Study of Matter at Extreme Conditions with ALICE

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(for the ALICE Collaboration)

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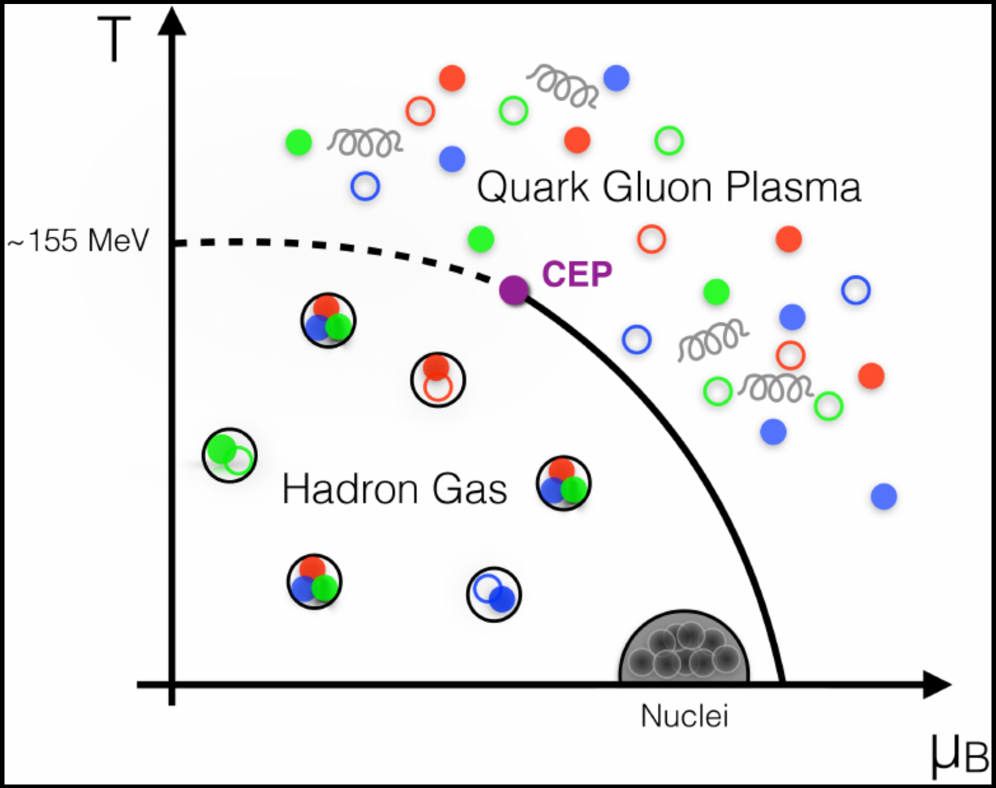
Outline

- Introduction
- A Large Ion Collider Experiment (ALICE)
- Selected results (LHC Run1 and Run2)
  - Global properties
  - Anisotropic flow
  - Nuclear modification factors

What do we measure?

Properties of nuclear matter formed in the early Universe ~10 μs after Big Bang (T ~ 10^{12} K)
QCD phase transition: Hadron Gas <-> Quark-Gluon Plasma (QGP)
(state of deconfined quarks and gluons)



LHC: $\mu_B = 0$ (net baryon density)

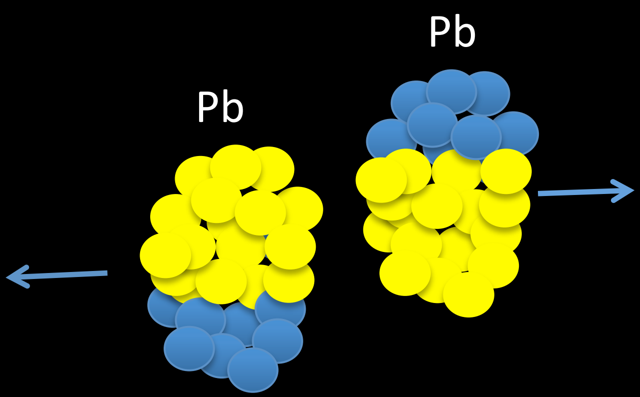
Lattice QCD calculations:

- phase transition (crossover)
- critical temperature: T_c~155 MeV
- critical energy density: ε_c~0.5 GeV/fm^3

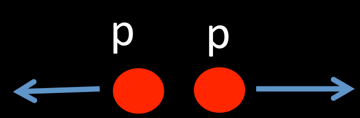
A. Bazavov et al. (hotQCD) , Phys. Rev. D90 (2014) 094503
S. Borsanyi et al. (Budapest-Wuppertal), Phys. Lett. B730, 99 (2014)

How do we measure?

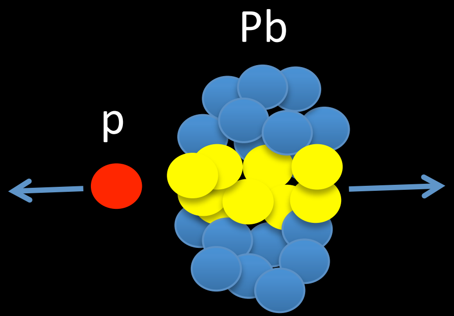
Collide Pb-Pb and compare results to reference measurements in pp and p-Pb



Thermal production, flow, recombination, jet quenching and fragmentation in the Quark-Gluon Plasma (QGP).

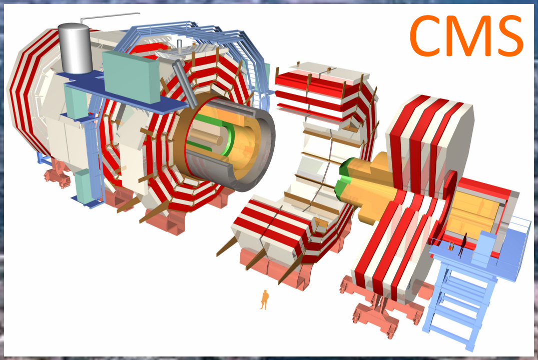


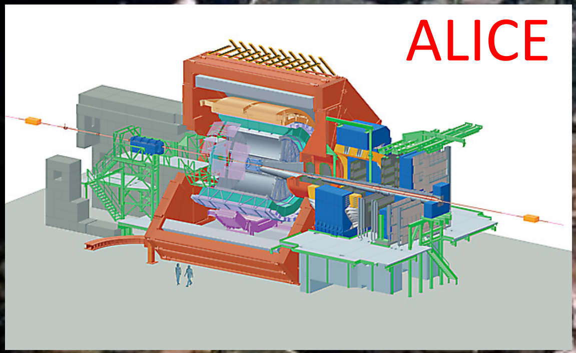
Soft QCD and pQCD and fragmentation in vacuum. Reference for p-Pb and Pb-Pb.

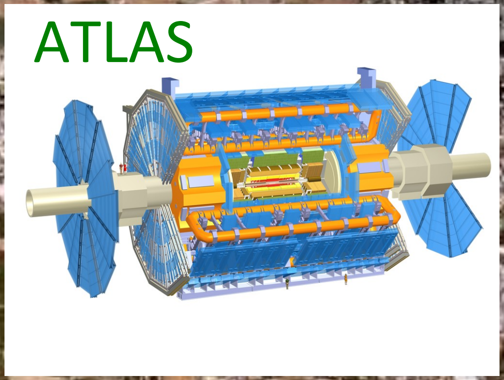


Initial state effects (shadowing/gluon saturation). Reference for Pb-Pb.

Heavy-Ion experiments at the LHC





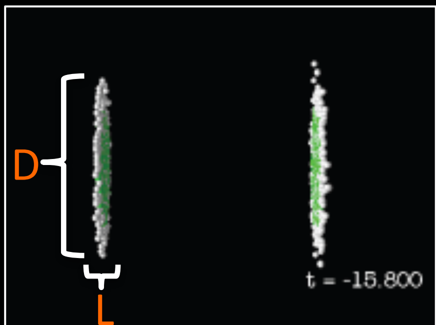


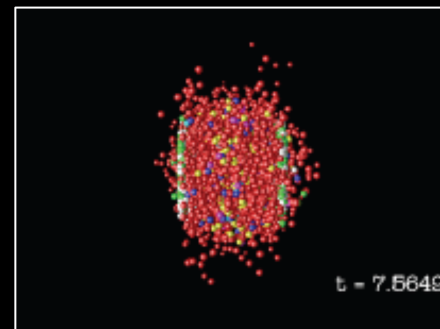
pp: $\sqrt{s}$ = 0.9 – 8 TeV (Run1), 5, 13 TeV (Run2)
p-Pb: $\sqrt{s_{NN}}$ = 5 TeV (Run1)
Pb-Pb: $\sqrt{s_{NN}}$ = 2.76 TeV (Run1), 5 TeV (Run2)

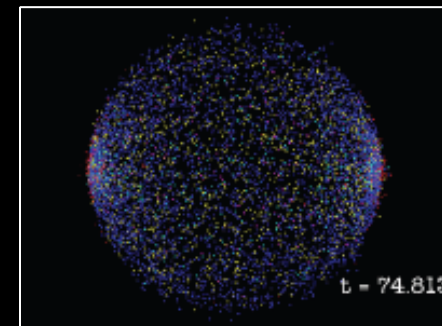
Heavy-ion collision at the LHC

Pb-Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)

Time







Lorentz contracted heavy ions

Lorentz Γ = 1350
D = 14 fm
L ~ 0.01 fm

hadron sizes ~ fm

Collision - hard scatterings

High p_T and high mass particle production – hard probes of QGP:

$\tau_{prod} = 1/p_T$
hadrons with charm and bottom quarks

QGP formation and thermalization ($T>T_C$), hadronization ($T \sim T_C$)

τ < 10 fm/c
Production of low p_T particles (bulk of matter > 95%)

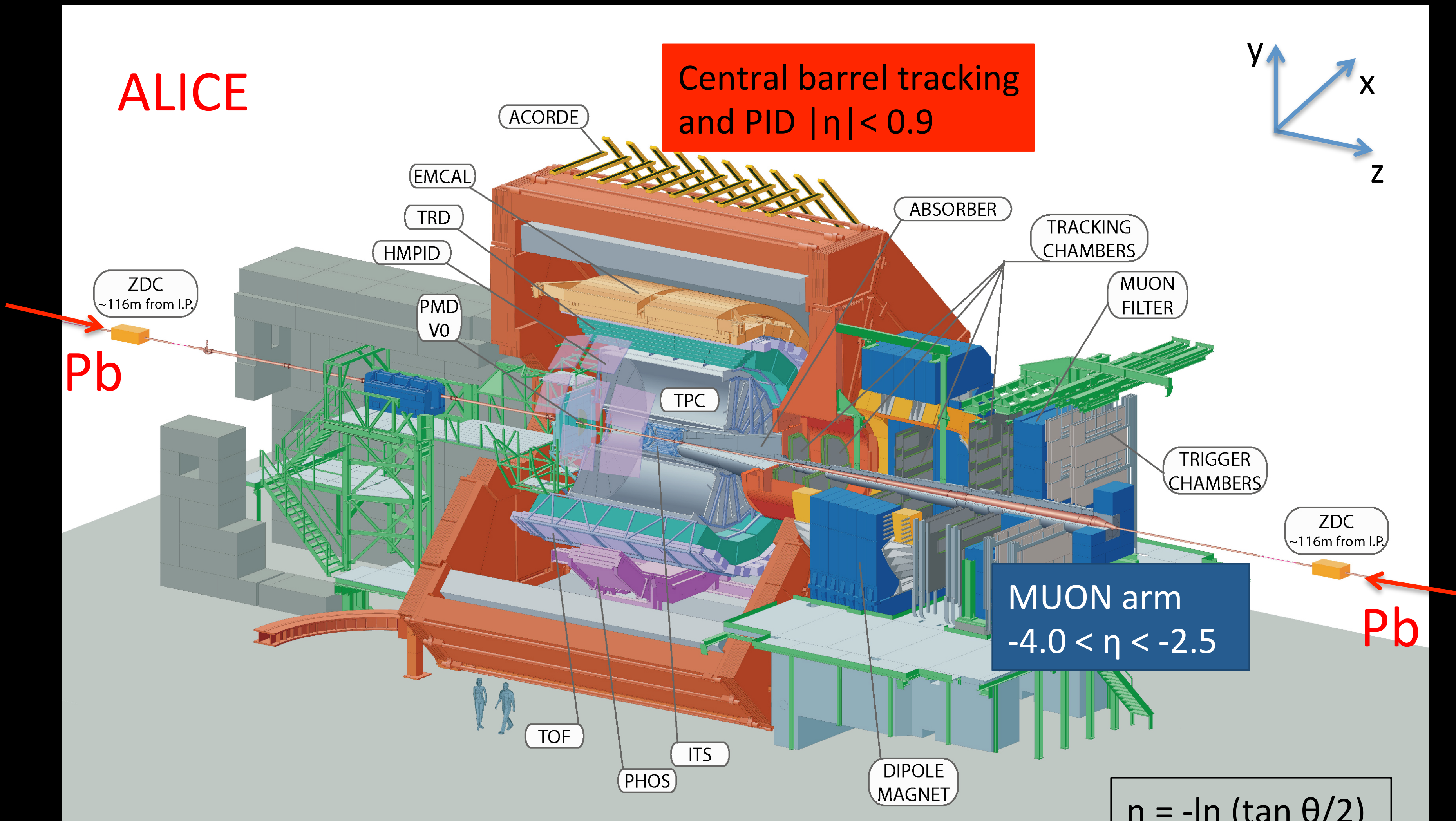
Non-perturbative QCD

Chemical and kinetic freeze-out ($T<T_C$)

τ > 10 fm/c
Transition from hot and interacting hadron gas to the system of free particles

A Large Ion Collider Experiment

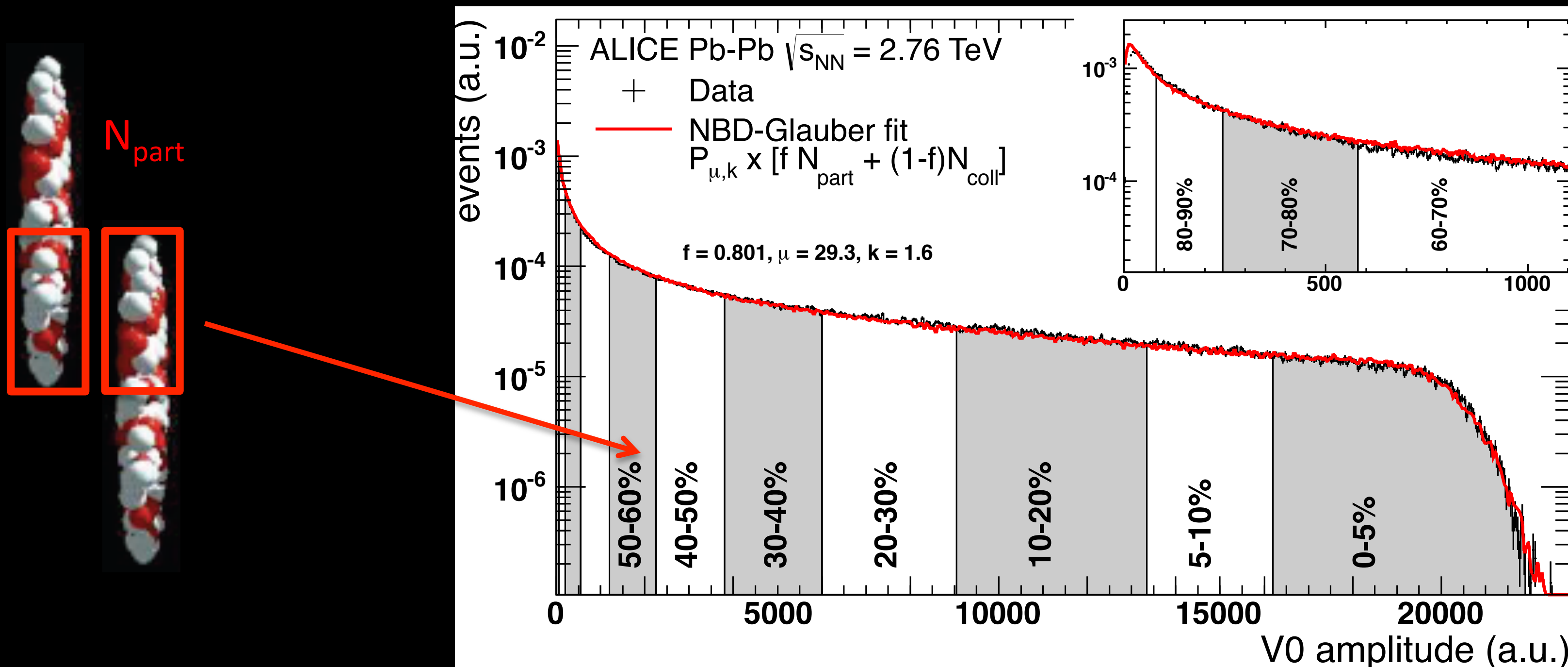
- Excellent particle identification capabilities in a large p_T range 0.1-20 GeV/c
- Good momentum resolution ~1-5% at p_T = 0.1-50 GeV/c



$\eta = -\ln(\tan \theta/2)$

Collision centrality

Correlate particle multiplicity with collision geometry i.e. impact parameter, volume and shape (ALICE, Int. J. Mod. Phys. A29 (2014) 1430044)



NBD-Glauber fit:

Number of participant nucleons: N_{part}

Number of binary inelastic nucleon-nucleon collisions: N_{coll}

Nuclear overlap function: $T_{AA} \cong N_{coll} / \sigma^{NN}_{INEL}$

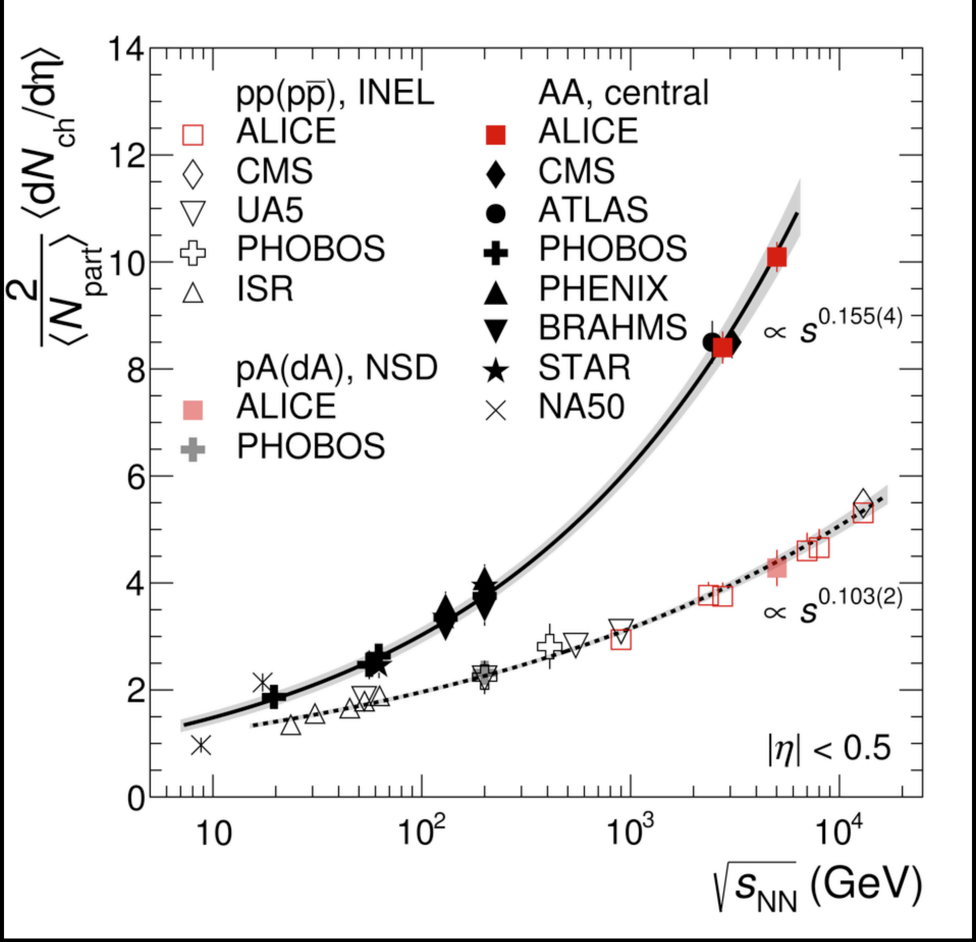
Pb-Pb (0-5%): $\langle N_{part} \rangle \sim 400$

GLOBAL PROPERTIES

Energy density, temperature, radial flow

Charged-particle multiplicity density vs. $\sqrt{s_{NN}}$

ALICE, arXiv:1512.06104



Measurements in Run1 and Run2.

Particle production follows the power law dependence:

- pp, pA (dA): ~$s_{NN}^{0.103}$
- A-A (0-5%, 0-6%): ~$s_{NN}^{0.155}$

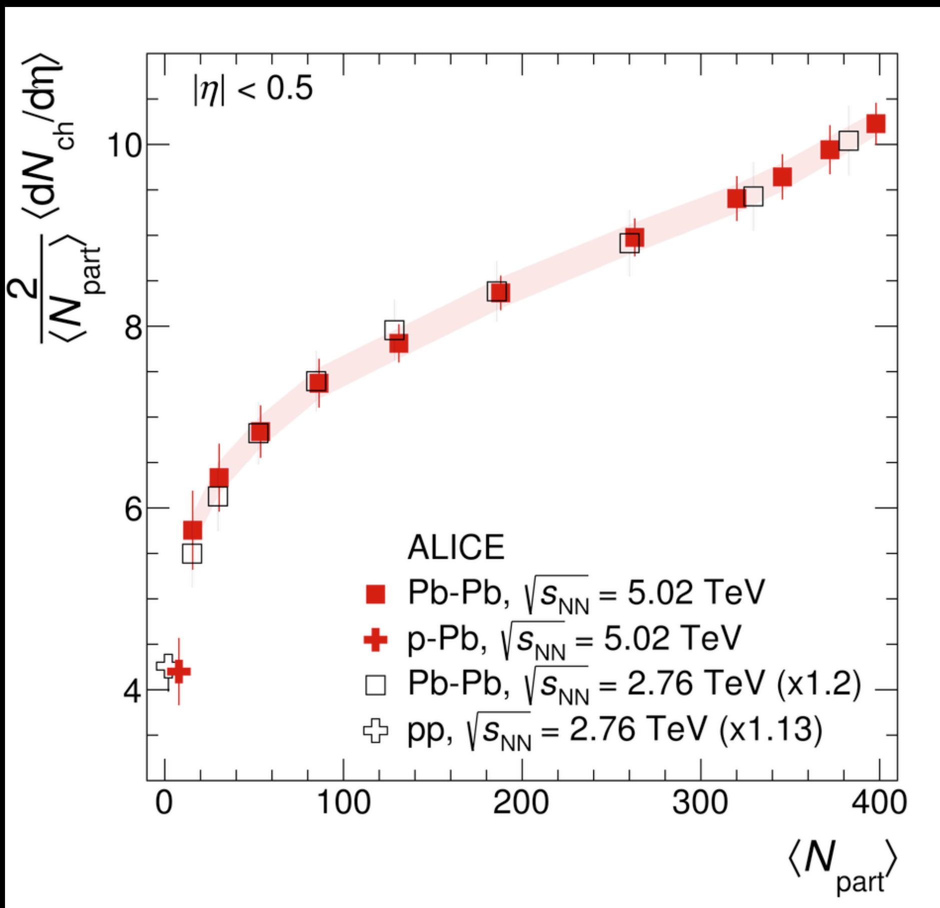
ALICE (Pb+Pb 0-5%):

- $dN_{ch} / d\eta = 1943 \pm 54$ ($\sqrt{s_{NN}}$=5.02 TeV)
- $dN_{ch} / d\eta = 1601 \pm 60$ ($\sqrt{s_{NN}}$=2.76 TeV)

ALICE, PRL 106, 032301 (2011)

Charged-particle multiplicity density vs. <N_{part}>

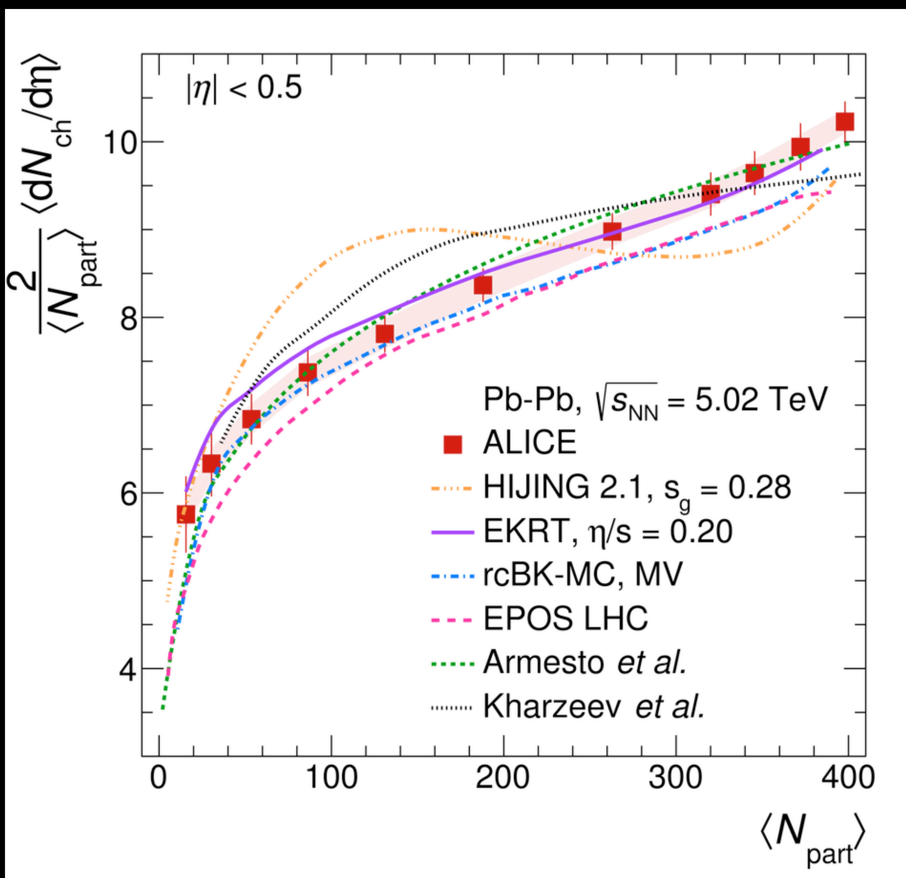
ALICE, arXiv:1512.06104



A constant factor ~1.2 increase in charged particle multiplicity density from $\sqrt{s_{NN}}$=2.76 TeV to $\sqrt{s_{NN}}$=5.02 TeV for all Pb-Pb centrality intervals.

Charged-particle multiplicity density vs. <N_{part}> comparison to models

ALICE, arXiv:1512.06104



HIJING 2.1 (soft QCD, gluon shadowing parameter sg = 0.28) W.-T. Deng et al. Phys. Rev. C83 (2011) 014915

EPOS LHC (soft QCD + parameterized hydro) T. Pierog et al. Phys. Rev. C 92 (2015) 034906

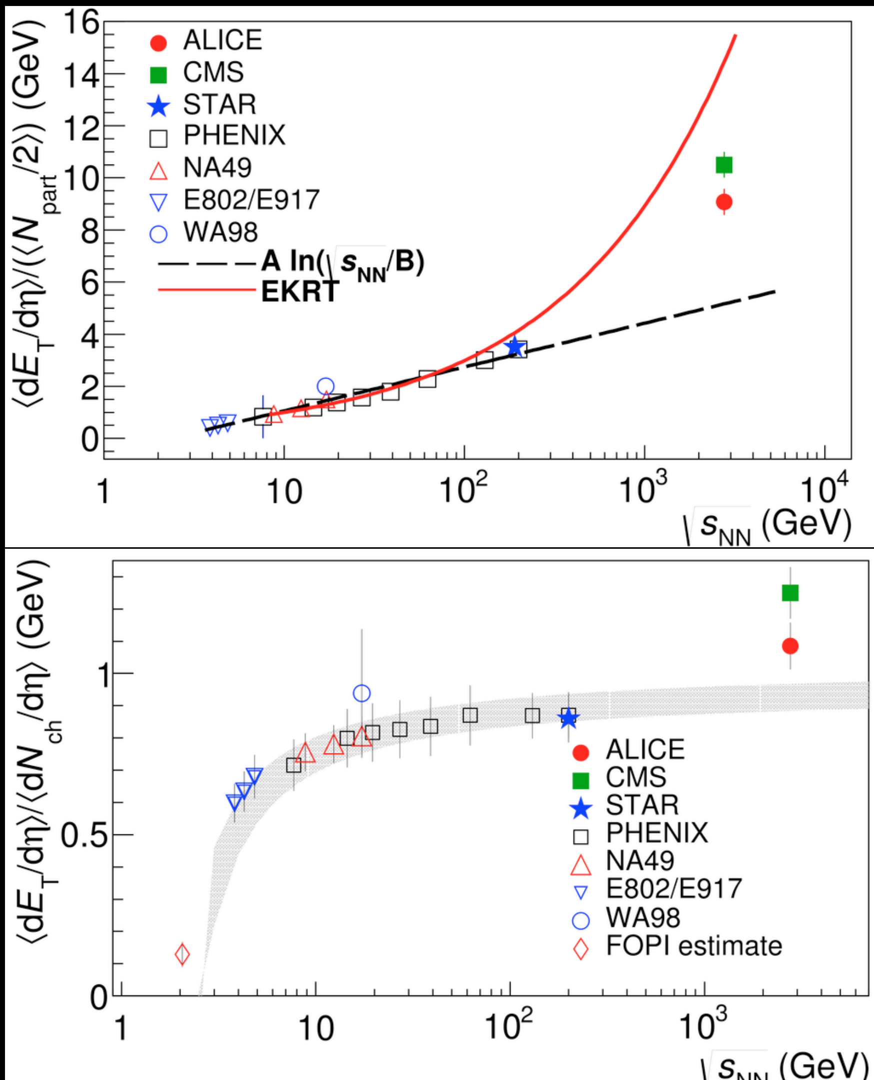
EKRT (pQCD + saturation + viscous hydro η/s = 0.2) H. Niemi et al. Phys. Rev. C 93, 014912 (2016)

Saturation inspired models (pQCD):

- rcBK-MC (J. L. Albacete et al. J. Phys. Conf. Ser. 316 (2011) 012011)
- Armesto et al. Phys. Rev. Lett. 94 (2005) 022002
- Khazreev at al. Nucl. Phys. A747 (2005) 609

Transverse Energy Density vs. $\sqrt{s_{NN}}$

ALICE, arXiv:1603.04775



ALICE Pb-Pb (0–5%) $\sqrt{s_{NN}}$=2.76 TeV:

- $dE_T/d\eta$ = 1737 ± 6(stat.) ± 97 (sys.) GeV
  - lower than by CMS

- Extrapolation from the lower energies underestimates data
- EKRT (pQCD + saturation + ideal hydro) overestimates data
  T. Renk et alPhys. Rev. C84 (2011) 014906

- Volume-averaged energy density J.D.Bjorken Phys. Rev. D 27, 140):

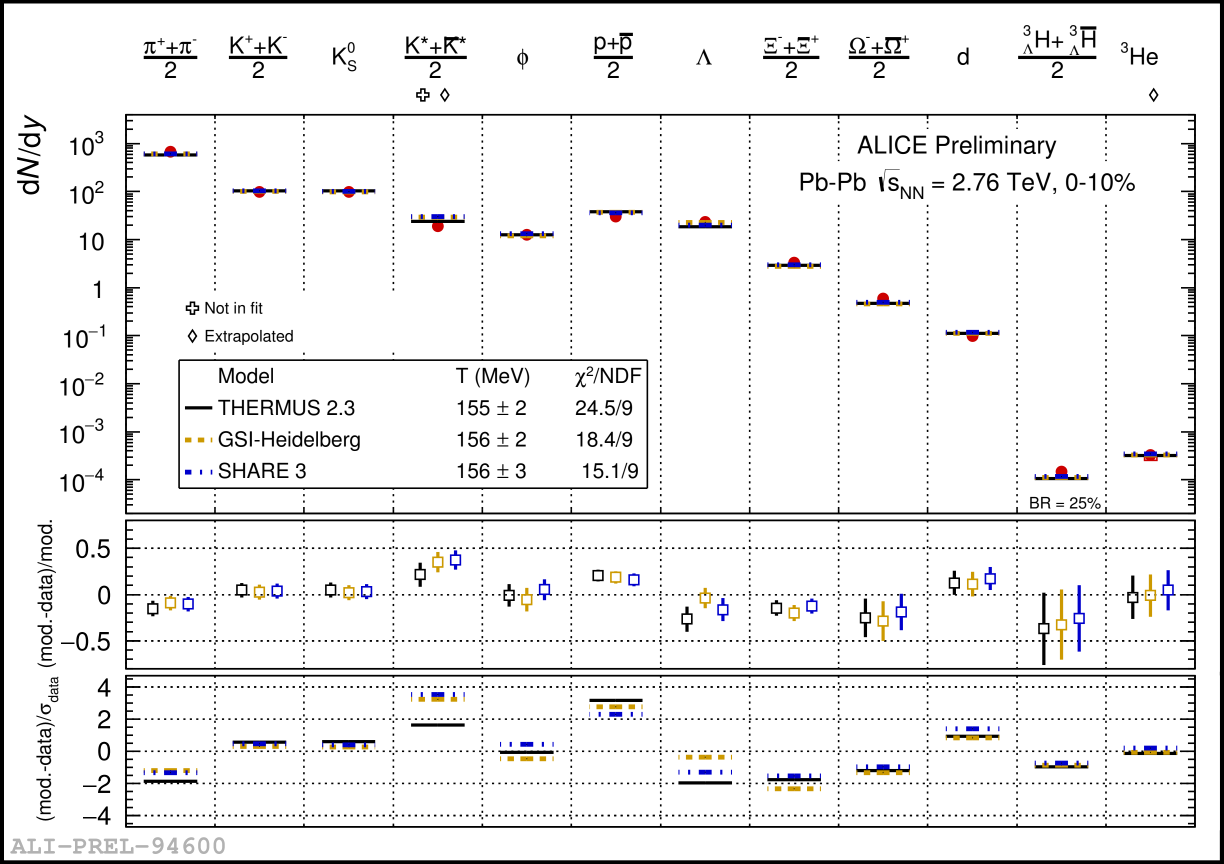
$$\varepsilon = \frac{1}{Ac\tau_0} J \left\langle \frac{dE_T}{d\eta} \right\rangle$$

τ_0 ~ 1 fm/c - formation time, A - transverse area

ε = 12.3 ± 1.0 GeV/fm^3

$\varepsilon \gg \varepsilon_c$ (lattice QCD)

Identified Particle Yields



Equilibrium statistical hadronization model fits:

- $T_{ch} \sim 155$ MeV
- $T_{ch} \sim T_c$ (lattice QCD)
- Largest deviation for K^{*0} resonances and protons?
- Good description for light nuclei?

Equilibrium statistical hadronization models:

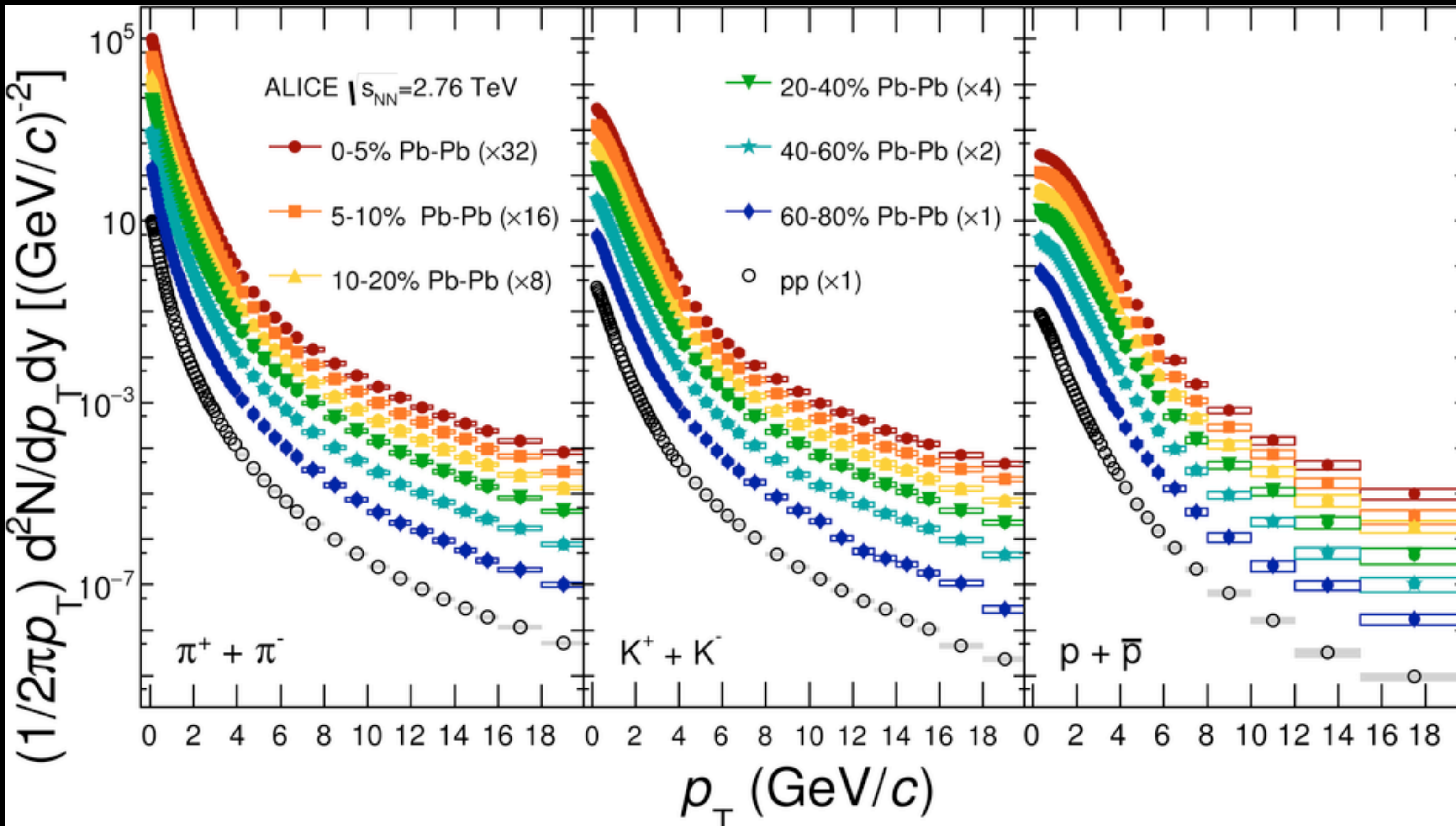
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 (2009) 84

GSI-Heidelberg: Andronic et al, PLB 673 (2009) 142

SHARE: Petran et al, Phys.Rev., C88 (2013) 034907

Identified Hadron p_T Spectra

ALICE, Phys. Rev. C 93, 034913 (2016)

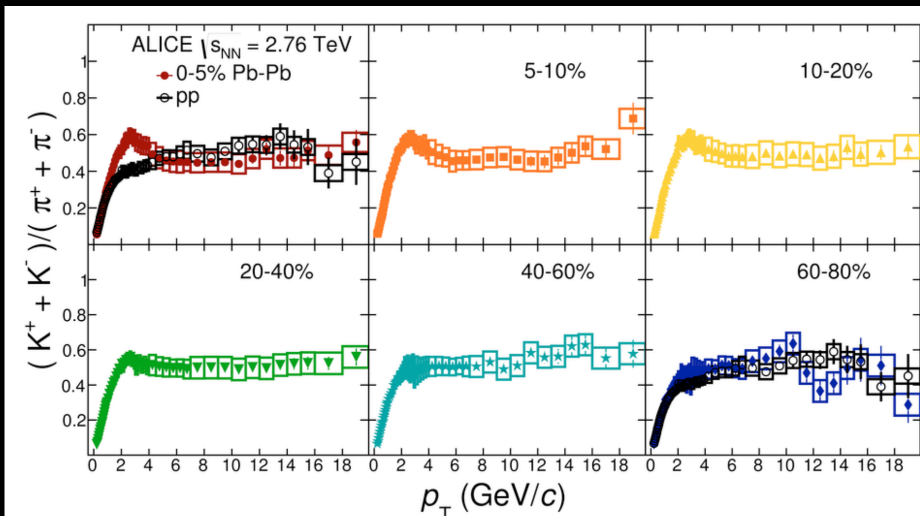


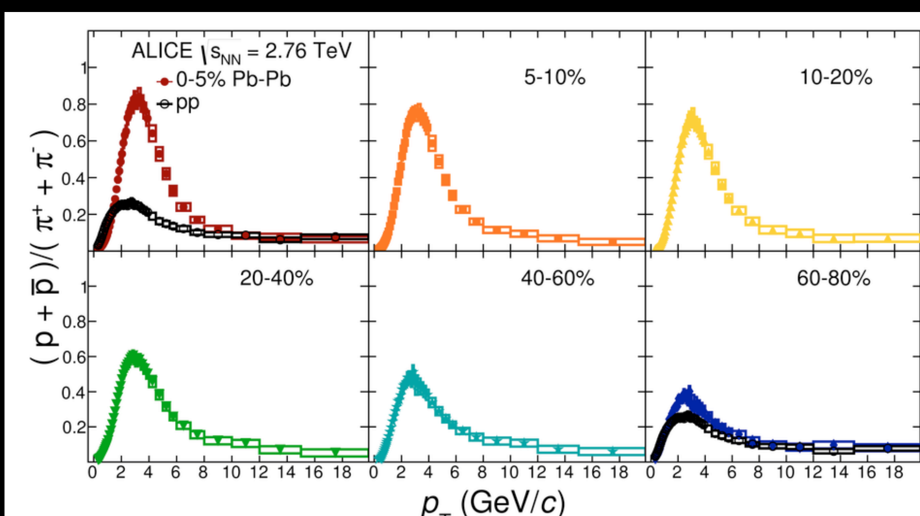
Spectra are modified depending on particle species and event centrality

→ Radial flow

Identified Hadron p_T Ratios

ALICE, Phys. Rev. C 93, 034913 (2016)





Pb-Pb to pp comparison.

Strong radial flow develops in Pb-Pb collisions.

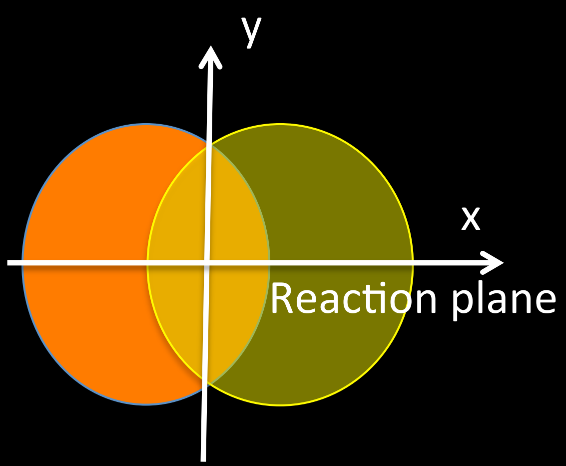
ANISOTROPIC FLOW

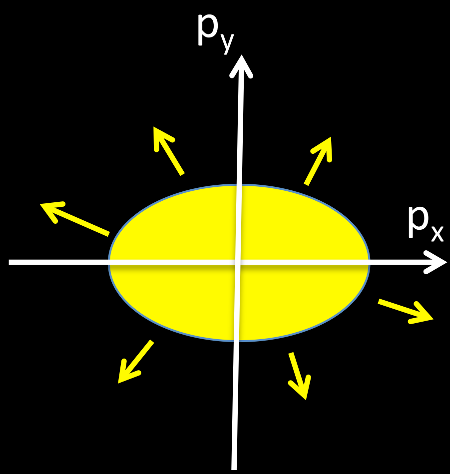
nature of the medium

Anisotropic flow

Overlap region - non central A+A collision

initial spatial anisotropy → momentum anisotropy





Azimuthal anisotropy in particle distribution w.r.t. reaction plane

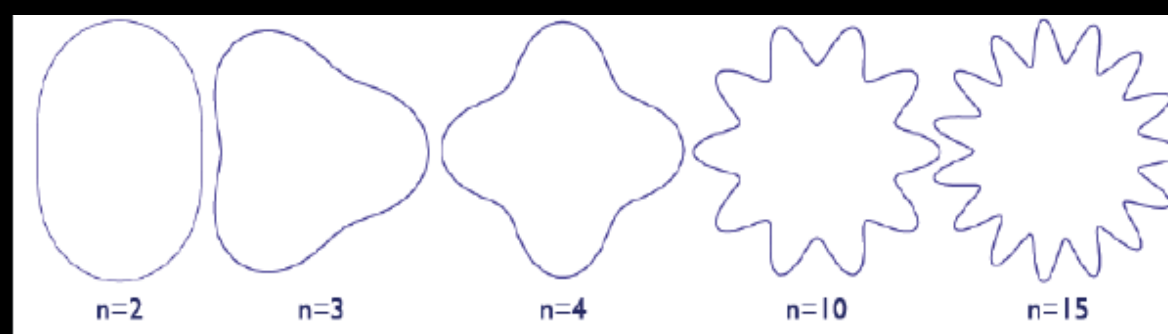
Fourier expansion:

$$\frac{dN}{d(\varphi-\psi_n)} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\varphi-\psi_n\right)\right]$$

v_n (p_T, η, centrality) – flow coefficient

→ System with shear viscosity

v_2 v_3 v_4 ...

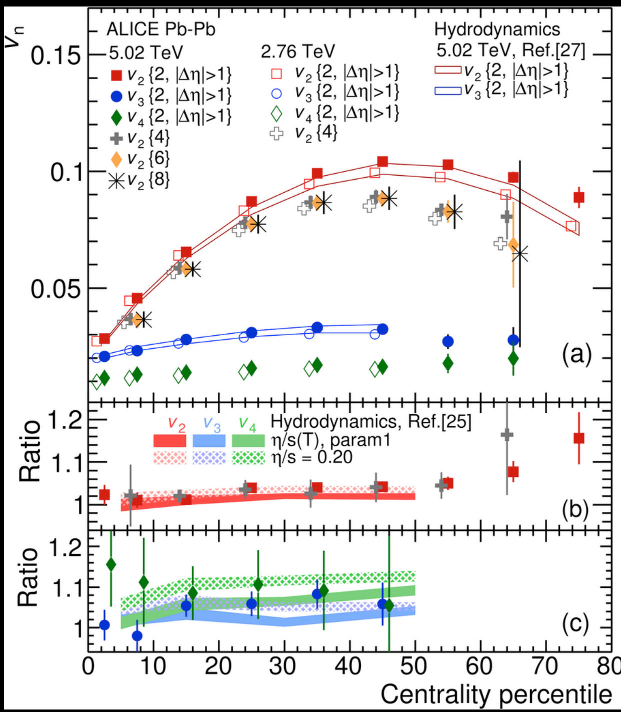


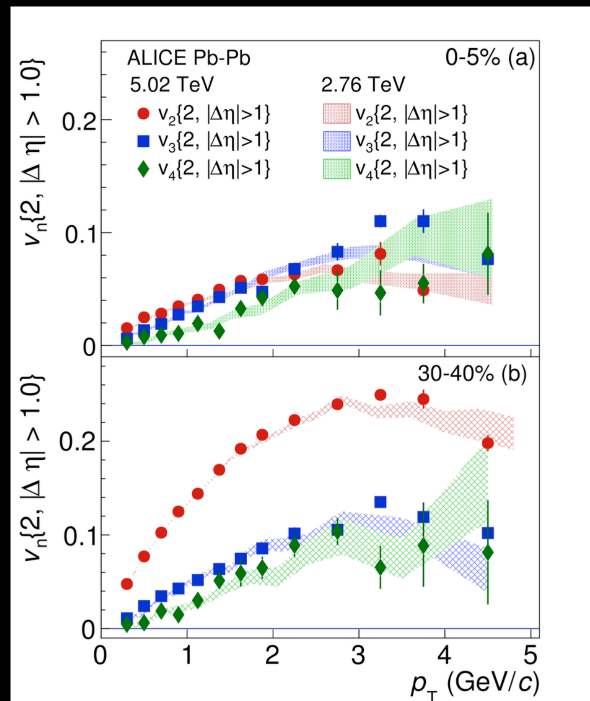
Elliptic flow v_2
(from almond shape)

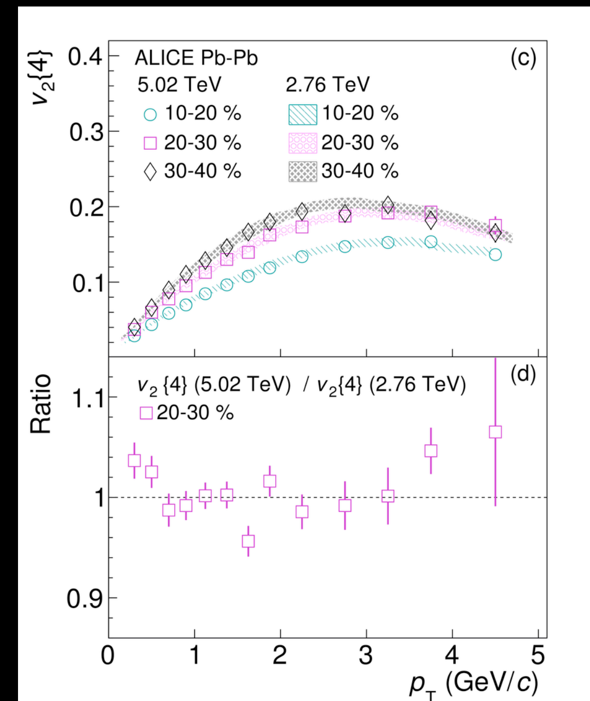
$$v_2 = \frac{\langle p_y^2 \rangle - \langle p_x^2 \rangle}{\langle p_y^2 \rangle + \langle p_x^2 \rangle}$$

Particle flow in Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV

ALICE, Phys. Rev. Lett. 116, 132302 (2016)







Anisotropic flow coefficients slightly increases from $\sqrt{s_{NN}}$=2.76 TeV to $\sqrt{s_{NN}}$=5.02 TeV

Comparison to models:

[25] EKRT (pQCD + saturation + viscous hydro) H. Niemi et al. Phys. Rev. C 93, 014912 (2016)

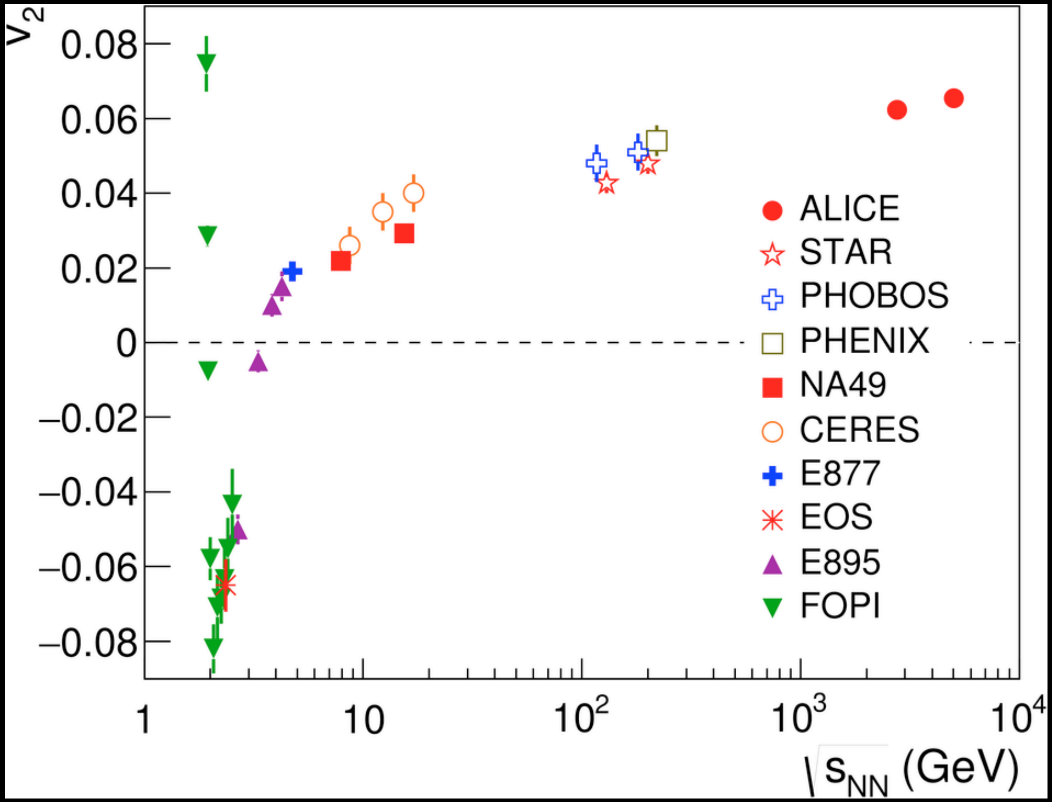
- Discriminating power between various parameterizations of η/s vs. T dependence

[27] pQCD + saturation + viscous hydro: Noronha-Hostler et al. Phys. Rev. C 93, 034912 (2016)

- Predictions for integrated p_T

Elliptic flow v_2 vs. $\sqrt{s_{NN}}$

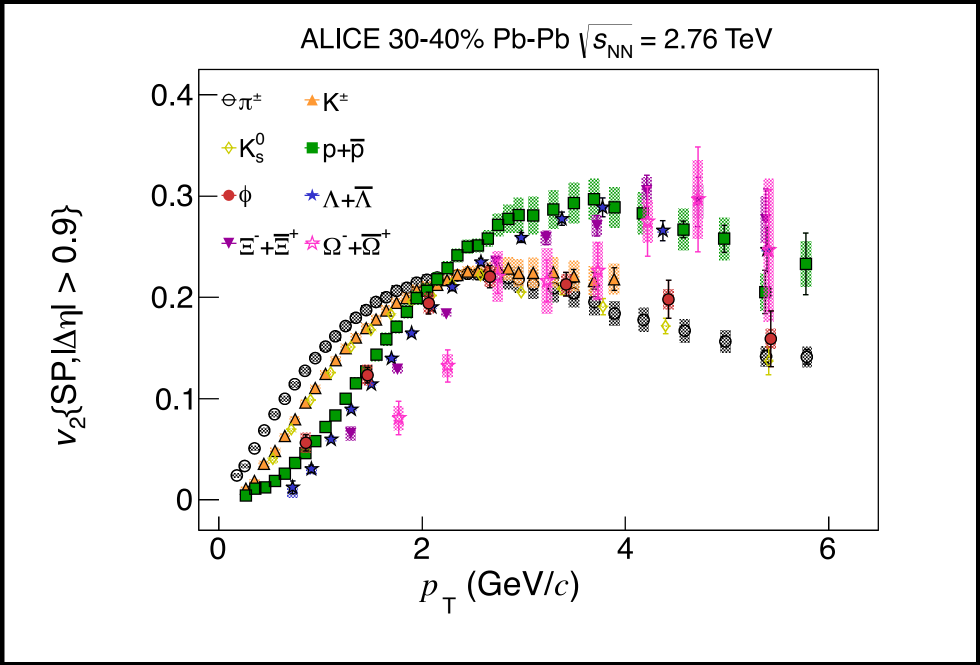
ALICE, Phys. Rev. Lett. 116, 132302 (2016)

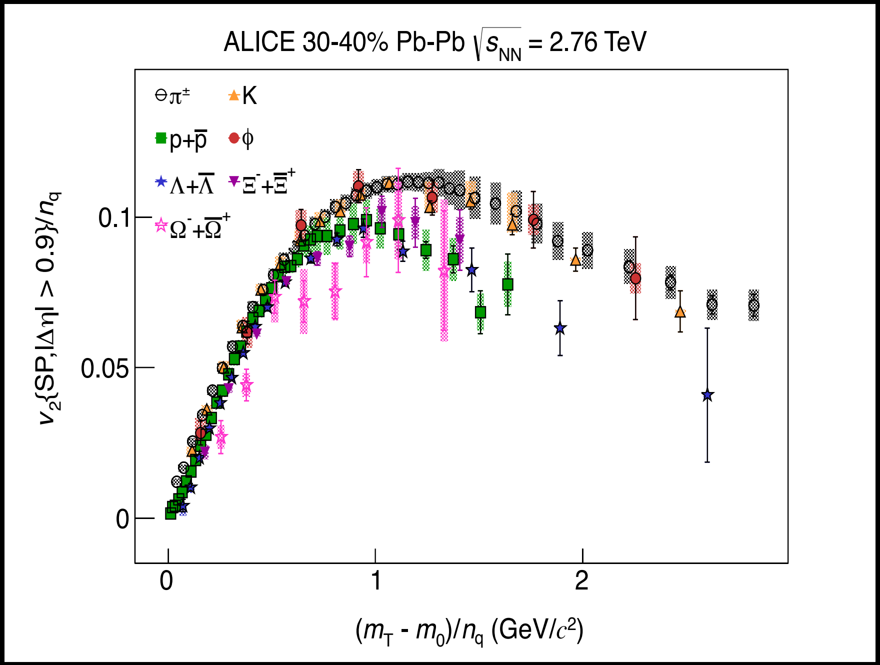


- $v_2\{4\}$ at $\sqrt{s_{NN}}$=5.02 TeV compared to measurements at lower energies
- ~5% increase in v_2 observed from $\sqrt{s_{NN}}$=2.76 TeV to $\sqrt{s_{NN}}$=5.02 TeV

v_2 for Baryons and Mesons

ALICE, JHEP 06 (2015) 190





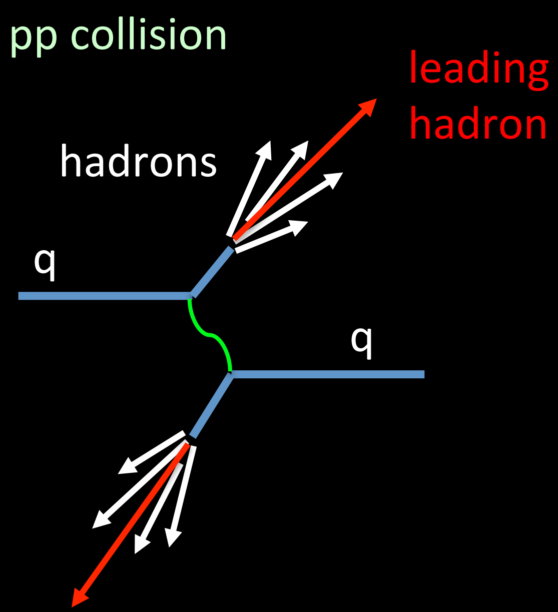
- p_T < 2 GeV/c: mass hierarchy in the meson and baryon v_2 (p_T) - flow equalizes velocities
- p_T > 2 GeV/c: v_2 determined by quark content rather than mass
- Scaling by n_q does not work at the LHC

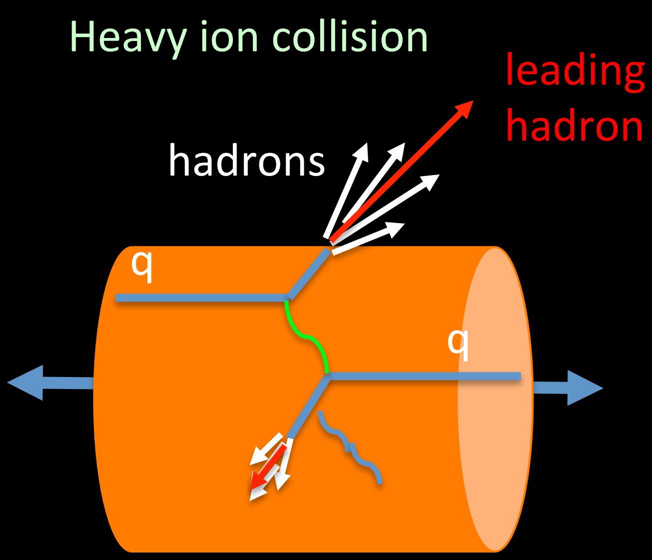
NUCLEAR MODIFICATION FACTORS

Medium density, transport properties

Jet Quenching

High p_T particles (partons): $\tau_{prod} \sim 1 / p_T$ ($\tau_{prod} \sim 0.1$ fm/c for $p_T = 10$ GeV/c)





Jet quenching

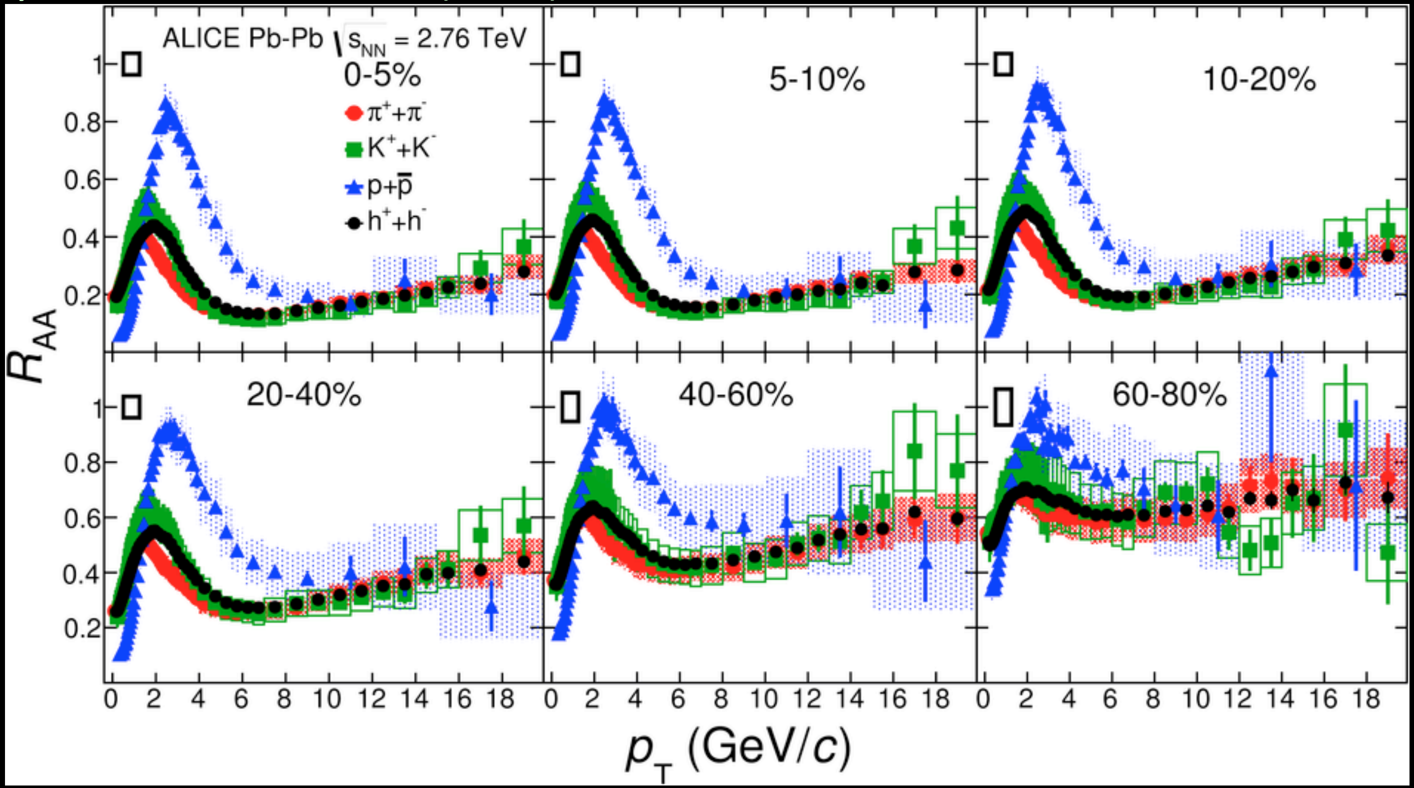
- Characterize medium properties via parton energy loss
  → Modification of leading hadron and jet spectra

R_{AA} for π, K, p

$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

R_{AA} – nuclear modification factor
$T_{AA} \cong N_{coll} / \sigma_{NN}$
$R_{AA} = 1 \Leftrightarrow$ no modification

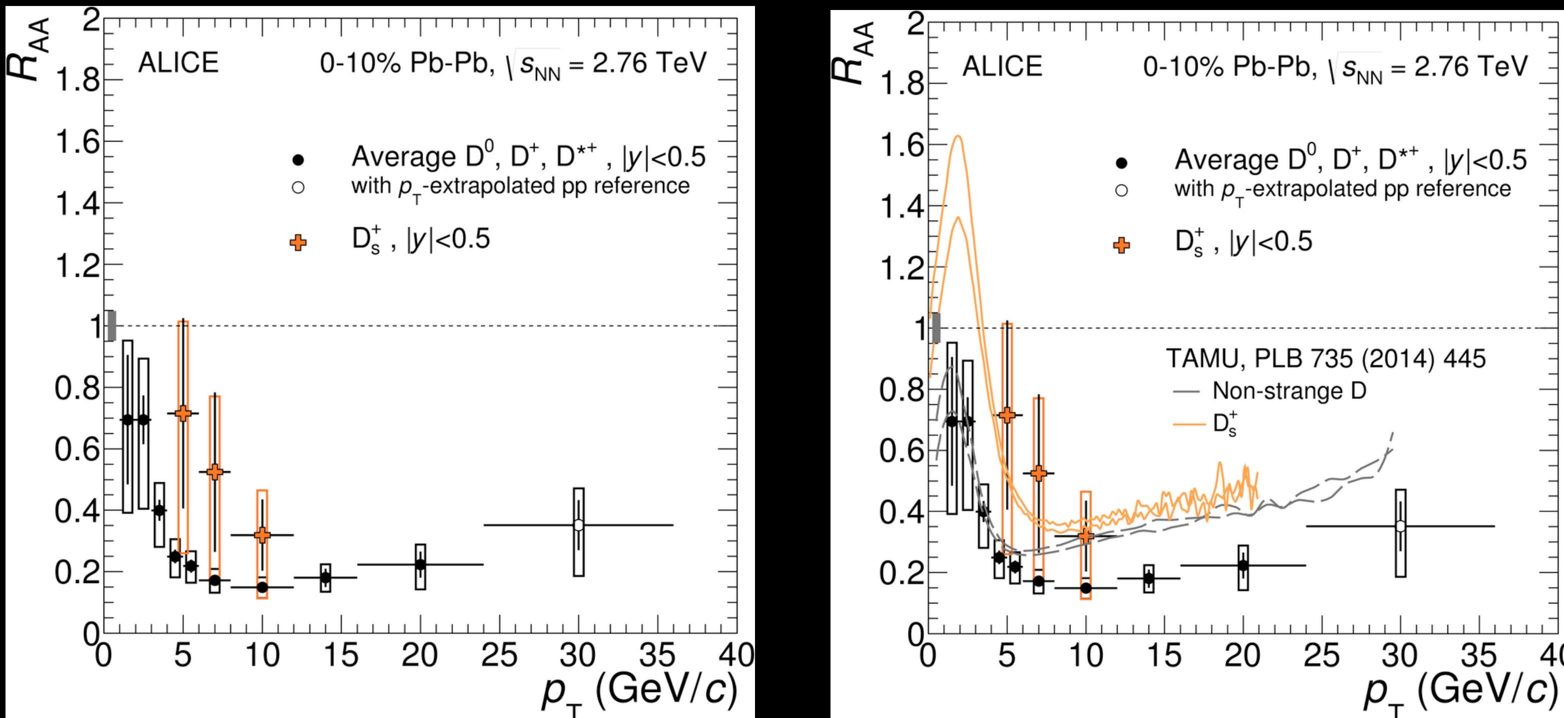
ALICE, Phys. Rev. C 93, 034913 (2016)



Strong suppression at high p_T in central collisions for all particle species

R_{AA} for D mesons

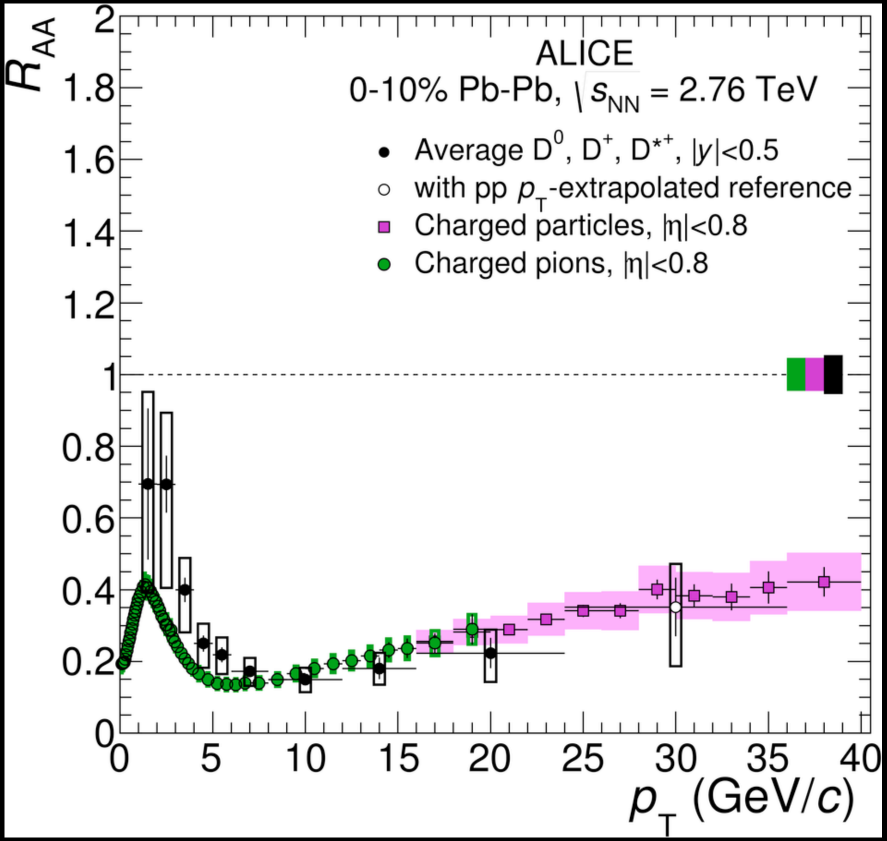
ALICE, JHEP 03 (2016) 081, JHEP 03 (2016) 082



- Strong suppression at high p_T for all D meson species
- Sign of smaller suppression of D^+s compared to non-strange D mesons at low and intermediate p_T
  - Enhanced strangeness production in QGP?
- TAMU model (heavy quark transport in expanding medium + hadronization) M. He et al. Phys.Rev. C86 (2012) 014903

R_{AA} for light and heavy hadrons

ALICE, JHEP 03 (2016) 081



The same suppression for D and pions at high p_T

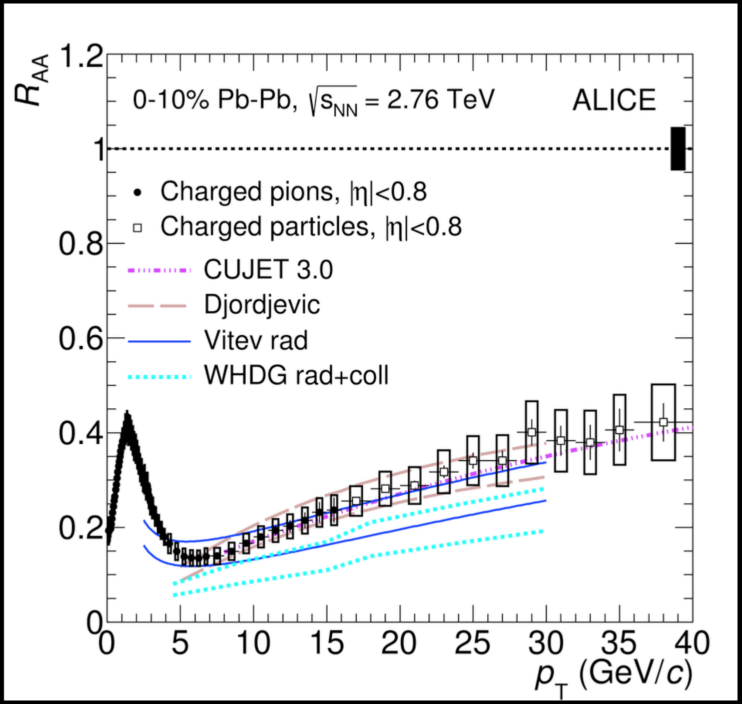
- Similar energy loss of heavy and light flavor in QGP?

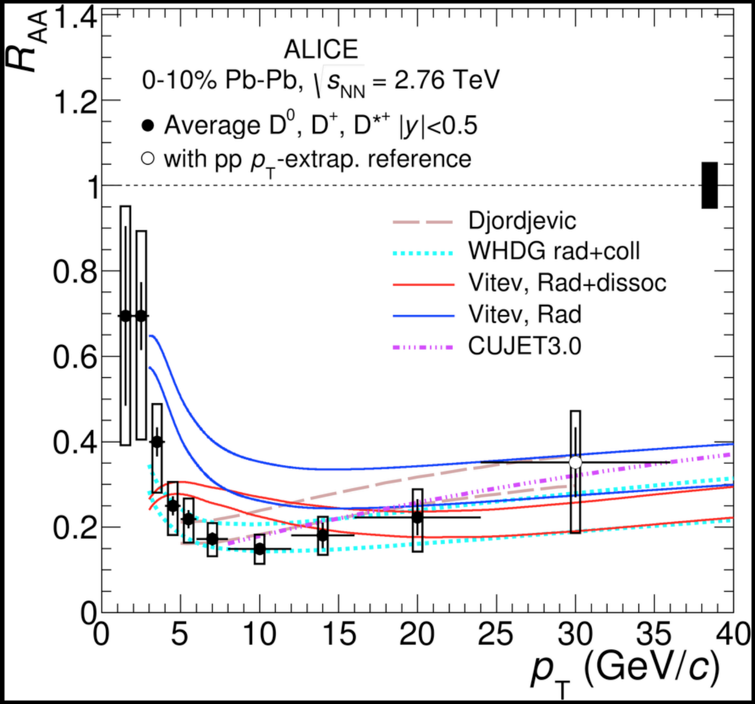
For p_T < 6 GeV/c D meson R_{AA} is higher than for pions

- Radial flow, hadronization …?

R_{AA} for light and heavy hadrons vs. models

ALICE, JHEP 03 (2016) 081





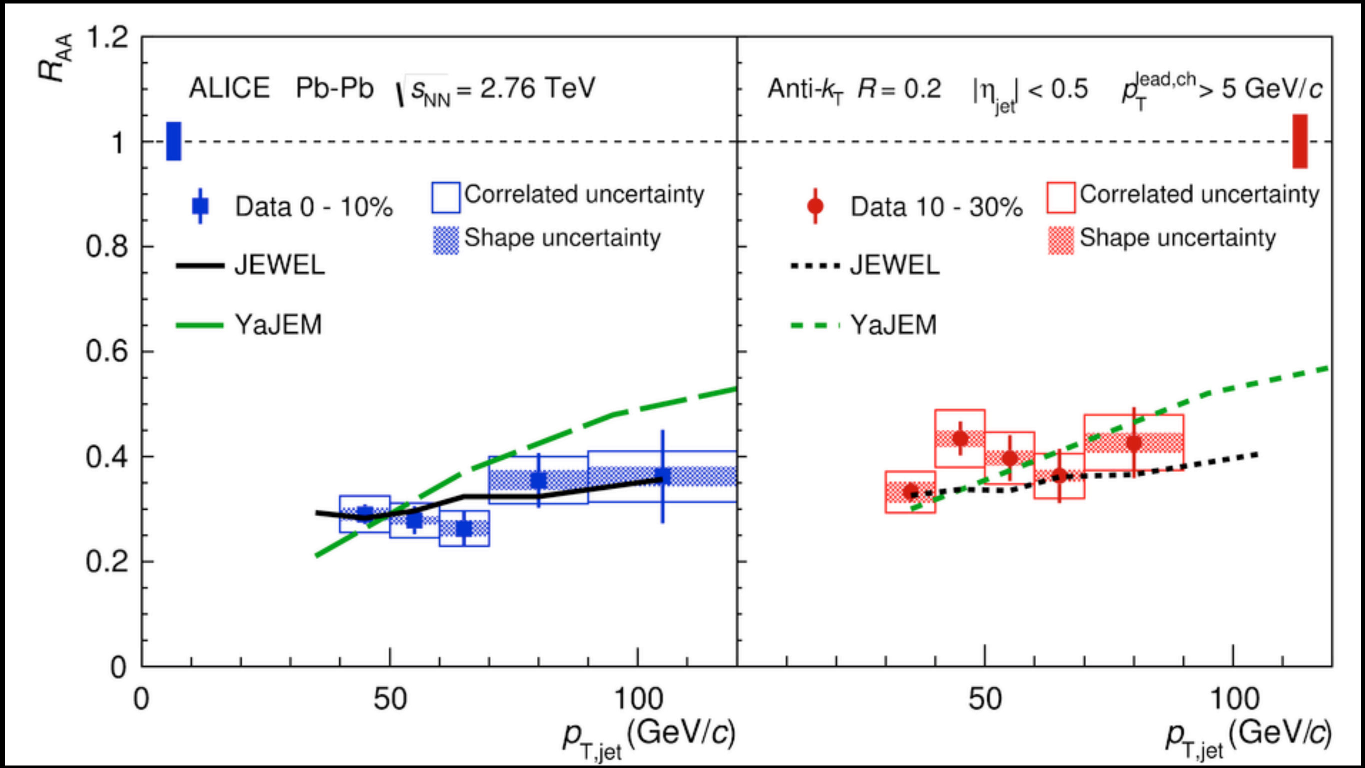
- Djordjevic, CUJET3.0 (hydro) and WHDG models include collisional and radiative parton energy loss
- Vitev model includes radiative parton energy loss and in-medium dissociation process for D mesons

Recent model review A. Andronic et al. Eur. Phys. J. C 76 (2016) 107

NB. The same models underestimate v_2 at high p_T

R_{AA} jets

ALICE, Phys. Lett. B 746 (2015) 1



- Similar suppression to single particle spectra
- JEWEL (elastic+radiative energy loss, Bjorken expanding medium) C. Zapp et al. JHEP03 (2013) 080
- YaJEM (parton showers modified by a medium-induced virtuality + hydro) T. Renk, Phys.Rev. C88 no. 1, (2013) 014905

Summary

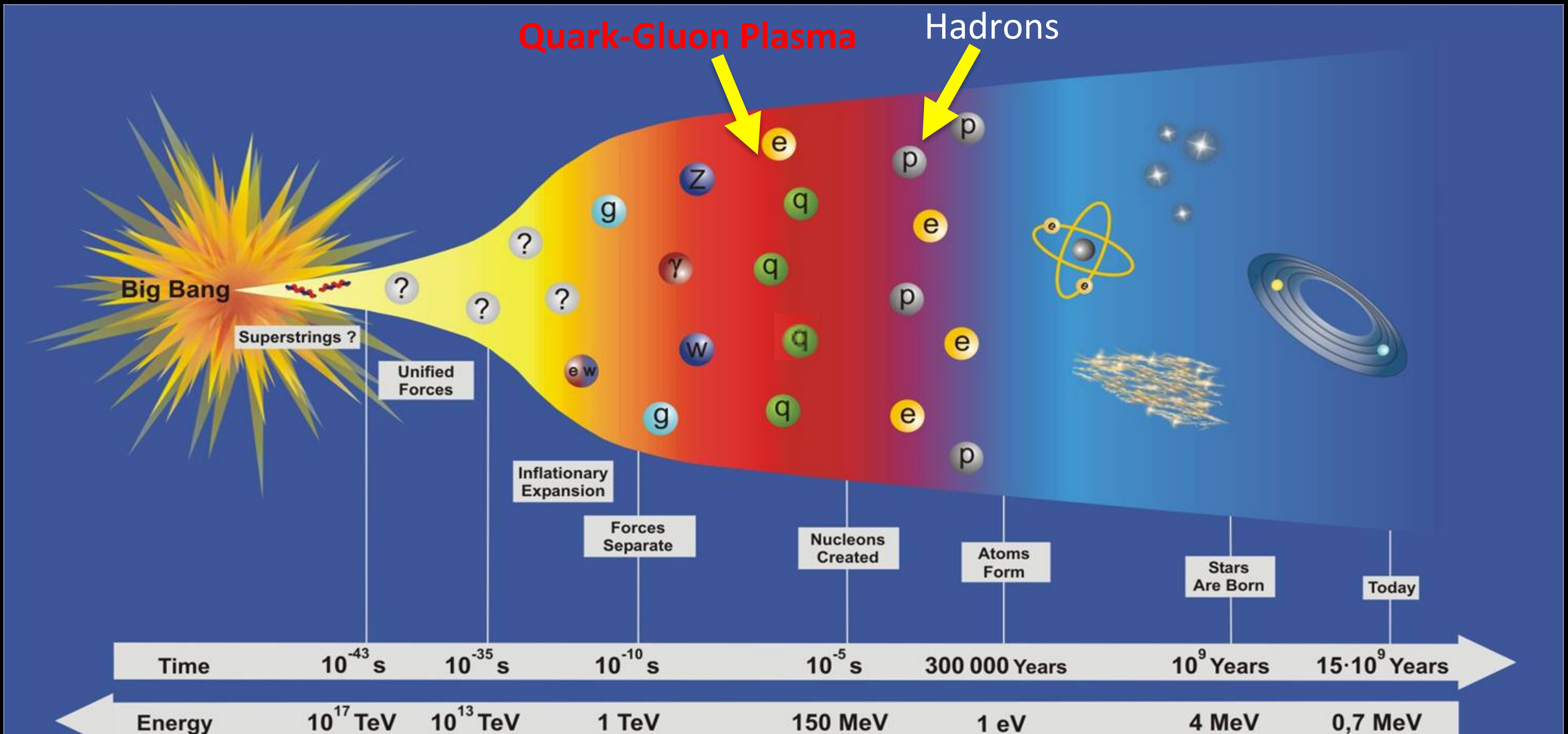
- Particle production follows the power law dependence
  - pp, pA (dA): $\sim s_{NN}^{0.103}$
  - A-A (central): $\sim s_{NN}^{0.155}$
- ~1.2x increase in charged particle multiplicity density from $\sqrt{s_{NN}}$=2.76 TeV to $\sqrt{s_{NN}}$=5.02 TeV independent of event centrality
- Particle production at T_{ch} ~ 155 MeV (from statistical hadronization model)
- Anisotropic flow observables well described by models including hydrodynamic evolution with sheer viscosity
- Sign of smaller suppression of D^{+}s compared to non-strange D mesons at low and intermediate p_T
- Strong suppression of hadron production in Pb-Pb at high p_T compared to pp reference (independent of particle species)
- Similar suppression of high p_T jets and hadrons

Backup

What do we measure?

Properties of nuclear matter formed in the early Universe
Phase transition: hadrons <-> quark-gluon plasma (QGP)
(state of deconfined quarks and gluons)

Time: t = 10 μs after Big Bang!
Temperature: T ~ 10^{12} K



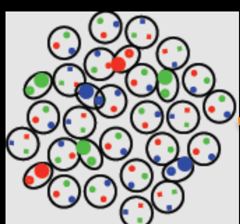
Quantum chromo-dynamics at high temperature

Lattice QCD calculations

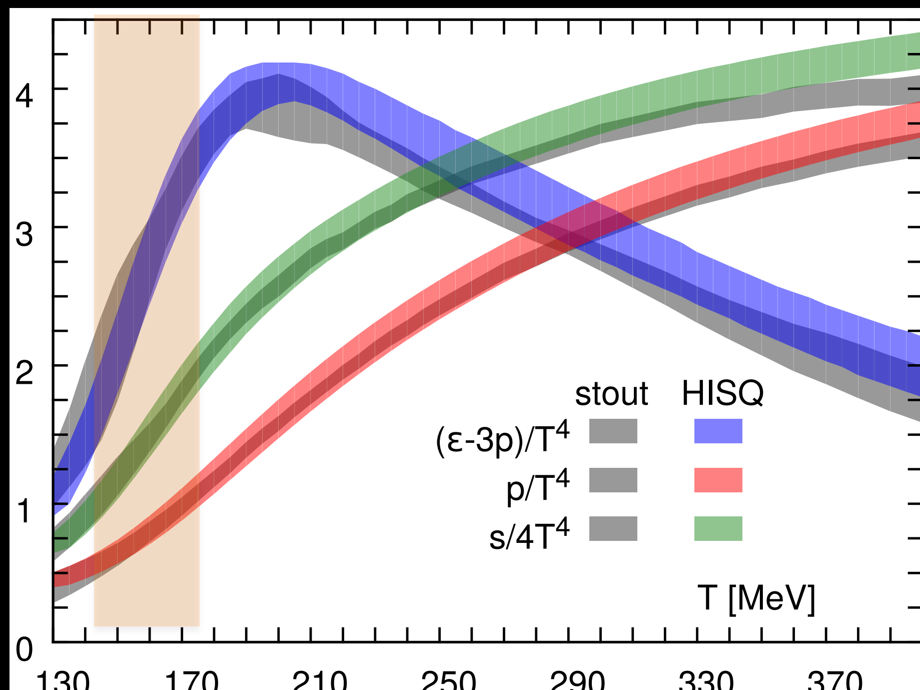
$\mu_B = 0$

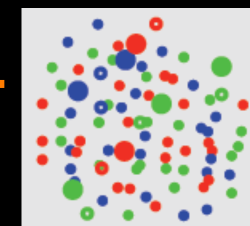
Critical temperature: T_c~155 MeV
Critical energy density: ε_c~1 GeV/fm^3

phase transition (crossover)



few d.o.f → confined (hadrons)

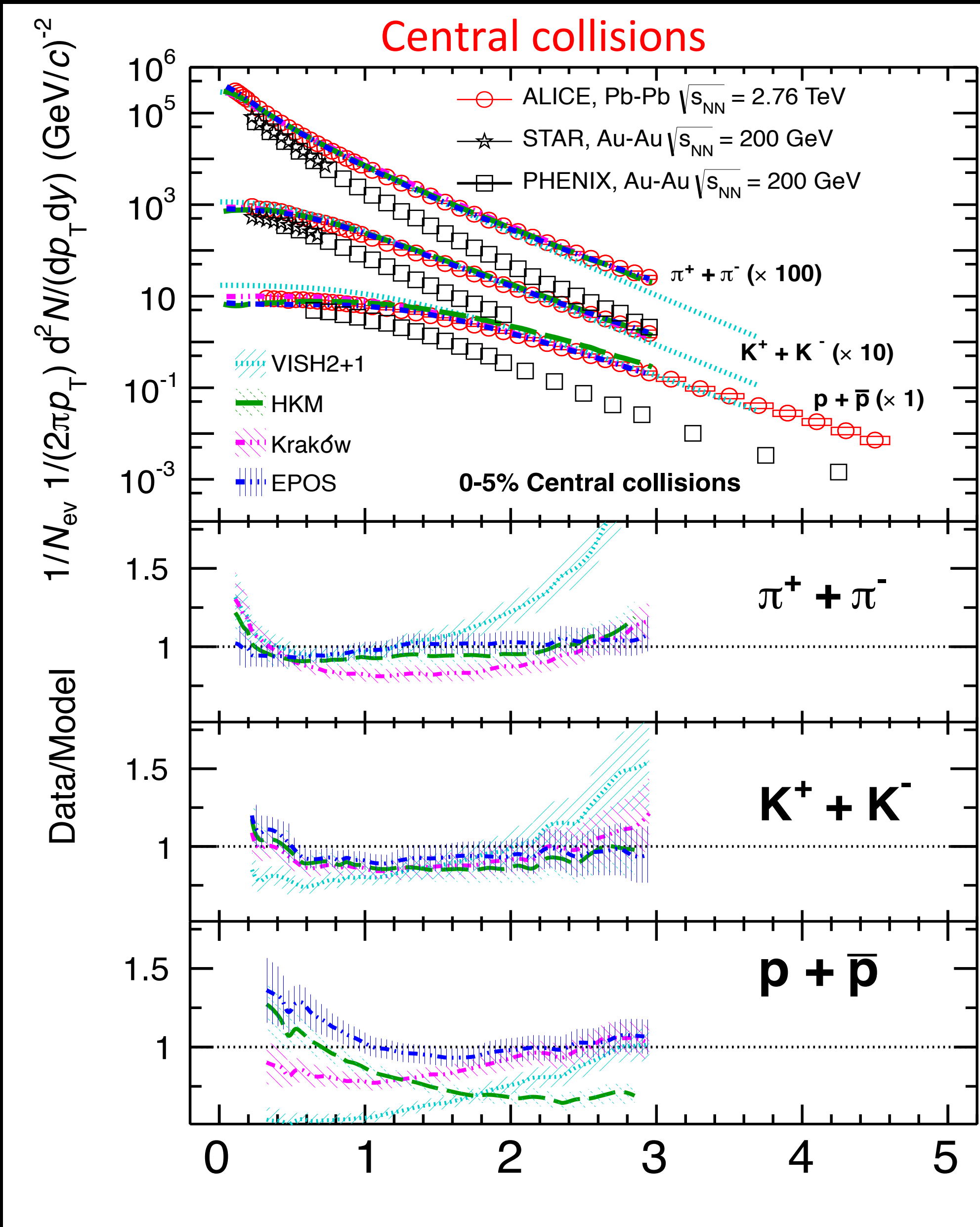




many d.o.f → deconfined (quarks and gluons)

HISQ - A. Bazavov et al. (hotQCD) , Phys. Rev. D90 (2014) 094503
stout - S. Borsanyi et al. (Budapest-Wuppertal), Phys. Lett. B730, 99 (2014)

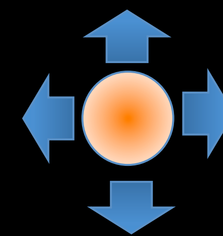
Identified hadron p_T spectra



ALICE, PRC 88 (2013) 044910

p_T spectra (thermal + collective)

From comparison to RHIC and hydrodynamic models
→ large radial flow at the LHC



From blast-wave fit (thermal + collective) to the p_T spectra:

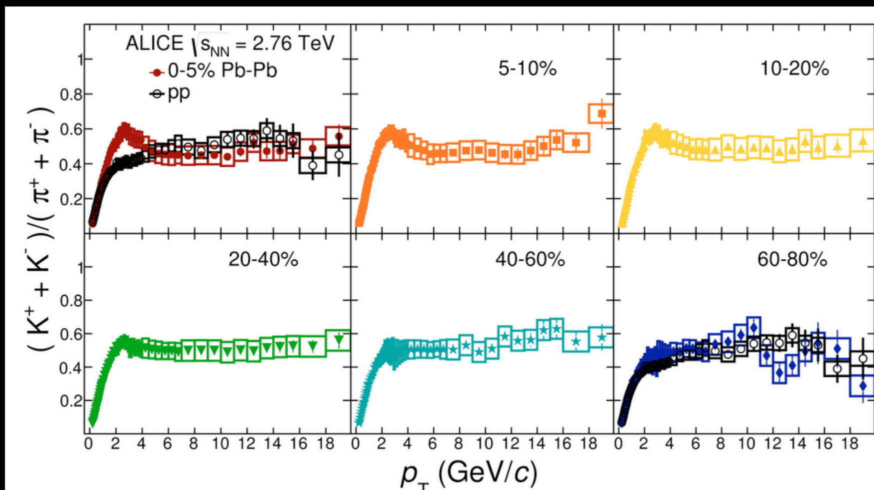
- Kinetic freeze-out temperature:
  T_{kin} ~ 95 MeV (similar to RHIC)
- Radial flow velocity:
  $\langle\beta_T\rangle$ ~ 0.65 c (~10% larger than at RHIC)

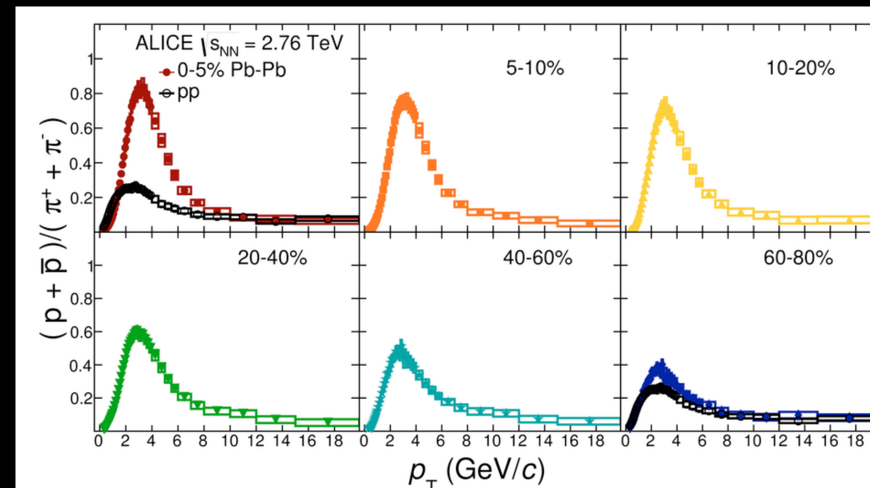
Hydrodynamic models:
- VISH2+1 (viscous hydro)
- HKM (hydro+UrQMD)
- Kraków (viscous corr., lower T_{ch})
- EPOS (hydro+UrQMD)

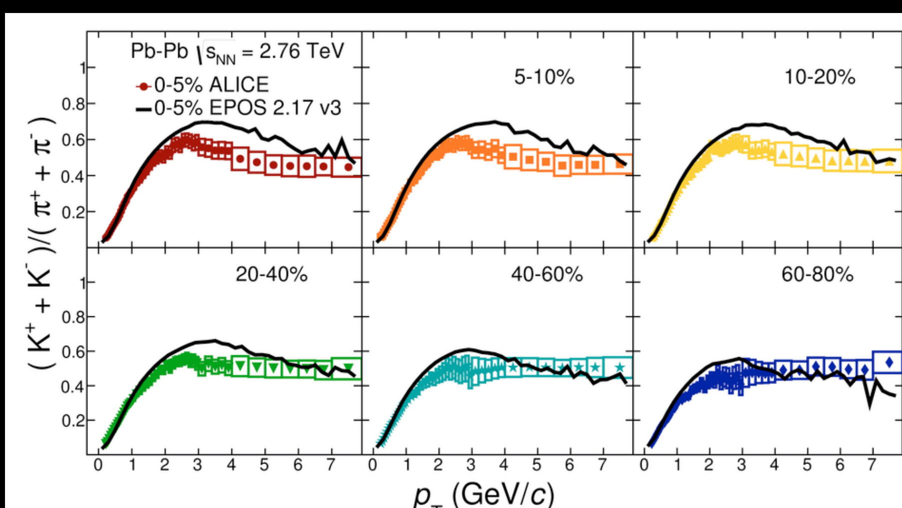
→ Good agreement for central collisions

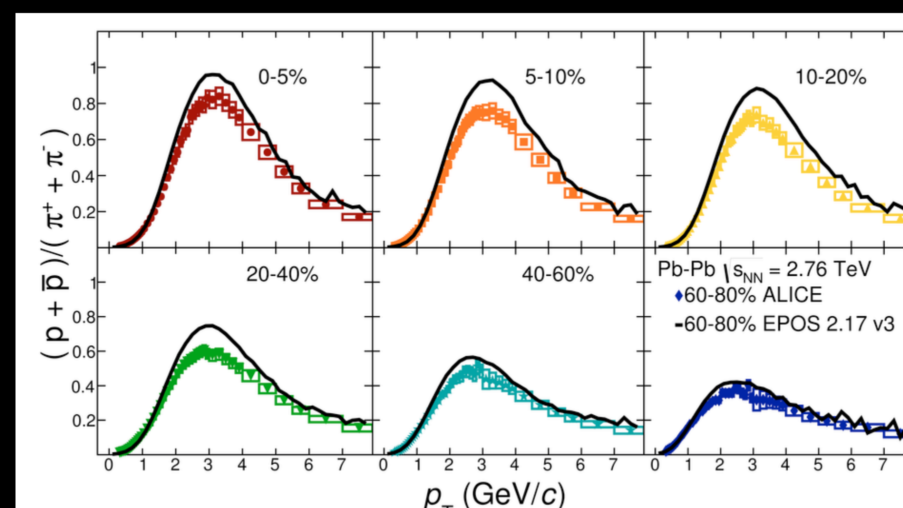
Identified Hadron p_T Spectra

ALICE, Phys. Rev. C 93, 034913 (2016)



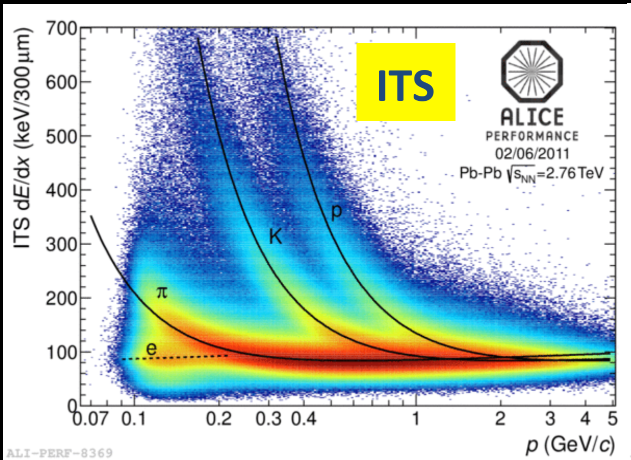


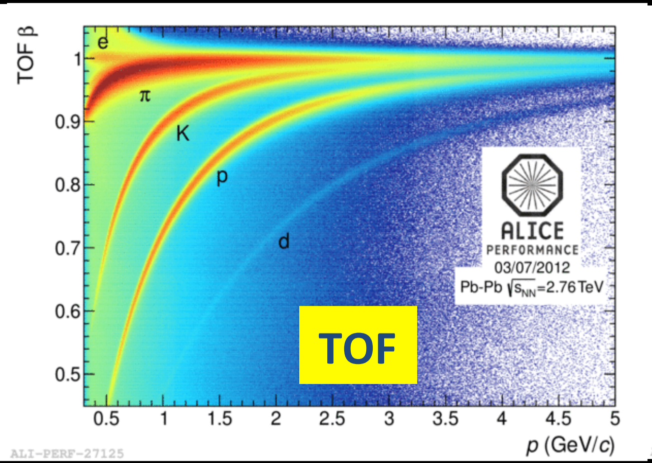


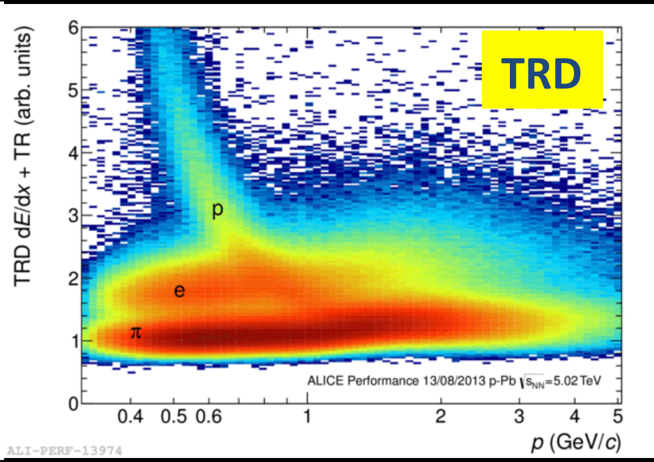


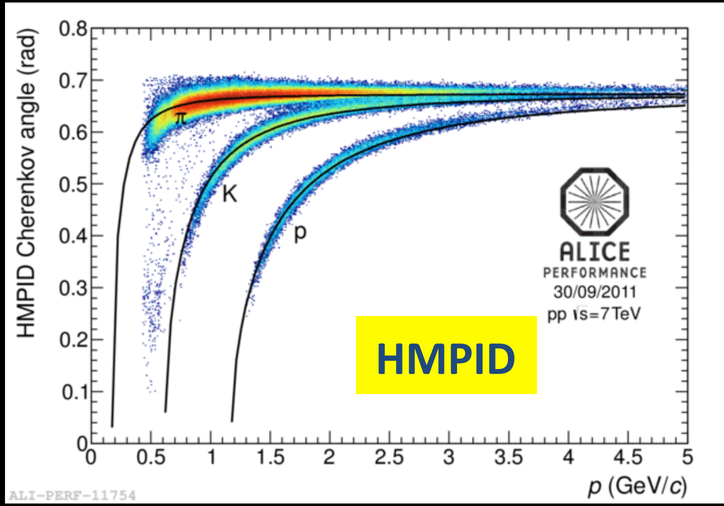
Excellent particle Identification with ALICE

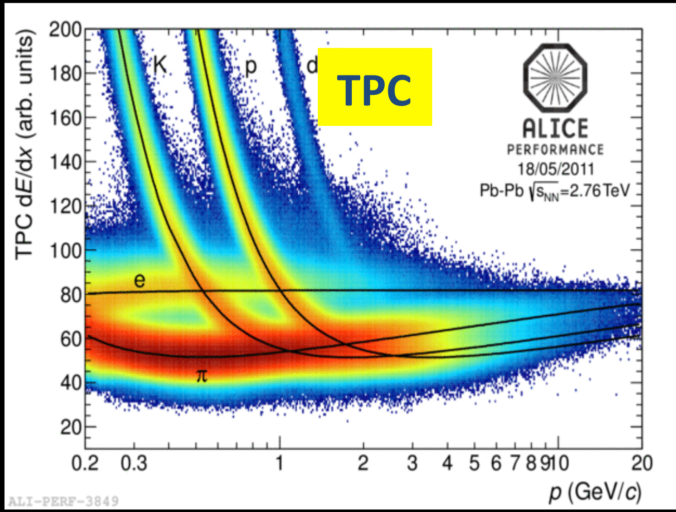
ALICE, Int. J. Mod. Phys. A29 (2014) 1430044



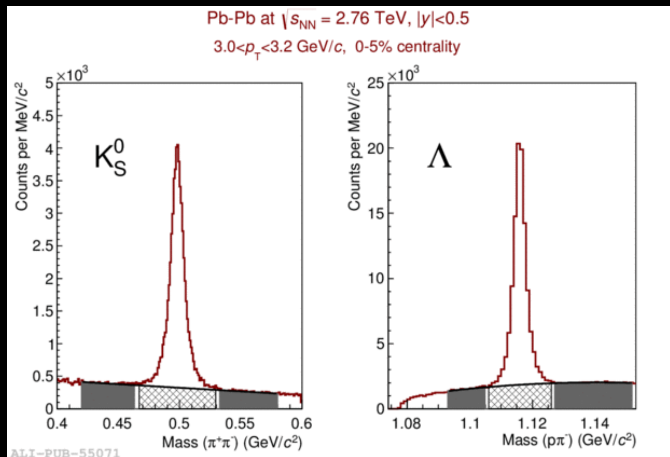


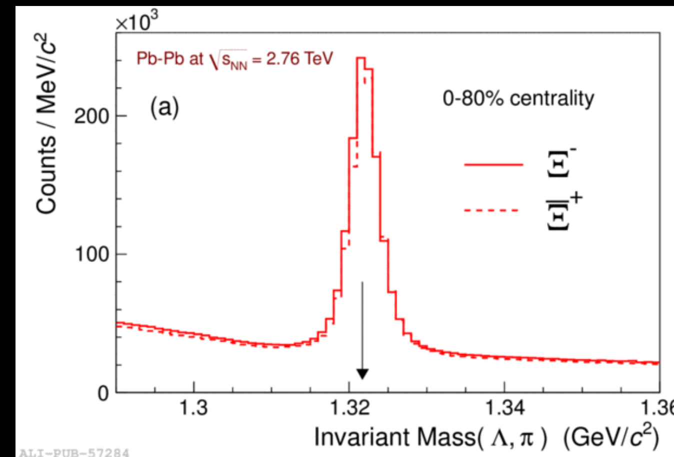


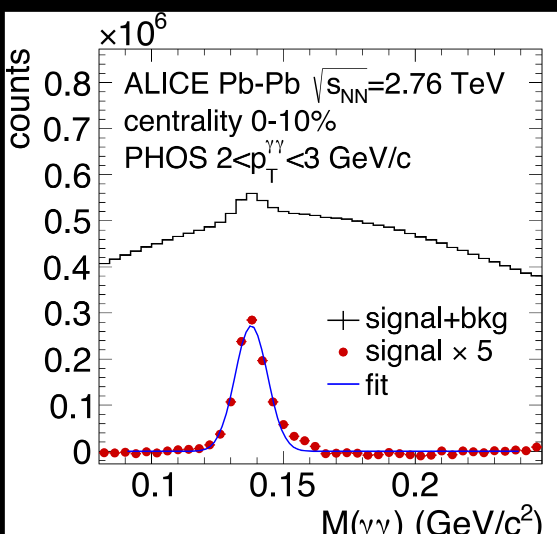


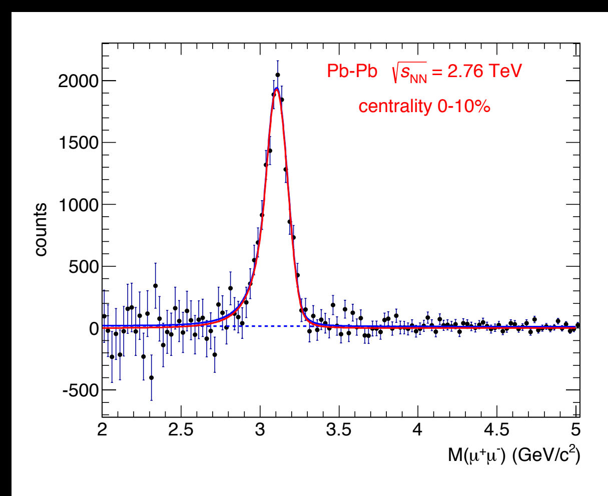


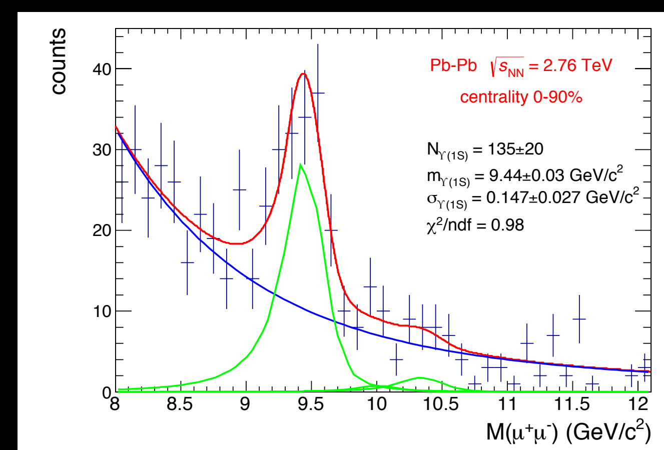
Reconstruction of decayed particles







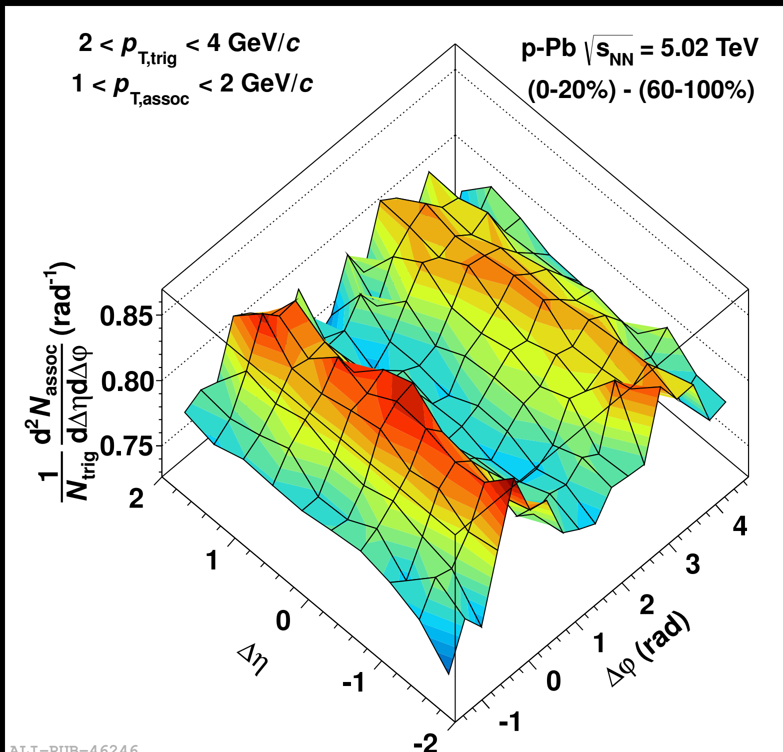




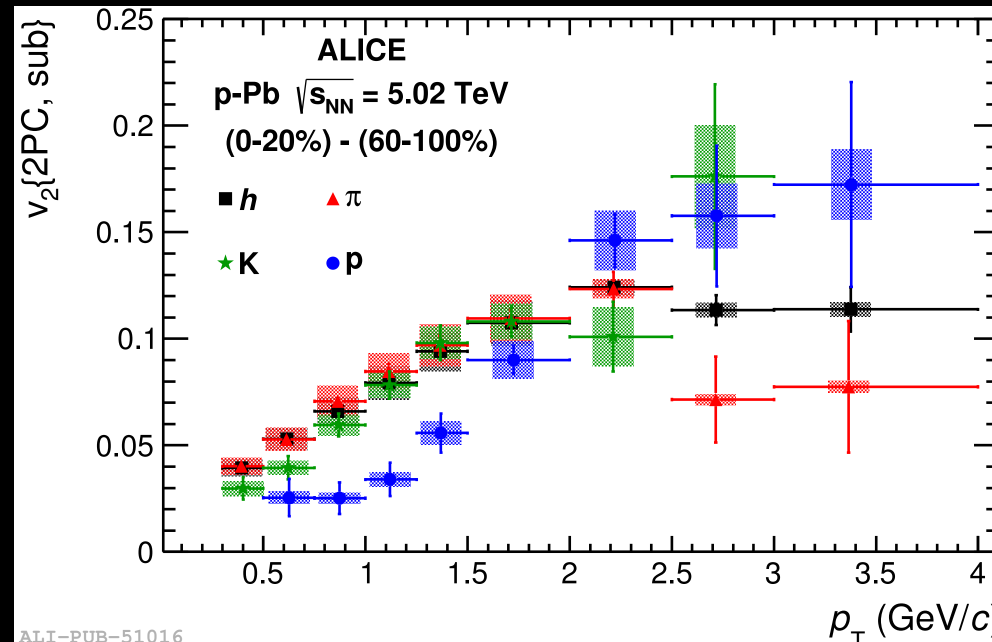
ALICE, Int. J. Mod. Phys. A29 (2014) 1430044

Flow in high multiplicity p-Pb?

ALICE: PLB 719 (2013) 29



ALICE, PLB 726 (2013) 164

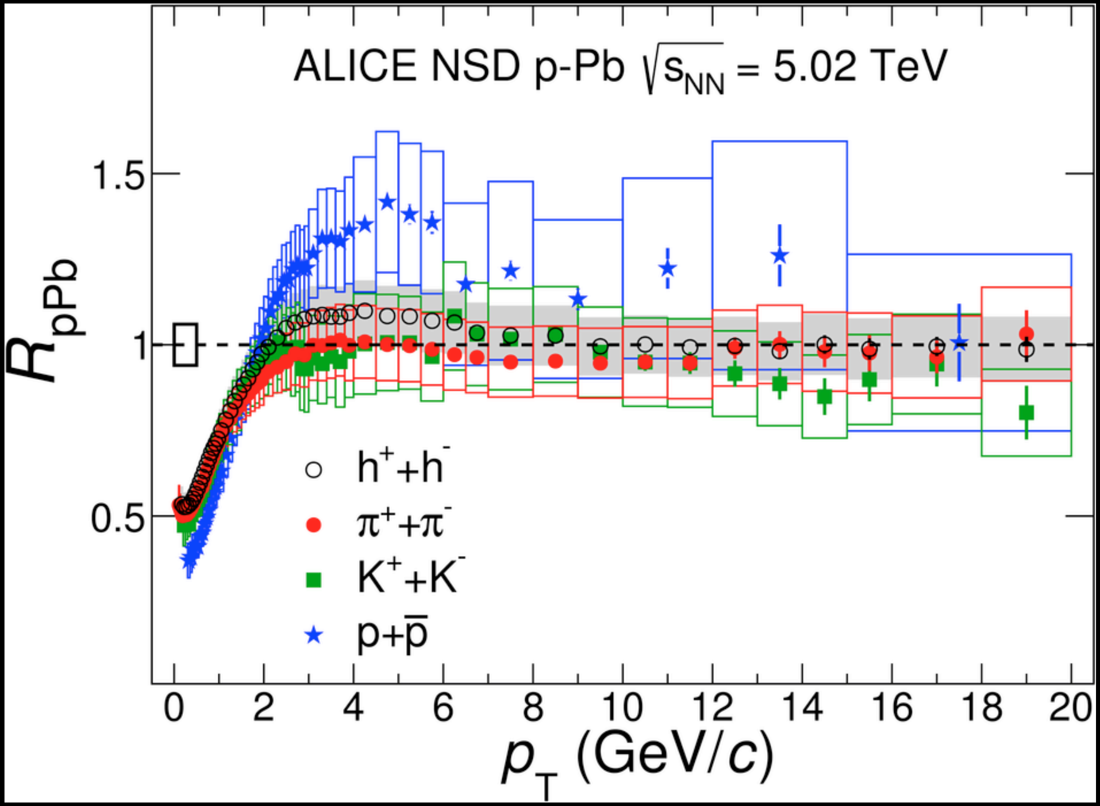


- Double ridge in high multiplicity p-Pb collisions (similar to Pb-Pb)
- v_2 for identified hadrons shows similar pattern to Pb-Pb

→ Indication of flow or other collective phenomenon?

R_{pPb} identified hadrons

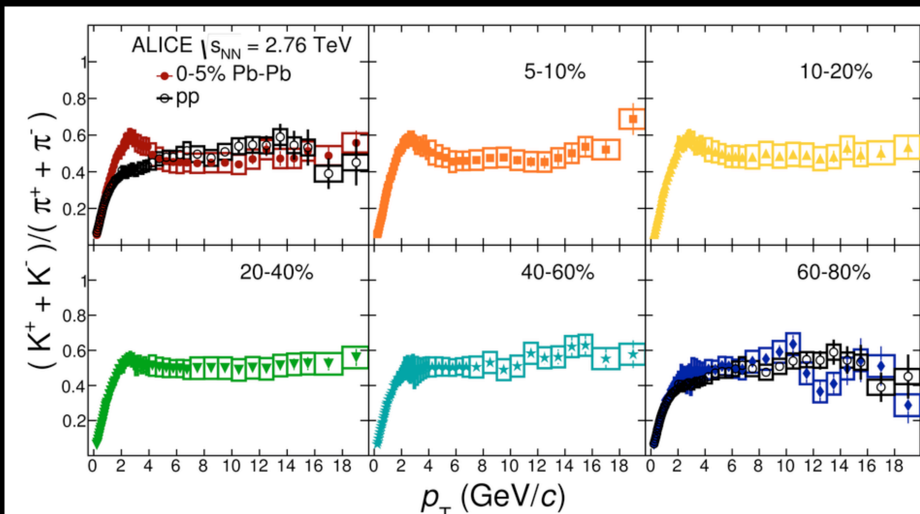
ALICE, arXiv:1601.03658

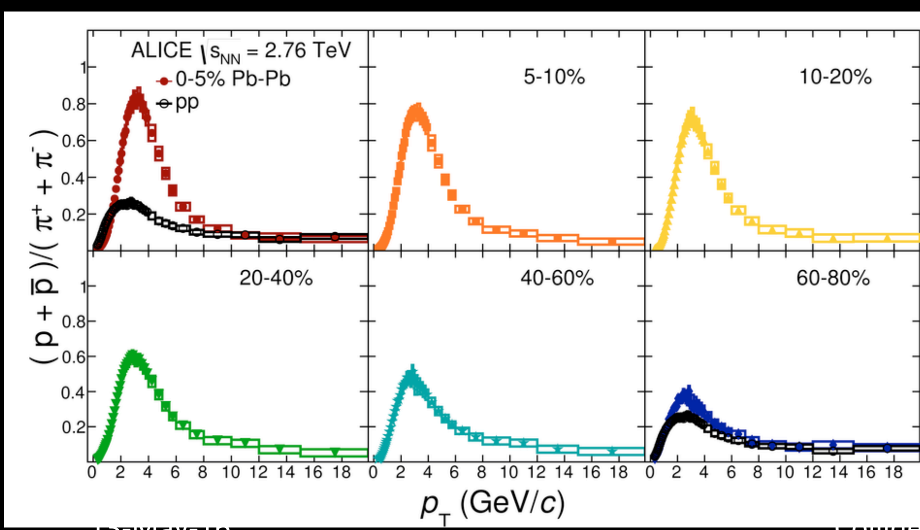


Identified Hadron p_T Spectra

ALICE, Phys. Rev. C 93, 034913 (2016)

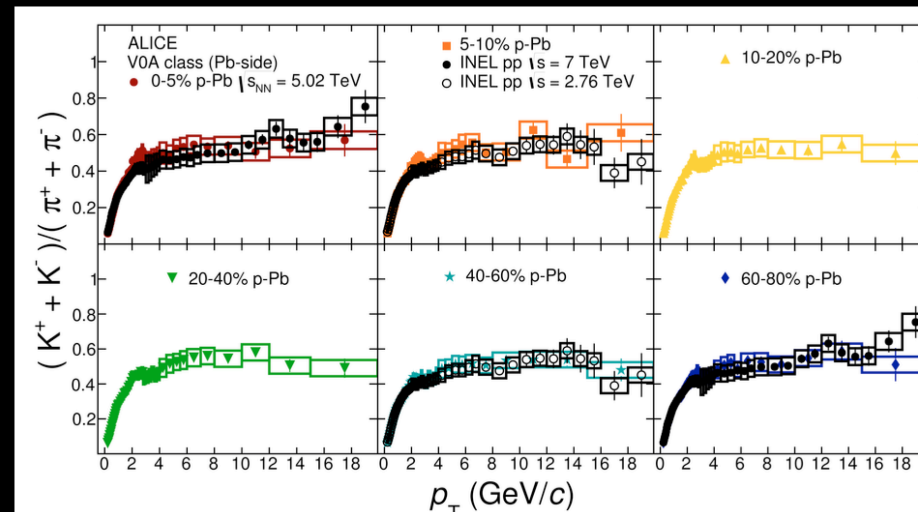
Pb-Pb

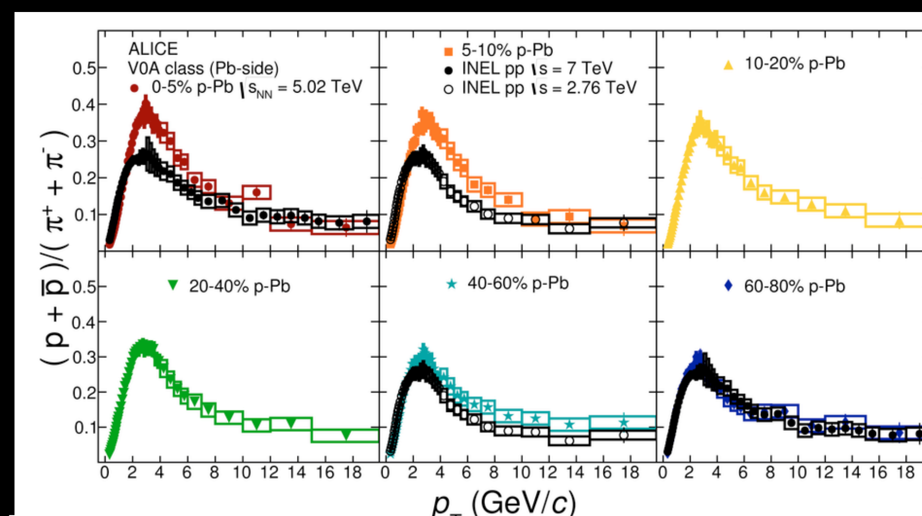




ALICE, arXiv:1601.03658

p-Pb

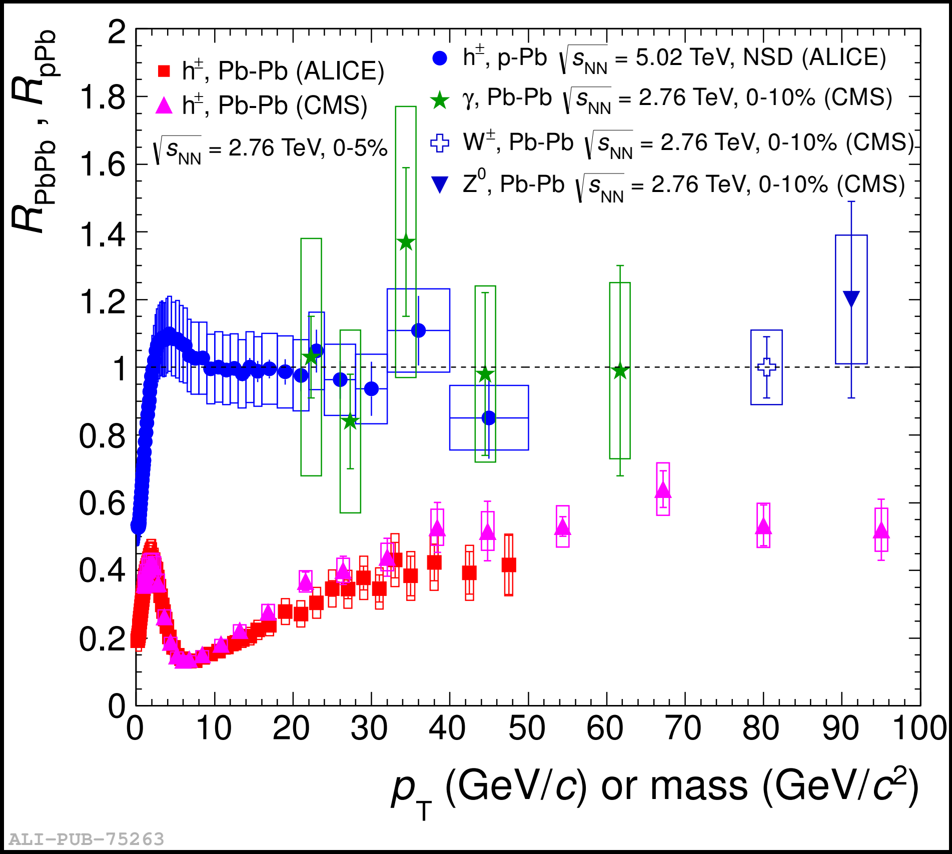




R_{AA} single particles

ALICE, EPJ C 74 (2014) 3054

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



R_{AA} – nuclear modification factor
$T_{AA} = N_{coll} / \sigma_{NN}$
R_{AA} = 1 ⇔ no modification

Particle Production at high p_T > 7 GeV/c

- Strong suppression of charged hadrons in central Pb-Pb collisions (R_{AA} < 0.5)
- No modification for bosons
- No modification for charged hadrons in p-Pb collisions (no centrality selection)

→ suppression is due to final state effects

Note: R_{pPb} in minimum bias collisions

ALICE Pb-Pb data:
Phys. Lett. B 696 (2011) 30-39 (235 citations WoS, the most cited heavy-ion paper from the LHC)
Phys. Lett. B 720 (2013) 52-62

R_{AA} identified hadrons

ALICE, JHEP 03 (2016) 081