IX Latin American Symposium on High Energy Physics
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LHC Heavy Ion Results

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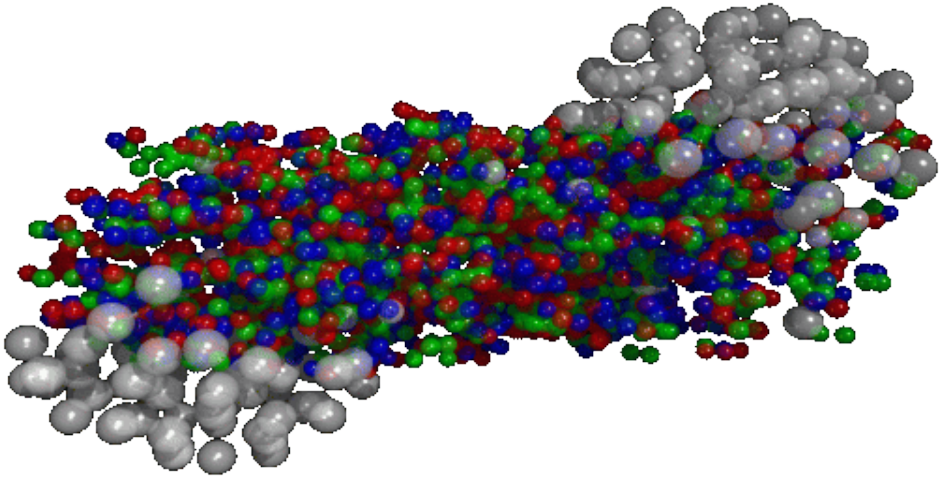
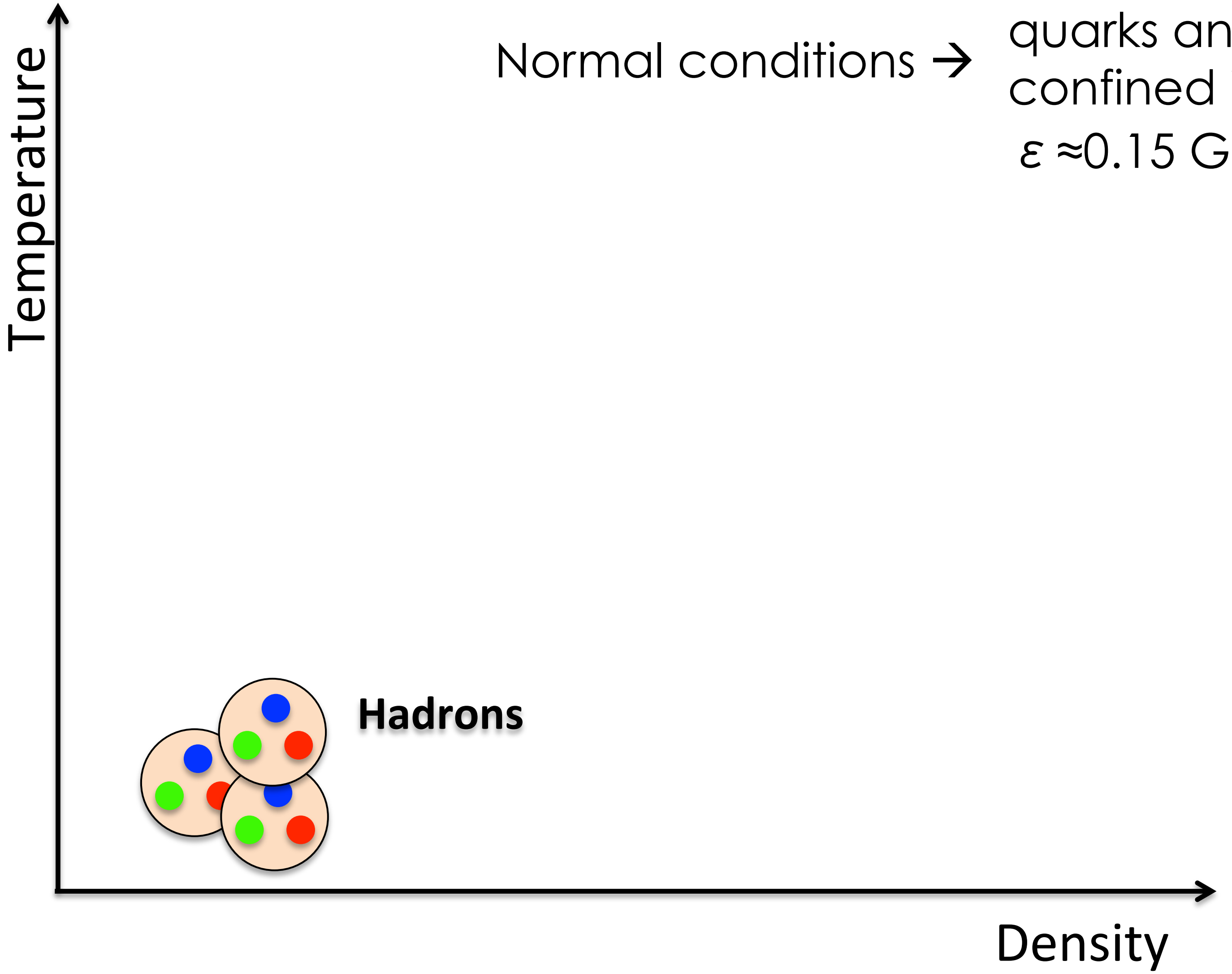
for the ALICE Collaboration

Heavy Ion Physics

The main goal of Heavy Ion Collisions is to study the behavior of **matter under extreme condition**, to explore and test QCD phase diagram and to address the fundamental question of hadron confinement and chiral symmetry breaking, which are related to the existence and properties of the **Quark-Gluon Plasma** (QGP).



QCD phase diagram

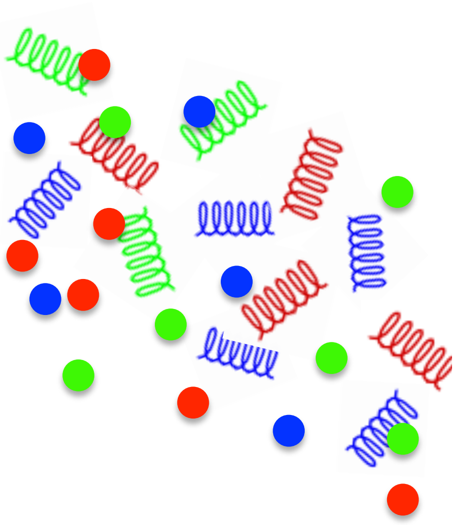


Normal conditions → quarks and gluons confined in Hadrons.

$\varepsilon \approx 0.15\ \mathrm{GeV/fm^3}$

QCD phase diagram

Temperature



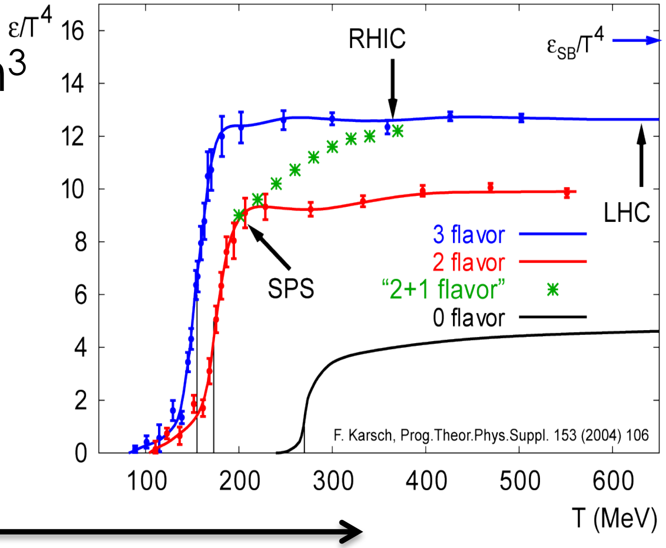
Normal conditions → quarks and gluons confined in Hadrons.

$\varepsilon \approx 0.15$ GeV/fm^3

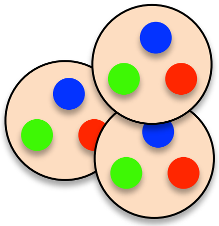
High T and low density, QCD predicts a phase transition to a deconfined state of Quarks and Gluons.

$T_C \approx 170$ GeV

$\varepsilon_C \approx 1.0$ GeV/fm^3



F. Karsch, Prog.Theor.Phys.Suppl. 153 (2004) 106

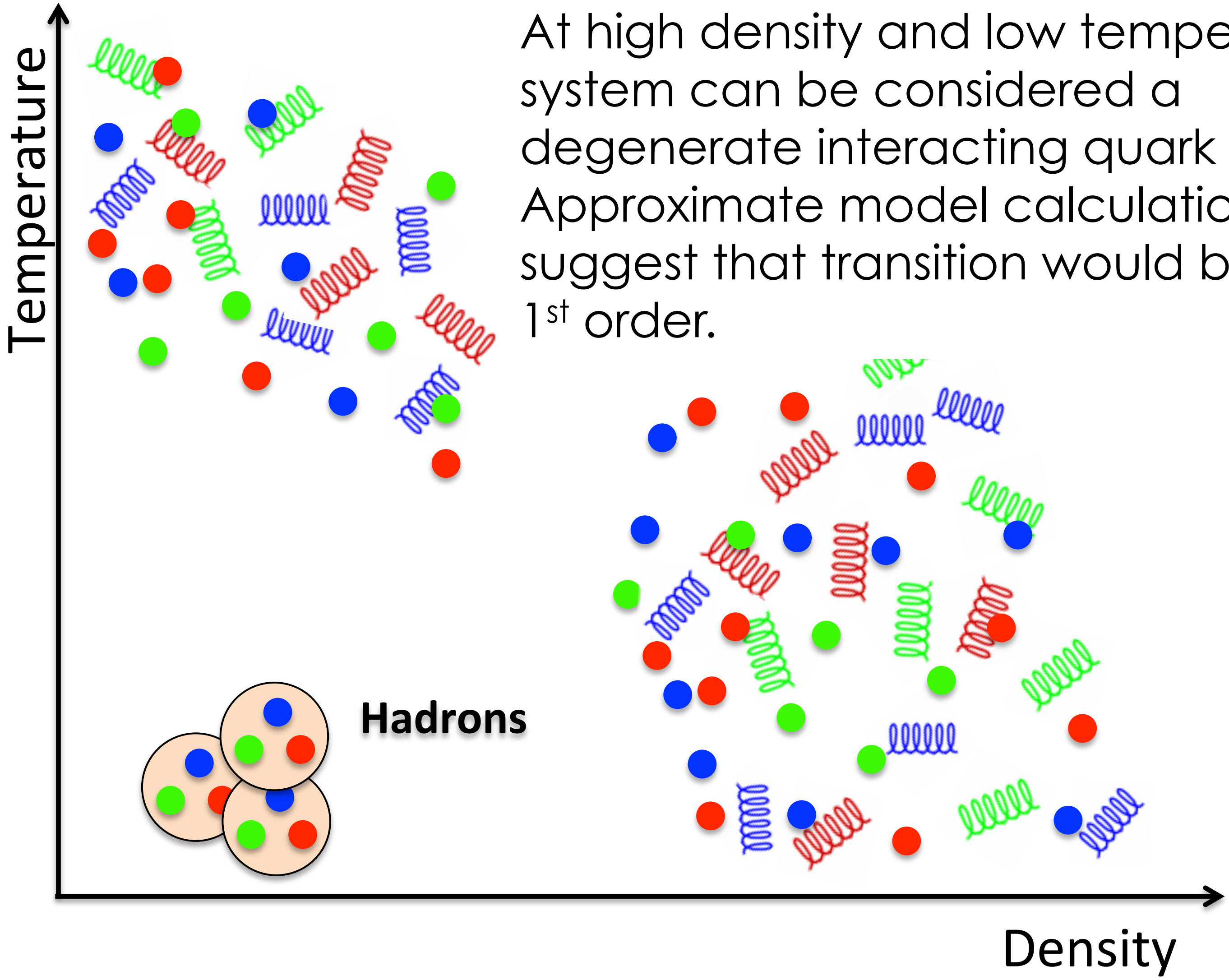


Hadrons

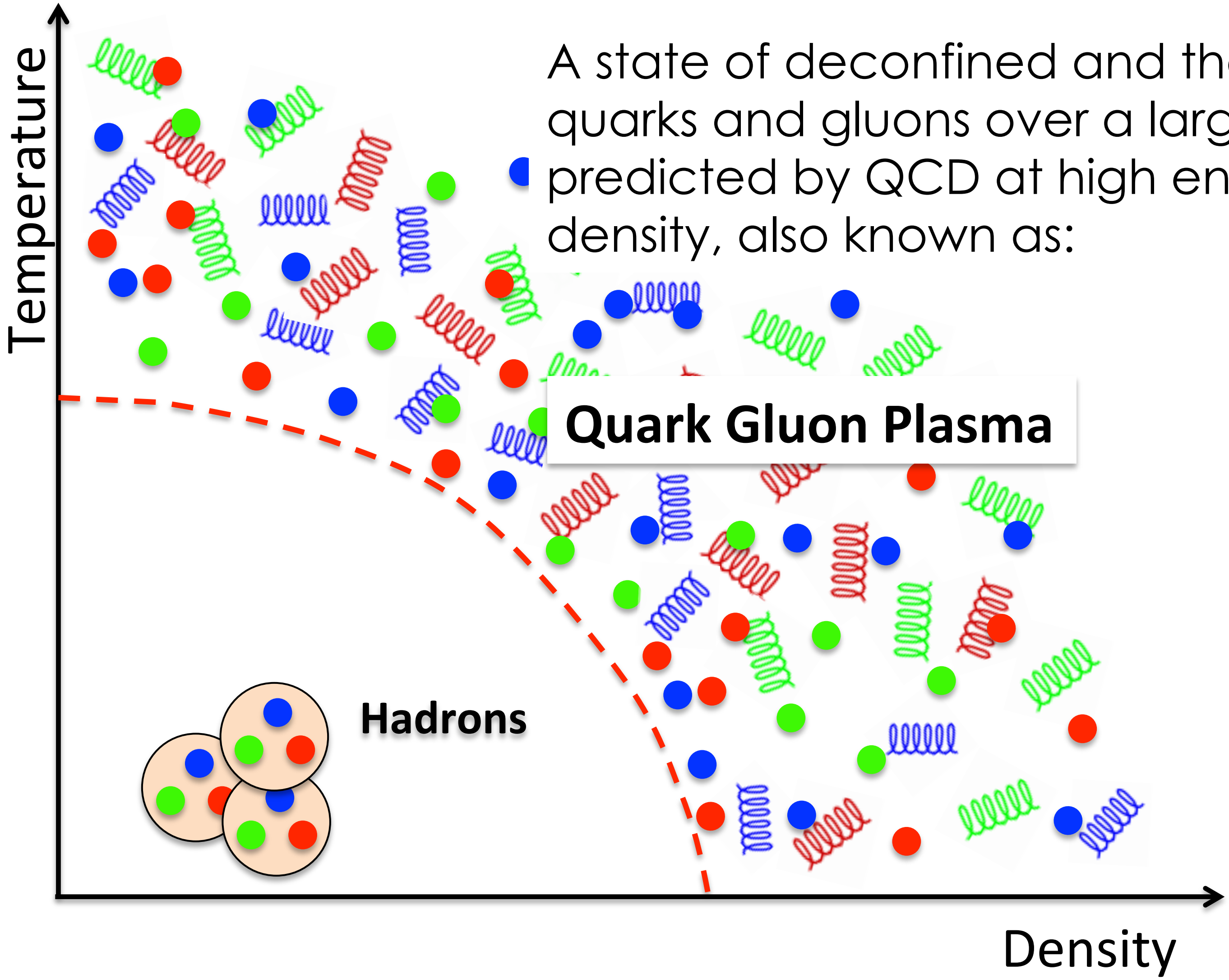
Density

QCD phase diagram

At high density and low temperature, system can be considered a degenerate interacting quark gas. Approximate model calculations suggest that transition would be of the 1st order.



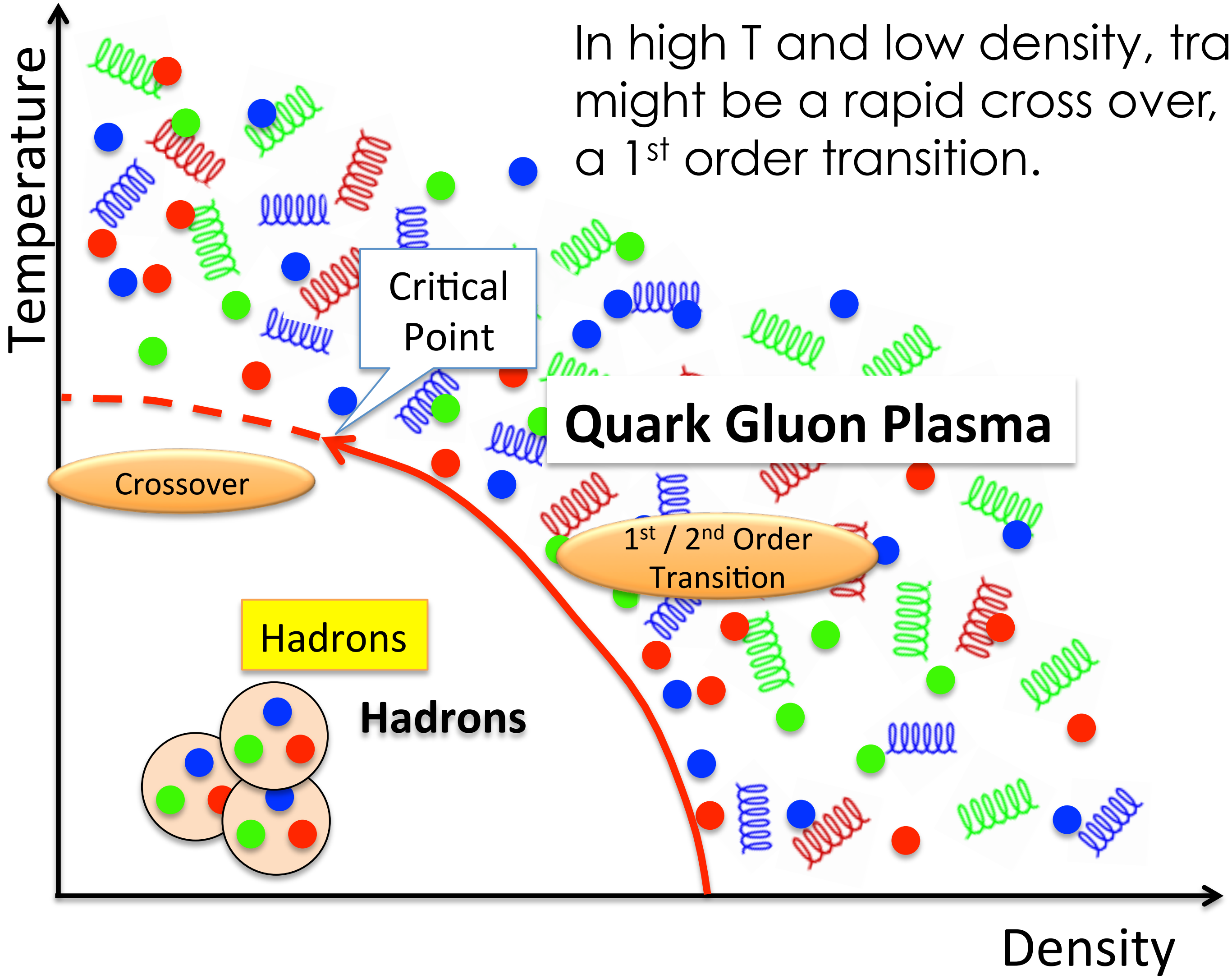
QCD phase diagram



A state of deconfined and thermalized quarks and gluons over a large volume predicted by QCD at high energy and density, also known as:

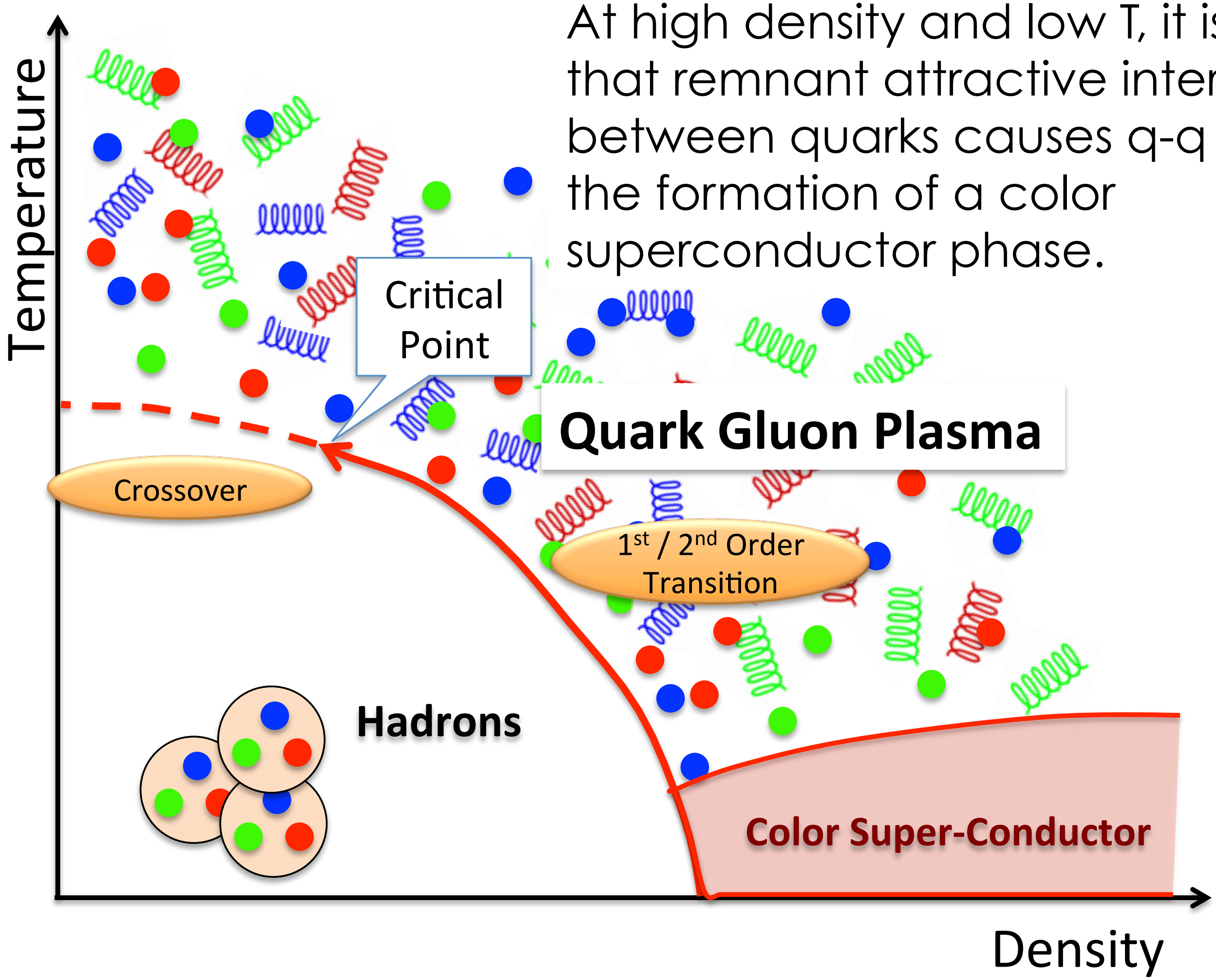
Quark Gluon Plasma

QCD phase diagram



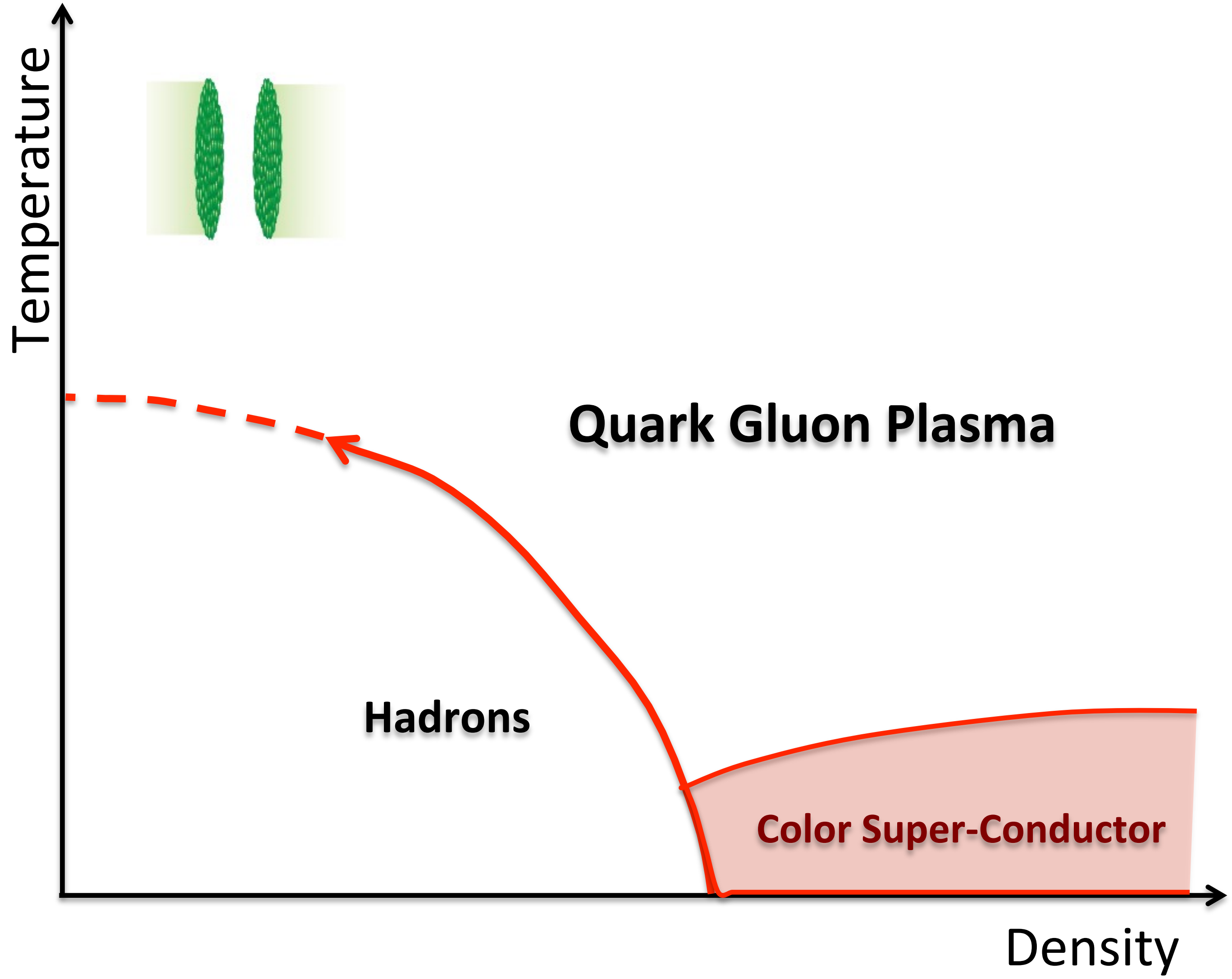
In high T and low density, transition might be a rapid cross over, instead of a 1st order transition.

QCD phase diagram

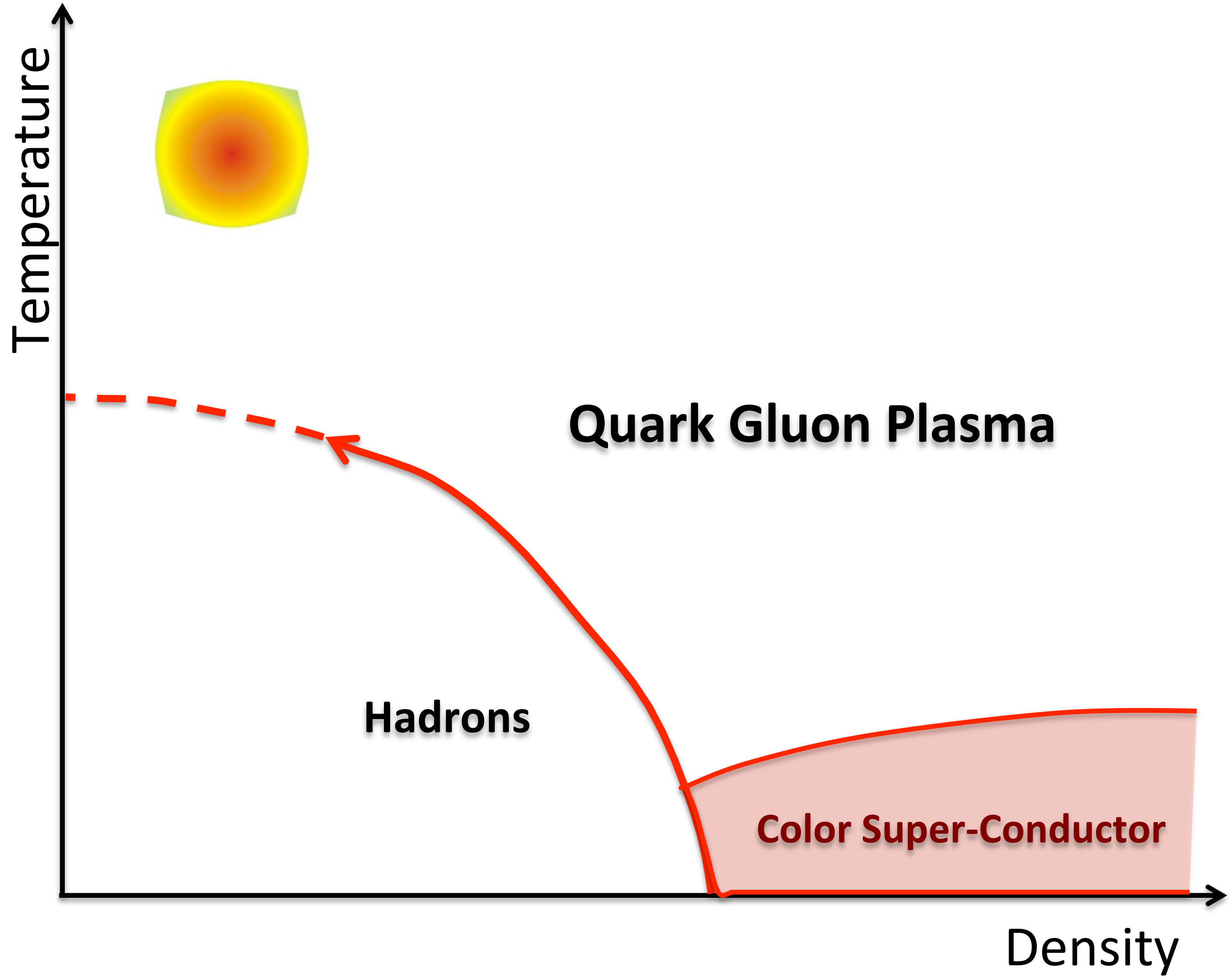


At high density and low T, it is predicted that remnant attractive interaction between quarks causes q-q paring and the formation of a color superconductor phase.

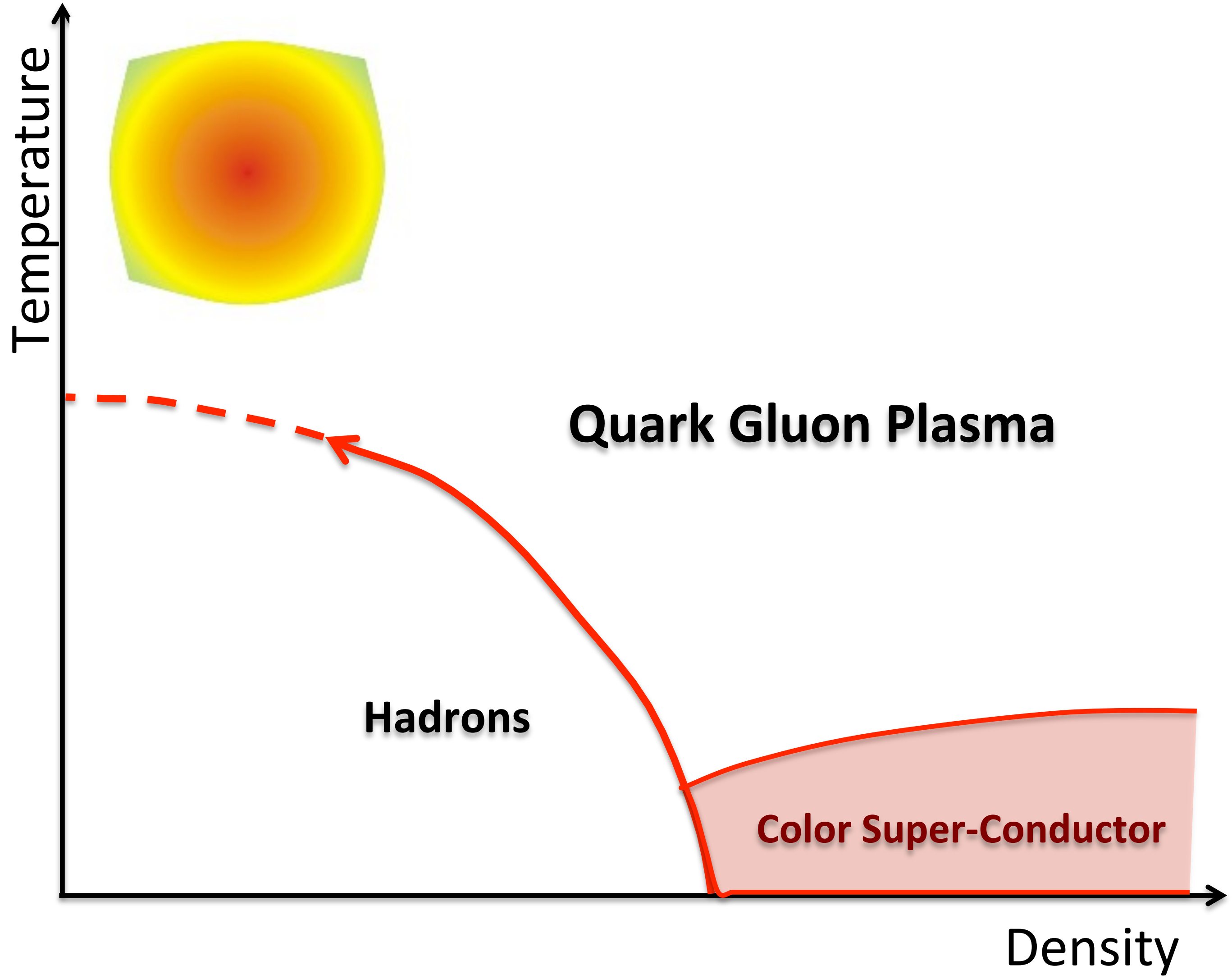
Heavy Ion Collisions



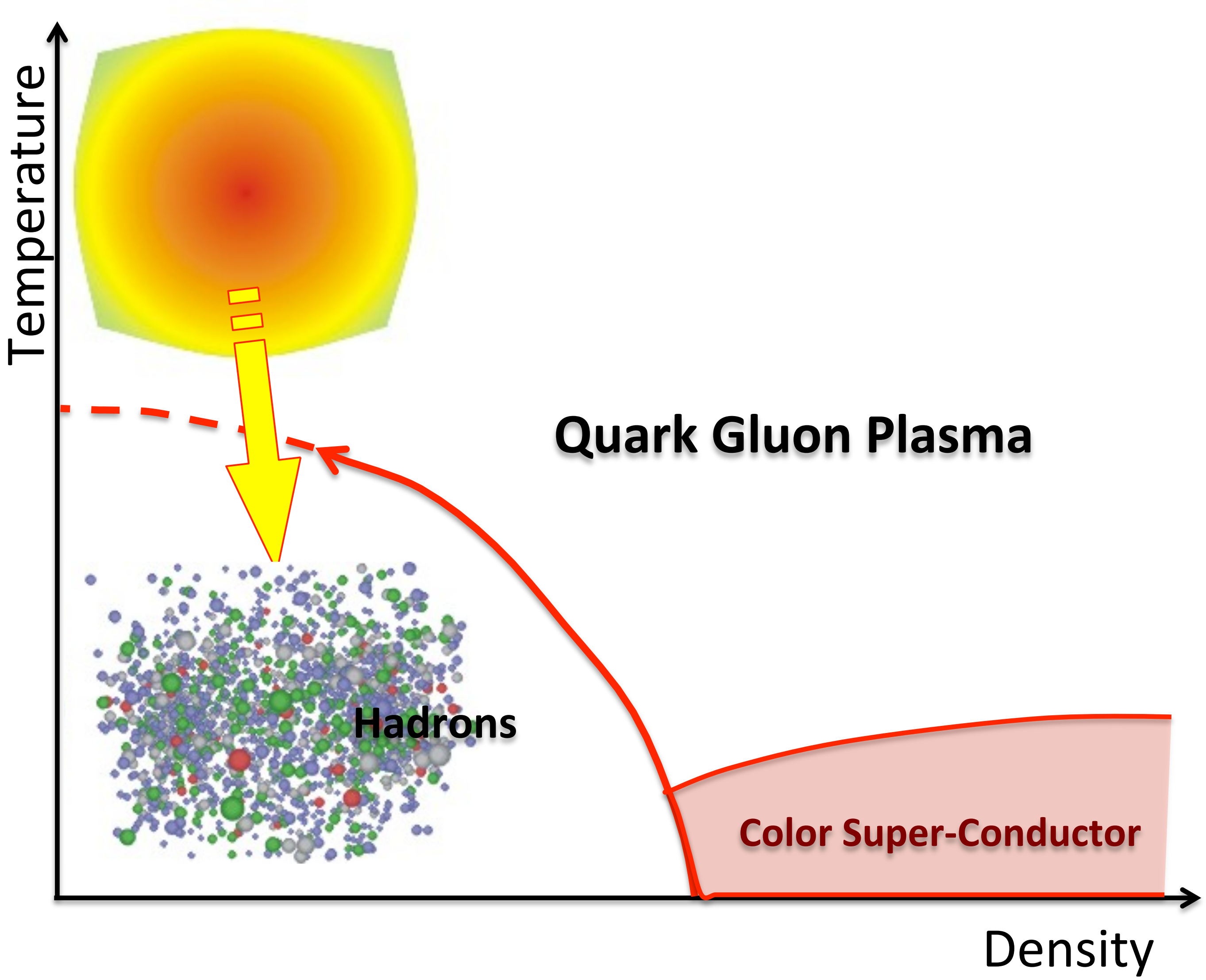
Heavy Ion Collisions



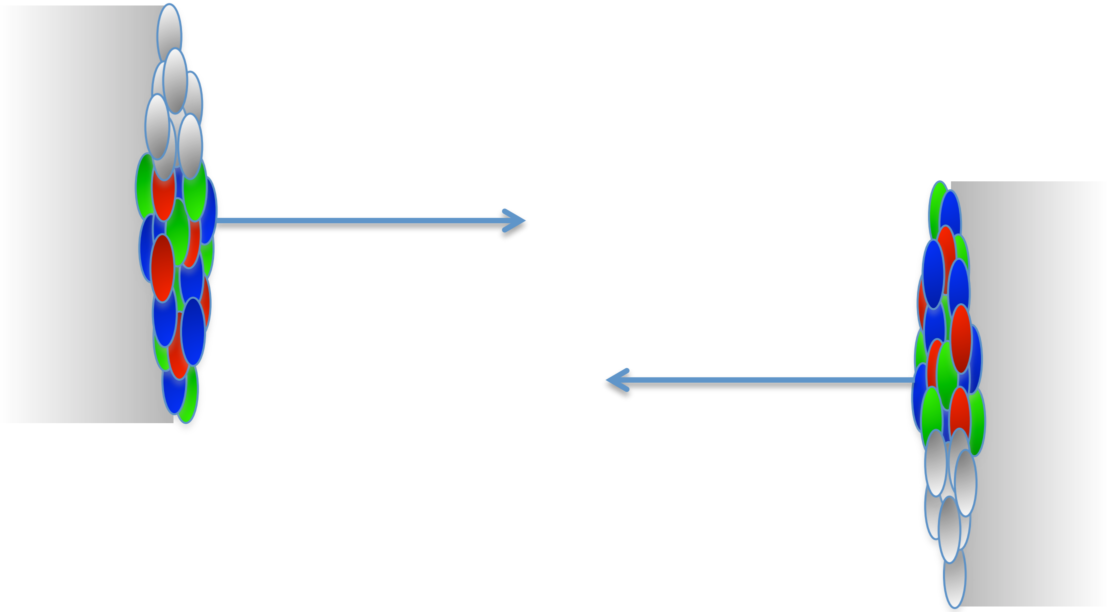
Heavy Ion Collisions



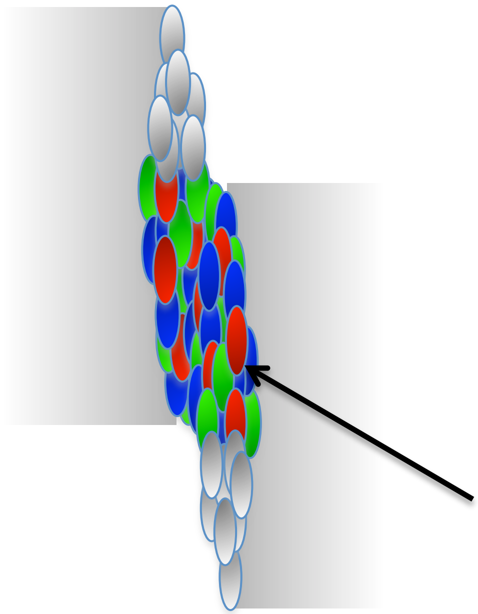
Heavy Ion Collisions



Heavy Ion Collisions



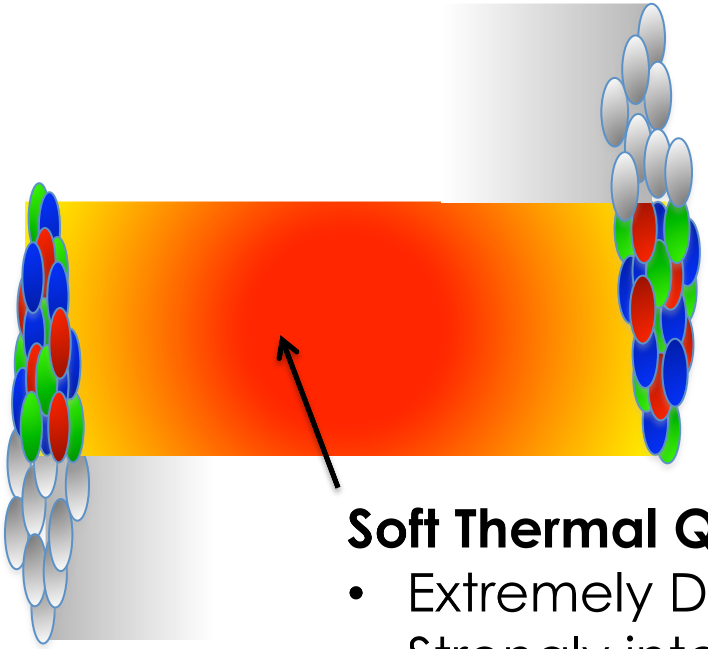
Heavy Ion Collisions



Initial Conditions:

- Lorentz Contracted colliding nuclei
- Color Glass Condensate
- Pre-equilibrium
- Hard Scattering
- Fluctuations

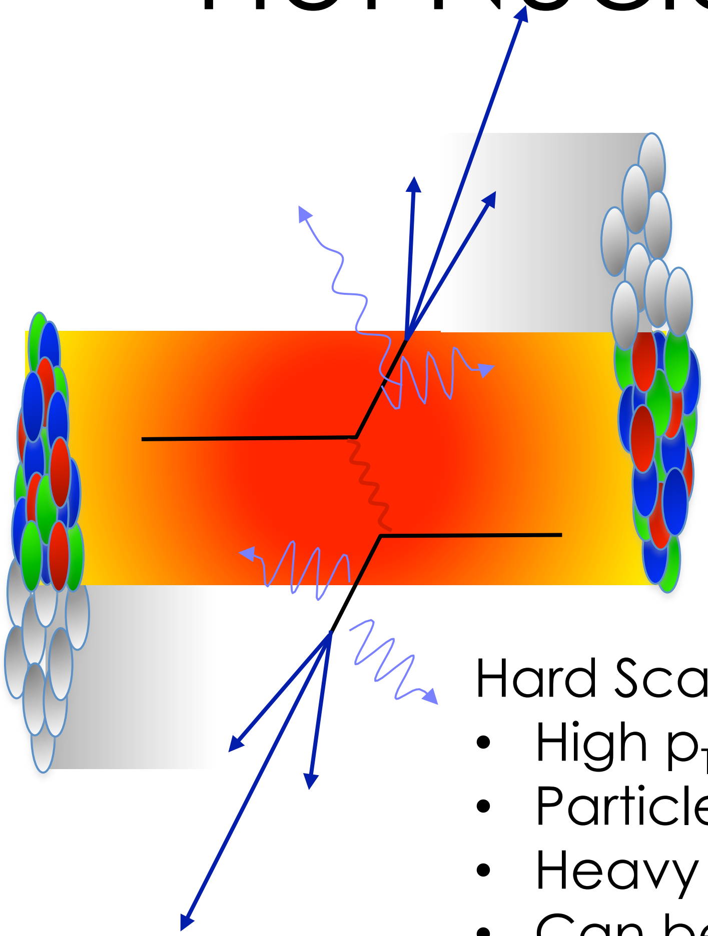
Hot Nuclear Matter



Soft Thermal QCD matter.

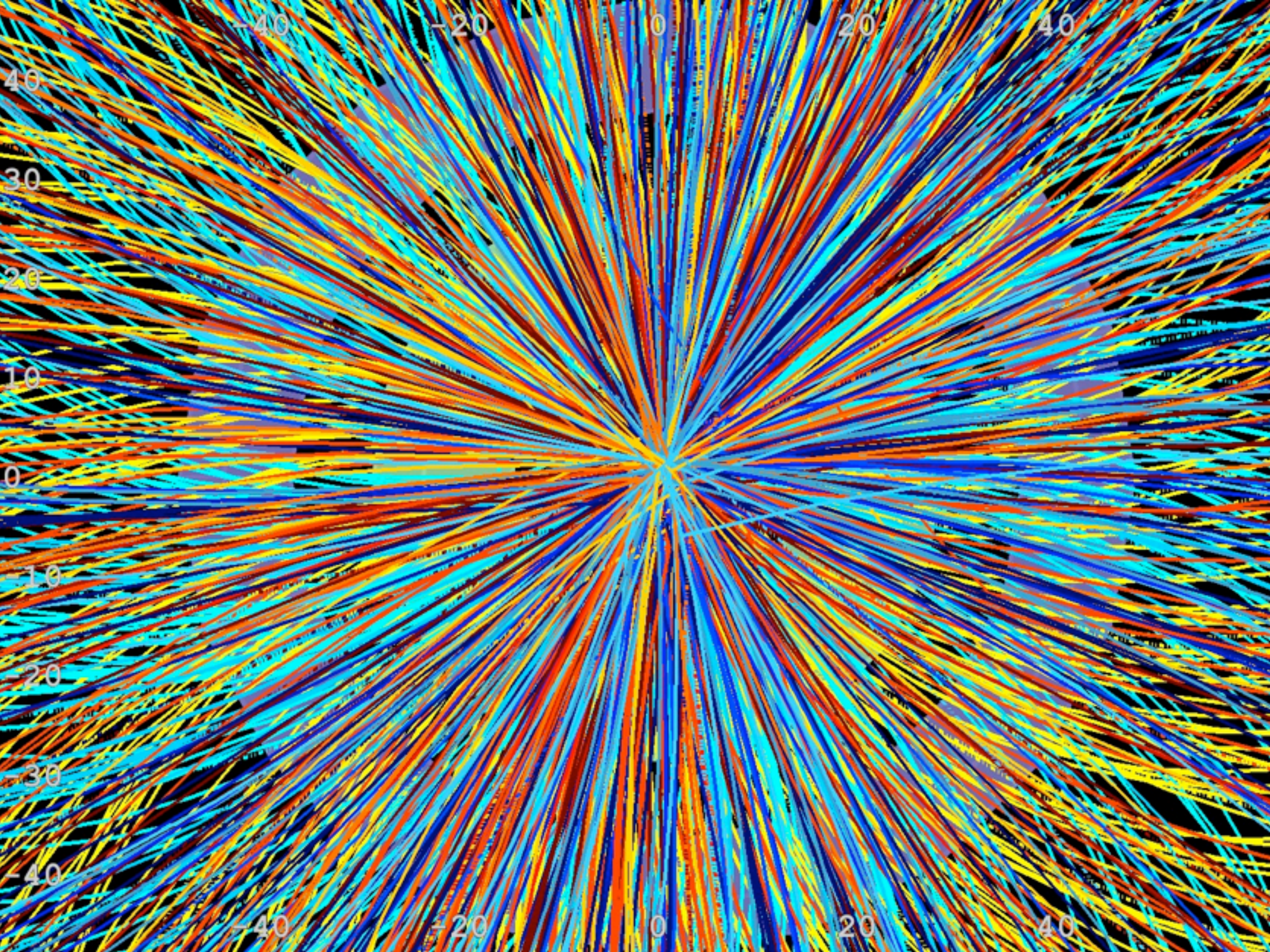
- Extremely Dense
- Strongly interacting
- Shows collective behavior
- Expansion dynamics well described by hydrodynamic models with viscosity very close to theoretical limit.
- Partonic degrees of freedom.

Hot Nuclear Matter



Hard Scatterings produce **hard probes**.

- High p_T particles
- Particle Jets
- Heavy flavored particles.
- Can be used to probe the medium through interactions: Jet modification and suppression, nuclear modification factors of light and heavy flavored particles.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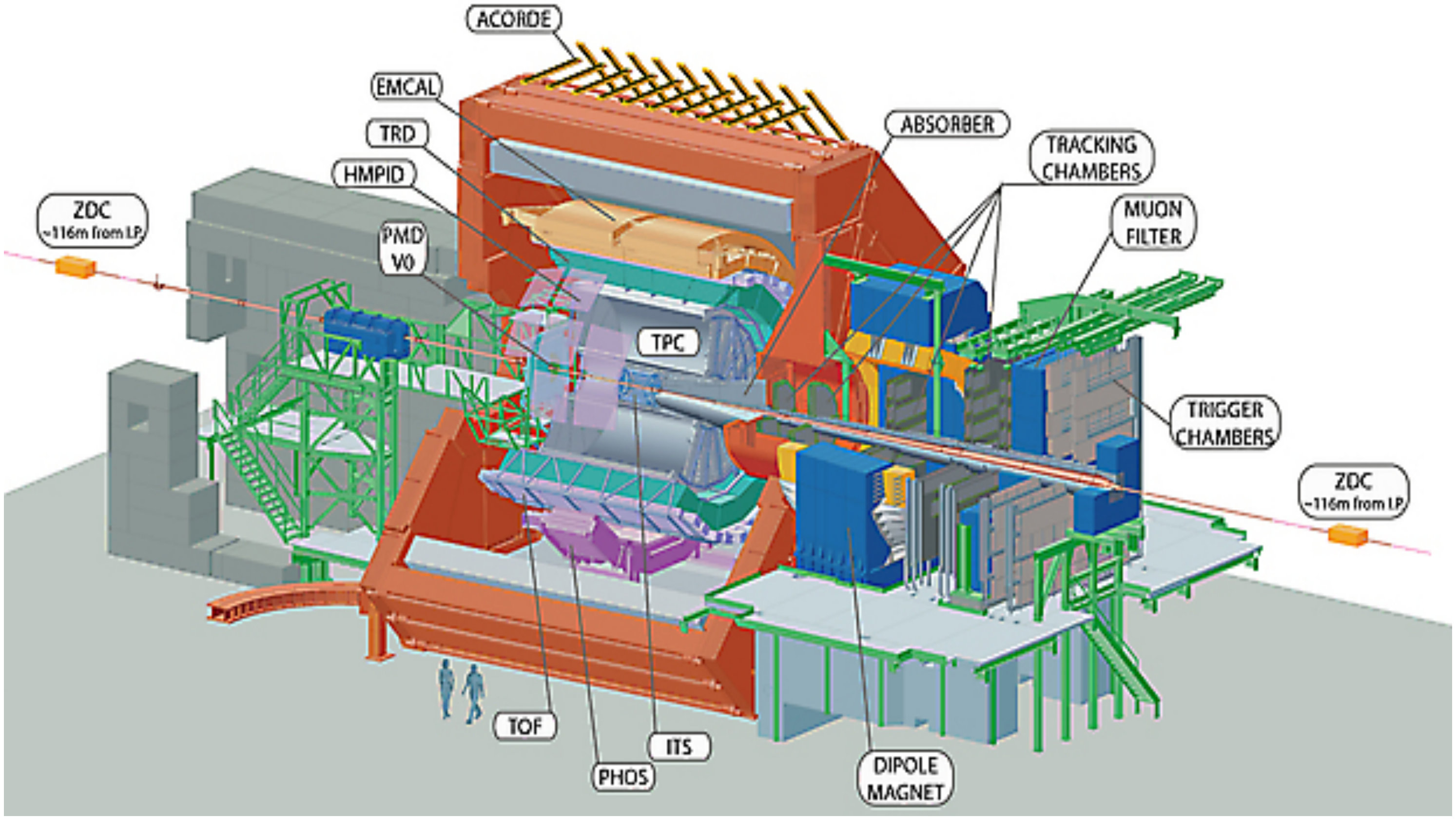
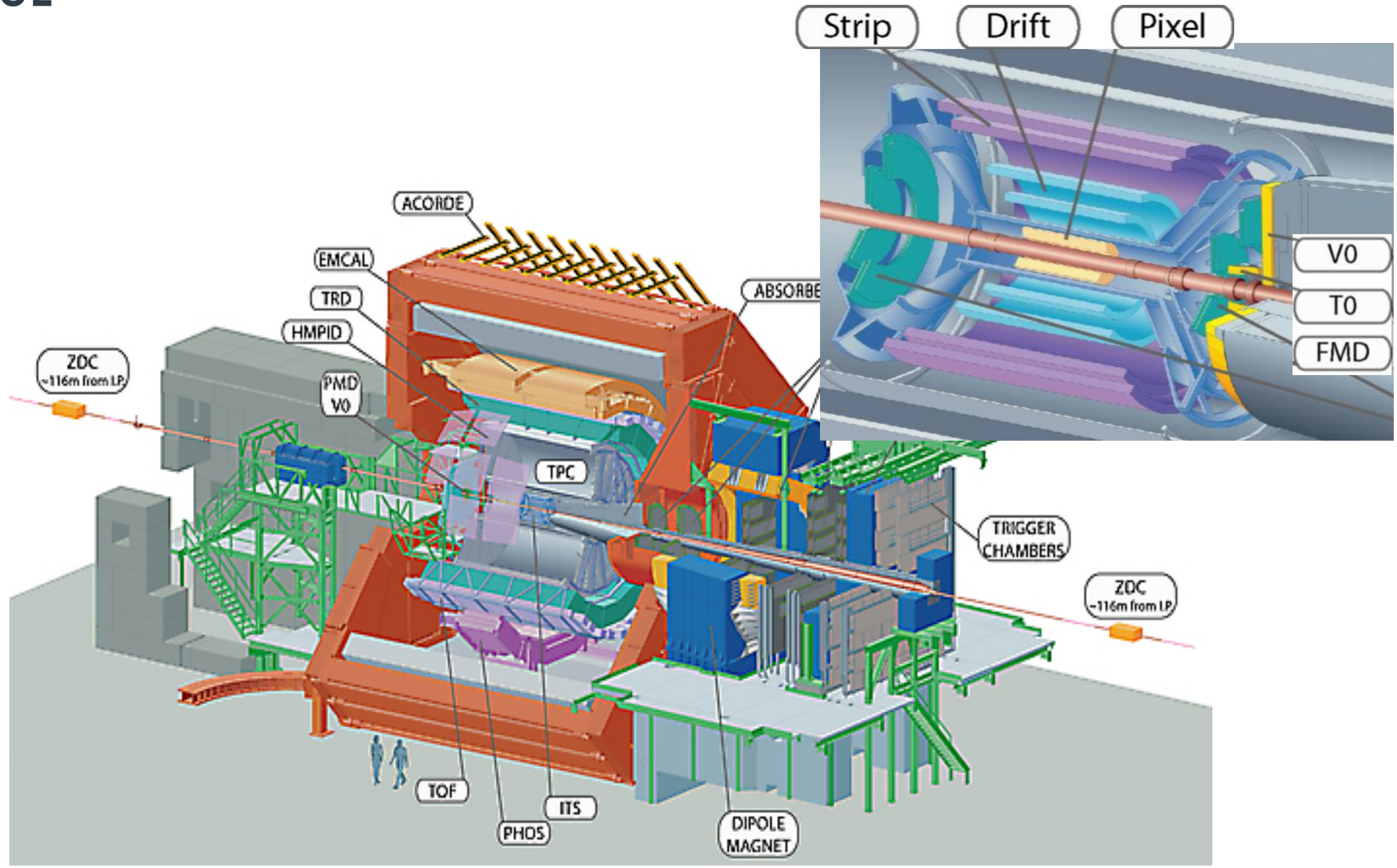
The ALICE experiment



The ALICE experiment

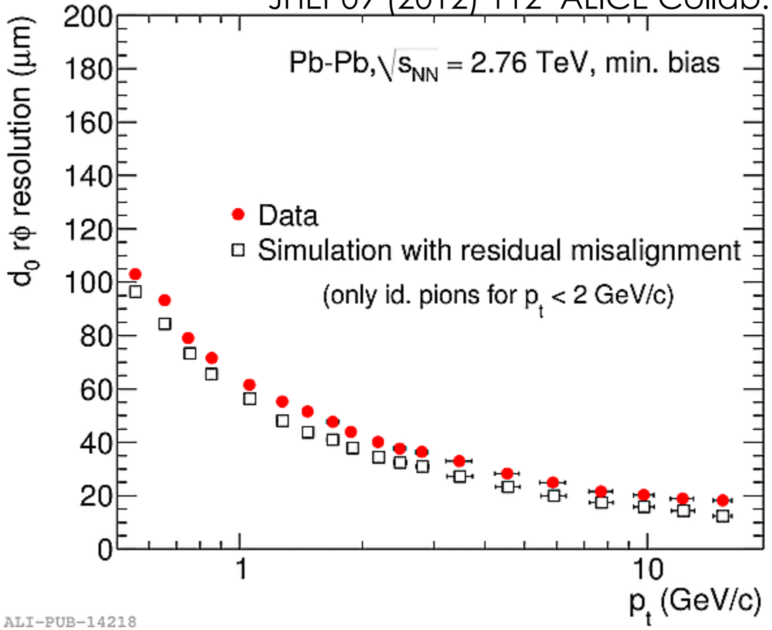


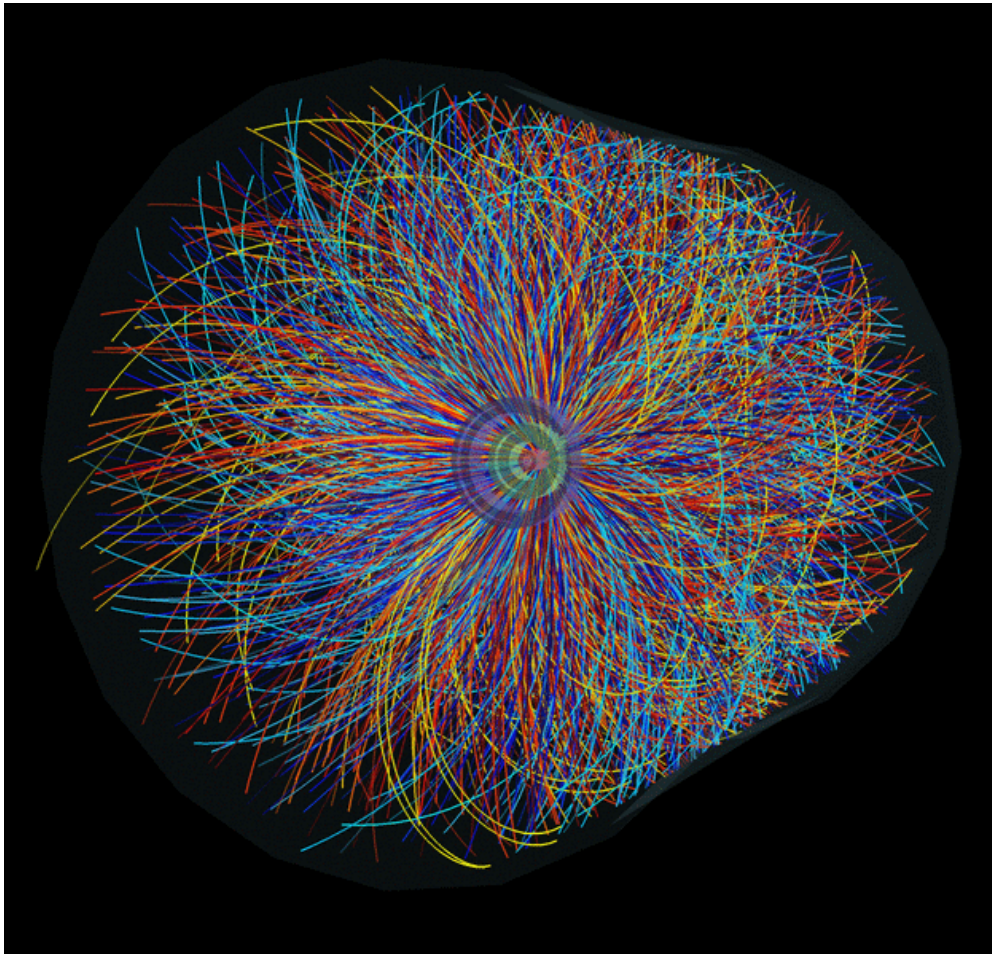
The ALICE experiment

Dedicated LHC experiment for Heavy Ion Physics

Central Barrel:
2π Tracking and PID
$|\eta| < 1$
$p_T > 100$ MeV/c
Excellent vertexing

JHEP09 (2012) 112 ALICE Collab.

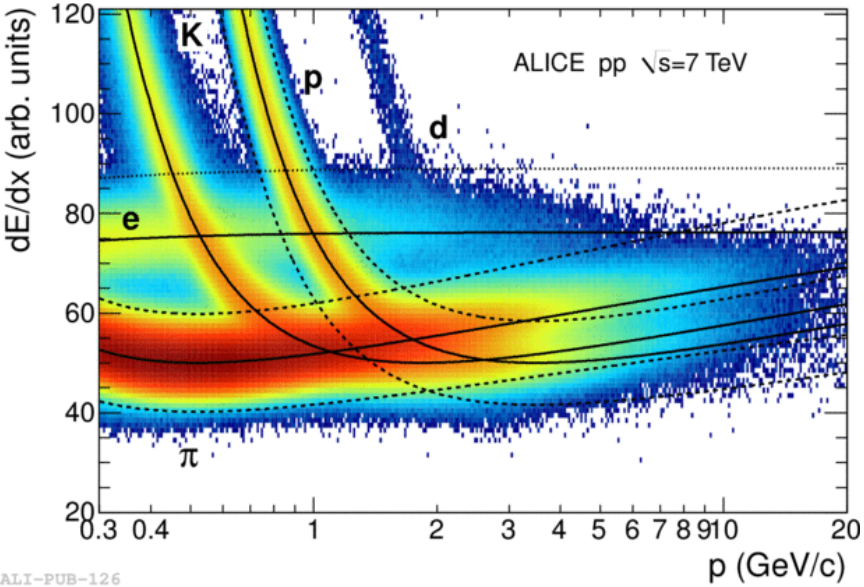




The ALICE experiment

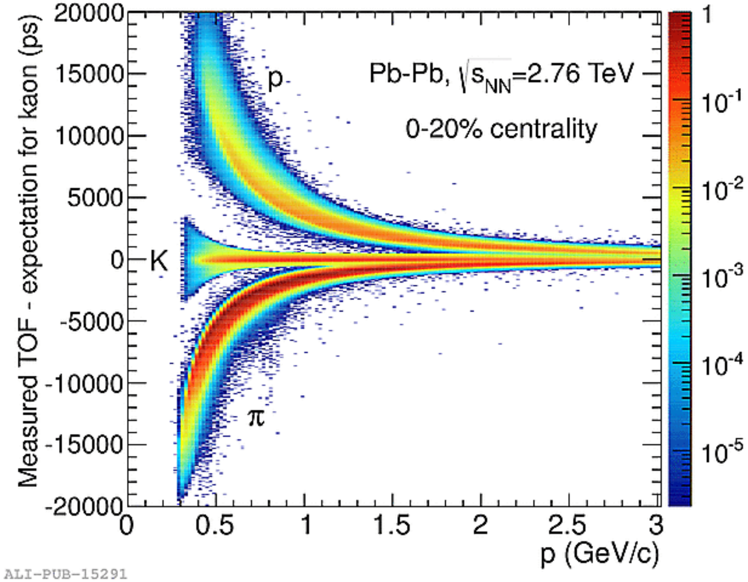
Dedicated LHC experiment for Heavy Ion Physics

PLB 704 (2011) 442, ALICE Collab.



ALI-PUB-126

JHEP09 (2012) 112 ALICE Collab.



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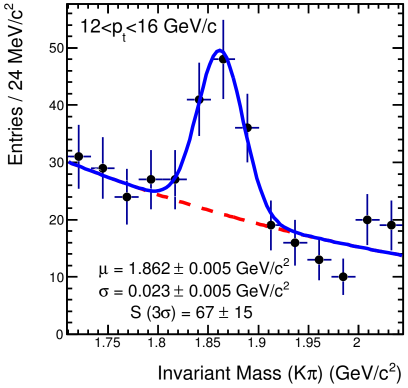
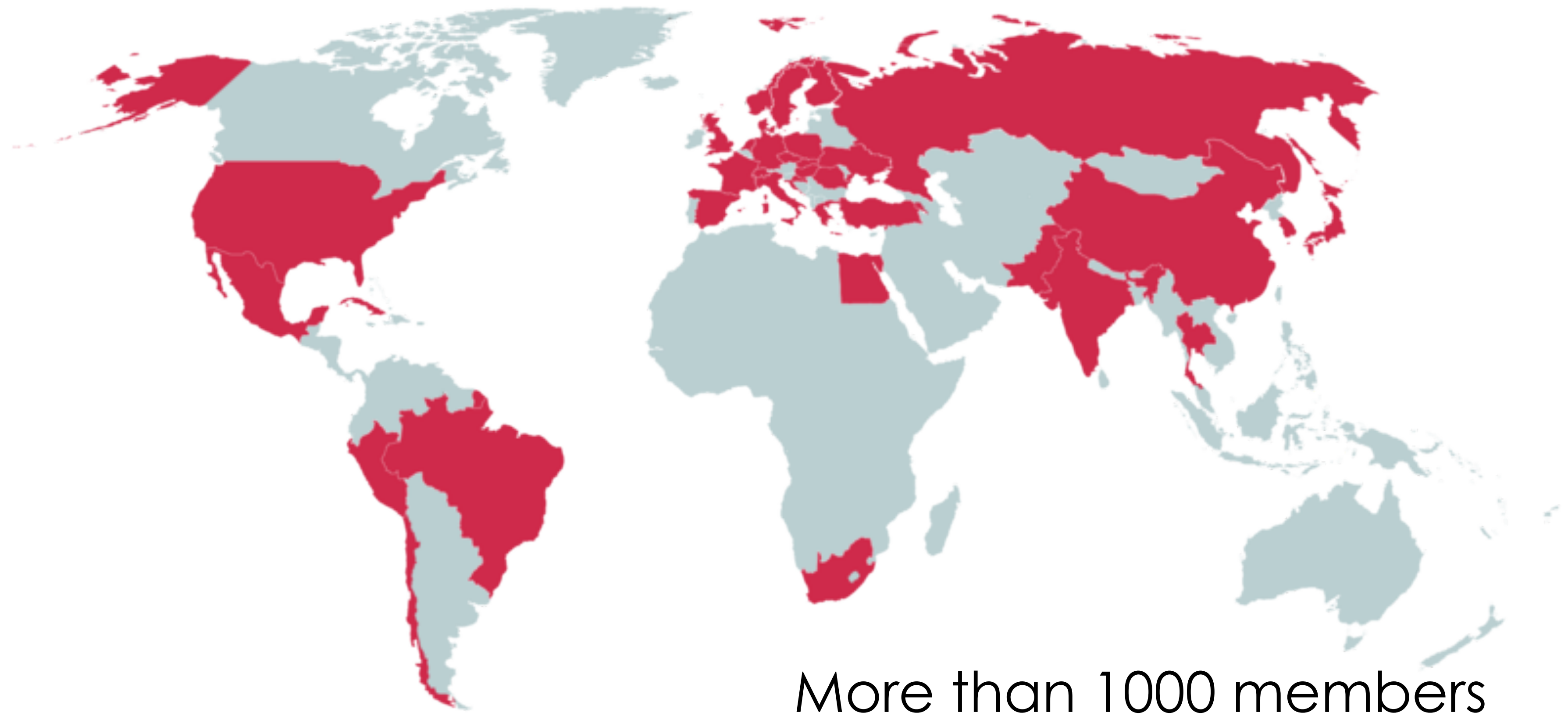


The ALICE Collaboration



More than 1000 members
More than 100 institutions
More than 30 countries

The ALICE Collaboration

LHC Heavy-Ion Run

2010 – Pb-Pb at 2.76 TeV, integrated lum. ~$10\ \mu b^{-1}$
Approx. 20 Million events,

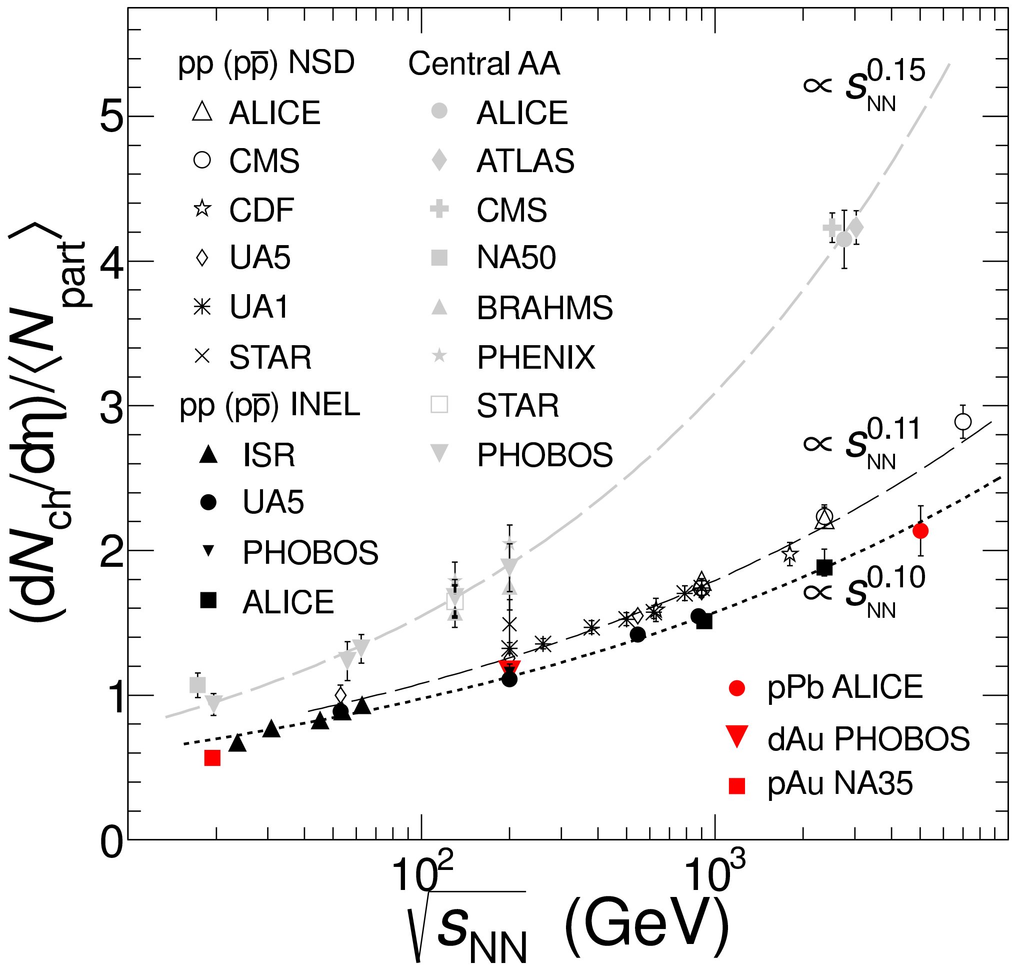
2011 – Pb-Pb at 2.76 TeV, integrated lum. ~$0.1\ nb^{-1}$
Approx. 140 Million events,
enriched with rare trigger events.

2012 – p-Pb at 5.02 short test run,
Approx. 2 Million events.

2013 – (Jan.-Fev.) p-Pb expected to run.

Charged particle multiplicity

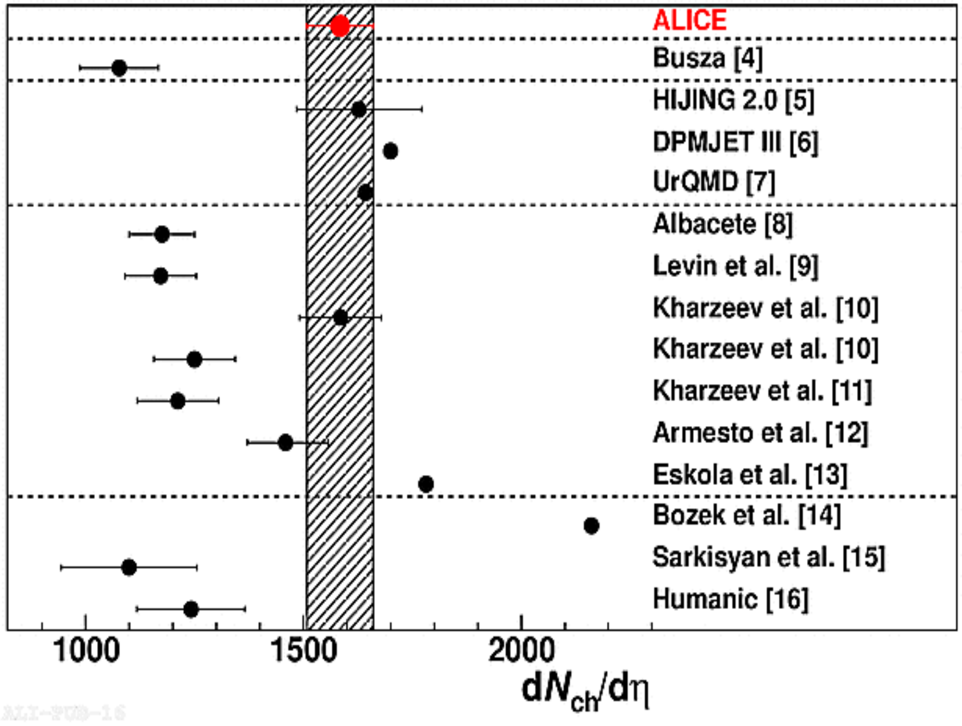
arXiv: 1210.3615 ALICE Collab.



Particle production

- Increase of x2.2 with respect to RHIC.
- Energy dependence is steeper for heavy-ion collisions than p-p.
- New p-Pb data, important for initial state effects.

Comparison to models



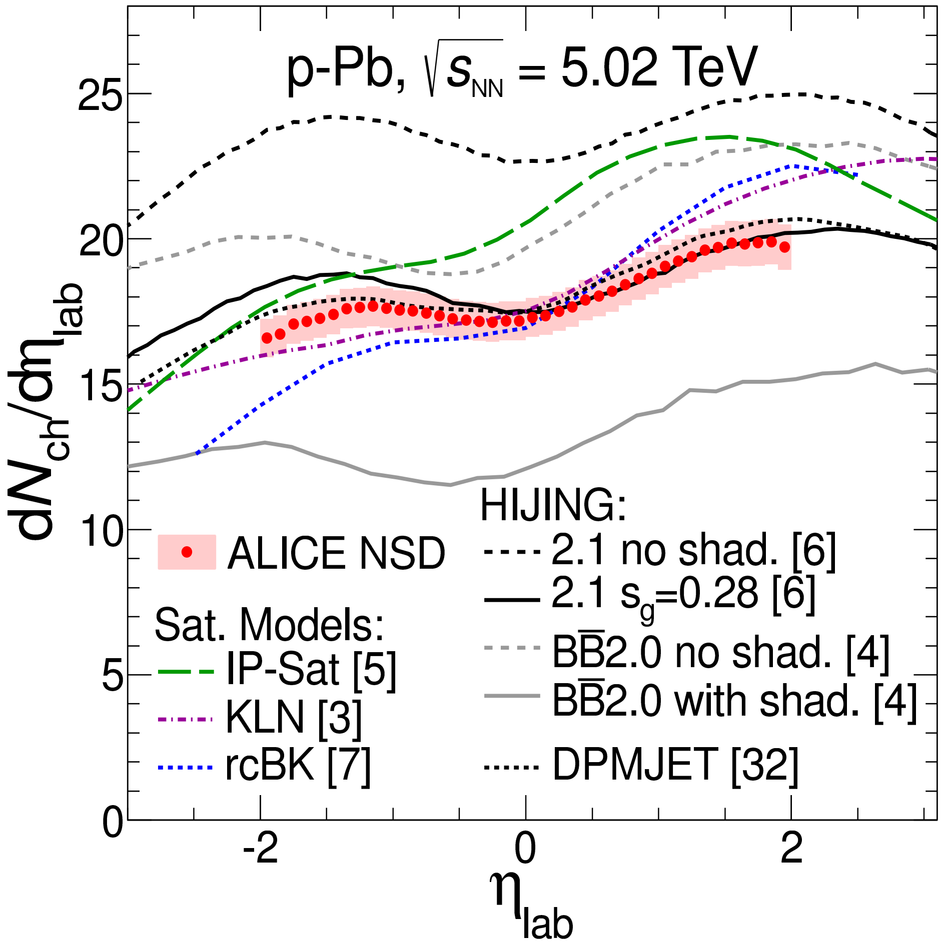
PRL 105, 252301ALICE Collab.

Pb-Pb

- Empirical extrapolation from RHIC data under predicts data.
- HIJING tuned to 7 TeV p-p data yields prediction consistent with data.
- Saturation models vary level of agreement.
- Hydro models with multiplicity scaled from p-p also under predicts or over predicts the data.

Comparison to models

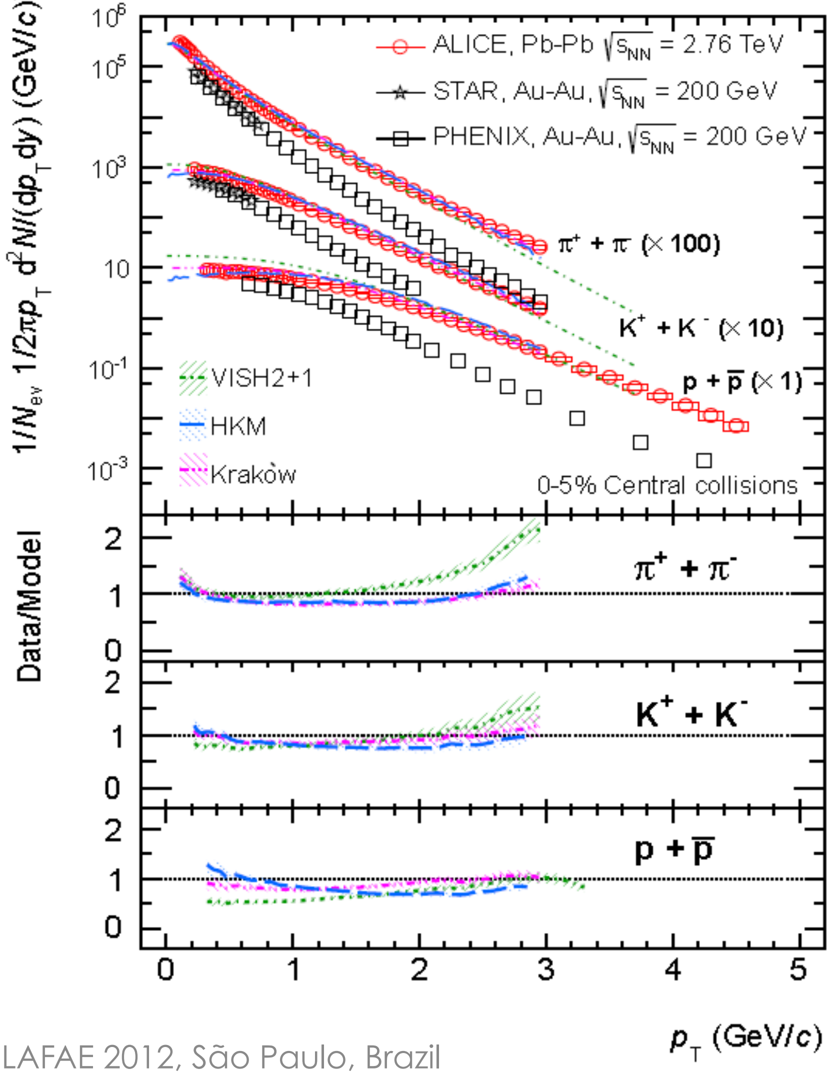
arXiv: 1210.3615 Collab.



p-Pb

- Important to discriminate initial and final state effects.
- Probe small x and the initial state.
- Set constrains to models.
- Models that include shadowing or saturation are consistent with data within 20%.

Transverse momentum spectra



arXiv: 1208.1974 ALICE Collab.

LHC spectra shows harder distribution than RHIC.

Consistent with stronger radial flow component.

Hydro models with late stage implementation describe well the data.

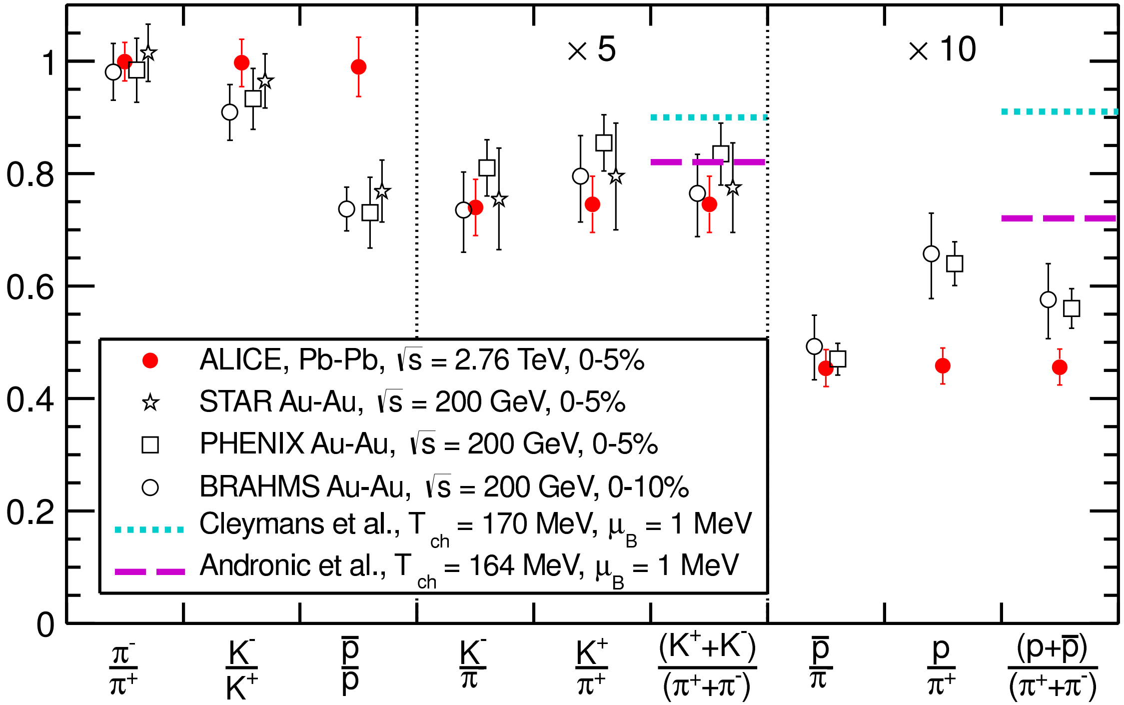
- VISH2+1: Viscous hydro model
- HKM: Hydro+UrQMD
- Krakòw: Viscous hydro, with effective T_{ch}.

Hadron Chemistry

Hadron Chemistry is used for statistical thermal models fits.

Very successful in describing RHIC data.

arXiv: 1208.1974 ALICE Collab.



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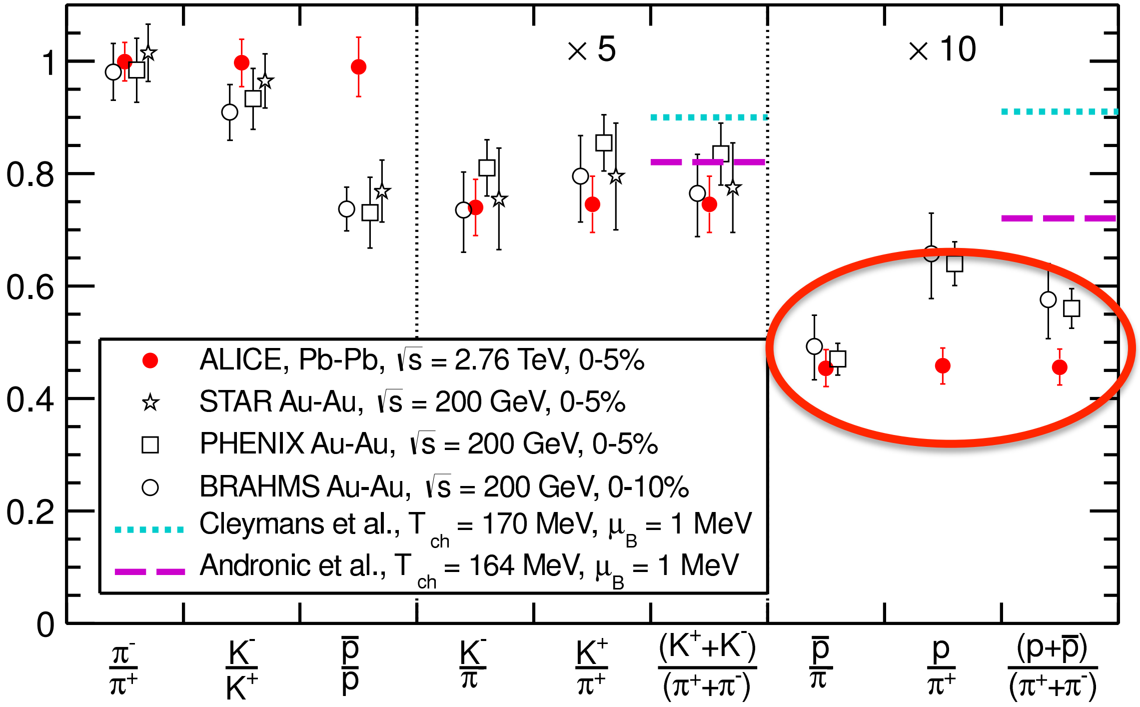
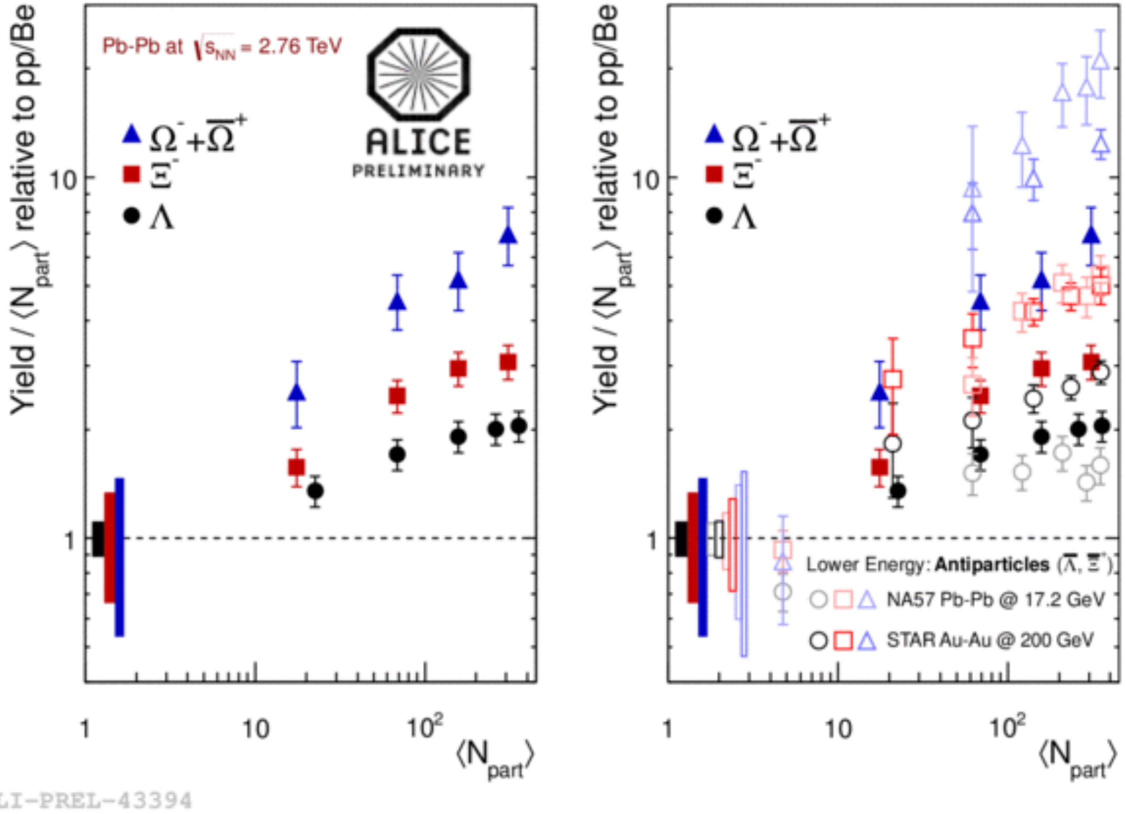


arXiv: 1208.1974 ALICE Collab.

At LHC, p/π is considerably lower than RHIC, and it is over predicted by thermal models. Perhaps final state hadronic interactions play more important role at LHC than at RHIC.
Strange particles are needed to further constrain thermal models.

Strangeness Enhancement

arXiv: 1211.7298

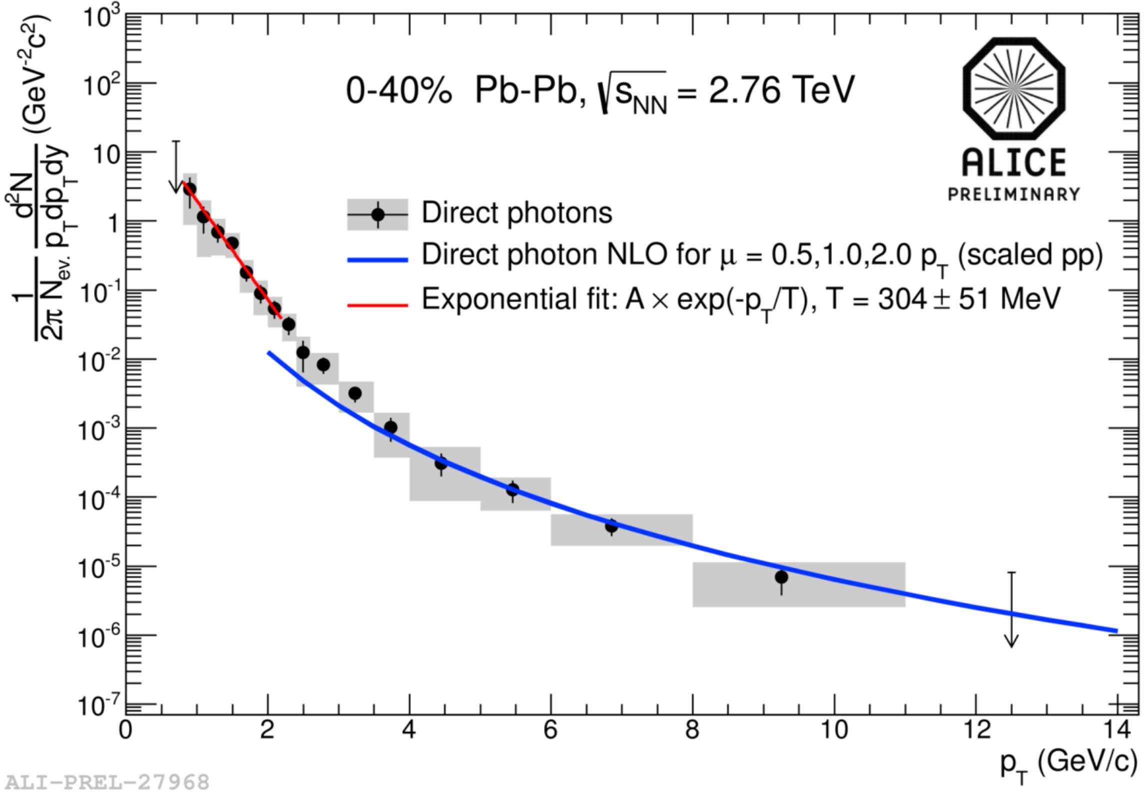


Strangeness enhancement → Proposed signature of QGP.

Relative enhancement of Strange and Multi-strange baryons is also observed at LHC.

Direct photon spectrum

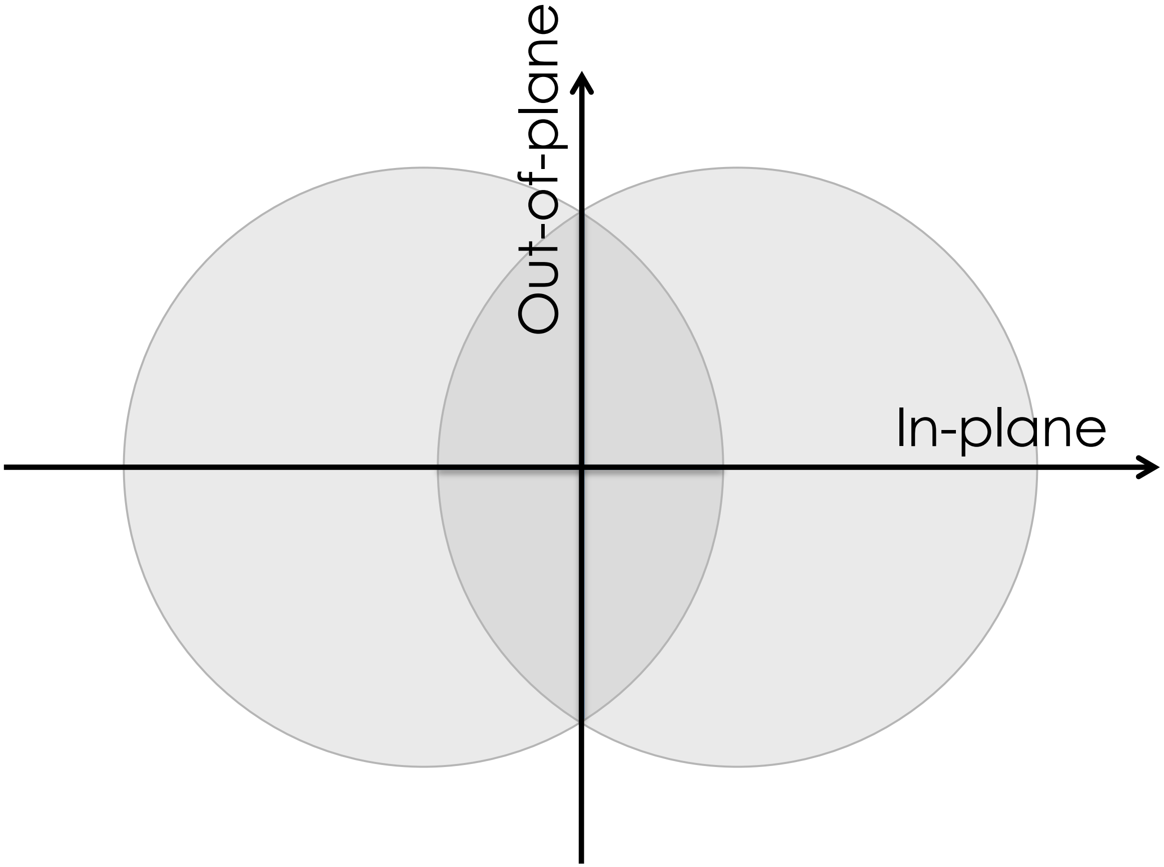
arXiv: 1210.5958



Inverse slope of an exp. fit to the low p_T spectrum: **T = 304 ± 51 MeV**

PHENIX/RHIC T = 221 ± 19 ± 19 MeV

Elliptic Flow



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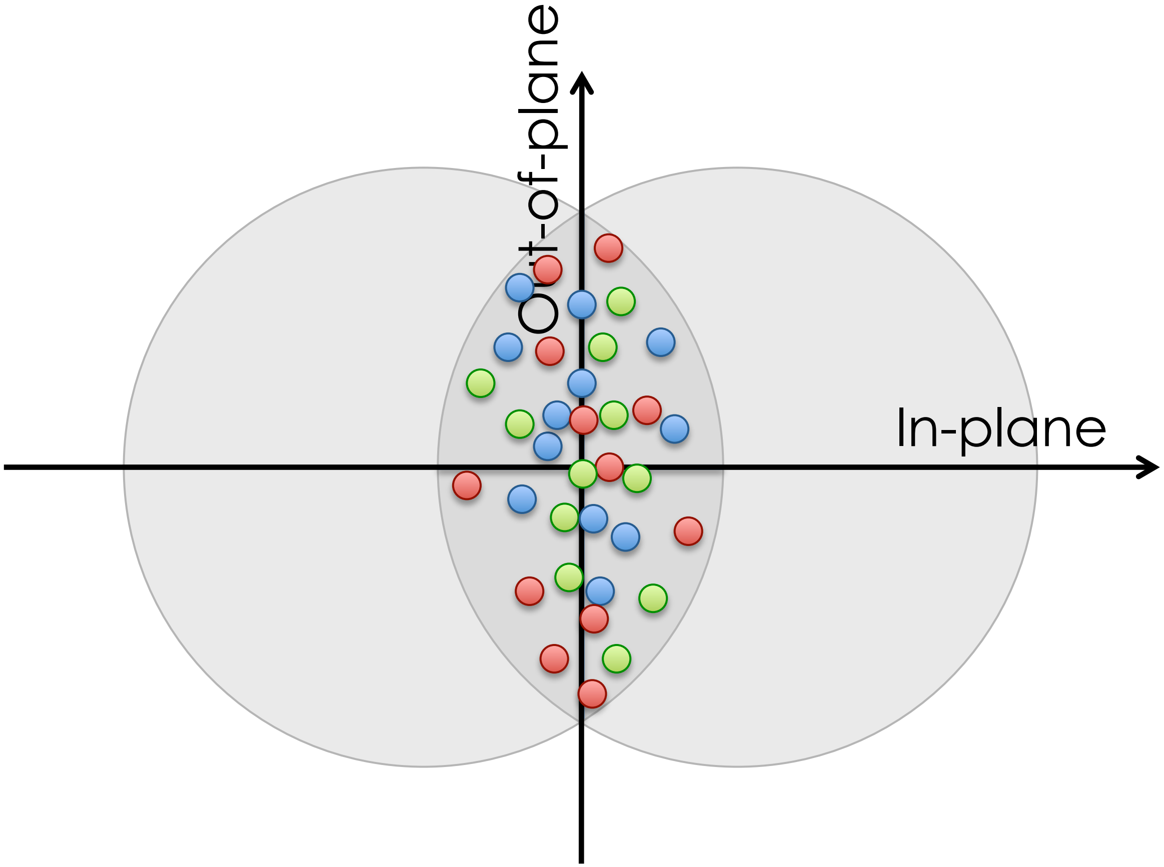
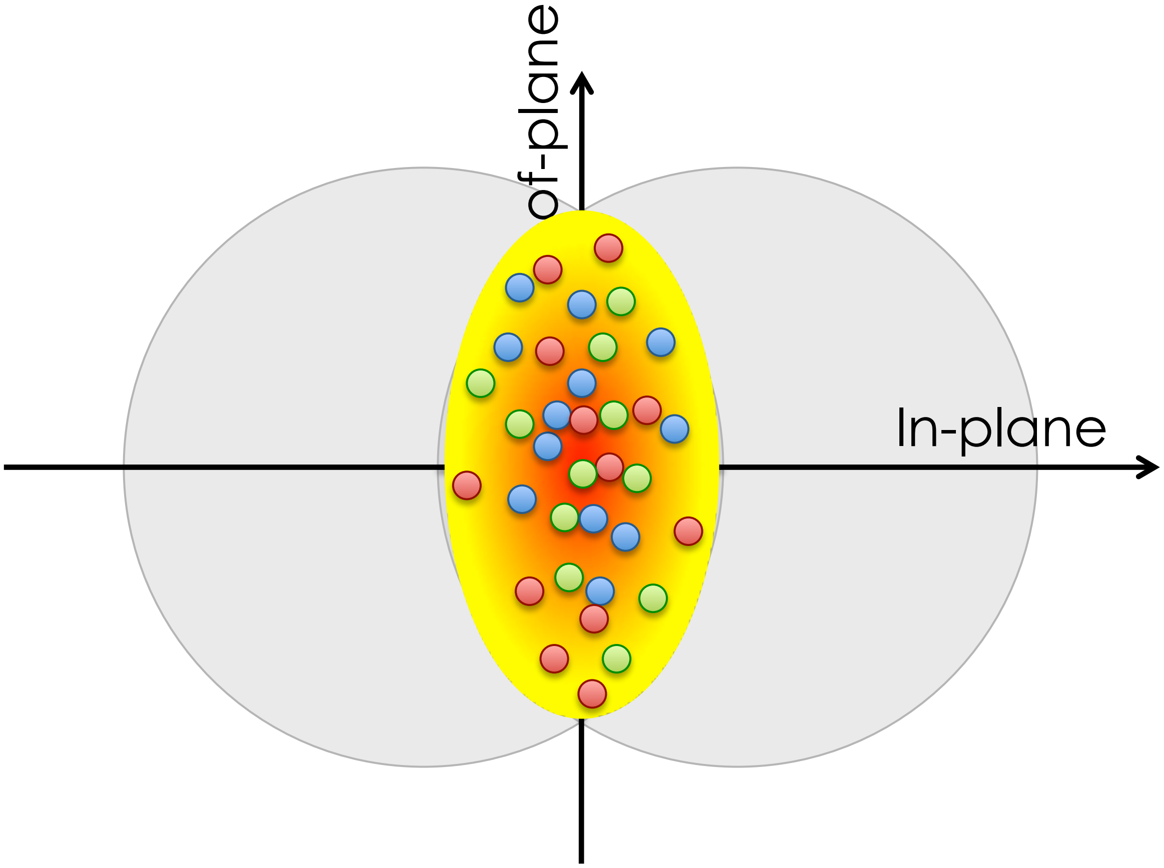


Elliptic Flow



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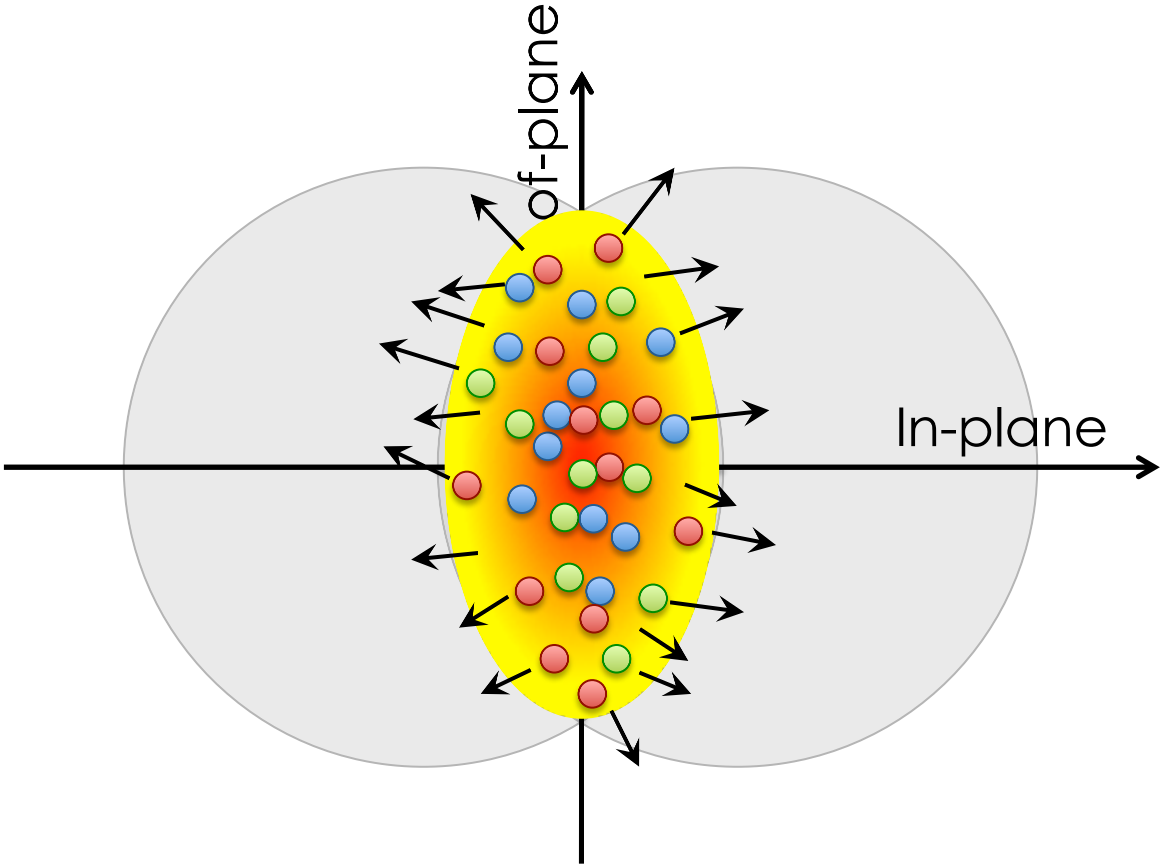
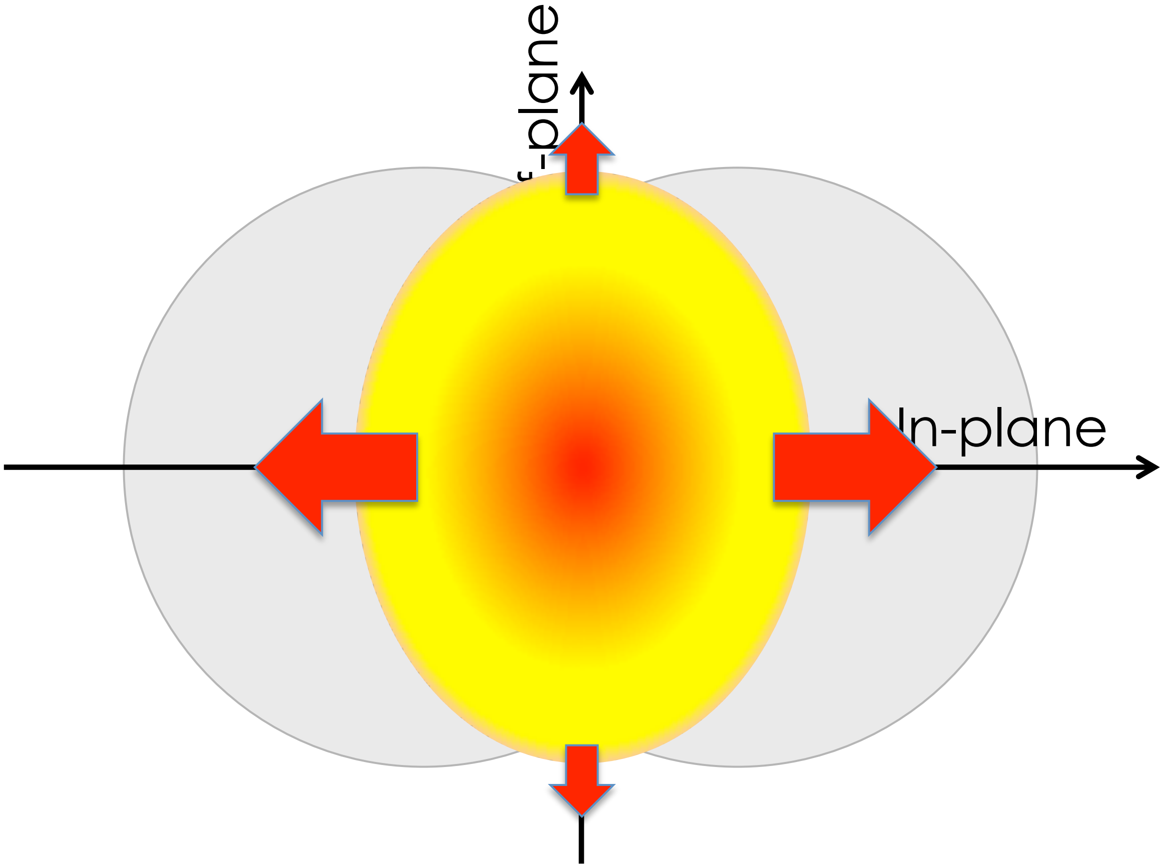


Elliptic Flow



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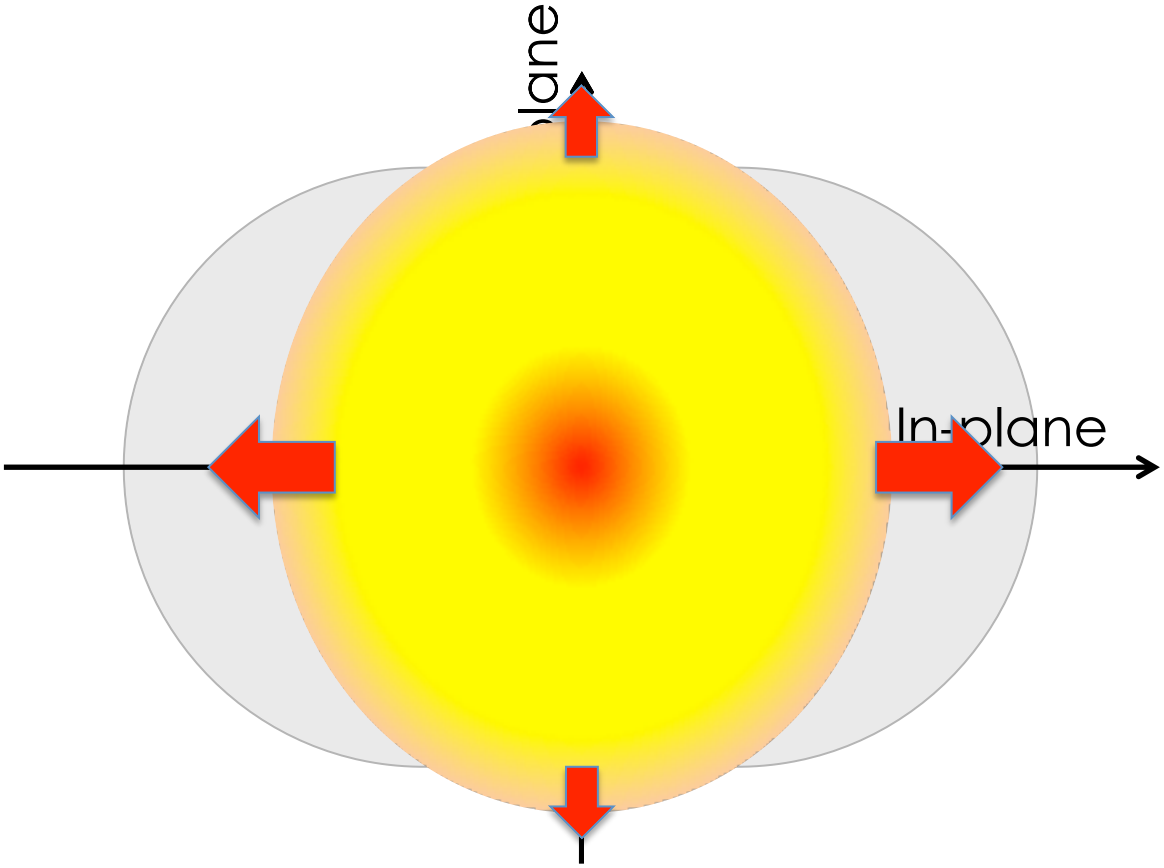

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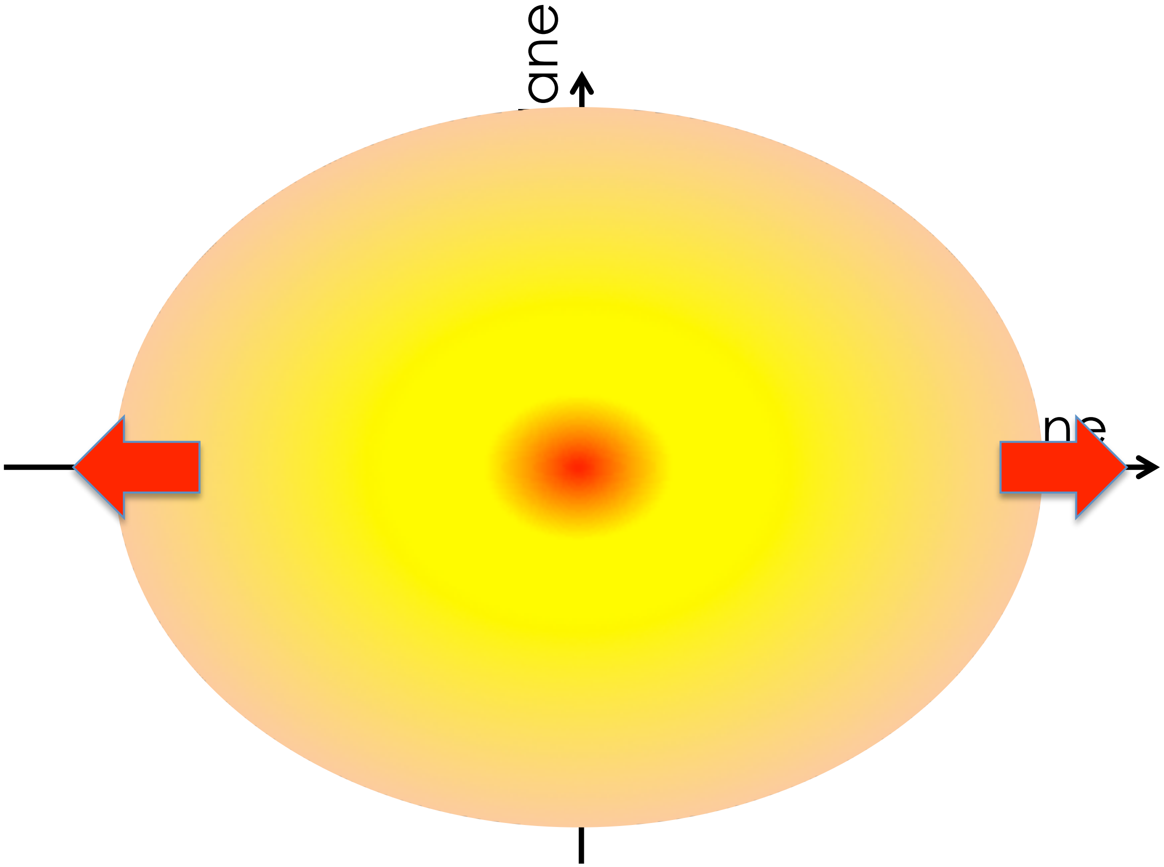

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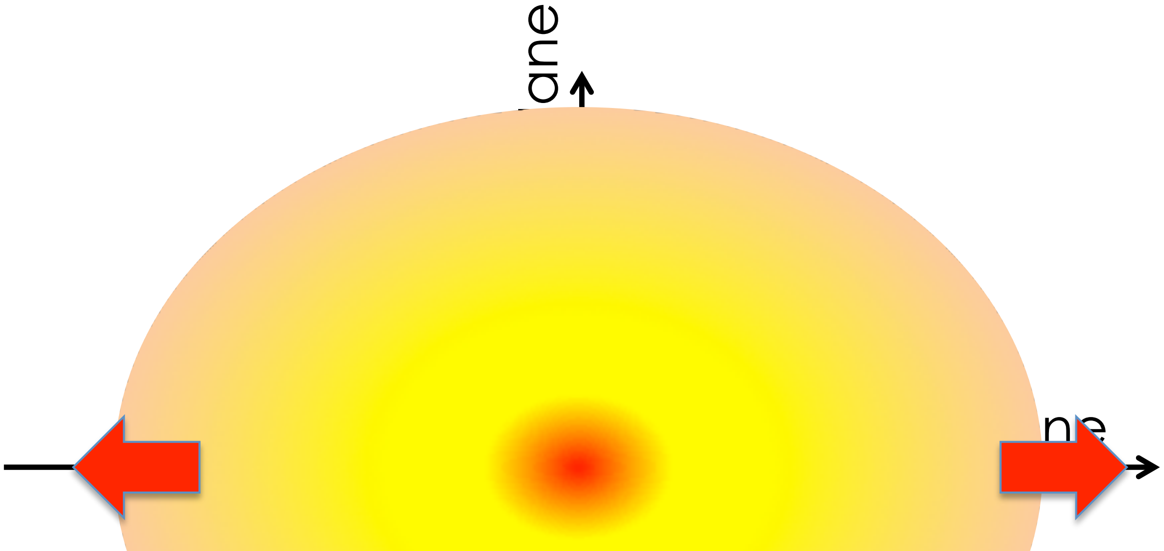


Spatial anisotropy → Momentum anisotropy → $d^2N/dp_T d\phi$

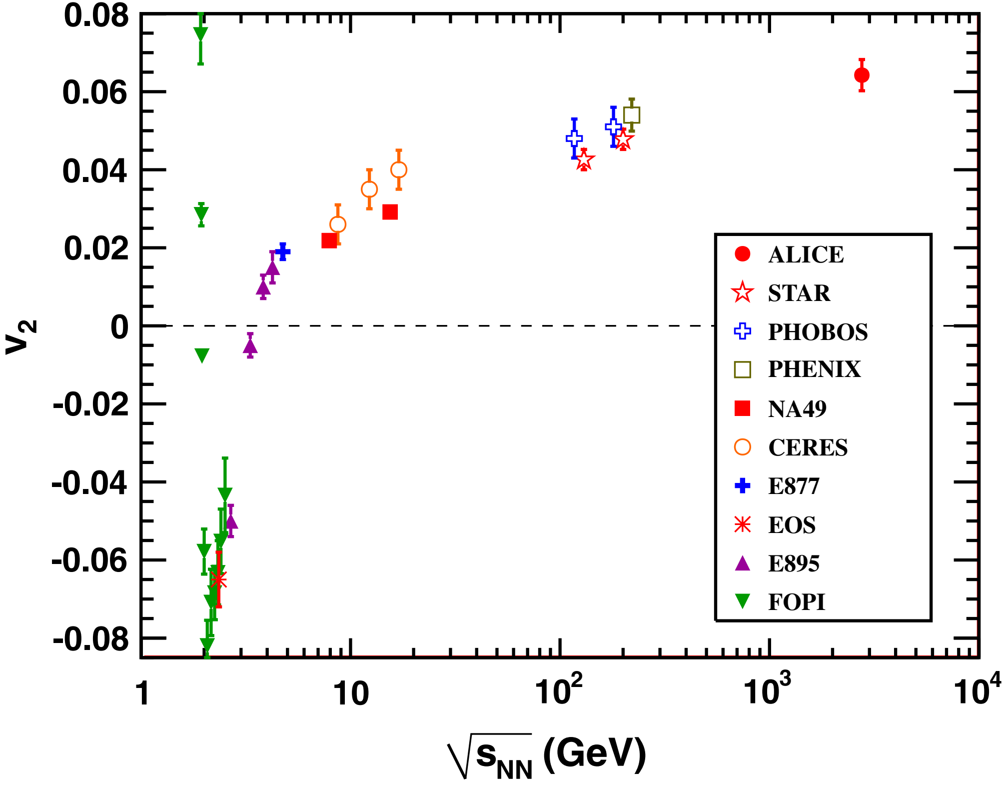
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right)$$

$$v_n(p_T,\eta) = \langle \cos[n(\phi - \Psi_n)] \rangle$$

→ Probe the system evolution.

Elliptic Flow

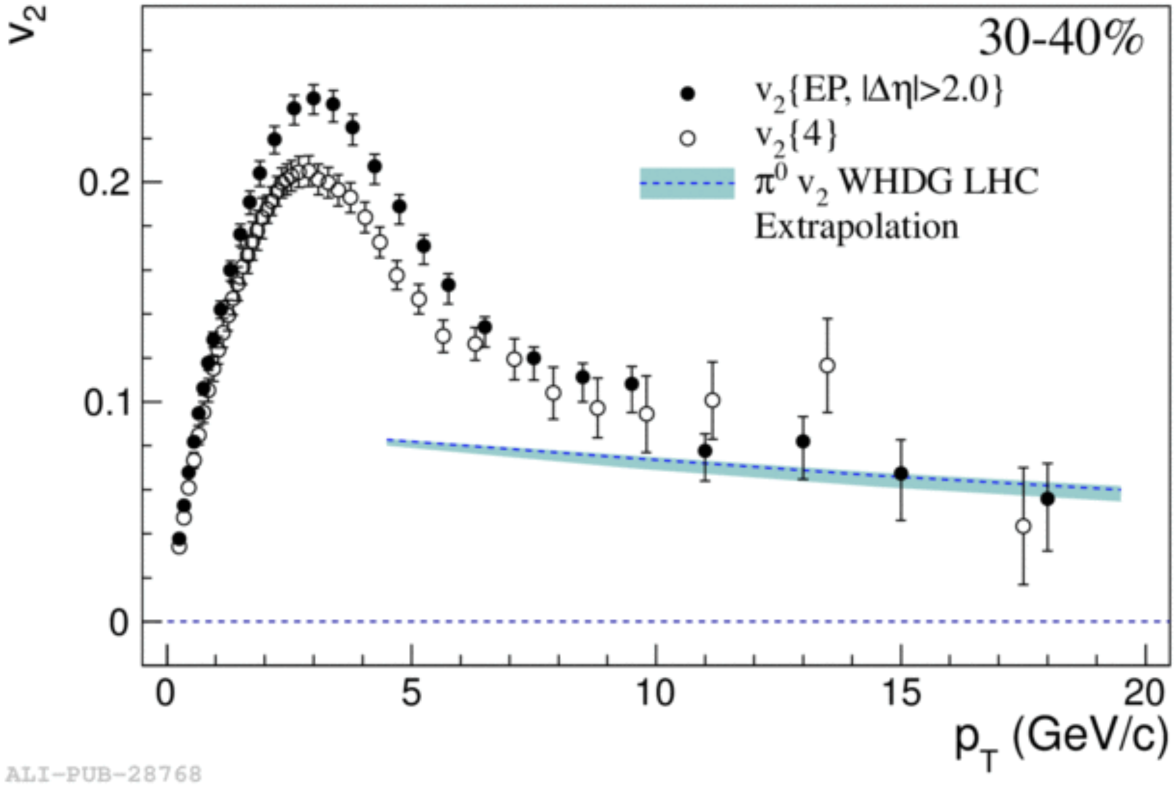
PRL 105, 252302 ALICE Collab.



v_2 measured at LHC is about 30% higher than at RHIC.

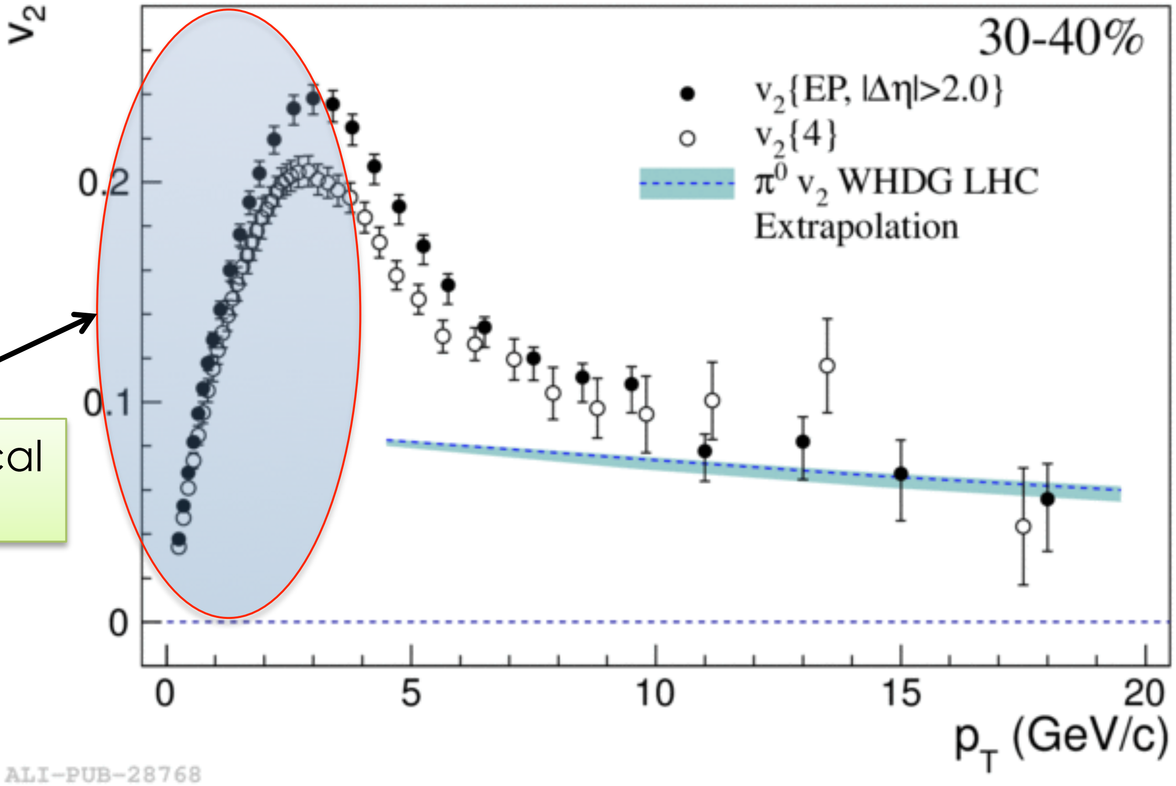
Elliptic Flow

arXiv:1205.5701 ALICE Collab.



Elliptic Flow

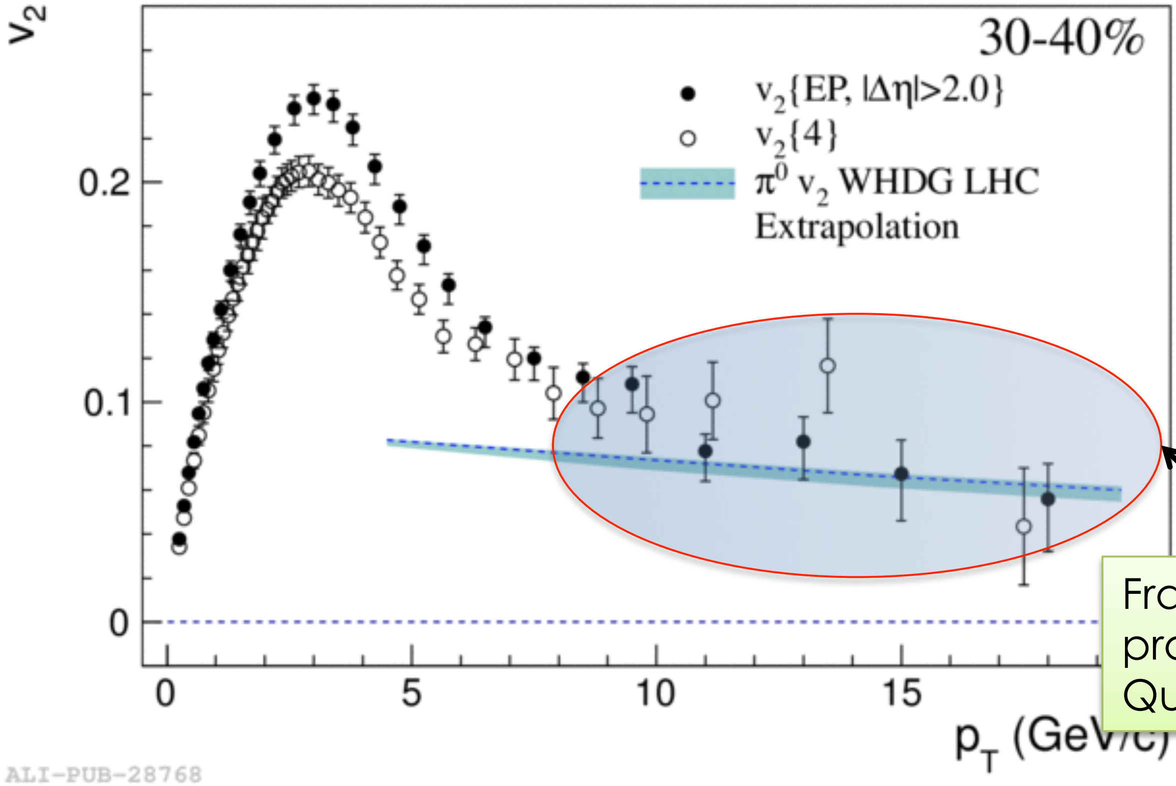
arXiv:1205.5701 ALICE Collab.



Hydrodynamical evolution

Elliptic Flow

arXiv:1205.5701 ALICE Collab.

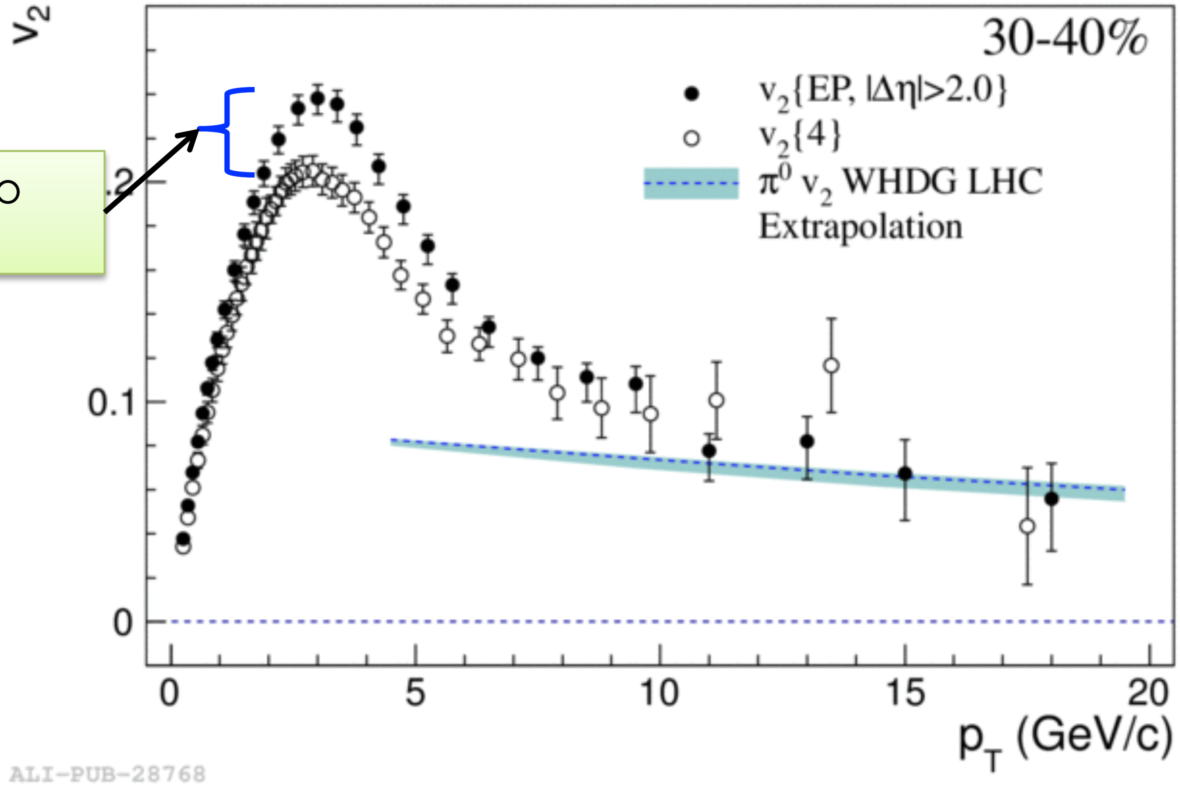


Fragmentation processes, Quenching

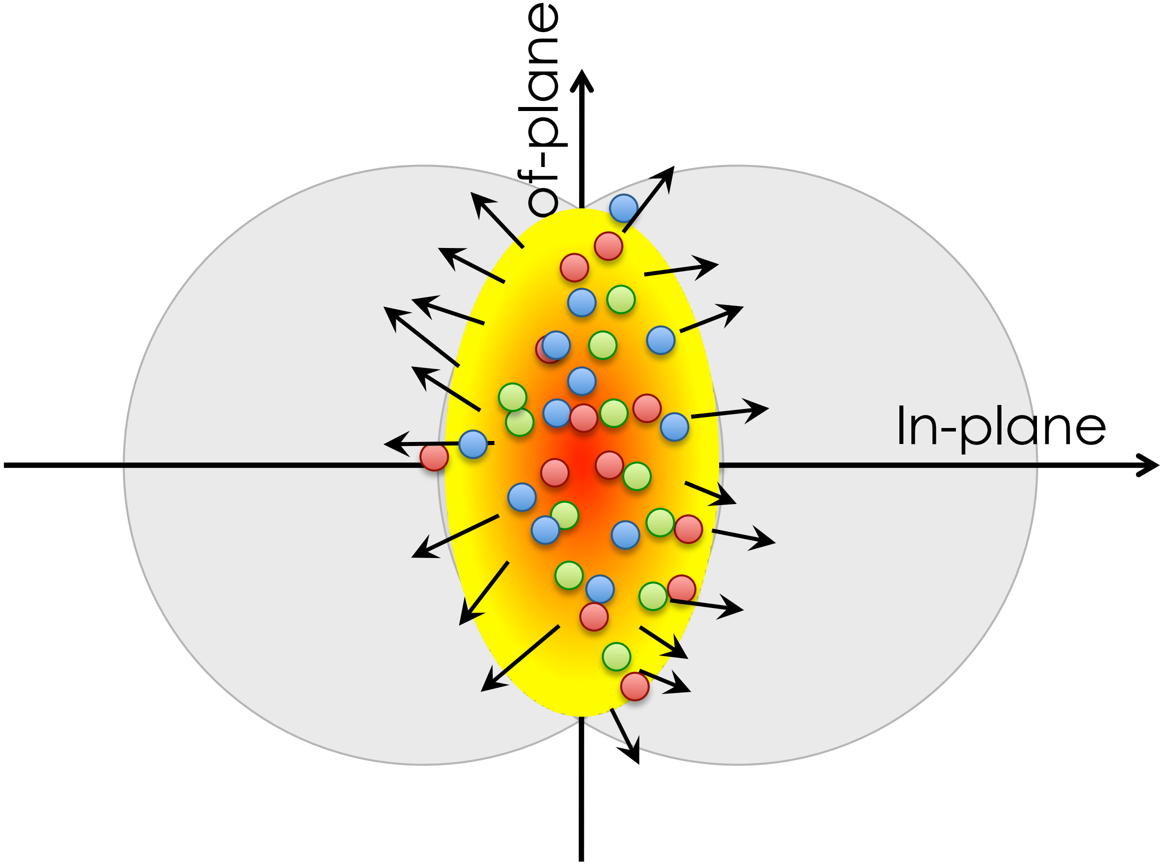
Elliptic Flow

Difference due to flow fluctuations

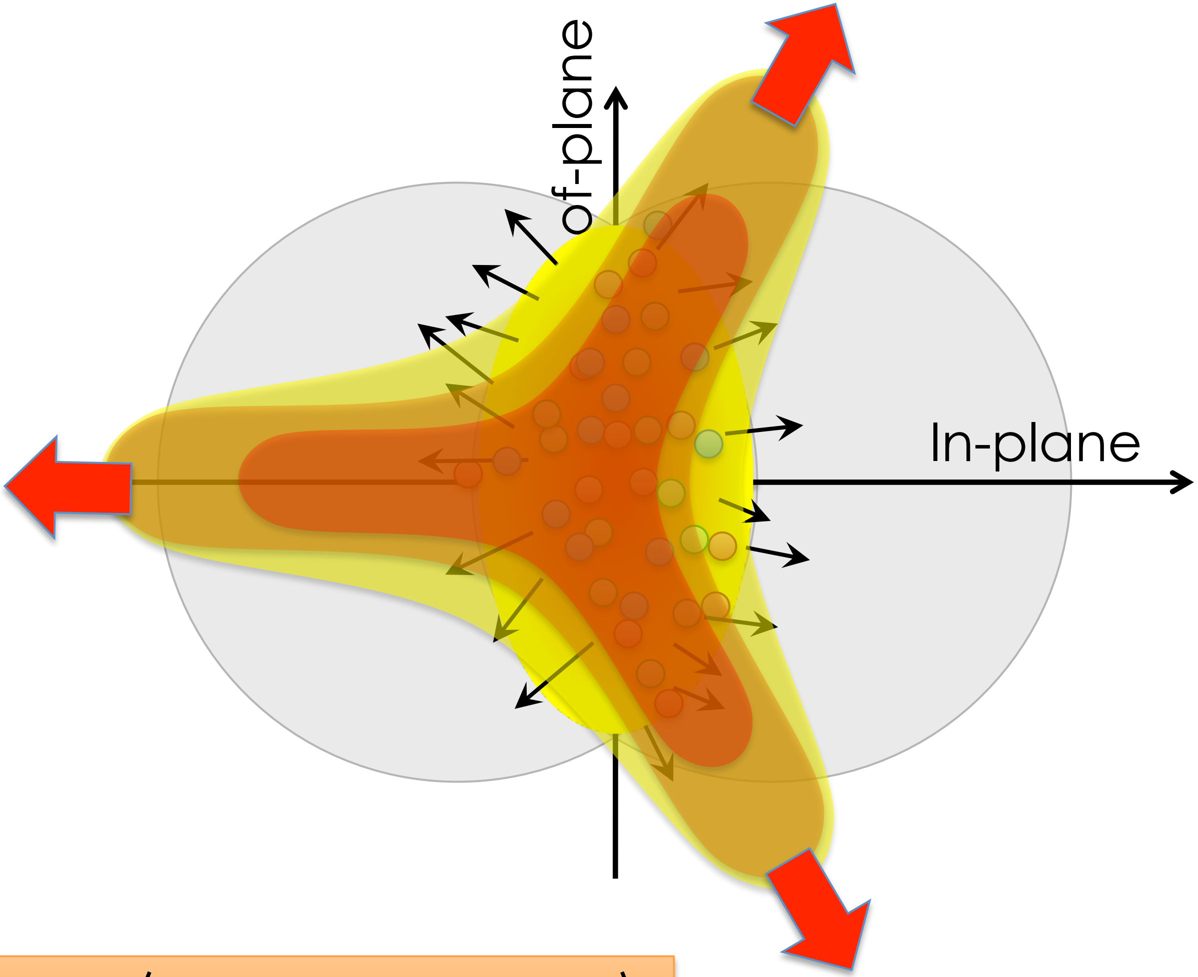
arXiv:1205.5701 ALICE Collab.



Higher order anisotropic flow: v_3



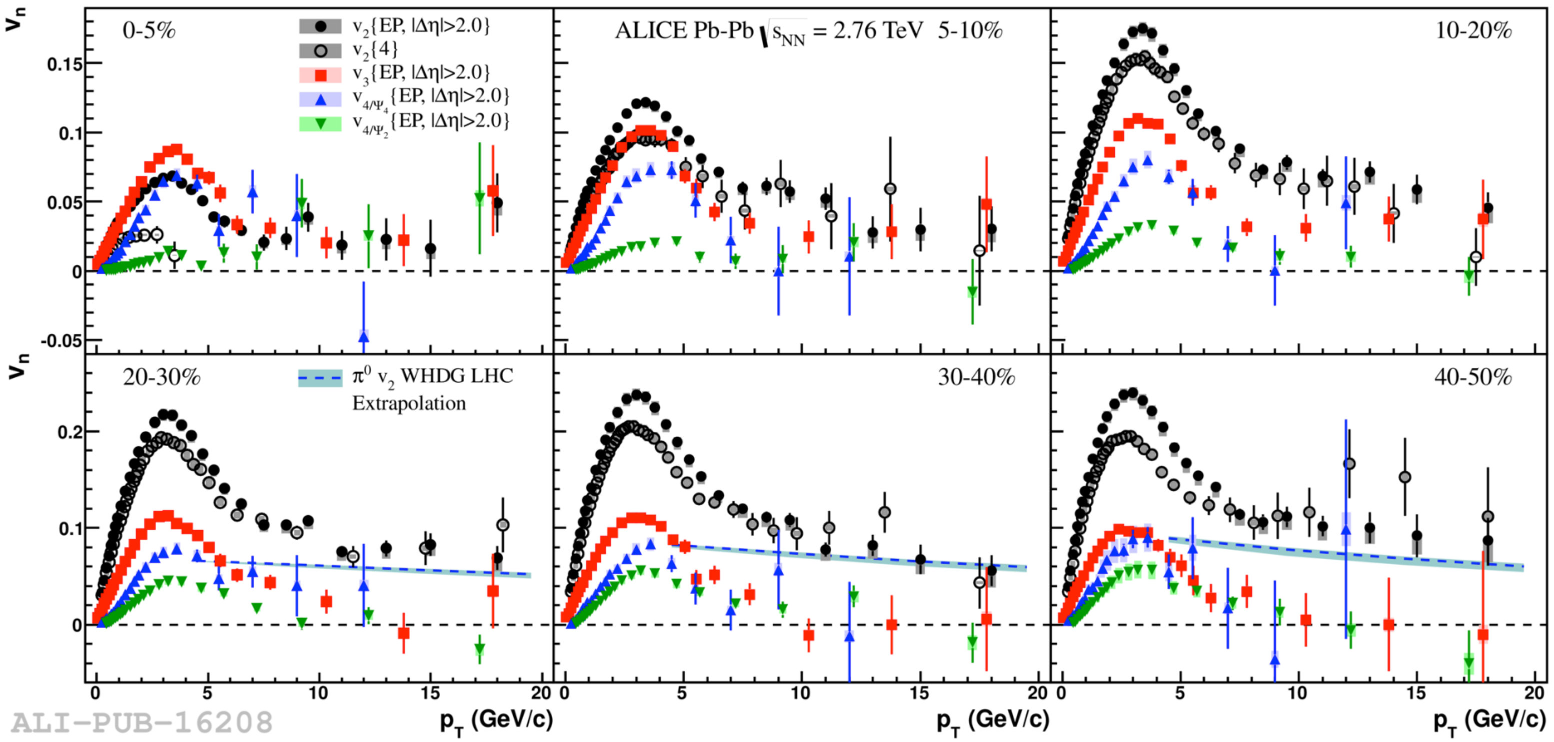
Higher order anisotropic flow: v_3



$$v_n(p_T,\eta) = \left\langle \cos\left[n(\phi - \Psi_n)\right]\right\rangle$$

Higher order anisotropic flow

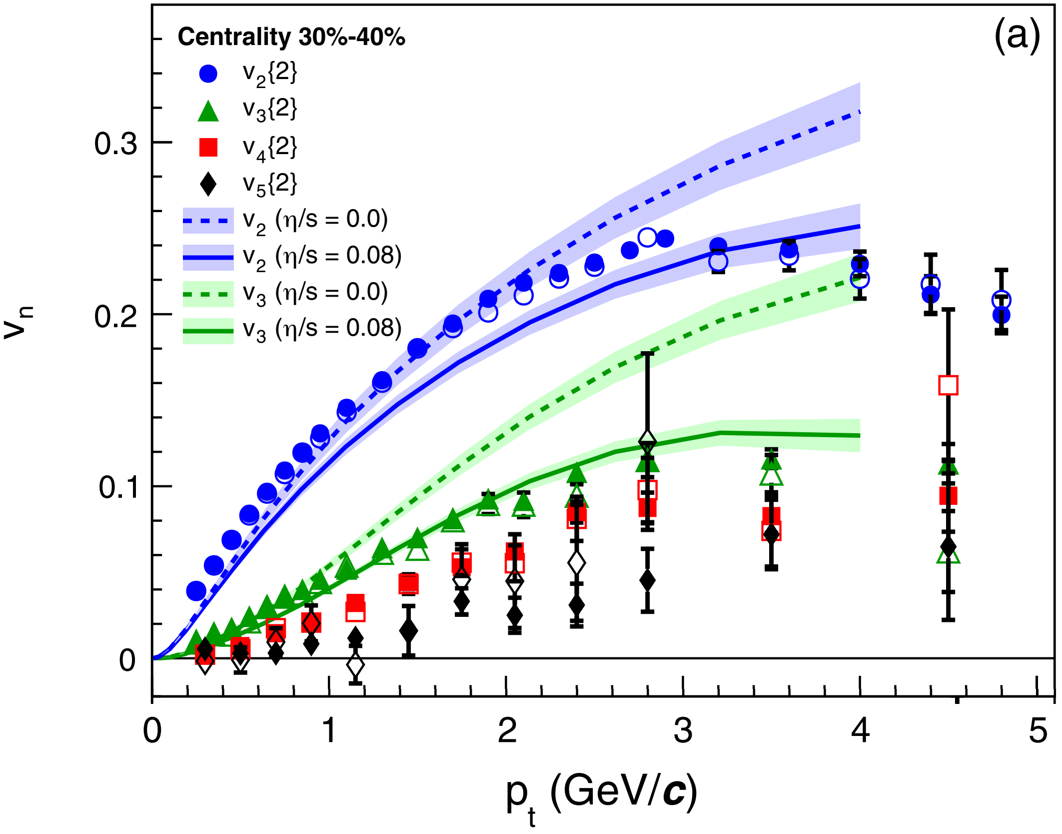
arXiv:1205.5701 ALICE Collab.



- Large elliptic and triangular flow observed at LHC.
- v_2 at low-p_T consistent with low viscous hydro evolution.
- v_2 at high-p_T increase with centrality and well described by model.

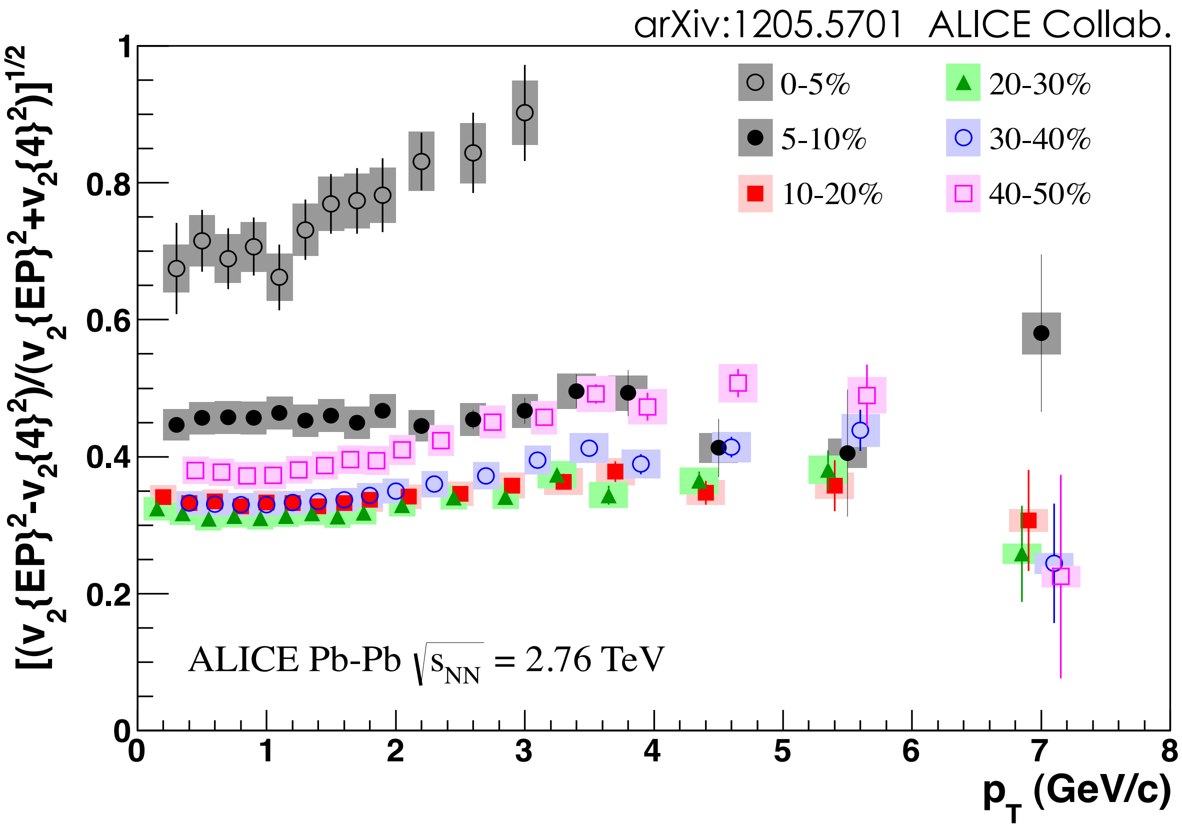
Hydrodynamic flow

PRL 107, 252301 ALICE Collab.



Low viscous hydro models describe well the data in the low p_T region.

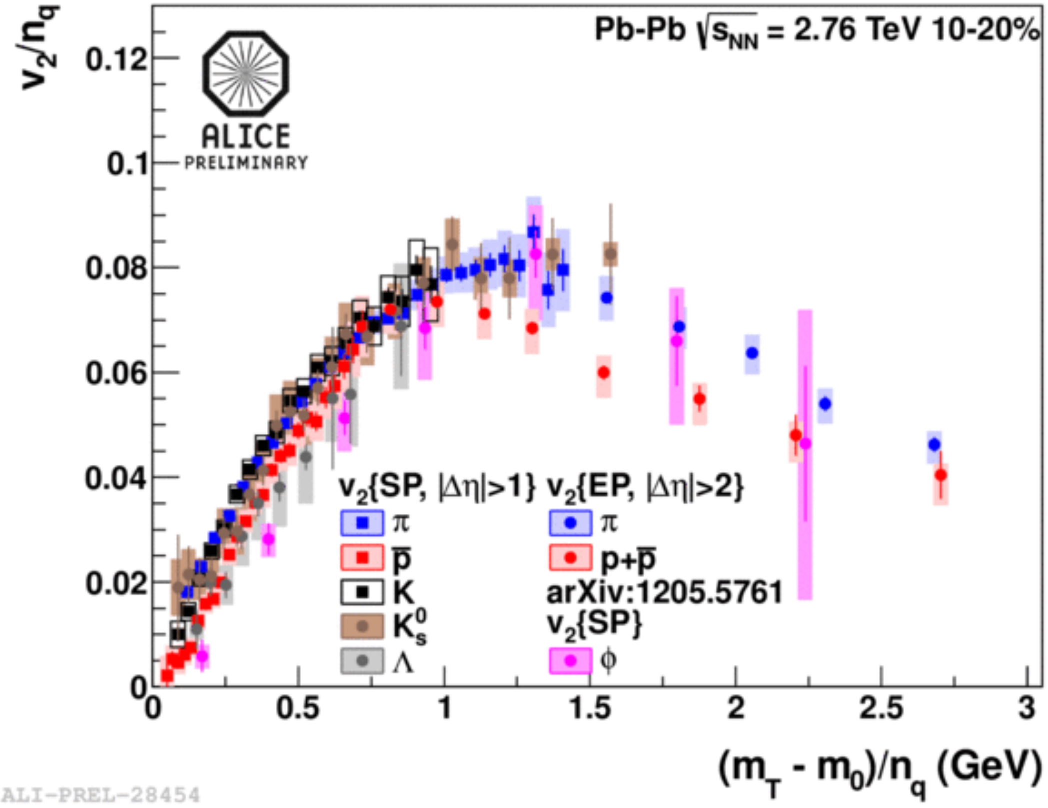
Elliptic flow fluctuations



- Flow fluctuations are associated with fluctuations of the initial collisions geometry.
- Flow fluctuations measured extends up to p_T=8 GeV/c, and does not change significantly, suggesting a common origin.

Particle identified elliptic flow

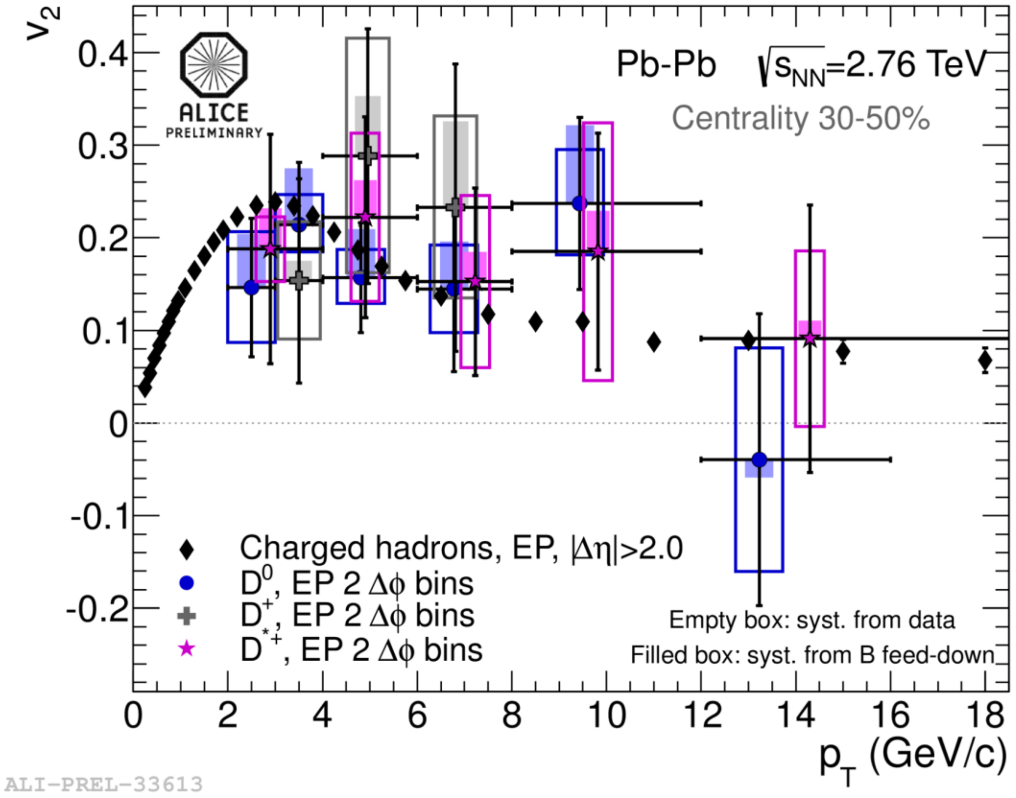
arXiv:1210.3392



Identified particle v_2 is an important probe for NCQ scaling, used as argument for partonic degree of freedom.

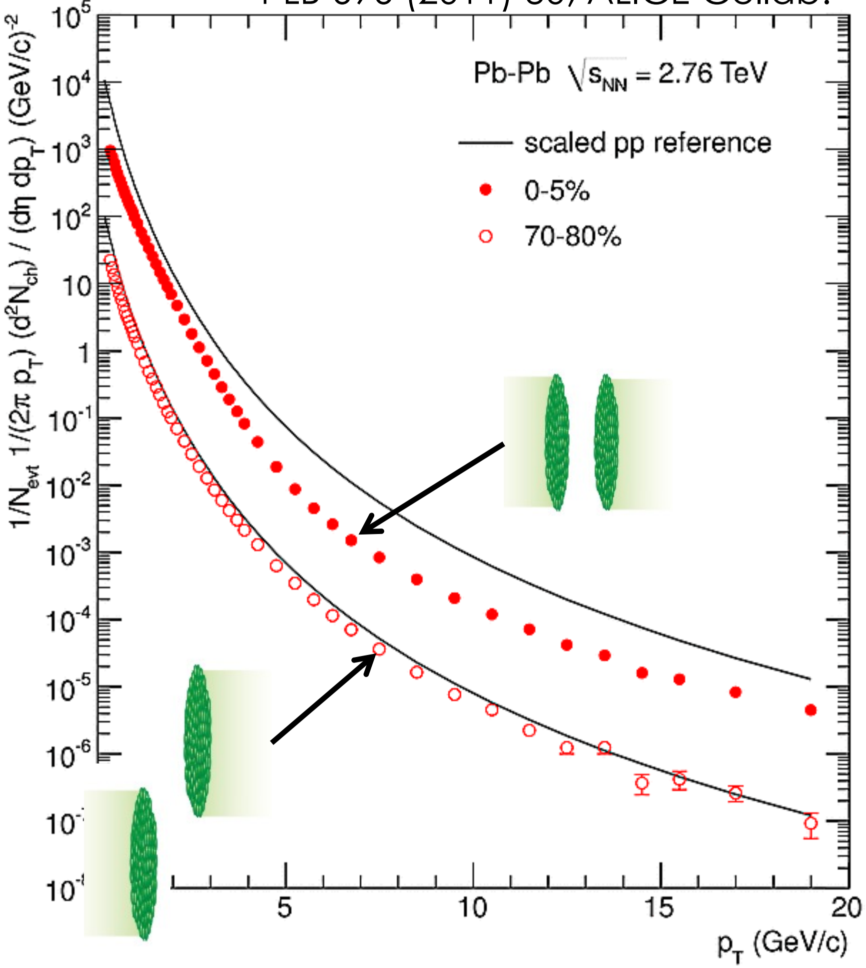
Particle identified elliptic flow

arXiv:1210.3392



Heavy-flavor quarks should feel less the collective expansion, but data shows non-zero v_2 for D and J/Ψ.

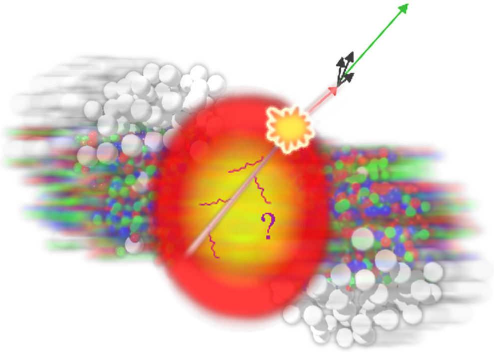
Comparing the spectra



PLB 696 (2011) 30, ALICE Collab.

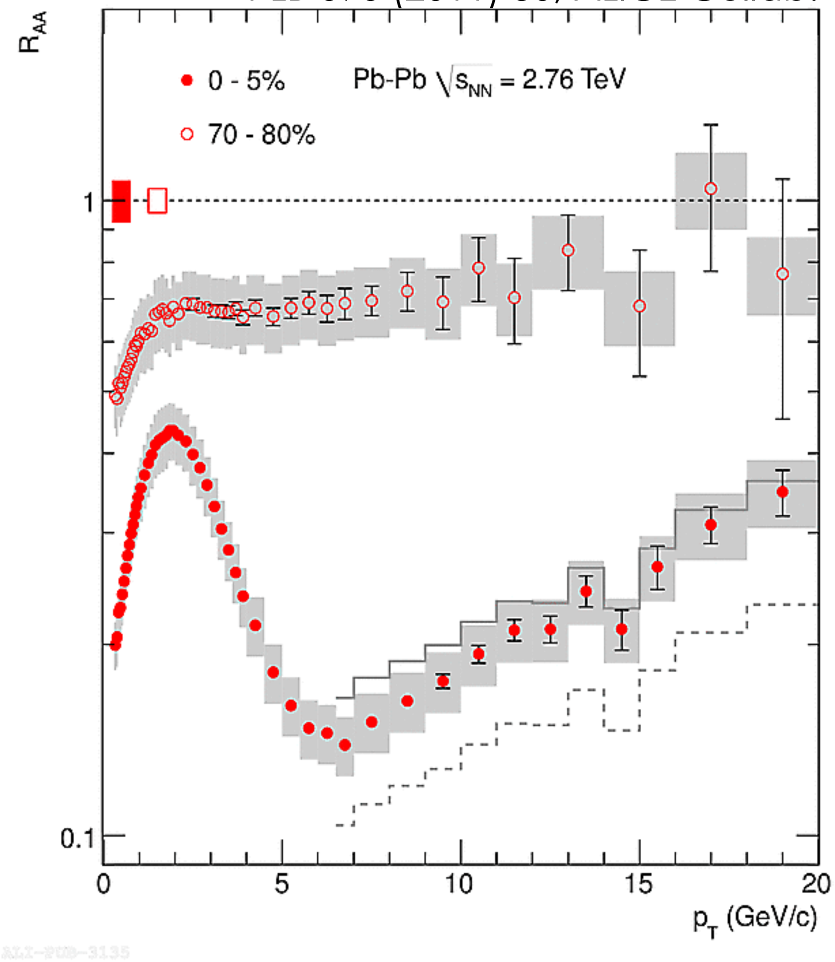
Pb-Pb spectra are compared to p-p data, normalized by the number of binary collisions $<N_{Bin}>$.

Spectra from Peripheral and Central collisions are compared and have different agreement to reference data.



Nuclear Modification Factor

PLB 696 (2011) 30, ALICE Collab.



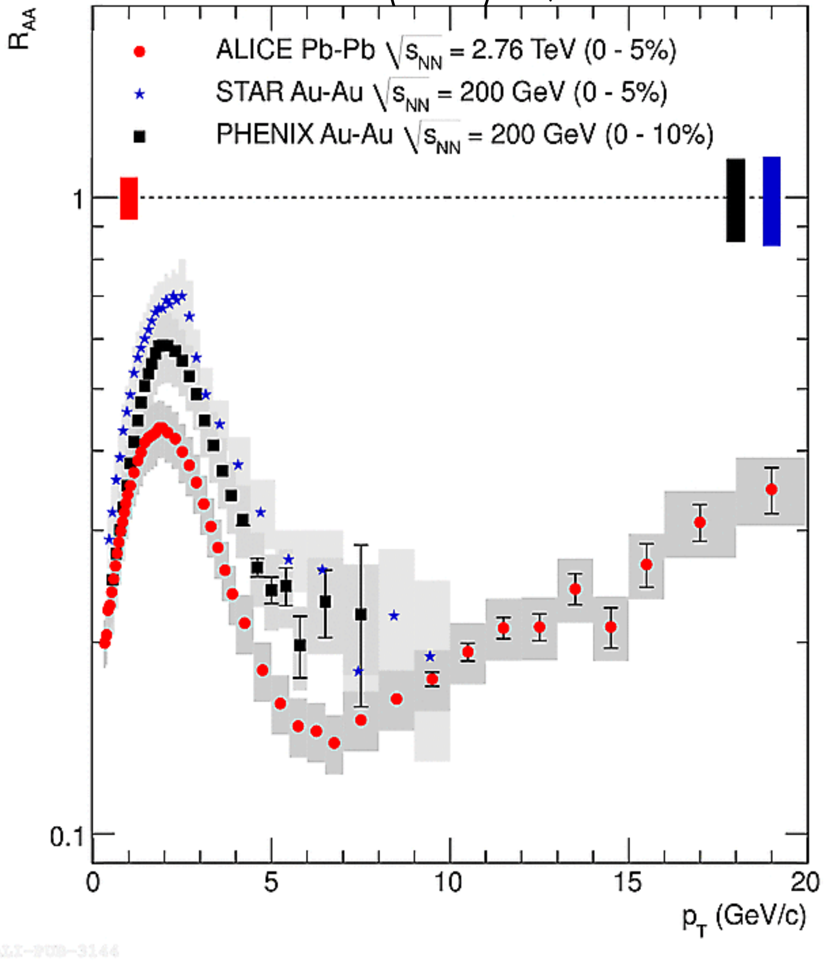
Detailed comparison between Pb-Pb spectra and p-p spectra is done by ratio known as the Nuclear Modification Factor:

$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$

Photon R_{AA}, presented by the CMS Collaboration (arXiv: 1210.3093) shows no suppression, as expected since photons should not be affected by QCD matter.

Nuclear Modification Factor

PLB 696 (2011) 30, ALICE Collab.



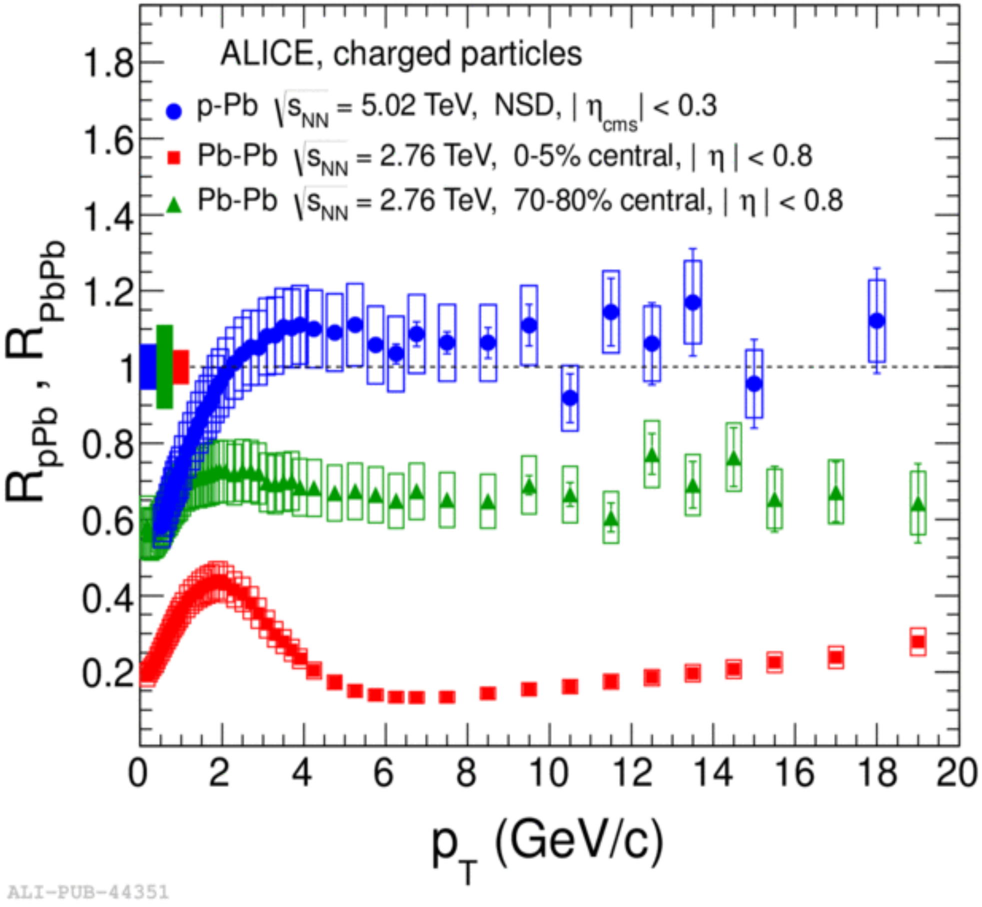
Detailed comparison between Pb-Pb spectra and p-p spectra is done by ratio known as the Nuclear Modification Factor:

$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_t}{dN_{pp}/dp_t}$$

LHC data extends the R_{AA} measurement to higher p_T and shows a slightly larger suppression than observed at RHIC, suggesting higher energy loss due to denser medium.

Nuclear Modification Factor

arXiv:1210.4520 ALICE Collab.

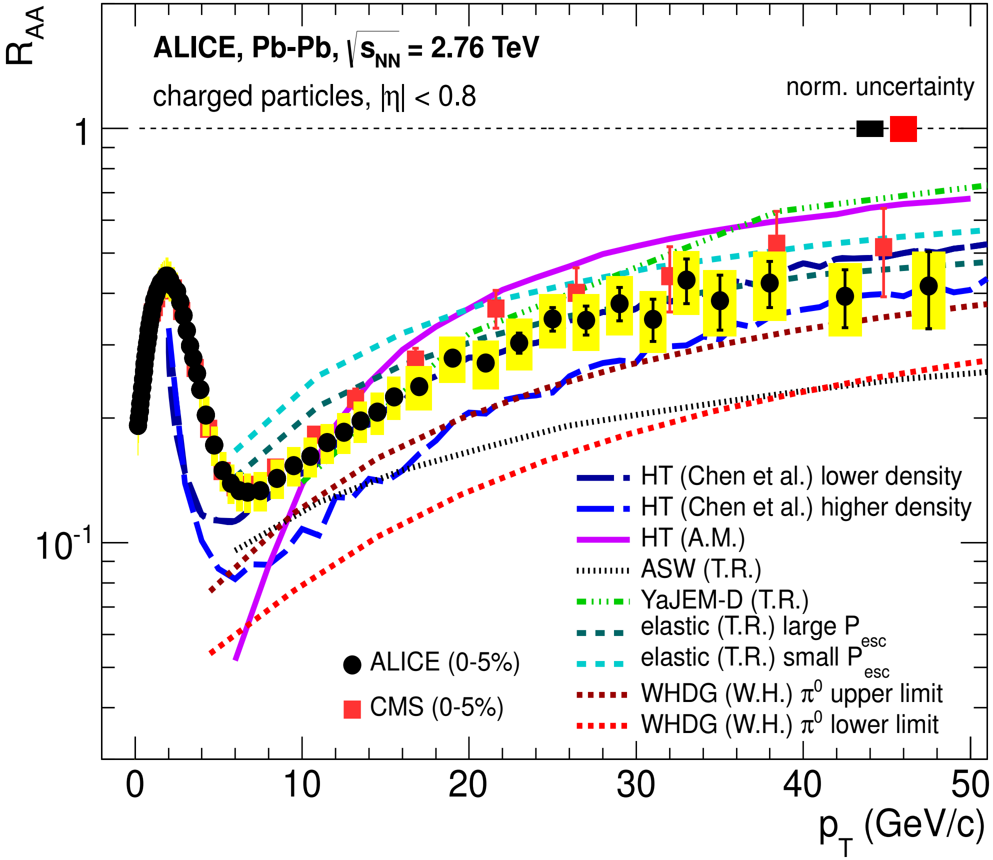


p-Pb data tests the effects due to initial state, no suppression is observed.

Suppression observed in central Pb-Pb collisions is not due to initial state effects, hence, related to the Jet interactions with the hot dense matter created in these heavy-ion collisions.

Constrains to models

arXiv:1209.0447

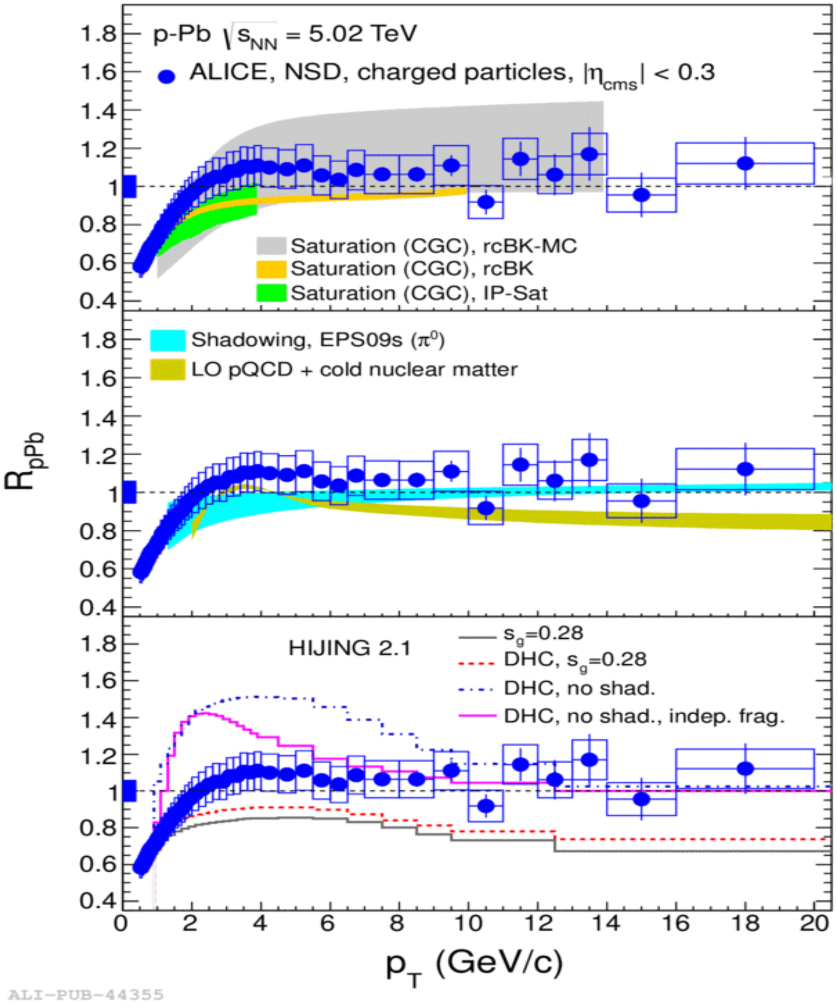


Result consistent with CMS.

Many models can reproduce suppression at high-p_T, but uncertainties are still large.

Constrains to models

arXiv:1210.4520 ALICE Collab.



p-Pb results can help with the understanding of cold nuclear matter.

Results are compared to different theoretical models:

- HIJING
- Color Glass Condensate.
- pQCD + cold nuclear matter effects and Shadowing calculations.

Heavy-flavor suppression at high p_T

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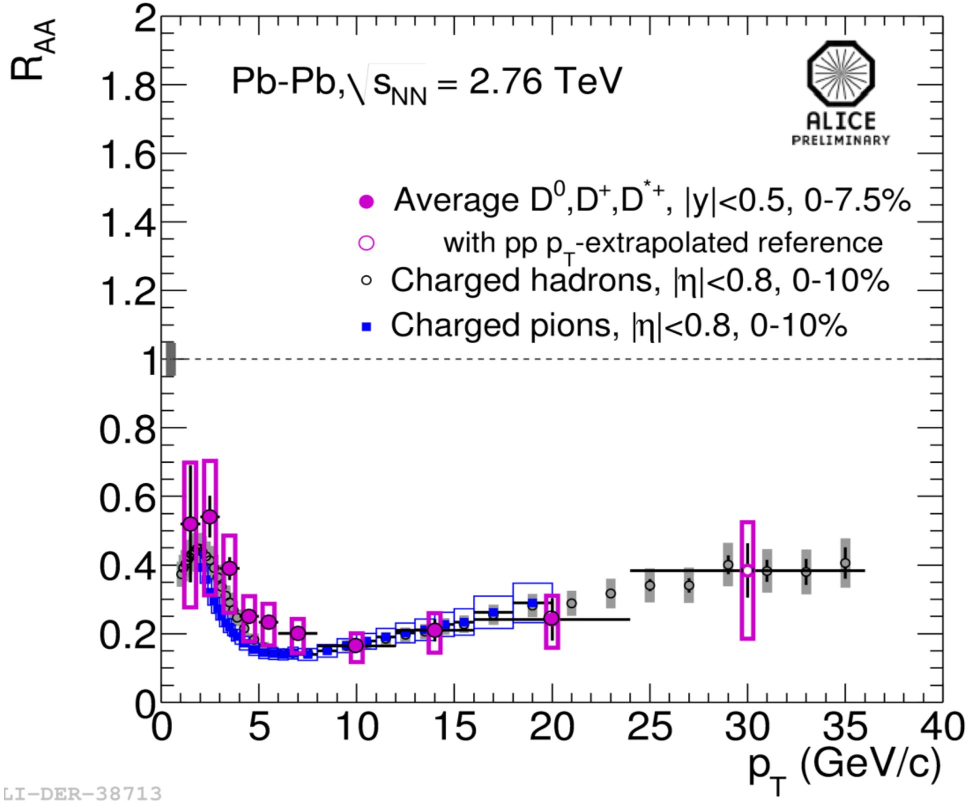

Strong in-medium energy loss for charm quarks with suppression almost as large as observed for charged particles.

Heavy-flavor suppression at high p_T

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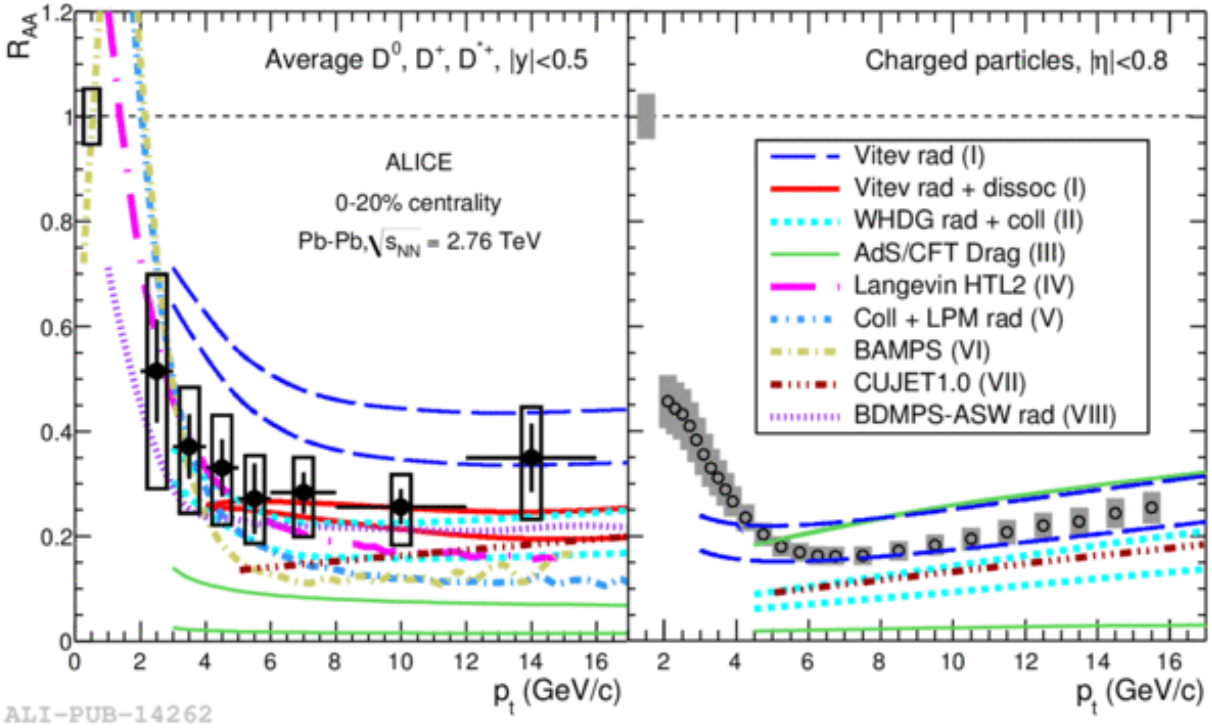
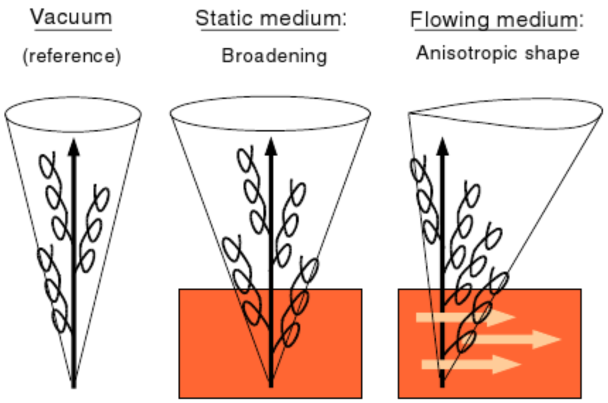


- At high p_T there is little shadowing effects (initial state) and suppression can be explained by parton energy loss models.
- New studies on R_{AA} relative to event plane test variation due to energy loss path length.

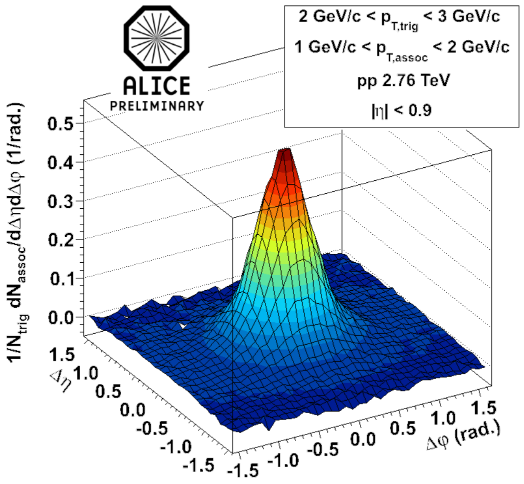
Jet Modification by the medium

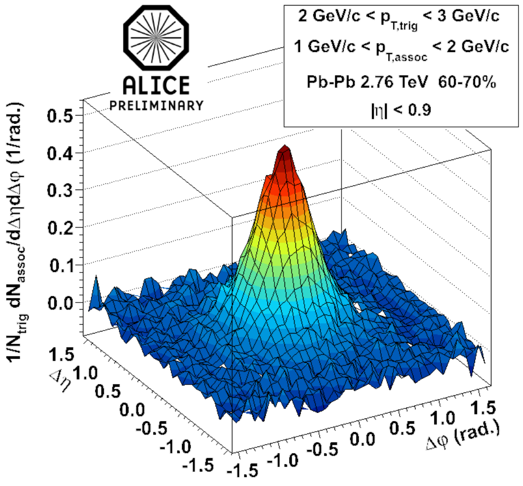


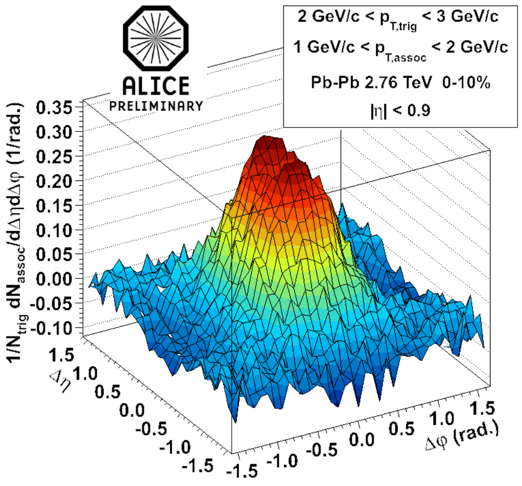
Jet interaction with the medium can result in:

- Quenching.
- Modification of shape due to interplay of flow with Jets.

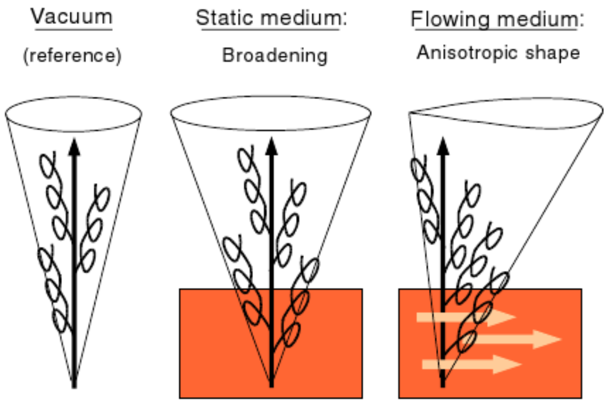
arXiv:1210.6162



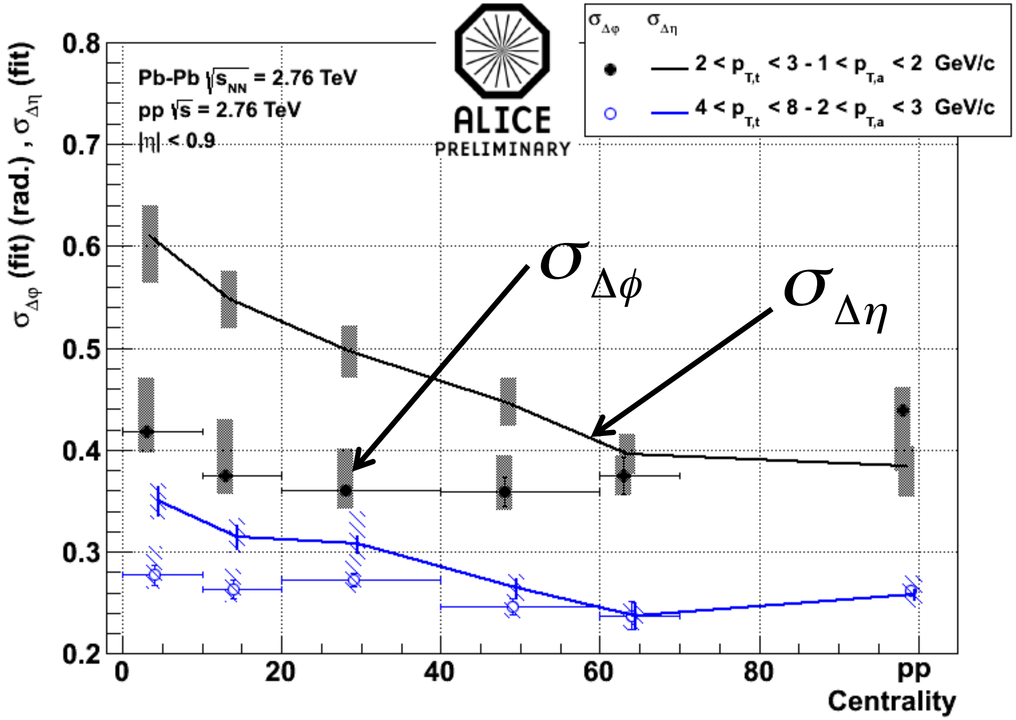




Jet Modification by the medium



arXiv:1207.7187



Increase of near-side correlation width in eta direction with centrality, while in the azimuthal direction, width is independent of centrality.

$$\sigma_{\Delta\eta} > \sigma_{\Delta\phi}$$

Conclusions

Higher energy collisions at the LHC take us into regions not accessible before at lower energy experiments.

- High statistics and higher density allows for detailed and precision measurements of bulk properties and improve constrain to theoretical models.
- High p_T probes and heavy-flavor observables can now be used to test the medium.

ALICE complete set of detectors and analysis methods allows for detailed studies of the hot and dense nuclear matter formed at LHC heavy-ion collisions. Ongoing analysis and upgrade program will bring much more new results.

Thank you !!!!!