Event-shape, multiplicity-, and energy-dependent production of (un)identified particles in pp collisions with ALICE at the LHC

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on behalf of the ALICE Collaboration

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Motivation

ALICE at the CERN LHC is optimized for heavy-ion physics

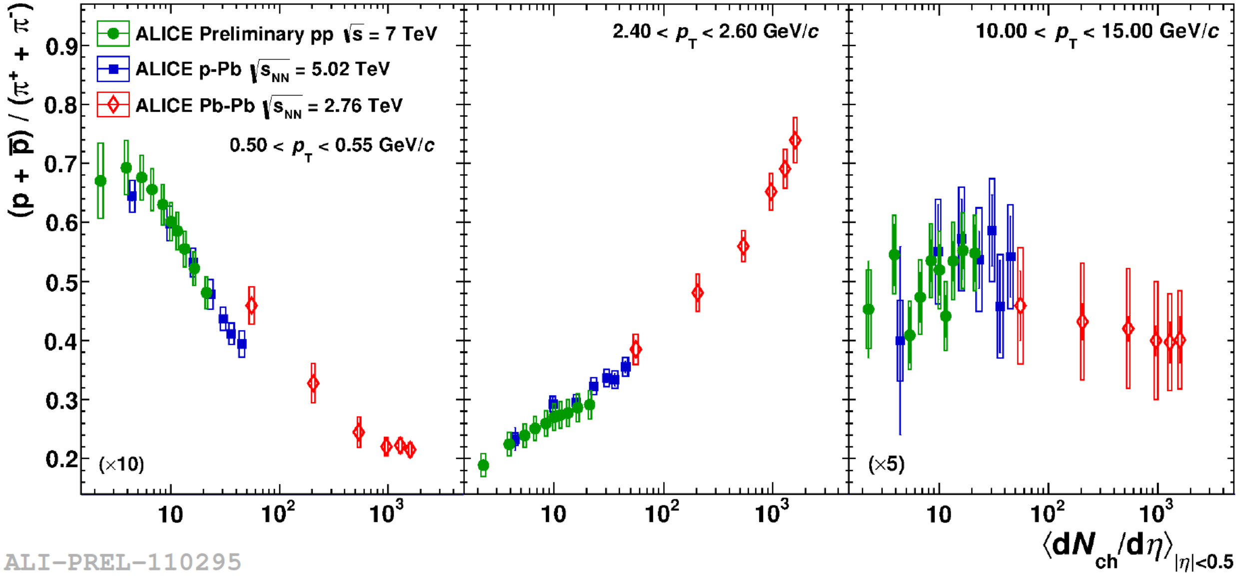
→ Also, **important contributions** to the LHC **pp physics** program
→ Provides baseline for the measurements of heavy ions

1) **Studies of particle production** at high energies in pp collisions aim
   - to constrain fragmentation functions (Ref. Daniel de Florian *et. al*, Phys. Rev. **D 95**, 094019) in perturbative *QCD calculations* based on the factorization theorem
     → **"hard"** scattering regime
   - to constrain *phenomenological (Monte Carlo) models*
     → **"soft"** scattering regime

Motivation

2) ***Understanding collective-like effects*** *seen at 7 TeV :*
smooth evolution of yield ratios in p–Pb and Pb–Pb collisions

Study the **evolution** of particle production with the center-of-mass energy **(√s)** and **multiplicity** by measuring identified particle production



ALI-PREL-110295

→ **To disentangle** the **energy** and **multiplicity dependences**, for a given multiplicity class, the p_T distributions are measured at new collision energies of **5.02 TeV** and **13 TeV**

Motivation

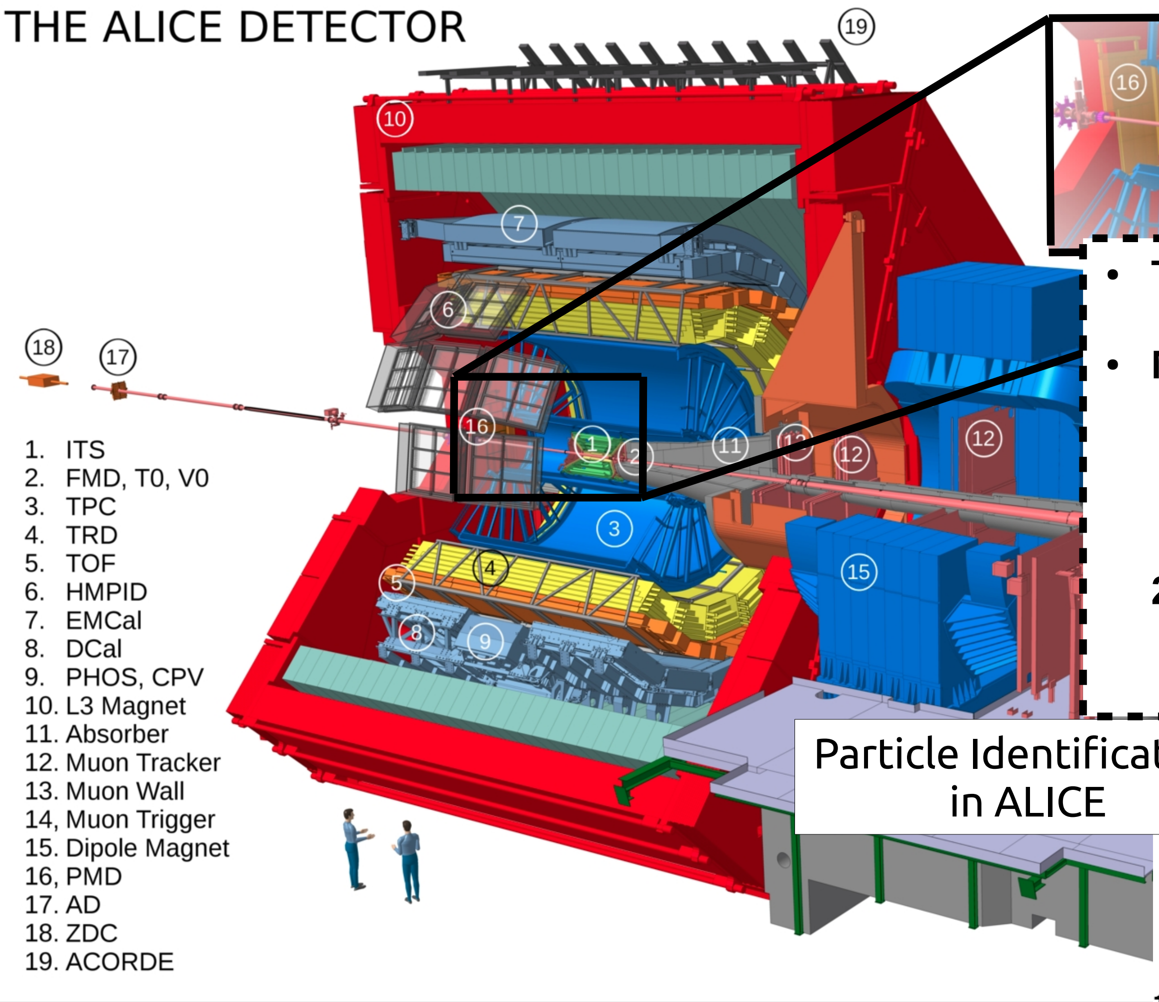
2) ***Understanding collective-like effects** seen at 7 TeV :*
smooth evolution of yield ratios in p–Pb and Pb–Pb collisions

Study the **evolution** of particle production with the center-of-mass energy (**√s**) and **multiplicity** by measuring identified particle production

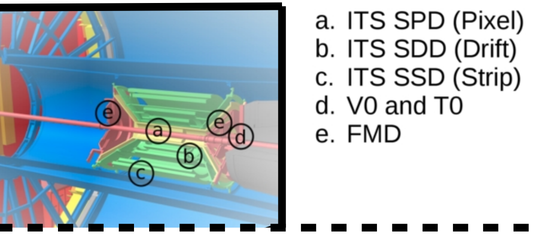
3) Using the observable ***transverse spherocity***

- to **differentiate** between **soft** and **hard** scattering **domains** of particle production
- to **investigate** the **importance of jets** in high multiplicity pp collisions

The ALICE apparatus



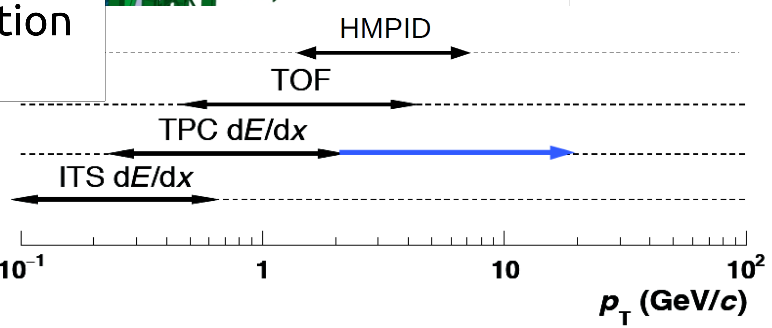
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE



a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

- **Trigger** and **event characterization:** V0A and V0C: forward/backward detectors
- **Measurement of charged-particle multiplicity:**
  1) "V0M" estimator (V0A"+"V0C):
  → to avoid auto-correlation bias, we measure the multiplicity via slices of percentiles of V0M amplitudes
  2) Mid-rapidity ($|\eta|<0.8$) estimator (SPD tracklets) applied in the analysis of charged particles

Particle Identification in ALICE



ALICE Collaboration: Int. J. Mod. Phys. **A 29** (2014) 1430044

Results I.

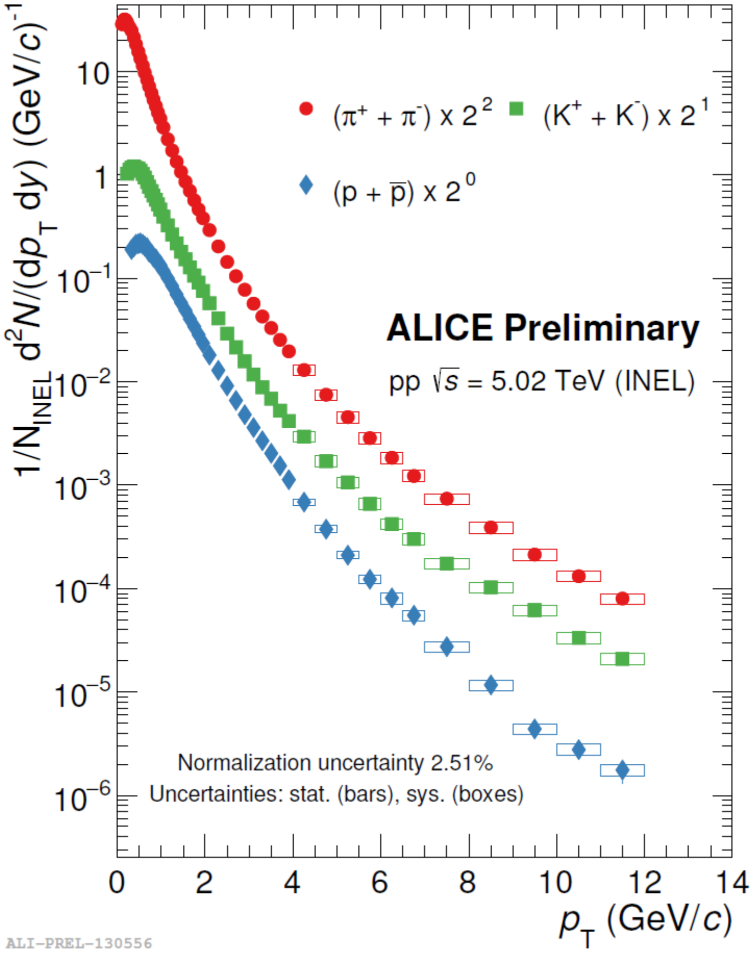
Transverse momentum (p_T) spectra of (un)identified hadrons

as a function of
collision energy and *charged-particle multiplicity*

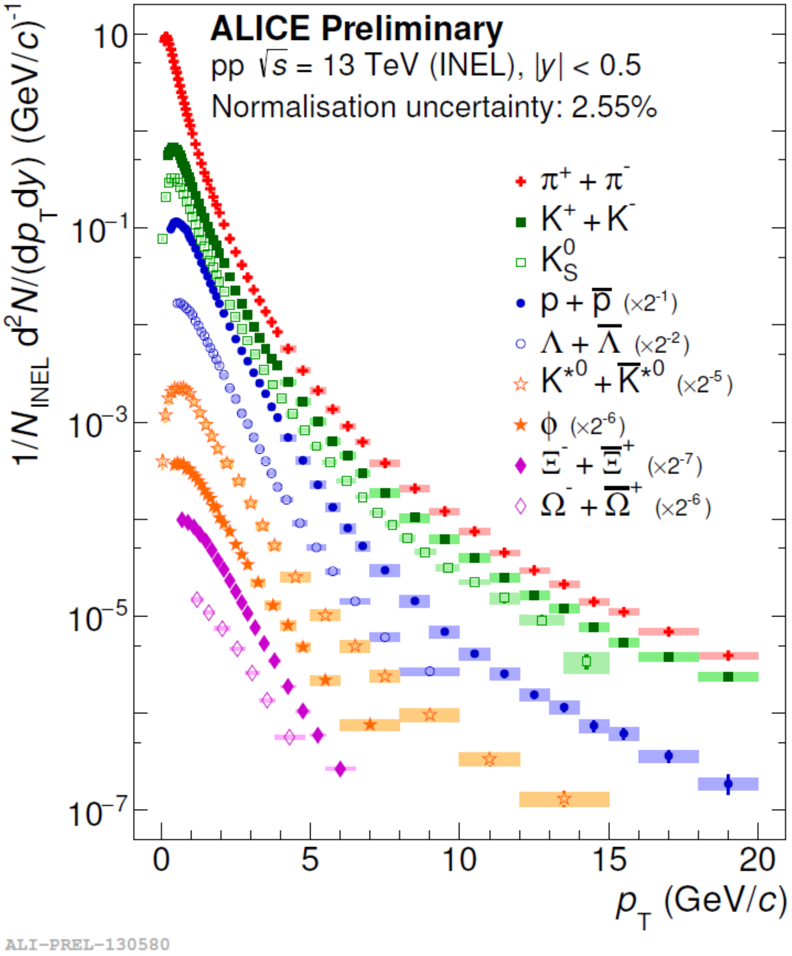
New:
LHC
Run 2

p_T spectra of **identified** hadrons in INEL pp collisions

$\sqrt{s}$ = 5.02 TeV



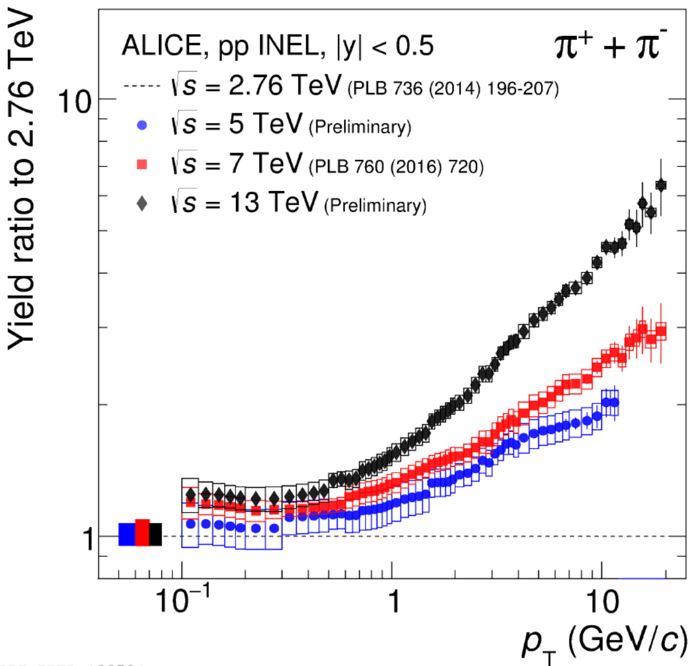
$\sqrt{s}$ = 13 TeV



New:
LHC
Run 2

***Energy dependence** of p_T-spectra*

1) Progressive hardening of the spectra with increasing **√s**
2) Ratios of spectra at different **√s** evidence the two different p_T ranges:
   - soft regime (p_T < 1 GeV/*c*): small increase with little or no p_T dependence
   - hard regime (at high p_T): very significant dependence on **√s**



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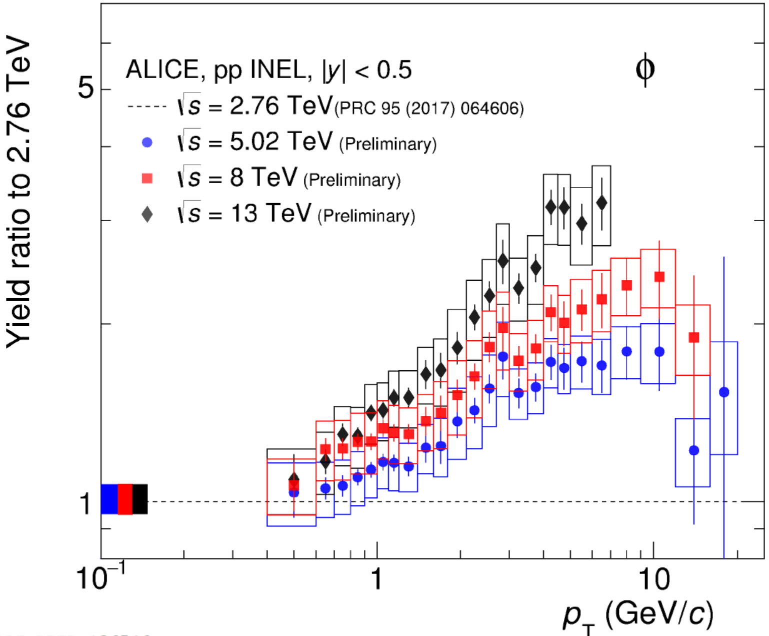

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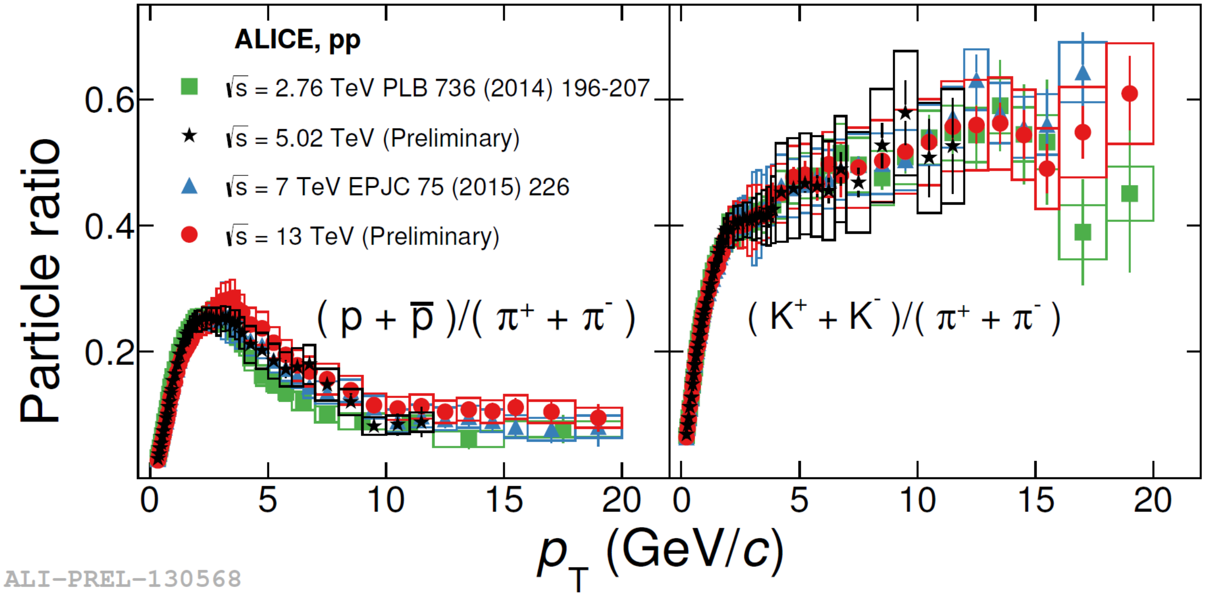
New: LHC Run 2

***Energy* dependence of p_T-differential particle ratios**



1) Kaon-to-pion ratios:
   - No **√s** dependence observed within uncertainties

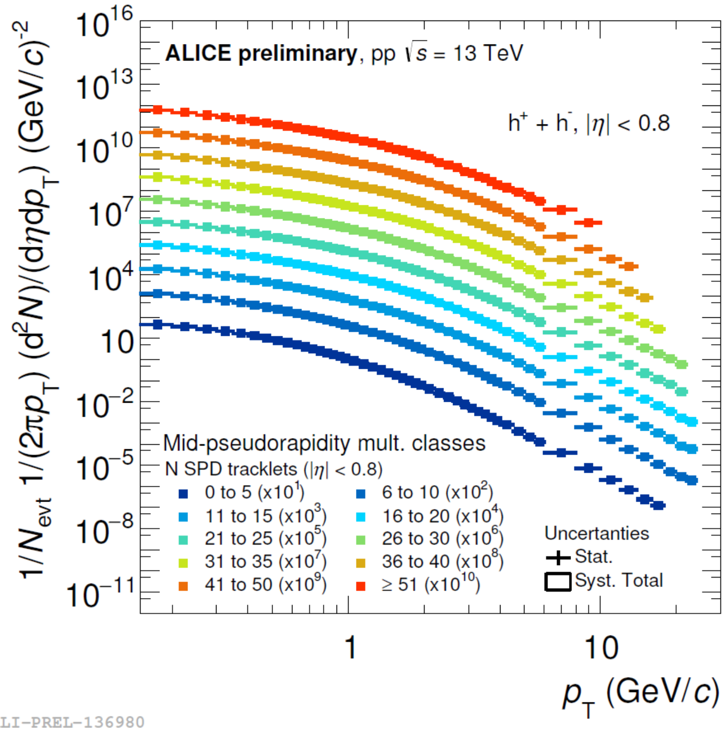
2) Proton-to-pion ratios:
   - For $p_T < 10$ GeV/*c:* modest √s dependence is seen
   - In the intermediate p_T region the peak with increasing **√s** shifts towards higher p_T
   - For $p_T > 10$ GeV/*c: no* evidence of evolution with √s within uncertainties

New:
LHC
Run 2

p_T spectra of **unidentified** charged hadrons

as a function of **charged-particle multiplicity**

Mid-rapidity estimator



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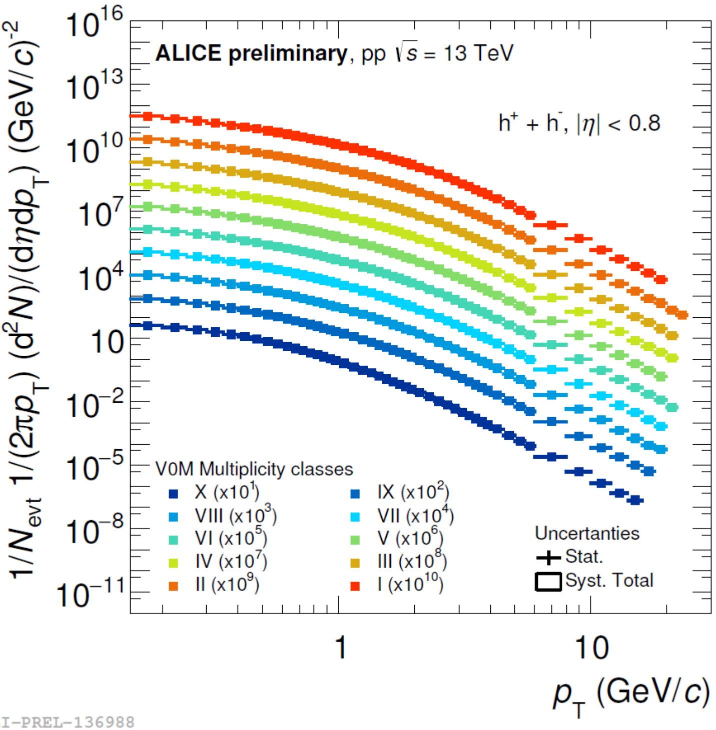
"V0M" estimator



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Class name	I′	II′	III′	IV′	V′
$N_{\mathrm{SPD\,tracklets}}$	≥ 51	41 - 50	36 - 40	31 - 35	26 - 30
$\langle dN_{ch}/d\eta \rangle$	56.55±2.71	46.94±2.28	40.83±1.99	35.90±1.76	30.83±1.50

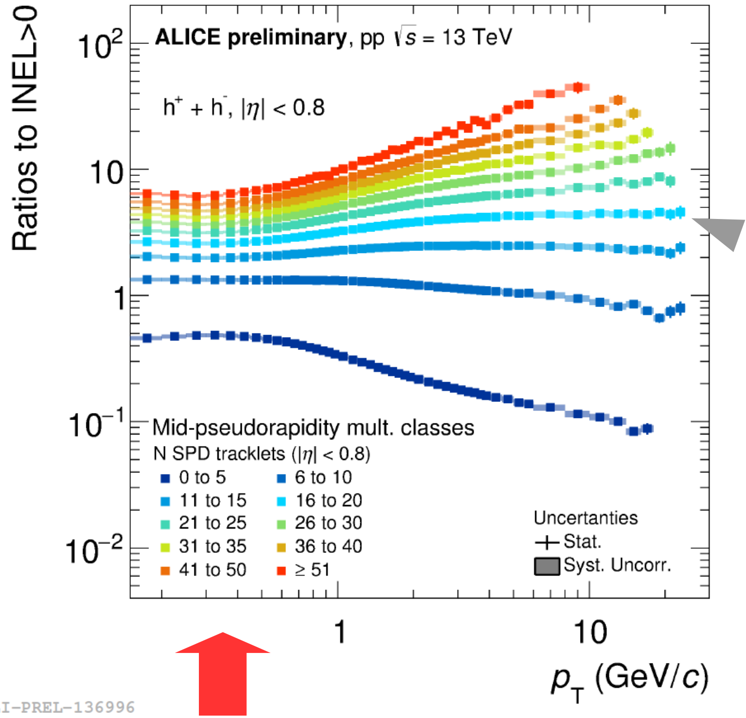
Class name	I	II	III	IV	V
V0M percentile	0-1%	1-5%	5-10%	10-15%	15-20%
$\langle dN_{ch}/d\eta \rangle$	27.61±1.07	21.37±0.82	17.40±0.66	14.88±0.56	13.07±0.49

→ Multiplicity reach is higher for the mid-rapidity estimator

New:
LHC Run 2

p_T spectra of **unidentified** charged hadrons

as a function of **charged-particle multiplicity**

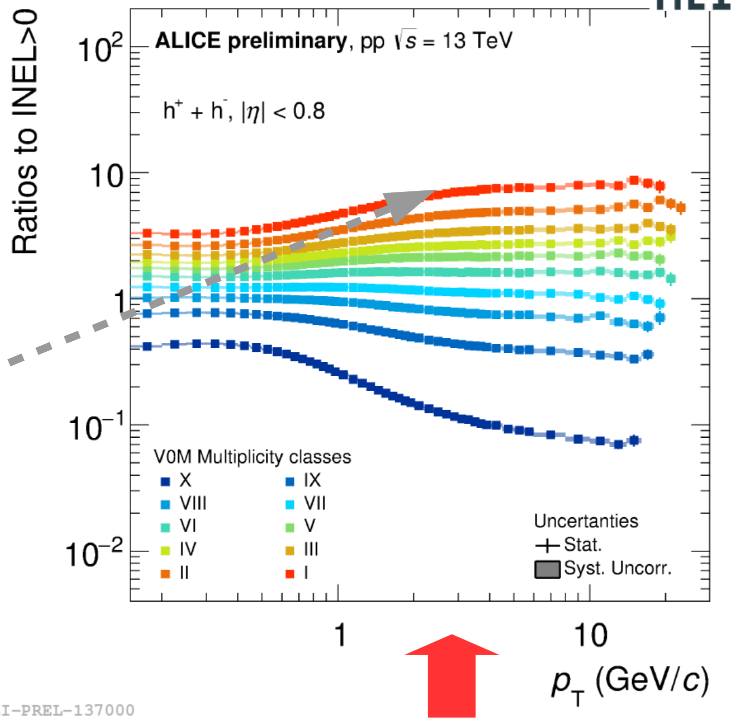


ALI-PREL-136996

Ratios at similar multiplicity:

$\langle dN_{ch}/d\eta \rangle \sim 25.7 \pm 1.2$

$\langle dN_{ch}/d\eta \rangle \sim 27.6 \pm 1.1$



ALI-PREL-137000

Mid-rapidity estimator

“V0M” estimator

Ratios to minimum bias (INEL>0)

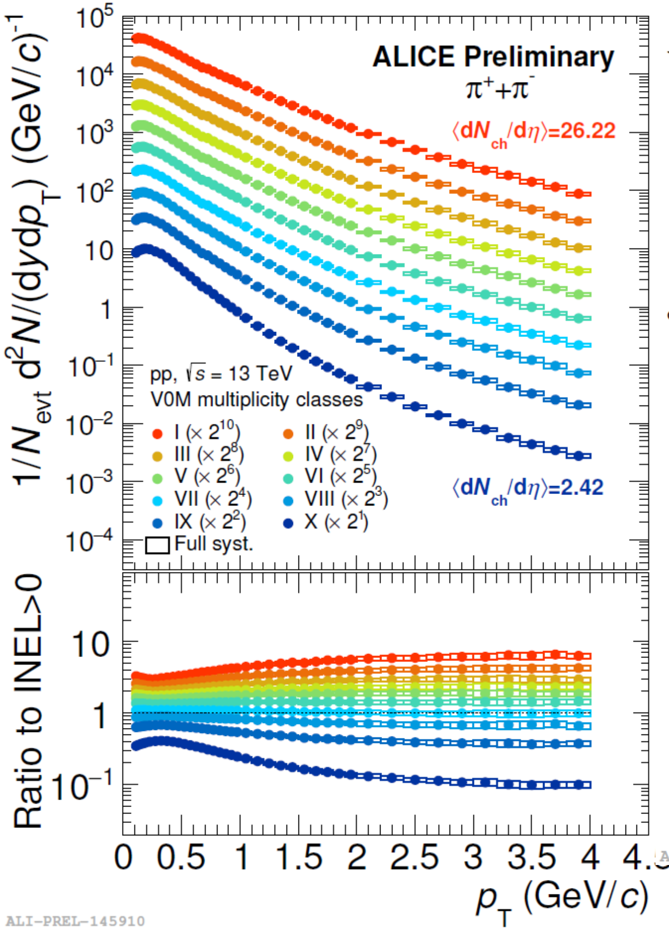
→ spectra become harder as the multiplicity increases

→ p_T < 1GeV/c: the ratios are flat

→ p_T > 1GeV/c: the ratios exhibit a strong dependence on p_T
(more pronounced towards higher multiplicities)

New: LHC Run 2

p_T spectra of **identified** hadrons *as a function of* ***charged-particle multiplicity***



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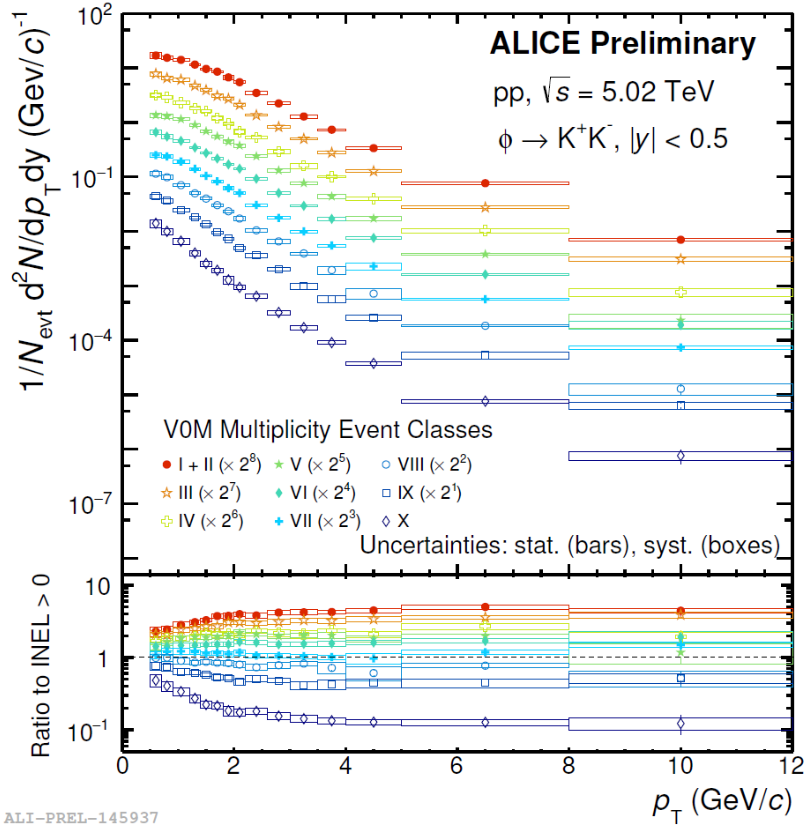


ALI-PREL-145937

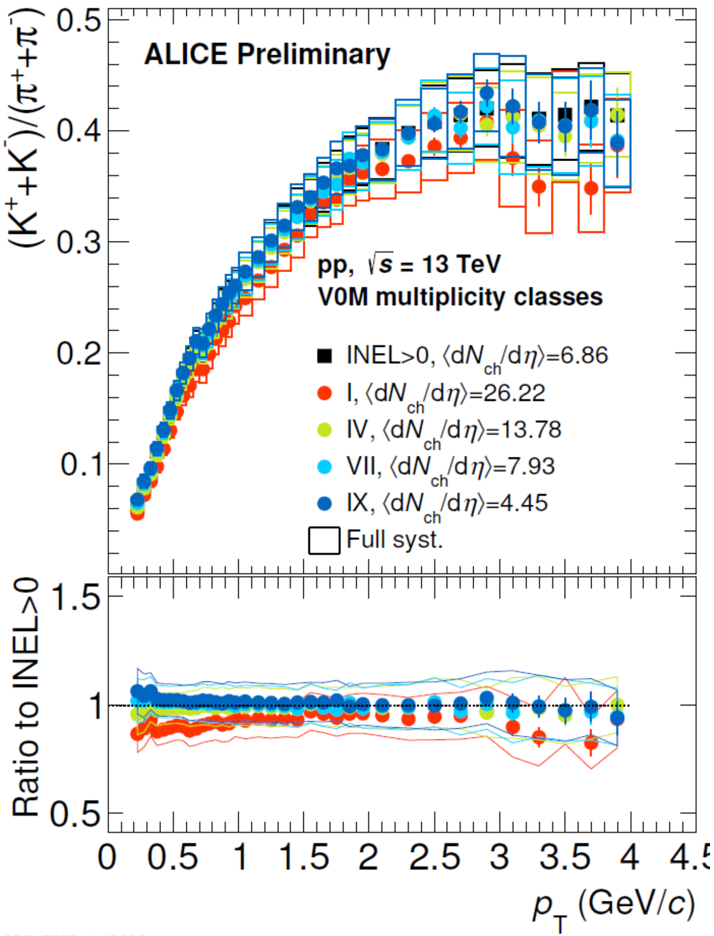
1) p_T **spectra** become **harder** as the multiplicity increases

2) Ratio to MB (INEL>0): above $p_T = 2$GeV/c only modest change with charged-particle multiplicity

3) Similar results have been reported for (multi-)strange hadrons at QM 2017

New:
LHC
Run 2 – 13 TeV

Multiplicity dependence of p_T-differential particle ratios



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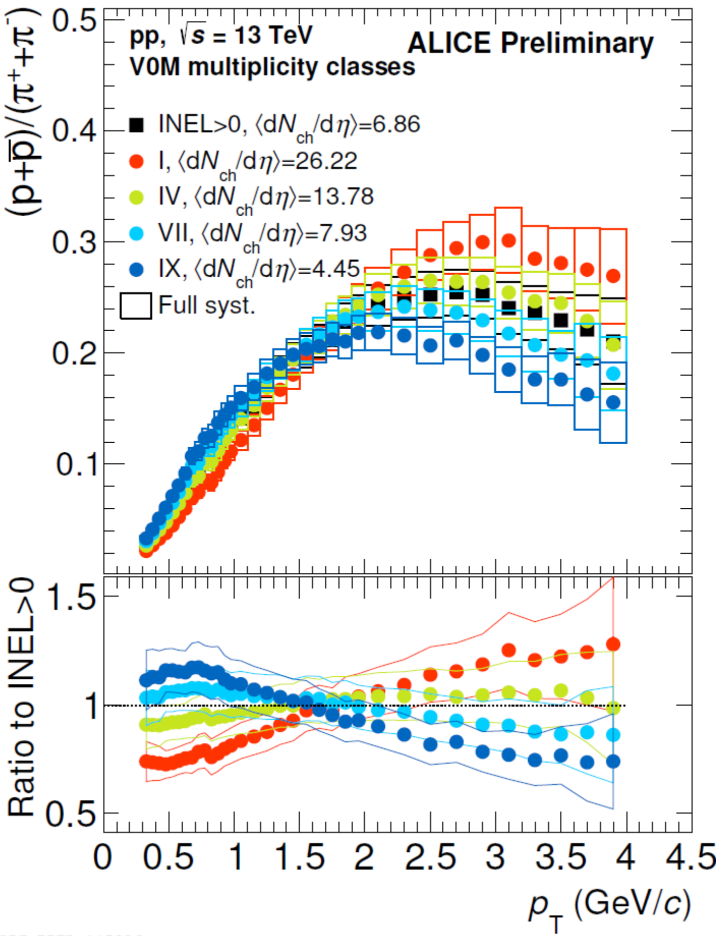


ALI-PREL-145926

Kaon-to-pion ratios:

→ No apparent modifications is observed in the reported multiplicity classes

→ Result is compatible with the observations reported at 7 TeV

Proton-to-pion ratios:

→ A characteristic *depletion* is observed *at high multiplicity* and at low p_T values

→ Enhancement at intermediate p_T => consistent with the presence of an expanding medium (radial-flow)

→ particle dynamics is similar to p–Pb and Pb–Pb systems

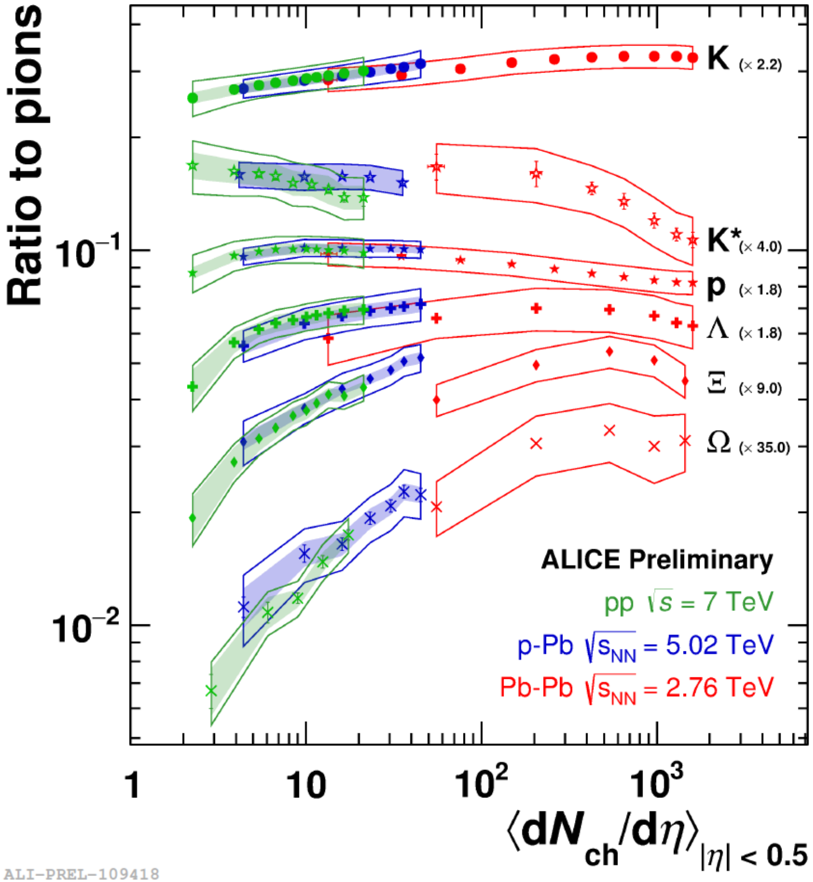
Results II.

Yield dN/dy and average transverse momentum
of identified hadrons

as a function of
collision energy and *charged-particle multiplicity*

Integrated Hadron Yields at 7 TeV

as a function of charged-particle multiplicity



ALI-PREL-109418

- Smooth evolution across different collision systems

  → ***hadrochemistry*** is dominantly **driven by** charged-particle **multiplicity**

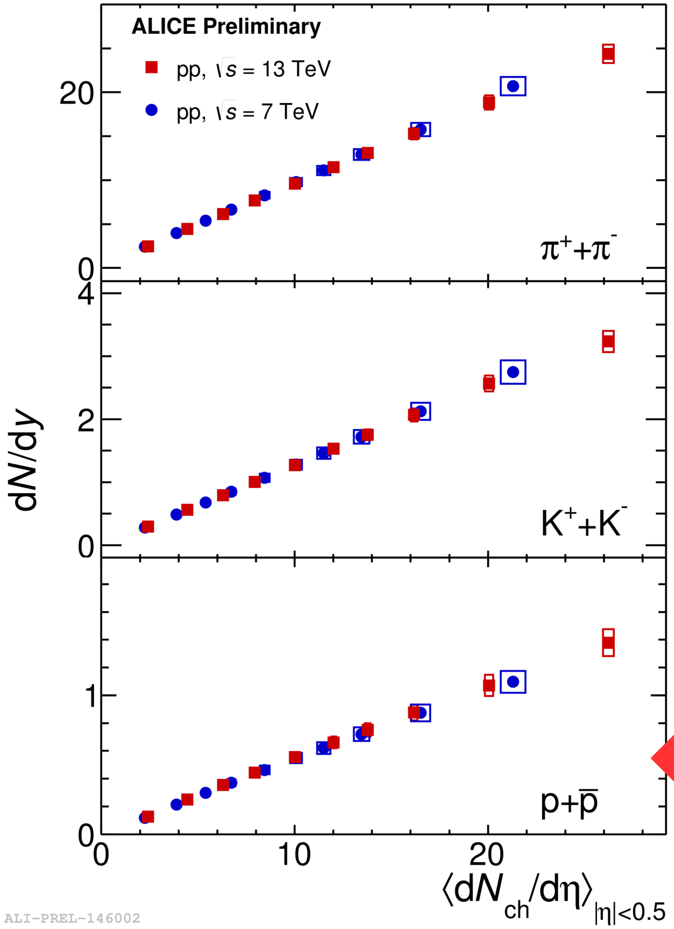
- *Soft particle production in **pp** collisions is **similar** to that in **p-Pb** and **Pb-Pb** collisions*

New:
LHC
Run 2 – 13 TeV

Integrated hadron yields

as a function of charged-particle multiplicity

Study the validity of multiplicity scaling at different collision energies



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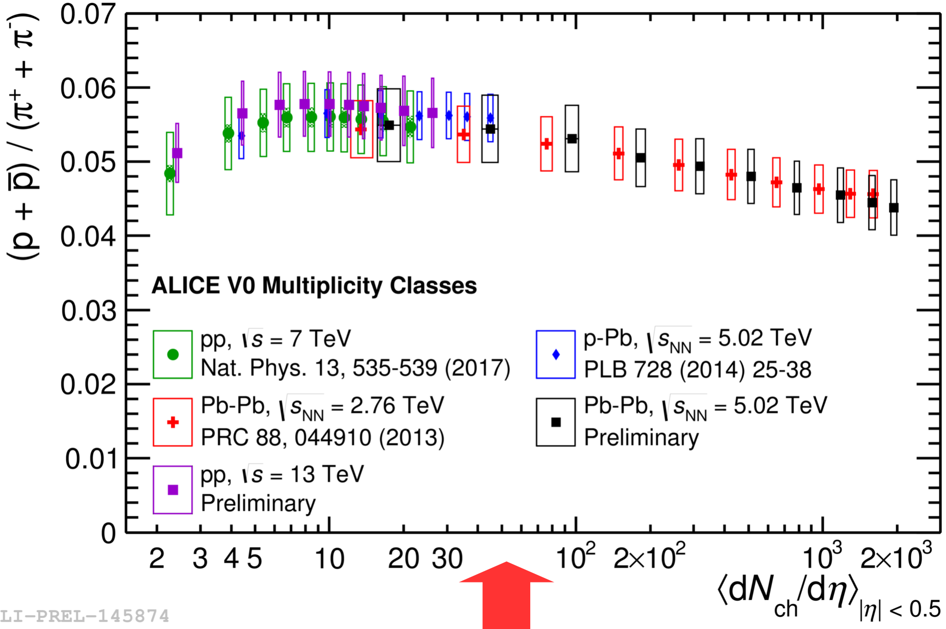


ALI-PREL-145874

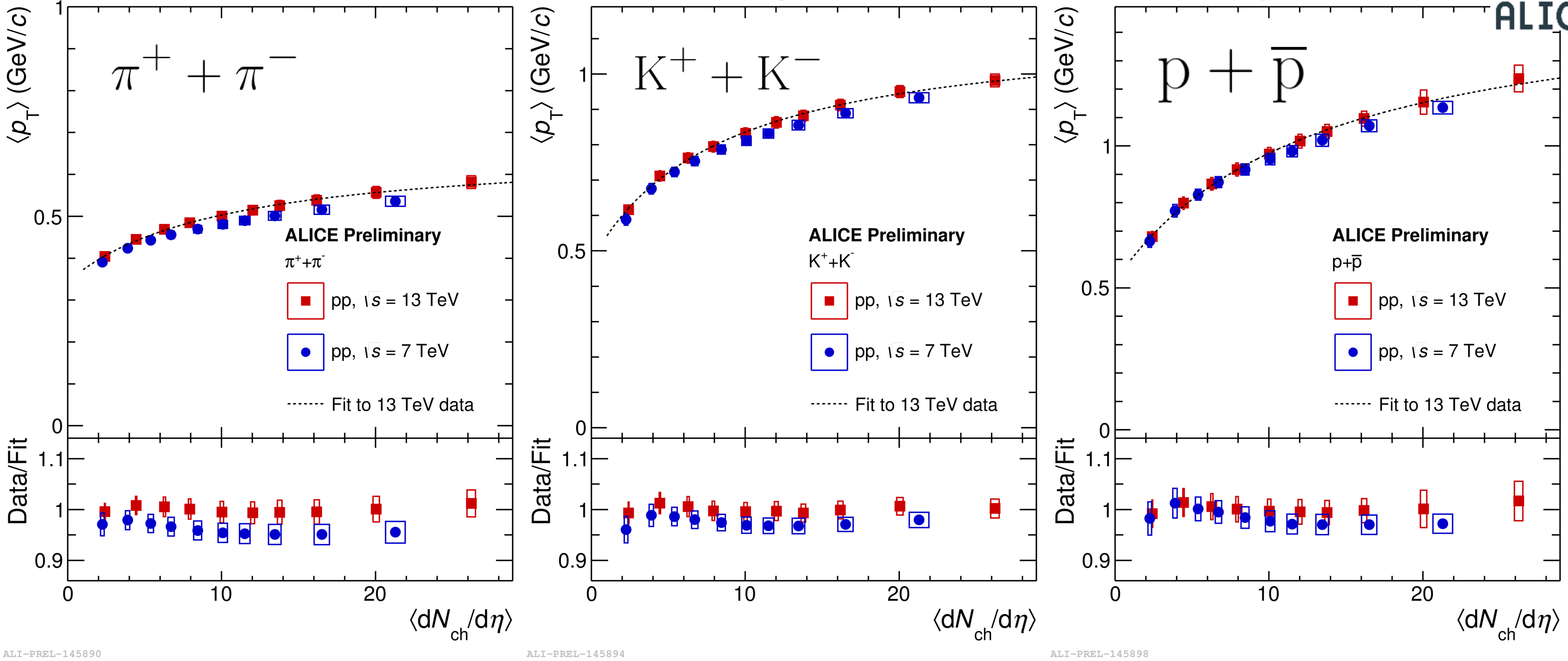
Hadrochemistry is dominantly driven only by the charged-particle multiplicity

Same patterns observed for 7 and 13 TeV at similar multiplicity

Energy scaling property applies for the yields of π / K / p
→ similar observation for (multi-)strange hadrons

New:
LHC – Run 2

Average transverse momenta
as a function of charged-particle multiplicity



Note the scale in y

- Average p_{T} for π , K and p indicates a **hardening** going from 7 to 13 TeV at comparable multiplicities
- Similar trends are seen for (multi-)strange hadrons and for all charged hadrons at lower collision energies

Scaling with multiplicity is not valid → similar observation for (multi-)strange hadrons

Results III.

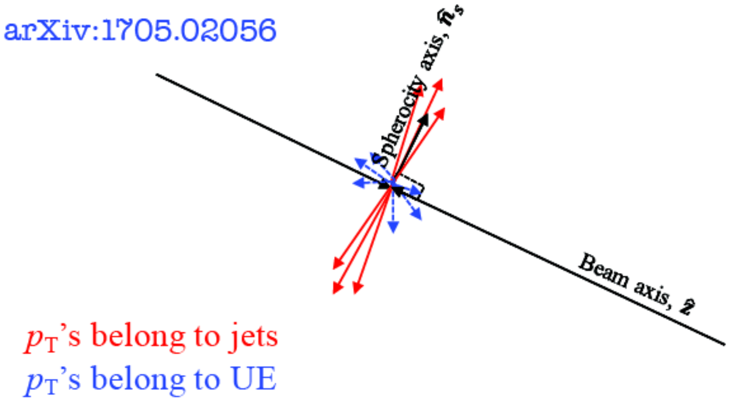
(Un)identified particle production

as a function of
transverse spherocity (S_0)

in high-multiplicity pp collisions at 13 TeV

Investigations of particle production using event shapes

- ***Aim:*** Study the importance of jets in high multiplicity pp collisions
- ***Tool:*** *Transverse spherocity* (to isolate “jetty”-like and “isotropic” events associated with underlying event (UE) suppressed or enhanced activity)



arXiv:1705.02056

By definition, transverse spherocity is sensitive to soft physics

$$S_0 \equiv \frac{\pi^2}{4} \min_{\hat{\boldsymbol{n}}_s} \left(\frac{\sum_i^{N_\mathrm{ch}} |\vec{p}_{\mathrm{T},i} \times \hat{\boldsymbol{n}}_s|}{\sum_i^{N_\mathrm{ch}} p_{\mathrm{T},i}} \right)^2$$

“Jetty”: $S_0 = 0$, “Isotropic”: $S_0 = 1$

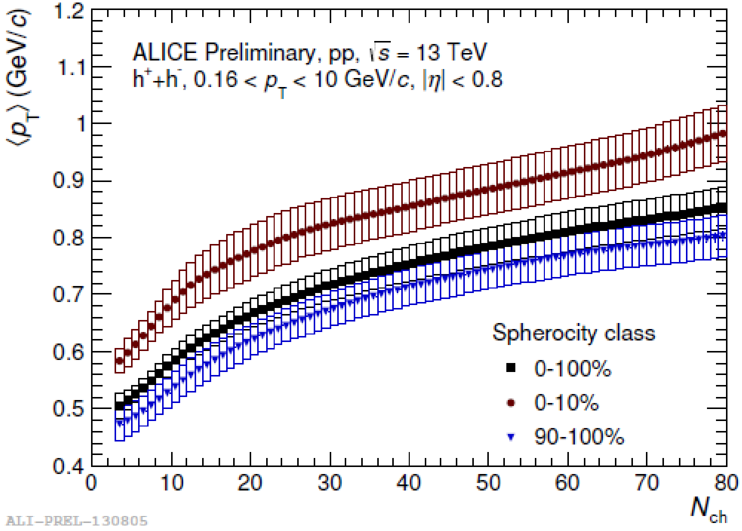
- *Collective* effects evidenced *in the soft* QCD *regime*
  → event shape observables are ideally suited to better distinguish the underlying physics of a pp collision
- For the studies of ***(un)identified*** particles, *events* are selected: *with more than* ***(2) 10 charged particles*** within $|\eta| < 0.8$ and $p_T > 0.15$ GeV/c
  → to minimize sensitivity to particle loss

New: LHC Run 2

Unidentified particle production – average p_T vs multiplicity and spherocity

ALICE

Mid-rapidity estimator is used



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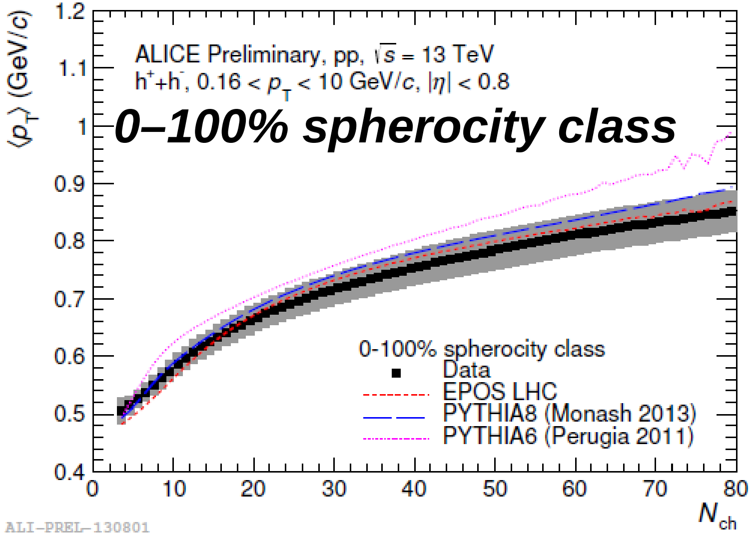


0–100% spherocity class

ALI-PREL-130801

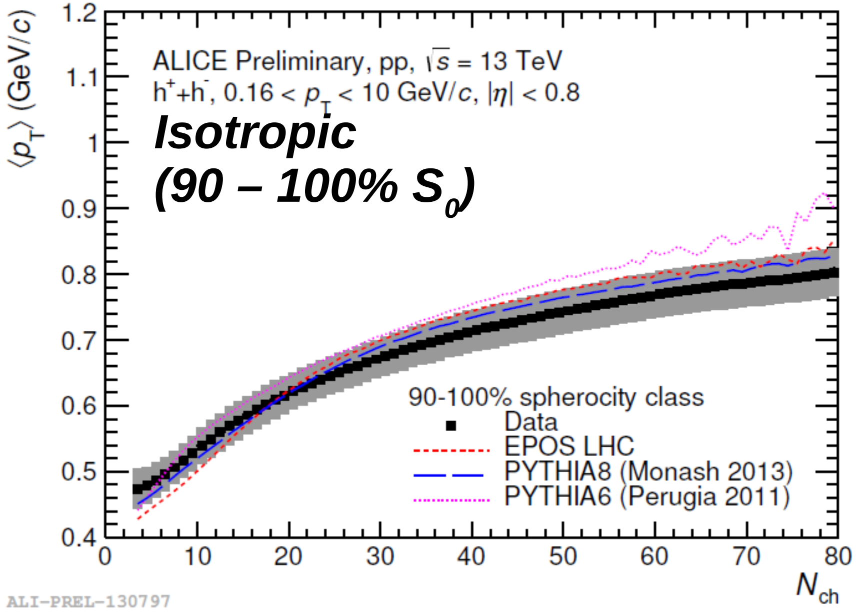
- ***For jetty events:*** steeper rise, systematically larger $<p_T>$ as compared to the 0 – 100% (S_0-unbiased) case → expected from jet production
- ***For isotropic events:*** systematically lower $<p_T>$ than the S_0-unbiased case
- ***So-integrated results:*** consistent to measurements at lower collision energies → No apparent energy dependence observed
- ***Model comparison:*** S_0-unbiased (0 – 100% S_0)

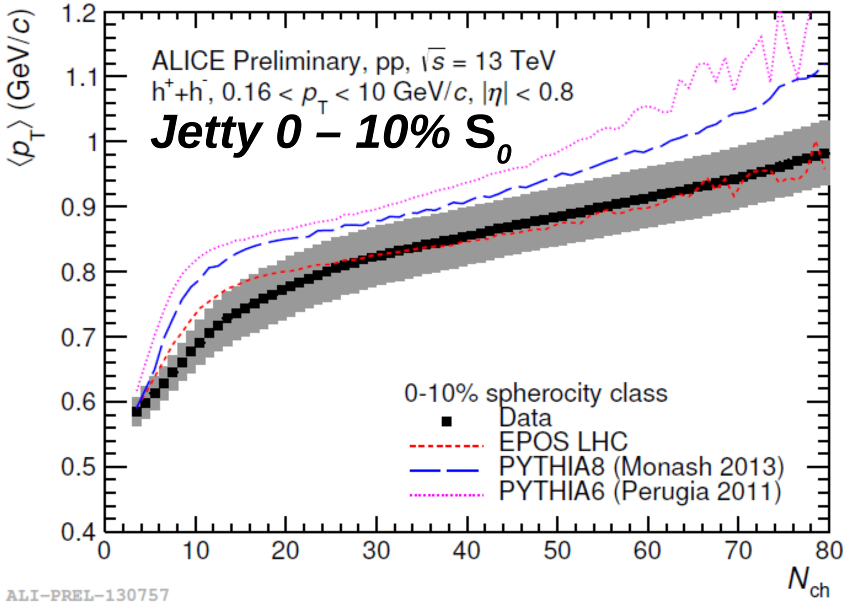
  → PYTHIA and EPOS-LHC models describe well the data

  (EPOS-LHC: small deviation at low N_{ch})

New:
LHC – Run 2

Average p_T vs multiplicity and spherocity **– Comparison to models**



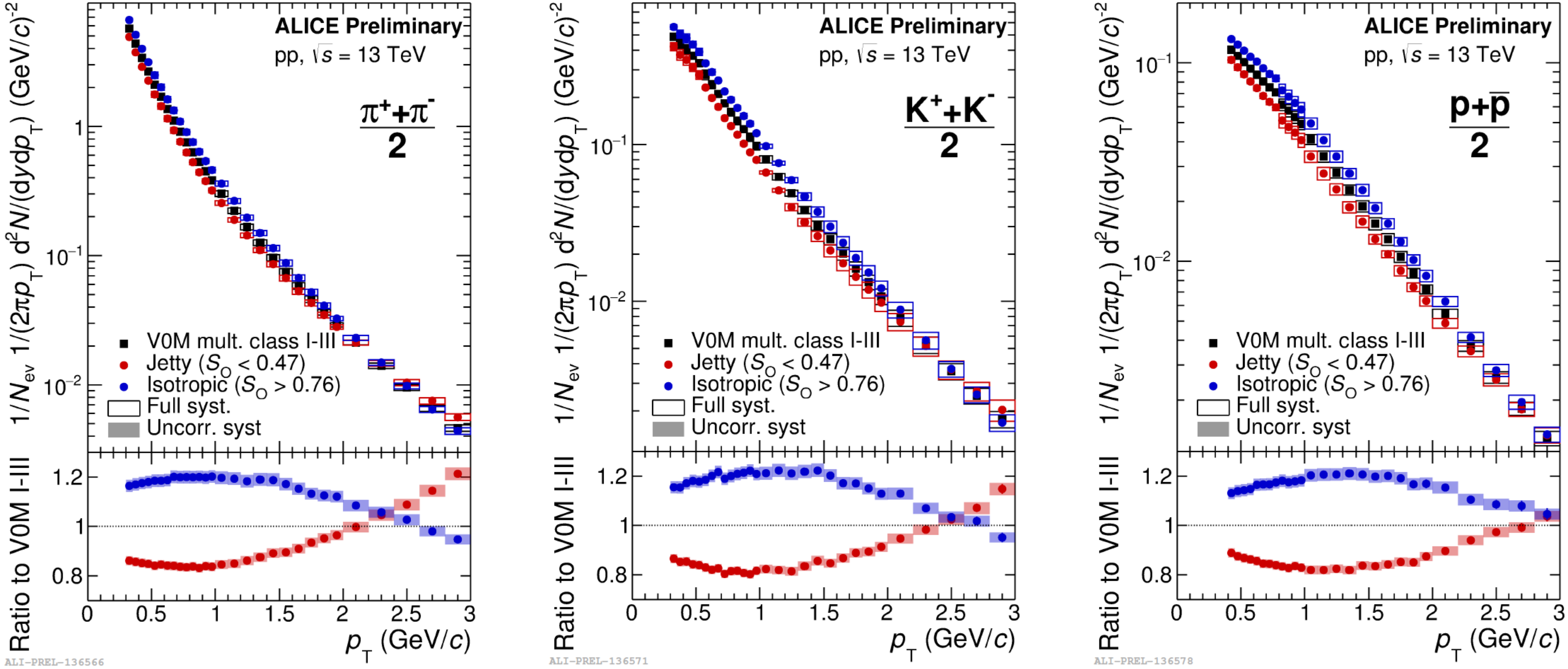


PYTHIA and EPOS LHC describe the $<p_T>$ evolution moderately well
(minor deviations for EPOS at very low N_{ch})

- PYTHIA overestimates $<p_T>$ for all N_{ch}
  (the contribution of underlying event is significantly underestimated)
- EPOS LHC gives the best description
  (overestimate the rise of $<p_T>$ at low multiplicities, it agrees very well with the data for $N_{ch} > 15$)

New: LHC Run 2
13 TeV

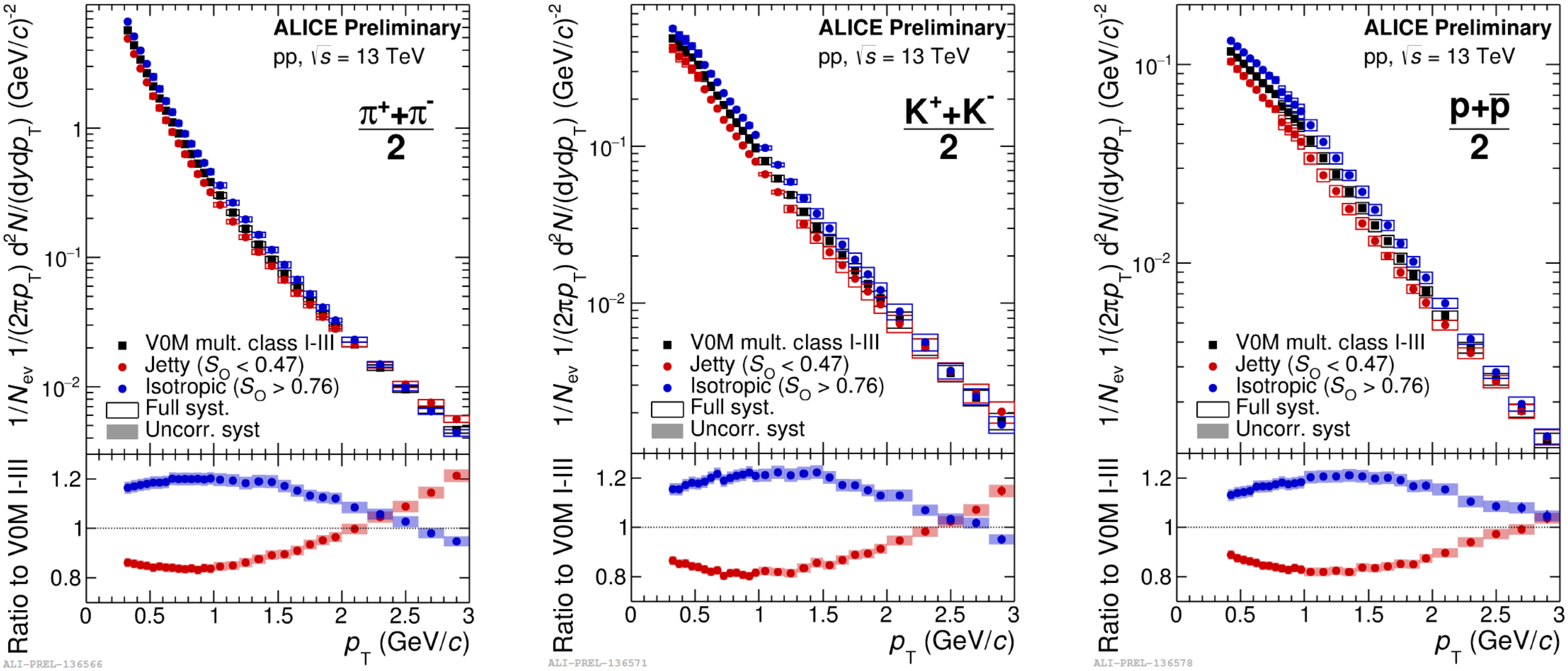
Identified particle spectra as a function of multiplicity and spherocity



- **Only** the **10% highest V0M multiplicity** events are considered
  → 97% of the events have at least ten charged tracks
- 20% of events with the highest (lowest) measured S_O
  → **isotropic**, $0.76 < S_O < 1$ (**jetty**, $0 < S_O < 0.46$)

New: LHC Run 2
13 TeV

Identified particle spectra
as a function of multiplicity and spherocity



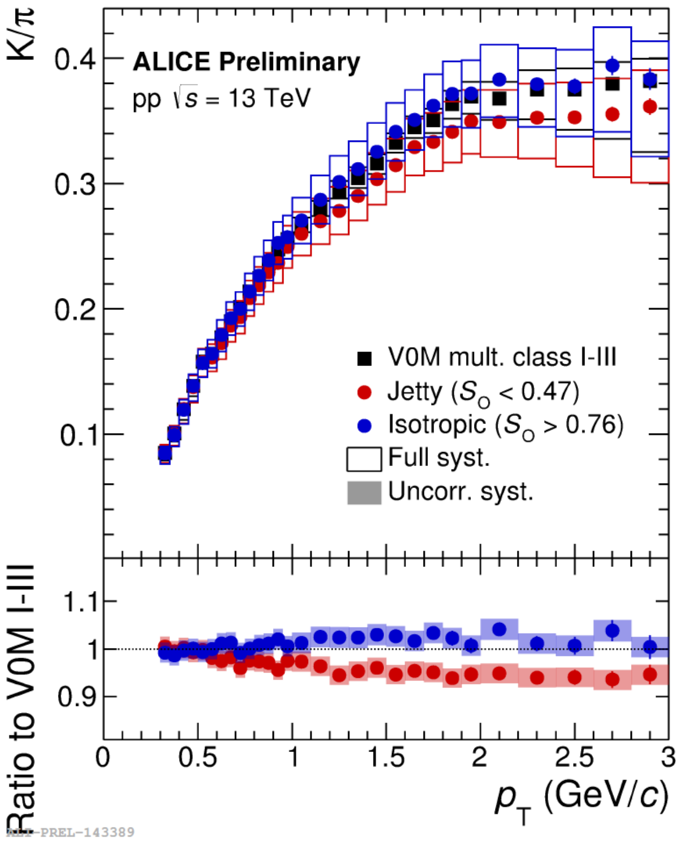
→ ***Isotropic events:*** spectra are enhanced at low p_T (compared to S_O-unbiased) and suppressed for p_T > 2.5 GeV/c for π and K

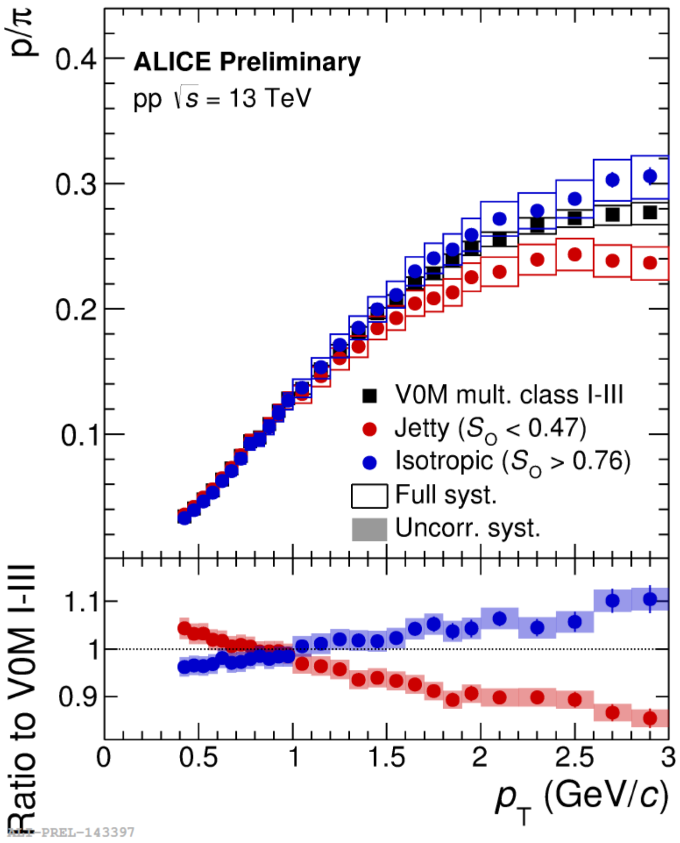
→ ***Jetty events:*** spectra are suppressed at low p_T and enhanced at intermediate p_T

→ *Crossing of "jetty" and "isotropic" spectra:* increase towards larger p_T for heavier particles
=> mass-dependent spectral modifications

New:
LHC
Run 2

Identified particle ratios
as a function of multiplicity and spherocity





Isotropic events:

Kaon-to-pion ratio:
→ consistent with those measured in the S_o-unbiased case

Proton-to-pion ratio:
→ apparent shift in p_T, similar to the multiplicity dependent modifications
→ **collective-like effects can be further enhanced**

Jetty events

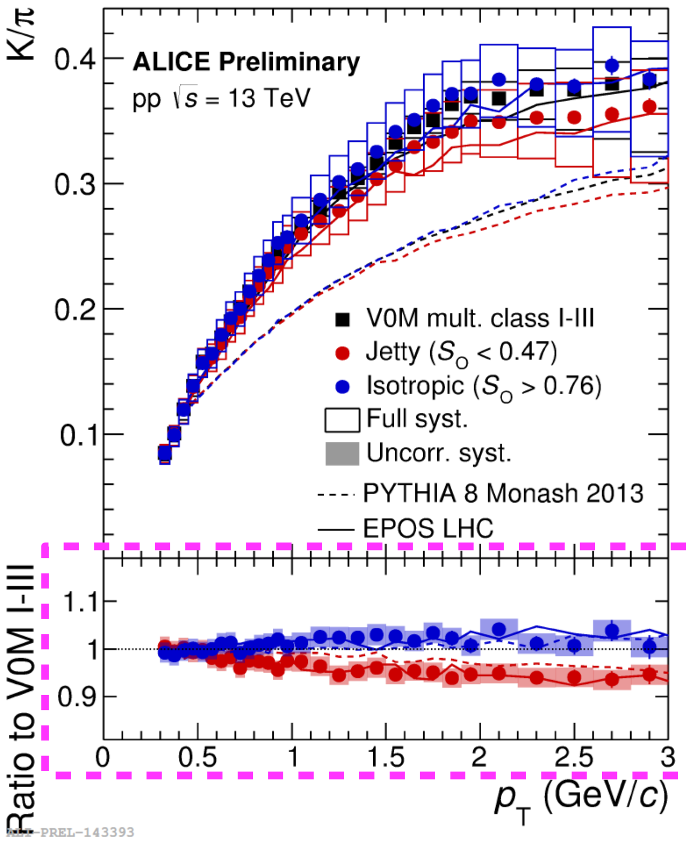
Kaon-to-pion ratio:
→ signatures of a suppression
→ species-dependent jet fragmentation

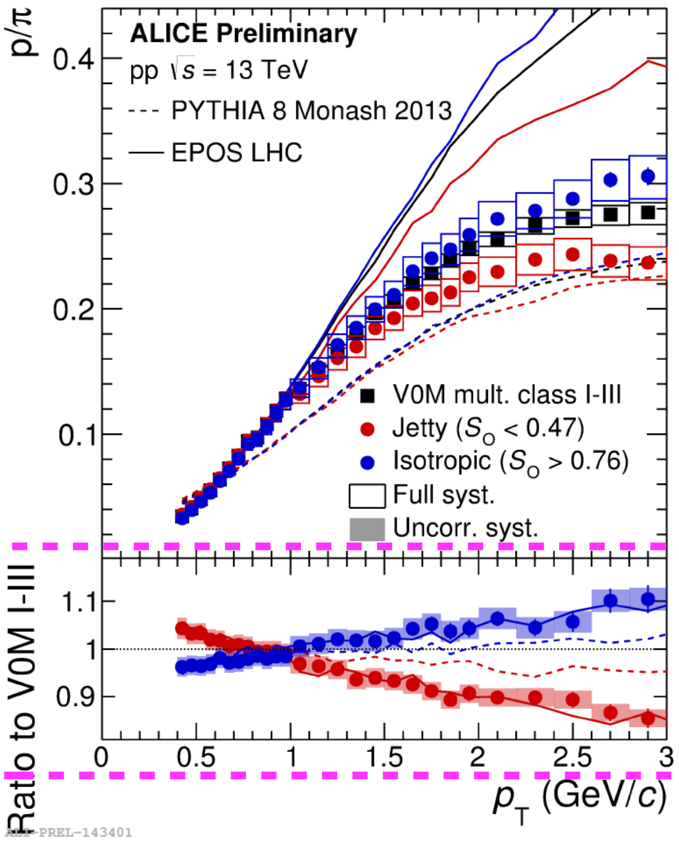
Proton-to-pion ratio:
→ suppression can be attributed to the production mechanisms of protons in jets

New:
LHC
Run 2

Comparison to models

Particle ratios as a function of multiplicity and spherocity





Ratios to S_0 unbiased (V0M class I – III)

Kaon-to-pion ratios (left)

→ double ratios are well-described by both PYTHIA 8 and EPOS-LHC generators (only fragmentation)

Proton-to-pion ratios (right):

→ PYTHIA 8: predicts the observed trends, but underestimates the magnitude of the modication
(Similar to evolution of average p_T
→ deviation might originate from underestimated underlying event)

→ **EPOS-LHC:**
=> **double ratio is described the best**
=> absolute ratio: further tuning is needed

Summary

Light-flavor hadron production studied as a function of

- $\sqrt{s}$ and charged-particle multiplicity N_{ch}

  → p_{T}-spectra and particle ratios exhibit a clear *evolution with* N_{ch}

  → p_{T}-integrated hadron yields scales with N_{ch} across different $\sqrt{s}$ and colliding systems:
  hadrochemistry is dominantly driven by multiplicity

  → Average p_{T} grows with $\sqrt{s}$ at similar N_{ch}:
  dynamics of particle production might be different at different $\sqrt{s}$

- $\sqrt{s}$ and charged-particle multiplicity N_{ch} and transverse spherocity S_0

  → Particle ratios: collective-like effects can be controlled with transverse spherocity

  → Average p_{T} is larger (smaller) in jetty (isotropic) events hinting at different dynamics of particle production

Microscopic (Pythia 8, DIPSY) and macroscopic (EPOS-LHC) models describe several aspects of data;
in most cases EPOS-LHC does a better job.

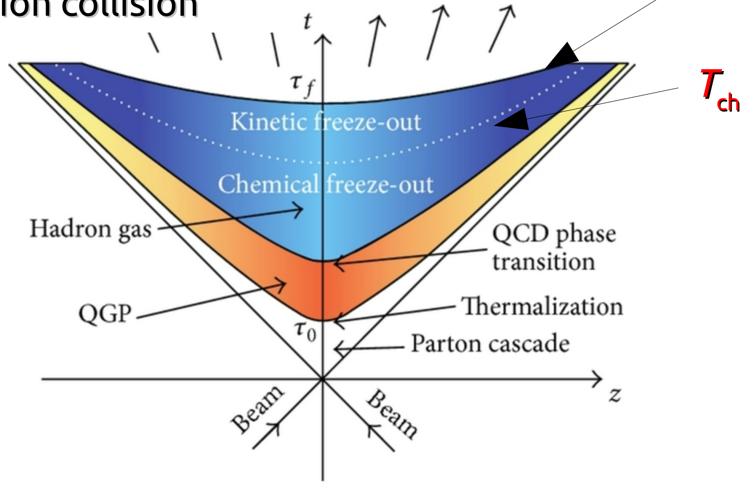
Thank you for your attention!

Backup slides

A Large Ion Collider Experiment (ALICE) at the LHC

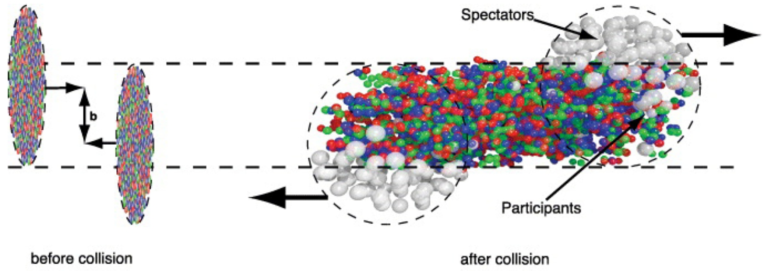
- ALICE at the LHC is optimized for heavy-ion physics
- ALICE aims to study the formation of the strongly interacting QCD matter, the Quark-Gluon Plasma (QGP) created in high energy heavy-ion collisions

Time evolution of the matter produced in heavy-ion collision



Thermal model:

- Particles in HI collisions are produced in apparent chemical equilibrium
- Description based on thermal-statistical models
  - Particle abundances ∝ exp($-m/T_{ch}$) with T_{ch} *being ~156 MeV*



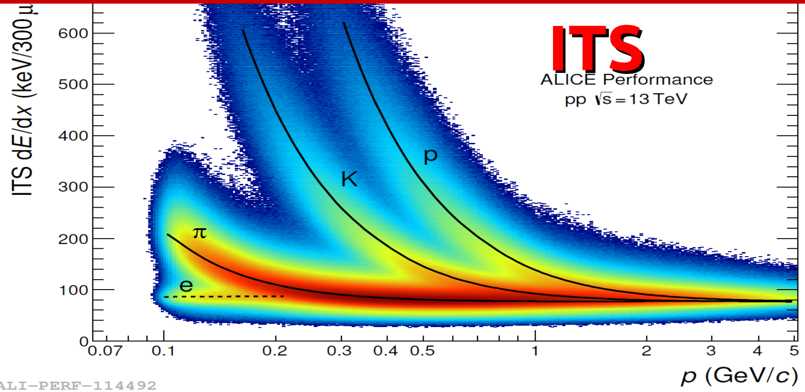
- Hot and dense system is created by colliding heavy ions (Pb ions)
  - high energy density (>> 1 GeV/fm^3) over large volume (>> 1000 fm^3)
- Transition from nuclear matter into deconfined phase at high *T*
- Collective expansion of the system
  → multiple interactions of partons
- Chemical freeze-out (T_{ch})
  - end of inelastic scatterings
- Kinetic freeze-out (T_{f0})
  - end of elastic scatterings

Particle Identification in ALICE

ALICE Performance, Int. J. Mod. Phys. A 29 (2014) 1430044

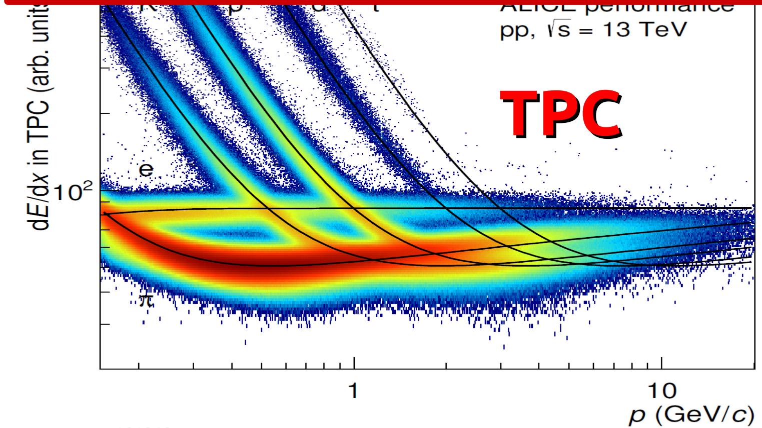
New: √s = 13 TeV (LHC Run 2)

- **Tracking + standalone reconstruction: PID via dE/dx from SDD and SSD**
- **Standalone tracking in the low-p_T region (down to 100 MeV/c)**



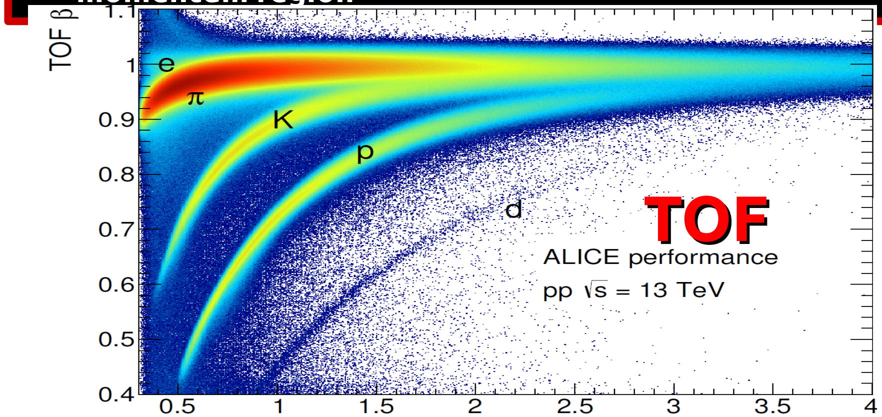
ALI-PERF-114492

- **Track-by-track ID (n-σ cut) in the 1/β² region**
- **PID in the relativistic rise using a statistical approach**



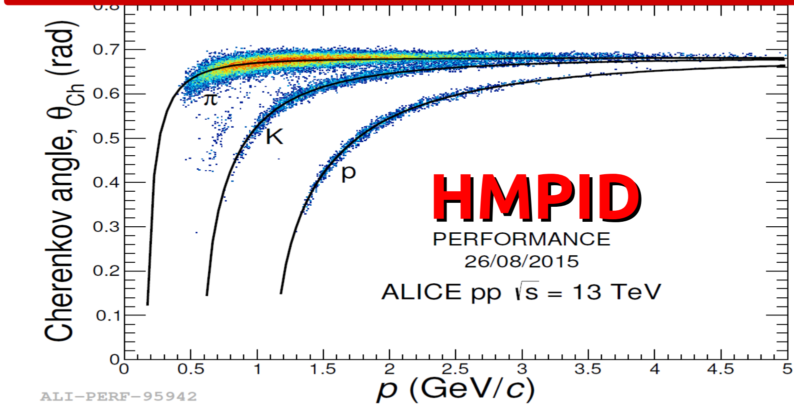
ALI-PERF-101240

- **PID via velocity measurement in the intermediate momentum region**



ALI-PERF-112141

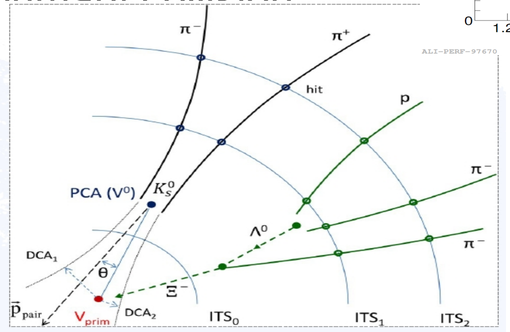
- **PID using RICH technique in the intermediate momentum region on a track-by-track basis**

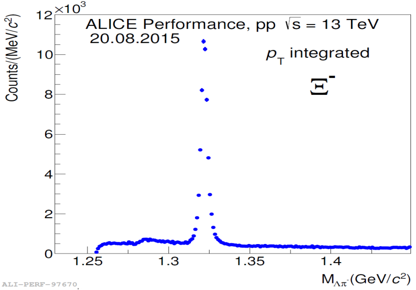


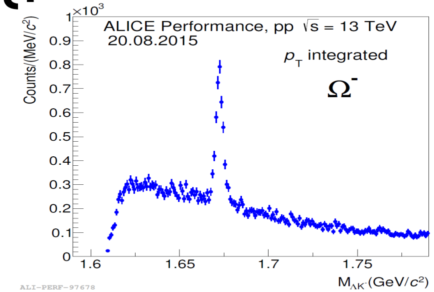
ALI-PERF-95942

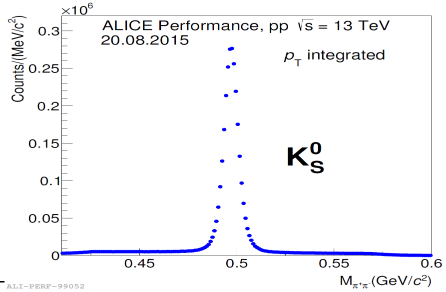
Measurement of light flavor particle p_T-spectra

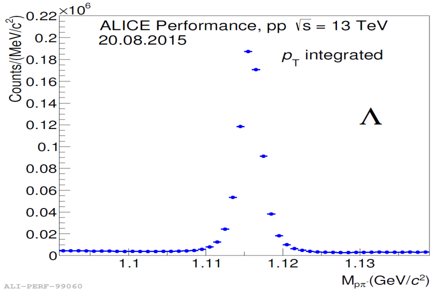
- Primary particles [1] *: particle with* cτ > 1 cm, which is either a) produced directly in the interaction, or b) from decays of particles with cτ < 1 cm, restricted to decay chains leading to the interaction – that is to the primary collision
    - ***Long-lived** particles*
    - *Topological identification of **weakly-decaying strange hadrons***
- Invariant-mass

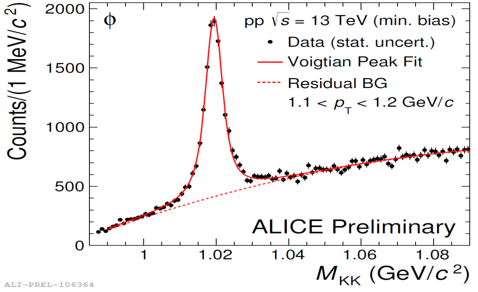


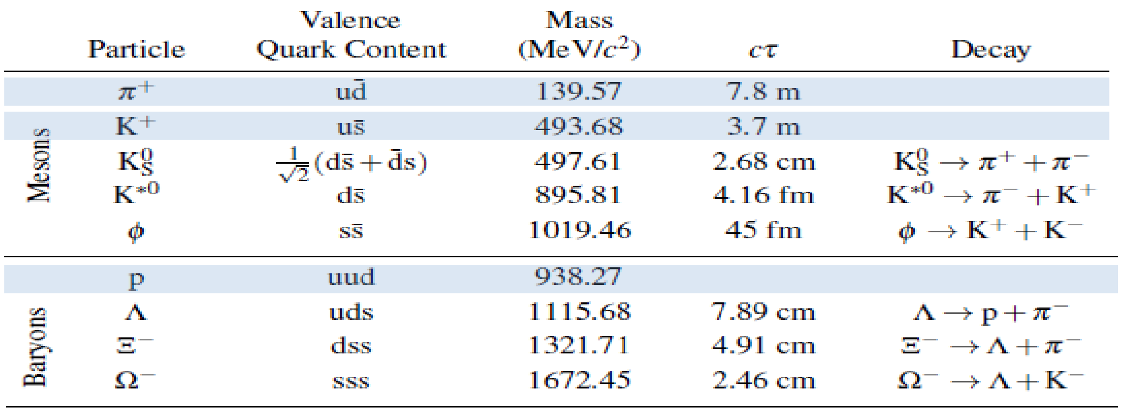




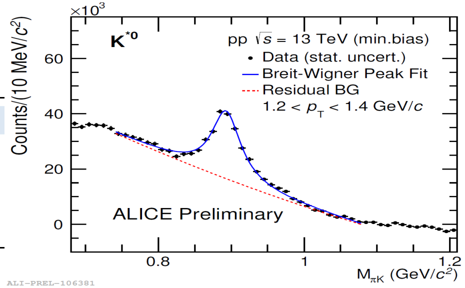








	Particle	Valence Quark Content	Mass (MeV/c^2)	$c\tau$	Decay
Mesons	π^+	$u\bar{d}$	139.57	7.8 m	
	K^+	$u\bar{s}$	493.68	3.7 m	
	K^0_S	$\frac{1}{\sqrt{2}}(d\bar{s}+\bar{d}s)$	497.61	2.68 cm	$K^0_S \to \pi^+ + \pi^-$
	K^{*0}	$d\bar{s}$	895.81	4.16 fm	$K^{*0} \to \pi^- + K^+$
	ϕ	$s\bar{s}$	1019.46	45 fm	$\phi \to K^+ + K^-$
Baryons	p	uud	938.27		
	Λ	uds	1115.68	7.89 cm	$\Lambda \to p + \pi^-$
	Ξ^-	dss	1321.71	4.91 cm	$\Xi^- \to \Lambda + \pi^-$
	Ω^-	sss	1672.45	2.46 cm	$\Omega^- \to \Lambda + K^-$



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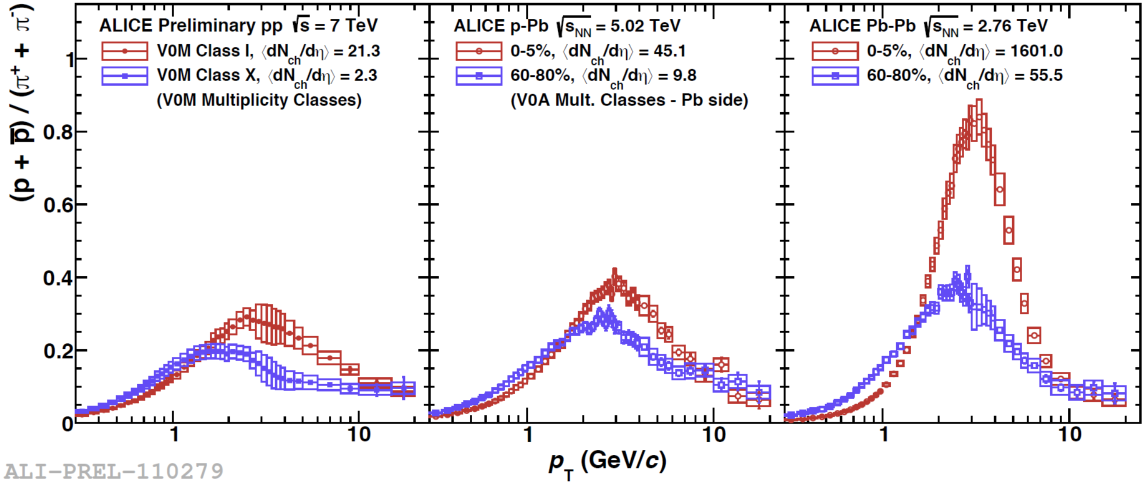
[1] ALICE-PUBLIC-2017-005. The ALICE definition of primary particles

Similarities among different colliding systems



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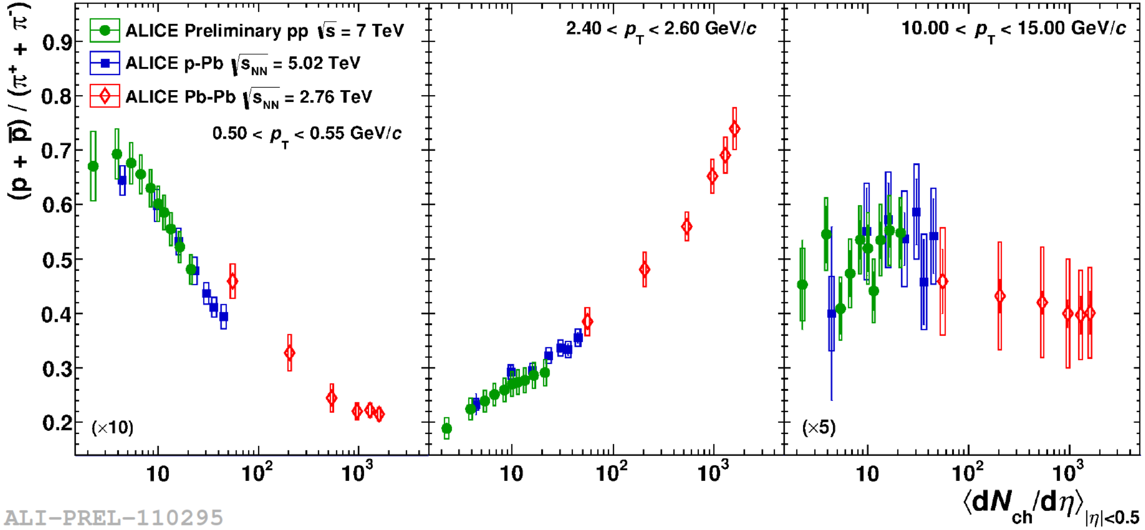


ALI-PREL-110295

Low-p_T*: < 2 GeV/c; Mid-*p_T*: 2 <* p_T *< 10 GeV/c; High-*p_T*: > 10 GeV/c*

Light flavor particle p_T-spectra *in pp*

$\sqrt{s}$ = 7 TeV

Multiplicity dependence

- Events classified according to event activity measured in the backward/forward region (by “V0M” estimator), in order to avoid auto-correlation biases.
- Charged-particle multiplicity measured at mid-rapidity for each event class

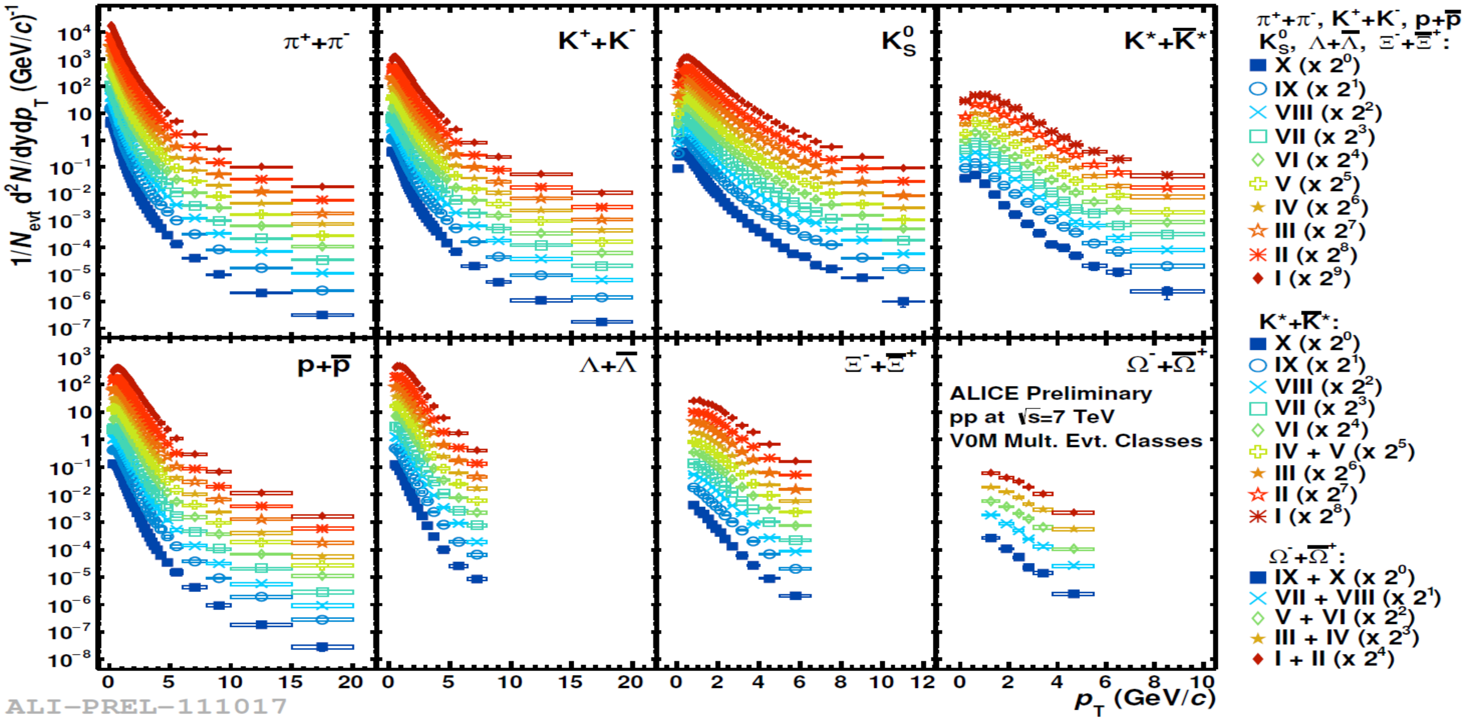
“V0M” multiplicity classes:

Inlusive

→ $(dN/d\eta)_{INEL>0} \approx 6.0$

I → $dN/d\eta \approx 3.5 \times (dN/d\eta)_{INEL>0}$

X → $dN/d\eta \approx 0.4 \times (dN/d\eta)_{INEL>0}$



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

$\sqrt{s}$ = 7 TeV

Evolution of spectral shapes with multiplicity

High Multiplicity

~ 3.5 x $(dN/d\eta)_{INEL > 0}$

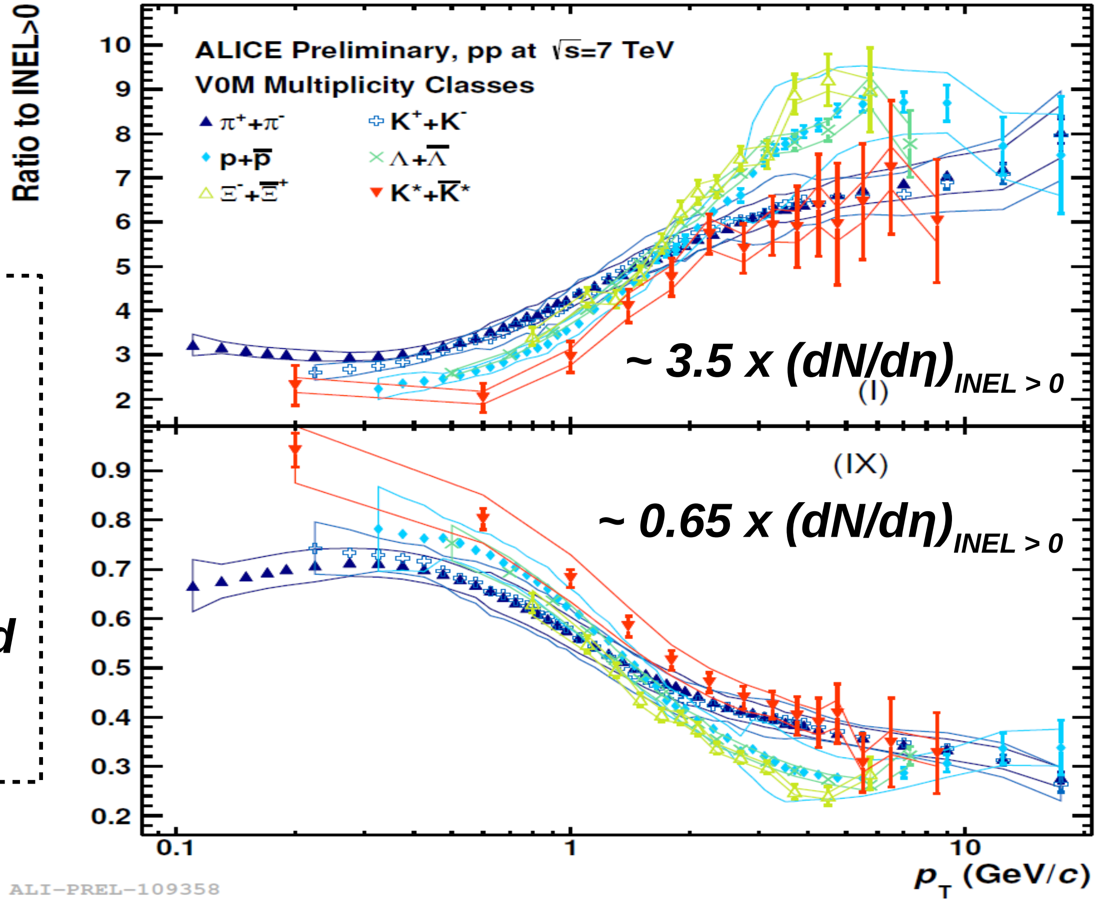
Flattening at high p_T

- ***Mass-dependent hardening with increasing event multiplicity*** *→ hardening for baryons more pronounced than for mesons*
- ***In Pb–Pb****: change in spectral shape interpreted in terms of* ***collective expansion of a locally thermalized system***

Low Multiplicity

~ 0.65 x $(dN/d\eta)_{INEL > 0}$

Flattening at Low p_T



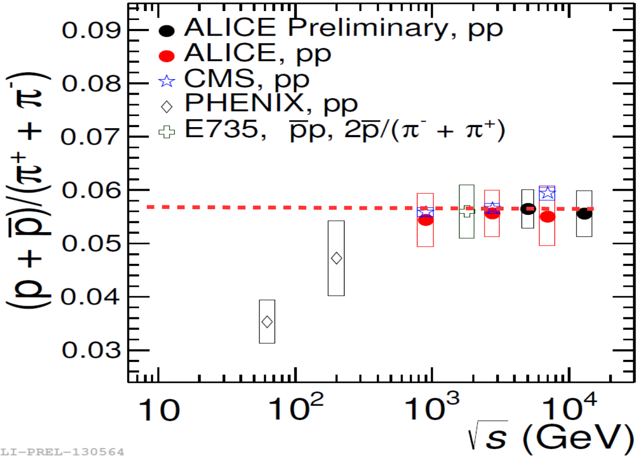
~ 3.5 x $(dN/d\eta)_{INEL > 0}$

~ 0.65 x $(dN/d\eta)_{INEL > 0}$

New:
LHC Run 2

√s dependence : p_T-integrated particle ratios

- Saturation in K-to-pion and p-to-pion ratios observed in the LHC-energy regime
- Hint of modest increase of hyperon-to-pion ratio with increasing **√s**
- **Can one factorize this increase to be only a function of $\langle dN_{\rm ch}/d\eta \rangle$ regardless of √s?**



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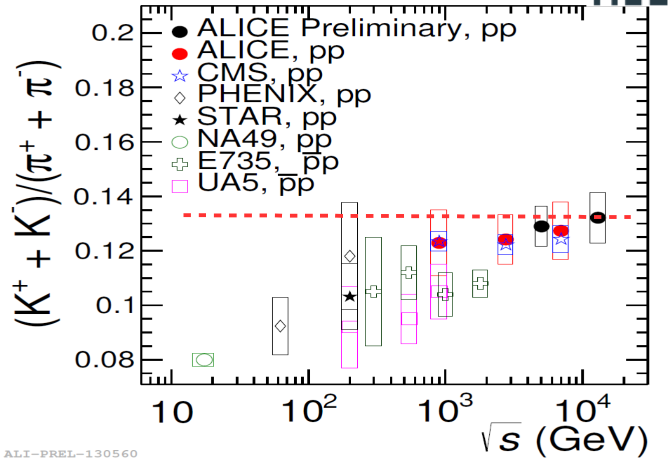

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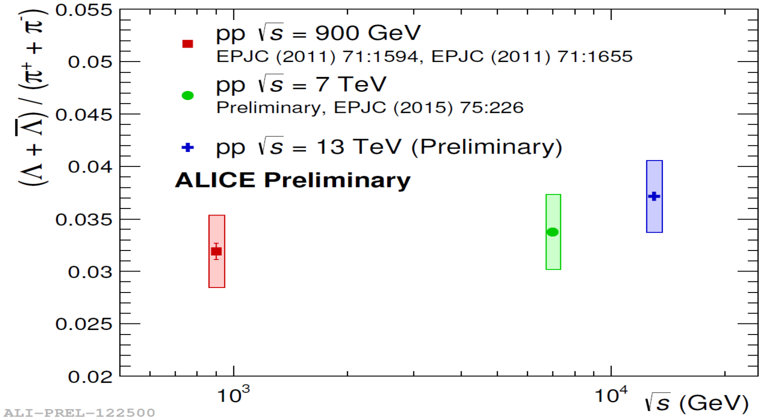

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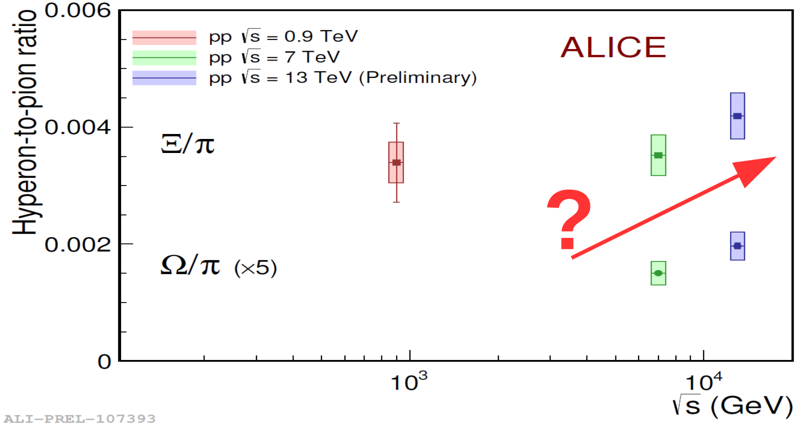
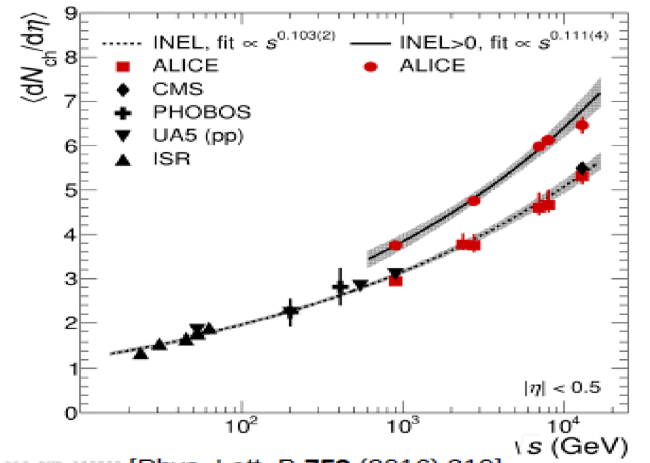


ALI-PREL-107393

$\sqrt{s}$ dependence : $\langle dN_{ch}/d\eta \rangle$



ALI-PUB-102502 [Phys. Lett. B **753** (2016) 319]

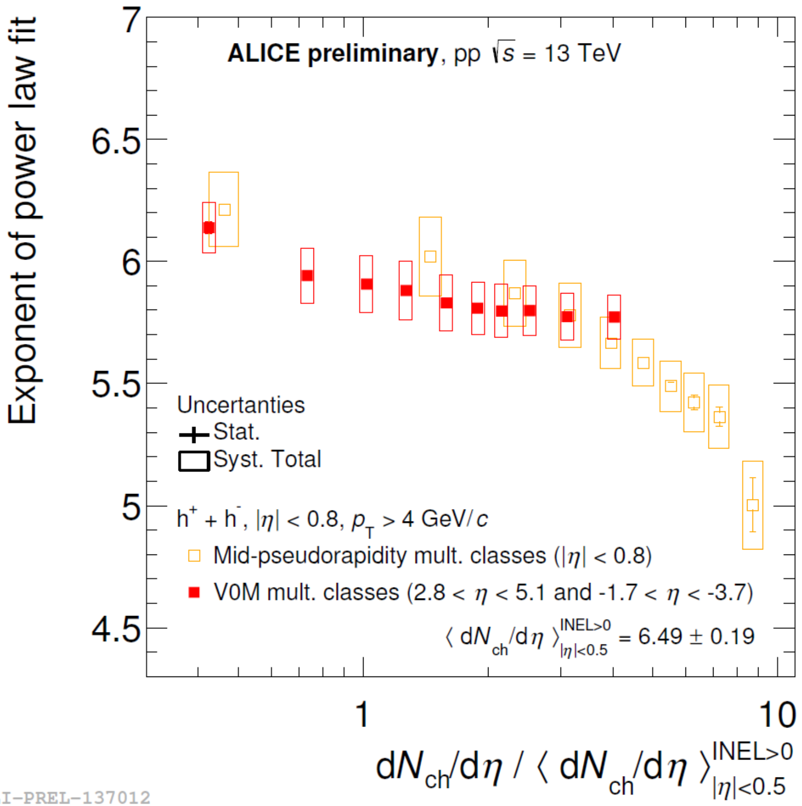
- $\langle dN_{ch}/d\eta \rangle$ follows a power law behavior as a function of $\sqrt{s}$
- *Only modest change (factor of < 2) in* $\langle dN_{ch}/d\eta \rangle$ *over 1 order of* magnitude increase in $\sqrt{s}$ (0.9 TeV → 13 TeV)
- Evolution of hyperon-to-pion ratios are consistent with the increase observed in $\langle dN_{ch}/d\eta \rangle$
- Is hadrochemistry dominantly driven by $\langle dN_{ch}/d\eta \rangle$?

An event-multiplicity differential study is performed

- *“V0M” estimator is used to slice in percentiles of multiplicity*
- $\langle dN_{ch}/d\eta \rangle$ *restricted to |η|<0.5 represents the average number of charged primary particles at midrapidity*

New:
LHC
Run 2

Particle production at high p_T:
multiplicity dependence of the power-law exponent



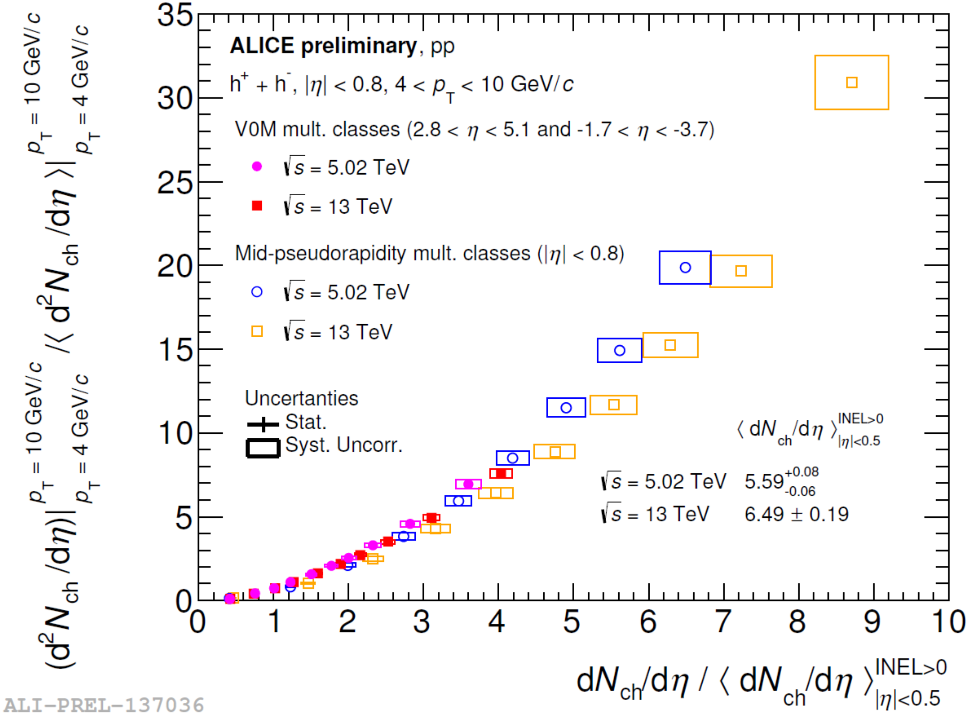
- Low multiplicity:
  → plateau observed regardless of used multiplicity estimator and collision energy

- High multiplicity:
  → mid-rapidity estimator: decreasing trend towards higher multiplicities

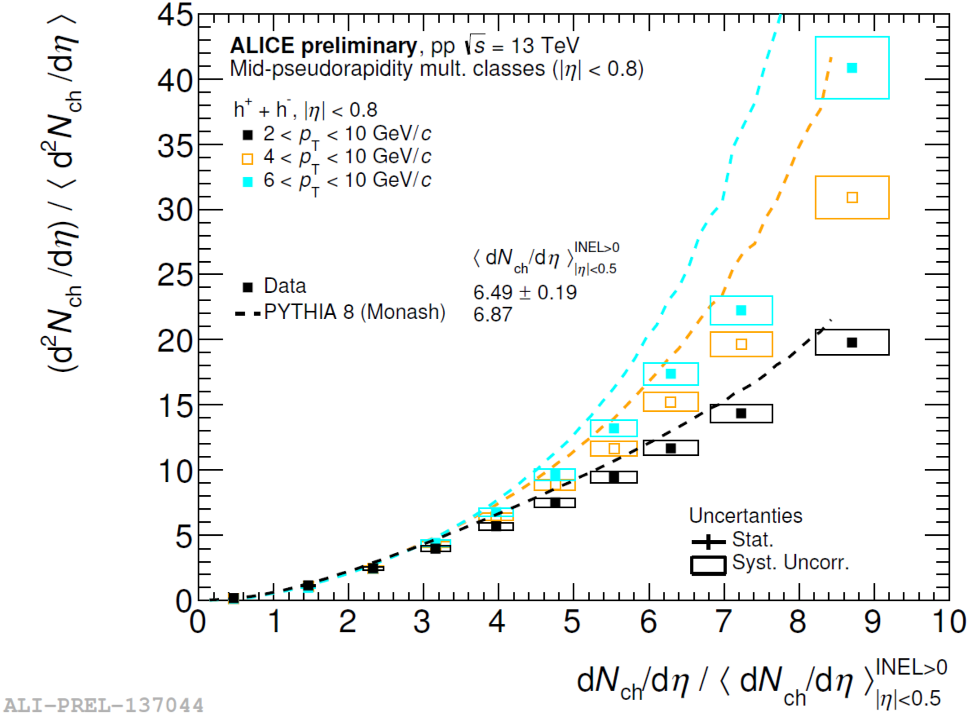
  → nonlinearity: similar result seen at lower energy and for identified particles

New:
LHC
Run 2

Relative yields of charged particles as a function of V0M and tracklets multiplicity estimators, pp at 5.02 and 13 TeV

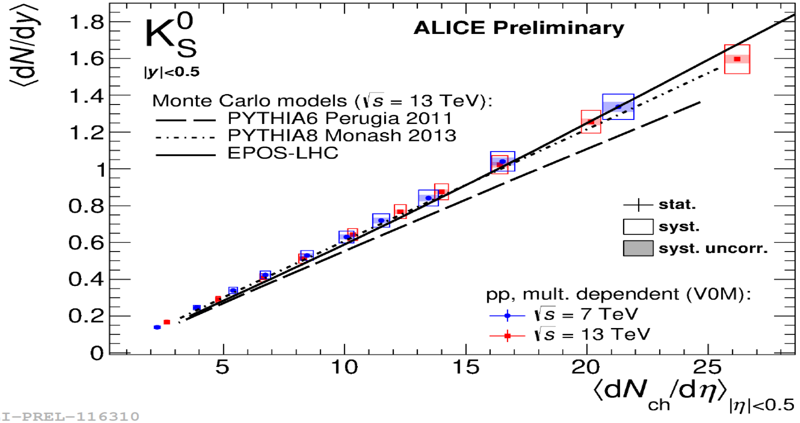


ALI-PREL-137036

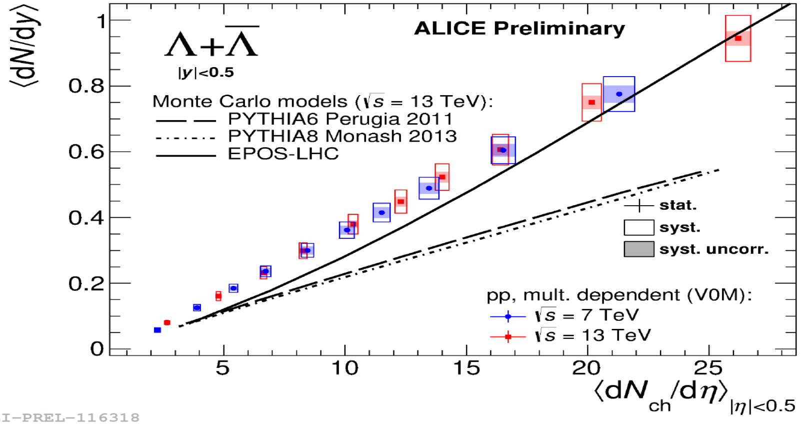


ALI-PREL-137044

Multiplicity dependence: strange hadron production at different √s

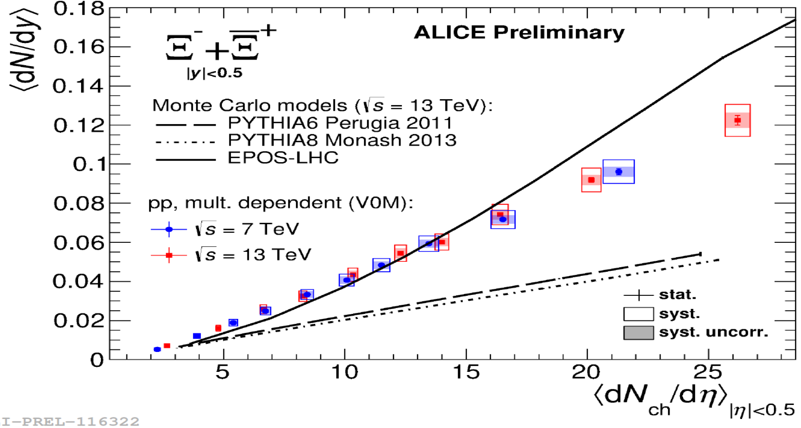


ALI-PREL-116310

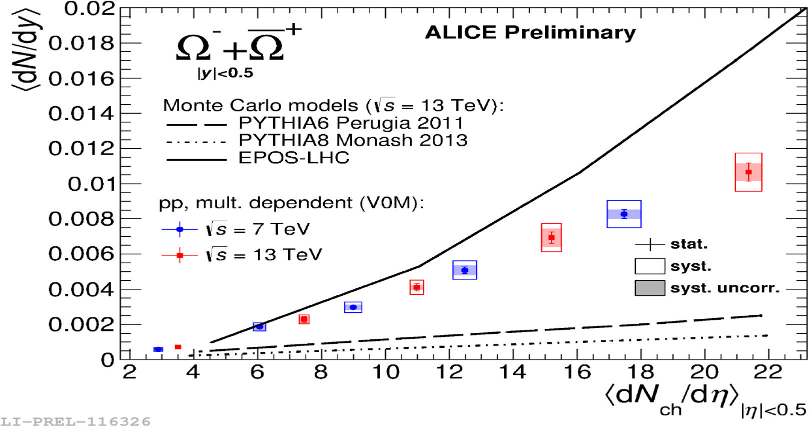


ALI-PREL-116318

Hadrochemistry is driven by multiplicity rather than √s



ALI-PREL-116322



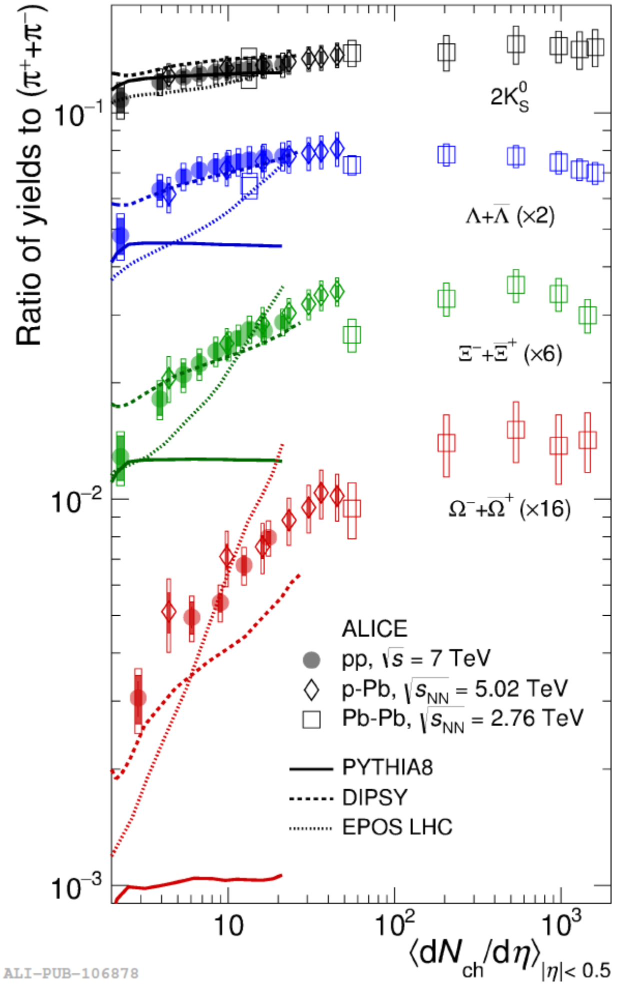
ALI-PREL-116326

Multiplicity dependence:
strange and multi-strange hadron production

- ***Significant enhancement of strange*** to non-***strange hadron*** production is observed ***with increasing*** *particle* ***multiplicity in pp***

- ***Similar behavior*** to that observed ***in p–Pb*** (both in terms of values and trend with multiplicity)

- ***Similar values*** reached ***in high-multiplicity pp***, ***p–Pb***, and ***peripheral Pb–Pb*** collisions (having at similar multiplicities)

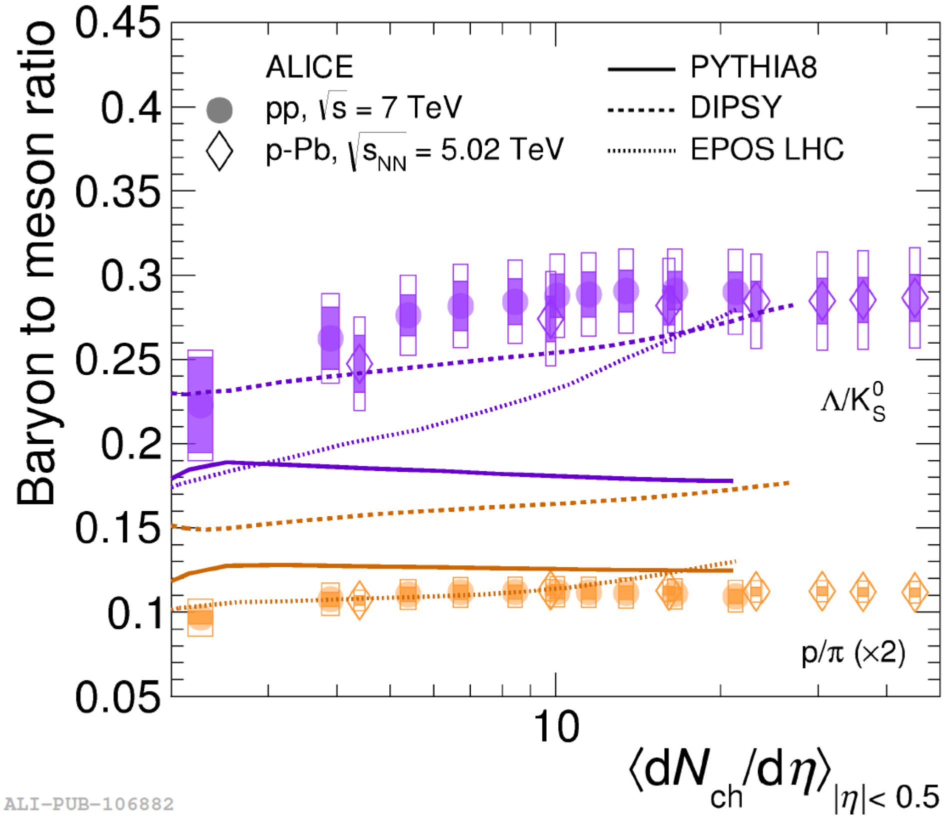


ALI-PUB-106878

Ref.: Nature Physics **13 (2017)** 535-539

Multiplicity dependence: Baryon to meson ratios

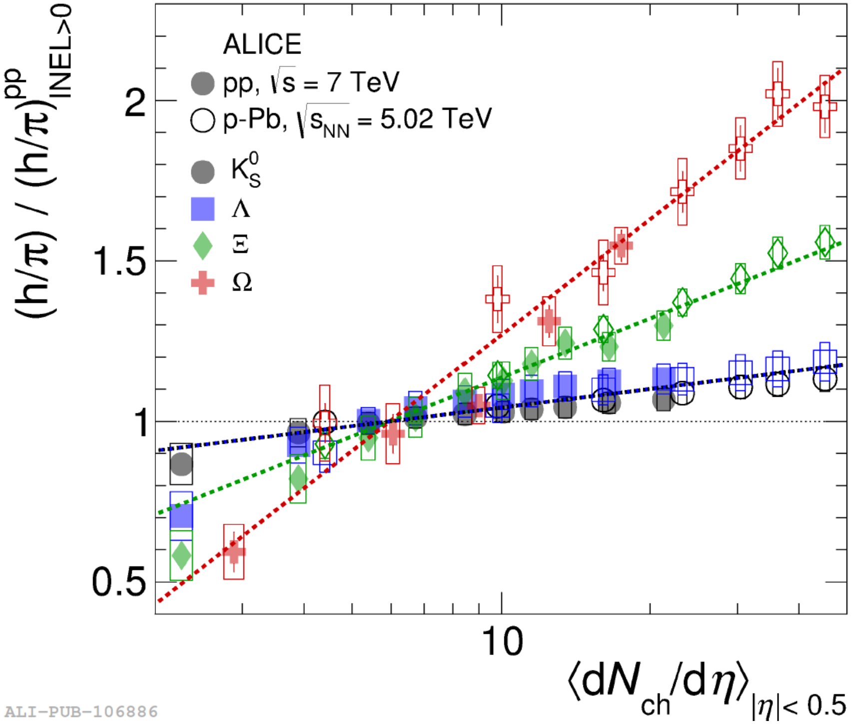
- ***Baryon-to-meson ratios*** *(with same strangeness content) but different masses*
  - No significant change with multiplicity
  - → Strangeness ***enhancement*** is ***neither*** due to the ***difference in the hadron masses nor*** *due to baryon nature of the particle*
- *Monte Carlo comparison*
  - *DIPSY [2] with color ropes describes qualitatively best the increase of strange particles, but fails to describe the p/pi ratio*
  - *EPOS describes the evolution qualitatively*



[1] Nature Physics **13 (2017)** 535-539; [2] *DIPSY, C. Flensburg et al., JHEP08 (2011) 103; C. Bierlich et al., JHEP03 (2015) 148*

Multiplicity dependence:
strange and multi-strange hadron production [1]

The multiplicity-dependent ***enhancement follows*** *a* ***hierarchy*** *determined by strangeness content of the hadron*



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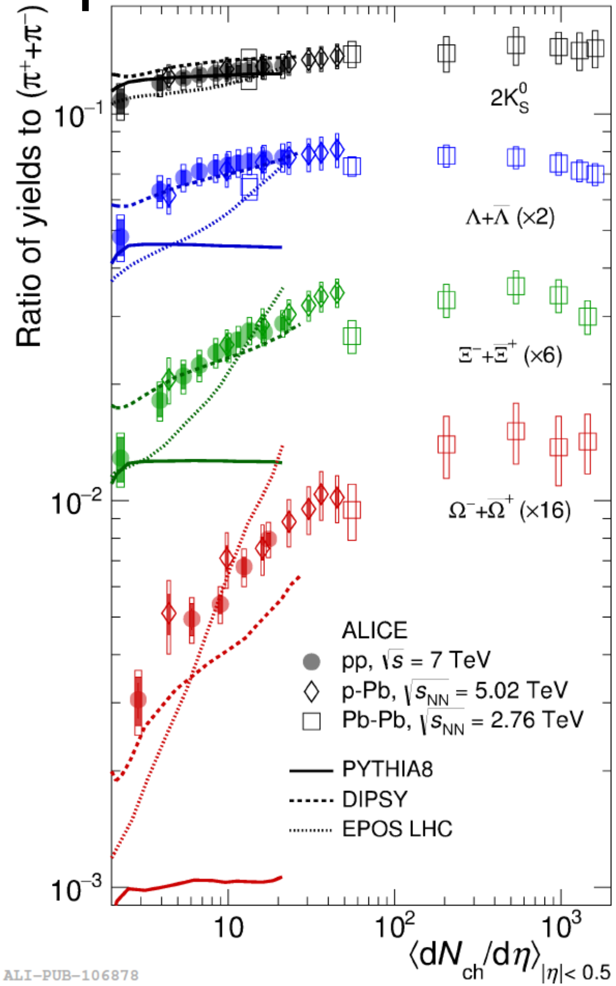
Ω (sss)

Ξ (dss)

Λ (uds)



ALI-PUB-106878

[1] Nature Physics 13 (2017) 535-539; [2] *DIPSY, C. Flensburg et al., JHEP08 (2011) 103; C. Bierlich et al., JHEP03 (2015) 148*