Heavy Ion Physics

Hot and dense QCD after the first LHC running period

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Garderen - the Netherlands - June 2014

@CASSalgado @HotLHC

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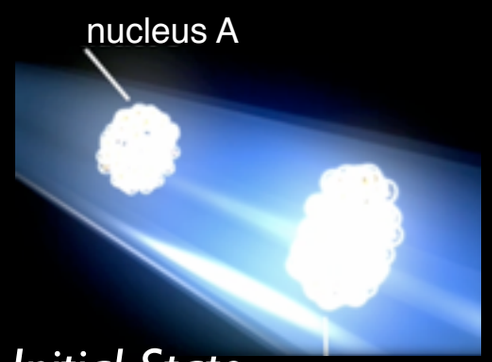
Some of the questions accessible with heavy-ion collisions



Initial State

Final State

What is the structure of hadrons/nuclei at high energy?

- *color coherence effects in the small-x partonic wave function*
- *fix the initial conditions in well-controlled theoretical framework*

Is the created medium thermalized? How?

- *presence of a hydrodynamical behavior*
- *what is the mechanism of thermalization in a non-abelian gauge theory?*

What are the properties of the produced medium?

- *identify signals to characterize the medium with well-controlled observables*
- *what are the building blocks and how they organize?*
- *is it strongly-coupled? quasiparticle description? phases?*

Menu

Initial state
Partonic densities
&
Multiparticle Production

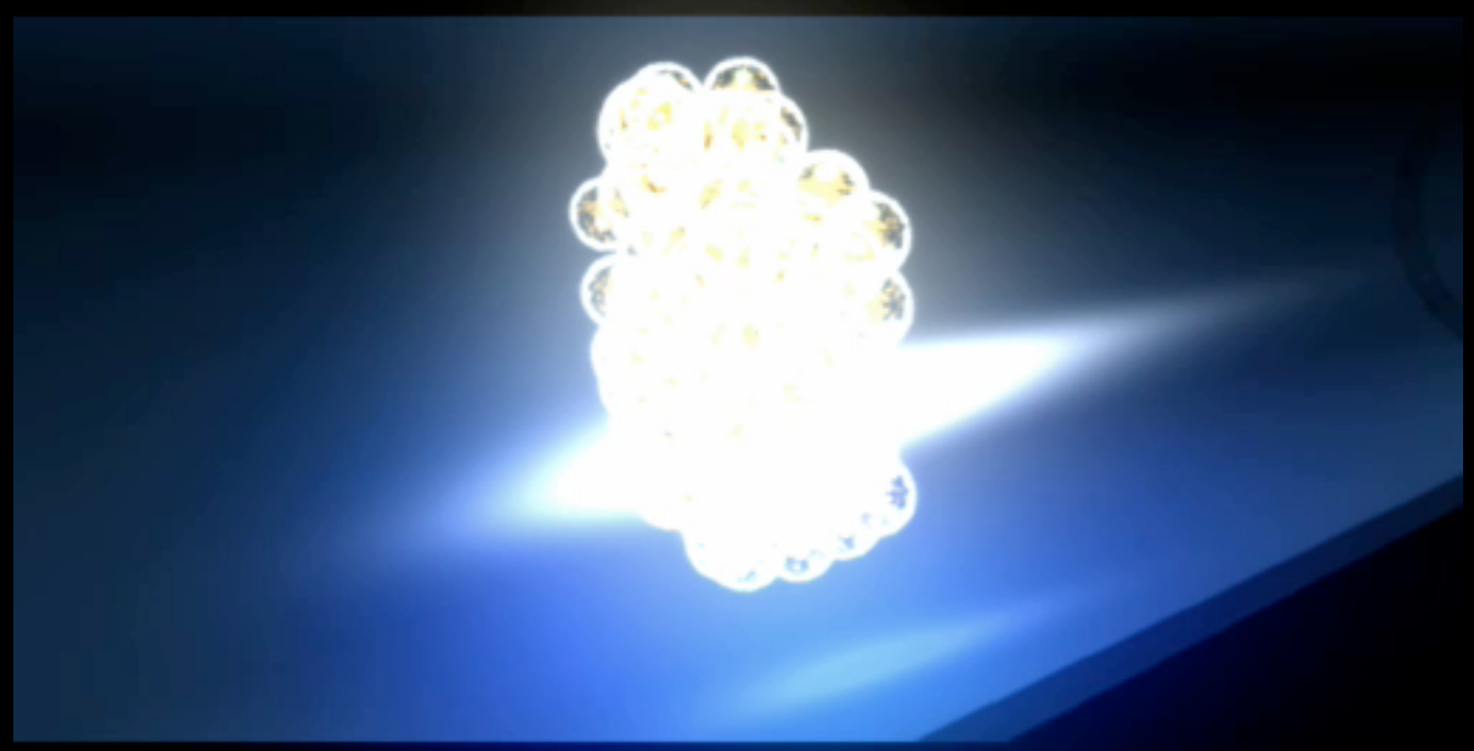
Hydrodynamics
&
Harmonics

Jets in medium
Jet quenching

INITIAL STAGES

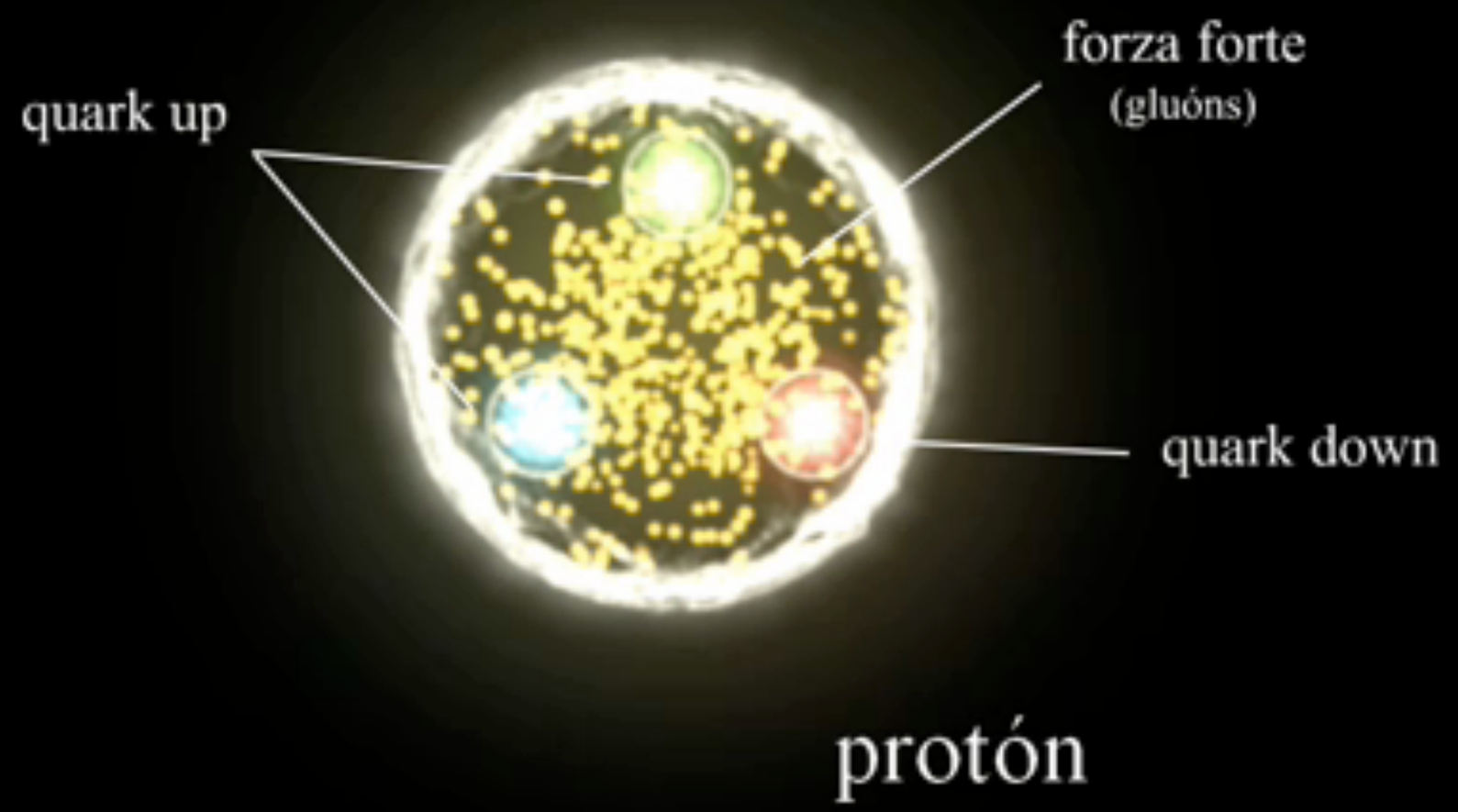
↳ Structure of the colliding objects

↳ Built of collective behavior



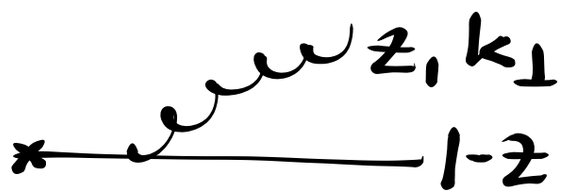
Structure of the collidy objects

QCD is a Quantum Field Theory
↳ Quantum fluctuations ↔ virtual particles



Splitting probability: the building block

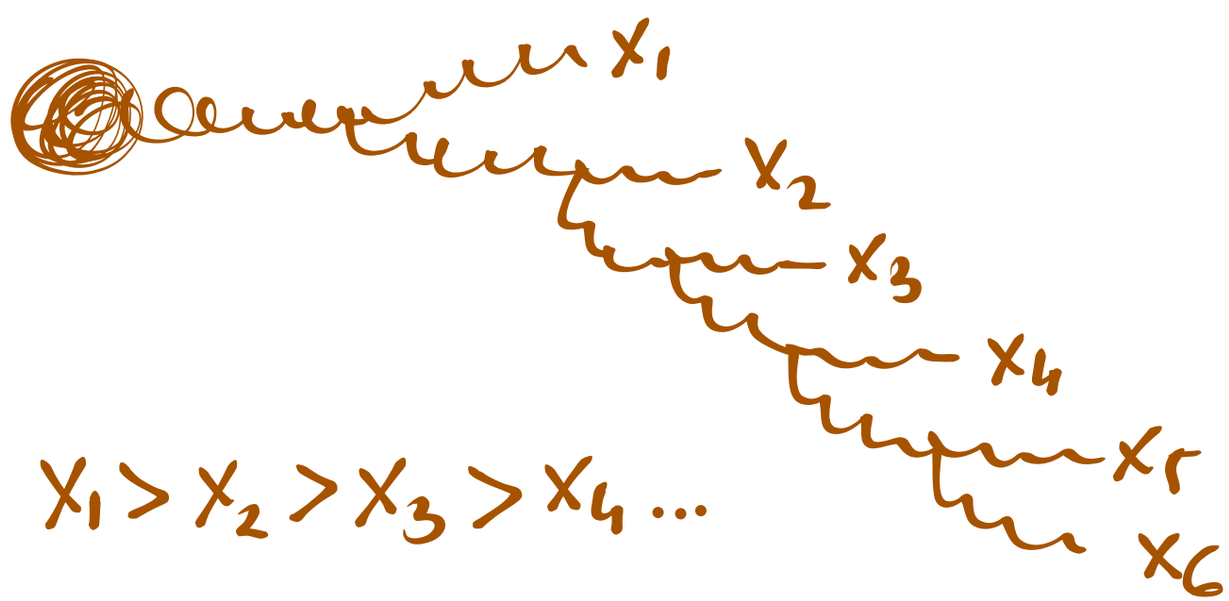
The splitting probability of an off-shell parton computed in pQCD



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

Soft and collinear divergent

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



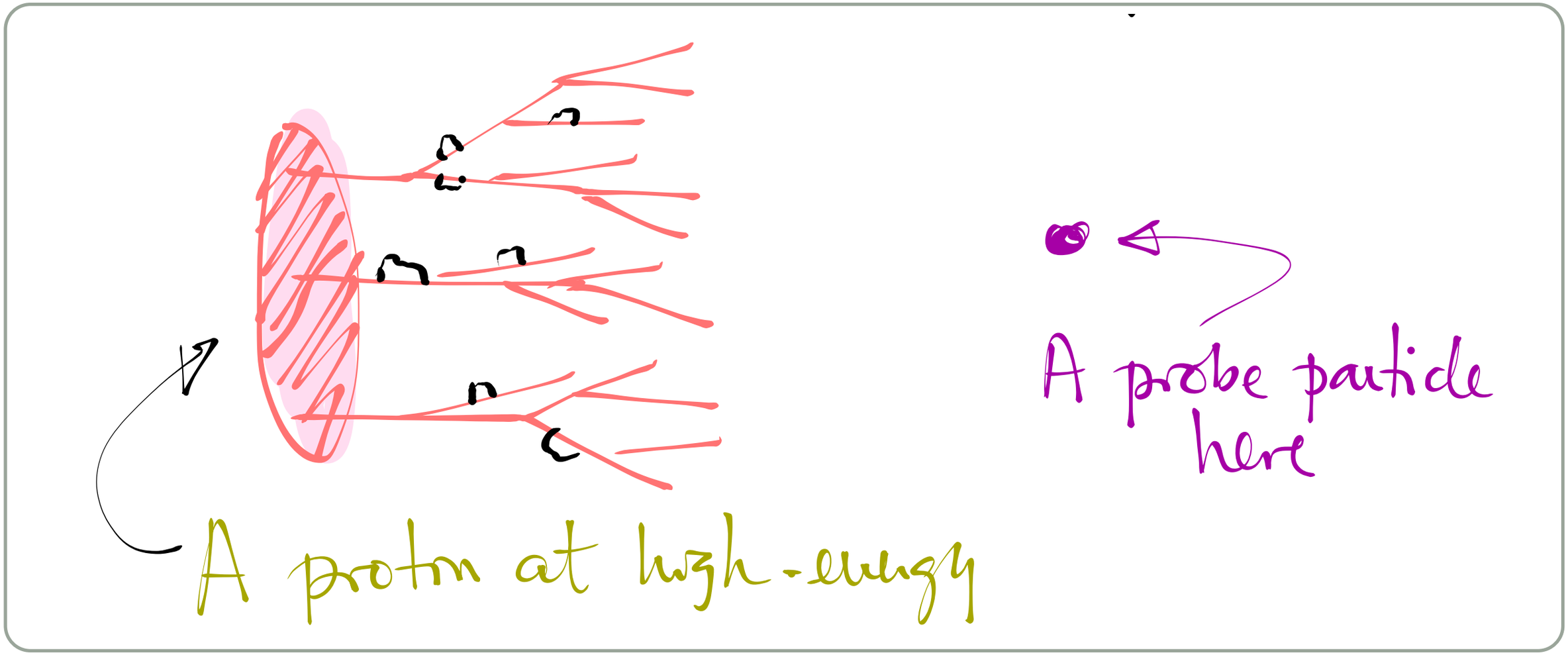
$x_1 > x_2 > x_3 > x_4 \ldots$

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



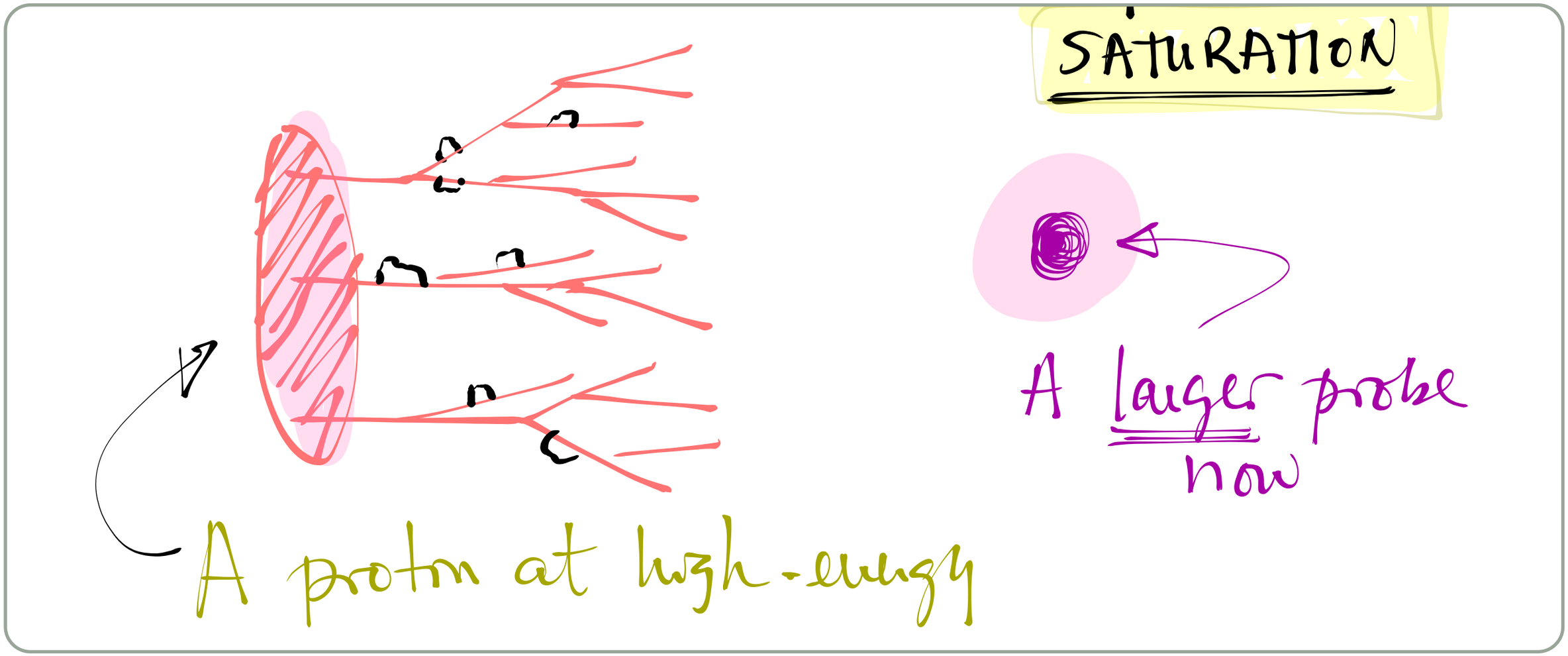
Lifetime of the fluctuation of the order of the size of the probe

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

Heuristic: Collision "counts" partons II

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

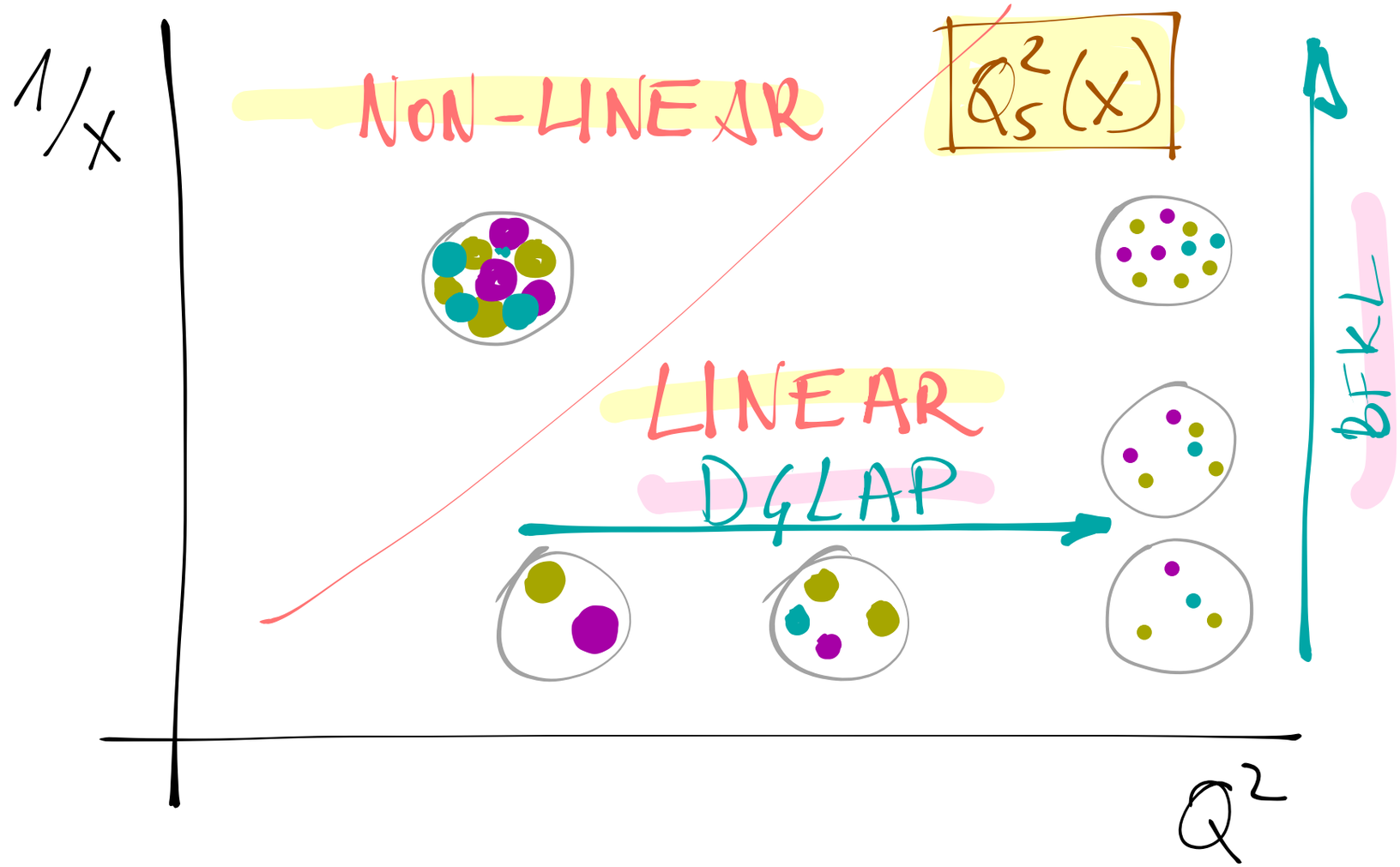
- TAMES the cross section



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

- **Color correlations among different partons in the proton/nucleus**

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)

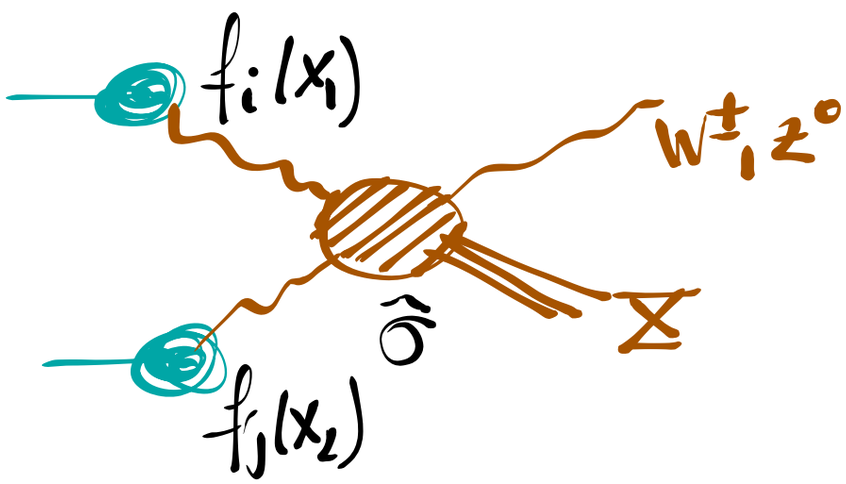
linear

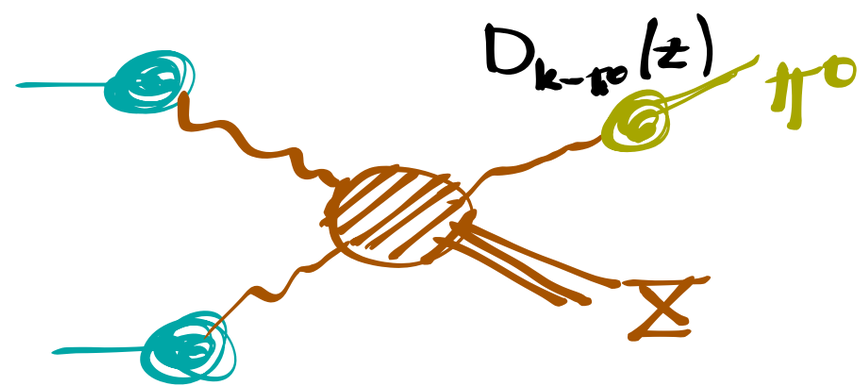
Collinear factorization

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

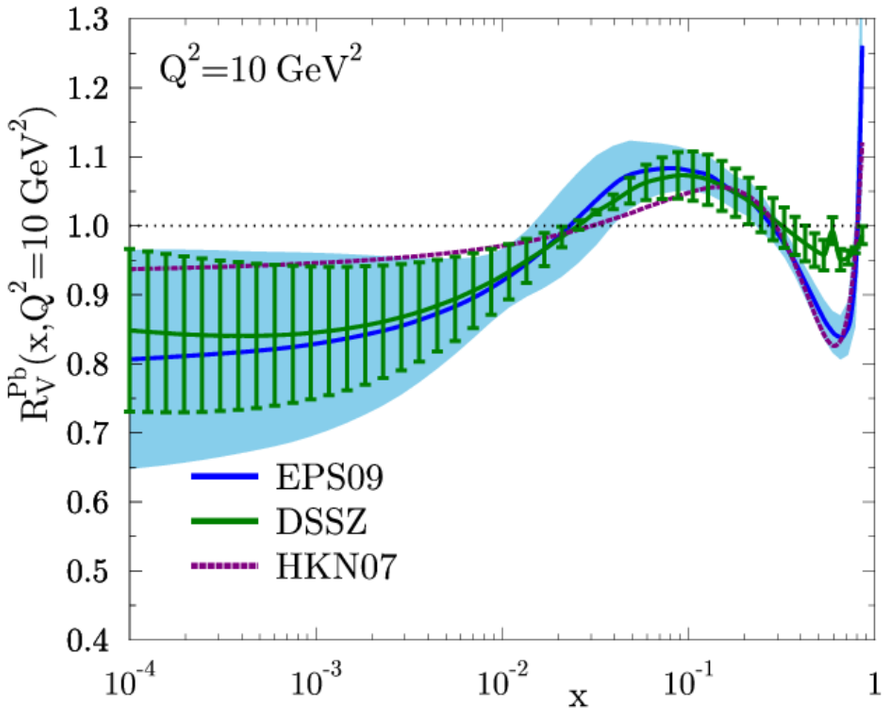


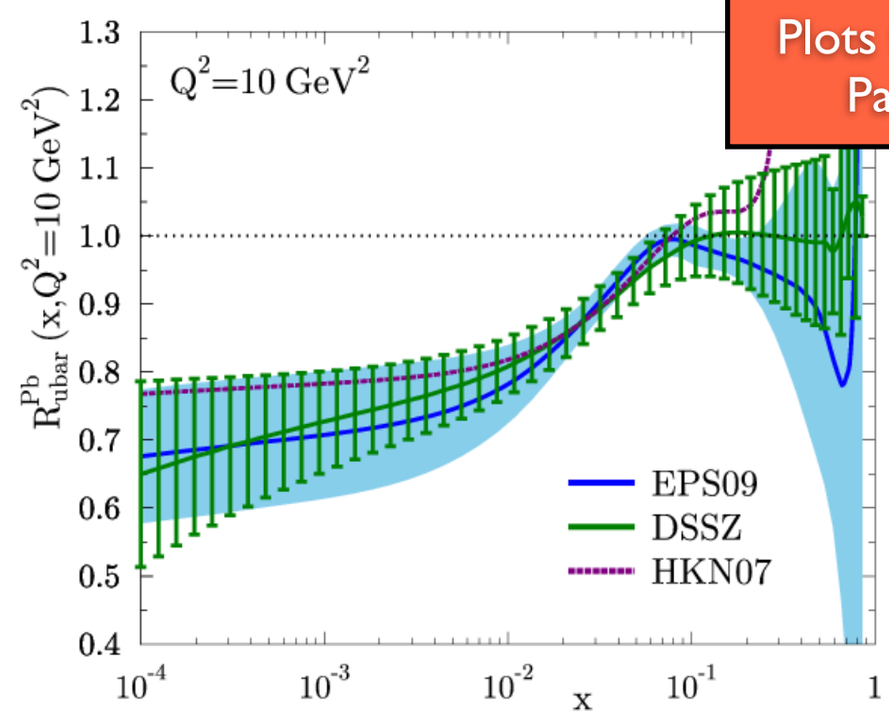


Factorization of long-distance and short distance terms in the cross section

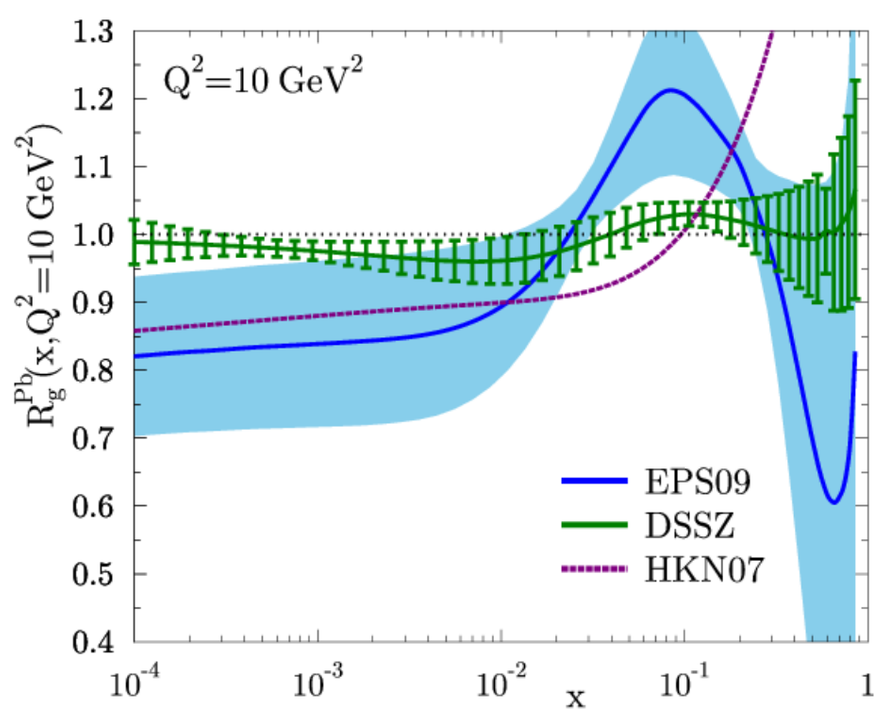
- Short-distance (perturbative) in the partonic cross section
- Long-distance (non-perturbative) in the PDFs and Fragmentation Functions (FF)

Global fits for nucleus





Plots from Hannu Paukkunen



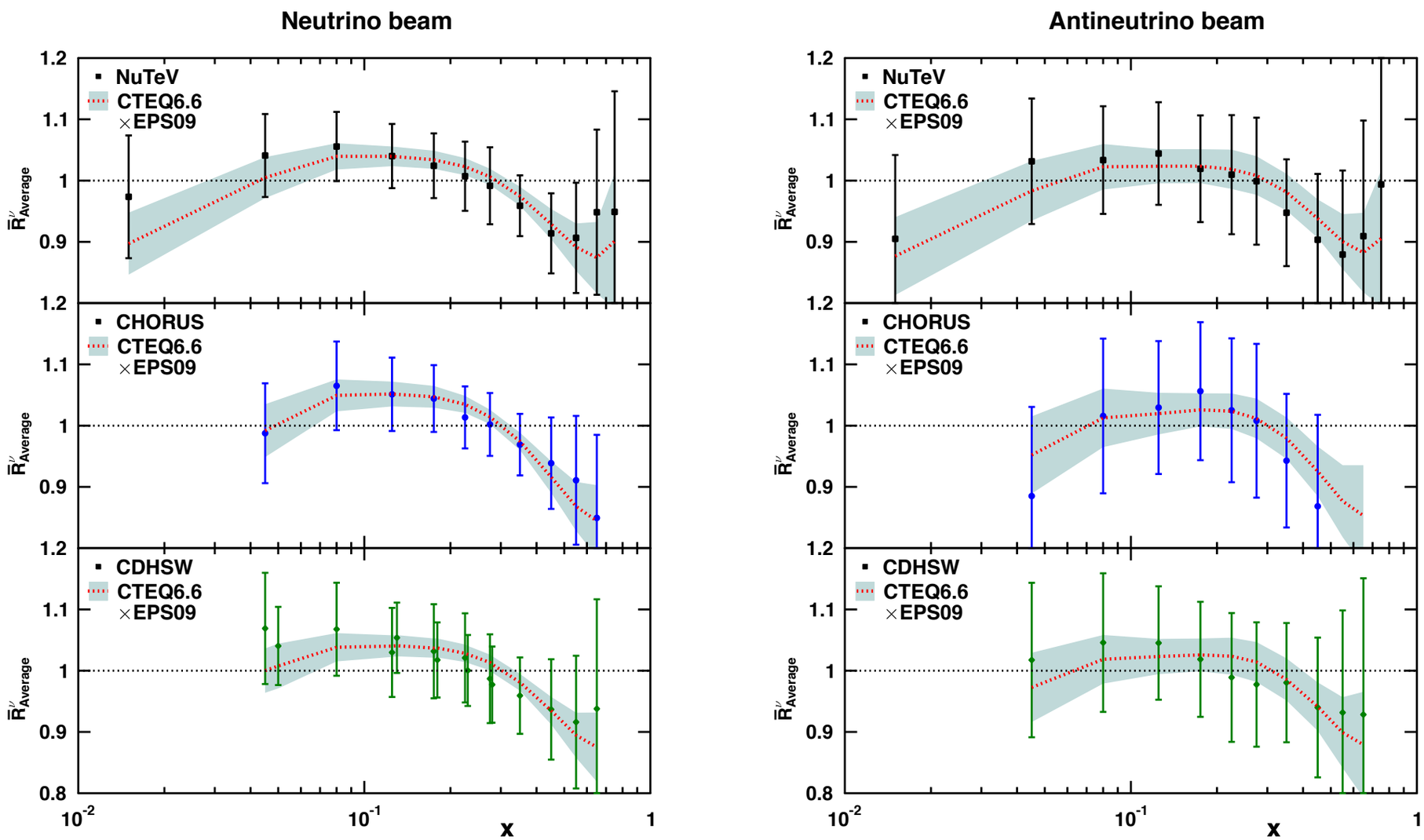
Ratios of the PDF of a proton inside a nucleus over that in a free proton

- 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**



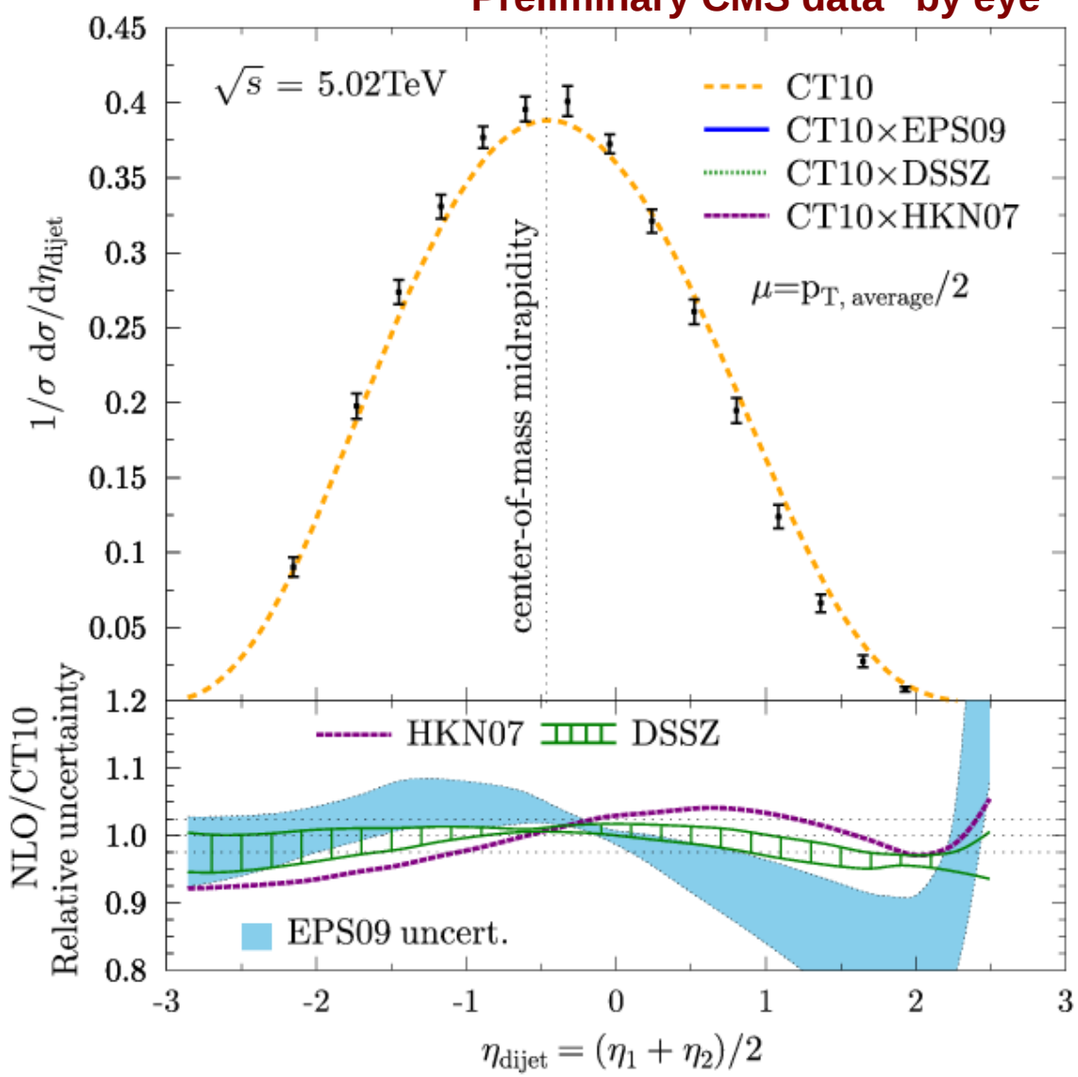
[Paukkunen, Salgado, 2013]

- **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**

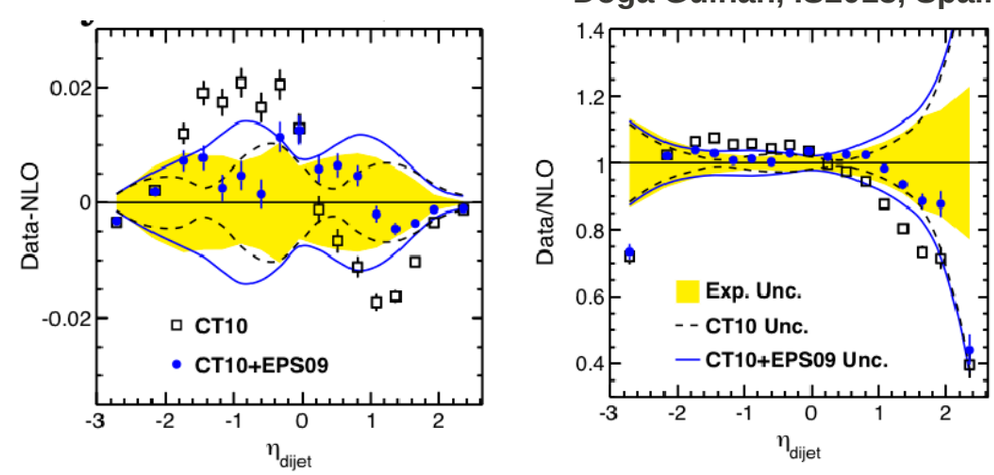
Preliminary CMS data "by eye"



[Eskola, Paukkunen, Salgado, 2013]

[Plots from Paukkunen - LHeC workshop - Jan 2014]

Doga Gulhan, IS2013, Spain

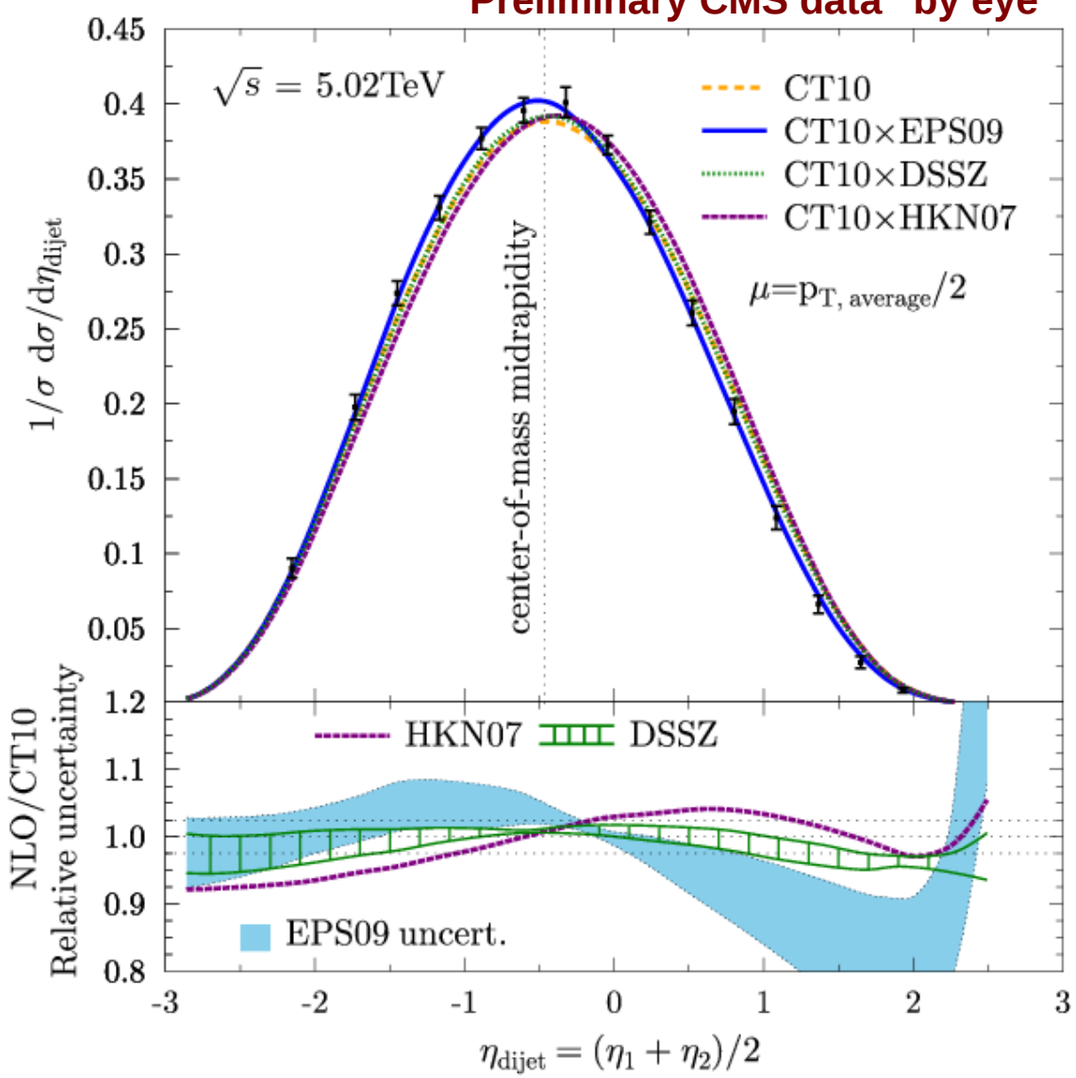


- **Provide new constraints to gluon distributions**

DGLAP approach - Some recent results II

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

Preliminary CMS data "by eye"



[Eskola, Paukkunen, Salgado, 2013]

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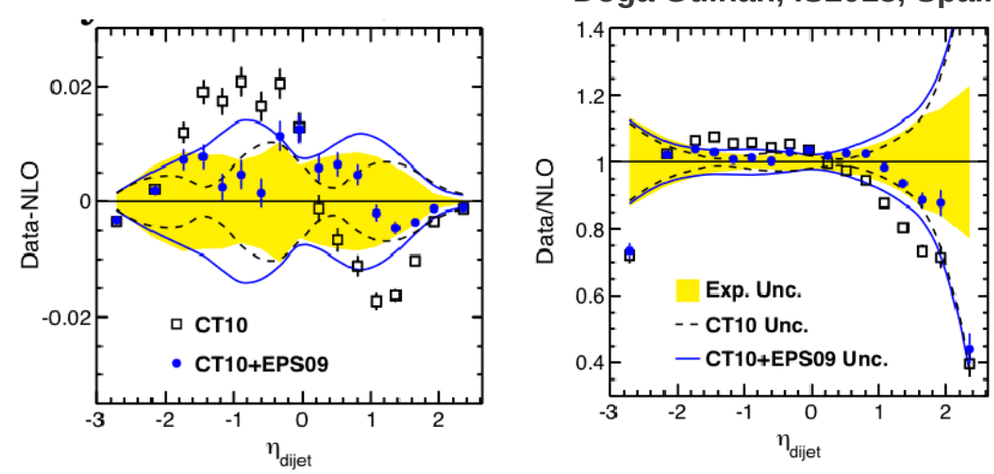
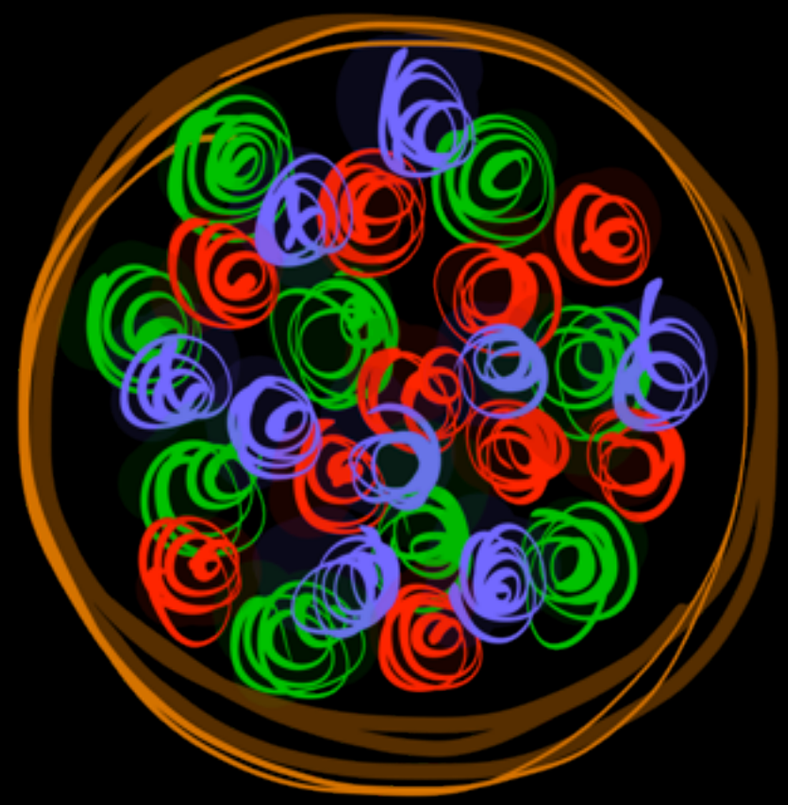


- **Provide new constraints to gluon distributions**

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 $\rightarrow 1/Q_{sat}$

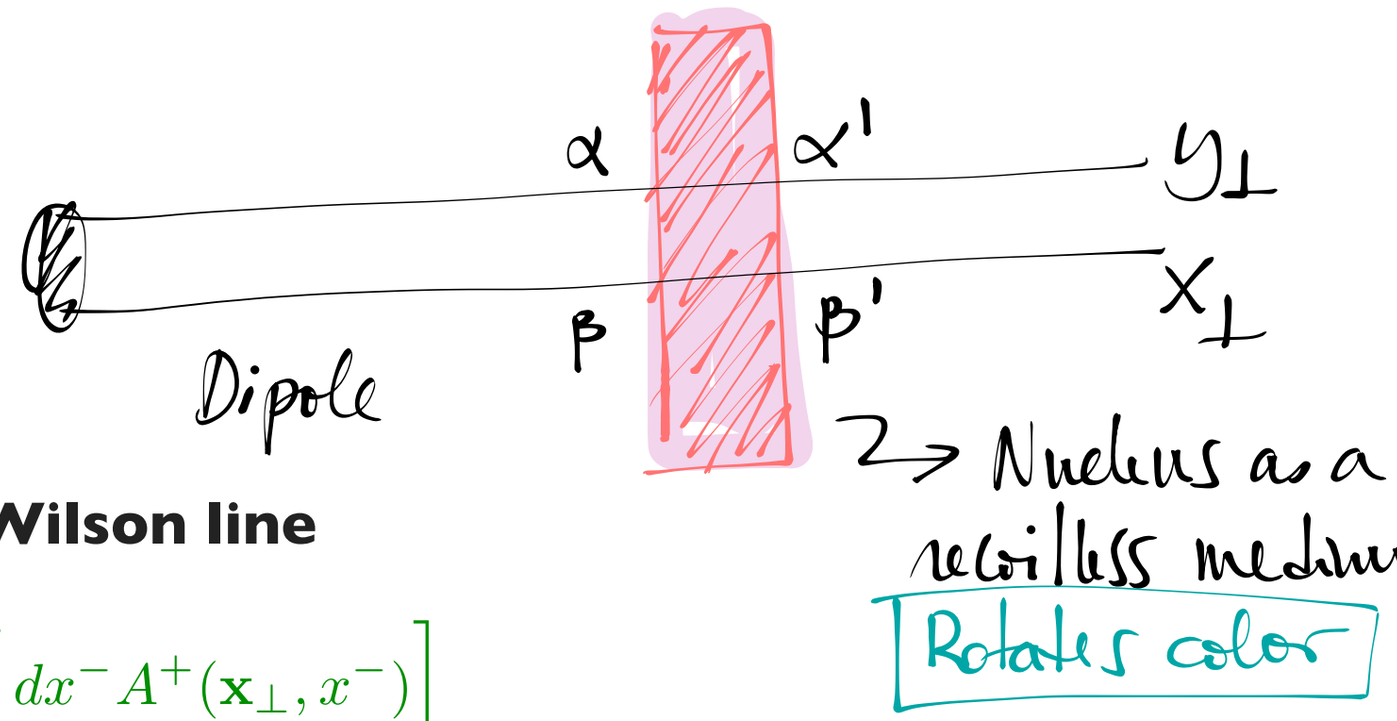
Color Glass Condensate $\rightarrow$ General framework

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

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)

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

Medium averages

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

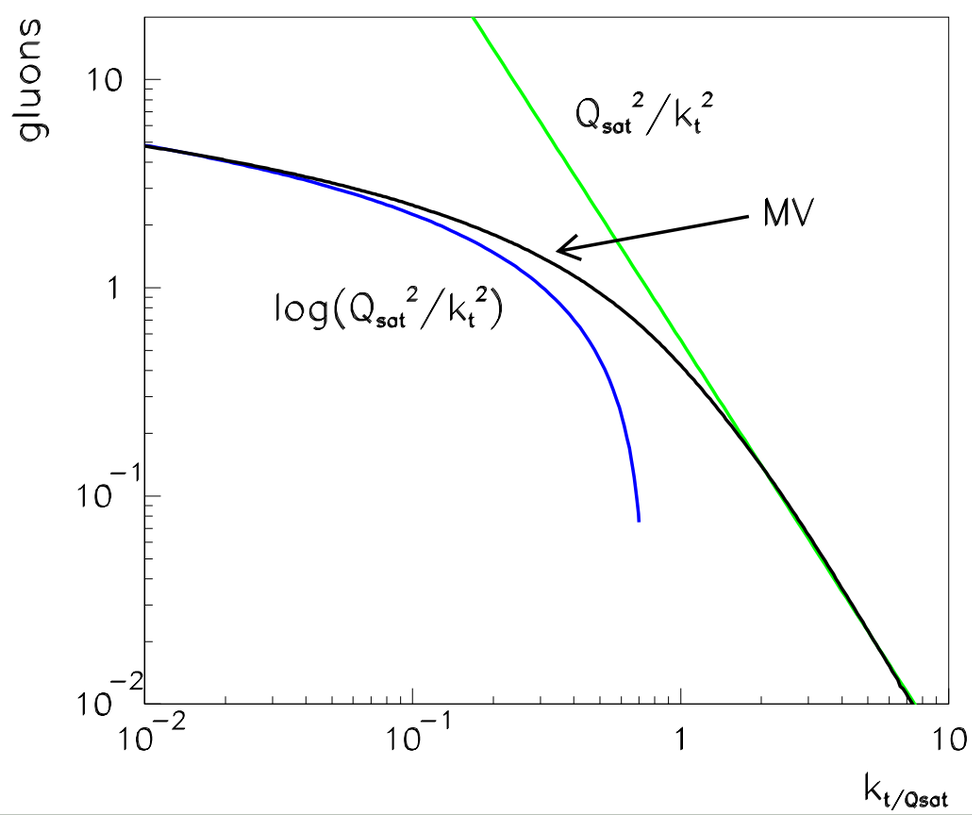
- Several prescriptions used. Here, just focus on a simple one

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

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

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

[up to logs: McLerran, Venugopalan 1994]



Two important consequences

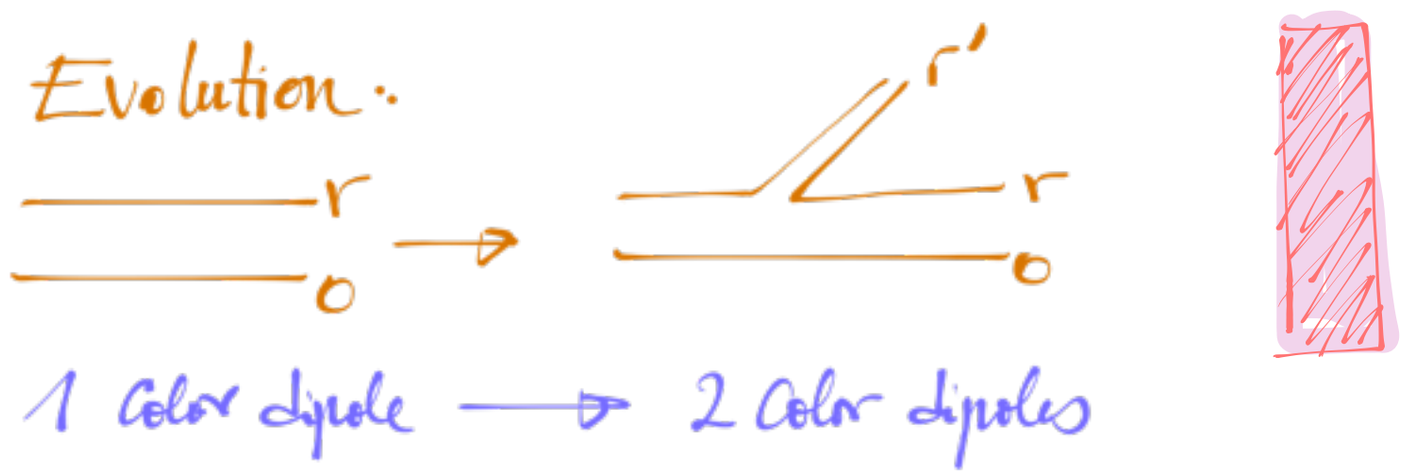
- Qsat cuts-off the low momentum
- Geometric scaling

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

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



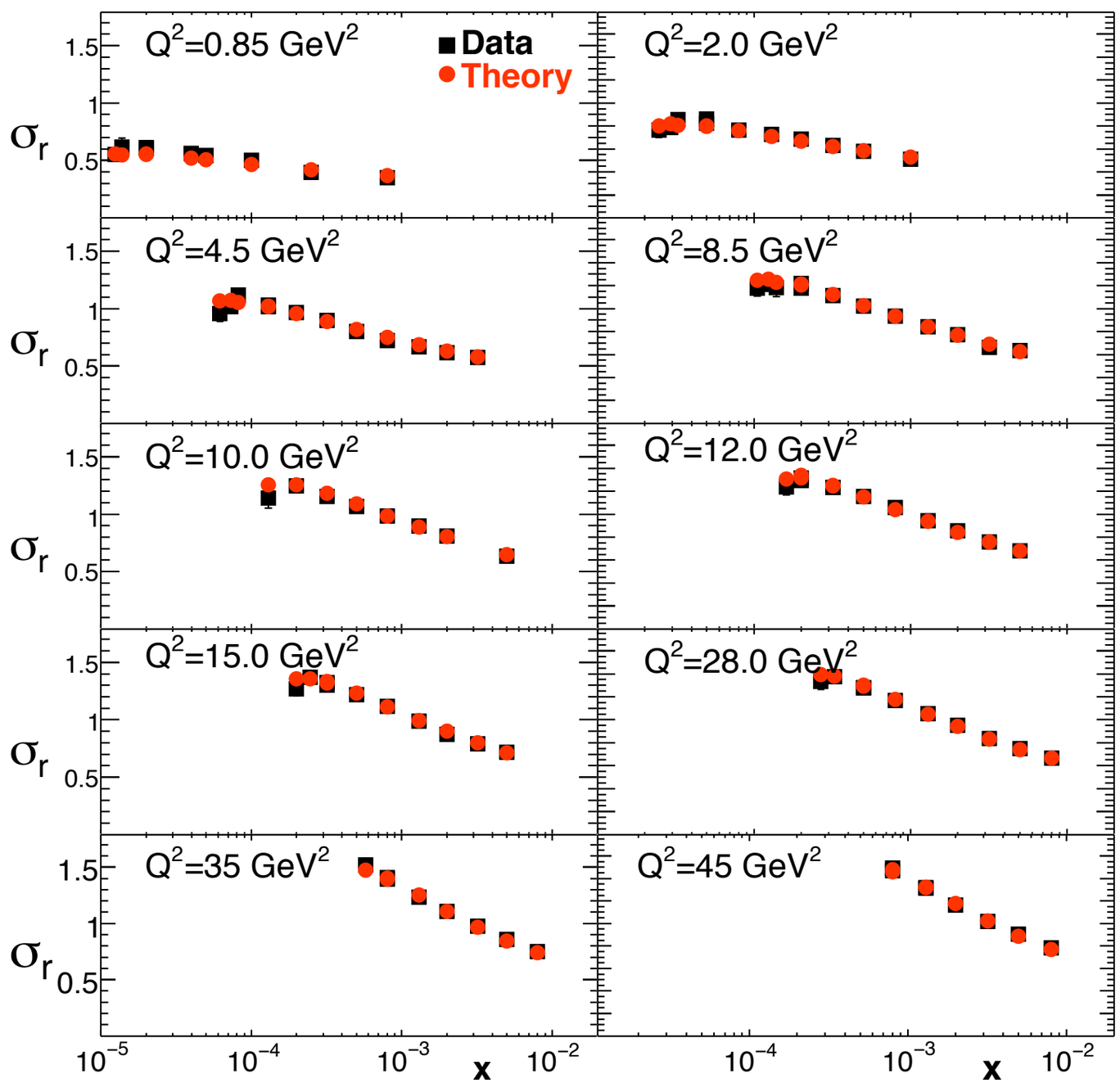
BFKL

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

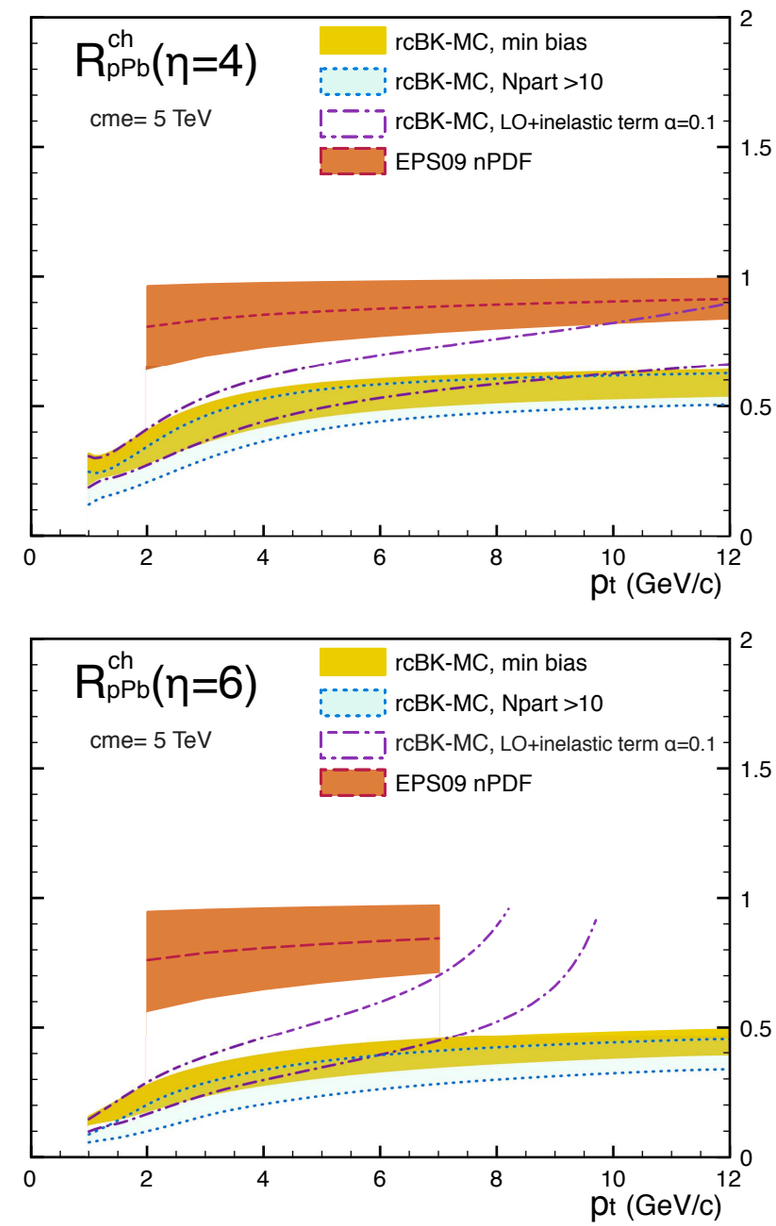
[Balitsky-Kovchegov eqs]

Fits using non-linear evolution eqs.

[AAMQs - 2010]



[Albacete, Dumitru, Marquet 2013]

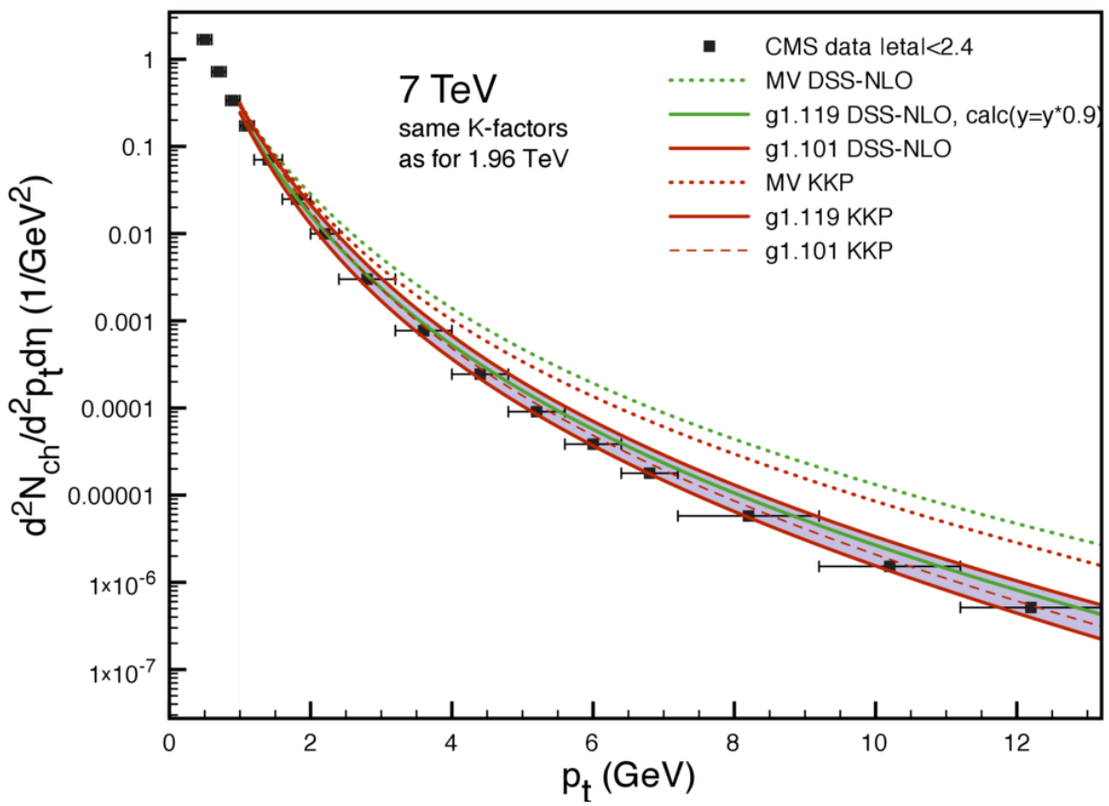


- **Checks of validity of the formalism with proton-nucleus data**

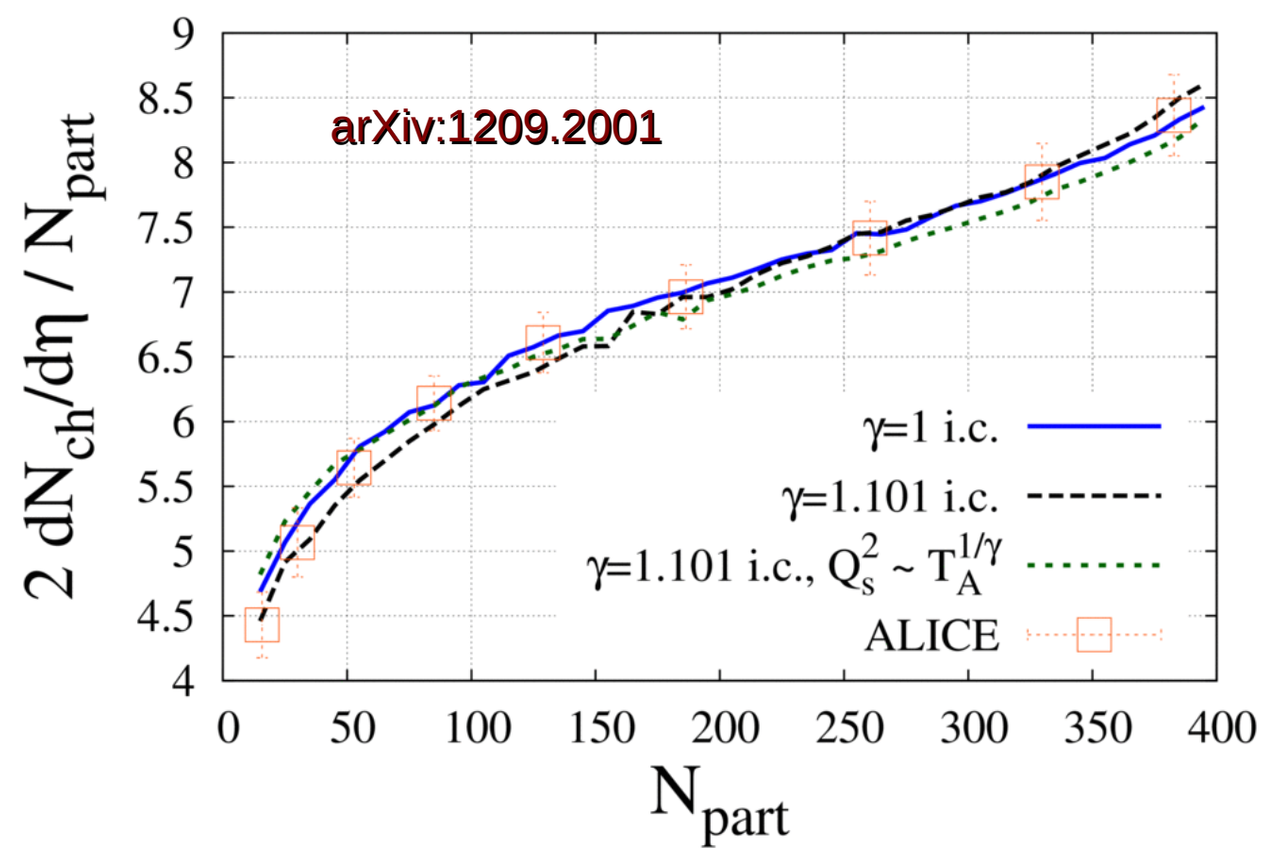
Multiparticle production and the CGC

Gluon distributions obtained in the fits with BK reproduce multiplicities

[From Dumitru at IS2014]

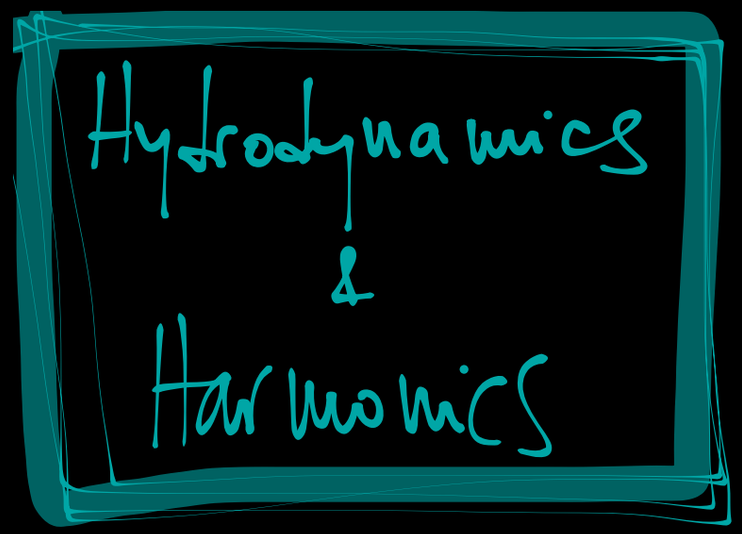


[Albacete, Dumitru, Fujii, Nara 2013]

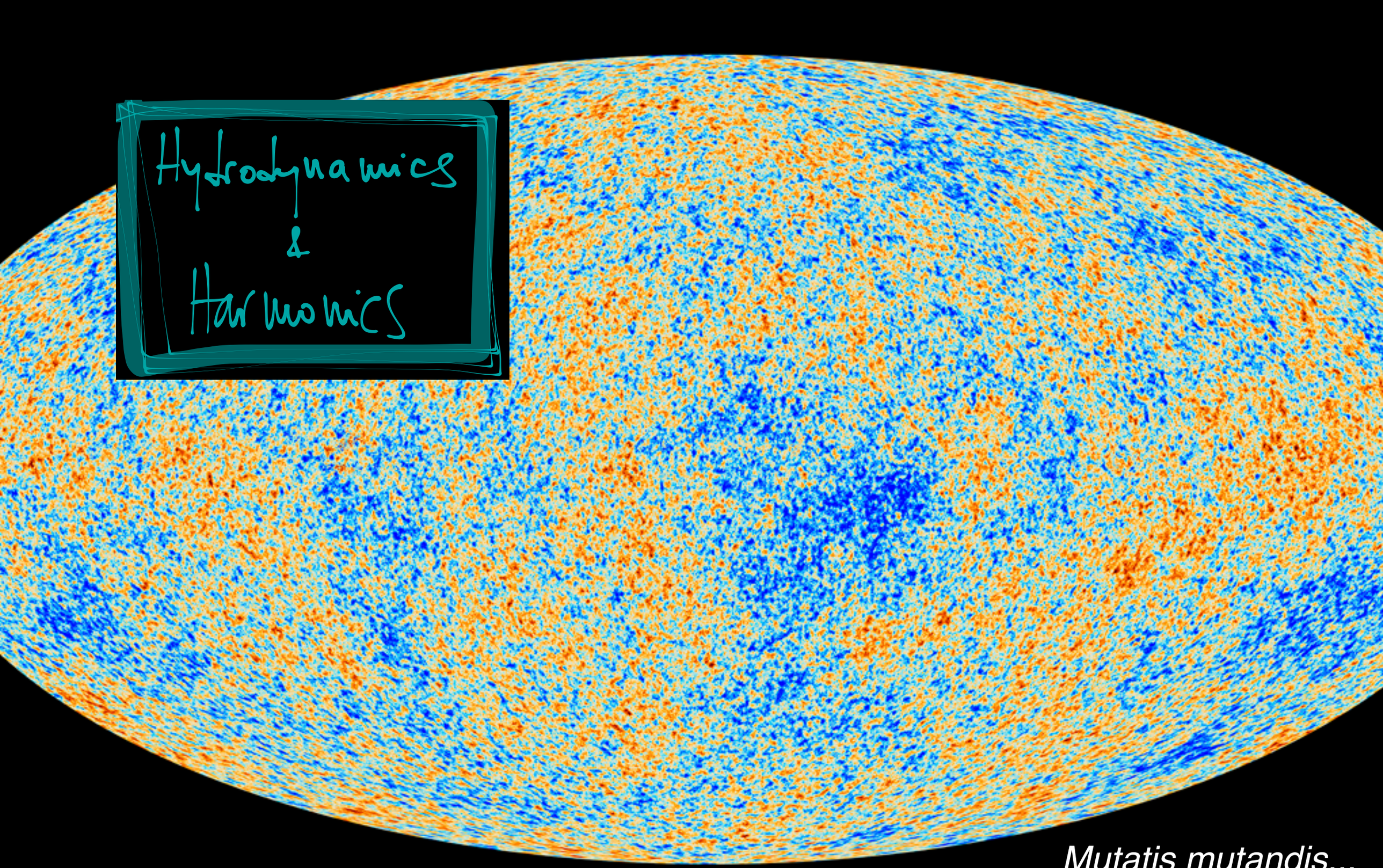


Multiplicities are reproduced in a QCD-based approach

- 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]



Mutatis mutandis...



Mutatis mutandis...

Checks of hydrodynamics

[degree of thermalization of the medium]

$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \text{viscosity corrections}$$

+ Equation of state

Does not address the question on **how thermal equilibrium is reached**

- *Far from equilibrium initial state needs to equilibrate fast (less than 1 fm)*

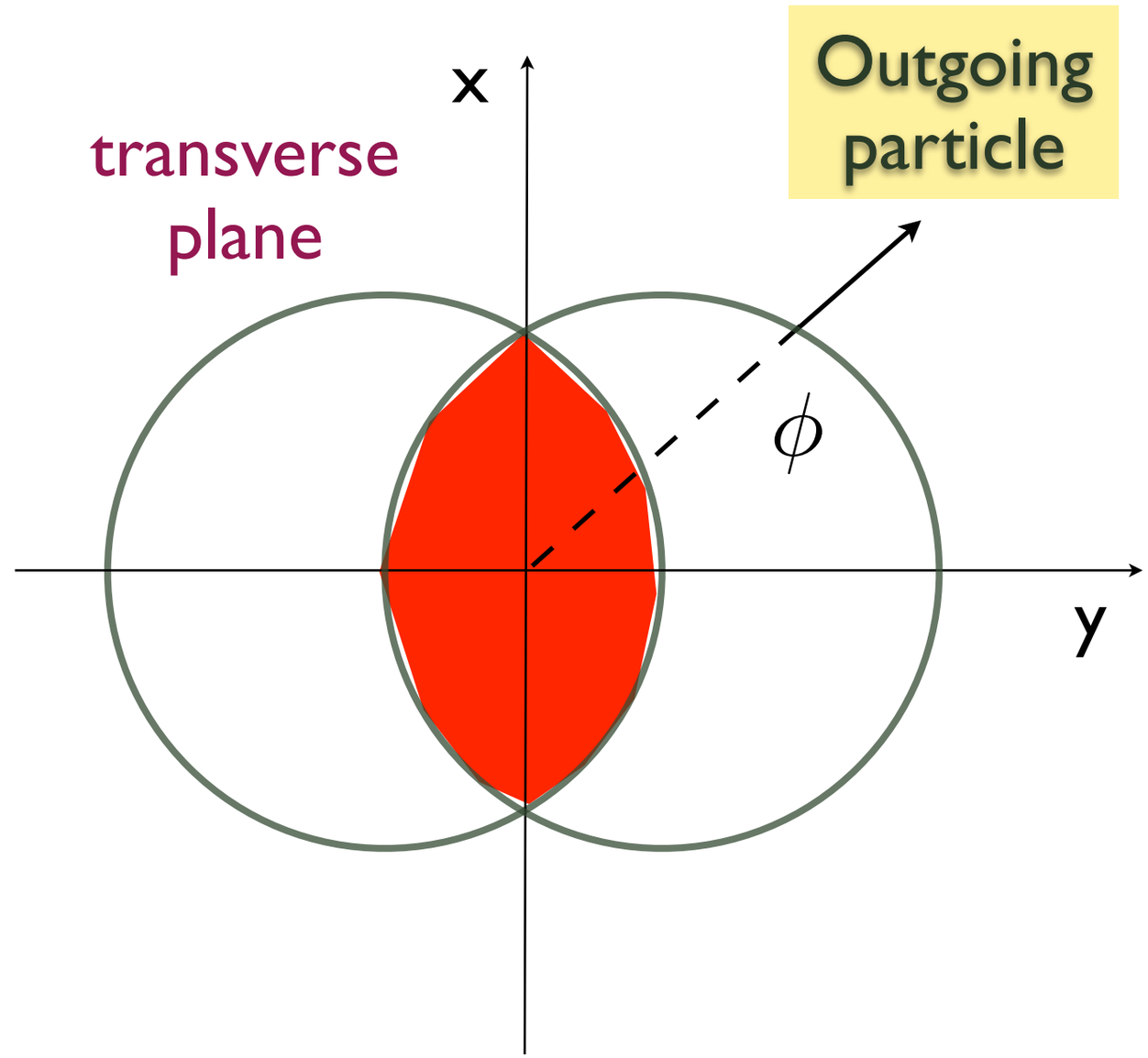
Most of the theoretical progress in the last years:

- *Viscosity corrections*
- *Fluctuations in initial conditions*

The essential measurement for hydro

⇒ Recall the Euler equation

$$\frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P$$



The essential measurement for hydro

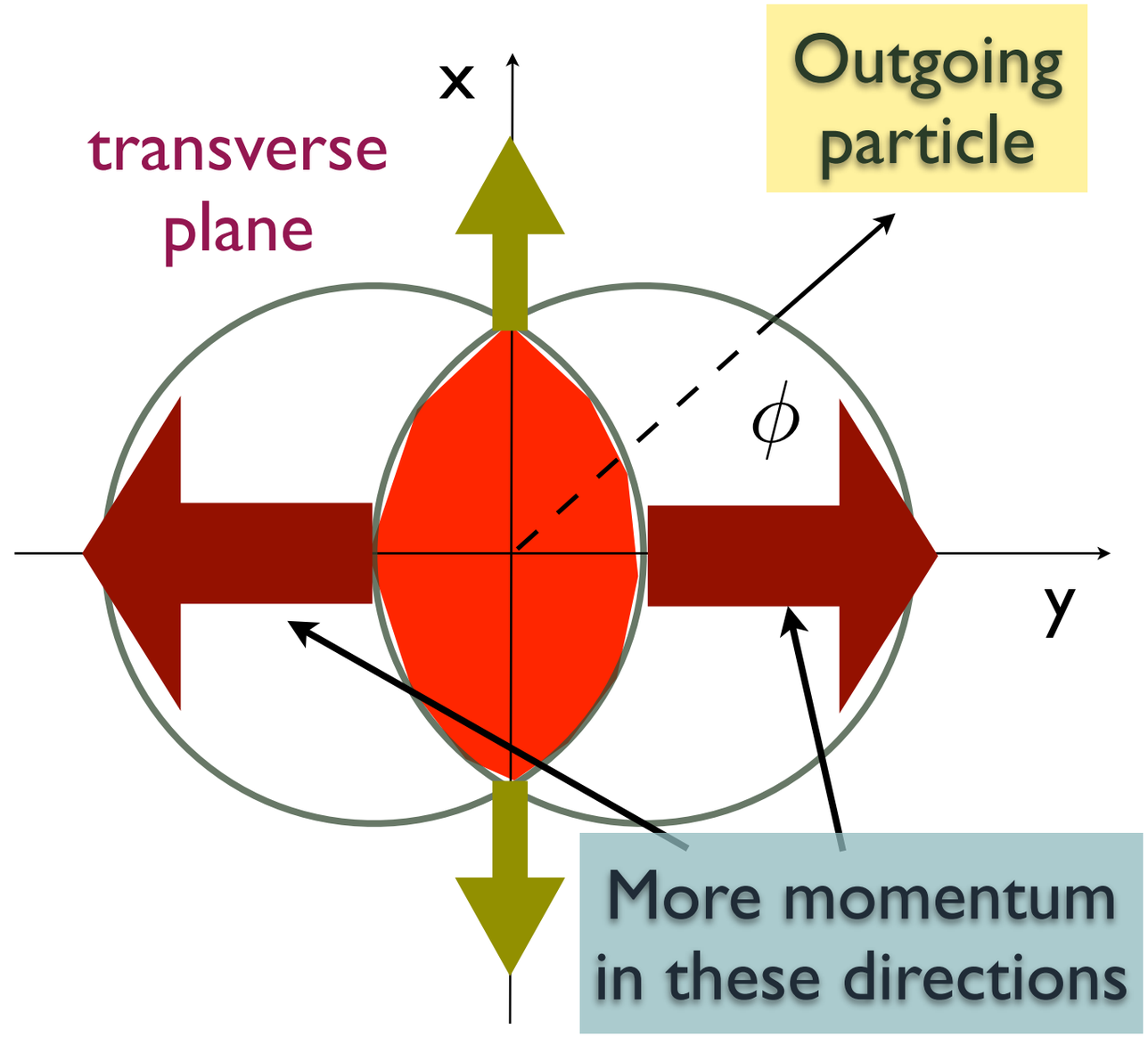
⇒ Recall the Euler equation

$$\frac{d\beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P$$

$$\epsilon = 3P \quad \Longrightarrow \quad \nabla_x P < \nabla_y P$$

⇒ **Elliptic flow** normally measured by the second term in the Fourier expansion

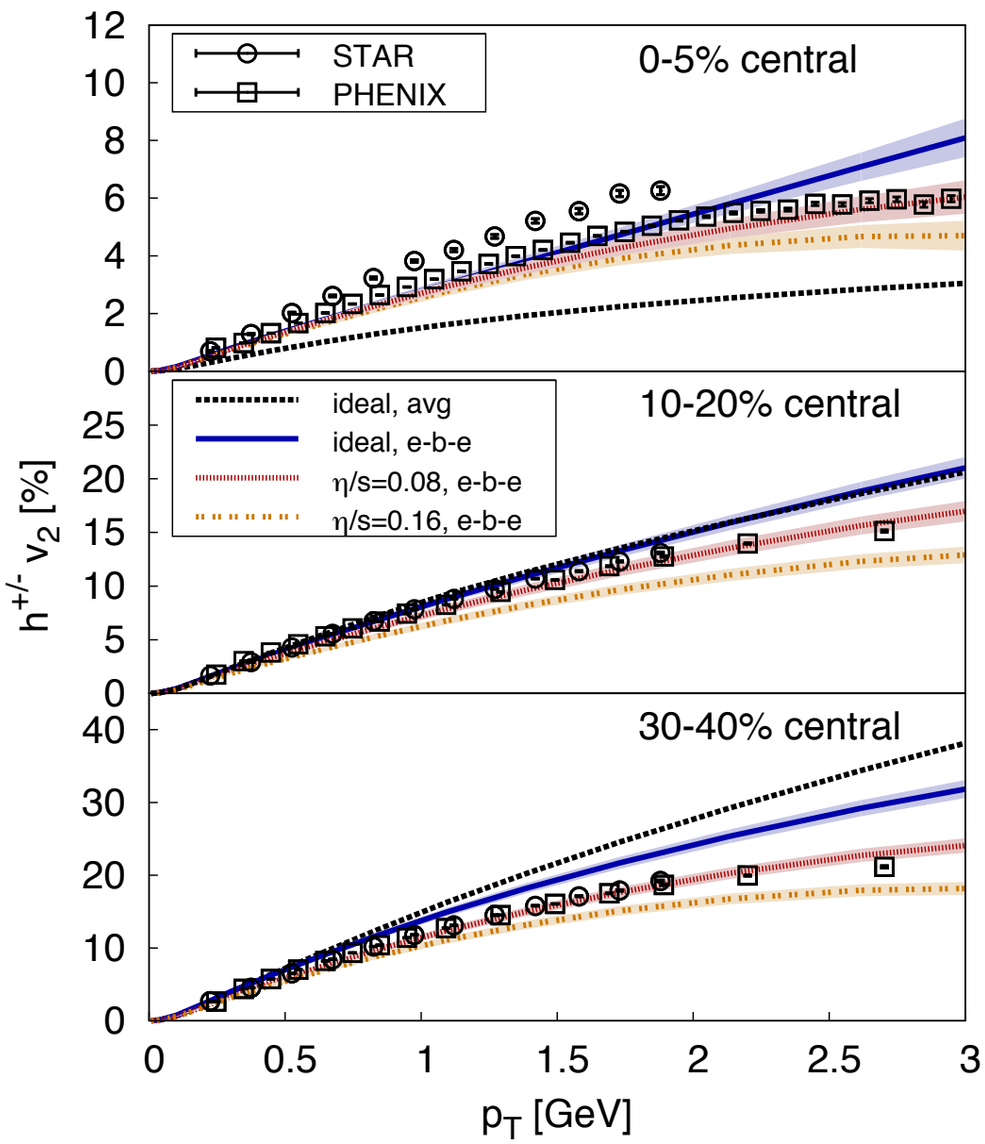
$$\frac{dN}{d\phi} \propto 1 + 2\, v_2 \cos(2\phi)$$

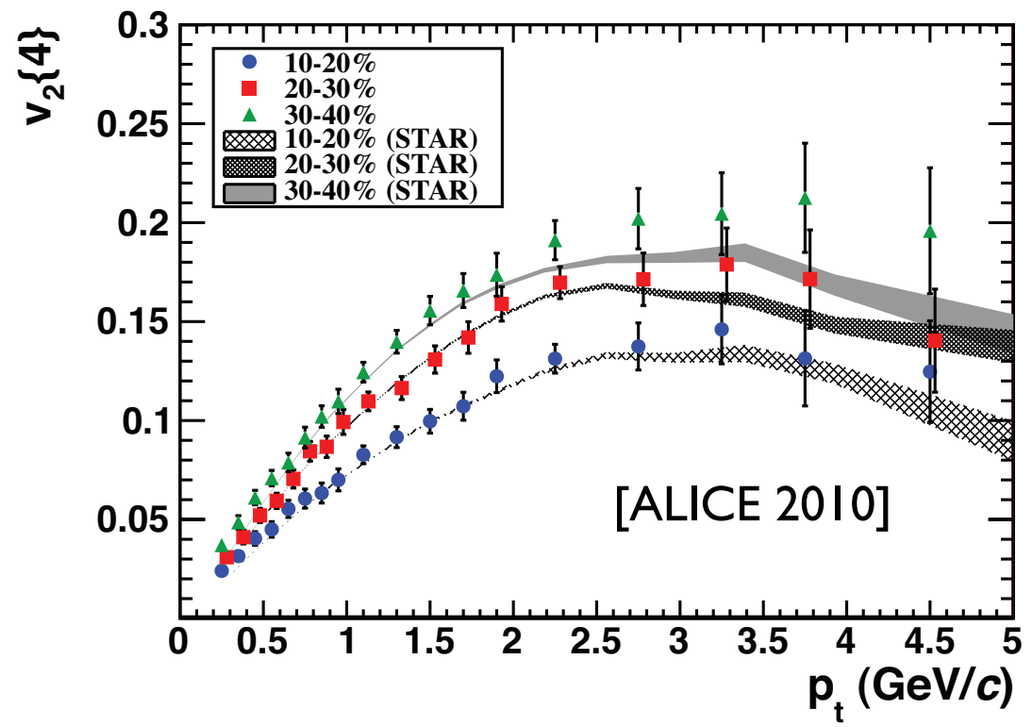


Initial anisotropies in spacial distributions translate into final (measurable) anisotropies in momentum

Fluid behavior from hydro: viscosity of the QGP

[Schenke, Jeon, Gale 2010]





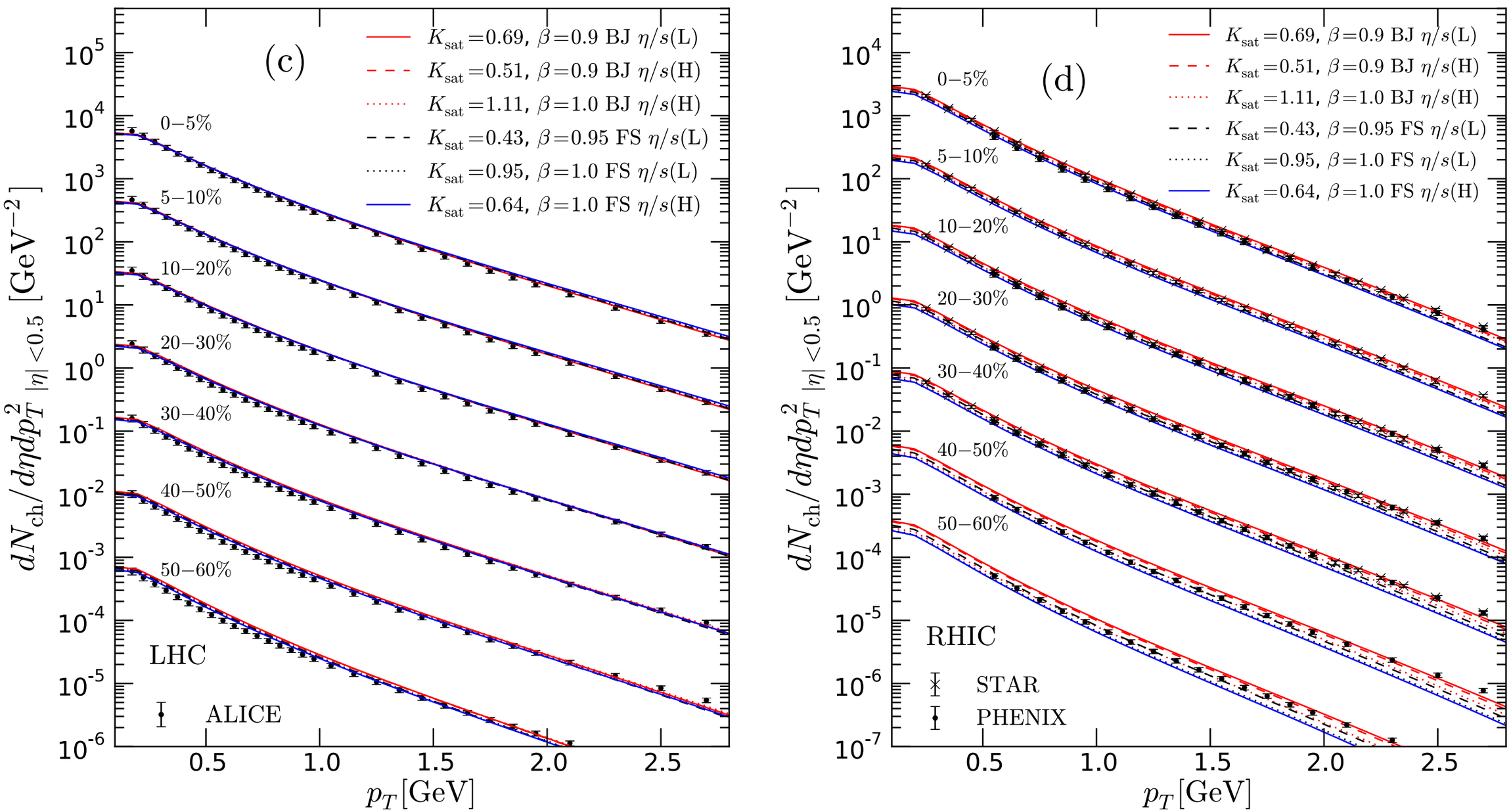
- **Lowest viscosity known**
  - "perfect liquid": sQGP
  - AdS/CFT bound

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

[Policastro, Son, Starinets, 2001]

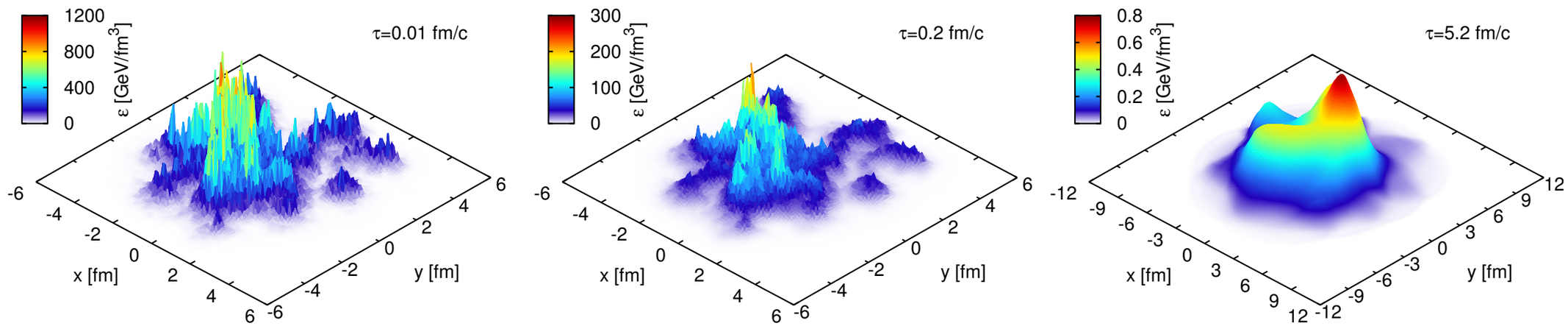
- **LHC similar to RHIC**

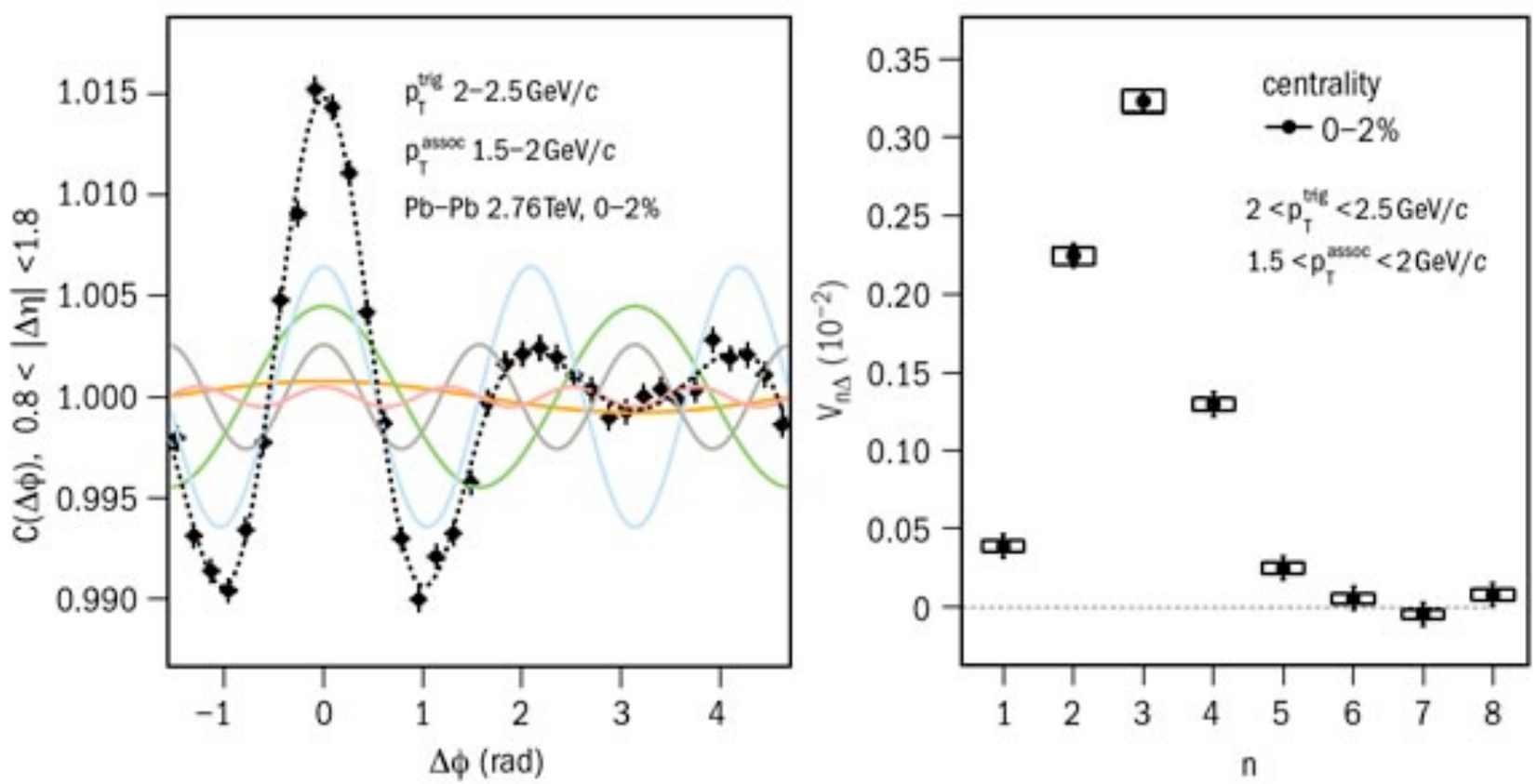
Hydro: description of the data



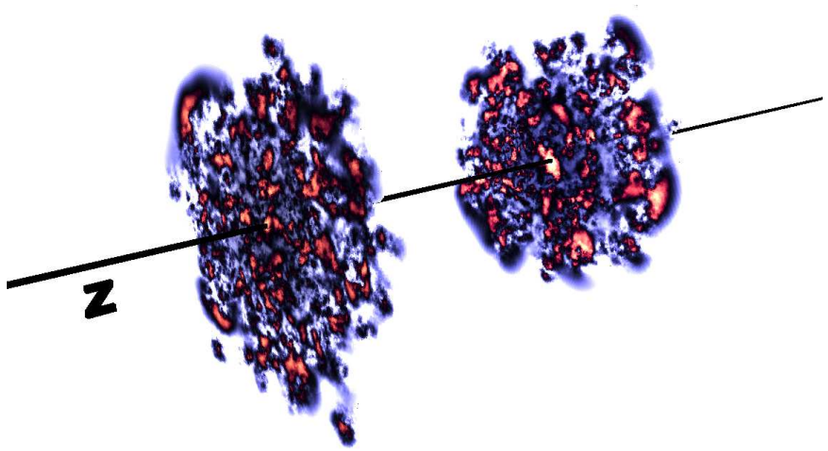
[Paatelainen, Eskola, Niemi, Tuominen 2013]

Event-by-event fluctuations

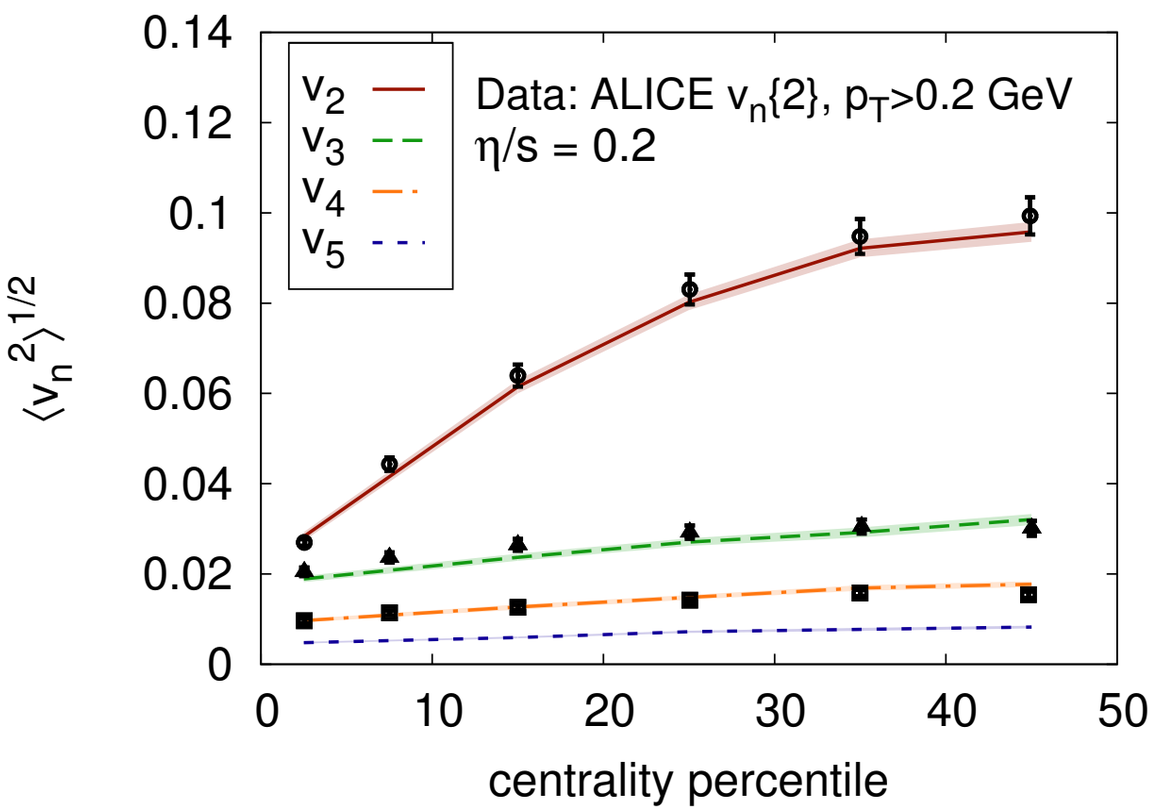


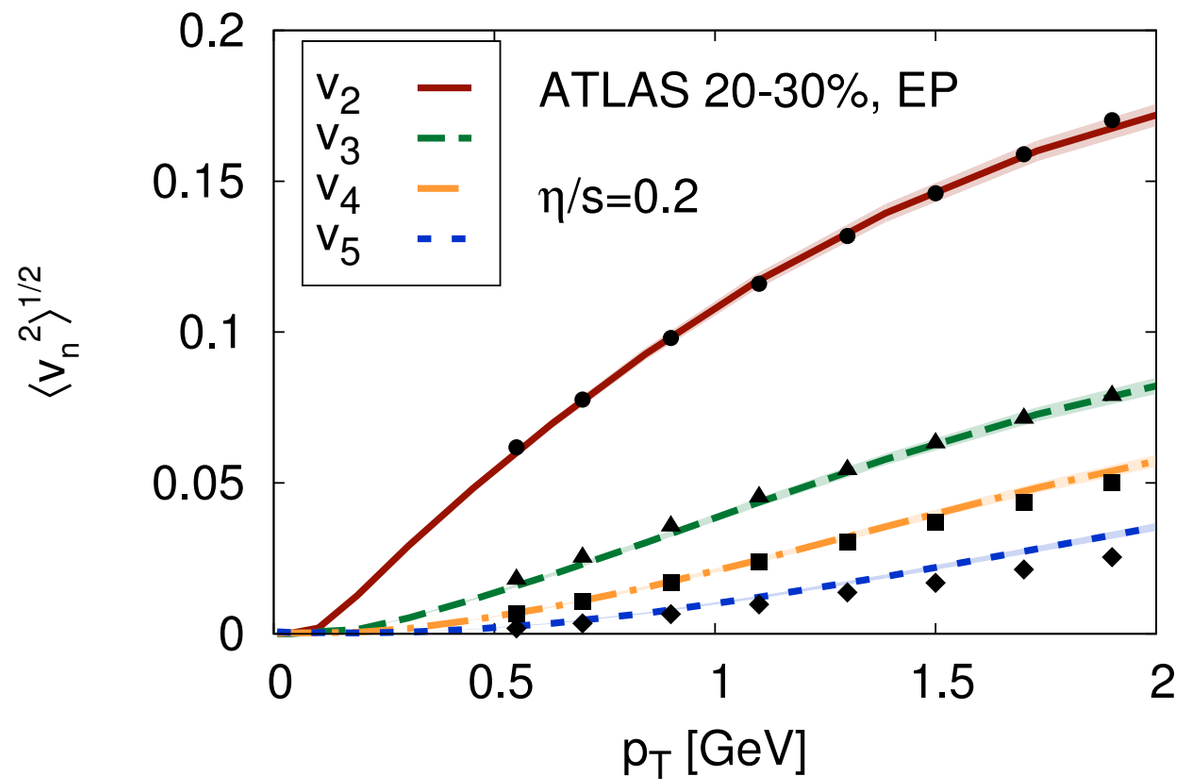


CGC as initial conditions for hydro



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





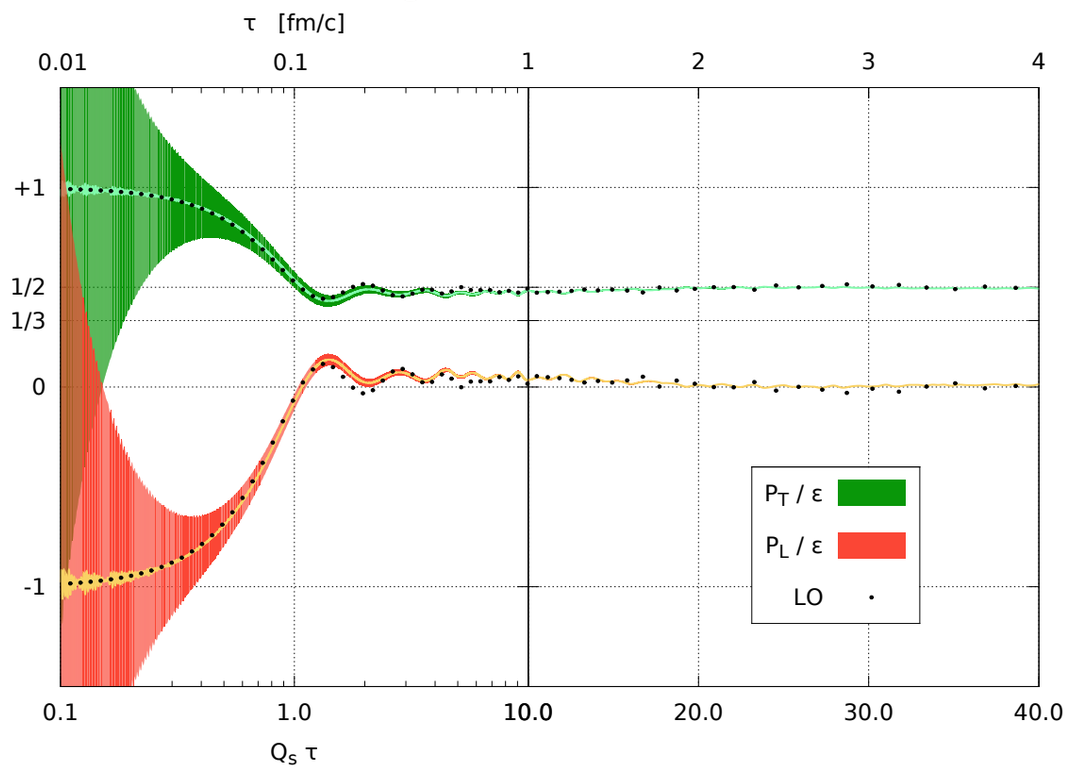
[Gale, Jeon, Schenke, Tribedy, Venugopalan 2013]

Towards isotropization...

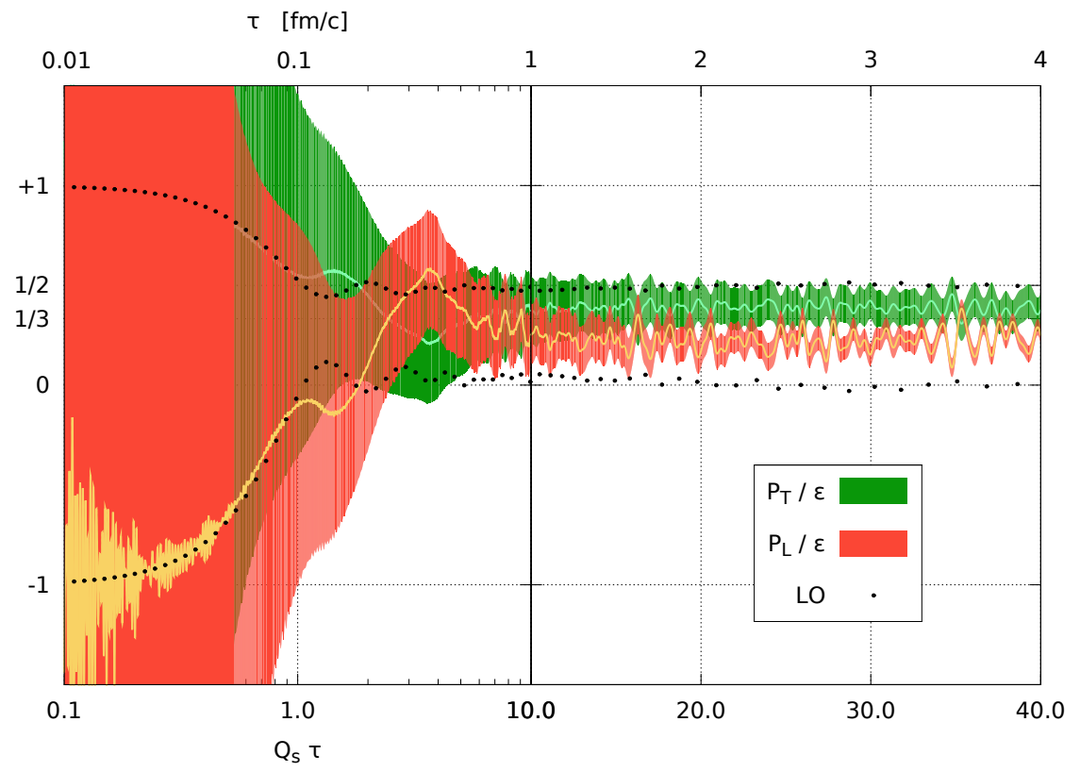
The CGC picture provides a framework to study the evolution to equilibrium

- 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

$\alpha_s = 0.0008$



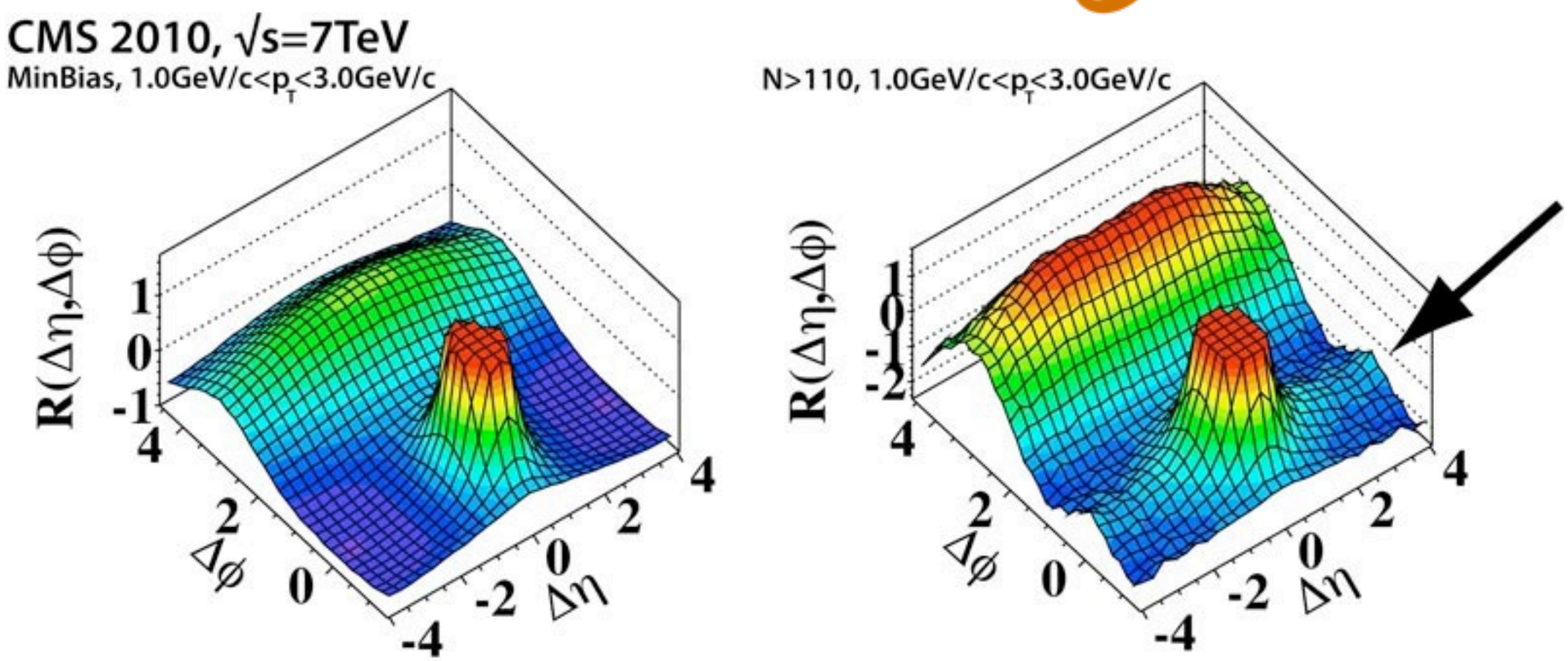
$\alpha_s = 0.02$



[Epelbaum, Gelis 2013]

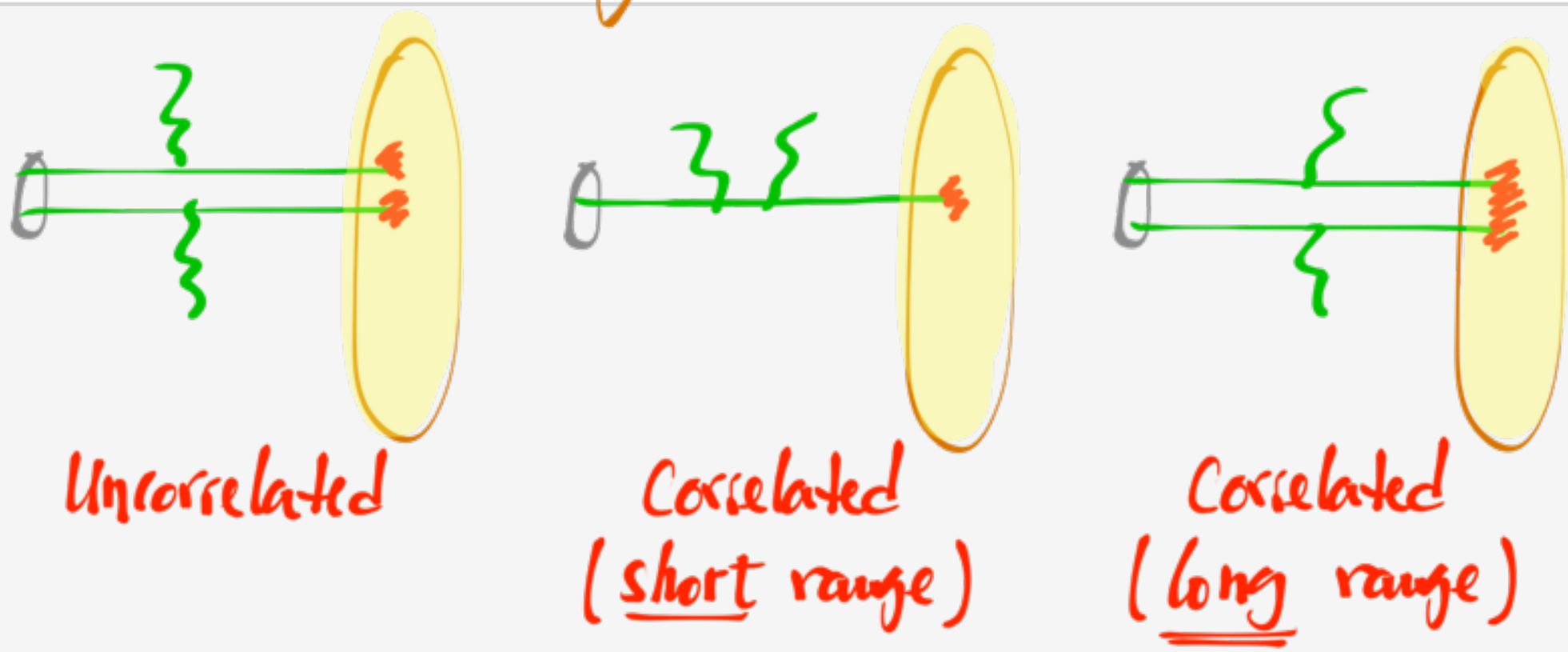
A lot of activity not quote here - both weak and strong (AdS/CFT) coupling

The Ridge



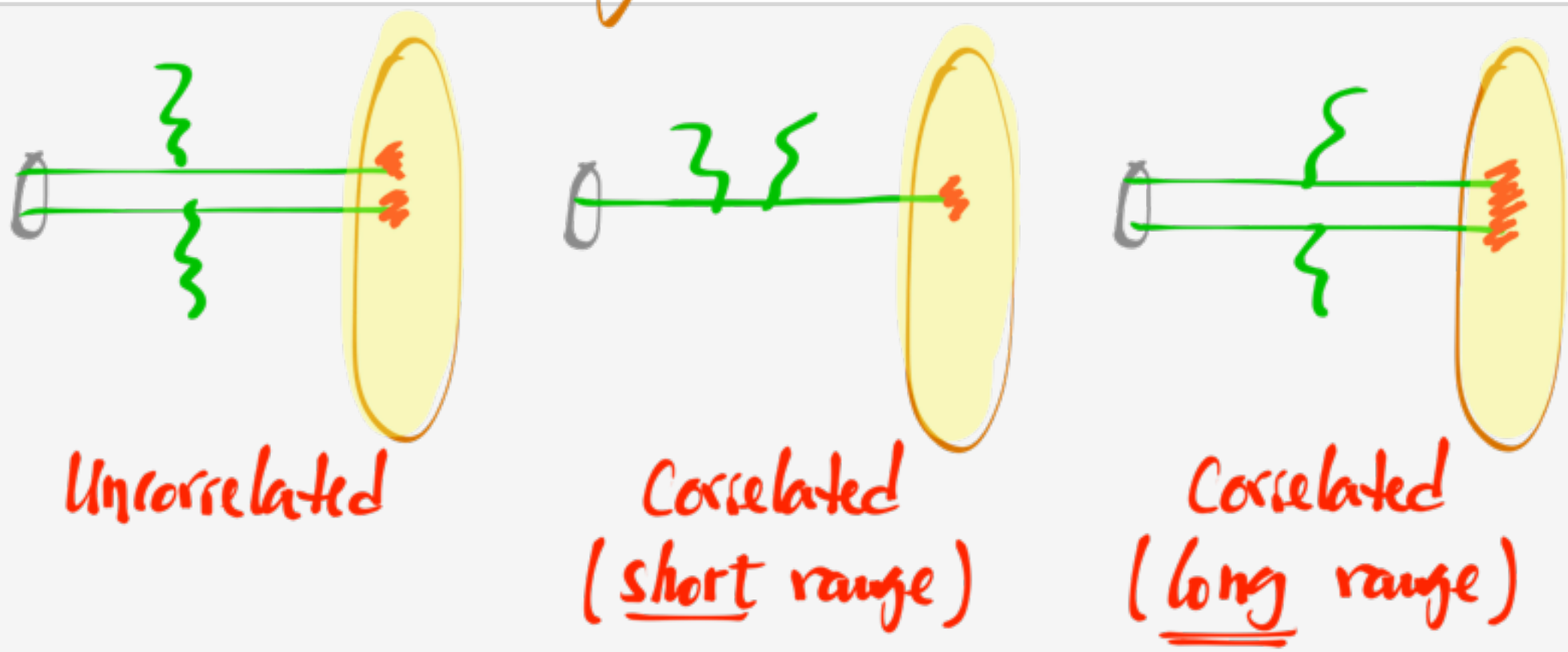
- **Structure needs to be formed very early by causality requirements**
- Observed in pp, pA (LHC) and AA (RHIC+LHC)

The Ridge & the CGC



COLOR Correlations in transverse plane $\sim Q_{sat}^{-1}$

The Ridge & the CGC



COLOR Correlations in transverse plane $\sim Q_{sat}^{-1}$

Is the Ridge Initial State / Final State / Both ?

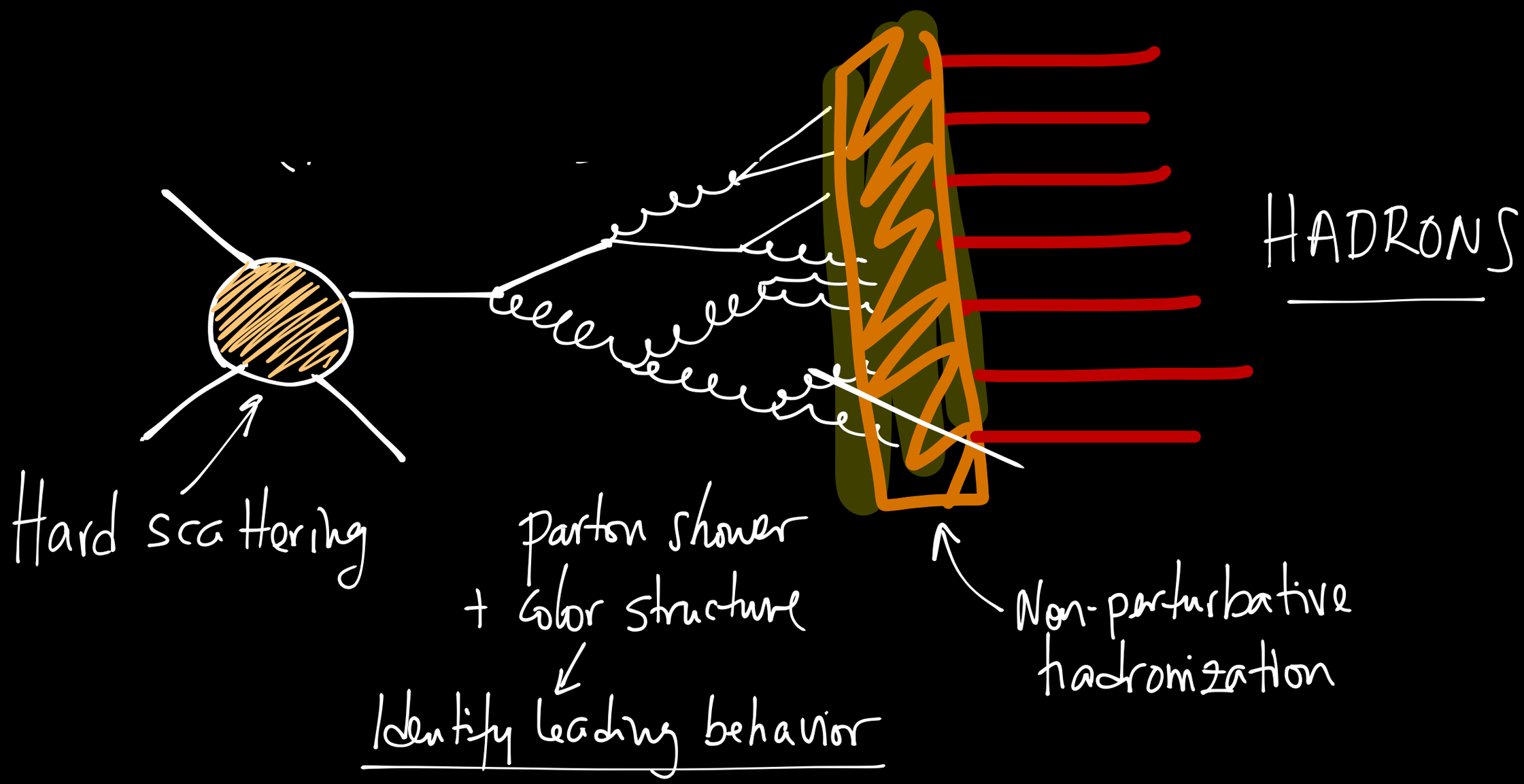
Summary

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

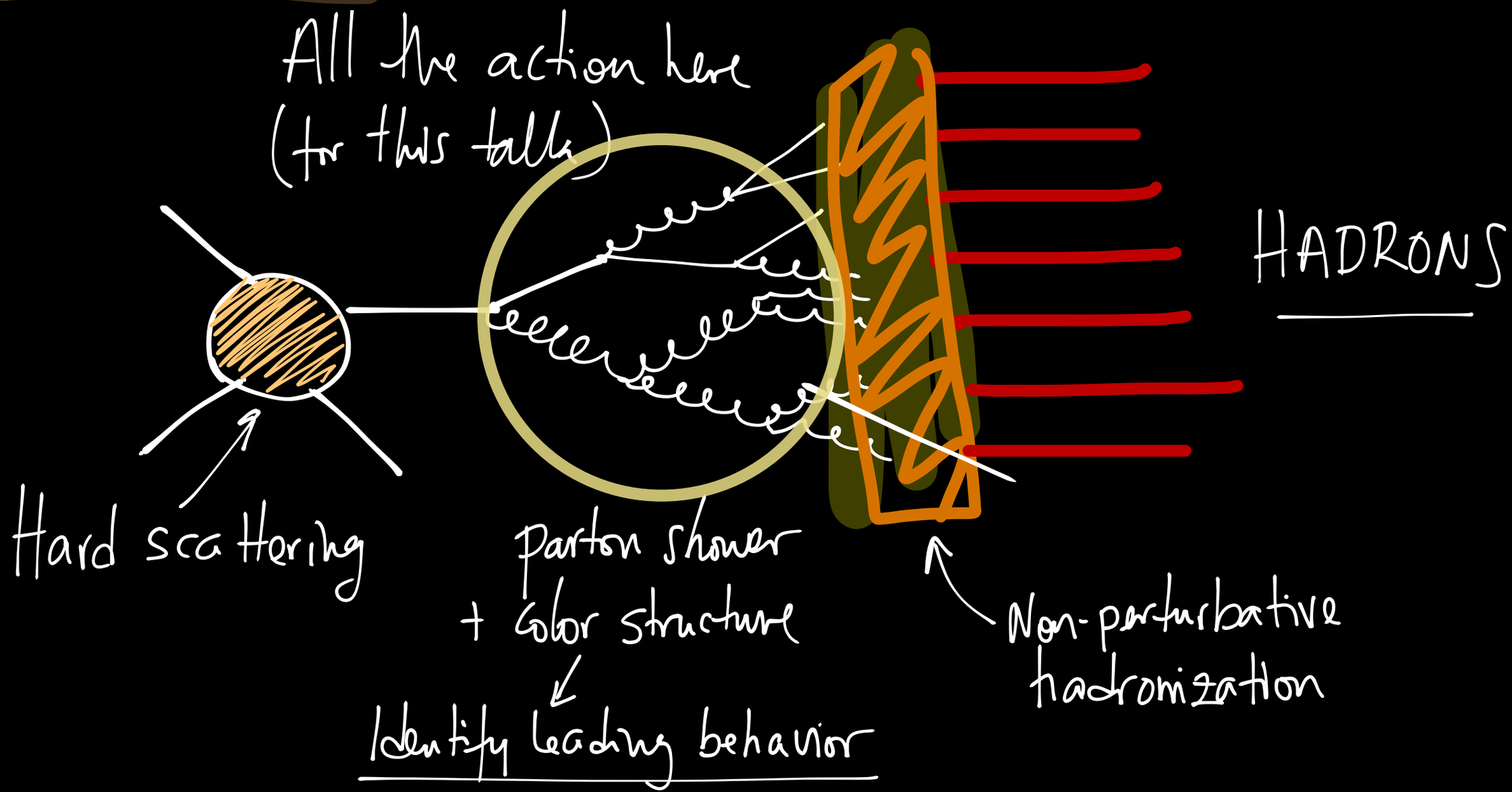
* Non linear evolution → CGC
  - ↳ General framework to include collectivity
  - ↳ Gluon saturation → Color coherence
    - ↳ Qsat
  - ↳ Towards equilibrium
    - ↳ CGC → hydro ?

Some of the most fundamental questions in QCD

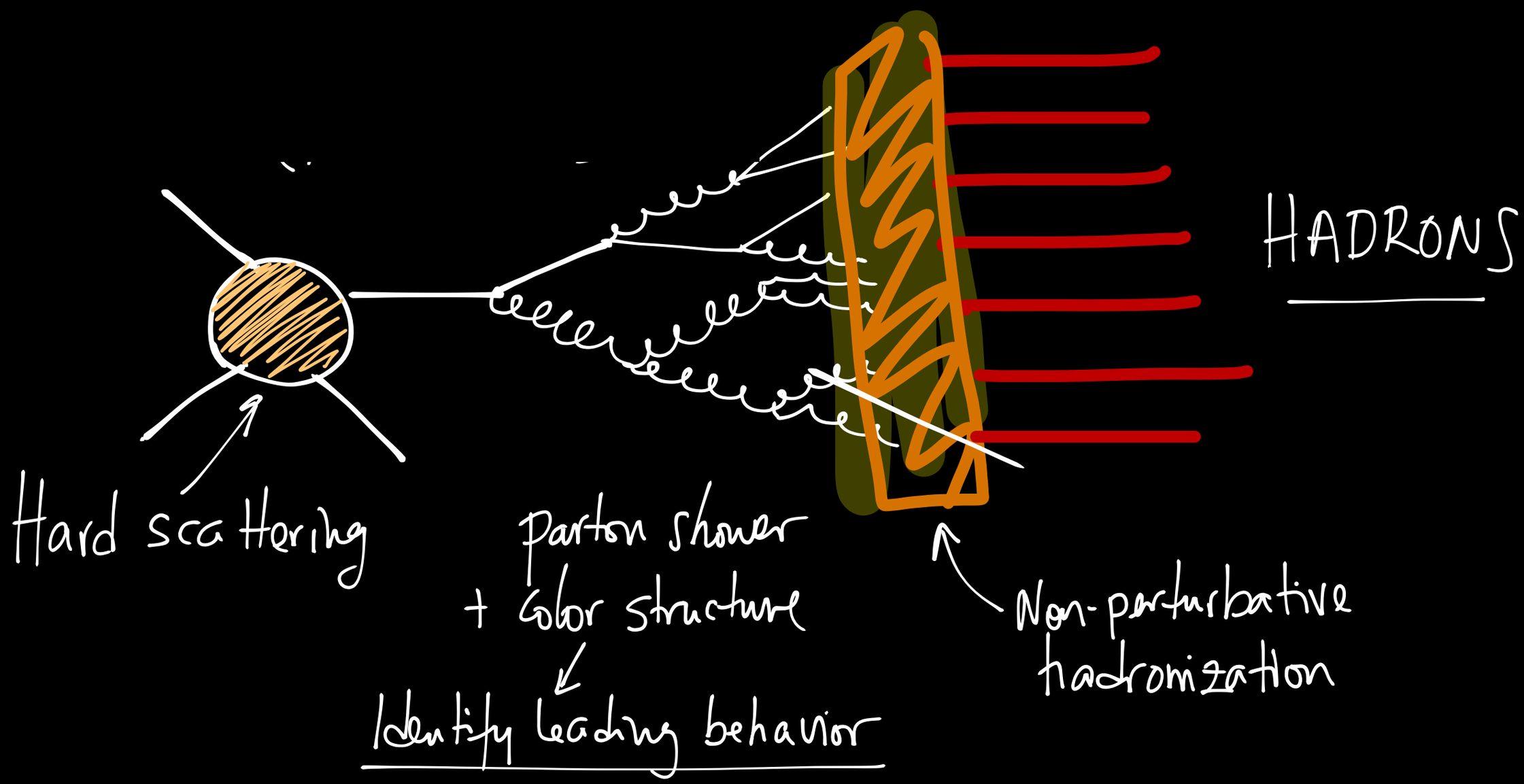
Jets in medium
Jet quenching



Jets in medium
Jet quenching

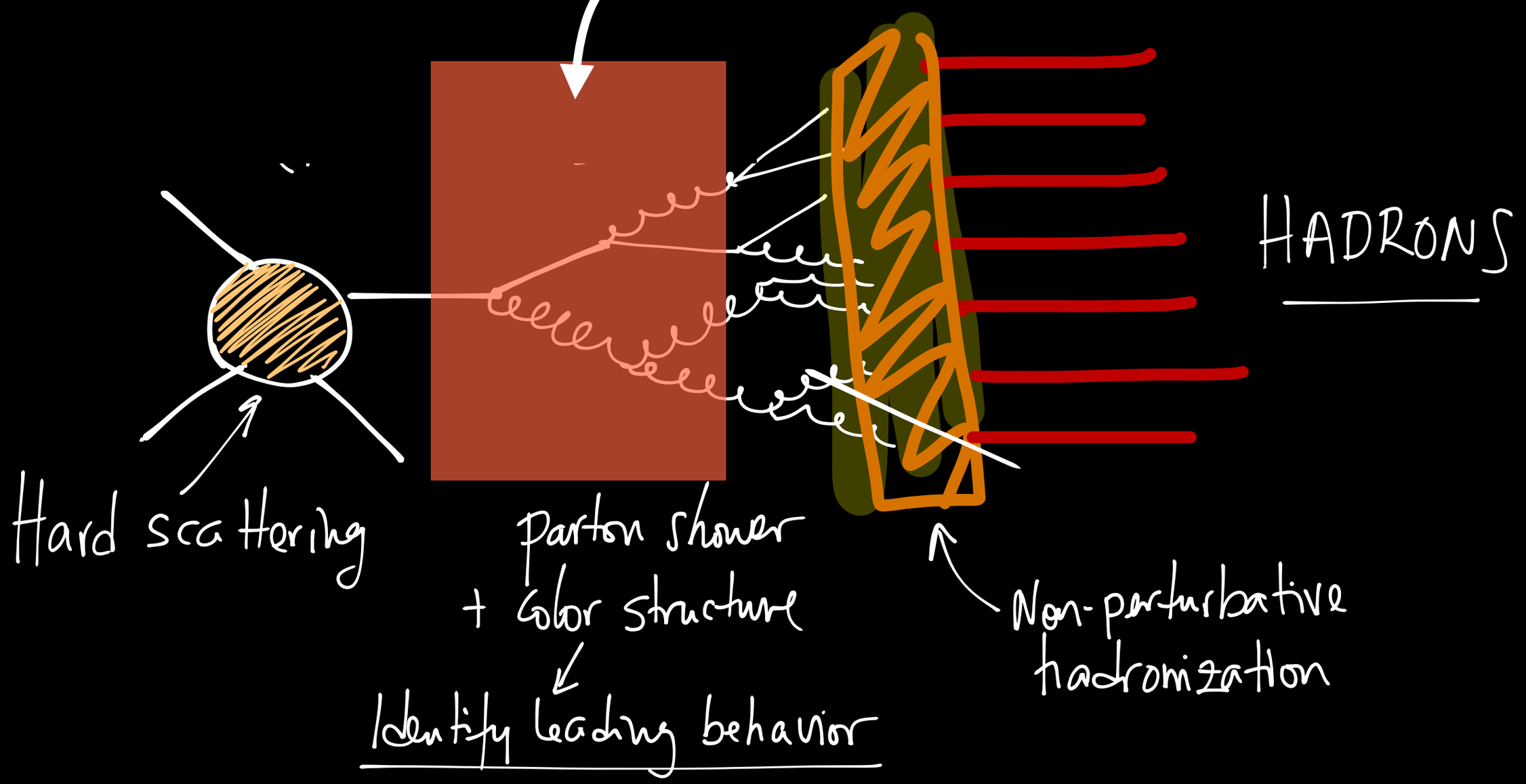


Jets in medium
Jet quenching

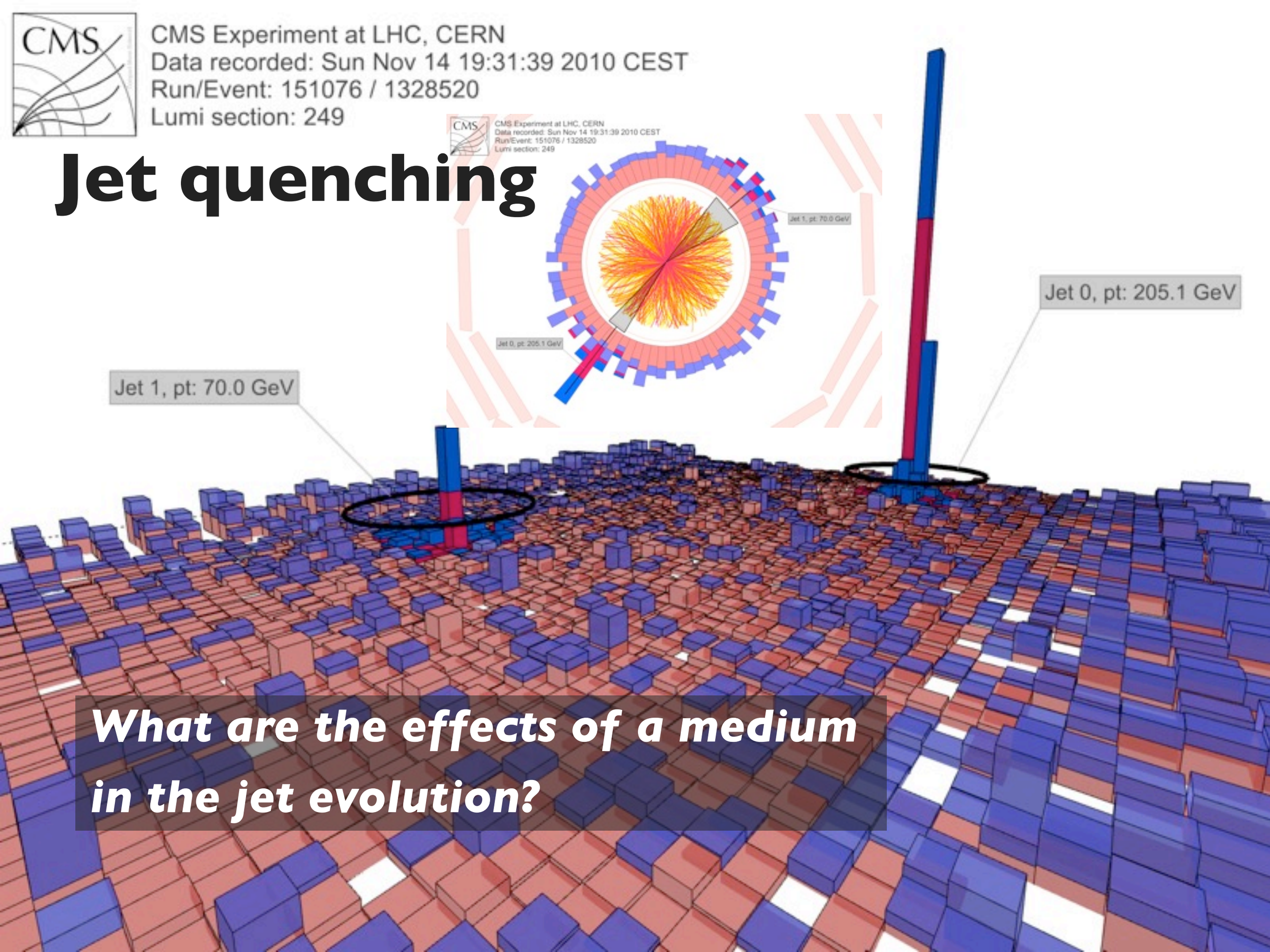


Jets in medium
Jet quenching

Put now a medium here

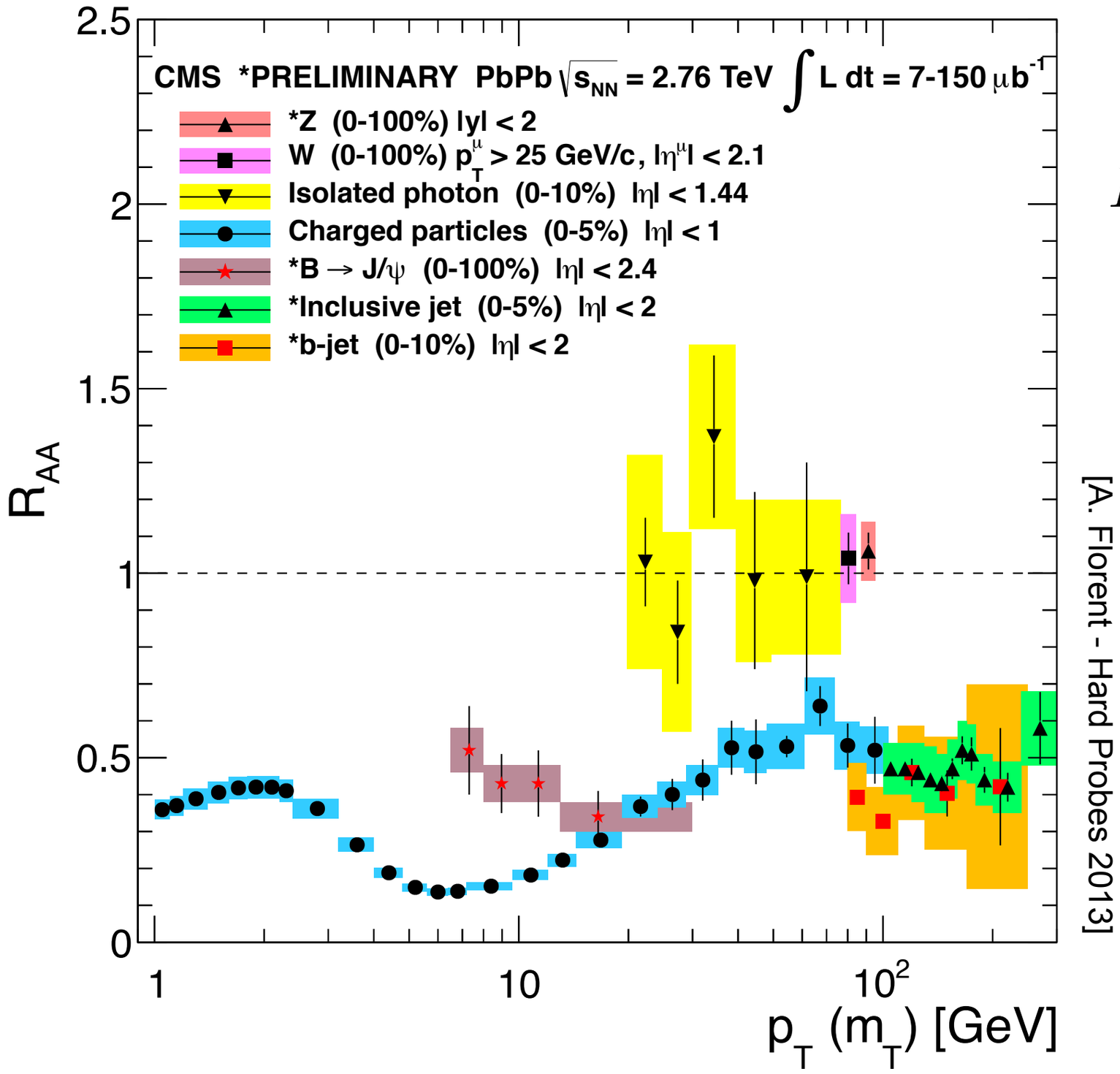


Jet quenching

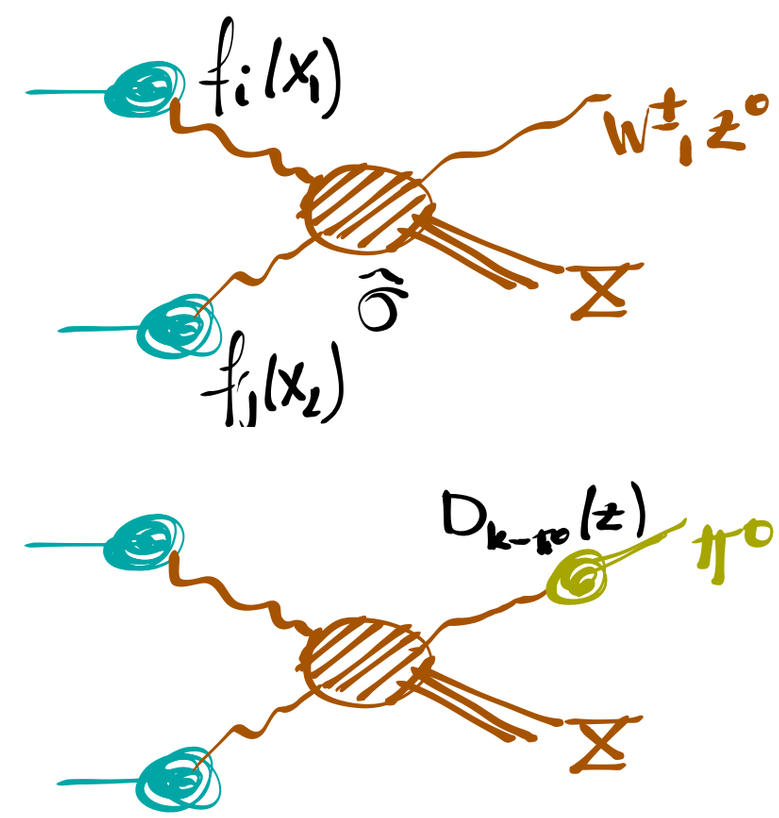


What are the effects of a medium in the jet evolution?

Suppression in one plot

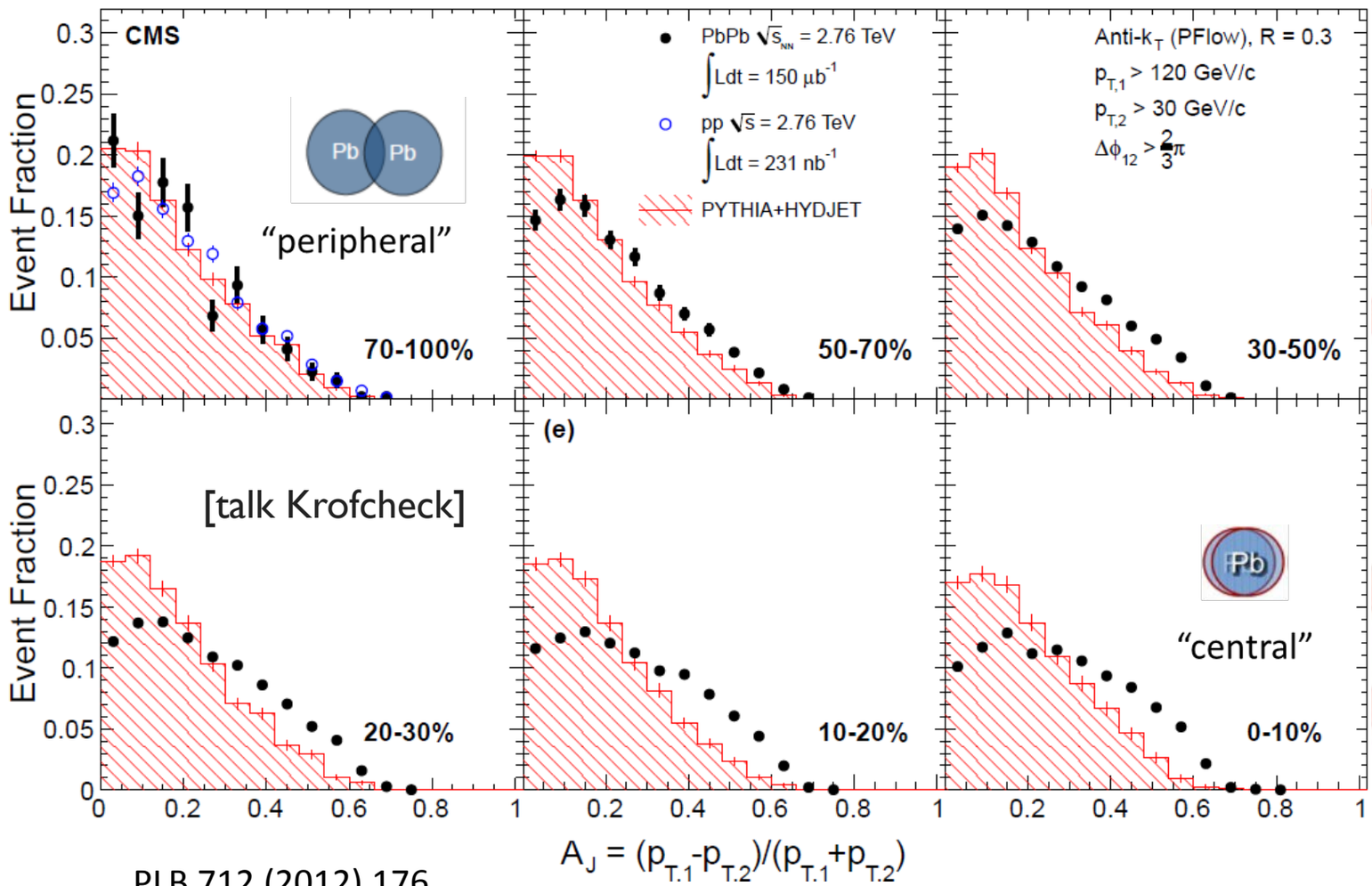


$$R_{AA} = \frac{dN^{AA}/dp_t}{\langle N_{coll}\rangle dN^{pp}/dp_t}$$

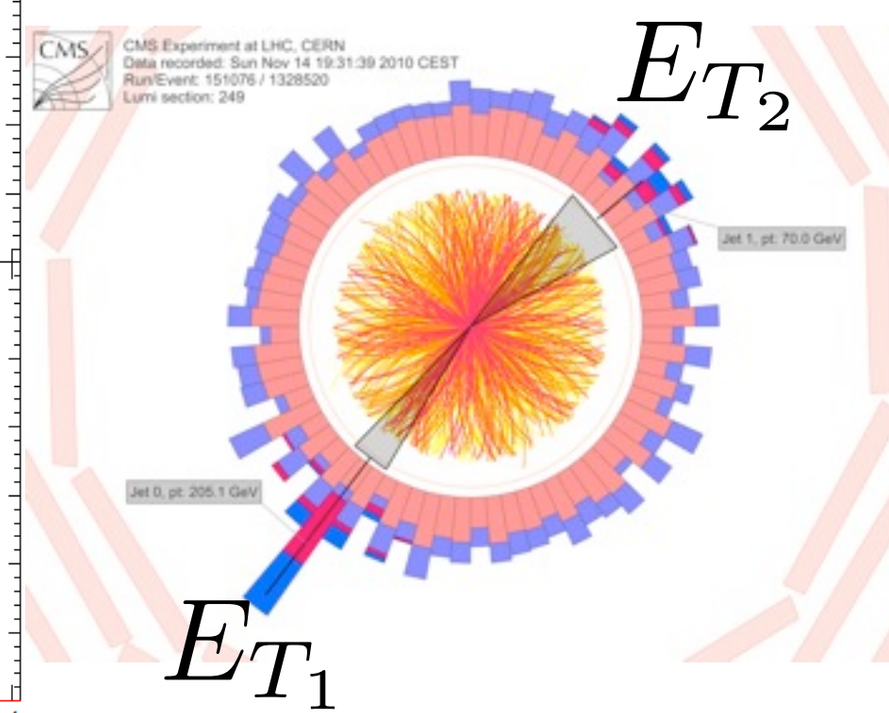


Di-jet asymmetry at the LHC

⇒ Energy imbalance indicates **strong energy loss** $A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$



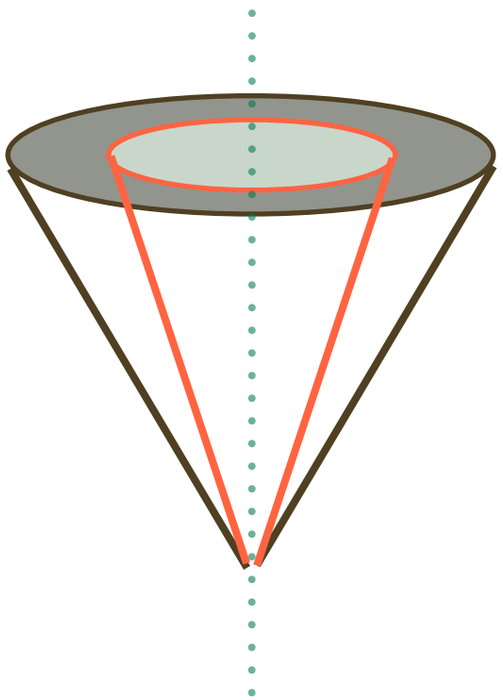
PLB 712 (2012) 176

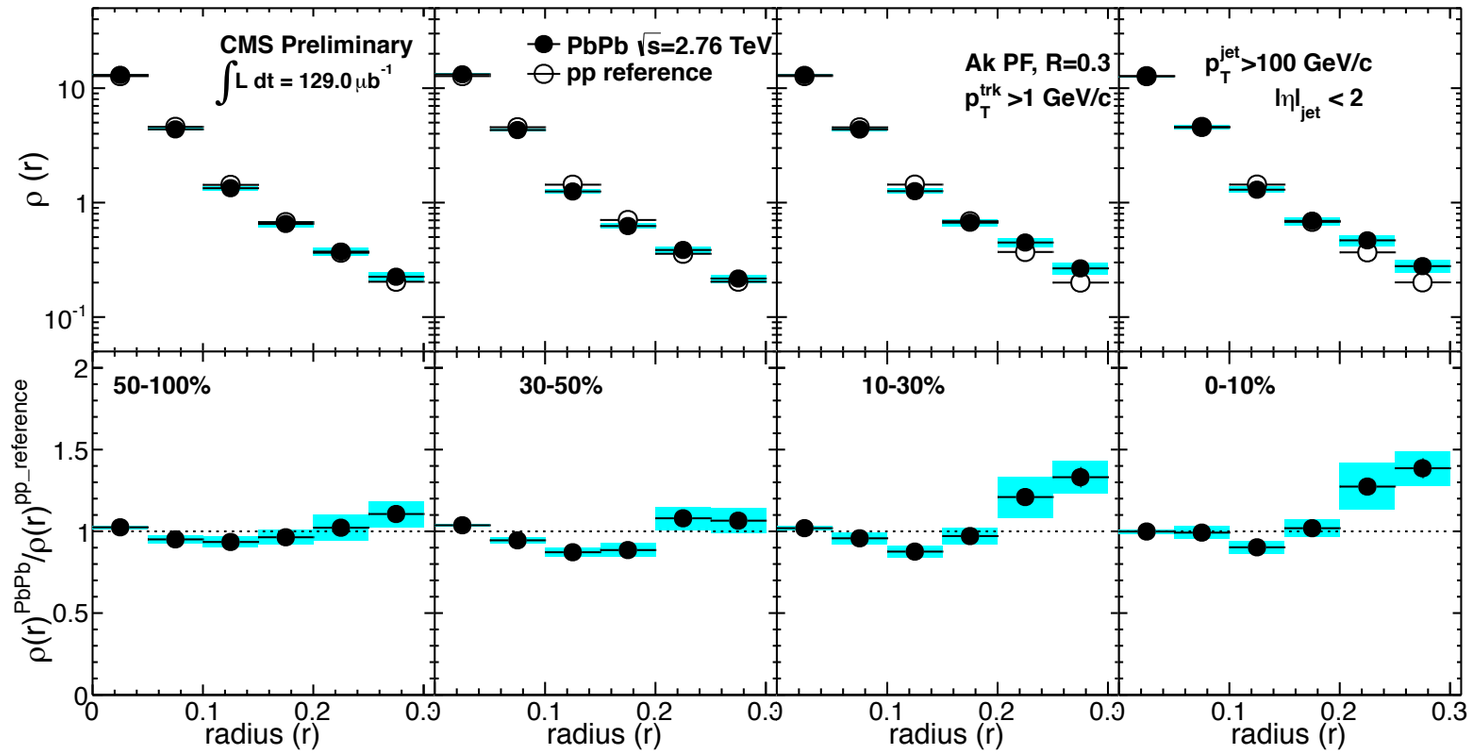


⇒ Reconstructed jet measurements **sensitive to broadening**

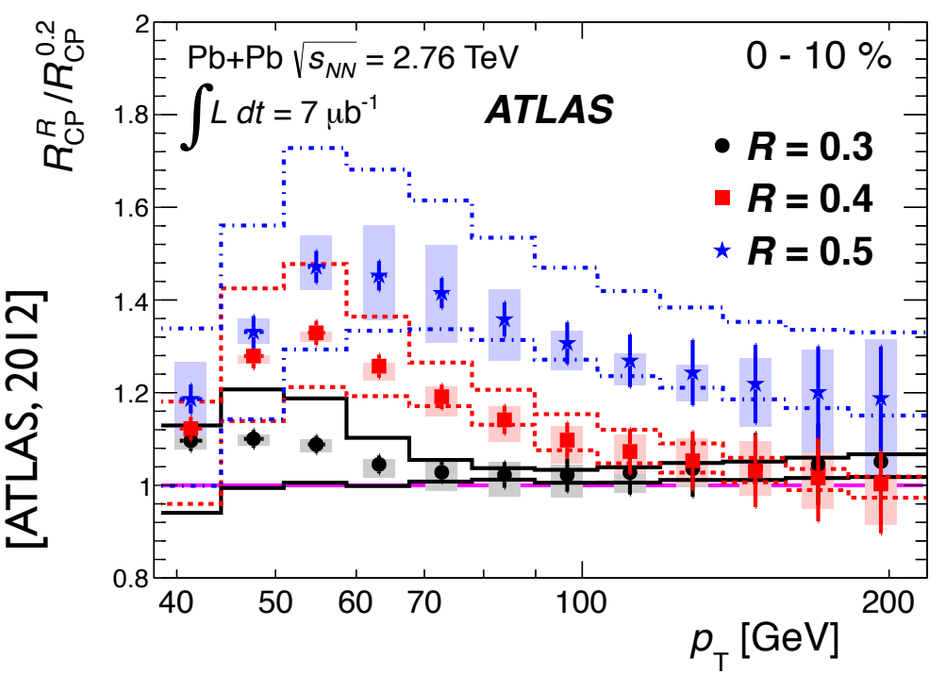
⇒ Jets are suppressed: **Studied sample is a subset of the total**

Reconstructed jets at the LHC - jet shapes





[CMS, Quark Matter 2012]



[ATLAS, 2012]

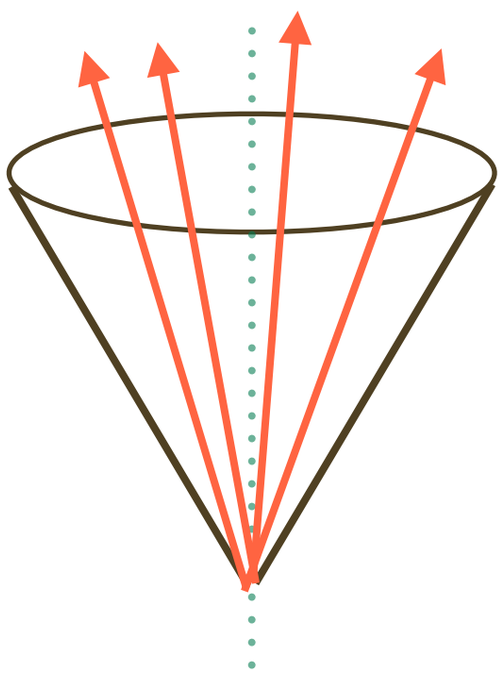
What is the **distribution in energy** for different jet angles?

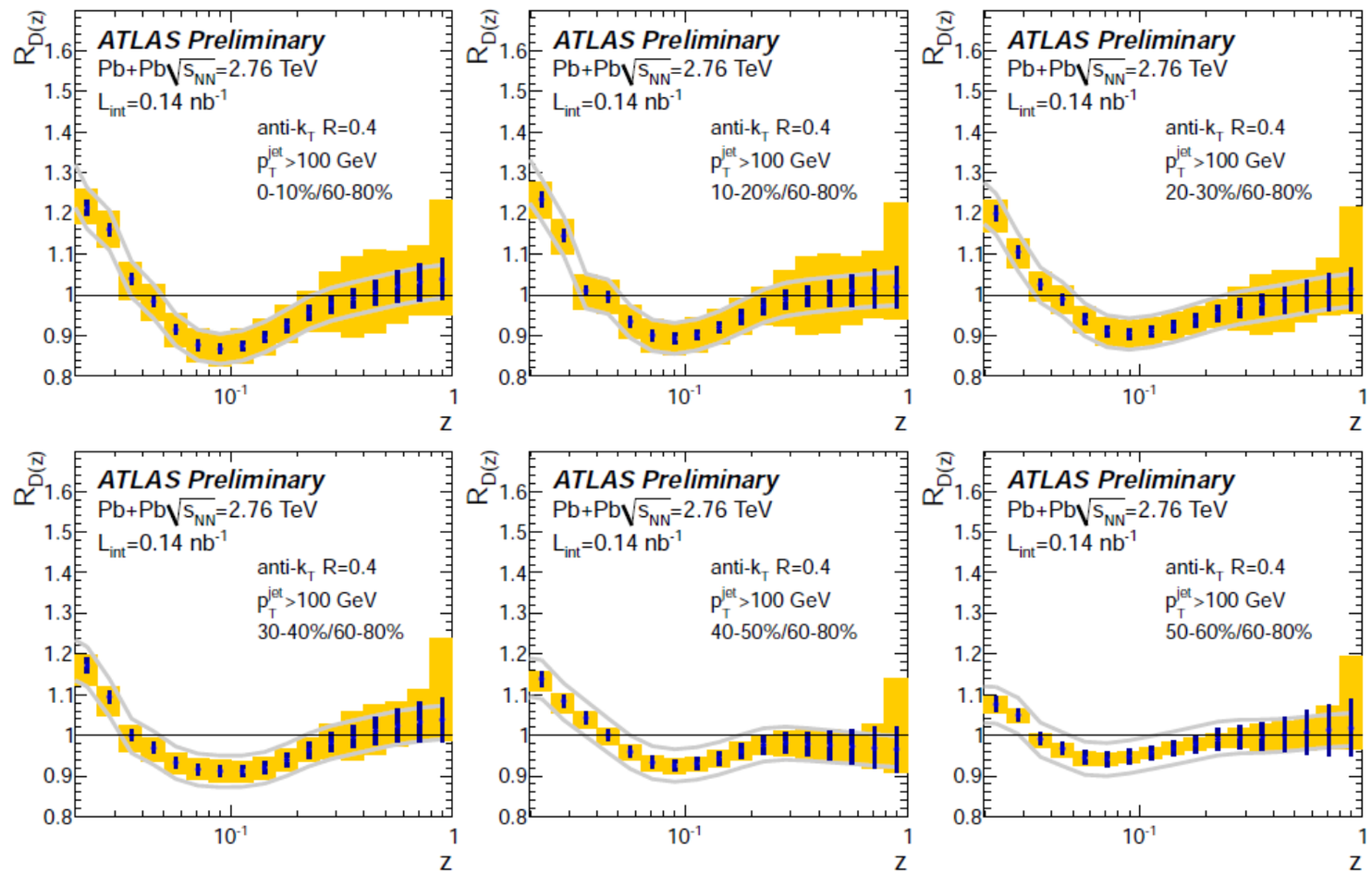
- **Not strong changes** with respect to pp
- **Small broadening seen**
- Jets with larger-R are less suppressed

Fragmentation functions

Distribution of particles inside a jet: fragmentation functions

$$z = \frac{p_T^{\text{hadron}}}{p_T^{\text{jet}}}$$





[ATLAS, Quark Matter 2012]

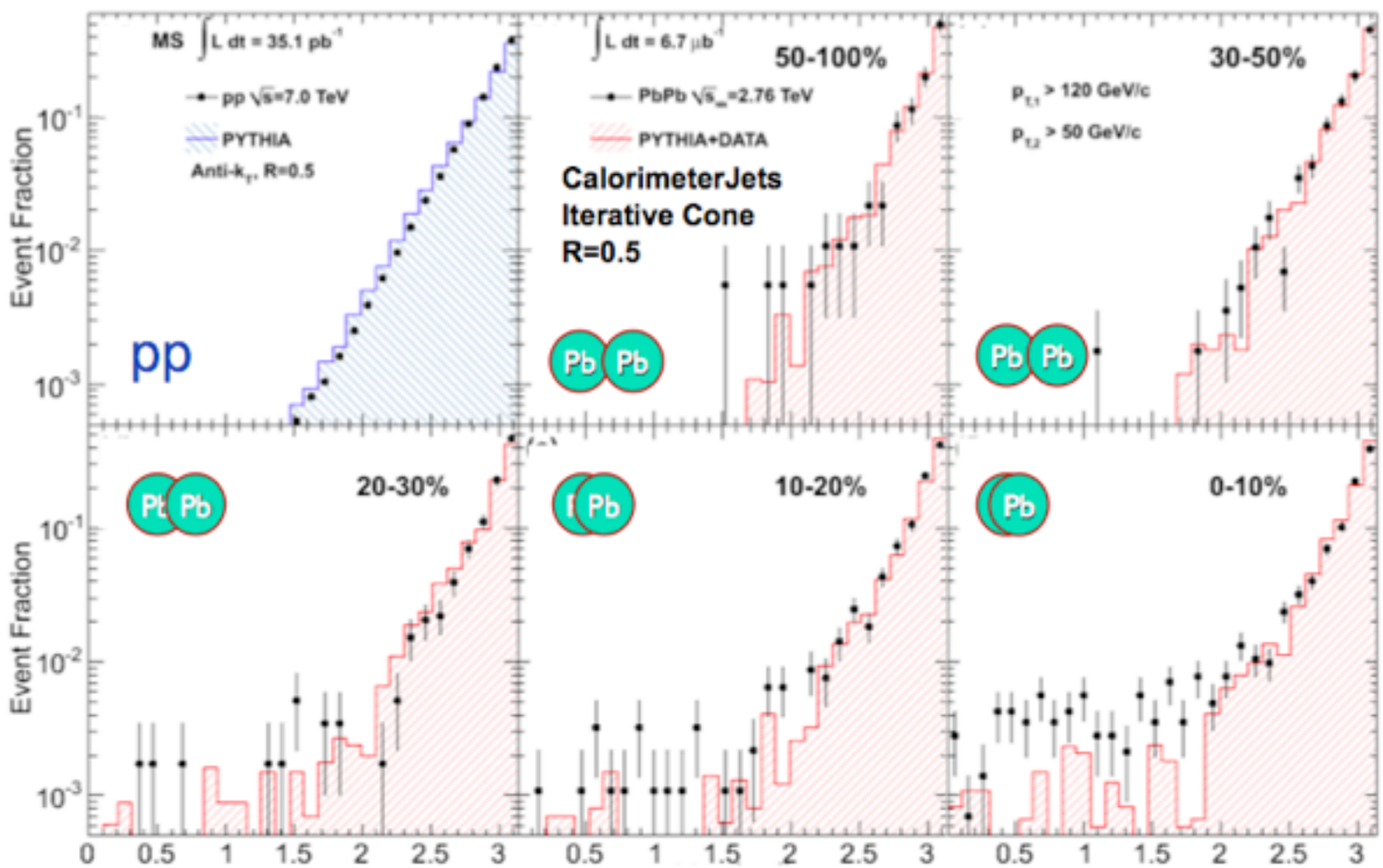
[CMS - similar results]

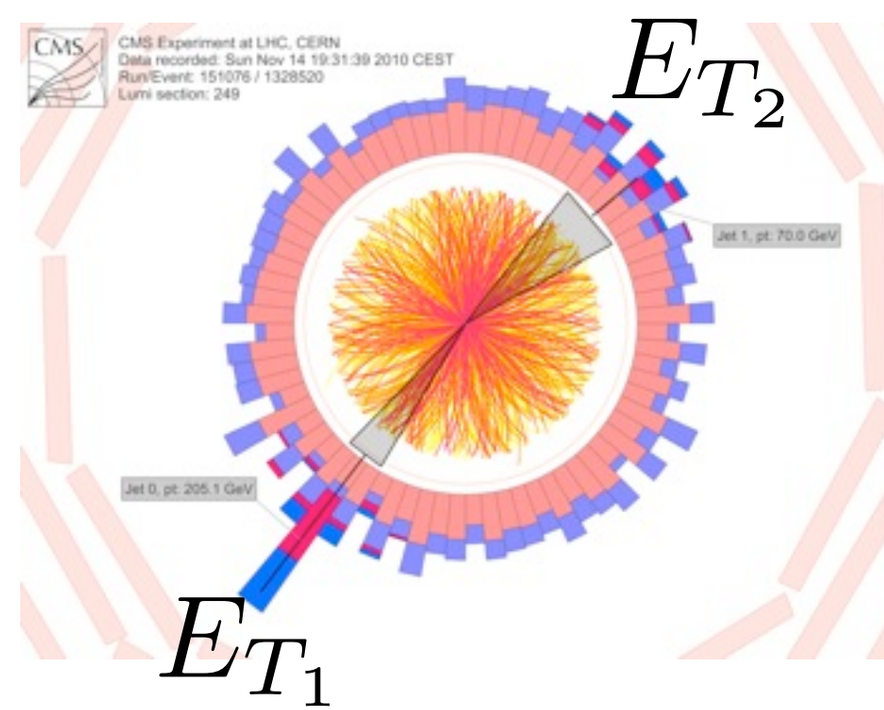
- Fragmentation functions carry "longitudinal" information
- **Modifications:** enhancement in soft (expected) no suppression at hard (unexpected)
- **Strong constraints to underlying dynamics**

Di-jet asymmetry at the LHC

⇒ Azimuthal distribution of two most energetic jets

[CMS 2011; ATLAS similar results]



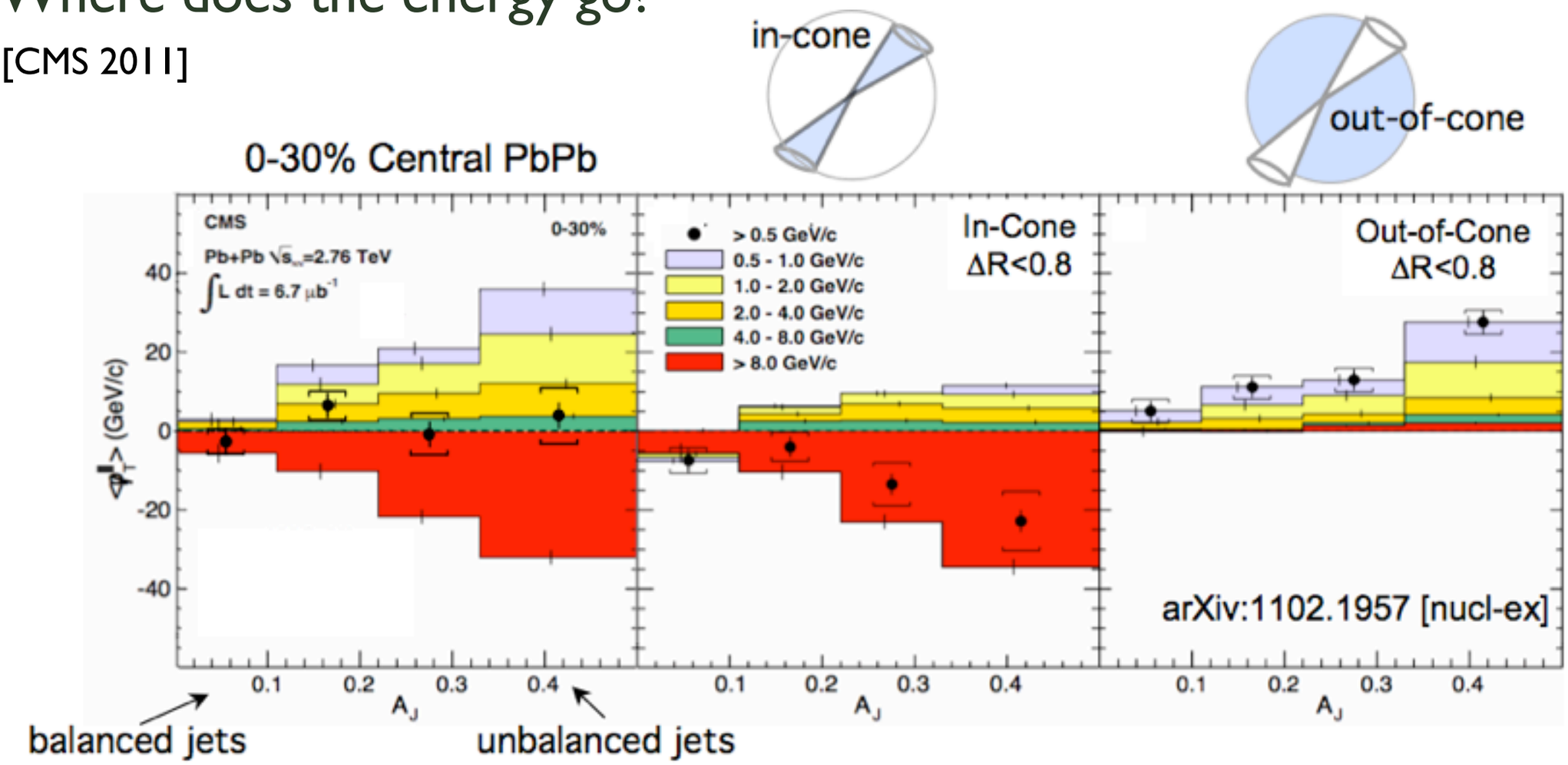


⇒ **No strong change with respect to the vacuum jets**

Di-jet asymmetry at the LHC

⇒ Where does the energy go?

[CMS 2011]



$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

⇒ **Energy taken by soft particles at large angles**

Summary of experimental data

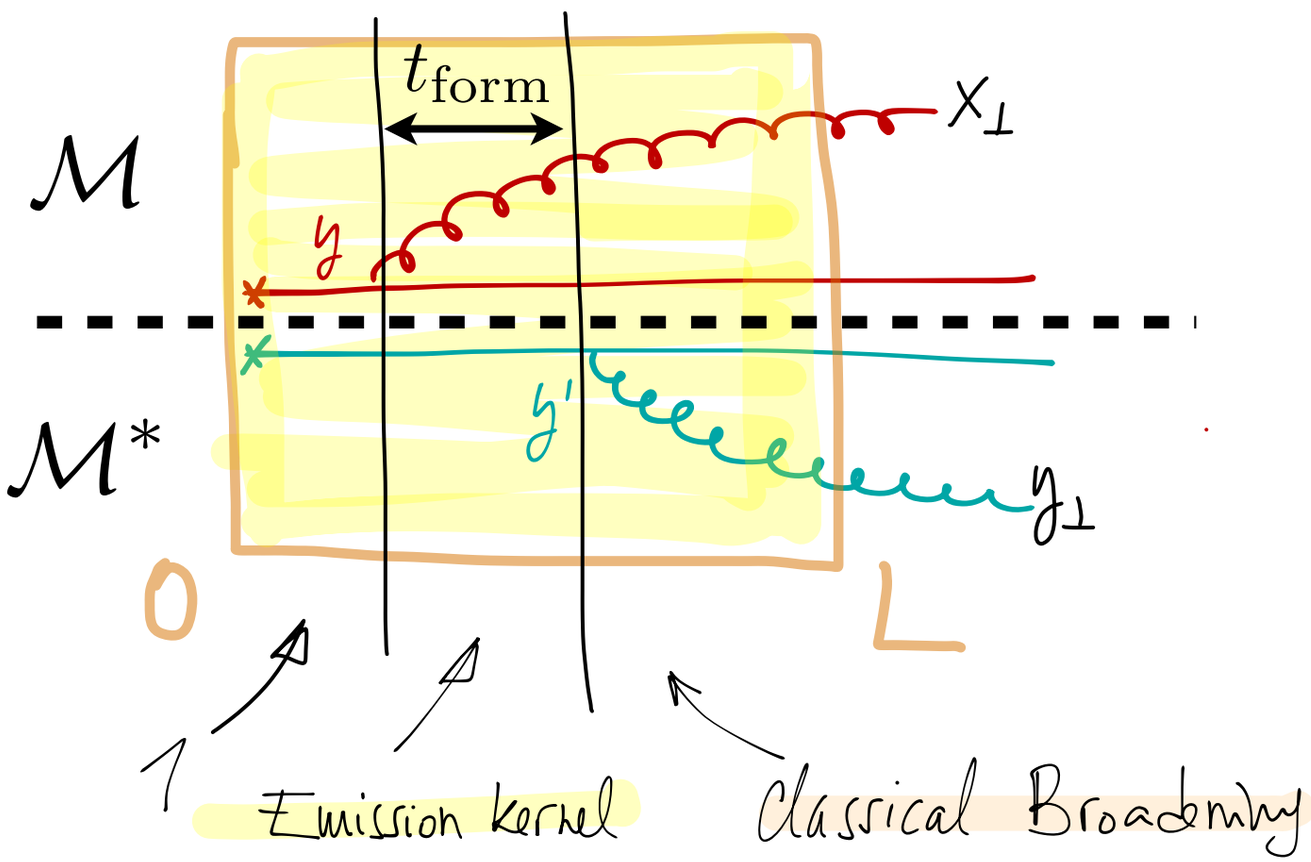
Reconstructed jets

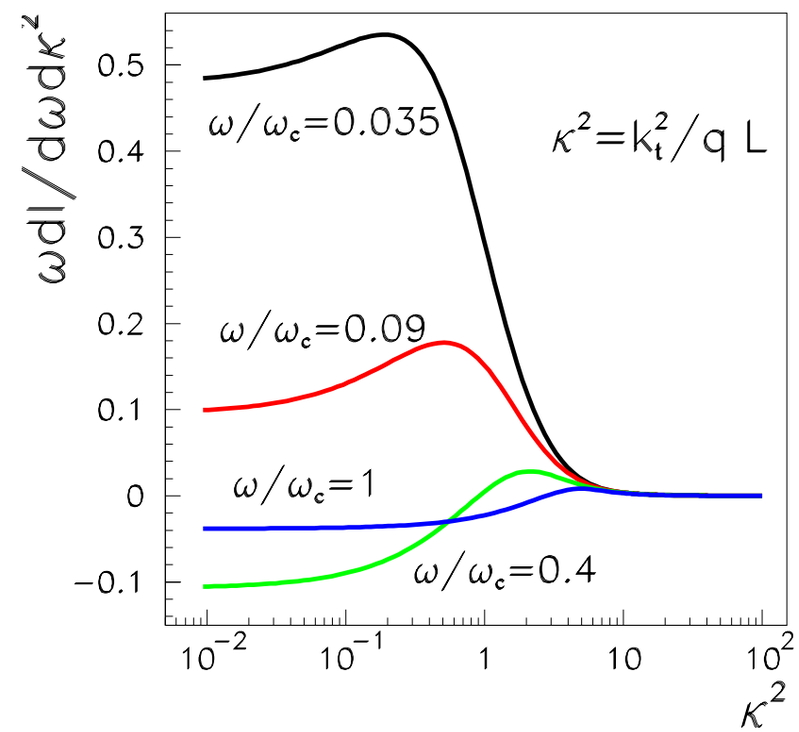
- *Suppression similar to inclusive hadrons for similar p_T*
- *Fragmentation functions are mildly modified - more in soft*
- *Jet shapes have mild modifications*
- *Azimuthal decorrelation of di-jets as in proton-proton*
- *Energy taken by soft particles at large angles*

Small modifications of the jet structure but energy loss

Medium-induced gluon radiation

$$\omega \frac{dI}{d\omega d\mathbf{k}} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u}\, \mathrm{e}^{i\mathbf{k}\cdot\mathbf{u}}\, \partial_{\mathbf{u}} \cdot \partial_{\mathbf{y}} \mathcal{K}(y', \mathbf{u}; y, \mathbf{y})\Big|_{\mathbf{y}=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u})$$





$$\mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) = \int_{\mathbf{y}(y)}^{\mathbf{u}(y')} \mathcal{D}\mathbf{r} \exp\left\{ i\frac{\omega}{2} \int d\xi \left(\frac{d\mathbf{r}(\xi)}{d\xi} \right)^2 \right\} \tilde{\mathcal{P}}(y', y, \mathbf{r})$$

kharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...]

Medium-induced gluon radiation

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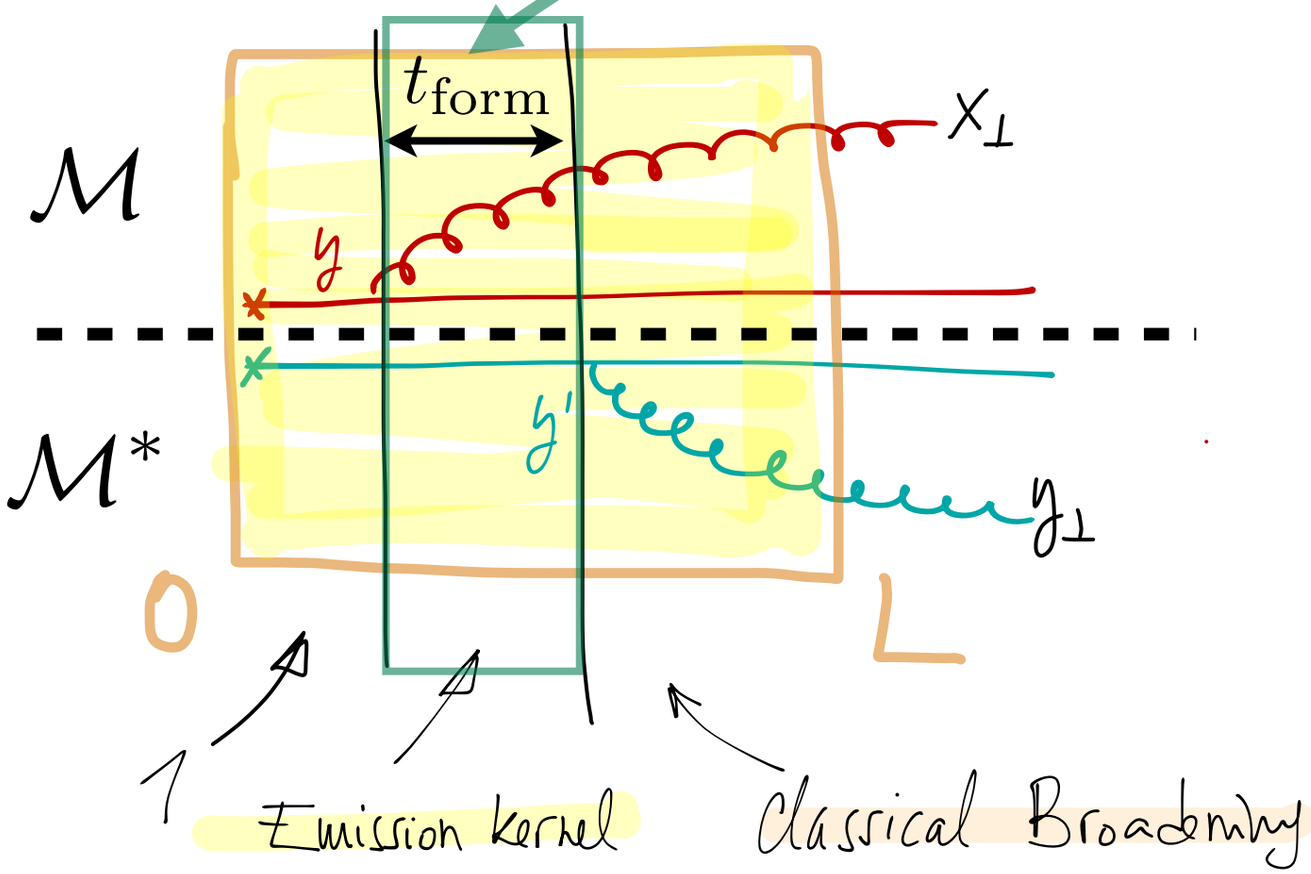

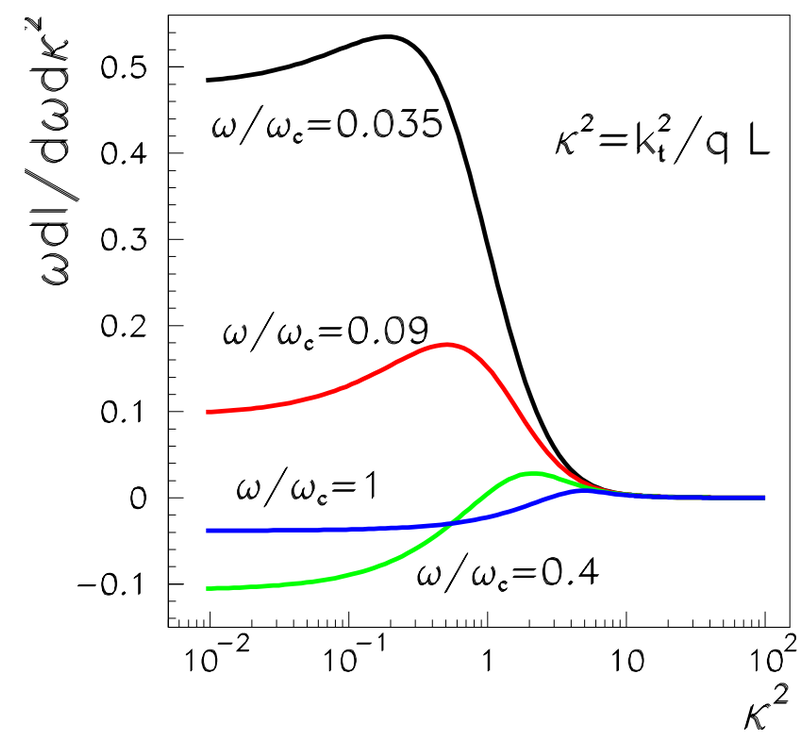

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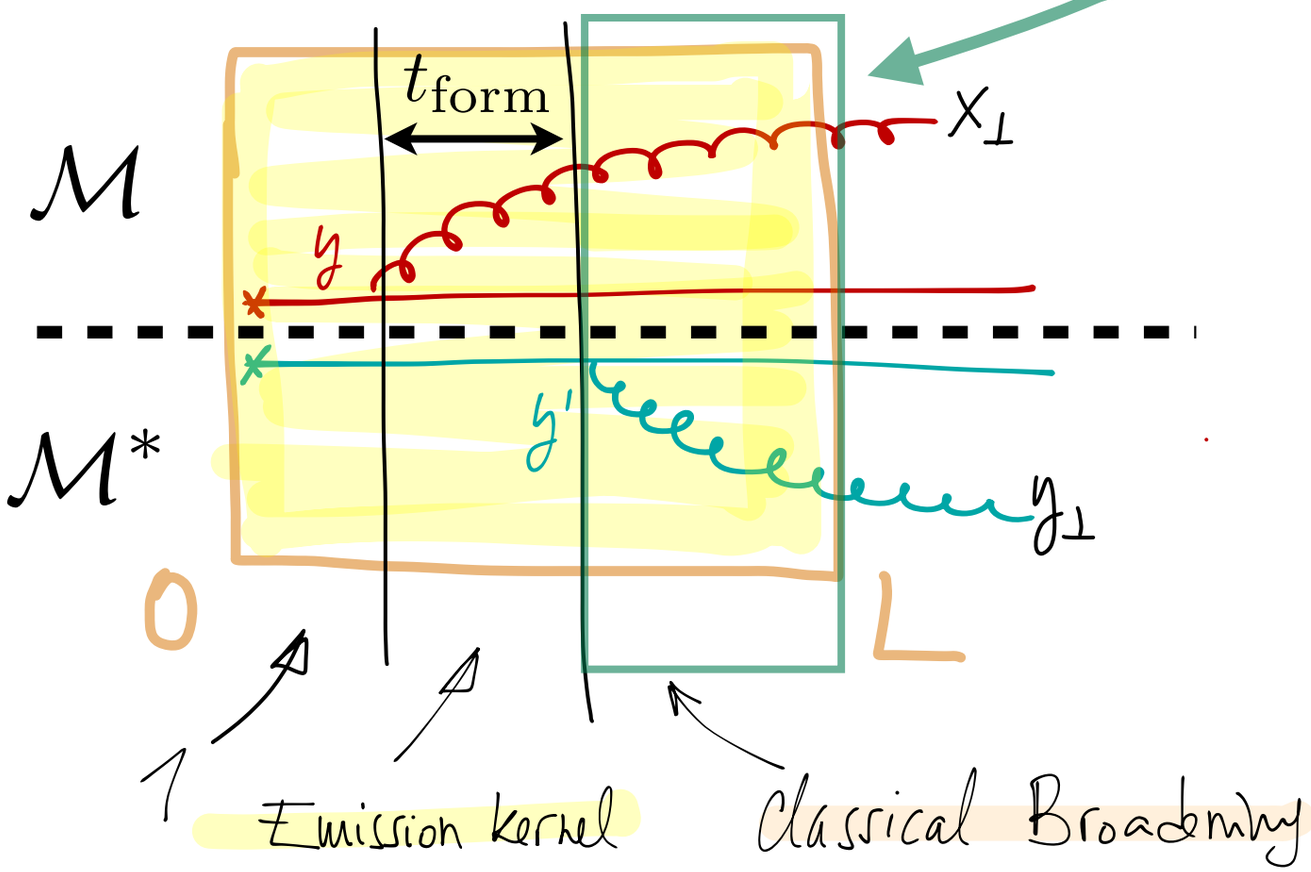

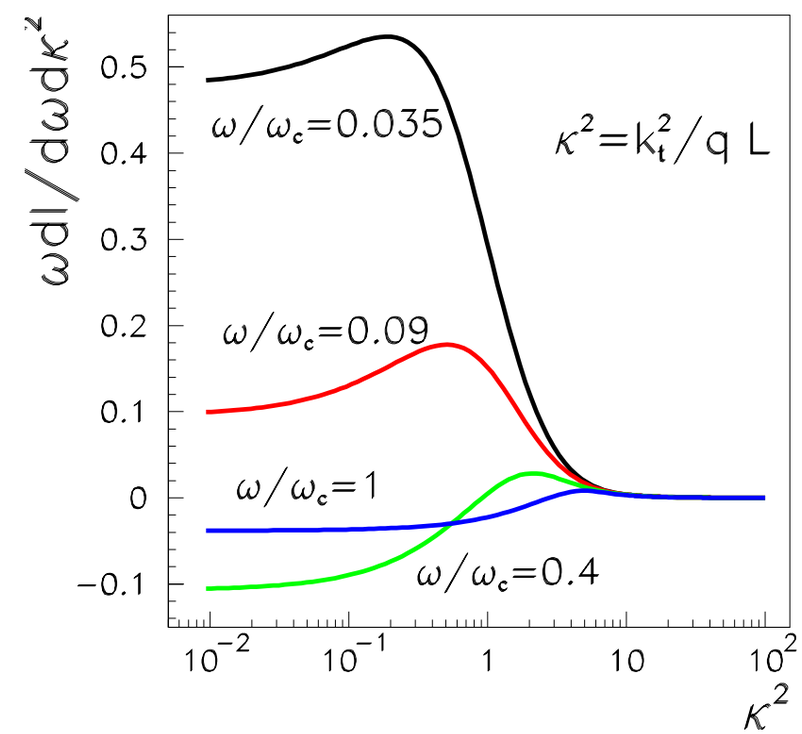

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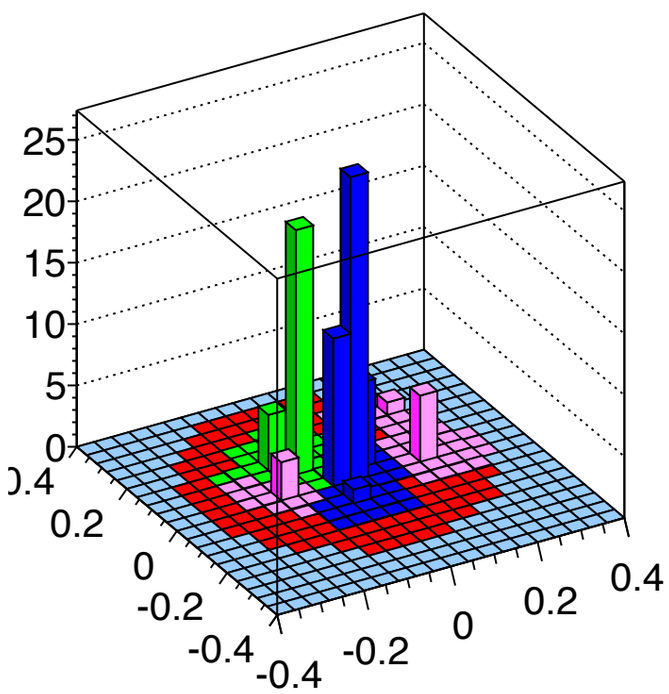
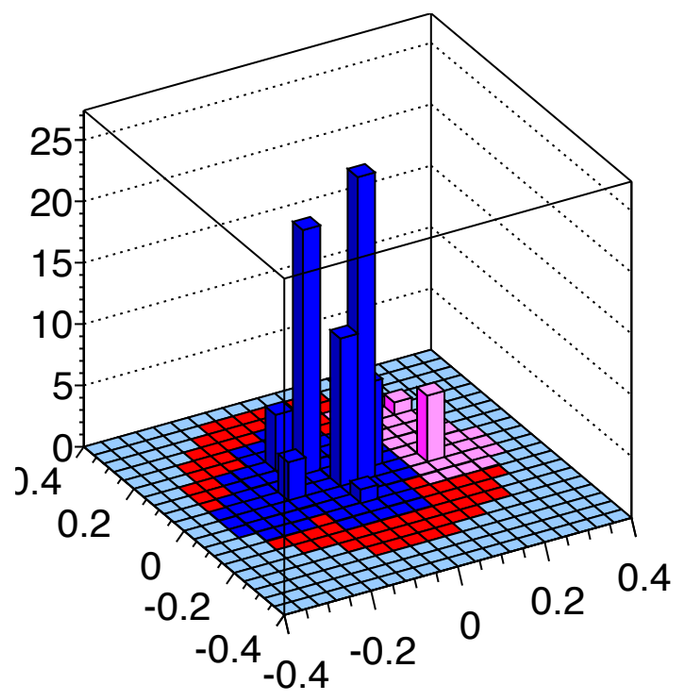
kharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...]

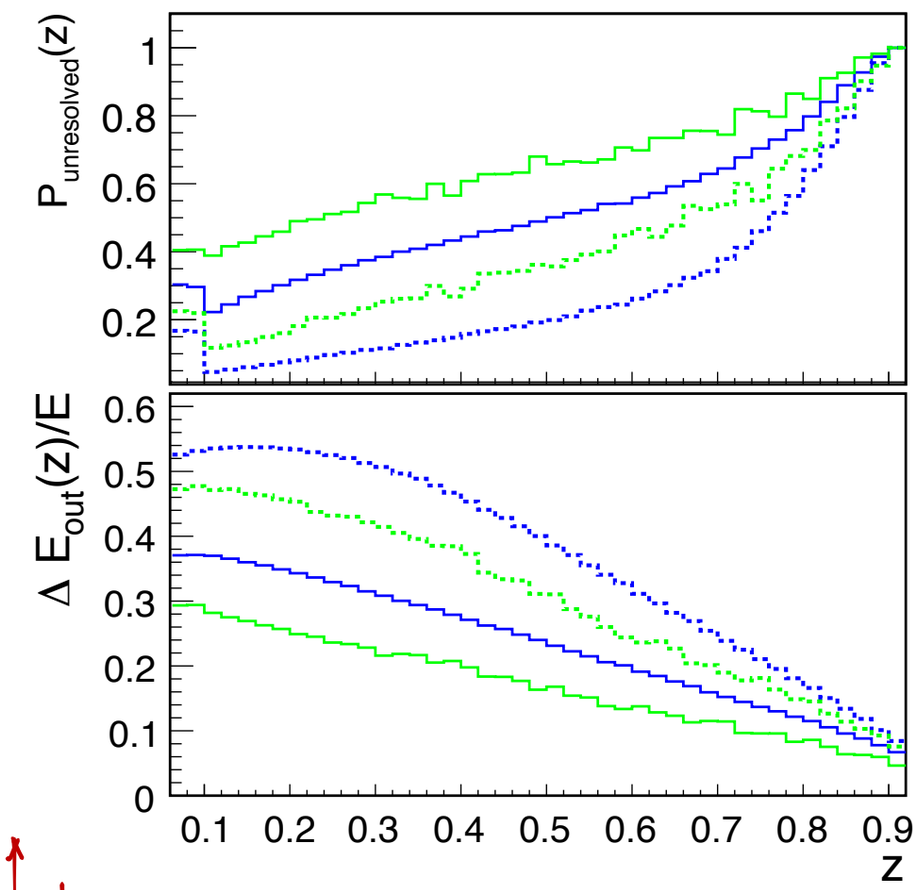
A new picture of jet quenching

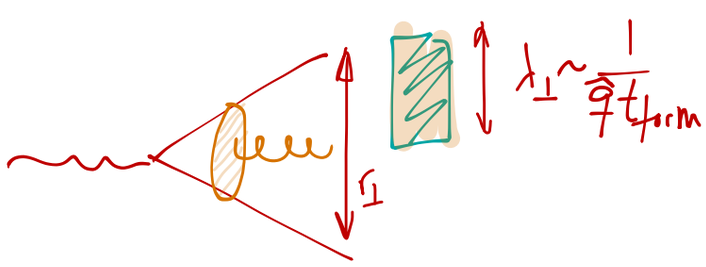
In the extreme case of only one subjet

- **The whole jet radiates (medium-induced) as a single object**
- The inner structure of the jet is (almost) unmodified





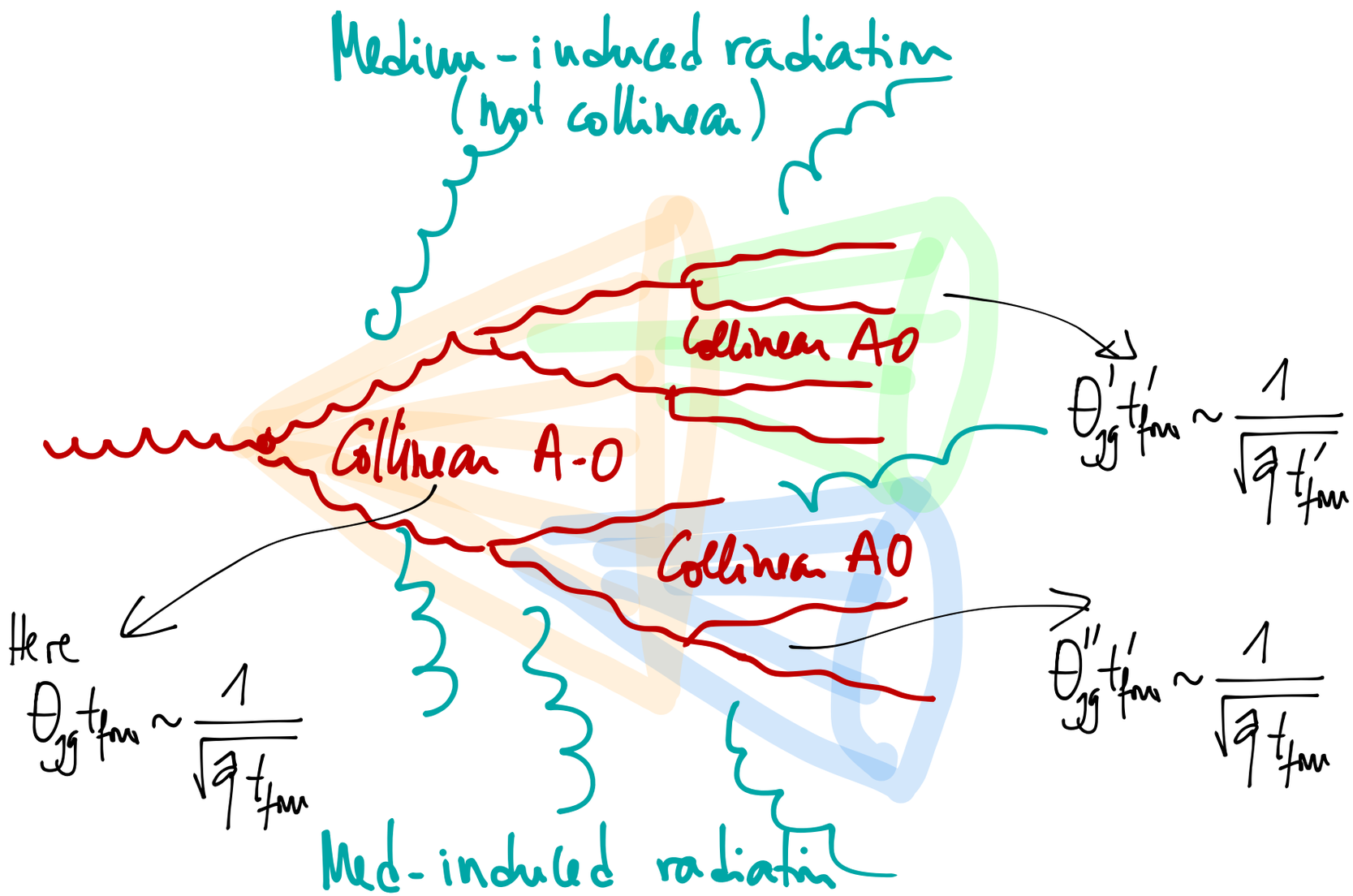




A new picture of jet quenching

The parton shower is composed of **un-modified subjets** (vacuum-like)

- **With a typical radius given by the medium scale**
- For medium-induced radiation **each subject is one single emitter**



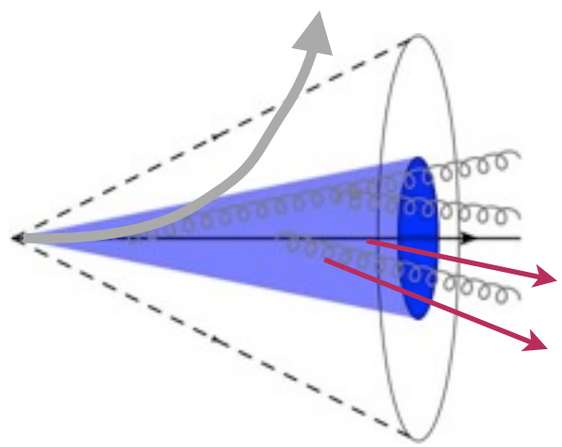
[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2013]

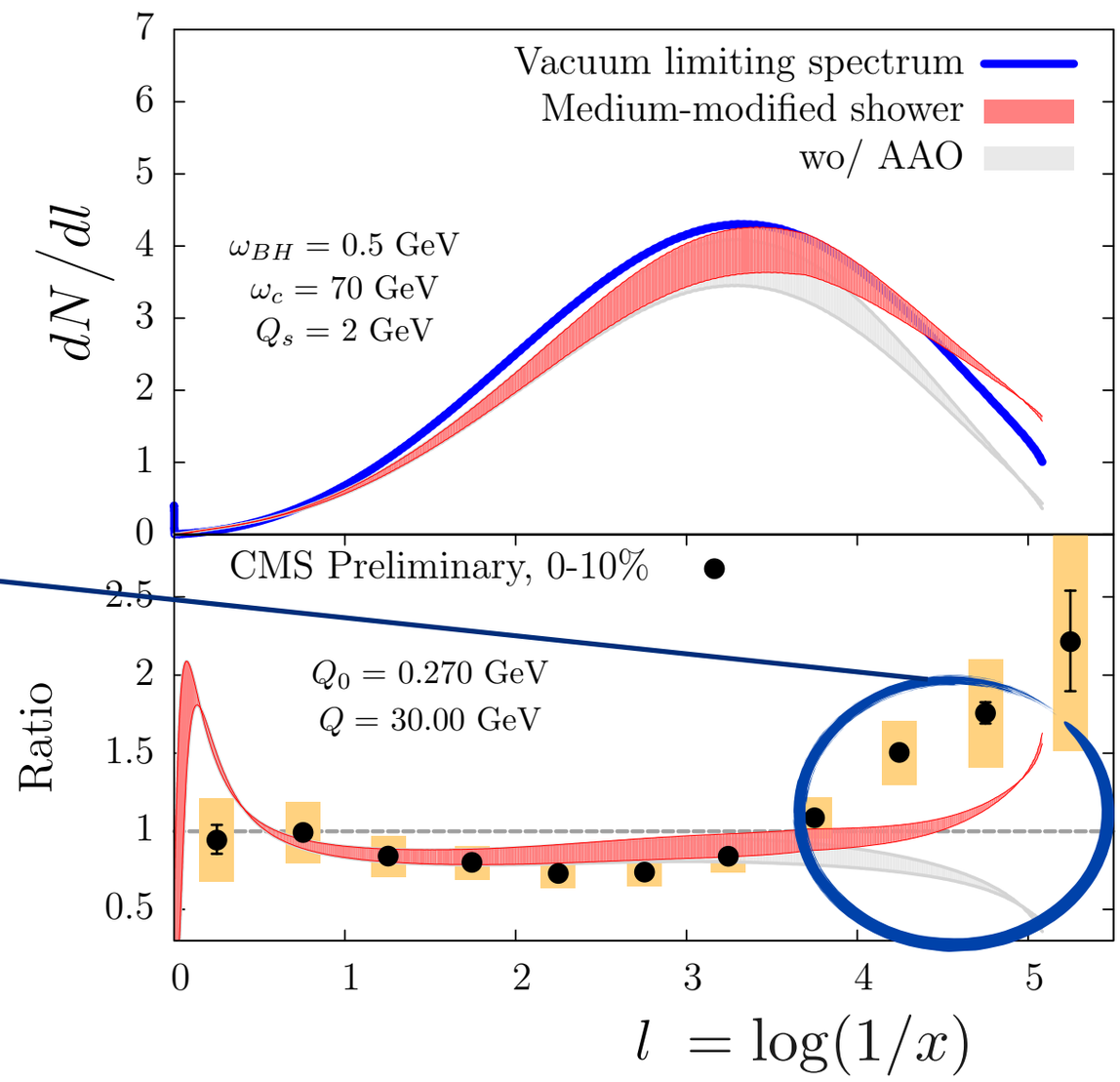
Observable consequences

A simple model implementation

- *Assume complete coherence*
- Include both BDMPS and anti-angular ordering (modifying MLLA)

K Tywoniuk
HP2013





i) intra-jet shape modified
ii) branching+broadening depletes energy inside
iii) AAO enhances soft gluons inside!

Summary

Remarkable progress in the last years

- *Saturation at NLO and fixing IC event-by-event for hydro*
- *Hydrodynamic models reaching precision*
- *Jet quenching calculations*

  Finite energy corrections; resummation; next orders in alphaS

  Computations of qhat in lattice, renormalization...

A complete picture of LHC data still work in progress

- *Proton-nucleus collisions showing unexpected behavior*

  Is a QCD medium created in proton-nucleus as well?