ALICE Experimental Overview

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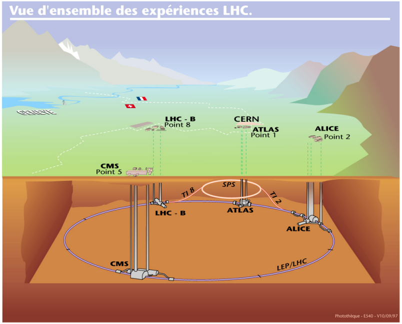
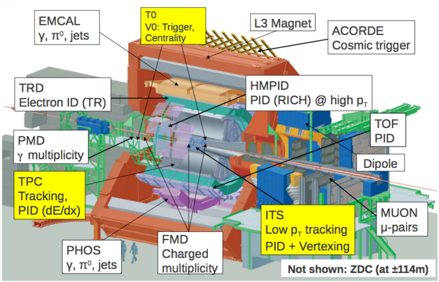
Particle Physics Day, 2017, Helsinki, Finland

UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

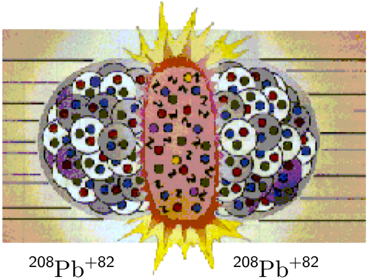
LHC and ALICE Experiment





- 26.659km(R = 4.24km) ring of superconducting magnets.
- They are maintained at 1.9 K (-271.3°C) colder than the 2.7 K of outer space($<$ 2.17 K, fluid $\rightarrow$ superfluid state).
- 26m $\times$ 16m, 10,000 tons
- Efficient low-momentum tracking, down to $\sim$ 100 MeV/c
- Particle identification (practically all known techniques)
- Excellent vertexing capability, Centrality resolution $\sim$ 1%.

QCD at Extreme Conditions



- 10g of lead costs \$12K, ∼ 500mg per fill, ∼ \$2/h.
- Reached an energy of 5.02 TeV per nucleon.

E.V. Shuryak, Phys. Lett. B78, 150(1978)

"Deconfined phase of QCD matter by creating a high density/temperature extended system composed by a large number of quarks and gluons" **Quark-Gluon Plasma**

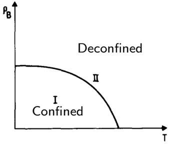


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Cabibbo and Parisi Phys.Lett. 59 B,67(1975)

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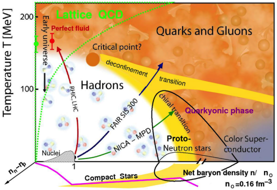
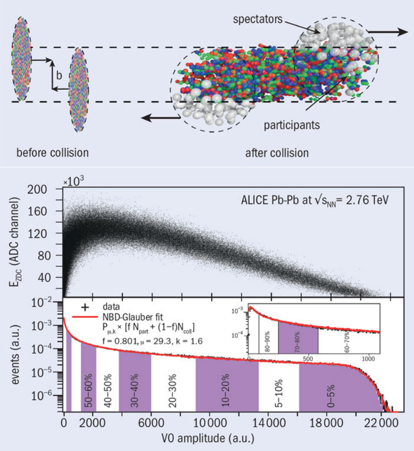
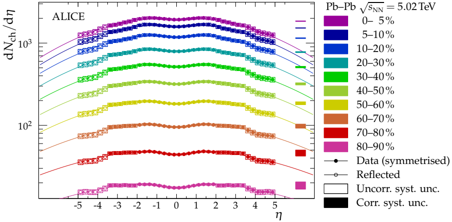


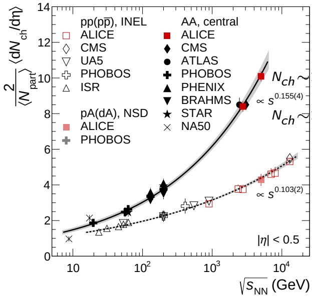
HeavyIon Collisions, Centrality and Particle productions



b=11.4-12.5fm
$N_{part} \sim 53$
$N_{coll} \sim 100$

b=0-3.5fm
$N_{part} \sim 382$
$N_{coll} \sim 1685$

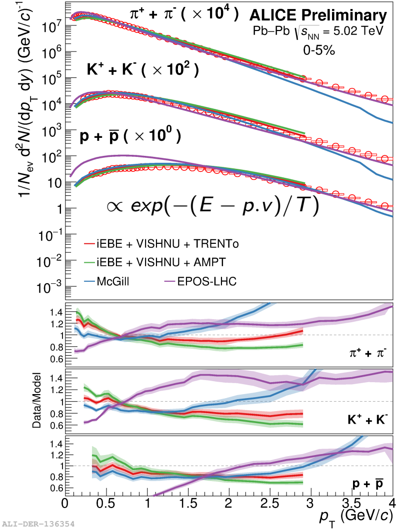


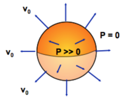


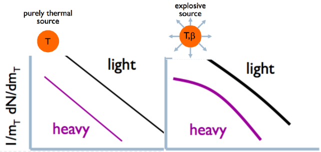
0–5%
$N_{ch} \sim 1943$ at 5.02TeV
$N_{ch} \sim 1584$ at 2.76TeV

ALICE, Phys. Rev. Lett. 116 (2016) 222302

Collective Radial Expansion, Momenta parallel to *v* preferred







Pressure gradient in transverse plane leads to collective **radial** expansion

→

Mass dependent hardening of spectrum
Transverse mass (m_T) **scaling broken**

- more pronounced for the heavier protons than for pions.
- Hydro models work well
- Blast-Wave fits (simplified hydromodel) to p_T spectra, two free parameters:

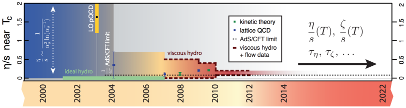
Radial Flow observed $T_{slope} \sim T_{fo} + \frac{1}{2} m v_T$

- Radial flow velocity $< \beta > \approx 0.65$
- Kinetic freeze-out temp. $T_{fo} \approx 90$ MeV

Space-time history of Heavy-Ion Collisions

Initial geometry fluctuations $\rightarrow$ Transport $\delta_\mu T^{\mu\nu} = 0$ (η/s) $\rightarrow$ final-state particles

Ideal hydrodynamics   Viscous hydrodynamics(η/s=0.16)

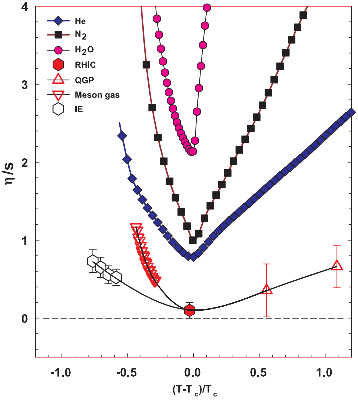


LO pQCD: P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051
AdS/CFT: P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601
Lattice QCD: A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305
H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C
Ideal hydro: P. F. Kolb, J. Sollfrank, U. W. Heinz, Phys.Rev. C62 (2000) 054909
P. F. Kolb, P. Huovinen, U. W. Heinz, H. Heiselberg, Phys.Lett. B500 (2001) 232-240
pQCD/kin. theory: Z. Xu, C. Greiner, H. Stöcker, Phys.Rev.Lett. 101 (2008) 082302
J.-W. Chen, H. Dong, K. Ohnishi, Q. Wang, Phys.Lett. B685 (2010) 277-282
Viscous hydro: P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915
H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033
H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev.Lett. 106 (2011) 192301

"String theory (AdS/CFT correspondence) finds $\eta/s \sim 1/4\pi$ a strongly coupled conformal theory $\rightarrow$ hints at a lower bound of that order."

Can we measure or estimate Transport property of QGP ?

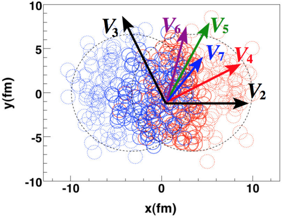
Initial geometry fluctuations → Transport $\delta_\mu T^{\mu\nu} = 0$ ($\eta/s(T)$) → final-state particles

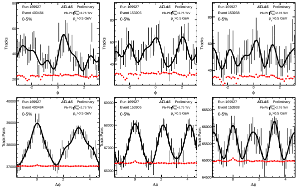


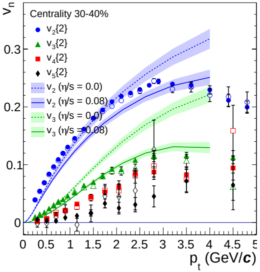
- He, N_2 and $\mathrm{H}_2\mathrm{O}$: taken from L. P. Csernai, J. I. Kapusta, and L. D. McLerran, Phys.Rev.Lett. 97, 152303 (2006)
- T$<T_c$: chiral perturbation theory with free cross sections, J.-W. Chen and E. Nakano, Phys.Lett.B647:371-375,2007
- T$>T_c$ and $T_c \approx$ 170 MeV : lattice QCD simulations, A. Nakamura and S. Sakai, Phys.Rev.Lett. 94, 072305(2005)

"It is argued that such a low value is indicative of thermodynamic trajectories for the decaying matter which lie close to the QCD critical end point.", R. A. Lacey et al., Phys. Rev. Lett. 98, 092301 (2007).

Higher Flow Harmonics Seen by All Experiments



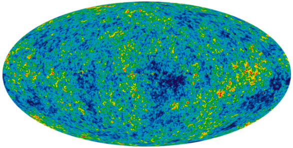


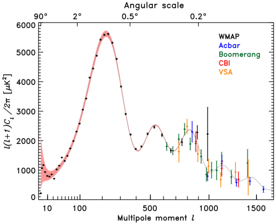


$$P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi}$$

$$V_n \equiv v_n\{\psi_n\} e^{in(\psi_n - \phi)}$$

$$v_n \equiv v_n\{\psi_n\} = \sqrt{\langle |V_n|^2 \rangle}$$

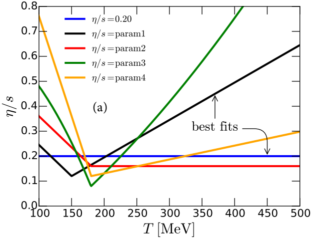


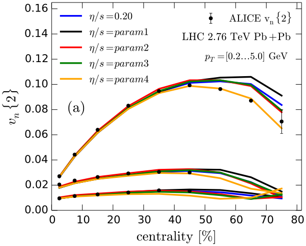


- Like measurements of early universe sound harmonics
- Heavy Ion harmonics measured give key constraints on viscous damping and initial spatial correlations

Correlations of v_m and v_n, $SC(m,n)=\langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle$

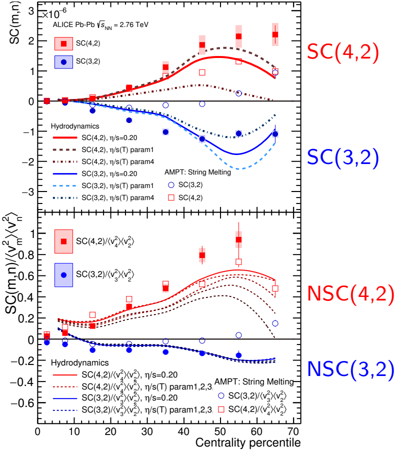
Hydrodynamics H. Niemi,K.J. Eskola,R.Paatelainen (Phys. Rev. C 93, 024907 (2016))





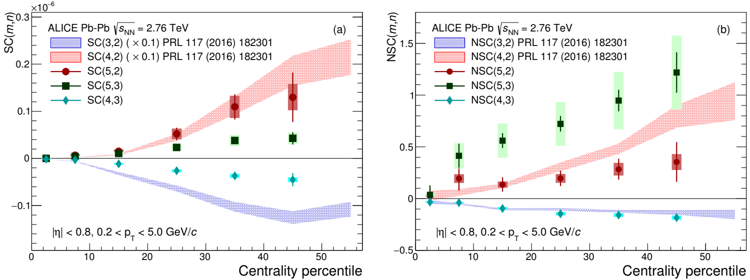
ALICE Phys. Rev. Lett. 117, 182301 (2016)

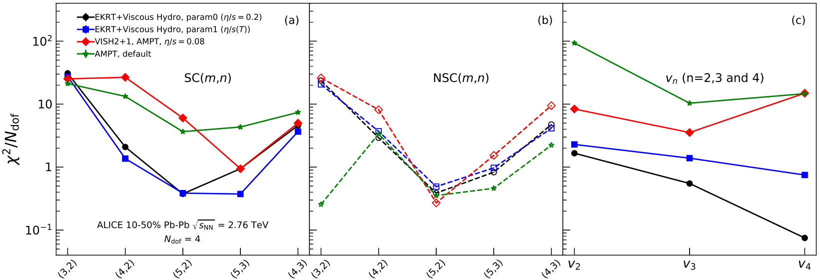
$NSC(m,n)=SC(m,n)/\langle v_m^2\rangle\langle v_n^2\rangle$



- Strong constraint on the $\eta/s(T)$ in hydrodynamic models.

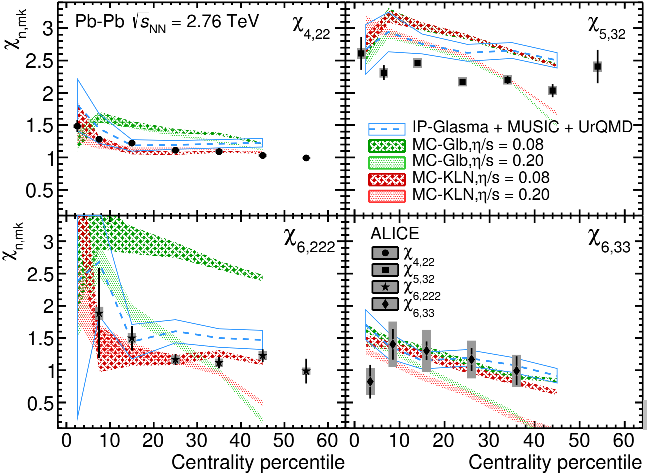
Strong Constraints for $\eta/s(T)$ and the initial conditions.





ALICE, arXiv:1709.01127

Quantifying Non-linear Hydrodynamic response, Jasper Parkkila's Talk



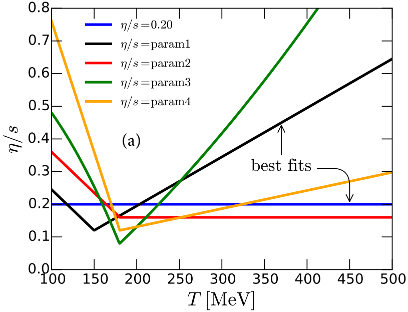
Phys.Lett.B773(2017)68-80

$$\chi_{4,22} = \frac{v_4\{\Psi_2\}}{\sqrt{\langle |V_2|^4 \rangle}}, \quad \rho_{4,22} = \frac{v_4\{\Psi_2\}}{v_4\{\Psi_4\}}$$

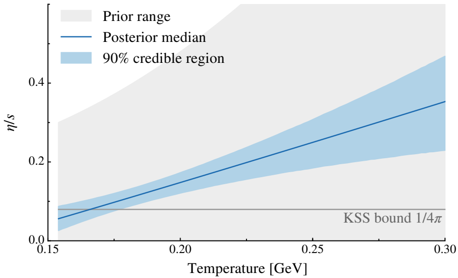
$$\chi_{5,23} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle |V_2|^2 |V_3^2| \rangle}}, \quad \rho_{5,23} = \frac{v_5\{\Psi_{23}\}}{v_5\{\Psi_5\}}$$

Implications of the flow measurements

H. Niemi, K.J. Eskola, R.Paatelainen(Phys. Rev. C 93, 024907 (2016))

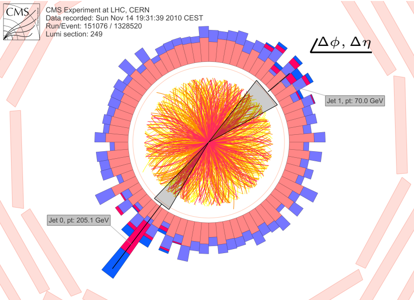


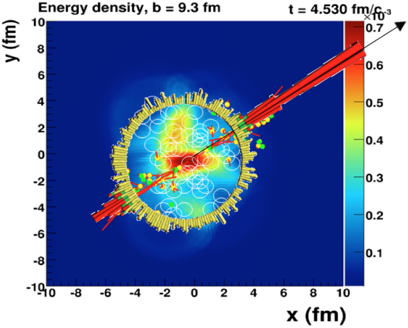
Steffen A. Bass et. al, Global Bayesian Analysis (arXiv:1704.07671)



- Best η/s(T) seems to indicate $\eta/s \approx 0.12$ around $T_c \approx$150 MeV, even less ?
- η/s(T) can be constrained further, new observables with v_n have discriminating power in separating the effects of $\eta/s(T)$ from the initial conditions.
- They are sensitive to the interaction of the constituents in the medium, sensitive to any angular distortion.

Di-Jet, Jet quenching can be seen visually



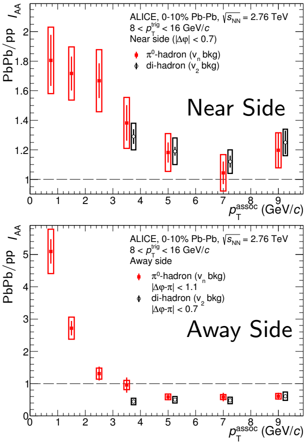


Hydrodynamics + Dijet

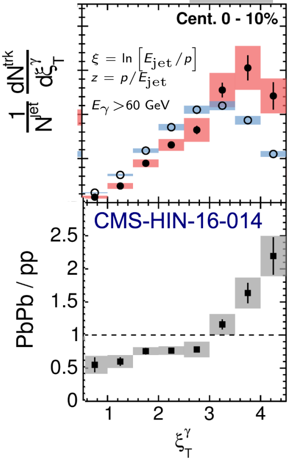
- It had been thought that Jet reconstruction would be impossible in LHC or difficult in heavy ion collisions.
- It had been shown that it is feasible and we can see a clear away side jet suppression for this special event (Jet Quenching in QGP).
- Thanks to the kinematic for LHC, however, most of the measurements were done with very hard events ($p_{T,1} > 120$ GeV$/c$, $p_{T,2} > 50$ GeV$/c$) .

Medium induced gluon radiation is Observed and Quark/Gluon suppression

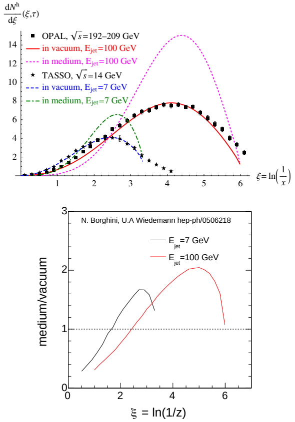
ALICE, PLB 763 (2016) 238-250



CMS γ-Jet



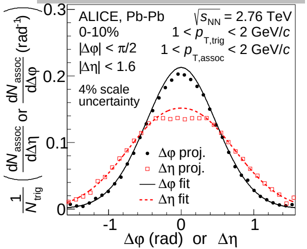
N. Borghini, U.A Wiedemann hep-ph/0506218

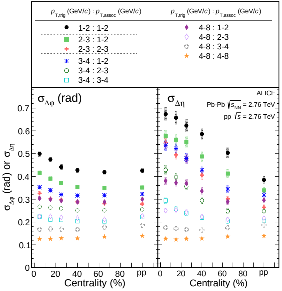


- The ratio of PbPb to pp at low $p_T \approx \times 2 \rightarrow$ Enhancement
- Medium induced gluon radiation is Observed !!!
- Intermidiate p_T or z regions, effective guark/gluon contribution $\approx \times 1/2 \rightarrow$ Suppression

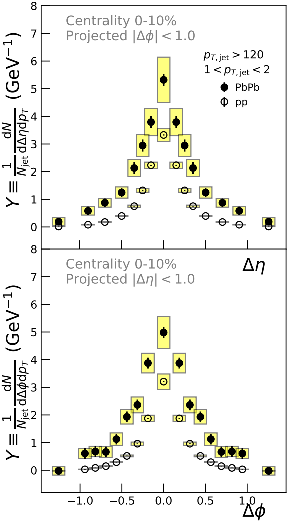
Broadening of the jet, Narrowing because of Quark/Gluon suppression

ALICE, Phys.Rev.Lett. 119 (2017) 102301

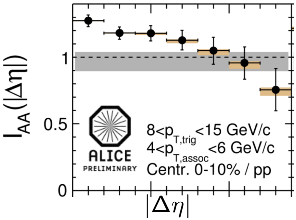


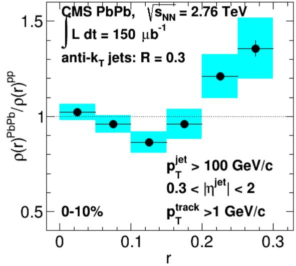


CMS, JHEP 02 (2016) 156



ALICE Preliminary

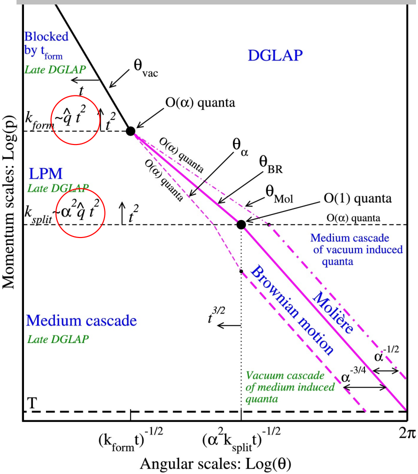




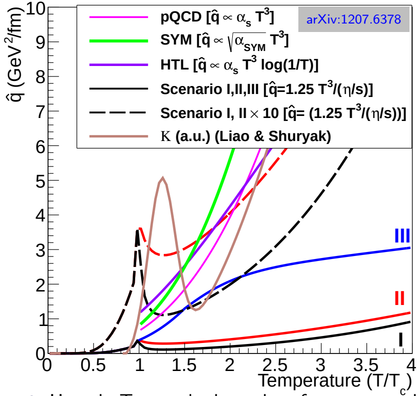
CMS, Phys. Lett. B 730 (2014) 243

Data permit a model independent, quantitative assessment?

A. Kurkela, U. A. Wiedemann, Phys.Lett. B740 (2015) 172-178



- constituents of medium accessible via large angle scattering



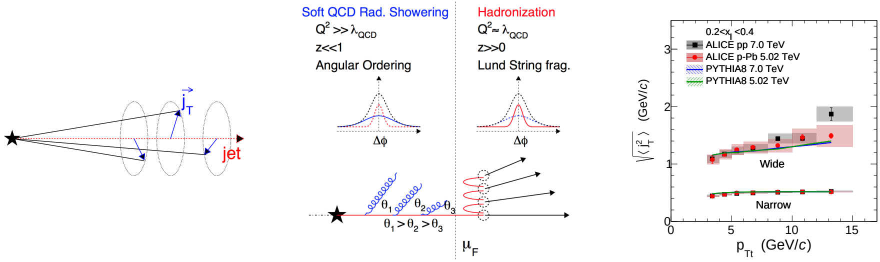
- How do T or scale dependent features translate to final state ?
- Medium influence becomes significant as virtuality of parton shower and medium become comparable.
- An unambiguous determination of both sides of [the equation] from experimental data ? (Phys. Rev. Lett., 99:192301, 2007)

$$\frac{\eta}{s} \left\{ \begin{array}{c} \approx \\ \gg \end{array} \right\} 1.25 \frac{T^3}{\hat{q}} \quad \left\{ \begin{array}{l} \text{for weak coupling,} \\ \text{for strong coupling.} \end{array} \right. \Leftarrow$$

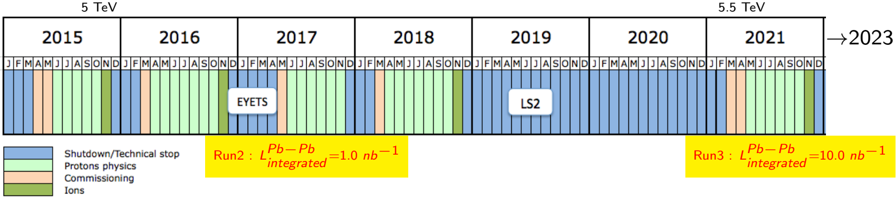
Experimental points of view ?

- Precision data for jet and di-hadron down to low p_T and to larger angle.
- Better understanding from Theory side is essential.
- Still have to see Shock Wave, a flow flux behind the propagating partons, if η/s is small enough.
- What about Bulk viscosity (ζ/s) ? (Phys. Rev. Lett. 115, 132301 (2015))

- One of the Experimental tools developed
  - QCD showering can be seperated from hadronization (Two component j_{T} - Jussi Viinikainen(two particle correlation), Tomas Snellmann(Jet) p–p and p–Pb)
  - QCD showering(wide) in Pb–Pb (angular ordering → anti-angular ordering)



ALICE Upgrade for Run3 and Beyond



Run2 : $L_{integrated}^{Pb-Pb}$=1.0 nb^{-1}

Run3 : $L_{integrated}^{Pb-Pb}$=10.0 nb^{-1}

FI⇒ Global observables.......
FI⇒ Light hadrons...............
Strange hadrons..........
Quarkonia....................
Open heavy flavours....
Electromagnetic probes
FI⇒ Jet and high p_T hadrons
Hypernuclei..................

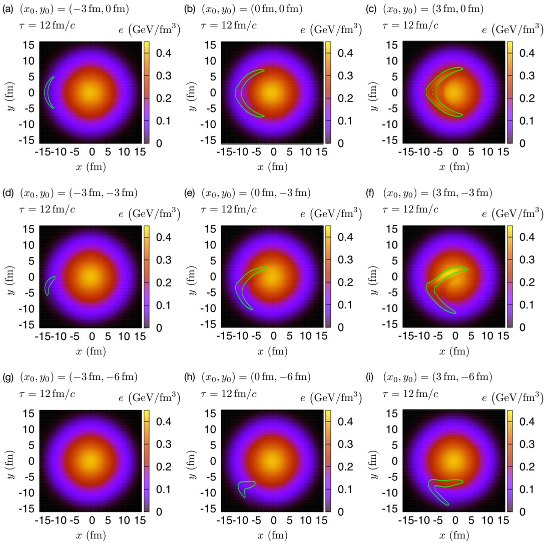
Better Significance:
- PbPb 50 kHz
- New RO electronics
- New TPC RO chambers ⇐FI
- ITS Upgrade (high-resolution, low-material, 2SPDx2SDDx2SSD)
- New Computing req.

New observables:
- ITS upgrade
- MFT tracker
- FoCal (2024)?

FI⇒ upgrade of the forward trigger detectors(FIT) and ZDC

- x10 with respect to Run 2, but actually x100 in minimum bias Pb-Pb collisions.

Mach cones in viscous heavy-ion collisions



T. Hirno et. al Phys. Rev. C 93, 054907 (2016)

- For small η/s, the formation of Mach cones can be proven.
- Radial flow changes the effective angle of a Mach cone.
- The geometrical relation between the jet production point and the medium.
- An idea at 12th high pT workshop in Bergen 2-5 Oct 2017(D. J. Kim, "Probing Soft-Hard Interactions in Heavy Ion Collisions-Return of the Mach Cone")

Summary

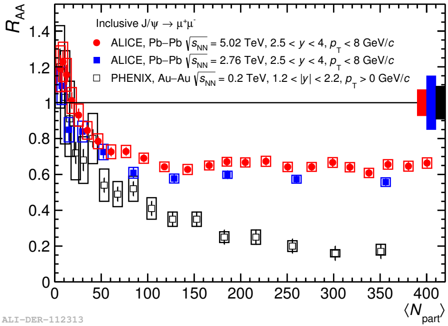
- Precision measurements on flow observables
  - Higher precision data on v_n become "Run"-ly routine.
  - The Symmetric Cumulants and the nonlinear mode of higher harmonic flows have different sensitivities to the initial conditions and the system properties. $\rightarrow$ Strong constraint on the η/s(T)
- Jet Quenching
  - Medium induced gluon radiation is observed and guark/gluon suppression can be accessed via experimental data.
  - Broading of jet is clearly observed.
  - Precision data to lower momemtum jet and hadrons and to larger angels.
  - Better understading on the theory side is essential to explore the quenching parameter $\hat{q}(T)$ quantitatively.
- ALICE is being ready for the future.
  - Upgrade will be prepared during LS2 to fully exploit the higher rate and to improve the physics performance.
  - Analysis on Soft-Hard interaction will give better insights or understandings on η/s(T) and $\hat{q}(T)$, relating them.

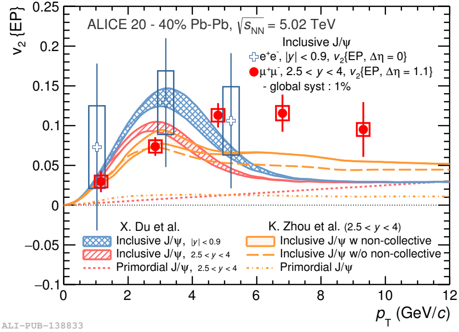
From Discovery via Precision to Dynamical Understanding

Kiitos!

Long waited J/ψ Suppression and Regeneration?

Bound states of $c\bar{c}$ and $b\bar{b}$ can be Debye color screened in the QGP as one increases the temperature (melting)



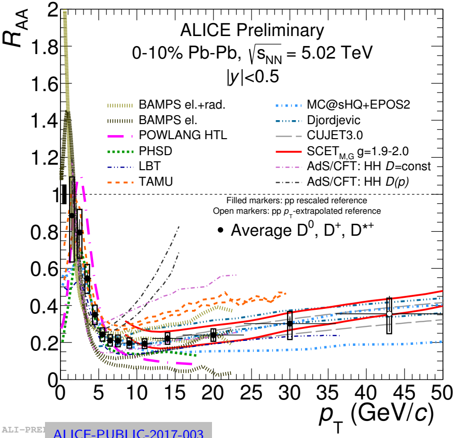


ALICE, Phys.Lett. B766 (2017) 212-224

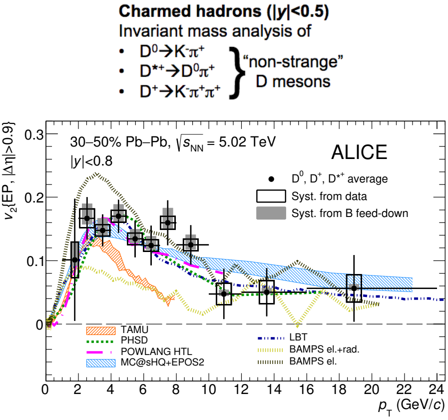
ALICE, arXiv:1709.01127

- Huge improvement on the measurements in LHC.
- Regeneration is more dominant in LHC energies.
- Regeneration gives rise a significant v_2 while Primordial J/ψ give minimal effect.

Mass dependence, $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$



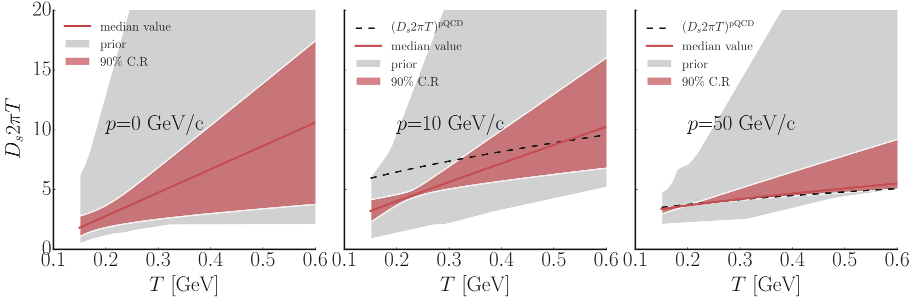
ALICE-PUBLIC-2017-003

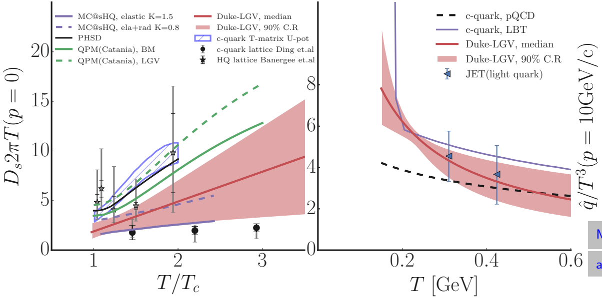


ALICE, arXiv:1707.01005

- Strong suppression of high p_T D-meson production in central Pb-Pb collisions.
- Similar for 2.76 TeV and 5 TeV.
- Strong constraints for models, Run1 2.76 TeV data were used for a Bayesian model-to-data analysis.

Global anaysis and Uncertainty in Theory, utilizing heavy flavor data

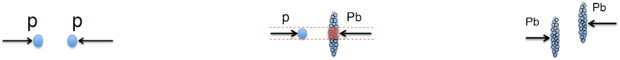




M. Nahrgang, S. A. Bass et. al.

arXiv:1710.00807

Small Sytems?



- Small Systems
  - Small systems still might have QGP phase.
  - Experimental Challenges
    - No clear evidence of jet quenching yet in pPb.
    - Possible to observe thermal photons?
    - Possible to discriminate flow and non-flow or suppress non-flow?
  - Theoretical Challenges
    - but smaller volume and shorter lived...
    - applicability of fluid dynamics (too large $Kn = \lambda/L$ for pPb even with small QGP $\eta/s = 0.08$)?