System size dependence of light-flavour hadron production

From the smallest to the largest collision system at the LHC with ALICE

ALICE

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ÖAW AUSTRIAN ACADEMY OF SCIENCES

EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

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EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
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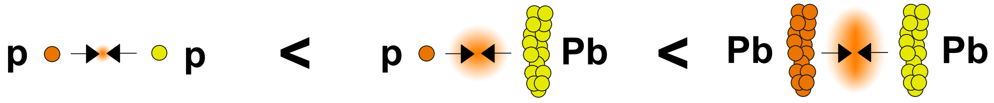
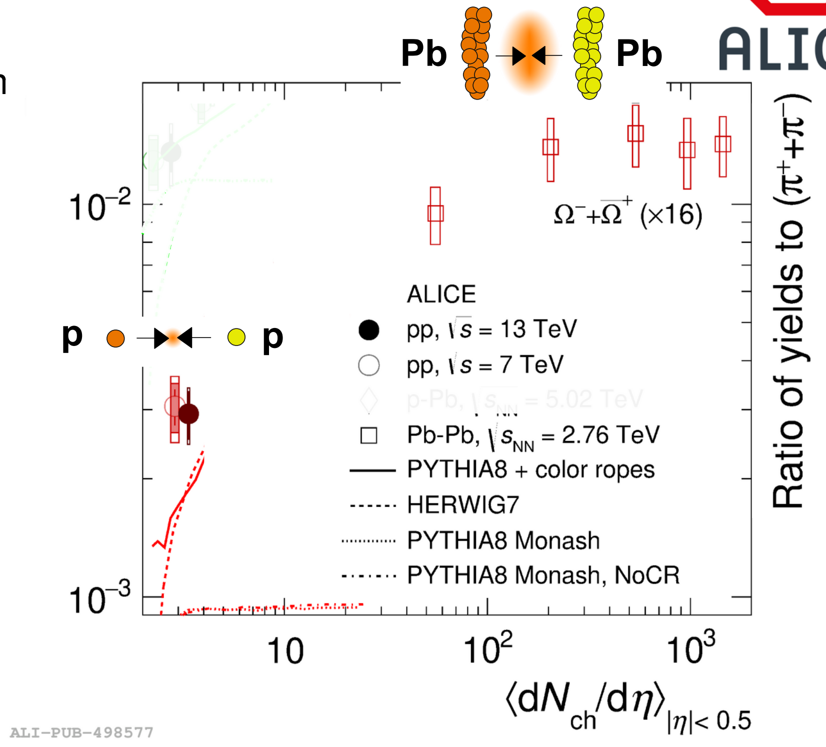
What is the "system size"?

- Traditionally defined by the physical size of the colliding system



Small system **Large system**



ALICE Collaboration, EPJC 80 (2020) 693

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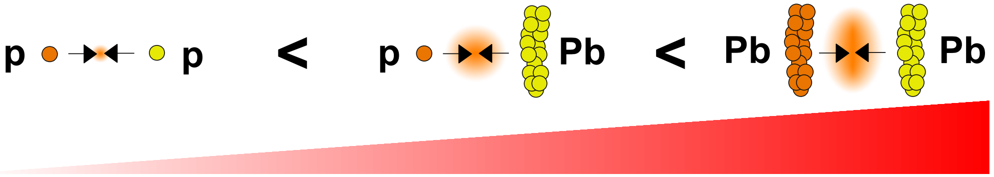


low multiplicity high multiplicity

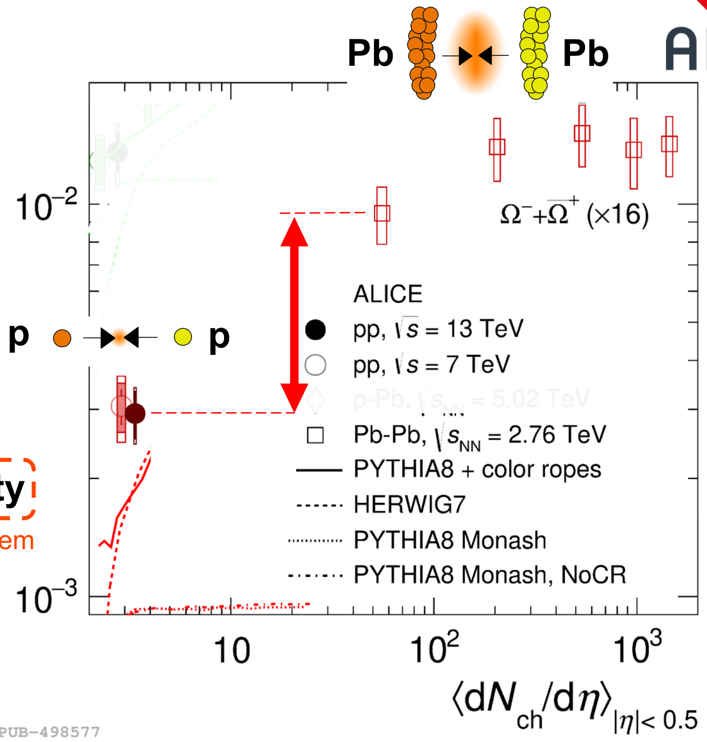
- In practice,
particle production often **scales with charged particle multiplicity**

proxy for the size of the system

→ well-defined observable, measurable across different systems

→ correlates with energy density and volume of the system

→ allows comparison between different systems



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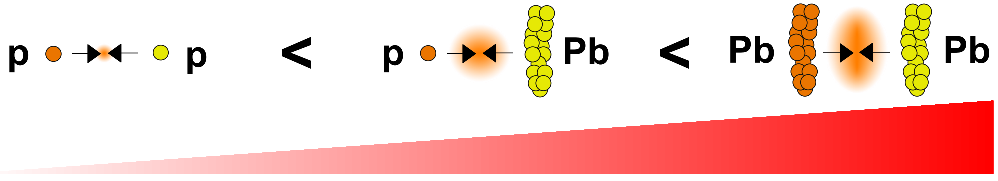

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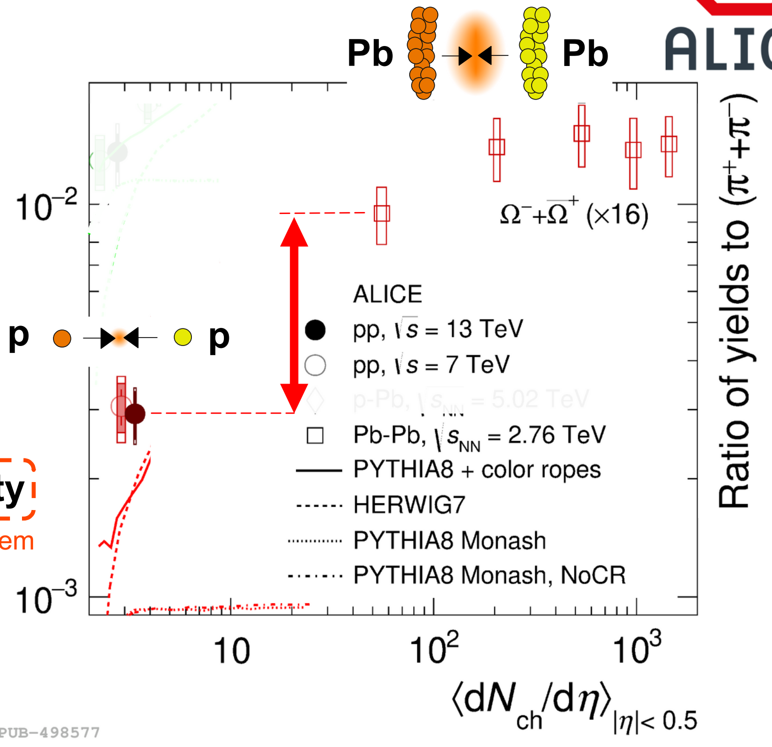

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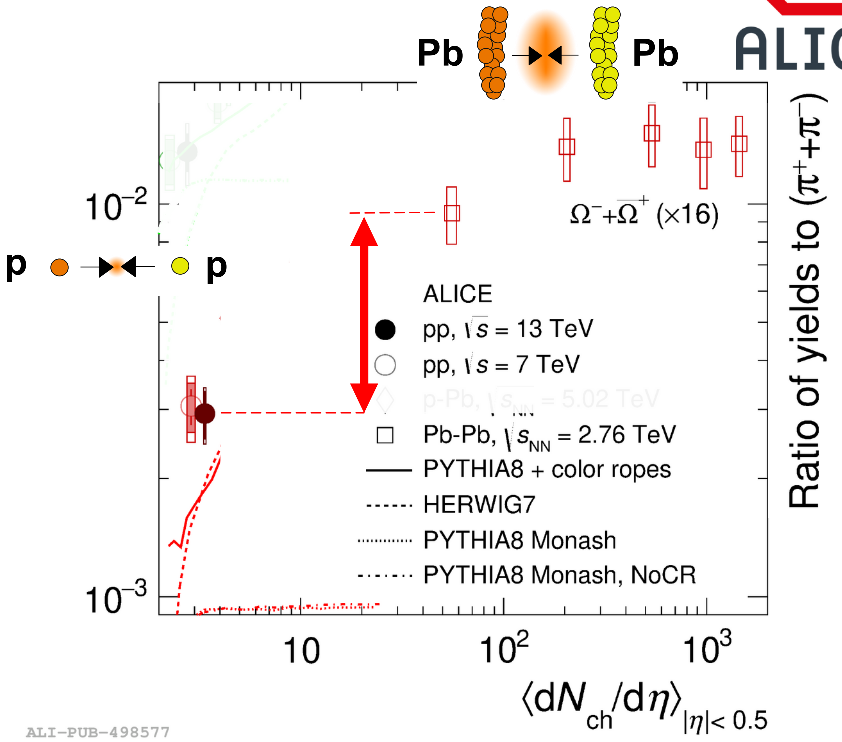
- **BUT**

Initial state		*Final state*
Energy density System volume	≠	Charged particle multiplicity

How does hadron prod. evolve with system size?



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How does hadron prod. evolve with system size?

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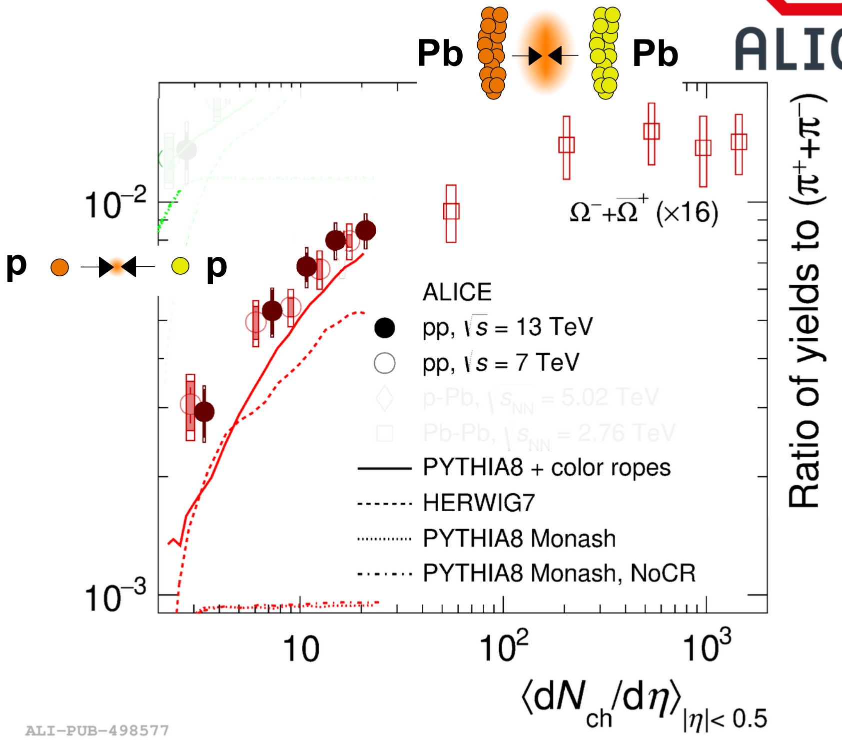

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How does hadron prod. evolve with system size?

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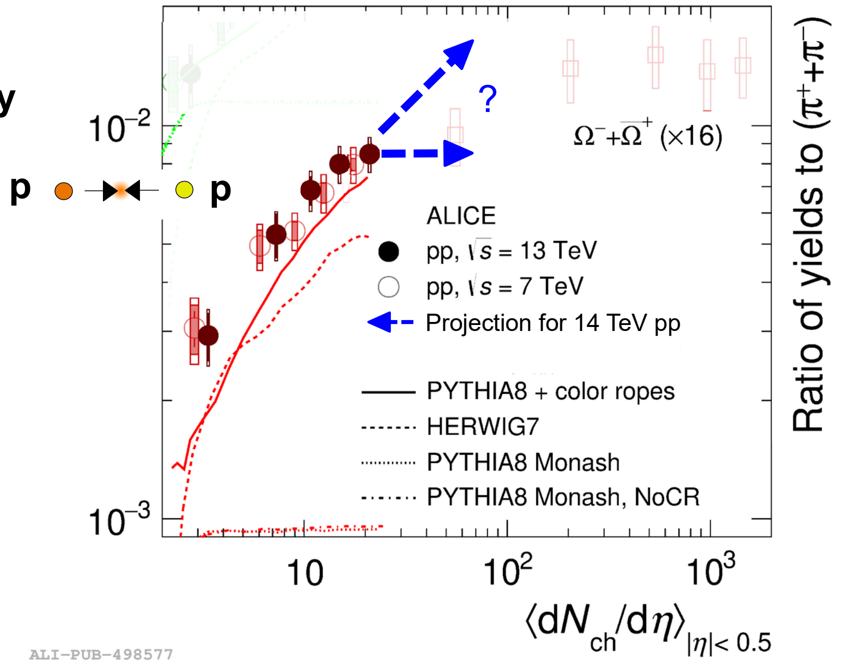
  → **Is the grand canonical limit respected or violated in very high-multiplicity pp collisions?**



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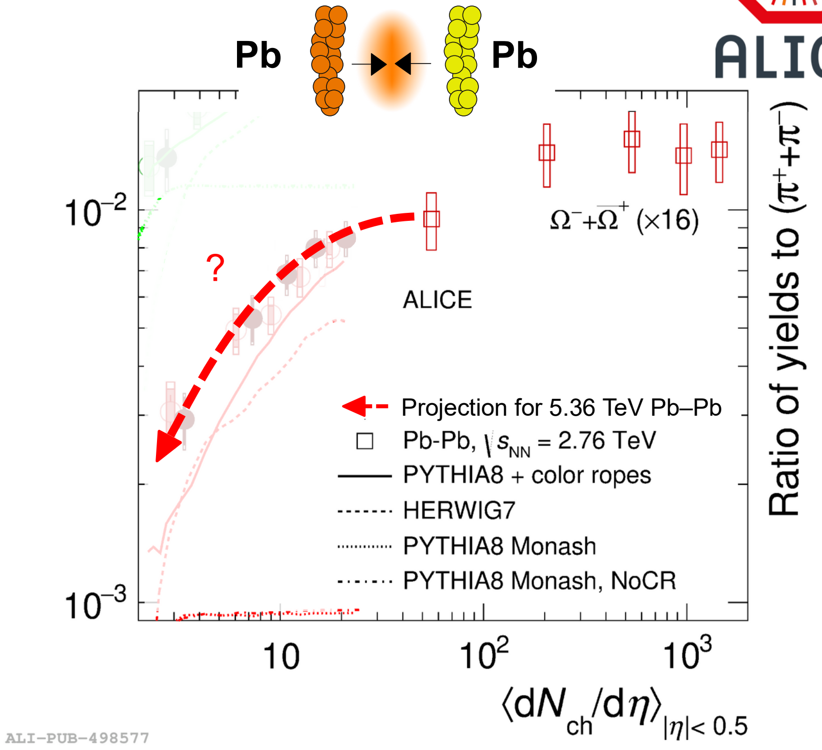

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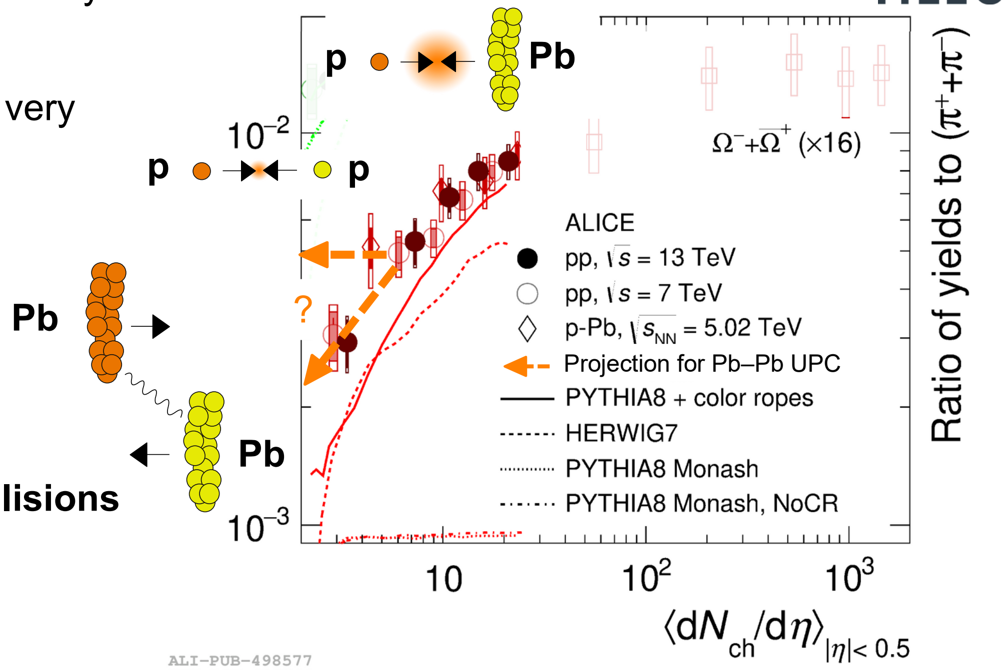
- How does particle production compare in collisions involving different processes?

  → **Hadronic** (pp, p–Pb) **Vs photo-nuclear** (γ–Pb) **collisions**



ALICE Collaboration, EPJC 80 (2020) 693

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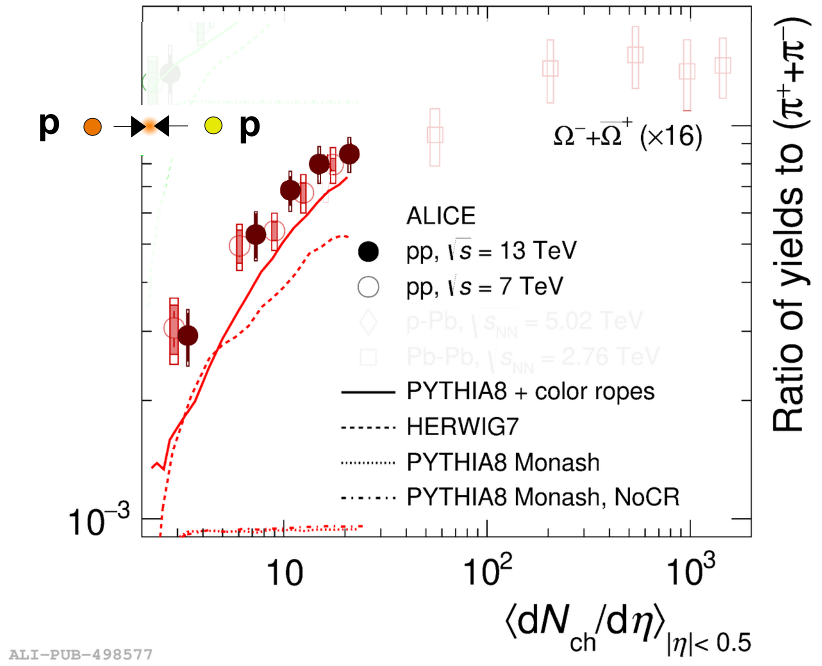
- How does particle production compare in collisions involving different processes?

  → Hadronic (pp, p–Pb) Vs photo-nuclear (γ–Pb) collisions

- Is multiplicity the only good proxy?

  → **Multiplicity Vs effective energy**

F. Ercolessi, T04+T05, Wednesday 09:30



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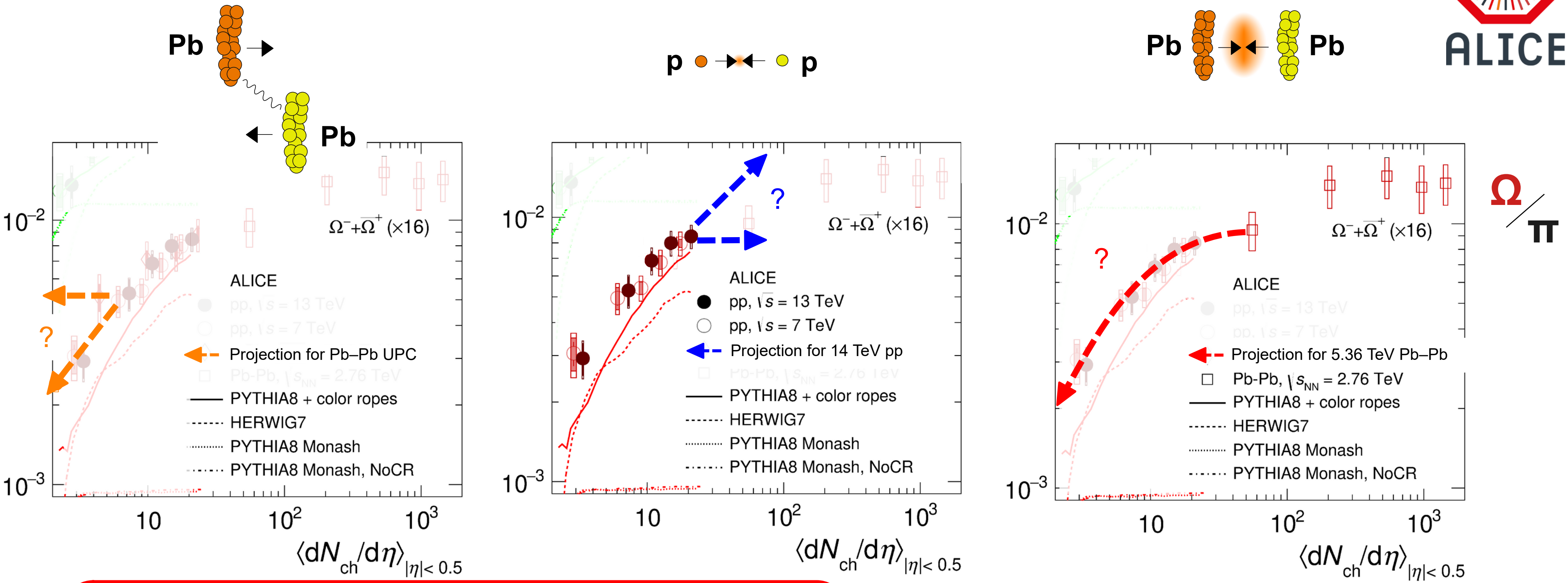
Aiming for a unified picture



Recent ALICE measurements provide new insights by:

→ **bridging the gap between small and large systems**

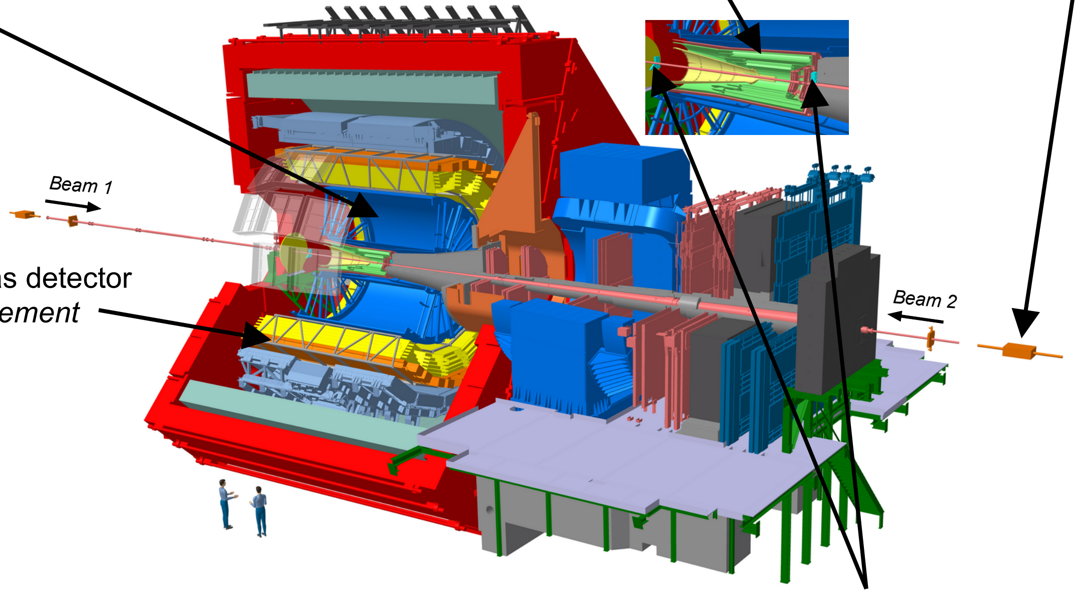
→ **exploring ultra-peripheral Pb–Pb collisions**

The ALICE apparatus during the LHC Run 3

New Inner Tracking System (ITS2), 7 layers of MAPS detectors
→ *Vertexing with an improved resolution by x3*
→ *Tracking*

Upgraded Time Projection Chamber (TPC), gas detector
→ *Tracking with a readout rate up to 50 kHz Pb−Pb*
→ *PID (dE/dx)*

Zero Degree Calorimeters (ZDC), calorimeters
→ *identification of photo-nuclear events*



Time-Of-Flight (TOF), gas detector
→ *PID via time-of-flight measurement*

New Online-Offline (O^2) framework
→ *Continuous readout*
→ *Increased data volume by x100 with respect to Run 2*

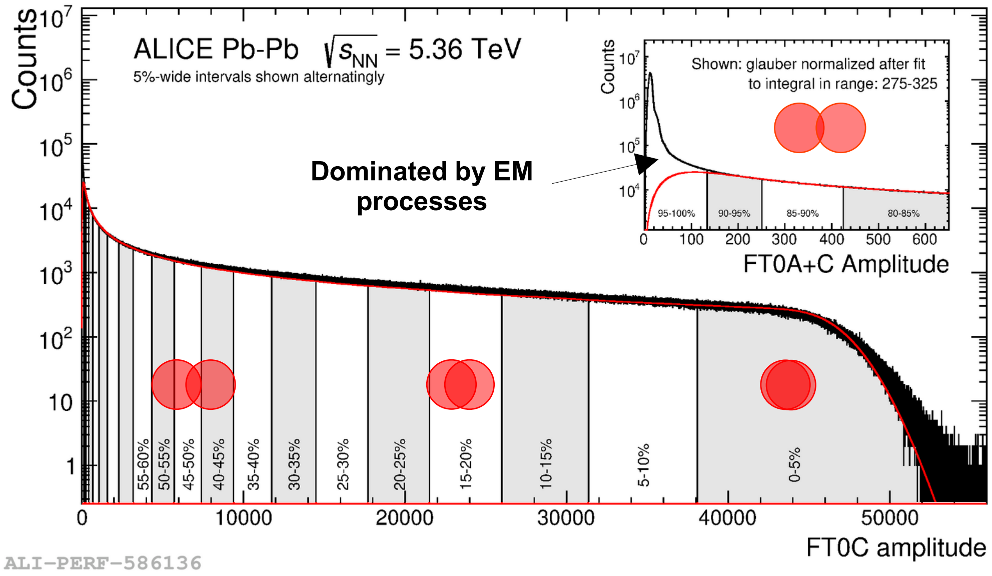
New Fast Interaction Trigger (FIT), scintillator detectors (FDD, FT0, FV0)
→ *Collision time with a x10 better resolution*
→ *Rejection of beam-gas interaction*
→ *Multiplicity estimation at forward rapidity*

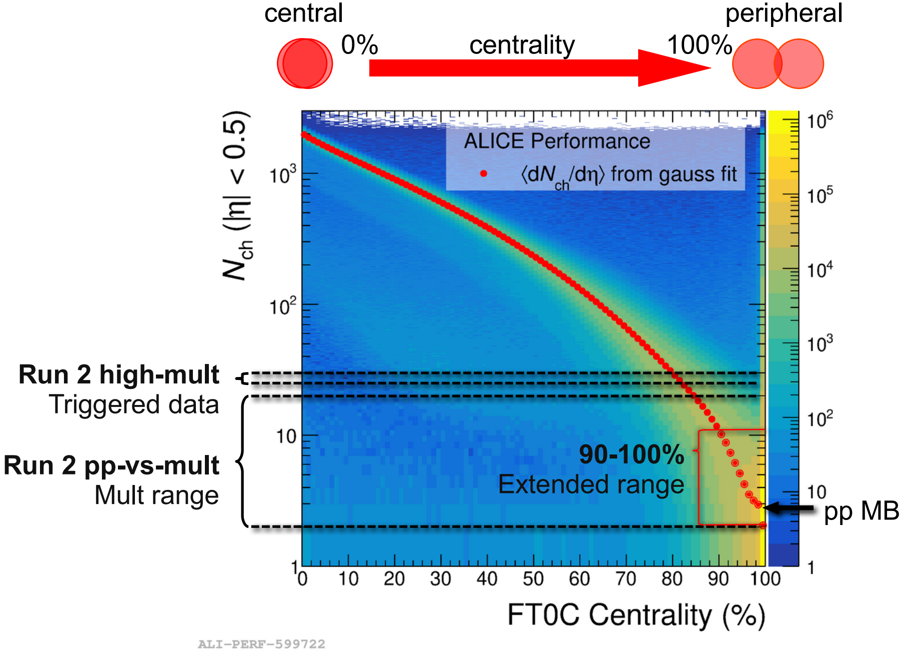
Multiplicity and centrality

- The multiplicity is estimated based on the signal amplitudes from FT0 detectors at forward rapidity
- In Pb-Pb collisions, it is linked through the impact parameter to the collision centrality
- **By exploring the most peripheral Pb−Pb collisions** (90-100%, where N_{ch} ≈ pp minimum-bias),

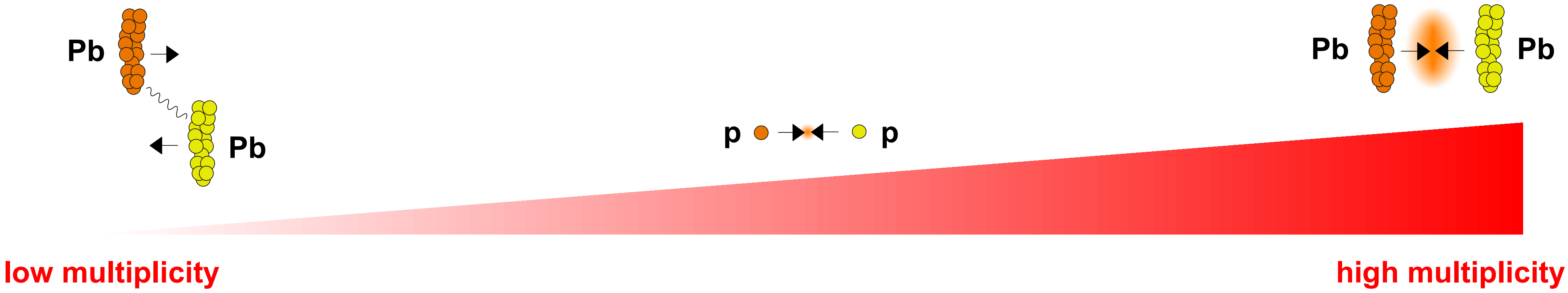
→ build a bridge from the lowest to the highest extremes
from 2 to 2000 charged particles

A. Modak, T04, Monday 14:40





From the smallest to largest collision systems



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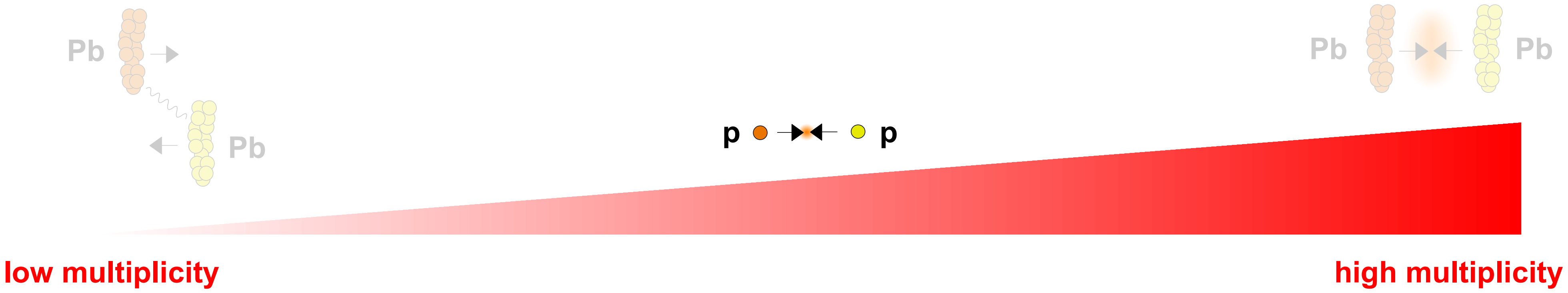
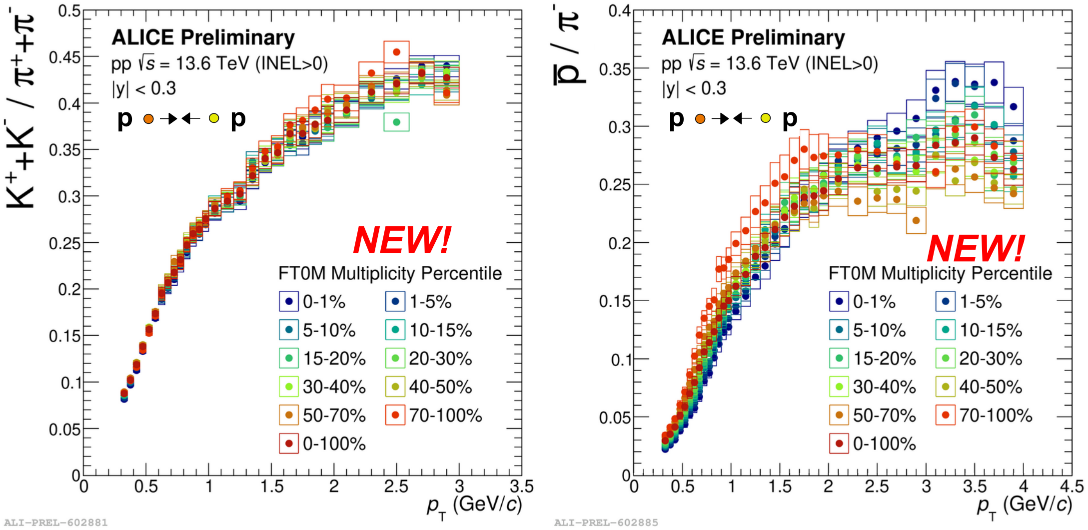


p_T-dependent yield ratio in pp collisions at 13.6 TeV



In pp collisions at 13.6 TeV:

- K/π ratio shows no evolution with increasing charged particle multiplicities
- p/π increases significantly at intermediate p_T from low to high multiplicity

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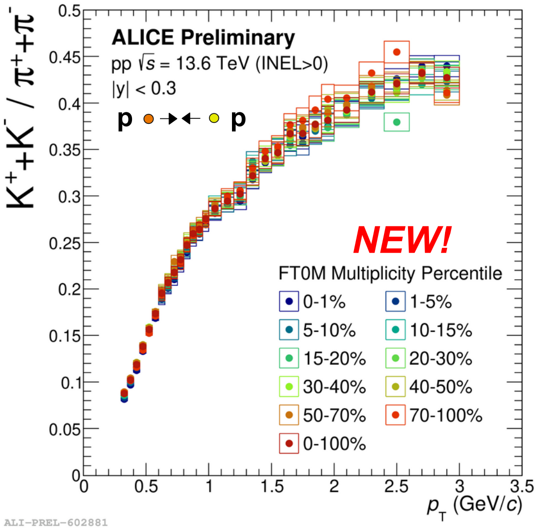

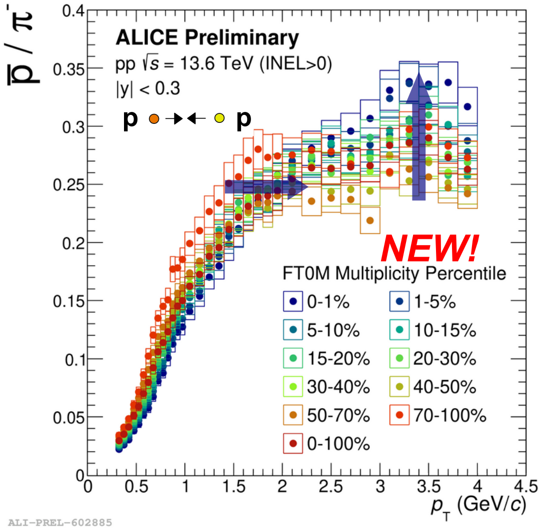

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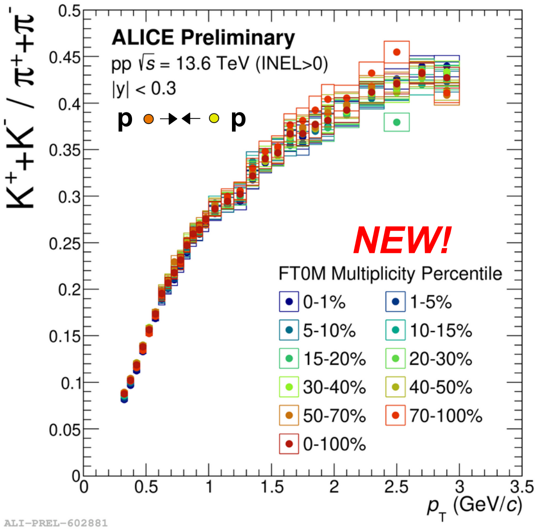

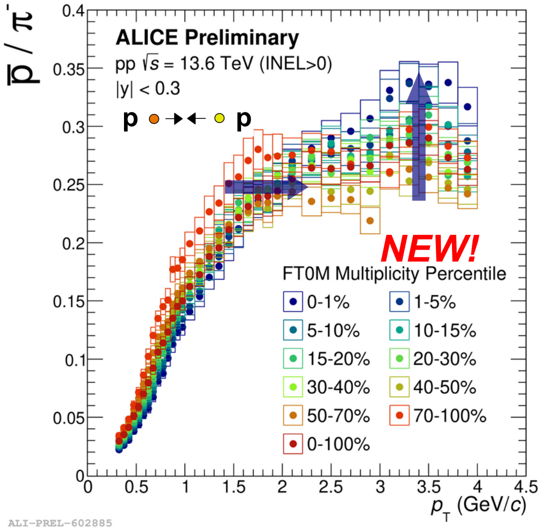

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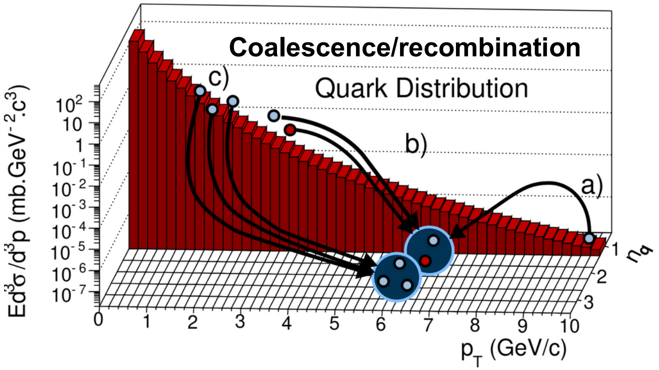
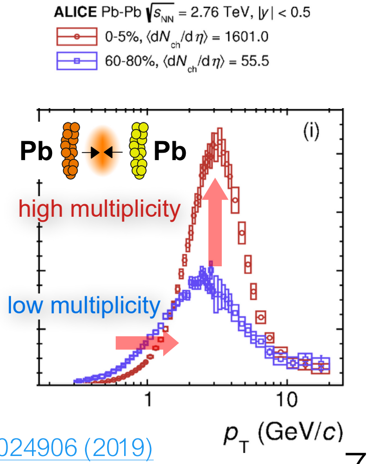
Similar behaviour observed at lower energies from pp to Pb−Pb:

→ **Baryon-meson splitting at intermediate p_T** can be explained by coalescence inside a collectively expanding medium in Pb−Pb collisions

Hippolyte, arXiv:0901.3176





ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)

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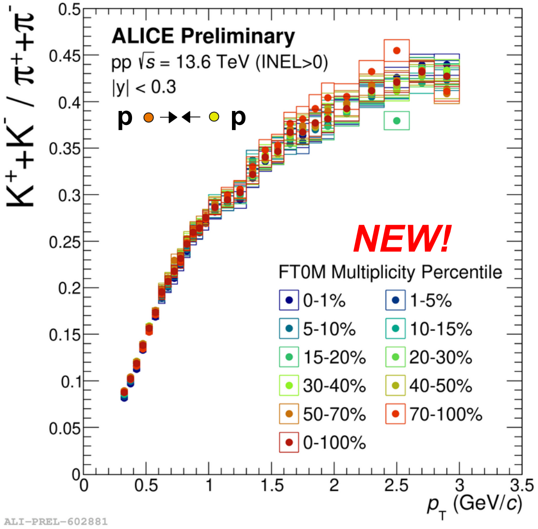

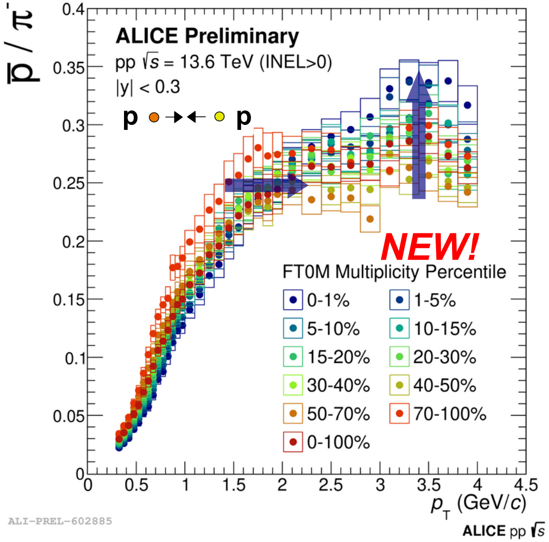

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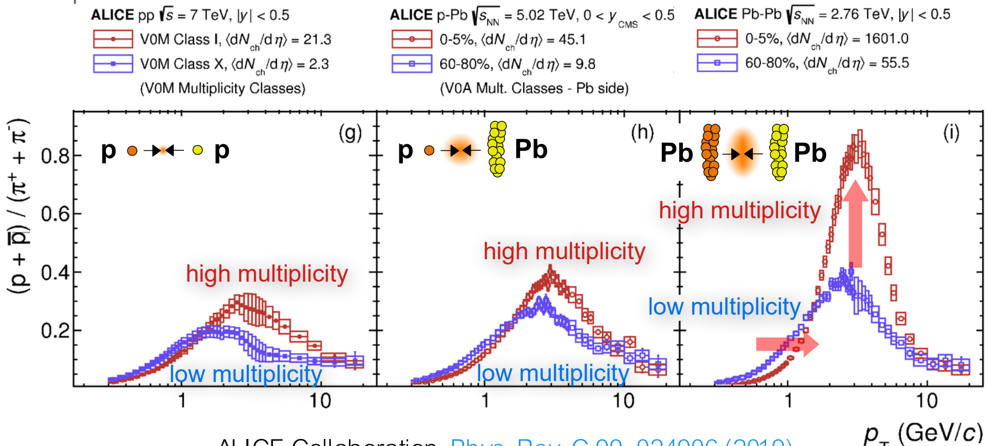
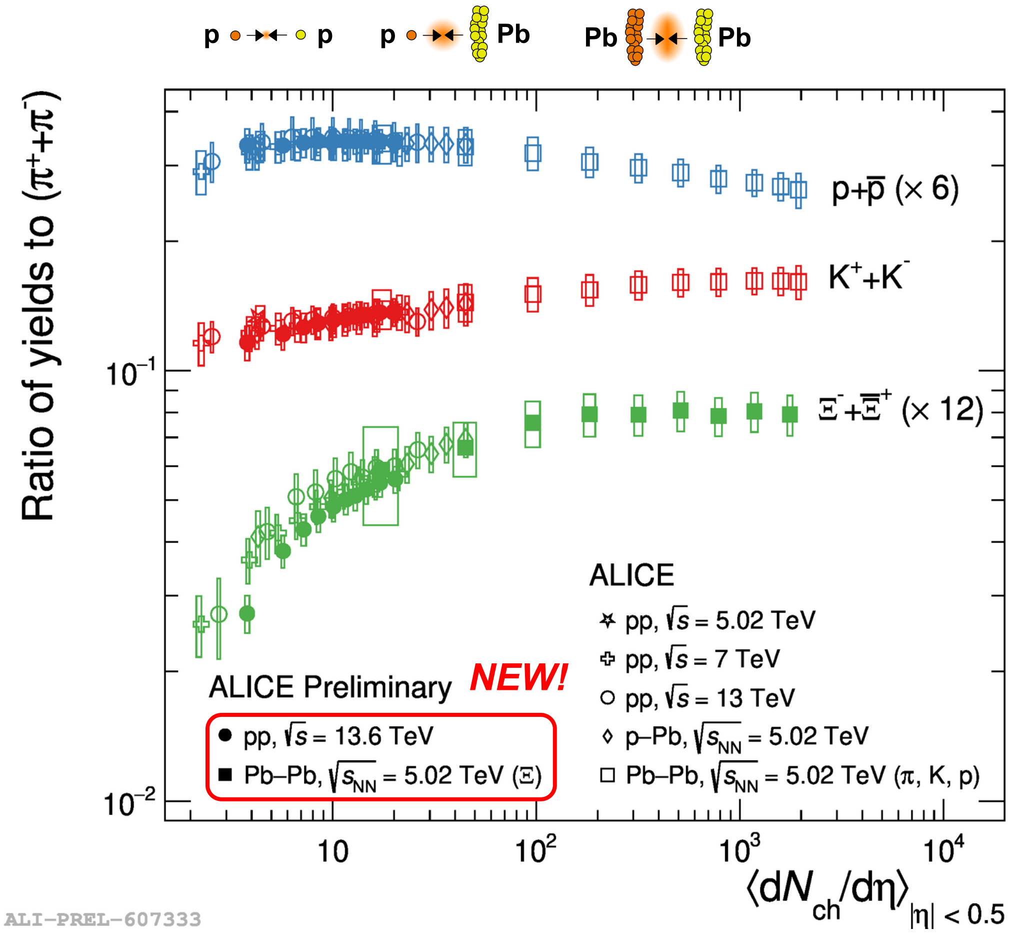


ALICE Collaboration, [Phys. Rev. C 99, 024906 (2019)]

Integrated yield ratio in pp at 13.6 TeV



Multiplicity dependence of light-flavour production in pp collisions at 13.6 TeV shows the **same trend as observed at lower energies**

- **Smooth evolution** of relative particle yields **with the charged particle multiplicity**

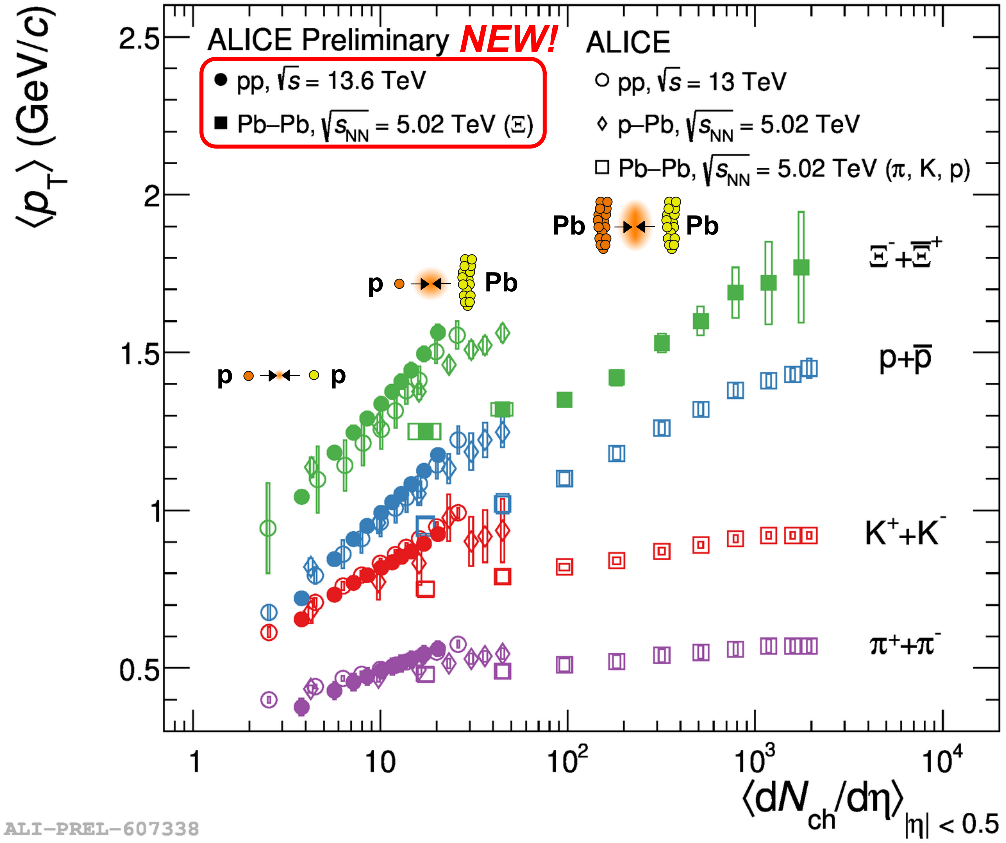
  → independent of **collision systems** and **energies**

- Decreasing trend of p/π ratio interpreted as antibaryon-baryon annihilation

- Increasing trend of the K/π and Ξ/π ratio with multiplicity **supports the strangeness enhancement**

  → More pronounced for hadrons with a larger strangeness content

Multiplicity-dependent $<p_T>$ in pp at 13.6 TeV



- $<p_T>$ follows a **similar trend as at lower energy**
- **Spectra get harder with increasing multiplicity**

→ steeper trend for hadrons with higher masses

M(π) < **M(K)** < **M(p)** < **M(Ξ)**

→ supports the picture of **collective motion** in Pb−Pb collisions (radial flow)

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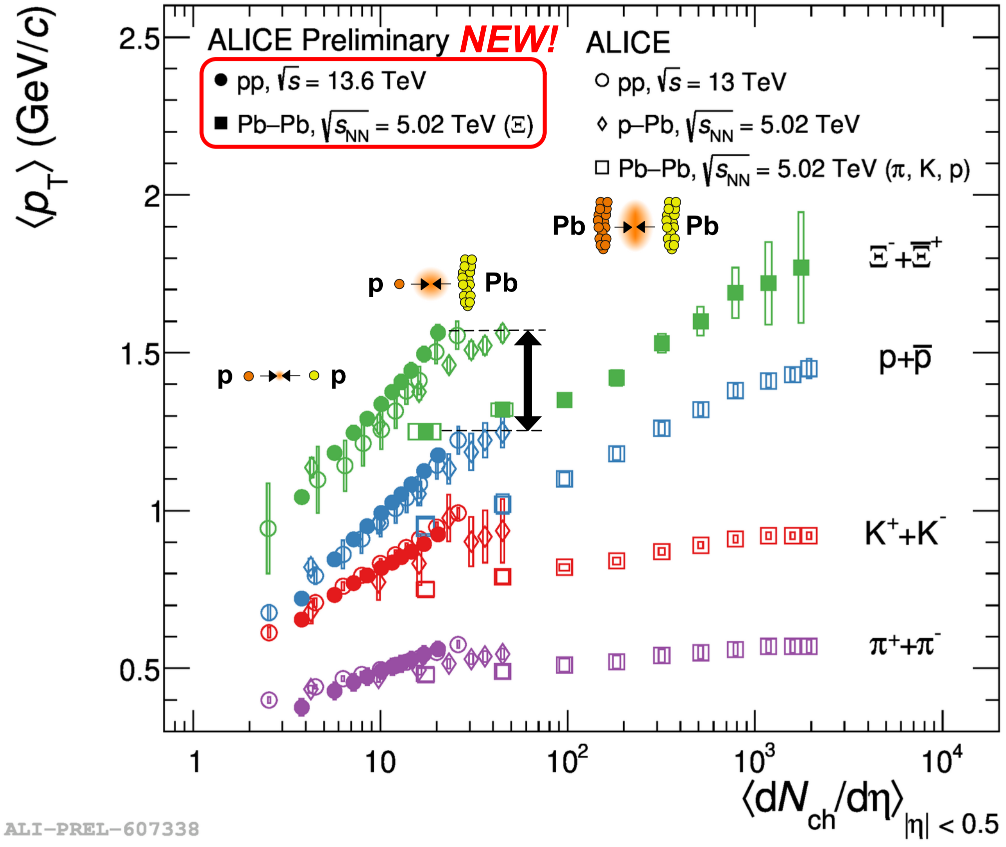

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- <p_T> does not connect different collision systems

  → **<p_T> in pp is larger than in Pb−Pb** at eq. multiplicities

  In pp, high-multiplicity is achieved via harder processes
  In Pb-Pb, it originates from soft QGP-like bulk production

  → particle production **dynamics in pp ≠ Pb–Pb**

From the smallest to largest collision systems

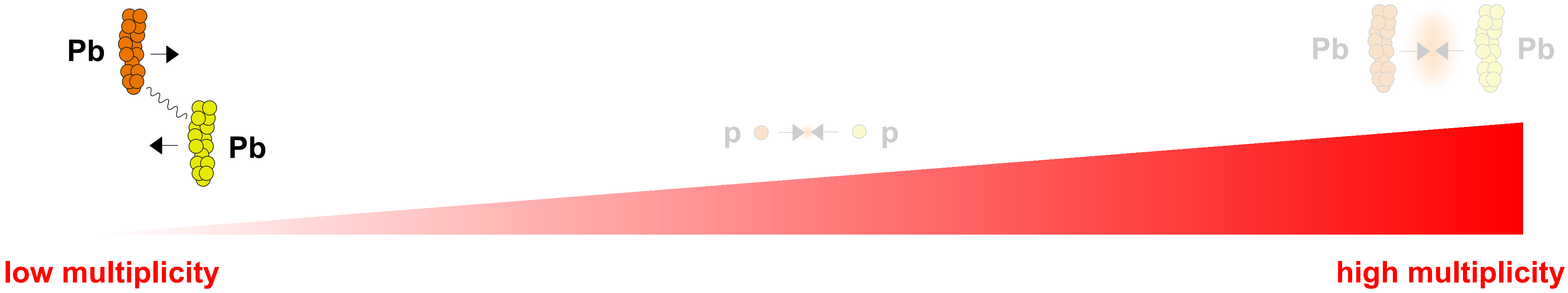
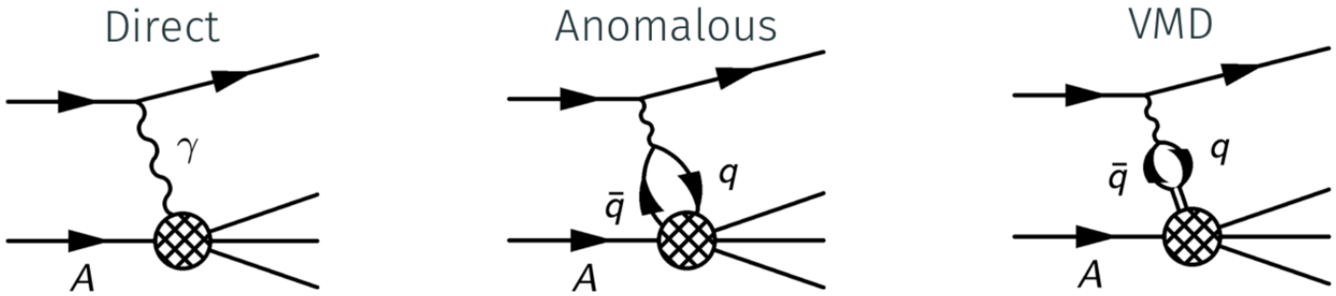
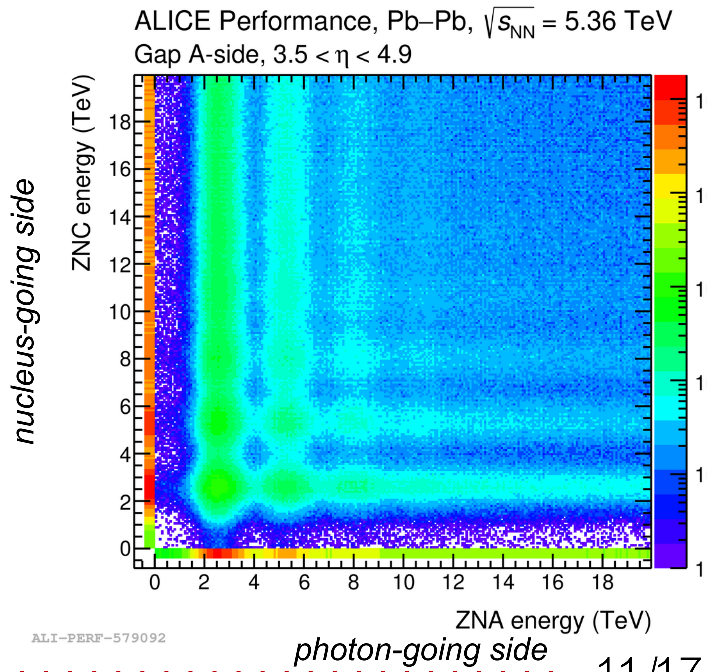


Photo-nuclear collisions



- **Direct photo-production**
  → photon interacts directly with the partons
- **Anomalous photo-production**
  → photon fluctuates into a $q\bar{q}$ pair
- **Vector Meson Dominance (VMD) model:**
  photon fluctuates into a vector meson (ρ, ω)
  → interacts with the nucleus through the strong interaction



- Photo-nuclear interaction often results in the break-up of the target nucleus (no activity on photon-going side, and activity on target-going side)
- Forward detectors (FIT and ZDC) are used to identify single-gap (SG) event topologies

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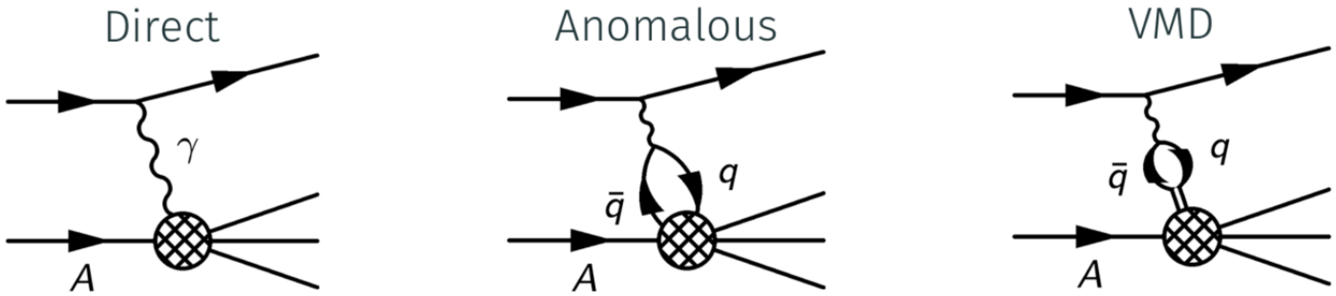

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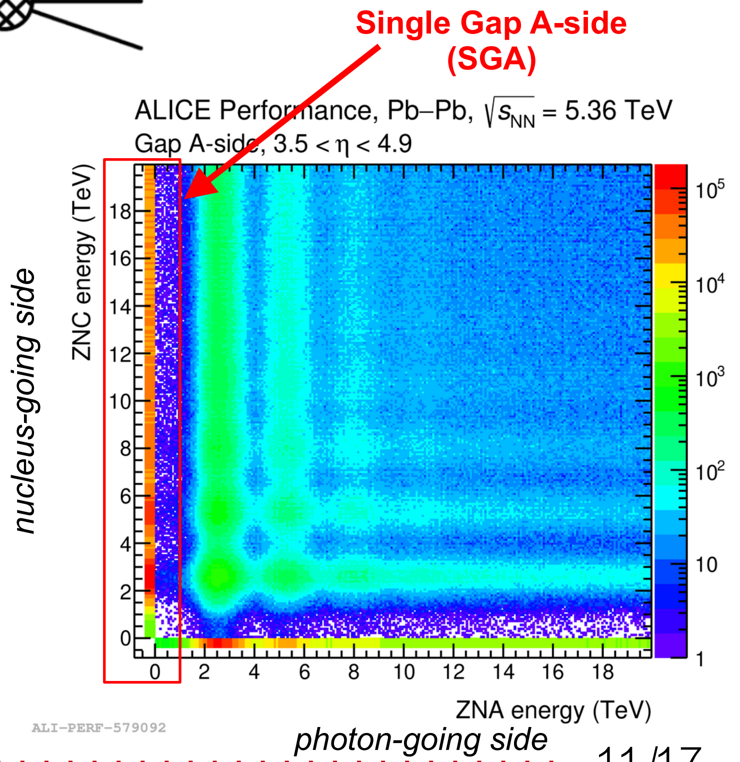
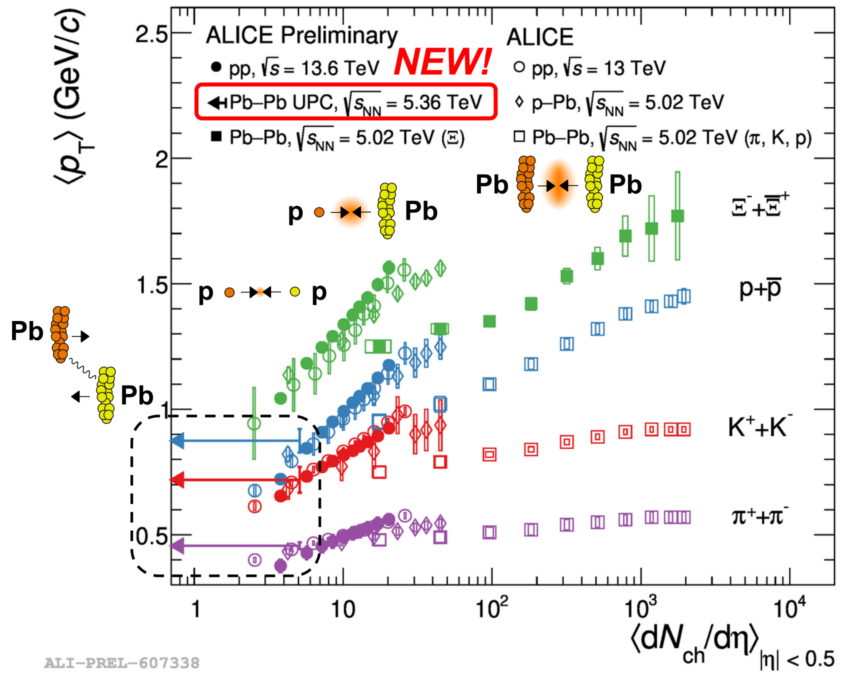
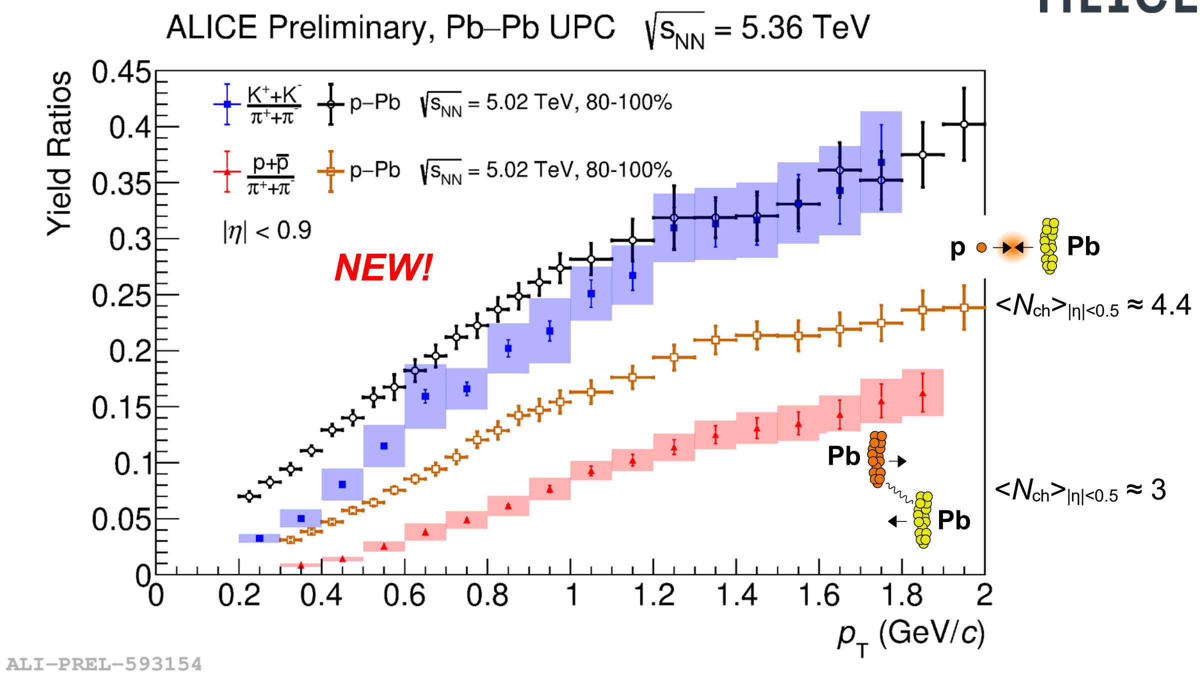


π, K, p in ultra-peripheral Pb–Pb collisions

S. Ragoni, T04, Tuesday 08:50



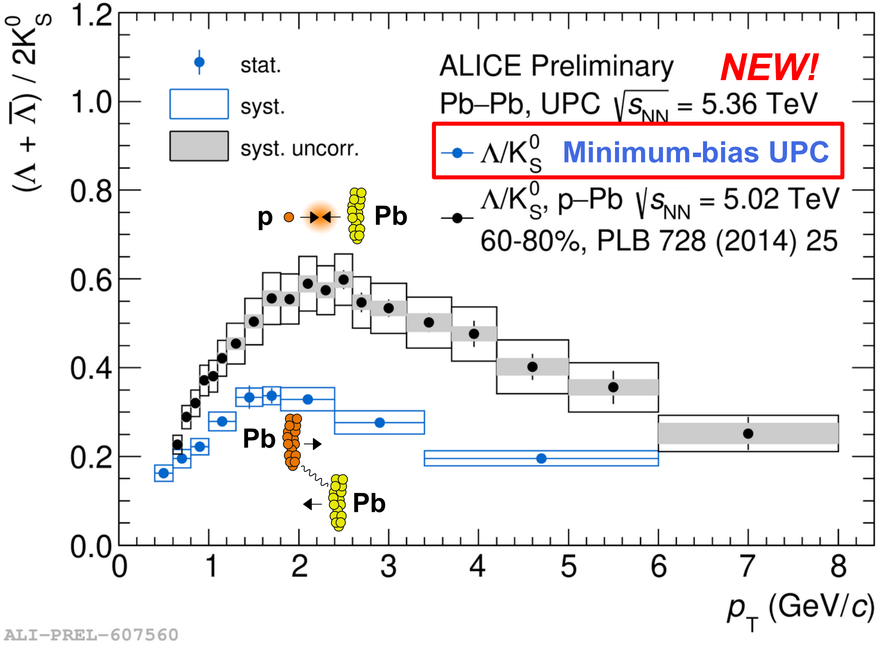


- $\langle p_T \rangle$ values in γ-Pb are consistent to the ones in low multiplicity pp and p–Pb collisions
- K/π and p/π show similar trends as in low-multiplicity p–Pb
  → baryon-to-meson ratio is significantly lower than in low-multiplicity p–Pb

Strange baryon-to-meson ratio in Pb–Pb UPC

S. Ragoni, T04, Tuesday 08:50

$\langle N_{ch} \rangle_{|\eta|<0.5} \approx 3$

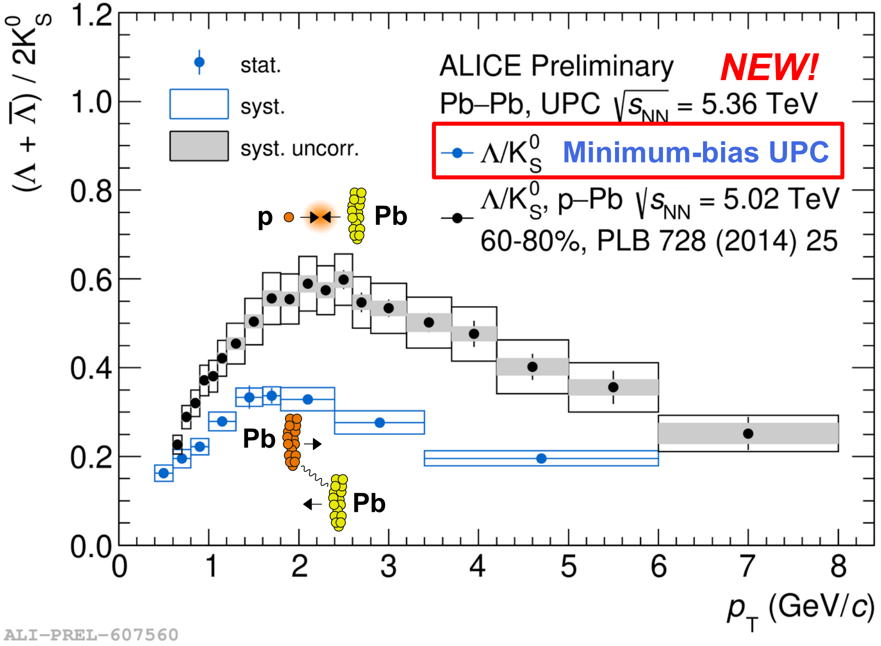


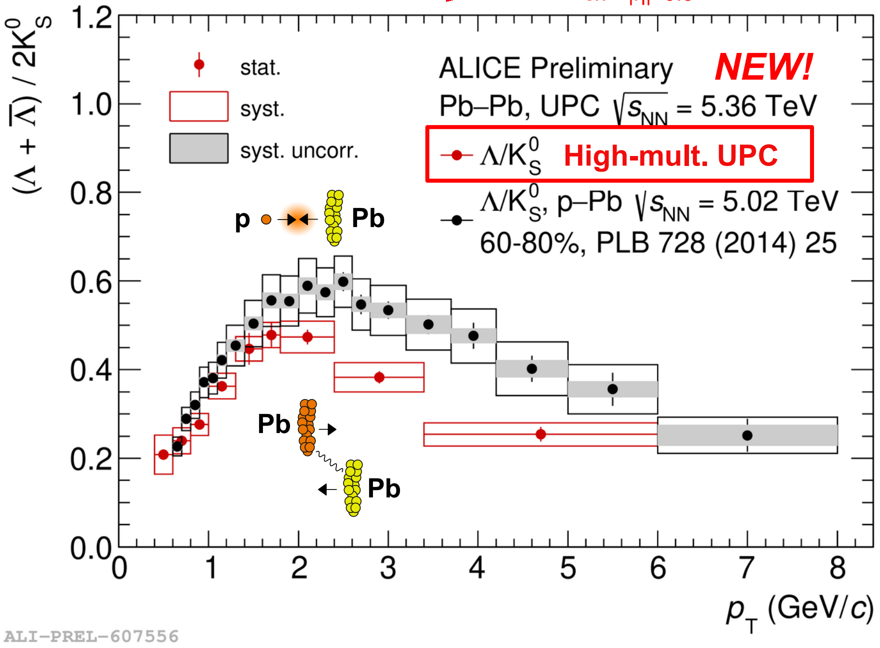
- Λ/K^0_S ratio enhancement in γ−Pb collisions at intermediate p_T is reminiscent of that measured in low-mult. p–Pb

Strange baryon-to-meson ratio in Pb−Pb UPC

S. Ragoni, T04, Tuesday 08:50

$\langle N_{ch} \rangle_{|\eta|<0.5} \approx 3$ — Reaching multiplicities typical of low-mult. p−Pb → $\langle N_{ch} \rangle_{|\eta|<0.5} \approx 9.5$



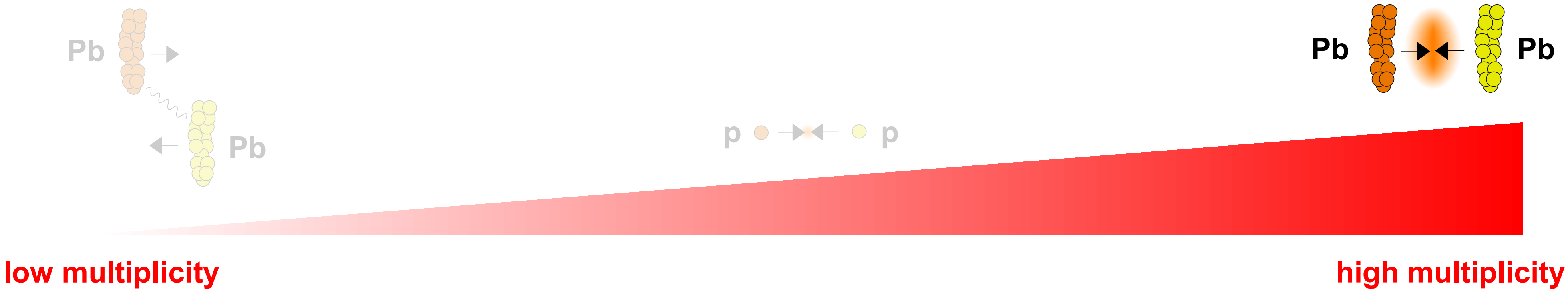


- Λ/K^0_S ratio enhancement in γ−Pb collisions at intermediate p_T is reminiscent of that measured in low-mult. p–Pb
- In **high-multiplicity γ–Pb**, the ratio approaches the values measured in low-multiplicity p–Pb ($\langle N_{ch} \rangle_{|\eta|<0.5} \approx 9.8$)

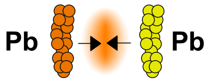
→ dominated by vector meson dominance

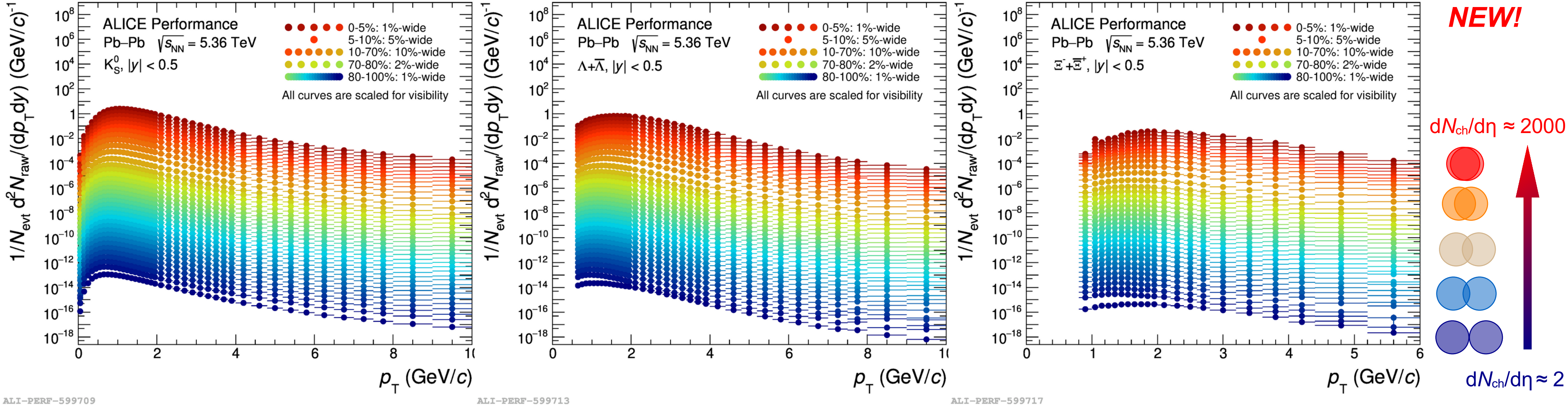
→ **γ−Pb effectively equivalent to hadronic vector meson–Pb collisions**

From the smallest to largest collision systems



Strangeness reconstruction performance in Pb−Pb





- **First raw spectra** (not efficiency corrected) showing the light-flavour hadron (K^0_S, Λ, Ξ) production **from 2 to 2000 charged particle multiplicities** using Pb−Pb collisions at 5.36 TeV

  → excellent performance for strange hadron reconstruction with ALICE in Run 3

  → wealth of statistics allows performing fine p_T- and centrality-differential studies in Pb−Pb collisions

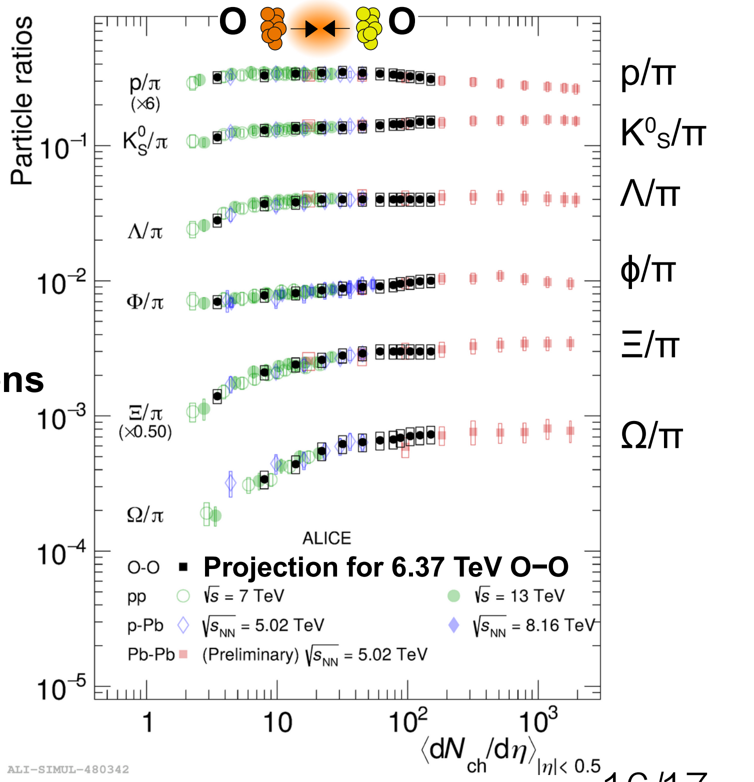
Summary and outlook

- $\langle p_T \rangle$ and baryon-to-meson ratio of light-flavour hadrons in **photo-nuclear γ−Pb collisions** are **similar to** those observed in **hadronic p−Pb collisions**
- **Light-flavour hadron production in pp collisions at 13.6 TeV** shows the same trend as observed at lower energies
- **Excellent performance** for strange hadron reconstruction **in Pb−Pb collisions with ALICE** in Run 3 in order to build a bridge from 2 to 2000 charged particle multiplicities
- These measurements will be **complemented using the O−O collisions**

  → Reach similar multiplicities to high-multiplicity pp/p–Pb

  BUT with a well-defined geometry and larger volume

  → Allow us to disentangle **final-state** from **initial-state effects**



Thank you!

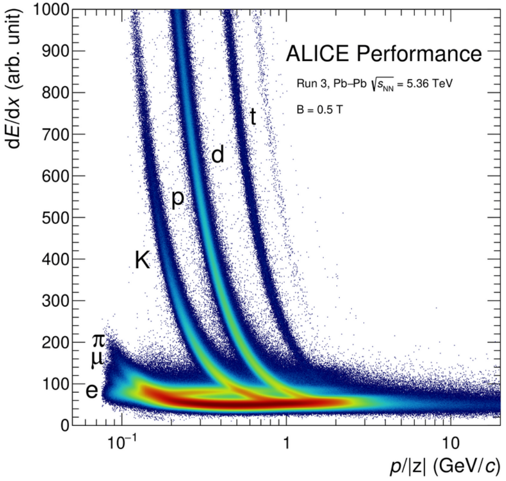
Backup slides

Particle identification with ALICE in Run 3

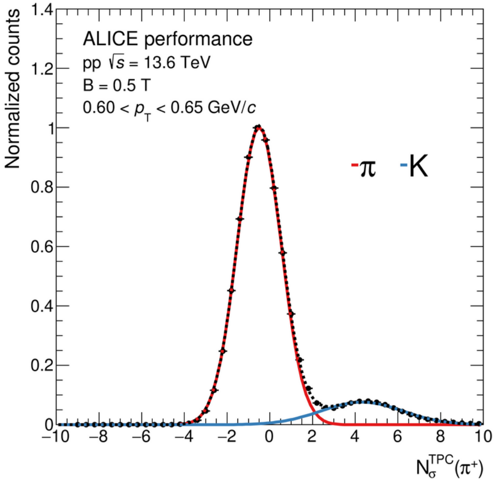
- π, K, p are identified from PID information provided by the TPC and TOF

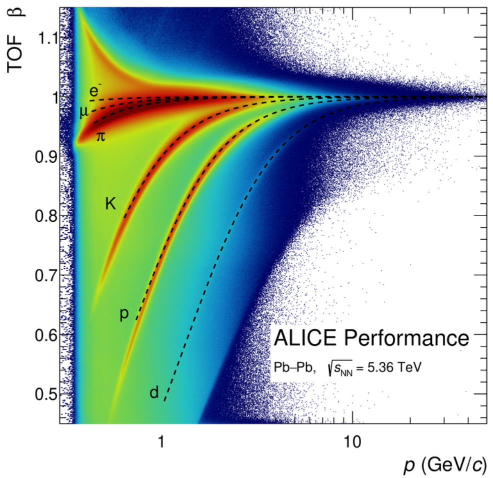
  → TPC ensures excellent particle separation for p_T < 1 GeV/*c* using specific energy loss (dE/dx)

  → TOF extends particle identification up to p_T < 4 GeV/*c* by measuring time of flight



- Particle yields extracted via a fit of the n_σ distribution





Strangeness reconstruction in ALICE

- The strange hadrons reconstruction relies on two weak decay topologies:

V⁰: neutral particle decaying into a pair of charged particles (V-shaped decay)

$$\mathrm{K^0_S} \rightarrow \pi^+\pi^-$$ B.R. 69.2%

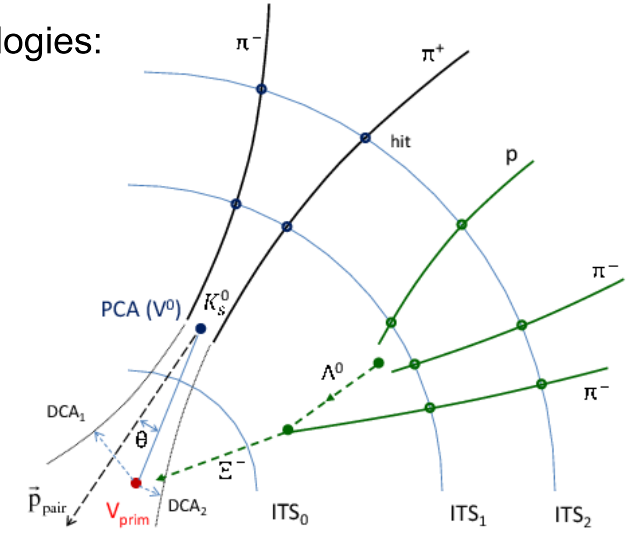
$$\Lambda\,(\overline{\Lambda}) \rightarrow \mathrm{p}(\overline{\mathrm{p}})\pi^-(\pi^+)$$ B.R. 63.9%

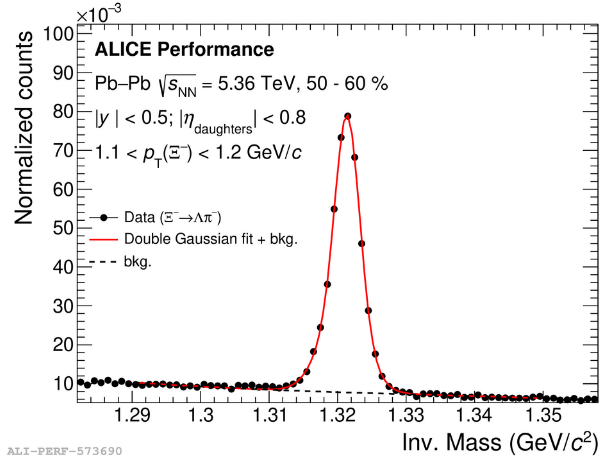
Cascade: charged particle decaying into a V^0 + charged particle

$$\Xi^-(\overline{\Xi}^+) \rightarrow \Lambda\,(\overline{\Lambda})\ \pi^-\ (\pi^+)$$ B.R. 99.9%

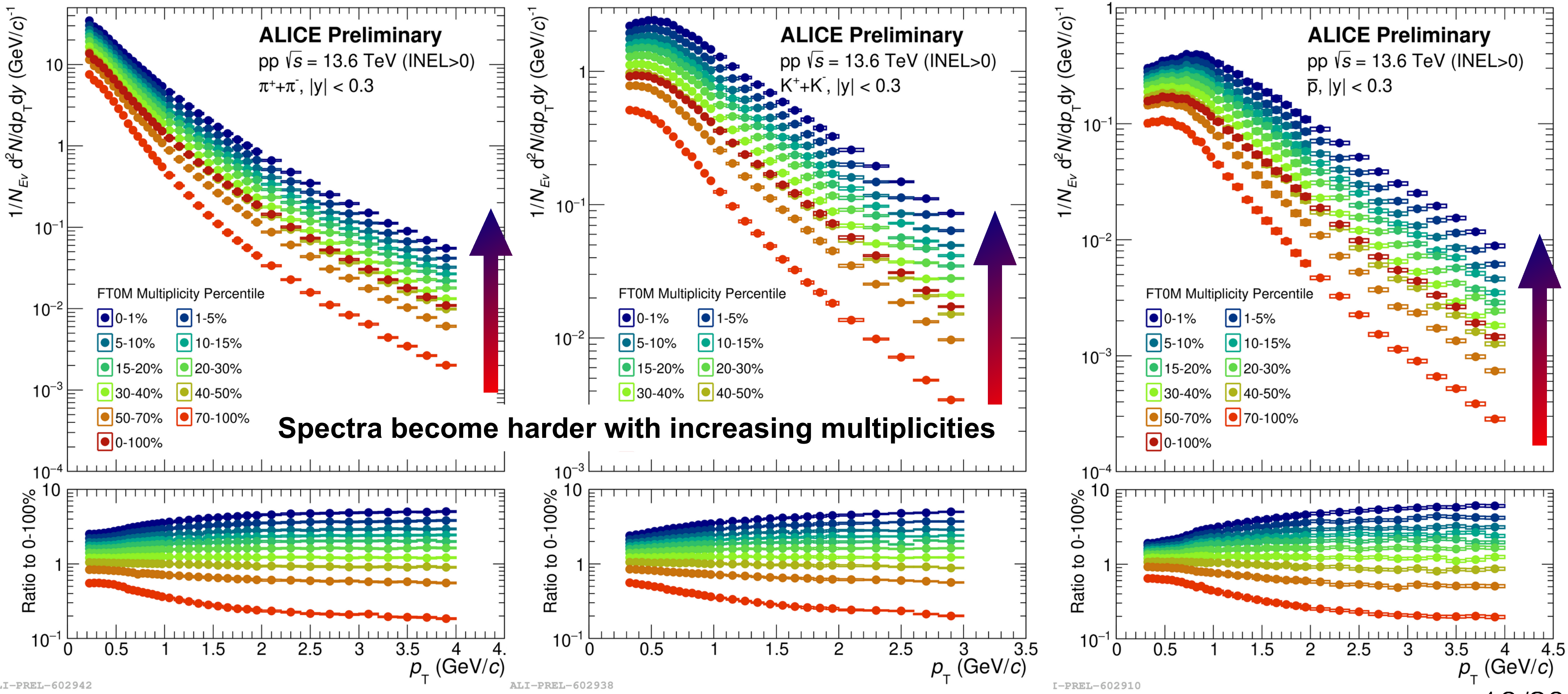
$$\Omega^-(\overline{\Omega}^+) \rightarrow \Lambda\,(\overline{\Lambda})\ \mathrm{K}^-\ (\mathrm{K}^+)$$ B.R. 67.8%

- Statistical identification using an invariant mass analysis



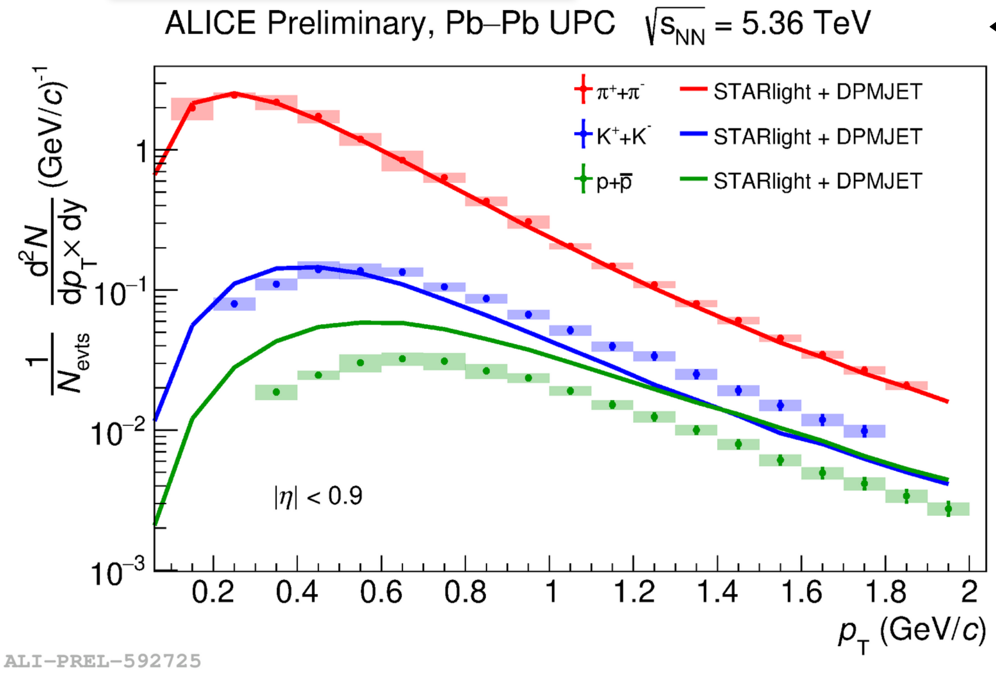


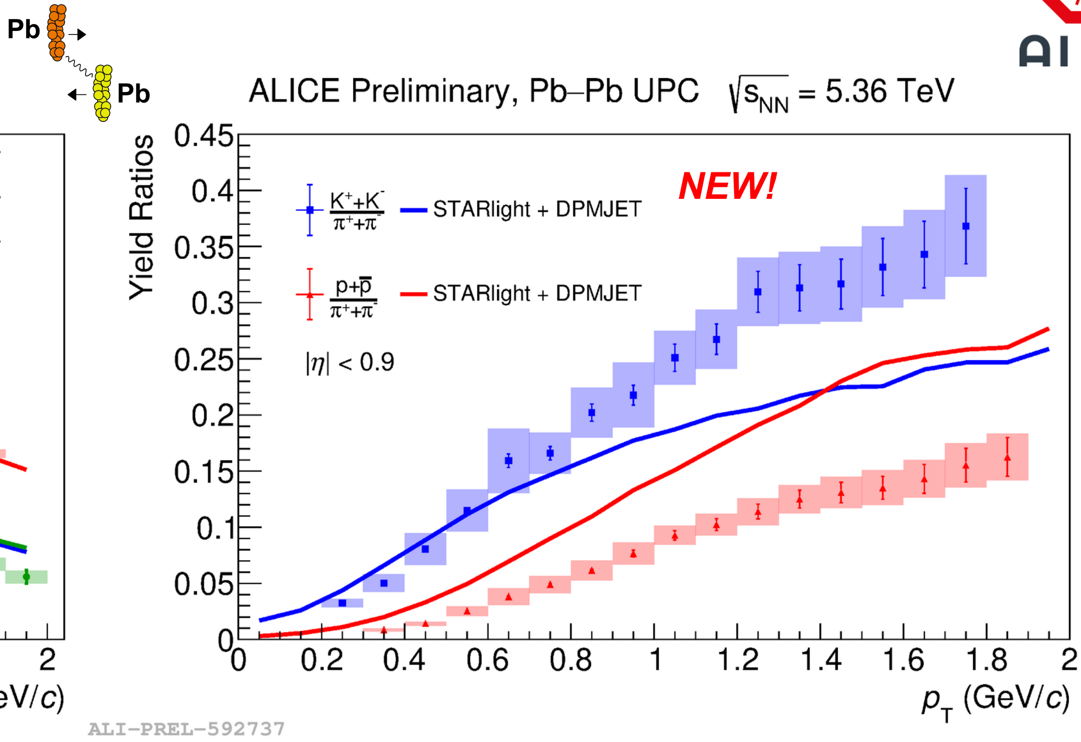
p_T spectra of identified particles



π, K, p in ultra-peripheral Pb–Pb collisions

S. Ragoni, T04, Tuesday 08:50



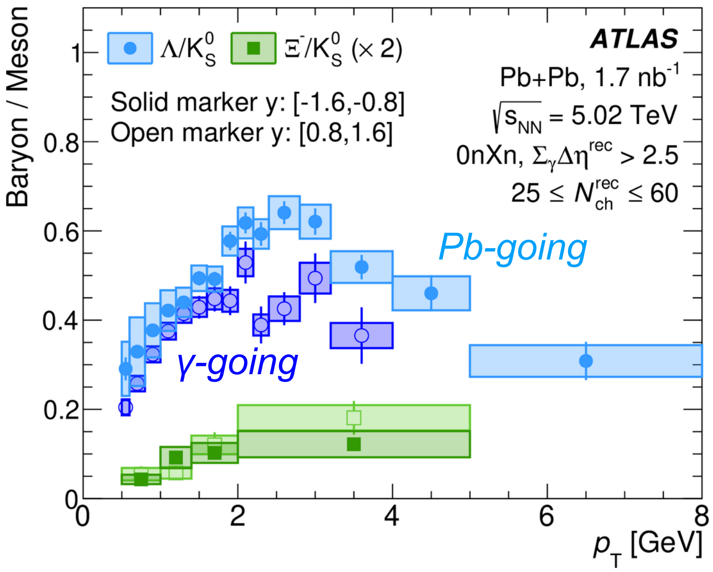


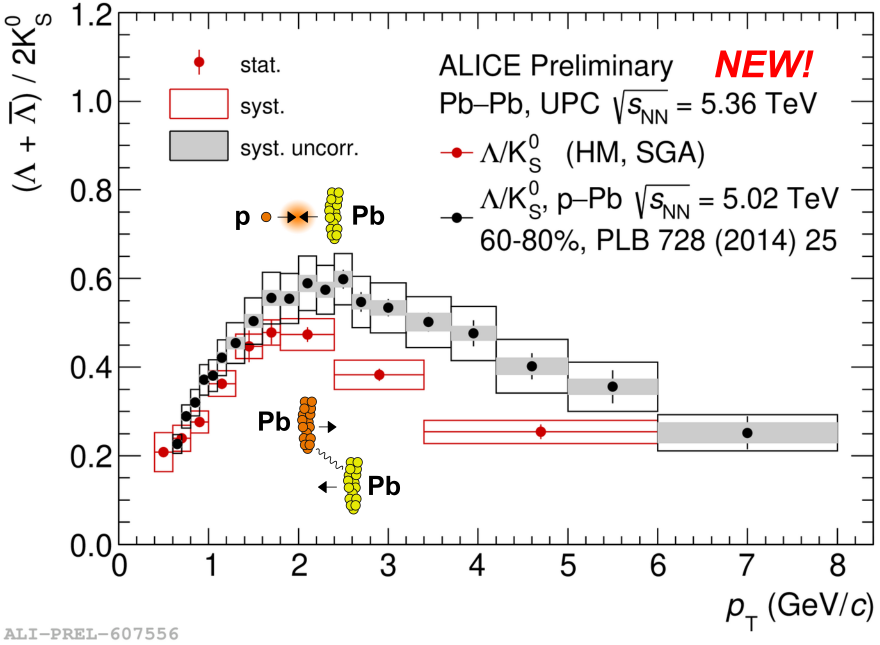
- STARlight (photon flux) + DPMJET (nuclear break up) describes well the π spectra, but only qualitatively for K and protons

  → fails to describe the K/π and p/π ratio

The smallest collision system: UPC

ATLAS Collaboration, [PRC 111 (2025) 064908]

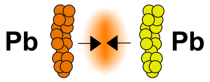




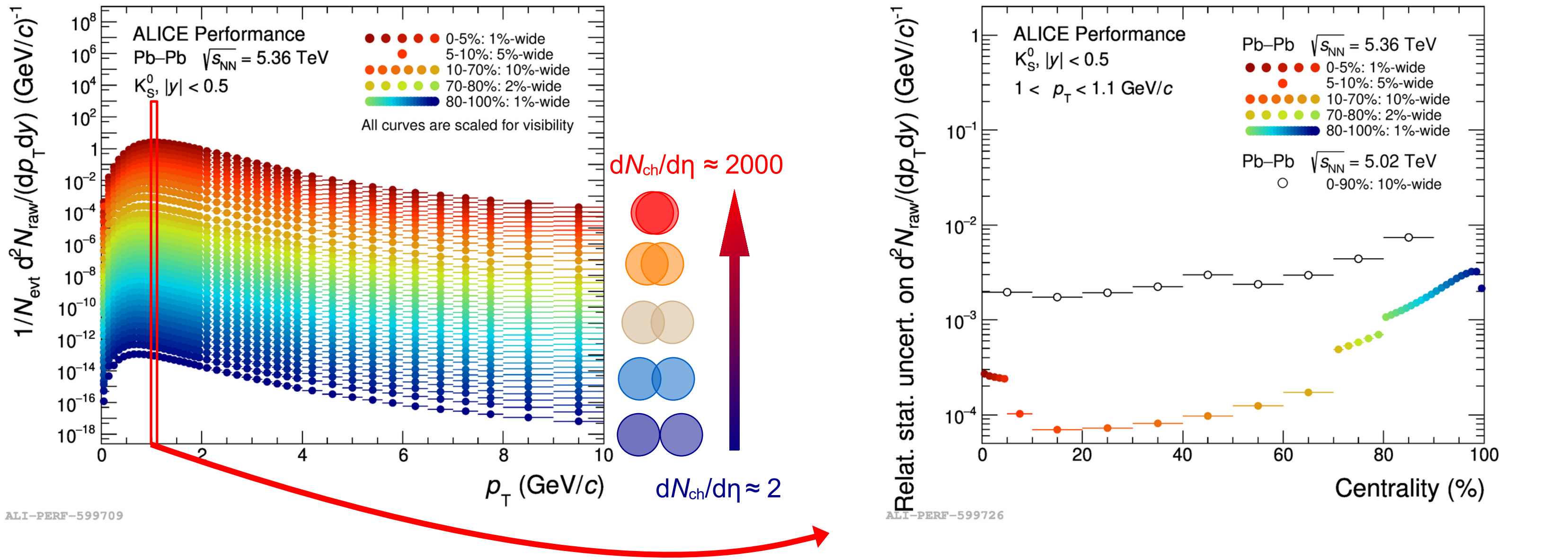
- In high-multiplicity events, the ratio approaches the values measured in low-multiplicity p–Pb (MB → HM)

  → dominated by vector meson dominance, making them **equivalent to hadronic vector meson + Pb collisions**
- Similar observation done by ATLAS

Strangeness reconstruction performance in Pb-Pb



NEW!



- **First raw spectra** (not efficiency corrected) showing the light-flavour hadron (K^0_S, Λ, Ξ) production **from 2 to 2000 charged particle multiplicities** using Pb-Pb collisions at 5.36 TeV

→ excellent performance for strange hadron reconstruction with ALICE in Run 3

→ wealth of statistics allows performing fine p_T- and centrality-differential studies in Pb−Pb collisions

→ **improve statistical precision between x4 and x10**