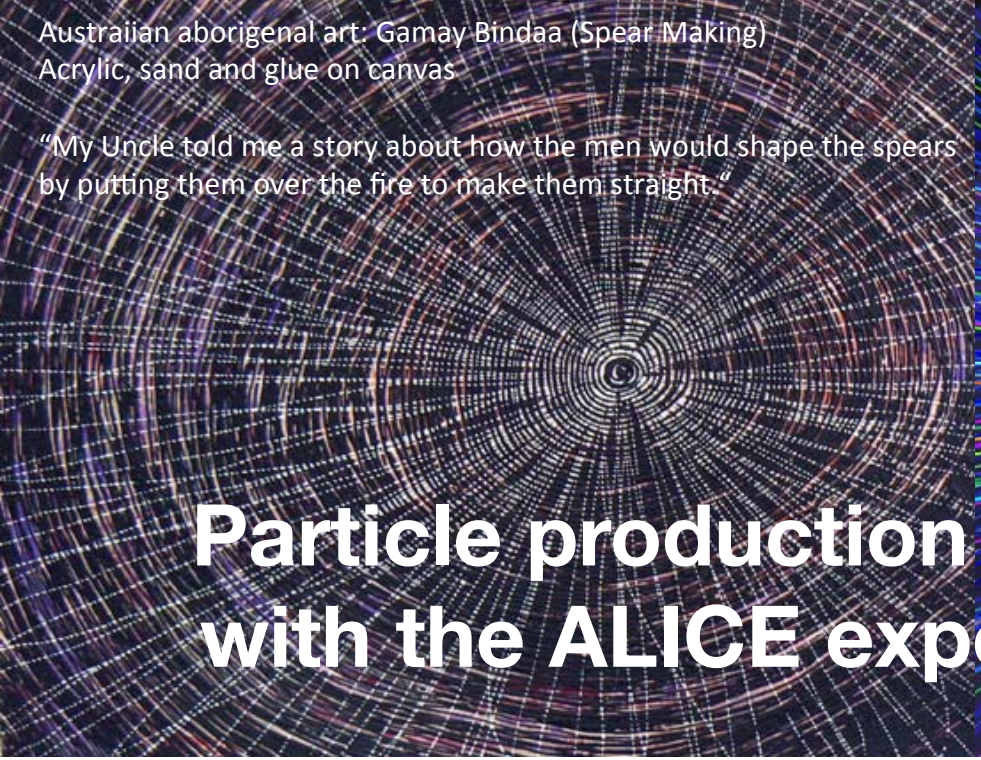
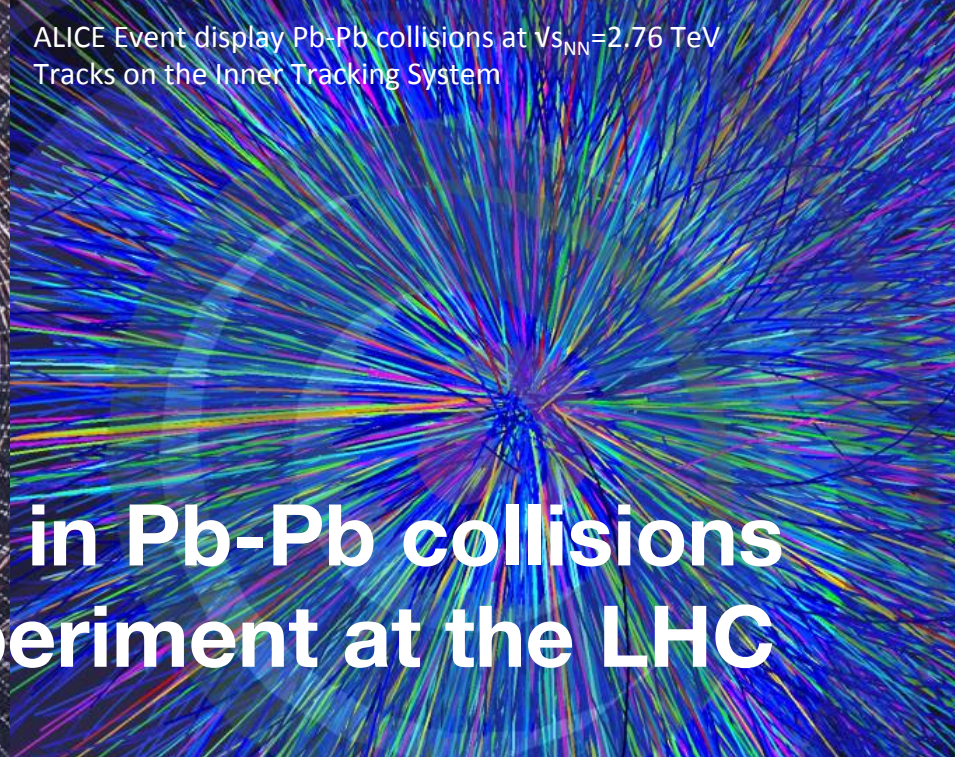




Particle production in Pb-Pb collisions with the ALICE experiment at the LHC

F. Bellini* for the ALICE Collaboration
*Università di Bologna, I.N.F.N Sez. di Bologna – Italy

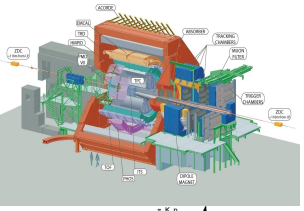
International Conference on High Energy Physics – ICHEP 2012
Heavy Ion physics session
Melbourne, 6th July 2012

ALICE

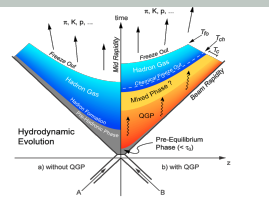
INFN Istituto Nazionale di Fisica Nucleare

ICHEP2012 Melbourne
36th International Conference on High Energy Physics
4 – 11 July 2012
Melbourne Convention and Exhibition Centre

Outline

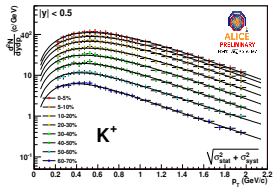


The ALICE experiment at LHC



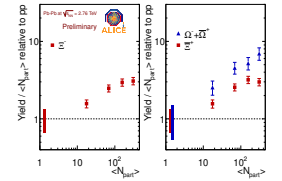
Physics of heavy ion collisions

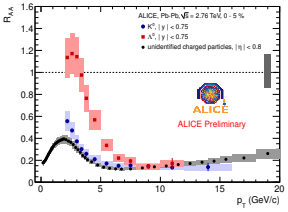
- How to probe medium evolution by measuring particle production

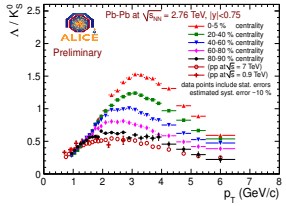


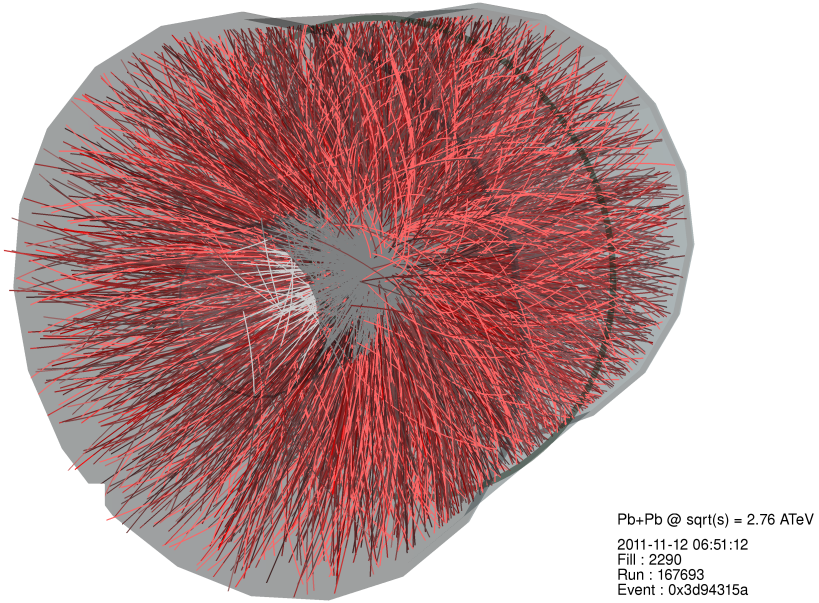
Results in Pb-Pb collisions

- Particle spectra
- Particle ratios
- Strangeness enhancement
- Light hadrons R_{AA}
- Baryon anomaly







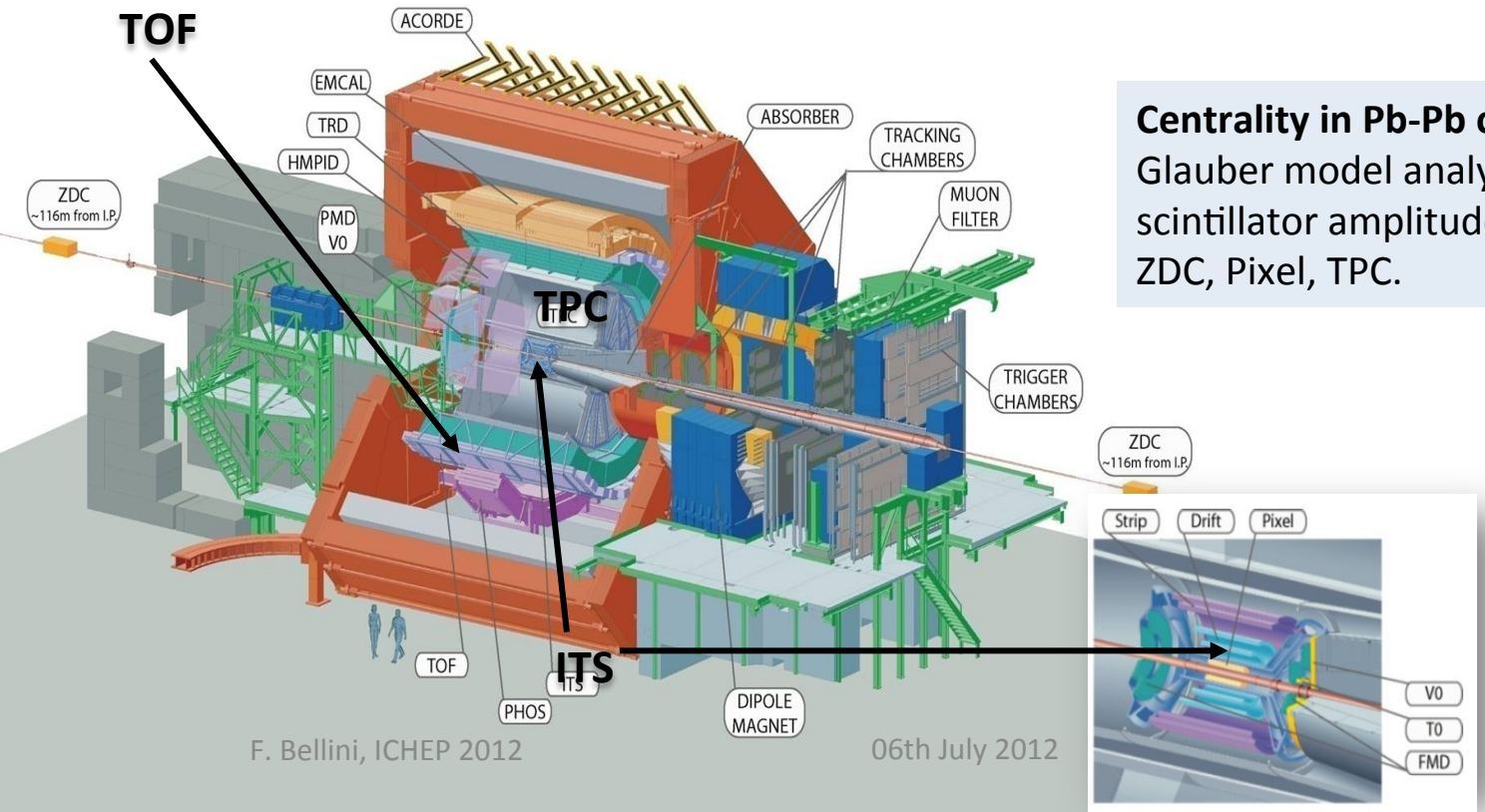


Summary and conclusions

The ALICE detector at LHC

- Unique PID capabilities: dE/dx, time-of-flight, Cherenkov, decay topology (V0, cascades), …
- Central region with the smallest material budget at the LHC

Central barrel: |η|<0.9, B=0.5 T
Inner Tracking System – ITS: Primary vertex, PID via dE/dx
Time Projection Chamber – TPC: Global tracking, PID via dE/dx
Time Of Flight system – TOF: PID via time-of-flight measurement



Centrality in Pb-Pb collisions:
Glauber model analysis of large-η V0 scintillator amplitudes, alternatively from ZDC, Pixel, TPC.

The ALICE detector at LHC

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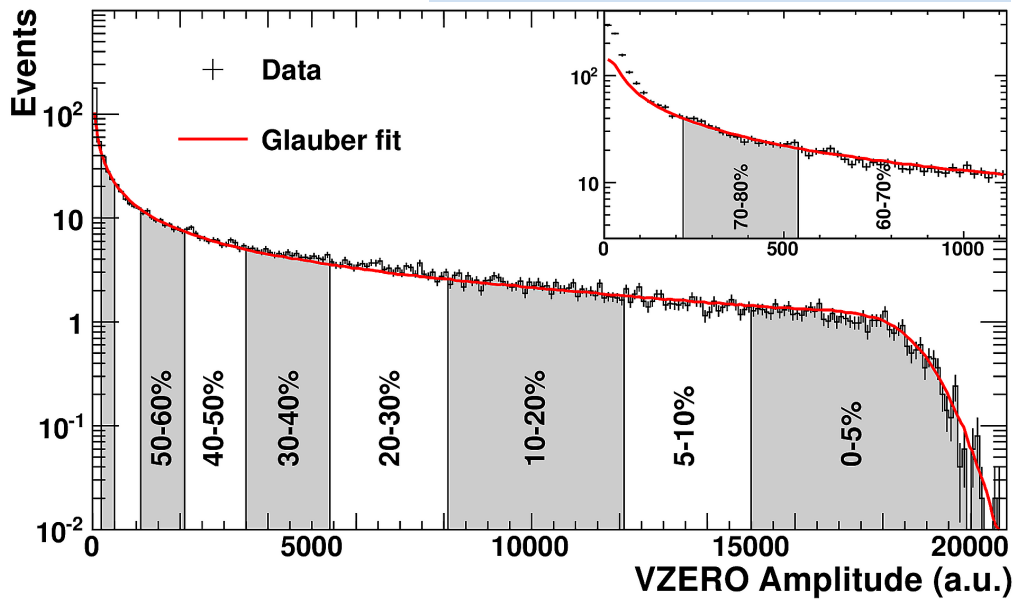
ALICE *Phys. Rev. Lett. 106, 032301 (2011)*



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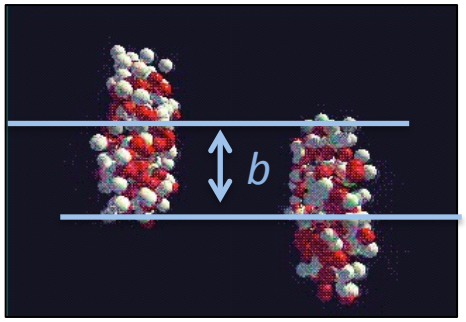


Heavy Ion collisions and medium evolution

Hadronic states provide many useful observables to characterize medium produced in ultra-relativistic heavy ion collisions and its evolution

Kinetic freeze-out
- stop elastic interactions

Chemical freeze-out
- stop inelastic interactions
- Fix particle ratios

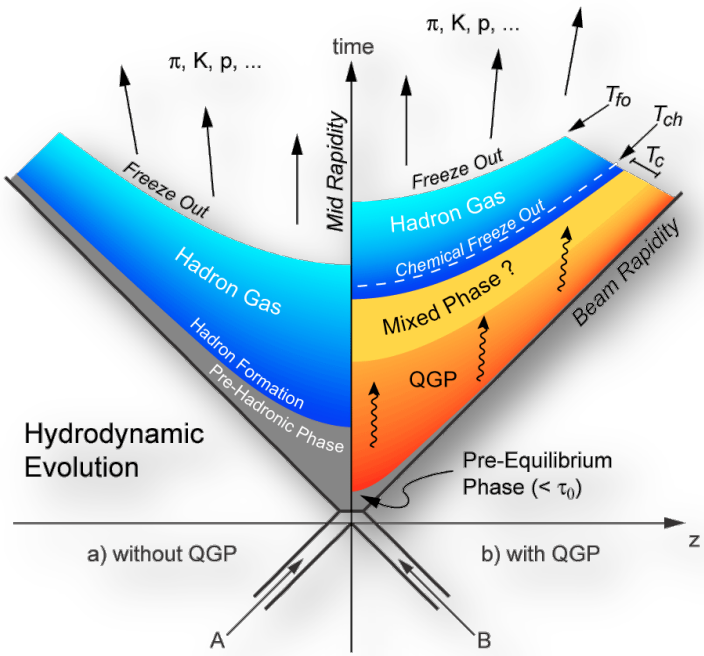
QGP expansion (lifetime @ LHC ~ fm/c)
- hadronization and re-scattering

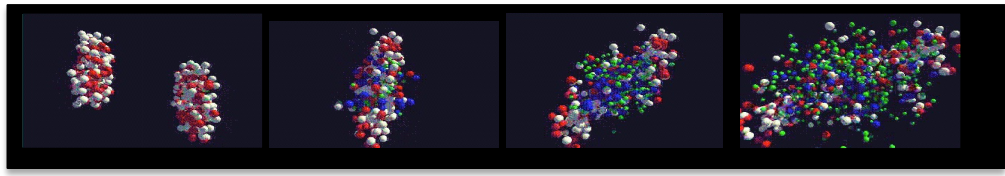
Hydrodynamics, thermalization
- radial and anisotropic flow

Quark-Gluon Plasma formation (t ~ 1 fm/c after collision)

Parton hard scattering/Jets
- pQCD regime

Pre-equilibrium state





Identified particle p_T spectra and ratios

Kinetic freeze-out
- stop elastic interactions

Chemical freeze-out
- stop inelastic interactions
- Fix particle ratios

QGP expansion (lifetime @ LHC ~ fm/c)
- hadronization and re-scattering

Hydrodynamics, thermalization
- radial and anisotropic flow terms

Quark-Gluon Plasma formation (t ~ 1 fm/c after collision)

Parton hard scattering/Jets
- pQCD regime

Pre-equilibrium state

The thermal parameters of the system at **freeze-out** can be extracted through a hydrodynamic-inspired (Blast-wave) fit to the p_T spectra of the primary identified particles.

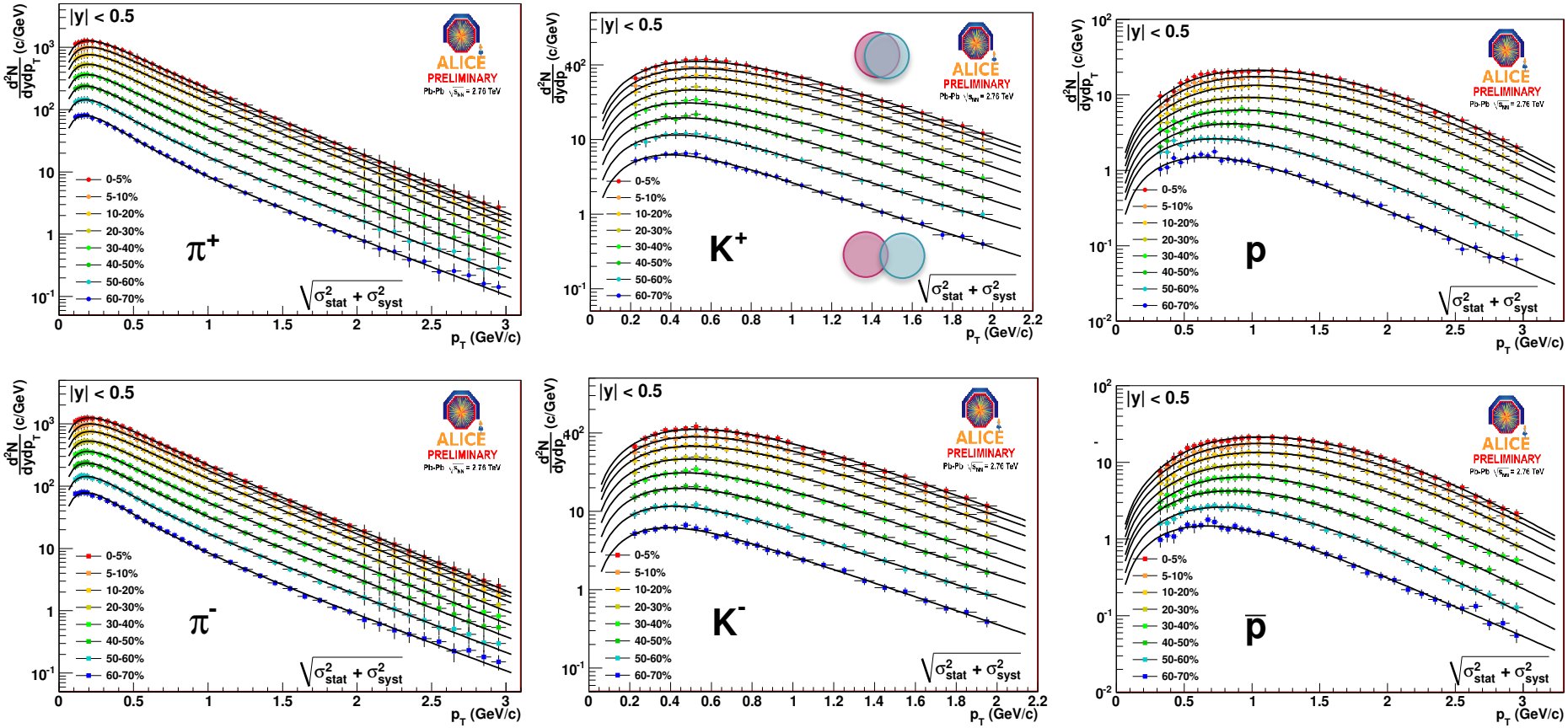
Particle ratios are compared with **thermal models** (statistical approach) which assume that particles are created in thermal equilibrium governed by a scale parameter defined as "temperature".

Collective expansion of the medium produced in HI collisions can be described by simple hydrodynamical models in terms of different flow terms.

Radial flow describes the expansion in the transverse plane and is derived by the measurement of primary particles average p_T.

Anisotropic flow: see Talks by Carlos Perez Lara, Anitha NYATHA

π/K/p spectra in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

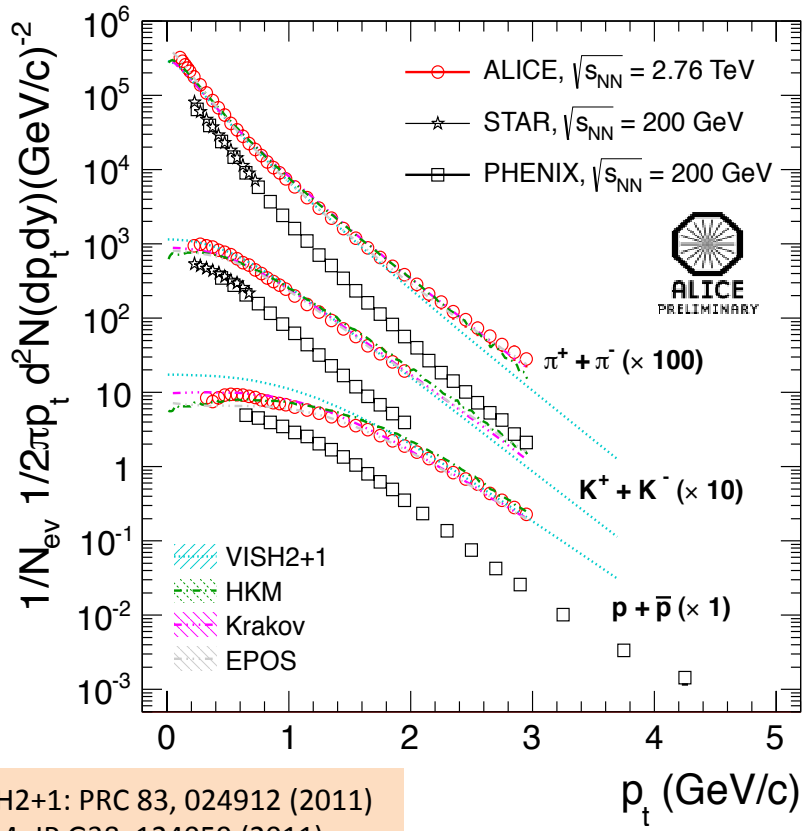


Each species spectrum has been fitted with a **Blast-Wave*** function to extract integrated yields and <$\mathbf{p_T}$>

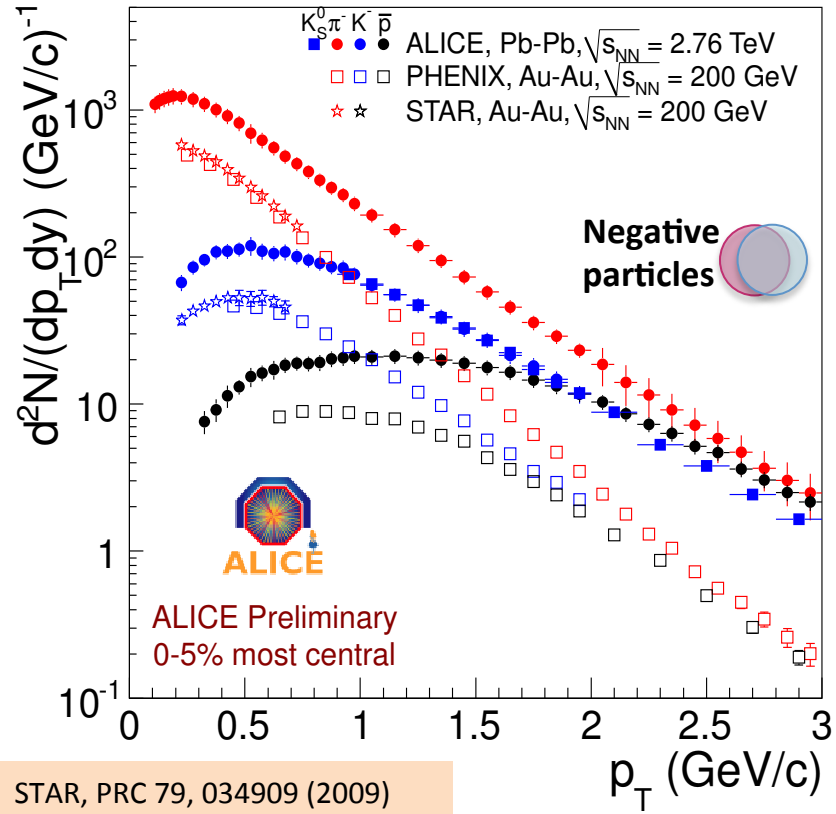
$$\frac{dN}{p_\perp dp_\perp} \propto \int_0^R r dr m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{kin}}\right) \qquad \rho = \tanh^{-1}\beta \qquad \beta = \beta_S (r/R)^n$$

*Schnedermann et al., Phys. Rev. C 48, 2462 (1993)

π/K/p spectra in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV



VISH2+1: PRC 83, 024912 (2011)
HKM: JP G38, 124059 (2011)
Krakow: PRC 85, 034901 (2012)
EPOS: arXiv:1203.5704 [nucl-th]



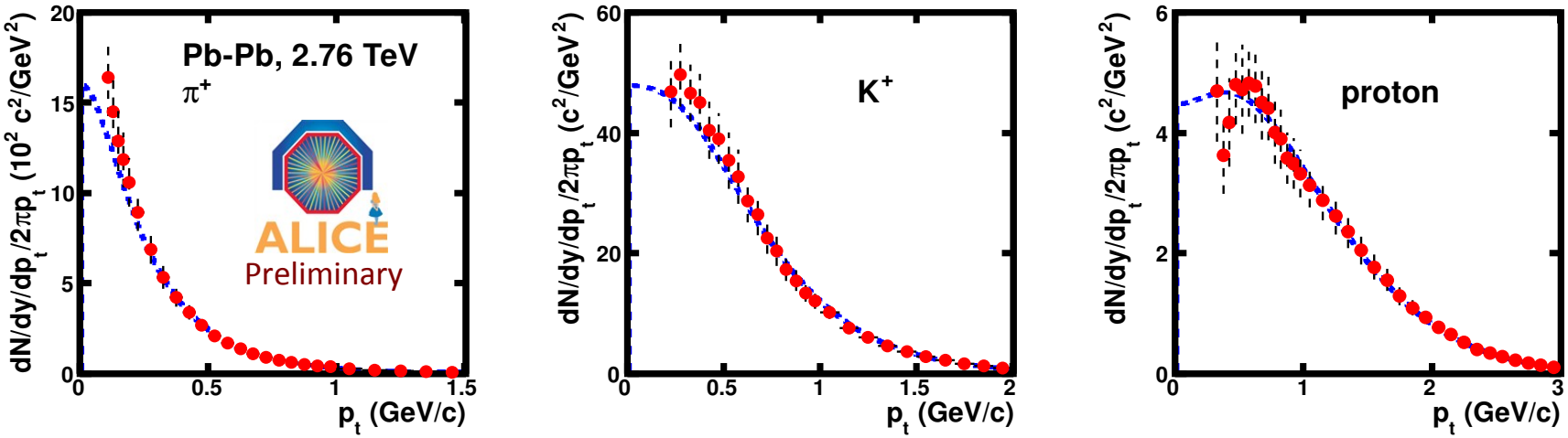
STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)

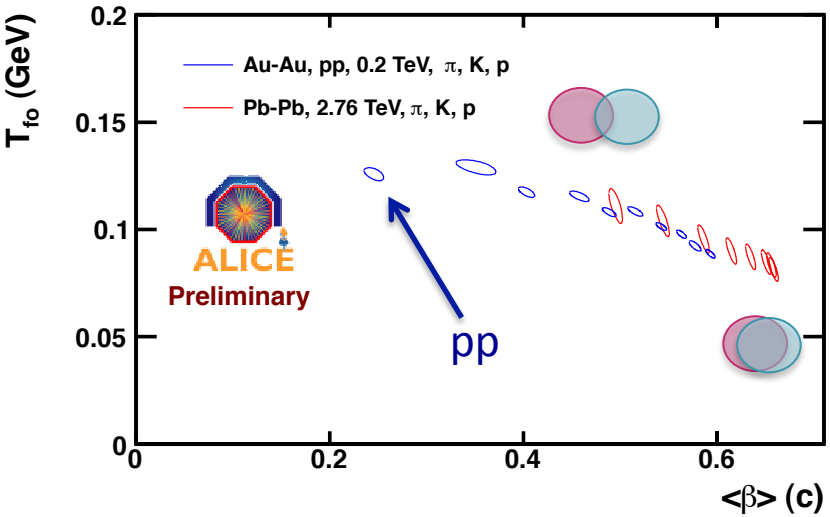
Comparison with hydro models:
Yields and shape of primary π, K and p are in **good agreement with hydrodynamic models**

Comparison with Au-Au at RHIC:
Harder spectra and flatter protons than at RHIC **indicate a stronger radial flow at LHC**

Blast-wave fit to π/K/p spectra

*Schnedermann et al., Phys. Rev. C 48, 2462 (1993)





Global Blast-wave fit* to extract (kinetic) freeze-out temperature (T_{fo}) and average radial flow **‹β›**

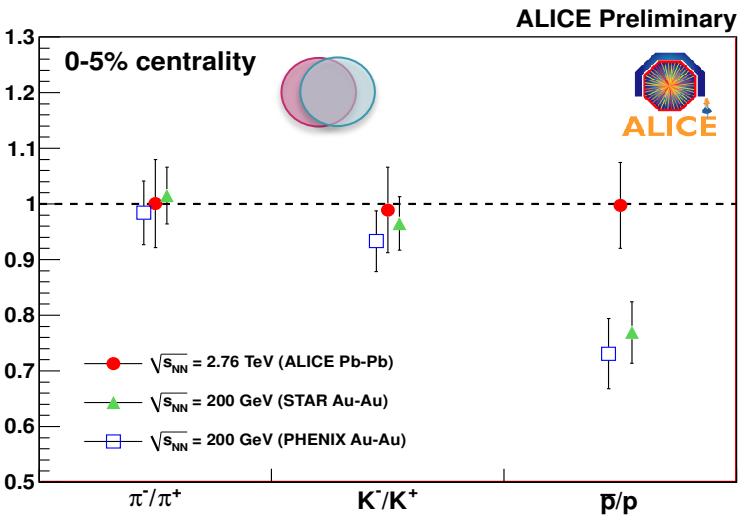
T_{fo} parameter of the model depends on **π** fit range, resonances effect to be investigated

‹β› ≃0.66 c ~10% higher than at RHIC
T_{fo} seems slightly lower than at RHIC

Au-Au STAR, PRC 79, 034909 (2009)

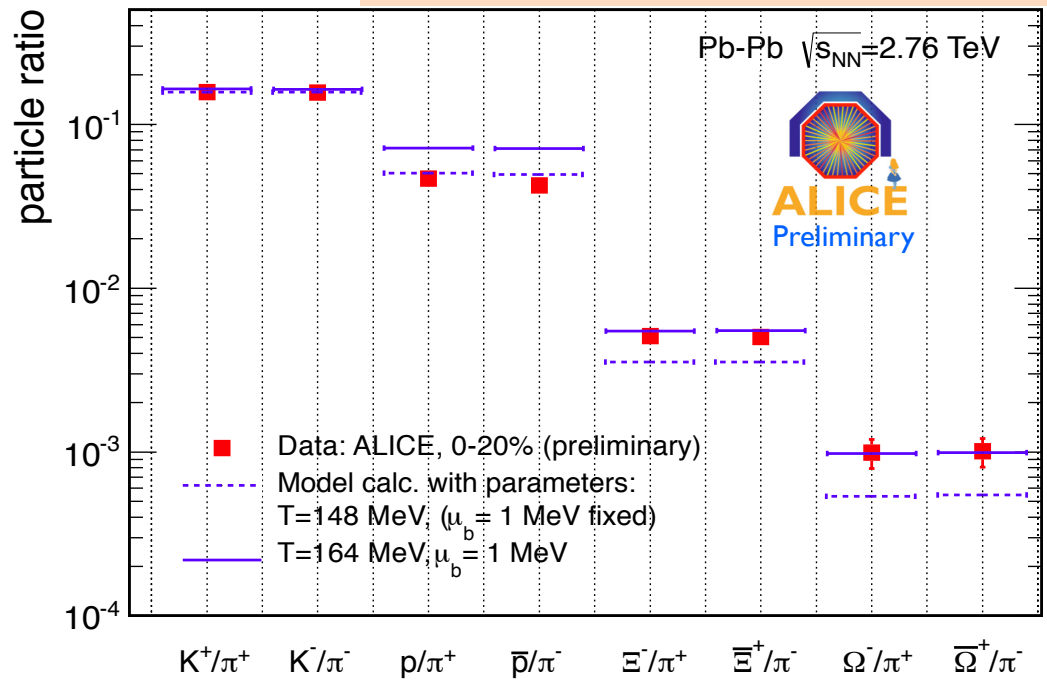
Particle ratios vs thermal model

At LHC anti-particle/particle ratios at mid-rapidity are compatible with 1, as expected due to $\mu_B \sim 0$



STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)

A.Andronic et al, Phys.Lett.B 673, 142 (2009)



Particle ratios compared with a thermal model which assumes a grand canonical description (also for Kaons and multi-strange particles).

Difficult to reproduce all ratios simultaneously

This unexpected deviation is still to be understood

Strangeness enhancement in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

Kinetic freeze-out
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Quark-Gluon Plasma formation
(t ~ 1 fm/c after collision)

Parton hard scattering/Jets
- pQCD regime

Pre-equilibrium state

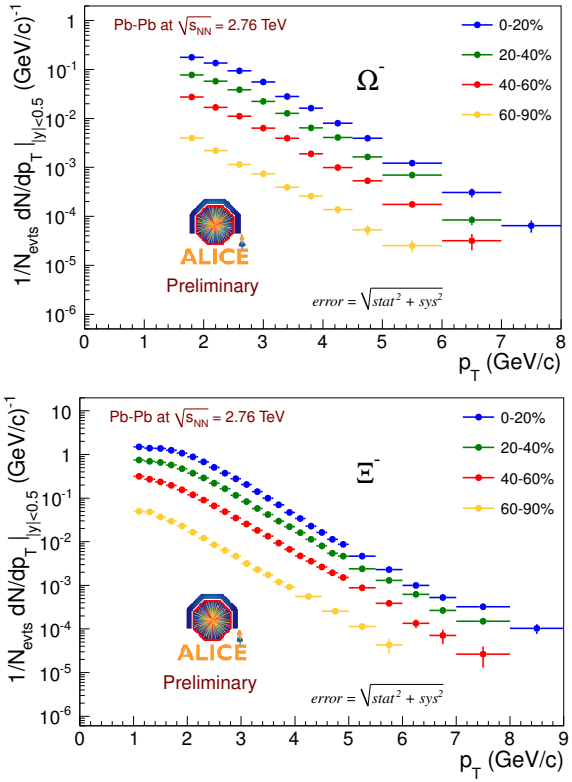
The **disappearance of strangeness suppression** (i.e. strangeness enhancement) in HI collisions was one of the first signals predicted for the QGP.

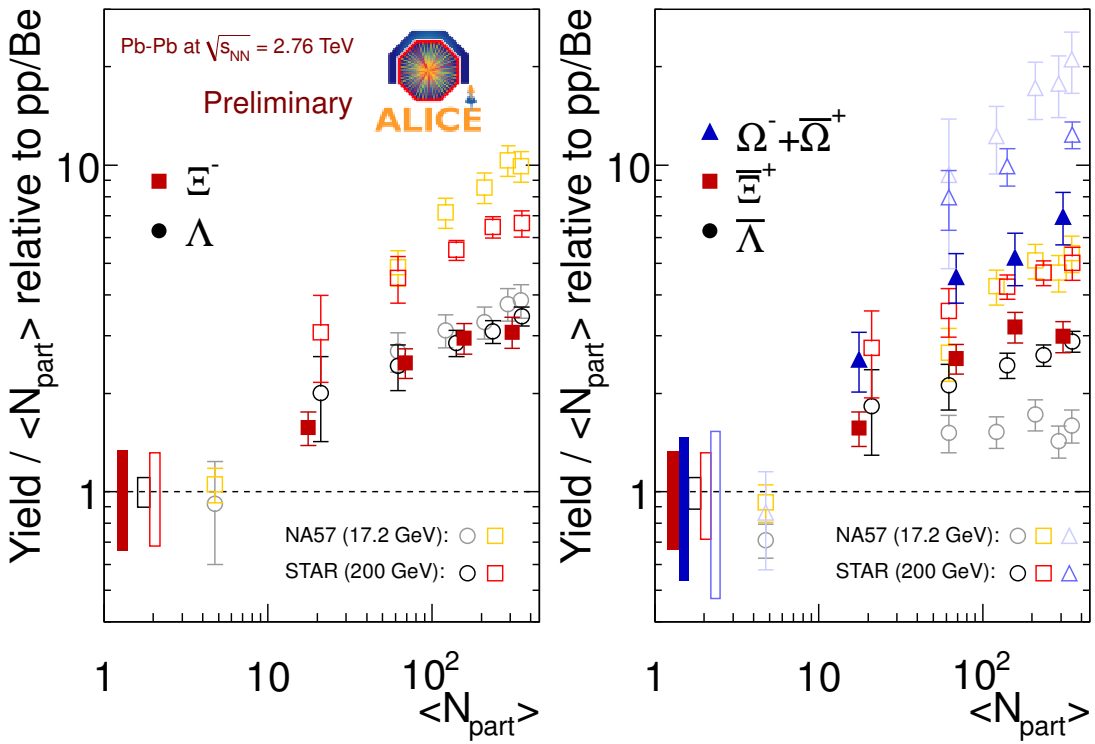
The abundance of strange quarks in the medium favours the production of hyperons.

Strangeness enhancement is defined with respect to pp collisions as:

$$E_i = \frac{Yield_i^{AA} / \langle N_{part} \rangle}{Yield_i^{pp} / 2}$$

Strangeness enhancement in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV





Strangeness enhancement with respect to pp collisions **increases following hierarchy of strangeness content (valence quarks) of baryons**

ALICE results compared with lower energy data (SPS, RHIC):

- **enhancement decreases as energy increases**
- **same trend observed from RHIC to SPS**

NA57 Nucl. Phys. A 698, 118c (2002)
STAR Phys. Rev. C 77, 044908 (2008)

Light hadrons suppression in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

Kinetic freeze-out
- stop elastic interactions

Chemical freeze-out
- stop inelastic interactions
- Fix particle ratios

QGP expansion (lifetime @ LHC ~ fm/c)
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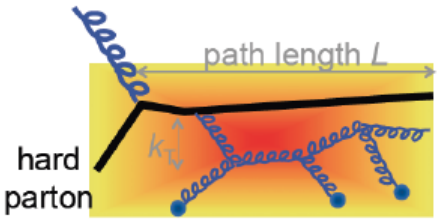
Hydrodynamics, thermalization
- radial and anisotropic flow

Quark-Gluon Plasma formation
(t ~ 1 fm/c after collision)

Parton hard scattering/Jets
- pQCD regime

Pre-equilibrium state

High p_T partons coming from hard-scattering processes (pQCD) undergo **energy loss in the medium**.



The **nuclear modification factor** is defined as:

$$R_{AA} = \frac{d^2N^{AA} / dp_T d\eta}{\langle N_{coll} \rangle d^2N^{pp} / dp_T d\eta}$$

to compare Pb-Pb and pp collisions scaled with number of binary collisions.

R_{AA} = 1 if no medium effect

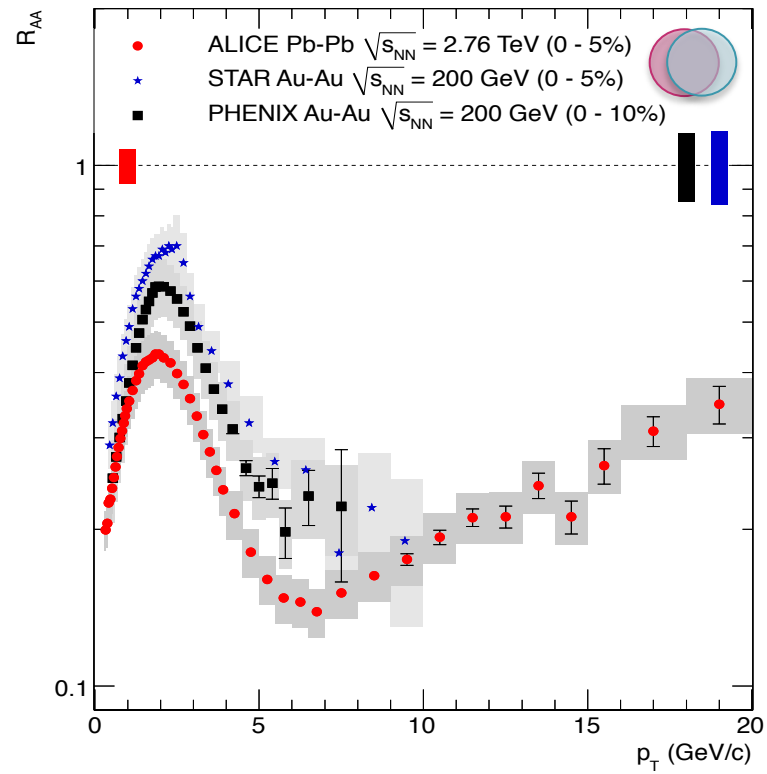
$$\langle N_{coll} \rangle = \langle T_{AA} \rangle \cdot \sigma_{pp}^{INEL}$$

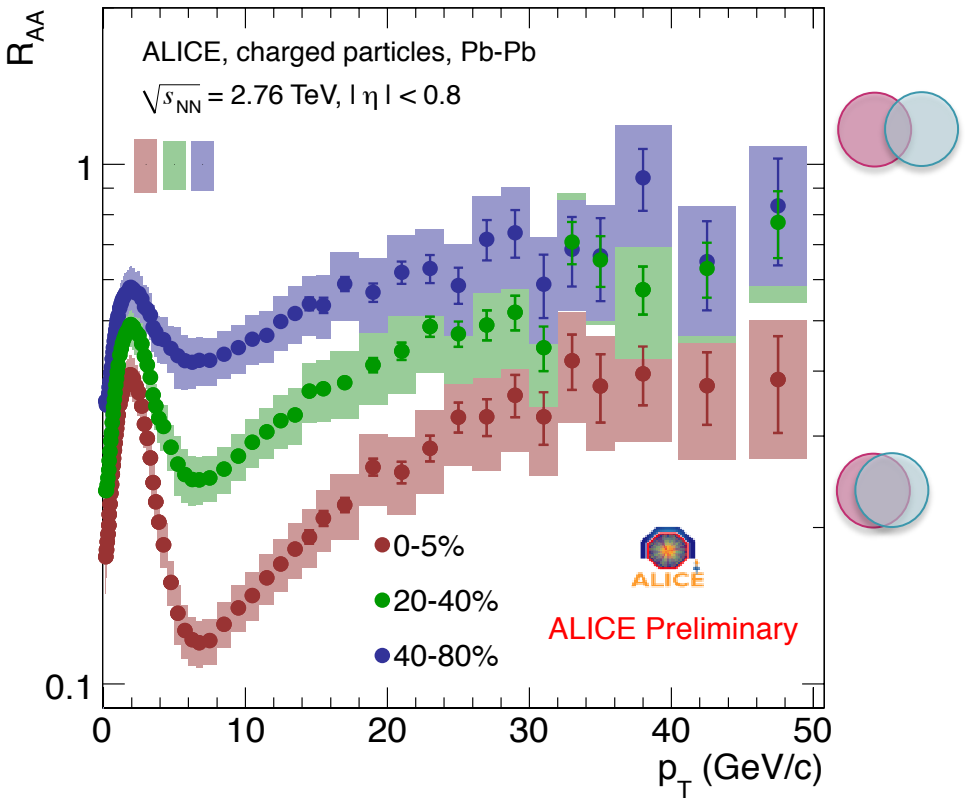
$\langle T_{AA} \rangle$ = Nuclear overlap function from Glauber model (related to the number of binary collisions)

$$\sigma_{pp}^{INEL} = 64 \pm 5 mb$$

Unidentified charged particles R_{AA}

ALICE, *Phys.Lett. B696 (2011) 30-39*

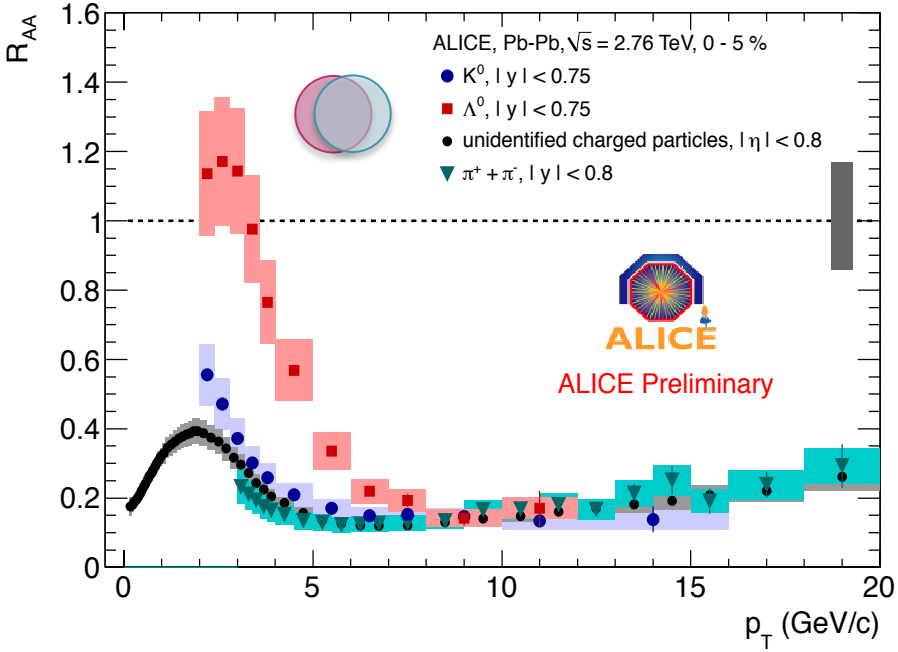


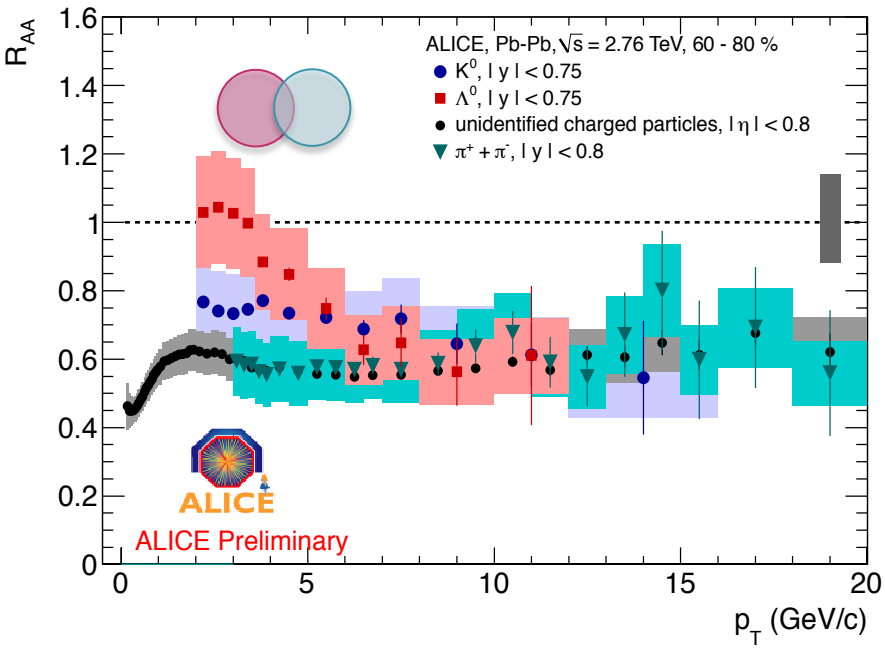


Suppression of high-p_T particles in central collisions is stronger than that observed RHIC
→ **a very dense medium is formed in central Pb-Pb collisions at the LHC.**

R_{AA} decreases with centrality
Minimum of R_{AA} occurs at 6-7 GeV/c for all centralities

Identified light hadrons R_{AA}





For central collisions and high p_T(> 8GeV/c), the R_{AA} of light hadrons is compatible

→ **No strong flavour dependence of R_{AA} is observed**

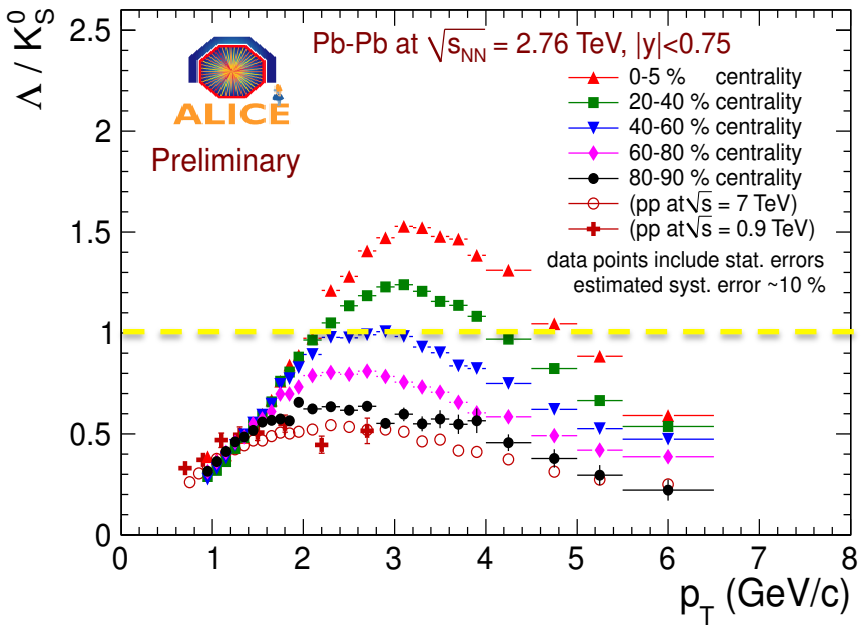
→ Baseline for understanding heavy quark energy loss (talk by Andrea Dainese)

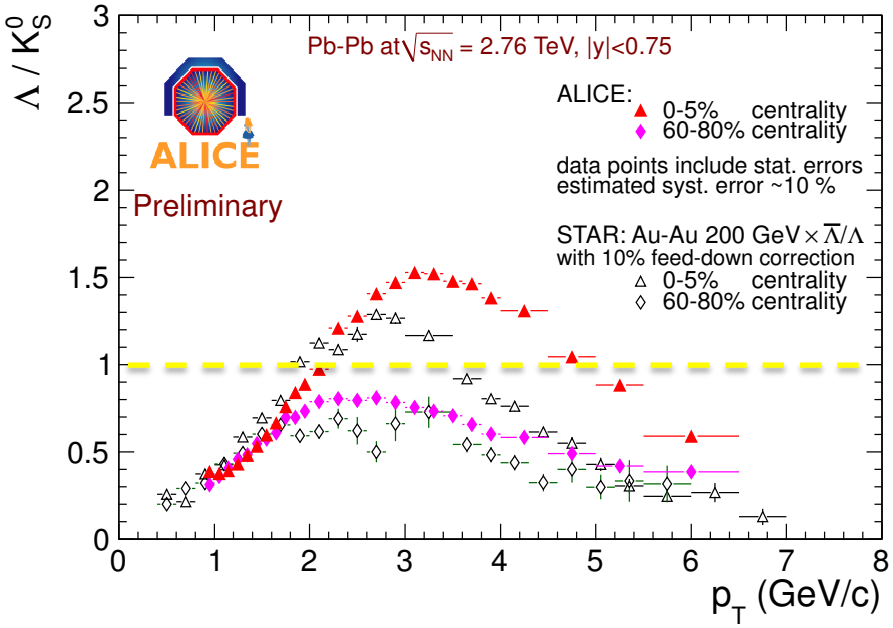
K^0_s: similar behavior as charged particles, meson suppression up to high p_T

Λ: enhancement at intermediate p_T and suppression at high p_T

→ Related to the so-called "**baryon anomaly**"

Λ/K^0_s ratio and the "baryon anomaly"





"Baryon anomaly":
baryon/meson ratio vs. p_T increases from pp to a value >1 for central Pb-Pb collisions at intermediate p_t → production via coalescence

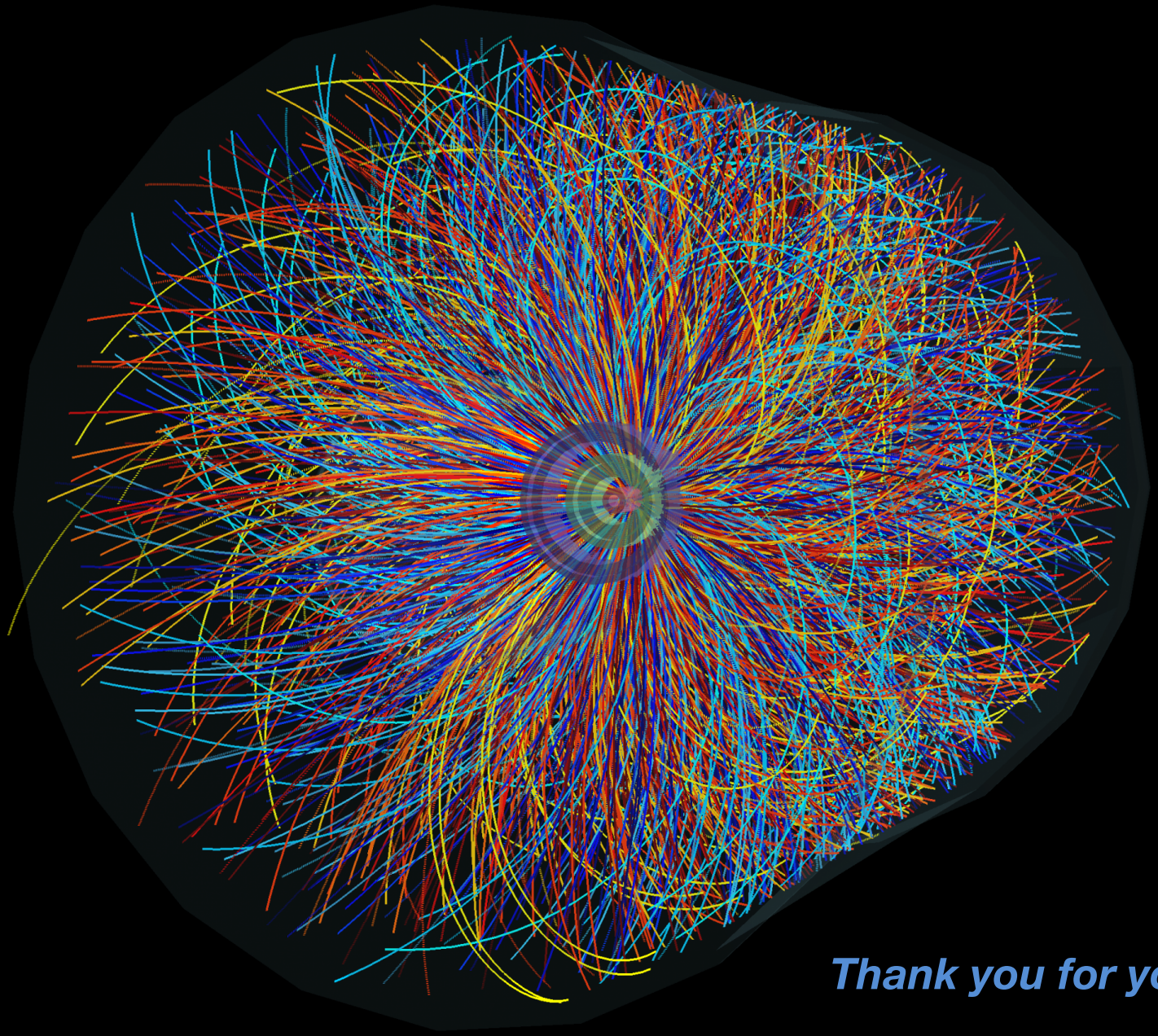
Λ/K^0_s Magnitude increases with both centrality and beam energy from RHIC to LHC.

Summary and conclusions

ALICE provides many observables to study the particle production in different energy regimes in heavy ion collisions at the LHC

- π/K/p spectra measurement provided indication for a **stronger radial flow at the LHC** than at RHIC
- **Anti-particle/particle ratio ~ 1,** as expected for μ_B~0 at the LHC
- **thermal model predictions** for particle ratios seem to be valid although some additional work is needed on proton yields
- **strangeness enhancement** has been observed and compared to results at lower energy
- **suppression of light hadrons (R_{AA})** shows no obvious flavour dependence
- the "**baryon anomaly**" provides insight on the interplay between soft and hard particle production mechanisms

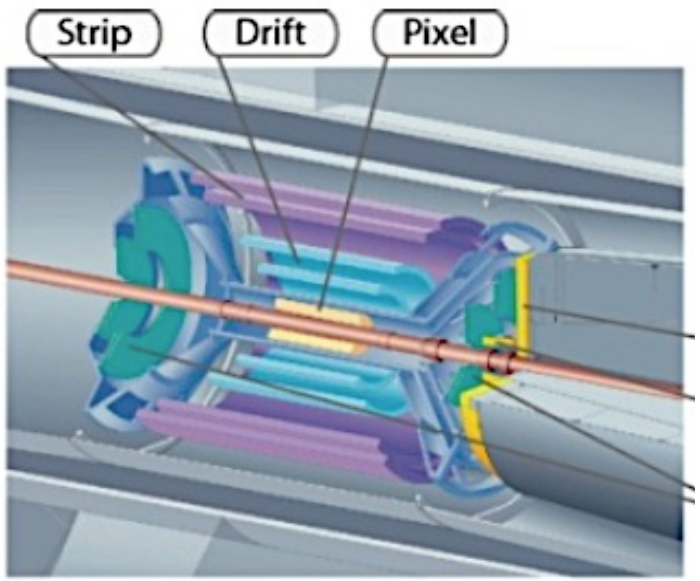
… and more in other talks at this conference or yet to come…



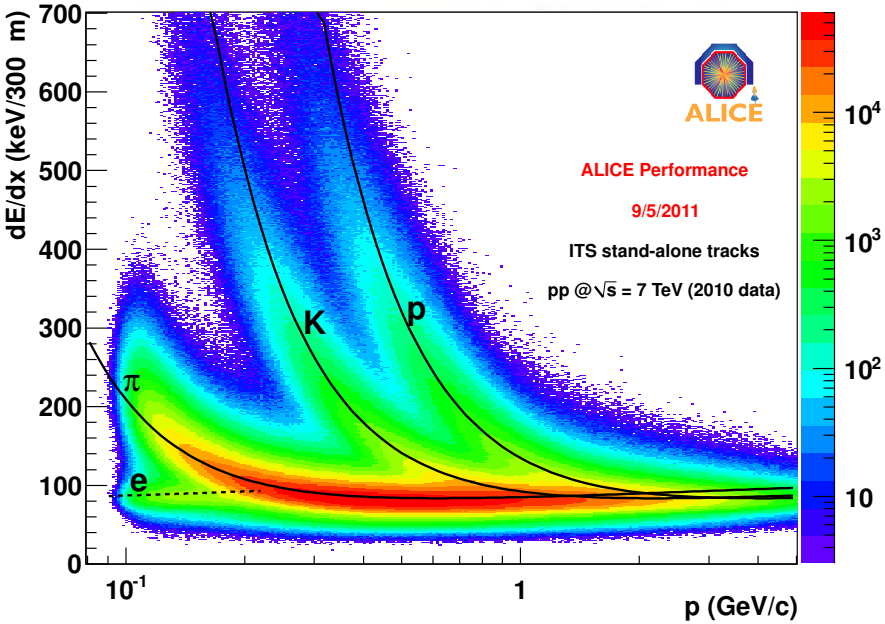
ALICE

Thank you for your attention!

ITS – Inner tracking system



Parameter		Silicon Pixel	Silicon Drift	Silicon Strip
Spatial precision $r\varphi$	(μm)	12	35	20
Spatial precision z	(μm)	100	25	830
Two track resolution $r\varphi$	(μm)	100	200	300
Two track resolution z	(μm)	850	600	2400
Cell size	(μm^2)	50×425	202×294	95×40000
Active area per module	(mm^2)	12.8×69.6	72.5×75.3	73×40
Readout channels per module		40 960	2×256	2×768
Total number of modules		240	260	1698
Total number of readout channels	(k)	9 835	133	2608
Total number of cells	(M)	9.84	23	2.6
Max. occupancy for central Pb-Pb (inner layer)	(%)	2.1	2.5	4
Max. occupancy for central Pb-Pb (outer layer)	(%)	0.6	1.0	3.3
Power dissipation in barrel	(W)	1350	1060	850
Power dissipation end-cap	(W)	30	1750	1150



ITS:

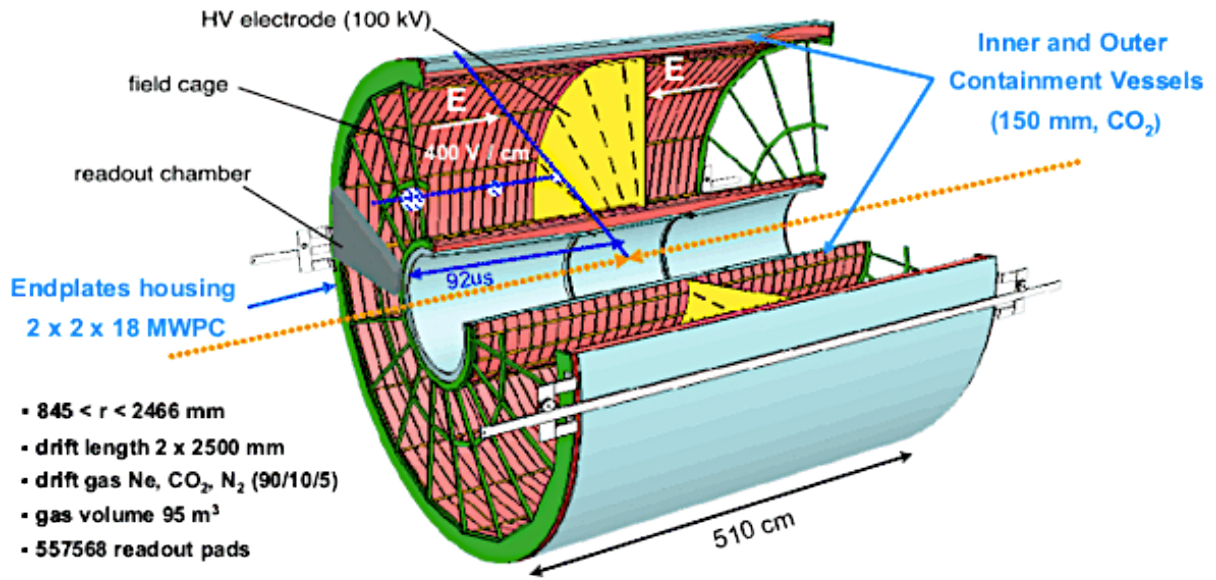
6 silicon layers, 3 technologies: pixel, strip, drift

Primary vertex reconstruction (SPD)

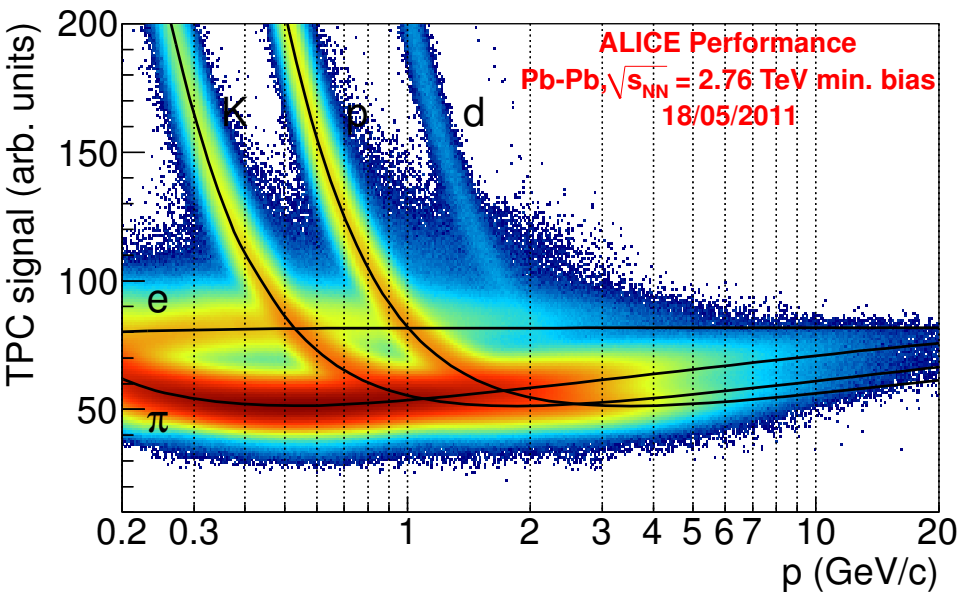
Standalone tracking

PID via dE/dx measurement in silicon with **resolution of 10-15% in PbPb**

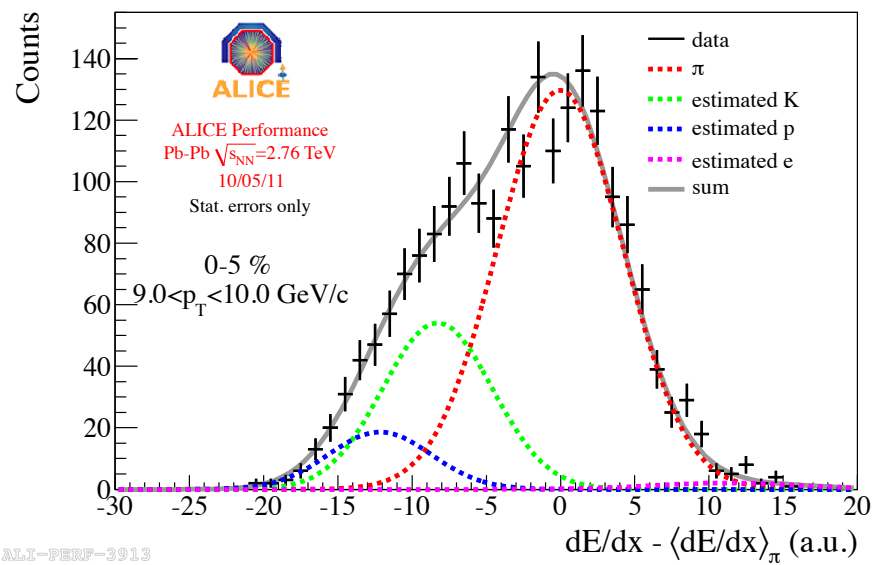
TPC – Time Projection Chamber



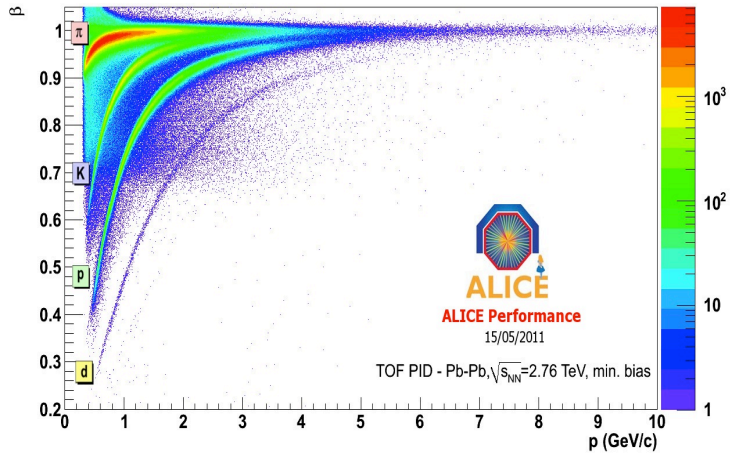
PID via dE/dx measurement in gas with **resolution of 5% in PbPb**

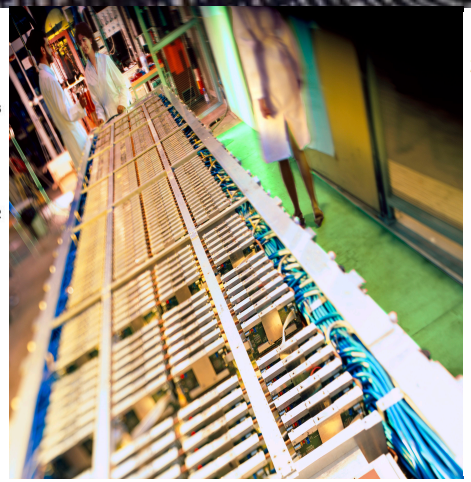


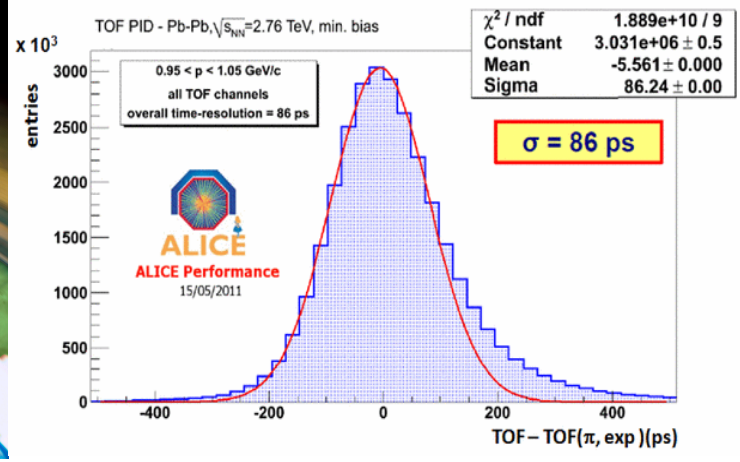
PID for high-p particles via simultaneous 4σ fit of TPC signal on the relativistic rise of dE/dx Bethe-Bloch



TOF - Time Of Flight







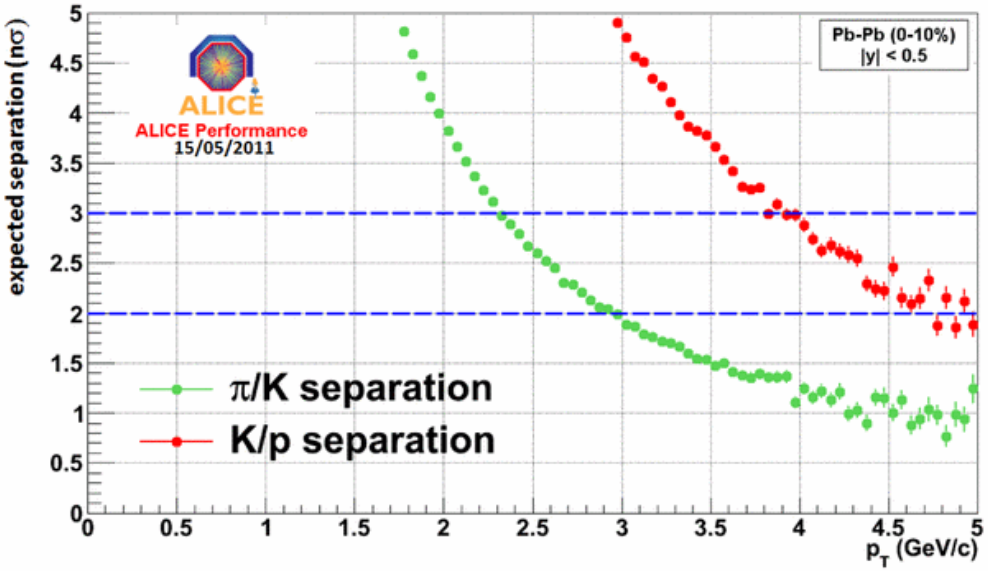
The ALICE Time-Of-Flight system:

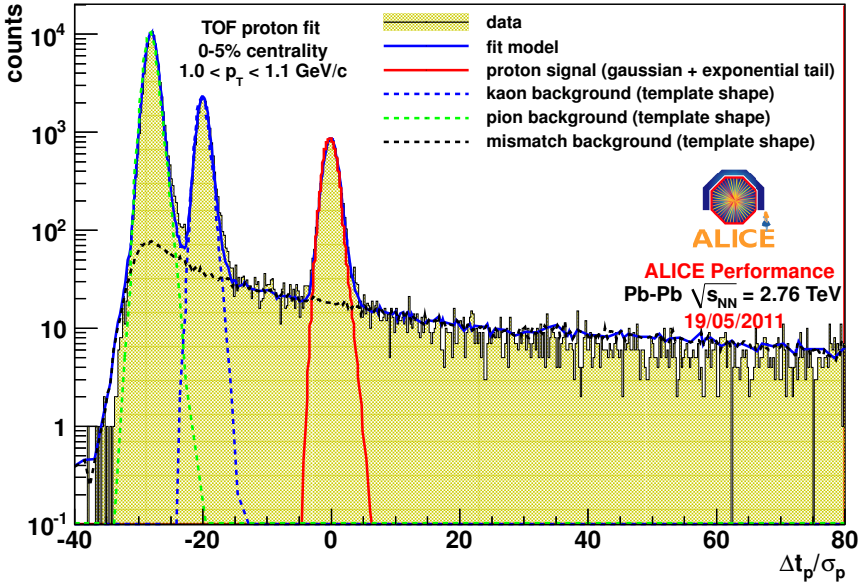
- Based on Multi-Gap Resistive Plate Chamber
- r_{in} = 370 cm, 0°≤φ≤360°, |η|< 0.9
- 18 sectors, >153,000 readout channels

PID via gaussian unfolding of TOF signal

Global* time resolution: ~86 ps in Pb-Pb

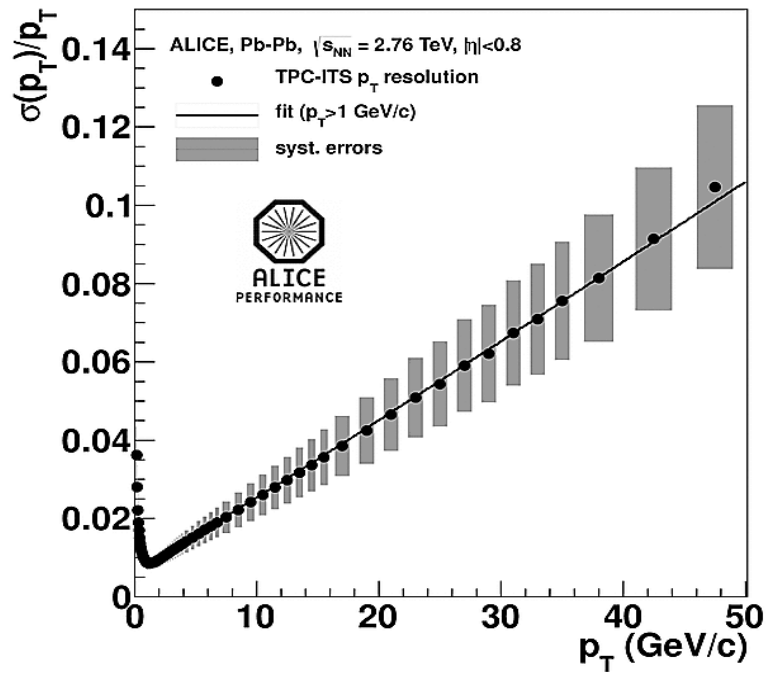
*Includes resolution on event time zero





Tracking performance

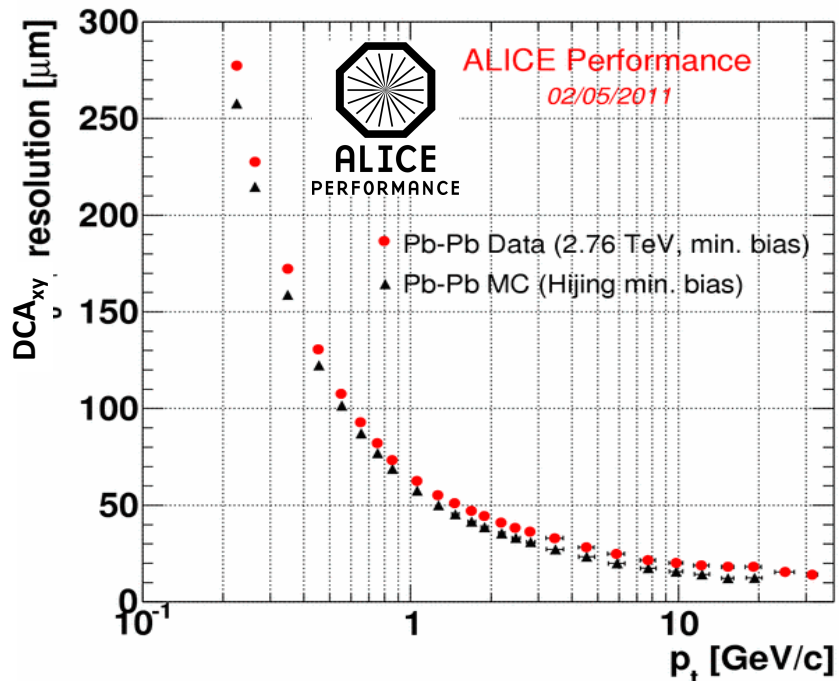
p_t resolution



p_t resolution ~10% at 50 GeV/c

- Small multiplicity dependence
- Estimate from track residuals

DCA_{xy}: Transverse distance-of-closest-approach



Good DCA_{xy} resolution

→ control contamination from secondaries

Strict DCA_{xy} cut (< 7σ), small contamination

Residual contamination less than 1% for p_t > 4 GeV/c

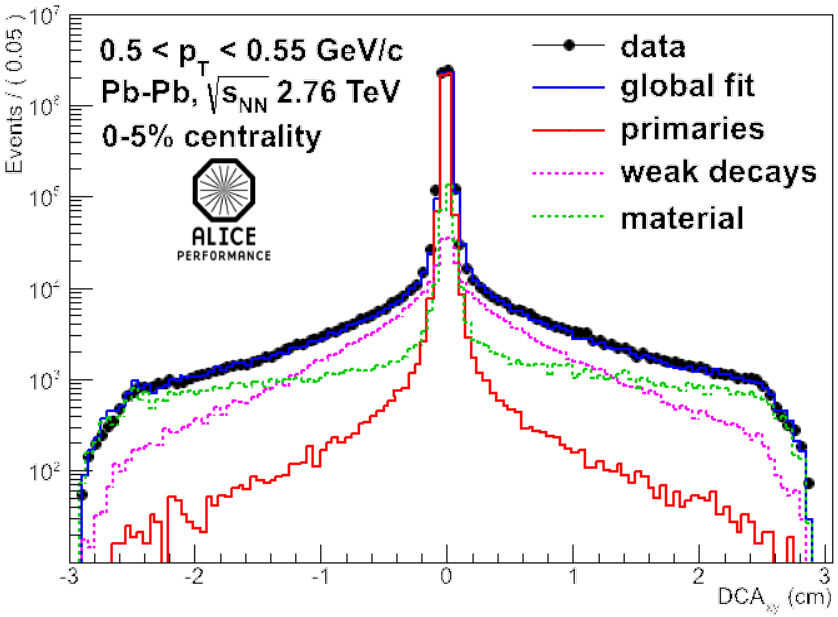
Feed-down correction for protons

Feed-down correction needed to eliminate contributions from weak decay of strange particle (Λ, Ξ,…) to the primary protons spectrum.

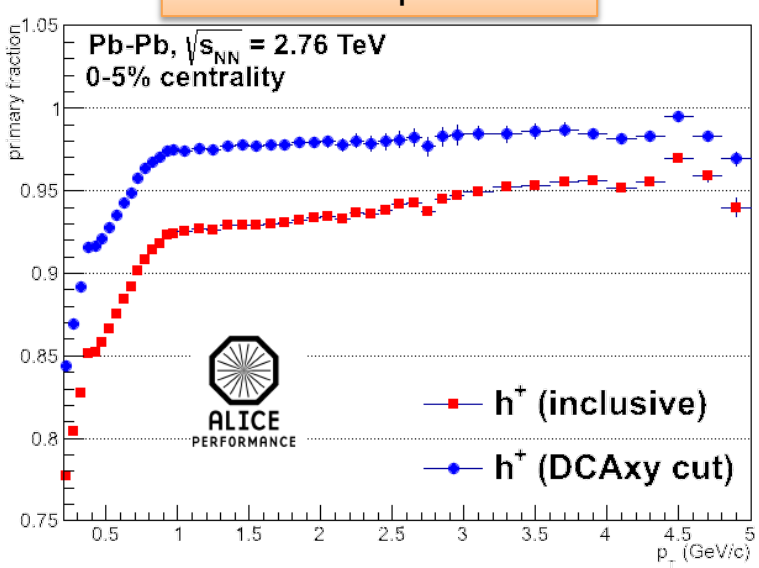
Distance of closest approach (DCA) in the bending plane used to correct.

Correction estimated from a fit using Monte Carlo templates for distributions of primaries and secondaries

- from weak decay of strange particles
- from interaction with the material.



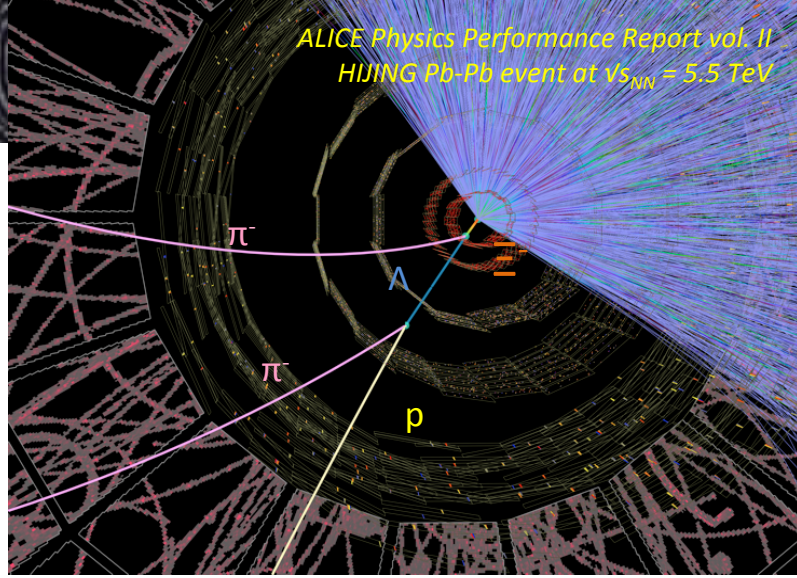
Fraction of primaries



- Strict DCA_{xy} cut (< 7σ) allow small contamination
- Residual contamination less than 1% for p_T > 4 GeV/c

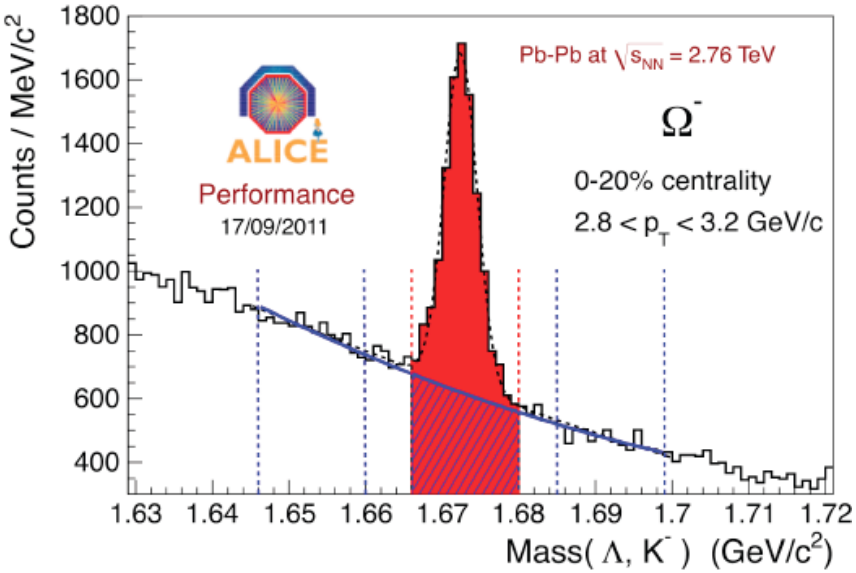
Multi-strange baryons analysis

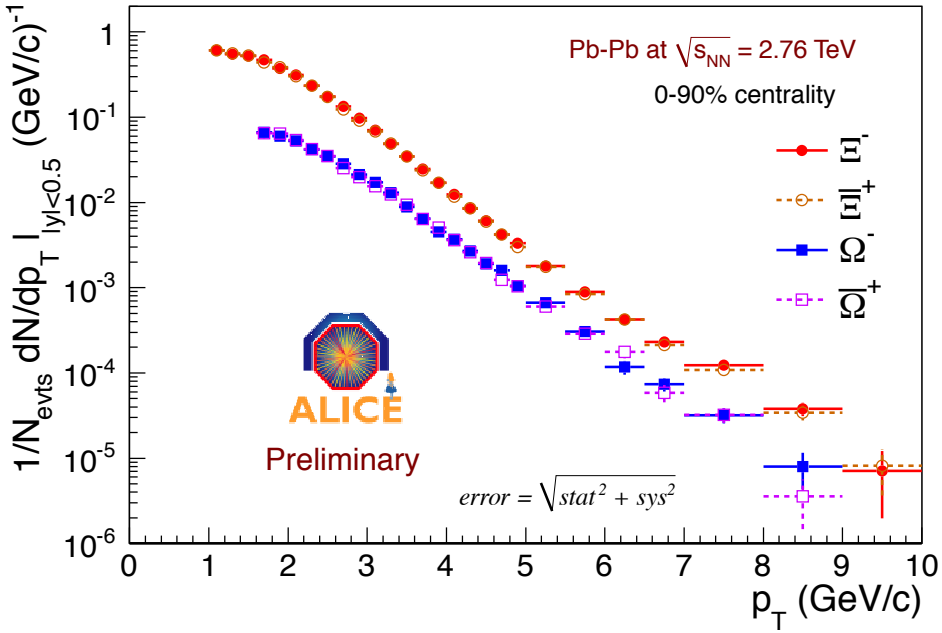
- ITS vertexing + tracking
- TPC tracking + PID (dE/dx)
- Topological reconstruction of decays:
  - Selection of Λ based on cuts on impact parameter and invariant mass
  - TPC PID for all decays products
- Signal extraction:
  - Polynomial+gaussian fit for mean and σ
  - Bin counting in (±3σ) signal region
  - Integral of background fit function in signal region
  - Signal = bin counting - integral



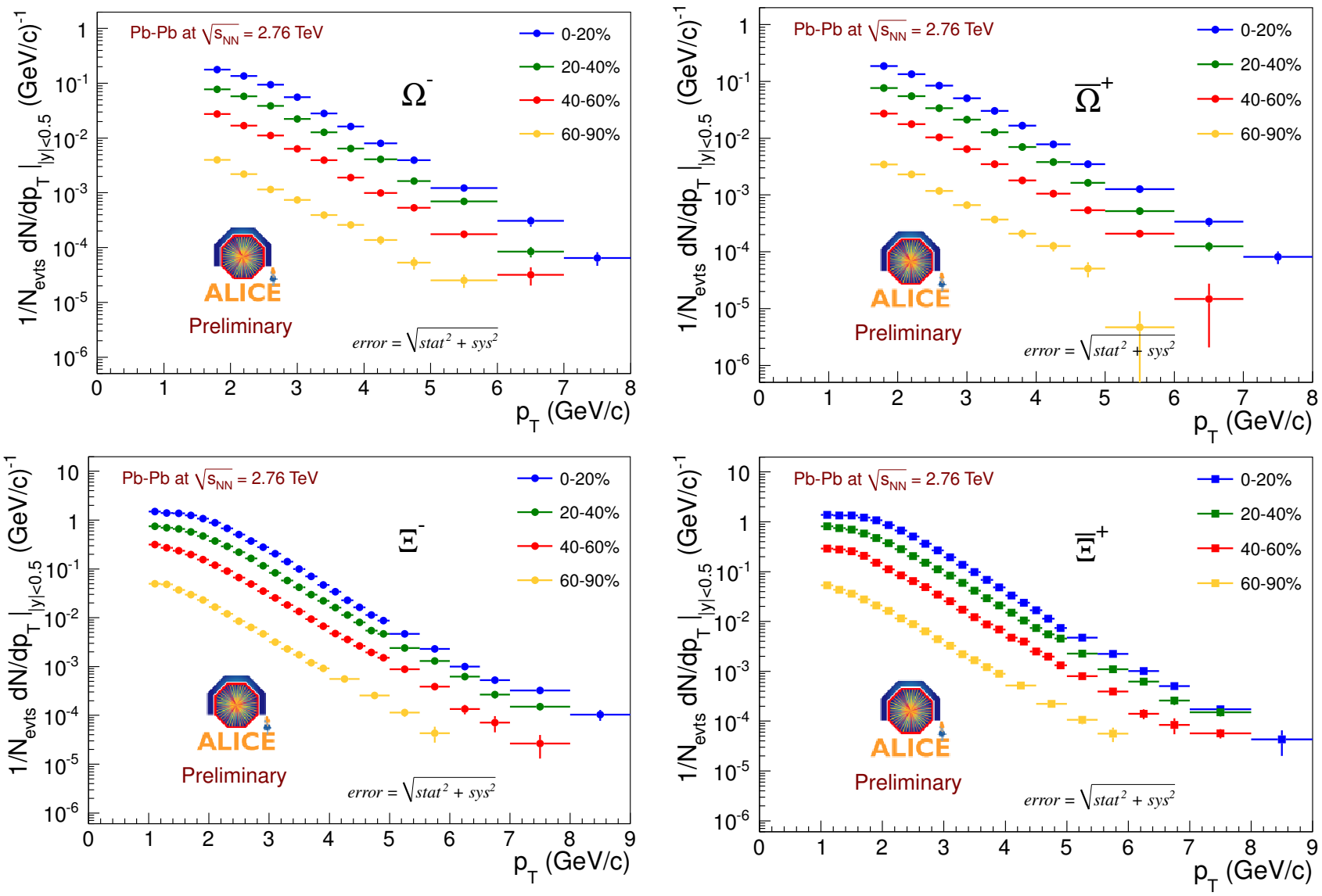
$$\Xi^-(dss) \to \Lambda\pi^- \to p\pi^-\pi^-$$
$$\bar{\Xi}^+(\bar{d}\bar{s}\bar{s}) \to \bar{\Lambda}\pi^+ \to \bar{p}\pi^+\pi^+$$

$$\Omega^-(sss) \to \Lambda K^- \to p\pi^- K^-$$
$$\bar{\Omega}^+(\bar{s}\bar{s}\bar{s}) \to \bar{\Lambda}K^+ \to \bar{p}\pi^+ K^+$$

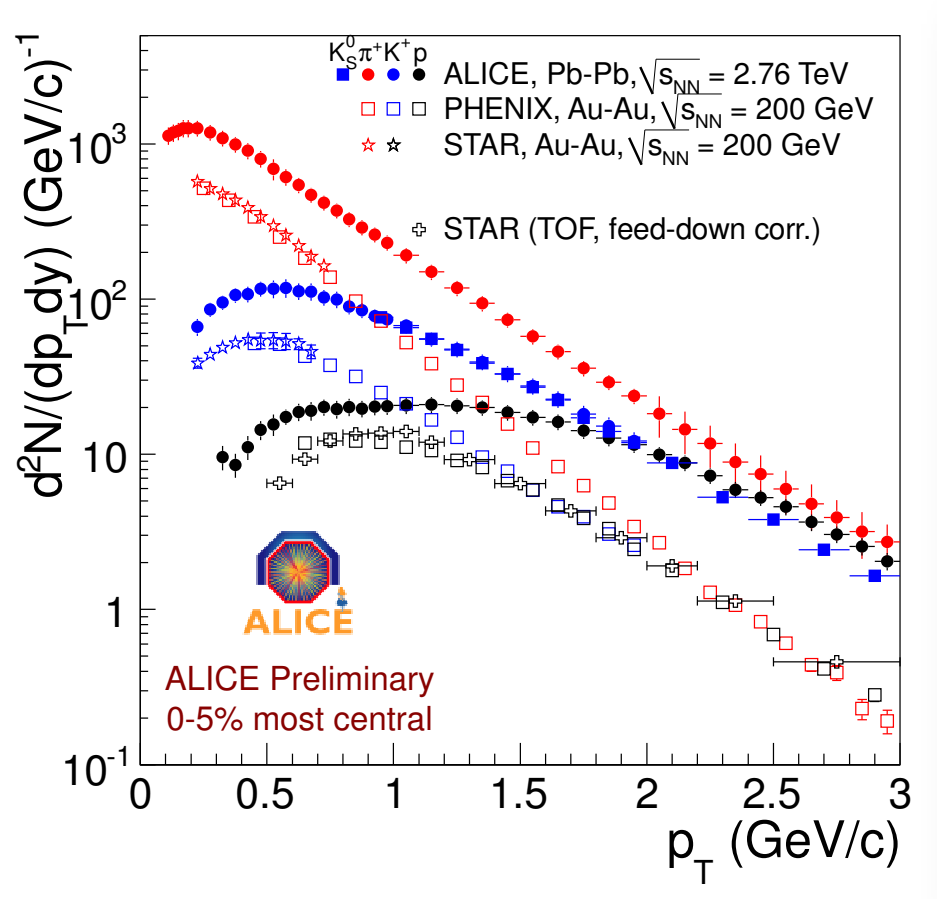


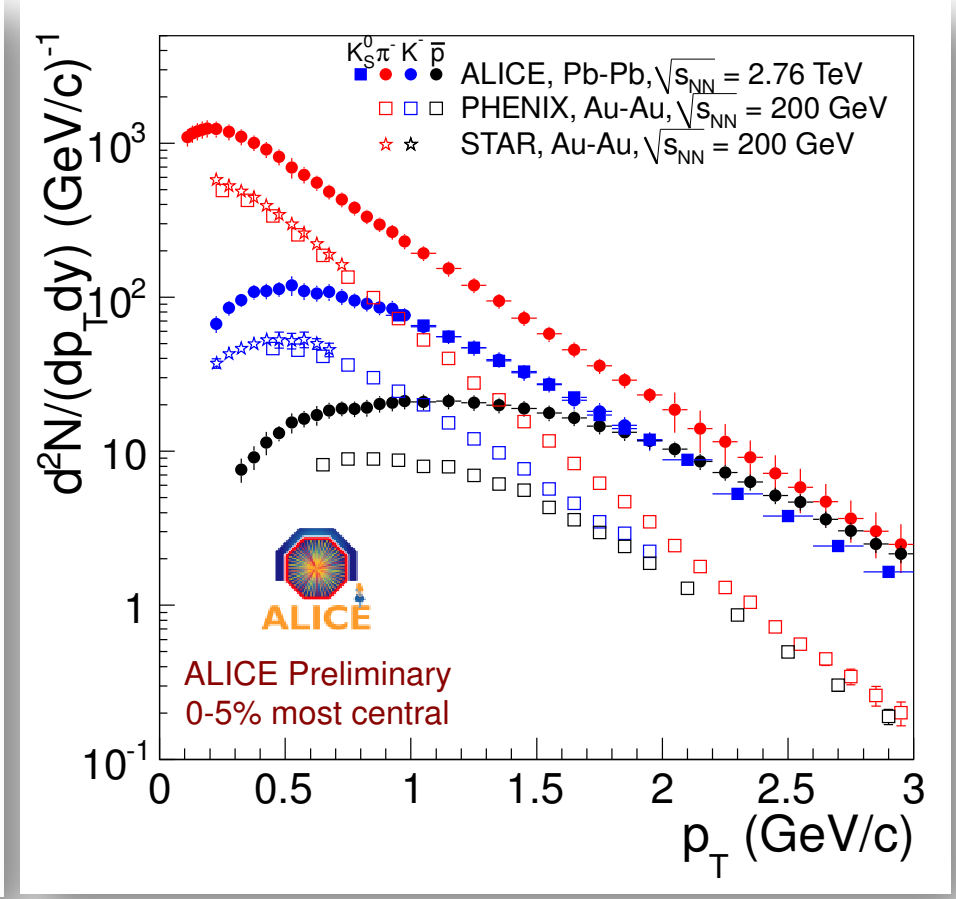


Multi-strange baryons spectra

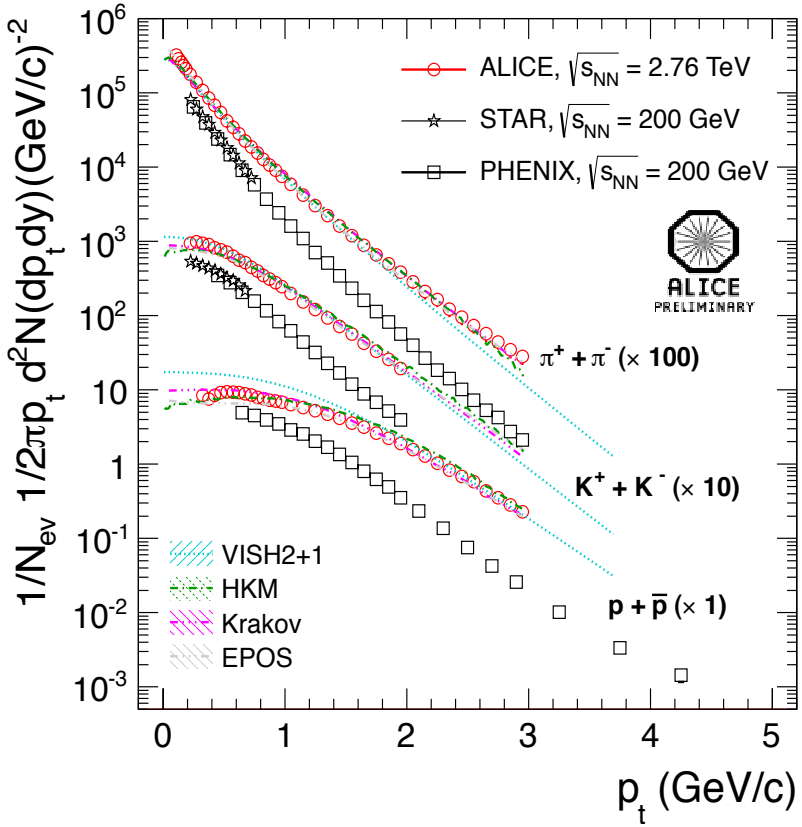


Measured spectra in Pb-Pb at LHC vs RHIC





Hydro models



VISH2+1: *PRC 83, 024912 (2011)*

- viscous hydrodynamic model (2+1)
- assumes longitudinal boost-invariance
- assumes thermal yields (T_{ch} = 165 MeV)
- no explicit description of the hadronic phase

HKM: *JP G38, 124059 (2011), PRC 78 034906 (2008)*

- hydrokinetic model + hadronic cascade model (UrQMD)
- the hydrokinetic model is based on dynamical decoupling described by escape probabilities

Krakow: *PRC 85, 034901 (2012)*

- viscous hydrodynamics (3+1) with shear and bulk viscosities
- assumes no longitudinal boost-invariance
- ansatz to describe deviation from equilibrium due to viscosity corrections in the transition from hydrodynamics to particles

EPOS 2.17v3: *arXiv:1203.5704 [nucl-th]*

- quantum mechanical multiple scattering approach for particle and jet production in high-density environment (energy loss) based on flux tubes (parton ladders)
- hydrodynamical (3+1) evolution + hadronic cascade
- Introduced to account for bulk matter, jets, and their mutual interaction

Blast-wave function

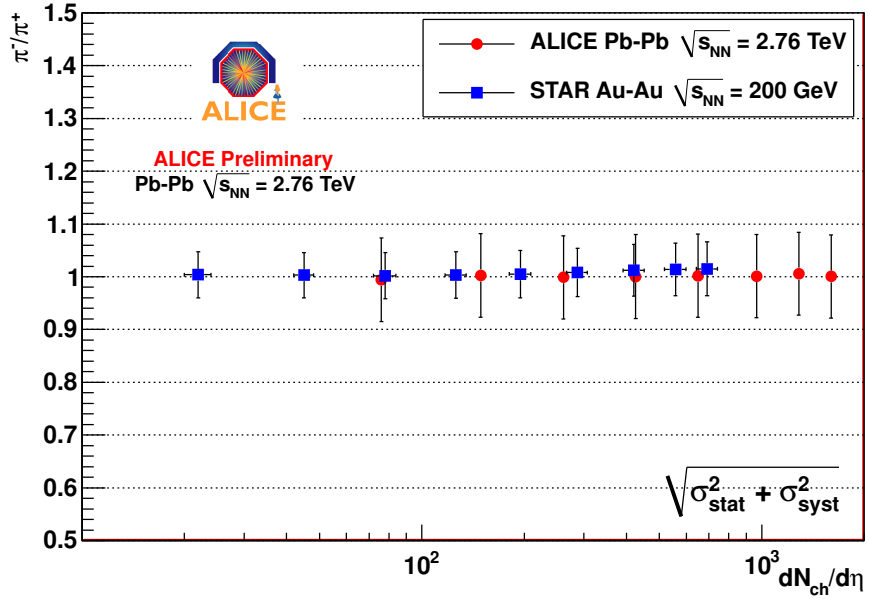
$$\frac{dN}{p_\perp dp_\perp} \propto \int_0^R r dr m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{kin}}\right)$$

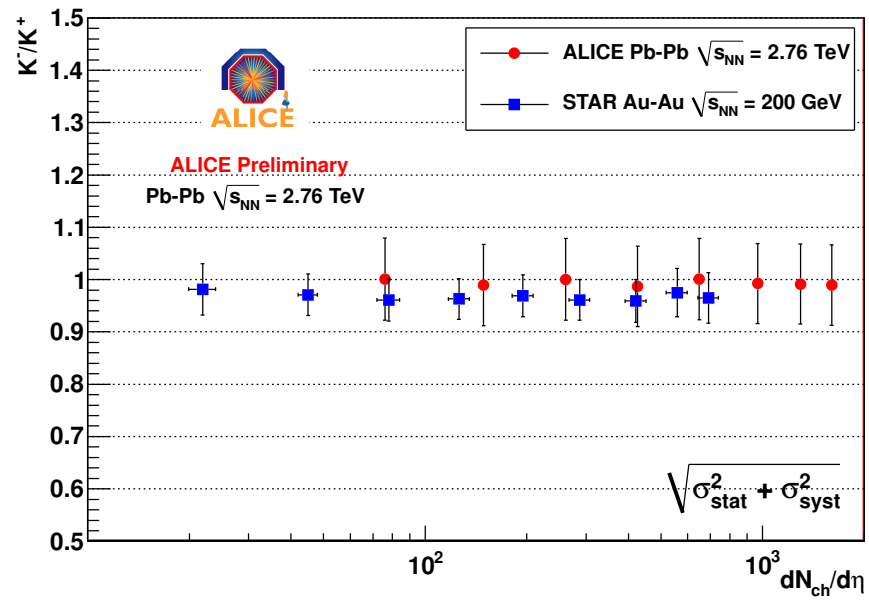
$$\beta = \beta_S (r/R)^n \qquad \rho = \tanh^{-1}\beta$$

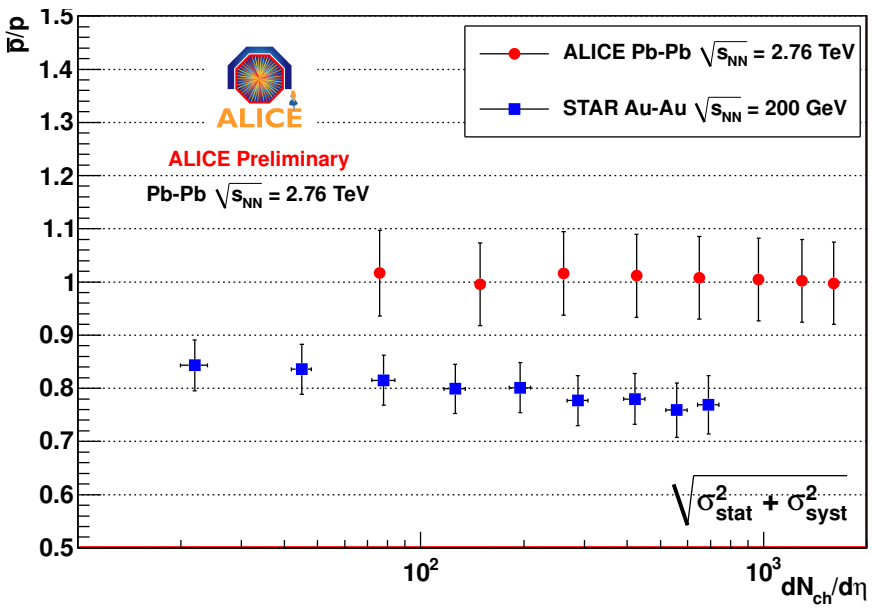
Free parameters: **T_{kin}, β_s, n**

- T_{kin} = kinetic (thermal) freeze-out temperature in the model
- β : transverse radial flow velocity
- β_s: surface transverse flow velocity
- n: velocity profile
- ρ_r: transverse boost
- R: transverse geometric radius of the source at the freeze-out

Anti-particle/particle ratios – from RHIC to LHC



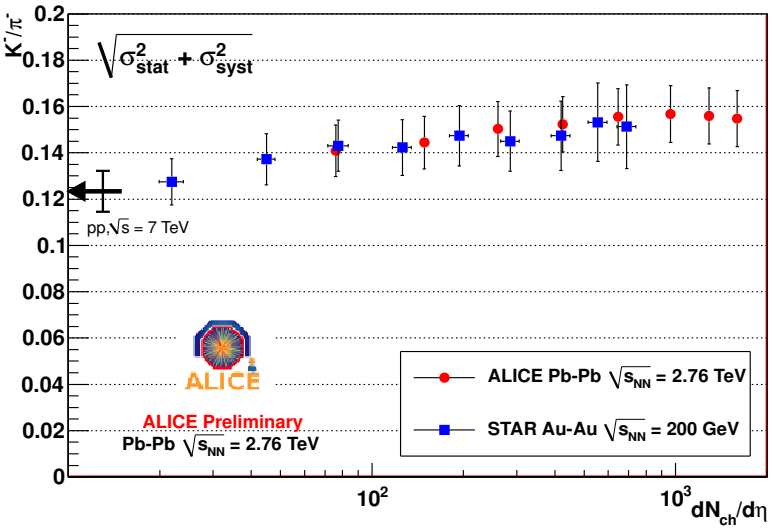


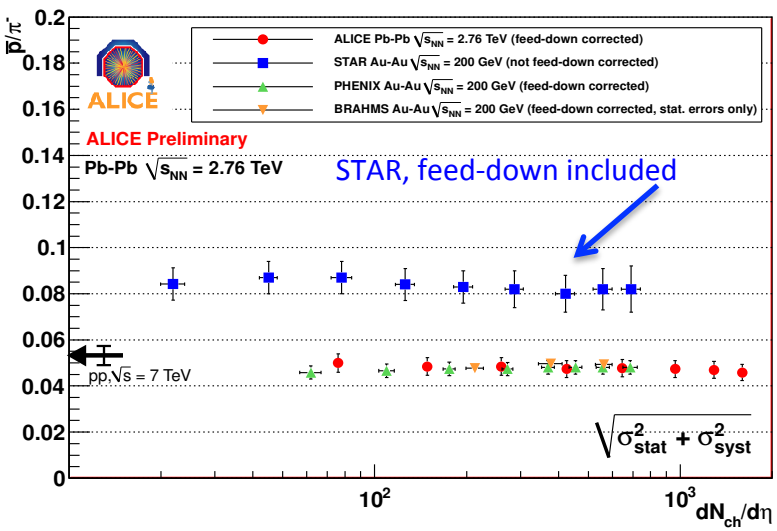


At the LHC **anti-particle/particle ratios at mid-rapidity are compatible with 1**, as expected
→ $\mu_B \sim 0$

STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)

Particle ratios – from RHIC to LHC



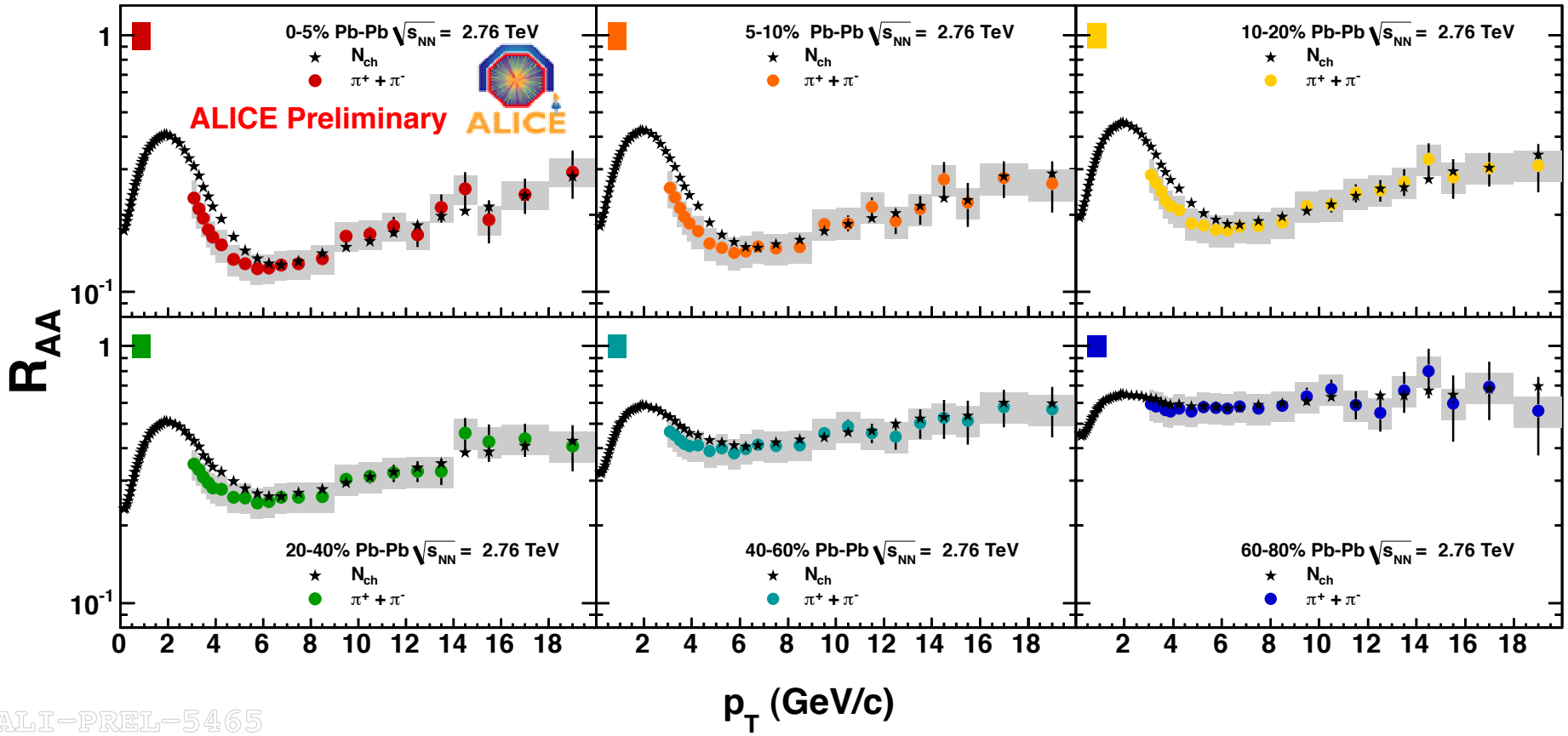


K/π and p/π ratios at LHC and RHIC exhibit similar centrality dependence.

K/π slightly increases with $dN_{ch}/d\eta$ from pp to very central events

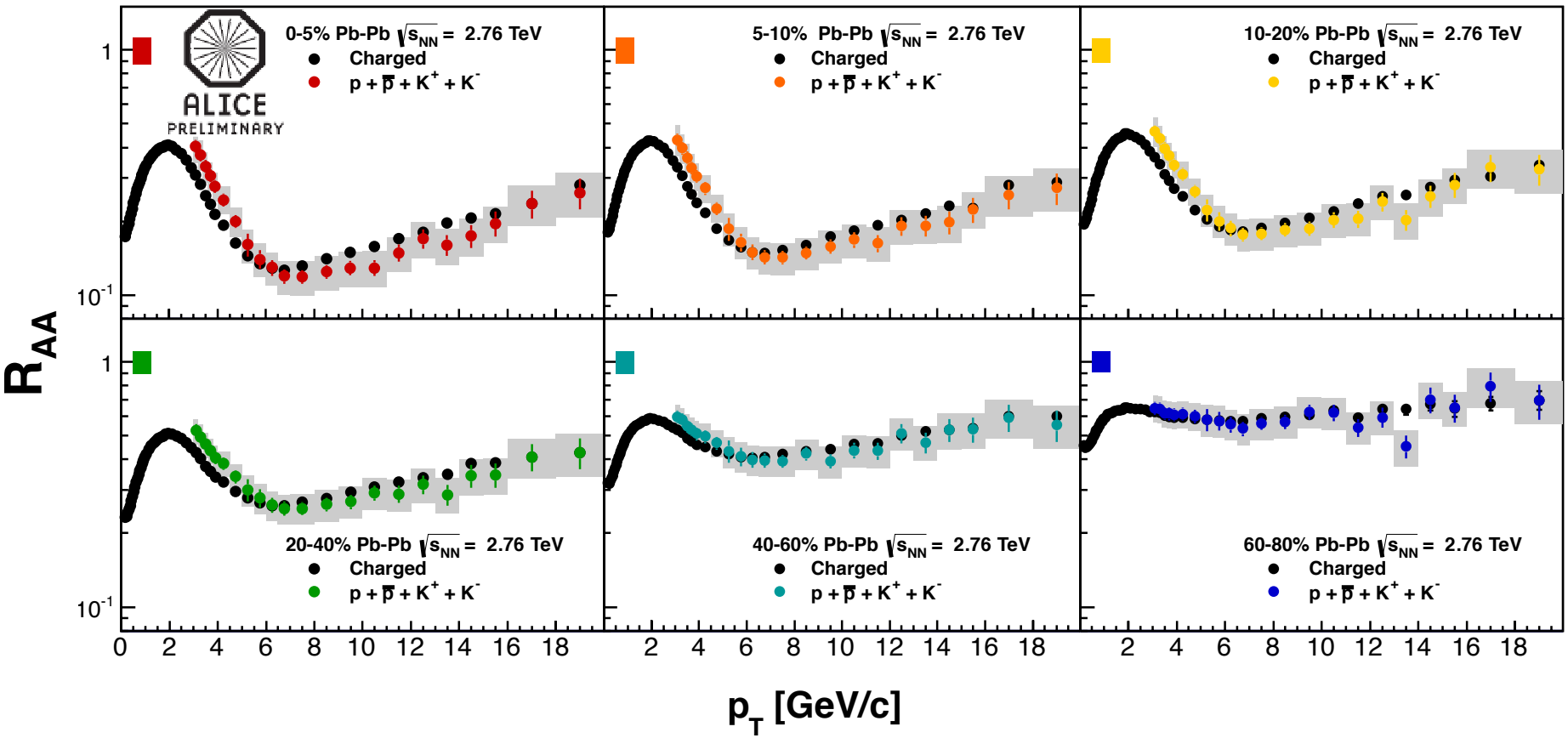
STAR, PRC 79, 034909 (2009)
PHENIX, PRC 69, 03409 (2004)
BRAHMS, PRC 72, 014908 (2005)

Pions R_{AA}



pp reference used is measured pp in √s = 2.76 TeV (ALICE 2011 data)

Kaons and protons R_{AA}



pp reference used is measured pp in √s = 2.76 TeV (ALICE 2011 data)