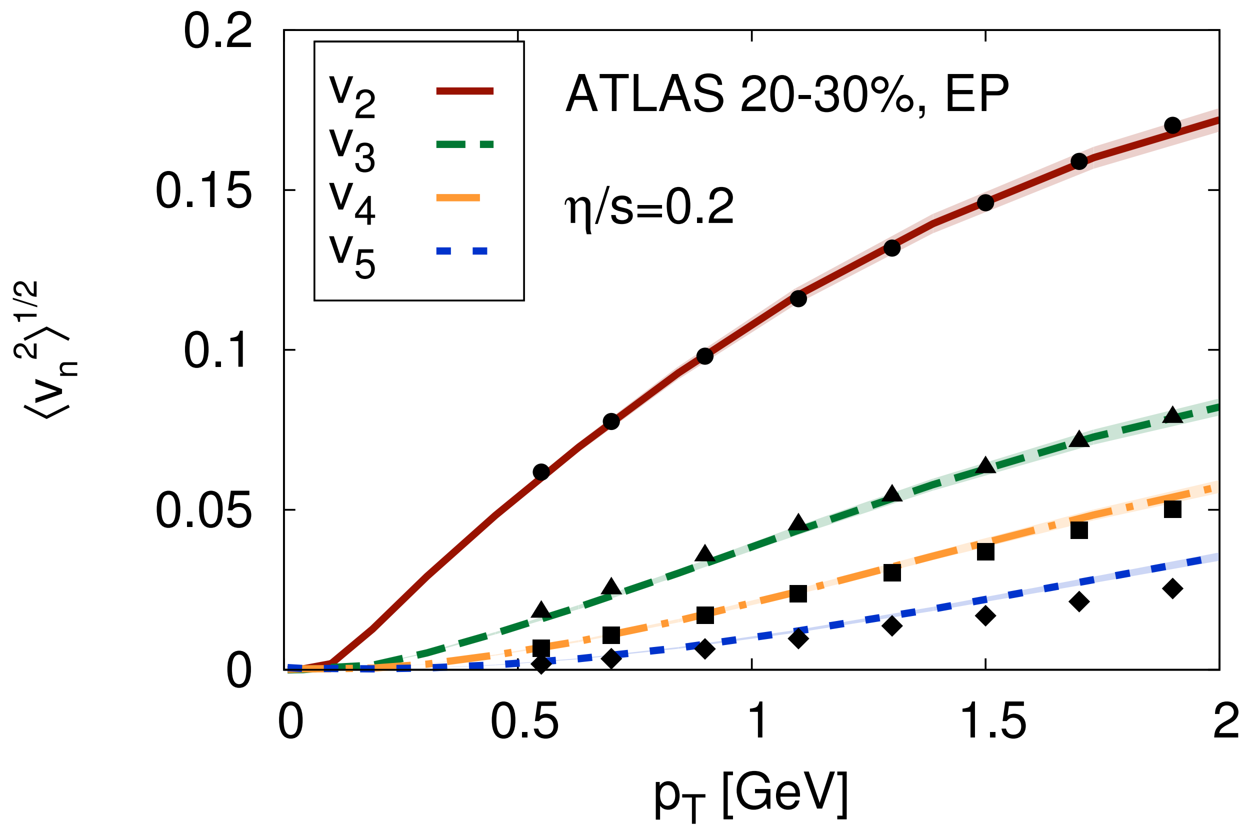
↳ Towards equilibrium (Glasma) ⟷

CGC as initial conditions for hydro



- **Initial conditions from MV model (IPsat)**
- **Hydro evolution with viscosity**
- (made event-by-event)





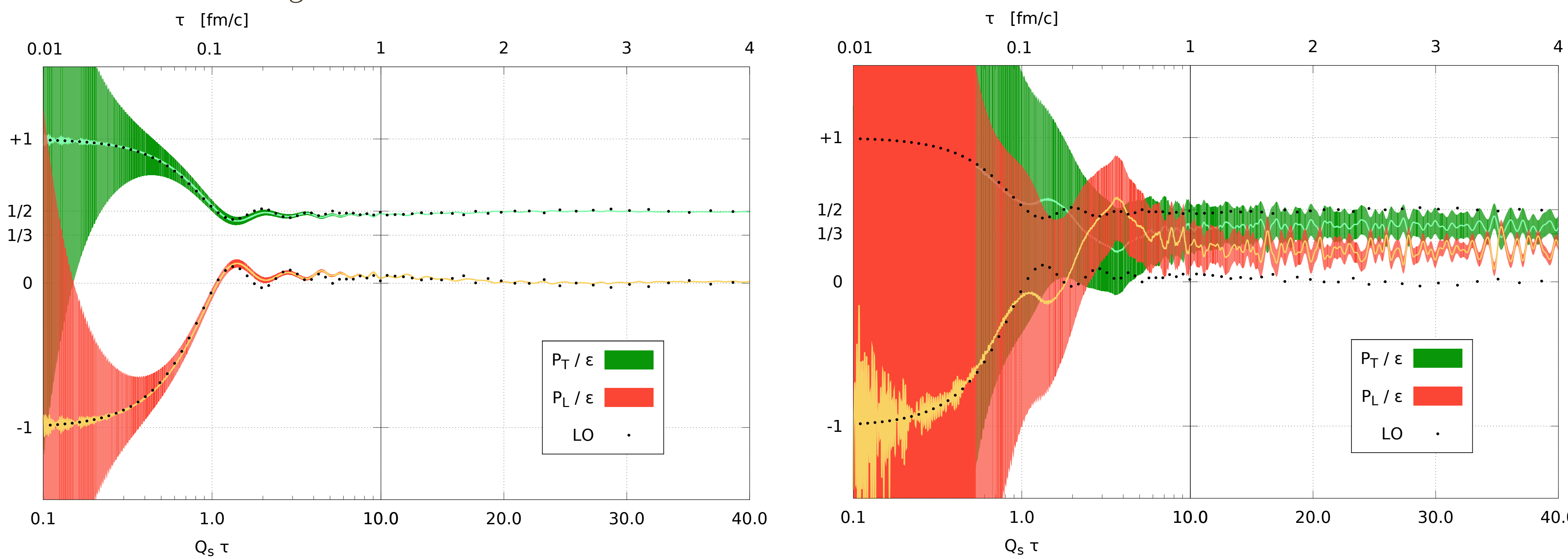
[Gale, Jeon, Schenke, Tribedy, Venugopalan 2013]

Towards isotropization...

The CGC picture provides a framework to study the evolution to equilibrium

- State just after the collision has a very strong anisotropy (MV model)
- Solving Color Yan Mills equations to larger times with NLO corrections
- Anisotropy greatly reduced with still tiny coupling constants

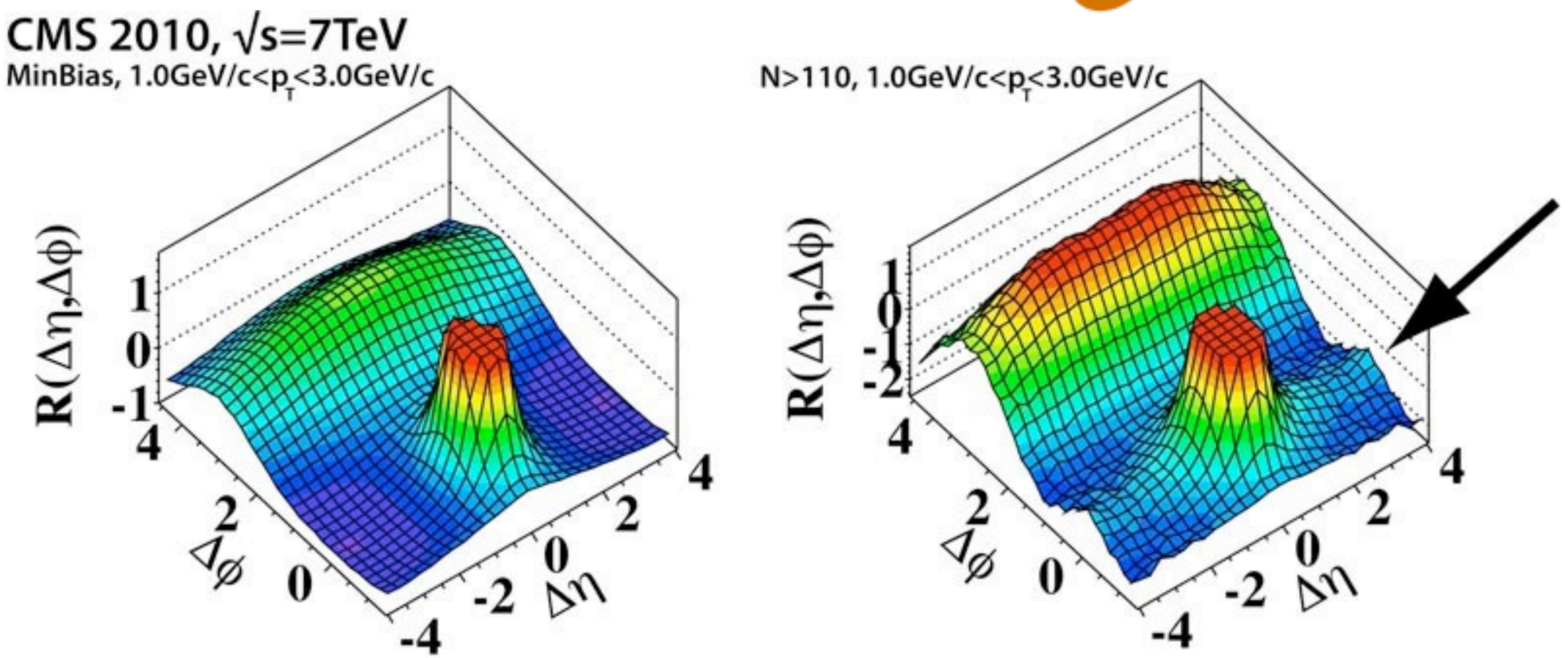
$\alpha_s = 0.0008$ $\alpha_s = 0.02$



[Epelbaum, Gelis 2013]

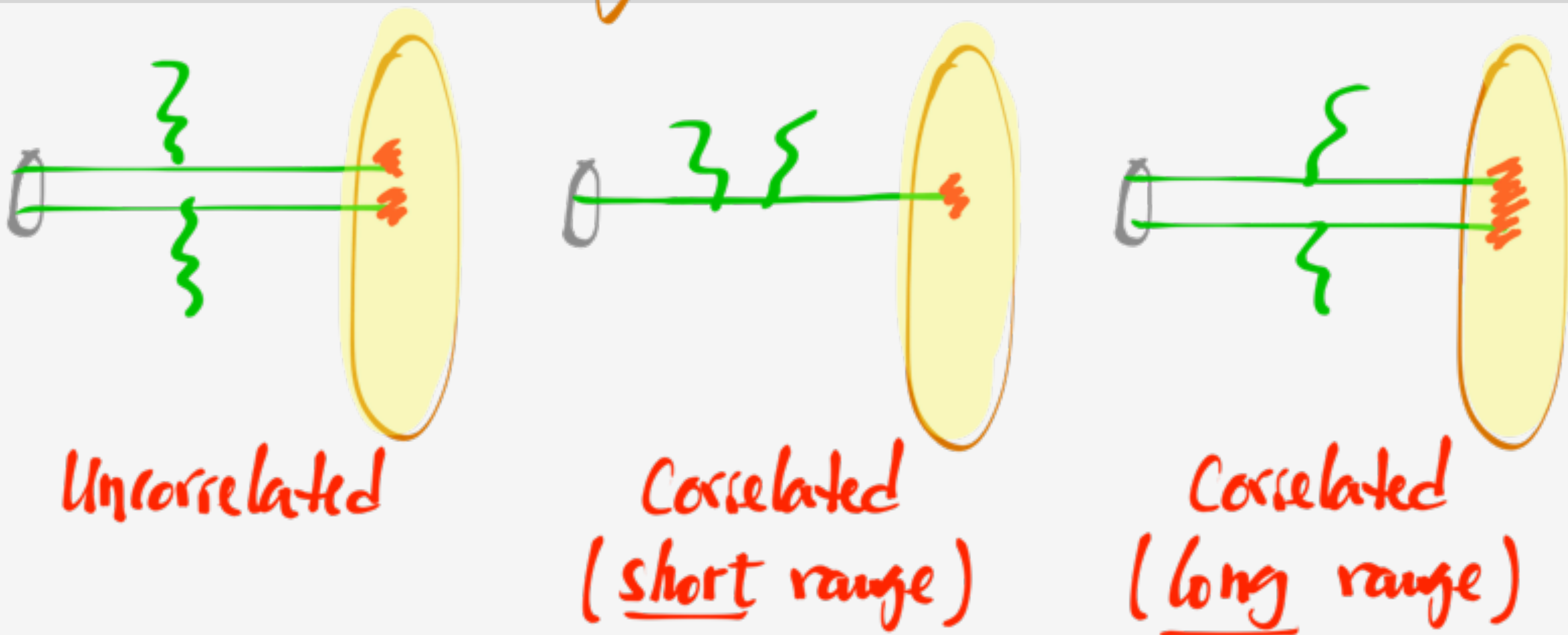
A lot of activity not quote here - both weak and strong (AdS/CFT) coupling

The Ridge



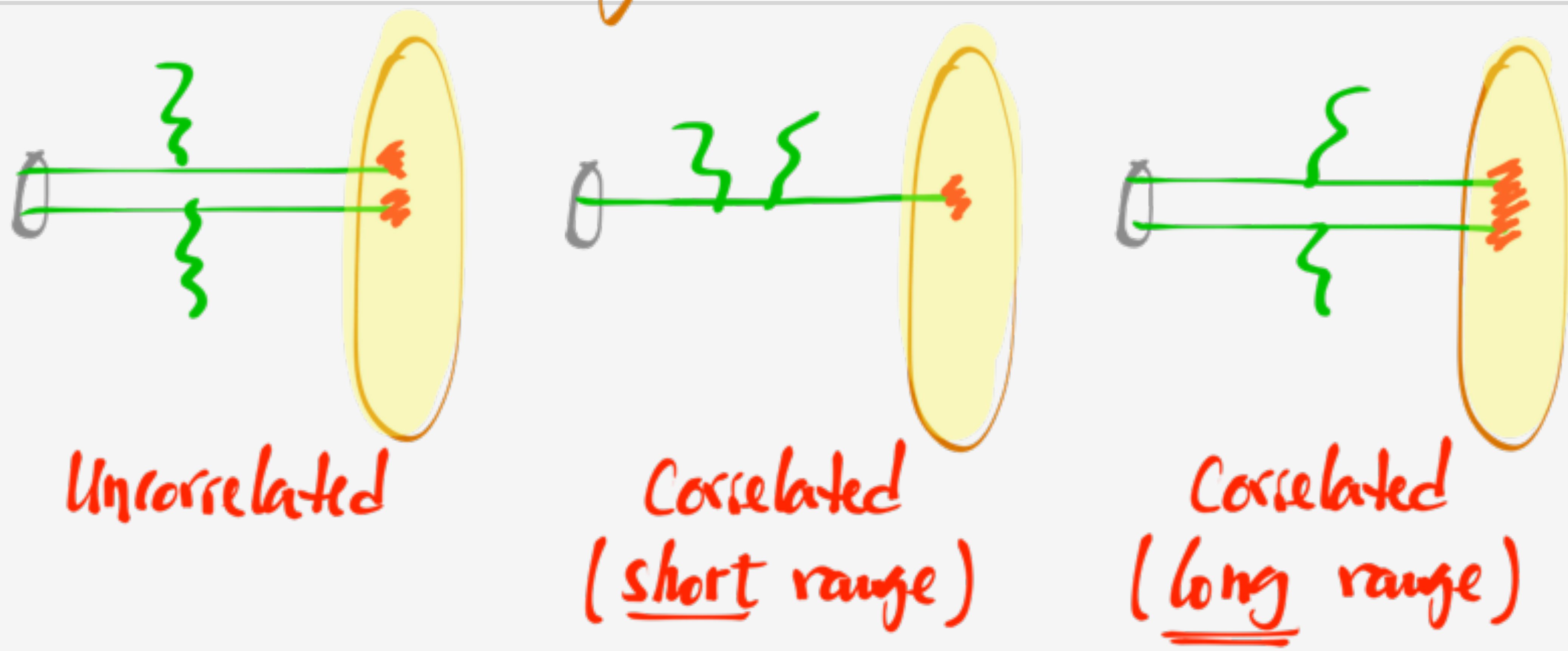
- **Structure needs to be formed very early by causality requirements**
- Observed in pp, pA (LHC) and AA (RHIC+LHC)

The Ridge & the CGC



COLOR Correlations in transverse plane ~ Q_{sat}^{-1}

The Ridge & the CGC



COLOR Correlations in transverse plane ~ Q_{sat}^{-1}

Is the Ridge Initial State / Final State / Both?

First (fractions of) fm/c → thermalization ?

Concepts/questions

* System created out-of-eq.
* hydro works for $\lesssim 1$ fm/c
* How is this built?
  - ↳ weak/strong coupling?
  - ↳ strong color fields?
  - ↳ Instabilities?

Observables

* harmonics, v_n
* correlations
* Ridge

Hopefully much more to come...

One of the most exciting lines for next years

(Go to IS2014 in December) http://is2014.lbl.gov

Summary

* Linear evolution
  - ↳ DGLAP → STANDARD
    - Make fits & check universality
  - ↳ New pPb results at this QM

* Non linear evolution → CGC
  - ↳ General framework to include collectivity
  - ↳ Gluon saturation → Color coherence
    - ↳ Qsat
  - ↳ Towards equilibrium
    - ↳ CGC → hydro ?

Some of the most fundamental questions in QCD