A Large Ion Collider Experiment

ALICE - HIGHLIGHTS

Boris HIPPOLYTE for the ALICE Collaboration

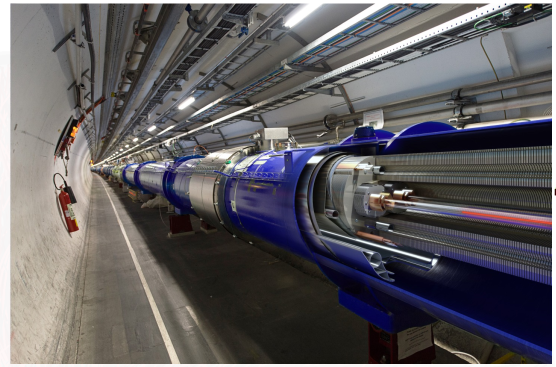
9th France-China Particle Physics Laboratory | Thursday March the 31st

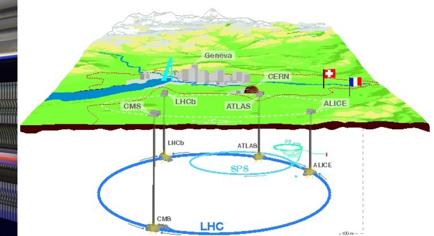
OUTLINE

- The Large Hadron Collider (LHC)
- Heavy ions at the LHC (w.r.t. other systems)
- The ALICE apparatus and Collaboration
- A selection of recent ALICE results
  - ➡ Global properties of Pb-Pb (2.76 and 5.02 TeV) and pp collisions (13 TeV)
  - ➡ Collectivity in Pb-Pb collisions
  - ➡ Direct photons and hard probes
  - ➡ More comparisons to pp and p-Pb collisions
- The upgrade of ALICE for LHC Run 3
- Conclusion

The Large Hadron Collider (LHC)

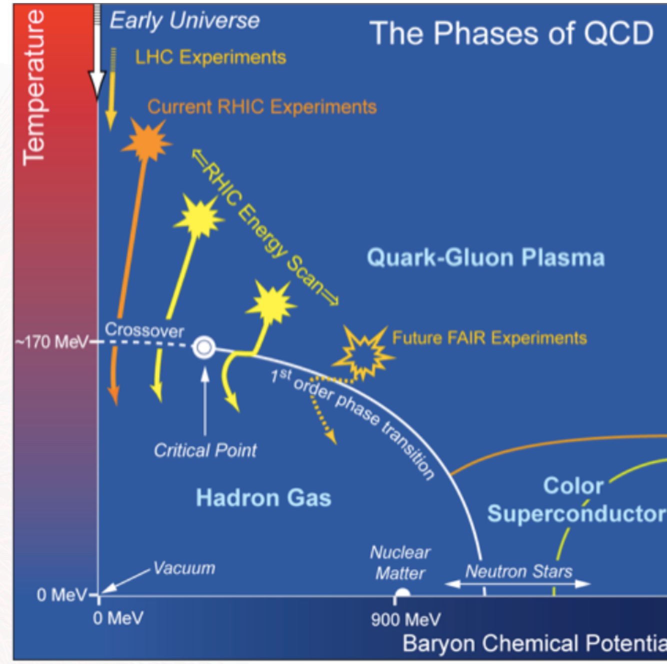
- The LHC is currently the largest and most powerful proton and ion collider in the world
  - ➡ present (Run 2) centre-of-mass energy is:
    - 13 TeV for pp collisions
    - 5.02 TeV per nucleon pair for Pb-Pb collisions
  - ➡ former (Run 1) c-o-m energy:
    - pp: 0.9, 2.76, 7 and 8 TeV
    - p-Pb: 5.02 TeV
    - Pb-Pb 2.76 TeV per nucleon pair
- ALICE (A Large Ion Collider Experiment) is designed primarily to study nucleus-nucleus collisions

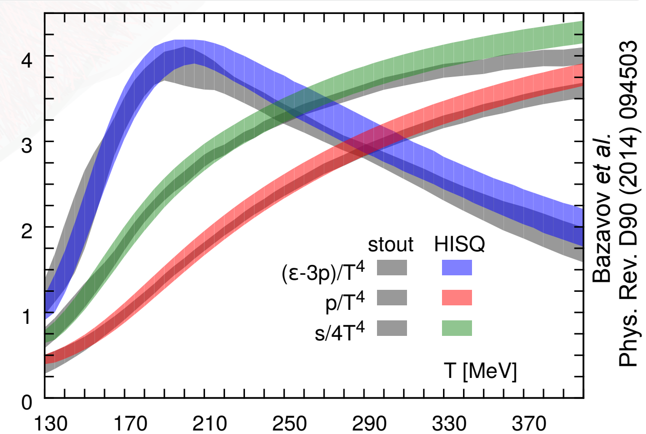




Heavy ions at the LHC (w.r.t other systems)

- Study nuclear matter under extreme conditions of temperature and density
- At LHC energies:
  - ➡ high temperature: $O(10^{12}$ K) .
  - ➡ vanishing baryon chemical potential: equal number of particles and anti-particles
- Study the properties of a state where quarks and gluons are deconfined (Quark-Gluon Plasma, QGP).
- Phase transition predicted by Lattice QCD calculations (state of the art):
  - ➡ $T_C \approx 155$ MeV $\varepsilon_C \approx 0.5$ GeV/fm^3
- Study the transition between QGP and hadron gas.
- QGP behaves as a perfect fluid
  - ➡ well described by ideal hydrodynamics
  - ➡ low shear viscosity/entropy density (η/S)





Fate of a Nucleus-Nucleus Collision at the LHC

➡ Initial state and pre-equilibrium
- gluonic fields (Color Glass Condensate) GLASMA

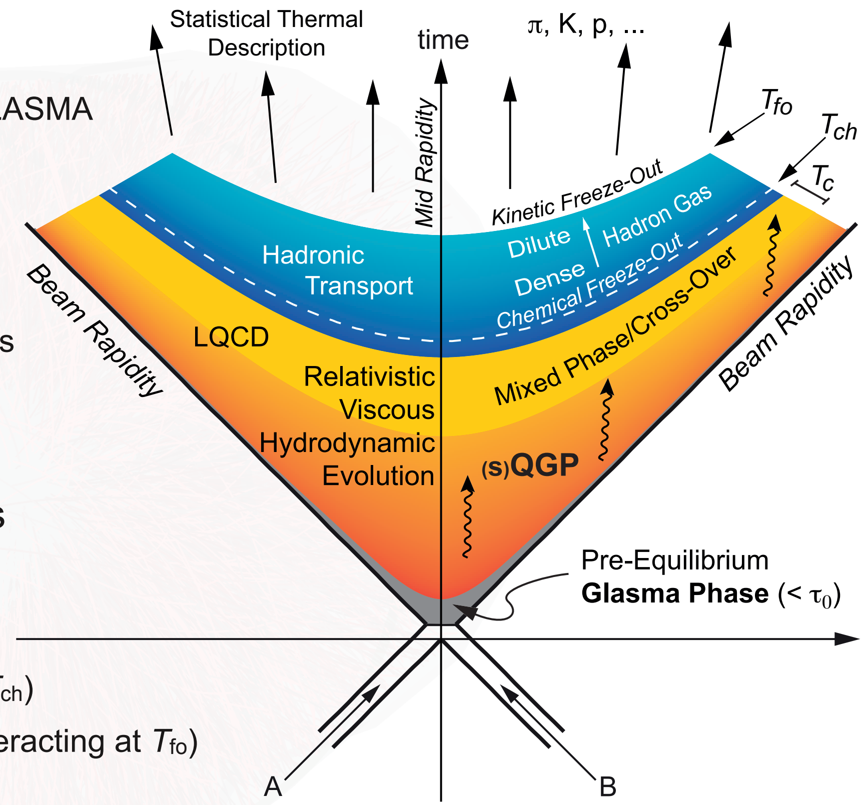
➡ Hard parton scattering
- jet and heavy flavour production

➡ Creation of a Quark-Gluon Plasma
- thermalisation of strongly interacting partons

➡ QGP expansion and cooling
- 3D+1 relativistic viscous hydrodynamics

➡ Phase transition (T_c): parton→ hadrons
- Lattice QCD, cross-over

➡ Hadronic phase
- chemical freeze-out (abundances fixed at T_{ch})
- rescattering and kinetic freeze-out (stop interacting at T_{fo})



PEDAGOGICAL PICTURE

- does not bring justice to the **tremendous progress** (measurements & models) recently made
- “guidelines” used to separate **hard** and **soft** probes of the QGP
- measurements often (but not always) correspond to **“integrated-over-time”** observables
  - for instance: charm, beauty and jets probe the whole evolution whereas photons are insensitive to hadronization

ALICE - the detectors

- Designed to reconstruct and identify charged particles in a central rapidity window → central barrel down to low transverse momentum (p_T~100 MeV/c for pions)
- Central barrel (|η|<1):

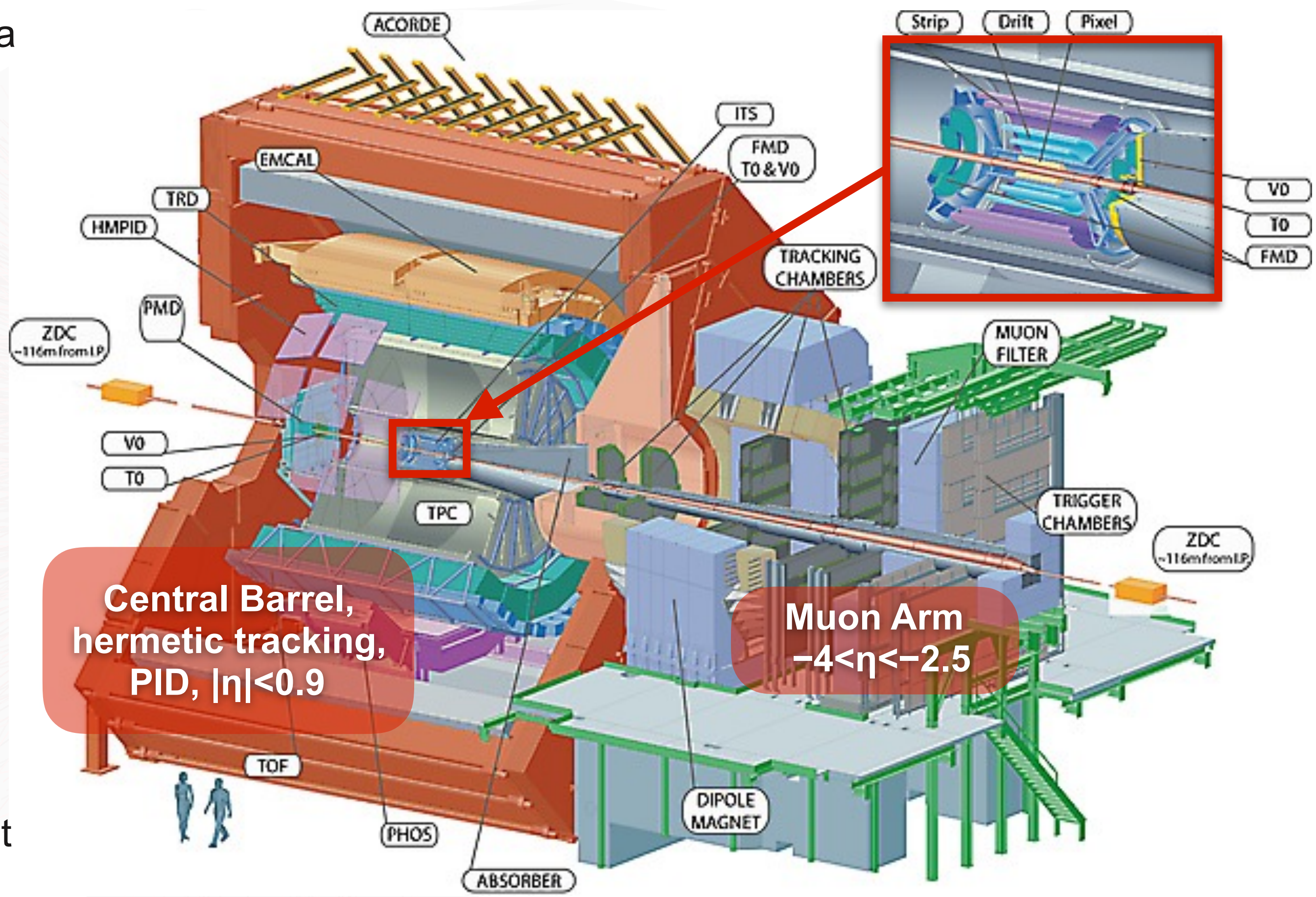
  tracking (ITS, TPC), PID (TOF,TRD), calorimeters.
- Muon spectrometer:

  $-4<\eta<-2.5$
- Forward detectors:

  triggering, centrality, timing.
- Event recording bandwidth: 1.25 GB/s for Pb-Pb events
- Overall data (MC, raw and reconstructed) on permanent storage:

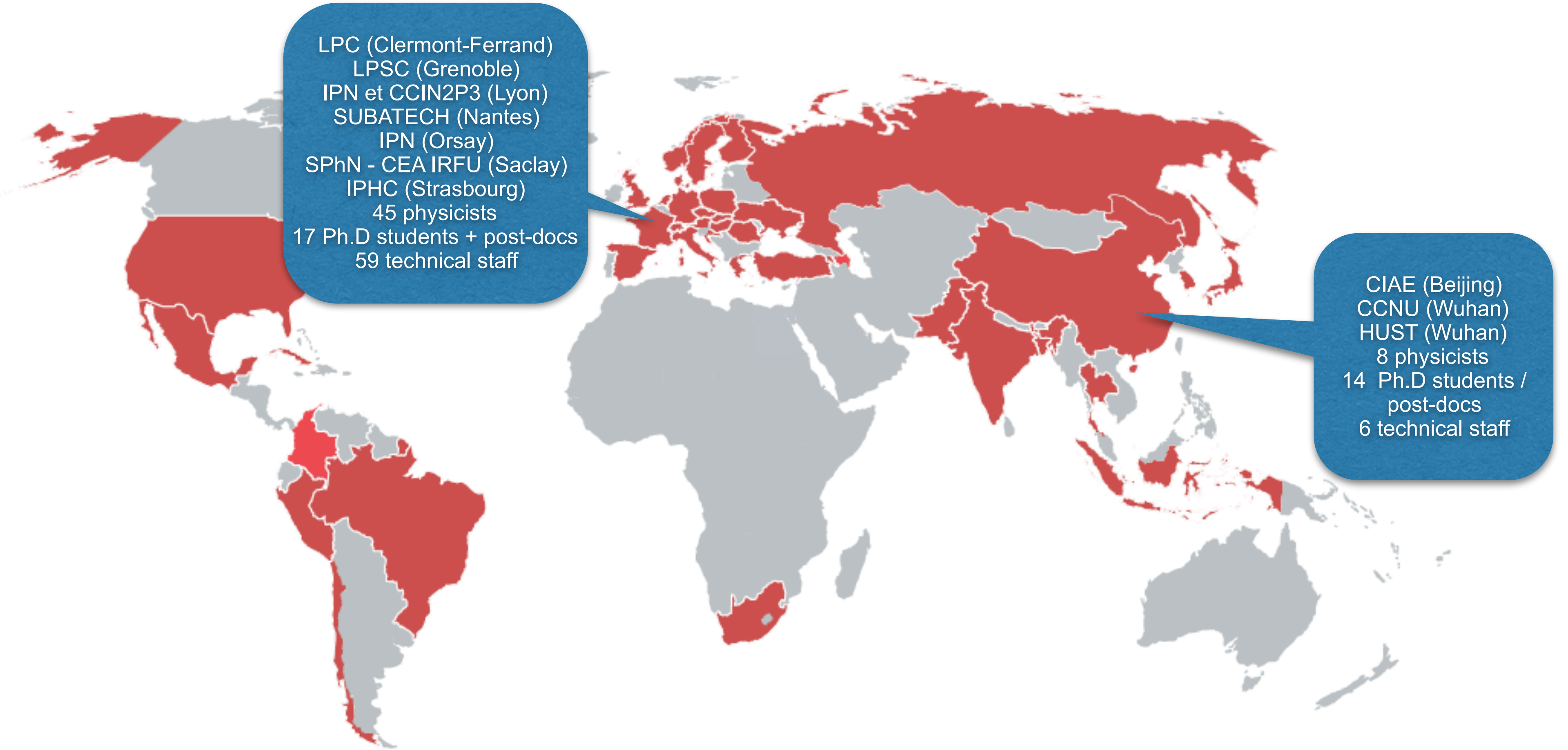
  ➡ **tape: ~45 PB**

Acronyms:
- ITS - Inner Tracking System
- TPC - Time Projection Chamber
- TOF - Time Of Flight

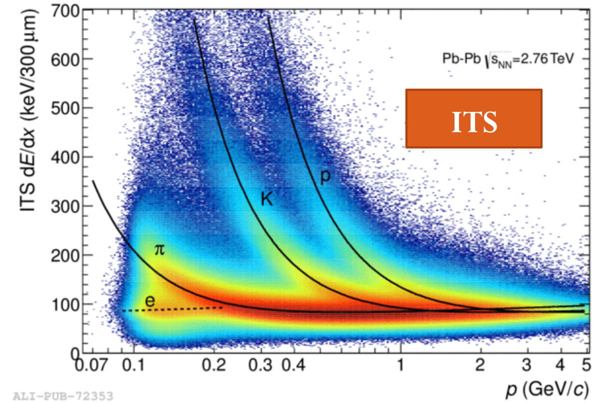


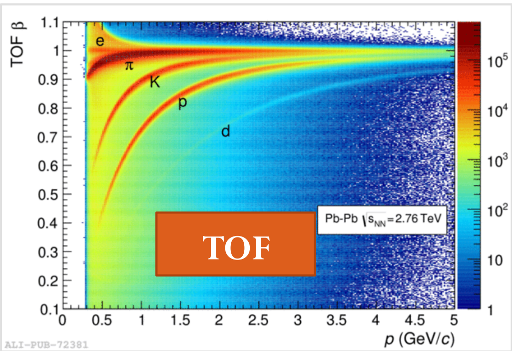
ALICE - the Collaboration

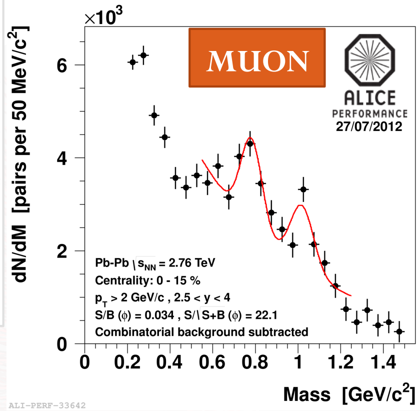
41 countries, 159 institutes, 1665 members



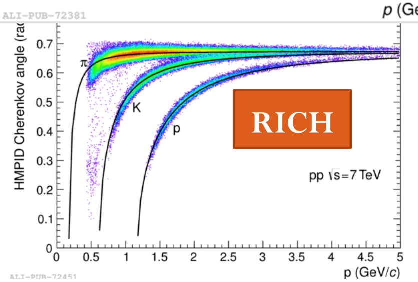
ALICE - the PID performance



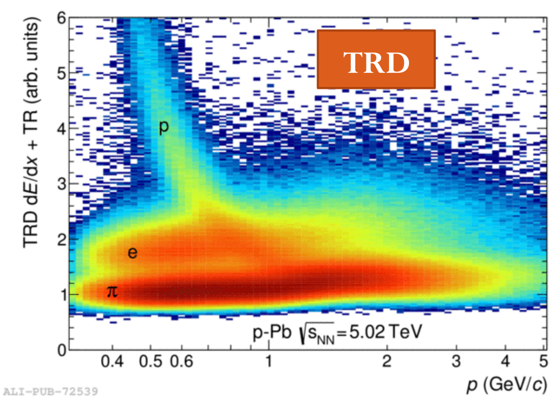


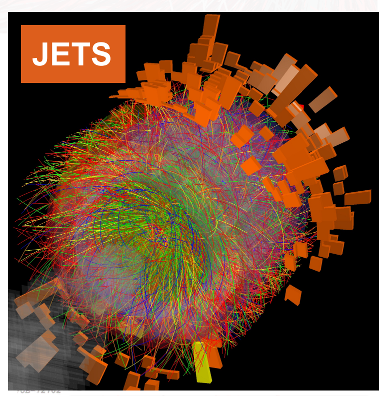


- ✓ **Lowest material budget tracker**

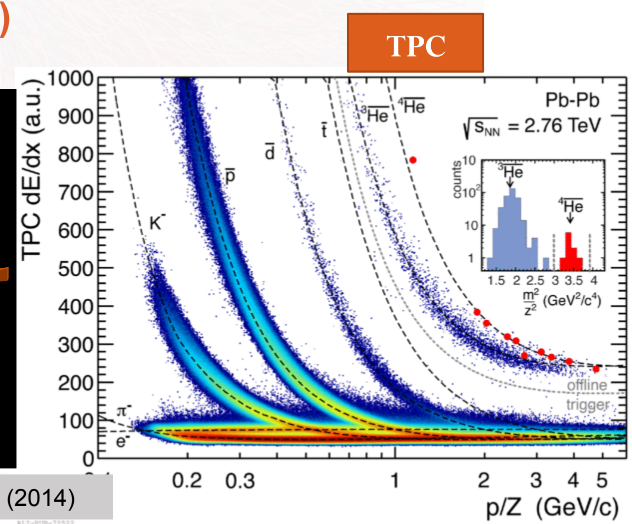


- ✓ **Particle identification in a wide momentum range**
- ✓ **Jets in Pb-Pb (EMCAL)**

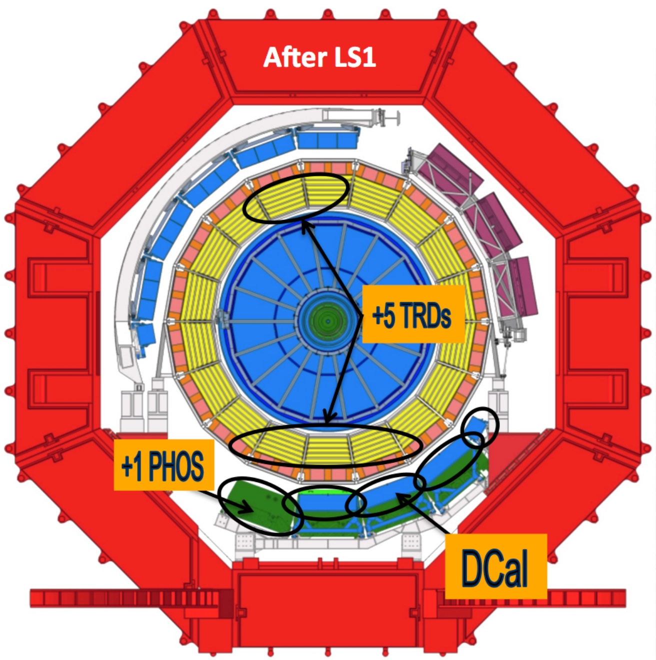




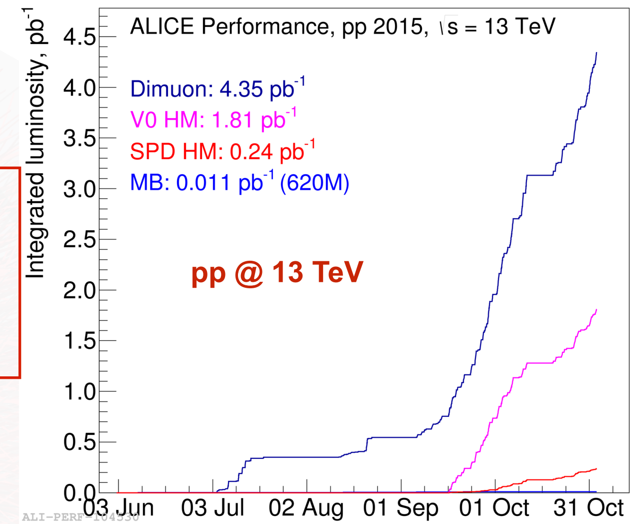
Int. J. Mod. Phys. A 29, 1430044 (2014)



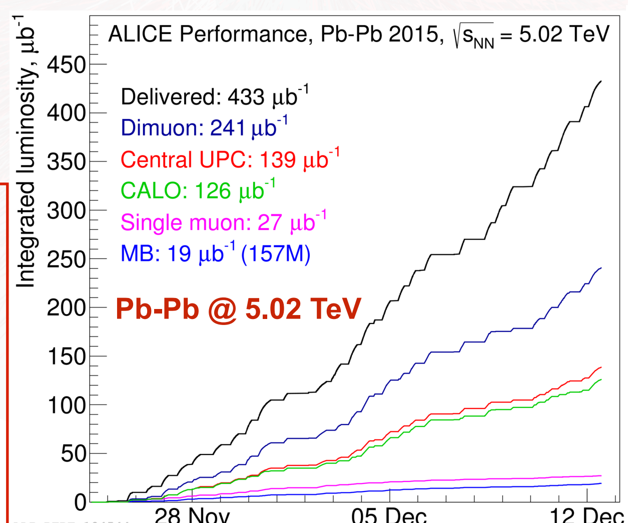
ALICE - Data taking for Run 2 (started in 2015)

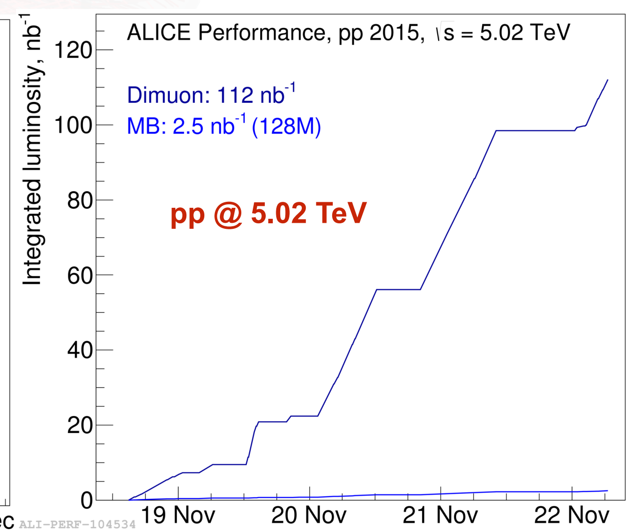


Data taking in 2015
- pp at 13 TeV started in June
- Pb-Pb at 5.02 TeV in Nov - Dec
- pp at 5.02 TeV for comparison



Detector status
- Complete TRD detector (+5 SMs)
- Installed DCal (8 SMs), including new support structure
- Extended PHOS (+1 SM)
- Installed Charged-Particle Veto (CPV)
- Installed AD detector





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pp at 13 TeV - Charged-particle multiplicity

Phys. Lett **B753** 319-329 (2016)

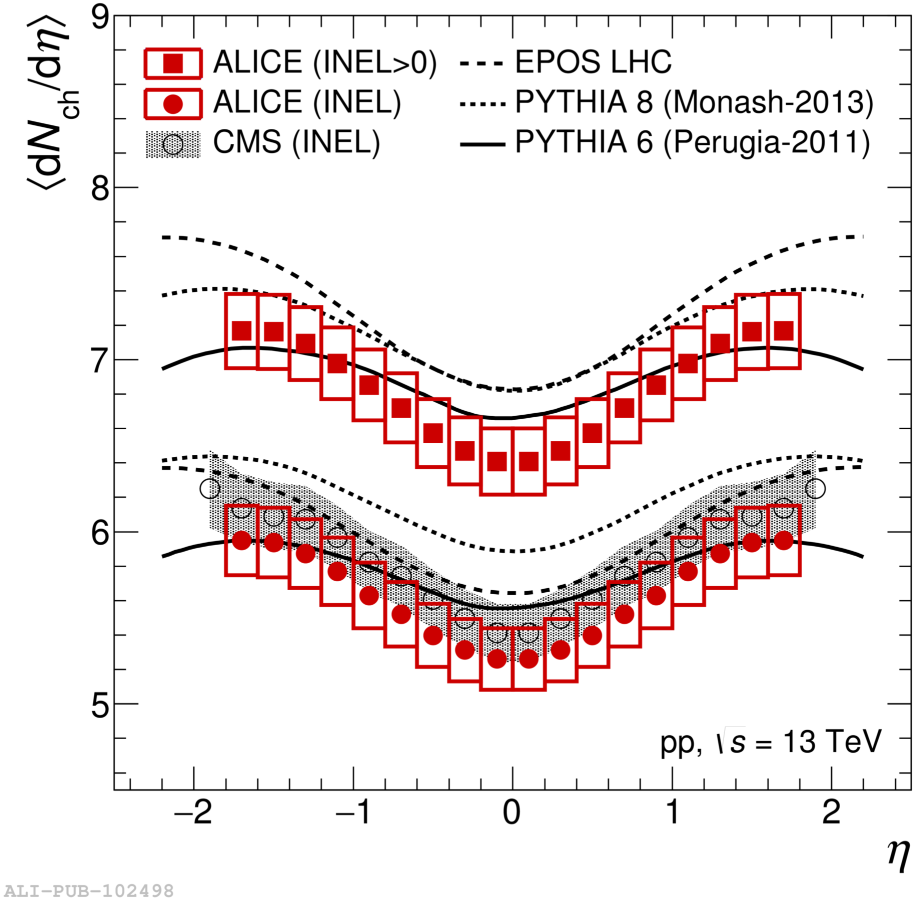
- Two normalization classes in $|\eta| < 0.5$
  - ➡ Inelastic events (INEL):

$$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle = 5.31 \pm 0.18$$

  - ➡ Events with at least one charged particle in the interval $|\eta| < 1$:

$$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle = 6.46 \pm 0.19$$

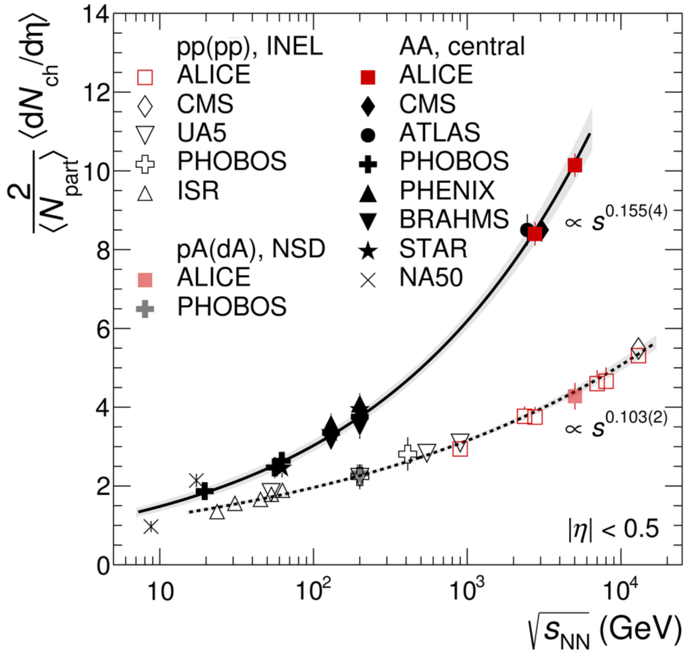
- Monte Carlo calculations are slightly higher than the data (from 3 to 12%)
- PYTHIA 6 is in better agreement with the data than PYTHIA 8

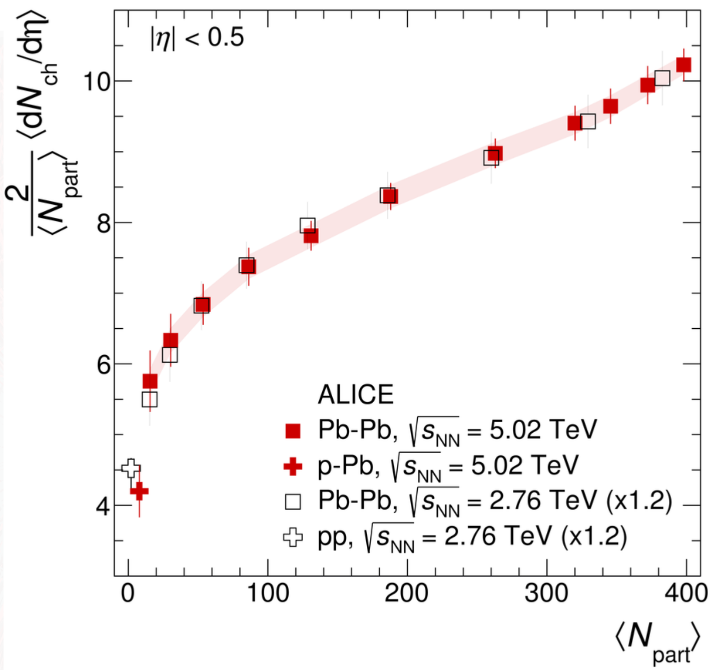


- The distributions for multiplicity as well as p_T spectra (not shown here) in proton-proton collisions provide a baseline for effects measured in high-energy heavy-ion collisions (and models)

Pb-Pb at 5.02 TeV - Charged-particle multiplicity

arXiv:1512.06104





- For the 5% most central collisions: $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle = 1943 \pm 54 \quad \mathrm{in}\ |\eta| < 0.5$
- The rise with the centre-of-mass energy is steeper than for pp collisions
- Centrality dependence shows that a factor of ~1.2 describes the increase from 2.76 to 5.02 TeV:
  - ➡ the trend with centrality is the same
  - ➡ dependency on centrality and energy are factorized
- Such results provide essential constraints for models describing high-energy heavy-ion collisions

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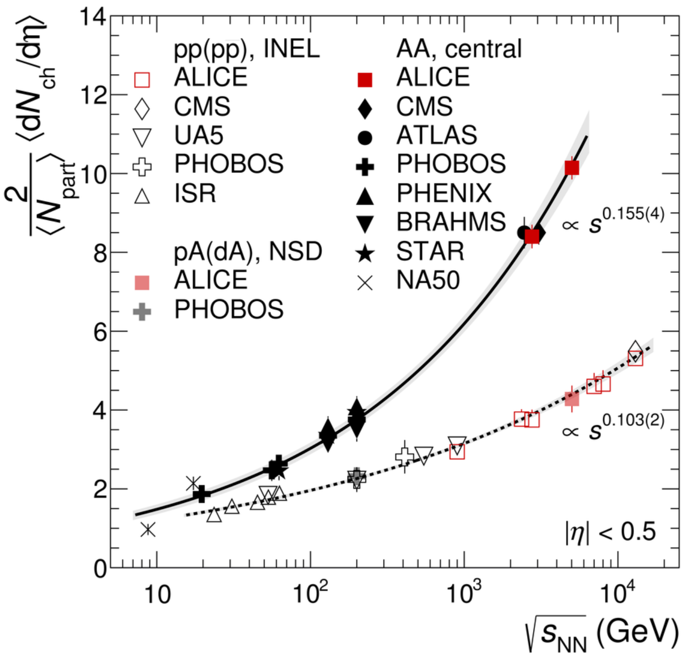

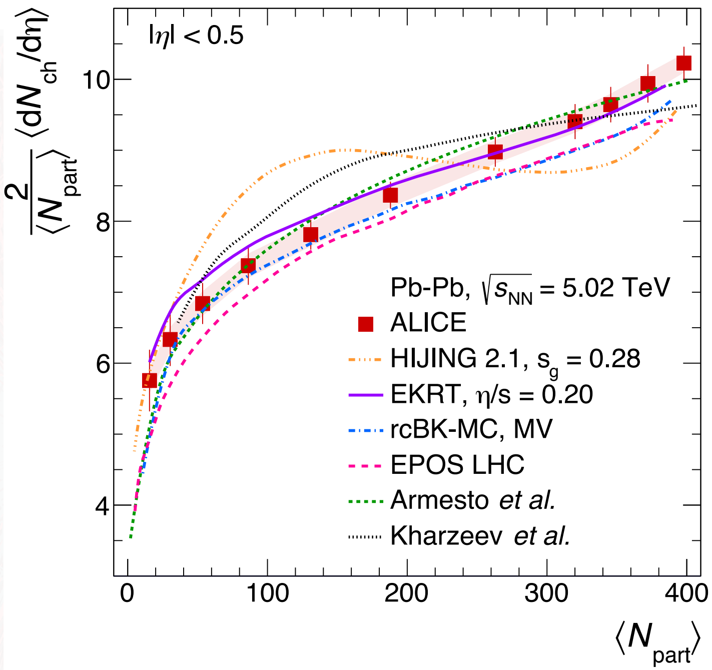

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Pb-Pb at 2.76 TeV - Charged-particle multiplicity

- for a broad pseudo-rapidity interval: -3.5< η <5

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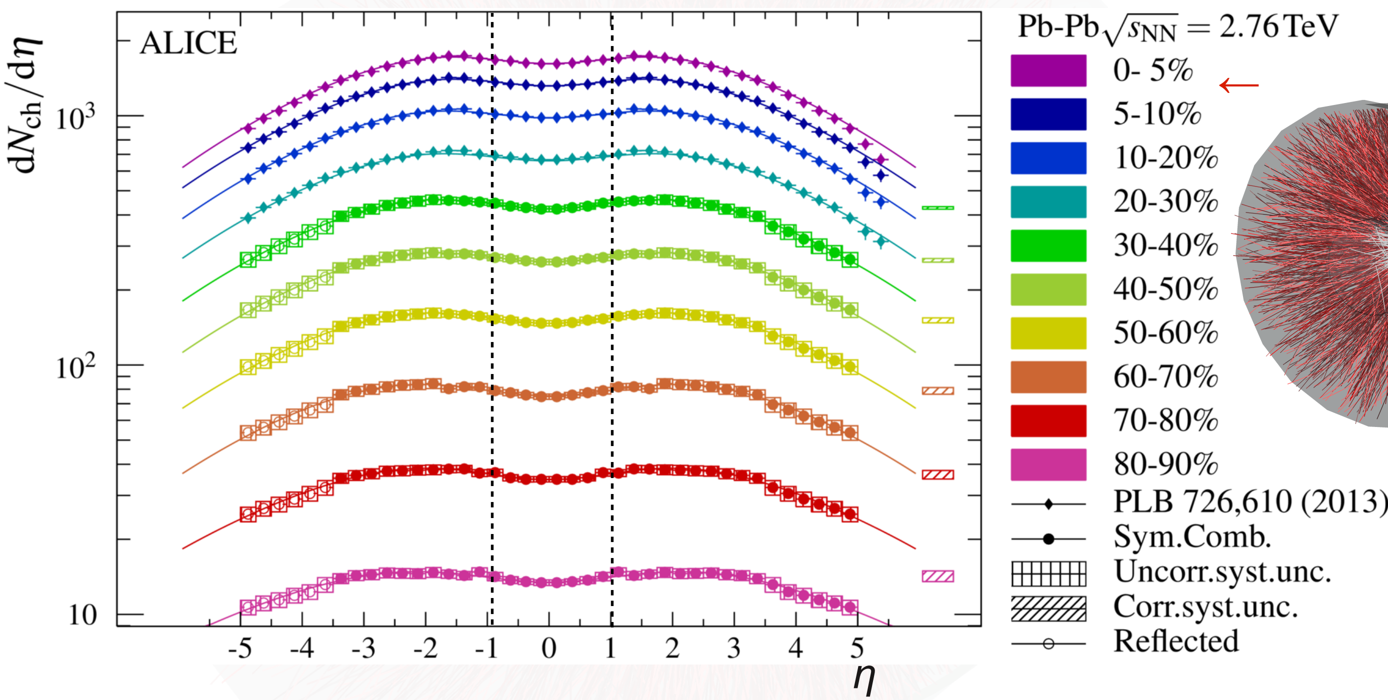

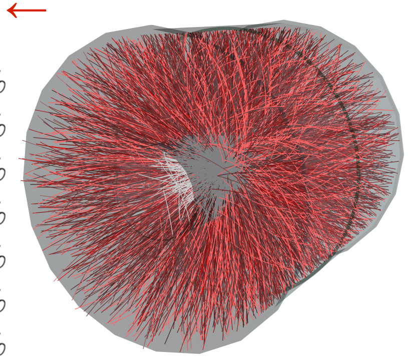

- Charged-particle multiplicity has been measured in a wide pseudo-rapidity range (-3.5< η <5):
- The total number of charged particles ranges from:
  162 +/- 22 for centrality class **80-90%** to **17170 +/- 770** for centrality class **0-5%**
- In the central barrel they can be also identified over a broad momentum range

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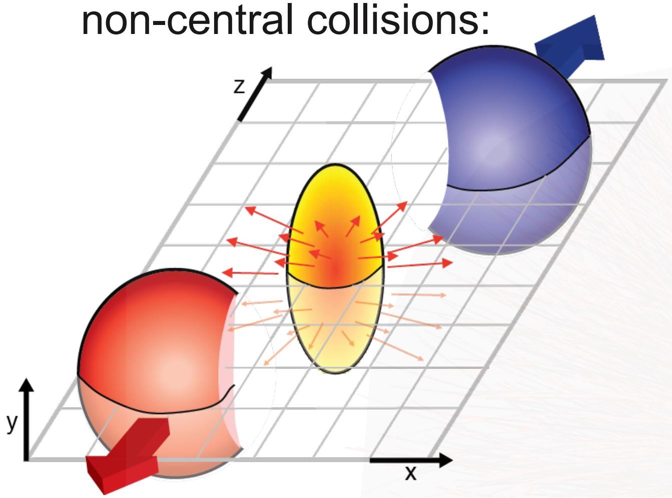
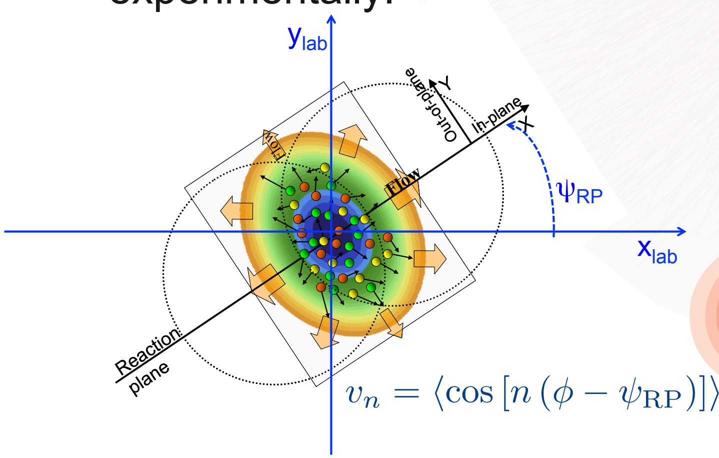
Eccentricity, flow coefficient and fluctuations

non-central collisions:



Initial **coordinate** space anisotropy

experimentally:



- The reaction plane contains the beam direction and the centers of the colliding nuclei

Anisotropy in azimuthal angle described by a Fourier series:

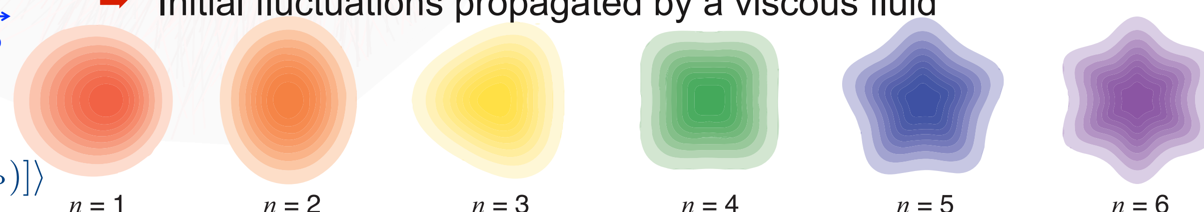
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Phi_n)$$

EXPERIMENTAL RESULTS

- ➡ 2nd order (v_2) dominates in non-central collisions
- ➡ Higher flow harmonics: sizable, own event plane angle
- ➡ v_n decreases with increasing n: typical of viscous fluid (damping)
- ➡ Odd harmonics with weak centrality dependence: **fluctuations**

CLEAR PICTURE

- ➡ How the system behaves collectively
- ➡ $v_n \propto \varepsilon_n$
- ➡ Initial fluctuations propagated by a viscous fluid



Eccentricity, flow coefficient and fluctuations

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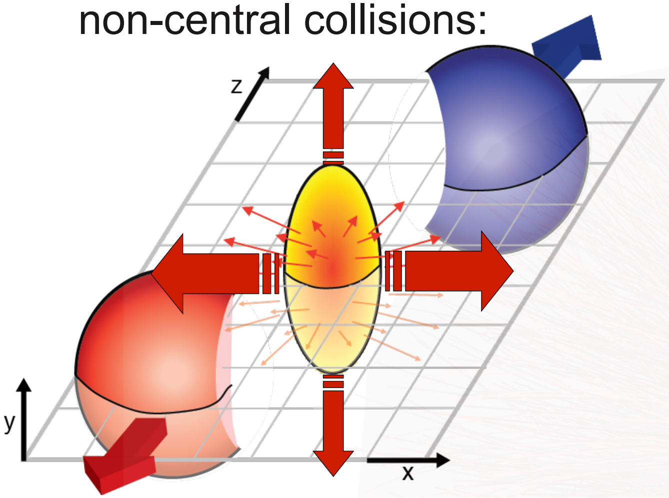
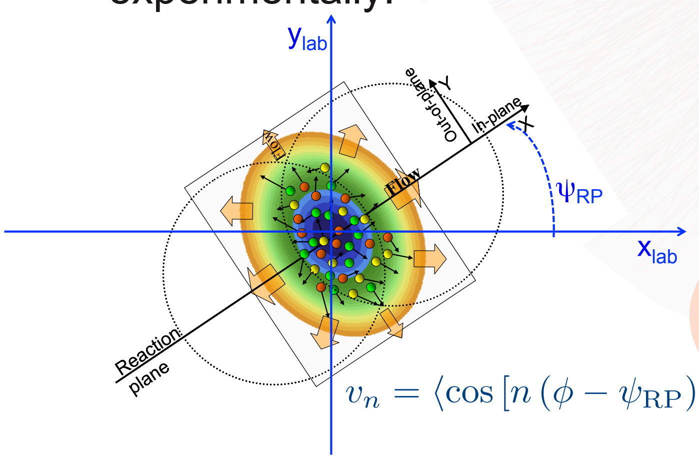


Initial **coordinate** space anisotropy

→ **momentum** space anisotropy

experimentally:



$$v_n = \langle \cos\left[n\left(\phi - \psi_{\mathrm{RP}}\right)\right]\rangle$$

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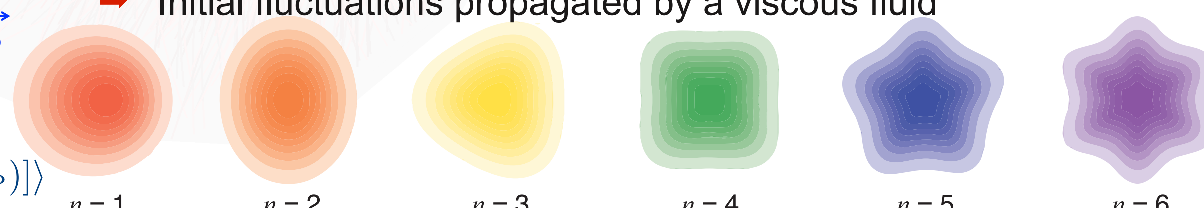
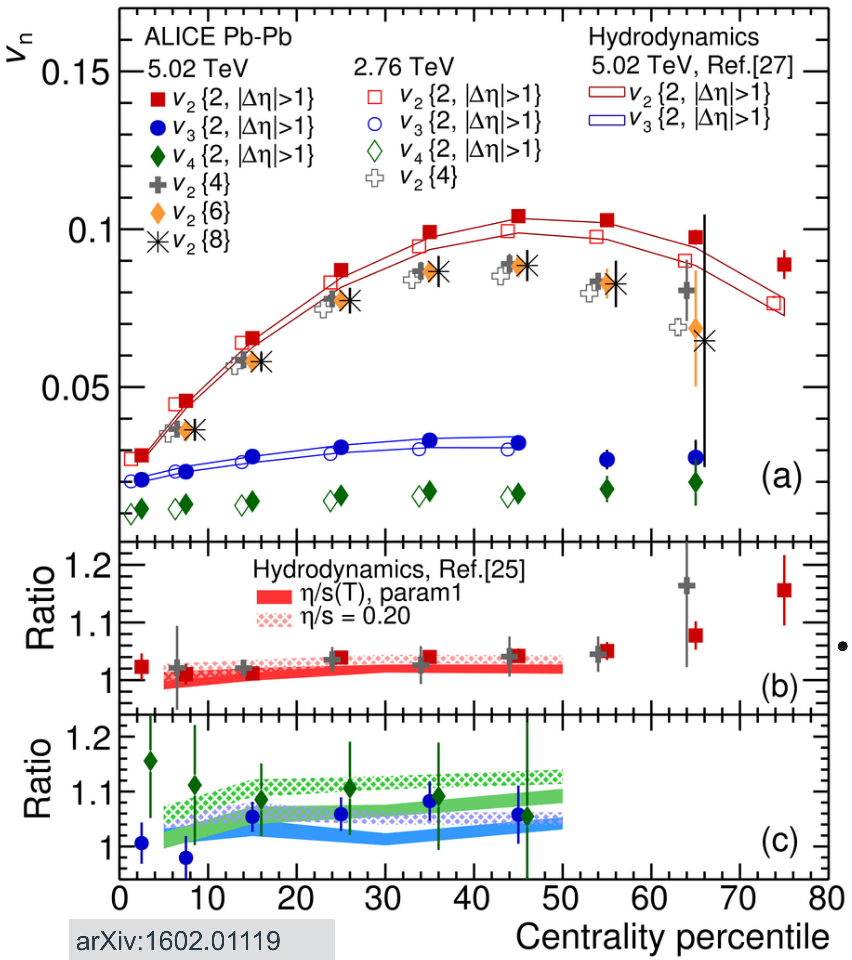
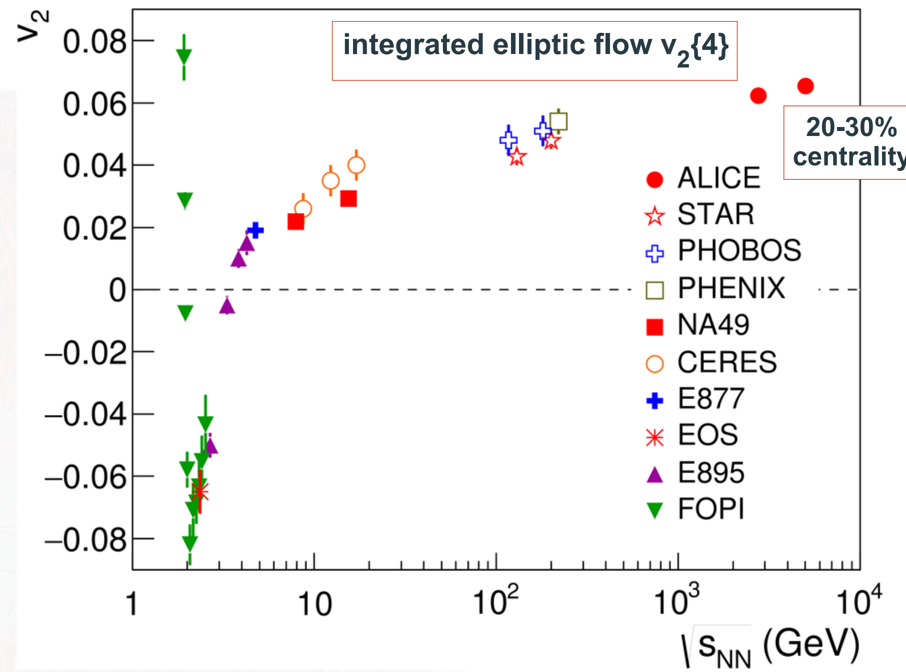


Anisotropic flow in Pb-Pb at 5.02 TeV



arXiv:1602.01119



- Anisotropic flow v_n integrated in range $0.2 < p_T < 5.0$ GeV/c as a function of centrality
  - ➡ Ratios computed between 5.02 and 2.76 TeV results.
  - ➡ From 2.76 to 5.02 TeV over centrality range 0-50%, the average increases are:

(3.0±0.6)% for v_2 (4.3±1.4)% for v_3 (10.2±3.8)% for v_4

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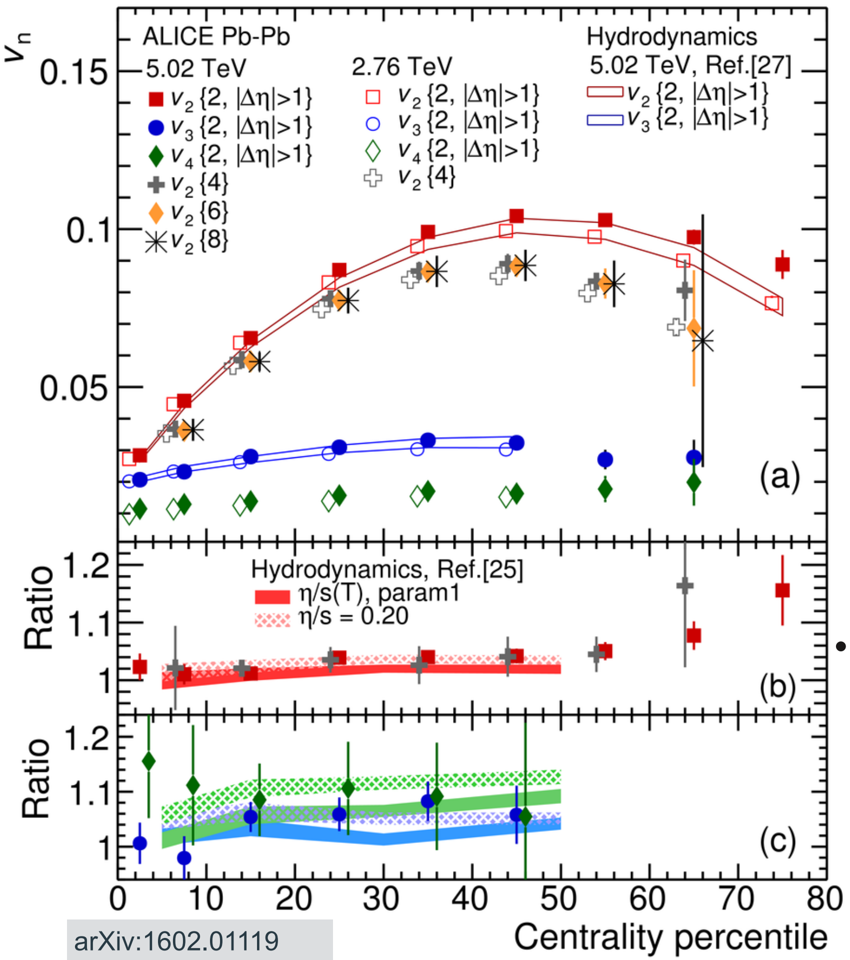

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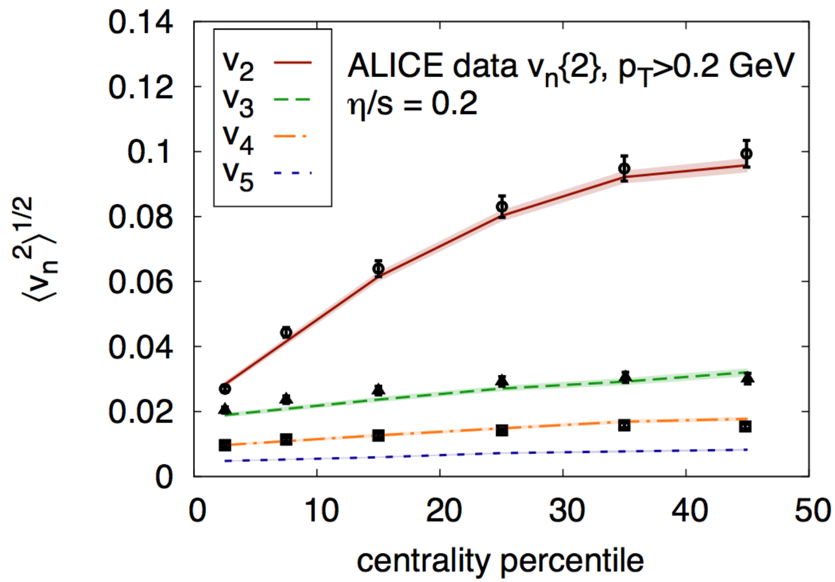

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    (3.0±0.6)% for v_2 (4.3±1.4)% for v_3 (10.2±3.8)% for v_4

➡ Results compatible with predictions from state-of-the-art hydrodynamic (3D+1 e-by-e relativistic viscous) models

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Direct photons

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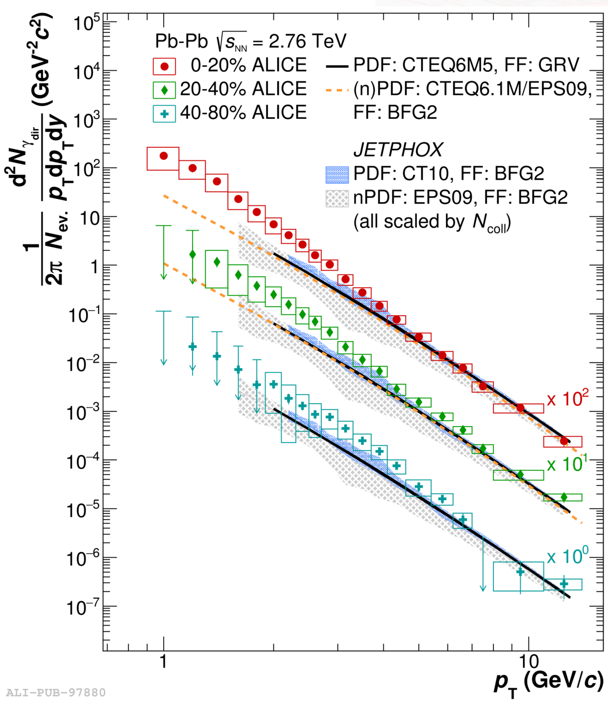
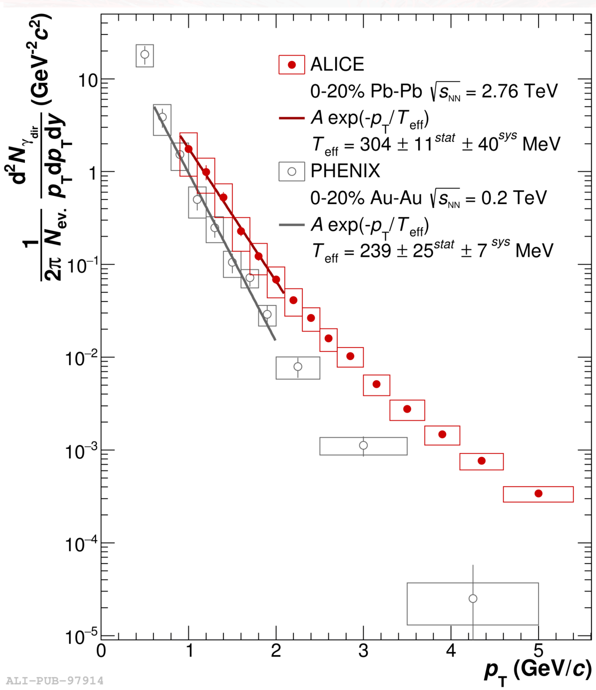
- The direct photon spectra at $p_T > 5$GeV/c are in agreement with pQCD calculations for pp collisions scaled by N_{coll}
- In central Pb-Pb collisions (0-20%): 2.6 σ excess over models for $0.9 < p_T < 2.1$ GeV/c
- At low momentum the photon spectrum is dominated by thermal contribution
- Extraction of T_{eff} : inverse slope of low-p_T direct photon distribution
  - ➡ T_{eff} = 304±11±40 MeV (T_{eff} =297±12±41 MeV after subtraction of the pQCD contribution)
  - ➡ 30% higher than at RHIC





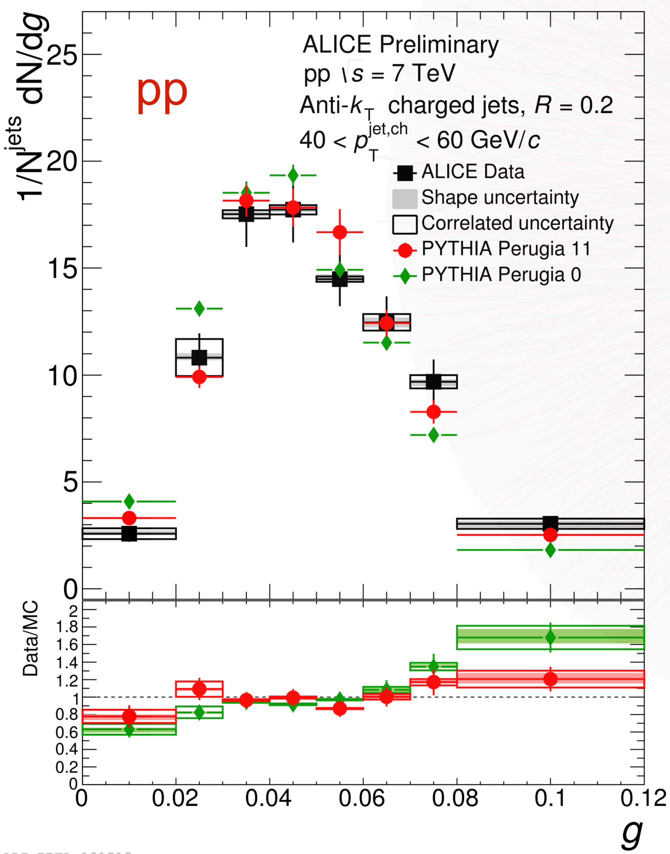
The interpretation of the inverse slope parameter is not trivial.
- A correlation with the initial temperature exists (model dep.)

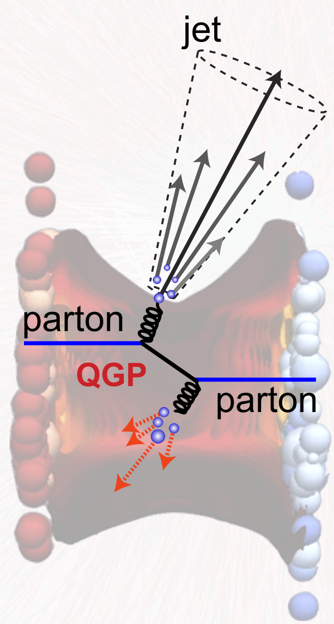
There are two contributions:
- blue-shifted photons from the late stages of the collision process with high radial flow velocities
- high temperature photons emitted in the early stages

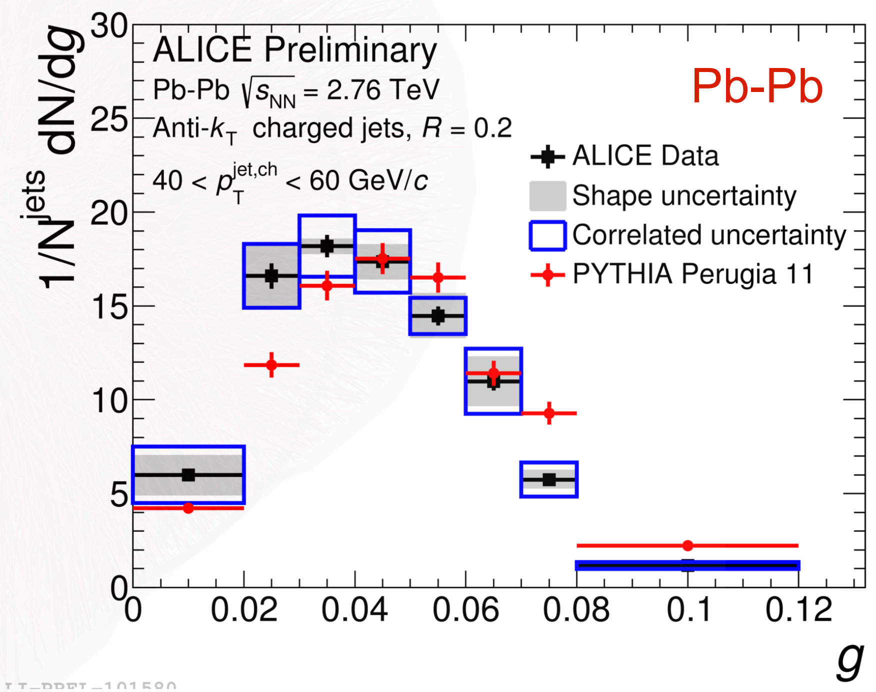
Jet Shapes

- New variable to characterize jet-core shape: the radial moment g
  - ➡ g is a p_T -weighted width of the jet: low g → highly collimated jet
  - ➡ g is consistent with PYTHIA in pp collisions

$$g = \sum_{i \in \text{jet}} \frac{p_{\mathrm{T}}^{i}}{p_{\mathrm{T,\,jet}}} |\Delta R_{i\ \text{jet}}|$$







➡ Core of jets in Pb-Pb differs from pp collisions and appears to be more collimated

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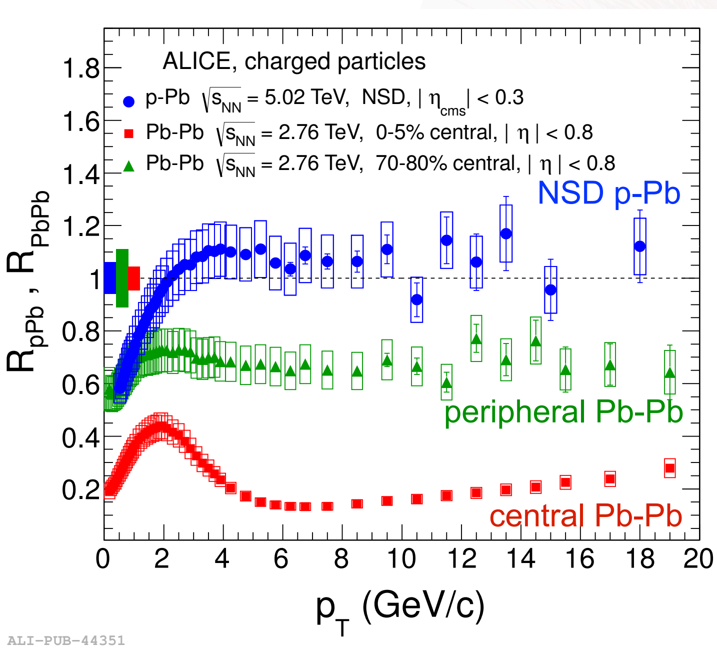
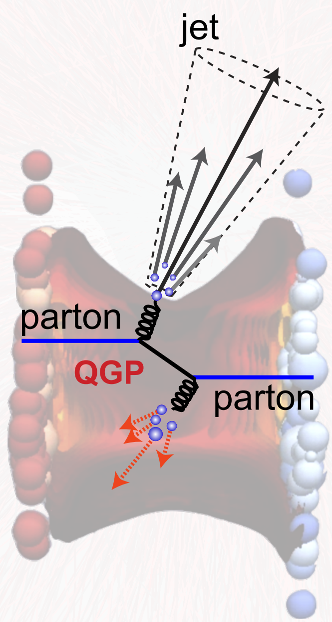
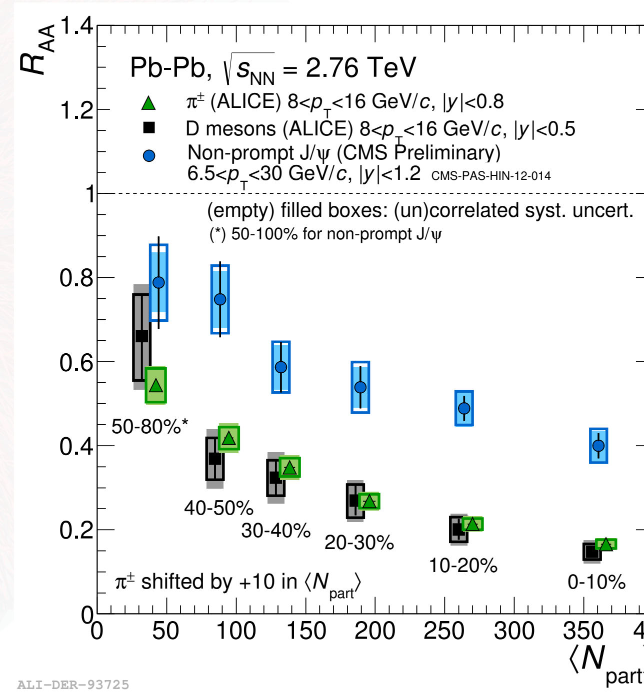
Nuclear modification factor

- Estimate the opacity of the created medium
  - ➡ R_{AA} is called the nuclear modification factor
  - ➡ R_{AA} equals unity means no modification at all

$$R_{AA} = \frac{\mathrm{AA}}{\mathrm{rescaled\ pp}} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll}\rangle d^2N_{pp}/dp_T dy}$$







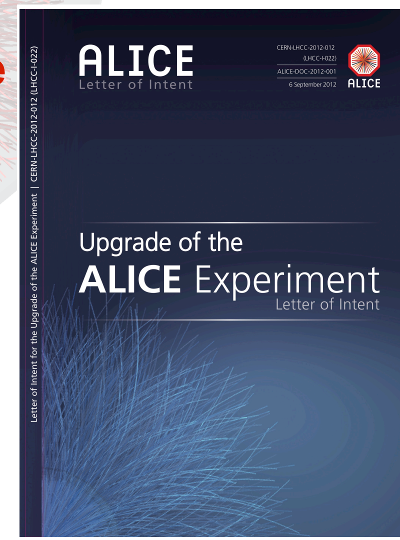
- ➡ p-Pb collisions is a control experiment for the nuclear modification factor
- ➡ first clear mass-dependence energy loss in the medium

properties of the parton: flavor, mass (“dead cone effect”), R_{AA}(u,d,s) < R_{AA}(D) < R_{AA}(B)

OUTLINE

- The Large Hadron Collider (LHC)
- Heavy ions and other colliding systems at the LHC
- The ALICE apparatus and Collaboration
- A selection of recent ALICE results
  - Global properties of Pb-Pb (2.76 and 5.02 TeV) and pp collisions (13 TeV)
  - Collectivity in Pb-Pb collisions
  - Direct photons and hard probes
  - pp and p-Pb collisions
- **The upgrade of ALICE for LHC Run 3**
- Conclusion

The Future

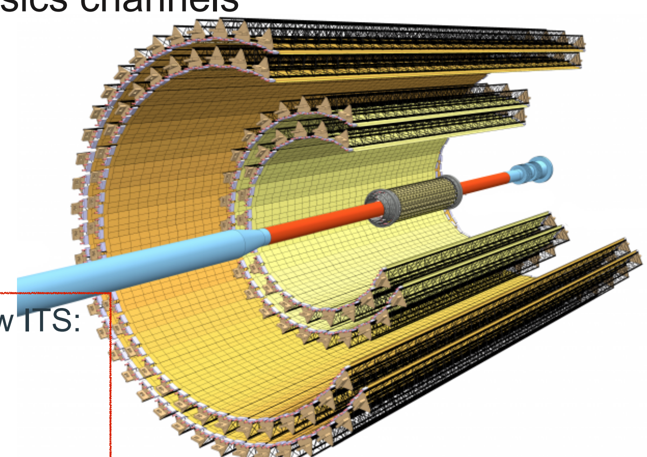


CERNLHCC-2012-012, LHCC-I-022, 2012.

FCPPL
France China Particle Physics Laboratory

ALICE Upgrade

- A major upgrade is currently being prepared for LHC Run3
  - ➡ ongoing R&D then construction and installation during second LHC Long Shutdown
  - ➡ new conditions to cope with during Run3:
    - expected Pb-Pb peak interaction rate: 50 kHz (now it is 8 kHz)
    - presently ALICE readout rate is limited to ~1 kHz
- Goals for Run3:
  - ➡ The main physics topics will exploit the specific ALICE potentials.
  - ➡ ALICE will carry out high precision measurements of rare signals with main focus on the low p_T region
  - ➡ triggering strategies not compatible with several physics channels
    - increase the readout rate to 50 kHz
  - ➡ improve pointing resolution both in
    - the barrel (new ITS) and
    - the Muon Arm (new Muon Forward Tracker)



The ALICE upgrade requires **major improvements** for the TPC and other detectors in order to increase the readout rate

Capability of reducing online the data volume delivered by the detectors, since the expected integrated luminosity is > 10 nb^{-1} for Pb-Pb (x100 w.r.t. Run1)

Layout of the new ITS:
–7 pixel layers
–10 m^2 of silicon
–12.5 Gpixel

CONCLUSIONS

- A selection of recent results was presented
- **From Pb-Pb, p-Pb and pp collisions:**
    - Global properties of Pb-Pb from 2.76 → 5.02 TeV:

  ➡ strong constraints: dependency on centrality and energy are factorized

    - Collectivity in Pb-Pb collisions

  ➡ Results compatible with state-of-the-art hydrodynamic models

    - Direct photons and hard probes (Pb-Pb and pp)

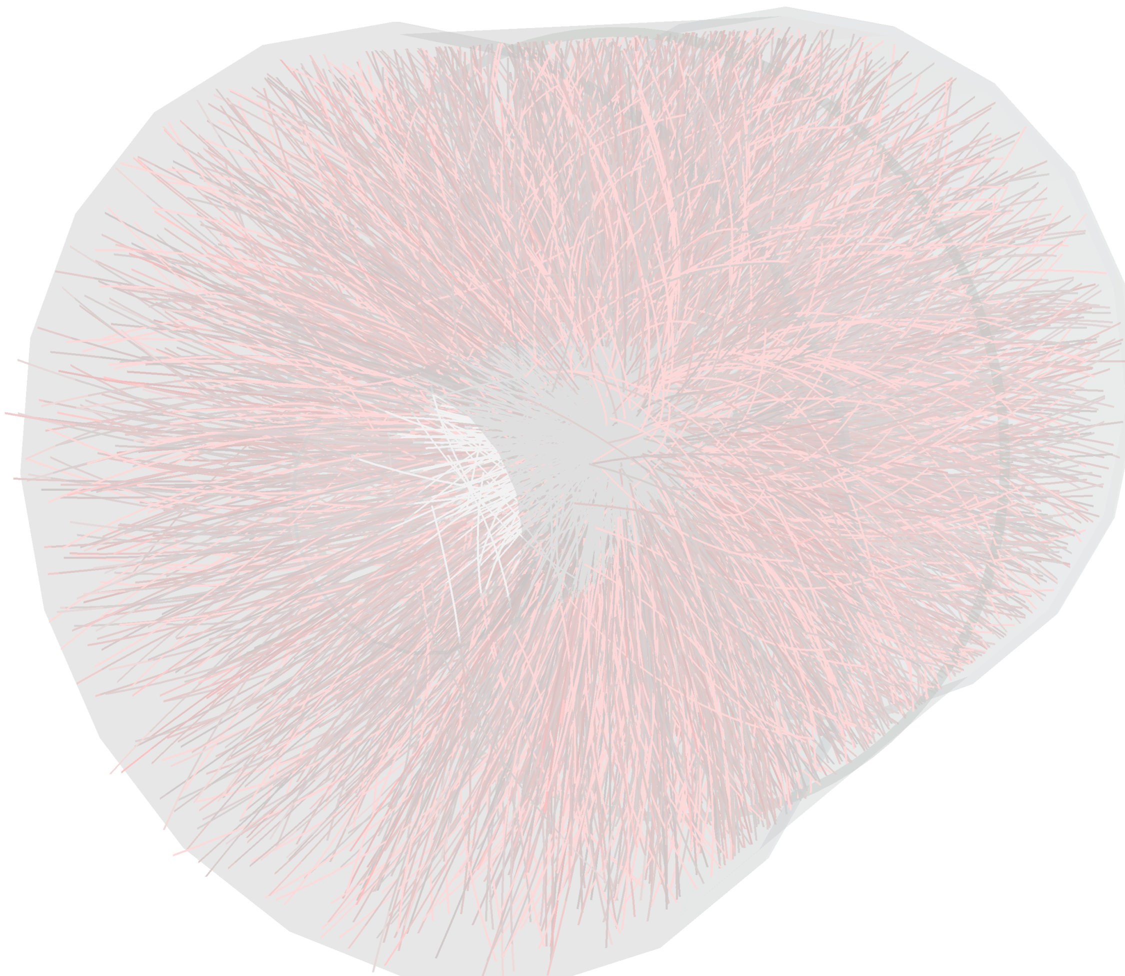
  ➡ T_{eff} ~ 300 MeV (model dependent but 30% higher than at RHIC)

  ➡ Core of jets in Pb-Pb differs from pp and appears to be more collimated

    - pp and p-Pb as a function of multiplicity → peripheral Pb-Pb

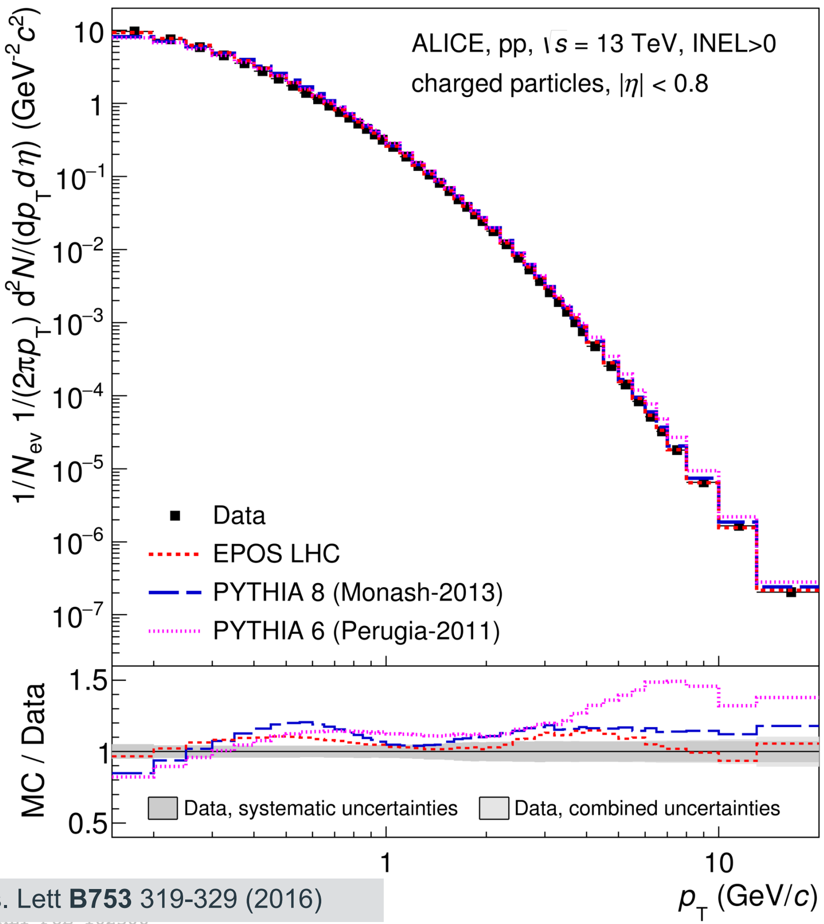
  ➡ Additional knob to switch on/off several intriguing effects

- **ALICE has a rich physics program for the future:**
    - the activity for the upgrade of the experiment is entering the construction phase and involving both China and France.

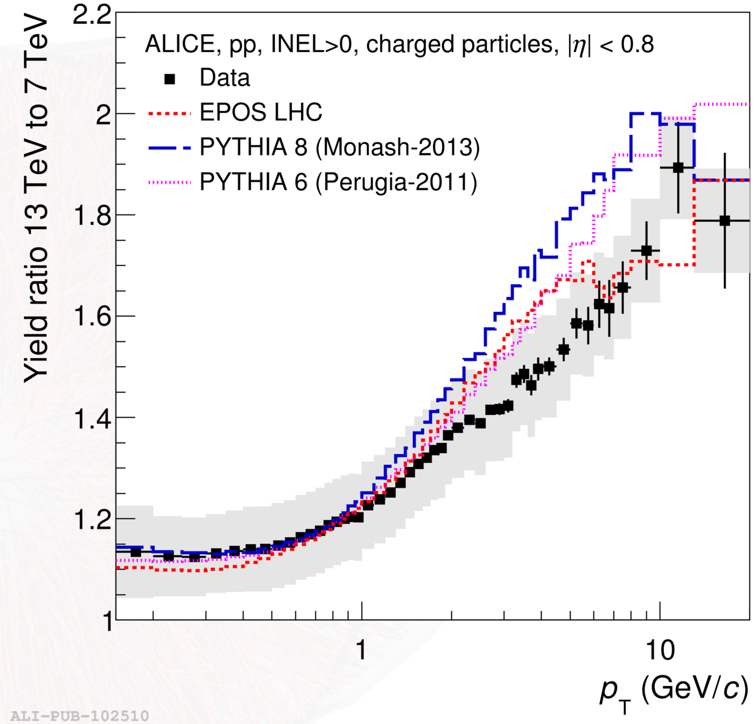


pp at 13 TeV - Charged-hadron p_T spectra

- Transverse momentum spectra for charged hadrons (~80% pions) in pp collisions at 13 TeV



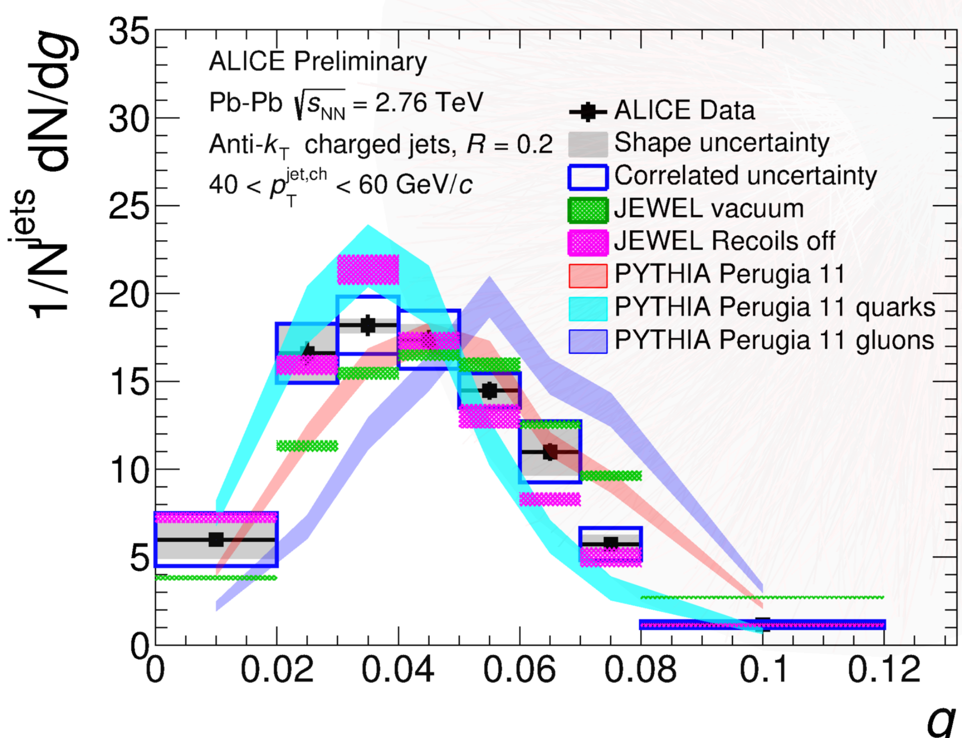
Phys. Lett **B753** 319-329 (2016)



- Comparison with results at 7 TeV
  - ➡ spectra are significantly harder
- Monte Carlo calculations provide a fair description but not in all detail

Jet Shapes - comparison to models

- Quark jets are more collimated than gluon jets, according to PYTHIA simulations
- JEWEL (Jet Evolution With Energy Loss) is in qualitative agreement with the data
- Quark and gluon vacuum jets (PYTHIA) are added to the plot: the observed jet shape is in agreement with a quark-like fragmentation
- Hint of jet-core modifications in Pb-Pb collisions



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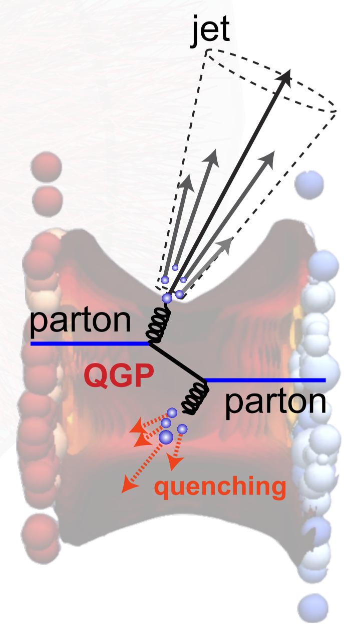

ALICE Upgrade: physics goals / 1

- ALICE will carry out high precision measurements of rare signals with main focus on the low p_T region:
  - ➡ Charm and beauty hadrons - spectra and flow:
    - Energy loss of HF in the hot and dense medium produced in AA collisions
    - Thermalization and hadronization mechanisms (coalescence vs. fragmentation)
    - Study possible thermal production
  - ➡ Quarkonia down to $p_T \sim 0$
    - wide rapidity range: e.g. $J/\psi \to e^+e^-$ at midrapidity and $J/\psi \to \mu^+\mu^-$ at forward rapidity
    - dissociation and recombination mechanisms in a deconfined medium

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ALICE Upgrade: physics goals / 2

- ALICE will carry out high precision measurements of rare signals with main focus on the low p_T region:
  - ➡ Low mass dileptons
    - e.m. radiation from the QGP
    - Temperature, EOS and space-time evolution
    - Chiral symmetry restoration (modification of the spectral function for ρ meson $\rightarrow$dileptons)
  - ➡ Jets:
    - quenching and fragmentation
    - PID of jet particle content
    - Heavy Flavour tagging
  - ➡ Light nuclei and hypernuclei (e.g. ^{4}He , $^5_{\Lambda\Lambda}$H)

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ALICE Upgrade: general strategy

- Boundary conditions and requirements:
  - ➡ very low signal/background ratio for many physics signals
    - → no trigger selection possible
  - ➡ large minimum bias samples required: L_{int}>10 nb^{-1}
  - ➡ High rate: $\mathcal{L} = 6 \times 10^{27}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \Rightarrow R = 50\ \mathrm{kHz}$
  - ➡ Focus on heavy flavours → improve track resolution and vertexing using new trackers and a smaller beam pipe
- Strategy:
  - ➡ New Inner Tracking System at mid-rapidity
  - ➡ New Muon Forward Tracker in front of the muon absorber
  - ➡ New readout chambers for the TPC & readout upgrades for several detectors and the online systems
  - ➡ Integrate Online and Offline (O2 project)
    - → data reconstruction online