Production of strange and multi-strange particles with ALICE experiment at LHC

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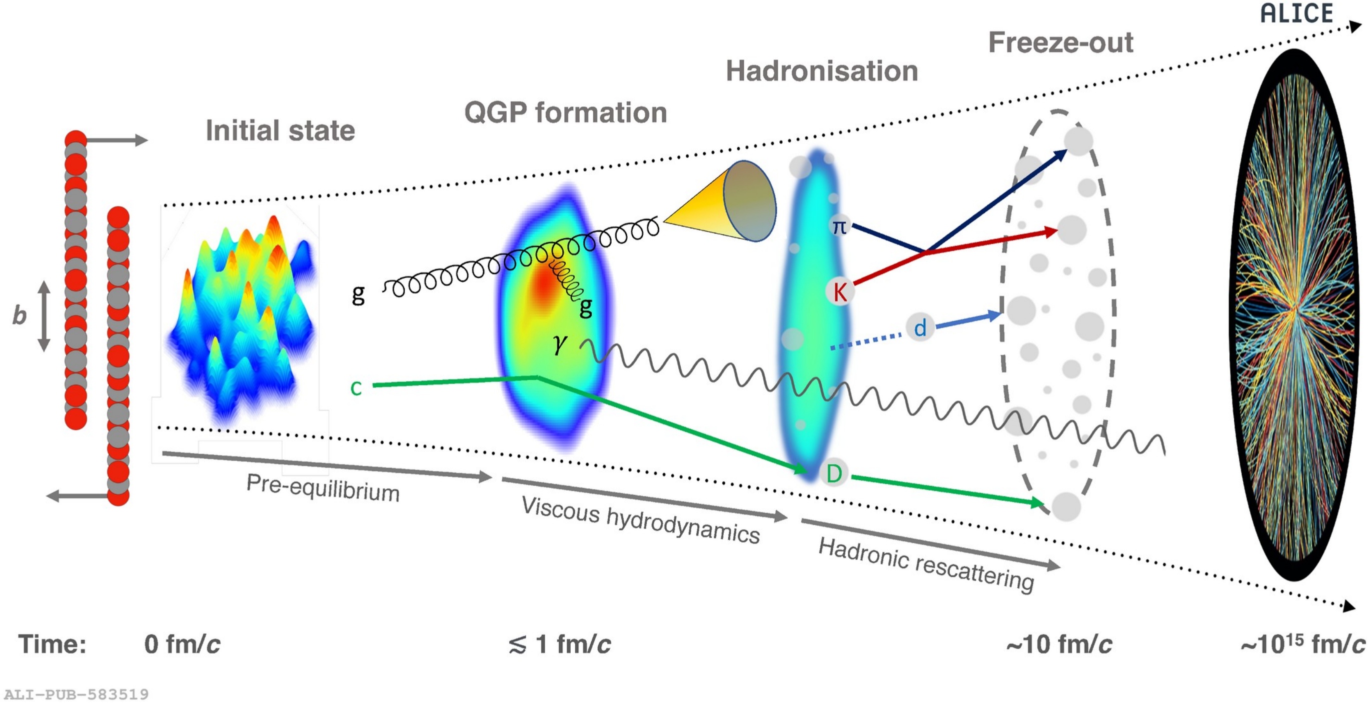
QGP formation and light flavour production in hadronic collisions

QGP 10^{-6}s after big-bang

- Tc ~ 150–160 MeV
- N coll ~ $A^{4/3}$ can reach values of ~ 2000 for Pb–Pb

1. initial state Lorentz contracted (b – impact parameter)
2. large Q^2 interactions "Hard process"
3. small Q^2 interaction – pre-equilibrium
4. equilibration and expansion of QGP
5. Hadron formation
6. Chemical freezout of hadrons



7. Kinematical freezout hadrons
8. Free passage of particles through detector

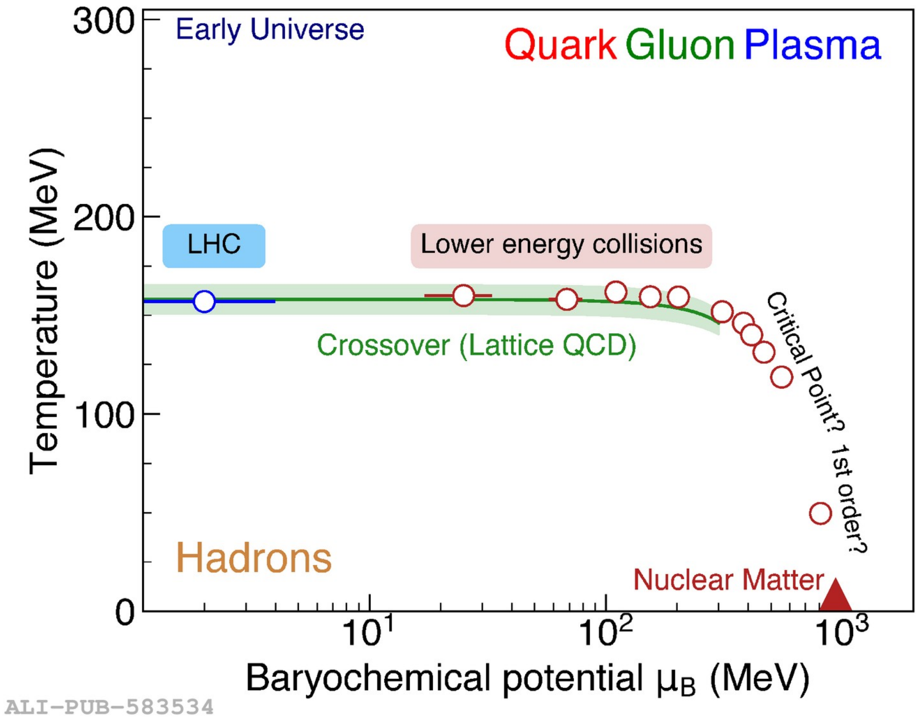
QGP formation and light flavour production in hadronic collisions

Lattice QCD 2+1-flavour QCD

Charm, bottom and top quarks :
- too heavy to significantly add to the dynamics of the system

- Strongly interacting system
- zero net baryon density
- deconfined (quarks and gluons) state, T ~ 155 MeV
- crossover transition - no latent heat is involved.

-cross-over occurs in coincidence with the restoration of the chiral symmetry.



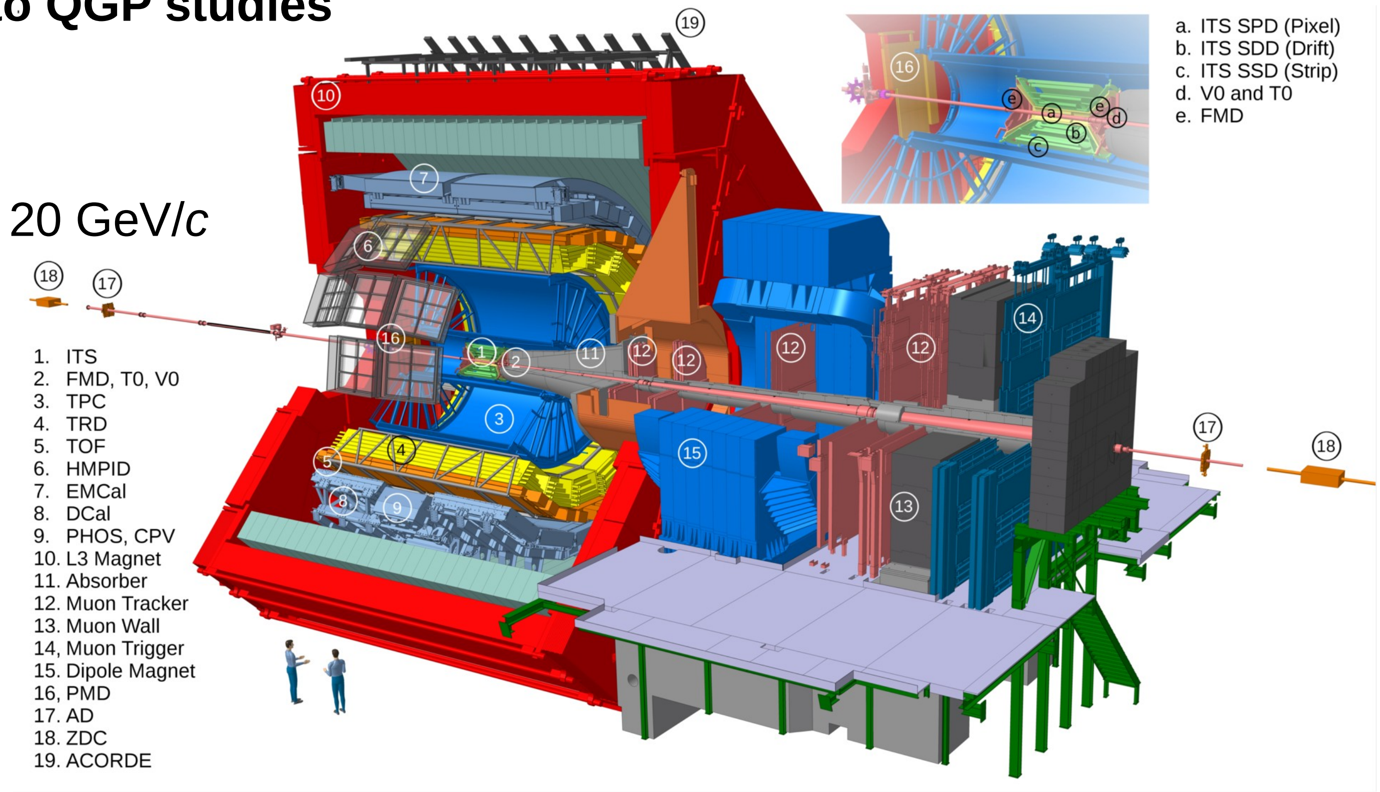
- strong increase in the energy density (ε): the liberation of many new degrees of freedom

ALICE experiment in Run 2

detector specifically devoted to QGP studies
proposed in March 1993

-pseudorapidity region |η| < 0.9
-particle identification up to p_T ~ 20 GeV/c

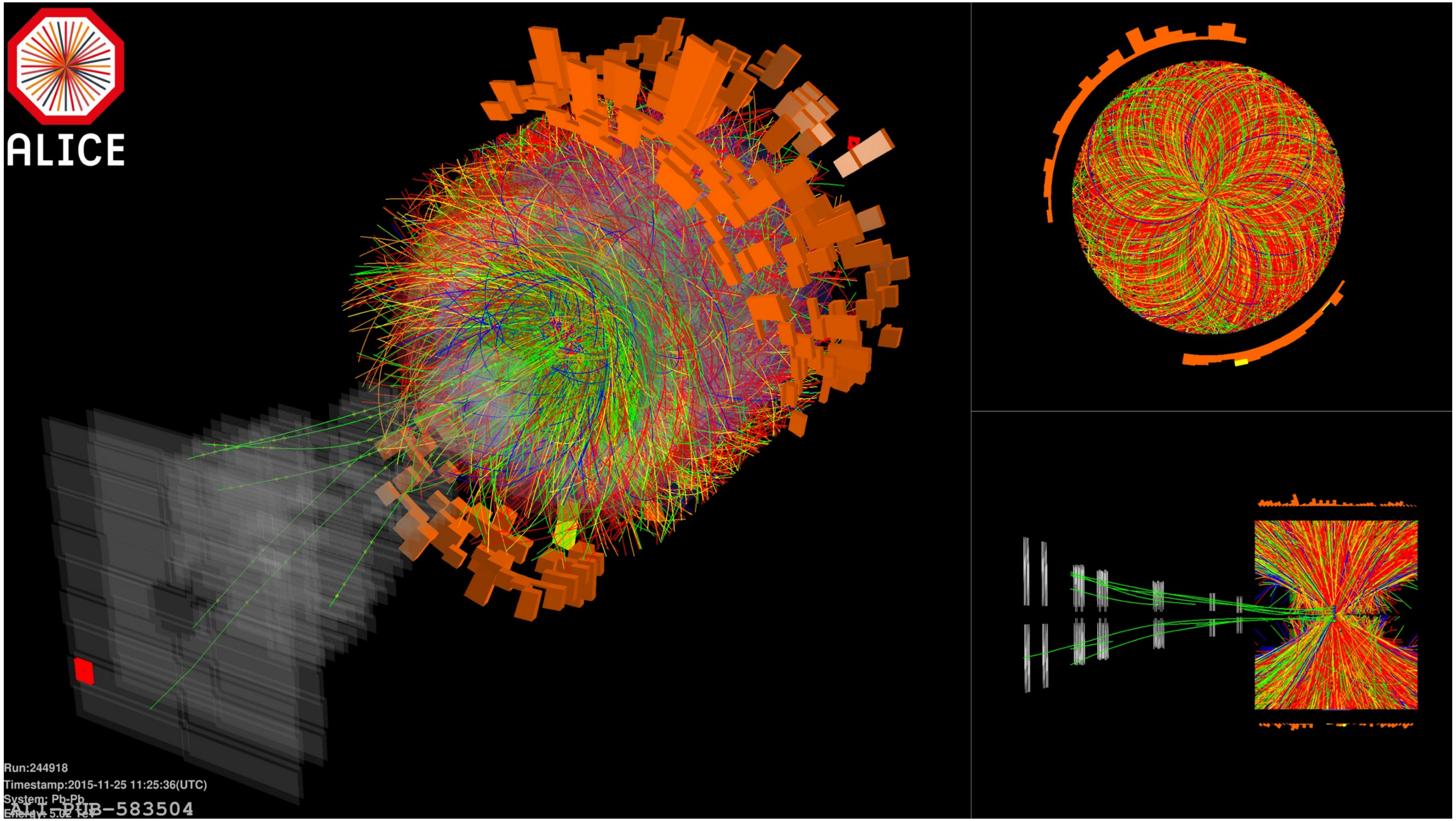
main charged-particle tracking detectors:
Inner Tracking System (ITS)
Time Projection Chamber (TPC)
 - track reconstruction
 -dE/dx particle identification
 -Vertex position reconstruction
L3 solenoid magnet (0.5T)



PID also TRD and TOF
V0 counters – event multiplicity (centrality) and MB trigger
ZDC – spectator nucleons (centrality, OOB Interaction, Eff energy)

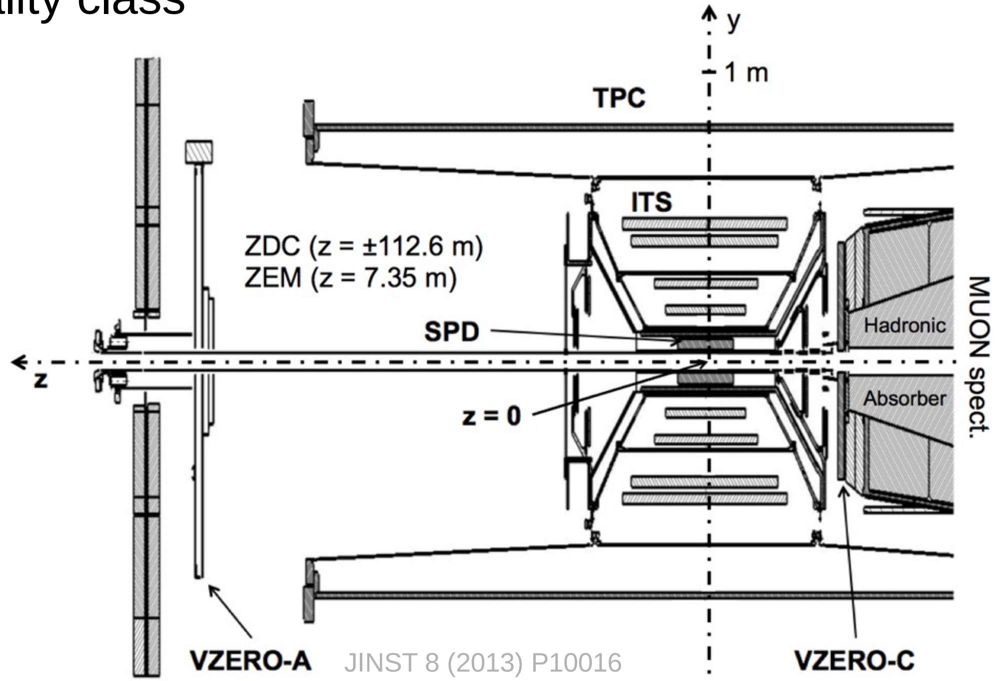
ALICE experiment Run 2

Online Pb-Pb envent
November 2015

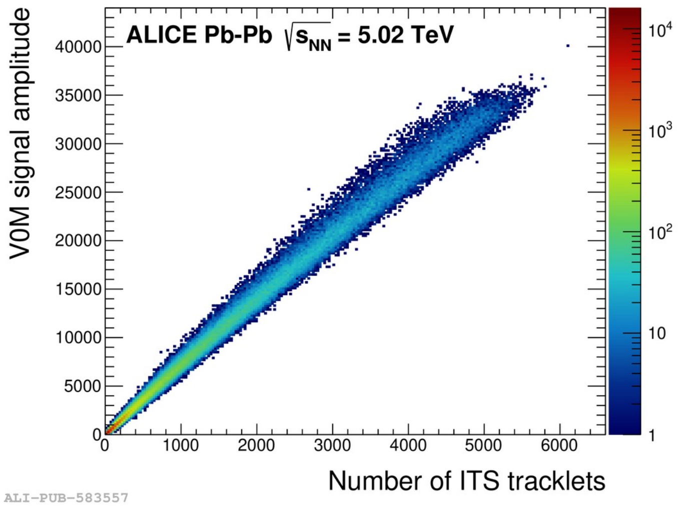


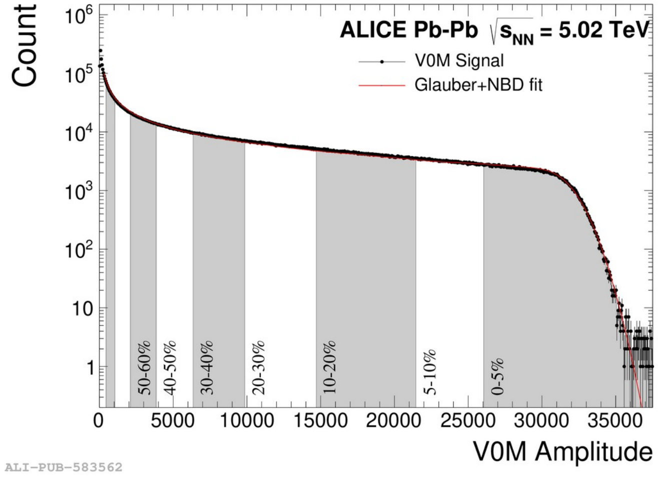
Event Centrality - multiplicity

-impact parameter b is not directly measurable!
  => centrality estimated with signal in V0 scintilator (also possible with ITS or ZDC)
- using Glauber model fit to determine N_{coll} and N_{part} for each centrality class



JINST 8 (2013) P10016

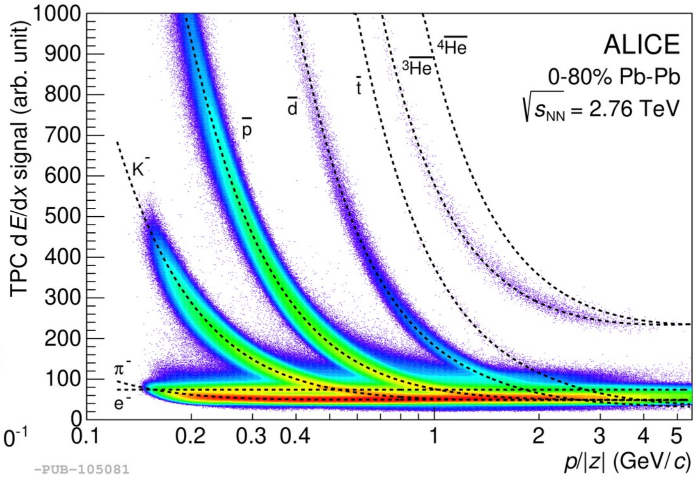




Particle identification and signal extraction with ALICE

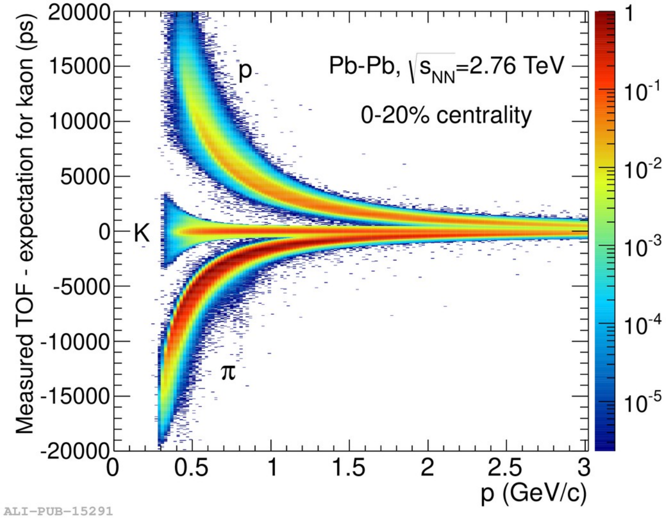
TPC d*E*/dx particle identification ->

- dashed lines : Bethe-Bloch parametrization



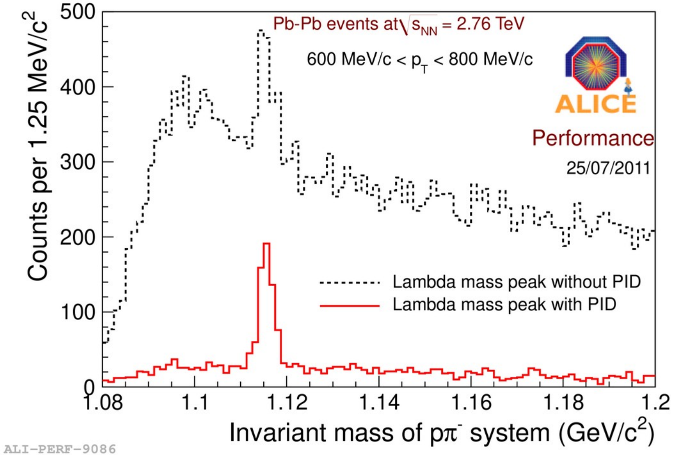
Demonstration of TPC PID on Λ

- Pb-Pb 2.76 TeV
- p_T bin 0.6-0.8 GeV/c



← TOF expectations

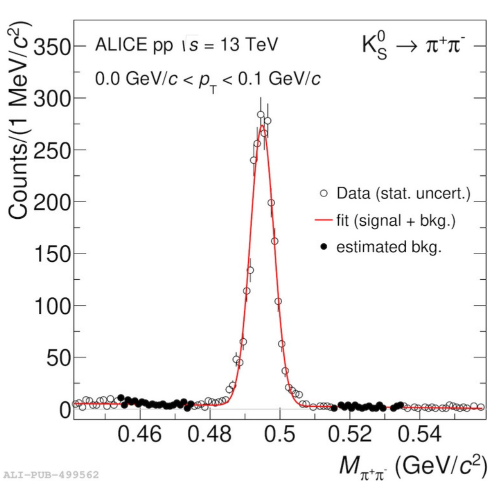
-time difference from expected values for proton, kaon and pion

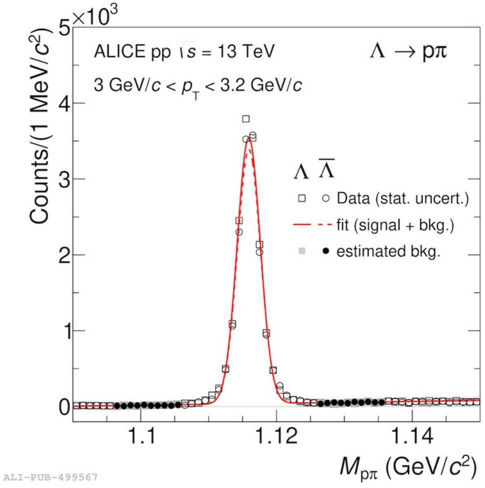


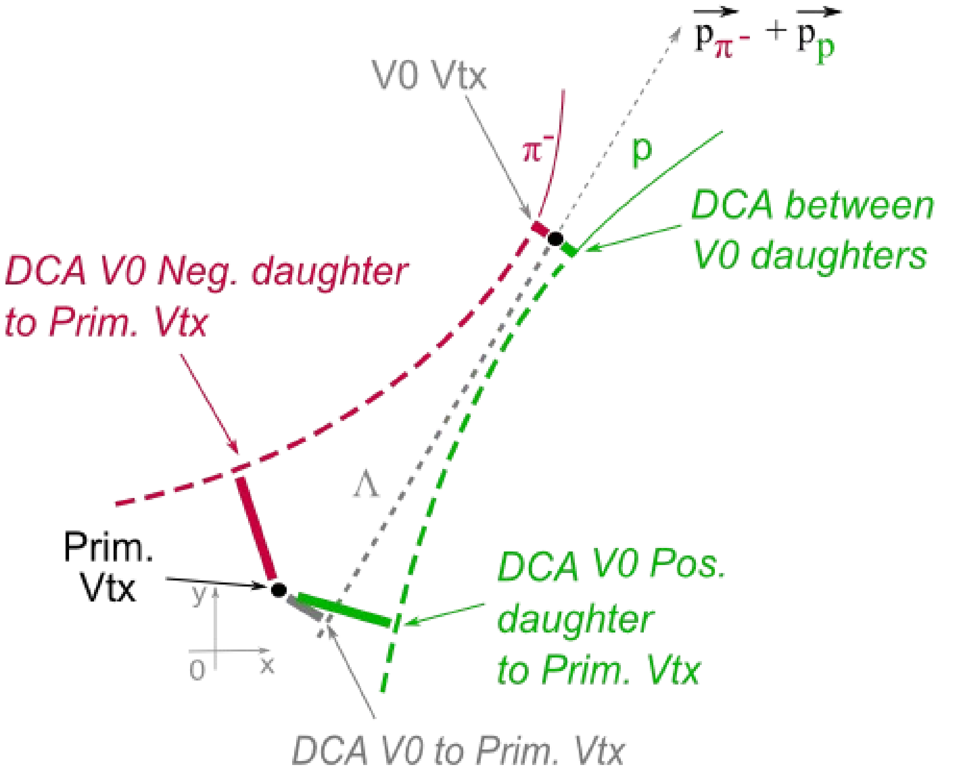
Particle identification and signal extraction with ALICE Λ, K^0_S

- Neutral hadrons identification based on the decay topology:

- Signal extracted from the distribution of invariant mass (mostly combinatorial background)





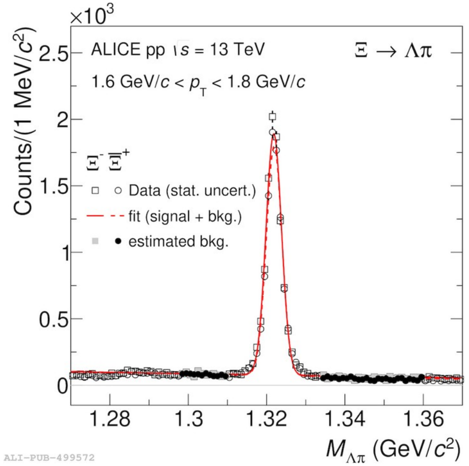


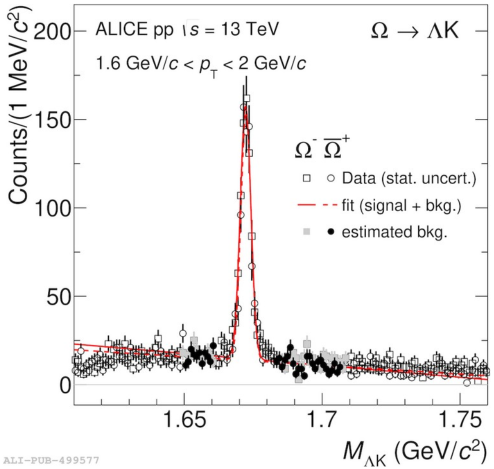
ALICE-PHO-SKE-2011-006-6

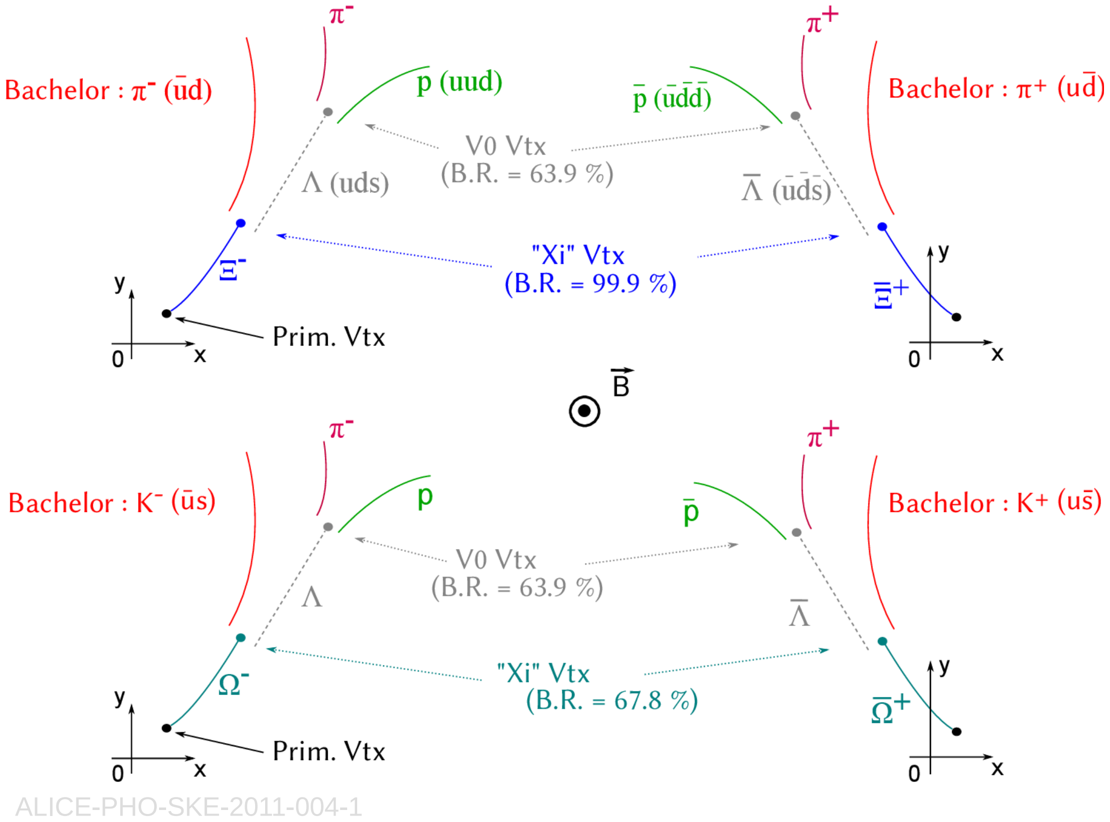
Particle identification and signal extraction with ALICE Ξ, Ω

- Neutral hadrons identification based on the decay topology:

- Signal extracted from the distribution of invariant mass (mostly combinatorial background)







Strange and multi-strange yields and p_T-distributions measured by ALICE in Run1 and Run 2

p_T distributions |y|< 0.5

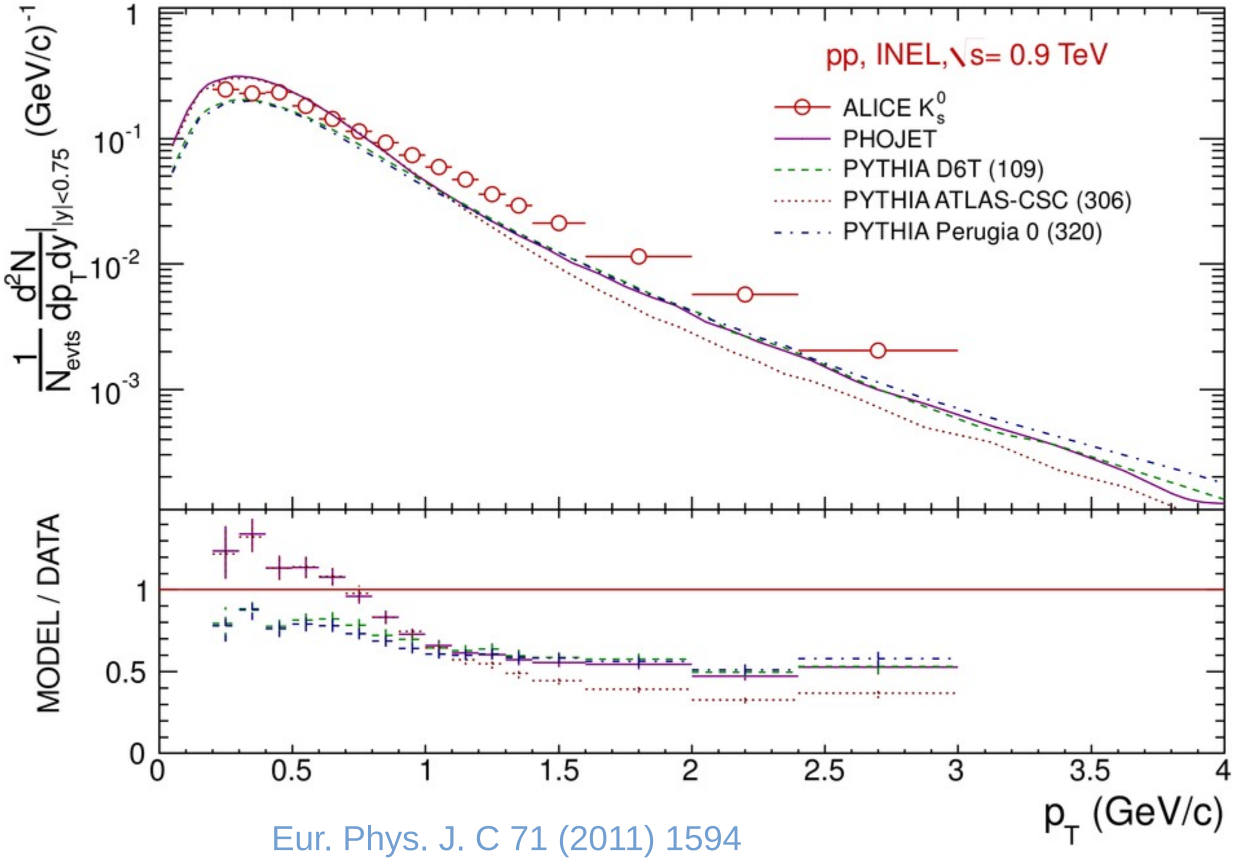
pp $\sqrt{s} = 0.9$ TeV

Minimum bias

K^0_S

- Spectra slightly harder then models

- underestimated by all models by factor ~ 2



Eur. Phys. J. C 71 (2011) 1594

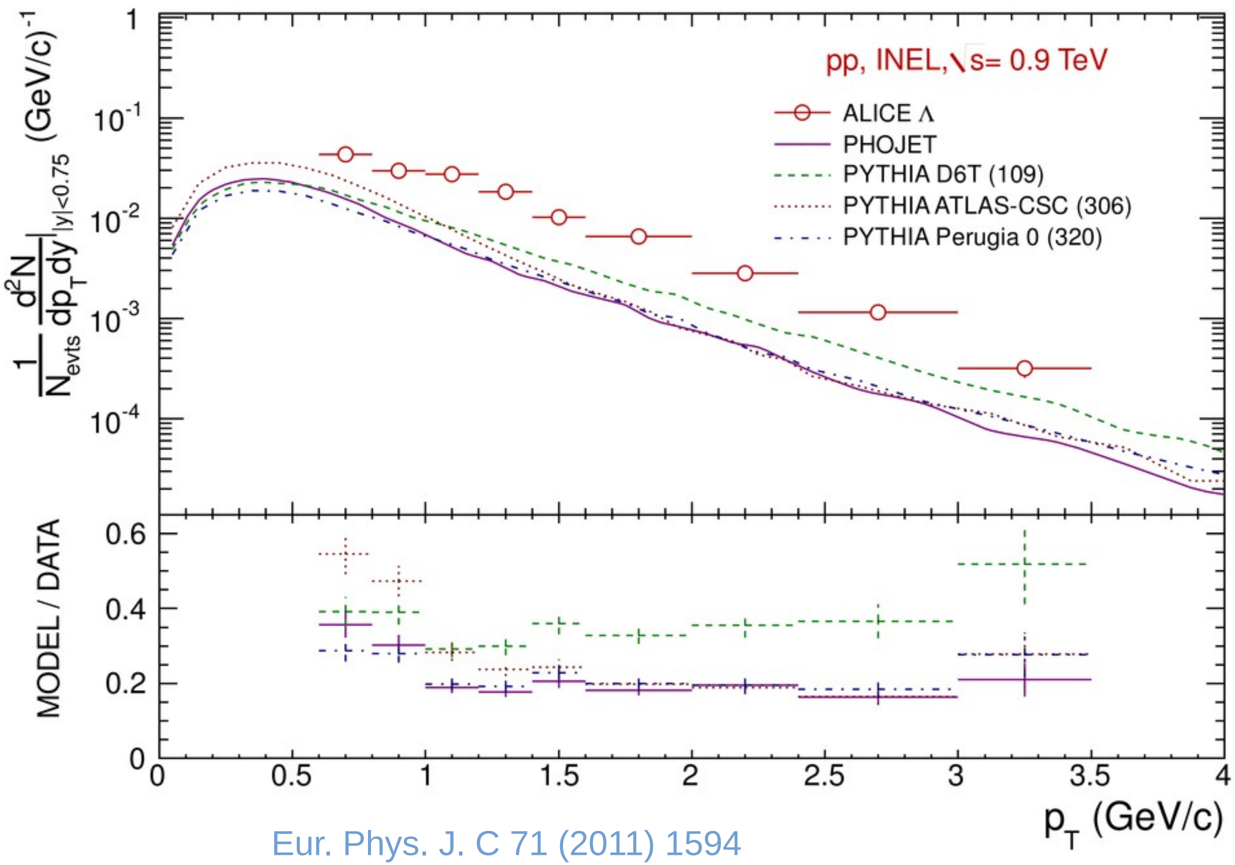
p_T distributions |y|< 0.5

pp $\sqrt{s}=0.9$ TeV

Minimum bias

Λ

- Spectra slightly harder then models
- underestimated by all models by factor ~ 3



Eur. Phys. J. C 71 (2011) 1594

p_T distributions |y|< 0.5

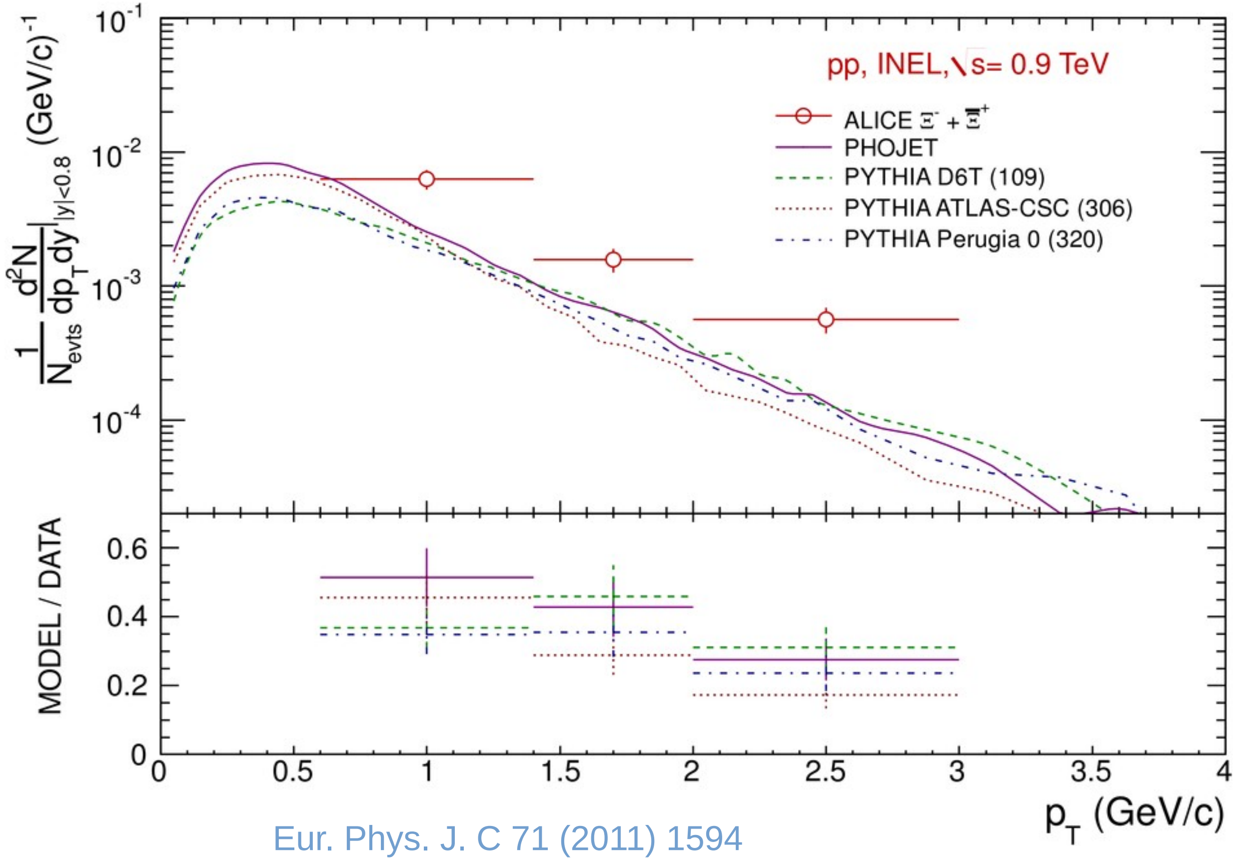
pp $\sqrt{s}=0.9$ TeV

Minimum bias

$\Xi^{-} + \bar{\Xi}^{+}$

- Spectra slightly harder then models

- underestimated by all models by factor ~ 3



Eur. Phys. J. C 71 (2011) 1594

p_T distributions |y|< 0.5

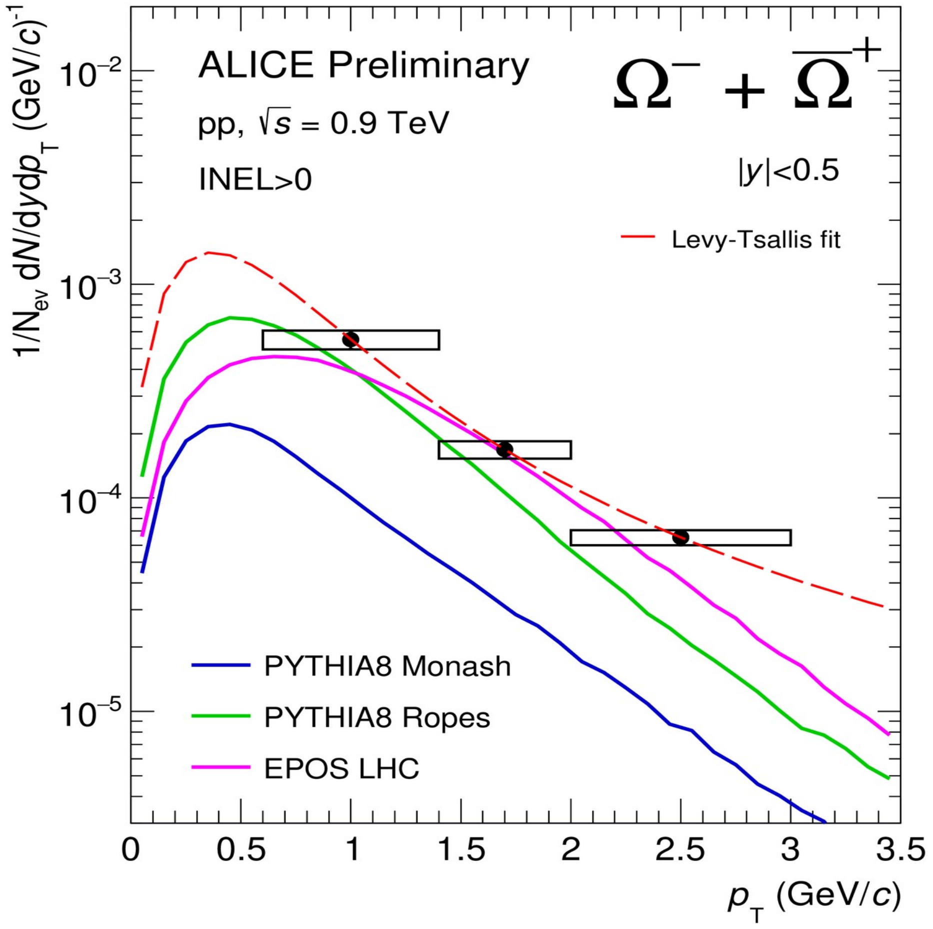
pp $\sqrt{s} = 0.9$ TeV

Minimum bias

$\Omega^{-} + \overline{\Omega}^{+}$

- Well described by Levy-Tsallis

- underestimated by PYTHIA8 Monash



ALI-PREL-571882

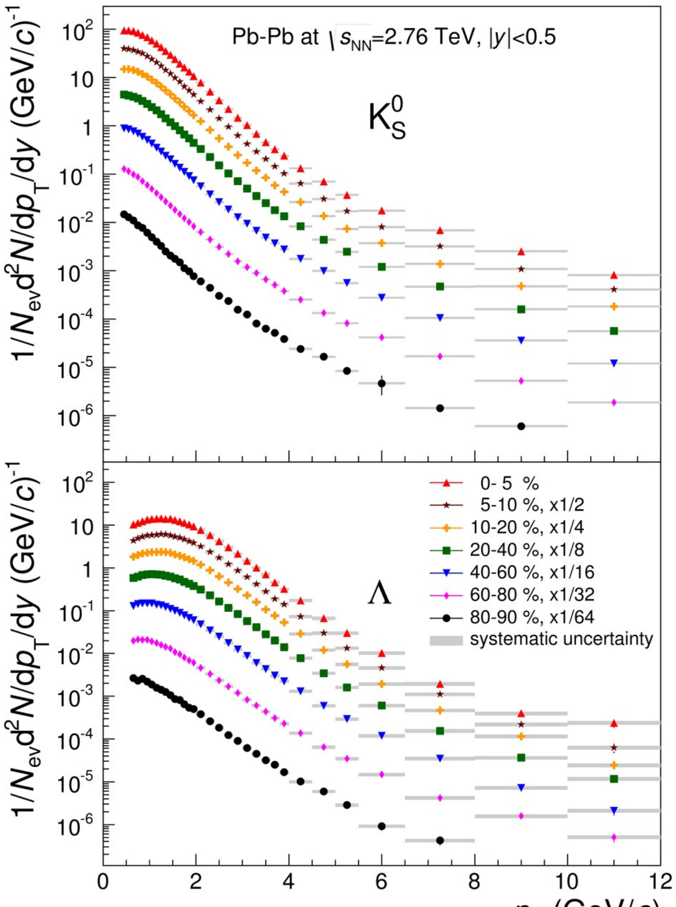
p_T distributions |y|< 0.5

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

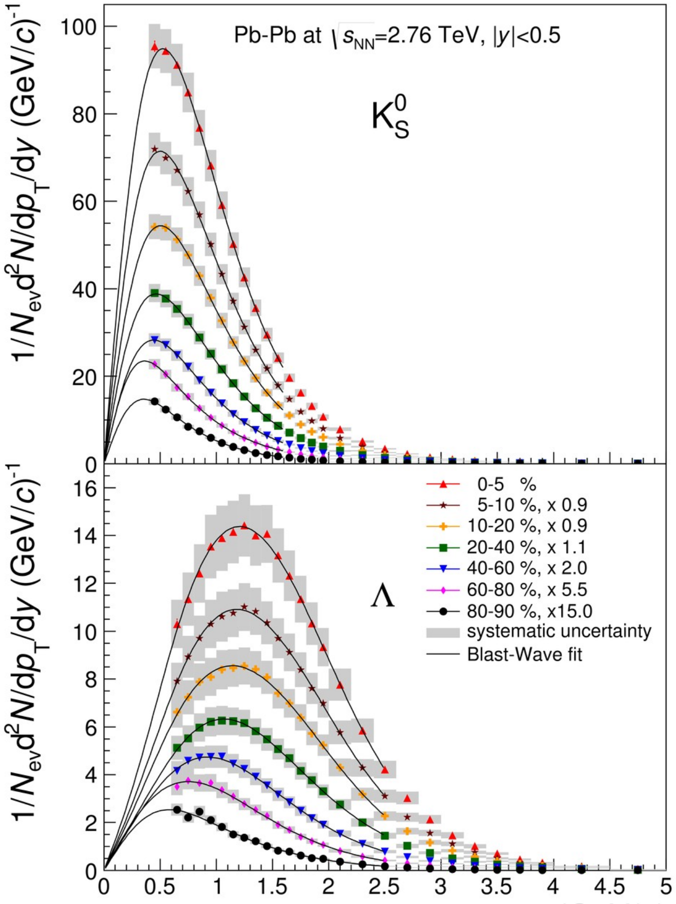
Λ, K^0_S

Spectra evolution with centrality

- Well described with Blaste-Wave fit (used for spectra extrapolation)
- Maximum moving towards higher p_T with centrality
- Spectra hardening with centrality



Phys. Rev. Lett. 111 (2013) 222301



Phys. Rev. Lett. 111 (2013) 222301

p_T distributions $|y| < 0.5$

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

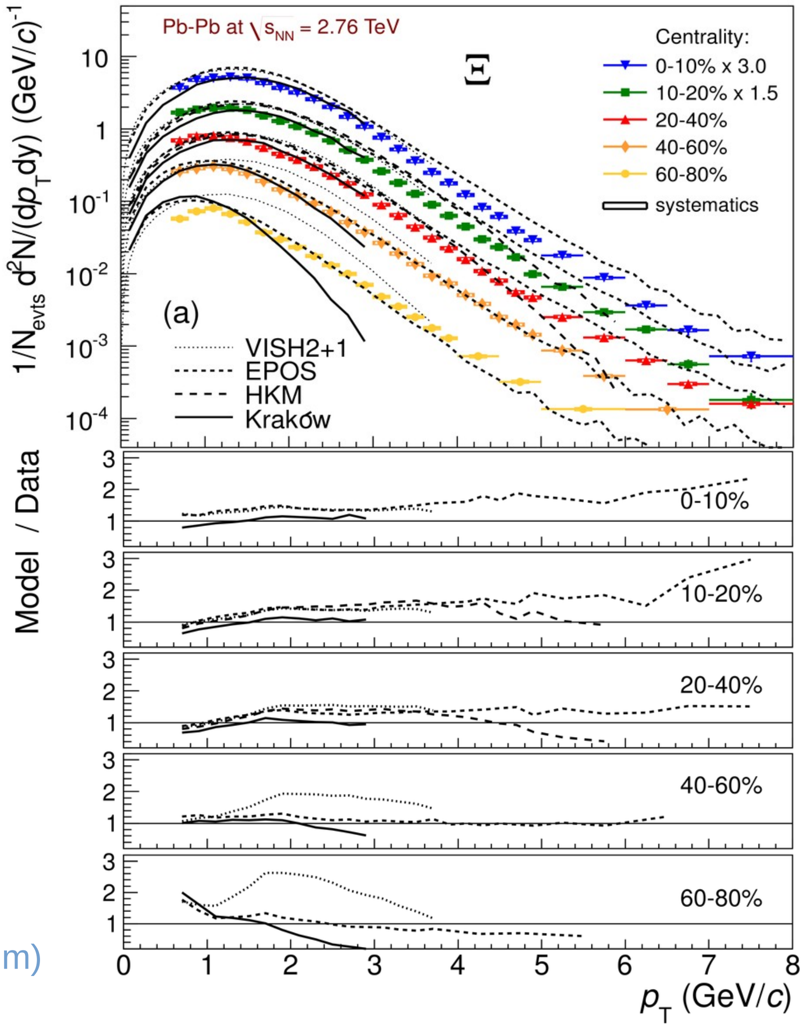
Ξ

Spectra evolution with centrality

- average yields of particle and anti-particle

- comparison to hydrodinamic models in five centrality bins

- closest description by Krakow model with in 3 GeV range and EPOS in wide p_T range



Phys. Lett. B 728 (2014) 216-227
Phys. Lett. B 734 (2014) 409-410 (erratum)

p_T distributions |y|< 0.5

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

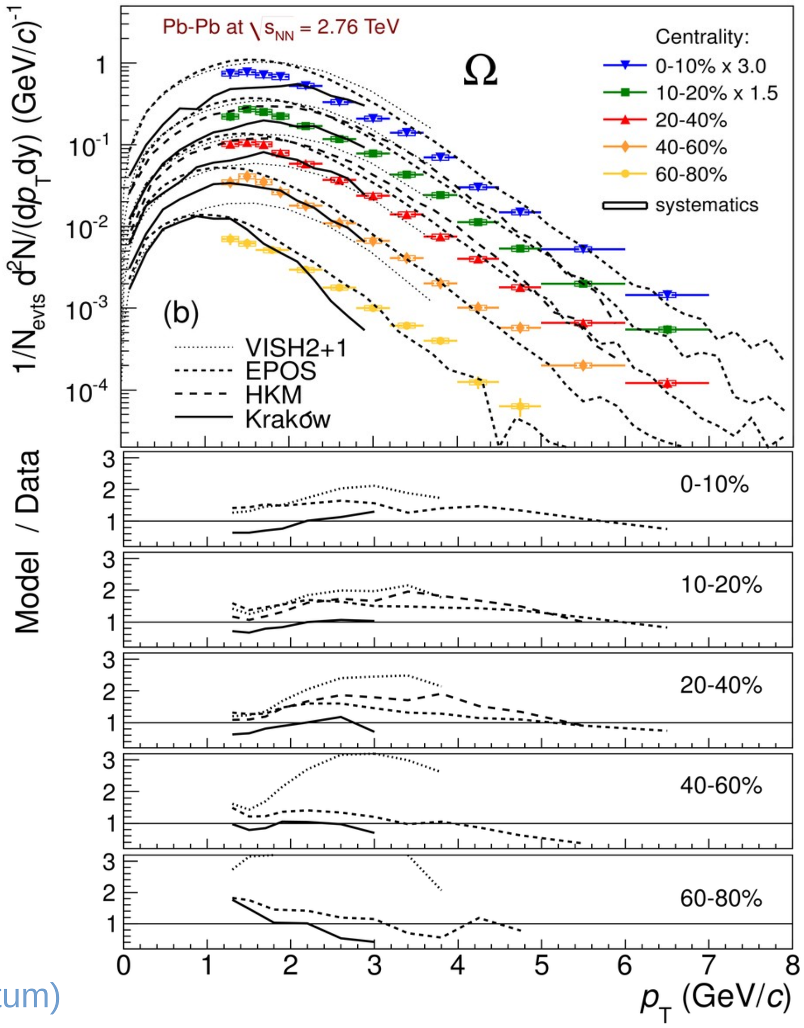
Ω

Spectra evolution with centrality

- average of particle and anti-particle yields

- comparison to hydrodinamic models in five centrality bins

- EPOS and Krakow reproduces the shape relatively well (~30%)
  VISH2+1 and HKM provide a less accurate description of the data



Phys. Lett. B 728 (2014) 216-227
Phys. Lett. B 734 (2014) 409-410 (erratum)

p_T distributions |y|< 0.5

pp $\sqrt{s}=7$ TeV vs. $\sqrt{s}=13$ TeV

Λ, K^0_S, Ξ, Ω

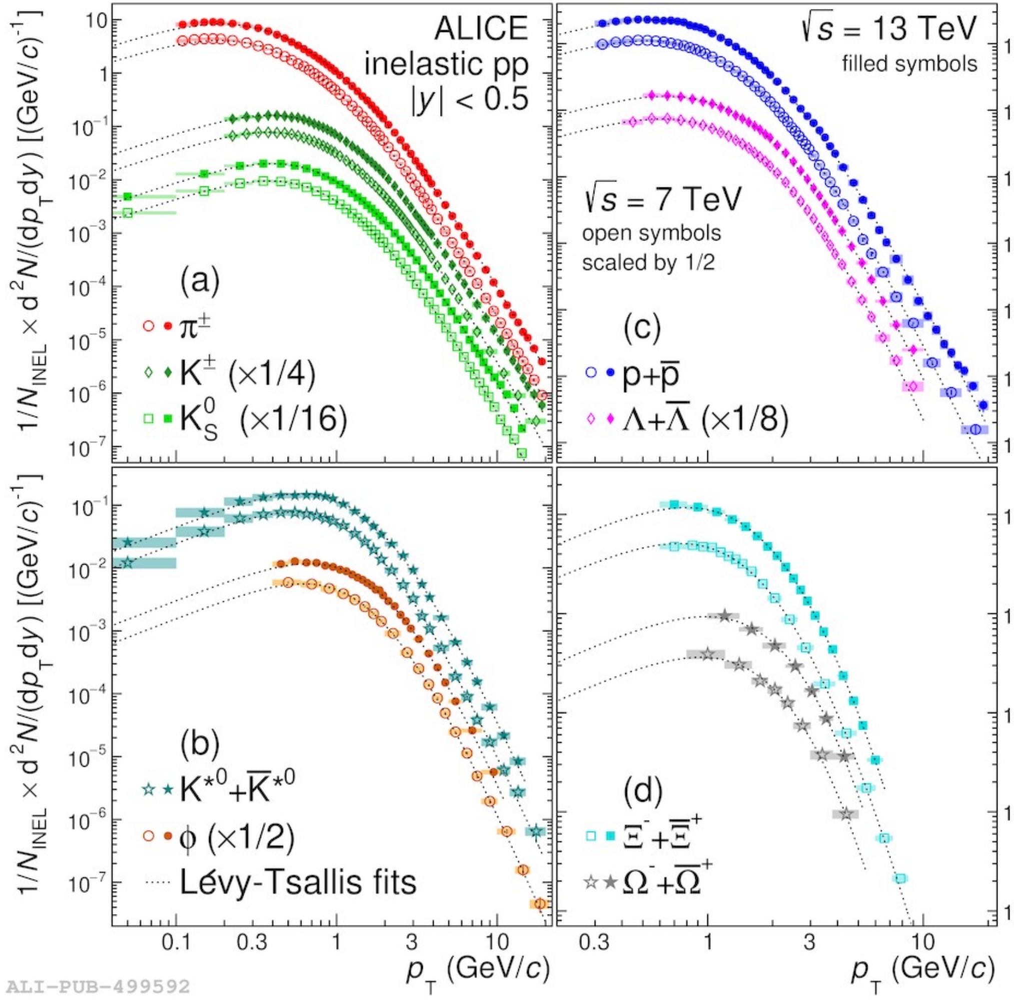
- inelastic, minimum bias p_T spectra

- praticle/anti-particle ratio ~1 => summed spectra

- Good description whti Lévy-Tsallis fits (spectra extrapolation to low p_T)

- slope parameter decreases with energy for all particles - hardening

Eur. Phys. J. C 81 (2021) 256



p_T distributions |y|< 0.5

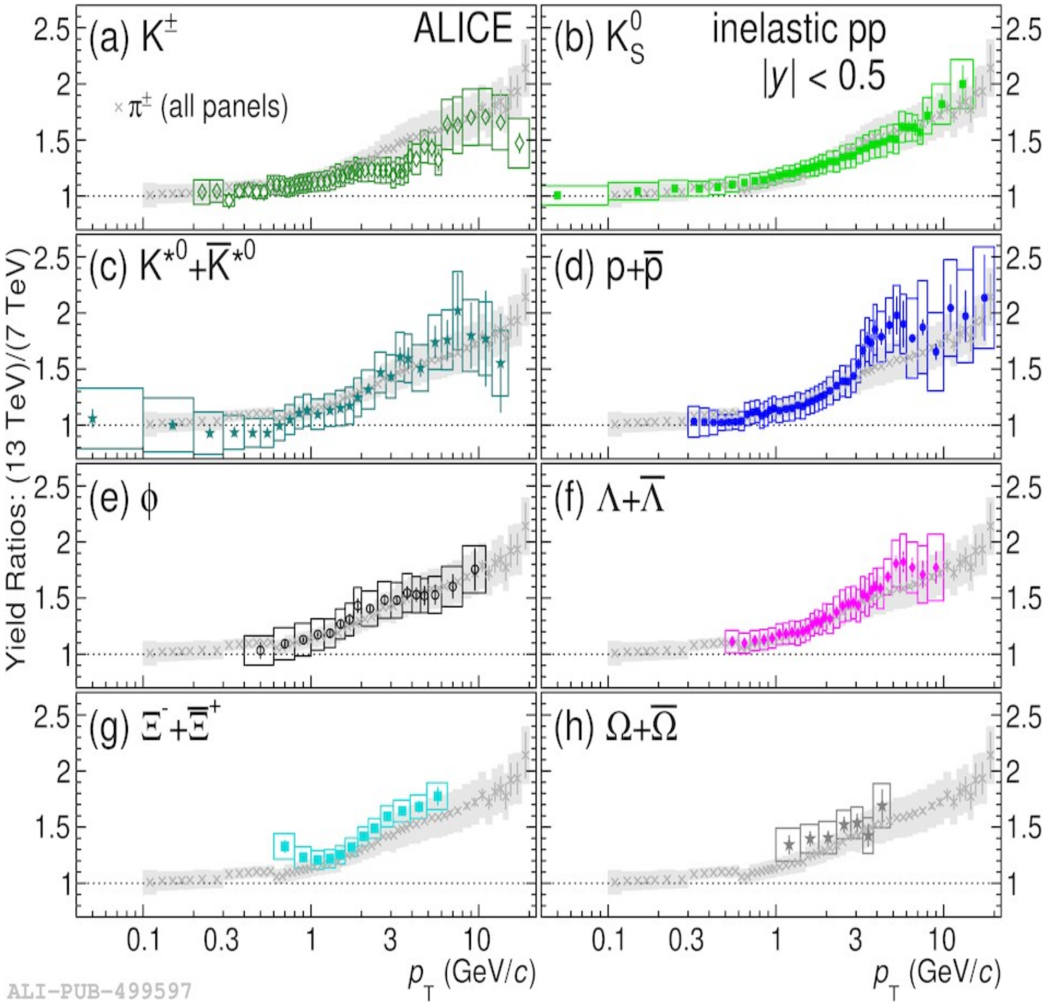
pp $\sqrt{s}=7$ TeV vs. $\sqrt{s}=13$ TeV

Λ, K^0_S, Ξ, Ω

- ratio of 13 TeV to 7 TeV yields

- Hardening of a spectra with energy
  significant evolution with energy
  for high p_T

- similar trends to pion ratios



p_T distributions |y|< 0.5

pp $\sqrt{s}=7$ TeV vs. $\sqrt{s}=13$ TeV

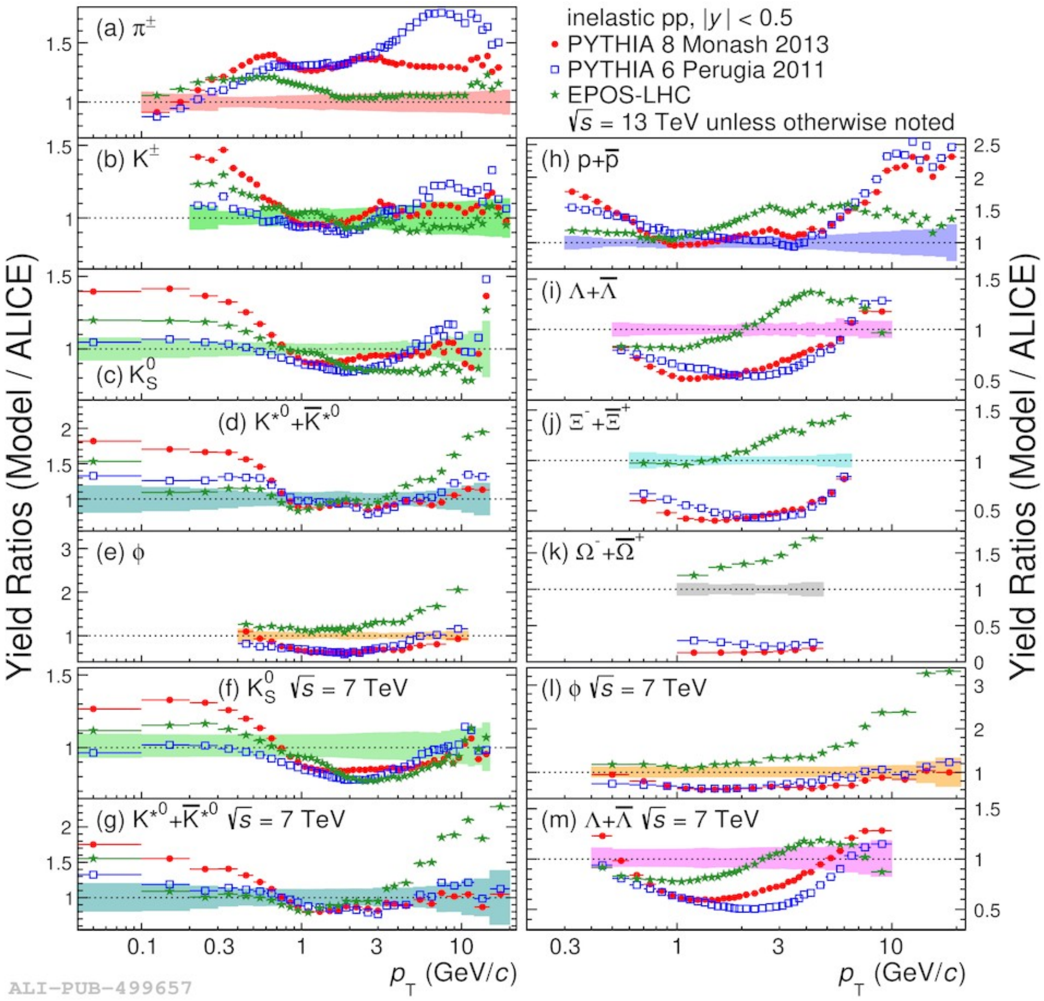
Λ, K^0_S, Σ, Ω

- comparison to models

- K^0_s pythia 6 better agreement than Pythia 8

- Λ, Σ and Ω: both pythias underestimate for almost whole p_T range

- EPOS better then pythia for multi-strange hadrons



p_T distributions |y|< 0.5

pp $\sqrt{s} = 13$ TeV

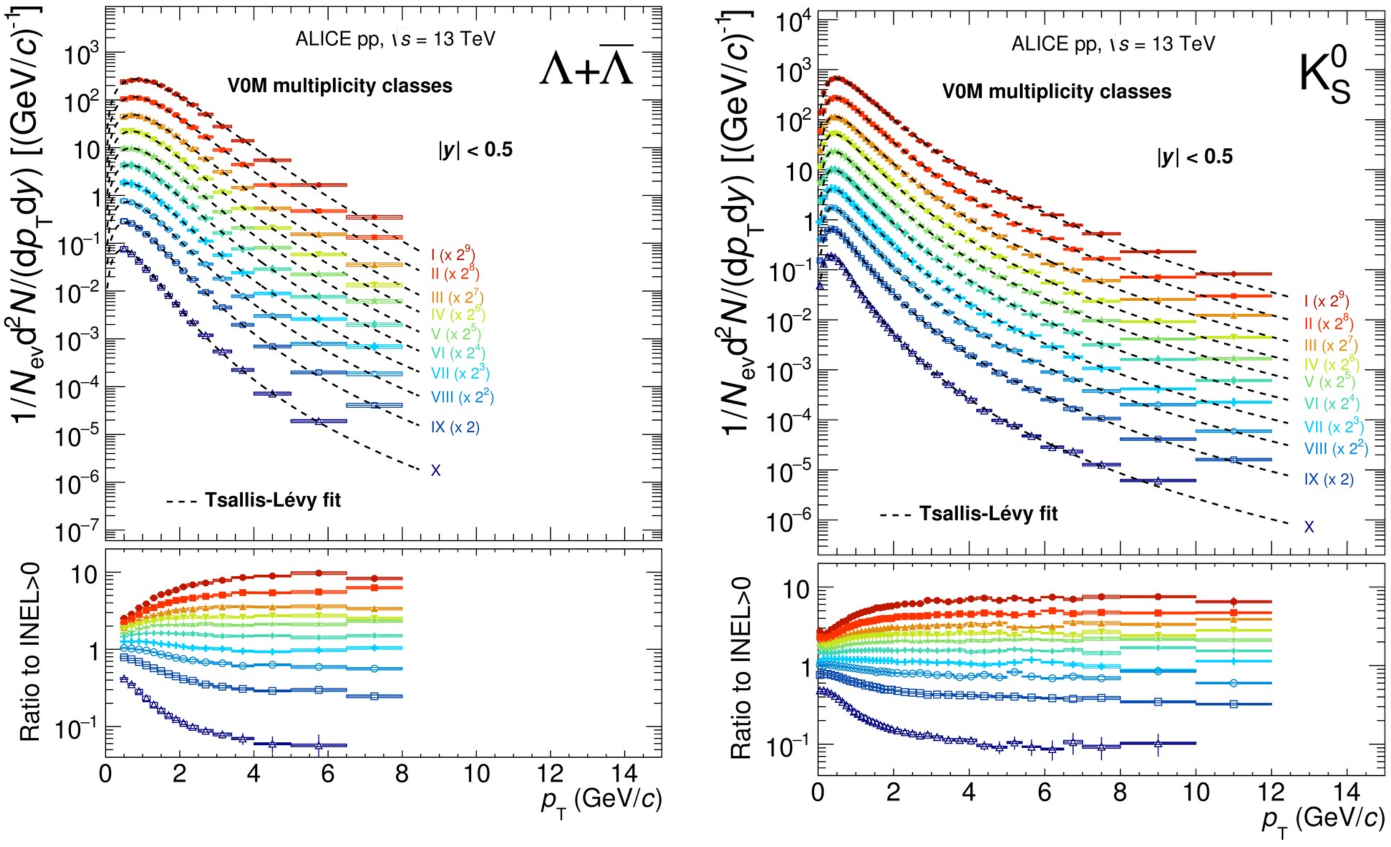
Λ, K^0_S

- V0M multiplicity classes

- similar evolution and hardening as in 7 TeV → effect of collectivity

- universal shape at soft regime (< 1 GeV/c)

- ratio to INEL>0 MB spectra reach plateau at ≳4 GeV/c



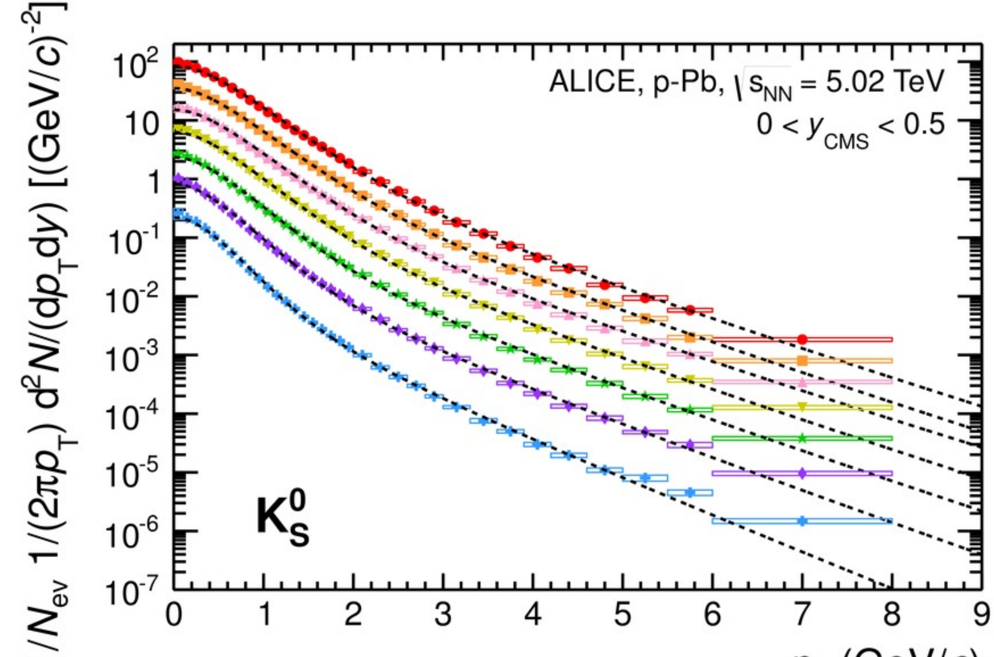
Eur. Phys. J. C 80, 167 (2020)

p_T distributions $0 < y < 0.5$

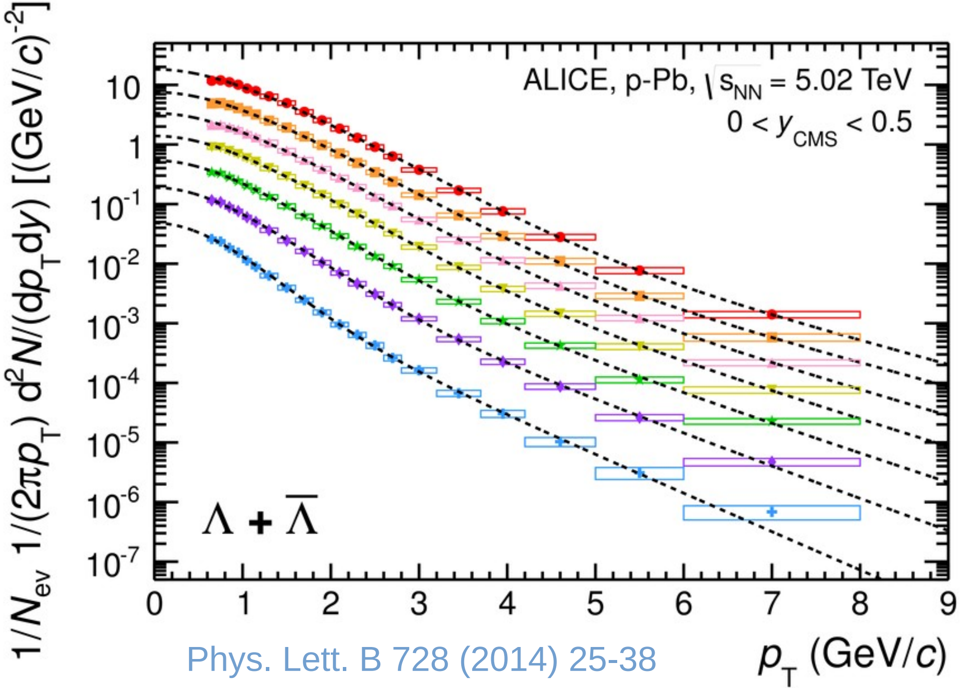
p-Pb $\sqrt{s} = 5.02$ TeV

Λ, K^0_S

- clear evolution with multiplicity
- becoming harder as the multiplicity increases (V0A)
- blast-wave fits to each individual distribution



Phys. Lett. B 728 (2014) 25-38



Phys. Lett. B 728 (2014) 25-38

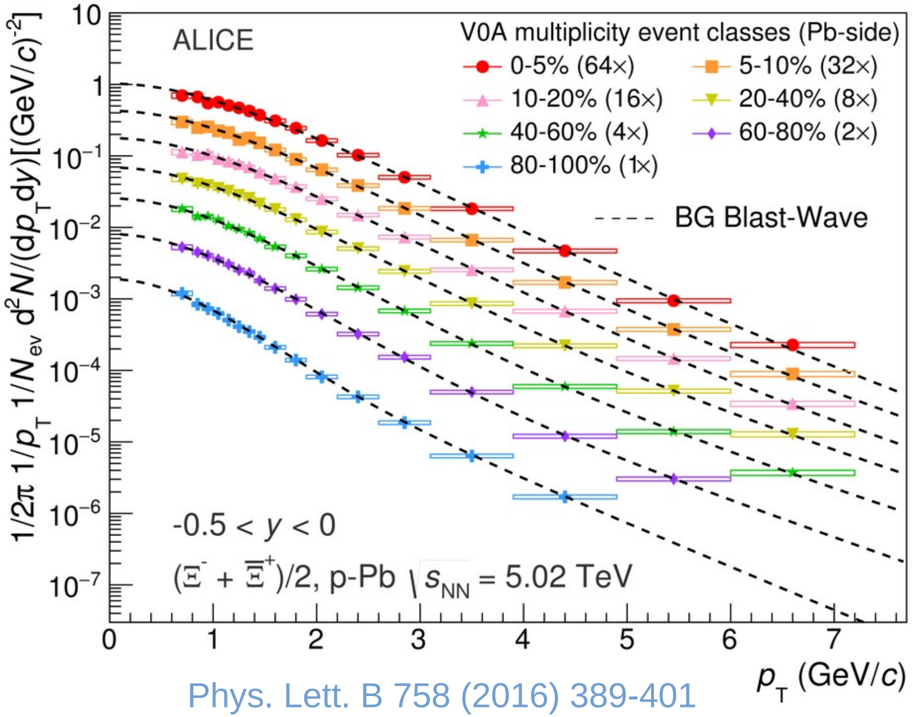
p_T distributions -0.5 < y < 0

p-Pb $\sqrt{s} = 5.02$ TeV

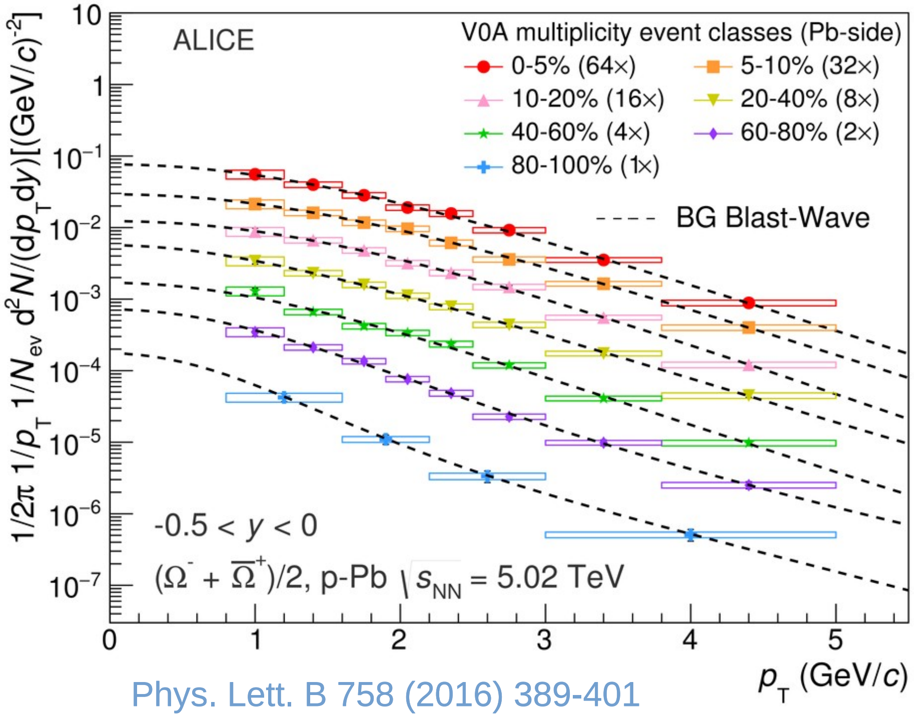
Ξ, Ω

- progressive hardening of the spectra with multiplicity (as in Pb-Pb)
- blast-wave model used for extrapolation and flow study

-



Phys. Lett. B 758 (2016) 389-401



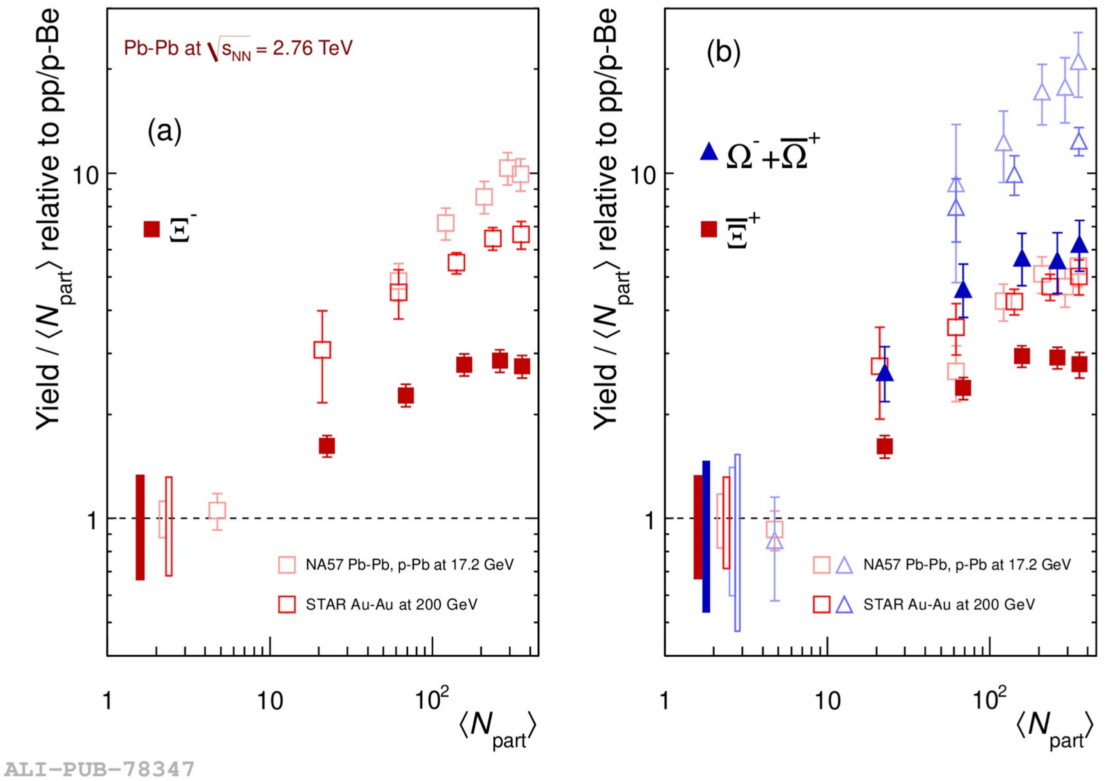
Phys. Lett. B 758 (2016) 389-401

Yields and strangeness enhancement

$$E = \frac{\left.\frac{dN}{dy}\right|_{PbPb} / N_{part}}{\left.\frac{dN}{dy}\right|_{pp} / 2}$$

Observed by STAR collaboration

- confirmation by SPS and ALICE



Phys. Lett. B 728 (2014) 216-227

Yields and strangeness enhancement

- first strangeness enhancement observed in pp systems

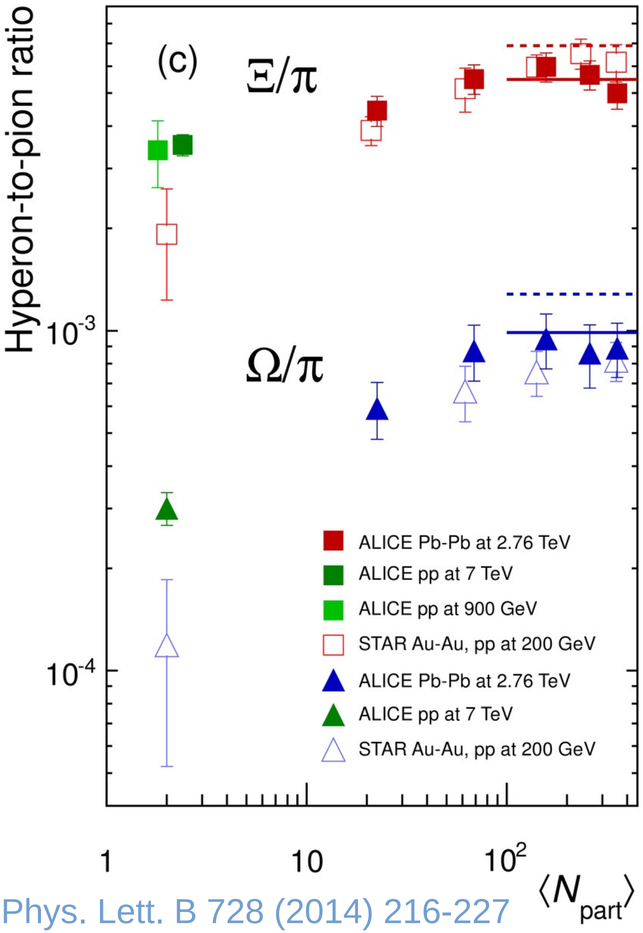
- Results from lower √s connect To results from higher √s

- dependence on the fireball volume not on energy

- significant enhancement with multiplicity (pp, p-Pb)

- agreement with STAR results

- best description with DIPSY (“color ropes”)



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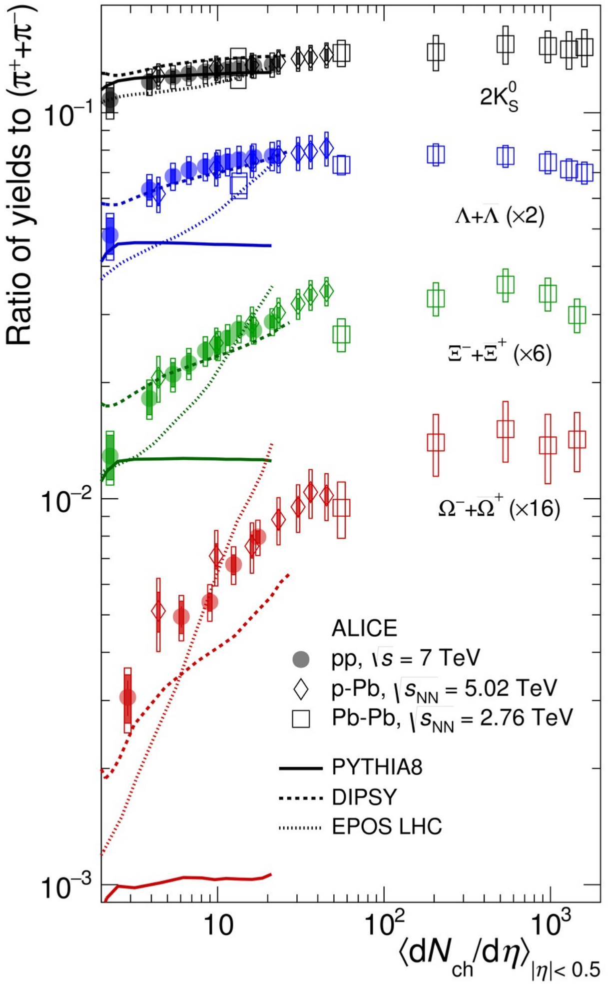
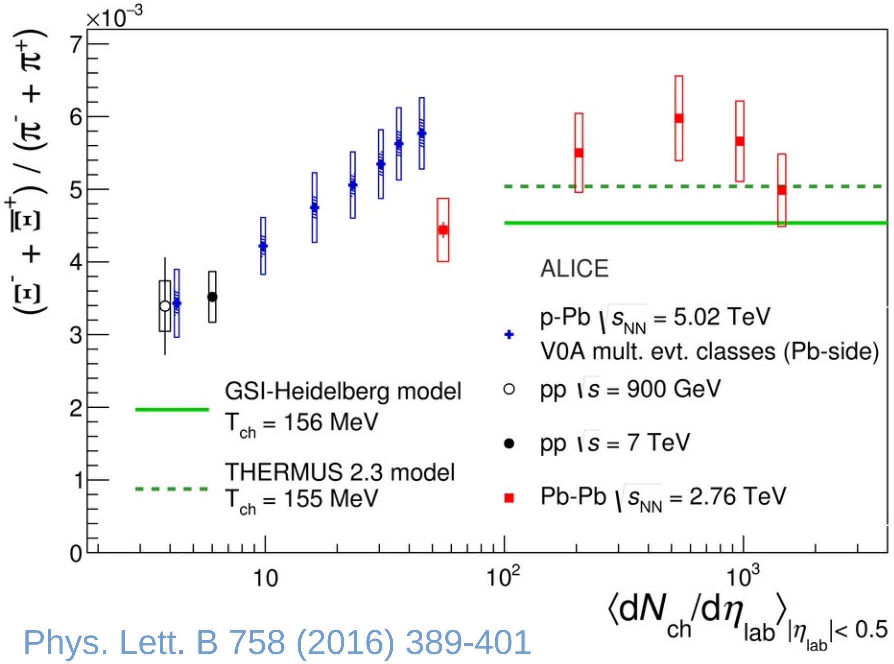


Nature Physics 13 (2017) 535-539

Yields and strangeness enhancement

- p-Pb yields connect 0.9 TeV and 7 TeV relative yields with Pb-Pb – fireball size dependence
- statistical models (chemical equilibrium lines) describe Pb-Pb results within errors
- significant strangeness enhancement in p-Pb relative to the pions



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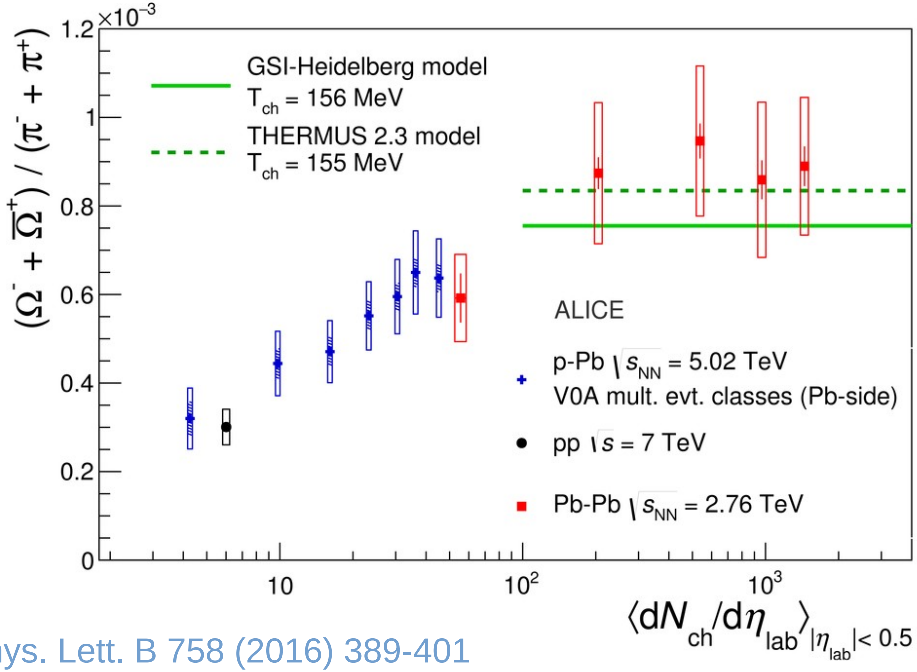


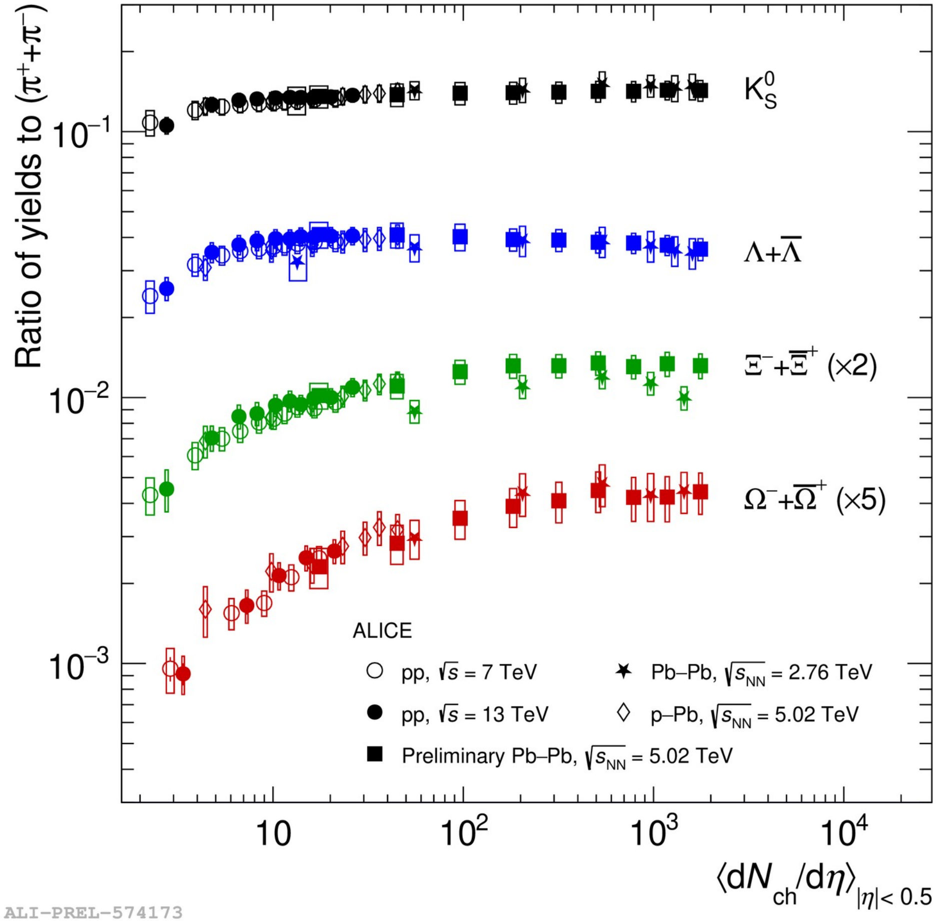
Phys. Lett. B 758 (2016) 389-401

Yields and strangeness enhancement

Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV preliminary results

- ratio to pions folow the trend of previous measurements for all strange hadrons

- dependence on the fireball volume not on energy

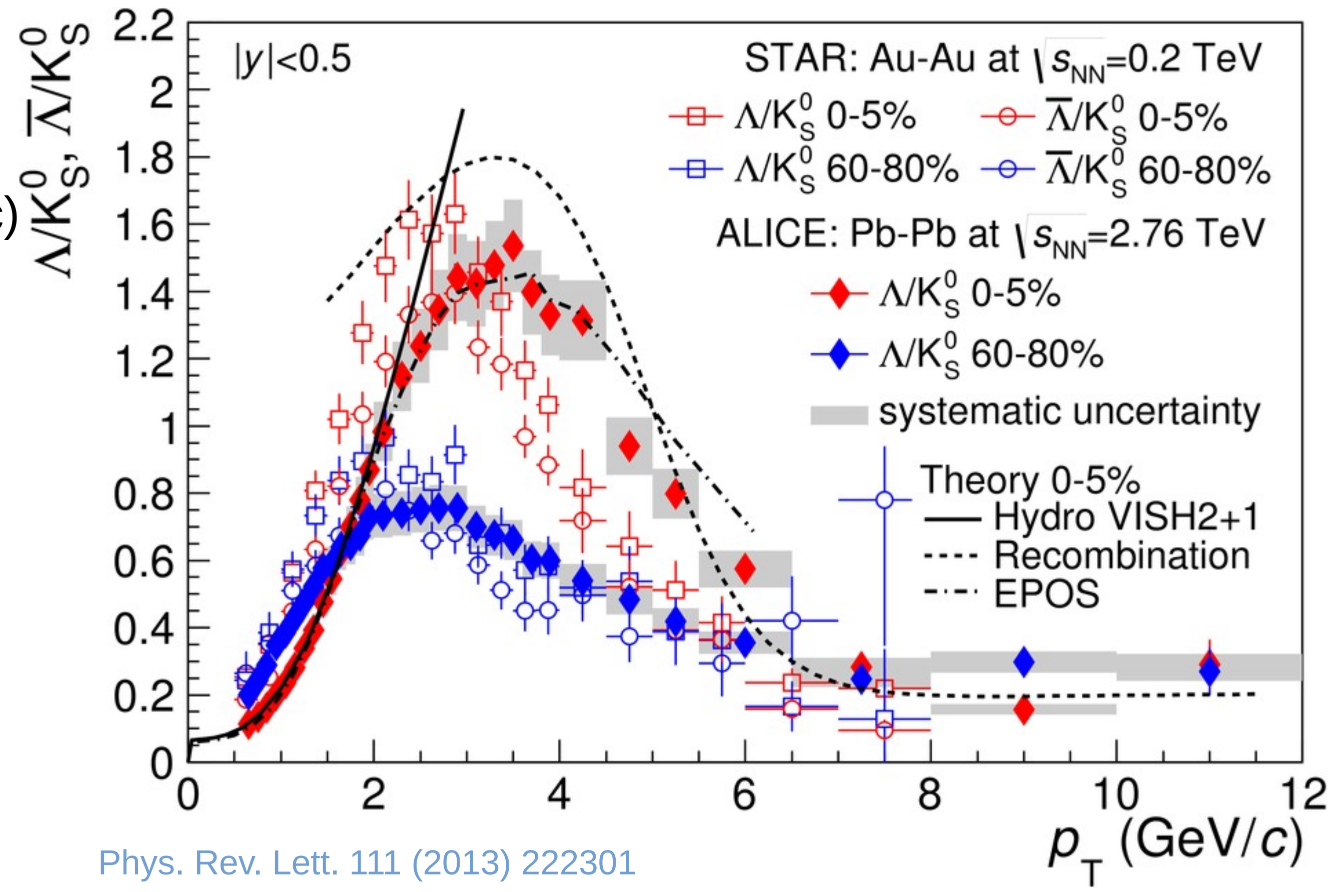


ALI-PREL-574173

Baryon to meson ratio "baryon anomaly"

Hydro + Recombination

- Low p_T region described by hydro (not valid above ~2 GeV/c)
- medium p_T – recombination effect and EPOS (jets and medium)
- recombination of hard showers also describe higher p_T region
- maximum shifting to higher p_T with energy and centrality
- slower decrease of baryon enhancement in ALICE data with p_T

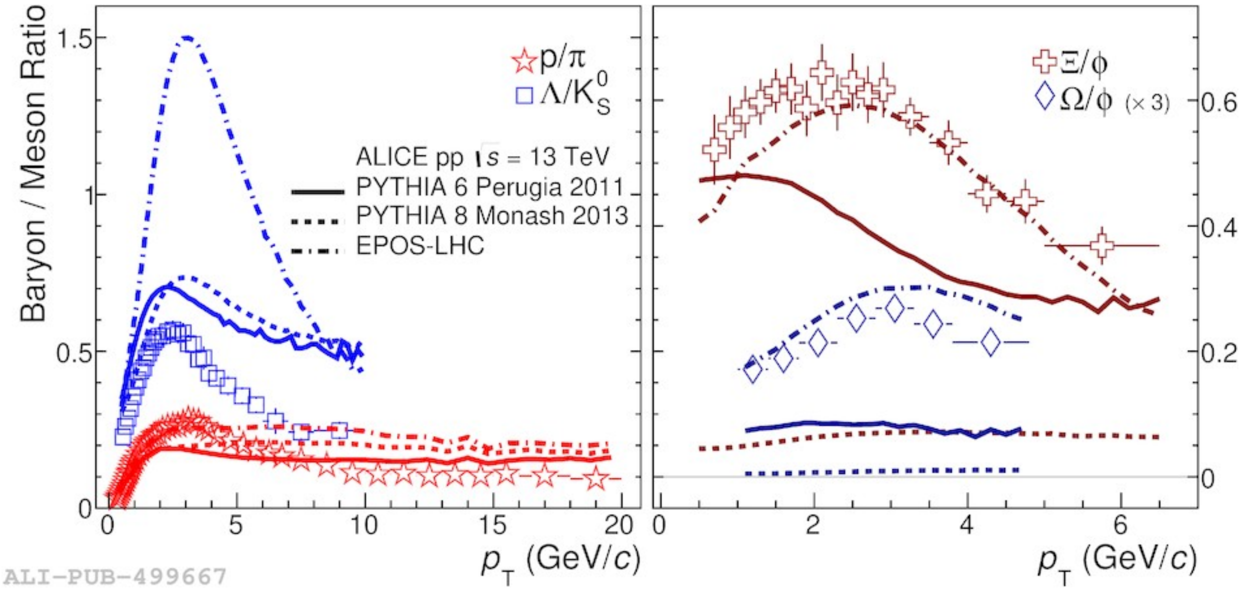


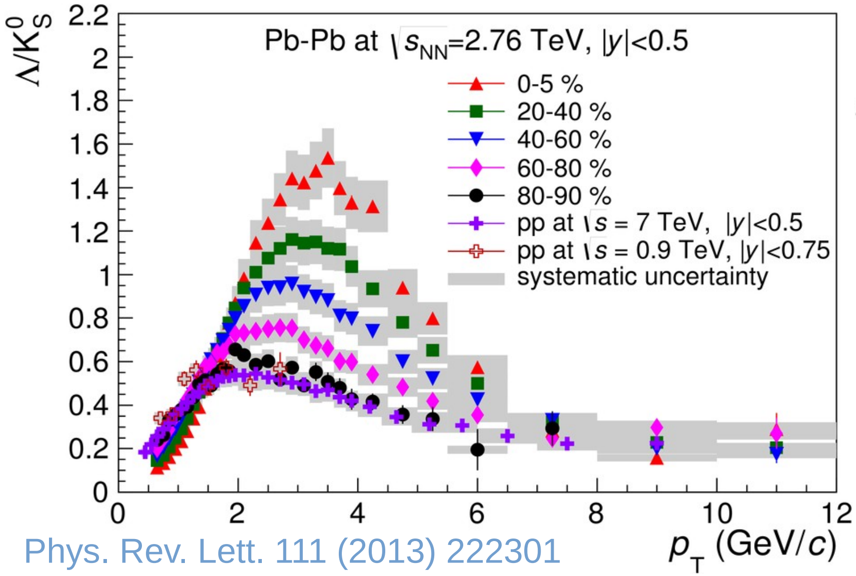
Phys. Rev. Lett. 111 (2013) 222301

Baryon to meson ratio

Baryon to meson ratios at 13 TeV pp →
Λ/K^0_s models overpredict maximum

- EPOS LHC describes Ξ/ϕ and Ω/ϕ ratio in whole p_T range





Phys. Rev. Lett. 111 (2013) 222301

← effect of system size (centrality) to a maximum and its position (~3x higher from central to peripheral)

- small effect in smaller systems (collision energies)
- not an effect of new production channel opening (constant dependence of integrated yields vs. centrality)

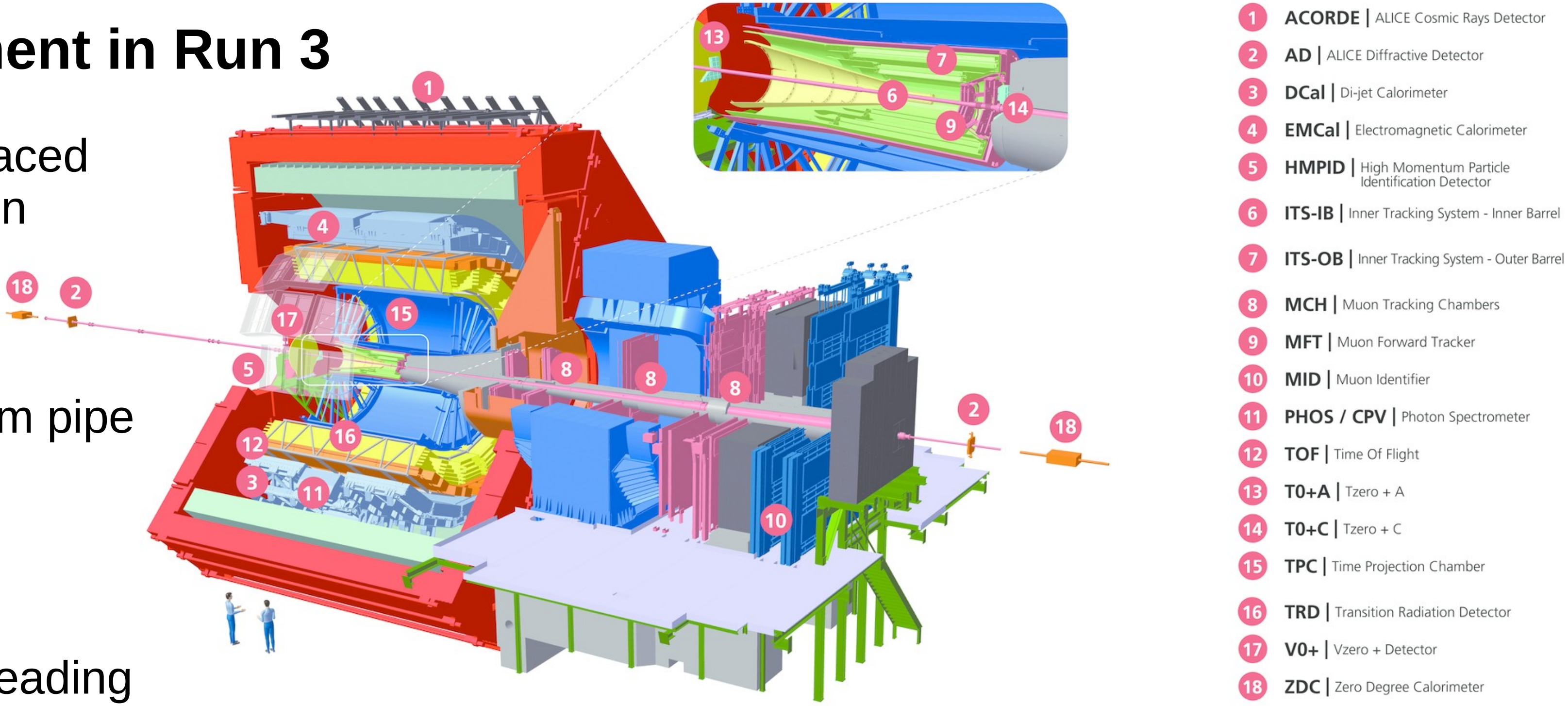
ALICE experiment in Run 3

- ITS completely replaced with 7 layers of silicon pixels

- First detection layer closer to IP new beam pipe (ITS L0 at 22mm)

- TPC equipped with GEMs readout 50KHz continuous reading in Pb-Pb

- New O2 framework
  One common Online Offline computing system
  faster Offline and Online processing



-New Fast interaction Trigger (FIT)
  - Four arrays of Cherenkov detectors and scintilators
- triggering, collision time, centrality estimation
- New Run 3 measurements at $\sqrt{s} = 13.6$ TeV pp and $\sqrt{s_{NN}} = 5.36$ TeV in Pb-Pb collisions

Conclusions

p_T spectra:

- p_T spectra measured by ALICE in wide energy range from $\sqrt{s}$ = 0.9 TeV up to $\sqrt{s_{NN}}$ = 5.02 TeV were shown. As a general pattern, p_T spectra consist of soft regime region (usually up to 1GeV/c) and higher p_T region where hard processes become dominant. For all considered energies and systems the hardening of a p_T spectrum is observed with increasing centrality (multiplicity) and particle mass.
- The comparison with models shows that PYTHIA (D6T, Atlas-CSC and Perugia 0) and PHOJET underestimate 0.9 TeV spectra by a factor ~2-3. PYTHIA 8 Monash and Perugia 6 aslo underestimate pp 0.9 TeV, 7 TeV and 13 TeV strange baryon spectra but describes K^0_s (and Ω 0.9 TeV pp spectra) reasonably well together with EPOS-LHC (PYTHIA 8 Ropes).
- Comparison of hydrodynamic models to multi-strange baryon p-Pb 2.76 TeV spectra shows that best agreements are obtained with the Kraków and EPOS models, with the latter covering a wider range.
- Majority of a spectra are reasonably well described by BG Blaste-Wave or Lévy-Tsallis parametrisations which are usually used also for signal extrapolation at low p_T region.

Conclusions

Enhancement and yields:

- Significant enhancement of multi-strange baryon yields (relative to pion yields) with multiplicity is observed for pp 7TeV. This is the first relative strangeness enhancement observed in pp system. Relative yields are smoothly evolving with multiplicity for each system and datapoints with same multiplicity overlap within systematic errors. This demonstrates that the strangeness signature of QGP is driven by the global properties of thermal fireball in particular by its volume and/or lifetime.

“Baryon anomaly”:

- Qualitative description of this effect by recombination model in medium-p_T range and high p_T region with recombination of hard showers. Low p_T region is described by hydrodynamic model but only up to ~2 GeV/c. The transition between low and high p_T regions is well described by EPOS which incorporates jets interaction with medium.

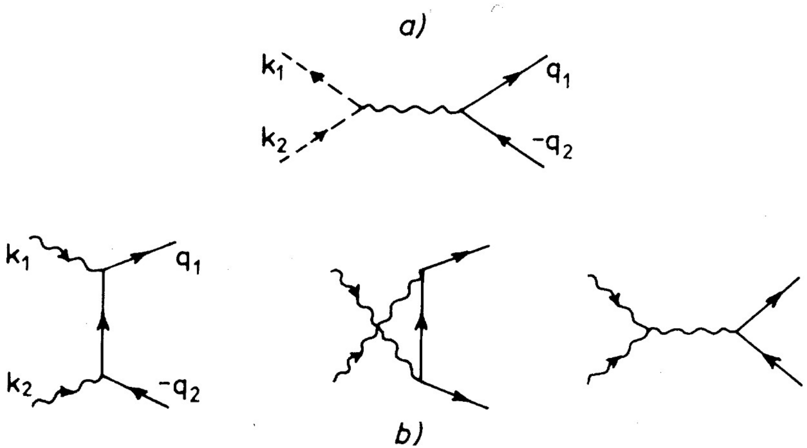
Thank you!

Backup slides

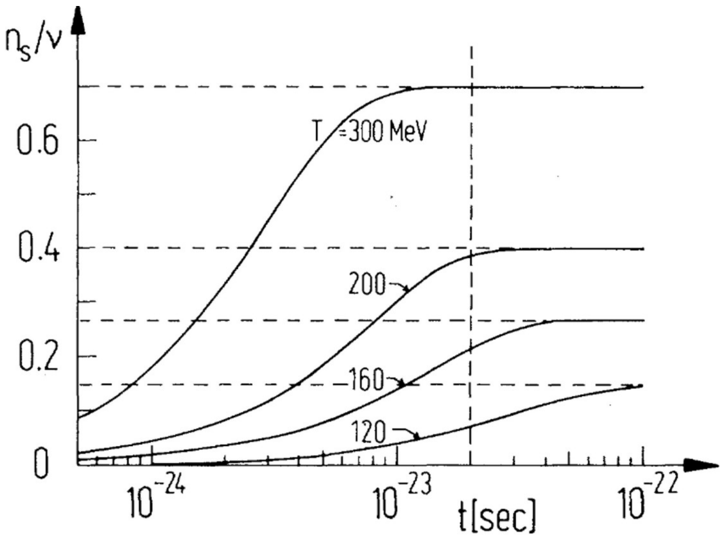
QGP formation and light flavour production in hadronic collisions

-Increased relative strangeness production
as a sign of QGP plasma prediction (1982)

- s quark mass close to a QGP temperature ~155 MeV



Lowest order QCD diagrams for $s\bar{s}$ production [1]
a) quark anti quark interaction (only 10%)
b) qluon anti gluon interaction

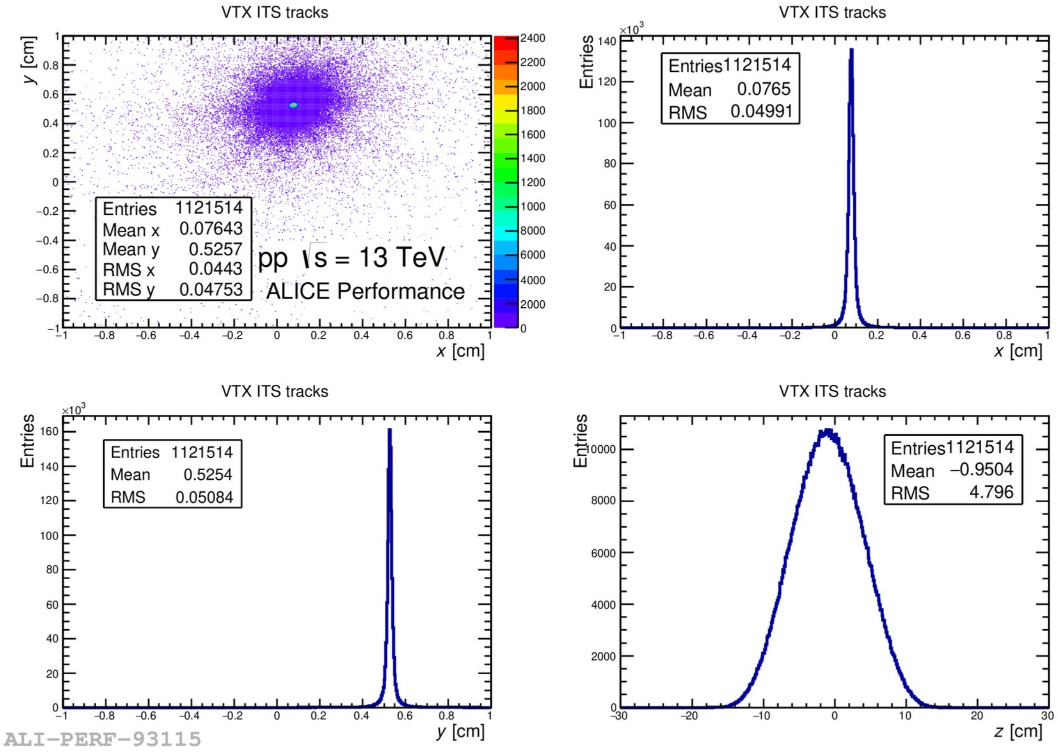


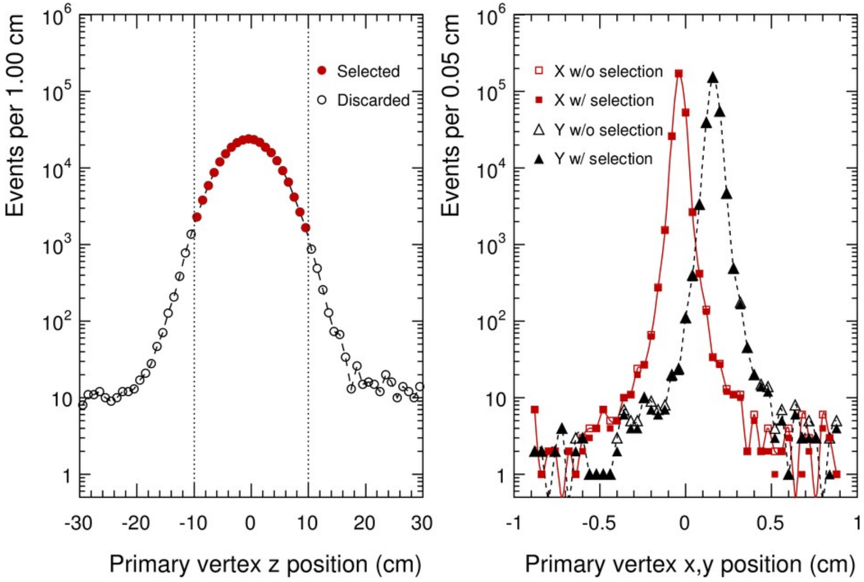
Evolution of relative strange-quark to Baryon-number for various temperatures. (M= 150 MeV, α_s = 0.6) [1]

[1] Phys. Rev. Lett. 48, 1066 – Published 19 April, 1982

ITS primary vertex reconstruction

Vertex reconstructed with ITS standalone tracks in 13 TeV pp beam:





Vertex selection in pp 0.9TeV analysis

- selected events with $|Vtx_z| < 10$ cm

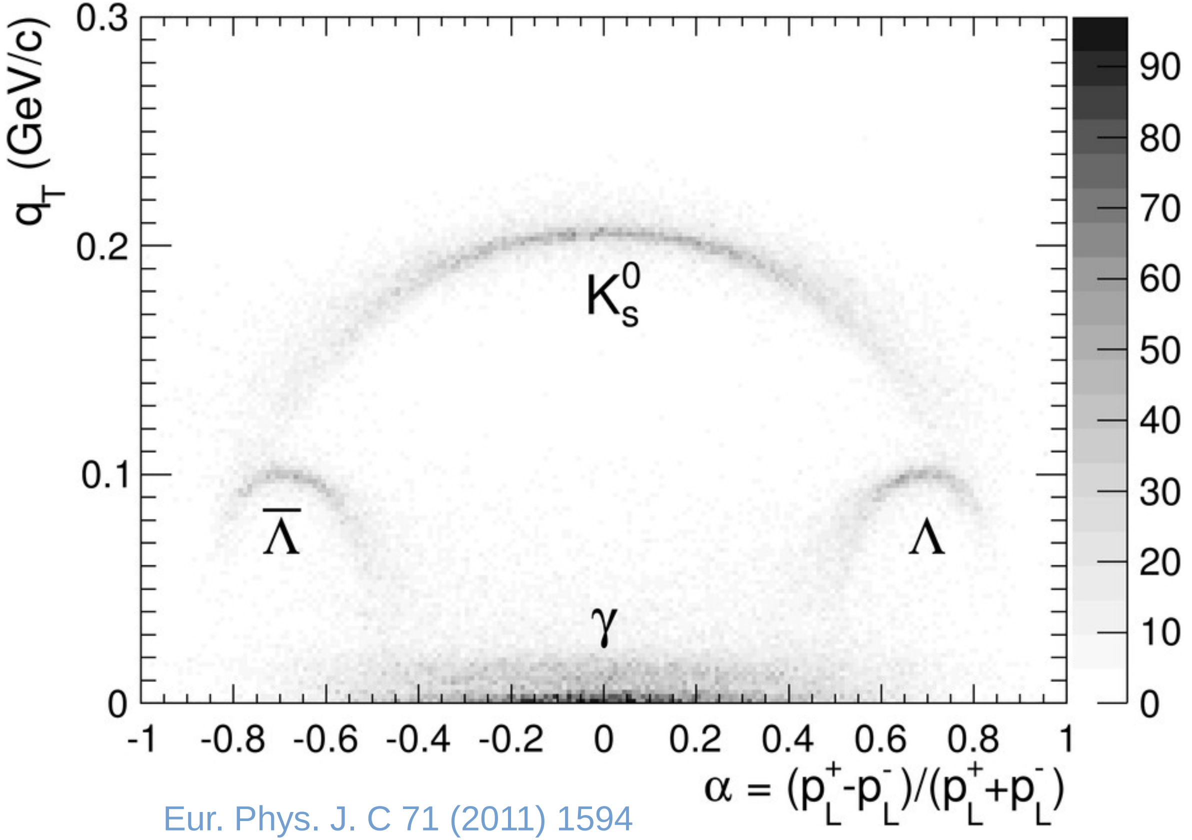
Eur. Phys. J. C 71 (2011) 1594

Additional selection: Armenteros-Podolansky

- V0 charged daughters well separated in Armenteros-Podolansky distribution.

- background V0 coming from γ conversion in the detector material

-q_T is the daughter momentum component perpendicular to the parent momentum vector



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p_T distributions $|y| < 0.5$

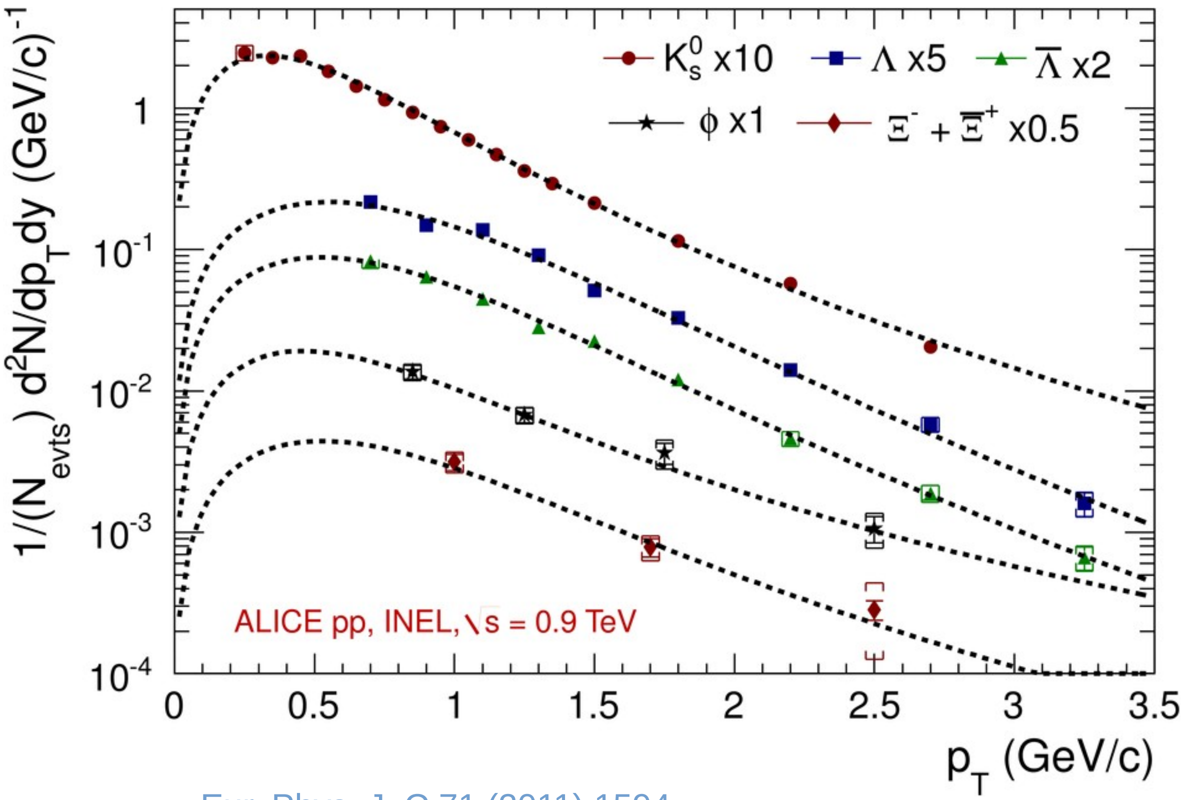
pp $\sqrt{s} = 0.9$ TeV

Minimum bias

Spetcra K^0_S, Λ, $\overline{\Lambda}$, ϕ, Σ^-, $\overline{\Sigma}^+$

- Inverse slope parameter increase with mass of the particle

- fitted with Lévy-Tsallis parametrisation



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p_T distributions |y|< 0.5

pp $\sqrt{s}=7$ TeV in multiplicity classes

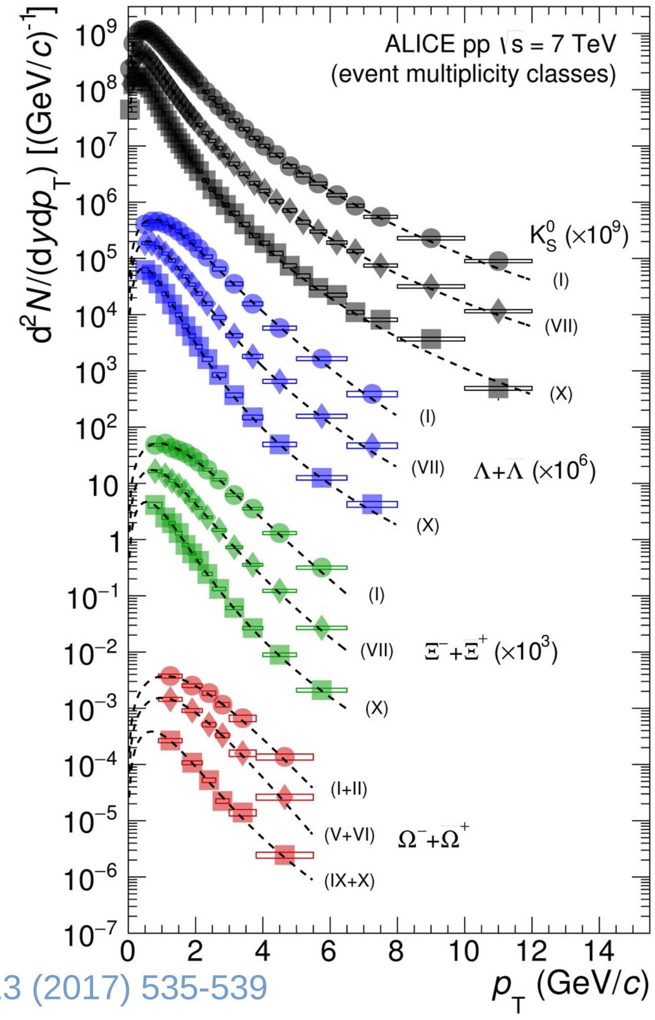
Λ, K^0_S, Ξ, Ω

- evolution with multiplicity

- spectra hardening with particle mass and multiplicity

- universal shape for K^0_S, Λ soft regime region (<1 GeV/*c*)

- extrapolation of yields with Lévy-Tsallis



Nature Physics 13 (2017) 535-539

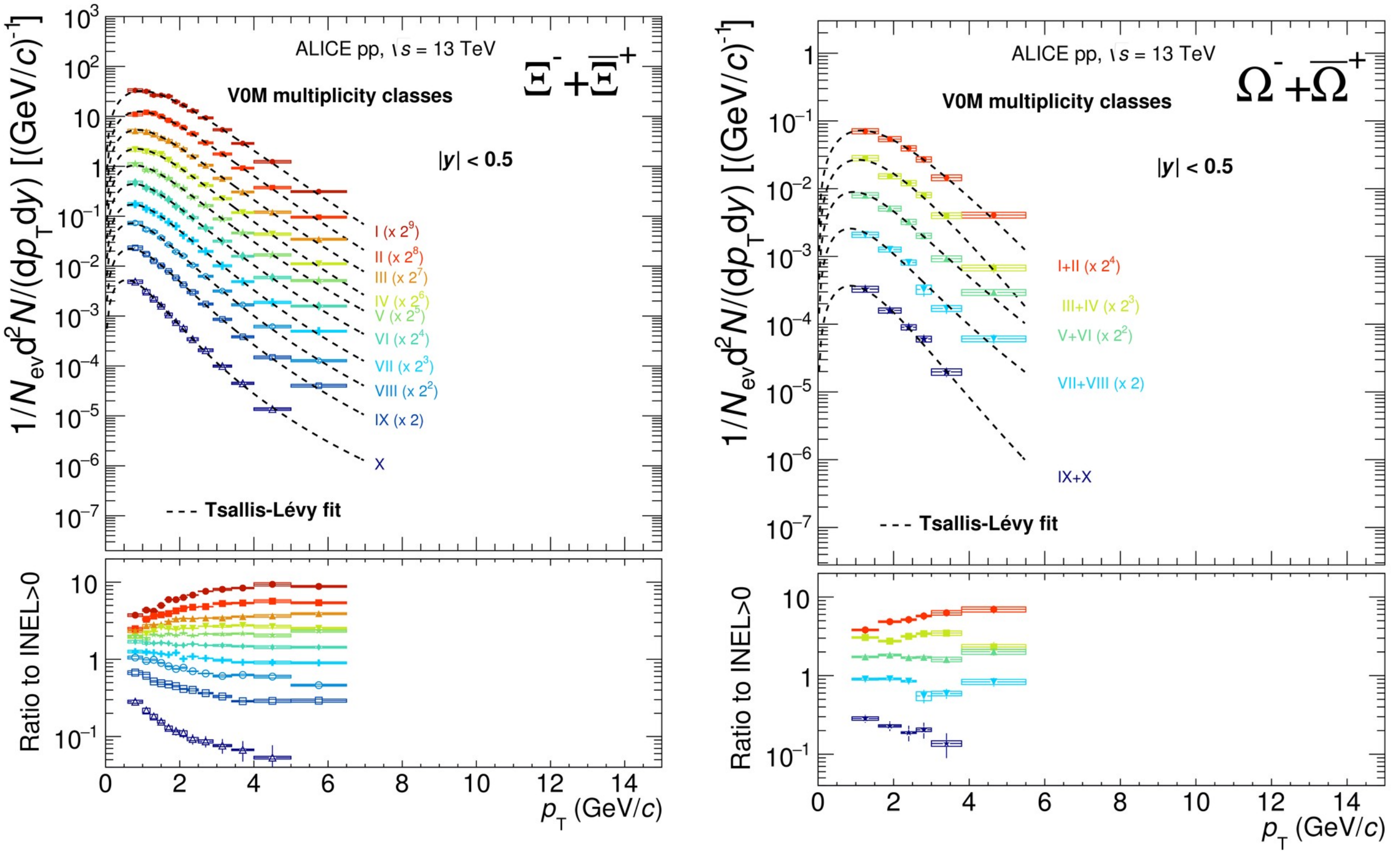
p_T distributions $|y|< 0.5$

pp $\sqrt{s} = 13$ TeV

Ξ, Ω

- V0M multiplicity classes

- extrapolation of yields with Lévy-Tsallis parametrization



Eur. Phys. J. C 80, 167 (2020)

Fit functions

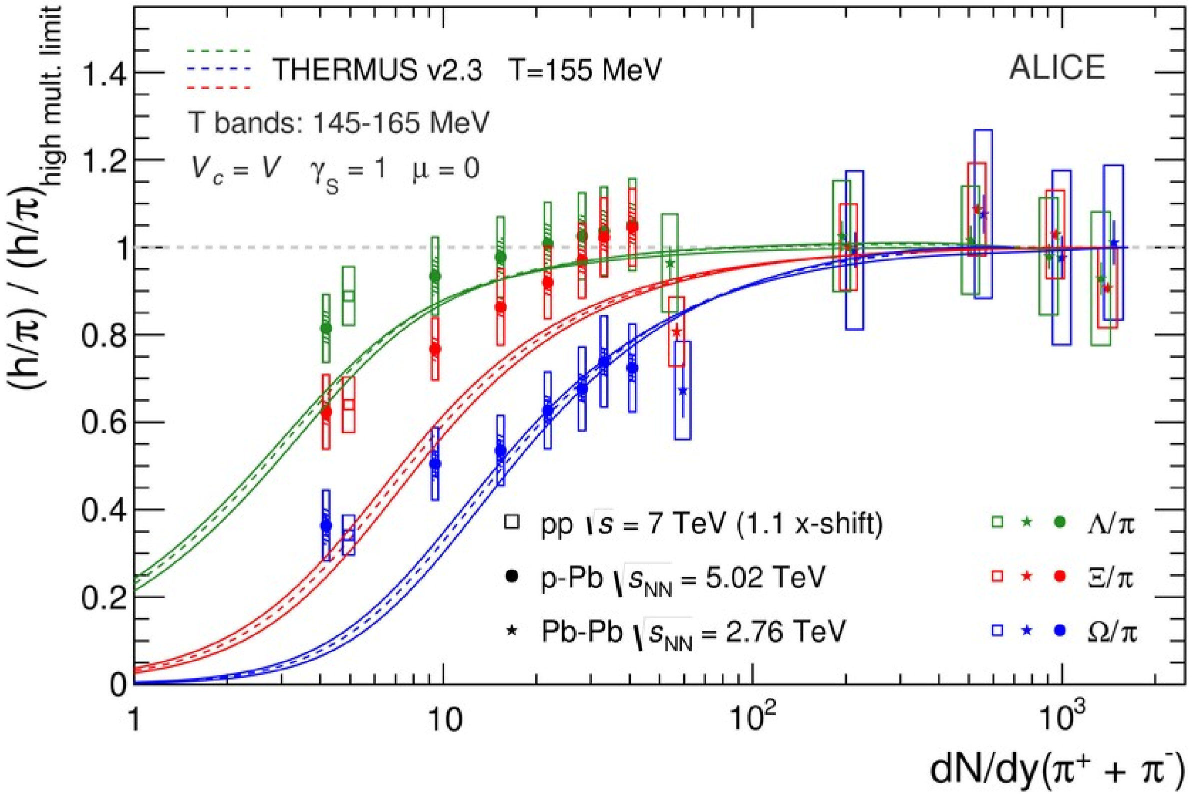
PT exponential with
A – normalisation
inverse slop parameter T

$$\frac{d^2 N}{dy\, d p_T} = A \times p_T \times e^{\frac{-p_T}{T}}$$

Lévy-Tsallis Parametrisation:

$$\frac{dN}{dydp_T} = \frac{(n-1)(n-2)}{nT[nT + m(n-2)]} \times \frac{dN}{dy} \times p_T \times \left(1 + \frac{m_T - m}{nT}\right)^{-n}$$

Yields and strangeness enhancement

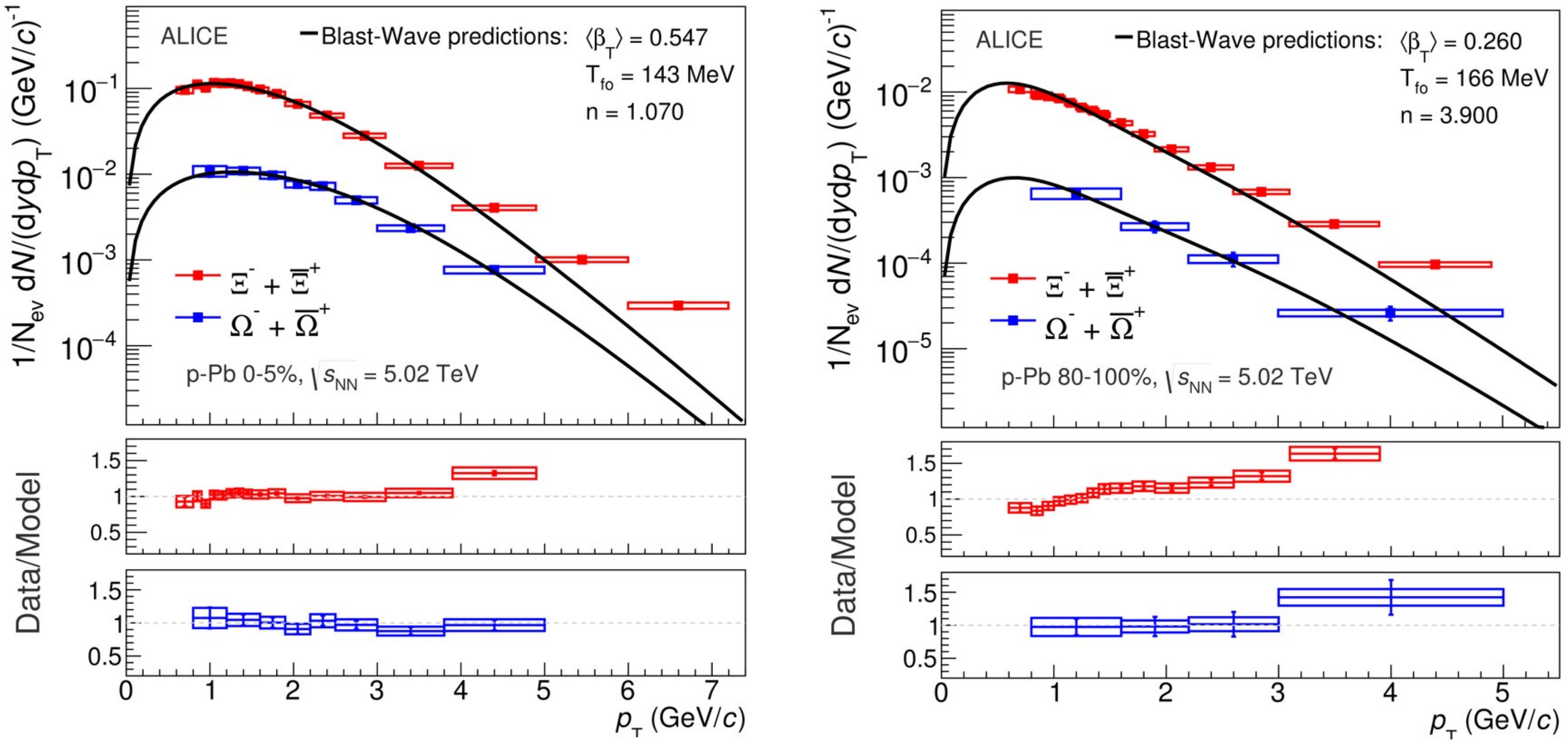


Phys. Lett. B 758 (2016) 389-401

p_T distributions |y|< 0.5

p-Pb $\sqrt{s} = 5.02$ TeV

-



Phys. Lett. B 758 (2016) 389-401