ALICE

Transverse Momentum Distributions of Identified Particles in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured with ALICE

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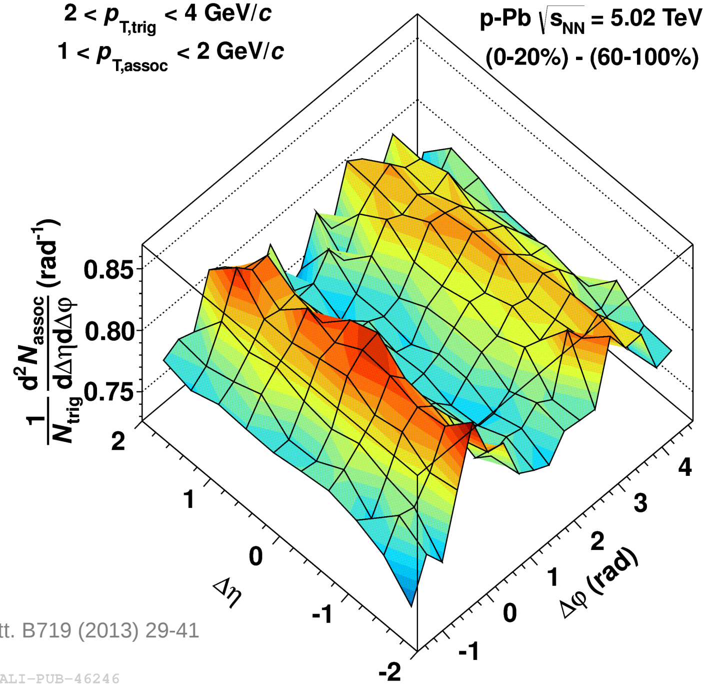
What Can We Learn From p-Pb?

Original purpose: control experiment to access cold nuclear matter effects in heavy-ion collisions



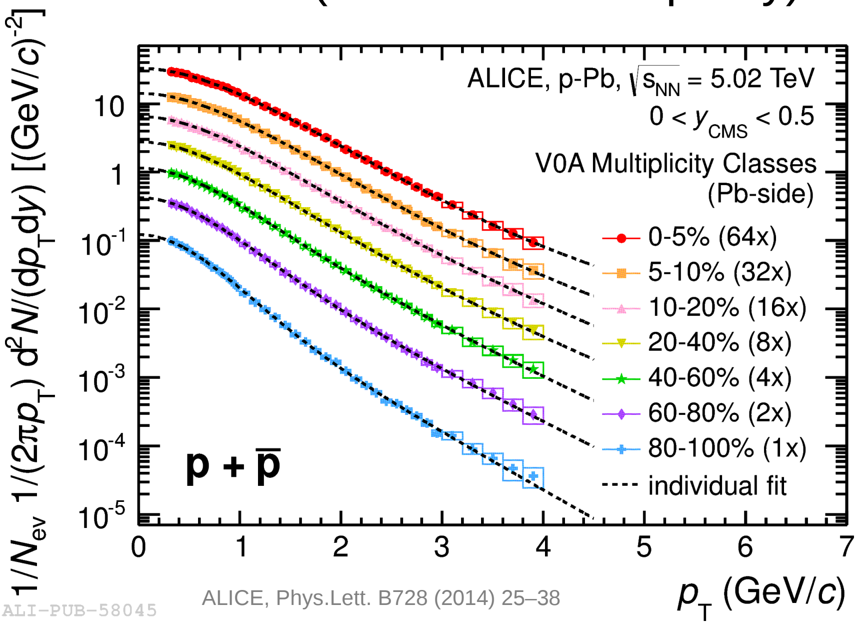
Search for collective effects:

Since the observation of the "double-ridge", p-Pb collisions are not solely a control experiment anymore

→ **exciting physics!**

Transverse momentum distributions of identified particles in p-Pb:

→ mass dependent effects (flow?)
→ particle production mechanisms
→ strangeness
→ evolution with multiplicity
→ particle ratios
→ bridge between pp and HI collisions (in terms of multiplicity)



Contents

- ALICE detector
- $\pi^{\pm}$, $K^{\pm}$, p, $\overline{p}$, K^0_s, Λ, $\overline{\Lambda}$ – light flavor particles
- Light nuclei (d and $\overline{d}$)
- Summary

For particle production in pp and Pb-Pb:
see Babara's talk Wednesday 18:50

The ALICE Experiment

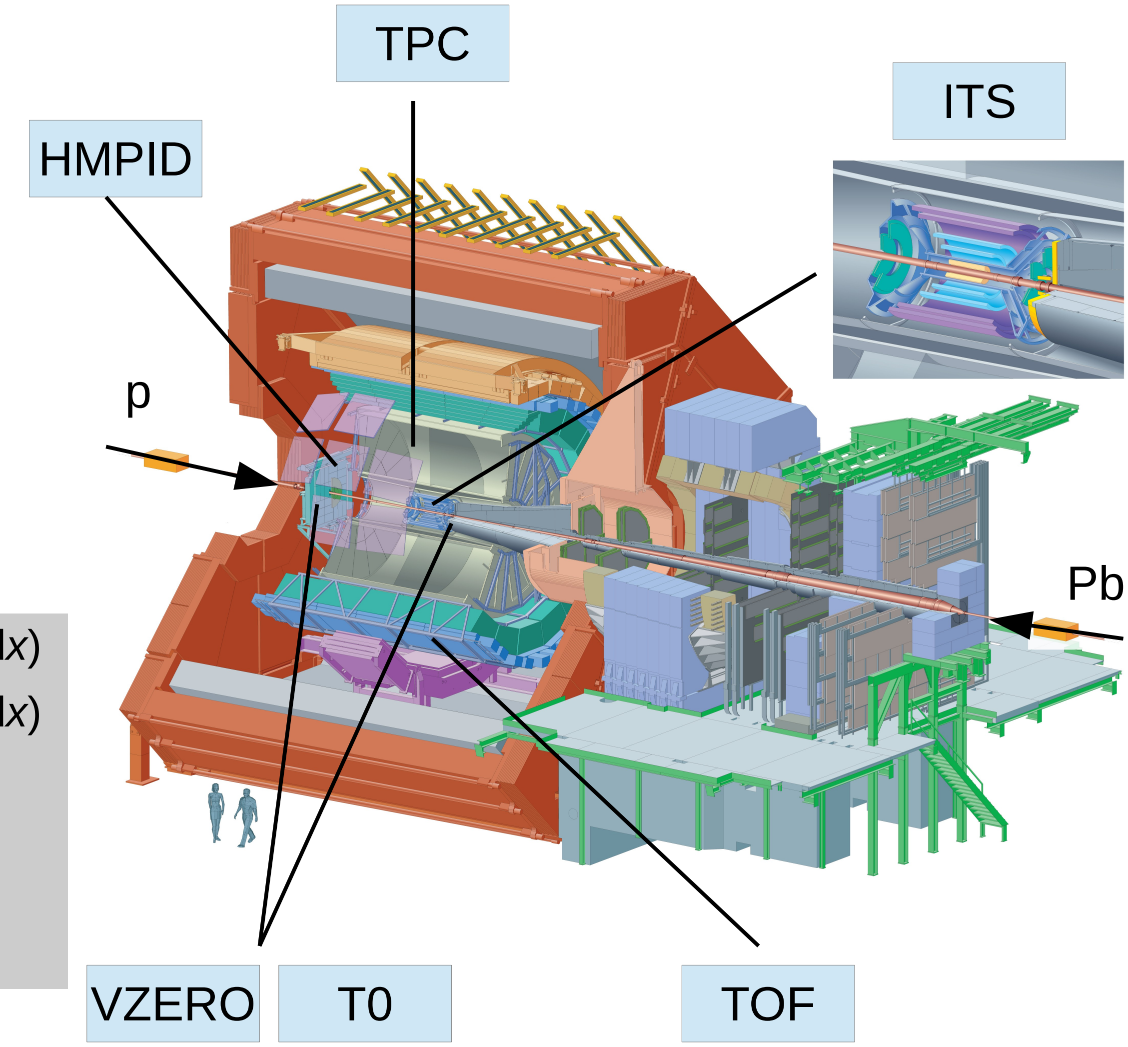
A Large Ion Collider Experiment

PID over wide p_T range with several techniques:

- Energy loss (d*E*/d*x*)
- Time-of-flight
- Decay topology
- Cherenkov radiation

Subdetectors (among others):

ITS	tracking + vertexing + PID (d*E*/d*x*)
TPC	tracking + vertexing + PID (d*E*/d*x*)
TOF (T0)	PID (time-of-flight)
HMPID	PID (RICH)
VZERO	trigger, beam-BKG rejection multiplicity/centrality classes

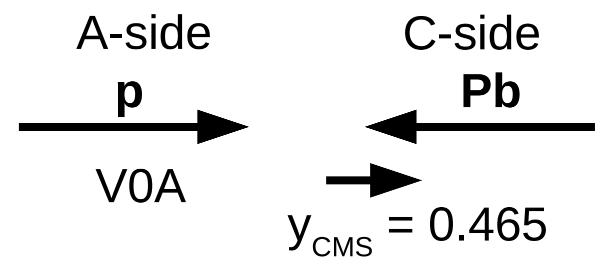


Data Sample

Data sample: **p-Pb collisions** collected in 2013 at the LHC **$\sqrt{s_{NN}}$ = 5.02 TeV**

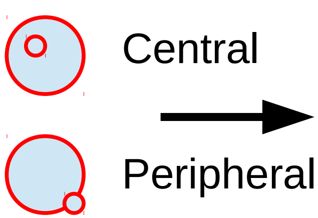
Asymmetric energy/nucleon in the two beams

- CMS moves with rapidity $y_{CMS} = 0.465$ *
- Acceptance of TPC and TOF $|\eta_{LAB}| < 0.9$

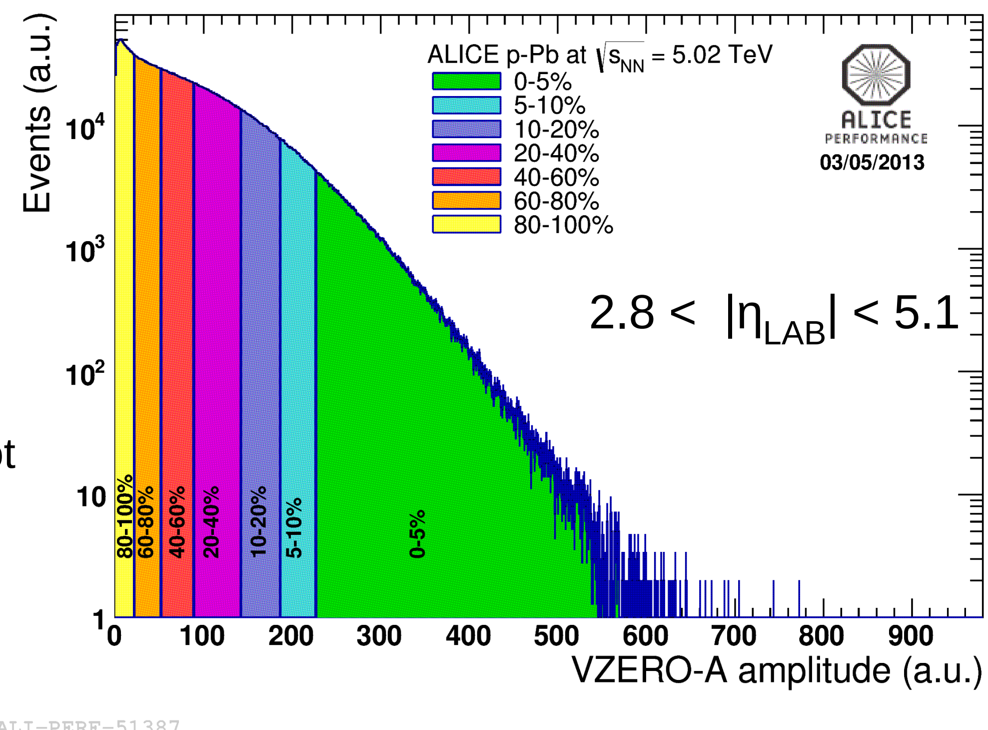


Definition of multiplicity classes:

- Slices in VZERO-A (V0A) amplitude



correlation between impact parameter and multiplicity is not as straightforward as in Pb-Pb



*Note: positive rapidity is the direction of the proton

$\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ Spectra

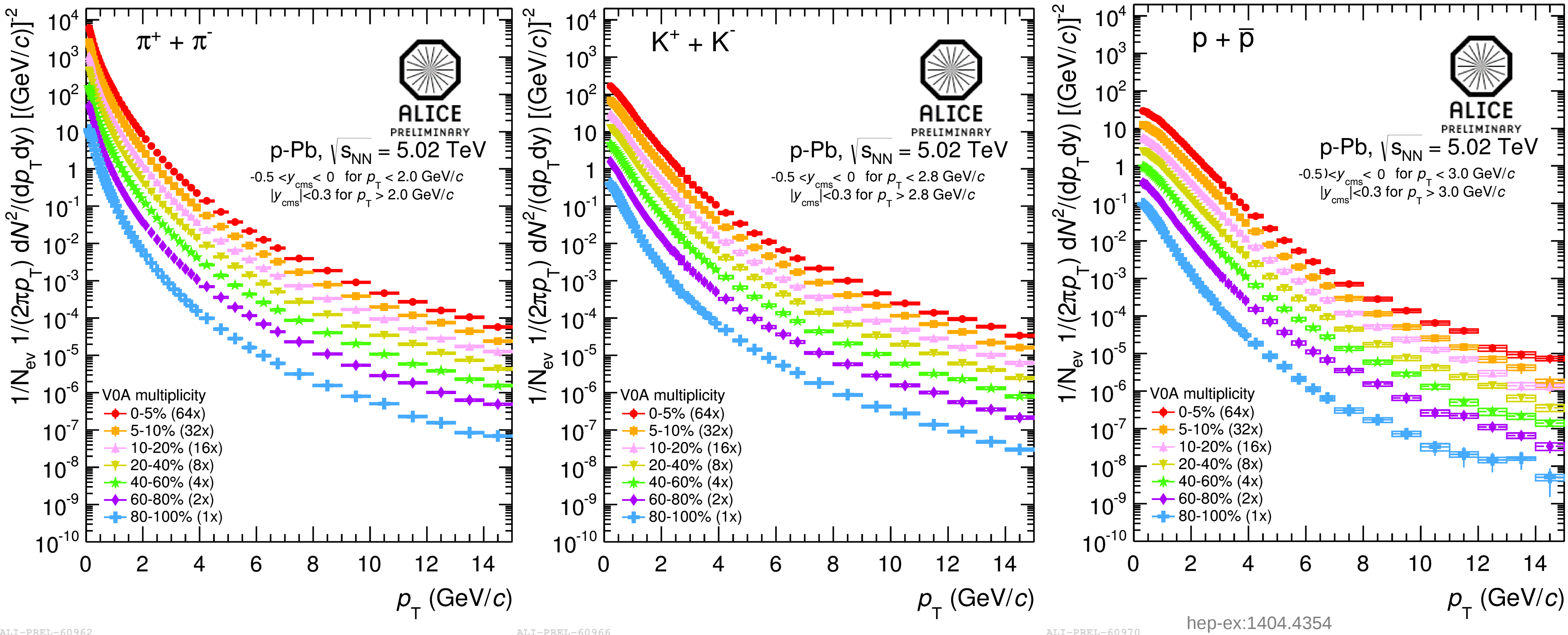
A Large Ion Collider Experiment

ALICE

- At LHC energies the particle and anti-particle production are consistent within errors
  - Shown is the sum of particle and anti-particle

- Hardening with multiplicity and particle mass
  - Indication for collective effects in p-Pb
  - Reminiscent of observed effects in Pb-Pb
    → Attributed to radial flow

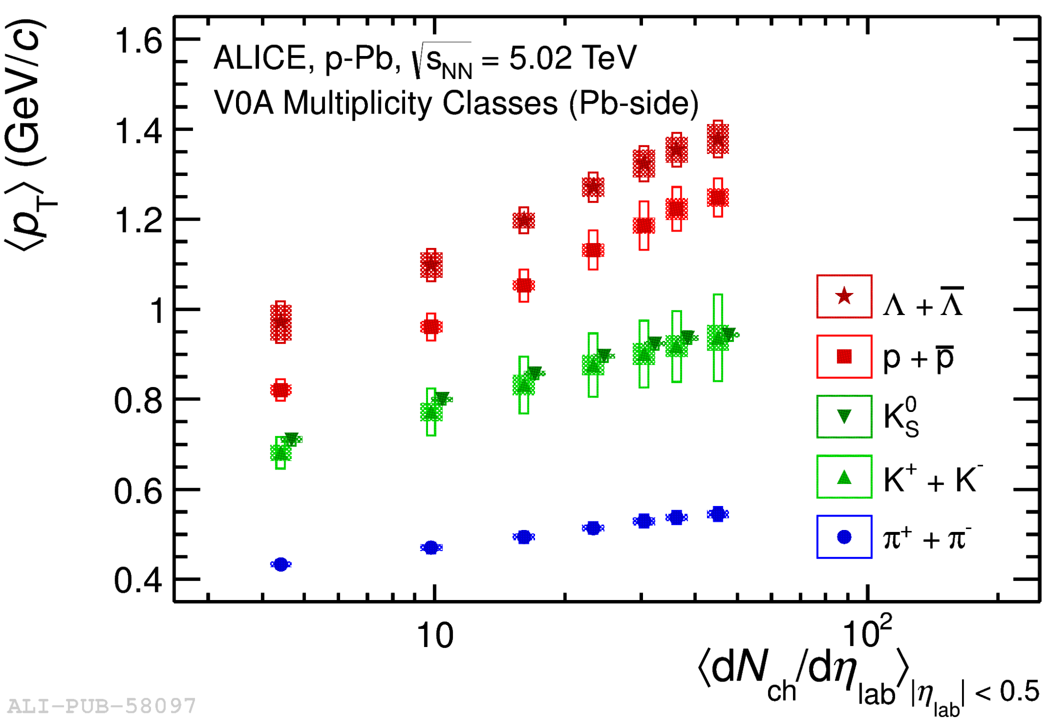
- In hydrodynamic picture particle velocities are pushed by the expanding hot medium
  - Sensitive to pressure gradient and particle mass

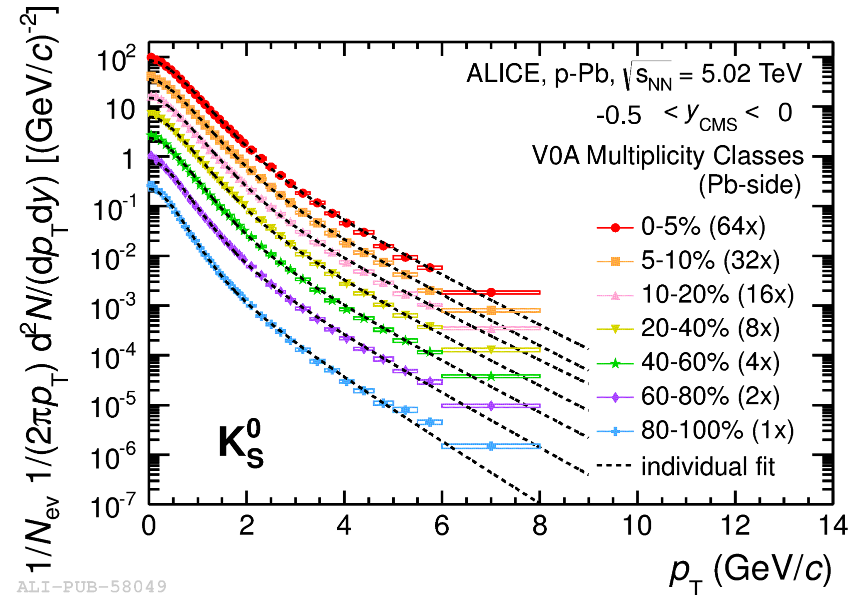


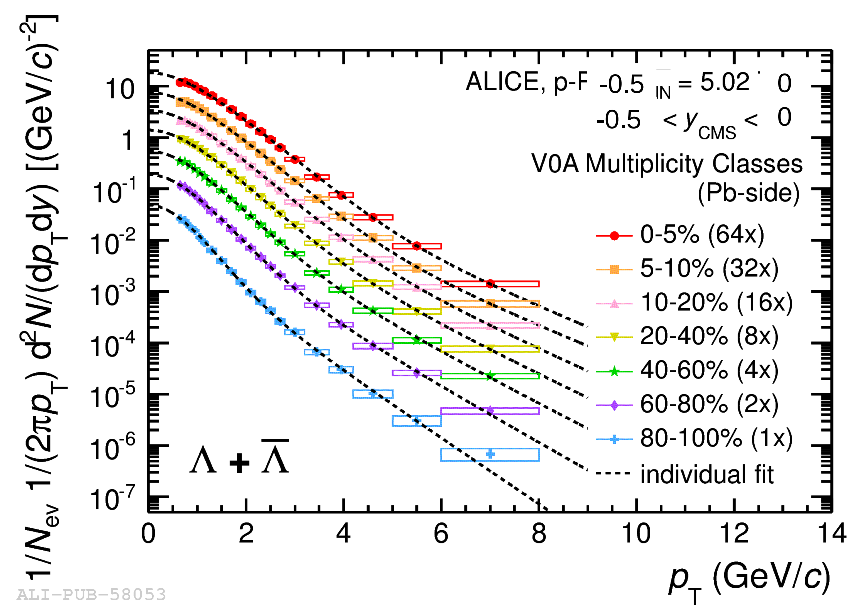
hep-ex:1404.4354

Strange Particle Spectra

- Dotted lines are individual Blast-Wave fits for extrapolation to low and high p_T
- Λ and $\overline{\Lambda}$ are in agreement, shown is the sum
- Hardening of spectra with particle mass and multiplicity is seen

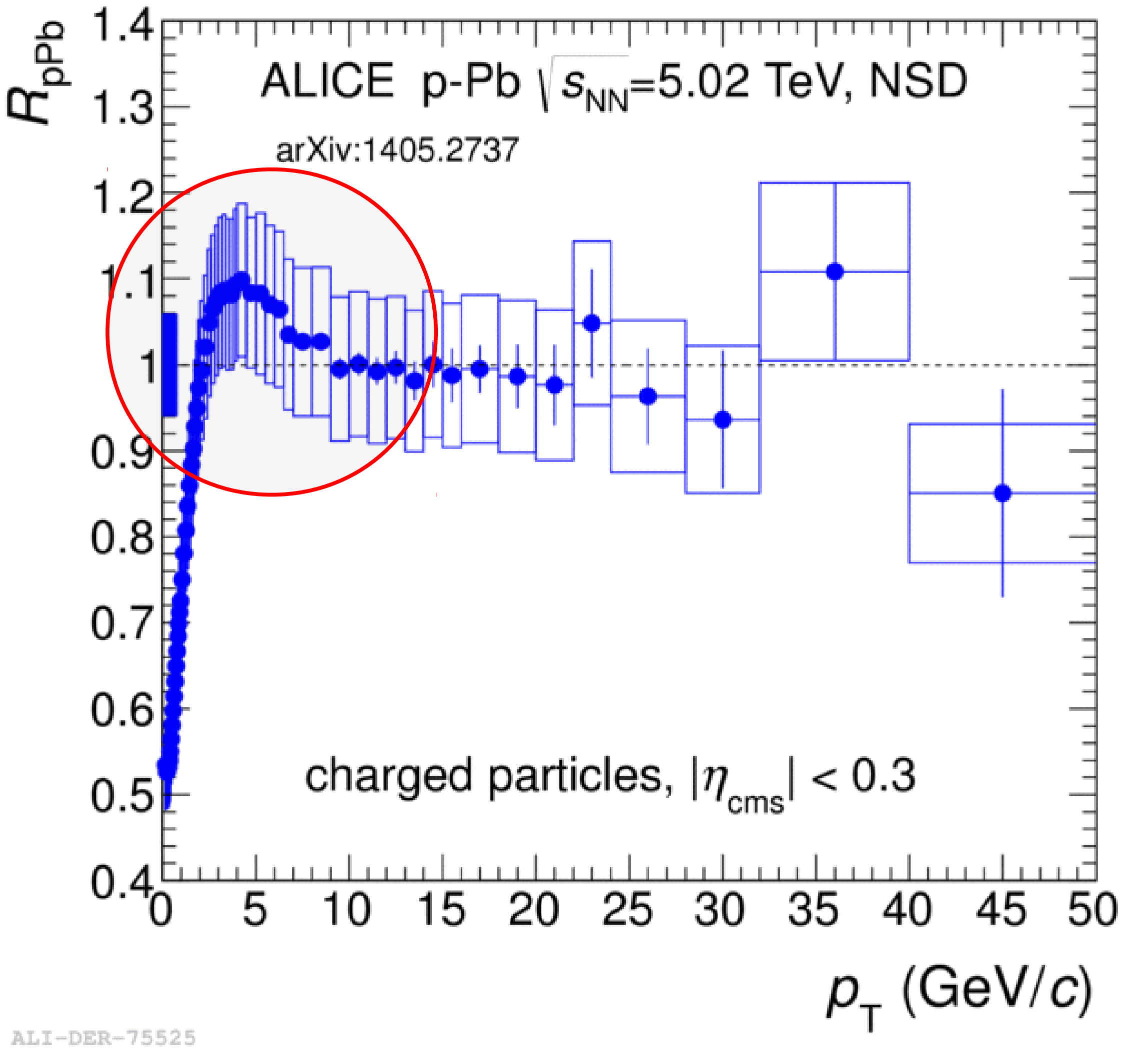






Nuclear Modification Factor

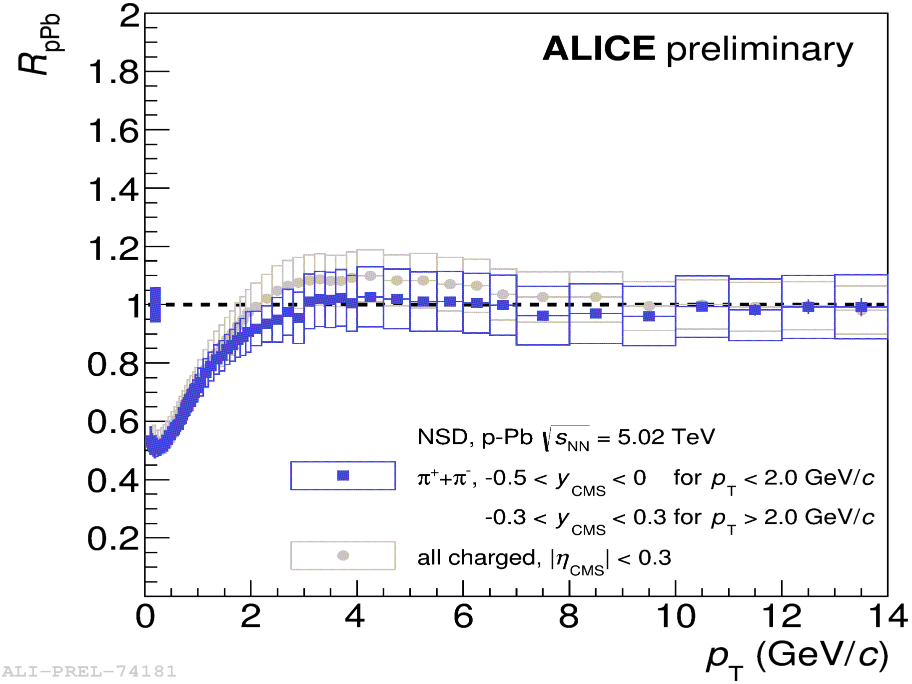
R_{pPb} of All Charged Particles

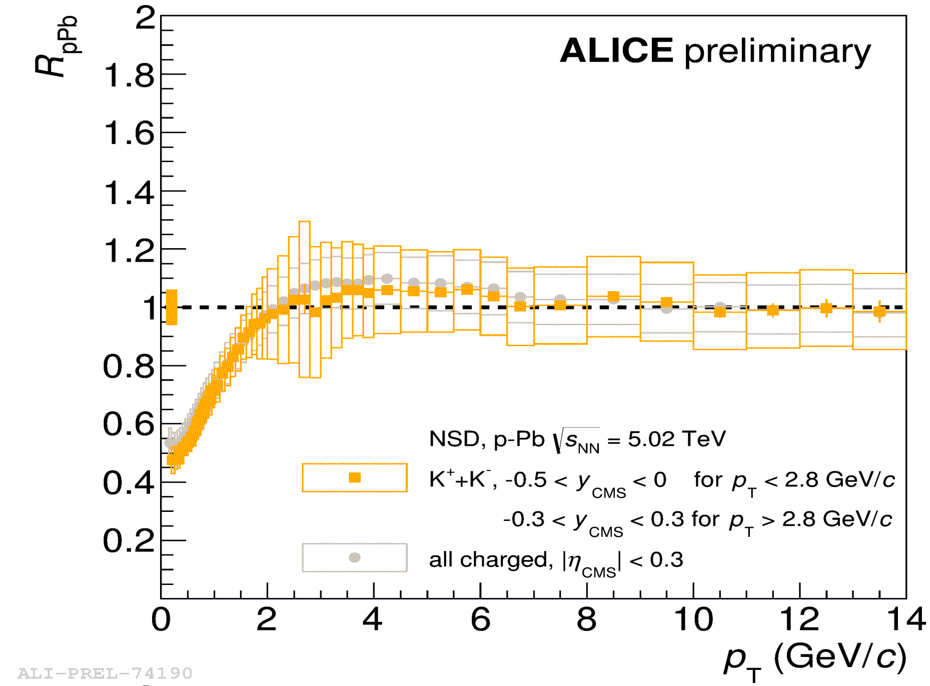


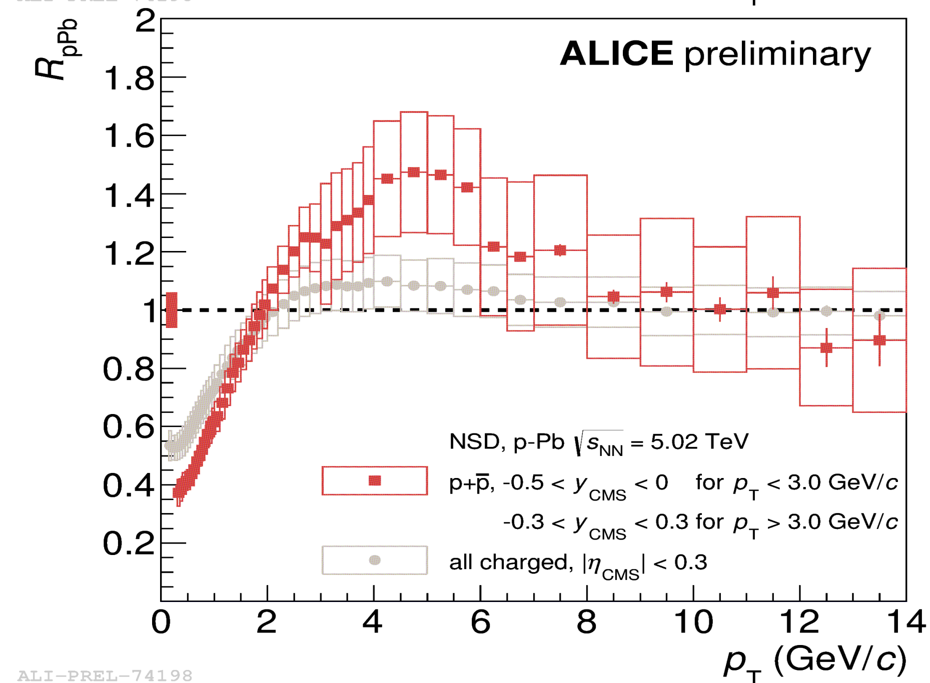
Eur. Phys. J. C 74 (2014) 3054

- Small Cronin peak at intermediate p_T
- Re-scattering
  → is there a mass dependence?
- How does it look for identified particles?

R_{pPb} for π, K, p







pp reference at $\sqrt{s_{NN}}$ = 5.02 TeV is interpolated with available data (2.76 TeV and 7 TeV)

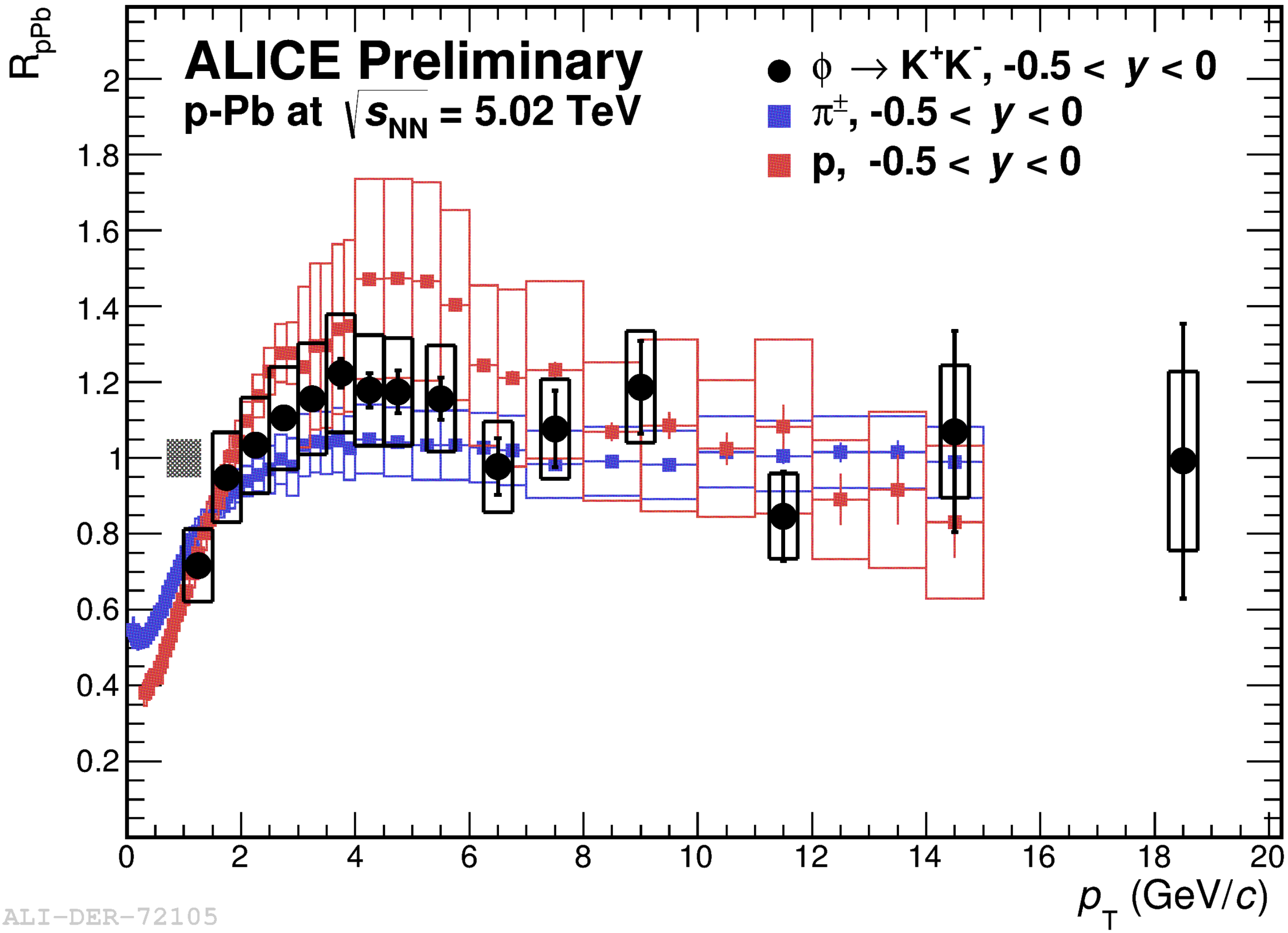
- Power-law fit: $(\sqrt{s})^{\alpha}$

→ **Protons show peak at intermediate p_T**

→ **R_{pPb} of π and K is flat over measured p_T range**

→ **Consistent with mass dependence**

R_{pPb} of Φ



see talk by Anders K.
Saturday 9:30

- Moderate peak for Φ, systematically lower than protons
  → Makes the mass dependence picture more complicated
- R_{dAu} at RHIC → no Cronin peak for Φ observed → valence quark dependence?

PhysRevC.88.024906

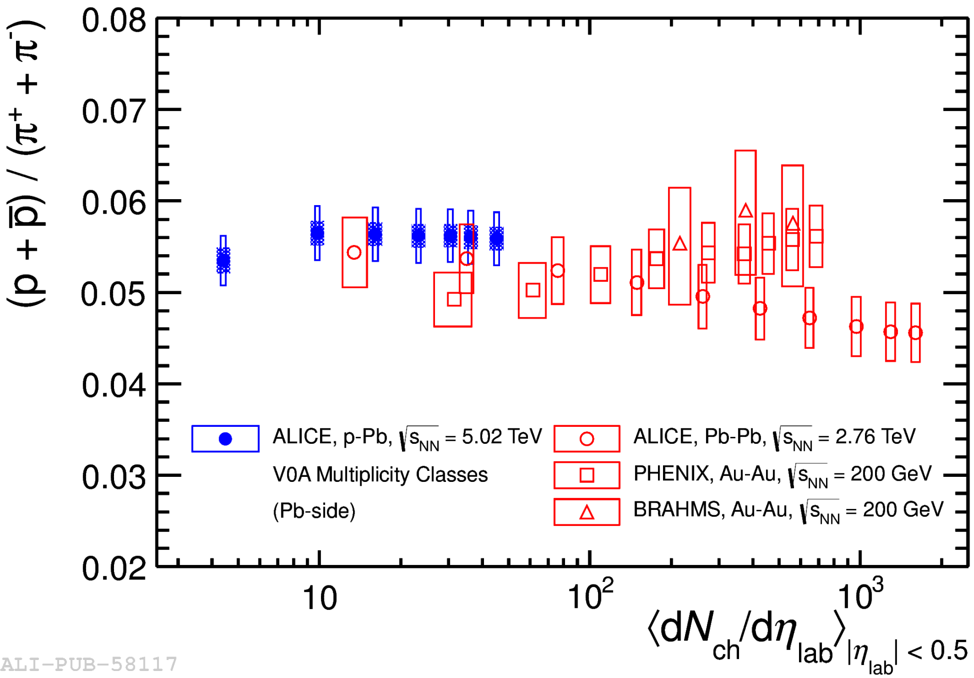
Particle Ratios

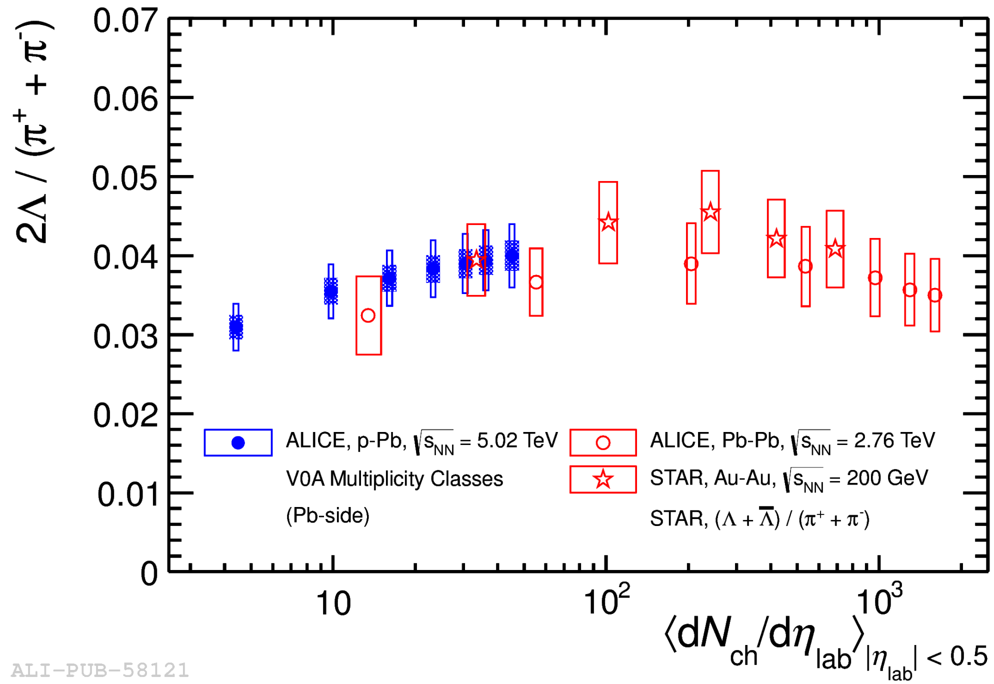
Integrated Yields Ratios

A Large Ion Collider Experiment

ALICE

PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)
ALICE, PLB 728 (2014) 25–38
STAR, PRC 79, 034909 (2009)
STAR, PRL 108, 072301 (2012)

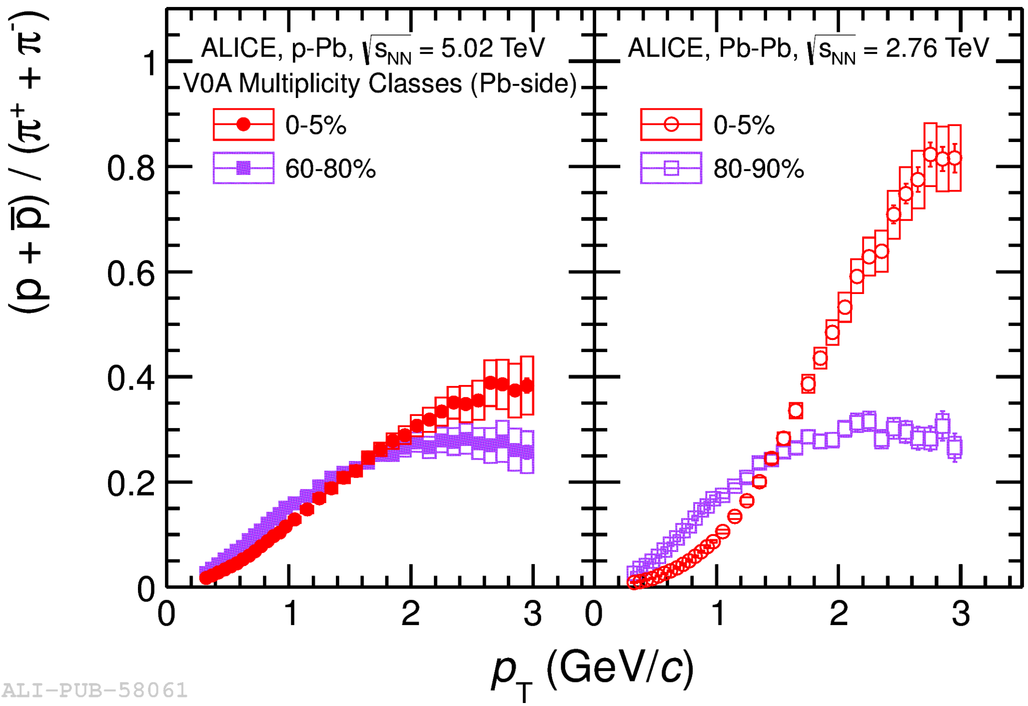


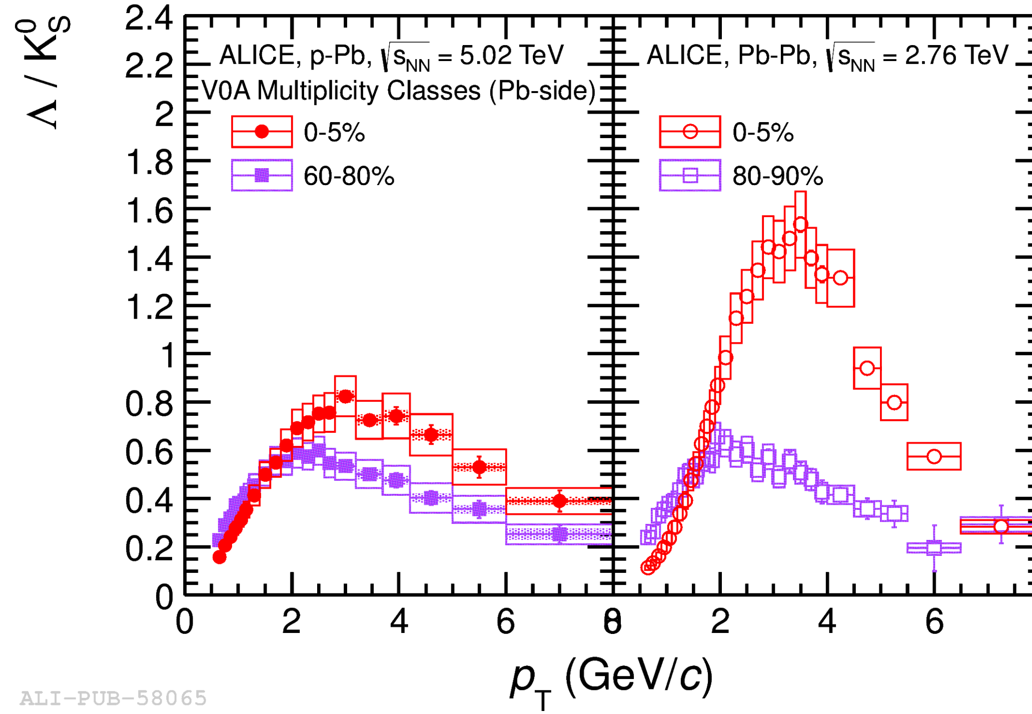


→ Small increase in the integrated Λ/π ratio with multiplicity

Particle Ratios

Phys. Rev. C 88, 044910 (2013)
Phys.Lett. B728 (2014) 25–38
Phys.Rev.Lett. 111 (2013) 22, 222301



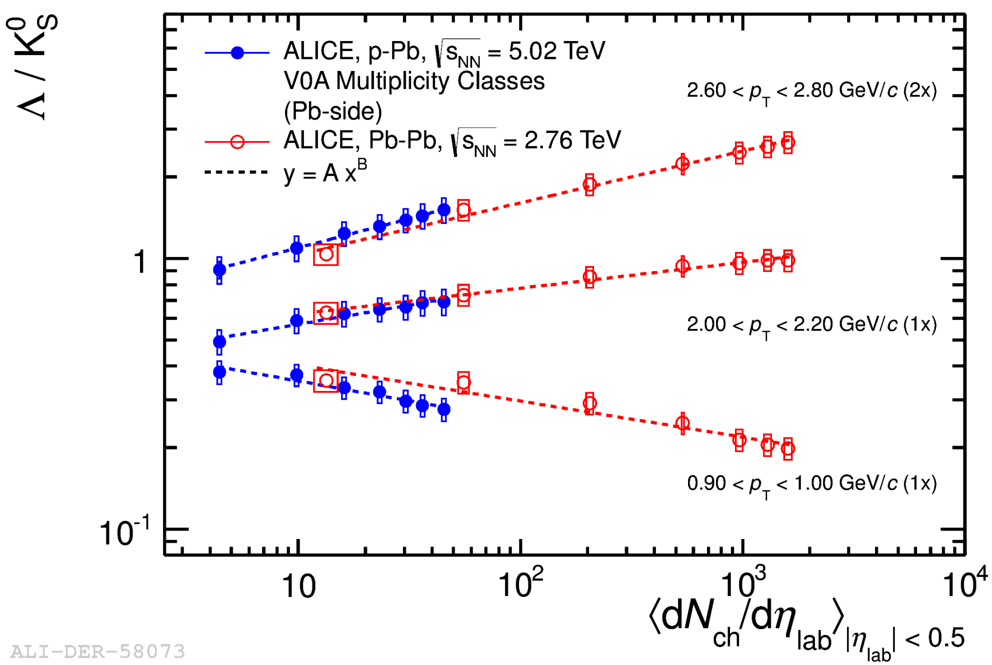


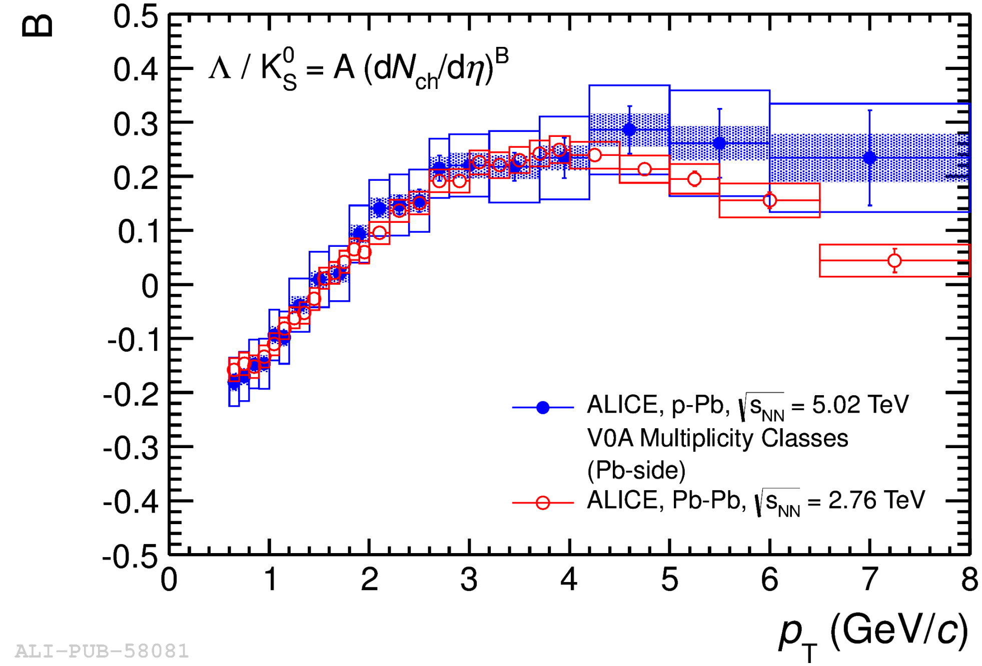
Note: systematic errors are largely correlated for different multiplicity bins → multiplicity uncorrelated errors are drawn as a band for p-Pb

- Increase at intermediate p_T with increasing multiplicity
- Corresponding depletion at low p_T
- Since integrated ratio is flat this indicates a shift in the shape of the spectra with multiplicity
- Reminiscent of radial flow in Pb-Pb

Multiplicity Scaling of Λ/K^0_s Ratio

- Plotted each p_T bin as a function of charged multiplicity
- Fitted with power-law (y=Ax^B) for each system (pA and HI)
- Plot power-law exponent B as function of p_T





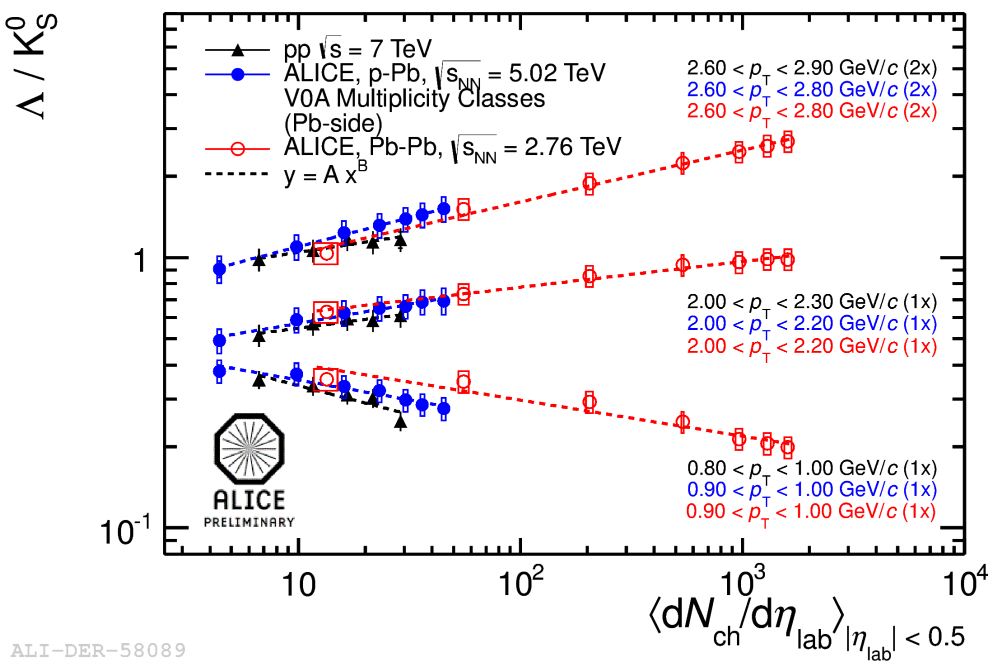
→ Similar increase of Λ/K^0_s for same increase of $dN_{ch}/d\eta$ in p-Pb and Pb-Pb

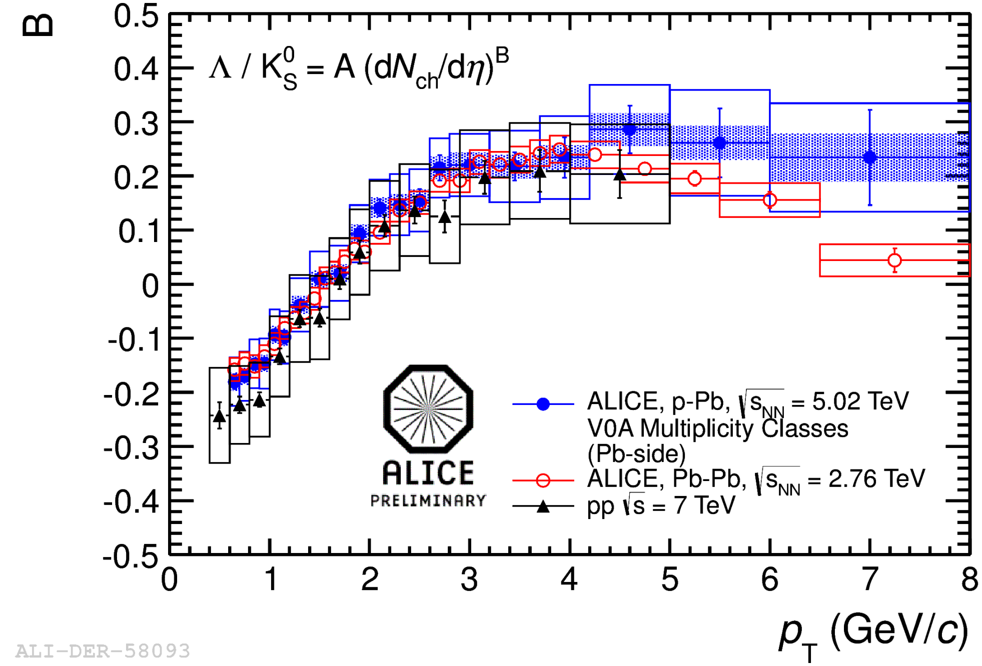
→ **Same power-law scaling exponent (B) in p-Pb and Pb-Pb**

→ Scaling also holds for p/π

Adding pp to the Picture

A Large Ion Collider Experiment





Power-law scaling exponent B from pp is also compatible with p-Pb and Pb-Pb collisions

Caveat: Λ/K^0_s ratio in pp collisions is sensitive to bias by multiplicity selection at mid-rapidity (p-Pb multiplicity selection with V0A (2.8 < $|\eta_{LAB}|$ < 5.1))

Blast-Wave Analysis

Global Blast-Wave Fit

A Large Ion Collider Experiment

Hydrodynamic-inspired model, that assumes

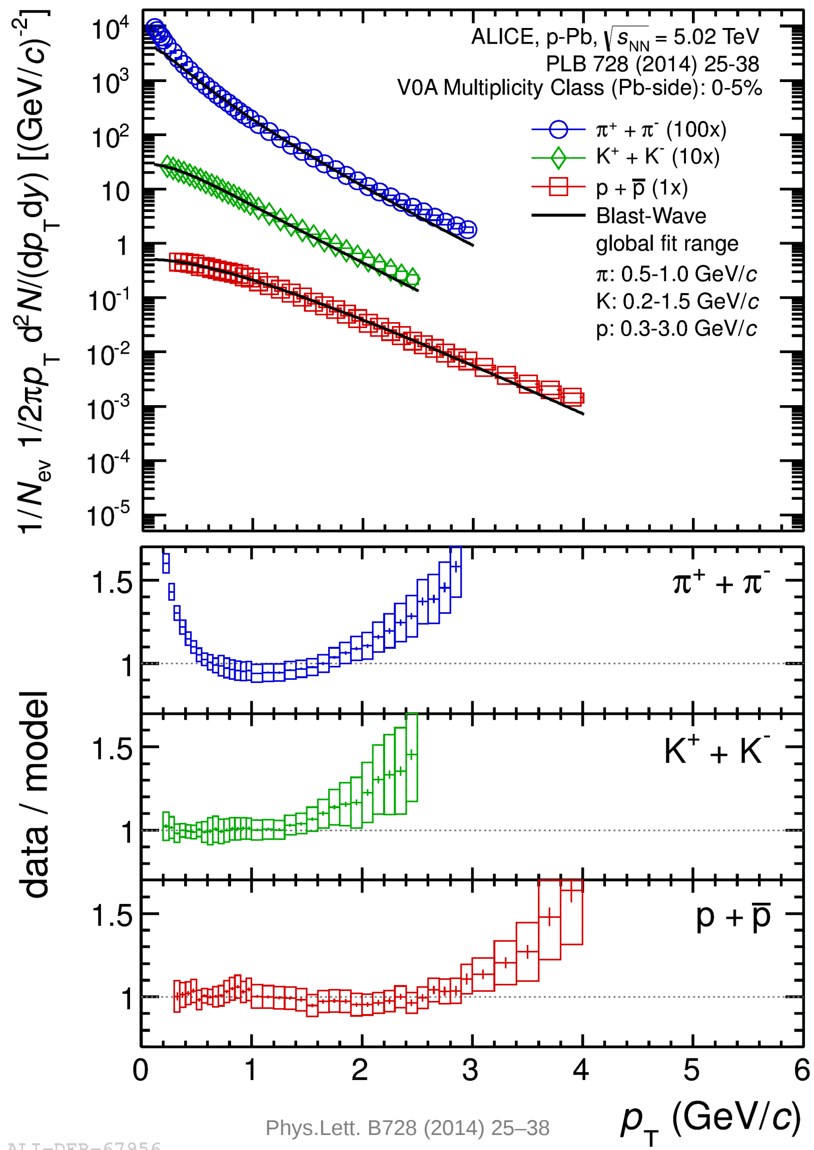
- hard sphere uniform density particle source with temperature T
- collective transverse radial flow velocity β

- Simultaneous fit of all particles with 3 free parameters:

$<\beta_T>$	radial flow $(2\beta_s/(2+n))$
T_{fo}	freeze-out temperature
n	velocity profile

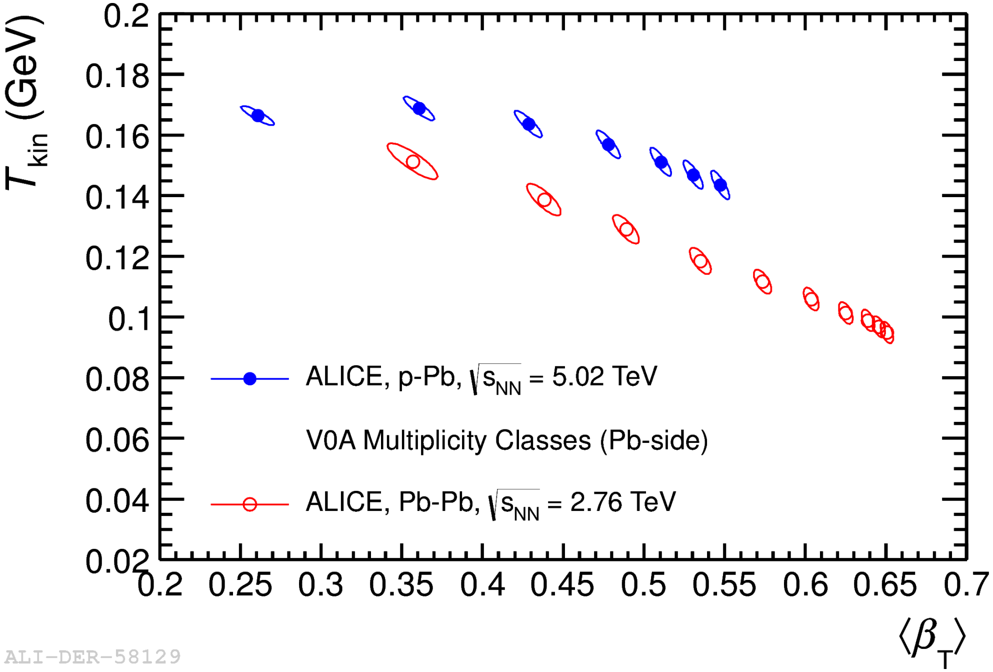
- Global fit performed in the following p_T ranges:

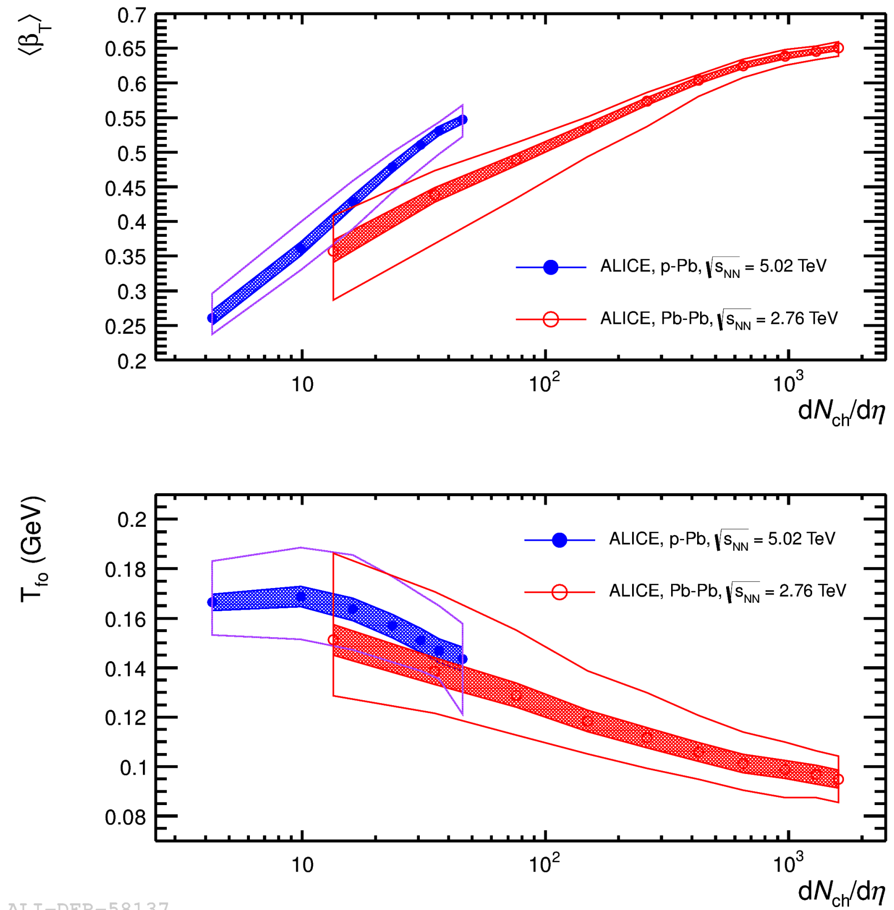
π	0.5 – 1.0 GeV/*c*
K	0.2 – 1.5 GeV/*c*
p	0.3 – 3.0 GeV/*c*



Blast-Wave Parameters

low mult ⟶ **high mult**





π/K/p Blast-Wave analysis:

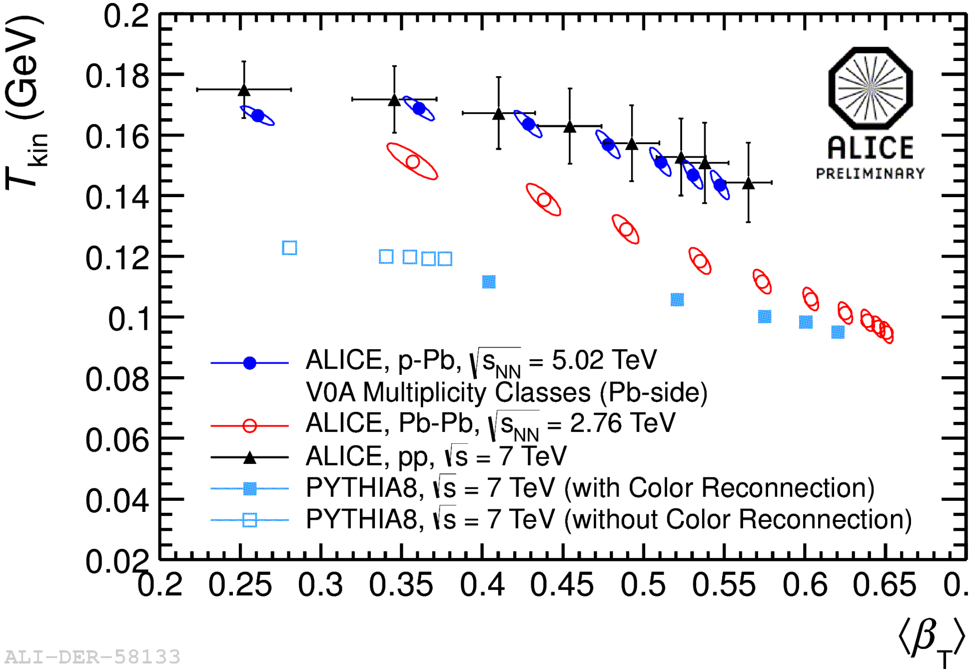
- Similar trend for p-Pb and Pb-Pb
- T_{fo} is similar in Pb-Pb and p-Pb for same multiplicities
- $<\beta_T>$ is larger in p-Pb for similar multiplicities

→ stronger collective flow for smaller system size?

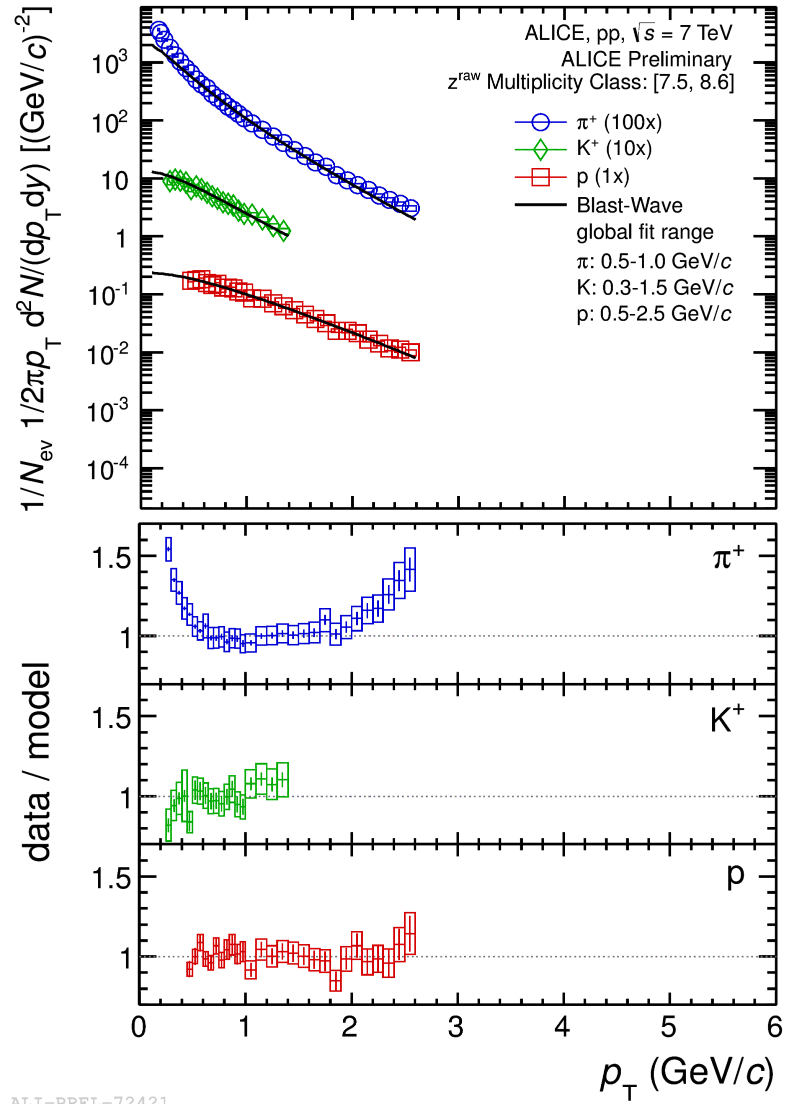
Shuryak, Phys.Rev. C 88, 044915

Blast-Wave Parameters – Adding pp

low mult → **high mult**



fit quality high multiplicity pp



π/K/p Blast-Wave analysis:

- pp data:
  - Shows similar behavior as p-Pb and Pb-Pb
  - Note: slightly different fit ranges for pp
- PYTHIA 8:
  - Blast-Wave fit results from PYTHIA (with Color Reconnection) show <u>similar trend, but this is not hydrodynamic flow</u>

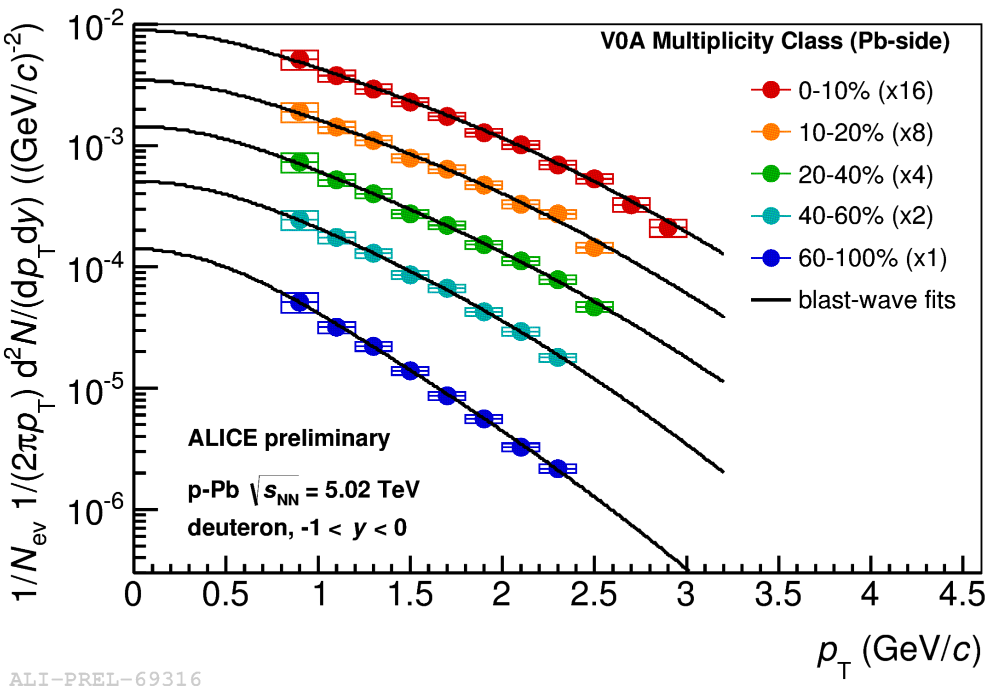
Caveat: potential bias by selecting multiplicity at mid-rapidity

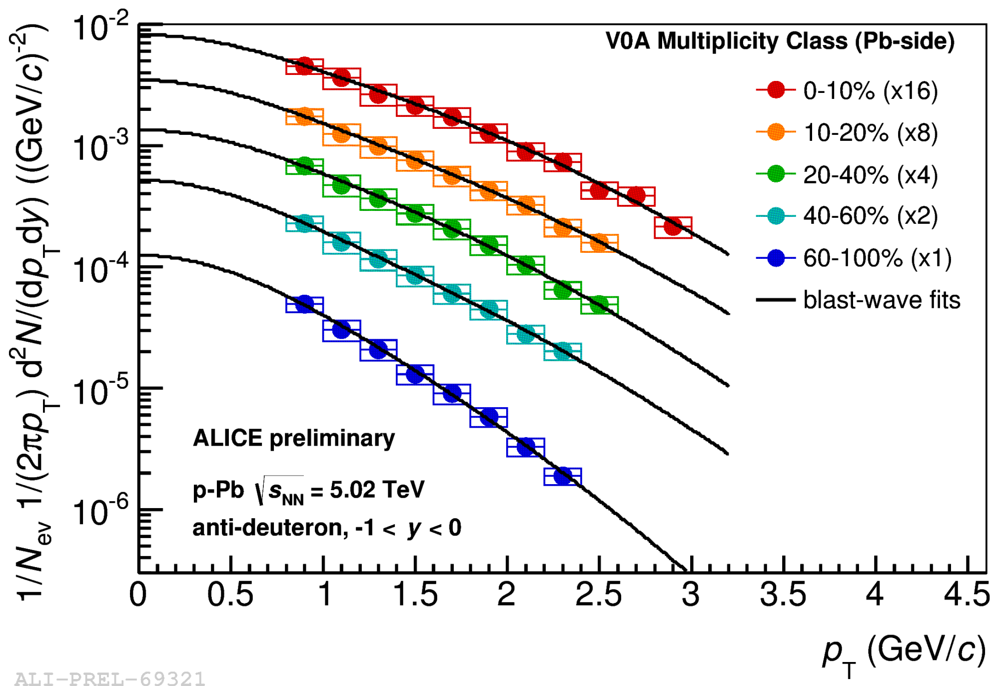
Deuteron Production

Deuteron Spectra

Deuteron spectra for several multiplicity classes:

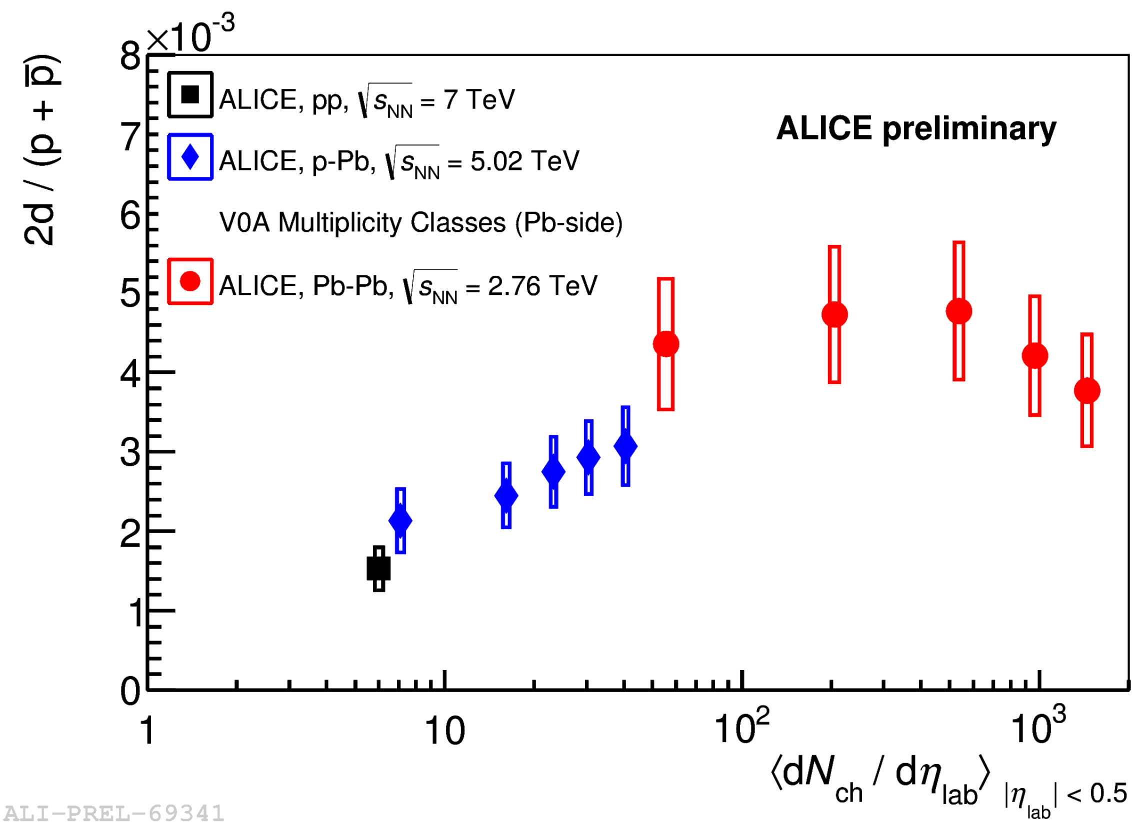
- Individual Blast-Wave fits to extrapolate to high and low p_T (21-32% of yield for high to low multiplicity)
- Hardening of spectra with multiplicity visible
- $\bar{d}$ and d are in agreement
  - because of big absorption uncertainty of $\bar{d}$, d are used for the following plots





d/p Ratio as a Function of Charged Multiplicity

- The d/p ratio rises with multiplicity in p-Pb collisions
- Consistent with pp at low multiplicities
- Consistent with Pb-Pb at high multiplicities



- The rise in **p-Pb** is consistent with an increased deuteron production for higher nucleon densities, predicted by the **coalescence model**
  - models, that use nucleon density (not multiplicity) are clearly favored

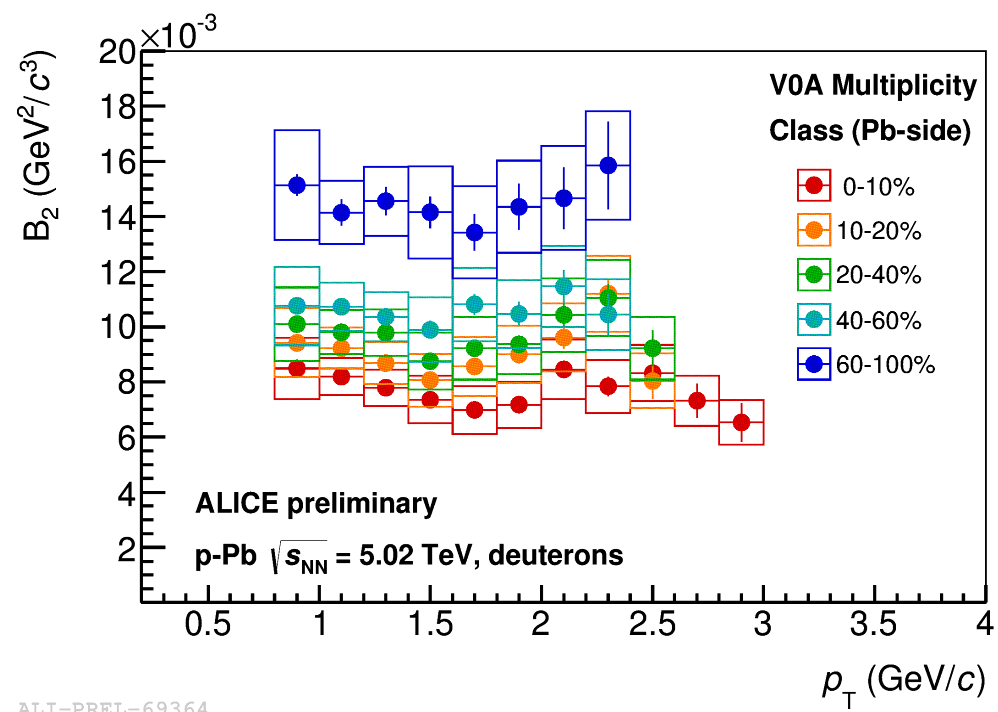
Coalescence Parameter B2

Coalescence model predictions

First order:

$$B_2 = \frac{E_d \frac{d^3 N_d}{dp_d^3}}{\left(E_p \frac{d^3 N_p}{dp_p^3}\right)^2}$$

- B_2 is flat over p_T
  - applies to p-Pb and peripheral Pb-Pb

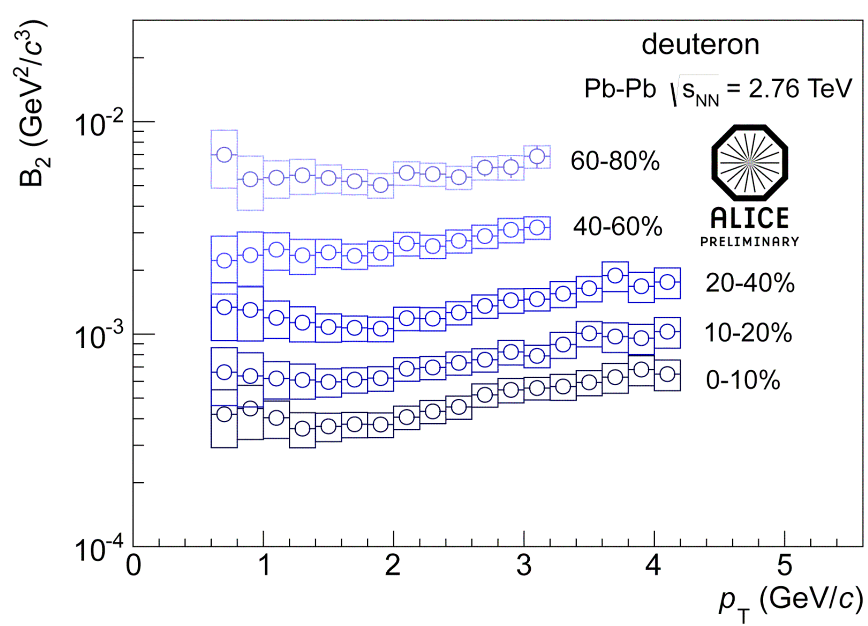


Second order:

$$B_2 = \frac{3\pi^{3/2} < C_d >}{2m_T R_\perp^2(m_T) R_\parallel(m_T)}$$

- B_2 scales like the HBT radii
  - decrease with multiplicity understood as an increase in source volume

Phys.Rev. C59, 1585 (1999)



Summary

Several observations that point to collectivity driven by mass of particles and multiplicity

- Hardening of spectra with mass and multiplicity
- Blast-Wave analysis
  - Note: similar trend for pp and PYTHIA 8 (with color reconnection)
- Particle Ratios
  - p/π and Λ/K^0_S enhancement at intermediate p_T (depletion at low p_T) in high multiplicity compared to low multiplicity p-Pb events
  - Ratios scale with multiplicity for pp, p-Pb and Pb-Pb
- Model comparison
  - Models that incorporate hydro seem to be more successful in describing the spectra, but color reconnection can mimic flow like patterns

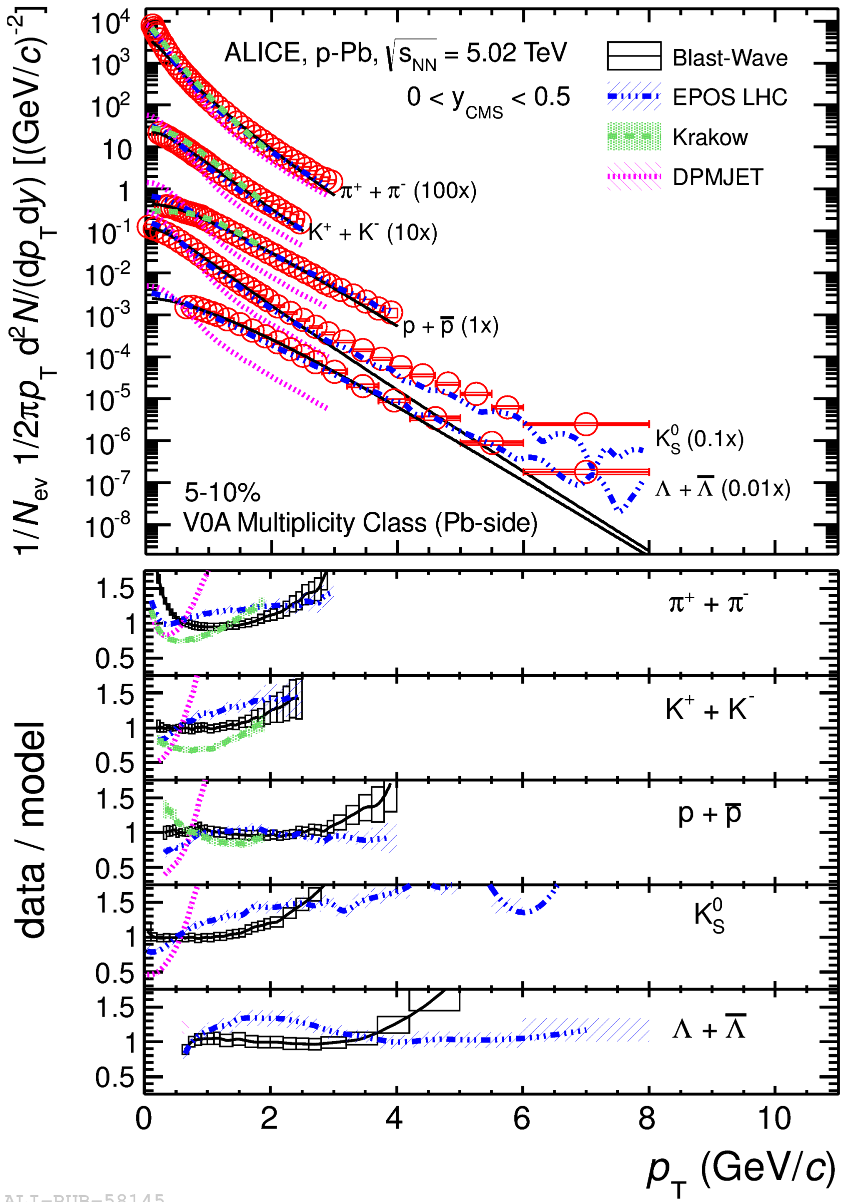
Deuteron production in p-Pb: coalescence models with nucleon densities are favored

THANK YOU

for the attention!

BACKUP

Comparison With Models π, K, p, Λ



EPOS LHC: Pierog et al., arXiv:1306.0121 [hep-ph]
- Initial hard and soft scattering create "flux tubes", which either escape the medium and hadronize as jets, or contribute to the bulk matter, described in terms of hydrodynamics
- Can reproduce the pion and proton spectra within 20%
- Stronger deviations for kaons and lambdas

Kraków: Bozek, PRC85, 014911 (2012)
- Hydrodynamical model
- Reproduces spectra reasonably well for protons
- Pion and kaon shape deviates for p_T >1 GeV/*c*
- Possible onset of non-hydro effect above 1 GeV/*c*

DPMJET: Roesler et al., arXiV:hep-ph/0012252
- QCD- inspired – based on the Gribov-Glauber approach and treats soft and hard scattering processes in an unified way
- Can reproduce $dN_{ch}/d\eta$
- Fails to describe p_T distributions of identified particles

Blast-Wave Model

ALICE

Hydrodynamic-inspired model, that assumes

- hard sphere uniform density particle source with temperature T
- collective transverse radial flow velocity β

Schnedermann, PRC 48, 2462 (1993)

Transverse velocity distribution $\beta_r(r)$ for $0 < r < R$ parametrized with

- surface velocity β_s
- velocity profile n

$$\beta_r(r) = \beta_s \left(\frac{r}{R}\right)^n$$

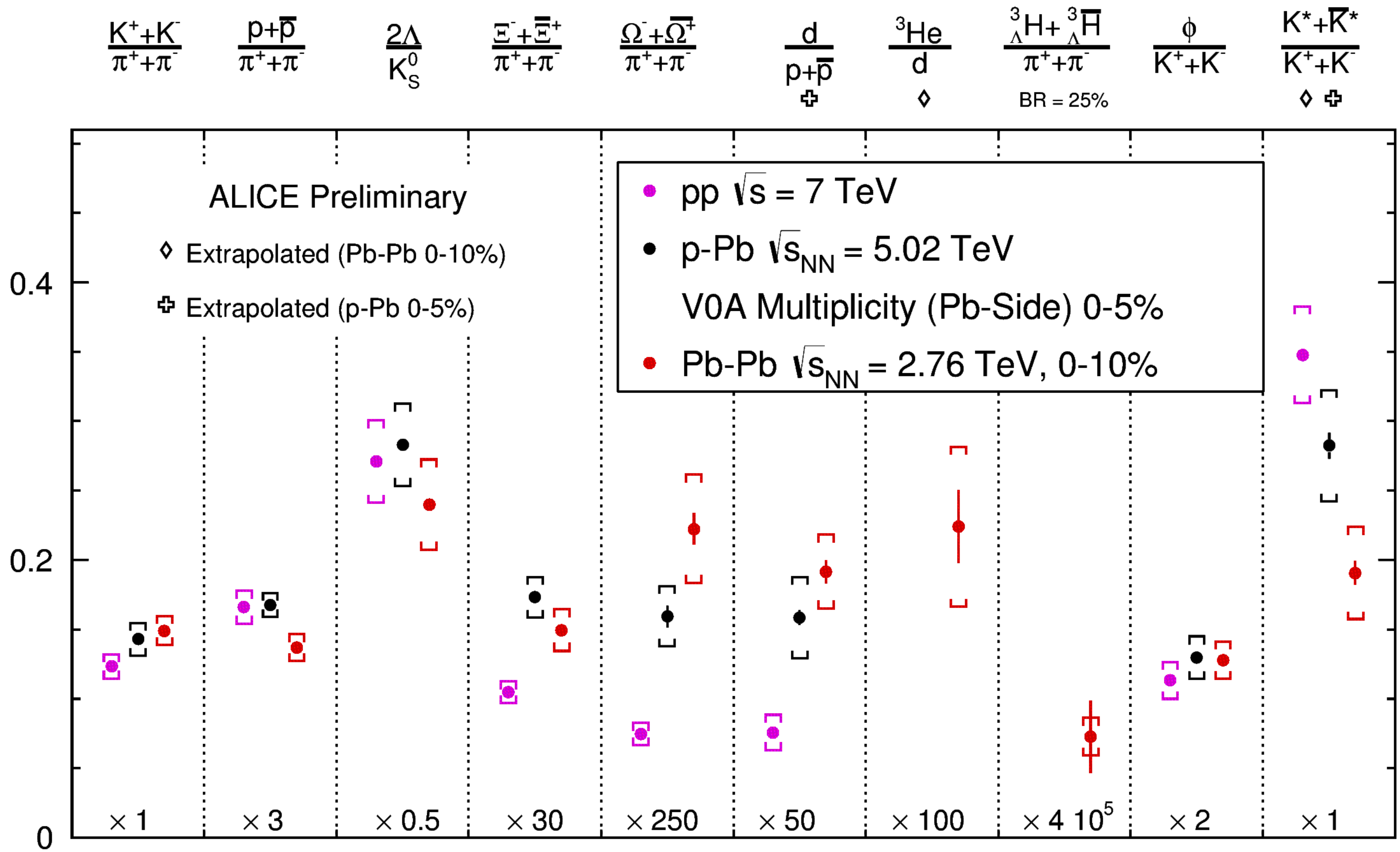
Resulting spectrum is superposition of the individual thermal components, each boosted with the boost angle ρ

$$\rho = \tanh^{-1} \beta_r$$

$$\frac{dn}{m_T dm_T} \propto \int_0^R r\ dr\ m_T I_0 \left(\frac{p_T \sinh \rho}{T}\right) K_1 \left(\frac{m_T \cosh \rho}{T}\right)$$

I_0 and K_1 modified Bessel functions

Particle Production – The Big Picture



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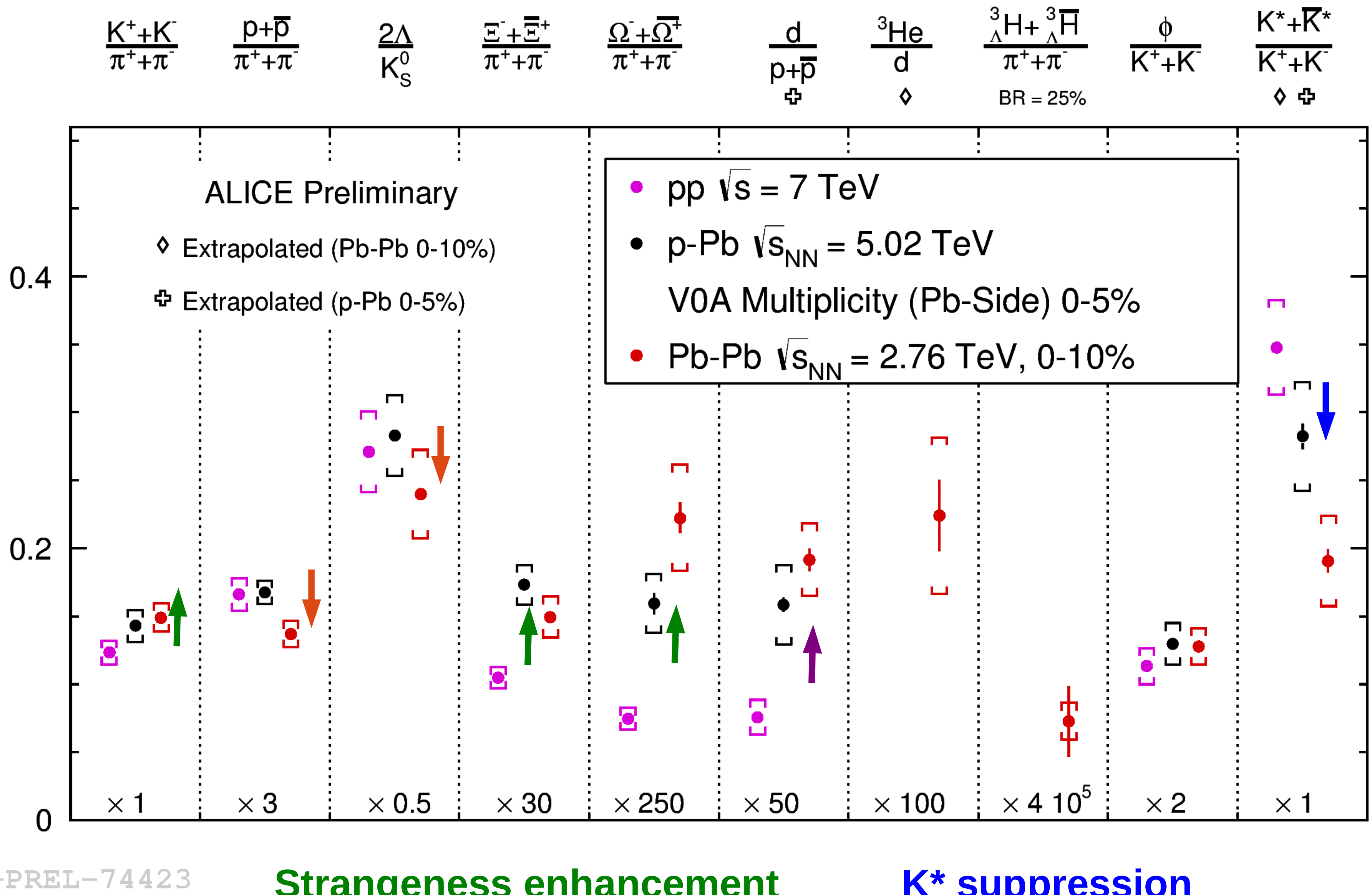
Particle Production – The Big Picture



Strangeness enhancement

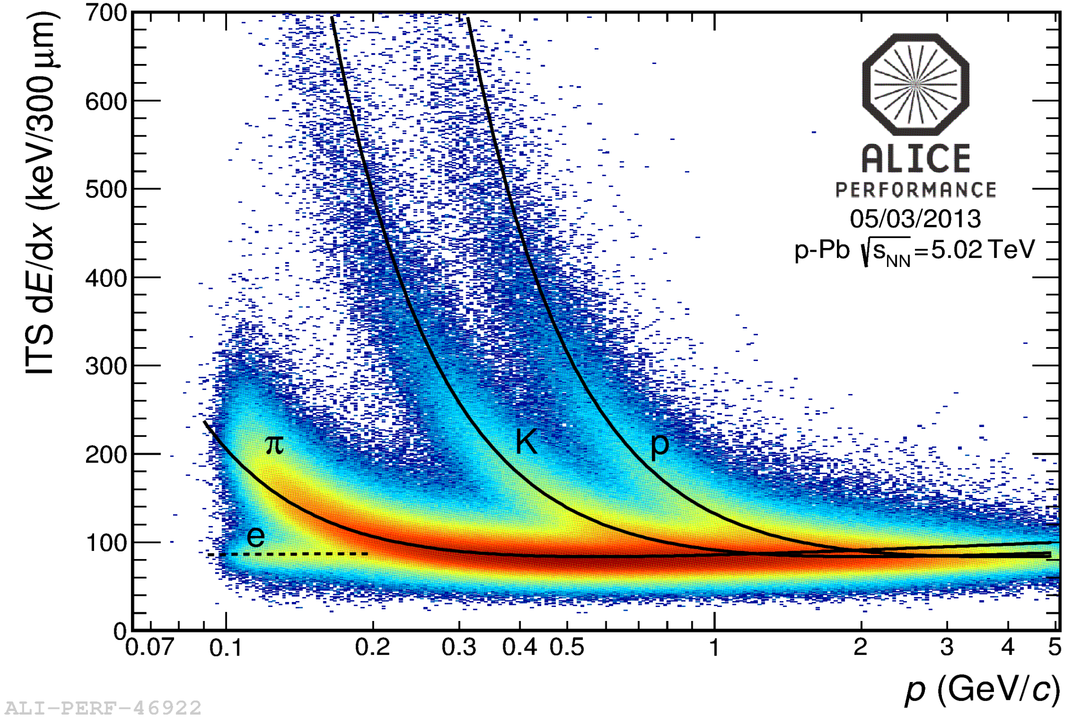
K* suppression

Deuteron enhancement

Baryon suppression?

ITS Standalone Method

Inner Tracking System

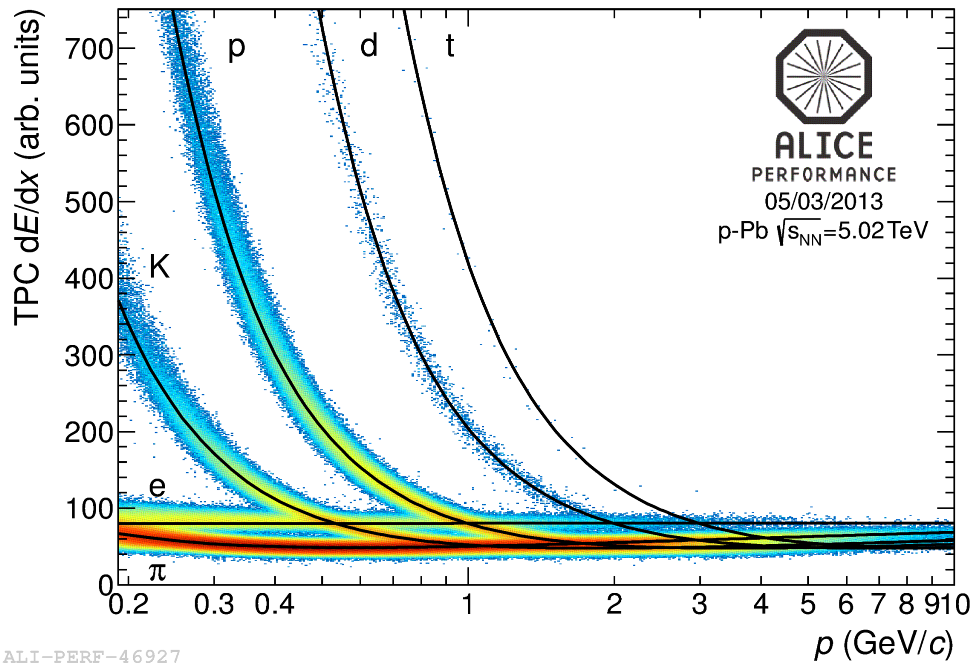


- Four of the six ITS layers give d*E*/d*x* signal (energy loss in silicon)
- Independent ITS tracking
  - low p_T reach: 100 MeV/*c*

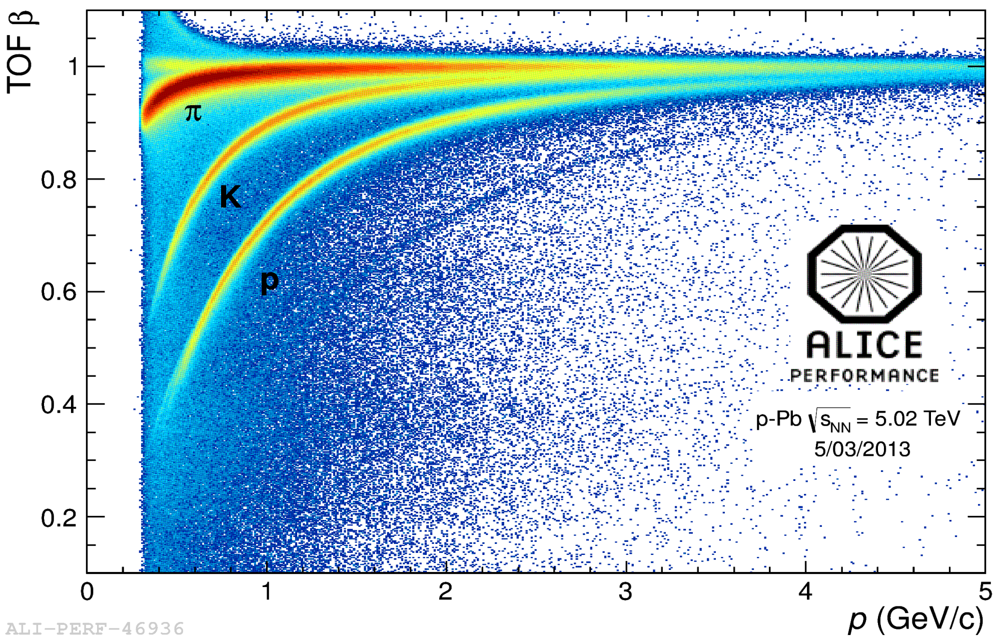
Particle	p_T range (GeV/*c*)
$\pi^{\pm}$	0.1 – 0.7
$K^{\pm}$	0.2 – 0.6
p ($\bar{p}$)	0.3 – 0.65

TPC/TOF Method

Time Projection Chamber



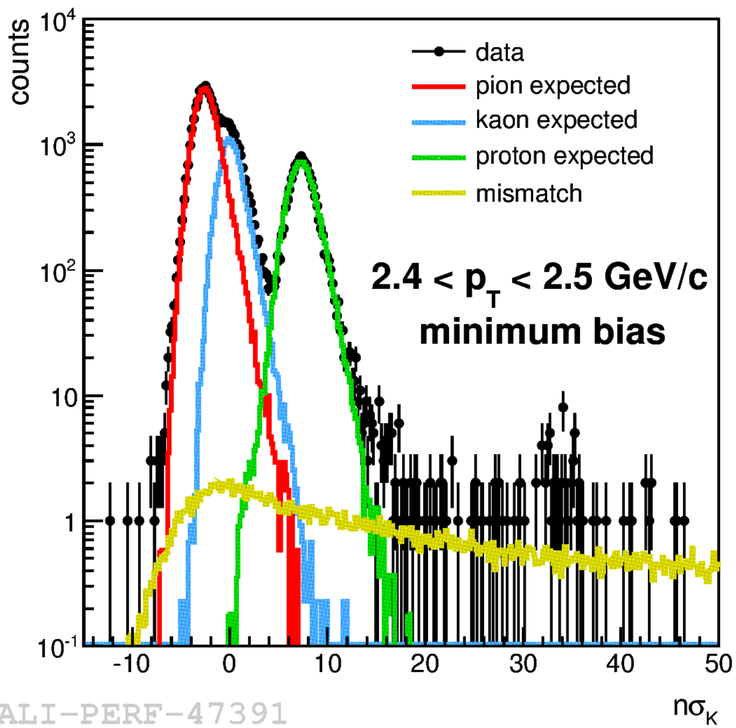
Time Of Flight

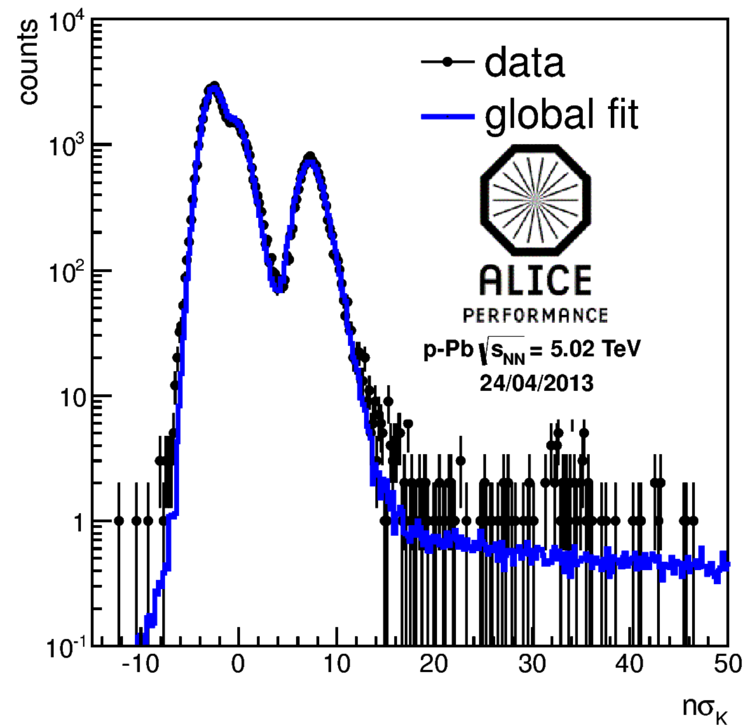


Particle	p_T range (GeV/c)
$\pi^{\pm}$	0.2 – 1.5
$K^{\pm}$	0.3 – 1.3
p ($\bar{p}$)	0.5 – 2.0

- PID with dE/dx in gas and time-of-flight
- Global ALICE tracking
- ± 3σ cut on expected energy loss in TPC signal
- Additional ± 3σ cut on expected TOF for p_T > 0.6 (0.55, 1.0) GeV/c

TOF Fits Method





Particle	p_T range (GeV/c)
$\pi^{\pm}$	0.5 – 3.0
$K^{\pm}$	0.5 – 2.5
p ($\bar{p}$)	0.5 – 4.0

- PID with time-of-flight
- Global ALICE tracking
- Fit to the TOF time distribution with expected shapes
- Based on knowledge of TOF response function

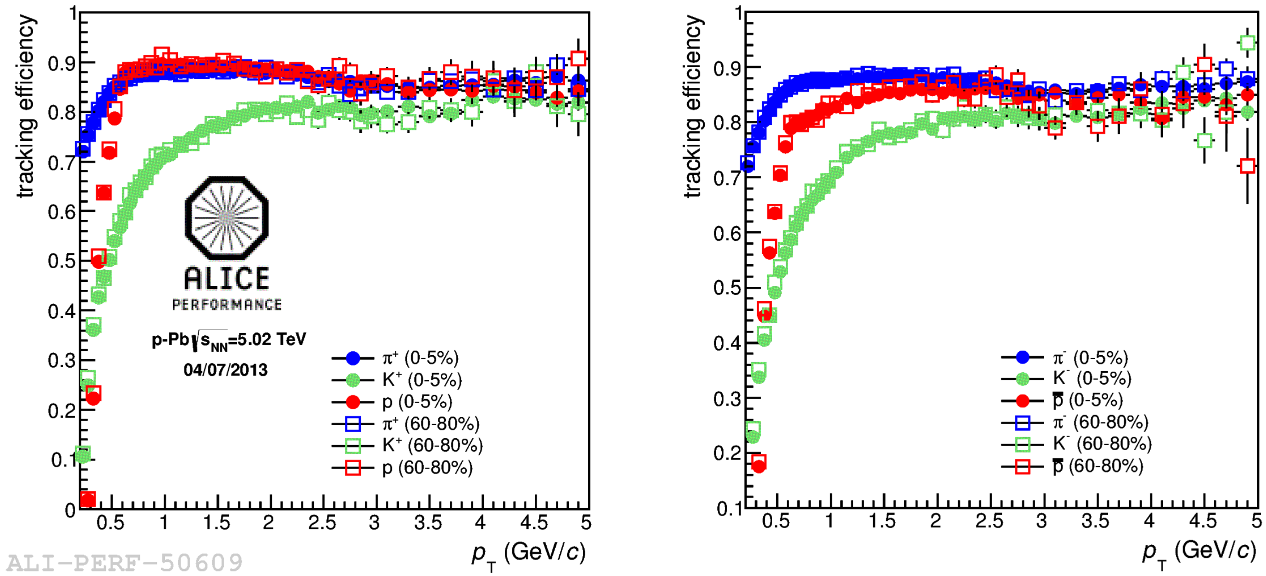
Efficiency and Correction for Secondaries

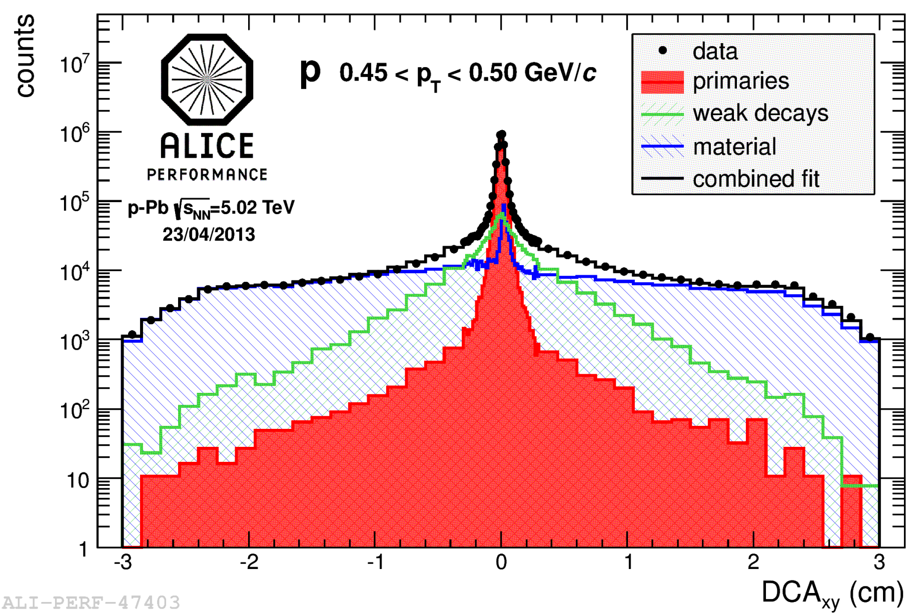
A Large Ion Collider Experiment

ALICE

Tracking efficiency:

- All particles reach 80-90%
- No multiplicity dependence observed
- Difference for p and $\bar{p}$ visible due to absorption

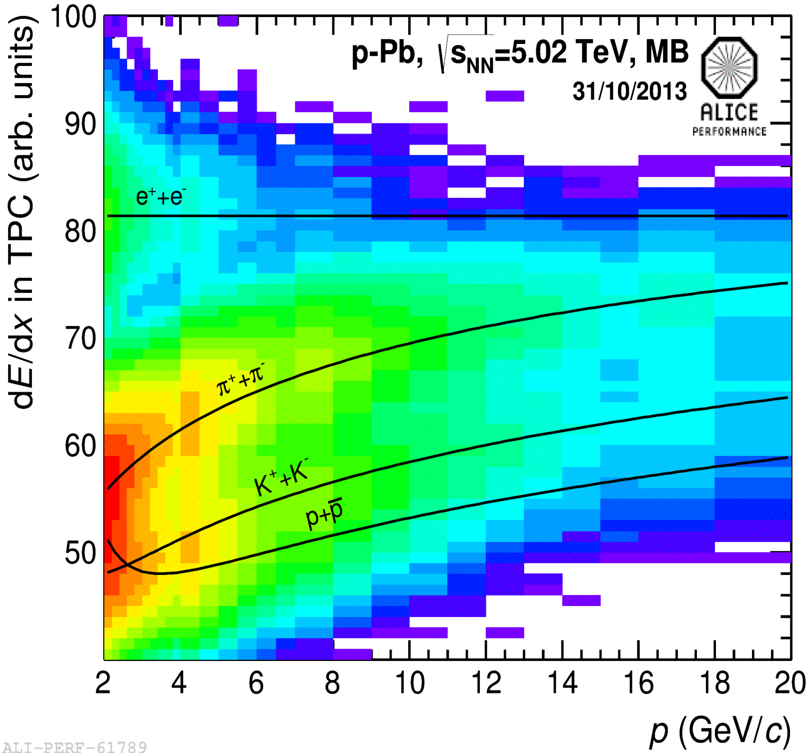


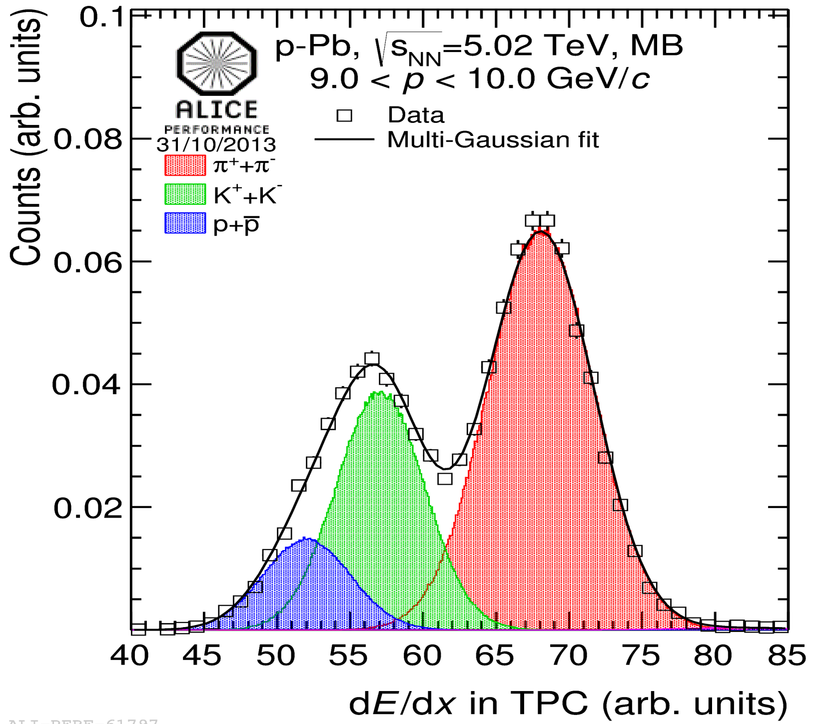


Correction for secondaries:

- Contribution is underestimated in MC
- Data-driven approach – fit distribution of “Distance of Closest Approach” to vertex with Monte Carlo templates for secondary and primary particles
  - Weak decays, protons from material and primaries are distinguishable → can be separated

Relativistic Rise TPC





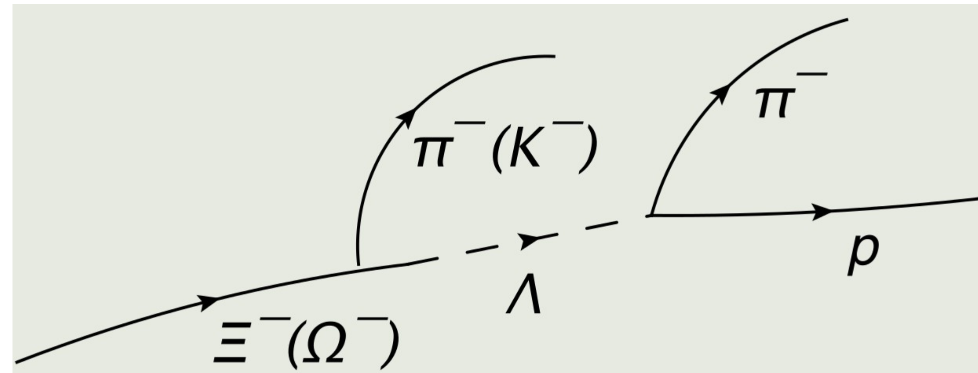
Particle	p_T range (GeV/c)
$\pi^{\pm}$	2.0 – 15
$K^{\pm}$	2.6 – 15
p ($\bar{p}$)	2.6 – 15

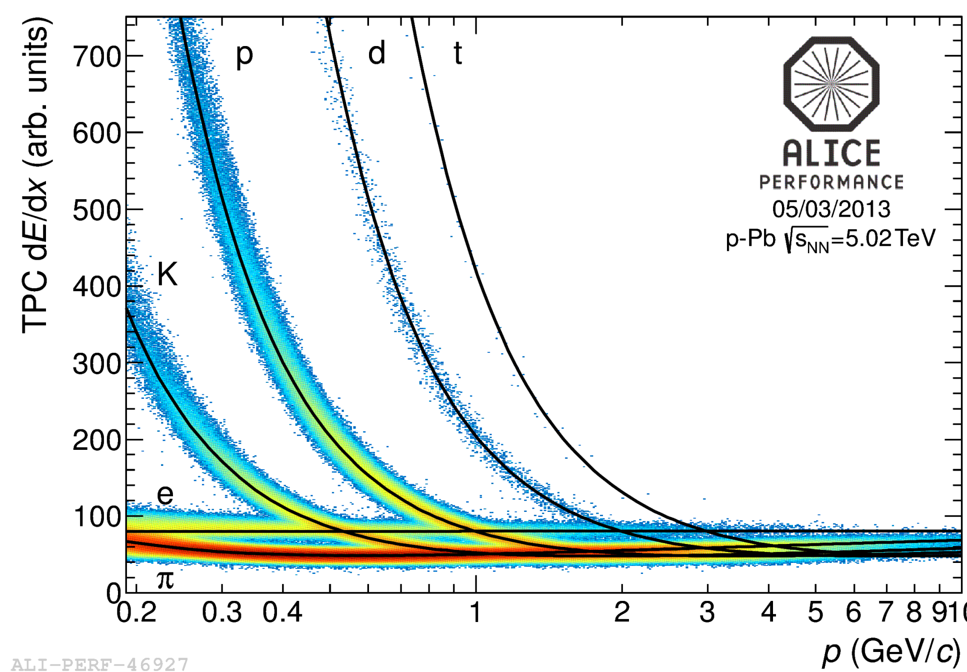
- PID with d*E*/dx in gas (TPC)
- Global ALICE tracking
- Fit to the TPC d*E*/dx distribution with multiple Gaussians to get fractions
- Requires careful tuning and knowledge of Bethe-Bloch parametrization in relativistic rise region

Strange Particle Identification

Topological reconstruction:

- PID over large p_T range
- TPC dE/dx PID for daughters
- In case of multi-strange: association of Λ with bachelor track → cascade



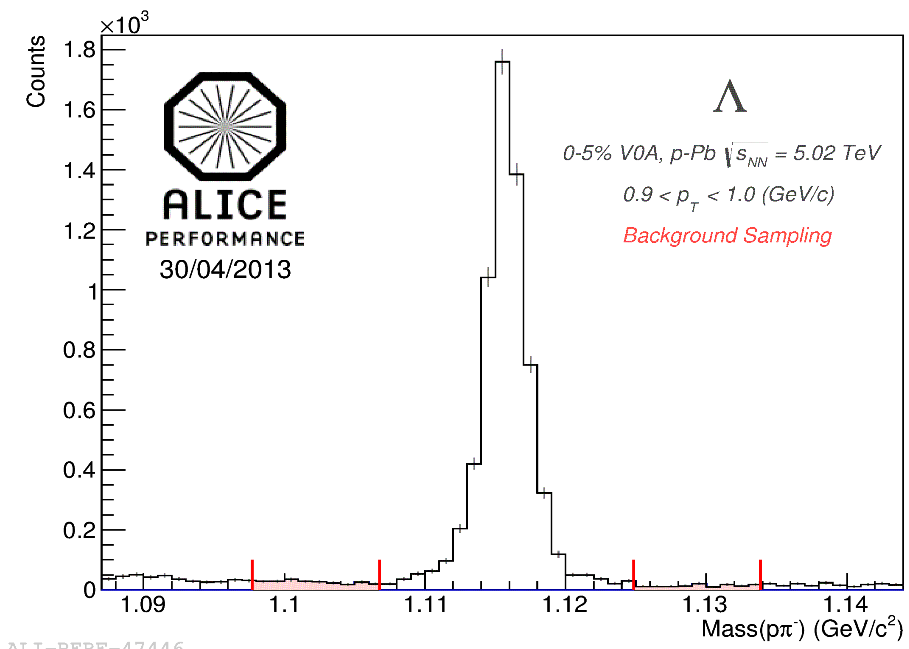


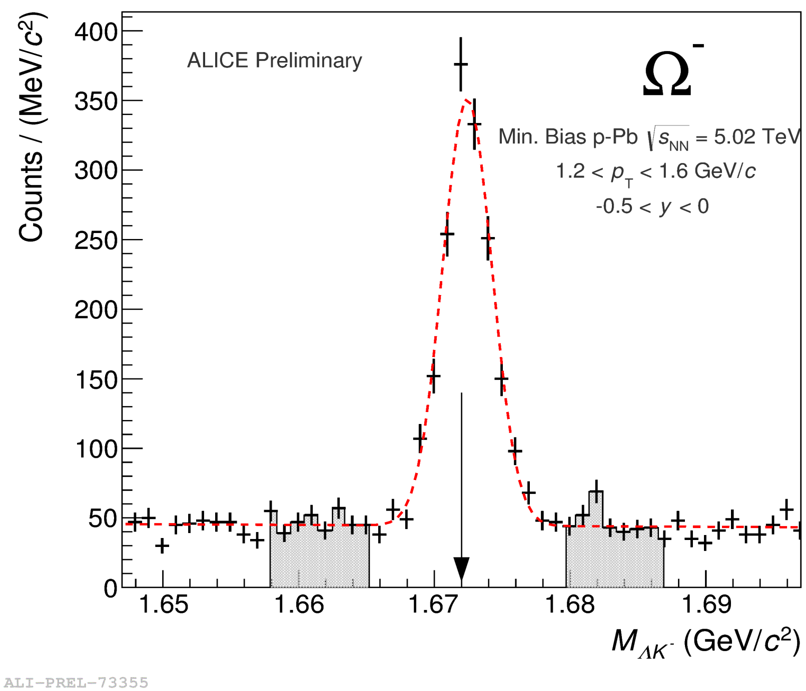
K^0_s	→	$\pi^+ \pi^-$	(B.R. 69%)
Λ	→	$p\, \pi^-$	(B.R. 64%)
Ξ^-	→	$\Lambda\, \pi^- \rightarrow p\, \pi^- \pi^-$	(B.R. 64%)
Ω^-	→	$\Lambda\, K^- \rightarrow p\, \pi^- K^-$	(B.R. 43%)

analogue for anti-particles

Strange Particle Identification

- Once we have the daughter tracks:
  - Invariant mass peaks integrated for each p_T bin
- Background is sampled in shaded areas (assumed linear)
- Λ are feed-down corrected

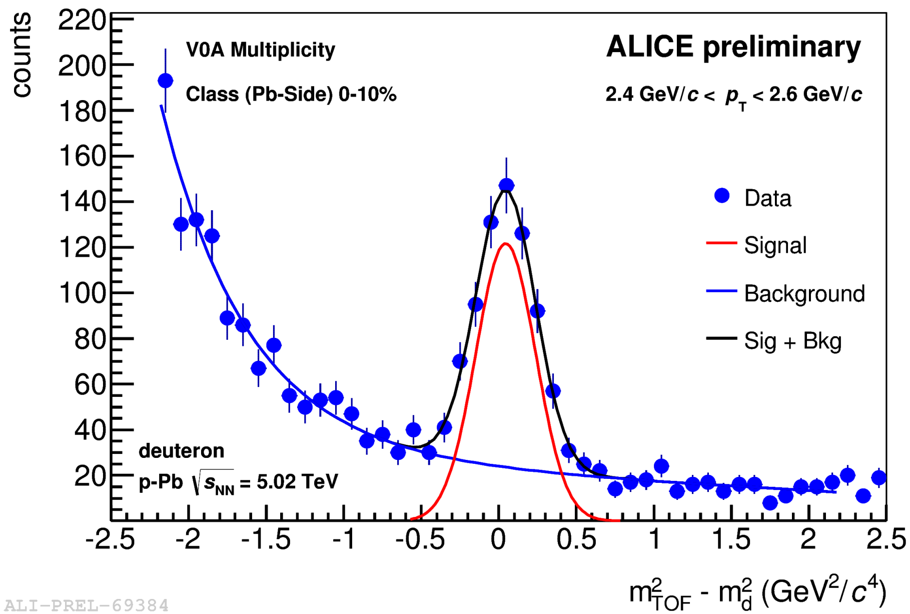




Deuteron Reconstruction

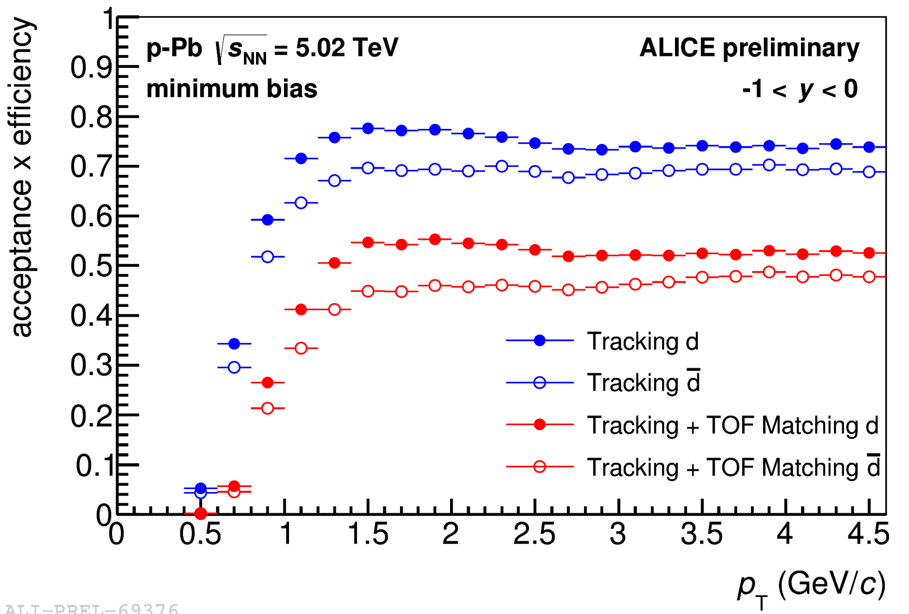
Deuteron identification:

- PID with dE/dx from TPC and time-of-flight with TOF
- TPC 3σ cut around expected signal
- Above 1 GeV/c fit to the squared mass measured with TOF

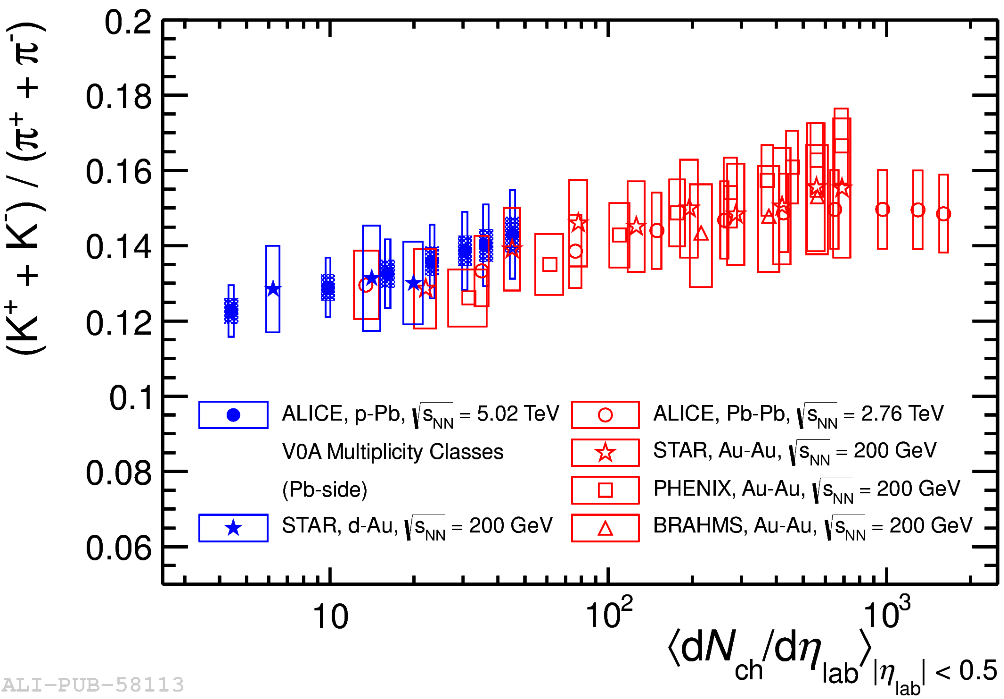


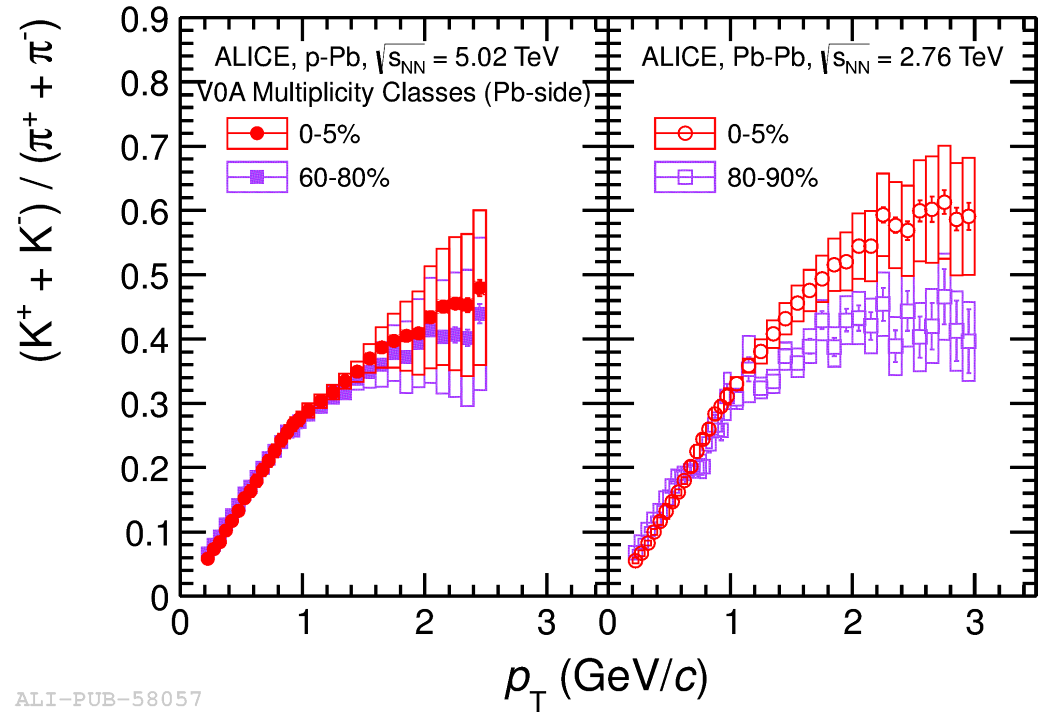
(Anti-)deuteron efficiencies:

- The $\bar{d}$ tracking efficiency is significantly lower than the d efficiency
- This is due to absorption
- Very little data for hadronic cross-section of $\bar{d}$
- Introduces large error on the absorption

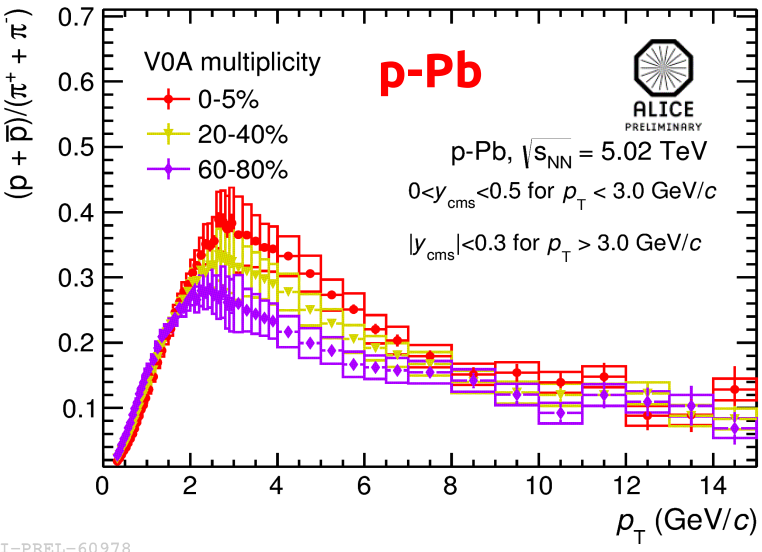


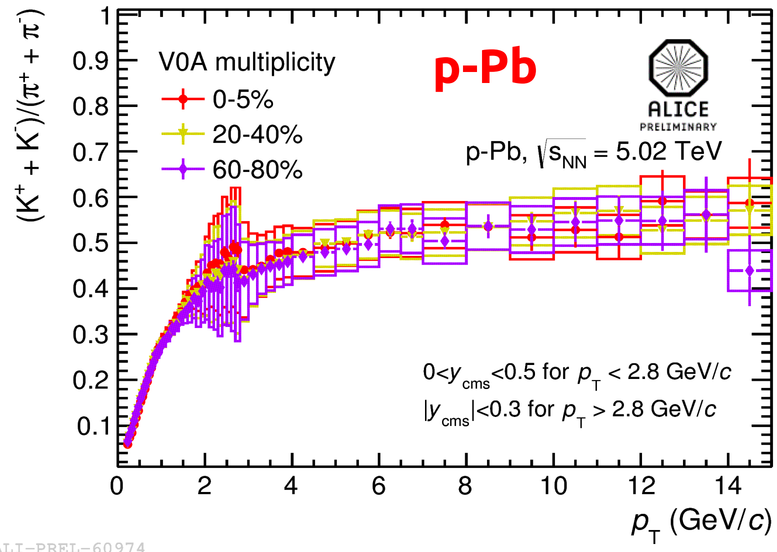
Particle Ratios Backup

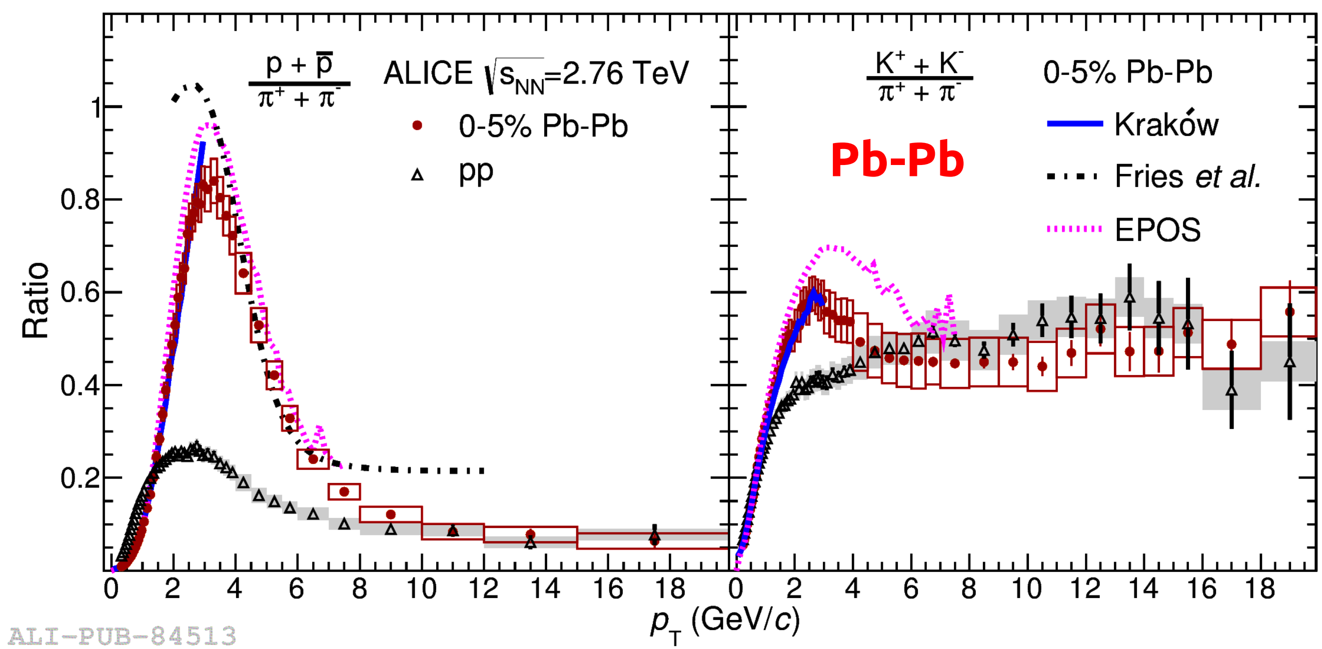




Particle Ratios at Higher p_T







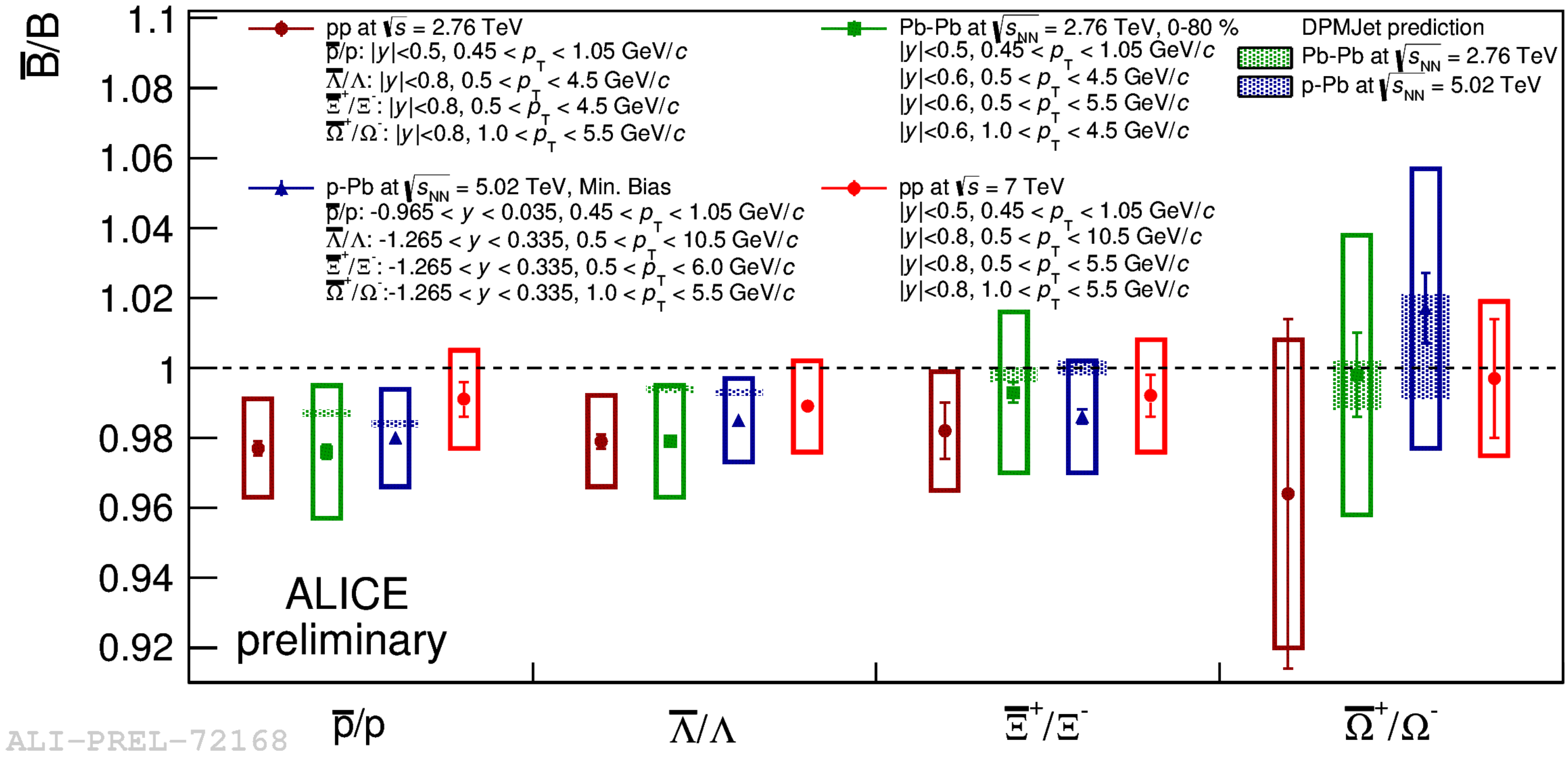
- p/π shows a peak, which is more pronounced for higher multiplicities
- Drops to 0.1 in both systems

- K/π saturates to 0.5 for high p_T in both systems
- No strong multiplicity dependence in p-Pb

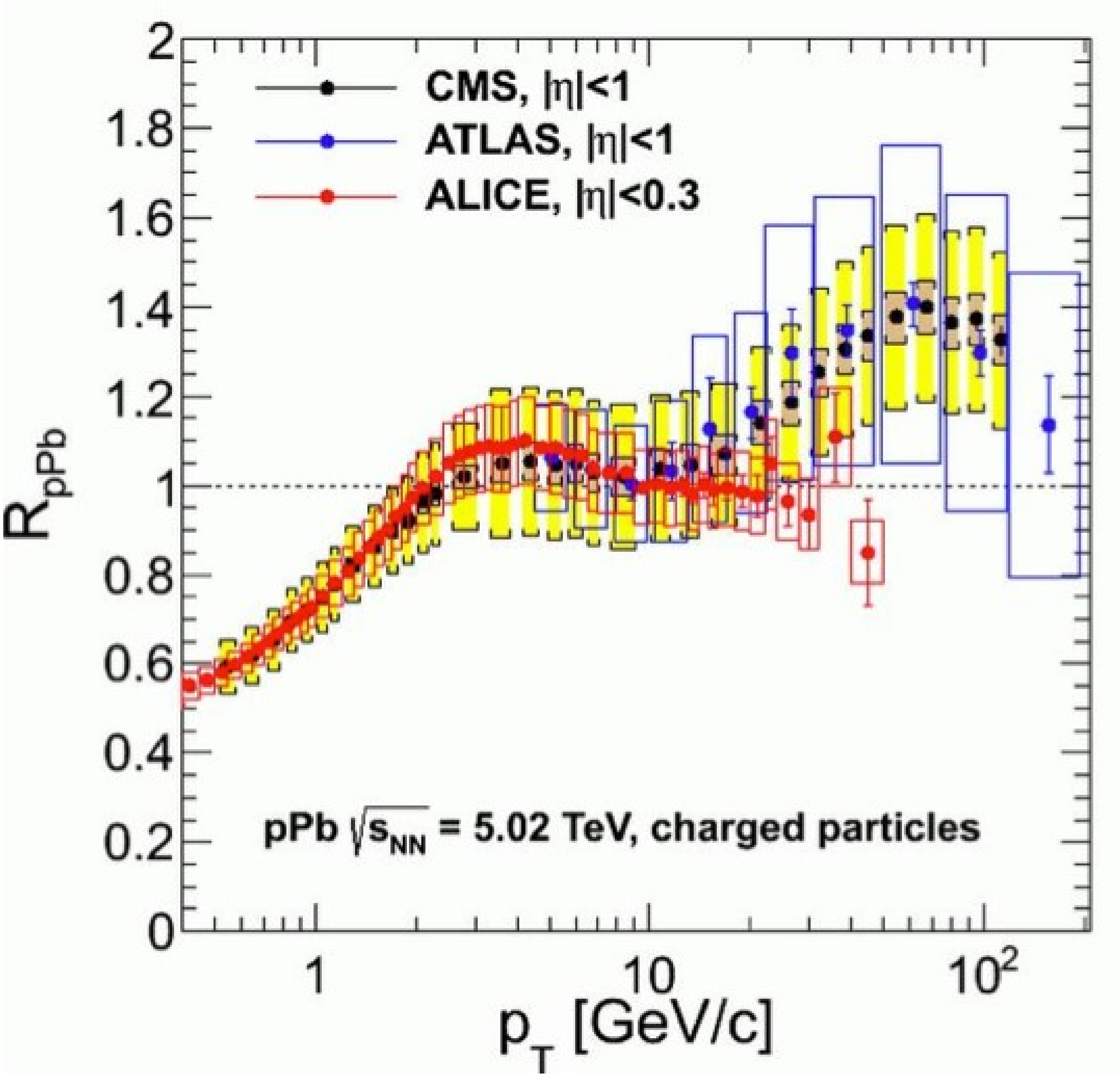
Anti-particle/Particle Ratios

A Large Ion Collider Experiment

ALICE



R_{pPb} CMS and ALTAS



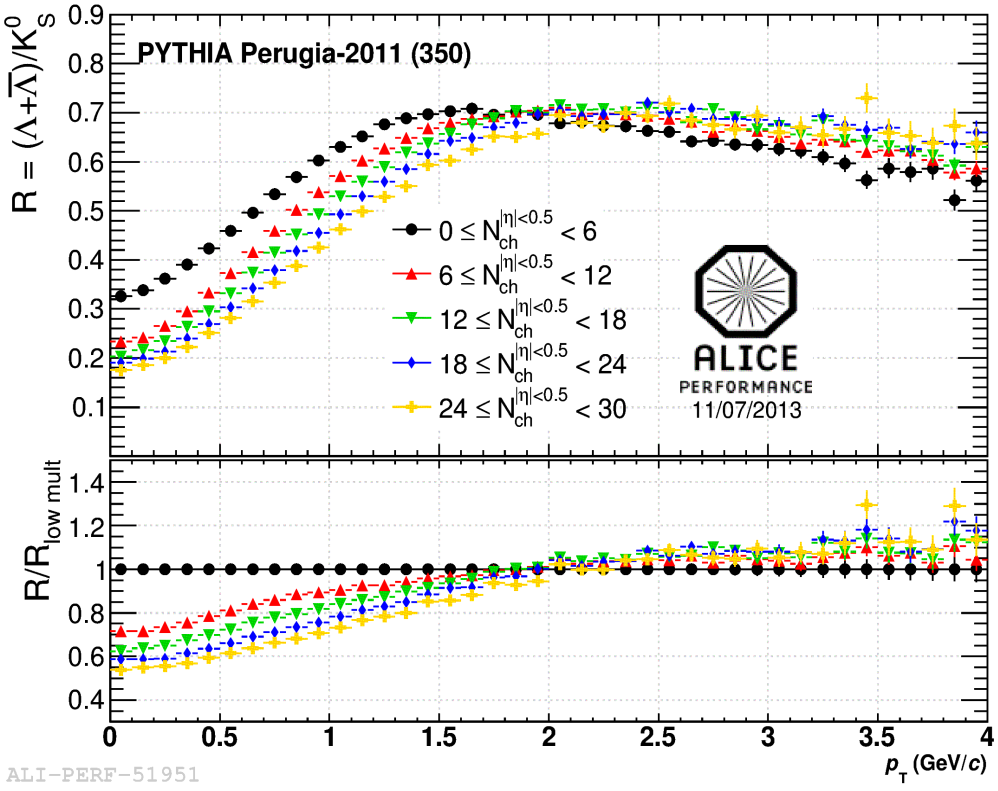
Different impression for CMS/ATLAS and ALICE

Charged jets are compatible with unity for all three experiments
→ jet fragmentation needs to be tested

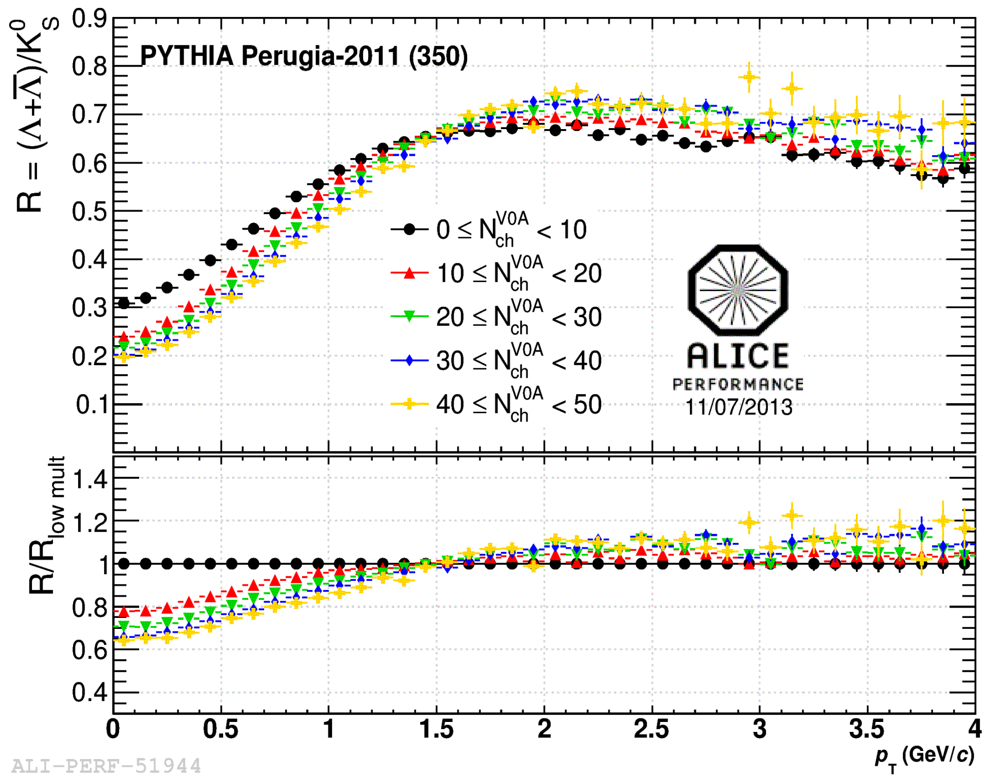
Selection Bias in pp

PYTHIA study: selecting multiplicity in different pseudorapidity ranges

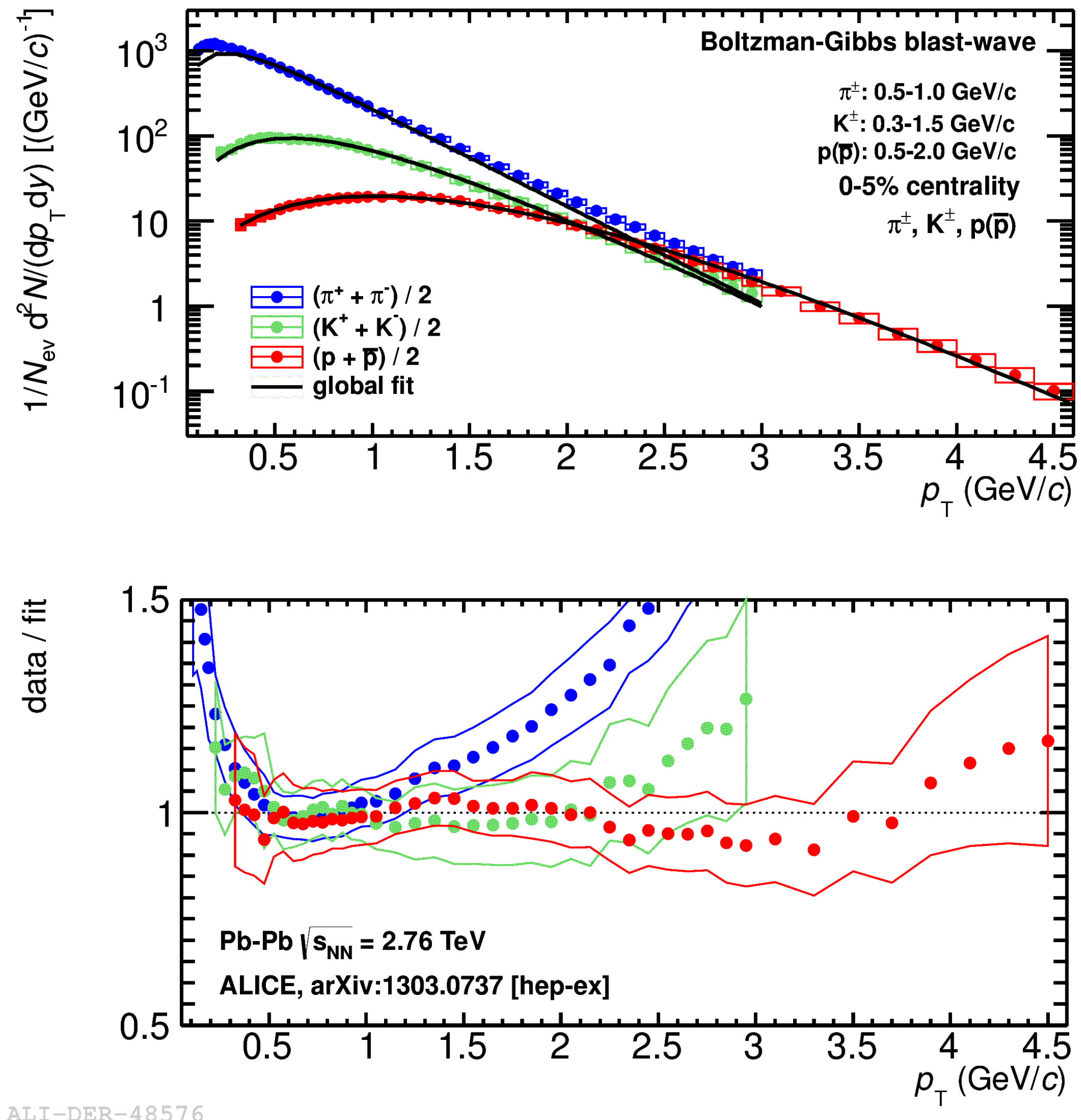
selection in |η|<0.5

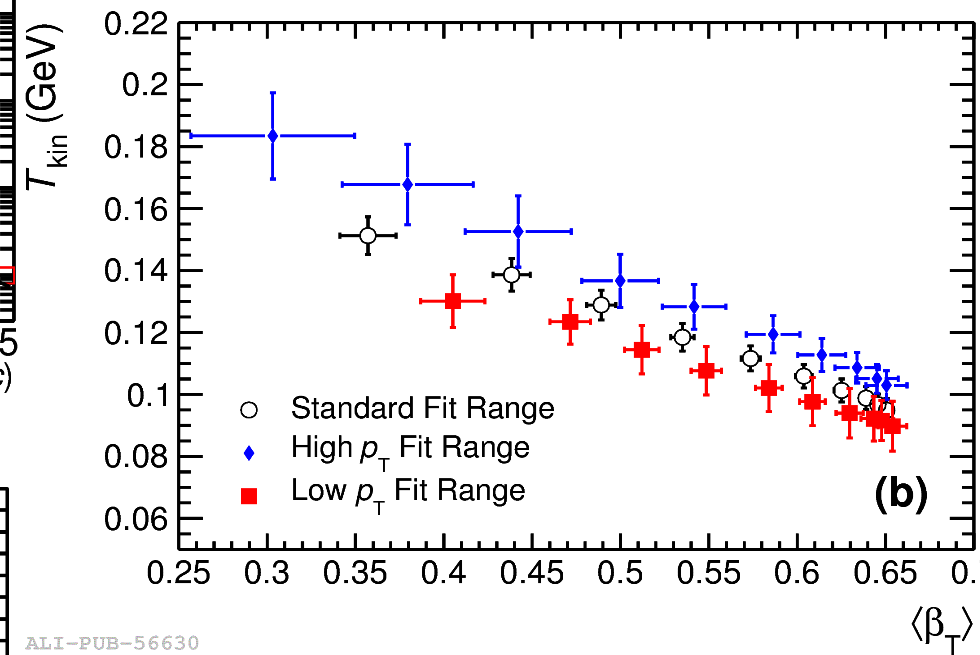


selection in 2.8 < η < 5.1 (V0A)



Blast-Wave Fit to Pb-Pb





range	Pi	K	p
stand	0.5 – 1.0	0.2 – 1.5	0.3 – 3.0
low	0.5 – 0.8	0.2 – 1.0	0.3 – 1.5
high	0.7 – 1.3	0.5 – 1.5	1.0 – 3.0

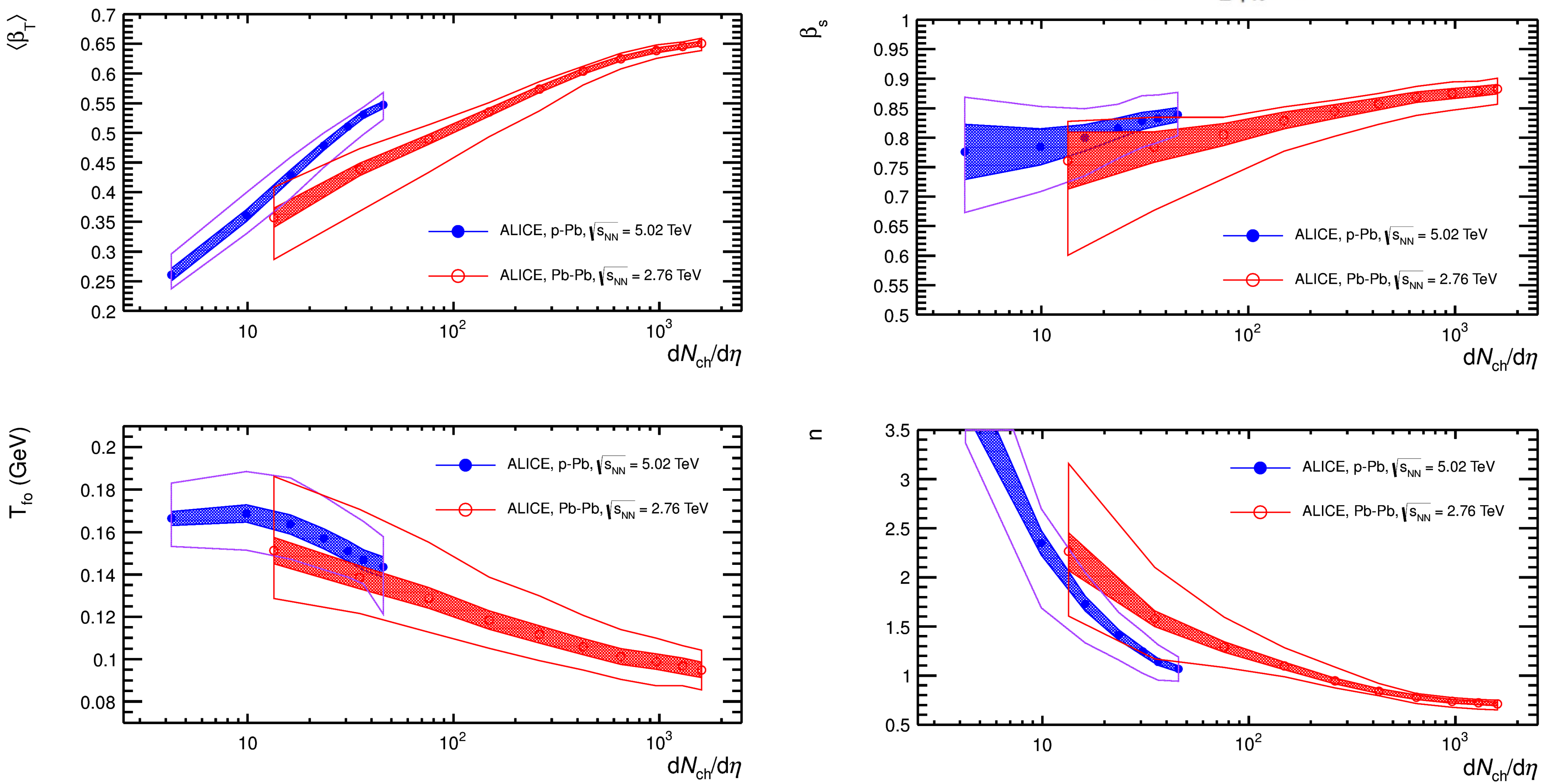
Blast-Wave Fit Parameters p-Pb and Pb-Pb

$$\frac{dN}{p_\perp dp_\perp} \propto \int_0^R r\,dr\,m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{\rm kin}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{\rm kin}}\right)$$

$$\rho = \tanh^{-1}\beta$$

$$\beta = \beta_S (r/R)^n$$

$$\langle\beta\rangle = \frac{2}{2+n}\beta_S$$



Φ/π in Pb-Pb

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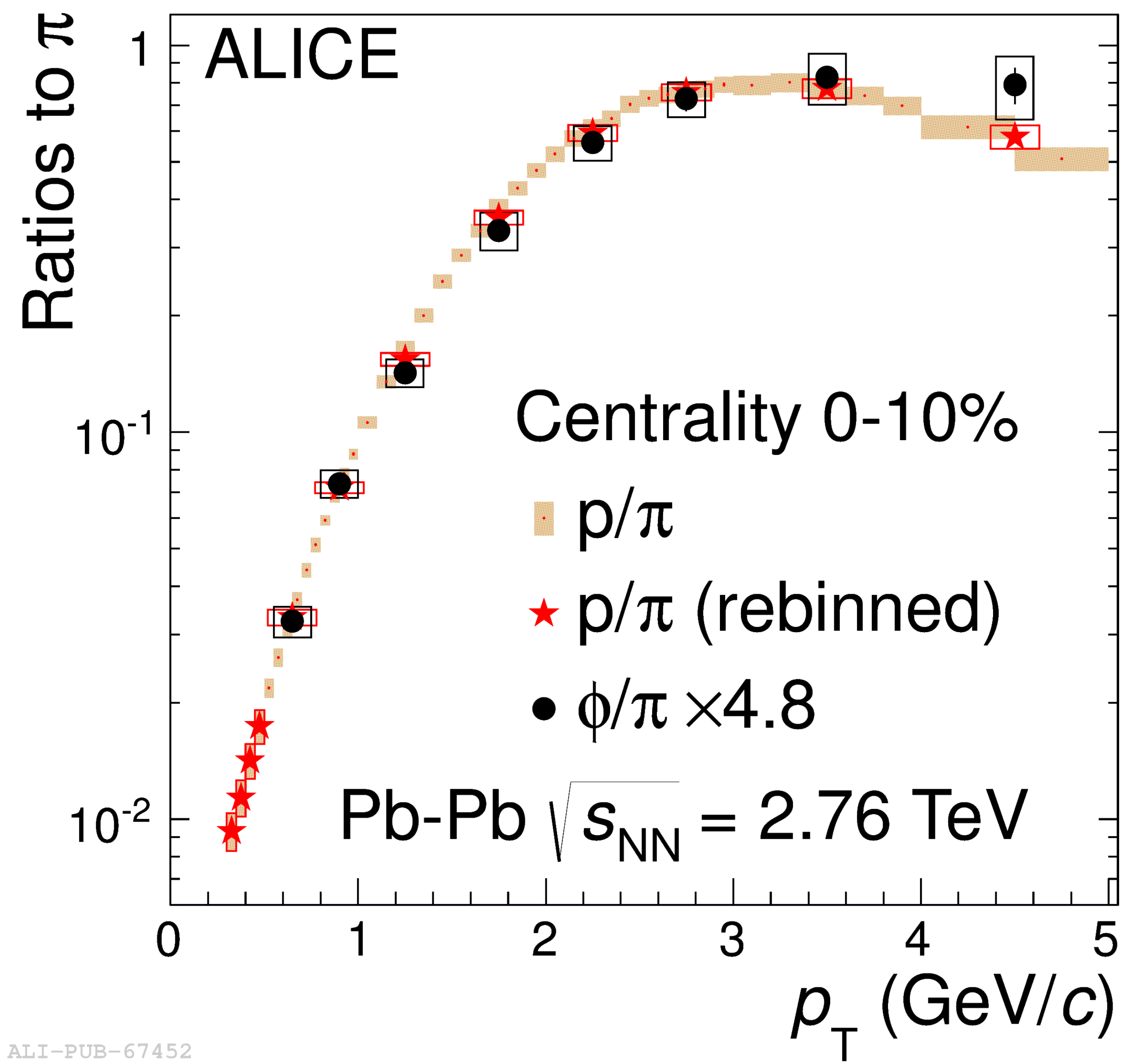


The shape of the Φ/π ratio is similar to the p/π ratio

→ shape seems to be driven by mass not number of quarks

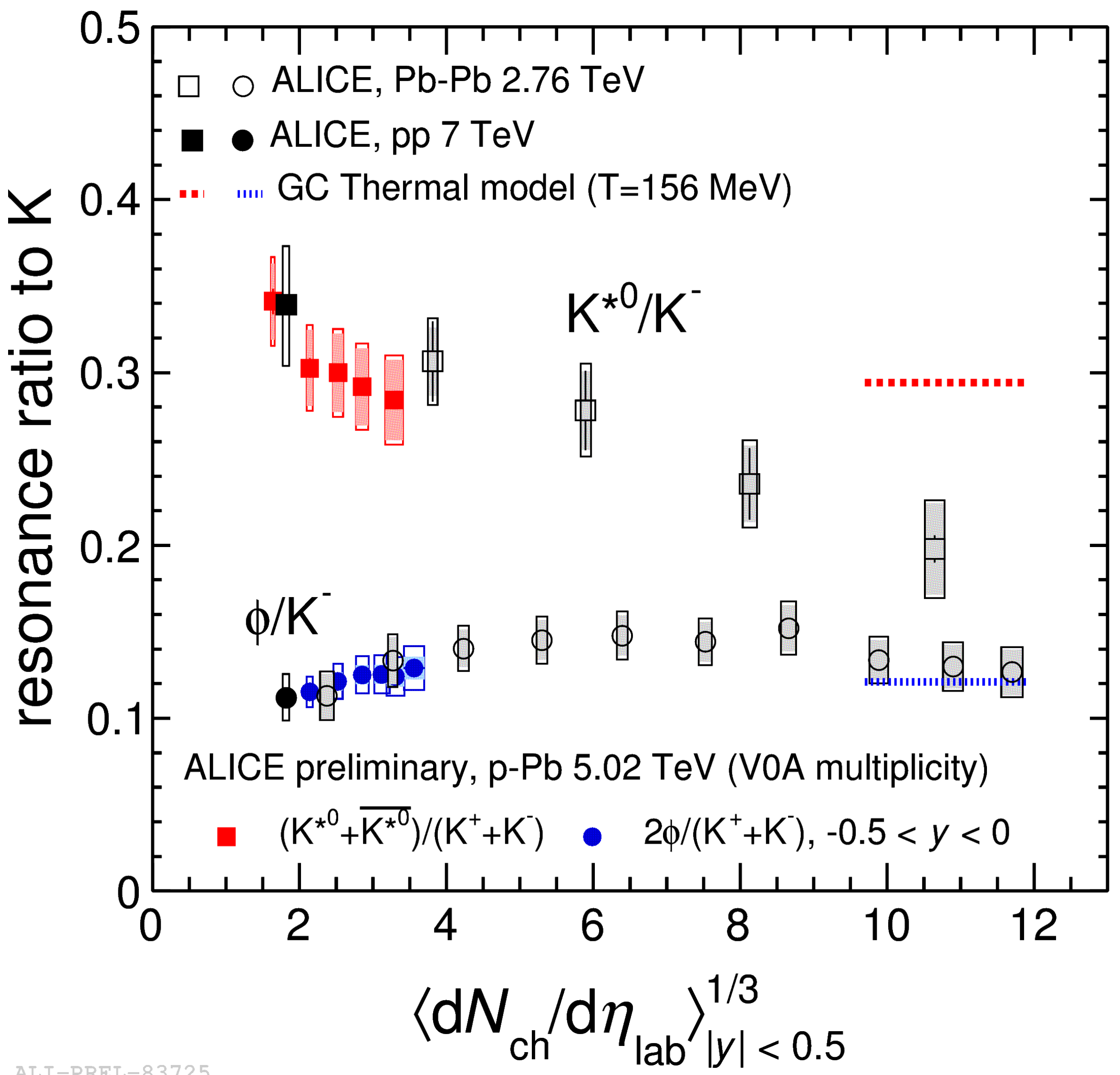
nucl-ex:1404.0495

System Size Dependence of K*⁰ and Φ

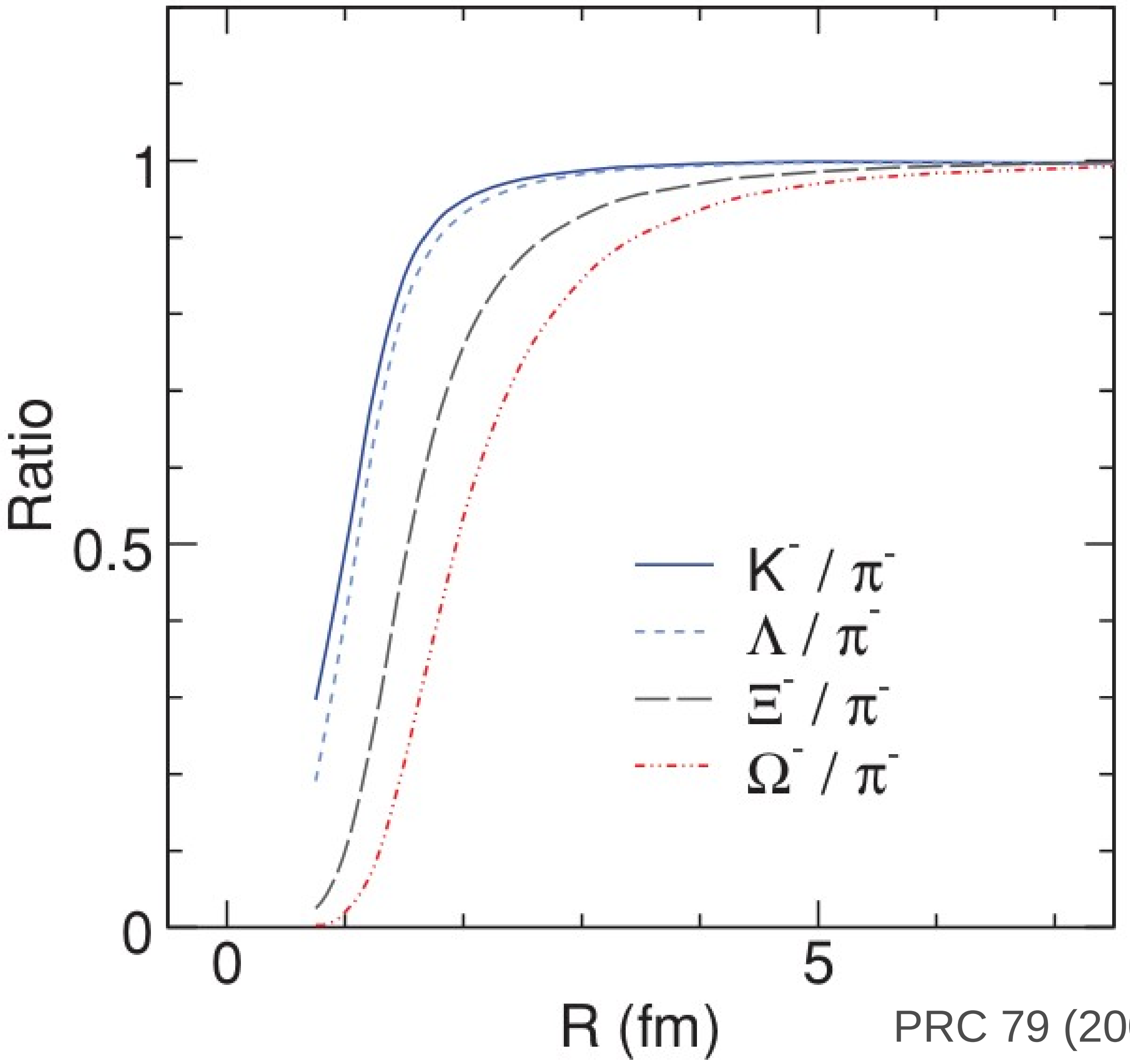
A Large Ion Collider Experiment

- Φ/K is flat for all systems and consistent with thermal model prediction

- K^{*0}/K suppressed for higher multiplicities / system size
  - consistent with hypothesis of dominating re-scattering
- Collisions systems are in agreement



Reduced Canonical Suppression



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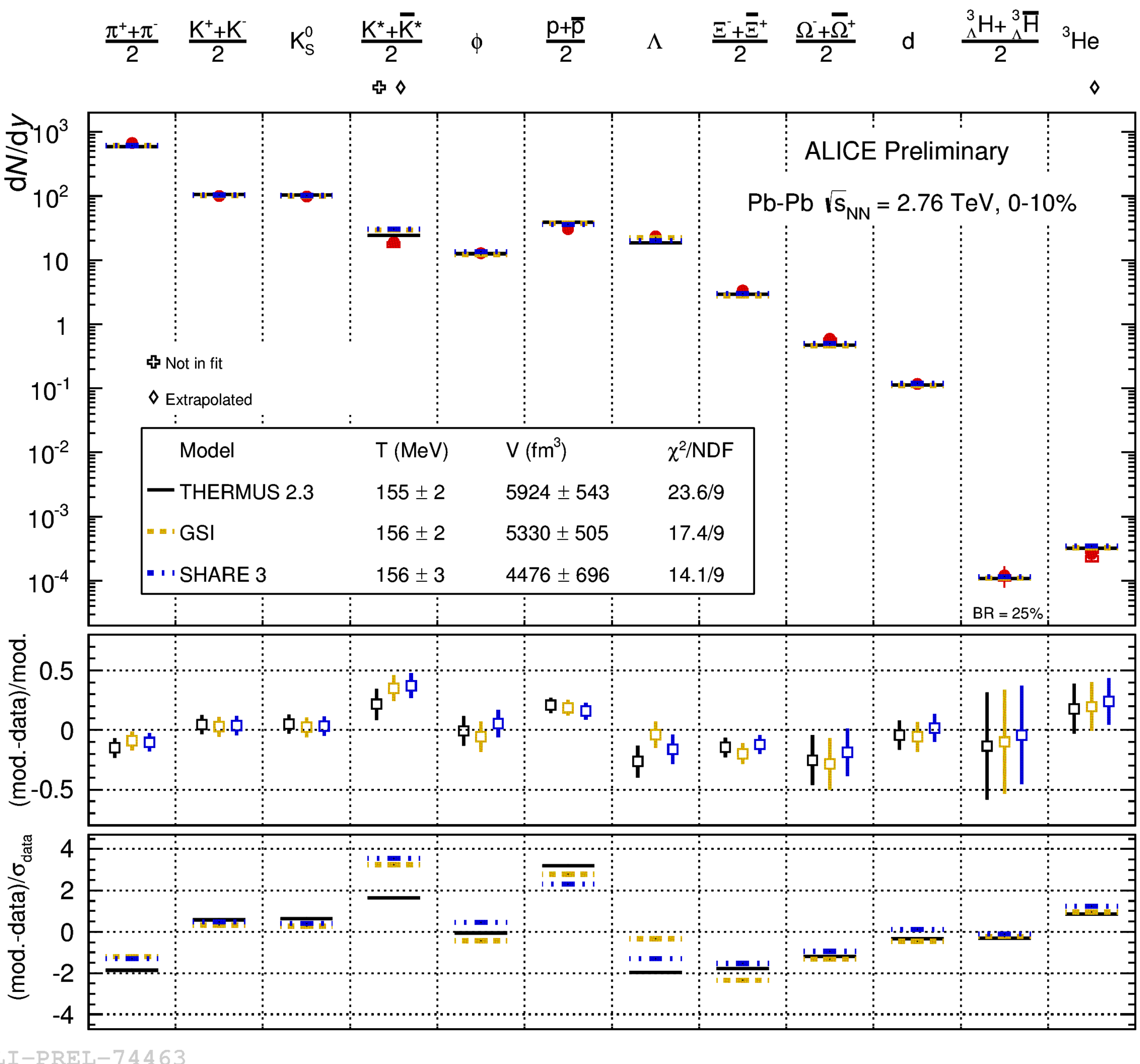
Particle ratios normalized to the grand canonical limit as a function of the system size

Thermal Model Pb-Pb



Fit quality reasonable

Better when excluding protons or pions

Thermal Model for p-Pb

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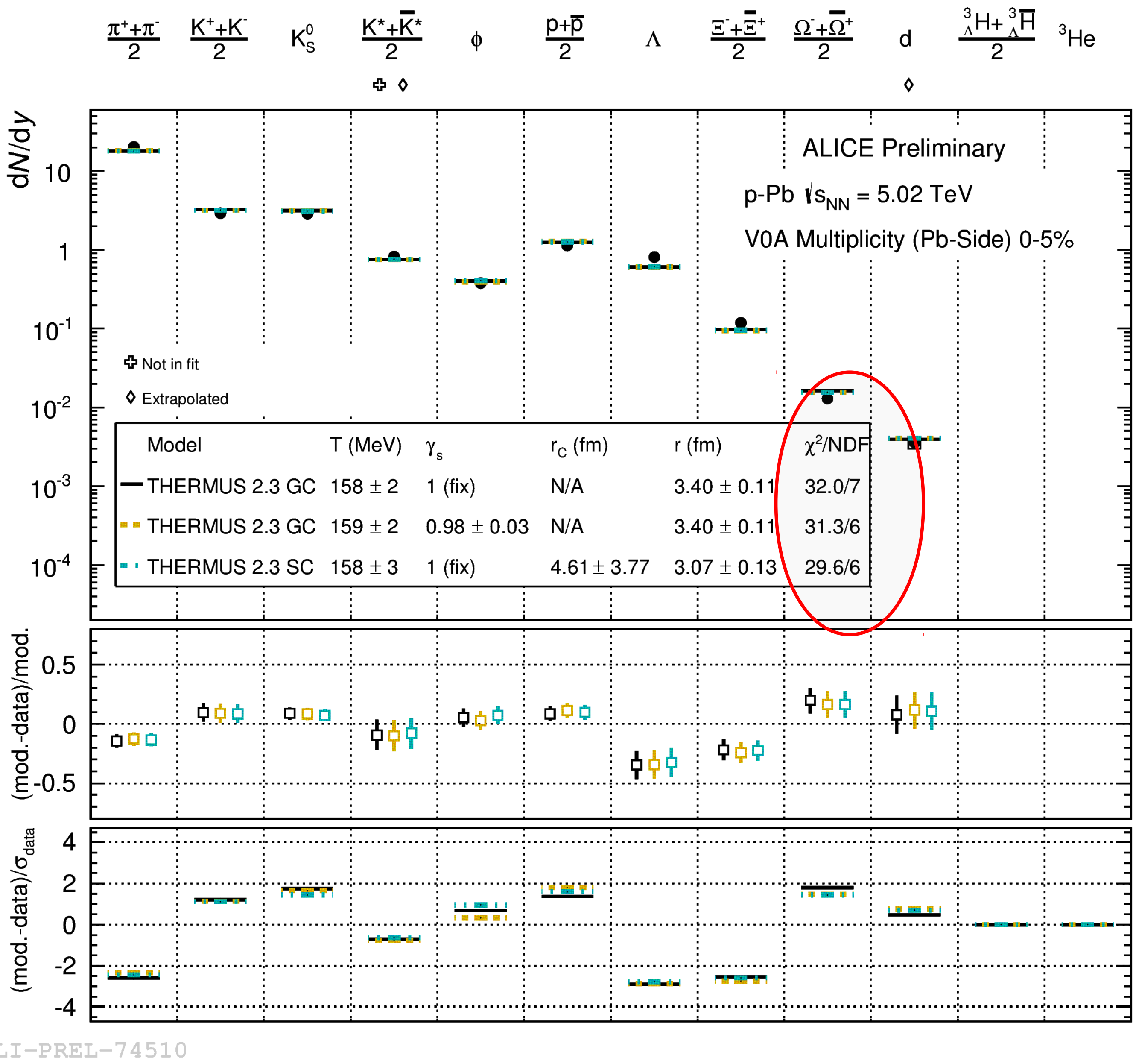

Fit quality not so good but reasonable

However Grand Canonical probably not best ensemble for small system like p-Pb