12th International Workshop on High-p_T Physics in the RHIC and LHC Era
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Identified charged hadron production at intermediate and high p_T measured by the ALICE detector at the LHC

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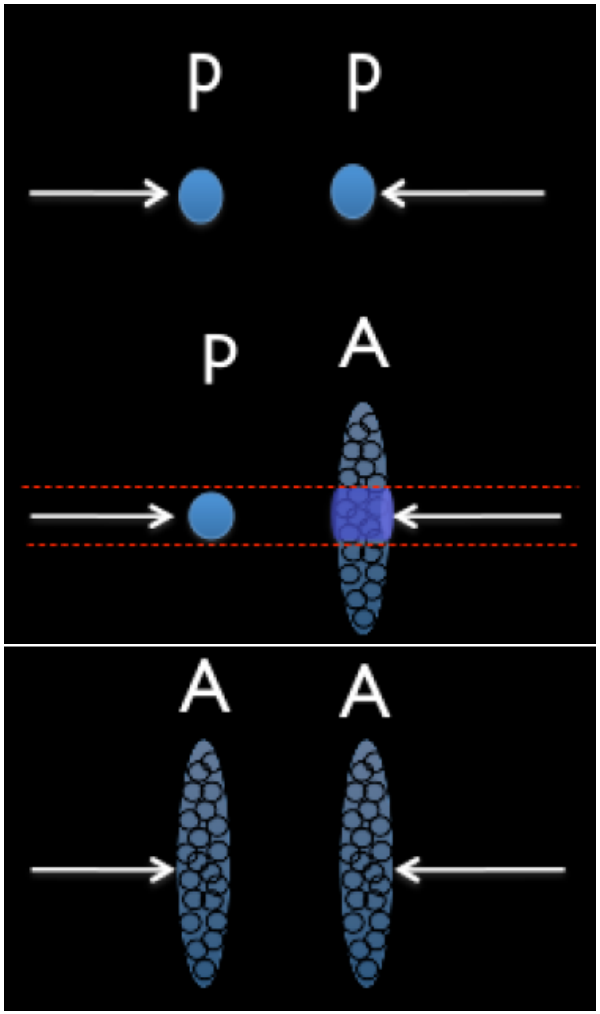
Outline

- ALICE goal
- Charged hadrons identification at intermediate (≈2 GeV/c - 10 GeV/c) and high p_T (≥ 10 GeV/c) with ALICE
- pp results
- p-Pb results
- Pb-Pb results
- nuclear modification factor in Pb-Pb and p-Pb collisions
- Conclusions

Goals of the ALICE experiment

ALICE is designed to study the physics of strongly interacting matter under extremely high temperature and energy densities to investigate the properties of the **quark-gluon plasma**.

- proton-proton collisions:
  - **high energy QCD reference.**
  - collected pp data at $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8, 13 TeV (2009-2012, 2015, 2016)
- proton-nucleus collisions:
  - **initial state/cold nuclear matter.**
  - collected p-Pb data at $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV (2012, 2013, 2016)
- nucleus-nucleus collisions:
  - **quark-gluon plasma formation!**
  - collected Pb-Pb data at $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV, (2010, 2011, 2015)



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- proton-proton collisions:
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  - collected pp data at $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8
  - collected p-Pb data at $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV (2012, 2013, 2016)

- nucleus-nucleus collisions:
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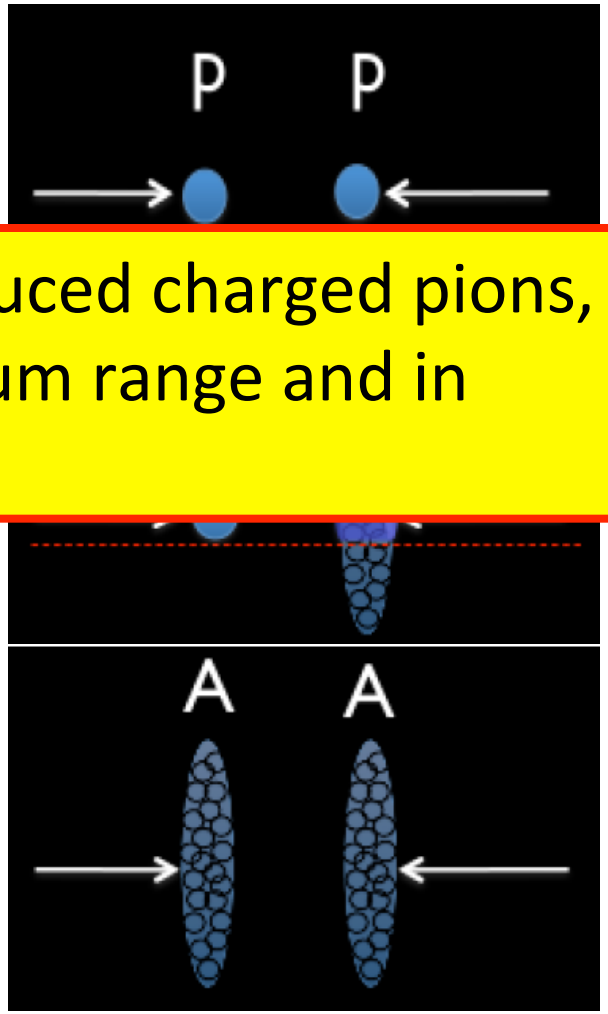
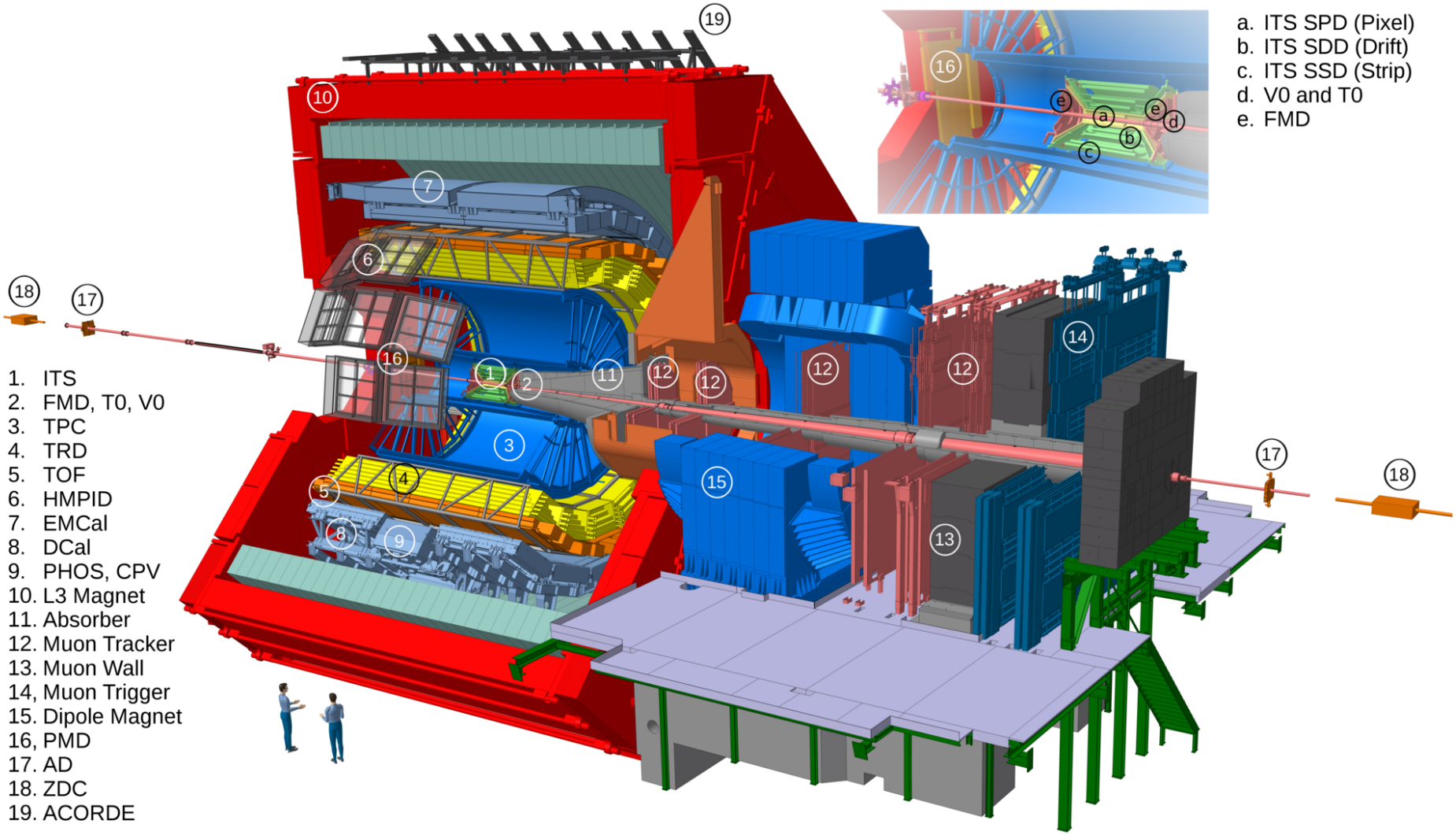
  - collected Pb-Pb data at $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV, (2010, 2011, 2015)

ALICE has measured the yields of produced charged pions, kaons and protons, in a wide momentum range and in several colliding systems.



ALICE detectors: $\pi^{\pm}$, $K^{\pm}$ and $p(\bar{p})$ PID



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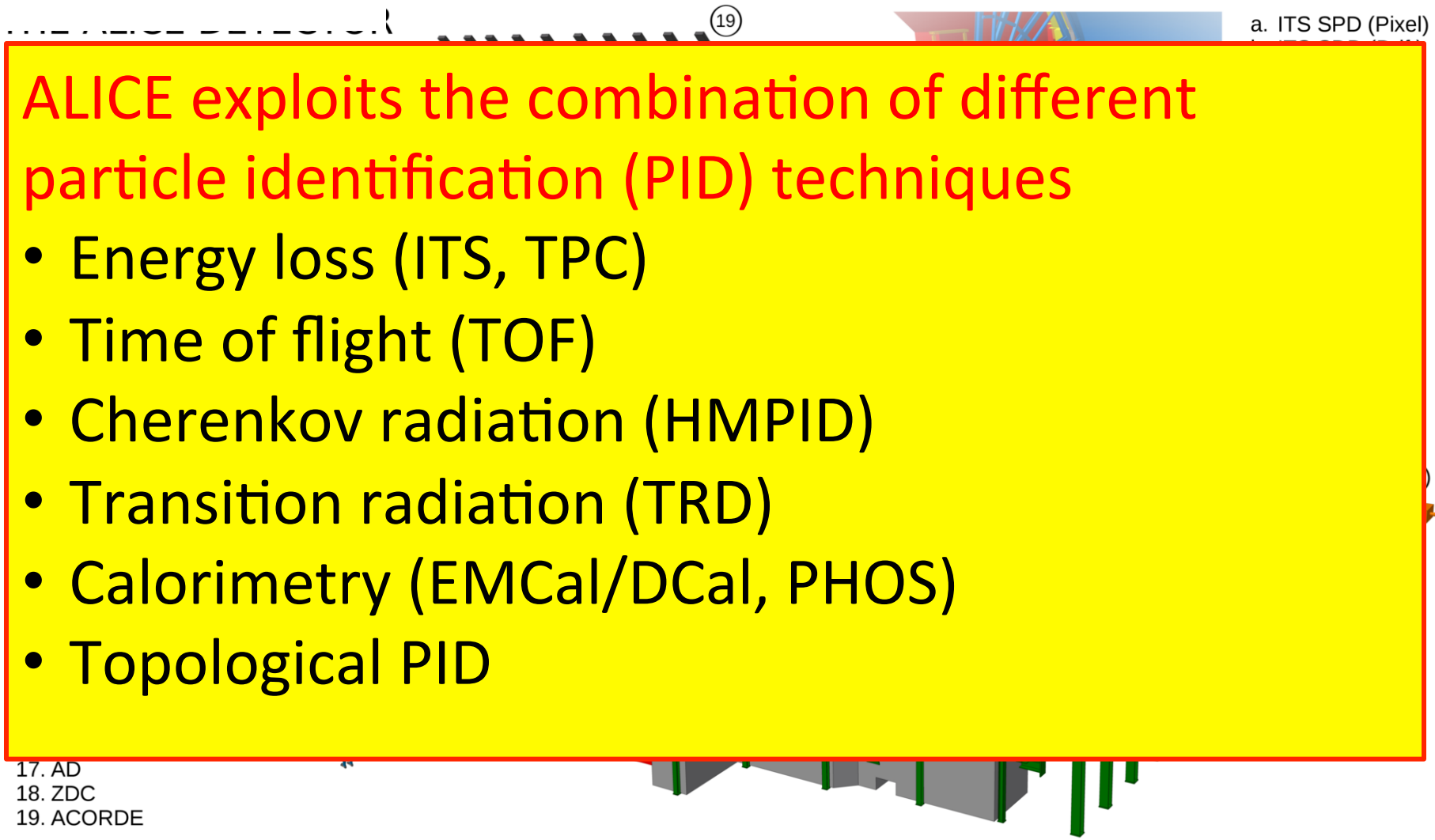

ALICE exploits the combination of different particle identification (PID) techniques

- Energy loss (ITS, TPC)
- Time of flight (TOF)
- Cherenkov radiation (HMPID)
- Transition radiation (TRD)
- Calorimetry (EMCal/DCal, PHOS)
- Topological PID

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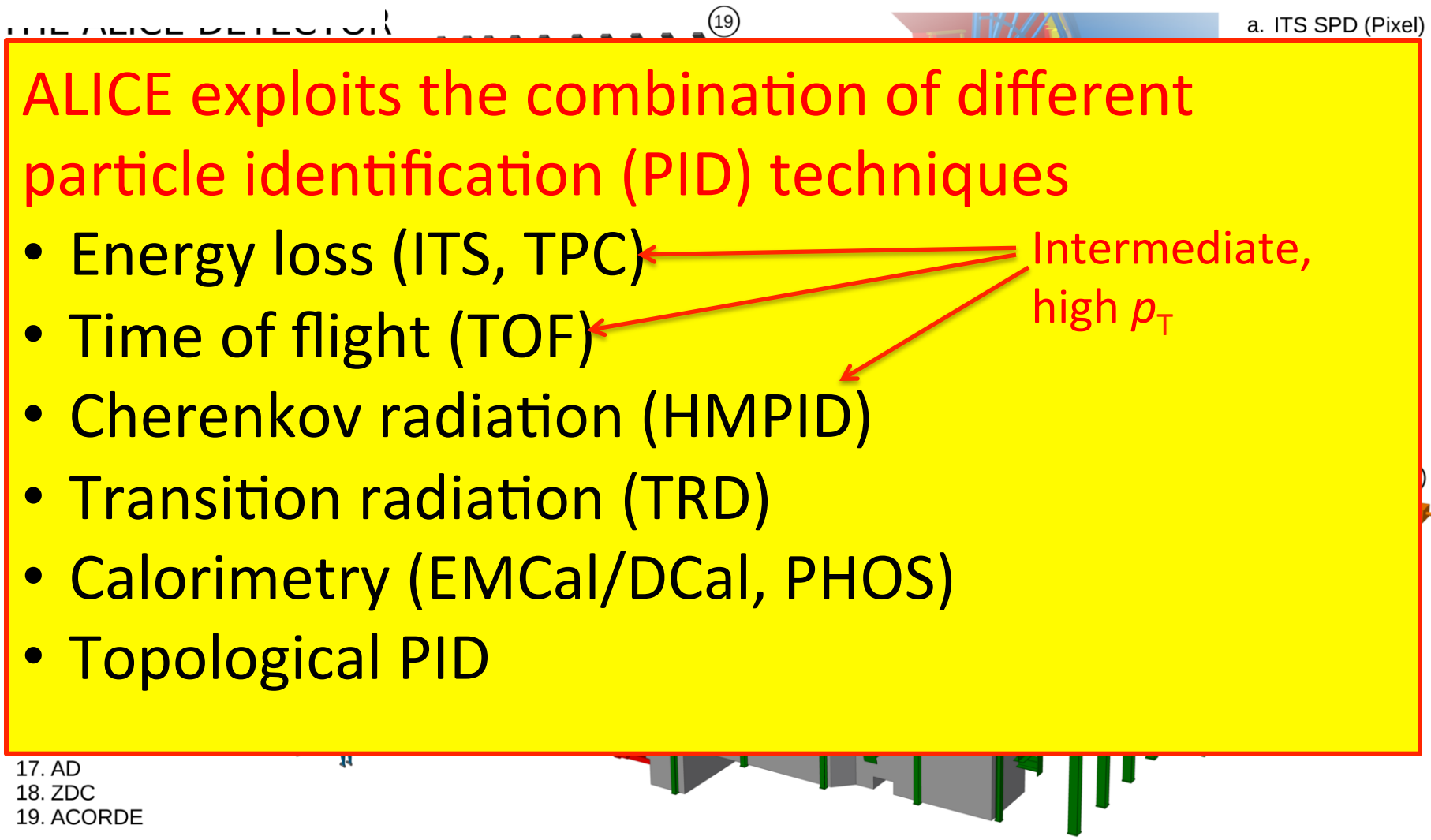

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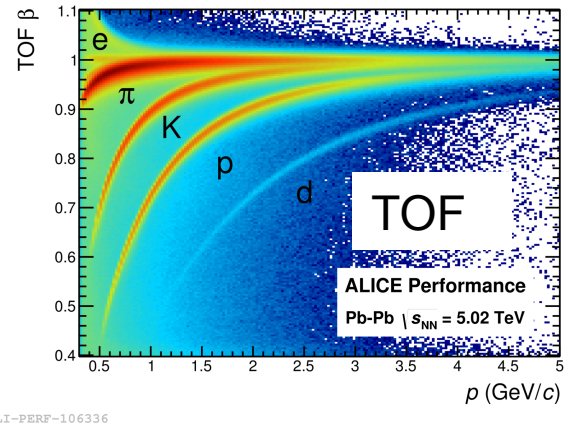
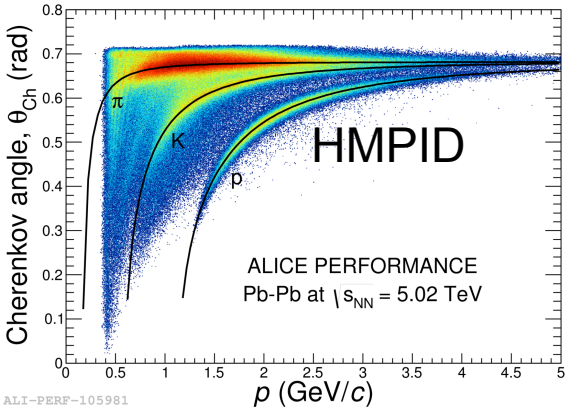
Intermediate, high p_T

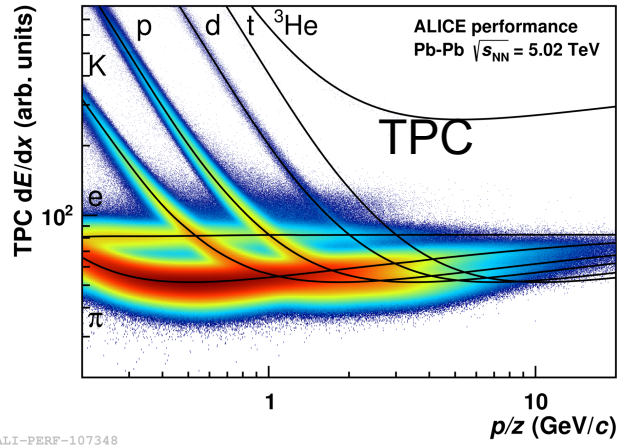
ALICE detectors: $\pi^{\pm}$, $K^{\pm}$ and $p(\bar{p})$ PID



- PID performed by means of statistical unfolding on the time of flight.
- Time of flight measurements enable 3σ separation for π/k up to 2.5 GeV/*c* and for K/p up to 4 GeV/*c*.

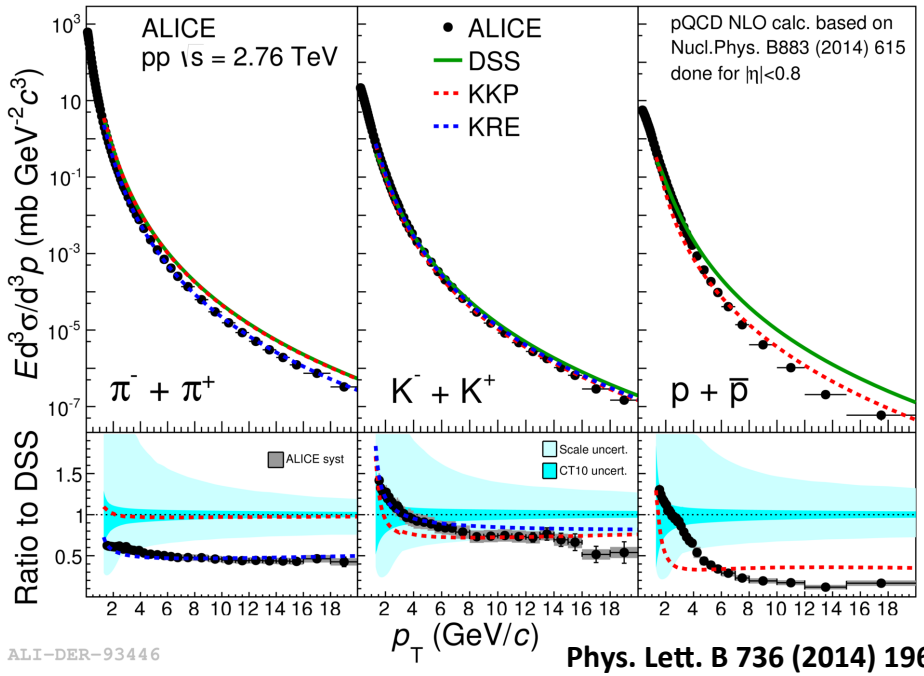


- PID performed by means of statistical unfolding on the Cherenkov angle.
- Cherenkov emission angle measurements enable 3σ separation for π/k up to 3 GeV/*c* and for K/p up to 5 GeV/*c*.



- Up to 159 pad rows in Ne-CO_2 (Ar-CO_2) gas mixture: $\sigma_{dE/dx} \approx 5\%$.
- The largest separation is achieved at low-p_T ($p_T \leq 0.7$ GeV/*c*).
- for higher p_T (3-20 GeV/*c*) statistical PID is done exploiting the features of d*E*/d*x* in the relativistic rise regime.

p_T pectra in pp collisions: comparison to NLO pQCD calculations



Phys. Lett. B 736 (2014) 196–207

DSS: de Florian, Sassot, and Stratmann,
PRD 75 (2007) 114010 and
PRD 76 (2007) 074033

KKP: Kniehl, Kramer, and Potter,
NPB 582 (2000) 514

KRE: Kretzer,
PRD 62 (2000) 054001

- The inclusive charged pion, kaon and (anti)proton spectra are compared with pQCD NLO calculations using 3 different sets of identified FF functions (no protons FF for KRE).
- The Kretzer Fragmentation Functions (KRE) describe well the charged particle spectra (Nucl. Phyis. B 883 (2014) 615) and also the pions and the kaons.
- Kaon spectra are well described by both DSS and KKP. Protons have largest differences.
- The pQCD understanding of particle spectra is also important to determine the relative weight of quark and gluon jets in energy loss calculations

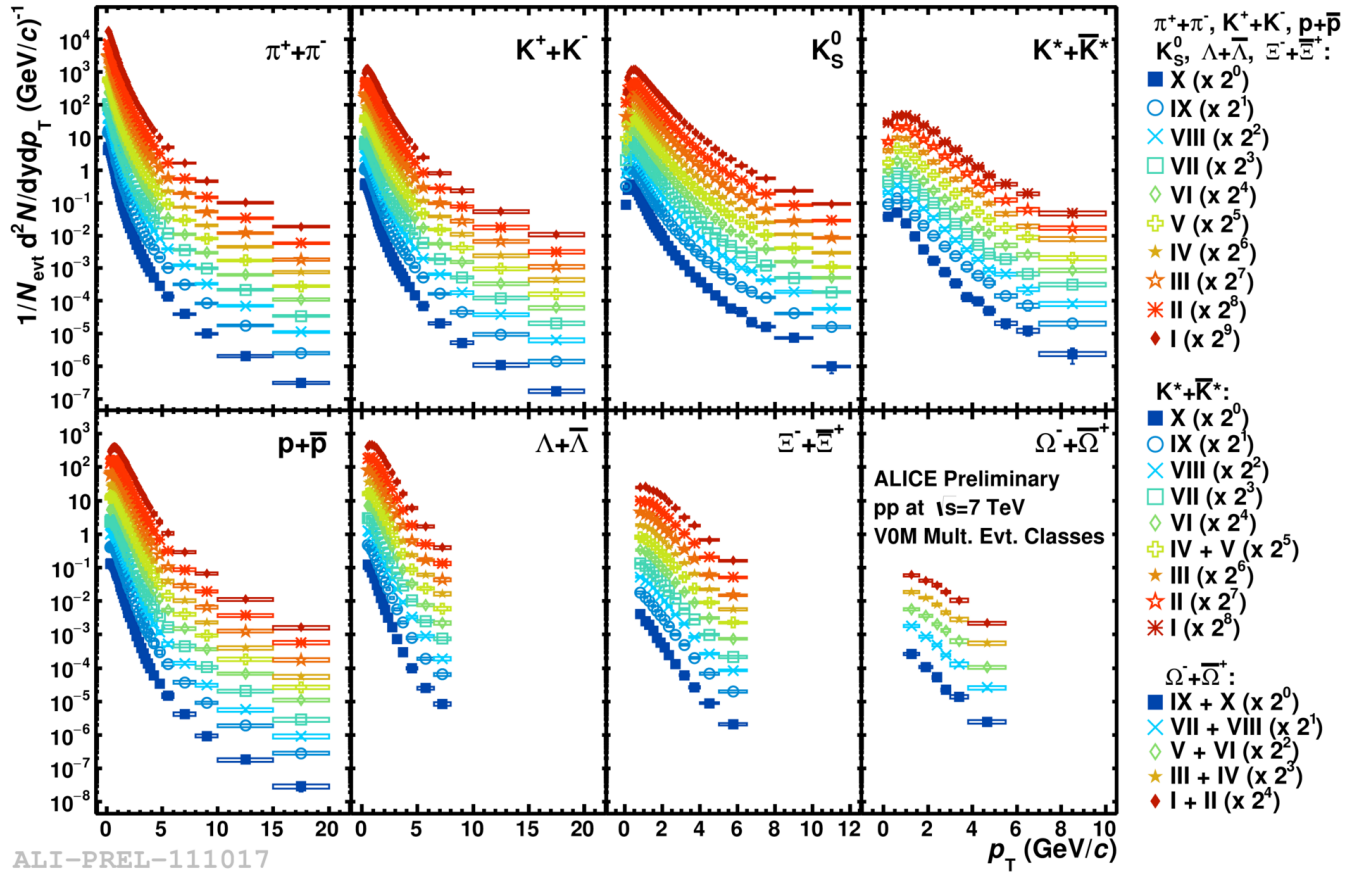
p_T spectra vs multiplicity in pp collisions

Class name	I	II	III	IV	V	VI	VII	VIII	IX	X
$\sigma/\sigma_{INEL>0}$	0–0.95%	0.95–4.7%	4.7–9.5%	9.5–14%	14–19%	19–28%	28–38%	38–48%	48–68%	68–100%
$\langle dN_{ch}/d\eta \rangle$	21.3±0.6	16.5±0.5	13.5±0.4	11.5±0.3	10.1±0.3	8.45±0.25	6.72±0.21	5.40±0.17	3.90±0.14	2.26±0.12

High mult.

Low mult.

pp @ 7 TeV



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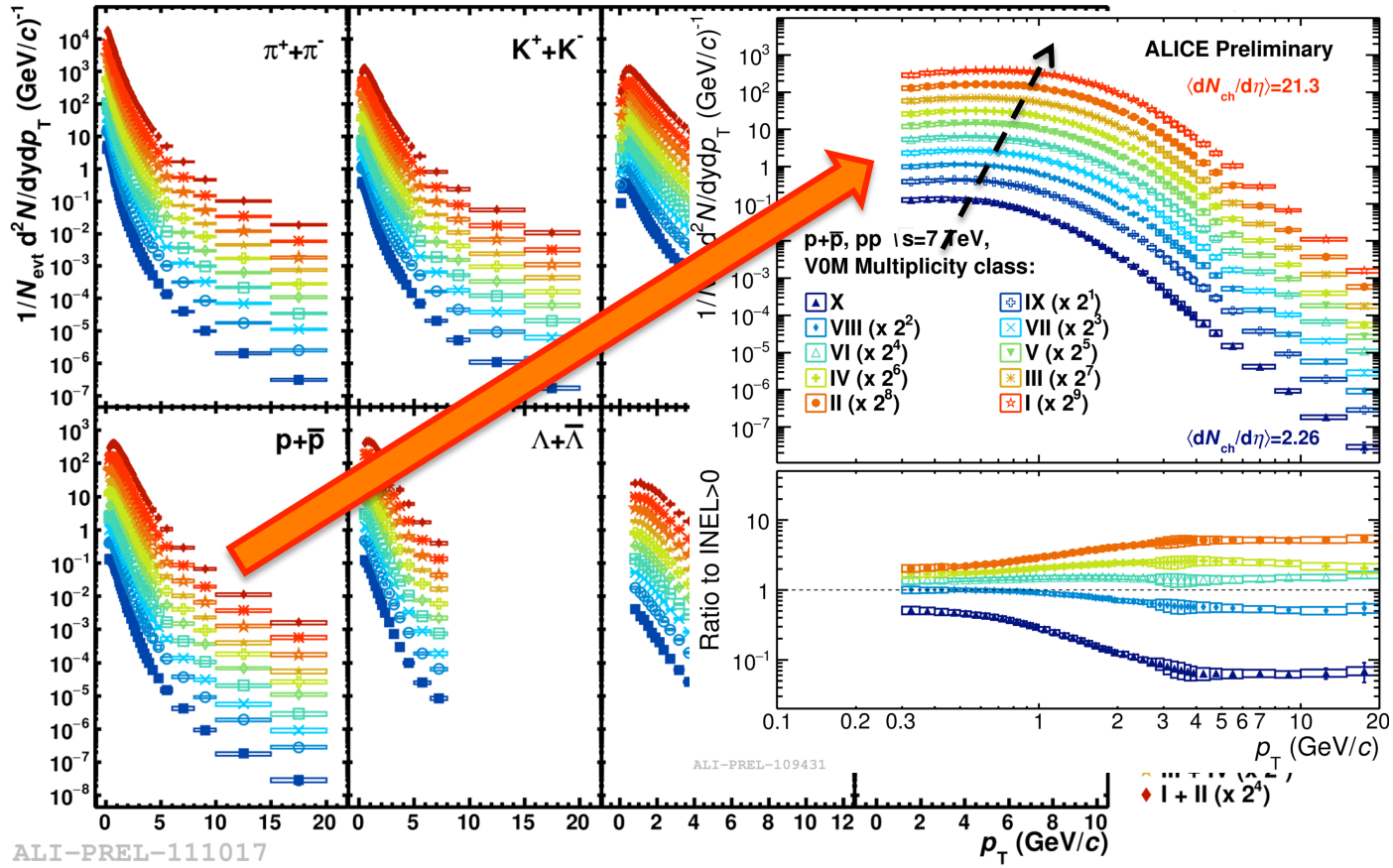
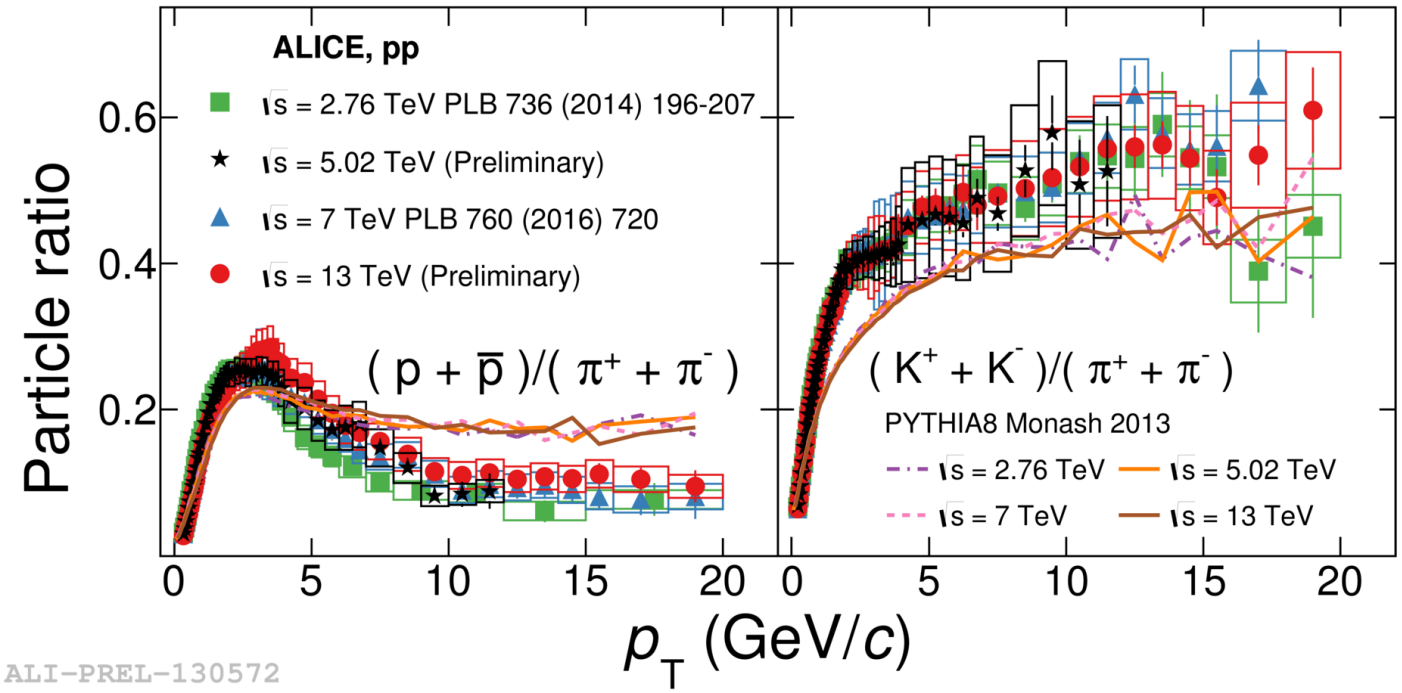


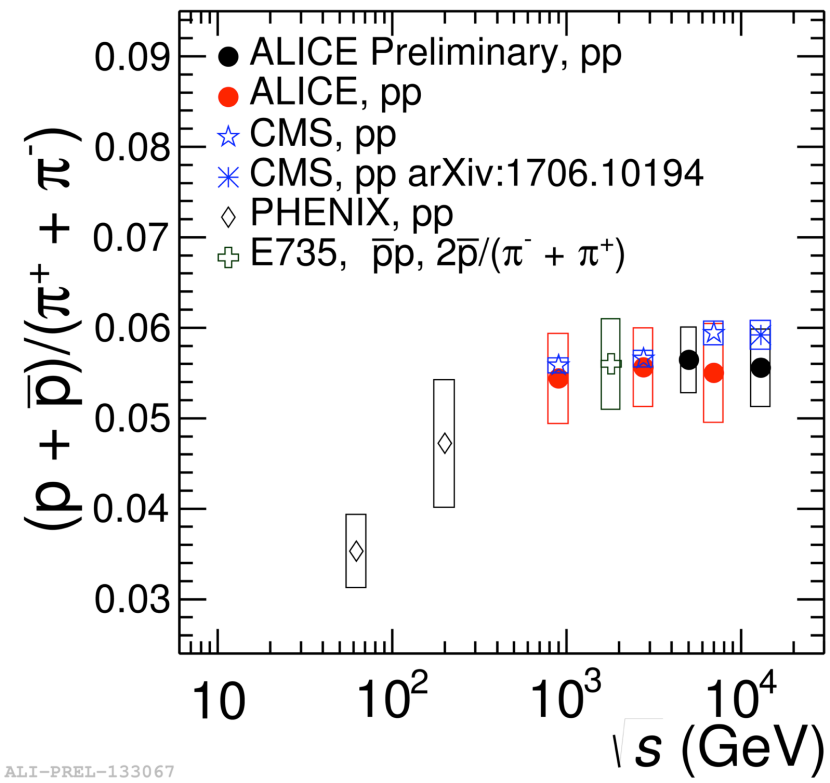
- Hardening with multiplicity and particle mass at low p_T (< 2 GeV/c)
- Indication for collective effects, reminiscent of observed effects in Pb-Pb → attributed to radial flow

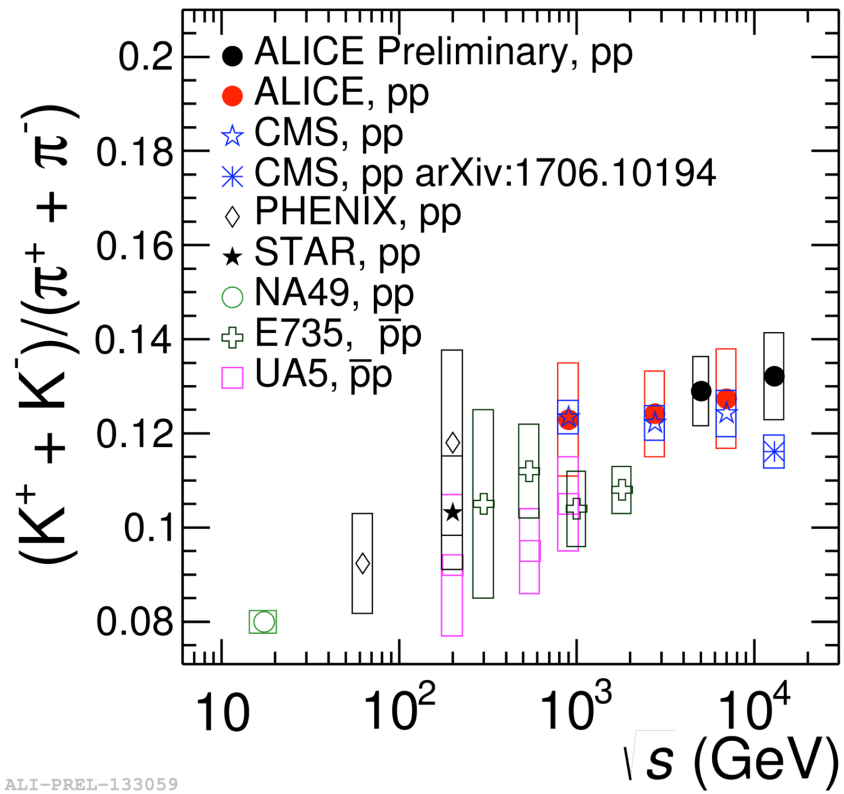
Particle ratios in pp collisions



- K/π shows no significant evolution with √*s*.
- The maximum value of the p/π ratio shifts to slightly larger values of p_T with increase of √*s*, consistent with hardening of the spectra with multiplicity across different energies.
- PYTHIA8 reproduces qualitatively the shape of the distribution but overestimates p/π and underestimates K/π at high p_T.

Particle ratios in pp collisions



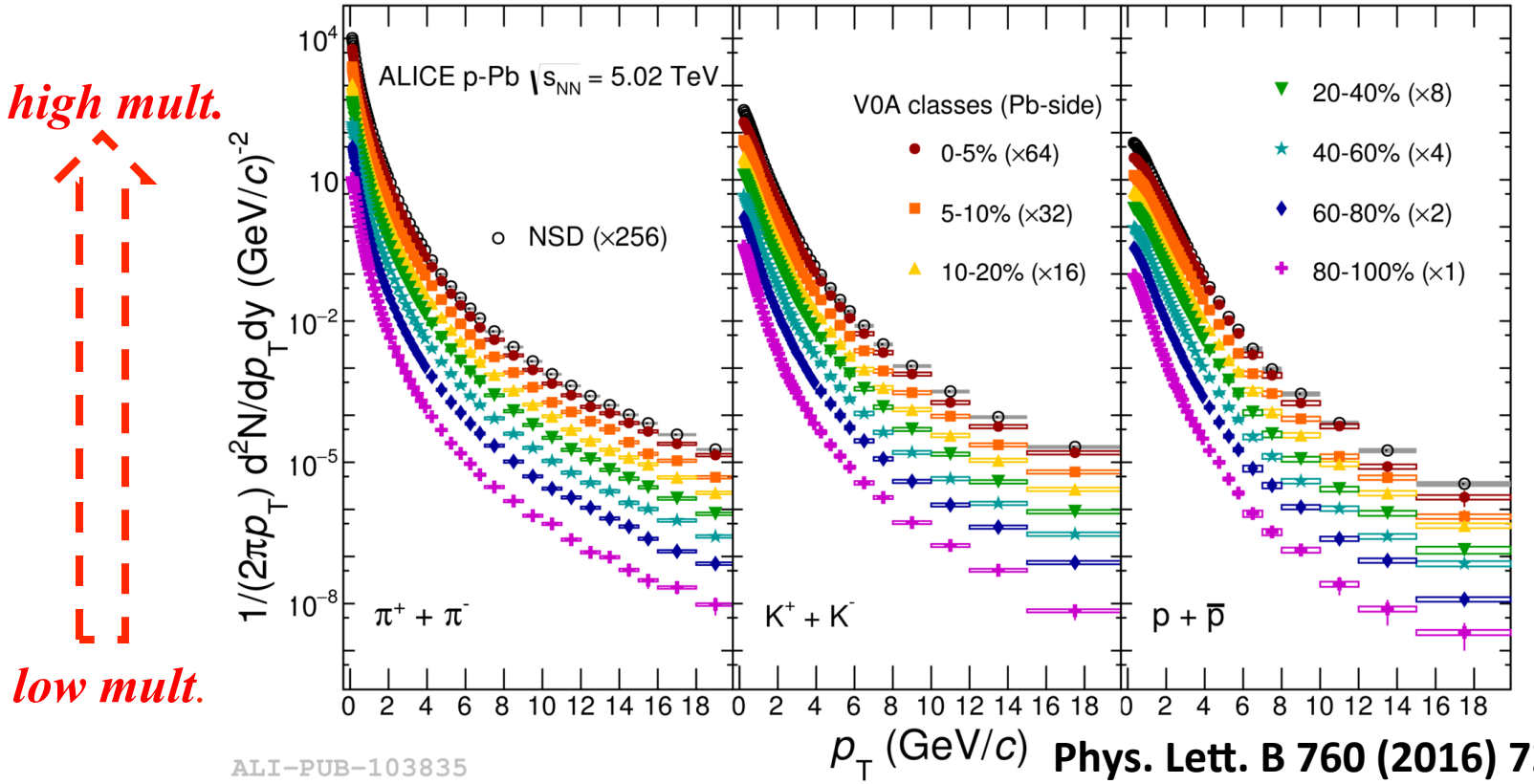


Comparison of p_T-integrated yield ratios, measured at different $\sqrt{s}$:

- p/π saturates at LHC energies
- K/π: no conclusion possible due to systematics

p_T spectra in p-Pb collisions

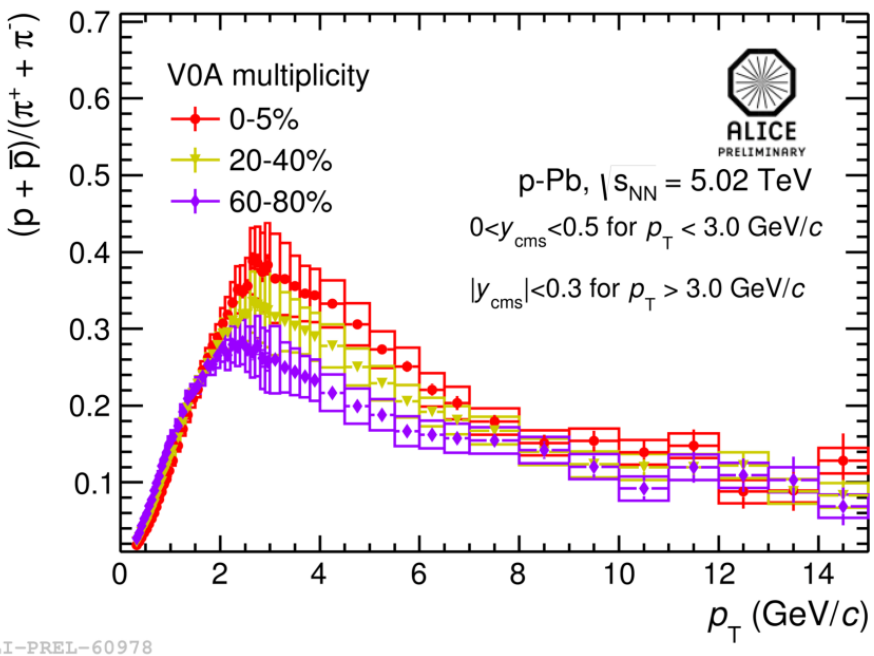
- Hardening with multiplicity and particle mass.
- Reminiscent of observed effects in Pb-Pb:
  - Attributed to radial flow/recombination.
  - In hydrodynamic picture particles are pushed by the expanding hot medium.
  - Sensitive to pressure gradient and particle mass, indication for collectivity in p-Pb?

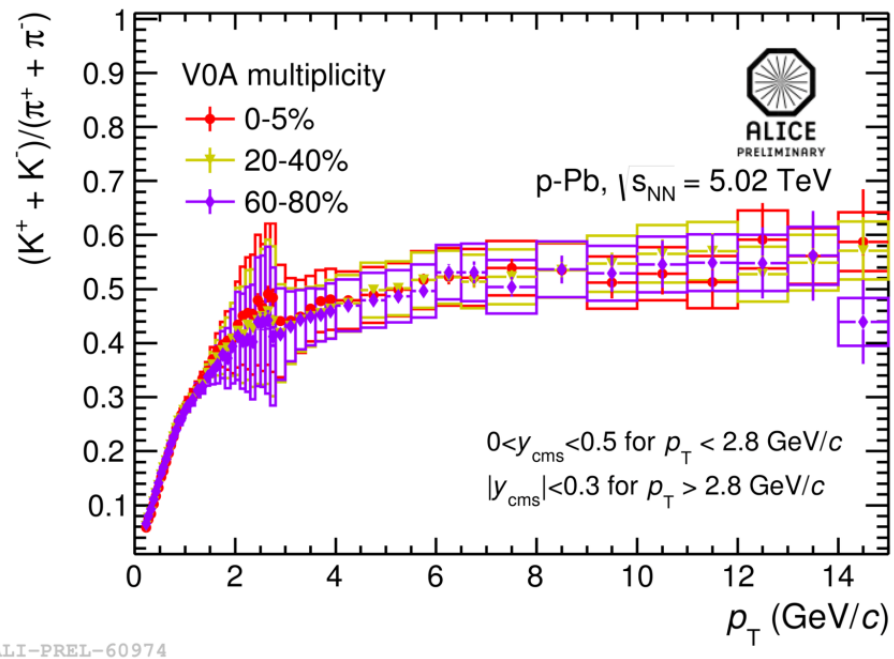


Phys. Lett. B 760 (2016) 720

Results for low p_T : **ALICE, PLB 728 (2014) 25-38**

Particle ratios in p-Pb collisions

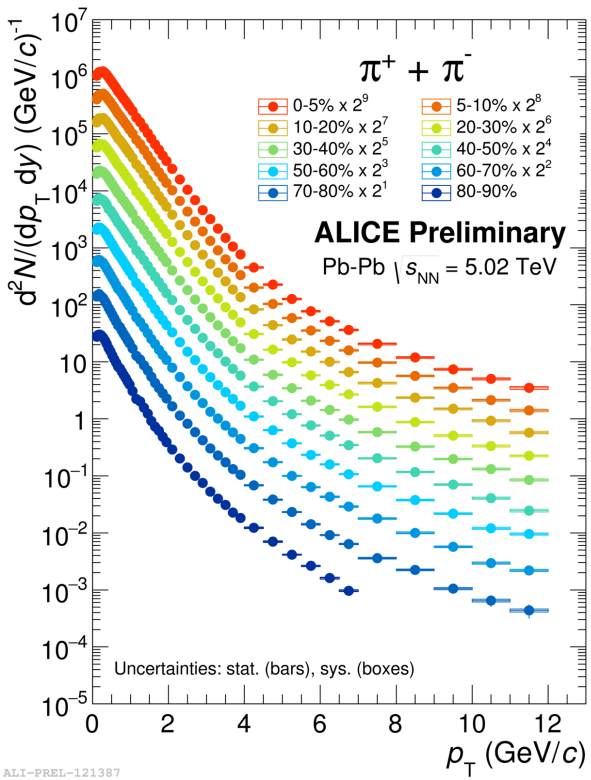


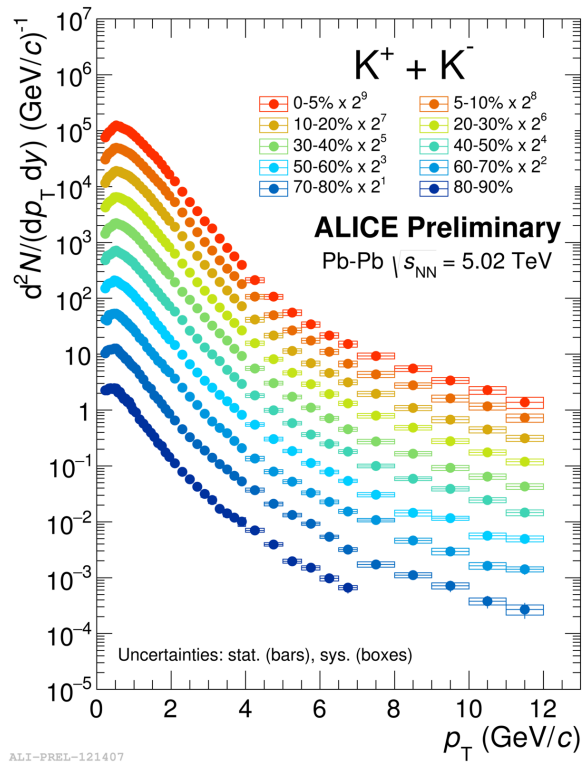


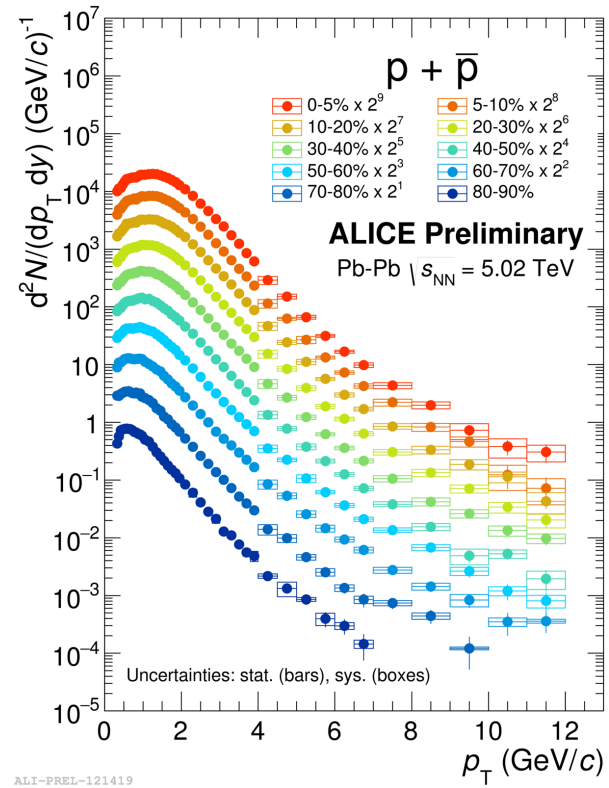
- p/π ratio:
  - shows a peak, which is more pronounced for higher multiplicities
  - drops to 0.1 at high p_T (as in Pb-Pb).

- K/π ratio:
  - saturates at 0.5 for high p_T (as in Pb-Pb).
  - does not shows strong multiplicity dependence

p_T spectra in Pb-Pb collsions ($\sqrt{s_{NN}}$ = 5.02 TeV)



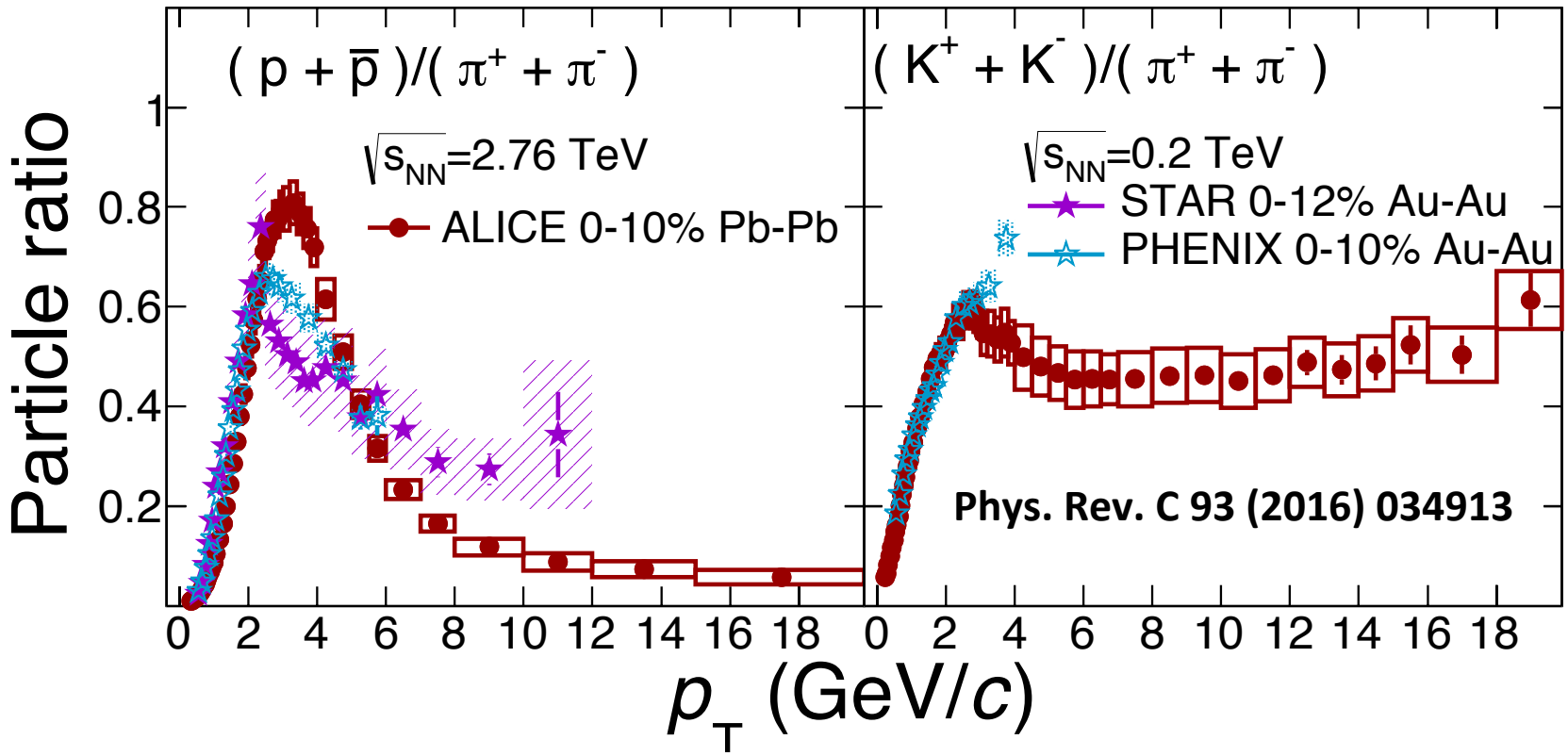




- For p_T < 3 GeV/c a hardening of the spectra is observed going from peripheral to central events. This effect is mass dependent and is characteristic of hydrodynamic flow.

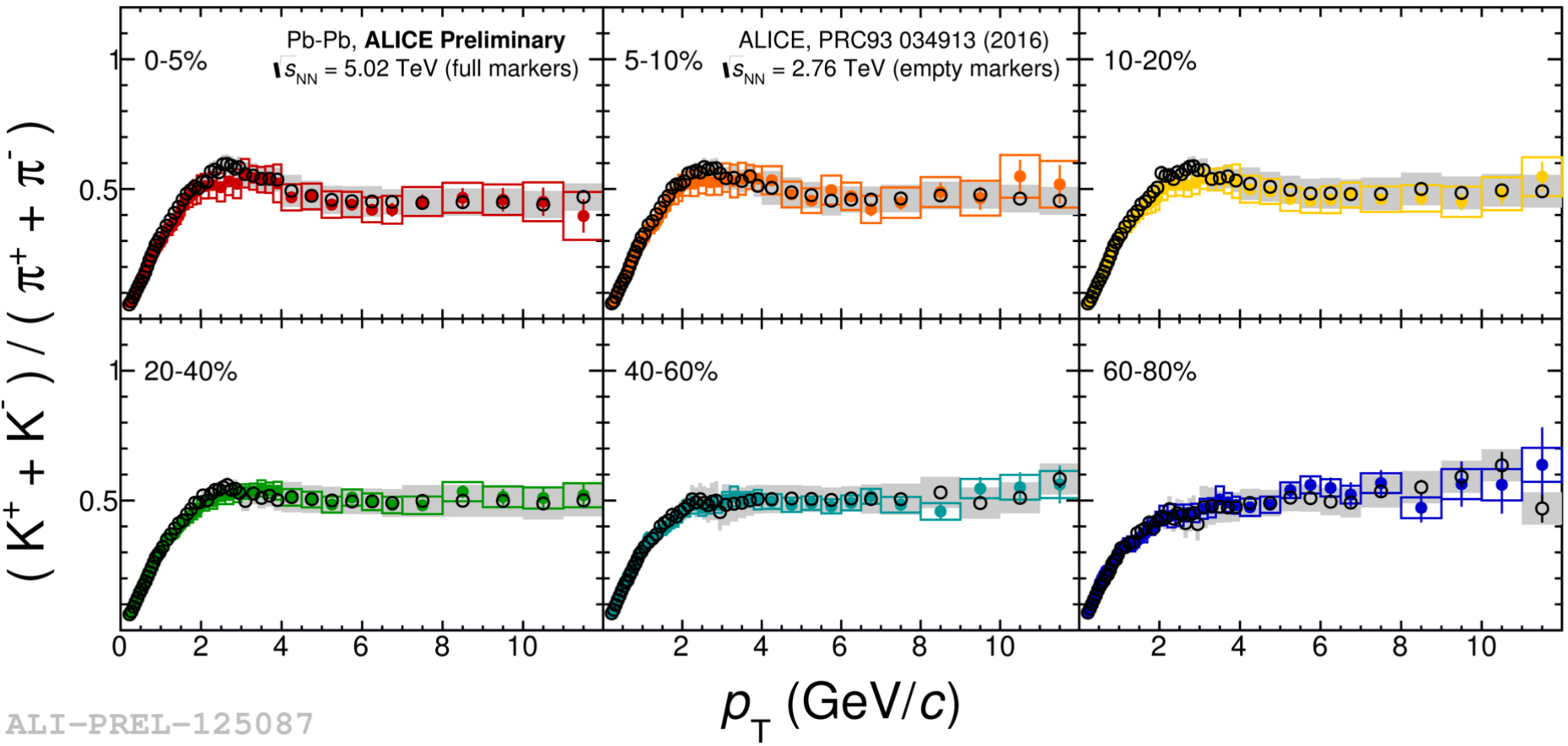
- For high p_T ($\gtrsim$ 10 GeV/c) the spectra follow a power law shape as expected from perturbative QCD.

Particle ratios in Pb-Pb collisions



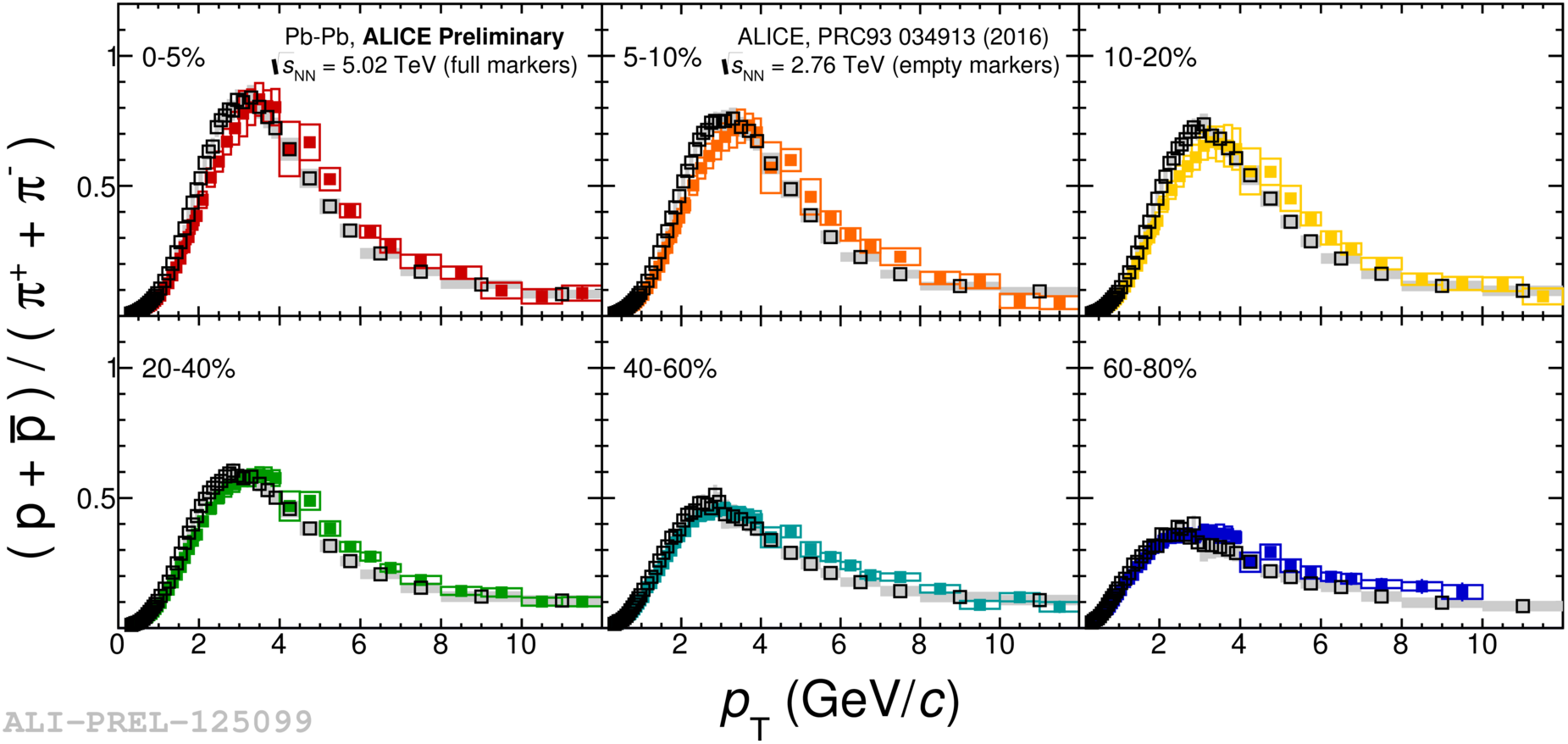
- The p/π peak at LHC is approximately 20% larger than at RHIC, consistent with an on-average larger radial flow velocity.
- The K/π ratio measured by PHENIX is similar to the ALICE one.

Particle ratios in Pb-Pb collisions



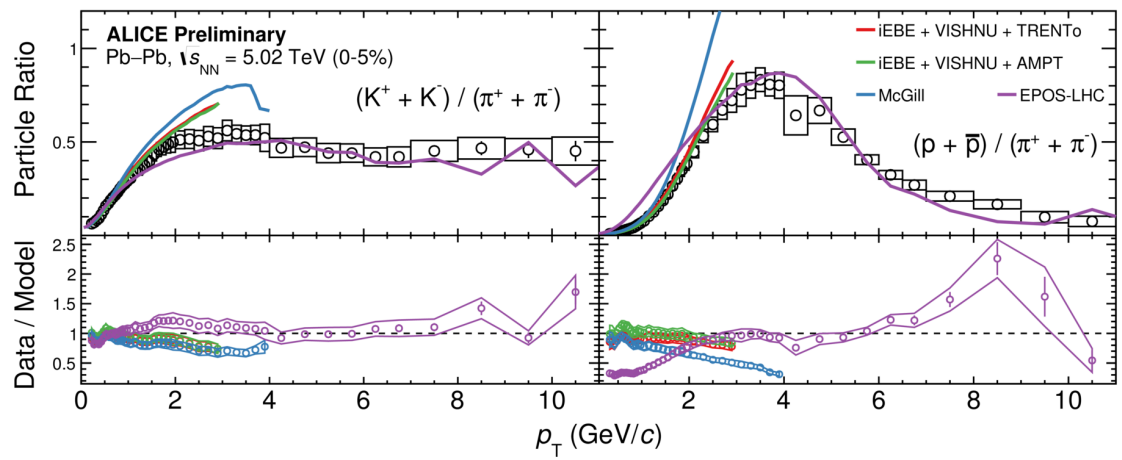
- Flat behavior of the K/π ratio above p_T > 2 GeV/*c*.
- No evident energy dependence.
- No centrality dependence.

Particle ratios in Pb-Pb collisions



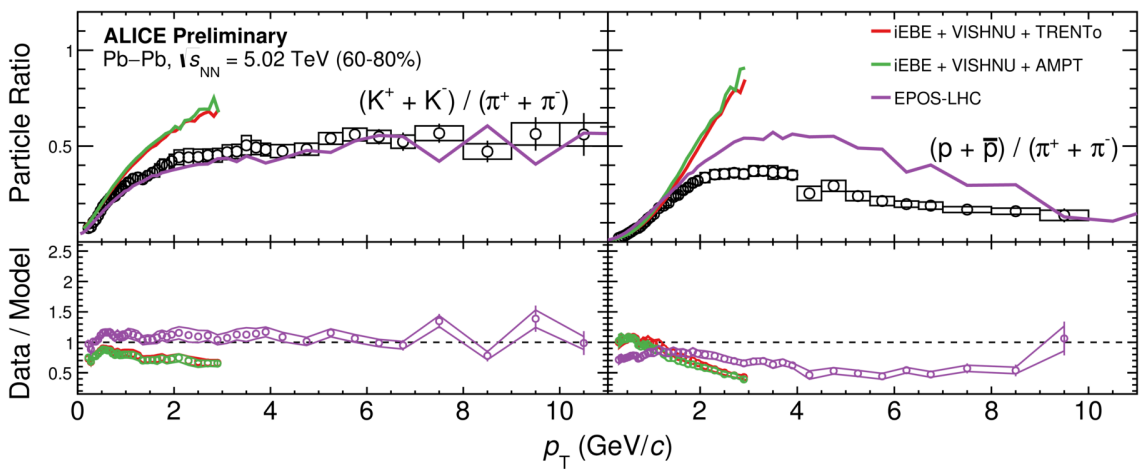
- Proton spectra are harder than pions due to larger mass (same radial flow)
- Larger radial flow at $\sqrt{s_{NN}}$ = 5.02 TeV with respect to 2.76 TeV resulting in a shift of the p/π maximum towards (slightly) higher p_T

Particle ratios in Pb-Pb collisions: model comparison



ALI-DER-136346

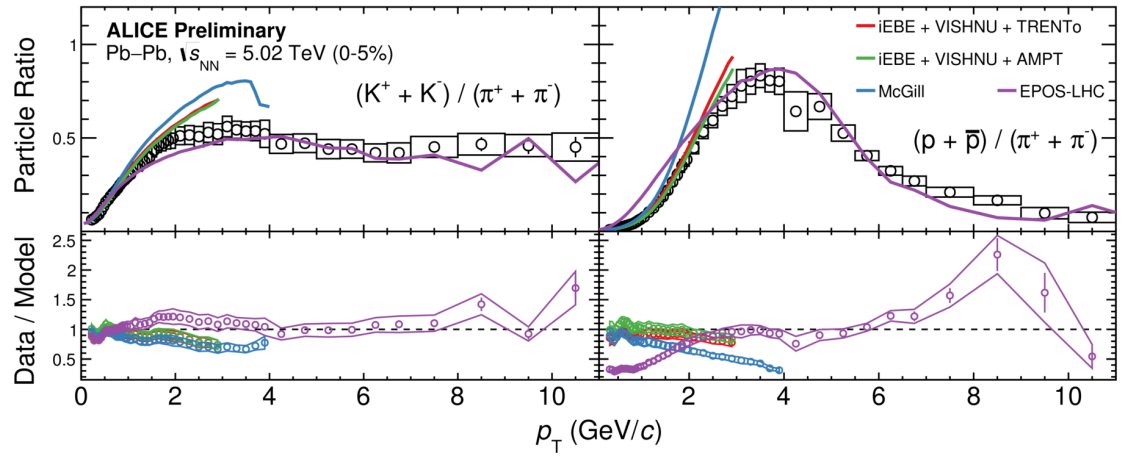
iEBE-VISHNU hybrid model (https://arxiv.org/abs/1703.10792) **TRENTo** and **AMPT** initial conditions. Viscous hydrodynamics to describe the expansion of the QGP fireball. Hadron cascade model (UrQMD) to simulate the evolution of the hadron resonance gas. Parameters are fine-tuned on data measured at 5.02 TeV.



ALI-DER-136350

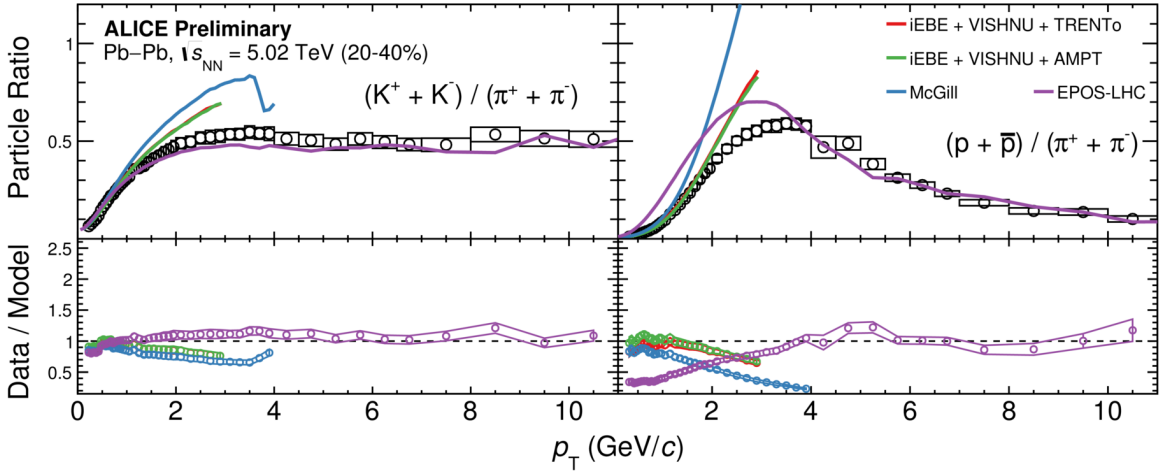
- K/π ratio: Qualitative agreement with the measured data. Agreement gets worse from central to peripheral collisions.
- p/π ratio: Qualitative agreement with the measured data below 2 GeV/*c*. Agreement gets worse from central to peripheral collisions.

Particle ratios in Pb-Pb collisions: model comparison



ALI-DER-136346

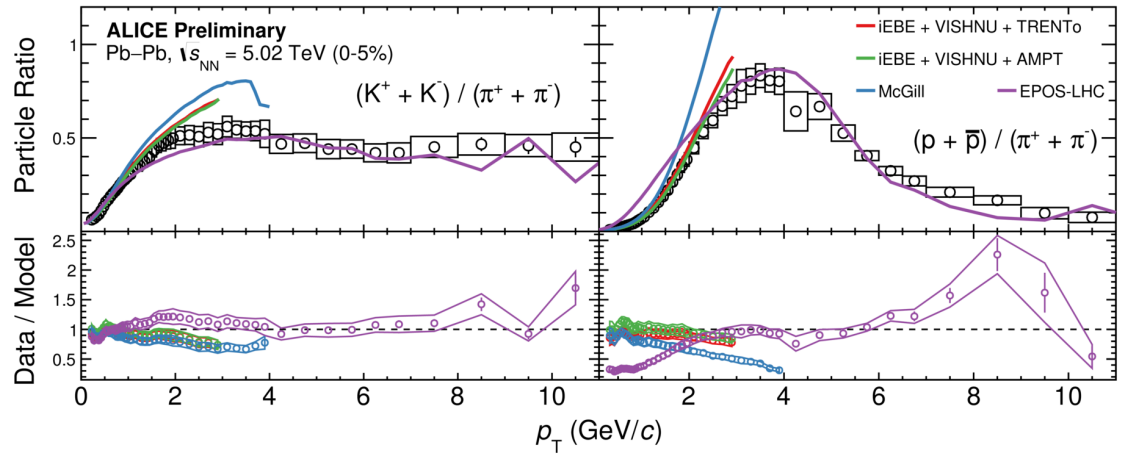
McGill (https://arxiv.org/abs/1609.02958) Hydrodynamics + hadronic cascade hybrid approach. Initial conditions are generated via a new formulation of the IP-Glasma model and then evolved using relativistic viscous hydrodynamics, and finally fed into transport cascade in the hadronic phase.



ALI-DER-136542

worse agreement with respect to iEBE-VISHNU + AMPT/ TRENTo. No significant centrality evolution of the ratio (**no predictions for 60-80% centrality bins**).

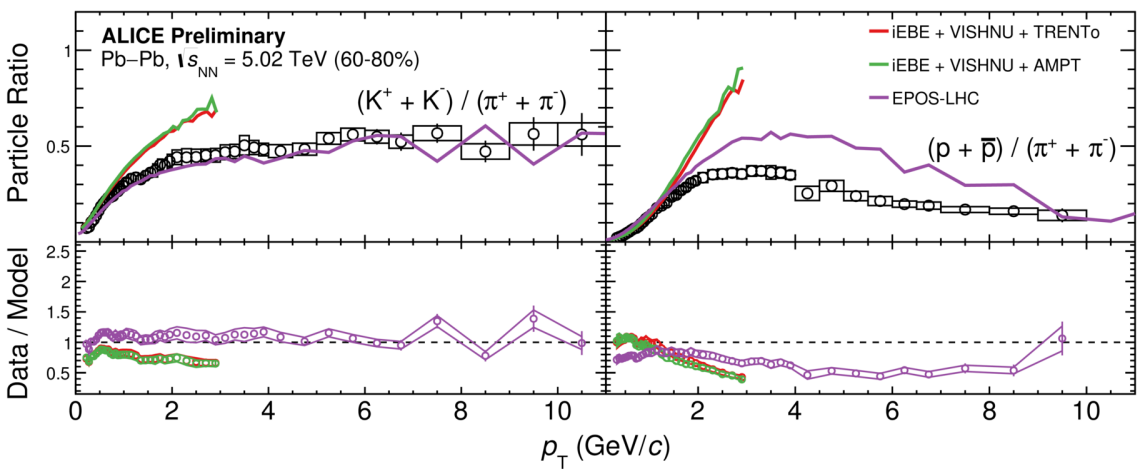
Particle ratios in Pb-Pb collisions: model comparison



ALI-DER-136346

EPOS- LHC model (Phys. Rev. C 92, 034906 (2015)), "fluid-jet interaction". Works over the entire p_T range.

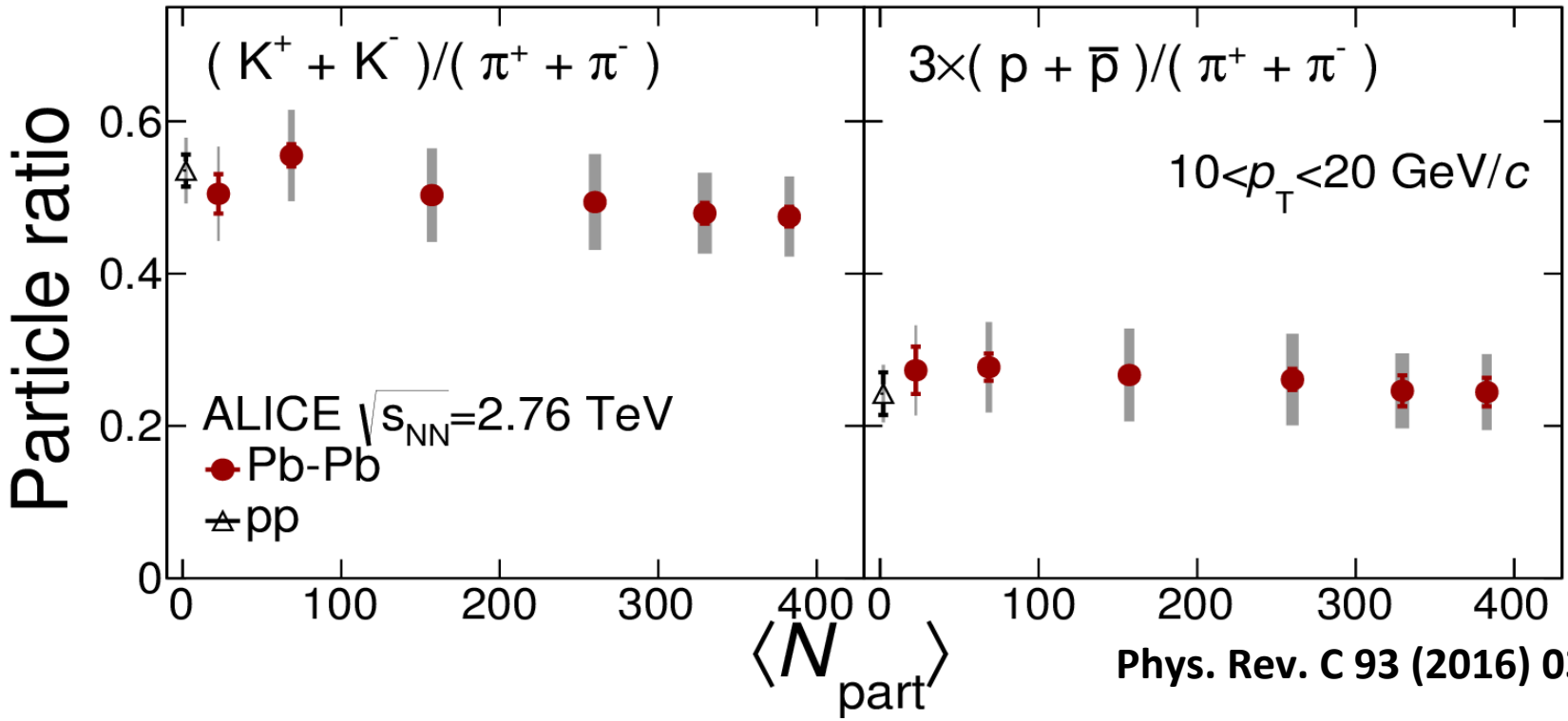
Non uniform fireball divided in the core (high density) and corona (lower density).



ALI-DER-136350

- K/π ratio: good agreement especially at low and high p_T. Intermediate p_T slightly off for central collisions.
- p/π ratio: bad agreement at intermediate and high p_T in peripheral collisions.

Particle ratios in Pb-Pb collisions at high p_T



Phys. Rev. C 93 (2016) 034913

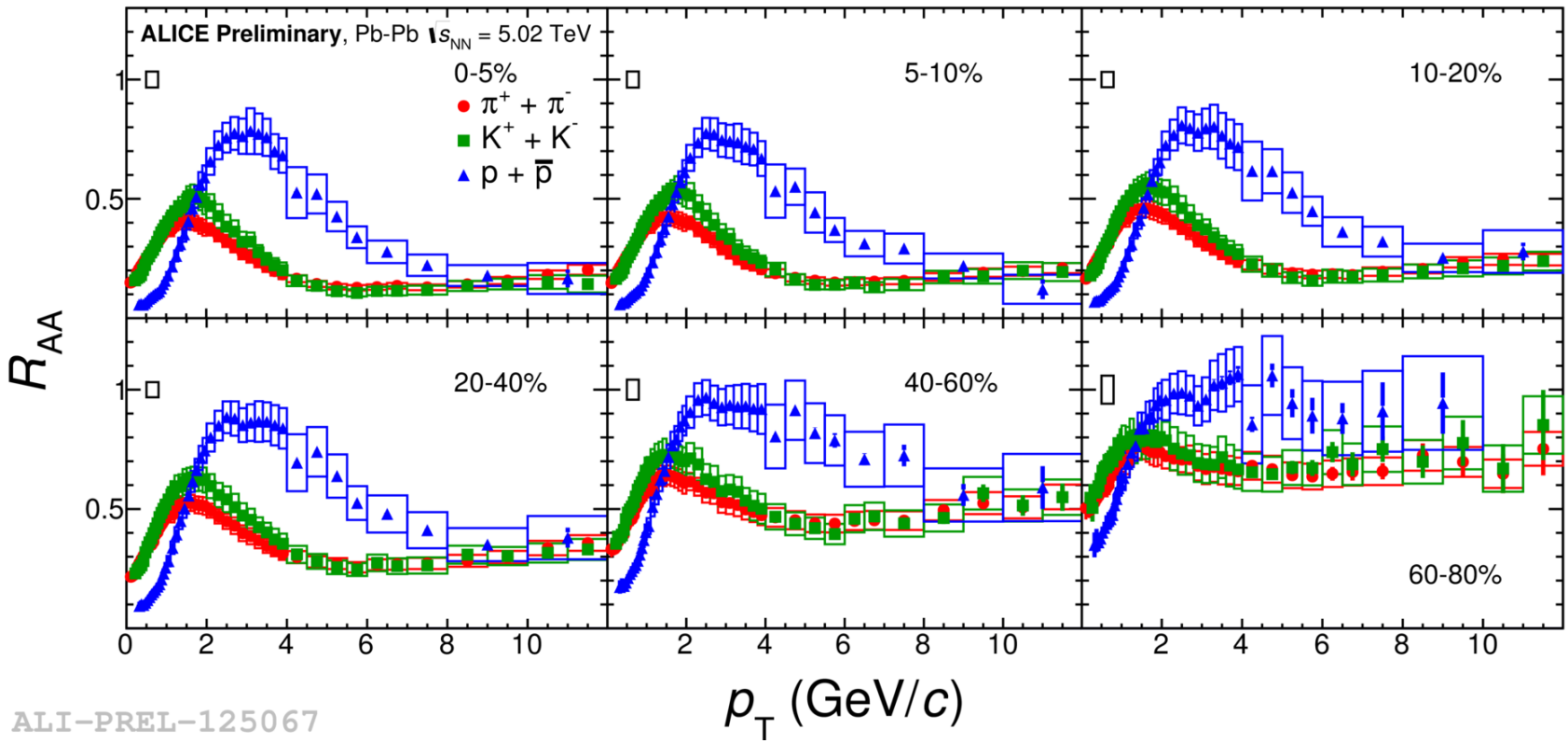
How similar are the high p_T ratios vs collision centrality?

- We have computed the integrated particle ratios for $10 < p_T < 20$ GeV/c.
  - charged particle tracking systematic uncertainty cancels.
  - K/π (p/π) ratio as a function of N_{part} is constant within the systematic uncertainty of ≈10% (≈20%) and it is consistent with the pp value (parton fragmentation in the vacuum).

The nuclear modification factor: R_{AA}

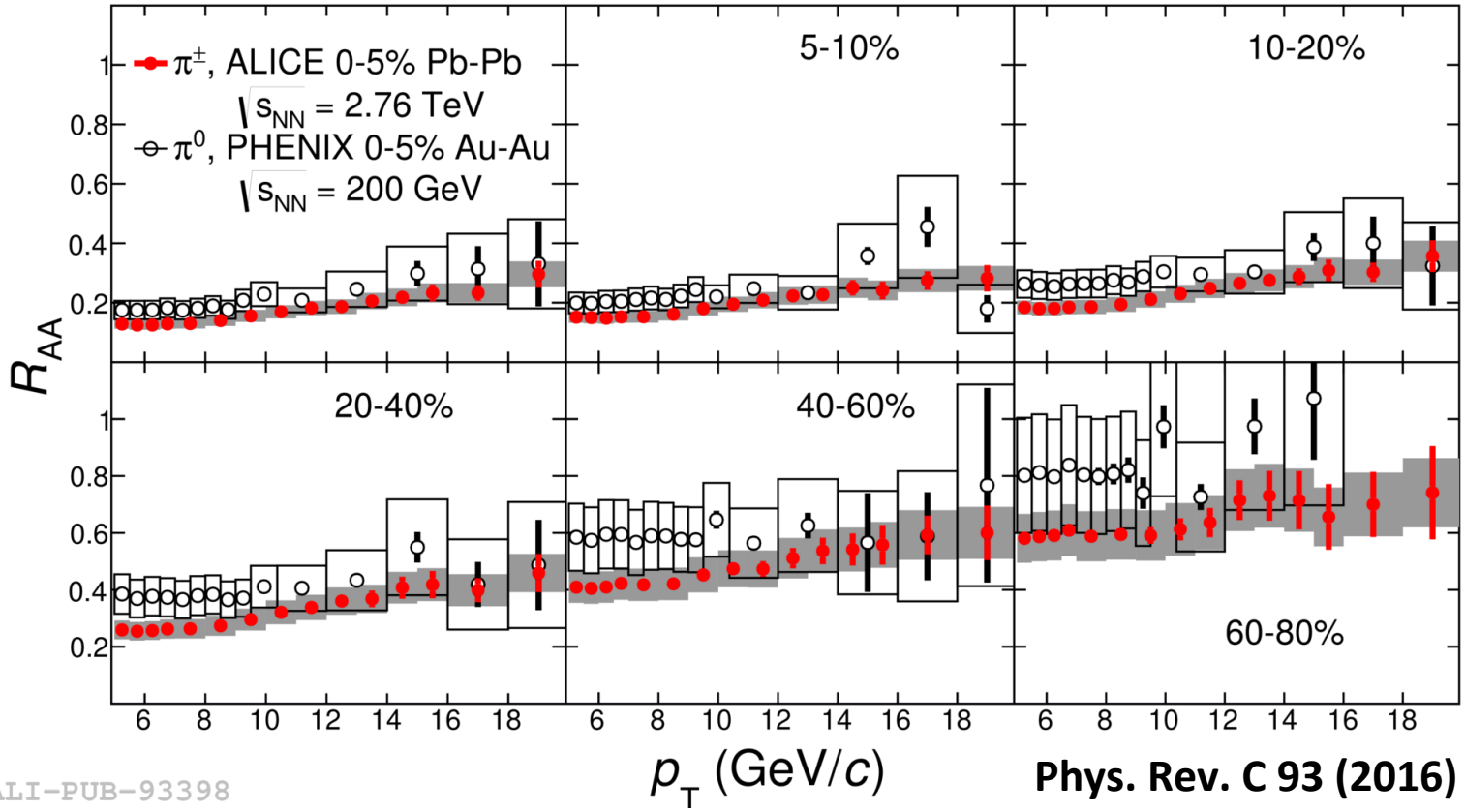
$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}/dp_T d\eta}$$

$\langle T_{AA}\rangle \sigma^{pp} = \langle N_{coll}\rangle$



- For $2 < p_T < 8 - 10$ GeV/c: R_{AA} for π and K are compatible and are smaller than R_{AA} of p.
- For $p_T > 8$-10 GeV/c: R_{AA} for π, K and p are compatible.

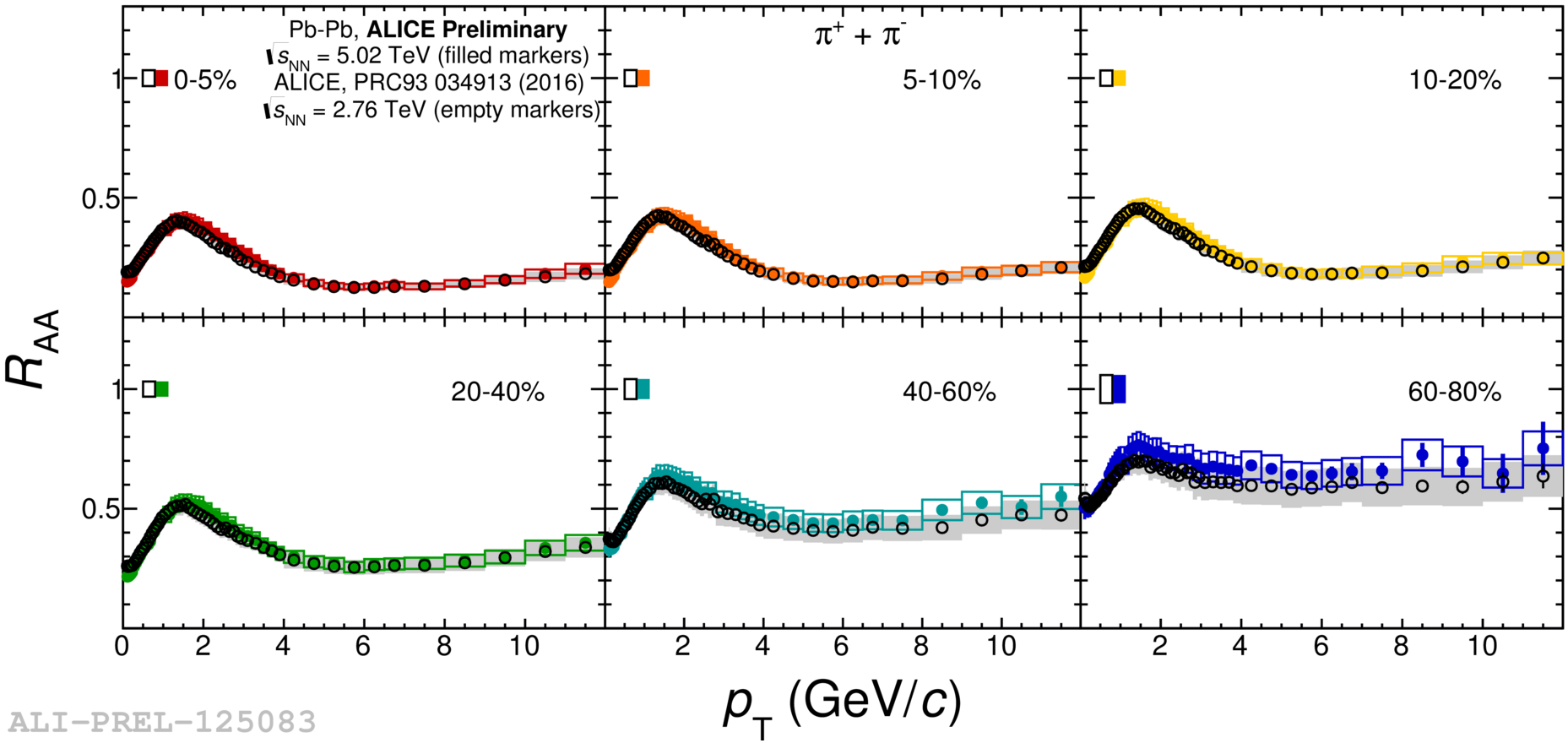
The pion R_{AA} at RHIC and at LHC



Phys. Rev. C 93 (2016) 034913

- ALICE results are below the PHENIX values.
- Centrality evolution very similar.
- The pp spectra at LHC energies are significantly harder, so a larger energy loss is needed to get a similar R_{AA}.

The pion R_{AA} at LHC

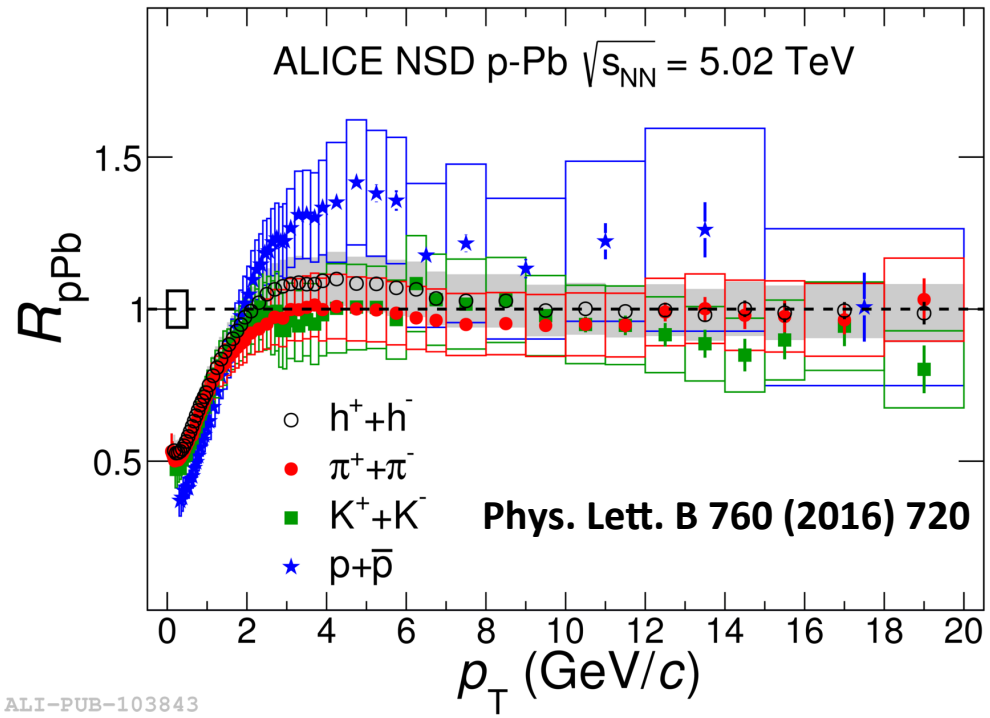


- Comparison between 2.76 and 5.02 TeV data shows that the R_{AA} does not depend on energy within uncertainties (other particle species can be found in the backup)

Nuclear modification factor: R_{pPb}

$$R_{pPb} = \frac{d^2N_{pPb}/dydp_T}{\langle T_{pPb}\rangle d^2\sigma_{pp}^{INEL}/dydp_T}$$

$$\langle T_{pPb}\rangle \sigma^{pp} = \langle N_{coll}\rangle$$



- pp reference at $\sqrt{s_{NN}}$ = 5.02 TeV is obtained interpolating available data (2.76 TeV and 7 TeV).
  - Power-law fit: $(\sqrt{s_{NN}})^{\alpha}$
  - Spectra in pp at $\sqrt{s_{NN}}$ = 5.02 TeV have been measured, R_{pPb} will be soon updated. The measured spectra are compatible with the interpolated ones.
- Mass ordering in the Cronin peak, enhancement of protons.
- No suppression at high p_T (> 8-10 GeV/c).

Conclusions

- The production of pion, kaon and proton at intermediate and high p_T measured by ALICE in pp, p-Pb and Pb-Pb collisions has been presented.

- The inclusive charged pion, kaon, (anti)proton spectra in $\sqrt{s}$ = 2.76 TeV pp collisions have been compared with pQCD NLO calculations. The Kretzer Fragmentation describes well pion and kaon spectra.

- Interesting similarities among different systems are observed: hints for the presence of collectivity in small systems.

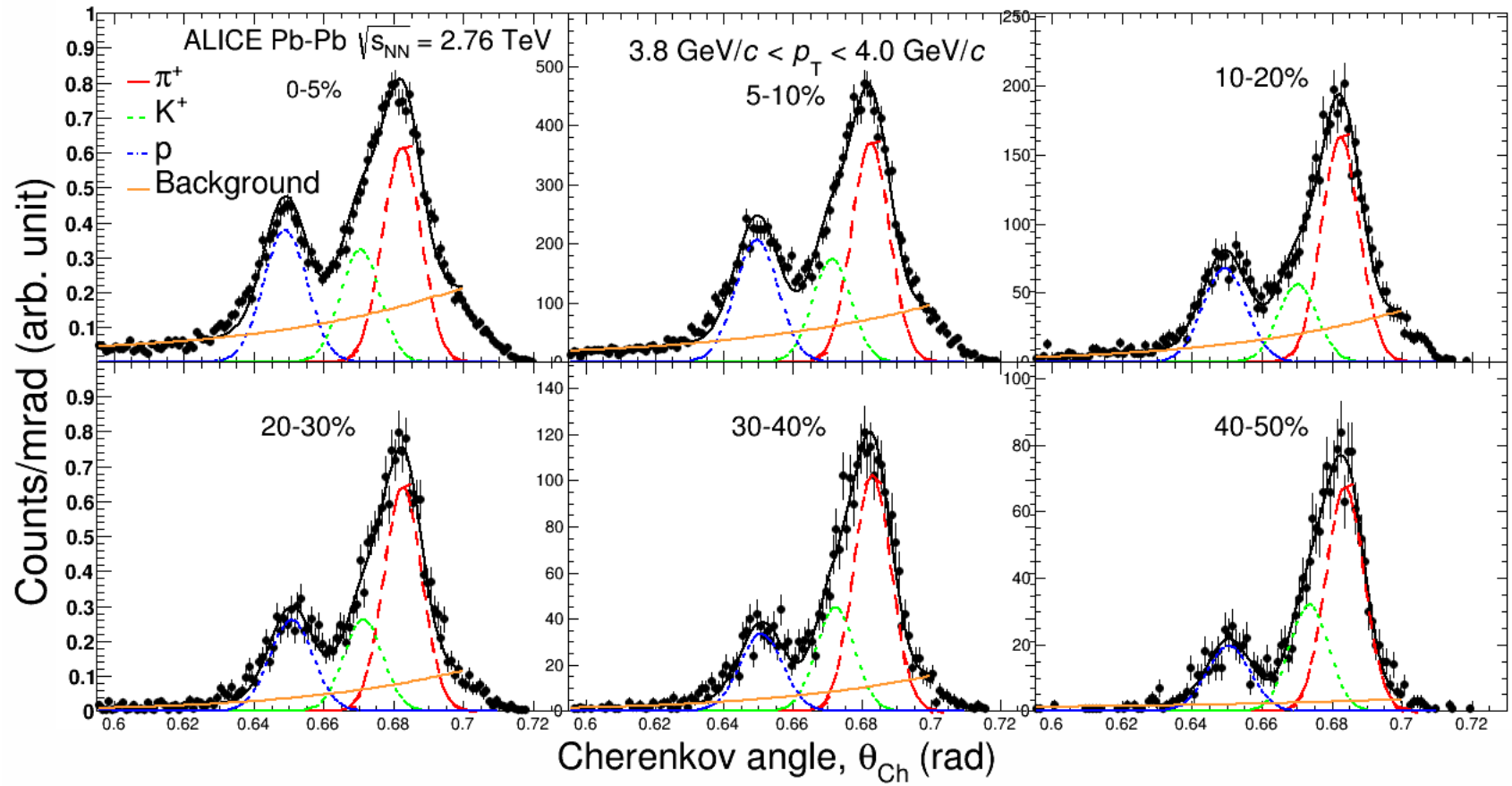
- Particle ratios in Pb-Pb collisions have been compared to different hydrodynamic models
  - Qualitative agreement at low p_T in central collisions. Agreement worsens in peripheral collisions. Hydro predictions have some difficulties at higher p_T .

- Nuclear modification factor in Pb-Pb collisions for high p_T (> ≈10 GeV/c) does not depend on particle species:
  - chemical composition of leading particles from jets traversing the medium is similar to that of vacuum jets.

- Nuclear modification factor in p-Pb collisions:
  - mass ordering in the Cronin peak, enhancement of protons.
  - No suppression at high p_T → suppression observed in central Pb-Pb collisions is not due to an initial-state effect but to the hot matter created in heavy ion collisions.

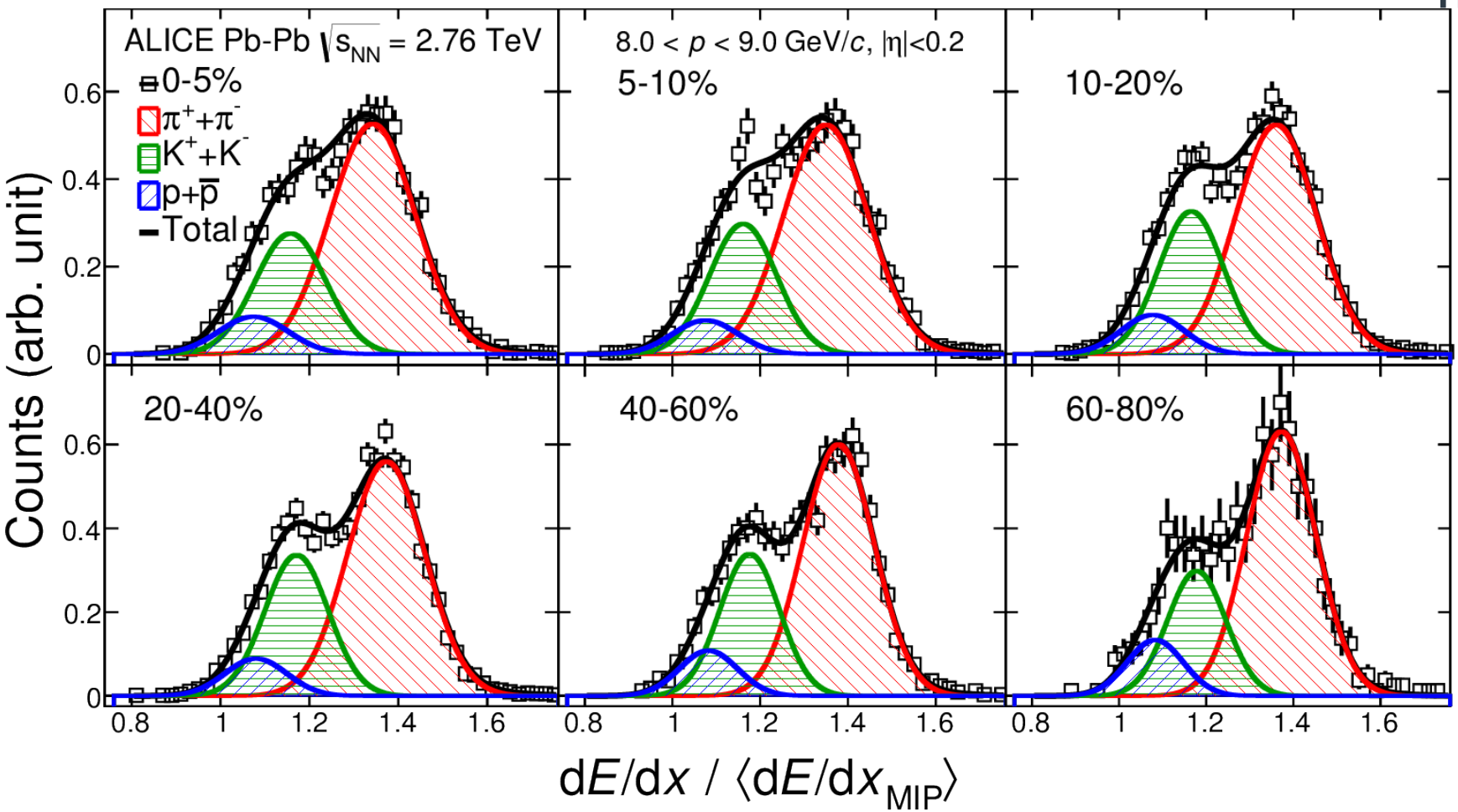
Backup

ALICE-HMPID detector



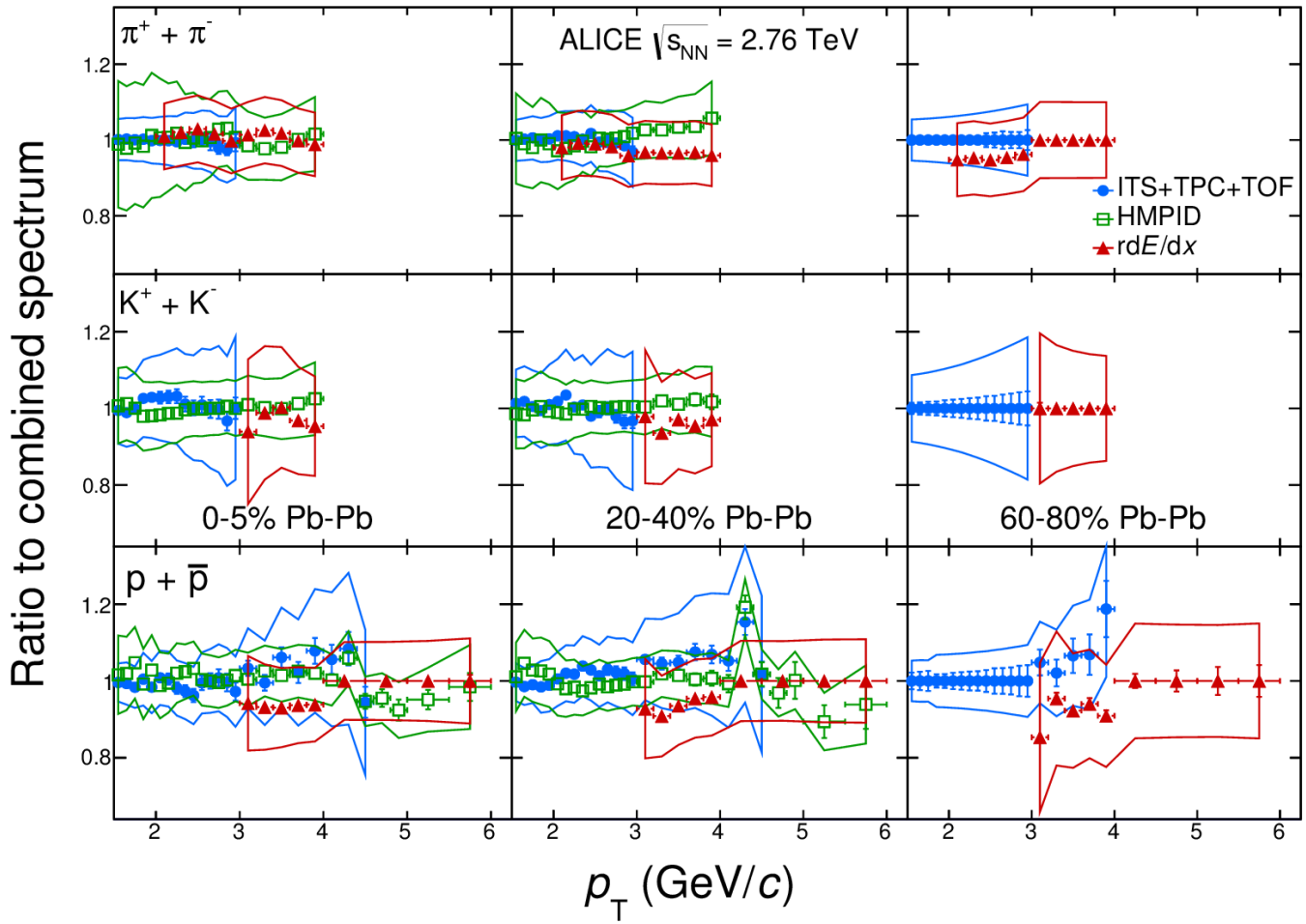
- The PID respsonses for π, K, and p are Gaussians and independent of centrality.
- The background is caused by wrongly assigned rings, well reproduced by MC. It is described by a 6th degree polynomial. The small shoulder at $\theta_{ch} \approx 0.7$ rad which is an effect of the chamber geometry.

ALICE-TPC detector



The PID responses for π, K, and p are Gaussians (e is < 1%). The means and widths are fixed to the calibrated values.

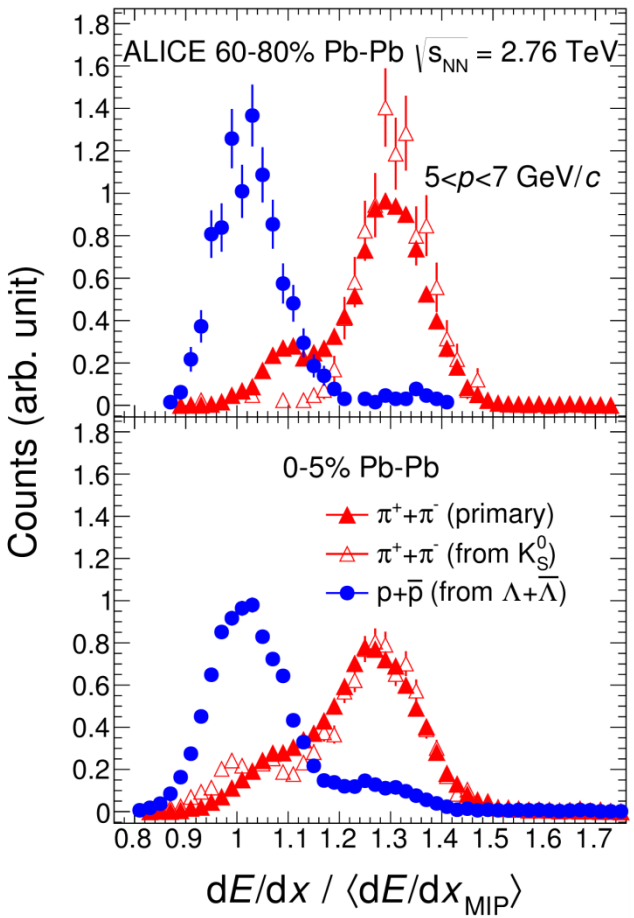
Spectra combination

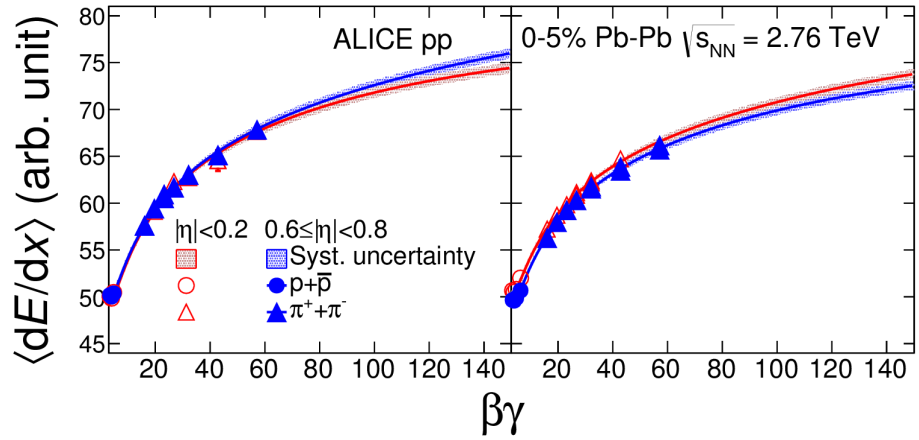


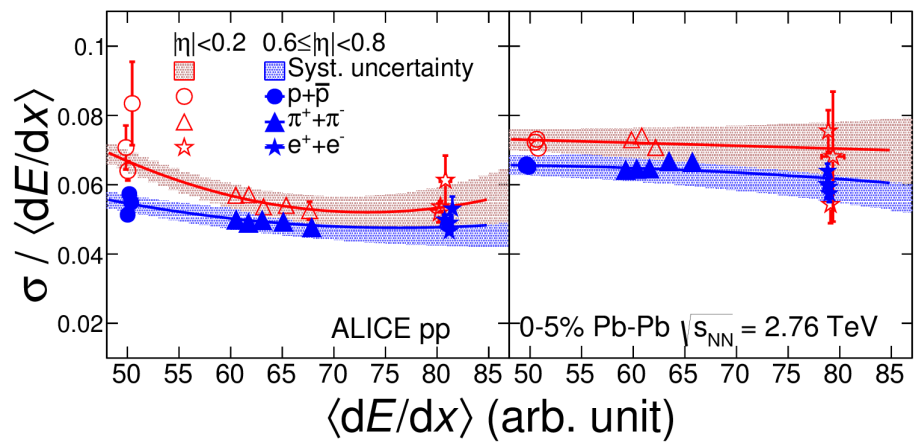
ALICE Lower p_T results (ITS+TPC +TOF) are from PRC 88 (2013) 044910.

Measurements are combined using a weighted average where the weights are the systematic uncertainties (except for a common 3% uncertainty that is subtracted and directly added to the final spectrum).

Calibrating the d*E*/d*x* response

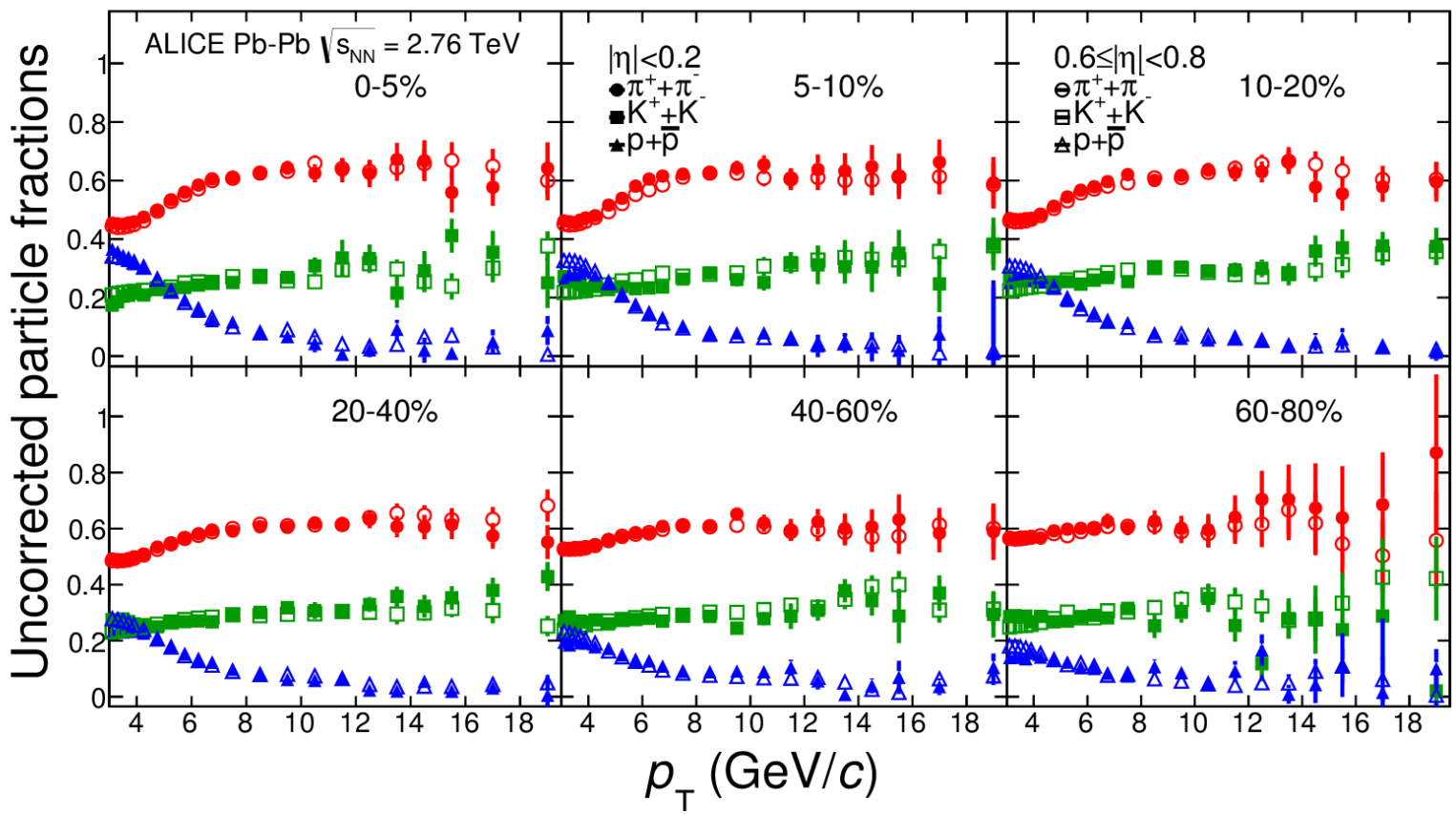






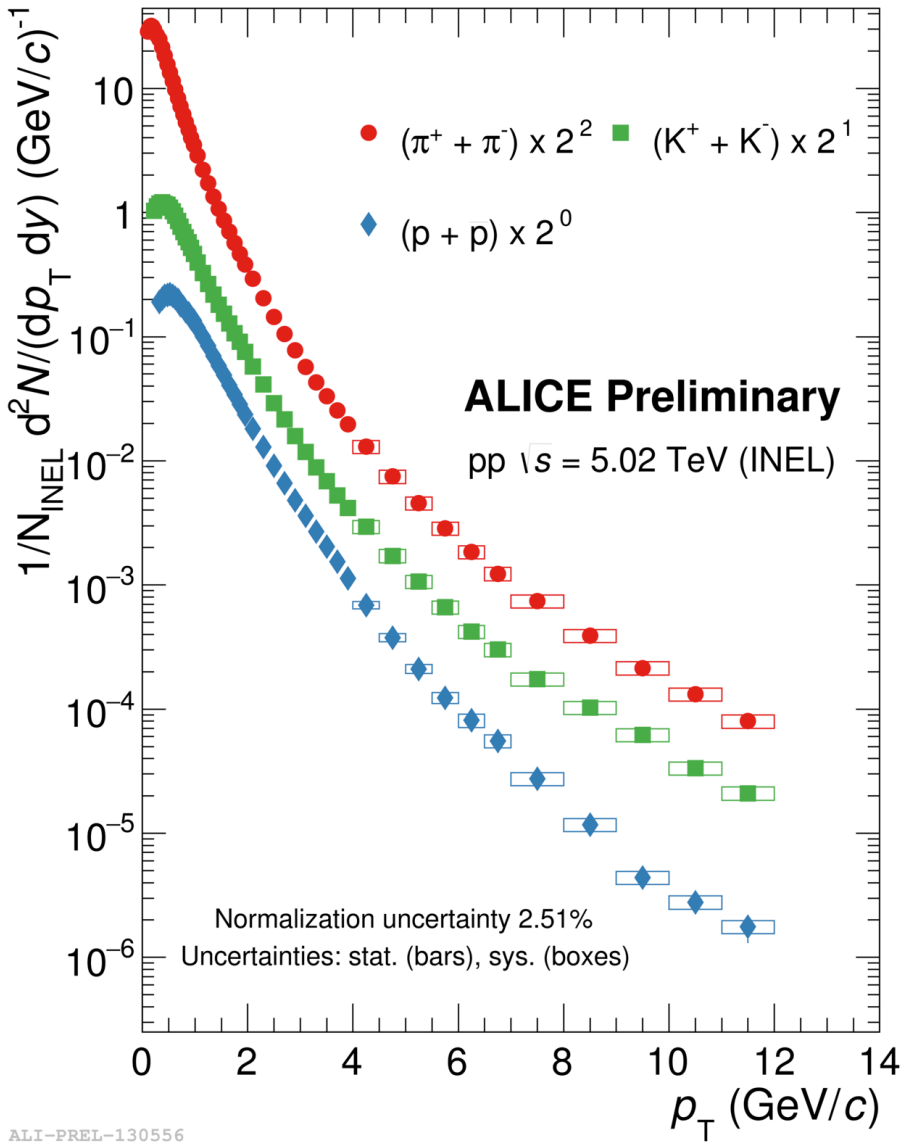
The d*E*/d*x* response is calibrated using tracks identified from their time-of-flight (TOF) or topology (V^0s and ϒ–conversions)

The relative particle composition as a function of p_T

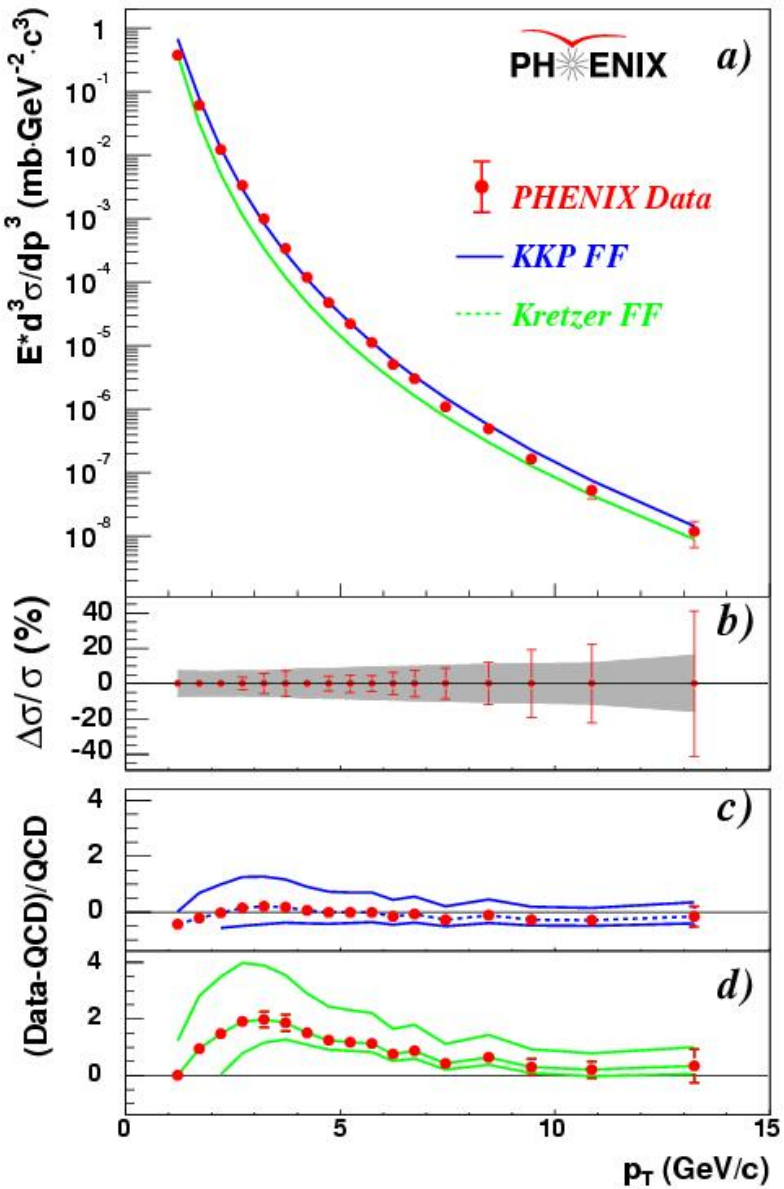


The fraction of π, K, and p are extracted for each $|\eta|$ slice and then averaged for $|\eta|<0.8$. The final spectra are essentially obtained by multiplying with the invariant charge particle yields.

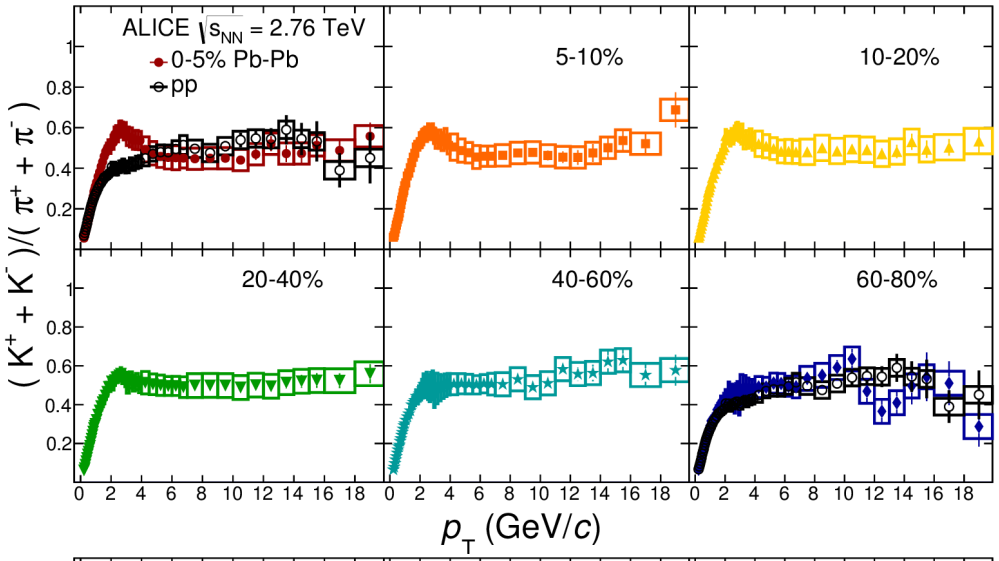
Spectra in pp collisions at 5 TeV

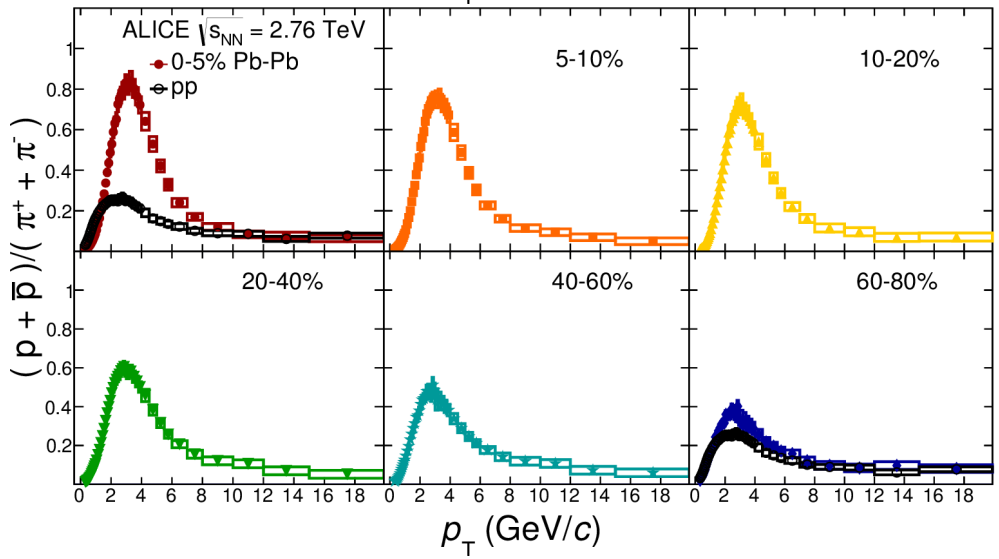


Invariant cross section for π^0 production at mid-rapidity in pp collisions at $\sqrt{s}$ =200 GeV



Particle ratios in Pb-Pb collisions at high p_T

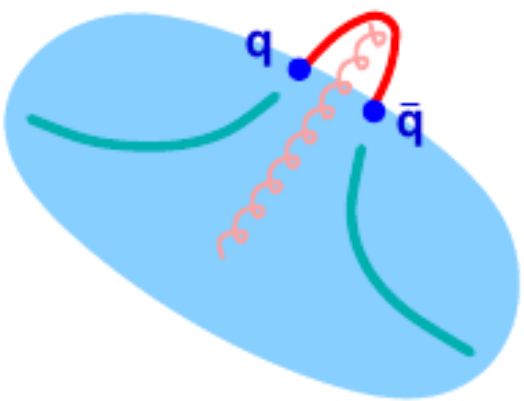


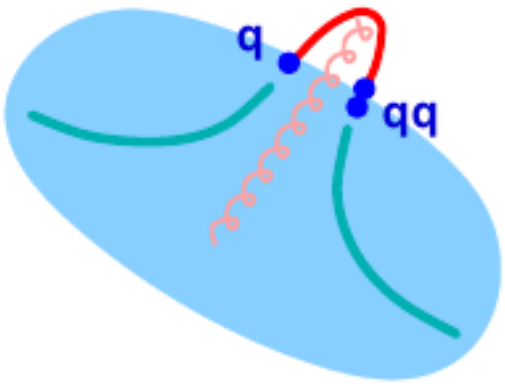


The behavior at high p_T (p_T>10 GeV/c) is independent of centrality (and the same as in pp collisions)

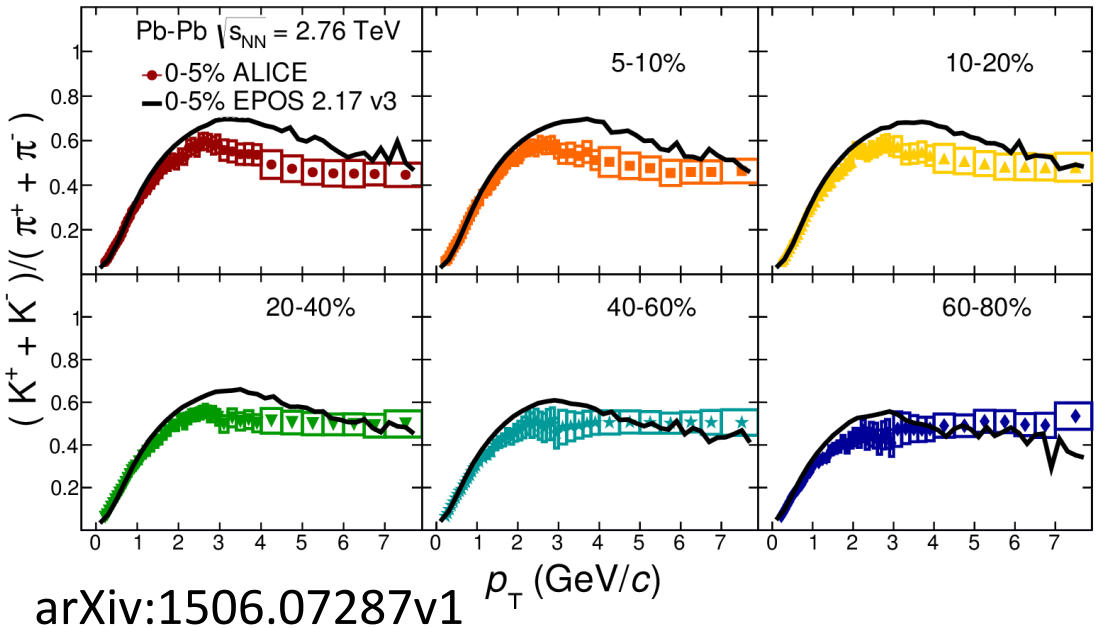
EPOS model 2.17-3
K. Werner, PRL 109, 102301 (2012) “fluid-jet interaction”

“Considering transverse fluid velocities up to 0.7*c*, and thermal parton momentum distributions, one may get a “push” of a couple of GeV to be added to the transverse momentum of the string segment. This will be a crucial effect for intermediate p_T jet hadrons.”

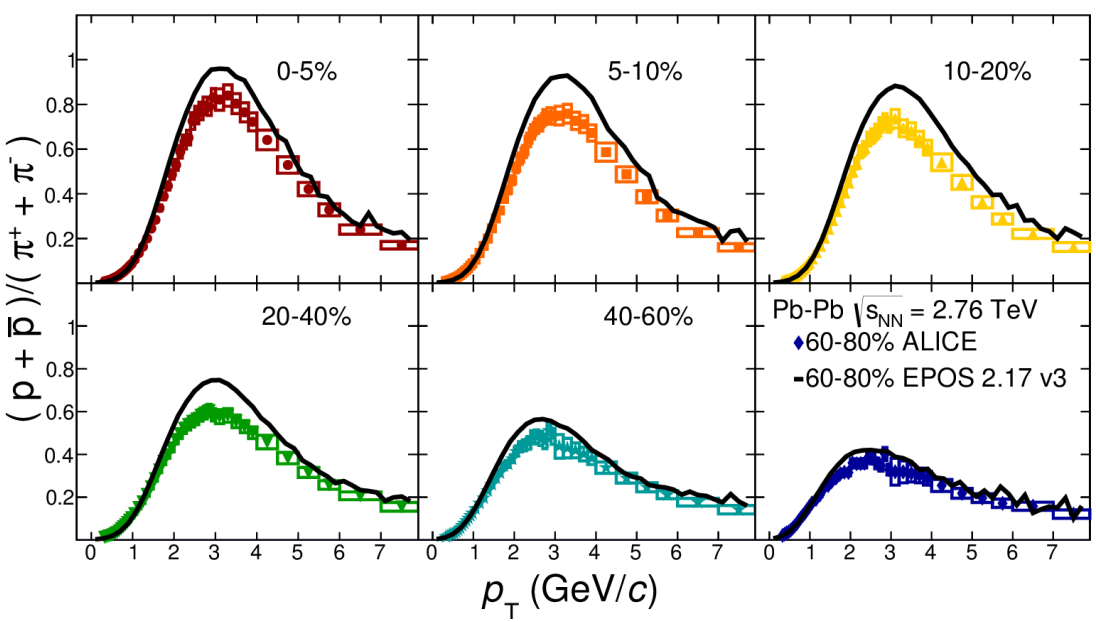




Intermediate p_T: comparison with EPOS



arXiv:1506.07287v1



EPOS model 2.17-3
K. Werner, PRL 109, 102301 (2012) "fluid-jet interaction". Works over the entire p_T range.

Hydrodynamical phase + hadronization processes at intermediate p_T where the interaction between bulk matter and jets is considered

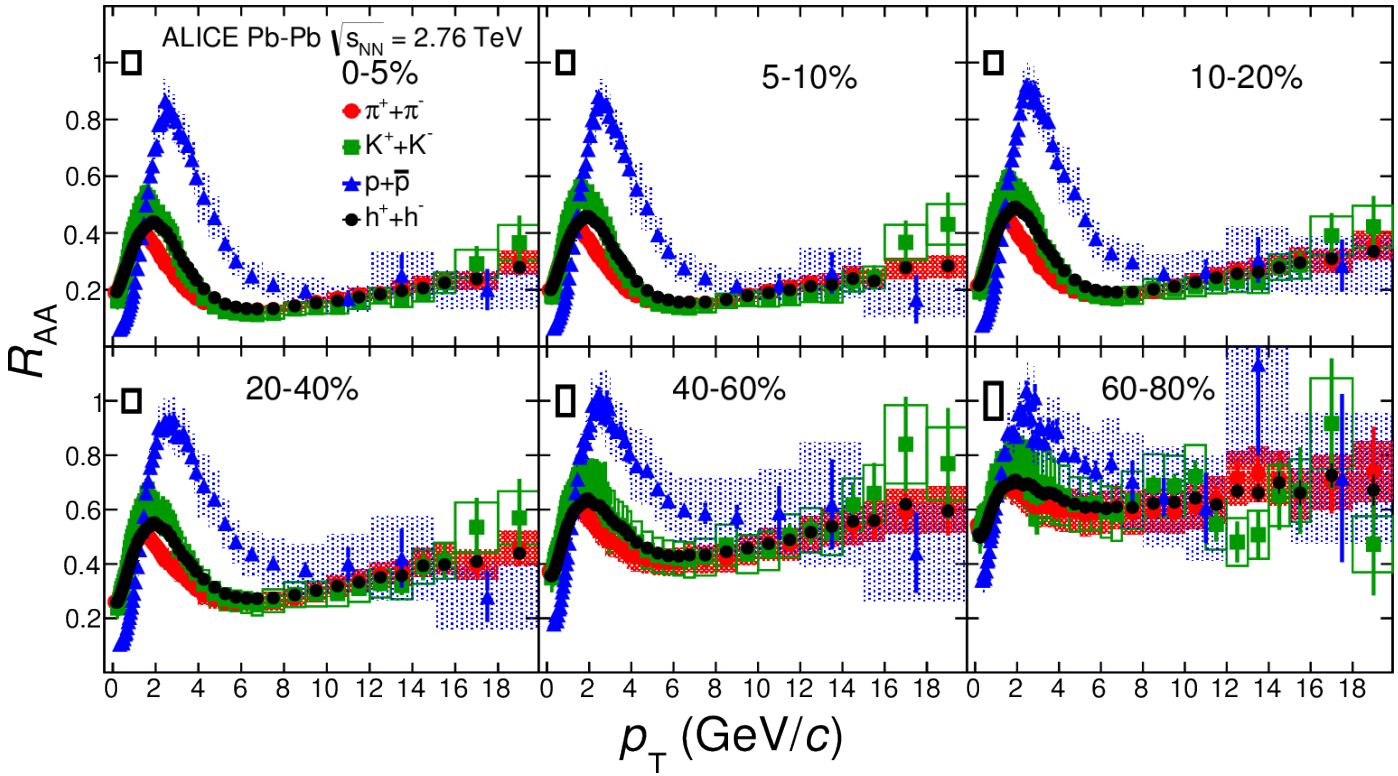
Baryon-meson effect where a quenched jet hadronizes with flowing medium quarks

- centrality dependence well reproduced, even for very peripheral events.
- magnitude of both the p-to-π and the K-to-π peak is overpredicted.

The nuclear modification factor: R_{AA}

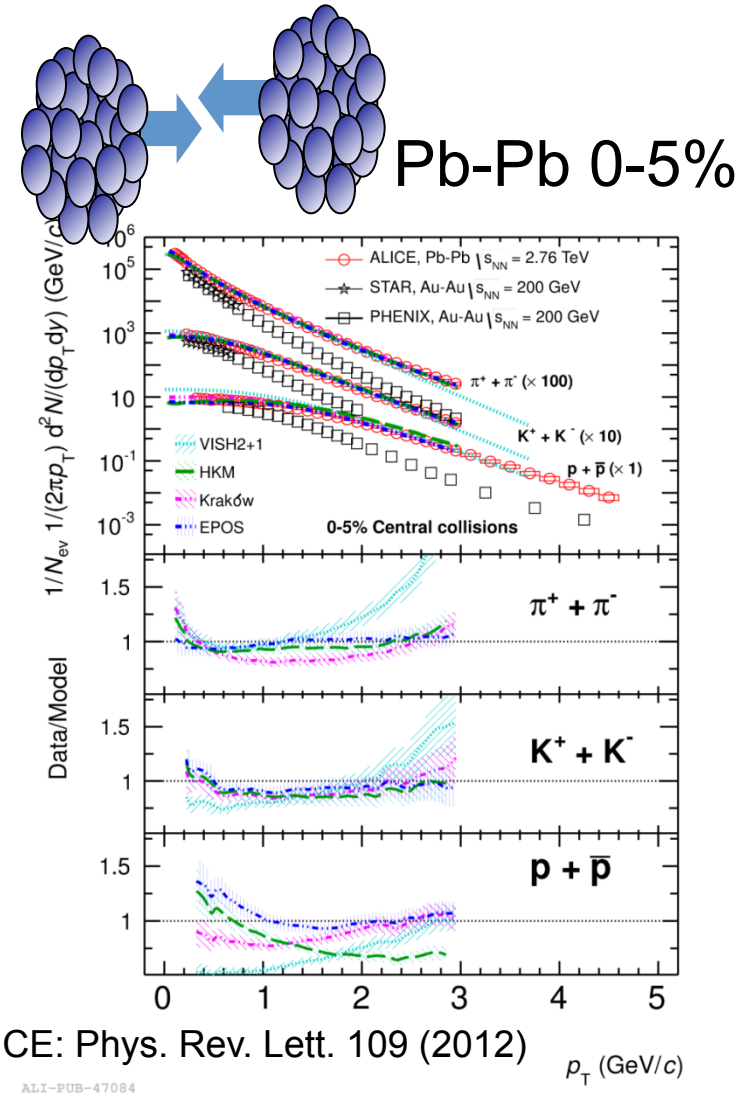
$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}/dp_T d\eta}$$

$\langle T_{AA}\rangle \sigma^{pp} = \langle N_{coll}\rangle$

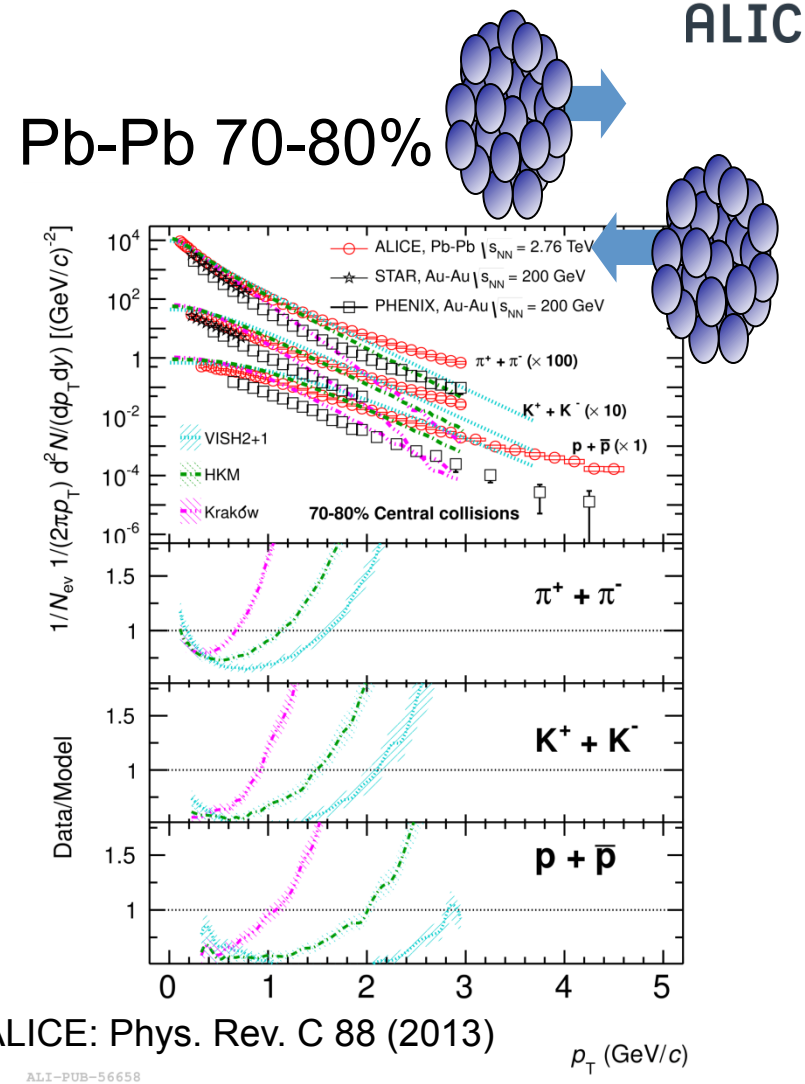


- For $p_T < \approx 8 - 10$ GeV/c: R_{AA} for π and K are compatible and are smaller than R_{AA} for p.
- At high p_T : R_{AA} for π, K and p are compatible.

Bulk production: low p_T spectra



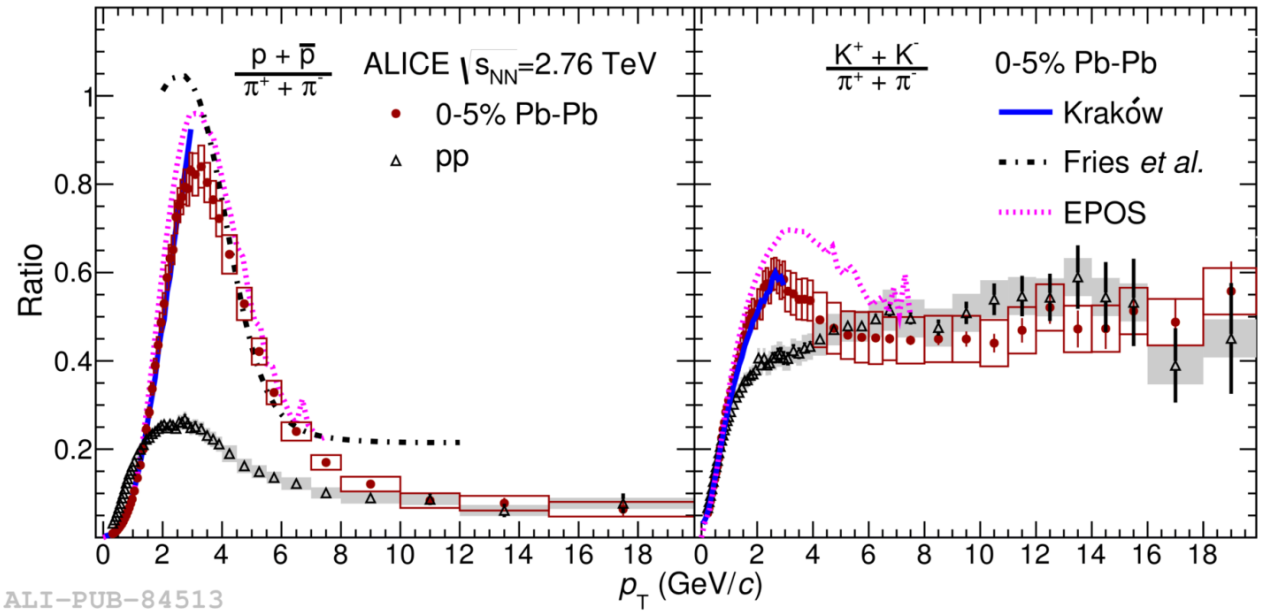
ALICE: Phys. Rev. Lett. 109 (2012)



ALICE: Phys. Rev. C 88 (2013)

- Hydrodynamic models describe well the spectra in central Pb-Pb collisions
- The same models typically fail to describe the p_T spectra in peripheral collision

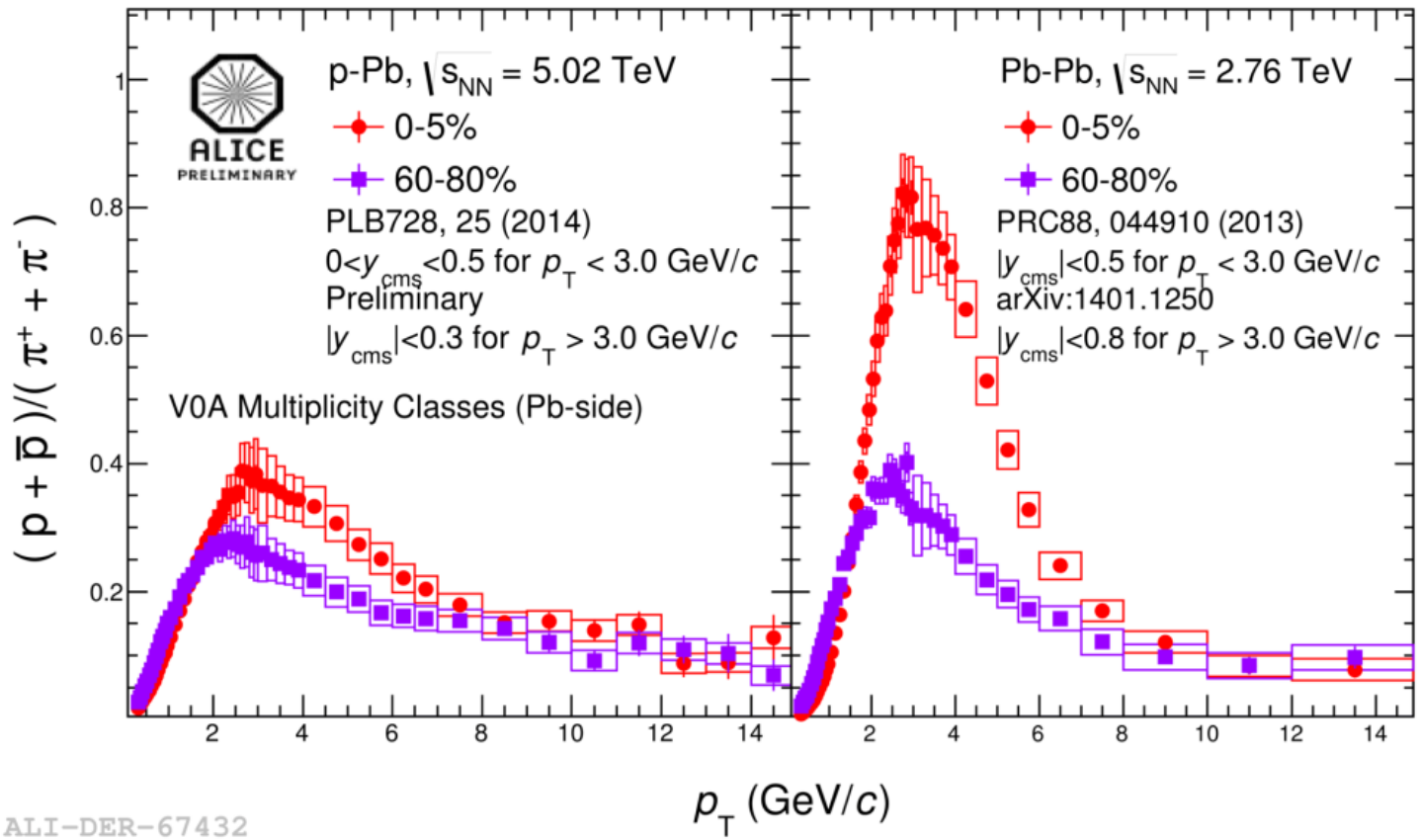
Particle ratios compared to models



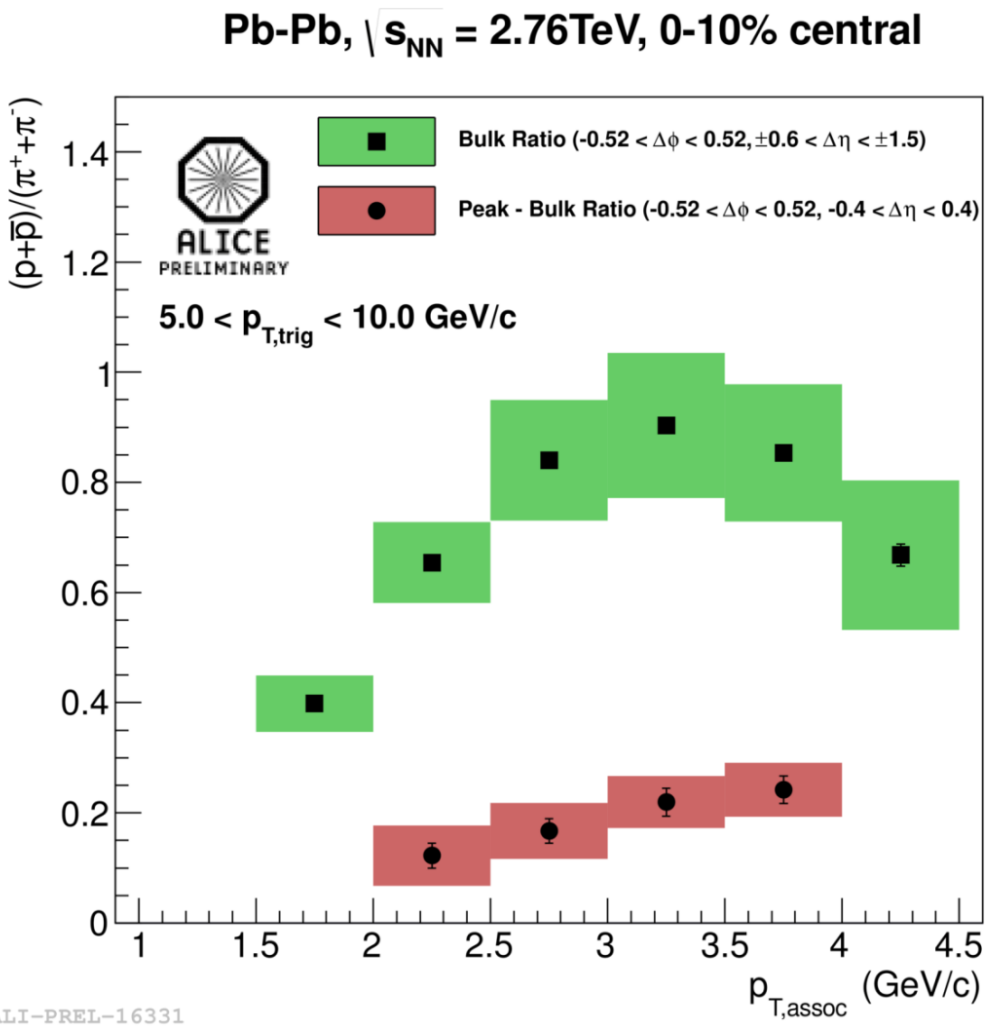
- Kraków: PRC85, 064915 (2012)
- HKM: PRC87, 024914 (2013)
- Fries: PRL90, 202303 (2003) and private communication
- EPOS: PRL109, 102301 (2012) and private communications

Kraków+HKM: hydrodynamic (low p_T) models
Fries: recombination
3 quarks → baryon,
2 quarks → meson
EPOS: hydrodynamics (low p_T) → medium modified fragmentation for quenched jets (intermediate p_T) → vacuum fragmentation (high p_T)

Comparisons between the different colliding systems: high p_T particle ratios in p-Pb and Pb-Pb



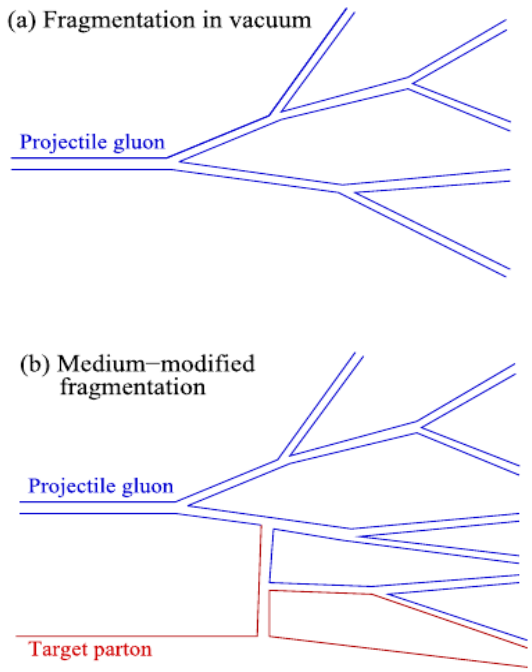
p/π ratio in peak-bulk



When the p/π ratio in the peak is corrected for bulk effects using an η gap one finds that the ratio is dominated by the bulk.
So the ratio does not seem to be driven by hard physics.

Why do we expect particle species dependent modifications even at higher p_T?

- Large effects at intermediate p_T – does this effect just disappear?
- The low value of R_{AA} suggests that most hard partons interacts strongly with the medium

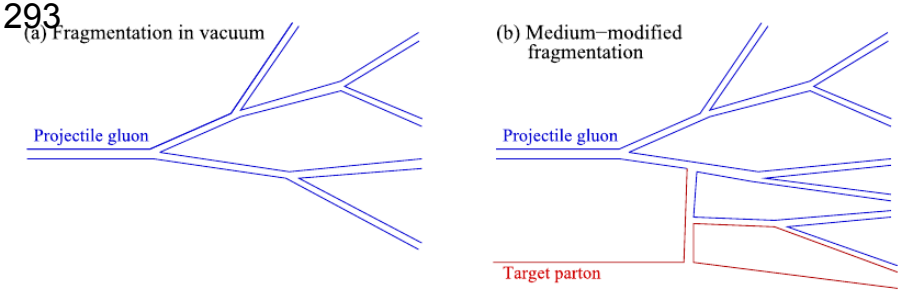


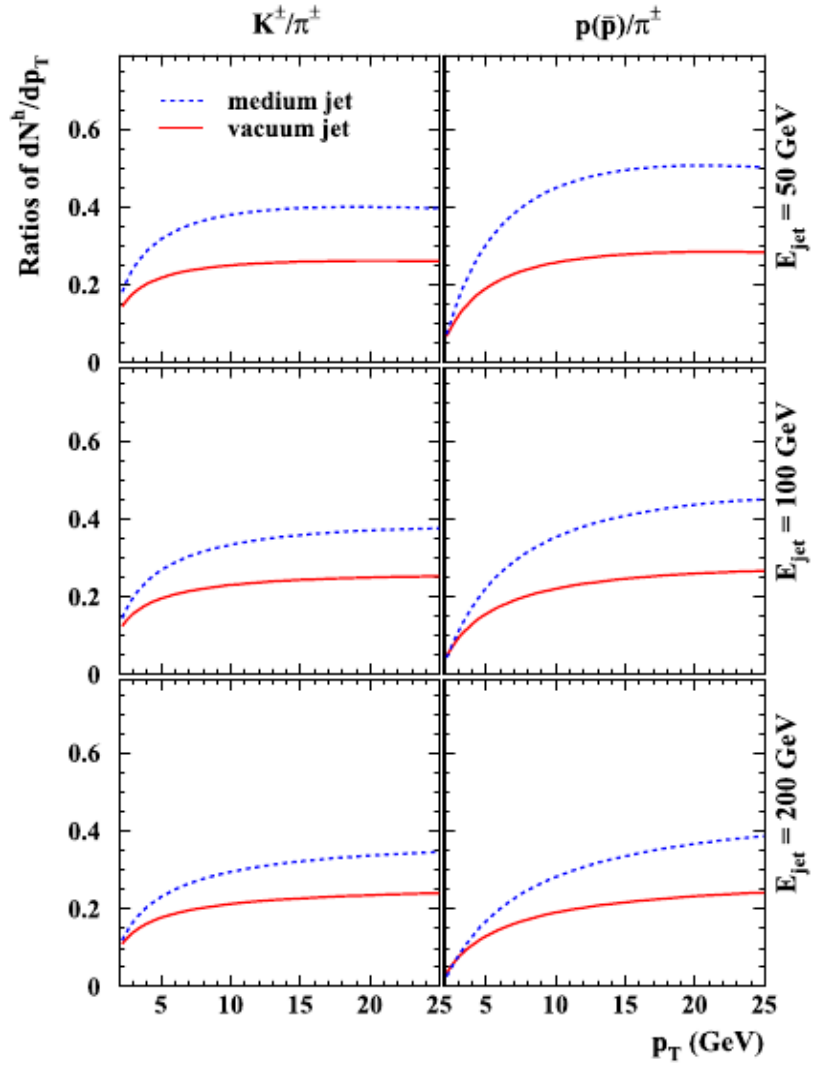
S. Sapeta and U.A. Wiedemann, Eur.Phys.J. C55 (2008) 293:

- Indirect
  - "in all models of radiative parton energy loss, the interaction of a parent parton with the QCD medium transfers color between partonic projectile and target. <u>This changes the color flow in the parton shower and is thus likely to affect hadronization</u>."
- Direct
  - "In addition, flavour or baryon number could be exchanged between medium and projectile."

A general model with particle species dependent modifications

S. Sapeta and U.A. Wiedemann, Eur.Phys.J. C55 (2008) 293





- Effect <u>inside jet</u>
- But for p_T >> 8 GeV/c we expect all hadrons to belong to jets
- Prediction incompatible with data
- Question: what do we learn about the interaction between parton and medium from this and similar models that are ruled out