Energy and system size dependence of multi-particle production in pp, p-Pb, Xe-Xe and Pb-Pb collisions in ALICE at the LHC

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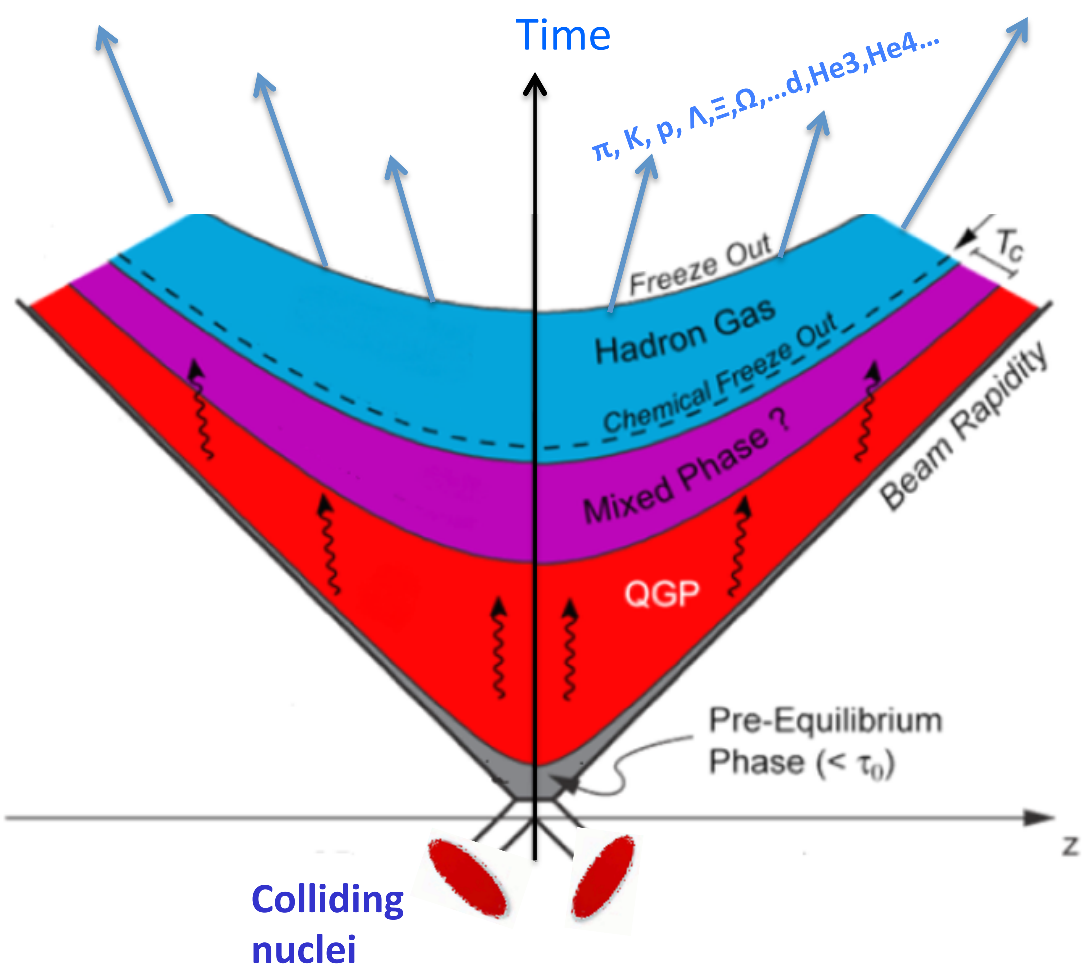
Report at the XXIVth International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", JINR, September 17 to 22, 2018, Dubna, Russia.

http://relnp.jinr.ru/ishepp/

Space-time stages of nucleus-nucleus collision



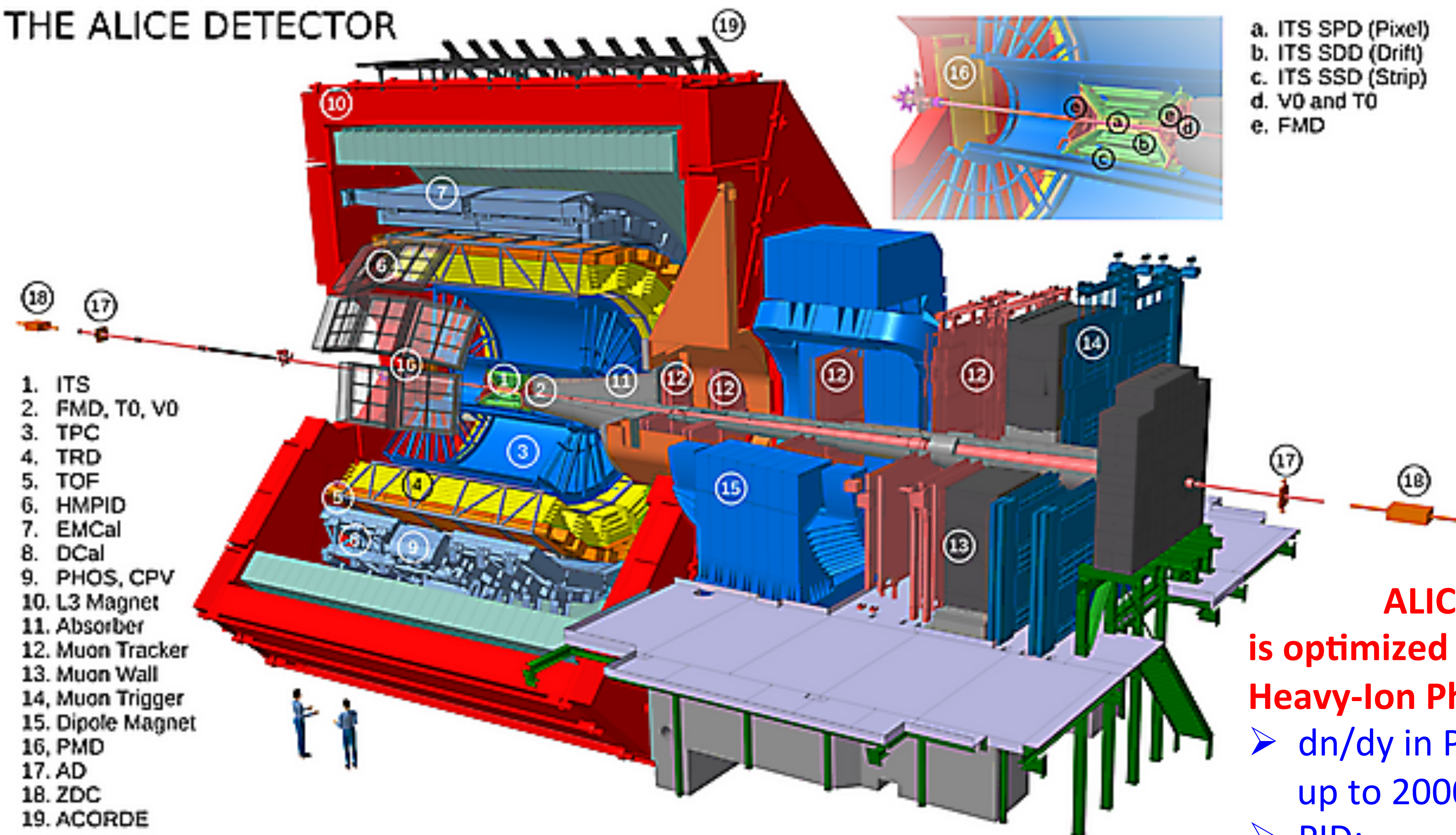
Some details:

- Pre-equilibrium phase
  τ_{eq}< 0.5 fm/c
- QGP
- Mixed phase
- Chemical freeze-out
  Particle composition is fixed
  T_{ch} ~ 155 MeV
- Thermal freeze-out
  Particle p_T spectra are fixed
  T_{tfo} ~ 100 MeV

Investigations of:

- **Multiplicity and Spectra**
- **Particle content and ratios**
- **Flows**
- **Correlations**
- Jet- medium interactions and high-p_T supression

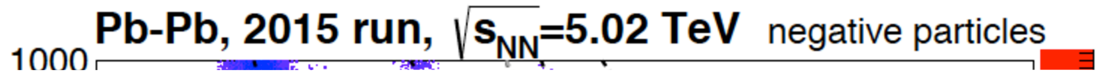
The ALICE detector



ALICE is optimized for Heavy-Ion Physics:

- dn/dy in Pb-Pb: up to 2000
- PID: $p_T > 0.2$ GeV/c

Example of PID performance of TPC : dE/dx vs. rigidity



ALICE Data accumulated since 2009

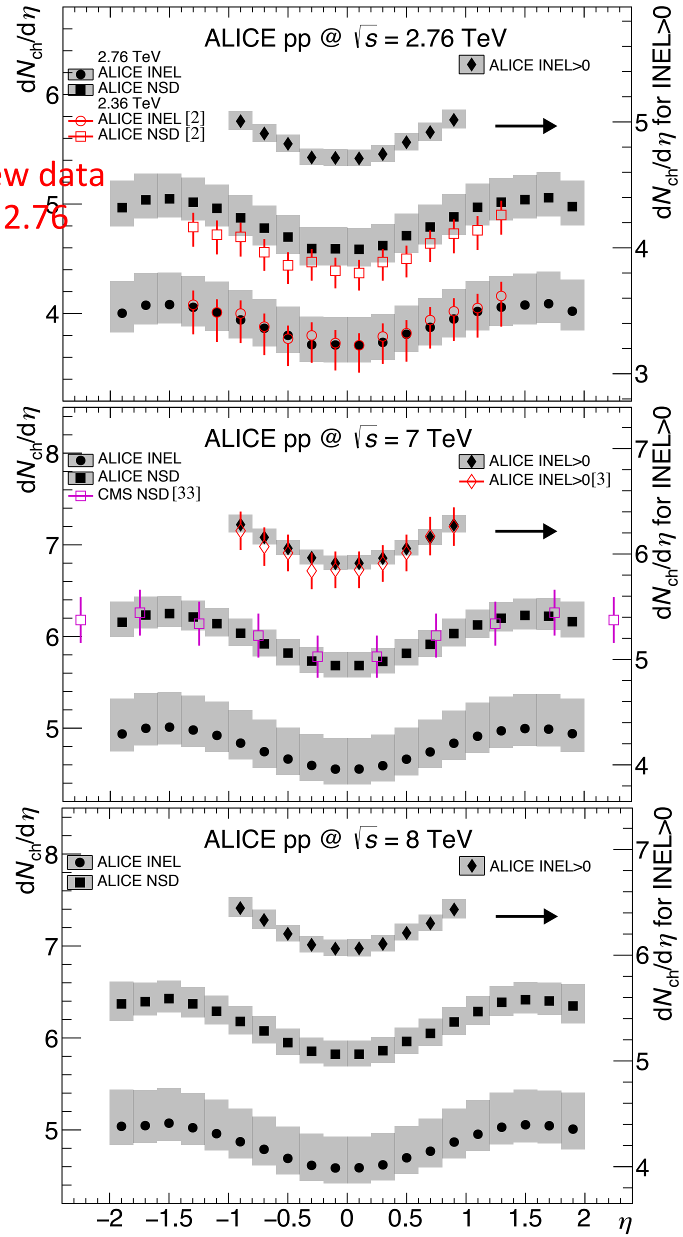
Run 1 (2009-2013	Run 2 (2015-now)
Pb-Pb@ 2.76 TeV	Pb-Pb@ 5.02 TeV, (~ 250 μb^{-1}) ~ 130 million MB events *By end of 2018* *-Pb-Pb@ 5.02 TeV, (~ 1 nb^{-1} is expected)*
p-Pb@ 5.02 TeV	p-Pb@ 5.02 TeV , (~3nb^{-1}), 8.16 TeV (~25nb^{-1})
pp@ 0.9, 2.76, 7, 8 TeV	pp@ 5.02 (~1.3 pb^{-1}) 13 TeV (~25pb^{-1})
	Some recent results of 2017: Xe-Xe@ 5.44 TeV, (~ 0.3 μb^{-1})

Multi-particle production in pp, p-Pb and A-A collisions

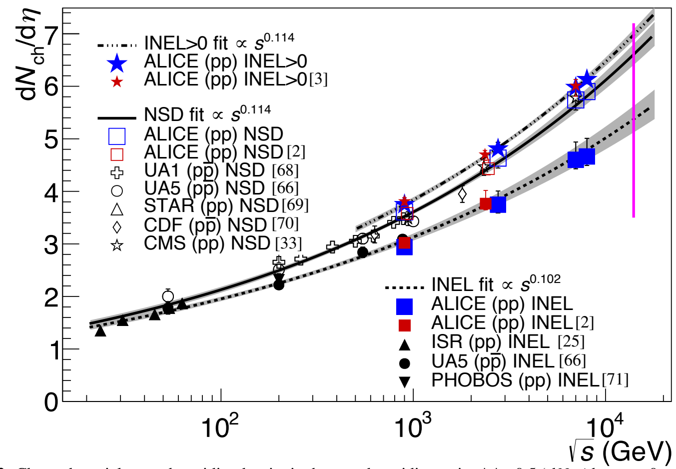
Energy and system size dependence

pp collisions: energy dependence of pseudorapidity distributions

New data
At 2.76



Eur. Phys. J. C 77 (2017) 33



Soft and hard interactions of hadrons at LHC energies

- "Soft" Pomeron as a Regge trajectory with t = 0 intercept:

$\alpha_P(0) = 1 + \Delta > 1$

- $dN/dy \sim dN/d\eta \sim s^{\Delta}$ - under some assumptions (including the non-interacting Pomerons)

Results from the data fit:

- $S^{0.102 \pm 0.003}$ -for INEL
- $S^{0.114 \pm 0.003}$ -for NSD
- $S^{0.114 \pm 0.001}$ -for INEL>0

pp collisions: Multiplicity distributions in comparison with models

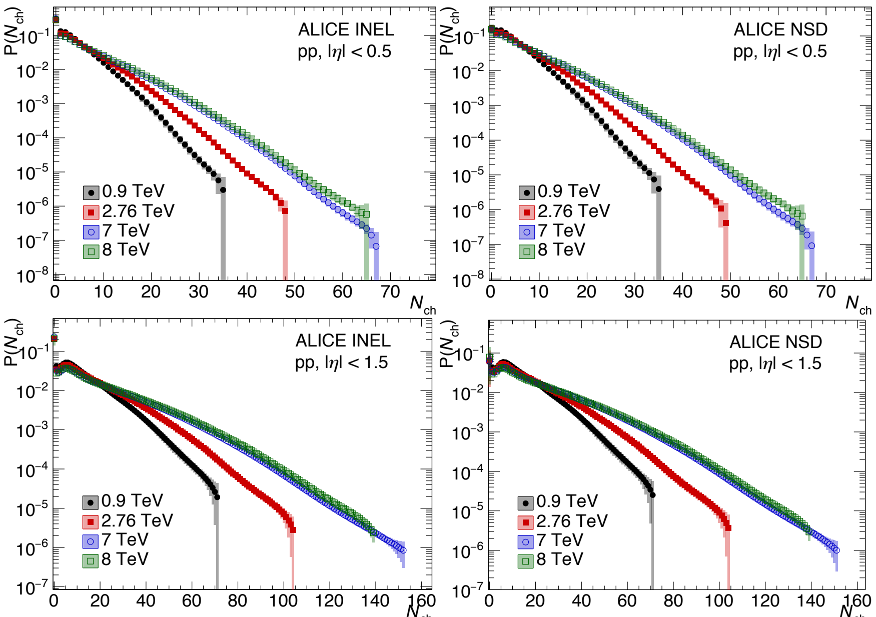


Fig. 16: Evolution of measured multiplicity distributions as a function of centre-of-mass energy (from 0.9 to 8 TeV), for INEL and NSD event classes and for $|\eta| < 0.5$ (top row) and $|\eta| < 1.5$ (bottom row).

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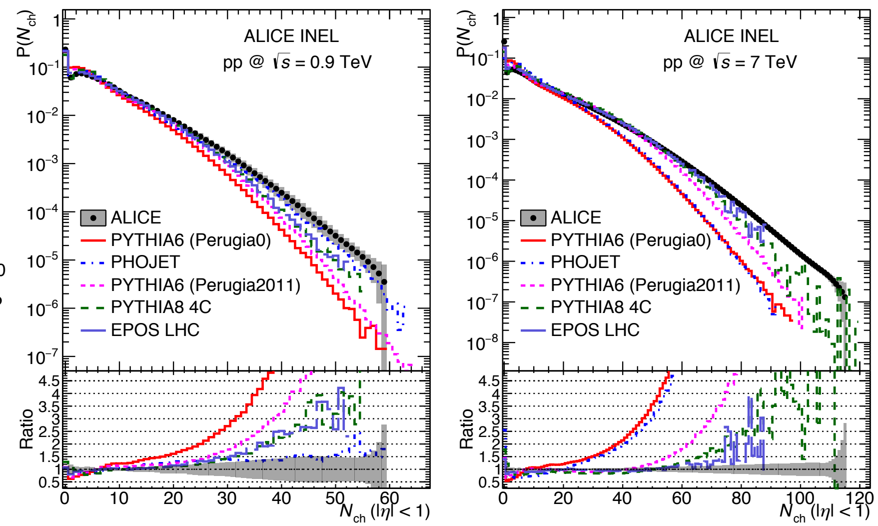
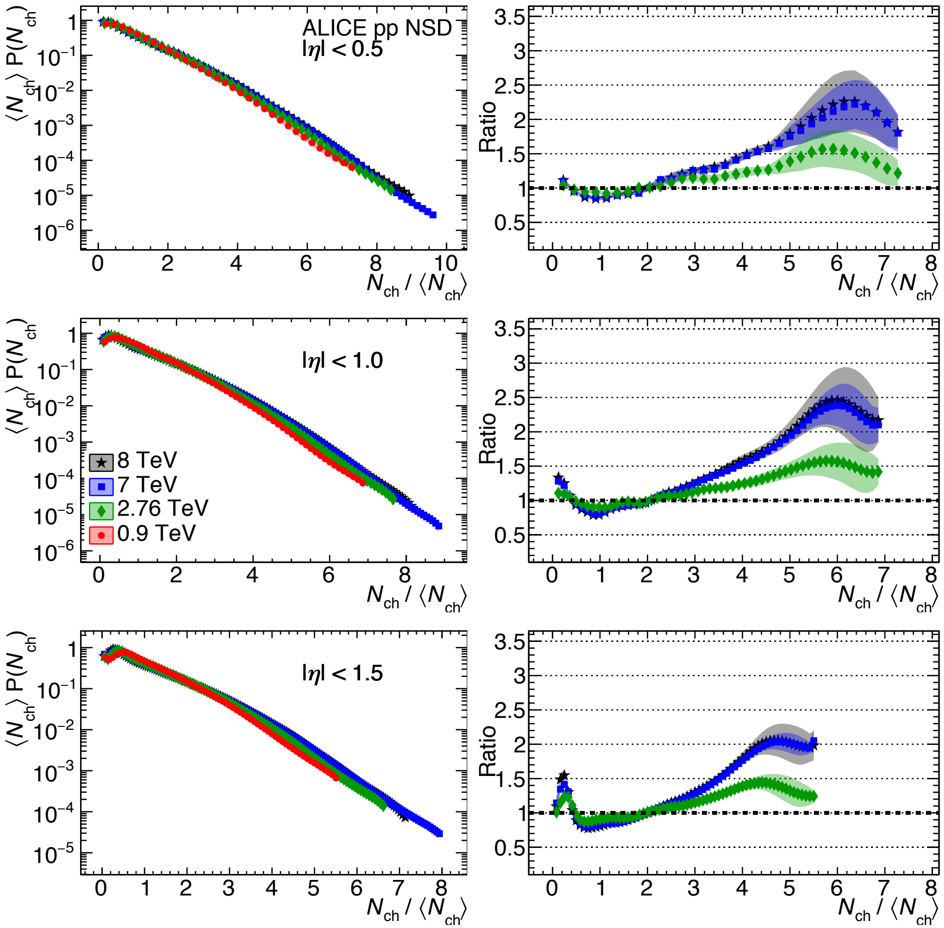
- ➢ *From low to high energies in pp collisions:* What is the main mechanism for changing the mulitplicity distributions -- ?
- ➢ MPI -?
- ➢ QGP-?
- ➢ Color string fusion -?



- ➢ *Remarkable change of high multiplicity distributions tails*
- ➢ *MC event generators fail*
- ➢ *A reference for heavy-ion collisions at the LHC.*

pp collisions
KNO variable: multiplicity scaled by mean multiplicity

KNO-scaled distributions vs. the KNO variable at 0.9, 2.76, 7 and 8 TeV



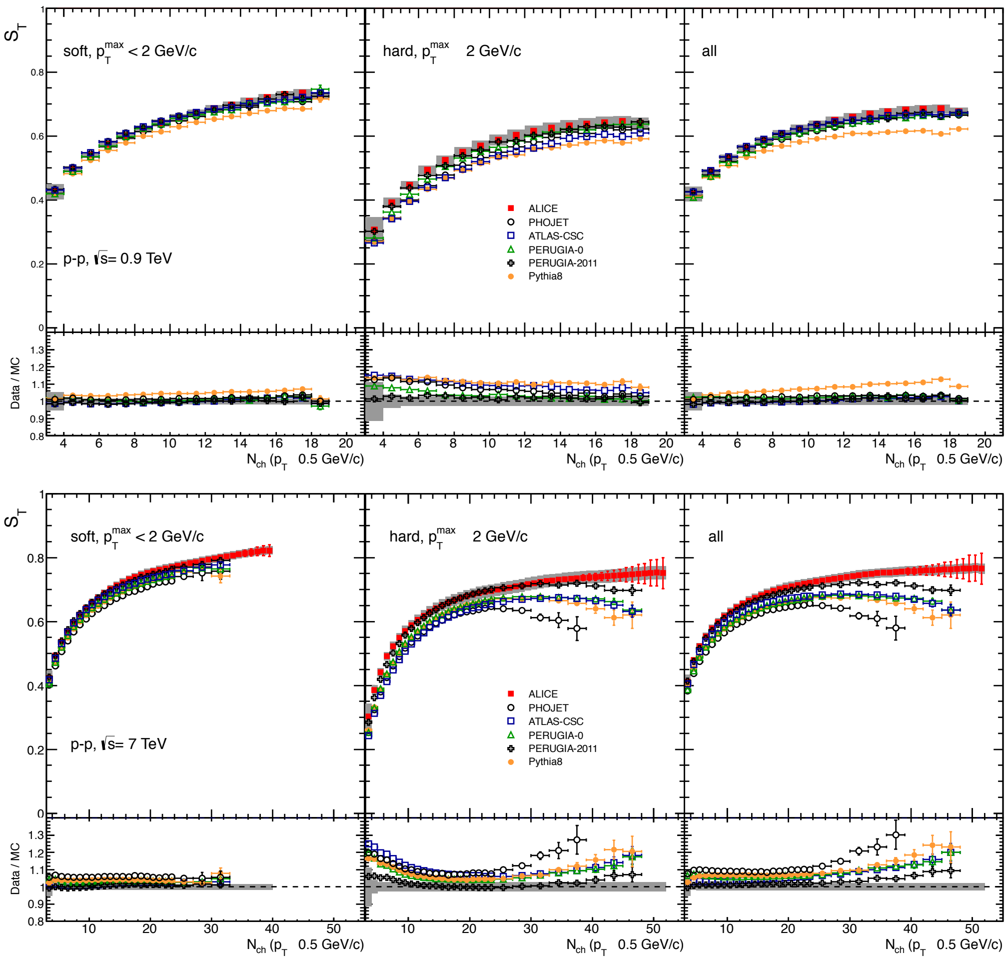
Eur. Phys. J. C 77 (2017) 33

- KNO scaling: Z. Koba, H.B. Nielsen and P. Olesen, *Nucl.Phys.* B40 (1972) 317–334.
- Violation of the shape of the KNO scaling -- fast increase of the high-multiplicity tail of the distribution:
  a) with increasing energy and
  b) with increasing pseudorapidity interval

… more on the high–multiplicity events in pp collisions →

pp collisions: Mean sphericity vs. multiplicity

Eur. Phys. J. C (2012) 72:2124



The transverse sphericity is defined in terms of the eigenvalues: $\lambda_1 > \lambda_2$ of the transverse momentum matrix:

$$\mathbf{S^L_{xy}} = \frac{1}{\sum_i p_{\mathrm{T}i}} \sum_i \frac{1}{p_{\mathrm{T}i}} \begin{pmatrix} p_{\mathrm{x}i}^2 & p_{\mathrm{x}i}\, p_{\mathrm{y}i} \\ p_{\mathrm{y}i}\, p_{\mathrm{x}i} & p_{\mathrm{y}i}^2 \end{pmatrix}$$

where ($p_{x\,i}$, $p_{y\,i}$) are the projections of the transverse momentum of the particle i.

The transverse sphericity $\mathbf{S_T}$:

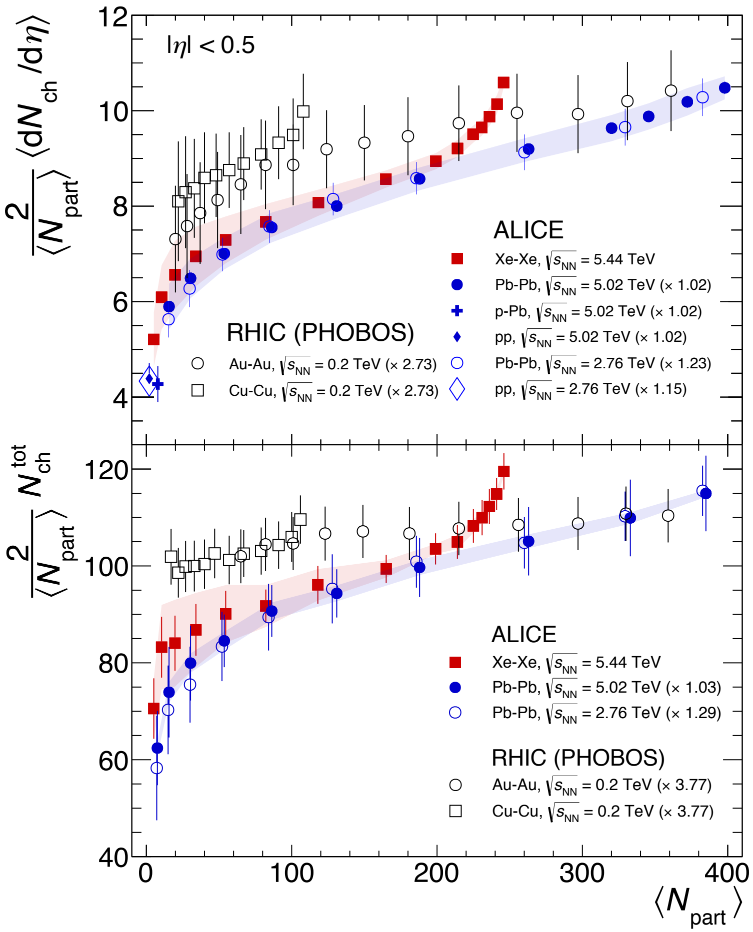
$$S_{\mathrm{T}} \equiv \frac{2\lambda_2}{\lambda_2 + \lambda_1}.$$

$$S_{\mathrm{T}} = \left(\left\{ \begin{array}{ll} = 0 & \text{“pencil-like” limit} \\ = 1 & \text{“isotropic” limit} \end{array} \right. \right.$$

- ***The high –multiplicity events are more isotropic***
- *Models fail at high multiplicity*

- **Indications on collectivity in small systems --?**

From pp to p-Pb and Pb-Pb collisions: multiplicity density and total multiplicity per $\langle N_{part} \rangle$ vs $\langle N_{part} \rangle$



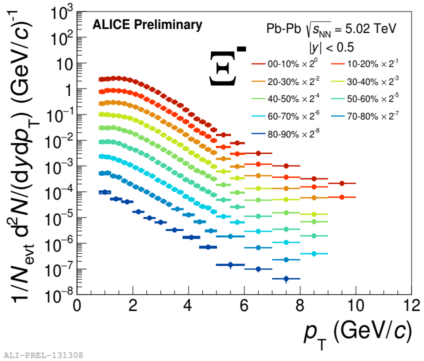
arXiv:1805.04432

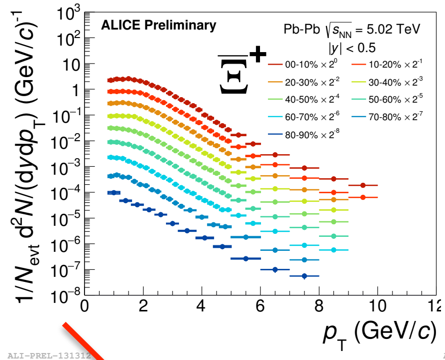
New data:
$dN_{ch}/d\eta$ in Xe–Xe at $\sqrt{s_{NN}}$ = 5.44TeV

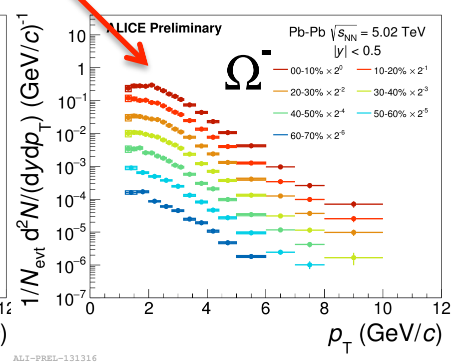
- Similar trends in pp, pA collisions and those of the mid-sized Cu-Cu, Xe–Xe and the large Pb–Pb and Au-Au systems.
- General violation of $\langle N_{part} \rangle$-scaling
- $\langle N_{part} \rangle$-scaling violation for very central Xe–Xe collisions - ?

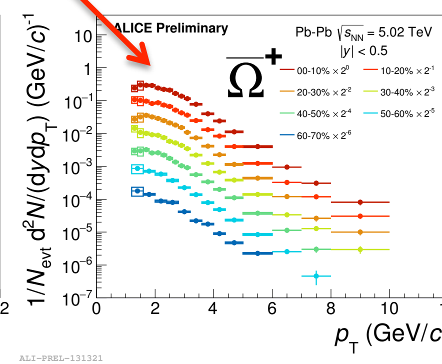
Strangeness yields in pp, p-Pb and Pb-Pb collisions

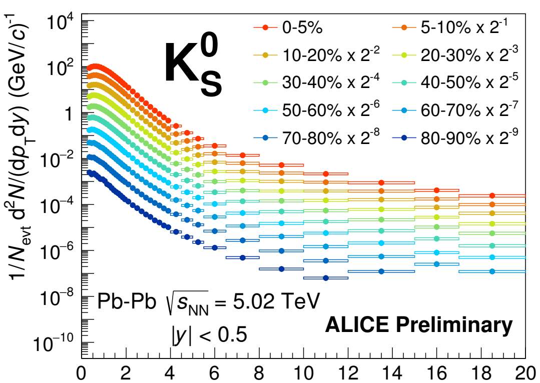
Spectra of K^0_s, Λ, Ξ^-, Ω^-, $\bar{\Lambda}$, $\bar{\Xi}^+$, $\bar{\Omega}^+$ in Pb-Pb at 5.02 TeV

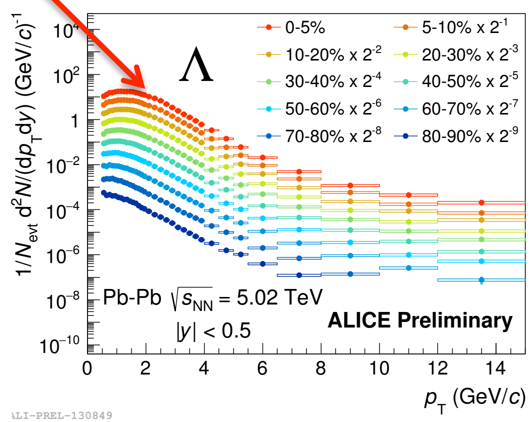


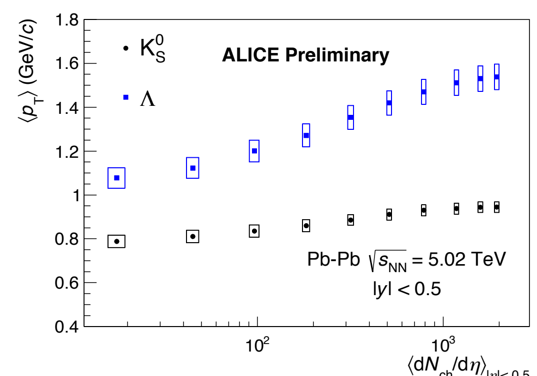








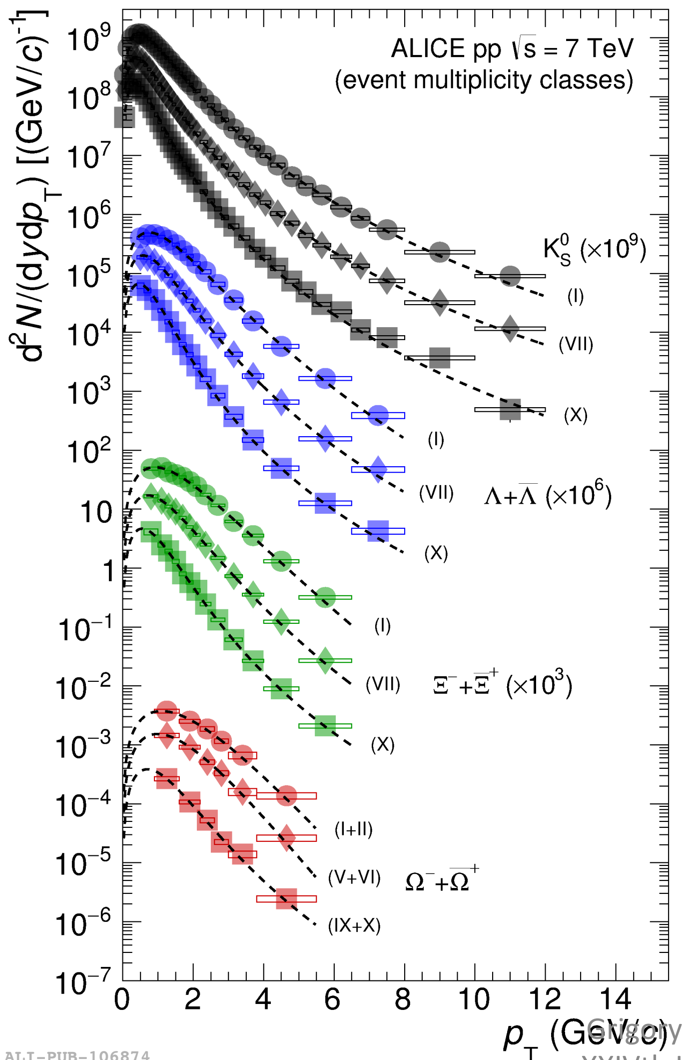




➢Hardening of spectra : from peripheral to central bins is more pronounced for heavier particles

p_T-differential yields of K^0_s,Λ,Ξ and Ω in pp collisions at 7 TeV

(DOI:10.1038/NPHYS/4111)



NB! The data are scaled by different factors to improve the visibility

Some observations:

- hardening of p_T spectra with increasing multiplicity
- the hardening of p_T spectra is more pronounced for higher-mass particles
- the appearance of collective behaviour at high multiplicity - ?
- particle emission from a collectively expanding thermal source - ?

U.Heinz, https://inspirehep.net/record/714564

Some event multiplicity classes in pp collisions, 7 TeV

Class name	I	…	VII	…	X
$\sigma / \sigma_{inel} > 0$	0 - 0.95%		28 - 38%		68 – 100%
$<dN_{ch}/d\eta>$	21.3+-0.6		6.72+-0.21		2.26+-0.01

p_T-integrated yield ratios to pions as a function of the <dN_{ch}/dη>

- A significant enhancement of strange to non-strange hadron production with increasing <dN_{ch}/dη>
- Smooth behavior of particle ratios with the <dN_{ch}/dη> regardless of colliding system and energy
- DIPSY rope hadronization model [1,2] is providing the best description
- PYTHIA8 [3] fails completely

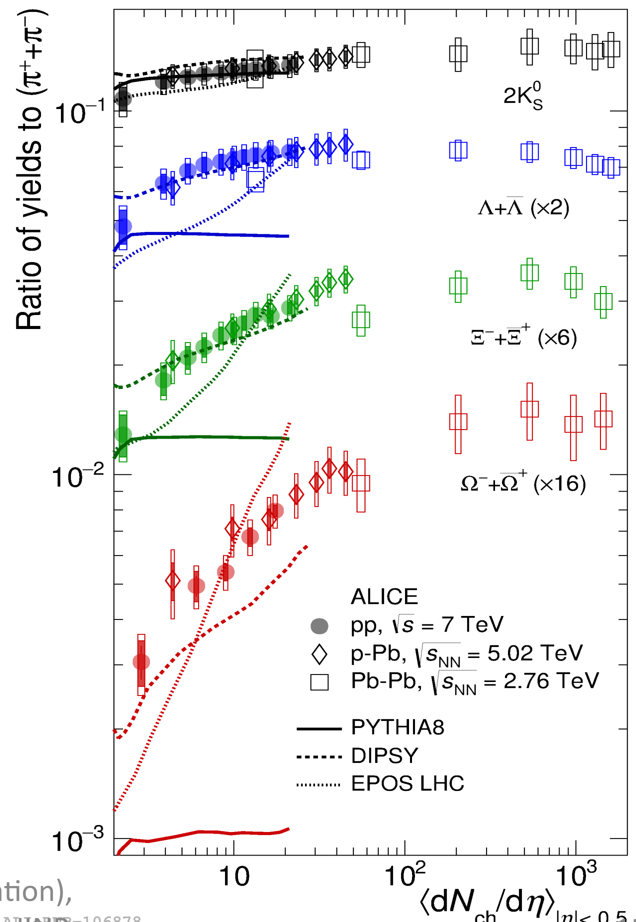
[1] C.Bierlich, G.Gustafson, L.Lonnblad, A.Tarasov, https://inspirehep.net/record/1335149 (2015)

[2] Bierlich, C. & Christiansen, J. R. *Phys. Rev. D* **92,** 094010 (2015).

[3] Sjöstrand, T., Mrenna, S. & Skands, P. Z. *Comput. Phys. Commun.* **178,** 852–867 (2008).

[4] EPOS LHC: T. Pierog et al., Phys. Rev. C 92, 034906 (2015).

DOI:10.1038/NPHYS/4111



The strange hadron hierarchy in pp and p-Pb collisions

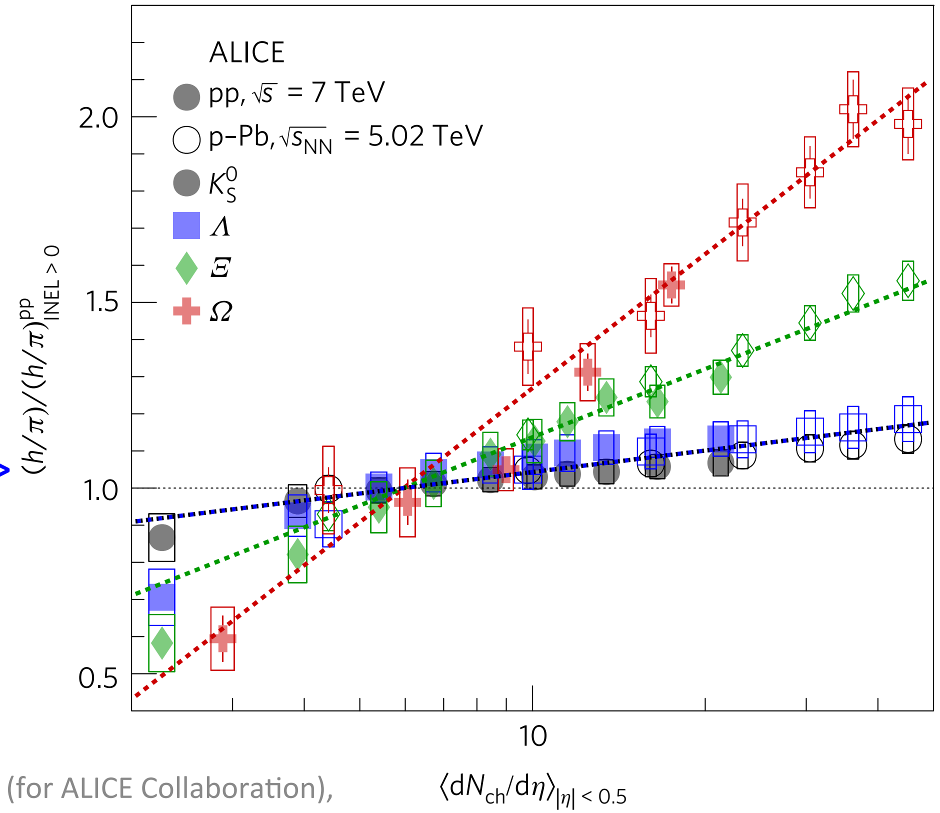
$$\frac{(h/\pi)}{(h/\pi)^{\mathrm{pp}}_{\mathrm{INEL}>0}} = 1 + a\,S^b \log\left[\frac{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle}{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle^{\mathrm{pp}}_{\mathrm{INEL}>0}}\right]$$

(DOI:10.1038/NPHYS/4111)

- *S* is the number of strange or anti-strange valence quarks
- *a* and *b* are free parameters:

  $a = 0.083 \pm 0.006$,

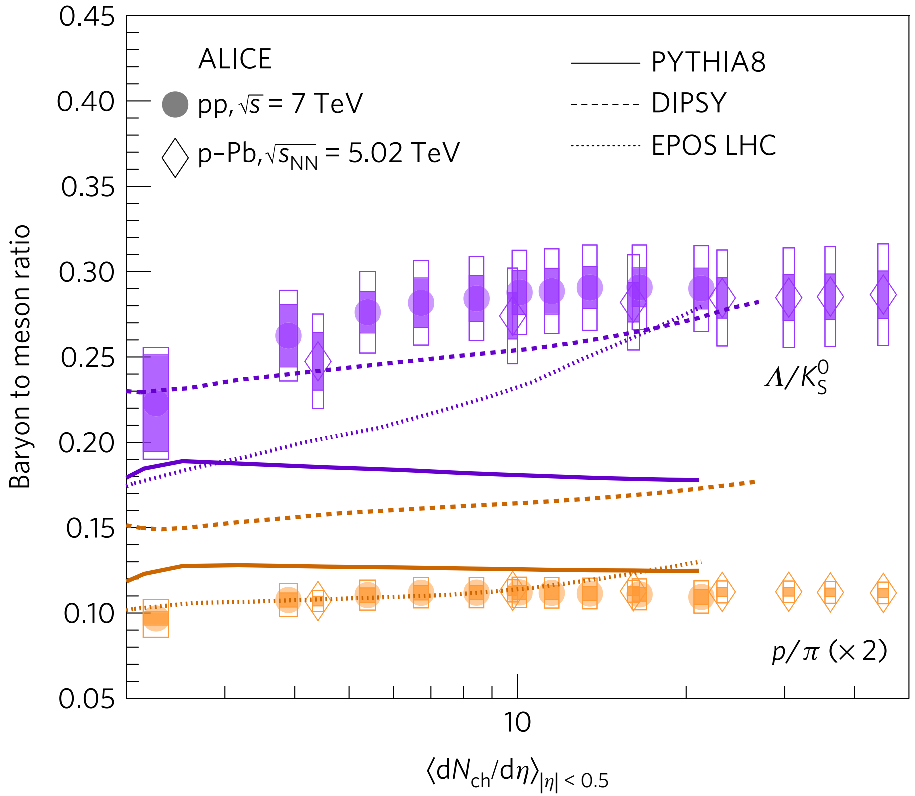
  $b = 1.67 \pm 0.09$



- No enhancement with the <dN_{ch}/dη> is observed for particles without no strangeness
- Enhancement with the <dN_{ch}/dη> depends on strange quark content

Mass dependence of particle ratios?

DOI:10.1038/NPHYS/4111



- Data shows practically no changes with multiplicity for proton/pion ratio
- None of the MC models can describe all particle ratios simultaneously.
- For example DIPSY [1] fails in describing p/π ratio in its original formulation, but qualitatively describes Λ/K^0_s
- EPOS[2] that uses Core/Corona model-- is OK for p/π ratio , PYTHIA8 [3] fails completely

[1] C.Bierlich, G.Gustafson, L.Lonnblad, A.Tarasov, https://inspirehep.net/record/1335149 (2015); Bierlich, C. & Christiansen, J. R. *Phys. Rev. D* **92,** 094010 (2015);

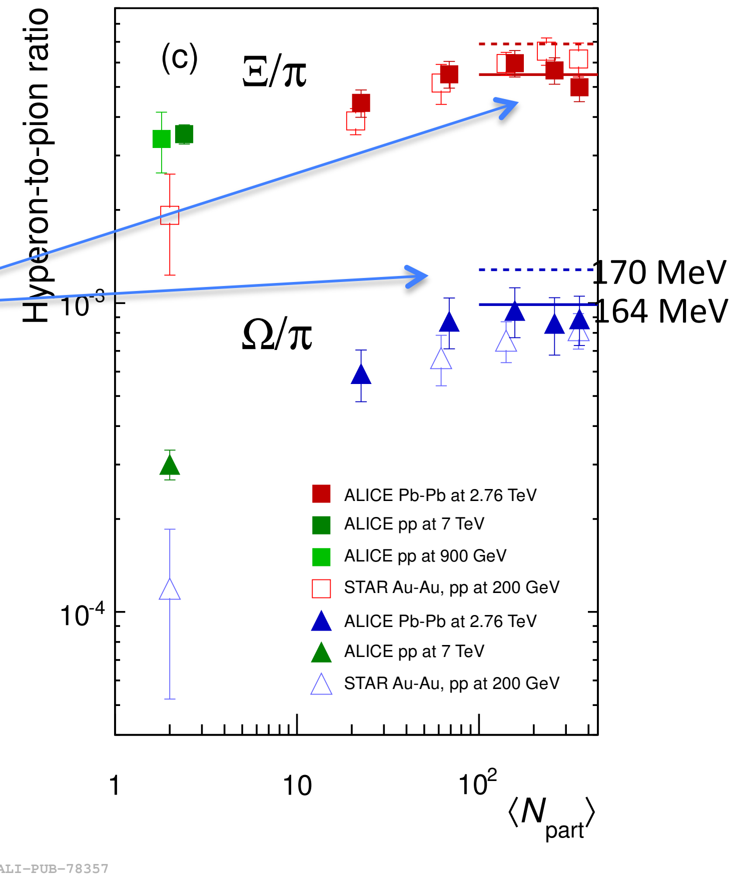
[2] Pierog,et al.,*Phys. Rev. C* **92,** 034906 (2015).

[3] Sjöstrand, T., Mrenna, S. & Skands, P. Z. *Comput. Phys. Commun.* **178,** 852–867 (2008).

Hyperon-to-pion ratios as a function of <N_{part}>, for A-A and pp collisions at LHC and RHIC energies.

- General smooth increase of ratio with system size (centrality)
- Flattening after <N_{part}>~150
- Ratios are similar at RHIC and LHC
- Increase in h/π ratios with energy is noticeable for pp collisions
- Lines – predictions of thermal statistical models based on a grand canonical approach [1],[2]

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



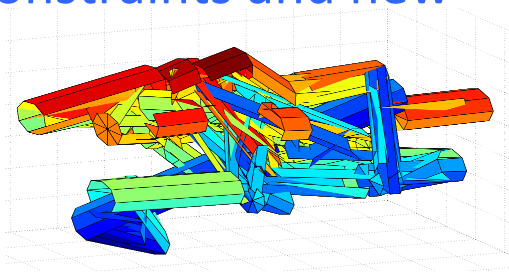
[1] A. Andronic , P. Braun-Munzinger J. Stachel Phys. Lett. B 673 (2009), p. 142

[2] J. Cleymans, I. Kraus, H. Oeschler, K. Redlich, S.Wheaton, Phys. Rev. C,74 (2006) 03490

Some theoretical approaches: *string fusion* in DIPSY[1]

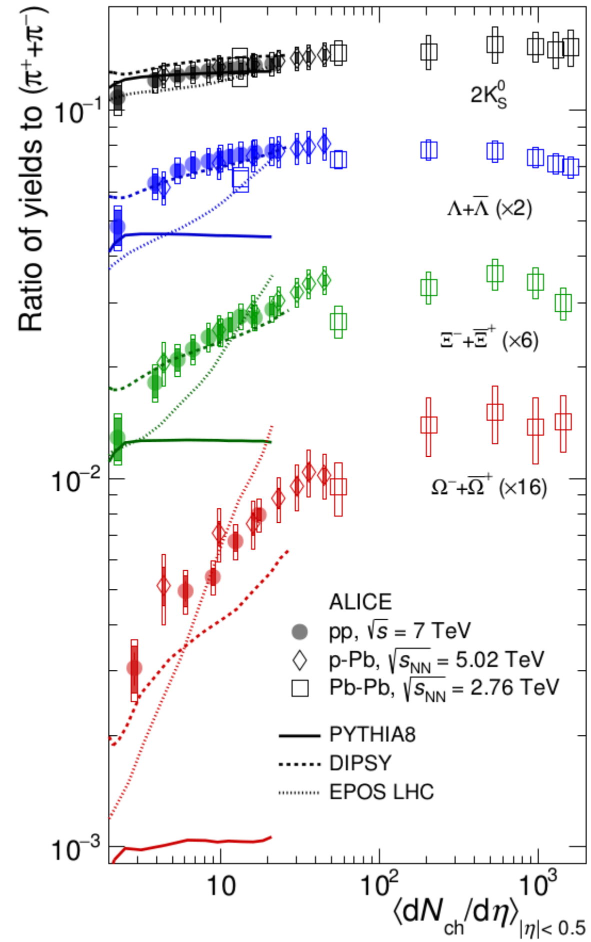
DOI:10.1038/NPHYS/4111

Data are bringing new constraints and new questions to the models



DIPSY:

- Strings close in space can fuse to form "the colour ropes"
- New type of particle emitting sources -- strings with higher tension
- Increased production of strange particles and baryons
- Pre-Equilibrium Phase for QGP formation - ?
- A reminiscent of a thermal system - ?



[1] C.Bierlich, J. R.Christiansen, Effects of Colour Reconnection on Hadron Flavour Observables, arxiv:1507.02091; Christian Bierlich et al., arXiv:1412.6259

[2] **String fusion model**: M.Braun,C.Pajares, Phys. Lett. B 287, (1992) 154-158

Some theoretical approaches:
Multi-Pomeron Exchange Model
with *string fusion[1]*

DOI:10.1038/NPHYS/4111

Schwinger mechanism of production of particles species of type *ν* production mass m_ν, momentum p_t *and* spin - S_ν,

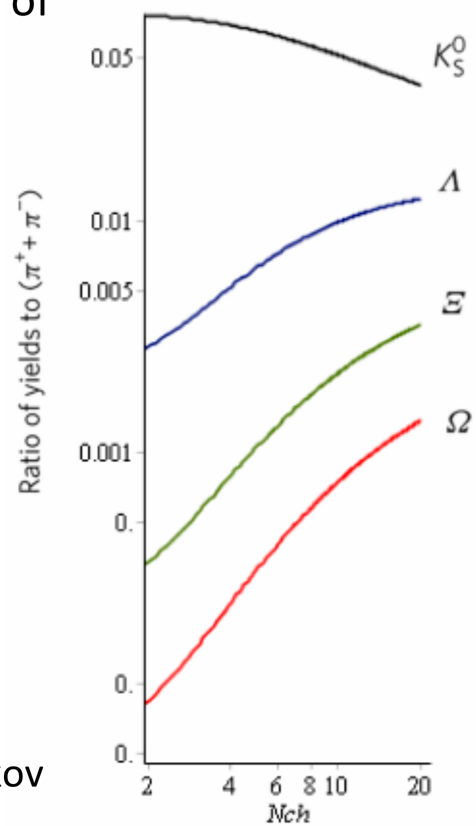
Here,
$$g_\nu \exp\left(-\frac{\pi\left(p_t^{2}+m_\nu^{2}\right)}{n^\beta t}\right)$$

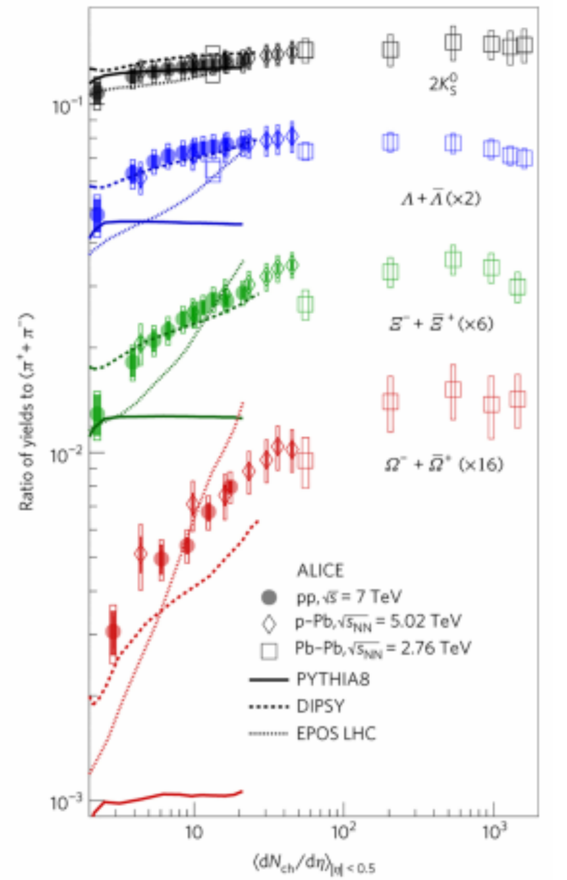
n - number of Pomerons,
t- string tension,
β – model collective parameter

$$g_\nu = 2S_\nu + 1$$

- Large set of hadron resonances with cascade decays
- The model qualitatively describes the data

[1]G.Feofilov,V.Kovalenko, A.Puchkov arxiv: 1710.08895 [hep-ph](2017)





Some theoretical approaches:
Multi-Pomeron Exchange Model
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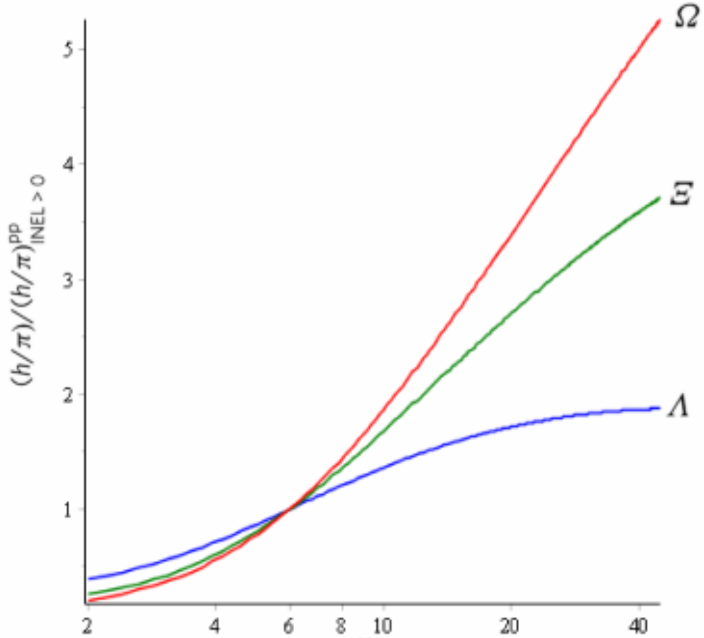
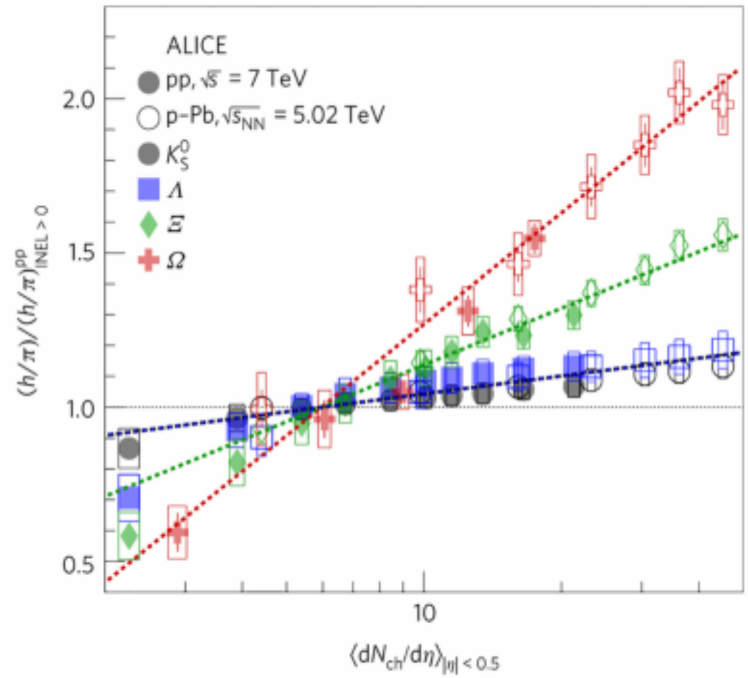
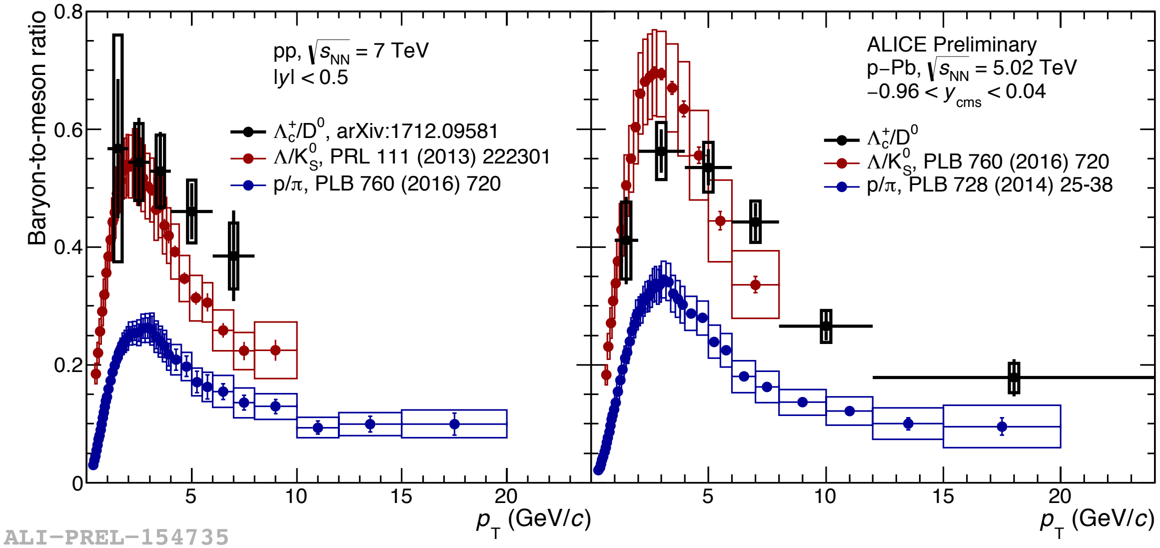




[1] G.Feofilov,V.Kovalenkro, A.Puchkov
arxiv: 1710.08895 [hep-ph](2017)

- The model qualitatively describes the data

Λ_c^+/D^0 ratio compared to Λ/K^0_S and p/π ratios (pp collisions at 7 TeV and p-Pb at 5.02 TeV)

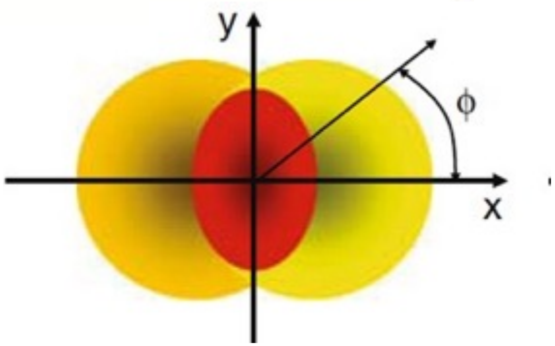


- New results: The baryon-to-meson ratios Λ^+_c/D^0 were measured in pp and p–Pb collisions
- Ratios are obtained and compared for the same systems
- Ratios are compatible within their statistical and systematic uncertainties.

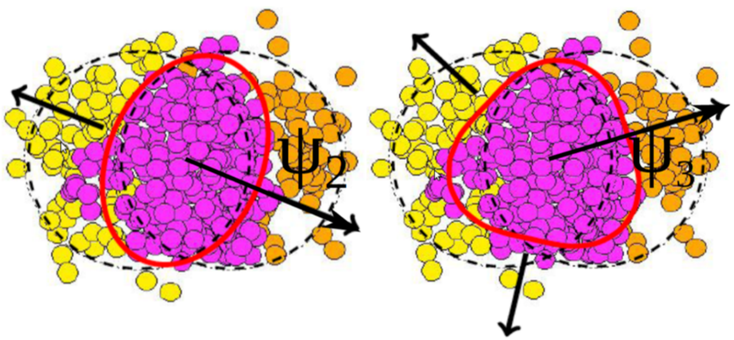
- **Charm and light flavour sectors show similar results**
- The input for theoretical pQCD models
- Test for different hadronization approaches

Flow of different particles

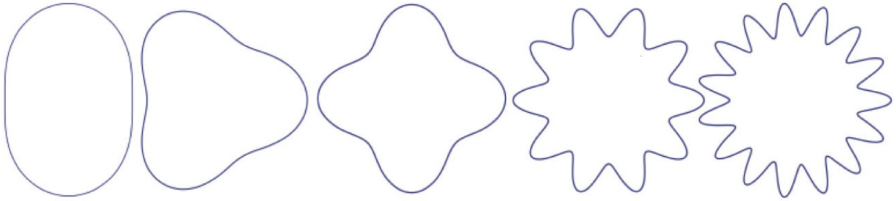
Flow in hadron collisions



→ Anisotropy in spatial space in A-A collision is converted to the momentum anisotropy
→ This motivated the fluid-like collectivity approach
→ Fourier transform of azimuthal momentum distribution with anisotropic flow coefficients v_n

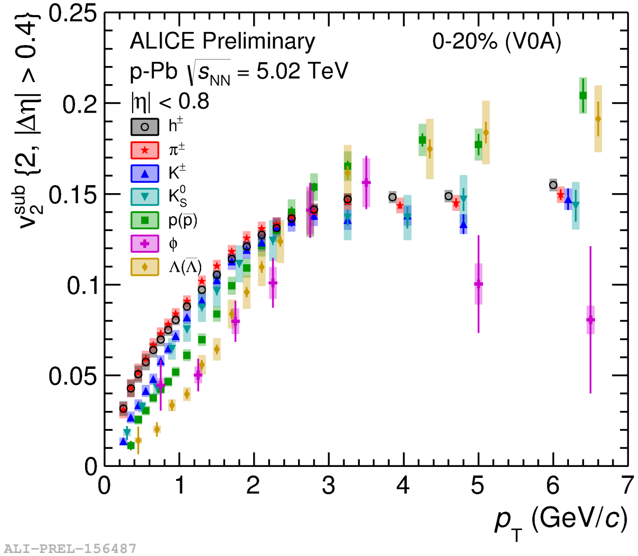


$$E\frac{dN}{d\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]\right]$$



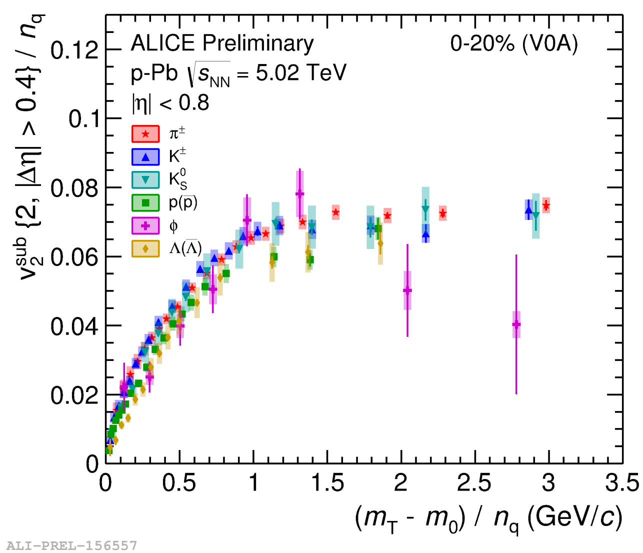
v_n -- Fourier coefficients
φ – azimuthal angle
Ψ_n -- Event plane angle of the n-th harmonics

Elliptic flow of identified hadrons in p-Pb



[arXiv:1807.04538 [nucl-ex]]

- Δη gap is introduced between the correlated particles to eliminate short-range contribution
- Non-flow subtracted using pp measurements
- For $p_T \leq 2.5$ GeV/c, a clear mass ordering of $v_2(p_T)$ for p-Pb collisions is observed similar to the previous results for Pb-Pb



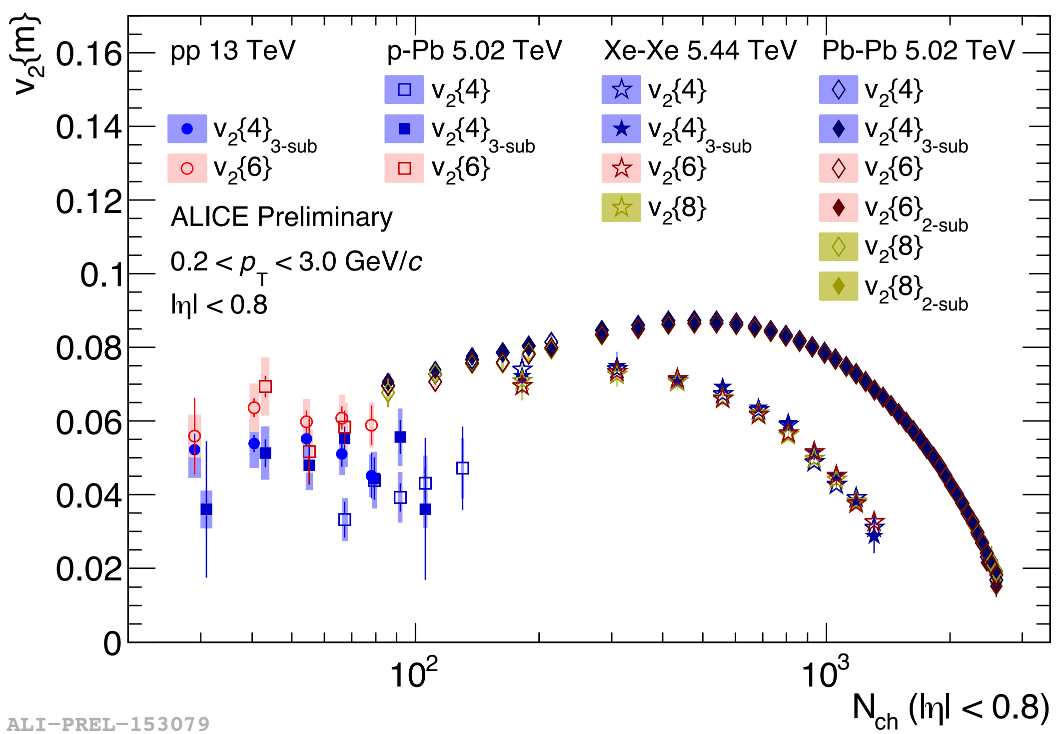
- Aproximate NCQ and KE_T scaling is observed
  NCQ -number of constituent quarks n_q

$$KE_T = m_T - m_0 = \sqrt{p_T^2 + m_0^2} - m_0$$

- An indication on the presence of collective behavior on the partonic level

Elliptic flow and multi-particle correlations for different systems

Investigation of anisotropic flow using multi-particle correlations in pp, p-Pb, Xe-Xe and Pb-Pb collisions



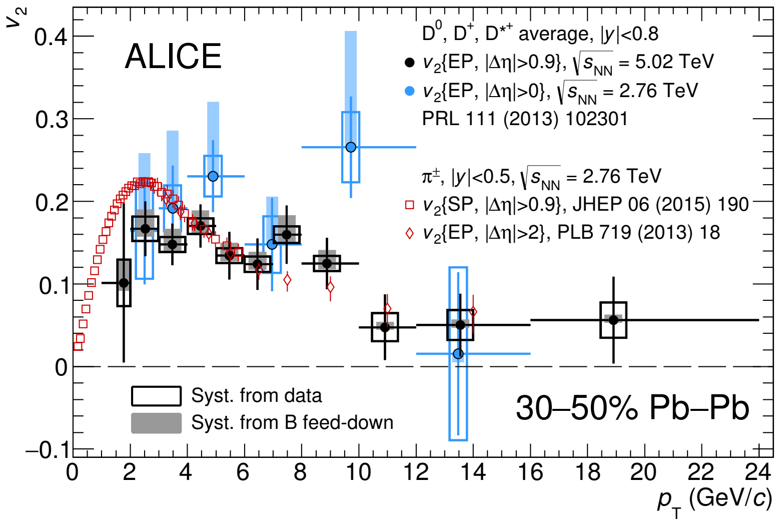
New results:

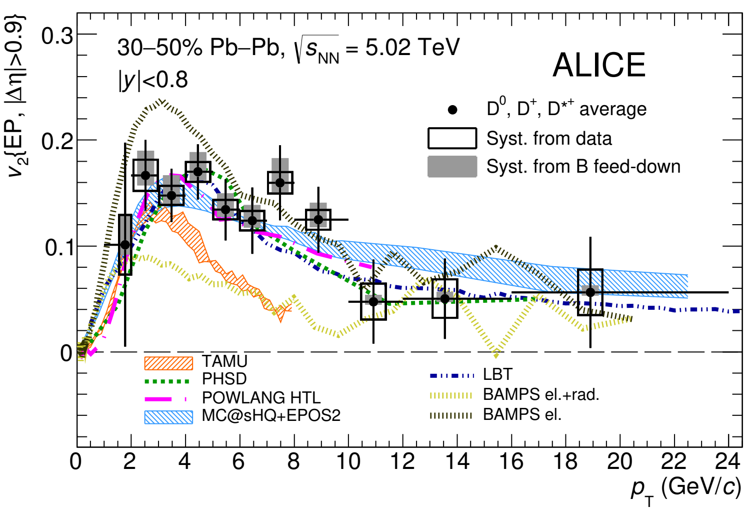
system size dependence of $v_2\{m\}$ on multiplicity of charged particles is measured

- Collective behavior is observed in multi-particle cumulants even in the smallest pp and p-Pb systems.
- Multi-particle cumulants suppress two-particle (non-flow) correlations

Elliptic flow of D^0, D^+, D^{*+} and D^+_s in Pb-Pb collisions

Phys. Rev. Lett. 120, 102301 (2018)





- D-meson v_2 is similar to that of pions

Theoretical calculations include:

- a hydrodynamical model for the QGP expansion
- hadronization via quark recombination, + independent fragmentation (except BAMPS)
- The BAMPS-el, POWLANG and TAMU

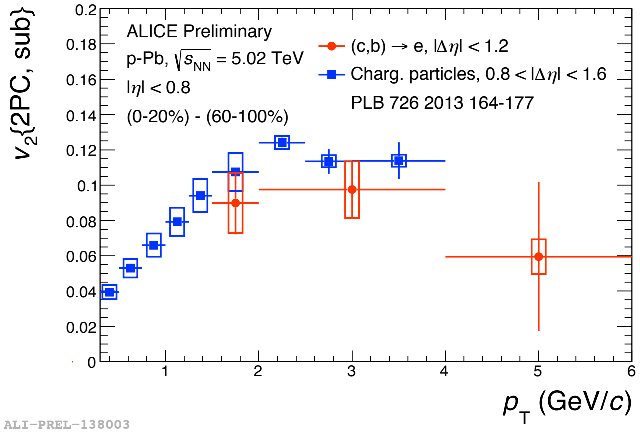
-- include only elastic interactions

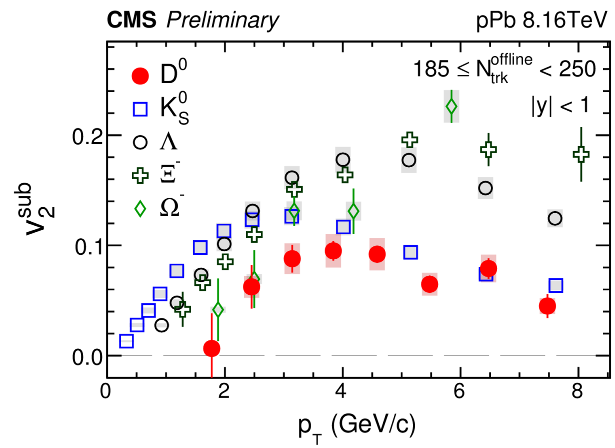
- BAMPS-el+rad, LBT, MC@sHQ and PHSD

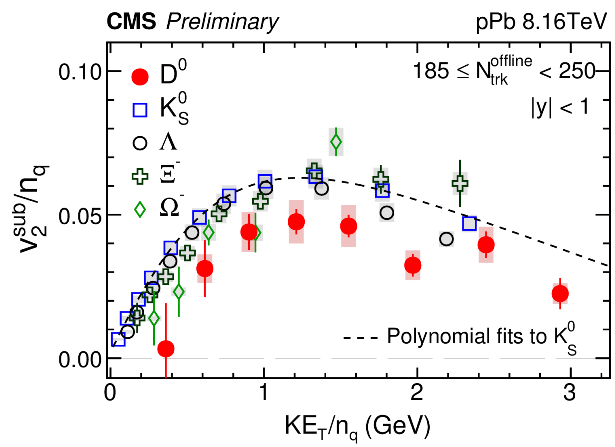
--- include energy loss via gluon radiation

- Low-momentum charm quarks take part in the collective motion of the QGP
- Both collisional interaction processes and recombination of charm and light quarks contribute to the observed v_2

Elliptic flow of heavy-flavour decay electrons and flow of D^0 in p-Pb collisions







CMS, arXiv://1807.04362

ALICE Preliminary, p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV.

- Positive v_2 (5 sigma significance)

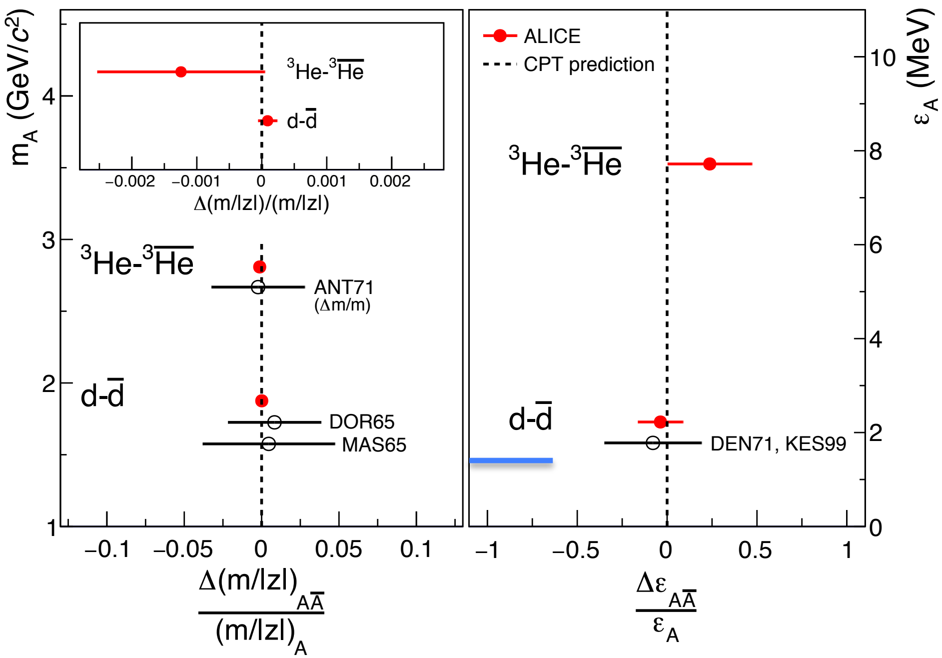
Right: v_2 of prompt D0 in p-Pb Collisions at $\sqrt{s_{NN}}$ = 8.16 TeV, as measured by CMS (see arXiv://1807.04362)

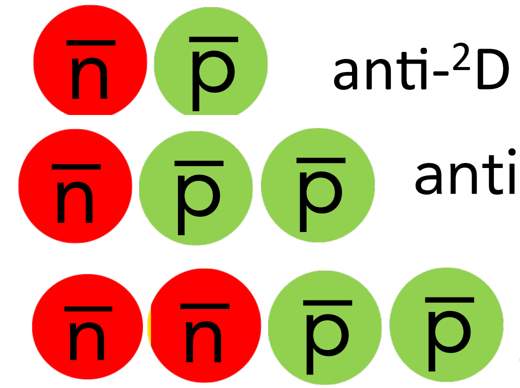
- v_2 for D0 are smaller then for the strange hadrons
- NCQ and KE_T scaling is not followed by D0 in p-Pb - ?
- A weaker coupling of charm quarks to small systems -?

Production of light nuclei in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Exotic states of some hypernuclei

Precision measurement of the mass difference between light nuclei and anti-nuclei

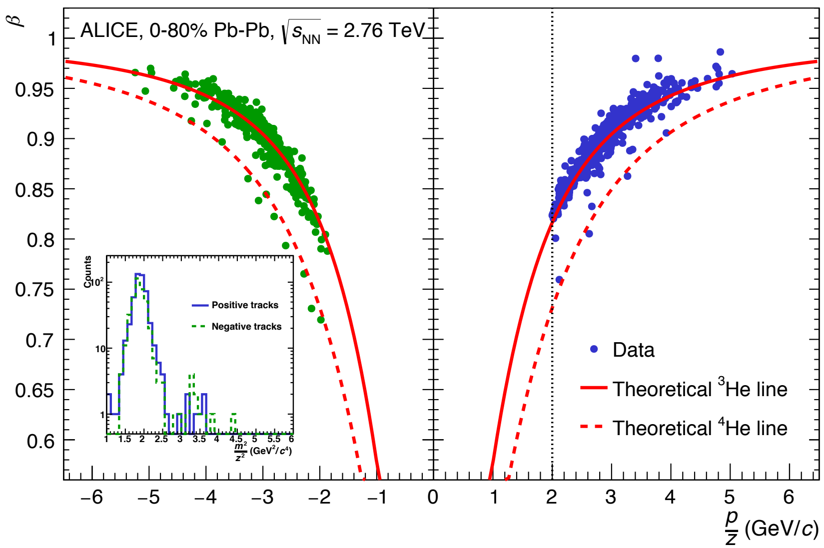
Nature Phys. 11 (2015) 811.





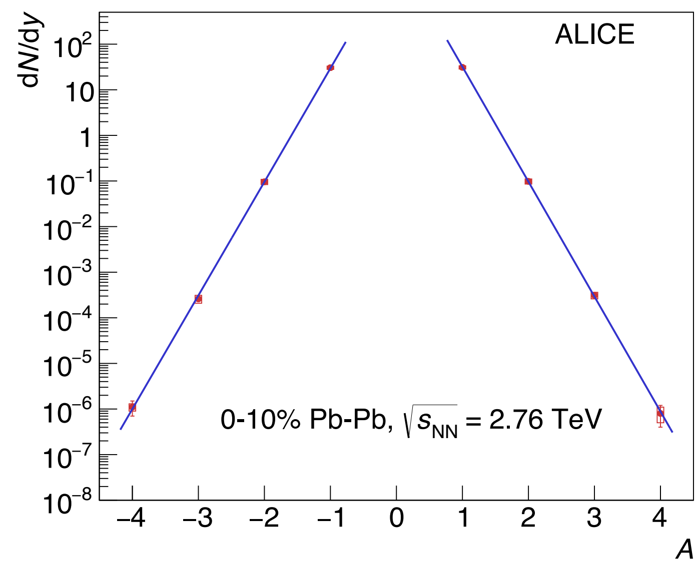
- Loosely bound states such as the deuteron and hypertriton and their anti-particles have been observedin Pb–Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV.
- The values of the mass- over-charge and binding energy are identical for nuclei and anti-nuclei
- Direct measurement confirm CPT invariance in systems bound by nuclear forces.
- The yields of nuclei and of the hypertriton are quantitatively reproduced within a thermal model calculations

Production of ^{4}He and anti-^{4}He in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



Velocity β as a function of the rigidity p/z.

Nucl. Phys. A 971 (2018) 1-20



Phys. Lett. B 752 (2016) 267–277

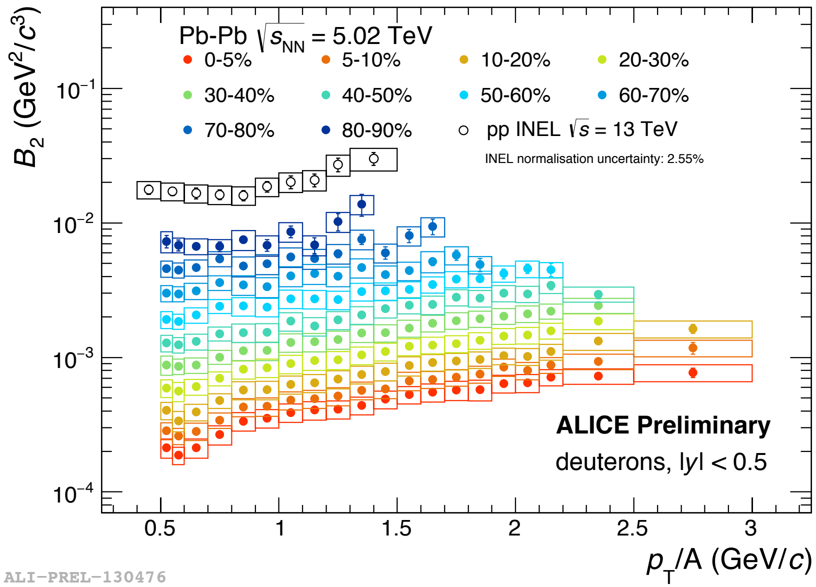
- Yields agree with the thermal model
- Decrease by roughly a factor 300 per extra baryon
- The yield of exotic Λn and ΛΛ should be also predicted by thermal model and with a high yield (?)

…see the experimental data →

ΛΛ ~ uuddss

- ALICE results do not support the existence of the H-dibaryon and the Λn bound state.

(anti-)deuteron production in pp, p-Pb and Pb-Pb

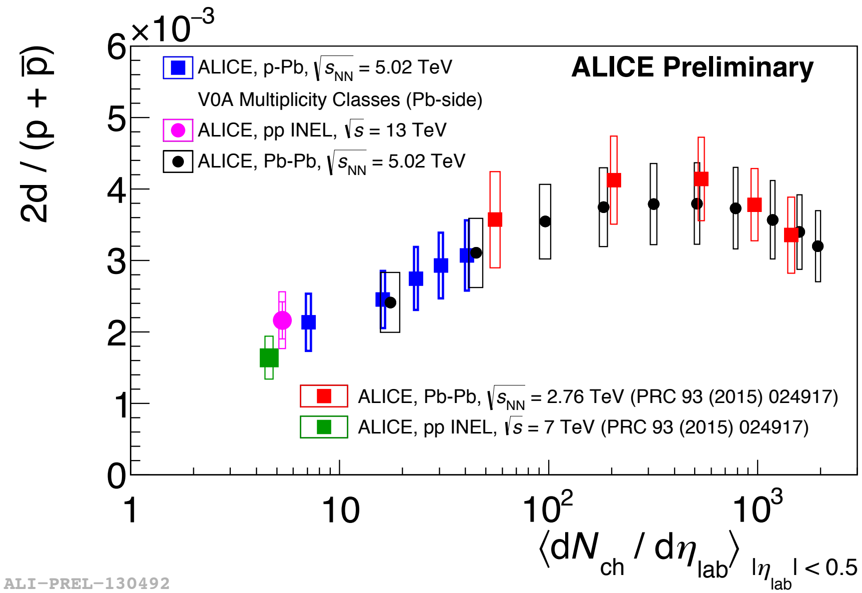


Deuteron coalescence parameter B_2 as function of p_T/A in Pb-Pb

$\bar{n}$ $\bar{p}$ -- anti-^{2}D

The coalescence parameter B_A:

$$\frac{1}{2\pi p_T^A}\frac{d^2N^A}{dy\,dp_T^A} = B_A \left(\frac{1}{2\pi p_T^p}\frac{d^2N^p}{dy\,dp_T^p}\right)^A, \qquad p_T^p = p_T^A/A$$



- ➢ d/p ratio as a function of the charged particle multiplicity in different collision systems (pp, p-Pb and Pb-Pb) at different energies is in qualitative agreement with the expectation from the coalescence model
- ➢ (anti-)deuteron formation mechanism is not fully understood

Future studies of rare processes in Run 3

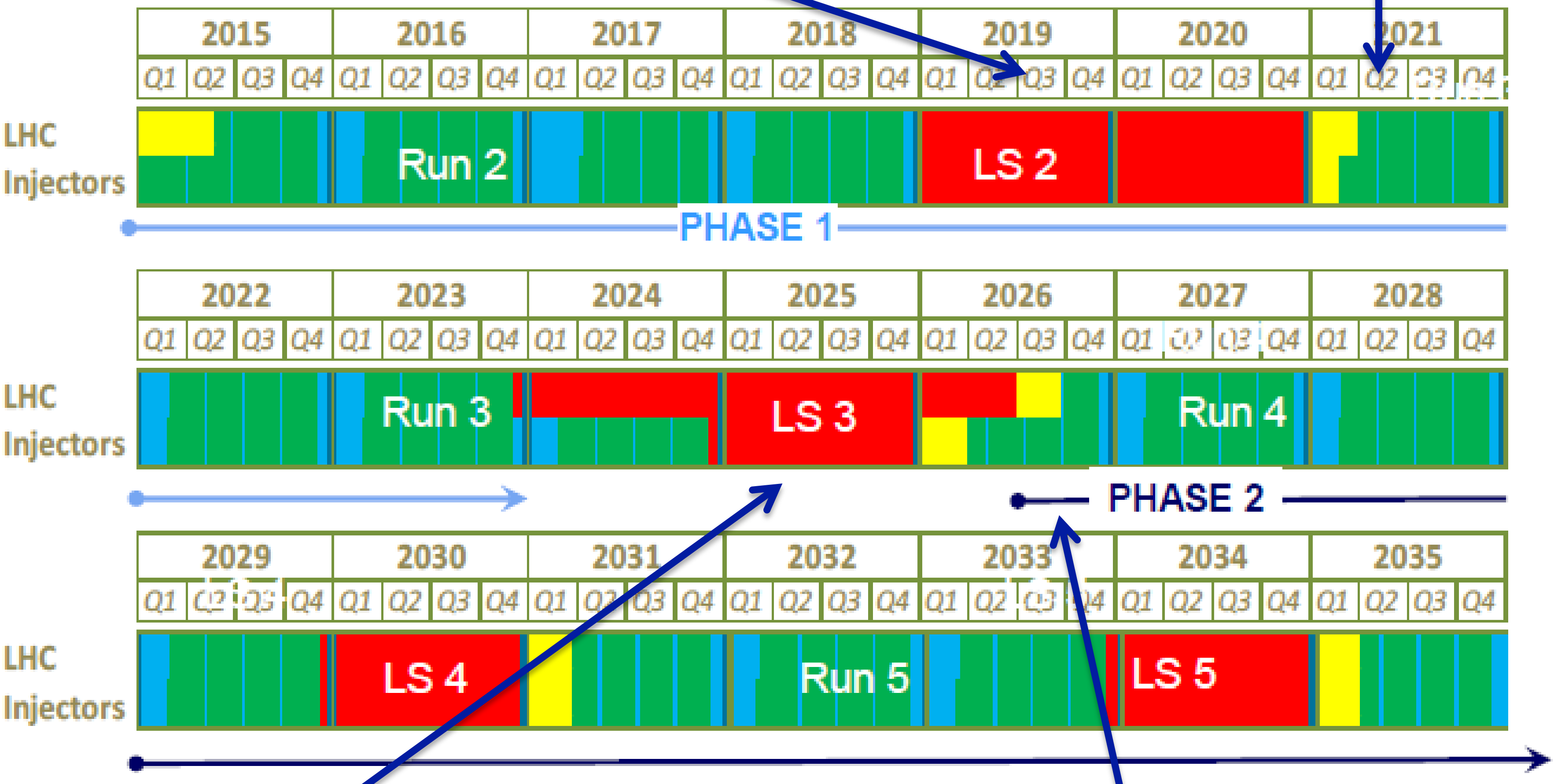
Future: LHC Schedule and upgrades

PHASE I Upgrade

ALICE, LHCb major upgrade

ATLAS, CMS ‚minor' upgrade

Heavy Ion Luminosity from 10^{27} to 7 x10^{27}

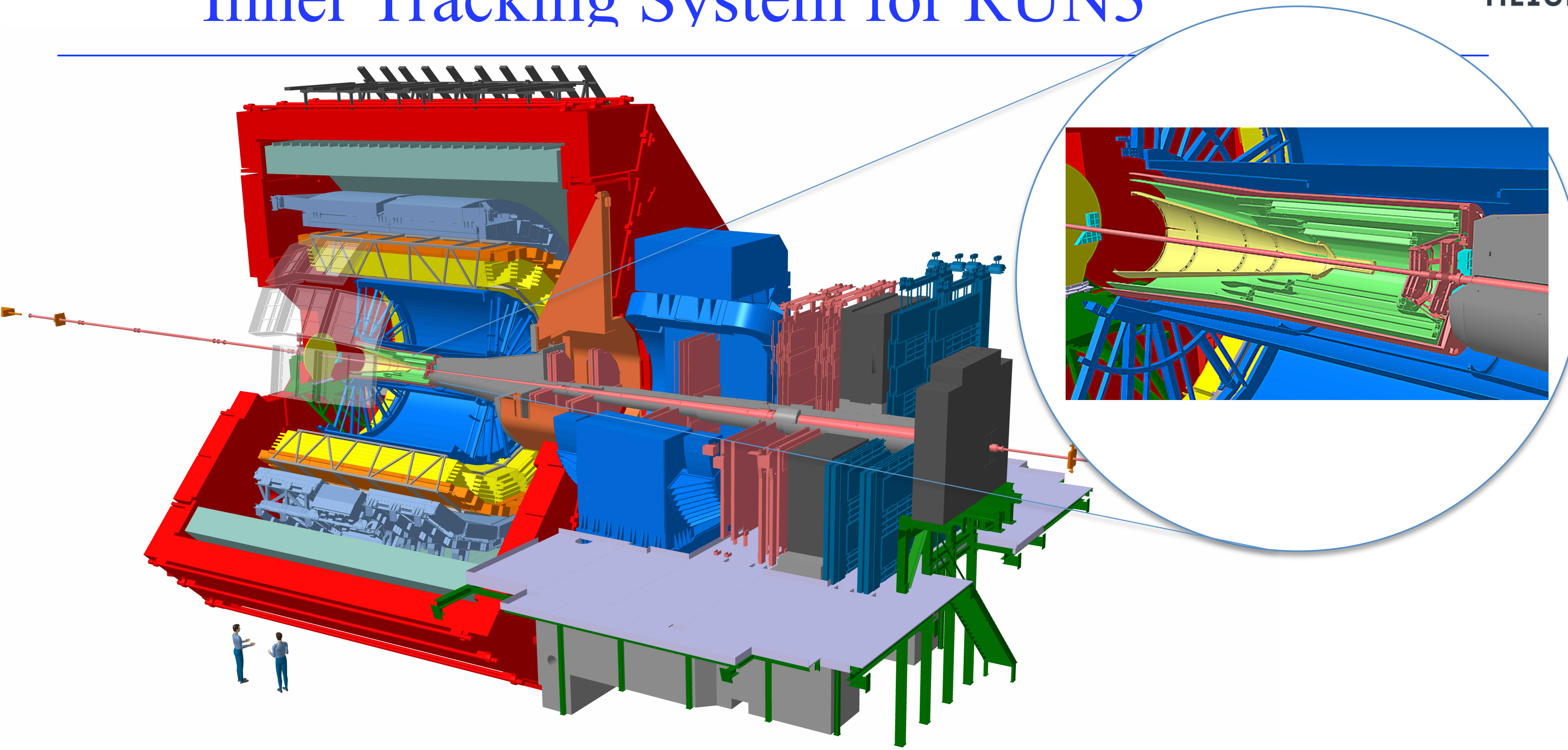


PHASE II Upgrade

ATLAS, CMS major upgrade

HL-LHC, pp luminosity from 10^{34} (peak) to 5 x10^{34} (levelled)

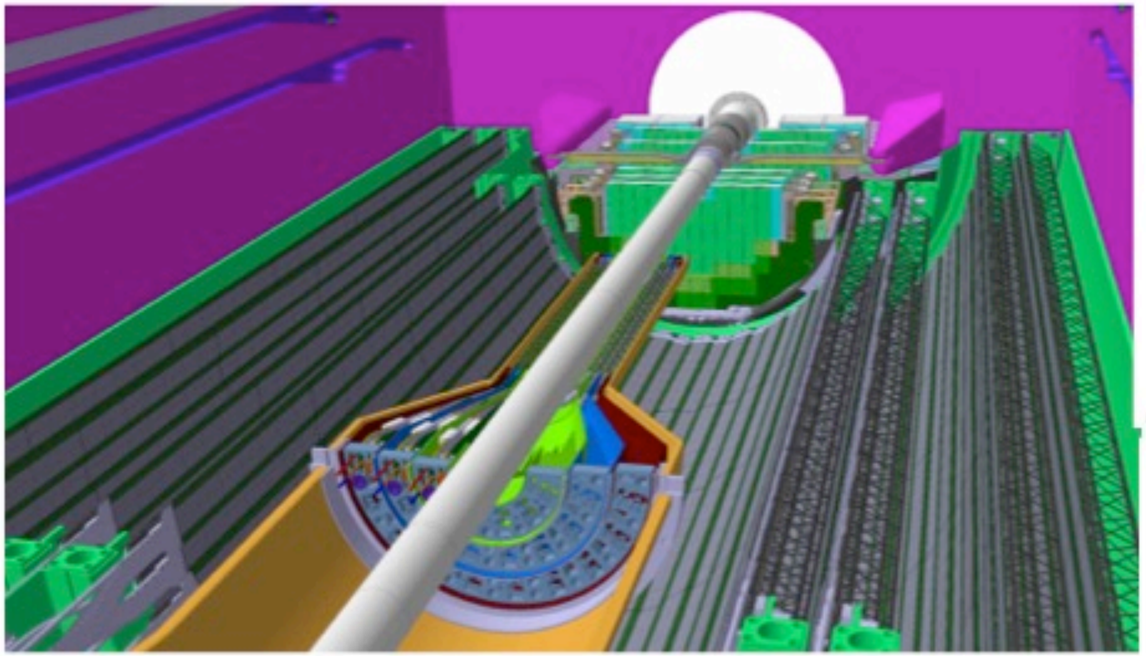
Upgrade of the ALICE Inner Tracking System for RUN3



➢ **New, high-resolution, low-material ITS**

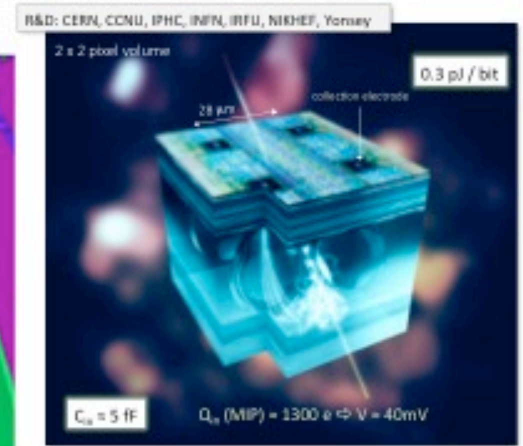
→Production of heavy flavours and study of early stages of heavy-ion collisions
→Probe for study thermalization of QGP
→Understanding of charmonium production

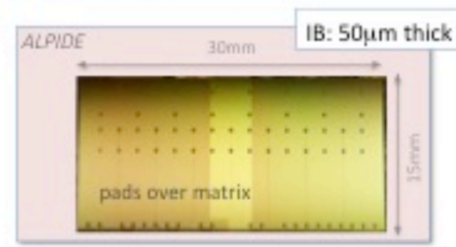
Upgrade of ALICE/ITS based on novel monolythic CMOS pixels



3D view of the new ITS

- ~10m^2 active area, ~25000 chips
- ~12.5 Gigapixels camera with binary readout
- 7 layers, grouped into two barrels





130,000 pixels / cm^2 27x29x25 µm^3

spatial resolution ~ 5 µm

max particle rate ~ 100 MHz / cm^2

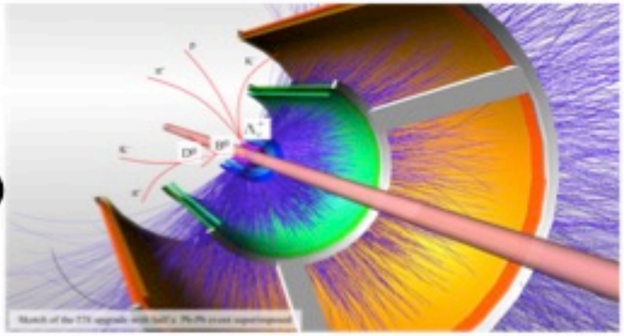
fake-hit rate: < 10^{-9} pixel / event

ALPIDE with modified CERN/Tower process:

⇨ 10^{15} n/cm^2 (HL LHC, 2000/fb, r > 15cm)

New physics possibilities with high luminosity $L = 7 \times 10^{27} cm^{-2} s^{-1}$ Pb beams

- Thermalization of partons in the QGP, **with focus on the massive charm and beauty quarks.**
- In-medium parton **energy loss mechanism**
- **Quarkonium dissociation (and regeneration)** pattern, as a probe of deconfinement
- Production of **thermal photons and low-mass dileptons** emitted by the QGP.



Technical Design Report for the Upgrade of the ALICE Inner Tracking System
J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002

Will be accessible for the first time:

- Production of D mesons down to zero p_T
- Charm and beauty baryons, Λ_c and Λ_b.
- Baryon/meson ratios for charm (Λ_c/D) and for beauty (Λ_b/B),
- The elliptic flow of charmed and beauty mesons and baryons down to low p_T
- Measurement of beauty via displaced D0 → Kp and displaced J/psi → ee,

- Gain a factor **100** in statistics over original program (Run1 + Run2)

- Acces to the larger hyper-nuclei (which have a larger radius and can be used to further probe the baryon formation mechanism)

Summary

ALICE

The main observations in multi-particle production in hadron collisions:

- Mass dependent hardening of particle spectra with centrality.
- Enhanced production rates of strange hadrons with respect to pions.
- Smooth behavior of particle ratios vs. $\langle dN_{ch}/d\eta \rangle$ regardless of colliding system and energy.
- Indications for collectivity effects in small systems similar to nucleus-nucleus collisions
- Measurements of strange and multi-strange baryon production confirm the strangeness enhancements in heavy-ion collisions at the LHC with respect to the smaller systems.

However, the microscopic origin of enhanced strangeness production and collectivity in small systems is still not known.

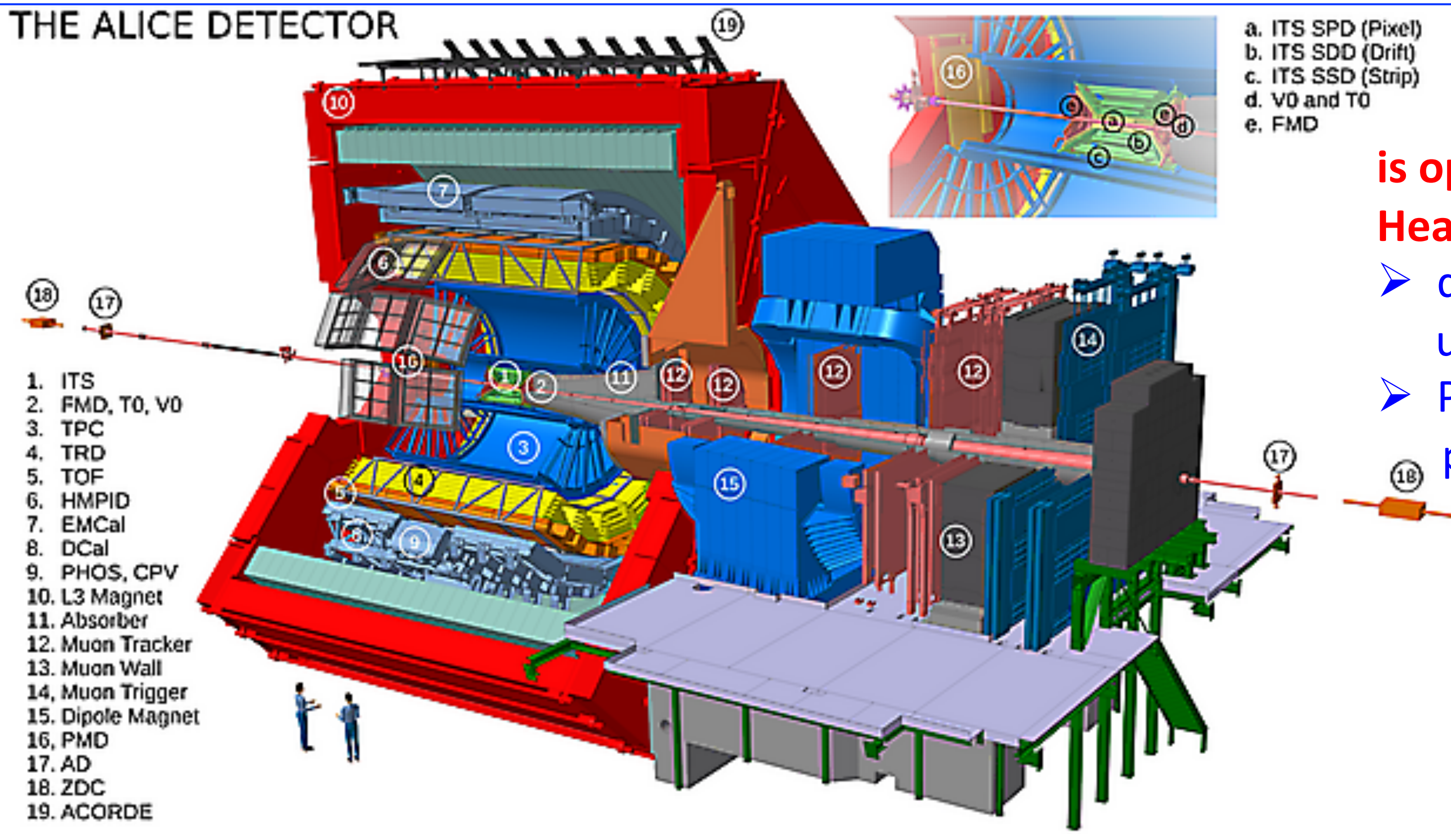
- Results on nuclei and hypernuclei production, measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and pp collisions at $\sqrt{s}$ = 13 TeV, could be described by thermal (Pb-Pb, p-Pb) and coalescence (pp, p-Pb) models.

However, the production mechanism of light (anti-)nuclei in ultra-relativistic collisions is an open question in high-energy physics.

- The ALICE upgrade preparations are well on-track for new high-precision studies after 2020.

Thank you!

The ALICE detector



ALICE is optimized for Heavy-Ion Physics:

- dn/dy in Pb-Pb: up to 2000
- PID: $p_T > 0.2$ GeV/c

Inner Tracking System (ITS) $|\eta|<0.9$
Time Projection Chamber (TPC) $|\eta|<0.8$
TOF-- $|\eta|<0.9$, $\Delta\varphi$: 45°-135°
HMPID -- $|\eta|<0.6$, $\Delta\varphi=100°$,
TRD -- $|\eta|<0.84$; **MUON --** $2.5<\eta<4$
V0 detector -- $2.8<\eta<5.1$, $-3.7<\eta<-1.7$

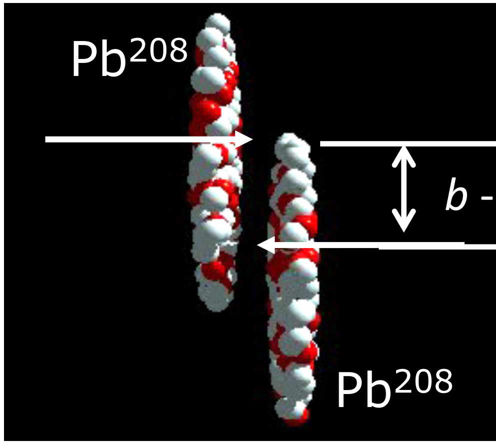
Calorimeters:
PHOS – ($|\eta|<0.12$, $\Delta\varphi=100°$): γ (0.5-10 GeV/c), π^0(1-10 GeV/c) , η(2-10 GeV/c)
EMCAL – $|\eta|<0.7$, $\Delta\varphi=107°$: jets, γ, π^0 (<30 GeV/c)
ZDC – the event selection

Determination of event collision centrality and the initial conditions

N_{part} – nucleons- participants
N_{part} – nucleons- participants
N_{coll} -- # of nn collisions

The Glauber Monte Carlo independent emitters:

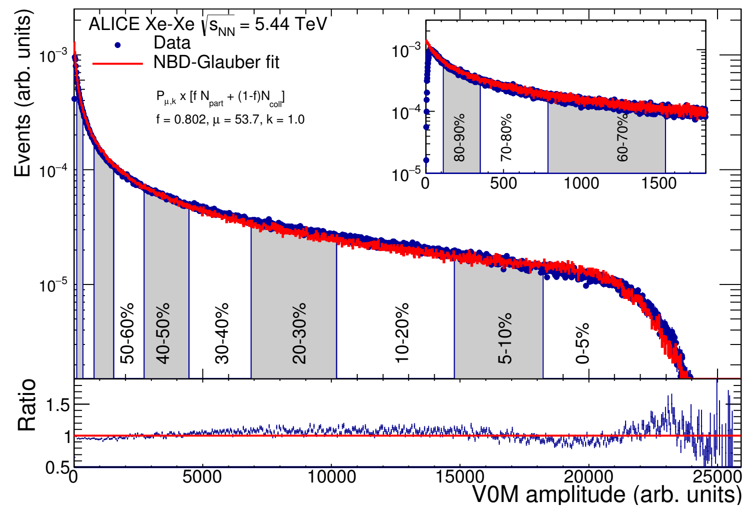
$$N_{ancestors} = f \cdot N_{part} + (1-f) \cdot N_{coll}$$



b - Impact parameter

Centrality

$$c = \frac{\int_0^b d\sigma/db'\,db'}{\int_0^\infty d\sigma/db'\,db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'}\,db'$$



ALICE-PUBLIC-2018-003

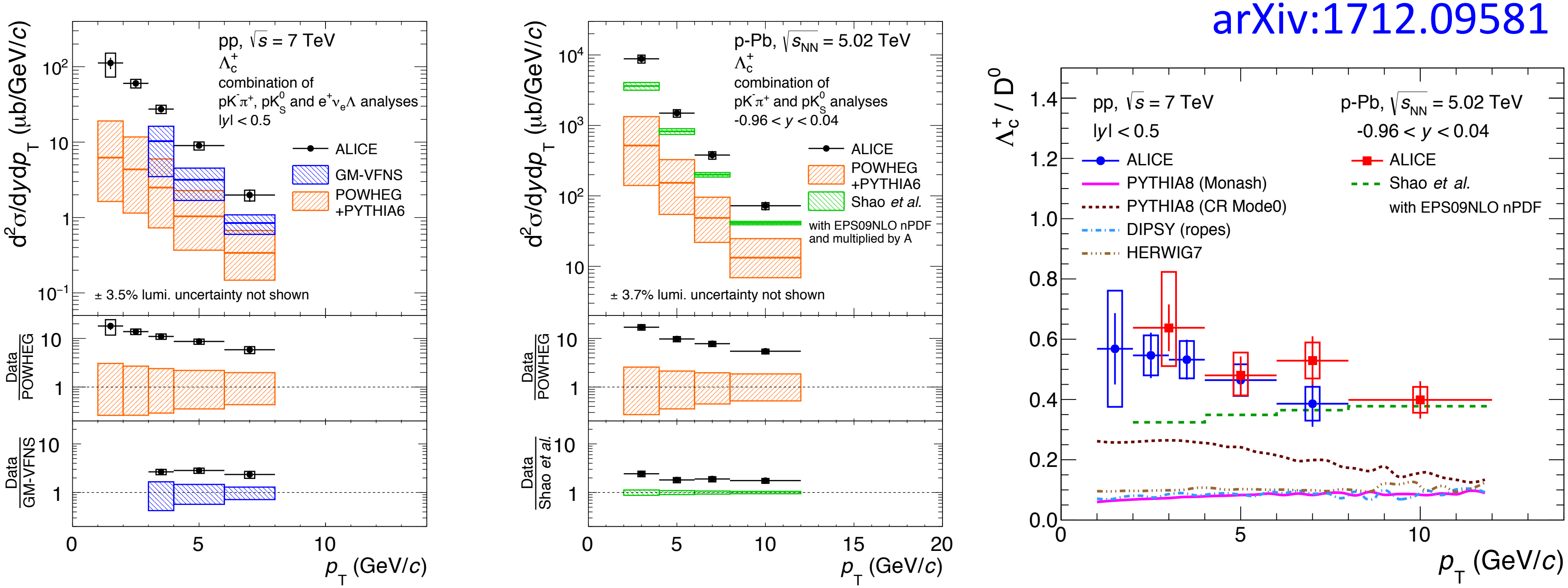
N_{part}, N_{coll}

ALICE Centrality Estimators:

- **Multiplicity**—in VO
- Energy of **Spectators** -- in ZDC

Λ_c in pp collisions at 7 TeV and p-Pb, collisions at 5.02 TeV

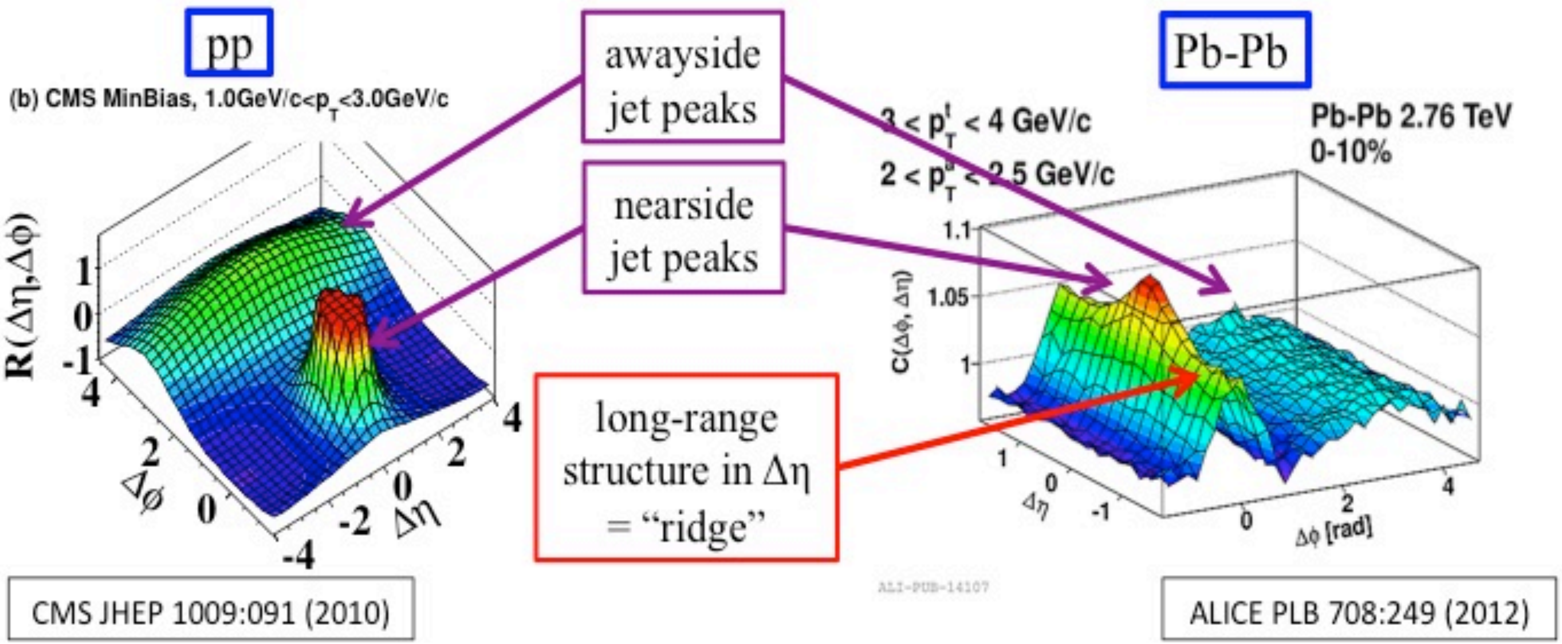
arXiv:1712.09581



- Λ^+_c/D^0 ratio is sensitive to the c-quark hadronisation mechanism
- GM-VFNS perturbative QCD calculations underpredict the measured values by a factor of 2.5.
- PYTHIA with CR – in a better agreement to the data
- DIPSY and HERWIG -- significantly lower values

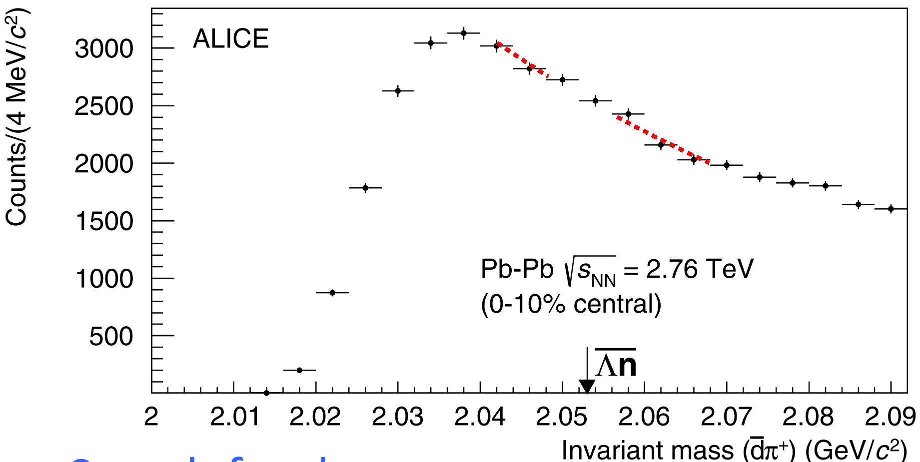
Topology of two-particle correlations in pp, p-Pb and Pb-Pb collisions

$$C(\Delta\phi,\Delta\eta) \equiv \frac{N_{\text{mixed}}}{N_{\text{same}}} \times \frac{N_{\text{same}}(\Delta\phi,\Delta\eta)}{N_{\text{mixed}}(\Delta\phi,\Delta\eta)}$$



- Particle momentum anisotropy in directions transverse to the beam
- Fourier components $Vn \equiv \langle\cos(n\phi)\rangle$ are extracted from the long-range azimuthal correlation functions
- Δη gap may be introduced between the correlated particles to eliminate the role of short-range contribution (e.g. in studies of flow of particles)

Search for weakly decaying $\overline{\Lambda}$n and ΛΛ exotic bound states in central Pb–Pb collisions at √sNN = 2.76 TeV



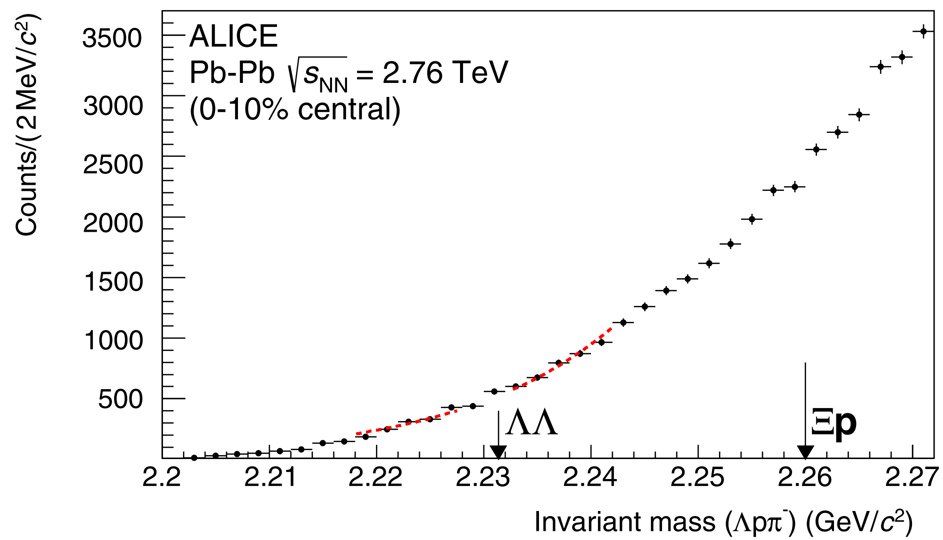
Phys.Lett. B 752 (2016) 267-277

Invariant mass distributions for $\bar{d}\pi^+$ and for $\Lambda p \pi^-$

Search for decays:

$\overline{\Lambda}$n → $\bar{d}\pi^+$

H-dibaryon → $\Lambda p \pi$–

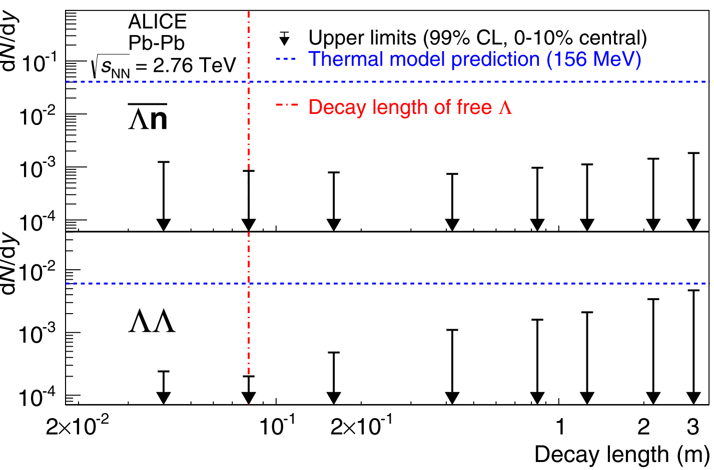


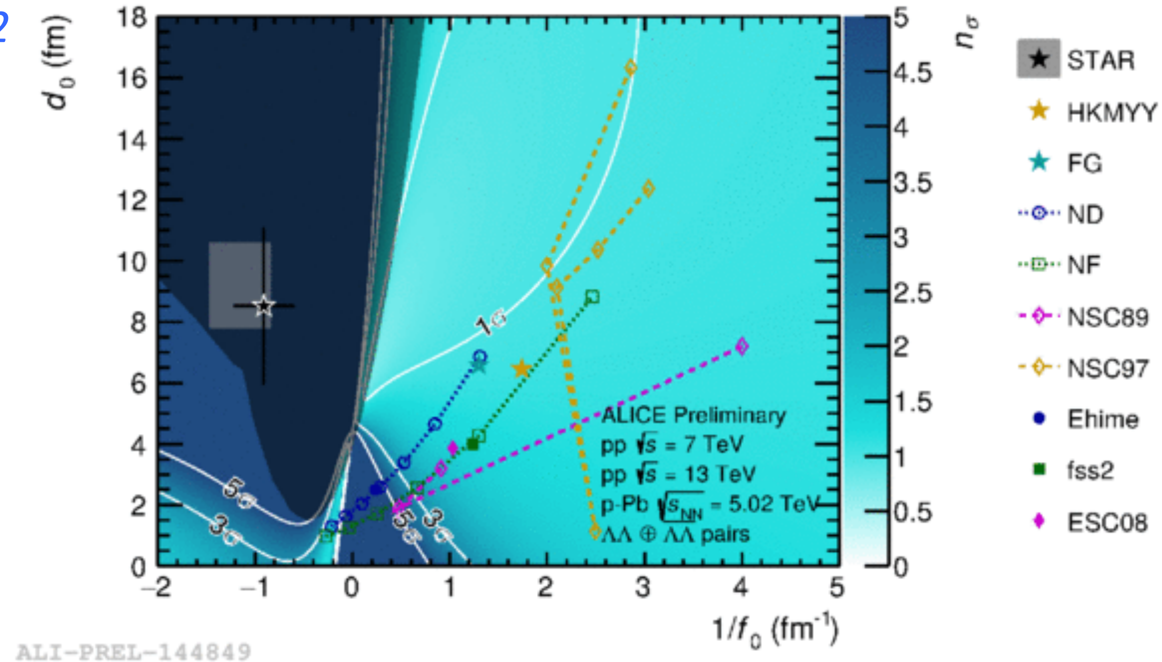
H-dibaryon (ΛΛ is a hypothetical bound state of uuddss

R.L. Jaffe, "Perhaps a stable dihyperon", Phys. Rev. Lett. 38 (1977) 195, Erratum, Phys. Rev. Lett. 38 (1977) 617.

Upper limits of dN/dy *for* $\overline{\Lambda}$n and H-dibaryon

Physics Letters B 752 (2016) 267–2





- The upper limits are obtained for different lifetimes.
- The values are well below the model predictions with realistic assumed branching ratios and Reasonable lifetimes
- Thus, ALICE results do not support the existence of the H-dibaryon and the Λn bound state.

- Measurements of the baryon-baryon correlations that are also sensitive to the binding potential disfavor the ΛΛ-baryon

Talk layout

- Introduction
- Multi-particle production in pp, p-Pb and A-A collisions
  - Indications on collectivity in small systems
  - Strangeness yields in pp, p-Pb and Pb-Pb collisions
  - Flow of different particles
- Production of light nuclei and exotic states of some hypernuclei
- Future studies of rare processes of heavy flavour formation