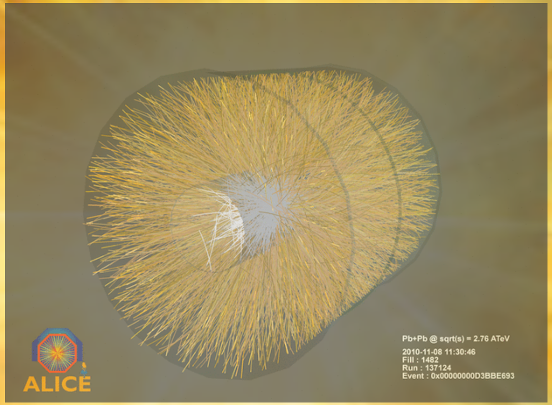
Physics from ALICE

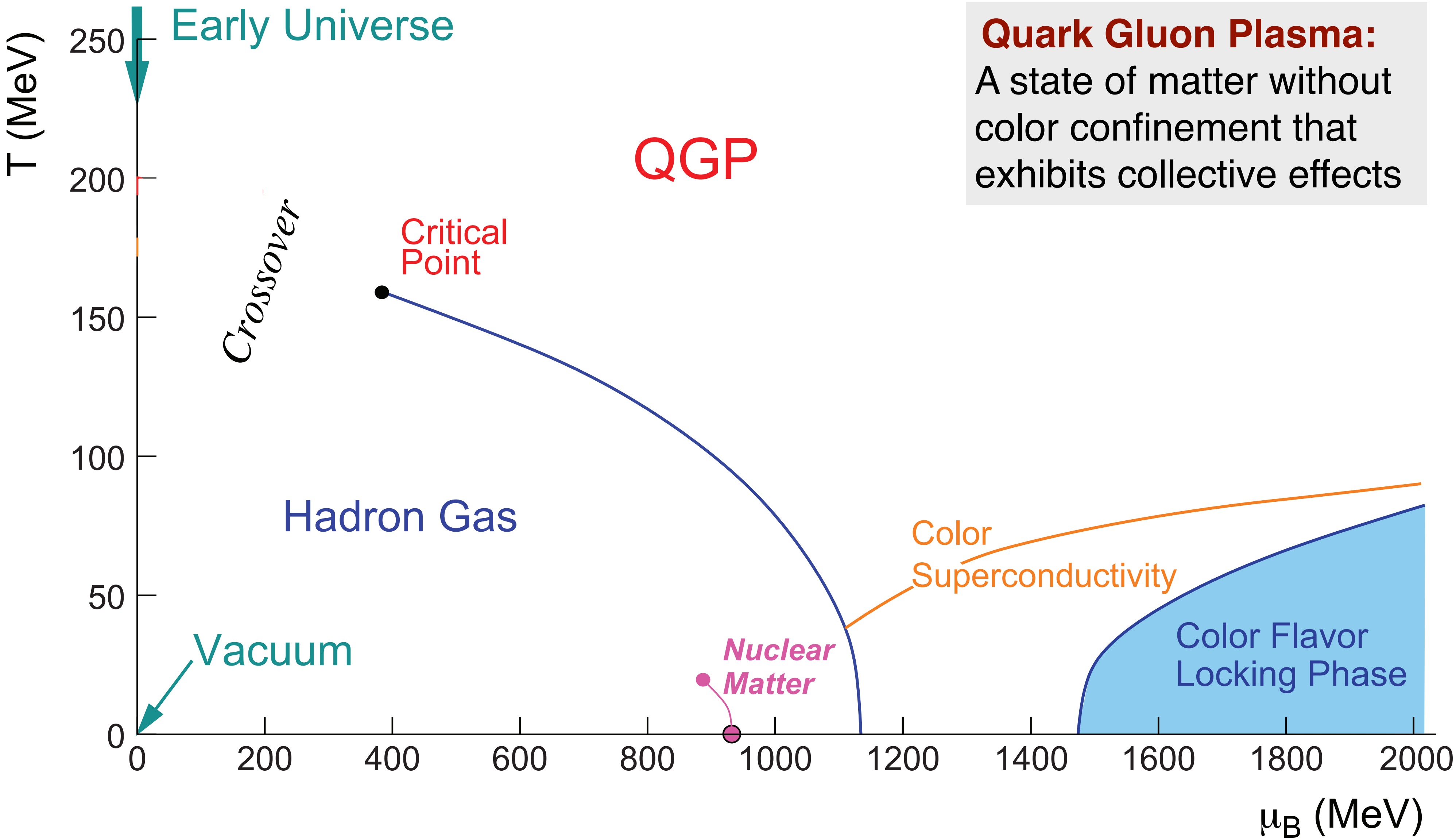
Jörn Putschke

for the ALICE Collaboration

(Wayne State University)

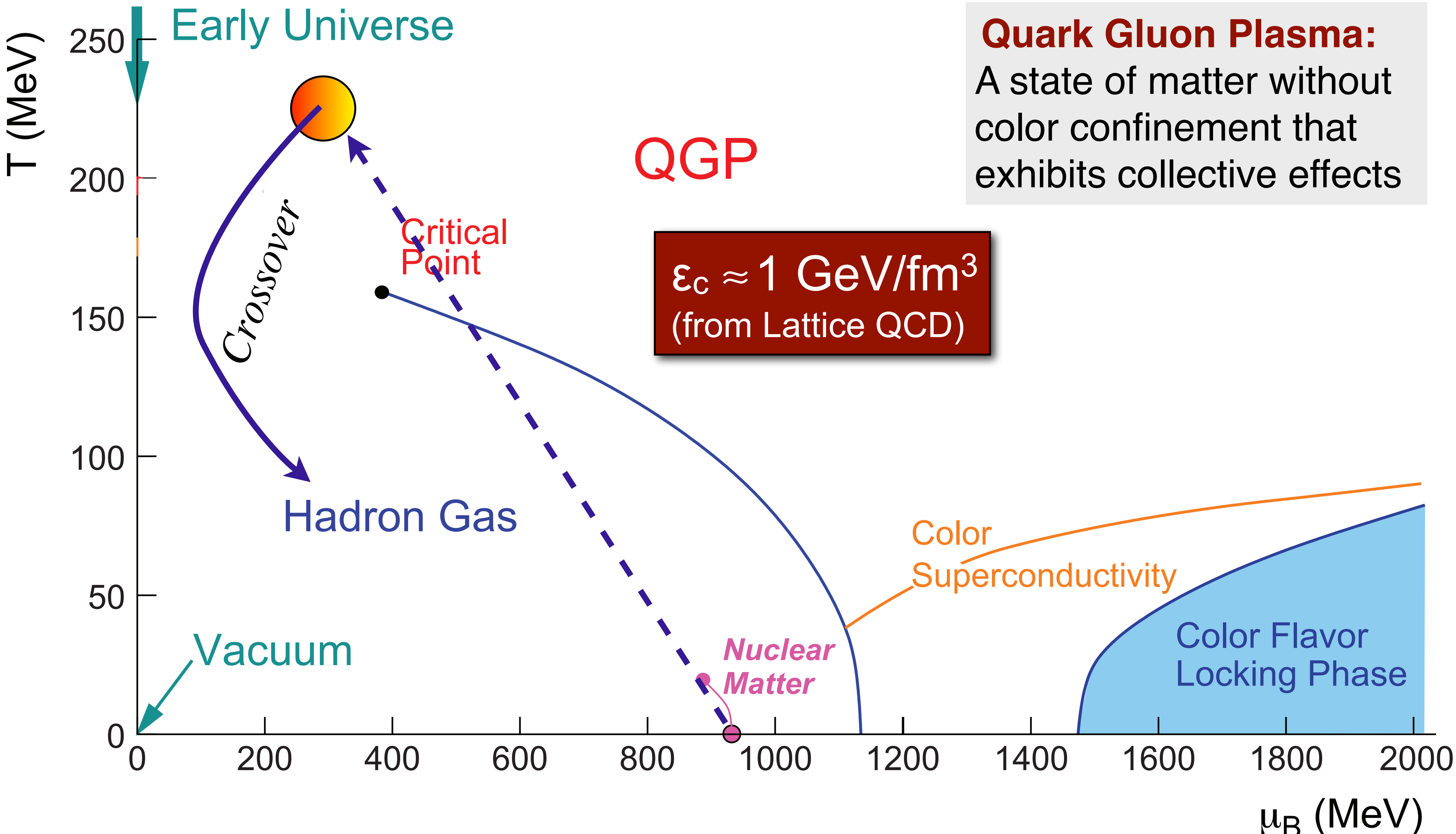


QCD Matter Phase Diagram



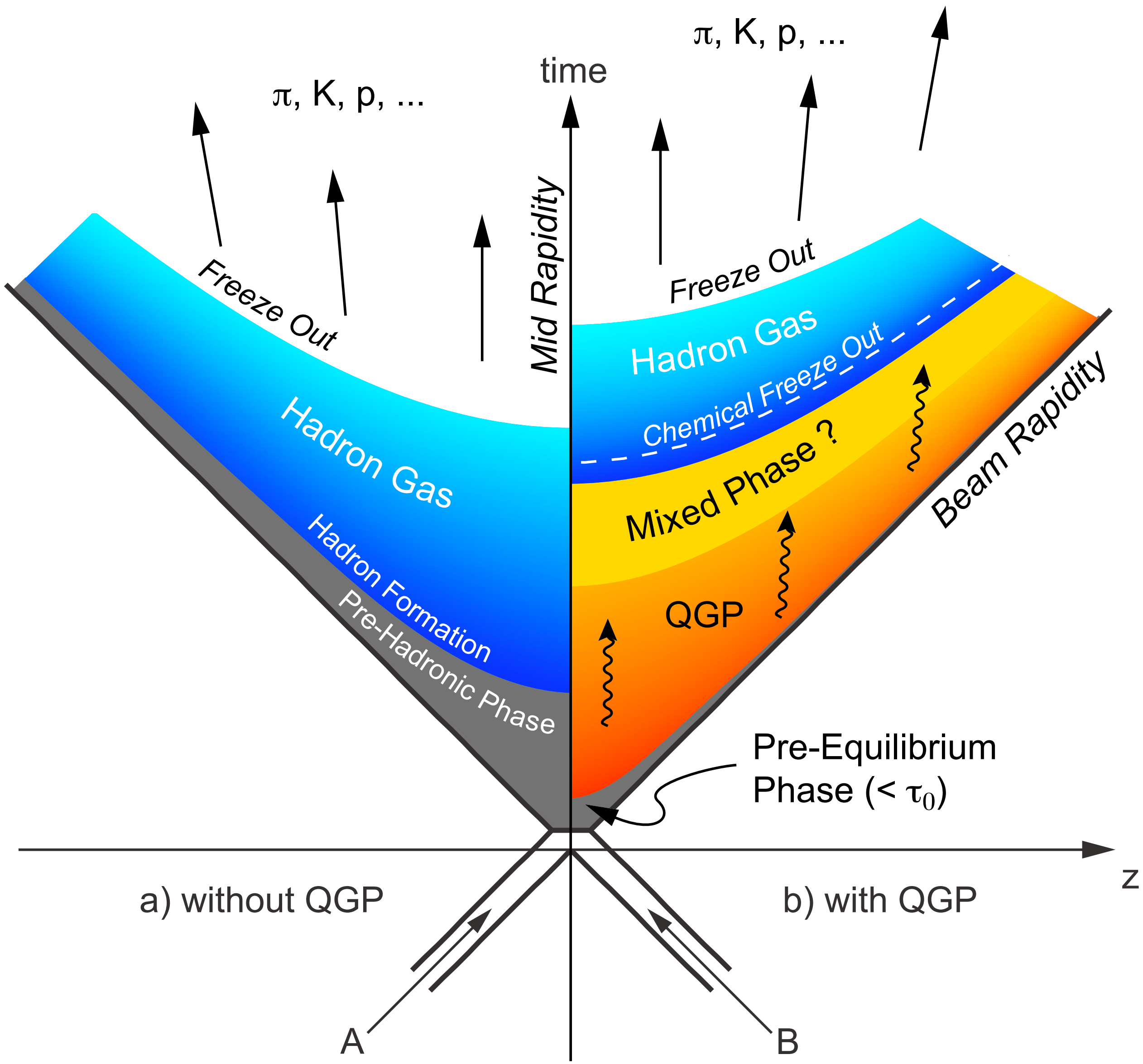
Quark Gluon Plasma:
A state of matter without color confinement that exhibits collective effects

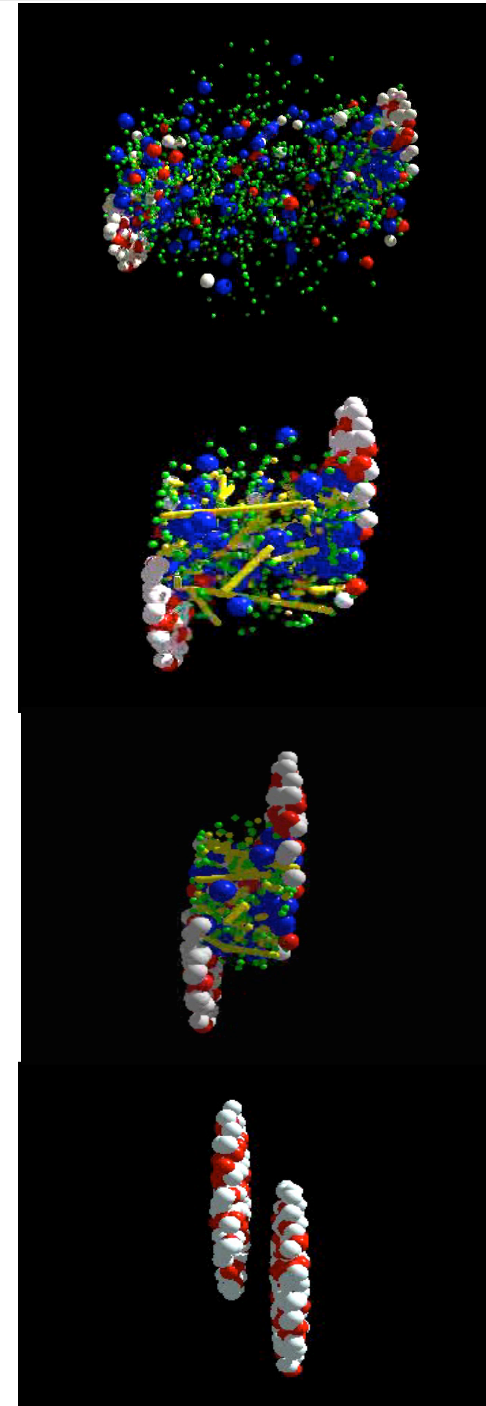
QCD Matter Phase Diagram



Basic Idea: *Smash* heavy nuclei (Pb) at highest possible energy (LHC)
⇒ create conditions (*hot* and *dense*) sufficient to "melt" matter into a QGP
(the state of all matter ~6 μs after the Big Bang)

Space-Time Picture of a Heavy-Ion Collisions





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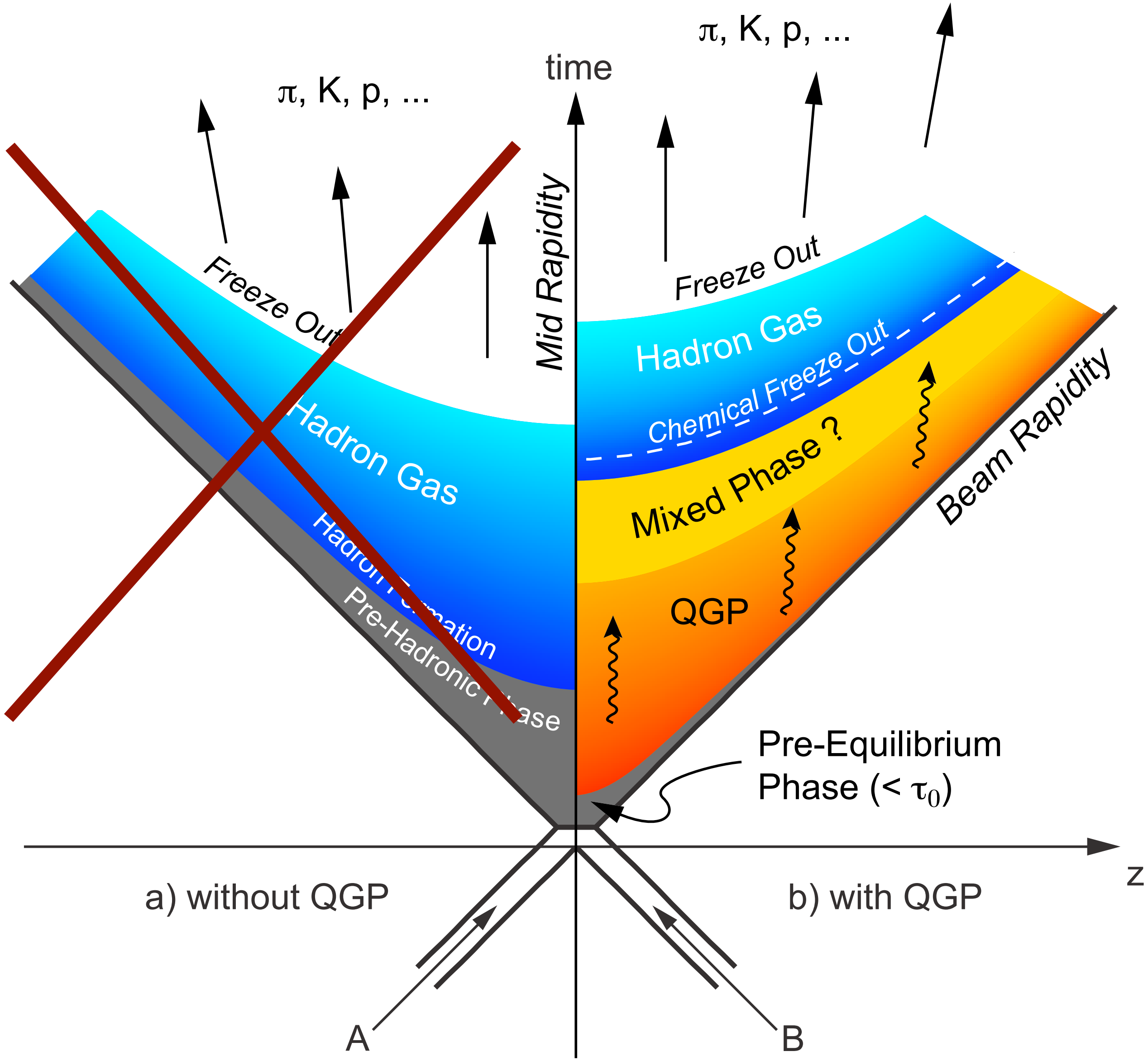
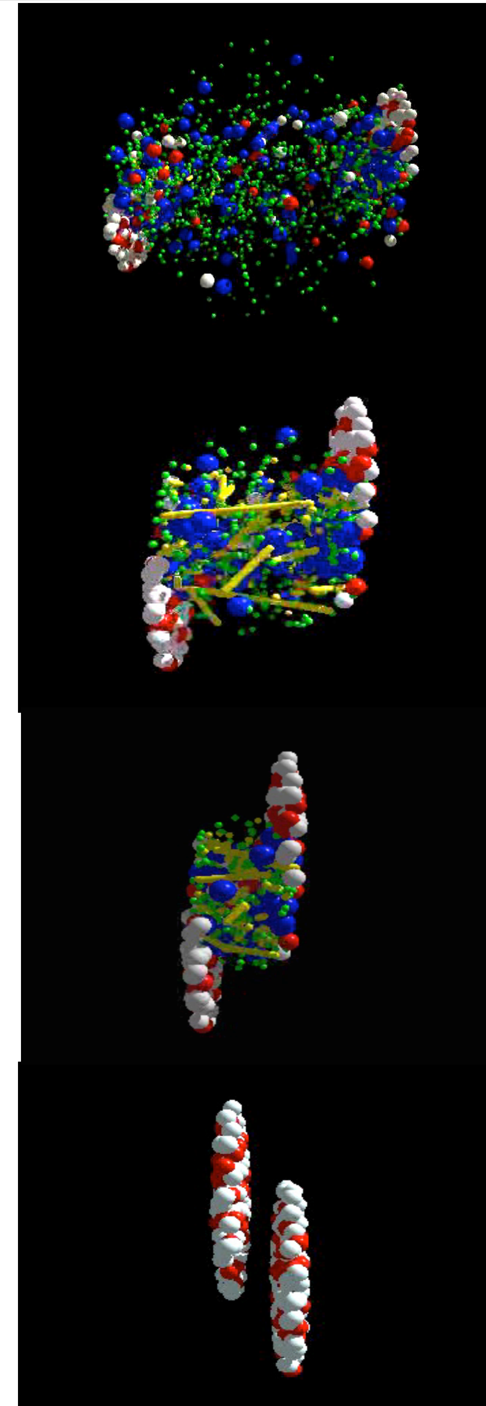
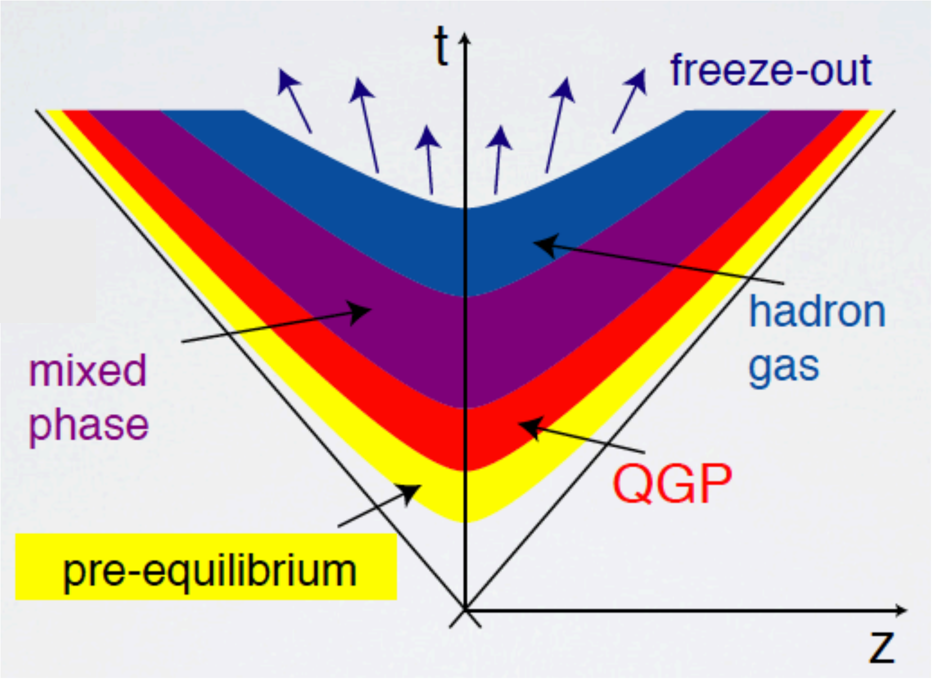




The “Standard Model” in Heavy-Ion Physics

and a (small) selection of measurements/probes
I will discuss in this talk ...



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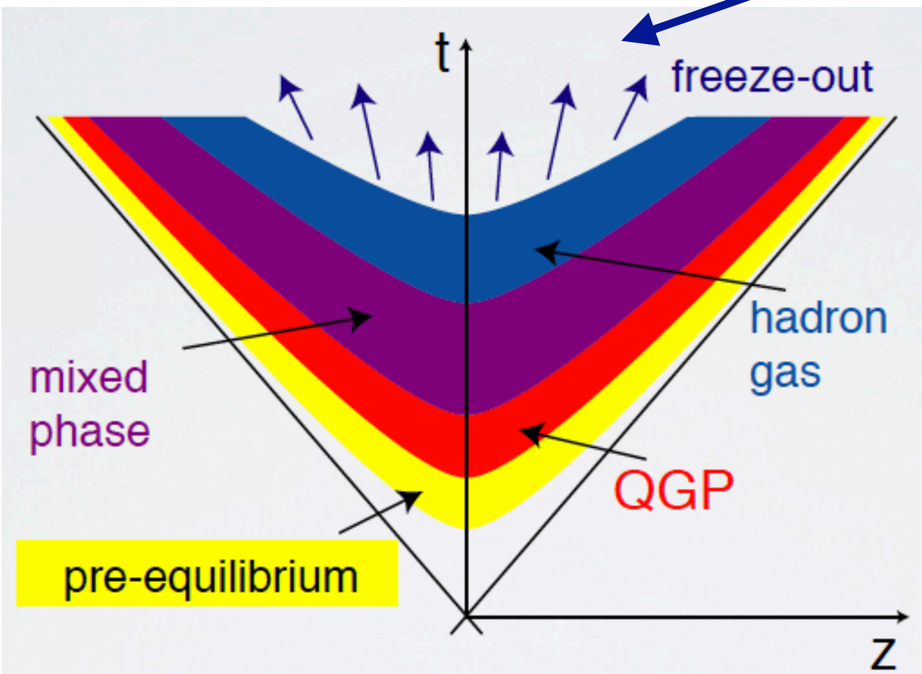

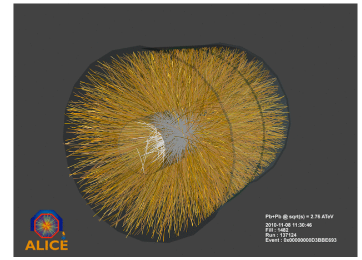

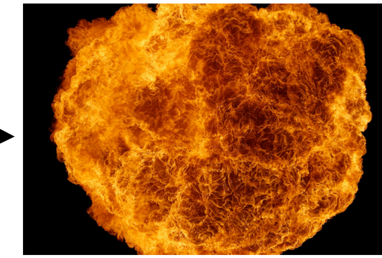

Bulk properties; radial flow

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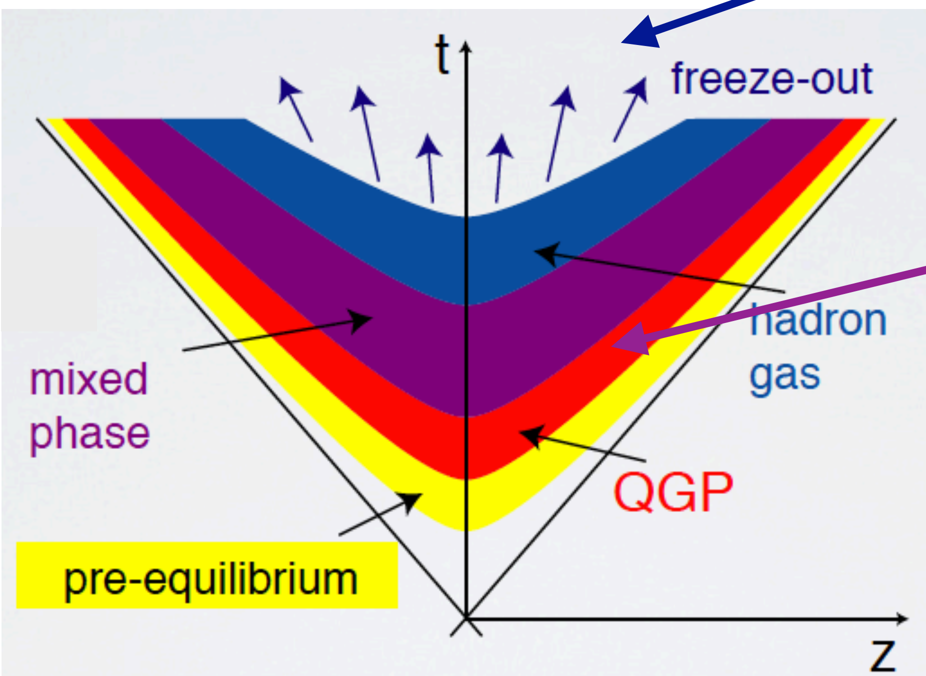

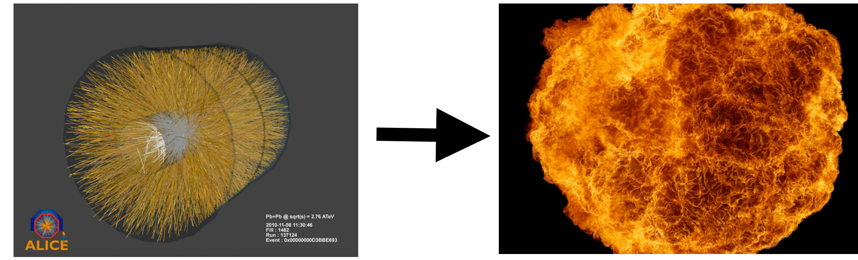

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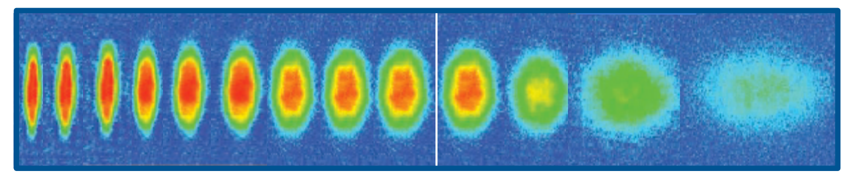

Elliptic (higher harmonic) hydrodynamic flow

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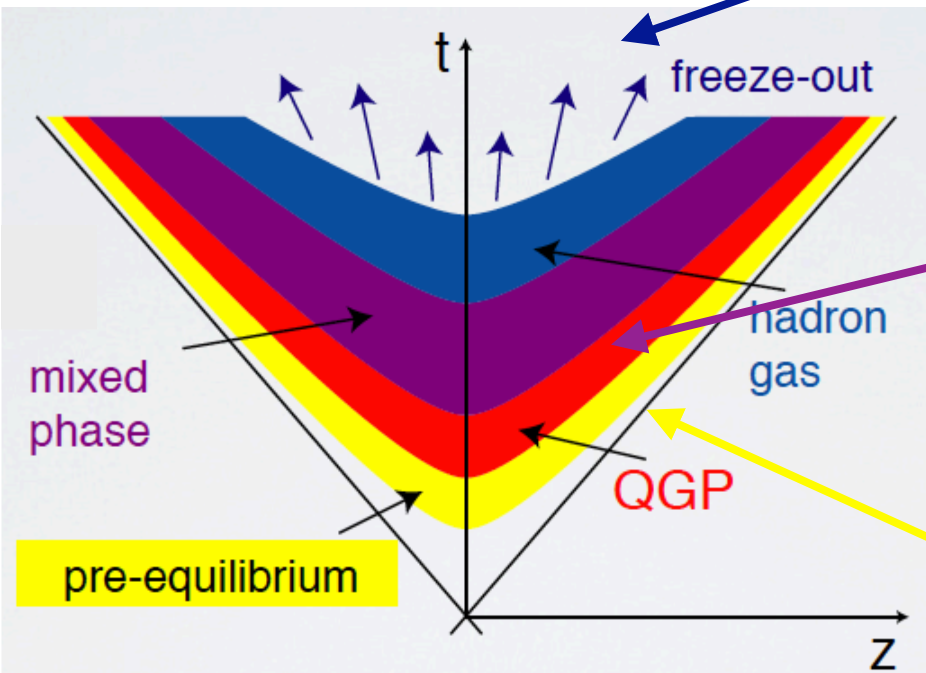

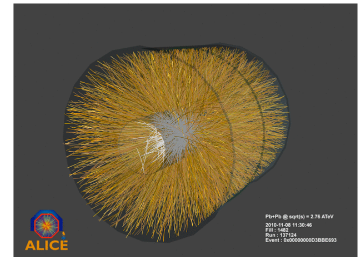

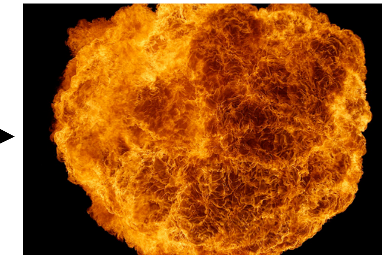

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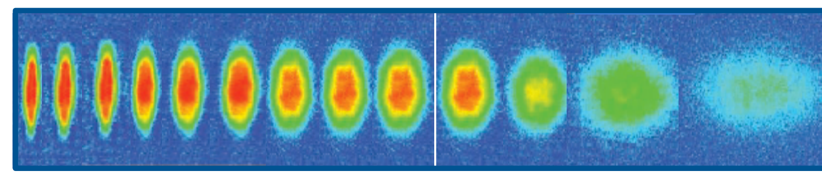
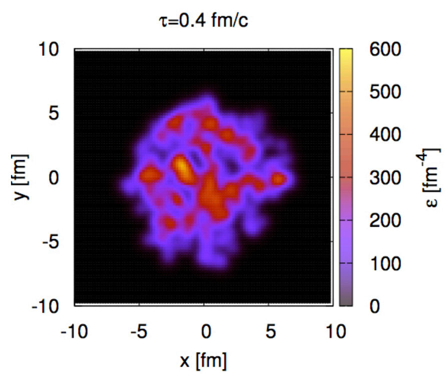


Elliptic (higher harmonic) hydrodynamic flow

Look at the initial state



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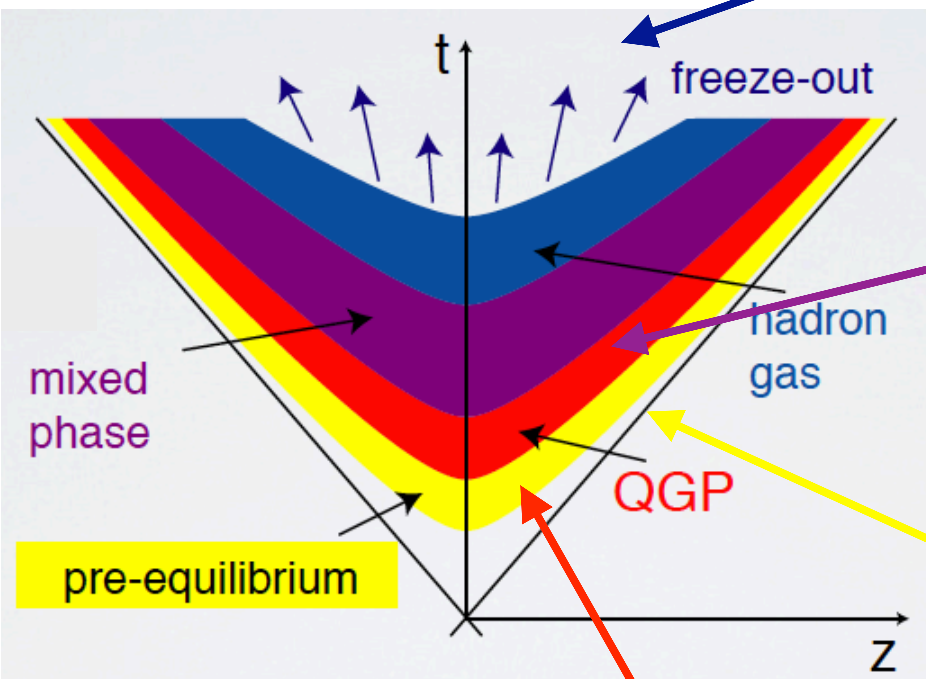

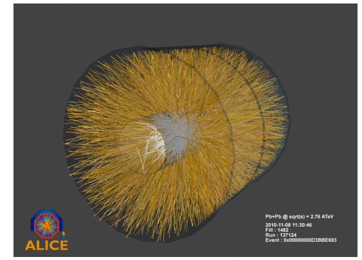

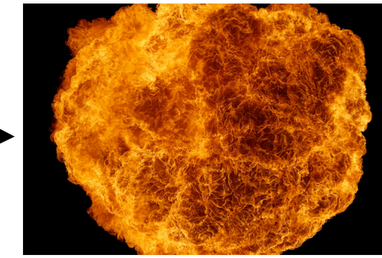

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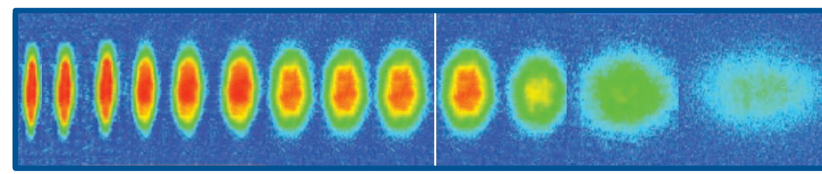

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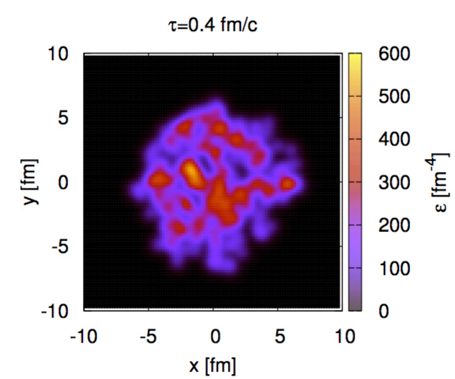
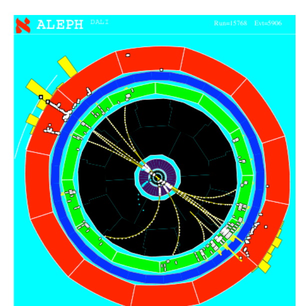
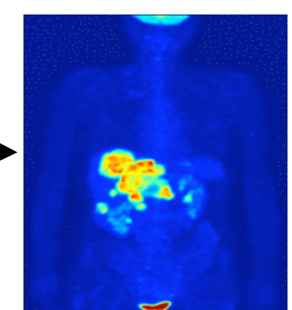


Jet (quenching) = QGP tomography





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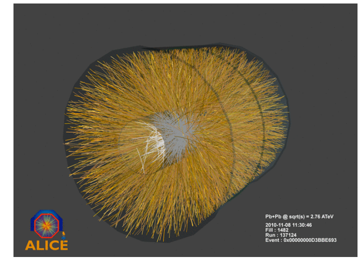

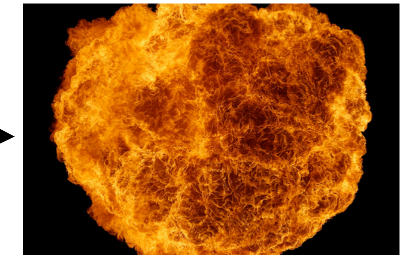

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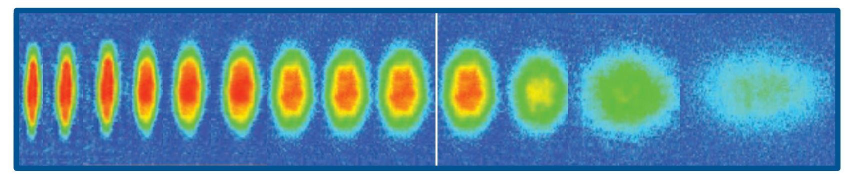

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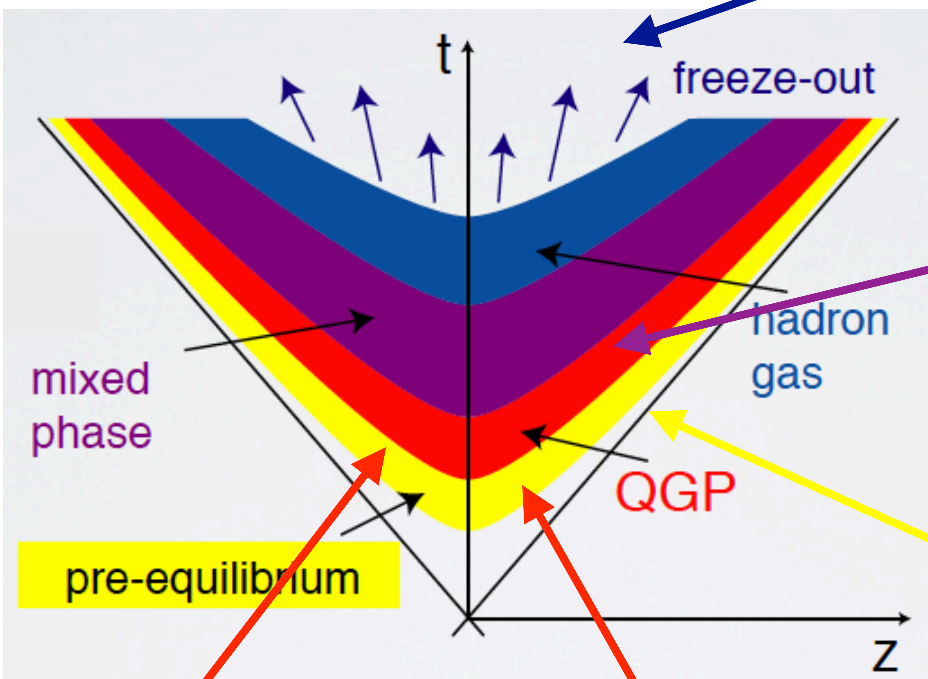

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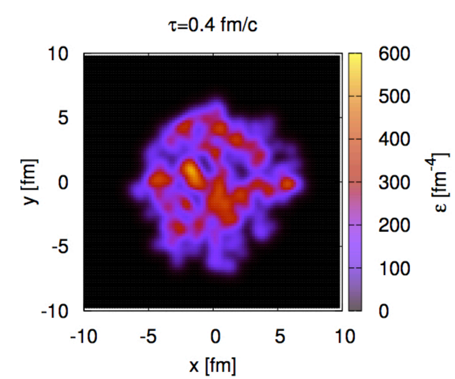
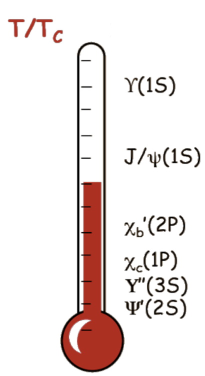


Quarkonia, J/ψ suppression as a thermometer



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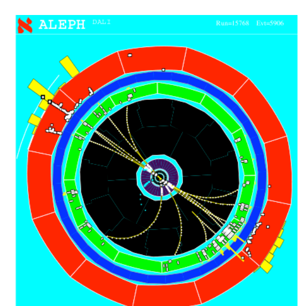
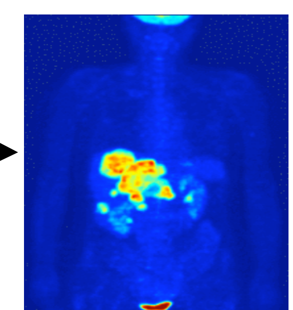
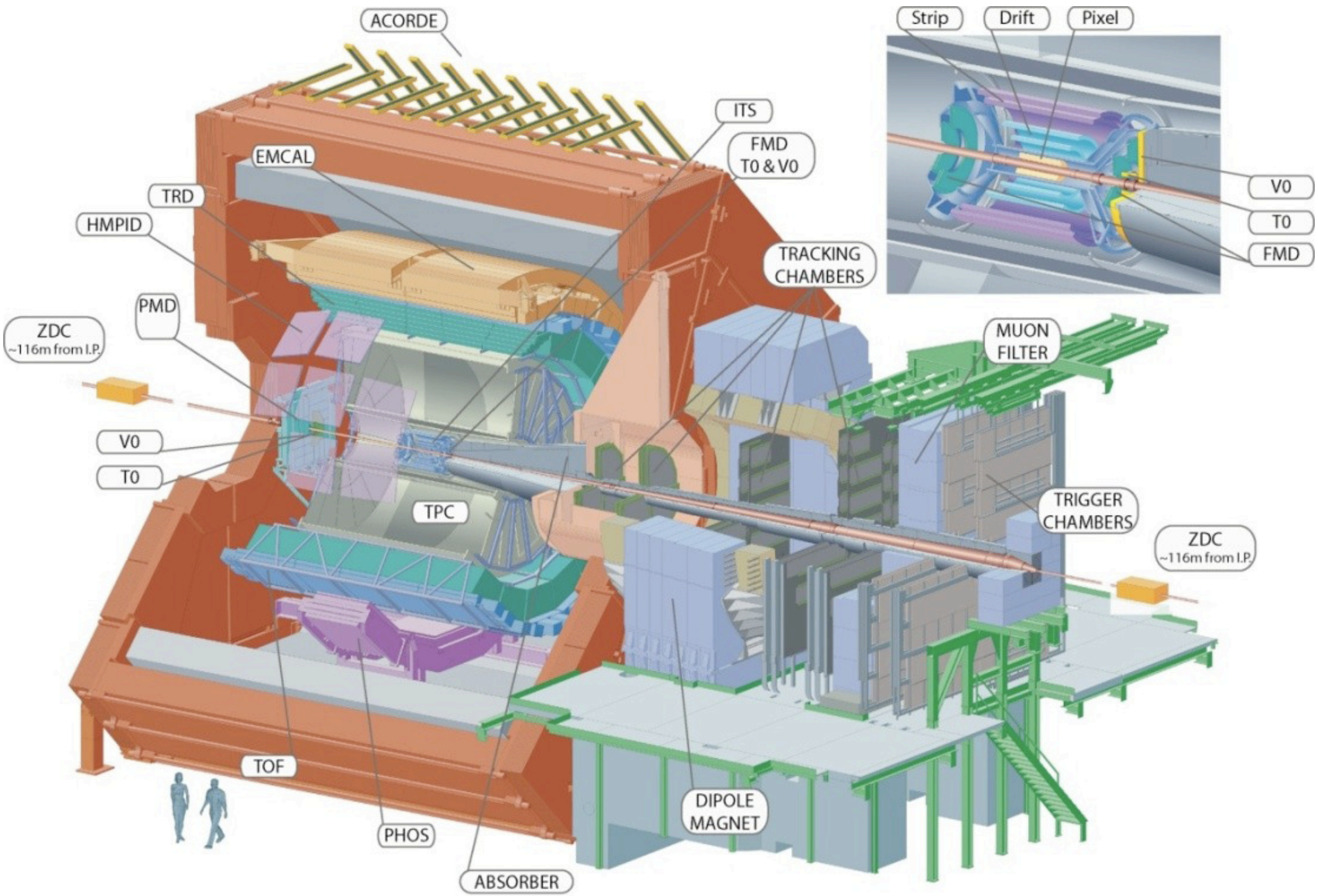
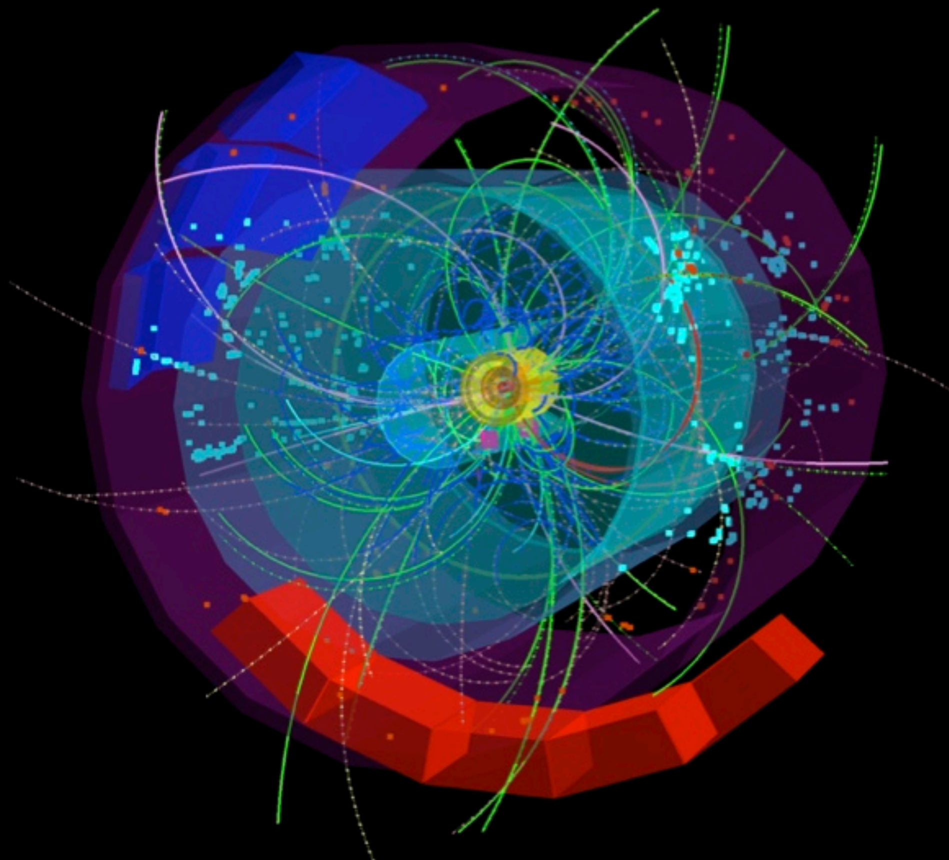




The ALICE Experiment

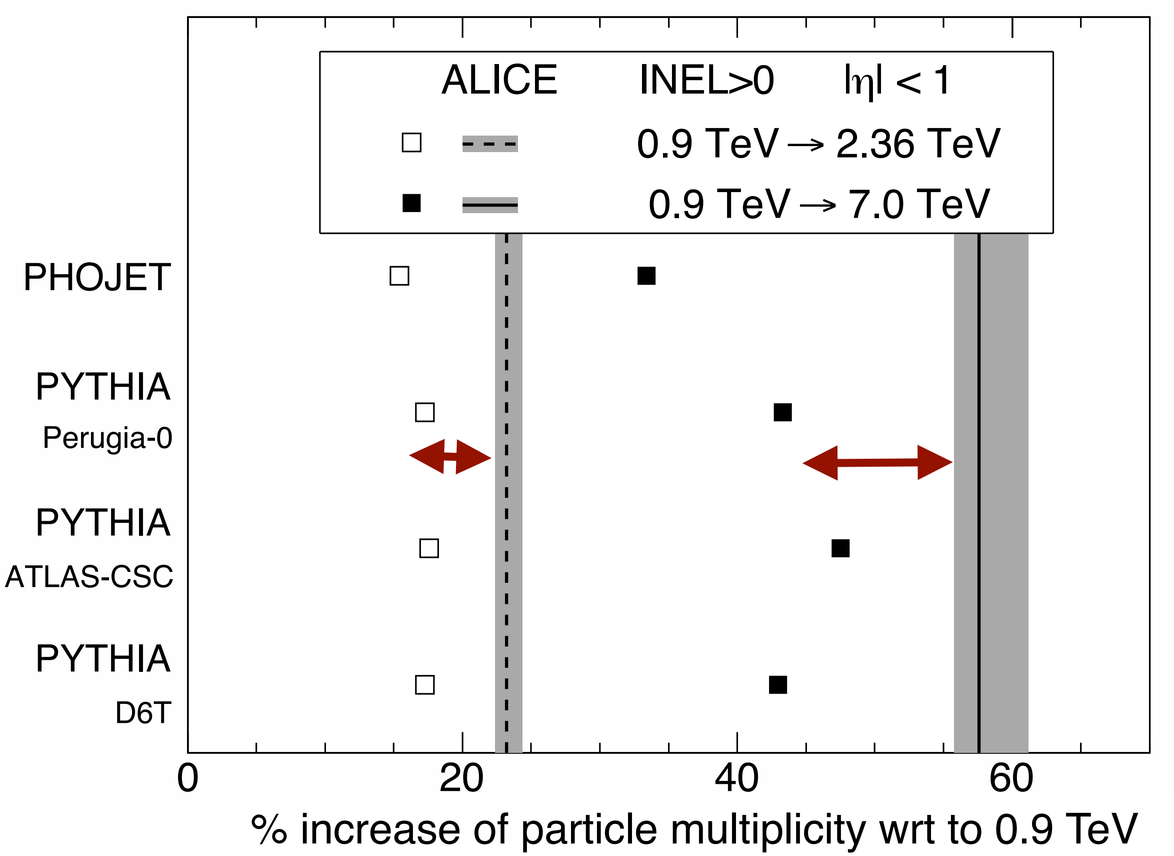


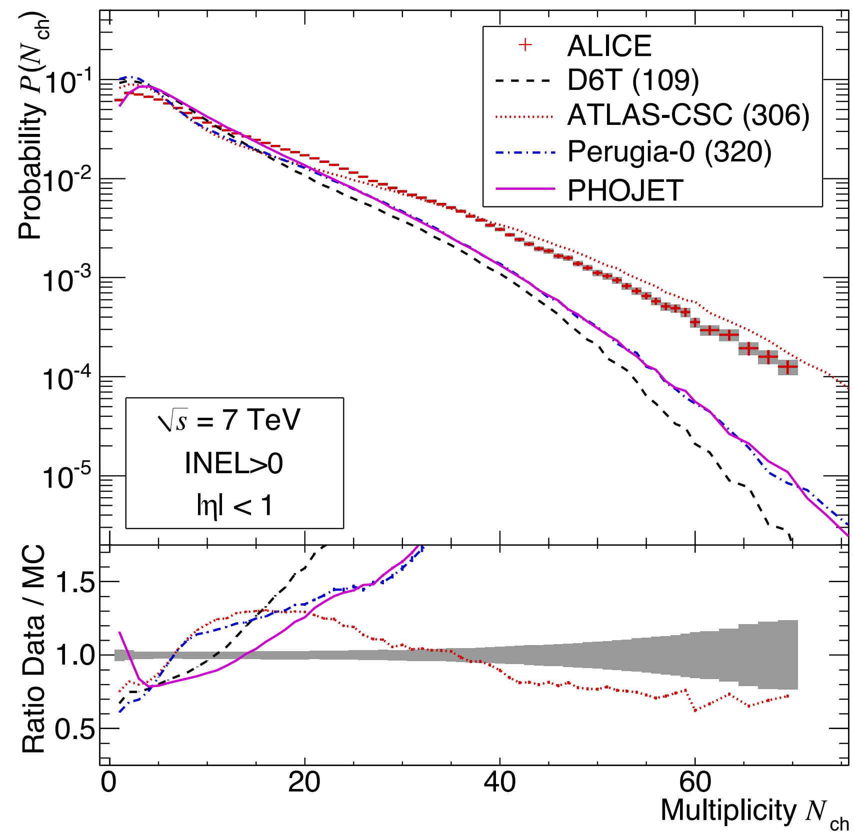
p+p collisions in ALICE
not only a reference ...



Particle Multiplicity in p+p Collisions

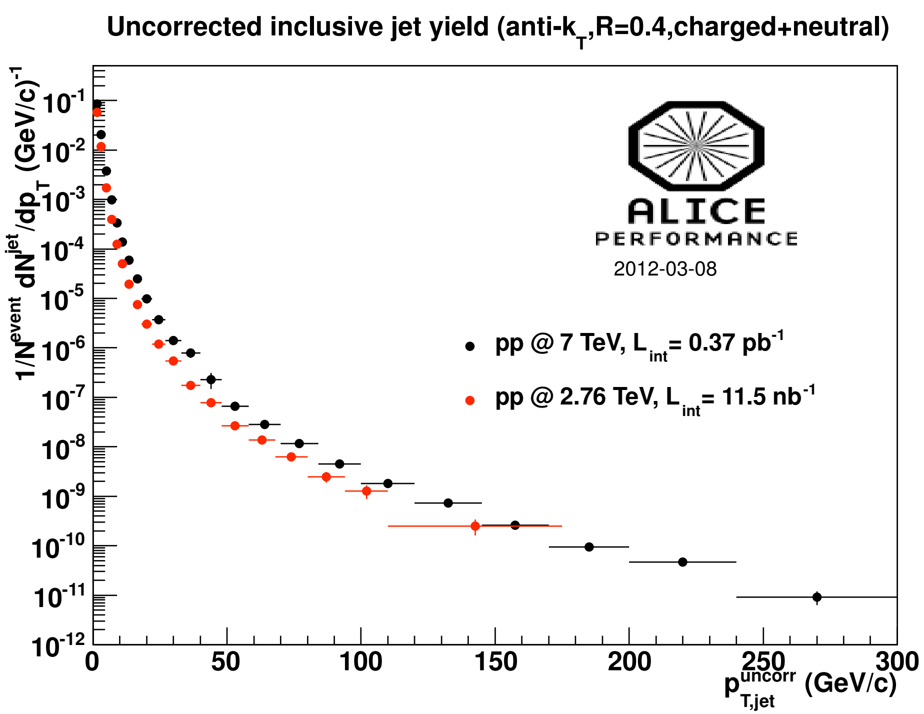
Eur. Phys. J. C68 (2010) 345-354

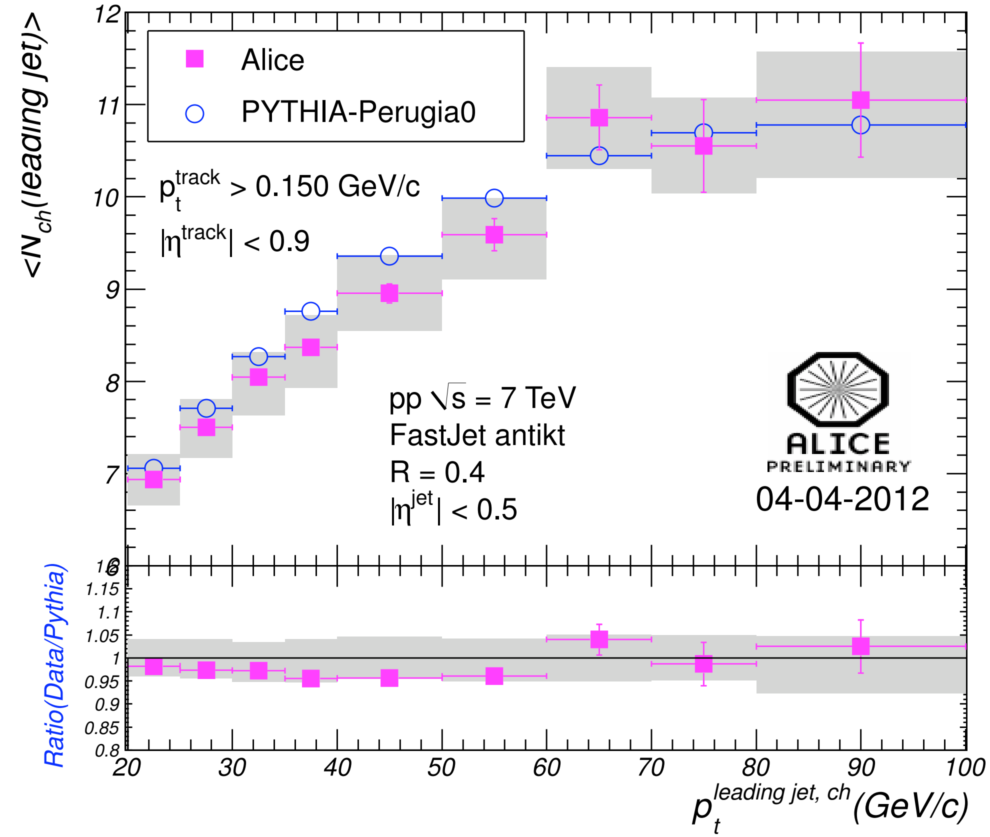




Particle multiplicity and density are sensitive measurements and can be used to tune p+p Monte Carlo Generators!

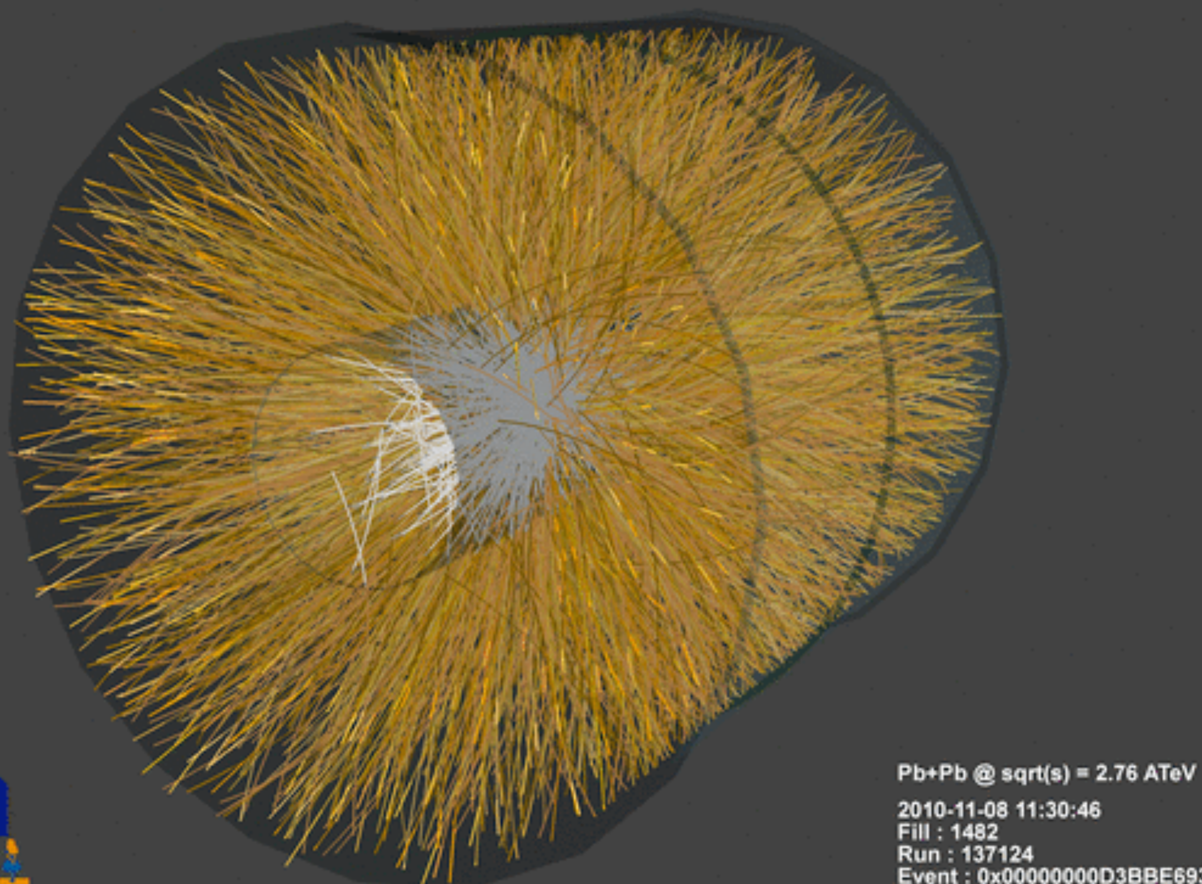
Jet Structure Observable(s) in p+p collisions





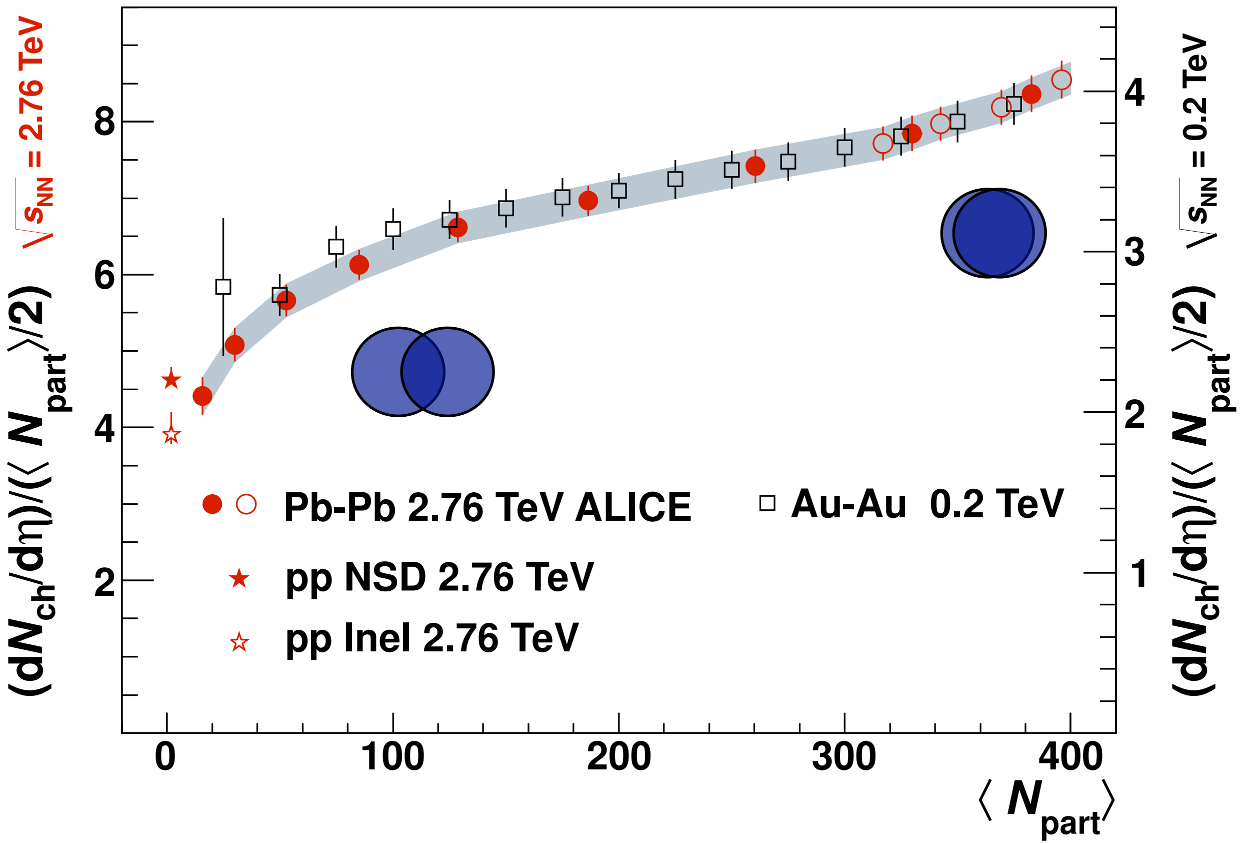
Excellent tracking and PID capabilities in ALICE over a wide p_T range will be used to measure jet structure observables and in particular particle identified jet fragmentation functions!

Heavy-ion Collisions in ALICE
- The Bulk -



The Bulk - Particle Multiplicity in HI Collisions

PRL 106 (2011) 032301



Particle Multiplicity increases with √s

Similar centrality dependence as at RHIC

The Bulk - Particle Multiplicity in HI Collisions

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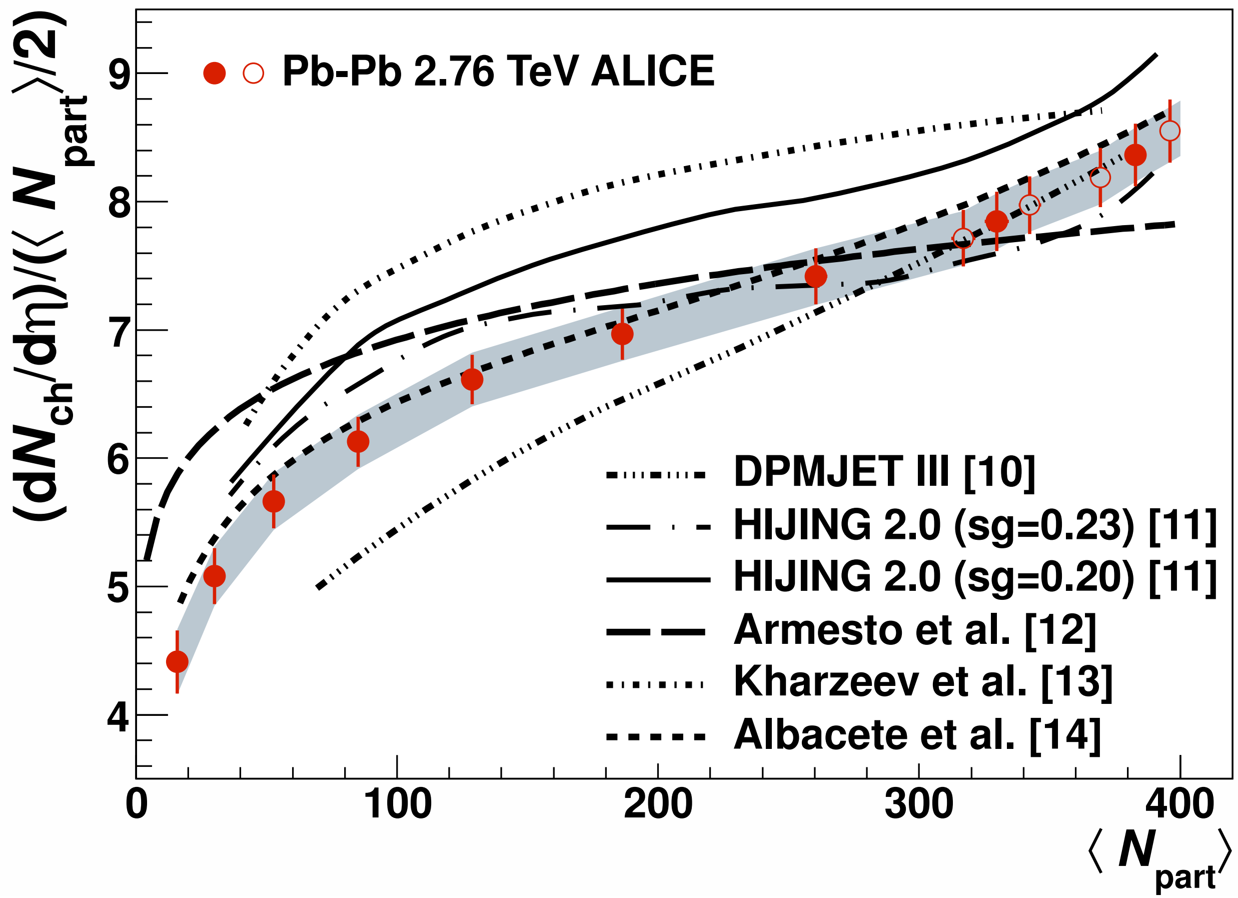
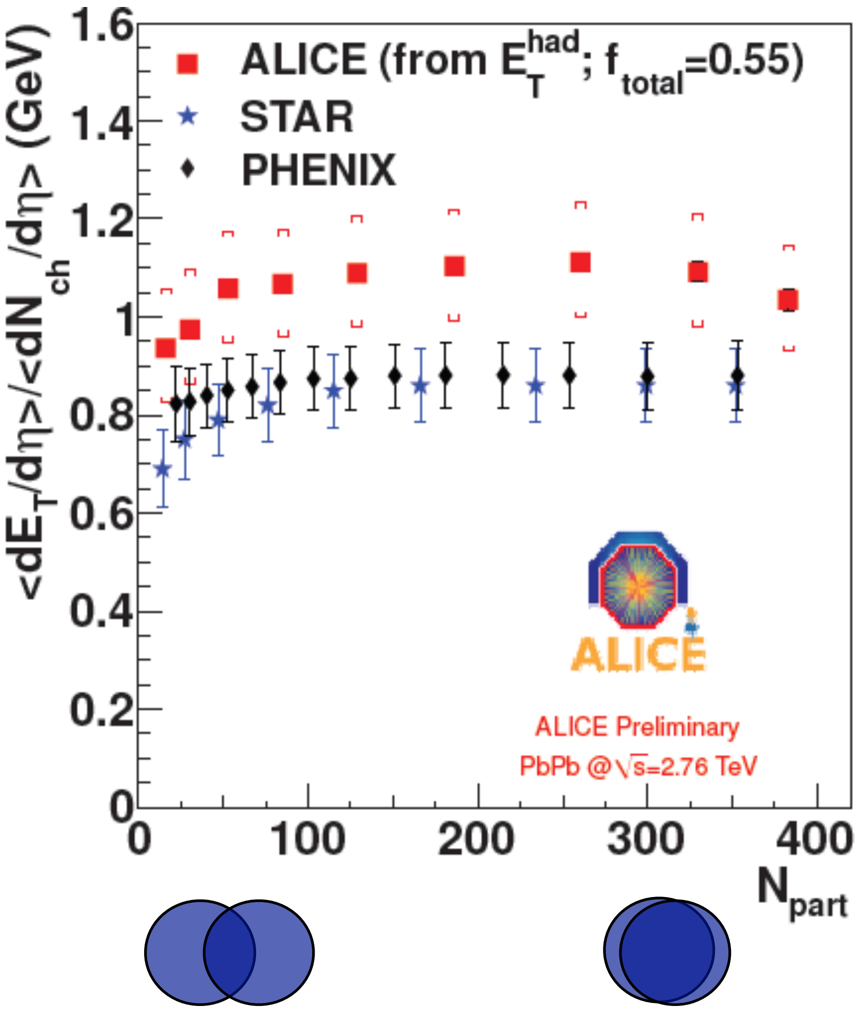


Particle Multiplicity increases with √s

Similar centrality dependence as at RHIC

Centrality dependence put strong constraints on theoretical calculations

The Bulk - Energy density in HI Collisions



Bjorken estimate of energy density:

$$\varepsilon_{Bj} = \frac{1}{\tau\pi R^2}\frac{dE_T}{d\eta}$$

Formation time τ unknown, but of the order < 1 fm/c

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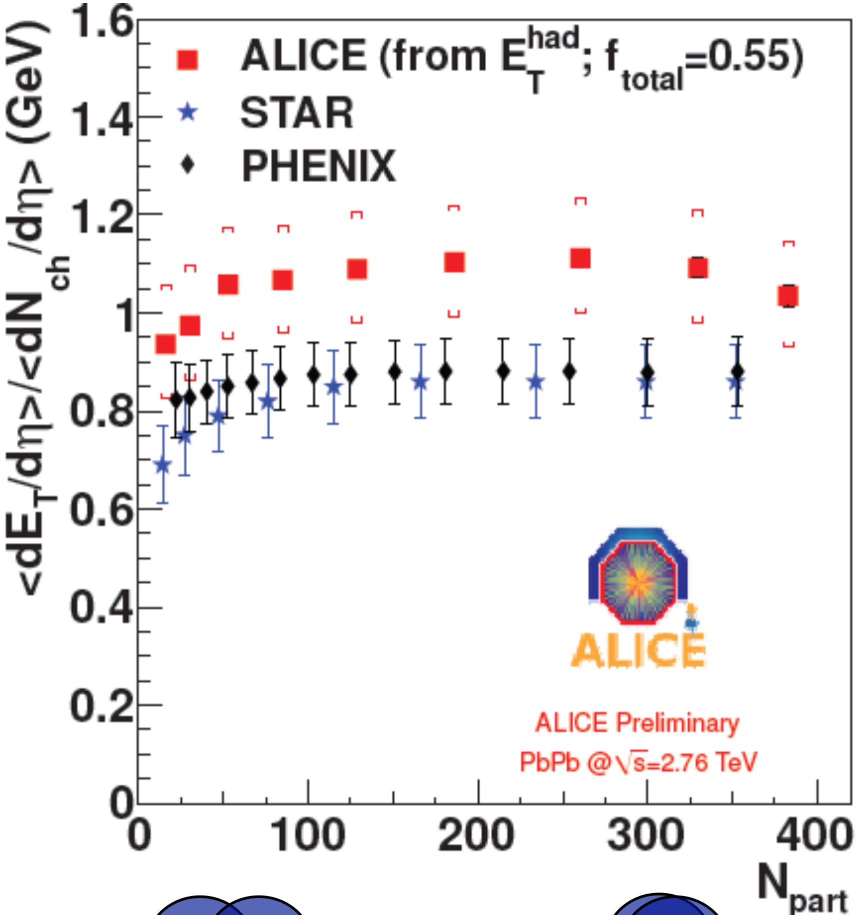

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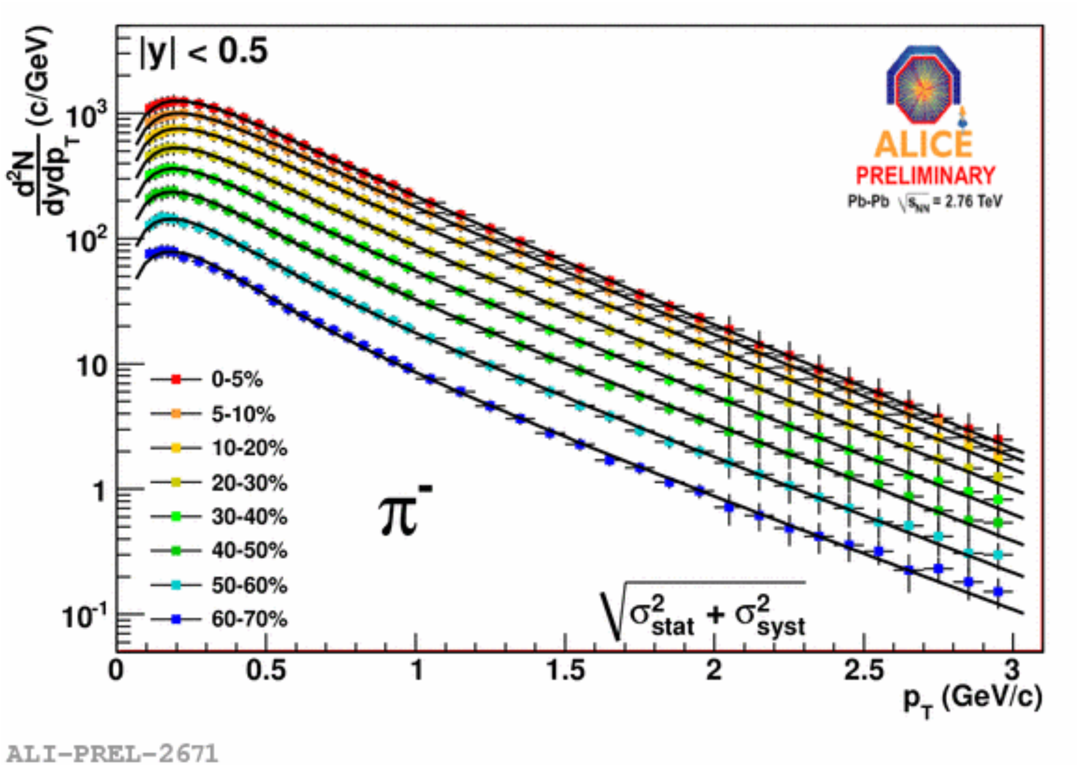
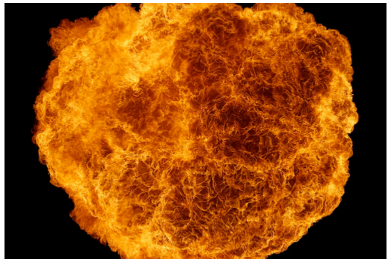
⇒ **ετ: LHC ~ 2.5 x RHIC**

⇒ **ε_{BJ} well above ε_C~1 GeV/fm^3**

Radial Flow - Collective Transverse Expansion





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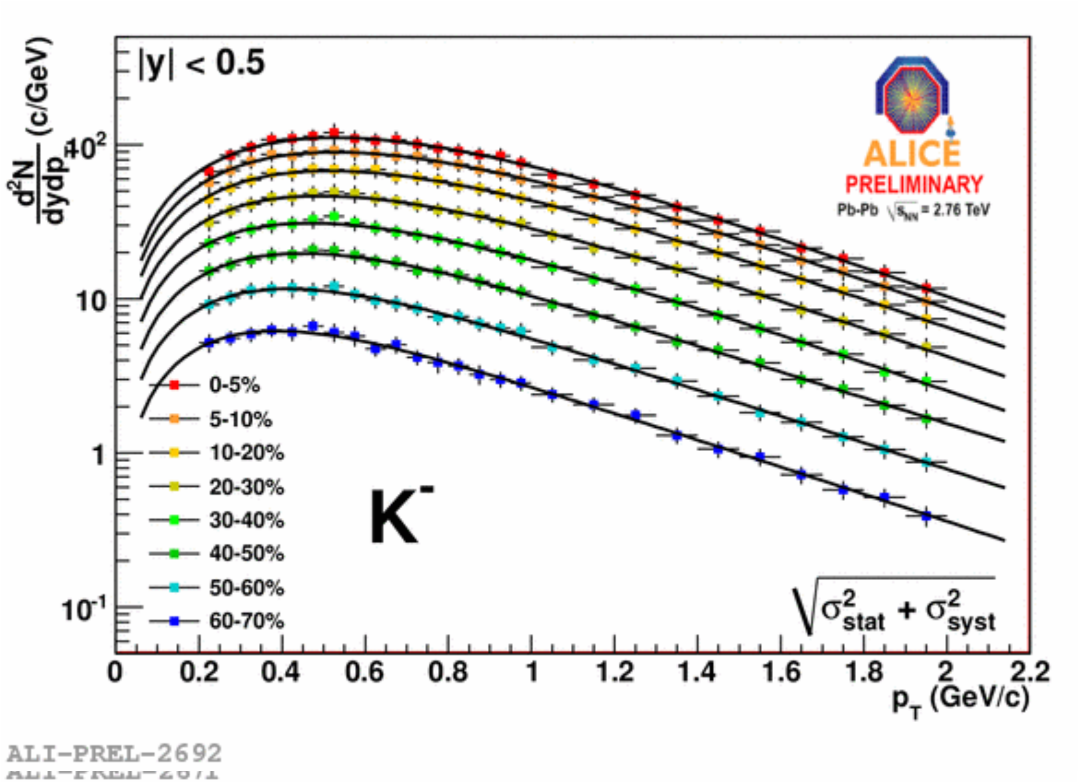

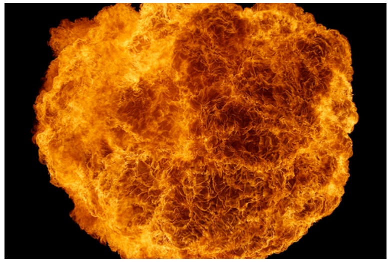

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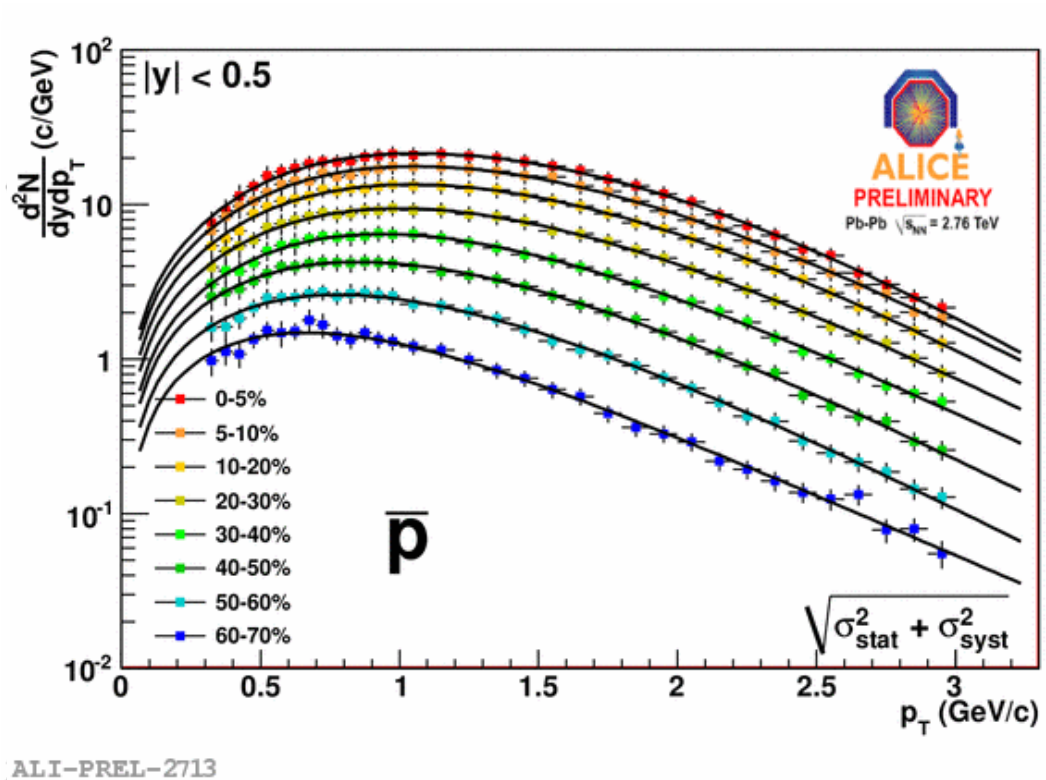

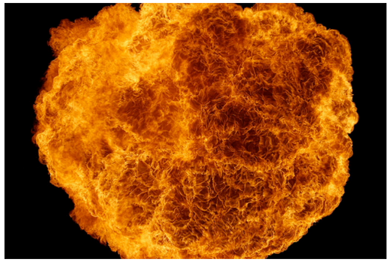

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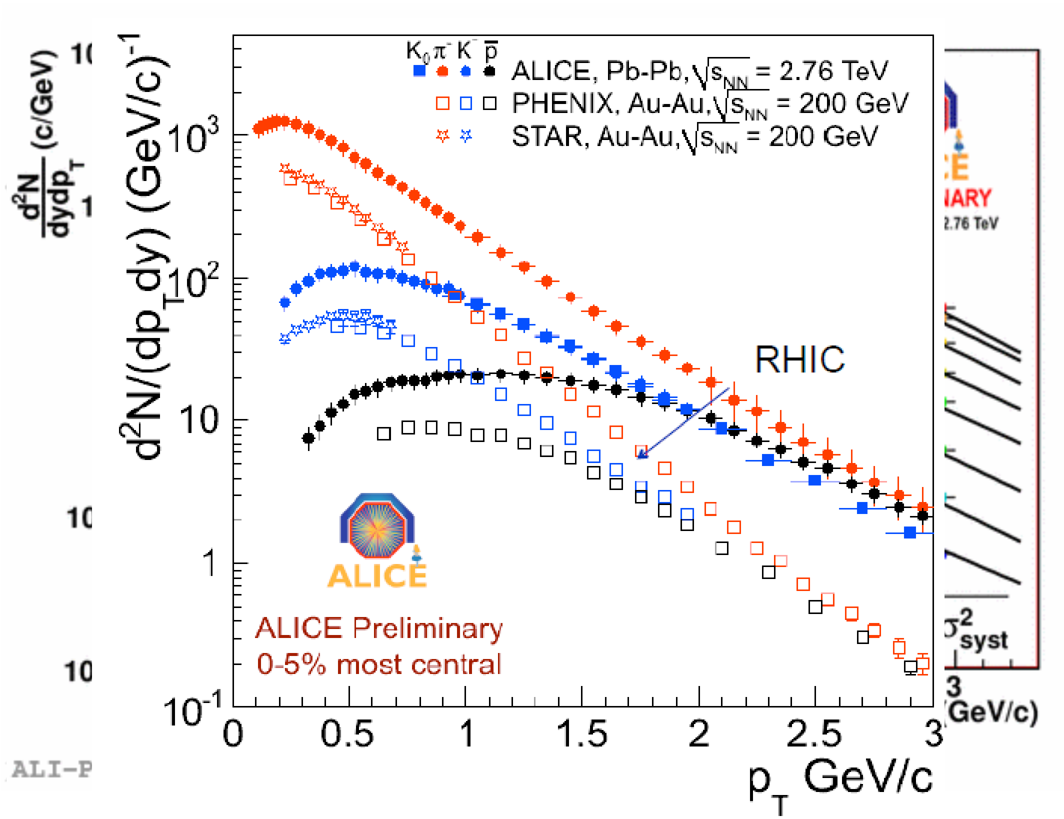

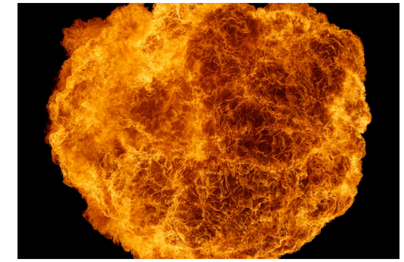

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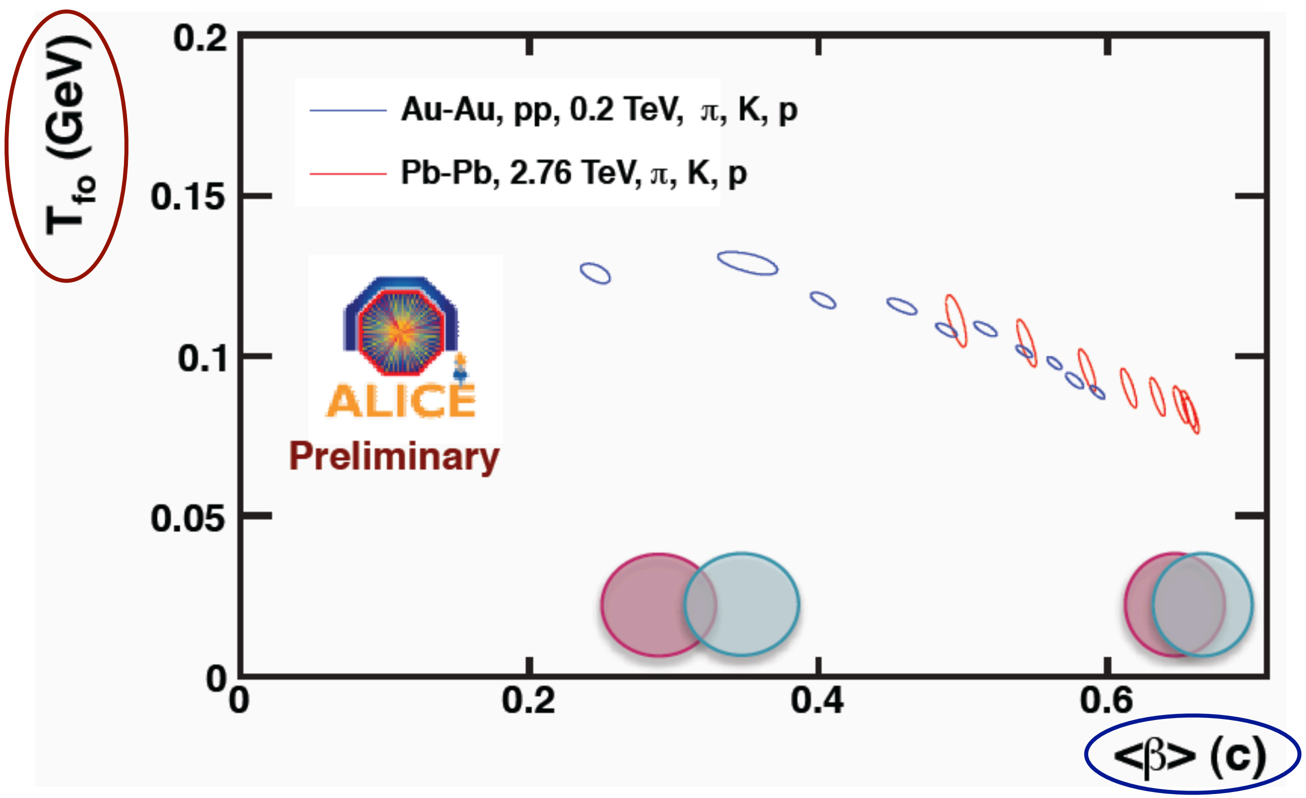
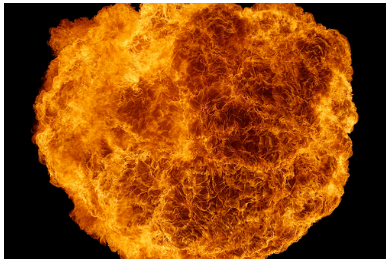




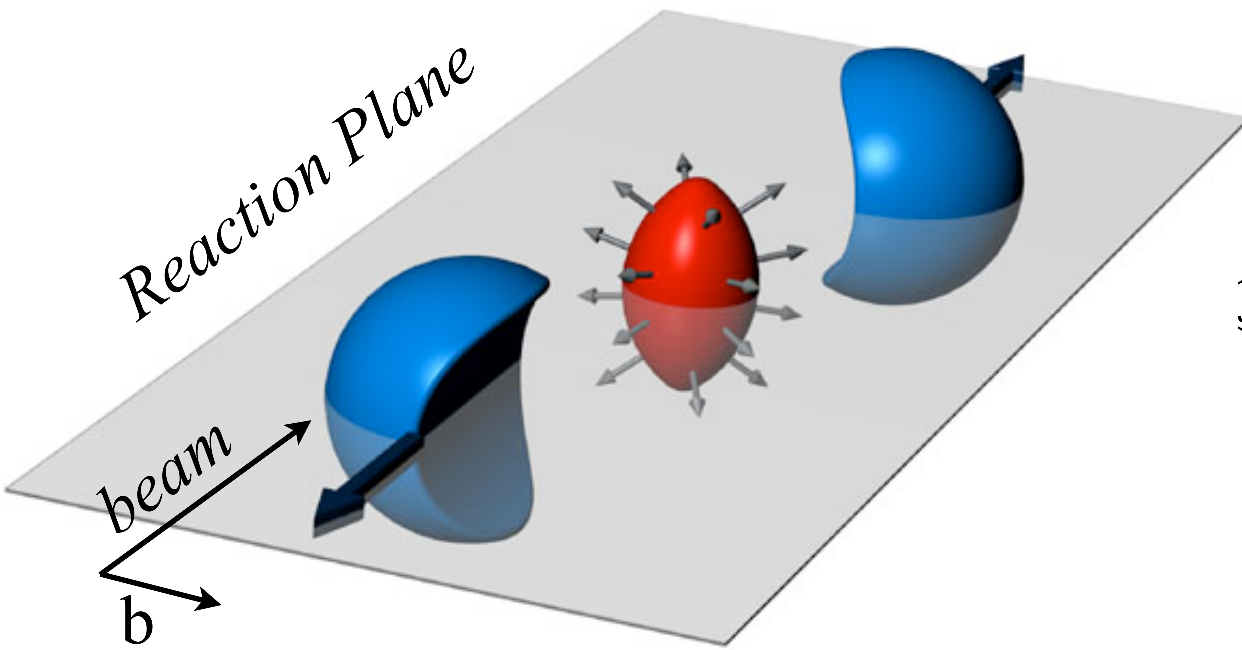
$$\frac{d^2 N_j}{m_T dy dm_T} = \int_0^{R_G} A_j m_T \cdot K_1\left(\frac{m_T \cosh\rho}{T}\right) \cdot I_0\left(\frac{p_T \sinh\rho}{T}\right) r dr$$

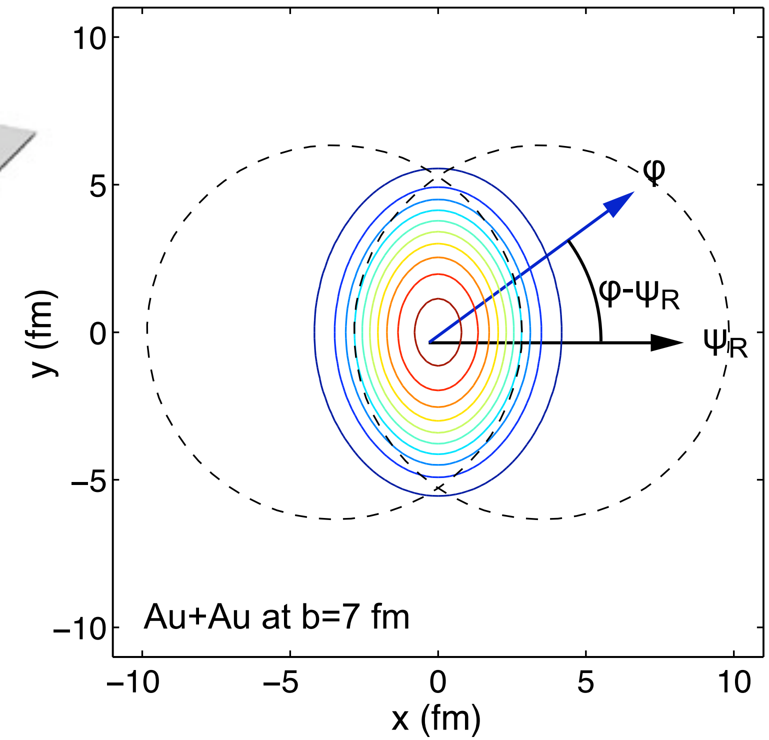
$$\rho(r) = \tanh^{-1} \beta_\perp(r)$$

Strong radial flow: β≈0.66 c for most central collisions

~10% higher than at RHIC

Elliptic Flow – Indicator for Early Thermalization





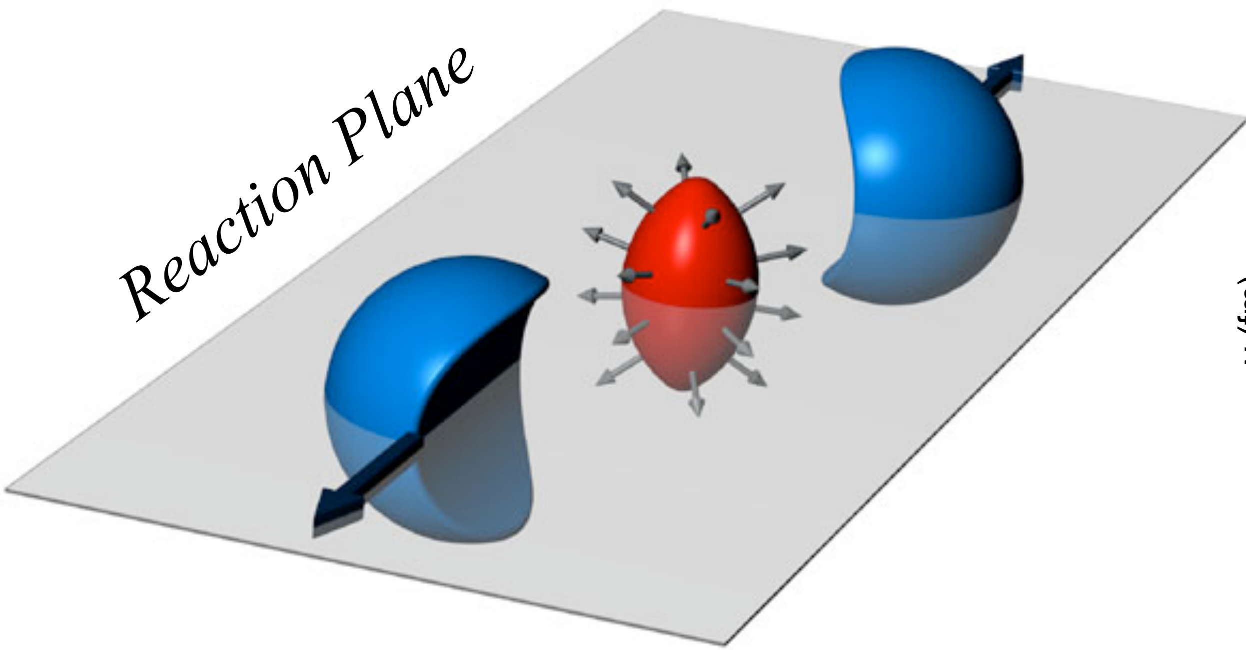
Initial spatial anisotropy → Interactions / Pressure gradient → Final state anisotropy in momentum space

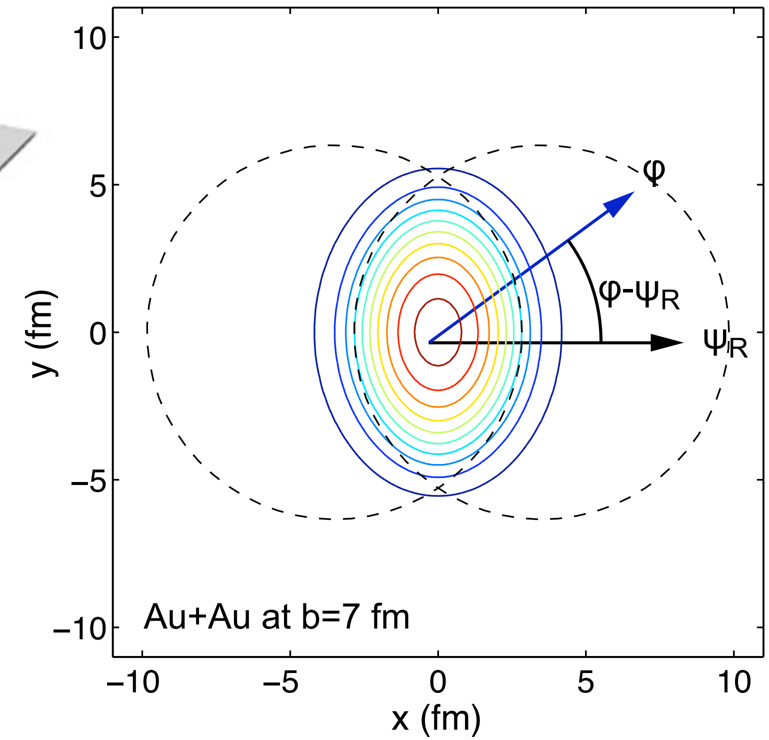
Use a Fourier expansion to describe the angular dependence of the particle density

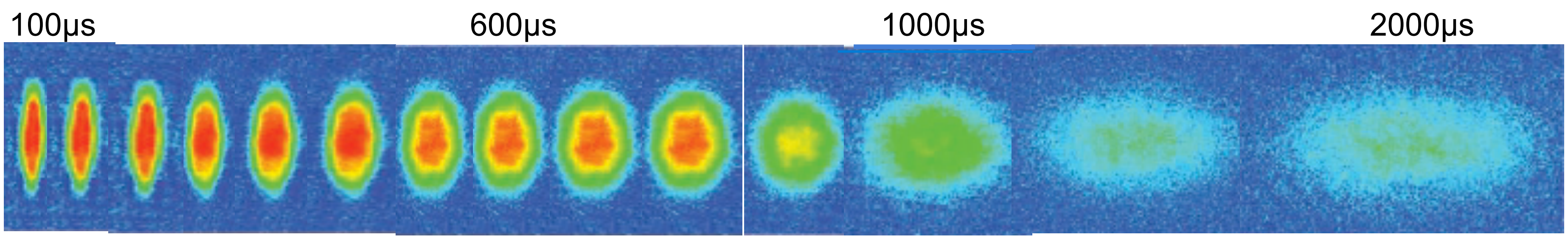
$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

$$v_2 = \langle \cos[2(\varphi - \psi_R)] \rangle$$

Elliptic Flow – Indicator for Early Thermalization





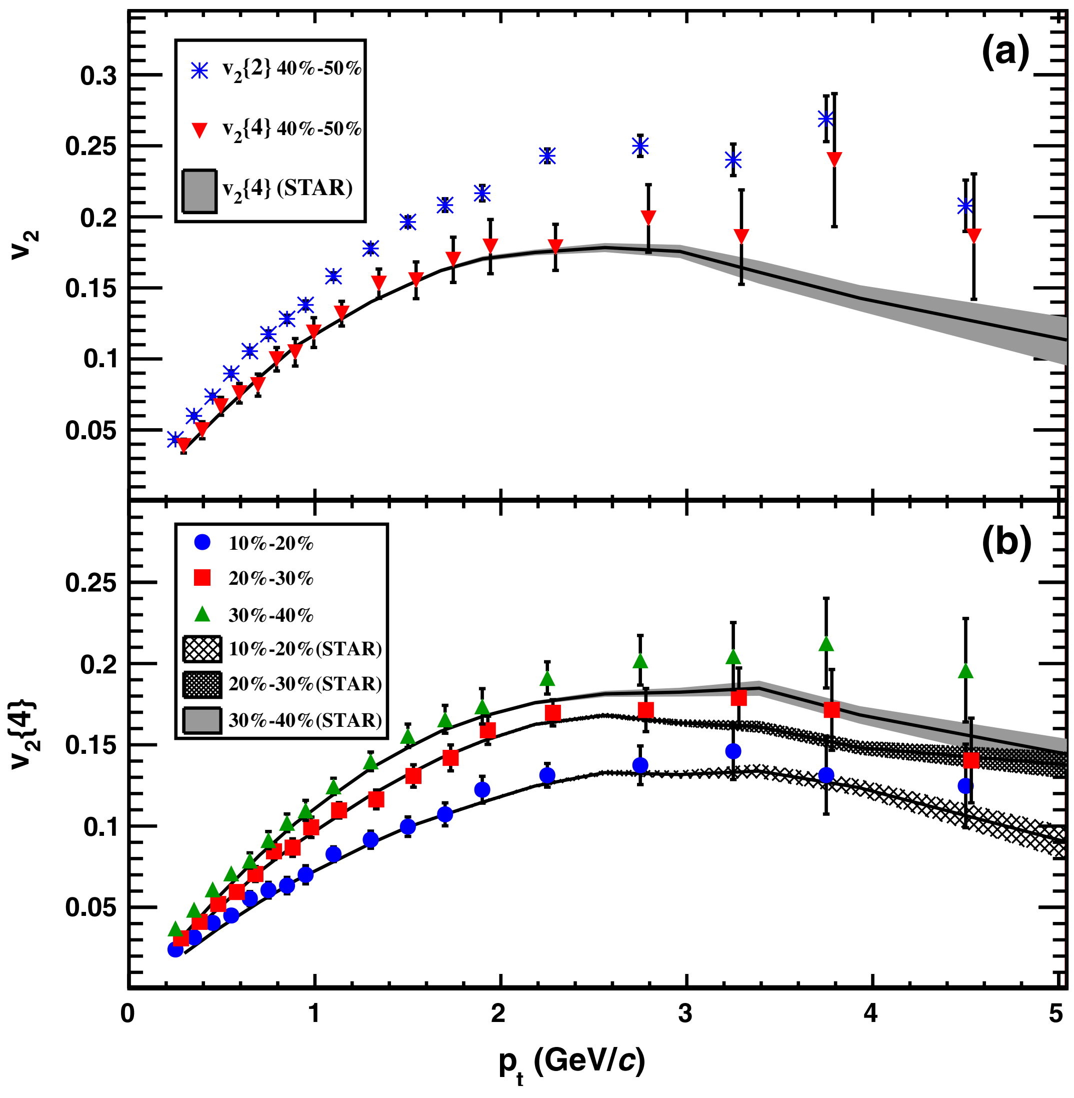


M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002):** strongly interacting Fermi gas of (Fermionic) lithium-6 atoms (superfluid)

- driving spatial anisotropy vanishes ⇒ self quenching
- v_2 → sensitive to **early** interactions and pressure gradients

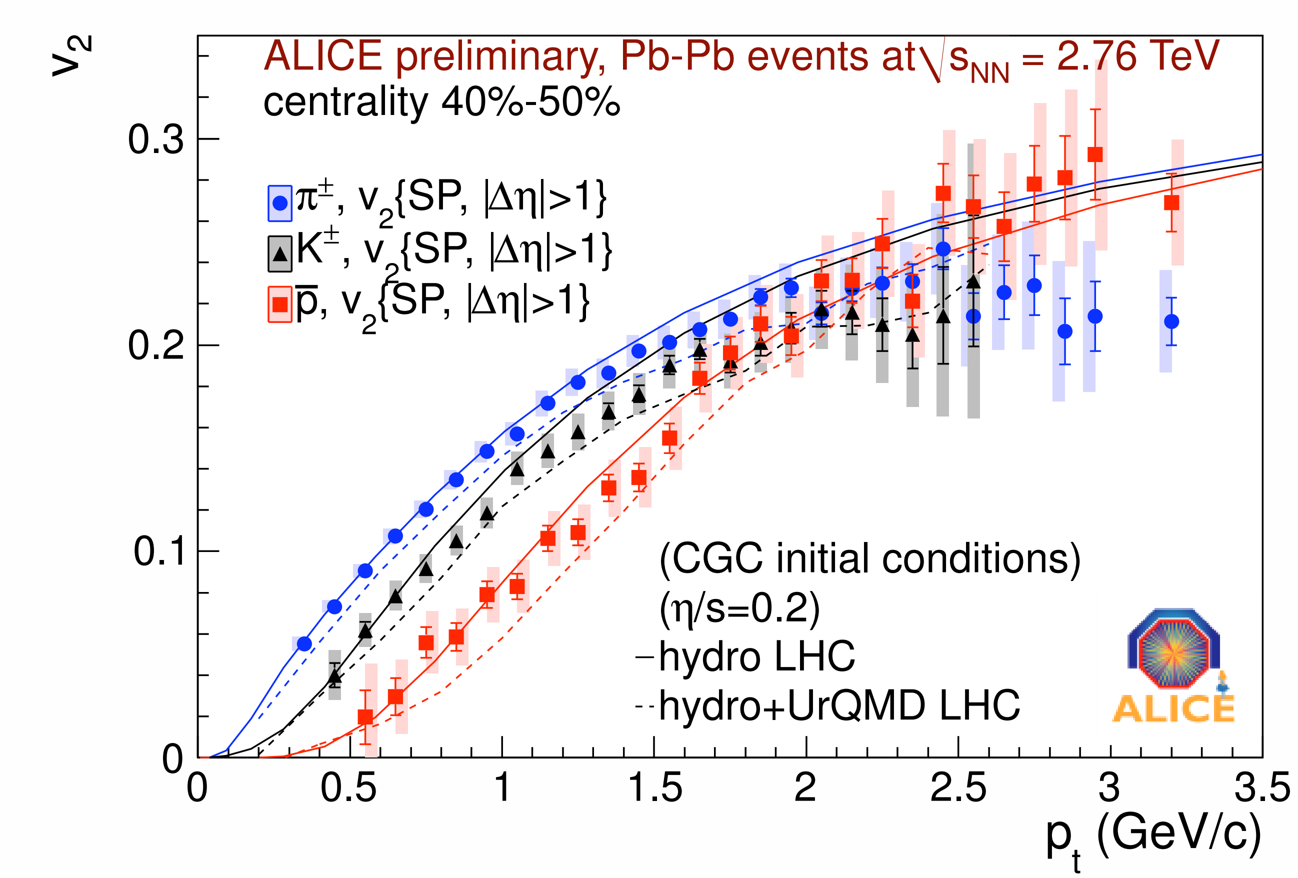
Elliptic Flow: RHIC vs. LHC

PRL 105, 252302 (2010)



Strikingly similar differential p_T dependence of elliptic flow at RHIC and LHC

QGP: The (almost) perfect Liquid ...



Expected mass dependence at low p_T<2 GeV (due to strong radial flow)

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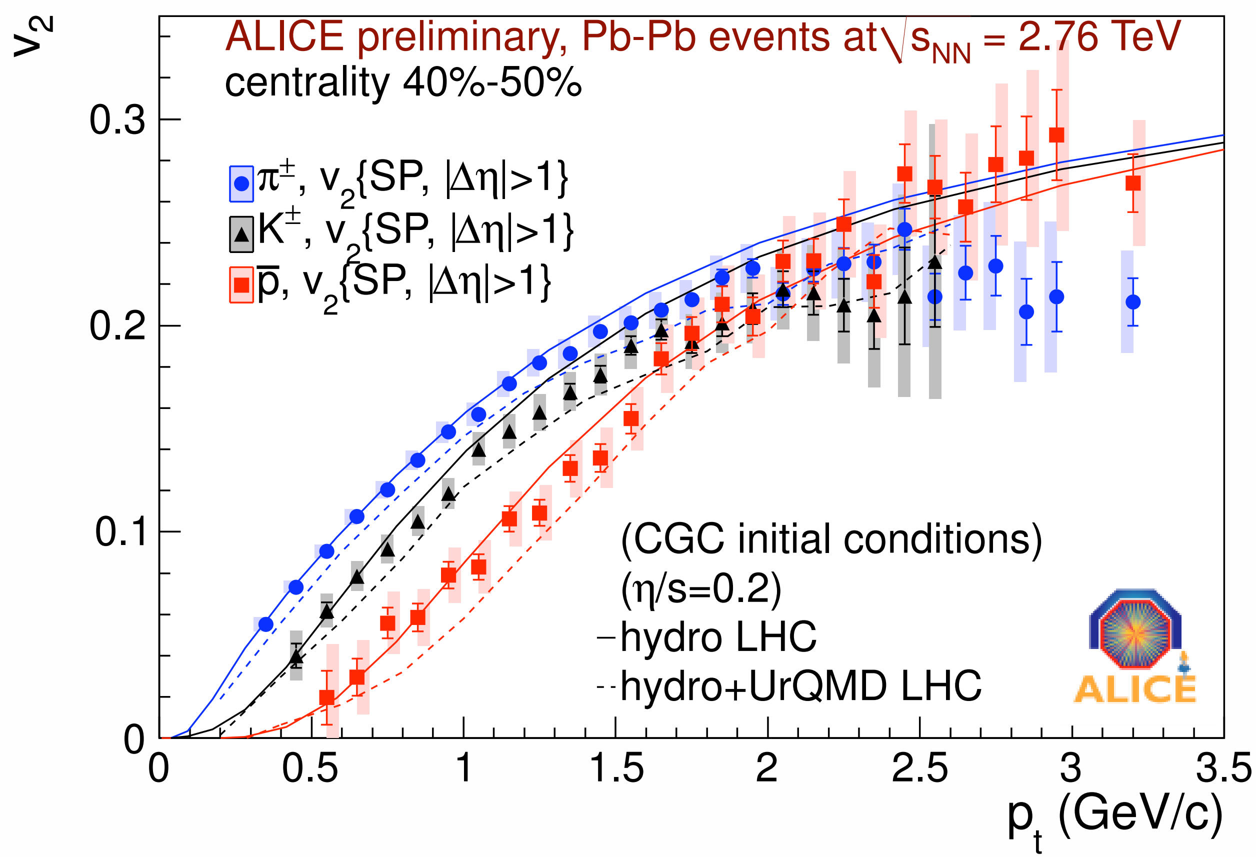
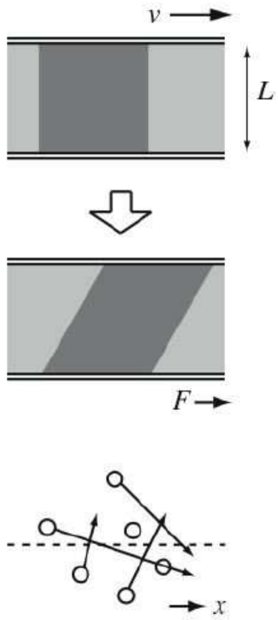




Ads/CFT (conjectured) absolute lower bound:

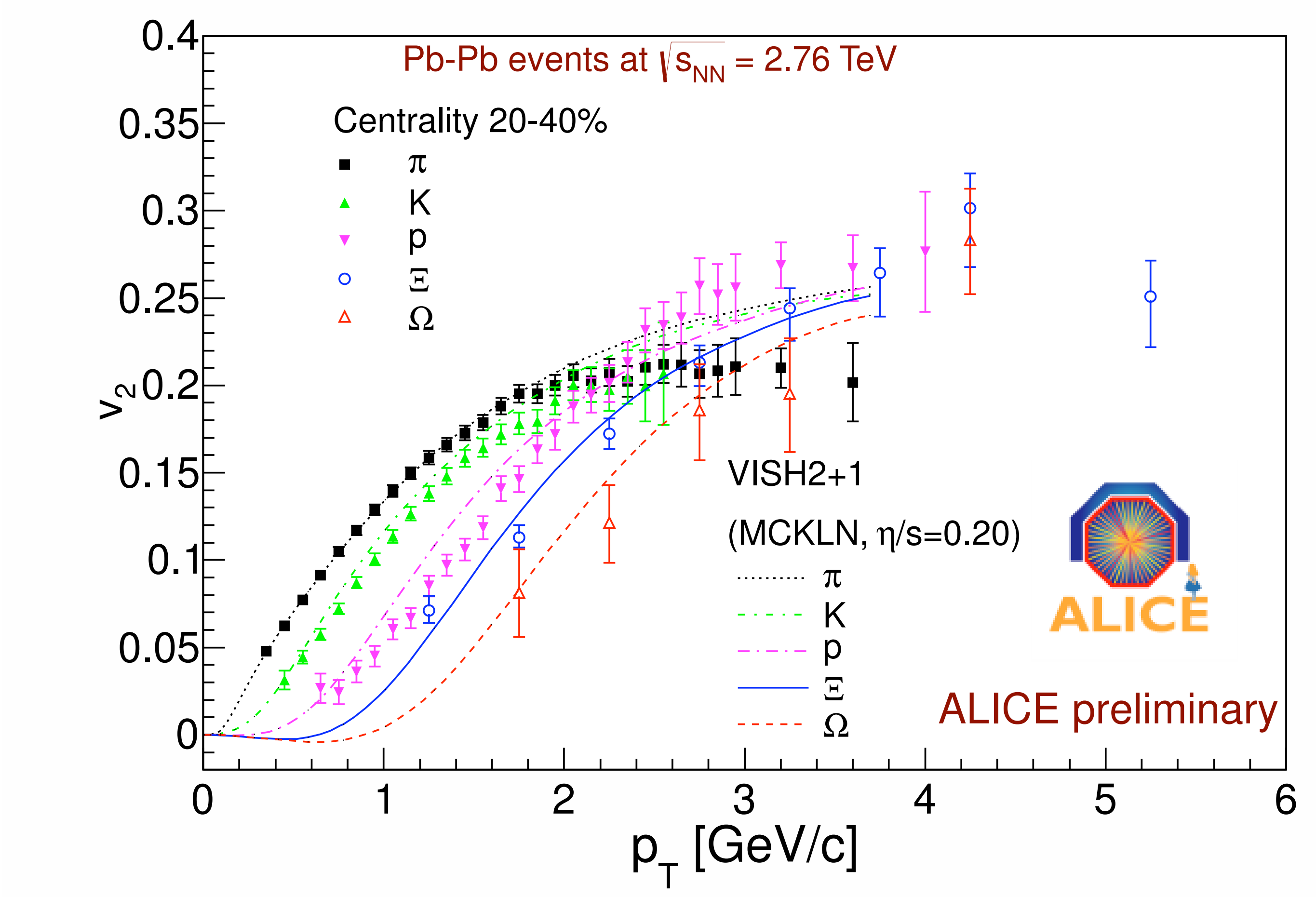
$$\frac{\eta}{s} = \frac{1}{4\pi} \sim 0.08$$

Expected mass dependence at low p_T<2 GeV (due to strong radial flow)

Elliptic flow well described by hydrodynamics with shear viscosity values η/s close to the absolute lower bound

QGP behaves like the (almost) perfect liquid!

What is flowing ?



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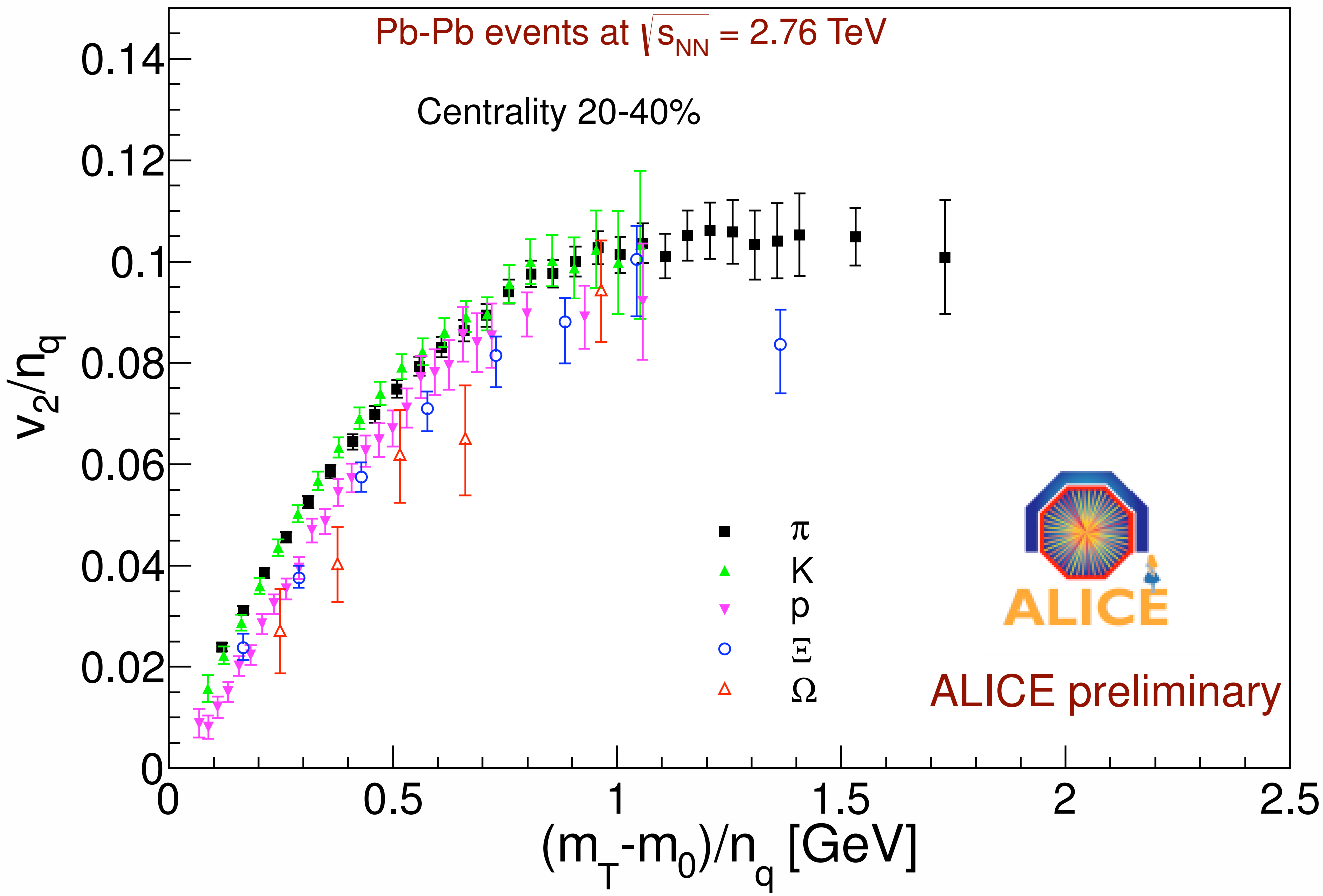
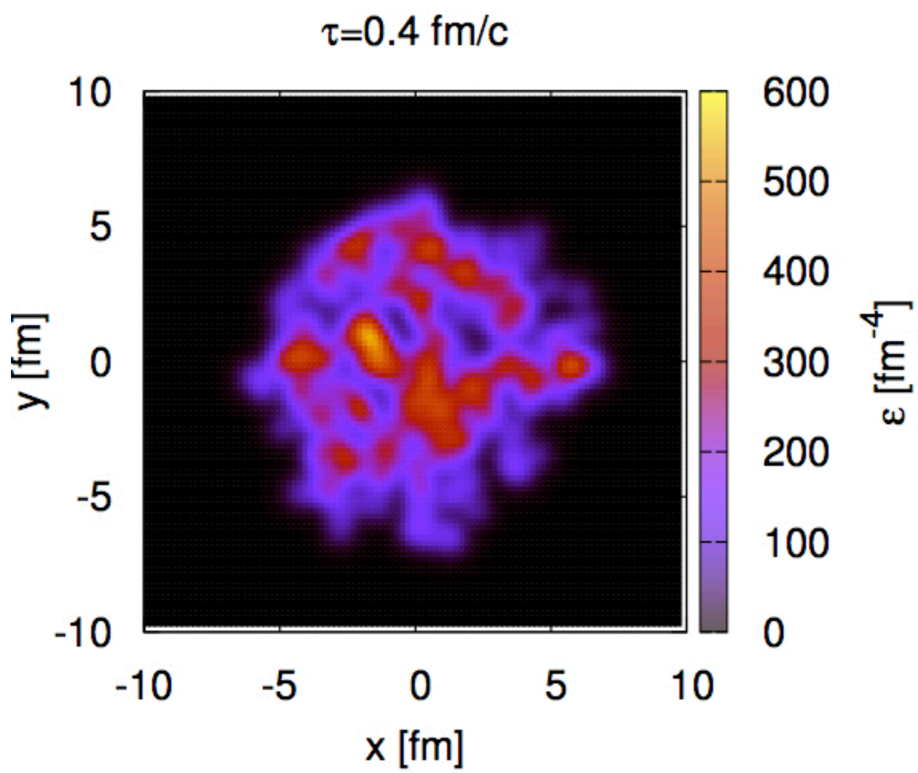


Constituent quark number scaling (p_T>2 GeV) observed

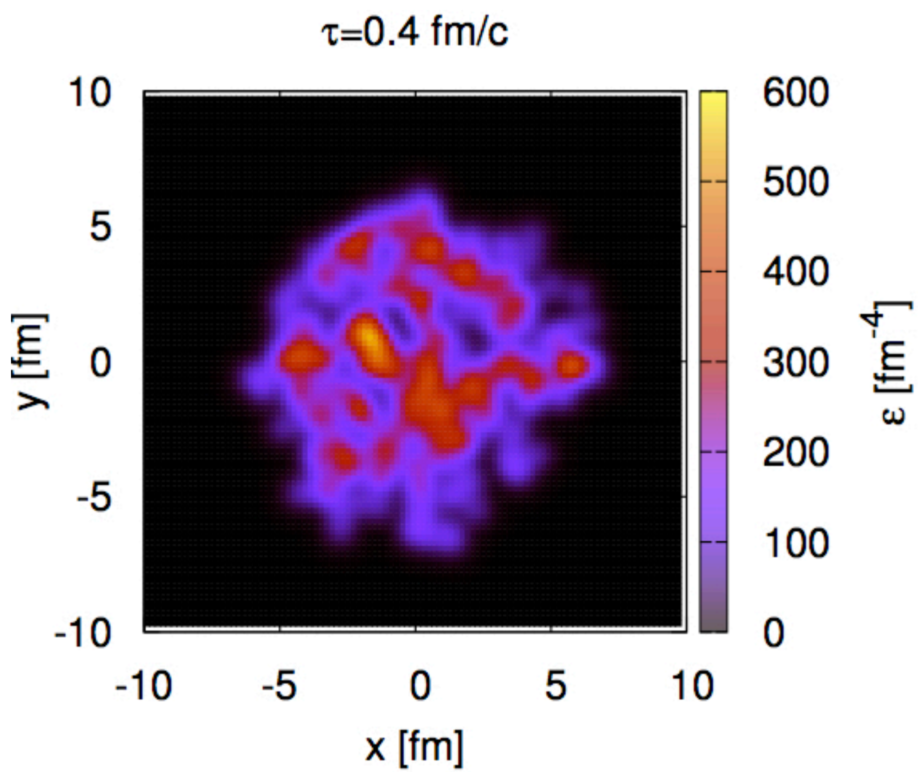
⇒ quarks/partons are flowing: partonic collectivity!

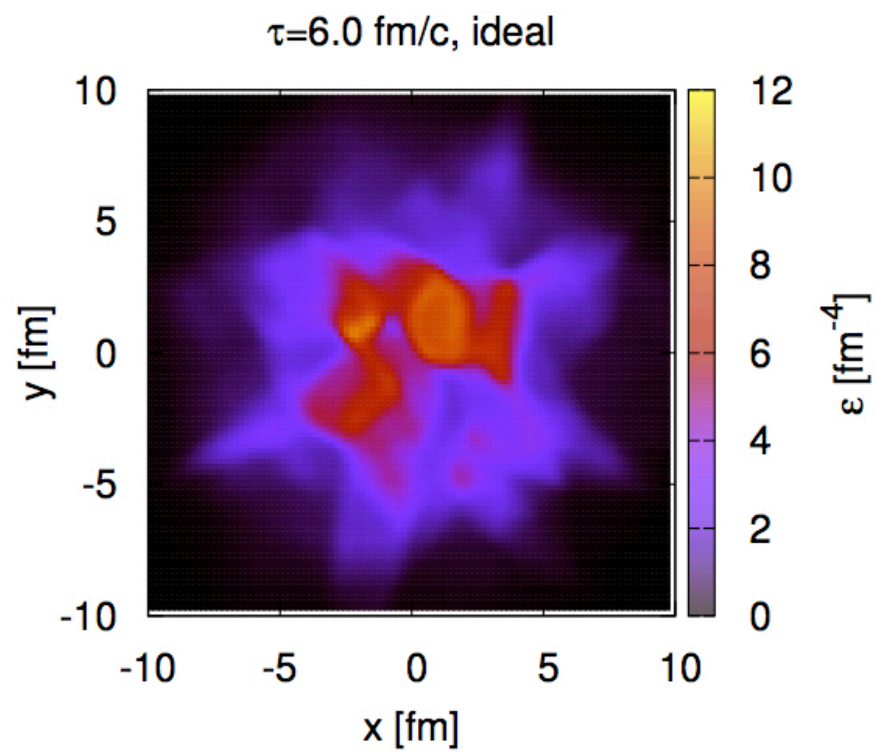
Initial Conditions, higher harmonics v_n and viscosity



Initial spatial geometry not a smooth "football"

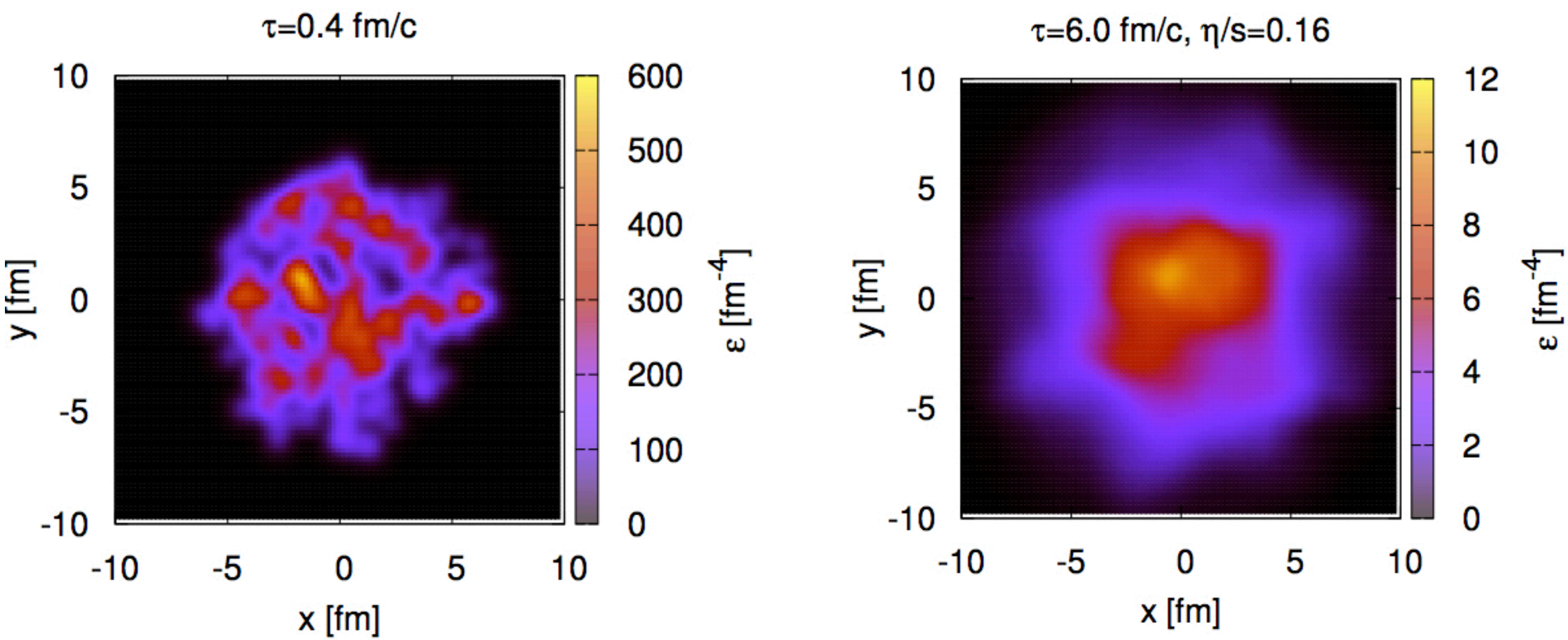
Initial Conditions, higher harmonics v_n and viscosity





Initial spatial geometry not a smooth "football"
⇒ give rise to higher harmonics/symmetry planes

Initial Conditions, higher harmonics v_n and viscosity



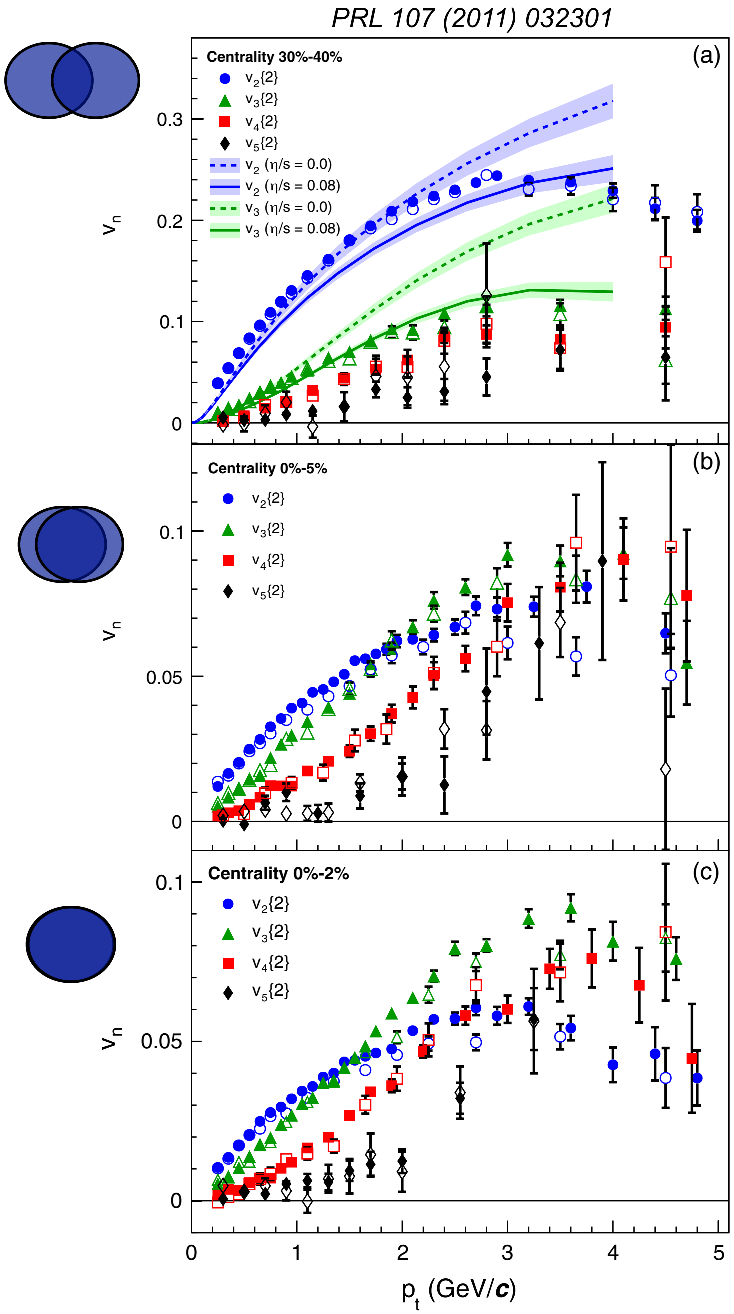
Initial spatial geometry not a smooth "football"

⇒ give rise to higher harmonics/symmetry planes

Viscosity smoothes the distributions → suppresses higher harmonics

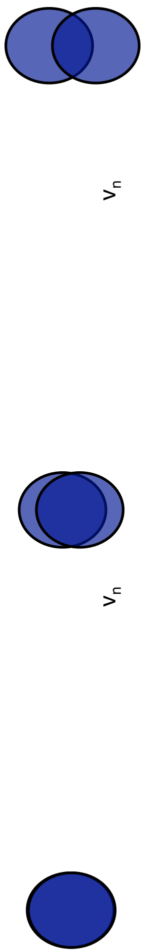
⇒ higher harmonics v_n more sensitive to η/s

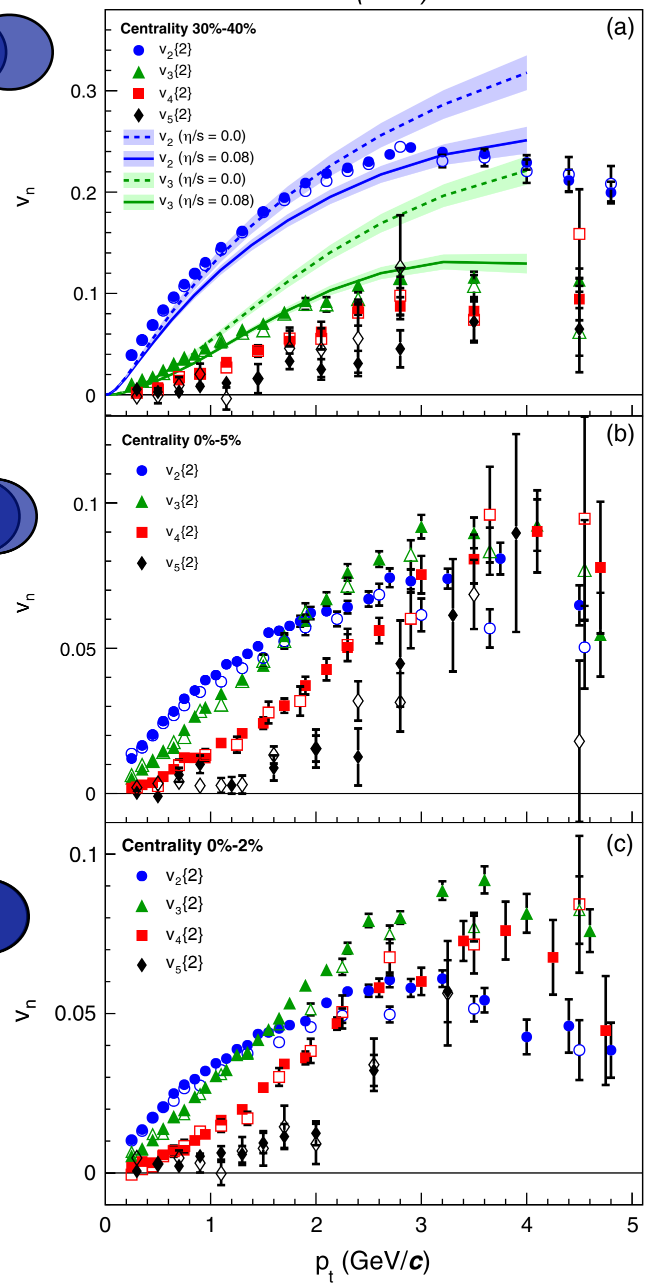
Higher Harmonics v_n

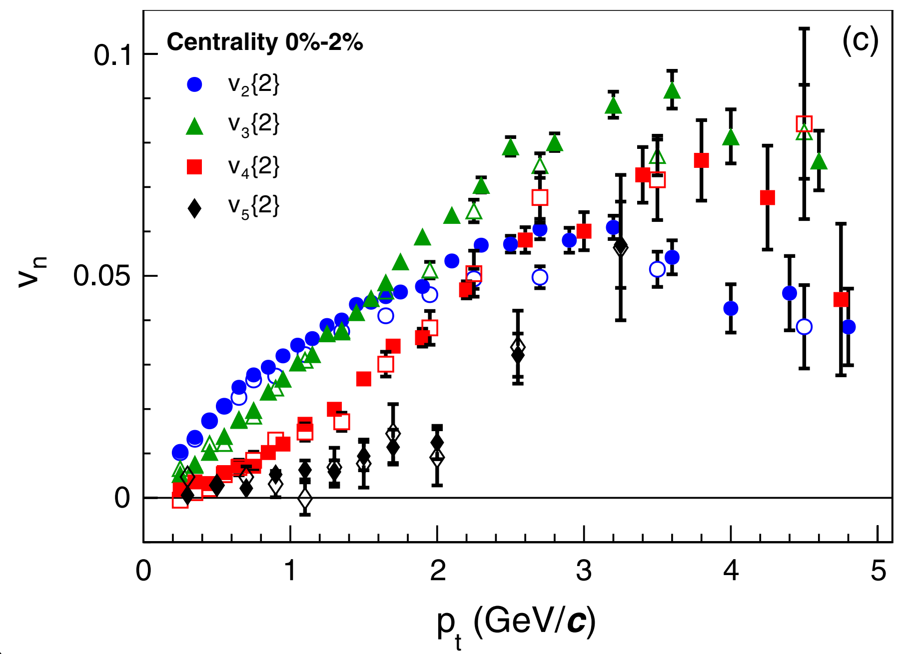


Higher Harmonics v_n

PRL 107 (2011) 032301



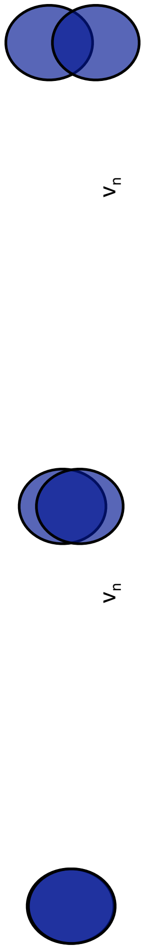


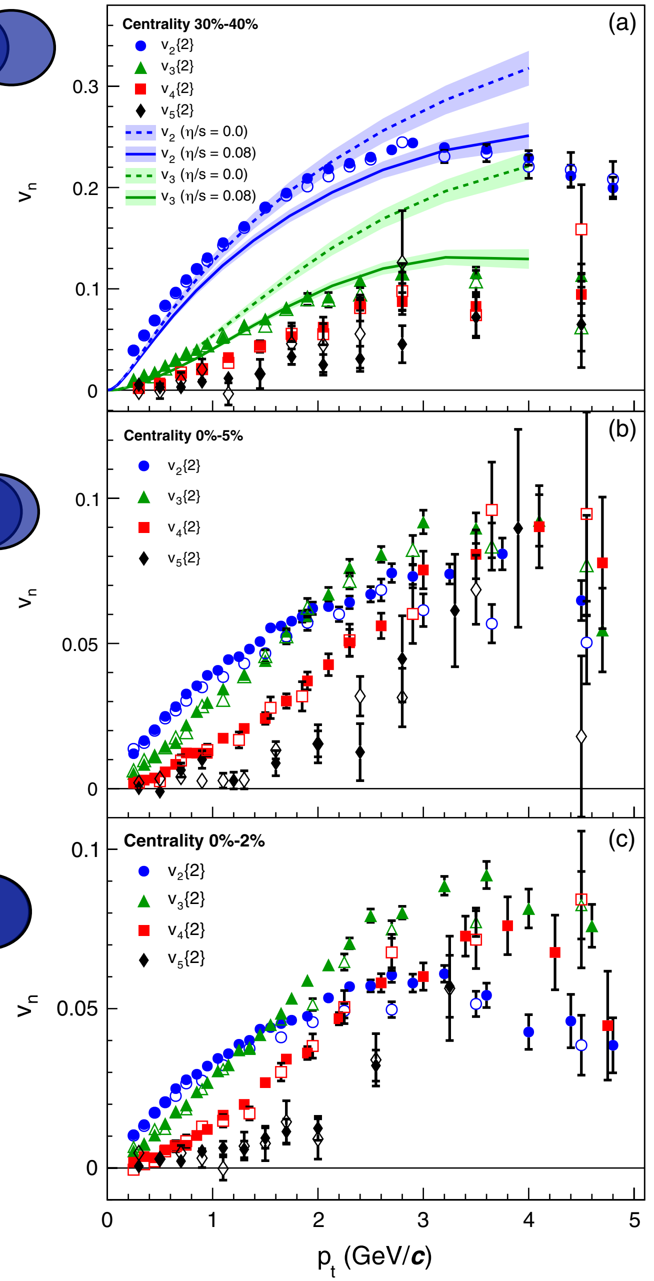


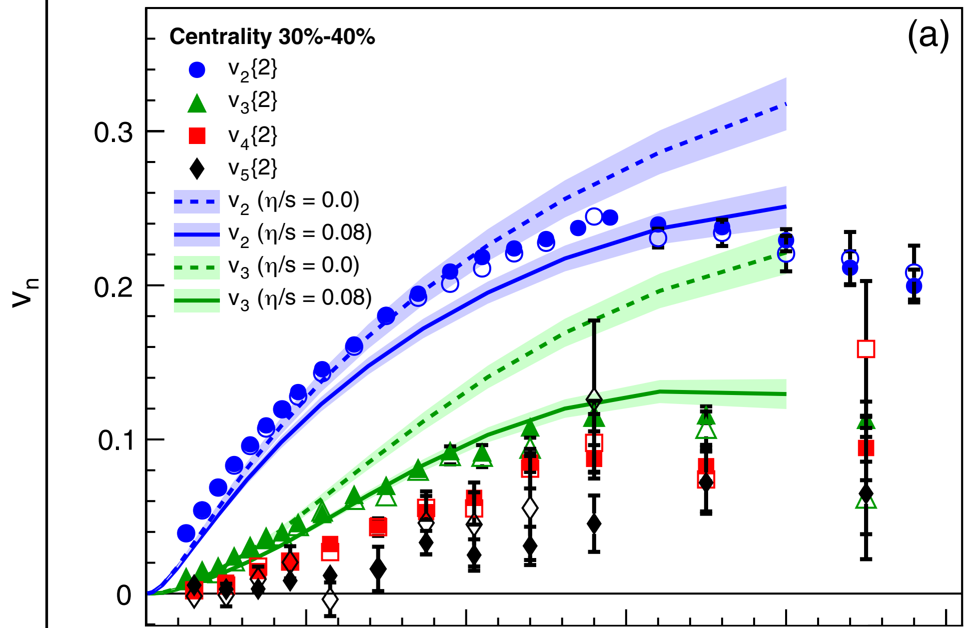
In very central collisions higher harmonics show similar strengths; driven by initial fluctuations

Higher Harmonics v_n

PRL 107 (2011) 032301



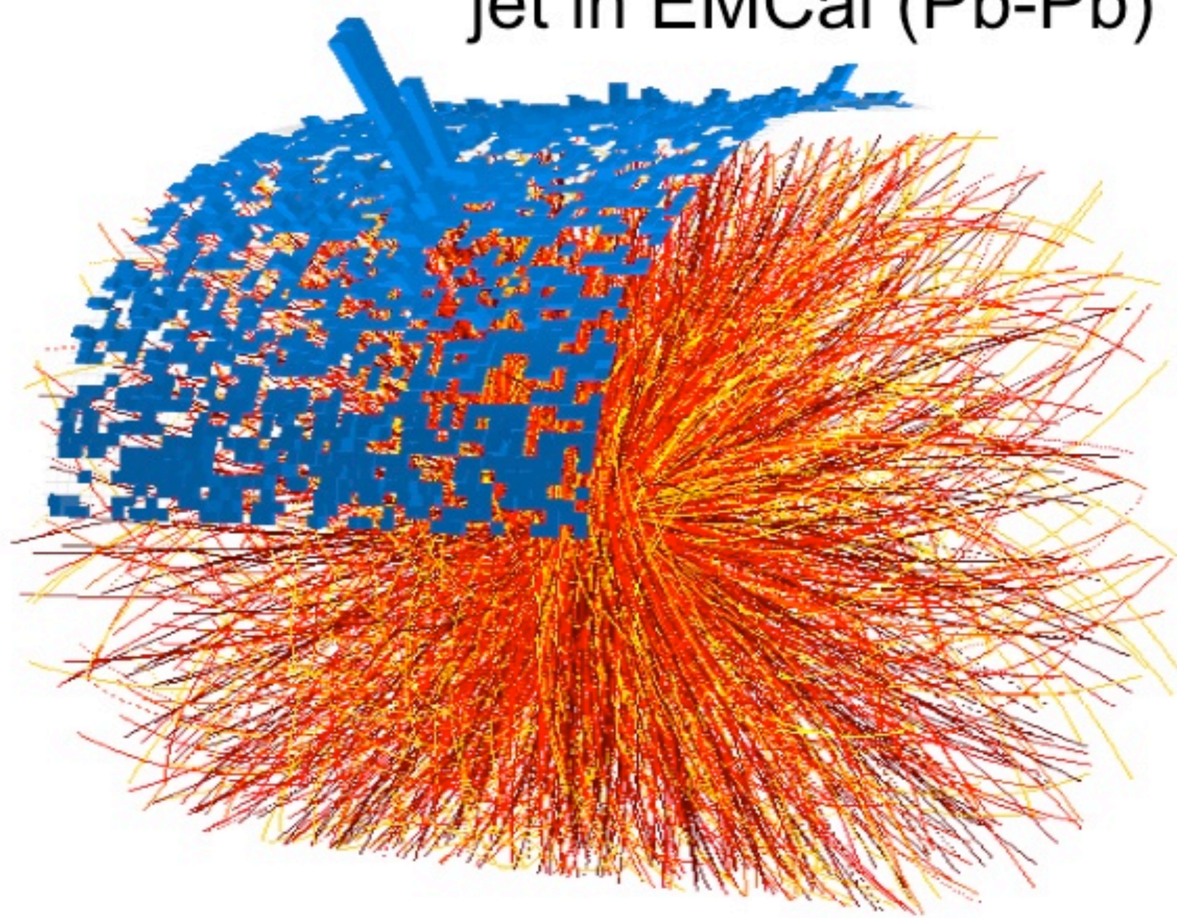




In very central collisions higher harmonics show similar strengths; driven by initial fluctuations

Different sensitivity of v_2 and v_3 (v_n) to viscosity η/s can be used to quantitatively constraint η/s an the initial conditions!

Jet-Quenching in ALICE
- QGP Tomography-

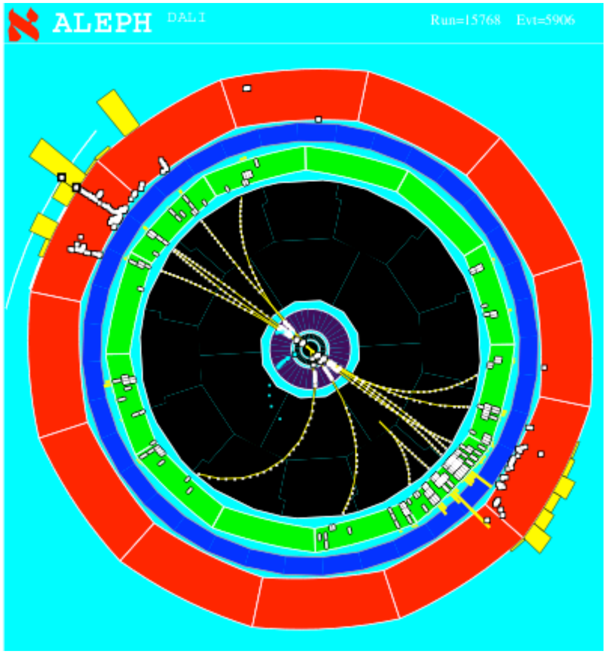


Probing Dense Matter with Jets - QGP Tomography

Calibrated probe (high-p_T partons instead of X-rays)

Calibrated interaction (beam of known energy and direction, geometry)

Calibrated/measured initial state and CNM effects



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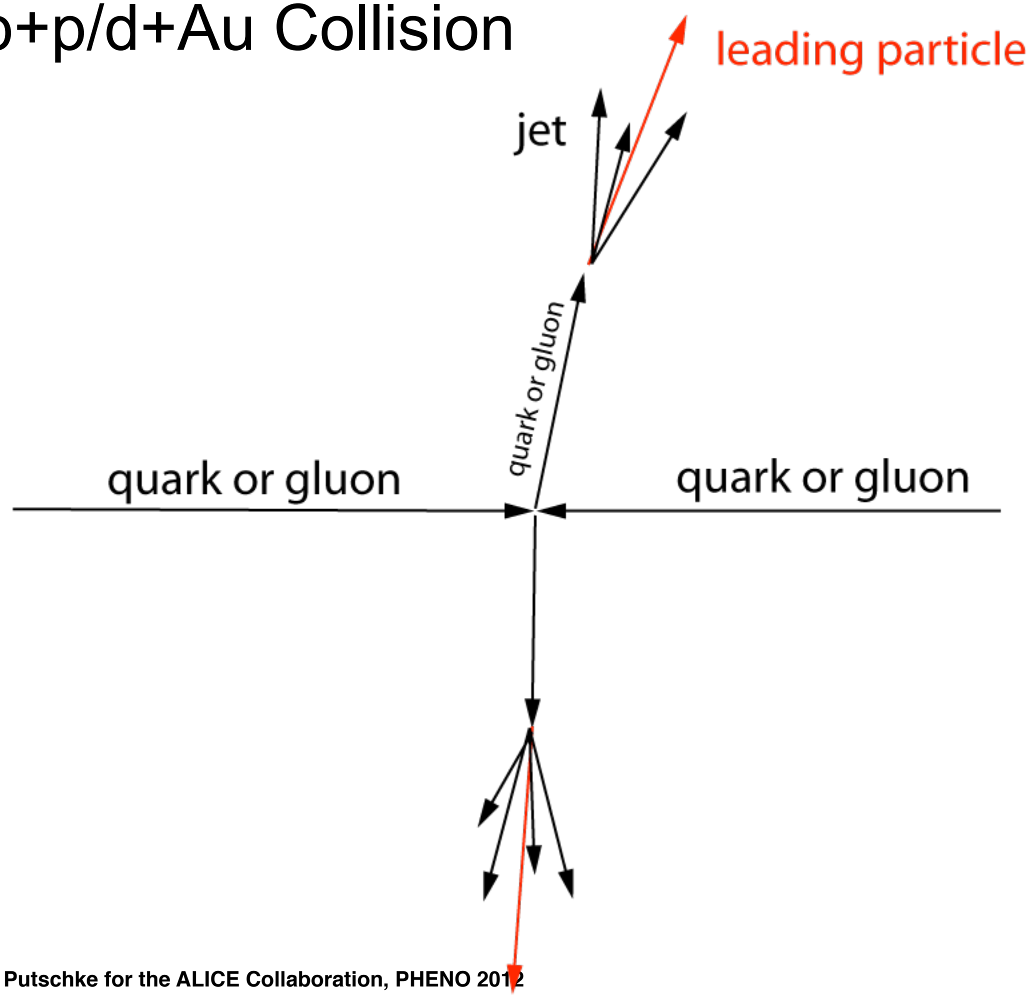
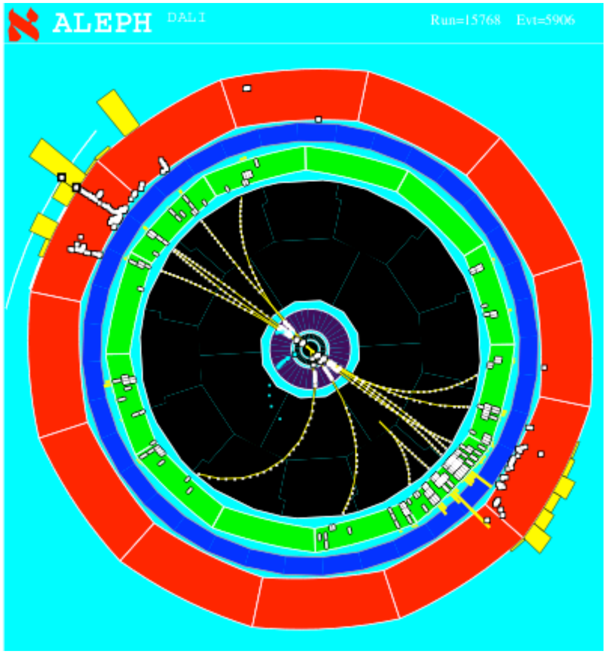
p+p/d+Au Collision





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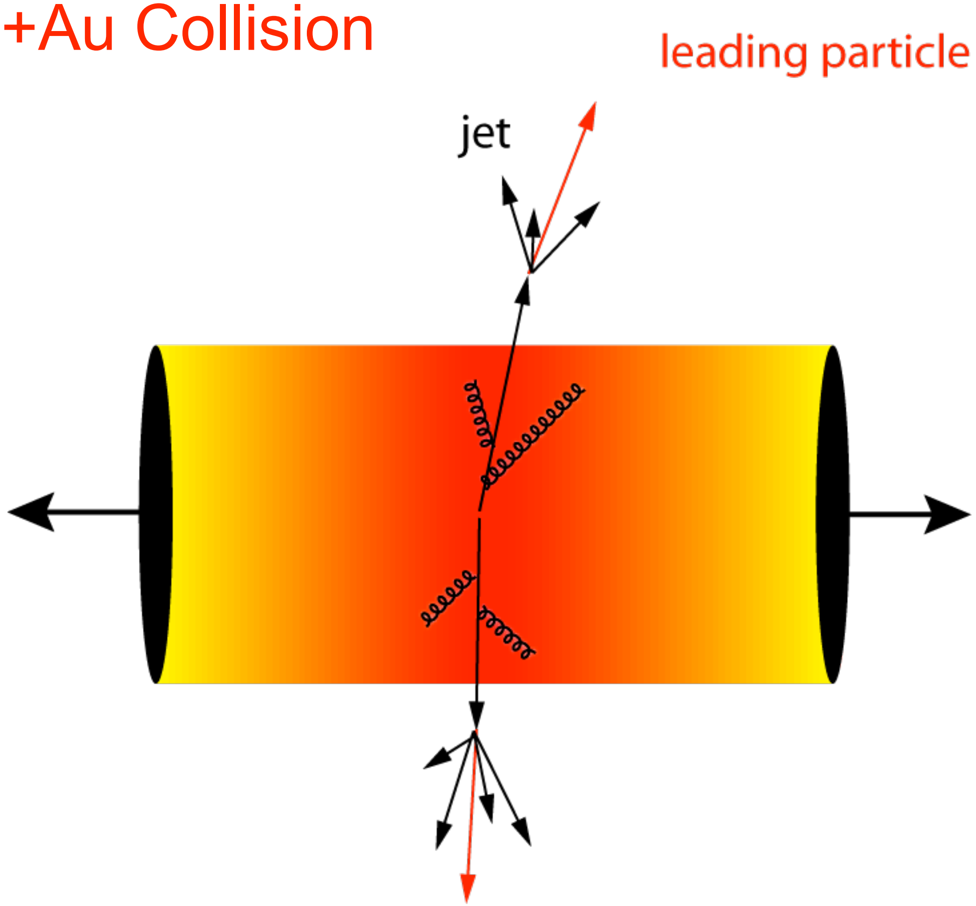
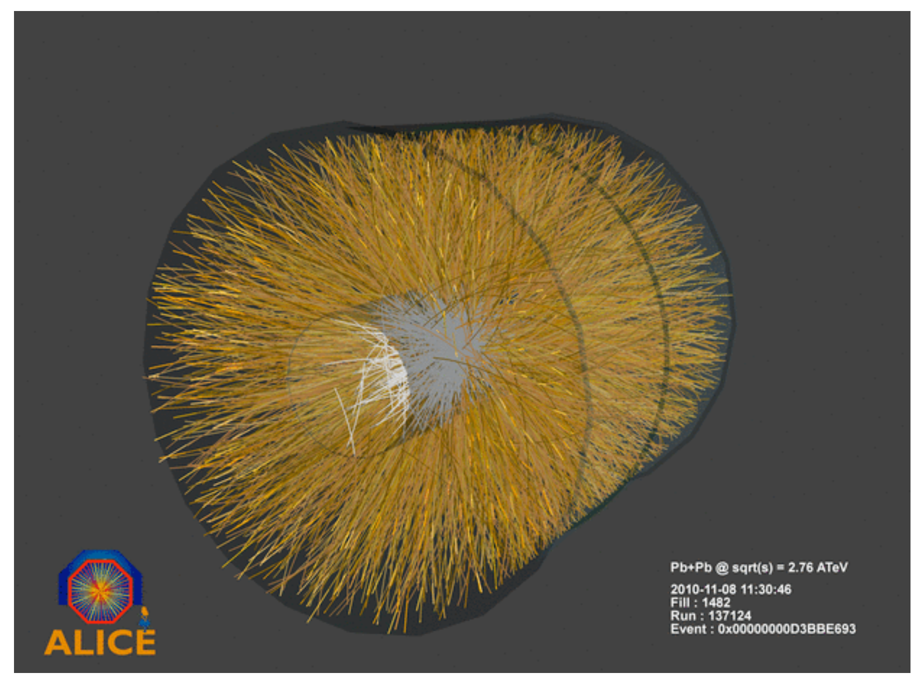
⇒ All modifications in the jet structure are due to interactions with the medium!

Au+Au Collision





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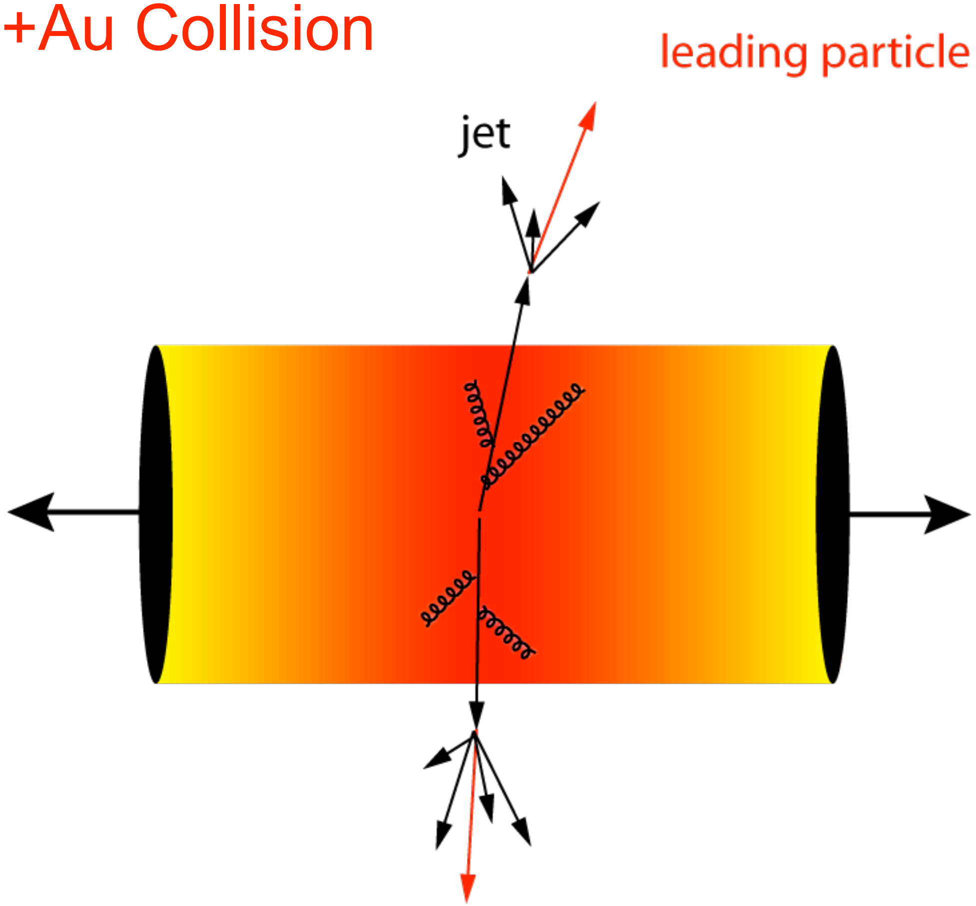
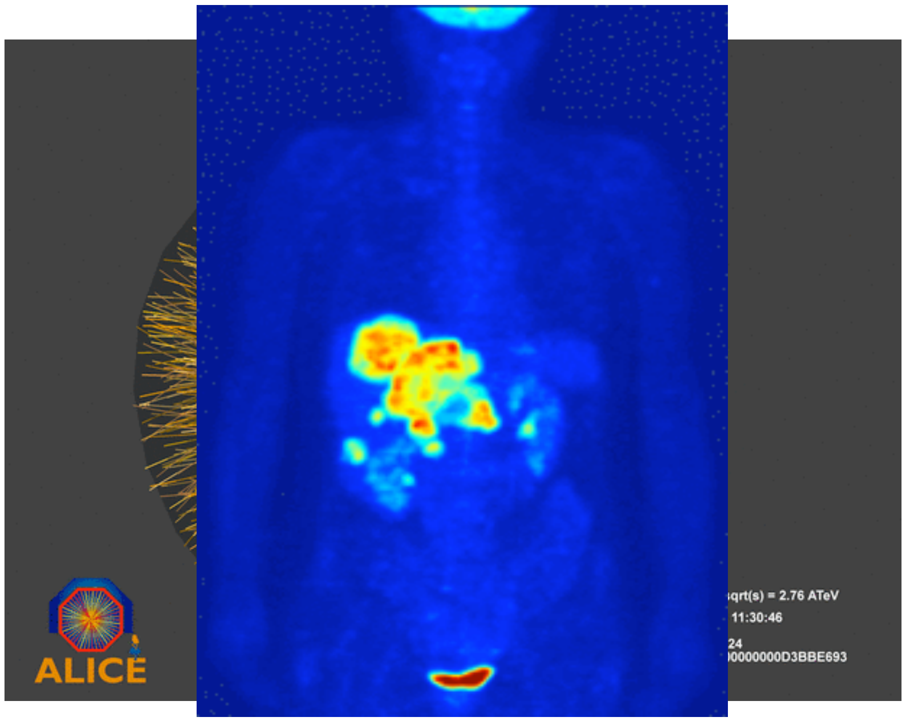


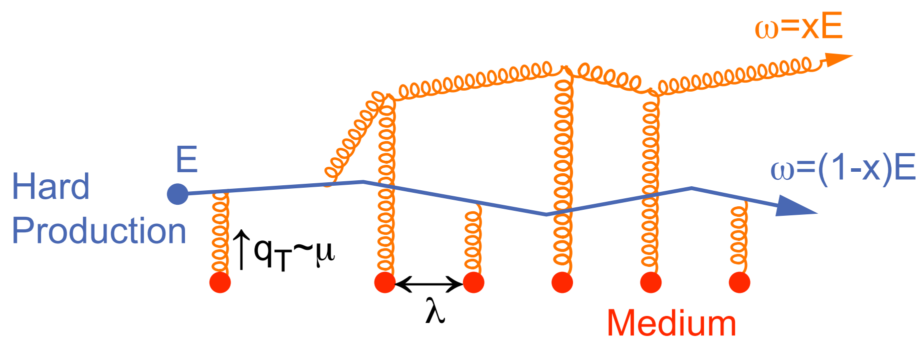


Human body

Jet-quenching theory from an experimentalists view

Gluon radiation

Multiple final-state gluon radiation off of the produced hard parton induced by the traversed dense colored medium



General form:	Partonic spectrum E_{jet}	⊗	Nuclear geometry L	⊗	Energy loss $\Delta E(E_{jet})$	⊗ Fragmentation $D(E_{jet}, \Delta E)$

- Mean parton energy loss $\propto$ medium properties:
  - $\Delta E \sim \rho_{gluon}$ (gluon density)
  - $\Delta E \sim \Delta L^2$ (medium length) $\Rightarrow \sim \Delta L$ with expansion

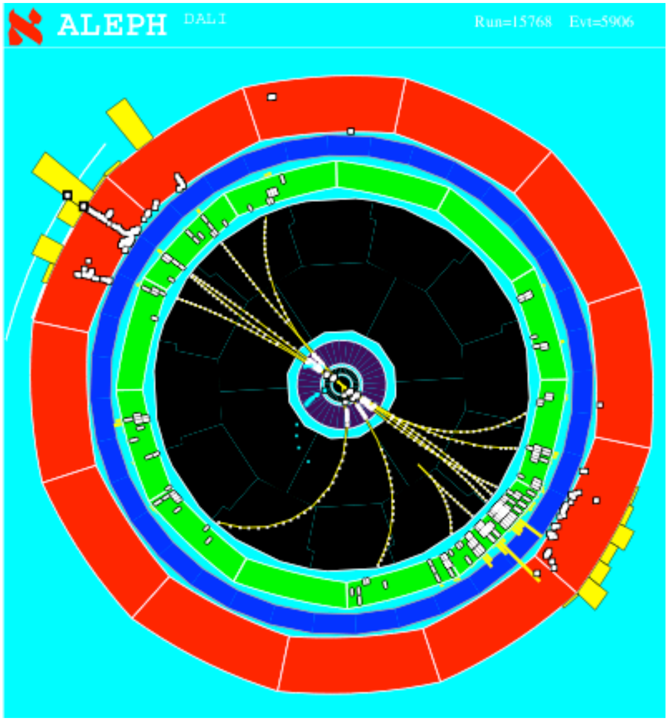
- Characterization of medium via transport coefficient $\hat{q}$ is mean p_T^2 transferred from the medium to a hard gluon per unit path length λ

A lot of theories/models on the market:

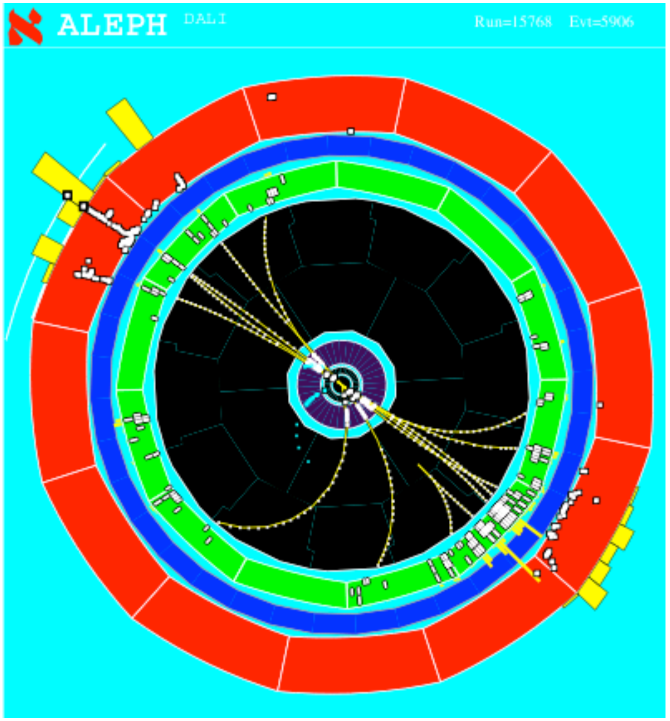
$\hat{q} \sim$ 2-10 GeV/fm

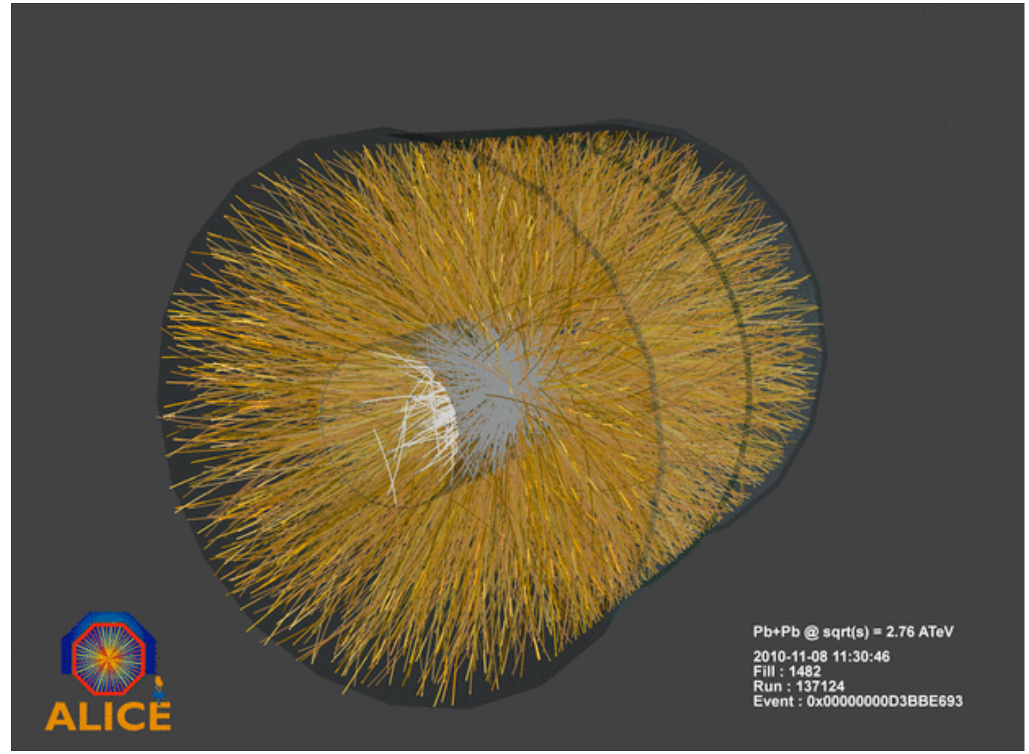
no theoretical quantitive agreement yet.

Naive summary:
To varying extent all theories (except AdS/CFT) predict a **softening** of the fragmentation and an overall **broadening** of the jet shape!



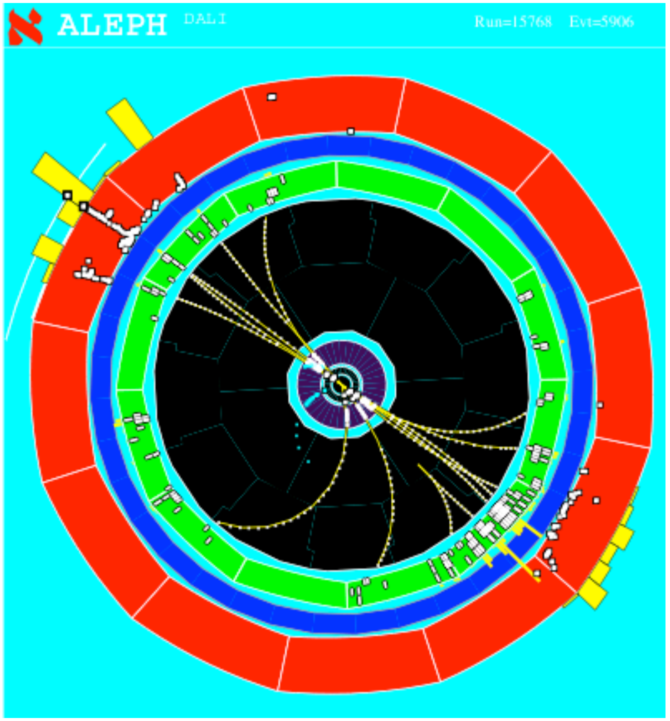
Finding this

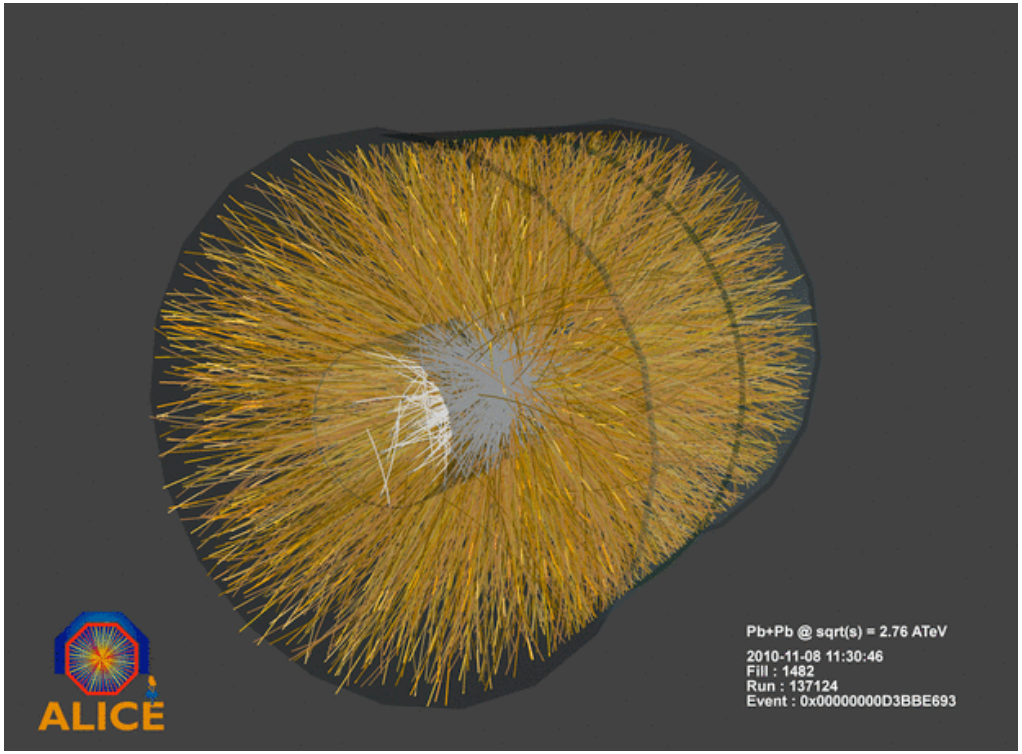




Finding this → in this, is not that easy ...

large heavy-ion background
fluctuations obscure jet energy scale





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large heavy-ion background fluctuations obscure jet energy scale

So lets look first at something easier, at least from the experimental side: Take a high-p_T particle as a jet proxy ...

“Jet quenching”: Looking for attenuation/absorption

Compare to p-p reference at same collision energy

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Average number of p-p collision in A-A collision

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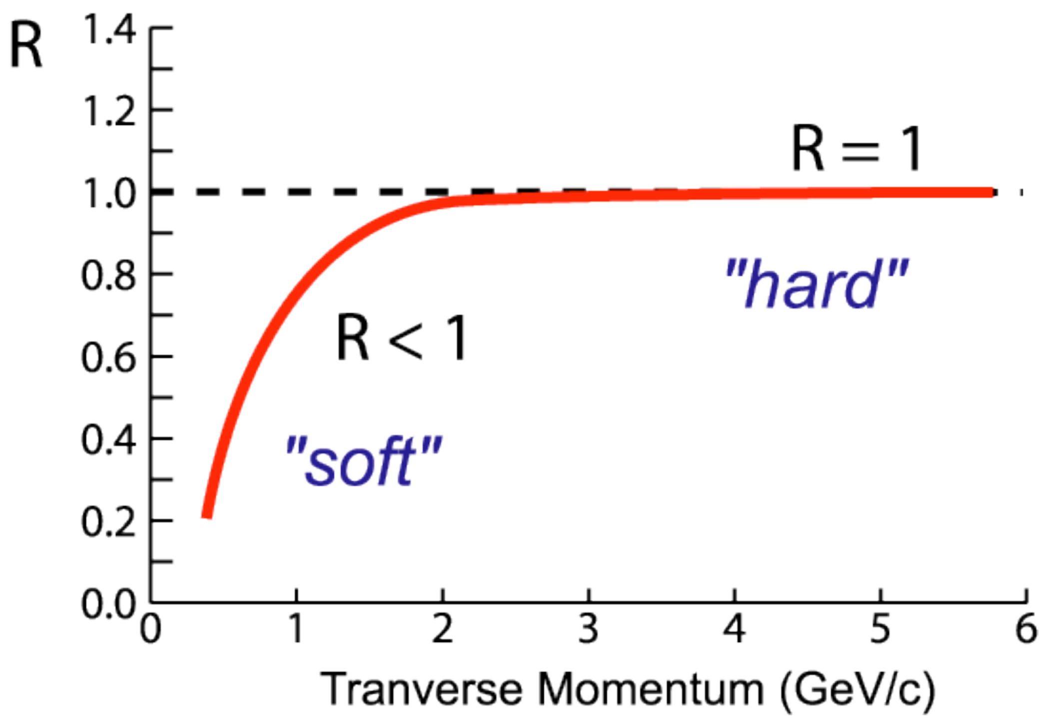

No "Effect":

- R < 1 at small momenta - production from thermal bath
- R = 1 at higher momenta where hard processes dominate (A-A superposition of p-p)

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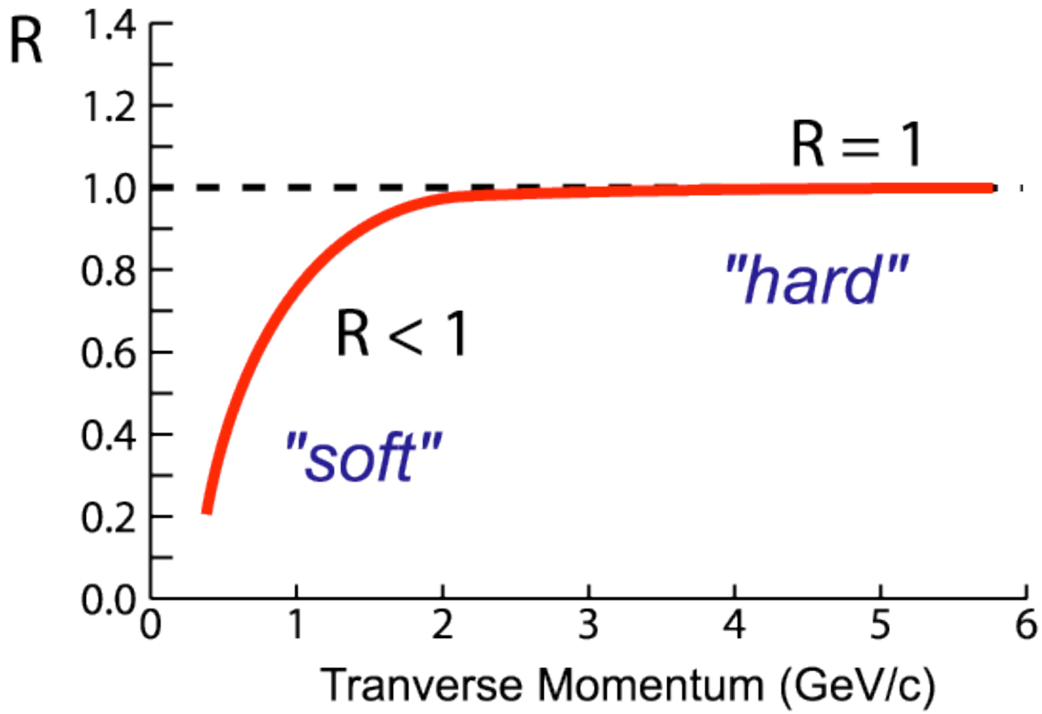

No "Effect":

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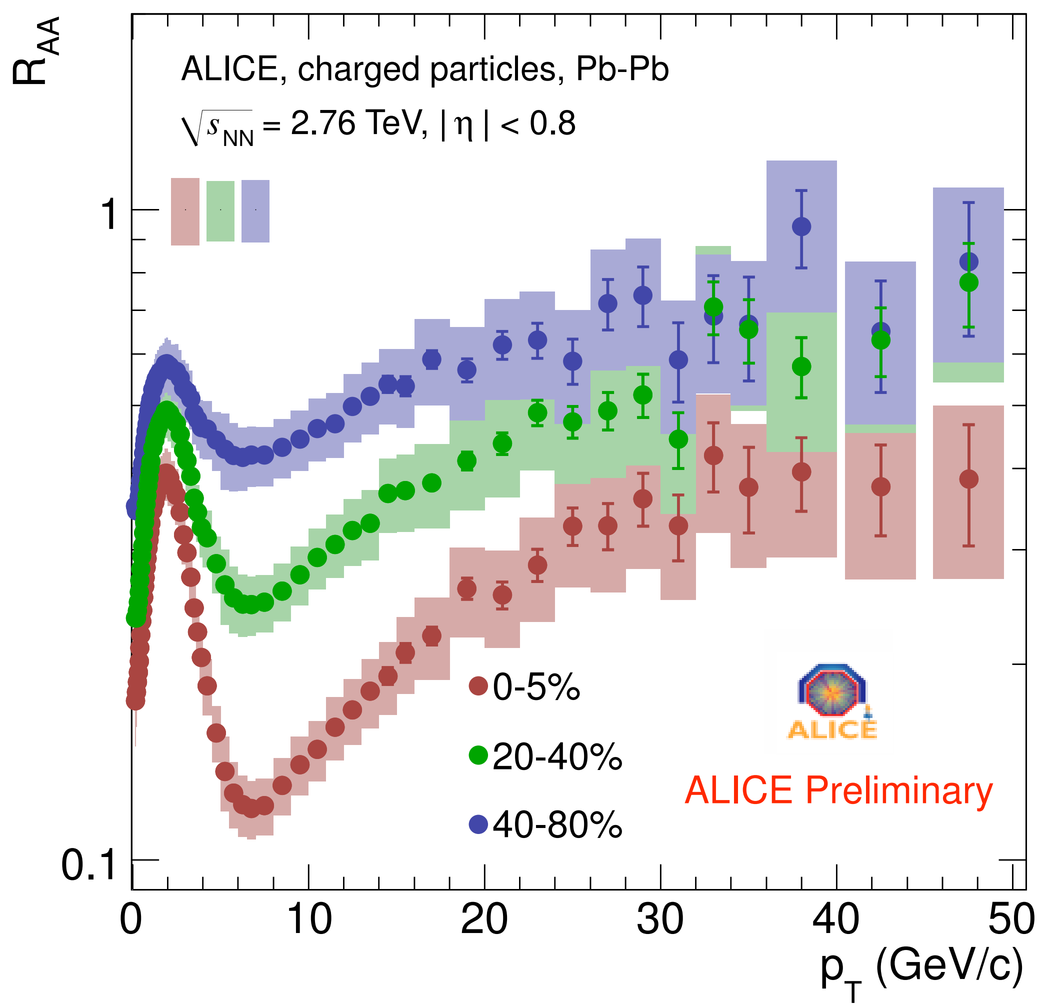
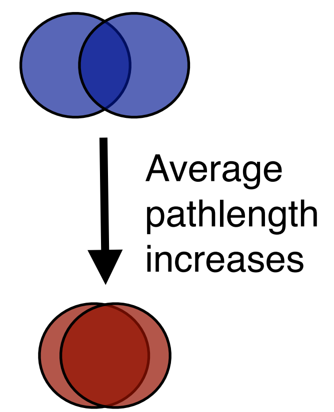
R<1 at high p_T if QGP affecting parton's propagation

Nuclear Modification Factor vs. Centrality

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{<N_{coll}> d^2N^{pp}/dydp_T}$$

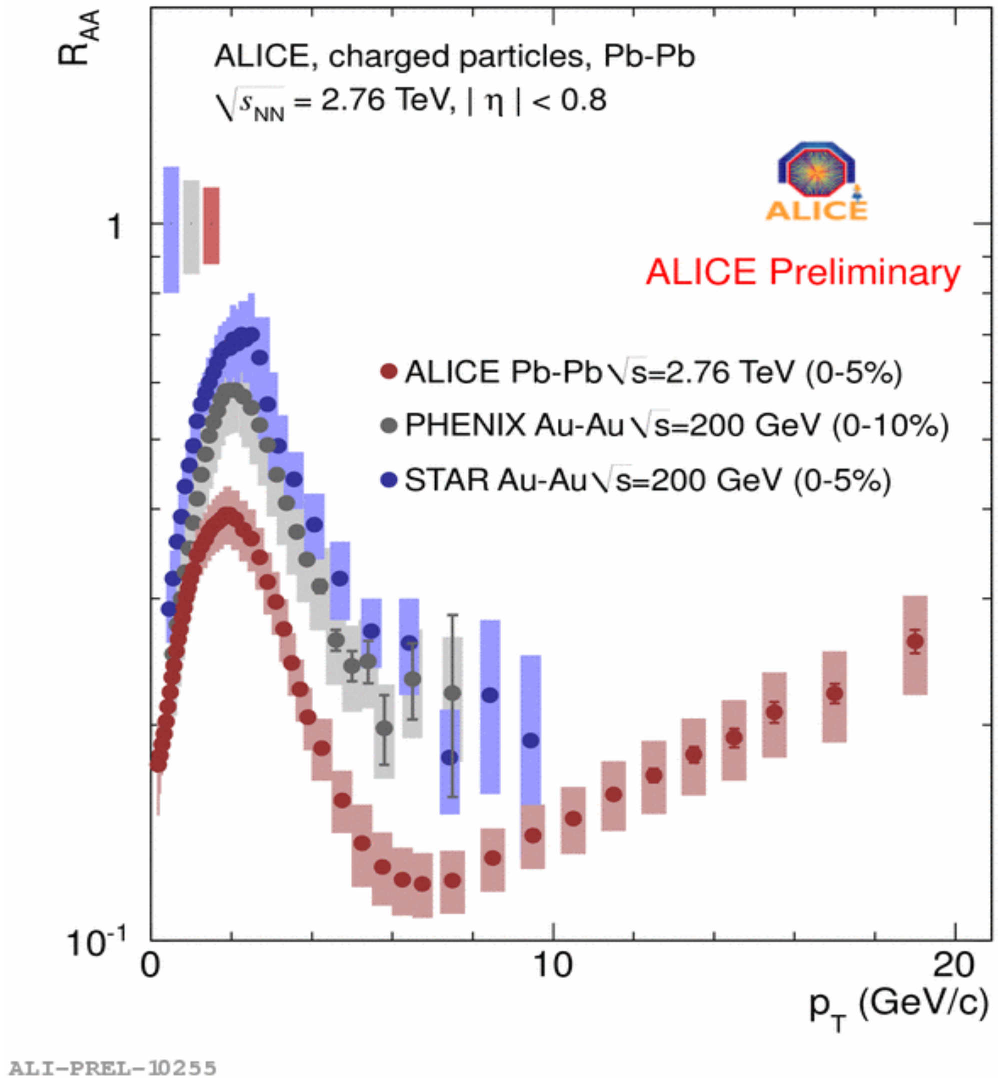




Suppression/jet quenching effects increase with centrality

Expected in a radiative energy loss picture due to increase of average pathlength of partons in the QGP

Nuclear Modification Factor: RHIC vs. LHC



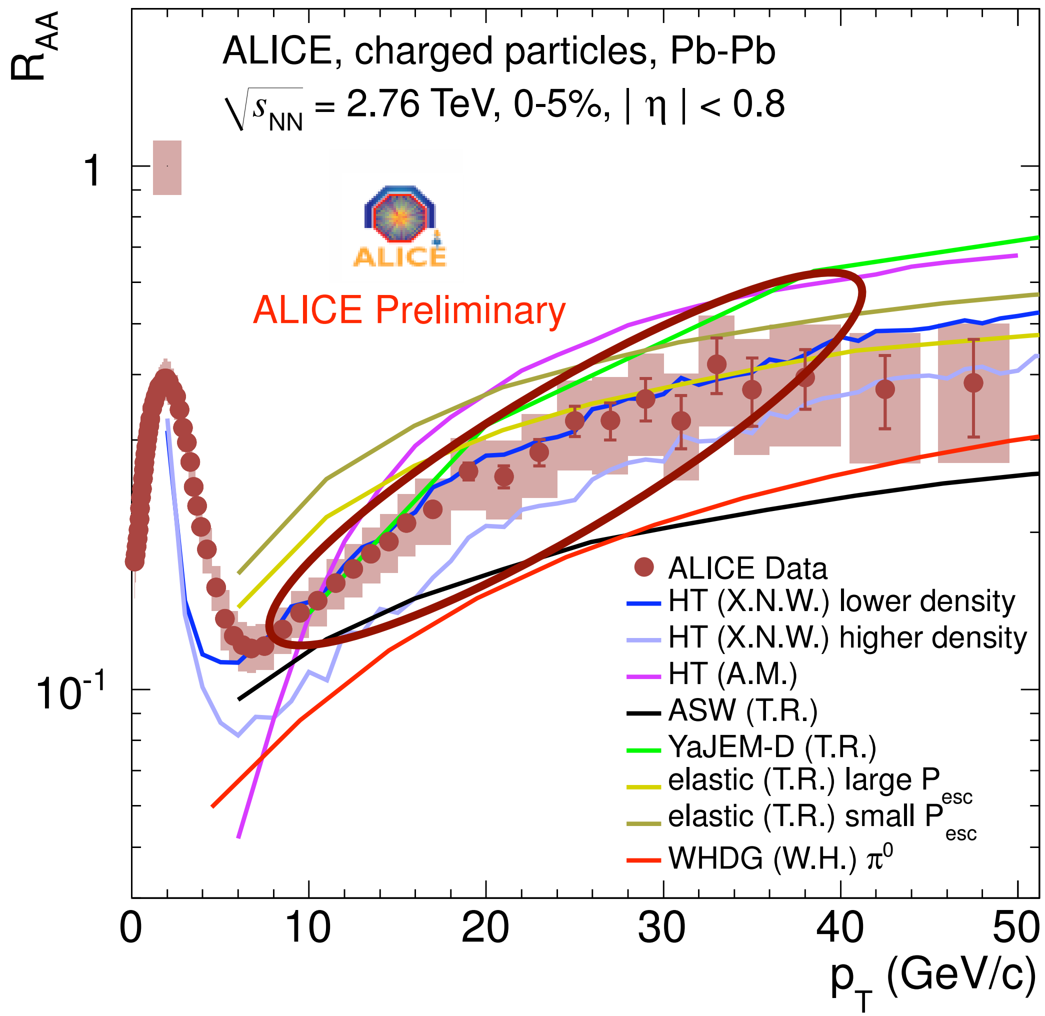
Stronger suppression at the LHC than RHIC

"Flatter" partonic spectrum at the LHC

→ larger partonic energy loss at LHC compared to RHIC

Comparison to Theory

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{<N_{coll}> d^2N^{pp}/dydp_T}$$



Rise of R_{AA} with increasing p_T characteristic of radiative energy loss models

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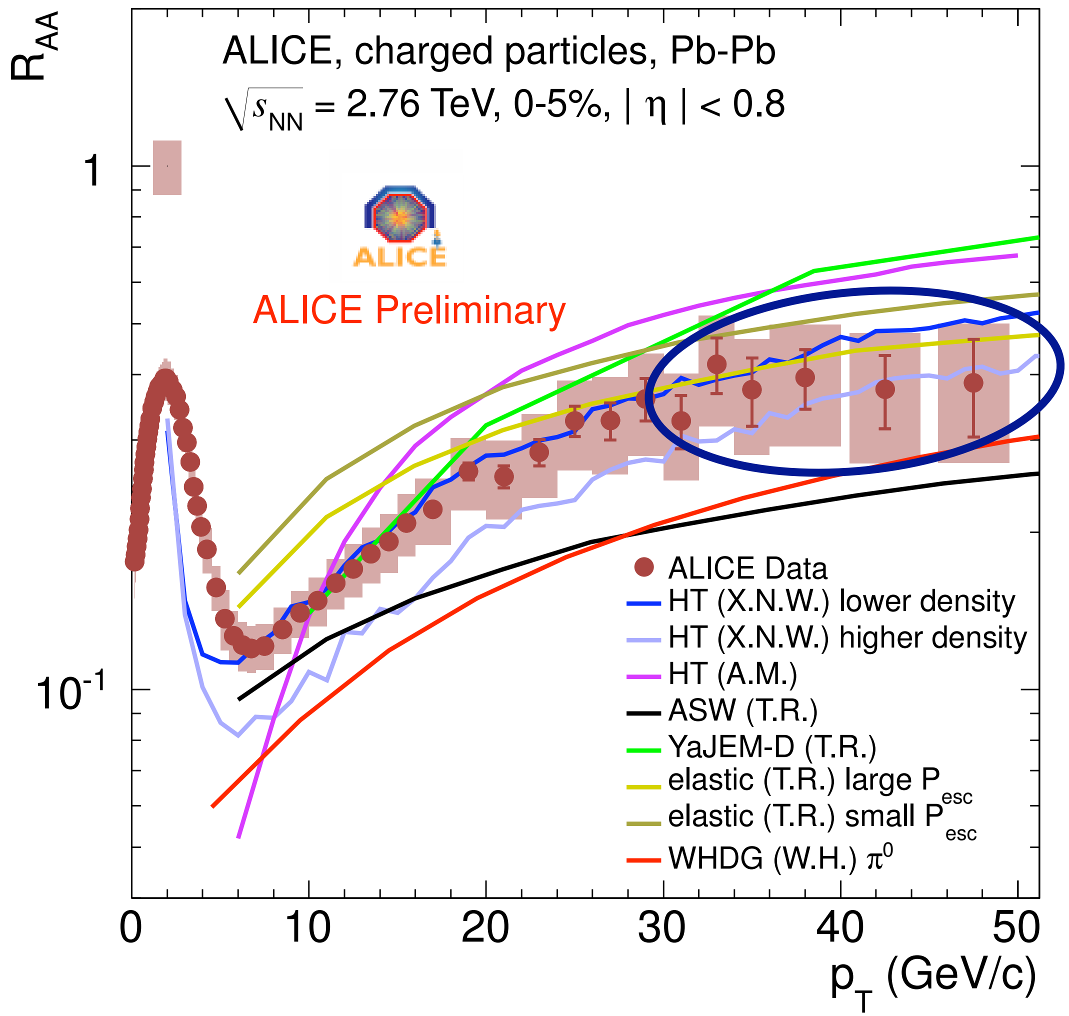

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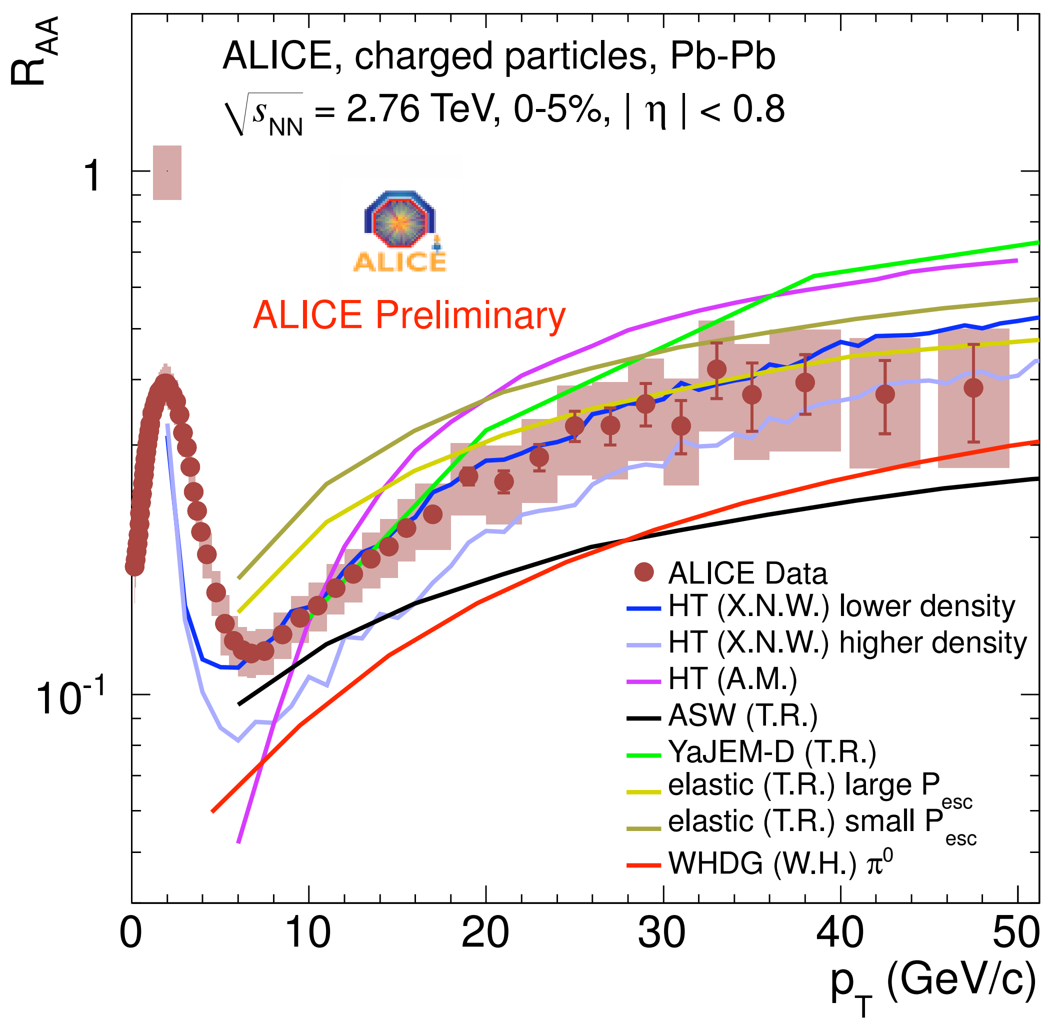

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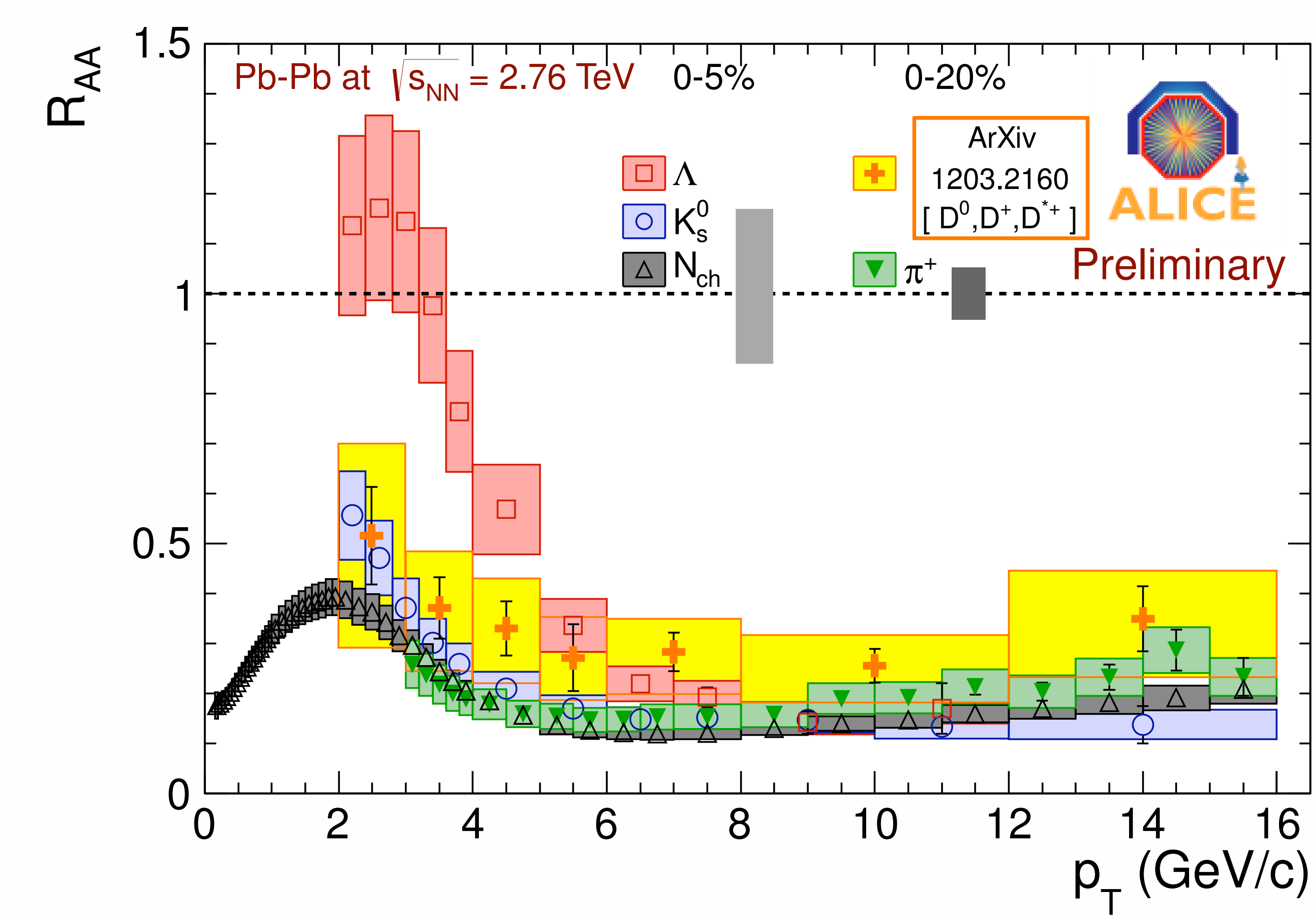
Possible flattening at high p_T

R_{AA} measurements put strong constraints on the theoretical description on partonic energy loss in the QGP!

PID Nuclear Modification Factor

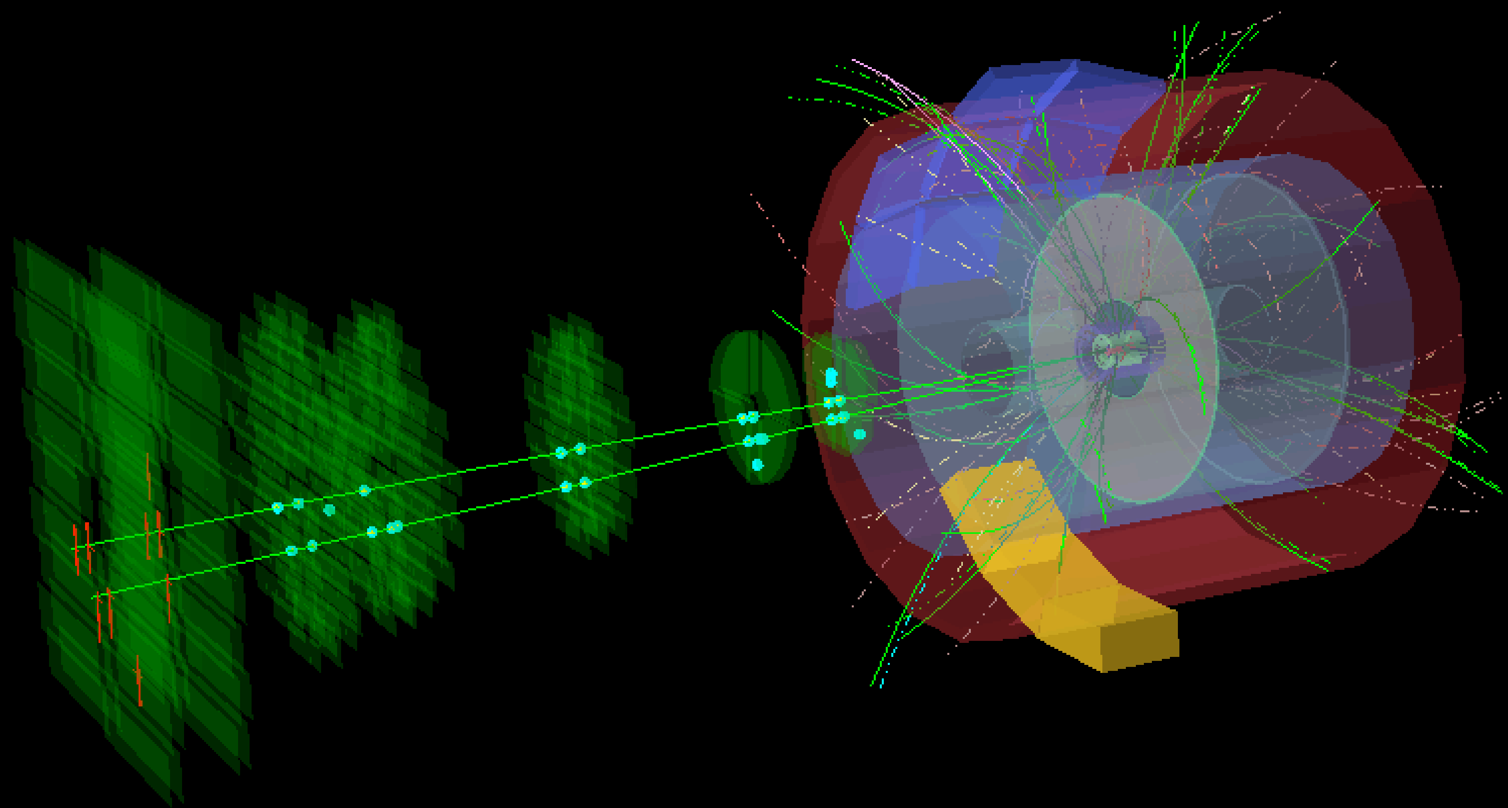


$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{<N_{coll}> d^2N^{pp}/dydp_T}$$

Similar suppression at high-p_T for all particle species (even D's)

PID R_{AA} measurements will put further strong quantitative constraints on theoretical models!

Quarkonia in ALICE
- The Thermometer -

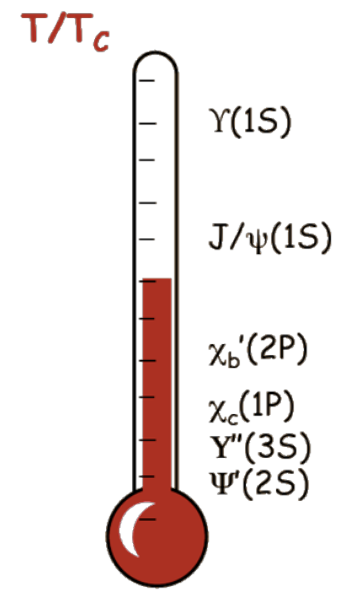


Quarkonia in the QGP - Thermometer

Charmonium suppression

Color screening prevents *c* anti-*c* (and *b* anti-*b*) from binding in de-confined (QGP) matter

Dissociation temperature depends on the binding energy
→ ”QGP thermometer“



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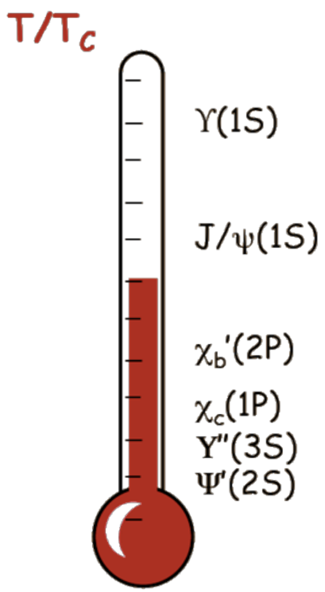
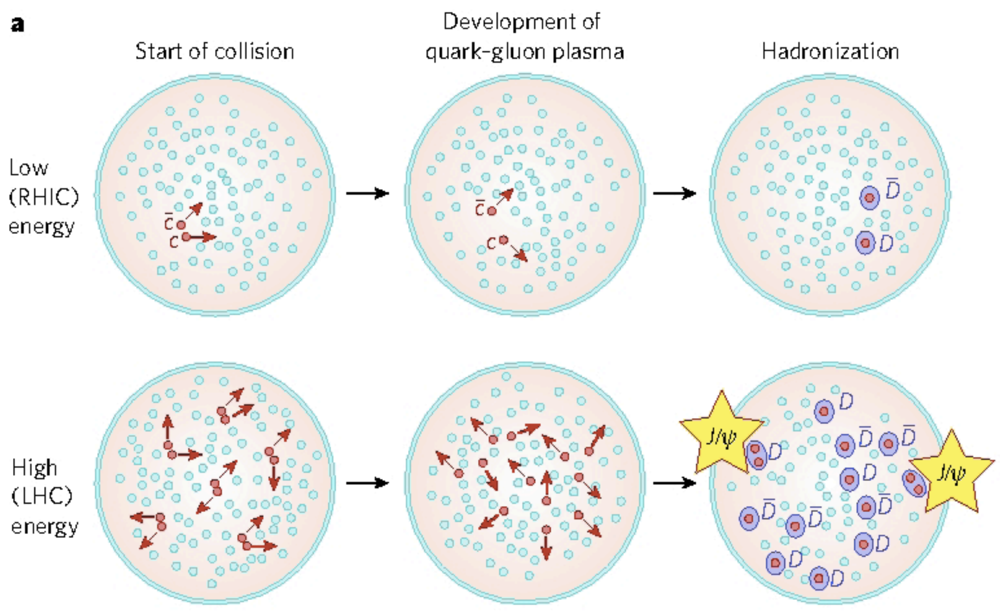
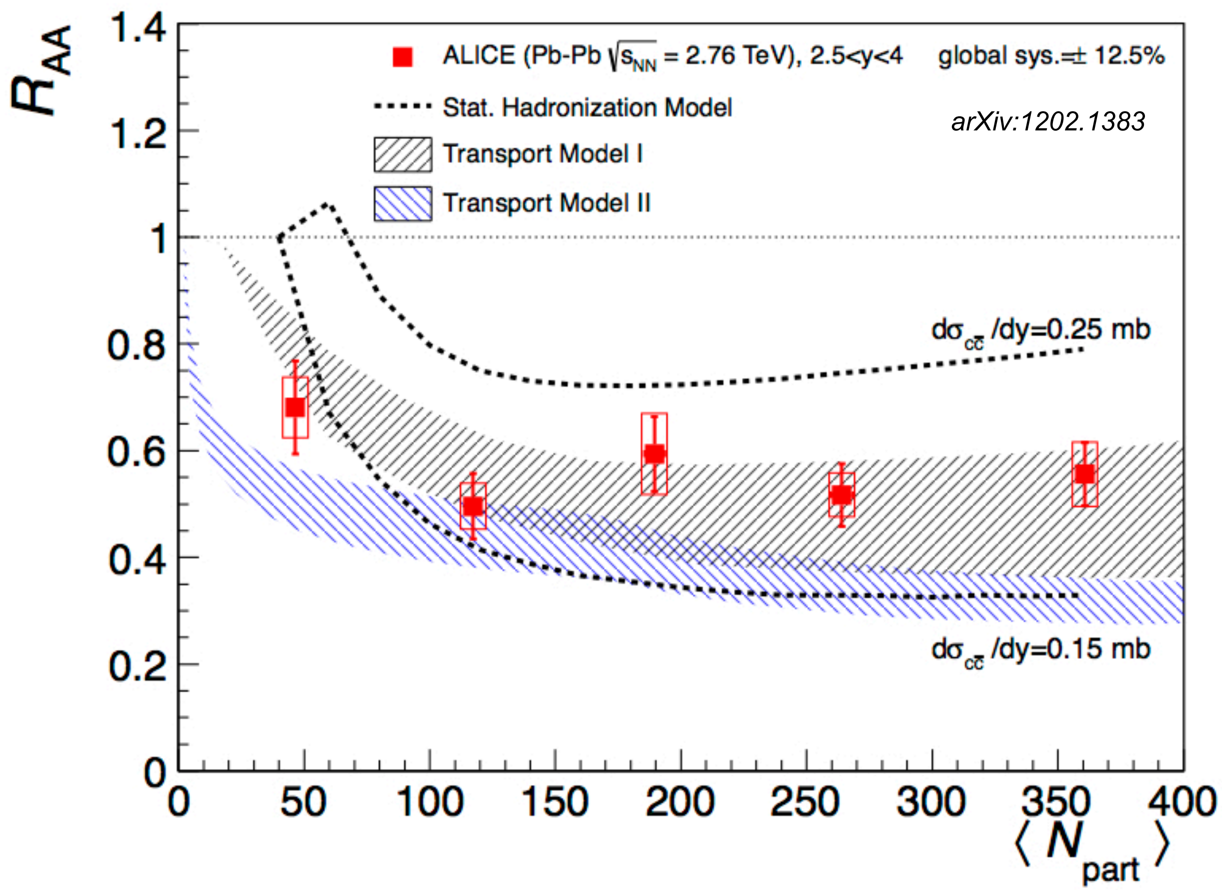


J/ψ Recombination



Quarkonia - J/ψ suppression in HI Collisions



Suppression ~ independent on centrality

Qualitatively consistent with recombination picture

But: Shadowing estimate from p+Pb data needed in order to draw a definite conclusion

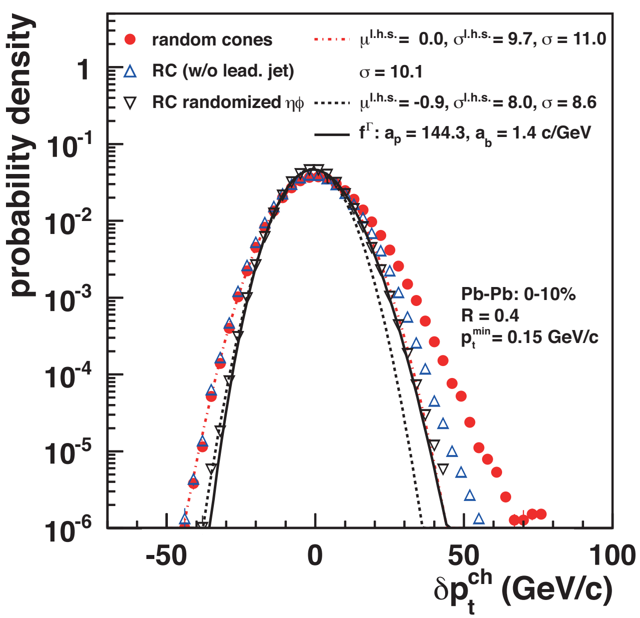
A short outlook ...

2011 Pb-Pb increased statistics significantly
→ important for hard and rare probes

For example: Full jet-reconstruction in heavy-ion collisions

Precision jet measurements = precision background correction

JHEP 1203 (2012) 053



- Improved understanding on how to characterize the underlying heavy-ion background fluctuations
- Fully operational EMCal and trigger capability
- Unique tracking capabilities down to very low p_T will minimize jet reconstruction biases, necessary for an unambiguous interpretation and comparison with theory

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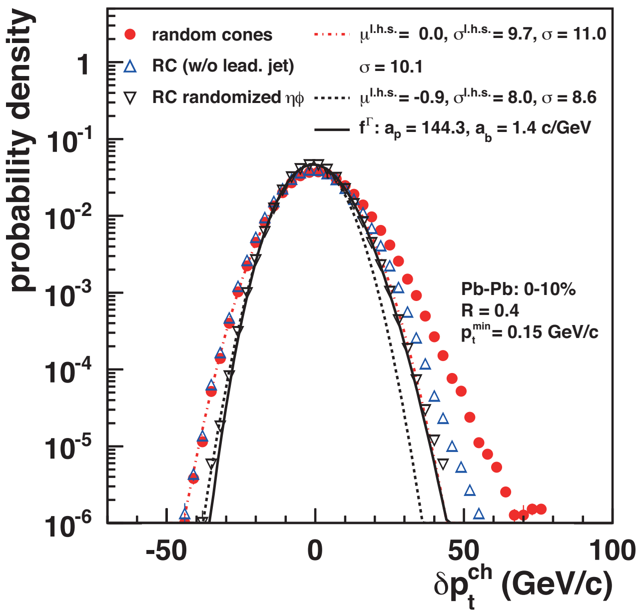

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Just a start, many more: J/ψ and heavy flavor elliptic flow, direct photon ...

Also crucial p+Pb reference run expected in 2012 ...

Summary

- ALICE at the LHC is an ideal place to study the QGP

- ALICE measurements of bulk properties and (higher) flow harmonics played a crucial role to confirm the stunning success of hydrodynamics in heavy-ion collisions from RHIC to LHC
→ precision measurements of QGP shear viscosity η/s

- The abundance of hard probes at the LHC combined with the unique ALICE detector capabilities (precision tracking and PID) will put strong quantitative constraints on theoretical models, for example concerning partonic energy loss and quarkonia

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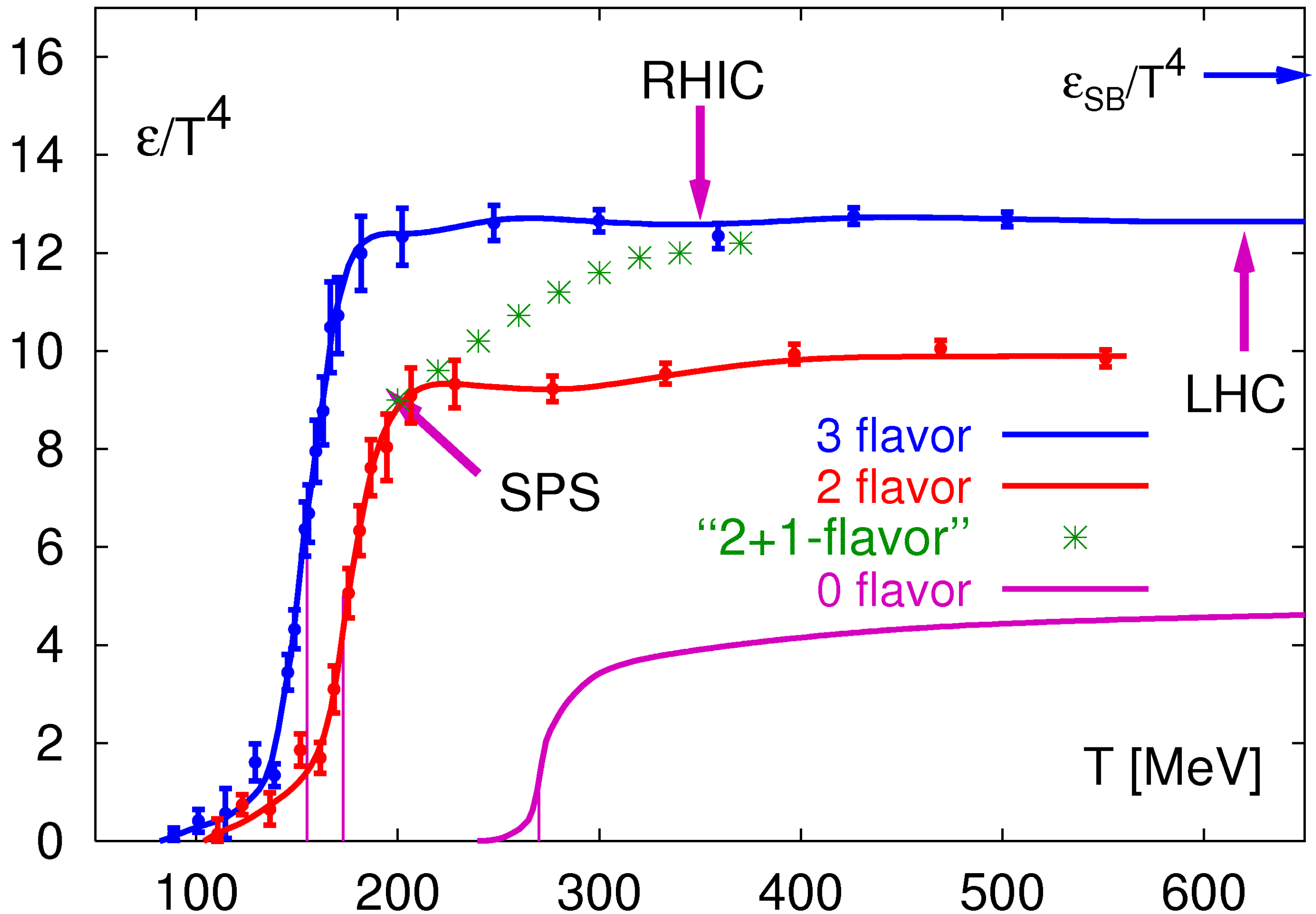
Beginning of a new era in heavy-ion physics with ALICE at the LHC

qualitative → quantitative (η/s, $\hat{q}$, ...)

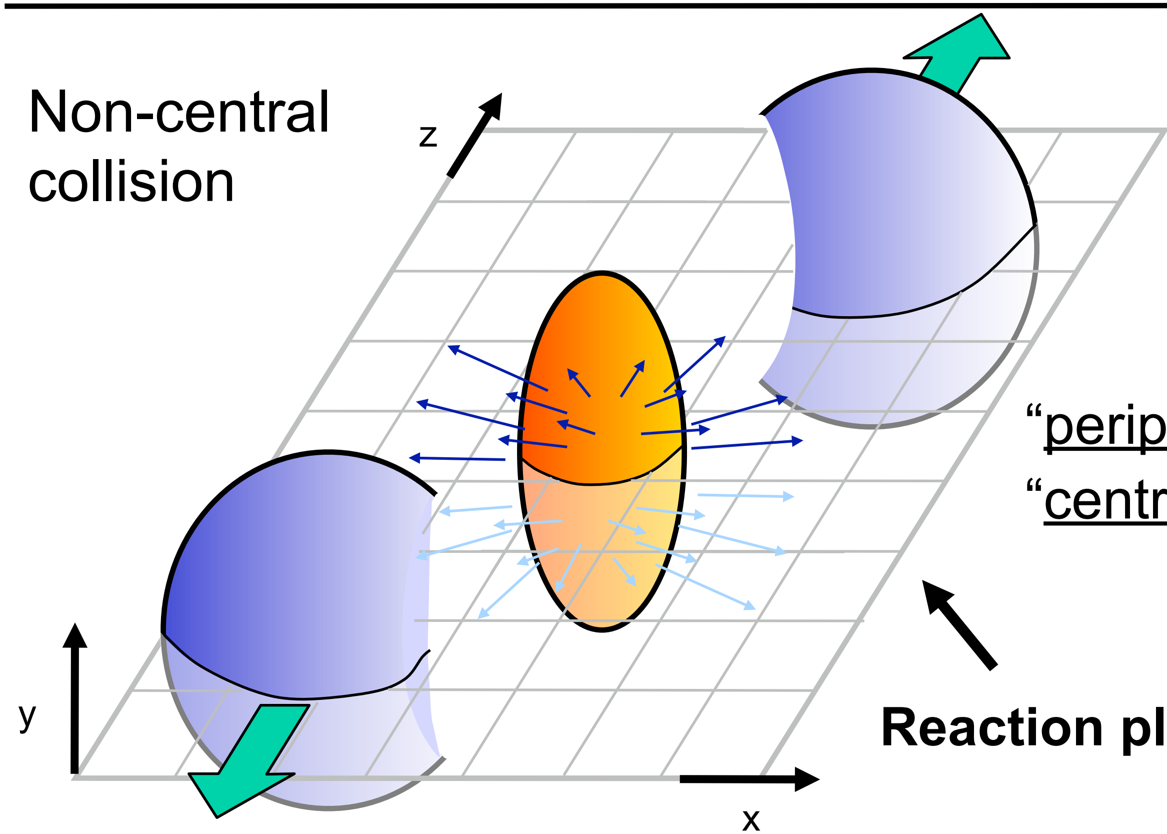
Backup

Lattice QCD


16
14
12
10
8
6
4
2
0
100
200
300
400
500
600
ε/T4
RHIC
εSB/T4
LHC
SPS
3 flavor
2 flavor
“2+1-flavor”
0 flavor
T [MeV]

Geometry of a Heavy-Ion Collision

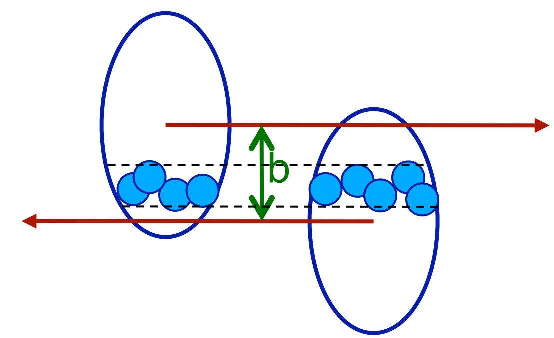
Non-central collision



Reaction plane

"peripheral" collision ($b \sim b_{max}$)

"central" collision ($b \sim 0$)



Number of participants (N_{part}):

number of incoming nucleons in the overlap region

N_{part}: $n_A + n_B$ (ex: 4 + 5 = 9 + …)

Number of binary collisions (N_{bin} or N_{coll}):

number of equivalent inelastic nucleon-nucleon collisions

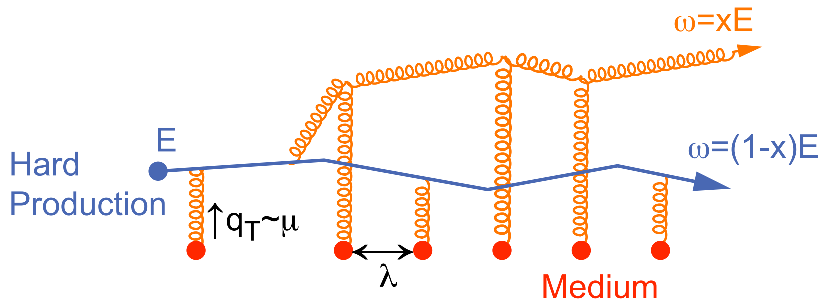
N_{bin}: $n_A \times n_B$ (ex: 4 x 5 = 20 + …)

Derived from multiplicity information and a simple version of **Glauber theory** (by now well under control)

What do we ideally want to measure?

Gluon radiation:

Multiple final-state gluon radiation off of the produced hard parton induced by the traversed dense colored medium ~ “Gluon Bremsstrahlung”



Manifestation in the modification of the Jet Structure/Fragmentation Function =fractional jet momentum carried by by the individual jet particles/constituents

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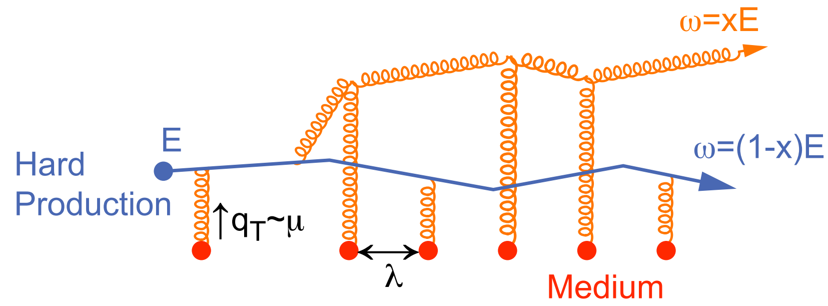

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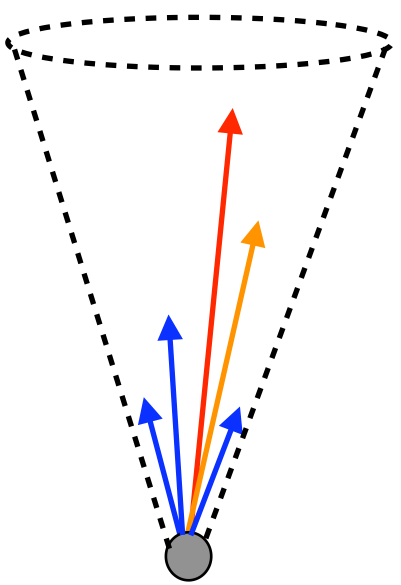
Jet in vacuum

E_{Vacuum}^{Jet}



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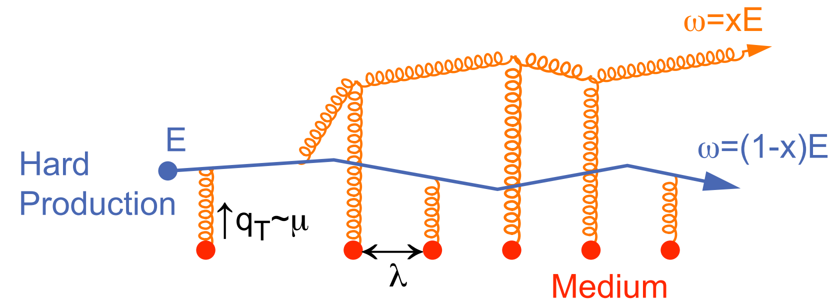
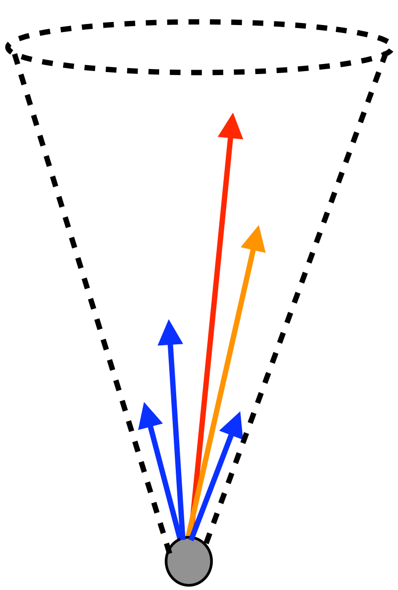


Manifestation in the modification of the Jet Structure/Fragmentation Function =fractional jet momentum carried by by the individual jet particles/constituents

Jet in vacuum

E^{Jet}_{Vacuum}

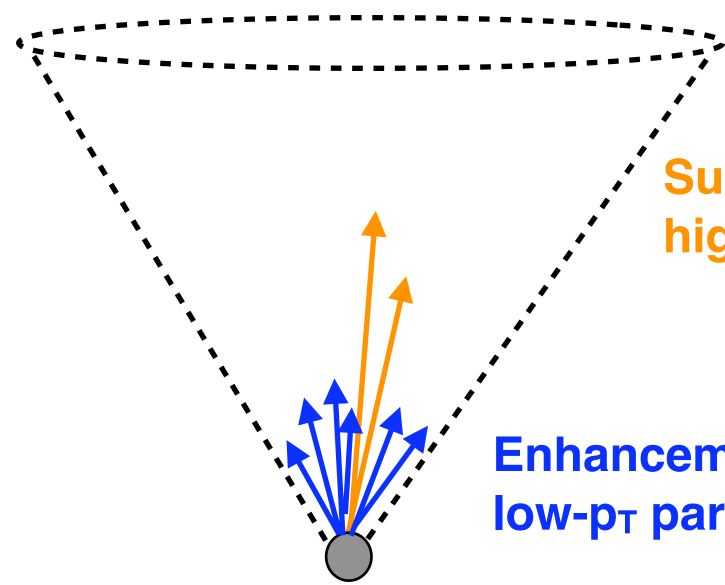


Jet quenching/ gluon radiation in QGP

Jet in medium

$E^{Jet}_{Medium} = E^{Jet}_{Vacuum}$

Jet broadening



Suppression of high-p_T particles

Enhancement of low-p_T particles

What do we ideally want to measure?

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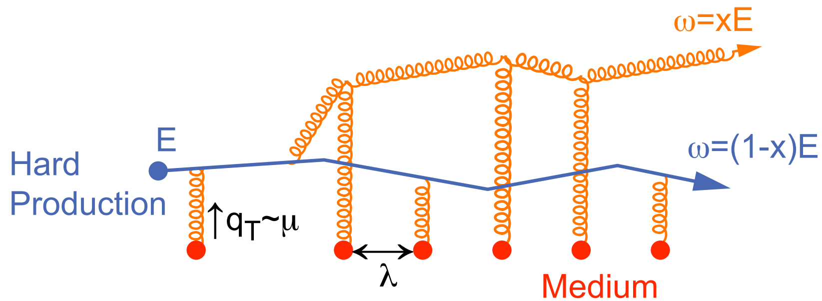

Manifestation in the modification of the Jet Structure/Fragmentation Function =fractional jet momentum carried by by the individual jet particles/constituents