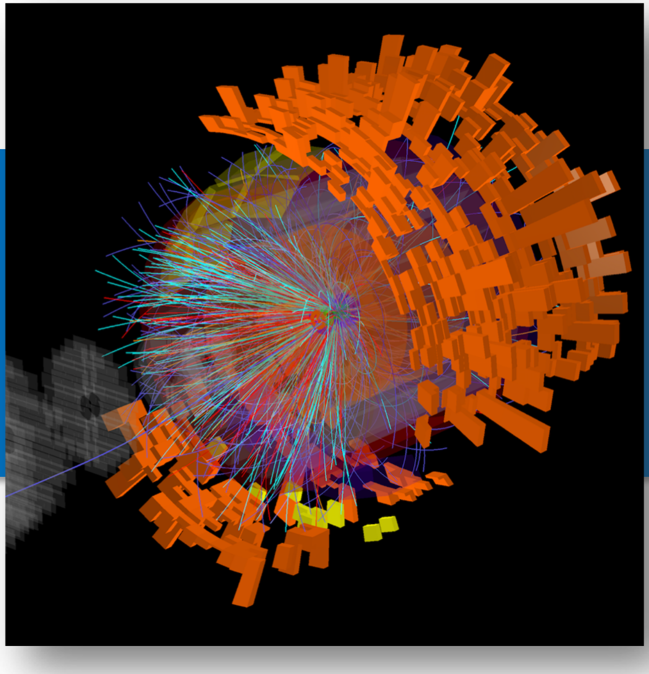


Strangeness production from large to small systems

Dr. Francesca Bellini (CERN, Switzerland)

Particle Physics Seminar

University of Birmingham, 17th October 2018

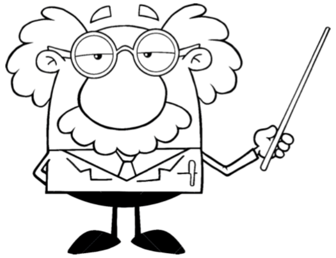
Outline

- Strangeness production
  - in Quark Gluon Plasma
  - in hadronic gas
  - from the perspective of pp modeling

- Experimental aspects
  - Strange hadron reconstruction with ALICE
  - Centrality and multiplicity in ALICE

- Evidence of strangeness enhancement in heavy-ion collisions
- Strangeness enhancement in high-multiplicity pp and p-Pb

- Outlook



Strangeness production

in Quark Gluon Plasma,
in hadron gas,
from the perspective of pp modeling

What is so special about the strange quark

Strange quarks are created during the collision

The hadronic cross section of (multi-)strange hadrons is small
⇢ carry information about production stages

The ***s*** quark is “light” (current mass)

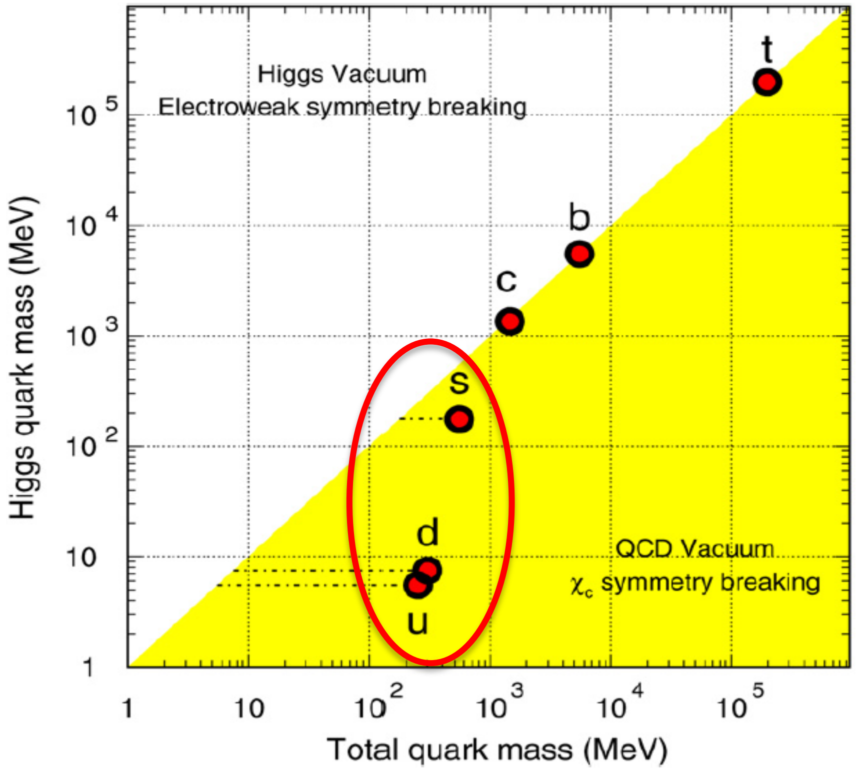
$$\left.\begin{array}{l} \boldsymbol{m_u} \approx 2.2\ \text{MeV}\\ \boldsymbol{m_d} \approx 4.7\ \text{MeV}\\ \boldsymbol{m_s \approx 96\ \text{MeV}}\end{array}\right\} < \Lambda_{QCD} \ll m_c \approx 1.3\ \text{GeV}$$

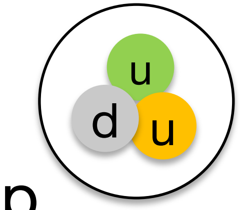
[C. Patrignani et al. (Particle Data Group), Chin. Phys. C. 40, 100001 (2016) and 2017 update]

Constituent light quarks masses are dominated by spontaneous breaking of chiral symmetry in QCD
⇢ **hadron mass generated “dynamically”**

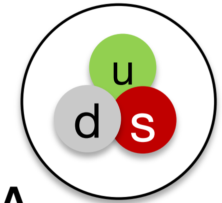
Light quarks can recover their **bare current masses** if chiral symmetry is (partially) restored
⇢ **near the QCD phase-transition boundary**

K. Schweda et al., arXiv:nucl-ex/0610043





p
m = 938 MeV



Λ
m = 1115 MeV

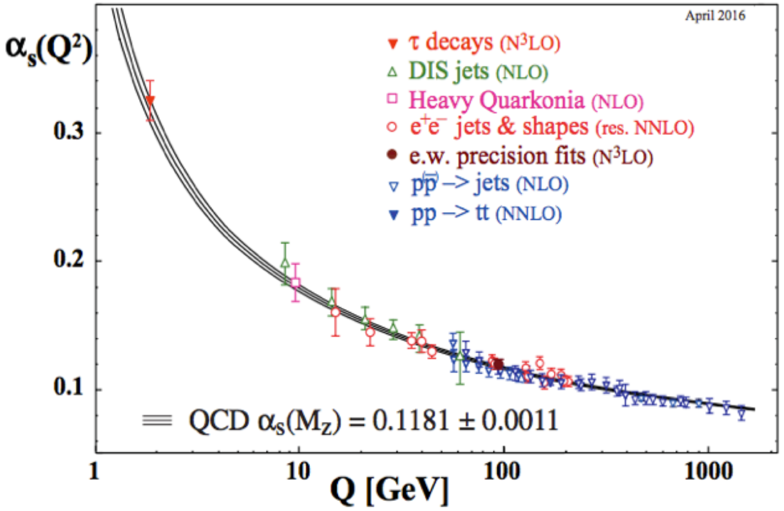
The QCD phase transition (a very simplified picture)

Quarks and gluons exist in nature as confined in colorless hadrons ⇢ **confining property of QCD**

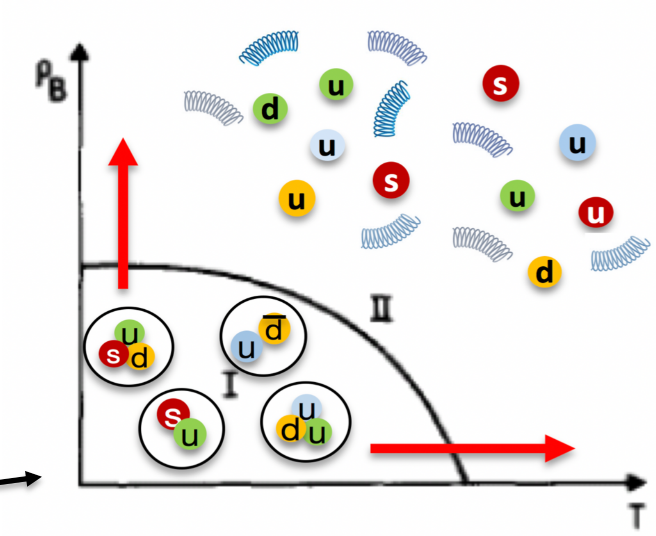
The strong coupling becomes weak for processes involving large momentum transfers ⇢ **asymptotic freedom**

A deconfined state of matter (Quark Gluon Plasma) can be reached by compressing the system to a high-density (ρ_B) and/or heating it up to a high-temperature (T) ⇢ **ultra-relativistic heavy-ion collisions**

M. Tanabashi et al. (PDG), PRD 98, 030001 (2018)

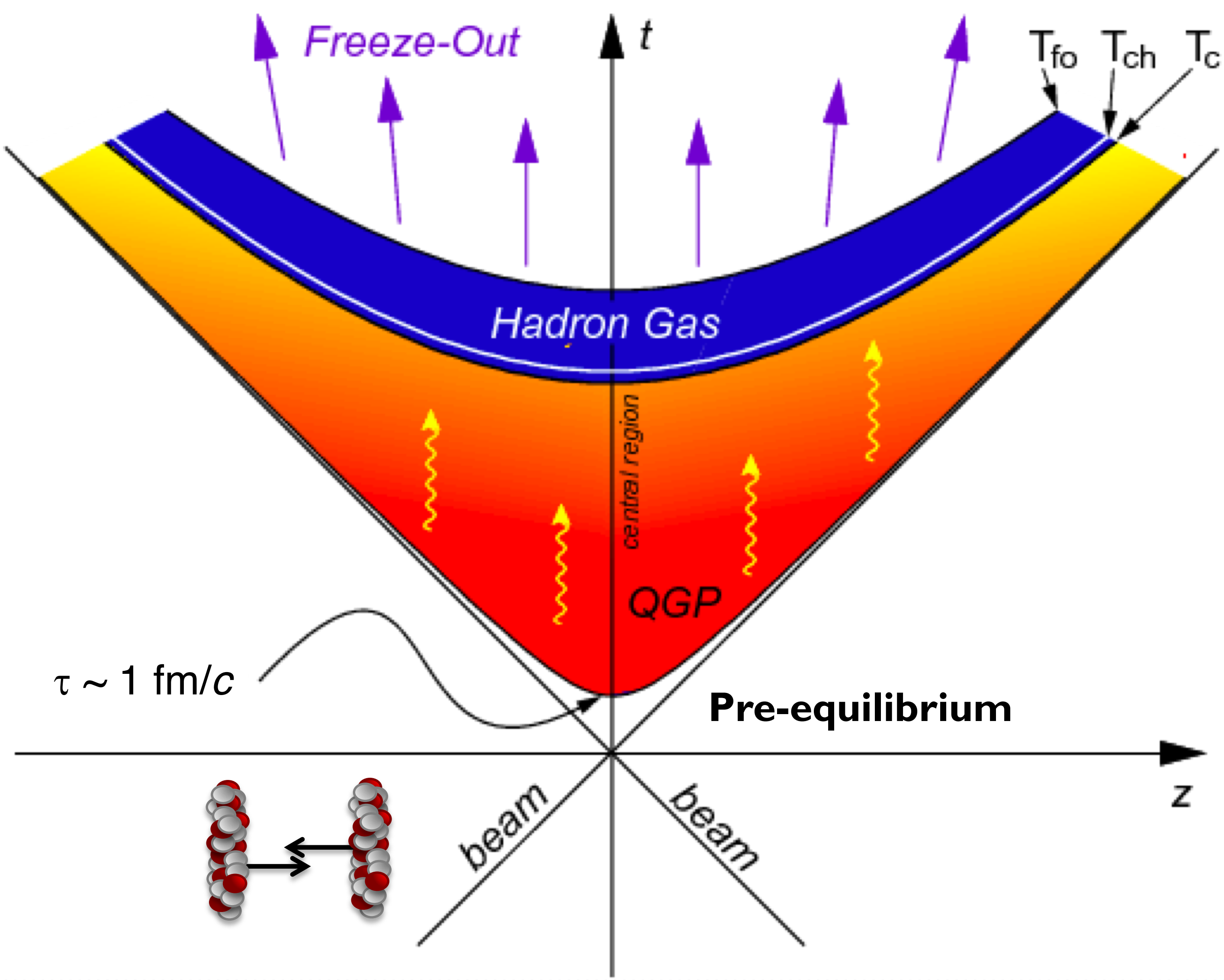


Cabibbo and Parisi, Phys. Lett. B 59, 67 (1975)

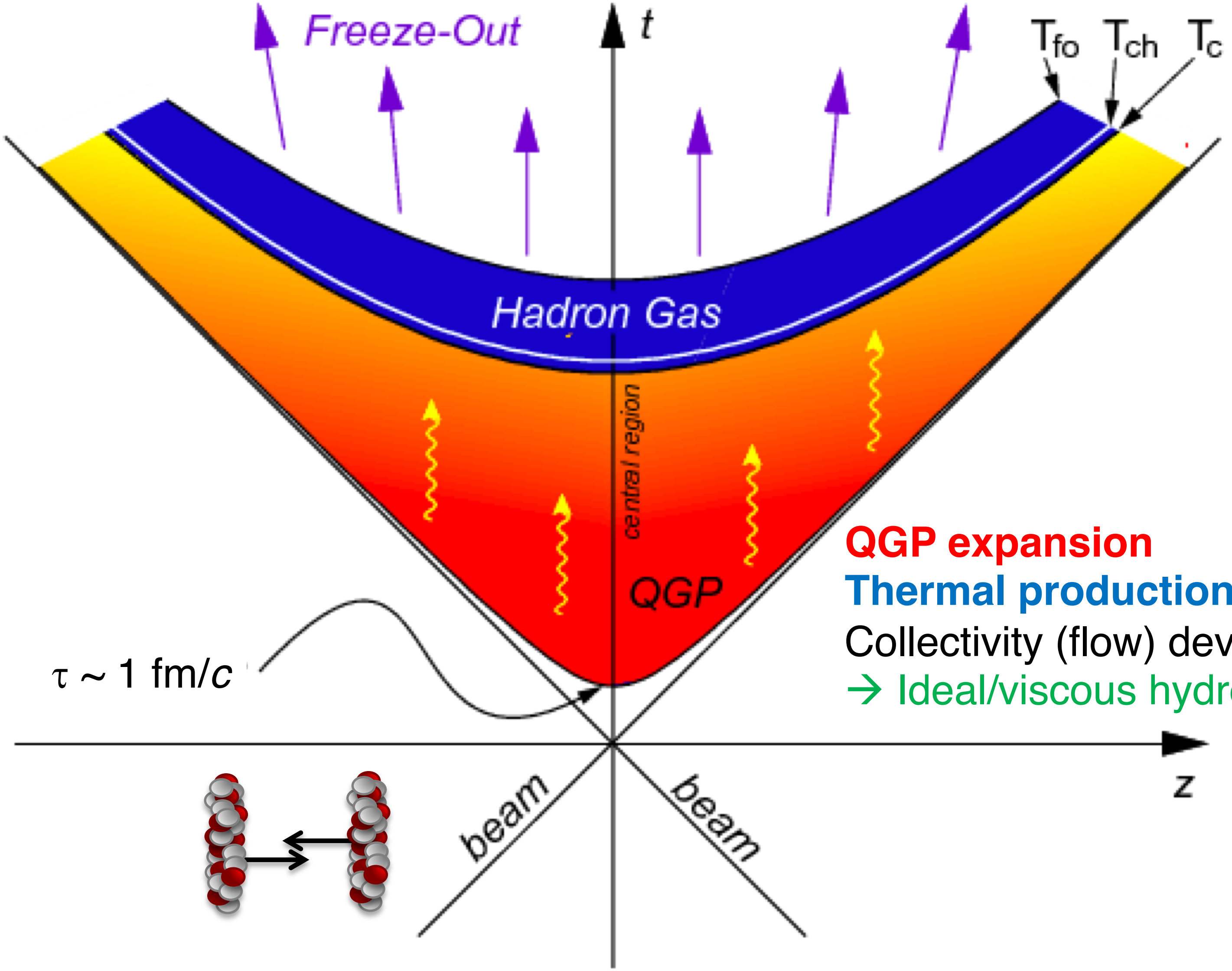


At the LHC: $\mu_B \sim 0$, ε ~16 GeV/fm³

Space-time evolution of heavy-ion collisions



Space-time evolution of heavy-ion collisions



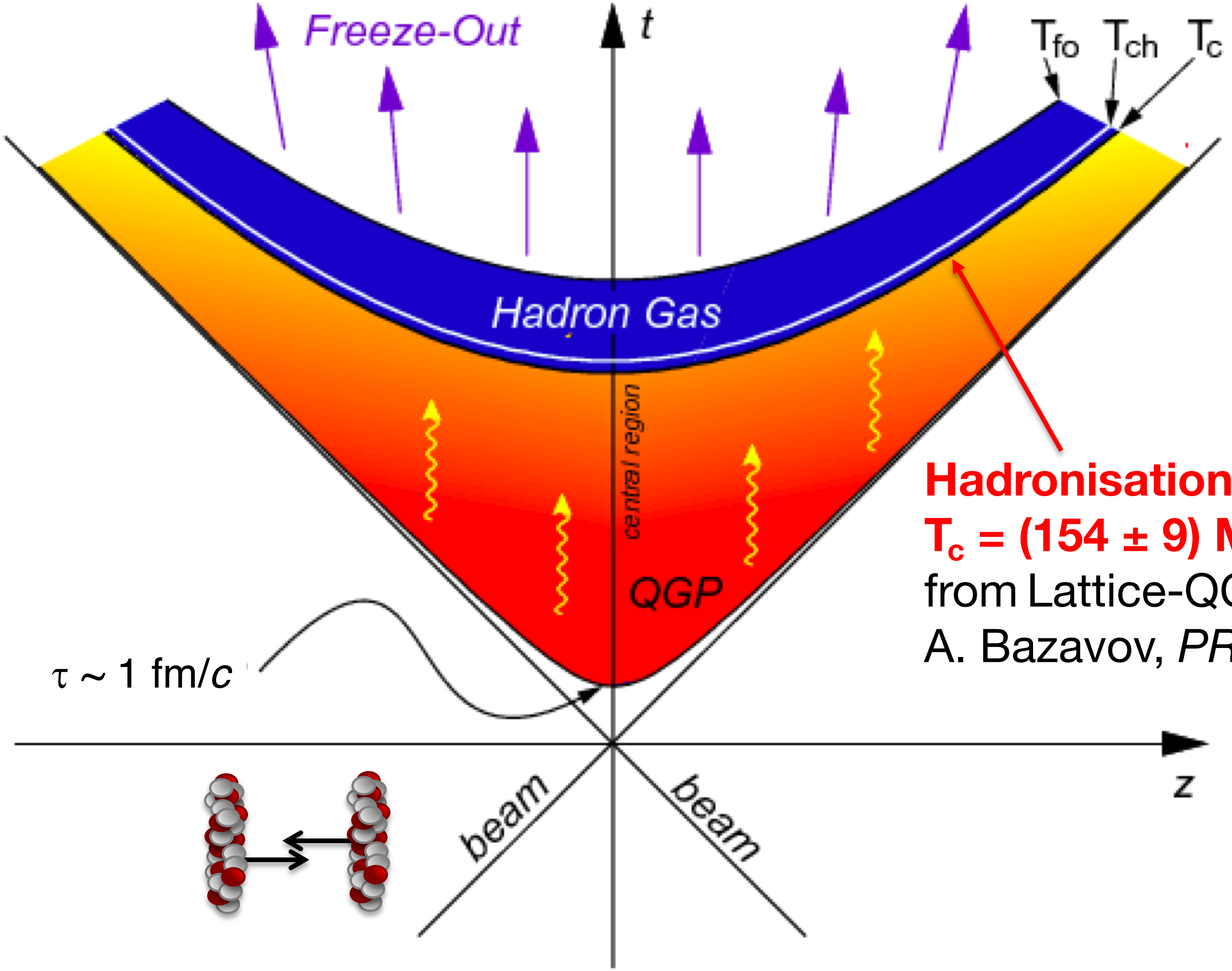
QGP expansion

Thermal production of s

Collectivity (flow) develops

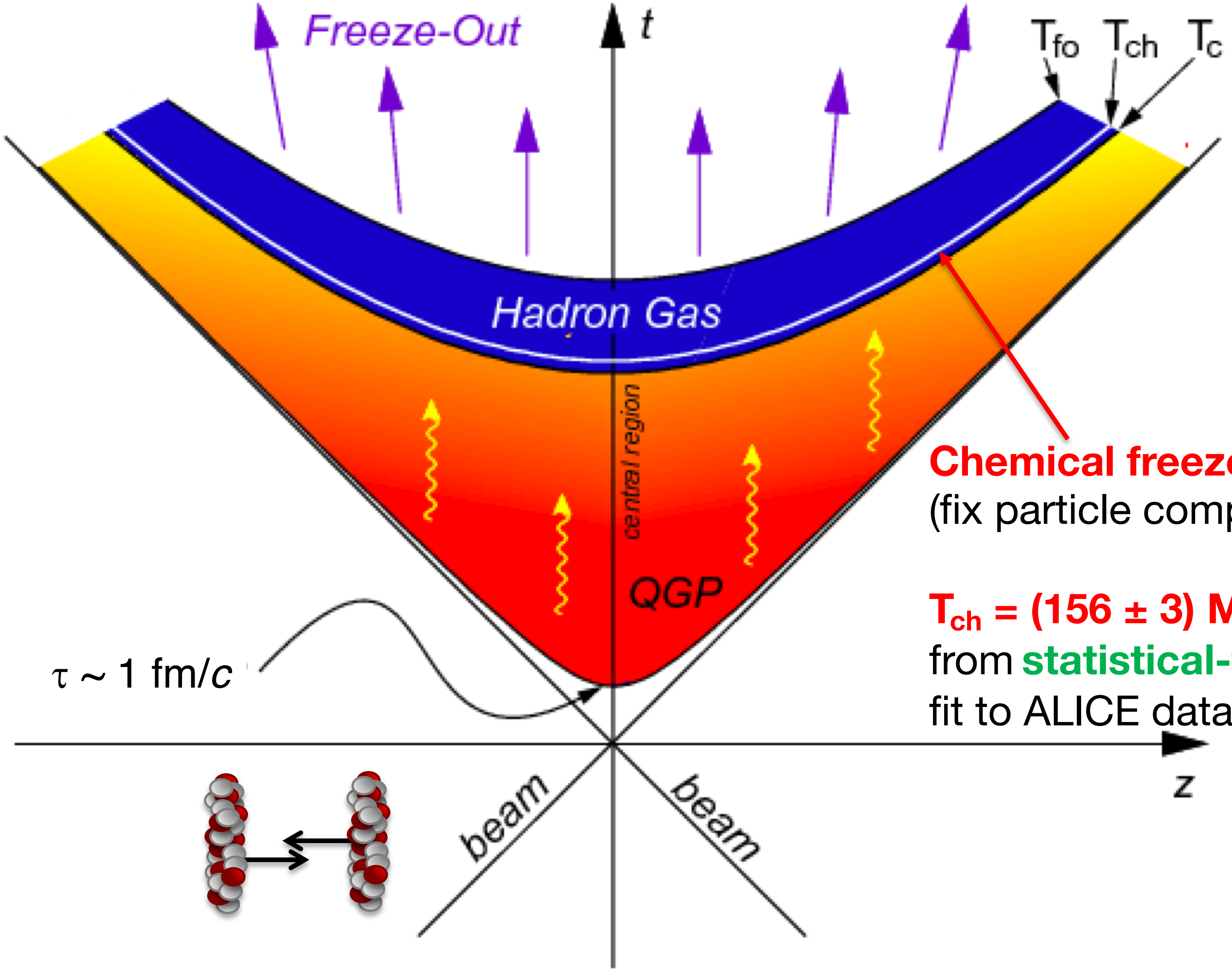
→ Ideal/viscous hydrodynamics

Space-time evolution of heavy-ion collisions



Hadronisation
T_c = (154 ± 9) MeV
from Lattice-QCD
A. Bazavov, *PRD 90 (2014) 094503*

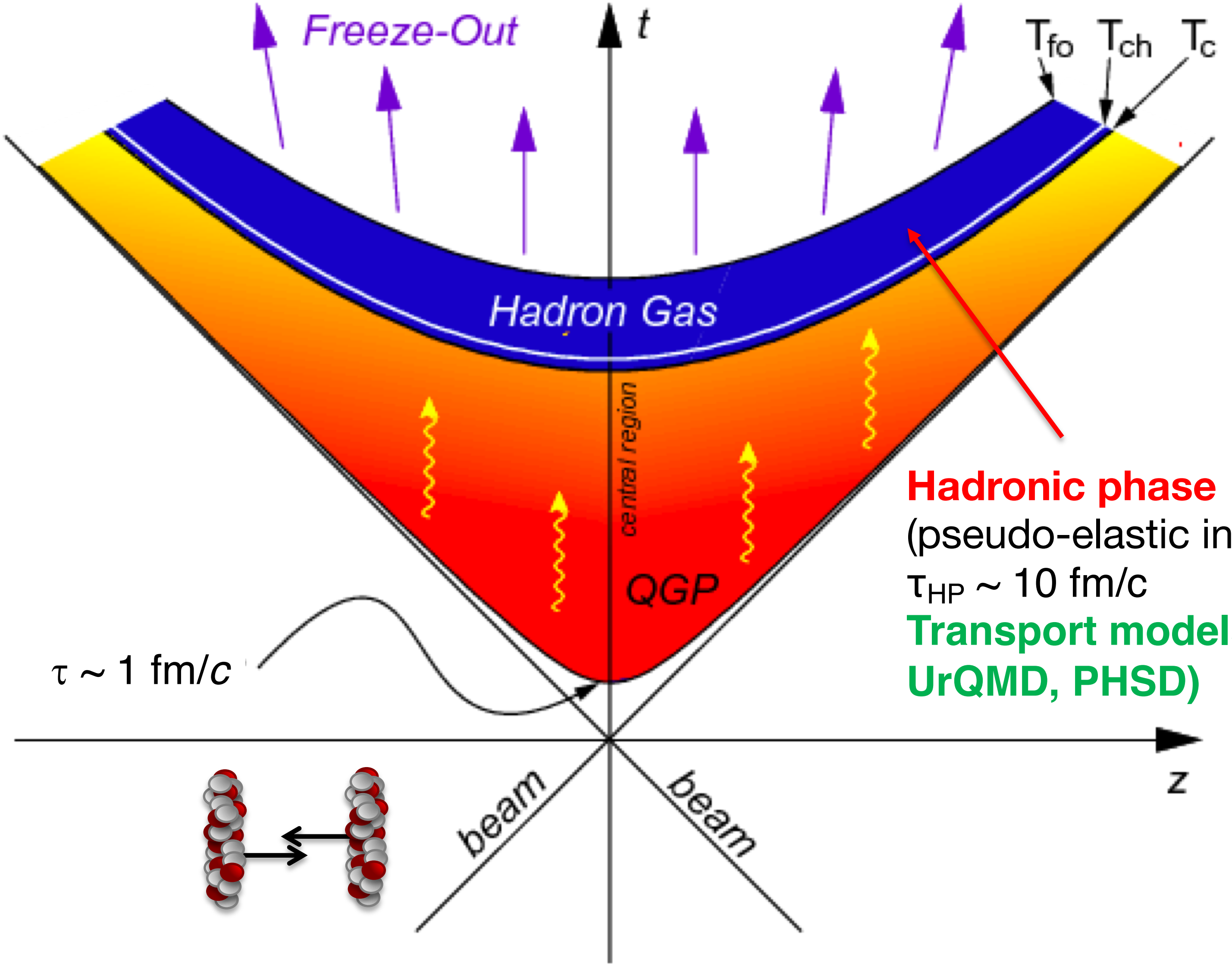
Space-time evolution of heavy-ion collisions



Chemical freeze-out
(fix particle composition)

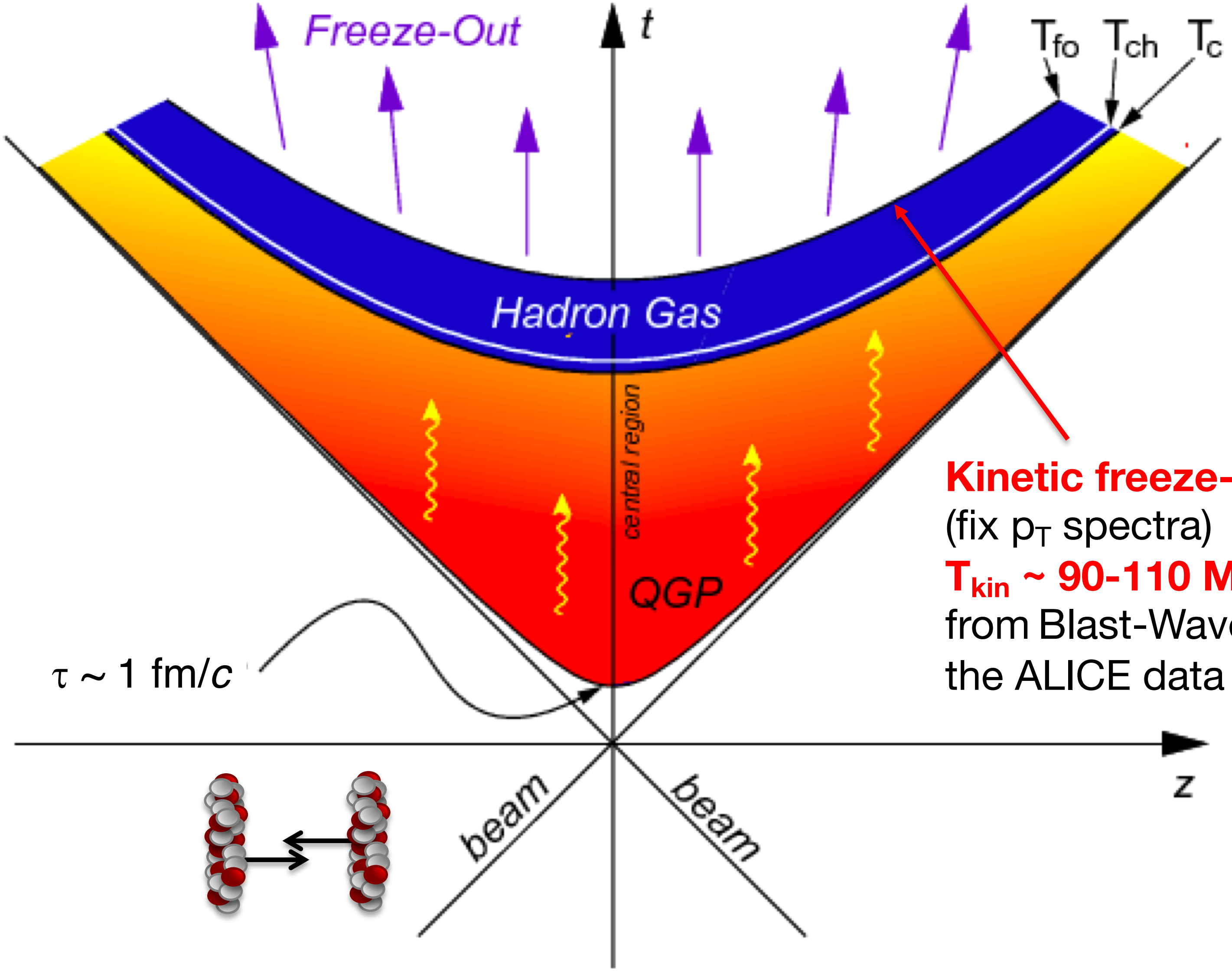
T_{ch} = (156 ± 3) MeV
from **statistical-thermal model**
fit to ALICE data

Space-time evolution of heavy-ion collisions



Hadronic phase
(pseudo-elastic interactions)
$\tau_{HP} \sim 10$ fm/c
Transport models (e.g. UrQMD, PHSD)

Space-time evolution of heavy-ion collisions



Kinetic freeze-out
(fix p_T spectra)
T_{kin} ~ 90-110 MeV
from Blast-Wave model fits of the ALICE data

Strangeness production in QGP

~300 MeV (or less if $m_s^{QCD} \longrightarrow m_s^{Higgs}$ by restoration of chiral symmetry) are enough to create an s-sbar pair

Gluon fusion (a) is the dominant mechanism for strangeness production over quark annihilation (b)

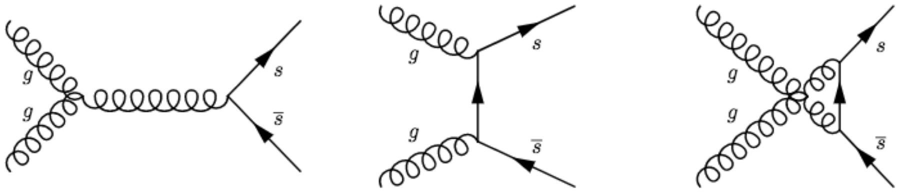
Gluons quickly thermalise in t < 1 fm/*c*
[E. Shuryak, Phys. Rev. Lett. 68 (1992) 3270]

The backward reaction of (b) depends on the s quark density, thus on the QGP lifetime
⇢ saturation of strangeness abundance

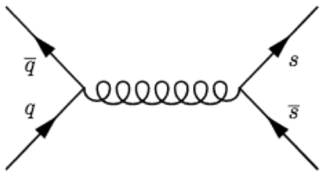
After hadronisation, the abundance of (multi)strange hadrons reflects that of strangeness in the partonic phase

- For short enough hadronic phase (no re-diffusion) and small hadronic cross sections

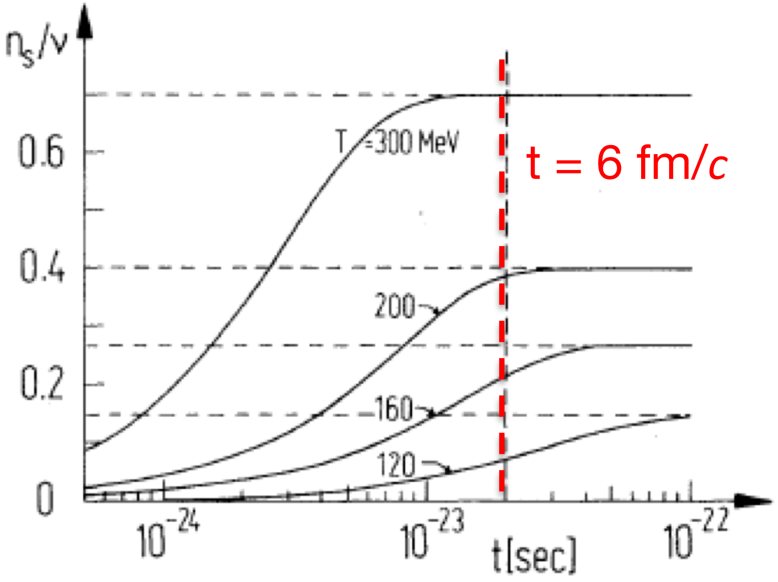
(a) $gg \rightarrow s\bar{s}$



(b) $q\bar{q} \rightarrow s\bar{s}$



Abundance of s quark relative to baryon number



t = 6 fm/*c*

QGP lifetime

J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066

Strangeness production in Hadron Gas

In a hadron gas at high temperature (e.g. $T = 150$ MeV $< T_c$), (multi-)strange hadron production is an energy threshold problem

By **multi-step hadronic processes**

e.g. $\pi + n \rightarrow K + \Lambda$, $E_{th} \sim 540$ MeV

$\pi + \Lambda \rightarrow K + \Xi$, $E_{th} \sim 560$ MeV

⇢ Requires longer medium lifetime

⇢ under-saturation of strangeness

By **direct production**

e.g. $\pi + \pi \rightarrow \pi + \pi + \Lambda + \bar{\Lambda}$ (Λ-bar), $E_{th} \sim 2200$ MeV

$\pi + \pi \rightarrow \pi + \pi + \Xi^- + \Xi^+$-bar, $E_{th} \sim 2600$ MeV

⇢ have to happen very early

⇢ by non-thermalised hadrons

Less efficient than production in QGP

Harder to reach equilibrium

Strangeness from the pp modeling perspective

In the Lund string model
[*Sjostrand, Mrenna, Skands,* JHEP 0605 (2016) 026,
N. Fischer, T. Sjostrand, JHEP 1701 (2017) 140]

- Confined colour fields described as strings with tension $\kappa = 1$ GeV/fm
- Hadrons given by breaking of strings
- Strangeness production determined by (which?) m_s

$$\mathrm{Prob}(m_q^2, p_{\perp q}^2) \propto \exp\boxed{\left(\frac{-\pi m_q^2}{\kappa}\right)} \exp\left(\frac{-\pi p_{\perp q}^2}{\kappa}\right)$$

Measurements of strange hadron production used as input for tuning Monte Carlo generators

⇢ Contribute to the understanding of underlying event arising from multi-parton interactions in pp, p-Pb collisions.
[P. Skands et al., EPJC 76(5) (2016) 1-12]

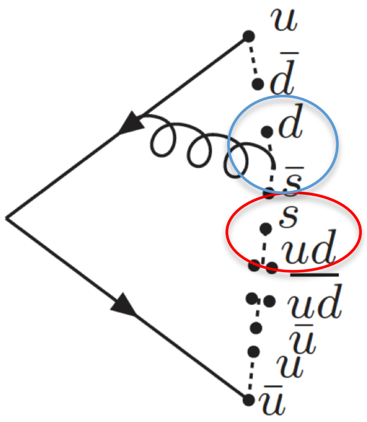
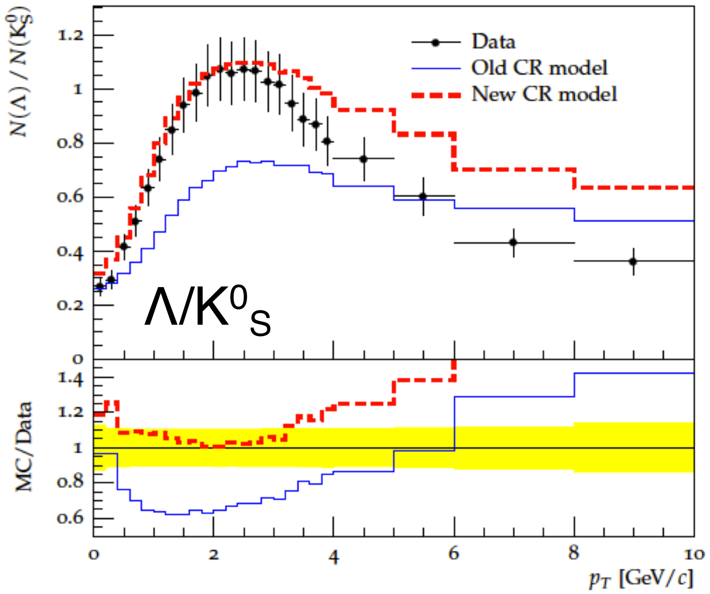


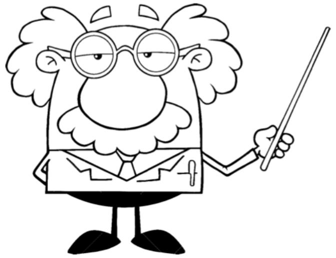
Figure by C. Bierlich

J.R. Christiansen, P. Skands, JHEP 08 (2015) 003



In heavy-ion collisions:
thermal production of strangeness at the QCD phase boundary
⇢ thermal properties of the medium

In pp collisions:
energy threshold and conservation of (strangeness) quantum numbers
⇢ production mechanisms and underlying event



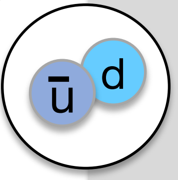
Experimental aspects

Strange hadron reconstruction with ALICE

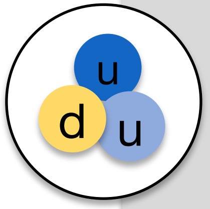
Centrality and multiplicity in ALICE

Strange and identified hadrons in ALICE

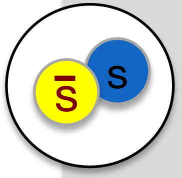
|S| = 0



π^-
M = 140 MeV
Primary*

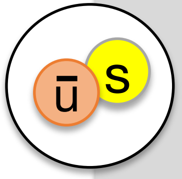


p
M = 938 MeV
Primary*

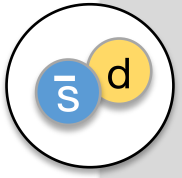


ϕ
M = 1020 MeV
$\phi \longrightarrow K^+K^-$ (48.9%)
$c\tau$ = 45 fm

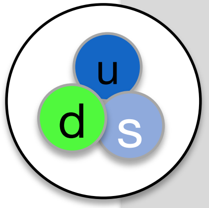
|S| = 1



K^-
M = 494 MeV
Primary*

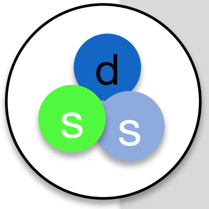


K^0_S
M = 497 MeV
$K^0_S \longrightarrow \pi^+\pi^-$ (69.2%)
$c\tau$ = 2.68 cm



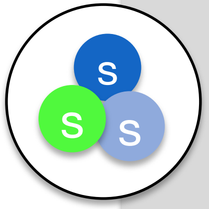
Λ
M = 1115 MeV
$\Lambda \longrightarrow p\pi^-$ (63.9%)
$c\tau$ = 7.98 cm

|S| = 2



Ξ^-
M = 1322 MeV
$\Xi^- \longrightarrow \Lambda\pi^-$ (99.9%)
$c\tau$ = 4.91 cm

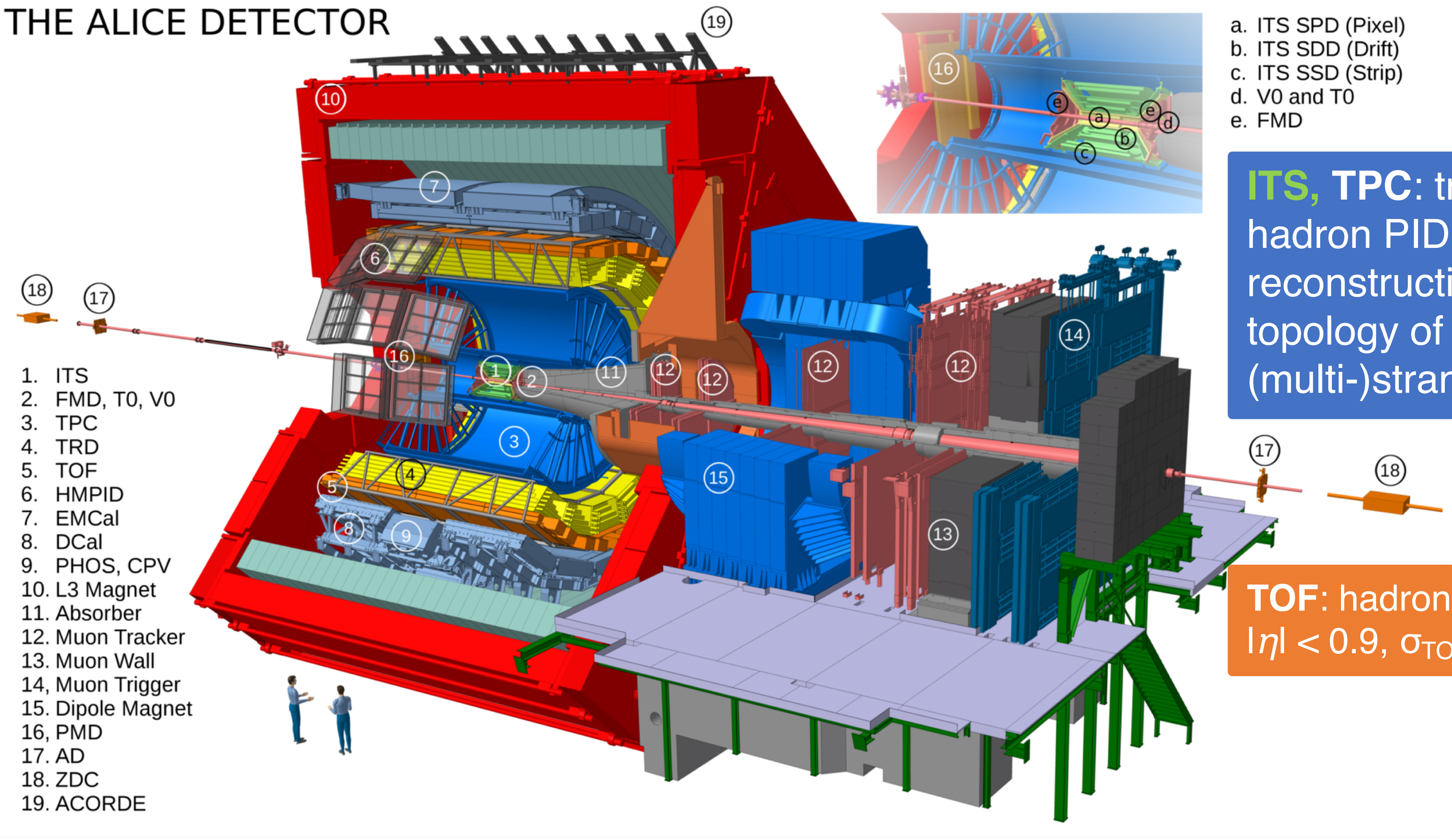
|S| = 3



Ω^-
M = 1672 MeV
$\Omega^- \longrightarrow \Lambda K^-$ (67.8%)
$c\tau$ = 2.46 cm

+ antiparticles + resonances (not today's topic…)

A Large Ion Collider Experiment at the LHC



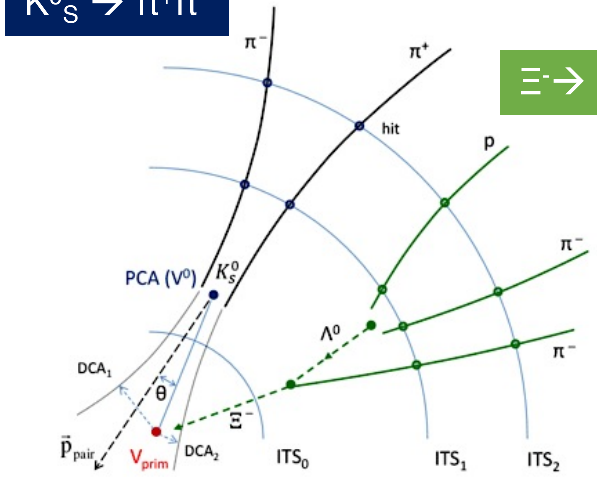
ITS, **TPC**: tracking, vertexing, hadron PID via d*E*/dx, $|\eta| < 0.9$, reconstruction of the decay topology of weakly-decaying (multi-)strange hadrons

TOF: hadron PID via Time-Of-Flight $|\eta| < 0.9$, $\sigma_{TOF} \sim 80$ ps

Multi-strange hadron reconstruction details

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

$\Xi^- \rightarrow \Lambda\pi^-$

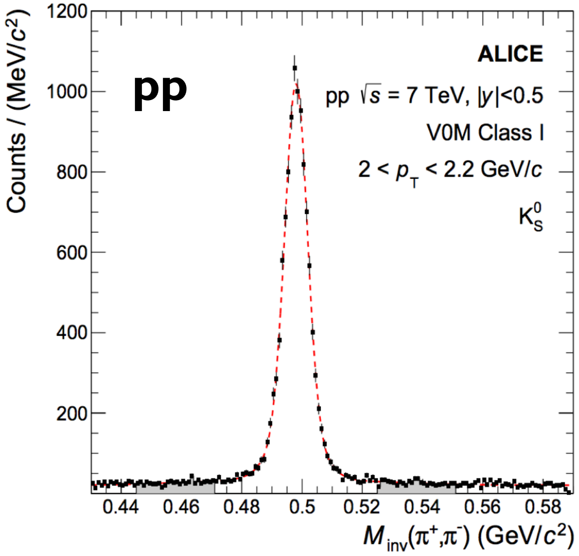


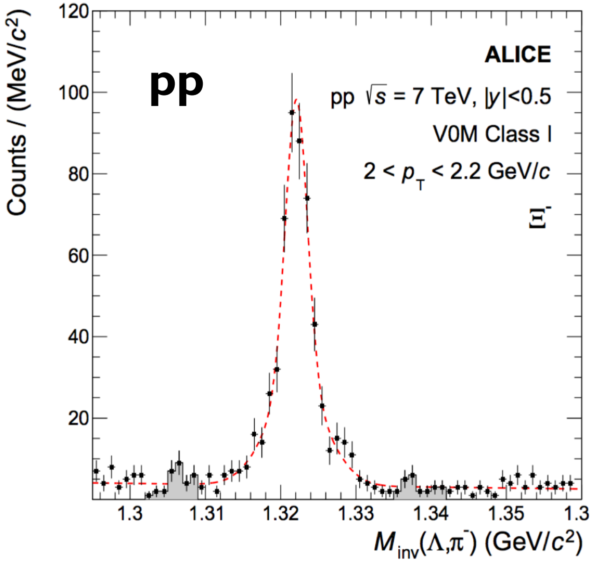
Reconstruction of the weak decay topology

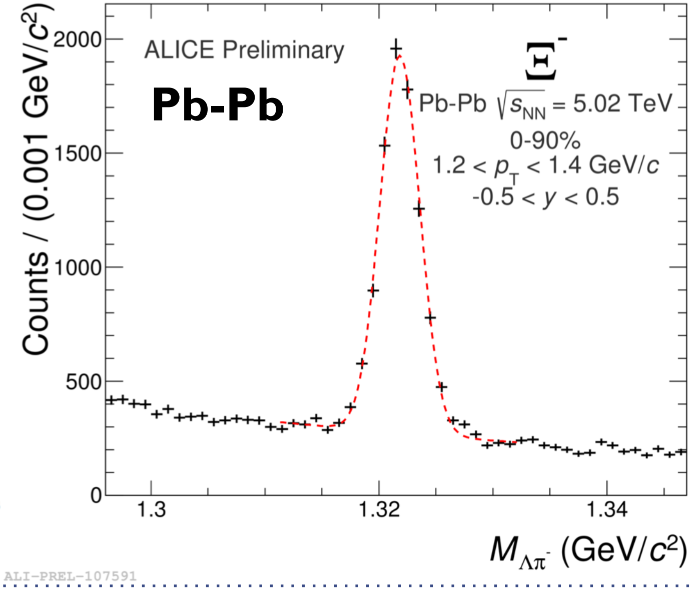
Yield extraction in each p_T bin:

- Fit polynomial + gaussian to get signal mean, σ
- Bin counting in the signal region (3σ)
- Fit background on side-bands
- Integral of background fit
- function in the signal region

⇢ Signal = Bin counting - Integral







Centrality

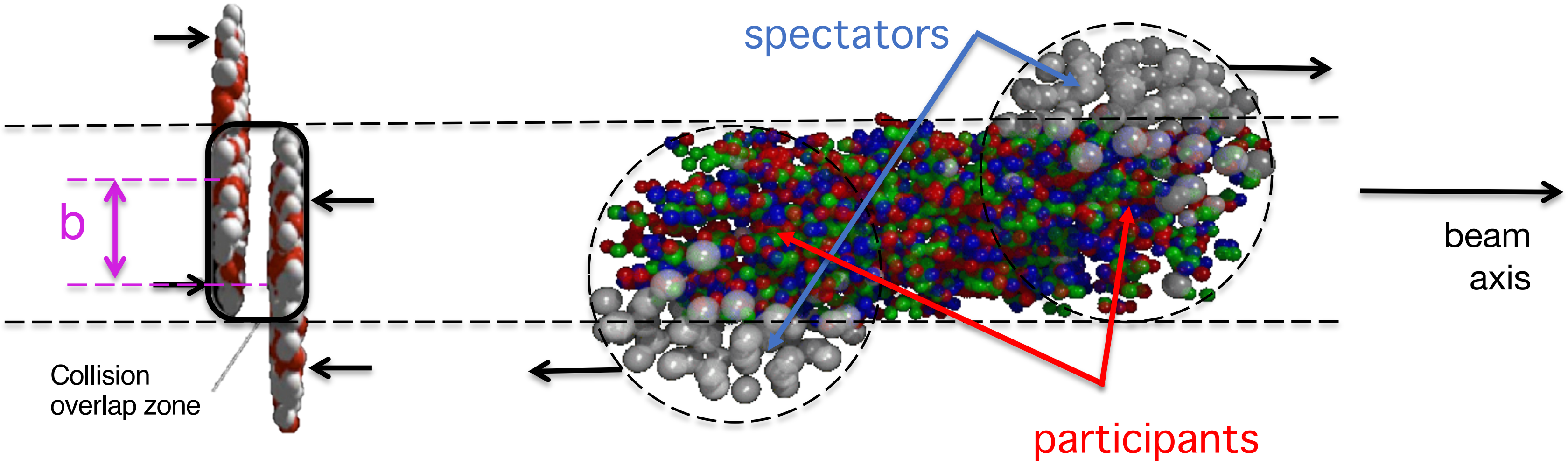
Centrality = fraction of the total hadronic cross section of nucleus-nucleus collisions
⇢ can be quantified by the impact parameter (**b**)

Peripheral collisions

- → Large impact parameter
- → Low particle multiplicity

Central collisions

- → Small impact parameter
- → High particle multiplicity



Centrality variables:

- N_{coll}, number of binary nucleon-nucleon collisions
- N_{part} (N_{wound}), number of participating (wounded) nucleons ⇢ energy available for particle production

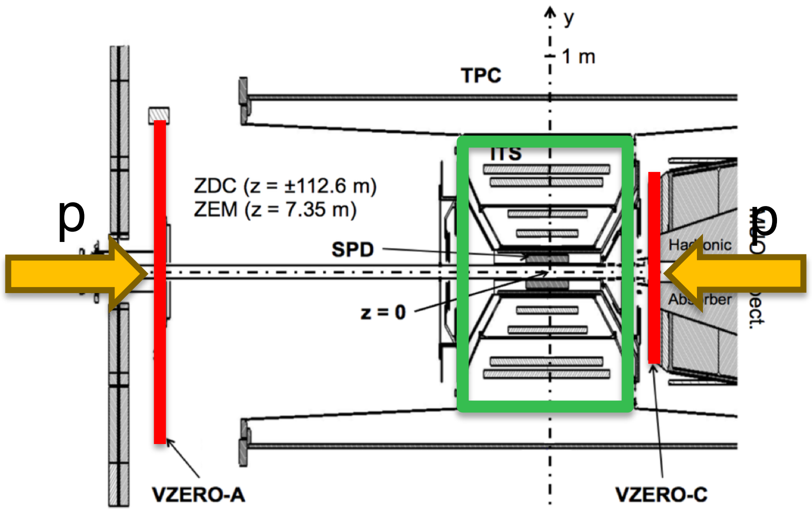
Event classes in Pb-Pb, p-Pb, pp

Event multiplicity/centrality classes are defined based on the amplitude measured in the V0 scintillators, placed at forward rapidity: $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C)

$\langle dN_{ch}/d\eta \rangle$ is measured in **SPD** in $|\eta| < 0.5$ to avoid "auto-correlation biases"

In **Pb-Pb** the Glauber* model is used to relate the V0A&V0C ("V0M") amplitude distribution to the geometry of the collision.

*[*M. L. Miller et al., An. Rev. Nucl. Part. Sci. 57 (2007) 205-243]*



At $\sqrt{s_{NN}} = 2.76$ TeV:

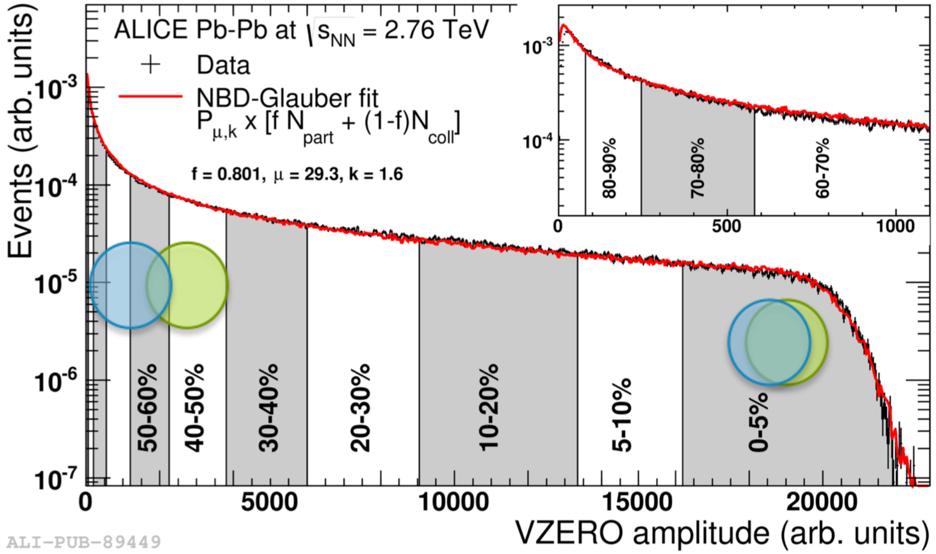
0-5%: $\langle dN_{ch}/d\eta \rangle = 1601 \pm 60$

$\langle N_{part} \rangle = 328.8 \pm 3.1$

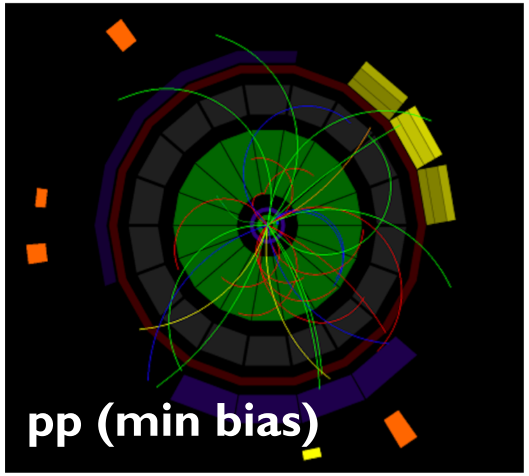
70-80%: $\langle dN_{ch}/d\eta \rangle = 35 \pm 2$

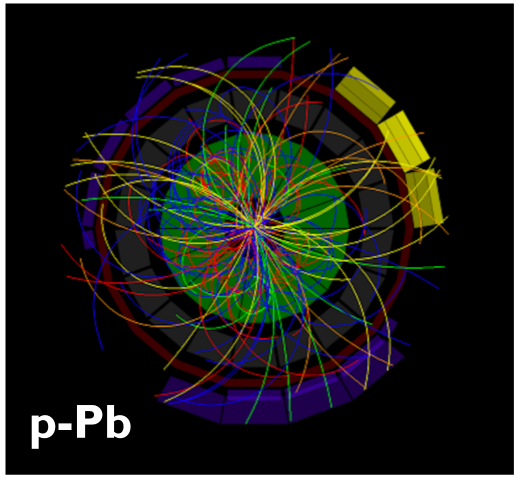
$\langle N_{part} \rangle = 15.8 \pm 0.6$

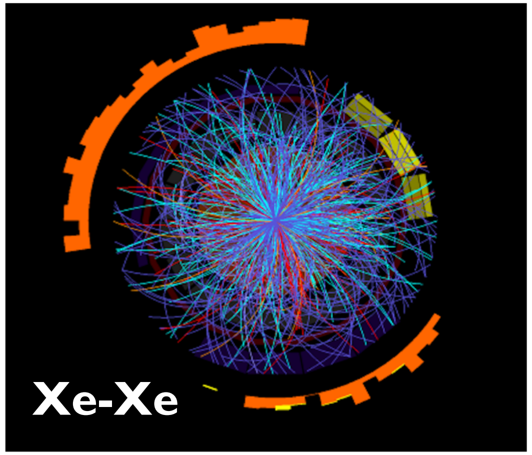
ALICE, PRL 106 (2011) 032301, PRC 91 (2015) 064905

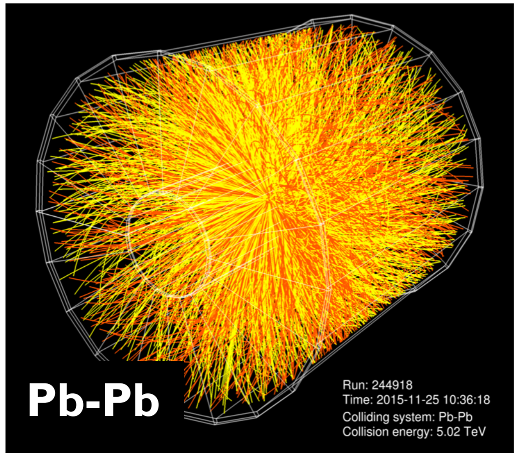


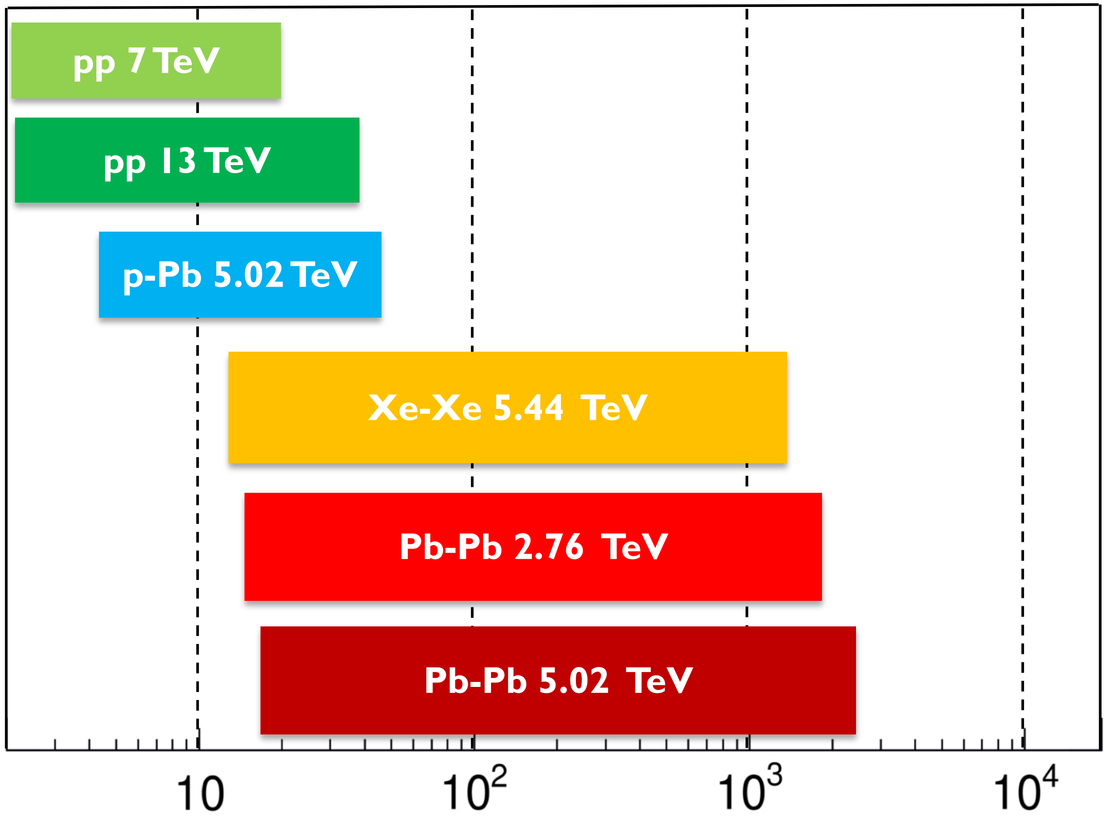
System size ⟺ charged particle multiplicity

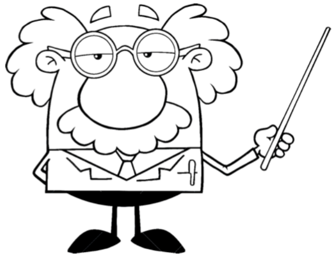








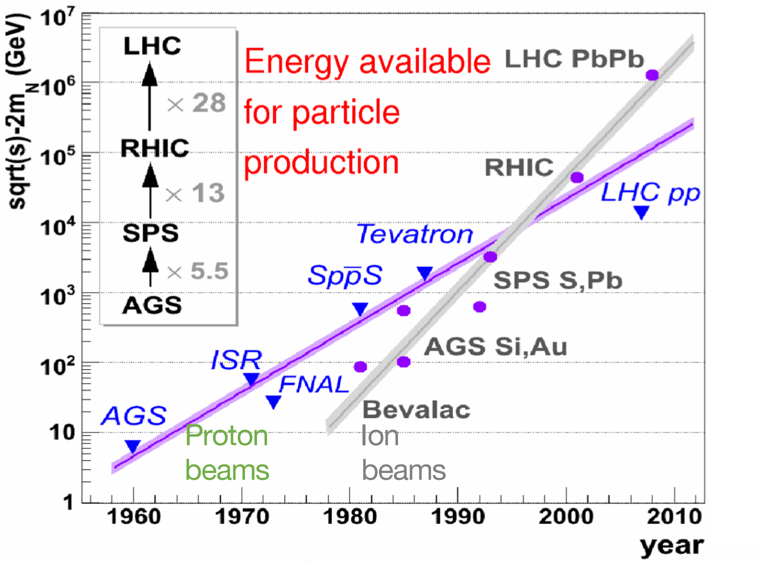


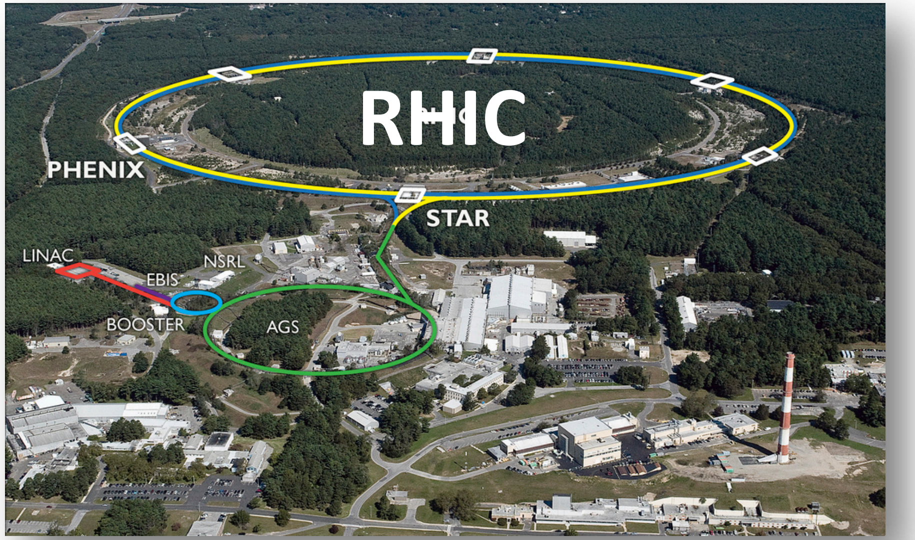


Small systems: pp, pA
Large systems: Pb-Pb, Xe-Xe

Experimental evidence of strangeness enhancement in heavy-ion collisions

30 years of heavy-ion collision experiments





Fixed target experiments:

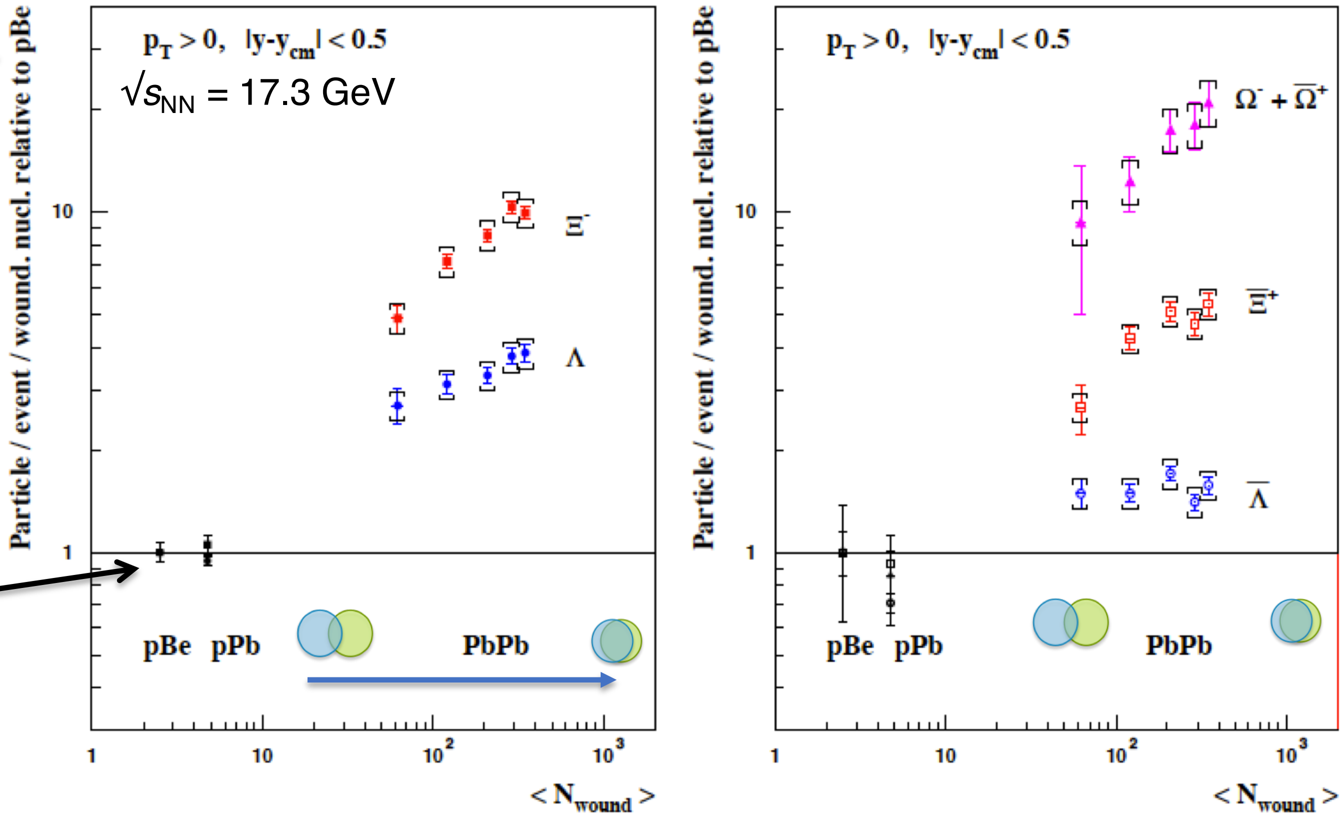
Bevalac @ LBL (1975-1986) √s <2.4 GeV
SIS @ GSI (1989-) √s <2.7 GeV
AGS @ BNL (1986-1998) √s <5 GeV
SPS @ CERN (1986-2003) √s <20 GeV
FAIR @ GSI (u.c.) √s <9 GeV

Collider experiments:

RHIC @ BNL (2000-) $\sqrt{s_{NN}}$ <200 GeV
[beam energy scan $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, and 62.4 GeV]
LHC @ CERN (Run I, 2009-2013) $\sqrt{s_{NN}}$=2.76 TeV
LHC @ CERN (Run II, 2015-2018) $\sqrt{s_{NN}}$=5.02 TeV

Observation of strangeness enhancement at SPS

NA57, J.Phys. G32 (2006) 427-442



Yields normalised to N_{wound} relative to p-Be

=> Not just an effect of having more participants in Pb-Pb!

p-Be used as a proxy for pp since N_{wound} is close to 2 (as in pp)

|S| = 3

|S| = 2

|S| = 1

Enhancement observed in Pb-Pb collisions wrt p-Pb, p-Pb for multi-strange (anti)baryons

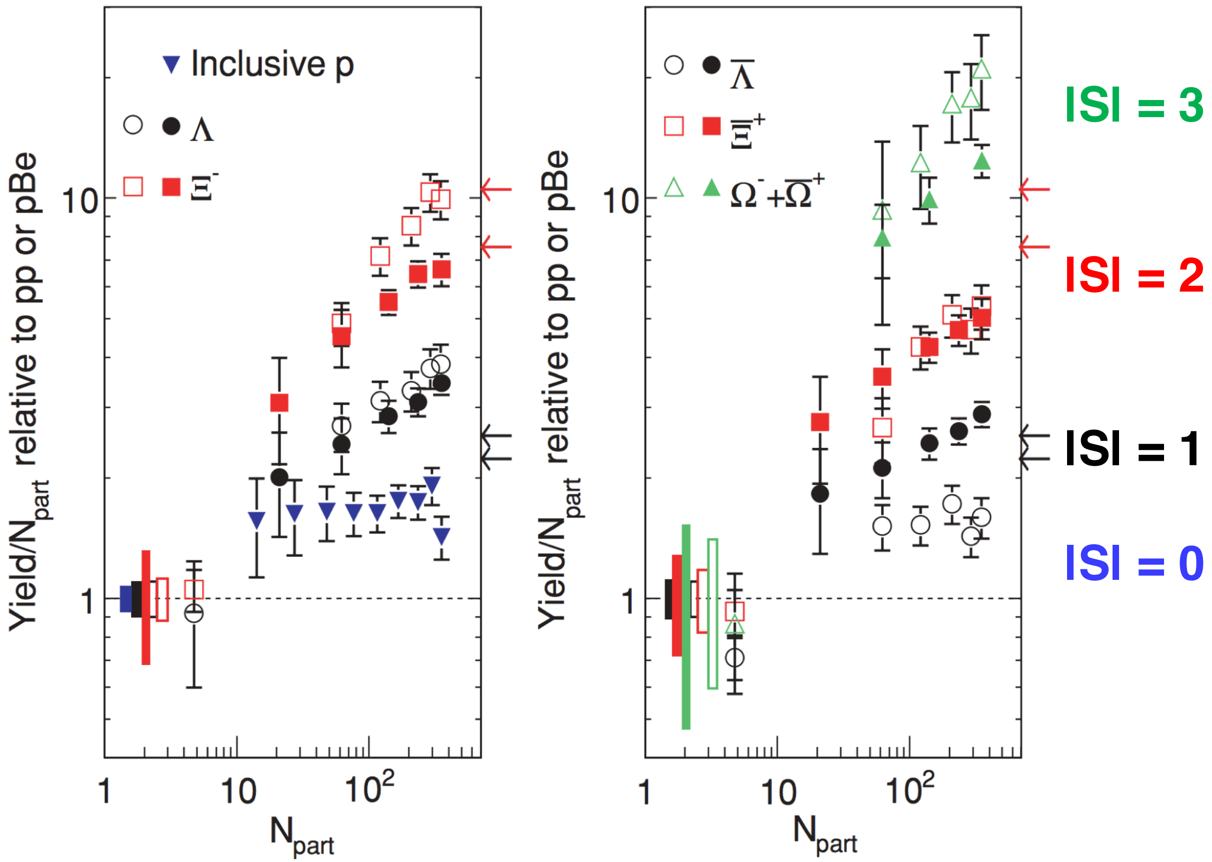
⇢ Anti-baryons less enhanced than baryons ⇢ quarks (not anti-quarks!) in the initial stage

⇢ **Hierarchy** of the enhancement with the strangeness content

⇢ **Increase** of the enhancement with the **centrality** of the collision

From SPS to RHIC

STAR, Phys. Rev. C 77, 044908 (2008)



Open symbols: NA57, $\sqrt{s_{NN}}$ = 17.3 GeV
Full symbols: STAR, $\sqrt{s_{NN}}$ = 130 GeV

Enhancement observed also at RHIC

Smaller effect for higher collision energy

Multiplicity per N_{part} saturates earlier in AA than in pp

Enhancement vs canonical suppression

Strange quarks are more abundantly produced
in nucleus-nucleus than in pp/pA collisions

Strangeness enhancement

[J. Rafelski and B. Muller, PRL 48 (1982) 1066]

Historically proposed as a first signature of the presence of a deconfined Quark Gluon Plasma where **strangeness is produced thermally** (mainly) by equilibrated gluons

Canonical suppression

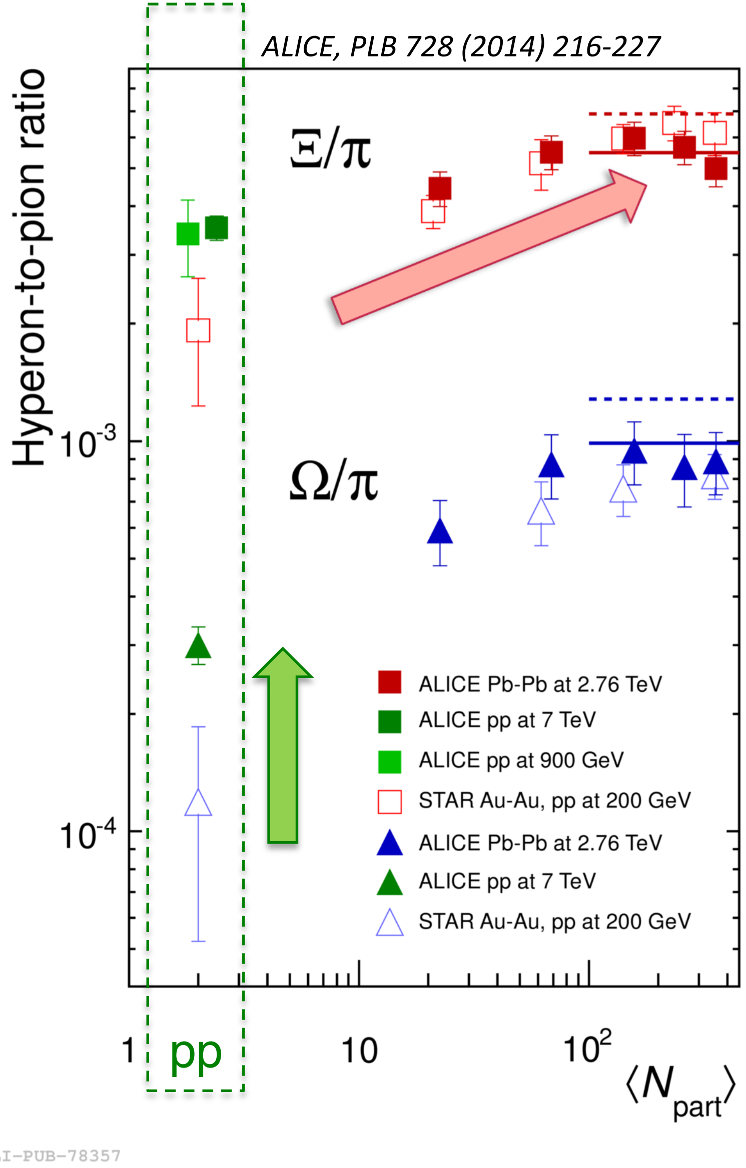
[K. Redlich, A. Tounsi, Eur. Phys. J. C 24, 589–594 (2002)]

suppression of production due to canonical quantum number conservation law i.e. **strangeness has to be conserved locally in a finite system**

⇢ Reduced phase space available for particle production

⇢ Relaxation of canonical suppression with increasing √s (and number of particles)

From RHIC to LHC



ALICE, PLB 728 (2014) 216-227

RHIC: $\sqrt{s_{NN}}$ = 200 GeV
LHC: $\sqrt{s_{NN}}$ = 2.76 TeV

In **pp collisions** the production of strangeness relative to π at LHC is larger than at RHIC
⇢ **crucial to understand the small system "reference"!**

From pp to Pb-Pb strangeness production increases

For N_{part} >150 the ratios saturate and match predictions from the grand-canonical statistical hadronisation models

——— GSI-Heidelberg: T_{ch} = 164 MeV *[Andronic et al, PLB 673 (2009) 142]*
-------- THERMUS: T_{ch} = 170 MeV *[Cleymans et al, PRC 74 (2006) 034903]*

In addition, a more recent fit with T_{ch} = 156 MeV…

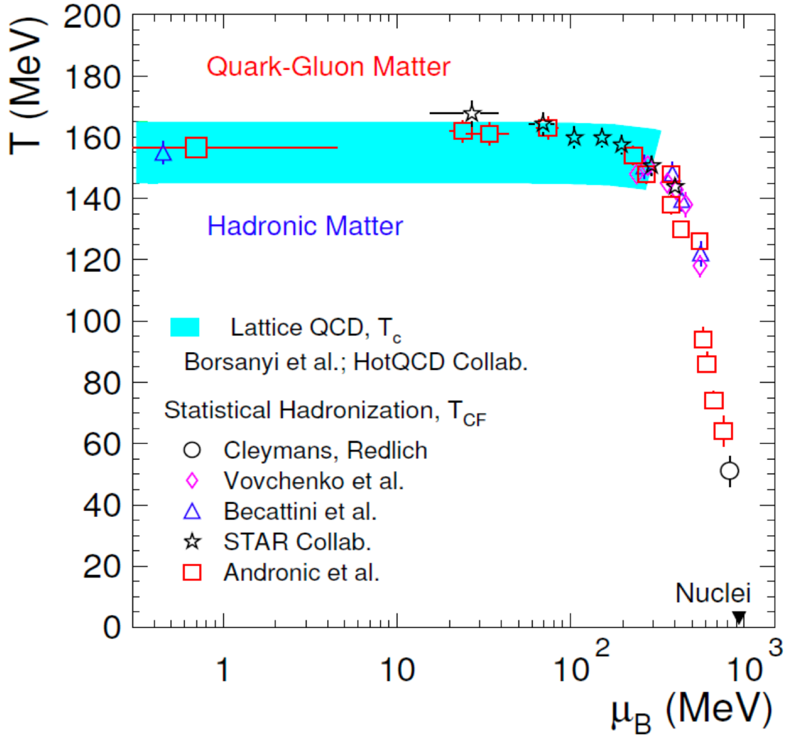
Statistical hadronisation model in a nutshell

Thermal fits map heavy-ion collisions to the QCD phase diagram and allow for comparison with lattice-QCD

Conventional picture: (ideal) hadron-resonance gas model in **chemical equilibrium** (based on **Grand Canonical ensemble**)

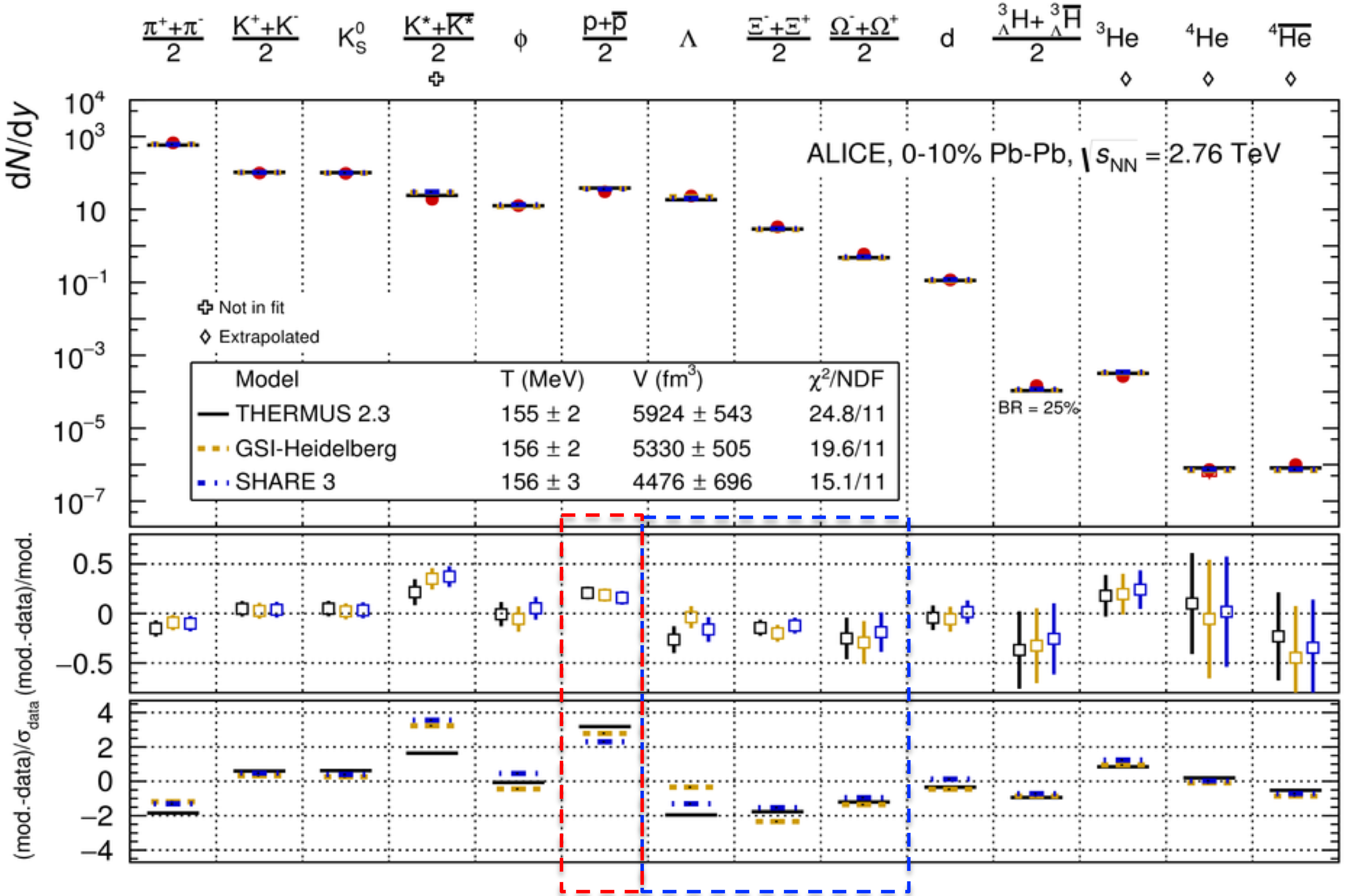
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}$$

- Measured particle yields (or ratios) are input to the fits
- Fit to yields: parameters μ_B, T_{ch}, V
- Thermal model fit to yield ratio: V cancels out
- Fits based on minimization of χ^2
- Deviations from (GC) equilibrium through empirical under(over)-saturation parameters for strange, charm or light quarks (γ_s, γ_c, γ_q)



A. Andronic et al., Nature 561, 321 (2018)
V. Vovchenko, LIGHT UP workshop 2018

Thermal model fit to Pb-Pb 2.76 TeV (0-10%)

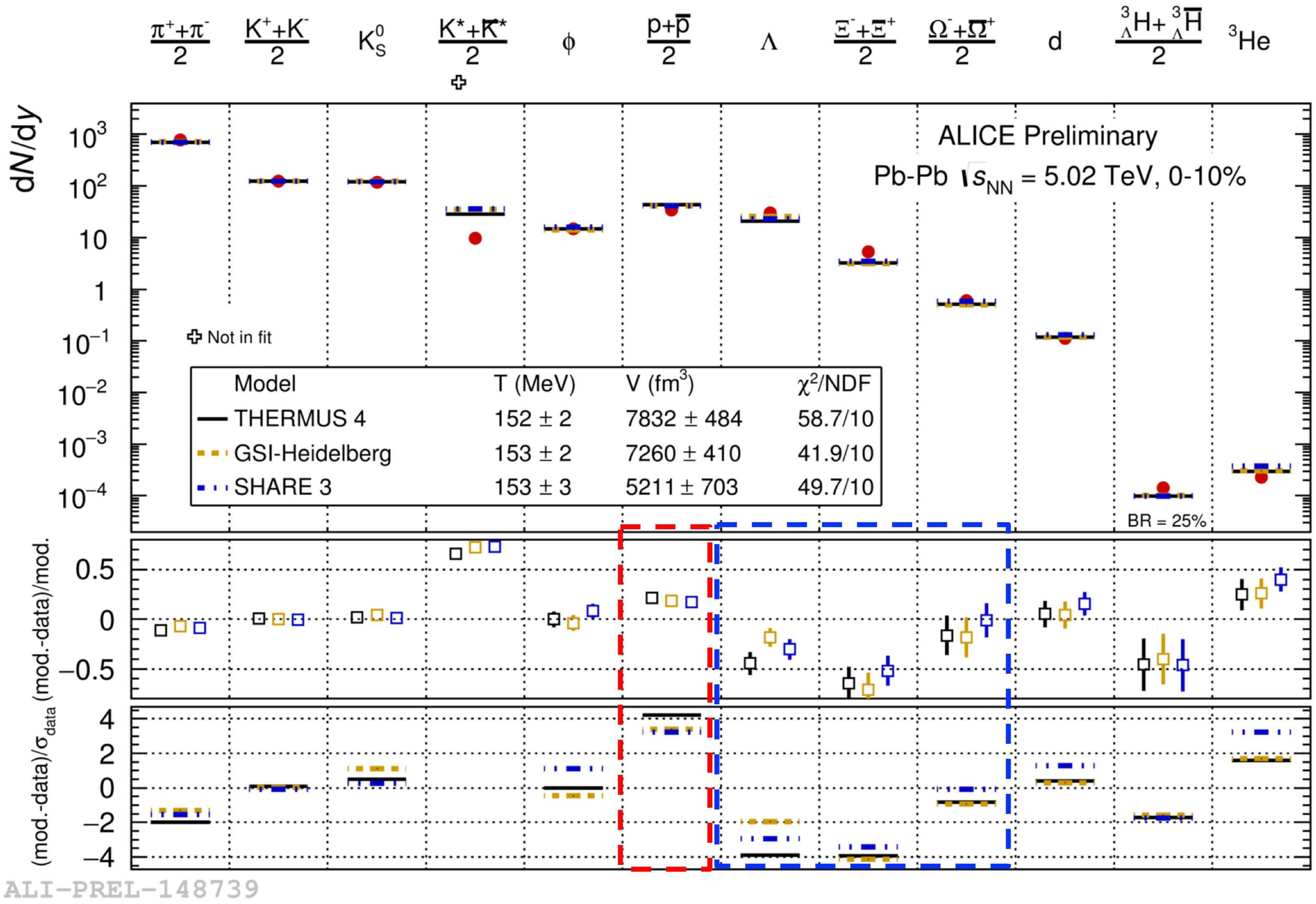


Production of (most) light-flavour hadrons (and anti-nuclei) described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature, **$T_{ch} \approx 156$ MeV**

⇢ Tensions between protons and multi-strange (tend to drive T_{ch} in opposite directions)

Figure from ALICE, Nucl. Phys. A 971 (2018) 1-20
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 (2011) 142
SHARE: Petran et al, arXiv:1310.5108

Thermal model fit to Pb-Pb 5.02 TeV (0-10%)



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

Preliminary ALICE data in **0-10% Pb-Pb at 5.02 TeV** can be fitted with a slightly lower temperature,
T ≈ 153 MeV
and higher χ^2/ndf ~ 4-6

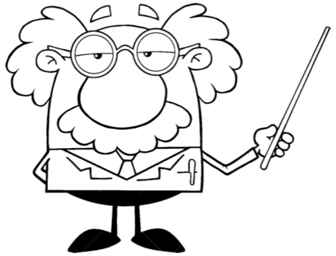
Tensions between protons and multi-strange are confirmed at the new energy

→ Strange particles prefer a higher temperature?

Figure from FB talk at Quark Matter 2018
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 (2011) 142
SHARE: Petran et al, arXiv:1310.5108

Strange quarks are observed to be more abundantly produced in nucleus-nucleus than in pp/pA collisions
→ strangeness enhancement in AA or canonical suppression in pp/pA?

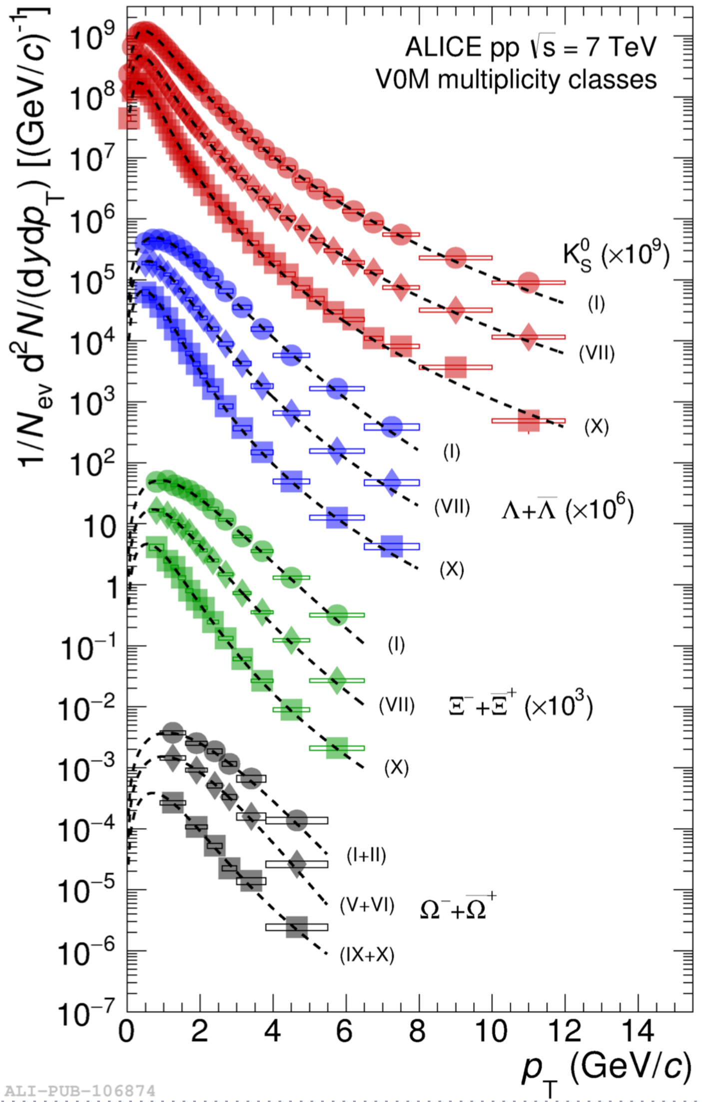
In thermal model fits with a single chemical freeze-out temperature, some tension is observed between protons and strangeness



Observation of strangeness enhancement in high-multiplicity pp, p-Pb collisions

Strange hadron p_T spectra - Multiplicity dependence

ALICE, Nature Physics 13 (2017) 535-539



p_T differential yields of strange and multi-strange measured in 10 multiplicity bins

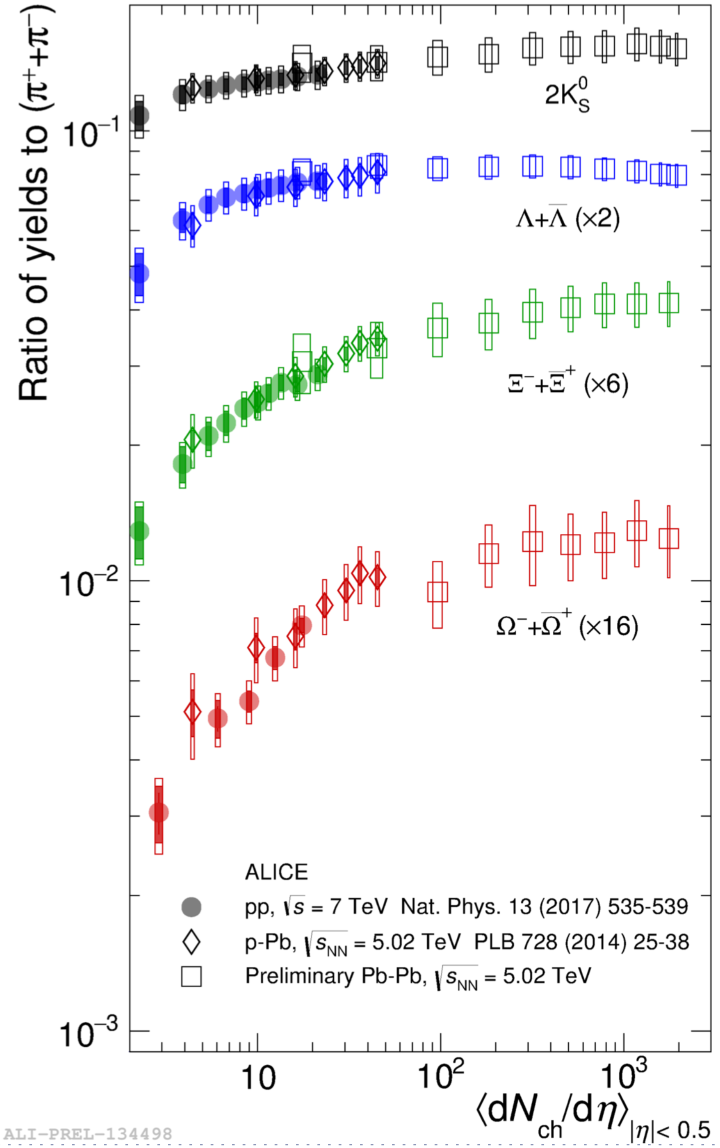
$$\begin{cases} \boldsymbol{I \rightarrow \langle dN_{ch}/d\eta\rangle \approx 3.5\times\langle dN_{ch}/d\eta\rangle^{INEL>0}} \\ \vdots \\ \boldsymbol{X \rightarrow \langle dN_{ch}/d\eta\rangle \approx 0.4\times\langle dN_{ch}/d\eta\rangle^{INEL>0}} \end{cases}$$

$$\left(\boldsymbol{\langle dN_{ch}/d\eta\rangle^{INEL>0} \approx 6.0} \right)$$

Spectra harden towards higher multiplicity (as observed in p-Pb and Pb-Pb)

p_T integrated yields extracted from measured points and extrapolation function at low p_T
(dashed line = Lévy-Tsallis function)

Strange hadron-to-π ratio - Multiplicity dependence



Multi-strange to non-strange yield ratios **increase significantly and smoothly with multiplicity** in pp and p-Pb collisions until saturation in Pb-Pb
[ALICE, Nature Physics 13 (2017) 535-539]

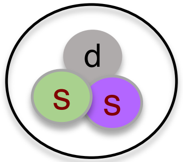
pp and p-Pb trends are remarkably consistent at similar multiplicities

⇢ *What is driving the increase in small systems (mass, baryon/meson, strangeness content)?*

⇢ *Can models reproduce the observations?*

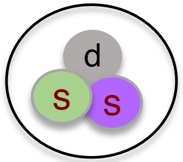
Not a mass nor baryon/meson effect

Ξ

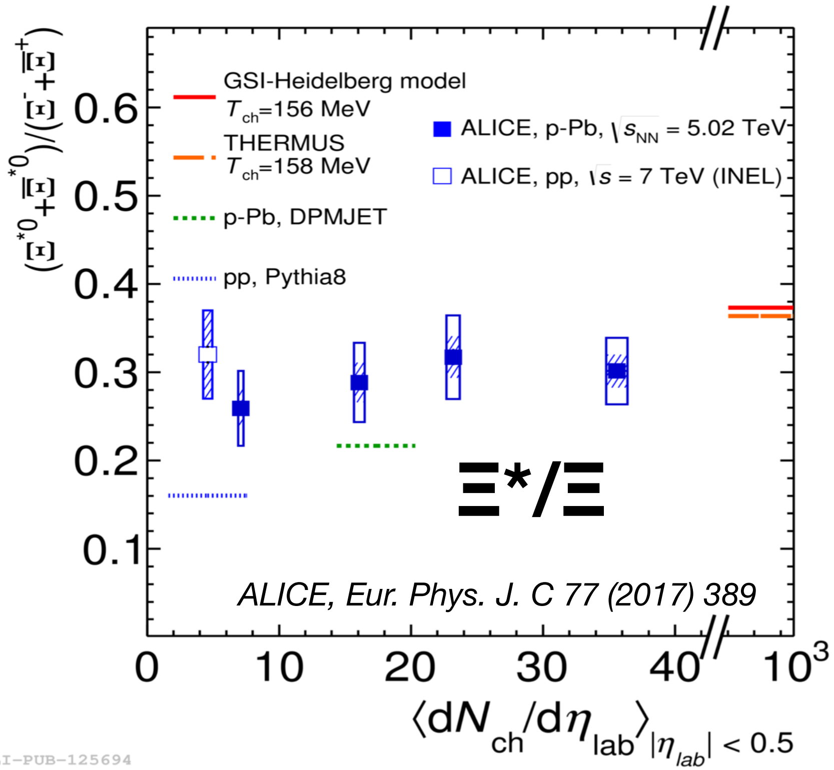


$m \sim 1320$ MeV

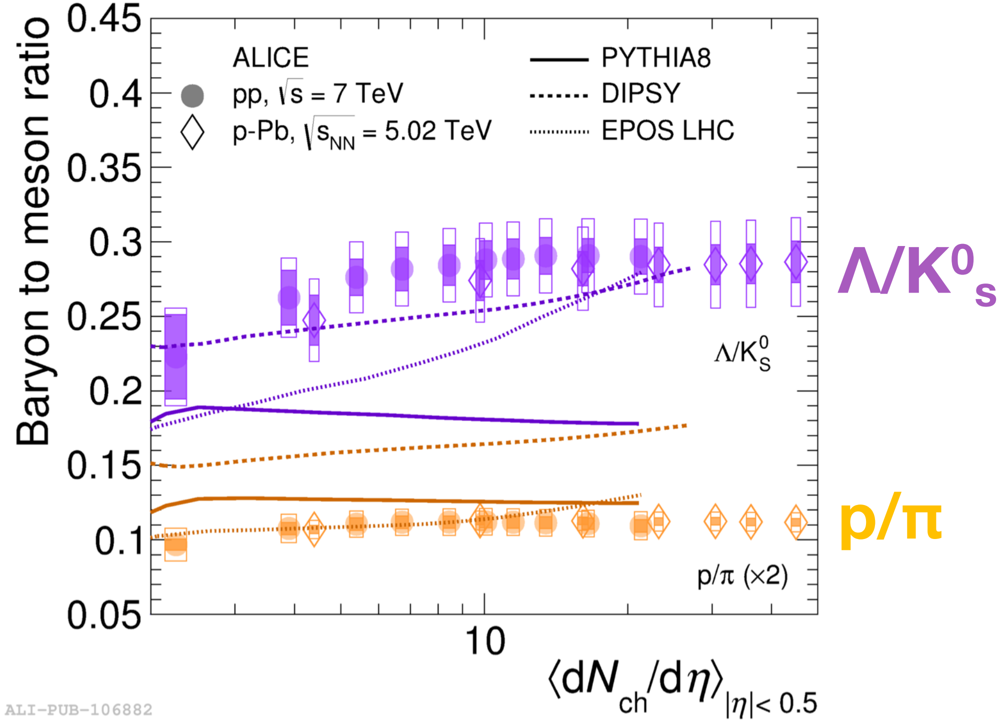
Ξ*



$m \sim 1530$ MeV



ALICE, Eur. Phys. J. C 77 (2017) 389



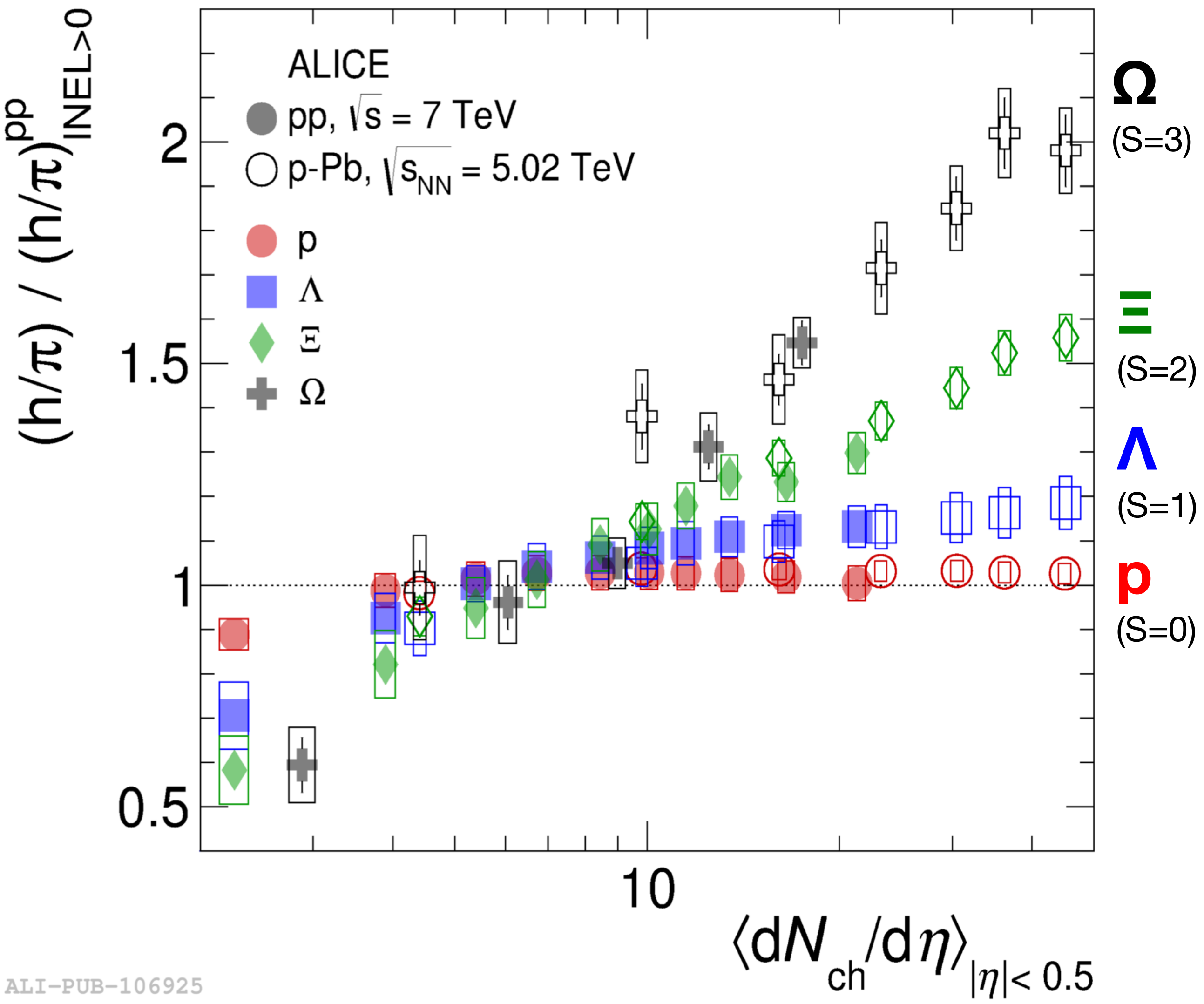
Ξ(1530)^0 relative to π exhibits same increase with multiplicity in p-Pb as Ξ/π (Ξ*/Ξ flat)

⇢ Strangeness content more relevant than mass

Baryon-to-meson ratios where the net strangeness content is zero, as p/π and Λ/K^0_S, are flat with multiplicity

⇢ Not a baryon/meson effect

Strangeness enhancement in pp

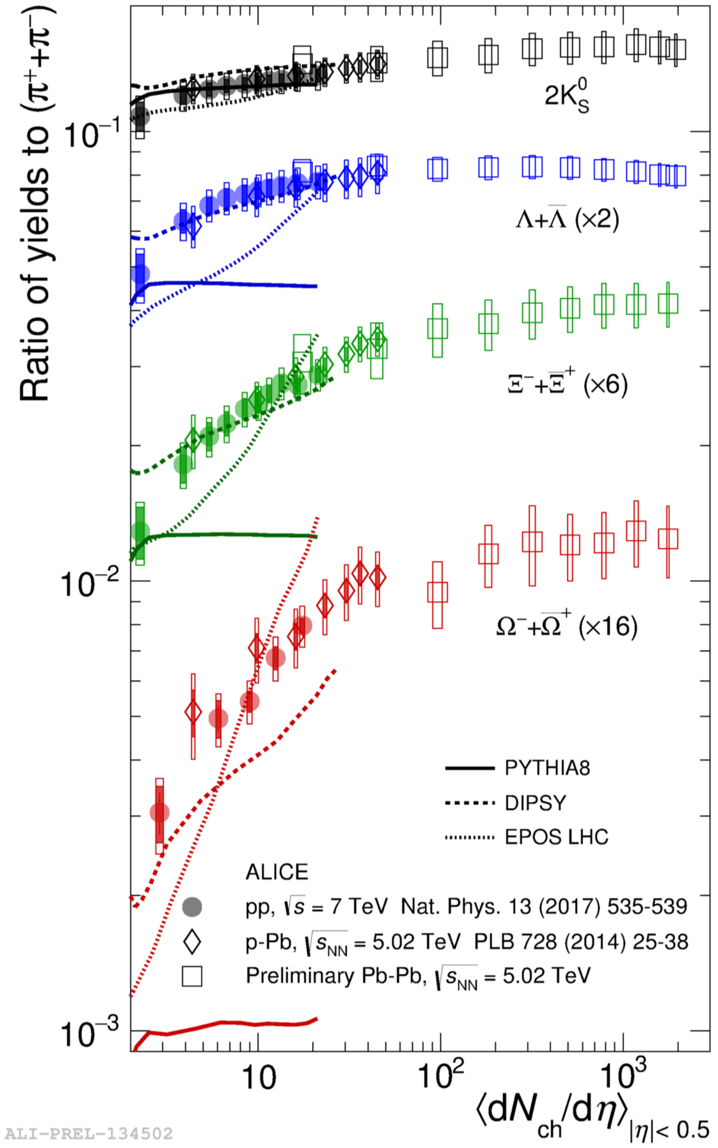


ALI-PUB-106925

No increase for p/π is observed

Hierarchy of the increase associated **with the strangeness content**

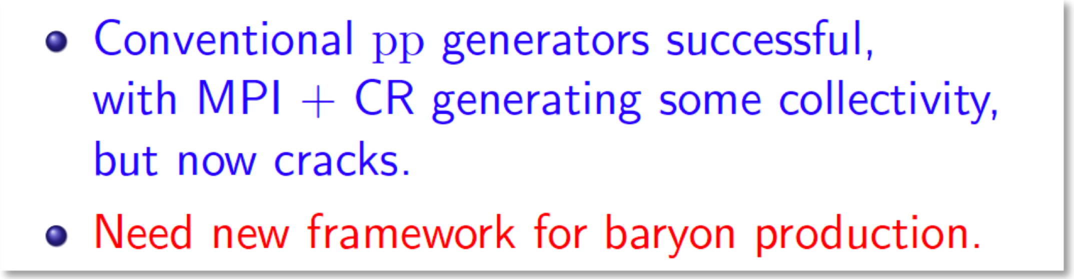
A “crack” in conventional pp generators



QCD-inspired models as

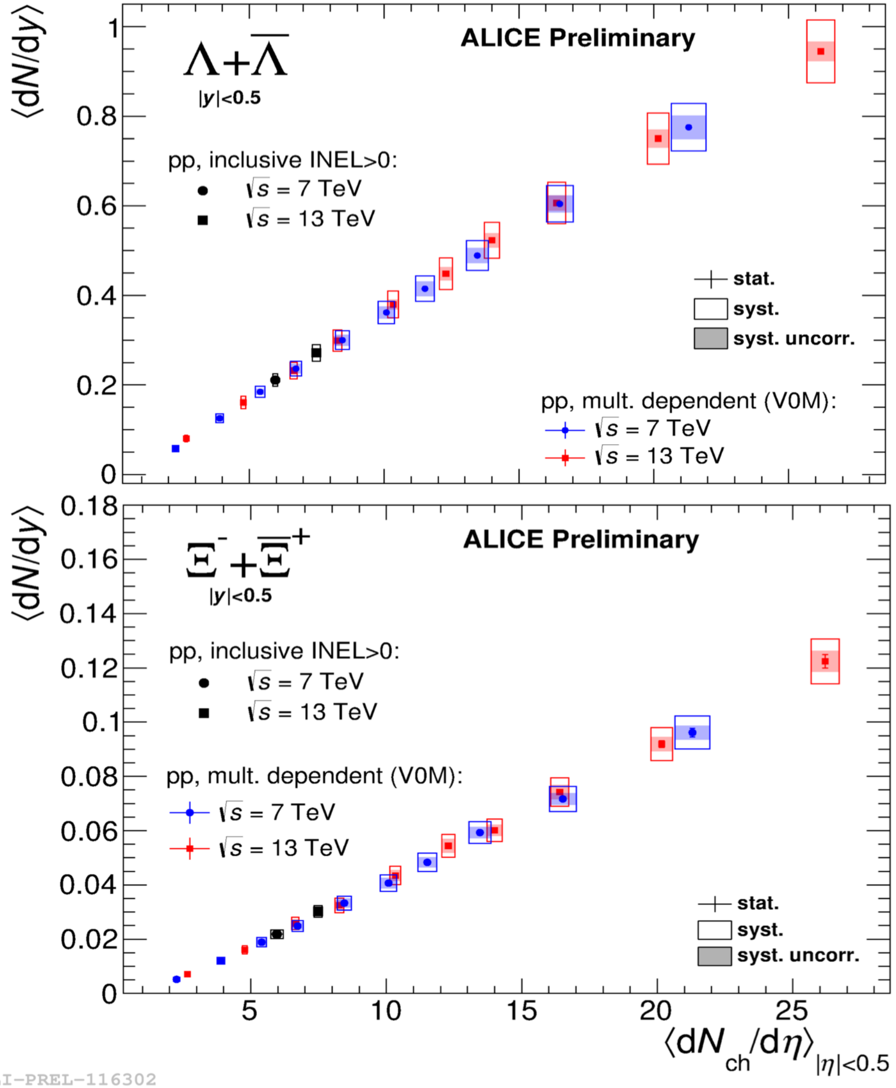
- PYTHIA8 (color reconnection)
  [T. Sjöstrand et al, Comput. Phys.Commun. 191 (2015) 159]
- DIPSY (color ropes)
  [C. Bierlich et al., JHEP 1503 (2015) 148]
- EPOS LHC (core+corona)
  [K. Werner et al., NPA 931 (2014) 83]

exhibit a trend with multiplicity but may still need tuning to reproduce all ratios simultaneously


- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.

T. Sjostrand, talk at Quark Matter 2018

Disentangle multiplicity and energy dependence



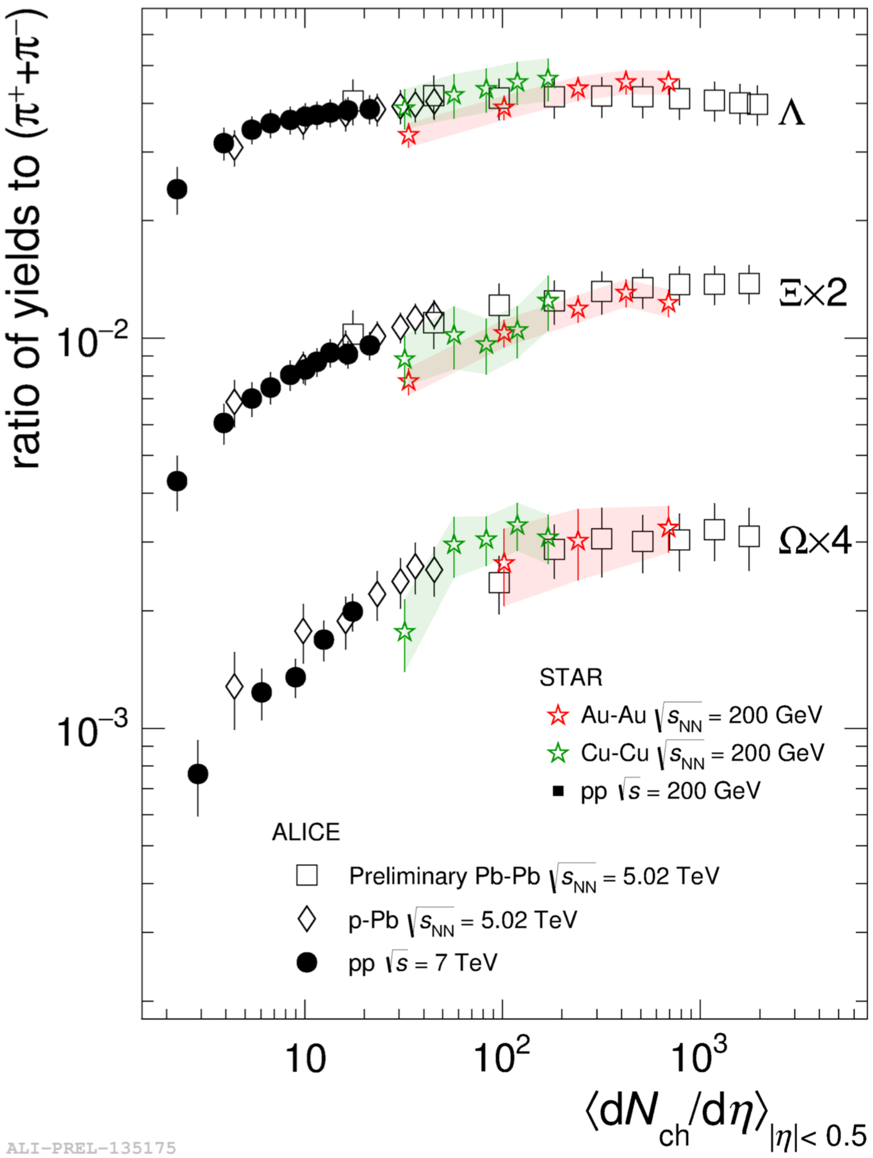
ALI-PREL-116302

Measurements in pp at 13 TeV can be used to disentangle multiplicity and energy dependence of particle production

Yields of (multi-)strange particles measured in pp 13 TeV as a function of multiplicity lie on the same trend as the 7 TeV data

⇢ Event activity drives particle production, irrespective of collision energy

Disentangle multiplicity and colliding-nucleus dependence



At RHIC, different colliding nuclei have been used (**Cu** and **Au**)

[STAR, Phys. Rev. Lett. 108 (2012) 72301]

Particle ratios in Cu-Cu, Au-Au, Pb-Pb and high multiplicity p-Pb are consistent at similar multiplicities

⇢ Event activity drives particle production, irrespective of colliding-nucleus species

⇢ New data in Xe-Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV from ALICE being analysed

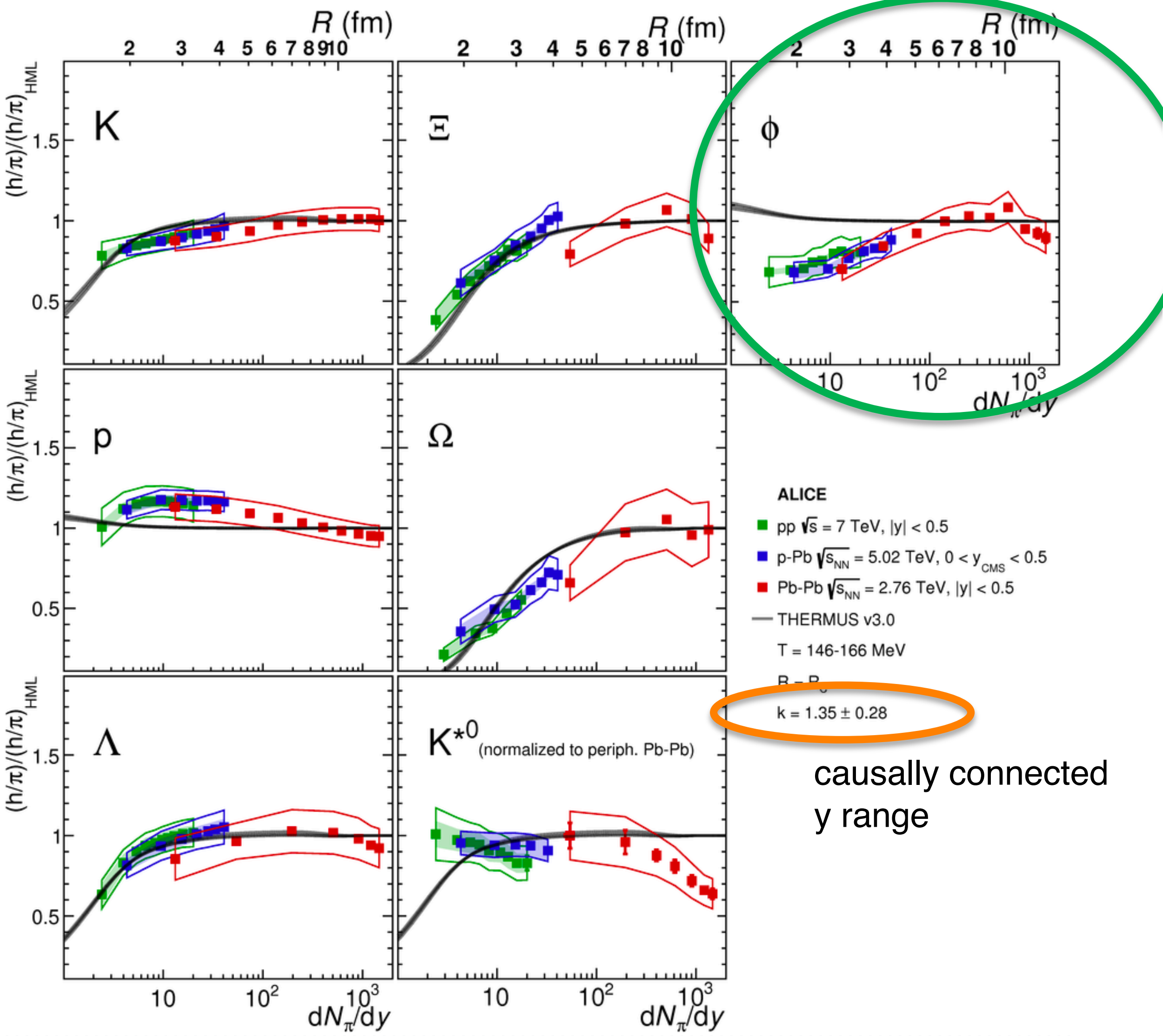
Strangeness canonical suppression

In equilibrium SHM models strangeness enhancement is a result of the canonical suppression of strangeness production in small systems due to the explicit conservation of the strangeness quantum number in a finite system

Comparison to model calculations based on THERMUS code

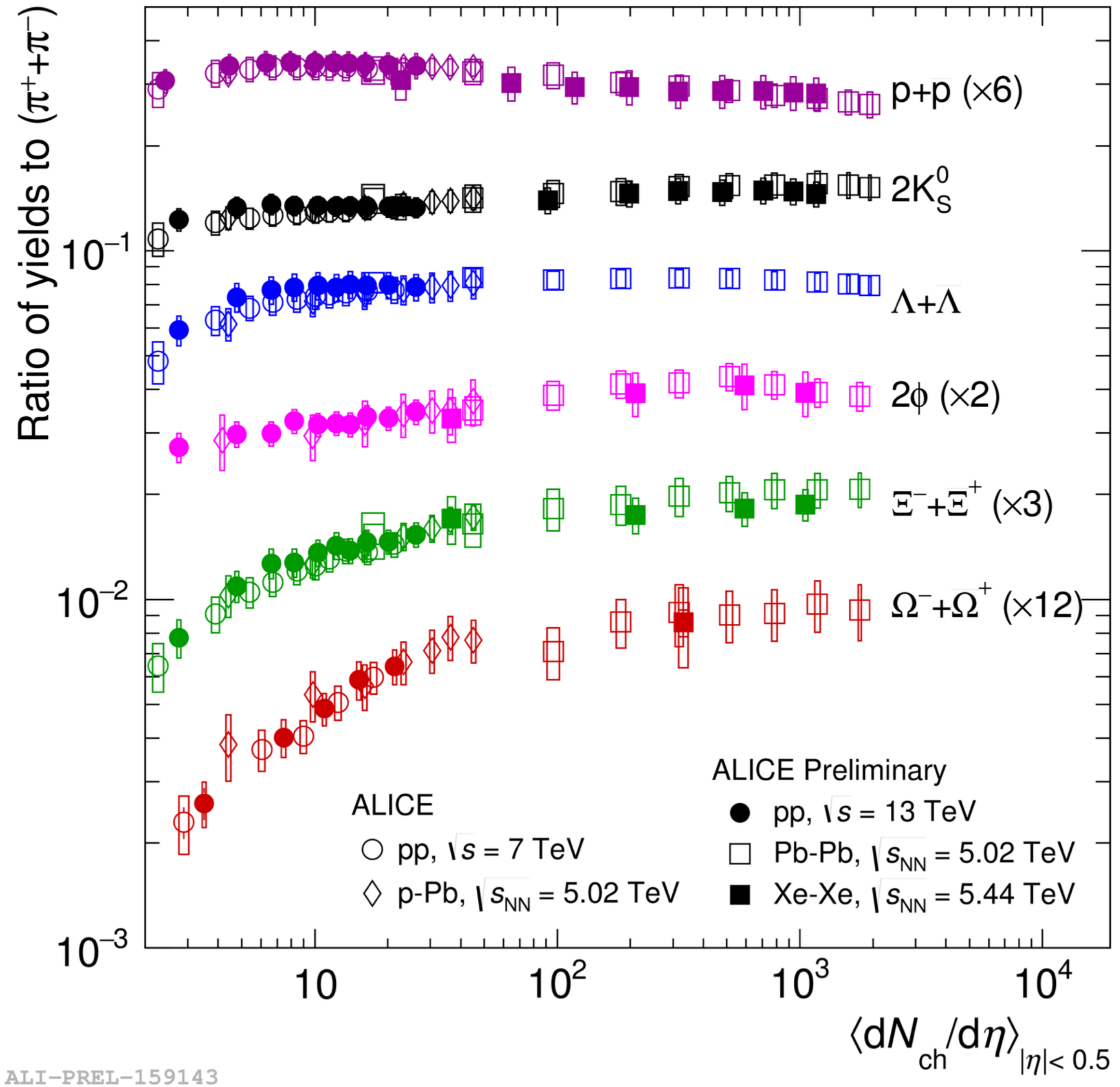
⇢ agreement with data within uncertainties, except for ϕ meson (also “immune” to canonical suppression)

ALICE, arXiv:1807.11321 (submitted to PRC)



causally connected y range

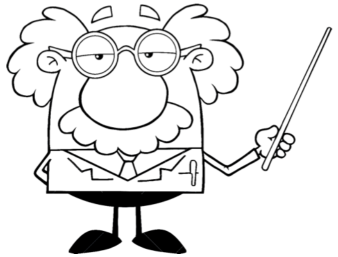
System size evolution of hadrochemistry



ALI-PREL-159143

Particle composition evolves smoothly across collision systems, depending on charged particle multiplicity.
→ Common origin in all systems?

For MC generators, work is still needed to reproduce evolution with system size in view of a unified description of all collision systems



Outlook

What’s next?

Does strangeness keep increasing with multiplicity in pp or saturate?

⇢ Measure in high multiplicity-triggered data sample of pp 13 TeV (2016, 2017), in p-Pb at 8.16 TeV

⇢ Bridge with Xe-Xe at 5.44 TeV, more differential in peripheral Pb-Pb collisions (2018)

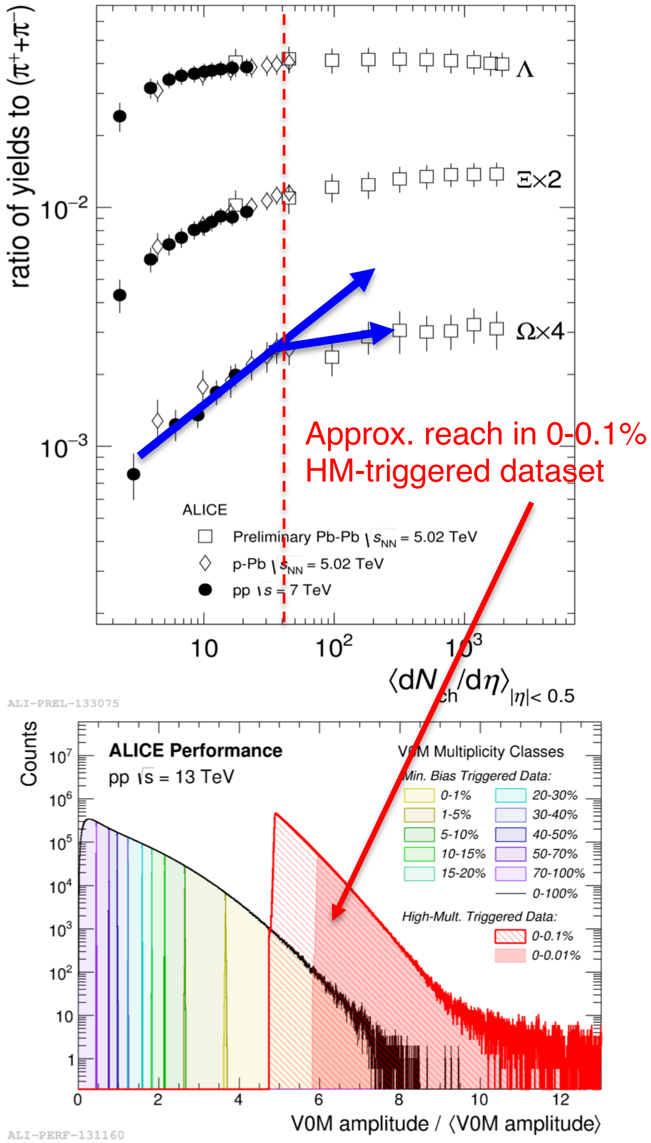
Can we relate high multiplicity with soft- or hard-QCD dominated processes?

⇢ Use event shapes as tools to select jetty/isotropic events in high multiplicity pp

Can the ϕ meson provide further insights on strangeness production vs multiplicity?

⇢ Measure more differential (event shapes?), improve precision

New observables…



Approx. reach in 0-0.1% HM-triggered dataset

A personal outlook…

The **intriguing similarities** among different systems do not end here but **extend to the dynamics** (see e.g. *FB, talk at LHCP 2018)*:

- Presence of collectivity (flow) is established in Pb-Pb
- we observe collectivity in small systems, whose origin and phenomenology is under investigation

What is next?

- Go to higher multiplicity in pp (more "extreme" events) and
- Go more differential

⇢ **Do we have an handle on the onset of deconfinement?**

pp used to be a reference for p-Pb and Pb-Pb collisions, now they look more alike than we thought

⇢ **Shall we "re-think" the reference (and how)?**

⇢ **Can we describe pp, p-Pb and Pb-Pb with a common framework?**

"From small to large systems" OR "from large to small systems"?

→ **QCD at high energy and density!**

Thank you

For more discussion:
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