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Strangeness production from small to large systems at the LHC

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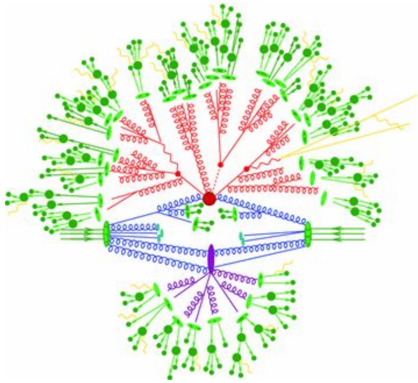
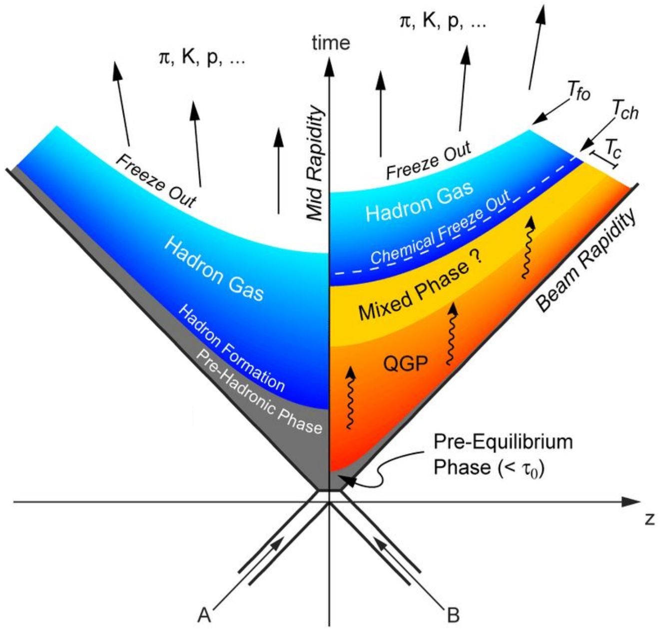
Small colliding systems:

- Early times dominated by hard jets
- Presence of several partonic primary collisions (MPI) set a semi-hard scale
- UE → soft scale
- hadronization described through effective description of QCD potential
- cross-talk among (mini-)jets (and UE?) necessary to explain dynamics (normally introduced ad-hoc)





Large colliding systems:

- Huge number of partonic collisions, softening through time →collective partonic motion →Viscous hydro
- hadronization when temperature drops T_{ch} →statistical approach to particle production
- s quark sufficiently light to participate to collective motion and to hadronize statistically

Large VS small systems

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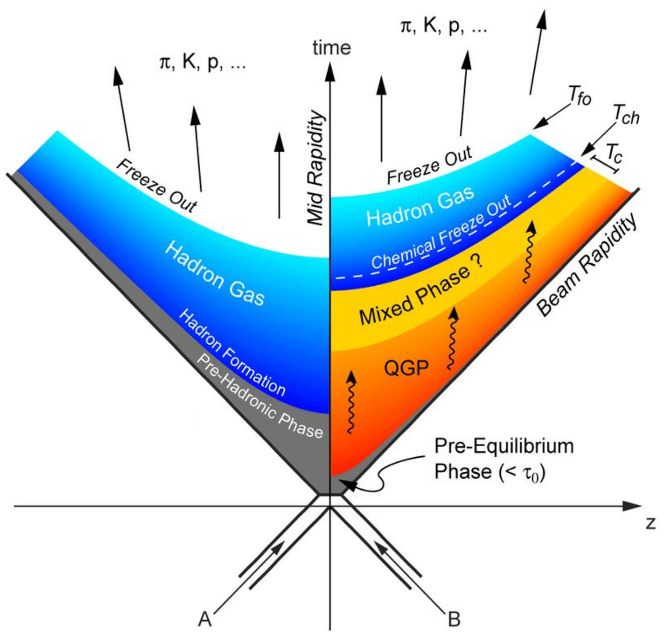

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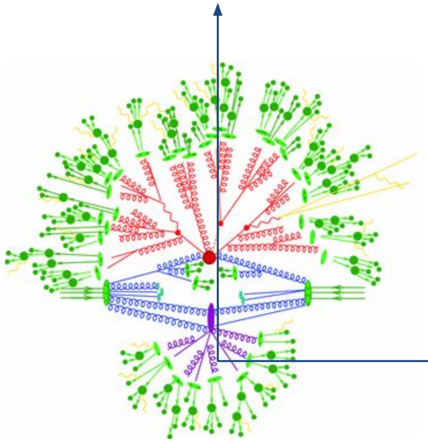
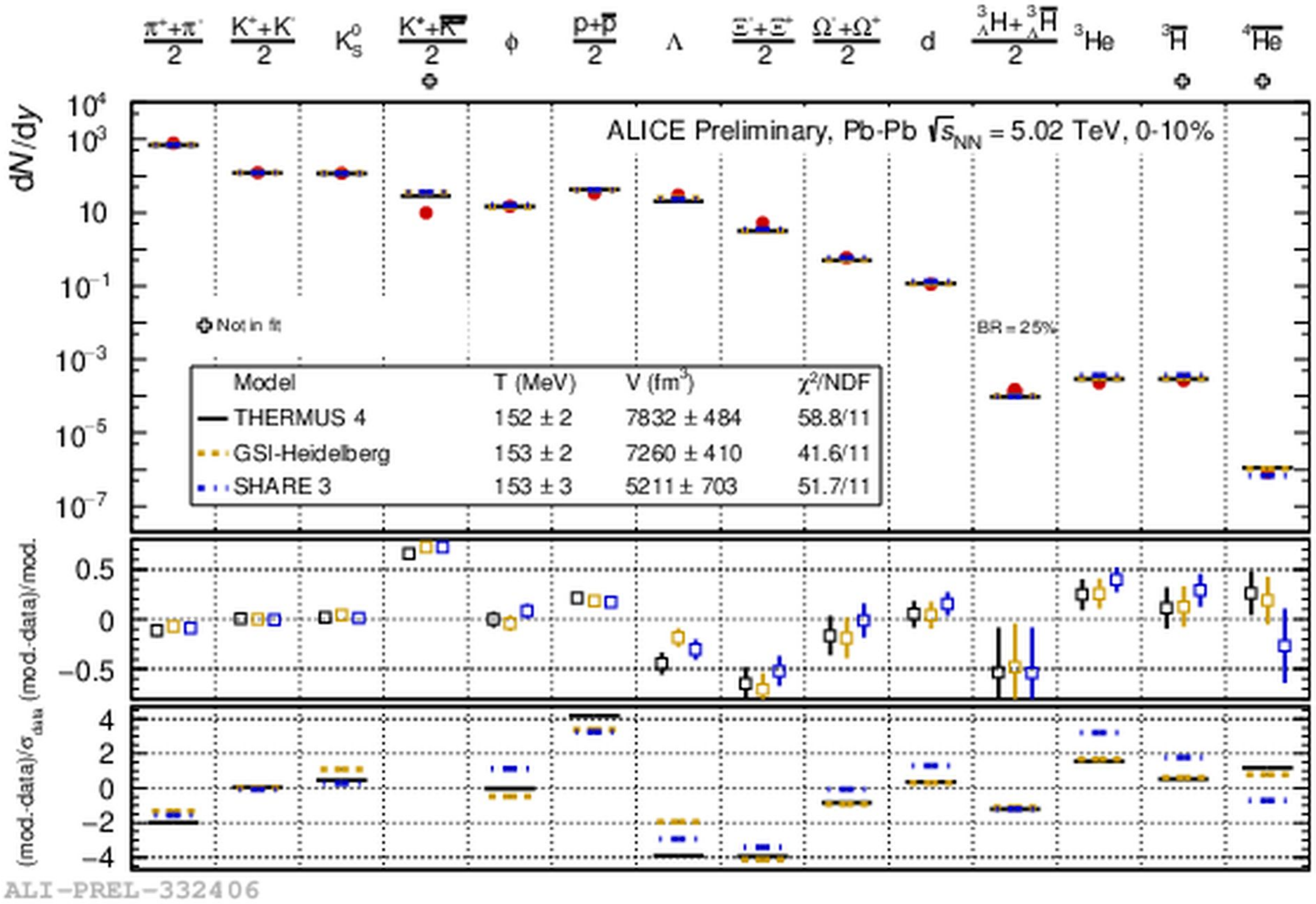


Large systems as an extension of in-vacuum hadronization with large #MPI?

can small system be described by statistical hadronization (canonical + hadron scattering, + s-undersaturation, +...?) and far from equilibrium hydro?

Large systems: the reign of statistical hadronization



Production of light flavor hadrons fit over 9 orders of magnitude by Statistical Hadronization Model (SHM) in its Grand Canonical Ensemble (GCE) formulation

Hadron yields can be described as emerging from a hot Hadron-Resonance Gas in thermal equilibrium

At LHC: μ_B~0 , T_{ch}~ 153 MeV

Nature 561 (2018) 7723, 321-330

Friction with p being addressed through S-matrix approach / re-scattering

Phys. Lett. B 792, 304-309 (2019)

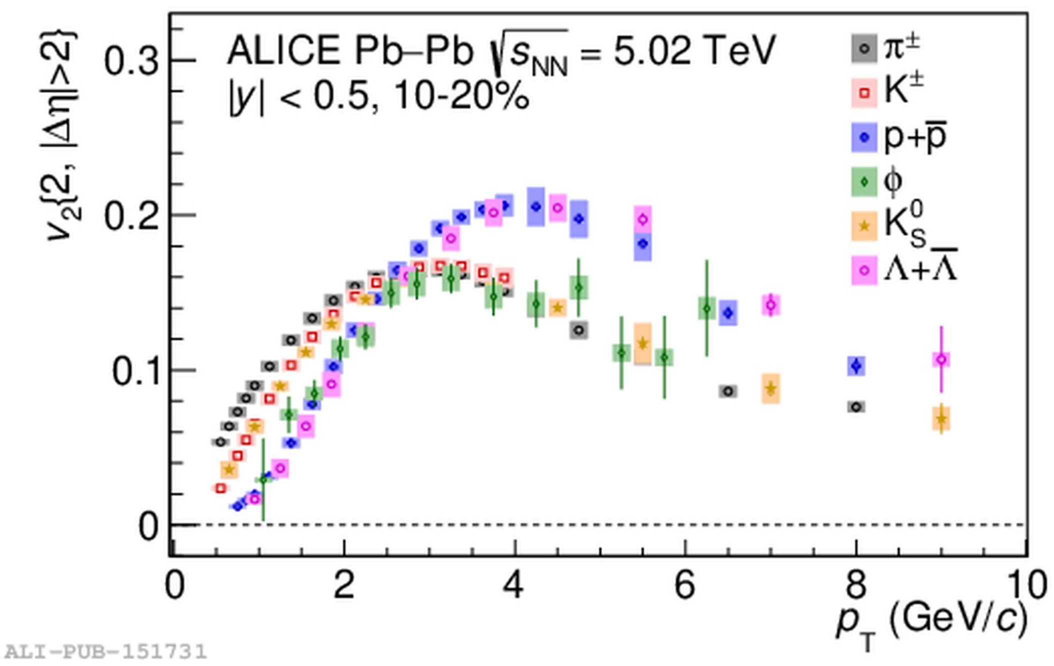
Phys. Rev. C 90 (2014) 5, 054907

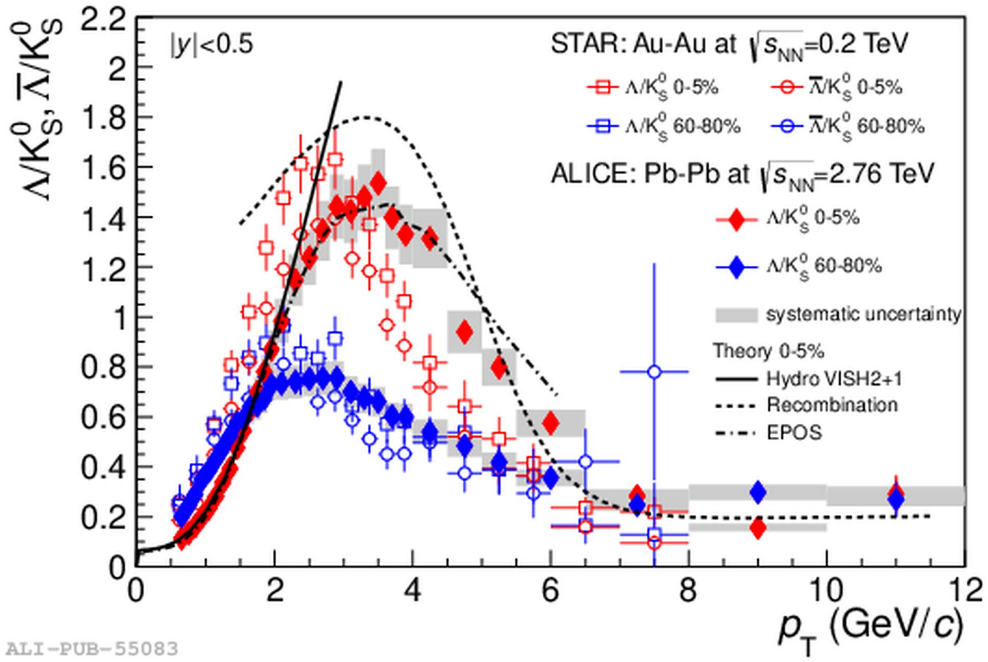
Other approaches try to solve p & *Ξ* issues with flavor-dependent T_{ch}

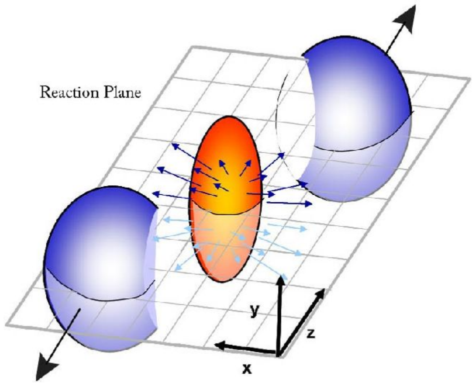
P. Alba et al., Phys. Rev. C 101, 054905 (2020)

- Short-living resonances not described (influence of hadronic phase)

Large systems: the reign of viscous hydro



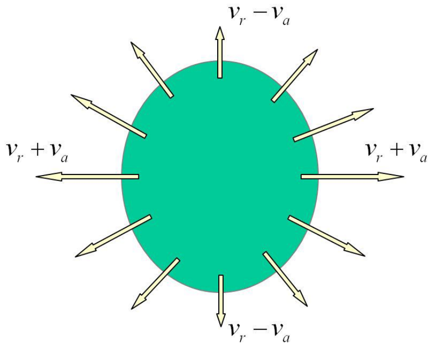




v_2 of strange particles follows mass ordering at low-p_T and meson-baryon splitting at intermediate

hydro explains the behaviour up to a 10-20% accuracy

pivotal role of ϕ

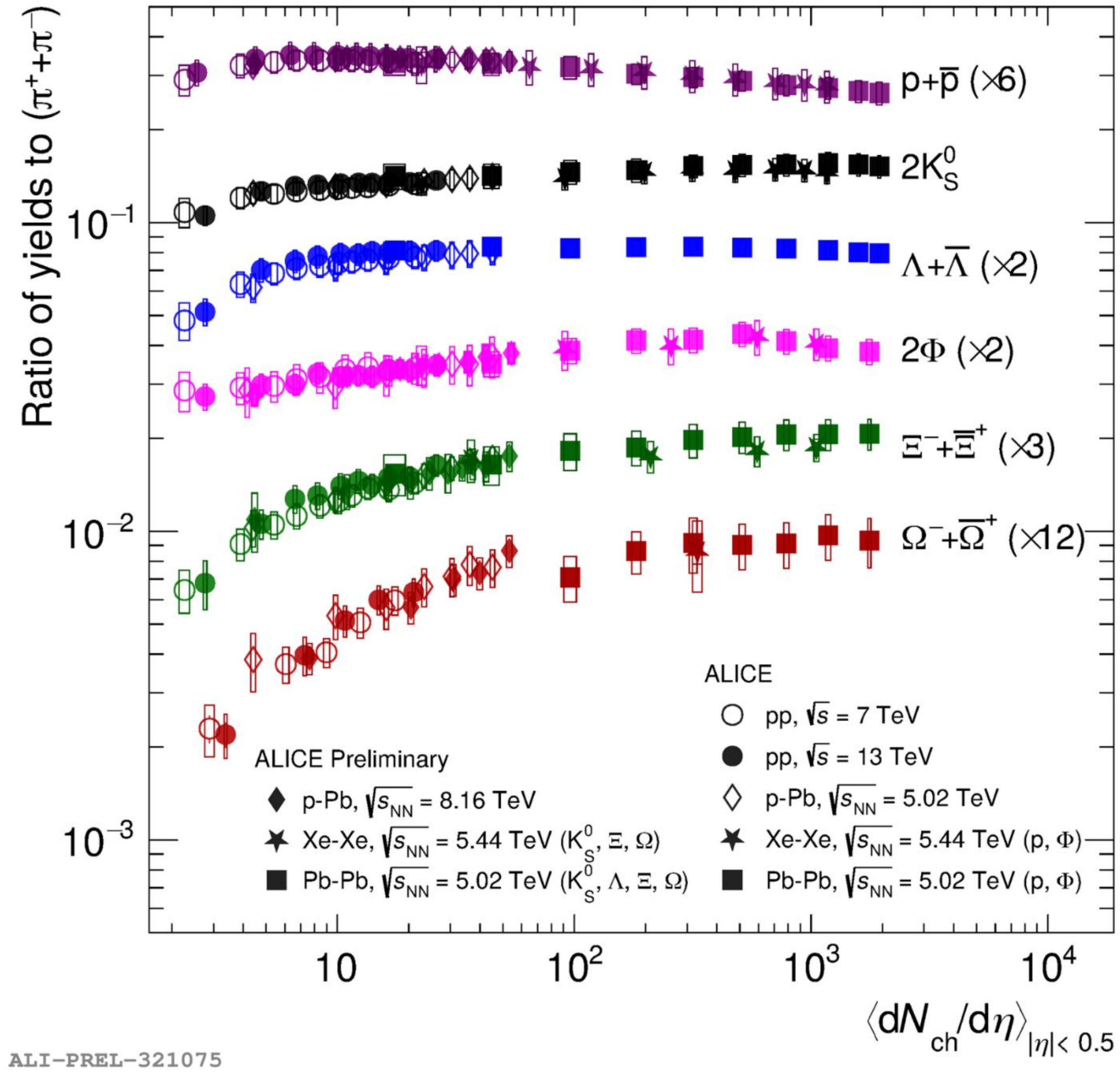


Centrality-dependent spectra hardening & Baryon/meson ratio featuring intermediate-p_T "bump"

↓

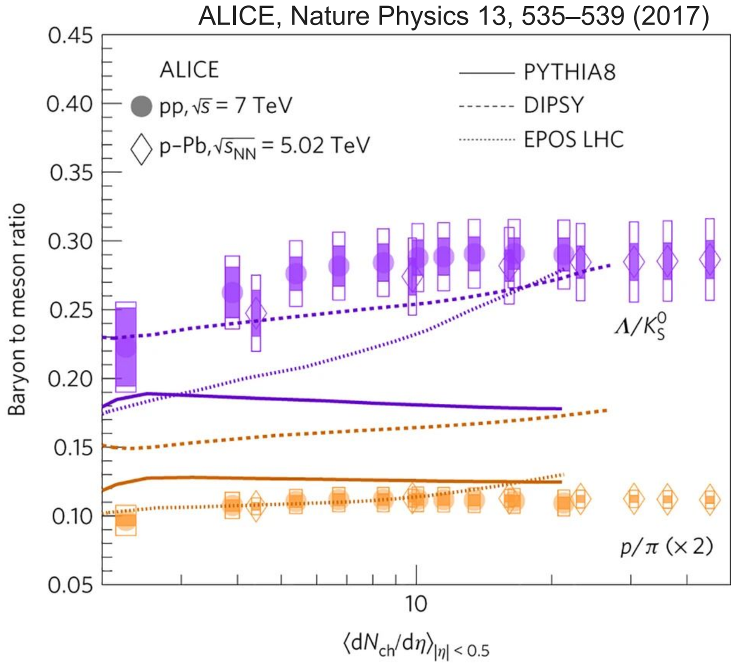
common expansion velocity of partons (radial flow)

Strangeness enhancement from small to large systems



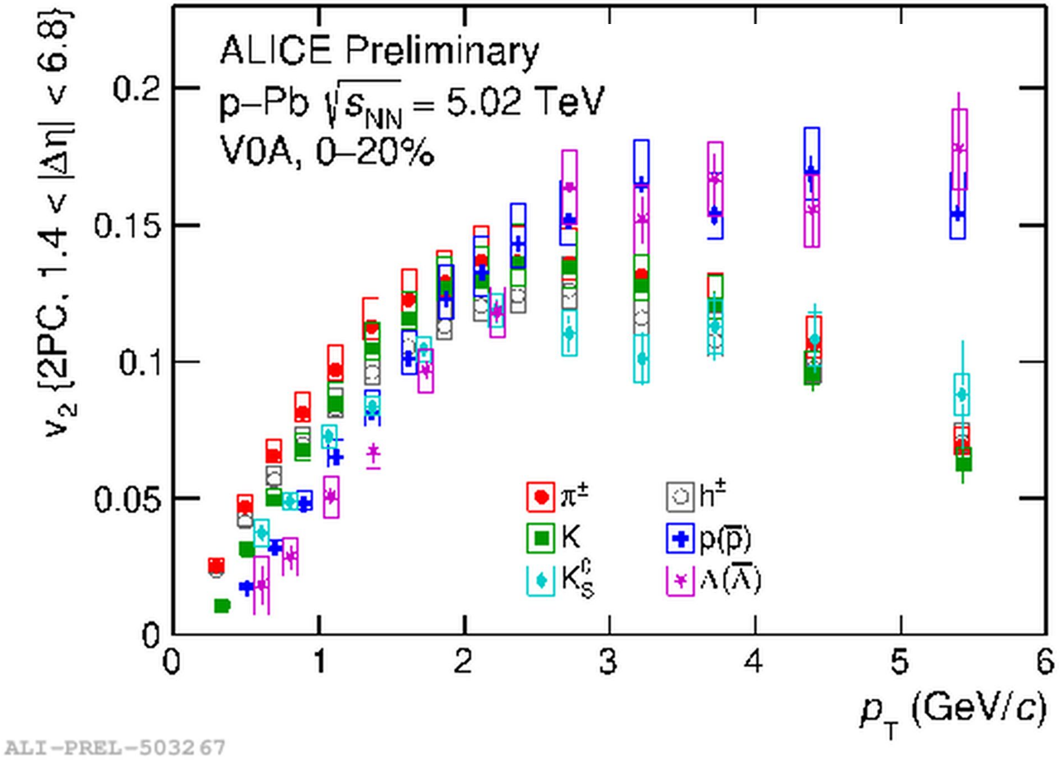
Iconic figure at the LHC:

- smooth strangeness enhancement (SE) VS final state multiplicity
- Strange content hierarchy: SE(Ω) > SE(Ξ) > SE(Λ,K^0_S)
- strangeness- and not baryon-related
- peculiar role of ϕ meson



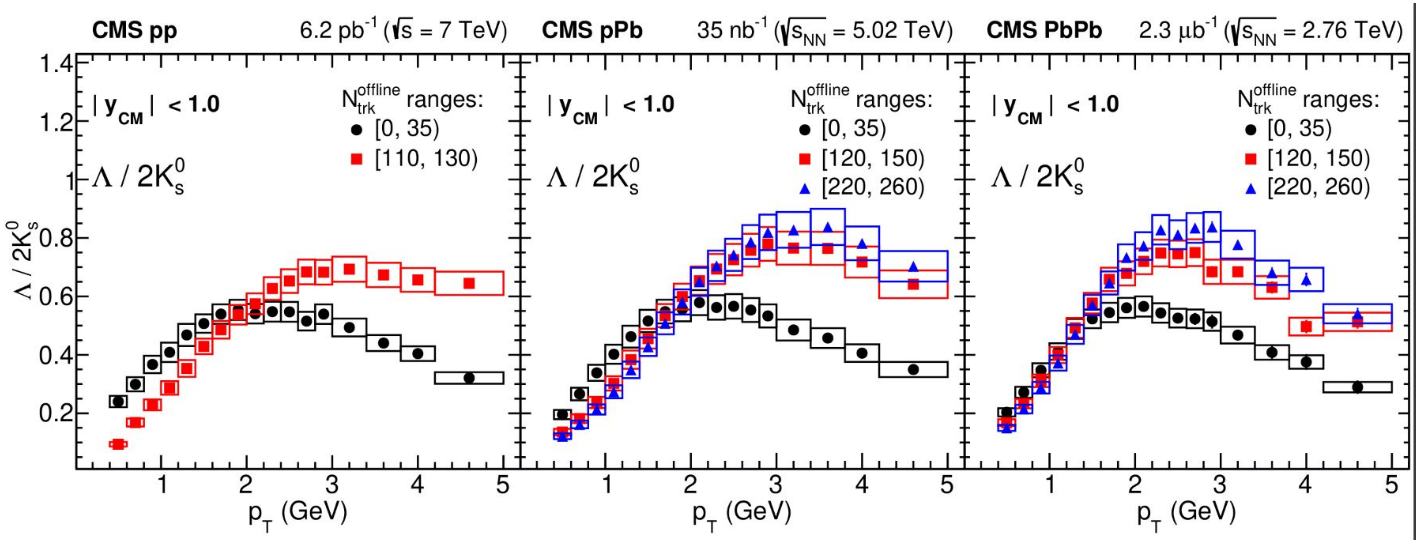
Radial and anysotropic flow…in pp and p-Pb?

V. Vislavicius, talk on Thursday



v_2 observed in small systems (pp and p-Pb) with the hierarchy expected from hydro

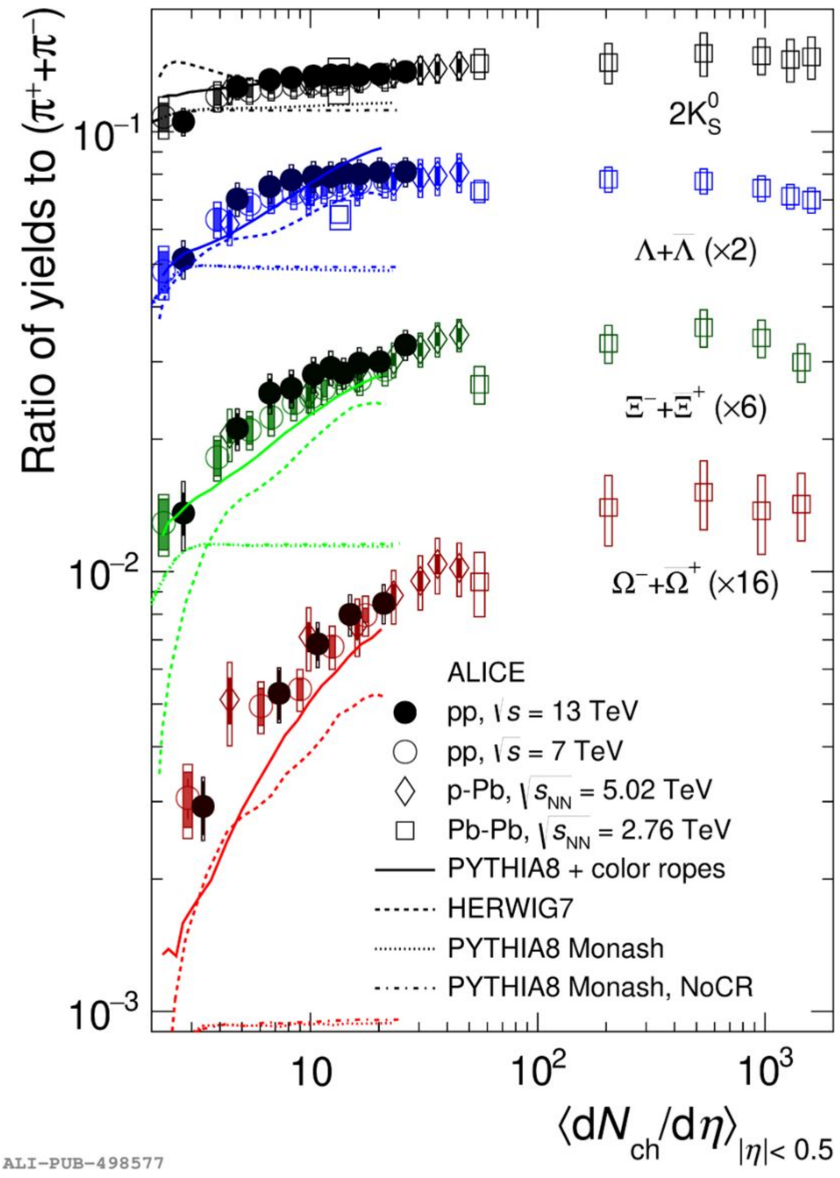
CMS, Phys. Lett. B 768 103(2017)



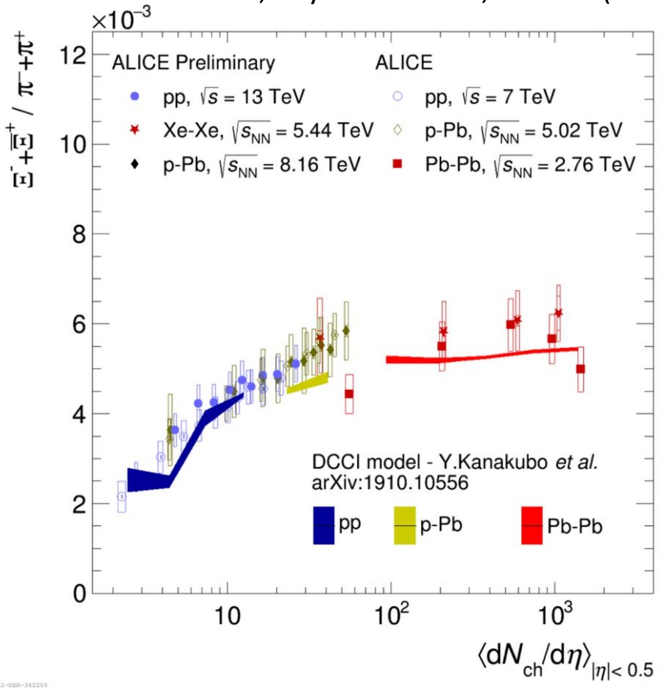
Radial-flow-like features also observed in pp and p-Pb at the LHC, with similar magnitude at similar multiplicities

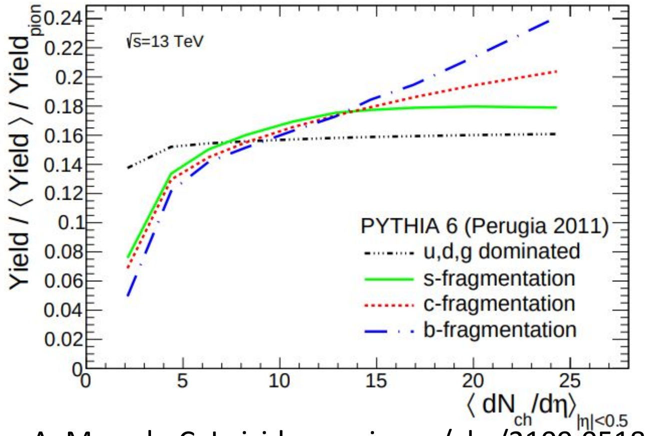
The progress in the interpretation

ALICE Collaboration, Eur. Phys. J. C 80 (2020) 693



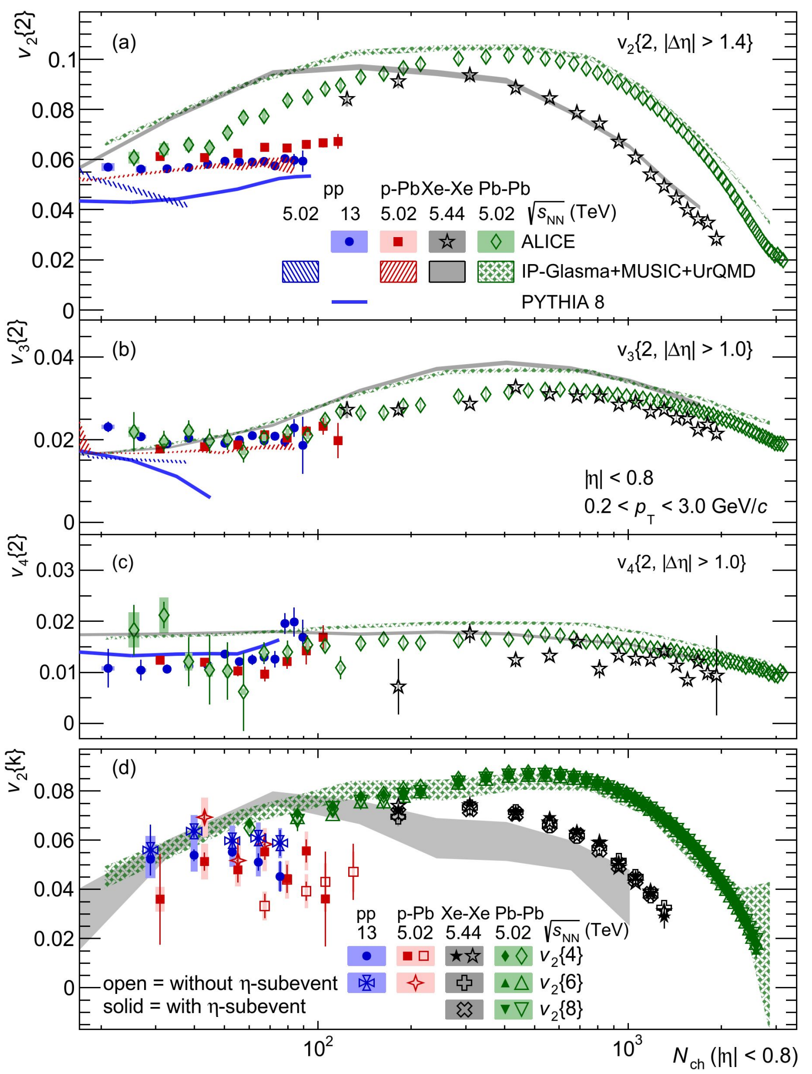
Y. Kanakubo at al., Phys. Rev. C 101, 024912 (2020)





A. Morsch, C. Loizides, arxiv.org/abs/2109.05181

ALICE Collaboration, Phys. Rev. Lett. 123, 142301 (2019)



Very exciting and very depressing

- **Large colliding systems:**
  - Statistical hadron production
  - Viscous hydro
  - Two-component models successful (large dominance of core)
  - Microscopic models (e.g. Pythia Angantyr) in the game

- **Small colliding systems:**
  - Microscopic models are improving hadrochemistry description (ropes) and achieve non-zero v2 (shoving)
    … but even pure MPI+CR attempts are recently emerging..!
  - Two component models ok for hadrochemistry (interplay between core and corona) and basic features of hydro-like phenomena (e.g. radial flow)
  - Hydro far from equilibrium in the game

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  - Hydro far from equilibrium in the game

CHOOSE YOUR WAY!

Need to find <u>FEATURES</u> in the data, cannot play at tuning models ourselves*!

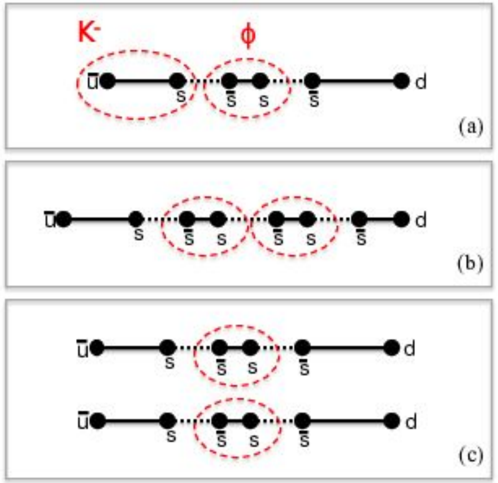
*the experimentalist talking

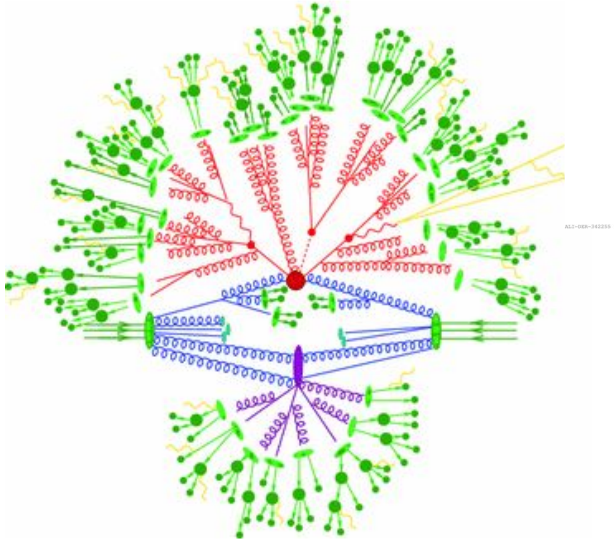
Took a breath, thought about it and tried several paths

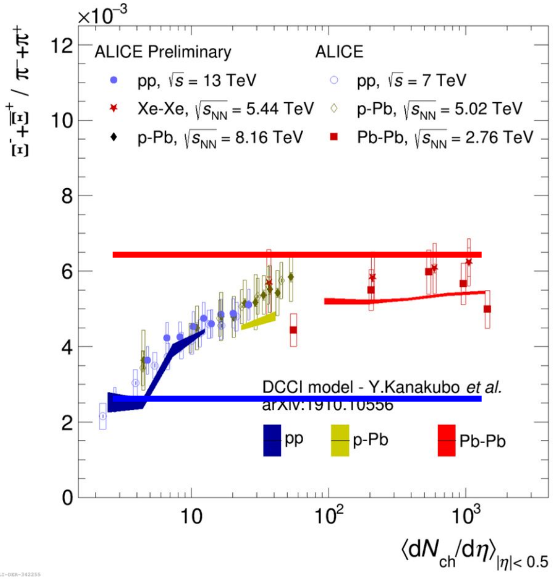
Recent developments trying to understand:

- multiple strange particle production in an event
- the connection to the jet presence
  - strangeness production in and out-of-jets
  - study as a function of the UE multiplicity
  - selection of specific event topologies (pencil-like, isotropic)
- the connection to early or late stage mechanisms

  (caveat: they are very much entangled in pp!)

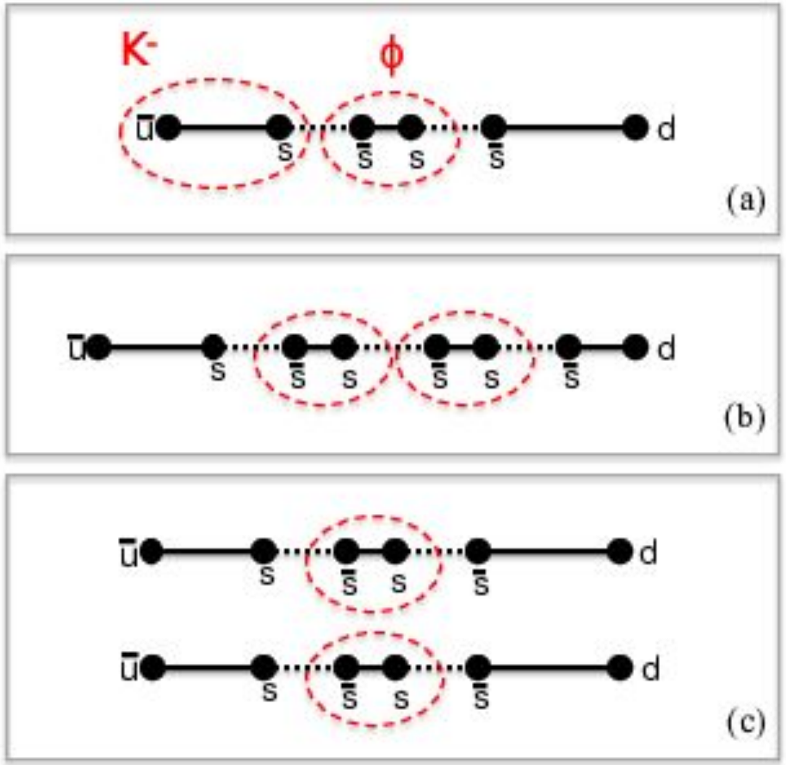


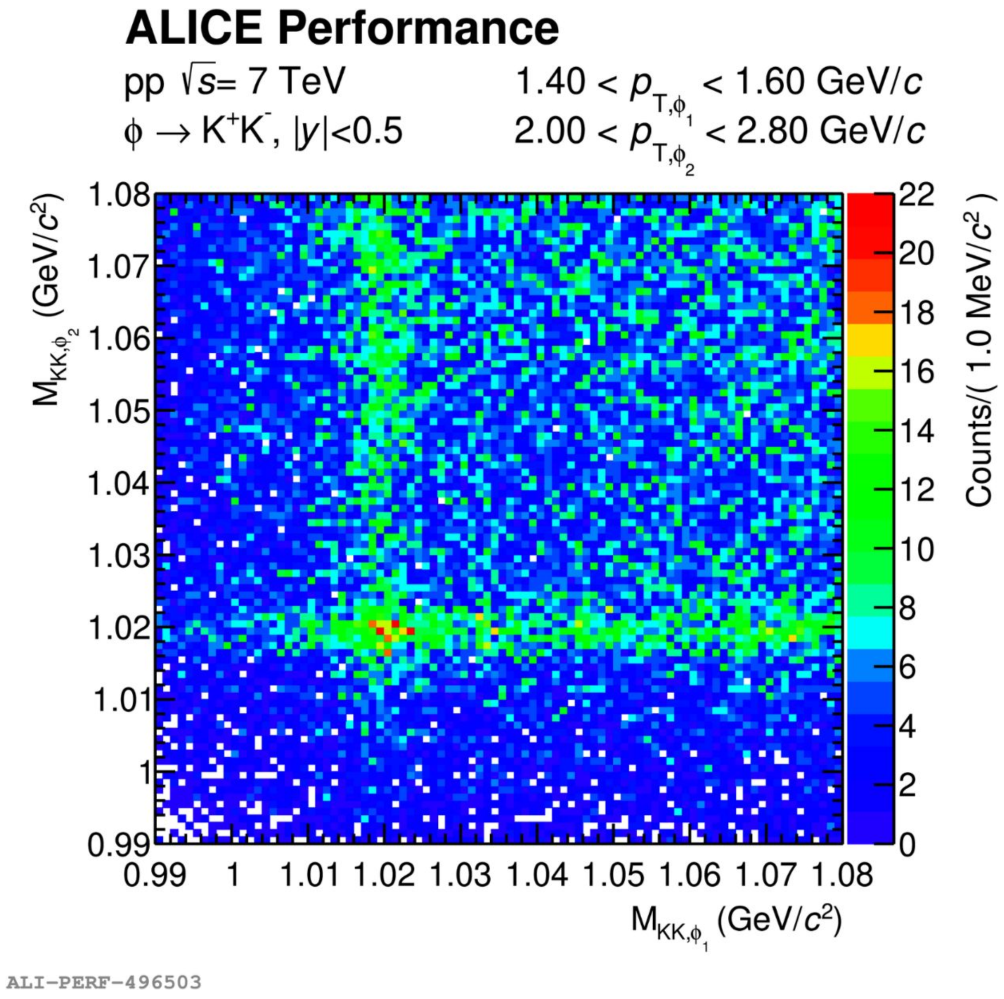




Enhance the lever arm for hadrochemistry: multi-ϕ prod

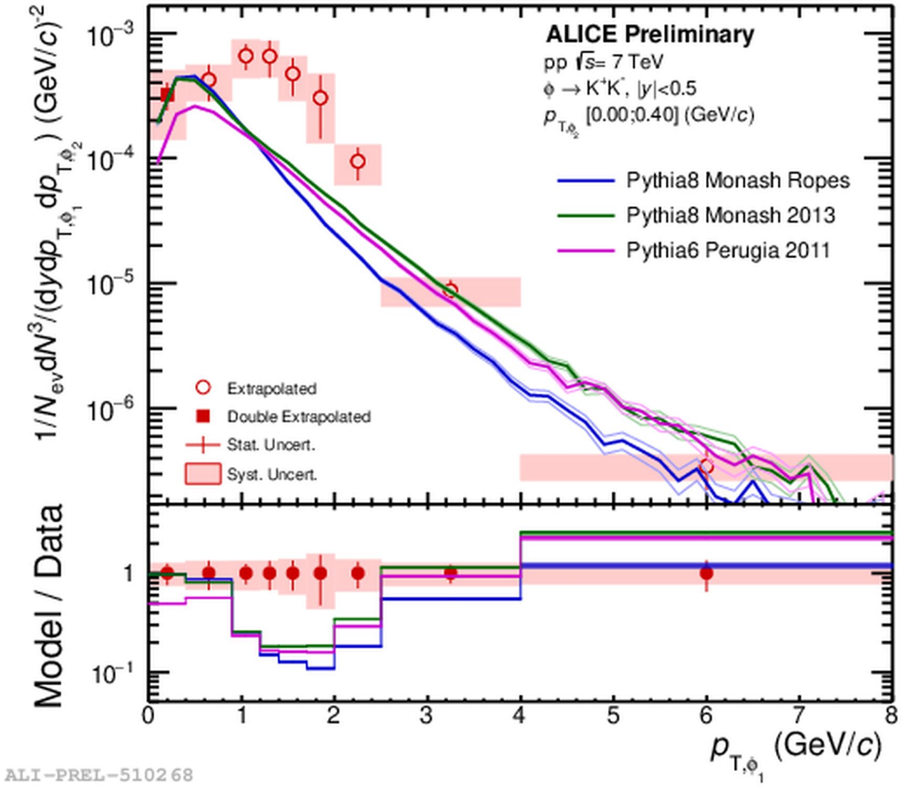
Double-ϕ production in pp collisions is a rather challenging observable for both statistical (canonical suppression) and string-breaking models



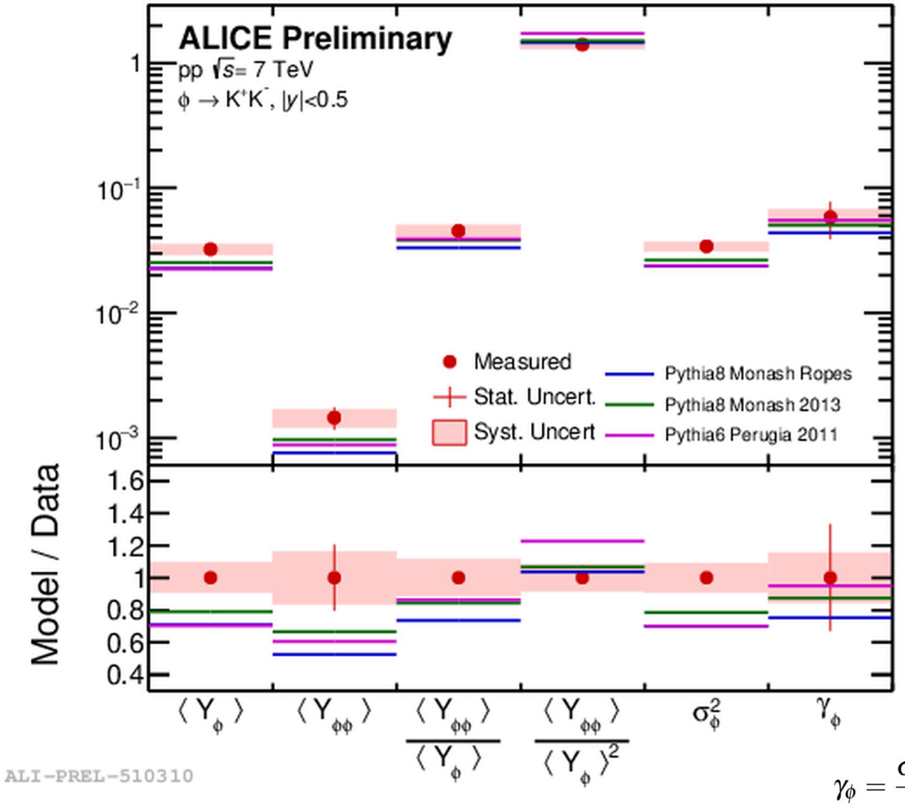


N. Rubini, QM2022

Double-ϕ production and PDF variance



Conditional p_T spectrum:
ϕ particle in presence of another low-p_T ϕ



$$\gamma_\phi = \frac{\sigma^2}{\mu} - 1 = \frac{2\langle Y_{\phi\phi}\rangle}{\langle Y_\phi\rangle} - \langle Y_\phi\rangle$$

Non-poissonian ϕ production
(importance of correlated production)

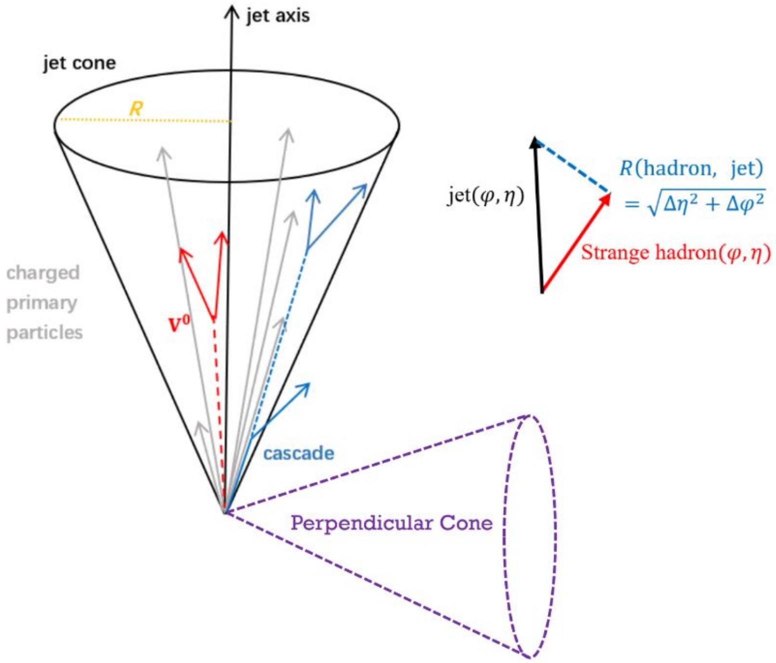
Many more to come (potentially extending e.g. to >2 Ξ production)

N. Rubini, QM2022

Strange hadrons and full-fledged reconstructed jets

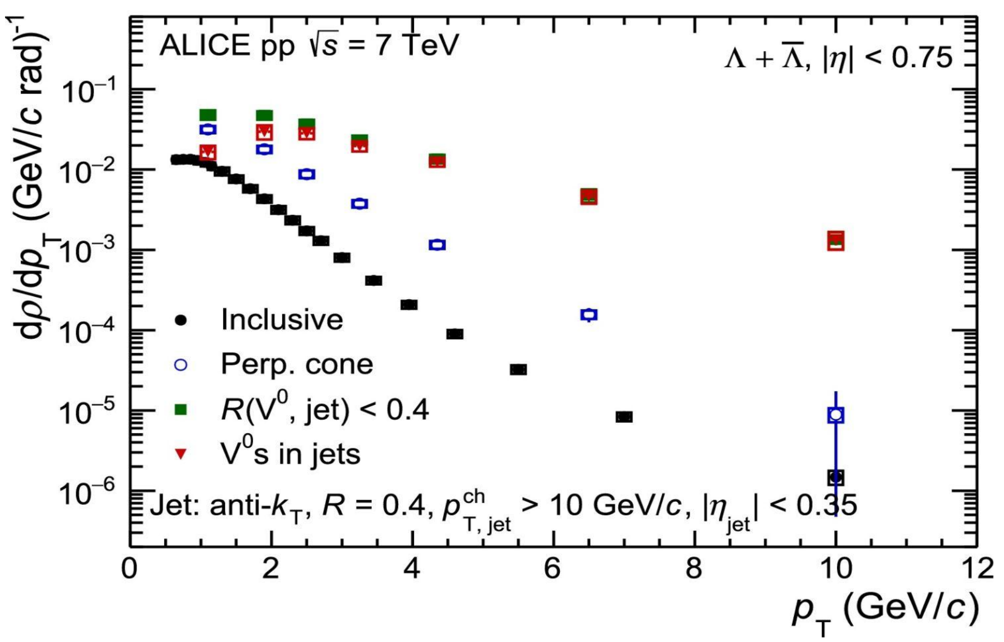
Jet finding:

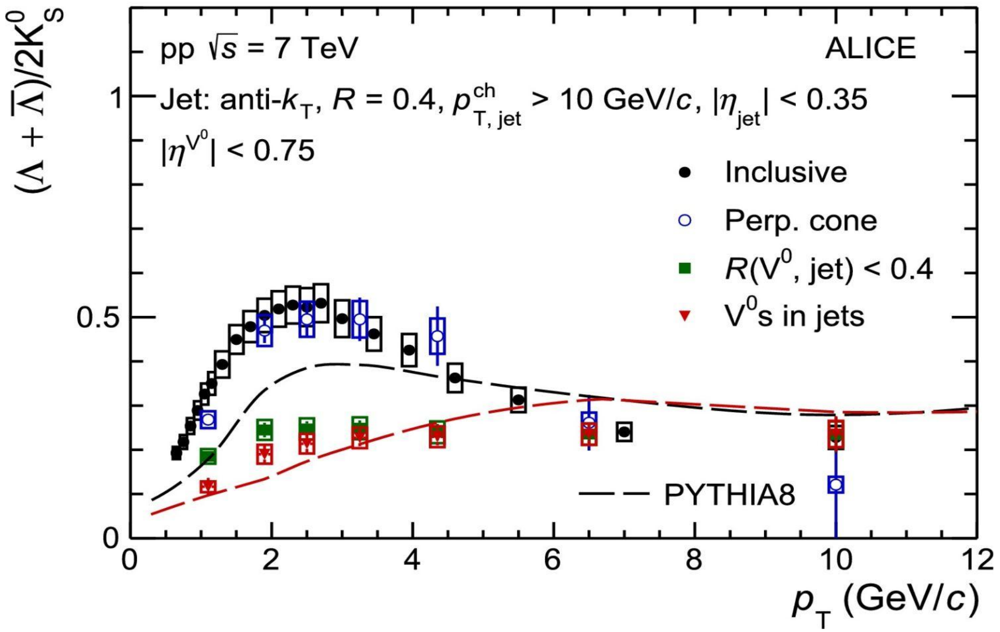
- Charged track selection: $|\eta| < 0.9$, $p_T > 0.15$ GeV/c
- Jet finder: anti-k_T, $R = 0.4$, $|\eta_{jet}| < 0.35$, $p_{T,jet} > 10$ GeV/c
- Strange particles found in:
  - Jet Cone ⟶ $R_{\text{Strange hadron, jet}} = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)} < 0.4$
  - Underlying Event ⟶ perp. cone method
  - Jet fragmentation ⟶ JE = JC - UE



The jet(tier) the harder

ALICE, Phys. Lett. B 827 (2022) 136984





Spectra are harder in the jet than in the perpendicular cone (UE)

Dynamics in the baryon/meson are dominated by what observed in the UE

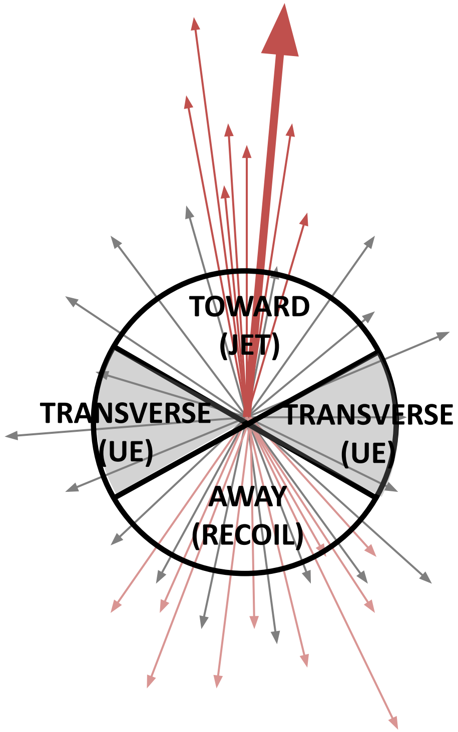
Statistics-hungry analysis, but missing the multiplicity dependence we miss part of the fun!

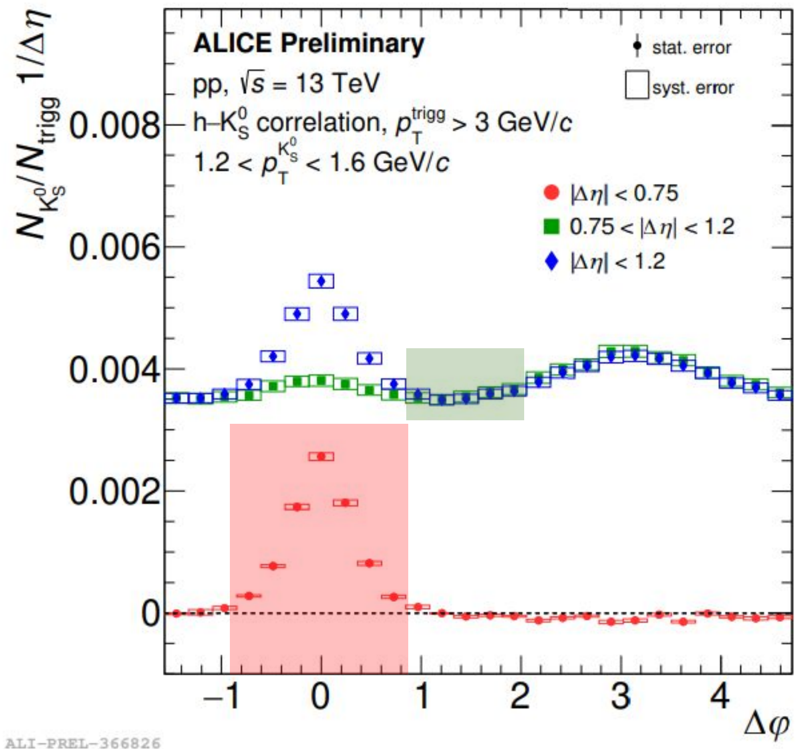
Need to change our “definition” of jet

Strange hadrons and leading tracks (probes for jets)

Topological classification of pp events, identifying:
- Toward region (triggering jet) + Away region (recoiling jet)
- Transverse region (Underlying Event - UE)

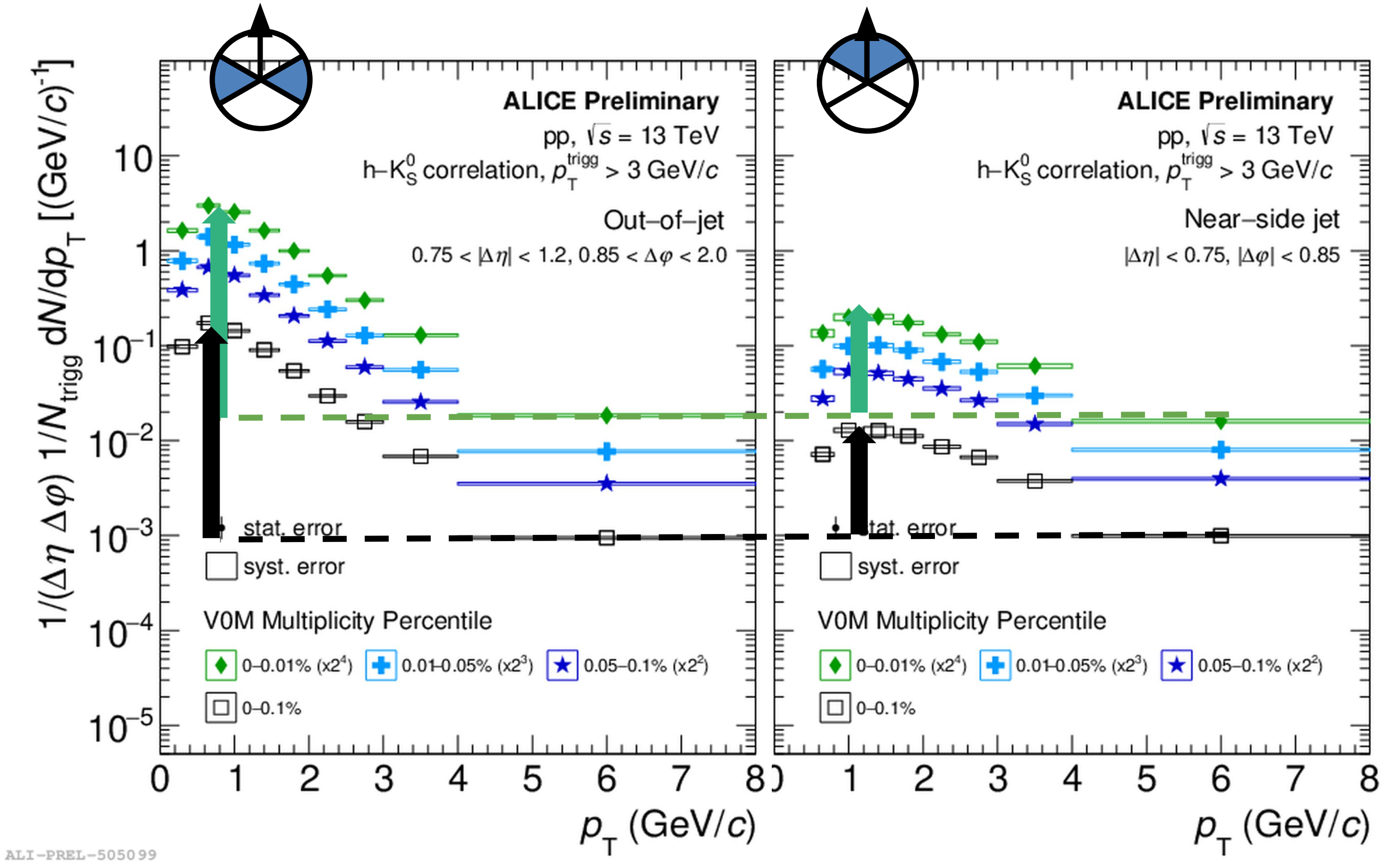
The jet direction is the direction of the highest-p_T hadron (p_T^{leading} > X GeV/c)





R. Schotter, talk on Tuesday

Is multiplicity not in the game anymore?

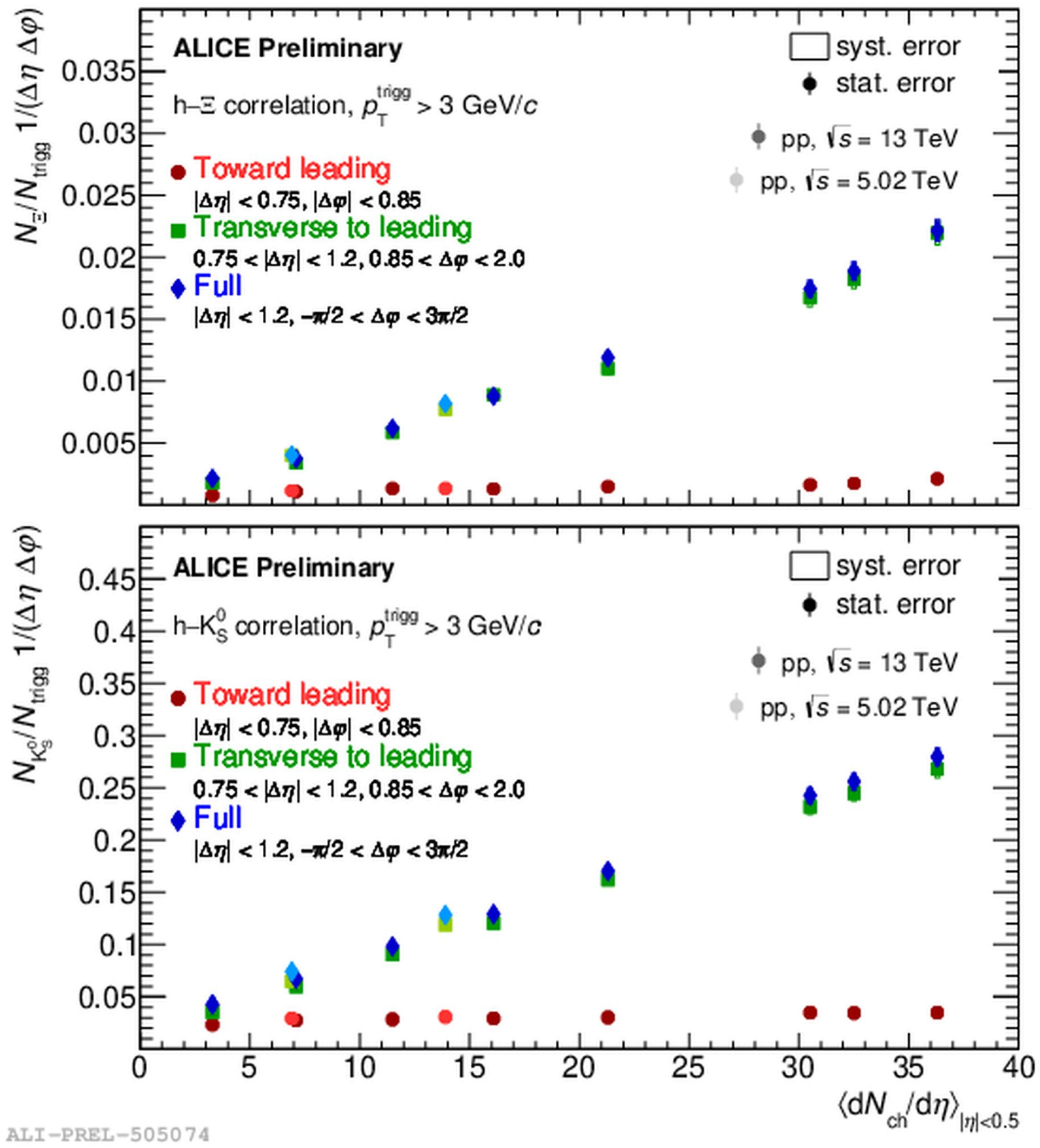


Difference in spectra in- and out-of-jet consistent with what observed with the anti-k_T algorithm

Evolution of the spectra with multiplicity not appreciable when looking at the two components separately.
Huge evolution in the inclusive spectra comes from relative contribution of jets and UE across multiplicities?

R. Schotter, talk on Tuesday

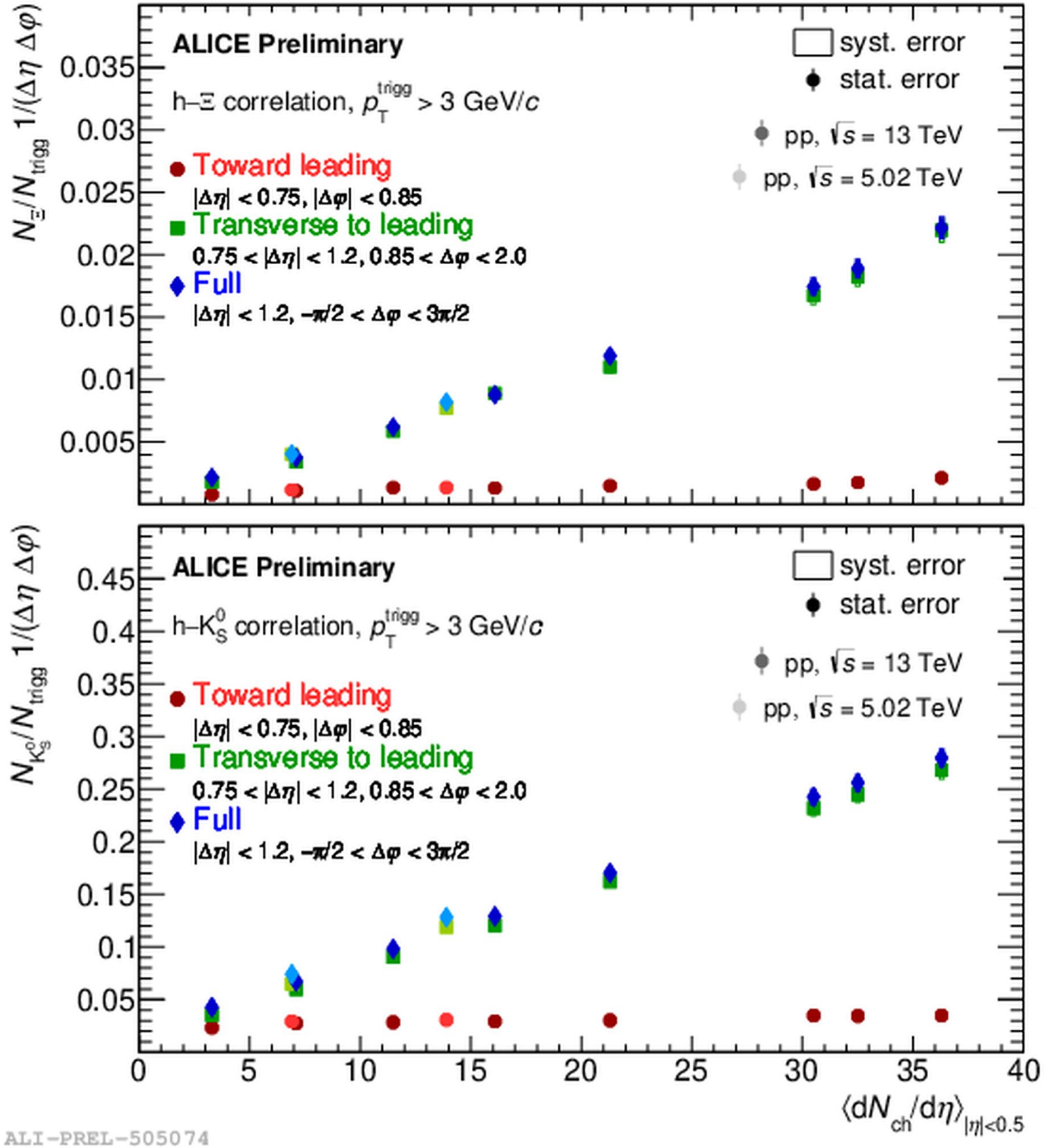
Yields in- and out-of-jet



(multi-)strange hadrons are mostly produced outside the jet
[in events with a leading particle with p_T > 3-4 GeV/c]

R. Schotter, talk on Tuesday

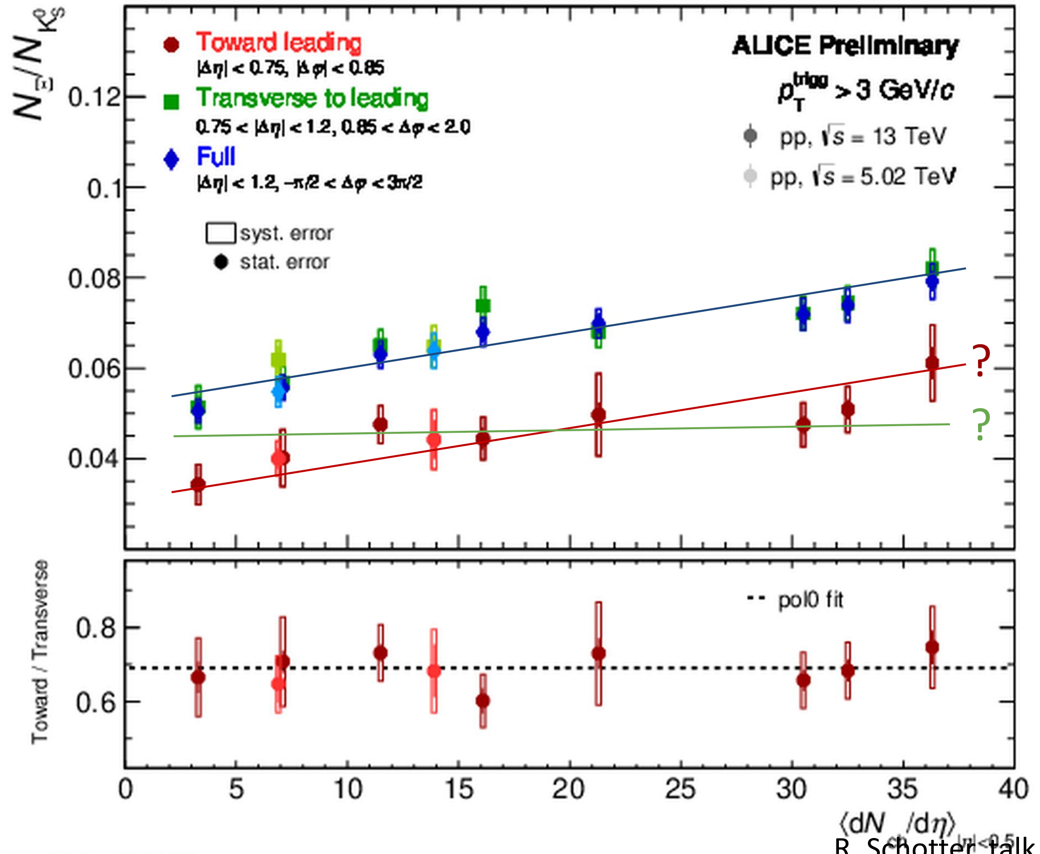
Yields in- and out-of-jet



ALI-PREL-505074

(multi-)strange hadrons are mostly produced outside the jet
[in events with a leading particle with p_T > 3-4 GeV/c]

… but (in-) and (out-of-)jet SE looks ~the same…



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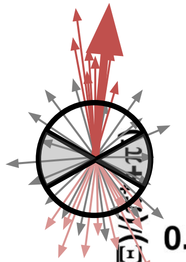
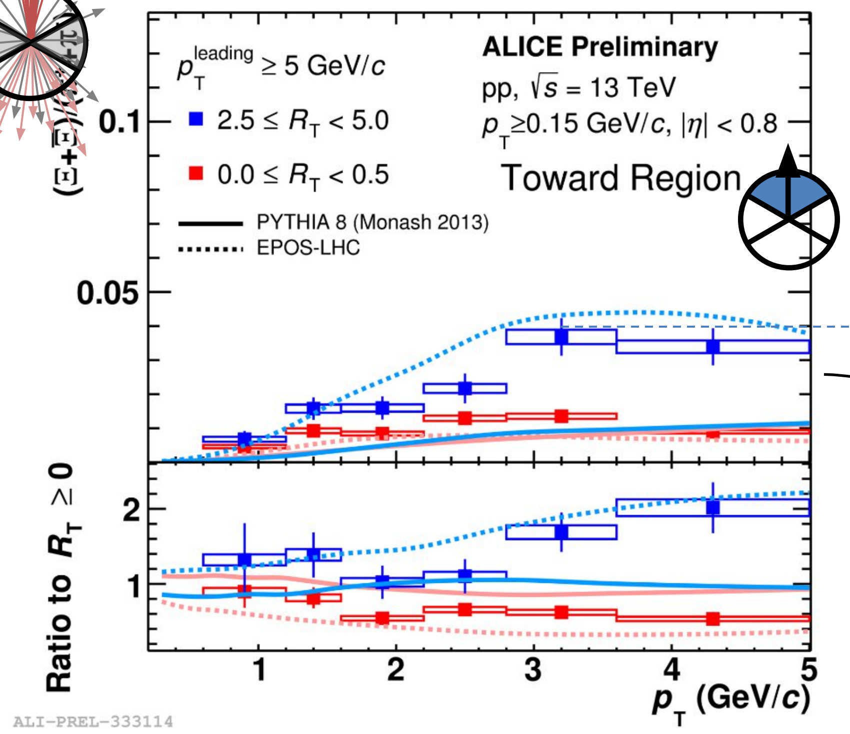
R. Schotter, talk on Tuesday

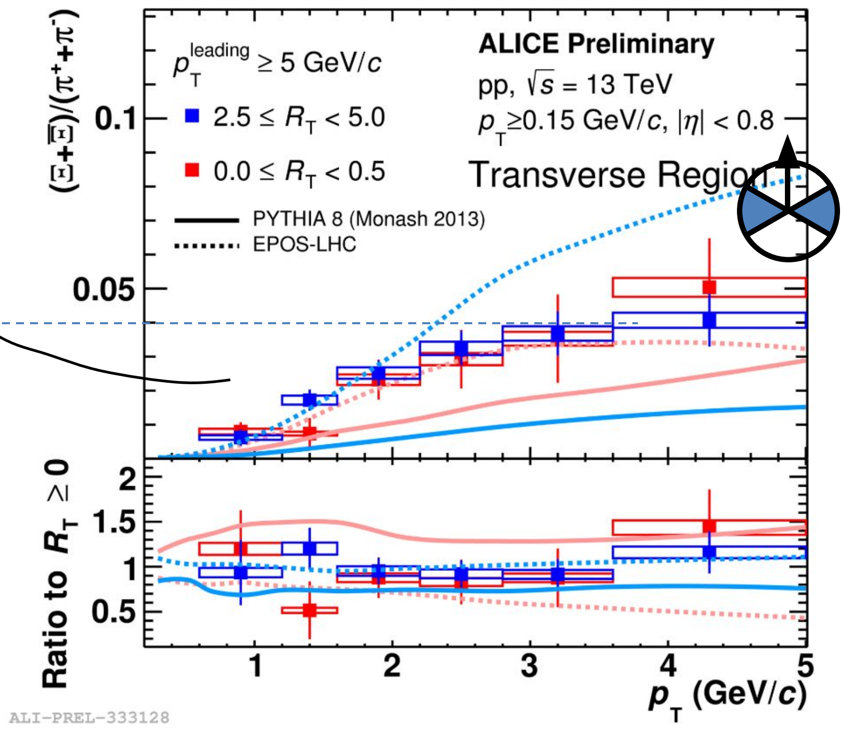
Event topology: in- and out-of-jet VS R_T



UE + JET



UE



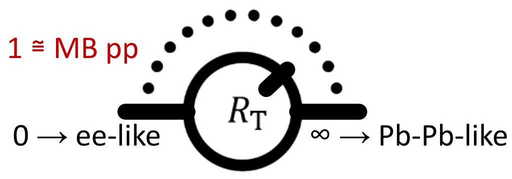
No evolution VS mult. in the UE!

NO strangeness enhancement in the UE

Strangeness enhancement in the toward region (**UE+JET**)

"UE multiplicity"

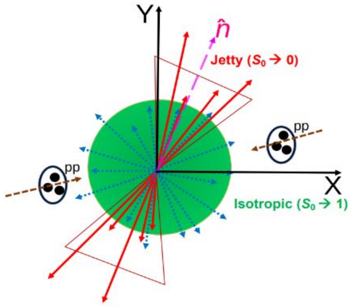
$R_T = N_T/\langle N_T \rangle$



Core-corona models may explain this as different Ξ/π ratios in jets (vacuum hadronization) and in the UE (core, statistical hadronization)

Need finalization to draw firm conclusions

LF particles VS spherocity



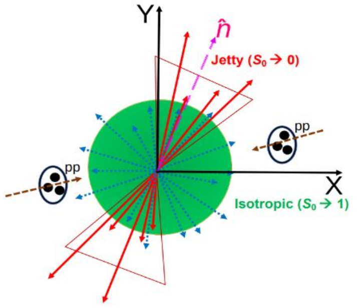
$$S_{\mathrm{O}}^{(p_{\mathrm{T}}=1.0)} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i |p\hat{\mathrm{T}}_{,i}|_{p_{\mathrm{T}}=1} \times \hat{n}|}{N_{\mathrm{trks}}} \right)$$

Spherocity is a measurement of the degree of isotropy in the charged particle emission:

- $S_o \rightarrow 0$: pencil-like event
- $S_o \rightarrow 1$: sphere-like event

A.Nassirpour, talk on Tuesday

LF particles VS spherocity



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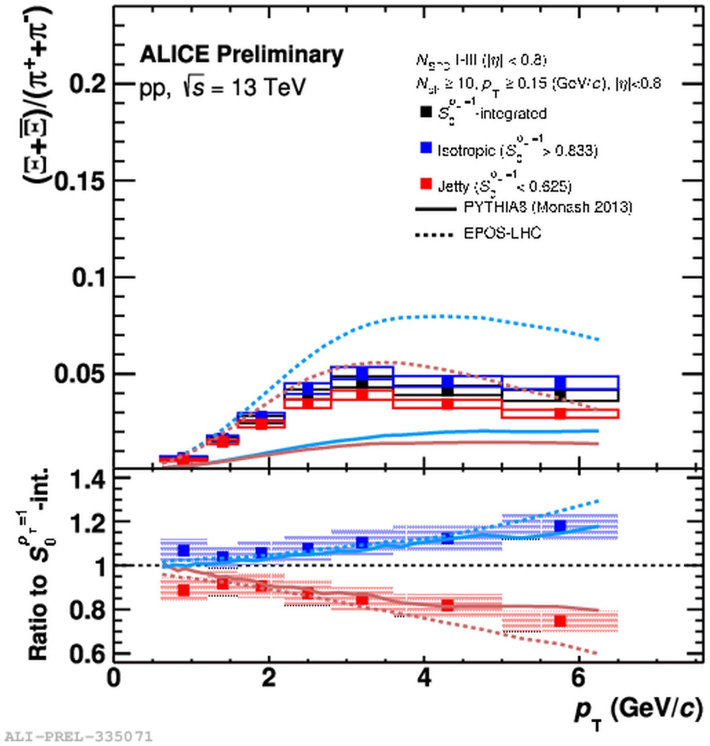
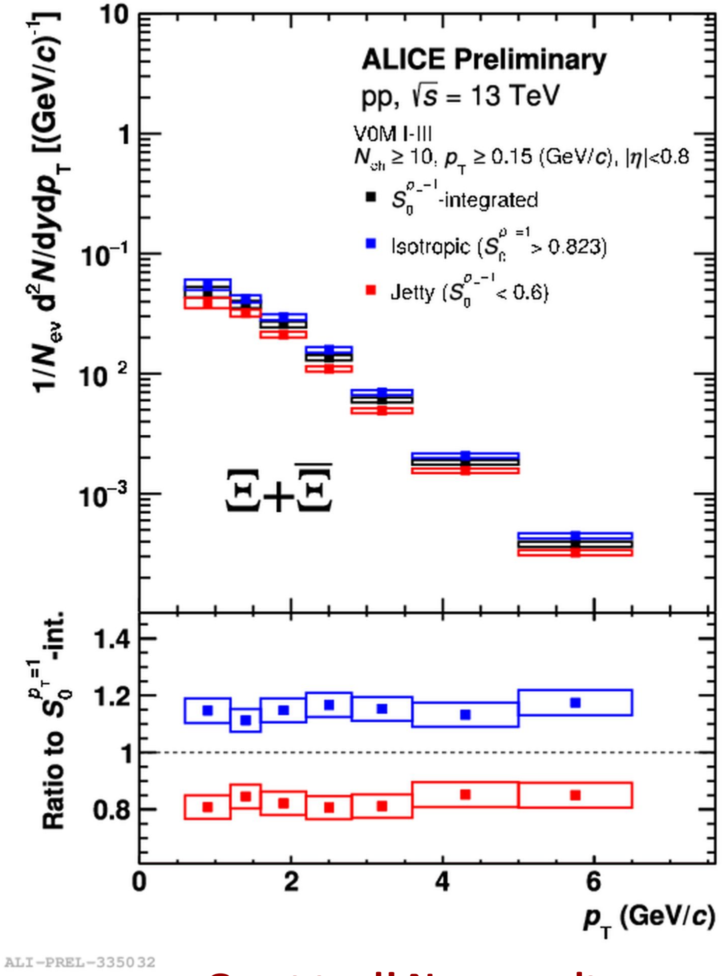


Fixed high multiplicity at forward:

- S_o selects different yields but similar p_T shapes

Fixed high multiplicity at mid-rapidity:

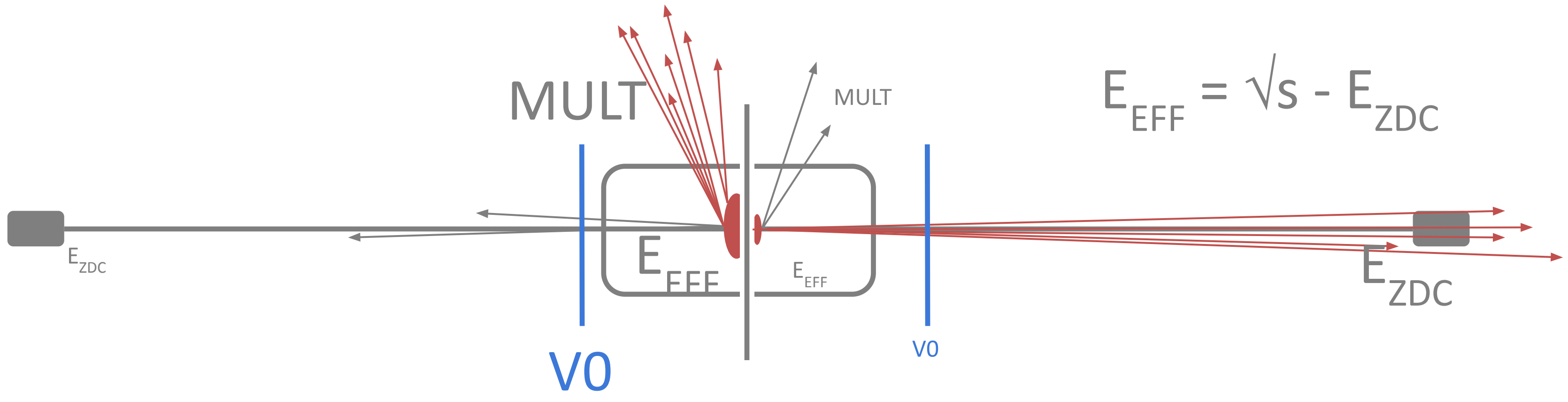
- S_o selects on the hardness of the spectrum



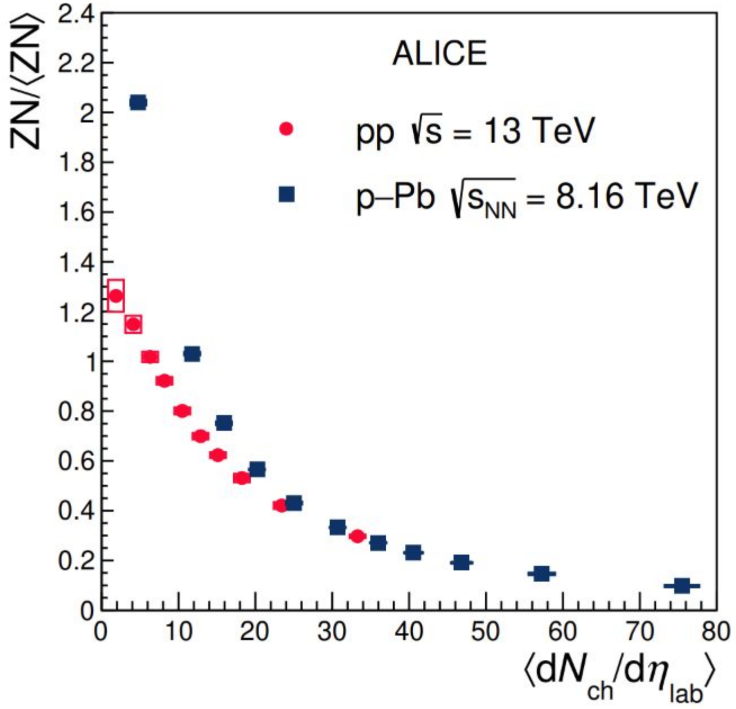
Great tool! New results will be soon released

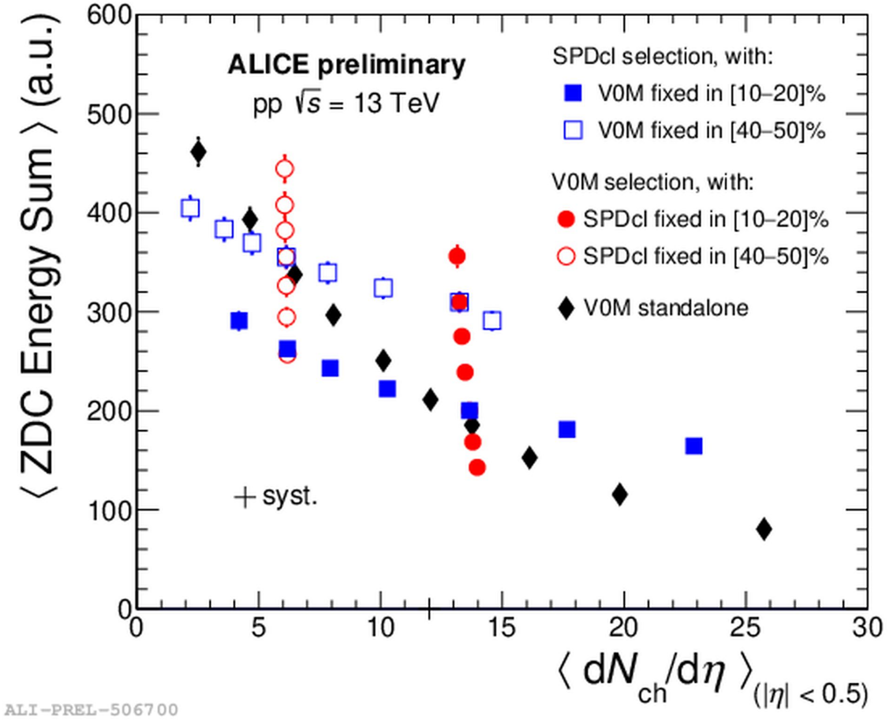
A.Nassirpour, talk on Tuesday

Bi-dimensional selections and Effective energy



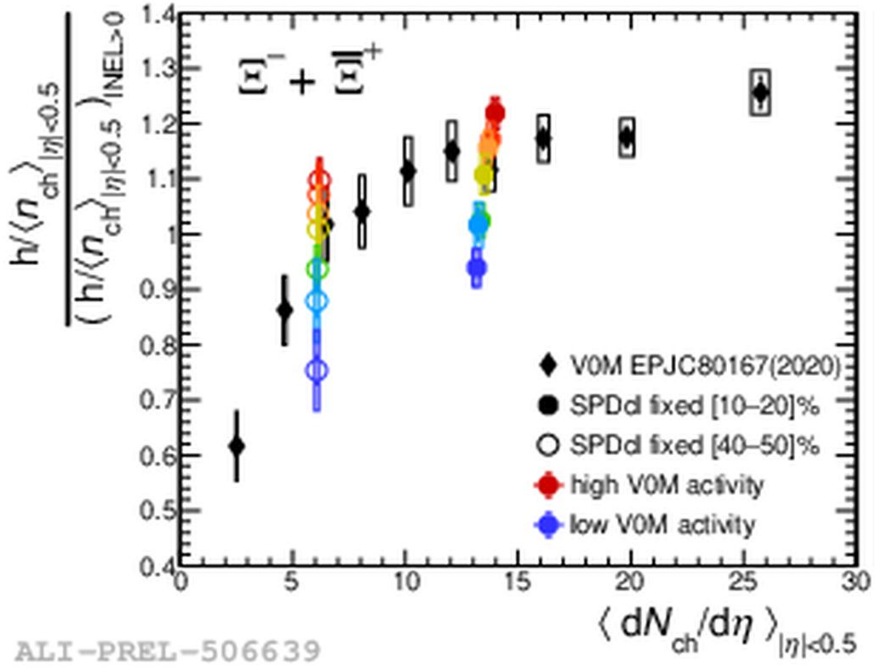
ALICE, arXiv:2107.10757

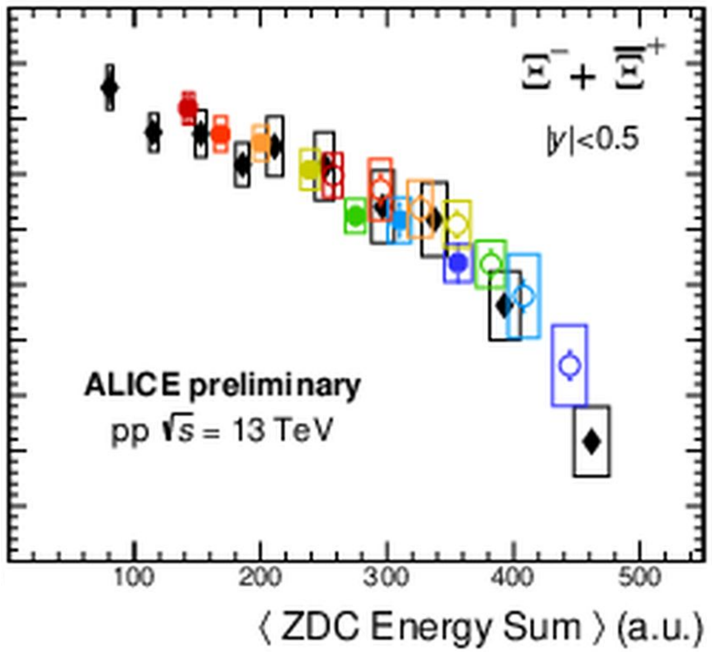




R. Schotter, talk on Tuesday

SE at fixed multiplicity!





At fixed mid-rapidity multiplicity:
SE VS V0M

The evolution of SE with E_{ZDC} does not depend on the multiplicity at mid-rapidity

Whatever the physics mechanism for SE is, it has to be strongly connected to the initial state of the collision, as the activity in ZDC is causally disconnected to the late-stage evolution of the hadronizing system

R. Schotter, talk on Tuesday

Conclusions and outlook

- **Solid observations on strangeness production from small to large systems at LHC:**
  - Enhancement VS multiplicity ∝ s-content. Saturation at high multiplicity
  - It flows in A-A. In pp and p-Pb spectra and v_2 look similar to A-A at similar multiplicity
  - Intense theoretical activity trying to reproduce these data (eventually everybody will manage!)

- **New developments with multi-differential analyses in small systems show that:**
  - ϕ is not produced with a Poisson PDF
  - p_T spectra are harder in jet than in the UE, with no significant change in shape with multiplicity
  - UE production dominates the yields, especially at high multiplicity
  - S_o and E_{eff} can be used to study SE at fixed mid-rapidity multiplicity
    - Preliminary results show hints of a significant correlation of SE with initial state conditions

- **Many more data about to come in all colliding systems in LHC Run3 and Run4**
  - triggering on event topology, multiplicity, particle decay chains, etc.: statistics will enhance dramatically, opening the era of precise characterization of pp interactions through strangeness production studies

Thank you