Proton-lead results from ALICE – part I

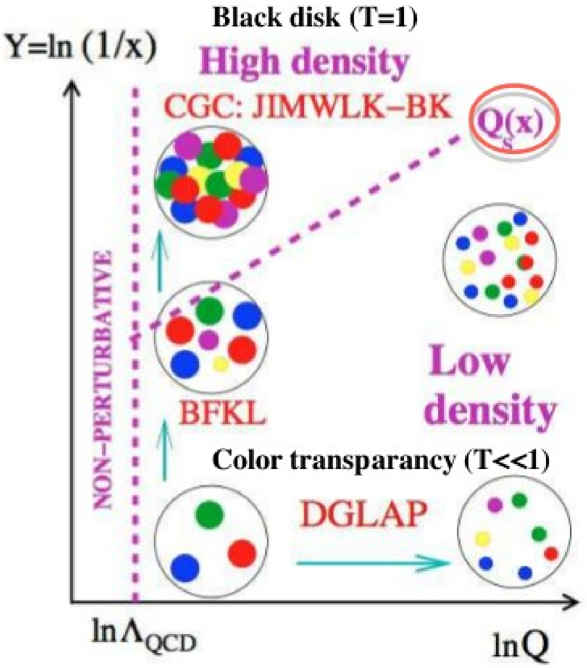
Constantin Loizides
(LBNL/EMMI)
on behalf of the ALICE collaboration

17 May 2013

pA physics workshop at MIT

Motivation for pPb at the LHC

- Study high-density QCD in saturation region
  - Saturation scale (Q_s) enhanced in nucleus ($\sim A^{1/3\lambda}$)
  - In perturbative regime at the LHC: Q_s~2-3 GeV/c
  - Qualitatively expect x~10^{-4} at η=0 (vs 0.01 at RHIC)
- Study pA as a benchmark for AA
  - Benchmark hard processes to disentangle initial from final state effects
  - Characterize nuclear PDFs at small-x
- Expect surprises
  - History of pA collisions (eg. see talk by W.Busza)
  - pA contains elements of both: pp and AA
- Other physics opportunities
  - Diffraction
  - Photo-nuclear excitation

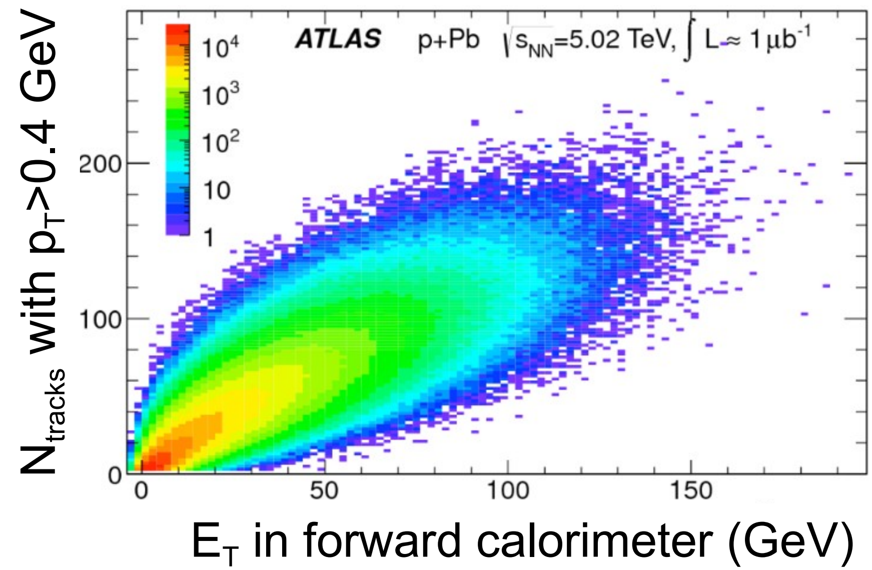


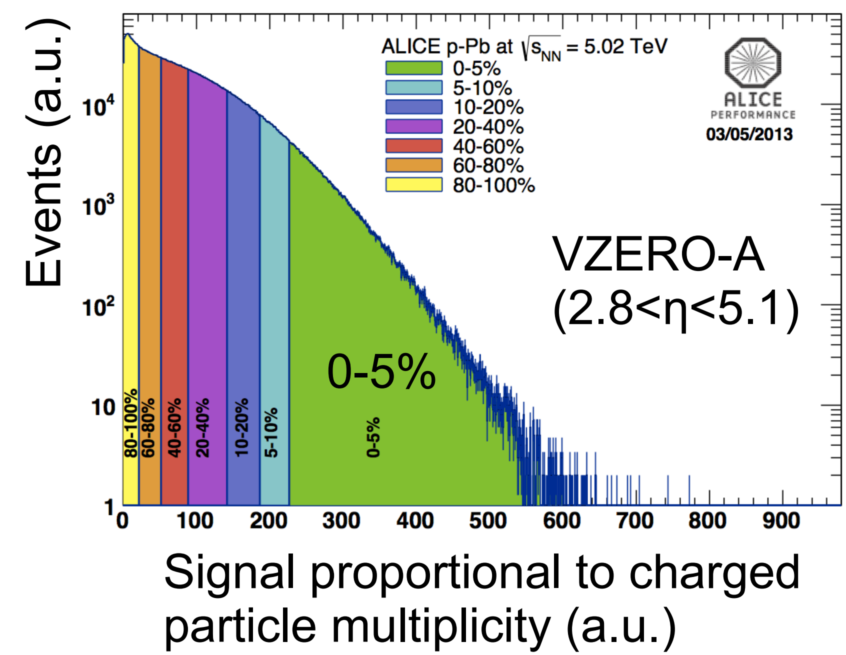
PRL 91 (2003) 072302

Motivations summarized in JPG 39 (2012) 015010

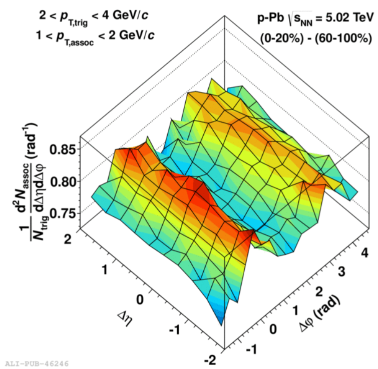
Event multiplicity classes in pPb

- Correlation between collision geometry and multiplicity not as strong as in AA
- System also exhibits features of biased pp (NN) collisions in the multiplicity tails
- Complicates precise extraction of Glauber related quantities
  - Use minbias values instead (σ_{pA} = A σ_{pp})
- Define event classes by slicing various multiplicity related distributions
  - Every experiment uses its own selection and usually provides (corrected) multiplicity at mid-rapidity
    - Forward multiplicity/energy on Pb side
  - Event class definition may matter for particular measurements
  - Systematics using different selections

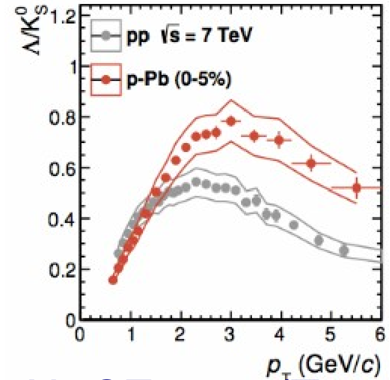




ALICE pPb results



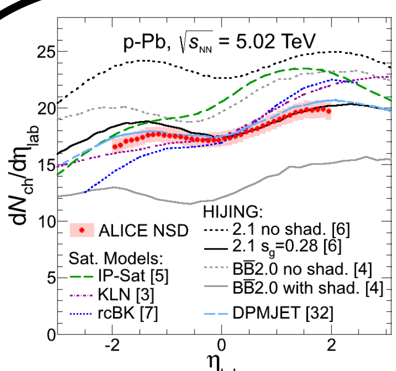
ALICE, PLB 719 (2013) 29



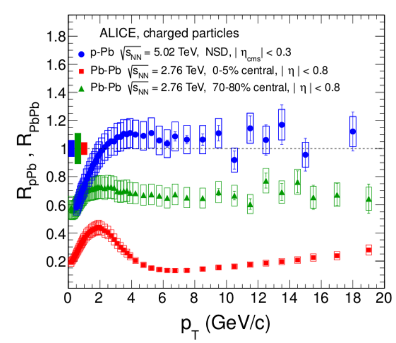
ALICE prel. (Trento)

Part 1 – Ridge, PID (today)

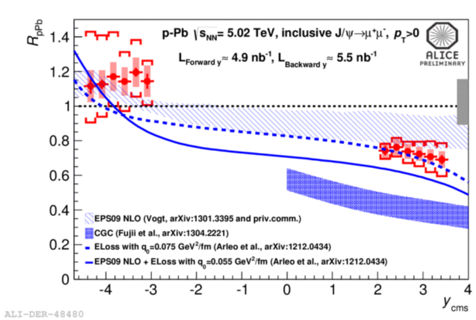
Part 2 – dN/dη, dN/dp_T and J/Ψ (John, tomorrow)



ALICE, PRL 110 (2013) 032301



ALICE, PRL 110 (2013) 082302

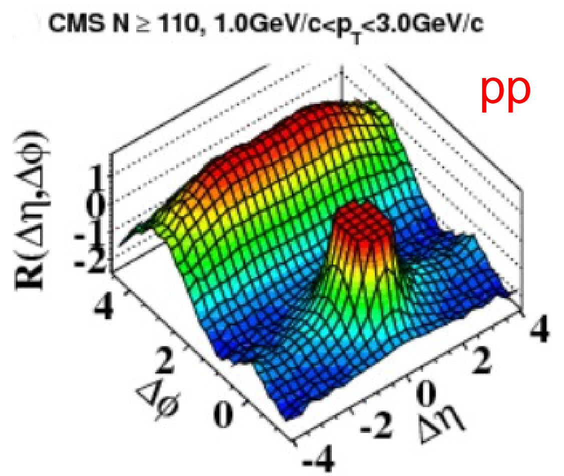


ALICE prel. (Trento)

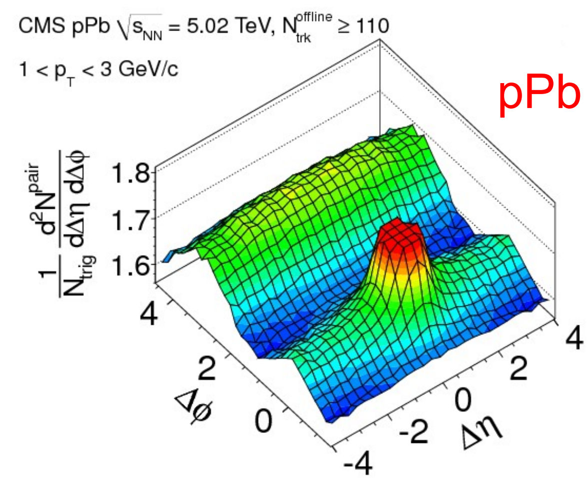
Di-Hadron Correlations (DHC)

- CMS: pp, pPb at LHC
  - Long-range near-side correlations (ridge) appear at high-multiplicity
    - Collective effects in pp and pPb?
    - CGC initial state effects?

CMS, JHEP 1009 (2010) 91

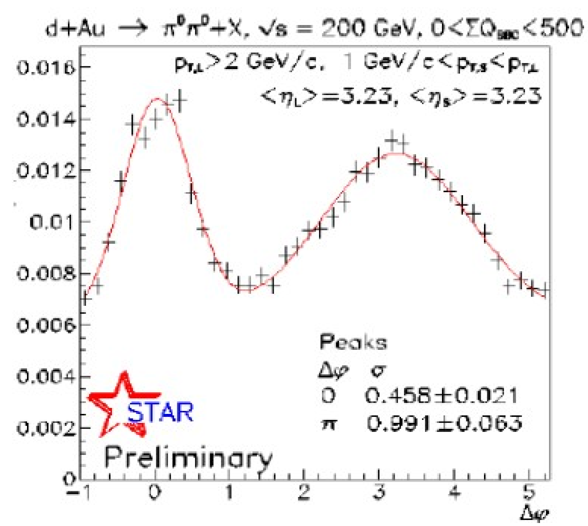


CMS, PLB 718 (2012) 795

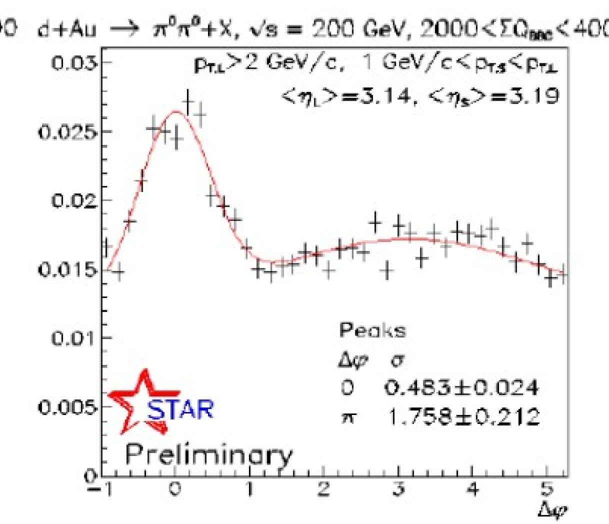


- STAR: dAu at RHIC
  - Back-to-back (jet-like) correlations in forward π^0 correlations disappear in high-multiplicity events
    - Compatible with CGC predictions
- LHC mid- and RHIC forward-η probe a similar x regime

STAR, arXiv:1005.2378



Peripheral



Central

DHC: Correlation measure

ALICE, PLB 719 (2013) 29

- Associated yield per trigger particle (with $p_T^{trig} > p_T^{assoc}$)

$$\frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm assoc}}{{\rm d}\Delta\eta\, {\rm d}\Delta\varphi} = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$$

- Signal (same event) pair yield

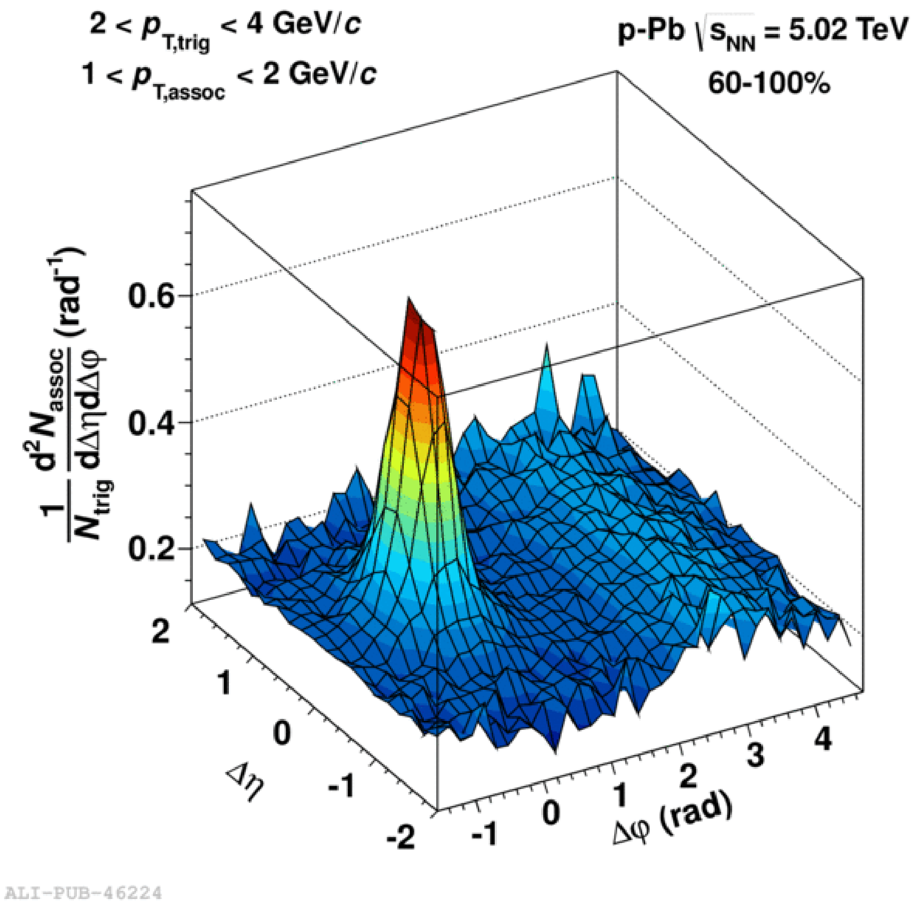
$$S(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm same}}{{\rm d}\Delta\eta\, {\rm d}\Delta\varphi}$$

  - Definition as ratio of sums is multiplicity independent

$$\frac{N_{pair}}{N_{trig}} = \frac{\sum_{i=1}^{N_{evt}} \sum_{j=1}^{N^i_{source}} \frac{1}{2} n_{ij}(n_{ij}-1)}{\sum_{i=1}^{N_{evt}} \sum_{j=1}^{N^i_{source}} n_{ij}} = \frac{N_{evt}\langle N_{source}\rangle \frac{1}{2}\langle n(n-1)\rangle}{N_{evt}\langle N_{source}\rangle \langle n\rangle} = \frac{1}{2}\frac{\langle n(n-1)\rangle}{\langle n\rangle}$$

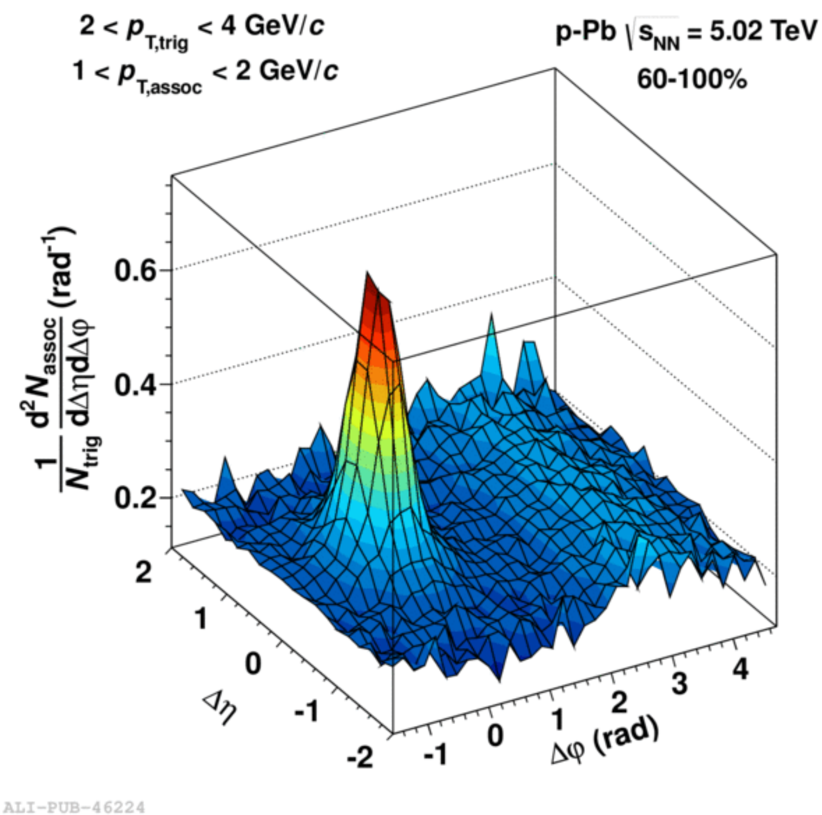
- Background (mixed event) pair yield

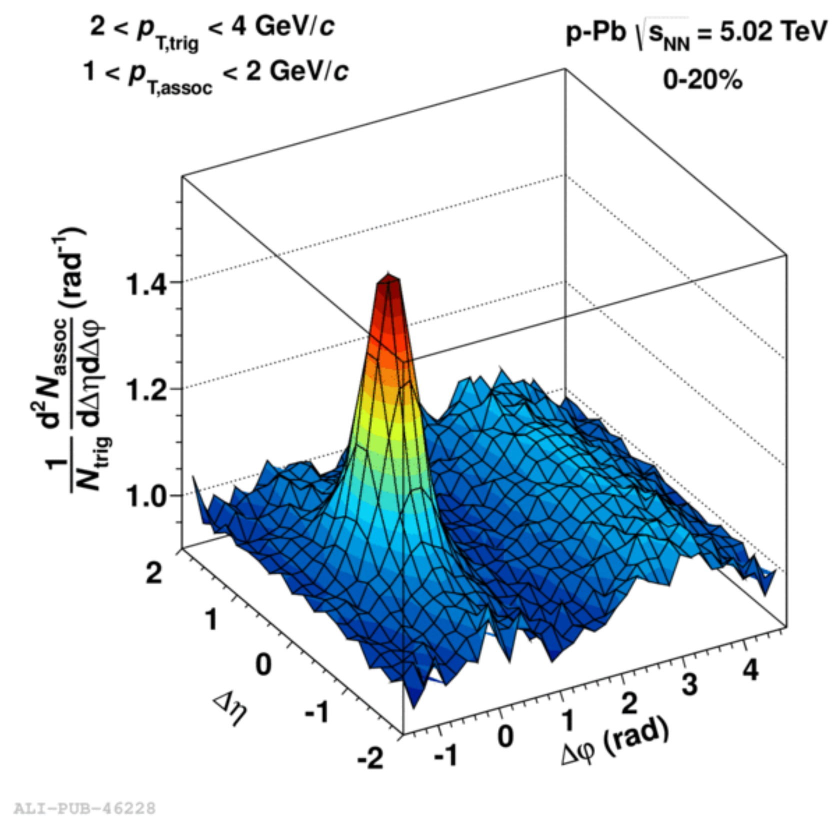
$$B(\Delta\eta, \Delta\varphi) = \frac{1}{B(0,0)} \frac{{\rm d}^2 N_{\rm mixed}}{{\rm d}\Delta\eta\, {\rm d}\Delta\varphi}$$



DHC: Multiplicity dependence

ALICE, PLB 719 (2013) 29

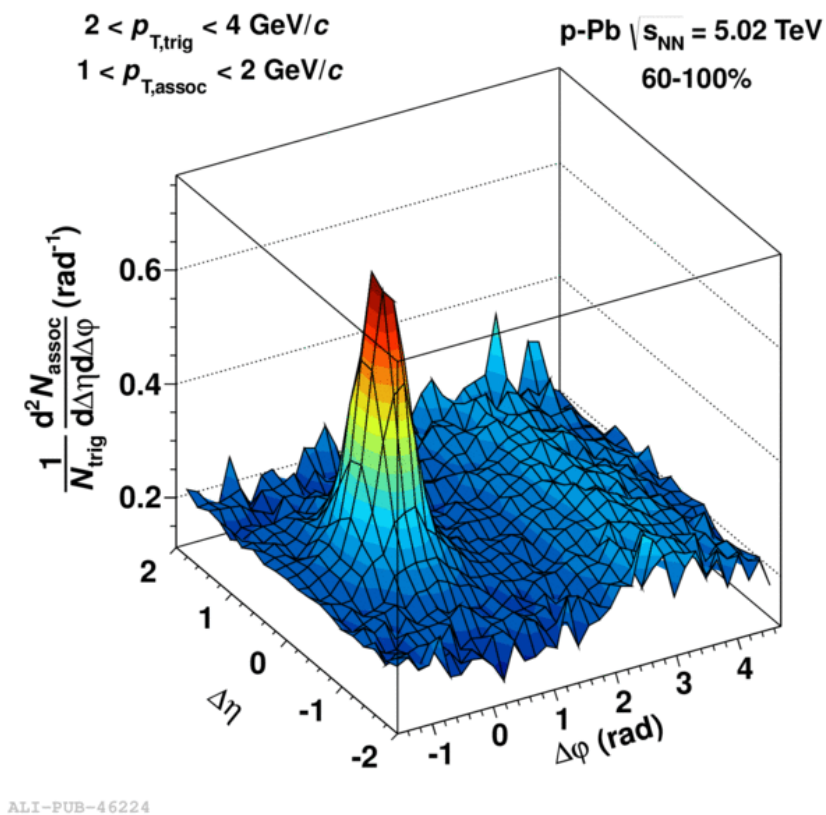


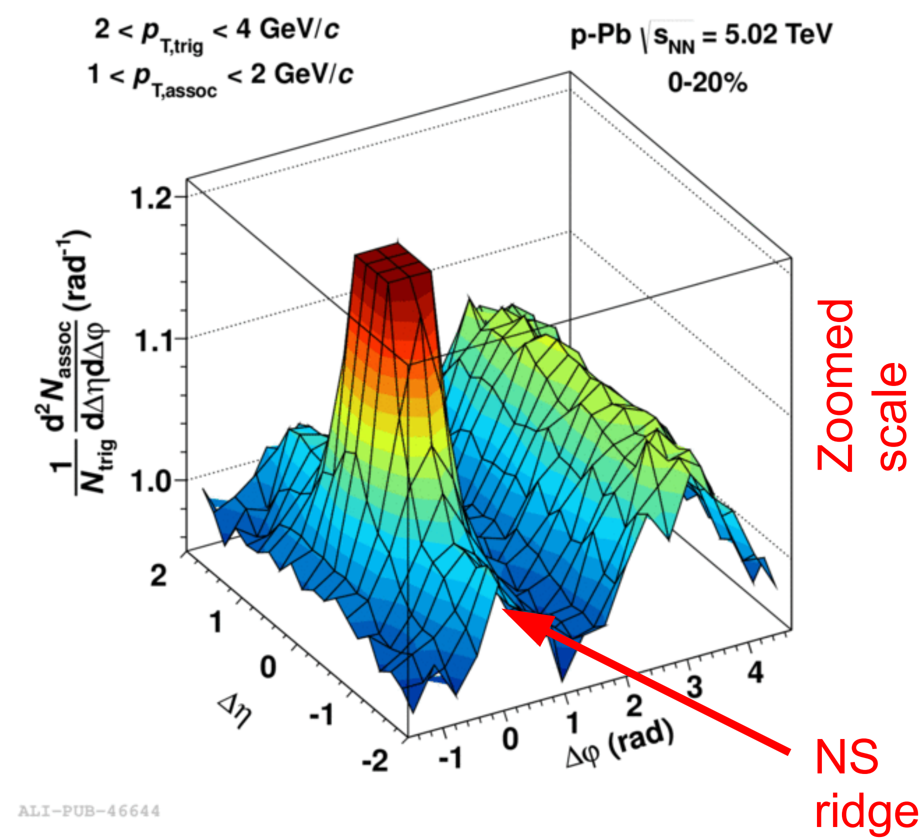


- Low-multiplicity p-Pb (60-100%)
  - pp-like (jet-like) correlation structures
- High-multiplicity p-Pb (0-20%)
  - Near-side ridge appears (first seen in CMS)
  - Higher yields on near- and away-side

DHC: Multiplicity dependence

ALICE, PLB 719 (2013) 29

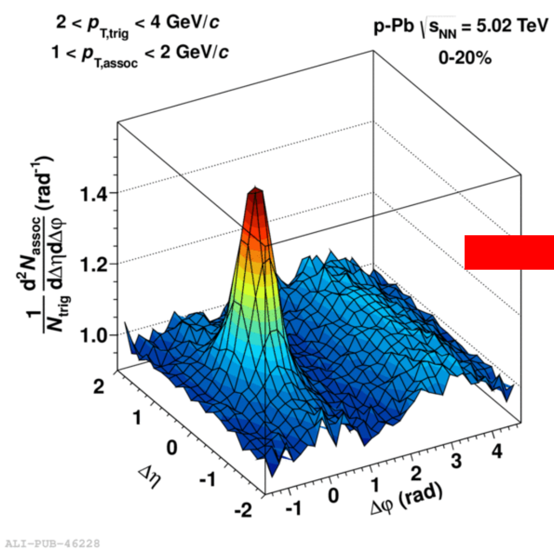




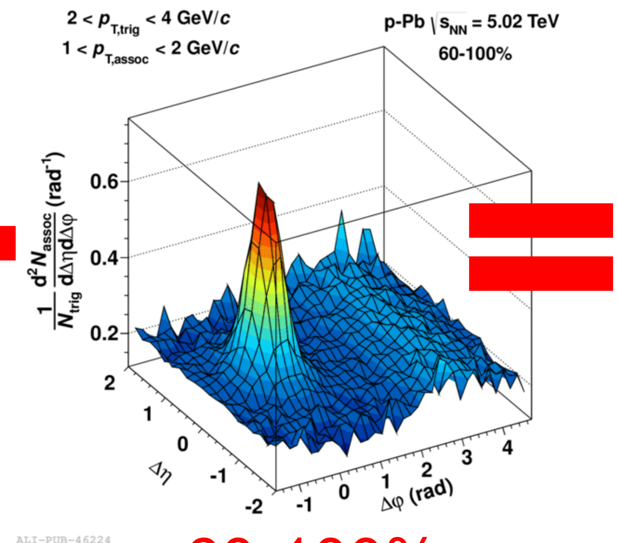
- Low-multiplicity p-Pb (60-100%)
  - pp-like (jet-like) correlation structures
- High-multiplicity p-Pb (0-20%)
  - Near-side ridge appears (first seen in CMS)
  - Higher yields on near- and away-side

Extraction of double ridge structure

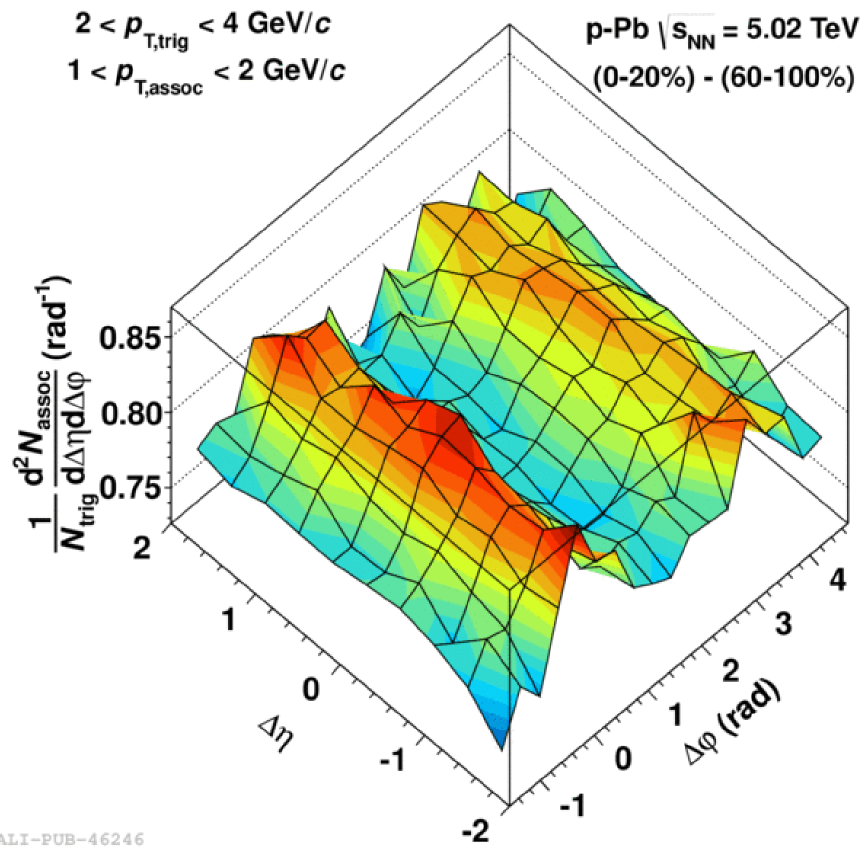
ALICE, PLB 719 (2013) 29



0-20%



60-100%

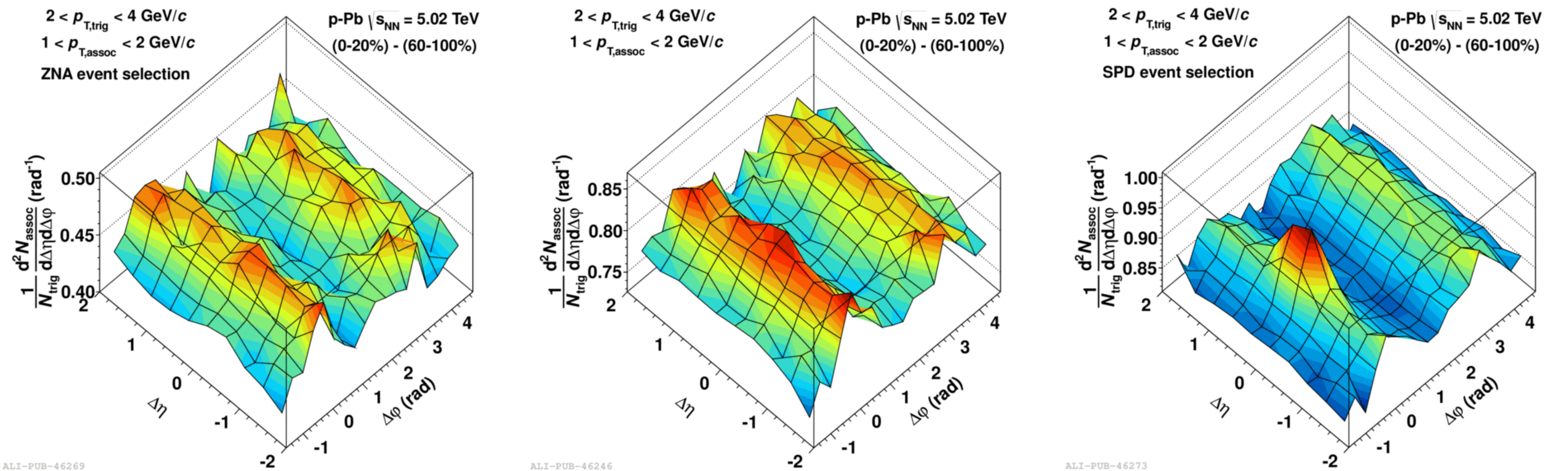


- Extract double ridge structure using a standard technique in AA collisions, namely by subtracting the jet-like correlations
  - It has been verified that the 60-100% class is similar to pp
  - The near-side ridge is accompanied by an almost identical ridge structure on the away-side

DHC: Two ridges

ALICE, PLB 719 (2013) 29

- A residual jet peak at (0,0) remains even after subtraction of 60-100% from the 0-20% multiplicity class
- Compare effects using different event class definition

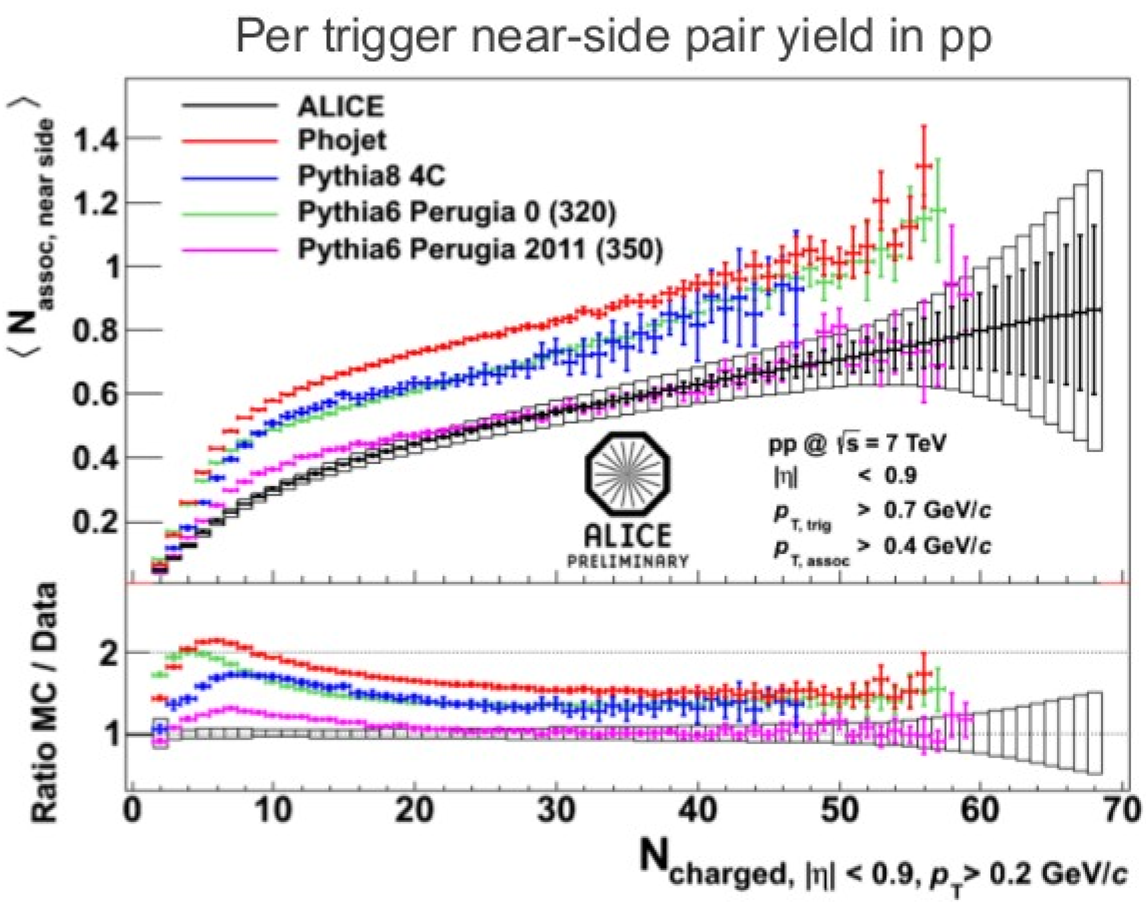


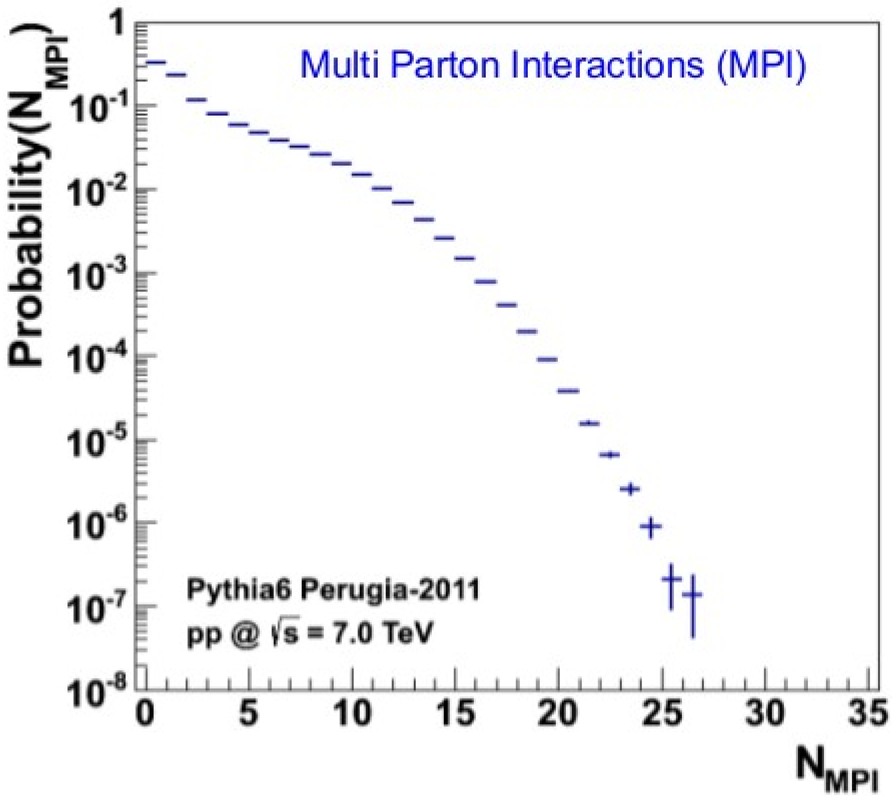
ZNA VZERO SPD

auto-correlation →

← η separation

DHC: Selection bias on fragmentation (pp) 11

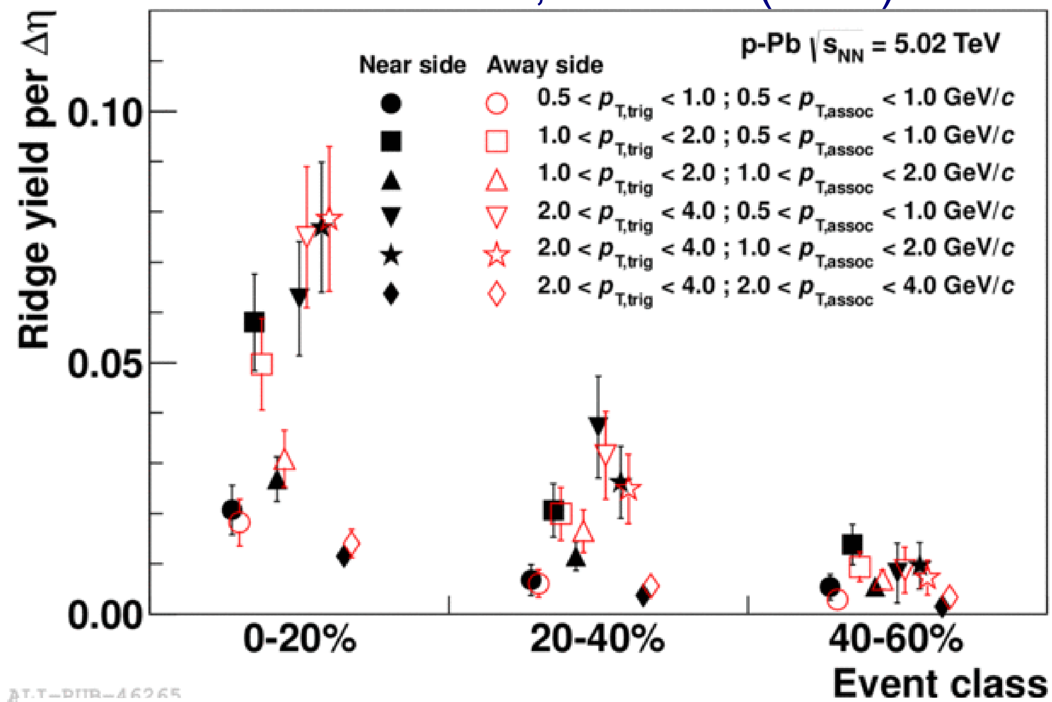


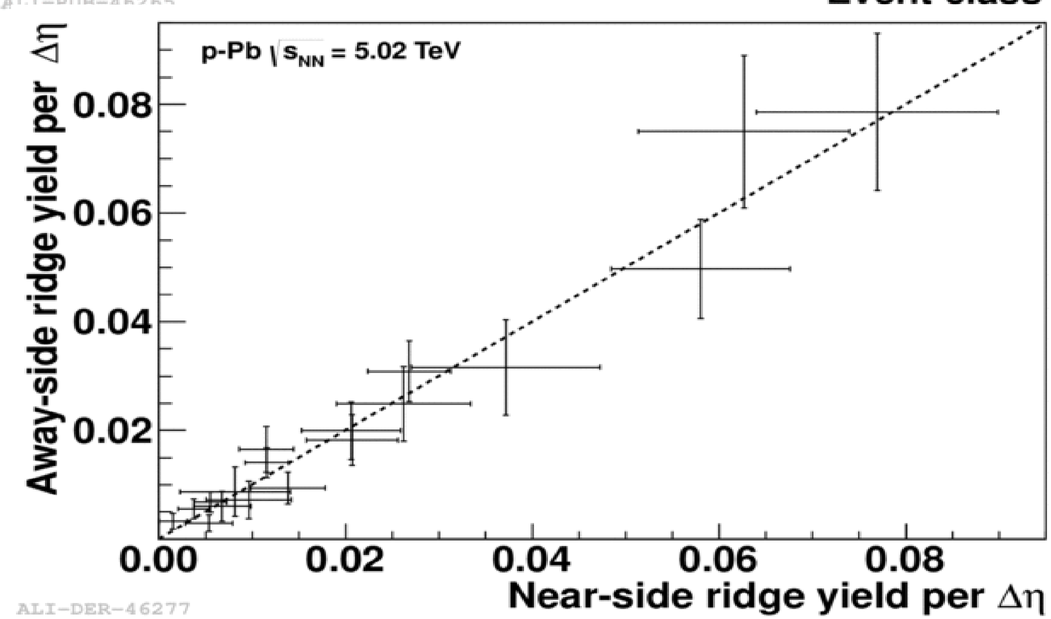


- By selecting on multiplicity, jet fragmentation is biased towards higher number of fragmenting products
- Competition between higher number of MPI and fragmentation

DHC: Ridge yields

ALICE, PLB 719 (2013) 29



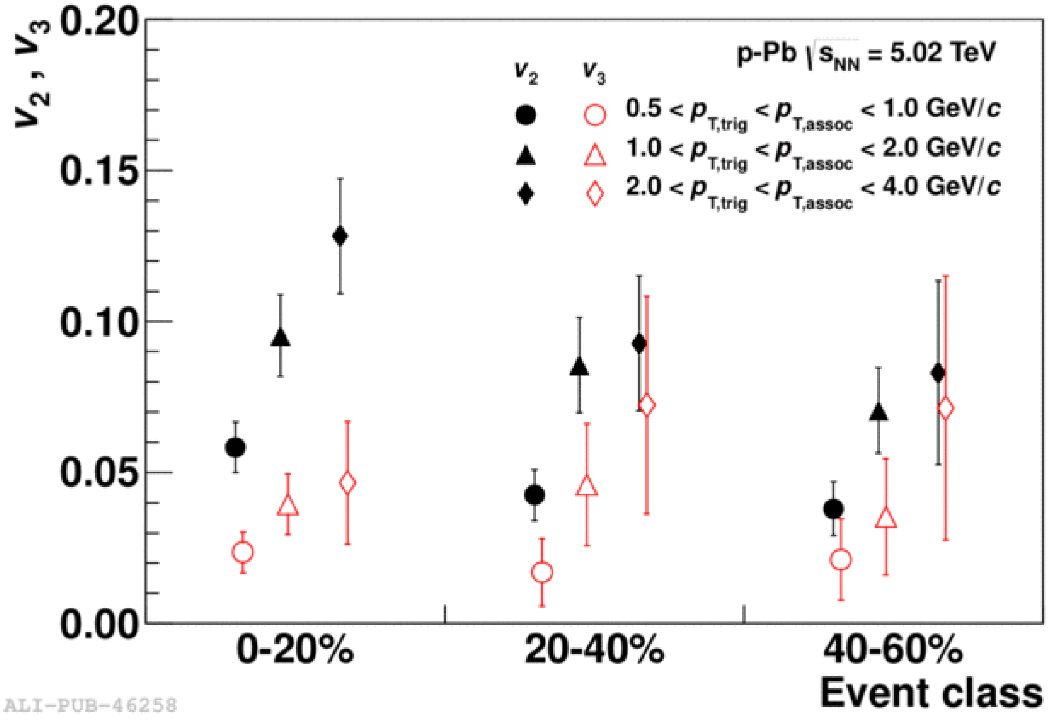


- Integrate two ridges above baseline on the
  - Near side (|Δ|<π/2)
  - Away side (π/2<|Δ|<3π/2)
- Near and away-side ridge yields
  - Change significantly
  - Agree for all p_T and multiplicity ranges
  - Increase with trigger p_T and multiplicity
  - Widths are approximately the same (not shown)
- The correlation between near- and away-side yields suggests a common underlying origin

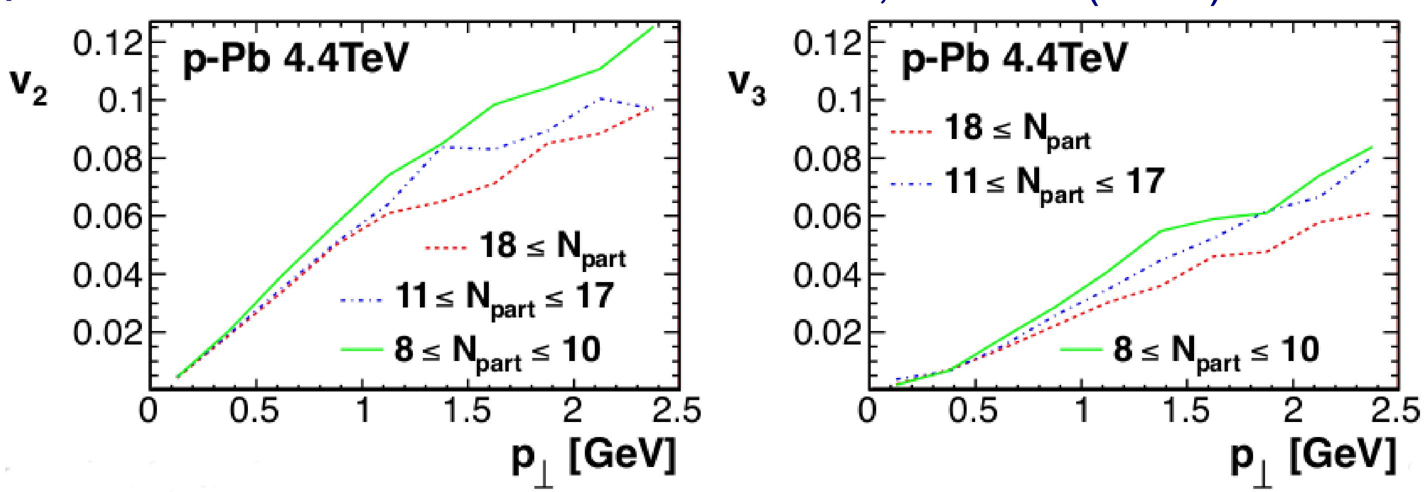
DHC: Ridge v_2 and v_3 and Hydro

ALICE, PLB 719 (2013) 29

- Obtain $v_n = \sqrt{(a_n/b)}$ from $a_0+2a_2\cos(2\Delta\varphi)+2a_3\cos(3\Delta\varphi)$ fit where b is baseline in higher multiplicity class
  - v_2 increases strongly with p_T and mildly with multiplicity
  - v_3 increases with p_T within large uncertainties
  - The p_T dependences are in qualitative agreement with hydrodynamical predictions

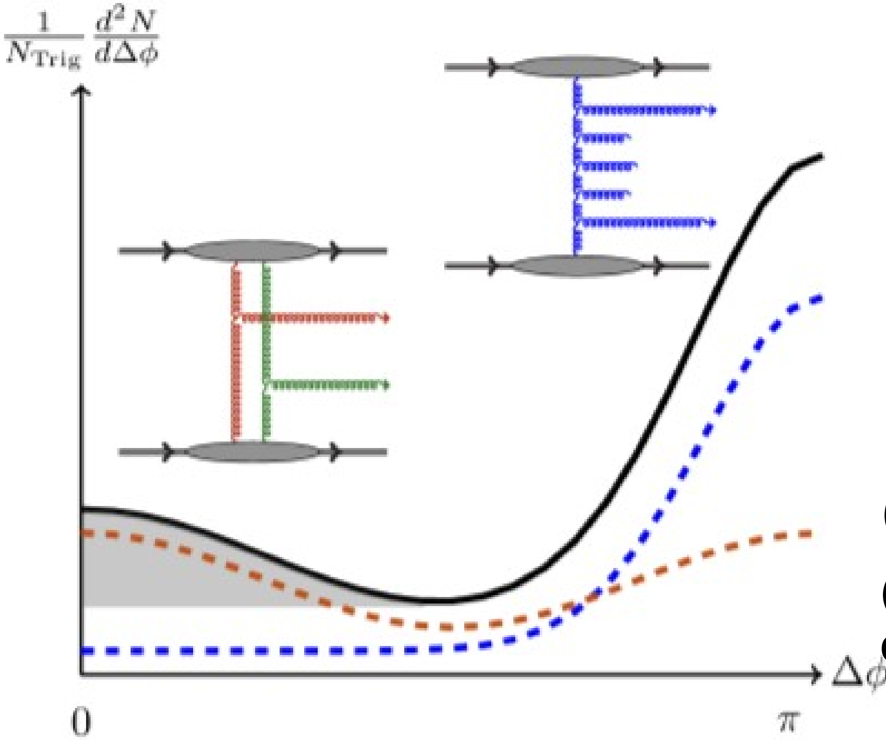


Bozek, PRC 85 (2012) 014911



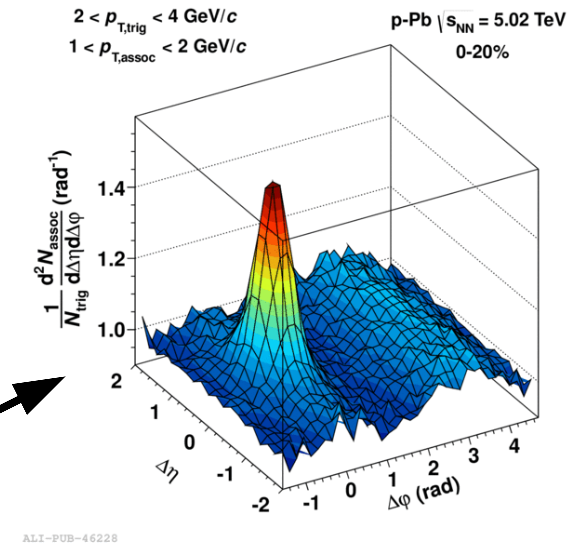
DHC: Ridge v_2 and v_3 and CGC

- Two symmetric ridges predicted by CGC glasma graphs found to describe the ridge yields and shape

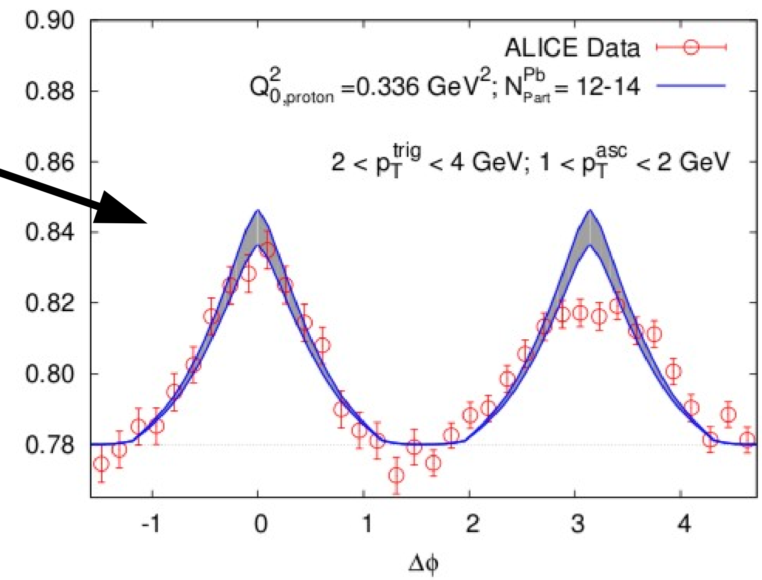


Dusling and Venugopalan, arXiv:1302.7018

BFKL-Minijets



Glasma (enhanced by α_s^{-8} for $k_T < Q_s$)



- However, a large v_3 component may be a challenge for the model

Identified particle spectra

Shuryak and Zahed, arXiv:1301.4470

From Edward's summary slide at BNL RBRC workshop:

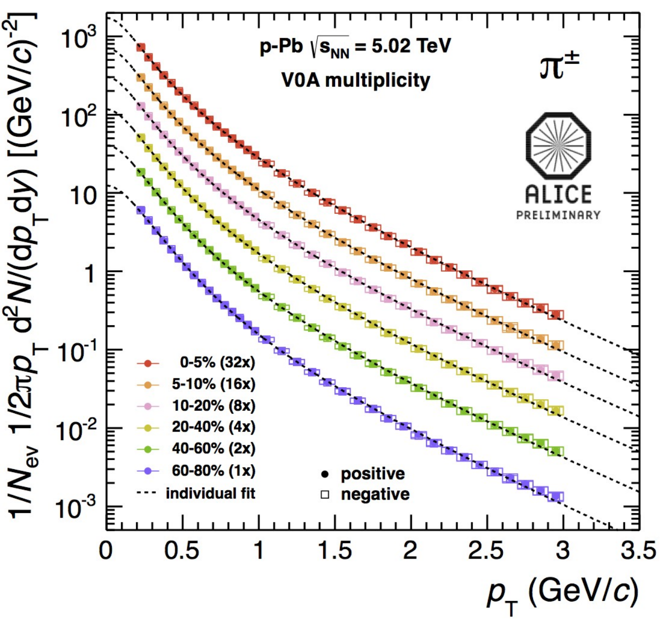
- the applicability of hydrodynamics rests on two small parameters: (i) **the micro-to- macro ratio 1/TR, (ii) the viscosity-to-entropy ratio η/s.** For central AA collisions, both are O(1/10). For high multiplicity pA and pp collisions, the first parameter is no longer small 1/TR = O(1), prompting us to ask which hydrodynamical predictions are preserved by the smallness of only the second parameter η/s.

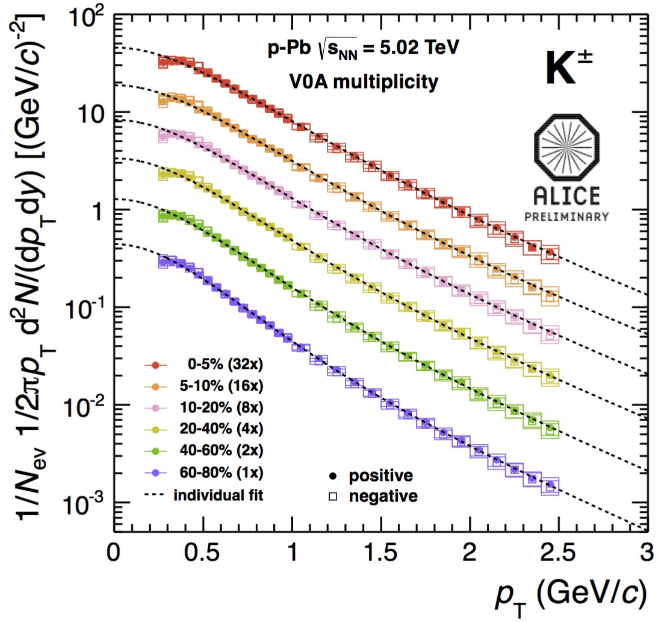
- After solving the hydrodynamical equations we found that **the radial (axially symmetric) flow is little modified by viscosity and is in fact enhanced** by higher transverse gradients. Thus our main prediction is an enhanced radial flow => a change in the observed pt spectra on the particle mass, or growing proton-to-pion-ratio with pt. The magnitude of the effect should be even larger **(=> ALICE ?)**

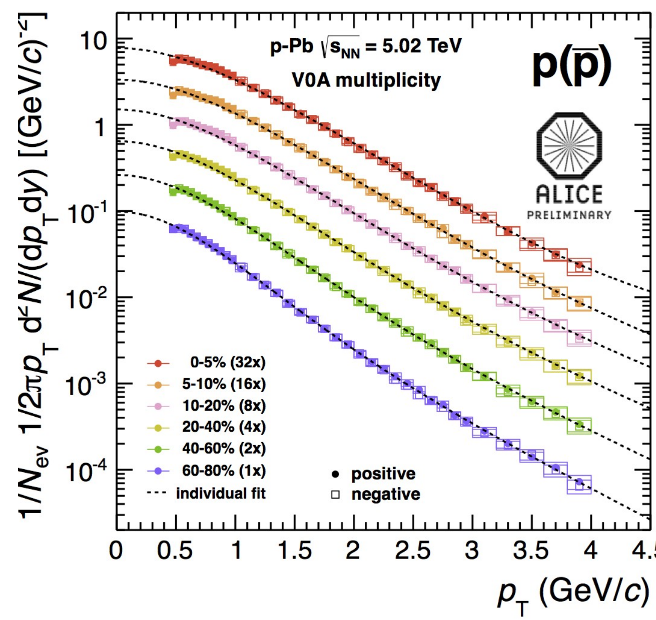
- **Higher harmonics are penalized by larger viscous corrections**. We obtained explicit solution for Gubser flow for m = 2, 3, 4 as shown in Fig.5. We have found a small v3/v2 ≈ 1/3 ratio for pA in agreement with the reported ALICE data (in contrast to v3/v2 >1 in central AA). The value of v2 itself is also suppressed by viscosity, and the relative suppression we have found between the pp and pA collisions agree reasonably with the CMS data.

Identified particle p_T spectra

ALICE preliminary (Trento)

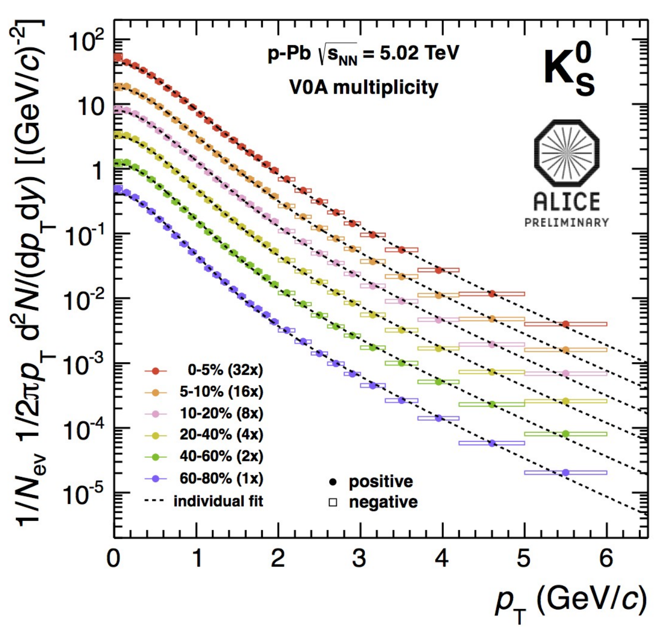


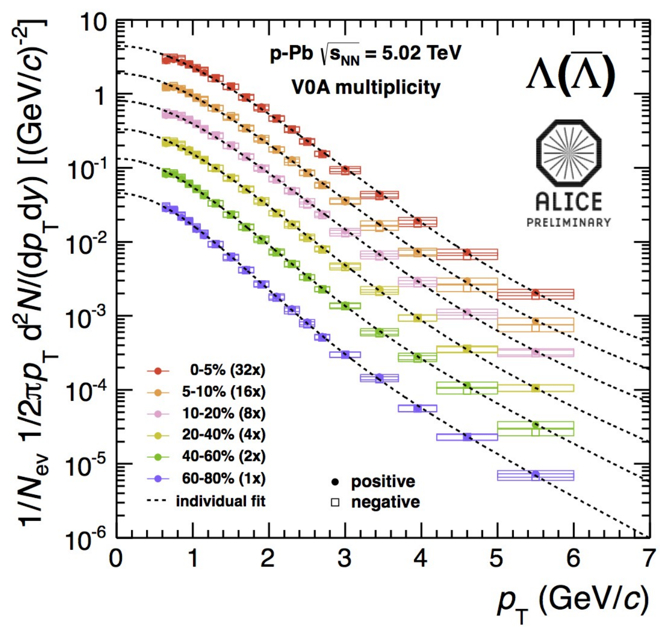




p_T spectra in several V0A multiplicity classes

$\pi^{\pm}$	0.2 – 3.0 GeV/c
$K^{\pm}$	0.25 – 2.5 GeV/c
$p(\bar{p})$	0.45 – 4.0 GeV/c
K^0_S	0 – 6.0 GeV/c
$\Lambda(\bar{\Lambda})$	0.6 – 6.0 GeV/c

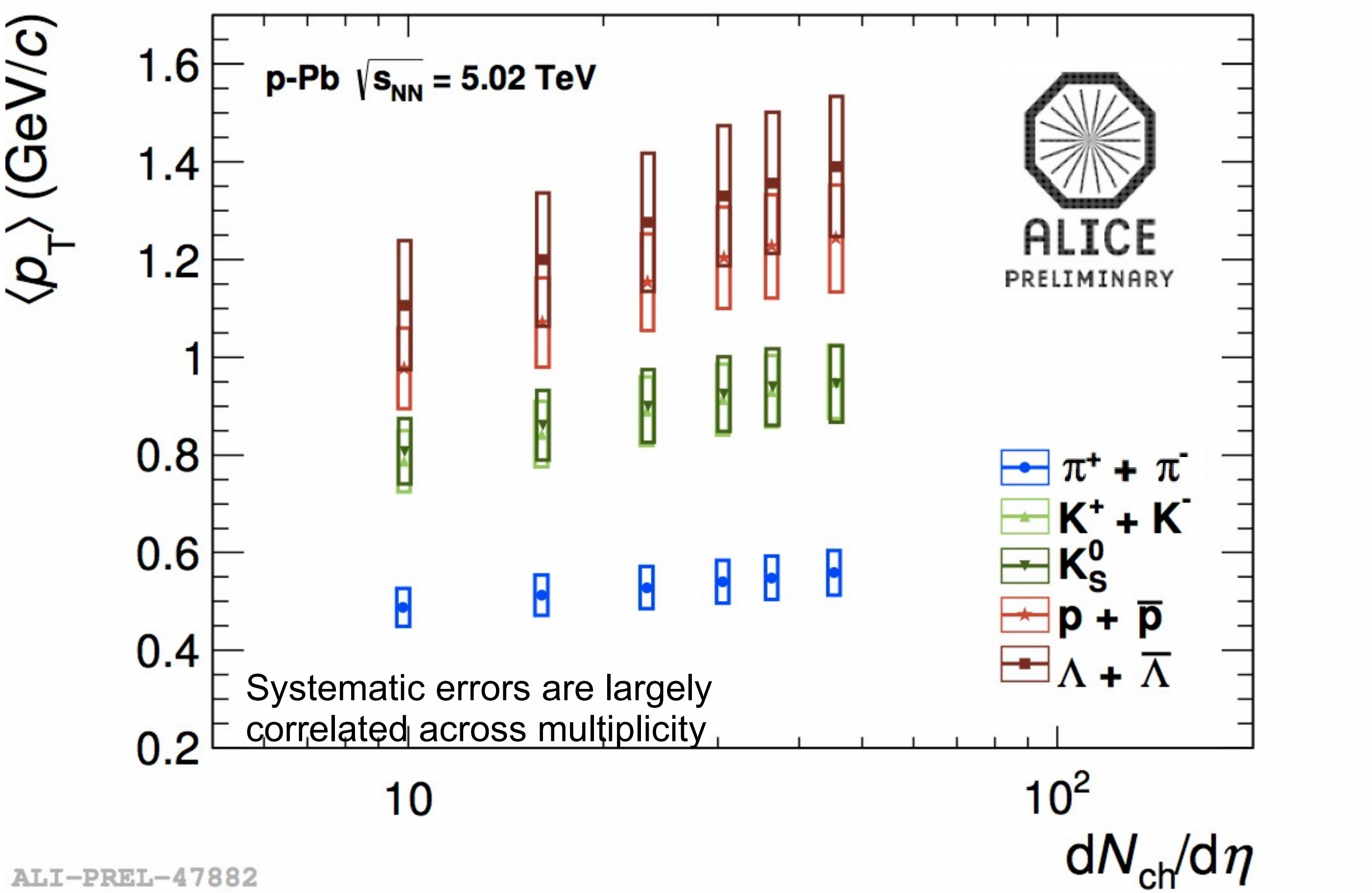




Dotted lines are individual (BW) fits for low-p_T extraplation

Average p_T vs $dN_{ch}/d\eta$ in pPb

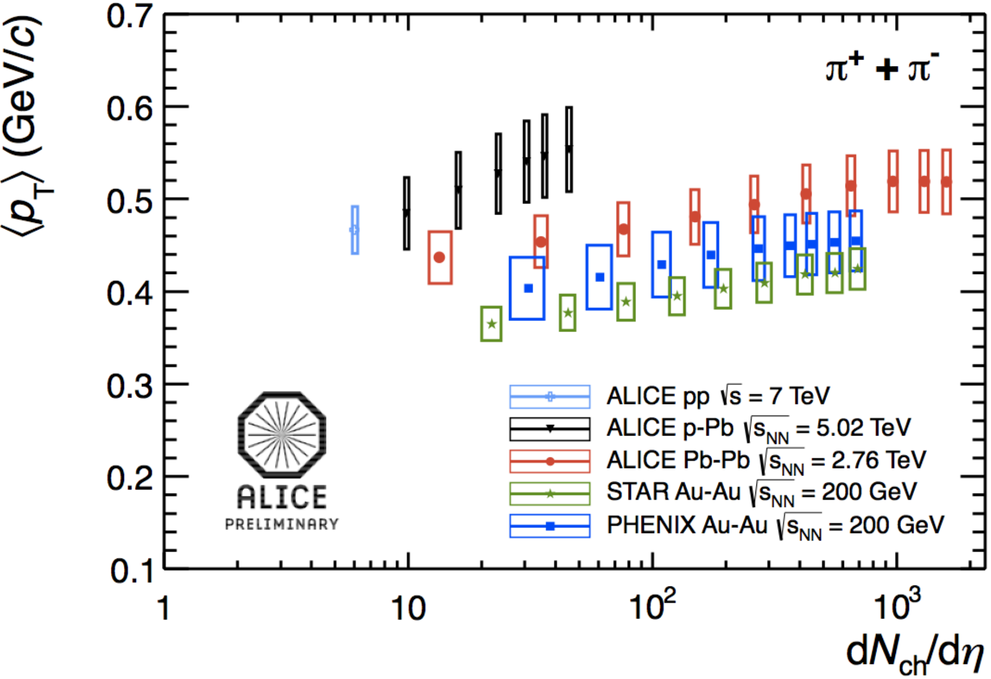
ALICE preliminary (Trento)

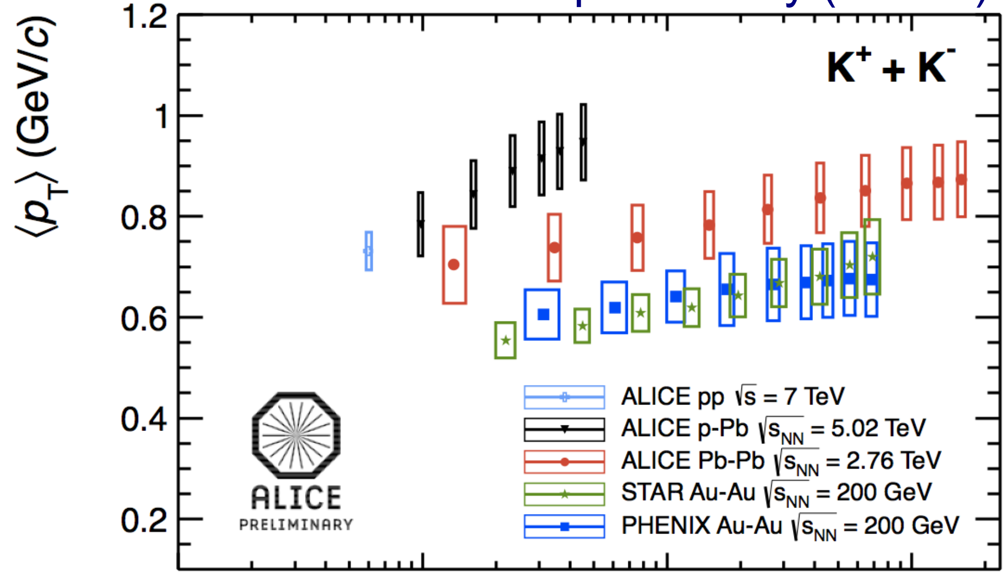


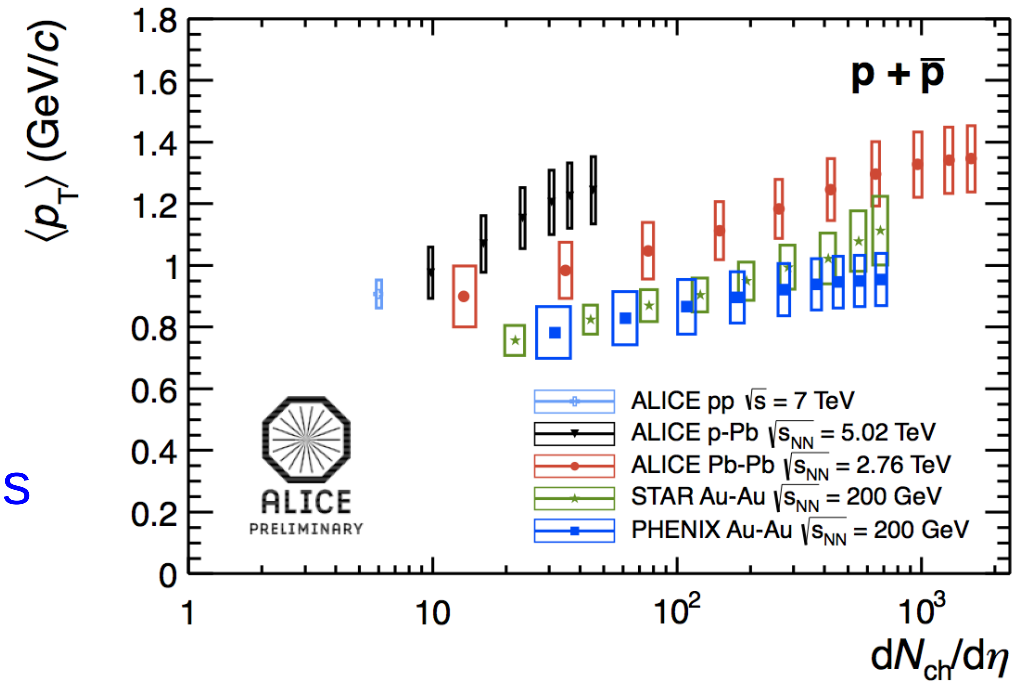
- Average p_T increases with multiplicity in all V0A multiplicity classes
- Mass ordering: Larger mass also larger average p_T
- Generators implementing incoherent superposition of nucleon collisions do not describe the data (not shown)

Average p_T vs $dN_{ch}/d\eta$ for various systems

ALICE preliminary (Trento)





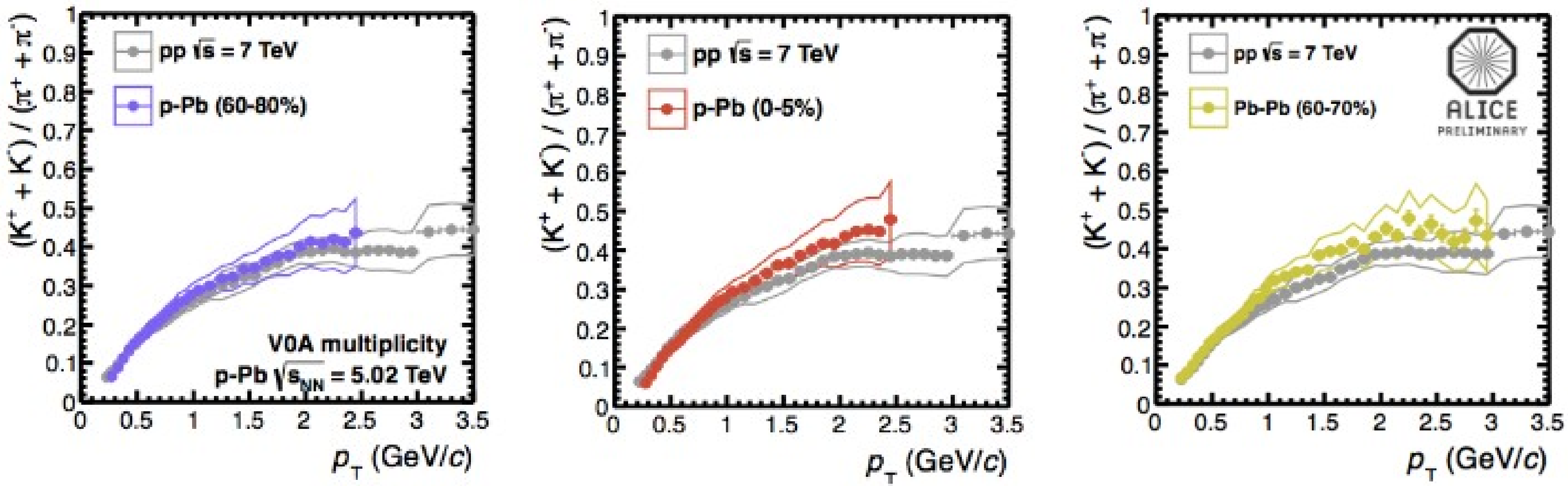


- Average p_T values higher than for PbPb at the same multiplicity
- Minimum bias pp point in line with pPb trend
- Caveat: Different collision energies

Kaon-to-pion ratio

Systematic errors are largely correlated across multiplicity

ALICE preliminary (Trento)

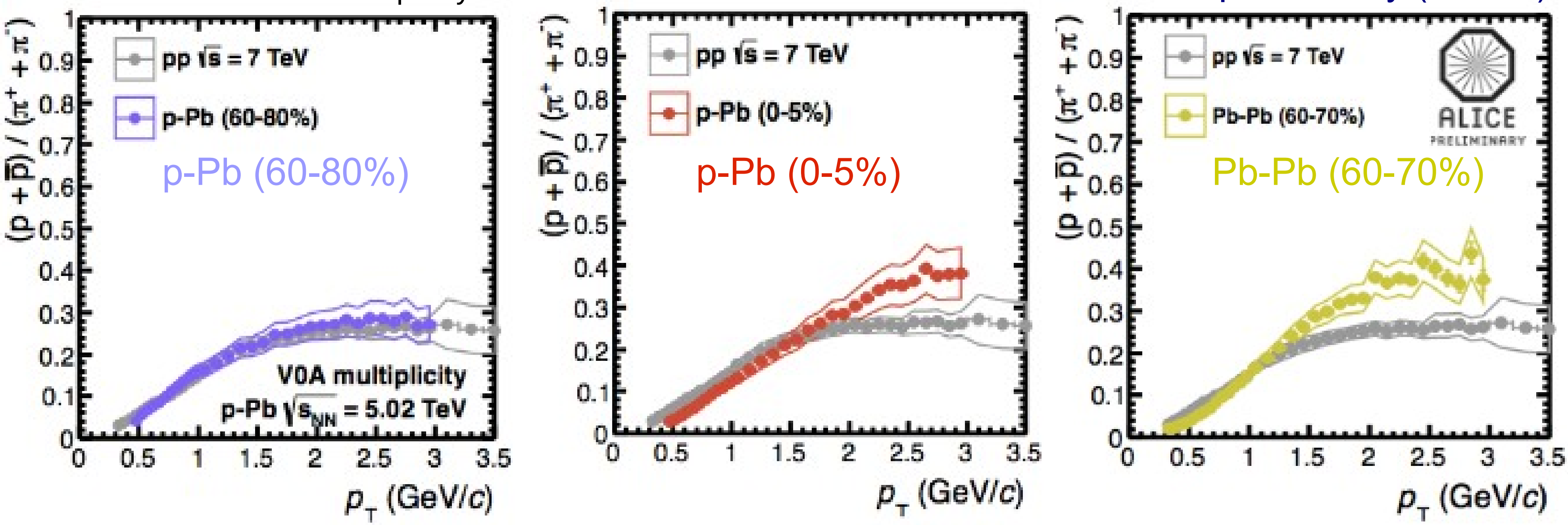


- Ratio shows weak evolution with multiplicity in pPb
  - Small increase at intermediate p_T with increasing V0A multiplicity
  - Corresponding small depletion in the low-p_T region
- Hints that similar behavior as observed in PbPb collisions

Proton-to-pion ratio

Systematic errors are largely correlated across multiplicity

ALICE preliminary (Trento)

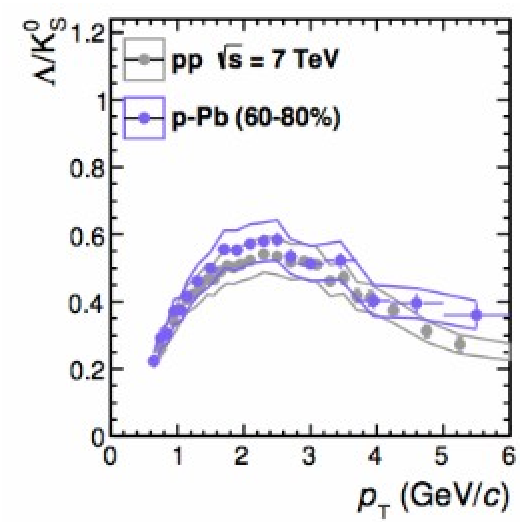


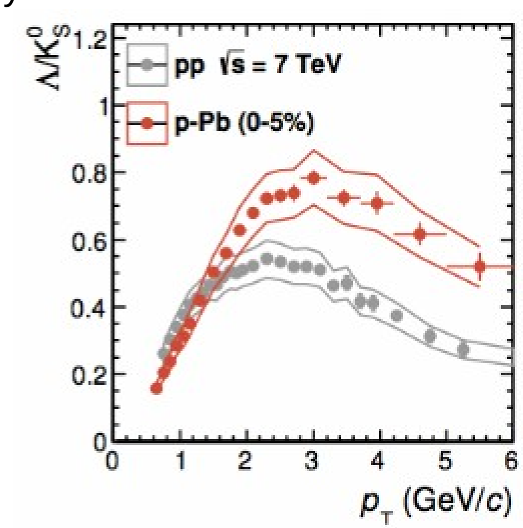
- Ratio shows similar p_T dependence as observed in peripheral PbPb
  - Significant increase at intermediate p_T with increasing V0A multiplicity
  - Corresponding significant depletion in the low-p_T region
- Dependence in Pb-Pb usually explained by radial flow
  - Dependence in pPb qualitatively as expected by eg. Shuryak and Zahed, arXiv:1301.4470

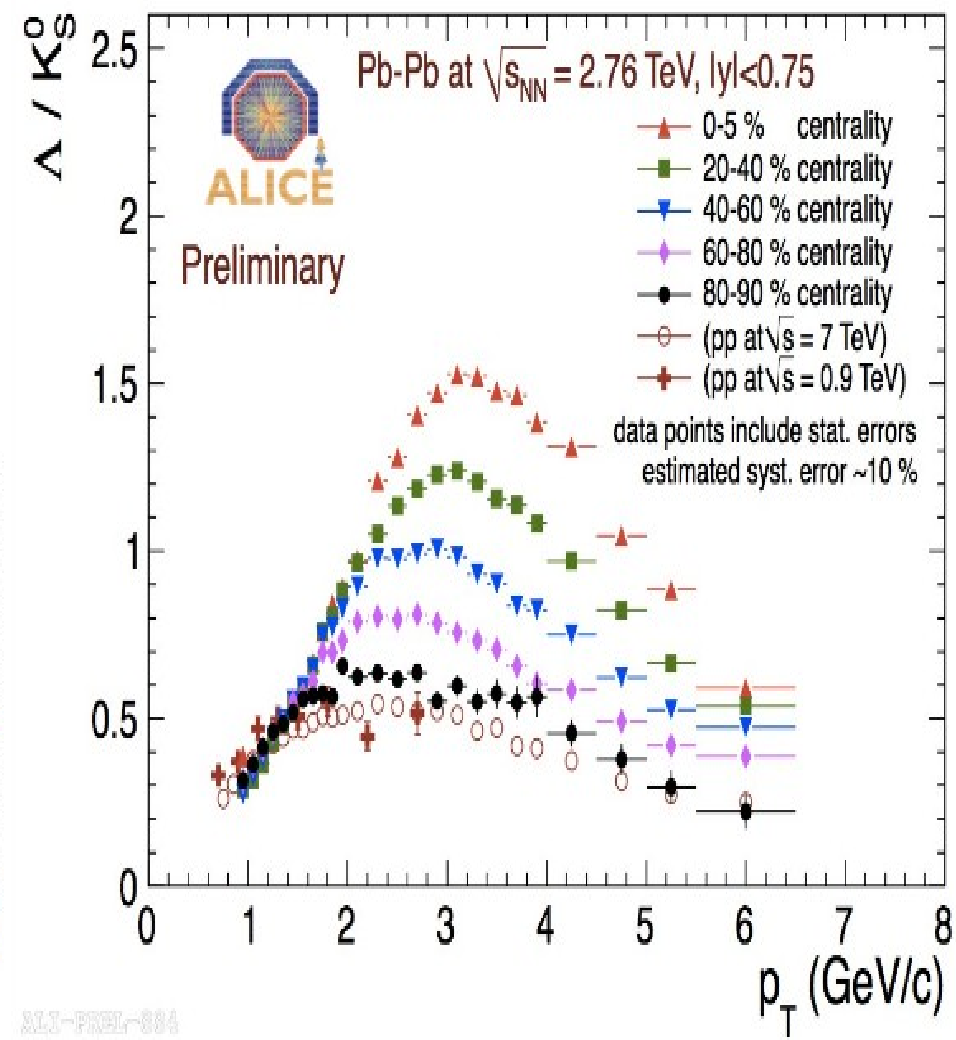
ALICE preliminary (Trento)

- Clear evolution of Λ/K^0_s ratio with increasing V0A multiplicity
- Also this is reminiscent of a similar trend observed in AA
- In AA this is generally explained by collective flow and parton recombination

Systematic errors are largely correlated across multiplicity







Spectra shape analysis: pPb

π/K/p spectral-shape analysis:

- performed with hydro-motivated Blast-Wave model

Schnedermann, PRC 48, 2462 (1993)

aims at characterizing spectral shapes in V0A multiplicity classes with a small set of parameters

- simultaneous fit of all particles with 3 parameters

$\langle\beta_T\rangle$ radial flow

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 0.3 – 1.5 GeV/*c*

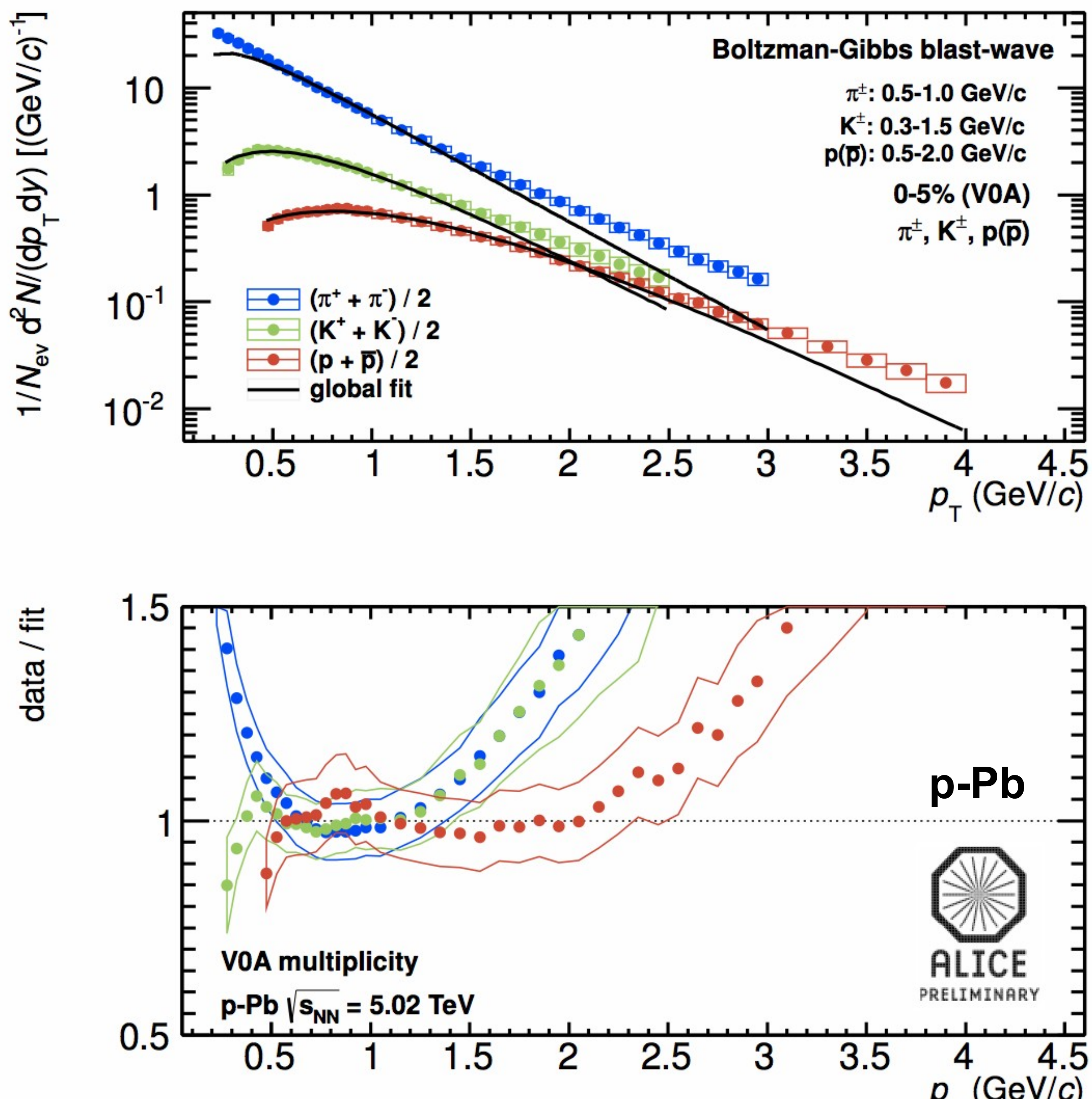
p 0.5 – 2.0 GeV/*c*

- Blast-Wave fits reasonable, though not very good

worse than central Pb-Pb

better than pp minimum bias

ALICE preliminary (Trento)



ALI-PREL-47407

Global Blast-Wave fit parameters

π/K/p spectral-shape analysis:

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)

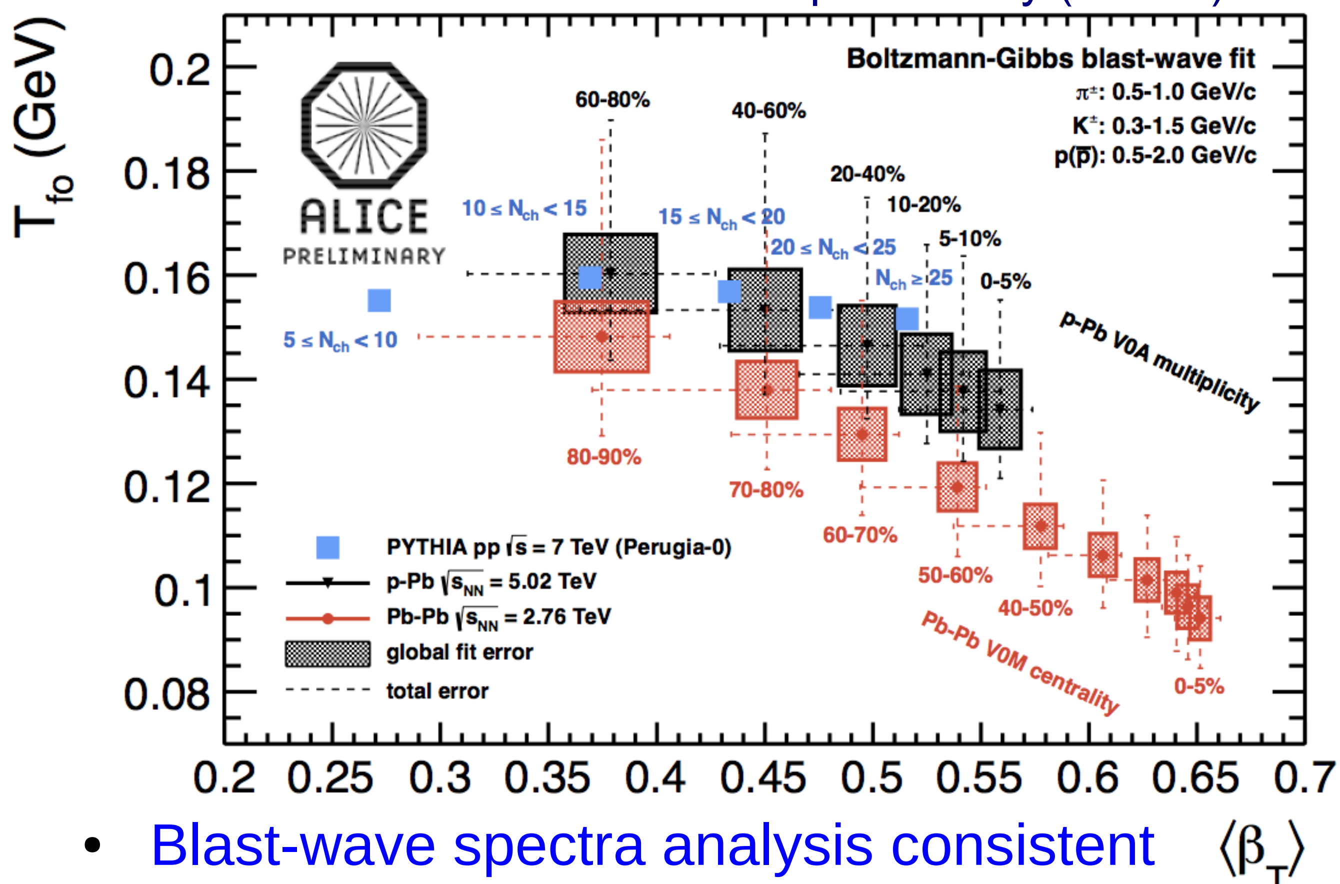
  aims at characterizing spectral shapes in V0A multiplicity classes with a small set of parameters
- simultaneous fit of all particles with 3 parameters

  $\langle\beta_T\rangle$ radial flow
  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 0.3 – 1.5 GeV/c
  p 0.5 – 2.0 GeV/c
- Blast-Wave fits reasonable, though not very good

  worse than central Pb-Pb
  better than pp minimum bias

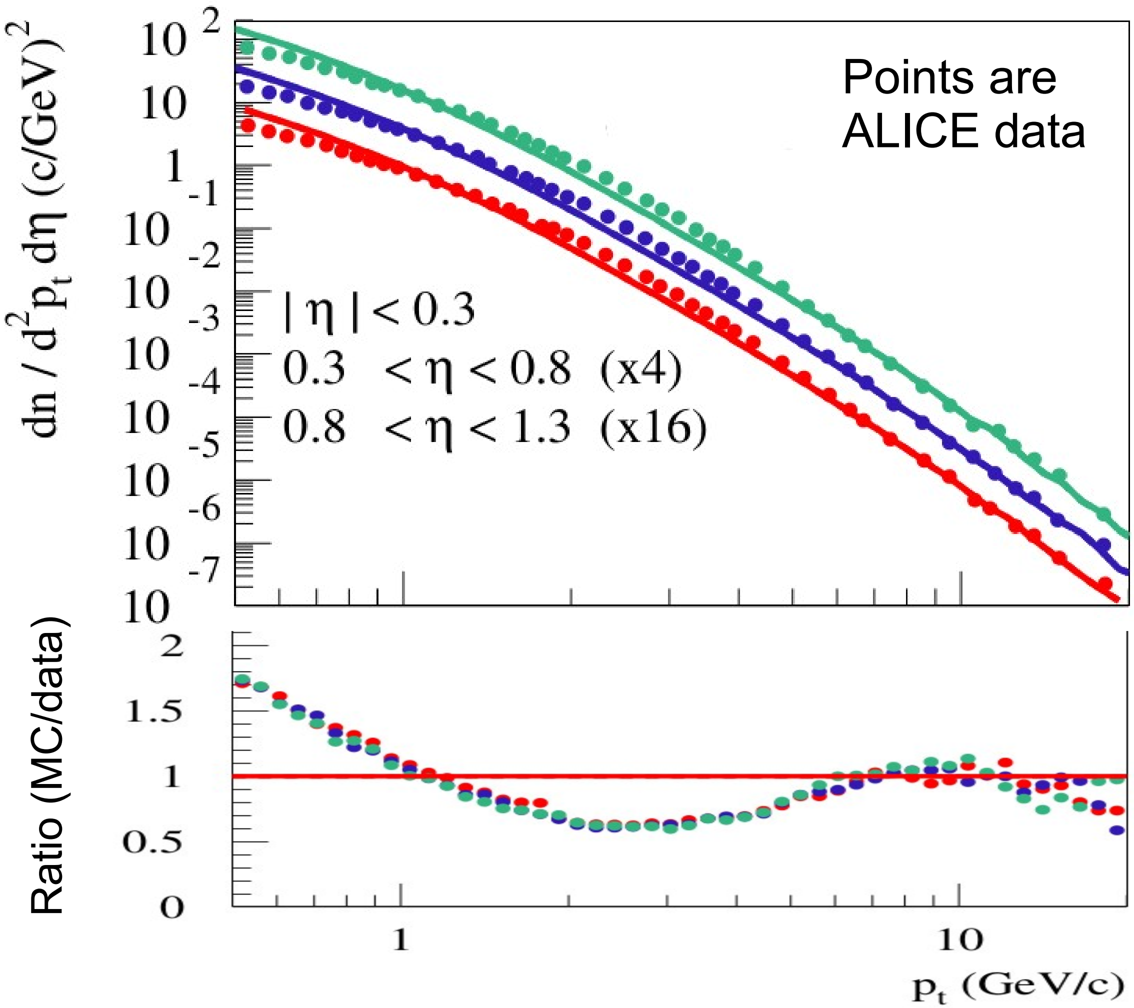
ALICE preliminary (Trento)



- Blast-wave spectra analysis consistent with radial flow present in pPb as in PbPb
- Not fully conclusive as also exhibited by PYTHIA (with color reconnections)
  - Caveat: MC sliced in track slices
  - 7 TeV pp data being worked on

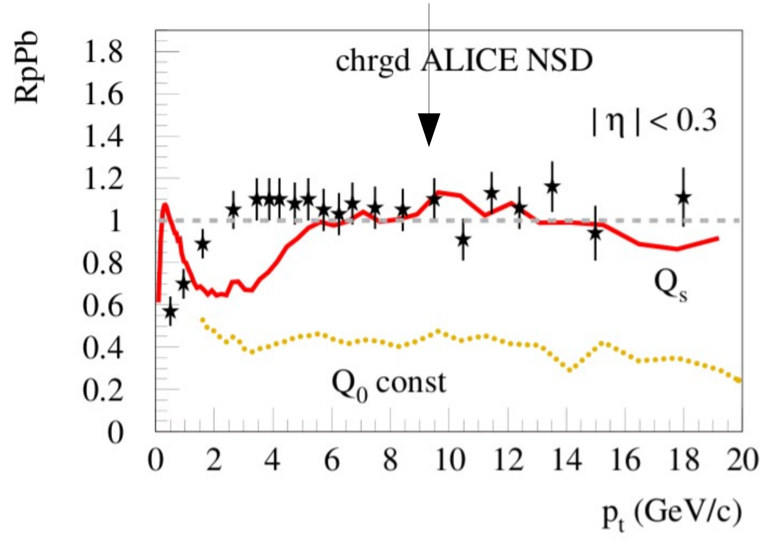
Saturation vs hydro: Which do we see?

Werner et al., EPOS3 (Trento)



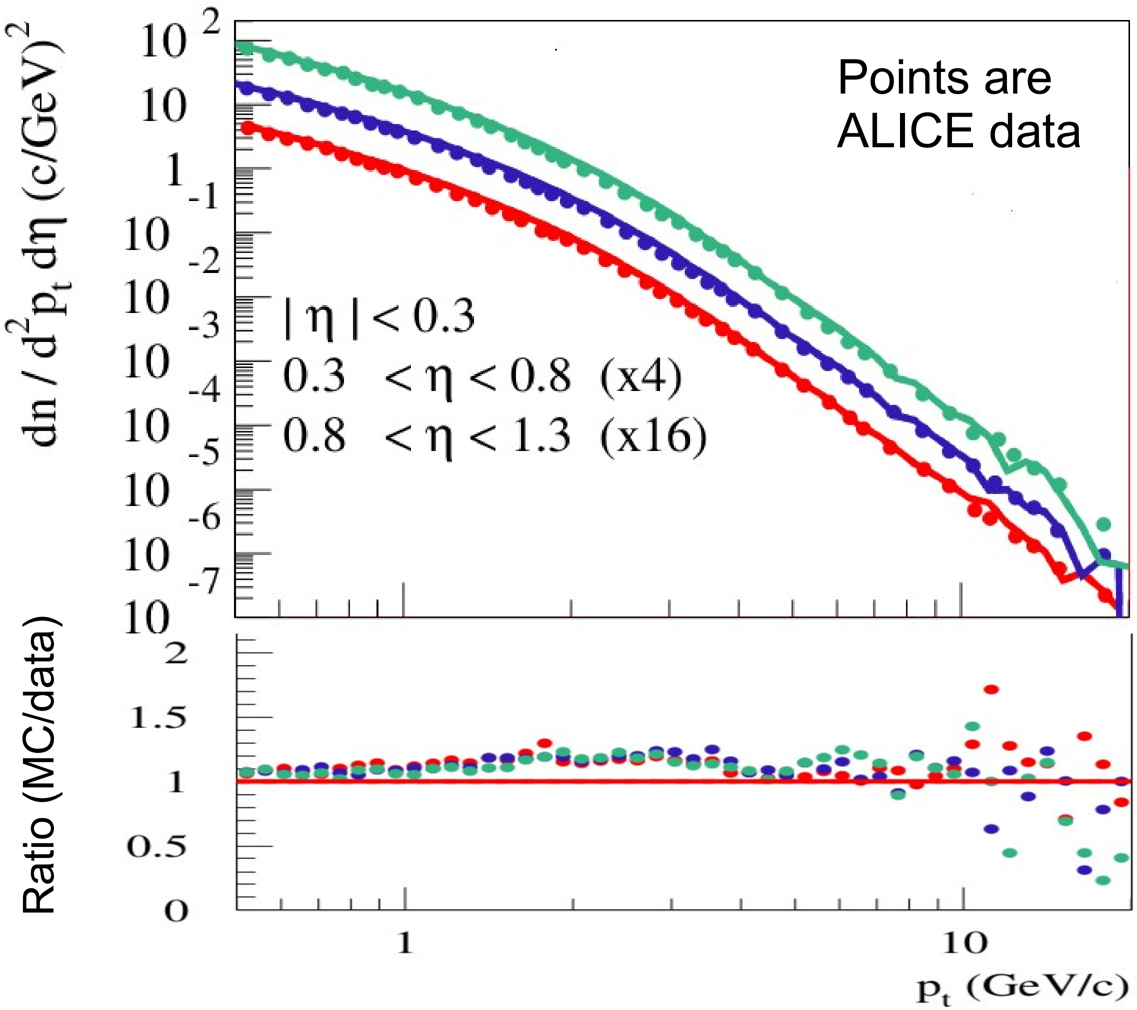
Measured spectra not described in low p_T region

- EPOS version 3
  - Gribov-Regge multiple scattering ansatz plus energy-momentum conservation with fixed scale breaks binary scaling
  - Introduction of ladder-by-ladder dependent saturation scale restores binary scaling



Saturation vs hydro: Which do we see?

Werner et al., EPOS3 (Trento)



- EPOS version 3
  - Gribov-Regge multiple scattering ansatz plus energy-momentum conservation with fixed scale breaks factorization
  - Introduction of ladder-by-ladder dependent saturation scale restores factorization
  - Integration of 3D viscous hydrodynamics allows to also describe low-p_T region

Probably data show us aspects of both!

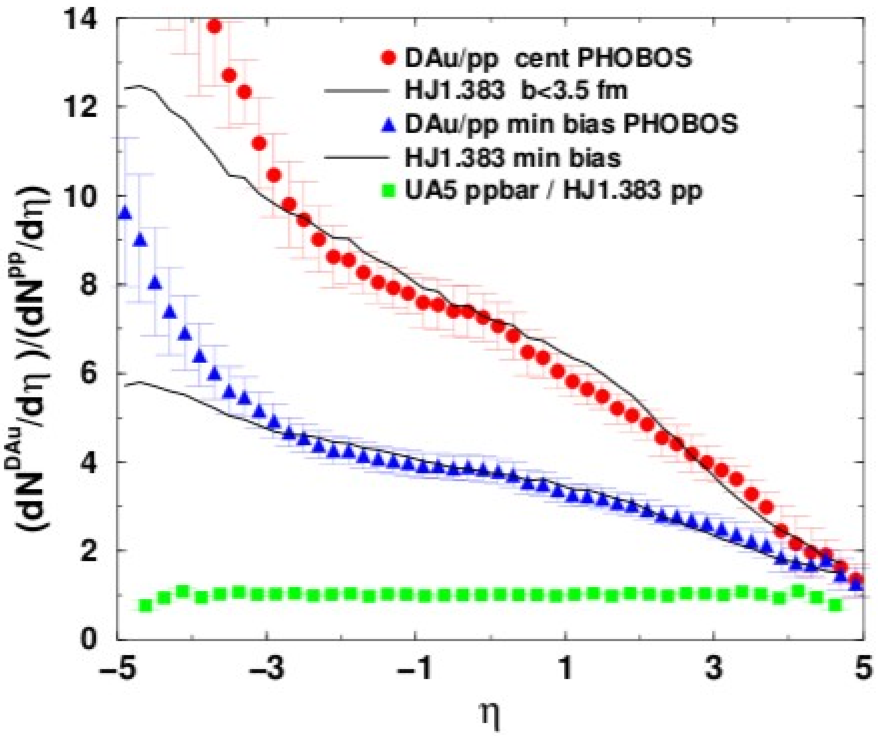
Summary

- Correlation analyses in pA started fundamental debate of initial and final state effects in high-multiplicity events
  - It is not inconceivable that we see aspect of both
- PID spectra consistent with radial flow and generally show trends also observed in peripheral PbPb
  - Outlook: Analysis of 7 TeV pp data (ongoing)
- Further pPb measurements expected soon
  - Identified particle v2
  - HBT radii

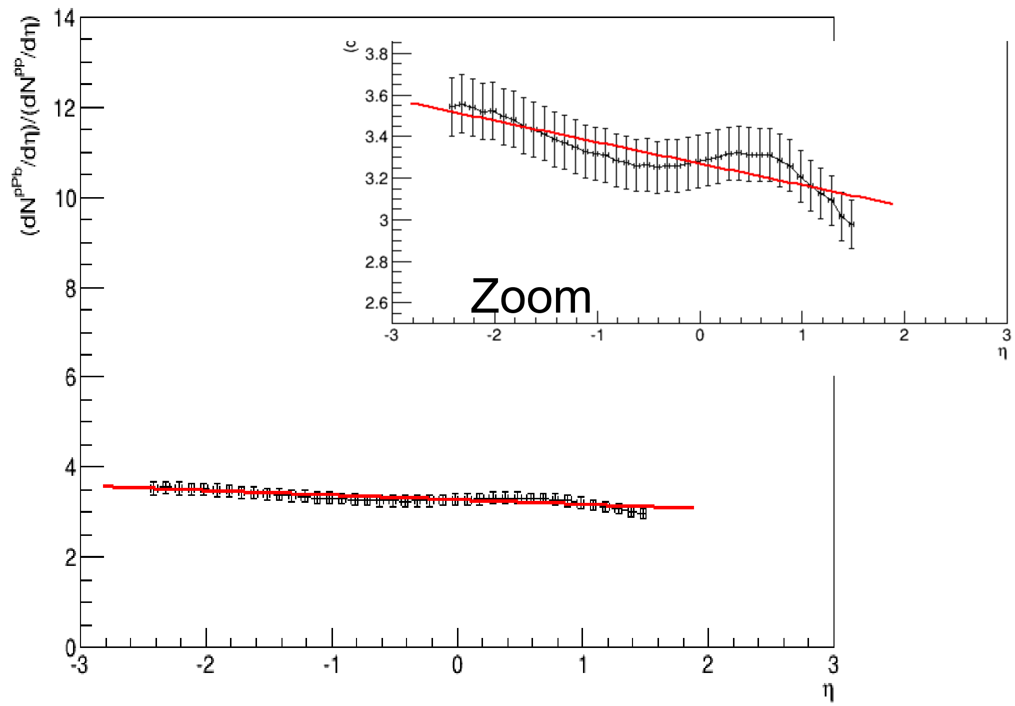
Extra

p+A triangle

Adil and Gyulassy, PRC 72 (2005) 034907



Ratio: ALICE pPb over scaled fit

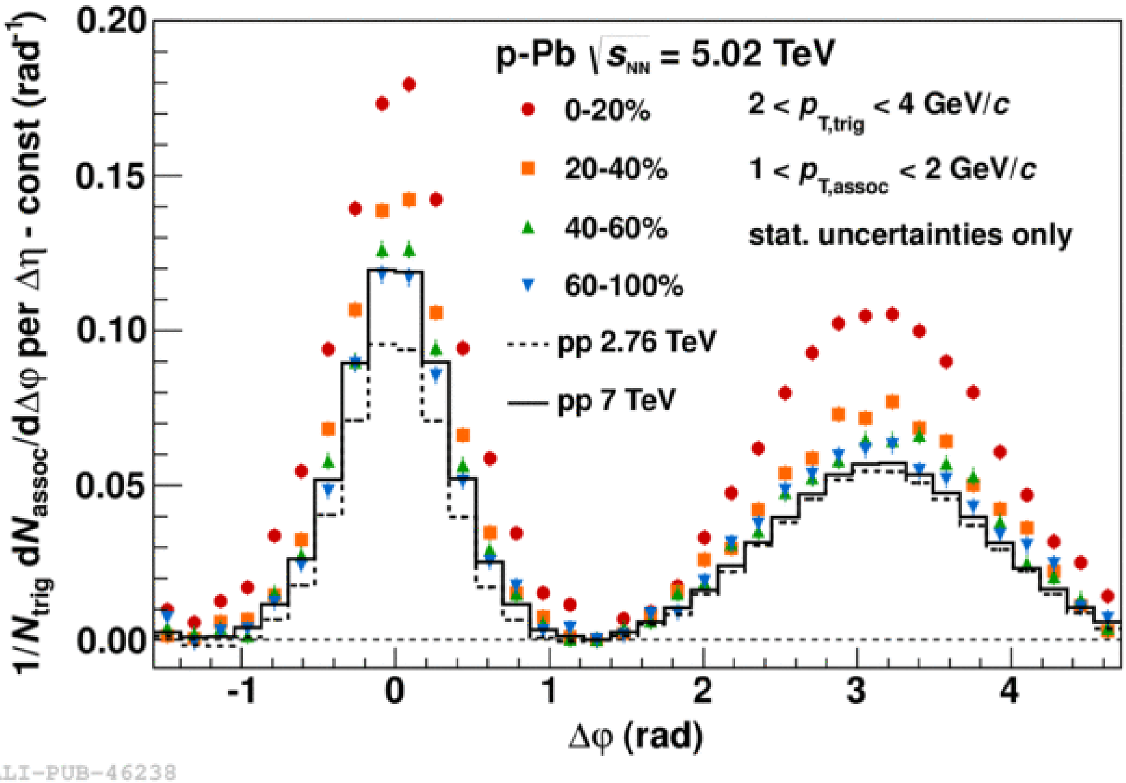


- Ratio obtained from
  - ALICE pPb data shifted to cm system (ΔY=0.467) and mirrored
  - NSD pp reference from CMS 2.36 fit by double Gaussian, scaled by 1.17 (~$s^{0.11}$)
    - Errors on ratio are just errors from pPb
- Value at Y=8.5 from linear fit: 4.2 ($A^{1/3}$≈6)

DHC: Multiplicity dependence

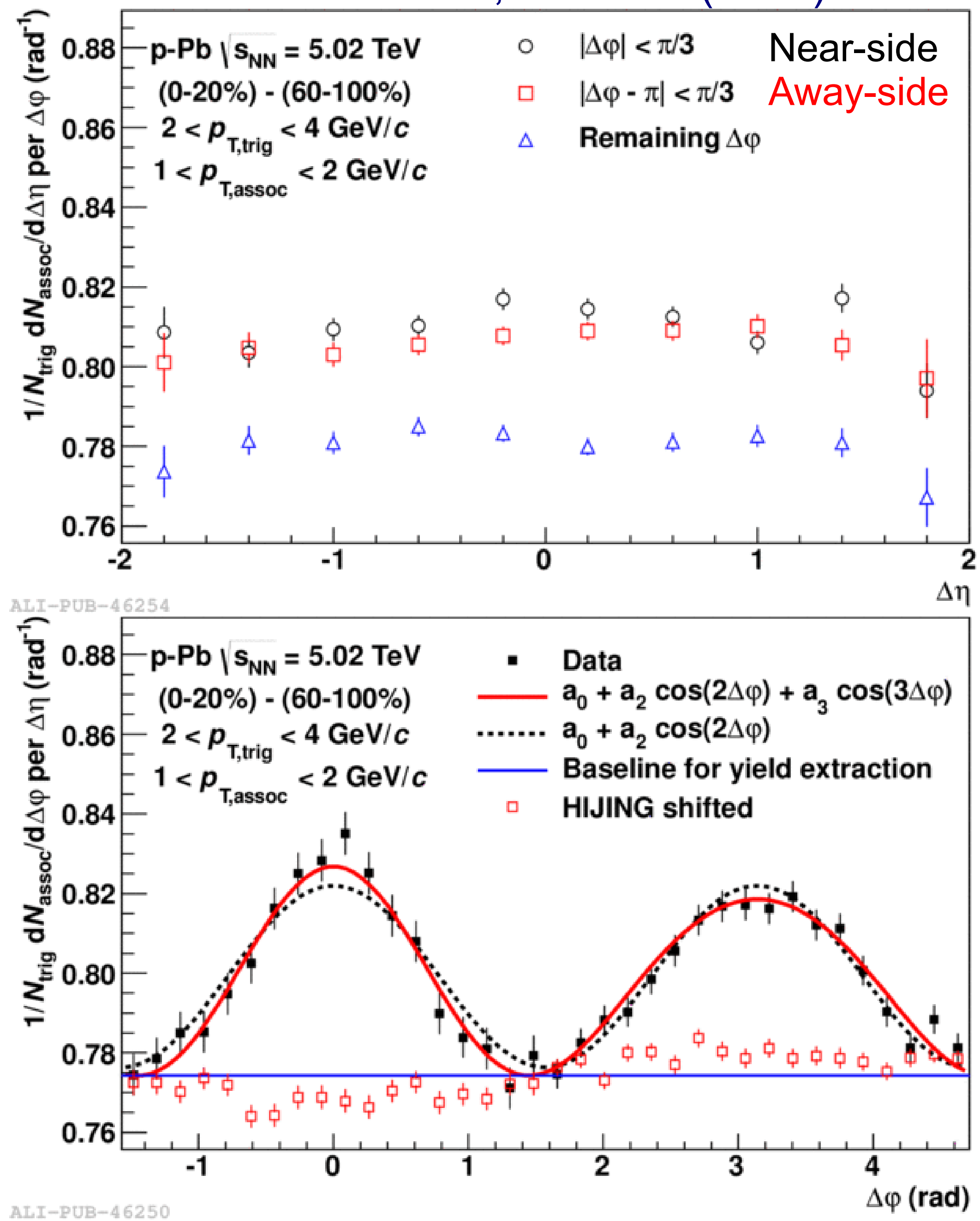
ALICE, PLB 719 (2013) 29

- Compare associated yield in pPb multiplicity classes and pp
  - Project to Δφ over |Δη|<1.8
  - Subtract baseline at Δφ~1.3
- Low multiplicity pPb is similar to pp (at 7 TeV)
- Yield rises on near and away side with increasing multiplicity
- In contrast with away-side suppression observed in dAu at RHIC at forward η (similar x)



- A closer look at the two ridges: the near- and away-side ridges
  - Are essentially flat in Δη
    - Slight excess on near side due to small residual jet peak
  - Have the same magnitude
- Projection to Δφ
  - Exclude residual peak (|Δη<0.8| on near-side) exhibits a modulation
  - In HIJING, the correlation shows no qualitative changes with multiplicity
  - Quantify the ridges
    - Ridge yields
    - Fourier coefficients

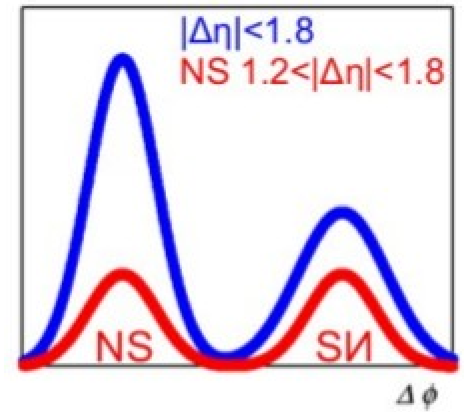
ALICE, PLB 719 (2013) 29

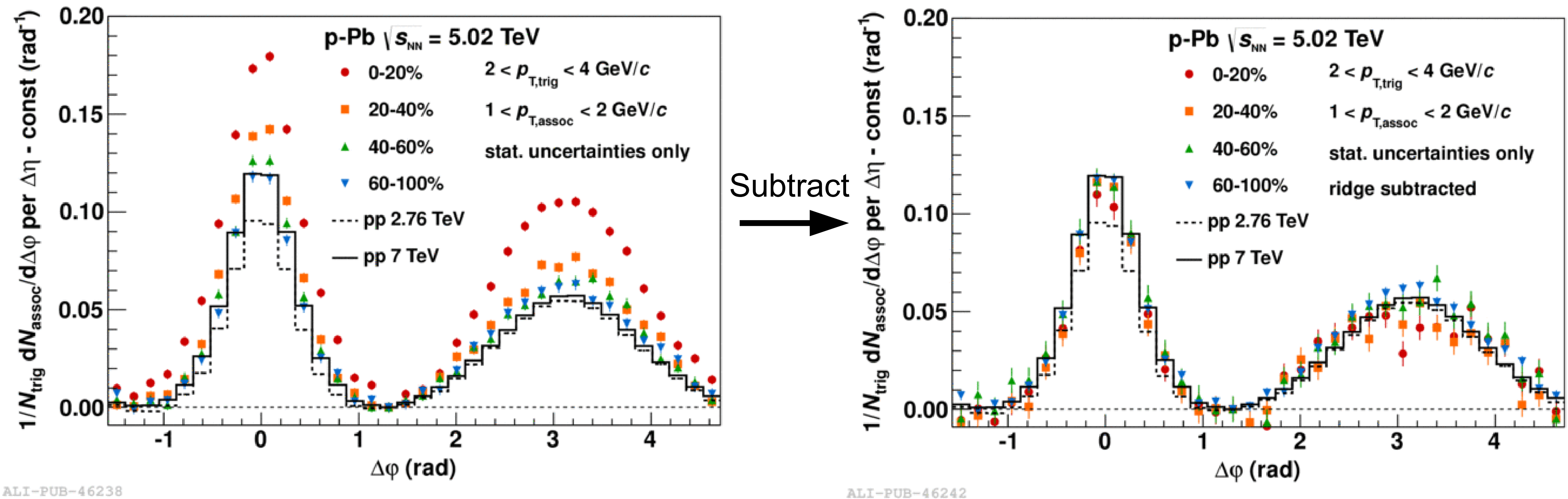


DHC: Symmetric ridge

ALICE, PLB 719 (2013) 29

- What would the assumption of a symmetric ridge give?
  - Determine the near-side ridge in $1.2 < |\Delta\eta| < 1.8$
  - Mirror to away-side and subtract



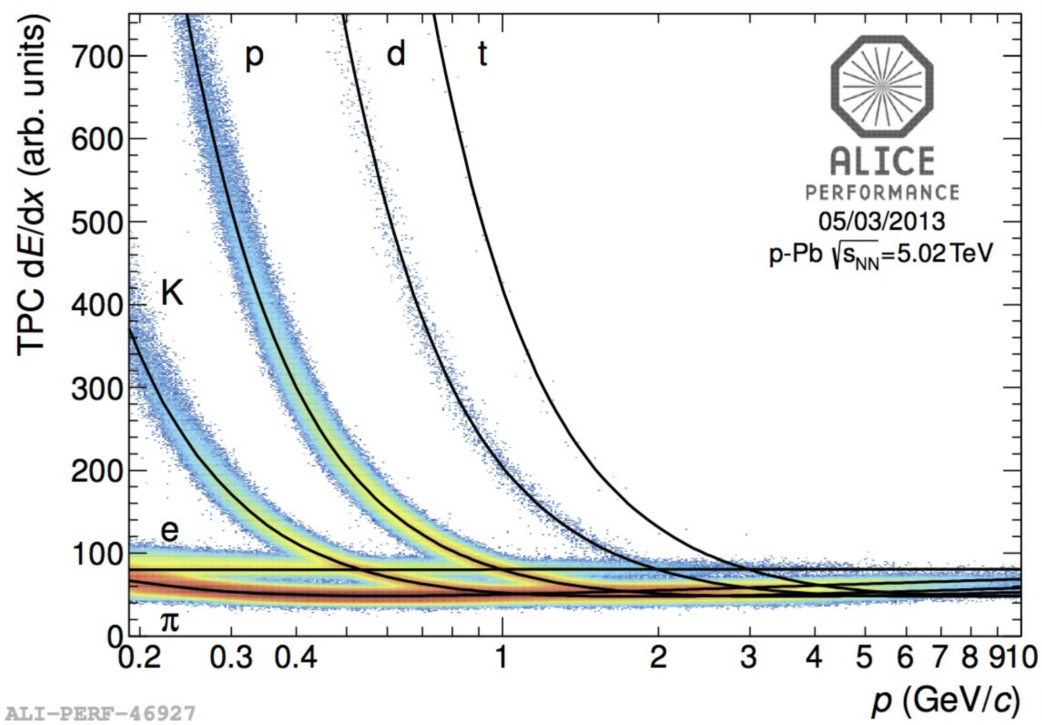


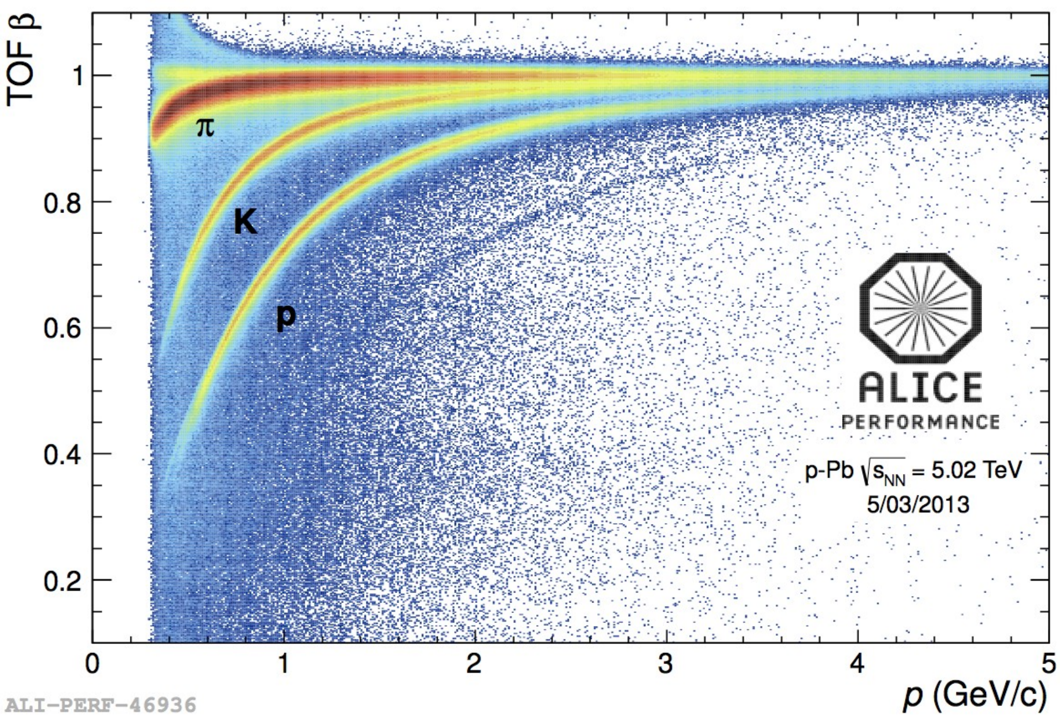
- No significant other multiplicity dependent structures left over

Particle-identification: $\pi^{\pm}$ $K^{\pm}$ $p(\bar{p})$

TPC: main tracking detector
PID via dE/dx in gas
up to 159 samples, σ ~5%

TOF: PID at intermediate momenta
PID via time-of-flight technique
σ < 100 ps
3σ K/π separation up to 2.5 GeV/c
3σ p/π separation up to 4.0 GeV/c

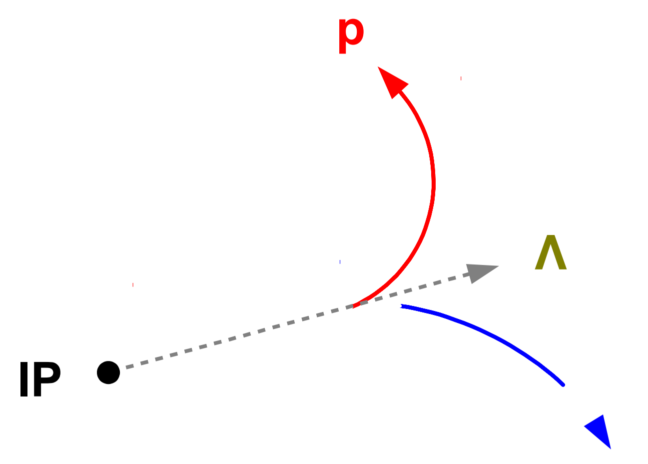




Topological reconstruction: K^0_S $\Lambda(\overline{\Lambda})$

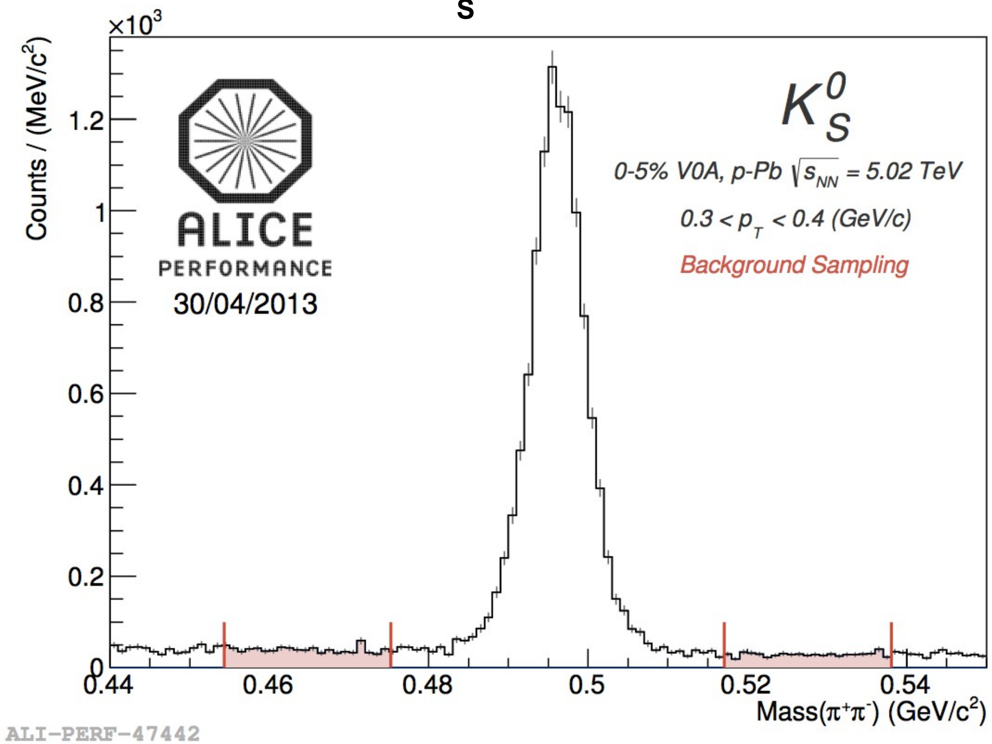
V0-decays: topological reconstruction identification over a large p_T range

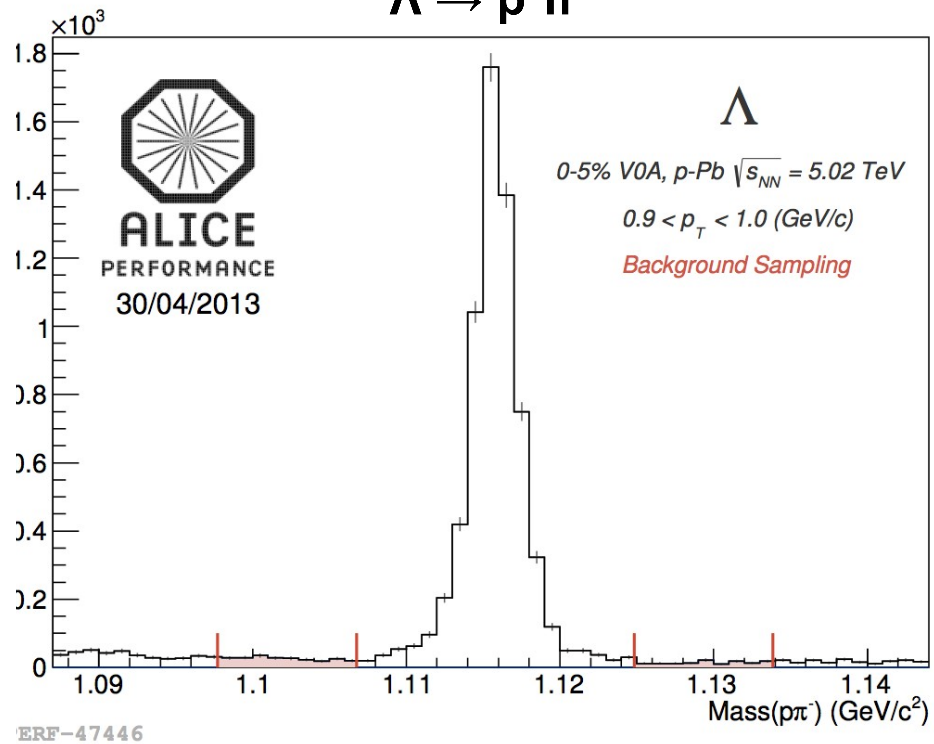
reconstruction of candidate weak-decays
TPC dE/dx selection of daughters
invariant mass extraction of signal



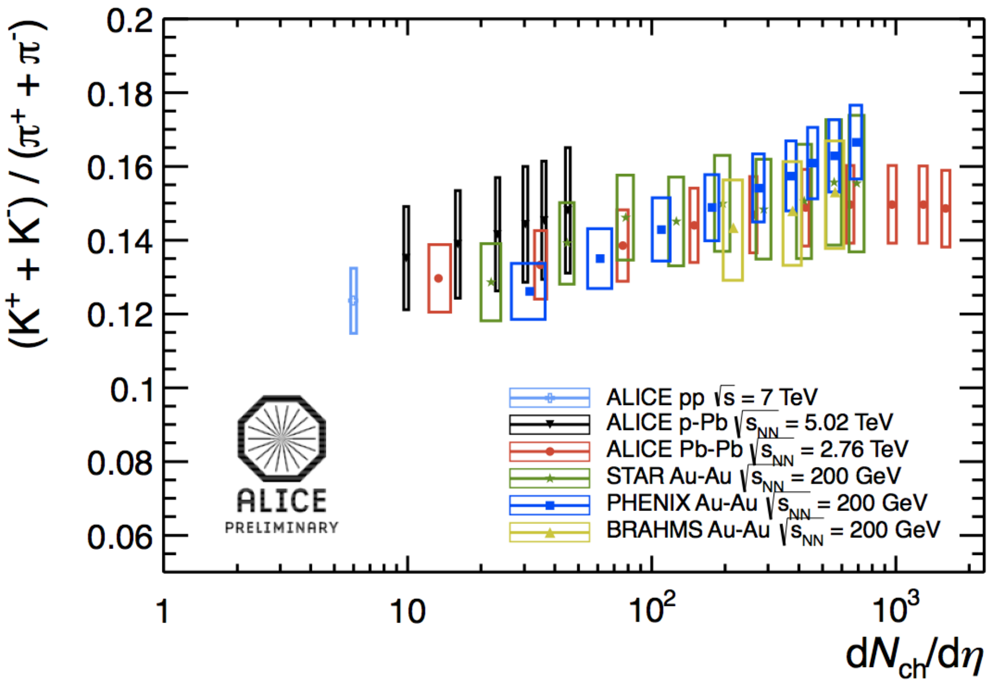
$K^0_S \rightarrow \pi^+ \pi^-$

$\Lambda \rightarrow p\, \pi^-$
$\overline{\Lambda} \rightarrow \overline{p}\, \pi^+$

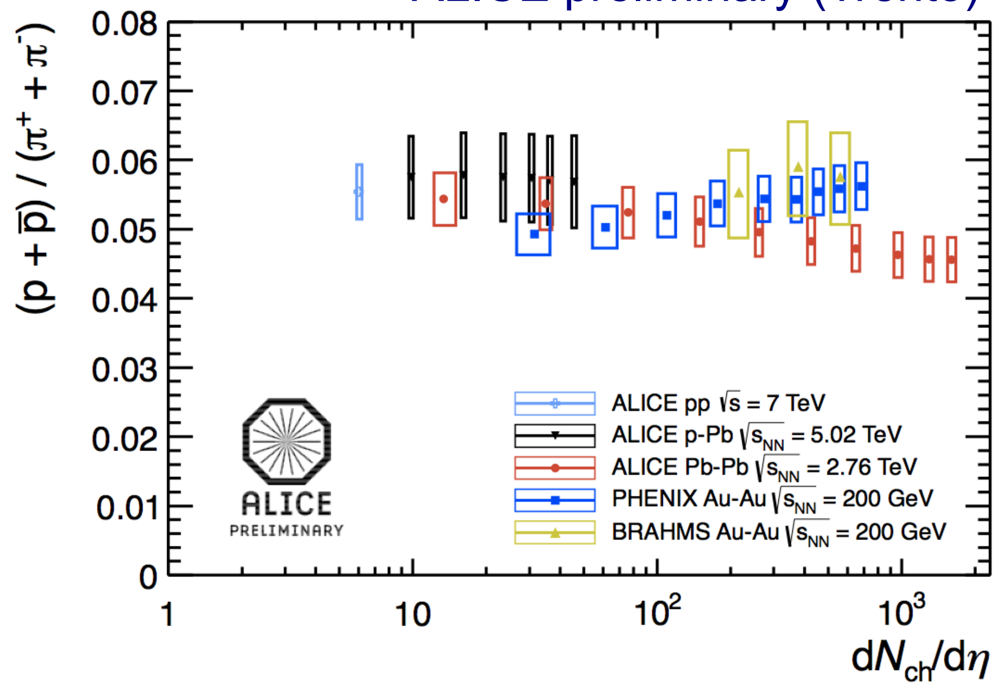




Particle ratios vs $dN_{ch}/d\eta$



ALICE preliminary (Trento)



K/π integrated ratio vs. $dN_{ch}/d\eta$:

- in line with the trend of Pb-Pb and lower-energy RHIC results
- hints at a small increase with multiplicity also in p-Pb collisions

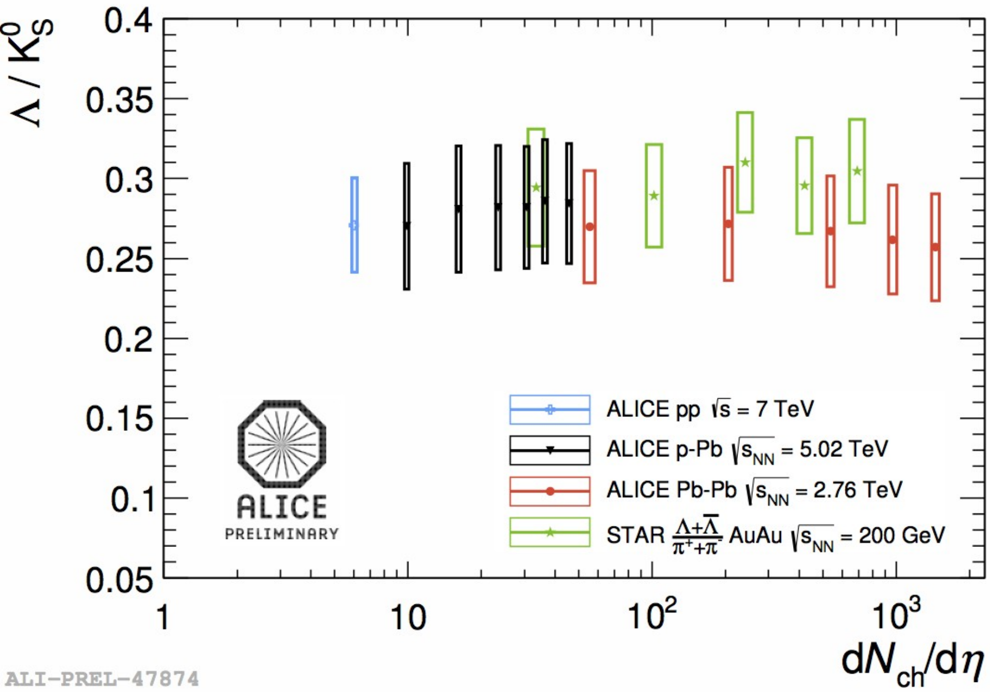
p/π integrated ratio vs. $dN_{ch}/d\eta$:

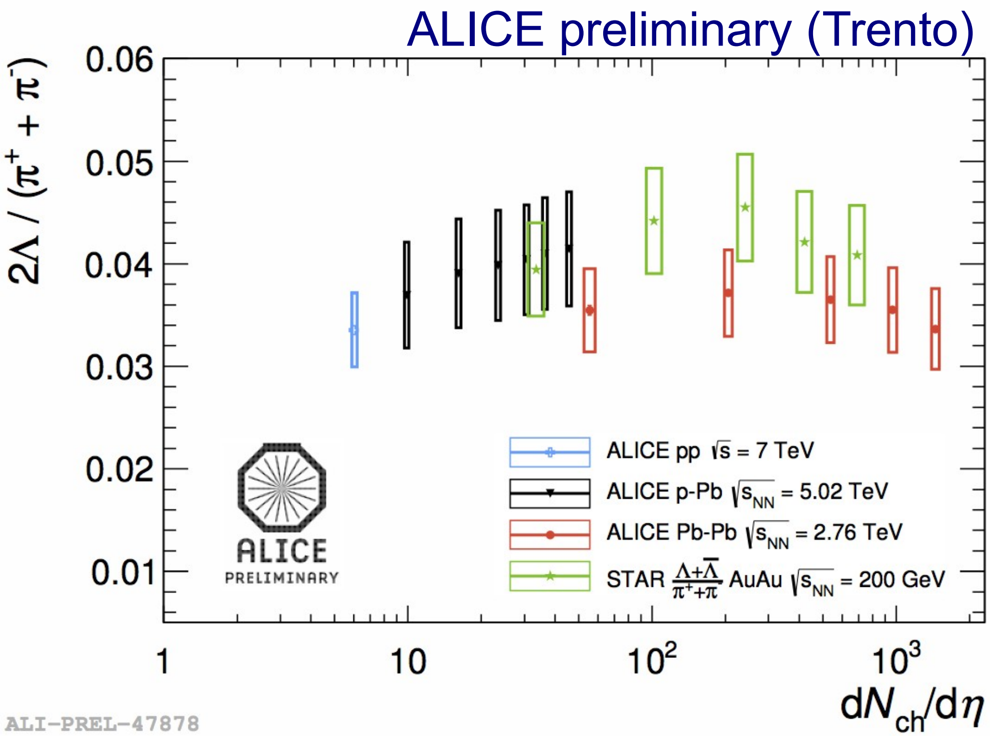
- in line with the values of pp, Pb-Pb and lower-energy RHIC results
- no significant evolution with multiplicity in p-Pb collisions

ALICE, arXiv:1303.0737 [hep-ex]
STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)

Systematic errors are largely correlated across multiplicity

Particle ratios vs $dN_{ch}/d\eta$





Λ/K^0_S integrated ratio vs. $dN_{ch}/d\eta$:

- in line with the values of pp, Pb-Pb and lower-energy RHIC results
- no significant evolution from low to high multiplicity

Λ/π integrated ratio vs. $dN_{ch}/d\eta$:

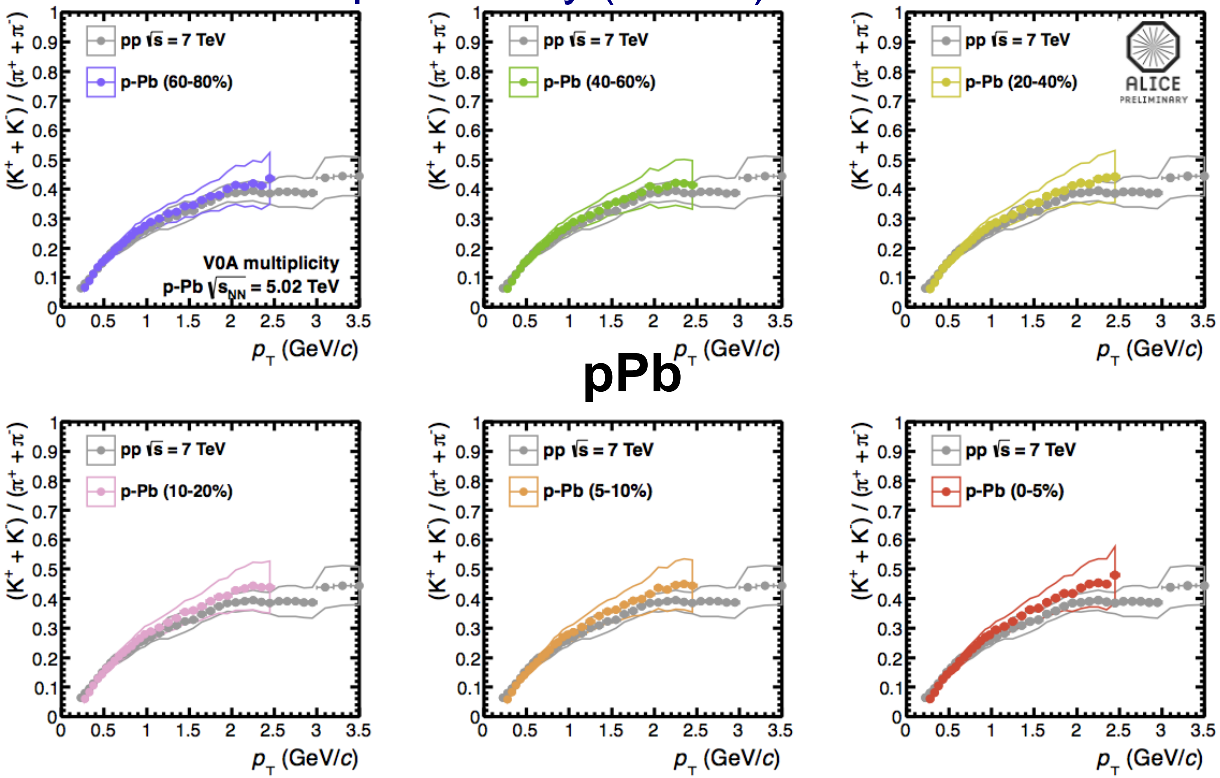
- in line with the values of pp, Pb-Pb and lower-energy RHIC results
- hints at a small increase at low multiplicity in p-Pb

STAR, PRC 79, 034909 (2009)
STAR, PRL 108, 072301 (2012)

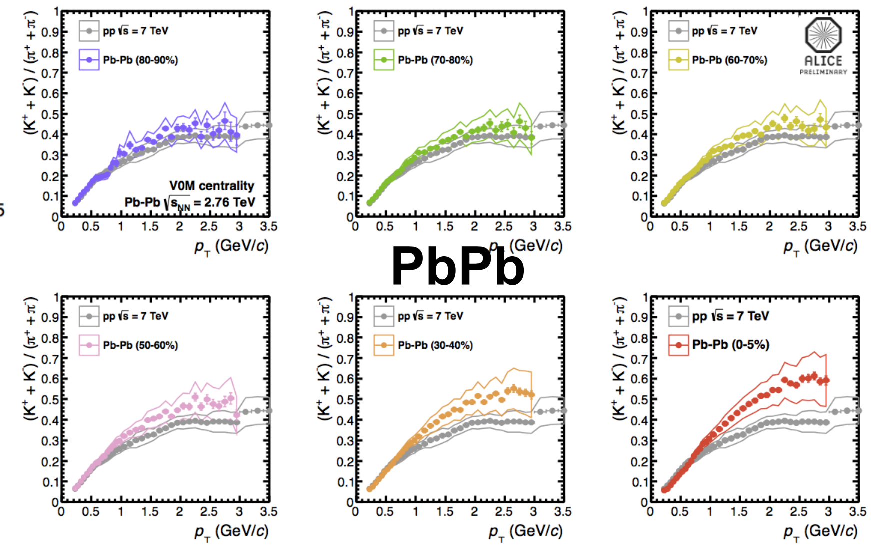
Systematic errors are largely correlated across multiplicity

K/π ratio versus p_T

ALICE preliminary (Trento)



ALICE, arxiv:1303.0737



Systematic errors are largely correlated across multiplicity

- <u>weak evolution with multiplicity</u> in p-Pb

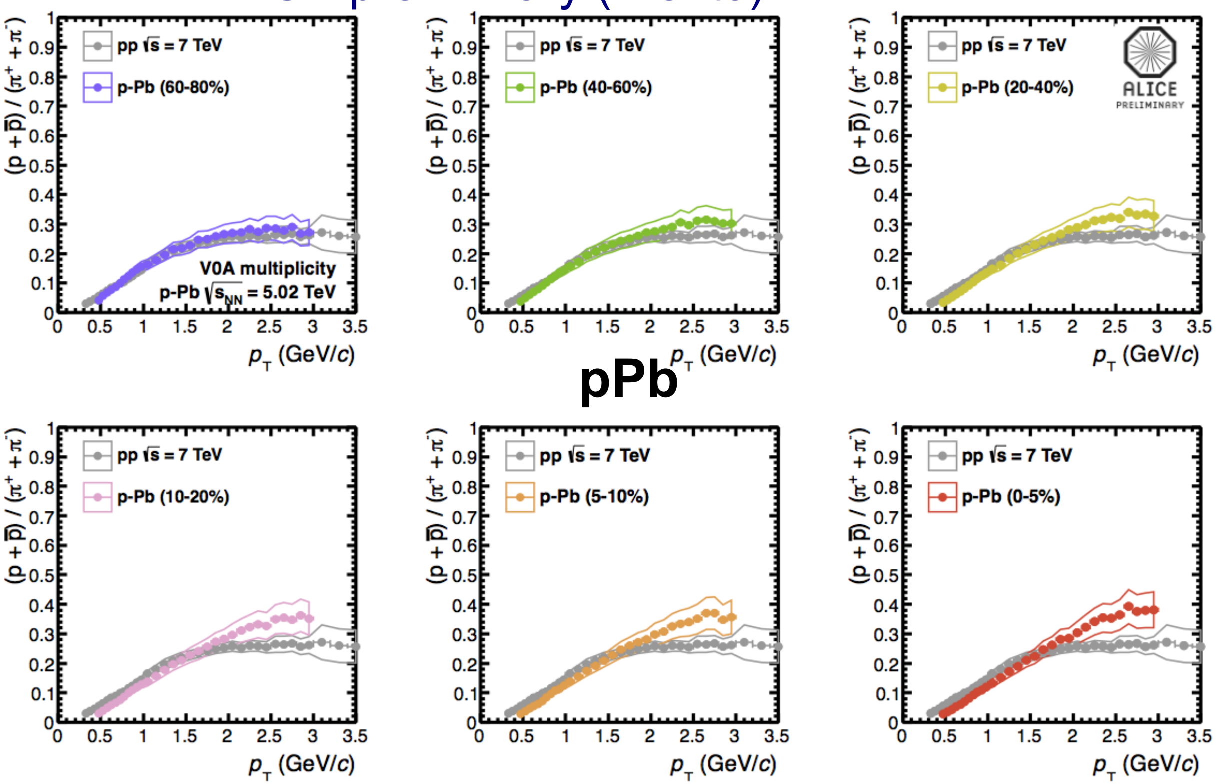
→ small increase at intermediate p_T with increasing V0A multiplicity

→ corresponding small depletion in the low-p_T region

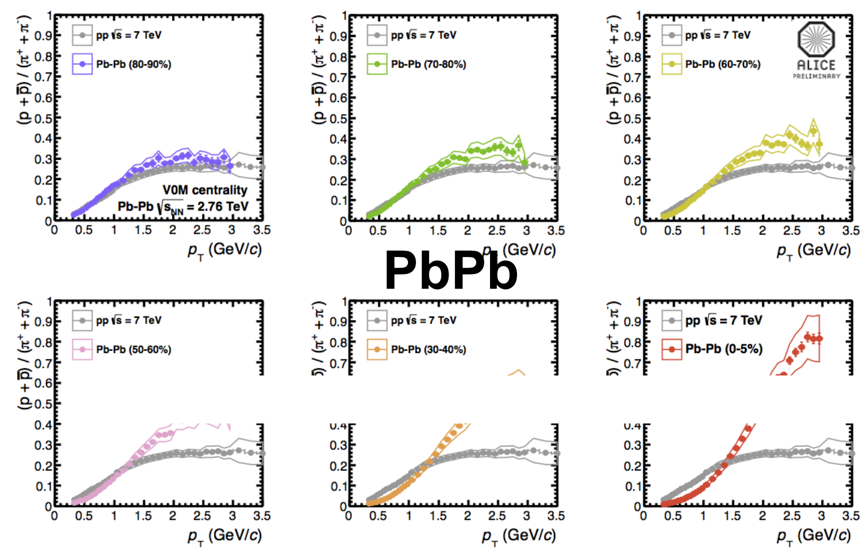
- <u>hints at similar behavior</u> as observed <u>in Pb-Pb</u> collisions

p/π ratio versus p_T

ALICE preliminary (Trento)



ALICE, arxiv:1303.0737



Systematic errors are largely correlated across multiplicity

- <u>shows similar behavior</u> as observed <u>in Pb-Pb</u> collisions

→ significant increase at intermediate p_T with increasing V0A multiplicity

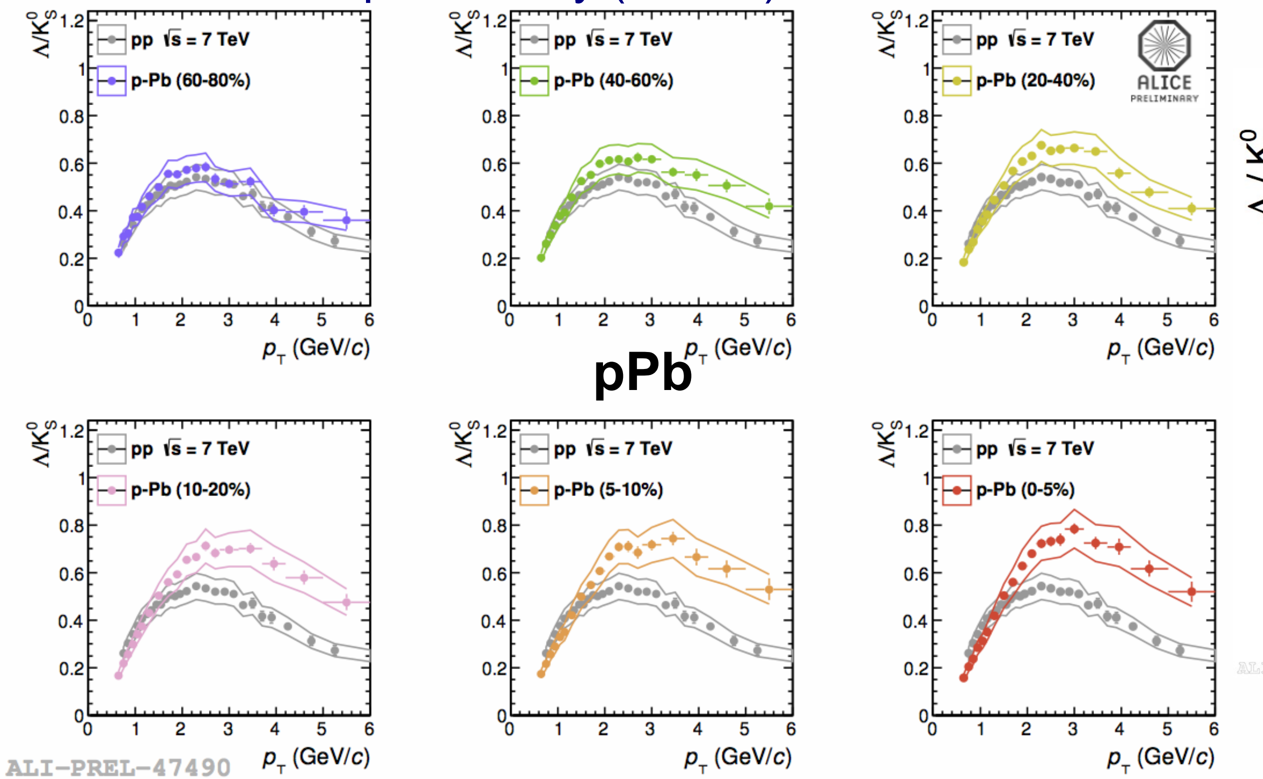
→ corresponding significant depletion in the low-p_T region

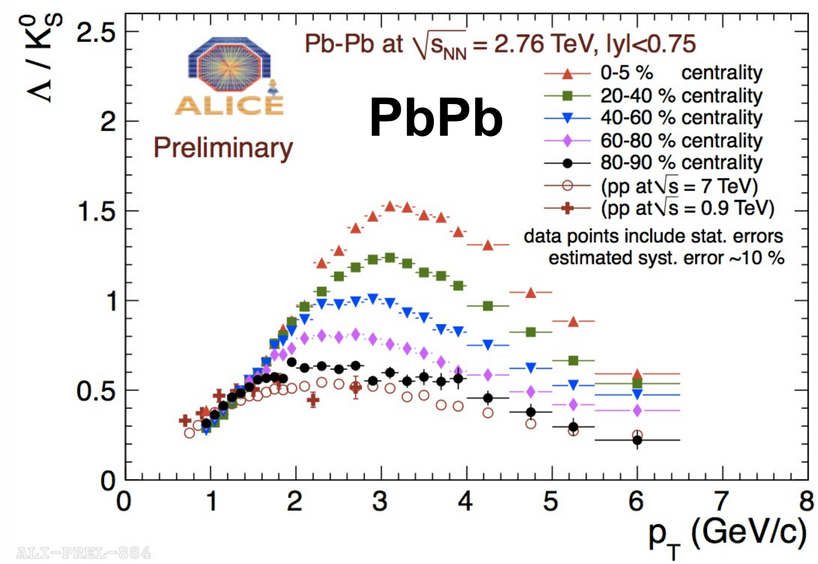
→ stronger enhancement than K/π

- Pb-Pb generally understood in terms of collective flow and/or recombination

Λ/K^0_s ratio versus p_T

ALICE preliminary (Trento)





Systematic errors are largely correlated across multiplicity

- <u>clear evolution with multiplicity</u> in pPb

→ significant increase at intermediate p_T with increasing V0A multiplicity

→ corresponding significant depletion in the low-p_T region

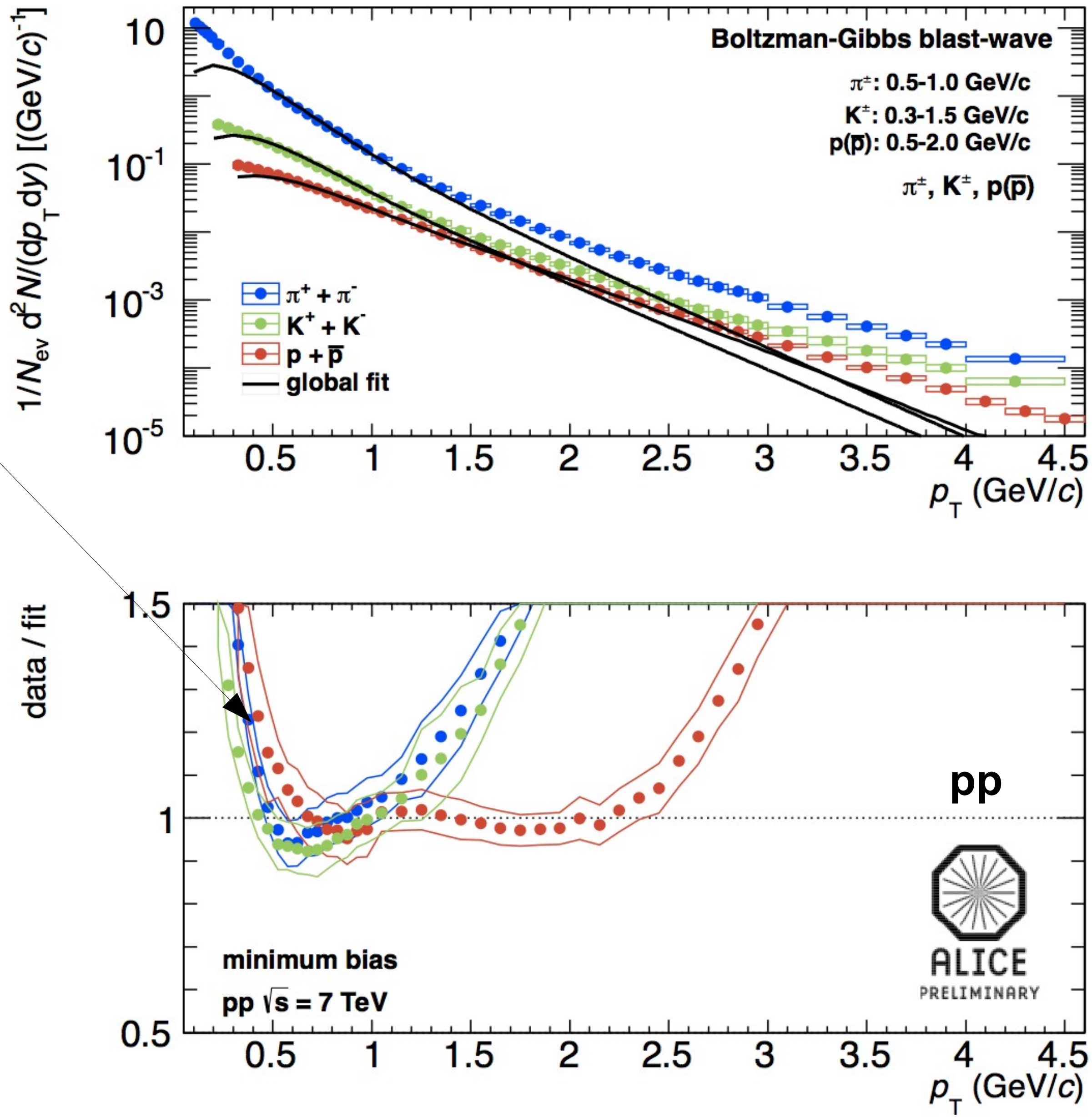
- also this is <u>reminiscent of nucleus-nucleus phenomenology</u>...

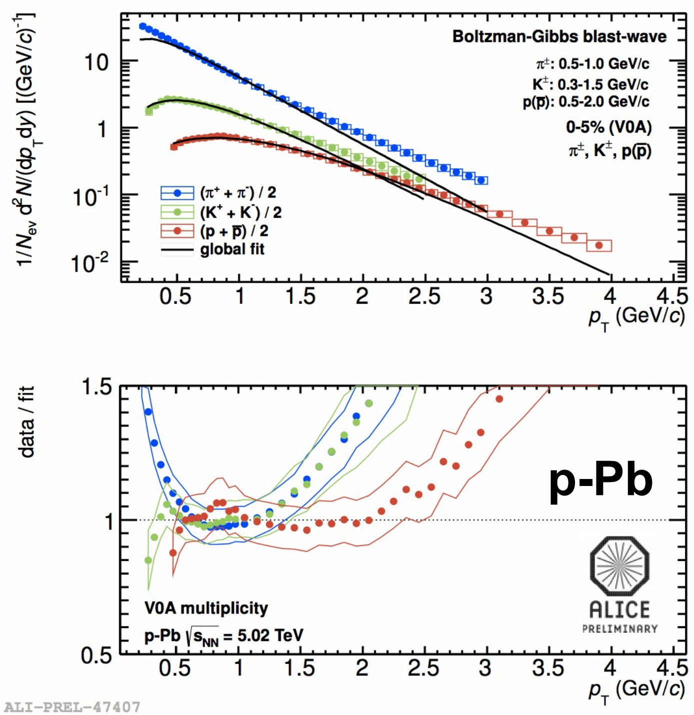
...generally understood in terms of collective flow and/or recombination π/K/p spectral-shape analysis:

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)
- Blast-Wave fits reasonable, though not very good

better than pp minimum bias: not successful at very low p_T

ALICE preliminary (Trento)



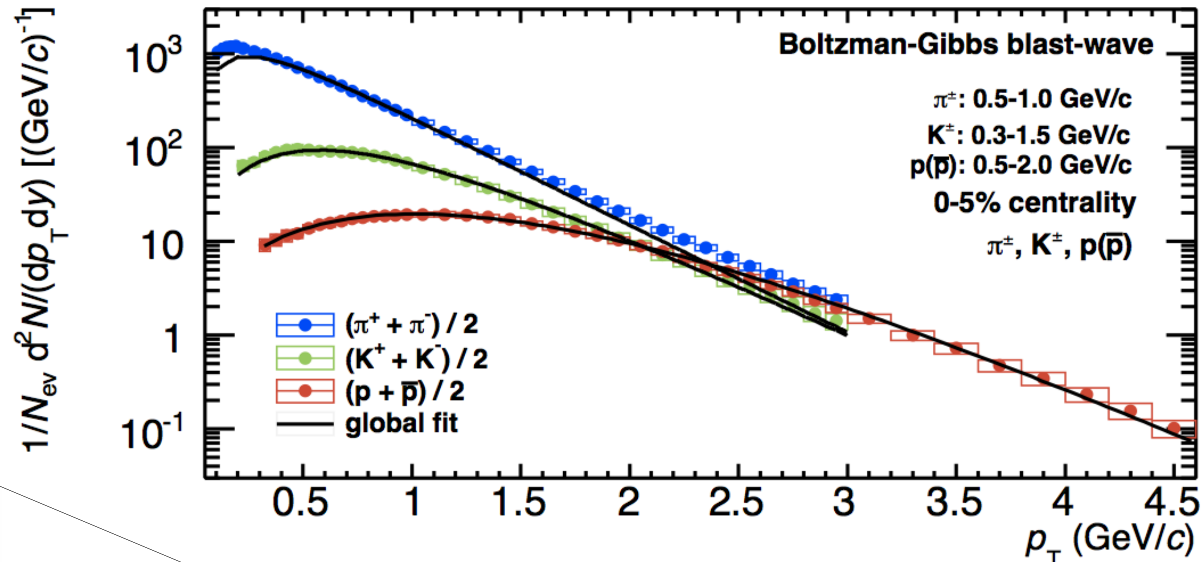


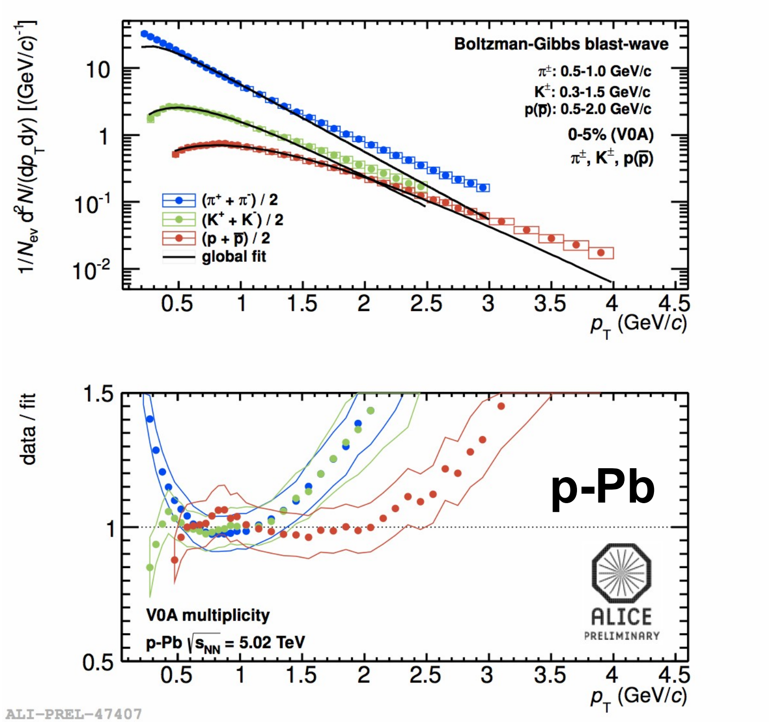
Spectra shape analysis: PbPb

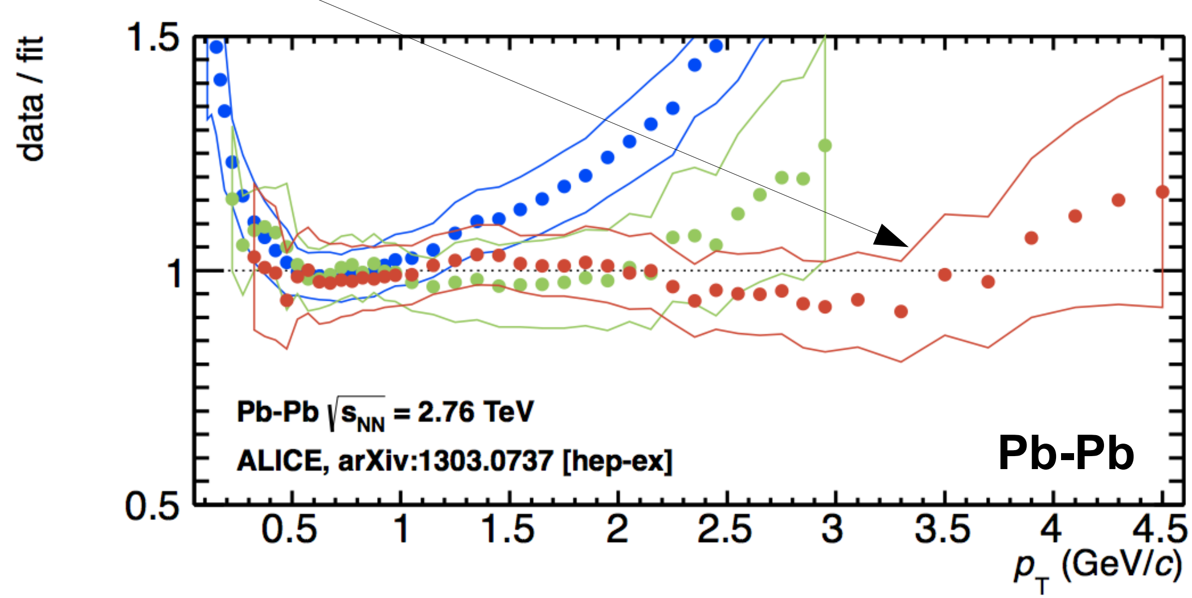
π/K/p spectral-shape analysis:

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)
- Blast-Wave fits reasonable, though not very good
  worse than central Pb-Pb: successful up to higher p_T

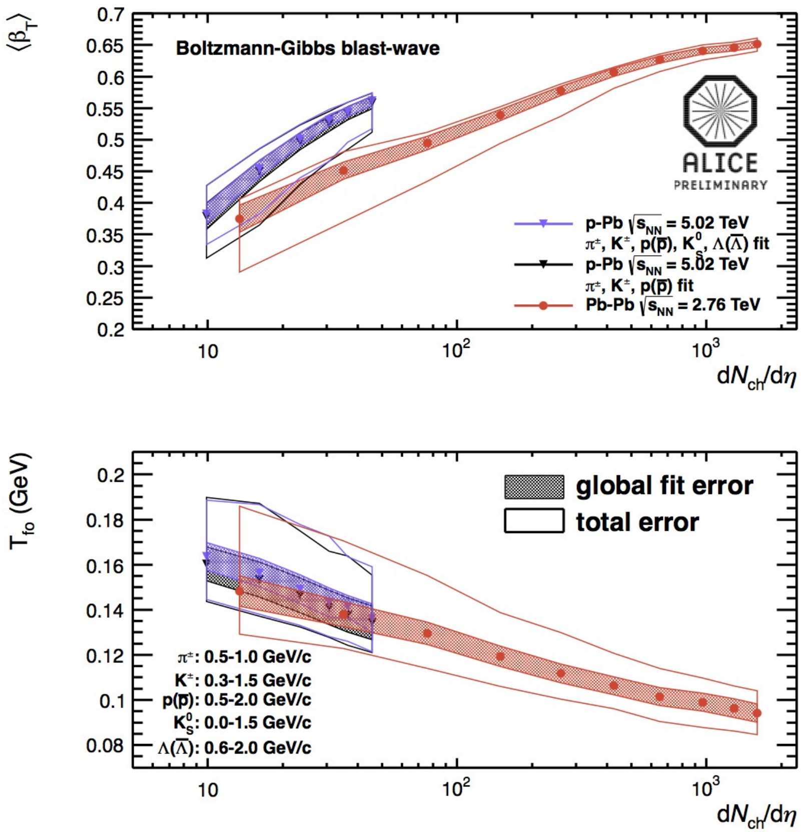
ALICE, arxiv:1303.0737



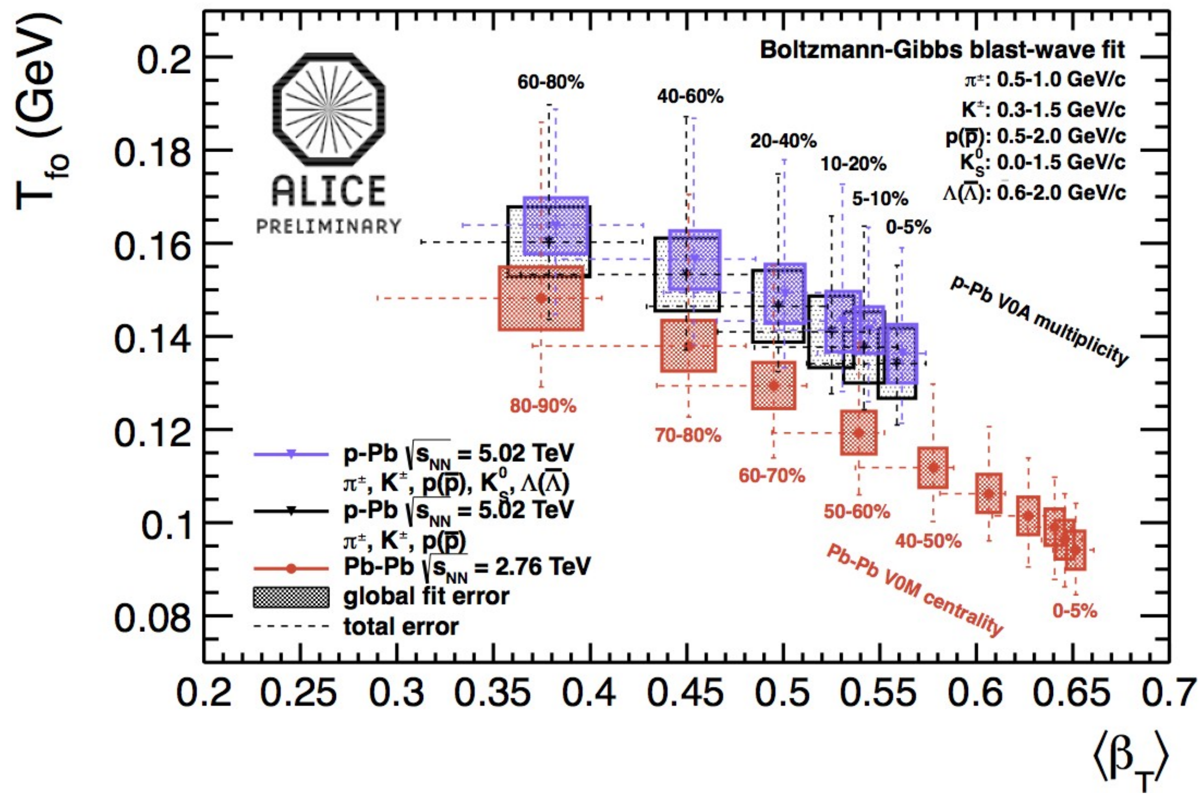




Global Blast-Wave fit parameters



ALICE preliminary (Trento)



- p-Pb presents <u>similar features as observed in Pb-Pb</u>

→ parameters evolve with increasing multiplicity: larger $\langle \beta_T \rangle$, smaller T_{fo}

→ T_{fo} is similar to Pb-Pb for similar multiplicity, $\langle \beta_T \rangle$ is larger in p-Pb

- same results when including also Λ and K^0_S in the p-Pb global fit

Comparison with hydrodynamical model

Prediction from Bozek model

Bozek, PRC 85, 014911 (2012)

- initial conditions form Glauber Monte Carlo
- E-by-E (3+1)-D viscous hydrodynamic expansion
- statistical hadronization at freeze-out (Cooper-Frye)

Comparison done for similar $dN_{ch}/d\eta$

ALICE (5-10% V0A)
$dN_{ch}/d\eta = 36.4 \pm 0.8$ $|\eta| < 0.5$

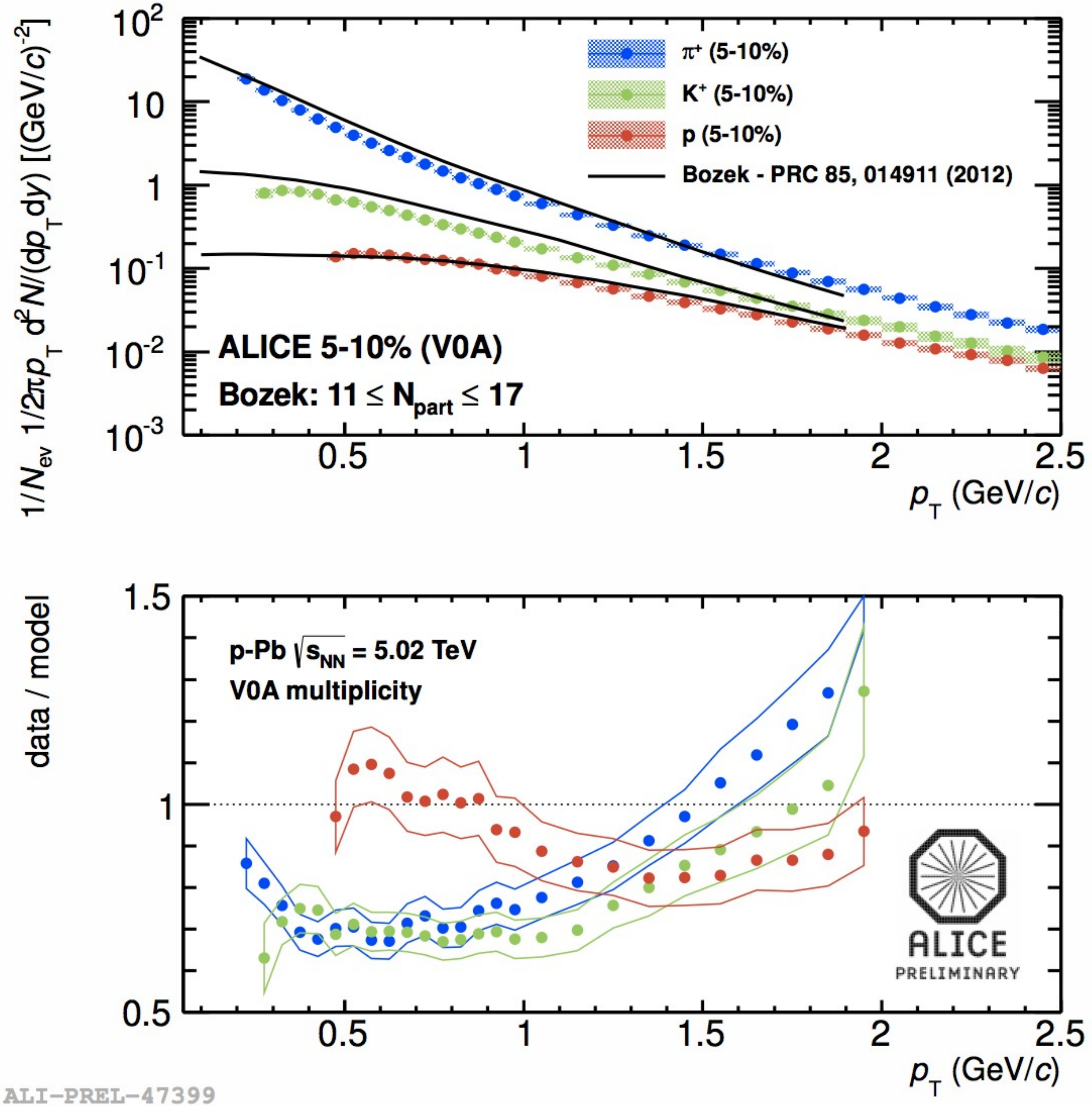
Bozek ($11 \leq$ Npart ≤ 17)
$dN_{ch}/d\eta = 38.9$ $|\eta| < 1.0$

- reasonable agreement between data and model

data/model ratio rather flat at low p_T (where hydro would dominate)

arbitrary absolute normalization (approximate multiplicity match)

ALICE preliminary (Trento)



Spectra shape analysis: pPb

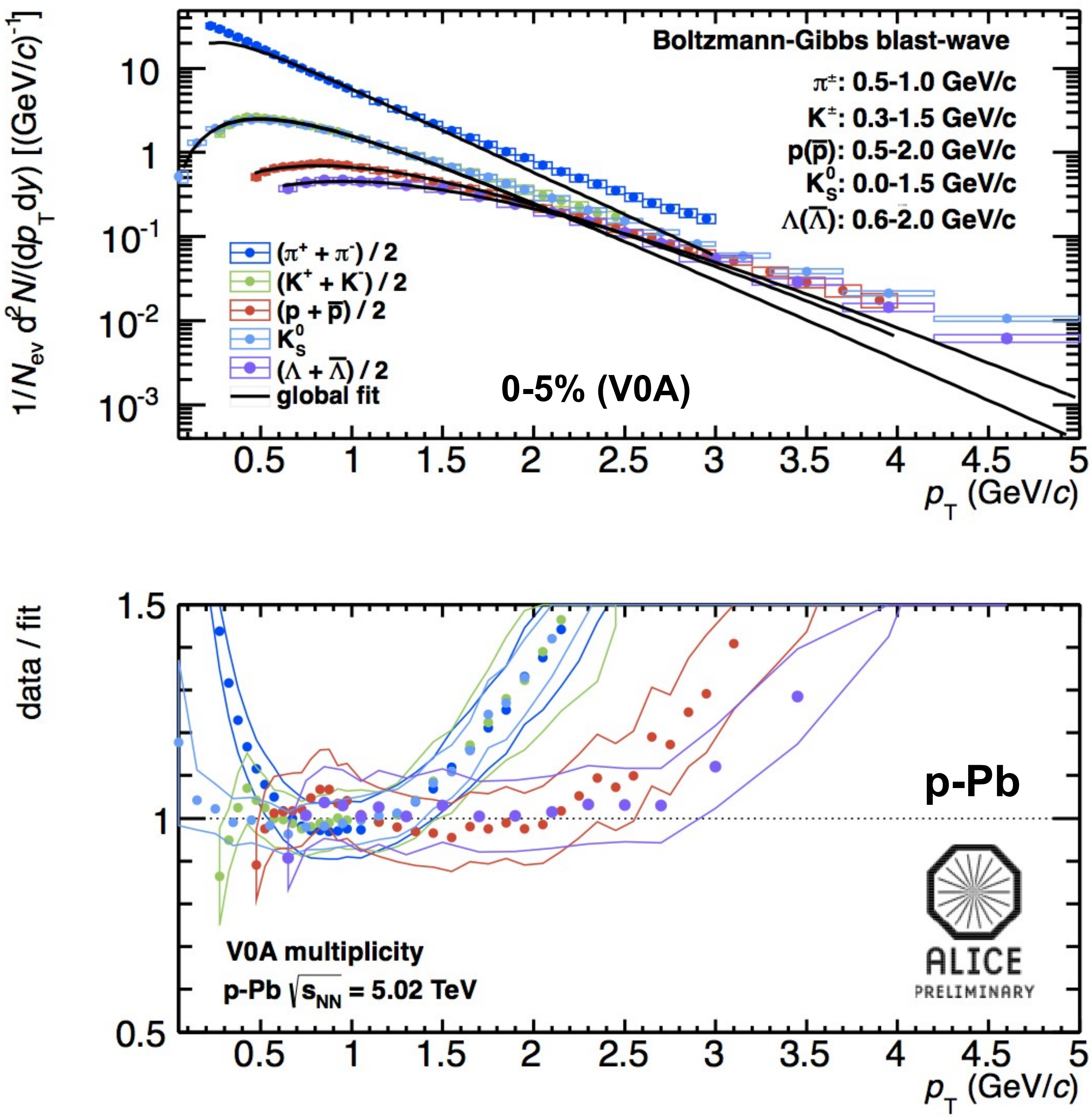
π/K/p spectral-shape analysis:

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)
- adding K^0_S and Λ
- global fit performed in the following p_T ranges:

π	0.5 – 1.0 GeV/*c*
K	0.3 – 1.5 GeV/*c*
p	0.5 – 2.0 GeV/*c*
K^0_S	0.0 – 1.5 GeV/*c*
Λ	0.6 – 2.0 GeV/*c*

- Blast-Wave fits reasonable, though not very good
  worse than central Pb-Pb
  better than pp minimum bias

ALICE preliminary (Trento)



Blast-Wave model – fit parameters

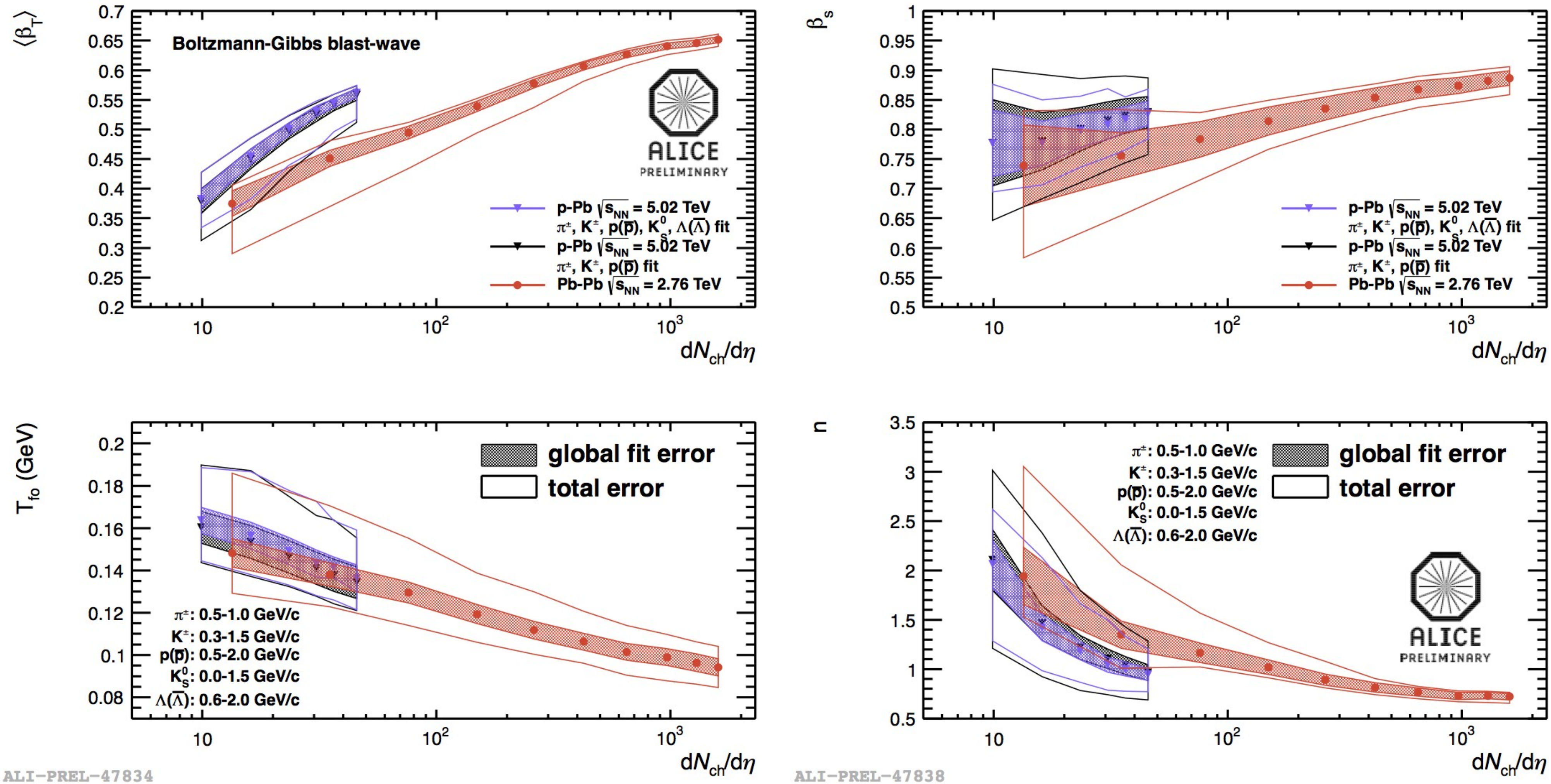
Schnedermann, PRC 48, 2462 (1993)

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

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

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

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



Blast-Wave model – fit parameters

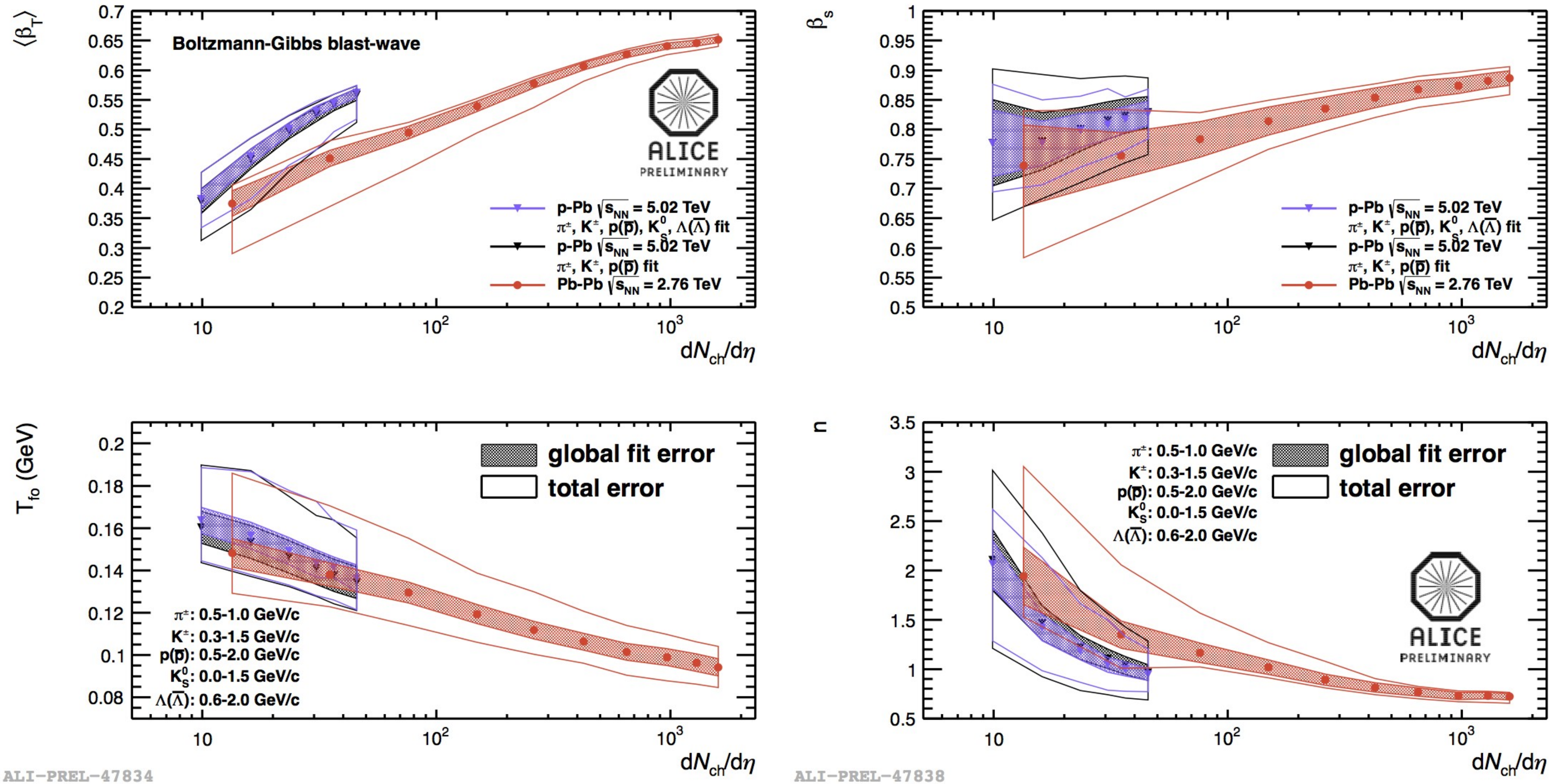
Schnedermann, PRC 48, 2462 (1993)

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

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

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

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



Blast-Wave model – fit parameters

spectral-shape analysis:

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)

- Blast-Wave fits in different momentum ranges