

XLVI International Symposium on Multiparticle Dynamics

29 August – 02 September 2016
Jeju Island (South Korea)



Antonio Uras – IPN Lyon (France)
on behalf of the ALICE Collaboration

**Soft and hard observables of the
QCD phase diagram in ALICE**



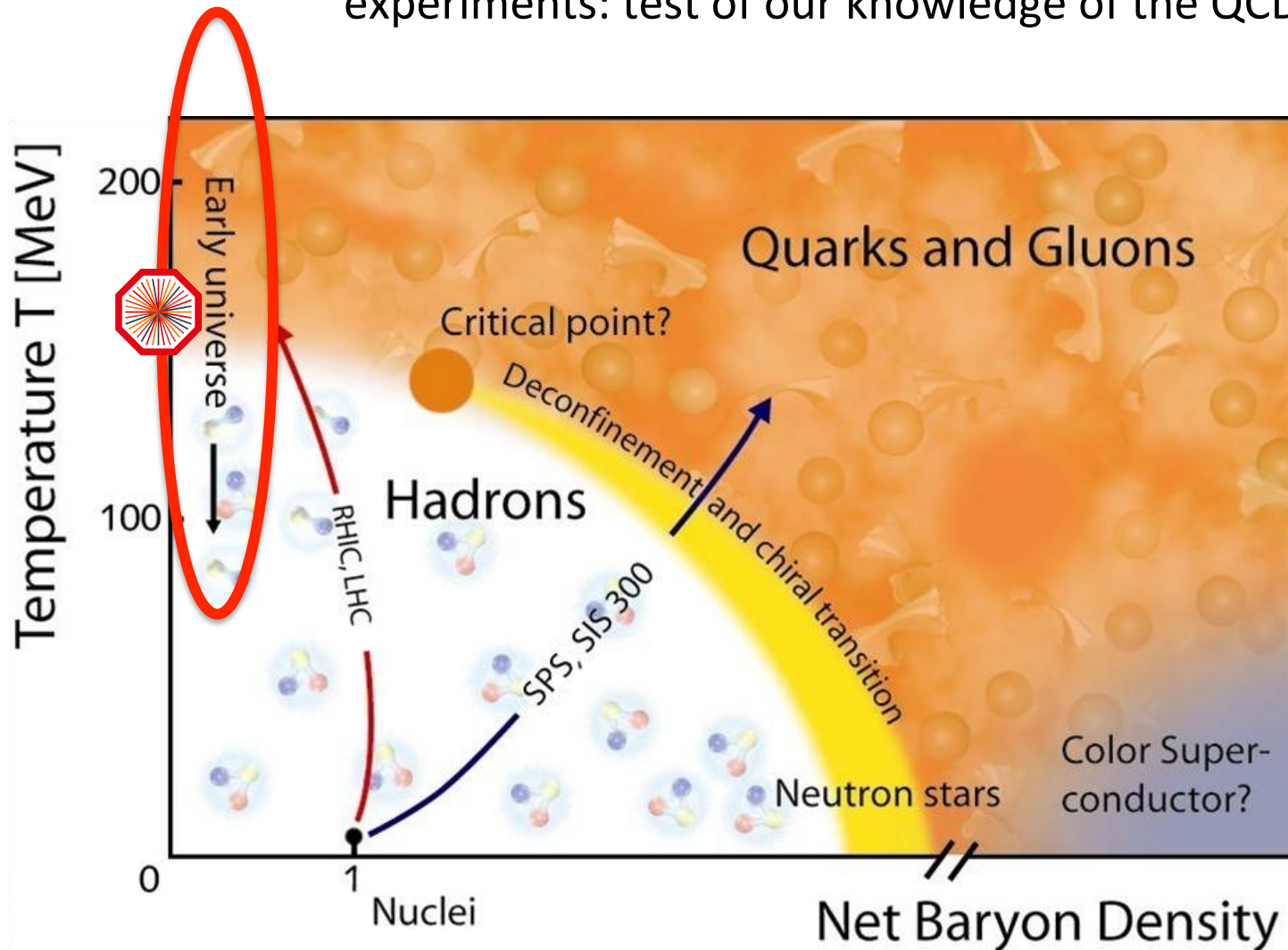
Outline

- **QCD Phase Diagram and the Quark-Gluon Plasma**
- **ALICE: A Large Ion Collider Experiment at the LHC**
- **QGP measurements in ALICE: a short selection**
 - ❖ Light-flavors: spectra and nuclear modification
 - ❖ Light-flavors: baryon/meson ratio
 - ❖ Light-flavors: particle ratios
 - ❖ Open heavy-flavors and quarkonia: nuclear modification and elliptic flow
 - ❖ Jets: quenching and broadening



The QCD Phase Diagram

- ❖ **Exploration of the QCD phase diagram** by heavy-ion collision experiments: test of our knowledge of the QCD as a multi-particle theory



- ❖ **LHC: large and long-living QGP**, large cross-sections for heavy-flavors. Vanishing net baryon density: Early Universe conditions

- ❖ **Experiments focus on collective and transport properties of the strongly coupled medium**



ALICE

The ALICE Detector

Inner Tracking System (ITS)

$(-0.9 < \eta < 0.9)$

Tracking + triggering

Time Projection Chamber (TPC)

$(-0.9 < \eta < 0.9)$

Tracking + particle identification (PID)

Time Of Flight (TOF)

$(-0.9 < \eta < 0.9)$ PID

VZERO scintillator arrays

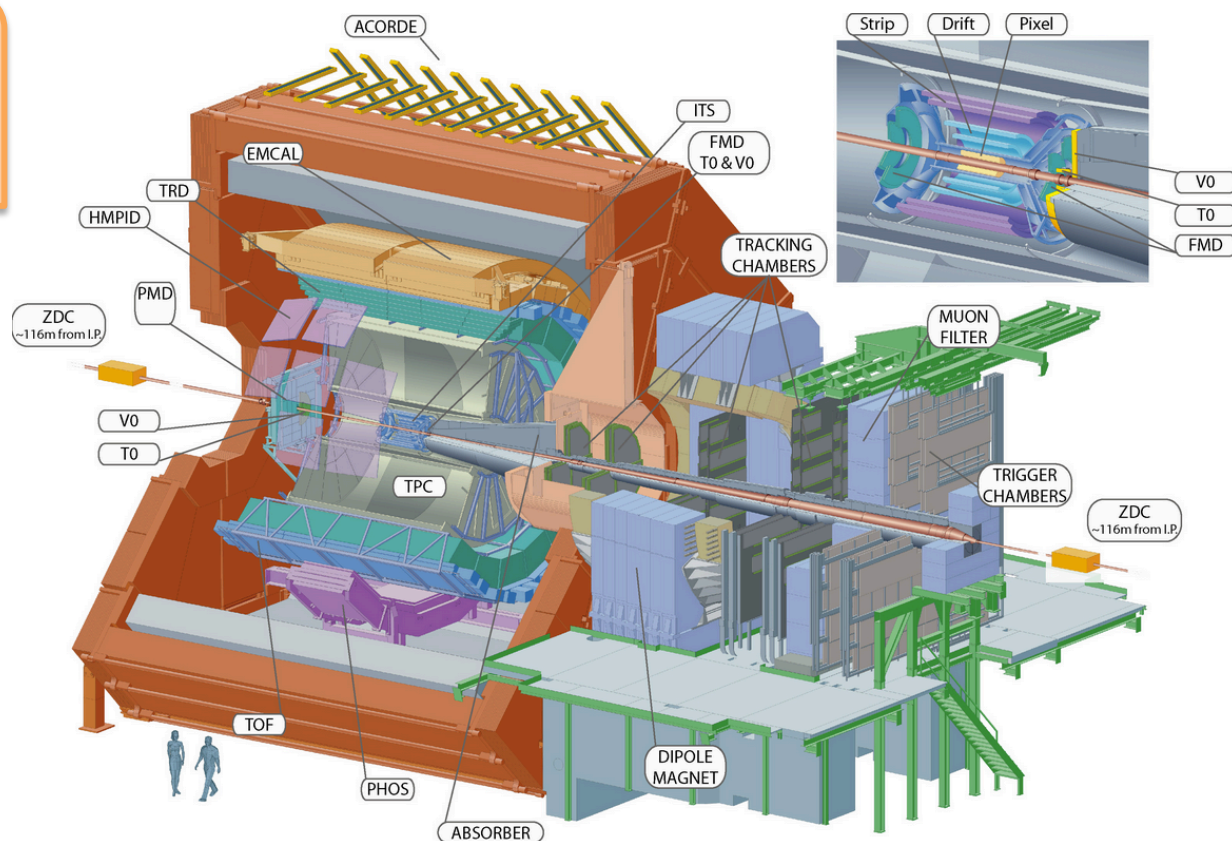
$(-3.7 < \eta < -1.7, 2.8 < \eta < 5.1)$

Centrality + triggering

Muon Spectrometer

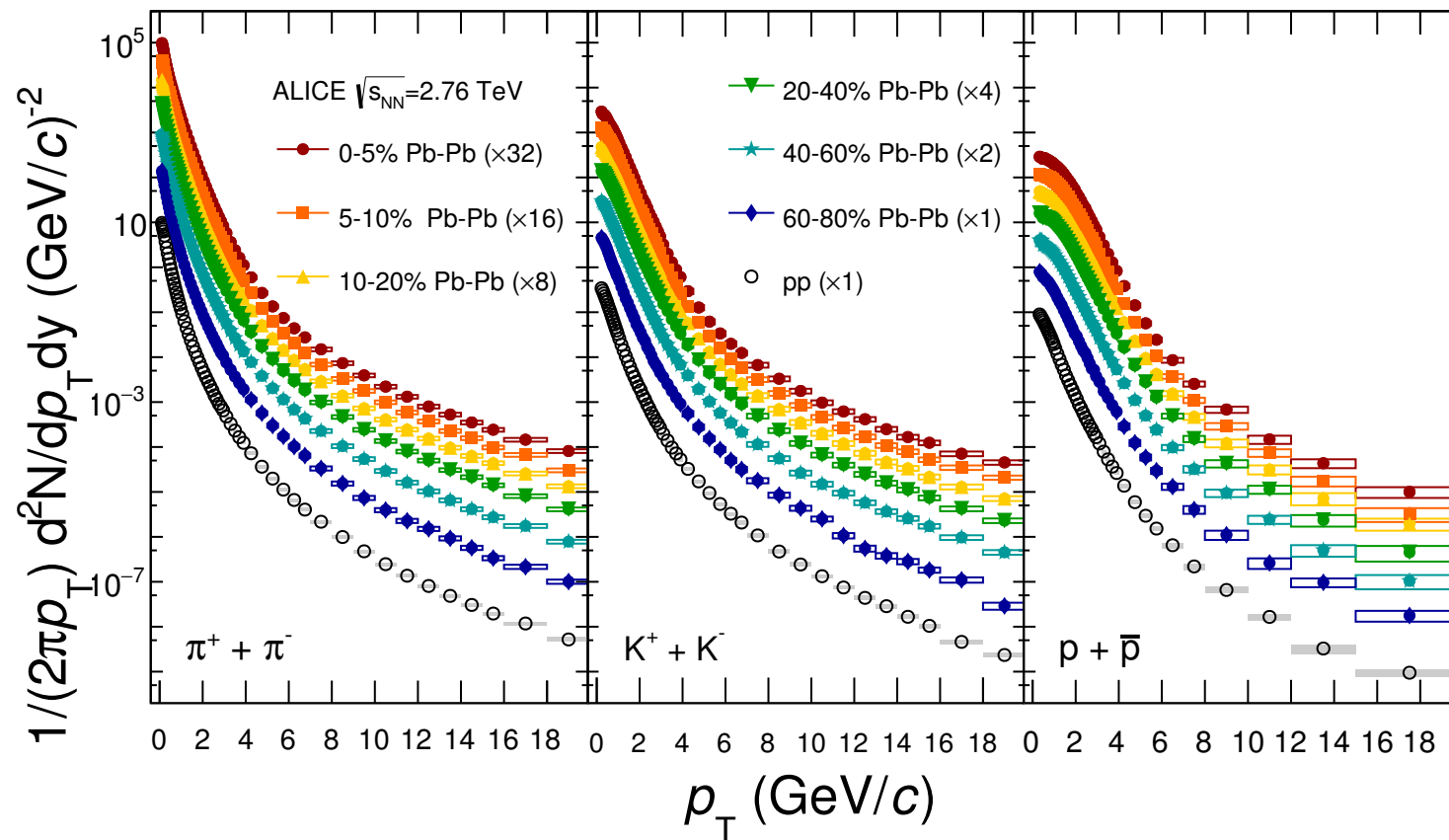
$(-4 < \eta < -2.5)$

Muon tracking + trigger



- ❖ **Tracking:** ITS+TPC ($p_T > 0.2$ GeV/c)
- ❖ **Particle identification:** ITS+TPC+TOF
- ❖ **Centrality estimators:** VZERO, ZDC, ITS

- ❖ p_T distributions and yields of identified particles: information on the collective and thermal properties of the deconfined medium



- ❖ Clear evolution of all spectra with centrality
- ❖ Exponential-like behavior at high p_T
- ❖ Flattening of the spectra at low p_T

ALI-PUB-93390

PRC 93, 034913 (2016)

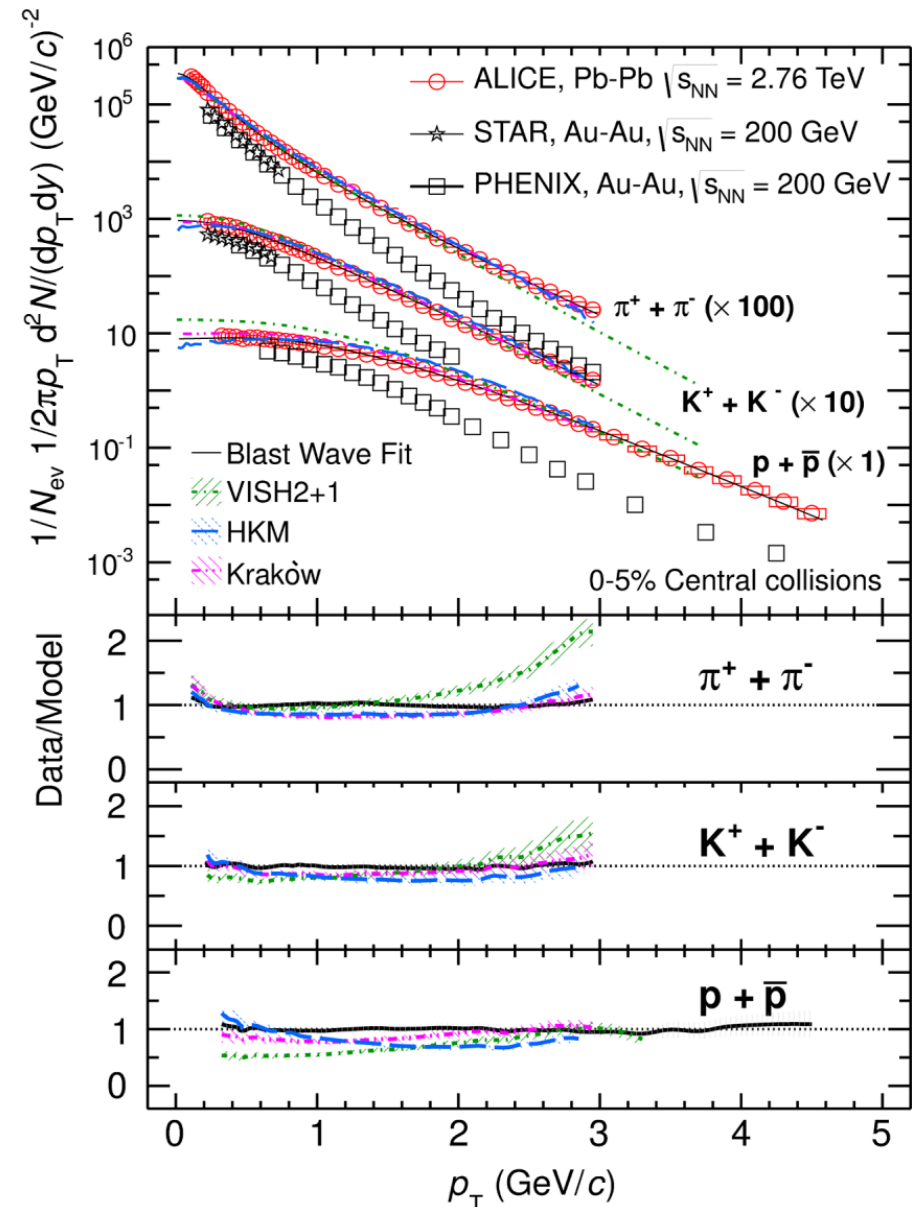
Almost exponential behavior at high p_T and flattening of the spectra at low p_T :

- ❖ Development of a strong collective flow with centrality, dominating the spectral shapes up to relatively high p_T in central collisions

Spectra become harder with centrality in a mass-dependent way (π , K, p)

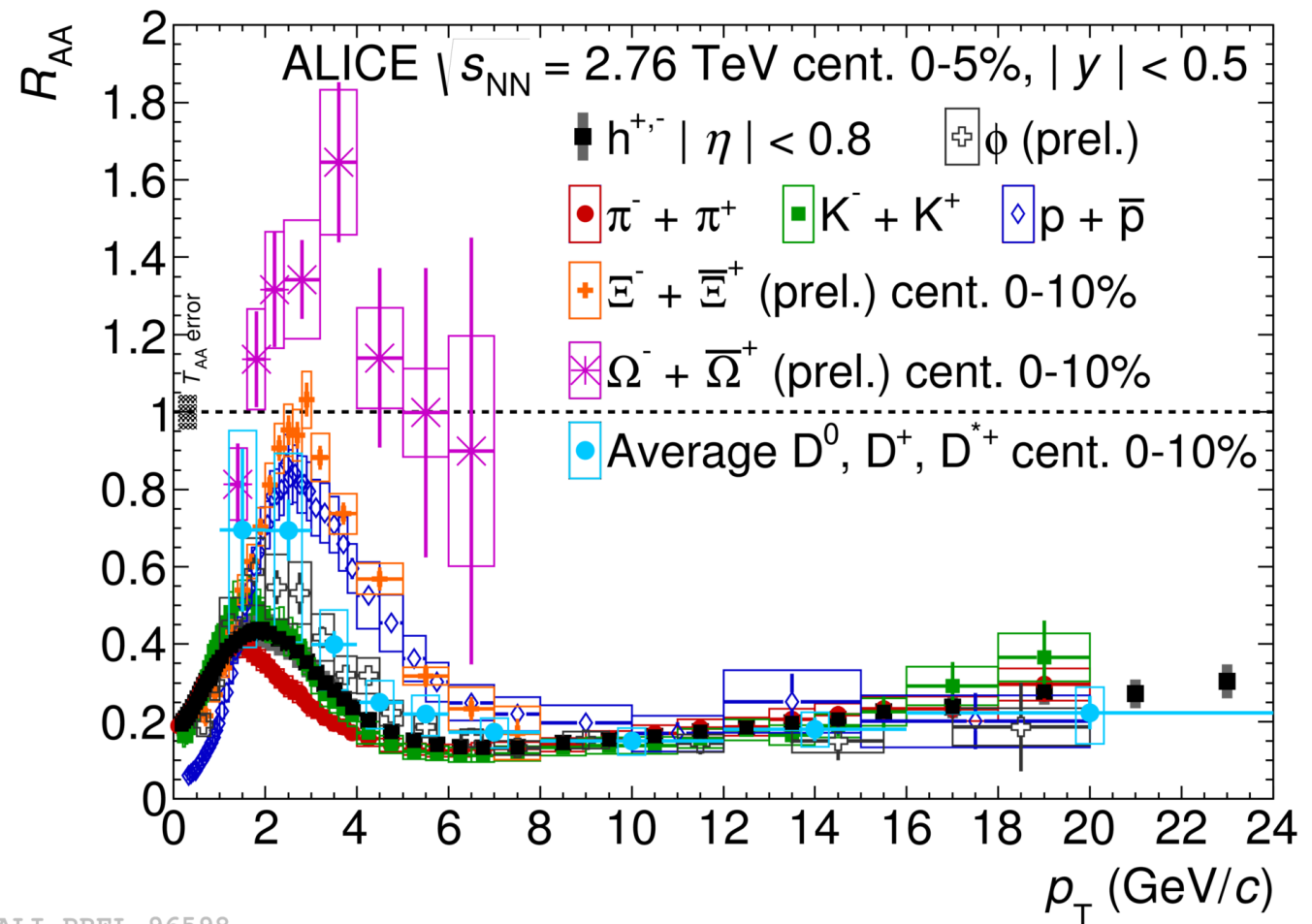
- ❖ Consistent with expectations from models implementing hydrodynamic mechanisms

PRL 109, 252301 (2012)



- ❖ **At high- p_T ($p_T > 8-10$ GeV/c)**
strong flavor-independent suppression in central Pb-Pb with respect to pp:
energy loss in the hot nuclear matter
- ❖ **At mid- p_T ($3 < p_T < 6$ GeV/c)**
different suppression for baryons and mesons in central Pb-Pb: flow, recombination or final state effects?

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / d\eta dp_T}{\langle T_{AA} \rangle d^2 \sigma^{pp} / d\eta dp_T}$$



ALI-PREL-96598

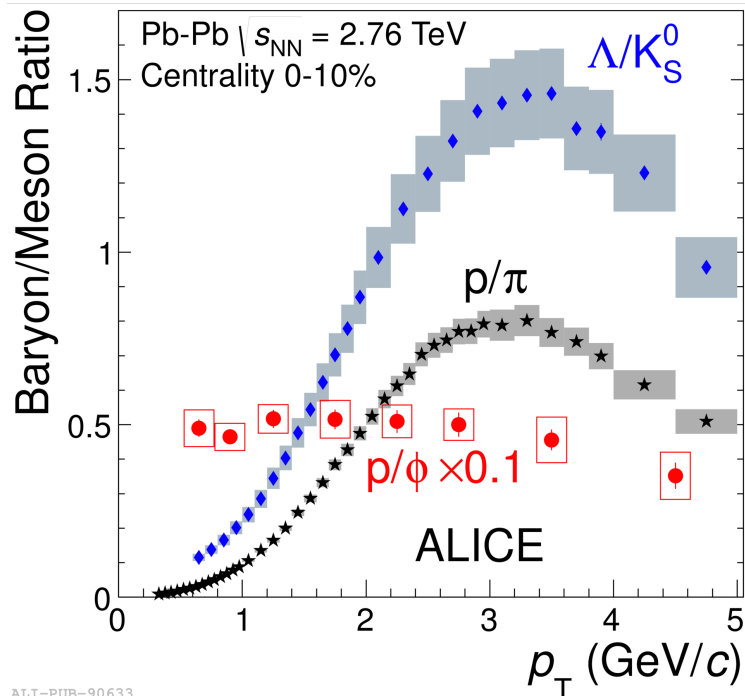
Light Flavor Production: Baryon/Meson Ratio

❖ p and ϕ have similar masses and the p/ϕ ratio is flat in central Pb-Pb: **mass is the parameter driving momentum distributions (as in hydrodynamics)**

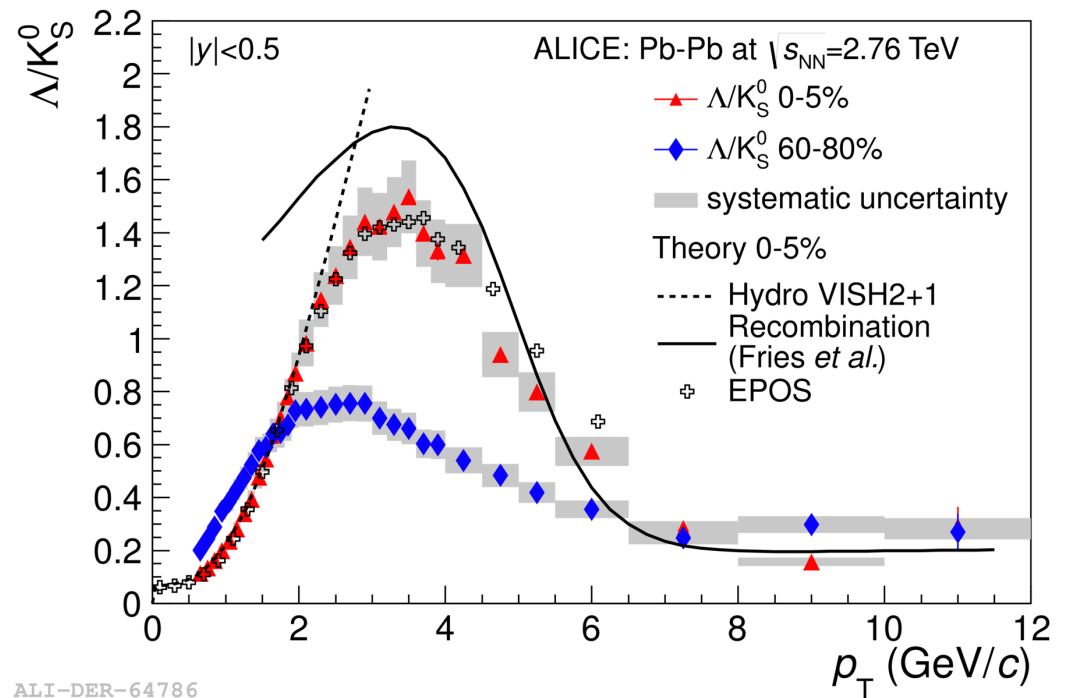
❖ **When masses are different, baryon/meson enhancement is observed at mid- p_T**

- Pure hydrodynamics describes only the rise at low- p_T
- Recombination reproduces the p_T dependence qualitatively but not quantitatively
- EPOS gives the best description of the data (hydrodynamics + flow)

PRL 111 (2013) 222301



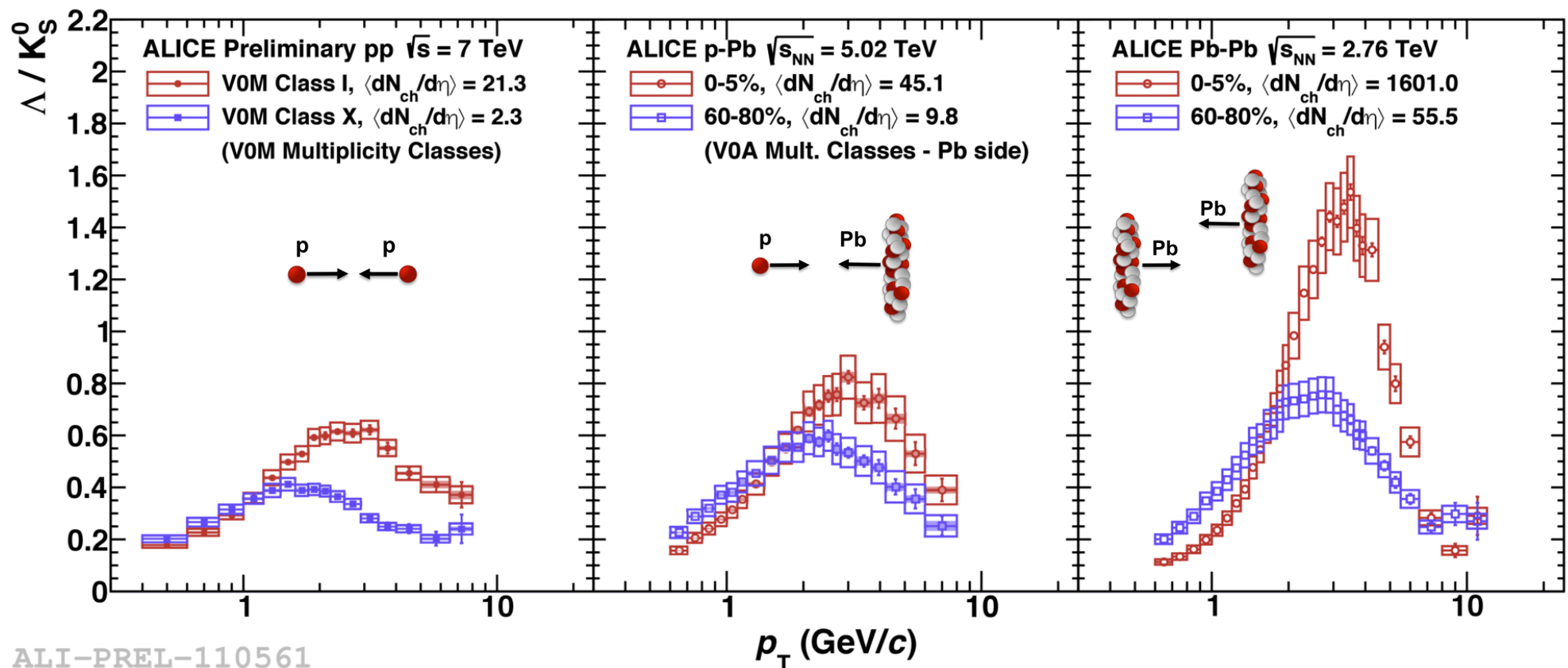
ALI-PUB-90633



ALI-DER-64786

Which role for hydrodynamics? When comparing pp, p-Pb and Pb-Pb collisions, the baryon/meson ratio as a function of multiplicity looks:

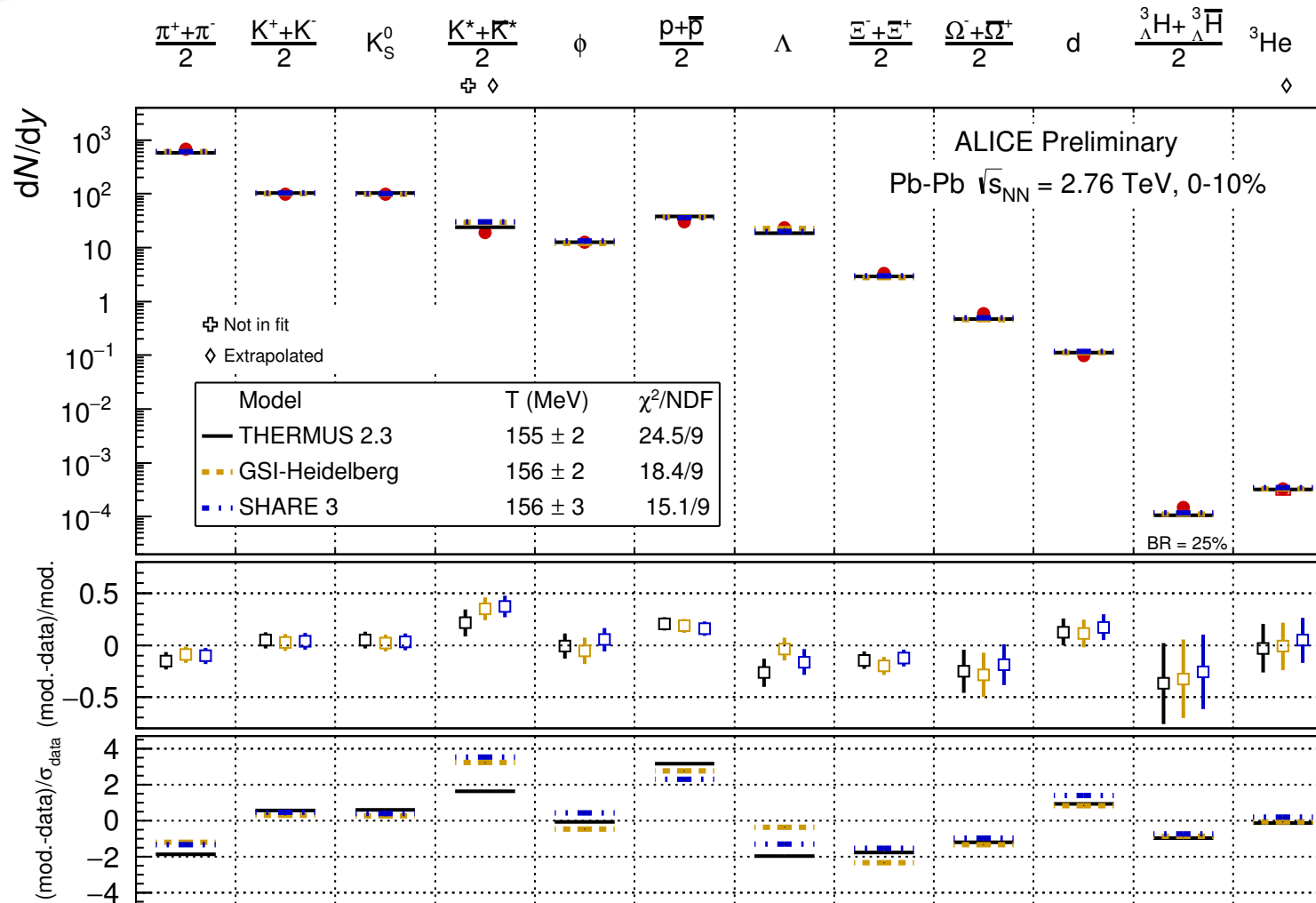
- Qualitatively similar: depletion at low p_T , enhancement at mid p_T
- Quantitatively different in the three systems





ALICE

Light Flavor Production: Particle Ratios



ALI-PREL-94600

Observed hadron yields described in the hypothesis of a thermally-equilibrate regime. Same conclusions from different implementations:
 $T_{ch} \approx 156$ MeV

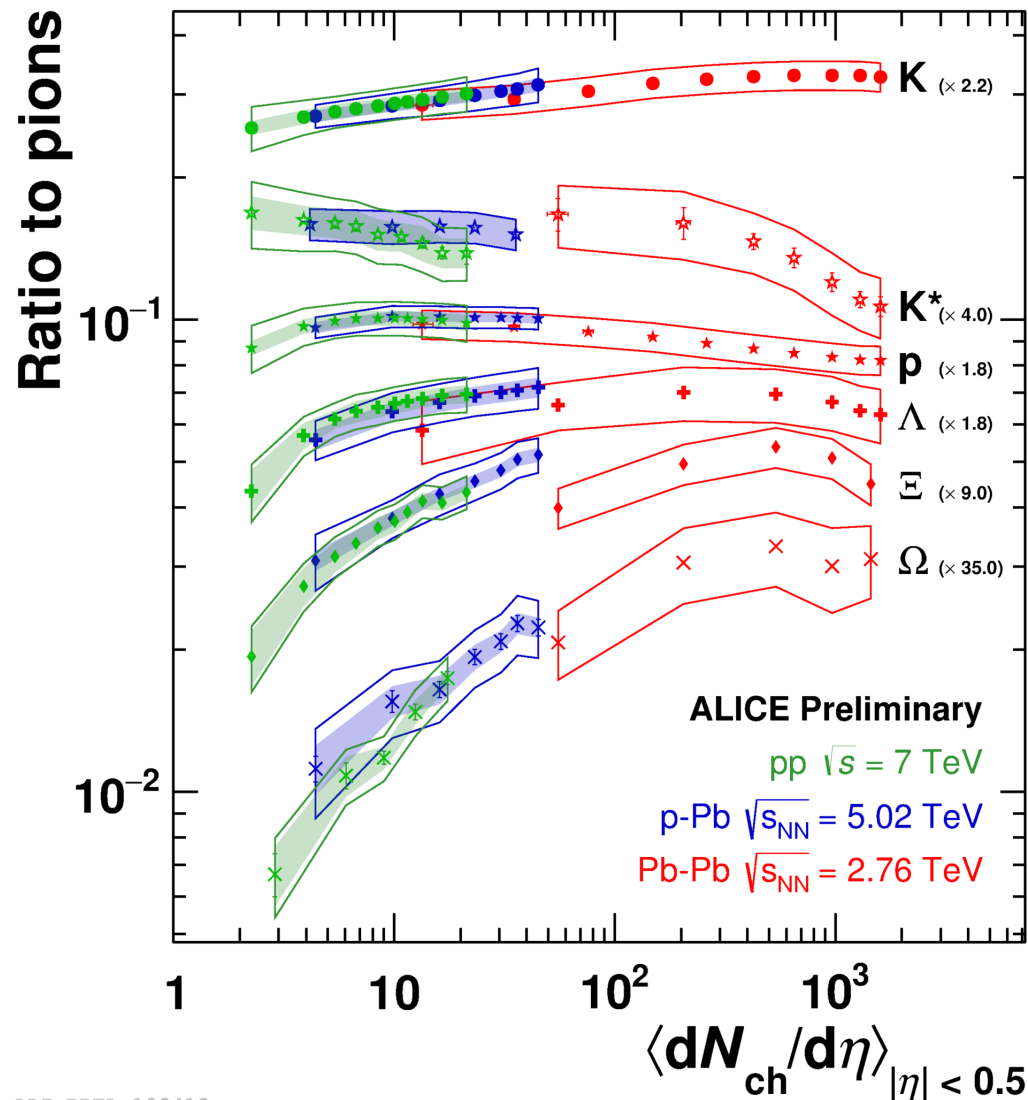
dN/dy of most species well described ($\chi^2/\text{ndf} \approx 2$)

arXiv:1602.02173



ALICE

Light Flavor Production: Particle Ratios

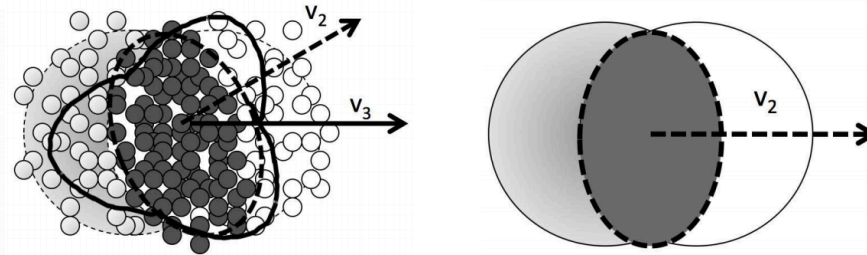
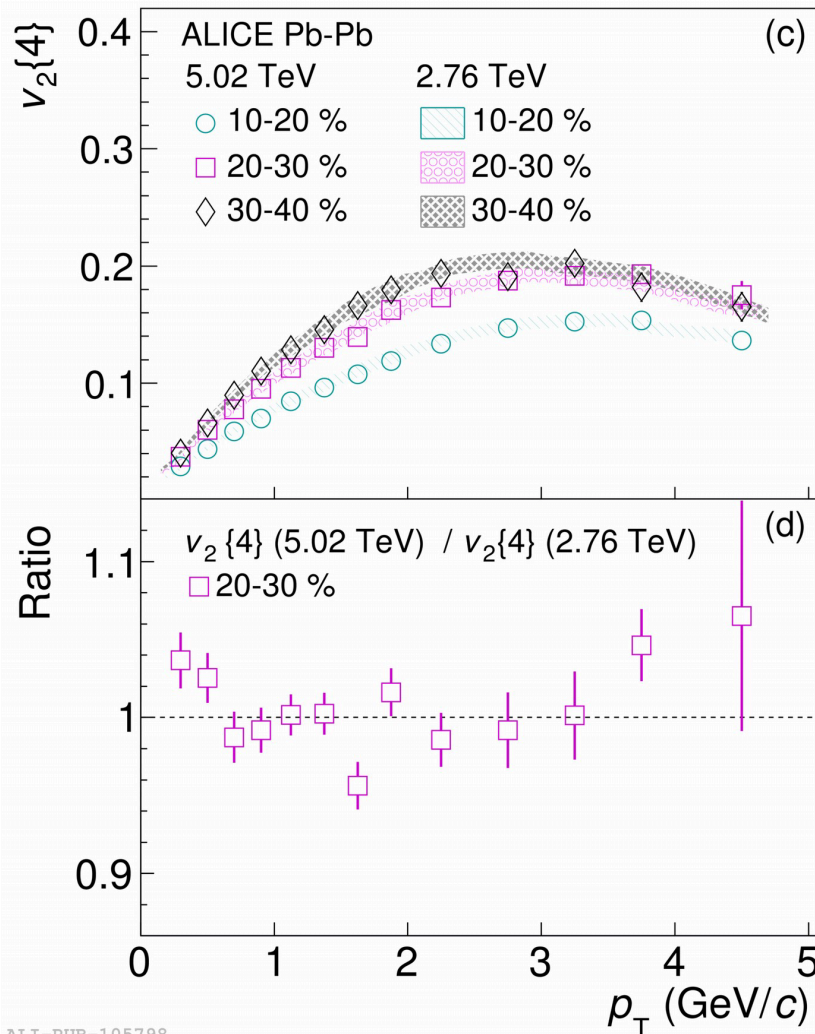


ALI-PREL-109418

- ❖ ALICE measurements of identified particle production in pp, p-Pb, Pb-Pb collisions have revealed interesting and **similar features across different systems**
- ❖ **Collectivity in small systems? Which origin?**
- ❖ Observations in smaller systems can still have an impact on the interpretation of the observations in Pb-Pb

❖ Anisotropic flow measurements using two- and multi-particle cumulants

PRL 116, 132302 (2016)



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2(\phi - \Psi_{RP})) + \text{higher harmonics } (v_3, v_4, \dots)$$

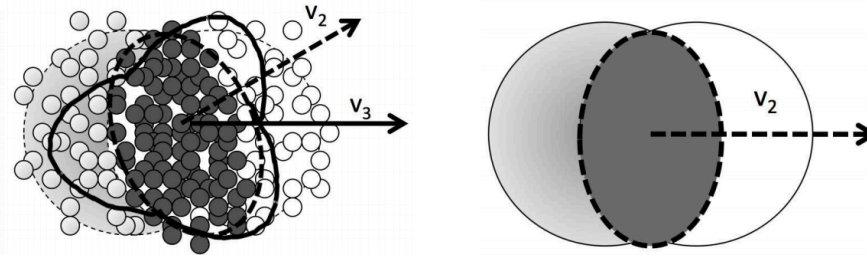
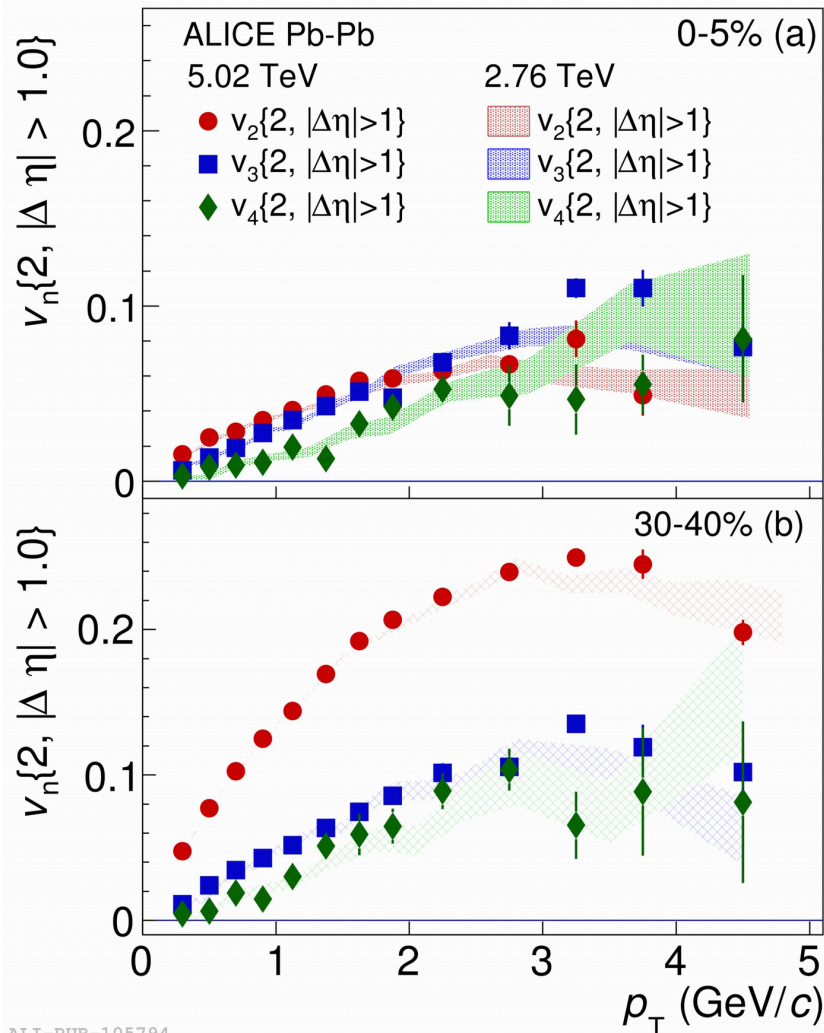
❖ Elliptic flow results $v_2(p_T)$ at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ show **very similar values to the ones seen at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$**

❖ Higher harmonics (v_3, v_4) as a function of p_T are also unchanged with energy

❖ v_3 becomes larger than v_2 for $p_T > 2 \text{ GeV/c}$ in central collisions

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PRL 116, 132302 (2016)



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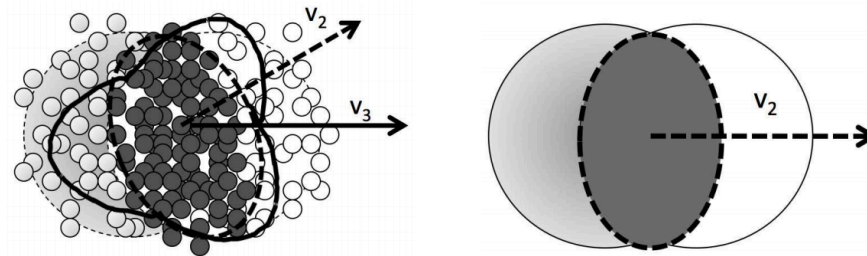
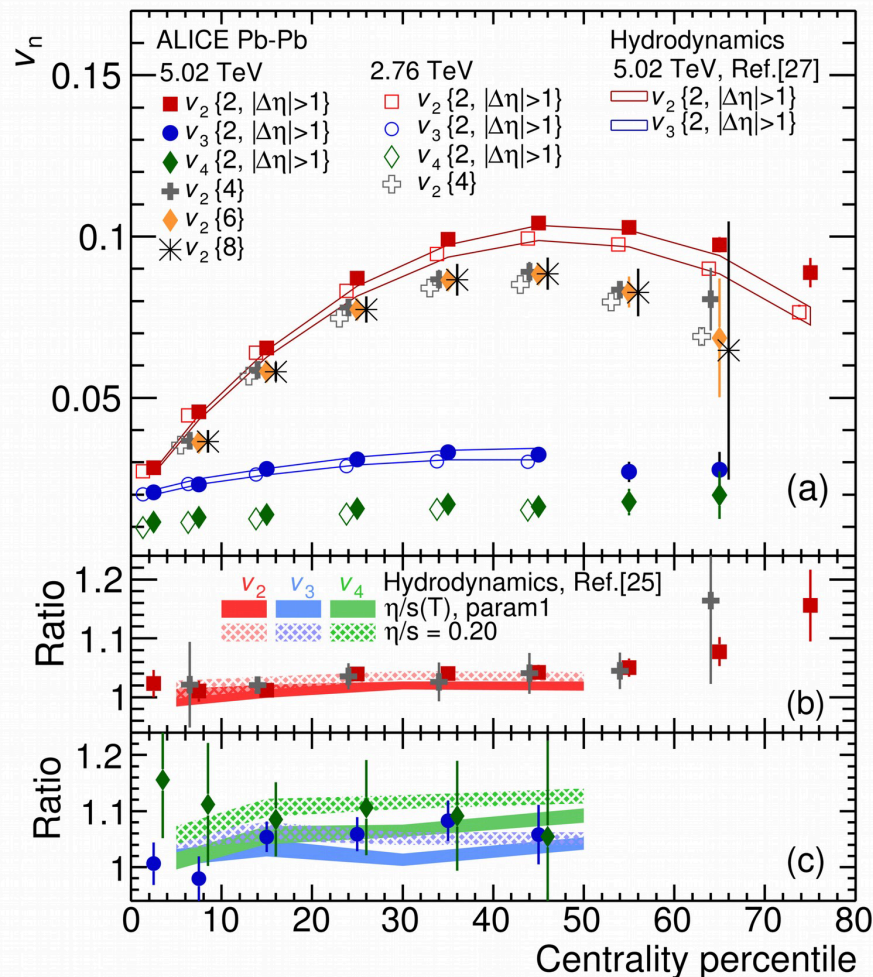
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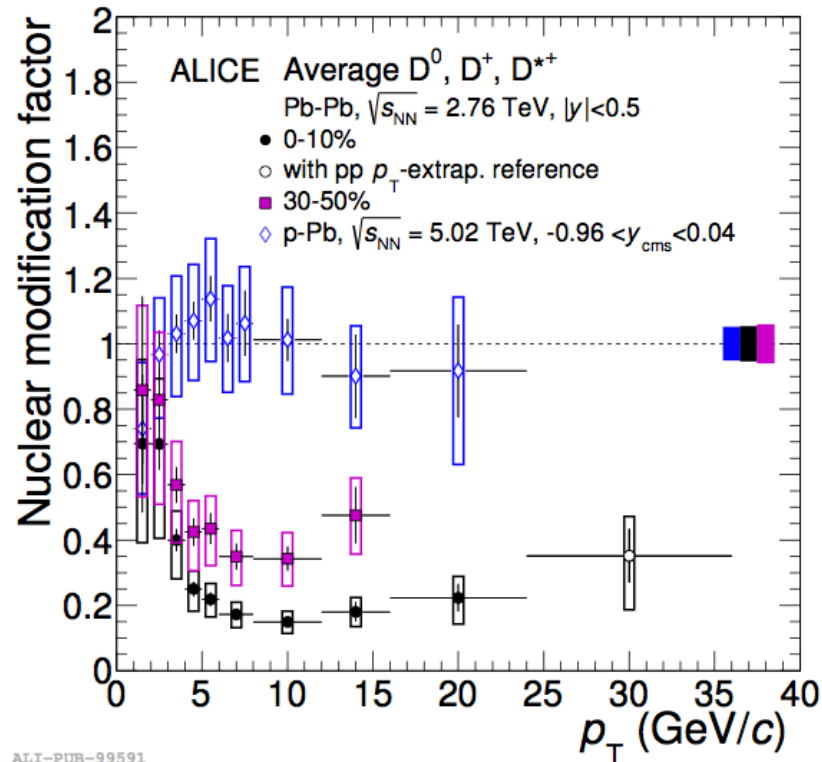
- ❖ p_T -integrated v_2 , v_3 and v_4 point to a **mild increase with collisions energy attributed to the increase in $\langle p_T \rangle$**
- ❖ **Good agreement with hydrodynamical calculations**
- ❖ Measurements support a **low value for the shear viscosity to entropy density ratio (η/s)**



ALICE

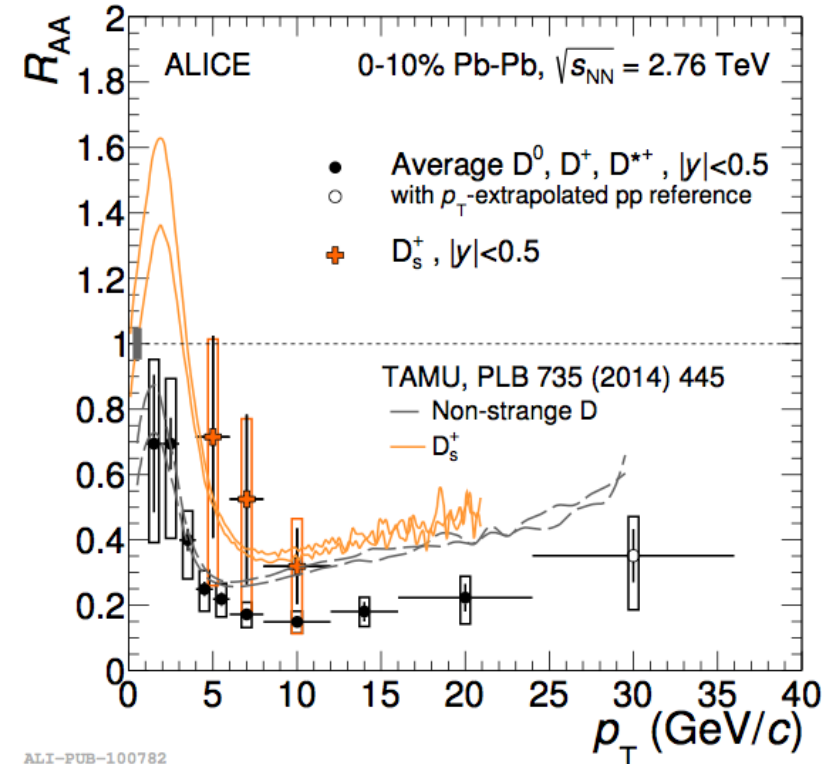
Open Heavy Flavors: D-Mesons R_{AA}

JHEP 1603 081 (2016)



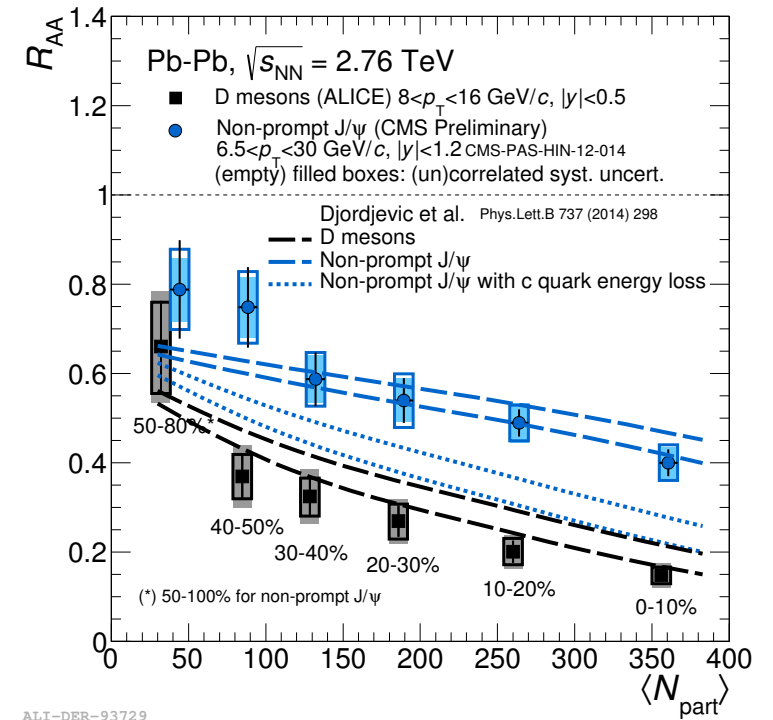
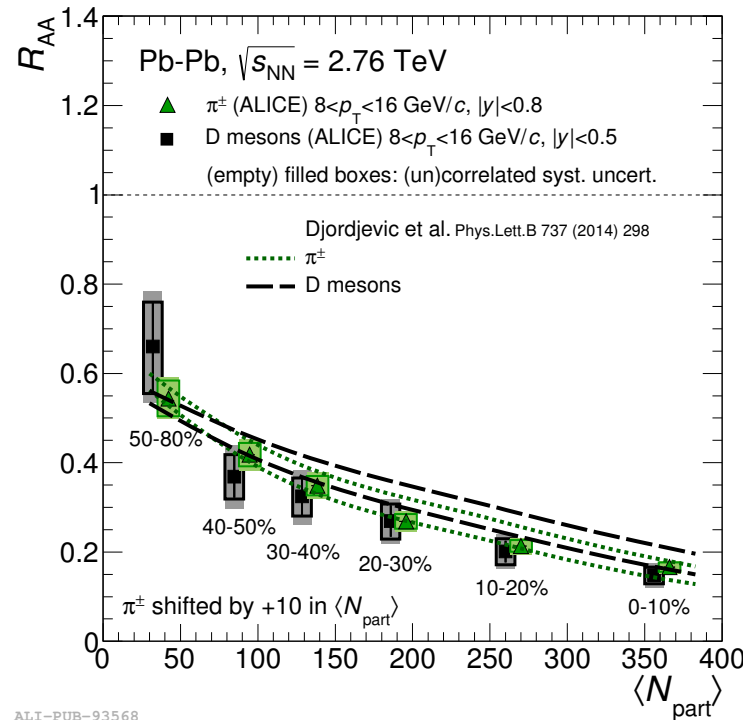
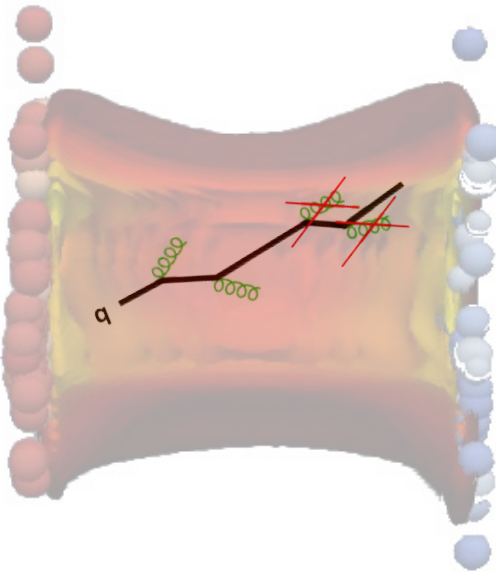
- ❖ **Strong suppression of D-mesons** for central and semi-central Pb-Pb collisions at intermediate and high- p_T : significant energy loss of heavy quarks in the medium

JHEP 1603 082 (2016)



- ❖ **Less suppression for D_s ?** Sensitive to the charm hadronization processes in the QGP. Large uncertainties, no conclusive interpretation at the moment

Open Heavy Flavors: Mass Dependence of R_{AA}



$$R_{AA}(D) \approx R_{AA}(\text{light flavors})$$

- Described by models that take into account color-charge dependence of energy loss and softer fragmentation and p_T spectrum of gluons w.r.t. c quarks

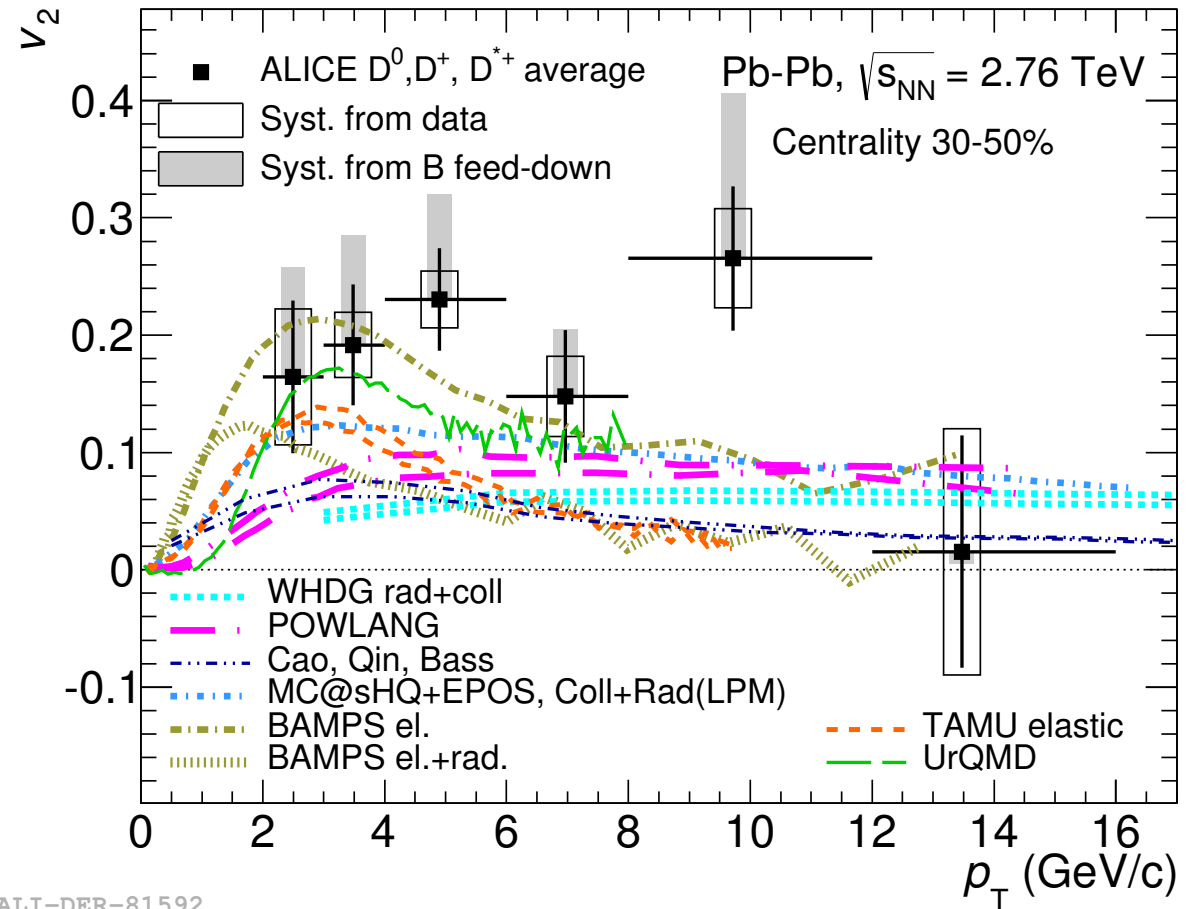
$$R_{AA}(D) < R_{AA}(J/\psi \leftarrow B)$$

- Hint for mass hierarchy of the partonic in-medium energy loss: described by a model including mass-dependent radiative and collisional energy loss

JHEP 1511 205 (2015)

PRC 90 034904 (2014)

- ❖ **Bulk (light hadron) flow** builds up as a fluid dynamical response to the initial spatial eccentricities, mediated by pressure gradients
- ❖ In order to transfer this bulk flow to the heavy quarks a high interaction rate with the medium constituents is required!
Do heavy quarks flow?



ALI-DER-81592

➔ **Indeed, a positive elliptic flow has been measured for open heavy-flavor particles!**
Heavy flavors participate to the collective expansion at low p_T : large interaction rate of heavy quarks with the deconfined medium

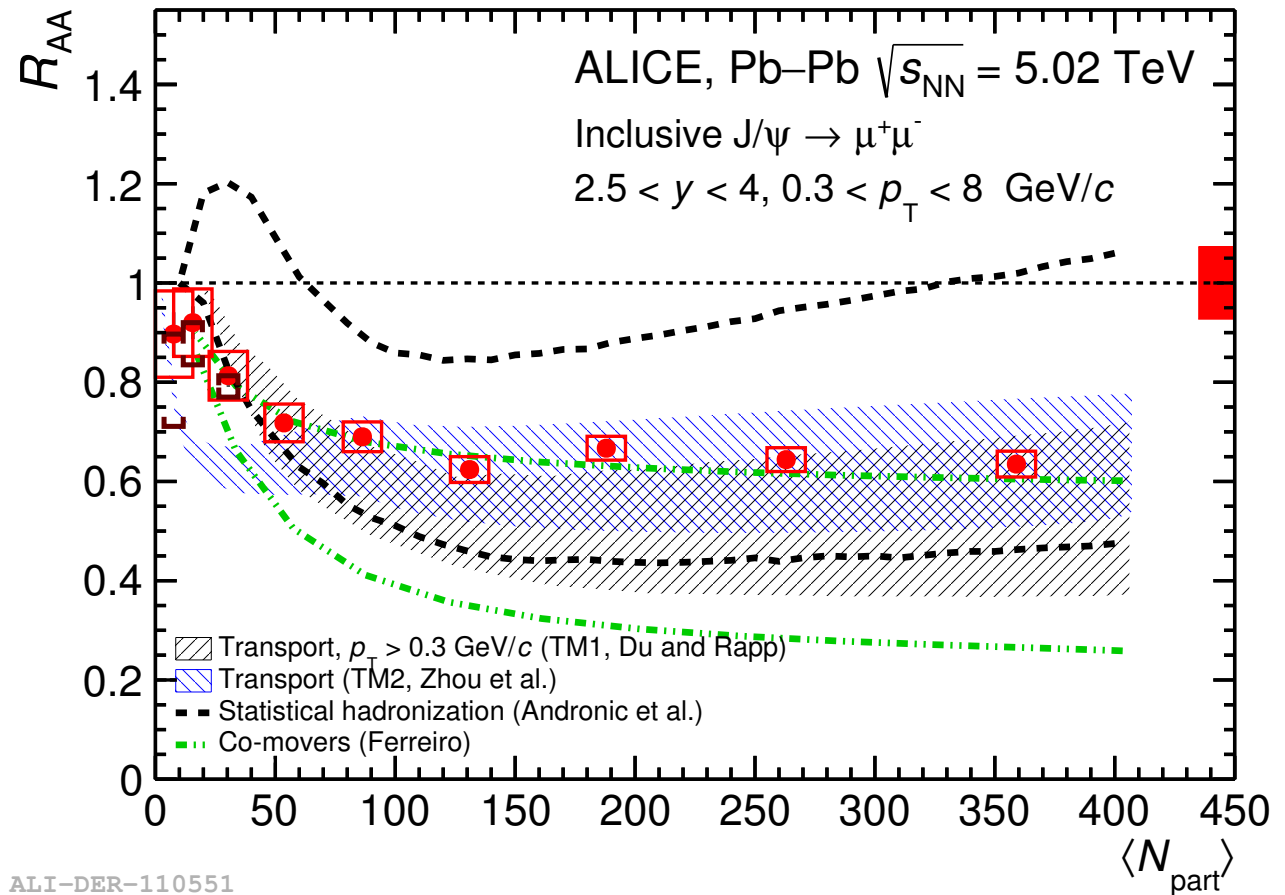
arXiv:1606.08197

Bound QQ states: privileged tools to probe the deconfined medium properties:

- Color screening strength
- Temperature

R_{AA} vs centrality described by various models:

- ✧ **SHM:** all J/ψ produced by statistical hadronisation at the QGP phase boundary
- ✧ **TM1/TM2:** rate equation of suppression and regeneration by/in the QGP
- ✧ **CIM:** suppression by the co-moving partonic medium and regeneration



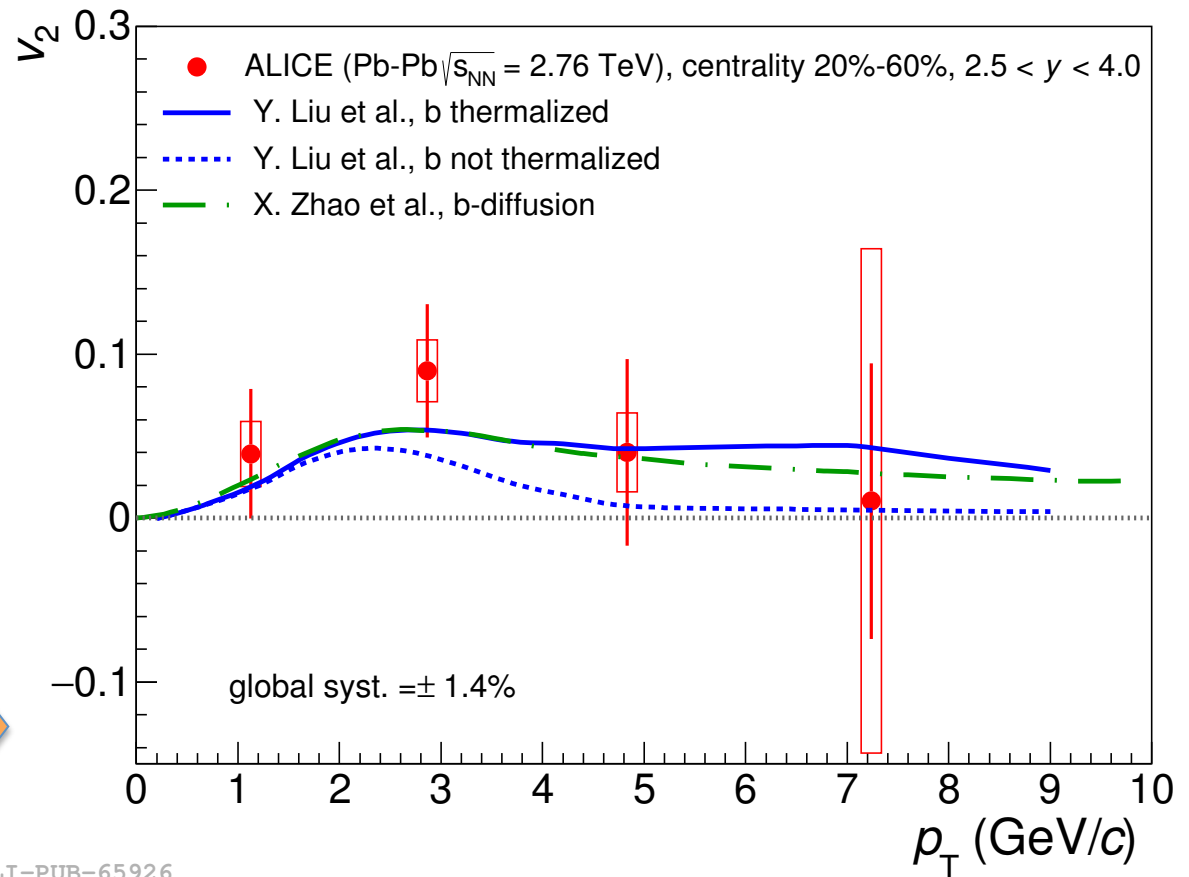
ALI-DER-110551

PRL 111 (2013) 162301

If charm quarks participate to the collective motion of the QGP, then they will acquire some elliptic flow

❖ Regenerated J/ψ will inherit the elliptic flow of the c quarks

Hint of non-zero J/ψ v_2 at intermediate p_T for semi-central collisions at the LHC



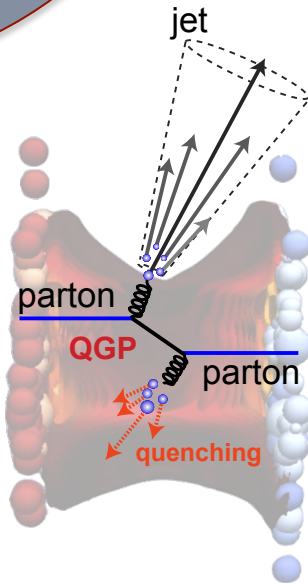
ALI-PUB-65926

❖ Qualitatively described by models including regeneration

❖ Larger effect than at RHIC. LHC larger statistics of run 2 will help

Jets: Quenching and Broadening

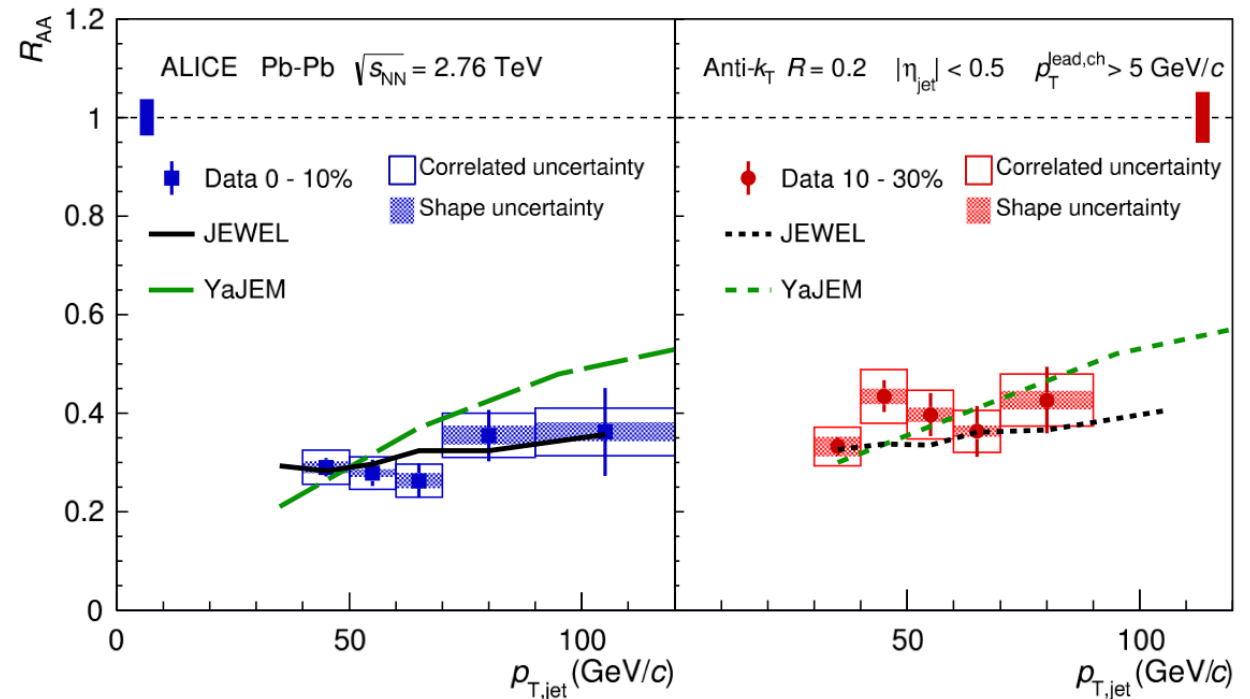
credits: B. Hippolyte



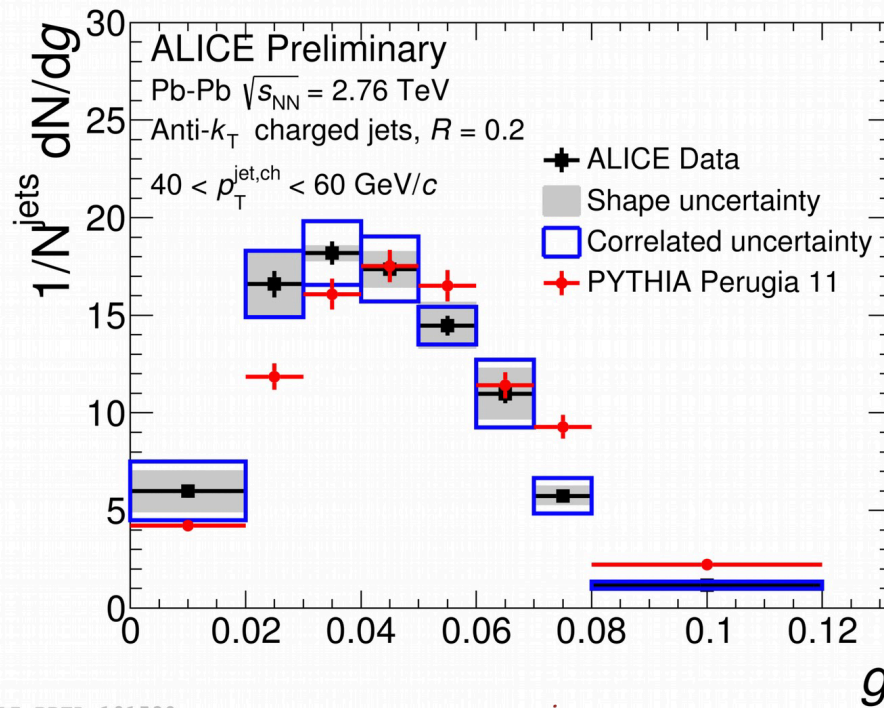
- ❖ **Strong quenching**, similar to hadron $R_{AA} \Rightarrow$ parton energy is not recovered inside jet cone
- ❖ **Quenching increases with centrality**, with a weak p_T dependence
- ❖ Different models reproduce the observed jet quenching: more differential measurements are needed

PLB 746 (2015) 1

- **JEWEL**: microscopic pQCD parton shower + gluon-induced emissions
- **YaJEM**: detailed fireball model + parameterisation of radiative and collisional energy loss



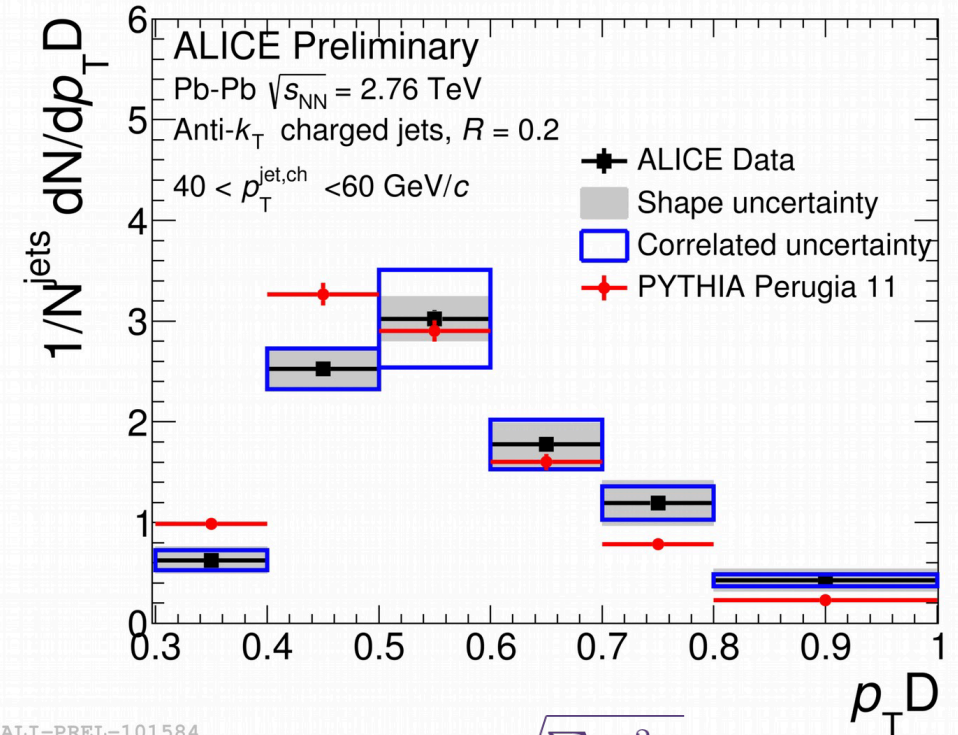
PYTHIA reference validated with results from pp collisions



ALI-PREL-101580

$$g = \sum_{i \in \text{jet}} \frac{p_{T,i}}{p_T^{\text{jet}}} |r_i|$$

- ❖ Radial moment shifted to lower values in Pb-Pb relative to PYTHIA: **jet cores are more collimated in Pb-Pb**

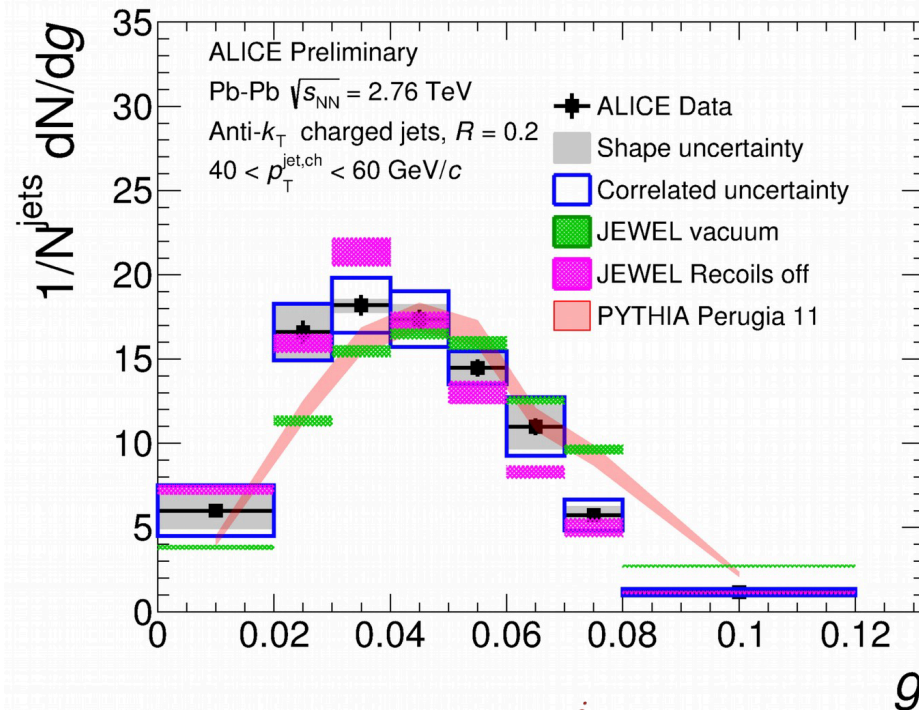


ALI-PREL-101584

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

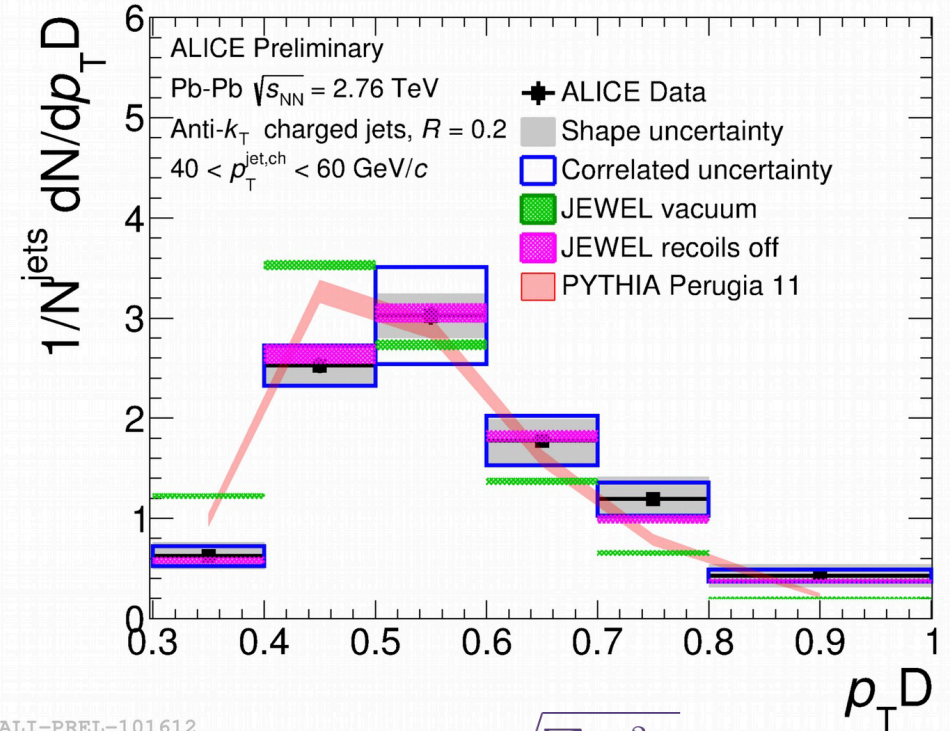
- ❖ $p_T D$ shifted to higher values in Pb-Pb relative to PYTHIA: **fewer jets constituents and/or larger p_T dispersion**

Qualitative agreement with JEWEL model calculations



ALI-PREL-101592

$$g = \sum_{i \in \text{jet}} \frac{p_{T,i}}{p_T} |r_i|$$



ALI-PREL-101612

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

- ❖ Jets in model calculations become collimated due to **soft particle emission at large angles, which ends up outside the jet cone**



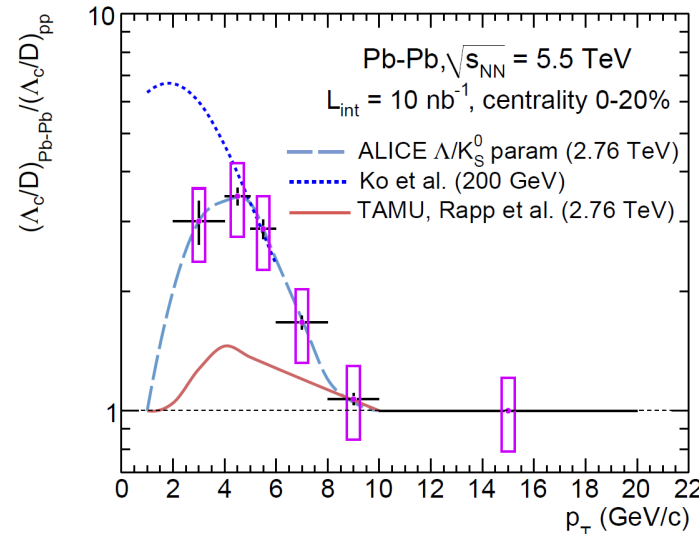
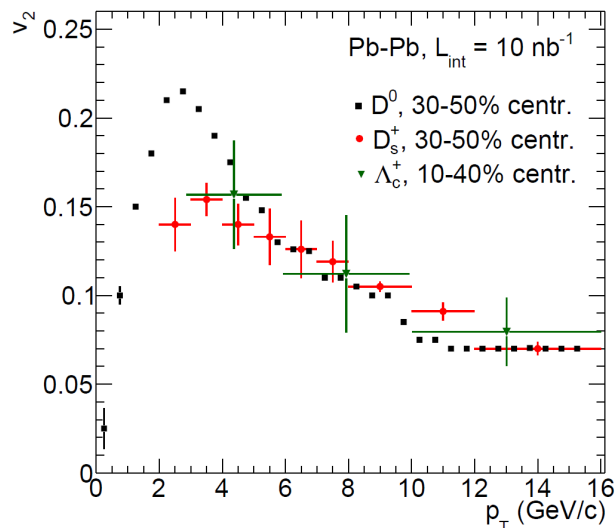
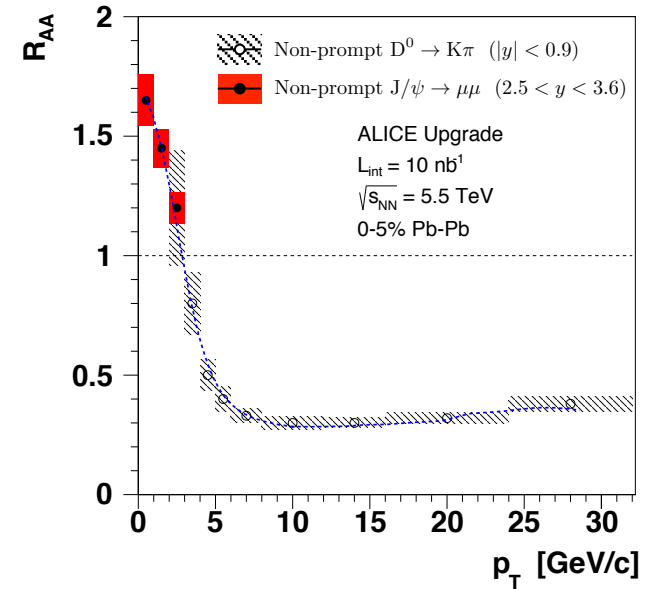
Summary and Conclusions

ALICE characterizes the QCD phase diagram at vanishing baryonic potential using the LHC as a QGP factory. What have we learnt until now on the QGP?

- ❖ The QGP presents collective, hydrodynamic evolution behaviors, indicative of perfect-liquid properties (however, similar behaviors are also observed to a lesser degree in pp and p-Pb...)
- ❖ The QGP is a thermally-equilibrated phase, with particle yield ratios described by thermal models with $T_{\text{ch}} \approx 156$ MeV, including enhanced strangeness production w.r.t. pp collisions (however, measured ratios seem to be a multiplicity-driven evolution of those observed in pp and p-Pb...)
- ❖ The QGP induces a significant (mass-dependent) energy loss on jets, heavy-flavored hadrons and high-pt light-flavored hadrons, not observed in cold nuclear matter
- ❖ The QGP manages to involve heavy quarks in its dynamics, when expanding against the vacuum
- ❖ The QGP induces color-screening dissociation of quarkonium states (however, similar observations have been reported in cold nuclear matter for the weaker bound state $\psi(2S)$...). Charmonium regeneration, if confirmed by data, could finally prove the partonic deconfined nature of the QGP

❖ Yield and elliptic flow in Heavy-Ion collisions accessible at mid- and forward-rapidity for both charm and beauty sectors:

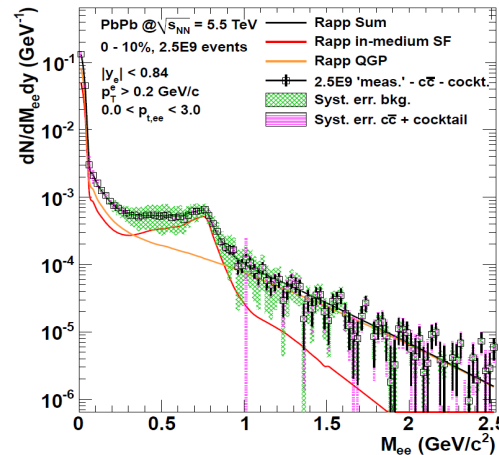
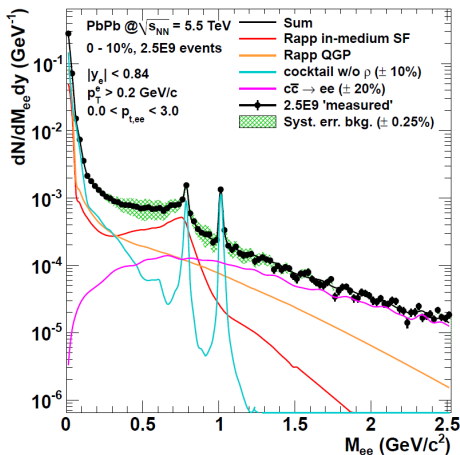
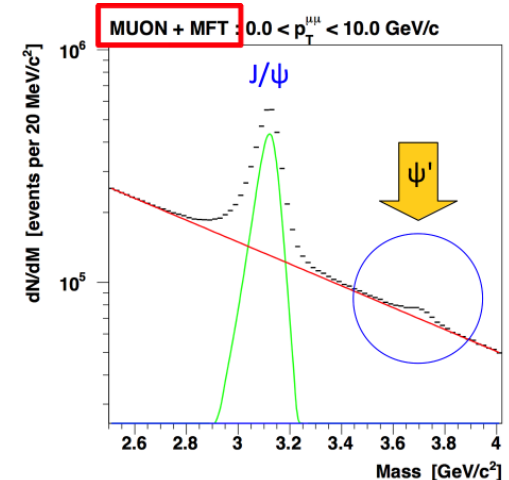
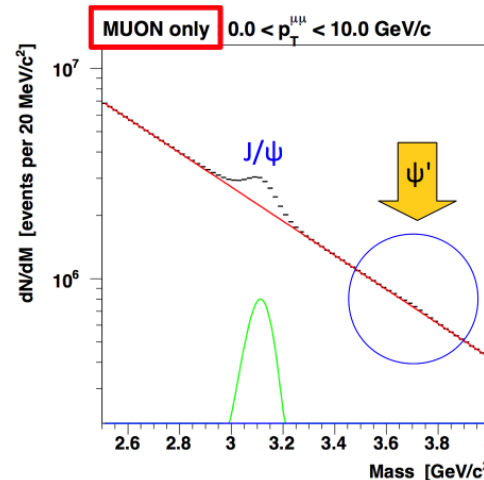
- **Central barrel:** prompt charm mesons/baryons; D mesons and J/ψ from B + full B reconstruction
- **Muon arm:** single muons from D; J/ψ from B + single muons from B



❖ Baryon/meson ratio: only available at mid-rapidity thanks to the upgraded ITS (upgrade especially needed for $\Lambda_c \rightarrow pK\pi$ with $c\tau \approx 60 \mu\text{m}$)

Improved discrimination of prompt/displaced dileptons thanks to the upgraded ITS (central dielectrons) and MFT (forward dimuons)

- ❖ **Isolation of forward prompt J/ψ**
(not possible without the MFT)
- ❖ **S/B improvement for $\psi(2S)$ in central Pb-Pb (dimuon channel)**
by a factor 6-7



- ❖ **Isolation of medium-modified ρ ; thermal radiation from QGP**
- ❖ **Excellent performance in the dielectron channel with a dedicated low magnetic field (low- p_T acceptance)**

Backup Slides



ALICE Upgrade Strategy (I)

❖ Detector specificities (strengthened with the upgrades):

- Hadron and lepton identification
- Light-weight and precise trackers
- Low magnetic field

❖ Main observables...

- Low- p_T Heavy Flavors
- Low- p_T Charmonium
- Prompt dileptons down to low-mass and low- p_T

ALICE Upgrade LOI + addendum: CERN-LHCC-2012-012,
CERN-LHCC-2013-014

ALICE TPC Upgrade TDR: CERN-LHCC-2013-020

ALICE ITS Upgrade TDR: CERN-LHCC-2013-024

ALICE MFT TDR: CERN-LHCC-2015-001

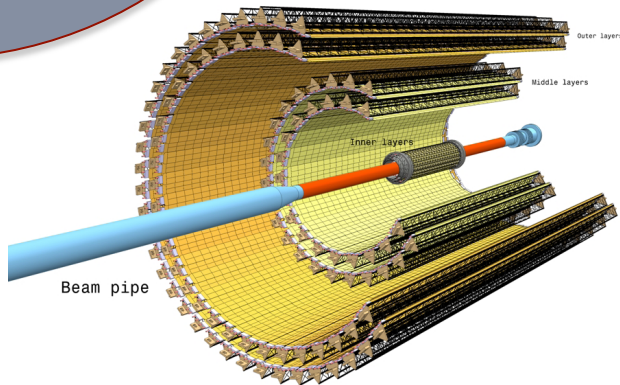
ALICE Online-Offline Upgrade TDR: CERN-LHCC-2015-006

❖ ... are based on “untriggerable” signals!

- Record all events at up to 50 kHz in Pb-Pb (currently 0.5 kHz): strong data reduction needed (from 1 TB/s to 50 GB/s via online reconstruction)
- HL-HI-LHC: increase of minimum-bias sample $\times 100$ w.r.t. Run 2



ALICE Upgrade Strategy (II)



New Inner Tracking System (ITS)

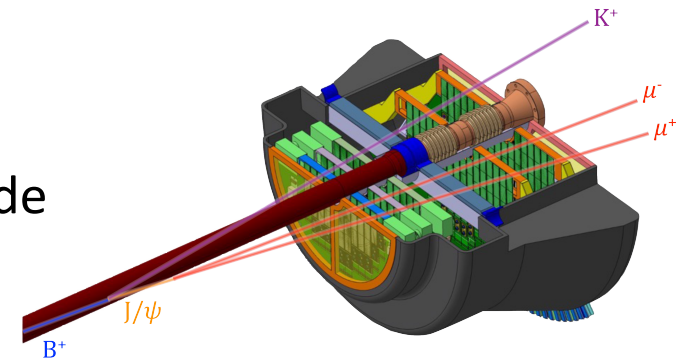
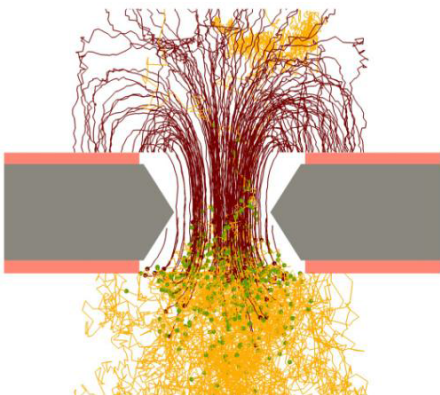
- New pixel technology: improved granularity and resolution, reduced material budget

New Forward Muon Tracker (MFT)

- Vertex tracker for the forward muon spectrometer: heavy flavor vertices, prompt/displaced muon discrimination

TPC Upgrade:

- Replacement of the MWPC-based readout by detectors employing GEMs to allow TPC operation in continuous mode



Upgraded read-out for many detectors, new integrated Online-Offline (O²), new Fast Interaction Trigger detector

- Upgraded ALICE records Pb-Pb data at 50 kHz (< 0.5 kHz in Run I)