Overview of heavy ion physics at ALICE

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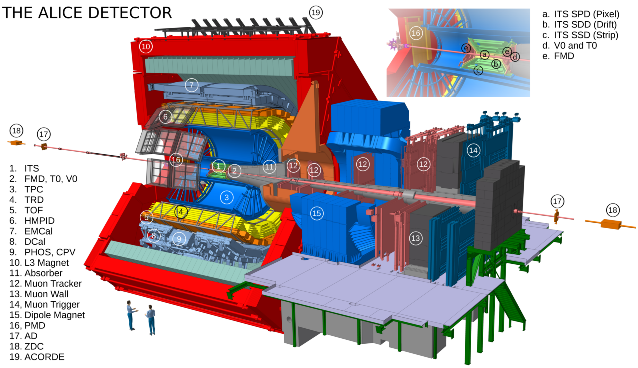
XXV Cracow EPIPHANY Conference on Advances in Heavy Ion Physics

UNIVERSITY OF JYVÄSKYLÄ

ALICE

HELSINKI INSTITUTE OF PHYSICS

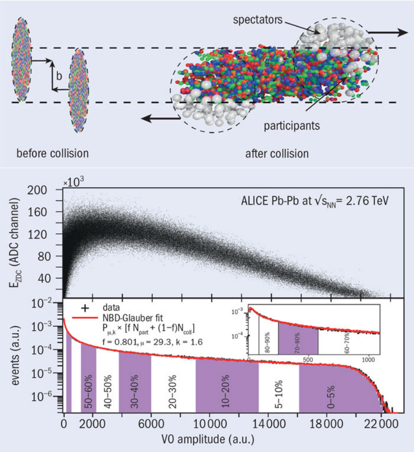
ALICE Experiment



Run 1 (2009-2013)		
pp	0.9 TeV	~ 200 μb^{-1}
	2.76 TeV	~ 100 nb^{-1}
	7.0 TeV	~ 1.5 pb^{-1}
	8.0 TeV	~ 2.5 pb^{-1}
p-Pb	5.02 TeV	~ 15 nb^{-1}
Pb-Pb	2.76 TeV	~ 75 μb^{-1}
Run 2 (2015-2018)		
pp	5.02 TeV	~ 1.3 pb^{-1}
	13 TeV	~ 25 pb^{-1}
p-Pb	5.02 TeV	~ 3 nb^{-1}
	8.16 TeV	~ 25 nb^{-1}
Xe-Xe	5.44 TeV	~ 0.3 μb^{-1}
Pb-Pb	5.02 TeV	~ 1 nb^{-1}

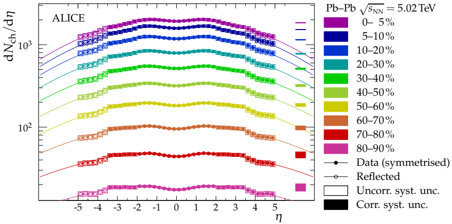
- 26m $\times$ 16m, 10,000 tons
- Efficient low-momentum tracking, down to $\sim$ 100 MeV/c
- Particle identification (practically all known techniques)
- Excellent vertexing capability, Centrality resolution $\sim$ 1%.
- Different systems and collision energies permit us to study the differences and similarities in particle production processes.

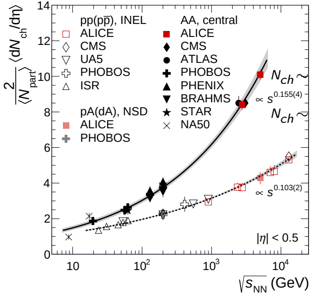
Heavy-ion Collisions, Centrality and Particle productions



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

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



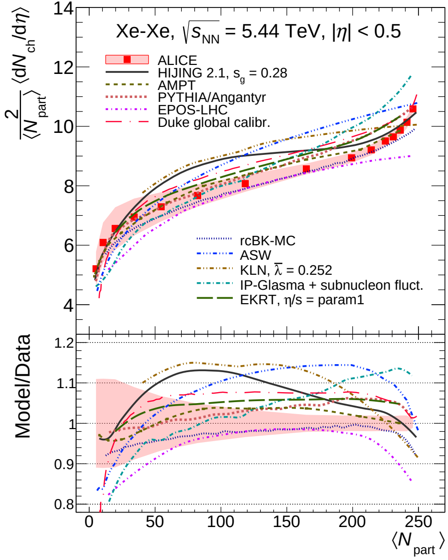


0–5%
$N_{ch} \sim$ 1943 at 5.02TeV
$N_{ch} \sim$ 1584 at 2.76TeV

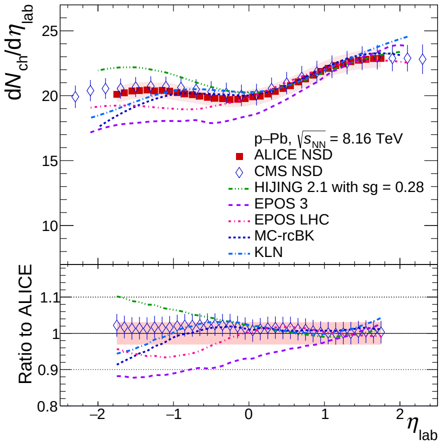
ALICE, Phys. Rev. Lett. 116 (2016) 222302

Multiplicity measurements

$\mathrm{Xe-Xe}$ Accepted in Phys. Lett. B (arXiv:1805.04432)

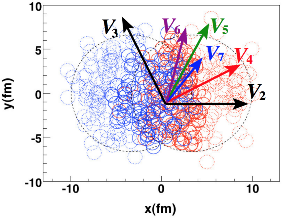


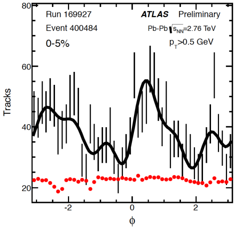
$\mathrm{p-Pb}$ arXiv:1812.01312

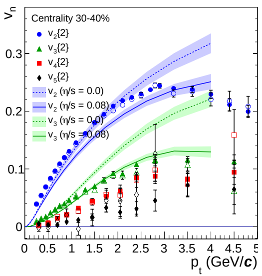


All models describe data within ±15%

Higher Flow Harmonics Seen by All Experiments



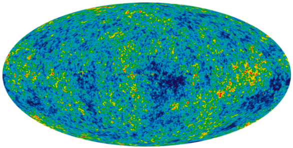


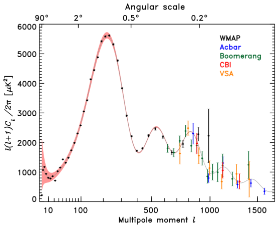


$$P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi}$$

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

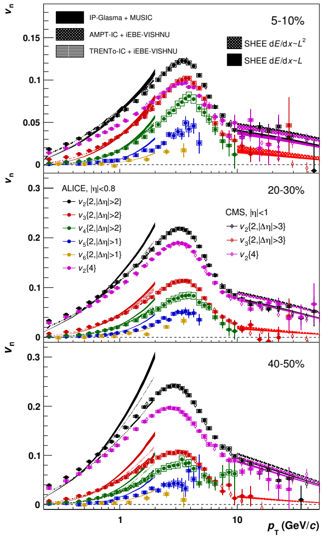
$$v_n \equiv v_n\{\psi_n\} = \sqrt{\langle |V_n|^2 \rangle}$$





- Like measurements of early universe sound harmonics
- Sensitive to initial state geometry and properties of the expanding QGP (viscosity(η/s), equation of state)

$\sqrt{s_{NN}}$= 5TeV Pb-Pb new flow results

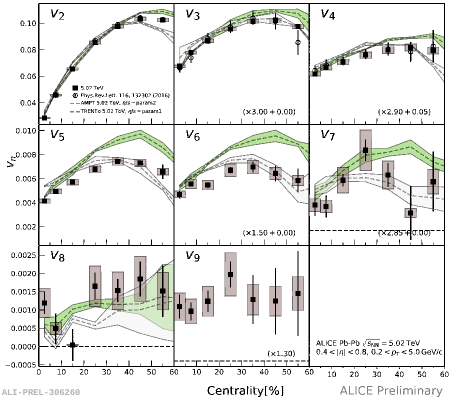


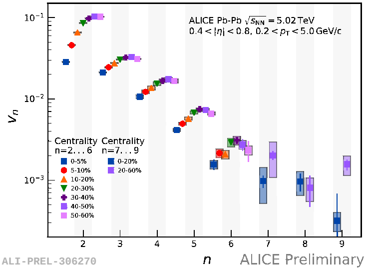
JHEP 07 (2018) 103(arXiv:1804.02944)

- The p_T dependence of v_n and its evolution with respect to centrality and n are investigated systematically.
- **most precise PID flow paper published** [a].
  - v_n(n=2, 3 and 4)
  - $\pi^{\pm}$, $K^{\pm}$, $p+\overline{p}$, $\Lambda+\overline{\Lambda}$, K^0_S, and the ϕ.
  - 0-70% including ultra-central(0-1%) collisions.

[a] JHEP 1809 (2018) 006(arXiv:1805.04390)

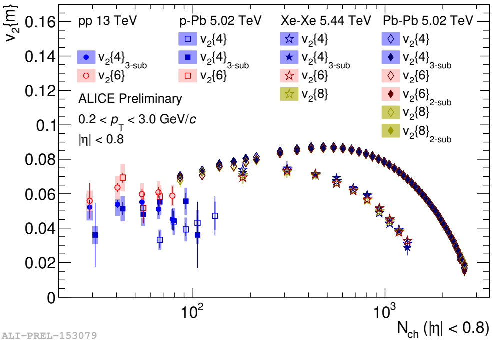
Higher order v_n

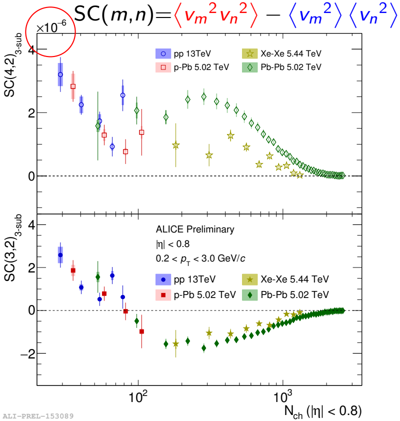




- Up to n=8, nonlinear hydrodynamic response($n > 3$) and searches for acoustic peak(E.Shuryak(arXiv:1710.03776), P. Sorensen et. al(arXiv:1008.3381)).
- $v_n(n > 3)$ are quantified as nonlinear flow mode, more with Jasper Parkkila's Talk(Wed Morning).
- Shown in Hot Quarks 2018 (talk)
- better constraints on hydrodynamic models, i.e. $\eta/s(T)$ and initial conditions.

v_n and flow correlations in small and large systems



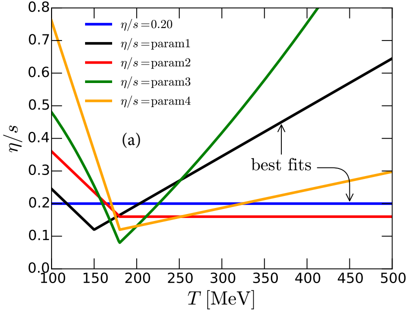


- n=2, 3 and 4 : m to 8.
- Higher harmonics, mostly due to fluctuations in the initial geometry, show weak multiplicity dependence.
- The origin of the flow in small system, initial conditions, collectivity or non-flow (minimized) : You Zhou's talk this afternoon.

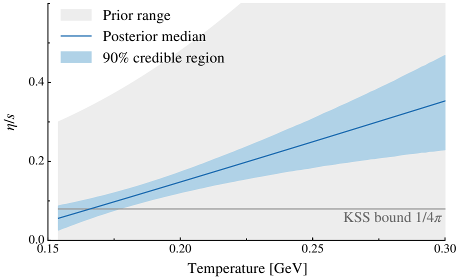
- Extensive studies on Symmetric cumulant up to n=5.
  - Phys. Rev. Lett. 117, 182301 (2016)(arXiv:1604.07663)
  - Phys. Rev. C 97 (2018) 024906(arXiv:1709.01127)
- Measured also in small systems.

Implications of the flow and spectra measurements

H. Niemi, K.J. Eskola, R.Paatelainen
(Phys. Rev. C 93, 024907 (2016), arXiv:1505.02677)



Steffen A. Bass et. al, Global Bayesian Analysis
(Nucl.Phys. A967 (2017) 67-73 , arXiv:1704.07671)

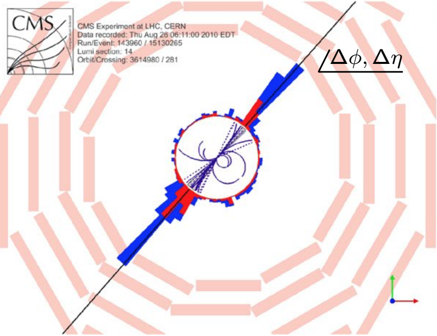


- ALICE data on multiplicity, spectra and flow are key inputs to estimate the properties of the QGP, i.e Global Bayesian Analysis and other theory groups.
- Best fit seems to indicate $\eta/s \approx 0.12$ around $T_c \approx 150$ MeV, very close to $1/4\pi (\approx 0.08)$ from string theory [1](AdS/CFT correspondence).
- η/s(T) can be constrained further, new observables(SC and flow modes) with v_n : separate the effects of $\eta/s(T)$ from the initial conditions.

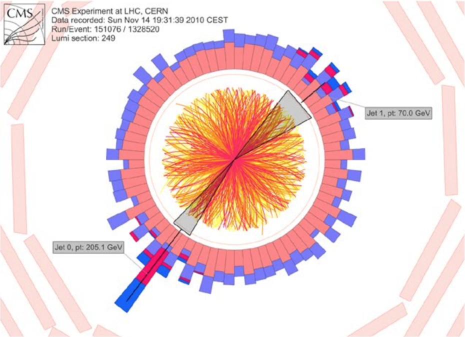
[1] D. T. Son et. al. Phys. Rev. Lett. 94 (2005) 111601

Di-Jet, Jet quenching can be seen visually

Proton + Proton

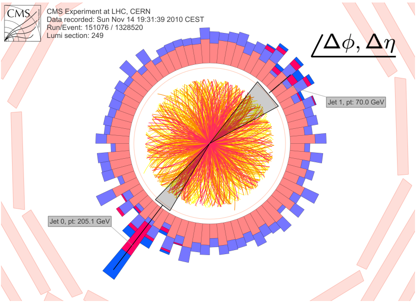


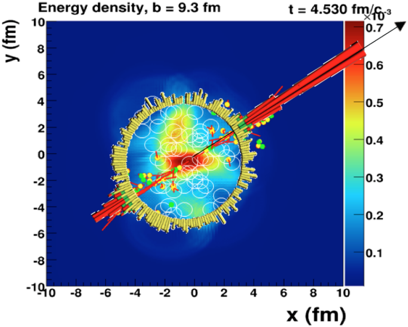
Pb + Pb



- We can see a clear away side jet suppression for this special event (Jet Quenching in QGP).

Di-Jet, Jet quenching can be seen visually





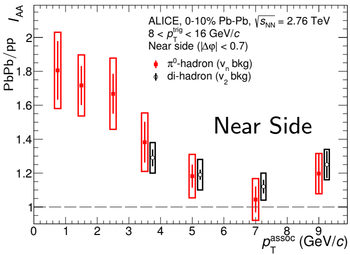
Hydrodynamics + Dijet

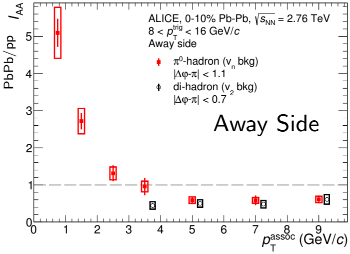
- It had been studied by the measurements by
  - Inclusive spectra of single particle or jet, R_{AA}.
  - Jet fragmentation of jet $\rightarrow$ correlation function from particle pairs or jet shape in η and ϕ spaces, I_{AA} or PbPb/pp.

$$R_{AA} = \frac{dN^{AA}/dp_T d\eta}{< N_{\rm coll} > dN^{pp}/dp_T d\eta} \quad (1)$$

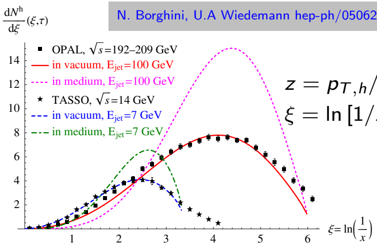
Medium induced gluon radiation

ALICE, PLB 763 (2016) 238-250

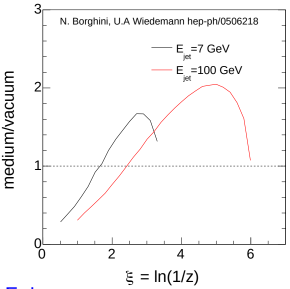




N. Borghini, U.A Wiedemann hep-ph/0506218

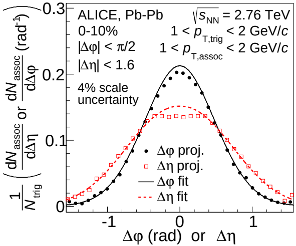


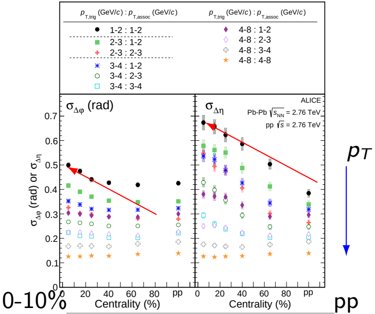
$$z = p_{T,h}/p_{T,jet}$$
$$\xi = \ln[1/z]$$



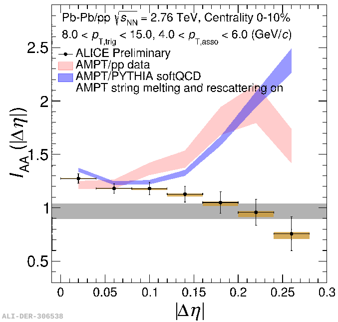
- At low p_T, both for Near and Away side ≈ × 2-5 → Enhancement
- At high p_T, moderate Enhancement for Near side and large Suppression for Away side.

Broadening and Narrowing of jets





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

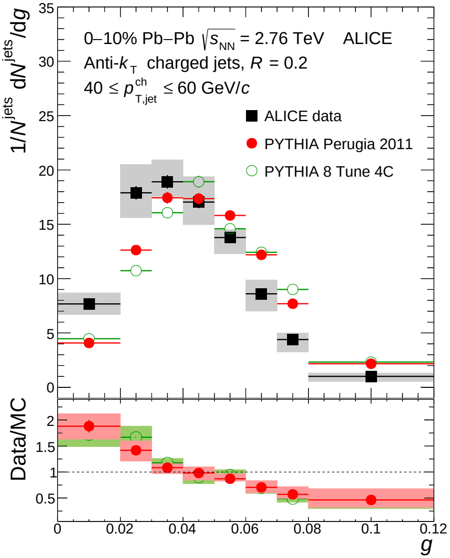


- Broadening and narrowing in different kinematic regions.
- The origins are still being debated
  - low p_T, jet medium interaction, effect of radial flow?
  - Intermediate p_T, effective guark/gluon contributions?
  - Multi-scale problem during jet shower in the medium [a].

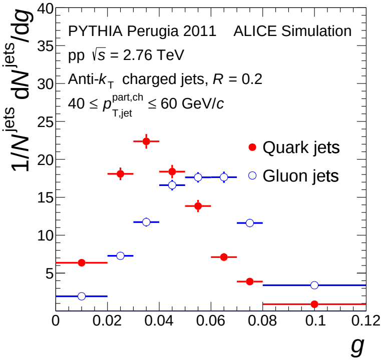
[a] http://jetscape.wayne.edu

Jet Shape modifications in Pb-Pb

ALICE, JHEP 10 (2018) 139, arXiv:1807.06854



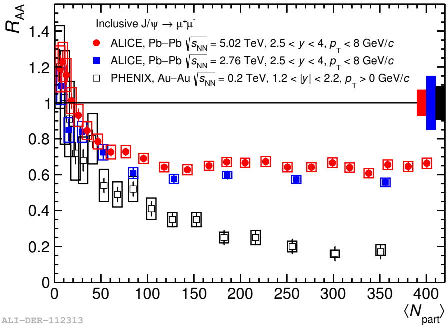
$$g = \sum_{i \in \text{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R_{\text{jet},i}, \qquad (2)$$

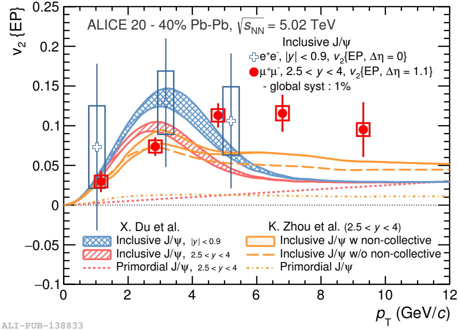


- The jet core is more collimated and fragments harder than in pp collisions
- More quark-like jet

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)



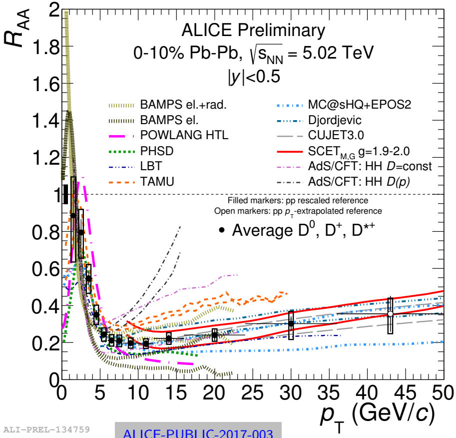


ALICE, Phys.Lett. B766 (2017) 212-224

ALICE, Phys. Rev. Lett. 119 (2017) 242301 arXiv:1709.05260

- Regeneration is more dominant in LHC energies.
- Regeneration gives rise a significant v_2 while primordial J/ψ give minimal effect(high p_T not explained by models).
- -Precision run 2 data allow us to measure v_3 and v_2 in fine centrality bins, submitted to JHEP, arXiv:1811.12727.
- -J/ψ v_2 in p-Pb, ALICE, Phys. Lett. B 780 (2018) 7-20 arXiv:1709.06807.

Simultaneous fit of R_{AA} and v_2 for D-mesons : Constraining models



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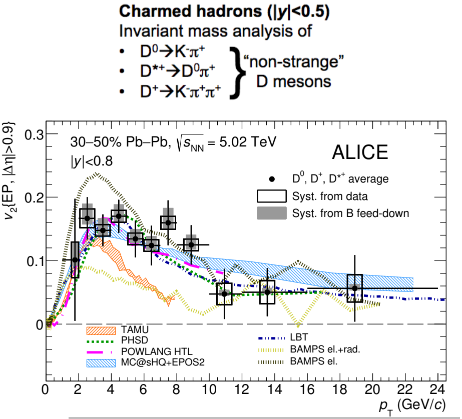
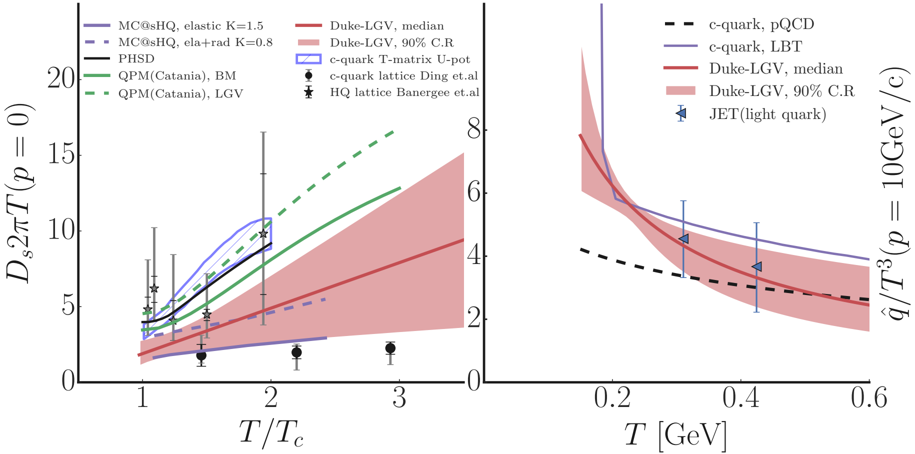


ALICE, Phys. Rev. Lett. 120 (2018) 102301, arXiv:1707.01005

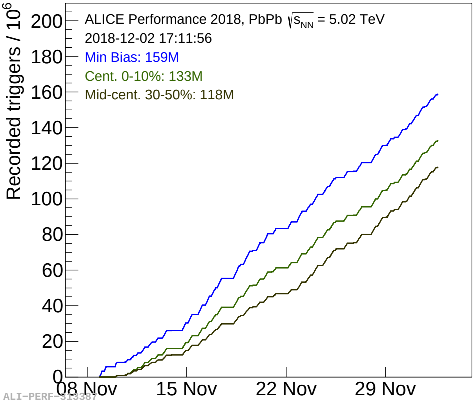
- Strong suppression of high p_T D-meson production in central Pb-Pb collisions.
- Similar for 2.76 TeV and 5 TeV.
- Challenging models with simultaneous fit of R_{AA} and v_2.
- Run1 2.76 TeV data were used for a Bayesian model-to-data analysis.

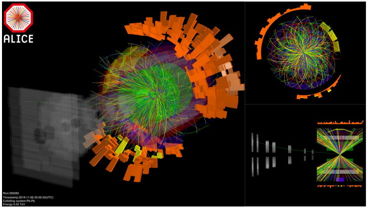
Global anaysis and Uncertainty in Theory, utilizing heavy flavor data



M. Nahrgang, S. A. Bass et. al., Phys. Rev. C 97, 014907 (2018)(arXiv:1710.00807)

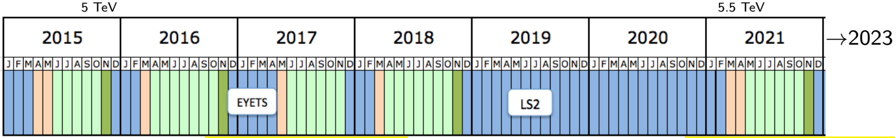
ALICE Run2 ended with Pb-Pb last month





- Smooth operation at max. int. rate of 8 kHz.
- Run-2 goal was achieved.
- 2018 vs 2015 : 9x larger sample of central collisions.
- pp 13 TeV: 10.4 pb^{-1} in 2018 (36 pb^{-1} in total during Run 2)

ALICE Upgrade for Run3 and Beyond



Shutdown/Technical stop
Protons physics
Commissioning
Ions

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

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

Global observables.......
Light hadrons................
P. Palni's(Wed) Strange hadrons...........
Quarkonia.....................
Open heavy flavours....
∗ Electromagnetic probes
Jet and high p_T hadrons
∗ Hypernuclei..................

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

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

upgrade of the forward trigger detectors(FIT) and ZDC

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

Summary

- Precision measurements on soft observables
  - Higher precision data on $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$, spectra and v_n become "Run"-ly routine.
  - The new observables like Symmetric Cumulants and the nonlinear mode of higher harmonic flows have different sensitivities to the initial conditions and the system properties. → Strong constraint on the η/s(T)
- Jet Quenching
  - Medium induced gluon radiation and guark/gluon suppression can be accessed via experimental data.
  - At low p_T, Broadening of jet is clearly observed.
  - Precision data to lower momentum jet and hadrons and to larger angles become available to explore the physics of jet quenching.
  - Improved precision on heavy flavor measurements helps to improve the modeling of heavy flavor dynamics.
- ALICE is being prepared for the future.
  - Pb-Pb 2018 run goals were achieved.
  - Upgrade will be prepared during Long Shutdown 2 to fully exploit the higher rate and to improve the physics performance.
    - x 3 more precise tracking
    - x 100 statistics increase for Run3 and Run4

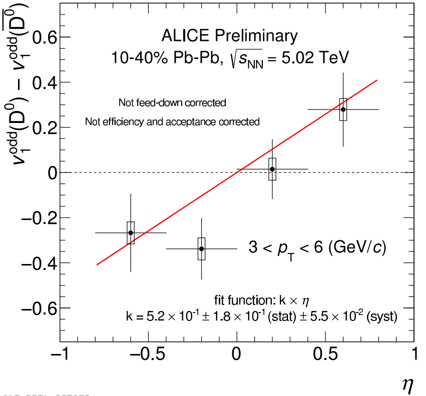
Thank You!

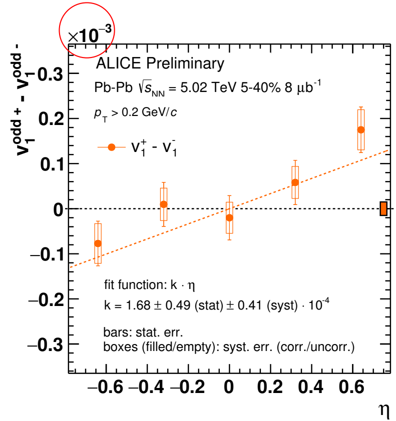
PbPb Papers in 2018, not covered in this talk

Direct photon elliptic flow in Pb-Pb collisions at 2.76 TeV	Accepted by: PLB	arXiv:1805.04
Inclusive J/ψ production in Xe-Xe collisions	Phys. Lett. B 785 (2018) 419-428	arXiv:1805.04
Flow in Xe-Xe collisions	Phys.Lett. B784 (2018) 82-95	arXiv:1805.01
CME searches via ESE	Phys. Lett. B 777 (2018) 151-162	arXiv:1709.04
p_T spectra and nuclear modification factors of charged particles in Xe-Xe collisions	Phys. Lett. B 788 (2019) 166-179	arXiv:1805.04
p_T spectra and nuclear modification factors of charged particles in pp, p-Pb and Pb-Pb collisions	JHEP 1811 (2018) 013	arXiv:1802.09
Suppression of Λ(1520) resonance production in central Pb-Pb collisions a	submitted to PRL	arXiv:1805.04
Azimuthally-differential pion femtoscopy relative to ψ_3 in Pb-Pb at 2.76 TeV	Phys.Lett. B785 (2018) 320-331	arXiv:1803.10
Neutral pion and η meson production in PbPb at 2.76 TeV	Phys. Rev. C 98, 044901 (2018)	arXiv:1803.05

The full list of paper status can be found here.

Heavy flavor and charged particle v_1





- Charge dependent directed flow is sensitive to the EM fields in the early stages of the collision.
- First measurement on D meson, hint of positive slope with a significance of 2.7σ(HP2018,talk).
- Similar trend observed for charged particles, but different magnitude.
- Large effect expected for heavy flavor due to the shorter formation time ≈ the time scale when B is maximum (K. Das et. al, Phys.Lett. B768 (2017) 260-264)

$\langle dN_{ch}/d\eta \rangle$ study at ALICE

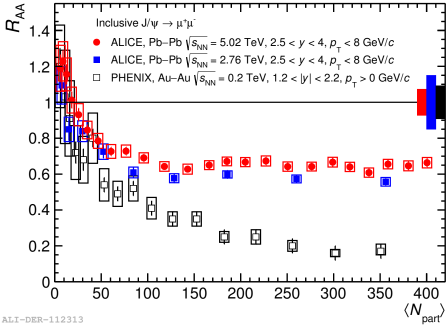
- System-size dependent study
  proton (A=1) — p–Pb ———- Xe (A=129) ——— Pb (A=208)
- Published multiplicity papers for inclusive charged particles

Type	$\sqrt{s}$, $\sqrt{s_{NN}}$ (TeV)	paper
pp	0.9, 2.76, 7 and 8	Eur. Phys. J. C 77 (2017) 33
pp	13	Phys. Lett. B 753 (2016) 319-329
p–Pb	5.02	Phys. Rev. Lett. 110 (2013) 032301
p–Pb	8.16	arXiv:1812.01312 (Centrality with ZDC)
Pb–Pb	2.76	Phys. Rev. Lett. 106, 032301 (2011)
Pb–Pb	5.02	Phys. Rev. Lett. 116 (2016) 222302
Xe-Xe	5.44	Accepted in Phys. Lett. B (arXiv:1805.04432)

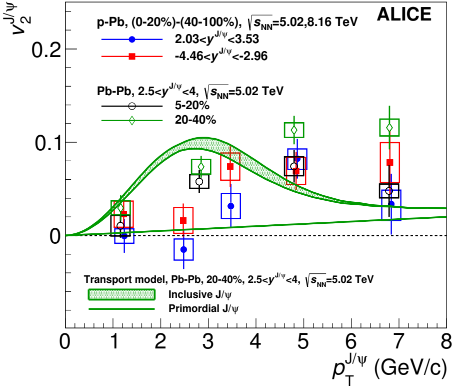
Prabhakar Palni's Talk on charged particles and Strangeness (Wed Morning)

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

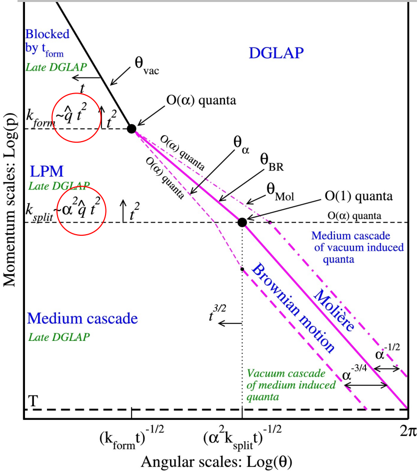


ALICE, Phys. Lett. B 780 (2018) 7-20 arXiv:1709.06807

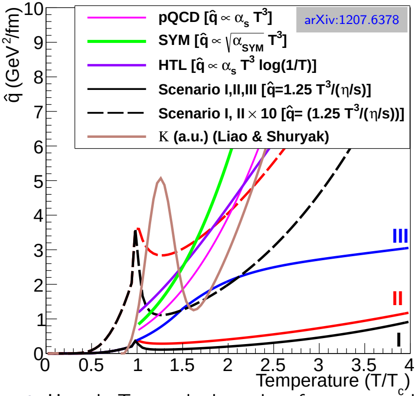
- Huge improvement on the measurements in LHC.
- Regeneration is more dominant in LHC energies.
- Regeneration gives rise a significant v_2 while Primordial J/ψ give minimal effect.

Data permit a model independent, quantitative assessment?

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



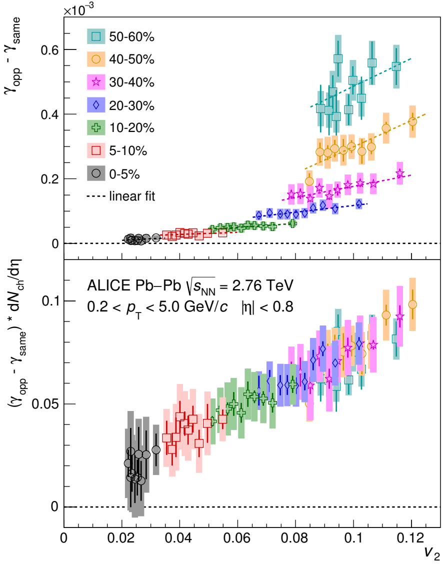
- constituents of medium accessible via large angle scattering



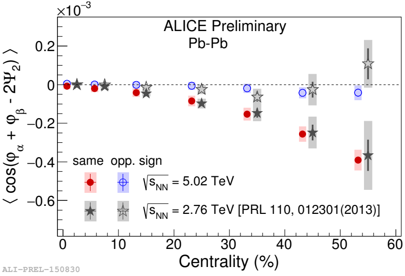
- How do T or scale dependent features translate to final state ?
- Medium influence becomes significant as virtuality of parton shower and medium become comparable.
- An unambiguous determination of both sides of [the equation] from experimental data ? (Phys. Rev. Lett., 99:192301, 2007)

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

Extensive CME searches



Phys. Lett. B 777 (2018) 151-162, arXiv:1709.04723



- Estimated CME fraction based on linear dependence of backgrounds to elliptic flow, the upper limit 16-33%,at 95% confidence level.
- 5TeV results in QM18.
- CME analyses in various collisions system XeXe, 5TeV PbPb and pPb are ongoing.