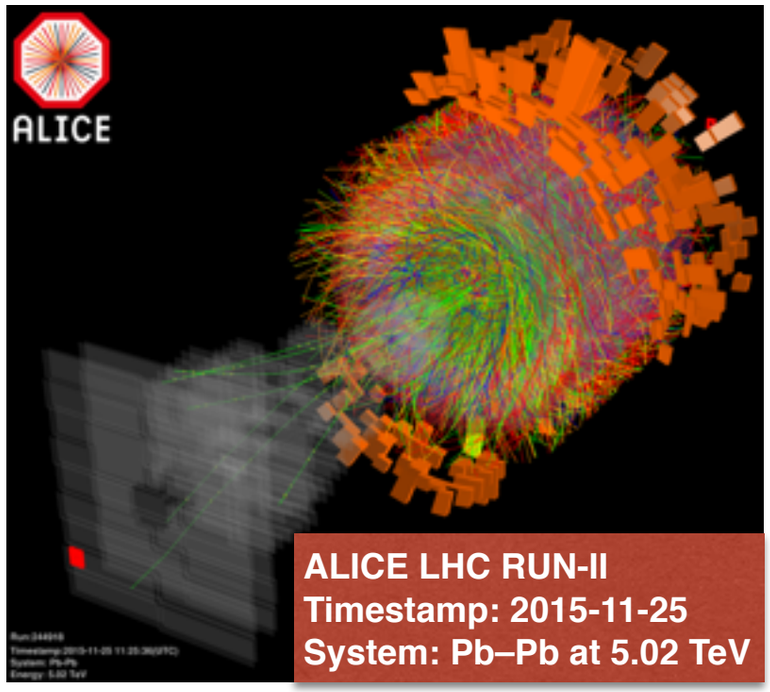
ALICE Overview

Xiaoming Zhang for the ALICE Collaboration



- **ALICE experiment at the LHC**
- **Collective effects**
- **Hard probes**
  - **High p_T particles, jets, heavy flavours…**
- **Small systems (pp and p–Pb collisions)**

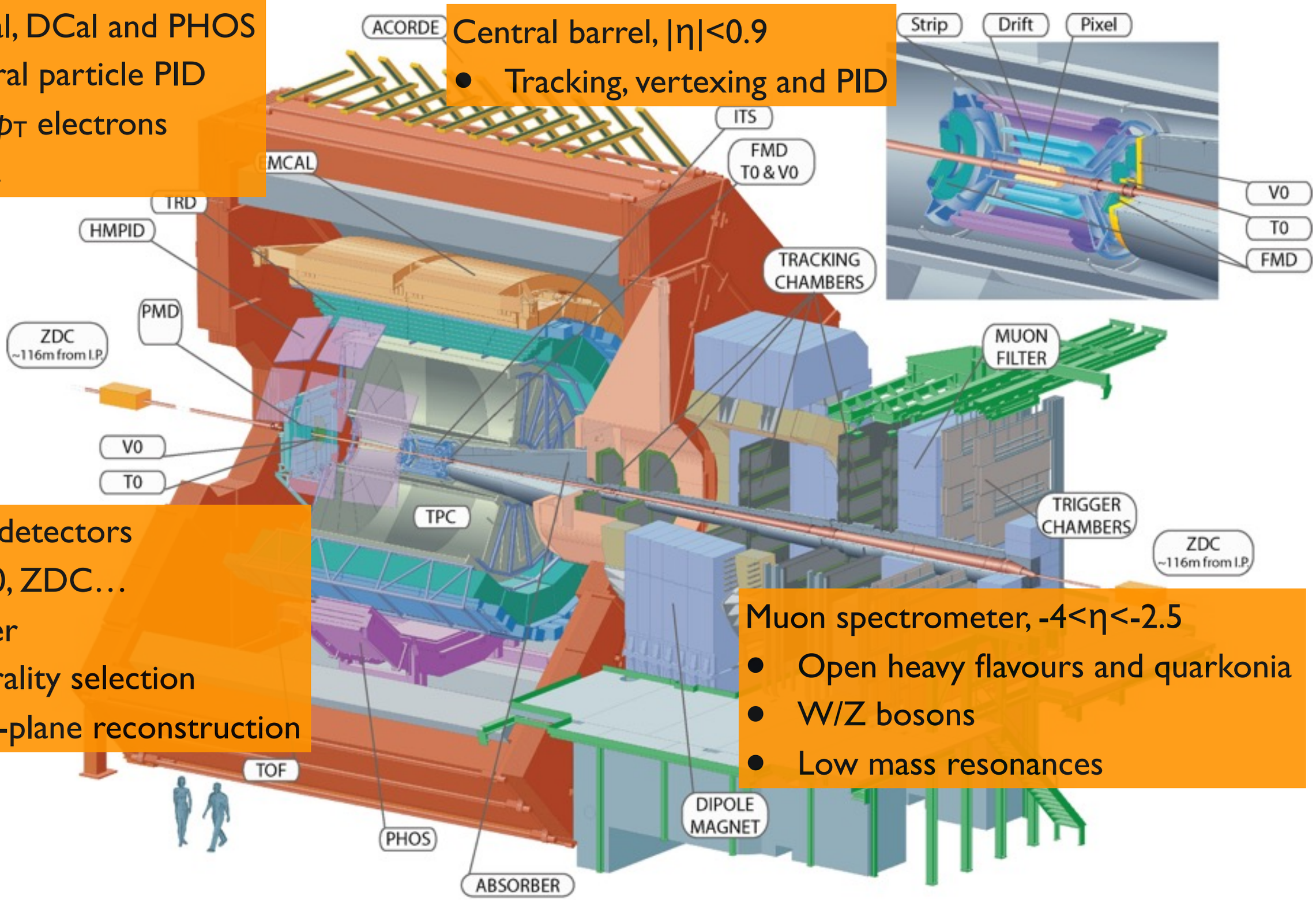
The ALICE Experiment

EM calorimeters, |η|<0.7

- EMCal, DCal and PHOS
- Neutral particle PID
- High-p_T electrons
- Jets…

Central barrel, |η|<0.9

- Tracking, vertexing and PID



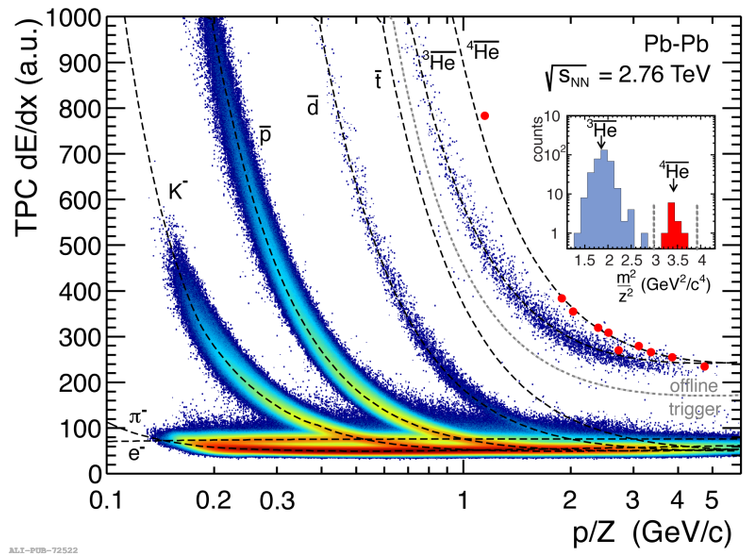
Forward detectors

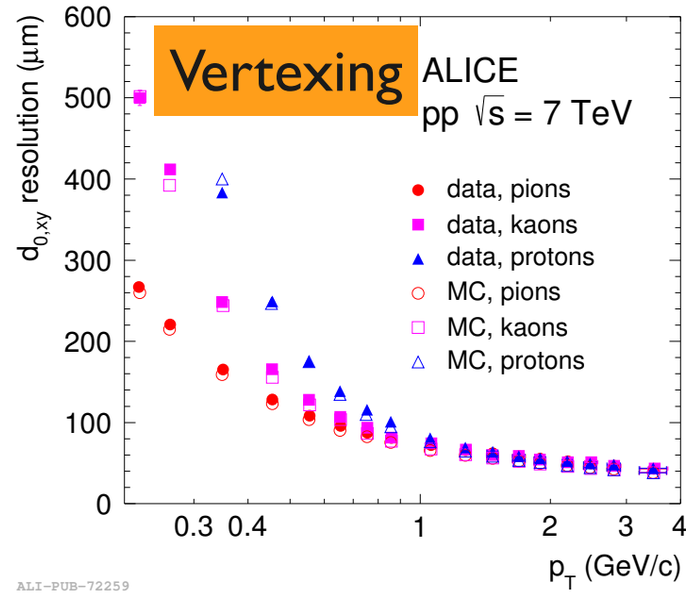
- V0, T0, ZDC…
- Trigger
- Centrality selection
- Event-plane reconstruction

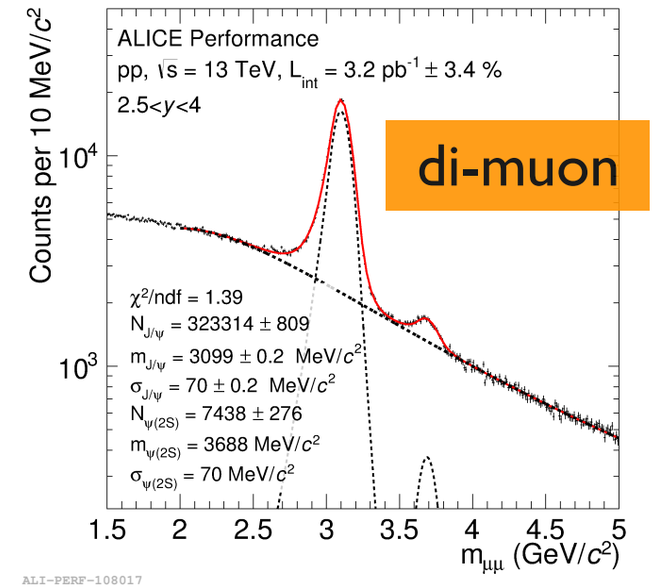
Muon spectrometer, -4<η<-2.5

- Open heavy flavours and quarkonia
- W/Z bosons
- Low mass resonances

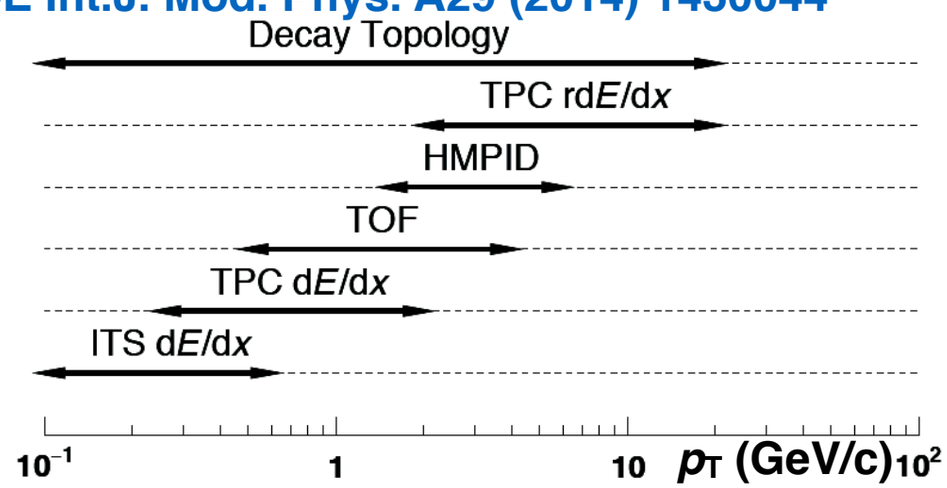
ALICE Performance

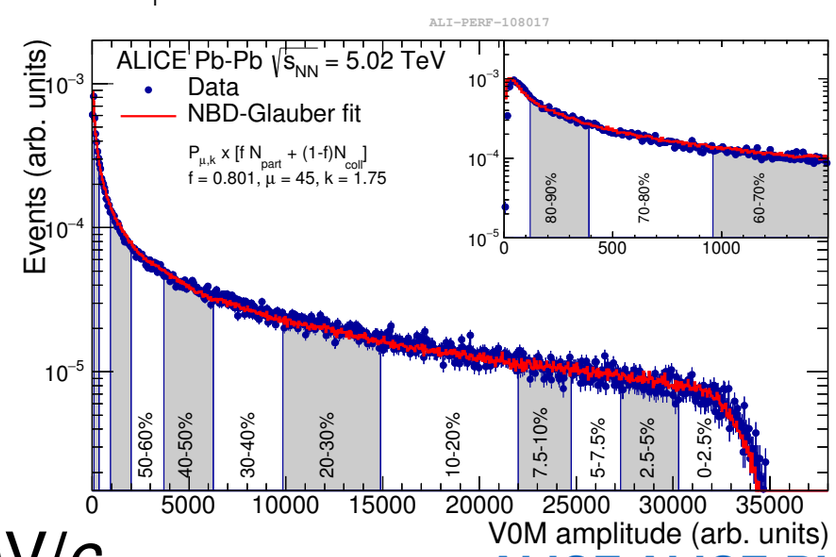






ALICE Int.J. Mod. Phys. A29 (2014) 1430044





ALICE ALICE-PUBLIC-2015-008

- Efficient low-p_T tracking — down to 150 MeV/c
- Excellent particle identification — anti-^{3}He observed directly, hadron, lepton and photon identification up to high momenta
- Excellent vertexing capabilities (heavy flavours, V^0, cascades, conversions)
- Forward muon spectrometer: J/ψ and Υ reconstruction down to p_T = 0
- Precise event characterization (most central collisions: 0-2.5% centrality class)

Data Collection

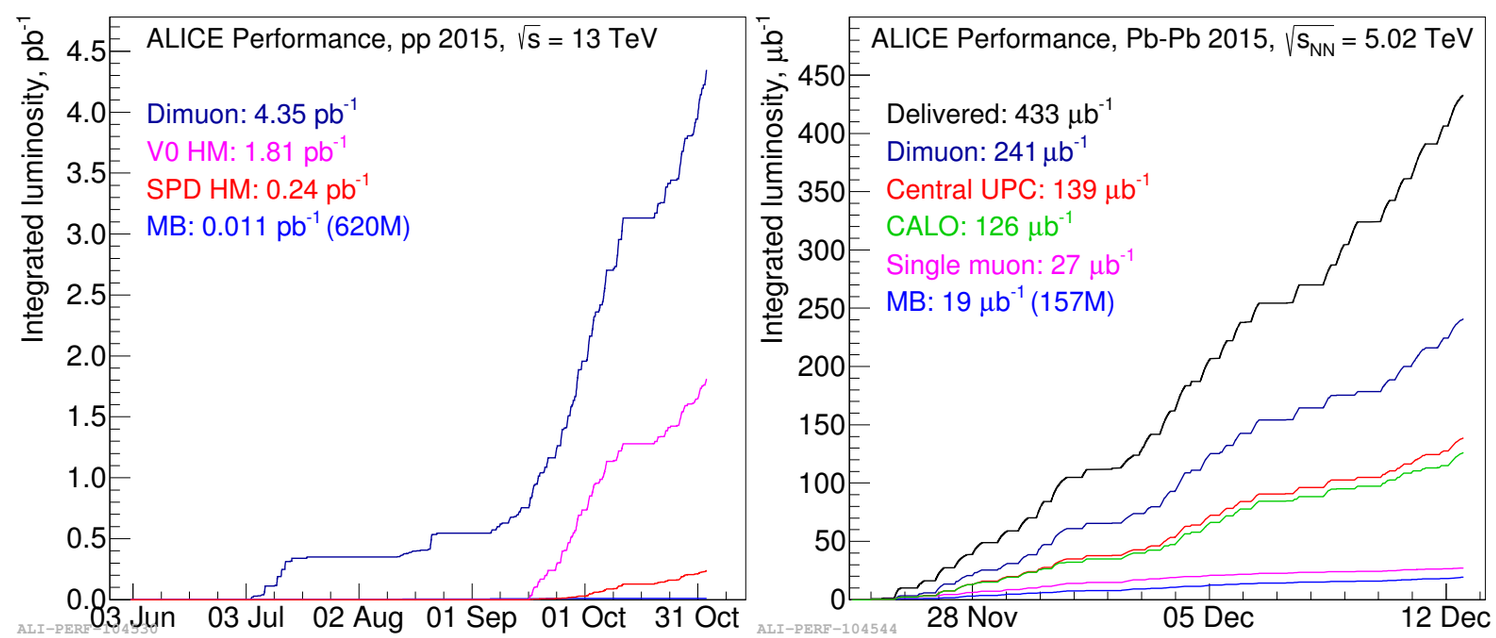
RUN-I milestone (2009 – 2013)

Year	System	Energy $\sqrt{s_{NN}}$ (TeV)	Integrated luminosity (nb^{-1})
2010	Pb–Pb	2.76	~ 0.01
2011	Pb–Pb	2.76	~ 0.1
2013	p–Pb	5.02	~ 30

- pp collisions at 0.9, 2.76, 7 and 8 TeV, total integrated luminosity up to ~20 pb^{-1}

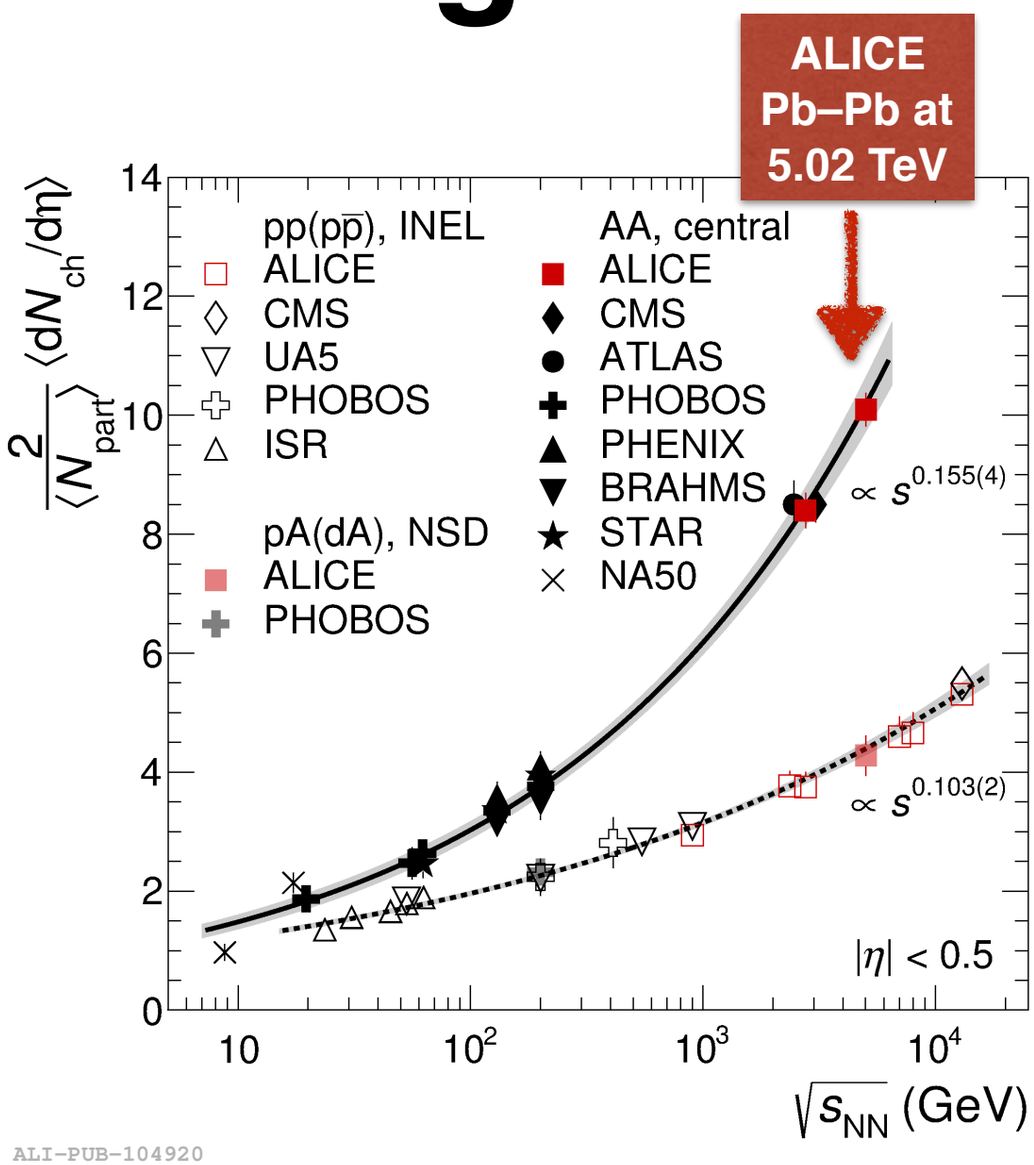
RUN-II, since 2015

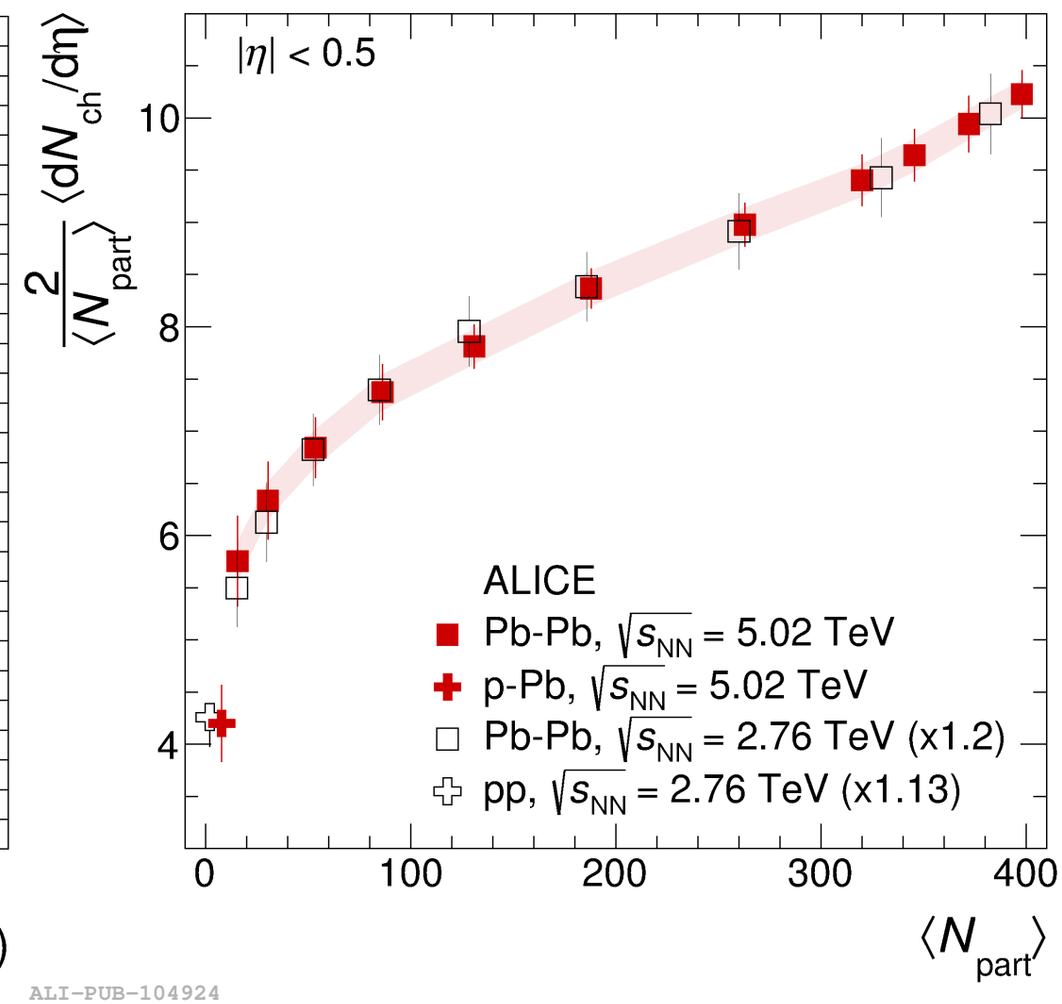
- Pb–Pb at 5.02 TeV: up to 0.5 nb^{-1}
- pp at 13 TeV and 4 days at 5.02 TeV (~100 nb^{-1})
- Upcoming p–Pb at 5.02 and 8 TeV: 10 times more statistics than in RUN-I



Charged-Particle Multiplicity

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



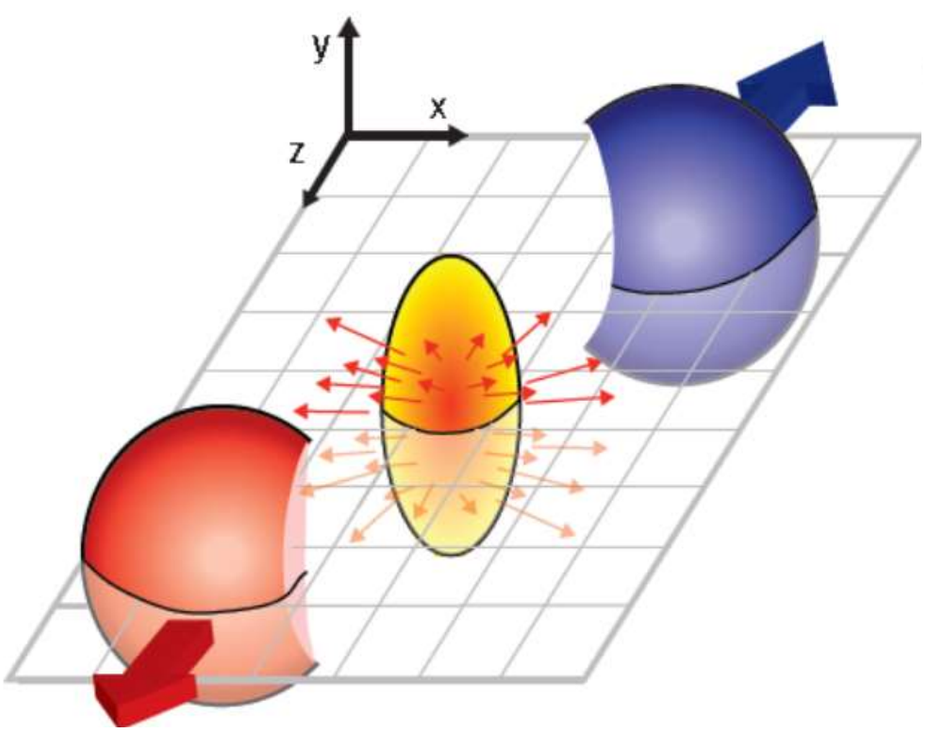


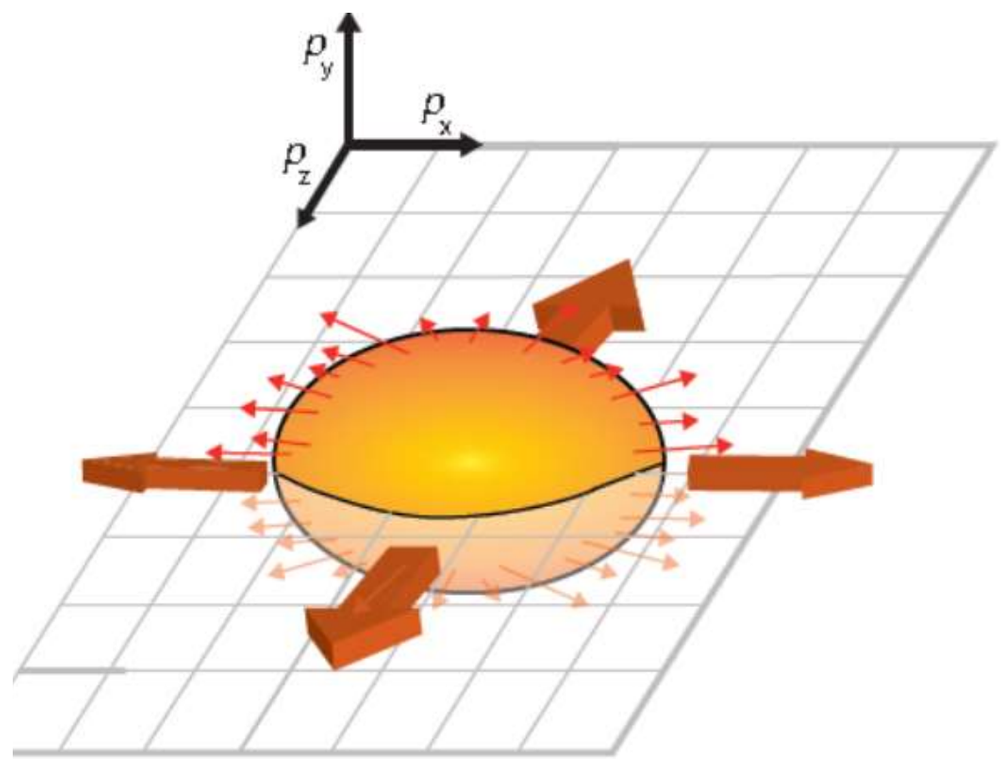
- ALICE: Pb–Pb at 5.02 TeV — highest energy so far
  - For 0–5% most central collisions, confirms trend from lower energies
- $\langle dN_{ch}/d\eta \rangle$ vs. $\langle N_{part} \rangle$: similar evolution with centrality between 5.02 and 2.76 TeV
  - ~20% increase going from 2.76 to 5.02 TeV
  - Provides further constraints for models

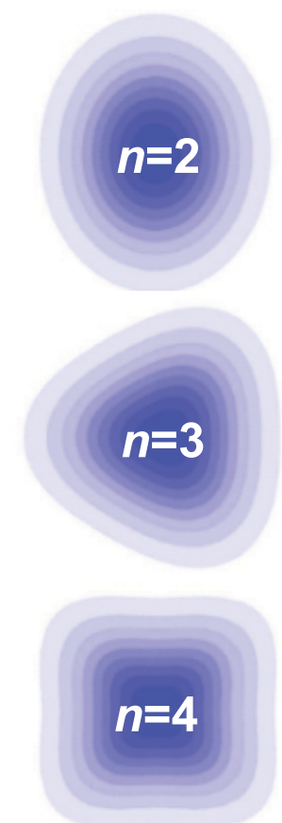
Azimuthal Anisotropy

- Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP}) — coefficients v_2, v_3, v_4… v_n
- Elliptic flow (v_2): spatial anisotropy — pressure gradients leads to momentum anisotropy — hydrodynamics
- Higher order flow: bring additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

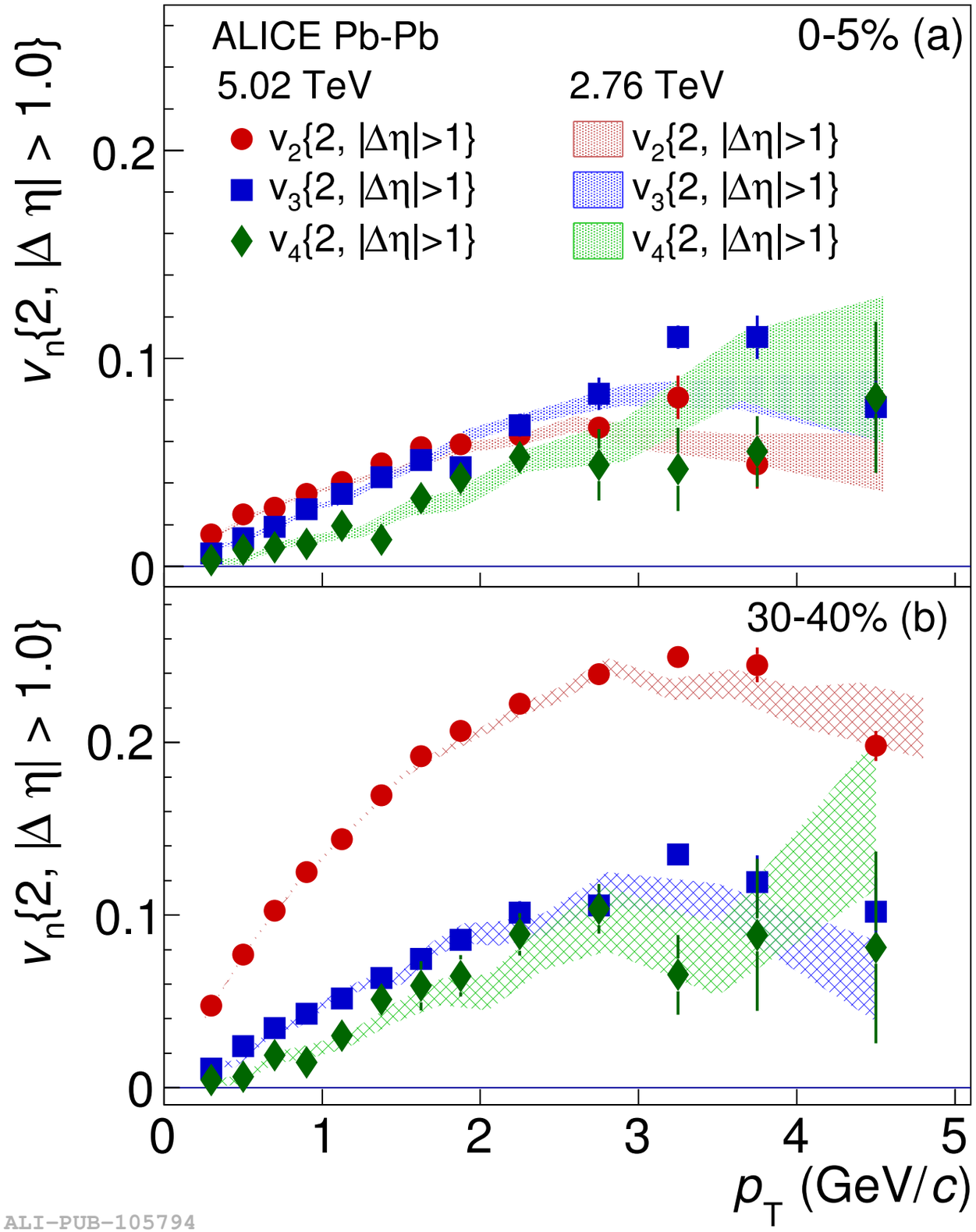
$$v_n = < \cos n(\varphi - \Psi_{\mathrm{RP}}) >$$







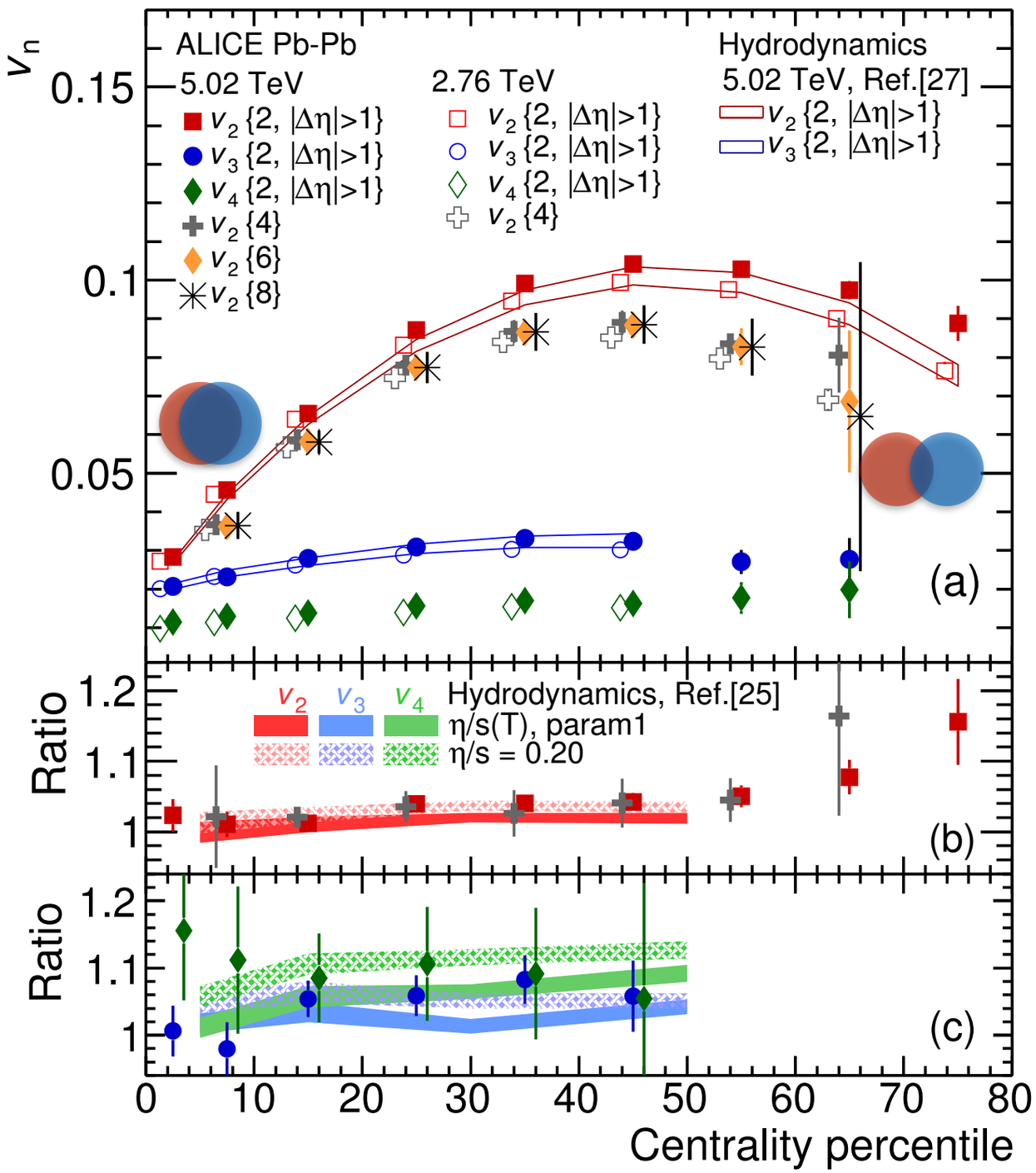
Anisotropic Flow



- Anisotropic flow coefficients v_2, v_3, v_4 measurements using two- and multi-particle cumulants
- Similar p_T-differential results at 2.76 and 5.02 TeV
  - v_3 becomes larger than v_2 for $p_T > 2$ GeV/c in central collisions

ALICE Phy. Rev. Lett. 116 (2016) 132302

Anisotropic Flow

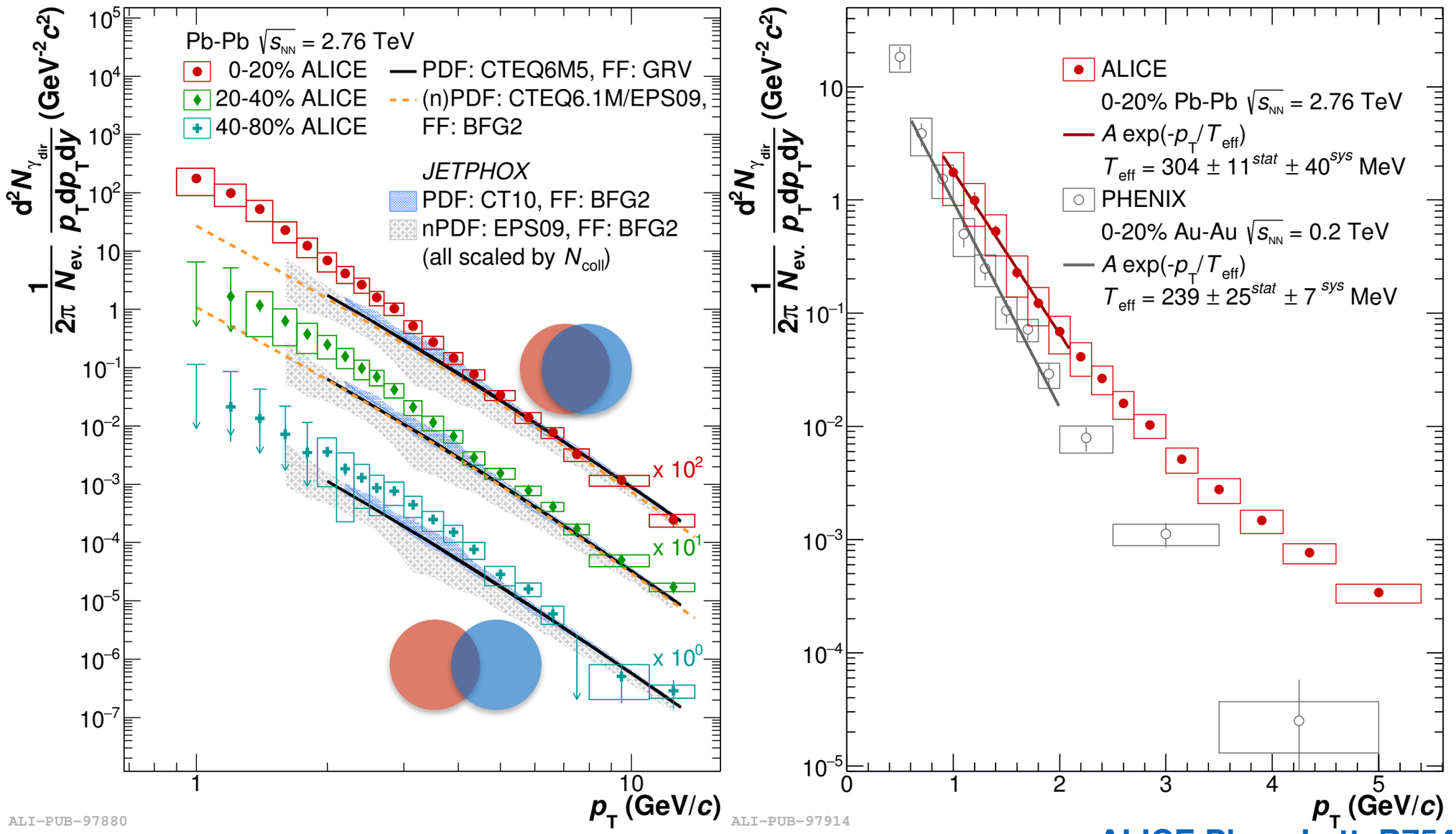


ALICE Phy. Rev. Lett. 116 (2016) 132302

- Anisotropic flow coefficients v_2, v_3, v_4 measurements using two- and multi-particle cumulants
- Similar p_T-differential results at 2.76 and 5.02 TeV
  - v_3 becomes larger than v_2 for $p_T > 2$ GeV/c in central collisions
- p_T-integrated values indicate an increase with collision-energy attributed to the increase in $\langle p_T \rangle$
- Good agreement with hydrodynamical calculations
  - Measurements support a low value for η/s ratio

Direct Photons in Pb–Pb Collisions

Talk: D. F. Lodato, Jing-Zhou hall, Saturday, Sep. 24th 8:30



ALICE Phys. Lett. B754 (2016) 235

- Low-p_T: 2.6σ excess w. r. t. models in 0–20% central — thermal contribution
- T_{eff} = 304 ± 11(stat.) ± 40 (syst.) MeV in central Pb–Pb collisions at 2.76 TeV
  - 30% higher than at RHIC (Au–Au at $\sqrt{s_{NN}}$=200 GeV)

Hard Probes: Medium Tomography

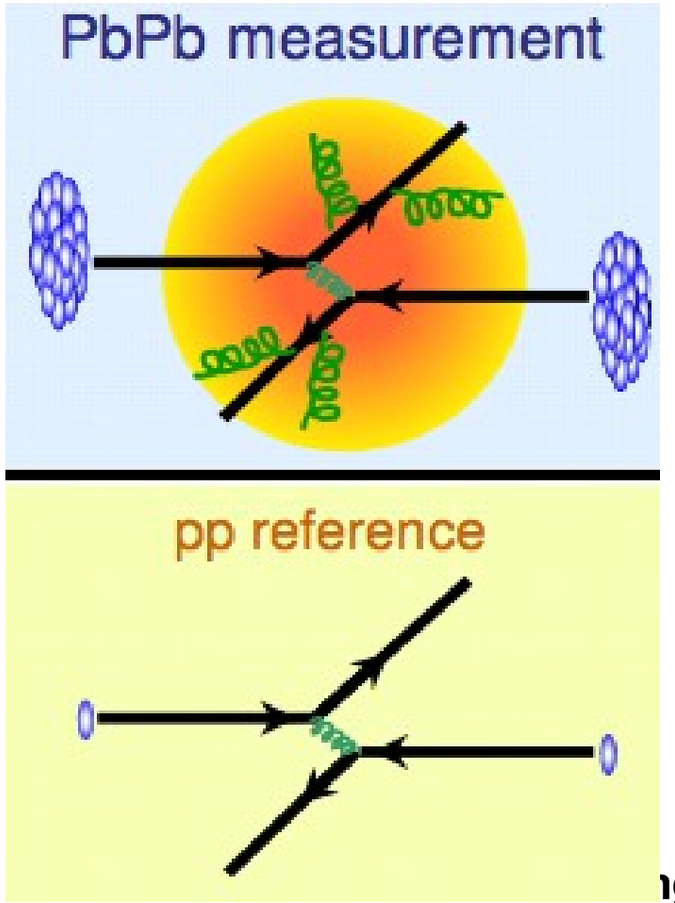
- Produced in the early stage of heavy-ion collisions
  - Experience the full evolution of the QCD medium, and interact with particles in the medium and loss energy
- Efficient probes for understanding the transport properties of the medium
- Nuclear modification factor, R_{AA}, sensitive to the presence of the medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

QCD medium

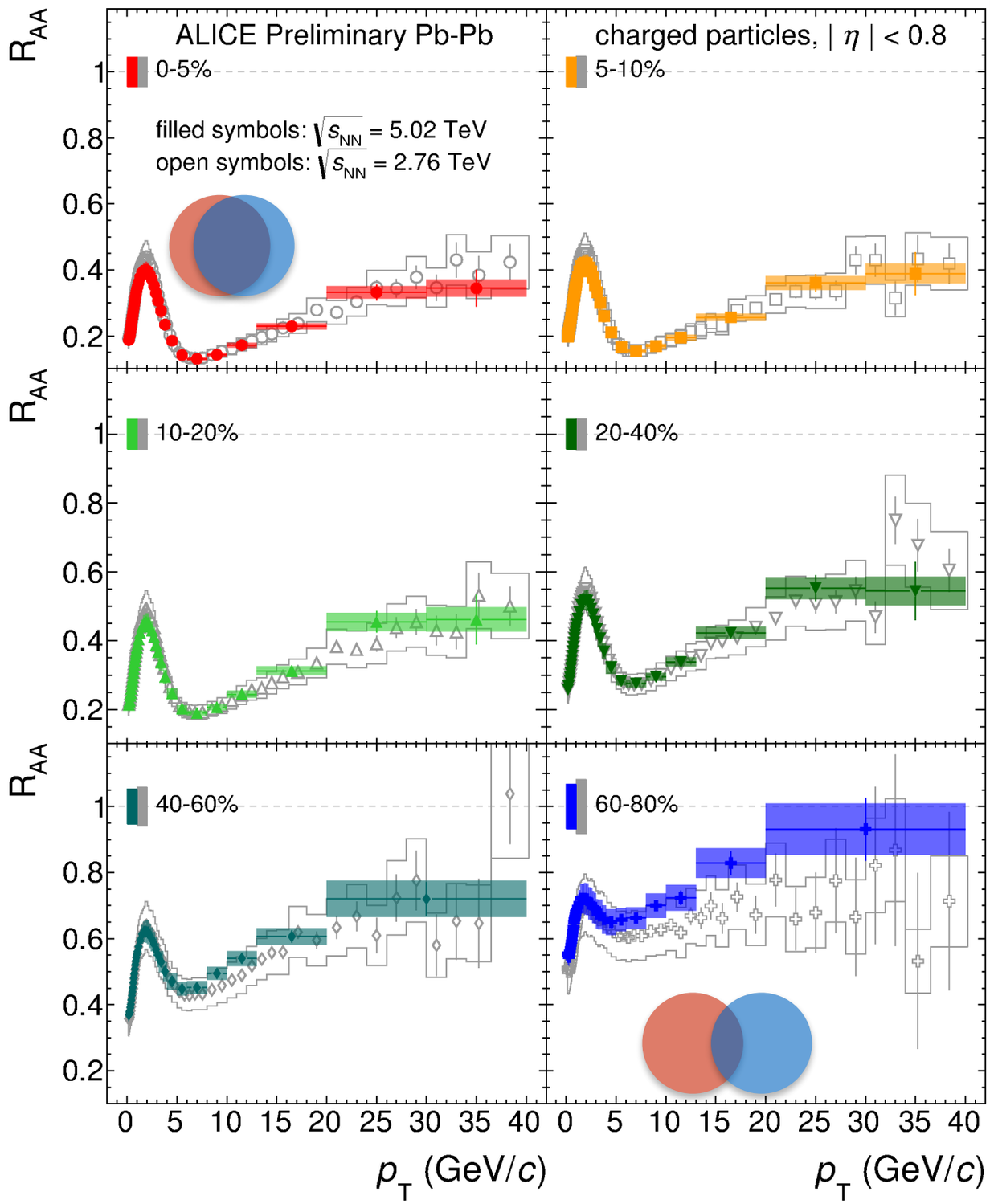
QCD vacuum

  - R_{AA} = 1, if there is no medium modification
- Shopping list
  - High p_T particles, jets
  - Open heavy flavours
  - Quarkonia (J/ψ, ψ'… Υ…)



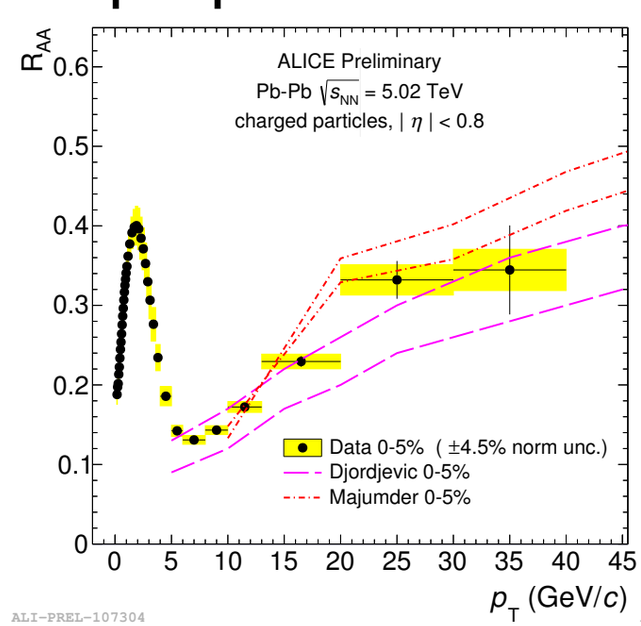
High-p_T Charged-Particle R_{AA}

Talk: M. L. Knichel, Wuhan hall, Sunday, Sep. 25th 8:30

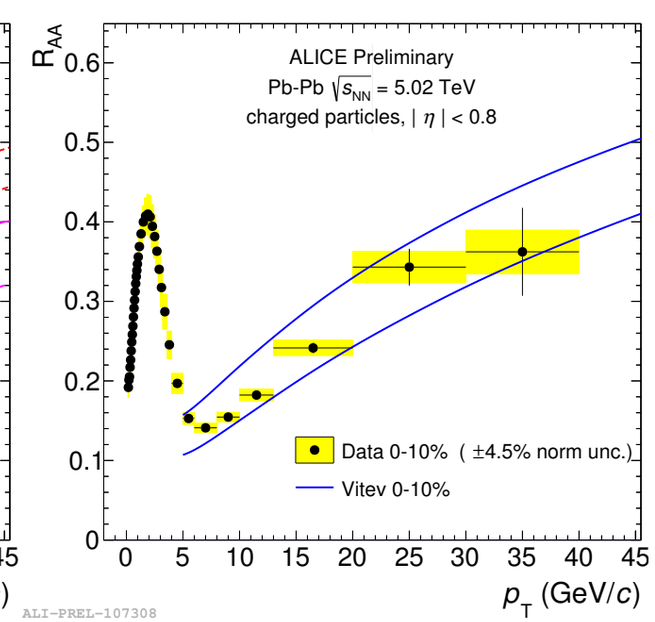


ALI-PREL-107300

- Strong modification of the spectrum shape in most central collisions
  - Minimum at $p_T \approx$ 6-7 GeV/c
  - Strong rise in $6 < p_T < 50$ GeV/c
  - Strong centrality dependence
- R_{AA} at 5.02 TeV similar to 2.76 TeV
- Further constraints on medium properties



ALI-PREL-107304

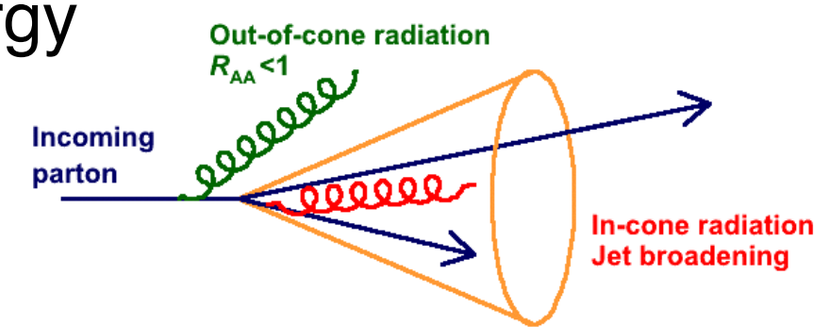


ALI-PREL-107308

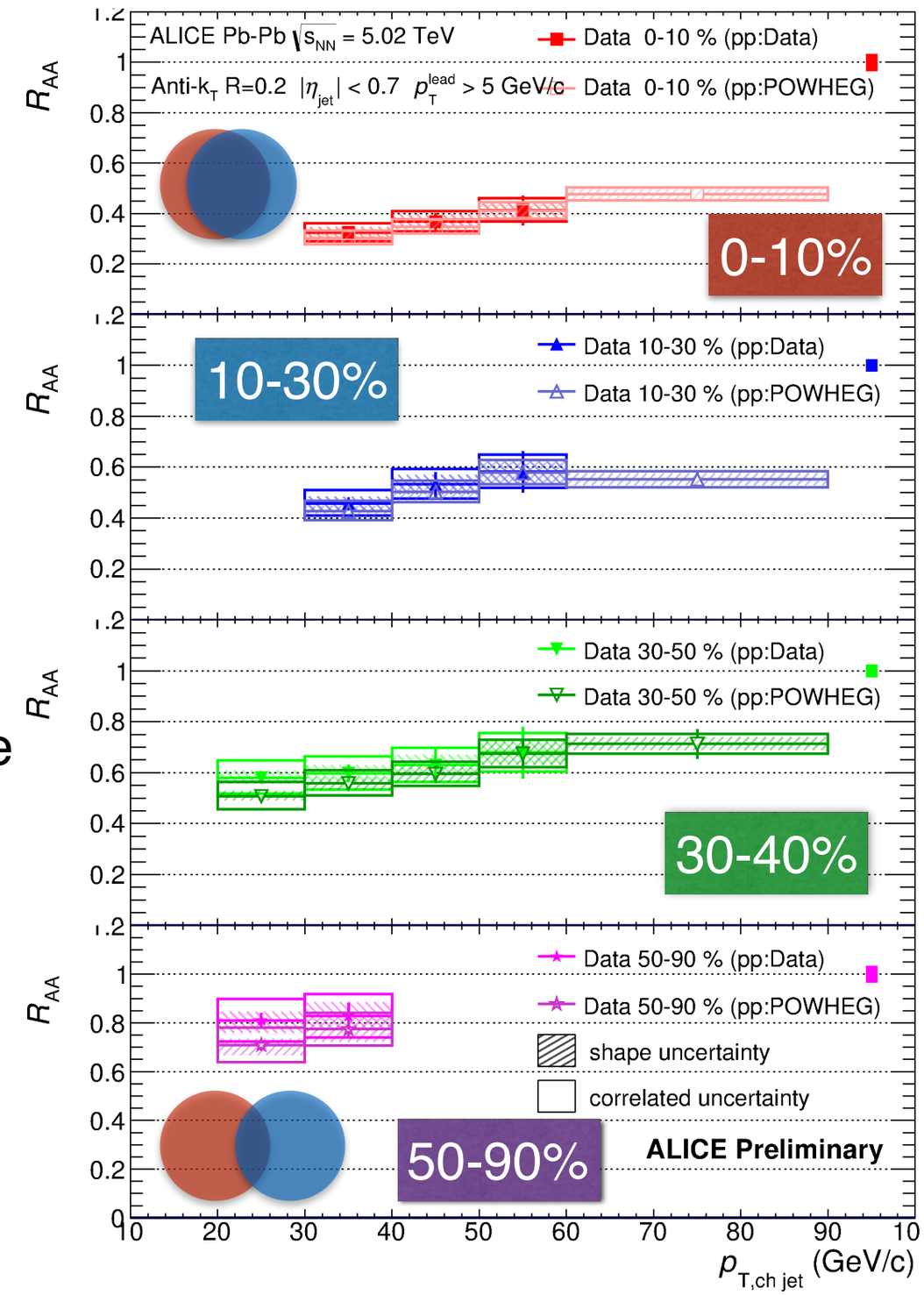
Jet R_{AA} in Pb–Pb Collisions at 5.02 TeV

Talk: H. Yokoyama, Xiang-Yang hall, Saturday, Sep. 24th 8:30

- Jet: a spray of particles from hard parton fragmentation — get closer access to parton energy



- Out-of-cone radiation: energy loss in jet cone
  - ➡ Jet yield suppression, di-jet energy imbalance, jet-jet/hadron-jet acoplanarity…
- In-cone radiation: medium modified fragmentation
  - ➡ Jet shape broadening, modification of transverse energy profile…



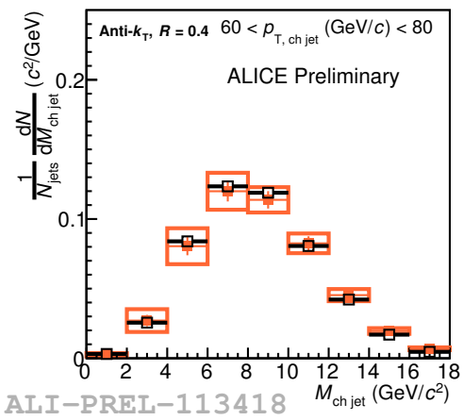
- Charged-particle jet R_{AA} at 5.02 TeV
  - Consistent with R_{AA} of charged particles and charged-jet R_{AA} at 2.76 TeV

Jet Structure

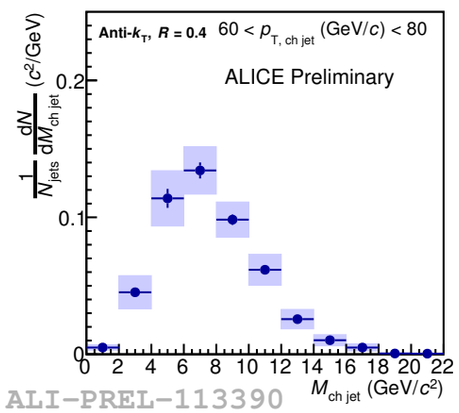
Talk: C. Bianchin, Xiang-Yang hall, Saturday, Sep. 24th 10:40

Jet mass

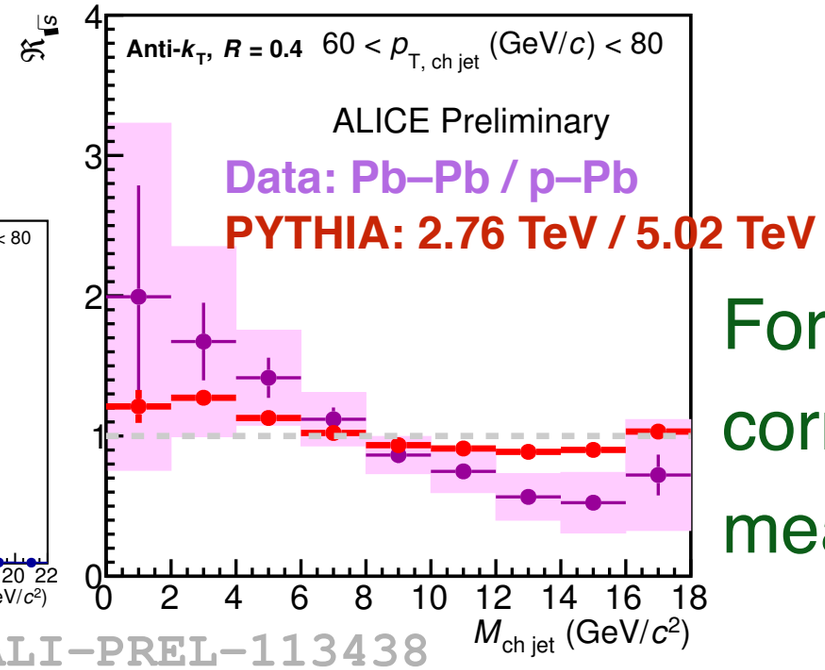
p–Pb at 5.05 TeV
Pb–Pb at 2.76 TeV



ALI-PREL-113418

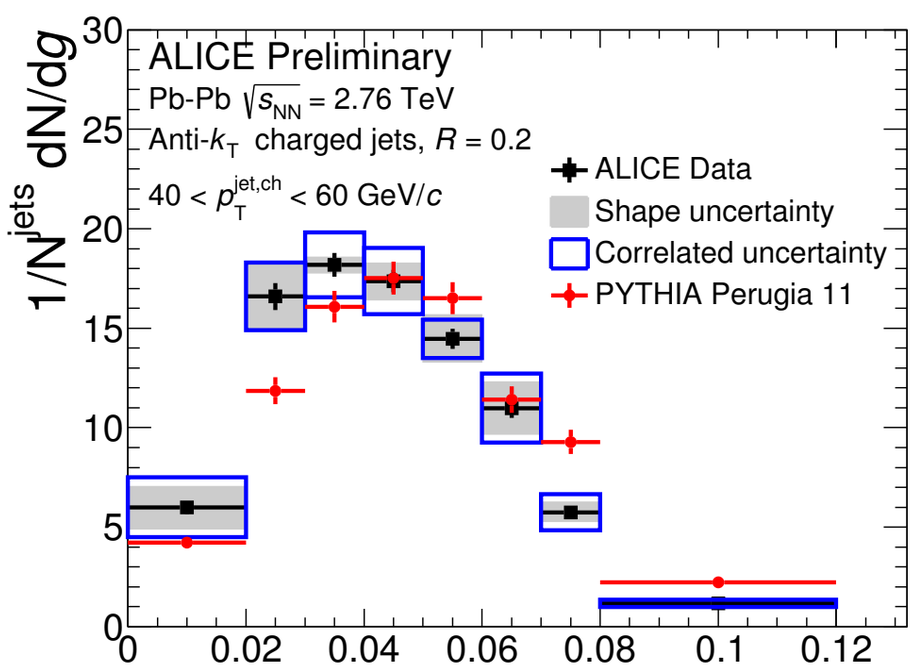


ALI-PREL-113390



ALI-PREL-113438

For the first time the fully corrected jet shapes are measured in Pb–Pb collisions



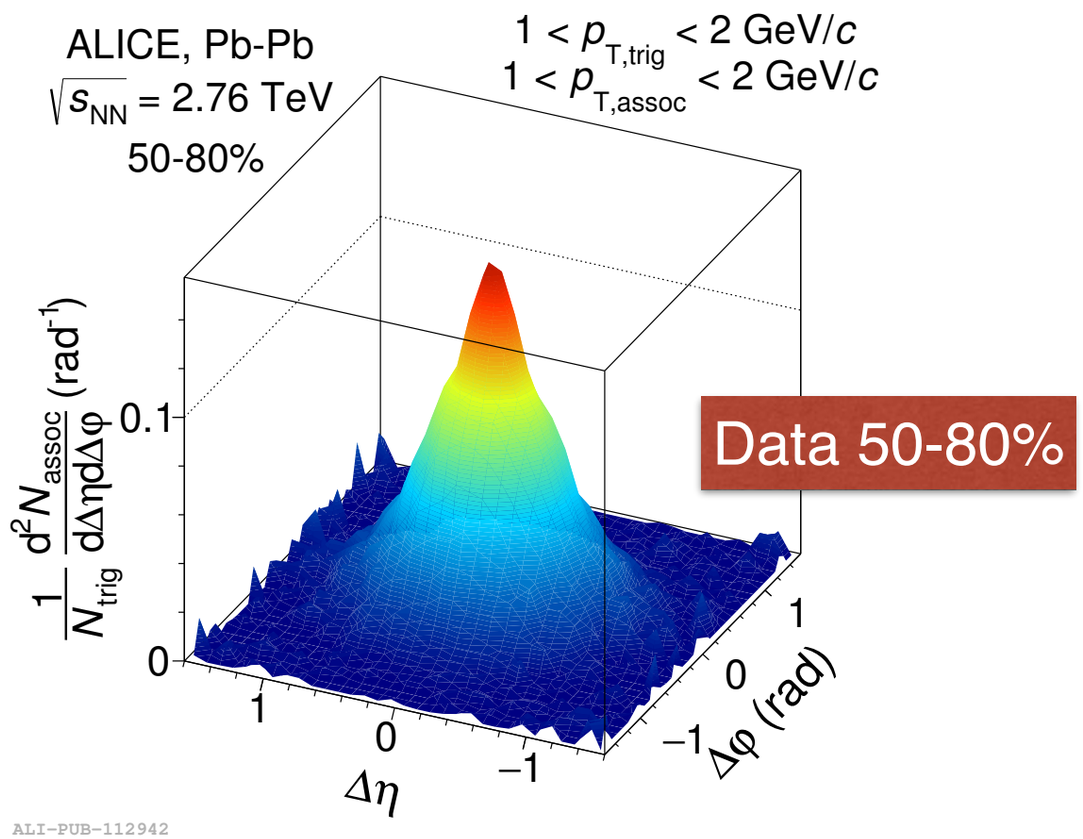
ALI-PREL-101580

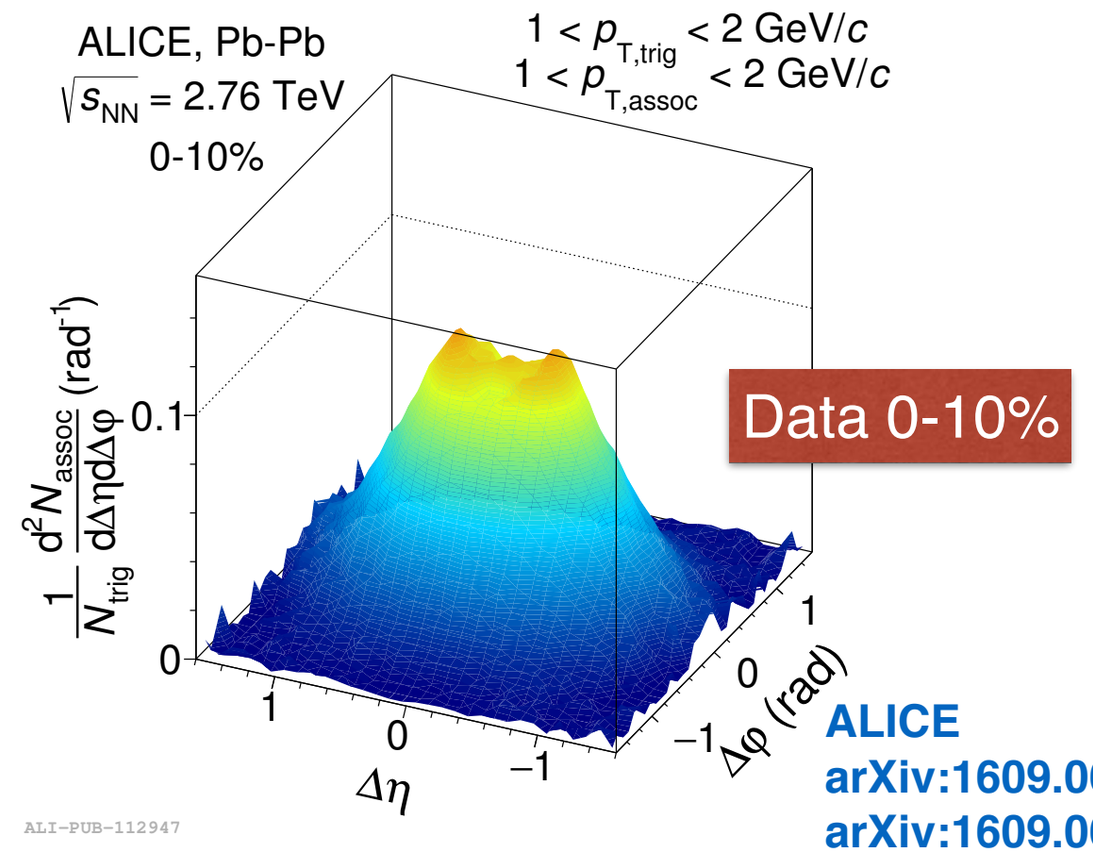
$$g = \sum_{i \in \text{jet}} \frac{p_{T,i}}{p_{T,\text{jet}}} \Delta R(i, \text{jet})$$

- Jet mass: Pb–Pb distribution is shifted towards smaller masses w. r. t. p–Pb collisions — indicate large angle out-of-cone radiation in the medium
- Radial momentum (g) — p_T-weighted jet width
  - g shifted towards lower values in Pb–Pb data relative to PYTHIA — indication of more collimated jet cores in data

Near-side Jet Peak Broadening

Talk: M. Kofarago, Shi-Yan hall, Saturday, Sep. 24th 17:00





ALICE
arXiv:1609.06643
arXiv:1609.06667

- Moderate broadening in Δϕ, while much larger broadening in Δη
  - Hint of strong interaction of jets with the medium

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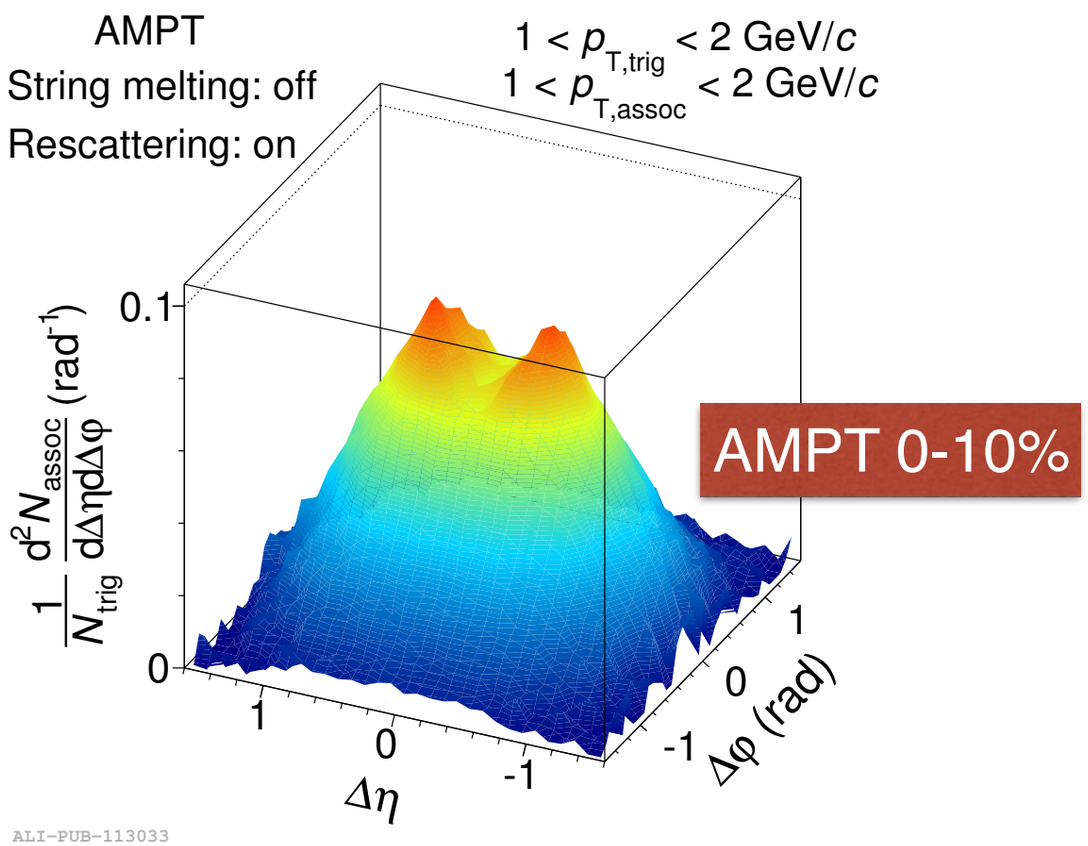

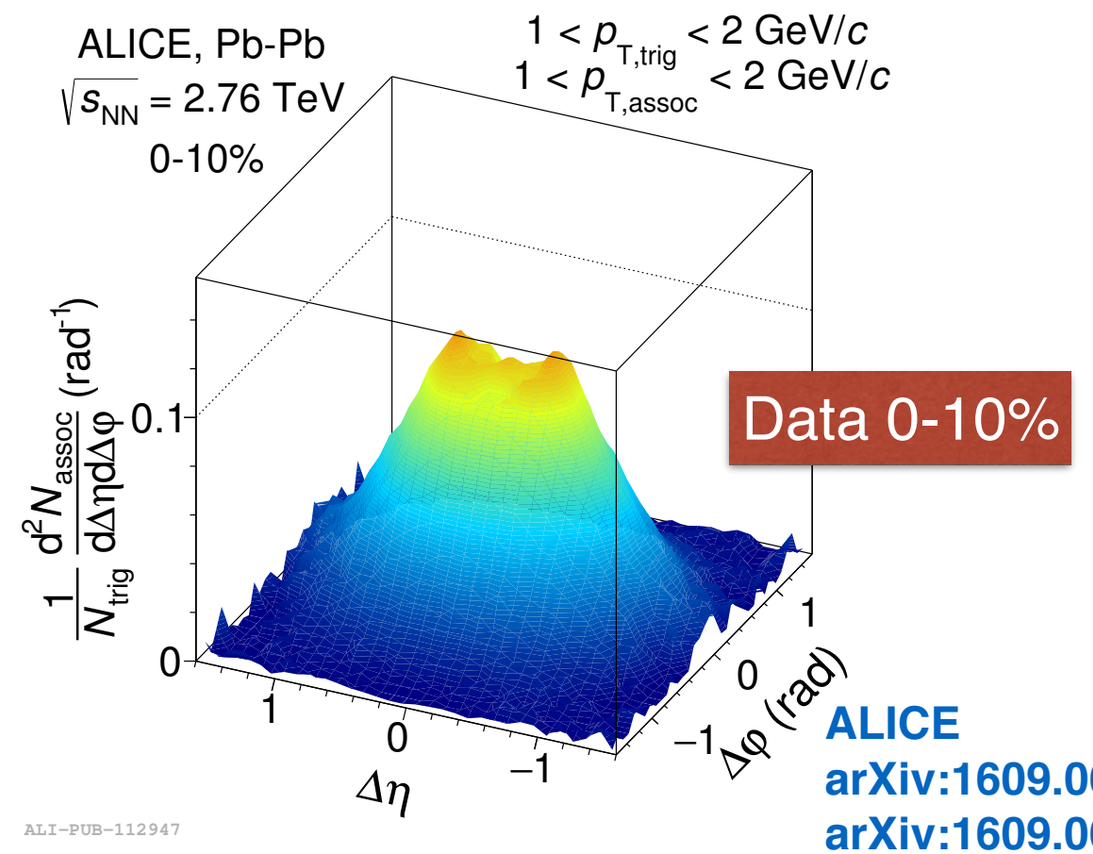

ALICE
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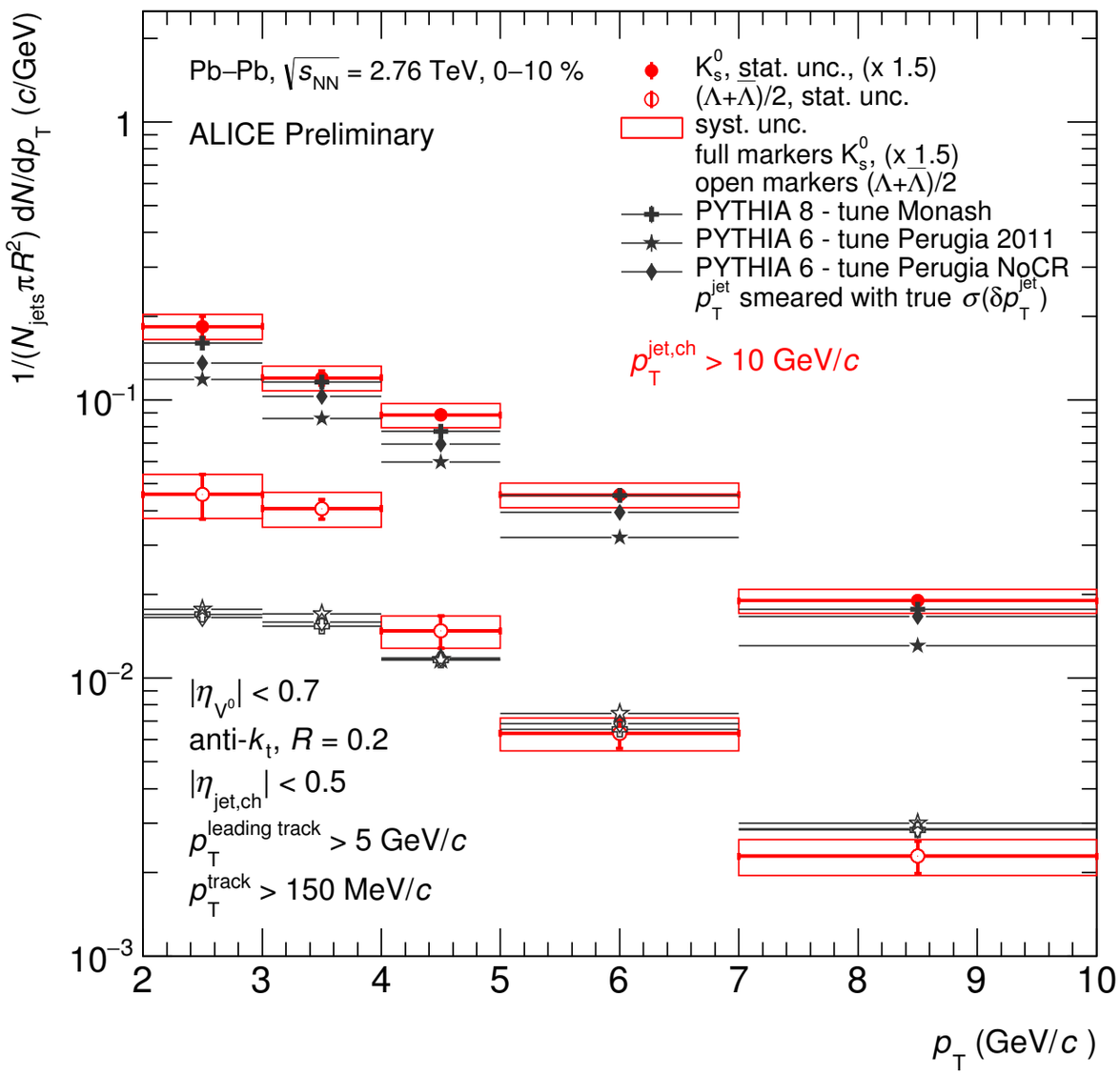
- Moderate broadening in Δϕ, while much larger broadening in Δη
  - Hint of strong interaction of jets with the medium
- AMPT without melting but with hadronic scattering describes data better than other options — describes both peak broadening and depletion in data
  - Depletion and broadening result from interplay of jets and collective medium, driving factor for depletion and broadening is radial flow

K_S^0 and Λ Production in Jets

Talk: Y. Zhang, Xiang-Yang hall, Saturday, Sep. 24th 15:20



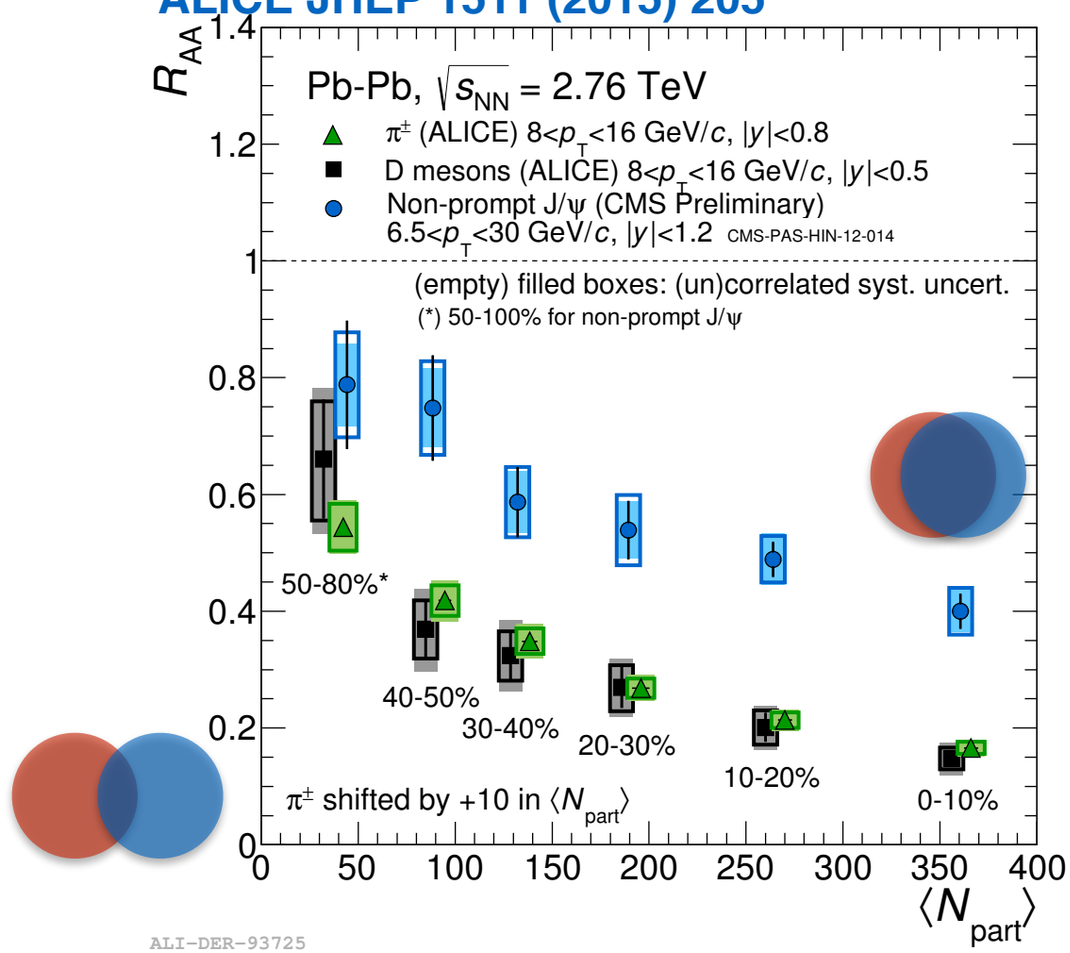
- K_S^0 and Λ production in charged-particle jets in Pb–Pb collisions
- Reference PYTHIA smeared with background fluctuations
- K_S^0: data consistent with PYTHIA within errors
  - Hint of low-p_T enhancement in data
- Λ: data significantly higher than PYTHIA at low p_T

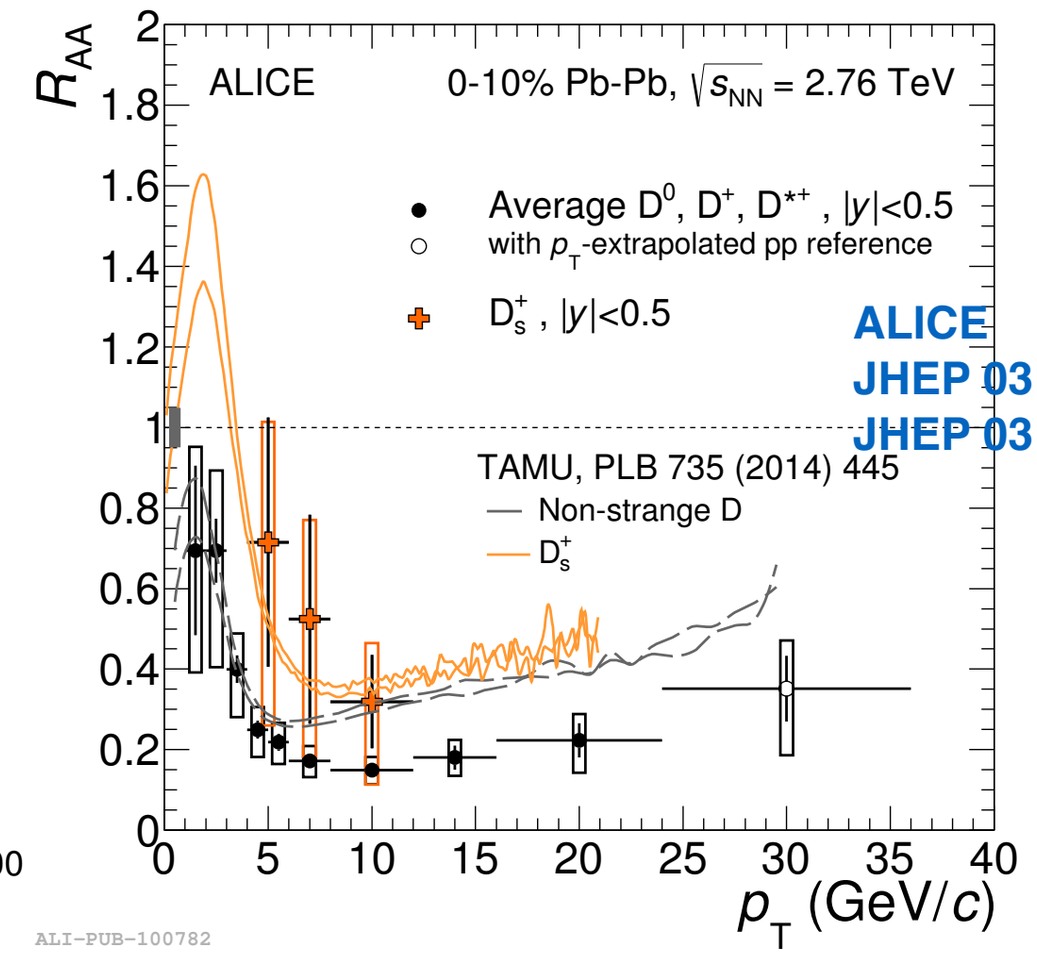
- Investigating medium modified fragmentation, effect seems to differ between baryons and mesons — further constraints on reference from data needed

R_{AA} of D mesons and non-prompt J/ψ

ALICE JHEP 1511 (2015) 205

Talk: A. Dubla, Wuhan hall, Saturday, Sep. 24th 16:00



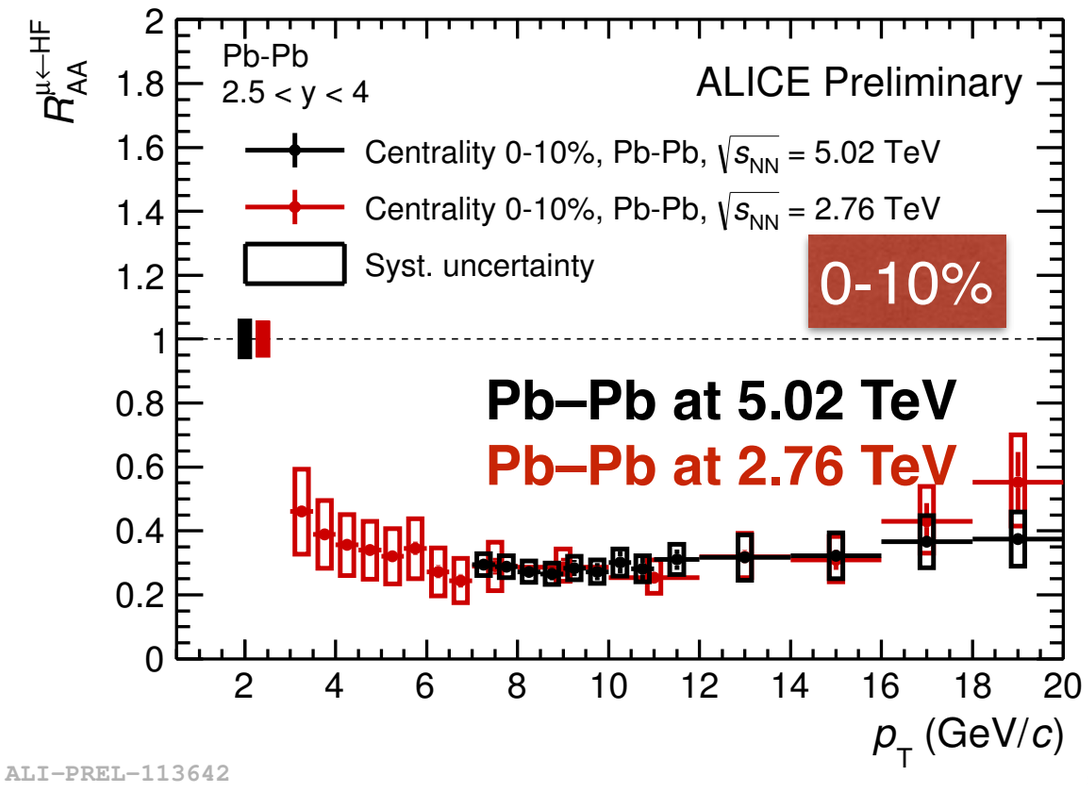


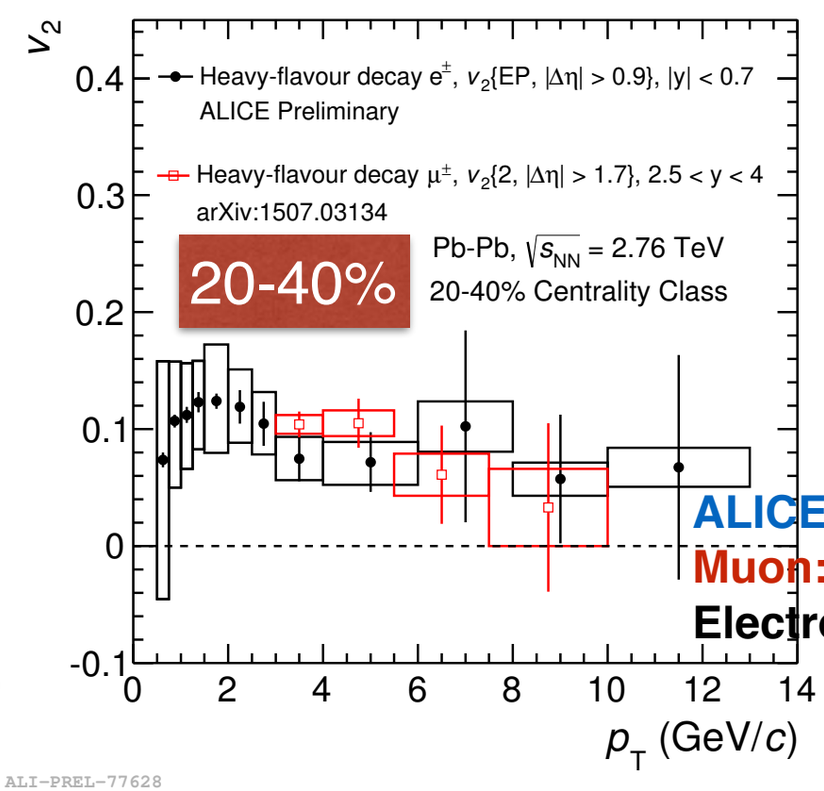
ALICE
JHEP 03 (2016) 081
JHEP 03 (2016) 082

- R_{AA}(D)<R_{AA}(J/ψ←B): $\Delta E_c > \Delta E_b$ — mass dependence of HF energy loss
- R_{AA}(D)≈R_{AA}(π): $\Delta E_c \approx \Delta E_g$(?) or different parton p_T distributions and fragmentation functions
- Charm hadronization through recombination in medium (?) — predicted in models — hint of R_{AA}(D)<R_{AA}(D_s^+) in data — to be confirmed with higher precision measurements

Heavy-Flavour Decay Muons

Talk: Z. Zhang, Jing-Zhou hall, Sunday, Sep. 25th 10:40





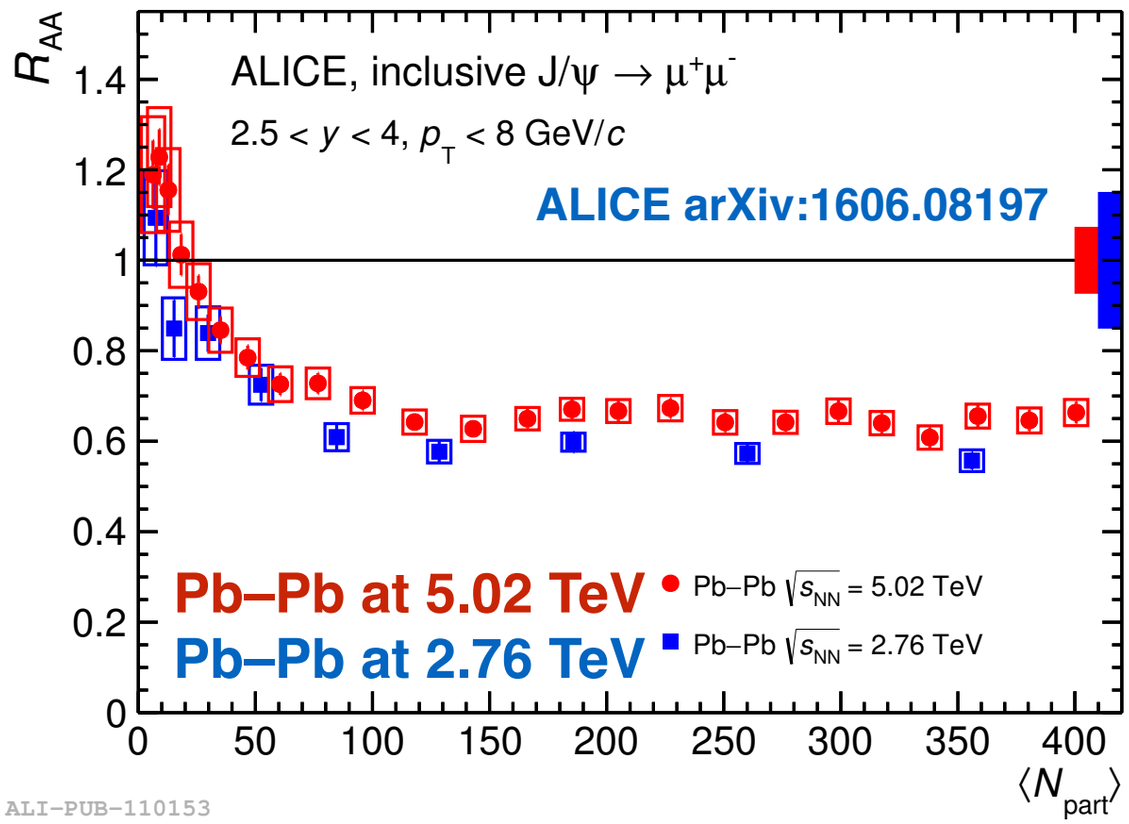
ALICE Pb–Pb at 2.76 TeV
Muon: Phys. Lett. B753 (2016) 41
Electron: JHEP 09 (2016) 028

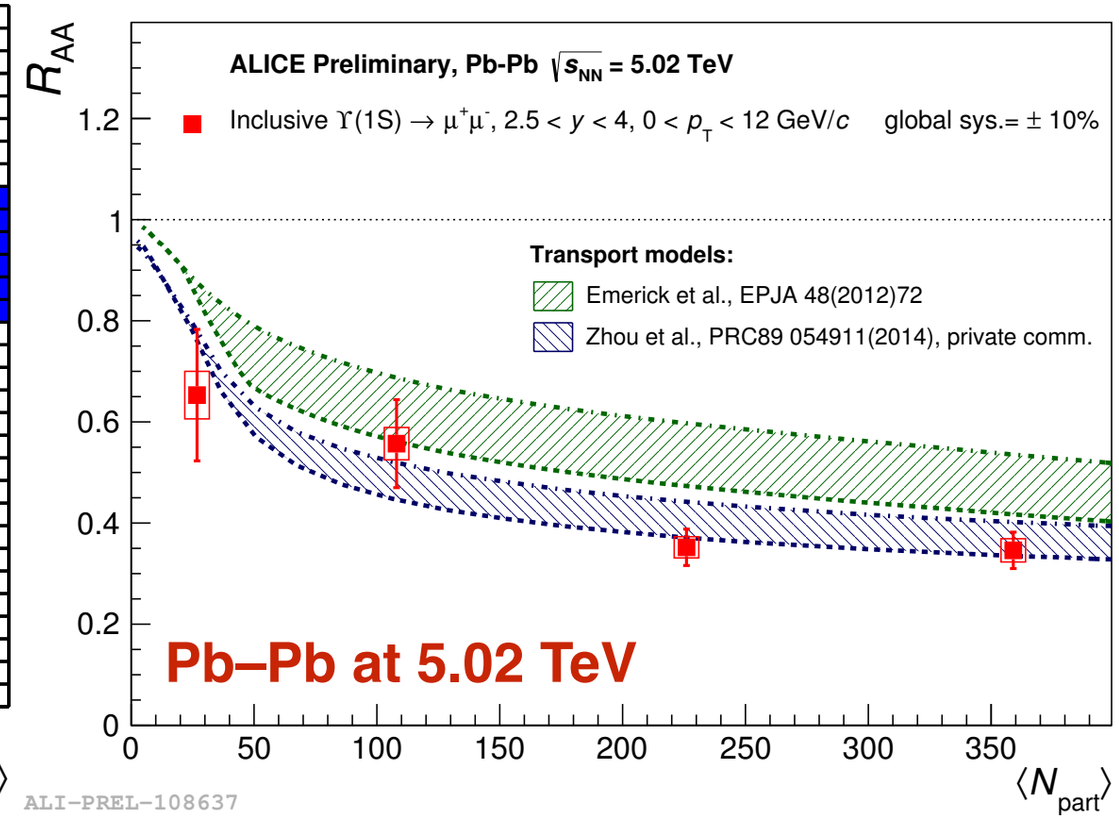
- R_{AA} of heavy-flavour decay muons
  - Large suppression observed in most central collisions
  - R_{AA} at 5.02 TeV consistent with that at 2.76 TeV in the overlap p_T region
- v_2 of heavy-flavour decay muons at forward rapidity (2.5<y<4) is compatible with heavy-flavour decay electrons at mid-rapidity (|y|<0.7)
  - Observed positive v_2 at intermediate-p_T (3σ effect) — similar to the one for D mesons — confirms the significant interaction of heavy quarks with the medium

Quarkonia Production in Pb–Pb Collisions

Talk: V. Feuillard, Jing-Zhou hall, Saturday, Sep. 24th 16:20

Talk: G. Luparello Shi-Yan hall, Saturday, Sep. 24th 8:30





Emerick et al.: regeneration + feed-down ± shadowing uncertainty

Zhou et al.: CNM effect ± feed-down uncertainty

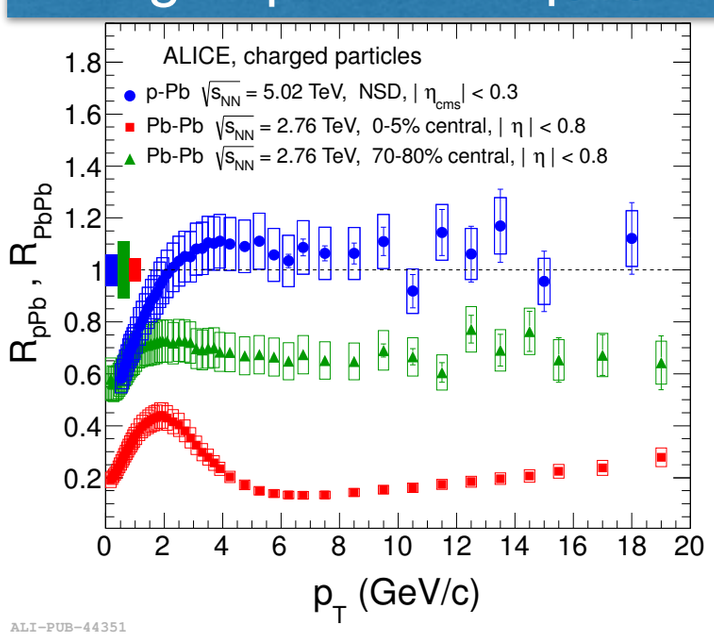
- Clear J/ψ suppression with almost no centrality dependence above N_{part} ~100
  - Suppression insensitive to the collision centrality in semi-central and central collisions — indication of regeneration
- Υ: comparisons with models — centrality dependence is qualitatively reproduced
  - Suppression is slightly underestimated when considering regeneration

Small Systems

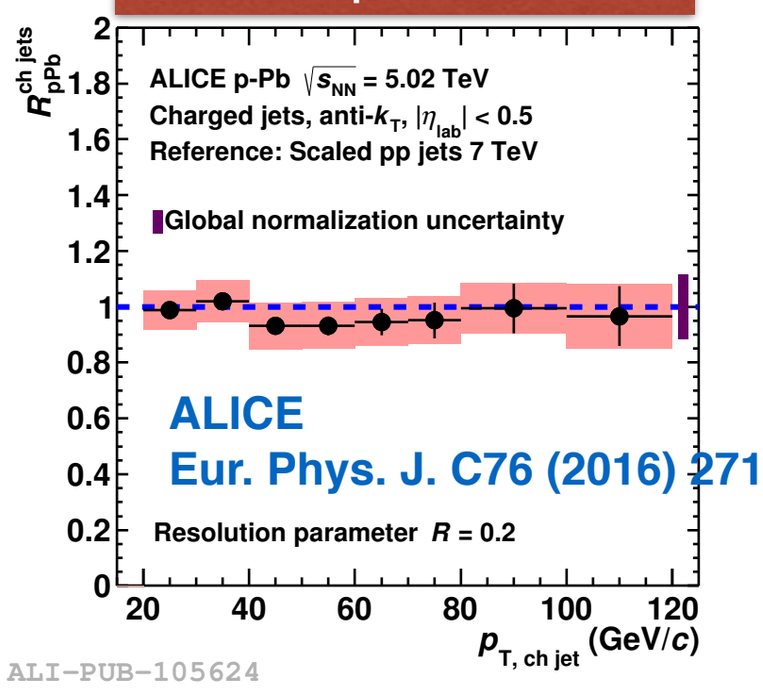
- Small systems
  - pp collisions: QCD vacuum, baseline for heavy-ion and p–Pb collisions
  - p–Pb collisions: quantify Cold Nuclear Matter (CNM) effects — nuclear modified PDF, k_T-broadening coherent energy loss of partons in nuclear medium…

ALICE Phys. Rev. Lett. 110 (2013) 082302

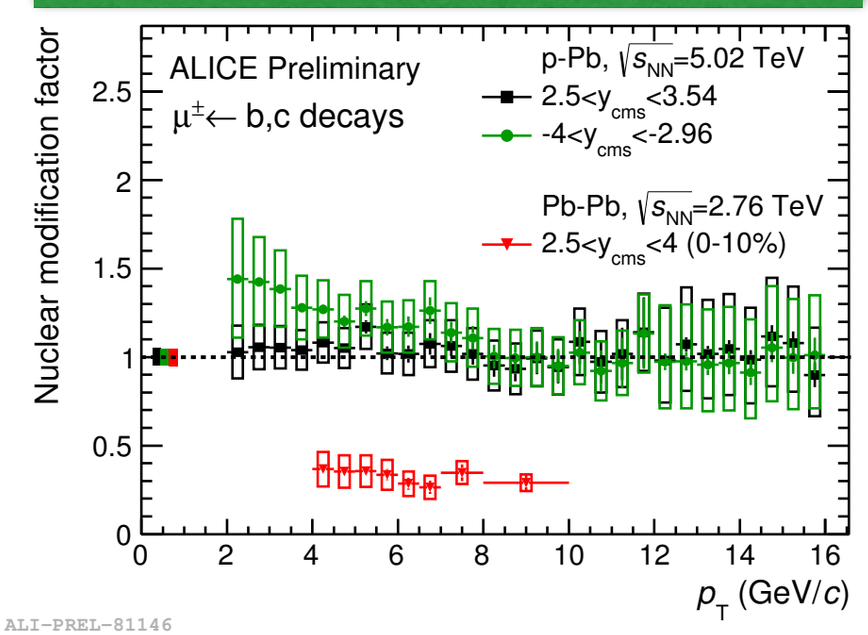
Charged particles $|\eta_{CMS}|<0.3$



Charged particle jets $|\eta|<0.5$



HF muons
$2.5<y_{CMS}<3.54$, $-4<y_{CMS}<-2.96$



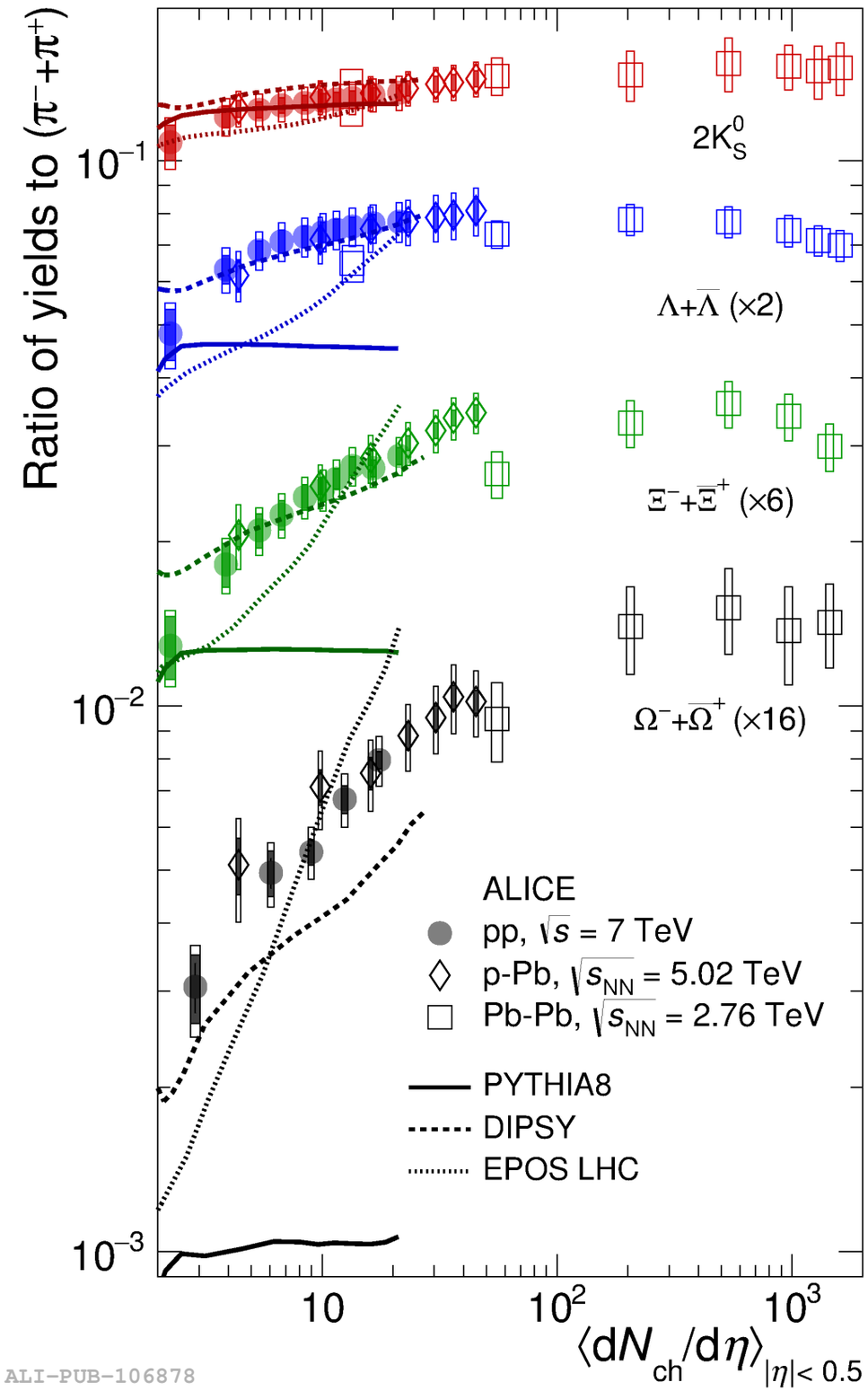
- R_{pPb} consistent with unity — strong suppression observed in central Pb–Pb collisions at mid-rapidity and forward rapidity is due to the QCD medium

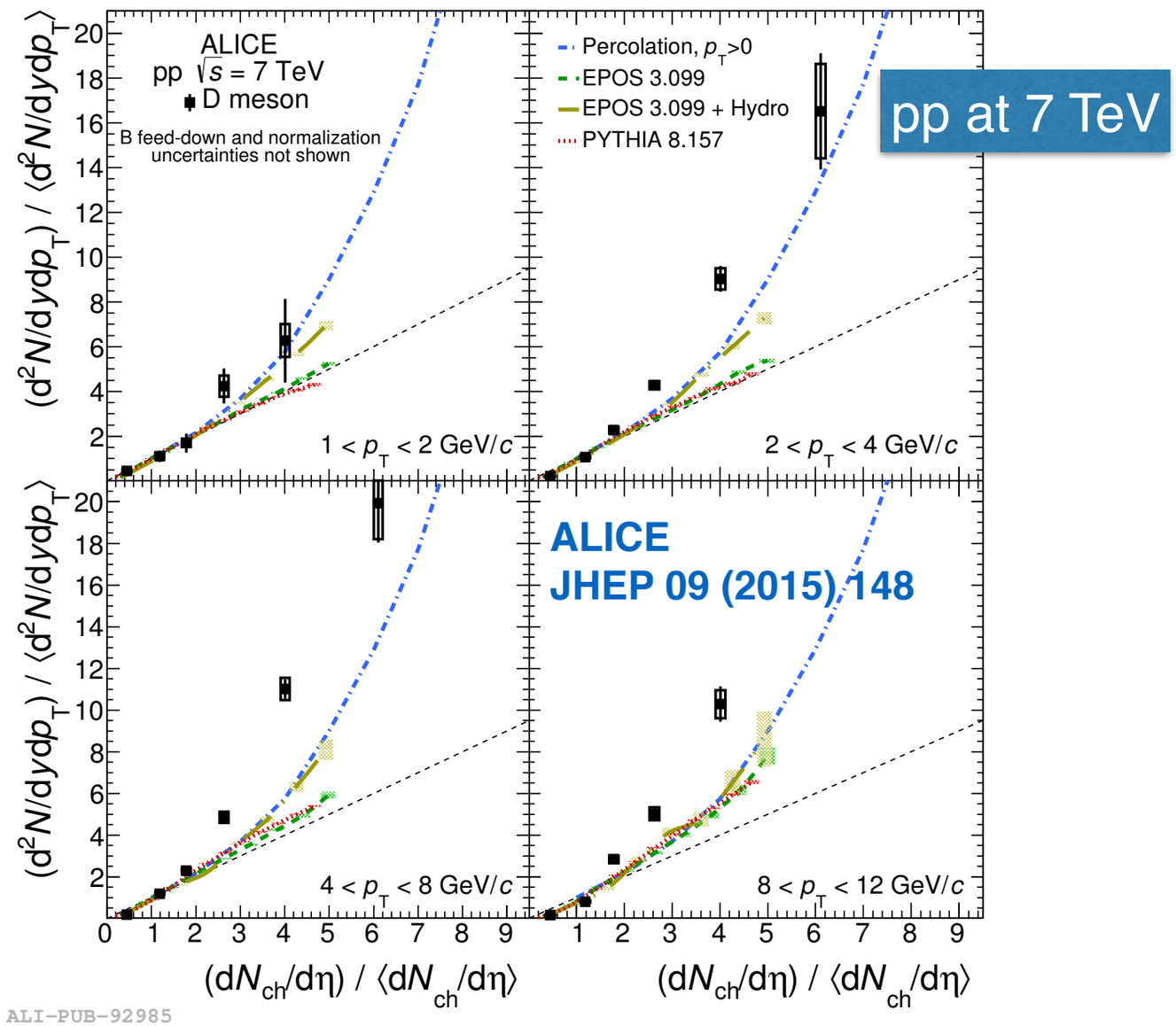
Particle production vs. Event Multiplicity

ALICE arXiv:1606.07424

Talk: O. Busch, Wuhan hall, Sunday, Sep. 25th 10:40

Talk: G. Luparello Shi-Yan hall, Saturday, Sep. 24th 8:30





- Open question for strangeness production at the LHC — onset of QCD-phase transition in small system?

Conclusion

- ALICE LHC RUN-II — Pb–Pb collisions at 5.02 TeV
  - The highest collision energy, 5 times higher integrated luminosity than RUN-I
- Heavy-ion collisions in ALICE RUN-I and RUN-II
  - Anisotropic flow: support a low value for η/s (~0.2)
  - Excess of low-p_T photon: $T_{eff} \approx 304$ MeV — 30% higher than at RHIC
  - Jet shapes: more collimated jet core and large angle out-of-cone radiation in the medium, jet peak depletion and broadening — interplay of jets and collective medium
  - Open heavy flavours: mass dependence of parton in-medium energy loss, collective motion of heavy quarks at both mid- and forward rapidity
  - Quarkonia: J/ψ results support a picture of J/psi suppression and regeneration in the medium; strong suppression of Υ production observed at forward rapidity
- Small systems
  - Baseline for hard probe production in QCD medium — strong suppression observed in central Pb–Pb is due to the QCD medium (high-p_T $R_{pPb} \approx 1$)
  - Hints of “QGP-effects” also seen in high-multiplicity pp, p–Pb collisions

ALICE Contribution List

Talks: total 16

- D. F. Lodato, Sep 24, Sat, 08:30, Jing-Zhou Hall, Direct photon yield in pp and in Pb–Pb collisions
- T. Okubo, Sep 25, Sun, 9:30, Wuhan Hall, Neutral meson production in pp, p–Pb and Pb–Pb collisions
- T. Gunji, Sep 24, Sat, 11:40, Jing-Zhou Hall, Low mass dielectron measurements in pp, p–Pb and Pb–Pb collisions
- J. Viinikainen, Sep 24, Sat, 10:40, Shi-Yan Hall, Jet transverse fragmentation momentum from h-h correlations in pp and p–Pb collisions
- M. Kofarago, Sep 24, Sat, 17:00, Shi-Yan Hall, Near-side jet peak broadening in Pb–Pb collisions at 2.76 TeV
- X. Peng, Sep 25, Sun, 8:30, Shi-Yan Hall, pi0-hadron correlations in pp and Pb–Pb collisions and pi0 elliptic flow in Pb–Pb collisions
- M. L. Knichel, Sep 25, Sun, 8:30, Wuhan Hall, Transverse momentum spectra and nuclear modification of charged particles at 5.02 TeV
- O. Busch, Sep 25, Sun, 10:40, Wuhan Hall, Strangeness production and nuclear modification
- H. Yokoyama, Sep 24, Sat, 09:30, Xiang-Yang Hall, Measurement of Inclusive Charged Jet Production in pp and Pb–Pb collisions at 5.02 TeV
- C. Bianchin, Sep 24, Sat, 10:40, Xiang-Yang Hall, Jet mass measurements in Pb–Pb and p–Pb collisions
- Y. Zhang, Sep 24, Sat, 15:20, Xiang-Yang Hall, Baryon to meson ratio in jets and underlying event in Pb–Pb, p–Pb and pp collisions
- G. Luparello, Sep 24, Sat, 08:30, Shi-Yan Hall, Measurements of heavy-flavour production vs. multiplicity and angular correlations in pp and p–Pb collisions
- A. Dubla, Sep 24, Sat, 16:00, Wuhan Hall, Measurements of the suppression and anisotropy of heavy-flavour particles in Pb–Pb collisions at 2.76 TeV
- Z. Zhang, Sep 25, Sun, 10:40, Jing-Zhou Hall, Production of Muons from Heavy-Flavour Hadron Decays in Pb–Pb Collisions at 5.02 TeV
- V. J. Gaston Feuillard, Sep 24, Sat, 16:20, Jing-Zhou Hall, Charmonium production in Pb–Pb collisions
- G. G. Fronze, Sep 25, Sun, 8:30, Jing-Zhou Hall, Upsilon production in p–Pb and Pb–Pb collisions

Posters: total 7, Sep 23, Fri, 17:00

- Q. Shou, Measurement of elliptic flow of neutral pions in Pb–Pb collisions at 2.76 TeV
- M. Kim, Particle-yield modification in jet-like azimuthal di-hadron correlations in Pb–Pb collisions at 2.76 TeV
- S. Kar, Measurement of angular correlations between D mesons and charged particles in pp and p–Pb collisions
- A. Festanti, Measurement of the D-meson prompt fraction with a data-driven approach
- A. Silva, Prospects for the measurement of D mesons in jets in Pb–Pb collisions
- R. Hosokawa, Measurement of inclusive charged jet cross section in pp collisions at 5.02 TeV
- D. Sekihata, Analysis of neutral mesons in pp and Pb–Pb collisions with the PHOS detector in the Run2

Backup

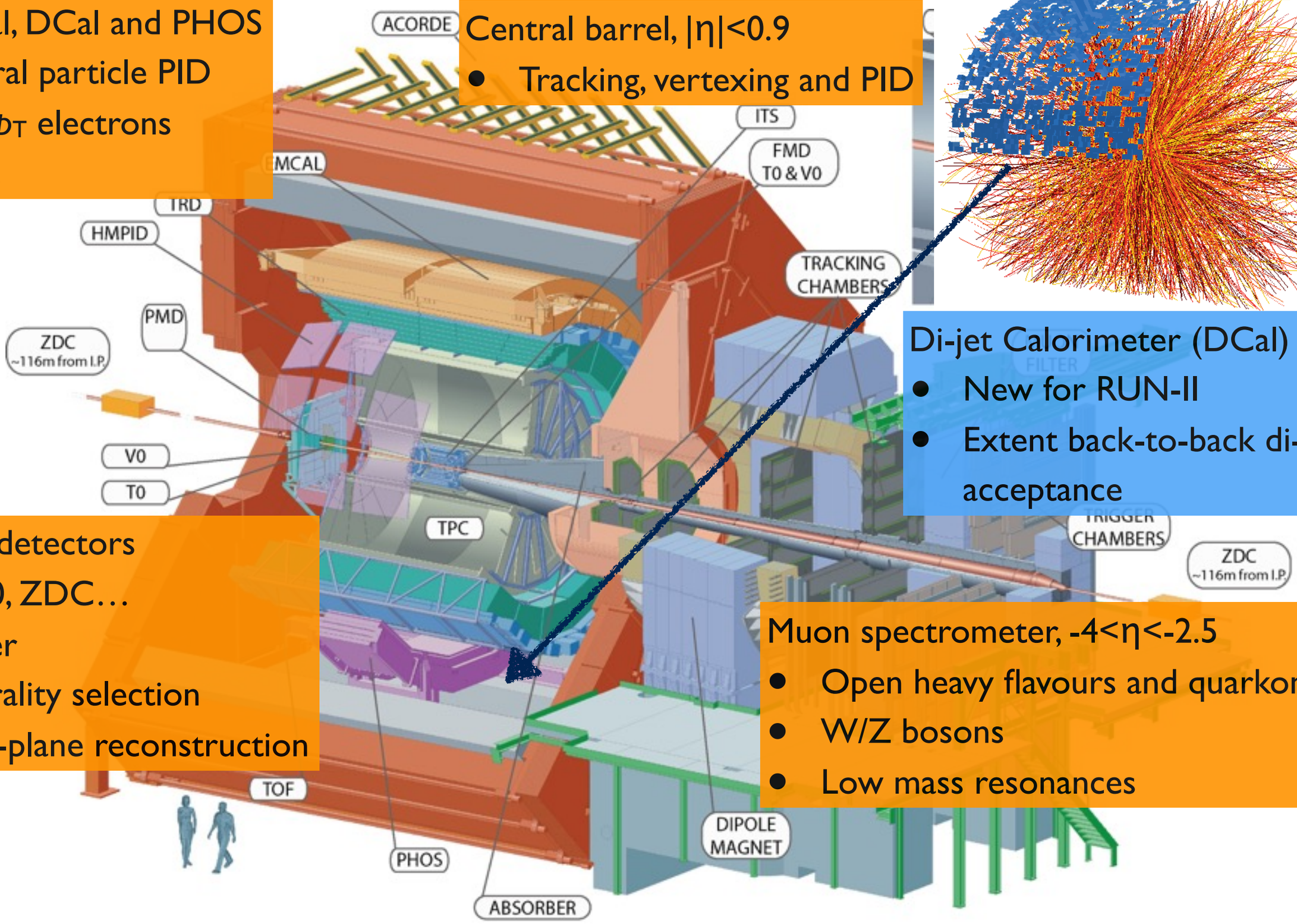
The ALICE Experiment

EM calorimeters, |η|<0.7

- EMCal, DCal and PHOS
- Neutral particle PID
- High-p_T electrons
- Jets…

Central barrel, |η|<0.9

- Tracking, vertexing and PID



Di-jet Calorimeter (DCal)

- New for RUN-II
- Extent back-to-back di-jet acceptance

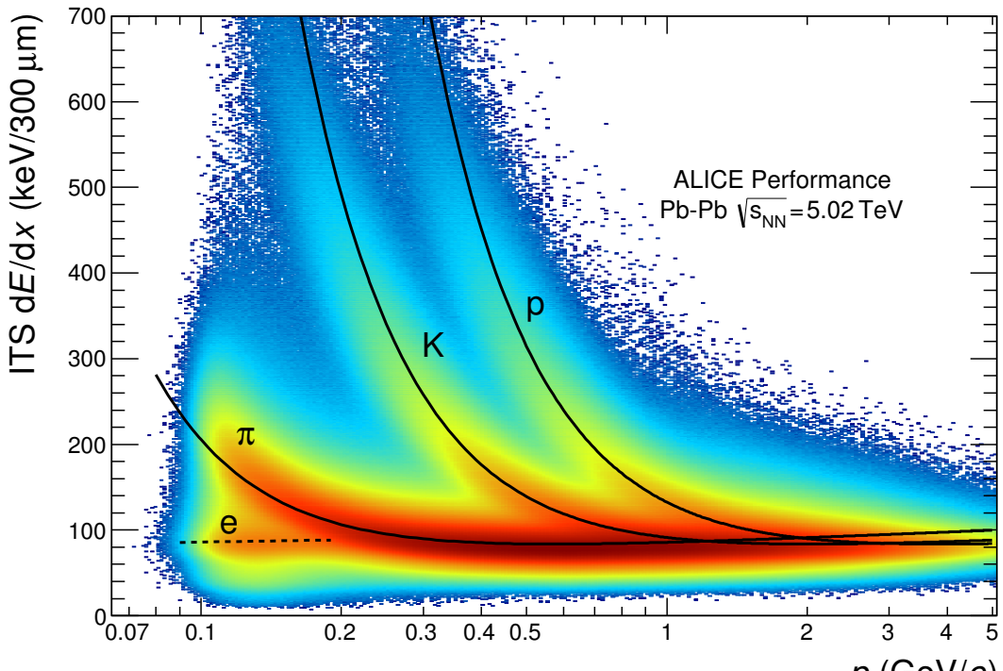
Forward detectors

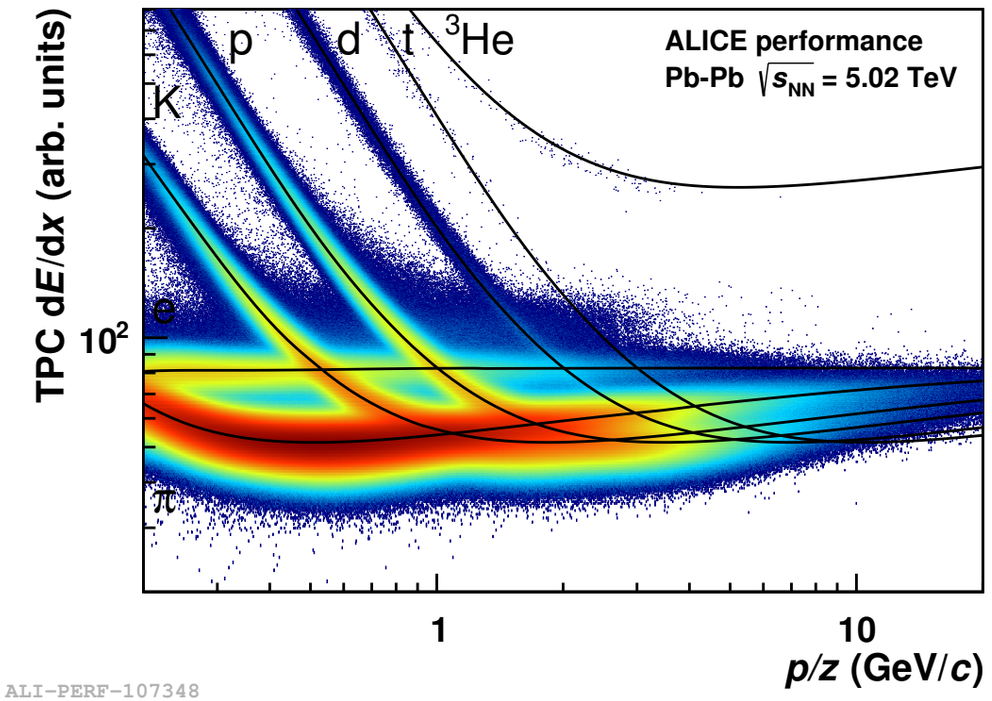
- V0, T0, ZDC…
- Trigger
- Centrality selection
- Event-plane reconstruction

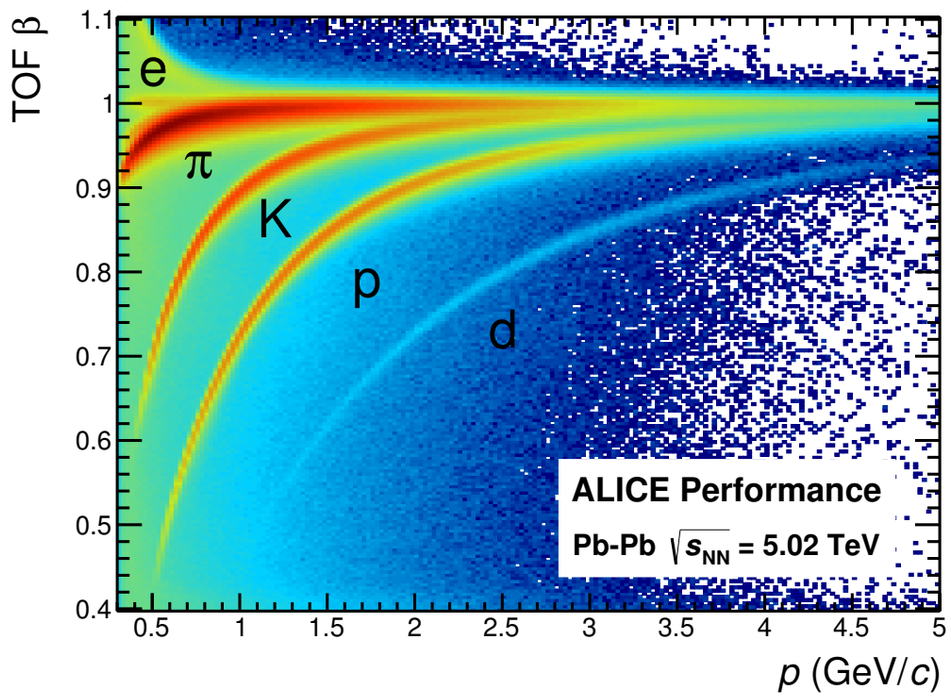
Muon spectrometer, -4<η<-2.5

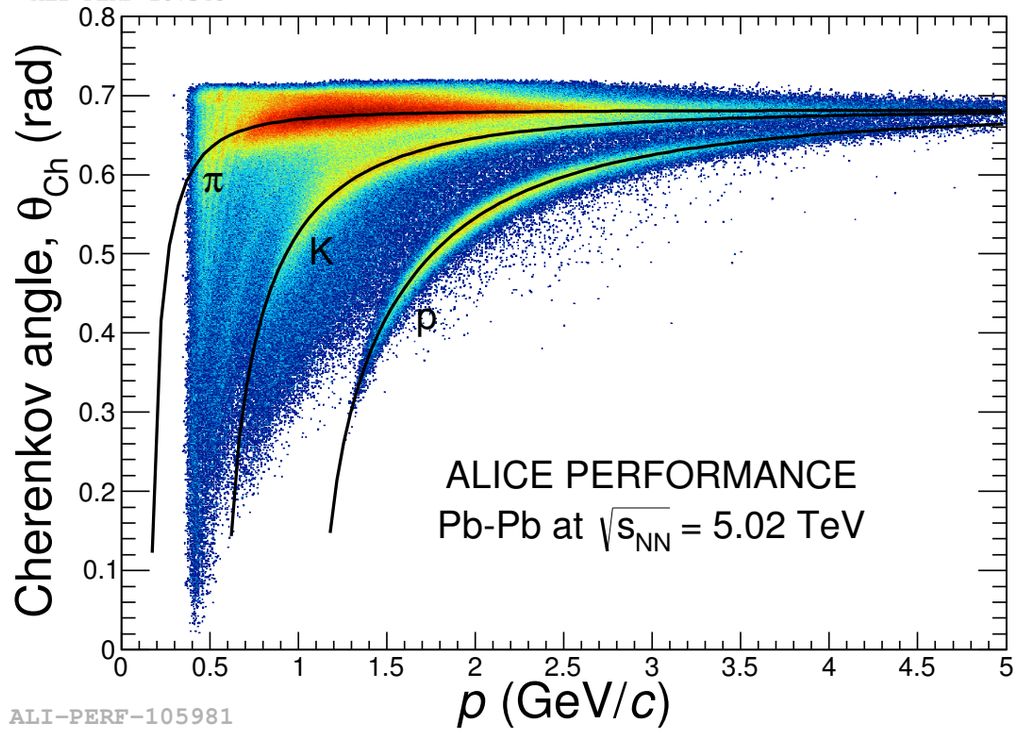
- Open heavy flavours and quarkonia
- W/Z bosons
- Low mass resonances

ALICE Performance

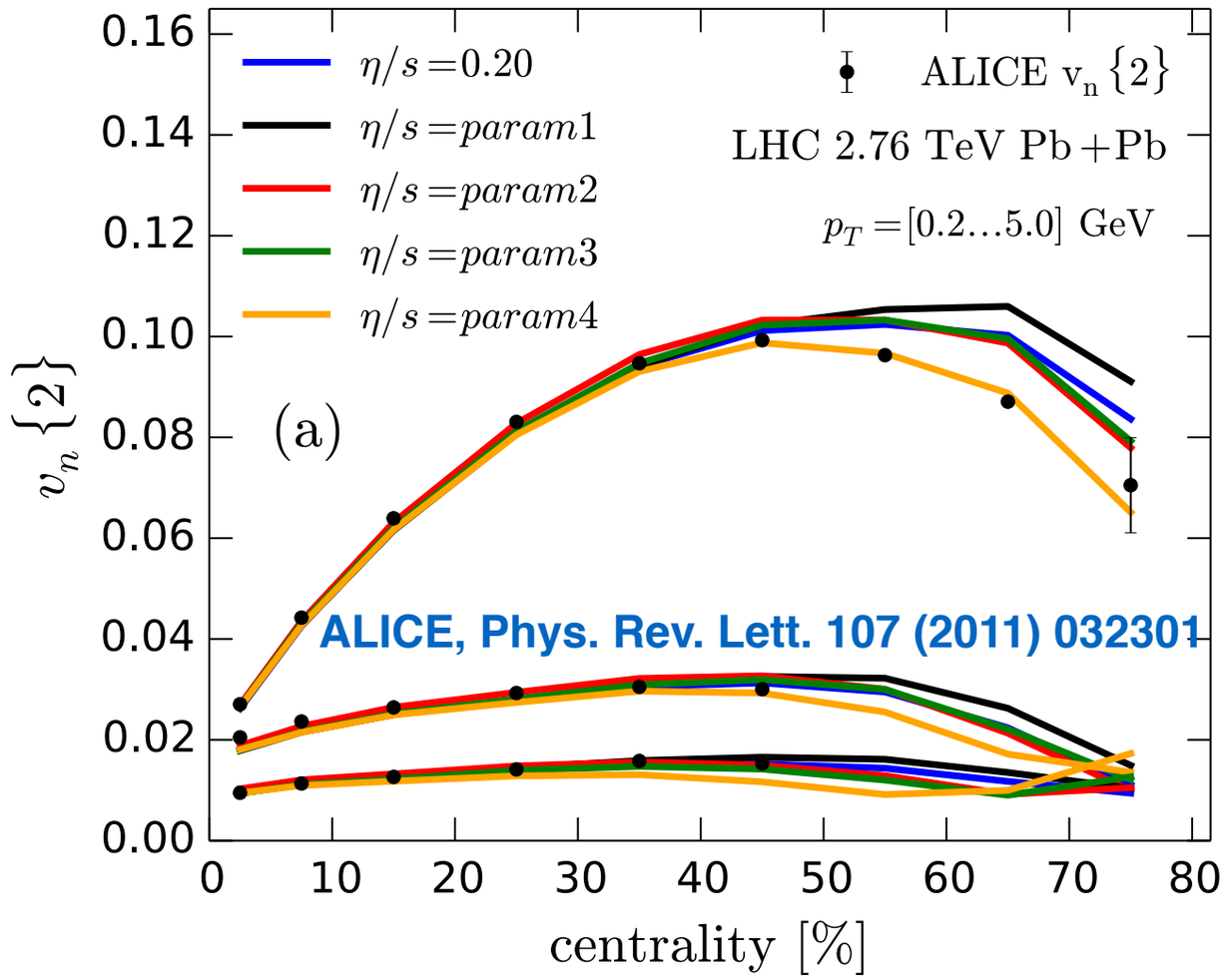


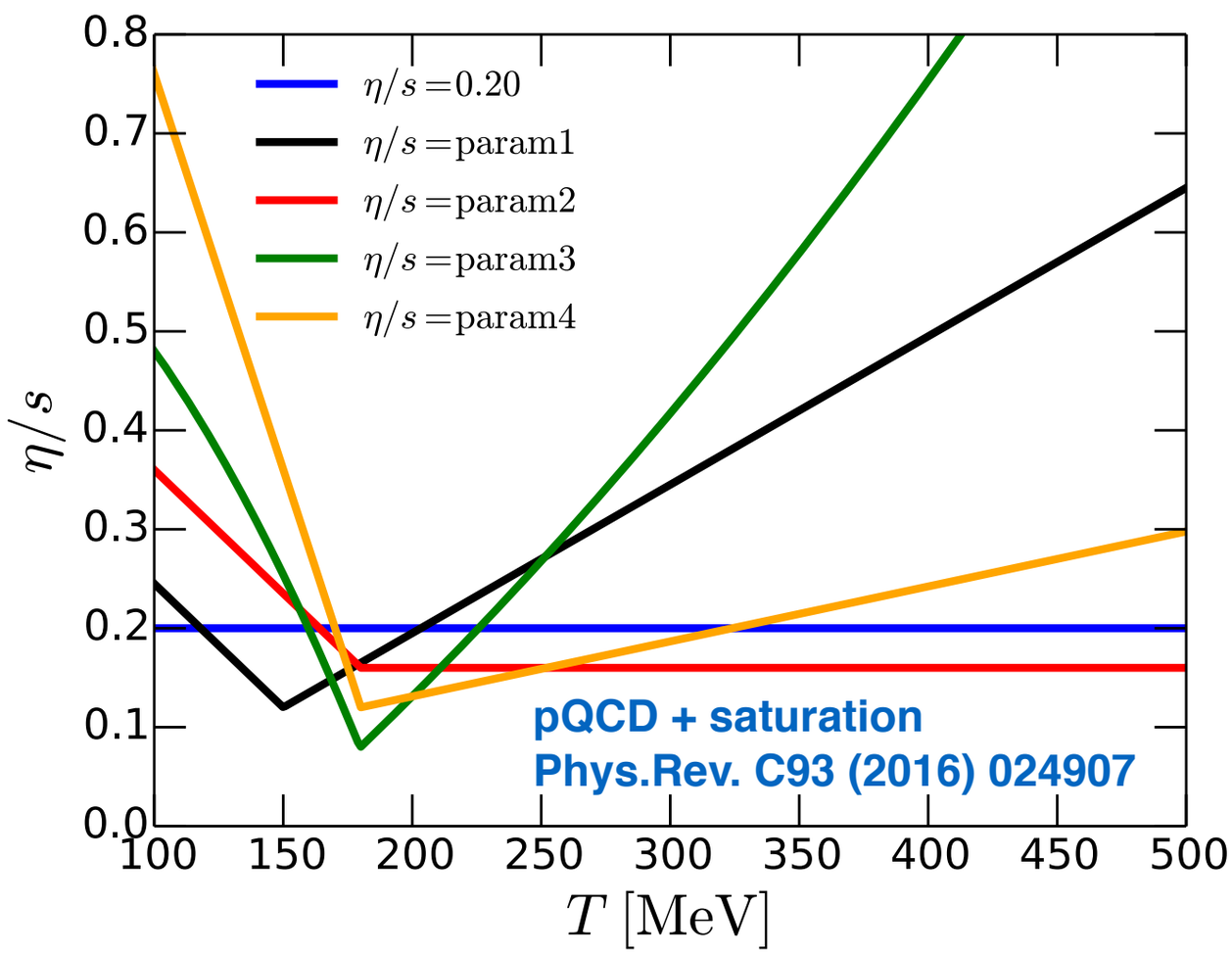






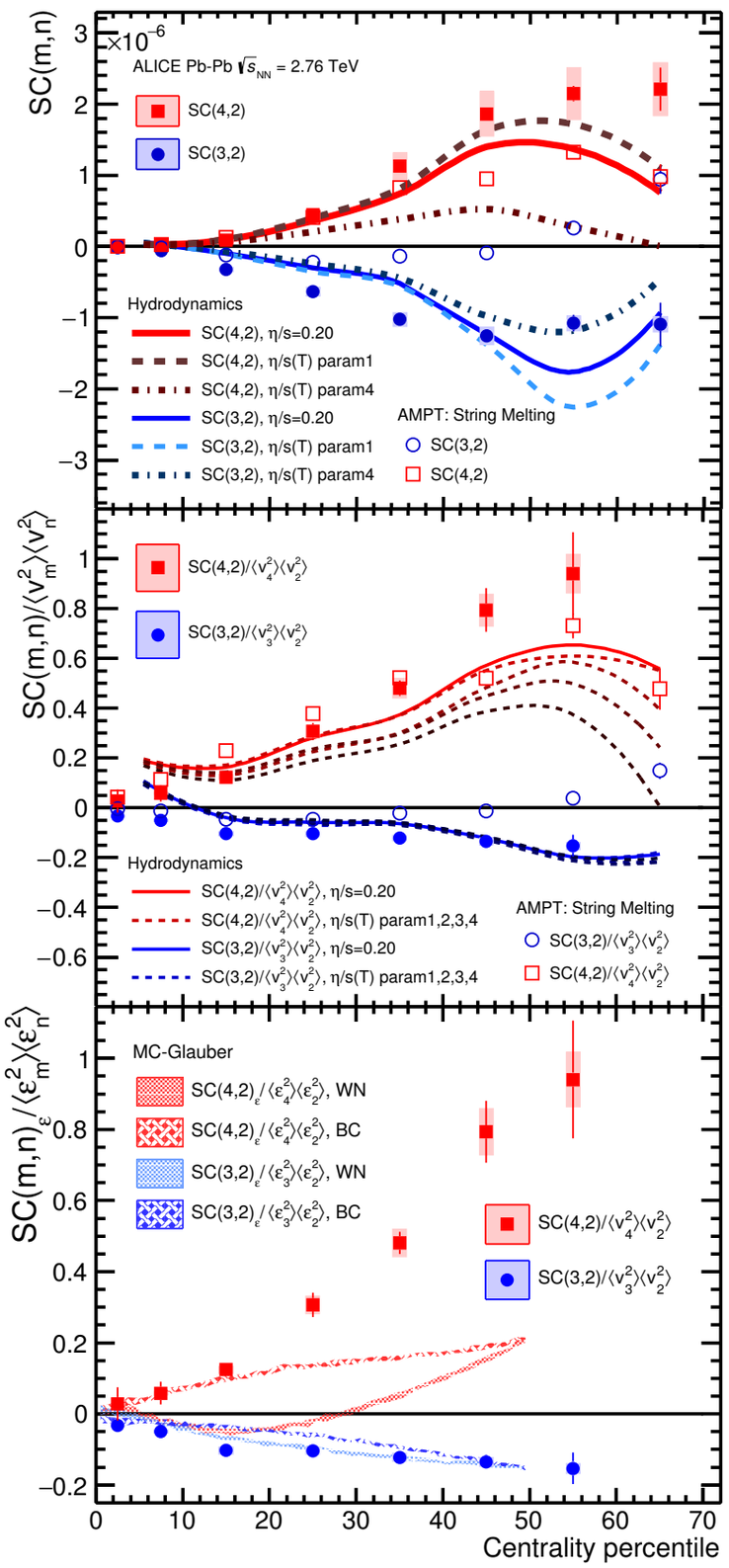
Flow Harmonic Correlations





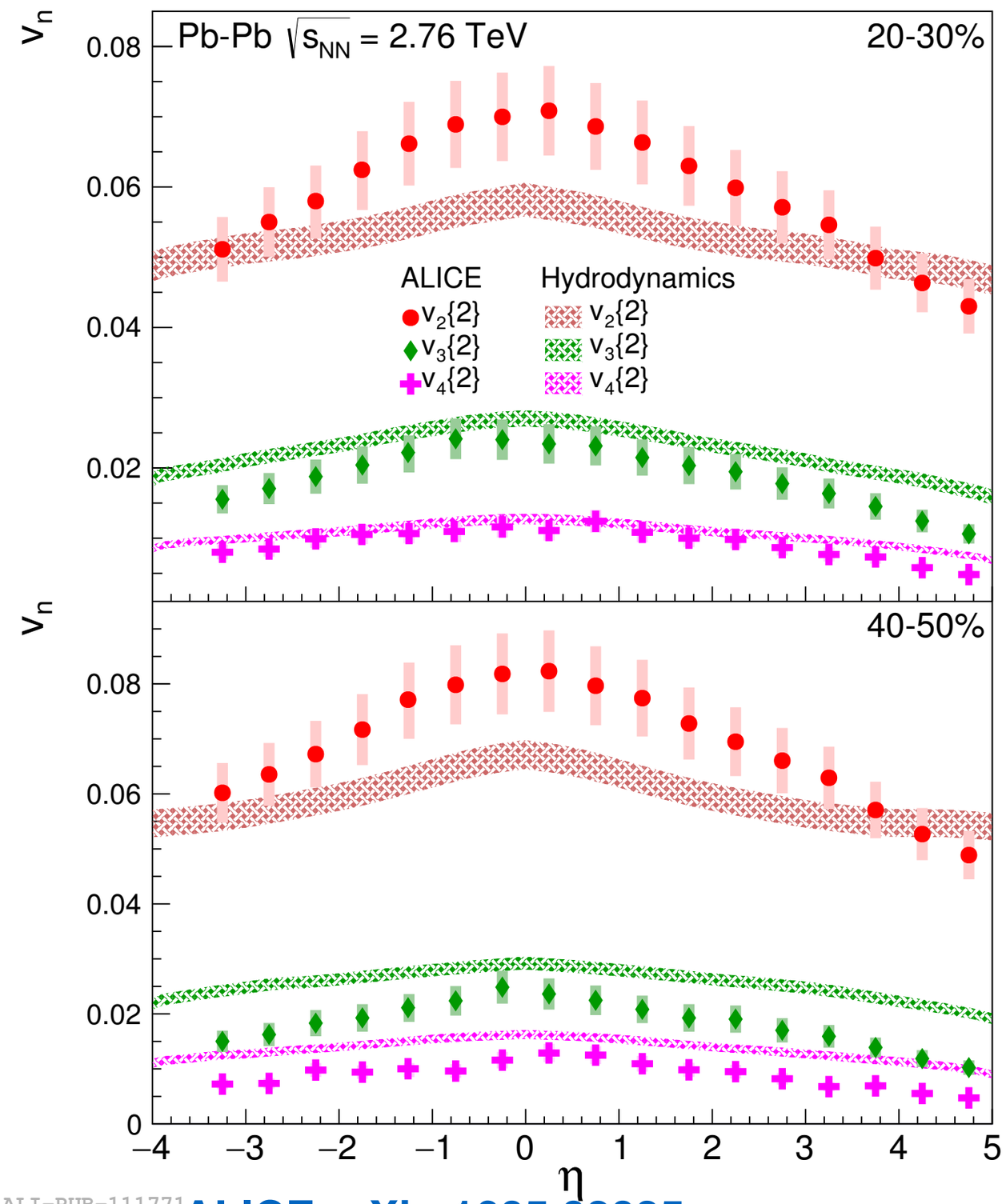
- It is necessary to look at more than v_n to extract $\eta/s(T)$
- Standard flow measurements are not very sensitive to $\eta/s(T)$
  - At least for central and semi-central collisions

Flow Harmonic Correlations



- New observable: Symmetric Cumulants (SC)
  - Insensitive to non-flow effects — due to multi-particle correlations
  - SC(3,2): sensitive to initial conditions
  - SC(4,2): sensitive to both initial conditions and η/s
  - Higher sensitivity to η/s and initial conditions than v_n alone

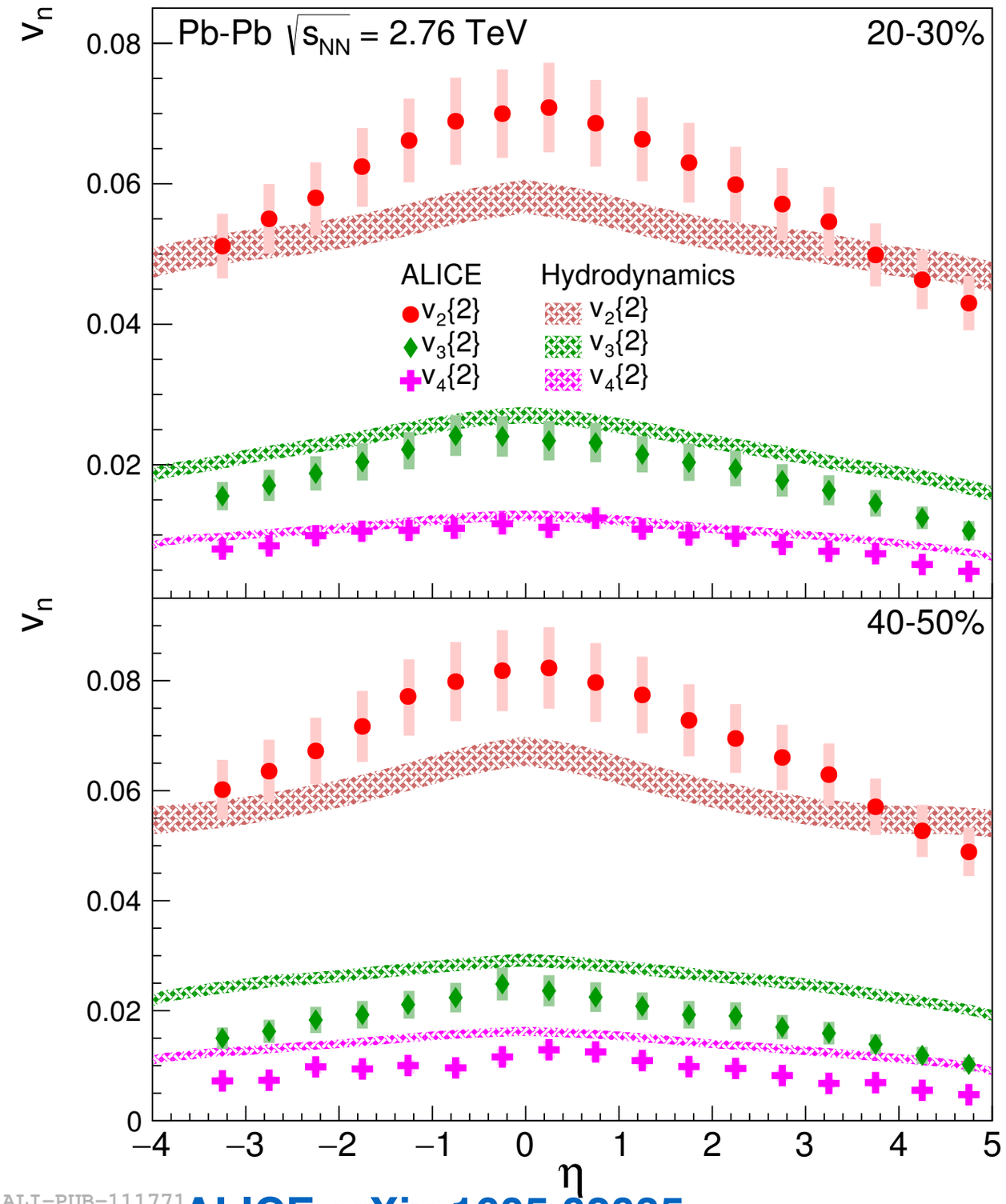
Anisotropy Flow in Wide Rapidity Range

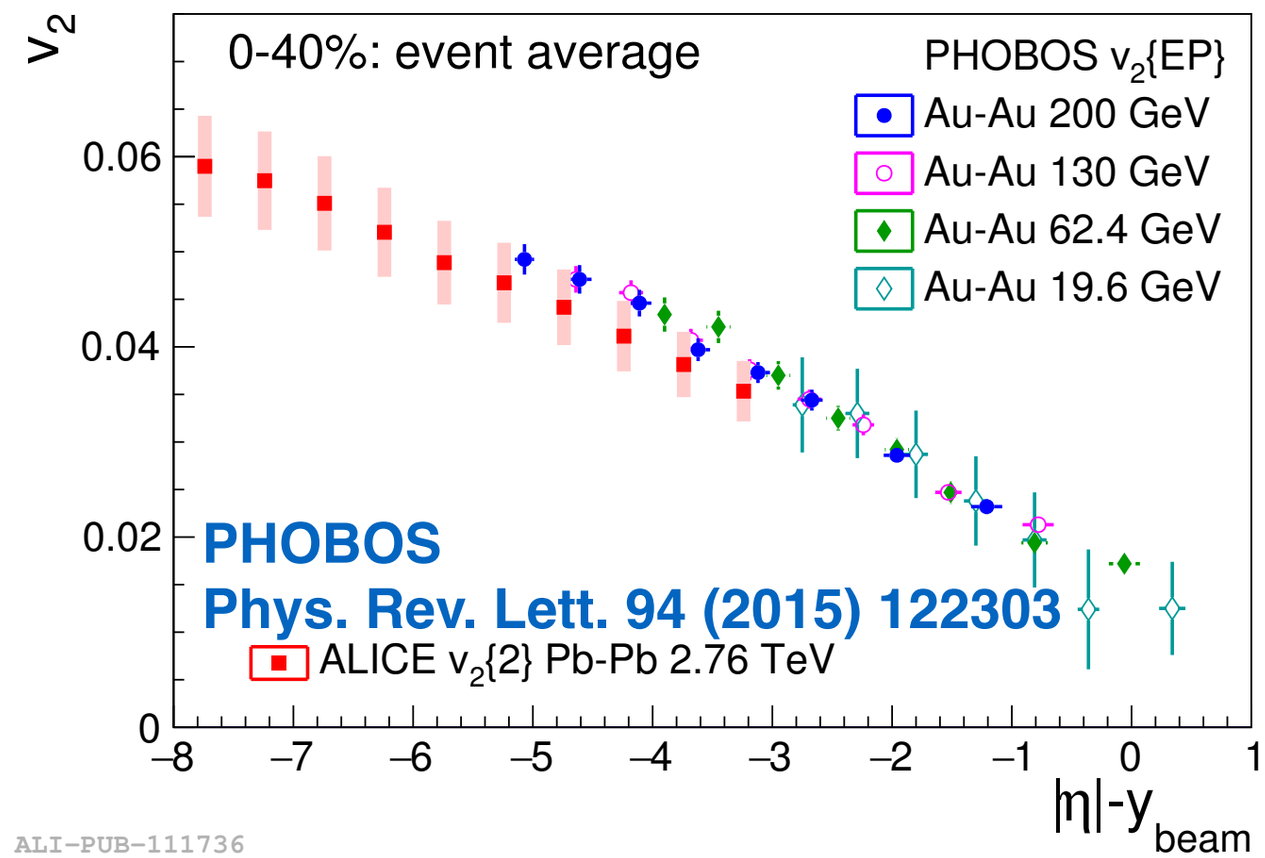


ALICE arXiv:1605.02035
Hydro Phys. Rev. Lett. 116 (2016) 212301

- Temperature dependence of η/s
  - *T* drops at forward rapidities
    - η/s change
    - the system spend less time in QGP phase
- Shape of $v_n(\eta)$ largely independent of centrality for the flow harmonics up to fourth order
- The higher harmonics fall off more steeply with increasing |η|.
- Results are not well reproduced by hydro, new challenge to the theory community

Anisotropy Flow in Wide Rapidity Range



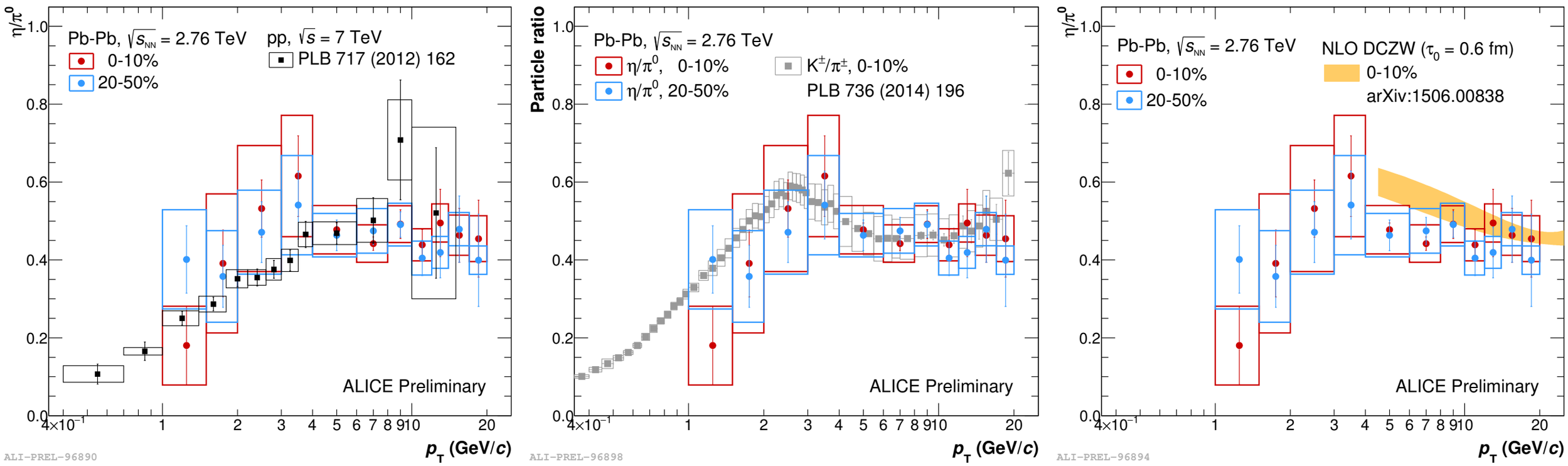


- Longitudinal scaling:
  - Particle production (multiplicity, v_1, v_2) is energy-independent in in the rest frame of one of the colliding nuclei — found at RHIC
  - Still valid up to the LHC energy

ALICE arXiv:1605.02035

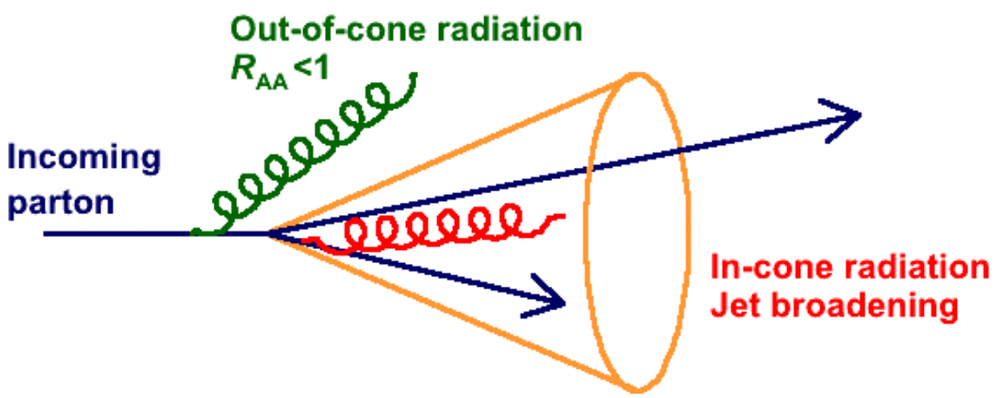
Hydro Phys. Rev. Lett. 116 (2016) 212301

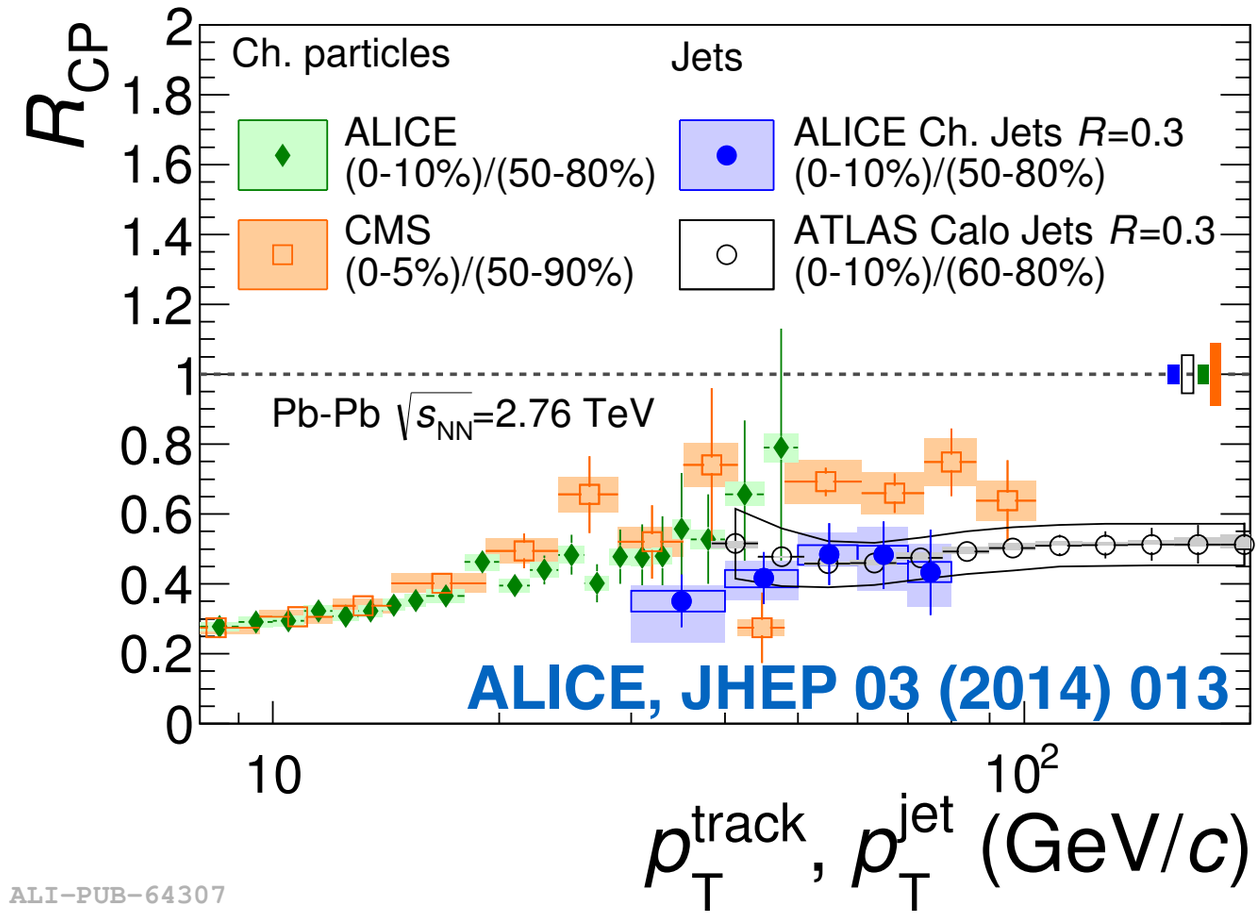
η/π^0 Ratio in Pb–Pb Collisions



- η/π^0 ratio in Pb-Pb
  - Consistent with that in pp — does not depend on collisions systems
  - Comparison to $K^{\pm}/\pi^{\pm}$ ratio — shows similar behavior
- pQCD NLO calculation at high p_T with energy loss reproduce the data
  - p_T in 4-6 GeV/c — sensitive to initial transport coefficient

Jet Yield Suppression





- ATLAS: calorimetric jets
- ALICE: charged-particle jets — more sensitive to the low-momentum fragments

- Agreement between ALICE and ATLAS

➡ Contribution of low momentum jet fragments to jet energy is small

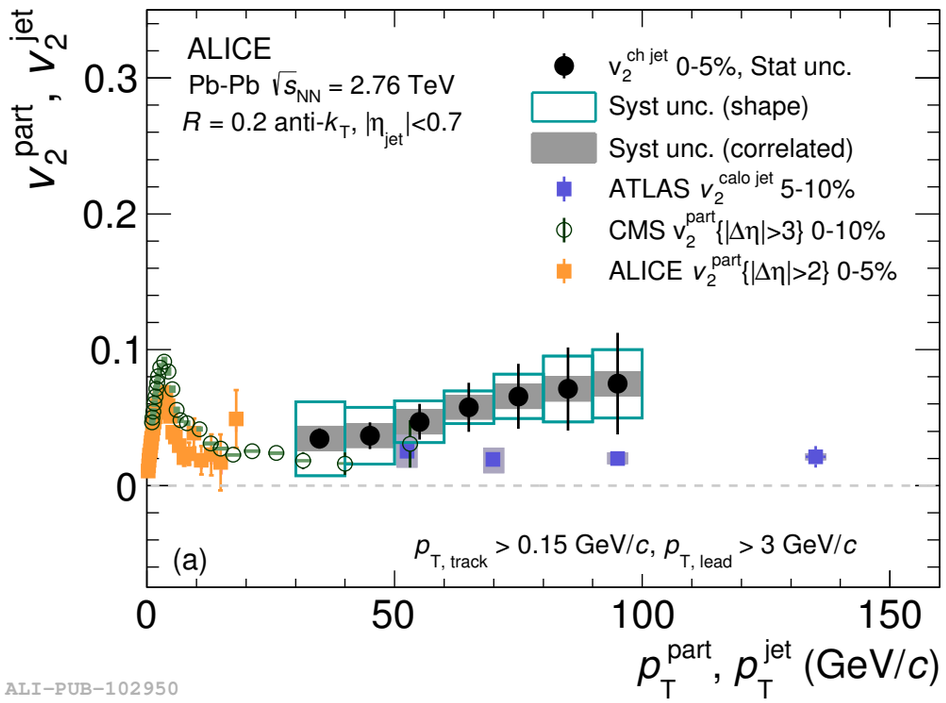
- R_{CP} of jets and single hadrons are compatible

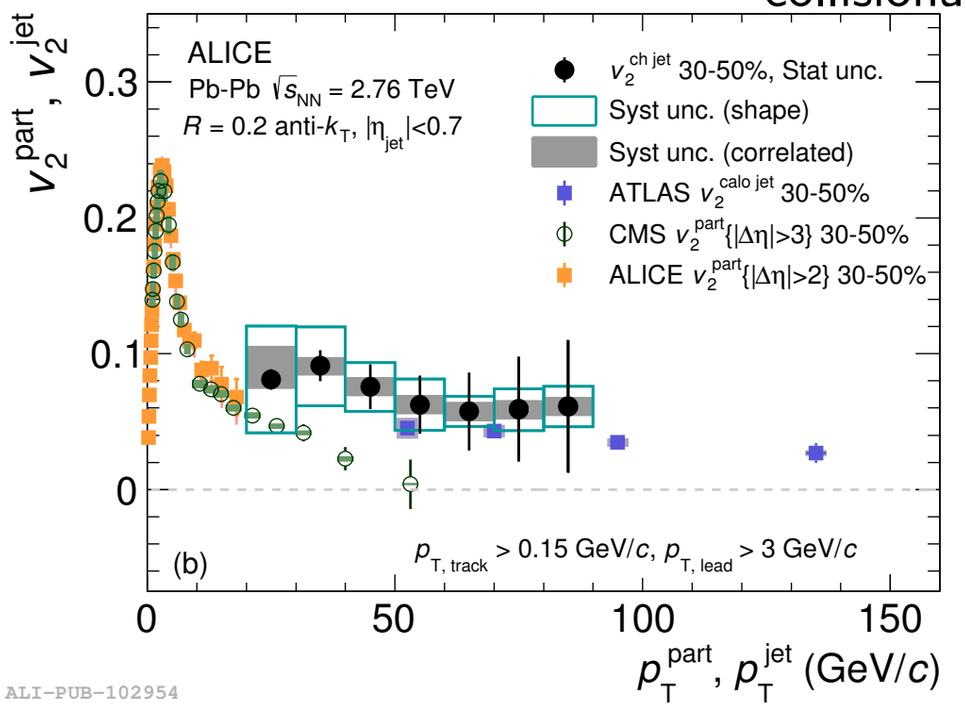
➡ Indication that the momentum is redistributed to larger angles

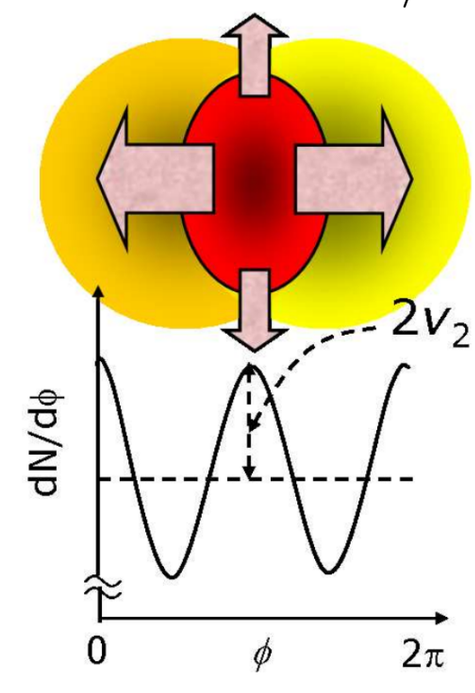
Jet Azimuthal Anisotropy

$$\underbrace{\Delta E \propto L}_{\text{collisional}} \leftrightarrow \underbrace{\Delta E \propto L^2}_{\text{radiative}} \leftrightarrow \underbrace{\Delta E \propto L^3}_{\text{AdS/CFT}}?$$

ALICE arXiv:1509.07334







- Central collisions (0–5%): null-hypothesis can not be excluded (1.5~2σ)

  ➡ Initial-state fluctuations (?)

- Semi-central collisions (30–50%): non-zero v_2 (3σ effect)

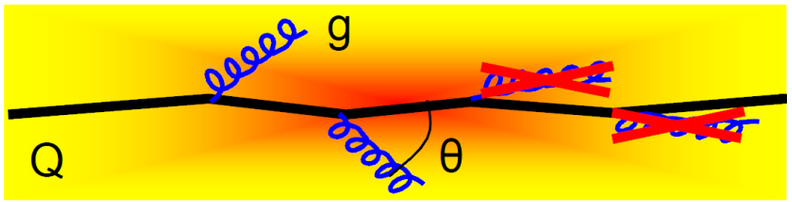
  ➡ Information of path-length dependence of parton in-medium energy loss

- Compatible with single particle and calo-jet v_2 at high p_T (with different energy scales)

  ➡ Large parton energy loss and that is sensitive to the collisions geometry

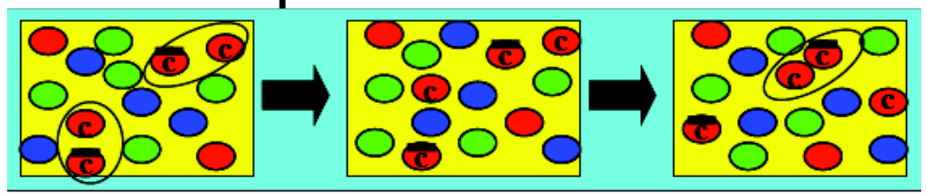
Heavy-Flavour and Quarkonia in QCD Medium

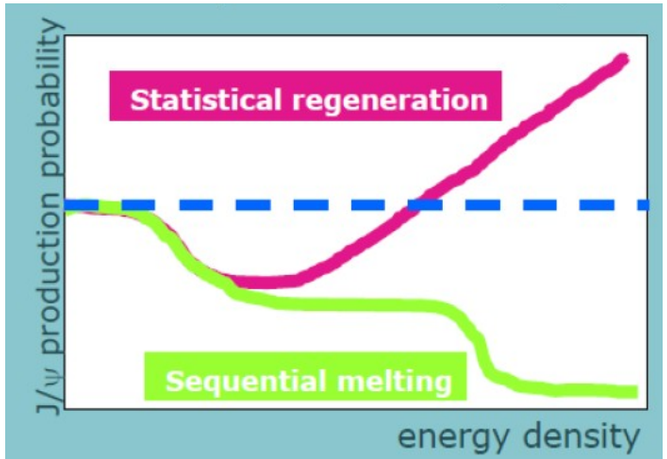
- Open heavy-flavours — HF (open charm and beauty hadrons)
  - R_{AA}: radiative energy loss vs. collisional energy loss
    - Mass and color charge dependence



$$\Delta E_g > \Delta E_{q\approx c} > \Delta E_b \Rightarrow R_{AA}^h < R_{AA}^D < R_{AA}^B \quad \textbf{(?)}$$

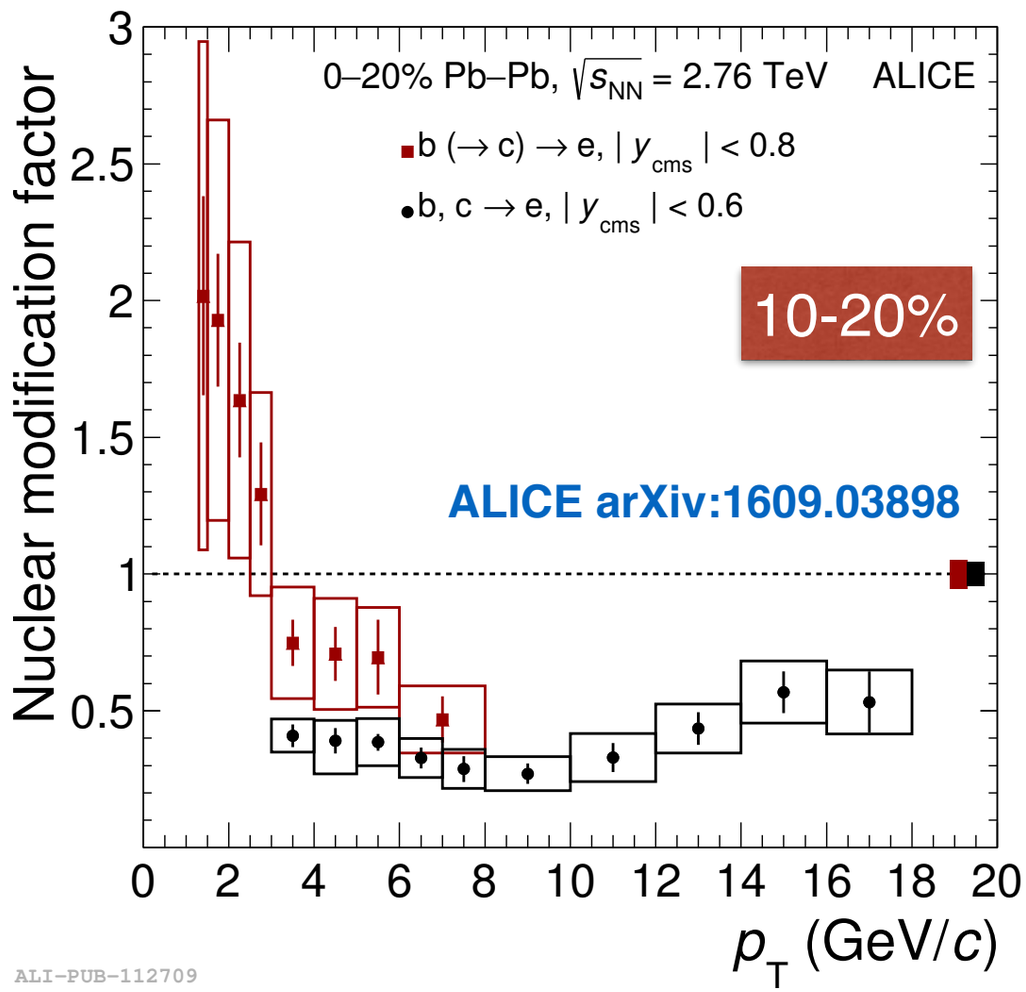
    - Models needed to disentangle differences in energy loss vs spectral shape/fragmentation function
  - Elliptic flow
    - Low-p_T: initial conditions and degree of thermalization of HF in QGP
    - High-p_T: path-length dependence of HF in-medium energy loss
- Quarkonia (J/ψ and Υ families): sequential melting (Debye screening) vs. recombination
  - Sensitive to medium temperature





Heavy-Flavour Decay Electrons

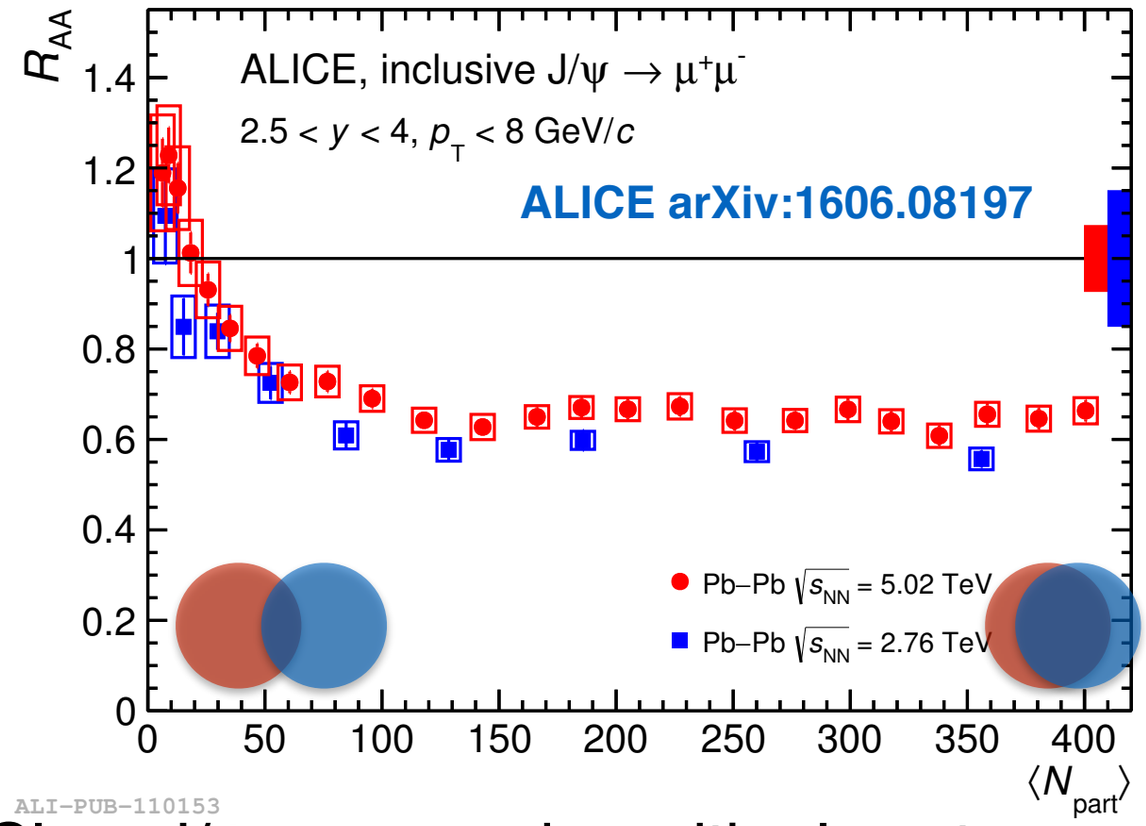
Talk: A. Dubla, Wuhan hall, Saturday, Sep. 24th 16:00

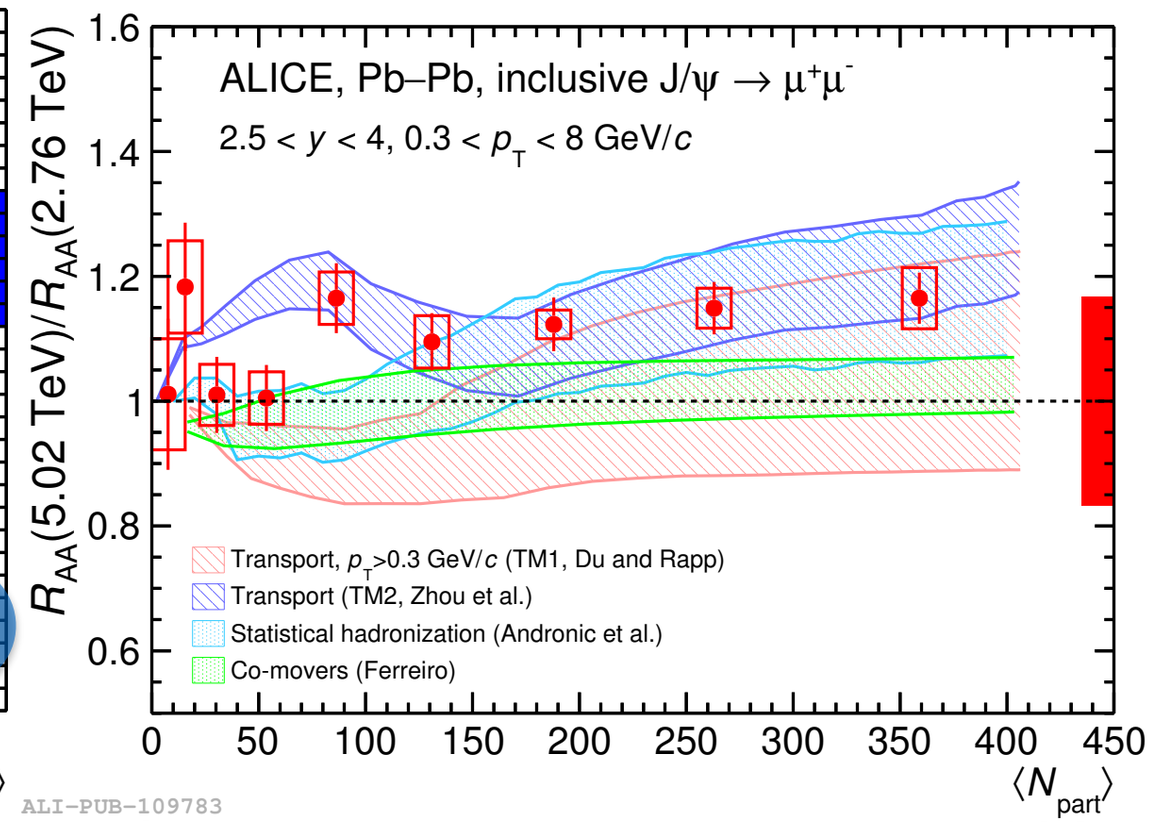


- First R_{AA} measurement of beauty-decay electron: $R_{AA} < 1$ for $p_T > 3$ GeV/c
  - Consistent with the picture of mass-dependent radiative and collisional energy loss

J/ψ Production in Pb–Pb Collisions

Talk: V. Feuillard, Jing-Zhou hall, Saturday, Sep. 24th 16:20



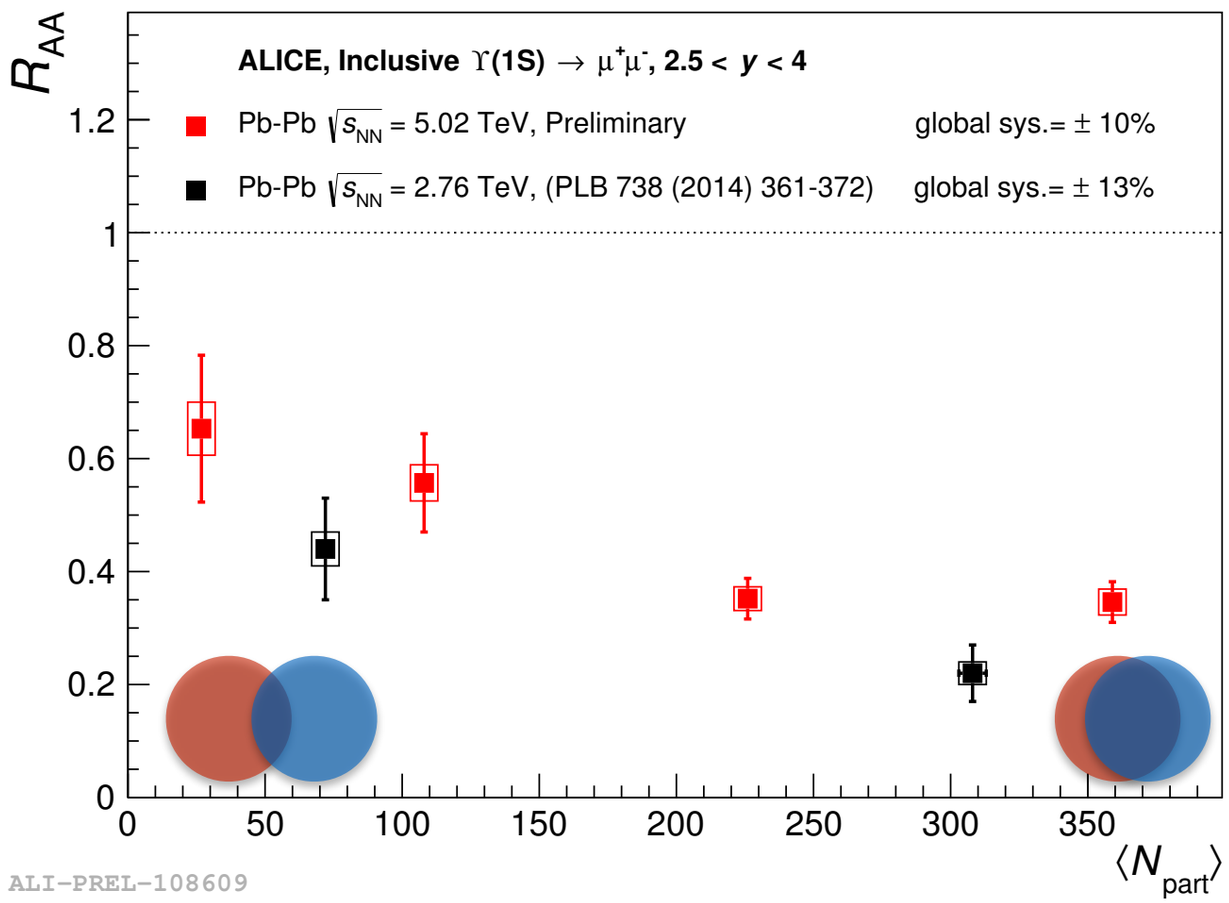


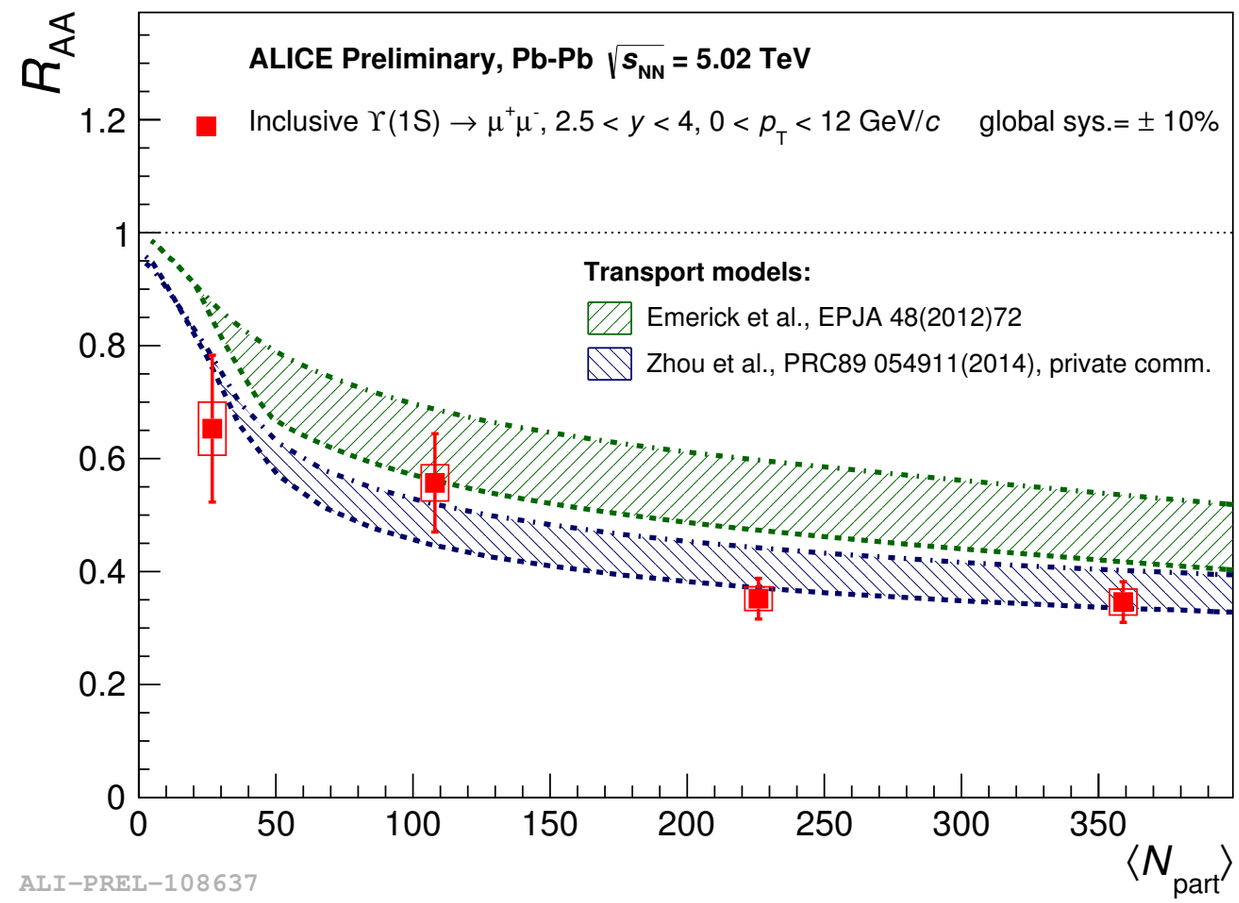
- Clear J/ψ suppression with almost no centrality dependence above N_{part} ~100
  - Excess in peripheral events is located at low p_T — photoproduction?

    ALICE Phys. Rev. Lett. 116 (2016) 222301
  - Suppression insensitive to the collision centrality in semi-central and central collisions — indication of regeneration
- Ratio of R_{AA} at 5.02 TeV and 2.76 TeV: data are, within uncertainties, compatible with the theoretical models, and show no clear centrality dependence
  - Consistent with unity within errors: 1.17 ± 0.04 (stat.) ± 0.2 (syst.)

Υ(1S) Production in Pb–Pb Collisions

Talk: G. G. Fronze, Jing-Zhou hall, Sunday, Sep. 25th 8:30

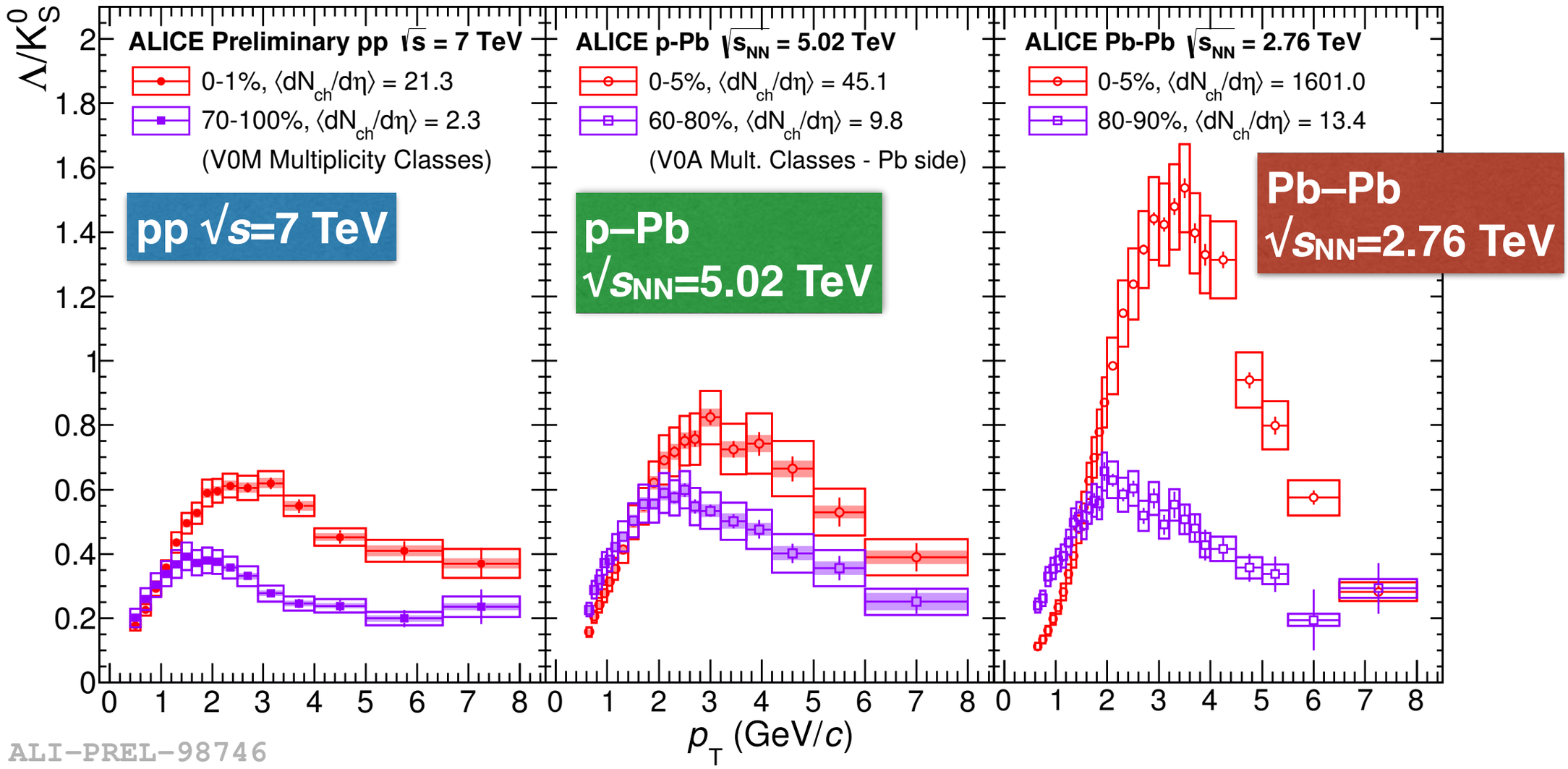




Emerick et al.: regeneration + feed-down ± shadowing uncertainty
Zhou et al.: CNM effect ± feed-down uncertainty

- R_{AA} at 5.02 TeV and 2.76 TeV are compatible within uncertainties
  - R_{AA}(5.02 TeV, 0–90%) / R_{AA}(2.76 TeV, 0–90%) = 1.3 ± 0.2 (stat.) ± 0.2 (syst.)
- Comparisons with model predictions: centrality dependence is qualitatively reproduced
  - Suppression is slightly underestimated when considering regeneration

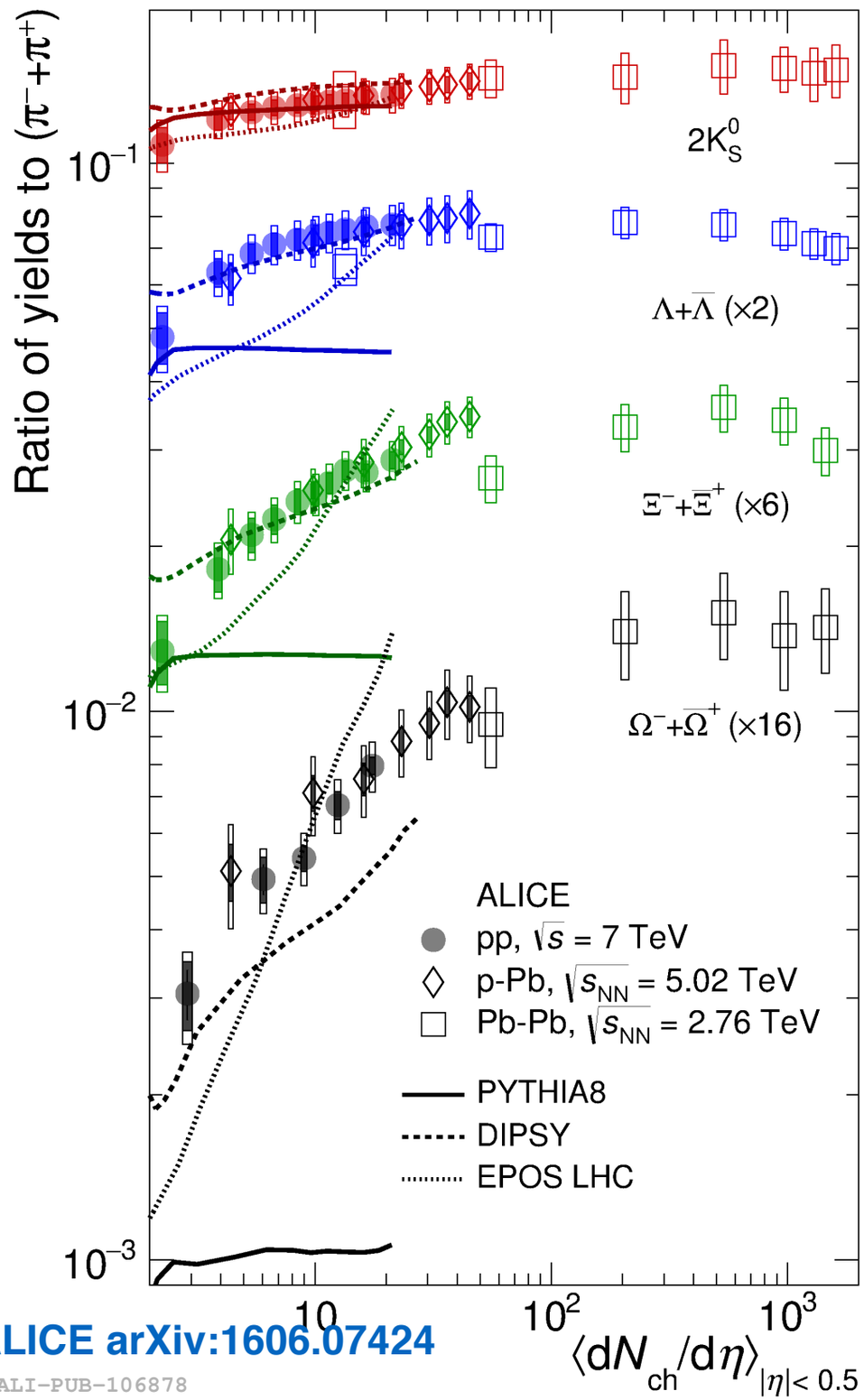
Λ/K_S^0 Ratio: Inclusive V^0s



- Increase of the ratio from low multiplicity (peripheral) to high multiplicity (central) collisions seen in pp, p–Pb, and Pb–Pb systems
- In Pb–Pb the enhancement at intermediate p_T can be explained by collective flow and/or quark recombination from QGP
- Same qualitative behavior seen in pp and p–Pb, but with smaller magnitude

Strangeness Enhancement

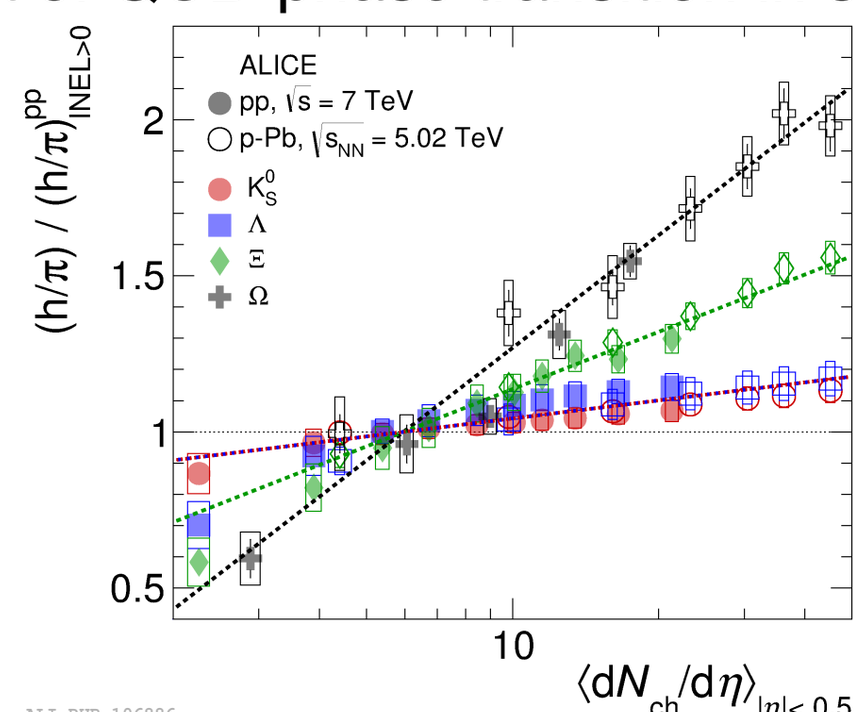
Talk: O. Busch, Wuhan hall, Sunday, Sep. 25th 10:40



ALICE arXiv:1606.07424

ALI-PUB-106878

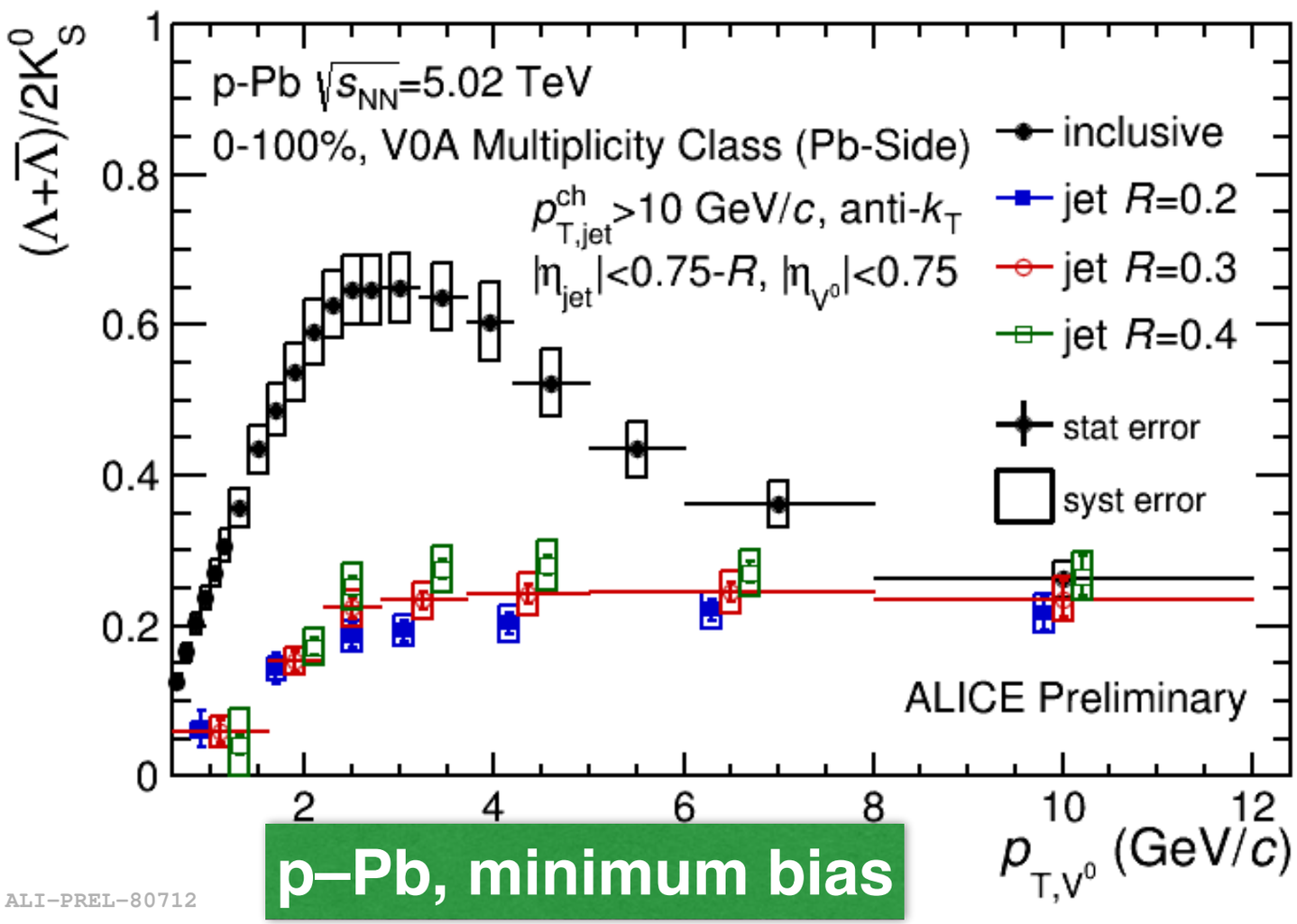
- Study yield-ratios vs. systems size
  - Significant enhancement of strange to non-strange hadron production is observed
  - The observed enhancement follows a hierarchy with the number of strange valence quarks
  - MC model predictions do not describe satisfactorily the behavior of the data
- Open question for strangeness production at the LHC — onset of QCD-phase transition in small system?



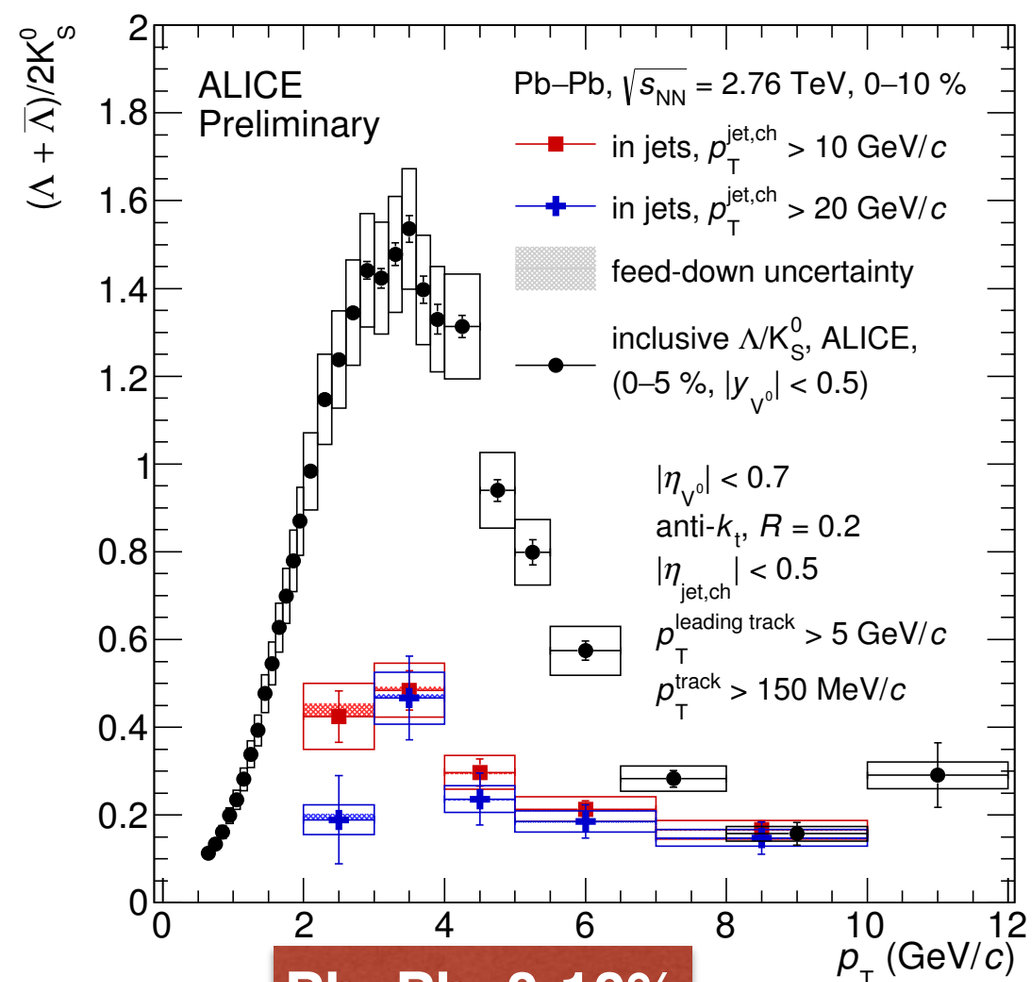
ALI-PUB-106886

Λ/K_S^0 Ratio in Jets

- The enhanced ratio of Λ/K_S^0 at inter-median p_T of inclusive V^0s in p–Pb and Pb–Pb collisions relative to pp collisions is not present within the jet region
  - Baryon enhancement does not origin from modified jet fragmentation
  - Results independent on jet radii and disfavor the hard-soft recombination



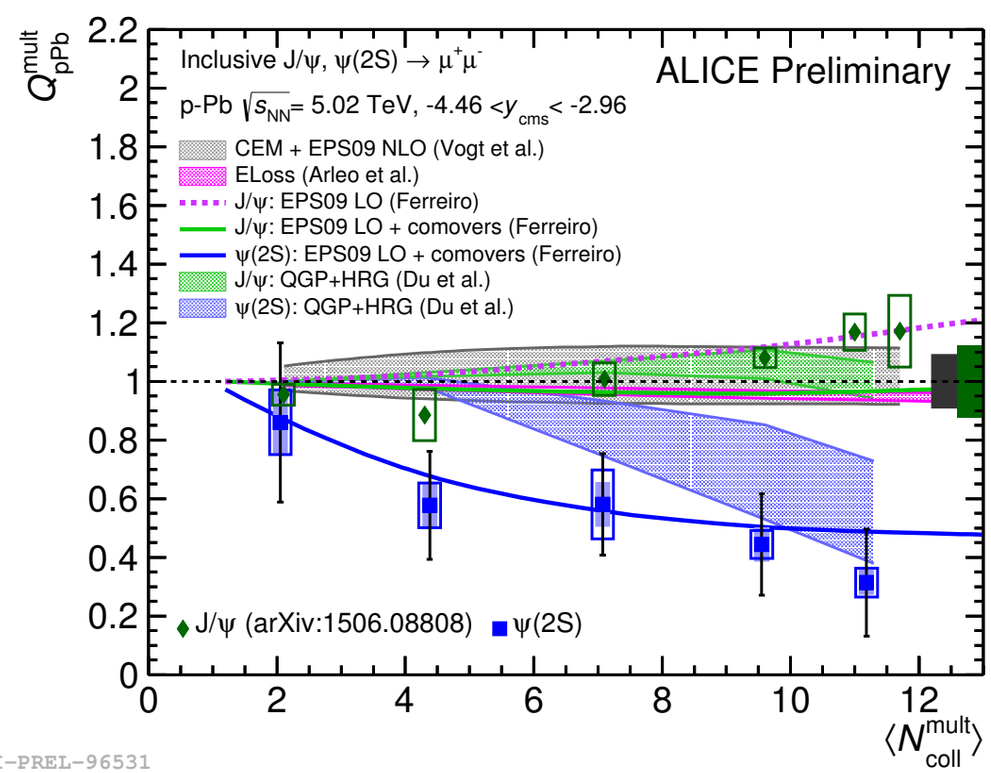
p–Pb, minimum bias

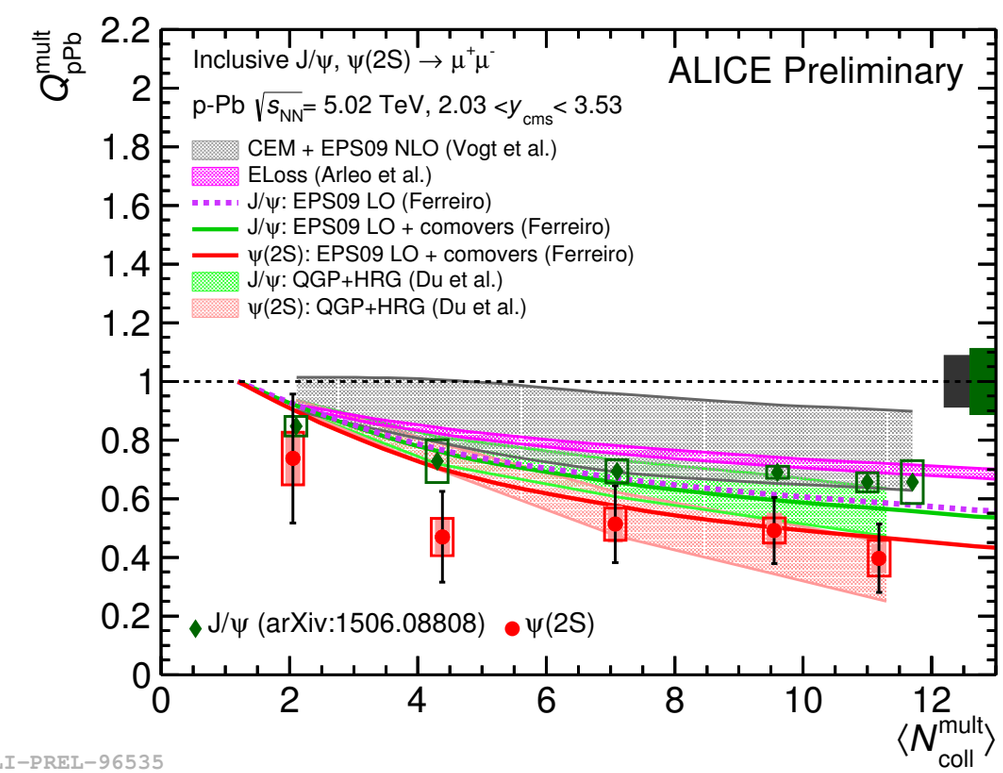


Pb–Pb, 0-10%

Charmonia in p–Pb Collisions

- $J/\psi \rightarrow \mu^+\mu^-$ measured at forward/backward rapidities
- Pb-going direction: different trends for J/ψ and ψ(2*S*) — ψ(2*S*) suppressed
- p-going direction: Indication of smaller Q_{pPb} for ψ(2*S*) relative to J/ψ
- Models with only CNM effects (shadowing, *E* loss) do not describe ψ(2*S*)
- Break-up due to interactions with hadronic resonance gas ("comovers") is a possible explanation for ψ(2*S*) suppression
- Models with QGP and Hadron Resonance Gas in fair agreement with data

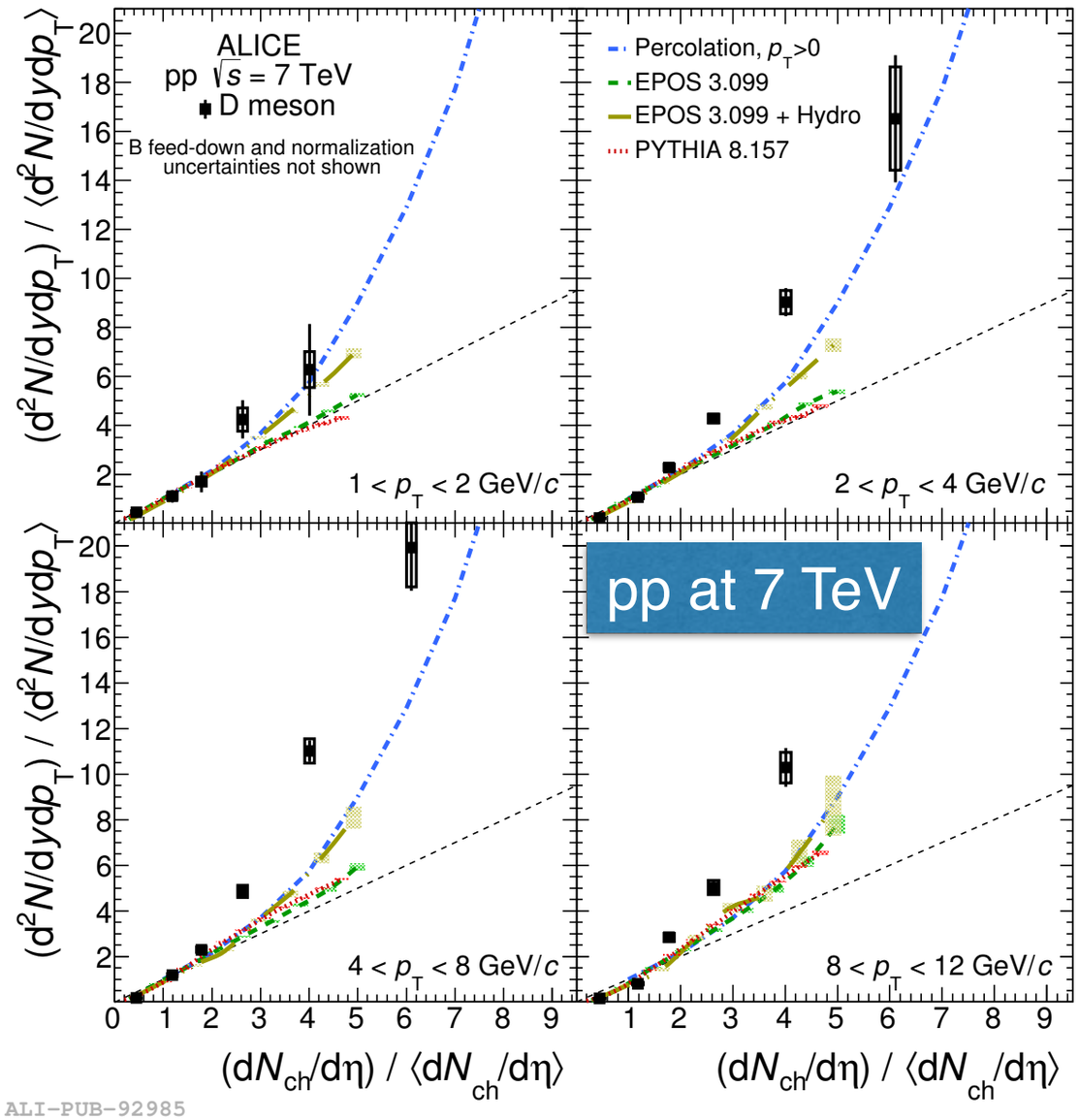


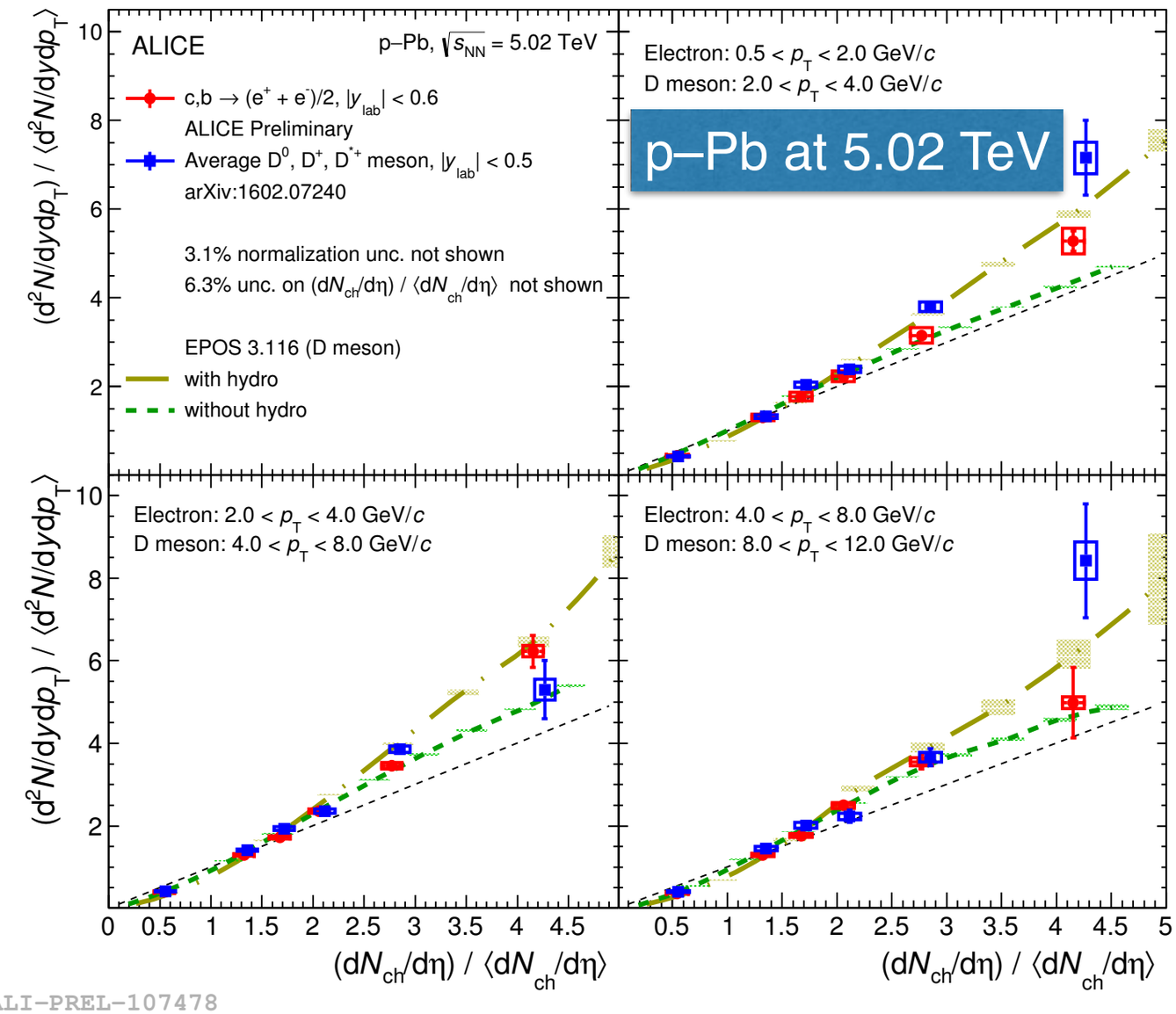


Heavy-Flavour Production vs Multiplicity

Talk: G. Luparello Shi-Yan hall, Saturday, Sep. 24th 8:30

ALICE JHEP 09 (2015) 148





- Faster-than-linear increase of self-normalized D-meson and heavy-flavour decay electron yields as a function of the charged-particle multiplicity at mid-rapidity
- Model with hydrodynamics describes fairly data in both pp and p–Pb collisions

ALICE Upgrade LS2 (2019~2020)

- New Silicon Inner Tracking System
- New or upgraded readout for all detectors to cope with higher rate, new CTP and Trigger Detectors
- New readout chambers for the Time Projection Chamber
- New Silicon Tracker in front of Muon Absorber
- New Data Acquisition System and High Level Trigger to handle continous readout, new Offline system