Highlights from the ALICE experiment

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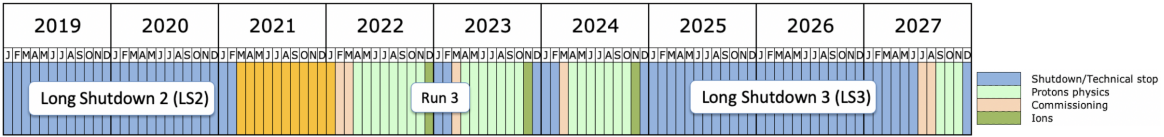
[1] University of Jyväskylä & Helsinki Institute of Physics, Finland

Nov, 16th, 2021

Particle Physics Days 2021, Jyväskylä Paviljonki

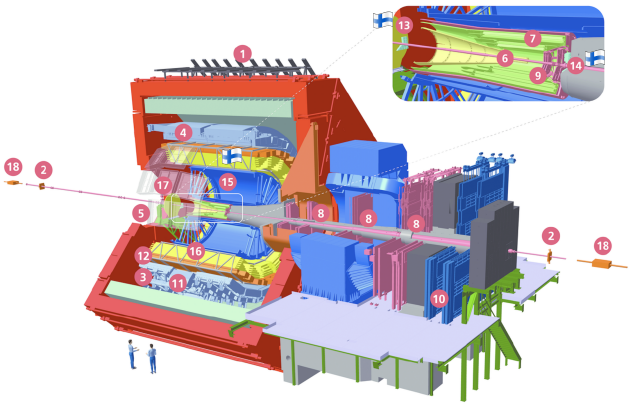
ALICE PRESENT AND NEAR FUTURE



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

- Start of the LHC Run 3
  - Extend Run 3 until end of 2024 (decided already pre-COVID)
  - LHC default scenario: cavern closes 1st February 2022
  - 4 months of ALICE Global Commissioning
- ALICE strategy for Run 3
  - 50 kHz Pb-Pb interaction rate (Run 2 $<$ 10 kHz)
  - Experiment upgrades during LS2
  - Continue to collect pp with high multiplicity trigger and achieve PbPb (x 3 more precise tracking and x 100 statistics increase)
- Physics goals : CERN Yellow Report, arXiv:1812.06772
  - High-precision measurement($h^{\pm}$, PID..) $\rightarrow$ viscosity and further QCD transport coefficients.
  - Heavy-flavours and jets $\rightarrow$ Investigating the quasi-particle structure of QCD matter.
  - Charmonium states $\rightarrow$ Testing colour screening and regeneration dynamics.
  - Dileptons and low-mass vector mesons $\rightarrow \chi$ symmetry restoration, initial temperature and EoS.

Upgraded Experiment – ALICE 2

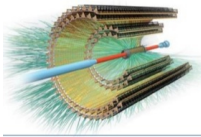


ALICE Collaboration:
40 countries, 170 institutes, 1972 members
360 papers.
ALICE Finland:
3 seniors, 1 post doc, 4+2 PhD-students
($\approx$ 0.5% of ALICE)

- Sami Räsänen (Team Leader, HIP project leader)
- Wladyslaw Trzaska (FIT project leader)
- DongJo Kim (Flow PWG coordinator)
- Maciej Slupecki (FIT Run coordinator)
- Jasper Parkkila (PhD-student, flow, TPC)
- Heidi Rytkönen (PhD-student, jets, FoCal+FIT)
- Oskari Saarimäki (PhD-student, jets, FIT)
- Anna Önnerstad (PhD-student, flow, TPC)
- Andreas Molander (PhD-student, flow, FIT) NEW
- Laura Huhta (PhD-student, jets, FoCal) NEW

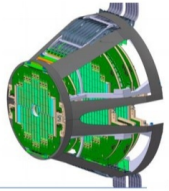
ALICE 2 is build on the great success of the past 10 years operation.
TPC(detector 15), FIT(2 + 13 + 14 + 17), ALICE Grid Tier-1 since 2007

Key elements of ALICE Upgrades for Run 3



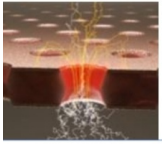
6 to 7 layers, $|\eta| < 1.0 \rightarrow 1.5, 1 \rightarrow 100$kHz(PbPb)

New Inner Tracking System (ITS)
-CMOS pixel, MAPS technology
-Improved resolution, less material, faster readout



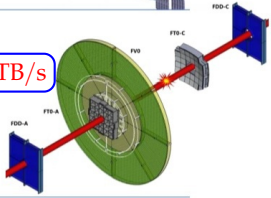
New Muon Forward Tracker (MFT)
-CMOS Pixels, MAPS technology
-Vertex tracker at forward rapidity

$\psi(2S)$ S/B x5



New TPC Readout Chambers (ROCs)
-Gas Electron Multiplier (GEM) technology
-New electronics (SAMPA), continuous readout

50kHz PbPb, $\approx$ 34 TB/s



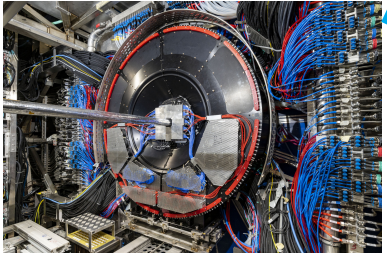
New Fast Interaction Trigger (FIT) Detector
-Centrality, event plane, luminosity, interaction time

Readout upgrade
-TOF, TRD, MUON, ZDC, Calorimeters

Integrated Online-Offline system (O^2)
-Record MB Pb-Pb data at 50 kHz

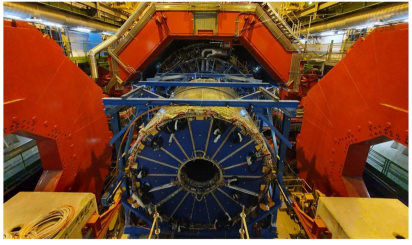
Completed LS2 upgrade of ALICE experiment, ready for Run 3

Return of the upgraded TPC, 4 August 2020

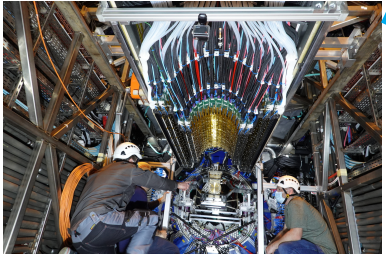


NEW

Reinsertion of the TPC 6 August 2020



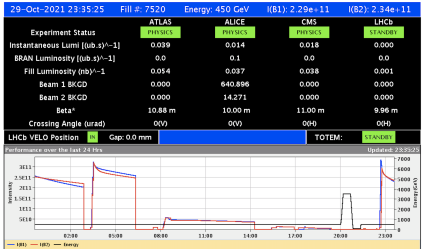
NUCLEUS 2020 W.H.Trzaska

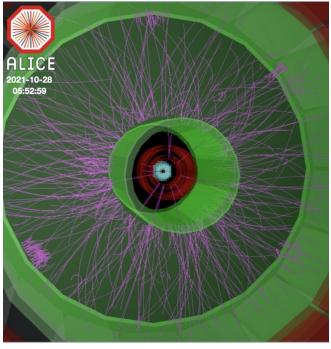


NEW

FIT installed in June, 2021(Link), ITS/MFT in May, 2021

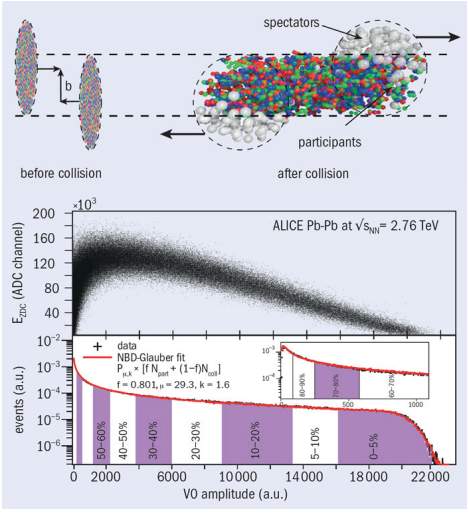
Activites at present and near future, Nov-2021





- The last fill of this pilot beam tests was dumped at 6:02 AM, 1st Nov 2021
  - beam energies: 450 GeV and 3.5 TeV
  - 6M collision events at $\sqrt{s} = 900$ GeV
  - data rate ≈ 40 GB/s, no major issues
- Global commissioning until 12 Nov 2021
- 11 weeks year-end technical stop (YETS) from 15 November 2021 to 31 Jan 2022
- Restart global commissioning on 1 Feb 2022
- LS2 end date: Monday 21 Feb 2022
- Beams in the machine from week 10 (7 March 2022)
- First stable beams expected by week 18 (6 May 2022)

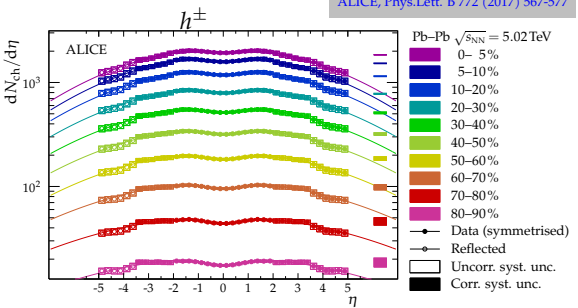
Heavy-ion Collisions, Centrality and Particle productions



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

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

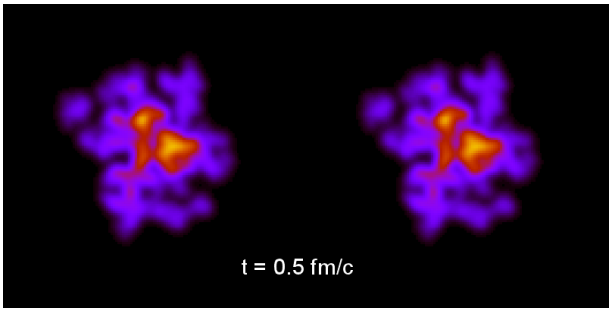
ALICE, Phys.Lett. B 772 (2017) 567-577



- 0-5% (0-3.5fm) in $|\eta < 0.5$
- $N_{ch} \sim$ 1943 at 5.02TeV
- $N_{ch} \sim$ 1584 at 2.76TeV

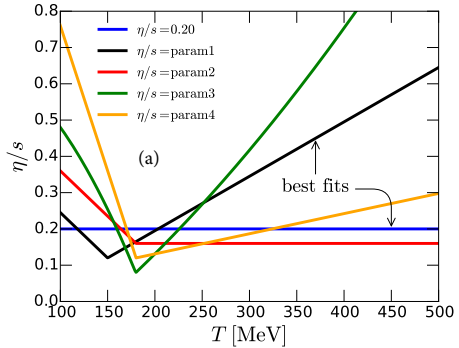
Space-time history of Heavy-Ion Collisions

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



Ideal hydrodynamics vs Viscous hydrodynamics(η/s=0.16)

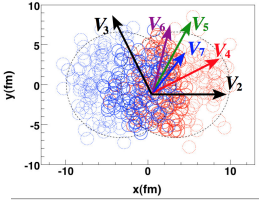
H. Niemi, K.J. Eskola, R.Paatelainen:EKRT+Hydrodynamics
(Phys. Rev. C 93, 024907 (2016), arXiv:1505.02677)

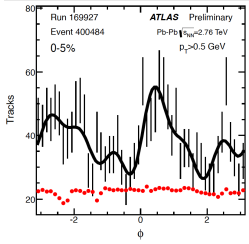


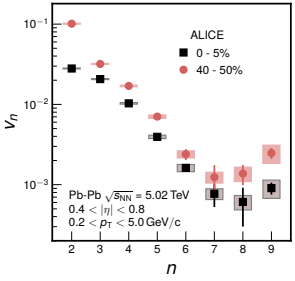
Quark-gluon plasma (QGP) is a nearly perfect guark-gluon fluid:
Best fit seems to indicate $\eta/s \approx 0.12$ around $T_c \approx 150$ MeV, very close to $1/4\pi$ (≈ 0.08) from string theory[a] (AdS/CFT correspondence).

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

Higher Flow Harmonics Seen by All Experiments

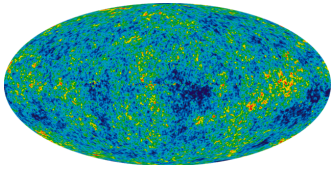


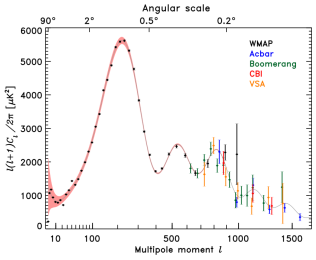




$$P(\varphi) \propto \frac{1}{2\pi} \sum_{n=-\infty}^{+\infty} V_n e^{-in\varphi}$$

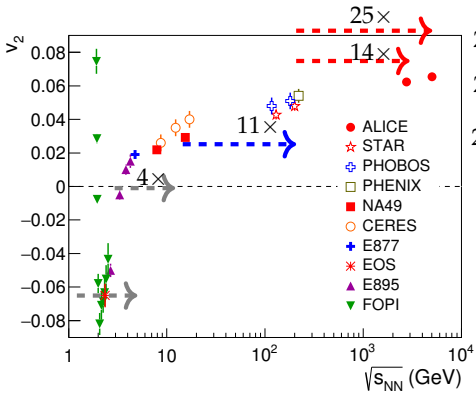
$$V_n \equiv v_n\{\psi_n\} e^{in(\psi_n - \phi)}$$





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

v_2 VS $\sqrt{s_{NN}}$ AND FLOW POWER SPECTRUM



2015 LHC 5.02TeV CERN

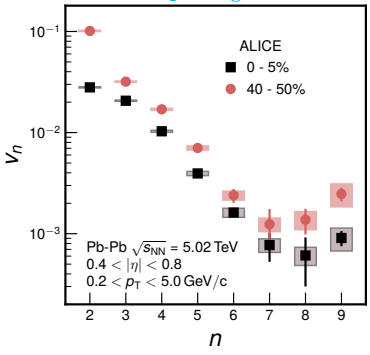
2010 LHC 2.76TeV CERN

2000 RHIC 200GeV USA

90s SPS 17GeV CERN

80s AGS 4GeV USA

2020, cerncourier[Going with the flow]

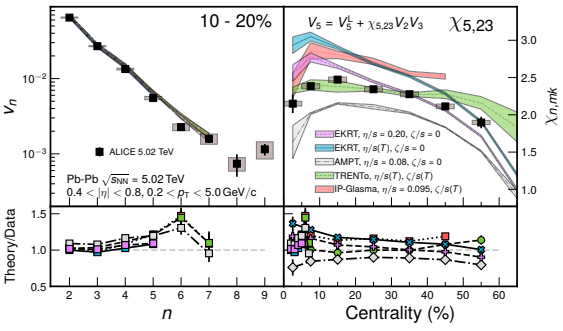


ALICE, PRL105 (2010) 252302 | ALICE, JHEP05 (2020) 085, Jasper Parkkila

ALICE had measured the largest flow v_2 in 2010!
ALICE has measured the largest harmonic order flow(up to v_9) so far, 2020

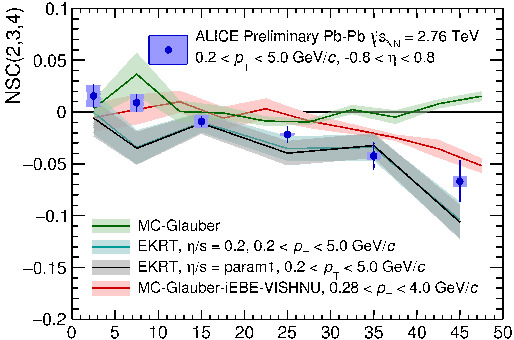
High precision flow results and New developments

Non-linear flow modes get dominant for $(n > 3)$



ALICE, JHEP05 (2020) 085, J.E. Parkkila

EbE three harmonic flow correlation, $\langle v_k v_l v_m \rangle$

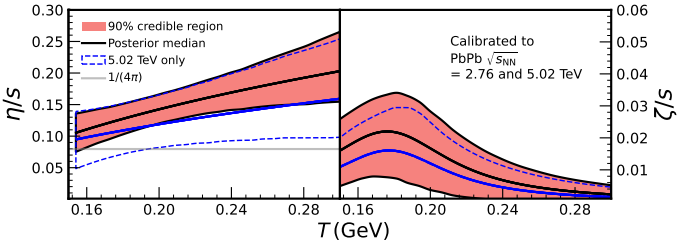


ALICE, PRL 127 (2021) 092302 , D.J Kim NEW

- Nonlinear components of high order harmonics are decomposed, showing better sensitivity for $\eta/s(T)$.
- Exponential decrease via viscosity damping, a hint that $v_9 > v_8$, acoustic peak?
- Provide new and independent constraints for initial conditions and QGP properties.

Two harmonic versions are published(PRL 117(2016)182301,PRC 97(2018) 024906).
Very challenging measurements because of their required high precisions (i.e 1e-6 SC(m,n), 1e-12 for SC(k,l,m))) and difficulties in correcting experimental biases.

Improved Bayesian parameter estimation with the latest LHC data

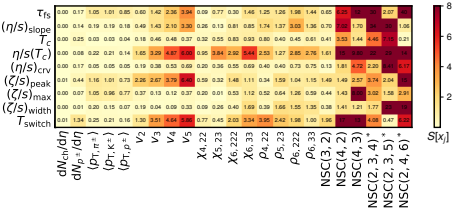


PRC 104, 054904(Nov. 2021), J.E. Parkkila, A. Onnerstad, D.J. Kim NEW

submitted to PRL(arXiv:2111.08145, Today), J.E. Parkkila, A. Onnerstad, D.J. Kim NEW

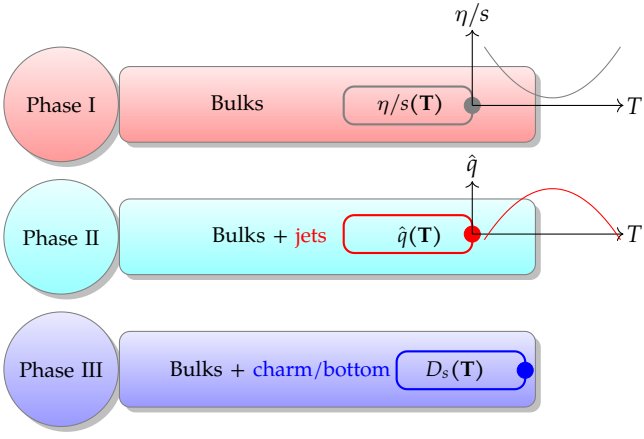
- Uncertainty is improved with the help of new sophisticated collective flow observables.
- More therotical work on initial conditions and hadronizations are essential.

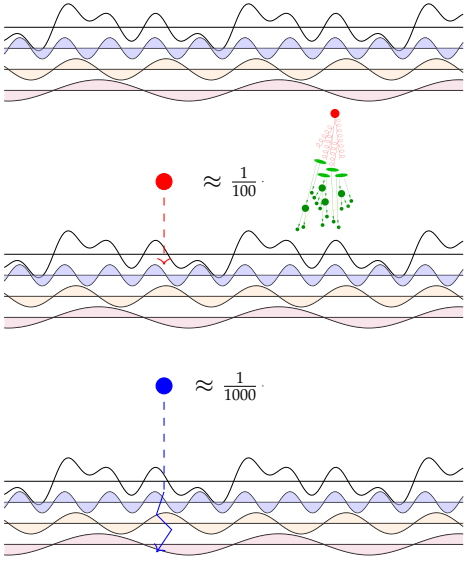
Sensitivity analysis



- The precision measurements of higher-order harmonic flow and their correlations are crucial.

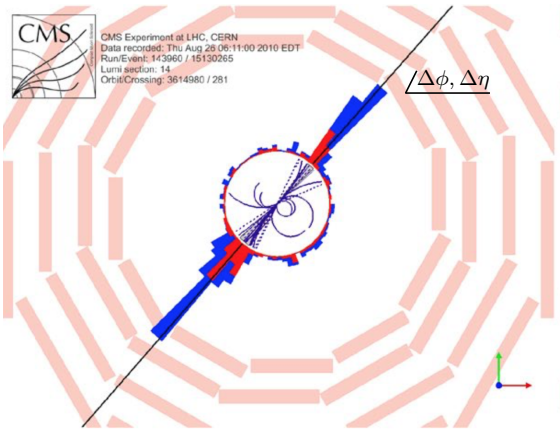
Transport properties



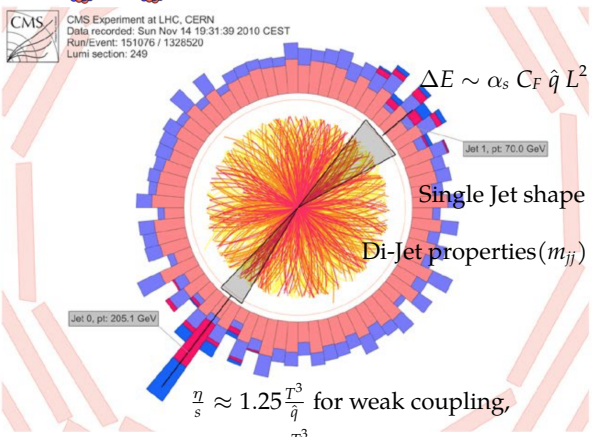


Di-Jet, Jet quenching can be seen visually

Proton + Proton



Pb + Pb



Single Jet shape

Di-Jet properties(m_{jj})

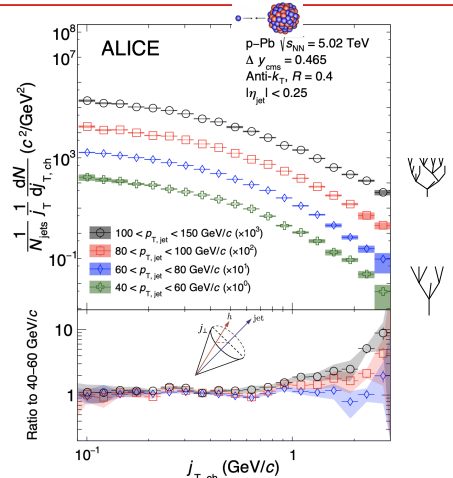
$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$ for weak coupling,

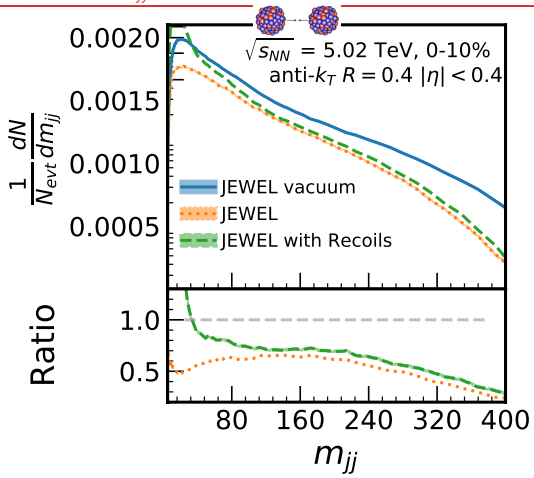
$\frac{\eta}{s} \gg 1.25 \frac{T^3}{\hat{q}}$ for strong coupling,

(Phys. Rev. Lett., 99:192301, 2007)

- We can see a clear away side jet suppression for this special PbPb event (Jet Quenching in QGP).
- Deeper understanding of jet quenching is not an option.

Further constraining Jet quenching model with j_T and m_{jj}, Jet virtuality evolution

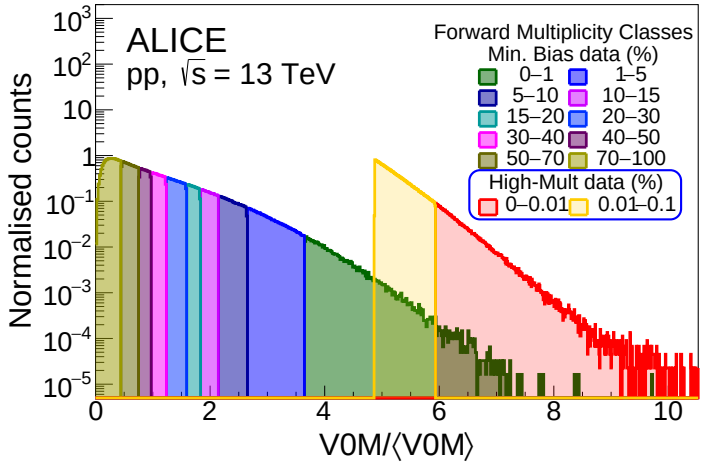




- Modification of transverse profile of jet fragmentation - published, JHEP09 (2021) 211. NEW
- Proving L dependence via di-jets[1]-[O. Saarimaki (pp, p-Pbfor QM22), L. Huhta(PbPb Run3)]

[1] PRC 75 (2007) 054910, JEWEL(JHEP 1707 (2017) 141)

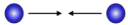
13TeV pp high multiplicity trigger

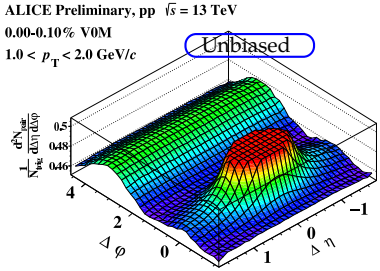


- Full 13TeV pp data sets including high multiplicity triggered events.
- The studies on different multiplicity selection biases - published EPJC 81 (2021) 630 NEW

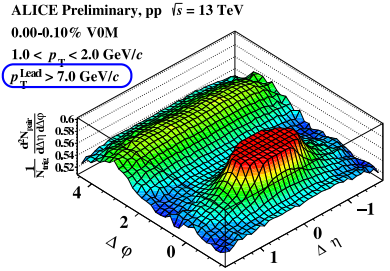
QGP in small systems?

Top 0.1% high multiplicity events





ALI-PREL-319153

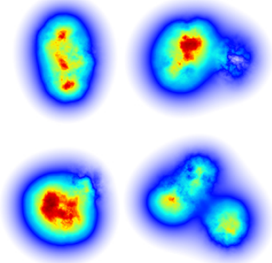


ALI-PREL-319168

ALICE, JHEP 05 (2021) 290, D.J Kim, J.E. Parkkila

NEW

Fluctuating gluon density in a proton



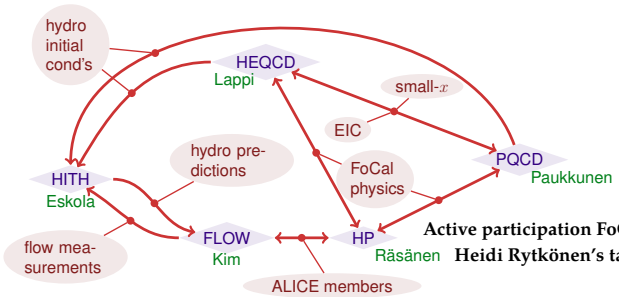
Heikki Mantysaari et al., PRL 117, 052301

- The ridge/flow is observed clearly for hard events for the first time.
- Testing experimental (N_{ch}/flow mangitute/bias) and theory limits
- Initial state or final state effects?
  - importance of detailed fluctuating gluon density in a proton and/or early dynamics

Summary

- LHC/ALICE is prepared for the future.
  - LS2 upgrade of ALICE is completion to exploit the higher rate and to improve the physics performance.
  - Running and development of FIT
- Precision measurements on soft observables
  - Higher precision data on $\langle dN_{ch}/d\eta \rangle$, spectra and v_n become "Run"-ly routine.
  - $\langle v_m v_n \rangle$ $\langle v_k v_l v_m \rangle$ correlations via the nonlinear response of v_n(n>3) $\rightarrow$ Strong constraint on the η/s(T)/ζ/s(T).
  - Testing experimental and theory limits in small systems
  - Significant role in the ALICE review paper in preparation.
- Significant pioneering contributions from Jyväskylä Univ.(Thanks to the collaborative efforts).
- A lot more to learn from Run 3 and 4 data.

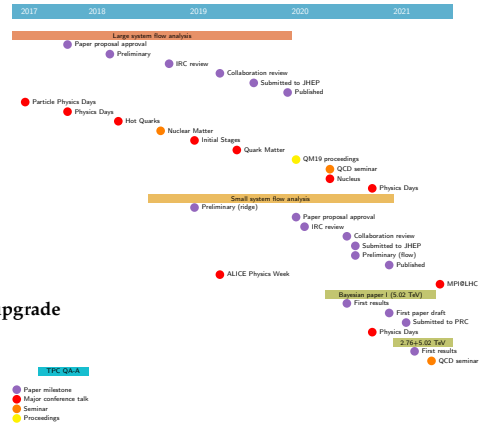
Center of Excellence in Quark Matter 2022-2029



Active participation FoCal upgrade

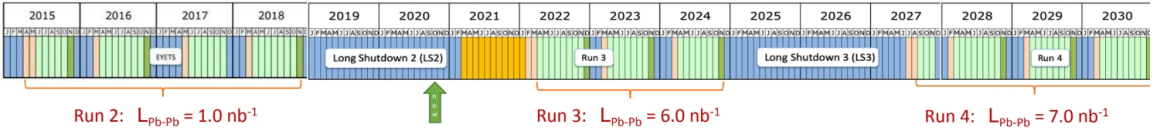
Heidi Rytkönen's talk

J.E. Parkkila, PhD defense 19/11/2021

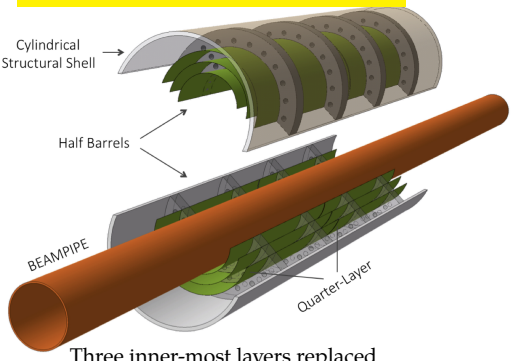


Thank You!

ALICE Upgrades for Run 4



Ultra-light Inner Tracking System 3

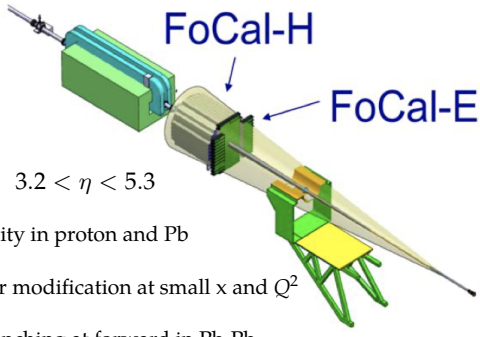


Three inner-most layers replaced

ALICE-PUBLIC-2018-013

Forward Calorimeter

LoI CERN-LHCC-2020-009



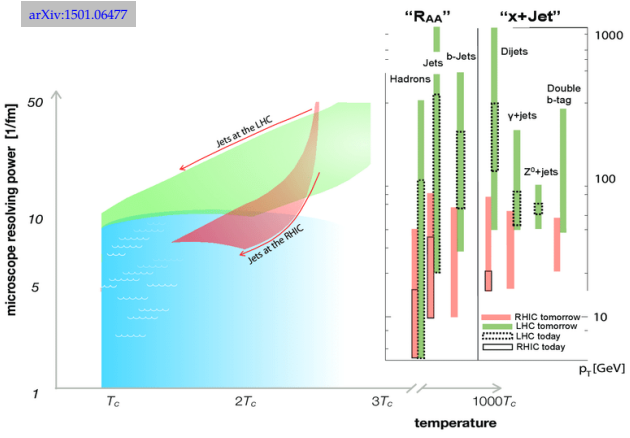
$3.2 < \eta < 5.3$

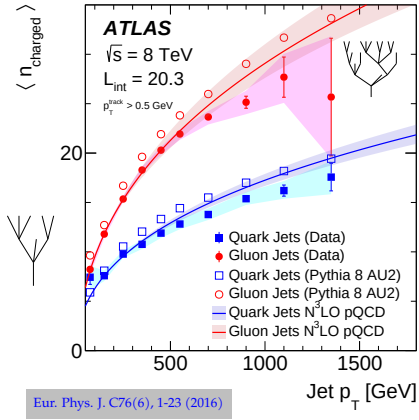
g-density in proton and Pb

nuclear modification at small x and Q^2

Jet quenching at forward in Pb-Pb

Jet virtuality evolution matters with medium temperature





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- Jet virtuality evolution paths simultaneous with the QGP temperature evolution for central Au+Au and Pb+Pb collisions at RHIC and the LHC
- Jet tomography in medium gets complicated with p_{T} or flavor dependent shower evolution.