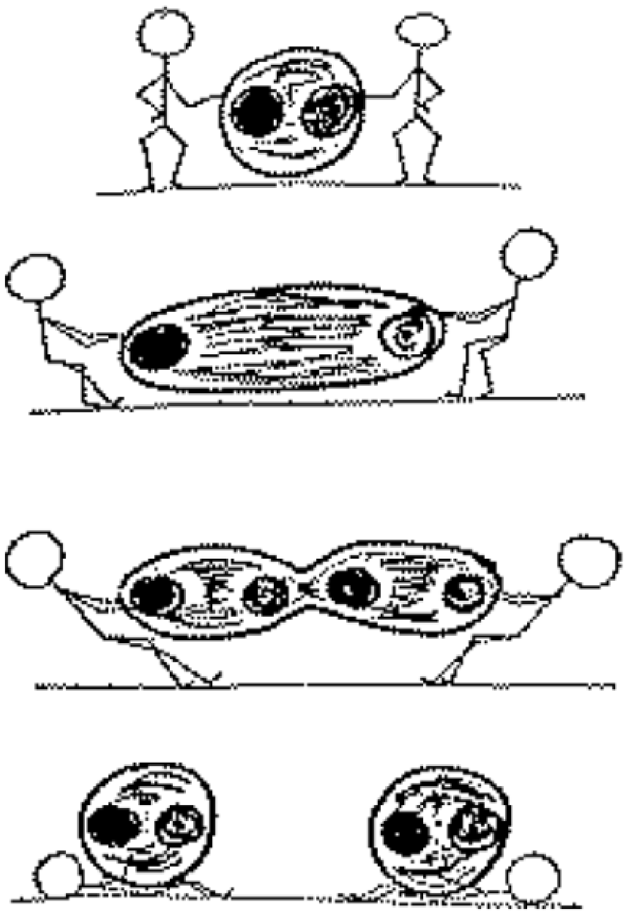
ALICE

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



Looking for collective phenomena in small systems with a comprehensive study of light flavour hadron production

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on behalf of the ALICE Collaboration

*Centro Fermi &
INFN-Laboratori Nazionali di Frascati

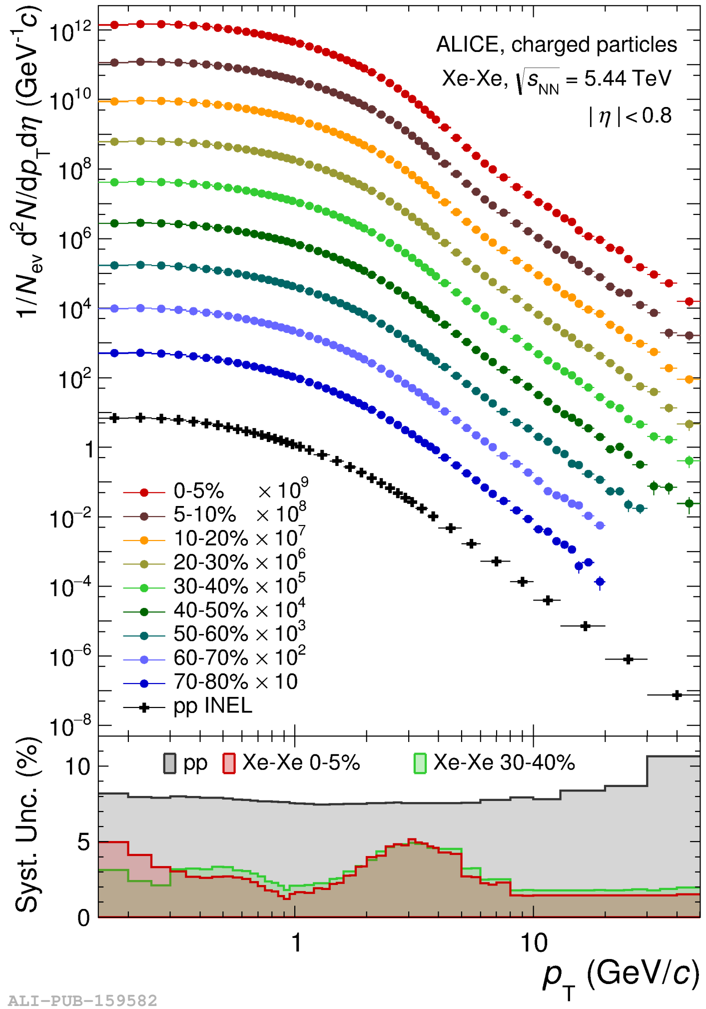
Light flavor hadron observables in small systems

Low-p_T hadrons containing light flavours (u, d, s) constitute the bulk of the particle production at LHC

They allow to study the the thermodynamic properties of the produced system and to explore the emergence of collective phenomena:

- **p_T – spectra of identified hadrons** carry information on collective flow, energy loss, chemical and kinetic freeze-out temperatures
- altered chemical composition expected in case of QGP formation (e.g. strangeness enhancement proportional to strange content in the hadron)

Are phenomena attributed to QGP also present in small systems?



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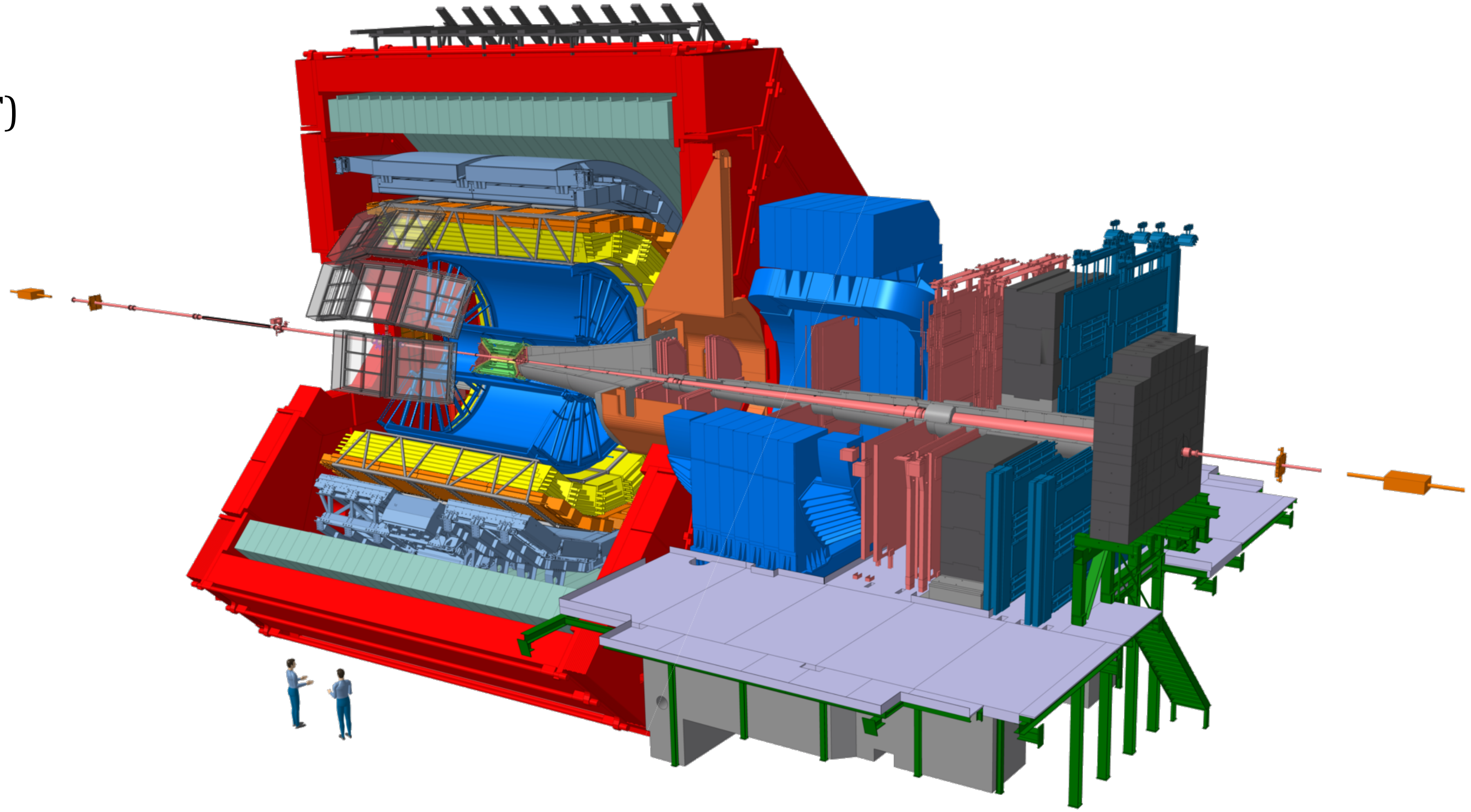
ALICE detector & data sets

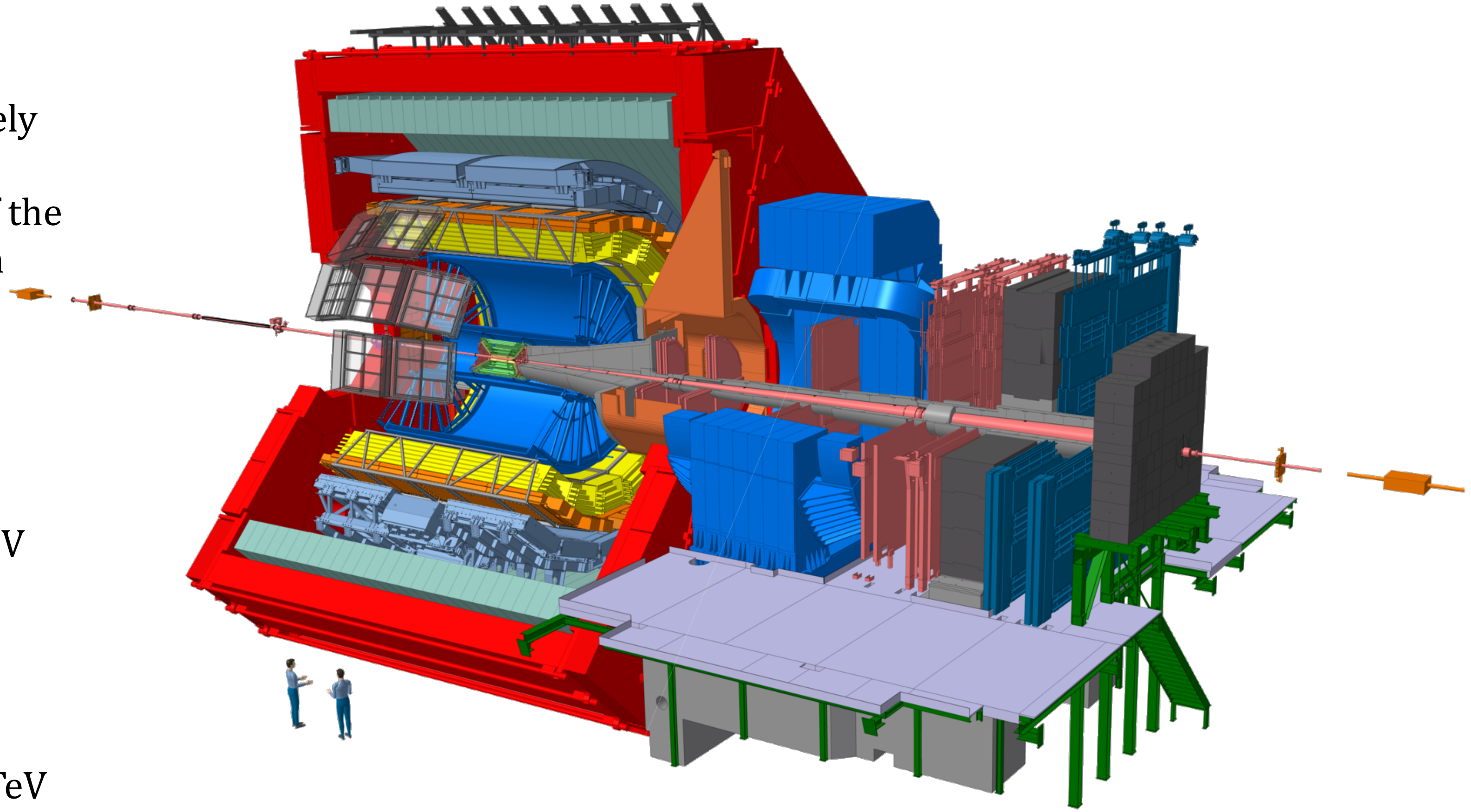
- Moderate magnetic field (B = 0.5 T, 0.2 T) in the midrapidity region $|\eta| < 0.9$
- Tracking down to $p_T \sim 100$ MeV/c
- High granularity to cope with the high occupancy in Pb-Pb collisions
- Extensive particle identification (PID) exploiting several techniques:
    1. Specific energy loss in the ITS and TPC
    2. Time Of Flight and Cherenkov information at intermediate p_T



ALICE detector & data sets

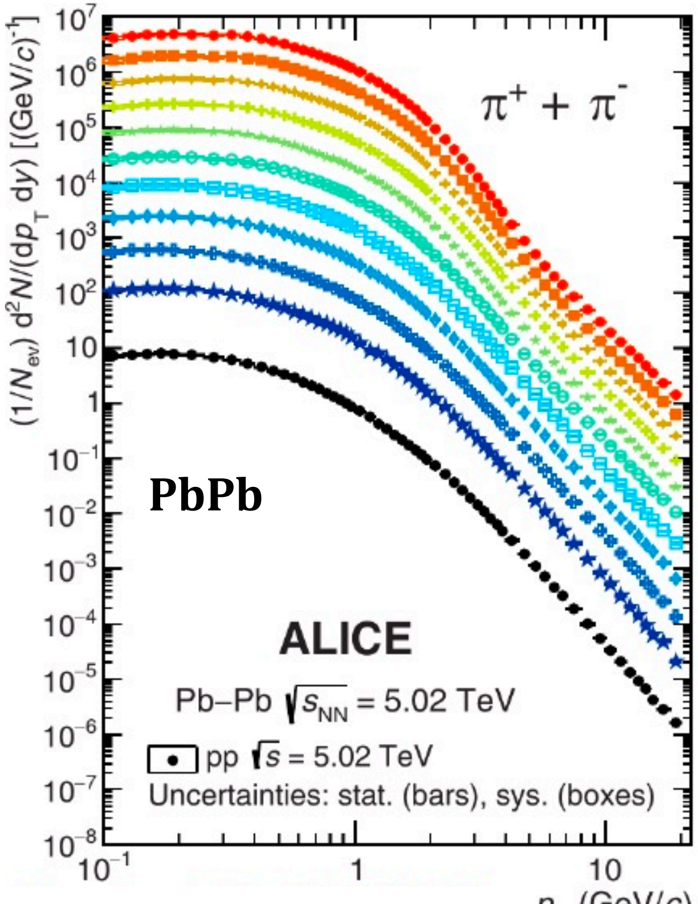
ALICE is designed to study the physics of strongly interacting matter under extremely high temperature and energy density conditions to investigate the properties of the quark-gluon plasma (QGP). Different data sets have been collected:

- pp collisions at $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8, 13 TeV
- p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02, 8.16 TeV
- Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.44 TeV to check dependence on the system size
- Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76, 5.02 TeV to study QGP and its evolution



Hints of collectivity in small systems

Comparing the spectral shapes of light hadrons in different collision systems



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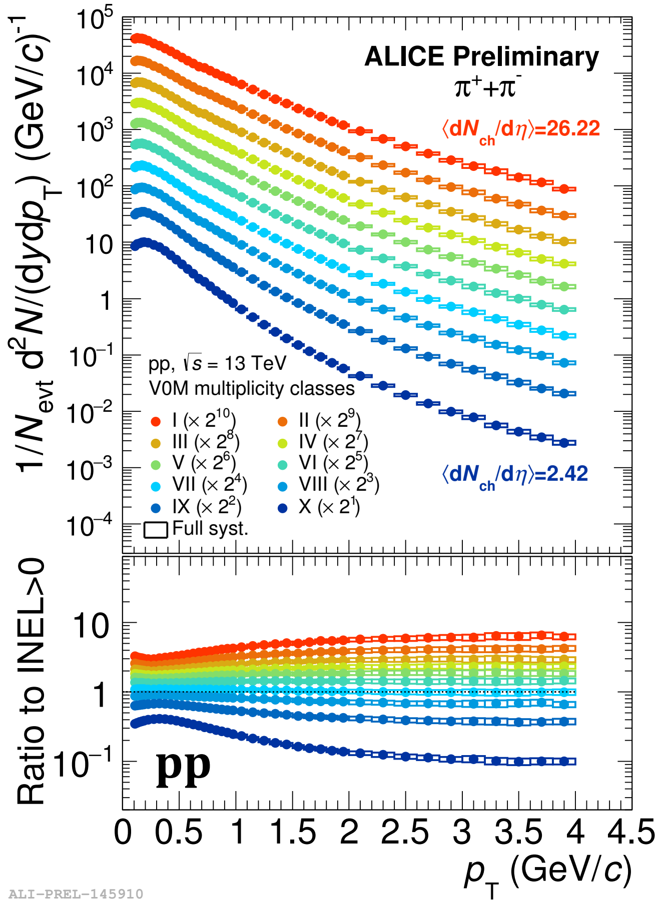


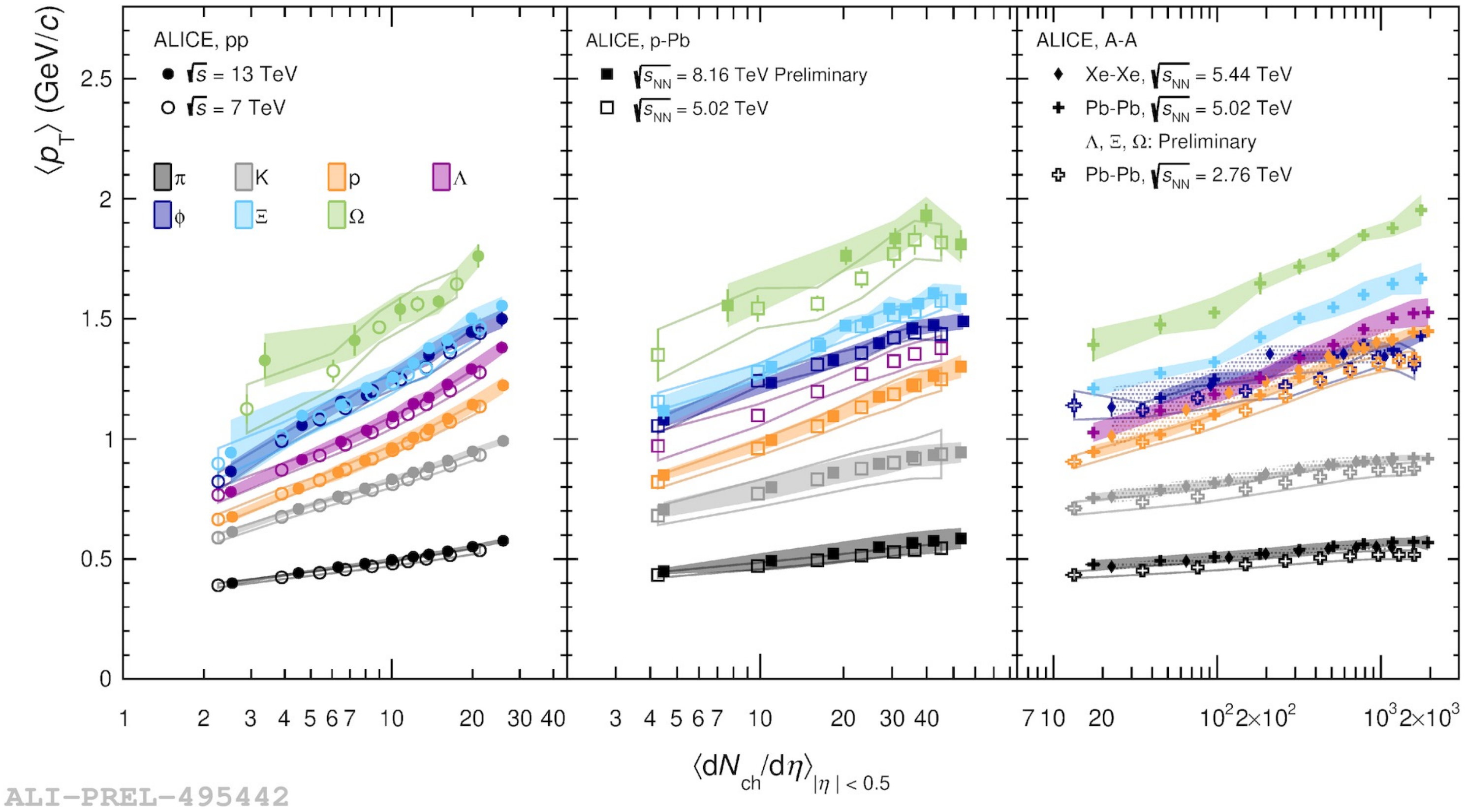
Pb-Pb: spectra become harder as the multiplicity increases (flattening visible at intermediate p_T) → «radial flow»

However, hardening has also been observed in pp and p-Pb data: do high-multiplicity pp events show «radial flow»-like effects in a limited p_T region?

Stronger multiplicity dependence of the spectral shapes for heavier particles

Same conclusions from spectra of the other particles (kaons, protons)

Mean tranverse momenta



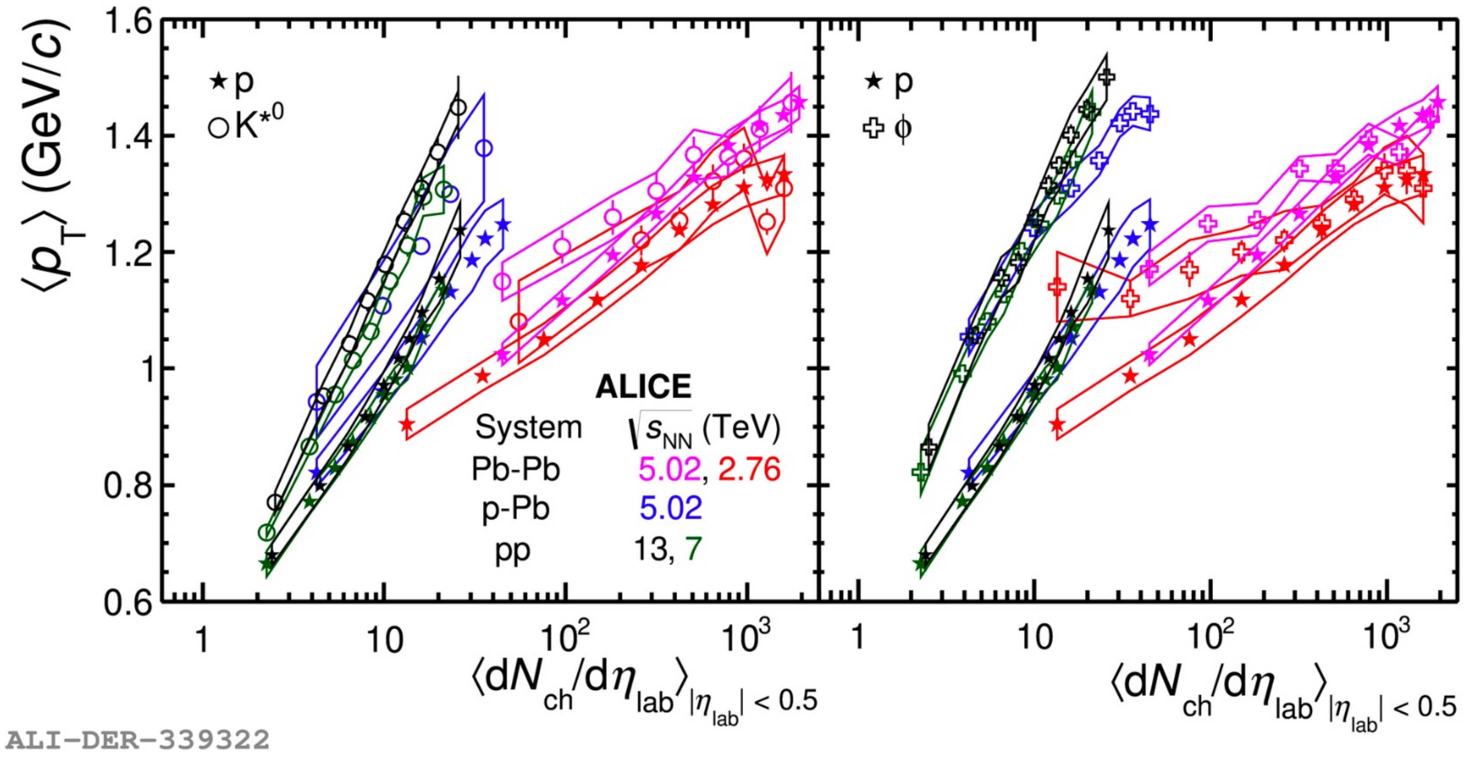
- Spectra get harder with increasing multiplicity, follow mass ordering ⟹ expected in central A-A collisions due to a collective hydrodynamic expansion: **consistent with radial flow**
- Mass ordering is violated by $\boldsymbol{\phi}$ for pp, p-Pb and peripheral Pb-Pb collisions
- Similar hierarchy is observed in all collision systems
- Moderate hardening of the spectra with increasing $\sqrt{s_{NN}}$

PRC 99, 024906 (2019)

π, K, p, Λ: PLB 728, 25-38 (2014)
ϕ: EPJC 76, 245 (2016)
Ξ, Ω: PLB 758, 389-401 (2016)

π, K, p: PRC 99, 044910 (2013)
ϕ: PRC 91, 024609 (2015)

Mean tranverse momenta



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Steeper increase of $\langle p_T \rangle$ with multiplicity in small collision systems

Blast-Wave global fit

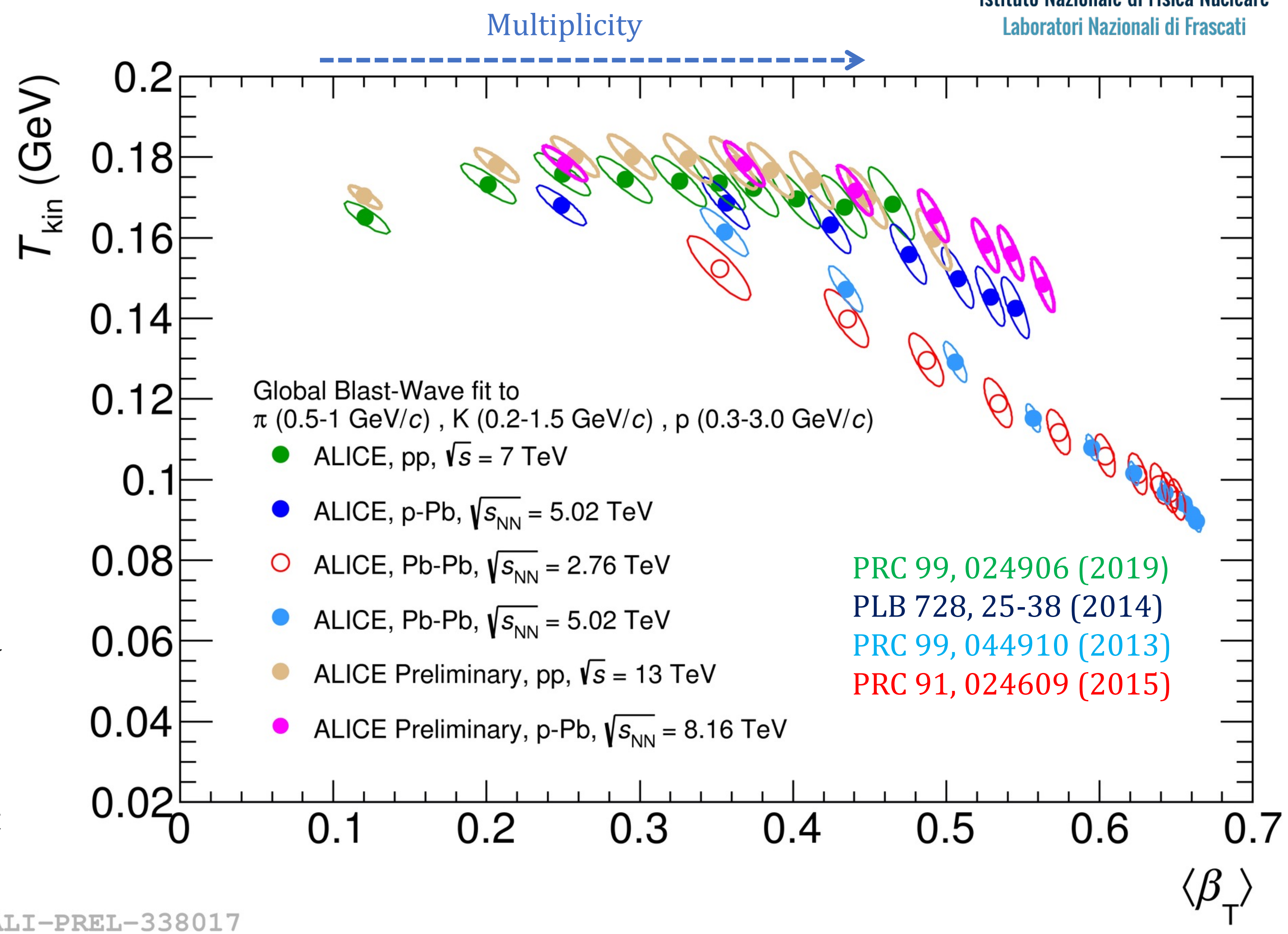
Boltzmann-Gibbs Blast-Wave fits are used to determine hydrodynamical parameters:

1. T_{kin}: kinetic freeze-out temperature
2. β_{T}: transverse flow velocity

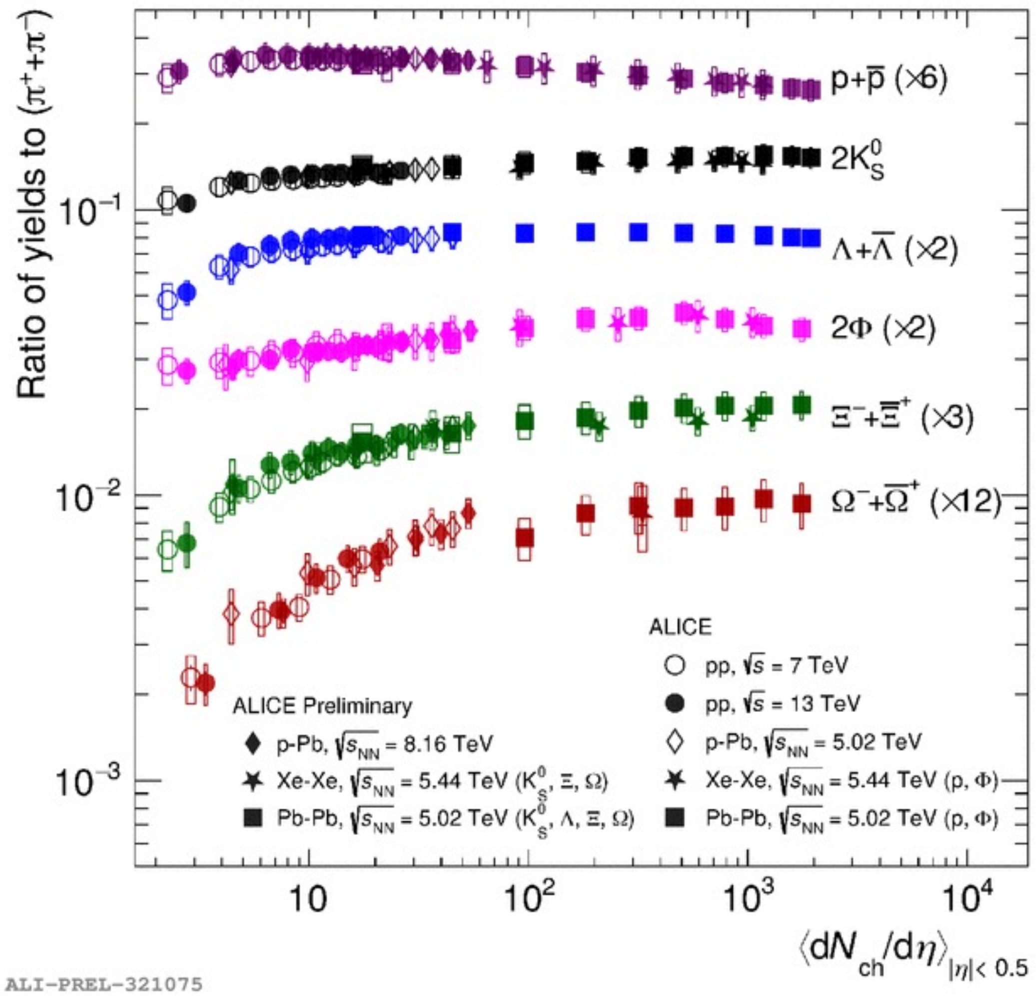
Continuous evolution as a function of the event multiplicity

pp and p-Pb show a similar trend and values are comparable: higher T_{kin} in p-Pb 8.16 TeV than in 5.02 TeV

Higher decoupling temperature with respect to heavy-ion collisions



Integrated particle yields



- The integrated particle yields exhibit a **continuous evolution with the charged particle multiplicity** independent of the collision system

- Abundances of strange hadrons are invariant with the collision energy at similar multiplicities

- At large multiplicities small systems reach the values observed in heavy-ions

- Chemical composition seems to be driven by $\langle dN_{ch}/d\eta \rangle$ and not by the collision system

PRC 99, 024906 (2019)
PLB 728, 25-38 (2014)
PRC 91, 024609 (2015)
PRC 99, 044910 (2013)
Eur. Phys. J. C 81 (2021)

What is happening in small systems?

Strangeness enhancement in heavy-ion collisions is expected because of volume/QGP effects.

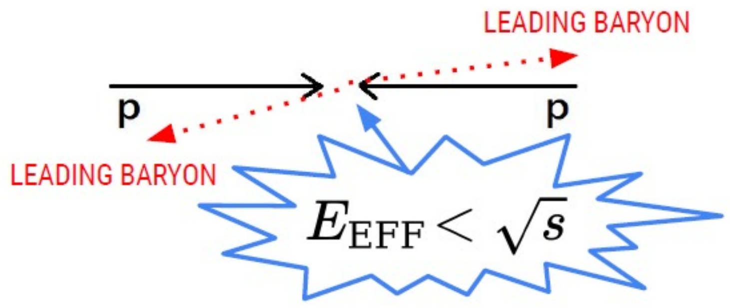
However, the relevant observables (*e.g.*, hadrochemistry) smoothly evolve within different colliding systems

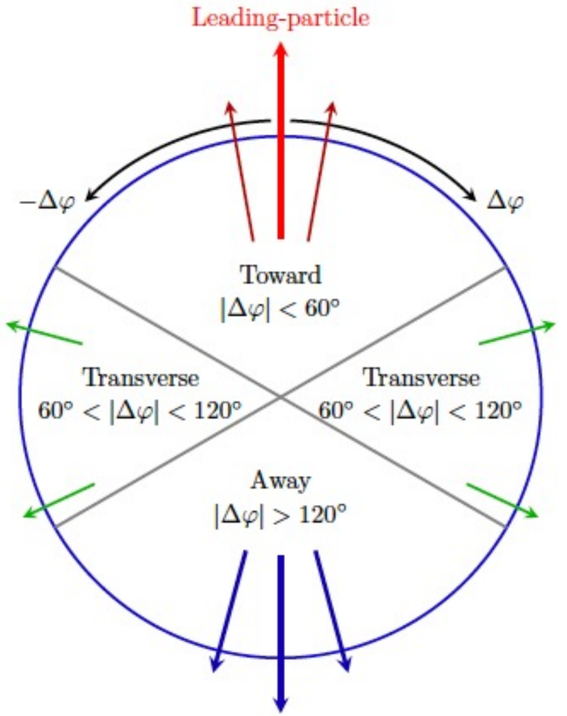
Some questions naturally emerge:

1. what underlying mechanisms are at play in small systems producing a strangeness enhancement?
   - Search for observables able to disentagle initial and final state effects → **effective-energy approach**

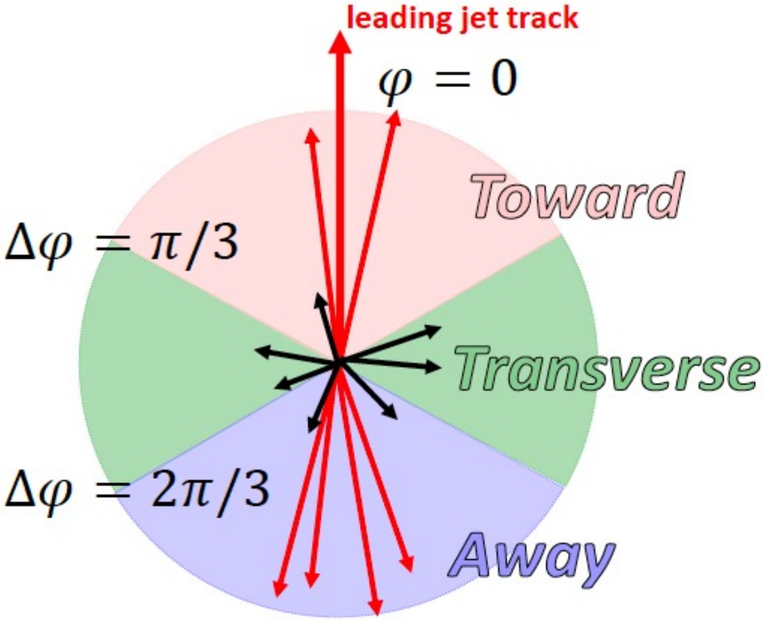
See talk by M. SHARMA in this session at 7:54!

2. what is the role of jets and underlying event in the production of strange hadrons?
   - → **event characterization**





Light-flavour hadrons *vs.* R_T



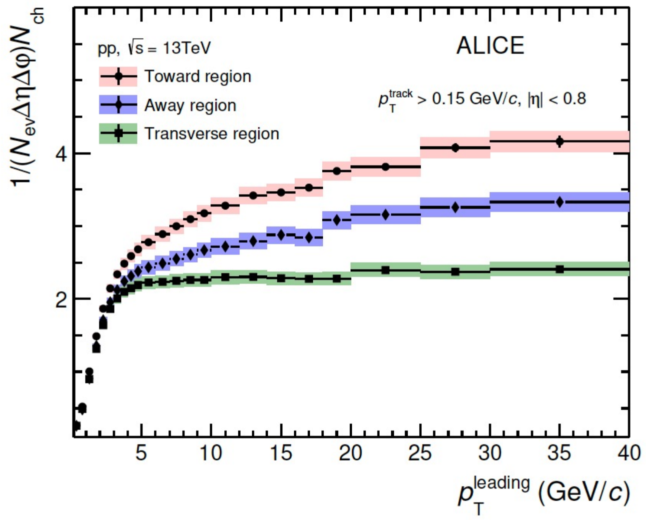
R_T: self-normalised charged-particle multiplicity in the Transverse region and above the onset of the plateau ($5 < p_T$ leading < 40 GeV/c)

$$R_T = \frac{N_T}{\langle N_T \rangle}$$

→ information on the underlying event activity

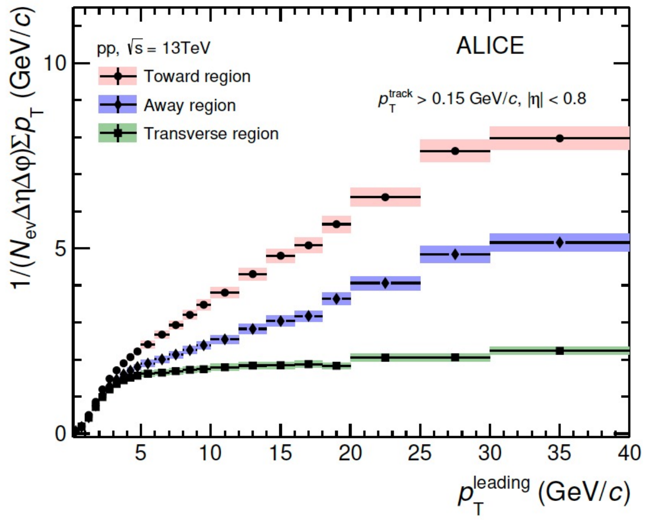
Average charged-particle density

$$\frac{1}{\Delta\eta \times \Delta\varphi} \frac{1}{N_{ev}(p_T^{leading})} N_{ch}$$



Average summed-p_T density

$$\frac{1}{\Delta\eta \times \Delta\varphi} \frac{1}{N_{ev}(p_T^{leading})} \sum p_T$$



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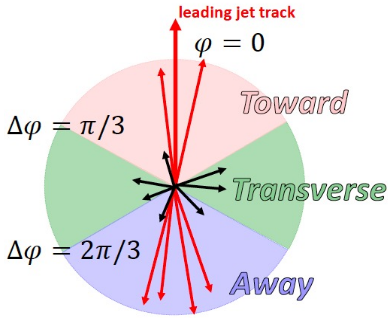
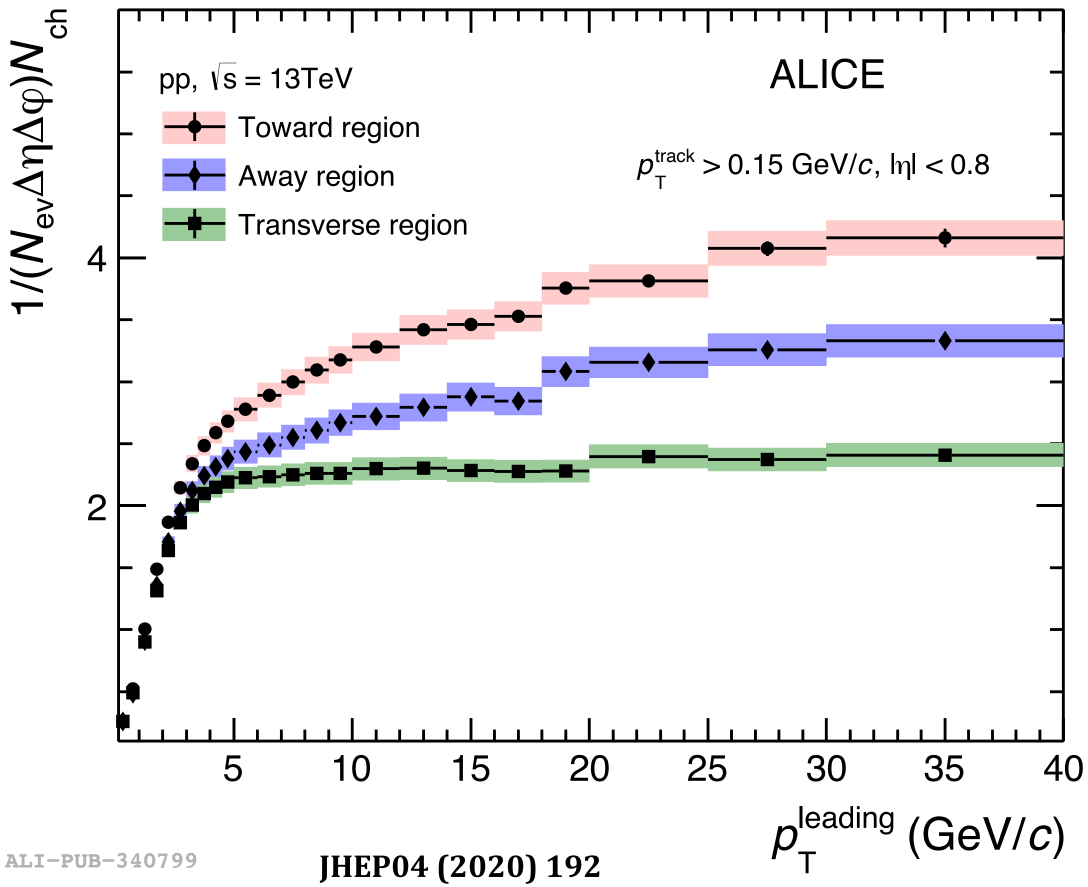
Light-flavour hadrons *vs.* R_T



- Dependence on $p_T^{leading}$ → similar behaviour in all regions
- Steep rise at low $p_T^{leading}$ and smaller gradient from $p_T^{leading} \sim 5$ GeV
- Transverse region: UE almost constant after $p_T^{leading} \sim 5$ GeV/c
- Toward/Away region: continue rising, even if with a weaker dependence → contribution from hard-scattering fragments, increasing with $p_T^{leading}$
- Factor 4 in the UE activity when moving $p_T^{leading}$ from 0.15 to 1 GeV/c
- PYTHIA: good description of the plateau, underpredicted by EPOS-LHC by 20% (underestimations of hard scattering events?)
- Dependence on $\sqrt{s}$: agreement on the plateau, ordering in the rise region (p_T < 5 GeV/c)



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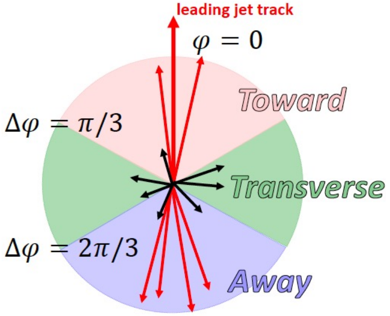

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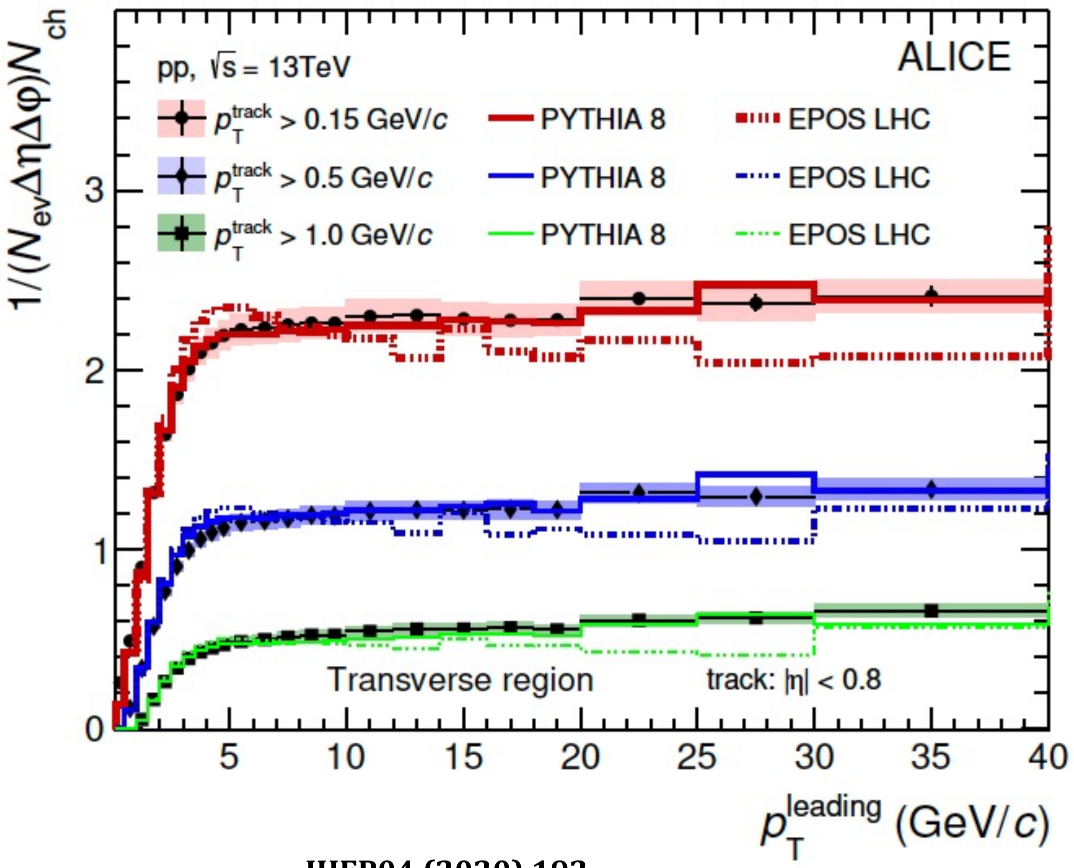

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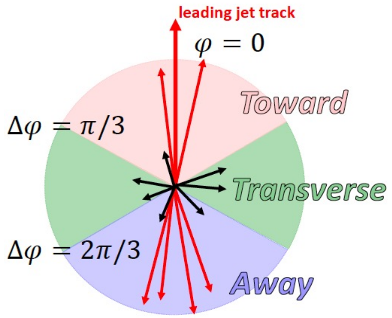

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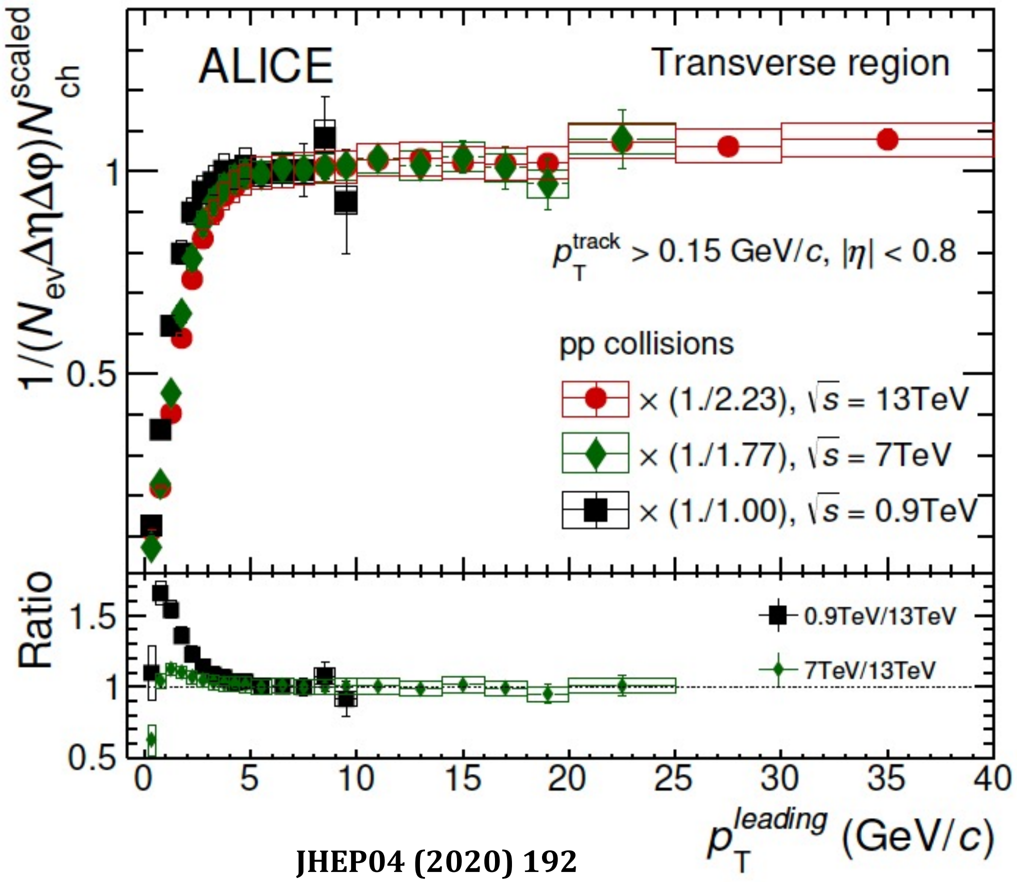

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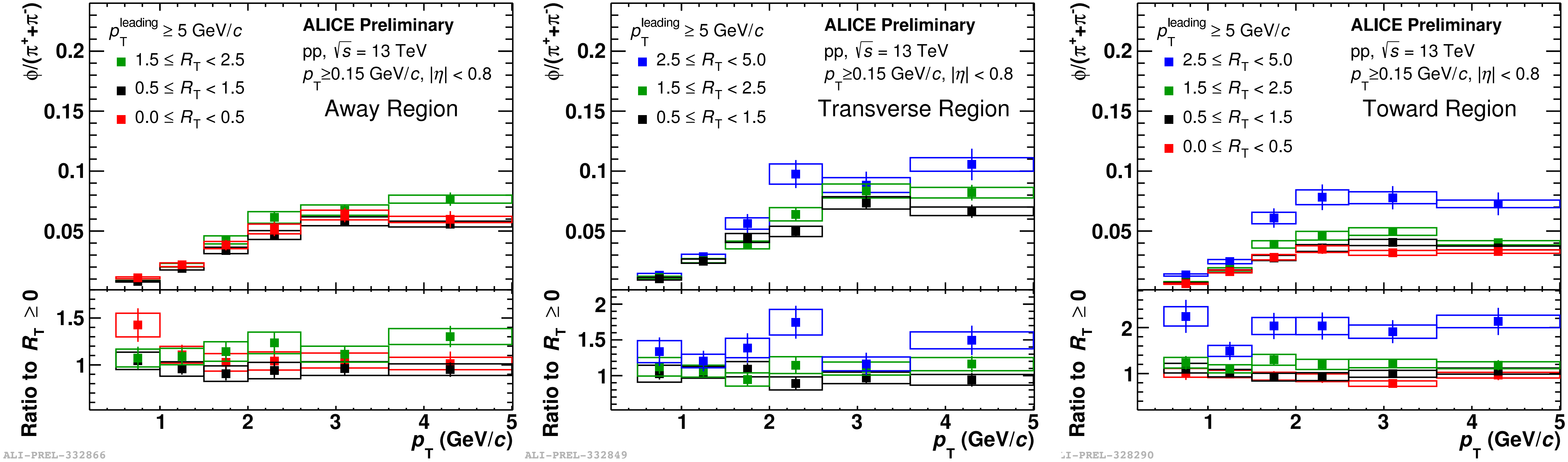
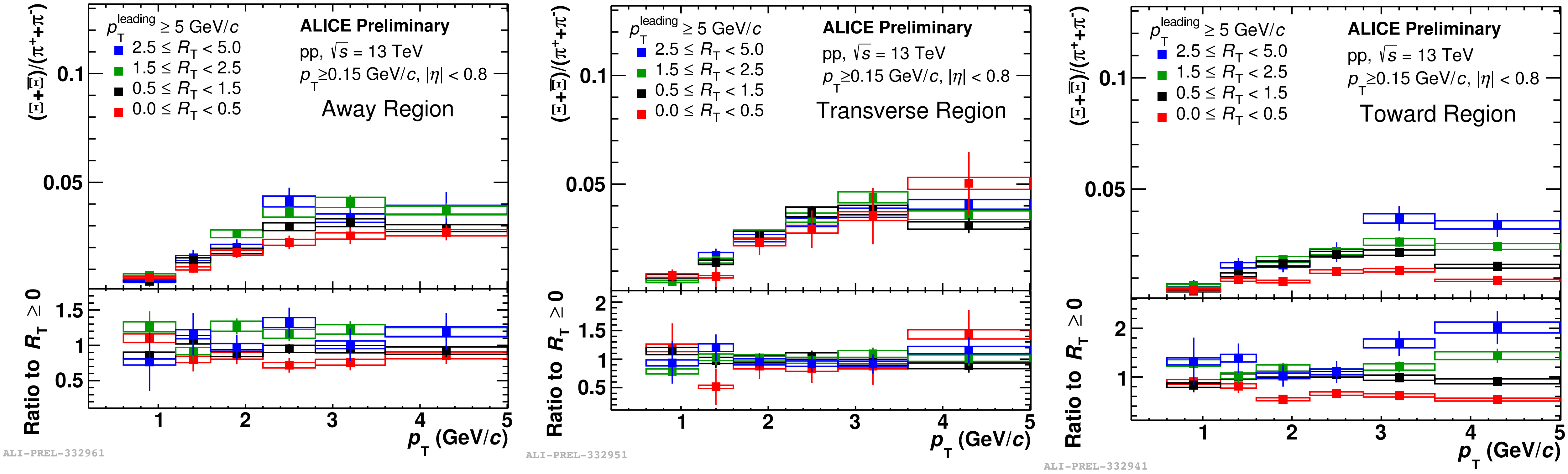


A weaker dependence on R_T is observed in the Tranverse Region than in the Toward Region
Interplay between the soft (~UE) and hard(~jet) components of the event?
→ **it could contribute to the observed flow-like pattern and strangeness enhancement in small systems**

Light-flavour hadrons *vs.* R_T



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Summary

1. Several similarities between pp, p-Pb, and Pb-Pb collisions have been reported: collectivity, baryon/meson ratio, strangeness production

2. Radial-flow effects are measurable in the hadron distributions (hardening) → hints of radial flow in small systems?

3. Hadron chemistry driven by charged-particle multiplicity density and not by collision energy nor system

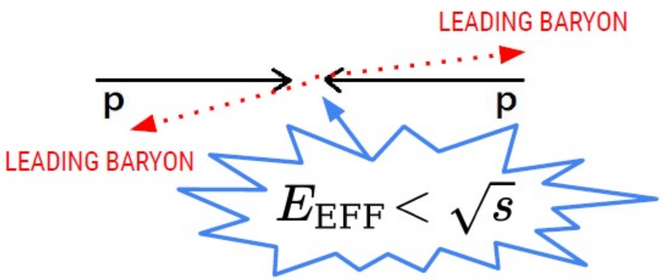
4. Alternative approaches based on multi-differential analyses involving new variables are being explored → No significant dependence of strangeness production on effective energy

See talk by M. SHARMA in this session at 7:54!

5. New analyses based on R_{T} suggest that the interplay between UE-dominated (soft) and jet-dominated (hard) events could play a role in the observed flow and strangeness enhancement in small systems

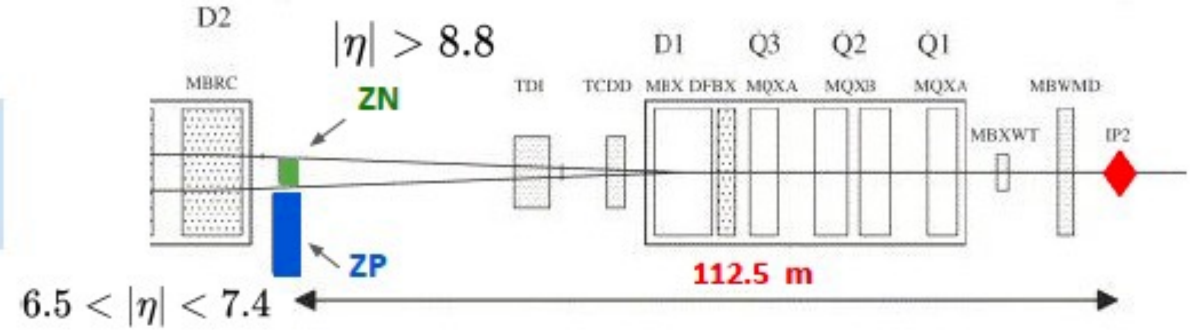
Backup

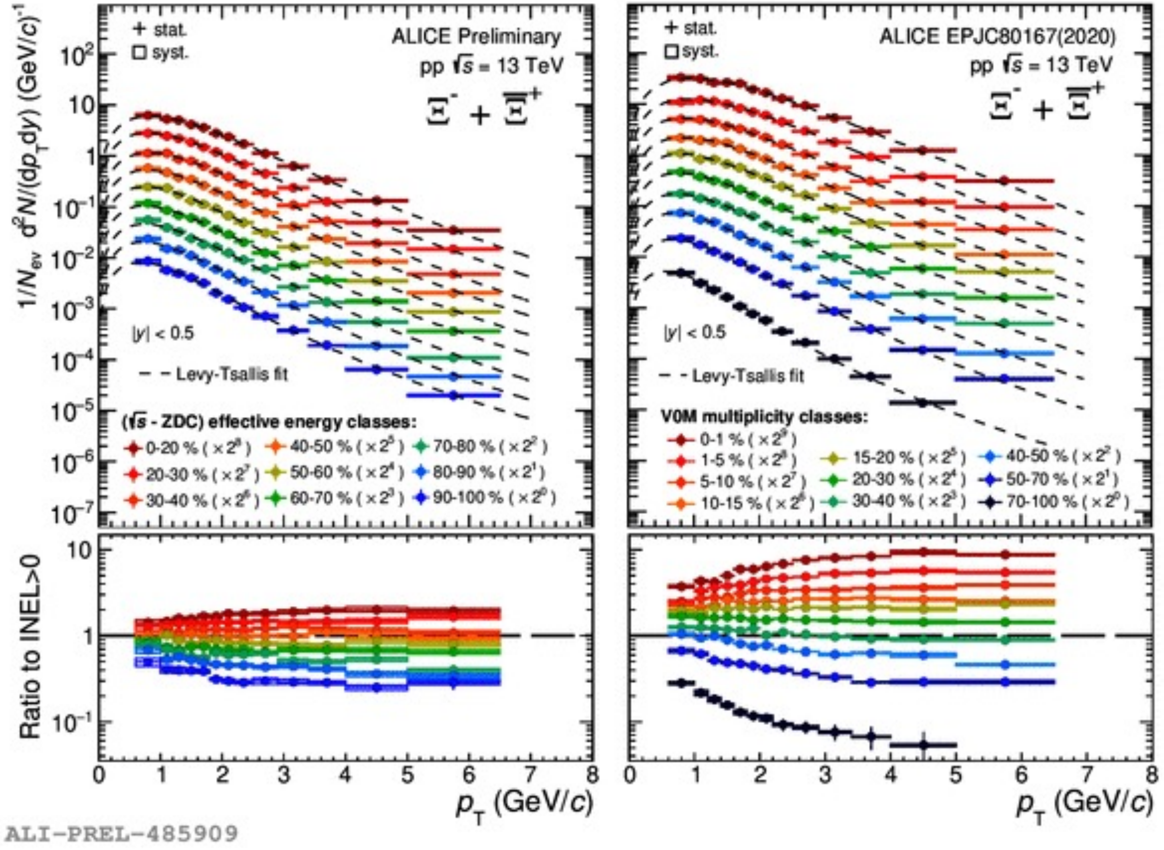
Strangeness *vs.* effective energy and multiplicity



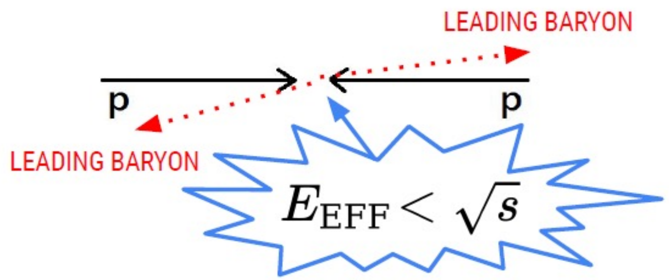
Effective energy: energy available for particle production in the initial phase of a pp collision:

1. Reduced with respect to the center of mass energy due to the leading baryon effect
2. Estimated through the measurement of the energy of forward baryons with the ZDC
3. Combined multiplicity and effective energy selections





Strangeness *vs.* effective energy and multiplicity



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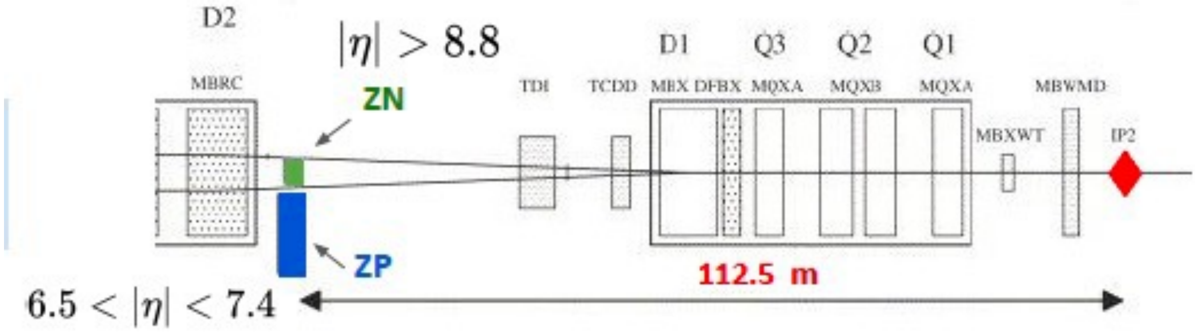
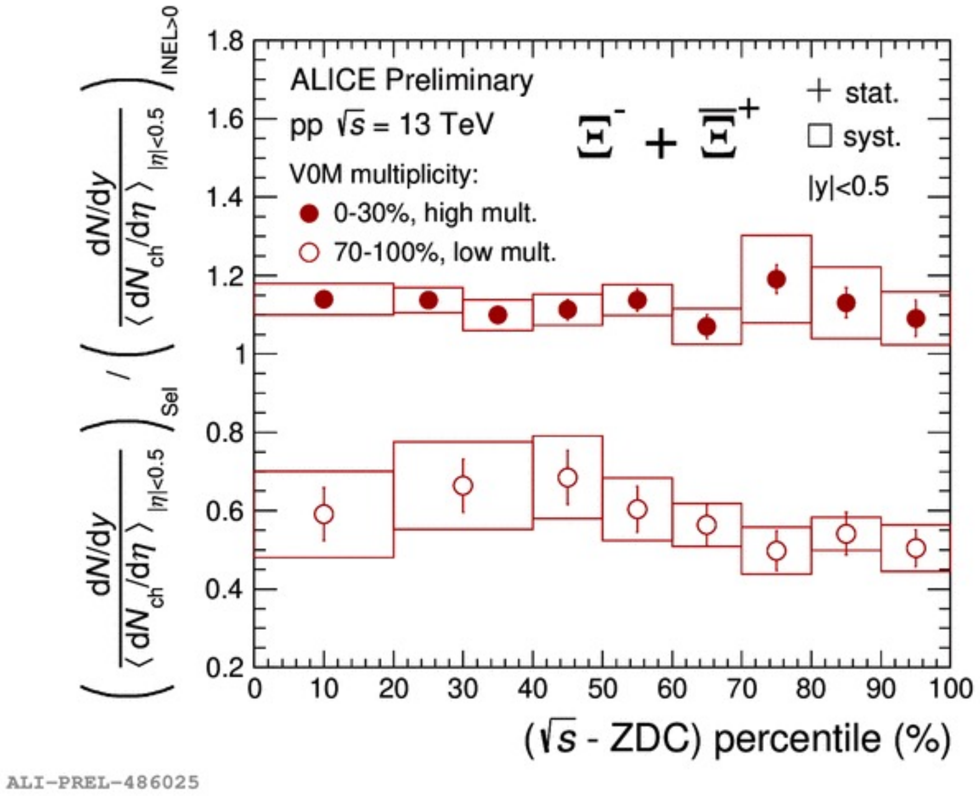
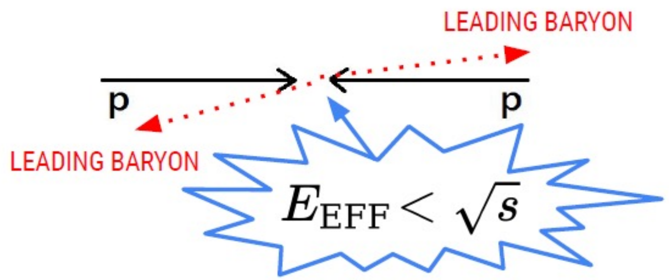




Flat behaviour across effective energy once V0 multiplicity classes are selected

Strangeness *vs.* effective energy and multiplicity



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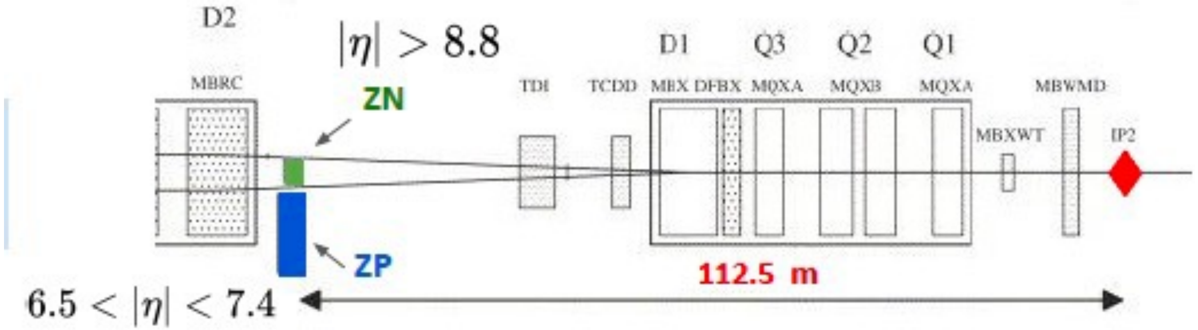

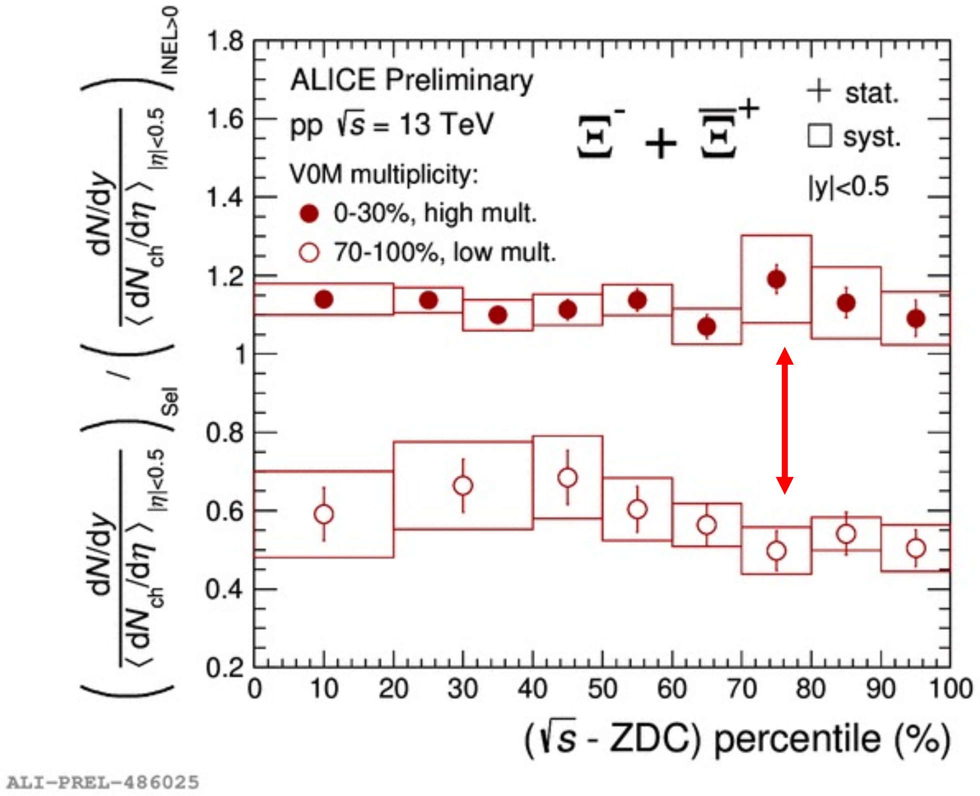

Strangeness enhancement due to multiplicity selection

Hints of collectivity in small systems

Comparing the spectral shapes of light hadrons in pp, pPb and PbPb

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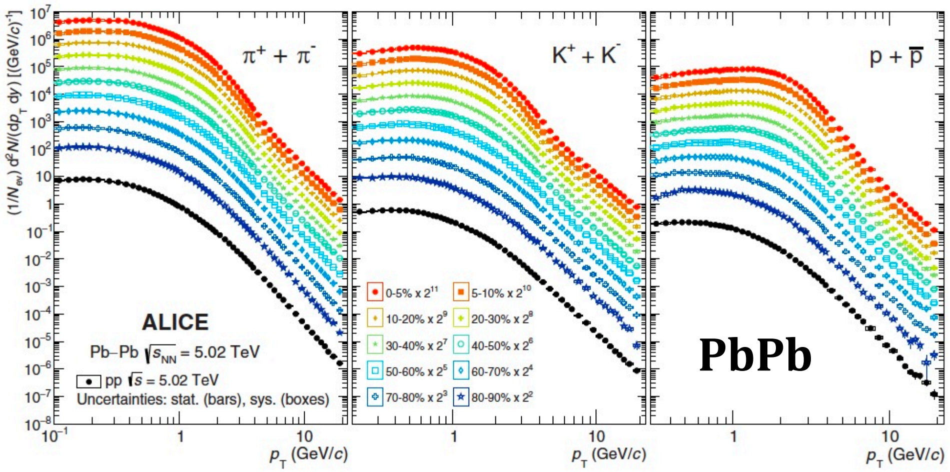

PbPb: spectra become harder as the multiplicity increases (flattening visible at intermediate p_T) → «radial flow»

However, hardening has also been observed in pp and pPb data: do high-multiplicity *pp* events show «radial flow»-like effects in a limited p_T region?

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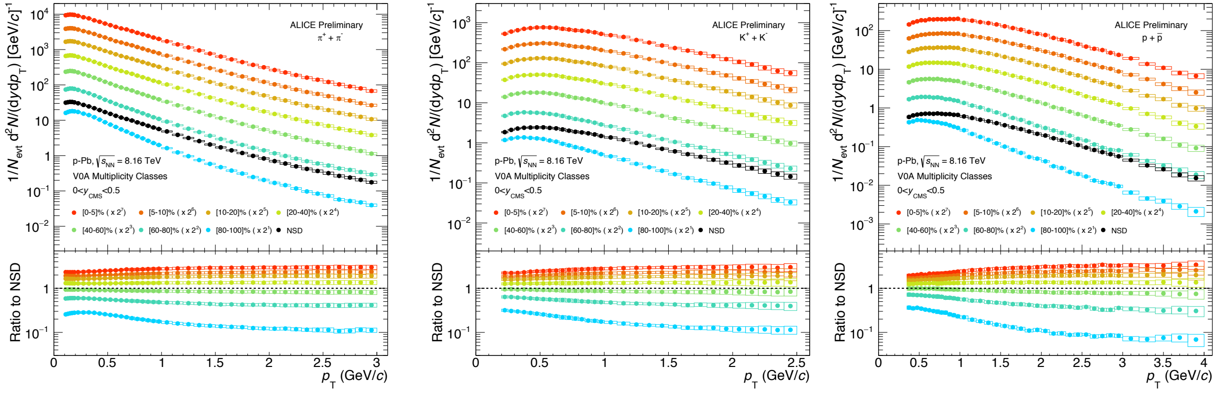
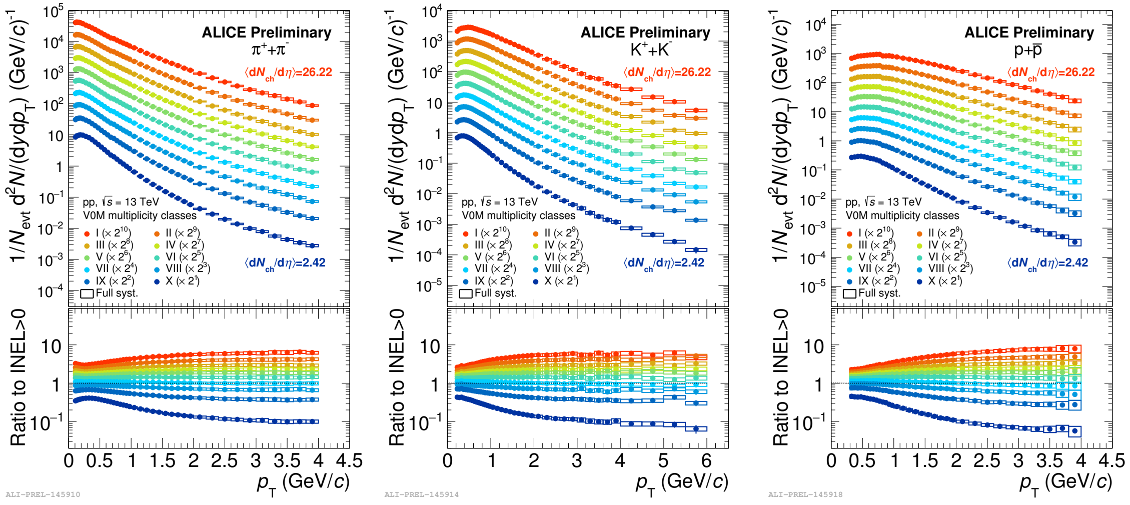
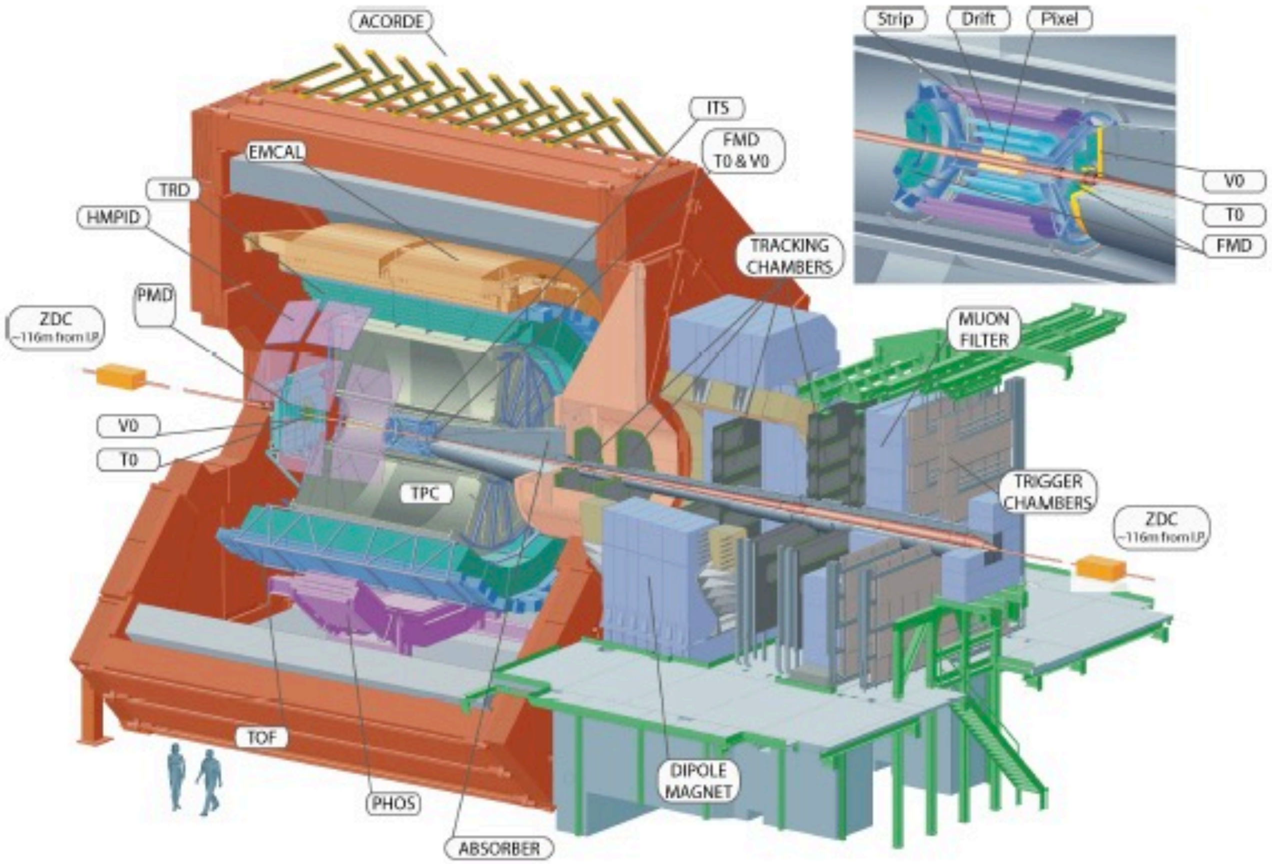


pPb



pp

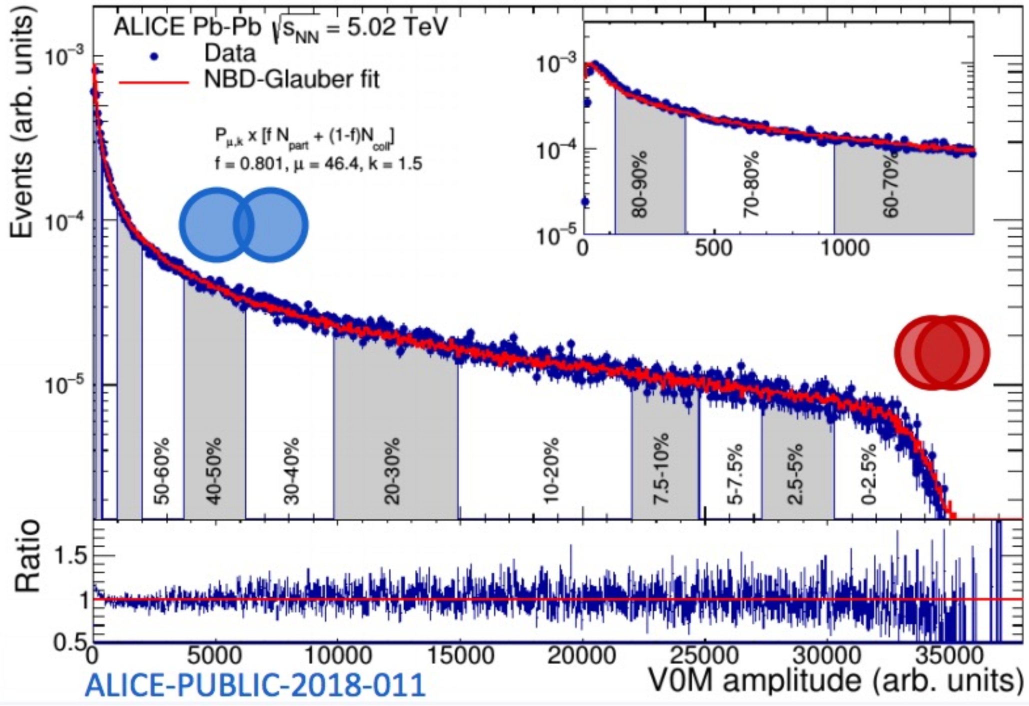
A Large Ion Colliding Experiment

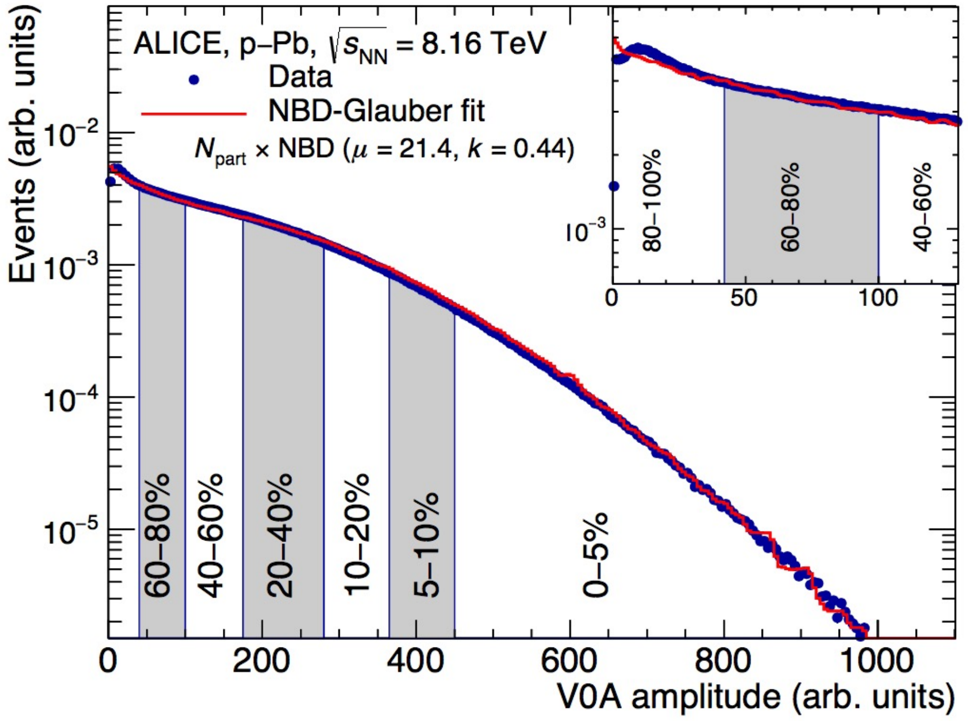


- Detectors used in this analysis are:
- ITS ($|\eta|$<0.9)
  1. 6 layers of silicon detectors
  2. Used for trigger, tracking, vertexing, PID (dE/dx)
- TPC ($|\eta|$<0.9)
  1. Gas-filled ionisation chamber
  2. Used for tracking, vertexing, PID (dE/dx)
- V0A (2.8< η <5.1 Pb-going direction)
  1. Forward scintillator arrays
  2. Used for trigger and multiplicity estimation

Event multiplicity & centrality

- Multiplicity is defined as the number of charged particles per event
- Linked through the impact parameter to the collision centrality in Pb–Pb
- ALICE measures the event activity at forward rapidity with the V0 detector
- Wide range of measured multiplicities from ≈ 2 in pp to ≈ 2000 in central Pb–Pb

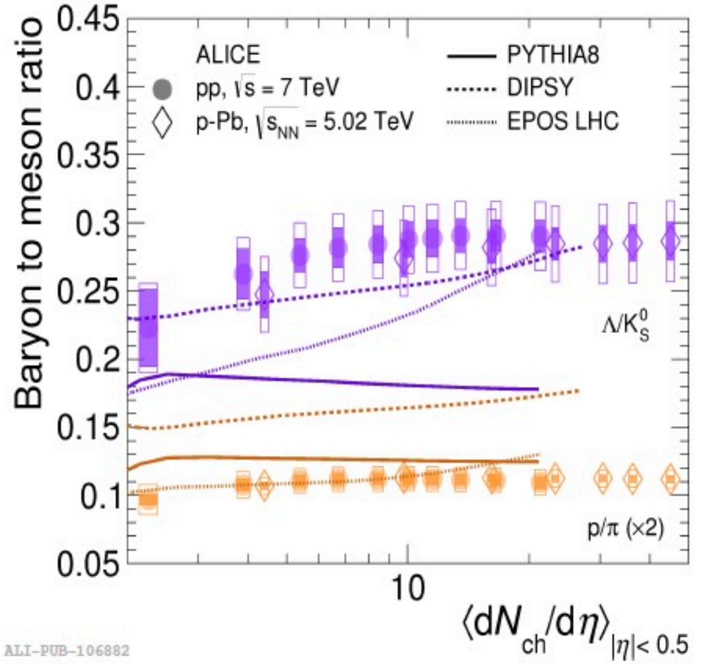


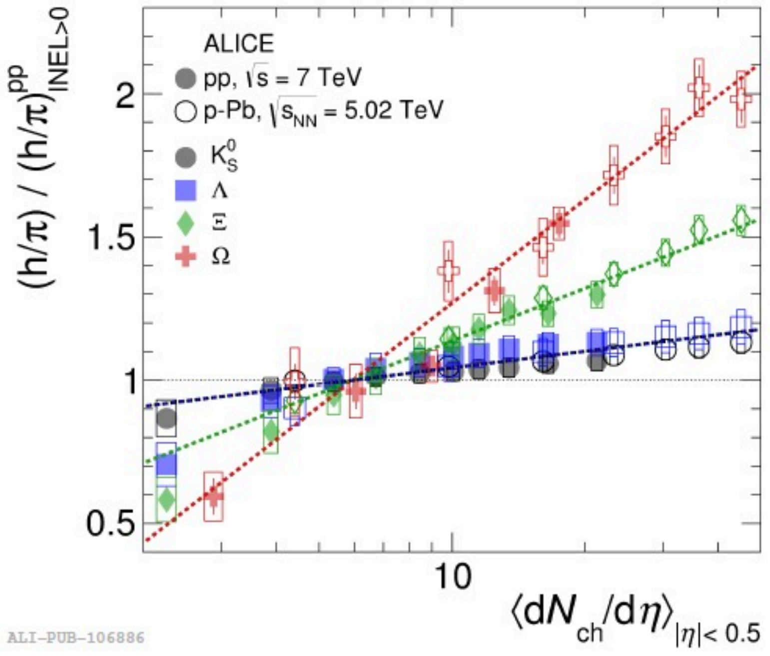


Strangeness

- Yield ratios do not change significantly with multiplicity → enhancement in the production rate of strange hadrons is not a mass-related effect
- Models cannot describe the ratios simultaneously

ALICE, Nature Physics 13 (2017) 535

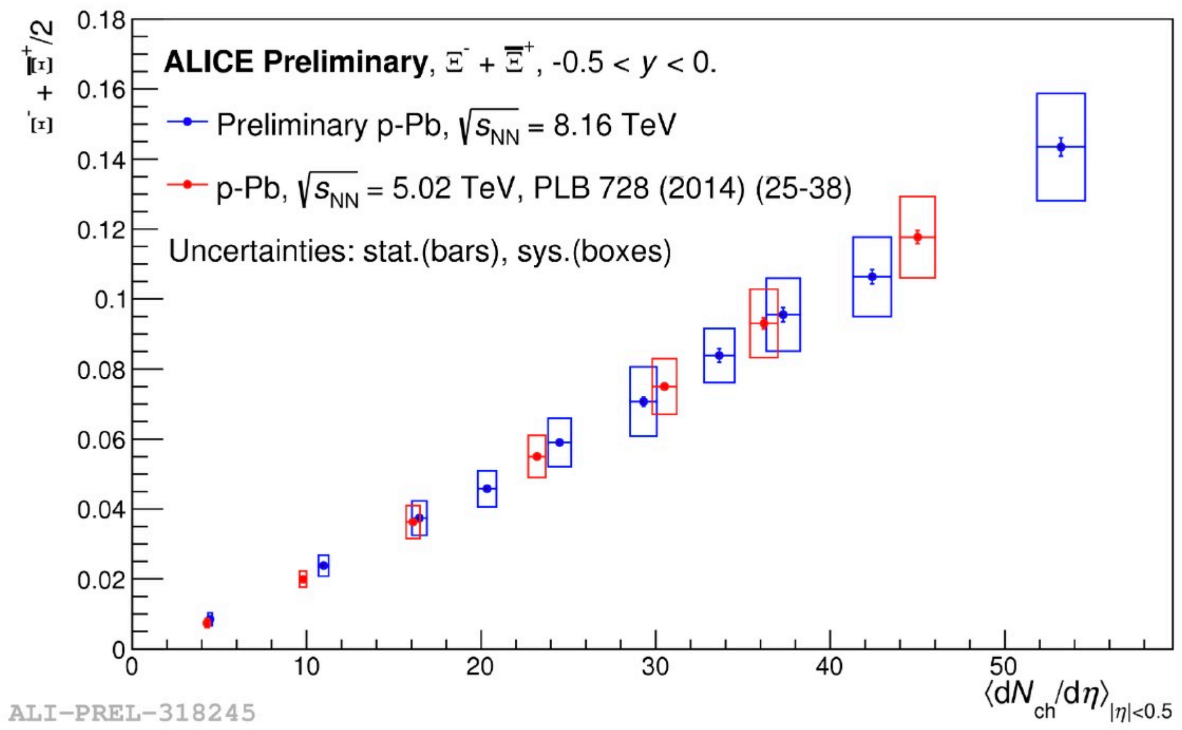


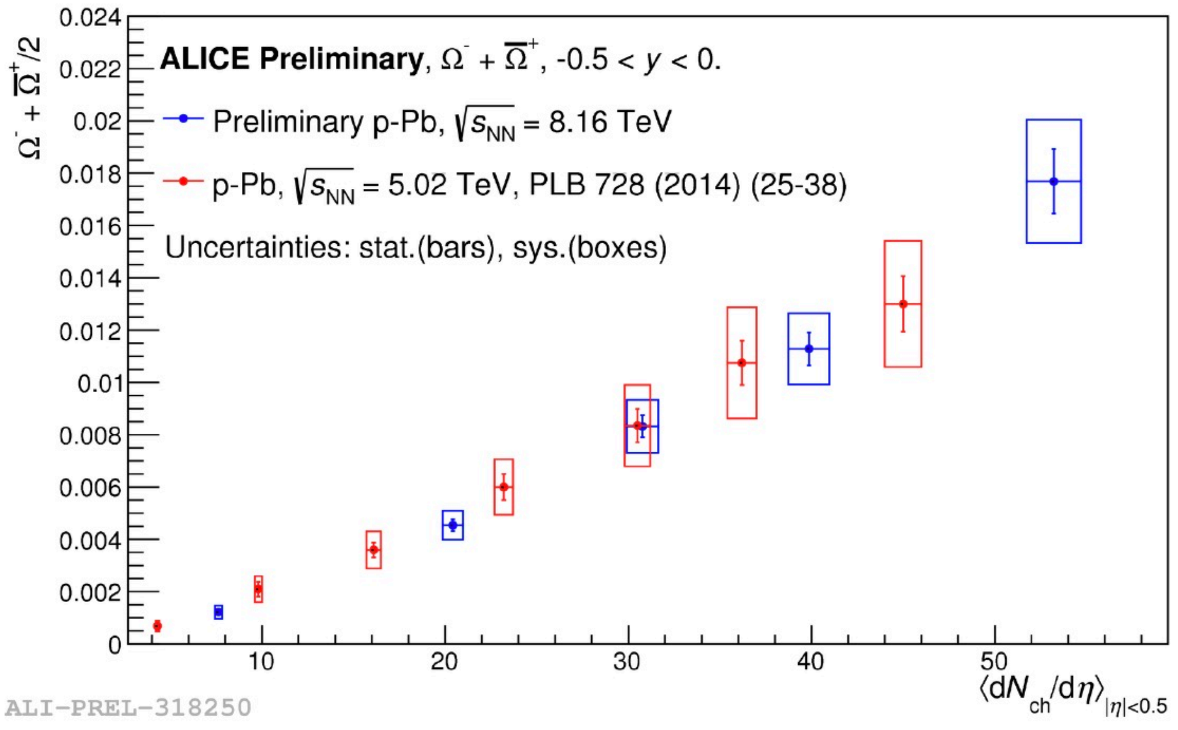


Yield ratios to pions divided by the values measured in the inclusive pp sample

The hierarchy in the observed multiplicity dependent enhancement is determined **by the hadron strangeness**

Strangeness: integrated yields on p-Pb data at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

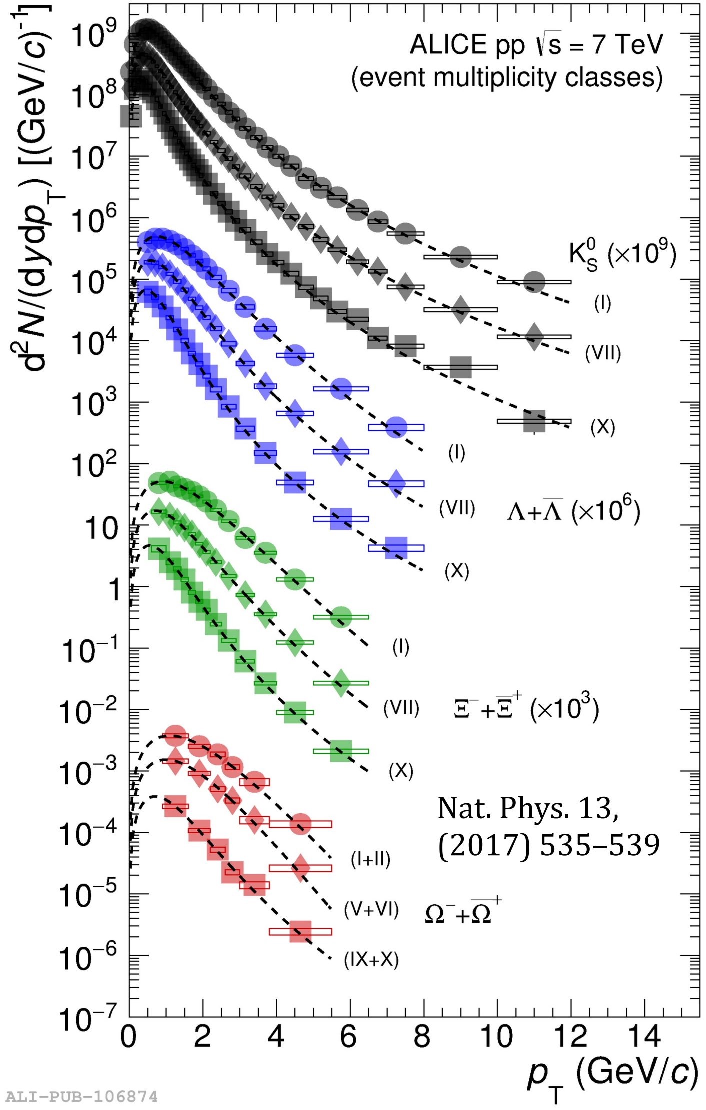


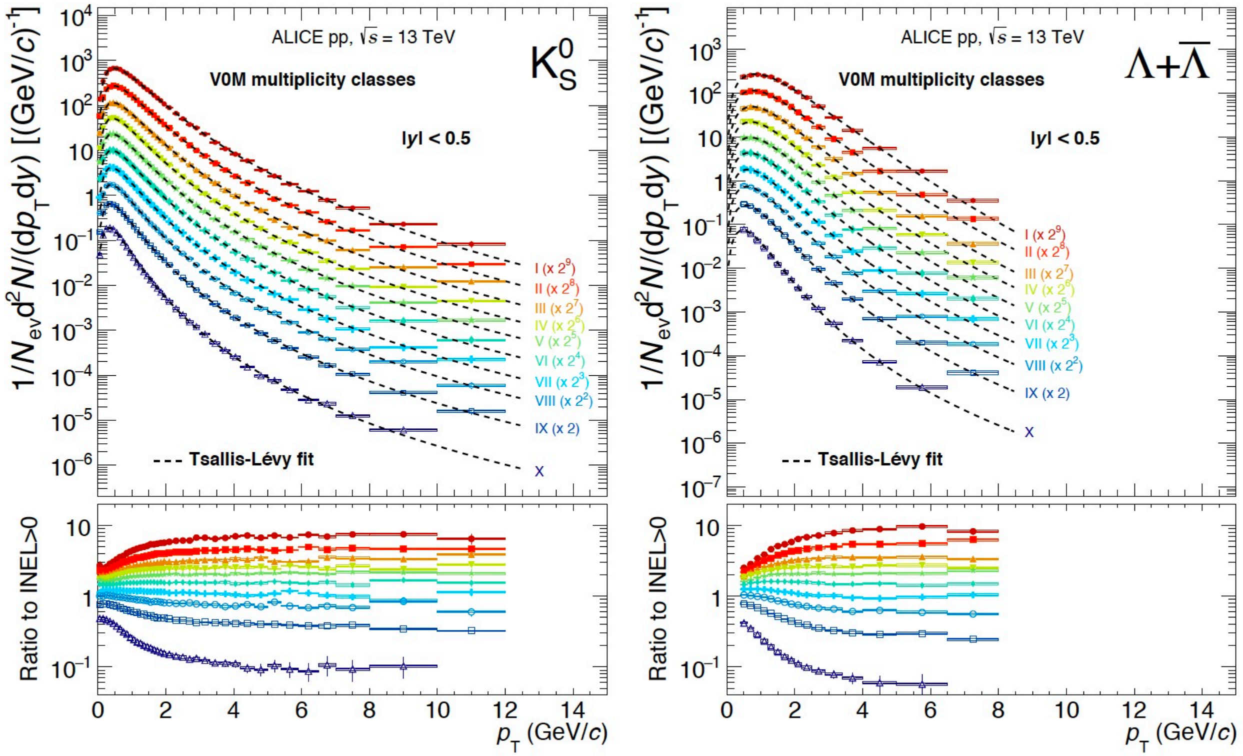


Integrated yields agree with p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV for a given multiplicity
→ no dependence on the collision energy is observed

Strangeness: p_T spectra in pp data at $\sqrt{s}$ = 7 and 13 TeV

arXiv:1908.01861v1 [nucl-ex]



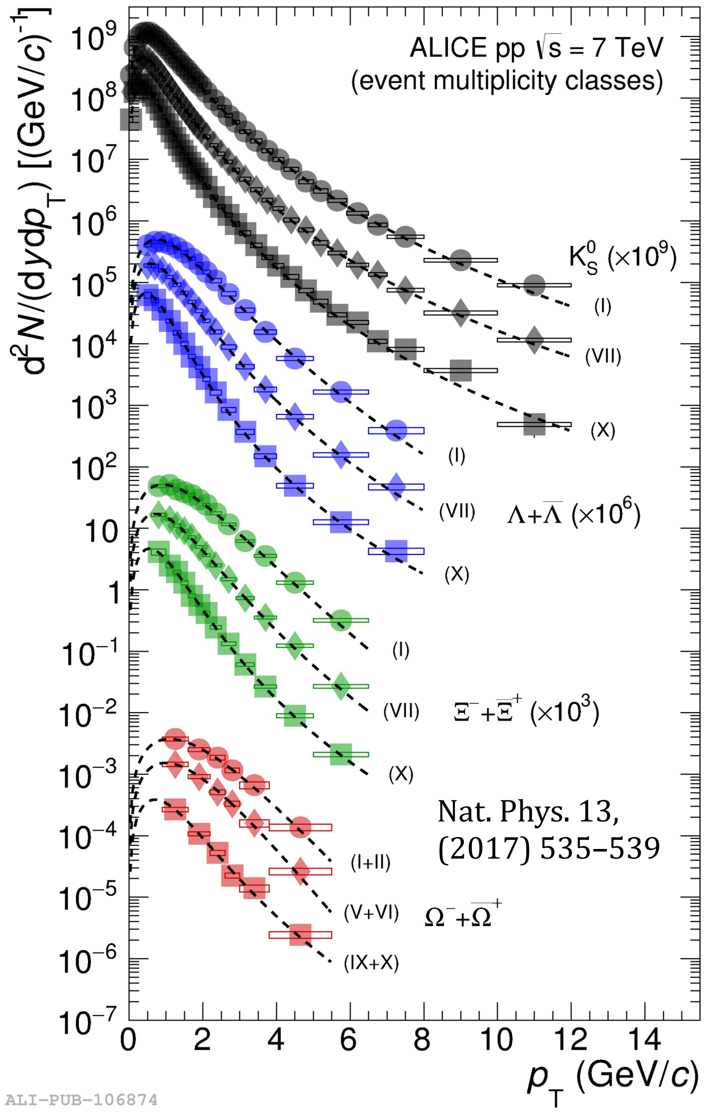


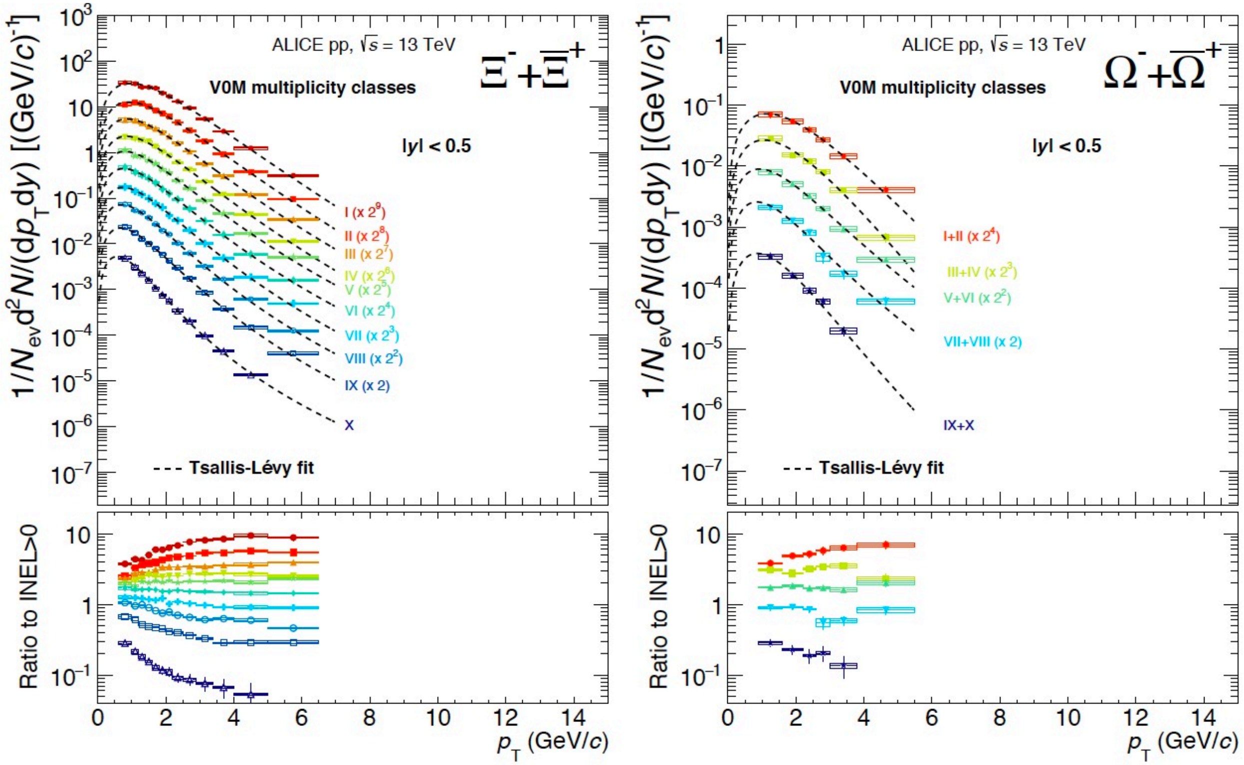
Spectra on pp show a shape evolution similar to the one in Pb-Pb

Hardening of the spectra with increasing multiplicity, more pronounced for higher mass → typically explained in Pb-Pb collisions through the emergence of collective behaviour, described by hydrodynamical models

Strangeness: p_T spectra in pp data at $\sqrt{s}$ = 7 and 13 TeV

arXiv:1908.01861v1 [nucl-ex]

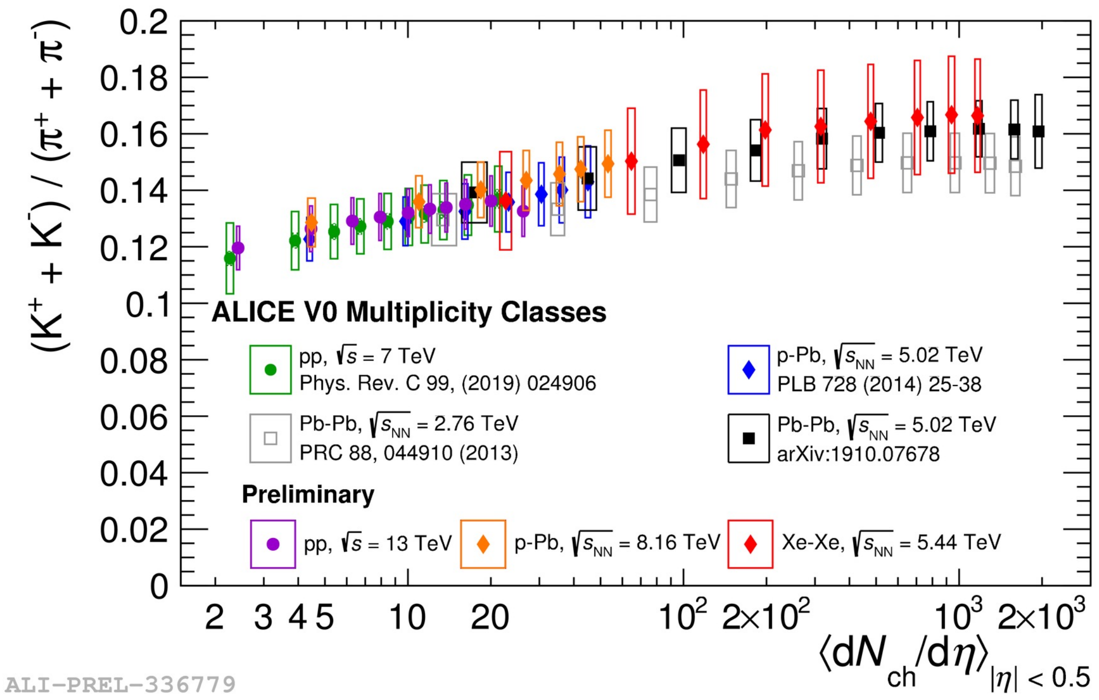


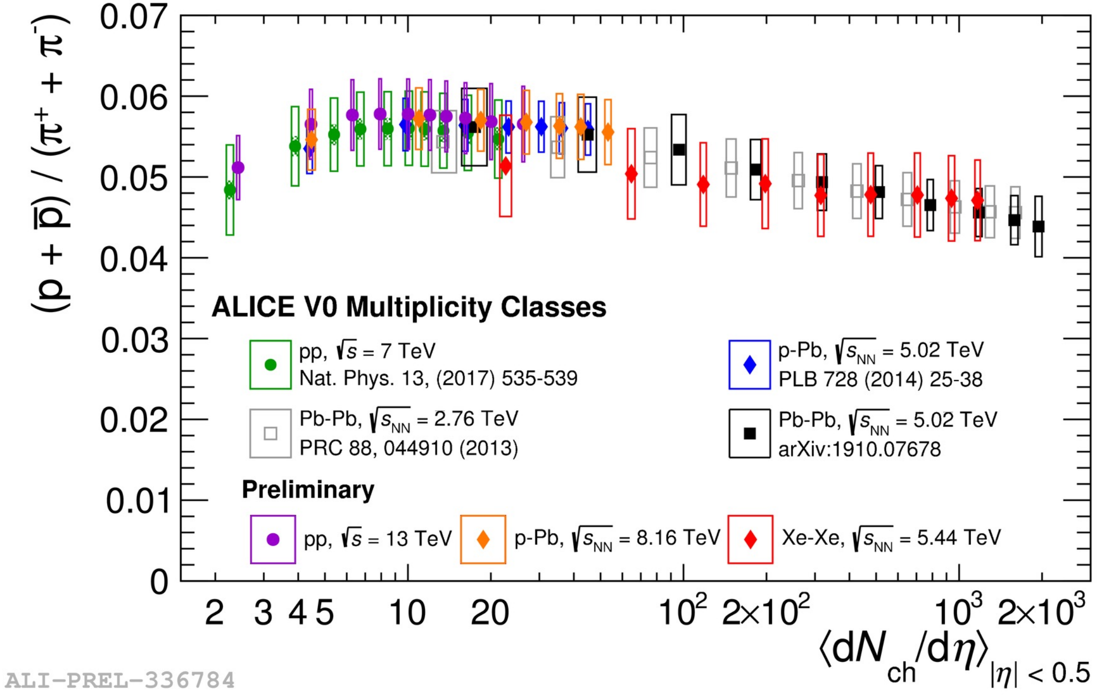


Spectra on pp show a shape evolution similar to the one in Pb-Pb

Hardening of the spectra with increasing multiplicity, more pronounced for higher mass → typically explained in Pb-Pb collisions through the emergence of collective behaviour, described by hydrodynamical models

Ratios of integrated yields



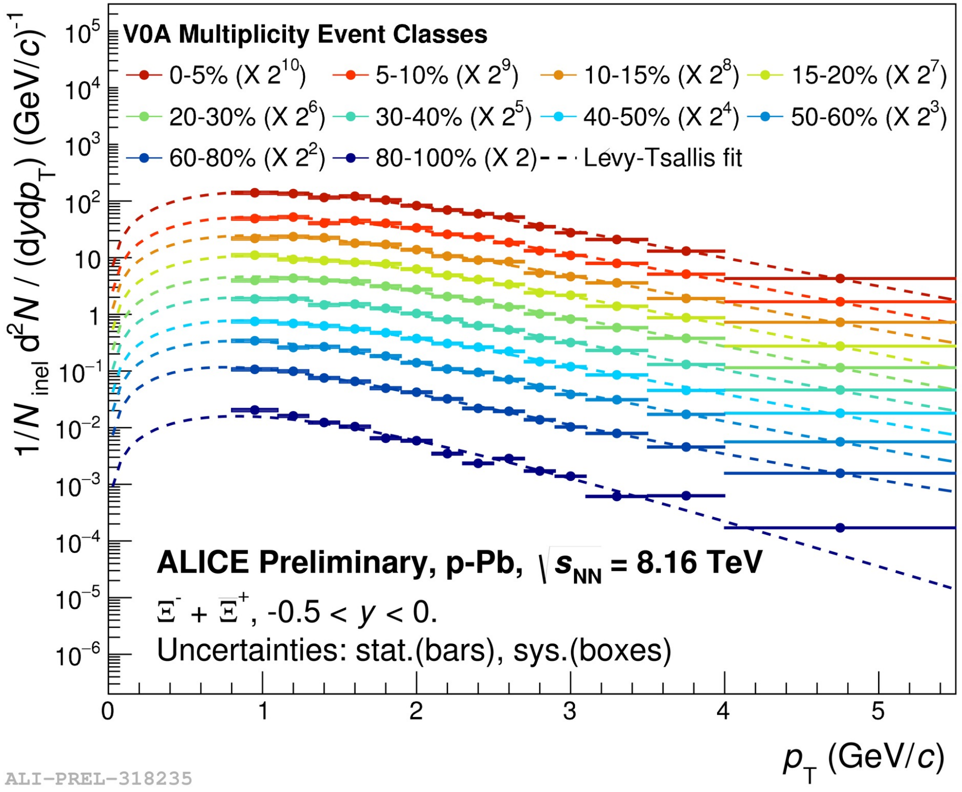


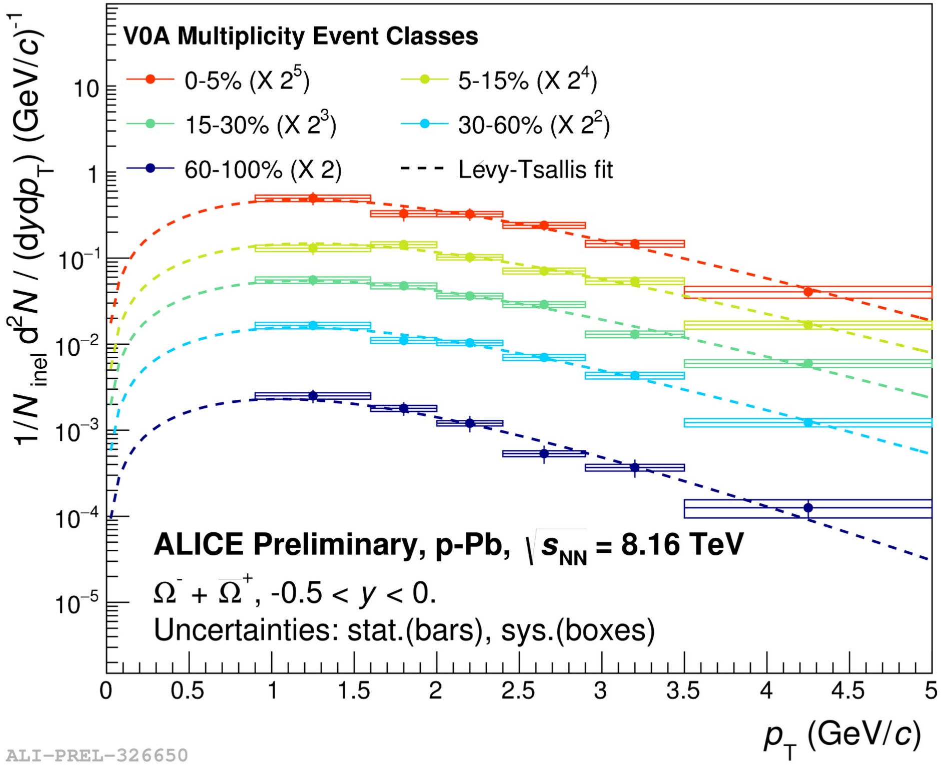
A continous evolution with multiplicity is observed, independent of the collision system

Latest results for π, K, p in p-Pb@$\sqrt{s_{NN}}$ = 8.16 TeV confirm the trend

Ratios in small collision systems at high multiplicity reach heavy-ion values

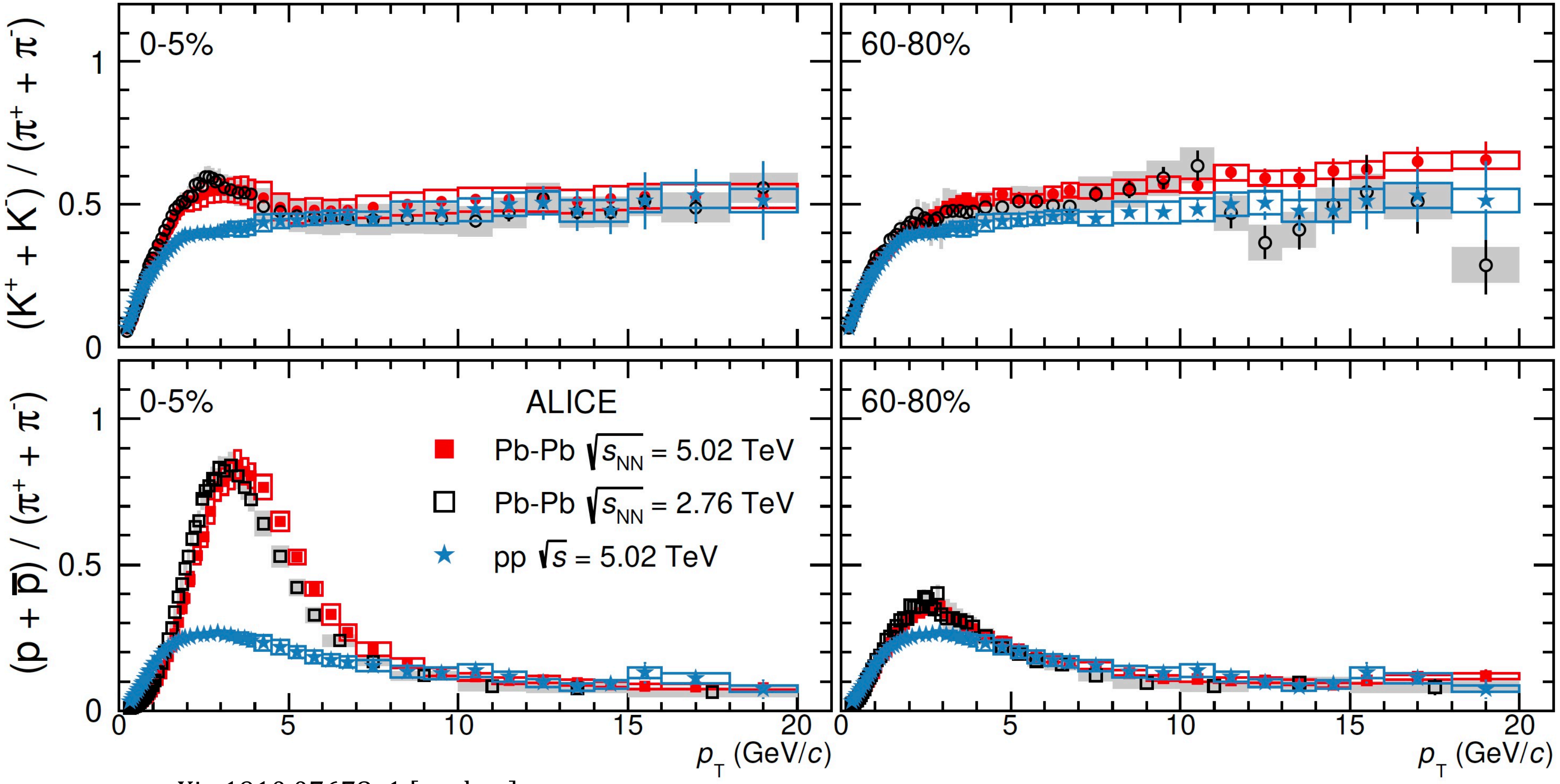
Multi-strange bayons: p_T spectra in p-Pb data at $\sqrt{s_{NN}} = 8.16$ TeV





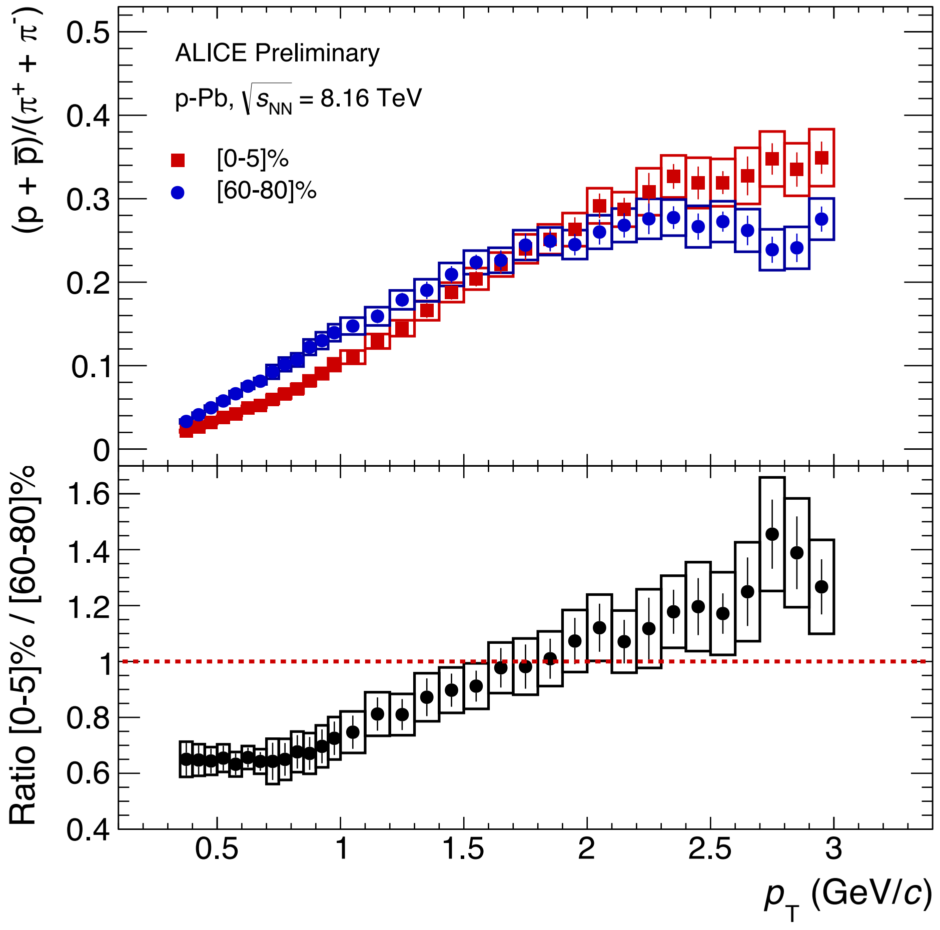
Latest results in p-Pb at $\sqrt{s_{NN}} = 8.16$ TeV

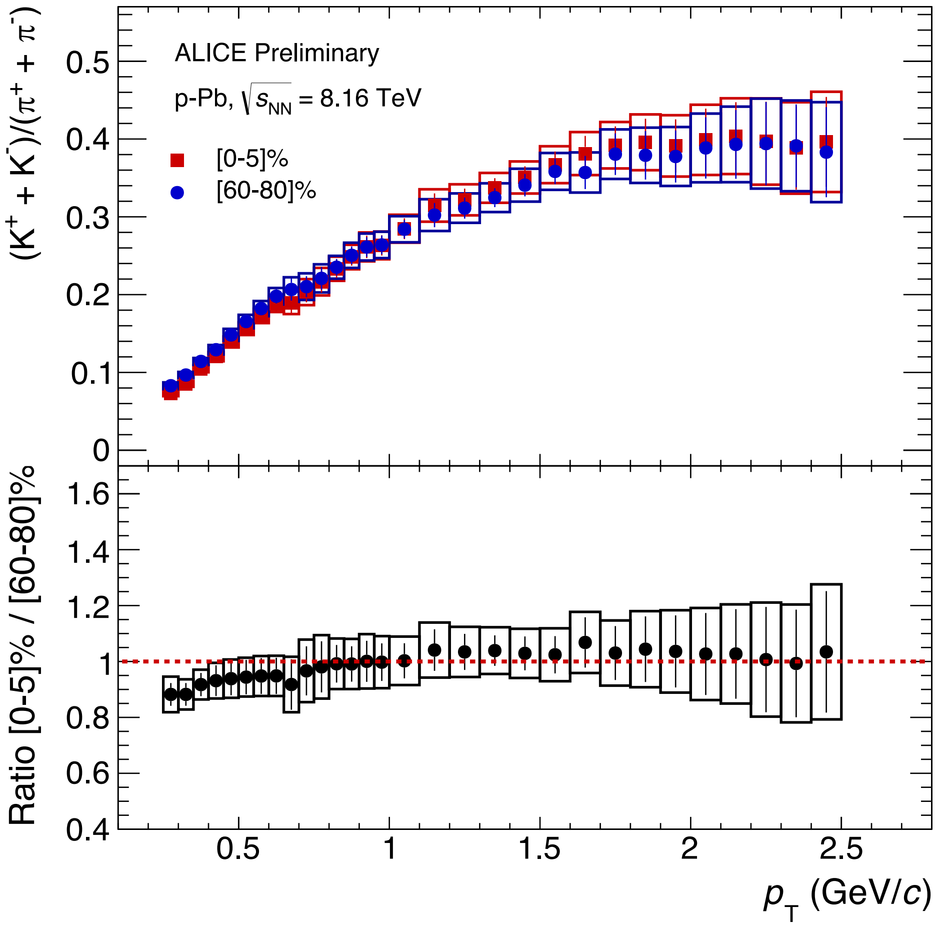
Ratios to pions: evolution with multiplicity



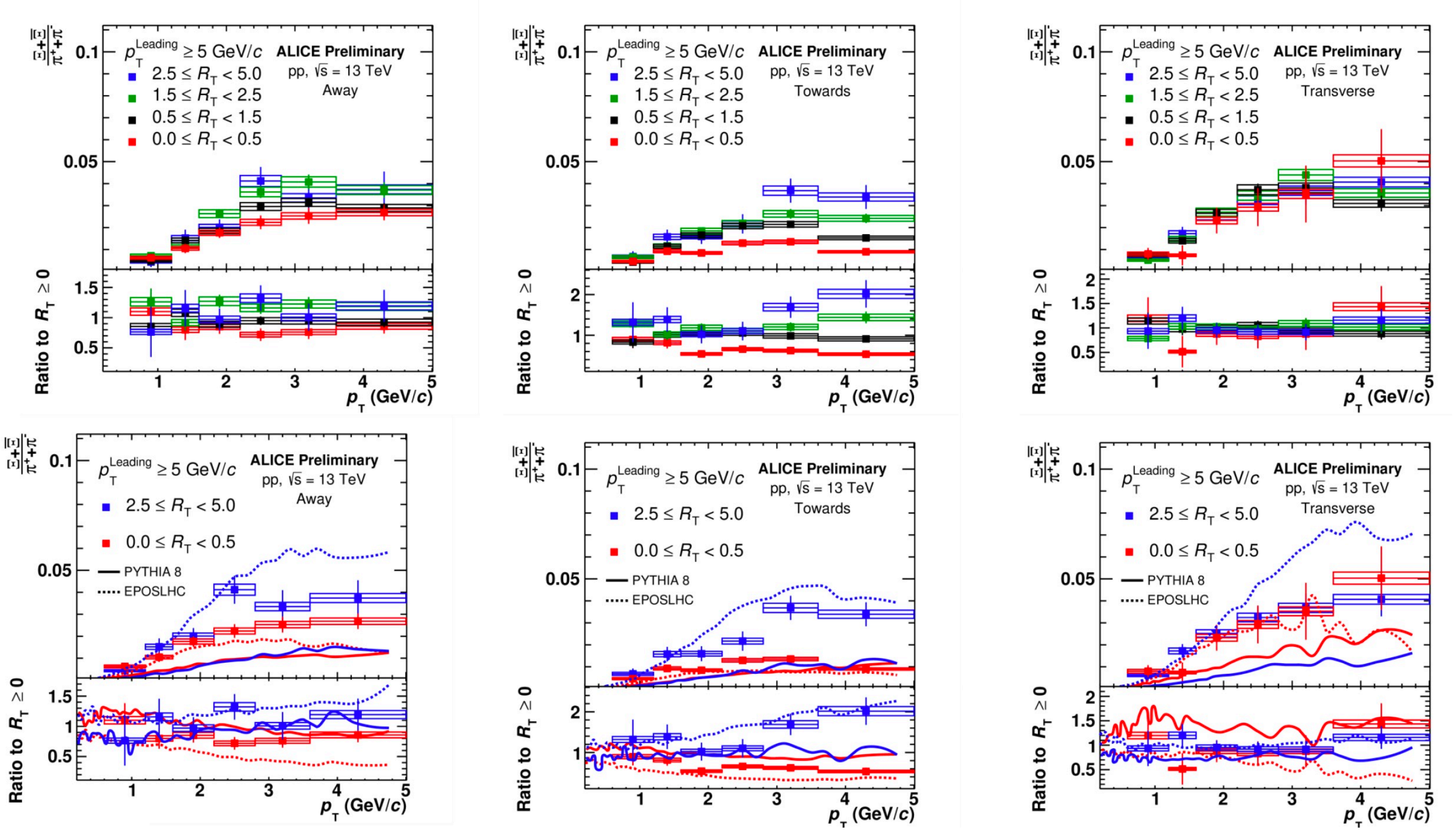
arXiv:1910.07678v1 [nucl-ex]

Ratios to pions: evolution with multiplicity





Light-flavour hadrons *vs.* R_T



p_T-spectra for π, p, Ξ in pp @$\sqrt{s}$ = 13 TeV

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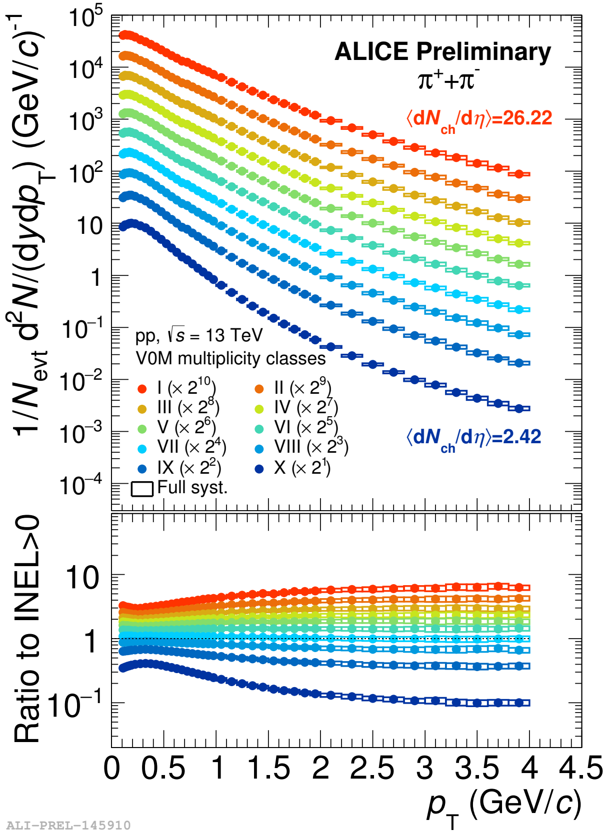
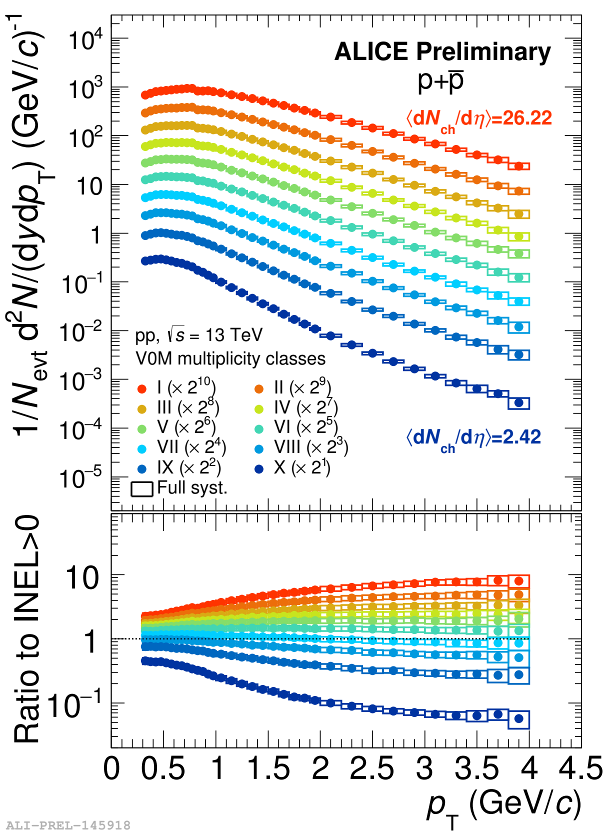
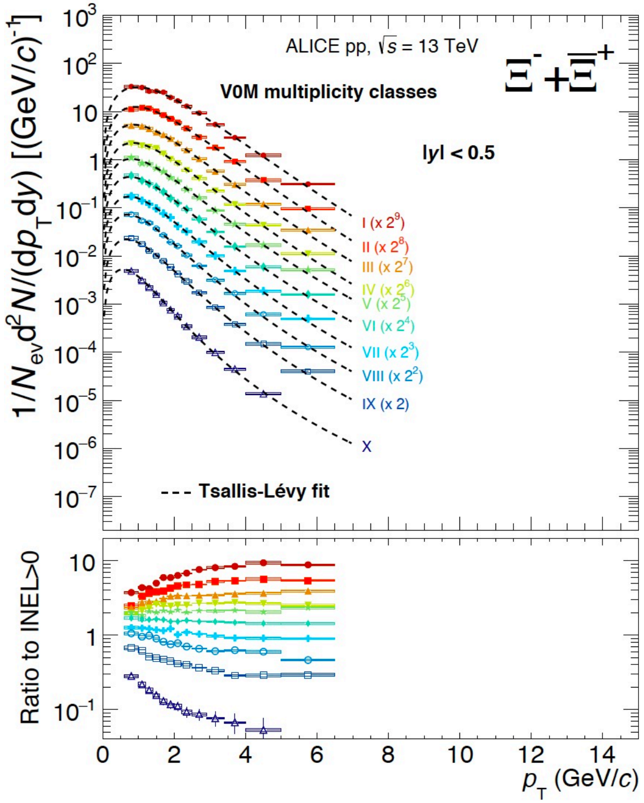
arXiv:1908.01861v1 [nucl-ex]







1. Spectra become harder as the multiplicity increases (flattening visible at intermediate p_T)
2. Hardening of the spectra with increasing multiplicity, more pronounced for higher mass → understood in Pb-Pb through radial flow

Integrated particle yields

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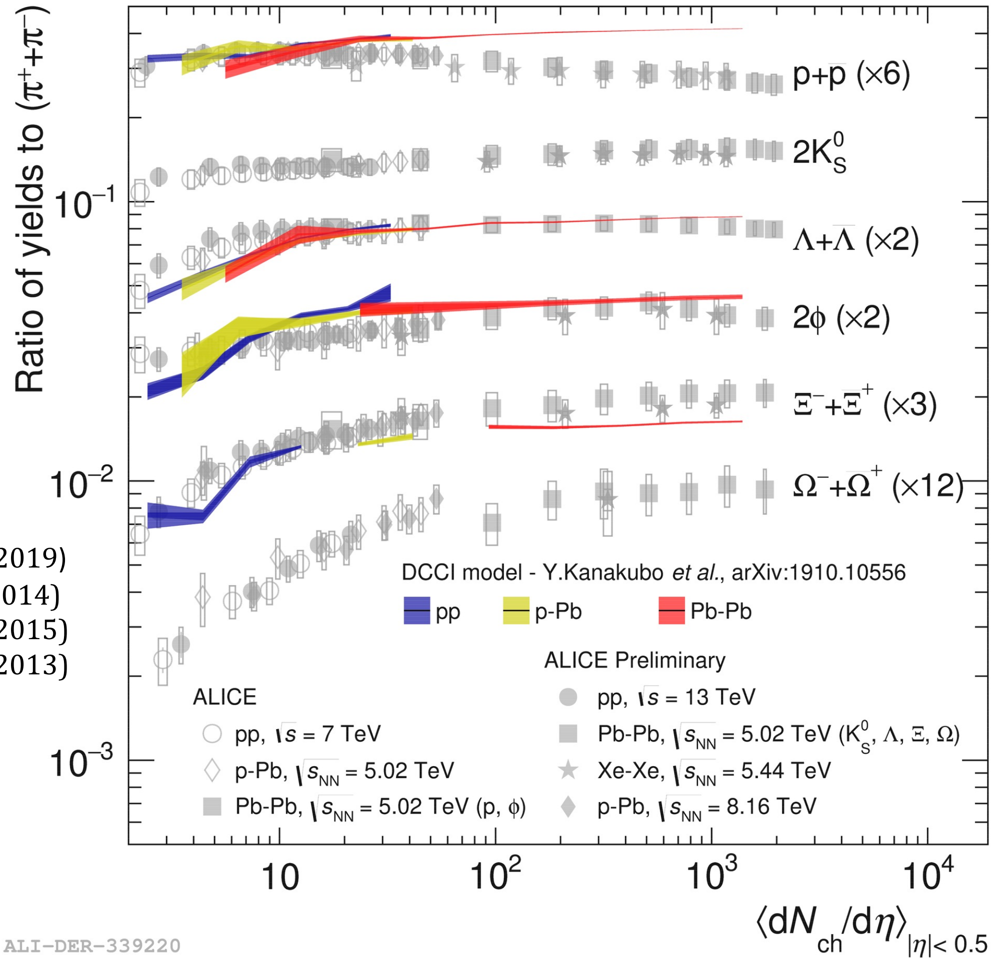

PRC 99, 024906 (2019)
PLB 728, 25-38 (2014)
PRC 91, 024609 (2015)
PRC 99, 044910 (2013)

- The integrated particle yields exhibit a **continuous evolution with the charged particle multiplicity** independent of the collision system
- Abundances of strange hadrons are invariant with the collision energy at similar multiplicities
- At large multiplicities small systems reach the values observed in heavy-ions
- Chemical composition seems to be driven by $\langle dN_{ch}/d\eta\rangle$ and not by the collision system