



# Nuclear PDF studies with proton-lead measurements with the ALICE detector



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for the ALICE Collaboration*

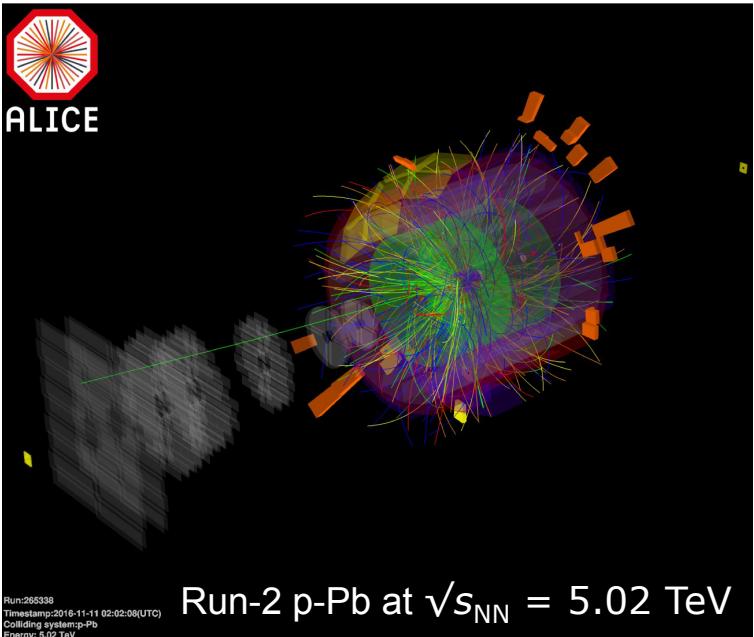
Utrecht University and  
University of Birmingham



# Outline



- Introduction: relevance of studying proton-lead collisions
- ALICE experiment
- Selected results
  - Light flavour and strangeness
  - Azimuthal angular correlations and jets
- Summary and outlook



**Open and hidden heavy-flavour**  
*Open heavy-flavour production in pp and p-Pb by R. Vertesi*  
*Energy dependence of exclusive J/ $\psi$  photoproduction in p-Pb by J.G. Contreras*

# Scientific approach

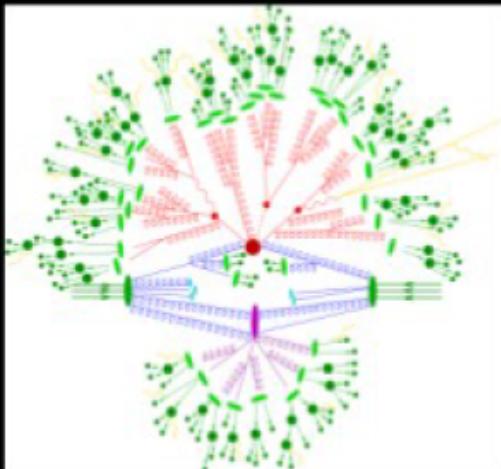
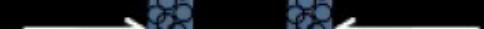
$p \ p$



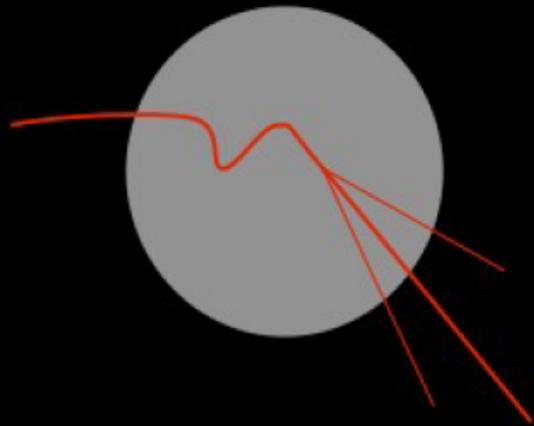
$p \ Pb$



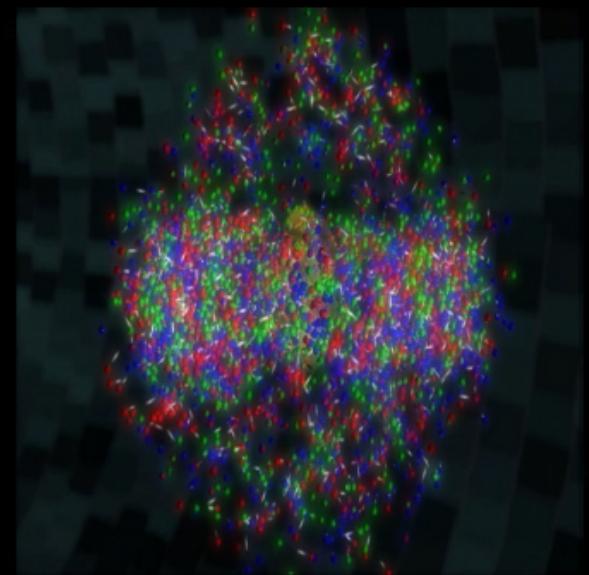
$Pb \ Pb$



Local structure of QCD vacuum



Local QCD  
+  
initial state/cold nuclear matter

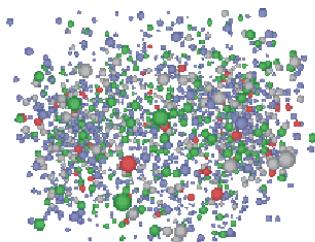


Local QCD  
+  
initial state/cold nuclear matter  
+  
Quark-Gluon Plasma (hot)

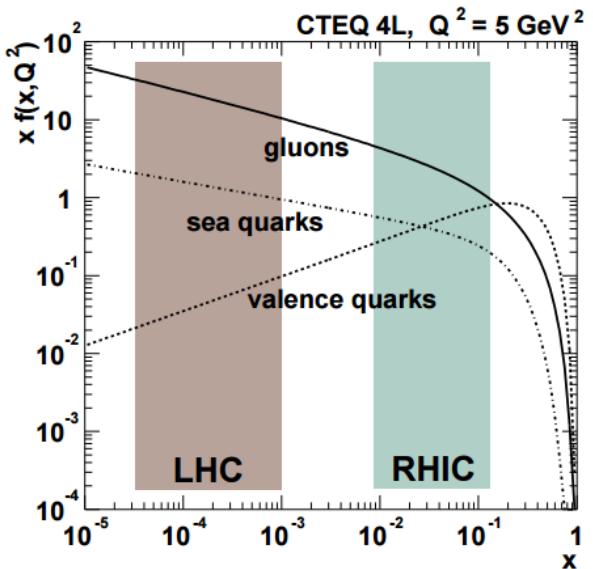
# Cold nuclear matter (CNM) effects



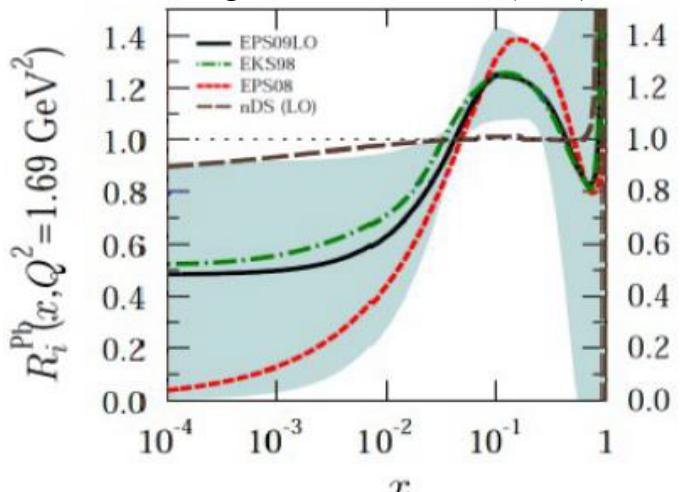
- Study cold nuclear matter effects (from initial state) such as
  - Nuclear modification of PDFs → **shadowing** at low Bjørken-x (dominant at LHC)
  - Gluon **saturation** from evolution equations (DGLAP and BFKL)
  - $k_T$  broadening and Cronin enhancement from multiple parton scatterings
  - Initial-state energy loss



- Final-state effects
  - Energy loss?
  - Interactions between final-state particles (collective expansion?)
- Crucial for test of pQCD calculations and interpretation of heavy-ion results

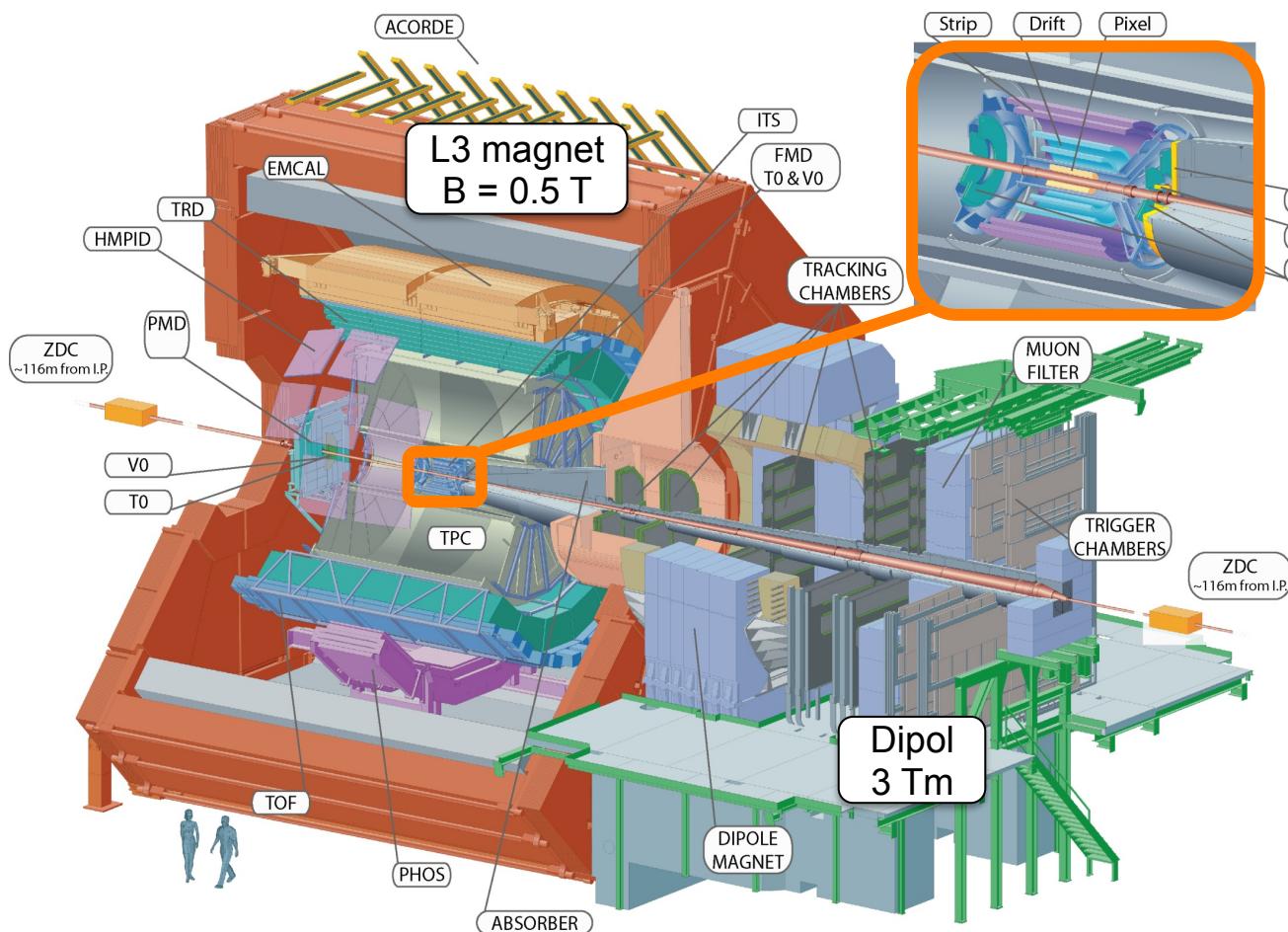


K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 0904, 65 (2009)



# A Large Ion Collider Experiment

*At the CERN  
Large Hadron Collider*



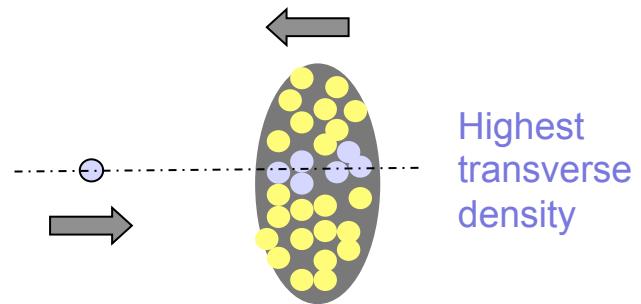
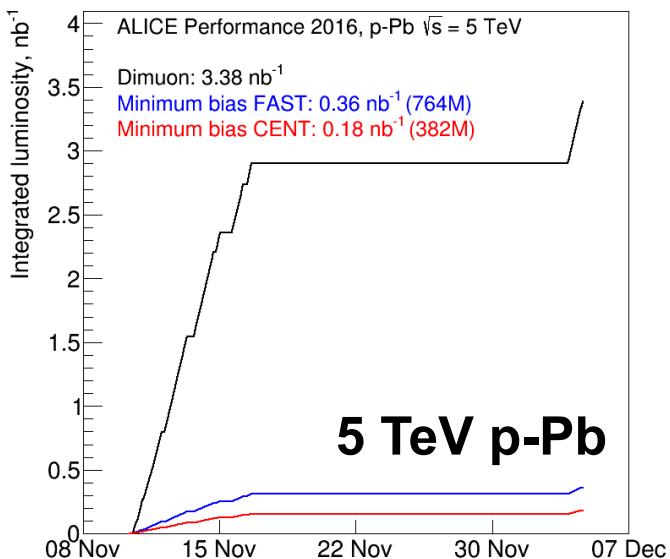
## Sub-detector systems

- Inner Tracking System
- Time Projection Chamber
- Time-Of-Flight
- EM-calorimetry: EMCAL, DCAL and PHOS
- Trigger: T0, V0 and ZDC
- Muon arm

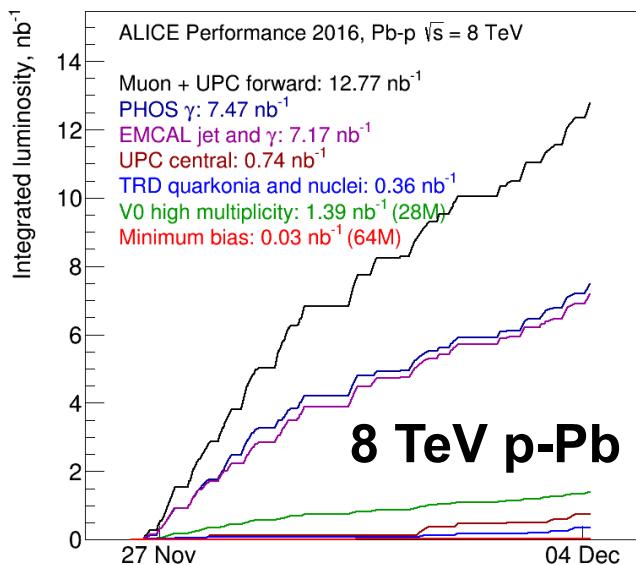
- PID over a very broad momentum range ( $> \sim 100 \text{ MeV}/c$ )
- Full acceptance in azimuth
- **Mid-rapidity coverage ( $|\eta| < 0.9$ ) and  $-4 < \eta < -2.5$  in forward region**

# Datasets

- Lead beam ( $^{208}_{\Lambda} \text{Pb}$ ) with an energy of 1.58 TeV per nucleon and counter rotating proton beam with an energy of 4 TeV
- **p-Pb collisions with cms energy of  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$**
- In 2013: 13 bunches were circulating with about  $10^{10}$  protons and  $6 \times 10^7$  Pb ions per bunch

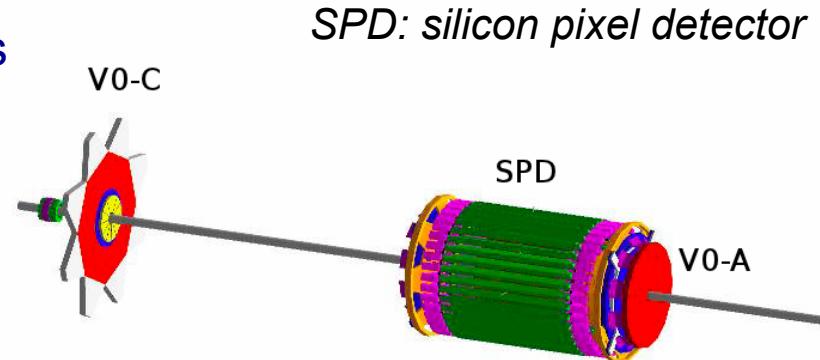


$$\Delta y_{\text{cms}} = 0.465 \text{ (in proton direction)}$$



# Trigger and data samples

- Minimum bias, based on interaction trigger:
  - SPD or V0-A side or V0-C side
  - at least one charged particle in 8  $\eta$  units
  - 95% efficient on  $\sigma_{\text{inel}}$
- Vertex determination: SPD
- Centrality in Pb-Pb: Glauber fit to V0 signal amplitude
- Single-muon trigger ( $p_T > 0.5$  and 4.2 GeV/c)
  - forward muon in coincidence with MB



$\sqrt{s}_{\text{NN}}$ (TeV)	year	#events	integrated luminosity
5.02	2013	120M	$\sim 50 \mu\text{b}^{-1}$
5.02	2016	764M	$\sim 0.36 \text{ nb}^{-1}$
8.16	2016	128M	$\sim 0.06 \text{ nb}^{-1}$

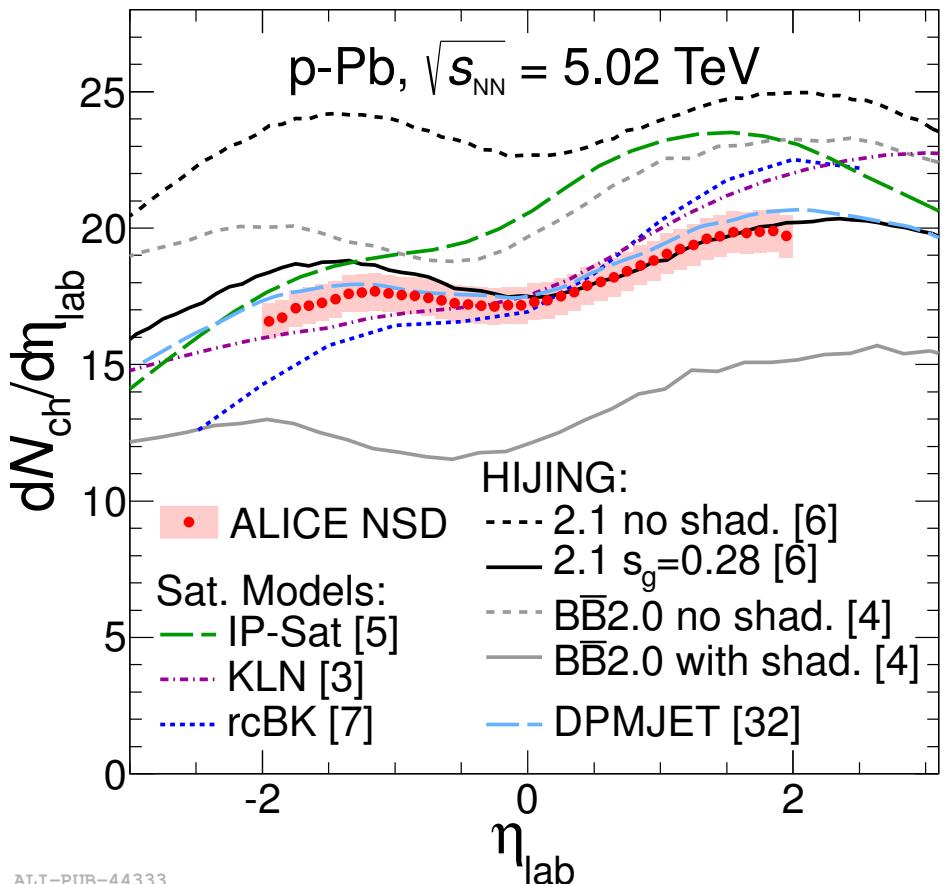
Datasets taken in Run-2 are  
7-8x larger than those from Run-1

Not covered in this talk: pp data  
at  $\sqrt{s} = 0.9, 2.76, 7, 8$  and 13 TeV

# Pseudorapidity density of charged particles



Phys. Rev. Lett. 110 (2013) 032301



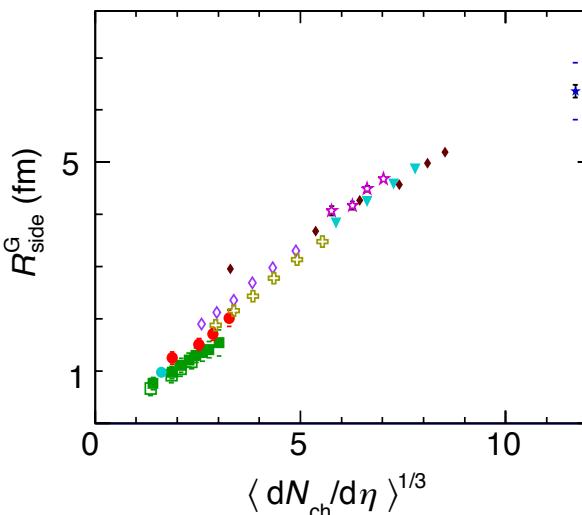
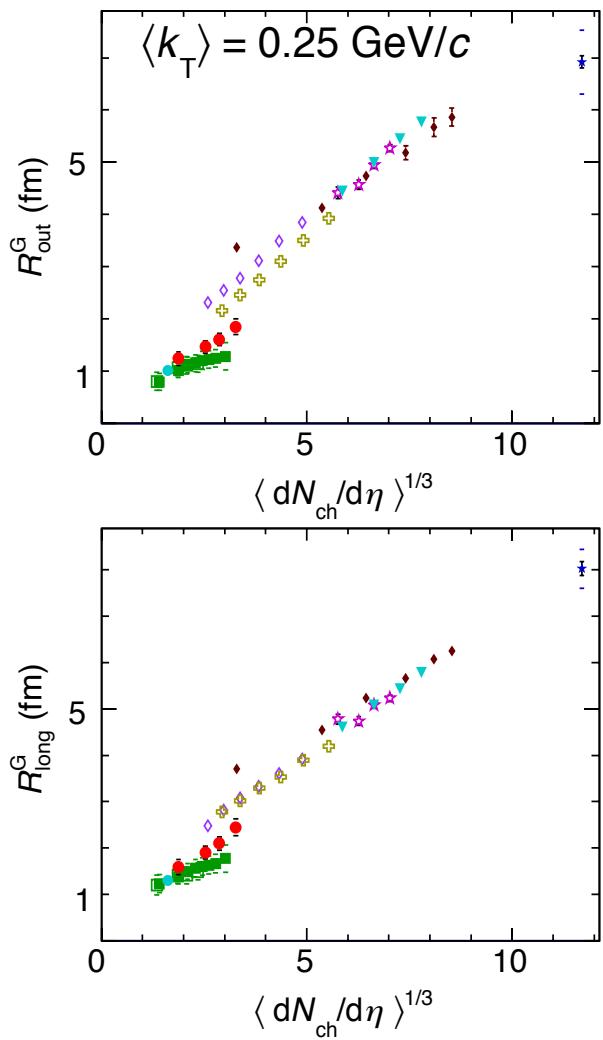
- Measured over 4 units of pseudorapidity in non-single diffractive (NSD)  $p\text{-Pb}$  collisions
- Most model predictions within 20% of data
- Saturation Models** rise too steeply with  $\eta_{\text{lab}}$
- pQCD-based Monte Carlo models** (HIJING and DPMJET) describe  $dN_{\text{ch}}/d\eta_{\text{lab}}$

$$\eta_{\text{lab}} = -\ln \tan(\theta/2)$$

# Two-particle correlations of identical pions

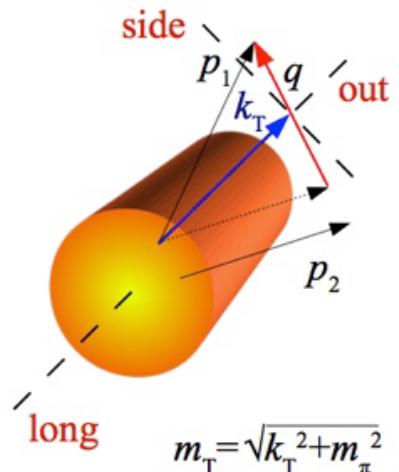


*Phys. Rev. C 91 (2015) 034906*



- ◆ STAR Au-Au  $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
- ◆ STAR Cu-Cu  $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$
- ◆ STAR Au-Au  $\sqrt{s_{\text{NN}}} = 62 \text{ GeV}$
- ◆ STAR Cu-Cu  $\sqrt{s_{\text{NN}}} = 62 \text{ GeV}$
- ◆ CERES Pb-Au  $\sqrt{s_{\text{NN}}} = 17.2 \text{ GeV}$
- ◆ ALICE Pb-Pb  $\sqrt{s_{\text{NN}}} = 2760 \text{ GeV}$
- ALICE pp  $\sqrt{s} = 7000 \text{ GeV}$
- ALICE pp  $\sqrt{s} = 900 \text{ GeV}$
- STAR pp  $\sqrt{s} = 200 \text{ GeV}$
- ALICE p-Pb  $\sqrt{s_{\text{NN}}} = 5020 \text{ GeV}$

Access size of  
particle-emitting region  
at freeze-out

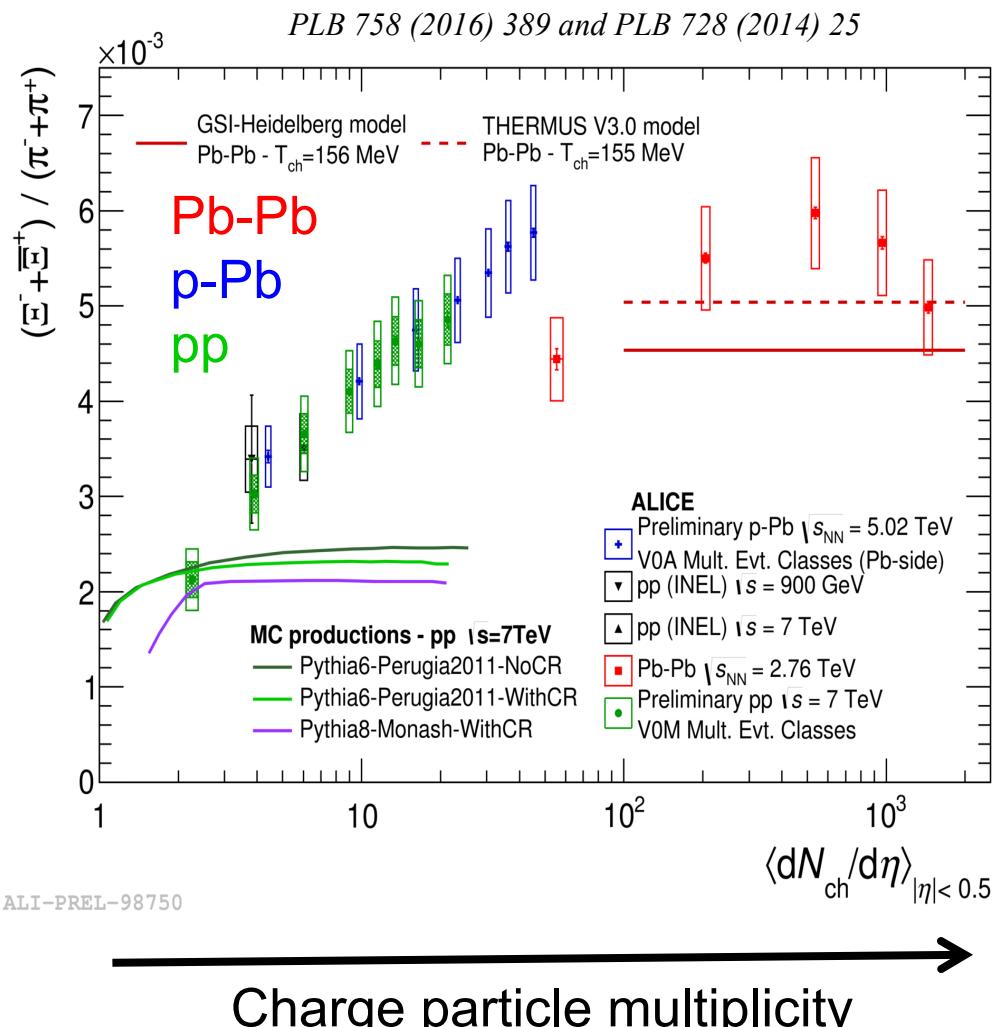


$$m_T = \sqrt{k_T^2 + m_\pi^2}$$

Averaged transverse pair  
momentum  $k_T$

Source volume  $\sim \langle dN/d\eta \rangle$   
 → Indicating a constant  
source density at the  
moment of freeze-out

# Multi-strange particles vs. multiplicity

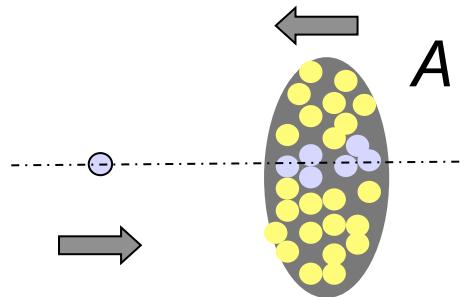


- Looser concept of ‘centrality’ in pp collisions
  - fluctuations in momentum transfer
  - internal proton structure
- Similar multiplicity dependence in pp and p-Pb
- **Neither PYTHIA 6 nor 8 reproduce data in any of the tunes tested**
- Continuous reduction of **canonical suppression** with increasing multiplicity

# Quantification of nuclear effects



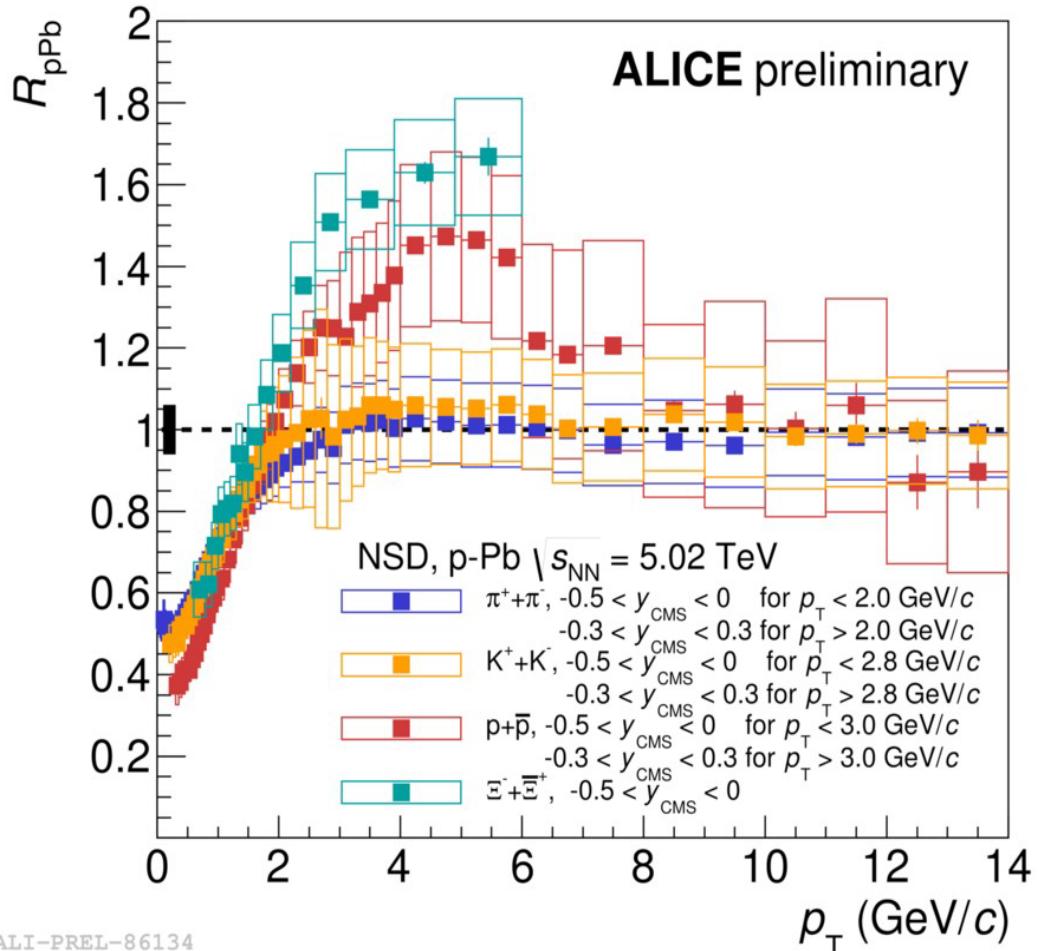
- Proton-lead collisions: single proton hits multiple nucleons, number depends on impact parameter  $b$  ( $\langle N_{\text{coll}} \rangle \approx 7$ )
- Nuclear modification factor  $R_{\text{pPb}}$



$$R_{pA} = \frac{d\sigma_{pPb} / dp_T}{A \times d\sigma_{pp} / dp_T}$$

- pp reference data at  $\sqrt{s} = 7 \text{ TeV}$   
(if not indicated otherwise)
- If  $R_{\text{pPb}} = 1$ 
  - no nuclear matter effects
  - binary collision scaling

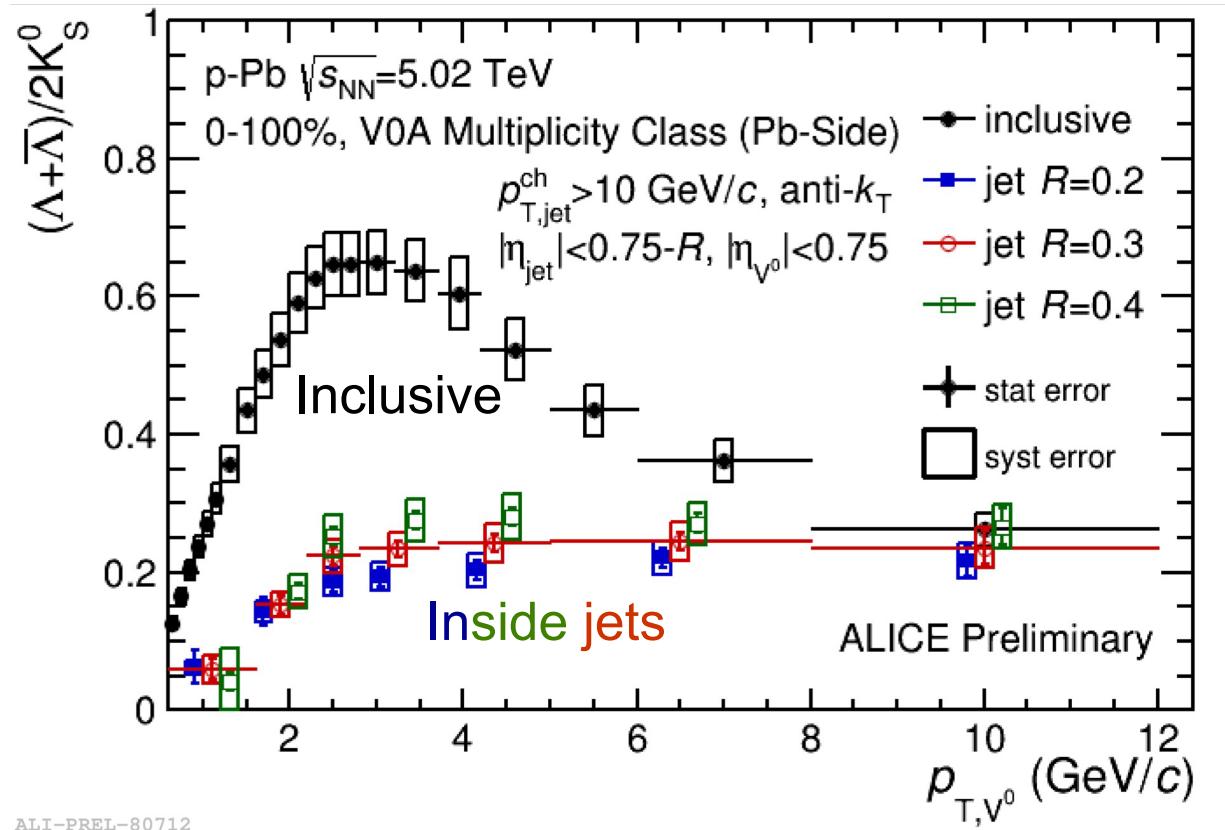
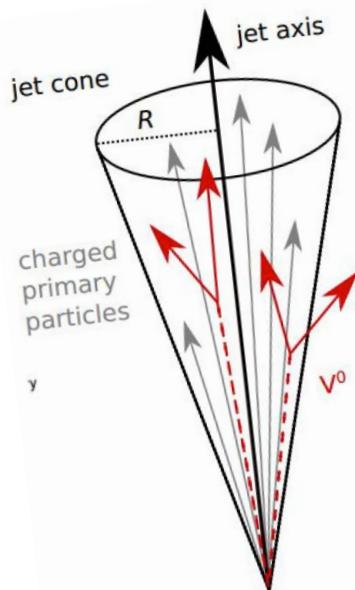
# Nuclear modification factor



- At intermediate  $p_T$  (Cronin region)
- Indication of mass ordering
  - No enhancement for **pions** and **kaons**
  - Pronounced peak for **protons**
  - Even stronger for **cascades**

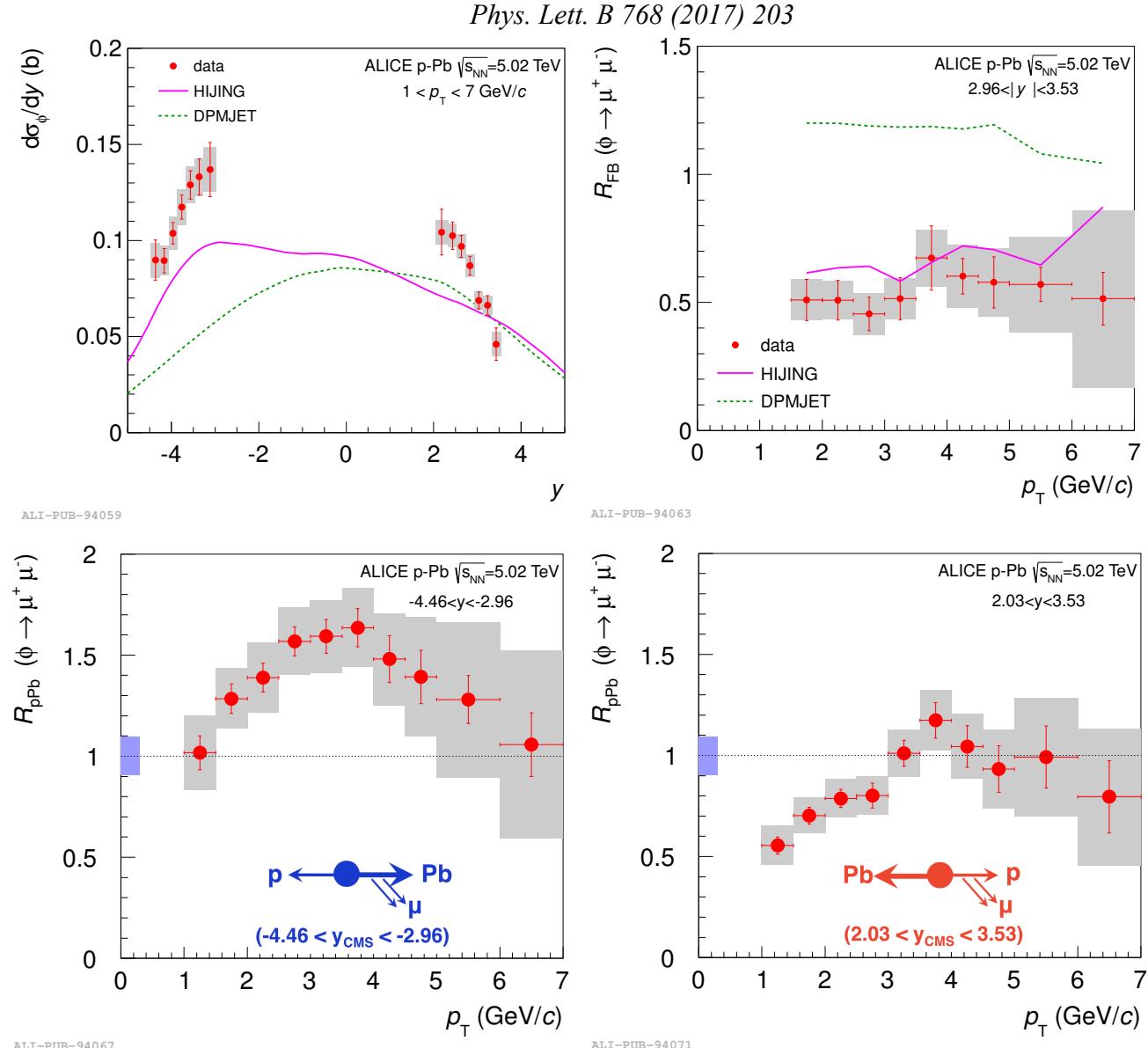
**Particle species dependence indicates relevance of final-state effects**

# Identified strange particles in jets



- Lambda-to-kaon ratio in jets significantly lower than inclusive; consistent with PYTHIA expectations
- Enhancement does not originate from jets

# $\phi(\rightarrow\mu\mu)$ meson production at forward rapidity

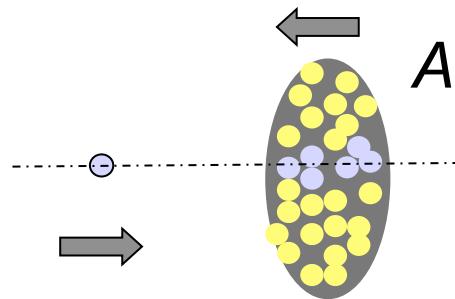



- HIJING and DPMJET underestimate data
  - Forward- backward asymmetry shows no significant  $p_T$  dependence
  - Initial-state (Cronin-like) effect or final-state effect related to radial flow?
- Urgent need for theoretical calculations for soft particle production at forward rapidity

# Nuclear modification factor $R_{pA}$ and $Q_{pA}$



- Proton-lead collisions: single proton hits multiple nucleons, number depends on impact parameter  $b$  ( $\langle N_{\text{coll}} \rangle \approx 7$ )
- Nuclear modification factor  $R_{pPb}$
- **Centrality/multiplicity-dependent nuclear modification factor  $Q_{pPb}$** 
  - Collision centrality expressed in terms of nuclear overlap function  $T_{pPb}$
  - $T_{pPb}$  and  $N_{\text{coll}}$  determination relies on assumption that charged-particle multiplicity at mid-rapidity scales linearly with  $N_{\text{part}}$
- pp reference data at  $\sqrt{s} = 7$  TeV  
(if not indicated otherwise)



$$R_{pA} = \frac{d\sigma_{pPb} / dp_T}{A \times d\sigma_{pp} / dp_T}$$

$$Q_{pA} = \frac{dN_{pPb} / dp_T}{\langle T_{pPb}^{\text{mult}} \rangle \times d\sigma_{pp} / dp_T}$$

If  $R_{pPb}$  and  $Q_{pPb} = 1$

- no nuclear matter effects
- binary collision scaling

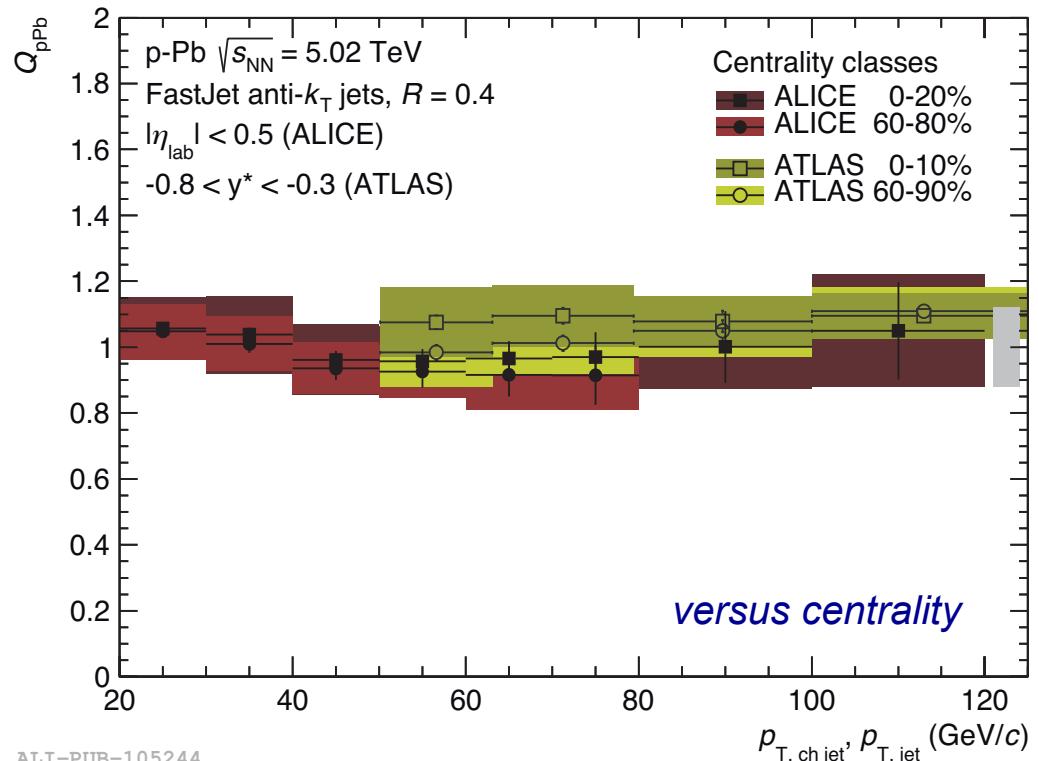
# Full and charged jet production

**Charged jets, ALICE:**

Eur. Phys. J. C76, 271 (2016) and Phys. Rev. C 91, 064905 (2015)

**Full jets, ATLAS:**

Phys. Lett. B 748, 392 (2015)



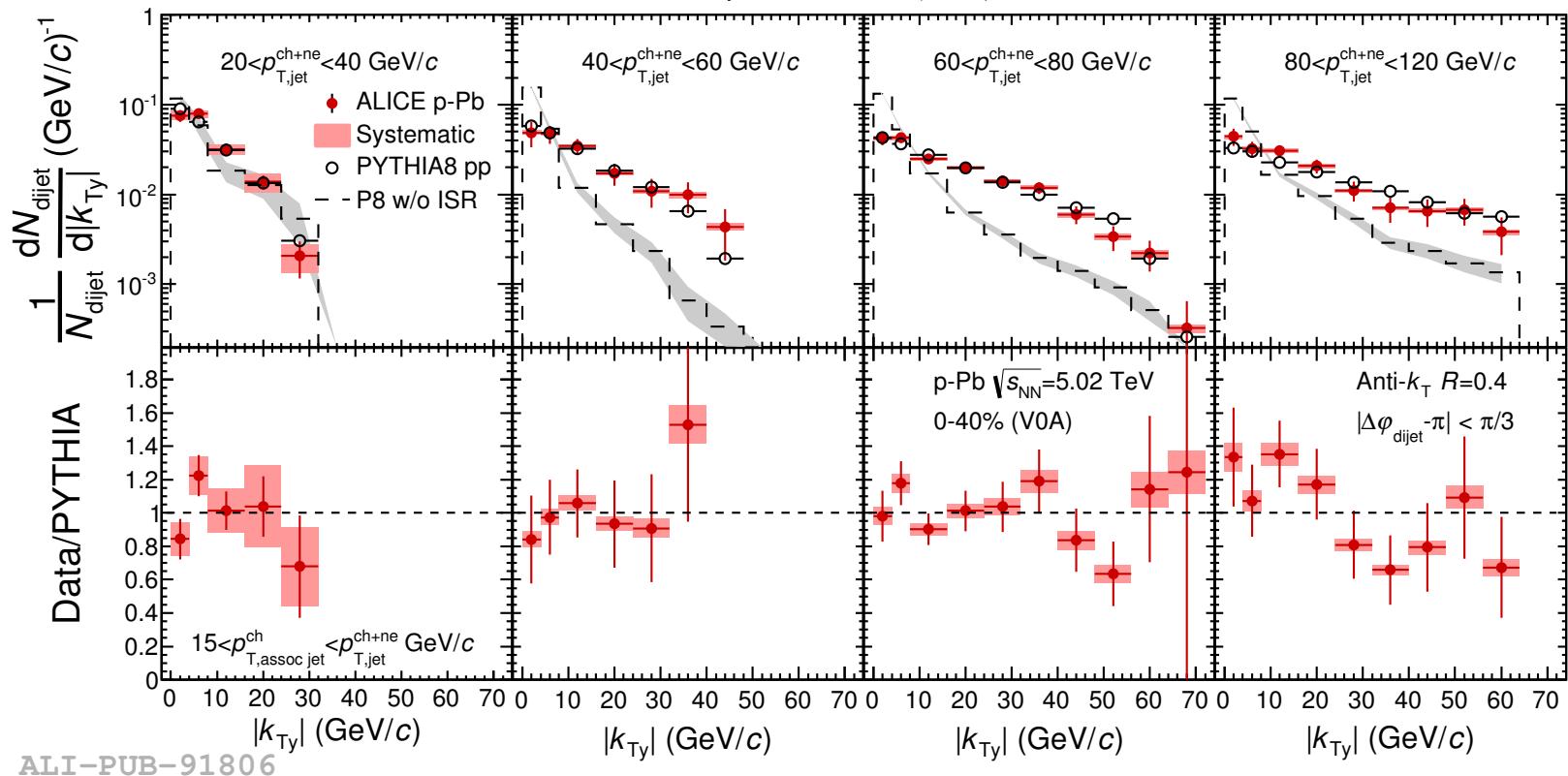
ALI-PUB-105244

- $Q_{pPb} \sim 1$  for all centralities and independent on jet  $p_T$
  - Dependence on resolution parameter  $R$  as expected in pp
  - Jet fragmentation function is unmodified with respect to the interpolated pp reference
- No CNM effects

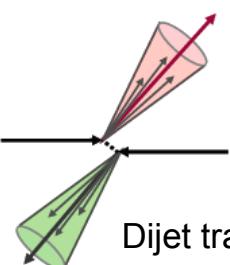
# Acoplanarity between full and charged jets



*Phys. Lett. B 746 (2015) 385*



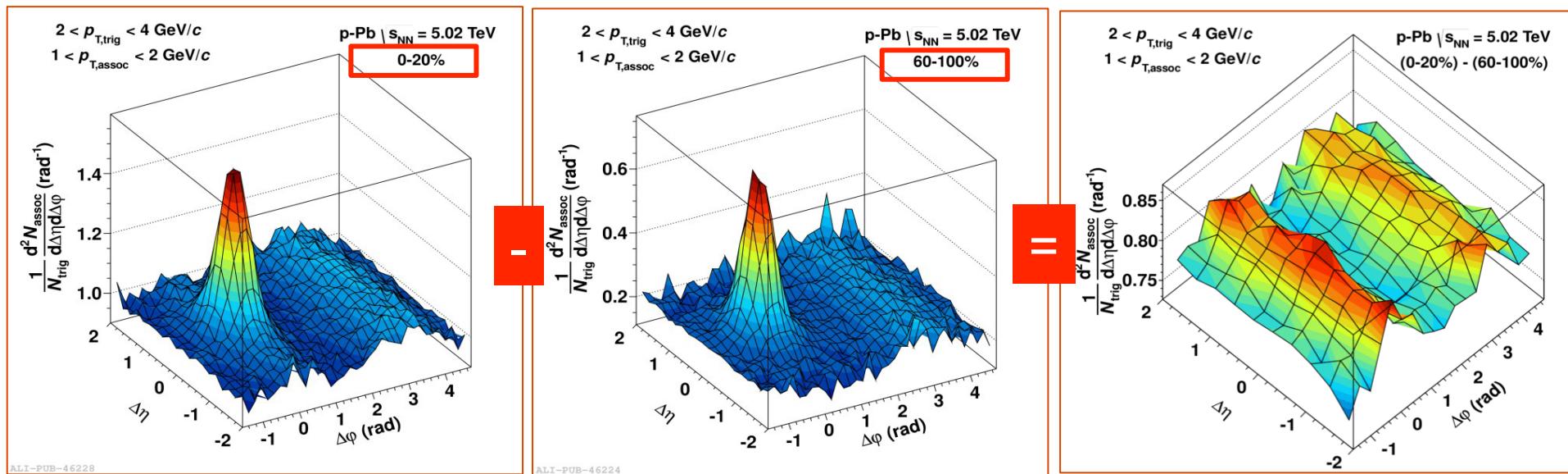
ALICE-PUB-91806



Dijet transverse momentum  
 $k_{Ty} = p_{T,jet}^{ch+ne} \sin(\Delta\varphi_{dijet})$ ,

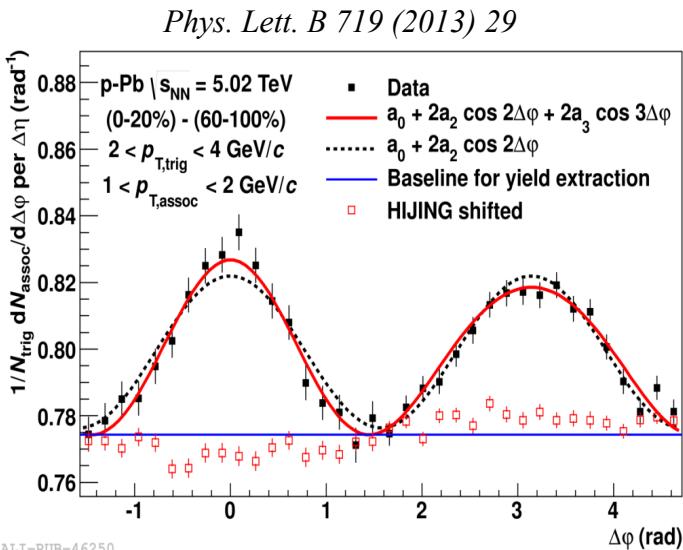
- Dijet  $k_{Ty}$  consistent with Pythia8 predictions (with ISR)
- No strong nuclear matter effects in measured kinematic range
  - For large  $Q^2$  mainly sensitive to increased available phase-space for QCD radiation processes

# Di-hadron azimuthal angular correlations



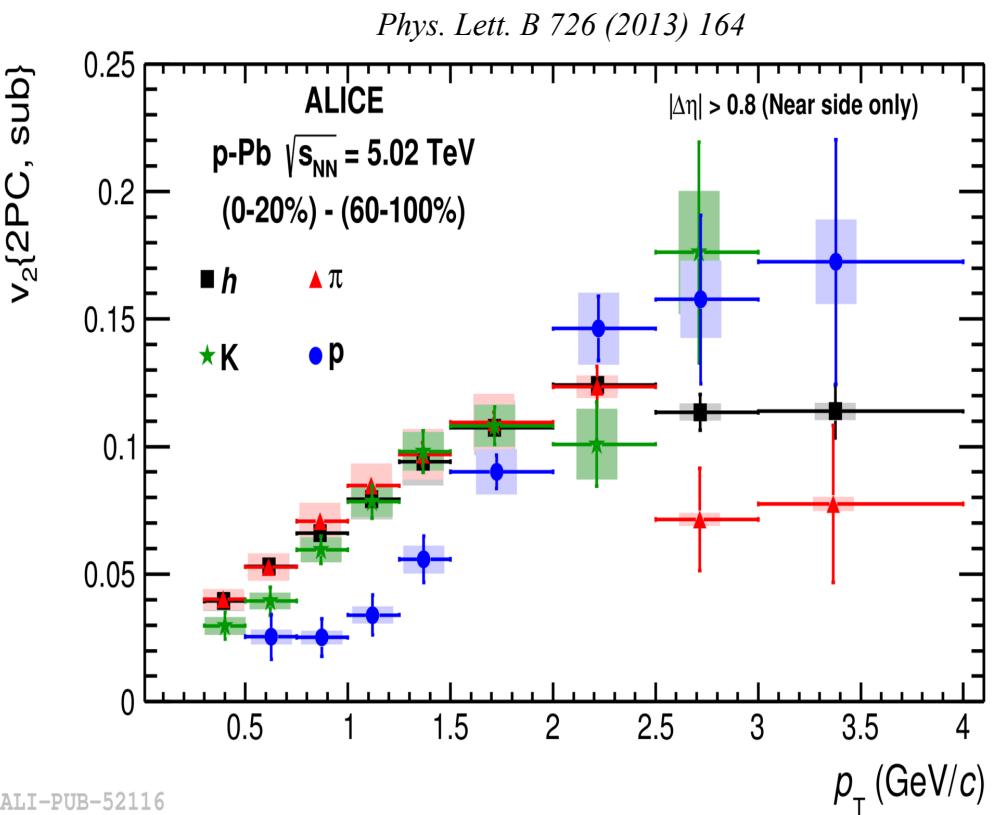
## Two long-range (double ridge) structure described by

- colour glass condensate (initial-state effect)
- hydrodynamics (final-state effect)



- Unexpected collective (?) behaviour in high-multiplicity events at low  $p_T$  seen even in the small p-Pb system
- Jets suggest no significant CNM effects

# Hadron – ( $\pi$ , K, p) azimuthal correlations



ALI-PUB-52116

$$\frac{dN}{d\varphi_{lab}} \propto 1 + 2v_2 \cos[2(\varphi_{lab} - \Psi_{Plane})]$$

- Elliptic-flow parameter  $v_2$  obtained from two-particles correlations

- Mass ordering at low  $p_T$
- Crossing at  $p_T \sim 2$  GeV/c

- Qualitatively similar to Pb-Pb and consistent with hydro calculations

→ Suggests similar physics (collectivity?) at place?

# Conclusions

- p-Pb data yielded many (unexpected) results: different hadronic probes and observables
- **Strangeness**: Continuous reduction of canonical suppression with increasing multiplicity
- **Jet fragmentation** exhibits no modification
  - No indication for substantial modification due to cold nuclear matter effects
  - Indication for **collective-like behaviour in small systems**, reminiscent of that observed in Pb-Pb collisions
  - Final-state modifications in p-Pb collisions?
- Future: high-precision measurements with Run-2 data