Heavy-ions theory

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ICHEP 2012 - Melbourne - July 2012

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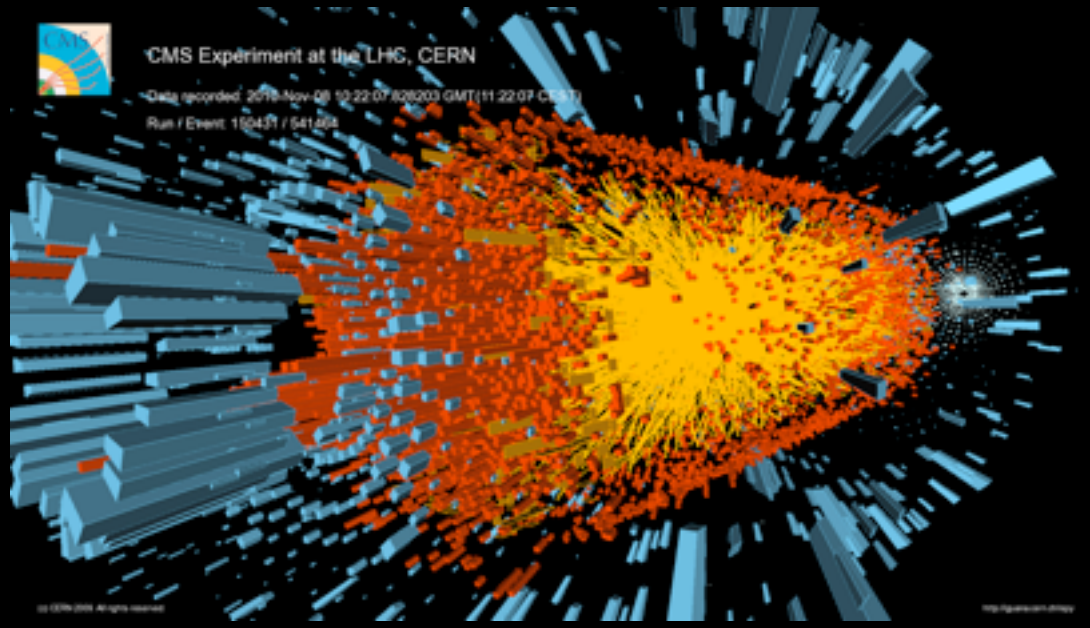
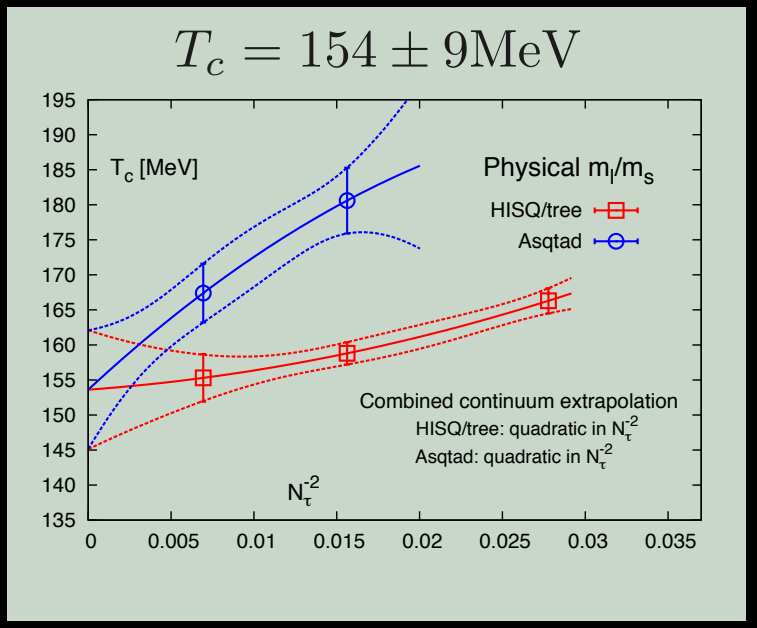
European Research Council
Established by the European Commission

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

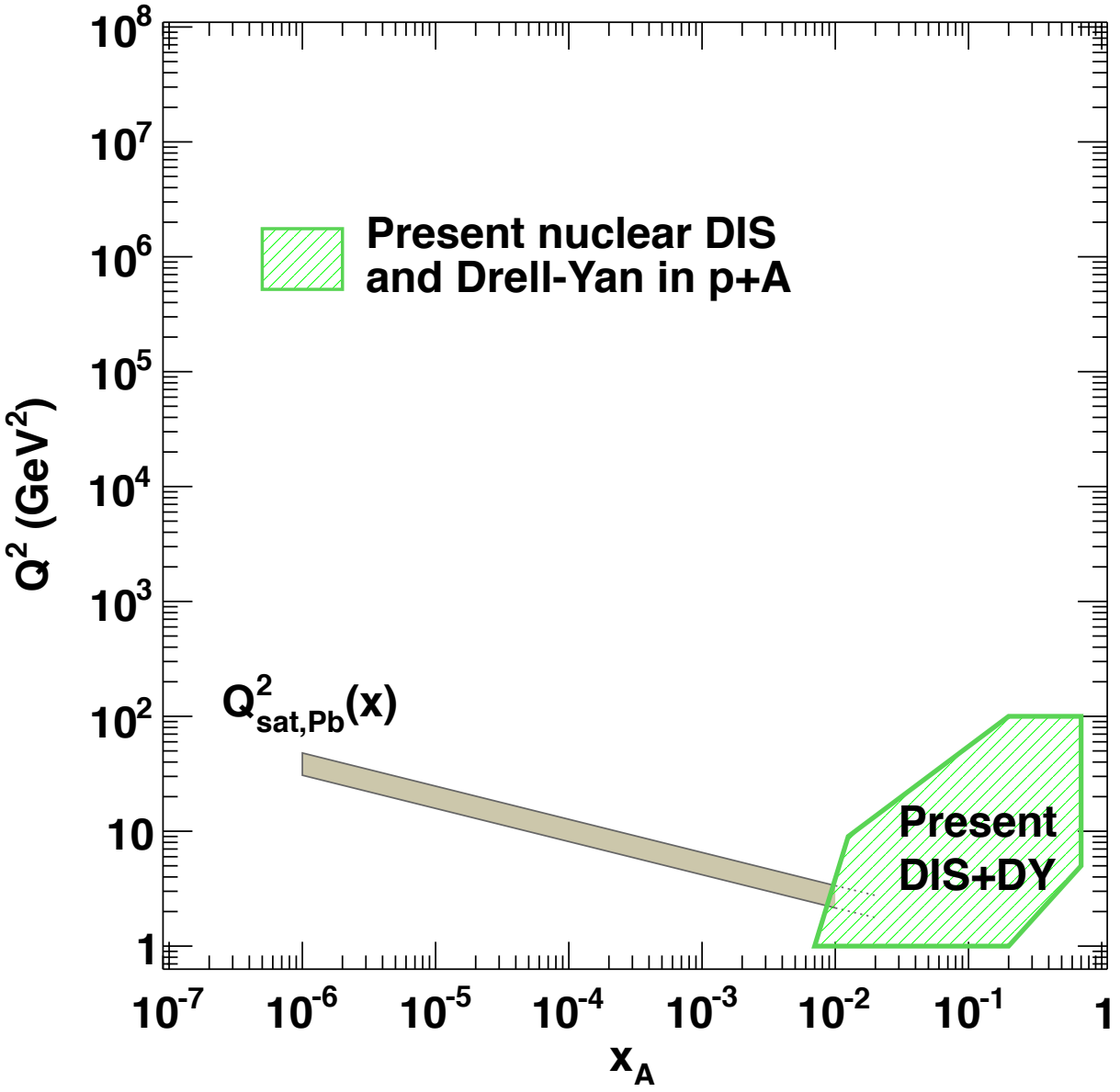
High-energy nuclear collisions are the experimental tools to access (some of) these collective properties - high density states of matter





HotQCD Coll. 2012, in agreement with previous results from Wuppertal-Budapest

Kinematical reach in nuclear collisions



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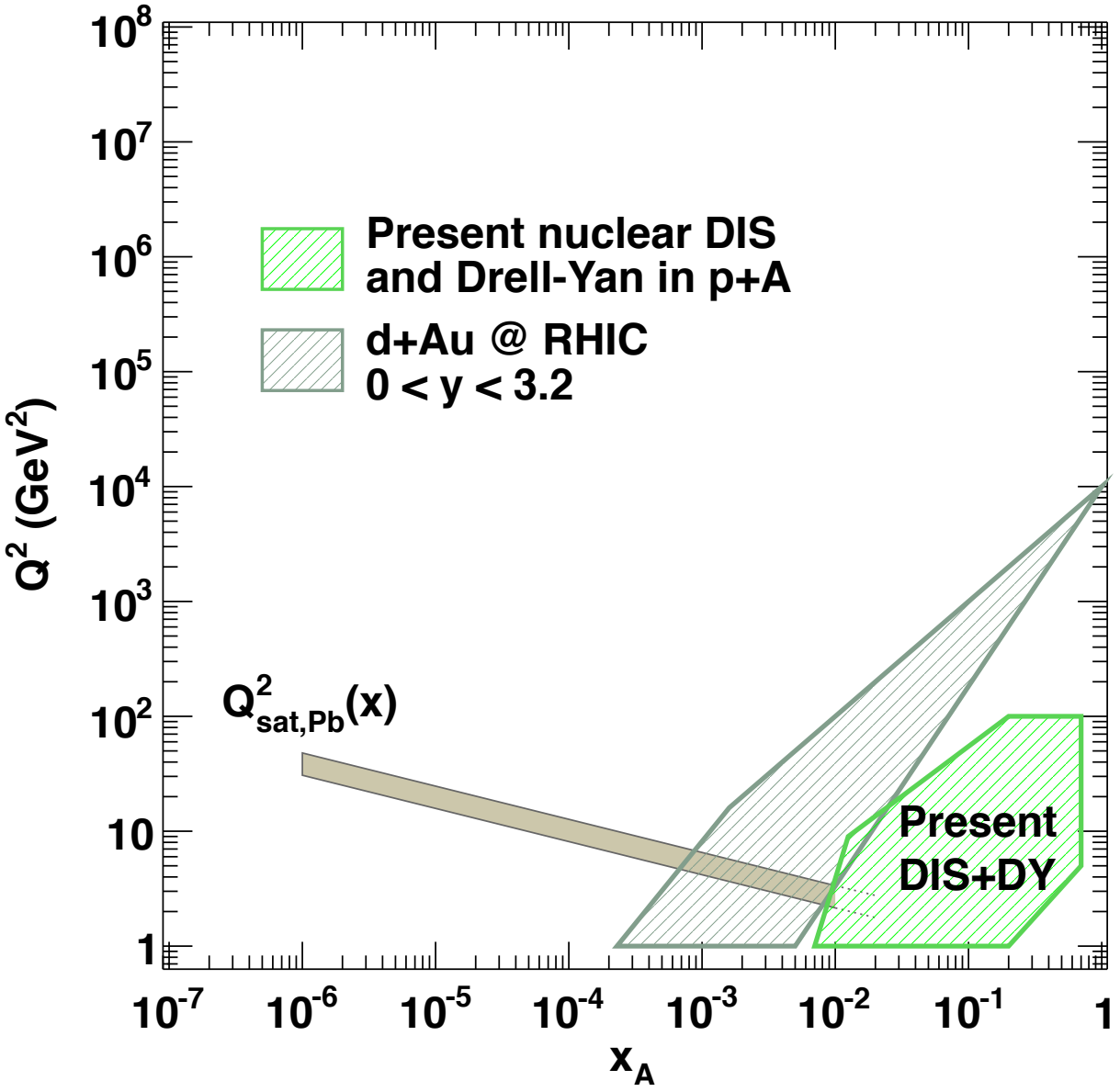

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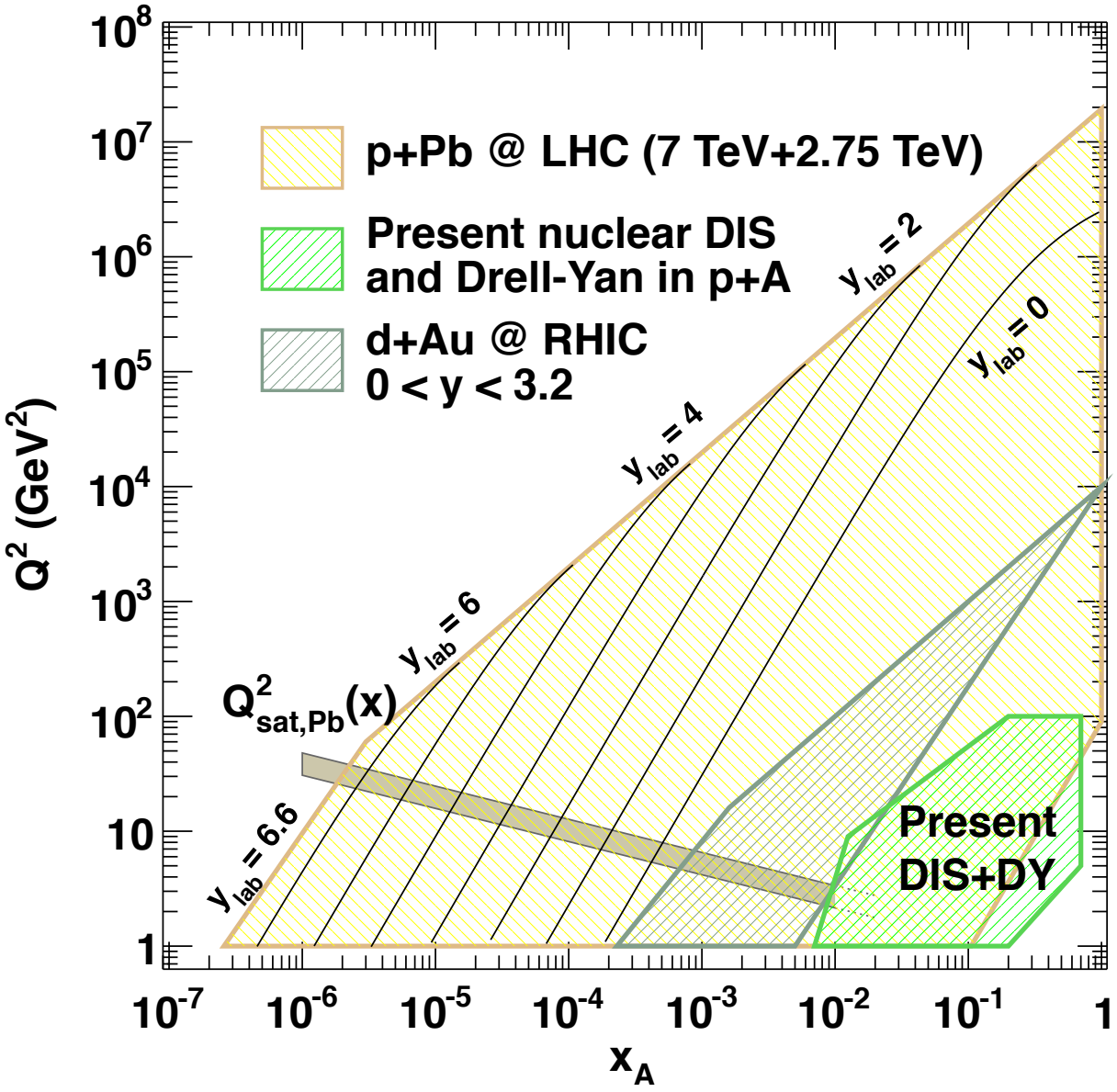

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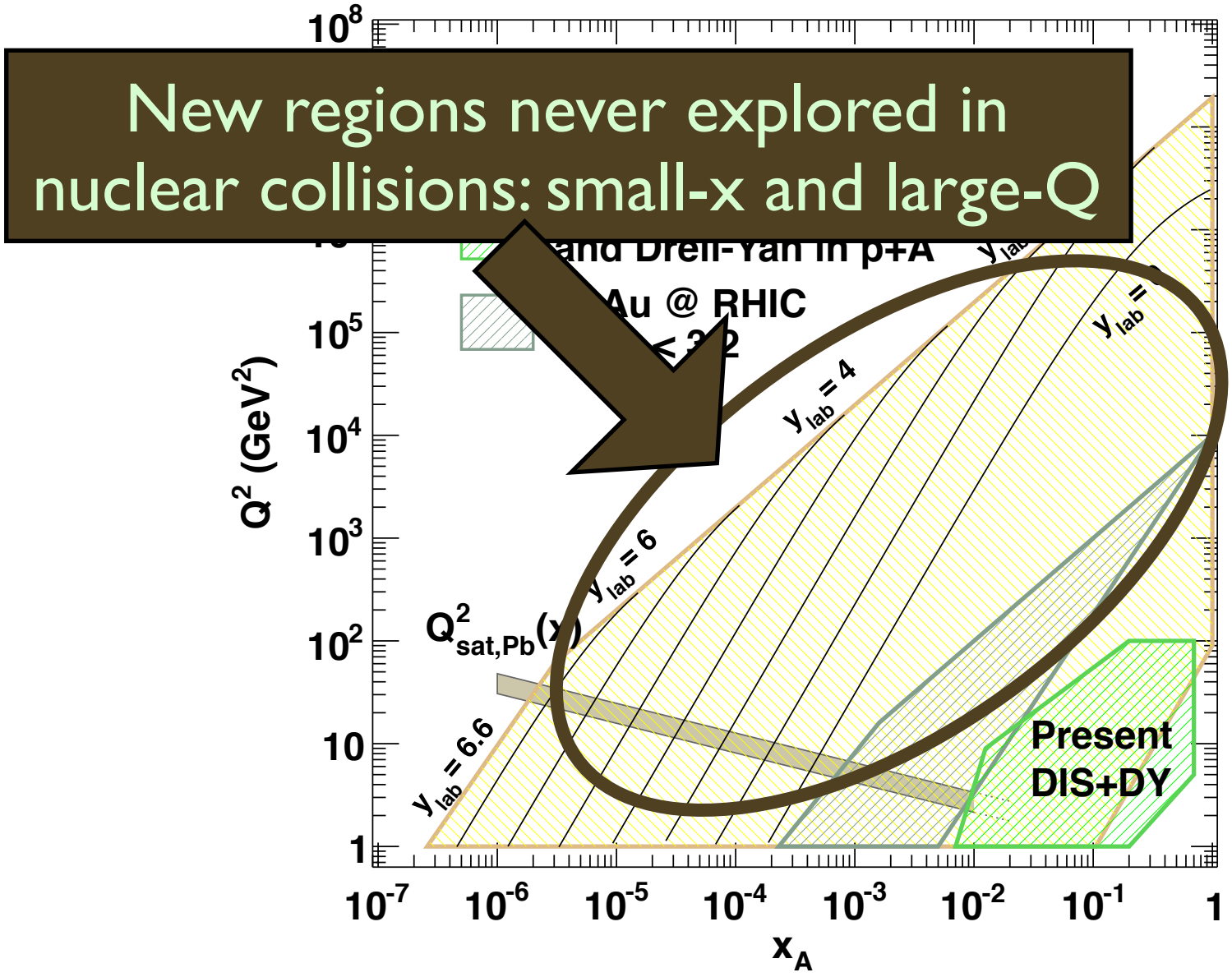
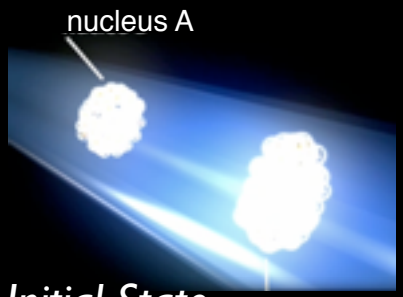


Some of the questions accessible with heavy-ion collisions



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?*

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

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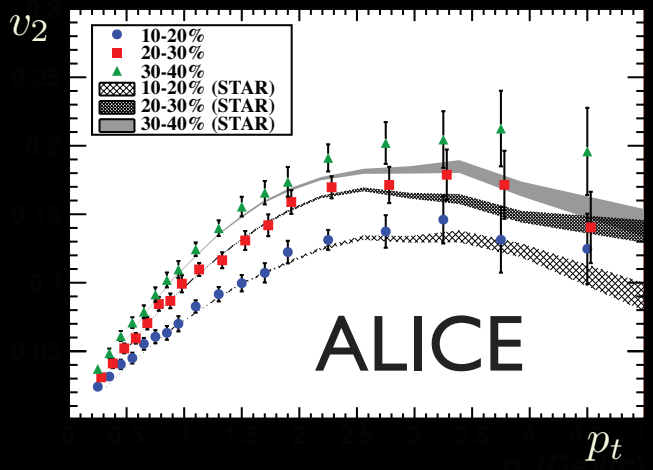
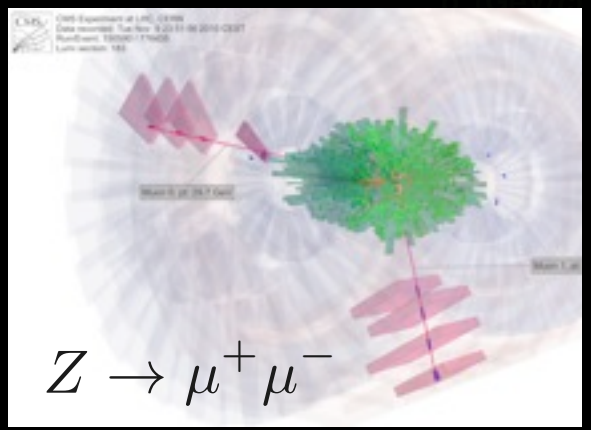
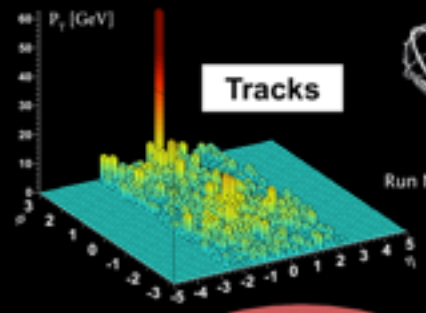
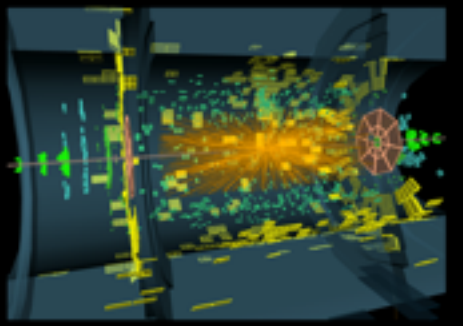
RHIC +LHC

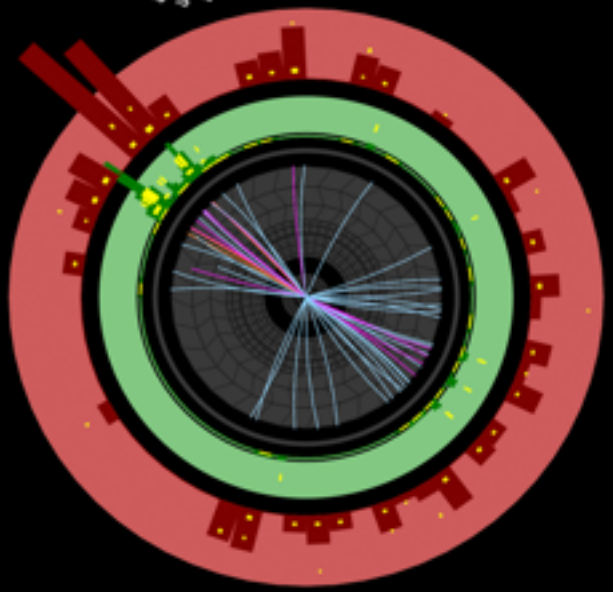
LHC first run: 2010

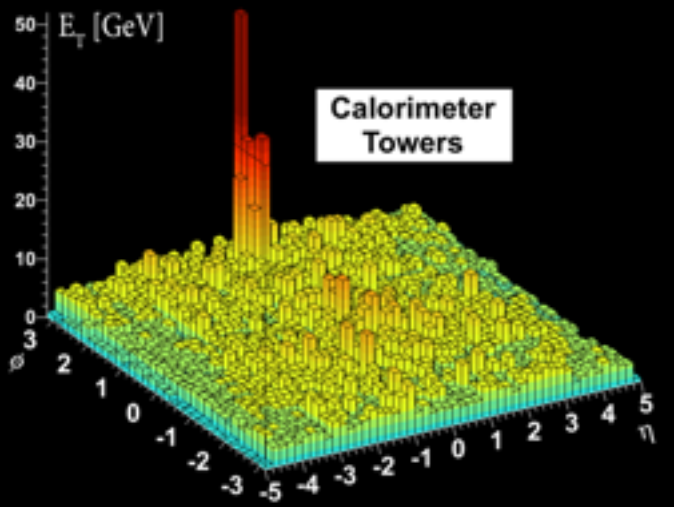






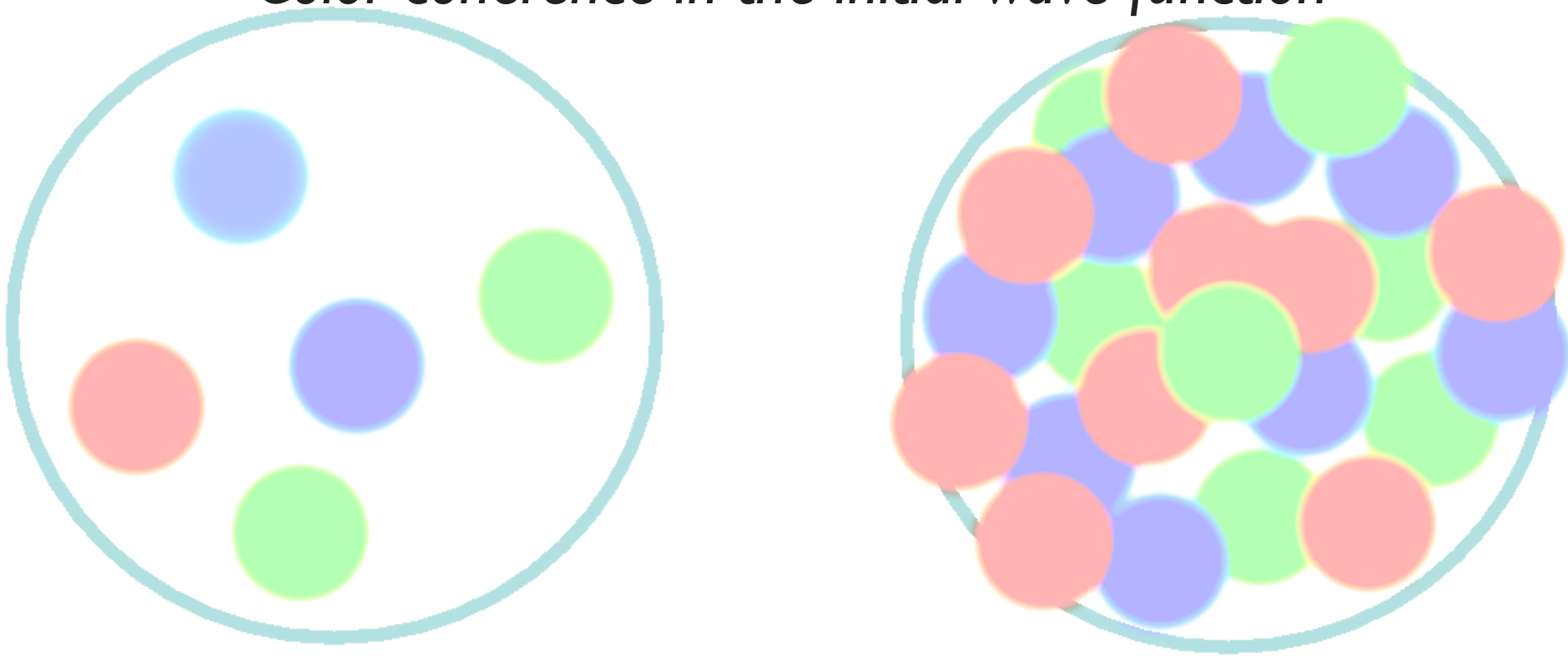






Initial state: Saturation of partonic densities

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

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

[Also, talk by L. Lonnblad]

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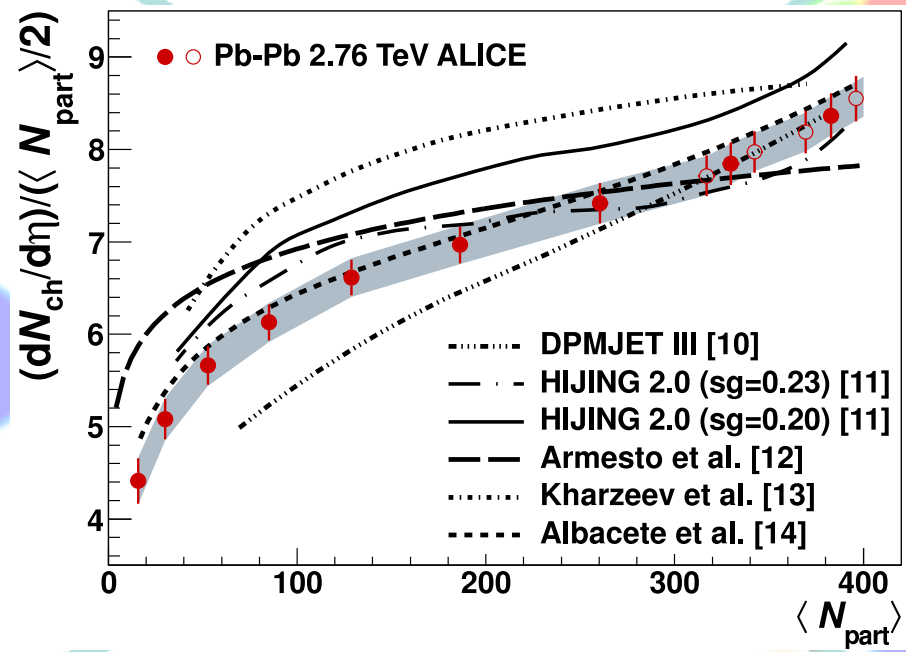

Notice that the underlying event is what we want to study...

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

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

[Also, talk by L. Lonnblad]

Non-linear evolution equations

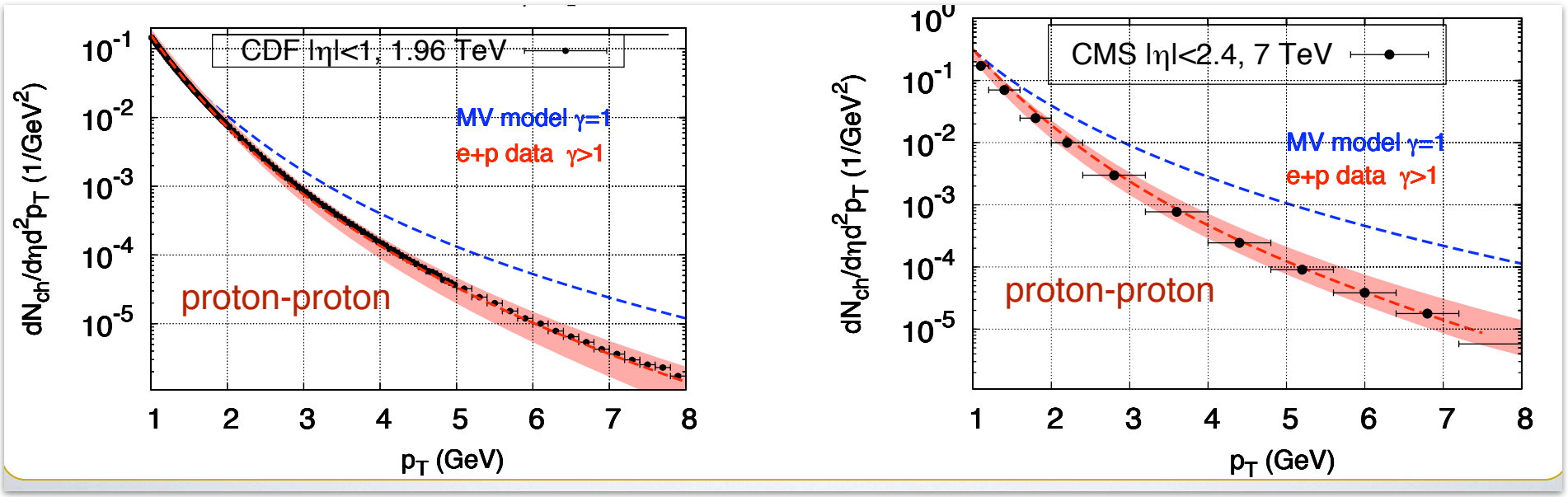
⇛ Screening leads to non-linear terms. E.g. Balitsky-Kovchegov eqs.

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

Splitting [BFKL] Merging [restores unitarity]

⇛ (unintegrated) gluon distributions fitted to HERA data reproduce pp

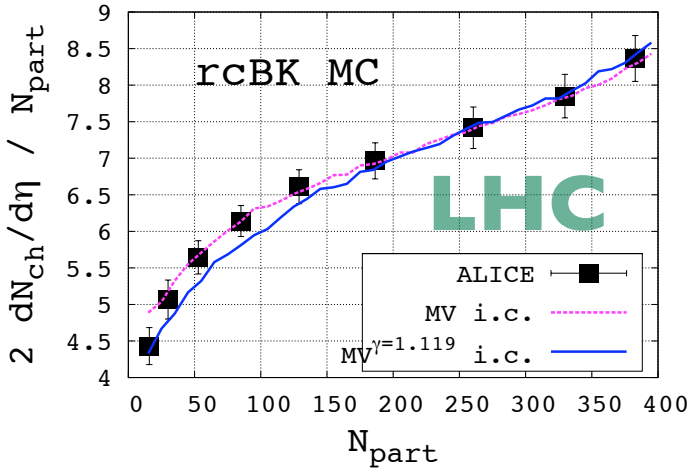
[Albacete, Dumitru 2011]

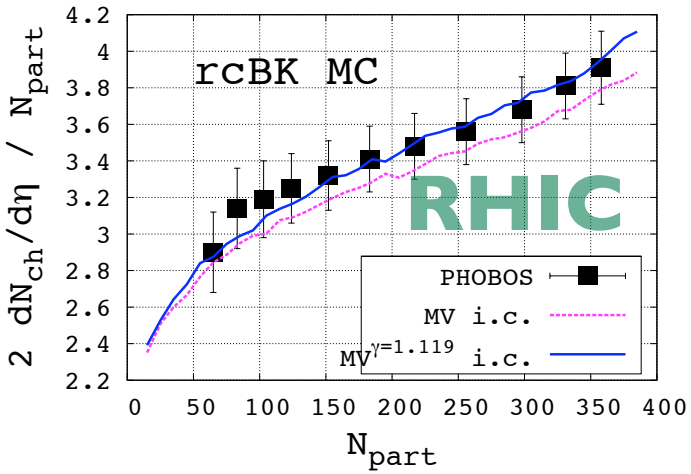


Extrapolation to nuclei

⇒ Small sensitivity to hard part of the gluon distributions in multiplicities

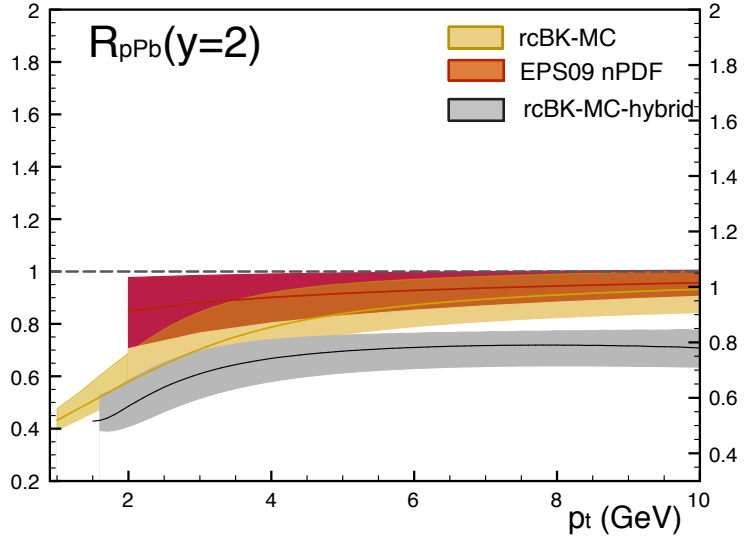
[Albacete, Dumitru 2011]





... which is **larger** in quantities affected by final state effects (hydro)

Proton-nucleus collisions to reduce these uncertainties and further constrain parton distributions



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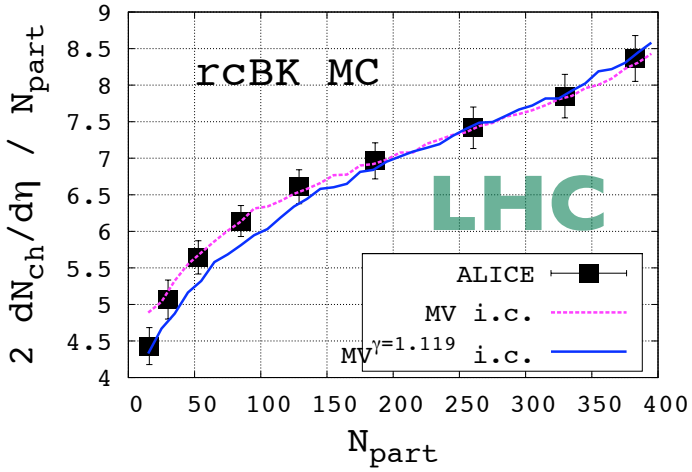

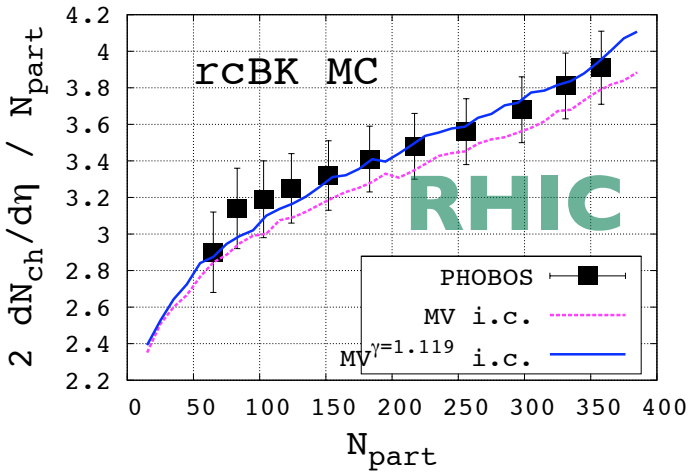

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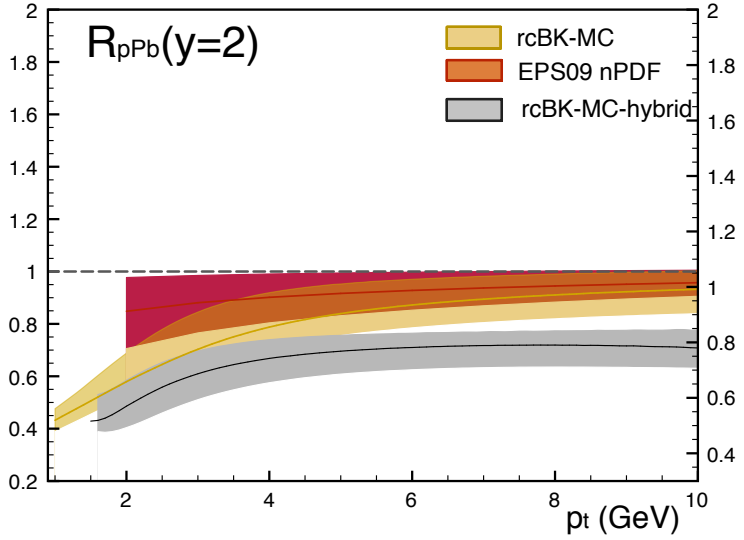
pPb collisions at the end of the present running period - December 2012



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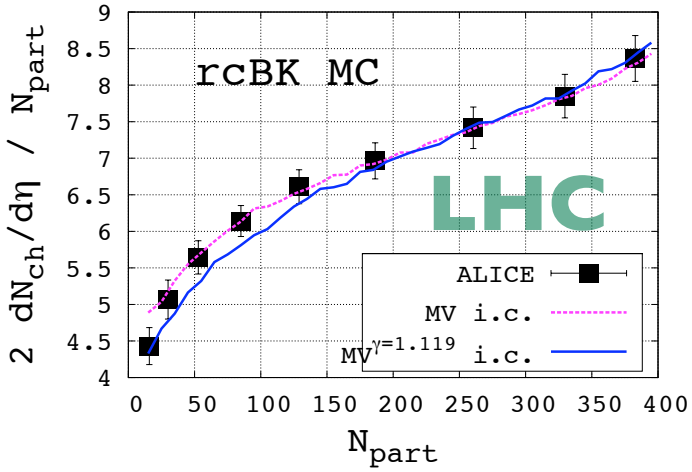

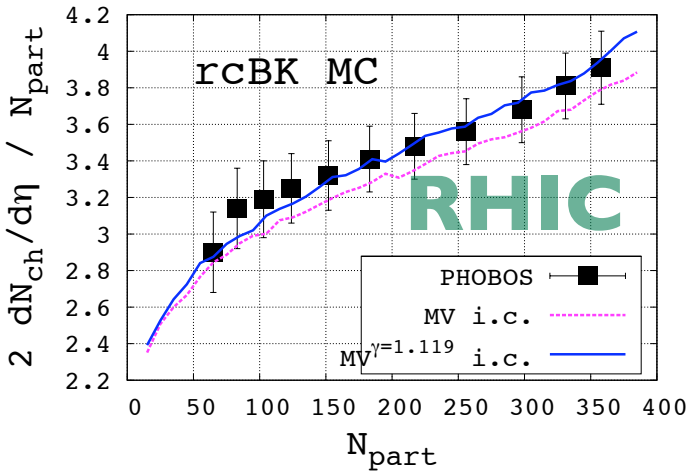

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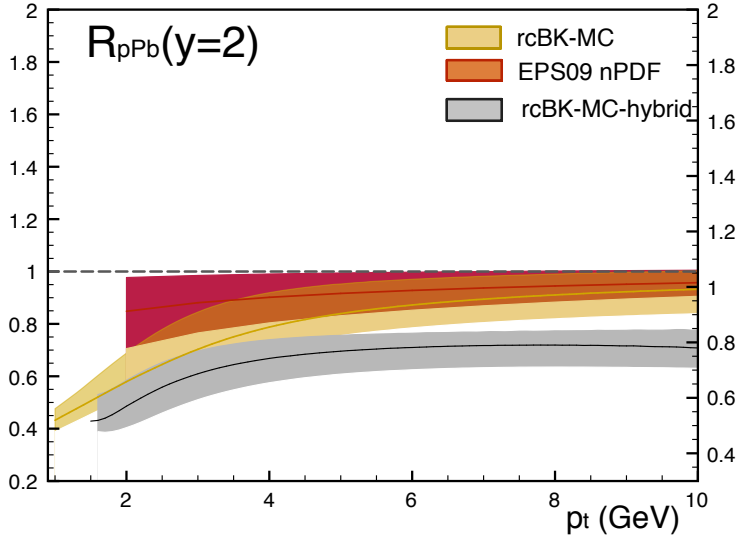


[Albacete, HP2012]

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

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

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

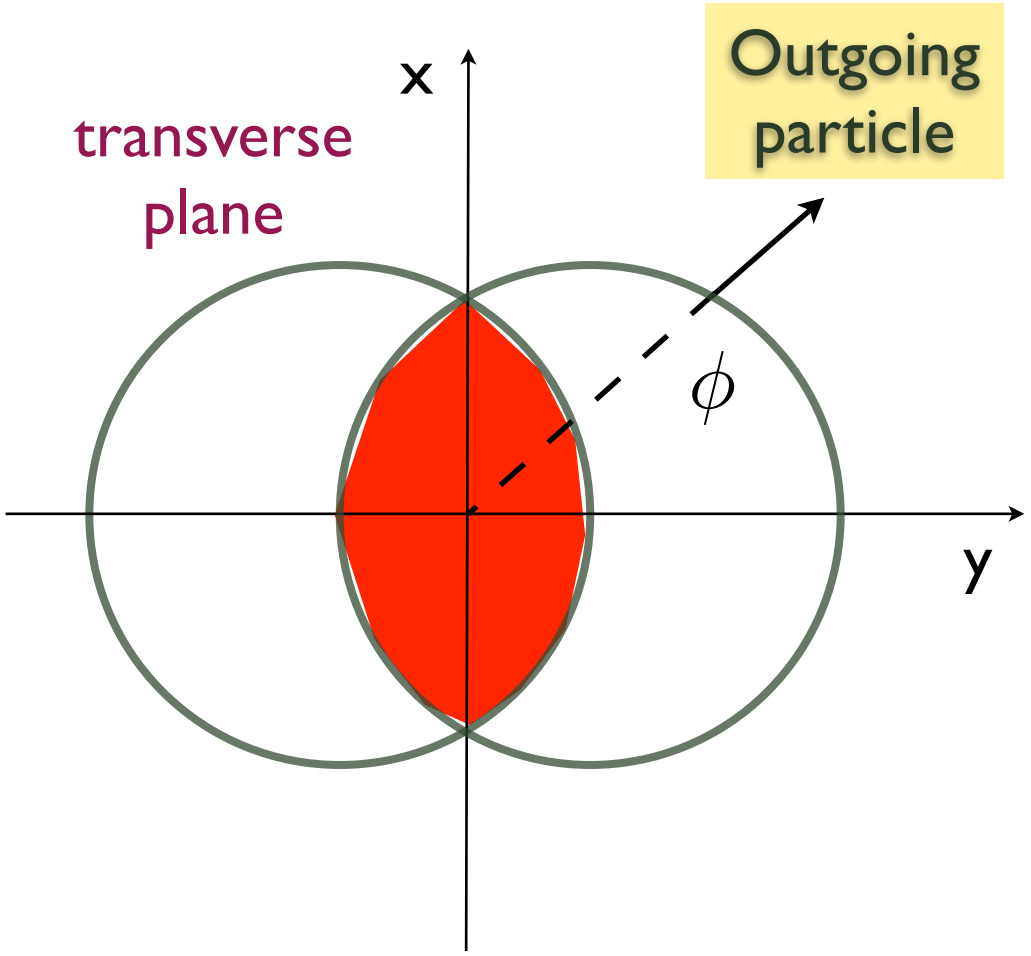
Most of the theoretical progress in the last years:

- *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

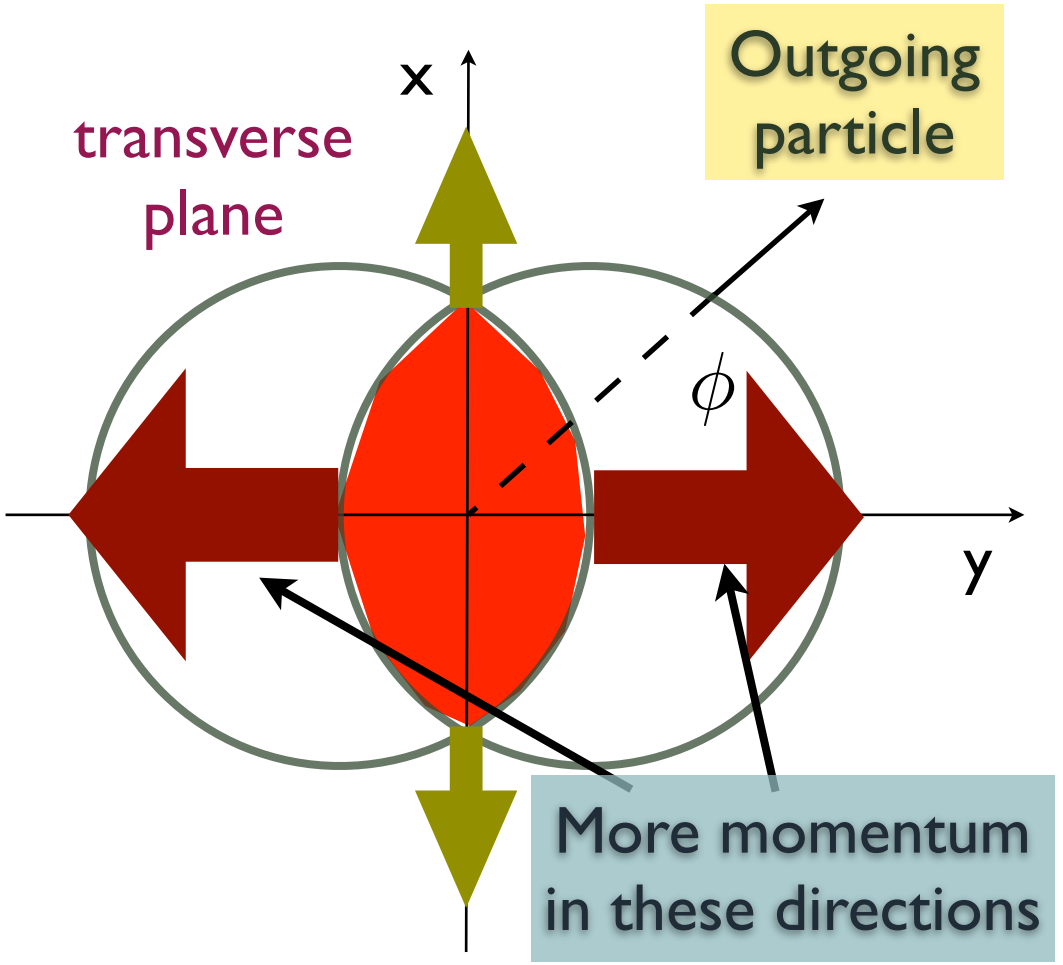
⇛ Recall the Euler equation

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

$$\epsilon = 3P \implies \nabla_x P < \nabla_y P$$

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

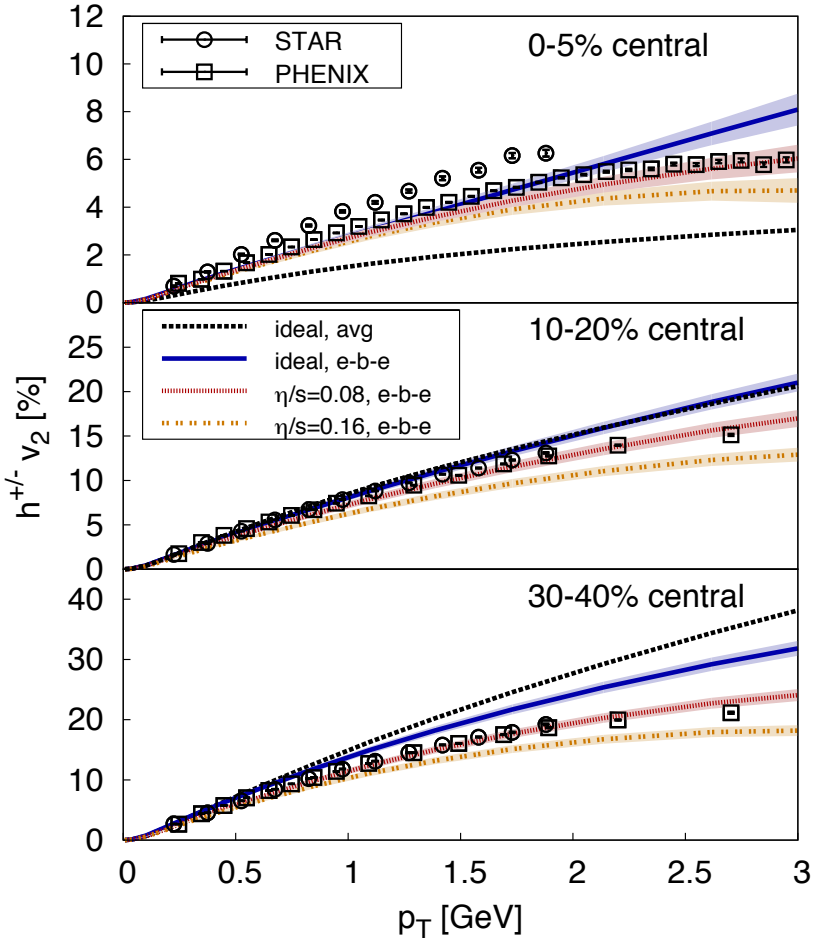
$$\frac{dN}{d\phi} \propto 1 + 2\, v_2 \cos(2\phi)$$

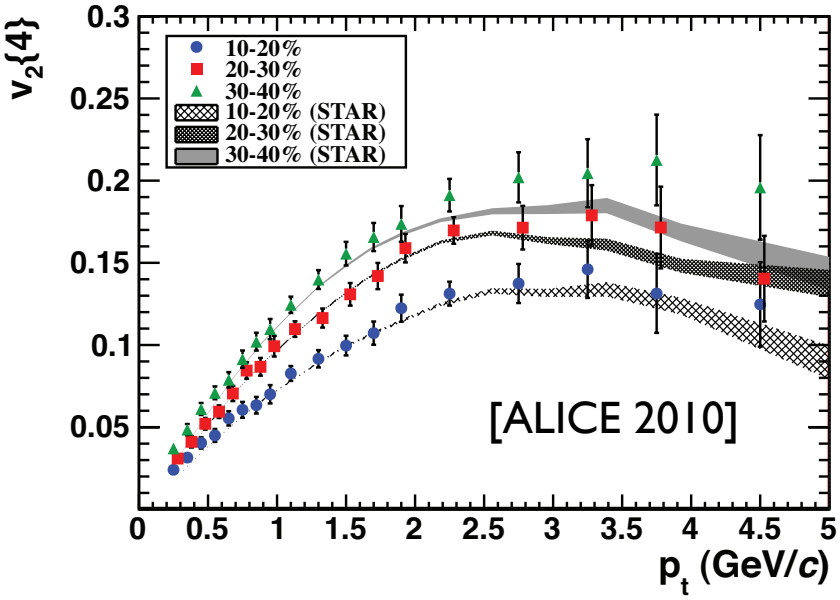


Initial anisotropies in spacial distributions translate into final (measurable) anisotropies in momentum

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]

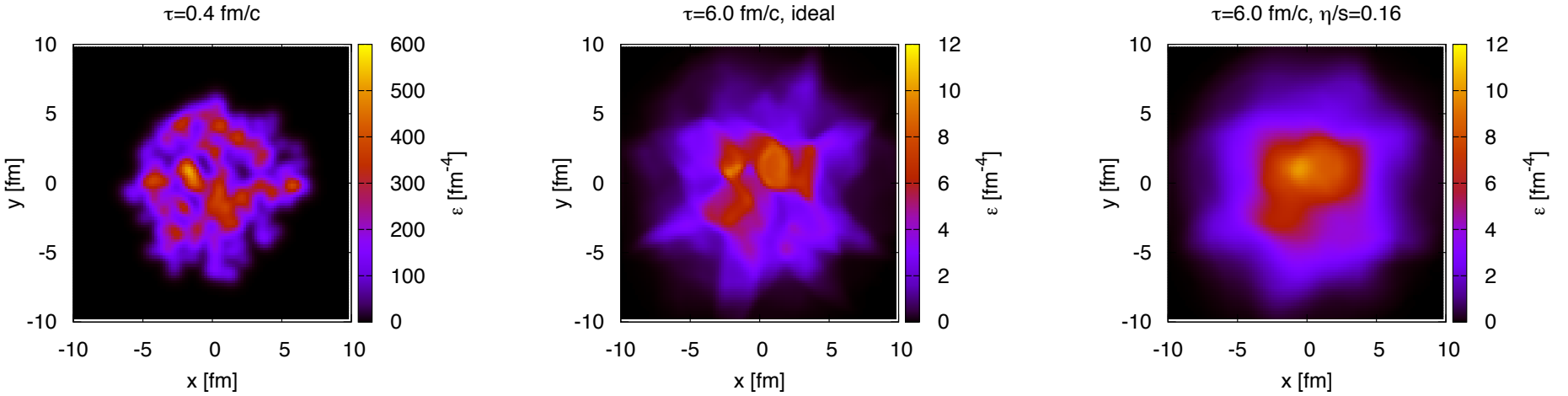
⇒ **LHC similar to RHIC**

Charm also flows

[ALICE: talk C. Perez Lara]

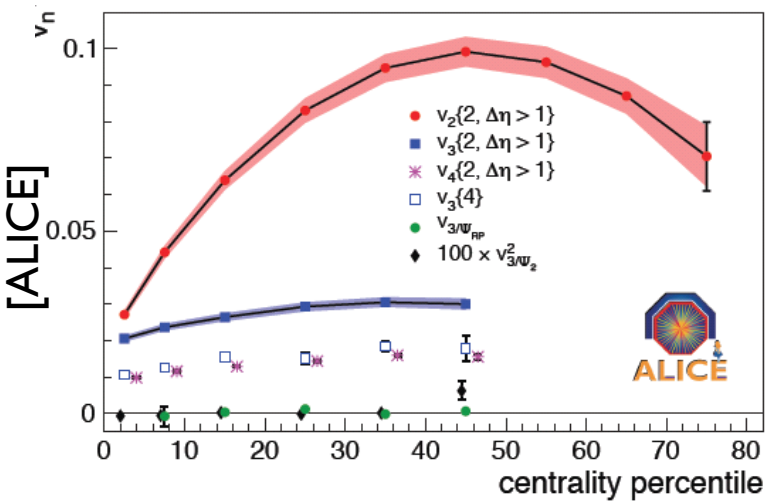
Higher harmonics v_n [talks M. Nyatha (ALICE), E. Duchovni (ATLAS) and S. Padula (CMS)]

⇛ Fluctuations in initial conditions show-up in higher harmonics



[Schenke, Jeon, Gale 2010]

Precise tests of hydro: constraints to viscosity



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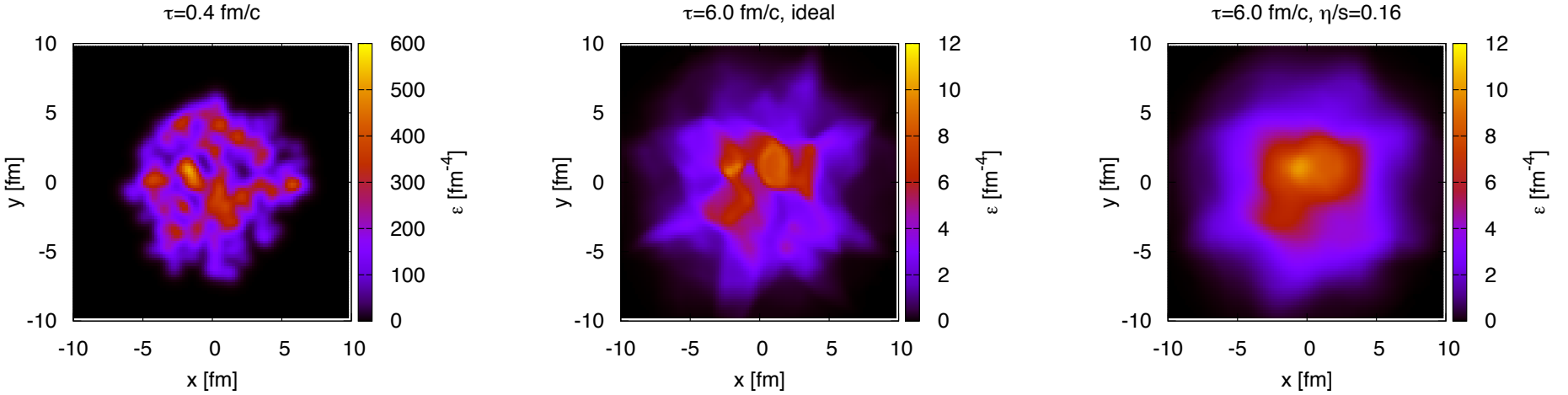

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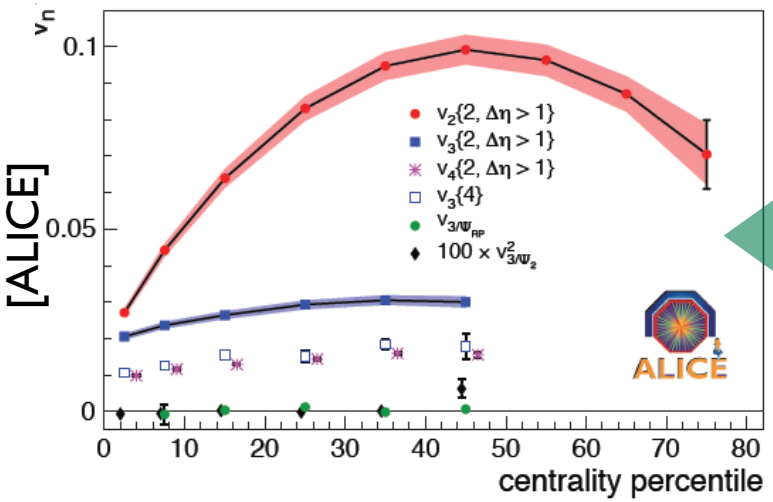
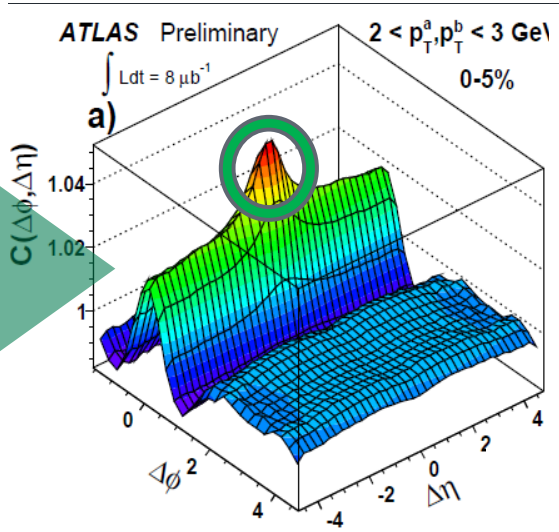
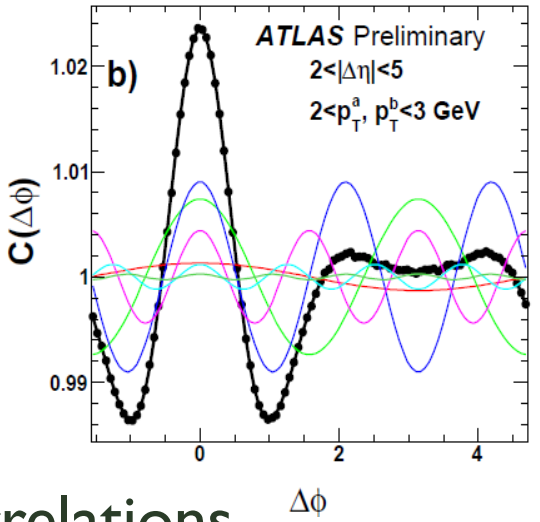


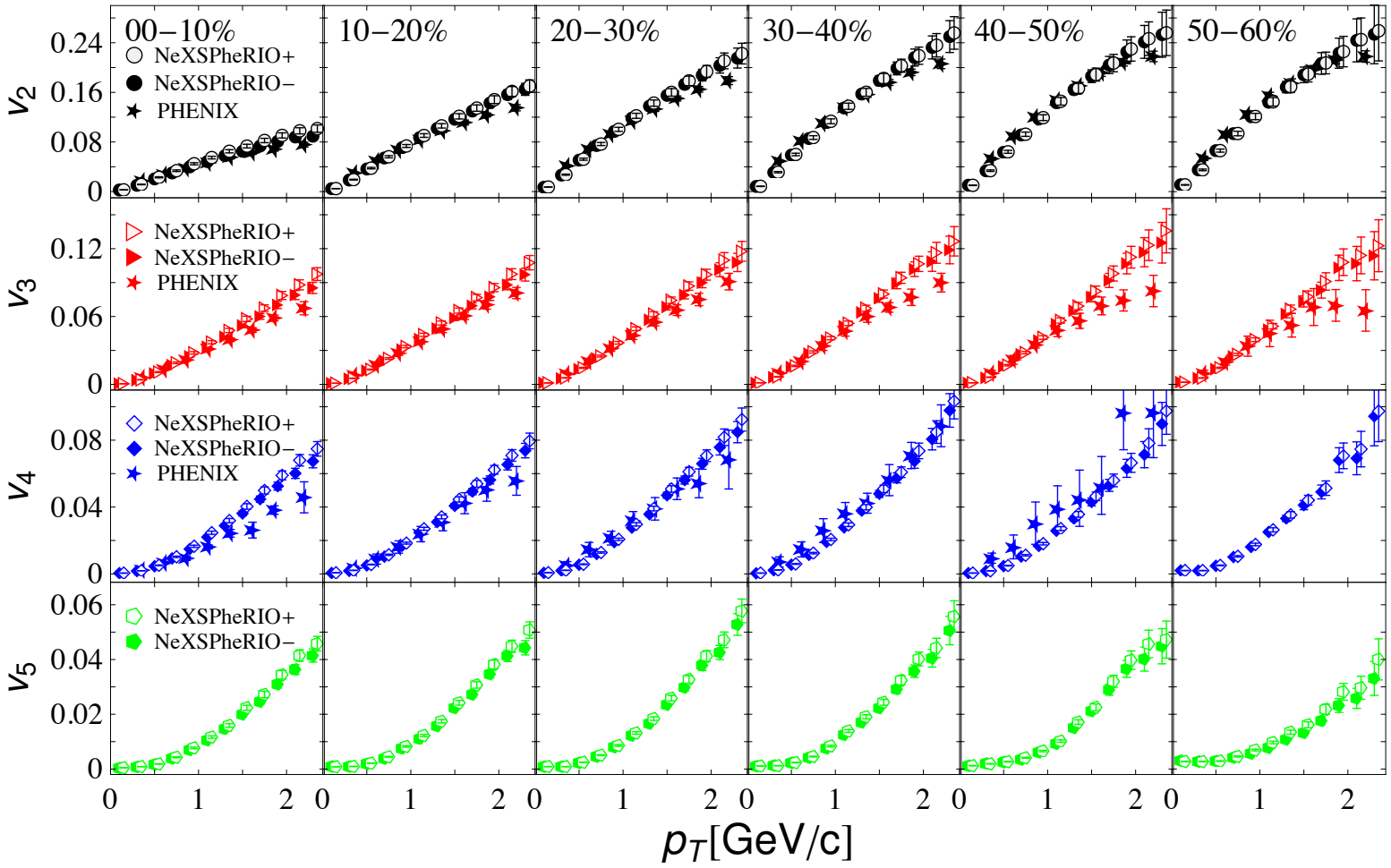




Consistency checks with 2-particle correlations

Higher harmonics v_n (RHIC)

[Gardim, Grassi, Luzum, Ollitrault 2012]



Remarkable theoretical description of the data

Hard Probes

Long distance terms modified by the presence of medium

- *Nuclear PDFs and new (non-linear) evolution equations*
- *Modification of hadronization probes the medium properties*
- *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

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Nuclear PDFs

Hadronization

J/Ψ paradigmatic example

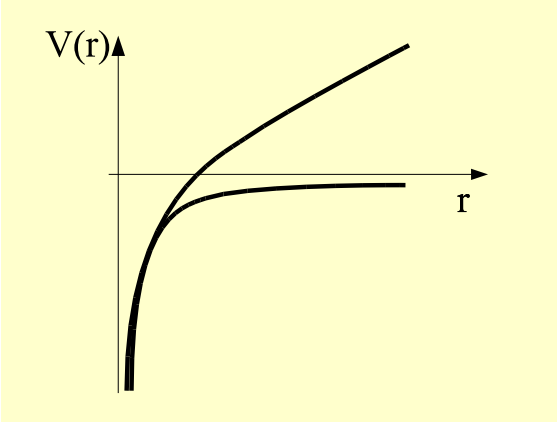
Background subtraction of "cold" nuclear matter effects

- *proto-nucleus needed: nuclear PDFs badly constrained at small-x*

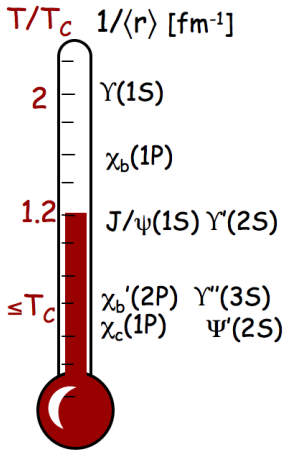
Quarkonia suppression

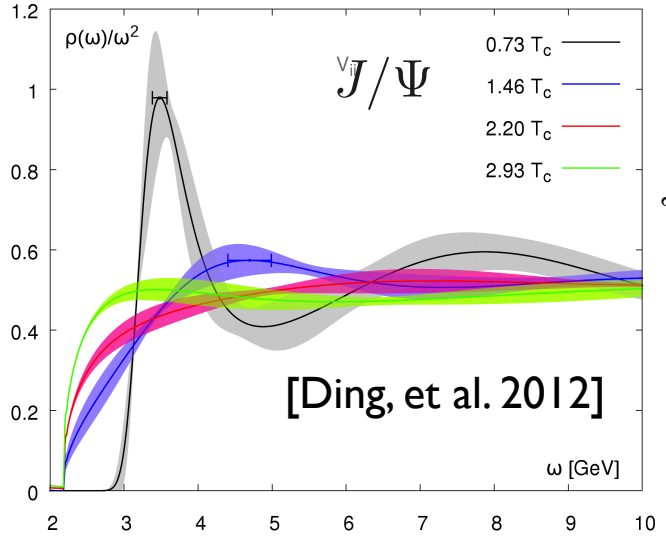
Simple intuitive picture [Matsui & Satz 1986]

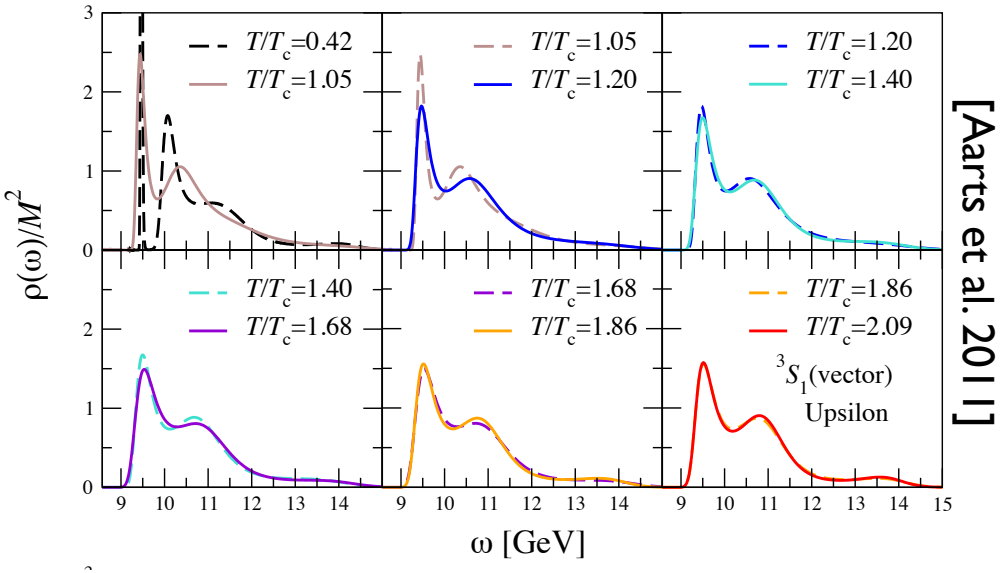
- *Potential screened at high-T*
- *Bound states not possible*
- *Suppression of J/Psi in nuclear collisions*
- *Sequential suppression of excited states*



Interpretation of the data traditionally difficult







Lattice results for spectral functions

Quarkonia at the LHC

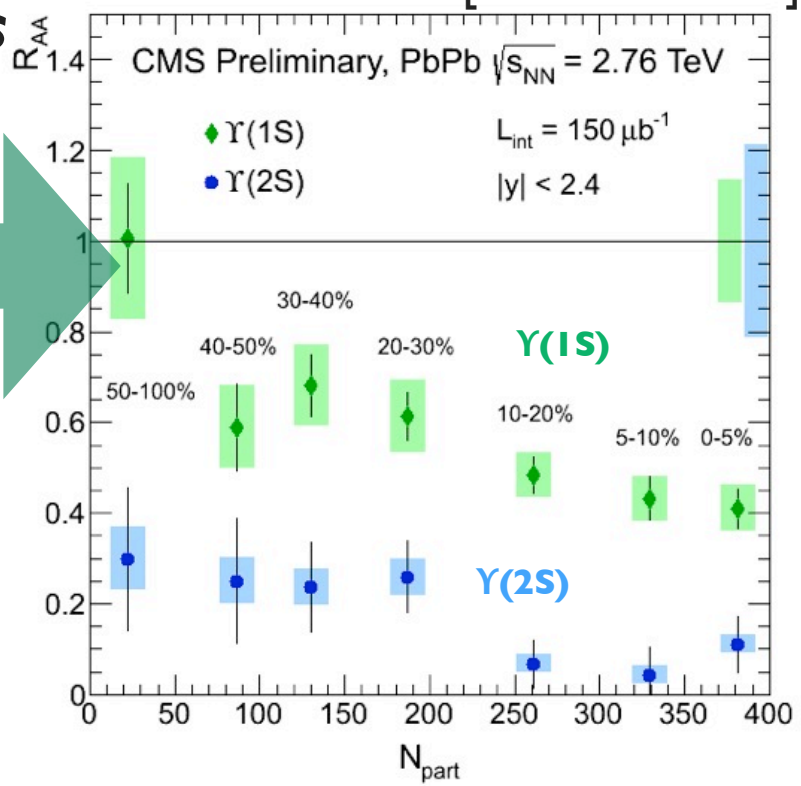
Larger suppression of excited states

$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07 \pm 0.02$$

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} < 0.17 \quad (95\%\ \text{C.L.})$$

Sequential suppression (lattice)?

[talk N. Leonardo]



[talk J-P Lansberg]

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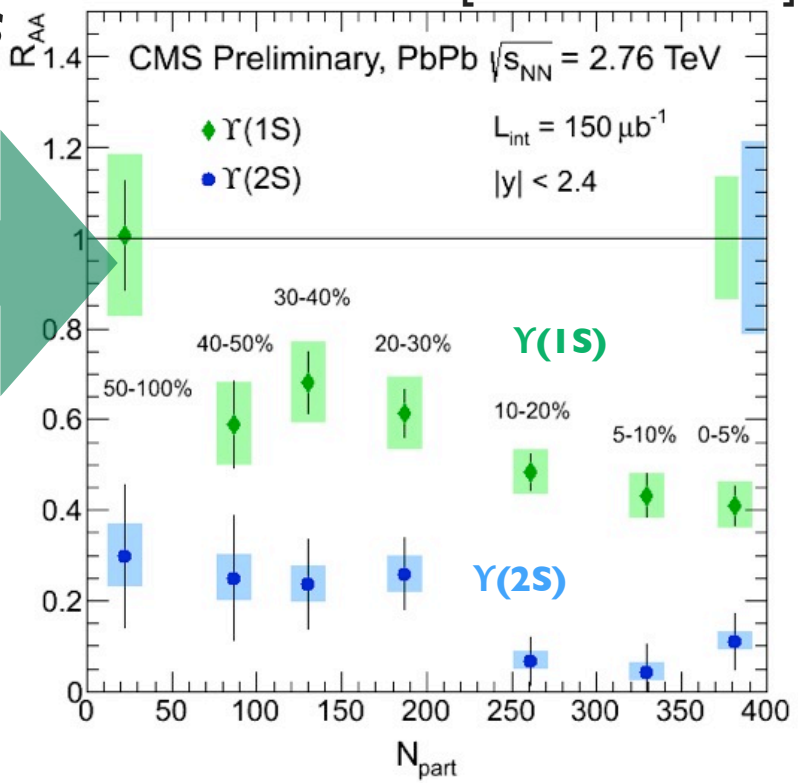
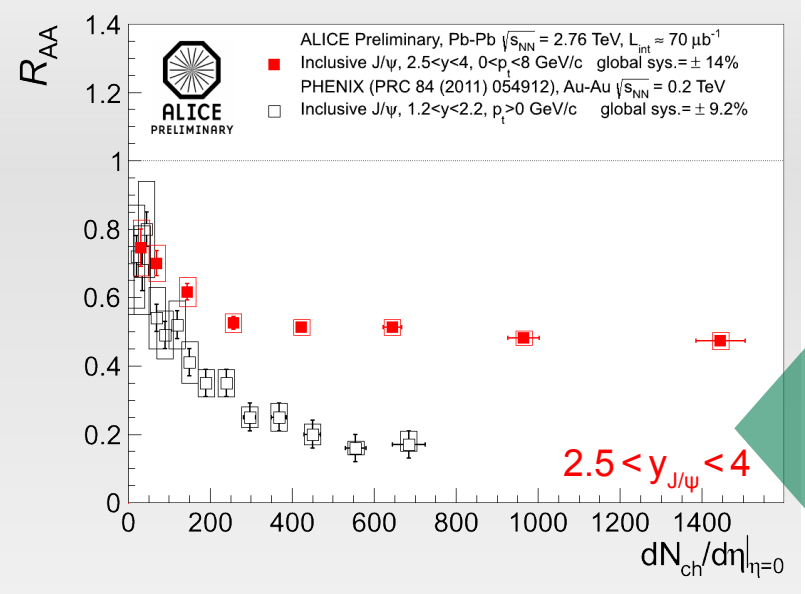
Larger suppression of excited states

$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07 \pm 0.02$$

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} < 0.17 \quad (95\%\ \text{C.L.})$$



Sequential suppression (lattice)?

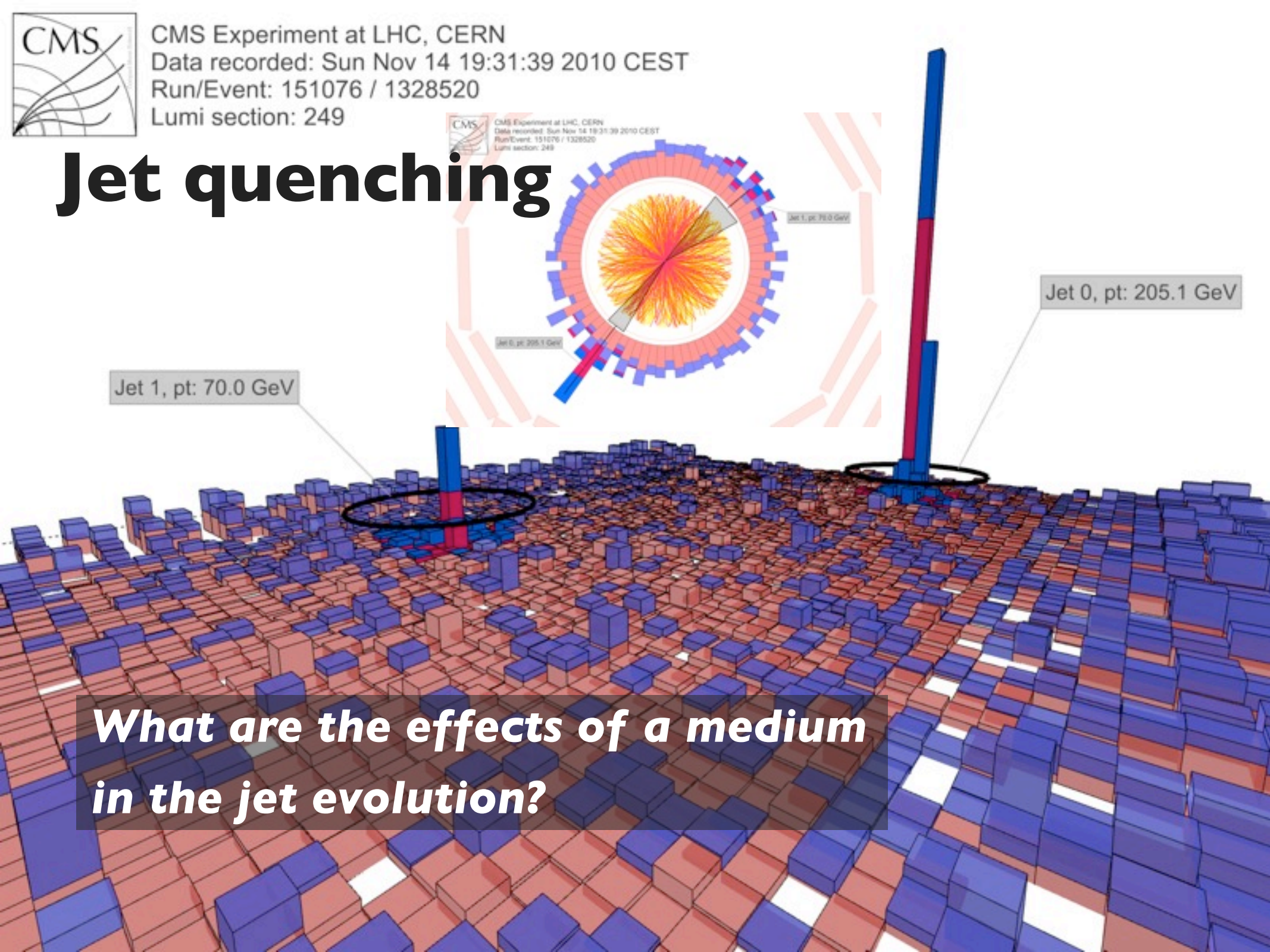


J/Psi less suppressed at the LHC than at RHIC?

Recombination?

A clearer picture is emerging, pPb data essential

[talk J-P Lansberg]

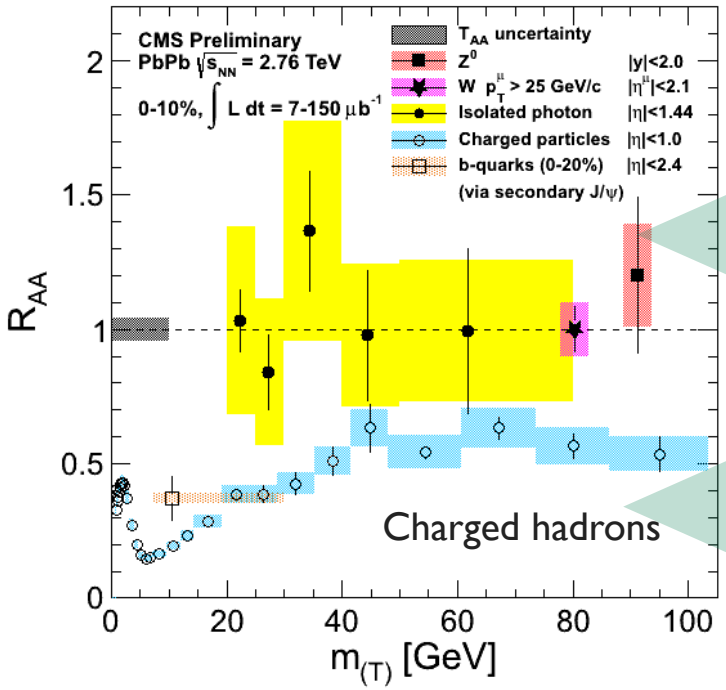


Jet quenching

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

Jet quenching with inclusive particles: LHC

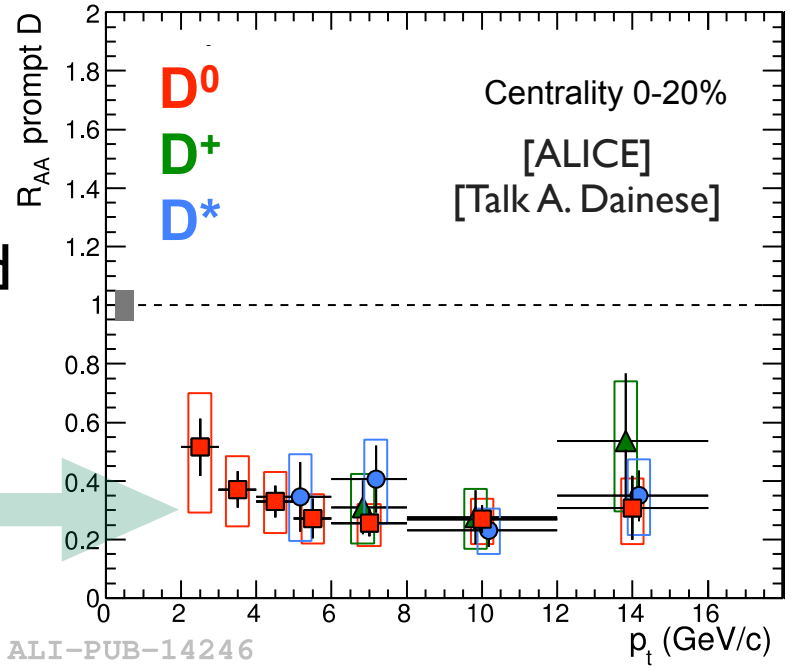
⇒ Suppression at the LHC is slightly stronger than at RHIC



EW probes not suppressed

[talk M. Klein]

Hadrons suppressed



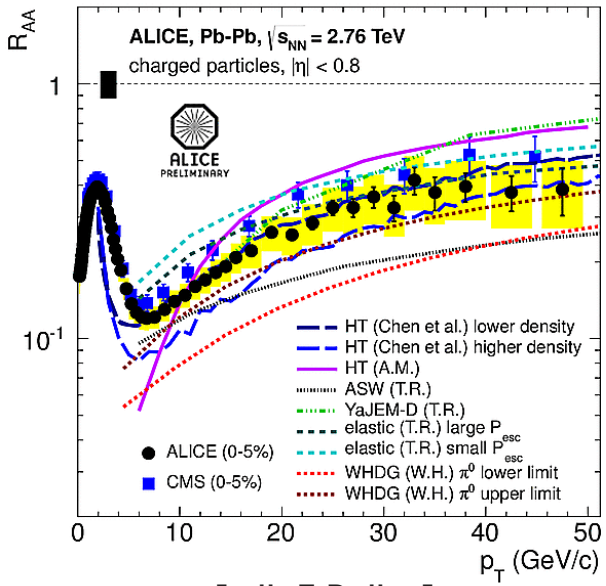
⇒ Formalisms tested at RHIC provides reasonable description

➘ **dense partonic system**

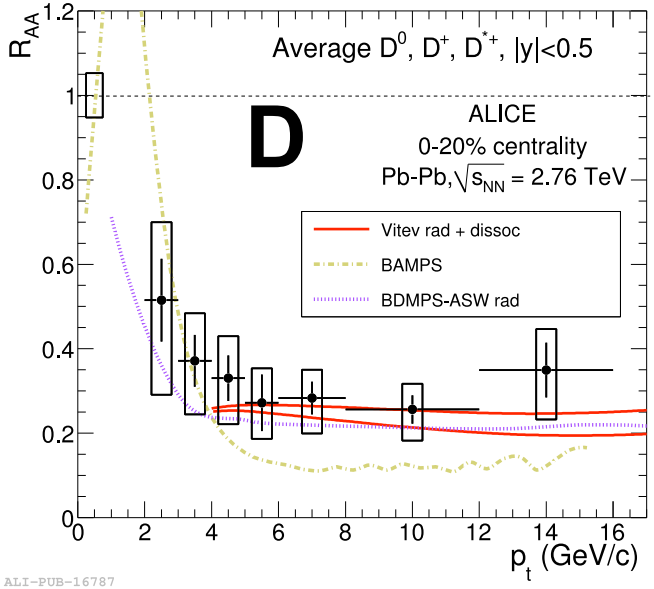
Inclusive particle suppression <u>sensitive to energy loss</u>

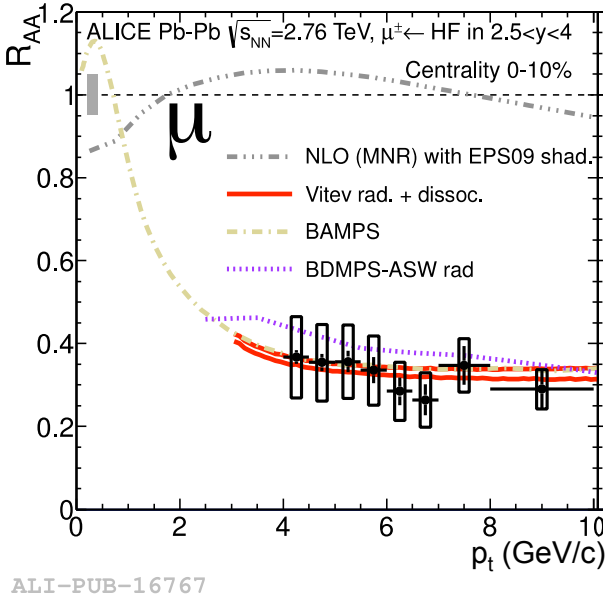
Jet quenching with inclusive particles: LHC

⇒ Suppression at the LHC is slightly stronger than at RHIC



[talk F. Bellini]





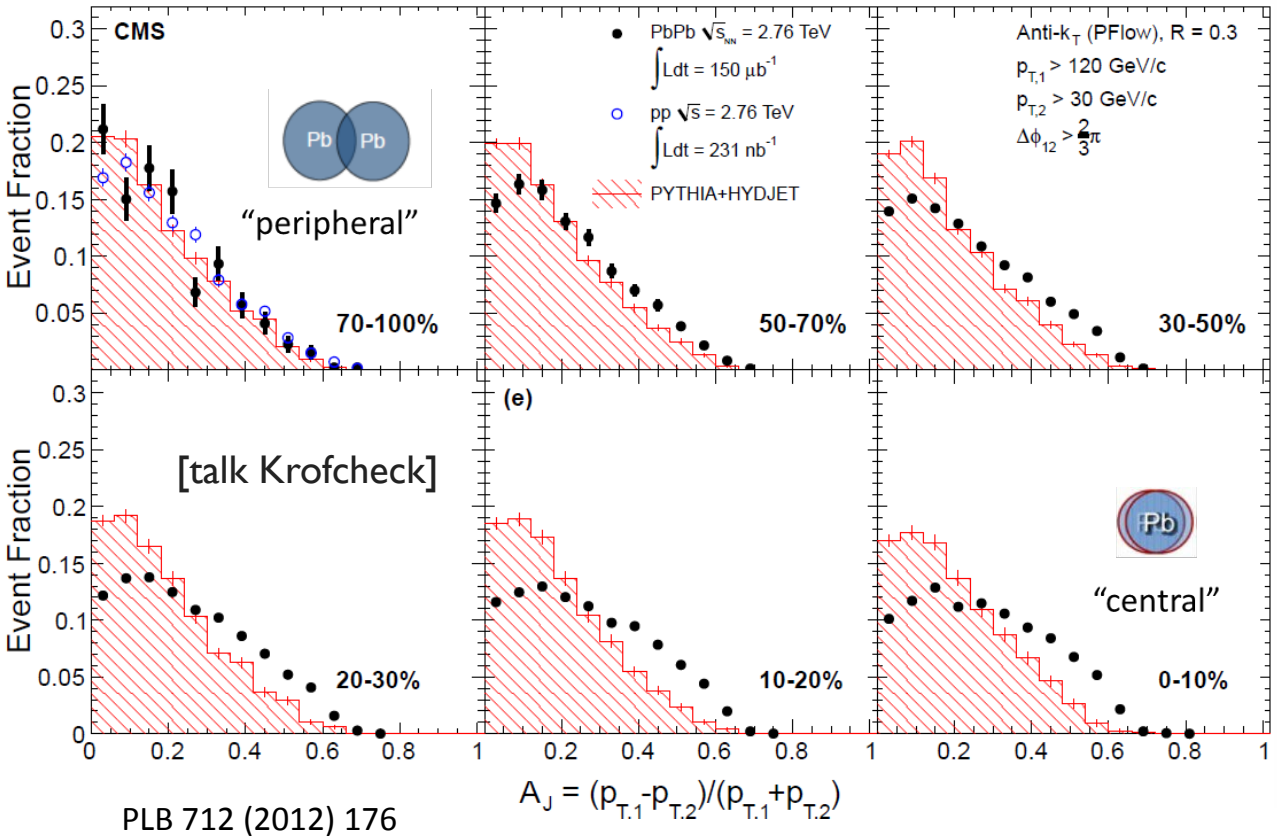
⇒ Formalisms tested at RHIC provides reasonable description

⇒ **dense partonic system**

Inclusive particle suppression <u>sensitive to energy loss</u>

Di-jet asymmetry at the LHC

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



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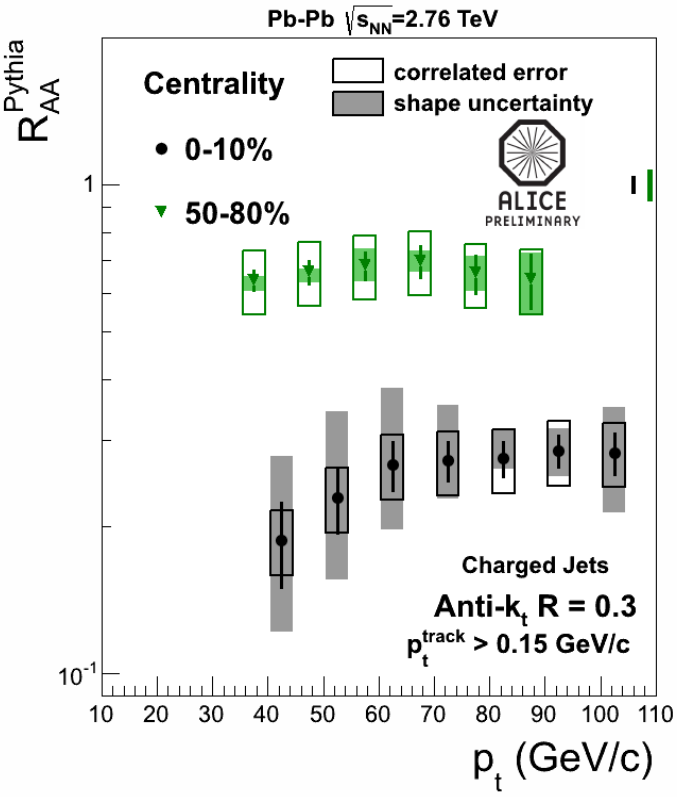


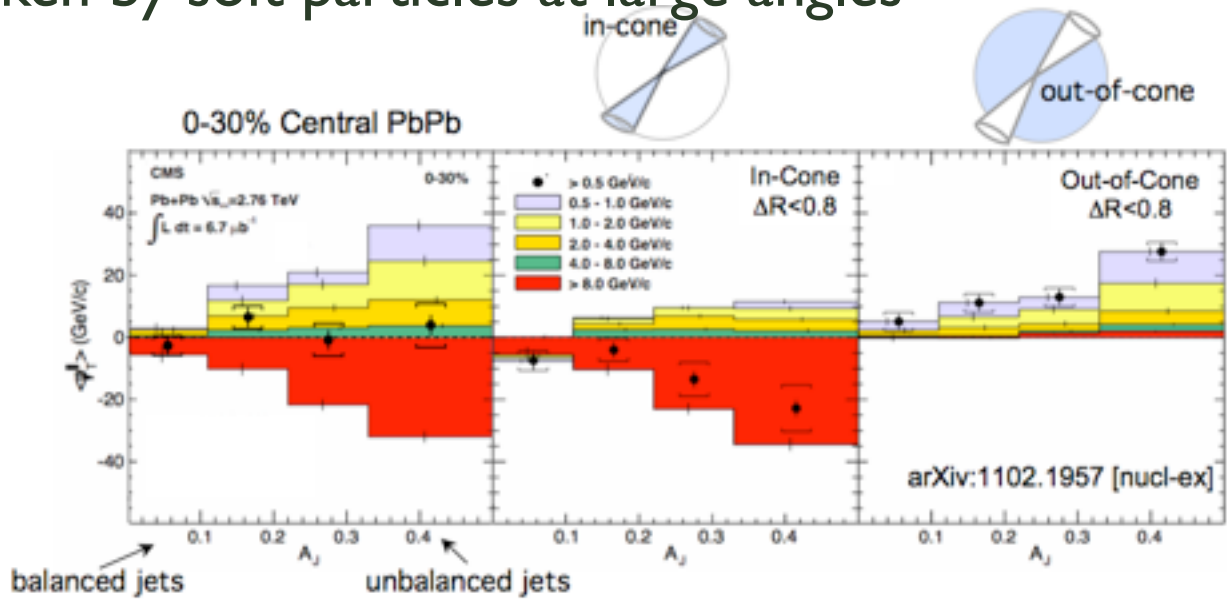
[ALICE - M.Verweij, HP2012]

⇛ Reconstructed jet measurements **sensitive to broadening**

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

Di-jet asymmetry at the LHC

⇛ Energy taken by soft particles at large angles



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

(My) summary of the experimental situation *(ALICE+ATLAS+CMS)*

- *Characterized jets are sub-samples of the total (jets are suppressed: inclusive jet RAA)*
- *Energy loss of the jets taken by soft particles at large angles (dijet analyses)*
- *No modification of dijet azimuthal correlations or fragmentation function (dijet analyses)*
- *Photon-jet qualitatively agree with this picture*

[ATLAS, talk Etzion]

The standard mechanism:

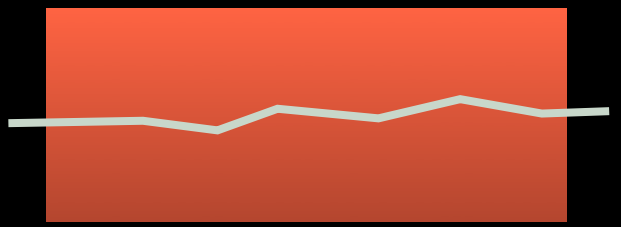
Medium-induced gluon radiation

A highly energetic quark or gluon traversing a medium can

A. Rotate color

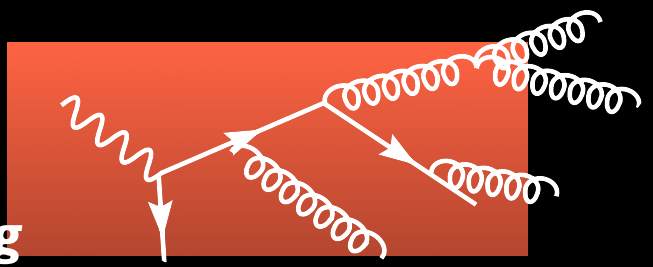
B. Change direction (kicks in transverse plane)

C. Lose energy by collisions



Asymptotically A >> B >> C

- ***Radiation dominates energy loss***
- ***Jet parton shower modified: broadening***



Medium-induced radiation: role of color coherence

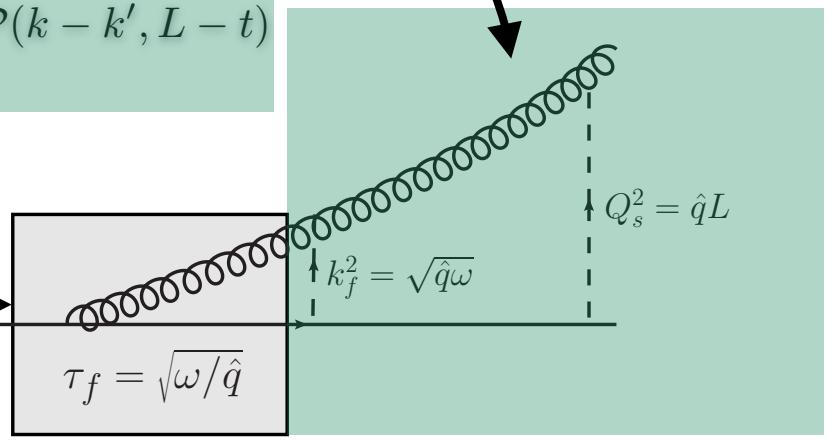
⇒ Medium-induced radiation off a single quark/gluon (dense medium)

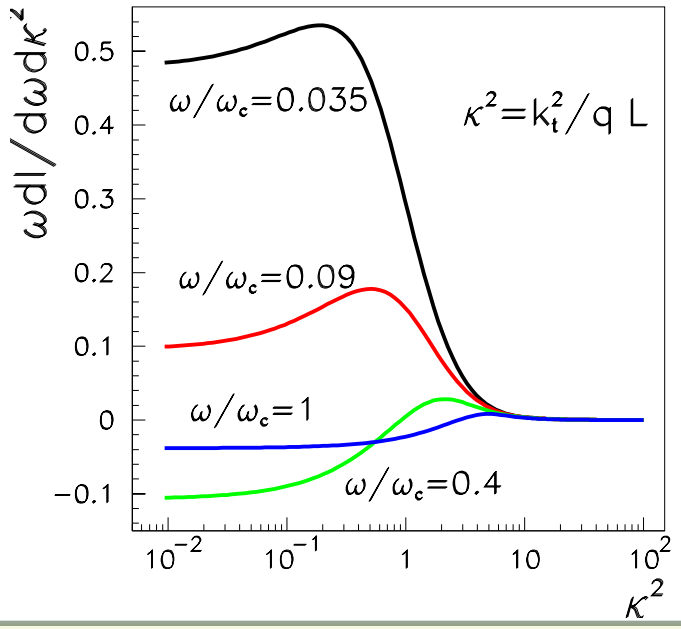
$$\mathcal{R}_q \simeq 4\omega \int_0^L dt \int \frac{d^2k'}{(2\pi^2)} \sin\left(\frac{k'^2}{2\sqrt{\hat{q}\omega}}\right) \exp\left(-\frac{k'^2}{2\sqrt{\hat{q}\omega}}\right) \mathcal{P}(k-k', L-t)$$

[Mehtar-Tani, Salgado, Tywoniuk 2012]

Classical broadening

Quantum emission during decoherence time





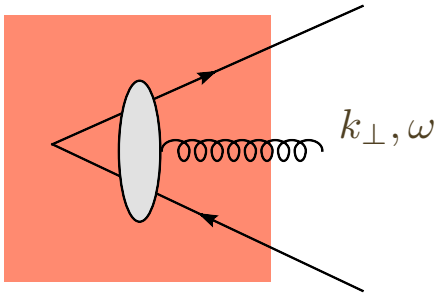
Medium length vs formation time

- *Radiation suppressed for $t_{form} > L$ (LPM suppression)*
- ***Spectrum IR and collinear finite***
- *Complete parton shower still unknown*

[Baier-Dokshitzer-Mueller-Peigne-Schiff, Zakharov and many others...]

Medium-induced radiation: role of color coherence

⇛ Subsequent emissions: **the antenna as a laboratory**



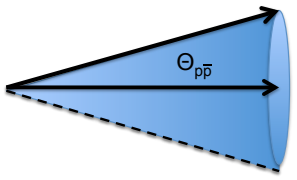
Color coherence of qqbar pair survival probability
(no color rotation)

$$\Delta_{\rm med} = 1 - \exp\left\{-\frac{1}{12}\hat{q}\theta_{q\bar{q}}^2 t^3\right\}$$

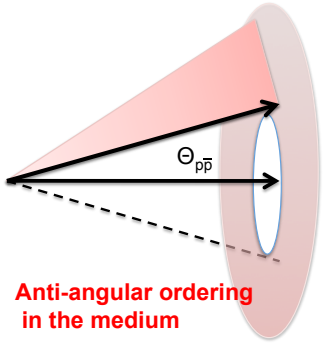
⇛ Defines time above which emitters are color decorrelated $\tau_d \sim \left(\frac{1}{\hat{q}\theta_{q\bar{q}}^2}\right)^{1/3}$

Total decoherence when $L > \tau_d$

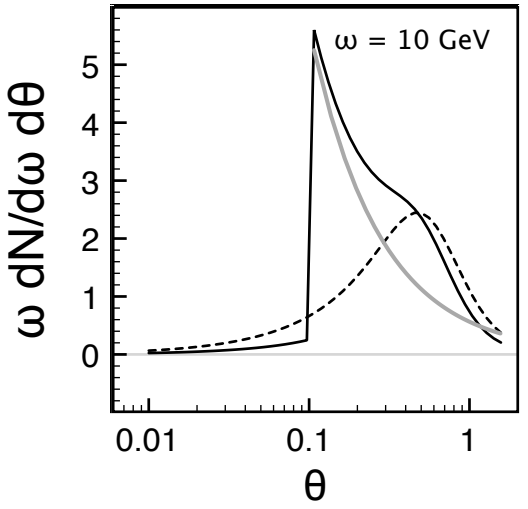
- *Enhances phase space for radiation (antiangular ordering)*
- *Total decoherence: two independent emitters*



Angular ordering in vacuum



Anti-angular ordering
in the medium

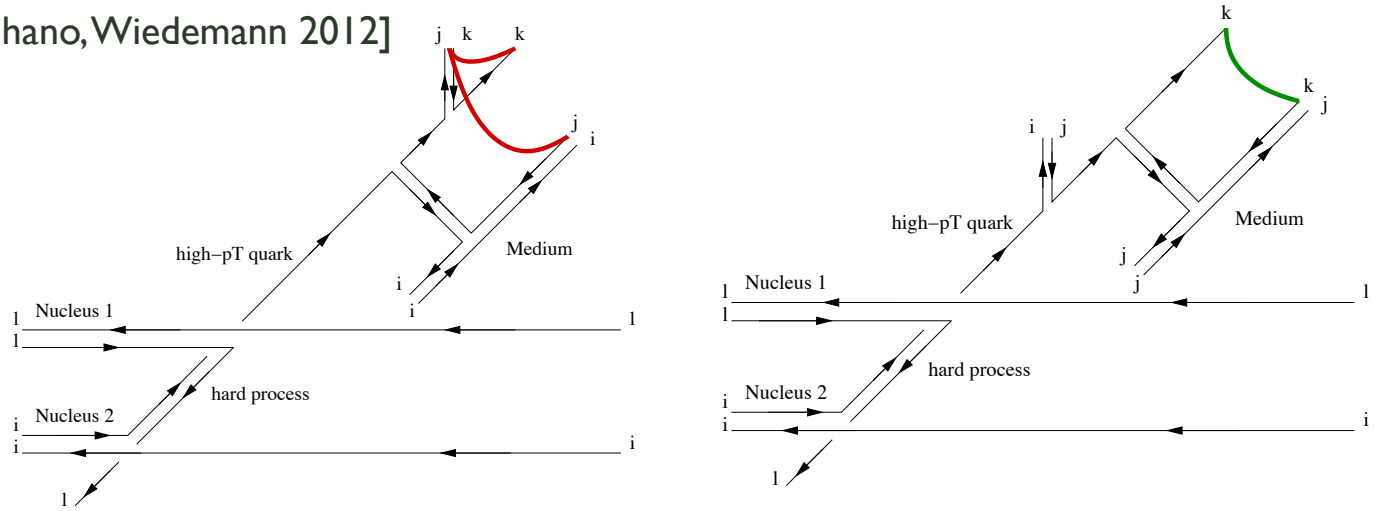


Total decoherence
Independent radiation

More theoretical developments, mostly work in progress

Color rotation with the medium changes jet color flow

[Beraudo, Milhano, Wiedemann 2012]



Role of finite kinematics studied in MCs

Jewell, Q-Pythia, Martini, YAJEM, Pyquen, etc... Big effort in developing a MC for jet quenching

First (very preliminary!) comp. of qhat in lattice *[Majumder]*

Strongly-coupled vs. quasiparticle *[D'Eramo, Lekaveckas, Liu, Rajagopal]*

$$\mathcal{P}(k_\perp) \sim \exp\left(-\#\frac{k_\perp^2}{T^3 L}\right) \longrightarrow \mathcal{P}(k_\perp) \sim \frac{1}{k_\perp^2}$$

Proton-nucleus at the LHC

LHC two-in-one magnet

- *Equal rigidity :: $p_{\mathrm{Pb}} = Z\, p_{\mathrm{proton}}$*

Estimated parameters for the 2012/2013 pPb run

- *Center of mass energy 5 TeV/A*
- *Integrated luminosity ~25 nb^{-1}*
- *Luminosity still* ***very uncertain***

Physics goals

- *Benchmarking: hard probes, Initial conditions, nuclear PDFs*
- *Study small-x region of the phase space (best experimental option before an eventual electron-ion collider)* [talk P. Newman]

Summary

With LHC new era also for nuclear collisions: TeV's

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

Created medium (RHIC+LHC) very dense ideal fluid

- *Very small viscosity - difficult to reconcile with weak-coupling*
- *Very large energy loss*
- *Jet measurements to characterize the medium parameters*
- *Knowledge on initial conditions essential : next pPb run*

Is it a liquid? Strongly coupled? Are quasiparticles the relevant d.o.f.? Mechanism of thermalization?