[Lecture 2]

Heavy Ions

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Building collectivity

The traditional direction in High Energy Physics — experimental conditions with the **highest possible degree of simplicity**

All particle content and interactions of the Standard Model discovered using this principle — greatest success of the reductionistic approach in Physics

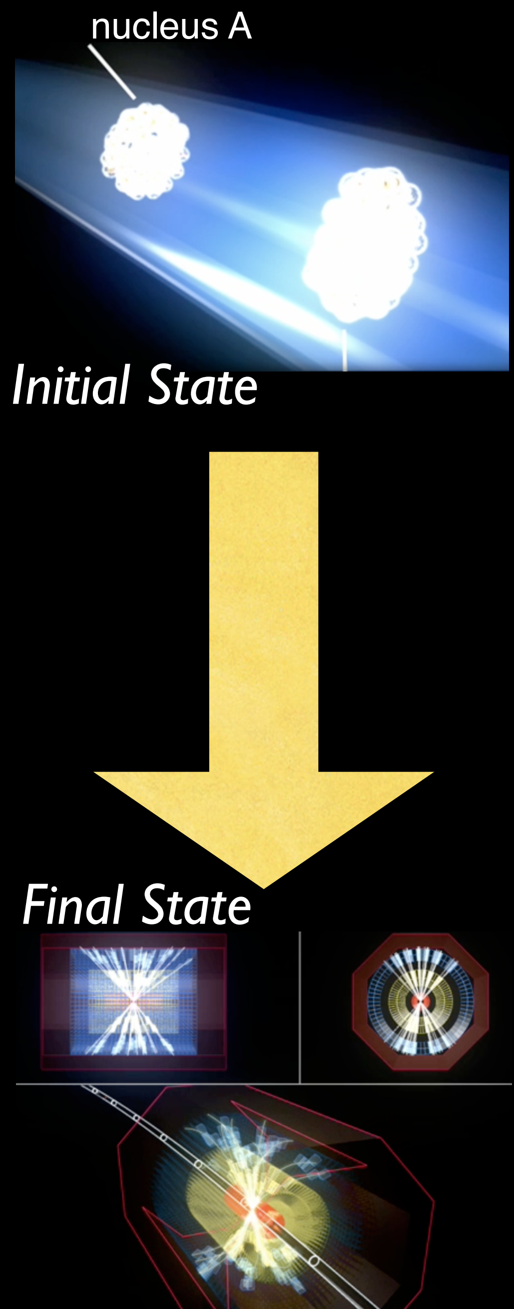
Also very successful — Complex systems with emerging behavior
[Strongly-coupling many body systems; quantum entanglement with many d.o.f…]

The region of transition between these two regimes is, however, largely unknown

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments

QCD is the only sector of the SM where the **exploration of the first levels of complexity,** built from fundamental interactions at the quantum level, is **experimentally feasible**

Some of the questions accessible with heavy-ion collisions



What is the structure of the initial stages?

- *color coherence effects in the small-x partonic wave function*
- *Fix* ***out-of-equilibrium*** *initial stages with well-controlled theoretical framework*

Is the created medium thermalized? How?

- *presence of a hydrodynamical behavior and* ***thermalization time***
- *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?*

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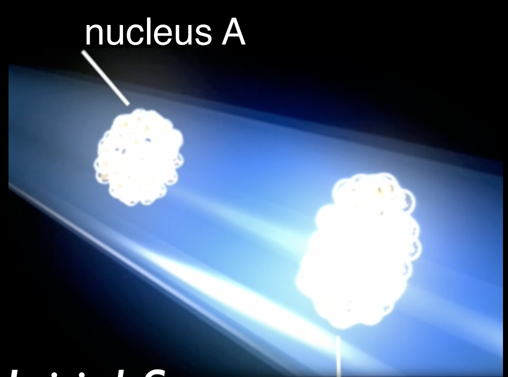
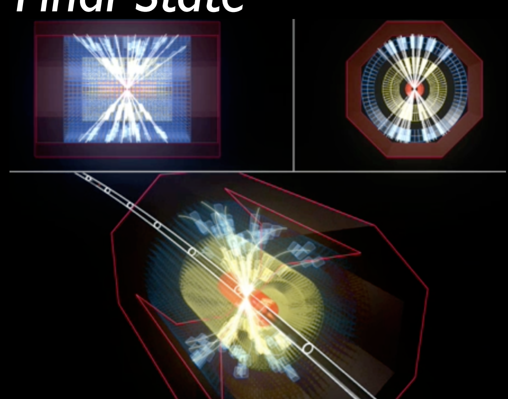


Initial State

Final State



First ~10 yoctoseconds

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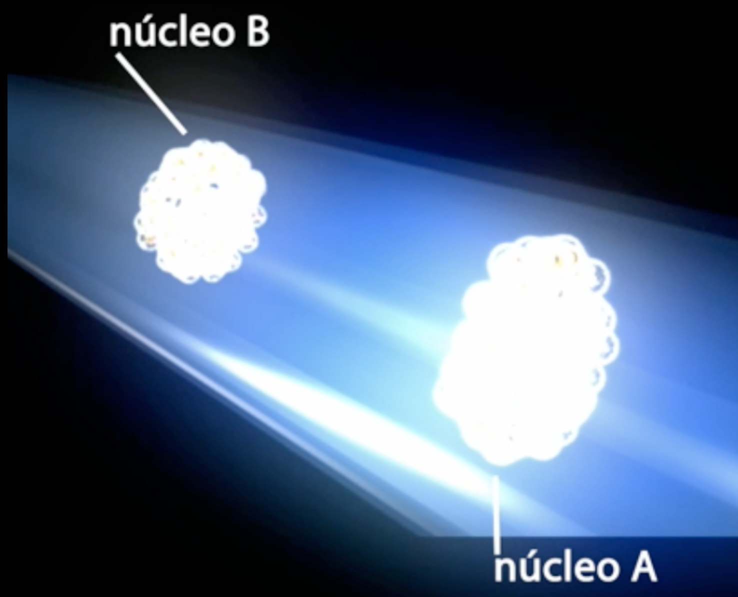


Initial state
Partonic densities
&
Multiparticle Production

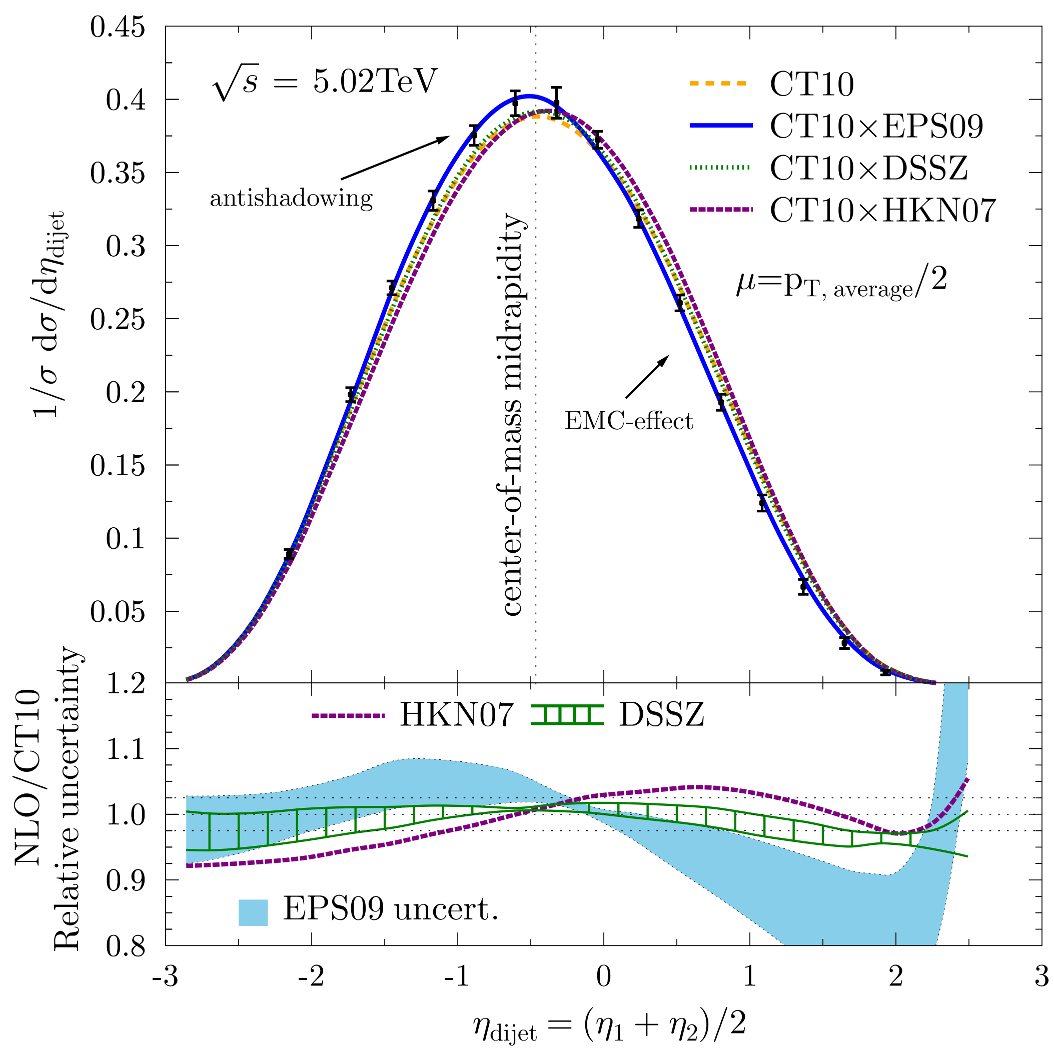
Processes with large virtualities will probe the inner part of the nucleons as usual — nuclear PDFs — **Dilute regime**

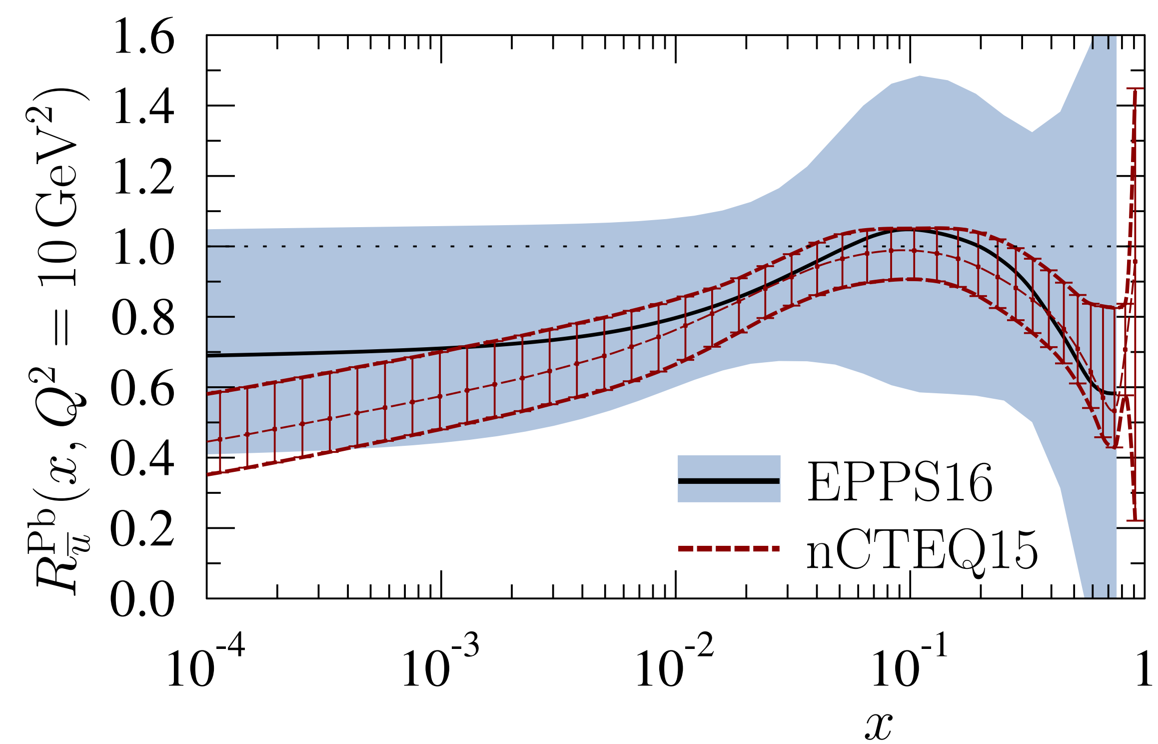
At smaller scales, however, the partons are densely packed — **Dense regime** — this regime **determines the production of the dense system**

Dilute regime

Nuclear PDFs extracted from global fits / DGLAP

- New constraints from the proton-lead runs at the LHC





[Eskola, Paukkunen, Paakkinen, Salgado 2016]

Excellent description of pPb data — needed as benchmark for QGP effects

- Everything you have learnt with Matteo Cacciari applies here… (with less statistics)

From Dilute to Dense

Parton Saturation

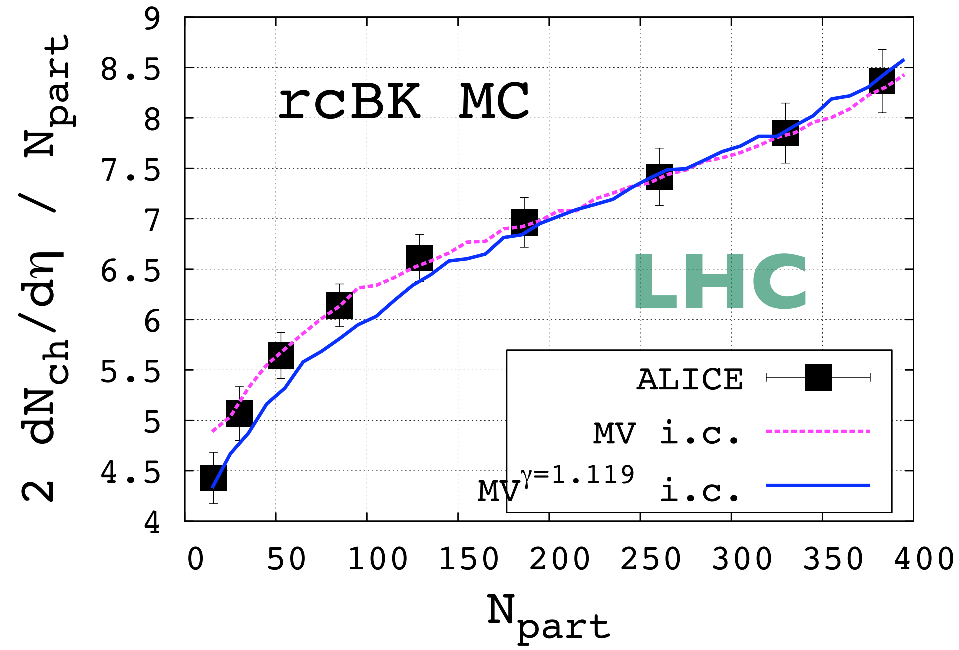
Color Correlation in the transverse plane $\rightarrow 1/Q_{sat}$

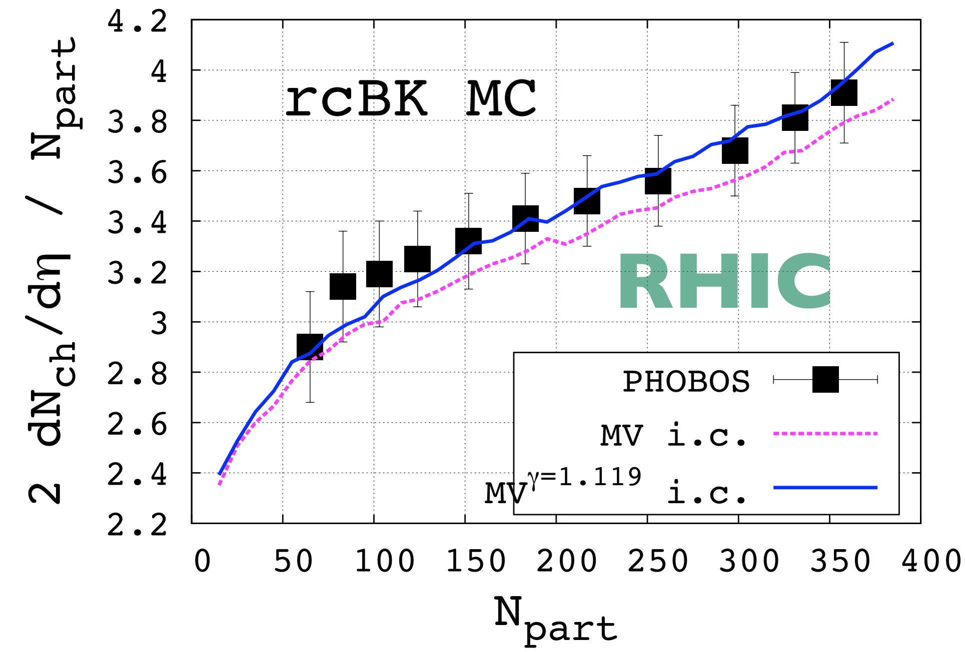
Color Glass Condensate $\rightarrow$ General framework

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

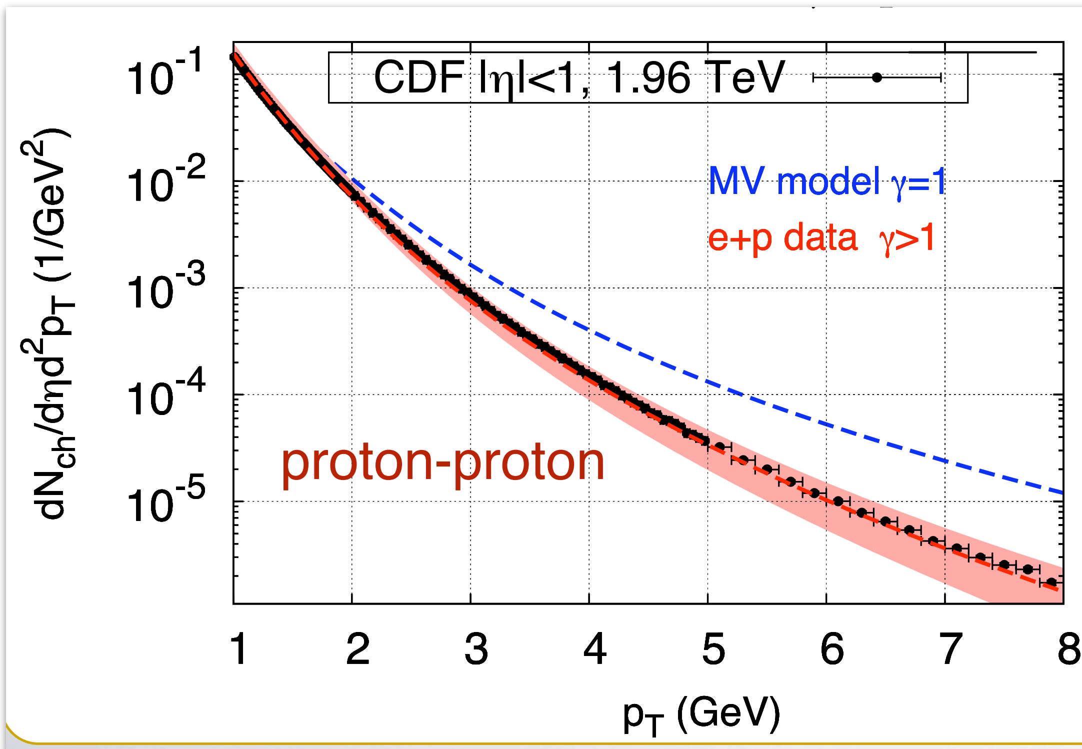
Multiparticle production

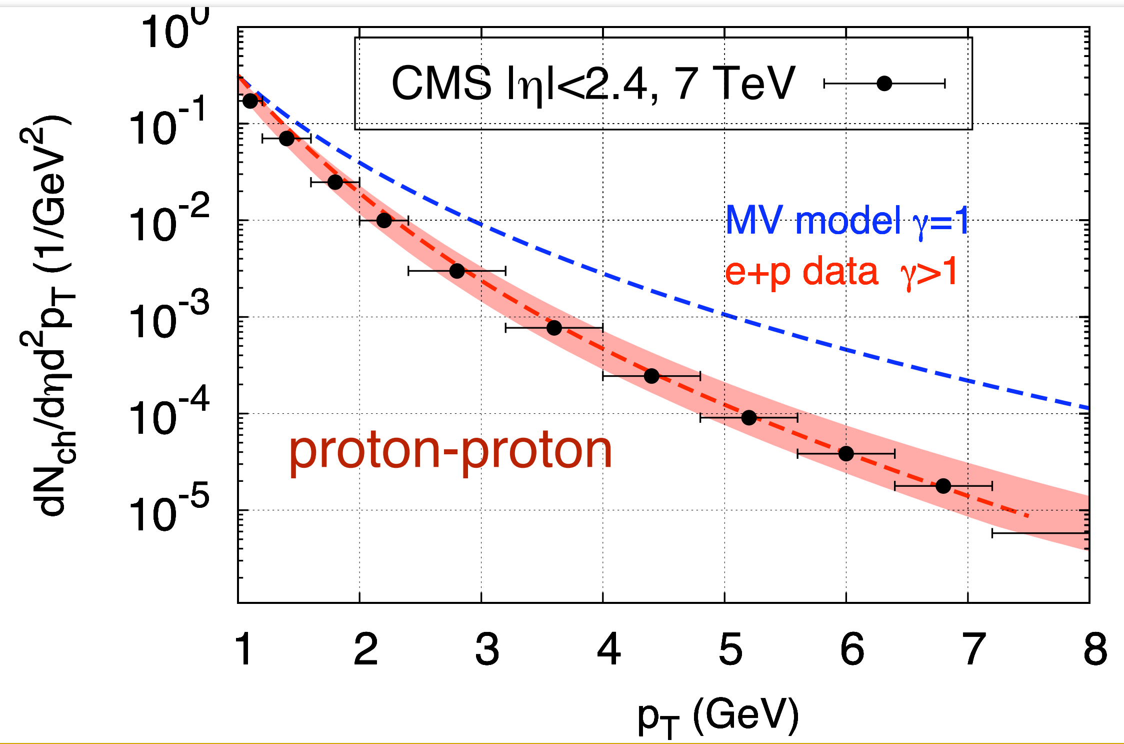
[Albacete, Dumitru 2011]



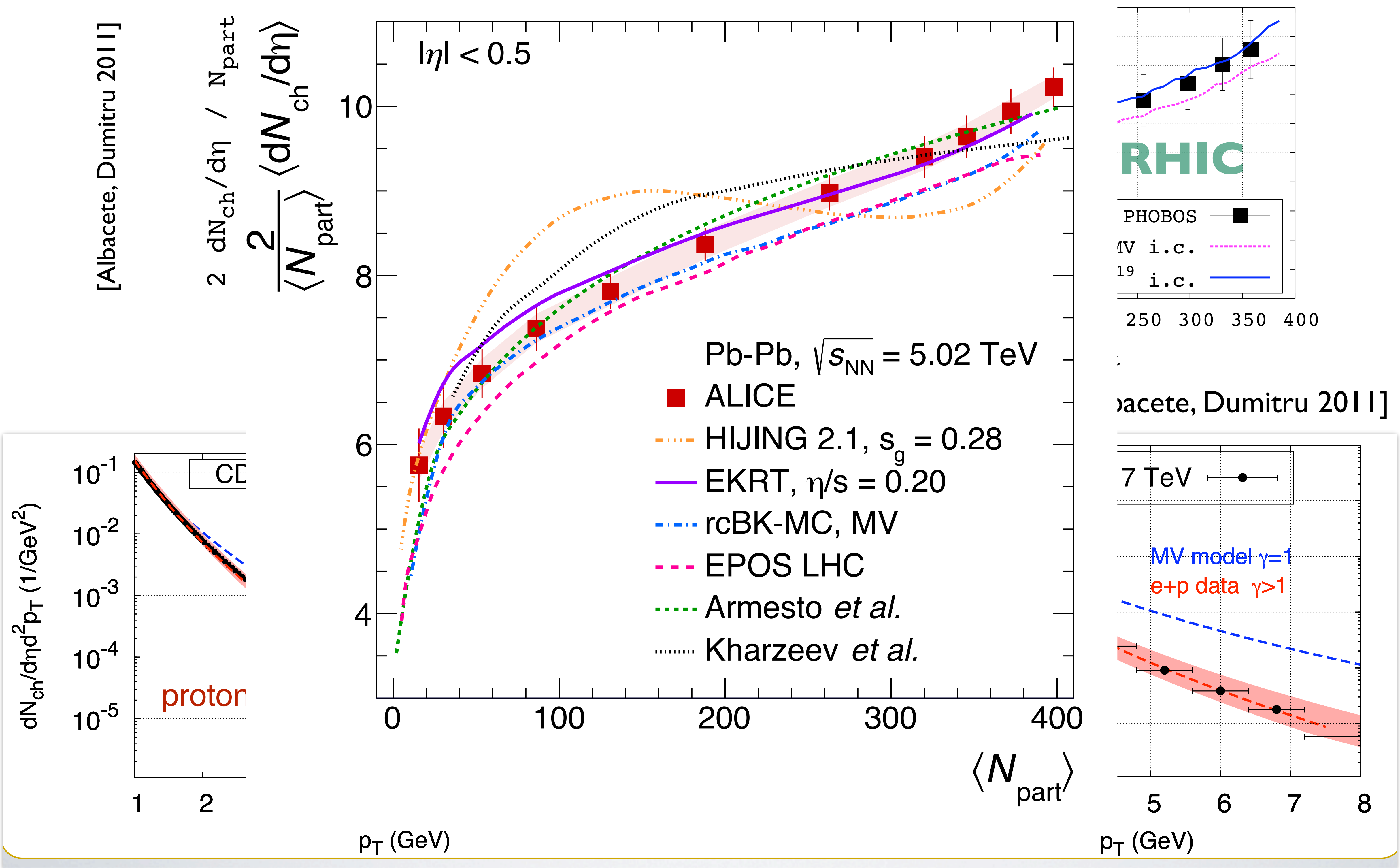


[Albacete, Dumitru 2011]





Multiparticle production



Glasma picture

High occupation numbers — can be described by **classical colour fields**

$$\left[D_\mu, F^{\mu\nu}\right] = J_1^\nu + J_2^\nu$$

Where J_1^ν, J_2^ν are sources given by the fast modes of the nuclei.

Anisotropic "pressure" in the energy momentum tensor at $\tau = 0$

— out of equilibrium system —

Hydro indicates (from data) that a very fast thermalization takes place **— How?**

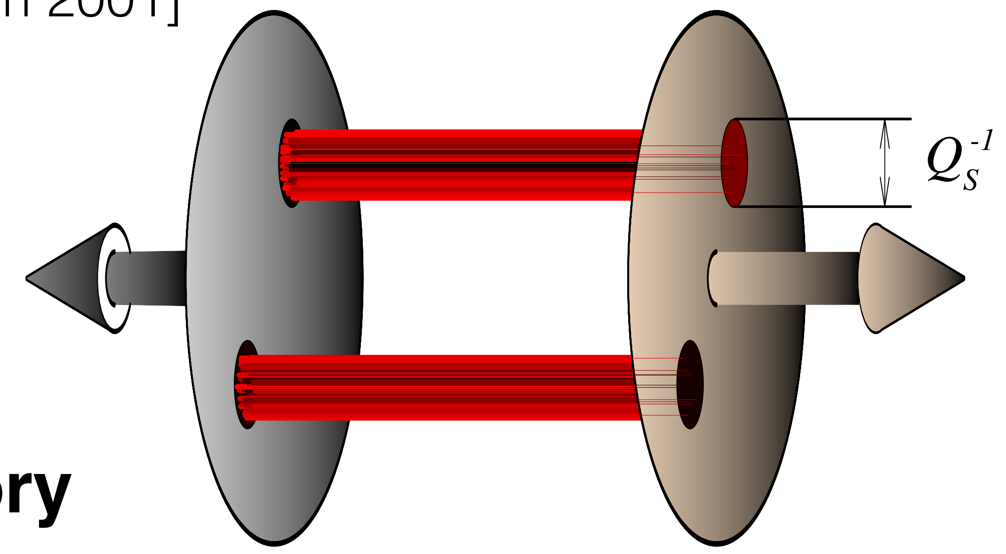
Bottom-up thermalization [Baier, Mueller, Schiff, Son 2001]

Classical fields parallel to beam axis at $\tau = 0$

Gluons with transverse momentum $\tau \sim 1/Q_{\rm sat}$

Gluons radiate a gluon bath

Interaction with the bath drives the system towards equilibration — **Effective kinetic theory**



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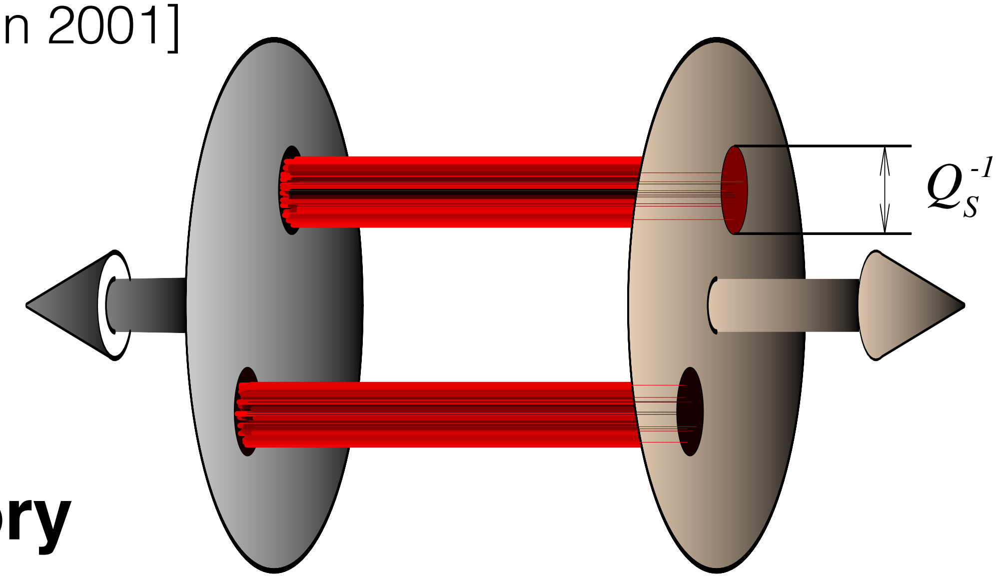


Hydrodynamics

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

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

(+ Equation of State)

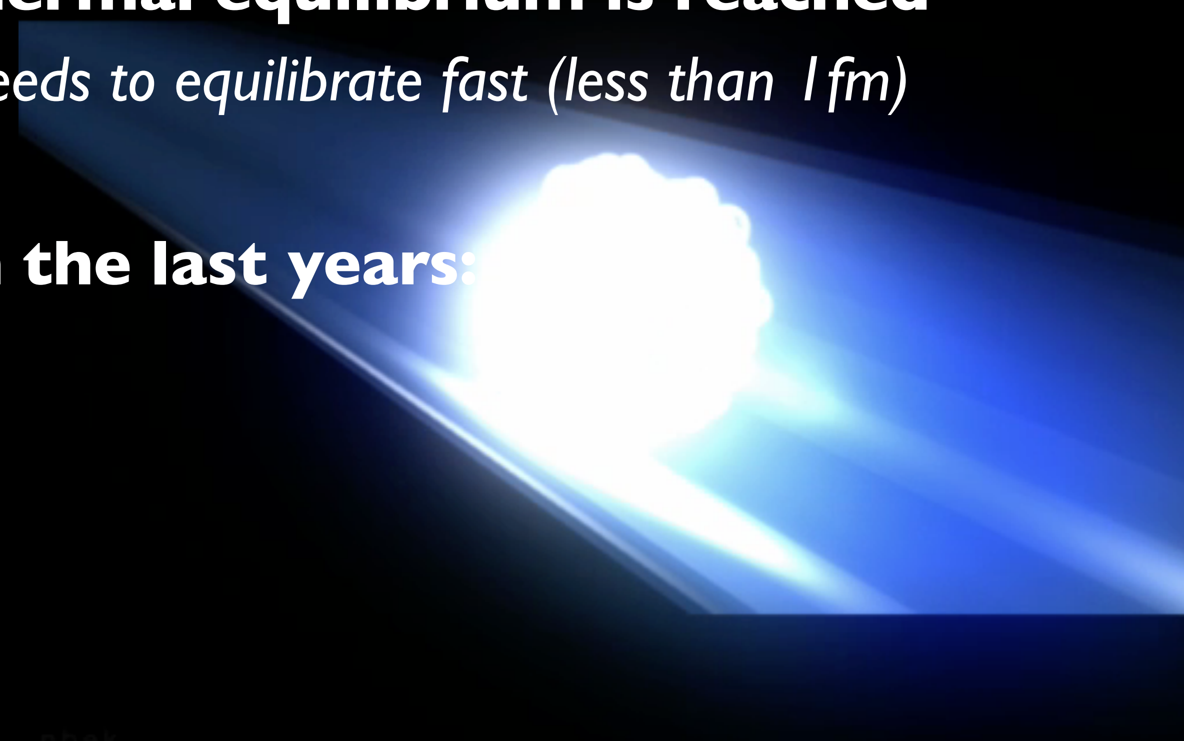
Does not address the question on **how thermal equilibrium is reached**

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

Most of the theoretical progress in the last years:

— *Viscosity corrections*

— *Fluctuations in initial conditions*



The golden measurement

Remember the Euler eq.

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

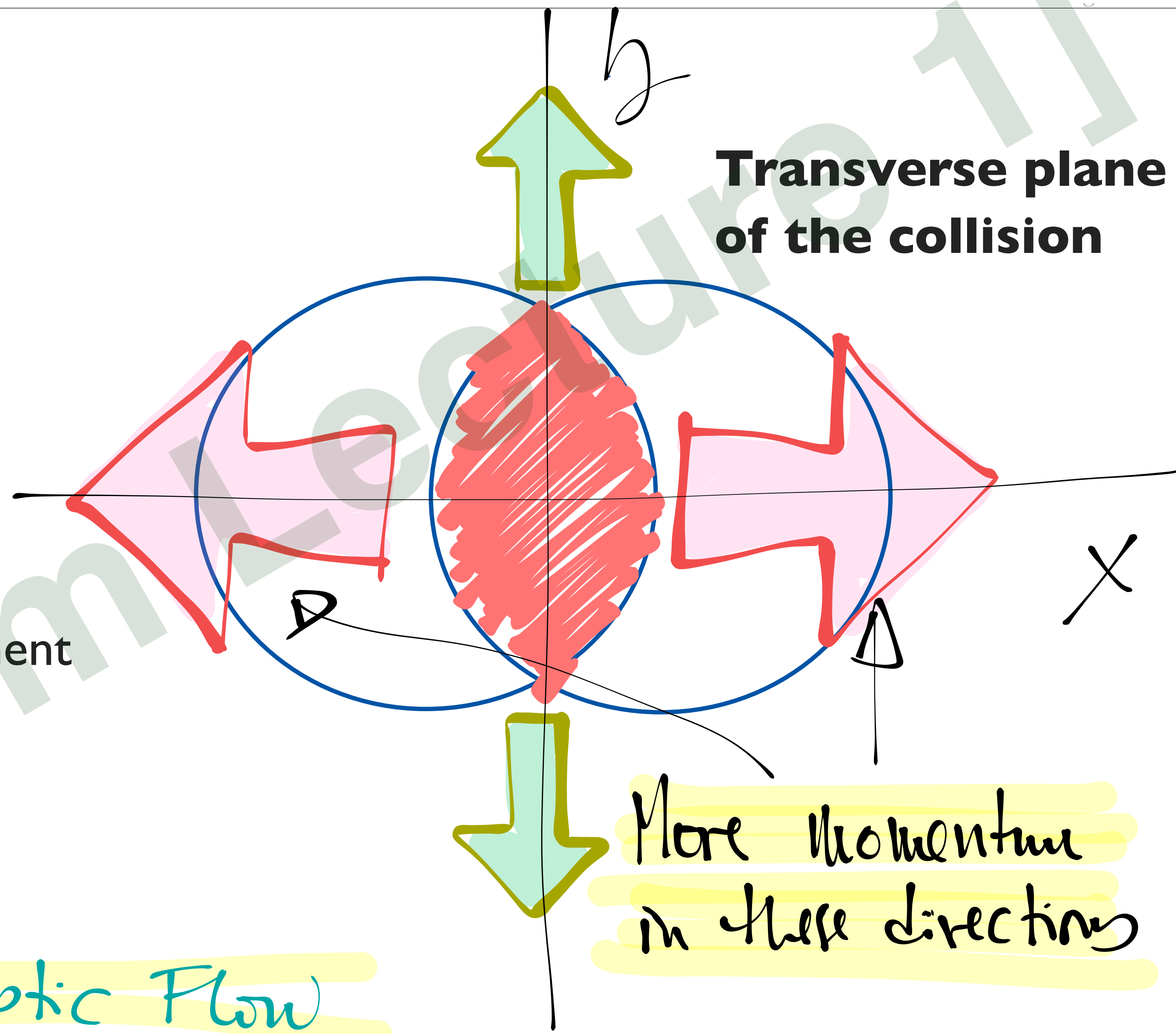
$$\epsilon = 3P \implies \partial_x P > \partial_y P$$

Make a Fourier decomposition

- Elliptic flow is the second component

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

Elliptic Flow

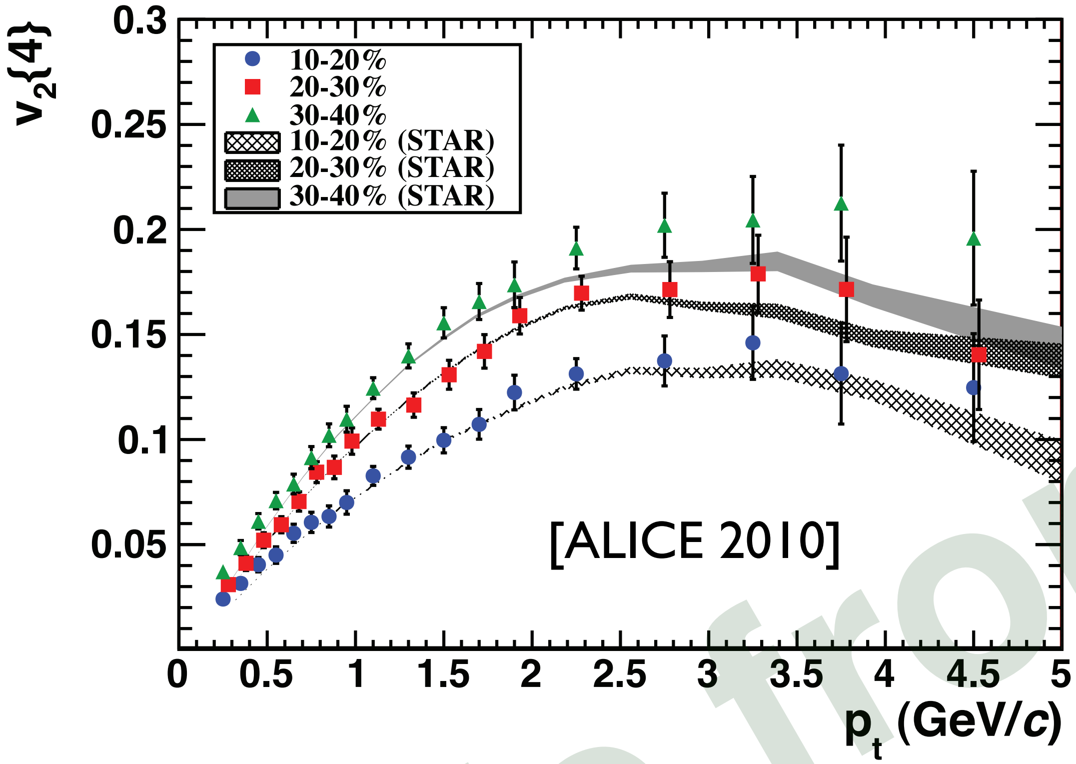


Anisotropies in the initial spacial distributions - <u>geometry</u> - translate into anisotropies in the momentum distributions

- Impossible with instantaneous, point-like, interactions unless initial- or final-state correlations

Viscosity from data

LHC flow similar to RHIC



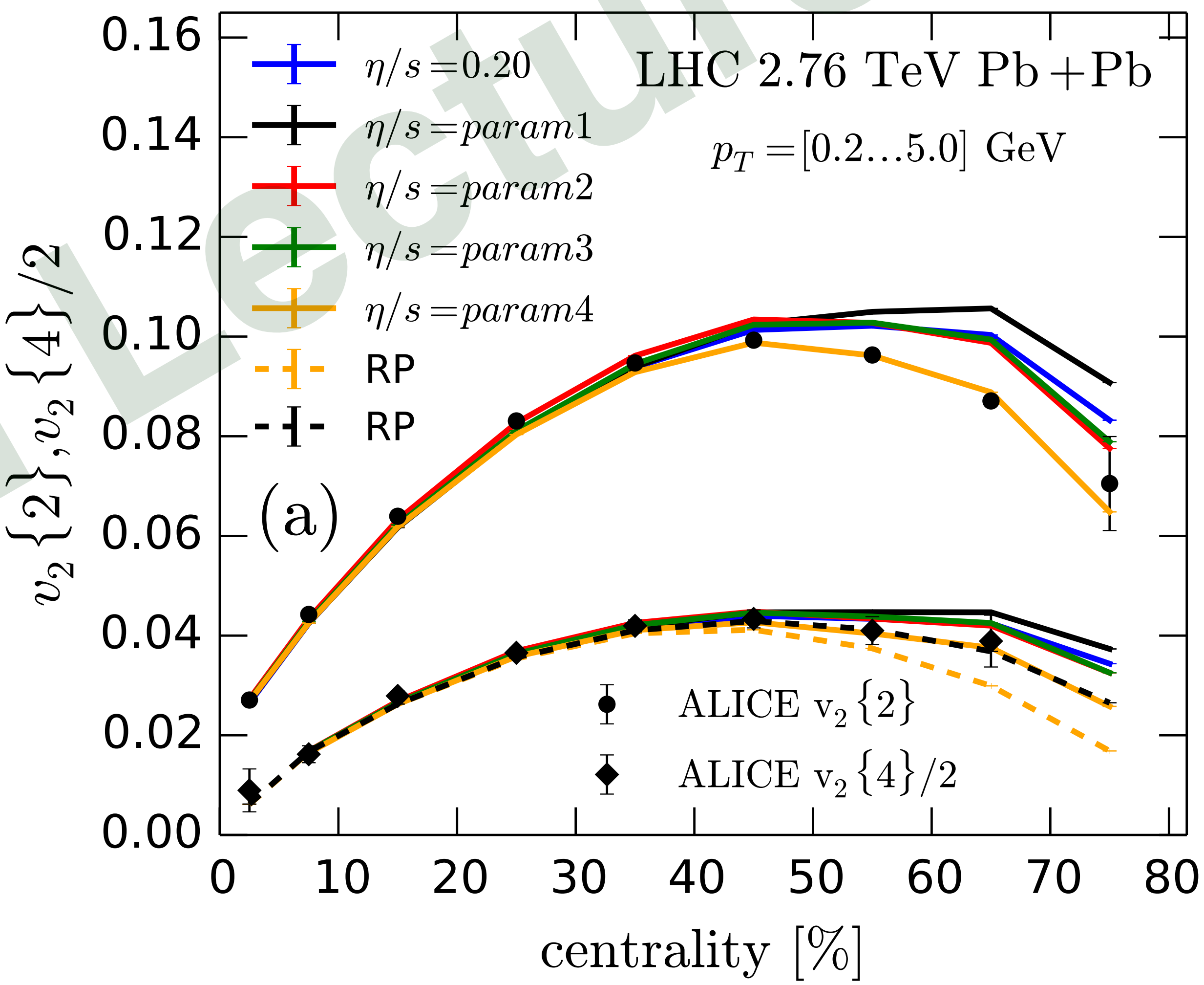
Lowest viscosity known

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

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

[Policastro, Son, Starinets, 2001]

Well described by hydro

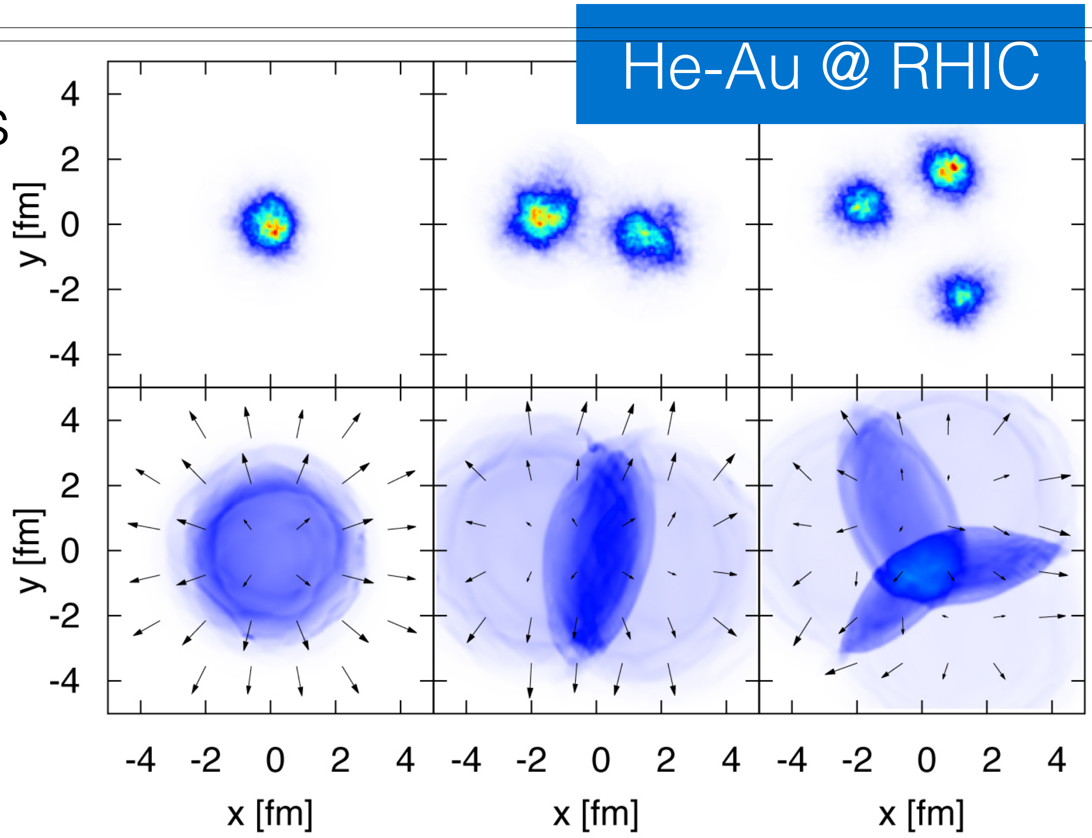


[Niemi, Eskola, Paatelainen 2015]

Higher harmonics

Fourier decomposition contains odd harmonics
[absent in symmetric collisions]

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n\phi$$



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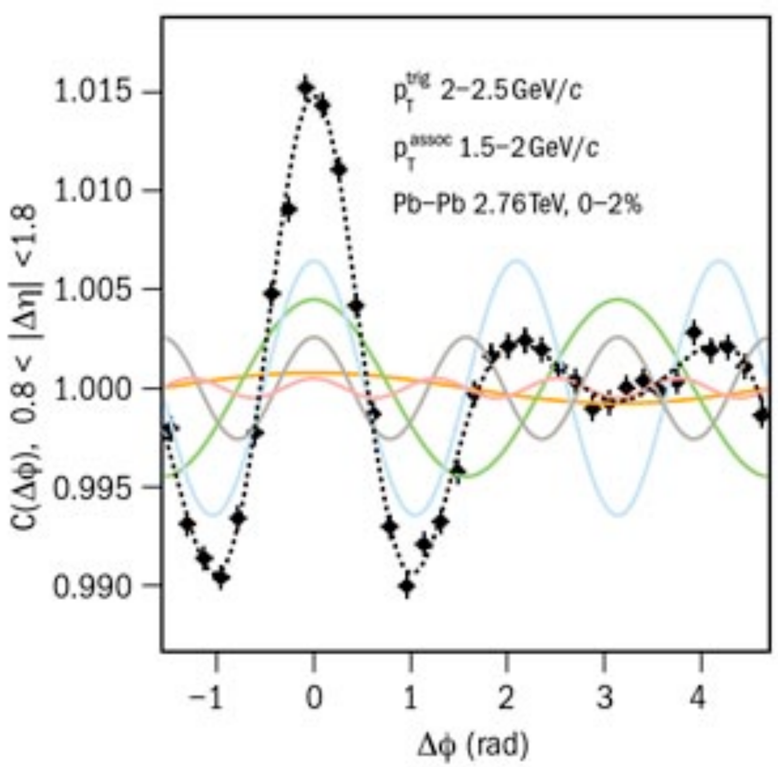
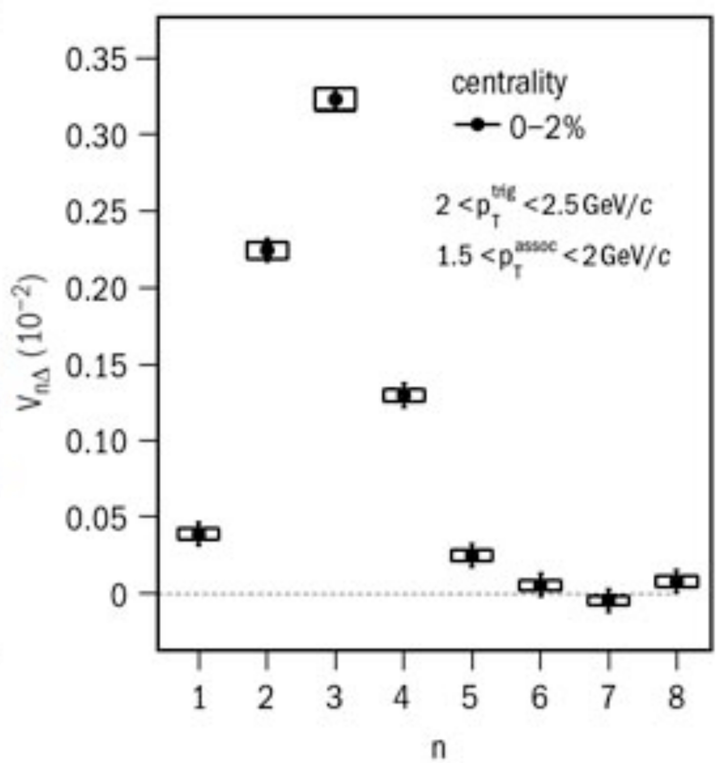
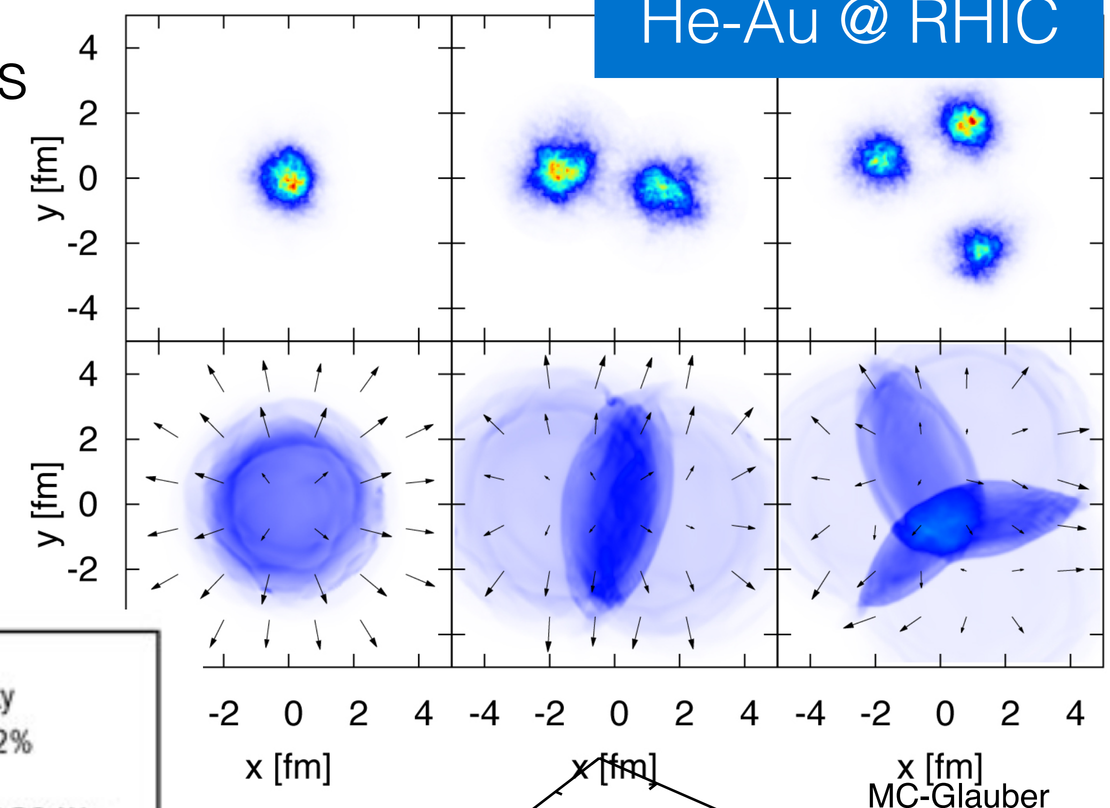
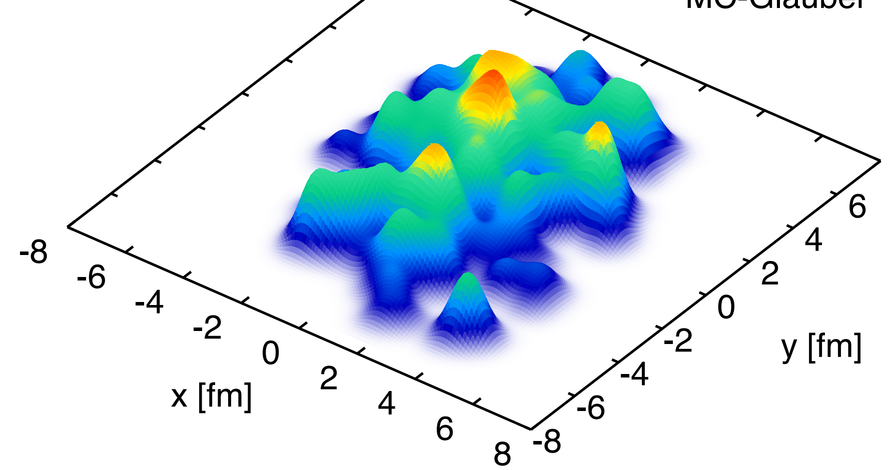
[ALICE 2011]





He-Au @ RHIC

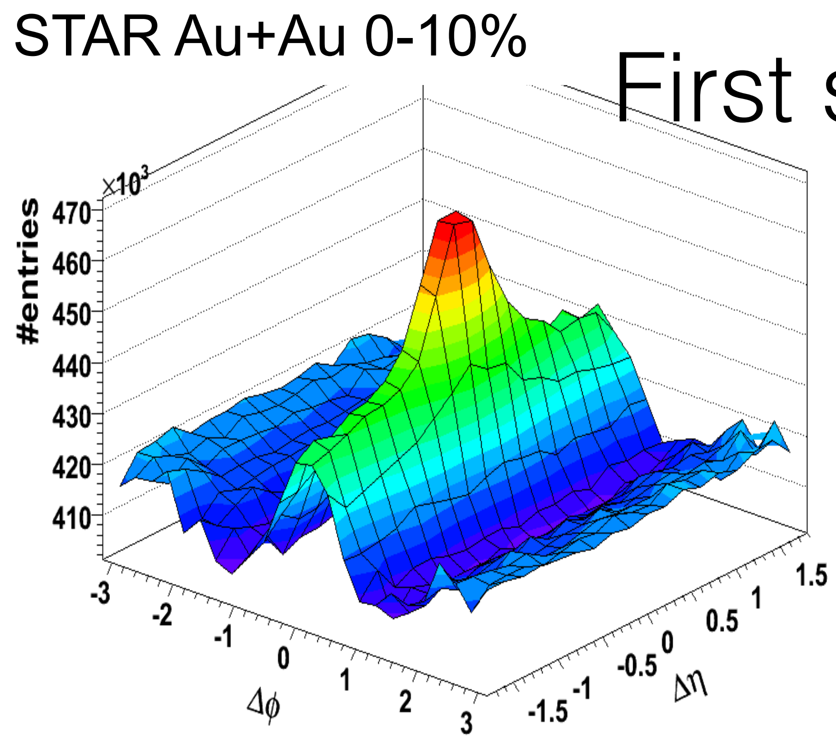




[Gale, Jeon, Schenke]

Odd harmonics are direct measurements of the initial state event-by-event fluctuations

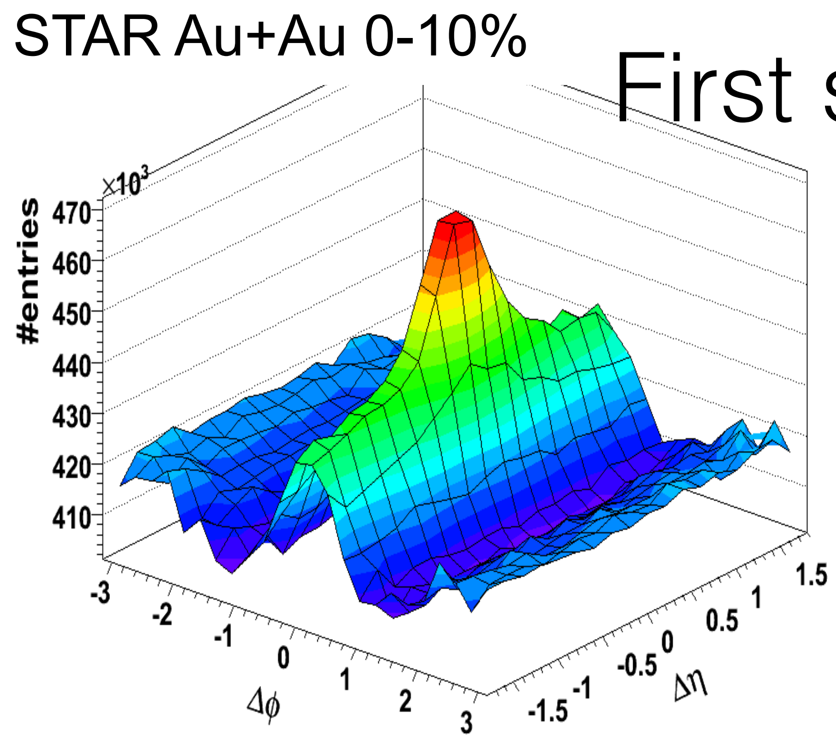
The ridge



First seen (2008) in AuAu, STAR @ RHIC.
Generated lot of discussion

- Long-range (in rapidity) angular correlations indicates collective phenomena
- By causality it needs to be formed **very early** in the collision

The ridge



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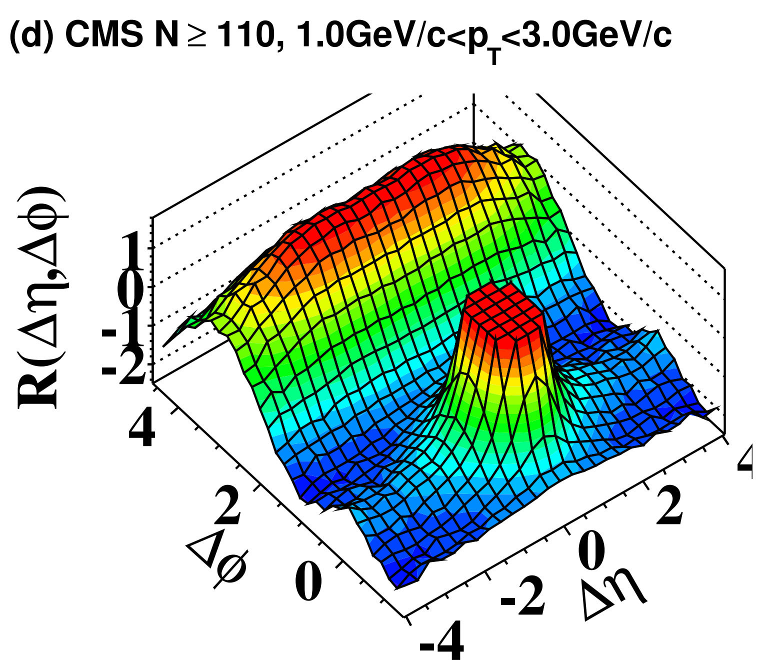
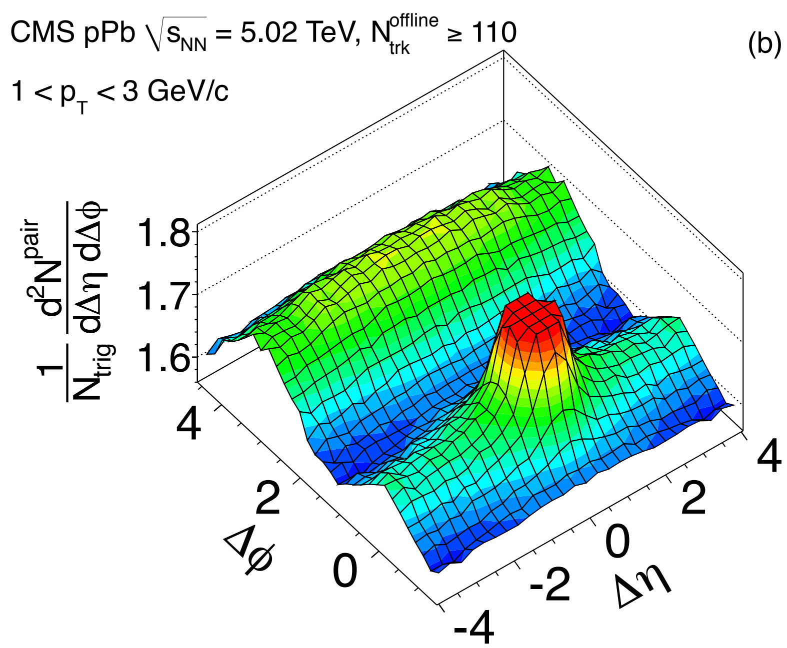
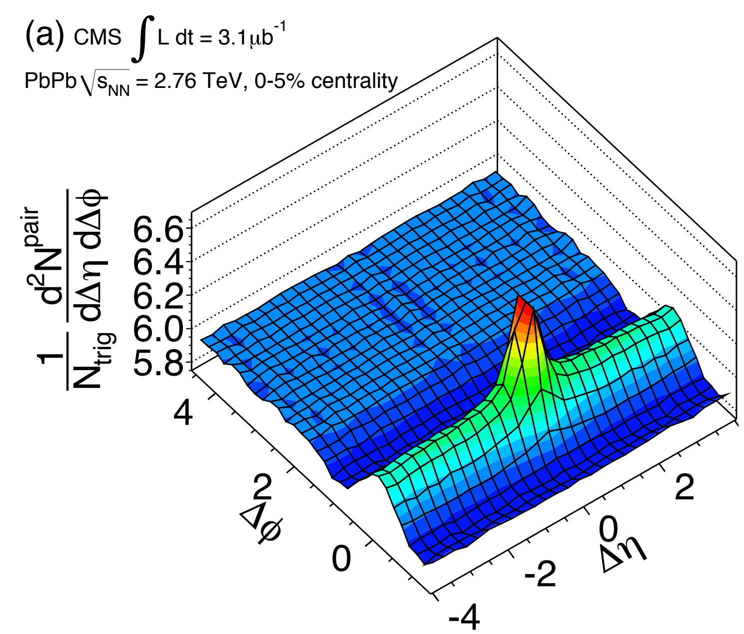


high multiplicity pp

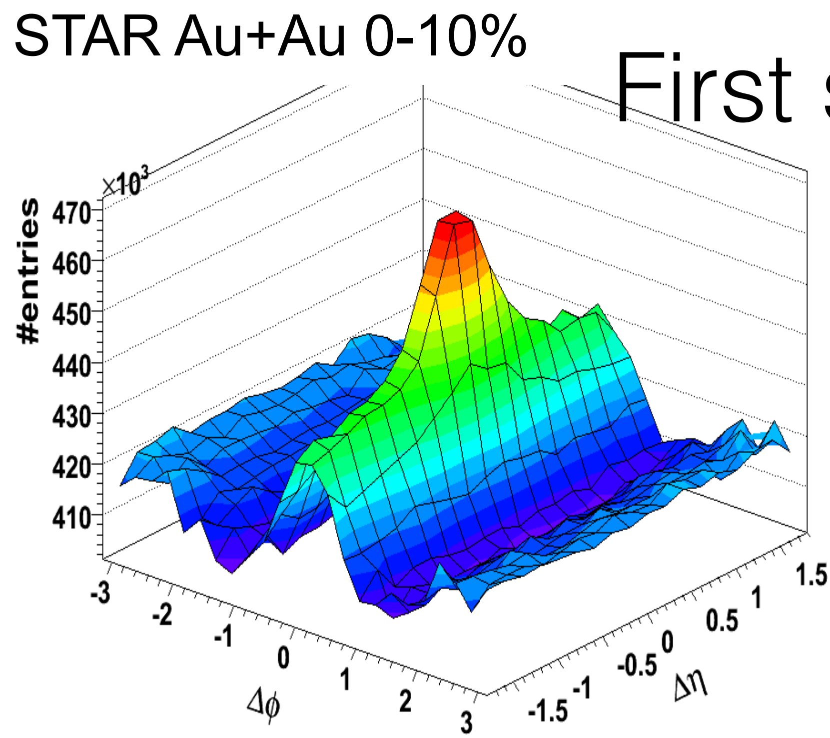


high multiplicity pPb



everywhere in PbPb

The ridge



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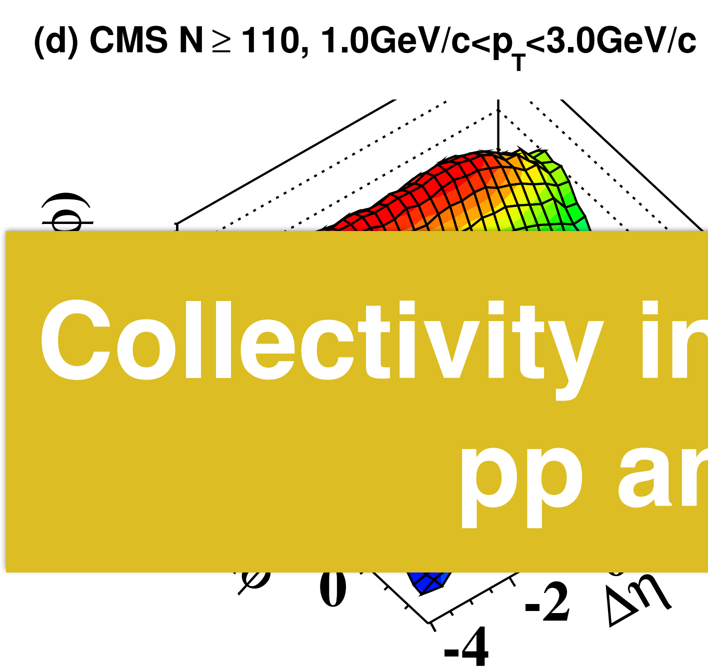
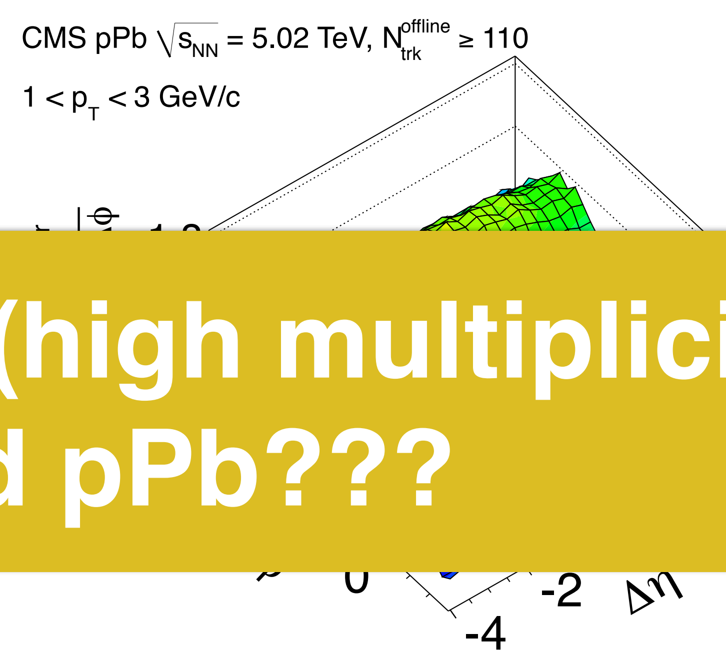
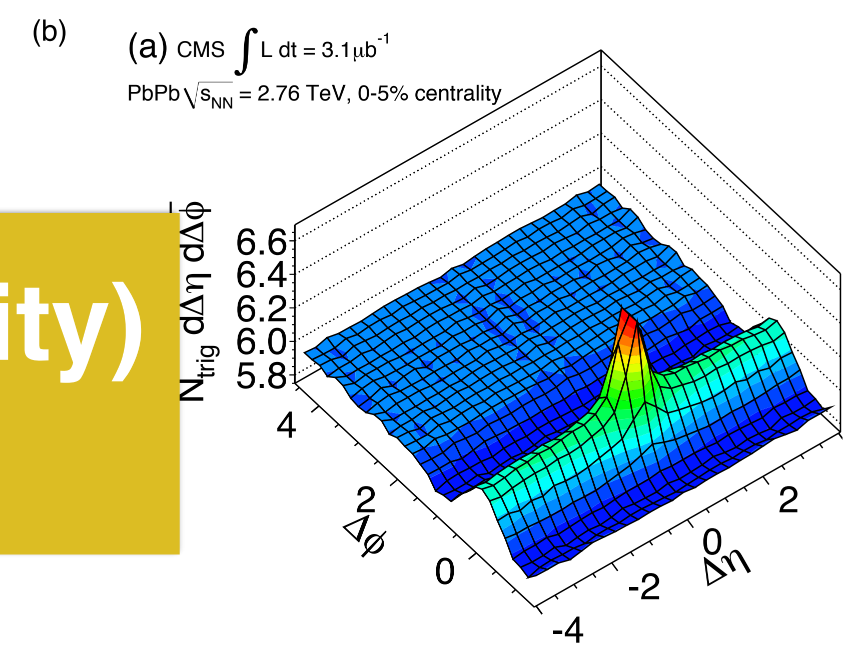


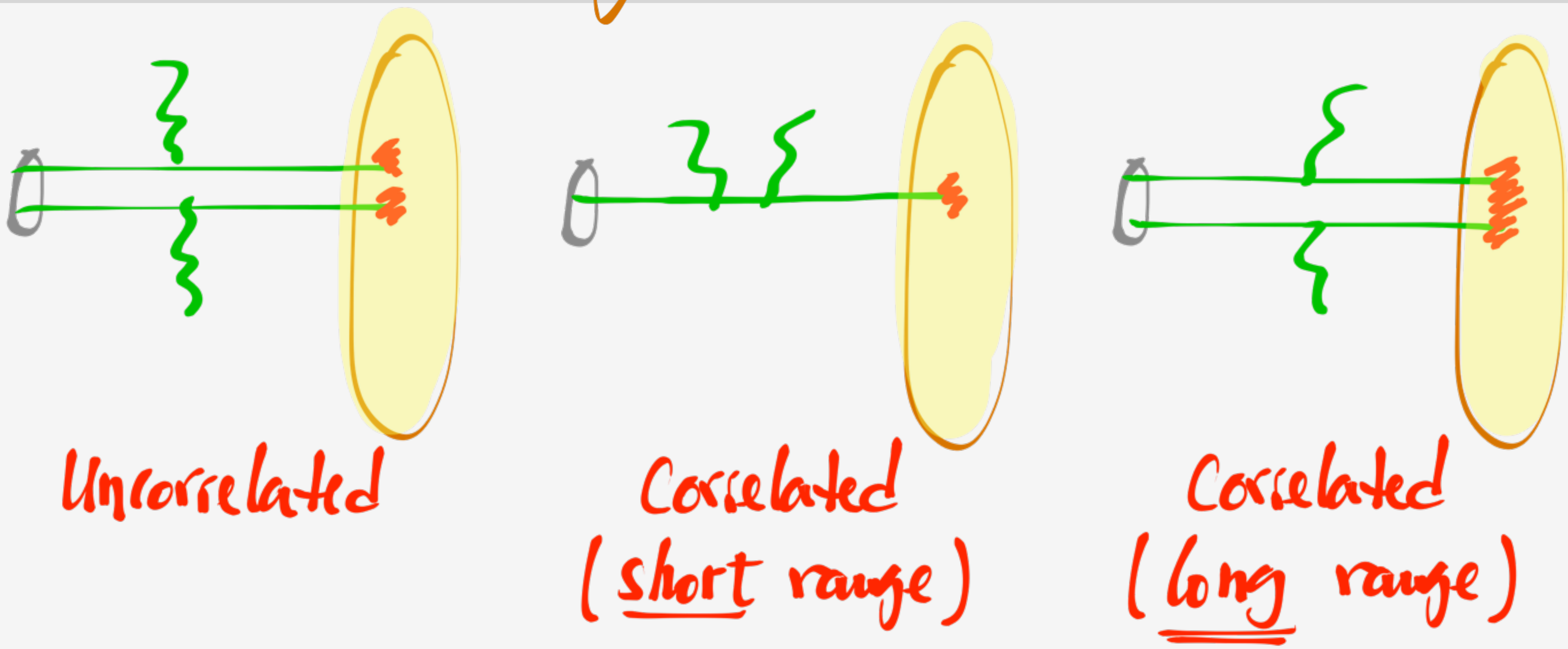




Collectivity in (high multiplicity) pp and pPb???

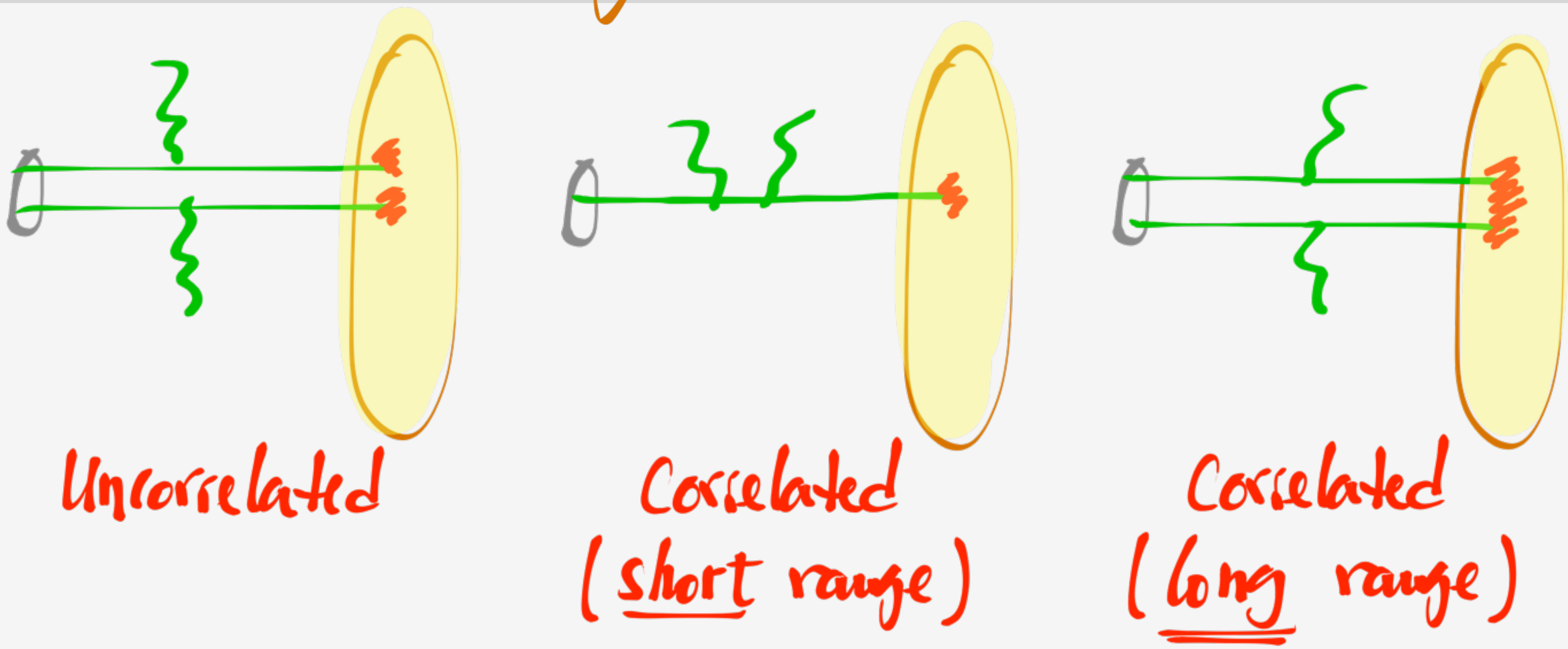
high multiplicity pp | high multiplicity pPb | everywhere in PbPb

The Ridge & the CGC



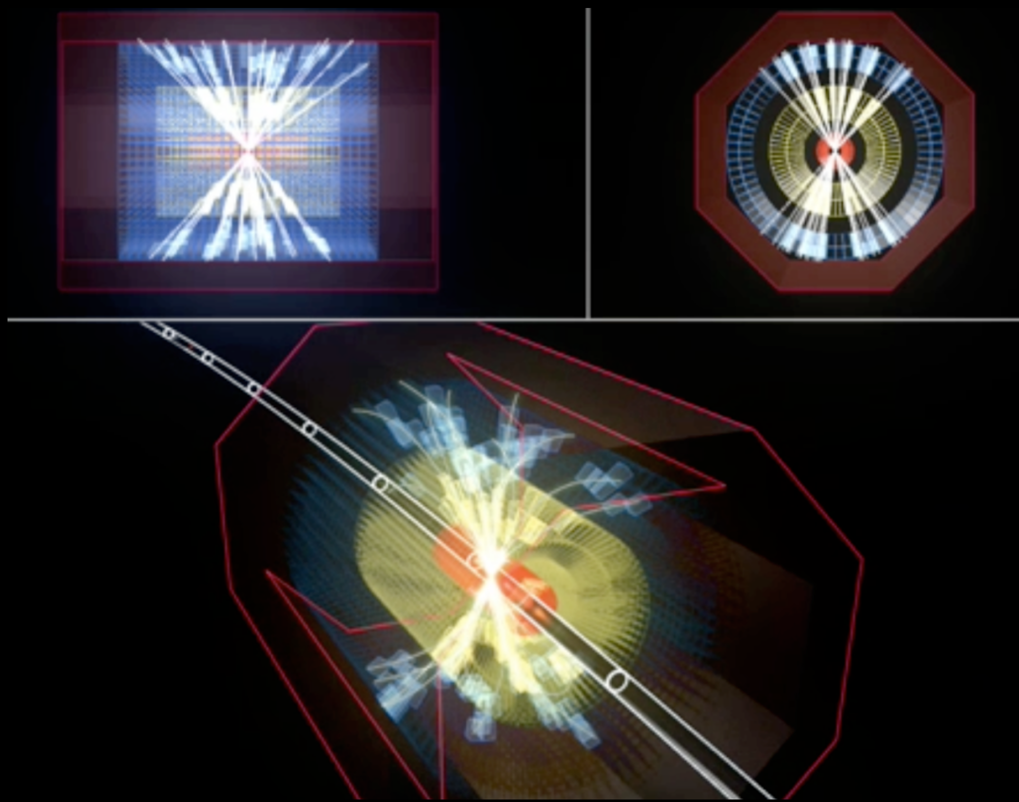
COLOR correlations in transverse plane ~ Q_{sat}^{-1}

The Ridge & the CGC



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

Is the Ridge Initial State / Final State / Both?



Hard Probes

Several different probes in the final state,
I will only concentrate on two of them
within the hard sector

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

Nuclear PDFs

Hadronization
J/Ψ paradigmatic example

Long distance terms modified by the presence of medium

- Nuclear PDFs and new (non-linear) evolution equations (explained before)
- Modification of hadronization probes the medium properties
- EW processes (no hadronization) used as benchmark

Quarkonia suppression

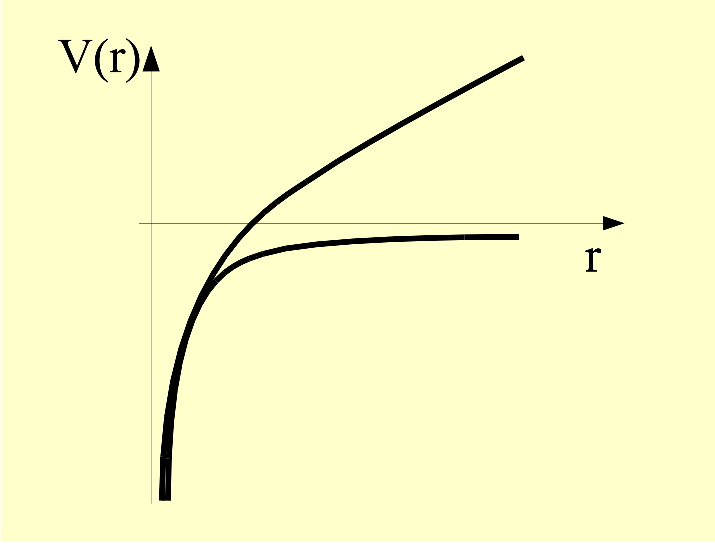
Simple intuitive picture [Matsui & Satz 1986]

Potential screened at high-T

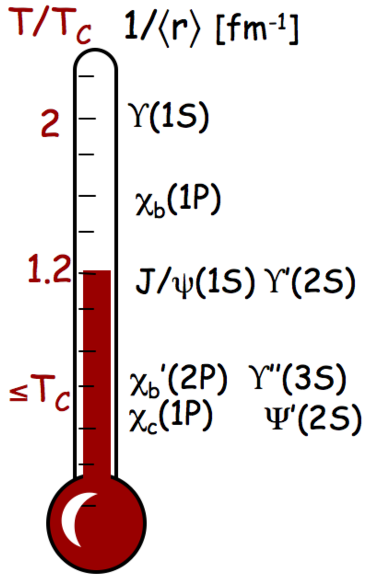
Bound states not possible

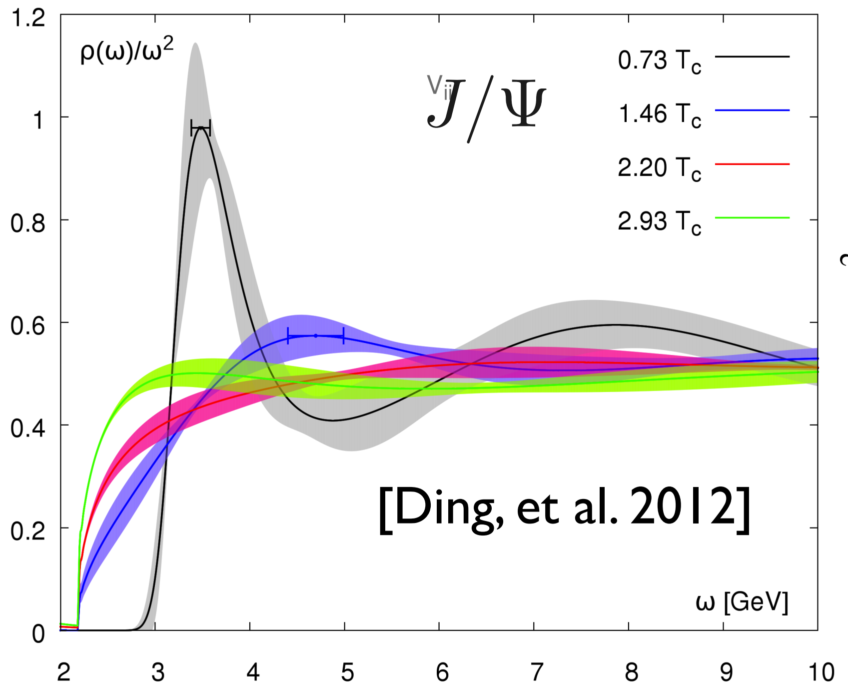
Suppression of J/Psi in nuclear collisions

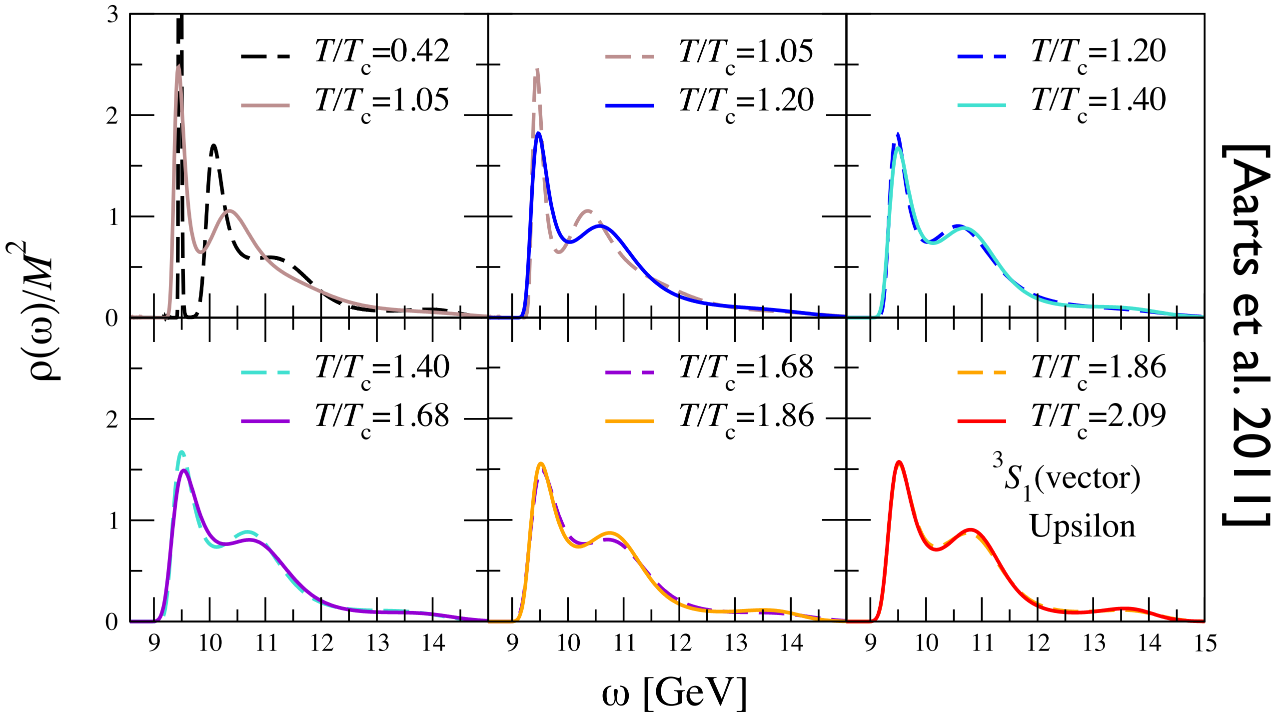
Sequential suppression of excited states



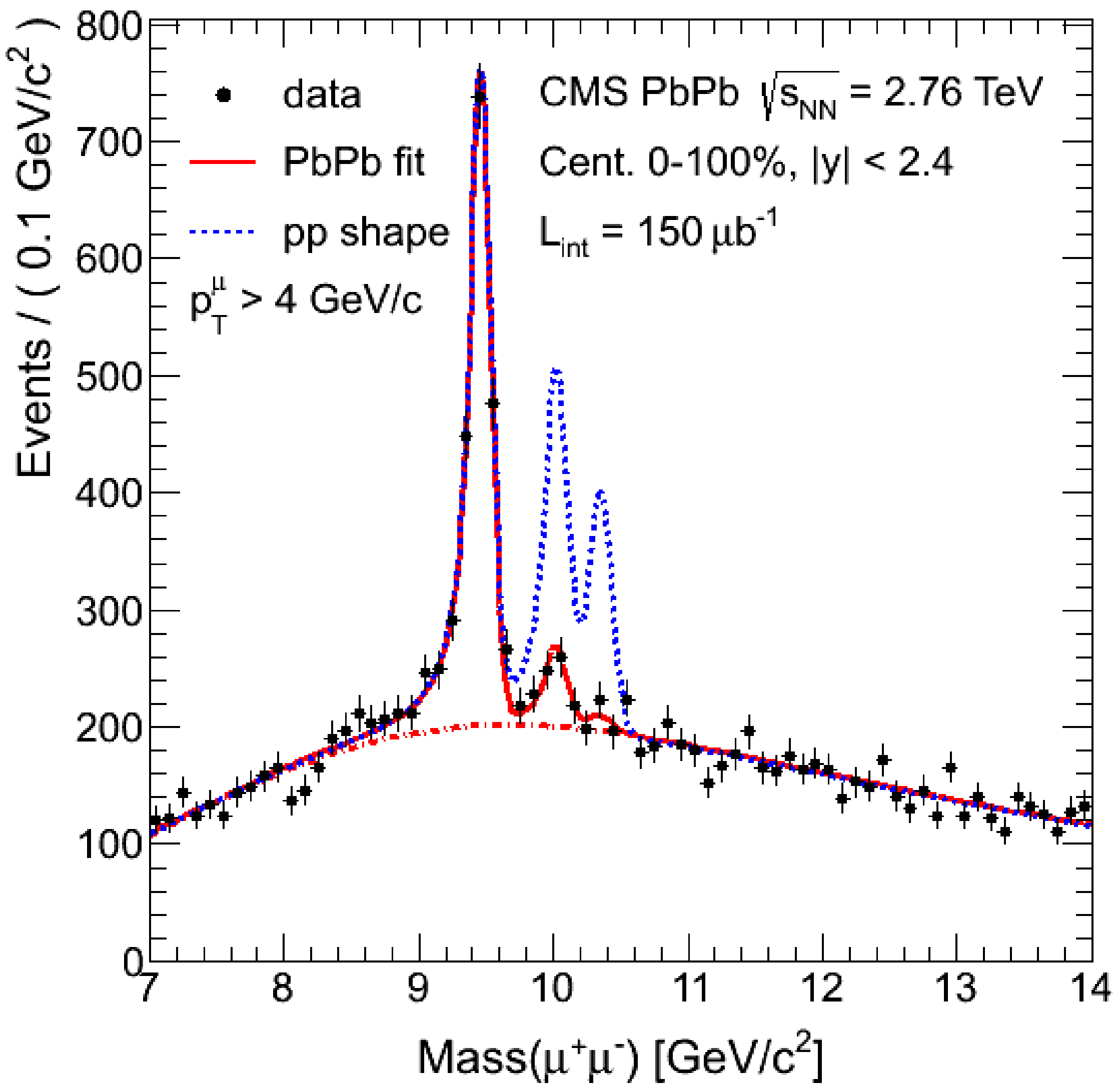
Interpretation of the data traditionally difficult - lot of progress in the last few years

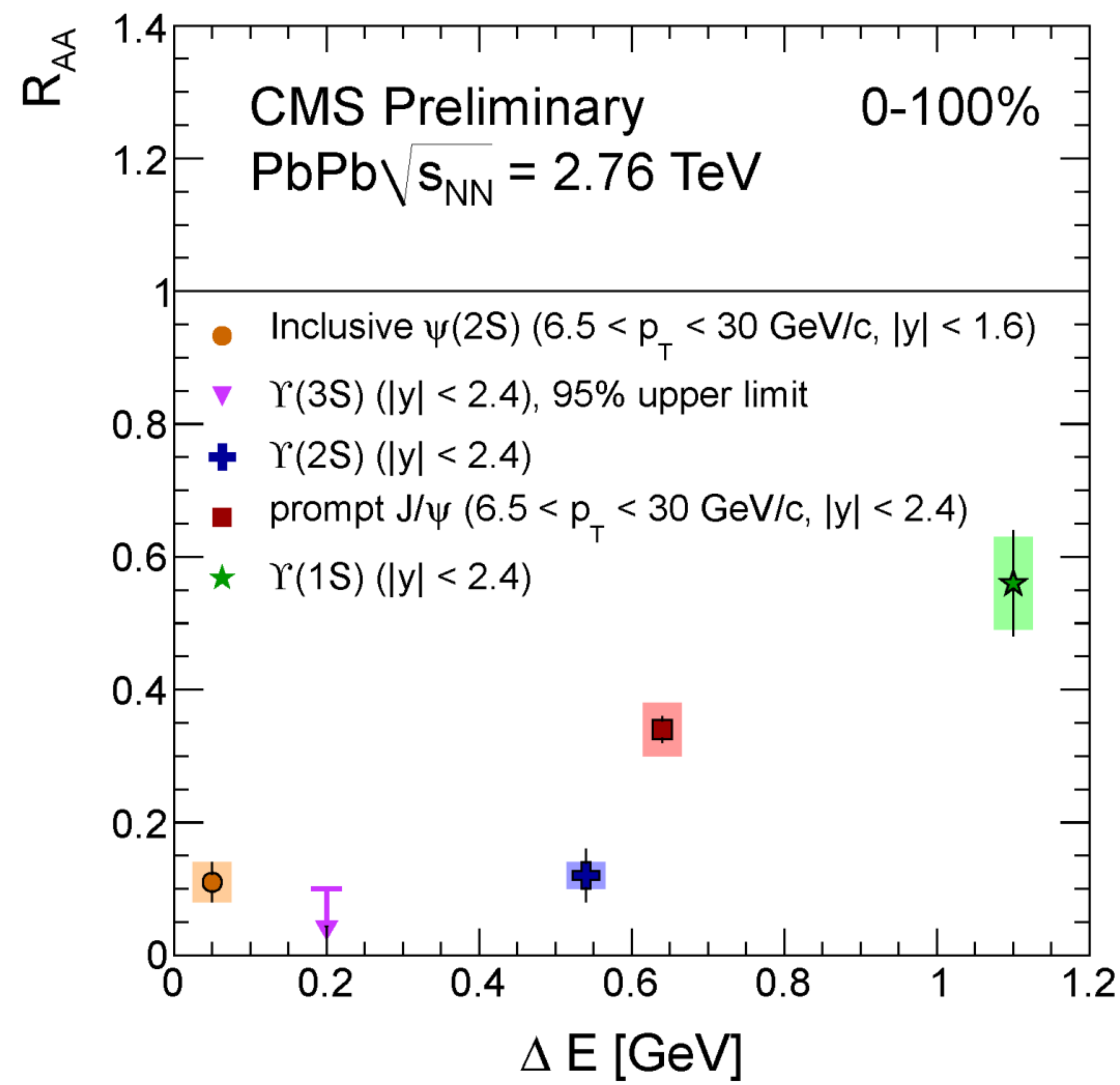






Upsilon suppression



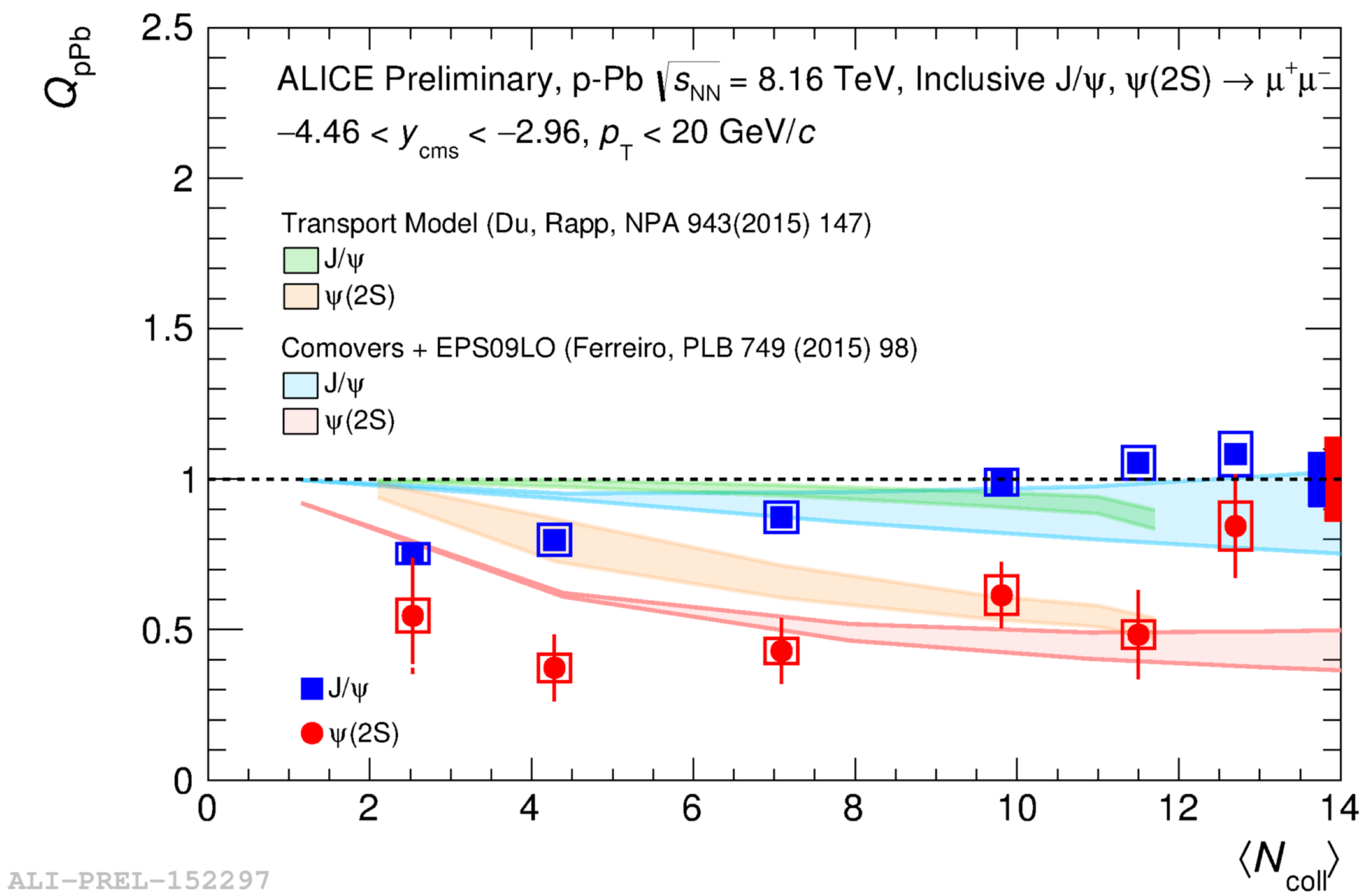


Suppression ordered by binding energy

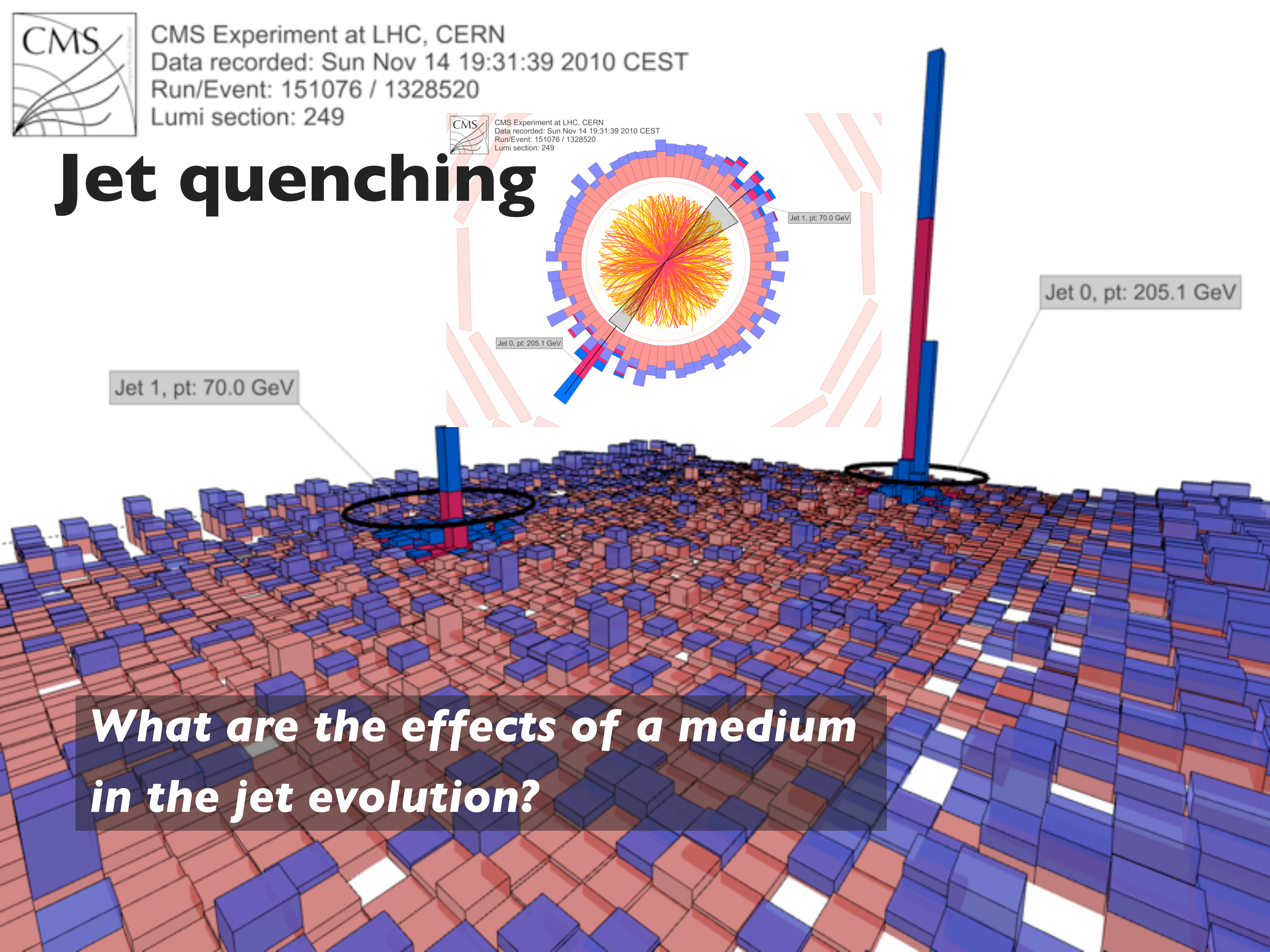
- **Quarkonia as a termometer** — abundant data (not shown) from all LHC experiments

Remember small systems?

Larger suppression for excited than for ground state charmonia in pPb



Jet quenching

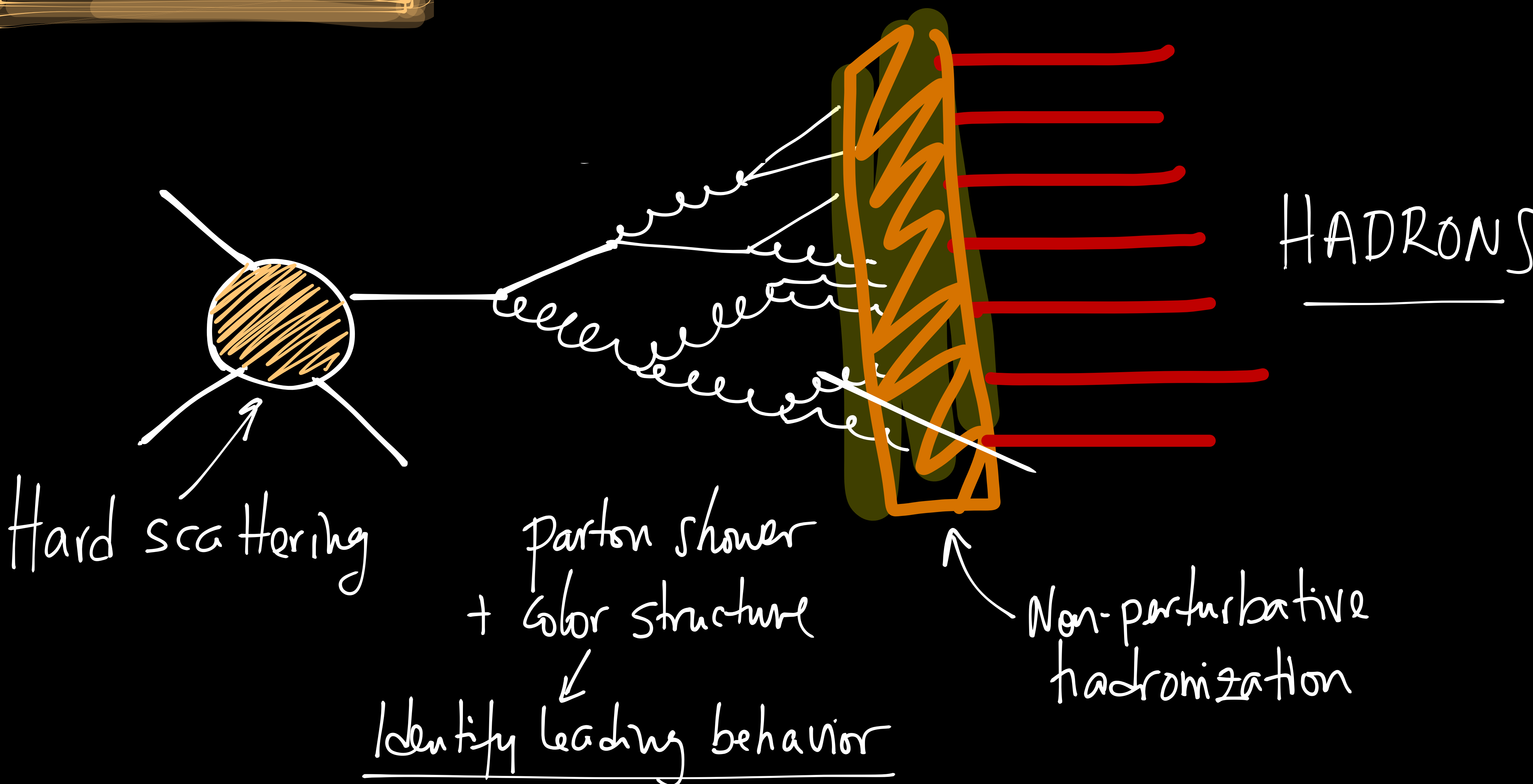


What are the effects of a medium in the jet evolution?

Matteo Cacciari's lectures

Jets in medium

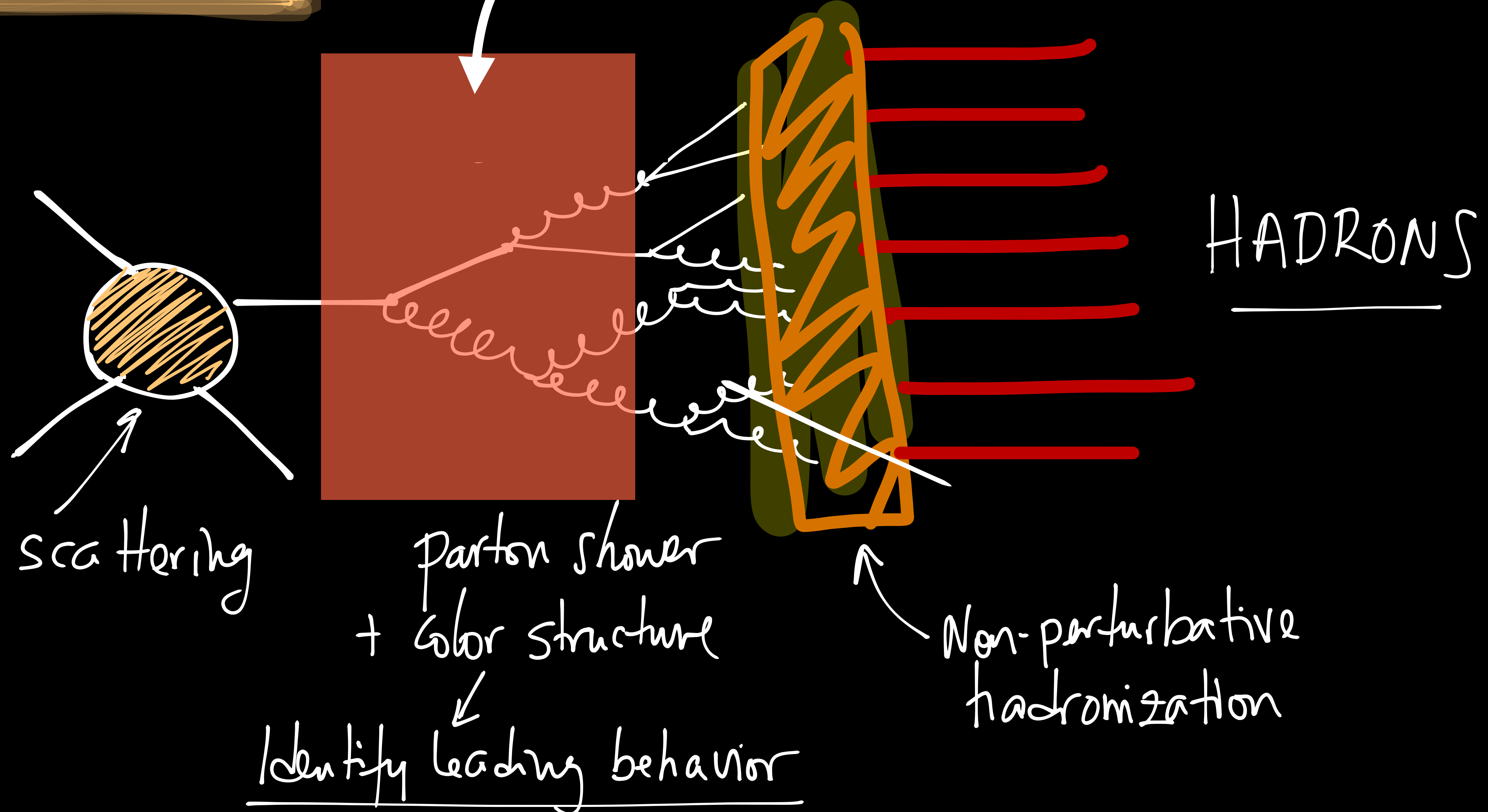
Jet quenching



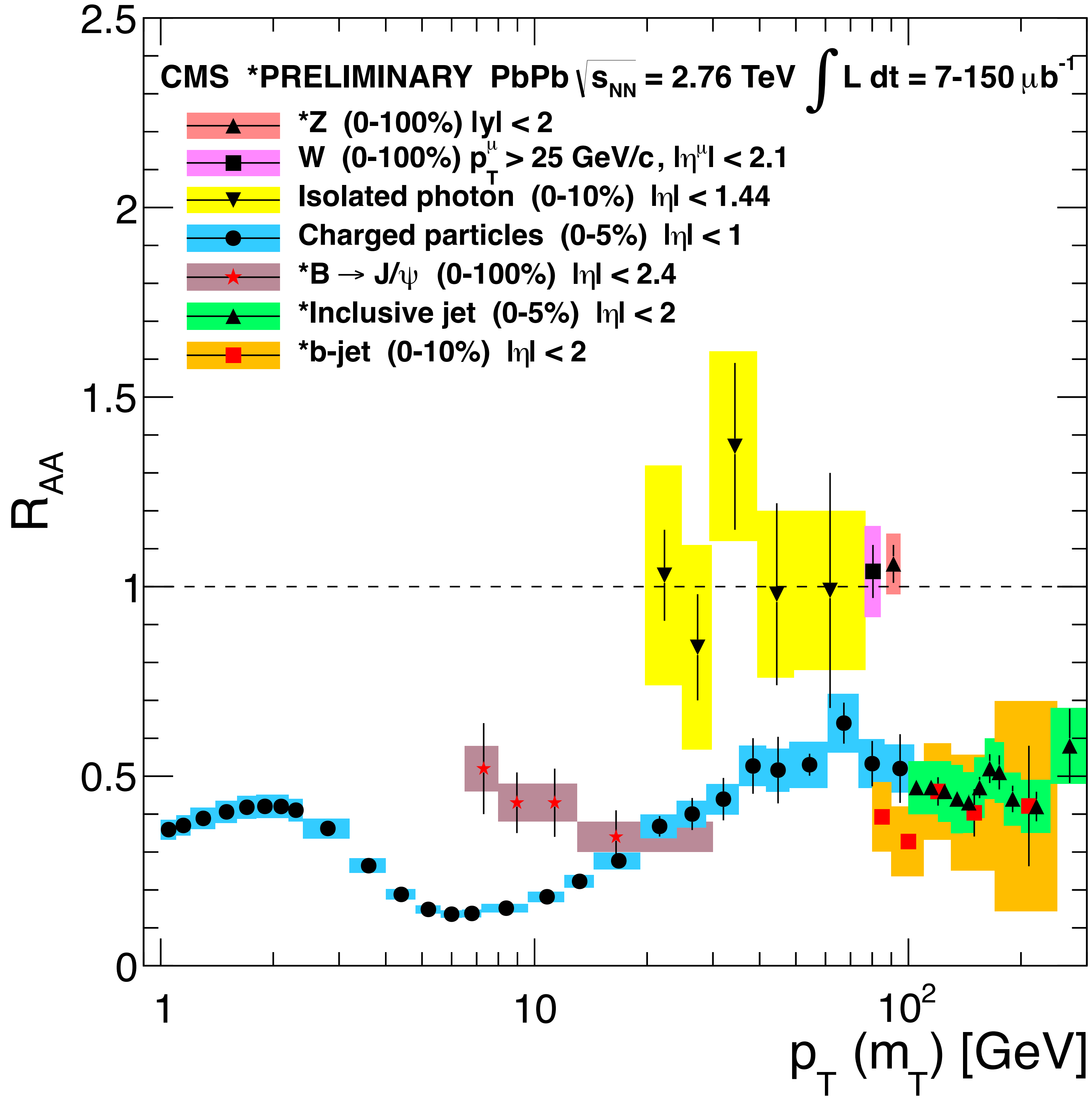
Jets in medium
Jet quenching

Matteo Cacciari's lectures

Put now a medium here

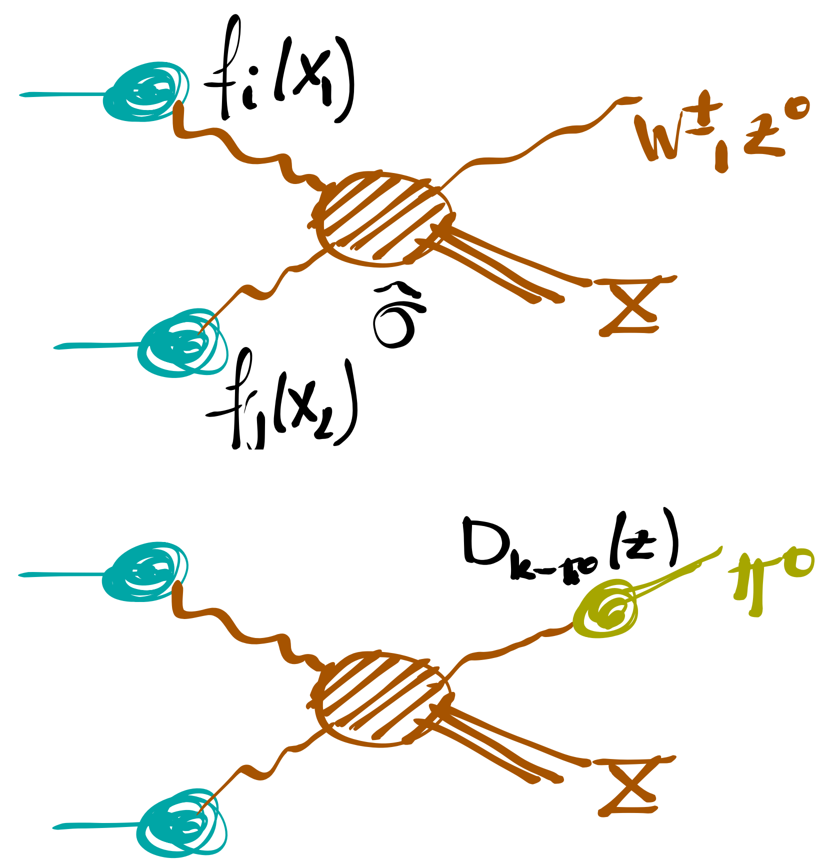


Suppression in 1 plot

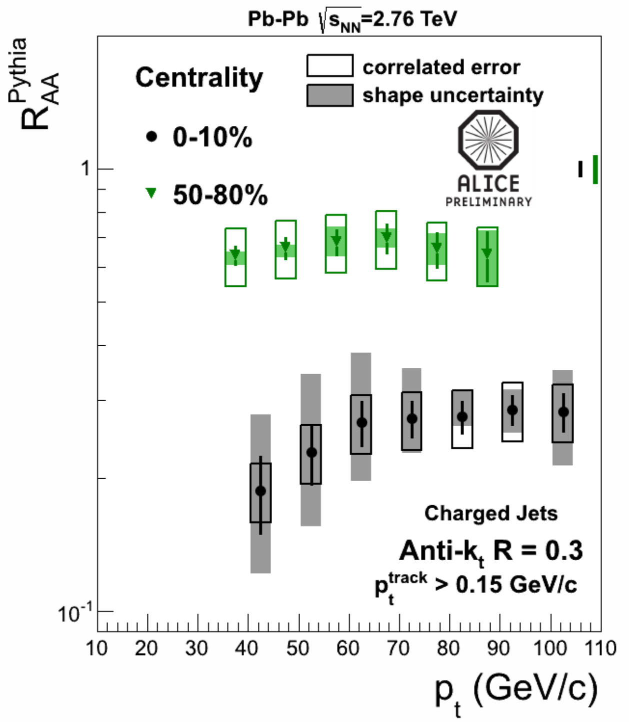


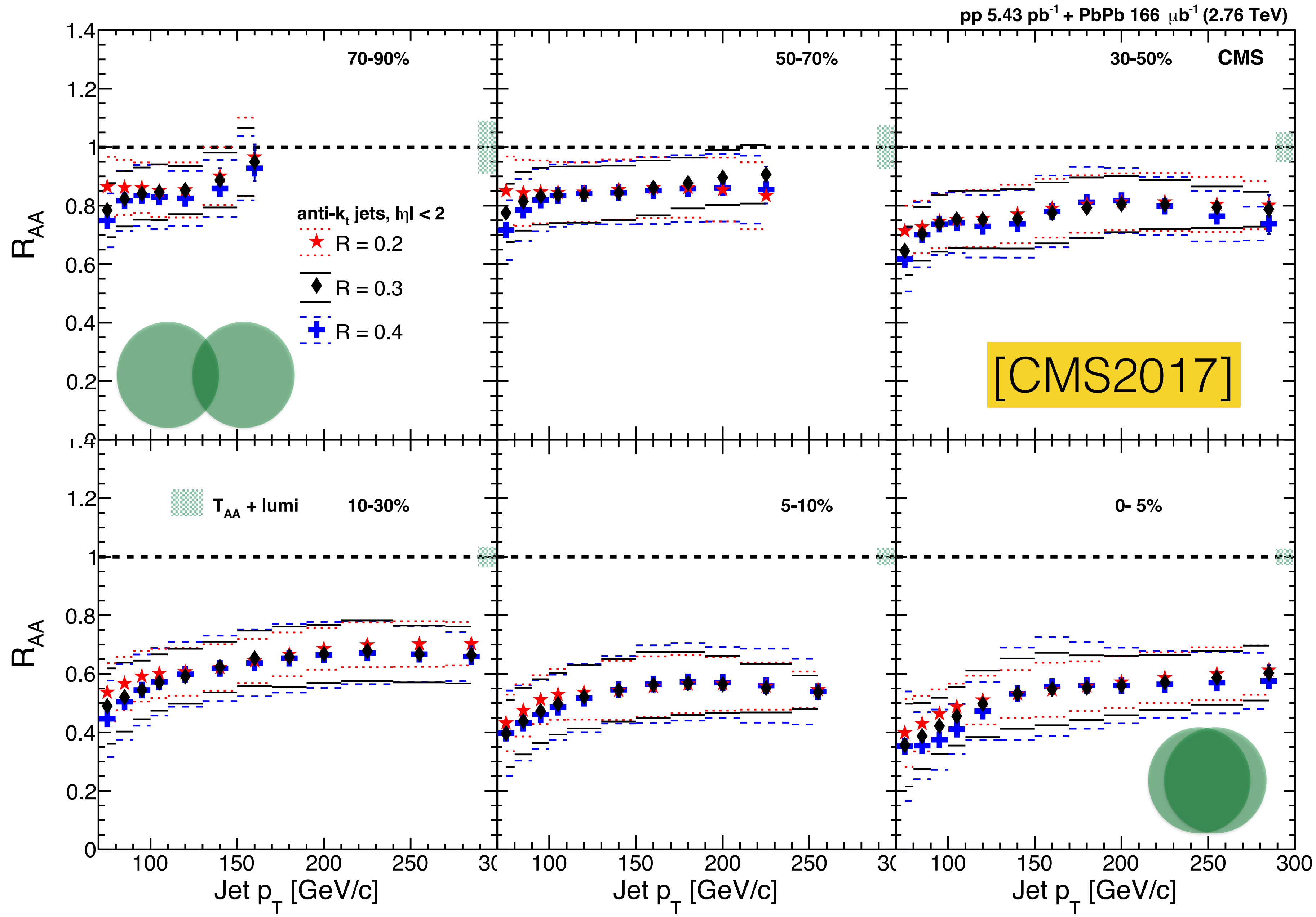
[A. Florent - Hard Probes 2013]

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



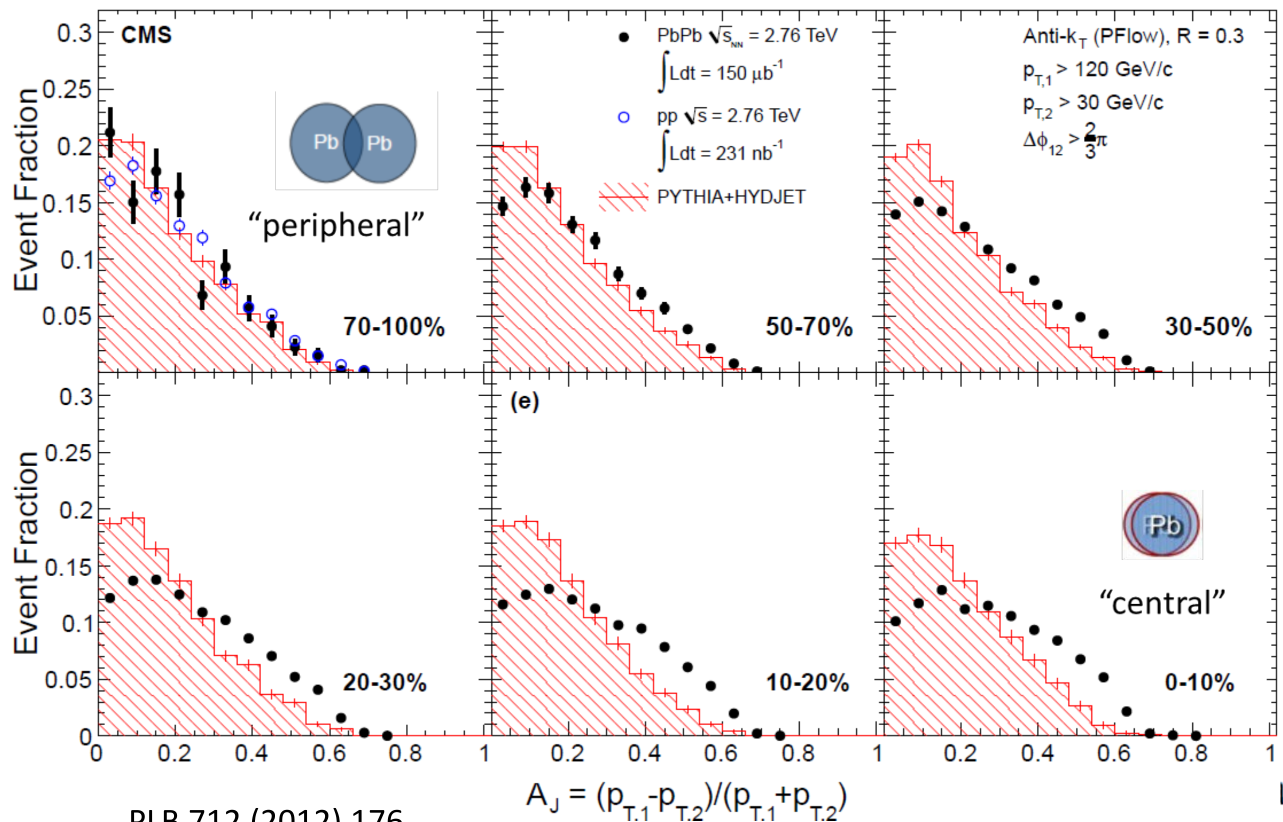
Reconstructed jets I





Reconstructed jets are suppressed — they lose energy

Reconstructed jets II



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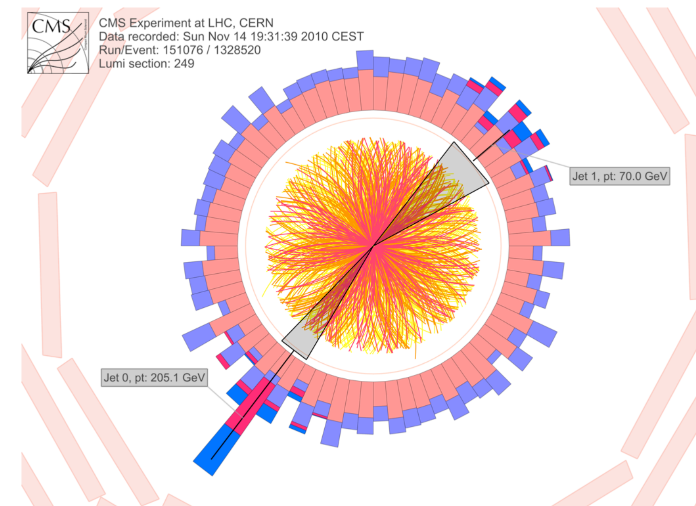
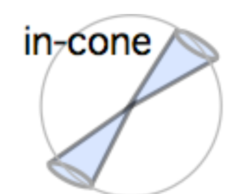
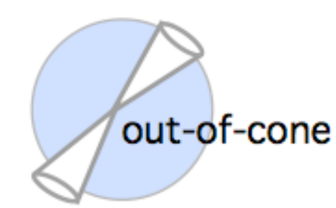
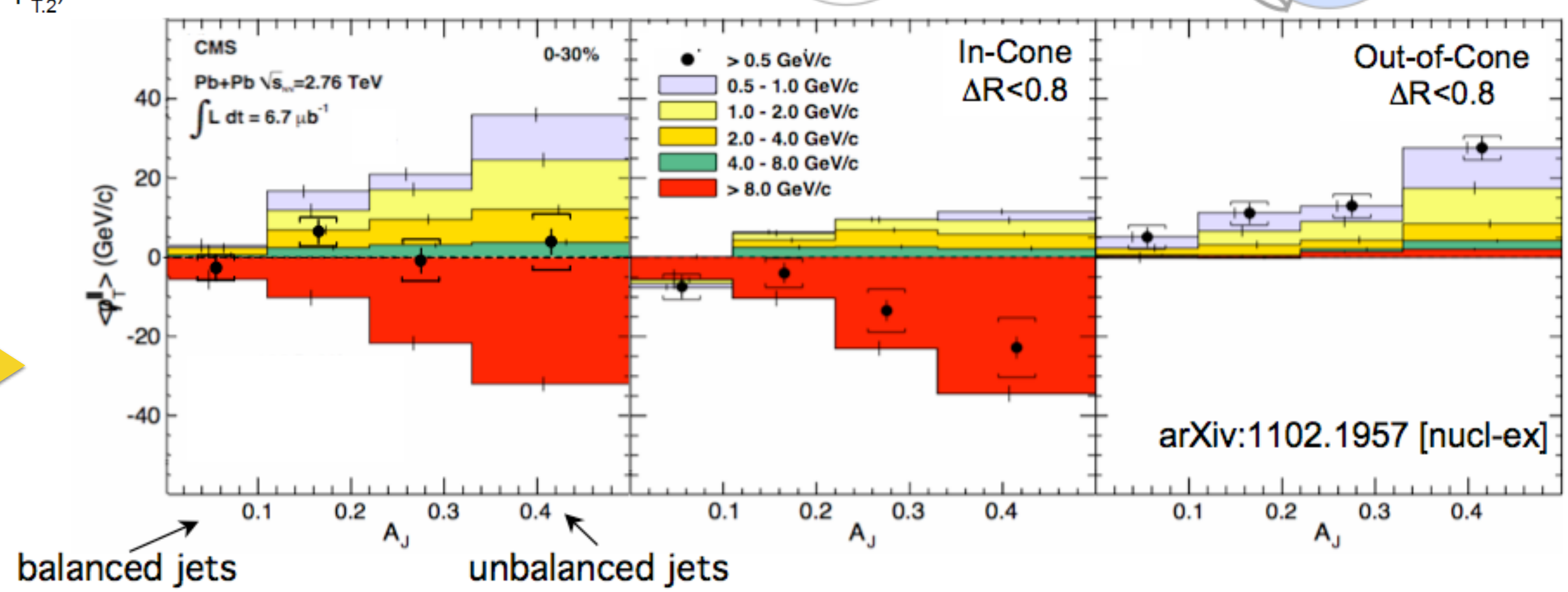




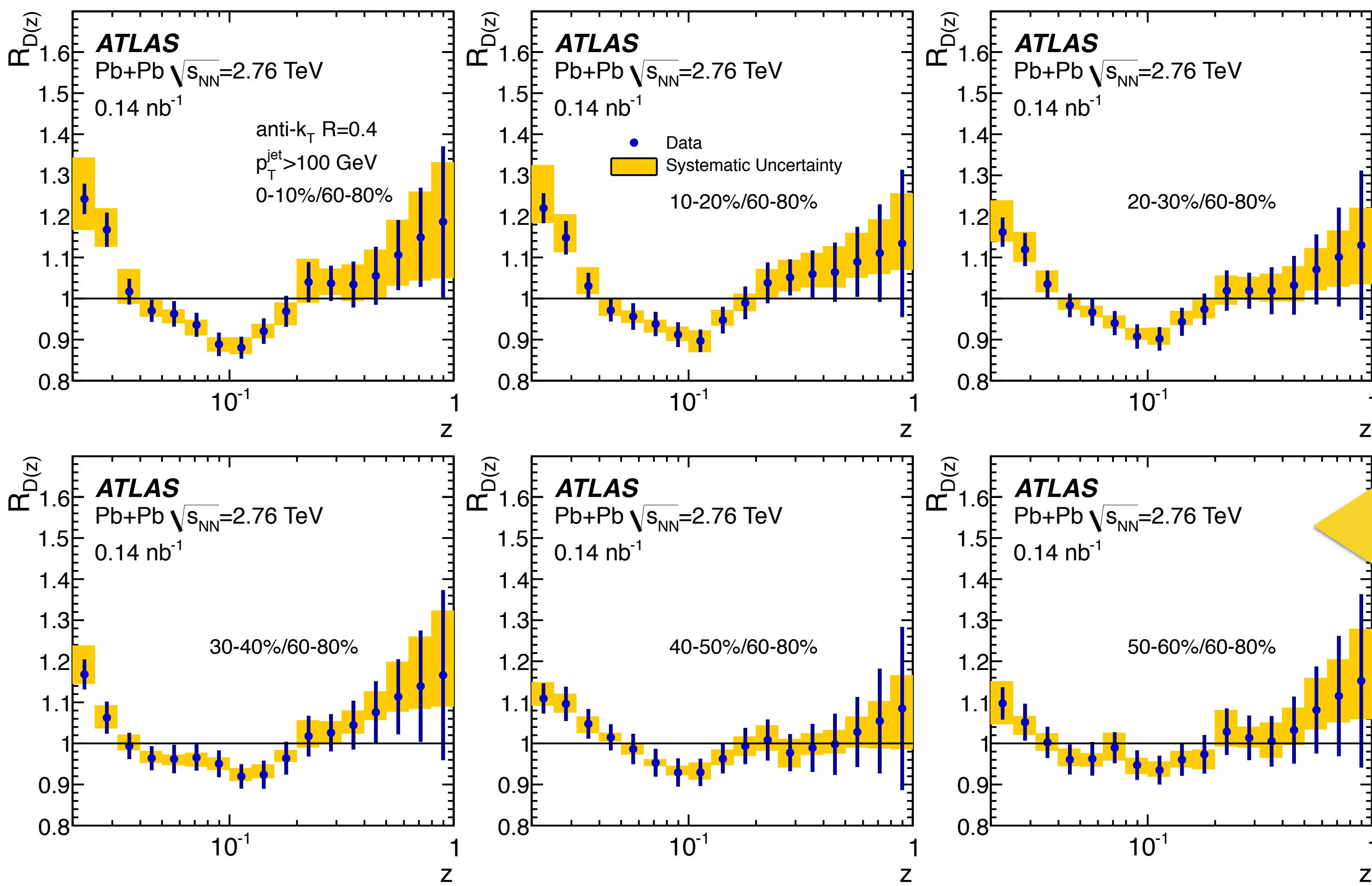


Energy imbalance

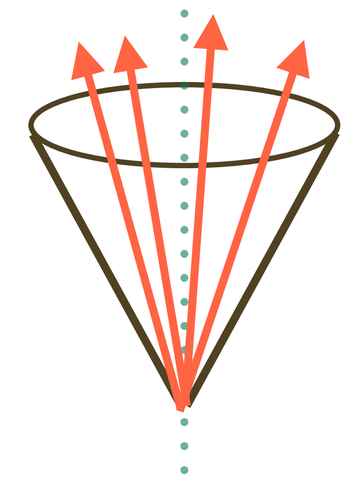
Energy appears at Large angle with soft particles



Reconstructed jets III

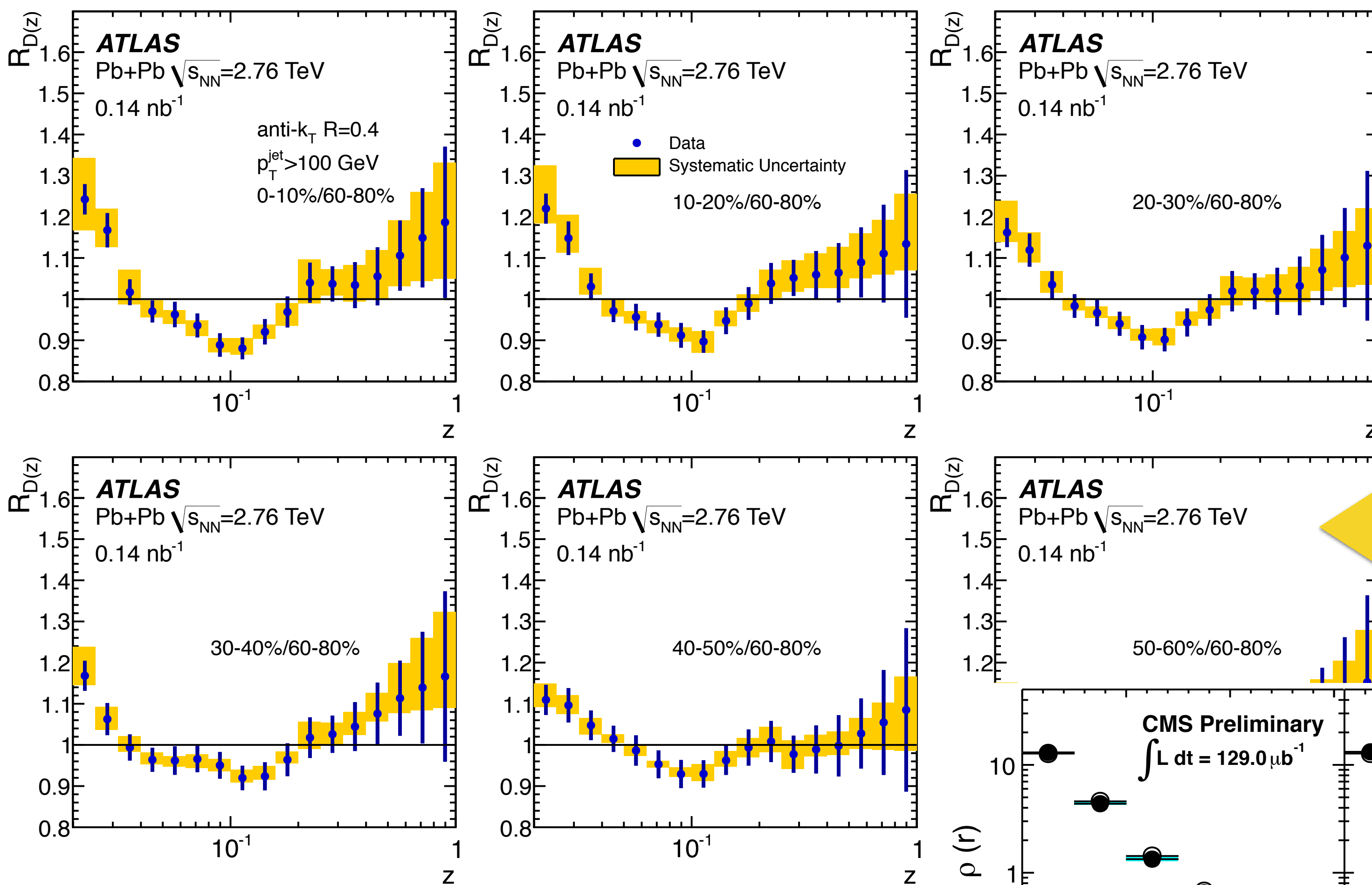


$$z = \frac{p_T^{\rm hadron}}{p_T^{\rm jet}}$$

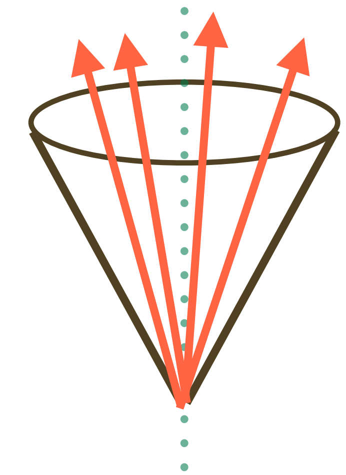


Fragmentation function

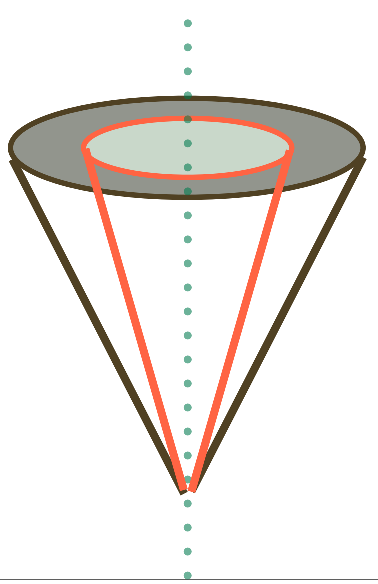
Reconstructed jets III



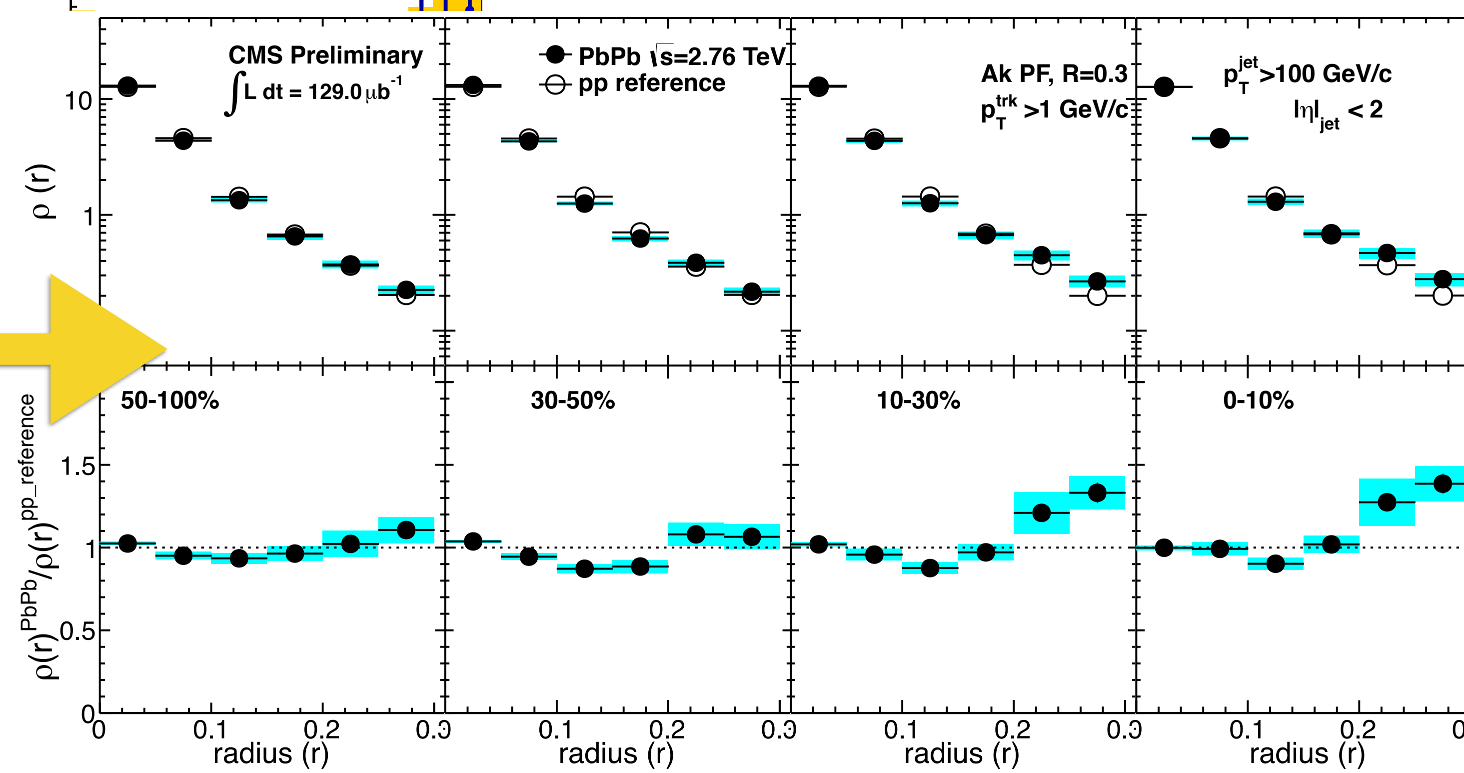
$$z = \frac{p_T^{\text{hadron}}}{p_T^{\text{jet}}}$$



Fragmentation function

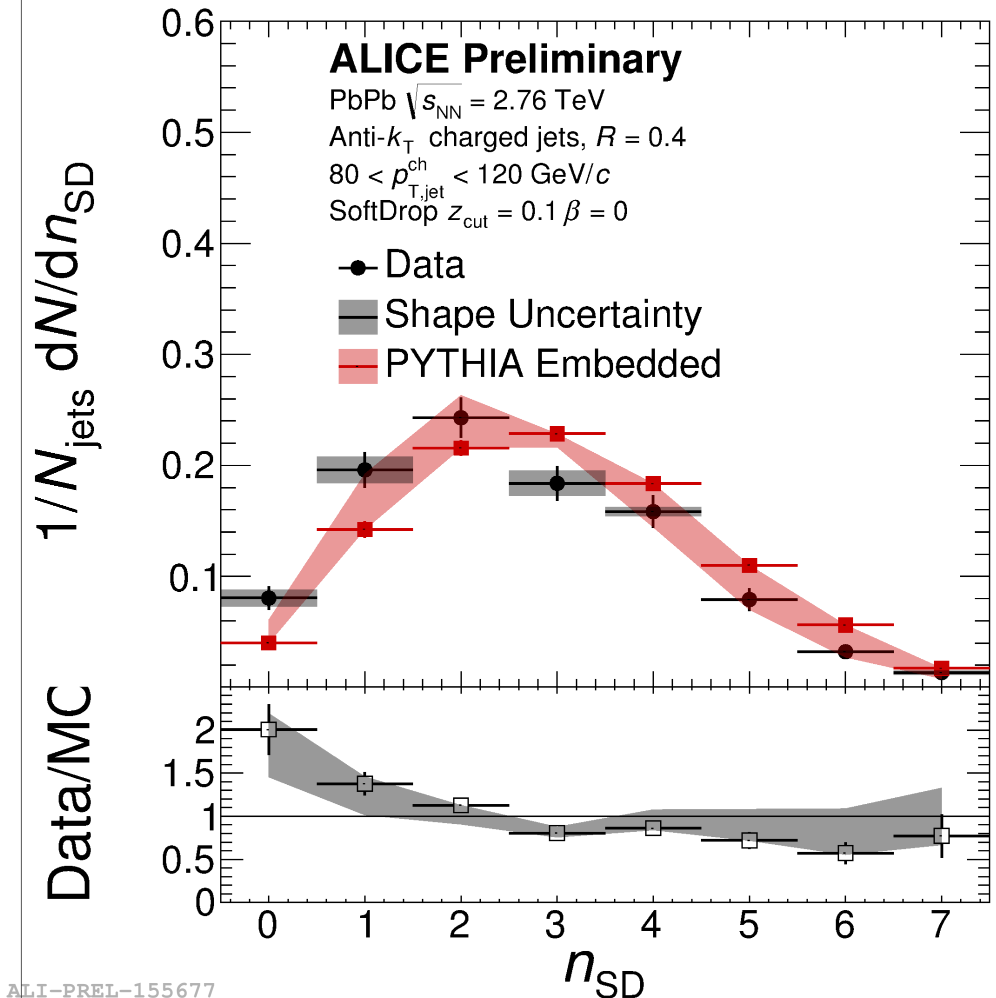


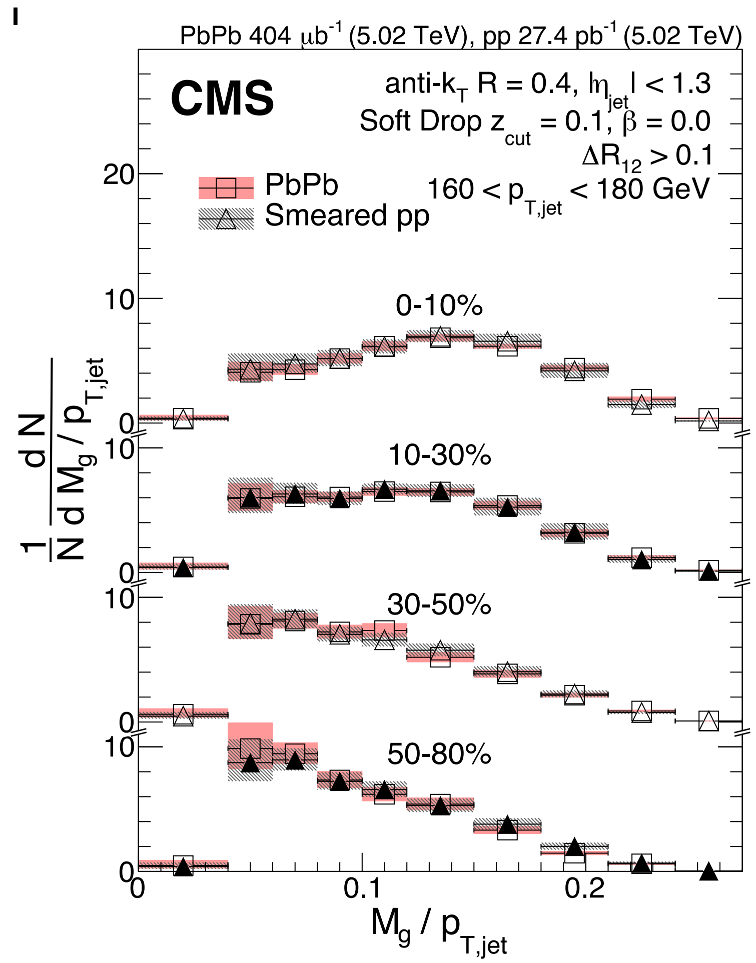
Energy distribution in subjets

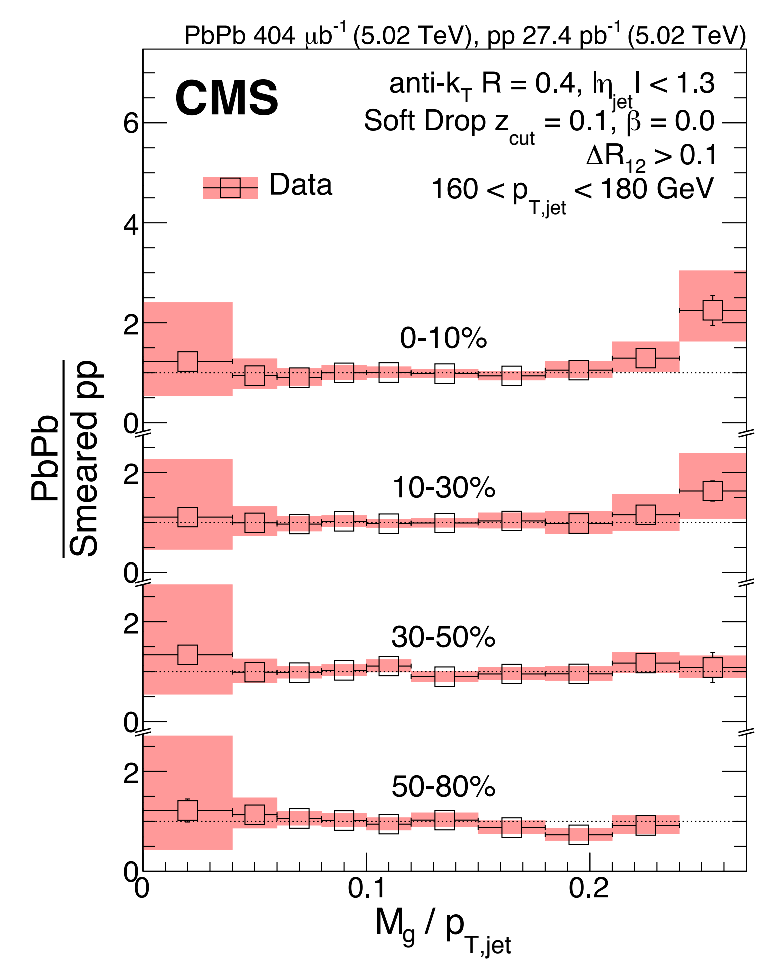


Reconstructed jets IV

New jet substructure techniques used in HIC







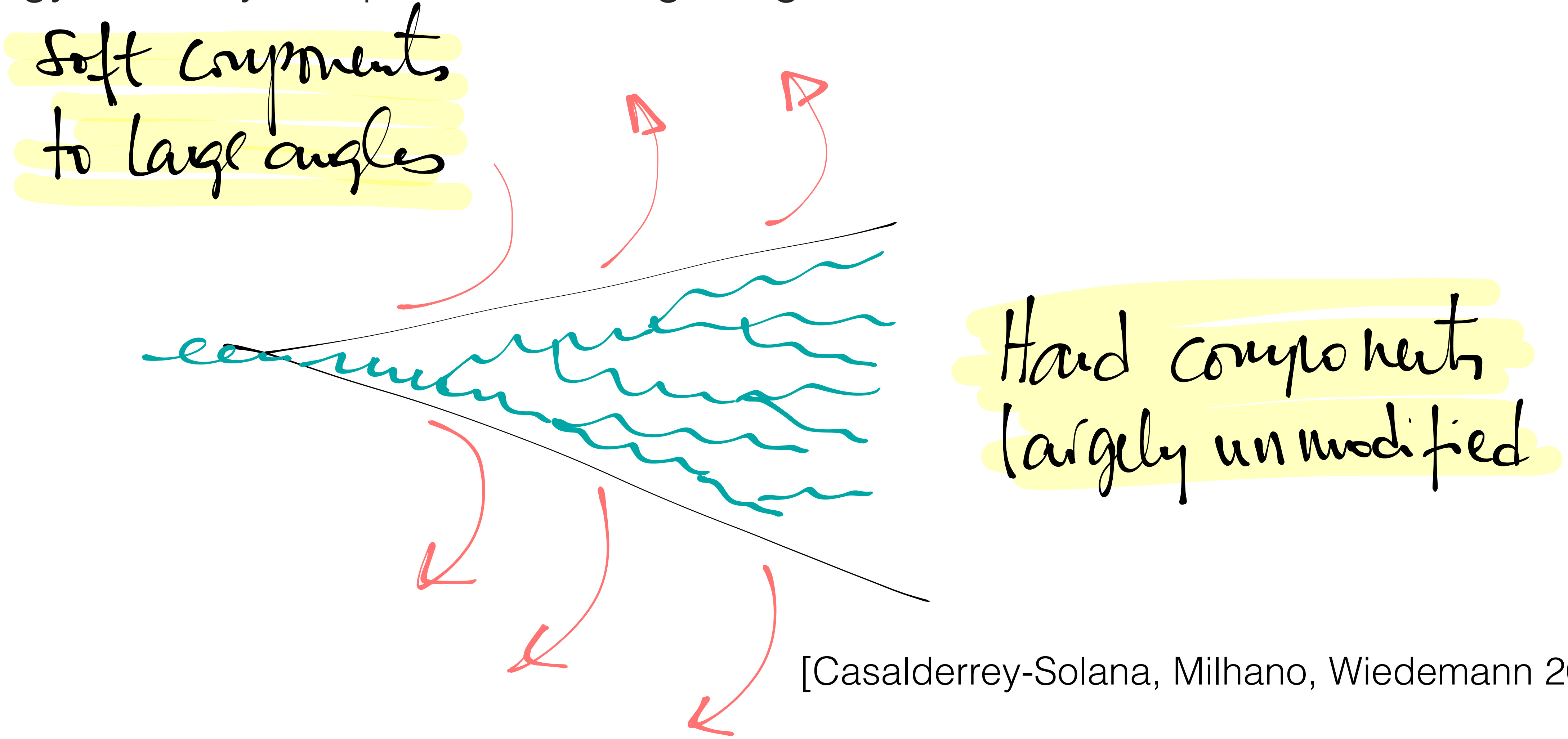
Jet grooming with soft drop

And much more….

Jet collimation

Lessons from experimental data on jet reconstruction

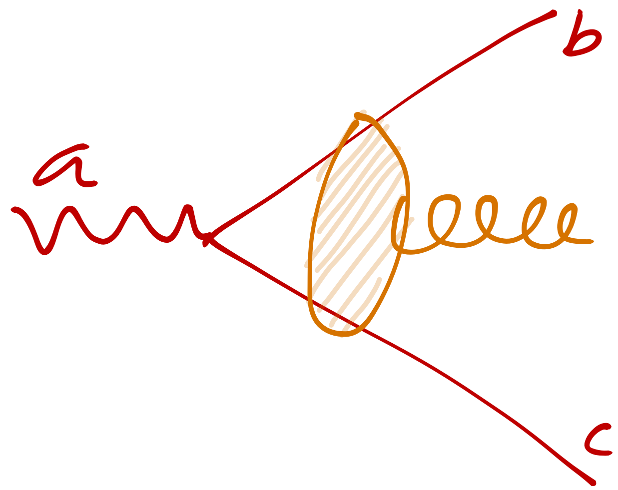
- Suppression similar to inclusive hadrons for similar pT
- Fragmentation functions are mildly modified - more in soft
- Jet shapes have mild modifications
- Azimuthal decorrelation of di-jets as in proton-proton
- Energy taken by soft particles at large angles



[Casalderrey-Solana, Milhano, Wiedemann 2011]

Coherence and decoherence

Antenna in the vacuum



$$r_\perp \sim \Theta\, t_{\rm form} \sim \frac{\Theta}{\theta^2 \omega}$$

$$\lambda_\perp \sim \frac{1}{k_\perp} \sim \frac{1}{\omega\theta}$$

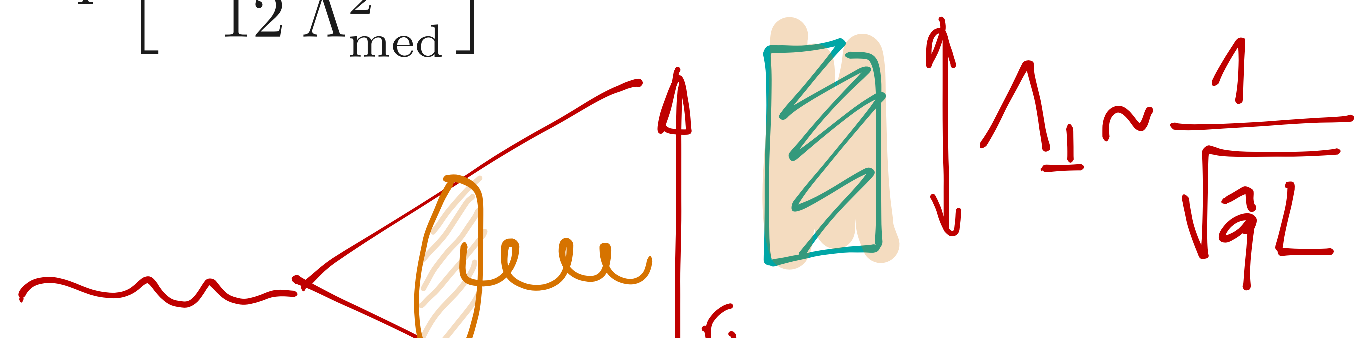
$r_\perp > \lambda_\perp \iff \Theta > \theta$

Coherent emission

Antenna in the medium

- Decoherence parameter

$$\Delta_{\rm med} = 1 - \exp\left[-\frac{1}{12}\frac{r_\perp^2}{\Lambda_{\rm med}^2}\right]$$



$$r_\perp \sim \Theta L$$

$$\Lambda_{\rm med} \sim \frac{1}{\sqrt{\hat{q}L}}$$

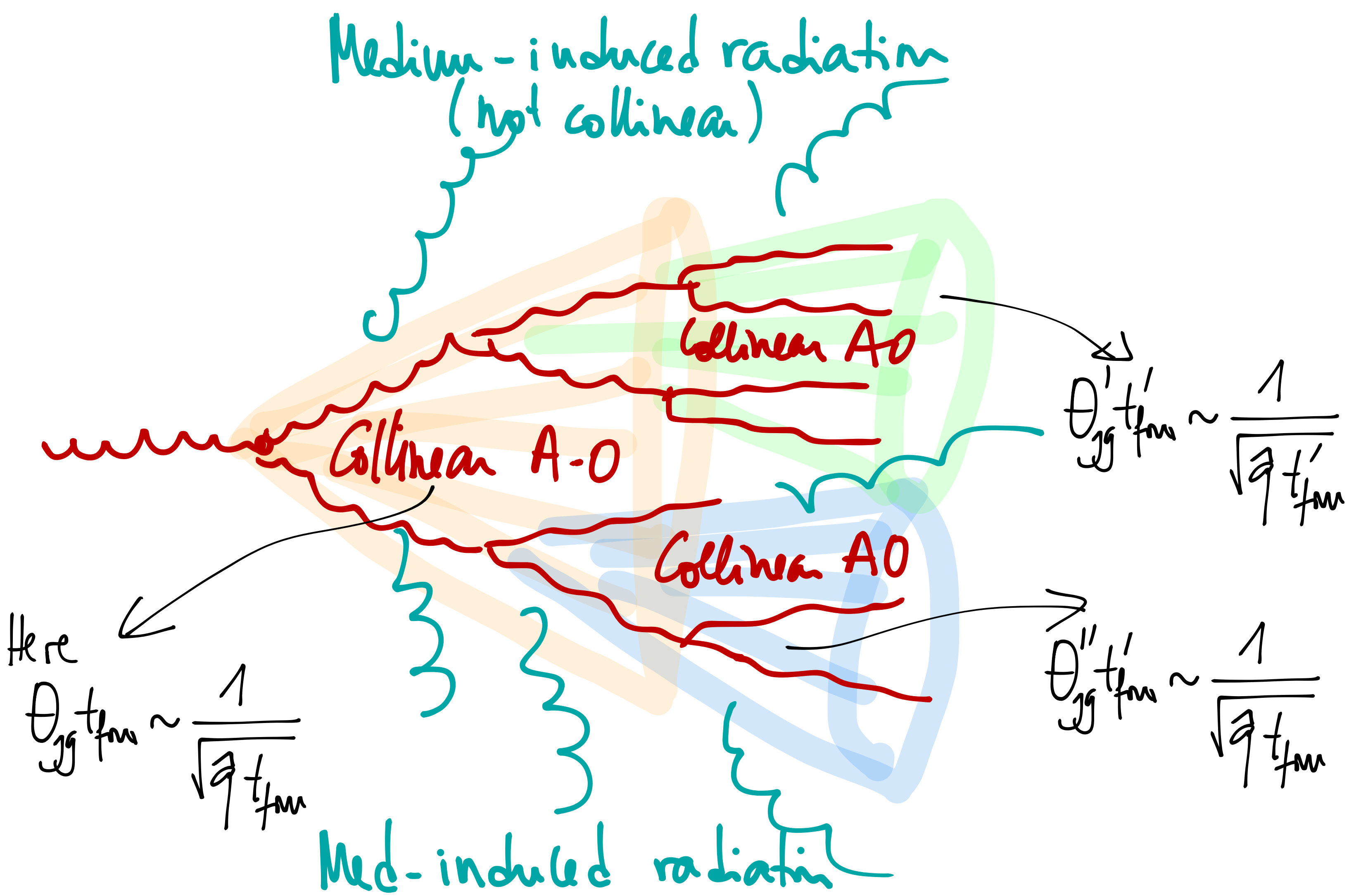
- The medium color-rotates the antenna which eventually looses color coherence

A new picture of jet quenching

[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

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**



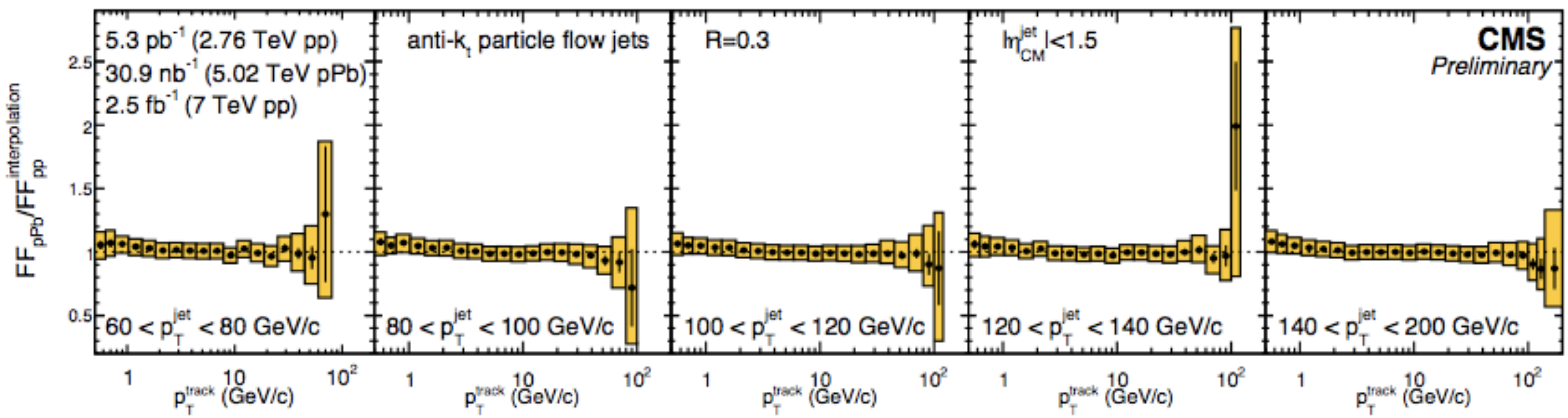
Color coherent sub-jets provide the organizational principle for the in-medium cascade

Jet quenching in pPb??

QGP-like effects observed in small systems (pp & pPb)

- Hydro behavior
- Strangeness enhancement [not shown here, see ALICE: Nature Phys. 13 (2017) 535-539]
- Quarkonia suppression

Is there also jet quenching in small systems



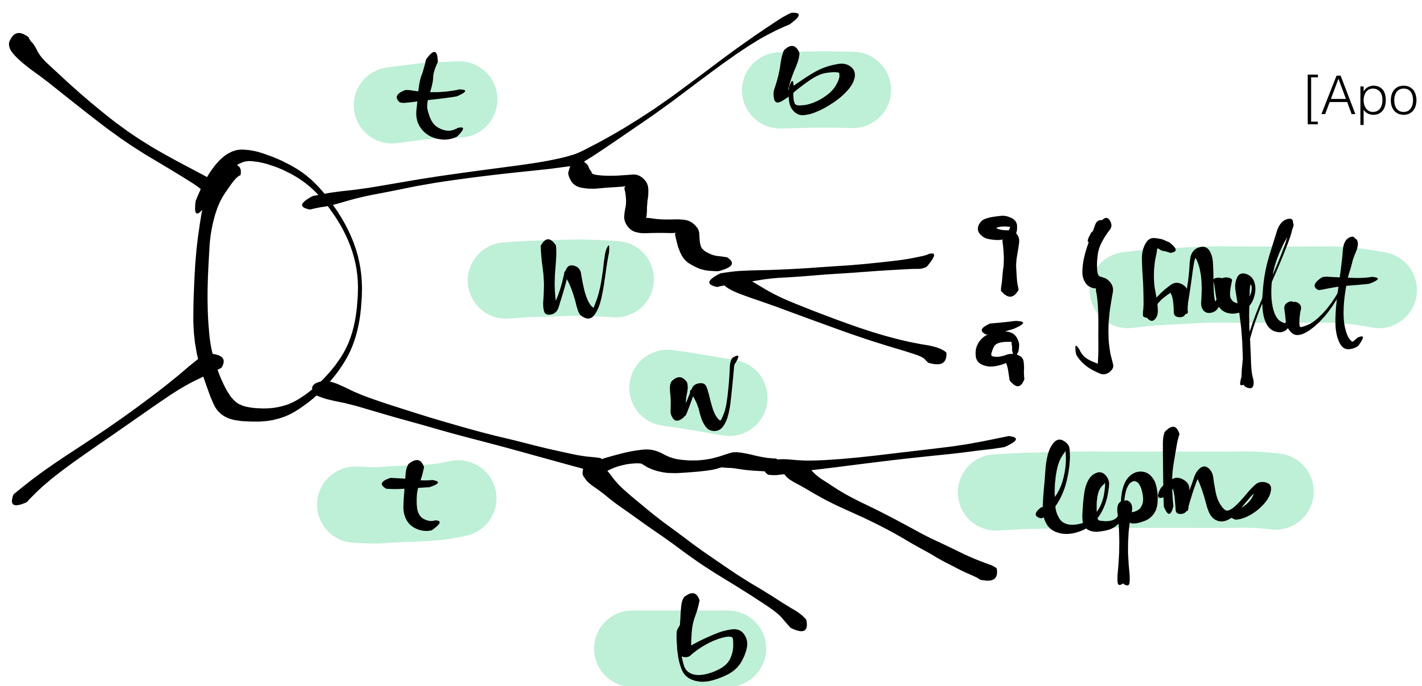
No sign of jet quenching in present data [also other not shown here]

A yoctosecond chronometer

Can we **more directly measure the space-time** development of the medium with jet observables? - including **late times**

Switch-off the cascade for some time

Use **color-singlet** configurations



[Apolinario, Milhano, Salam, Salgado 2018]

Boosted tops
a possibility

Main limitation: very rare - **high statistics needed (HL-LHC & FCC)**

Conclusions - lecture 2

Heavy-ion collisions to explore the first levels of complexity in the SM

>20 years program — a hot and dense QCD system created in AA collisions
— small viscosity: **a perfect liquid**

We know that the hot system is created, **but how?**

- What is the mechanism that so efficiently (less than 10ys) drives the system towards equilibrium
- Is there thermalization in small systems? (pp & pPb) typical size ~1fm or 3ys
- If there is thermalization, why there is no effect in jet quenching?

Possibility to collide **smaller ions** at the LHC (XeXe this year in a pilot run).

Main advantage — **large gain in integrated luminosity for hard processes**

Lot of new experimental tools available to explore the first 10ys of the collision