# Open Questions in the Understanding of Strangeness Production in HIC

# Experiment

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Goethe-University of Frankfurt

17th International Conference on Strangeness in Quark Matter
Utrecht, Netherlands, July 10th – 15th, 2017

# Outline

**Strangeness in nucleus-nucleus collisions**
Energy dependence of strangeness enhancement
High and low (sub-threshold) energies ⇒ intermediate energies?

**Understanding of small systems**
Role of pp collisions
Multiplicity dependence of strangeness production in pp and pA

**Strangeness production in A+A collisions at low energies**
Microscopic (had. cross sections, potentials) vs. macroscopic (thermal) picture
Role of the $\phi$ meson

**Hyperon interaction and hypernuclei**
Understanding of hyperon-hyperon interaction
Thermal description of hypernuclei production
Possible modifications of hyperon properties in nuclei (lifetime, branching ratios, …)

# Overview on Strangeness Measurements

Experiments

**GSI-SIS**

FOPI, KAOS, <u>HADES</u>

**BNL-AGS**

E866, E877, E891, E895, …

**CERN-SPS (Pb beam)**

WA97, NA44, NA45, NA50

NA49, NA57, <u>NA61</u>

**BNL-RHIC**

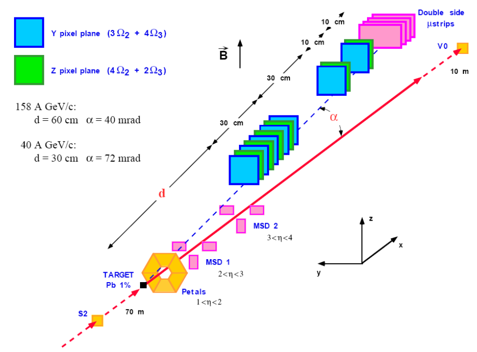
<u>STAR</u>, PHENIX, BRAHMS

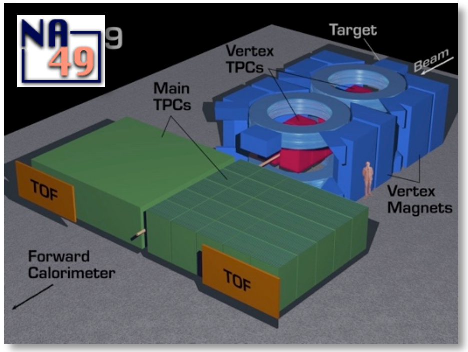
**CERN-LHC**

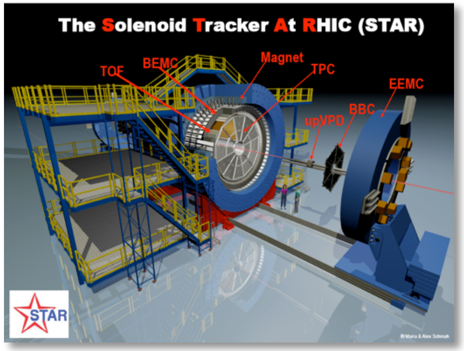
<u>ALICE</u>

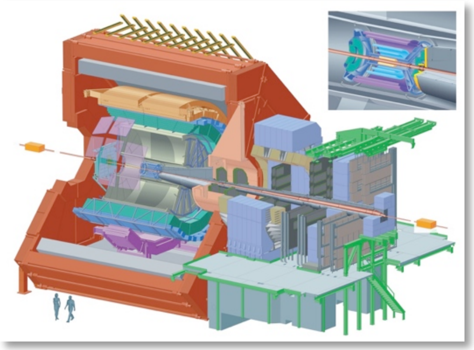
**New low energy programs**

CBM@FAIR, NICA



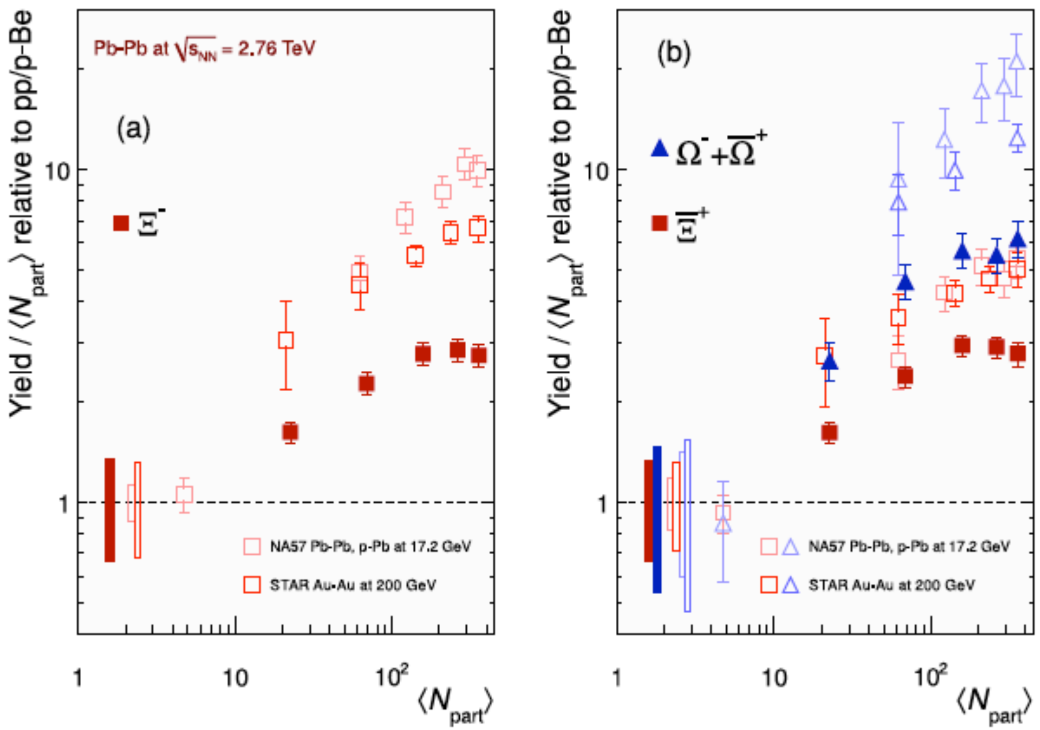


# Strangeness in A+A

## Energy Dependence of Strangeness Enhancement




ALICE
PLB **728** (2014) 216

**Enhancement factor**

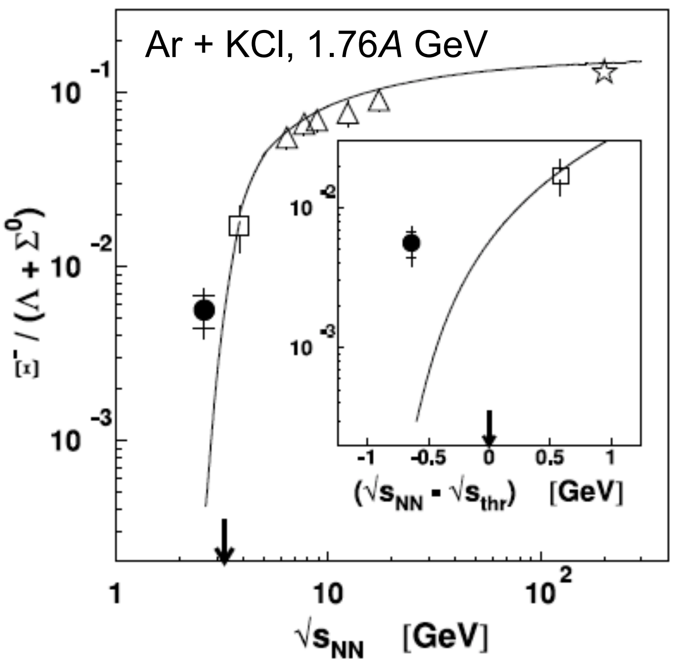
Defined relative to p+p

$$E = \frac{2}{\langle N_{part} \rangle} \left[ \left. \frac{dN(Pb+Pb)}{dy} \right|_{y=0} \Big/ \left. \frac{dN(p+p)}{dy} \right|_{y=0} \right]$$

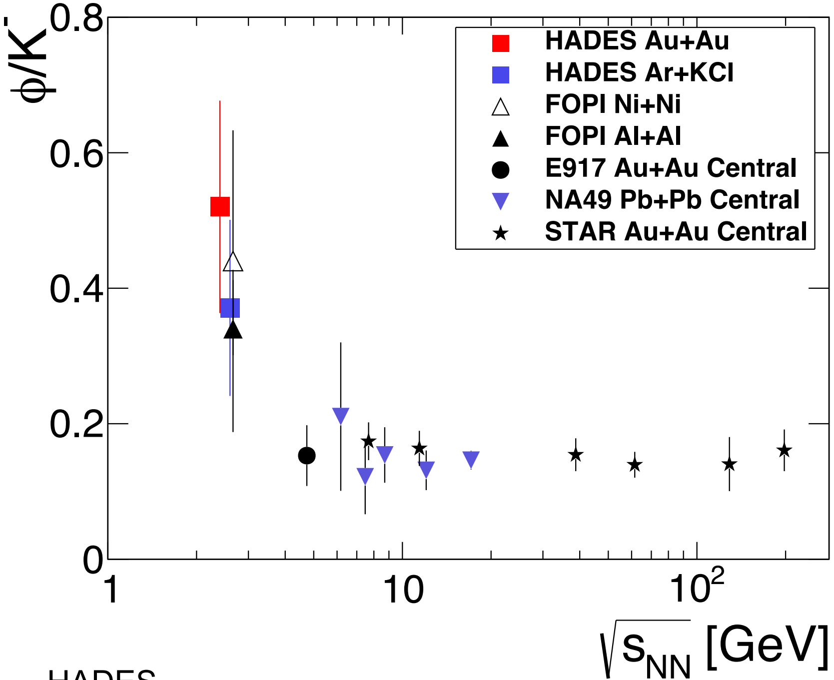
Enhancement factor for Ω: ≈ 20@SPS ≈ 12@RHIC ≈ 6@LHC

# Strangeness in A+A

## Sub-Threshold Energies ($\Xi^-$, $\phi$)




HADES
PRL **103** (2009) 132301




HADES
arXiv:1703.08418

**Non-trivial energy dependence at very low energies**

Surprisingly high $\Xi^-$ yield, data clearly above model expectation

Dramatic rise of $\phi/K^-$ ratio towards low energies

# Strangeness in A+A

## Strangeness Enhancement?

**High energies**

Decrease of enhancement factor

Caused by increase of strangeness production in pp-reference

**Low energies**

Increase of strangeness production at sub-threshold energies

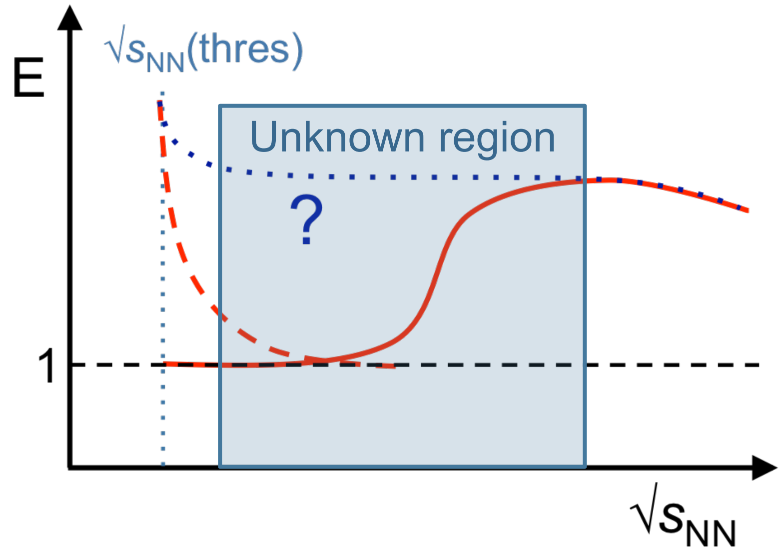
**Intermediate energies**

Any onset observable (multi-strange) due to partonic degrees of freedom?

Or continuous enhancement everywhere?

Effects in nuclear (hadronic) medium (multi-step processes, resonances, multi-meson fusion, …)

Enhancement factor for e.g. Ξ or Ω




$$E = \frac{2}{\langle N_{part} \rangle} \left[ \left. \frac{dN(Pb+Pb)}{dy} \right|_{y=0} \Big/ \left. \frac{dN(p+p)}{dy} \right|_{y=0} \right]$$

# Strangeness in A+A

## Energy Dependence of Total Yields

### Covered CM-energies

SIS: $2.0 \leq \sqrt{s_{NN}} \leq 2.6$ GeV

AGS: $2.7 \leq \sqrt{s_{NN}} \leq 4.9$ GeV

SPS: 5.1 GeV $\leq \sqrt{s_{NN}} \leq$ 17.3 GeV

RHIC: 7.7 GeV $\leq \sqrt{s_{NN}} \leq$ 200 GeV

LHC: 2.76 TeV $\leq \sqrt{s_{NN}} \leq$ 5.02 TeV

### High energies

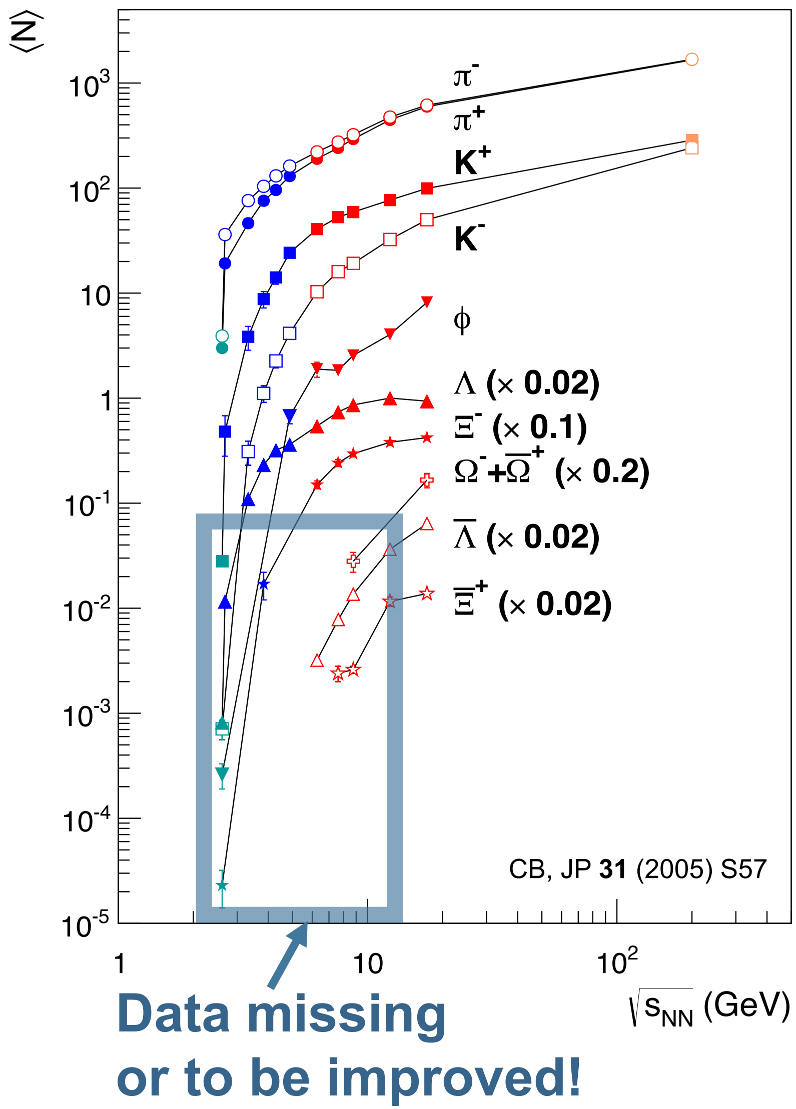
All particle species measured
(only mid-rapidity)

### Low energies

Mostly limited to bulk particles

Almost no rare multi-strange (anti-)particles (Ξ, Ω) at low energies

Future prospects → Dan Cebra's talk



# Strangeness in A+A

## Open Questions

**What is the energy dependence of strangeness enhancement (esp. (multi-)strange) over the whole energy region?**

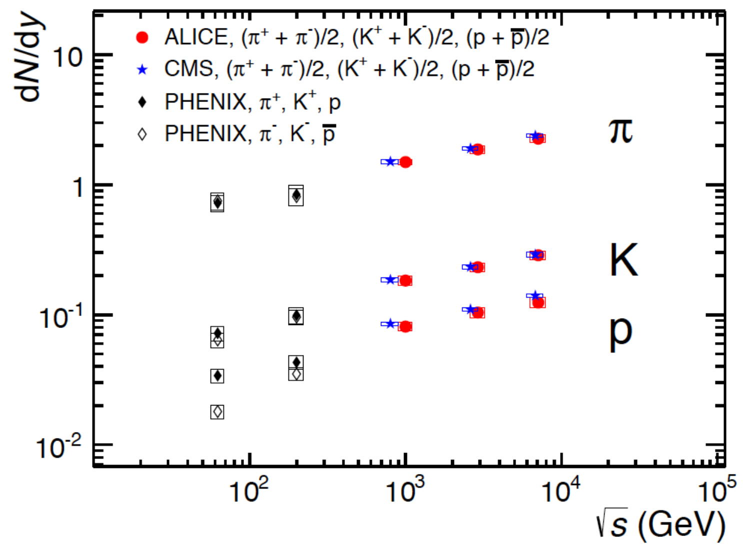
**Could there be an onset somewhere?**

**Enhancement due to hadronic effects at intermediate (SPS and below) energies?**

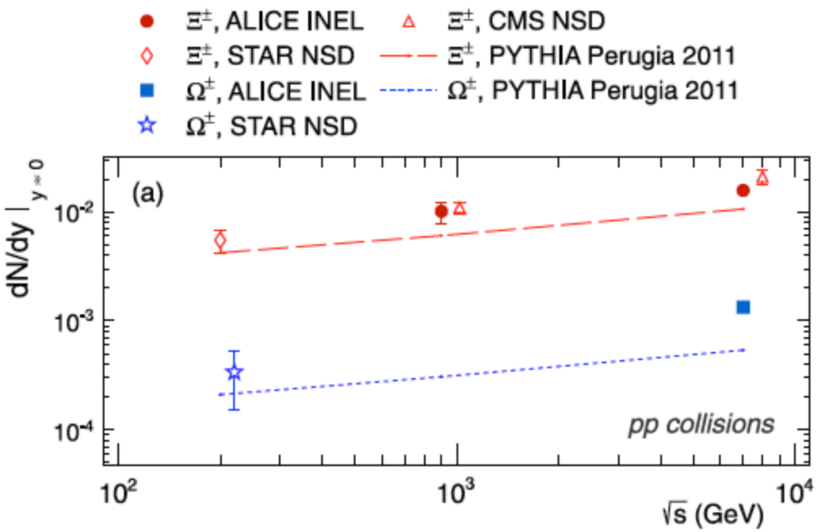
**Do we understand the dramatic effects at sub-threshold energies?**

# Small Systems

Energy Dependence of pp Data (RHIC and LHC)




ALICE
EPJC **75** (2015) 226




ALICE
PLB **712** (2012) 309

**Continuous increase of yields with $\sqrt{s}$**

Stronger than model expectation for multistrange particles

# Small Systems
## Energy Dependence of pp Data

**Ratio strange/non-strange**
Hyperon-to-pion ratios

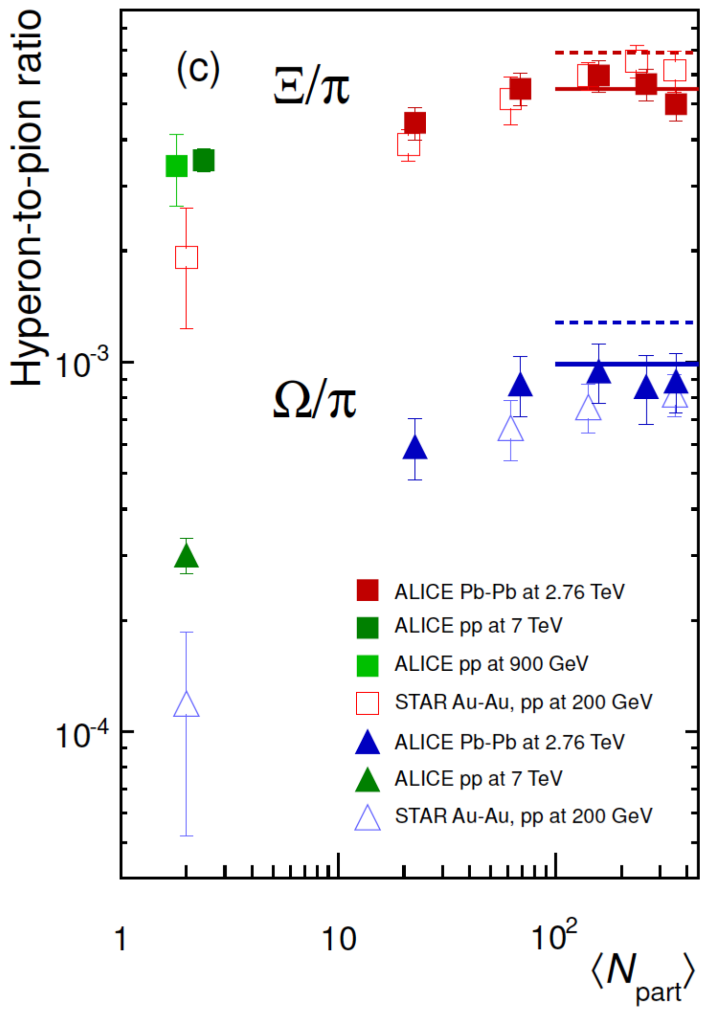
Increase with √*s* stronger in pp than in A+A

AA: Ξ/π(LHC) ≈ Ξ/π(RHIC)
Ω/π(LHC) ≳ Ω/π(RHIC)

pp: Ξ/π(LHC) > Ξ/π(RHIC)
Ω/π(LHC) ≫ Ω/π(RHIC)

SHM predictions
full line: A. Andronic et al., PLB **678** (2009) 516
dashed line: J. Cleymans et al., PRC **74** (2006) 034903

**Release of strangeness-suppression in pp at high energies**




ALICE
PLB **728** (2014) 216

# Small Systems

Particle Ratios in pp, p-Pb and Pb-Pb Compared

### Multiplicity Dependence

pp event classes, measure of reaction violence: $\langle dN_{ch}/d\eta \rangle$

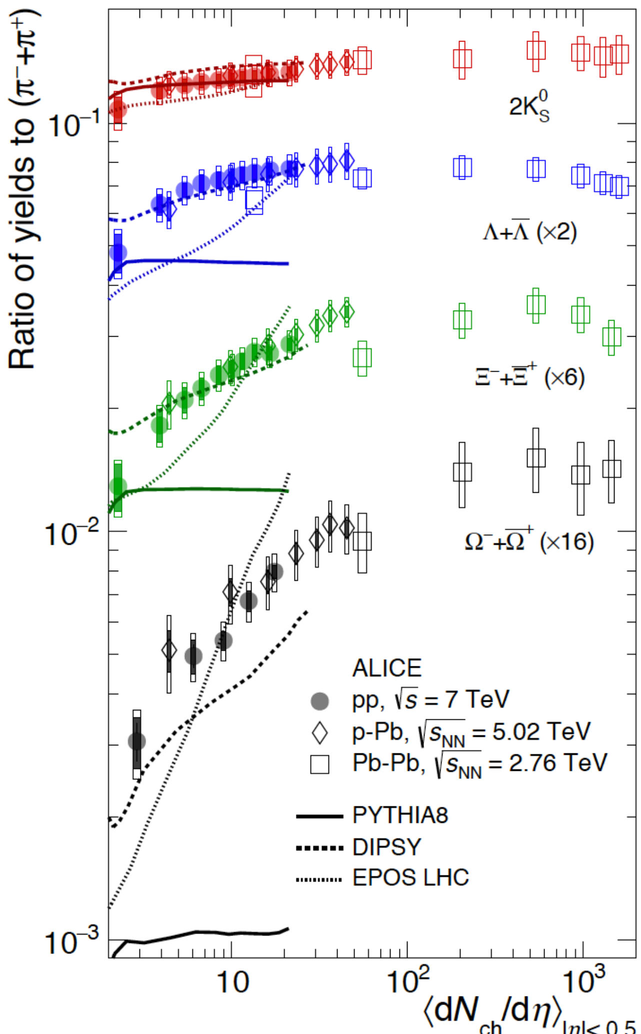
### Universal scaling?

Strangeness enhancement evolves with multiplicity dependence

Similar dependence pp and p-Pb
Not trivial, since physics in
high mult. pp ≠ high mult. p-Pb!

How good is the overlap with peripheral Pb-Pb ($K^0_s$, $\Lambda$)?

Model description




ALICE
Nature Phys. **13** (2017) 535

# Small Systems

Particle Ratios in pp and p-Pb Compared

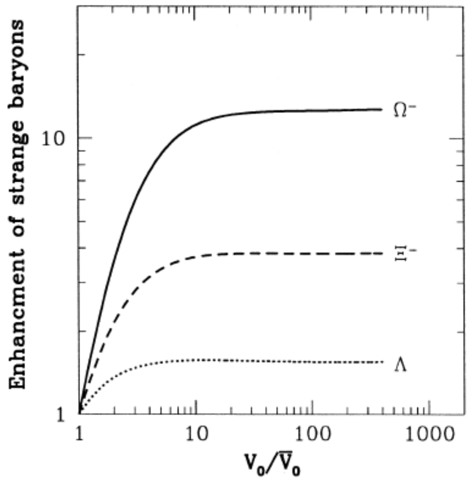
## Strangeness hierarchy

Stronger multiplicity dependence for higher strangeness content

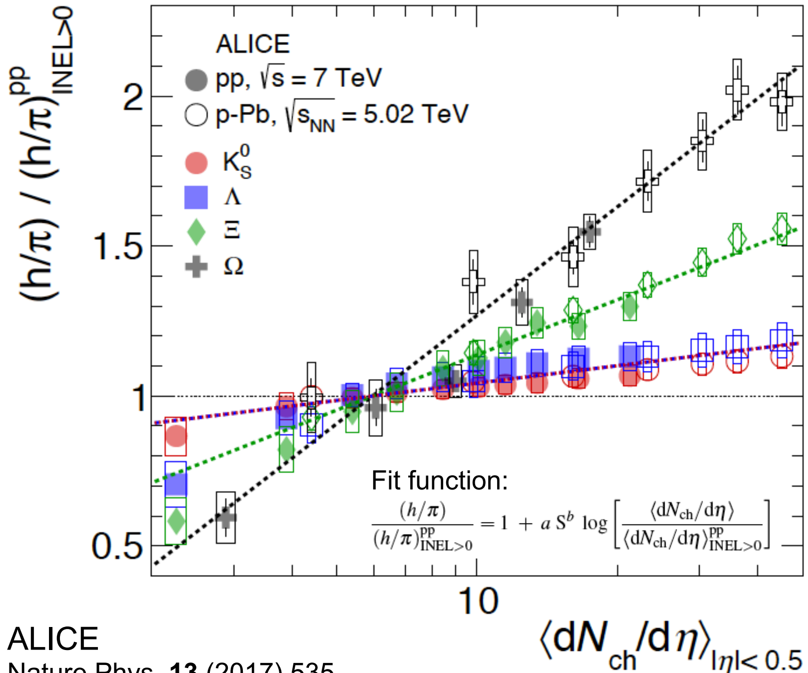
## Statistical model

Transition from canonical
⇒ grand-canonical ensemble

Saturation volume depends on strangeness content




S. Hamieh et al., PLB **486** (2000) 61




ALICE
Nature Phys. **13** (2017) 535

**Multiplicity dependence in pp in agreement to stat. model?**

Assumption $V_0 \propto dN_{ch}/d\eta$

# Small Systems

## Statistical Model

### Statistical model

Transition from canonical
⇒ grand-canonical ensemble

THERMUS model comparison

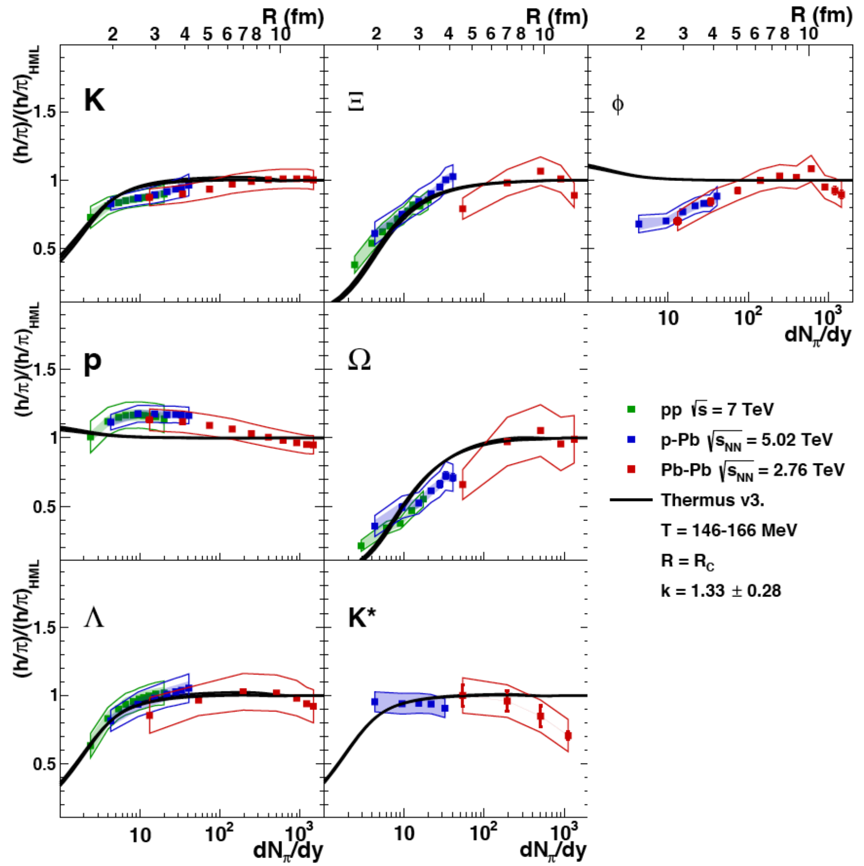
Good description achieved
for all particles

### Exception ϕ meson!

Seems to exhibit also a suppression
not expected in model ($S$ = 0)

### Other energies?

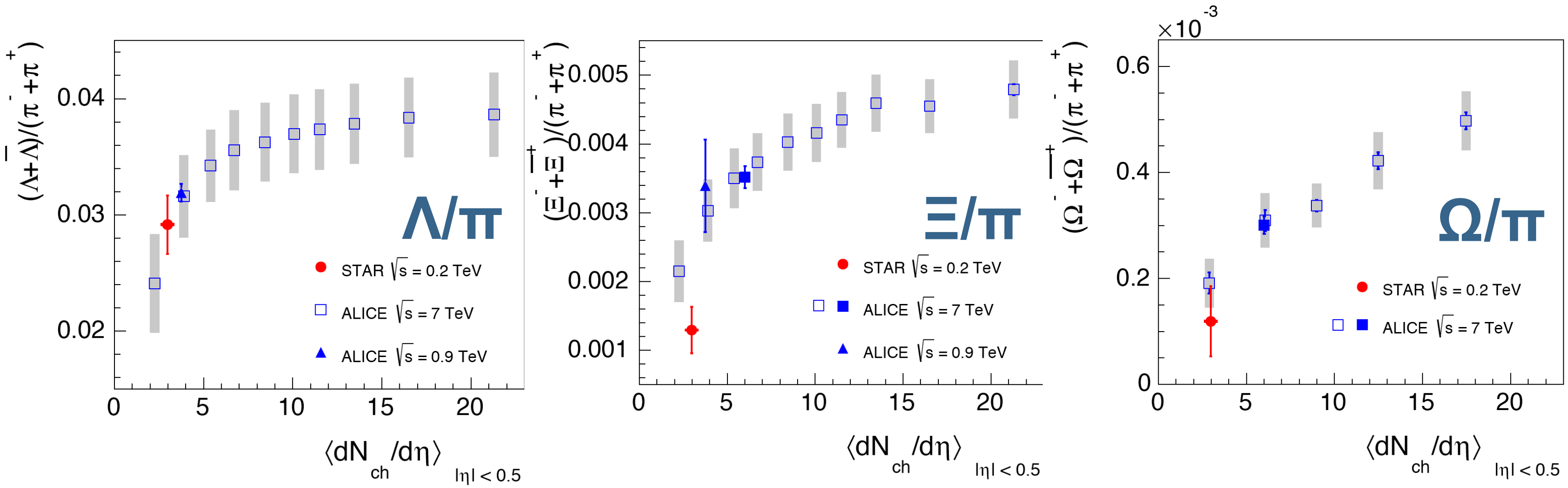
Multiplicity dependence
at lower energies to be studied




V. Vislavicius and A. Kalweit
arXiv:1610.03001

# Small Systems

## Energy and Multiplicity Dependence in pp Collisions




**Saturation of particle ratios observed?**

Possibly for Λ/π and Ξ/π

Ω/π increases continuously up to d$N_{ch}$/d$\eta$ ≈ 17

ALICE
Nature Phys. **13** (2017) 535
PLB **712** (2012) 309
EPJC **71** (2011) 1594

**Does d$N_{ch}$/d$\eta$ provide common scaling in pp collisions ?**

STAR: minimum bias pp data at $\sqrt{s}$ = 0.2 TeV

ALICE: multiplicity-selected pp data at $\sqrt{s}$ = 7 TeV

STAR
PRC **75** (2007) 064901
PRC **79** (2009) 034909

Low d$N_{ch}$/d$\eta$ region should be looked at in detail

How about d$N_{ch}$/d$\eta$ dependences other (lower) energies?

# Small Systems

Open Questions

**Does d$N_{ch}$/d$\eta$ provide an universal scaling for system size dependencies (pp → pA → AA)?**

**Is the relation of d$N_{ch}$/d$\eta$ to the reaction volume the only relevant factor? Also look at other observables …**

**Does the multiplicity dependence match the transition from canonical to grand-canonical ensemble at all energies ?**

**Is a saturation of particle ratios observed in very high multiplicity pp collisions?**

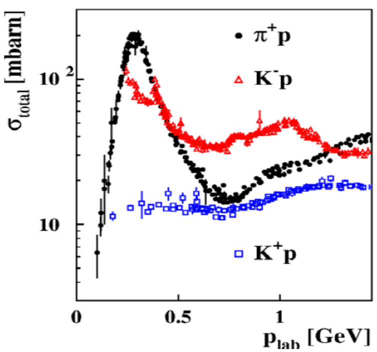
# Low Energies

## In-Medium Cross Sections and Potentials

### *T*($K^+$) > *T*($K^-$) observed

### $K^+$ and $K^-$ cross sections

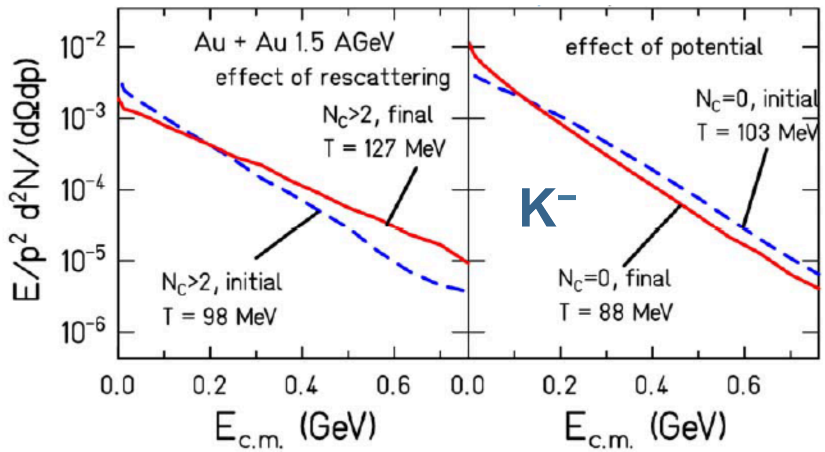
$\sigma(K^-) > \sigma(K^+)$, due to strangeness exchange $\pi + \Lambda \leftrightarrow K^- + N$




Rescattering should cause different freeze-out for $K^+$ and $K^-$

### K-N potentials

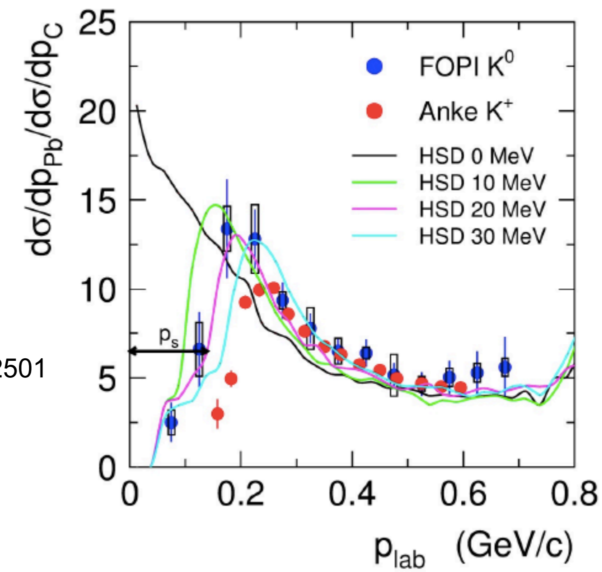
$K^-$: attractive / $K^+$: repulsive
→ modify inverse slopes




C. Hartnack et al.
PR **510** (2012) 119

FOPI
PRL **102** (2009) 182501

ANKE
EPJA **22** (2004) 301



# Low Energies

SIS-18: HADES Data on ϕ Meson

**Φ/K⁻-ratio**

Rapid rise towards low energies

**Feeddown into kaons**

Can explain the different slope parameters of $K^+$ and $K^-$

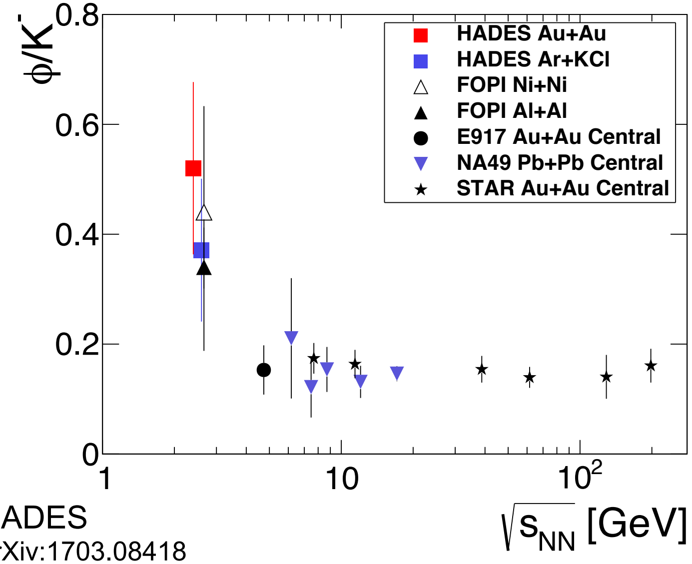
No evidence for sequential freeze-out

Important role of ϕ at low energies

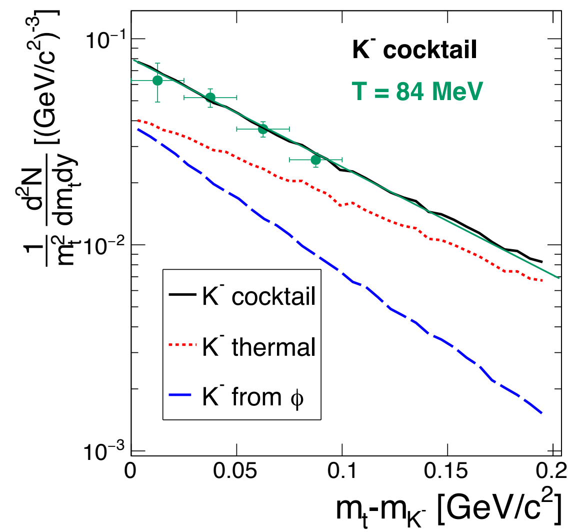
**Kaons in medium**

Different cross sections for $K^+$ and $K^-$

Role of in-medium potentials




HADES
arXiv:1703.08418



# Low Energies

Statistical Model

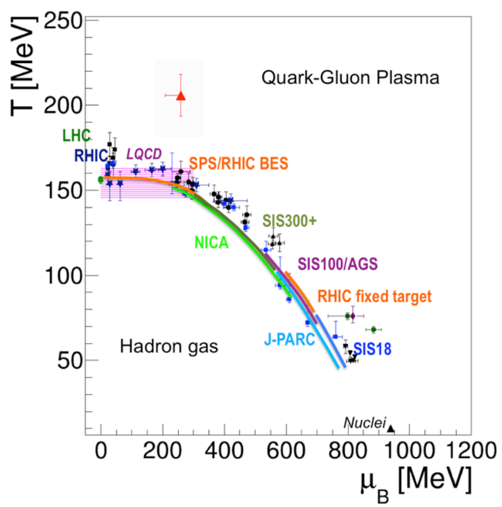
### Fit to hadron yields

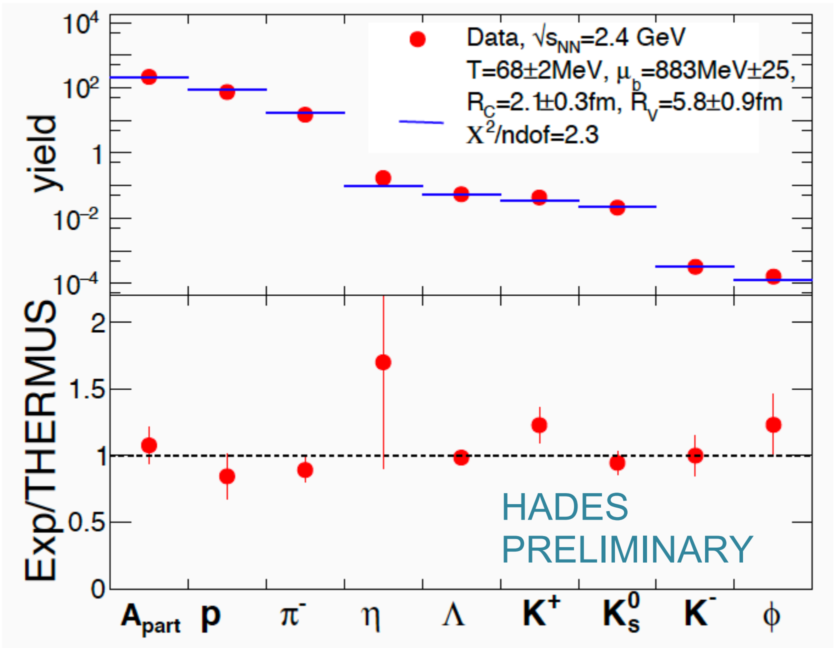
Works generally quite well at high energies (SPS, RHIC, LHC)

Parameters: $V$, $T$, $\mu_B$, ($R_c$ or $\gamma_s$)

<u>But</u>: also low energy data can be described surprisingly well

### Freeze-out curve




HADES

H. Schuldes, SQM2017

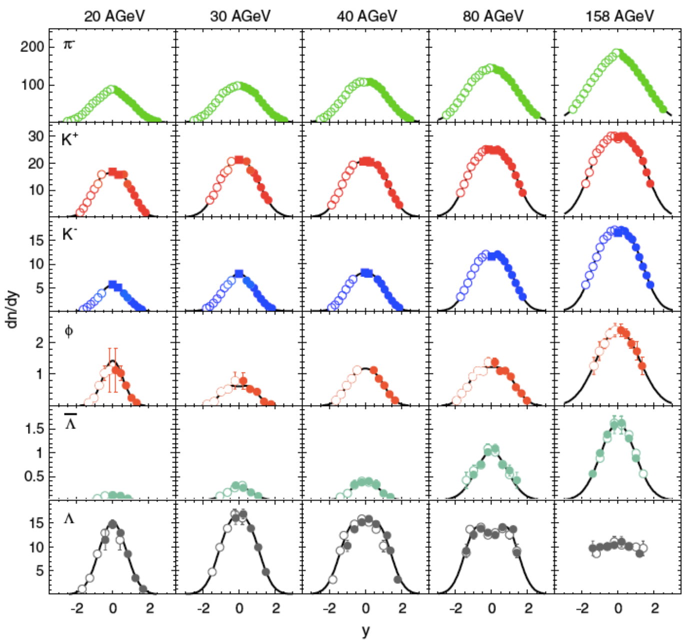
# The Role of the ϕ Meson

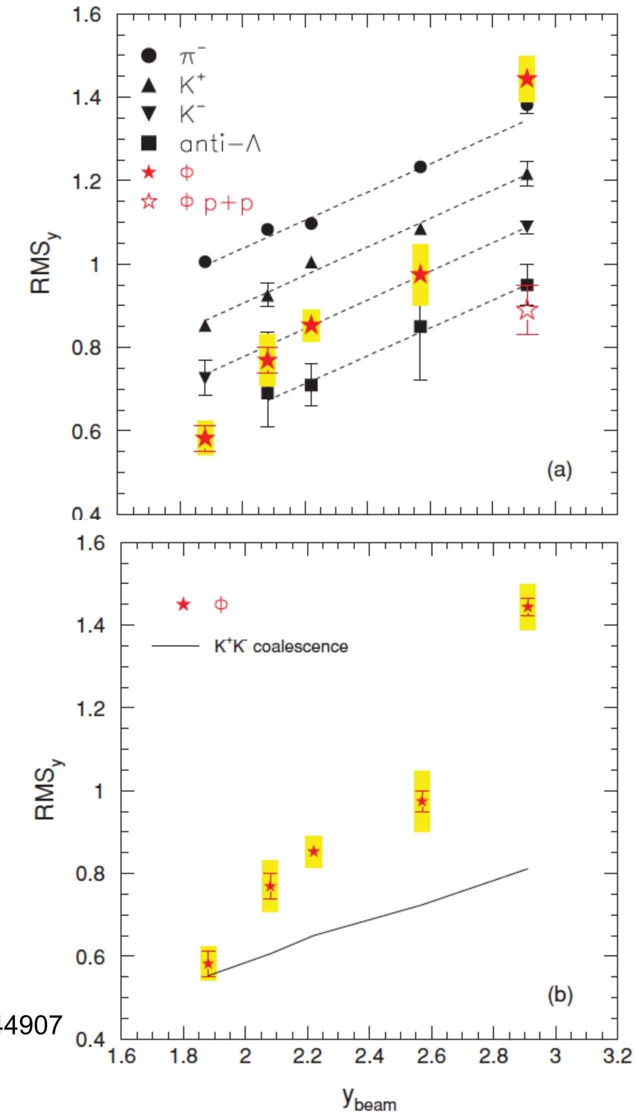
Energy Dependence of Rapidity Widths (SPS)

## RMS of *y*-distributions

Rapidity distribution broadens faster with increasing $\sqrt{s_{NN}}$ than for other particles

Disagrees with expectation for kaon coalescence at higher energies



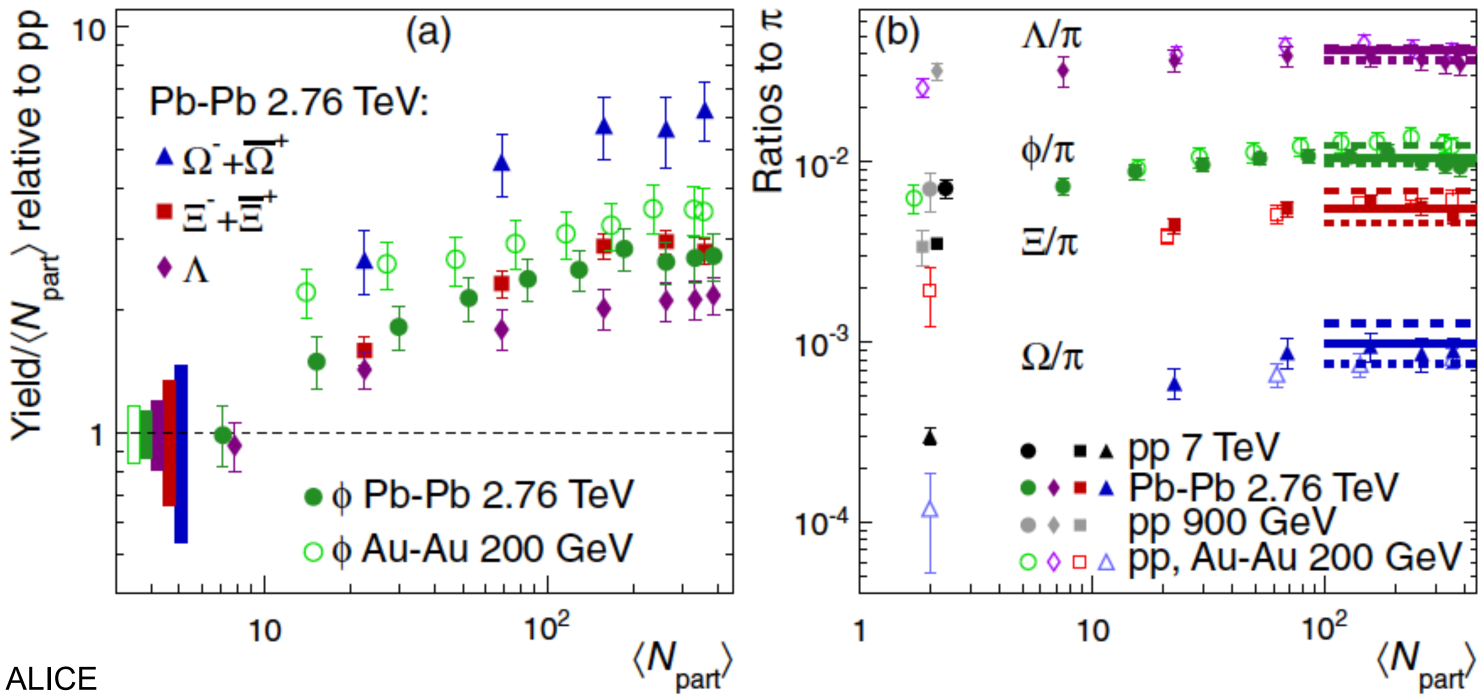




NA49

PRC **78** (2008) 044907

# The Role of the ϕ Meson

## Comparison of Enhancements




ALICE
PRC **91** (2015) 024609

**Enhancement of ϕ between Λ and Ξ**

Effective strangeness between 1 and 2

Ratio $\phi/(\pi^- + \pi^+)$ between $(\Lambda + \bar{\Lambda})/(\pi^- + \pi^+)$ and $(\Xi^- + \bar{\Xi}^+)/(\pi^- + \pi^+)$

SHM predictions
full line: A. Andronic et al., PLB **678** (2009) 516
dashed line: J. Cleymans et al., PRC **74** (2006) 034903
dotted line: J. Stachel et al., JP **509** (2014) 012019

# Low Energies / $\phi$ Meson

## Open Questions

**Do we understand kaon propagation in medium?**

**Is there any evidence for a sequential freeze-out due to different cross section?**

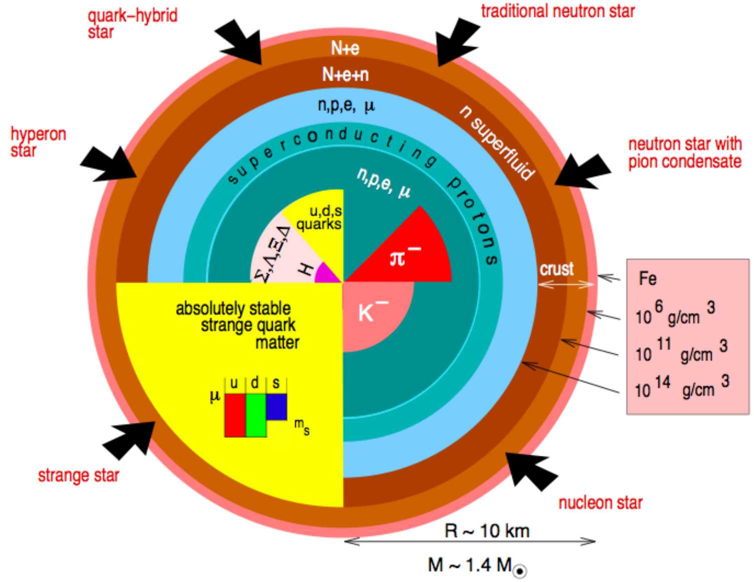
**Does the medium also at low energies behave macroscopically, fully described by statistical model?**

**Why does a non-strange particle behave so strange?**

# Hyperon Interaction

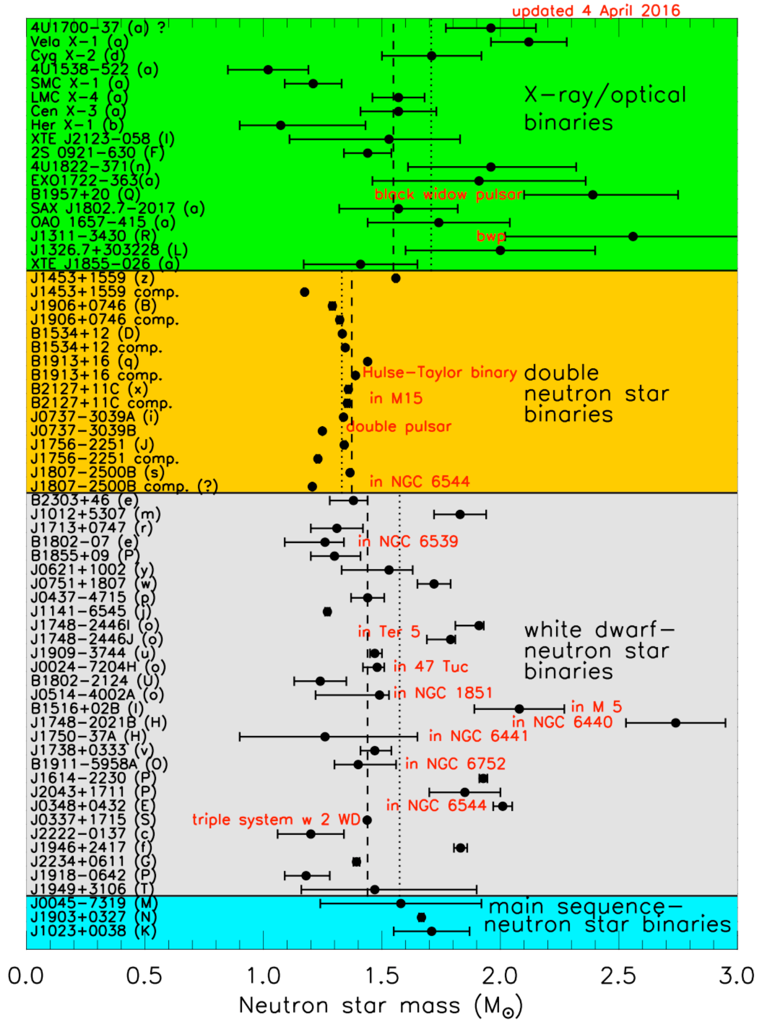
## Astrophysical Relevance

### Neutron stars




Understanding of high mass stars
$M > 2\ M_{\odot}$

Hyperon interaction important ingredient in calculation of EOS




J. Lattimer
ARNPS **62** (2012) 485

# Hyperon Interaction

## ΛΛ Correlations

### High statistics measurement

Corrected ΛΛ two-particle c.f. obtained by STAR:

$$C'(Q) = \frac{C_{measured}(Q) - 1}{P(Q)} + 1$$

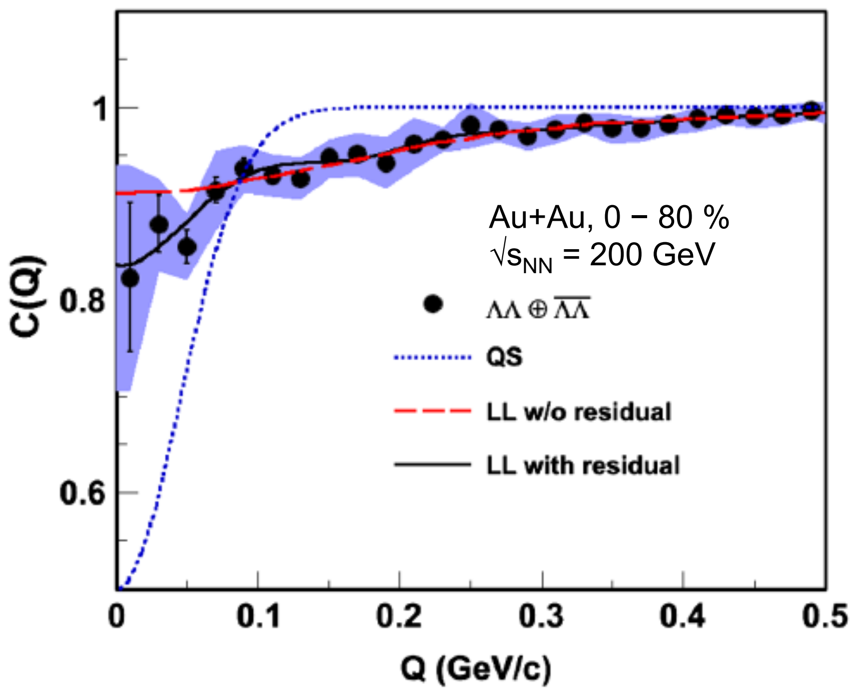
Corrections: Λ purity ($P(Q)$)

Feed down: $\Sigma^0\Lambda$, $\Sigma^0\Sigma^0$, $\Xi^-\Xi^-$ interaction not known
⇒ effect not subtracted here

### Effects in ΛΛ c.f.

Quantum statistics ⇒ anti-correlation

Strong interaction between ΛΛ pairs
⇒ $C(Q = 0) \neq 0.5$




STAR
PRL **114** (2015) 022301

# Hyperon Interaction

Strong Interaction between Λs

## ΛΛ scattering length

Fit with Lednicky-Lyuboshitz model

Parameters:

S-wave scattering length $a_0$

Effective radius $r_{eff}$

Emission radius $r_0$

(Normalization $N$ and suppr. par. $\lambda$)

Term for residual correlations ($a_{res}$, $r_{res}$)

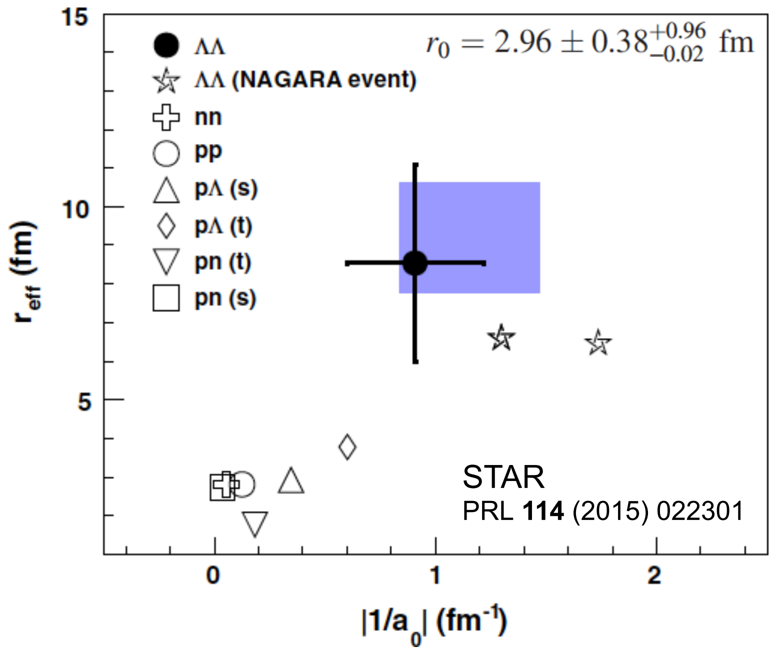
## Interaction is weak

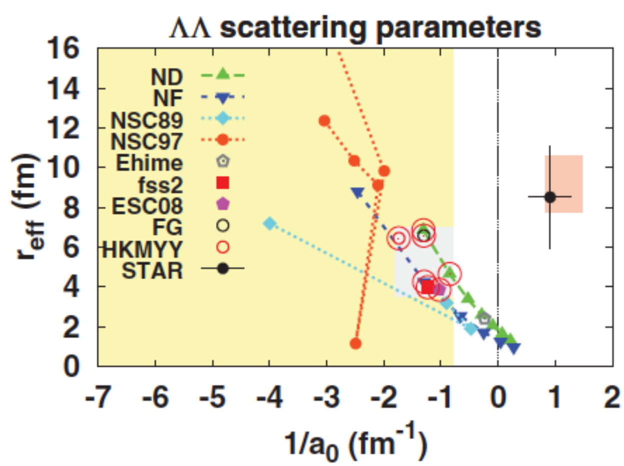
$|a_{\Lambda\Lambda}| < |a_{p\Lambda}| < |a_{NN}|$

## Sign not yet conclusive

Fit suggests weak repulsive interaction

Morita et al. favor weak attraction (radial expansion included)

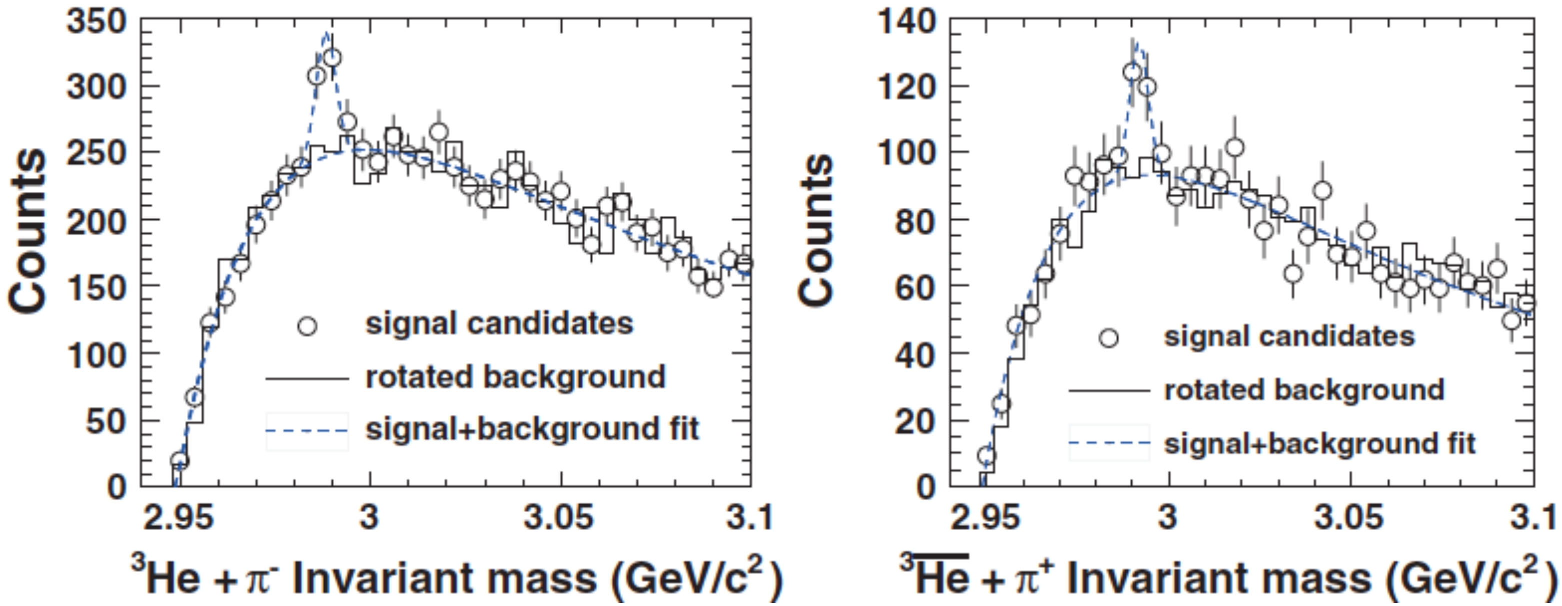



K. Morita et al. PRC **91** (2015) 024916

# Hypernuclei

## Hypertriton Measurement by STAR



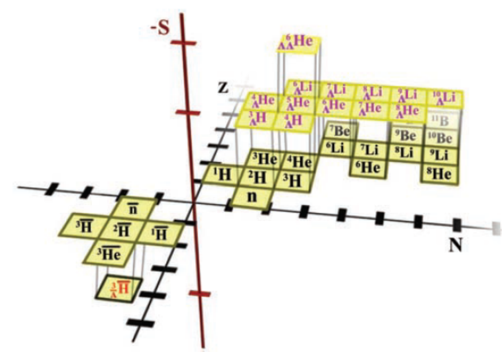

STAR
Science vol.**328** (2010) 58

**First observation of an anti-hypernucleus**

Extends chart of nuclei

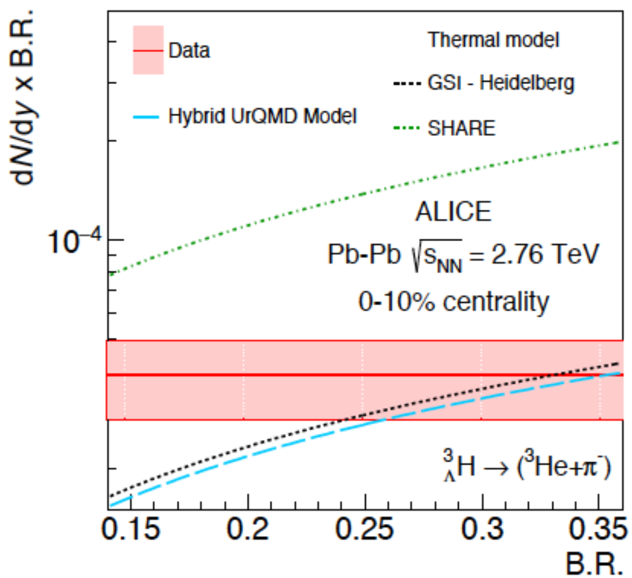
**Bound Λ-nucleon states**

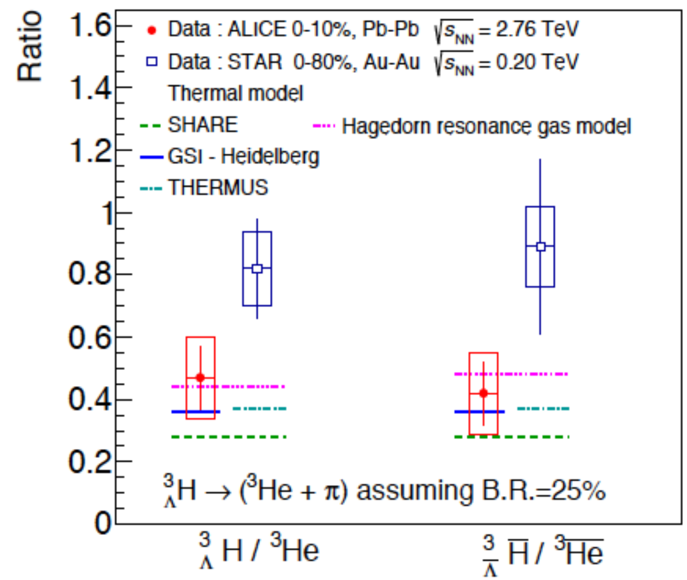
Good agreement with thermal model expectation
in contrast to ΛΛ and $\overline{\Lambda}$n



# Hypernuclei

## Hypertriton Measurement by ALICE




ALICE
PLB **754** (2016) 360

**Yield of hypertriton**

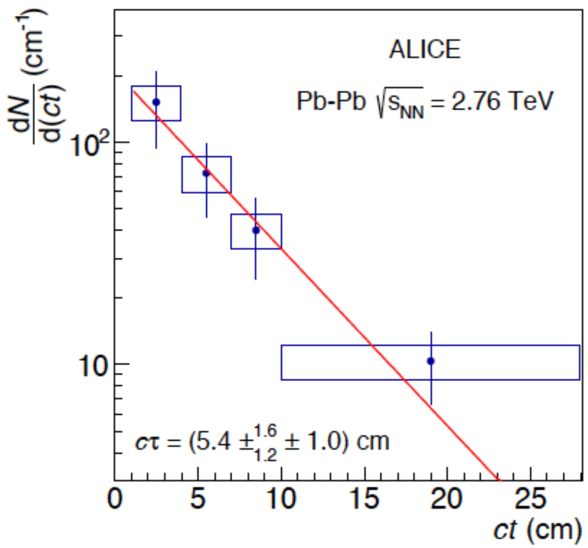
Good agreement with equilibrium thermal models and hybrid UrQMD

**Ratio hypertriton/$^{3}$He**

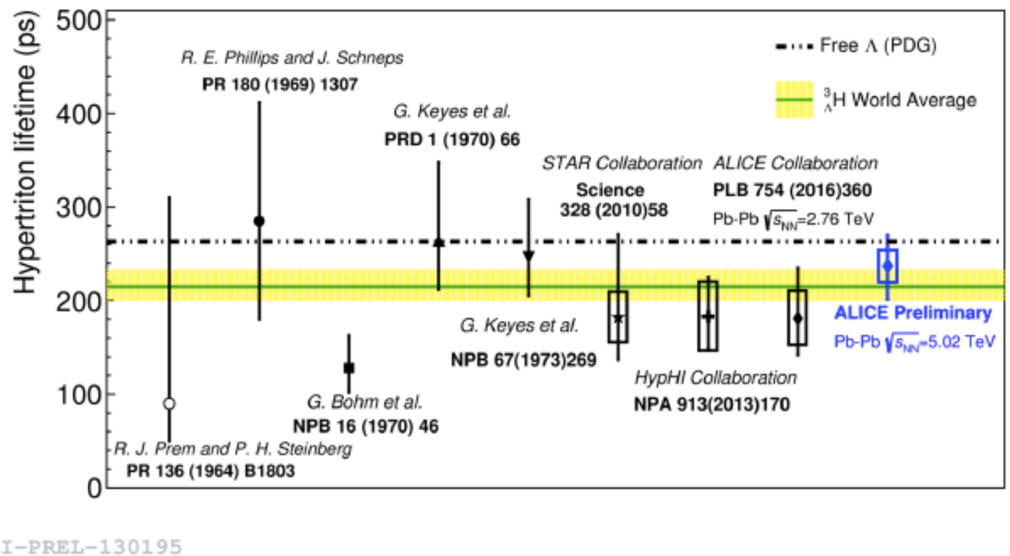
Good agreement with thermal model expectations

# Hypernuclei

## Lifetime of Hypertriton




ALICE
PLB **754** (2016) 360




A. Grelli
SQM2017

**New world average $\tau = 215^{+18}_{-16}$ ps**

Good agreement with STAR and ALICE measurement

Slightly below expectation for free Λ

(but: new ALICE measurement at $\sqrt{s_{NN}}$ = 5.02 TeV is again closer to free Λ)

# Hyperon Interaction and Hypernuclei

## Open Questions

**What do we really know up-to-now about hyperon-hyperon interactions?**

**What is the contribution to an understanding of large-mass neutron stars?**

**Why are the yields of very weakly bound objects (e.g. $^{3}_{\Lambda}H$) so well described by the statistical model ("snowball in hell")?**

**Are the properties of hyperons modified inside nuclei?**

# Conclusions

**Plenty of new data at high and very low data**

**Still many open questions concerning the role of strangeness in heavy-ion collisions**

**High precision data (intermediate energies!) needed**

Many thanks to B. Doenigus, D. Cebra, C. Ko, M. Lorenz, H. Ströbele, …

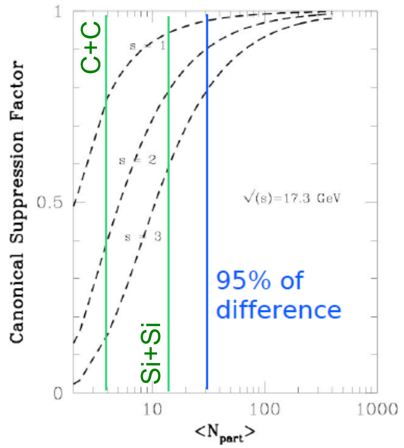
# Small Systems

## Canonical Suppression vs. Core-Corona in A+A

### Canonical suppression

Onset of suppression (e.g. $S = 1$)

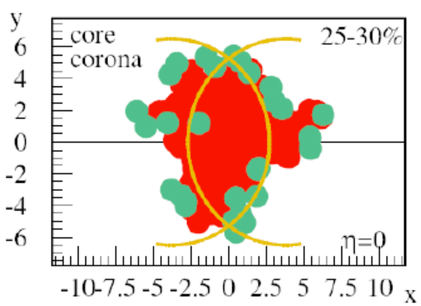
Model: $\langle N_{part} \rangle \approx 30 \leftrightarrow$ Data: $\langle N_{part} \rangle > 60$



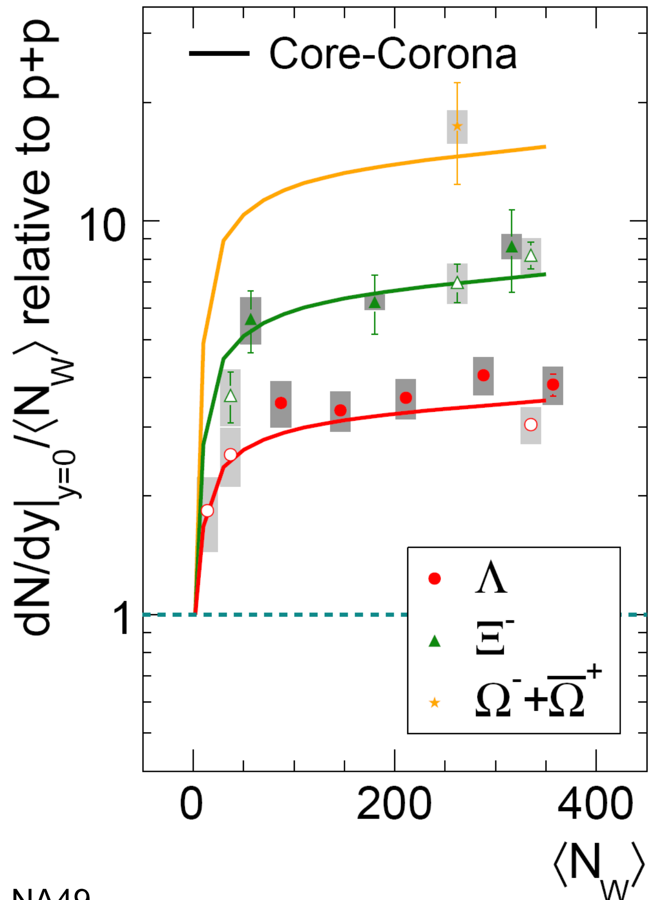

S. Hamieh et al., PLB **486**, 61 (2000)

### Core-Corona

Seems to fit the data better




K. Werner




NA49
JP **230** (2010) 012003

# Strangeness in A+A

## $K^+$ and $\Lambda$ Towards Low Energies

### |S| = 1 Particles

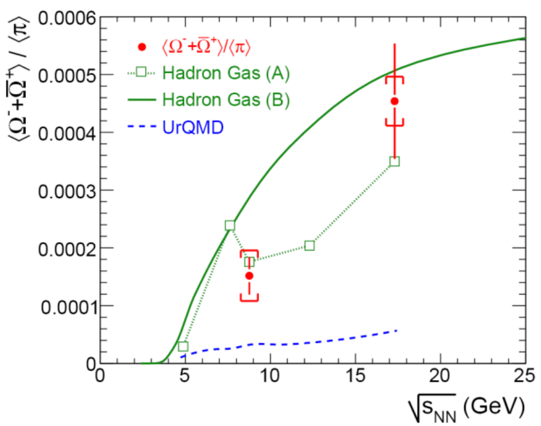
Continuous decrease with increasing $\sqrt{s_{NN}}$

Most dramatic change at lower energies
Threshold effects

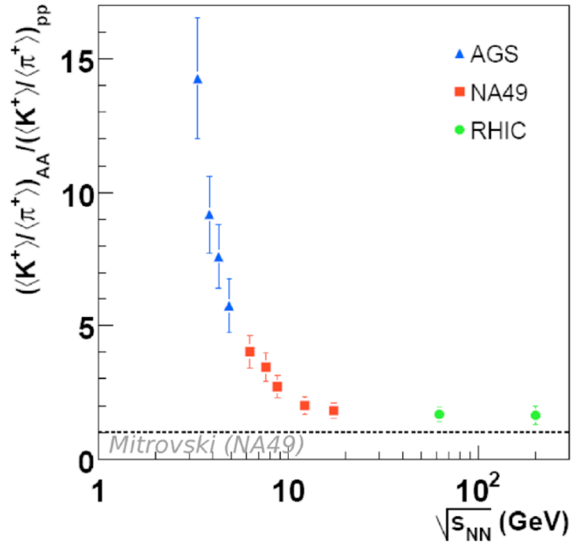
Reasonably described by
transport models

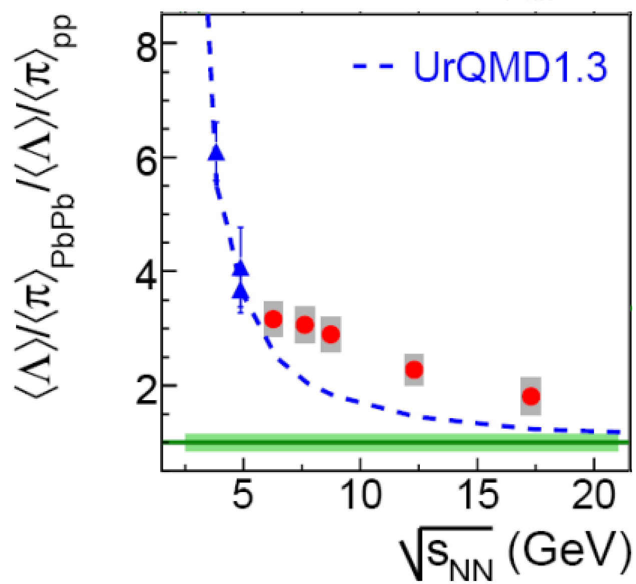
### Multistrange particles

Scarce data, pp reference missing




NA49
PRL **94** (2005) 192301



# Small Systems

Canonical Suppression

## Statistical model

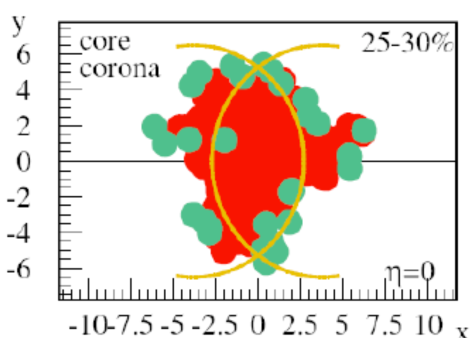
Transition from canonical to grand-canonical description

Hierarchy of suppression depends on strangeness content

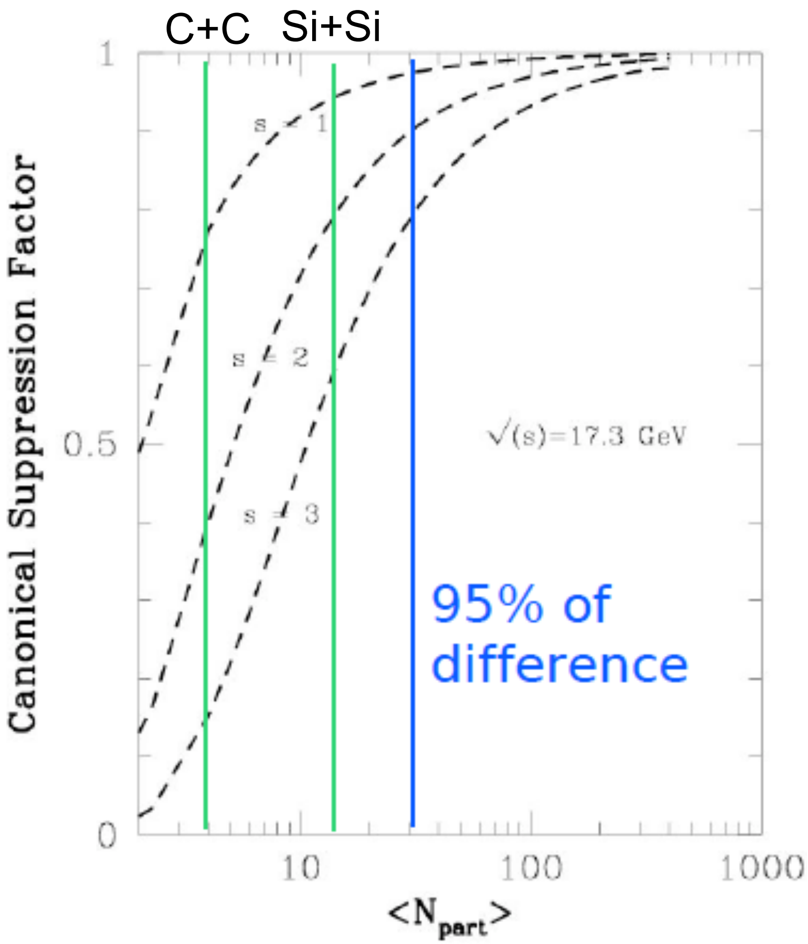
## Onset of suppression does not match data

Model: $\langle N_{part} \rangle \approx 30$
Data: $\langle N_{part} \rangle > 60$

## Core corona



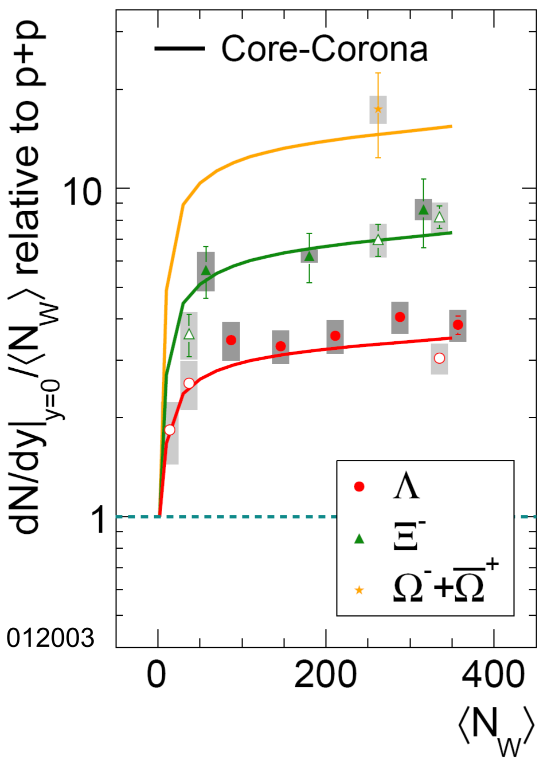

K. Werner



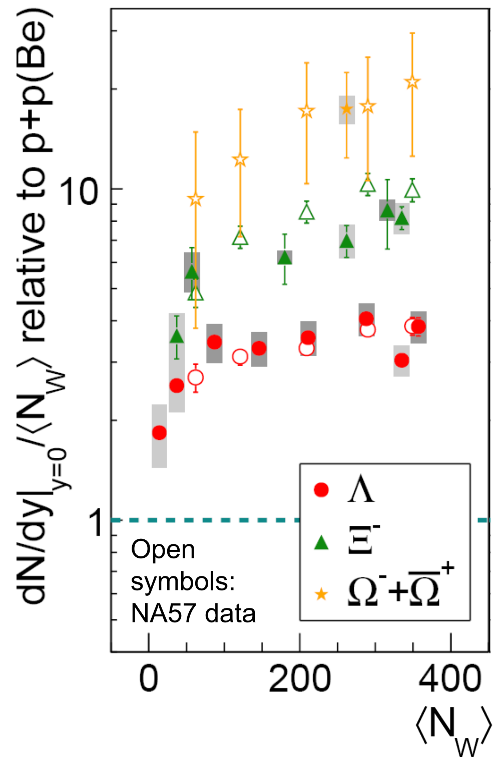

S. Hamieh et al., PLB **486**, 61 (2000)

# Small Systems

SPS Data (NA49)




NA49
JPC **230** (2010) 012003




**Enhancement factor**

Relative to p+p

$$E = \frac{2}{\langle N_{part} \rangle} \left[ \left. \frac{dN(Pb+Pb)}{dy} \right|_{y=0} \Big/ \left. \frac{dN(p+p)}{dy} \right|_{y=0} \right]$$

Enhancement for Ω up to factor ≈ 20

# Low Energies

## System Size Dependence

### $A_{part}$ Dependence

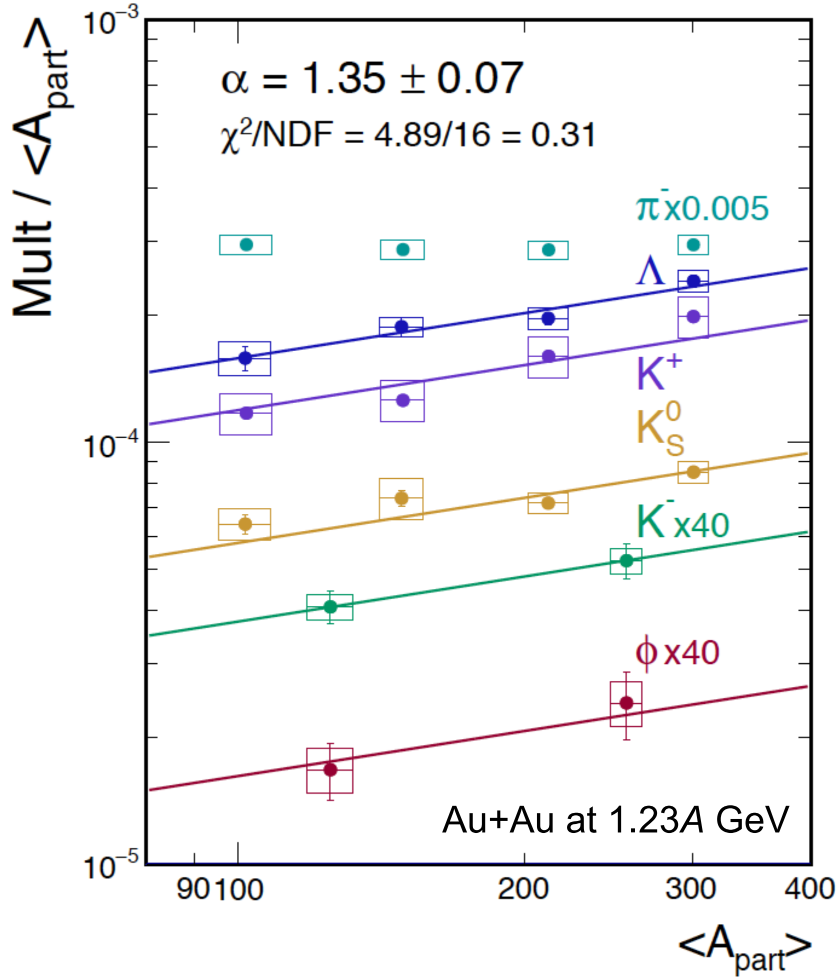
Fit with $Mult \propto \langle A_{part} \rangle^{\alpha}$

Common description of all strange particles with $\alpha \approx 1.35$

Different than pions

### Global behaviour

Not expected if different hadronic cross sections dominate



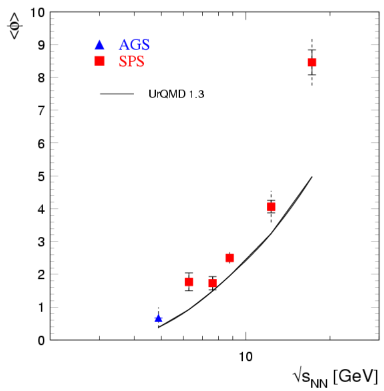

HADES
Heidi Schuldes, SQM2017

# The ϕ Meson

## Total Yields

**At SPS yields not fully described by models**

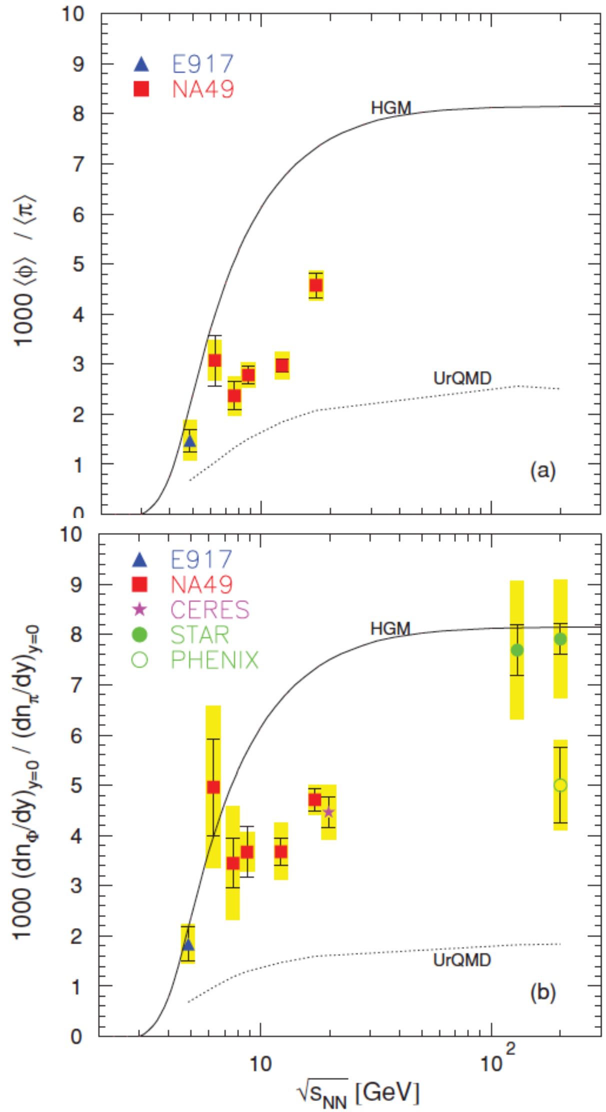
UrQMD1.3 underestimates ϕ/π-ratio but good description of ϕ yield at lower energies




Statistical model ($\gamma_s$ = 1) above ϕ/π-ratio

NA49
PRC **78** (2008) 044907

HGM: P. Braun-Munzinger et al.,
NPA **687** (2002) 902



# Small Systems

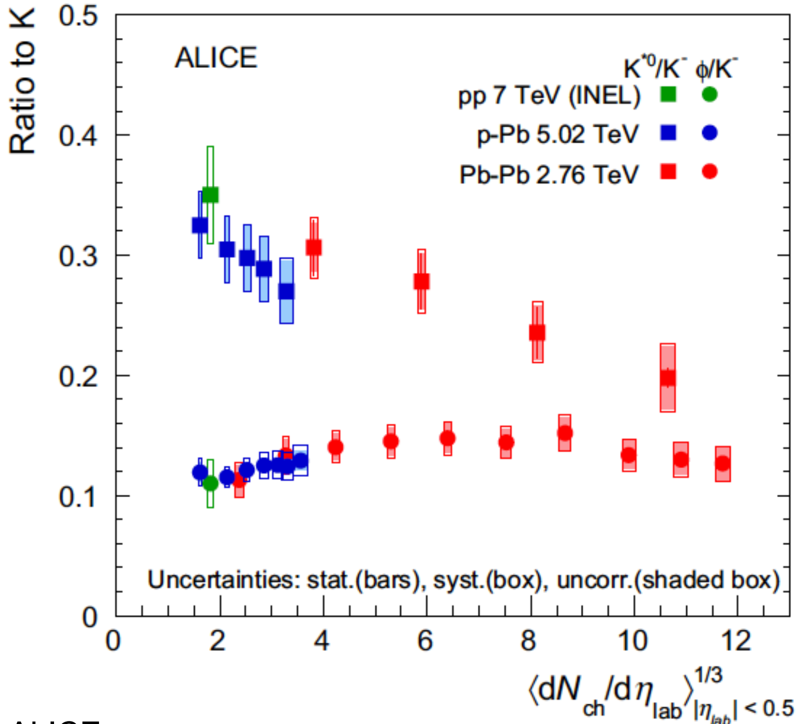
Particle Ratios in pp, p-Pb and Pb-Pb Compared

**Multiplicity Dependence**

p-Pb provides qualitative connection between pp and Pb-Pb also for resonances

Stronger suppression at higher multiplicity densities for K* (rescattering)

No suppression for ϕ




ALICE
EPJC **76** (2016) 245

# Small Systems

Particle Ratios in pp, p-Pb and Pb-Pb Compared

**Multiplicity Dependence**

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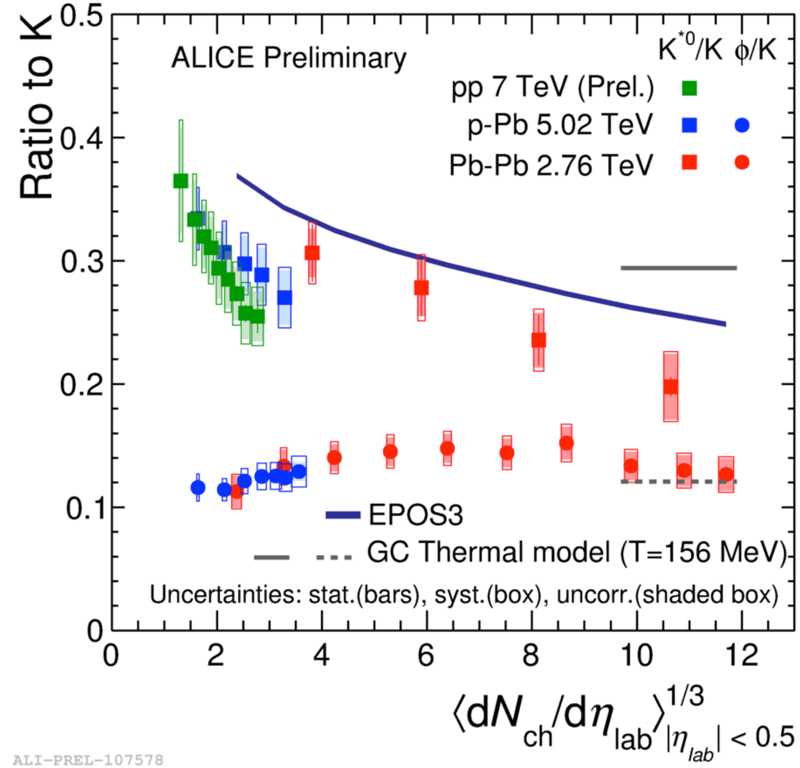
No suppression for ϕ

**Stronger trend seen in pp!**

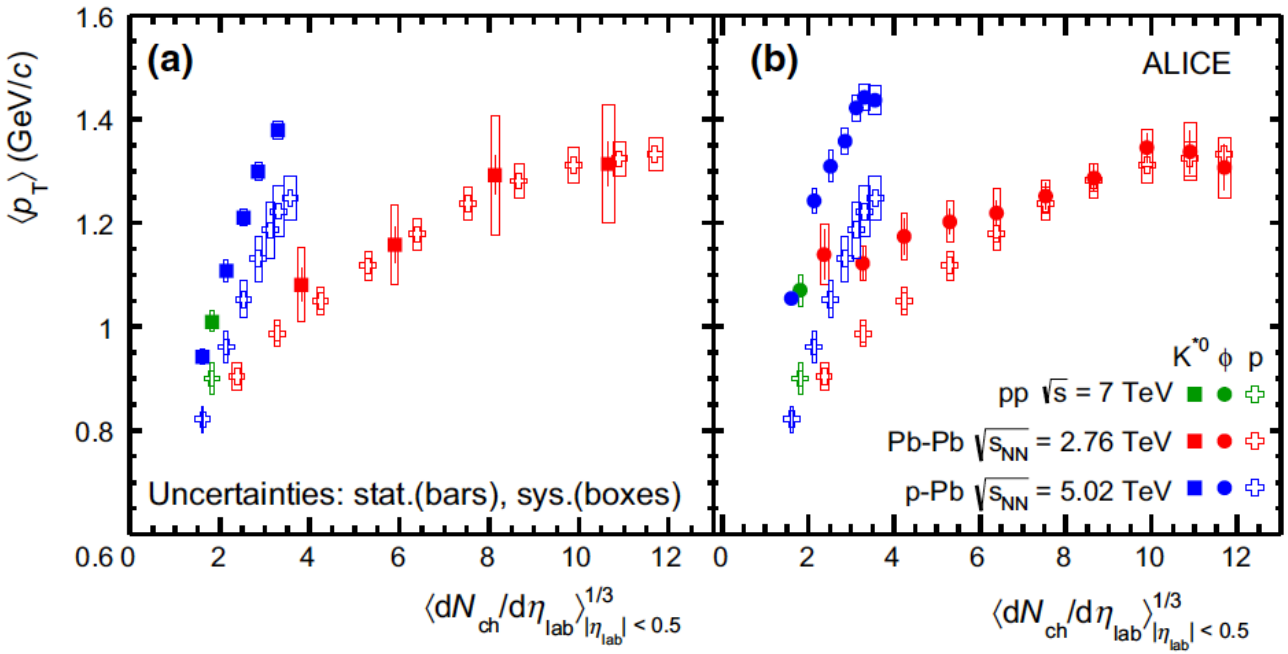
Different physics …




ALICE
Anders Knospe, SQM16

# Small Systems

## $\langle p_T \rangle$ in pp, p-Pb and Pb-Pb Compared




ALICE
EPJC **76** (2016) 245

**No universal scaling for dynamical quantities**

$\langle p_T \rangle_{\text{p-Pb}} > \langle p_T \rangle_{\text{Pb-Pb}}$ at the same $\langle dN_{ch}/d\eta \rangle$, also true for higher moments