New results on the multiplicity and centre-of-mass energy dependence of identified particle production in pp collisions with ALICE

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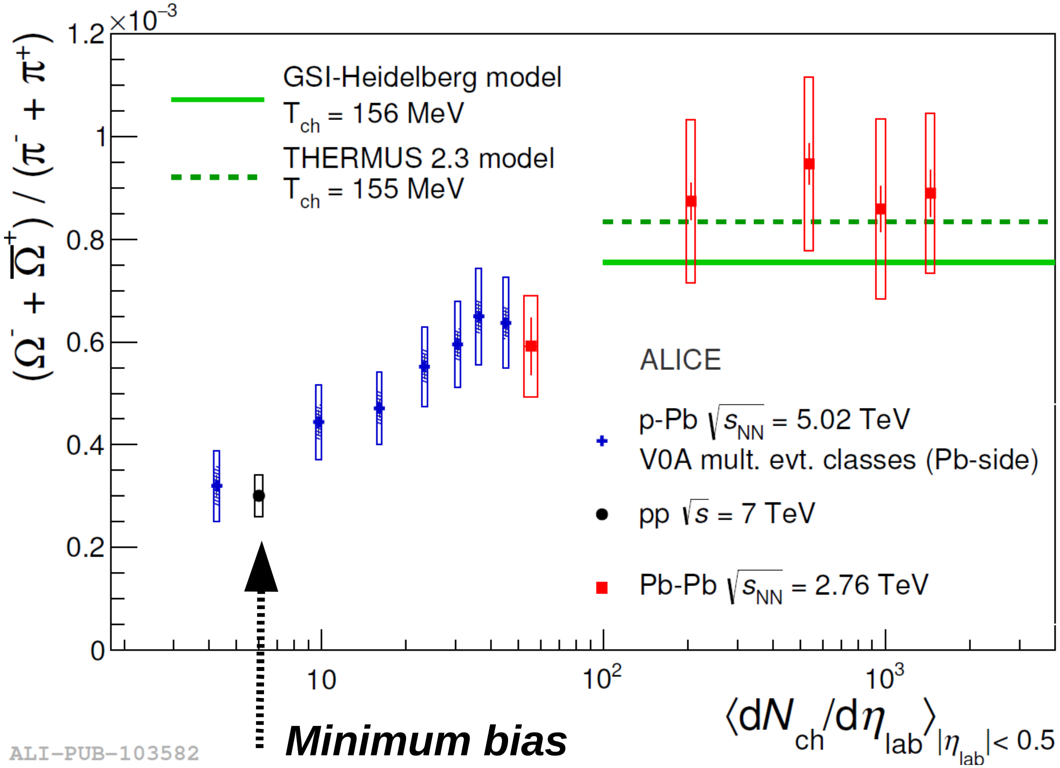
on behalf of the ALICE Collaboration

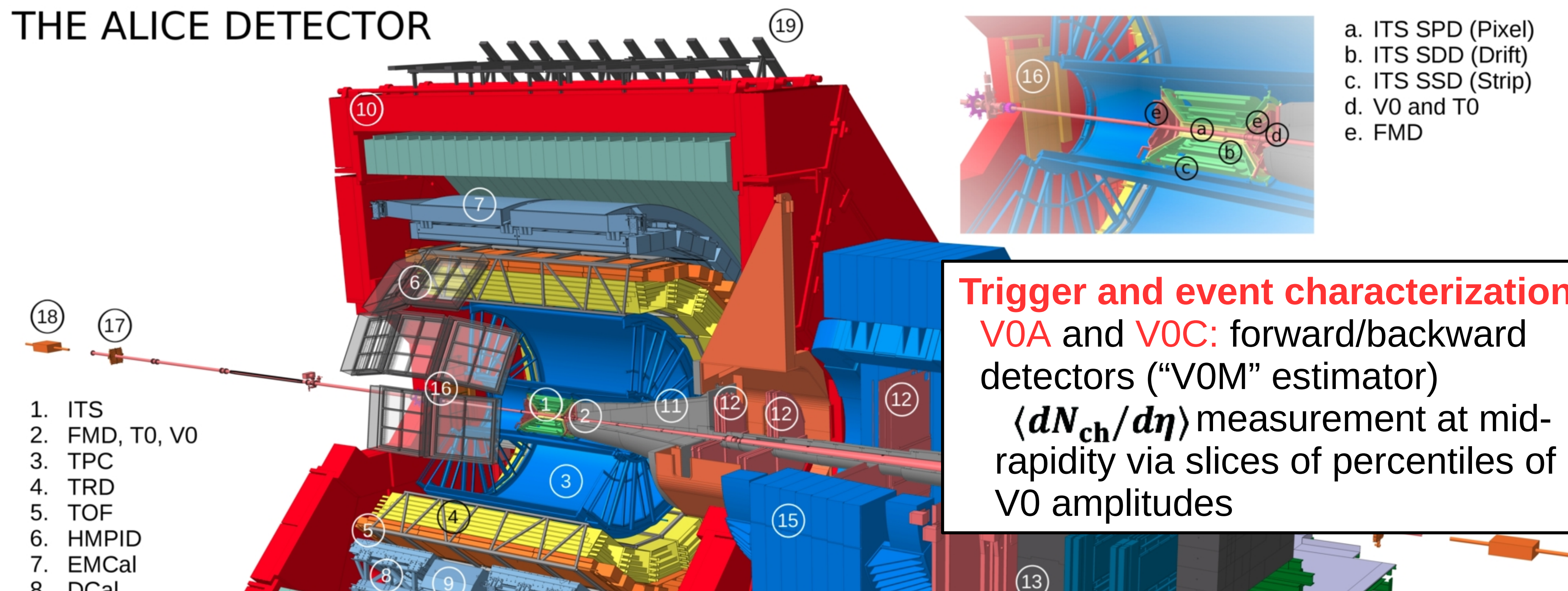
Motivation

- A Large Ion Collider Experiment (ALICE) at the LHC is optimized for heavy-ion physics
- **ALICE** also has **important contributions** to the LHC **pp physics** program
- Studies of particle production at high energies in pp collisions aim to
  - Constrain fragmentation functions **[1]** in pQCD calculations at high p_T (hard interactions)
  - Constrain phenomenological (pQCD inspired) models (soft interactions)
- Understanding the similarities among p-Pb and Pb-Pb systems:
  - Smooth evolution of yield ratio in p–Pb and Pb–Pb → Is it also observed as a function of multiplicity in pp?
  - **Study** the **evolution** of particle production with center-of-mass energy **(√s)** and **multiplicity** by measuring identified particle production

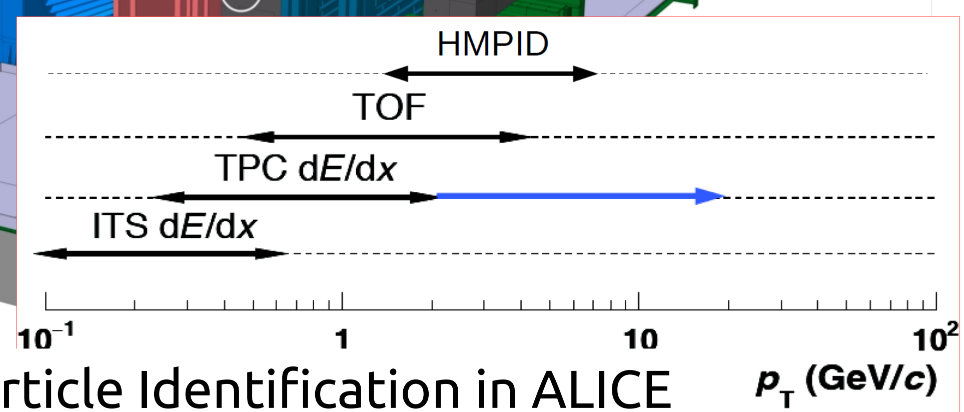


[1] Daniel de Florian *et. al*, Phys. Rev. **D 95**, 094019

ALICE detector



Trigger and event characterization:
V0A and V0C: forward/backward detectors ("V0M" estimator)
$\langle dN_{ch}/d\eta \rangle$ measurement at mid-rapidity via slices of percentiles of V0 amplitudes



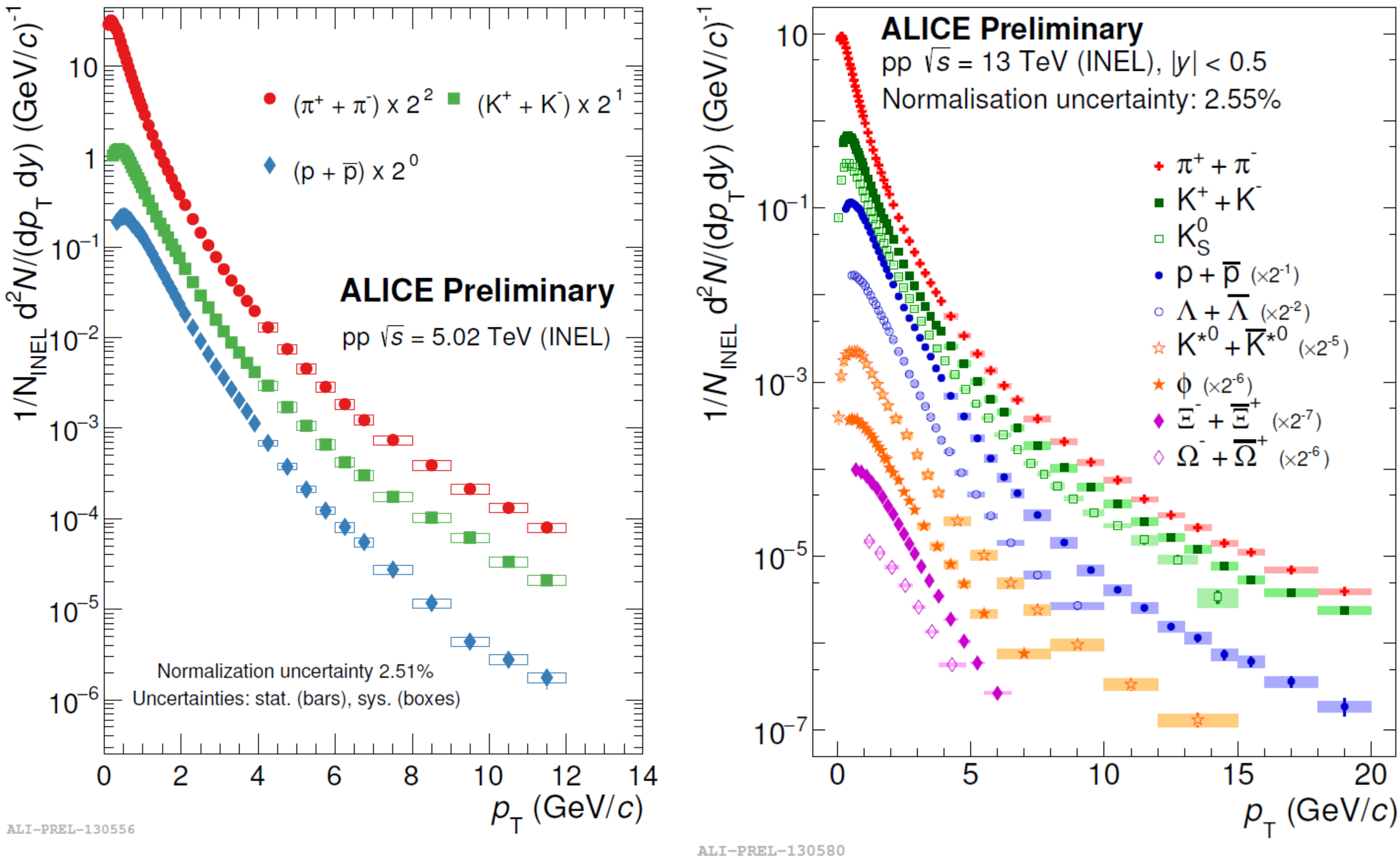
Particle Identification in ALICE

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

New: LHC Run 2

Transverse momentum spectra in INEL pp collisions

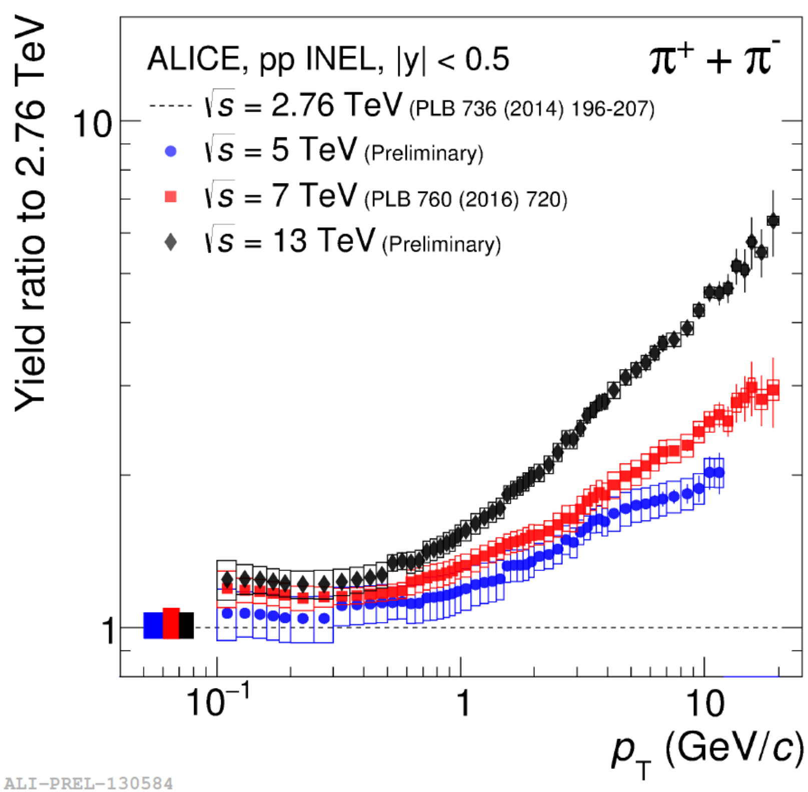
$\sqrt{s}$ = 5.02 TeV $\sqrt{s}$ = 13 TeV

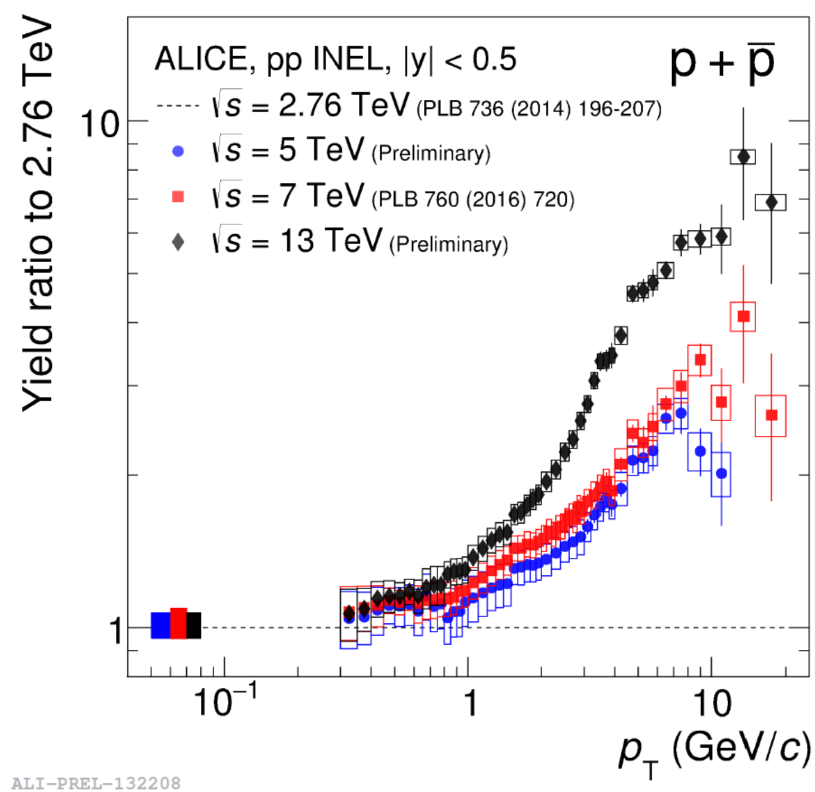


New:
LHC Run 2

Energy dependence: p_T-spectra

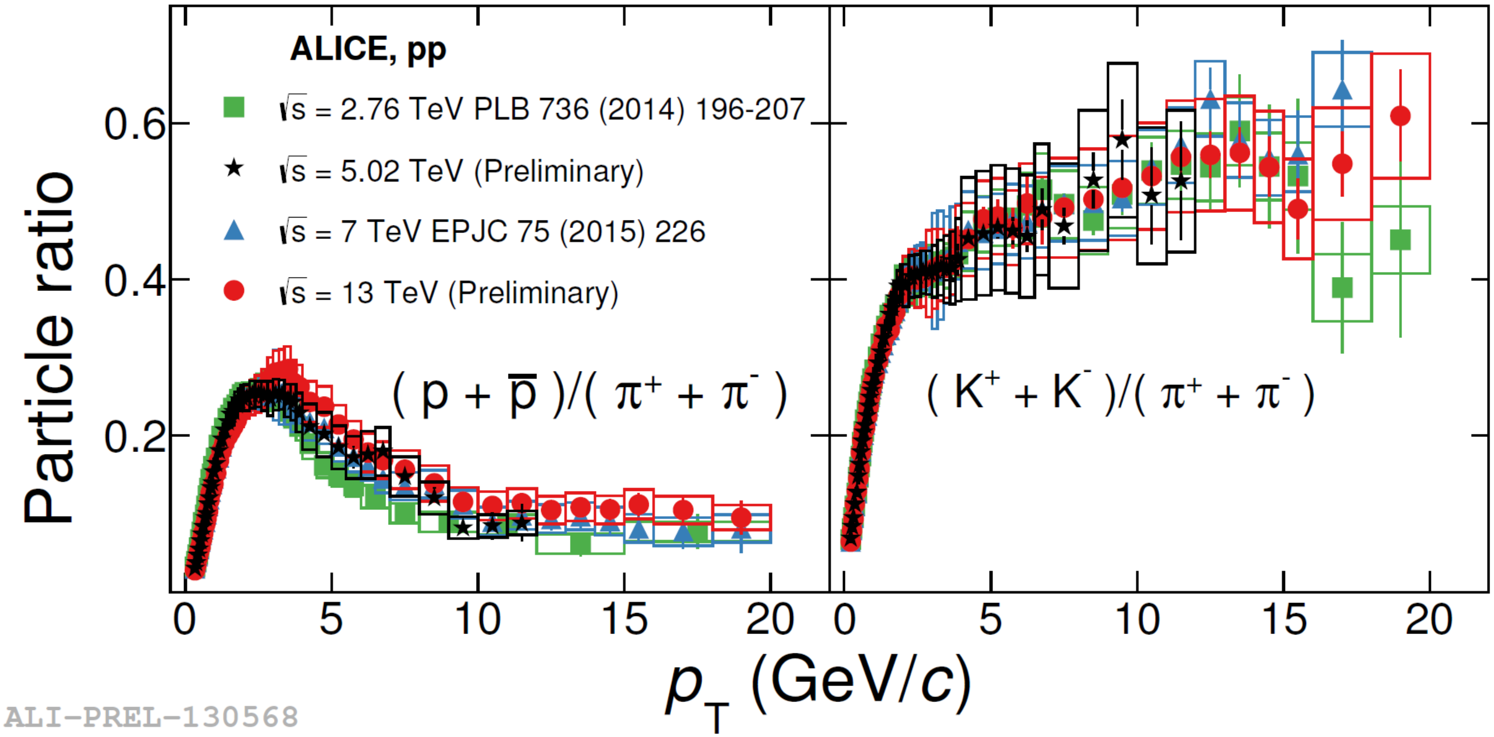
1) Progressive hardening of the spectra with increasing **√s**
2) Ratios of spectra at different **√s** evidence the two different p_T ranges:
   - soft regime ($p_T < 1$ GeV/c): no change
   - hard regime: high p_T very significant dependence on **√s**





New:
LHC Run 2

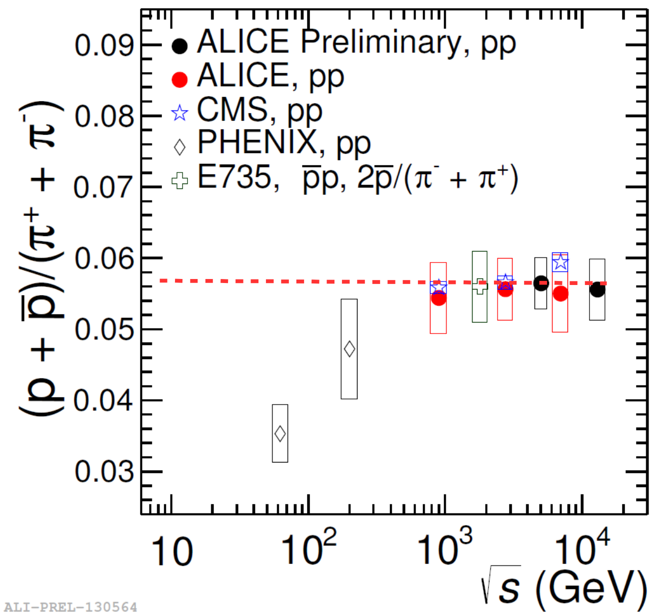
$\sqrt{s}$ dependence : p_T-differential particle ratios

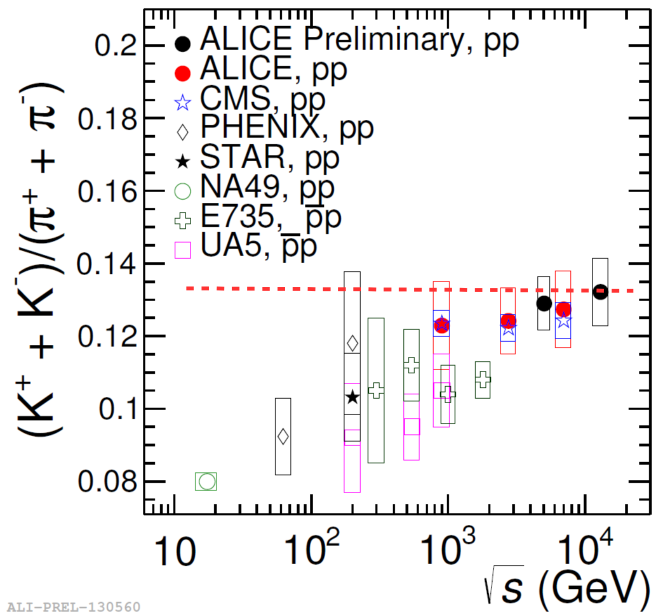


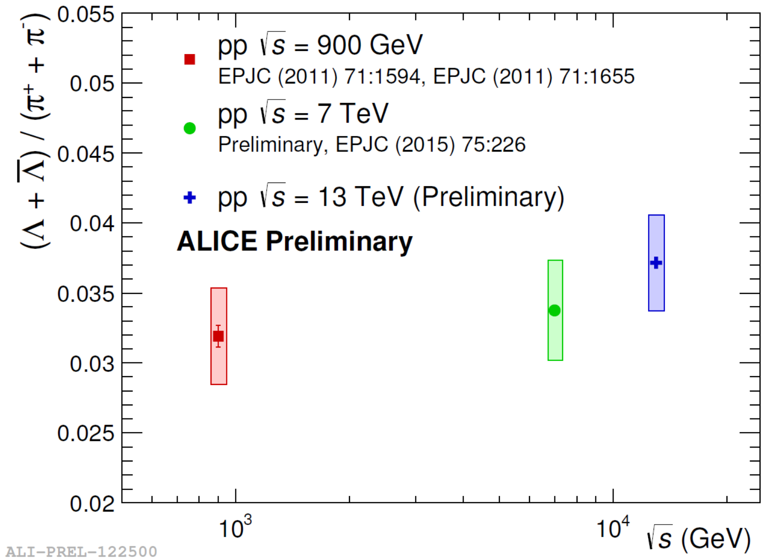
- Kaon-to-pion ratios:
  - No $\sqrt{s}$ dependence observed within uncertainties
- Proton-to-pion ratios:
  - For p_T < 10 GeV/c: modest $\sqrt{s}$ dependence is seen
  - In the intermediate p_T region the peak with increasing $\sqrt{s}$ shifts towards higher p_T
  - For p_T > 10 GeV/c: *no* evidence of evolution with $\sqrt{s}$ within uncertainties

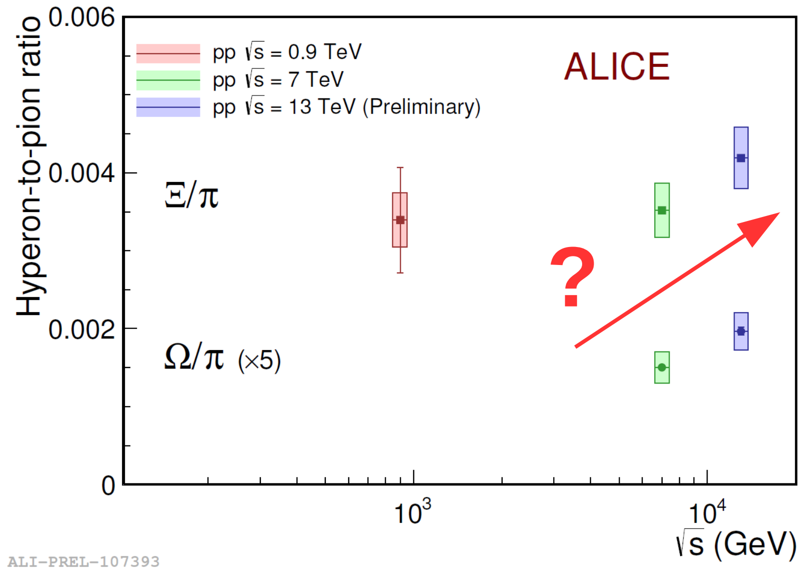
$\sqrt{s}$ dependence : p_T-integrated particle ratios

- 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 **$\sqrt{s}$**
- **Can one factorize this increase to be only a function $\langle dN_{ch}/d\eta \rangle$ of regardless of $\sqrt{s}$?**

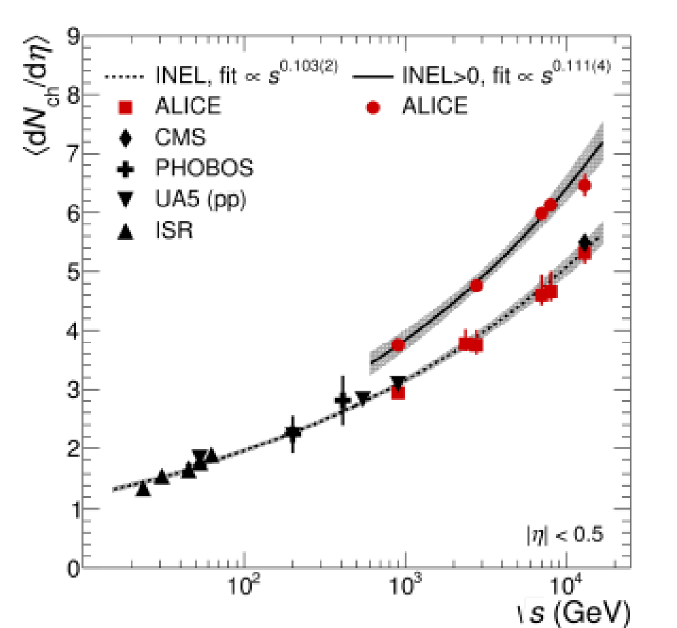








√s dependence : $\langle dN_{ch}/d\eta \rangle$



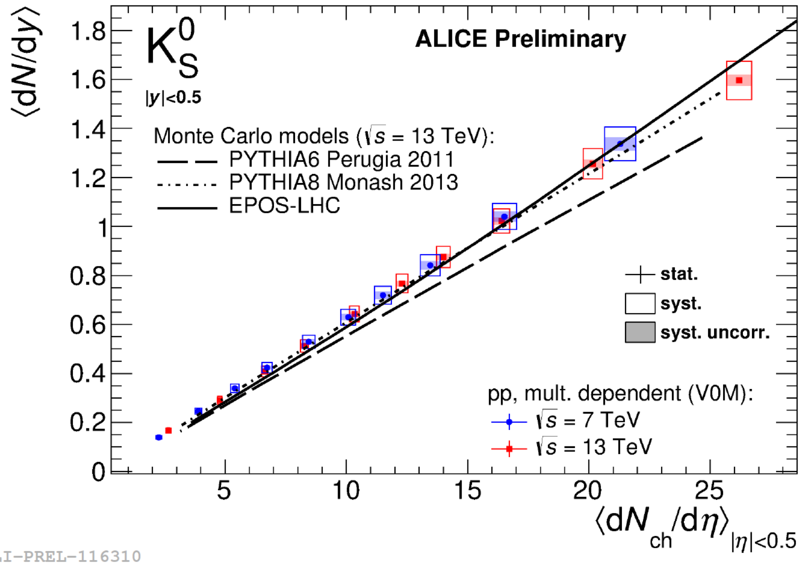
[Phys. Lett. B **753** (2016) 319]

- $\langle dN_{ch}/d\eta \rangle$ follows a power law behavior as a function of √s
- *Only modest change (factor of < 2) in* $\langle dN_{ch}/d\eta \rangle$ *over 1 order of* magnitude increase in √*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*

Multiplicity dependence: strange hadron production at different √s



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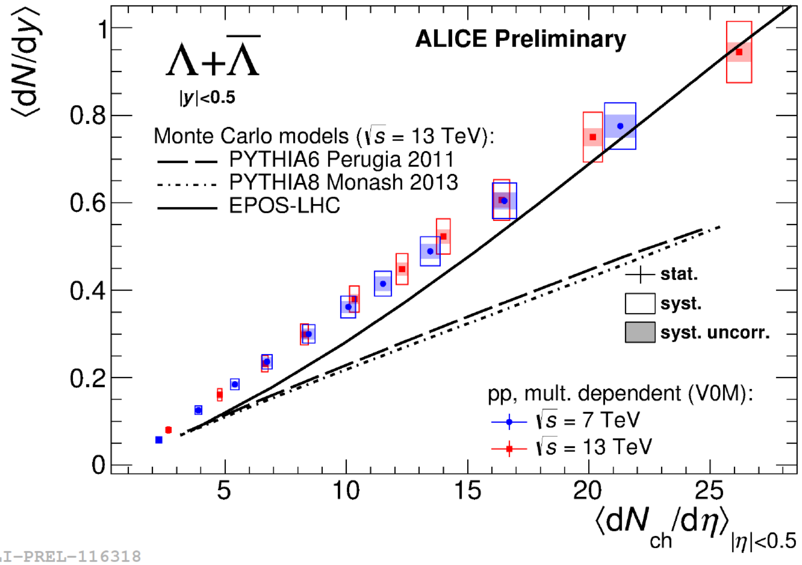
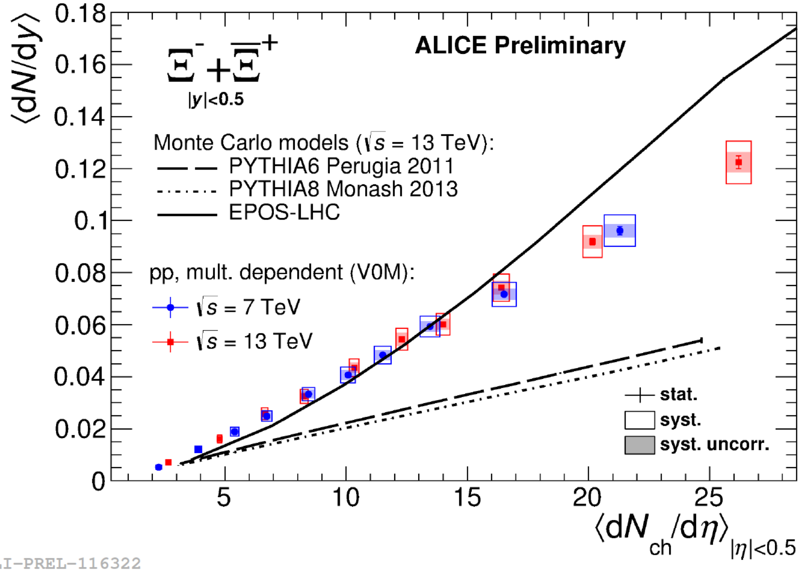


ALI-PREL-116318

Hadrochemistry is driven by multiplicity rather than √s



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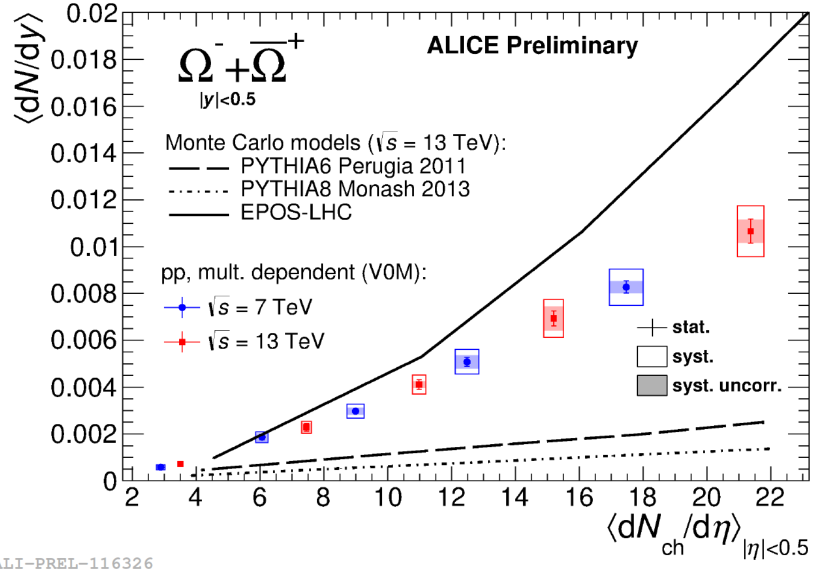
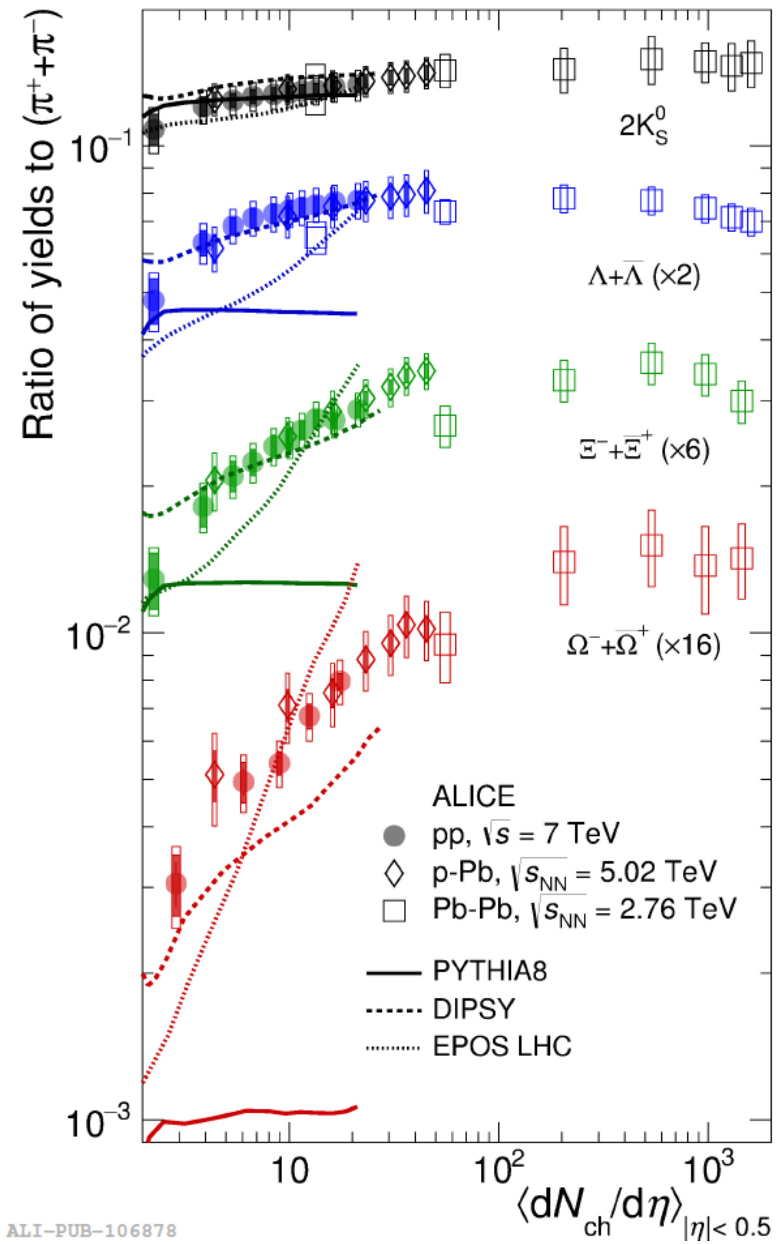


ALI-PREL-116326

Multiplicity dependence:
strange and multi-strange hadron production

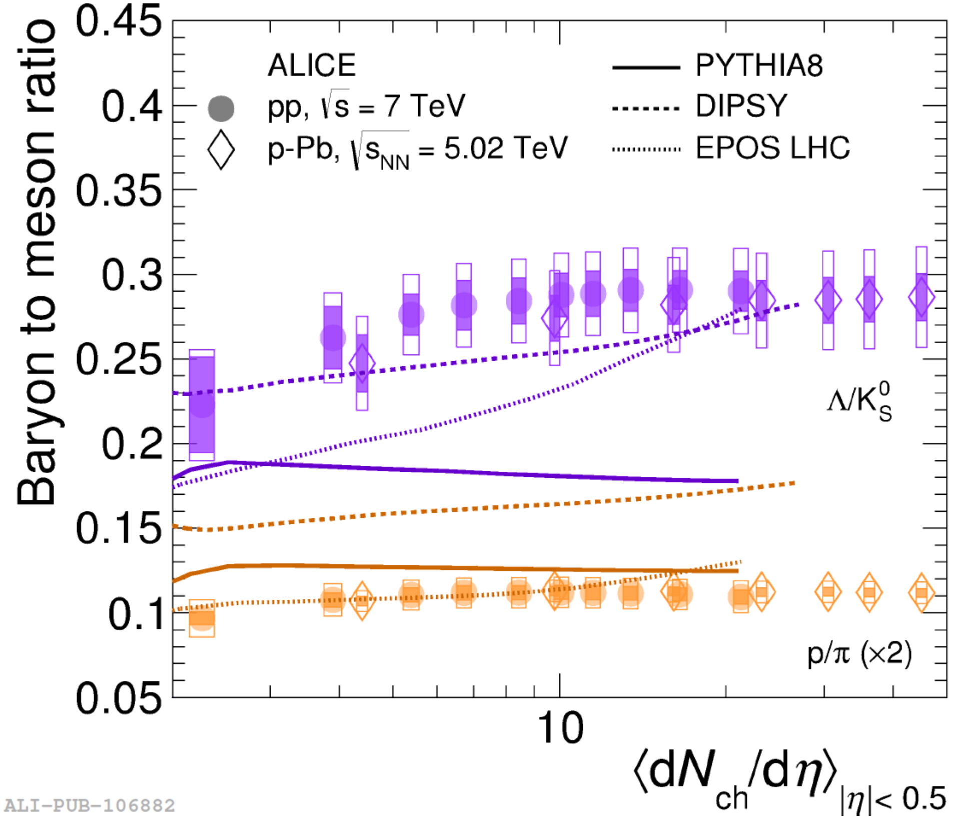
- ***Significant enhancement of strange*** to non-***strange hadron*** production is observed ***with increasing*** *particle* ***multiplicity in pp***
- ***Similar behavior*** to that observed ***in p–Pb*** (both in terms of values and trend with multiplicity)
- ***Similar values*** reached ***in high-multiplicity pp***, ***p–Pb***, and ***peripheral Pb–Pb*** collisions (having at similar multiplicities)



[1] Nature Physics **13 (2017)** 535-539

Multiplicity dependence: Baryon to meson ratios

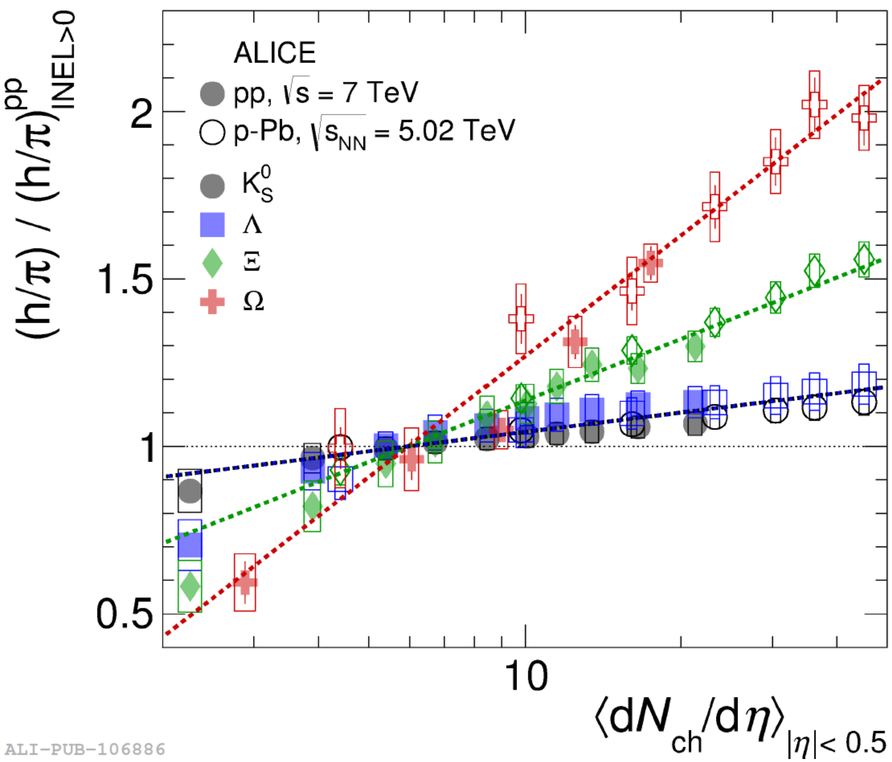
- ***Baryon-to-meson ratios*** *(with same strangeness content) but different masses*
  - No significant change with multiplicity
  - → Strangeness ***enhancement*** is ***neither*** due to the ***difference in the hadron masses nor*** *due to baryon nature of the particle*
- *Monte Carlo comparison*
  - *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]

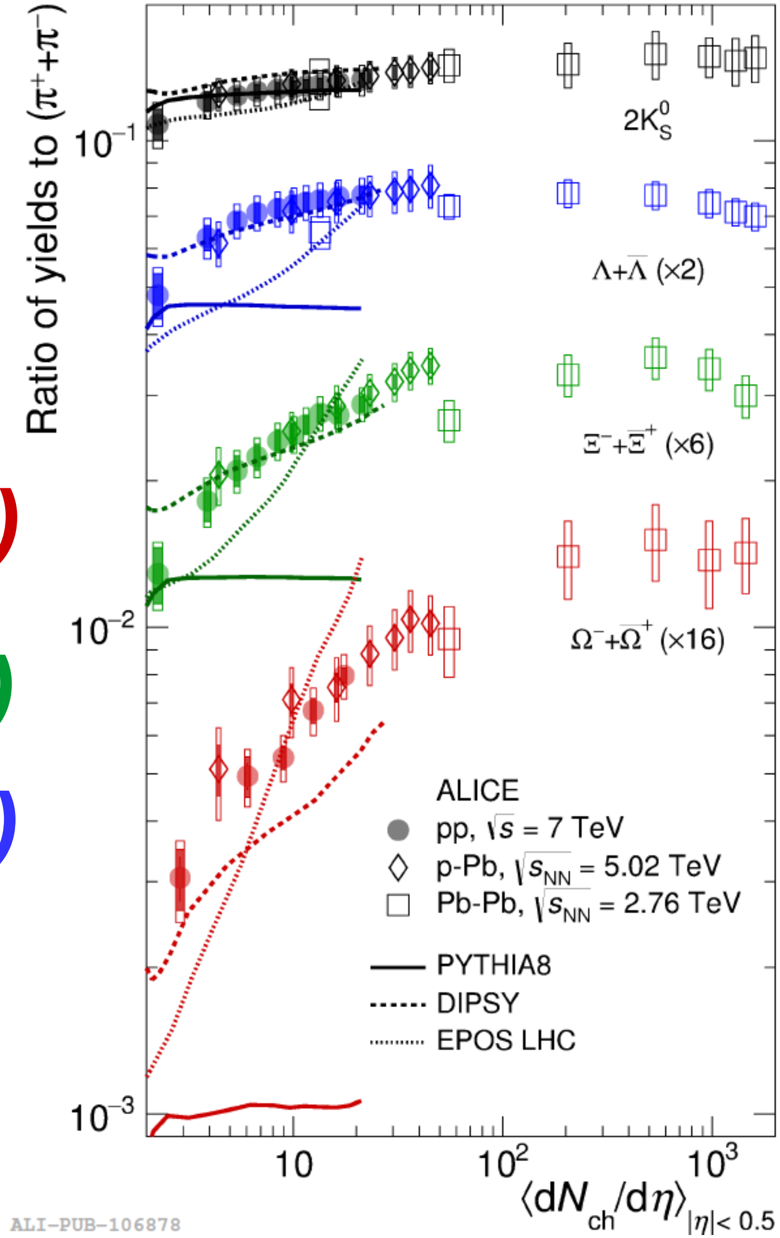
*The multiplicity-dependent **enhancement follows** a **hierarchy** determined by strangeness content of the hadron*



Ω (sss)

Ξ (dss)

Λ (uds)



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

Summary and outlook

- Light-flavor hadron production studied as a function of $\sqrt{s}$ and charged-particle multiplicity
- p_T-spectra exhibit **clear *evolution with charged-particle multiplicity***
  - Smooth evolution of particle ratios across different collision systems with multiplicity
  - Evolution of particles yields with $\sqrt{s}$ can be explained with the corresponding increase in minimum bias multiplicity
  - Strangeness-driven enhancement of particle ratios observed from low to high multiplicity in pp collisions
  - Monte Carlo models ***fail to describe*** the observed enhancement with increasing multiplicity

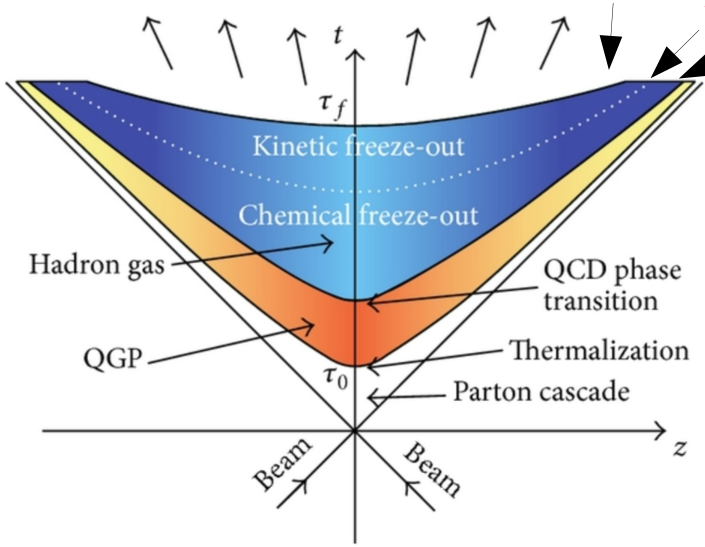
Thank you for your attention!

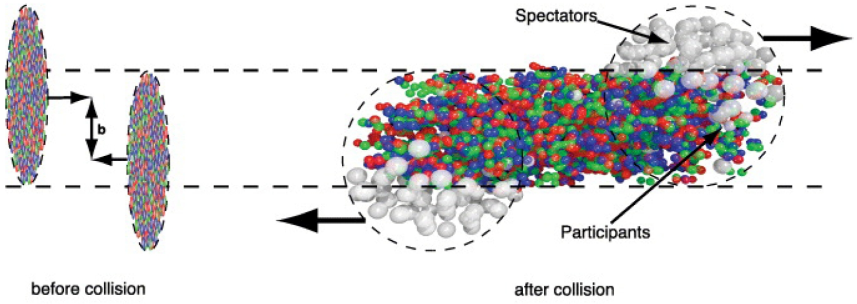
Backup slides

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





- 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

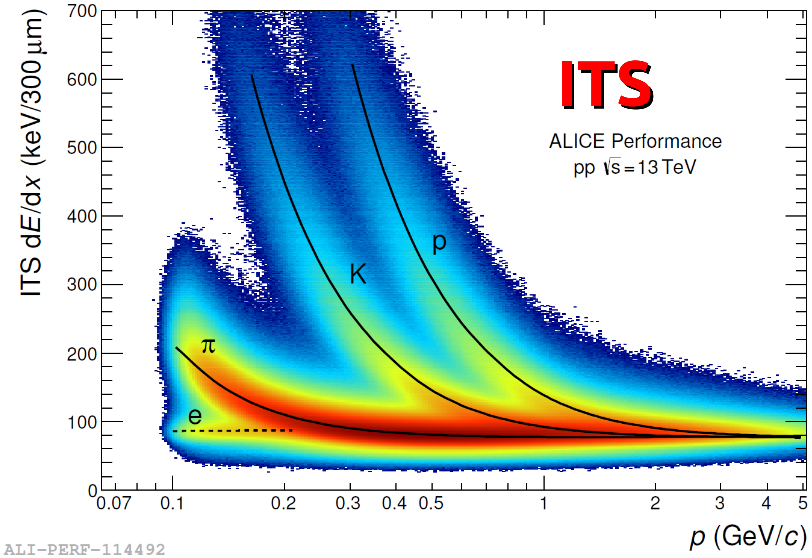
Thermal model:
- Particles in HI collisions are produced in apparent chemical equilibrium
- Description based on thermal-statistical models
  - Particle abundances ∝ exp($-m/T_{ch}$) with T_{ch} *being ~156 MeV*

Particle Identification in ALICE

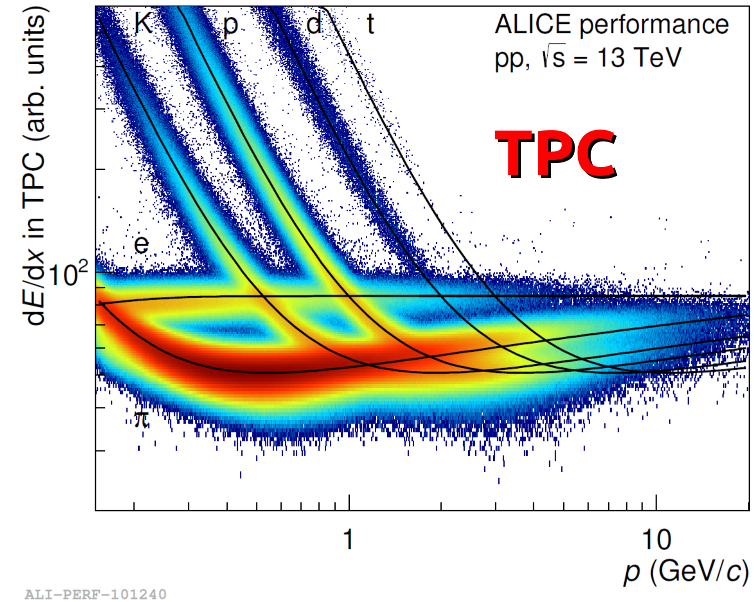
ALICE Performance, *Int. J. Mod. Phys. A* 29 (2014) 1430044

New: √s = 13 TeV (LHC Run 2)

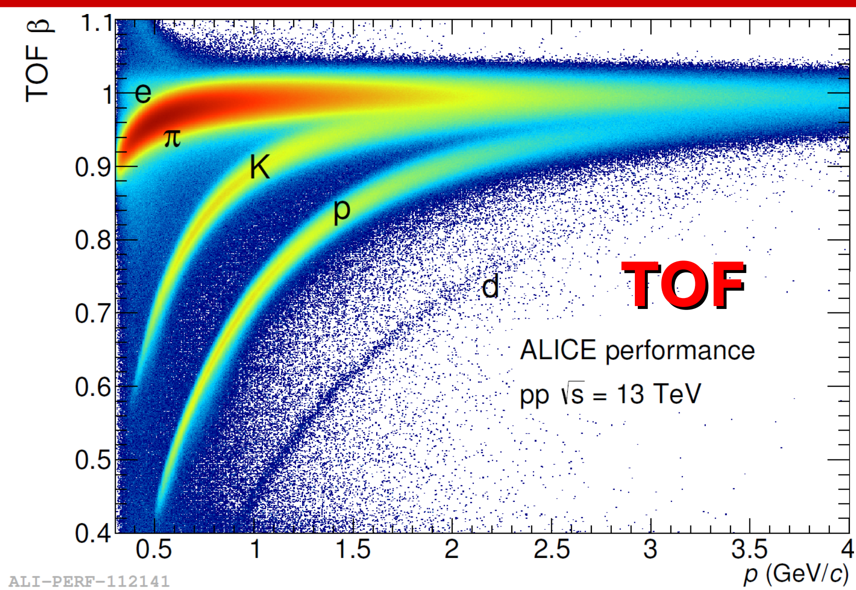
- **Tracking + standalone reconstruction: PID via d*E*/d*x* from SDD and SSD**
- **Standalone tracking in the low-p_T region (down to 100 MeV/*c*)**



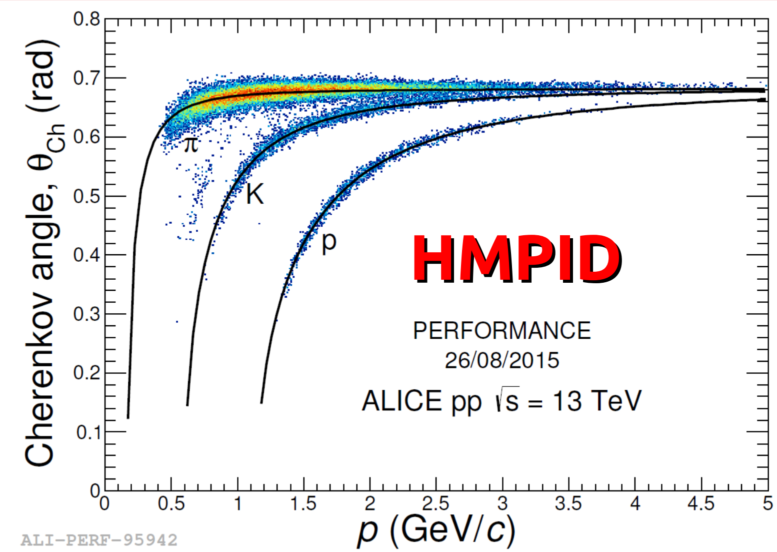
- **Track-by-track ID (n-σ cut) in the 1/β² region**
- **PID in the relativistic rise using a statistical approach**



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

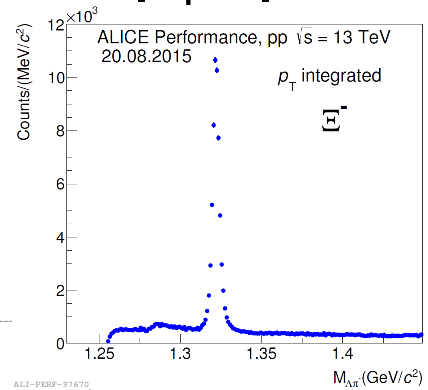


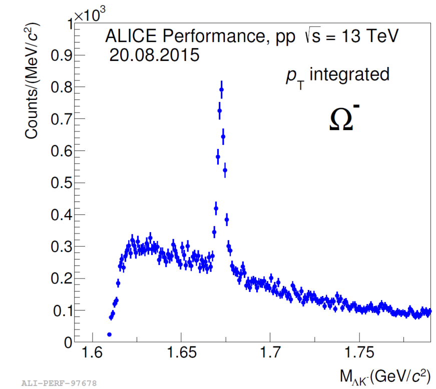
- **PID using RICH technique in the intermediate momentum region on a track-by-track basis**

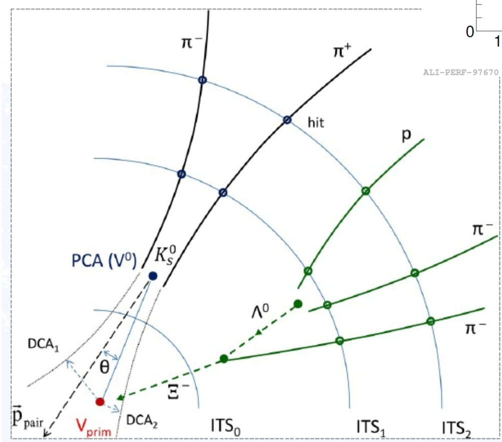


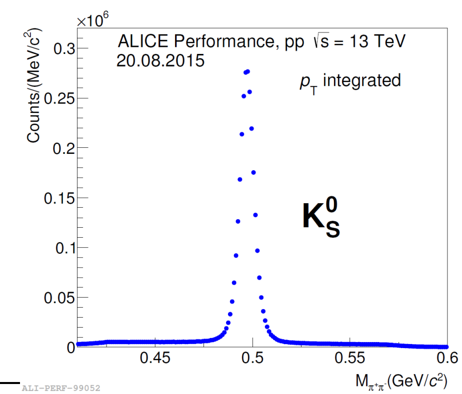
Measurement of light flavor particle p_T-spectra

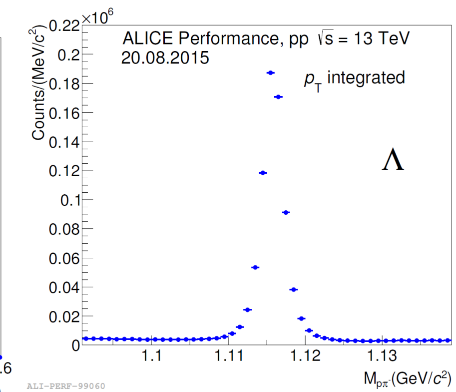
- Primary particles [1] *: particle with cτ > 1 cm,* which is either a) produced directly in the interaction, or b) from decays of particles with cτ < 1 cm, restricted to decay chains leading to the interaction – that is to the primary collision
  - ***Long-lived*** *particles*
  - *Topological identification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



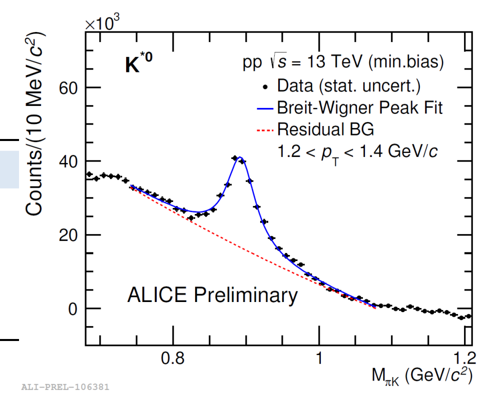


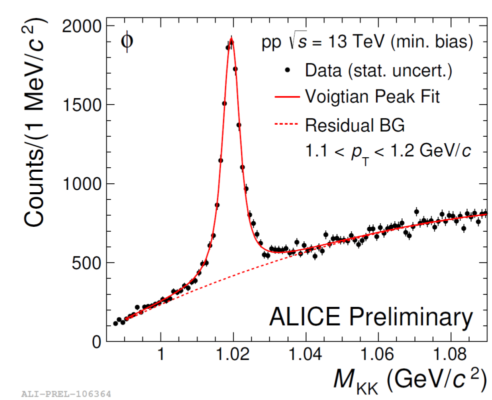






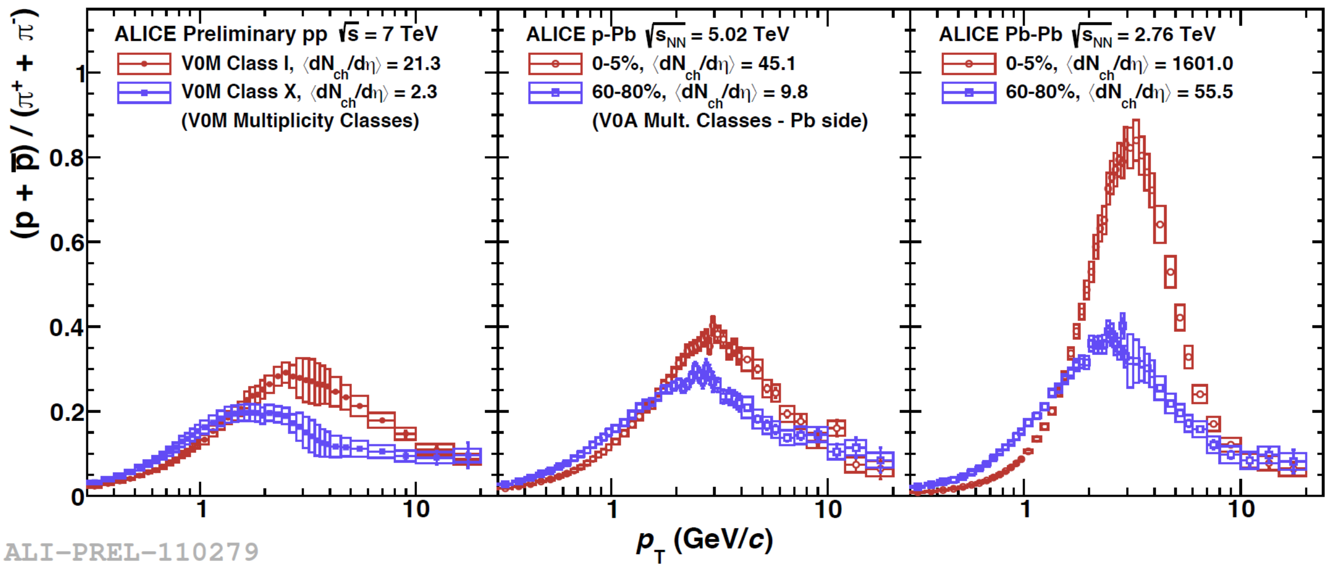
	Particle	Valence Quark Content	Mass (MeV/c^2)	$c\tau$	Decay
Mesons	π^+	$u\bar{d}$	139.57	7.8 m	
	K^+	$u\bar{s}$	493.68	3.7 m	
	K^0_S	$\frac{1}{\sqrt{2}}(d\bar{s}+\bar{d}s)$	497.61	2.68 cm	$K^0_S \to \pi^+ + \pi^-$
	K^{*0}	$d\bar{s}$	895.81	4.16 fm	$K^{*0} \to \pi^- + K^+$
	ϕ	$s\bar{s}$	1019.46	45 fm	$\phi \to K^+ + K^-$
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	$\Omega^- \to \Lambda + K^-$

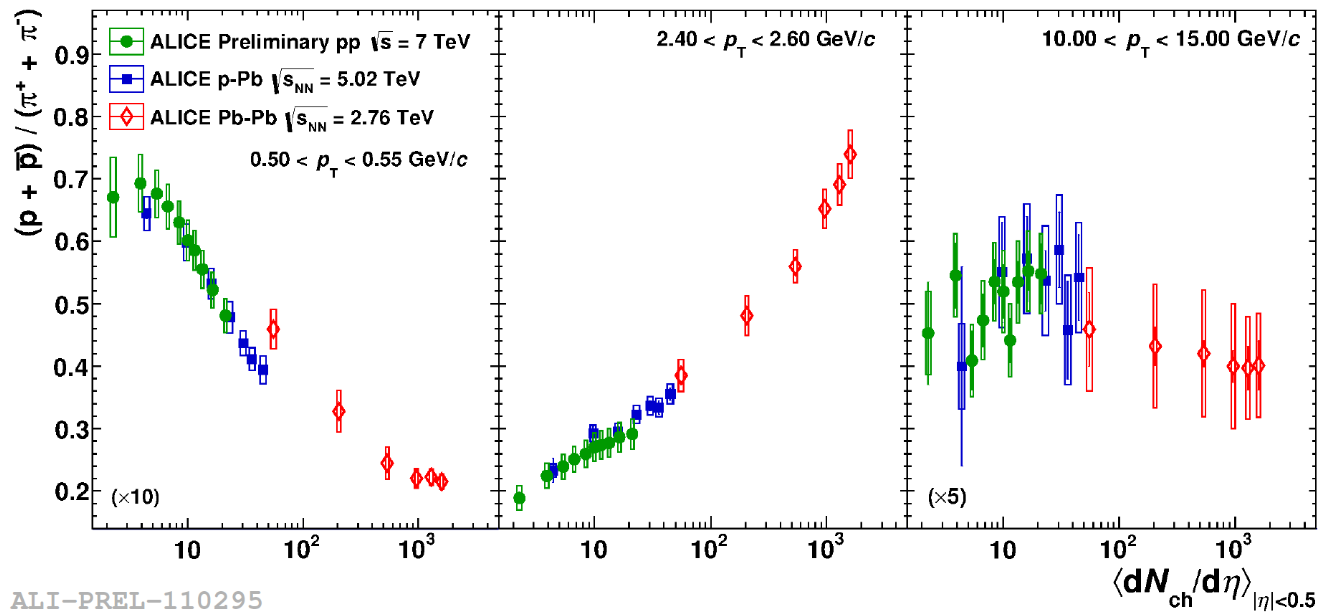




[1] *ALICE-PUBLIC-2017-005, The ALICE definition of primary particles*

Similarities among different colliding systems





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*

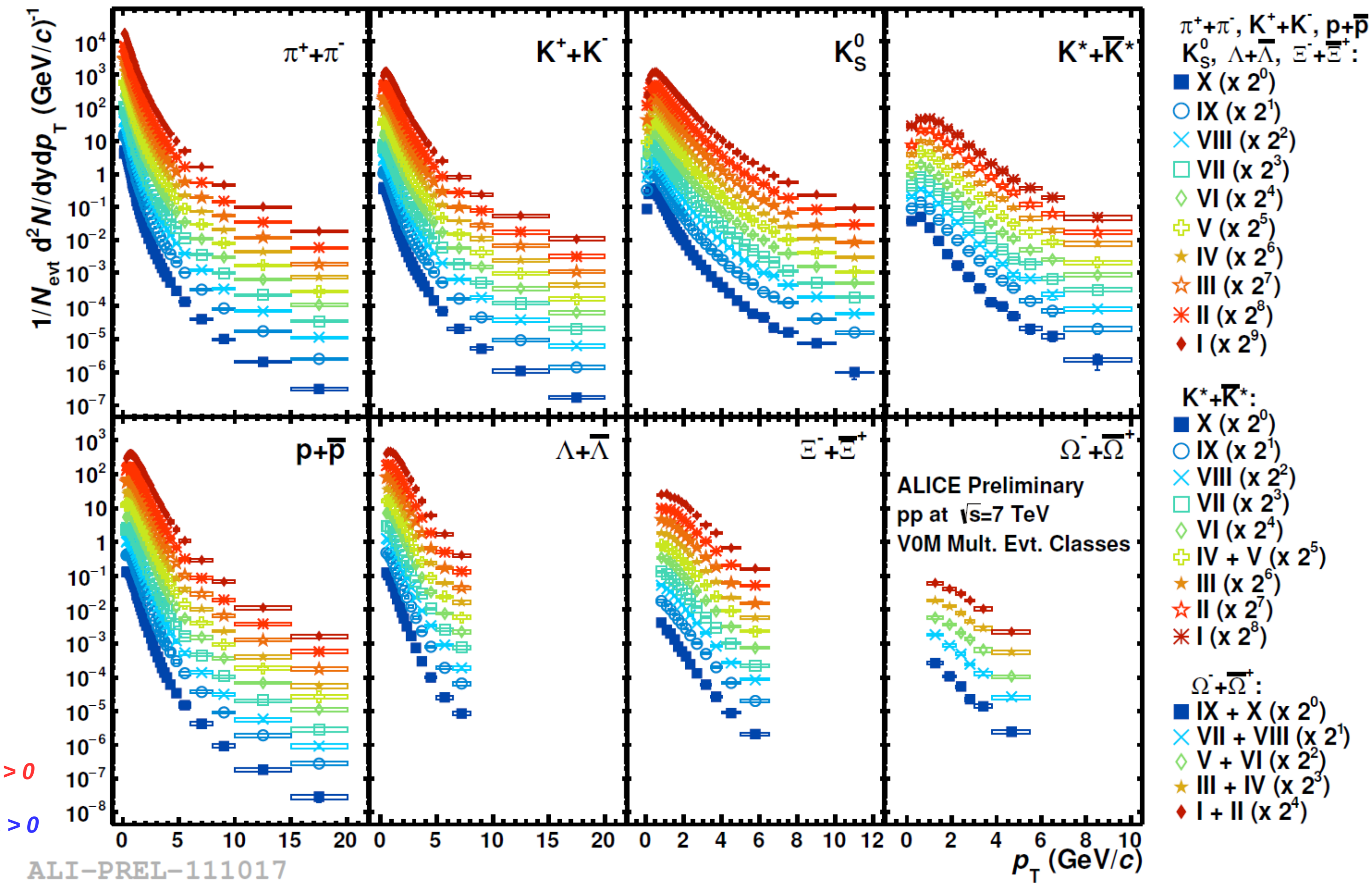
- Events classified according to event activity measured in the backward/forward region (by "V0M" estimator), in order to avoid auto-correlation biases.

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



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

Light flavor particle p_T-spectra *in pp*

Evolution of spectral shapes with multiplicity

$\sqrt{s}$ = 7 TeV

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