Heavy Ions: theory

Carlos A. Salgado
Universidade de Santiago de Compostela

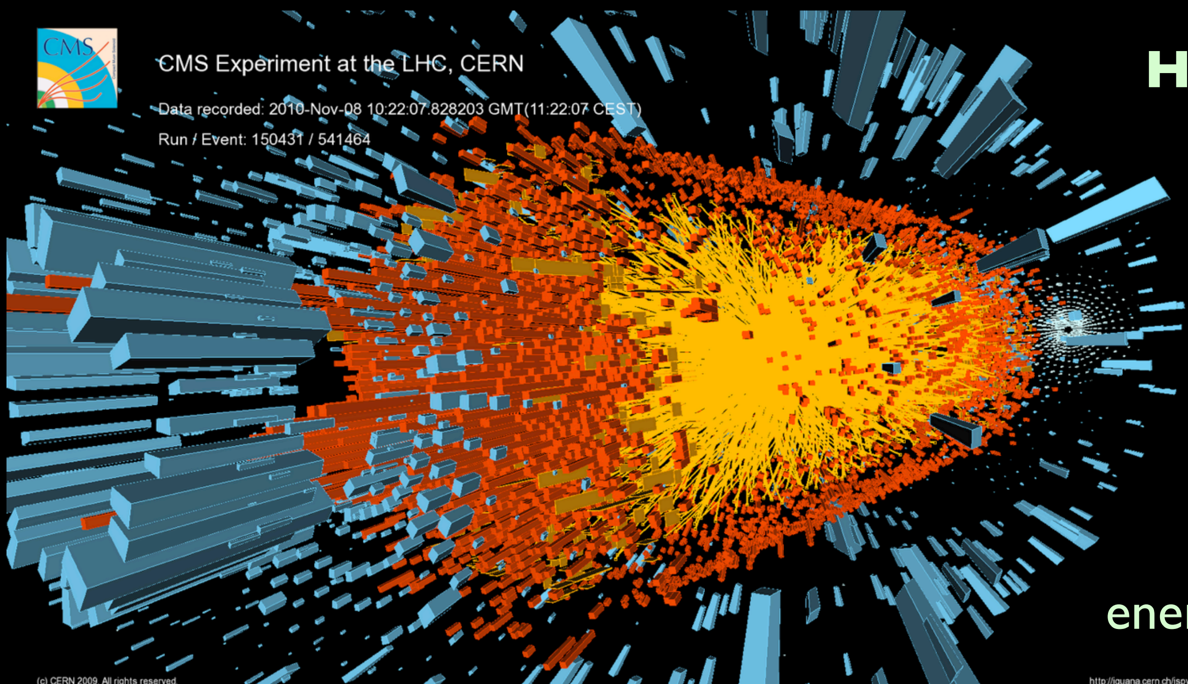
I will mostly refer to the new theoretical needs in view of the LHC capabilities

Europhysics Conference on High-Energy Physics 2011. Grenoble - France

QCD: An apparently simple lagrangian hides a wealth of **emerging phenomena**

Asymptotic freedom; confinement; chiral symmetry breaking;
mass generation; new phases of matter; a rich hadronic spectrum; etc

High-energy nuclear collisions are the experimental tools to access (some of) these properties



High density states of matter

Distributing a large energy density in a **large volume**

nuclear collisions at the highest energies ever, reaching the **TeV scales**

What do we expect to learn?

What is the structure of the hadrons at high energy?

→ *color coherence effects in the partonic wave function*

Is the created medium thermalized? How?

→ *presence of a hydrodynamical behavior*

→ *what is the mechanism of thermalization?*

What are the properties of the produced medium?

→ *identify signals to characterize the medium with well-controlled observables*

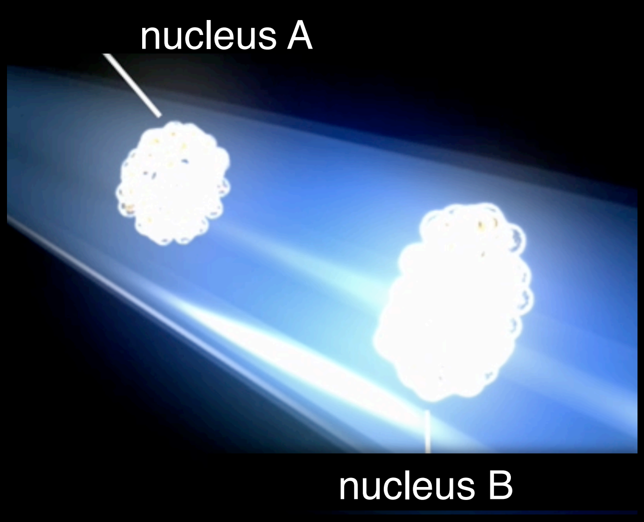
→ *what are the building blocks and how they organize?*

Towards the highest energies

SPS@CERN - Fixed target

pA, SU, PbPb - 90's

$\sqrt{s} \simeq 20\text{AGeV}$



Towards the highest energies

SPS@CERN - Fixed target

pA, SU, PbPb - 90's

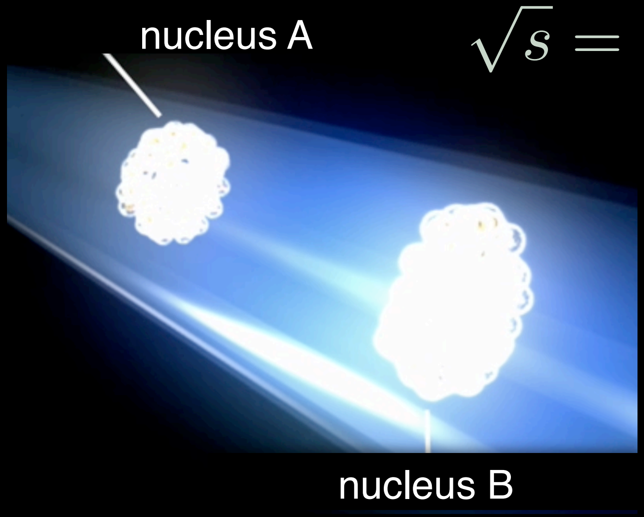
$\sqrt{s} \simeq 20\mathrm{AGeV}$

x10

RHIC@BNL - Collider

CuCu, AuAu, dAu
2000 - ...

$\sqrt{s} = 20...200\mathrm{AGeV}$



Towards the highest energies

SPS@CERN - Fixed target

pA, SU, PbPb - 90's

$\sqrt{s} \simeq 20\mathrm{AGeV}$

x10

RHIC@BNL - Collider

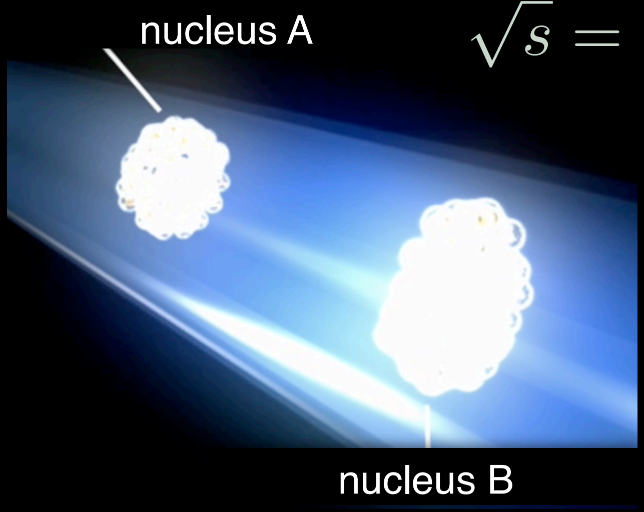
CuCu, AuAu, dAu
2000 - ...

$\sqrt{s} = 20...200\mathrm{AGeV}$

x30

LHC@CERN - Collider

$\sqrt{s} = 2.76...5.5ATeV$



Present knowledge

- Screening in the partonic wave functions → ***color coherence effects***
- Very low viscosities in hydrodynamics → ***ideal fluid behavior***
- Strong suppression of high-p_t : jet quenching → ***dense deconfined matter***

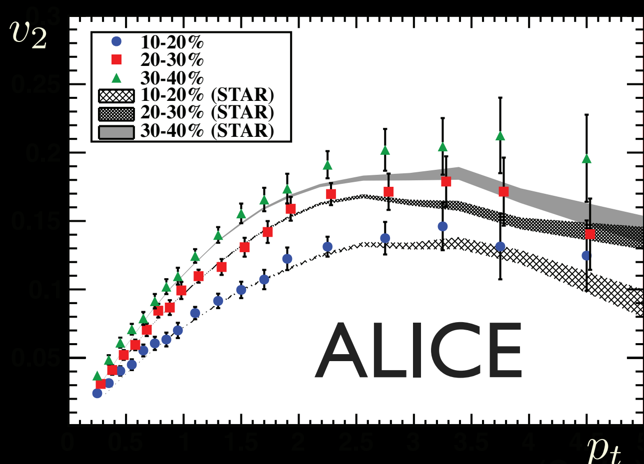
RHIC

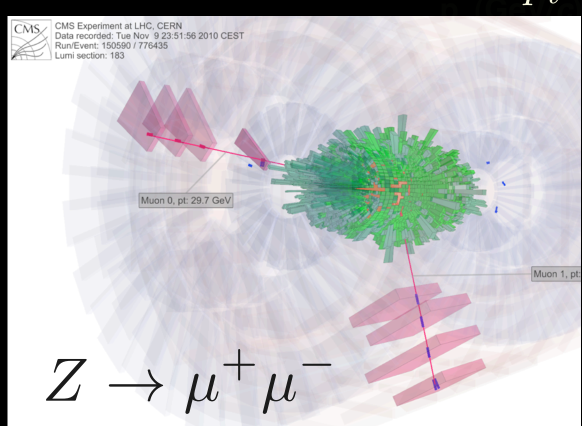
Present knowledge

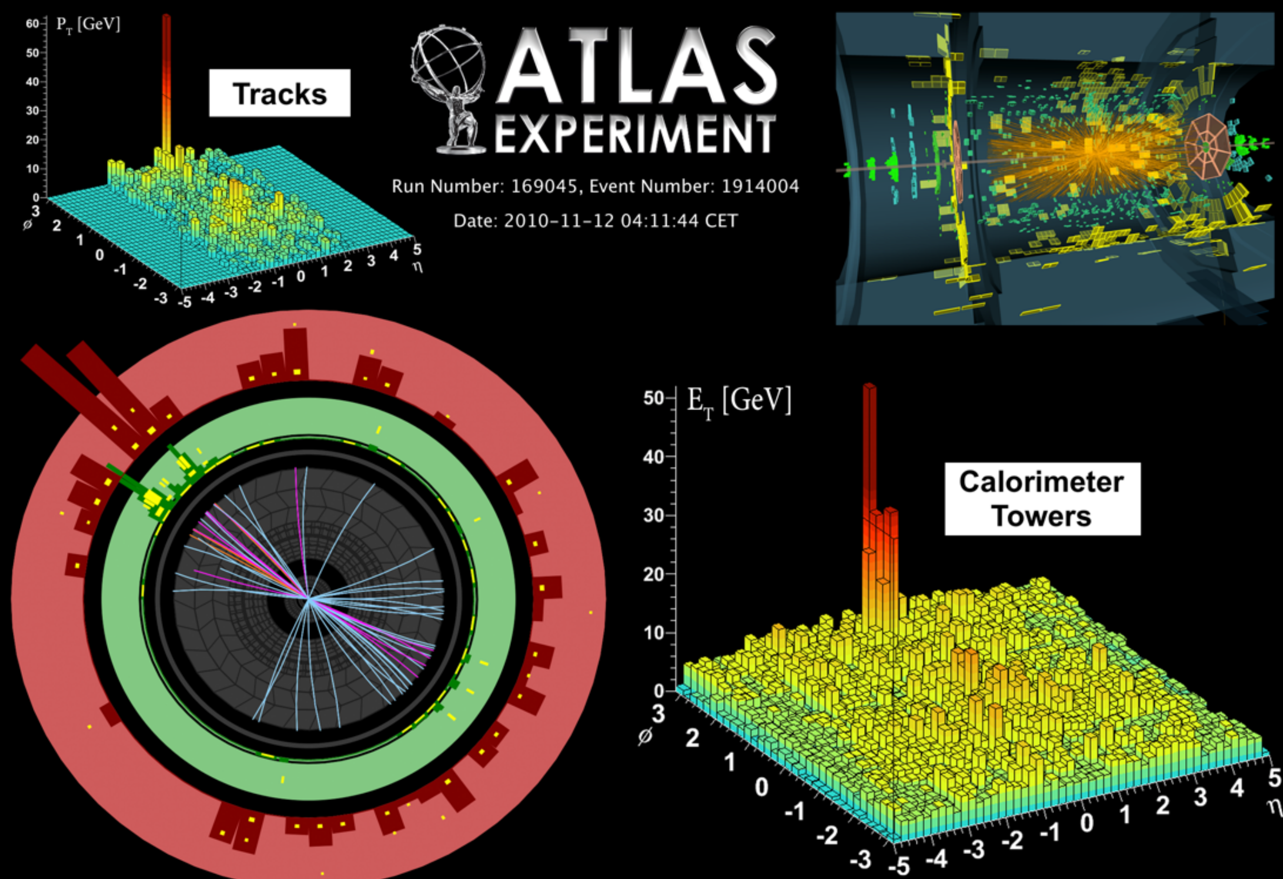
- Screening in the partonic wave functions → ***color coherence effects***
- Very low viscosities in hydrodynamics → ***ideal fluid behavior***
- Strong suppression of high-p_t : jet quenching → ***dense deconfined matter***

RHIC +LHC

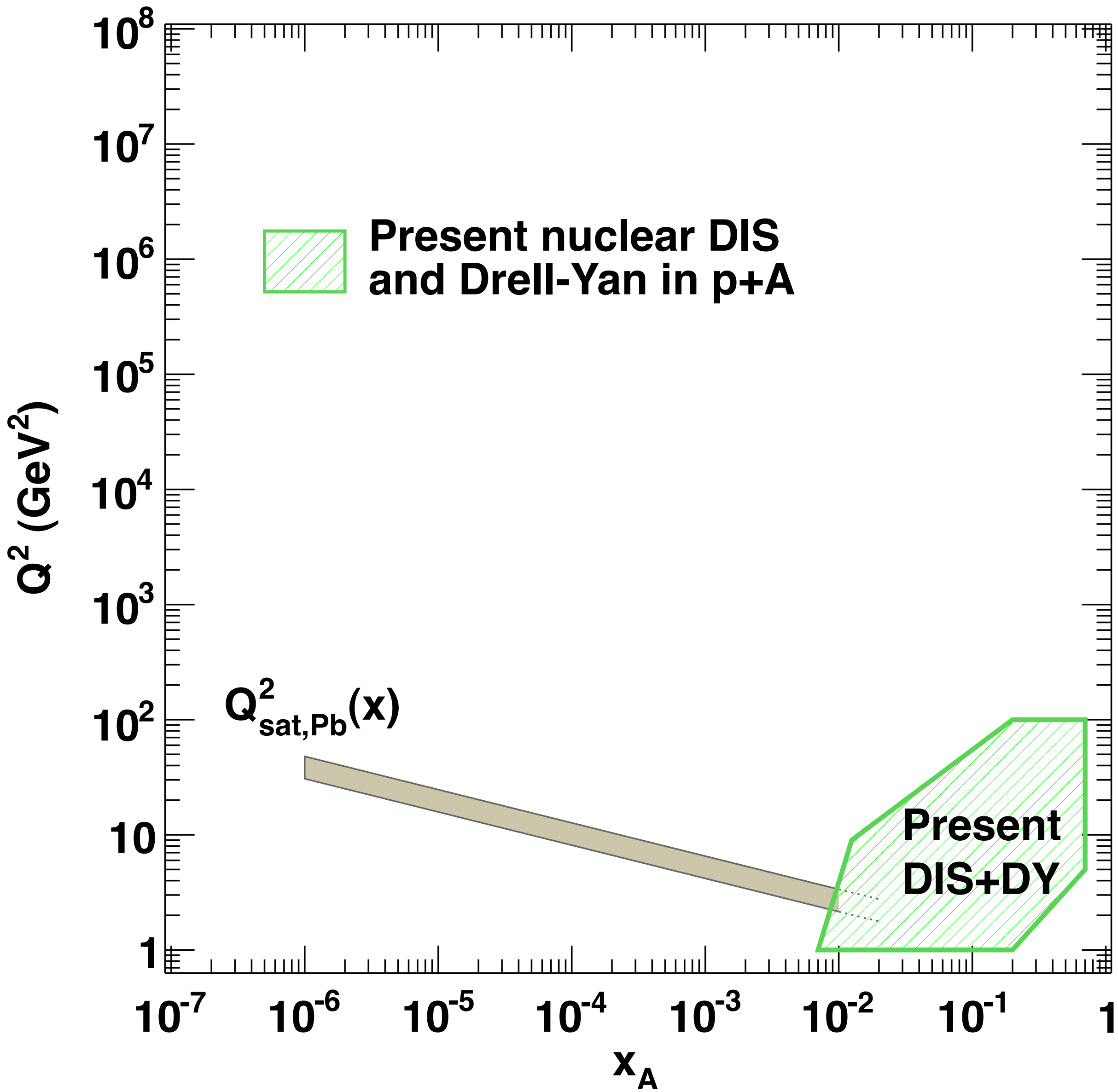
LHC December 2010



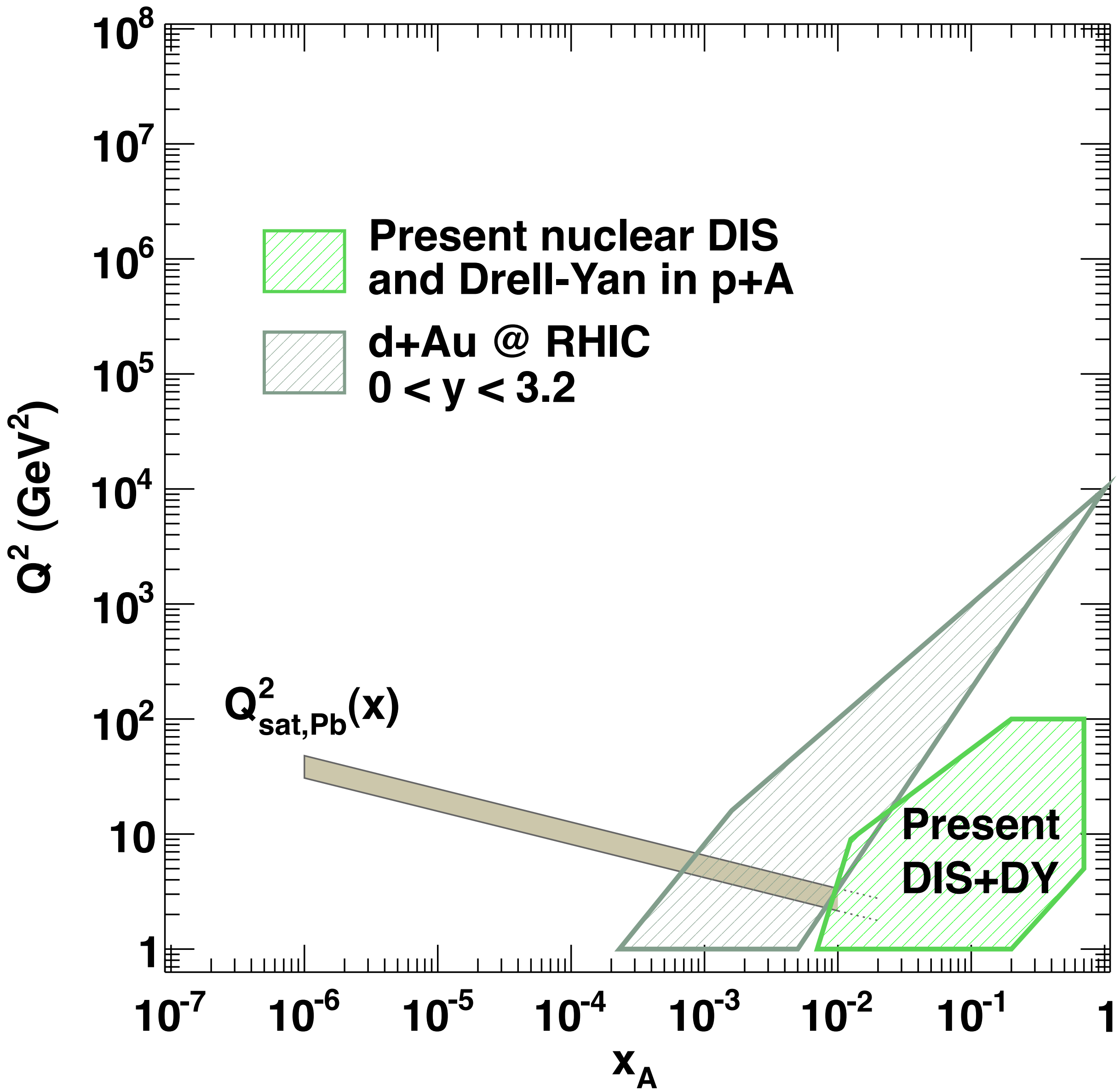




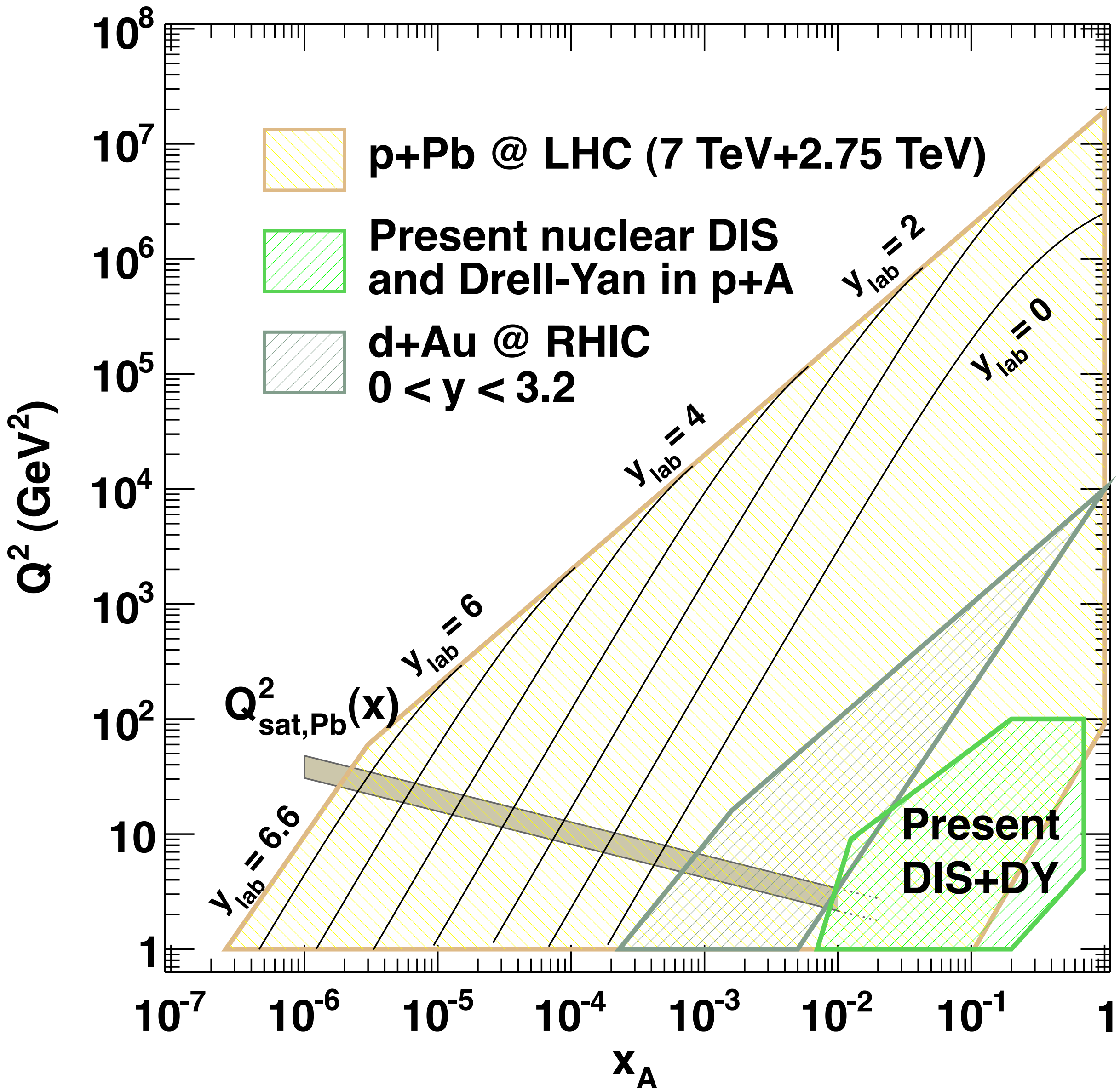
Kinematical reach in nuclear collisions



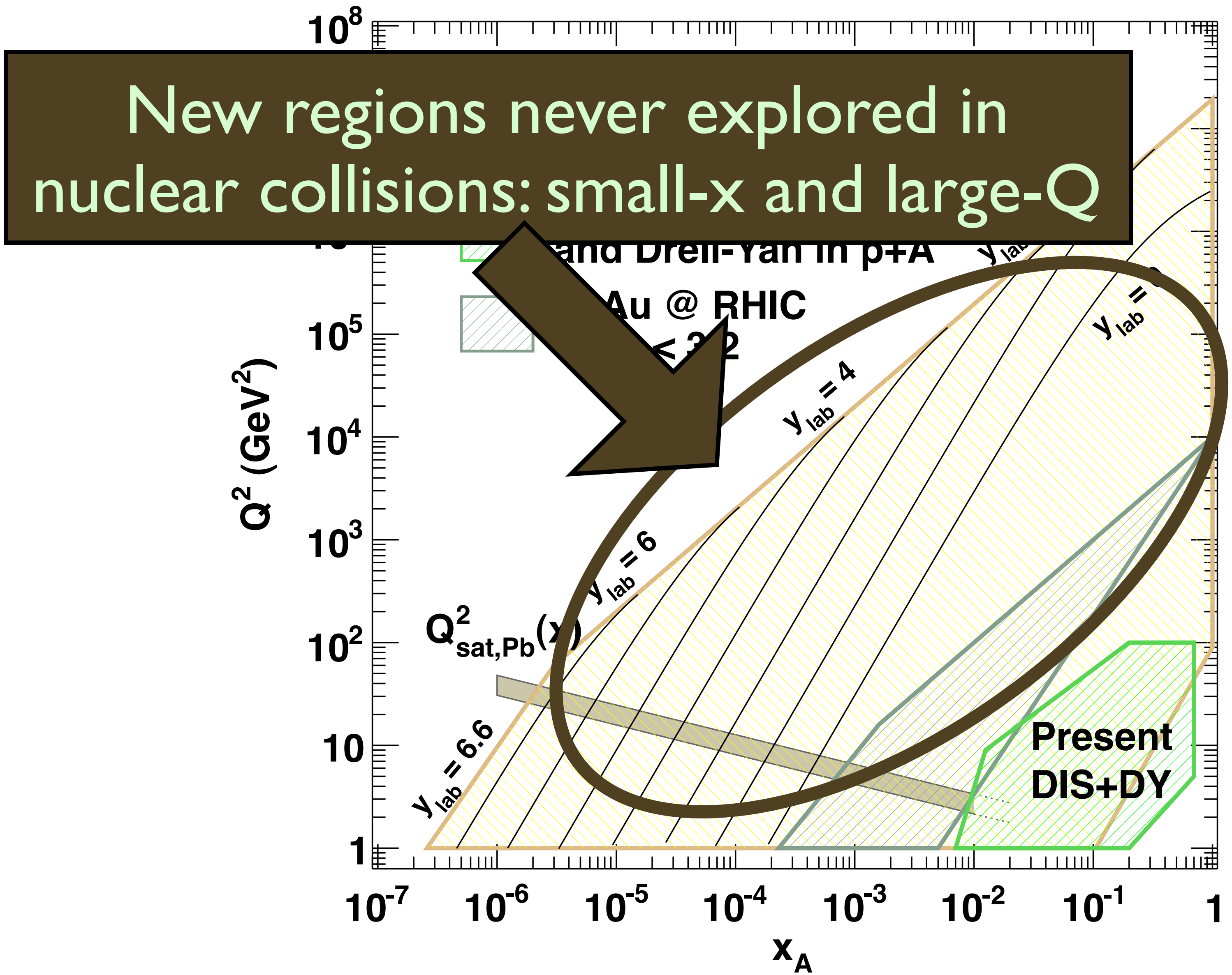
Kinematical reach in nuclear collisions



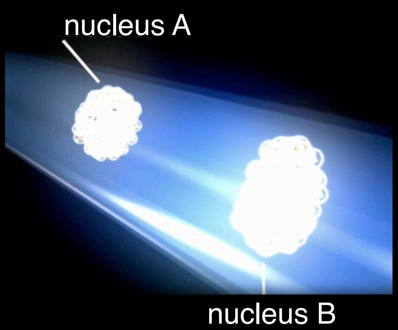
Kinematical reach in nuclear collisions



Kinematical reach in nuclear collisions



New theory needs for the LHC



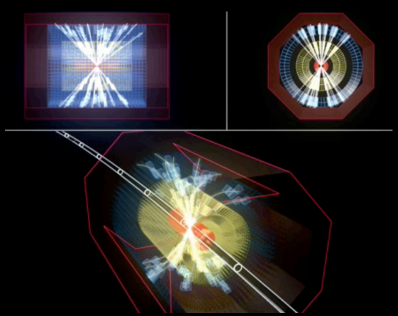
LHC explores new regimes of <u>small-x</u> in nuclear partonic structure

— *Large uncertainties:* ***Interesting physic to be done***

— *Nuclear PDFs in DGLAP analyses: standard procedure*

— *Non-linear evolution and saturation of partonic densities*

— *Precise knowledge of the initial state is essential for a correct interpretation of the data. E.g. for the determination of viscosity*



LHC explores new regimes of <u>large-Q</u> with jets and other hard probes

— *In-medium parton shower not know from first principles*

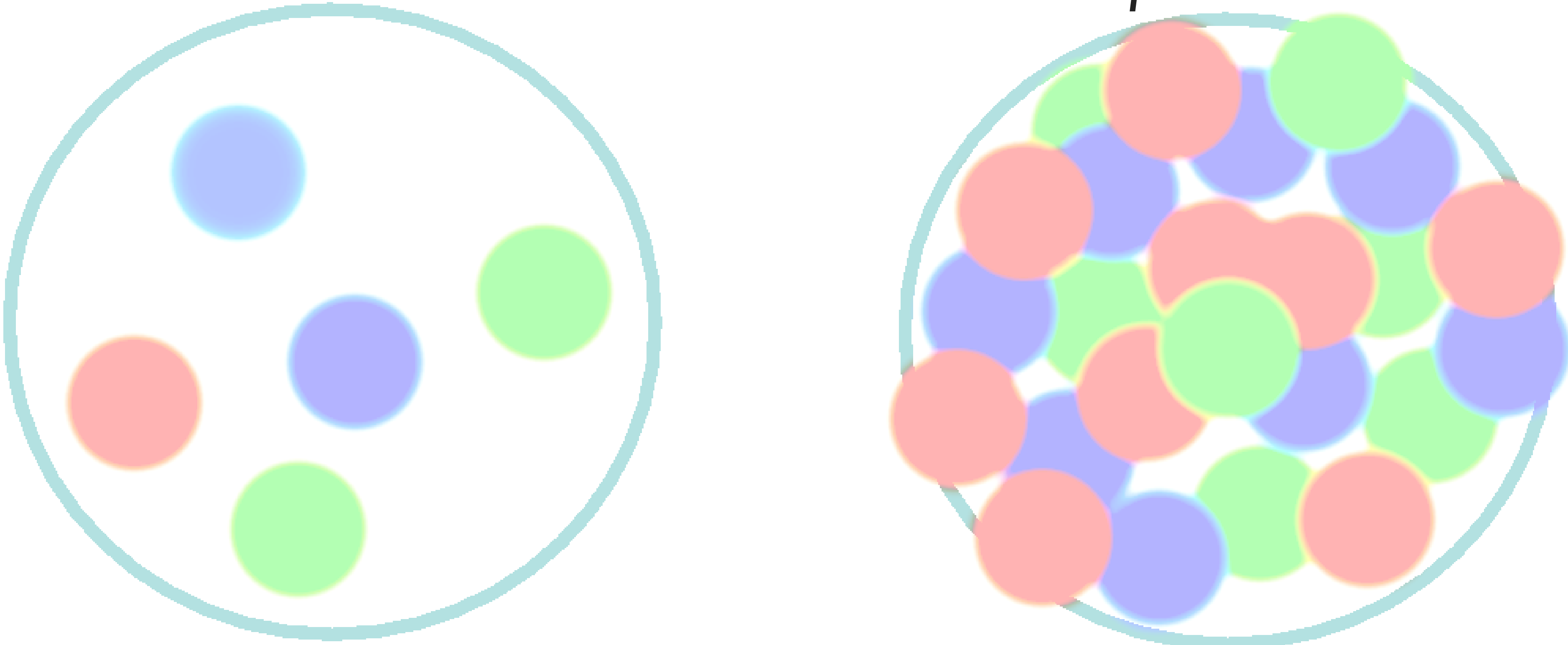
— *Interpretation of data needs a controlled theoretical framework*

— *Also, heavy quarks, Z+jets, different quarkonia states*

[Obviously, theoretical developments needed for other observables.
These are the qualitatively novel regimes due to extended kinematics of LHC]

Initial state: Saturation of partonic densities

Color coherence in the initial wave function



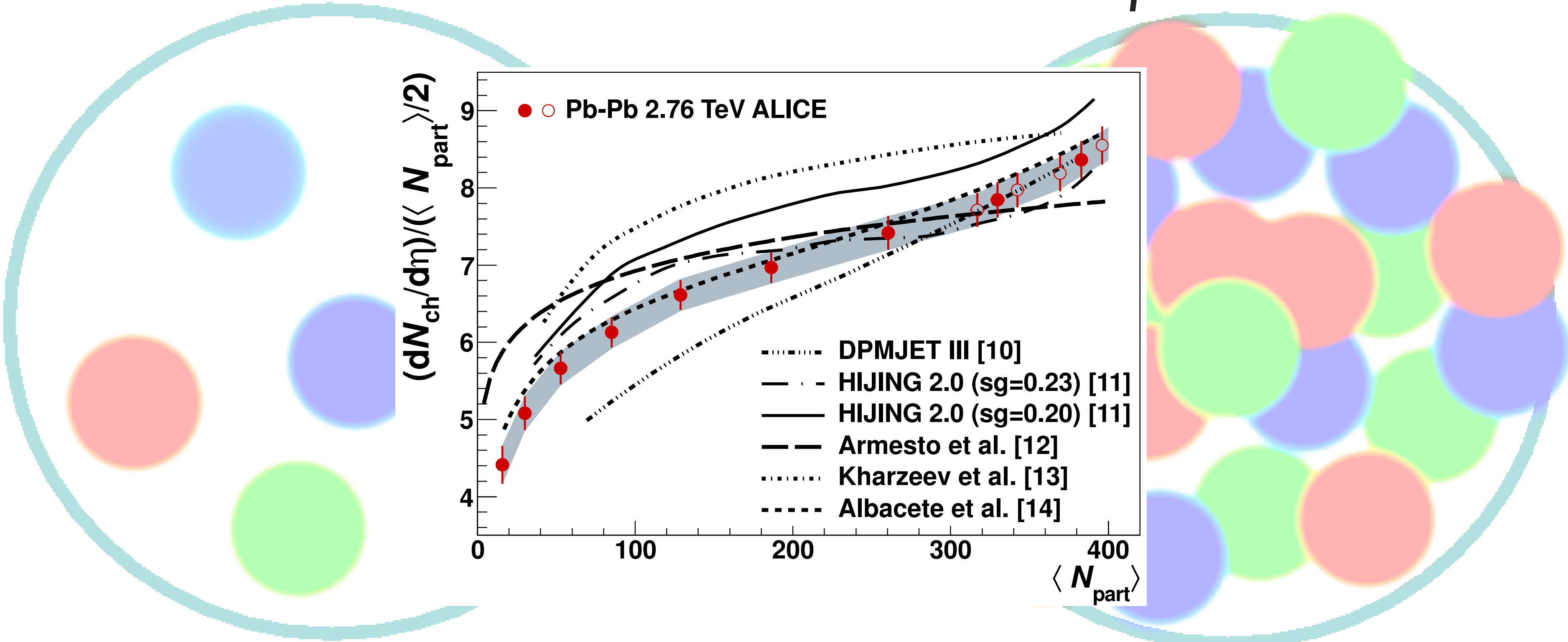
⇒ A new scale expected to determine partonic properties at high energies

- Strong fields and large occupation numbers.
- Semiclassical approach: Color Glass Condensate

$$Q^2_{\rm sat} \sim \frac{A^{1/3}}{x^\lambda}$$

Initial state: Saturation of partonic densities

Color coherence in the initial wave function



⇒ A new scale expected to determine partonic properties at high energies

- Strong fields and large occupation numbers.
- Semiclassical approach: Color Glass Condensate

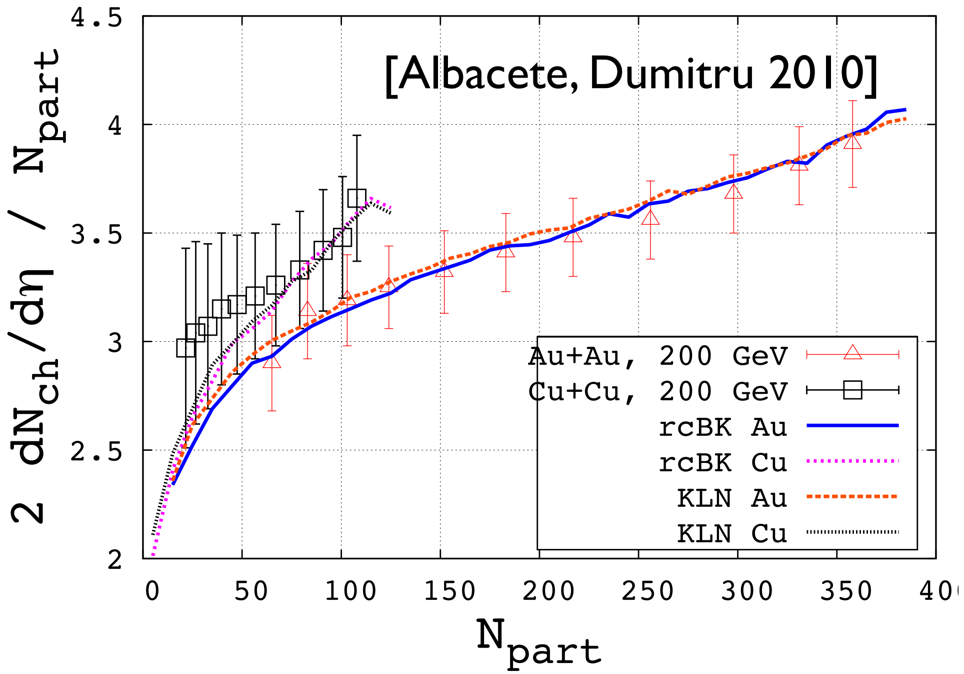
$$Q^2_{\rm sat} \sim \frac{A^{1/3}}{x^\lambda}$$

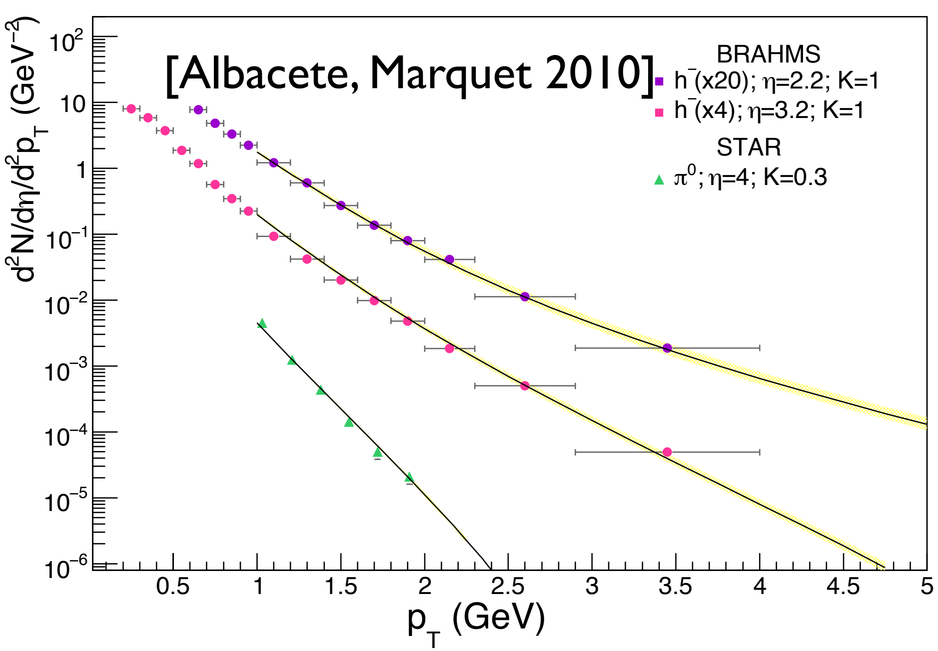
Non-linear evolution equations [Talk: Albacete]

- ⇛ Screening leads to non-linear terms. E.g. Balitsky-Kovchegov eqs.

$$\frac{\partial N(r,x)}{\partial \log(x_0/x)} = \int d\mathbf{r_1}\, K(\mathbf{r},\mathbf{r_1},\mathbf{r_2})\,[N(r_1,x)+N(r_2,x)-N(r,x)-N(r_1,x)N(r_2,x)]$$

- ⇛ New TH developments: NLO BK equations
- ⇛ Provides a solid theoretical framework to do phenomenology





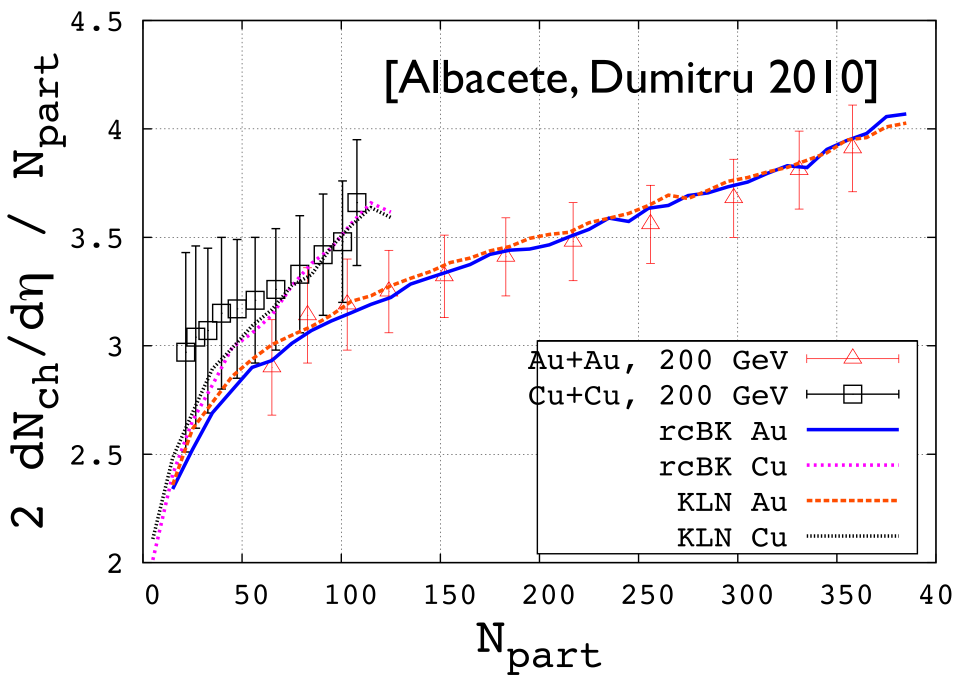
Non-linear evolution equations [Talk: Albacete]

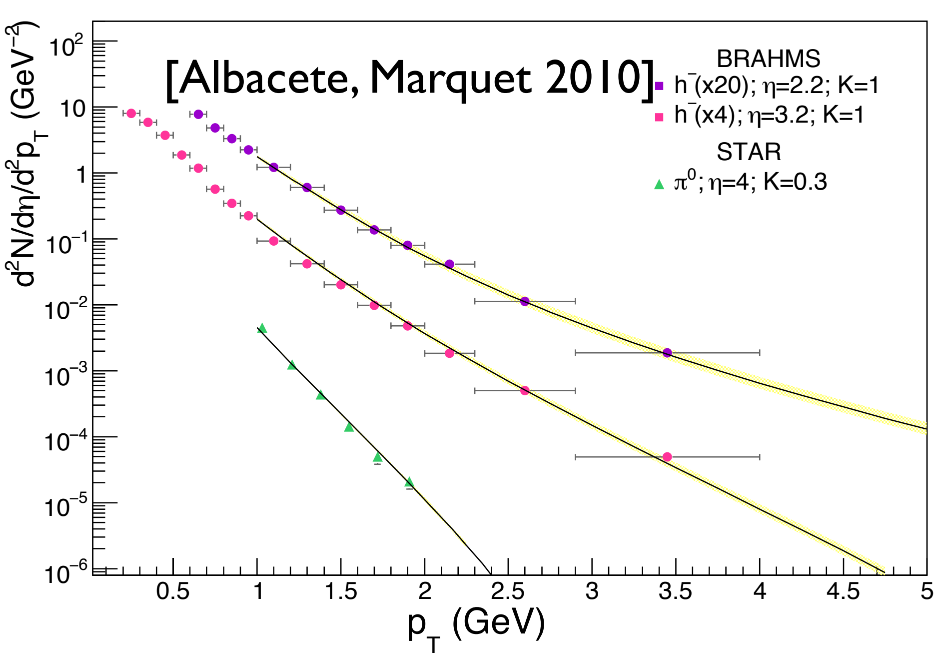
- Screening leads to non-linear terms. E.g. Balitsky-Kovchegov eqs.

$$\frac{\partial N(r,x)}{\partial \log(x_0/x)} = \int d\mathbf{r}_1\, K(\mathbf{r},\mathbf{r}_1,\mathbf{r}_2)\,[N(r_1,x)+N(r_2,x)-N(r,x) - N(r_1,x)N(r_2,x)]$$

Linear: Balitsky-Fadin-Kuraev-Lipatov — Non-linear term

- New TH developments: NLO BK equations
- Provides a solid theoretical framework to do phenomenology





Checks of hydrodynamics

[degree of thermalization of the medium]

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

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

+ Equation of state

Checks of hydrodynamics

[degree of thermalization of the medium]

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

Most of the theoretical progress in the last years

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

+ Equation of state

Checks of hydrodynamics

[degree of thermalization of the medium]

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

Most of the theoretical progress in the last years

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

+ 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 1fm)*

Difficult question: a variety of techniques used/essayed

— *Perturbative approaches (usually too slow)*

— *Plasma instabilities*

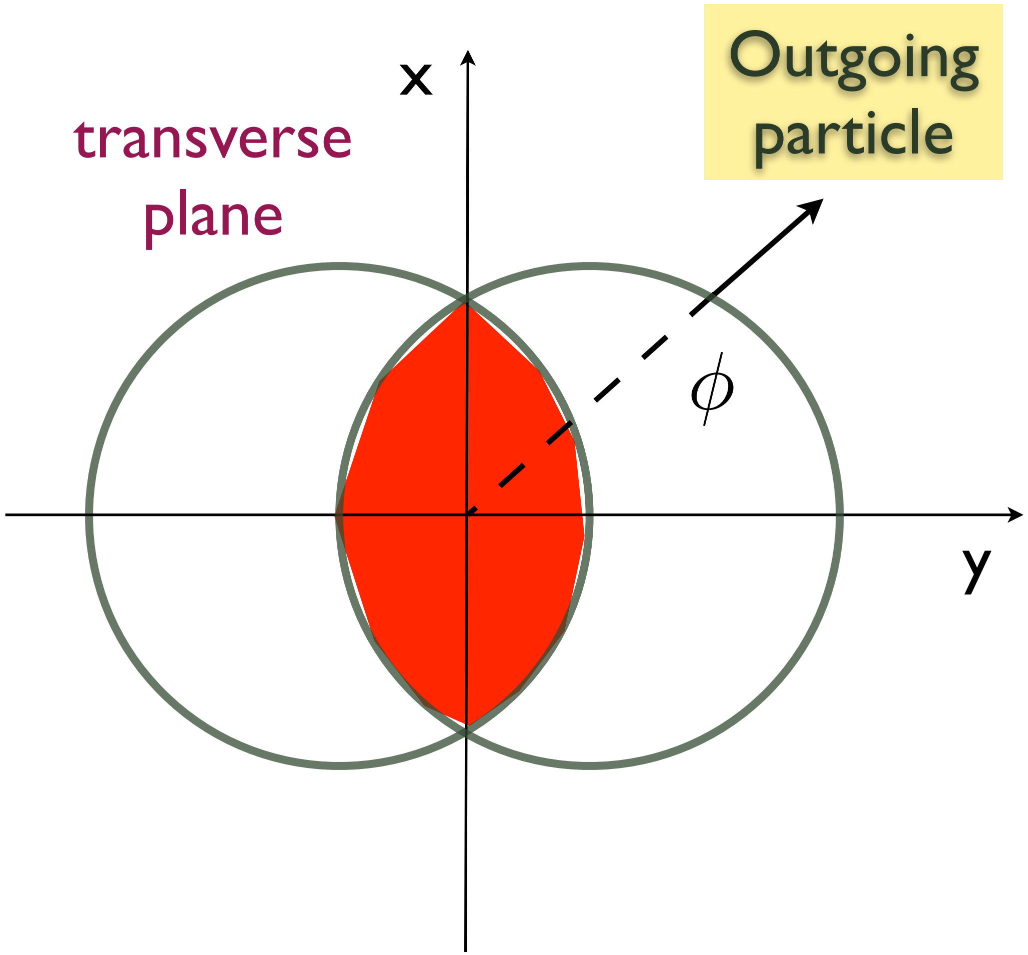
— *Strongly coupled calculations (AdS/CFT)*

[Talks Kiritsis; Heller AdS/CFT session]

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

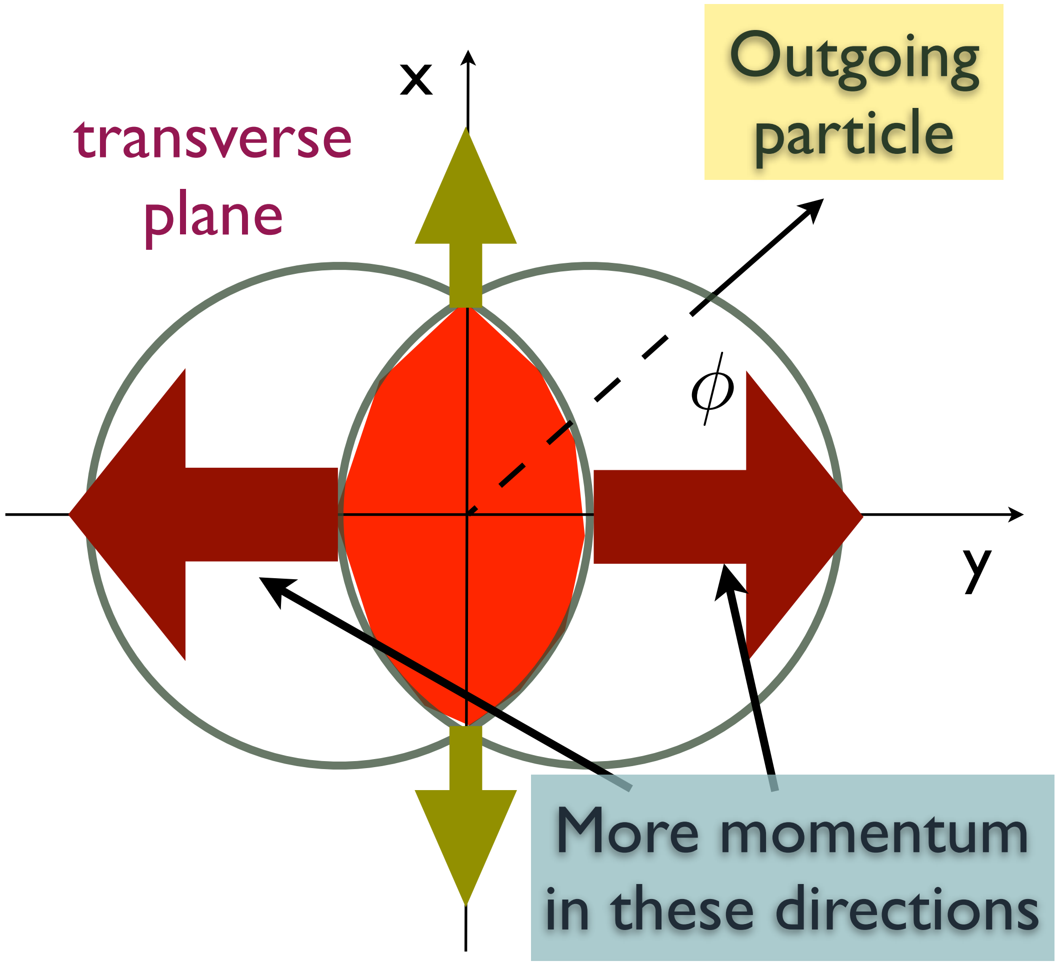
- Recall the Euler equation

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

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

- Elliptic flow normally measured by the second term in the Fourier expansion

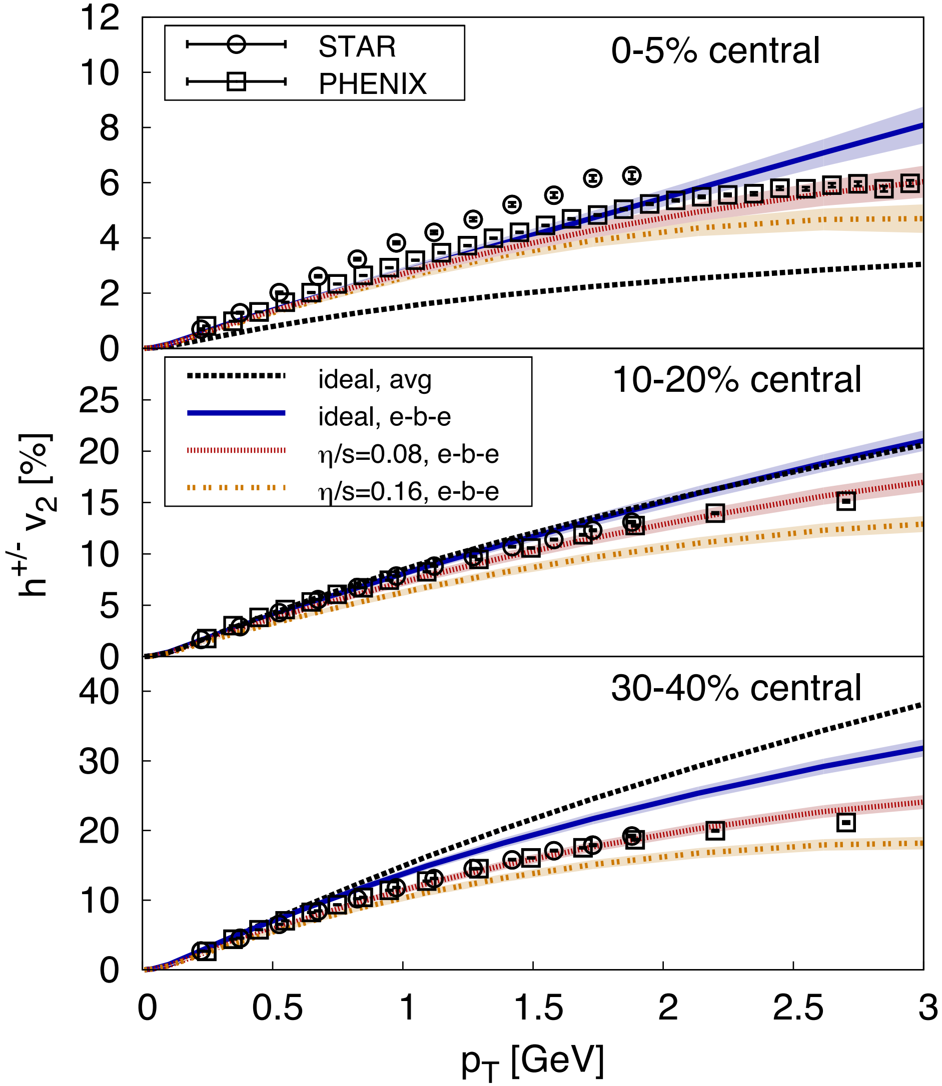
$$\frac{dN}{d\phi} \propto 1 + 2\,v_2 \cos(2\phi)$$



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

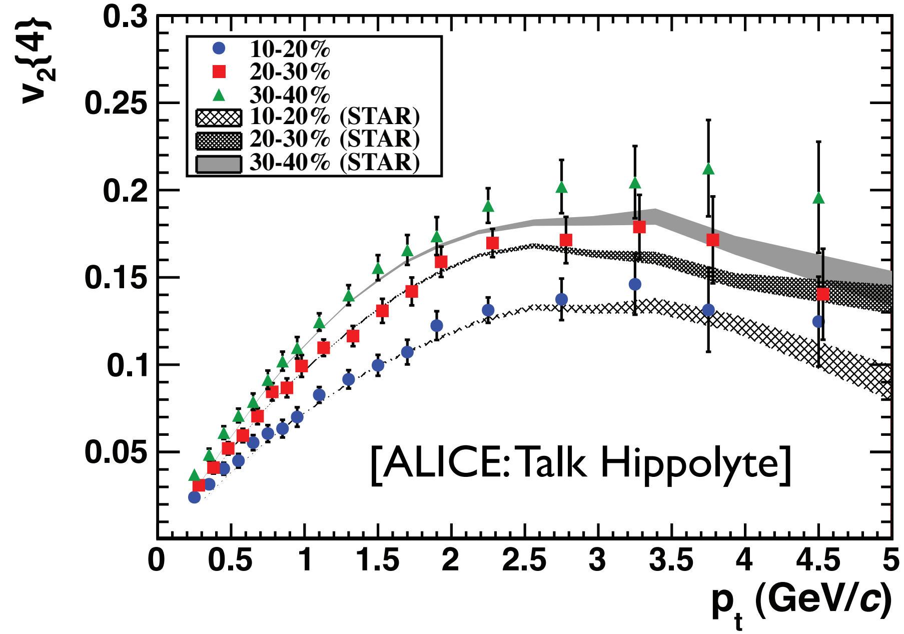
Fluid behavior from hydro: viscosity of the QGP

RHIC



[Schenke, Jeon, Gale 2010]

LHC



⇒ **Lowest viscosity known**

- "perfect liquid": sQGP
- AdS/CFT bound

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

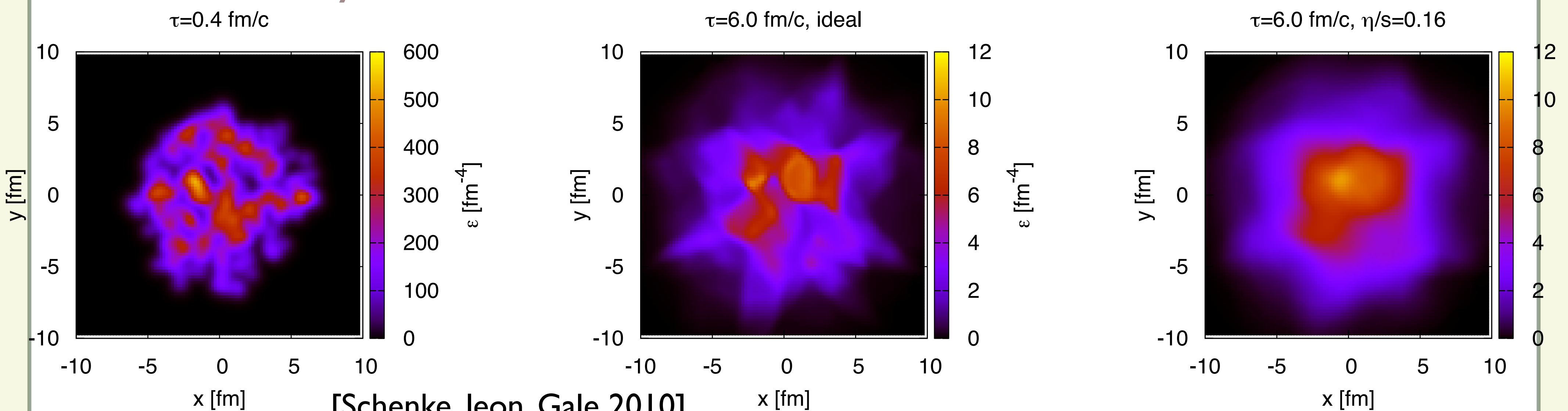
[Policastro, Son, Starinets, 2001]

⇒ **LHC similar to RHIC**

Higher harmonics

- With high precision data, higher terms in the expansion identified
  - For a symmetric medium odd terms are 0
  - Even-by-event fluctuations make them finite

[Talks by Santos; Lee; Pinkenburg; Pak]



[Schenke, Jeon, Gale 2010]

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)$$

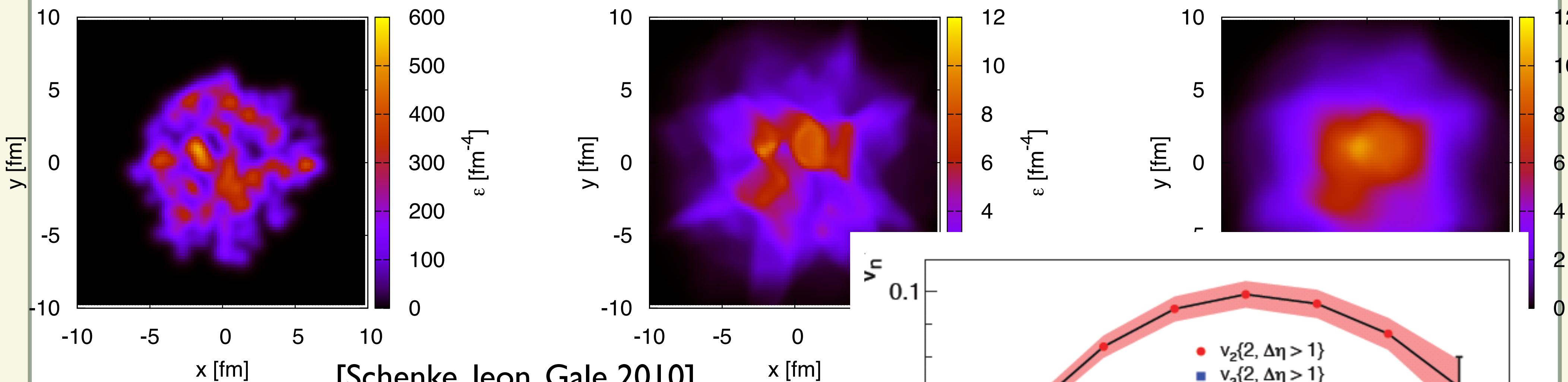
- Will allow precise tests of hydro

Constraints to viscosity

Higher harmonics

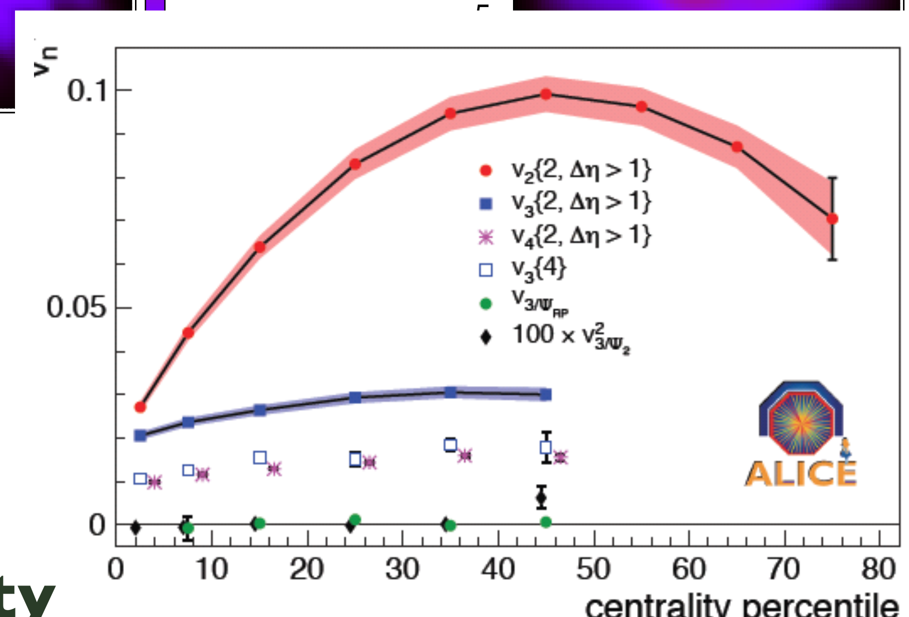
- ⇛ With high precision data, higher terms in the expansion identified
  - For a symmetric medium odd terms are 0
  - Even-by-event fluctuations make them finite

[Talks by Santos; Lee; Pinkenburg; Pak]



[Schenke, Jeon, Gale 2010]

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos(n\phi)$$



- ⇛ Will allow precise tests of hydro

Constraints to viscosity

Hard Probes

Long distance terms modified by the presence of medium

- *Nuclear PDFs and new (non-linear) evolution equations*
- *Probes of hot matter created in the interaction*
- *EW processes (no hadronization) used as benchmark*

$$\sigma^{AB\to h} = f_A^i(x_1,Q^2) \otimes f_B^j(x_2,Q^2) \otimes \sigma(ij \to k) \otimes D_{k\to h}(z,Q^2)$$

Nuclear PDFs

Hadronization
J/Ψ paradigmatic example

Hard Probes

Long distance terms modified by the presence of medium

- *Nuclear PDFs and new (non-linear) evolution equations*
- *Probes of hot matter created in the interaction*
- *EW processes (no hadronization) used as benchmark*

$$\sigma^{AB\to h} = f_A^i(x_1,Q^2)\otimes f_B^j(x_2,Q^2)\otimes\sigma(ij\to k)\otimes D_{k\to h}(z,Q^2)$$

Nuclear PDFs

Hadronization

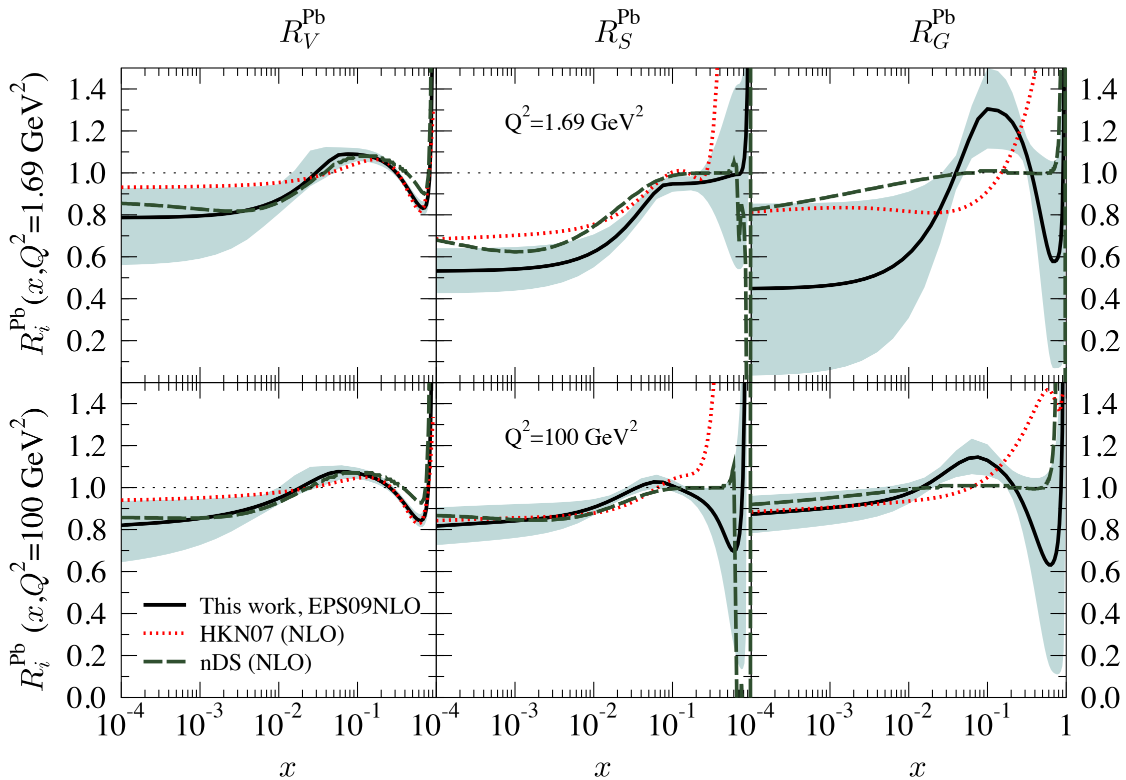
J/Ψ paradigmatic example

Background subtraction of "cold" nuclear matter effects

- *If you know two ingredients you can extract the other...*
- *Usually proton-nucleus collisions needed (in absence of nuclear DIS)*

Nuclear PDFs

⇛ Initial conditions and error analysis for different NLO sets



	Chi²/dof
EPS09	0.79
HKN	1.58
nDS	0.76

[Talks by Stavreva; Yu (QCD session)]

⇛ Large uncertainties especially for gluons - smaller at large virtuality

⇛ Notice that parametrization bias effects are present

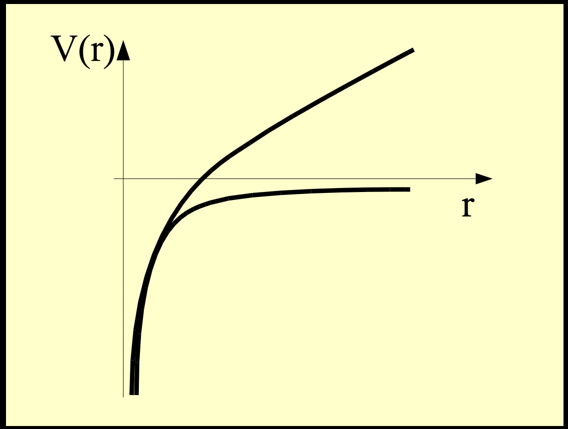
- Bands to be considered as lower bounds

Quarkonia suppression

[The first in a list of hard probes...]

Simple intuitive picture [Matsui & Satz 1986]

- *Potential screened at high-T*
- *Bound states not possible*
- *Suppression of J/Psi in nuclear collisions*
- *Sequential suppression of excited states*

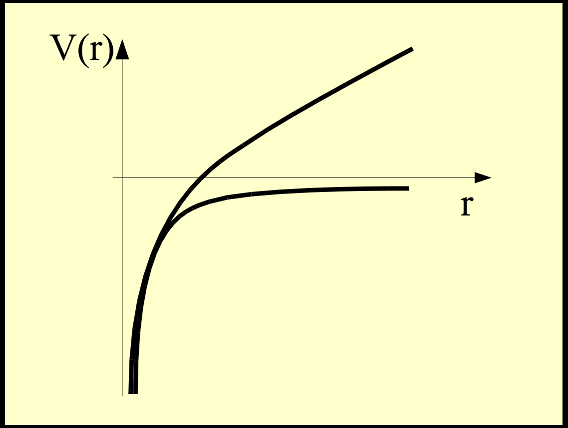


Quarkonia suppression

[The first in a list of hard probes...]

Simple intuitive picture [Matsui & Satz 1986]

- *Potential screened at high-T*
- *Bound states not possible*
- *Suppression of J/Psi in nuclear collisions*
- *Sequential suppression of excited states*

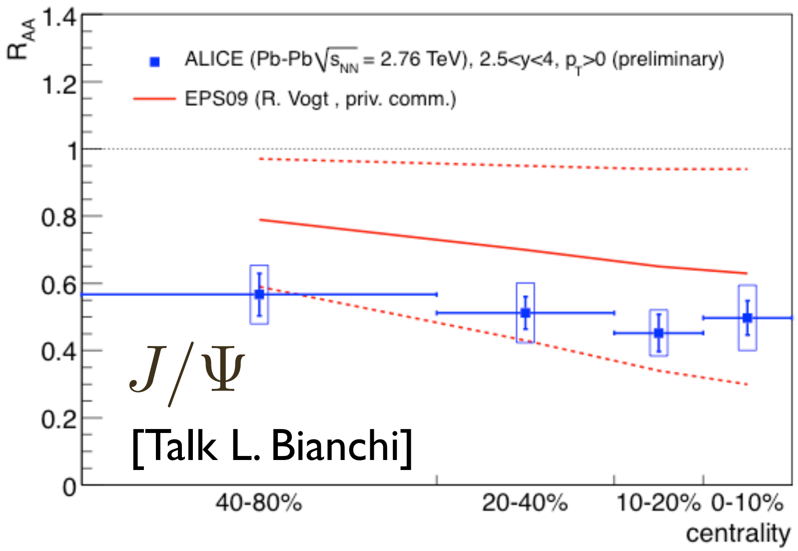


However, interpretation of the data is not yet clear

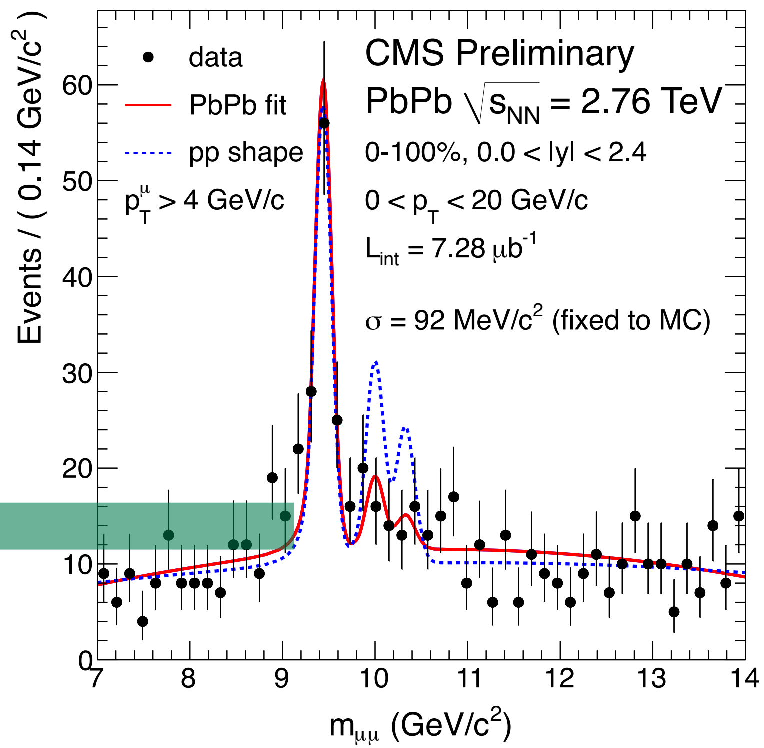
- *Quarkonia suppressed also in pA*
- *Not good theoretical control over the suppression*
- *Could LHC/RHIC improve the situation?*

Quarkonia at the LHC

- Different quarkonia states are suppressed differently



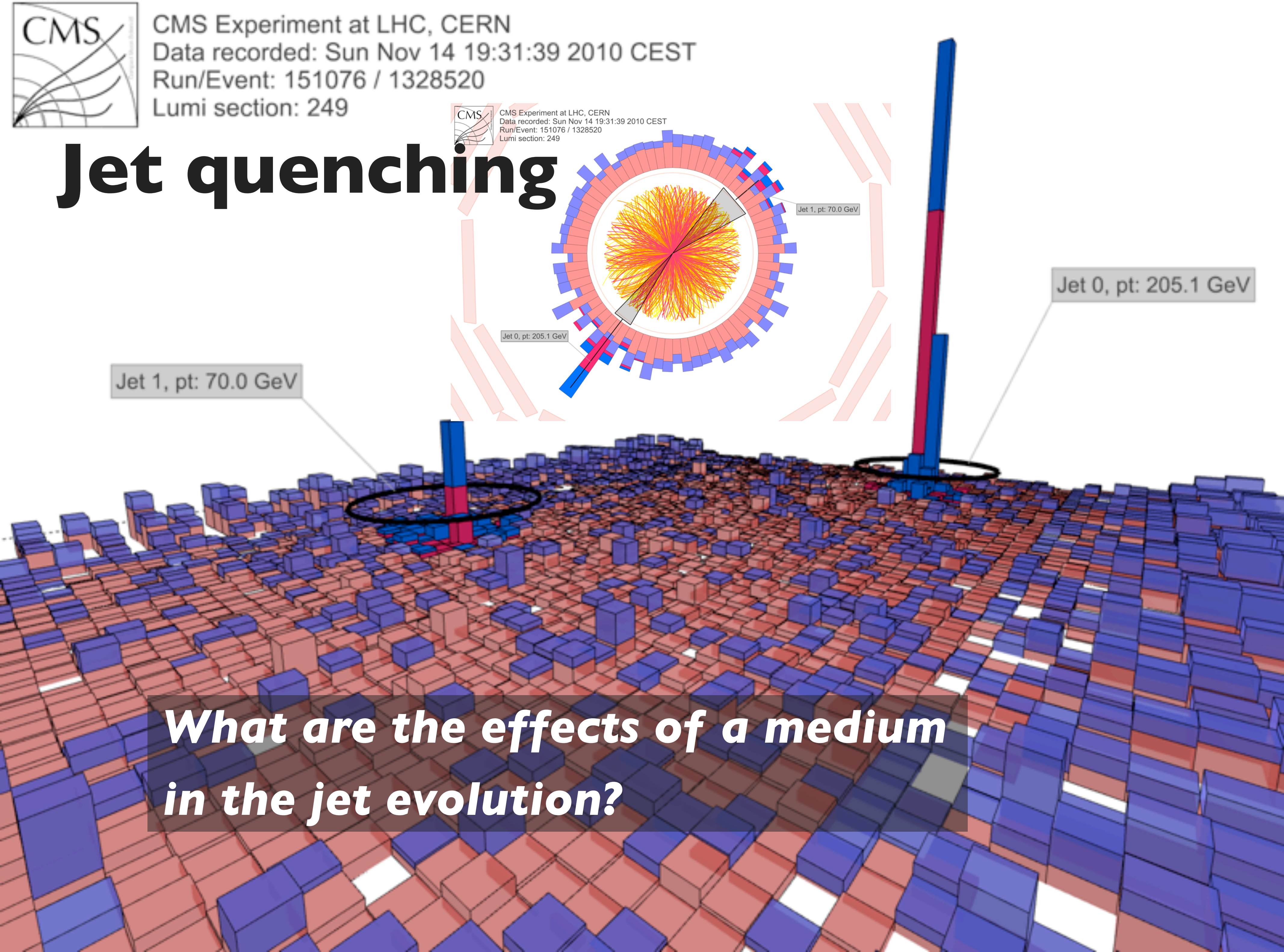
[Talk C. Silvestre (CMS)
also C. Powell (STAR)]



$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Sequential suppression?
  - Lattice QCD suggest that 1S quarkonia states melt at $T \sim 2T_c$
  - Excited states melt at $T \sim T_c$
- Control over the "cold" nuclear matter needed for clean picture

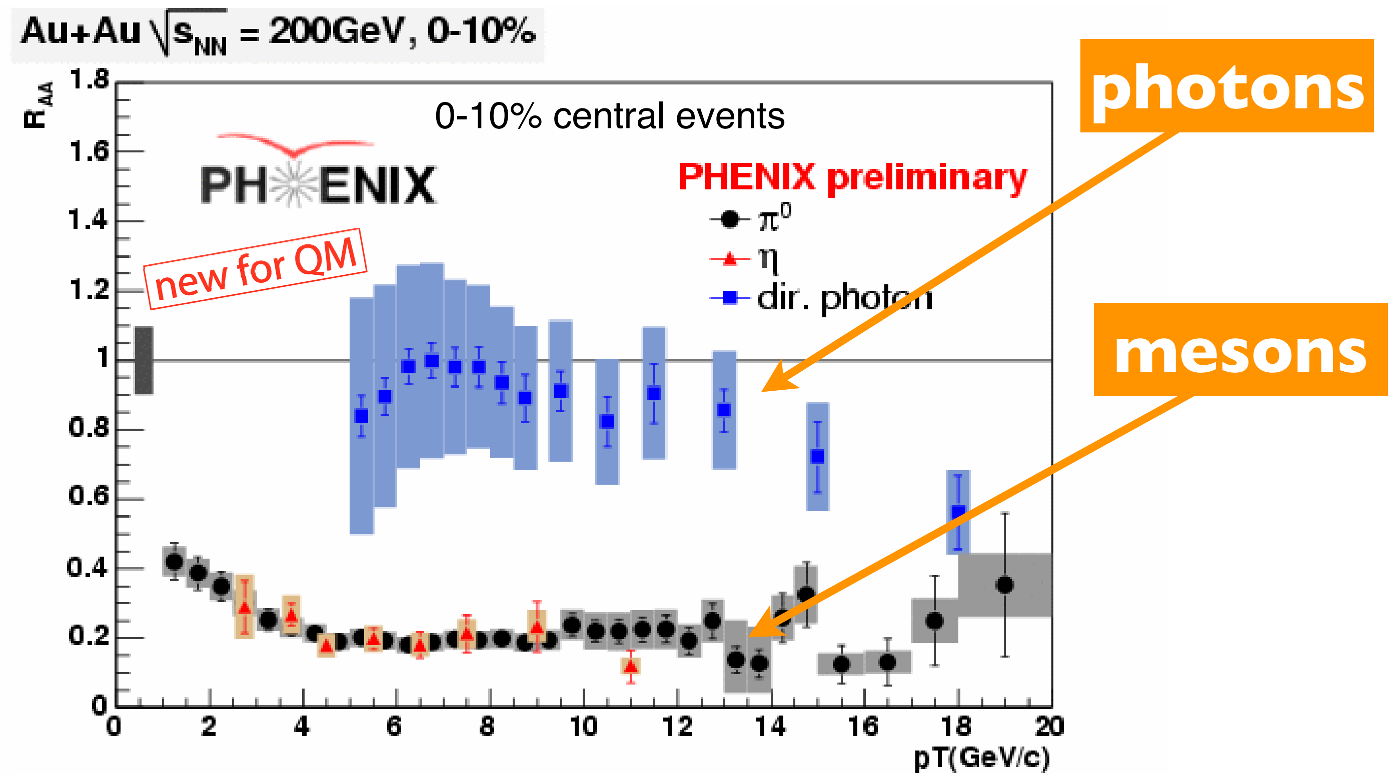
Jet quenching



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

Jet quenching with inclusive particles

⇛ Photons don't interact (no effect) quarks and gluons do (suppression)

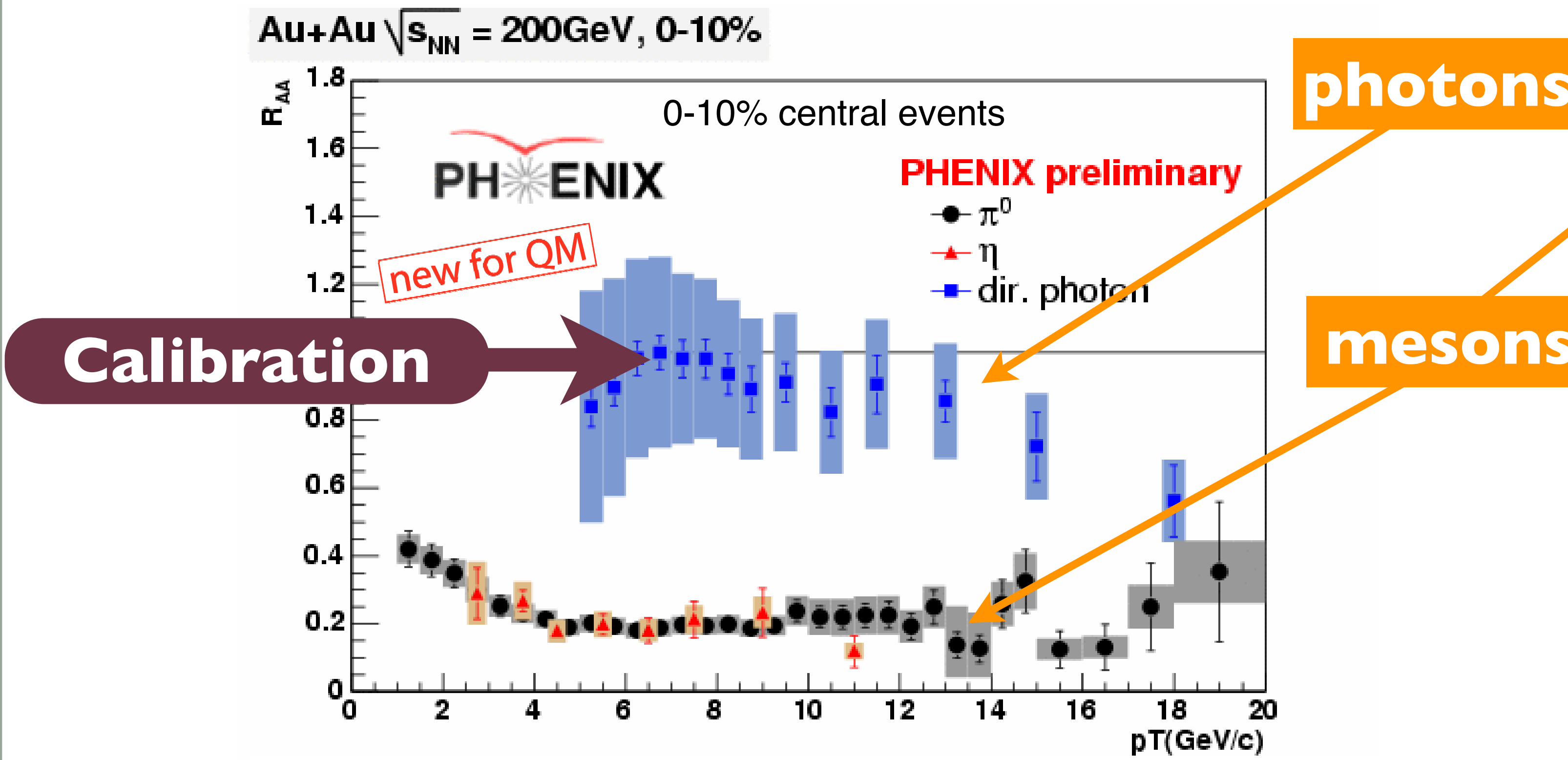


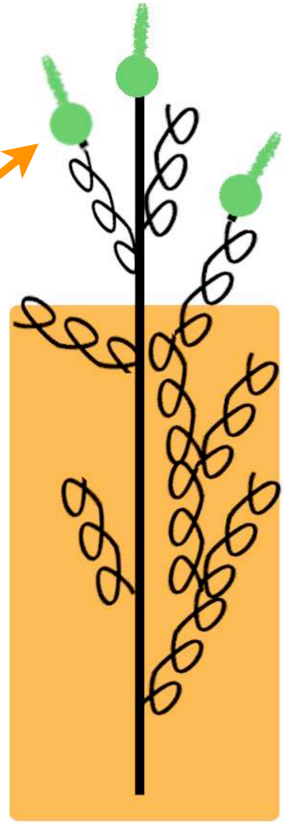
⇛ Very large energy loss - **large jet quenching parameter**

➘ **dense partonic system**

Jet quenching with inclusive particles

⇒ Photons don't interact (no effect) quarks and gluons do (suppression)



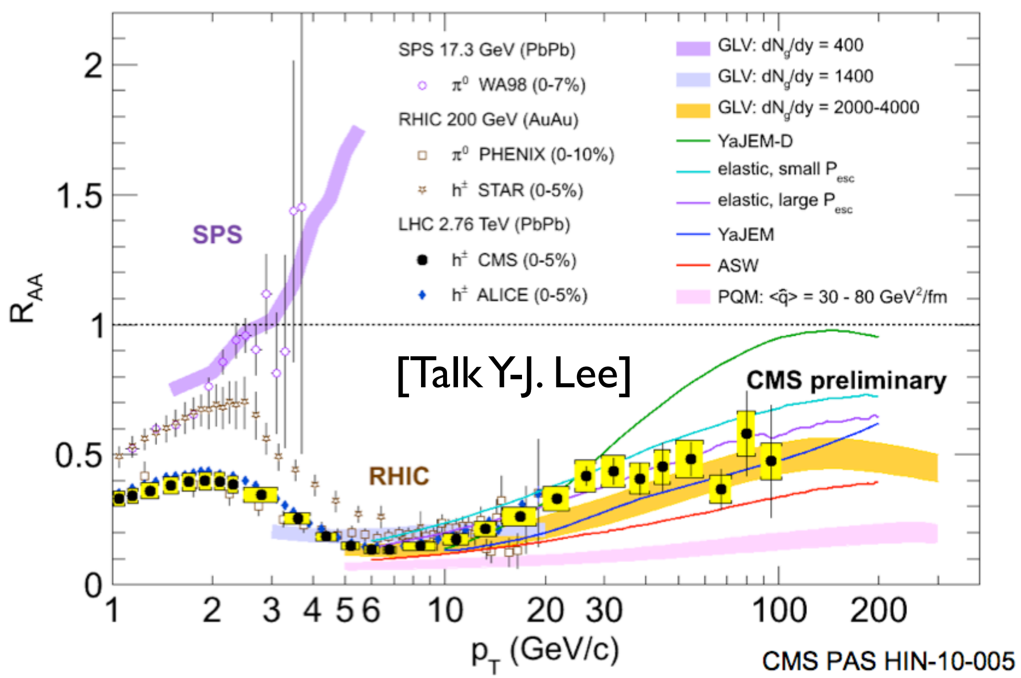


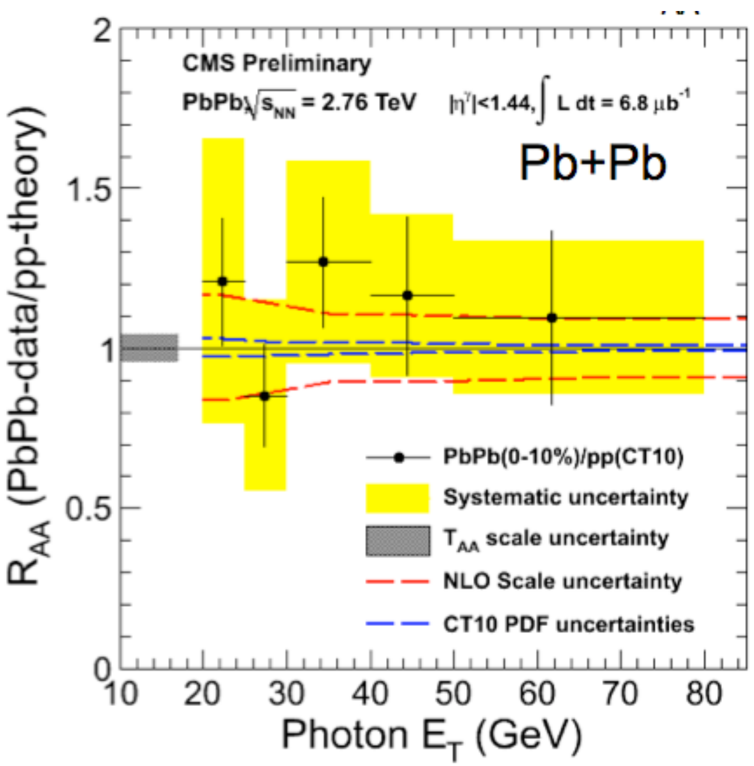
⇒ Very large energy loss - **large jet quenching parameter**

➘ **dense partonic system**

Jet quenching with inclusive particles: LHC

⇛ Suppression at the LHC slightly stronger than at RHIC





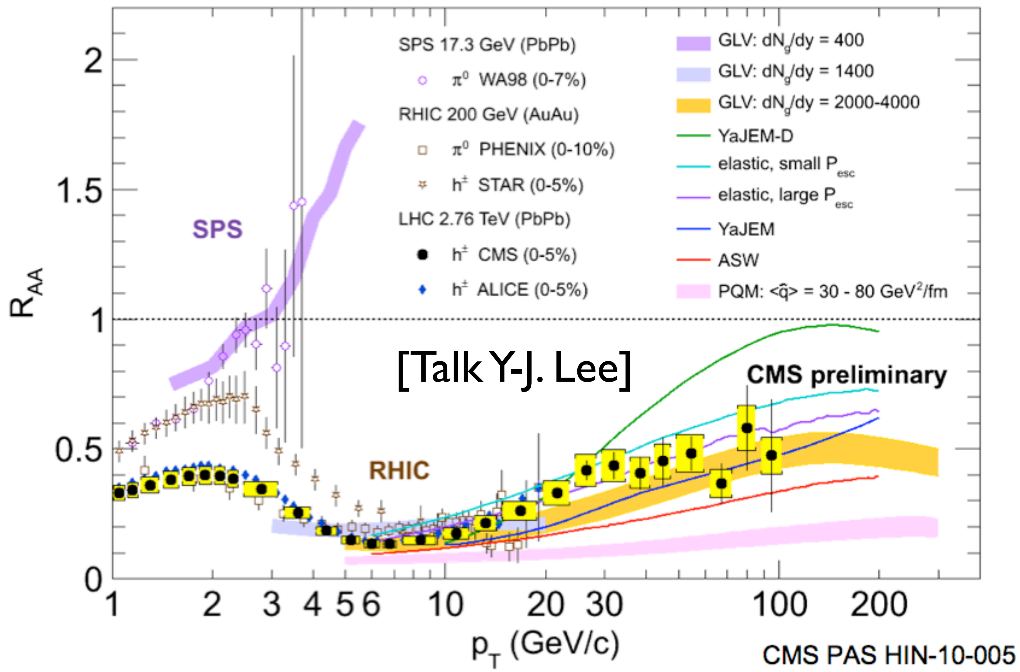
⇛ Formalism tested at RHIC provides reasonable description

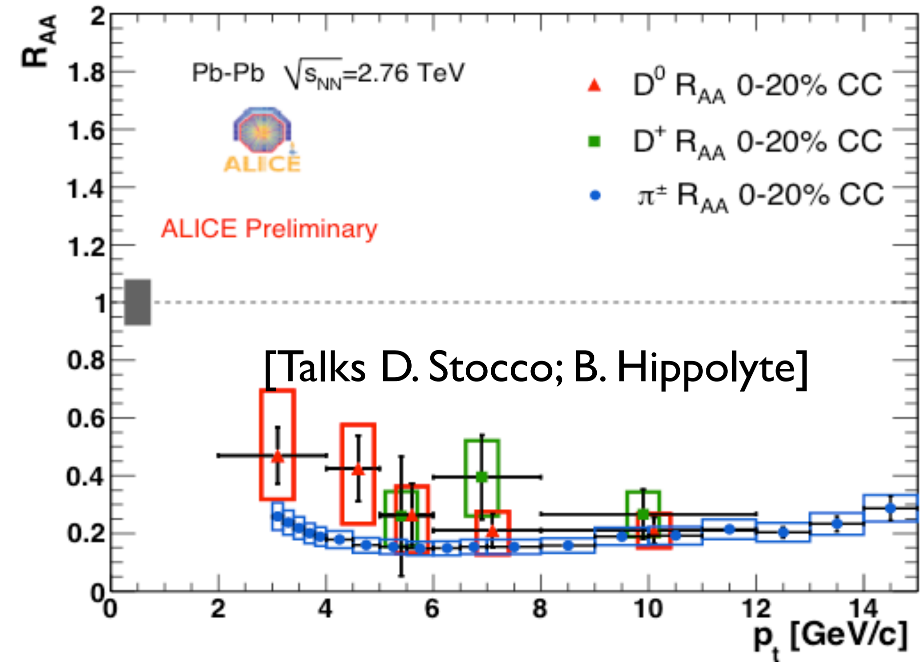
↘ **dense partonic system**

⇛ Suppression of heavy quarks: one remaining puzzle at RHIC

Jet quenching with inclusive particles: LHC

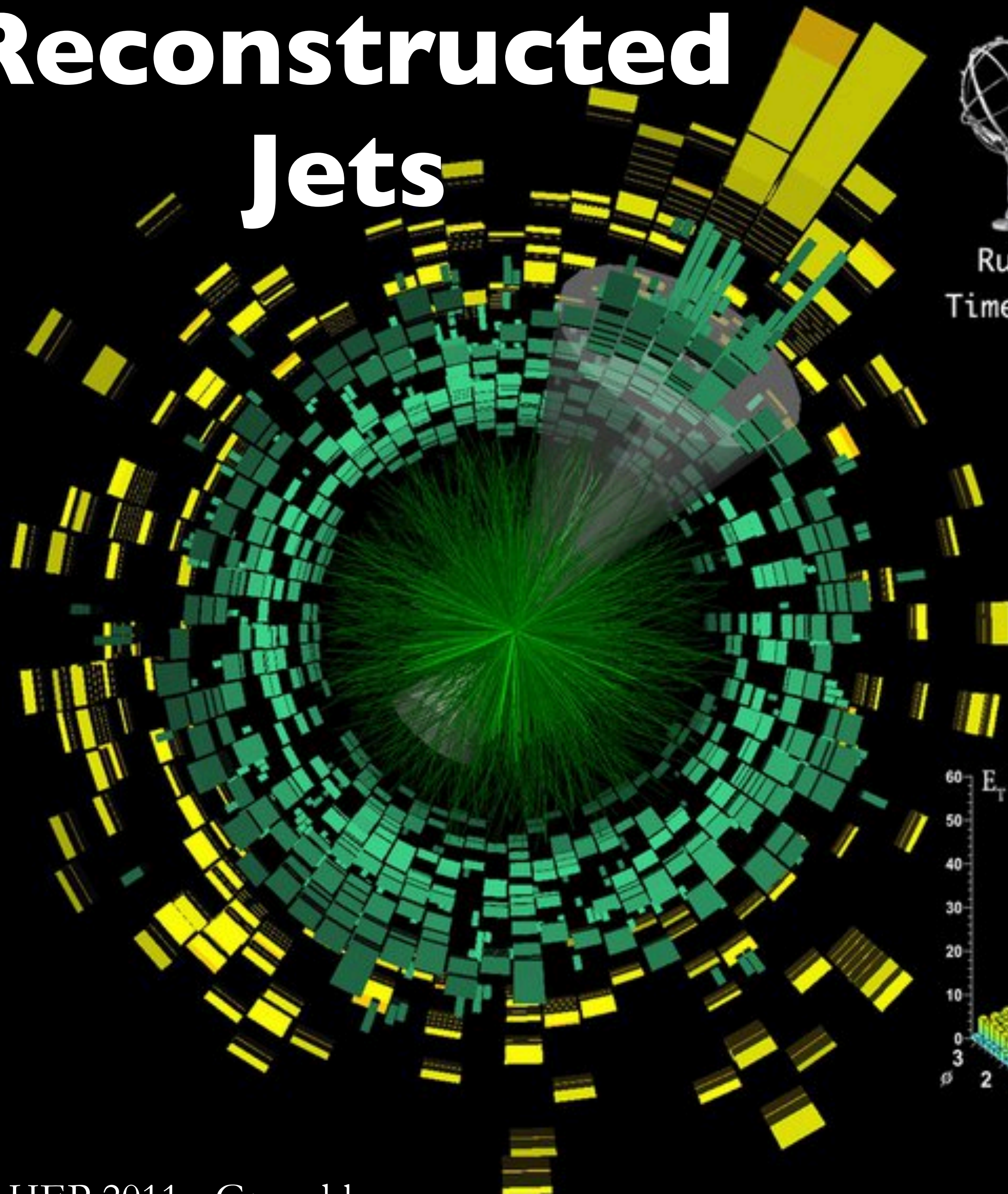
- Suppression at the LHC slightly stronger than at RHIC





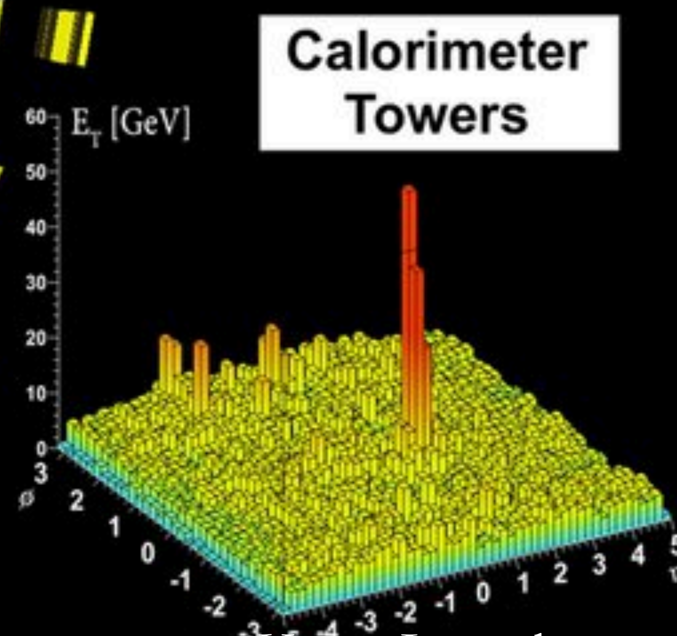
- Formalism tested at RHIC provides reasonable description
  - **dense partonic system**
- Suppression of heavy quarks: one remaining puzzle at RHIC

Reconstructed Jets



ATLAS EXPERIMENT
Run 168795, Event 7578342
Time 2010-11-09 08:55:48 CET

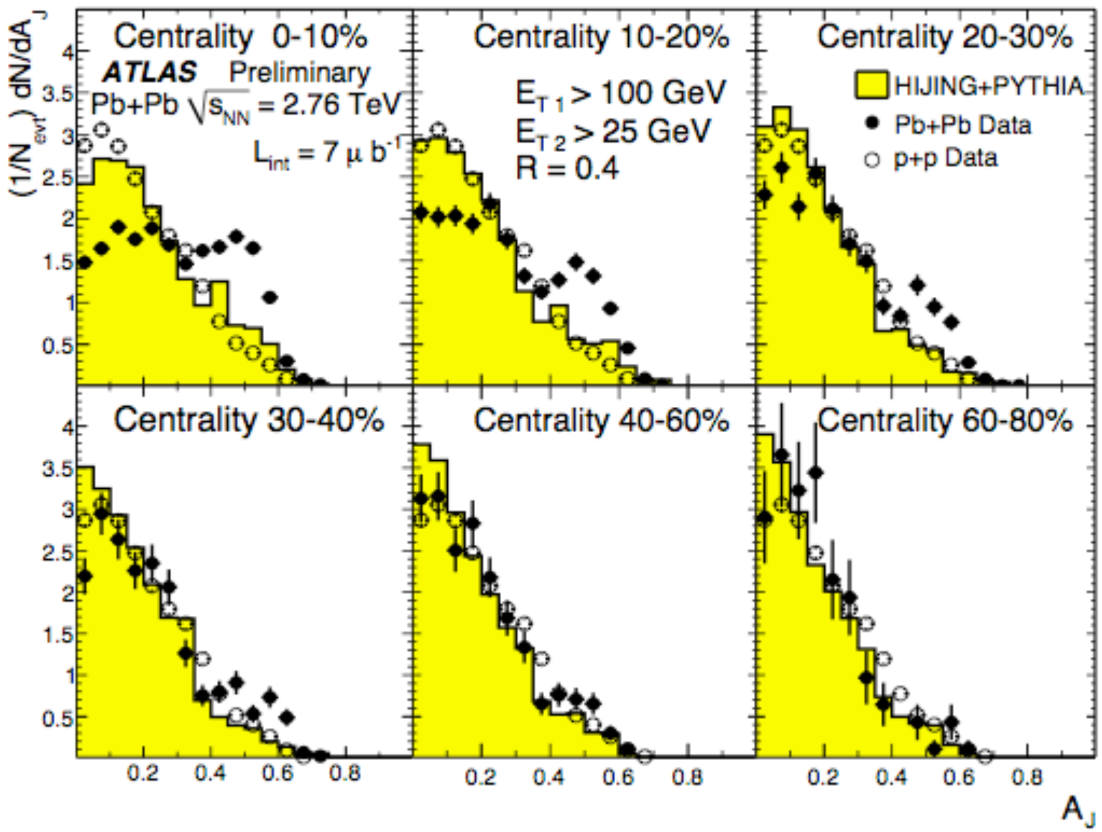
[Jet reco in HIC: Cacciari, Rojo, Salam, Soyez 2010]

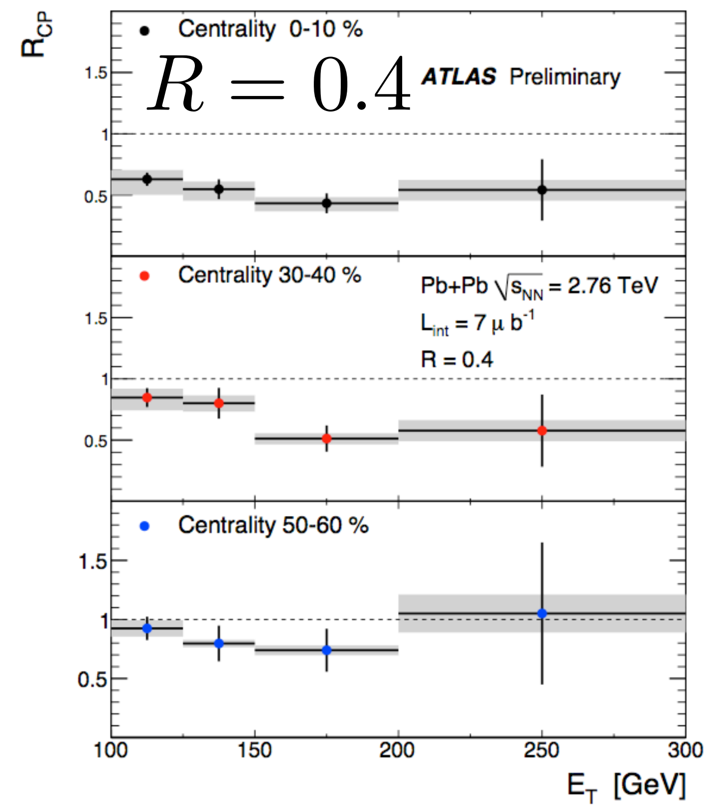


Di-jet asymmetry at the LHC

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

[Talk H. Santos]





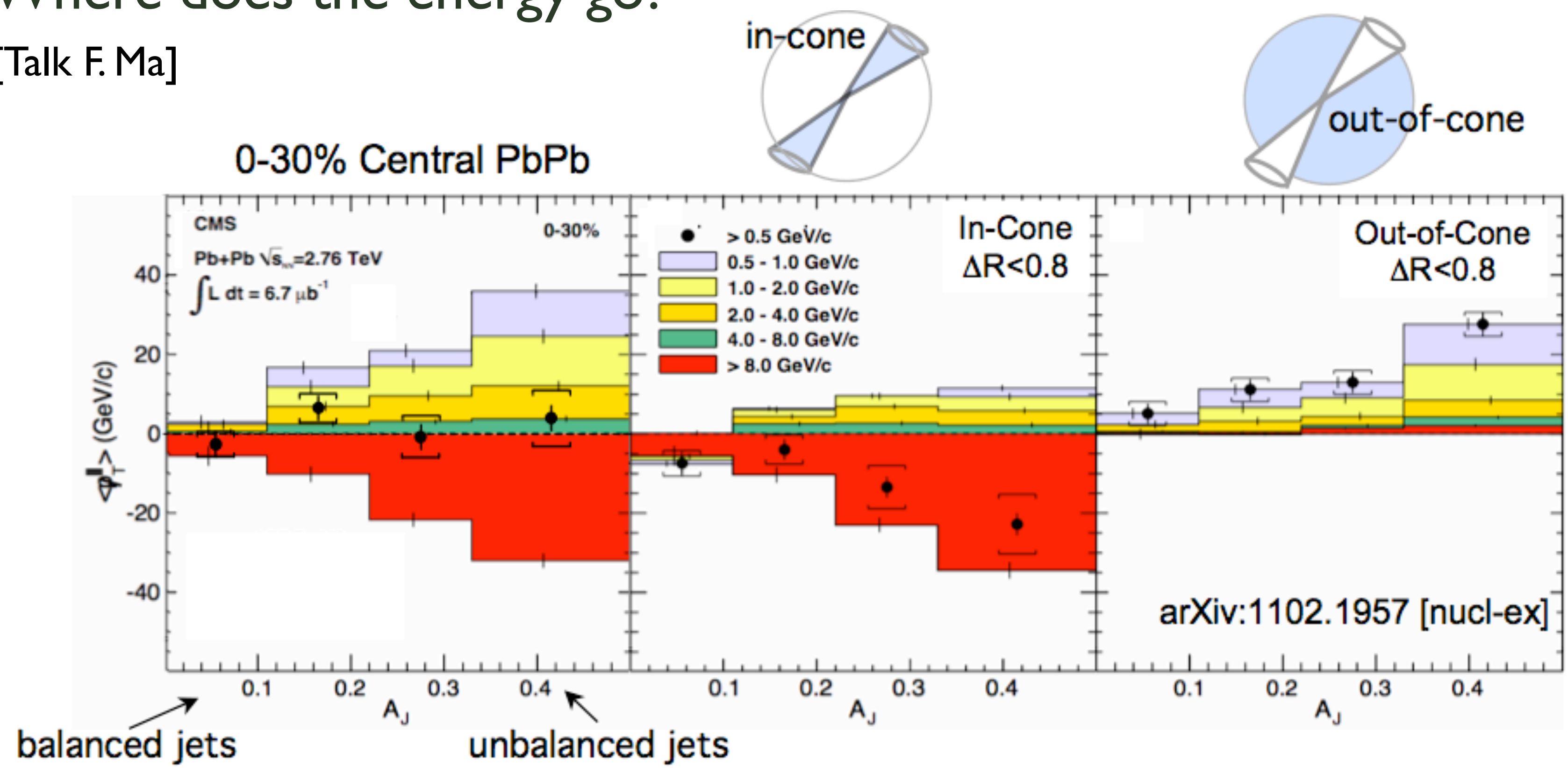
⇛ Jets are suppressed: Studied sample is a subset of the total

Progress in jet reconstruction TH/EX [Cacciari, Rojo, Salam, Soyez 2010]

Di-jet asymmetry at the LHC

⇛ Where does the energy go?

[Talk F. Ma]



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

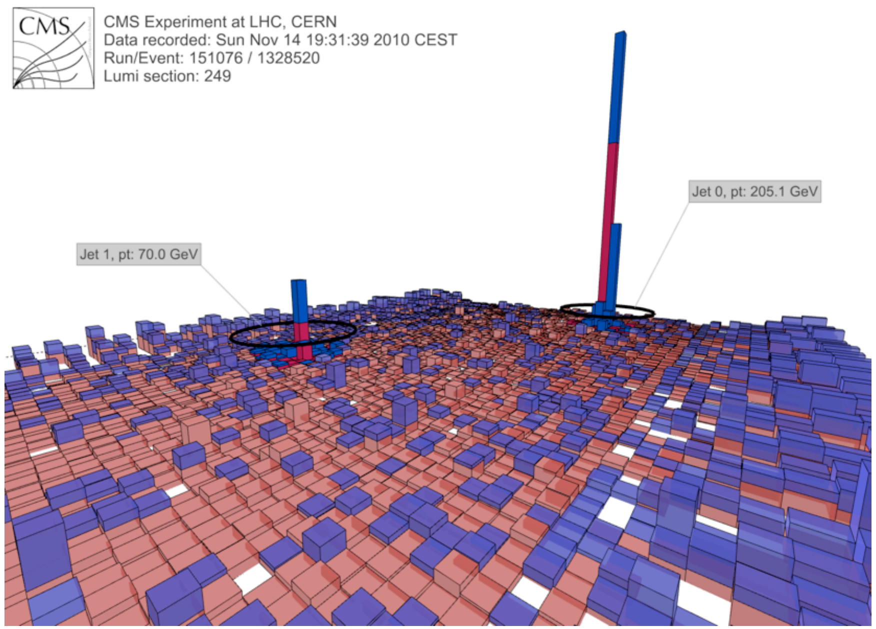
⇛ **Energy taken by soft particles at large angles**

A new theory of jets in a medium

In-medium jets needs to be under theoretical control

⇛ Medium-induced radiation off a single quark/gluon used (RHIC pheno)

- Energy loss of leading particle [BDMPS-Z/GLV, etc...]



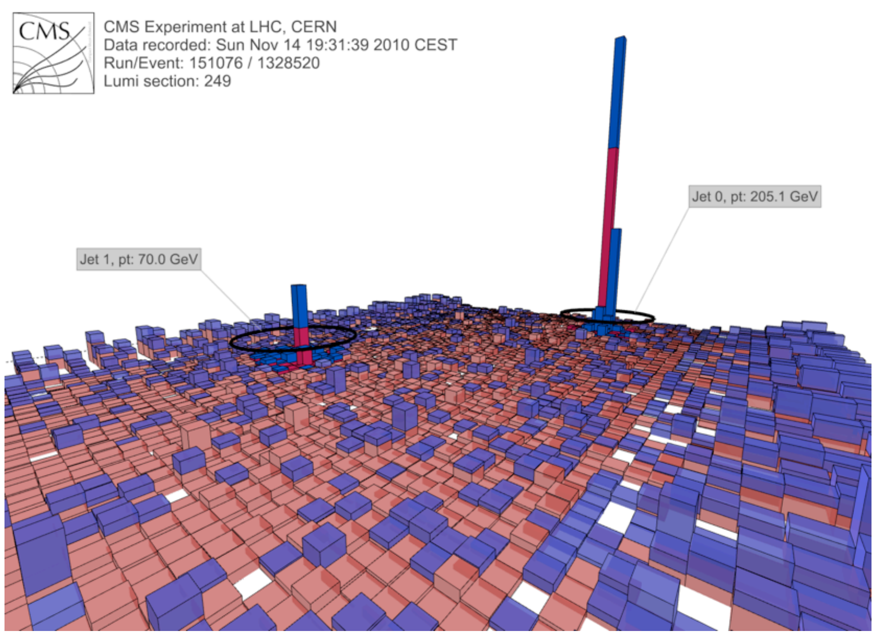
- Multigluon emissions: color coherence
- Ordering variables
- Color flow from/to medium
- Recoil... [Talk G. Milhano]

A new theory of jets in a medium

In-medium jets needs to be under theoretical control

⇛ Medium-induced radiation off a single quark/gluon used (RHIC pheno)

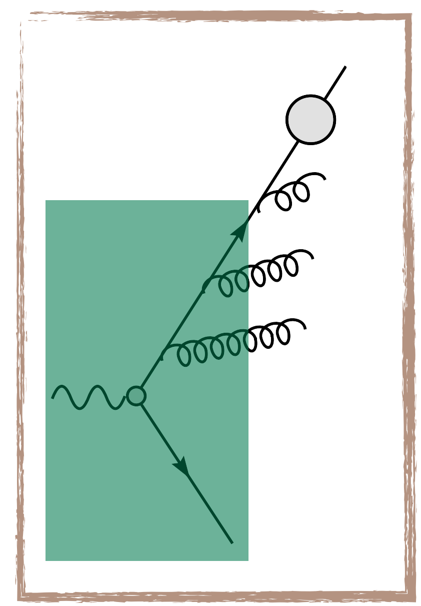
- Energy loss of leading particle [BDMPS-Z/GLV, etc...]



- Multigluon emissions: color coherence
- Ordering variables
- Color flow from/to medium
- Recoil...

[Talk G. Milhano]

Fill this gap

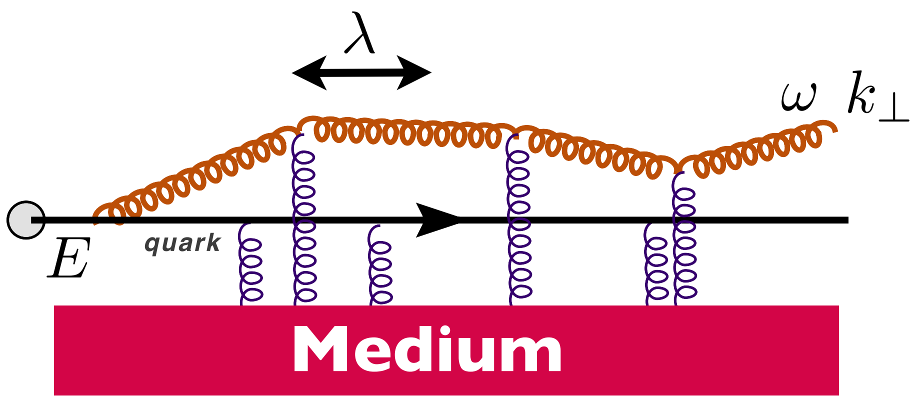


Main effort in the theory of in-medium jets with different methods

Multigluon emissions; Monte-Carlo; Effective theories,....

The medium-induced gluon radiation

⇛ Medium-modification of the splitting probability [BDMPS-Z/GLV, etc...]



Jet-quenching parameter

$$\hat{q} \simeq \frac{\langle k_\perp^2 \rangle}{\lambda}$$

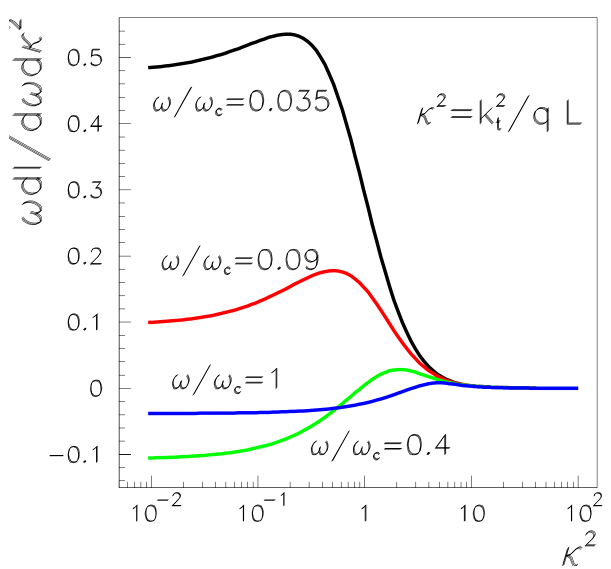
⇛ Medium-average of two light-like Wilson lines defines $\hat{q}$

[Effective theory: talk: D'Eramo]

$$\frac{1}{N^2-1}\mathrm{Tr}\langle W^{A\dagger}(\mathbf{x}_\perp)W^A(\mathbf{0})\rangle \simeq \exp\left\{-\frac{1}{4\sqrt{2}}\hat{q}\,L_+\,\mathbf{x}_\perp^2\right\}.$$

⇛ Radiation is IR and collinear finite

- Landau-Pomeranchuk-Migdal effect in QCD
- Broadening



By construction, no color coherence among different emitters is included

Antenna radiation in medium

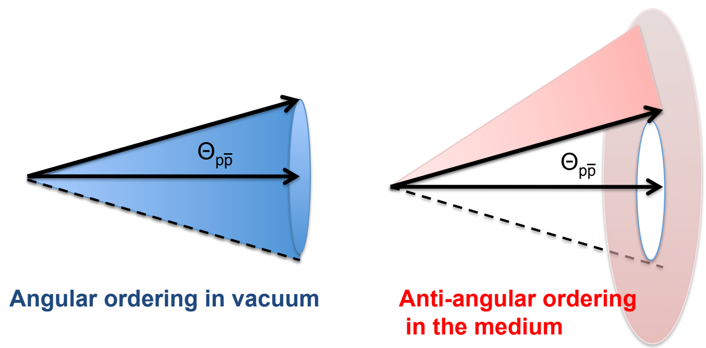
⇛ **In vacuum color coherence leads to angular ordering**

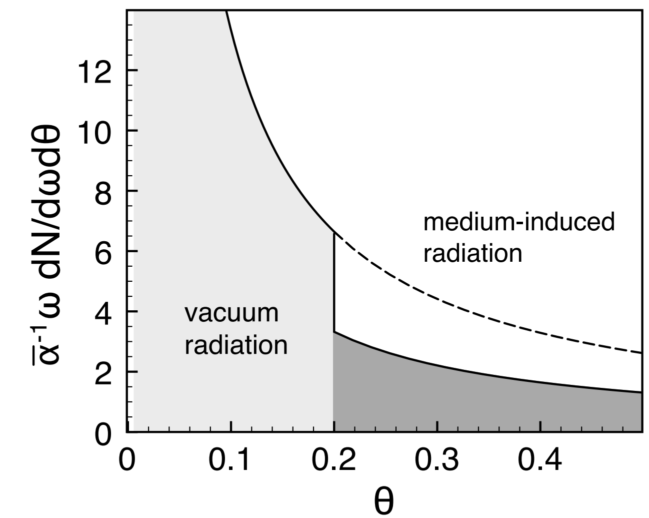
- At the basis of jet parton shower algorithms

⇛ Medium breaks the coherence of the pair [Mehtar-Tani, Salgado, Tywoniuk 2010]

- Strict out-of-cone emission - "anti-angular ordering" in the soft region

$$\langle dN_q \rangle_\phi = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{d\theta}{\theta} \left[\Theta\left(\theta_{q\bar{q}} - \theta\right) + \Delta_{\rm med}(\theta_{q\bar{q}}, \hat{q}, L) \Theta\left(\theta - \theta_{q\bar{q}}\right) \right]$$





⇛ In the limit of **opaque medium**

- Complete **decoherence** (vacuum-like)
- **Memory loss** effect: radiation equal for singlet or octet pairs

Encouraging results in view of the data on reconstructed jets

[Also: Mehtar-Tani, Salgado, Tywoniuk 2011; Casalderrey-Solana, Iancu 2011]

Summary

With LHC nuclear collisions at the TeV for the first time

- *Access to the small-x and large virtualities jets, EW bosons, HQ ...*
- *New theoretical tools (evolution equations, in-medium jet evolution)*

Created medium (RHIC+LHC) very dense ideal fluid

- *Progress on initial conditions and hydro theory: constrain viscosity*

Higher statistics and new tools

- *Will allow to characterize the medium with unprecedented precision*

Is it a liquid? Strongly coupled? Are quasiparticles the relevant degrees of freedom?..