Das ALICE Experiment – Ergebnisse und Upgrade

KHuK Jahrestagung 2016

Christian Klein-Bösing
IKP Münster and EMMI/GSI

ALICE @ LHC

Electro Magnetic Calorimeter (EMCal)

Time-of-Flight (TOF)

Transition Radiation Detector (TRD)

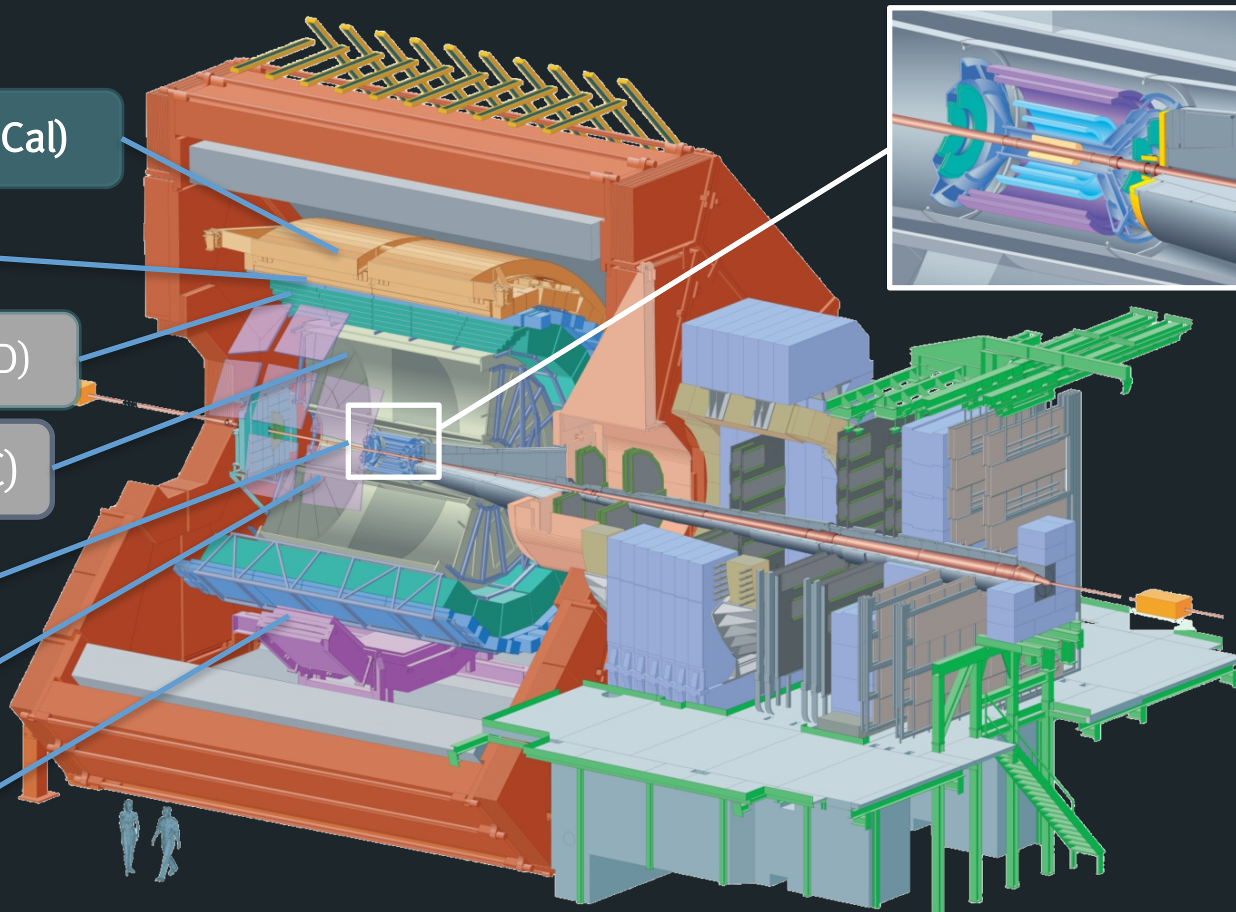
Time Projection Chamber (TPC)

Inner Tracking System (ITS)

High Momentum Particle Identification (HMPID)

Photon Spectrometer (PHOS)

High Level Trigger (HLT)



Forward Muon Arm

German Contributions

- **TPC** H. Appelshäuser (U Frankfurt, PL), C. Garabatos (GSI, DPL), C. Lippmann (GSI, TC)
- **TRD** J. Stachel (U Heidelberg, PL), J. Wessels (U Münster, DPL), J. Mercado (U Heidelberg, TC)
- **HLT** V. Lindenstruth (U Frankfurt, PL), M. Krzewicki (U Frankfurt, DPL/TC), T. Alt (U Frankfurt, DTC)

- **Collaboration Board Chair** P. Braun-Munzinger (GSI/EMMI)
- **Deputy Spokesperson** J. Wessels (U Münster)

- BMBF Forschungsschwerpunkt 201-ALICE
  - GSI/EMMI
  - Universität Heidelberg
  - Universität Frankfurt
  - Universität Münster
  - Universität Tübingen
  - Technische Universität München
  - Universität Bonn
  - FIAS Frankfurt
  - FH Worms

ALICE@LHC in 2016

- pp at 13 TeV:
  exciting prospects with a very large min. bias (and high multiplicity) sample
  (ALICE IR: 100 - 550 kHz)

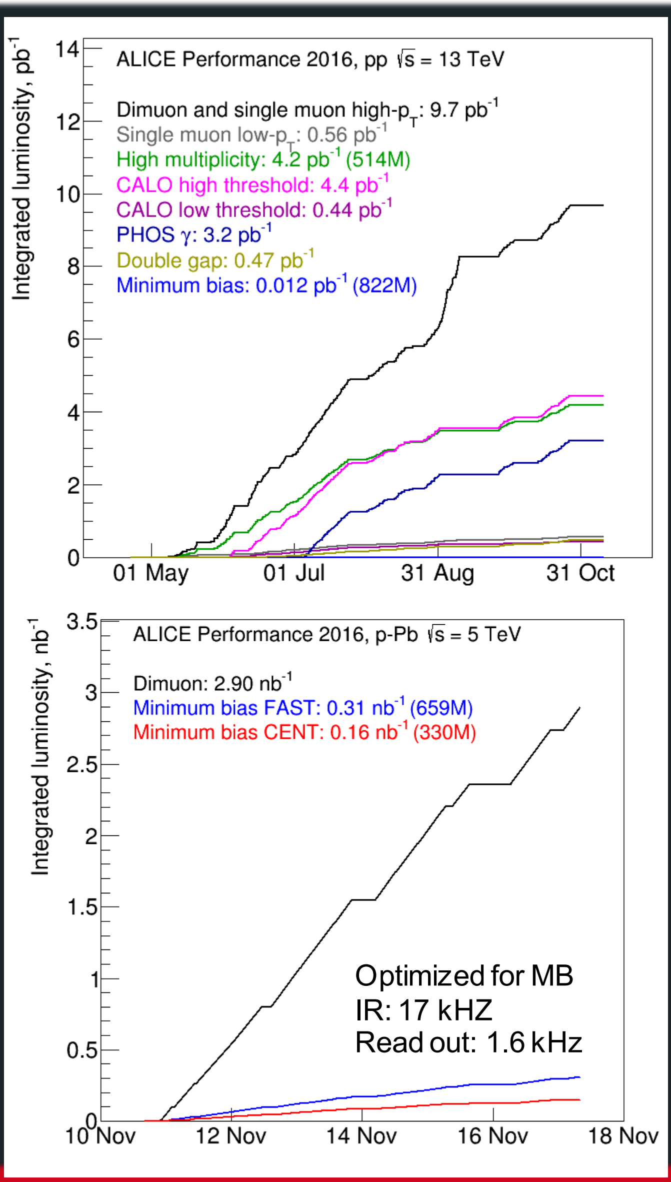
- pPb: Ion run this year (finishes on Monday):

Complementary physics questions lead to two periods of pPb

  – $\sqrt{s_{NN}}$ = 5 TeV, Pb-Pb reference energy, low lumi, small burn off, long fills
  from soft to hard probes and
  from minimum bias to high multiplicity
  study QGP-like signals in small systems
  (ALICE IR: 17 kHz)

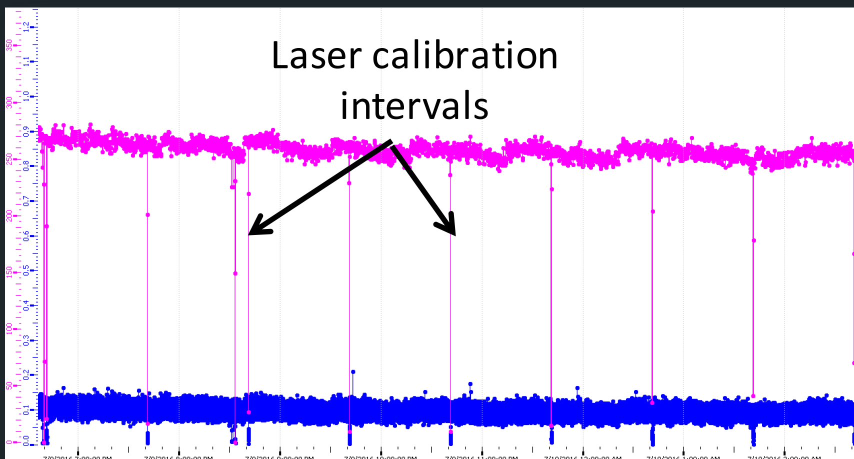
  – $\sqrt{s_{NN}}$ = 8 TeV, larger cross sections, high lumi, beam reversal, short fills
  focus on hard probes and quarkonium physics
  (ALICE IR: 300 kHz)

ALICE: very stable, **operational efficiency > 92%**



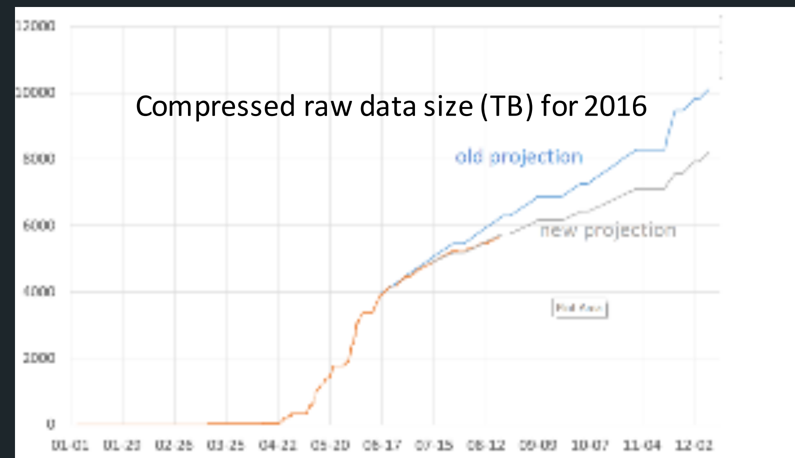
Detector Performance in Run02

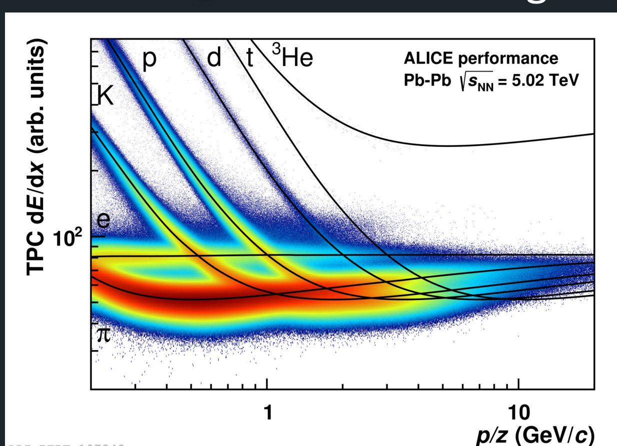
Example: TPC currents stability



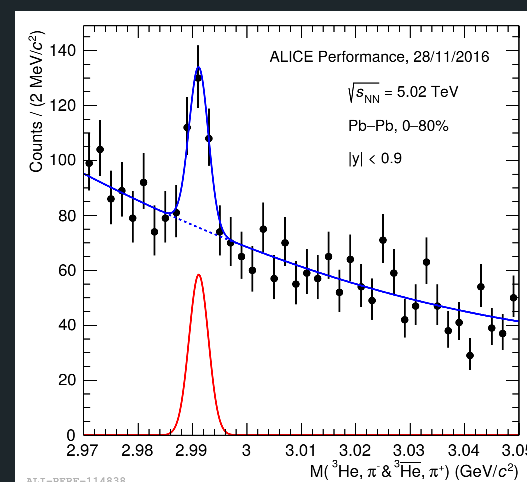
time ⟶ 7+ h data taking

Example: HLT compression improved by 20%



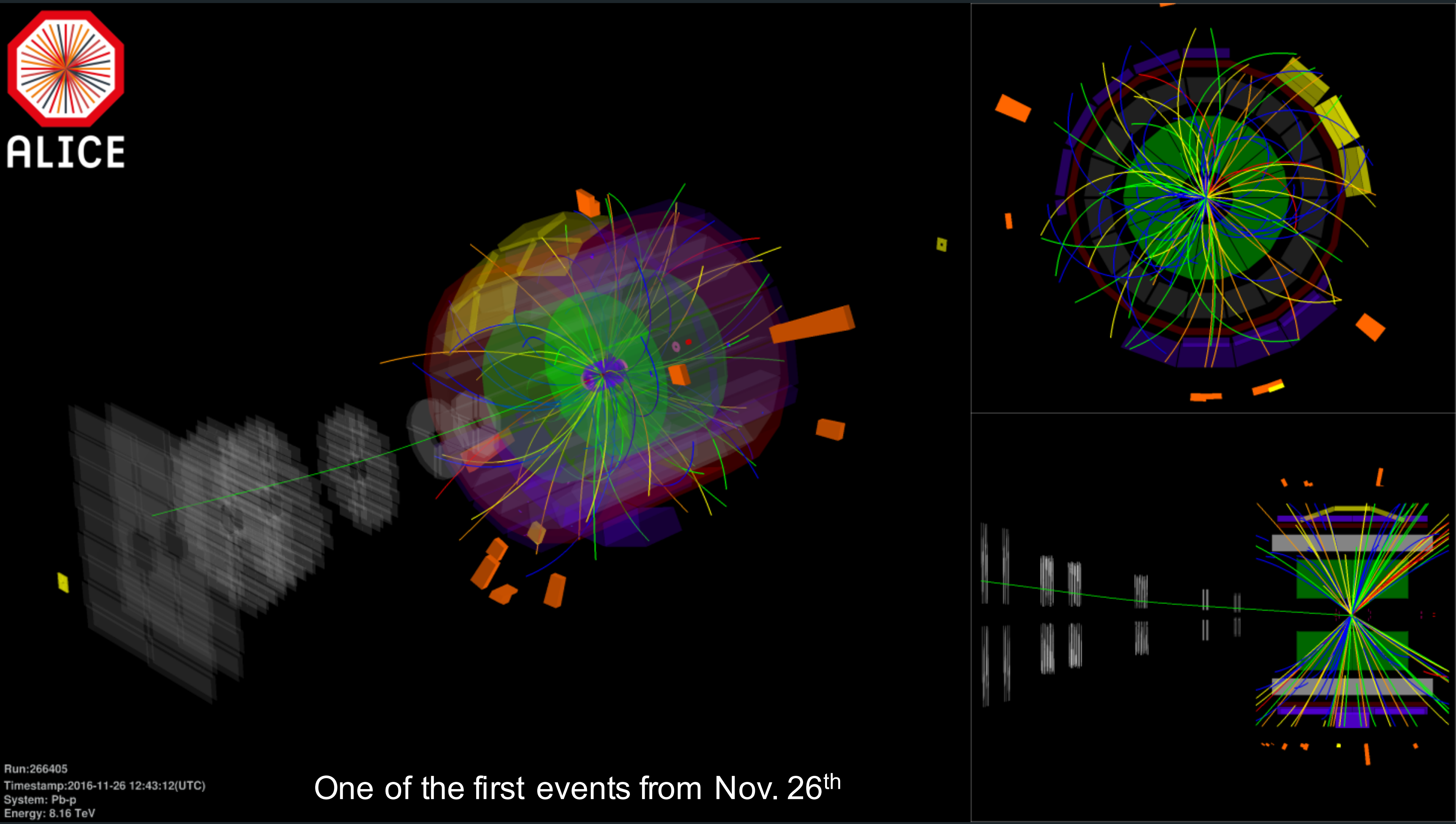


Example: TPC PID: dE/dx



Example: Hypertriton reconstructio

p-Pb@8.16 TeV in ALICE

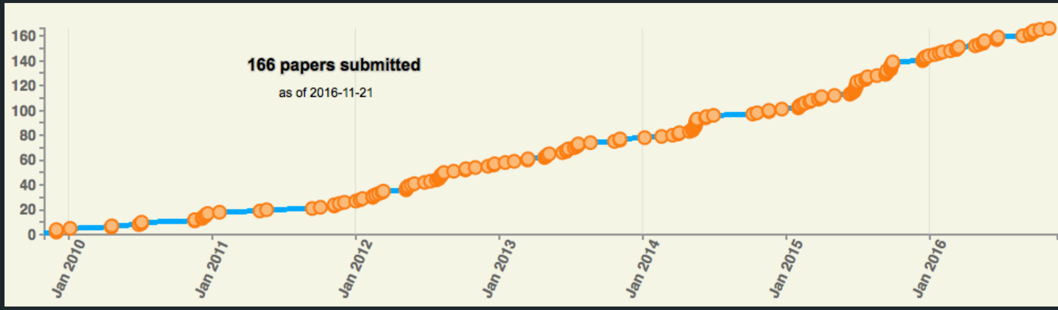


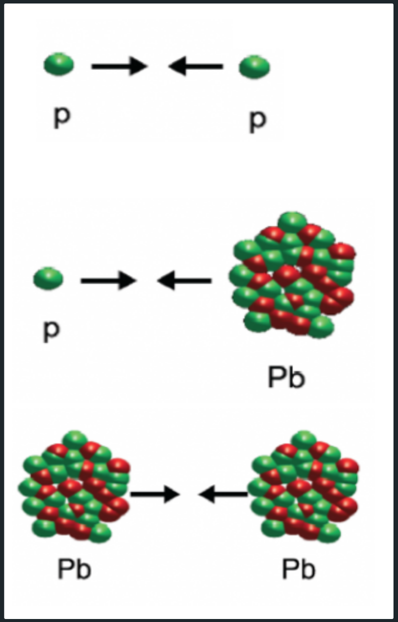
One of the first events from Nov. 26th

Impact on Physics Results

- Physics Board (ad personam): A. Androic (GSI)
- Physics Working Group Conveners (8 PWGs)
  - O. Busch (U. Heidelberg/Tsukuba)
  - designated: A. Marin (U. Heidelberg), L. Cunqeiro (U. Münster)
- Editorial Board
  - Y. Pachmayer (U Heidelberg)
- Conference Committee
  - C. Klein-Bösing (U Münster)
  - designated CC Chair: R. Averbeck (GSI)

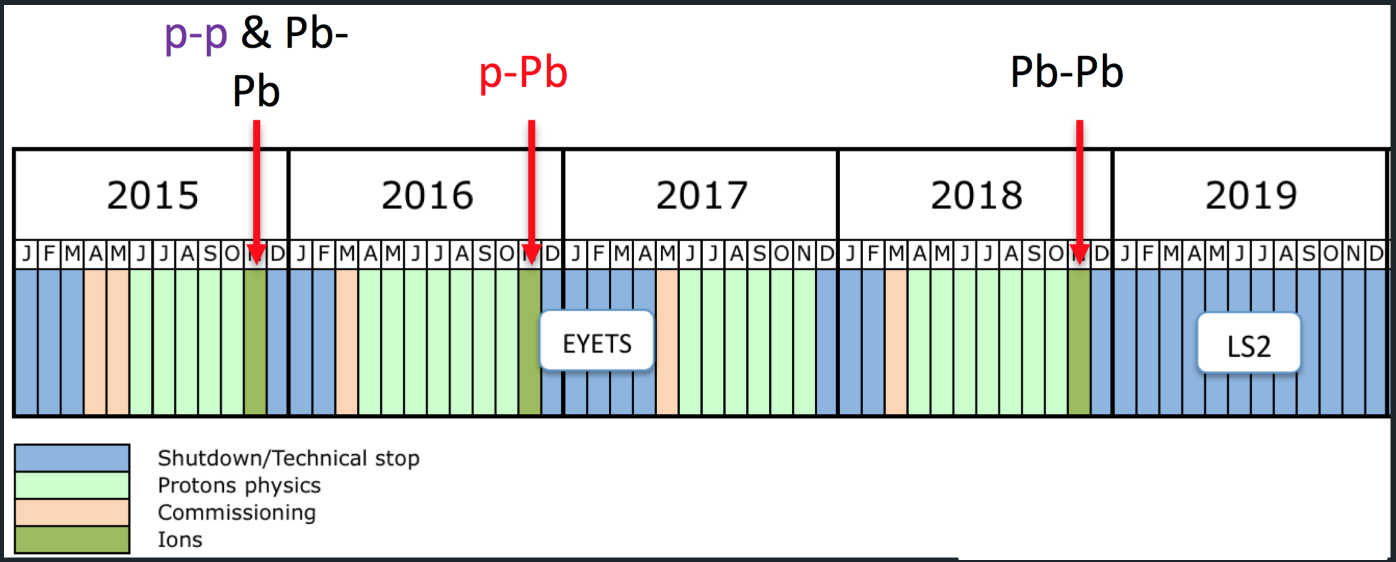
- 40 PhD Students, 18 PostDocs + 29 Physicists
- Essential contributions analysis, calibration, paper committees and internal review committees
- Supported by Tier2 center (GSI)
- Publications in 2016: 29 (all time high)
  - 2015/16 56 publications
  - Total: 152 publications, 166 submitted
  - More than 18000 citations
    4×500+, (4+10)×250+,
    (4+10+36))×100+,





		non-perturbative (low p_T/soft)	perturbative QCD (high p_T/hard)
pp	vacuum QCD	string breaking, MC-tuning	PDF x pQCD x FF
p-Pb	+ initial state and (cold) nuclear matter effects	scaling laws CGC? “Cronin”-Effect	PDF → nPDF final state interactions?
Pb-Pb	+ Quark-Gluon Plasma	thermodynamics energy density, temperature, collectivity, chemical composition	jet quenching modified FF

Key questions: **What are the properties of the QGP?**
Evolution/connection of particle production in the soft regime from small to large systems?



Run02: Pb-Pb

HEAVY IONS AT 5 TEV

Pb-Pb 5.02 TeV Multiplicity

Multiplicity in AA measure for initial energy density

$$\varepsilon_{Bj} = \frac{\langle m_T \rangle}{\tau_0 A_{T,0}} \cdot \left.\frac{dN}{d\eta}\right|_{\eta=0}$$

formation time × overlap area= initial volume

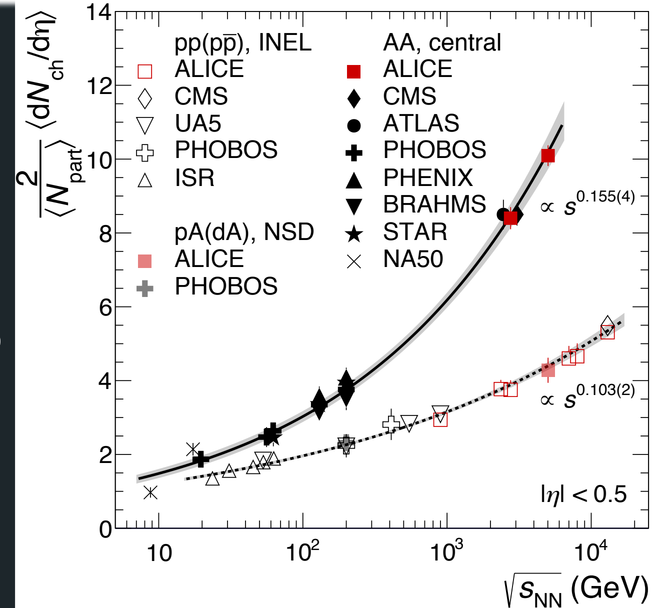
*Bjorken PRD 27, 140 (1983)

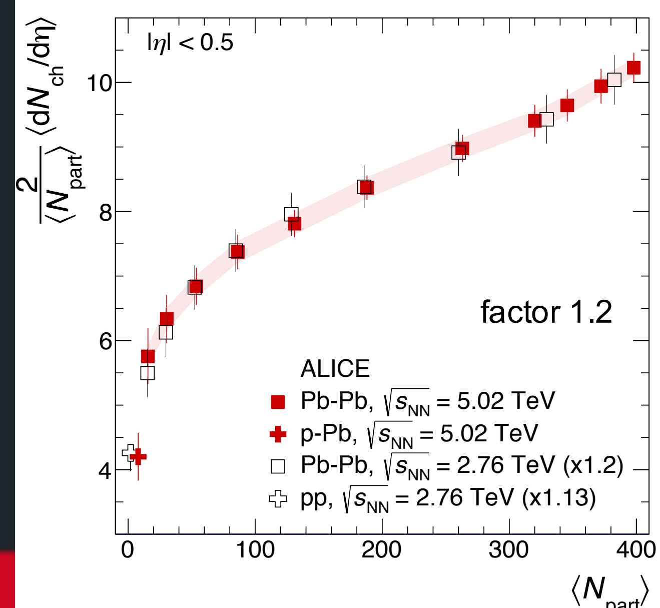
- 0-5% most central $dN_{ch}/d\eta = 1943 \pm 54$

- Particles per participant pair:
  Trend for AA confirmed,
  stronger increase than for pp and pA

- Remarkable agreement of centrality dependence
  (similar also to 200 GeV, factor 2.1 to 2.76 TeV)

Phys. Rev. Lett 116 (2016) 222302

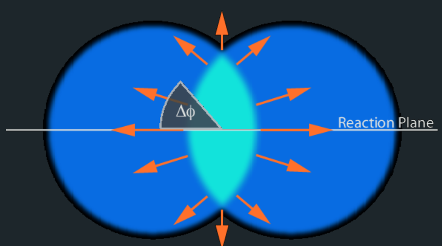




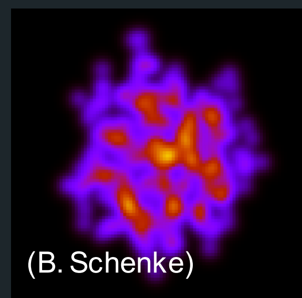
Pb-Pb 5.02 TeV Flow Harmonics

For collective system **spatial anisotropy** of collision zone causes different pressure gradients
→ **momentum anisotropy**

on average



single event

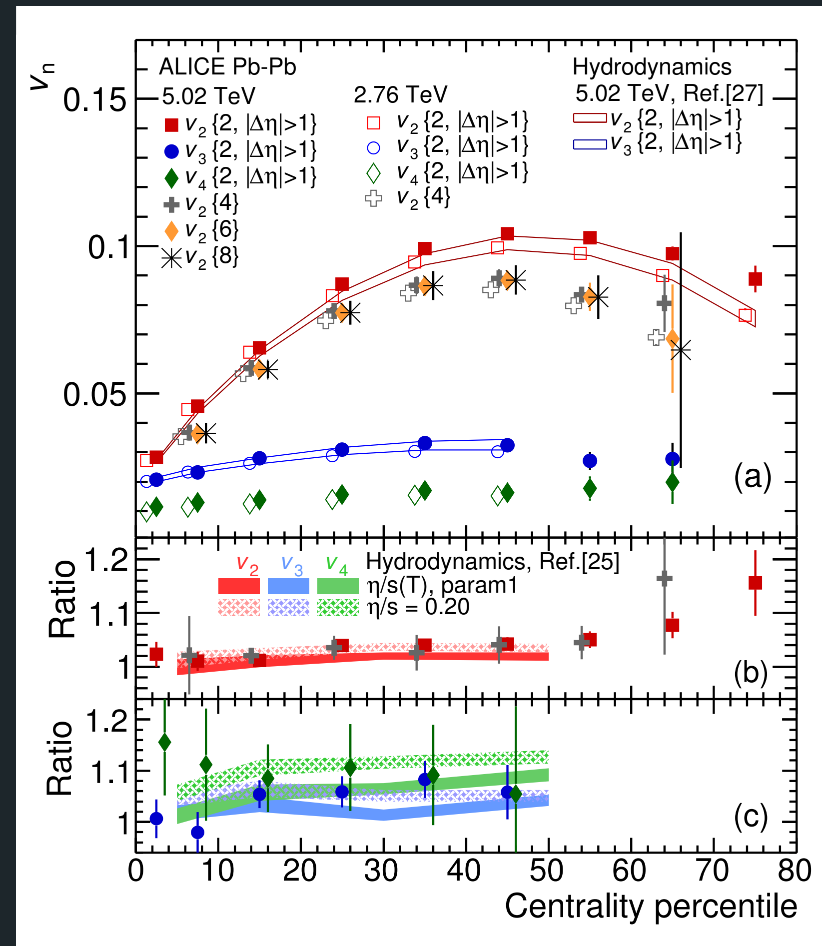


- Momentum anisotropy characterized by harmonic series

$$C \propto 1 + \sum v_n \cos(n \cdot \Delta\phi_n)$$

  - v_2: elliptic flow, v_3 triangular
- Test of equation of state and initial conditions via hydrodynamic calculations
- How perfect is the fluid?

Phys. Rev. Lett. 116 (2016) 132302



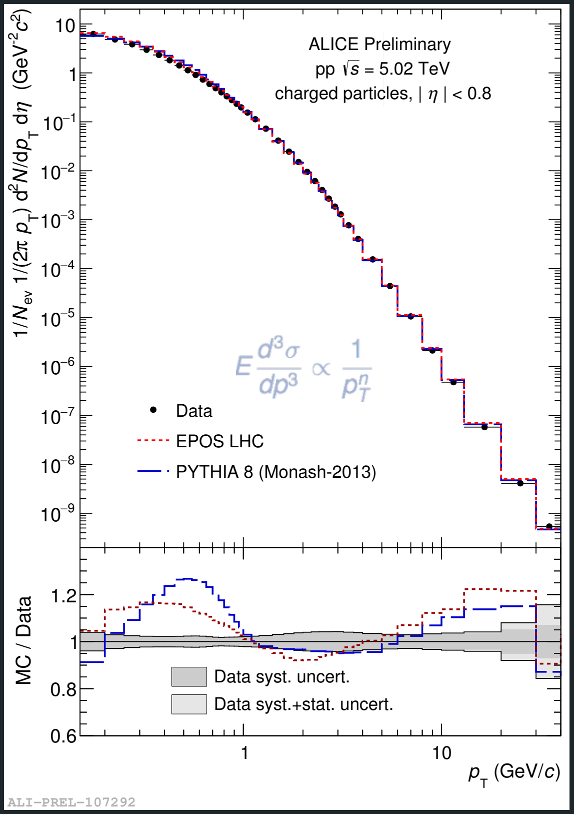
Further constraints on η/s via temperature dependence of higher harmonics v_3 and v_4.
Consistent with models using either constant η/s or η/s(T).

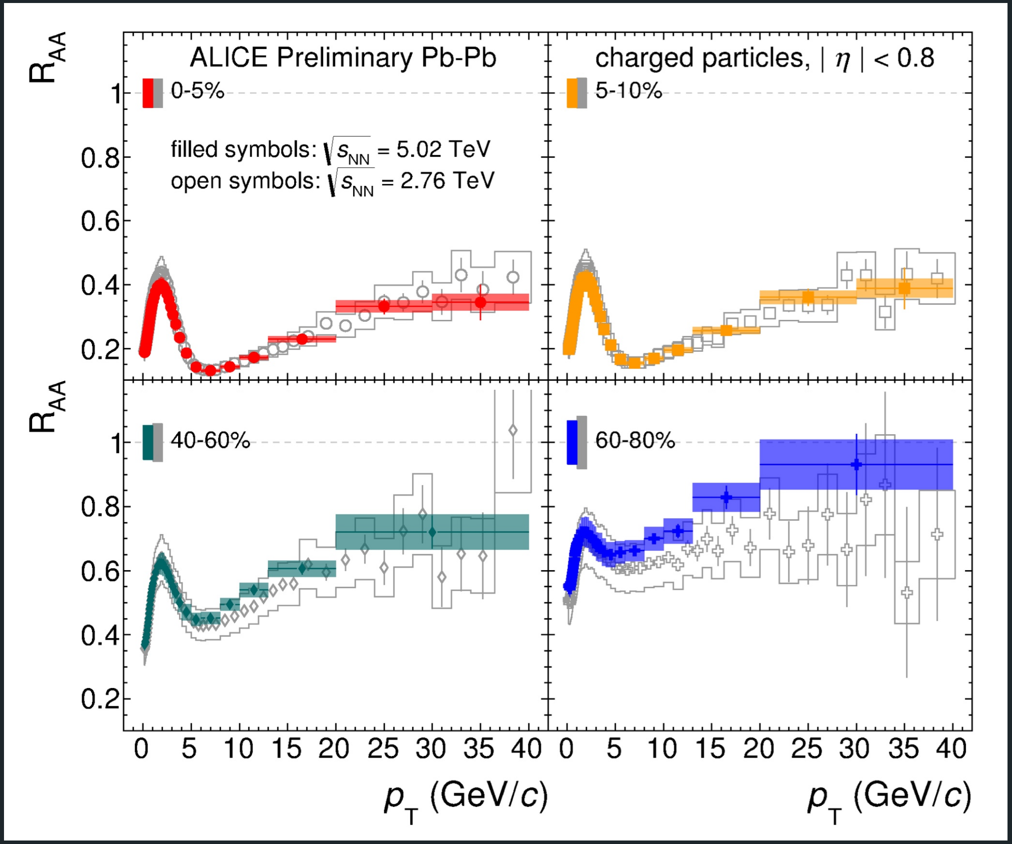
Pb-Pb 5.02 TeV
Nuclear Modification Factor

pp-Reference spectrum
hard scattering → power law

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{N_{coll}\, dN_{pp}/dp_T}$$

$R_{AA} \approx 1$ for hard scattering,
in absence of nuclear effects

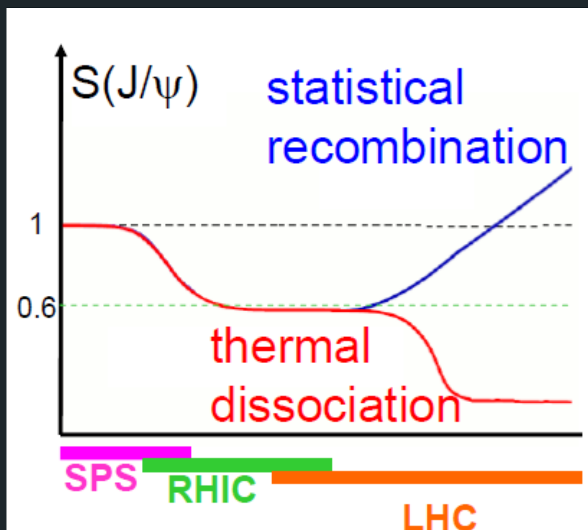




Common explanation: Strong final state interaction of leading parton (energy loss).
Little change from 2.76 TeV, hotter medium partially compensated by flatter parton spectrum.

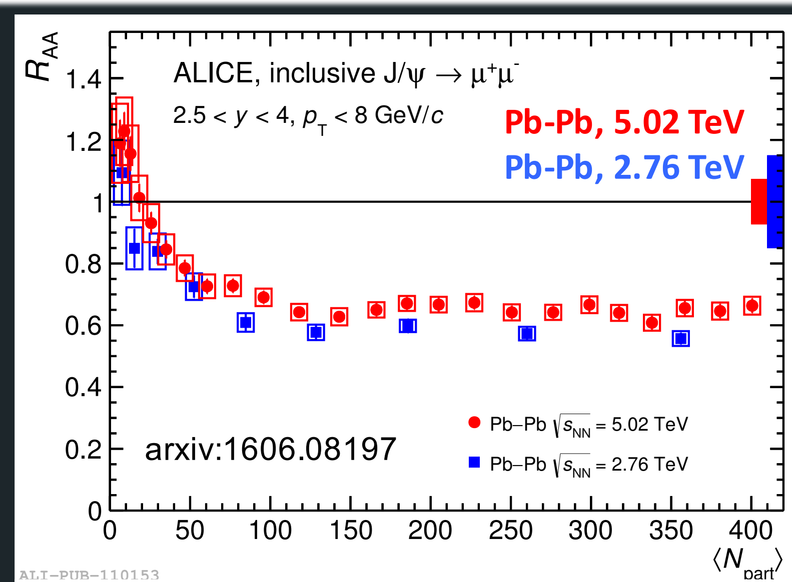
Pb-Pb 5.02 TeV Forward J/ψ Production

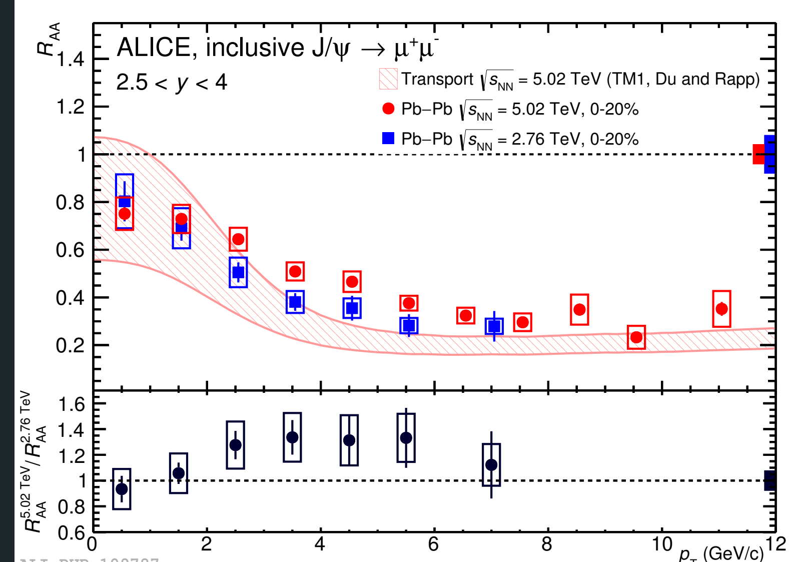
- Charm quarks produced in hard scatterings
- Charmonia dissolved in QGP (Matsui and Satz 1986)
- At LHC energy, J/psi is dominantly formed by statistical hadronization or recombination (Andronic et al. 2003



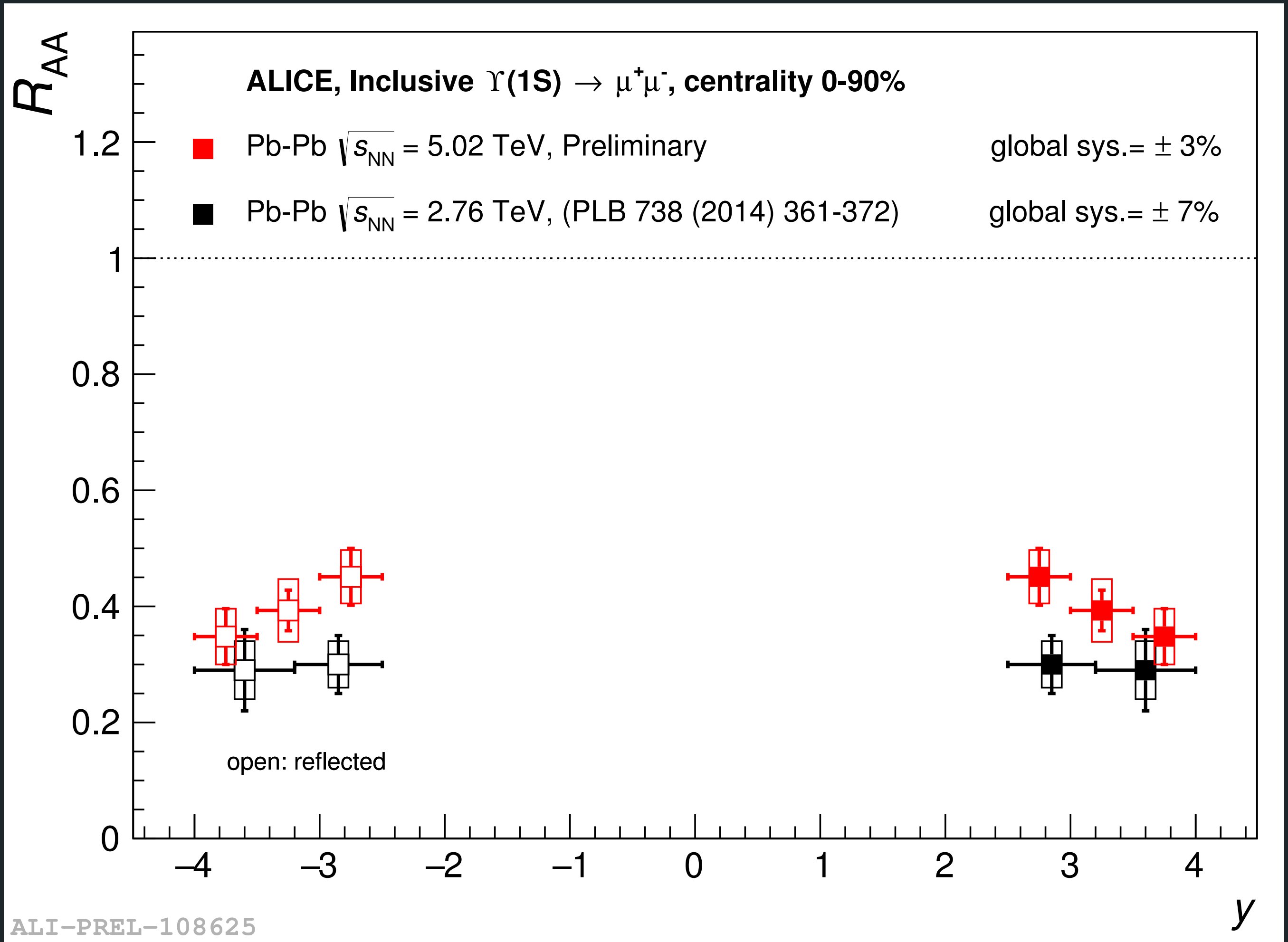
- Expect R_{AA}(5 TeV) > R_{AA}(2.76 TeV) for integrated yield
- Confirmed via ratio of R_{AA} at the two energies
  → reduced uncertainties on R_{AA} and models
- **R_{AA} 15% larger than at lower energy**

Very versatile probe testing dissociation/recombination and parton energy loss





Pb-Pb 5.02 TeV
Latest Results



Minimum Bias: Enhancement even for much heavier Υ

pp p-Pb and Pb-Pb

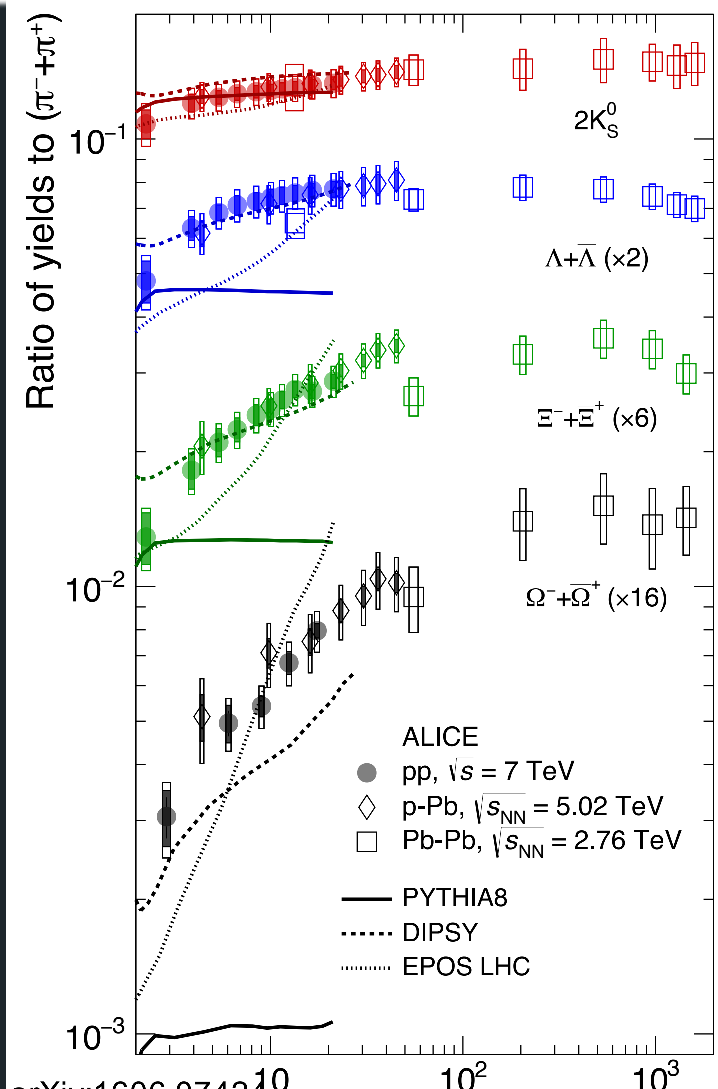
A CLOSER LOOK AT RUN01

Evolution of Particle Ratios

- Smooth evolution of particle ratios with multiplicity.
- Slope strongly species dependent
- steepest for multi-strange baryons.
- Values of (geometrically large) fireball reached with pp and p-Pb collisions
- Plateau in strangeness production demonstrates that grand-canonical limit is reached for large systems with T_{ch} at QCD phase boundary
- String hadronization models do not describe data well

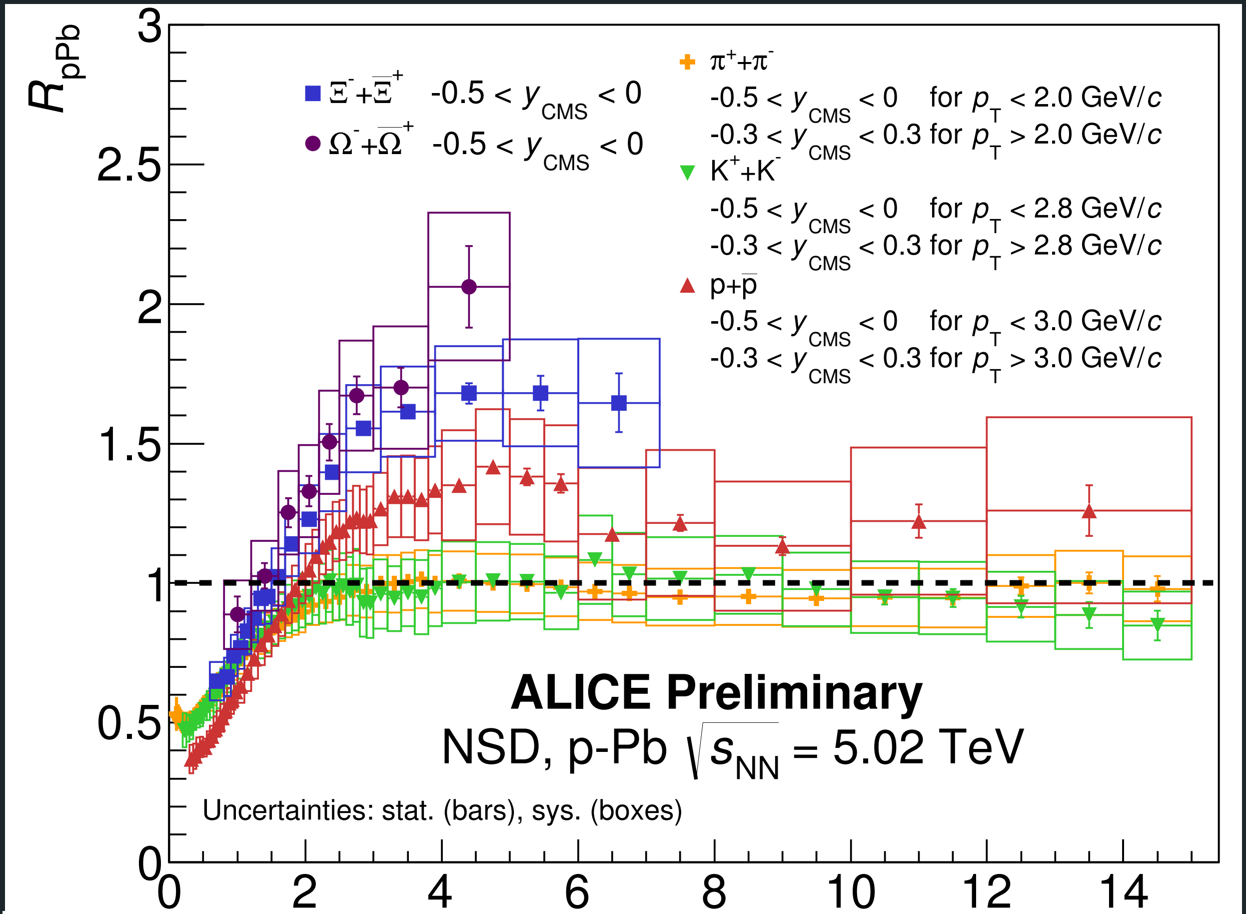
How well do we understand hadronization?

Is there a fundamental difference between pp and Pb-Pb or are the same mechanisms at work for large multiplicities in small systems?



arXiv:1606.07424 (submitted to PRL)

Identified Particles in p-Pb



π/K/p Phys. Lett. B 760 (2016) 720

Species (mass?) dependent enhancement of particle production in p-Pb persists to large p_T.

High p_T → back to unity (confirmed by ALICE jets)

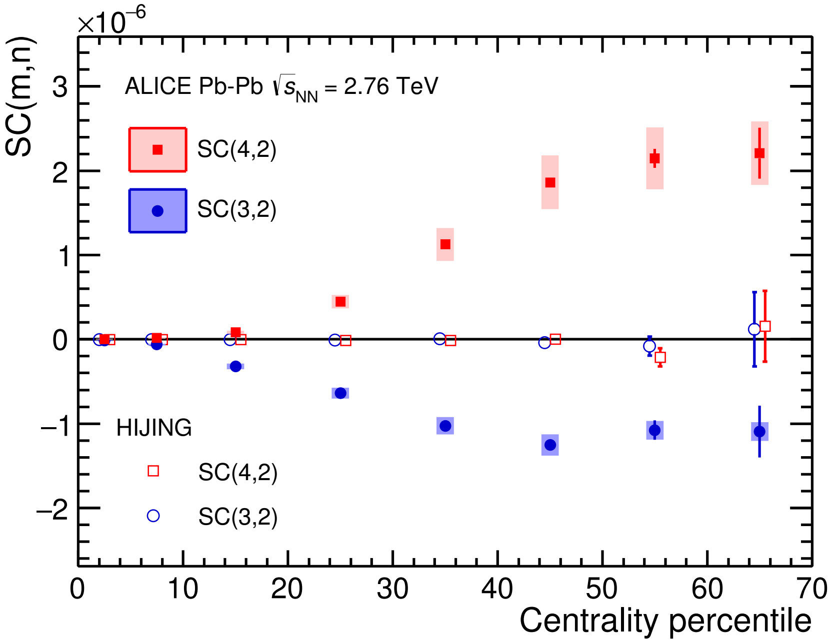
Are there collective effects at work?
(Previously observed by ALICE: Long range angular correlations, mass ordered v_2)

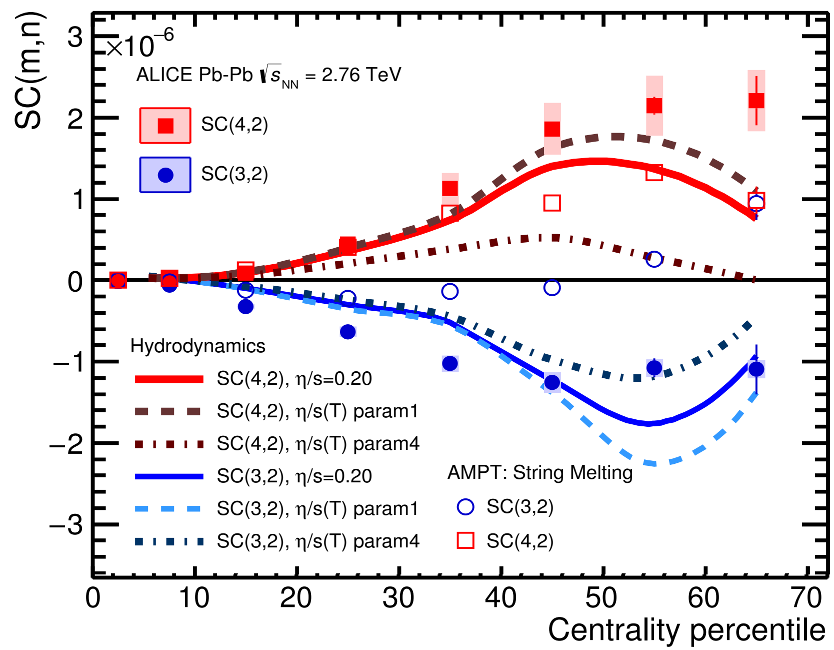
Flow Harmonic Correlations in Pb-Pb

Test correlation between different flow harmonics via 4-particle correlations (**S**ymmetric **C**umulants)

$$\langle\langle \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4)\rangle\rangle_c = \langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle$$

Phys. Rev. Lett. 117 (2016) 182301
Editors' Suggestion





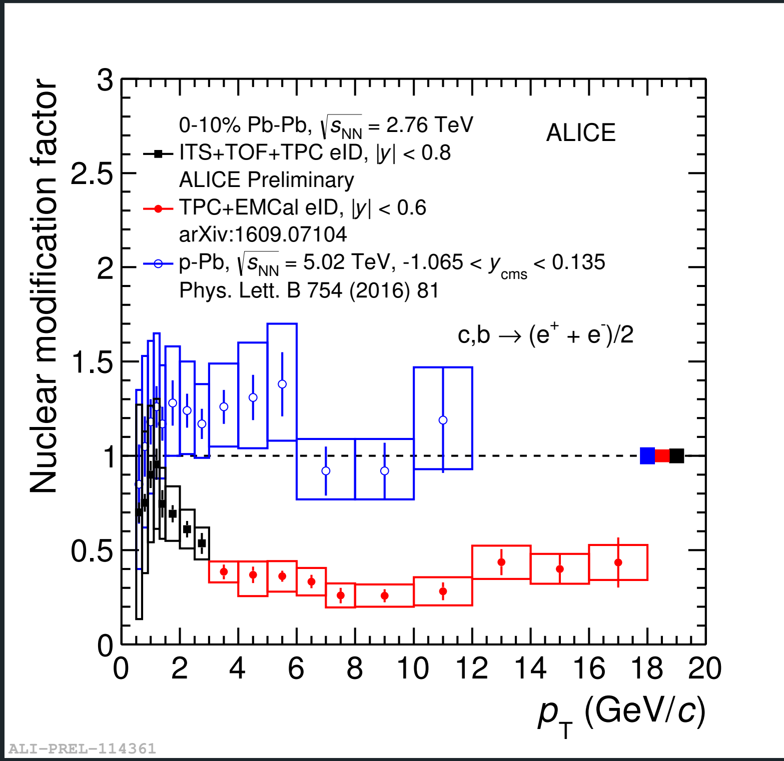
(Anti-)correlations between v_2 and v_4 (v_3) observed.
Non-flow effects modeled by HIJING show no correlations → true collective origin.

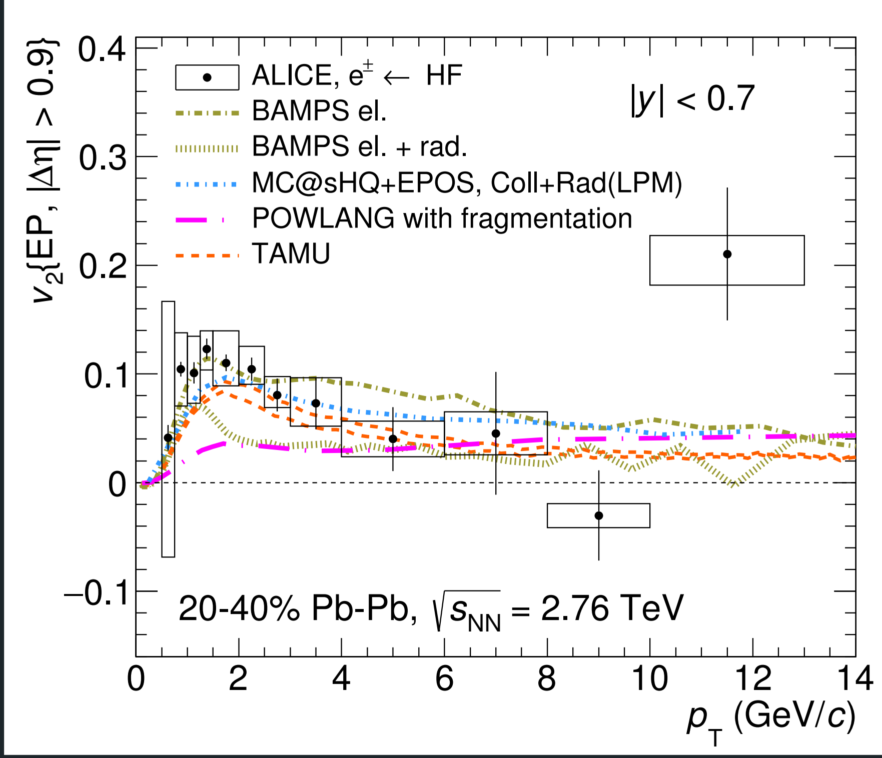
Further/better constraints on medium η/s and initial conditions.
Currently, neither constant nor T dependent η/s provide consistent description

Heavy Flavor

p-Pb: Phys. Lett. B 754 (2016) 81-93
Pb-Pb: arxiv:1609.07104

JHEP 09 (2016) 028

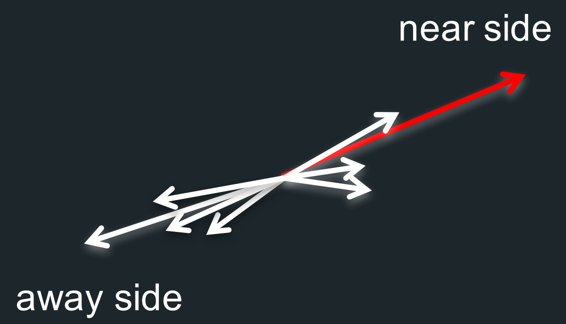


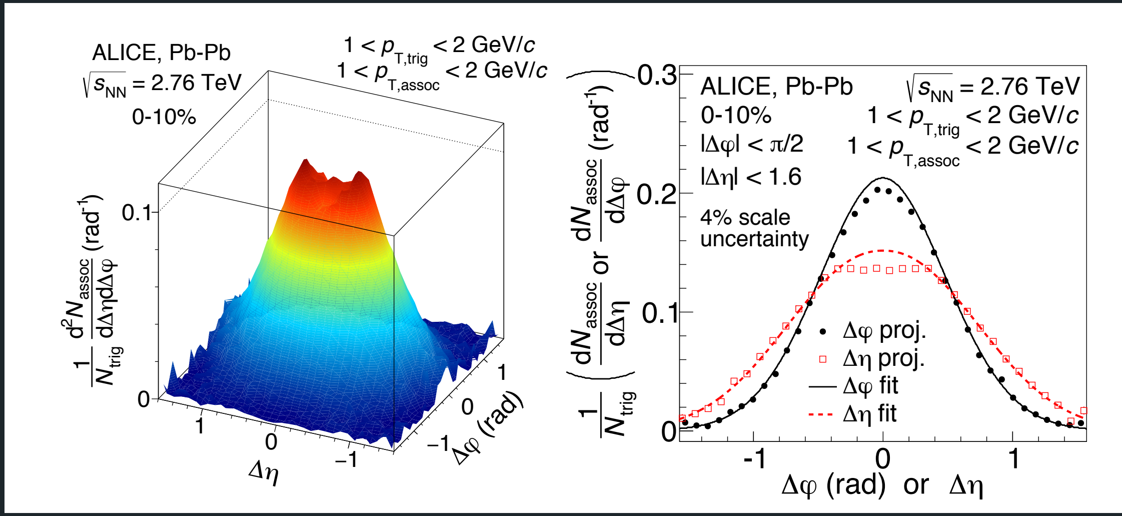


Towards extraction of heavy quark transport coefficients
(together with data on D mesons, incl. v_2)

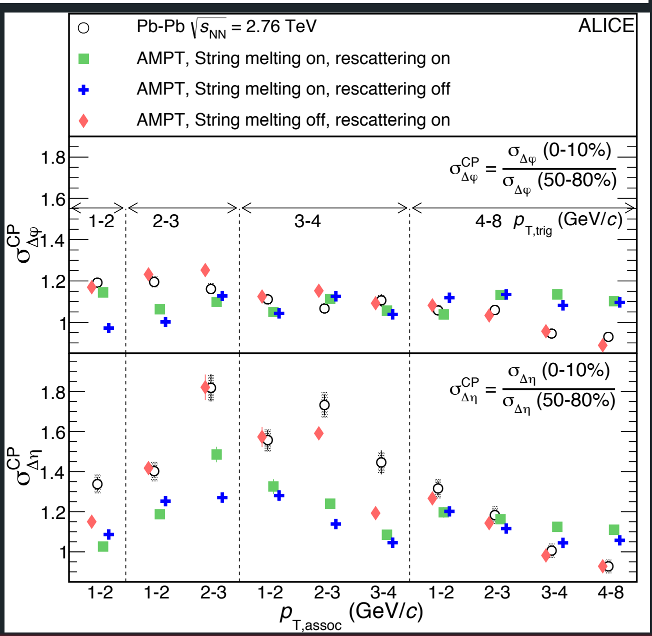
Correlations and Jets in Pb-Pb

hadrons associated with
a trigger particle





arxiv:1609.06643



Combinatorial background and long-range correlations (collective flow) subtracted

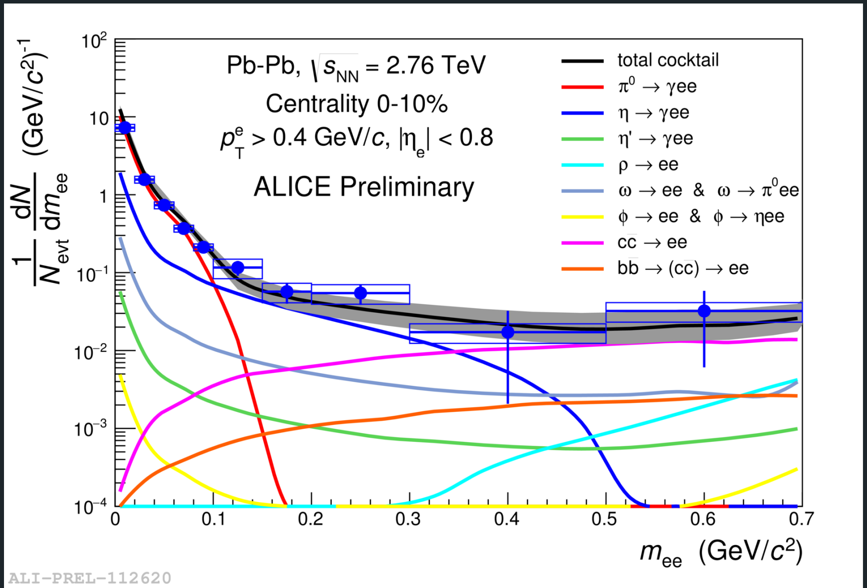
Remaining jet peak broadened in η and depleted at mid rapidity

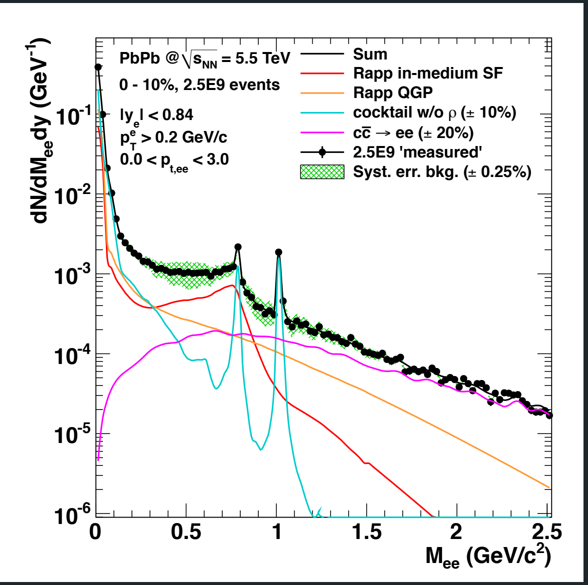
Impact of collective effects on jet fragments:
Hadronic rescattering is essential.
Broadening correlated with strength of radial expansion.

Dielectrons in Pb-Pb

Penetrating probes emitted throughout the evolution of the system, similar to photons but additional handle via invariant mass + potential in-medium modified spectral functions (e.g. ρ broadening)

First measurement in Pb-Pb (low mass: m_{ee} < 700 MeV/c^2)

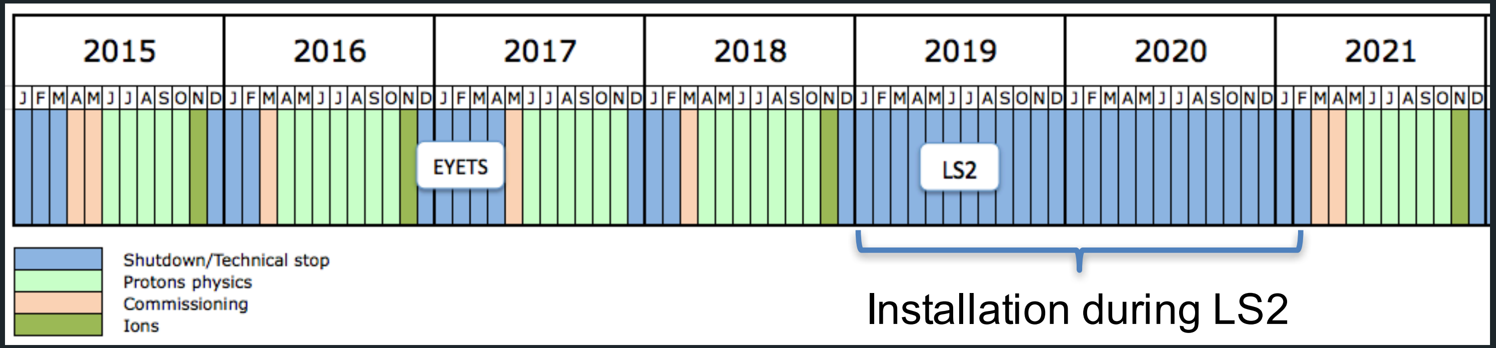




Within large uncertainties no enhancement of dielectron production for p_T > 0.4 GeV observed,

ALICE upgrade: better suppression of background and increased event rate and lower p_T cut-off (0.2 GeV)

ALICE



end of 2020s
(beyond LS3)

UPGRADE

ALICE Upgrade

Further develop ALICE unique strengths

- low p_T tracking
- particle identification
- vertexing
- small radiation length

Focus on high-precision measurement of low p_T rare probes, which often do not allow for low level triggering

Target

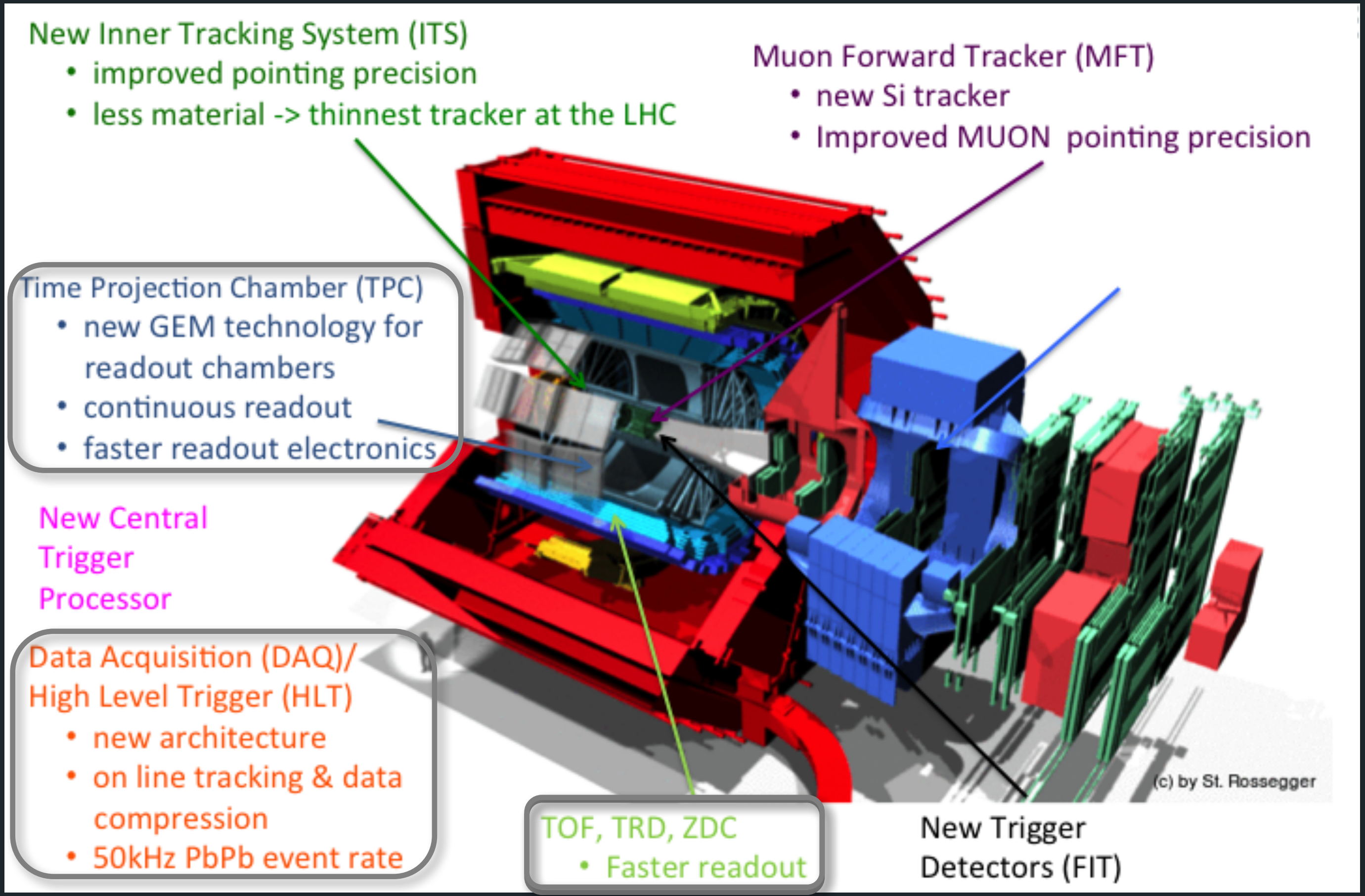
Pb-Pb recorded luminosity: ≥ 10 nb^{-1}
(factor 100 increase in sampled events)

Strategy

Read out all Pb-Pb interactions with 50 kHz (continuous e.g. for TPC + online data reduction), lower material budget

Complementary to ATLAS and CMS

ALICE Upgrade German Contributions



Involved groups (TPC, TRD, HLT)

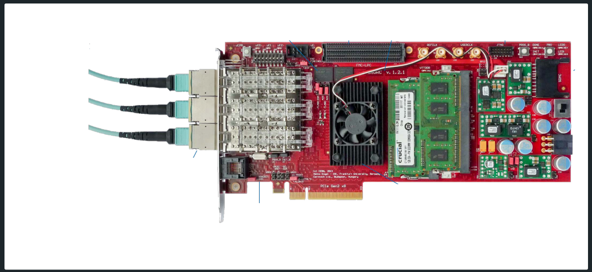
GSI/EMMI
Universität Heidelberg
Universität Frankfurt
Universität Münster
Universität Tübingen
TU München
Universität Bonn
FH Worms

TPC Upgrade
H. Appelshäuser (U. Frankfurt, PL), C. Garabatos (GSI, DPL), C. Lippmann (GSI, TC)

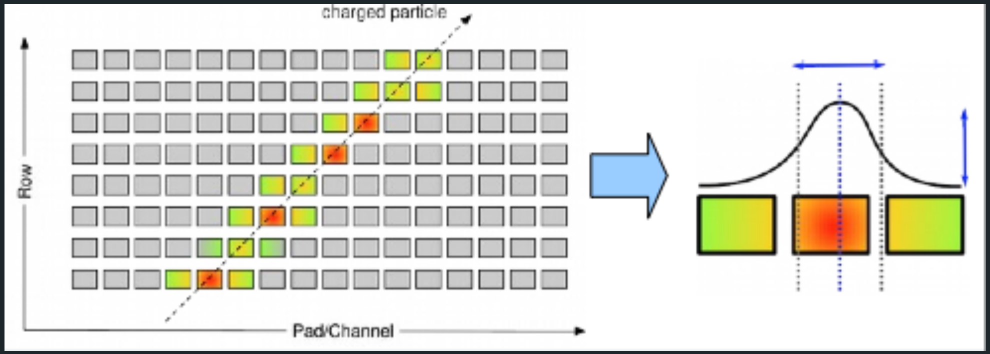
HLT Upgrade
V. Lindenstruth (U Frankfurt, PL), T. Kolleger (GSI, TC)

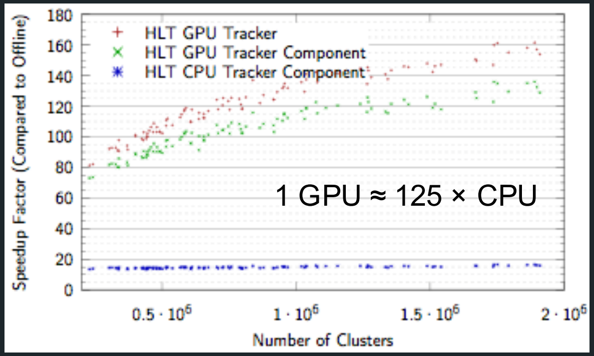
Upgrade: Online-Offline (O^2)

- Design, prototyping and testing new O^2 related concepts in Run02 HLT
  - Further development for compression
  - Online reconstruction, calibration,
  - …



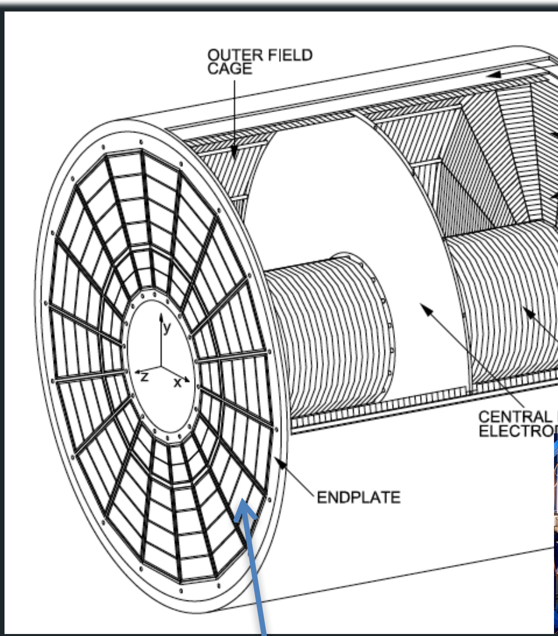
FPGA clusterfinder.

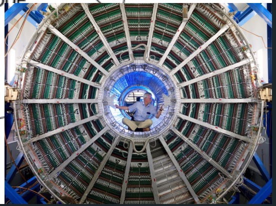


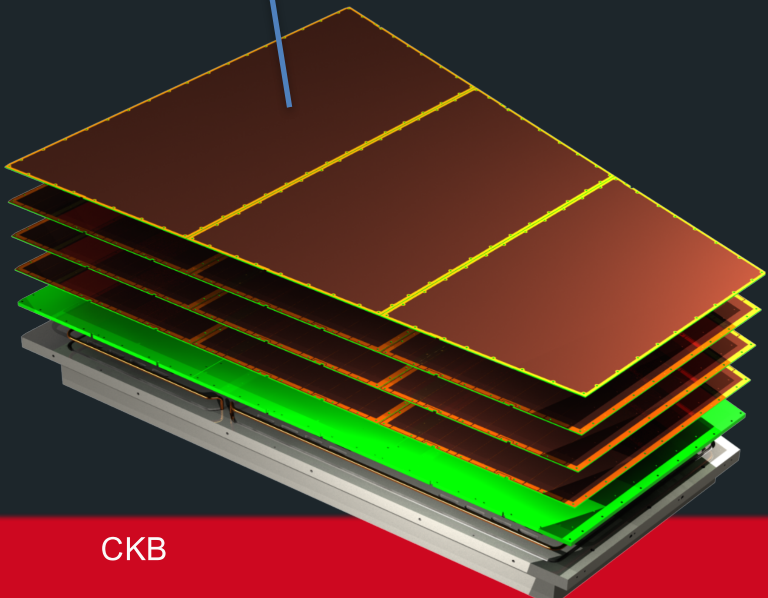


- HLT handles a significant part of the MC generation workload when not used online.
- HLT supplies the largest infrastructure for the computing upgrade project development and testing

TPC Upgrade with GEMs



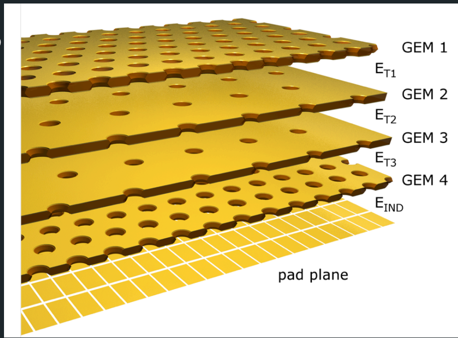




To operate at 50 kHz
=> no gating grid
=> need to minimize ion back-flow to keep space charge distortions at a tolerable level

Replace wire-chambers with quadruple Gas Electron Multipliers (GEMs)

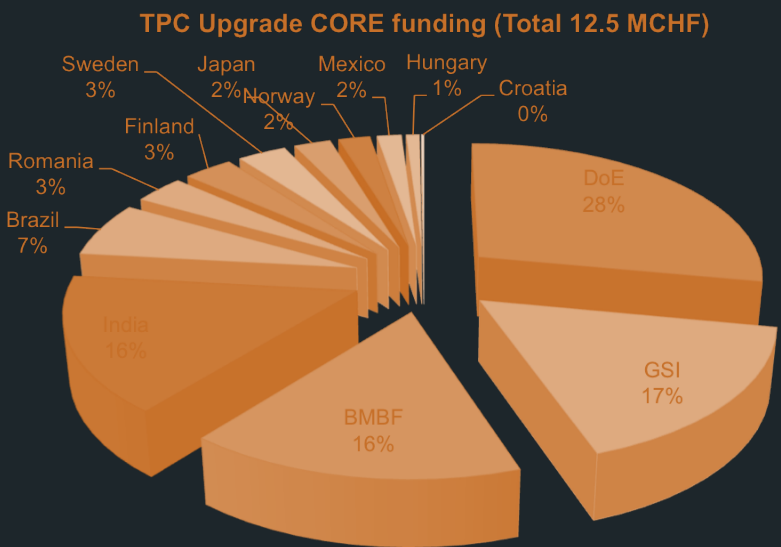
- 100 m^2 single-mask foils
- Alternating standard and large pitch
- Limits ion back-flow into drift volume
- Maintains excellent dE/dx resolution



plus new readout electronics

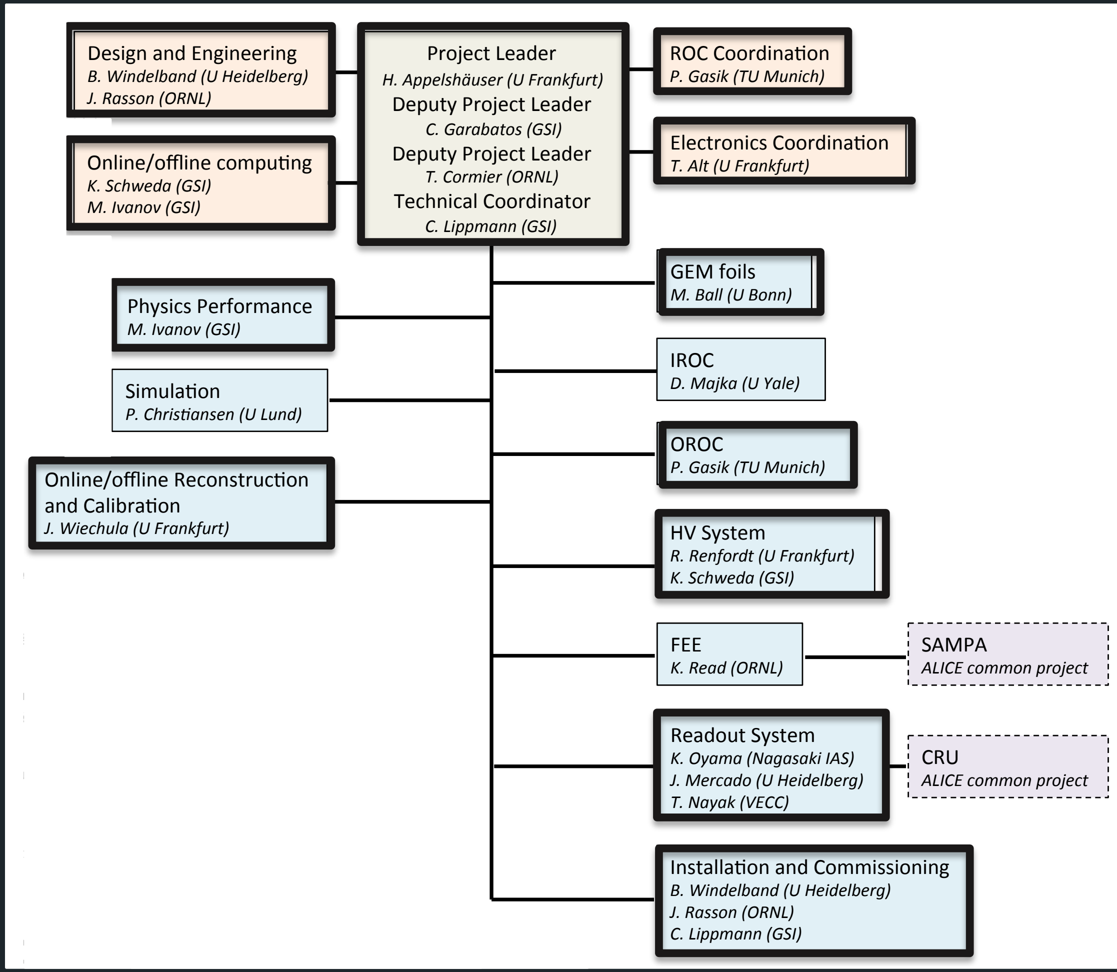
ALICE

TPC Upgrade



MOU 2016: 45 institutes
Leading German contributions

- GEM frames
- Chamber assembly
- Electronics development
- Online calibration and reconstruction
- Integration, commissioning and testing



SAMPA and FEC

ROC
pre-production (final design) of GEM **r**ead**o**ut **c**hambers almost completed

IROC chamber installed in the ALICE cavern for p-Pb run

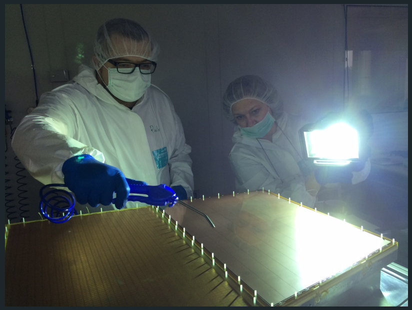
Start of mass production in 2017

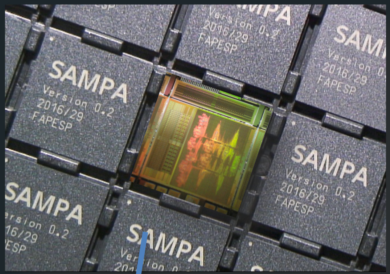
SAMPA (common TPC, MUON readout ASIC):
MPW2 (Multi-Project Wafer) under test

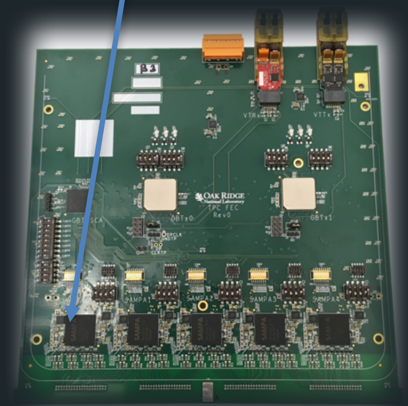
Noise within specifications Gain, signal shaping, linearity, and crosstalk according to specifications

Confirm all TPC specifications by end of the year

First **FEC** Rev0 prototype cards available, tests ongoing







Conclusions

- Fundamental measurements at a energy regime
  - Pb-Pb 2.76 → 5.02 TeV, exploring temperature dependence
  - All systems at one energy 5 TeV pp, p-Pb, Pb-Pb
- **More differential understanding of the QGP** at 2.76 TeV
  - New sensitivity to evolution, initial state and viscosity η/s
  - Modification of jet structure and interplay of soft and hard processes
  - Regeneration of quarkonia
  - Constraining heavy quark transport in QGP
- **And new questions on our understanding of small "reference" systems arise**
- **Upgrade program well under way and concepts already gradually integrated into ALICE**
- Exciting physics program for the coming **15 years** to answer fundamental questions about
  - Survival of hadrons in the QGP,
  - Hadronization at the phase boundary
  - production of loosely bound objects at high temperature
  - modified jet quenching via correlation measurements with photon and Q-tagged jetst
  - thermal radiation, temperature of the medium, chiral symmetry

2016 in Papers

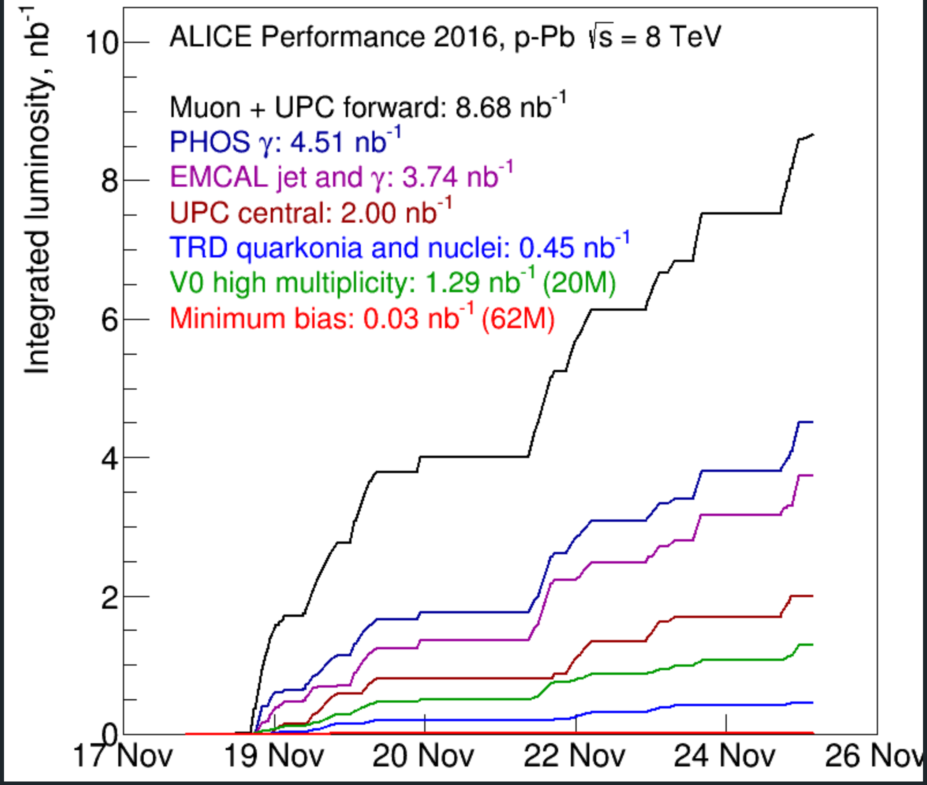
Measurement of D-meson production versus multiplicity in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, JHEP 08 (2016), 078.
$^{3}_{\Lambda}$H and $^{3}_{\bar{\Lambda}}$H production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B754 (2016), 360–372.
Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Rev. Lett. 116 (2016), 132302.
Azimuthal anisotropy of charged jet production in $\sqrt{s_{NN}}$ = 2.76 TeV Pb-Pb collisions, Phys. Lett. B753 (2016), 511–525.
Centrality dependence of charged jet production in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C76 (2016), 271.
Centrality dependence of ψ(2S) suppression in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, JHEP 06 (2016), 050.
Centrality dependence of pion freeze-out radii in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C93 (2016), 024905.
Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Rev. Lett. 116 (2016), 222302.
Centrality dependence of the nuclear modification factor of charged pions, kaons, and protons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C93 (2016) 034913.
Centrality evolution of the charged-particle pseudorapidity density over a broad pseudorapidity range in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B754 (2016), 373–385.
Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C93 (2016), 044903.
Correlated event-by-event fluctuations of flow harmonics in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. Lett. 117 (2016), 182301.
Differential studies of inclusive J/ψ and ψ(2S) production at forward rapidity in Pb-Pb collisions s_{NN} = 2.76 TeV, JHEP 05 (2016), 179.
Direct photon production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B754 (2016), 235–248.
Elliptic flow of electrons from heavy-flavour hadron decays at mid-rapidity in Pb-Pb collisions $\sqrt{s_{NN}}$ = 2.76 TeV, JHEP 09 (2016), 028.
Elliptic flow of muons from heavy-flavour hadron decays at forward rapidity in Pb-Pb collisions $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B753 (2016), 41–56.
Event shape engineering for inclusive spectra and elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C93 (2016), 034916.
Measurement of electrons from heavy-flavour hadron decays in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Lett. B754 (2016), 81–93.
Measurement of transverse energy at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C94 (2016), 034903.
Multi-strange baryon production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Lett. B758 (2016), 389–401.
Multipion Bose-Einstein correlations in pp,p -Pb, and Pb-Pb collisions at energies available at the CERN Large Hadron Collider, Phys. Rev. C93 (2016), 054908.
Multiplicity and transverse momentum evolution of charge-dependent correlations in pp, p-Pb, and Pb-Pb collisions at the LHC, Eur. Phys. J. C76 (2016), 86.
Multiplicity dependence of charged pion, kaon, and (anti)proton production at large transverse momentum in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Phys. Lett. B760 (2016), 720–735.
Particle identification in ALICE: a Bayesian approach, Eur. Phys. J. Plus 131 (2016), 168.
Production of K*(892)$_0$ and φ(1020) in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, Eur. Phys. J. C76 (2016), 245.
Production of light nuclei and anti-nuclei in pp and Pb-Pb collisions at energies available at the CERN Large Hadron Collider, Phys. Rev. C93 (2016), 024917.
Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider, JCAP 1601 (2016), 032.
Transverse momentum dependence of D-meson production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, JHEP 03 (2016), 081.

Anomalous evolution of the near-side jet peak shape in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, arxiv:1609.06643
D-meson production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and in pp collisions at $\sqrt{s}$ = 7 TeV, arxiv:1610.03055
Determination of the event collision time with the ALICE detector at the LHC, arxiv:1605.07569
Evolution of the longitudinal and azimuthal structure of the near-side jet peak in Pb-Pb collisions $\sqrt{s_{NN}}$ = 2.76 TeV, arxiv:1609.06667
J/ψ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, arxiv:1606.08197
Measurement of azimuthal correlations of D mesons and charged particles in pp collisions at $\sqrt{s}$ = 7 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, arxiv:1605.06963
Measurement of electrons from beauty-hadron decays in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, arxiv:1609.03898.
Measurement of the production of high-p_T electrons from heavy-flavour hadron decays in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, arxiv:1609.07104
Multiplicity-dependent enhancement of strange and multi-strange hadron production in proton-proton collisions at $\sqrt{s}$ = 7 TeV, arxiv:1606.07424

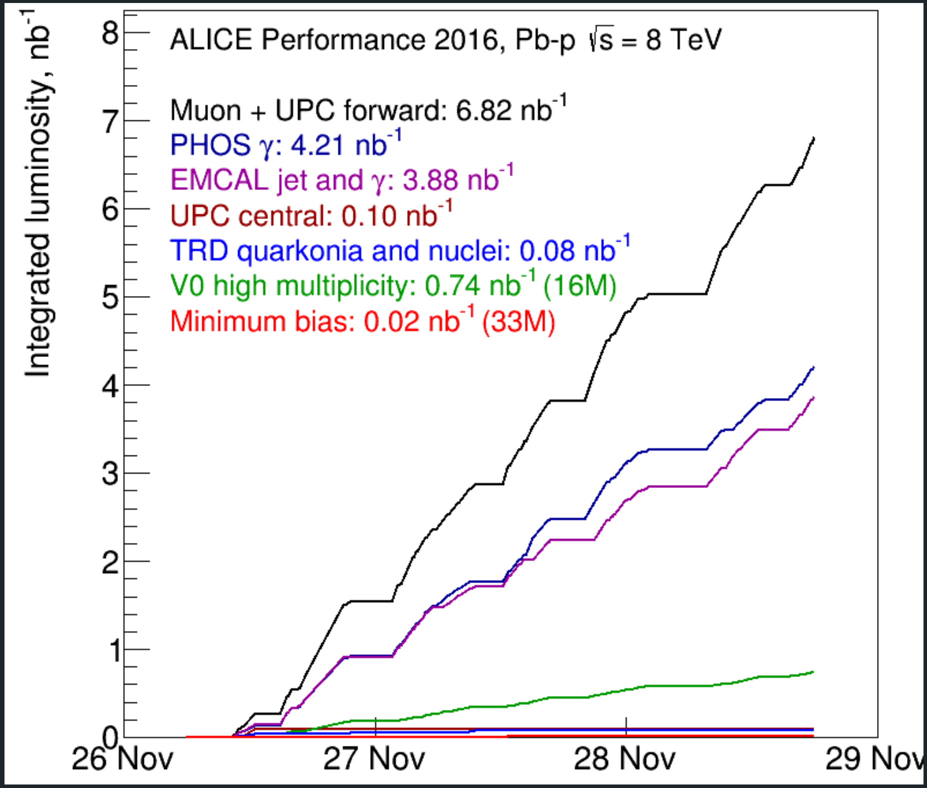
EXTRAS

8 TeV pPb

p–Pb

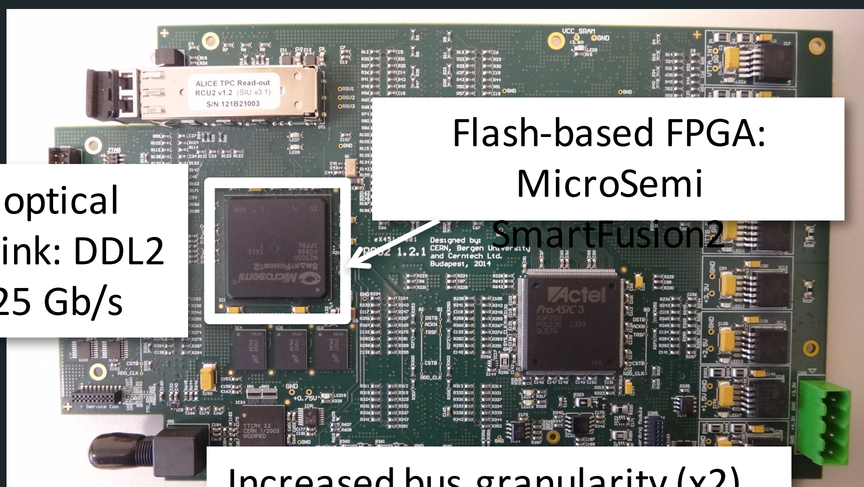


Pb–p



Detector Performance

- New Readout Control Unit (RCU2) for **better radiation tolerance** and **faster readout** (factor 2 for central Pb-Pb)
- Operation since 04/2016, some firmware updates during pp



Faster optical readout link: DDL2 @ 3.125 Gb/s

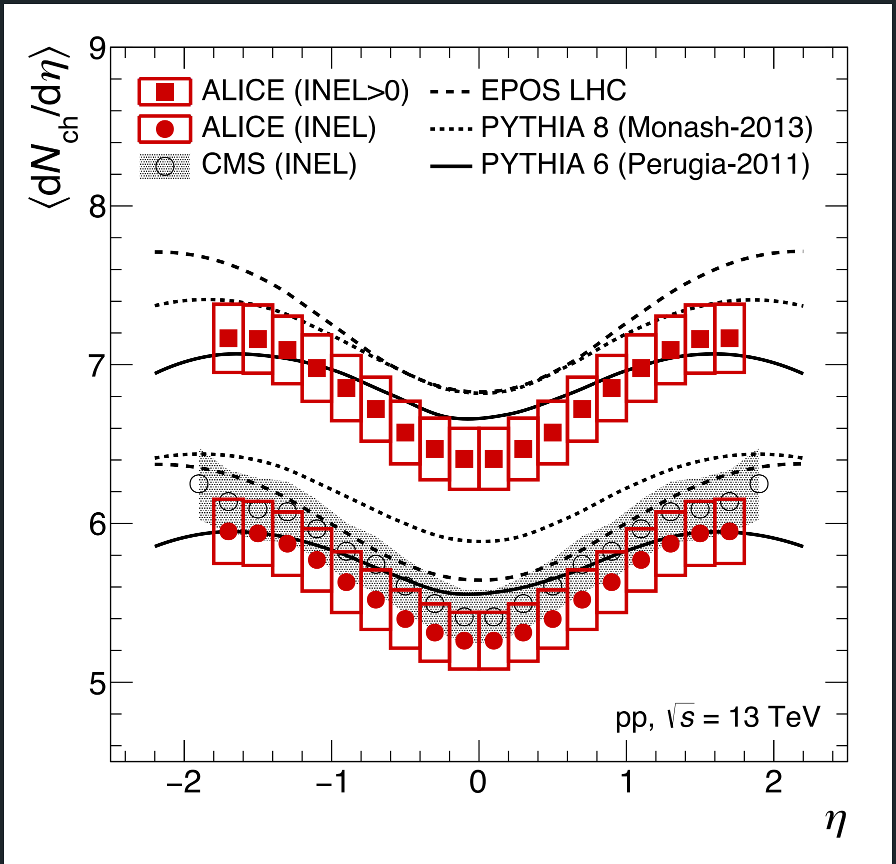
Flash-based FPGA: MicroSemi SmartFusion2

Increased bus granularity (x2)
➔ highly parallelized readout

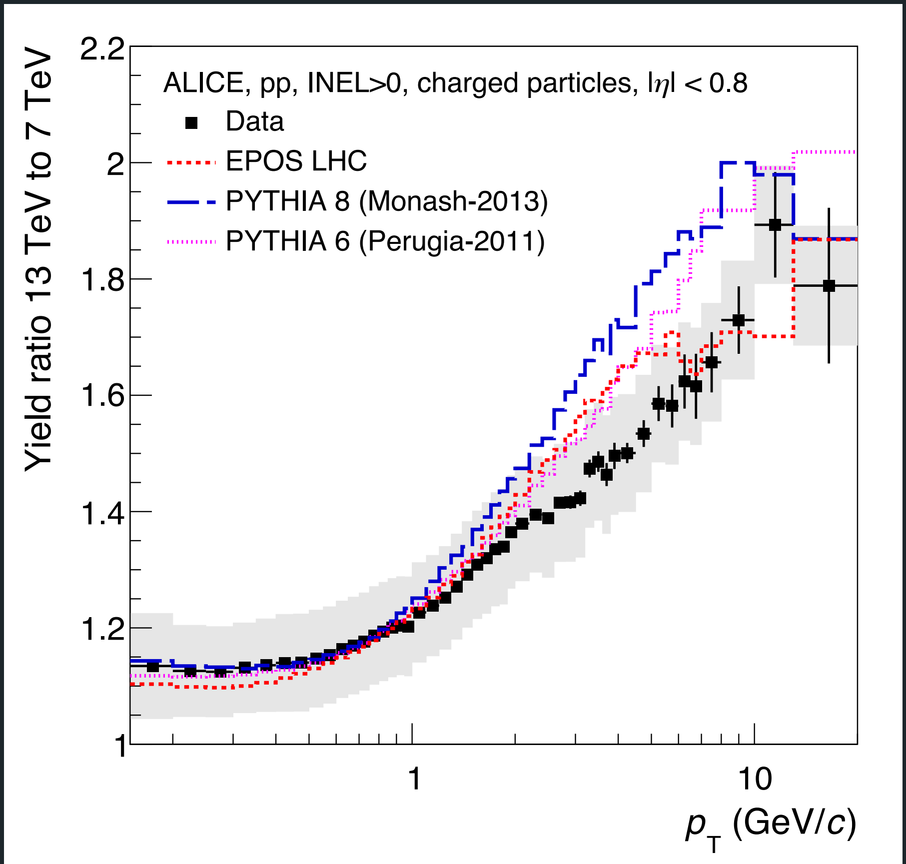
- Experience: **very stable**
  - 1 issue every ~50h of running time
  - Automatic error recovery during data taking (PAUSE AND RESET)

Run 2: 13 TeV pp

Multiplicity distribution pp 13 TeV



Evolution of spectral shap 7 → 13 TeV

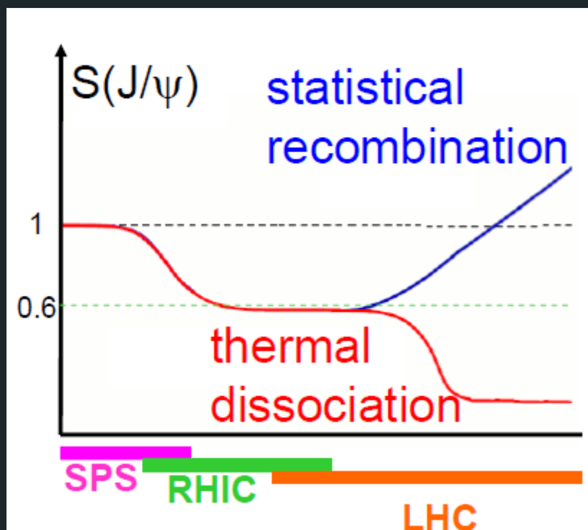


ALICE: Phys. Lett. B 753 (2016) 319-329

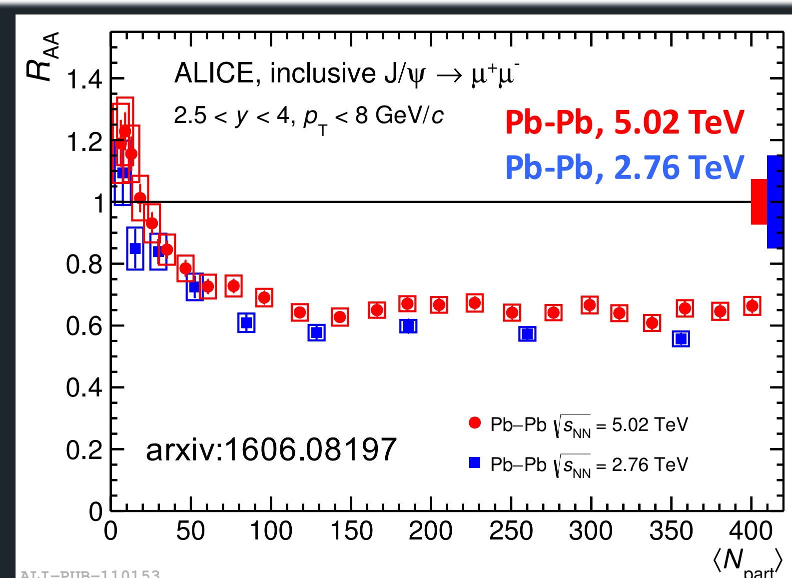
Reasonably well reproduced by MC, but no consistent picture for soft processes

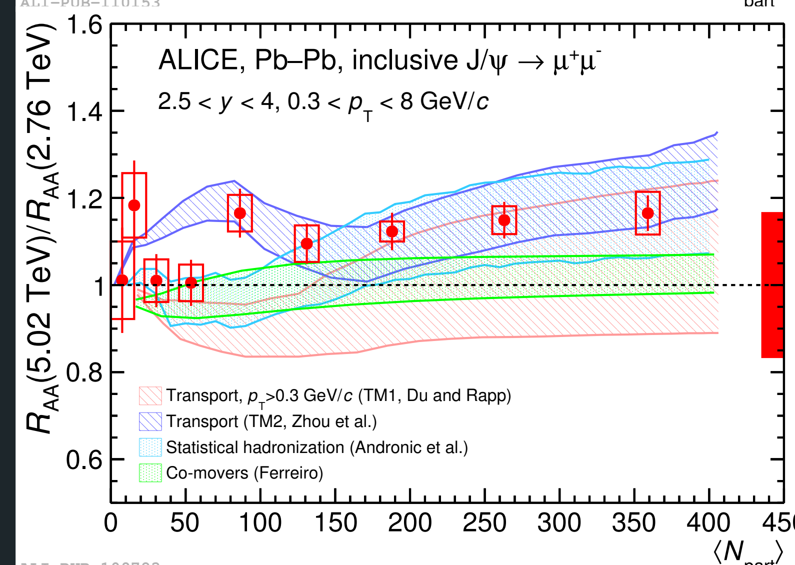
Pb-Pb 5.02 TeV
Forward J/ψ Production

- Charm quarks produced in hard scatterings
- Charmonia dissolved in QGP (Matsui and Satz 1986)
- At LHC energy, J/psi is dominantly formed by statistical hadronization or recombination (Andronic et al. 2003



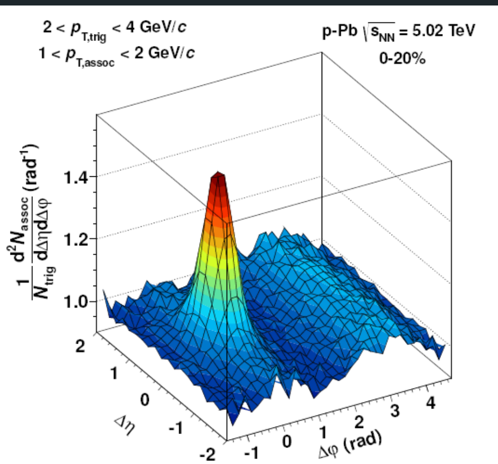
- Expect R_{AA}(5 TeV) > R_{AA}(2.76 TeV) for integrated yield
- Confirmed via ratio of R_{AA} at the two energies → reduced uncertainties on R_{AA} and models
- **R_{AA} 15% larger than at lower energy**





Reminder
Double Ridge in p-Pb

high multiplicity - low multiplicity = double ridge



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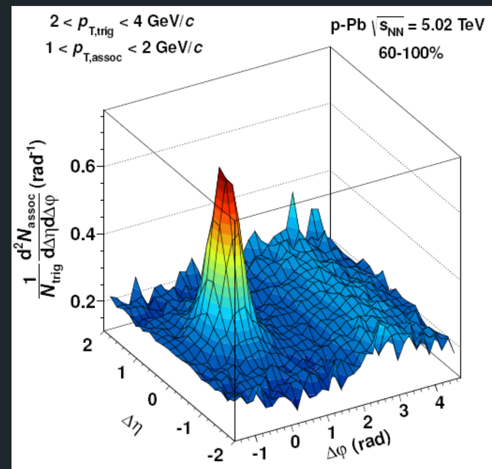

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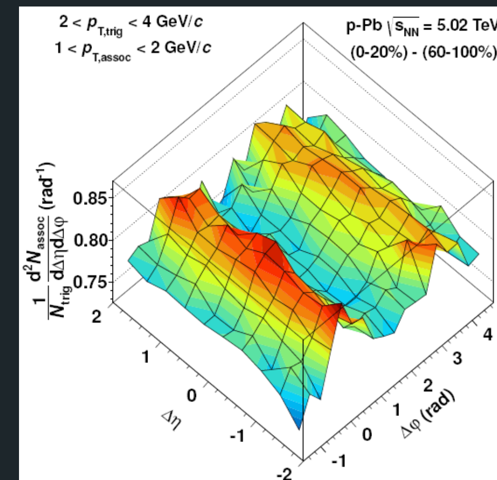
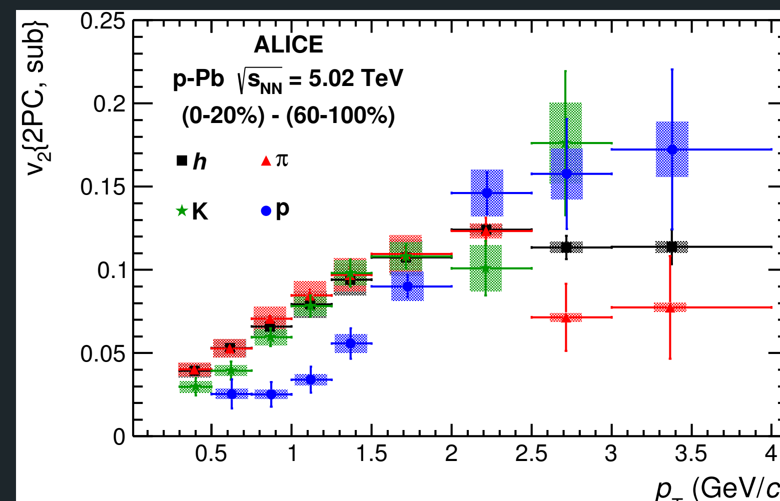


Near and away side ridges have similar magnitude quantified by Fourier decomposition dominated by v_2 and v_3

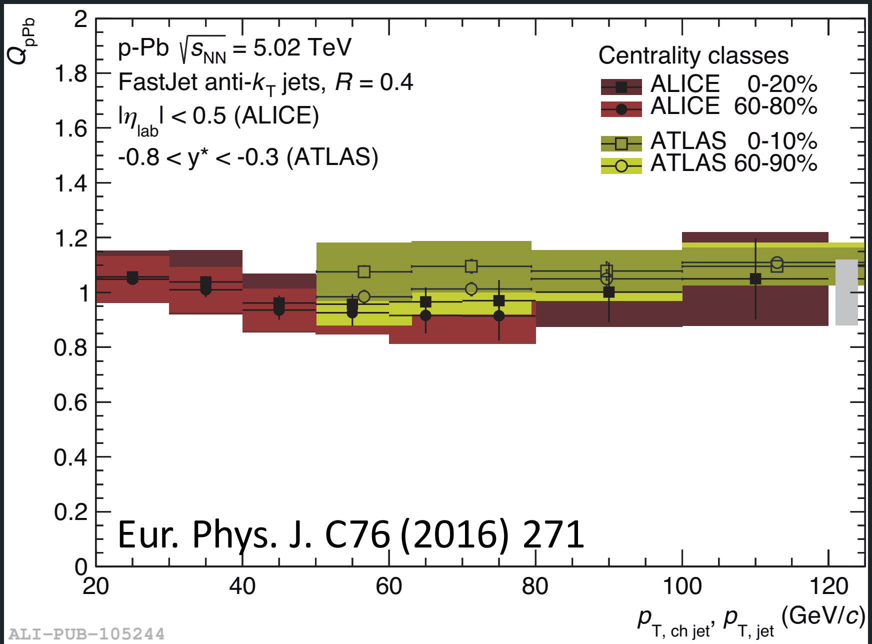


Phys. Lett. B 726 (2013) 164–177

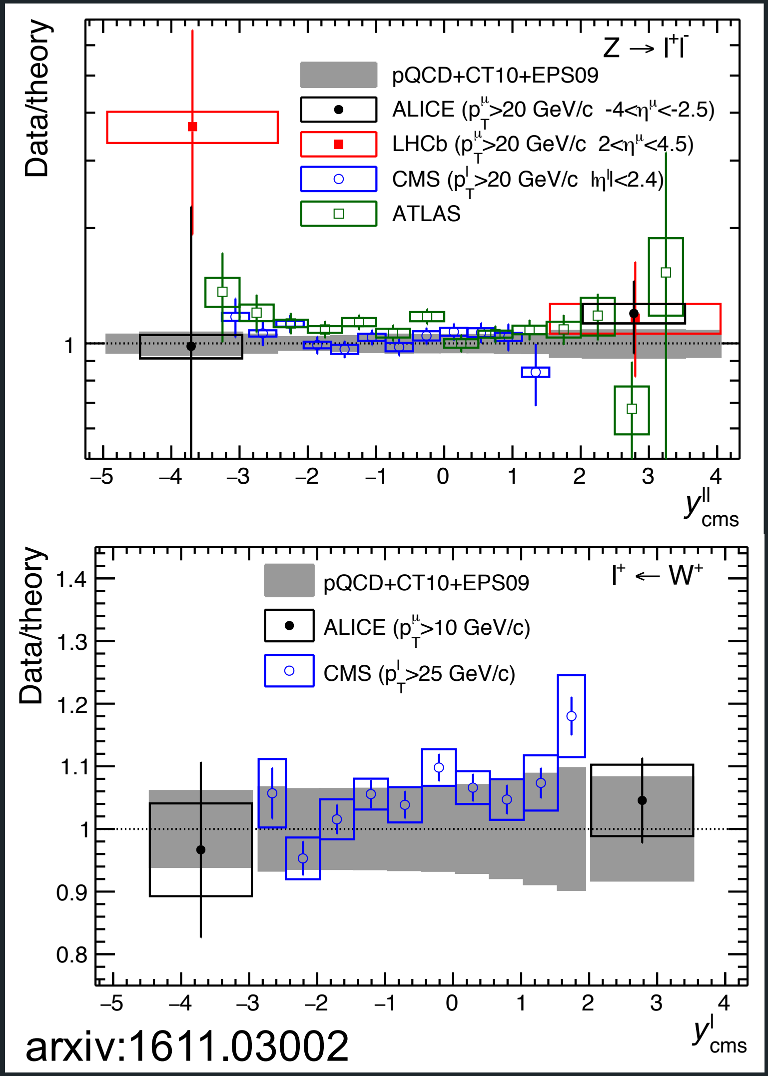
Typical mass ordering seen in Pb-Pb reappears in v_2 for p-Pb.

Hard Probes in pPb

Centrality dependent jet production



Electroweak gauge bosons



No major effects on jets for “central” and “peripheral” p-Pb collisions.

No strong nuclear effects on electroweak bosons.

Currently no surprises for hard probes in small systems.