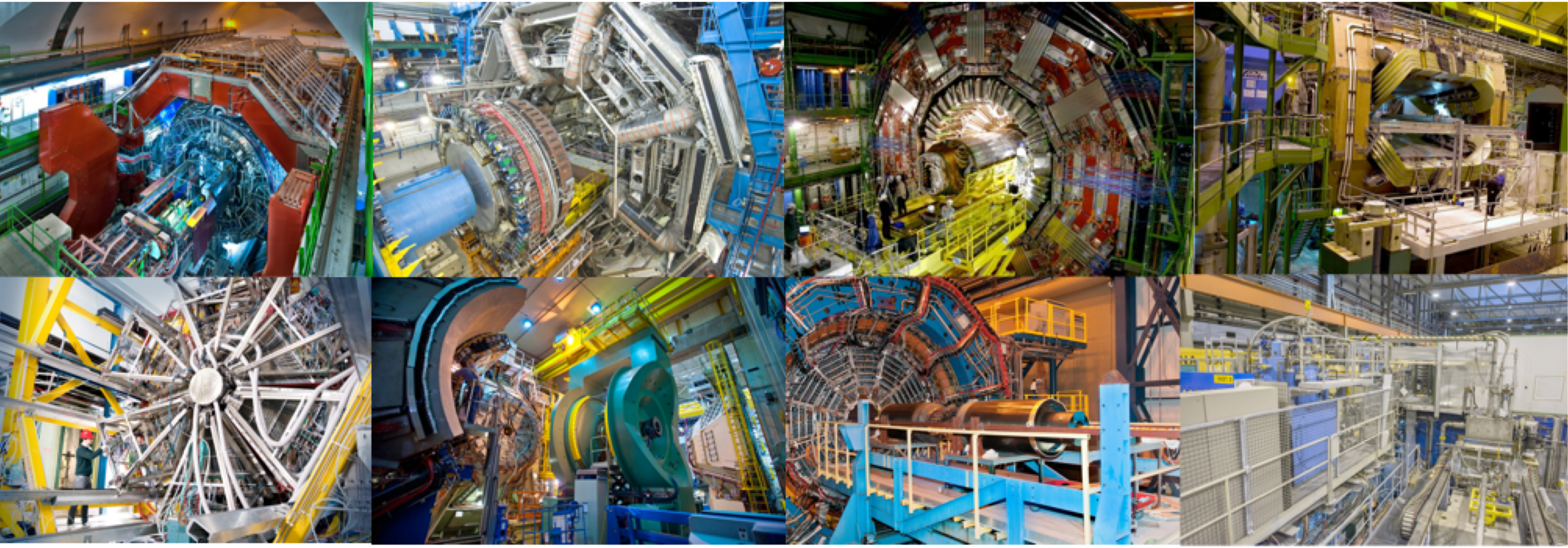
Particle production and its connection to the QCD phase diagram

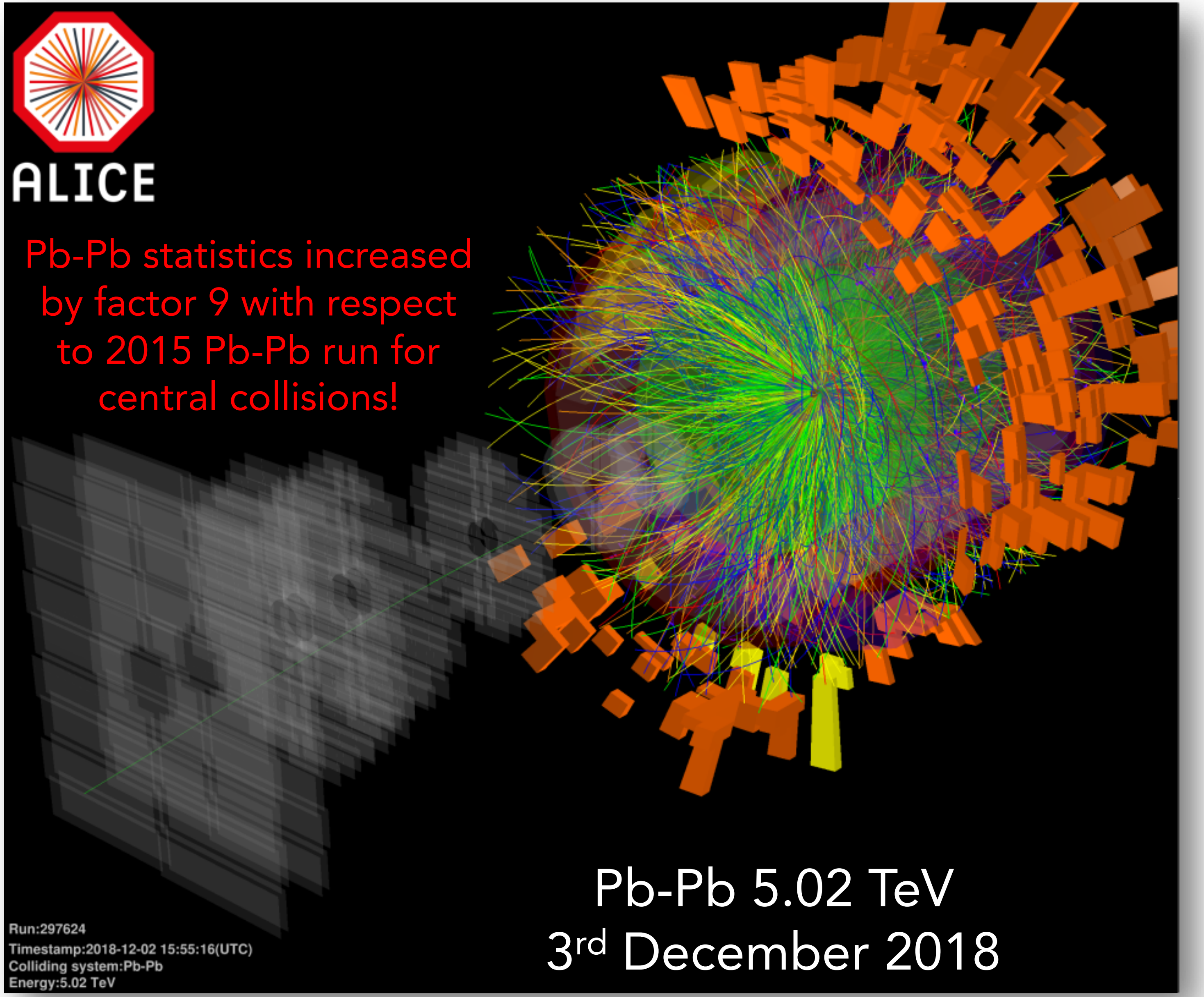


Alexander Kalweit, *CERN*

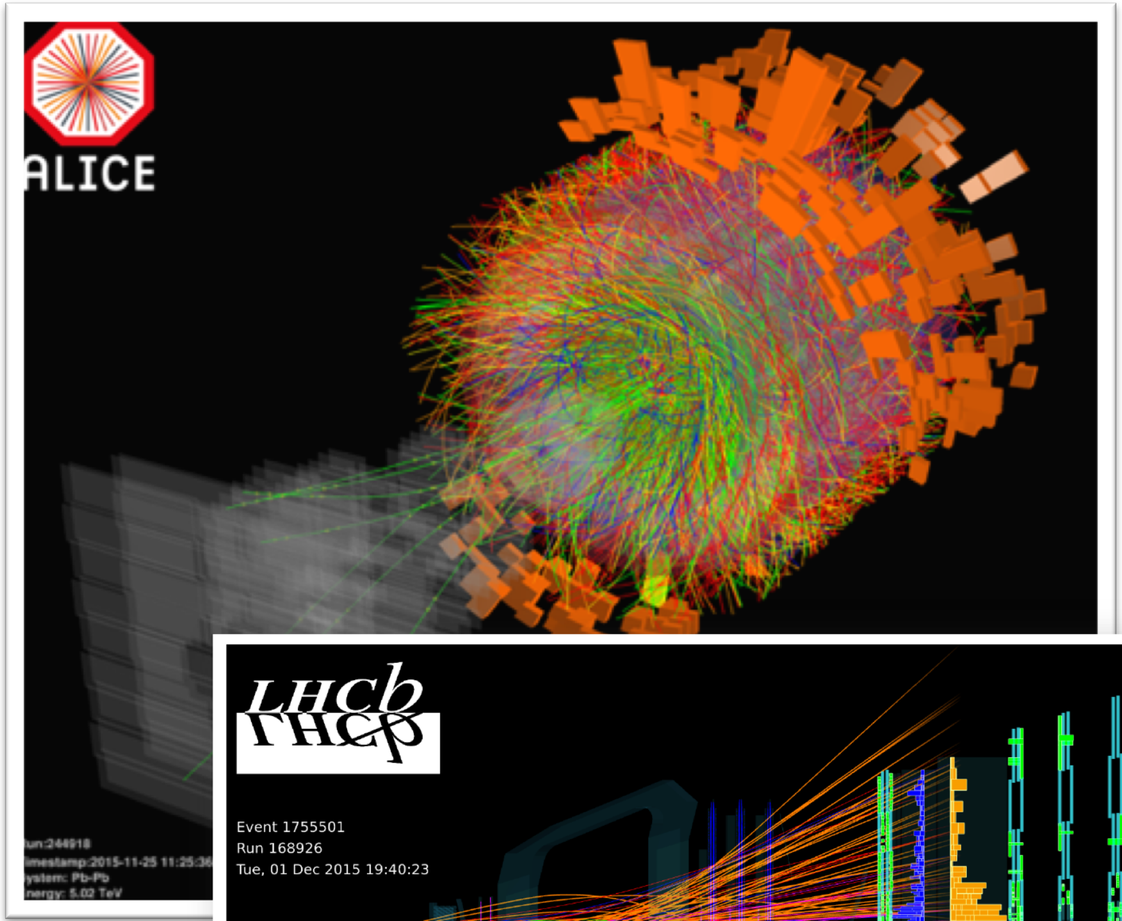
Hirschegg, 14th January 2019

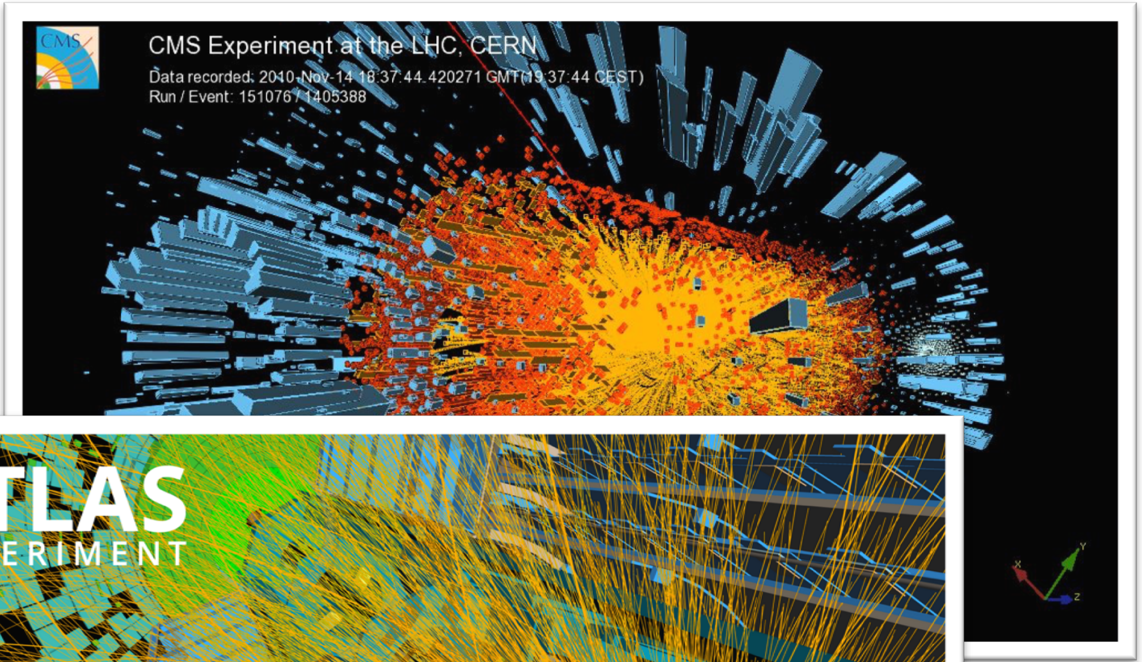
Overview

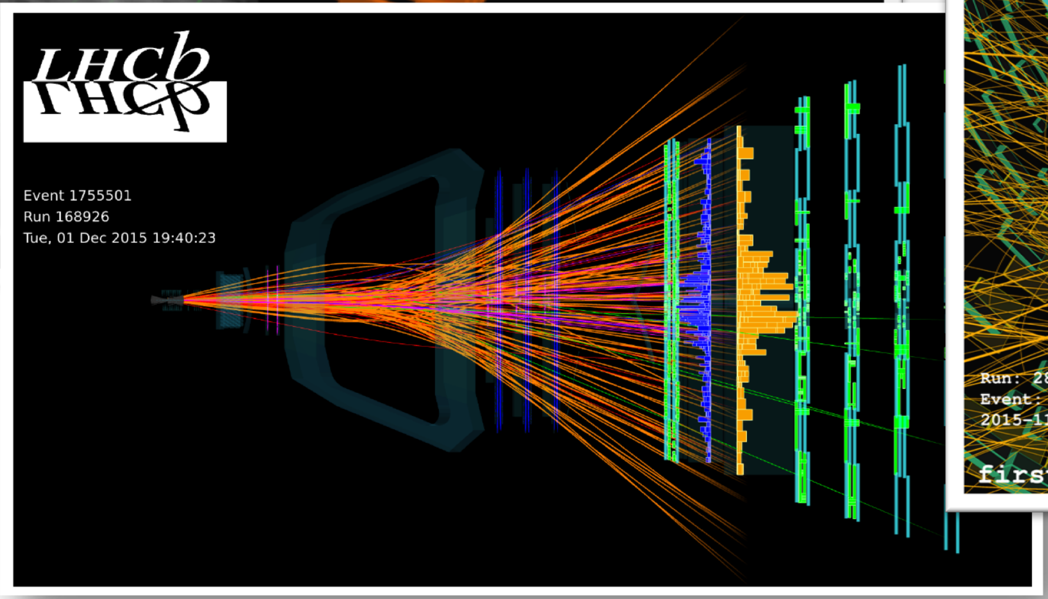
- Introduction to thermal hadron production
- Experimental challenges and basic results
- Measurements of (anti-) proton production at RHIC and LHC
- New horizons: small systems, anti-nuclei and exotica.

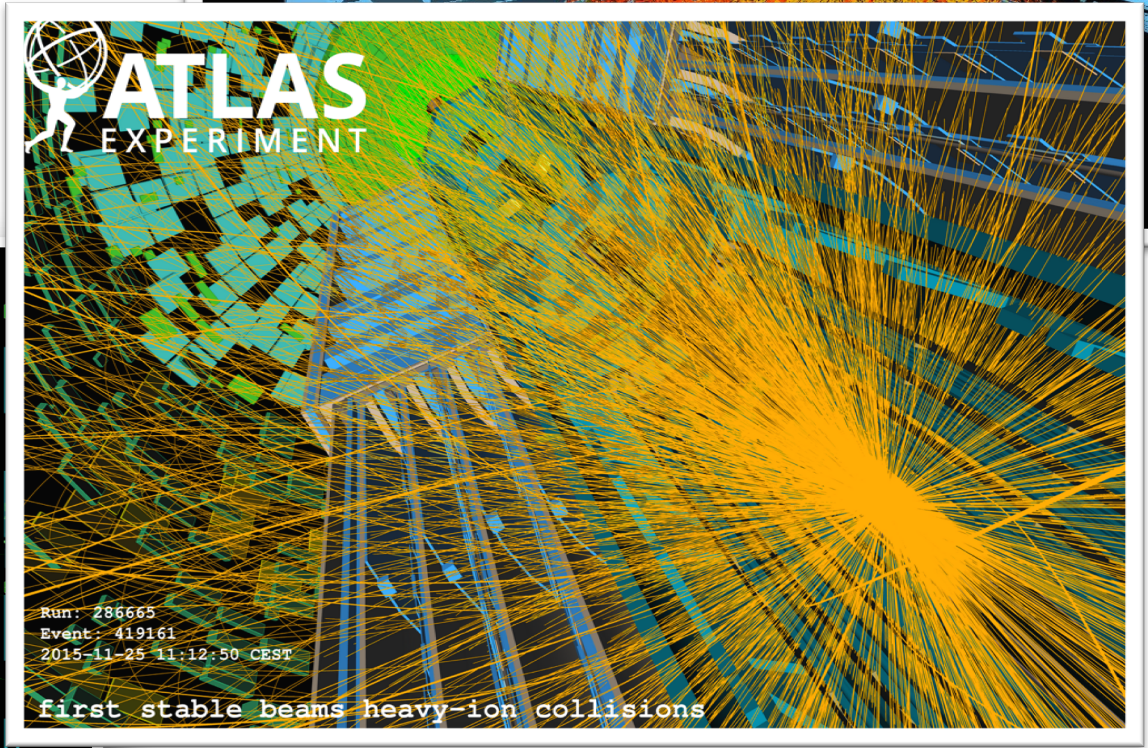


How many particles are created in such a collision?

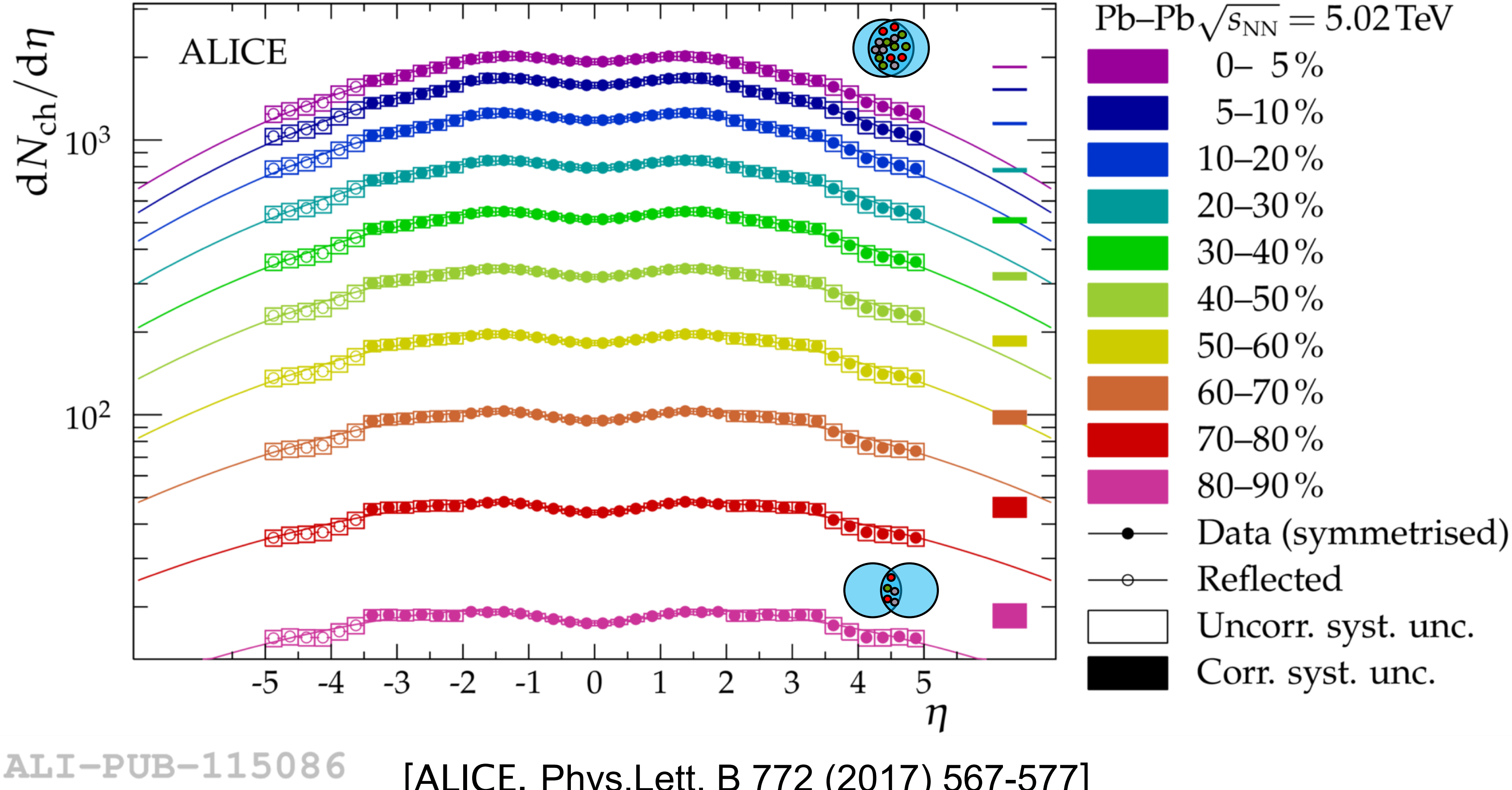








dN_{ch}/dη in 5.02 TeV Pb-Pb collisions at the LHC



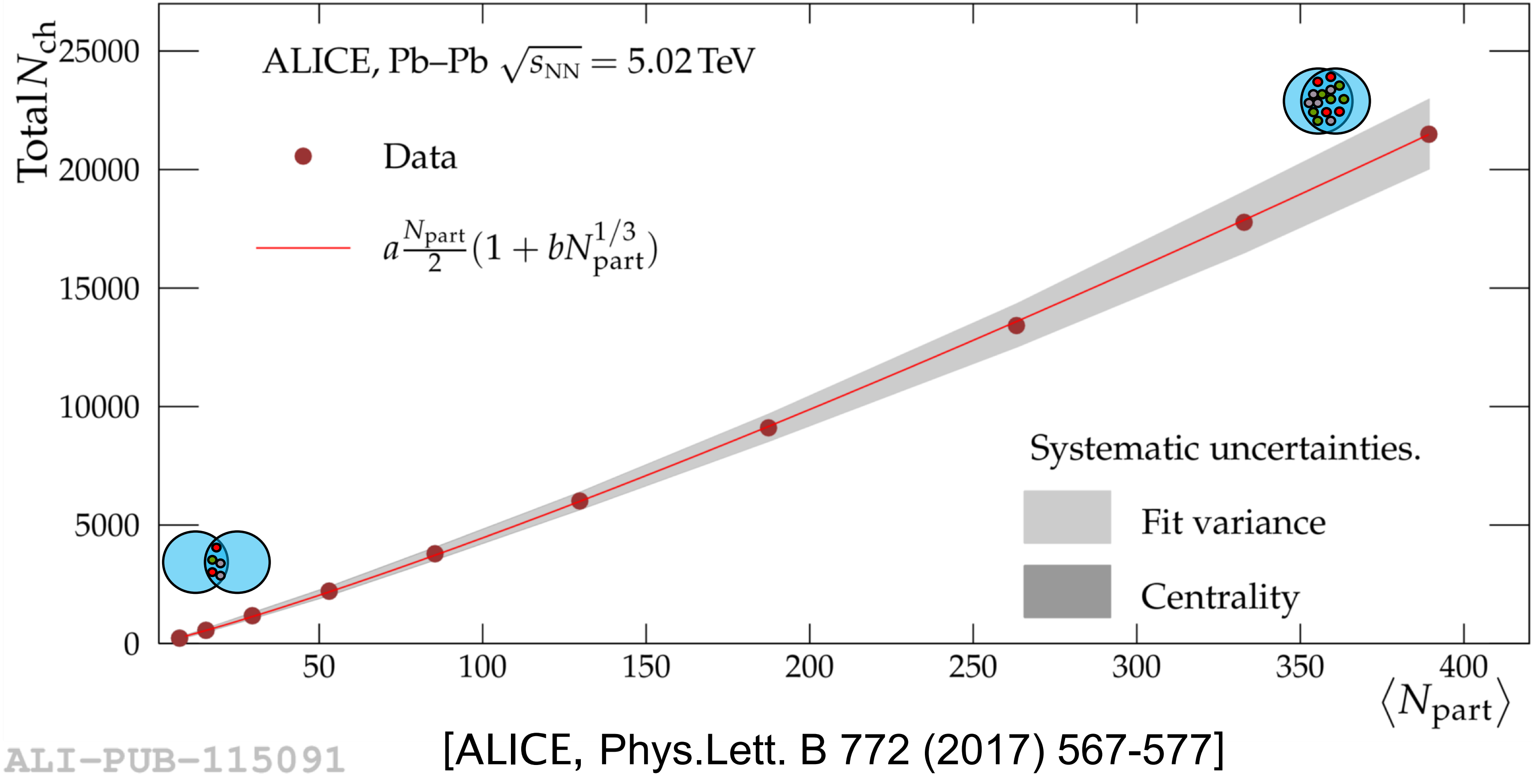
[ALICE, Phys.Lett. B 772 (2017) 567-577]

→ Bulk particle production and the study of collective phenomena are associated with ***"soft" physics*** in the non-perturbative regime of QCD.

dN_{ch}/d**η** ≈ 1943 ± 54 at midrapidity at LHC energies.

Total number of charged hadrons in Pb-Pb collisions

→ Collisions of heavy-ions at high energy accelerators allow the creation of several tens of thousands of hadrons (1 << *N* << 1mol) **in local thermodynamic equilibrium** in the laboratory.



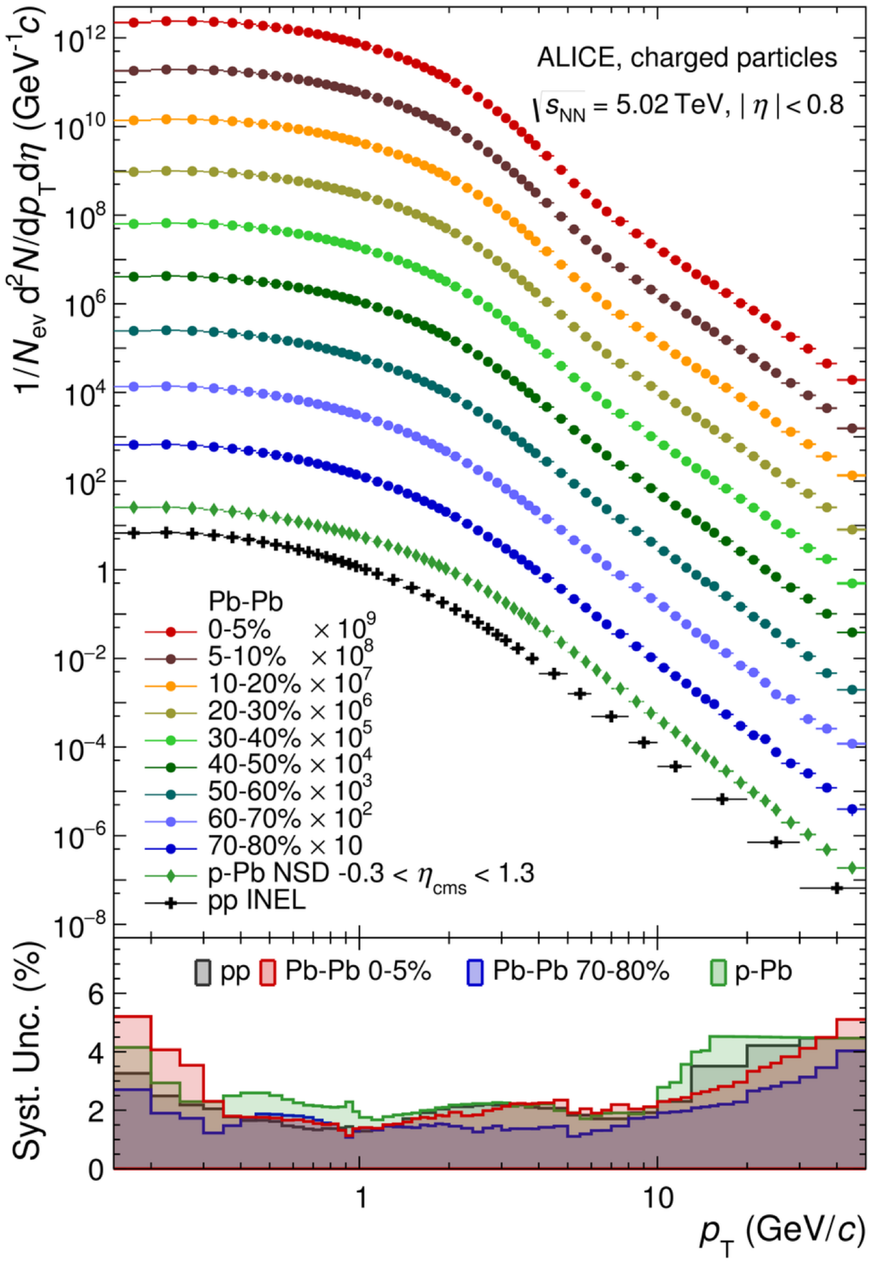
[ALICE, Phys.Lett. B 772 (2017) 567-577]

Success of **hydro models** describing **spectral shapes and azimuthal anisotropies** supports idea of matter in local thermal equilibrium (*kinetic*).

Success of **thermal models** describing **yields of hadrons composed of up, down, and strange quarks** supports idea of matter in local thermal equilibrium (*chemical*).

Equilibrium models such as hydro typically need 5-6 interactions to work. Where does this picture break down? Does it work in pp and pPb? → **What is the smallest possible QGP droplet?**

Particle production at LHC energies

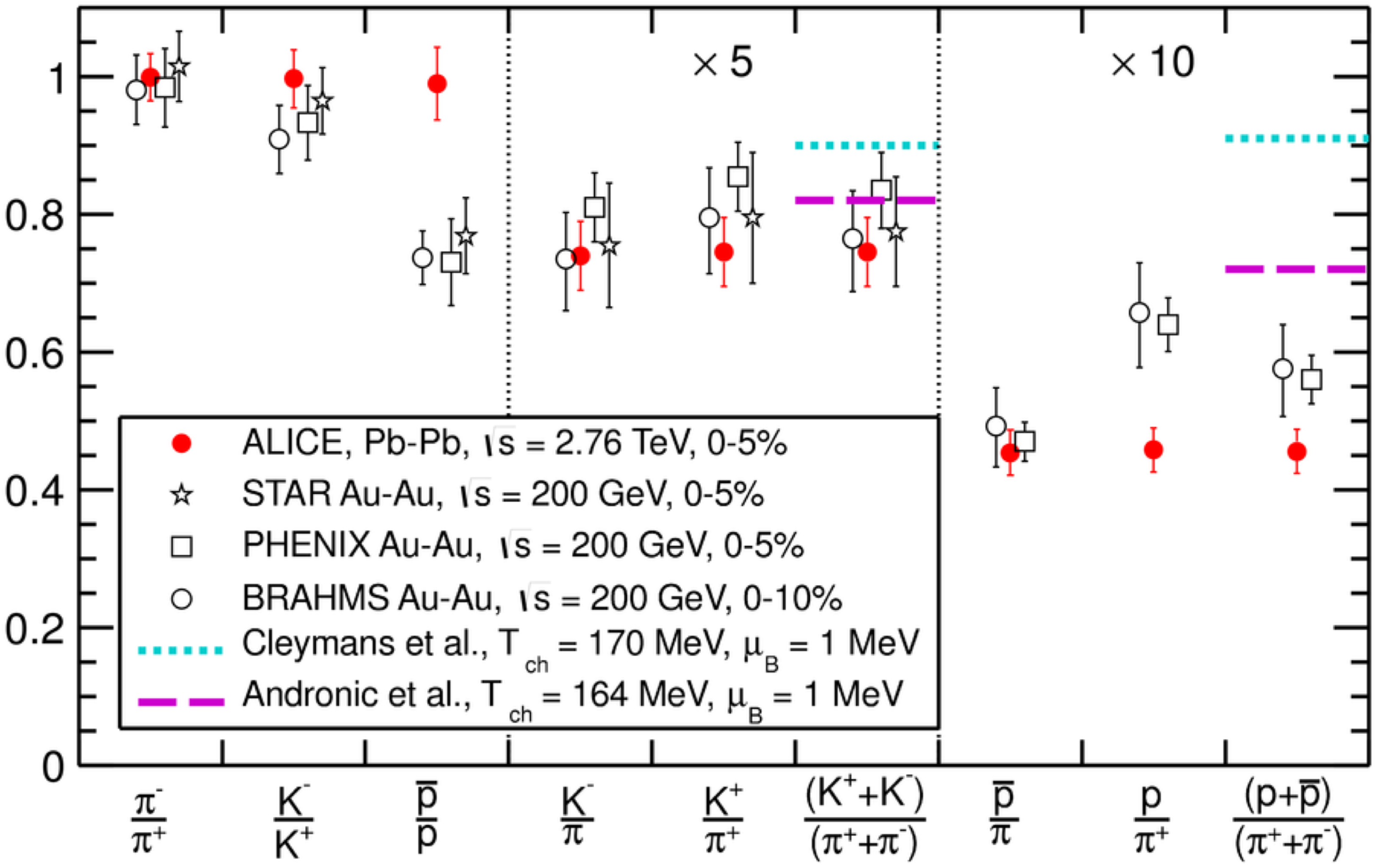


→ Even at LHC energies, 95% of all particles are produced with p_T < 2 GeV/c in pp and Pb-Pb collisions.

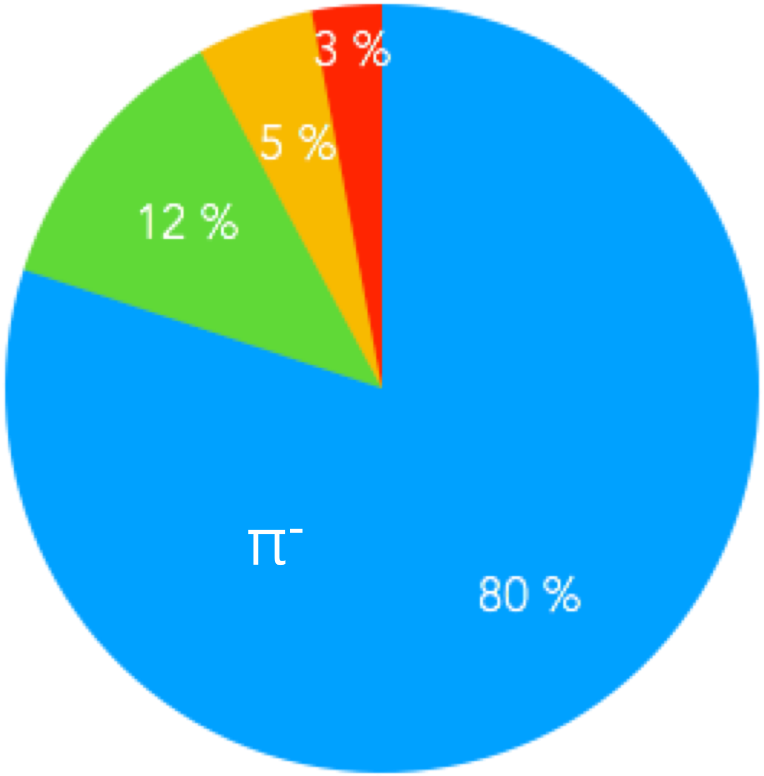
→ Bulk particle production and the study of collective phenomena are associated with ***"soft" physics*** in the non-perturbative regime of QCD.

[ALICE, arXiv:1802.09145]

Particle production at LHC energies

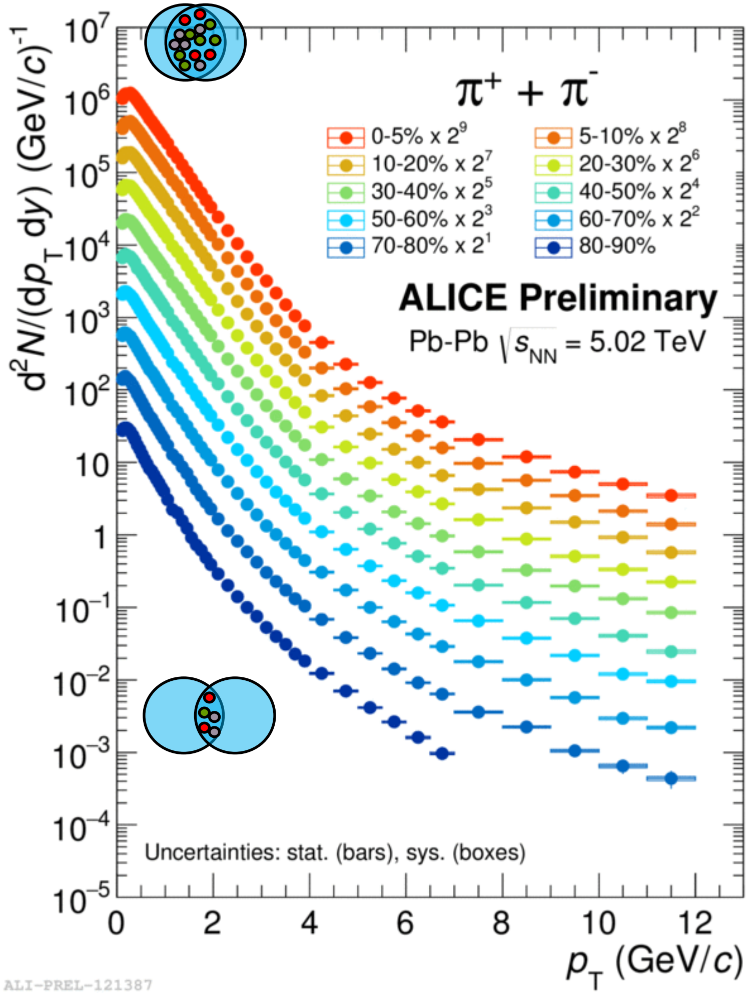


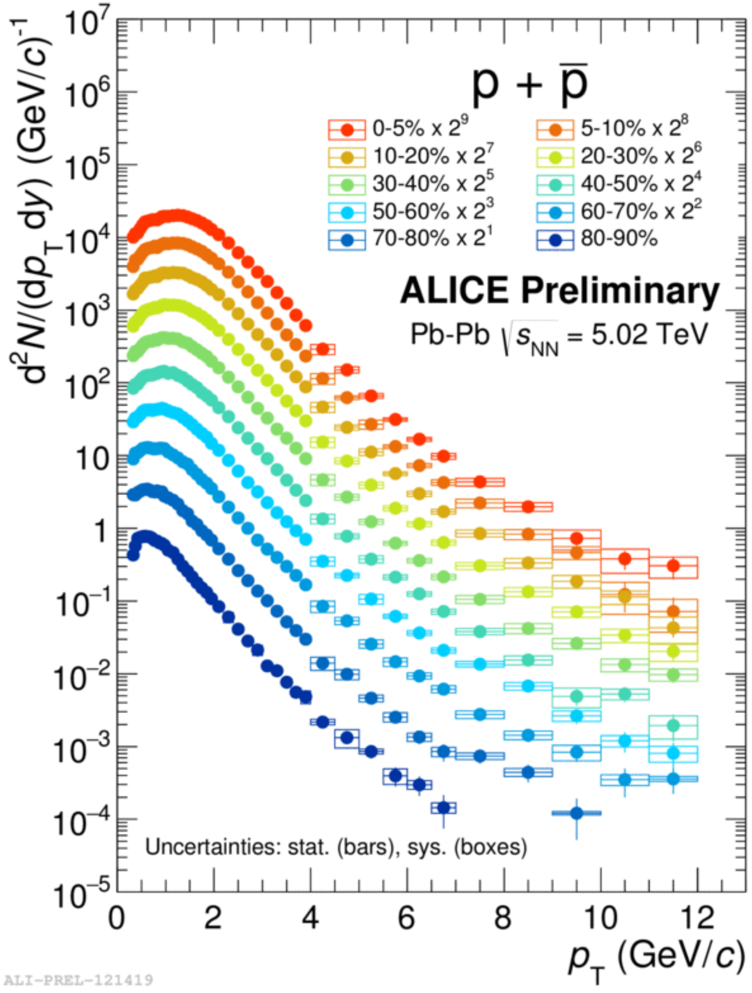
(negative particles)



[ALICE, Phys. Rev. Lett. 109 (2012) 252301]

p_T-spectra of identified particles





1. Identify particle in the detector (pion, kaon, proton, Lambda, Xi, Omega, anti-deuteron…)
2. Fill p_T-spectrum
3. Interpolate unmeasured region at low p_T (at high p_T negligible)
4. Integrate:

$$\frac{dN}{dy} = \int \frac{d^3N}{dp_T dy d\varphi} \, d\varphi dp_T$$

→ Even at LHC energies, 95% of all particles are produced with $p_T < 2$ GeV/c in pp and Pb-Pb collisions.

$$\frac{dN}{dy} = \int \frac{d^3N}{dp_T dy d\varphi} d\varphi dp_T$$

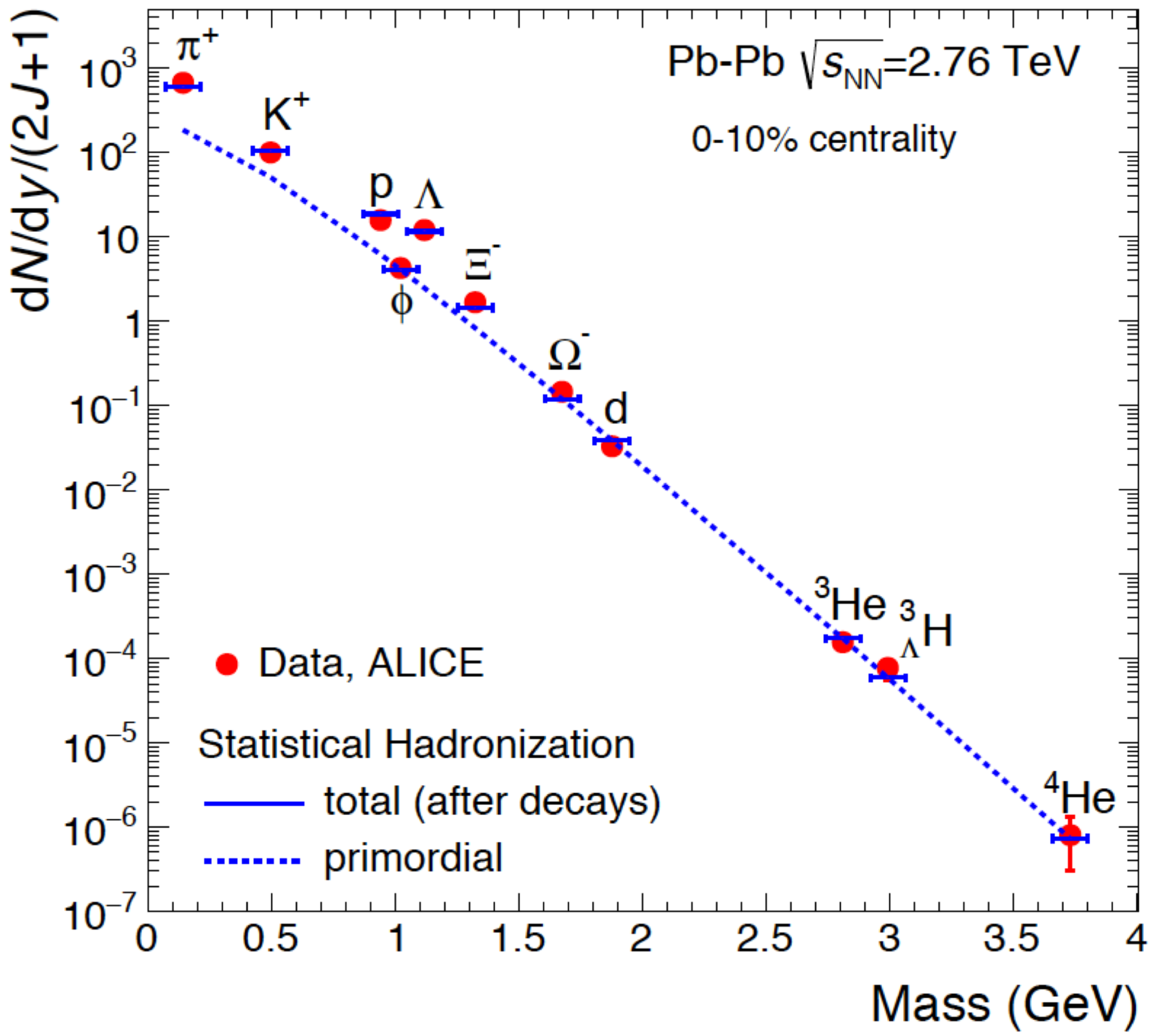
Is it really correct to compare with the thermal model just the integrated yield dN/dy as they are or should one make an effort to separate *hard* and *soft* contributions to the p_T spectrum?!!

Chemical equilibrium at the LHC

Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by statistical-thermal models (roughly $dN/dy \sim \exp\{-m/T_{ch}\}$, in detail derived from partition function)

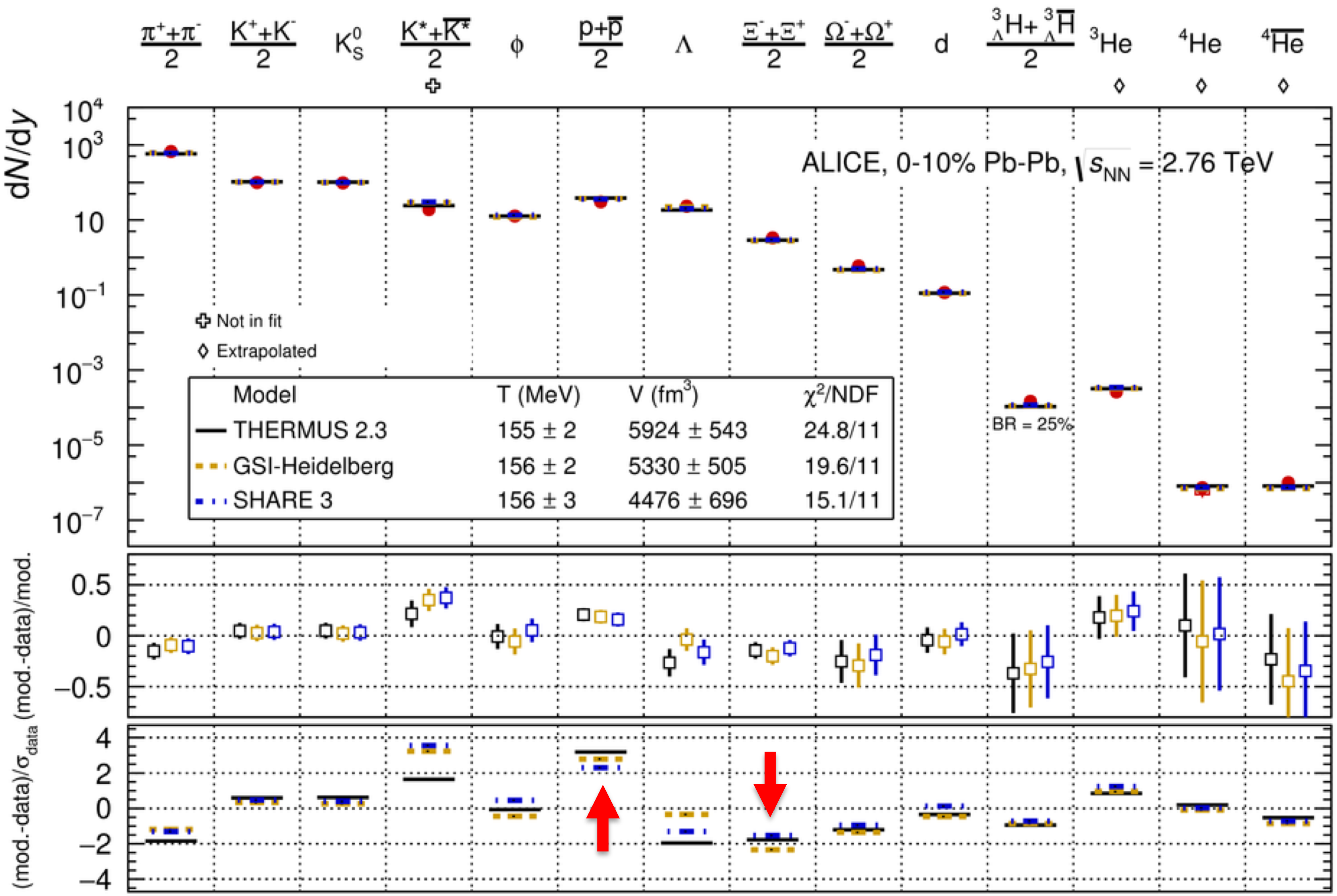
→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 7 orders of magnitude with a **common** chemical freeze-out temperature of $T_{ch} \approx 156$ **MeV**.

→ Light (anti-)nuclei are also well described despite their low binding energy ($E_{b,d}$ = 2.2 MeV << T_{ch}).
→ so called "anti-nuclei puzzle".



[A. Andronic *et al.*, Nature 561 (2018) no.7723, 321-330]

Thermal statistical model fits Pb-Pb 2.76 TeV (final)



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11

[ALICE, Nucl. Phys. A 971 (2018) 1-20]

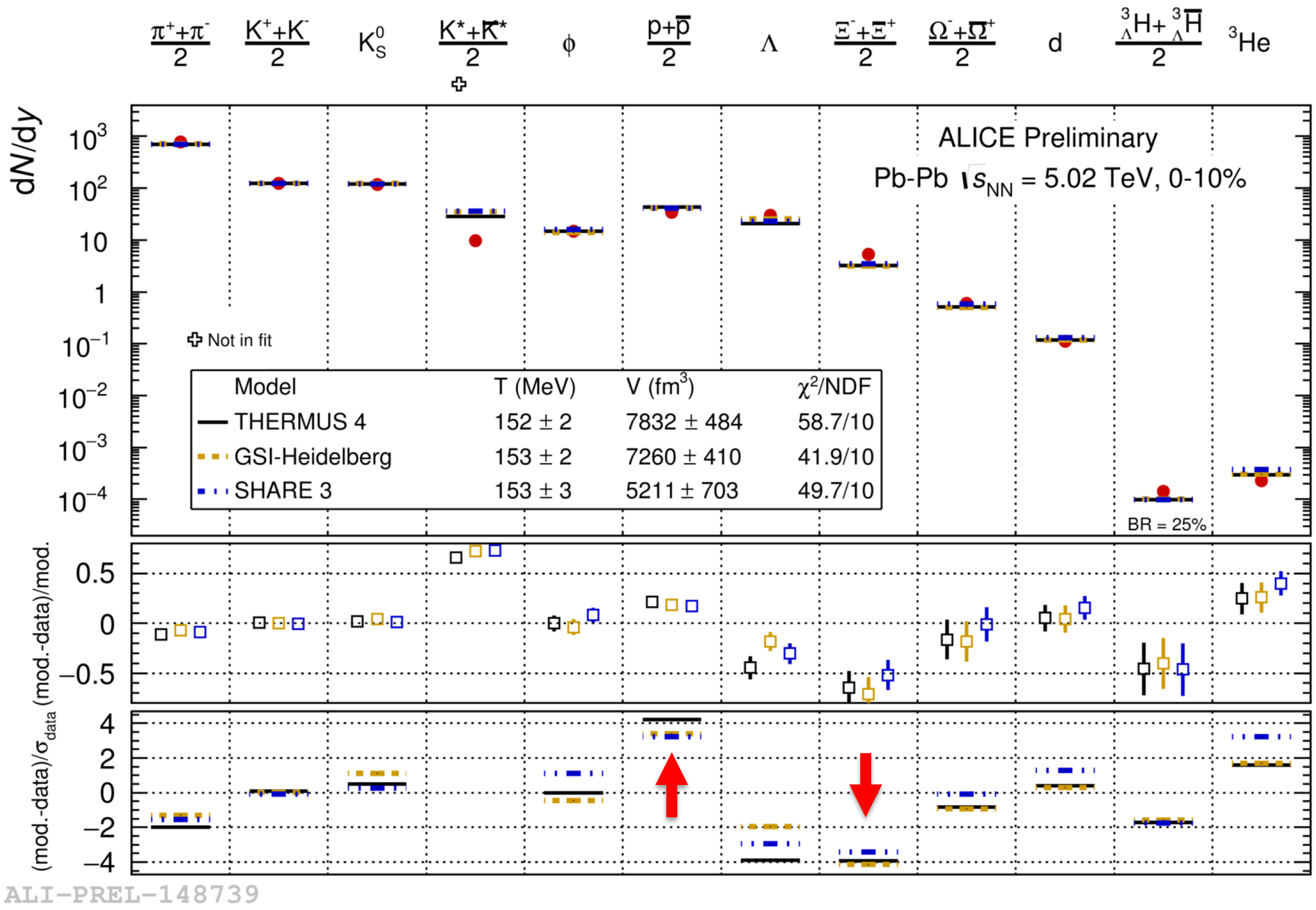
Particle yields of light flavor hadrons are described over 7 orders of magnitude within 20% with a common chemical freeze-out temperature of $T_{ch} \approx 156$ MeV **(prediction from RHIC extrapolation was ≈ 164 MeV).**

Hadrons are produced in apparent chemical equilibrium in Pb-Pb collisions at LHC energies.

Largest deviations observed for protons (2.8σ) and for K^{*0} (re-scattering in hadronic phase).
→ so called “proton anomaly”.

Three different versions of thermal model implementations give similar results.
[Wheaton et al, Comput.Phys.Commun, 18084]
[Petran et al, arXiv:1310.5108]
[Andronic et al, PLB 673 142]

Thermal statistical model fits Pb-Pb 5.02 TeV (prel.)

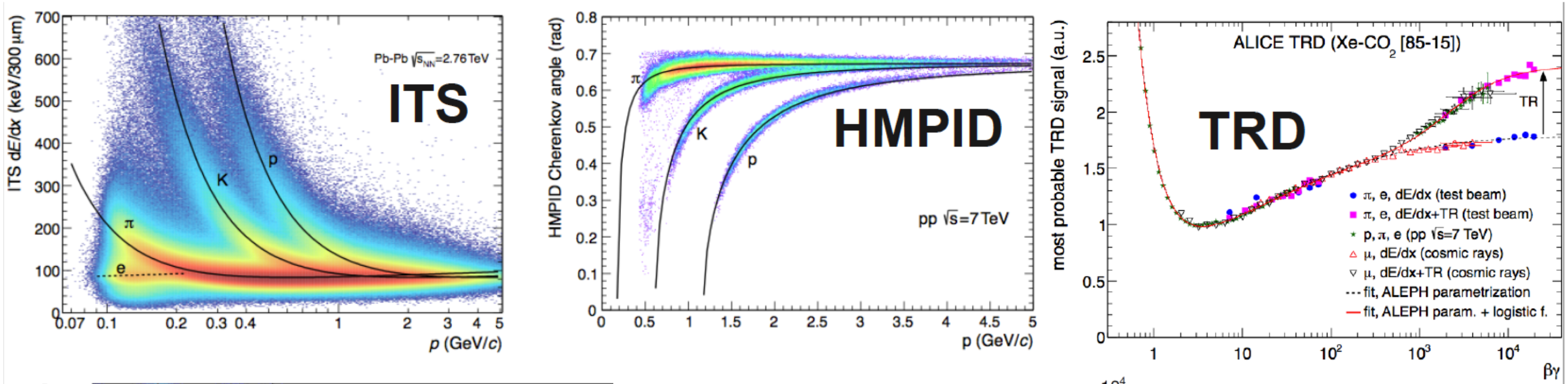


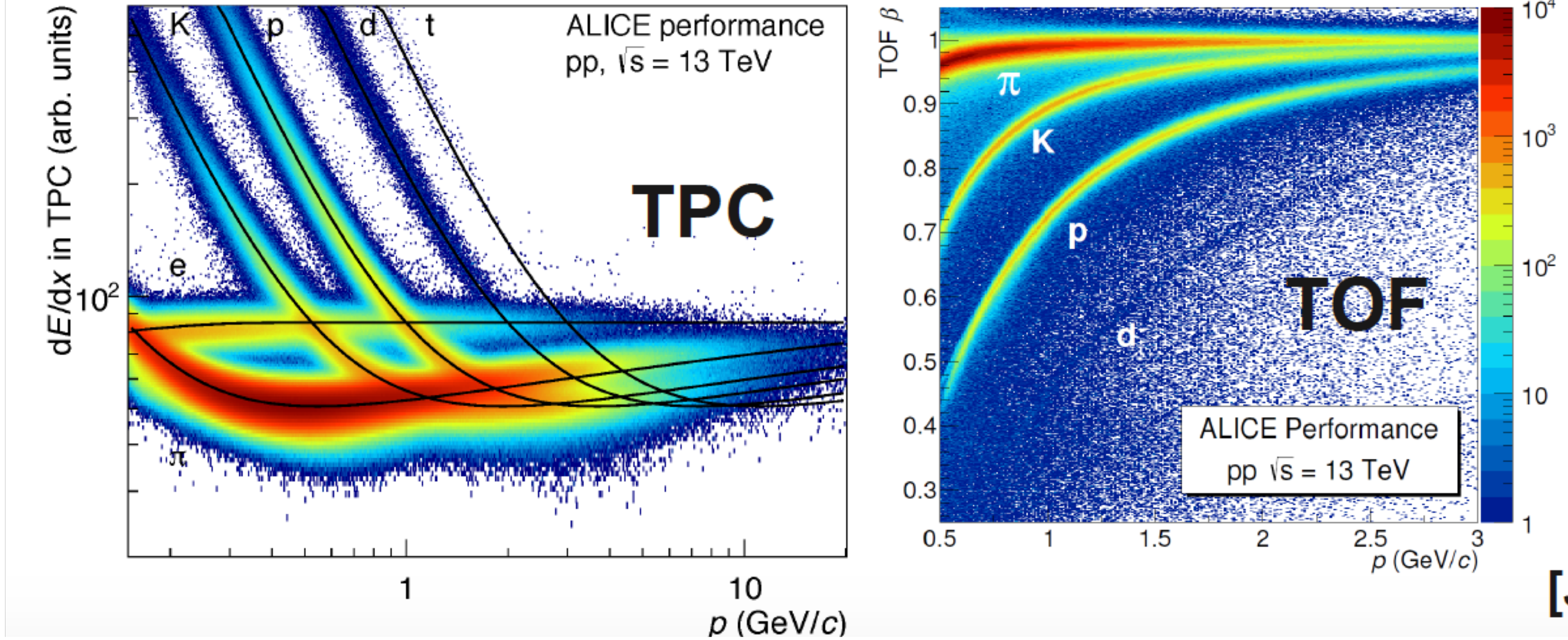
→ Also at 5.02 TeV, yields of light flavor hadrons are qualitatively well described by equilibrium thermal models over 7 orders of magnitude.

→ Fit at 5.02 TeV converges to slightly lower T_{ch} than at 2.76 TeV (153 w.r.t to 156 MeV).

→ Deviations remain the same at the two energies.

Particle identification





→ Protons are cleanly identified in ITS, TPC, TOF, HMPID.

[JMP A29 (2014) 1430044]

What is a primary particle?

Many particles (~50%) are of secondary origin (decays, knock-out, conversions…).
→ Precise data to model comparisons need to take care of that.

A primary charged particle is defined to be a charged particle with a mean proper lifetime τ larger than 1 cm/c which is either produced directly in the interaction, or from decays of particles with τ smaller than 1 cm/c, excluding particles produced in interactions with the detector material.

Out of the hundreds of known particles, these are the only hadrons that have a lifetime long enough to produce a track of >1um before they decay (at GeV Level).

Some of them decay after flying only a few hundred um.

Others traverse the entire detector.

All Particles with $c\tau$ > 1µm @ GeV Level   19

Particle	Mass (MeV)	Lifetime τ (s)	$c\tau$
$\pi^{\pm}(u\bar{d}, d\bar{u})$	140	$2.6 \cdot 10^{-8}$	7.8 m
$K^{\pm}(u\bar{s}, \bar{u}s)$	494	$1.2 \cdot 10^{-8}$	3.7 m
$K^{0}(d\bar{s}, \bar{d}s)$	497	$5.1 \cdot 10^{-8}$ $8.9 \cdot 10^{-11}$	15.5 m 2.7 cm
$D^{\pm}(c\bar{d}, \bar{c}d)$	1869	$1.0 \cdot 10^{-12}$	315 µm
$D^{0}(c\bar{u}, u\bar{c})$	1864	$4.1 \cdot 10^{-13}$	123 µm
$D_s^{\pm}(c\bar{s}, \bar{c}s)$	1969	$4.9 \cdot 10^{-13}$	147 µm
$B^{\pm}(u\bar{b}, \bar{b}u)$	5279	$1.7 \cdot 10^{-12}$	502 µm
$B^{0}(b\bar{d}, d\bar{b})$	5279	$1.5 \cdot 10^{-12}$	462 µm
$B_s^{0}(s\bar{b}, \bar{s}b)$	5370	$1.5 \cdot 10^{-12}$	438 µm
$B_c^{\pm}(c\bar{b}, \bar{c}b)$	~6400	$\sim 5 \cdot 10^{-13}$	150 µm
$p\,(uud)$	938.3	$> 10^{33}$ y	∞
$n\,(udd)$	939.6	885.7 s	$2.655 \cdot 10^{8}$ km
$\Lambda^{0}(uds)$	1115.7	$2.6 \cdot 10^{-10}$	7.89 cm
$\Sigma^{+}(uus)$	1189.4	$8.0 \cdot 10^{-11}$	2.404 cm
$\Sigma^{-}(dds)$	1197.4	$1.5 \cdot 10^{-10}$	4.434 cm
$\Xi^{0}(uss)$	1315	$2.9 \cdot 10^{-10}$	8.71 cm
$\Xi^{-}(dss)$	1321	$1.6 \cdot 10^{-10}$	4.91 cm
$\Omega^{-}(sss)$	1672	$8.2 \cdot 10^{-11}$	2.461 cm
$\Lambda_c^{+}(udc)$	2285	$\sim 2 \cdot 10^{-13}$	60 µm
$\Xi_c^{+}(usc)$	2466	$4.4 \cdot 10^{-13}$	132 µm
$\Xi_c^{0}(dcs)$	2472	$\sim 1 \cdot 10^{-13}$	29 µm
$\Omega_c^{0}(ssc)$	2698	$6.0 \cdot 10^{-14}$	19 µm
$\Lambda_b(udb)$	5620	$1.2 \cdot 10^{-12}$	368 µm

"Secondary Vertices"

[W. Riegler, CERN-Fermilab school 2016]

→ 1cm/c is chosen as it is between the longest lived weak decays of heavy quark hadrons (only small contribution to the yield of LF hadrons) and the shortest lived weak decay of light flavor hadrons.

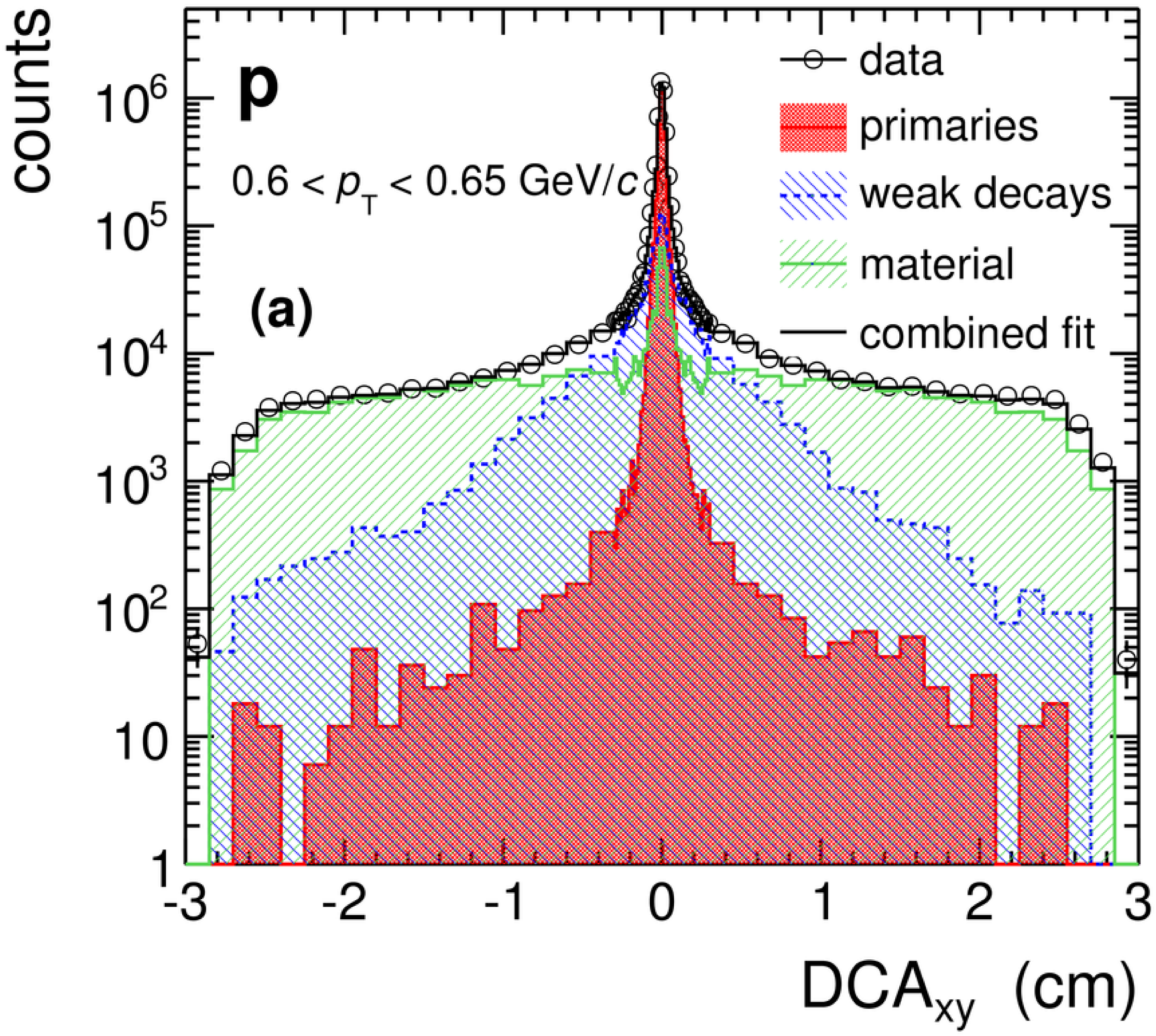
=> Products of weak decays of light flavor hadrons are subtracted from the primary particle sample.

Feed-down subtraction

- Main contaminators to the sample of primary protons:

$\Sigma^+ \rightarrow p\,\pi^0$ (51.6%)
$\Lambda \rightarrow p\,\pi^-$ (63.9 %)
$\Xi^- \rightarrow \Lambda\,\pi^-$ (99.87 %)

- Careful subtraction based on the different distance of closest approach to the primary vertex (dca).

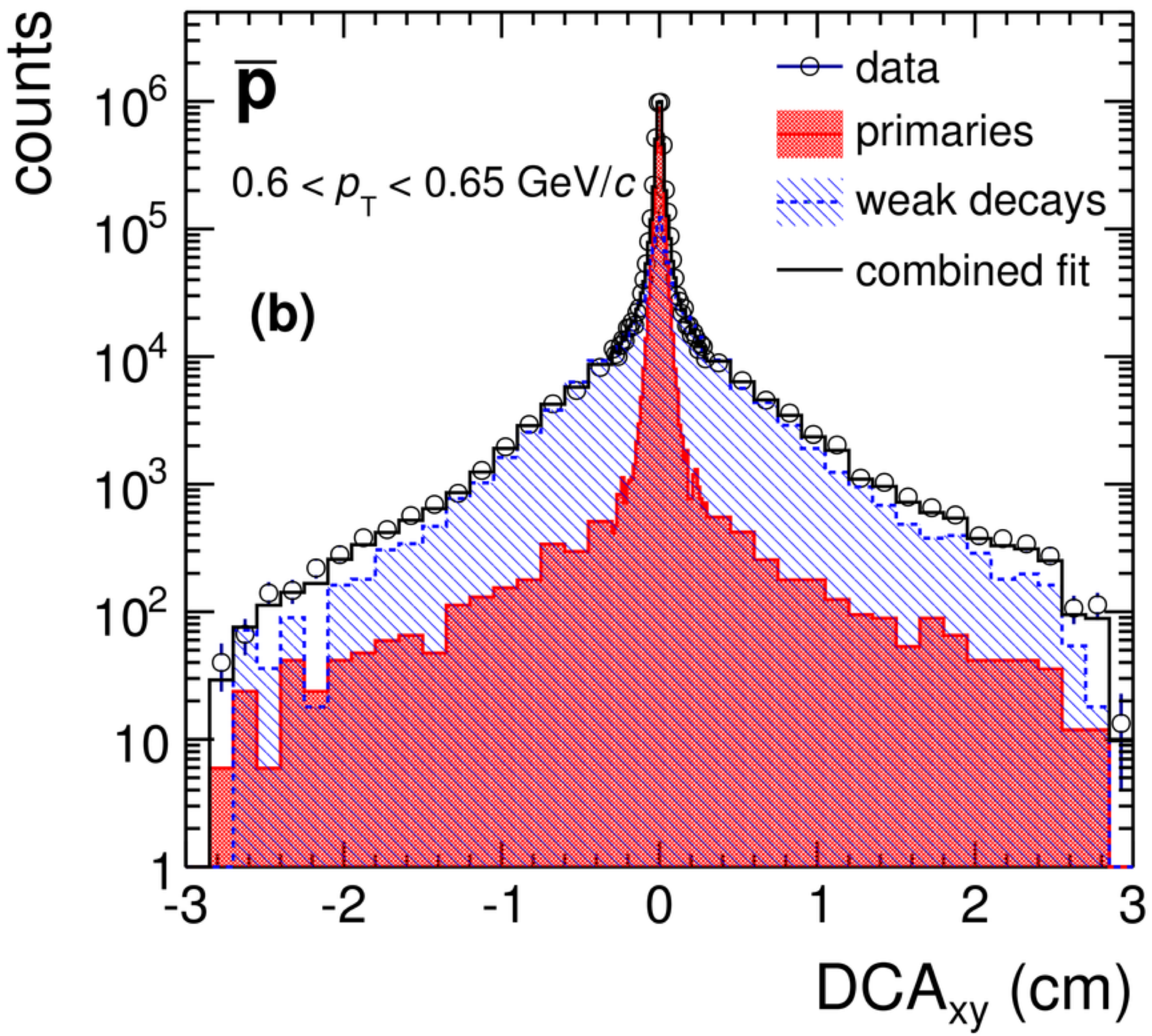


Feed-down subtraction

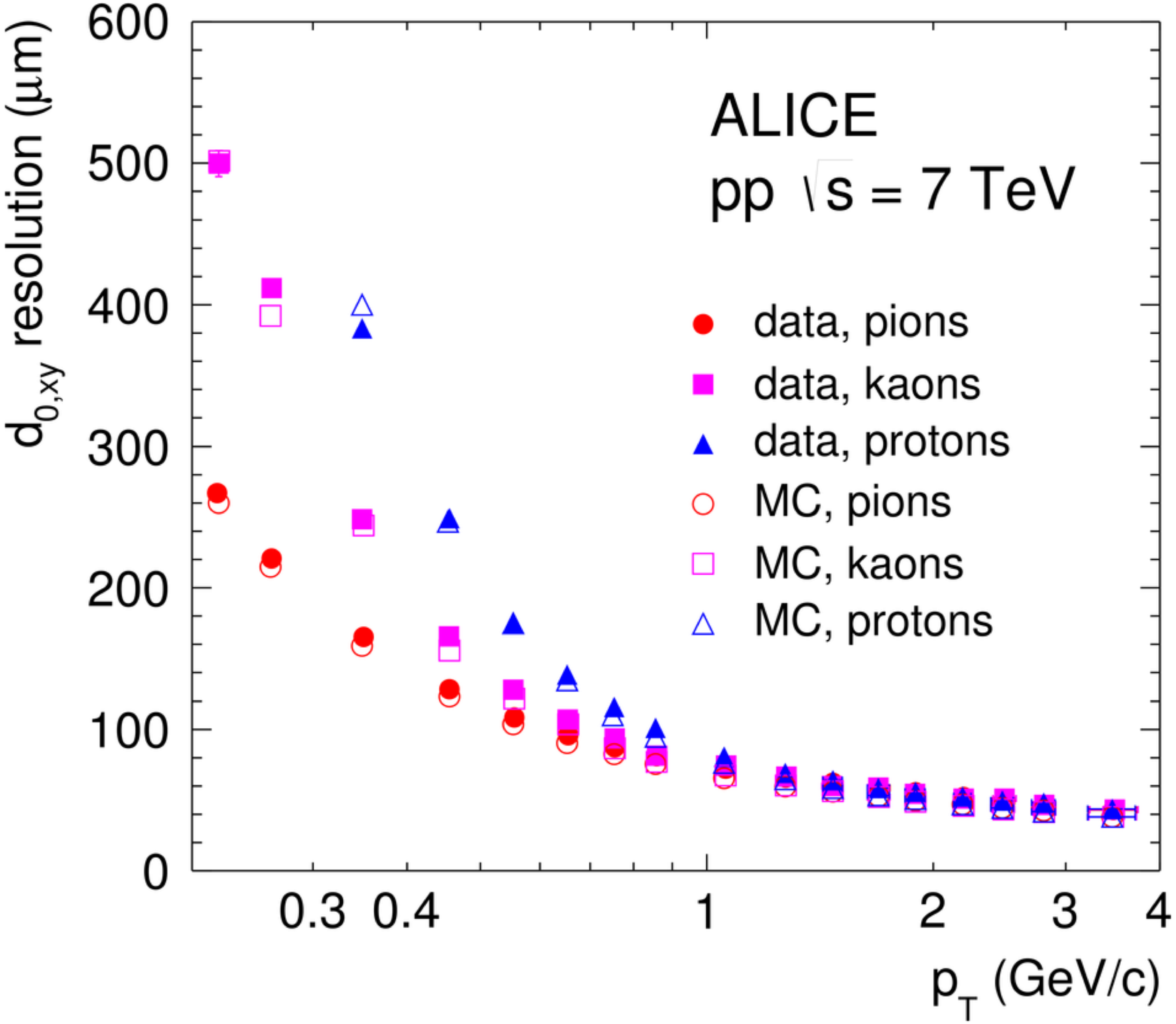
- Main contaminators to the sample of primary protons:

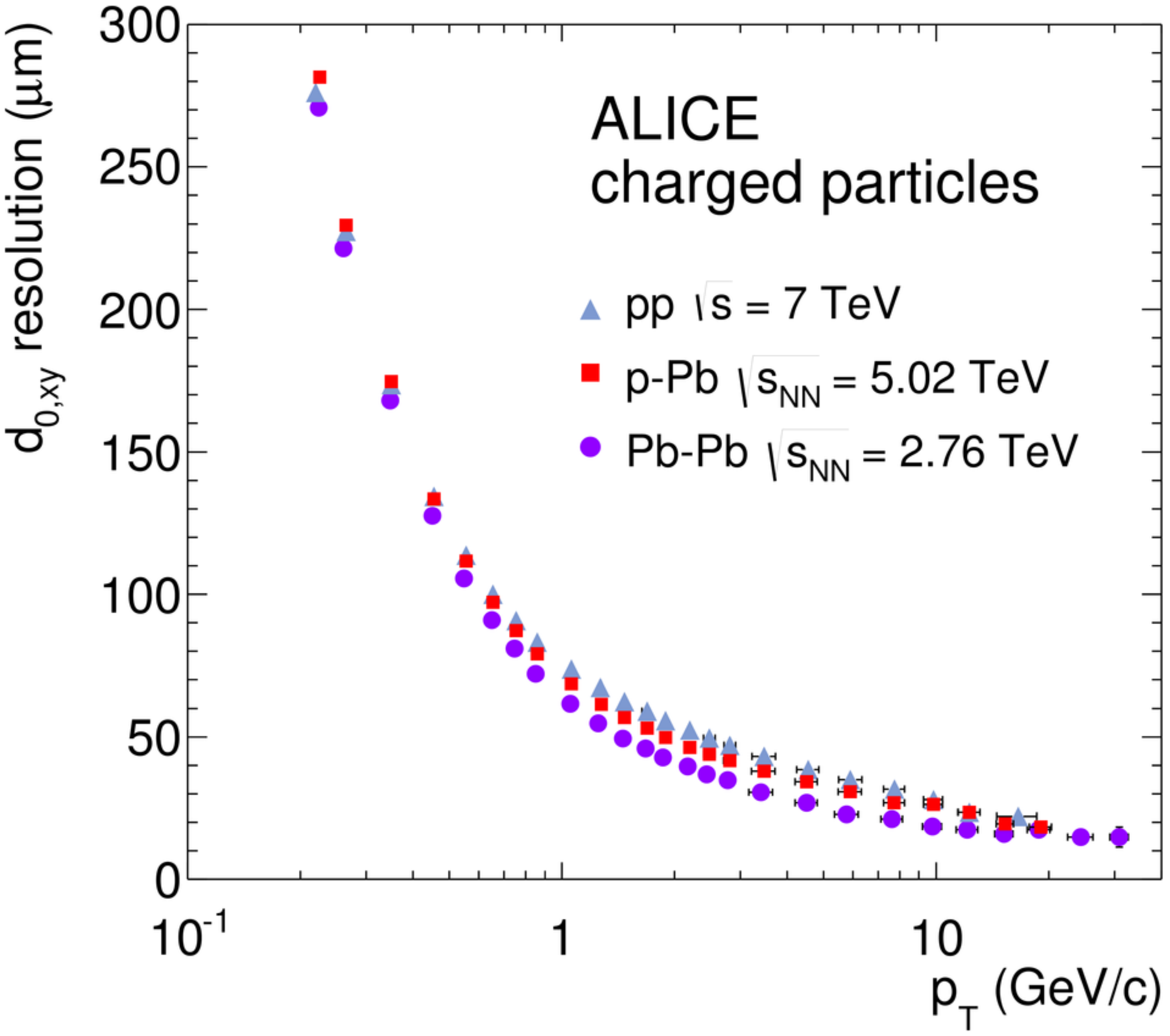
$\Sigma^+ \rightarrow p\,\pi^0$ (51.6%)
$\Lambda \rightarrow p\,\pi^-$ (63.9 %)
$\Xi^- \rightarrow \Lambda\,\pi^-$ (99.87 %)

- Careful subtraction based on the different distance of closest approach to the primary vertex (dca).



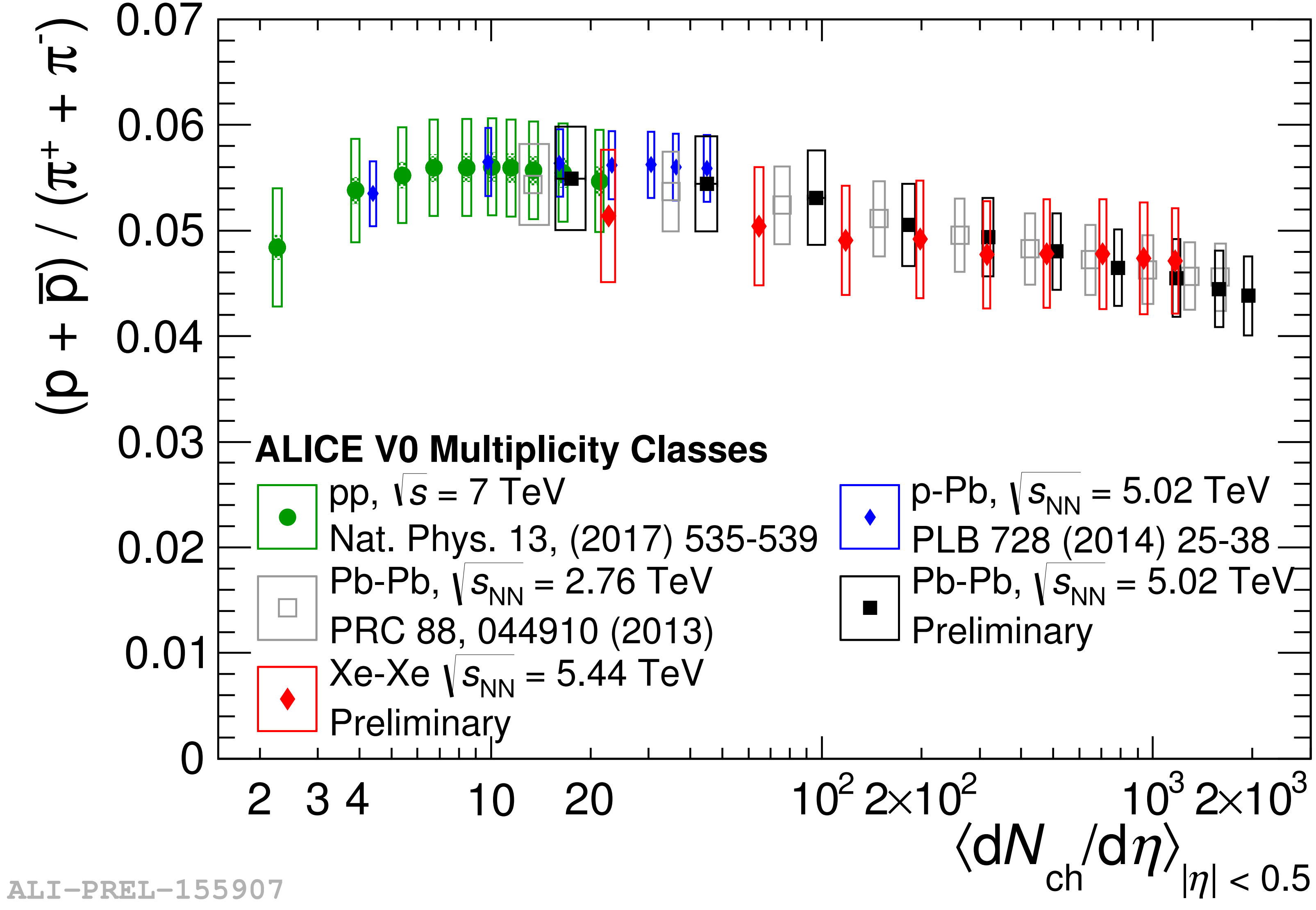
DCA resolution in ALICE





[Int. J. Mod. Phys. A 29 (2014) 1430044]

(anti-)proton-to-pion ratio vs system size

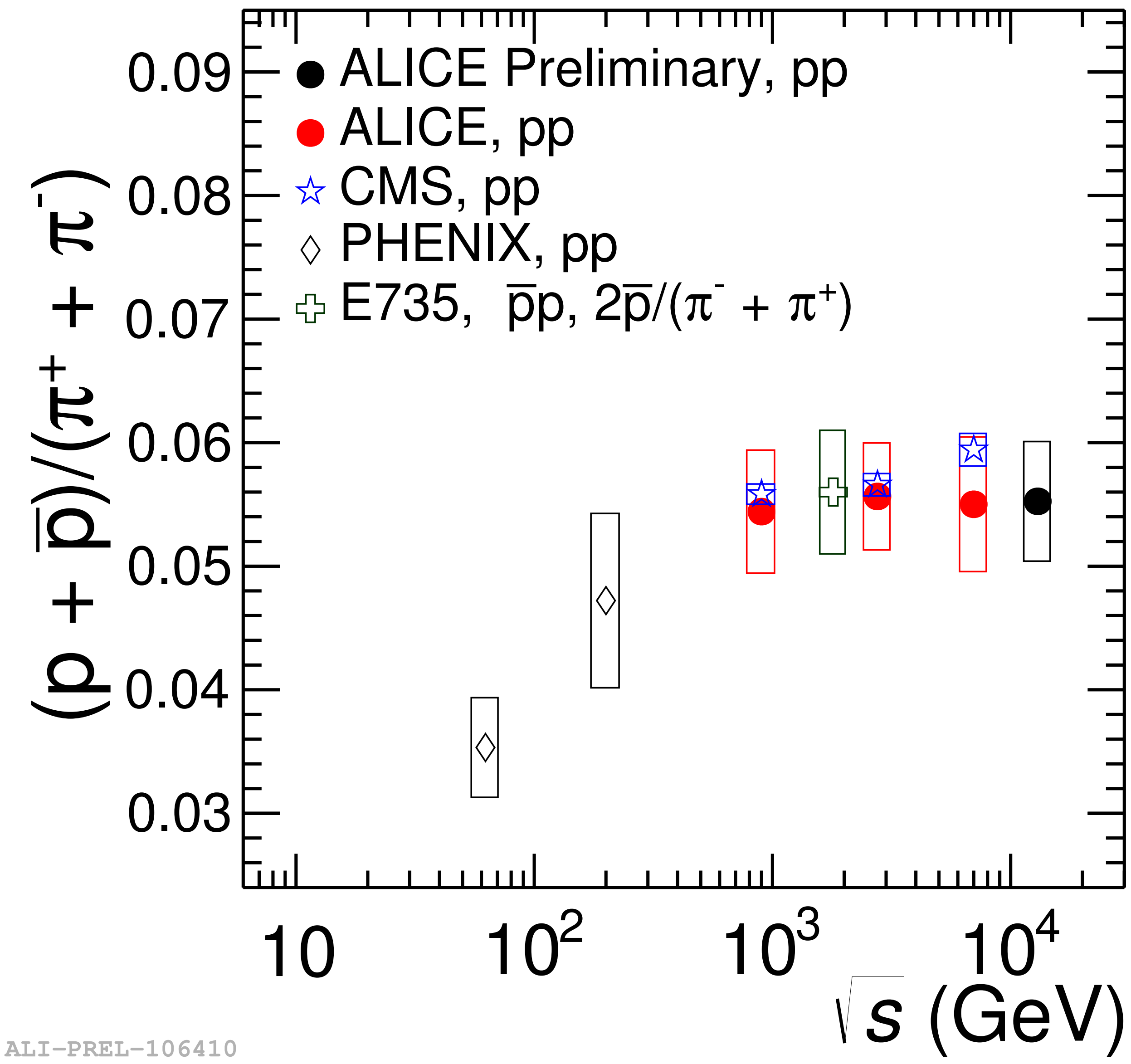


→ Smooth behaviour of p/π ratio observed from small to large collision systems.

→ Same behavior in Pb-Pb collisions at two energies and also in Xe-Xe collisions (taken at lower B=0.2T field) and among different experiments in pp.

→ While the deviation from the thermal model is ~2.8**σ**, this only corresponds to only 15-18% in absolute terms.

(anti-)proton-to-pion ratio vs system size



→ Smooth behaviour of p/π ratio observed from small to large collision systems.

→ Same behavior in Pb-Pb collisions at two energies and also in Xe-Xe collisions (taken at lower B=0.2T field) and among different experiments in pp.

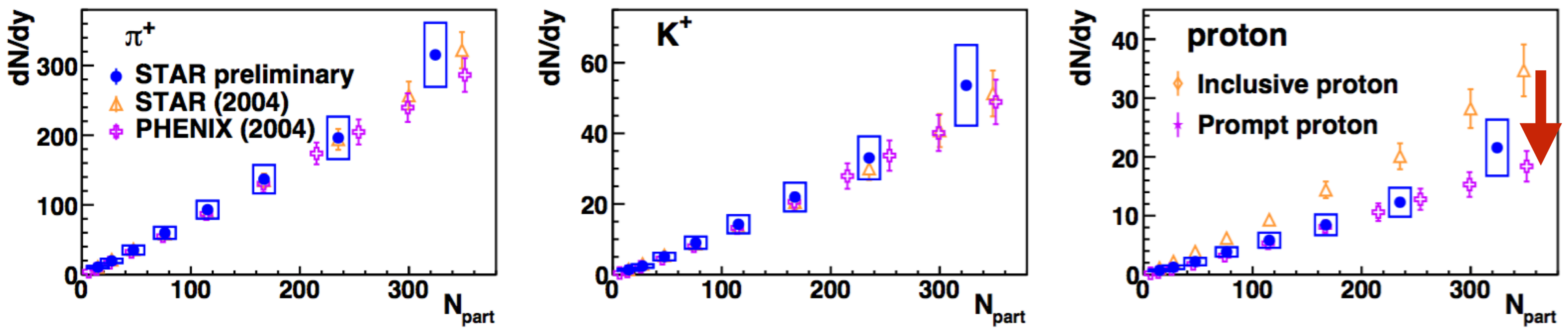
→ While the deviation from the thermal model is ~2.8**σ**, this only corresponds to only 15-18% in absolute terms.

Proton-to-pion ratio at RHIC

- STAR heavy flavor tracker allows to measure light flavor hadrons much more precisely also at RHIC energies.

- Change in π yield is small, but significant reduction of protons is observed.

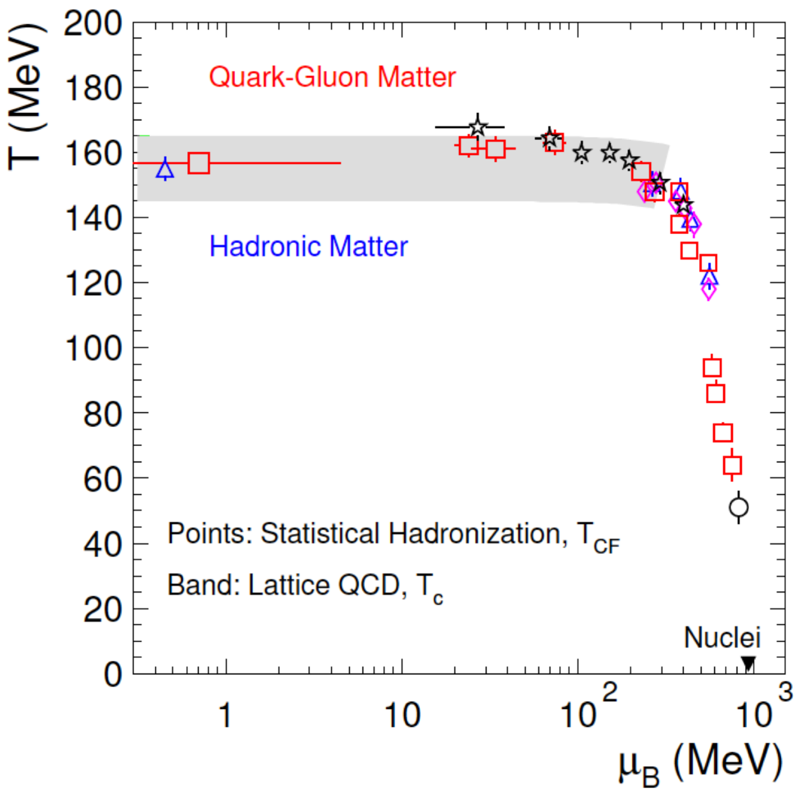
→ Is there a more recent update of this measurement?

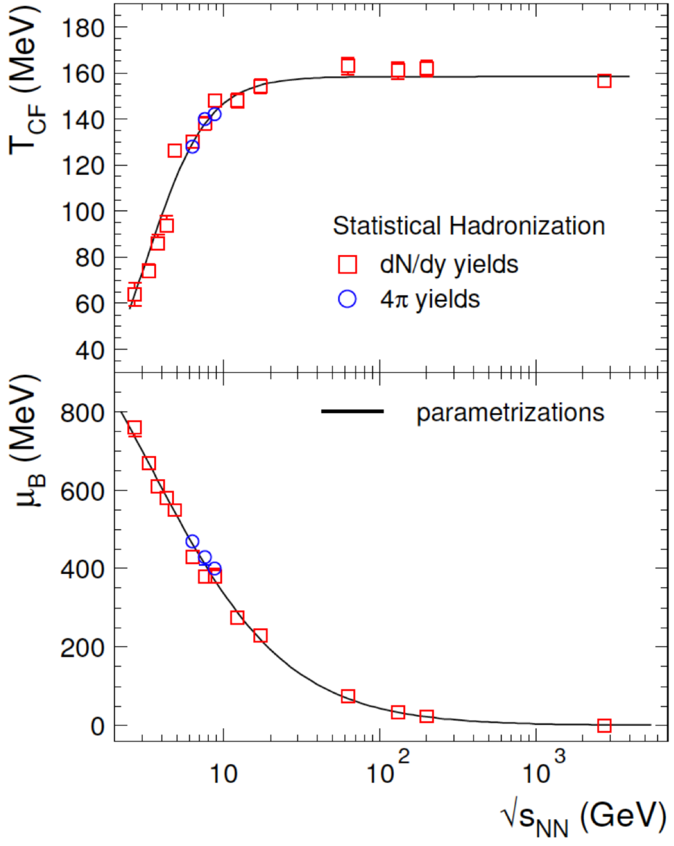


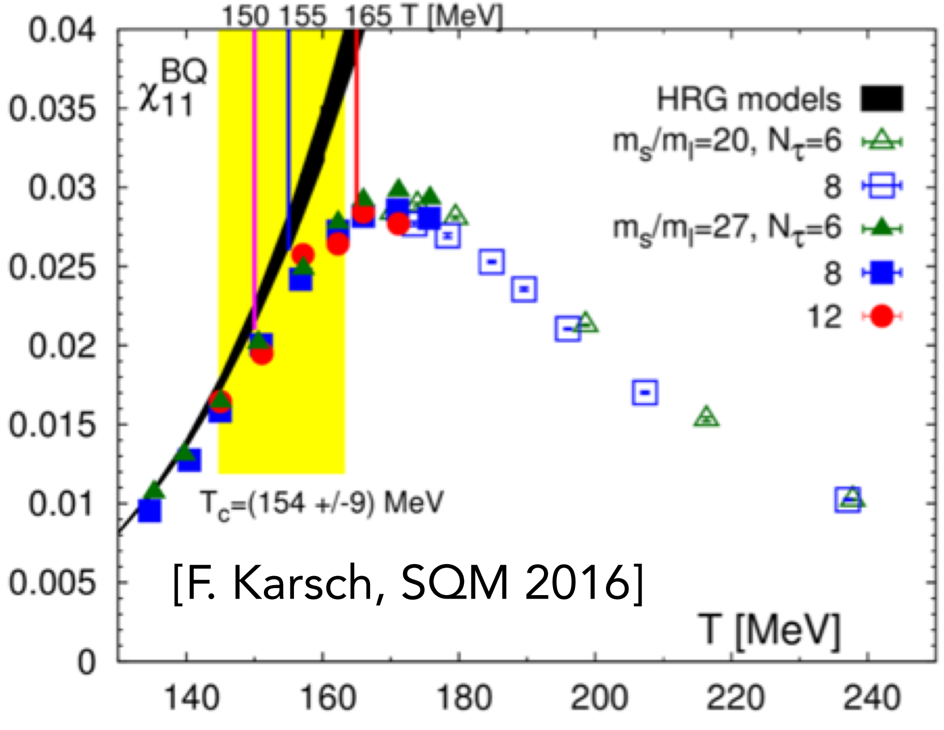
[S. Mizuno, SQM2016]

Particle production and the QCD phase diagram

[A. Andronic *et al.*, Nature 561 (2018) no.7723, 321-330]







[F. Karsch, SQM 2016]

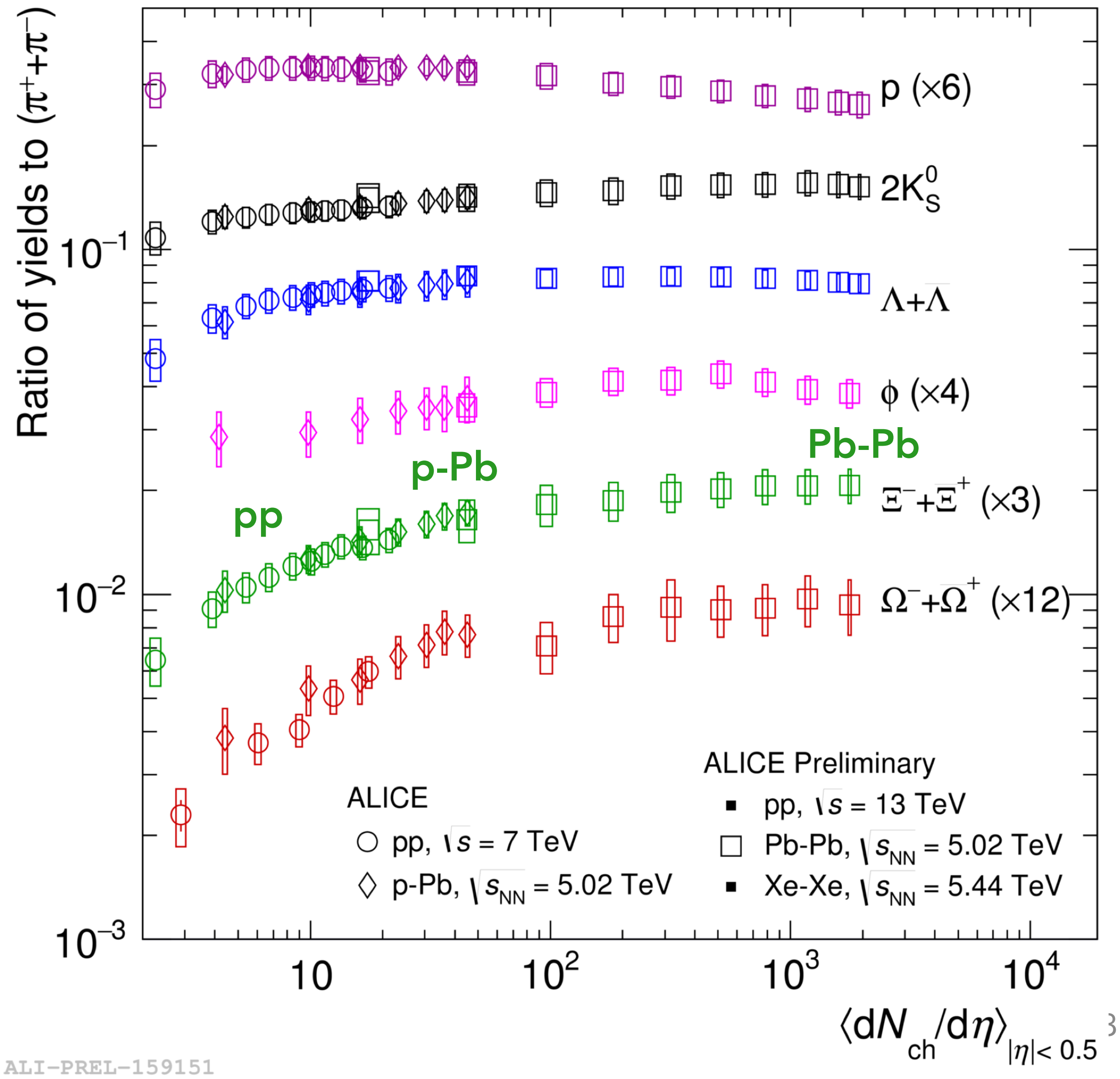
The proton yield drives the fit and thus the determination of T_{ch}.

→ An exact measurement of these yields is not just a boring detail.
It is the experimental determination of the limiting temperature at which hadrons can still exist!

Particle chemistry across system size (1)

→ Smooth evolution of particle chemistry from small to large systems as function of charged particle multiplicity
⇒ common origin in all systems?

→ Increasing strangeness production with increasing multiplicity until saturation (grand-canonical plateau) is reached.

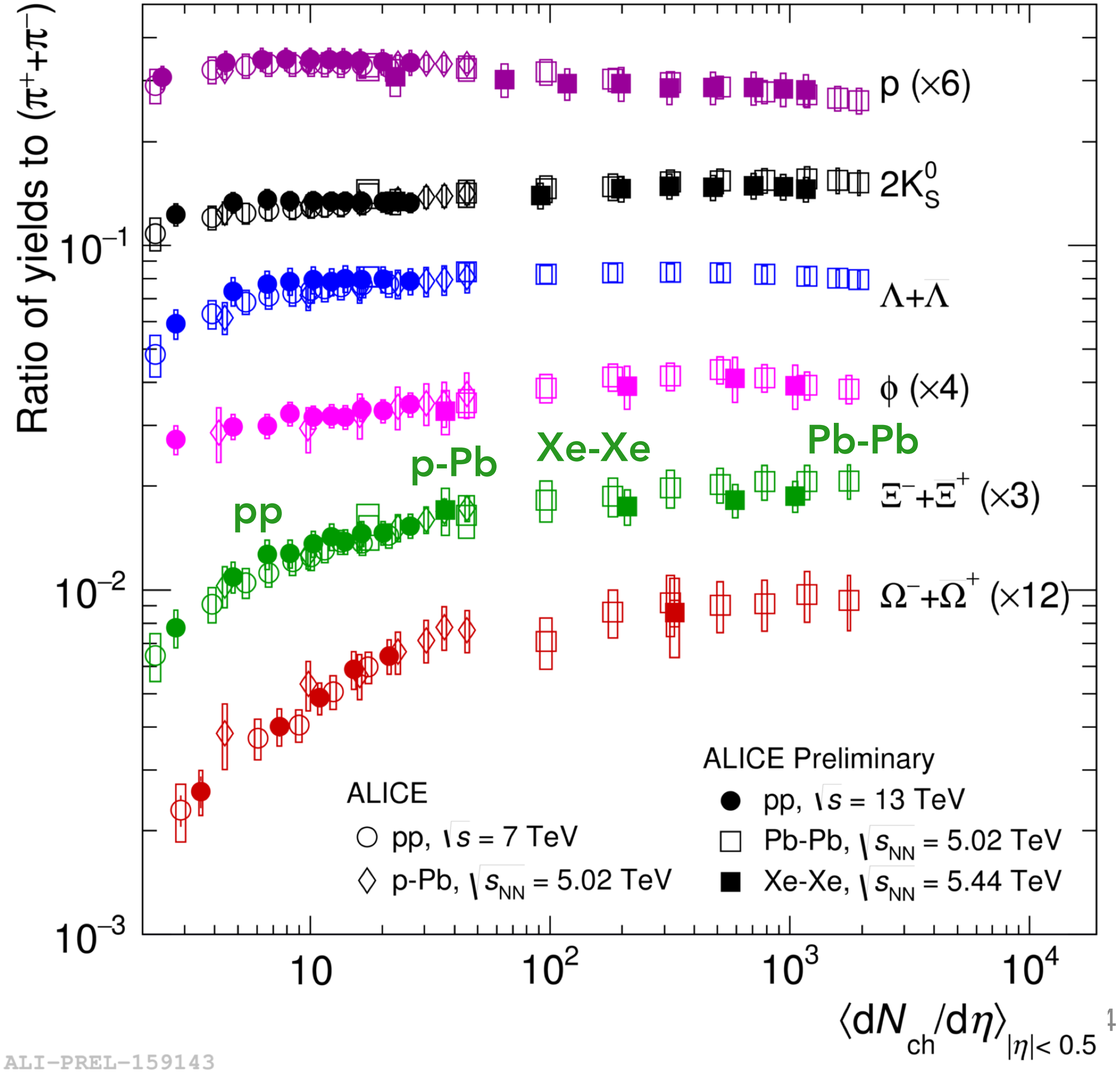


Particle chemistry across system size (2)

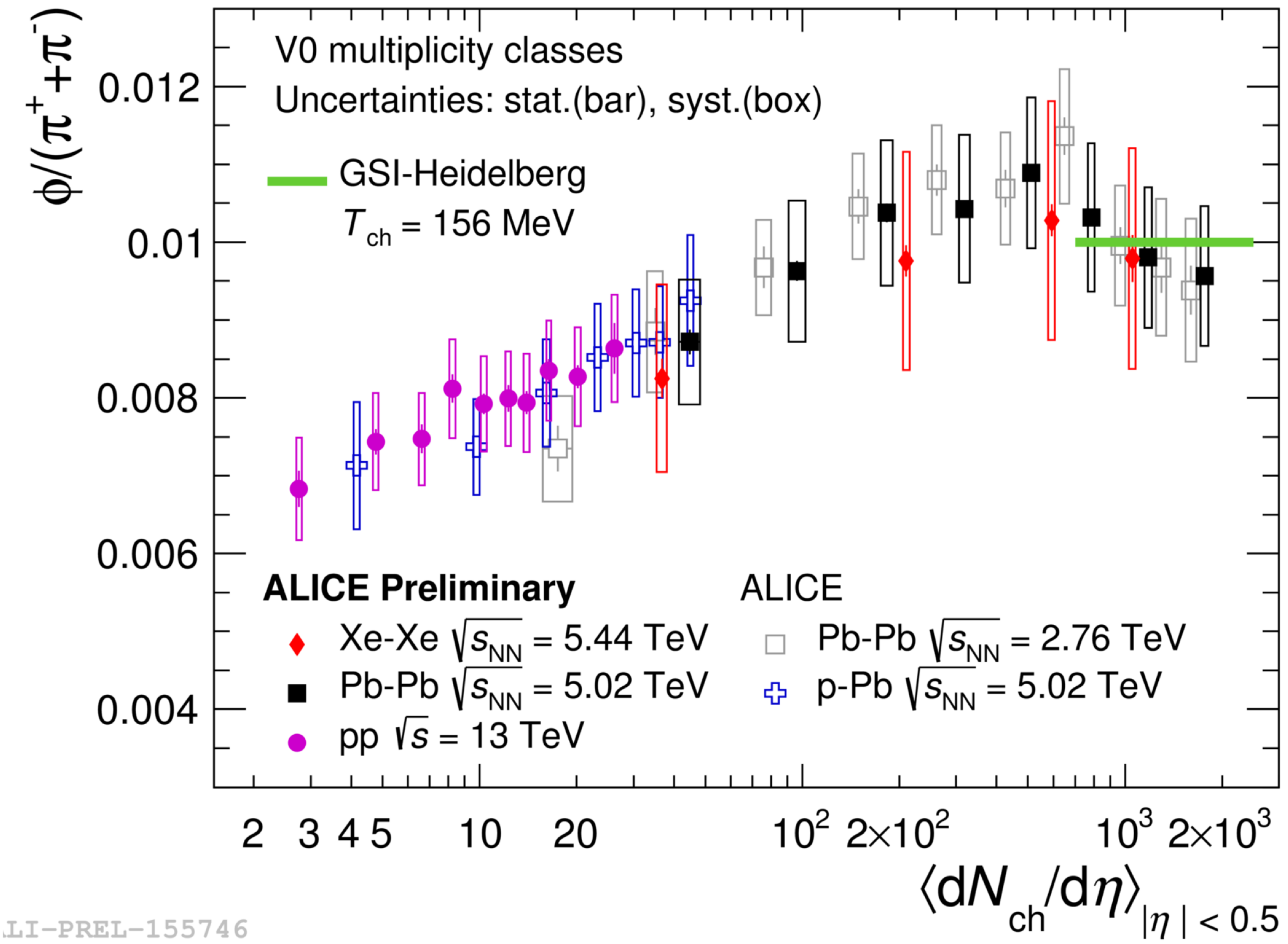
→ Smooth evolution of particle chemistry from small to large systems as function of charged particle multiplicity
⇒ common origin in all systems?

→ Increasing strangeness production with increasing multiplicity until saturation (grand-canonical plateau) is reached.

→ **Confirmed with new pp √s=13 TeV and Xe-Xe data!**



Particle chemistry across system size (3)



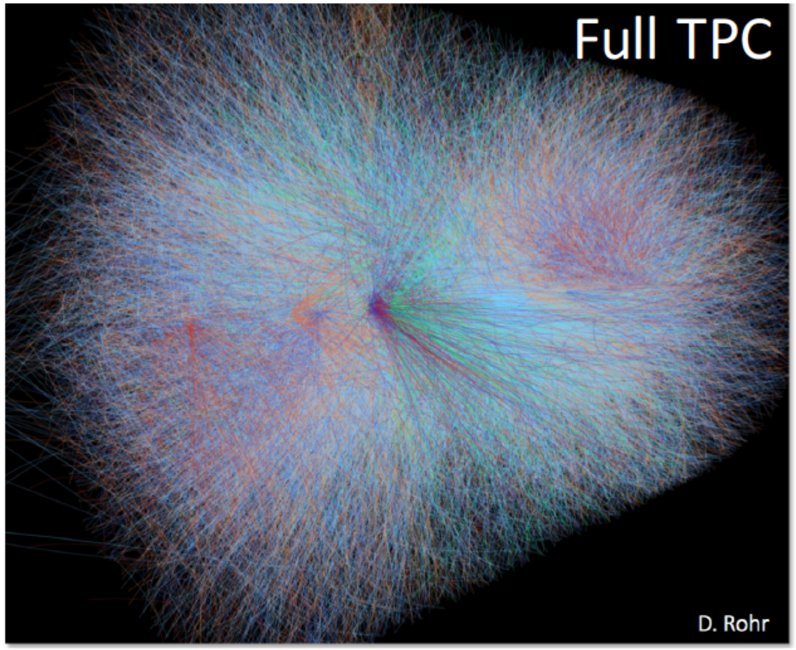
Significantly increasing trend of ϕ-meson ($s\bar{s}$) to pion ratio with increasing multiplicity

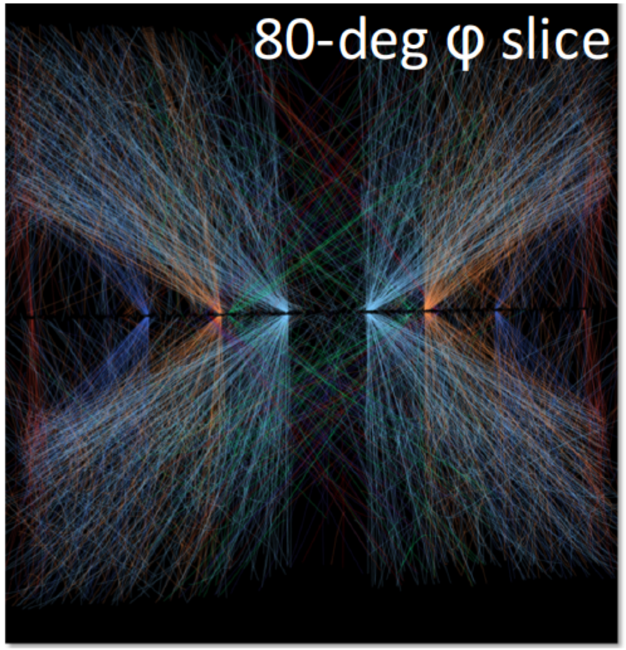
→ In contrast to expectation from simple strangeness canonical suppression.

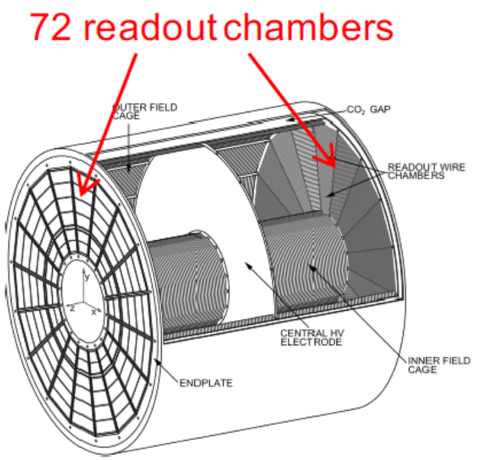
→ Pivotal role of the ϕ-meson in the understanding of strangeness production with thermal-statistical, core-corona, and MC models.

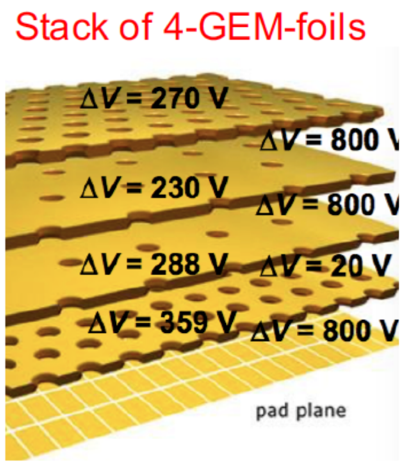
TPC with GEM readout for Pb-Pb at 50 kHz

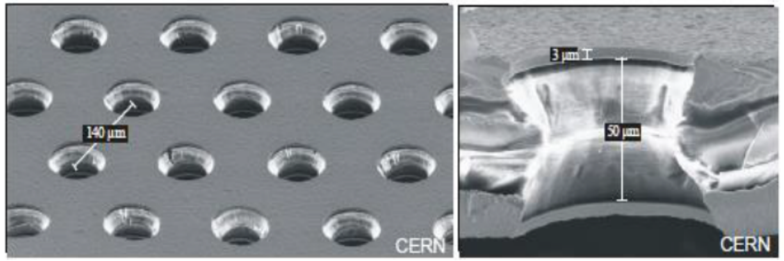
- Current MWPC: readout limited by ion backflow
- New readout chambers (GEM) continuous readout
  - Preserve momentum and dE/dx resolution
- 5 interactions on average during TPC drift time (83μs)
- Calibration and track-to-event assignment in O²-system









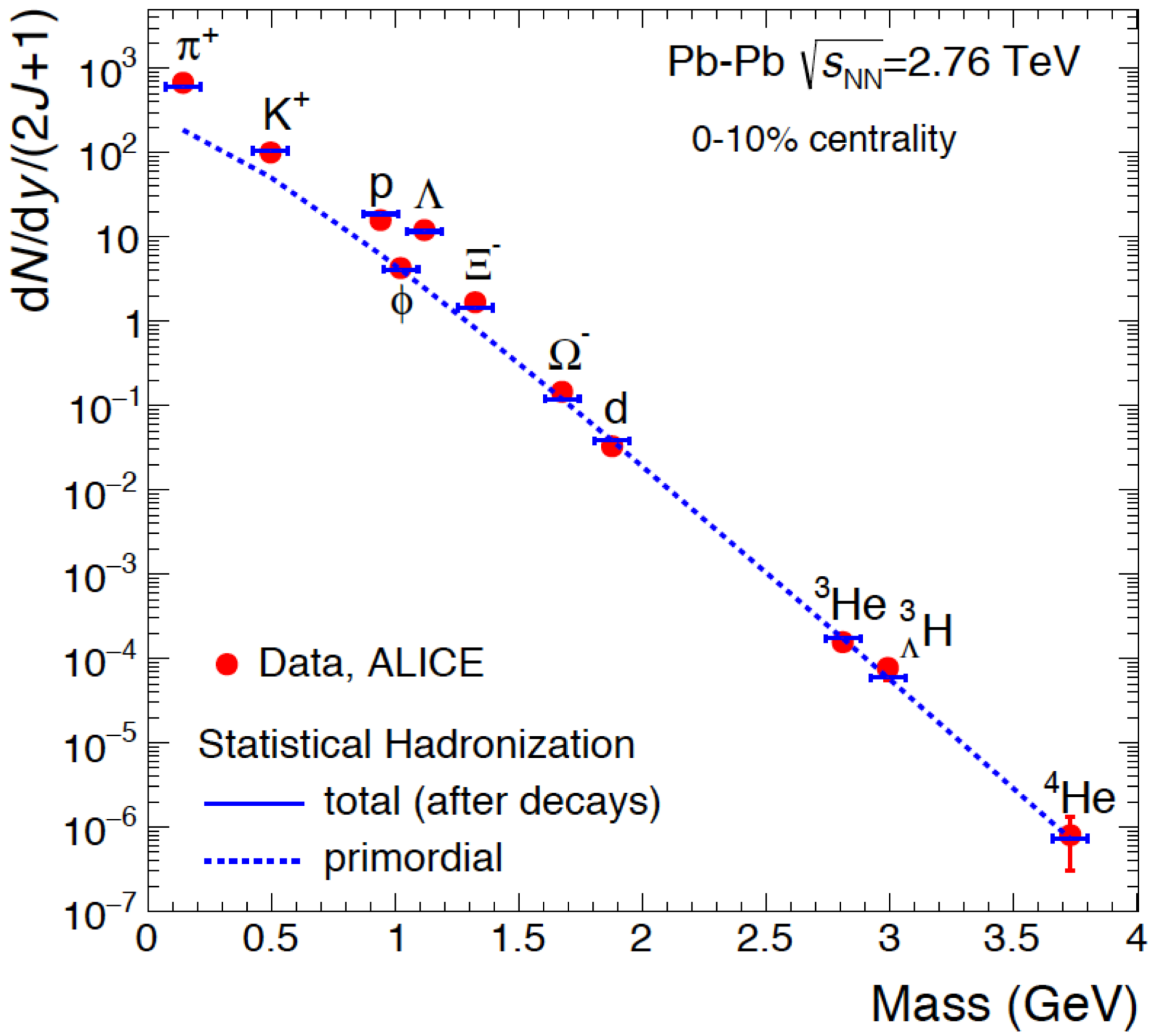


Electron microscope photograph of a GEM foil

Outlook to LHC Run 3 and 4 (A)

The measurement of the **coalescence parameters** for composite objects with **different sizes** studied as a function of the **multiplicity** can be used to compare the light (anti-)(hyper-)nuclei production scenarios.

(anti-)nuclei yields are not subject to feed-down from strong decays!



[A. Andronic *et al.*, Nature 561 (2018) no.7723, 321-330]

Outlook to LHC Run 3 and 4 (B)

The measurement of the **coalescence parameters** for composite objects with **different sizes** studied as a function of the **multiplicity** can be used to compare the light (anti-)(hyper-)nuclei production scenarios

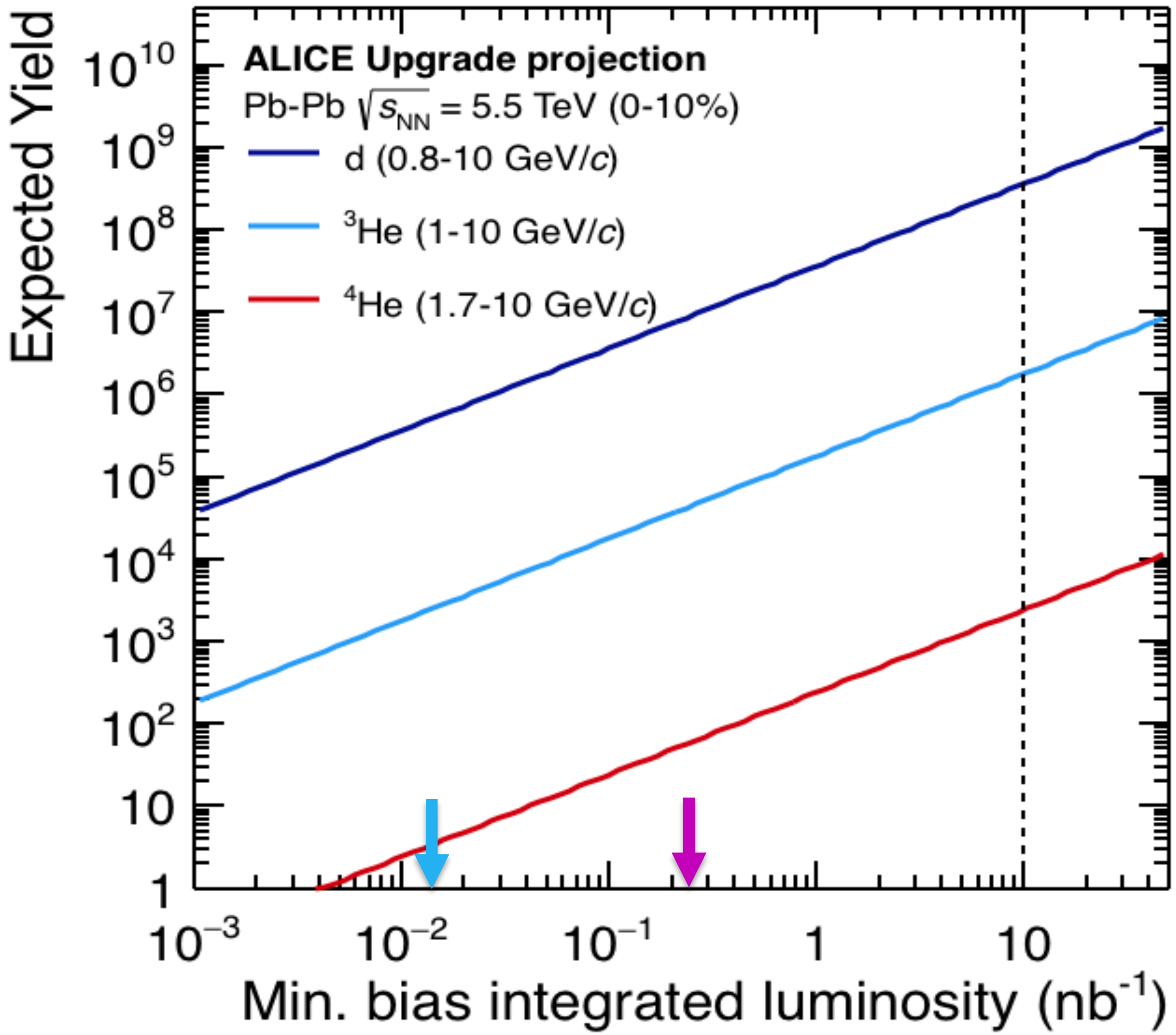
Physics case for Run3&4:

→ Measure centrality dependence of the hypertriton in Pb-Pb

→ Can we produce at all the hypertriton in pp collisions?

→ Go more differential for A = 3

→ Measure B_4 for ^{4}He, $^4{}_\Lambda$H, $^4{}_\Lambda$He



Outlook to LHC Run 3 and 4 (C)

The measurement of the **coalescence parameters** for composite objects with **different sizes** studied as a function of the **multiplicity** can be used to compare the light (anti-)(hyper-)nuclei production scenarios

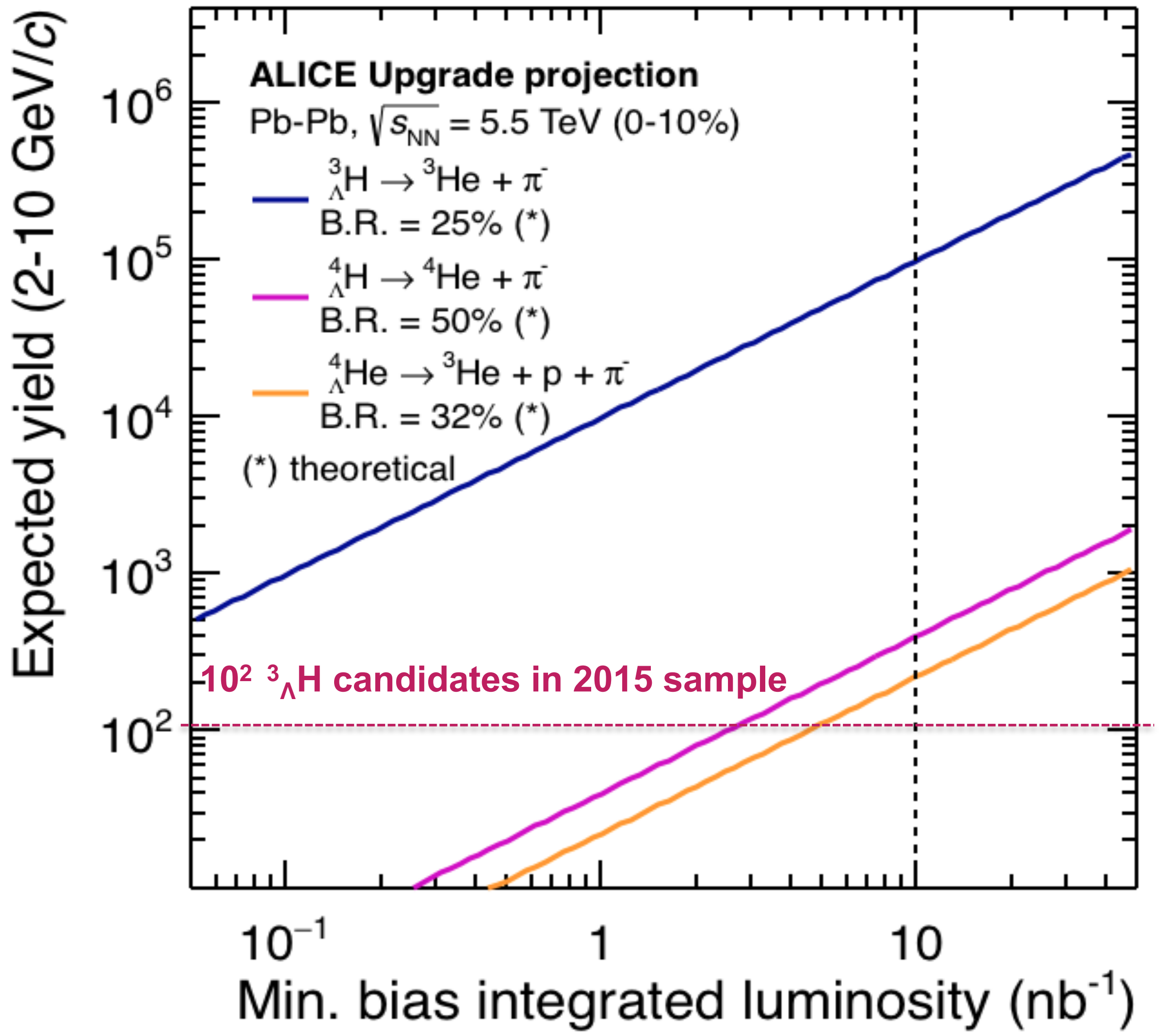
Physics case for Run3&4:

→ Measure centrality dependence of the hypertriton in Pb-Pb

→ Can we produce at all the hypertriton in pp collisions?

→ Go more differential for A = 3

→ Measure B_4 for ^{4}He, $^4{}_\Lambda$H, $^4{}_\Lambda$He



Outlook to LHC Run 3 and 4 (4)

→ Check out the entire LHC physics program at LHC Run 3 & 4 which is summarized in the recently released CERN yellow report: arXiv:1812.06772

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Z. Citron (Ben Gurion U. of Negev), A. Dainese (INFN, Padua), J.F. Grosse-Oetringhaus, J.M. Jowett (CERN), Y.-J. Lee (MIT), U.A. Wiedemann (CERN), M. Winn (AIM, Saclay & Orsay, LAL), A. Andronic (Munster U.), F. Bellini (CERN), E. Bruna (INFN, Turin) *et al.* *Zeige alle 185 Autoren*

Dec 17, 2018 - 207 pages

Conference: C18-06-18.8
CERN-LPCC-2018-07
e-Print: arXiv:1812.06772 [hep-ph] | PDF

Abstract (arXiv)
The future opportunities for high-density QCD studies with ion and proton beams at the LHC are presented. Four major scientific goals are identified: the characterisation of the macroscopic long wavelength Quark-Gluon Plasma (QGP) properties with unprecedented precision, the investigation of the microscopic parton dynamics underlying QGP properties, the development of a unified picture of particle production and QCD dynamics from small (pp) to large (nucleus--nucleus) systems, the exploration of parton densities in nuclei in a broad (x, Q^2) kinematic range and the search for the possible onset of parton saturation. In order to address these scientific goals, high-luminosity Pb-Pb and p-Pb programmes are considered as priorities for Runs 3 and 4, complemented by high-multiplicity studies in pp collisions and a short run with oxygen ions. High-luminosity runs with intermediate-mass nuclei, for example Ar or Kr, are considered as an appealing case for extending the heavy-ion programme at the LHC beyond Run 4. The potential of the High-Energy LHC to probe QCD matter with newly-available observables, at twice larger center-of-mass energies than the LHC, is investigated.

Summary and conclusions

- The physics of thermal light flavor hadron production was considered as final in the RHIC (pre-LHC) era, but the increased precision of LHC experiments has brought surprises and many new insights, e.g.:

  1. Detailed investigation of the proton yield (see also talks of C. Ratti, Pok-Man Lo,…)

  2. anti-nuclei puzzle

  3. Textbook measurements of the approach to the grand-canonical saturation from small to large collision systems

- While the study of the proton yield now gets finalized by theorists, the measurements of anti-nuclei and high multiplicity pp collisions enter a golden era with LHC Run 3 & 4 in 2021-2029.

Additional slides