Strangeness in Heavy-Ion Collisions

ad nauseam …

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HIC for FAIR
Helmholtz International Center

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Outline

Starting point

Review: “Strange hadron production in heavy ion collisions from SPS to RHIC”
CB and C. Markert, Prog. Part. Nucl. Phys. 66, 834 (2011)

Status before LHC heavy-ion run

What has changed since then?

New data, mainly from LHC and RHIC-BES

Keep an eye on low energies (⇒ FAIR)

Any new point of views or developments?

Outline

Strangeness in heavy-ion physics
Overview on strangeness measurements by different experiments

Strangeness enhancement
Strangeness as QGP signal
Evolution from SPS via RHIC to LHC
Results from low energies

Small systems
Proton-proton collisions
Proton-nucleus collisions

Baryon-meson ratios
Hadronization mechanisms, evidence for recombination?

The ϕ meson

Hypermatter and hyperon interaction

Overview on Strangeness Measurements

Experiments

GSI-SPS
FOPI, KAOS, HADES

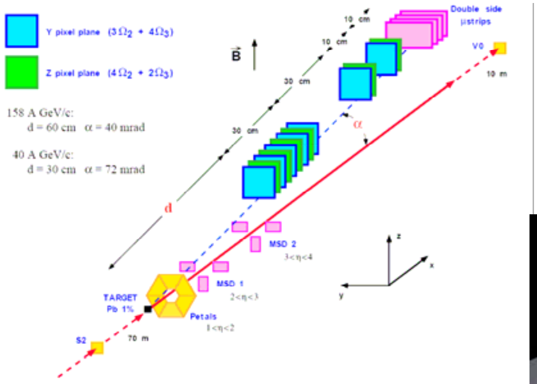
BNL-AGS
E802, E810, E866, E895, …

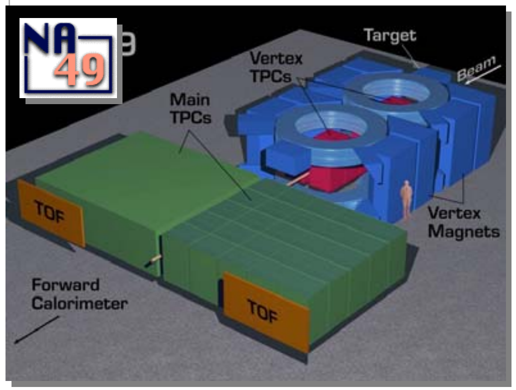
CERN-SPS (Pb beam)
WA97, NA44, NA45, NA50
NA49, NA57, NA61

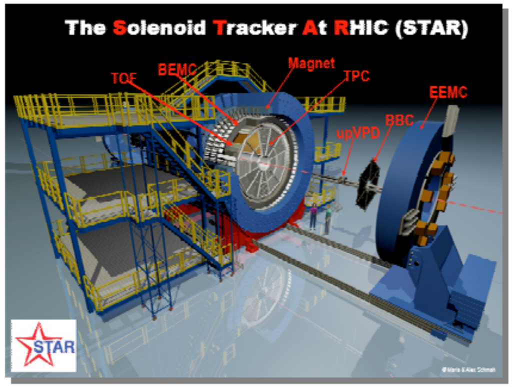
BNL-RHIC
STAR, PHENIX, BRAHMS

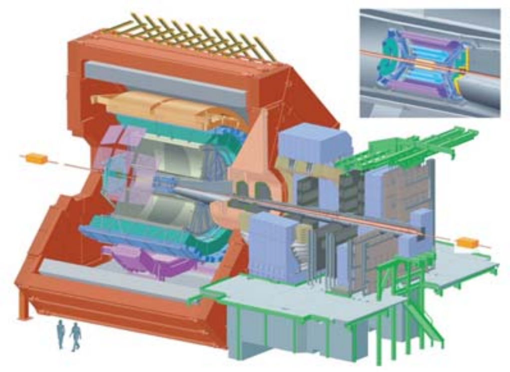
CERN-LHC
ALICE

New low energy programs
CBM@FAIR, NICA









Overview on Strangeness Measurements

Energy Dependence of Total Yields

Covered CM-energies

AGS: $2.4 \leq \sqrt{s_{NN}} \leq 4.8$ GeV

SPS: $6.3 \text{ GeV} \leq \sqrt{s_{NN}} \leq 17.3$ GeV

RHIC: $7 \text{ GeV} \leq \sqrt{s_{NN}} \leq 200$ GeV

LHC: $\sqrt{s_{NN}} = 2760$ GeV

High energies

All particle species measured

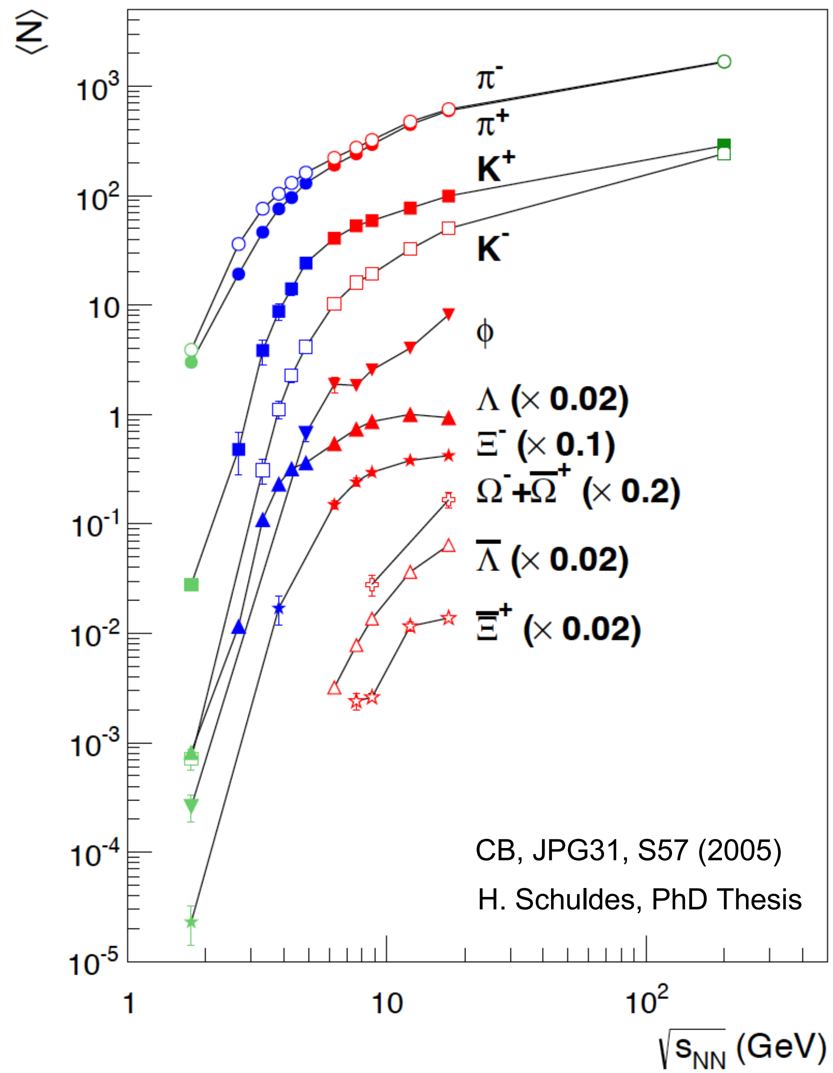
Only mid-rapidity data

Low energies

Mostly limited to bulk particles

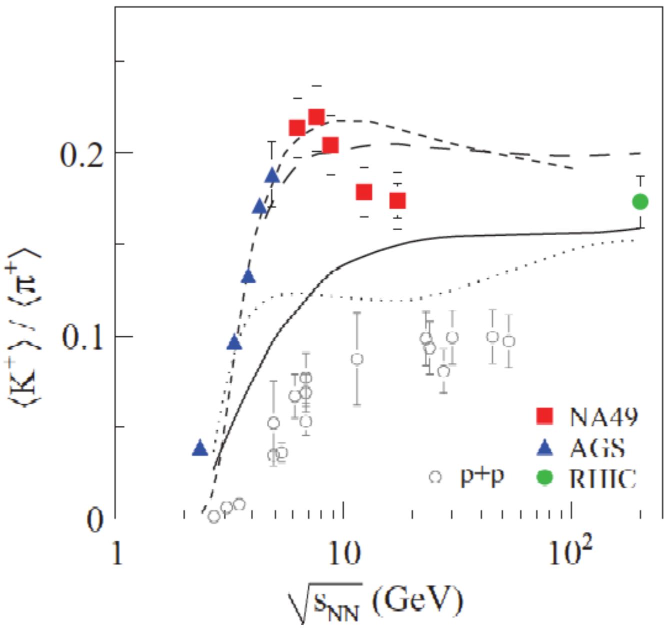
Almost no rare strange (anti-)particles (Ξ^-, Ω^-) at low energies

4π data available

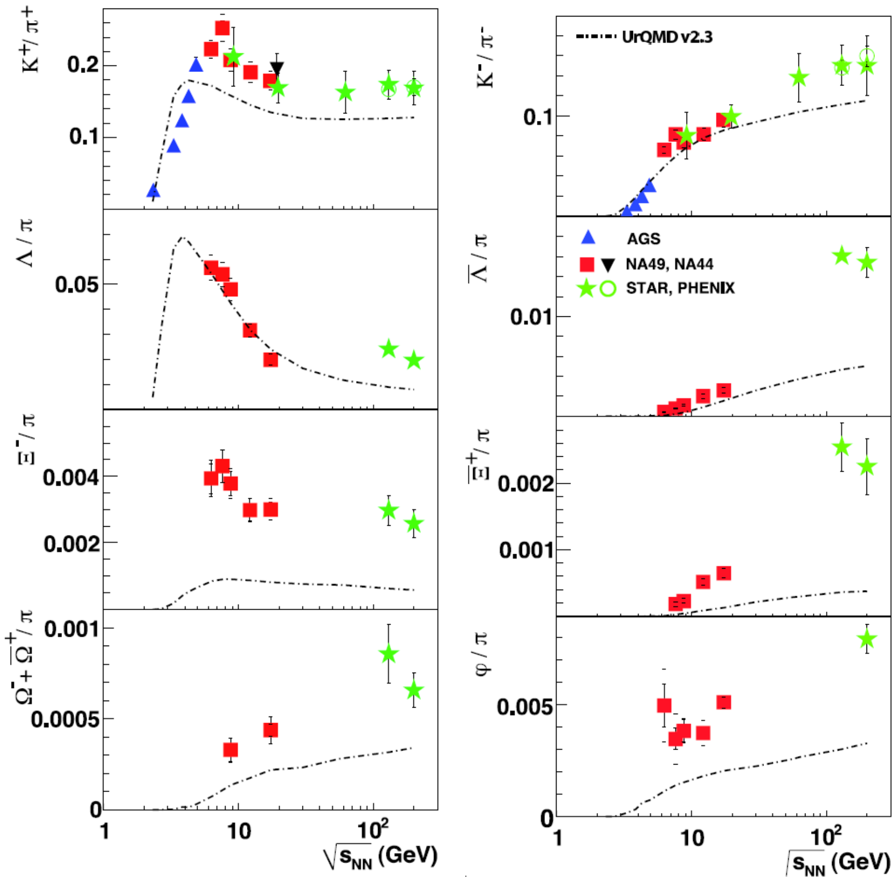


Overview on Strangeness Measurements

Yields at Lower Energies (NA49 + AGS)



NA49
PRC66, 054902 (2002)
PRL93, 022302 (2003)
PRL94, 192301 (2005)
PRC77, 024903 (2008)
PRC78, 034918 (2008)
PRC78, 044907 (2008)



Available data

Central events: π, K, p, Λ (statistics ok) and Λ*, K*, Ξ, Ω, ϕ (low statistics)

System size: π, K, p, (Λ), not at all energies

Overview on Strangeness Measurements

Yields at Lower Energies (NA49): System Size Dependence

Transport models

OK for Λ

Slightly below $\bar{\Lambda}$

Too low for Ξ

UrQMD: H. Petersen et al.
arXiv: 0903.0396

HSD: W. Cassing and
E. Bratkovskaya,
PR 308, 65 (1999)
and private communication

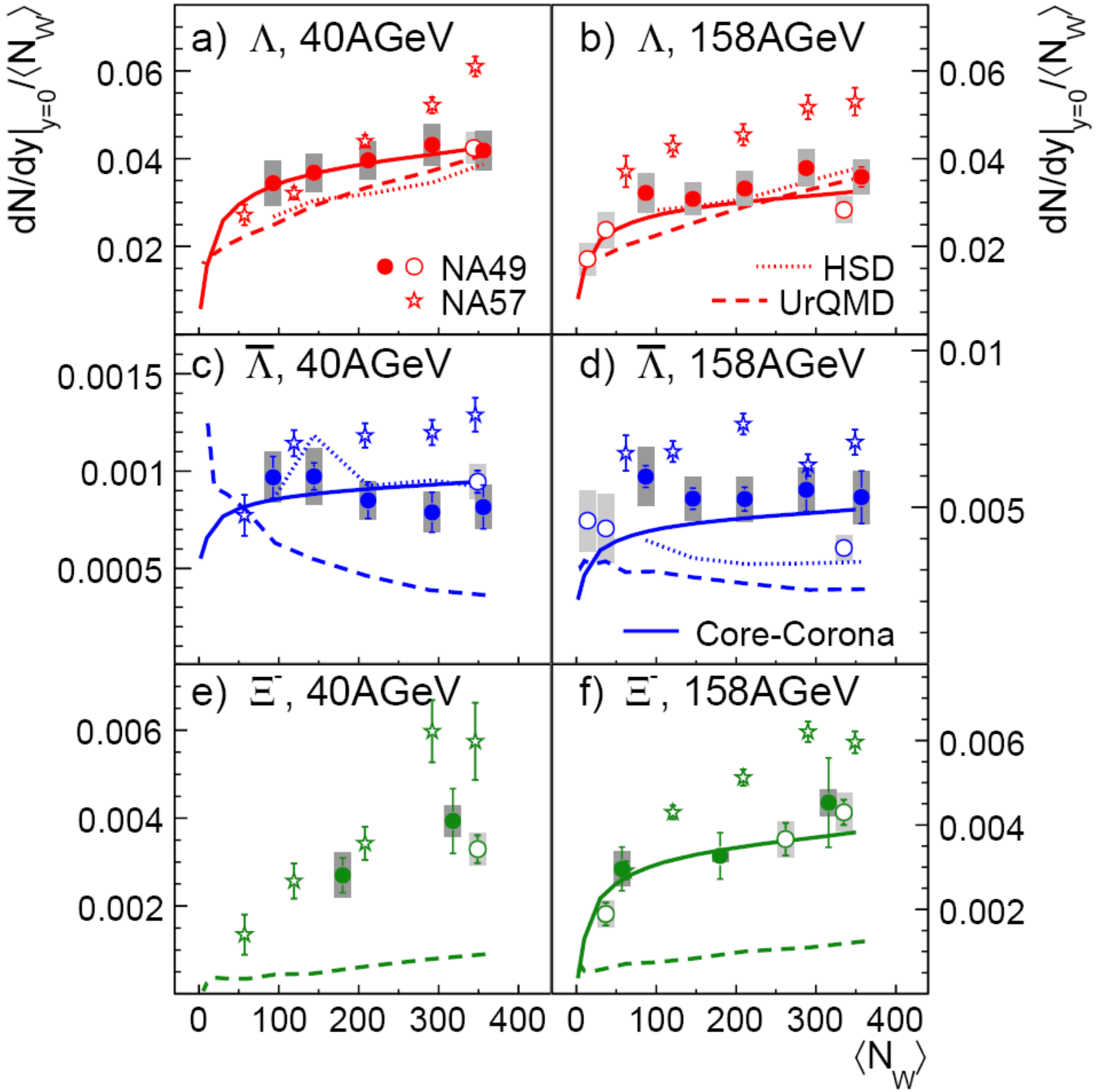
Core Corona model

OK for Λ and Ξ

F. Becattini and J. Manninen,
PLB673, 19 (2009)

J. Aichelin and K. Werner,
arXiv:0810.4465

NA49
PRC80, 034906 (2009)



Overview on Strangeness Measurements

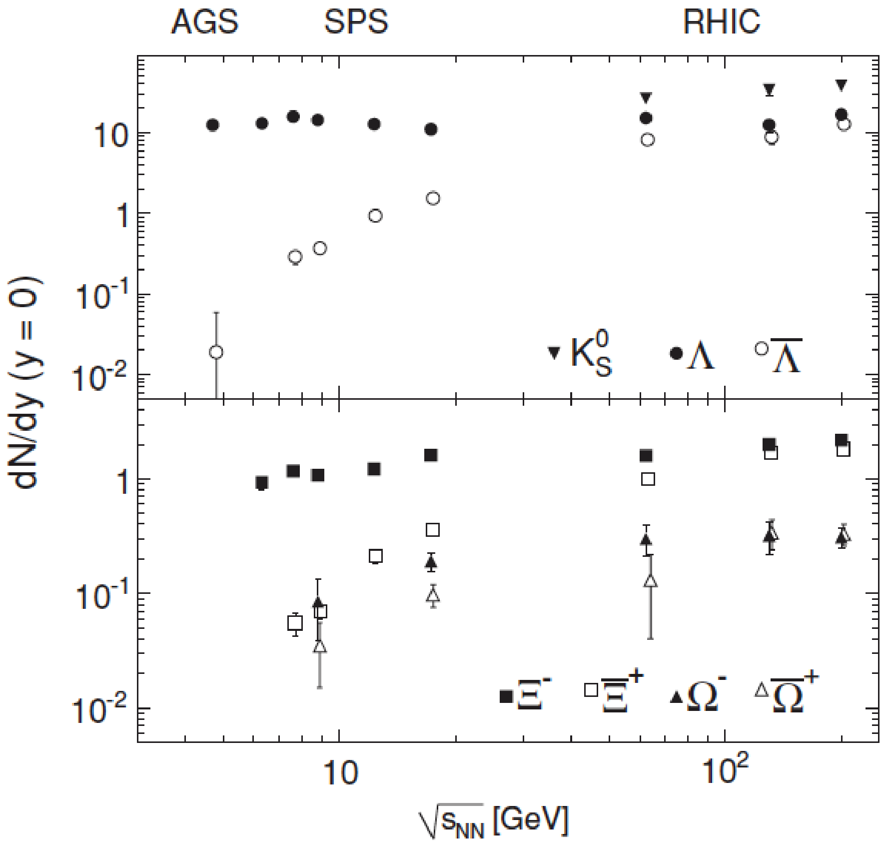
Yields at Lower Energies (NA49, NA57, STAR)

Energy Dependence

Gap between SPS and RHIC is being closed

Overlap with SPS → cross checks

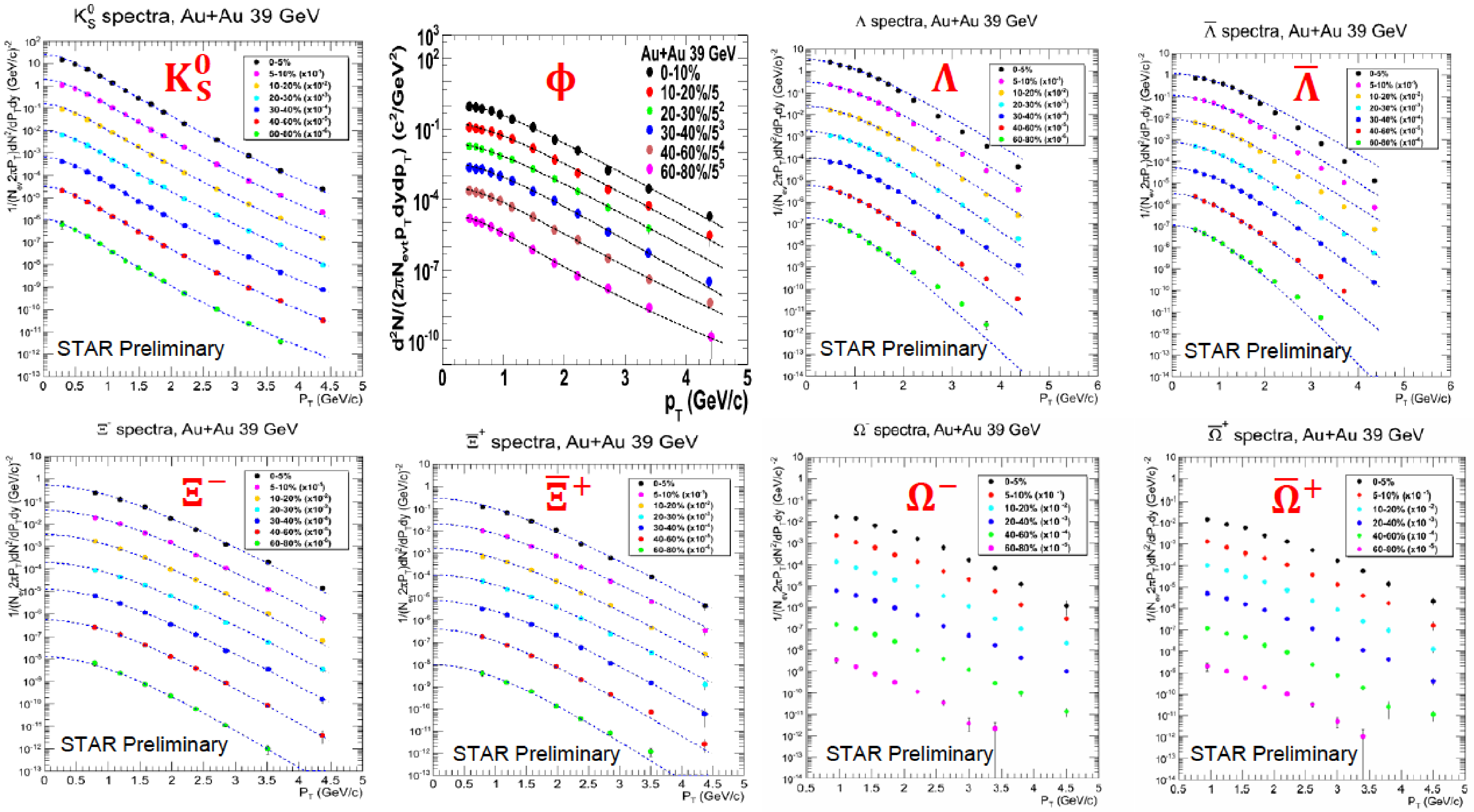
From top SPS energy up to LHC all particle species, including rare Ξ and Ω, are covered



STAR
PRC83, 024901 (2011)

Overview on Strangeness Measurements

Beam Energy Scan (BES) at RHIC: STAR



X. Zhang, SQM 2015

Overview on Strangeness Measurements

Beam Energy Scan (BES) at RHIC: STAR

Antibaryon-baryon ratios

Mid-rapidity yields

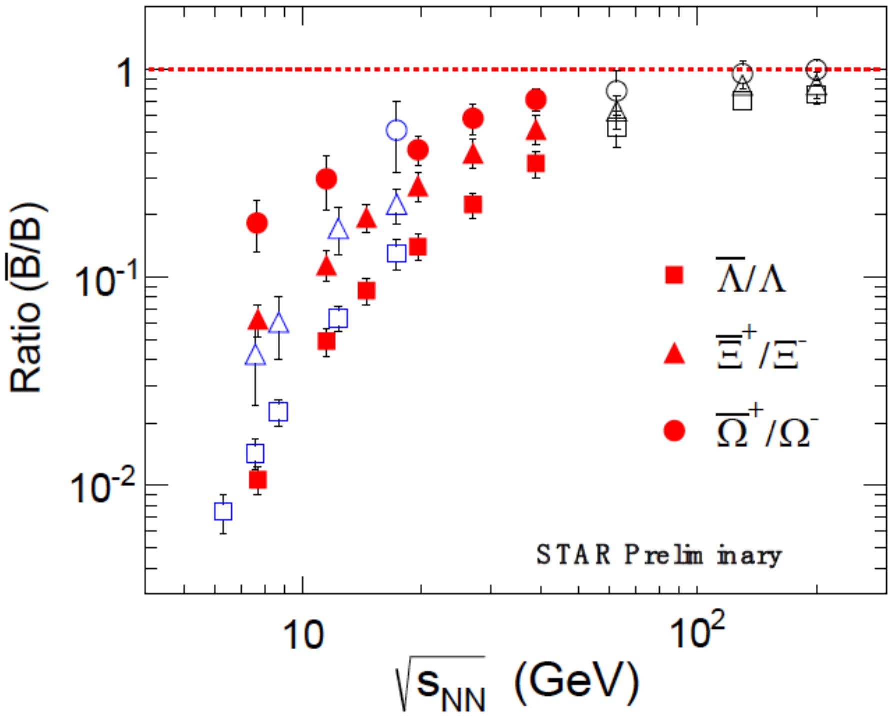
Continuous evolution from SPS to RHIC

Ratios converge towards unity at high energies

$R(\bar{\Omega}^{+}/\Omega^{-}) > R(\bar{\Xi}^{+}/\Xi^{-}) > R(\bar{\Lambda}/\Lambda)$

Overlap with SPS data

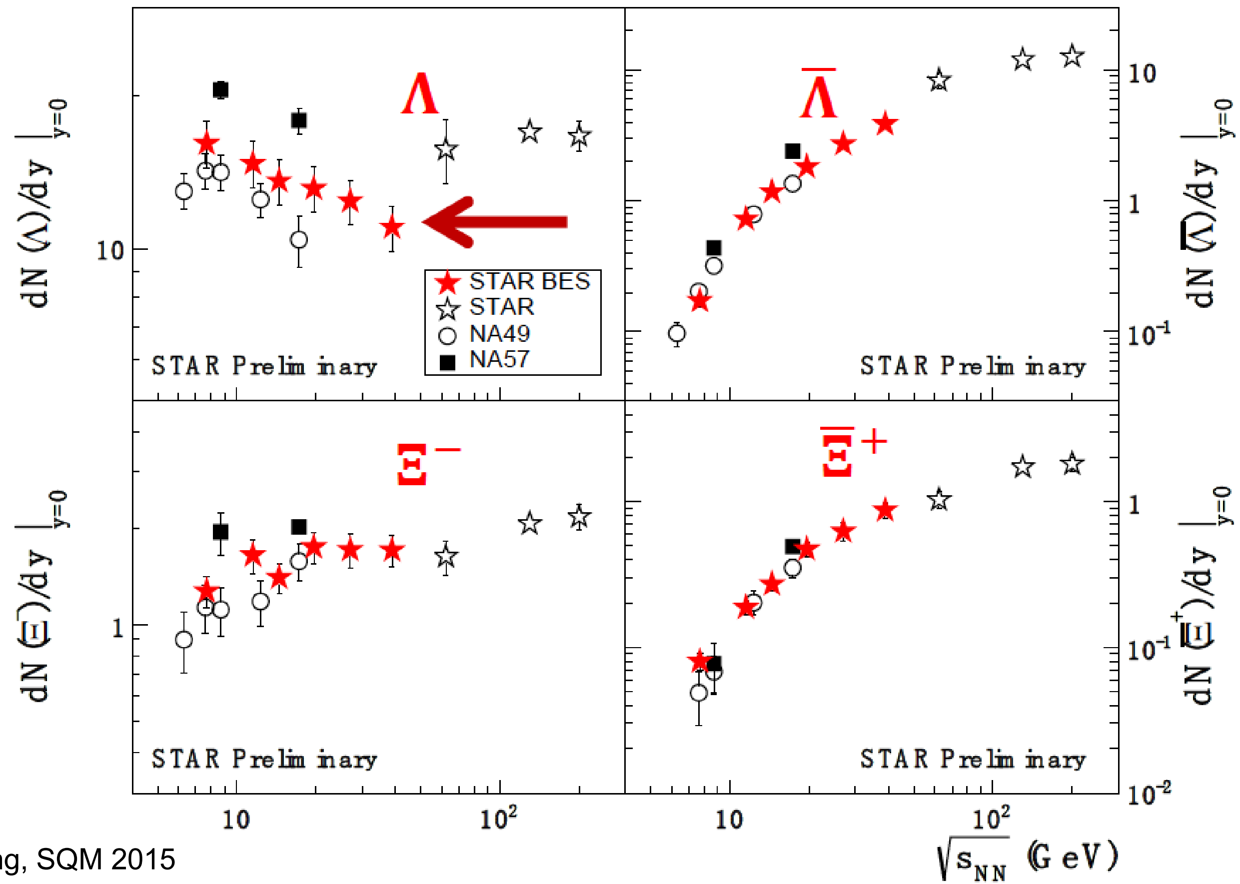
Good agreement with NA49 ratios



X. Zhang, SQM 2015

Overview on Strangeness Measurements

Yields at Lower Energies (NA49, NA57, STAR)



X. Zhang, SQM 2015

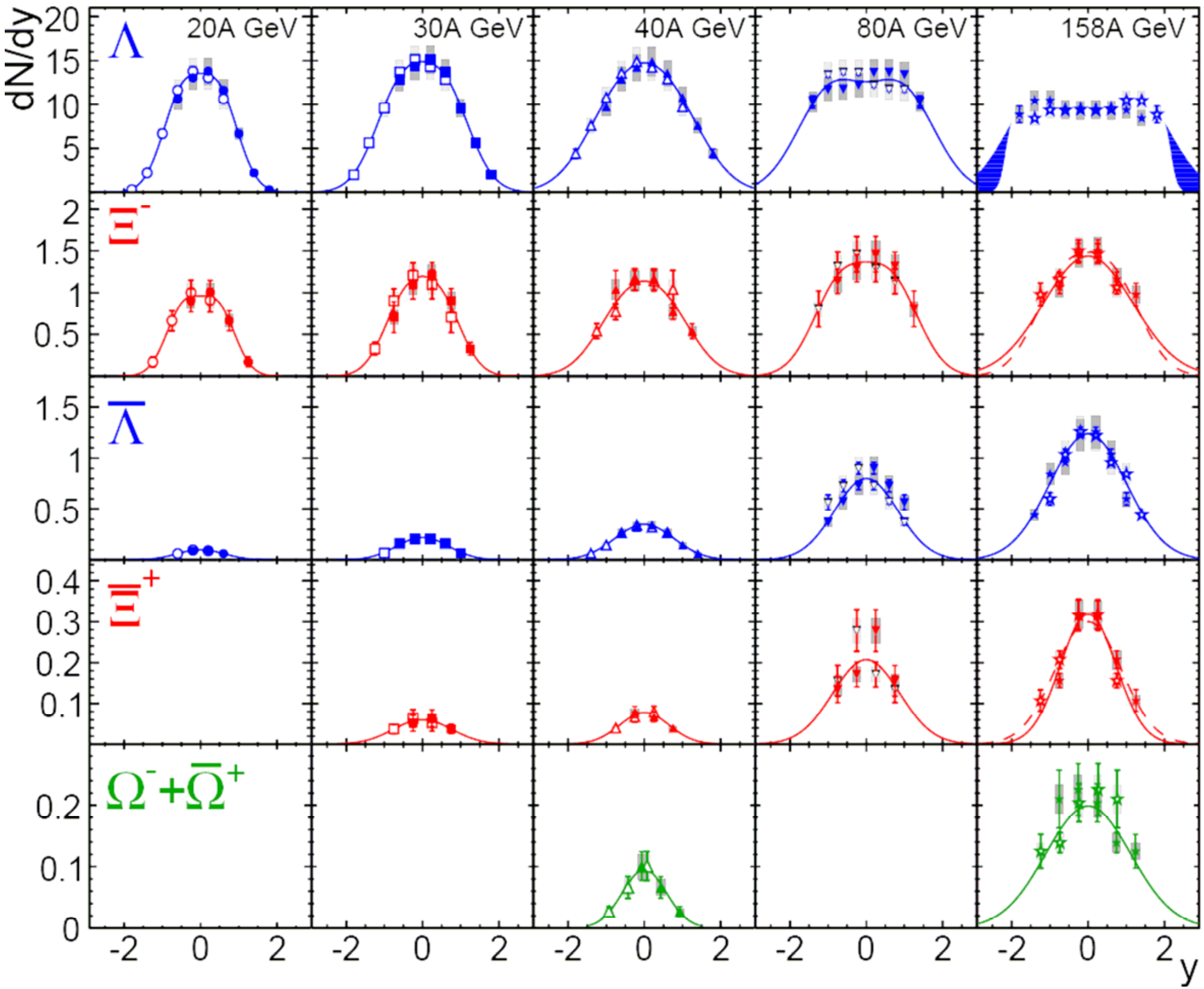
Overlap with SPS data

Reasonable agreement with NA49 yields

STAR data indicate minimum in Λ yields at higher $\sqrt{s_{NN}}$

Overview on Strangeness Measurements

Rapidity Distributions at Lower Energies (NA49)



NA49
PRC78, 034918 (2008)
PRL94, 192301 (2005)

Overview on Strangeness Measurements

Beam Energy Scan at the CERN-SPS: NA61 / SHINE

Systematic study of pp
Beam energies
20, 31, 40, 80, 158 GeV

Before: collection of “historic” data as reference

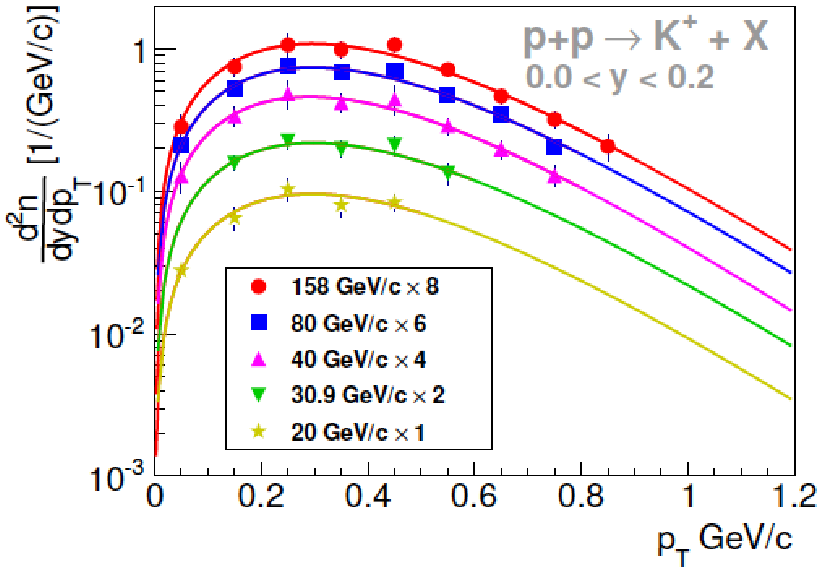
Data on charged kaons available up to now

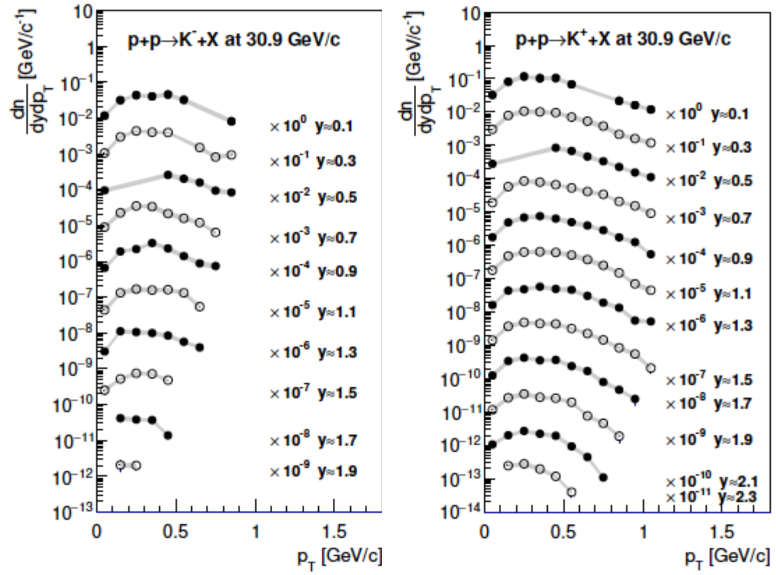
Large rapidity coverage

Results from Be+Be
Beam energies
13, 19, 31, 40, 75, 150 *A*GeV

Charged pions shown so far

Heavier systems
Analysis of Ar+Sc ongoing

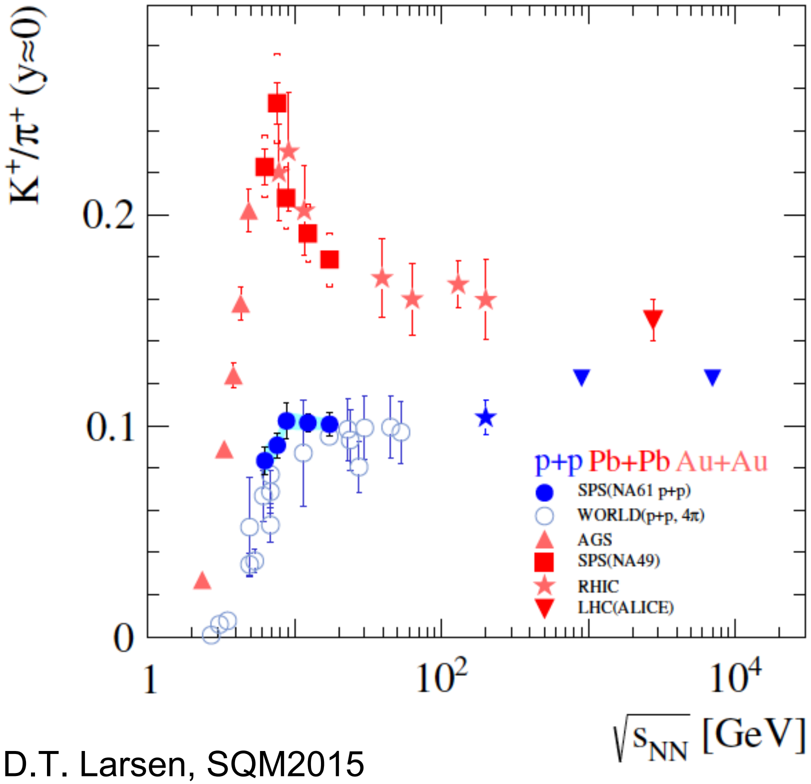




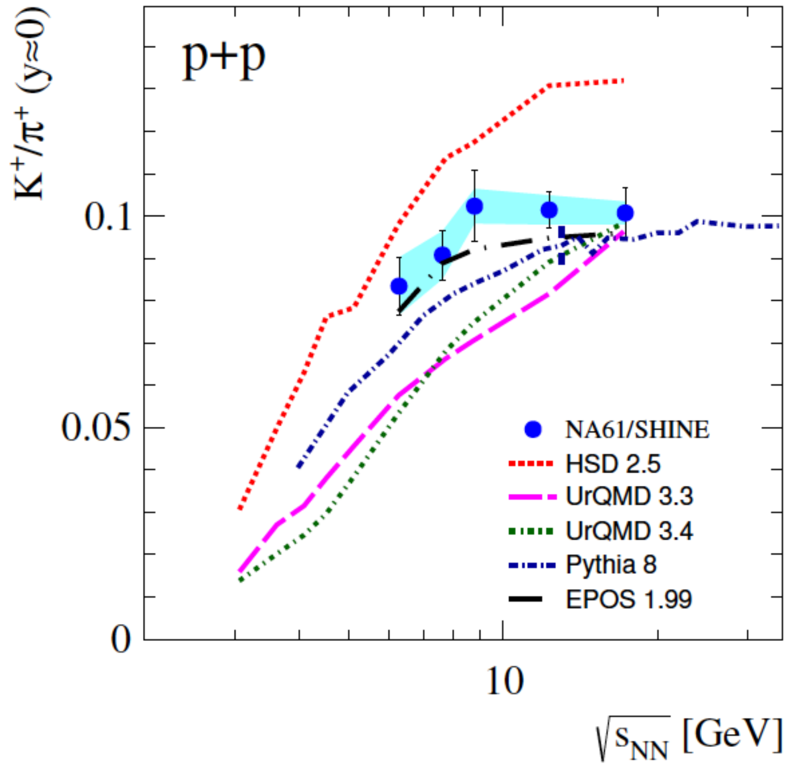
D.T. Larsen, SQM2015

Overview on Strangeness Measurements

Beam Energy Scan at the CERN-SPS: NA61 / SHINE



D.T. Larsen, SQM2015



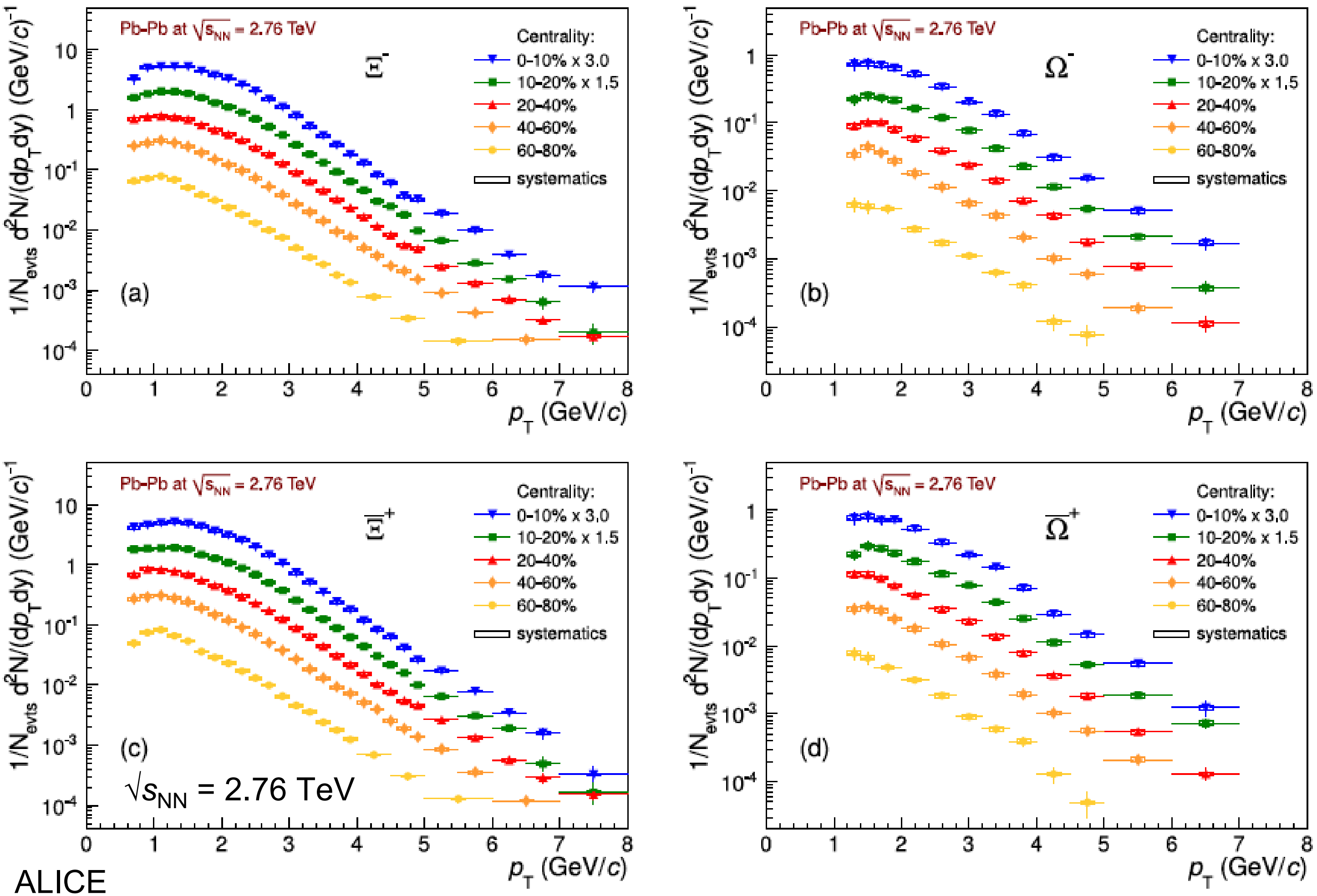
Energy dependence of K^+/π^+ yields

Reduced statistical and systematic errors in comparison to "historic" data

Important benchmark for models

Overview on Strangeness Measurements

LHC



ALICE
PLB728, 216 (2014)

Strangeness Enhancement

Strangeness as QGP Signature

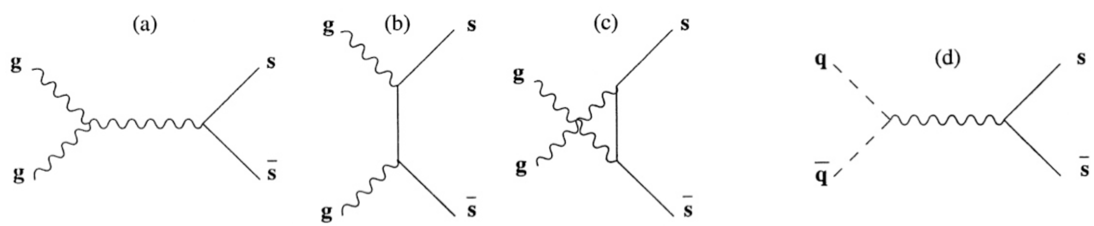
Quark Gluon Plasma (QGP) signature

J. Rafelski and B. Müller, Phys. Rev. Lett. **48**, 1066 (1982)
P. Koch, B. Müller, and J. Rafelski, Phys. Rep. **142**, 167 (1986)

Strangeness is newly produced (no *s*-Quarks in nucleons)

Thresholds are high in hadronic reactions,
e.g..: $N + N \rightarrow N + K^{+} + \Lambda$ ($E_{thres} \approx 700$ MeV)

Fast equilibration in QGP via partonic processes, e.g. gluon-fusion

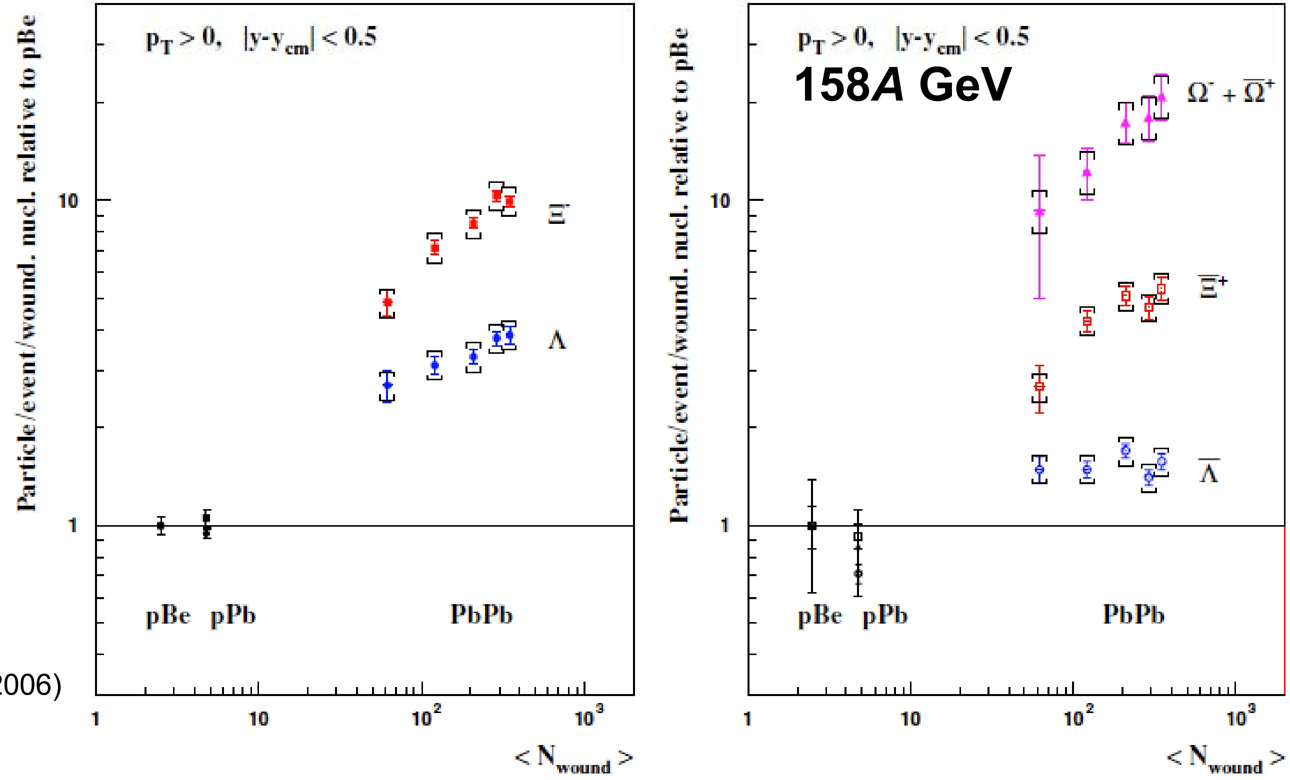


⇒ Enhanced strangeness production relative to p+p

experimentally observed: NA35, WA97, NA49, NA57, STAR, ALICE, ...

Strangeness Enhancement

SPS Data (NA57)



NA57
JPG32, 427 (2006)

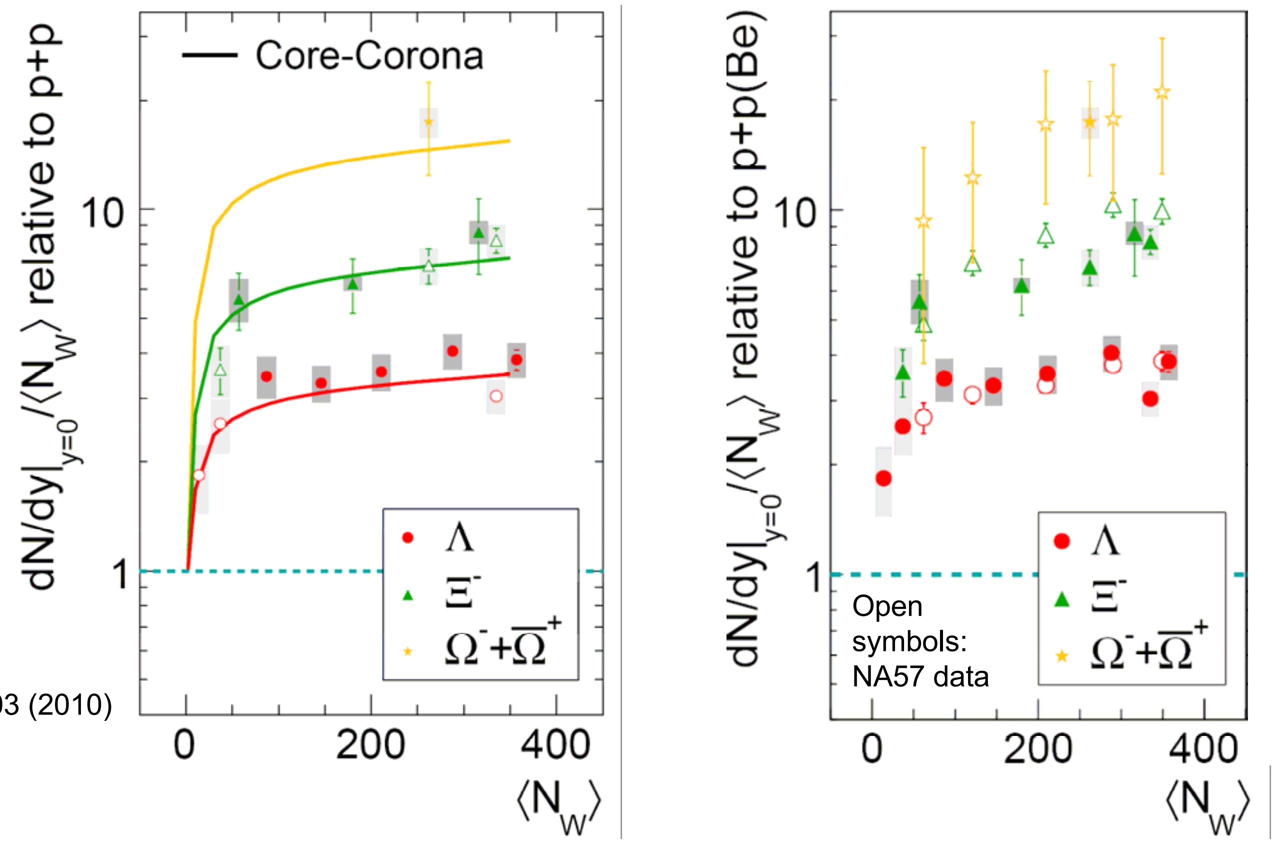
Enhancement factor
Relative to p+Be(!)

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

Enhancement for Ω up to factor ≈ 20

Strangeness Enhancement

SPS Data (NA49)



NA49
JP230, 012003 (2010)

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

Strangeness Enhancement

Canonical Suppression

Statistical model

Transition from canonical to grand-canonical description

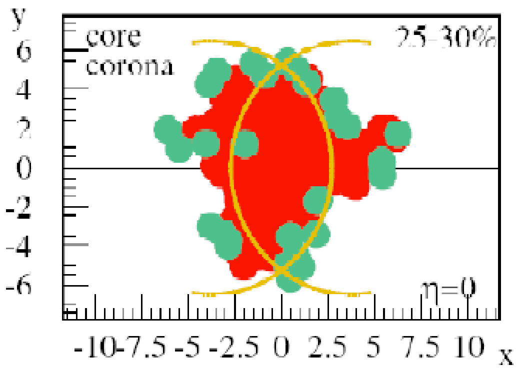
Hierarchy of suppression depends on strangeness content

Onset of suppression does not match data

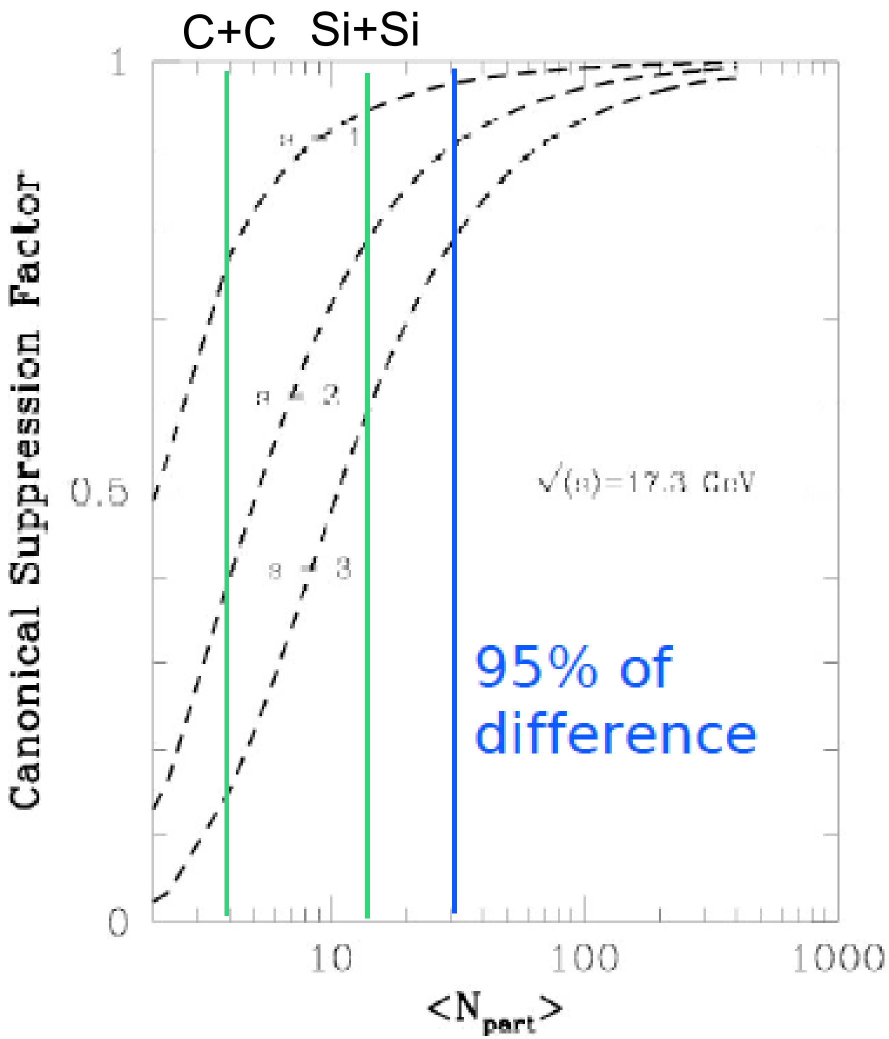
Model: $\langle N_{part} \rangle \approx 30$

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

Core corona



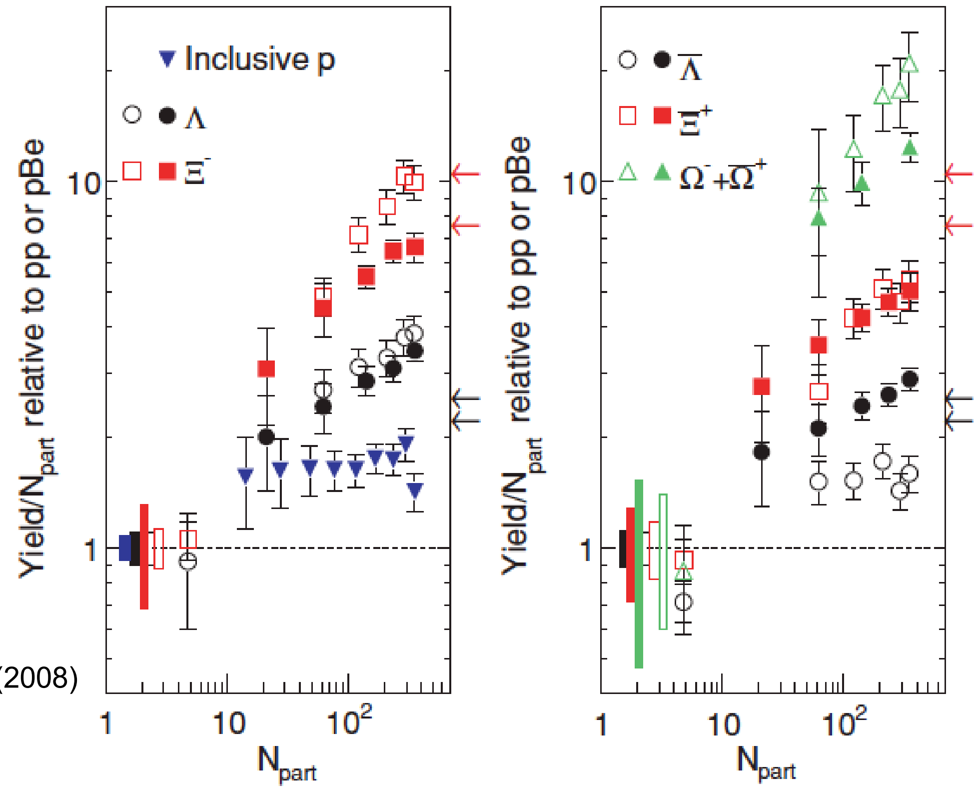
K. Werner



S. Hamieh et al.,
PLB486, 61 (2000)

Strangeness Enhancement

RHIC Data (STAR)



STAR
PRC77, 044908 (2008)

Enhancement factor

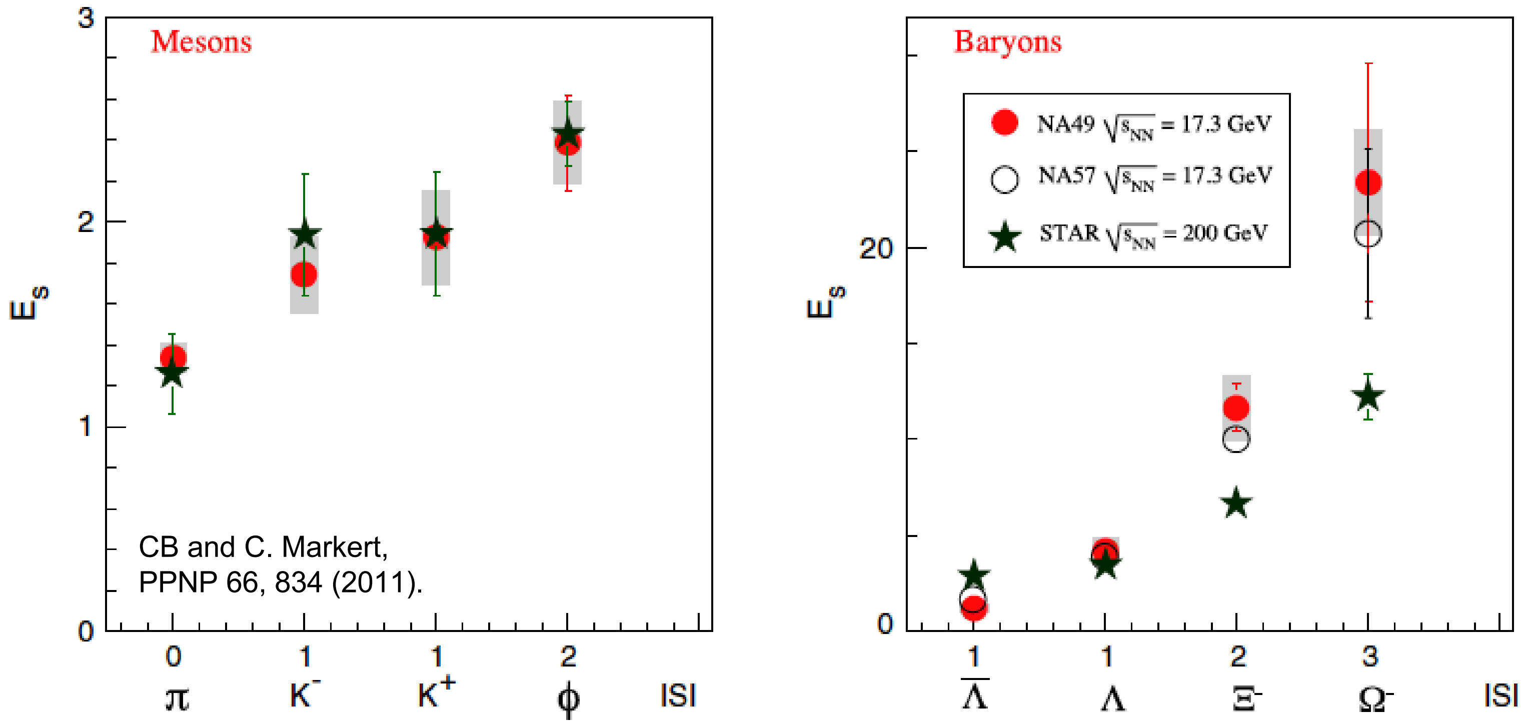
Relative to p+p

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

Enhancement for Ω factor ≈ 12

Strangeness Enhancement

SPS and RHIC Compared



Enhancement factor

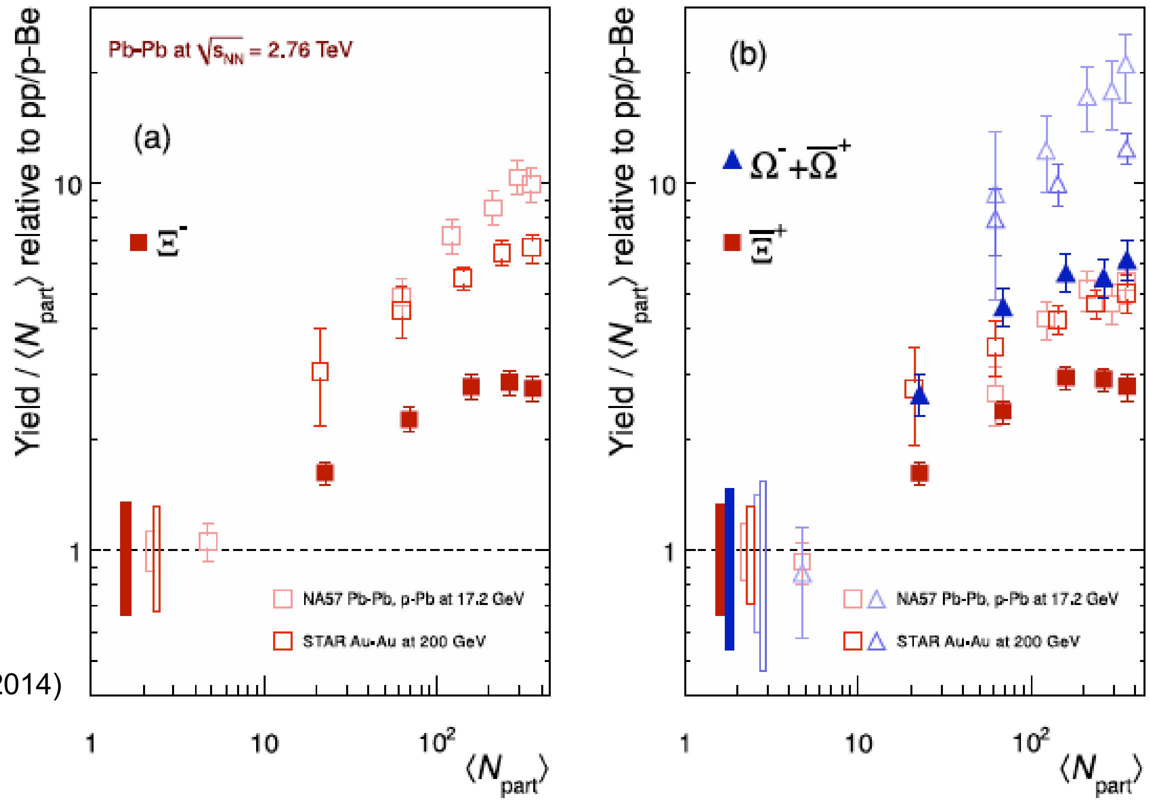
As function of the number of strange valence quarks |*S*|

E_s similar for mesons and Λ, large difference for Ξ and Ω

Opposite trend for $\bar{\Lambda}$

Strangeness Enhancement

LHC Data (ALICE)



ALICE
PLB728, 216 (2014)

Enhancement factor

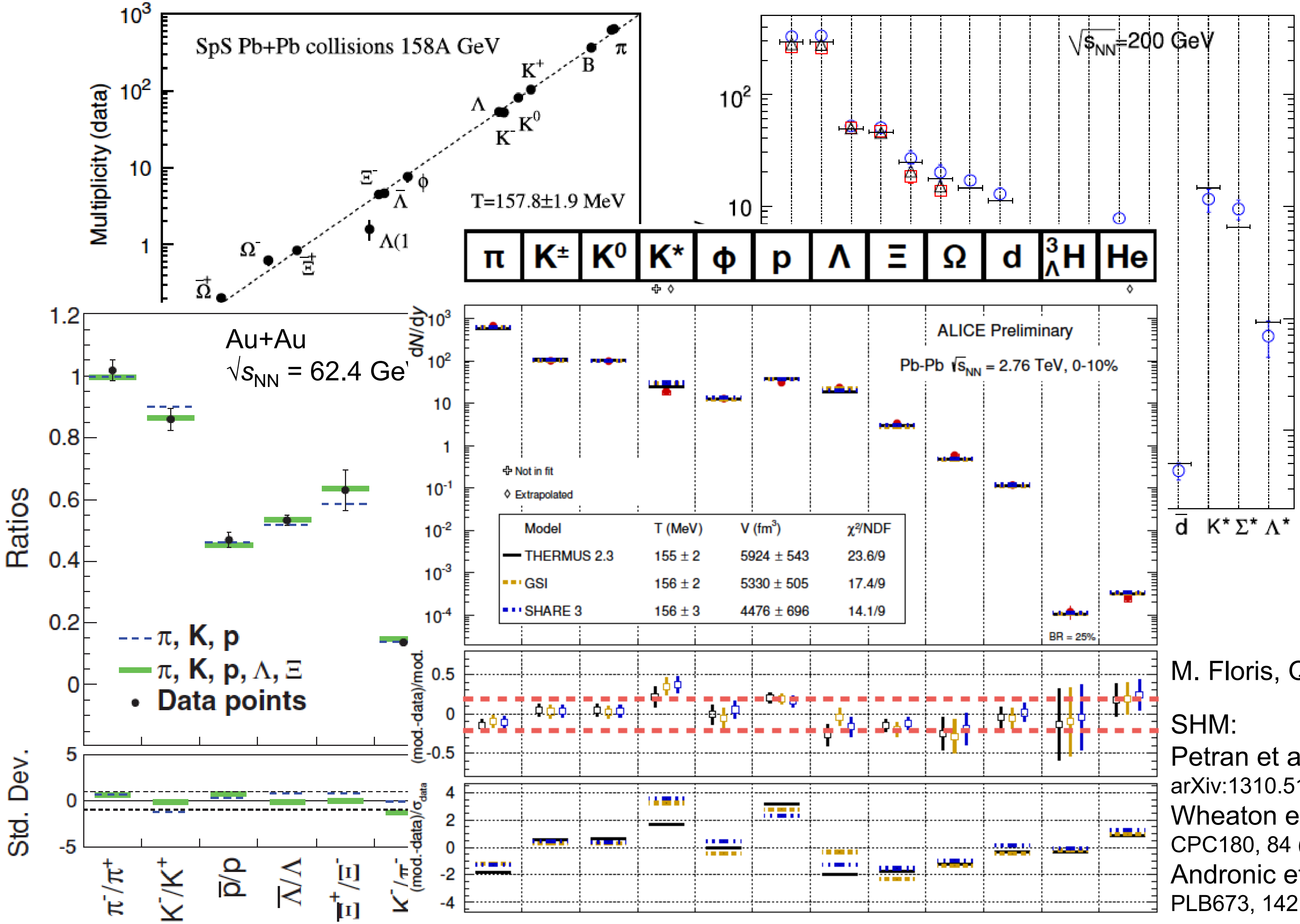
Relative to p+p

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

Enhancement for Ω factor ≈ 6

Strangeness Enhancement

Statistical Model Comparison in A+A



M. Floris, QM 2014

SHM:
Petran et al., arXiv:1310.5108
Wheaton et al., CPC180, 84 (2009)
Andronic et al., PLB673, 142 (2009)

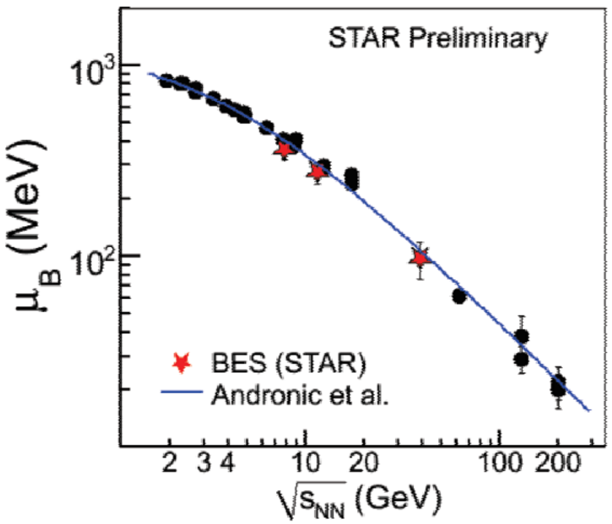
Strangeness Enhancement

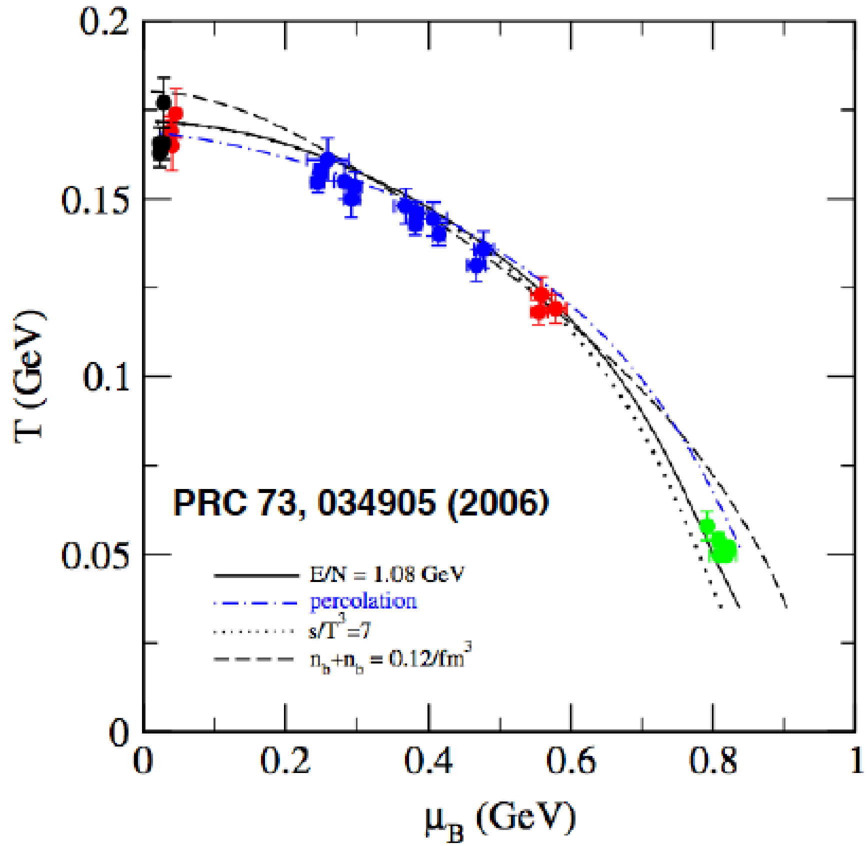
Statistical Model Comparison in A+A

Chemical Freeze-Out

Universal freeze-out curve

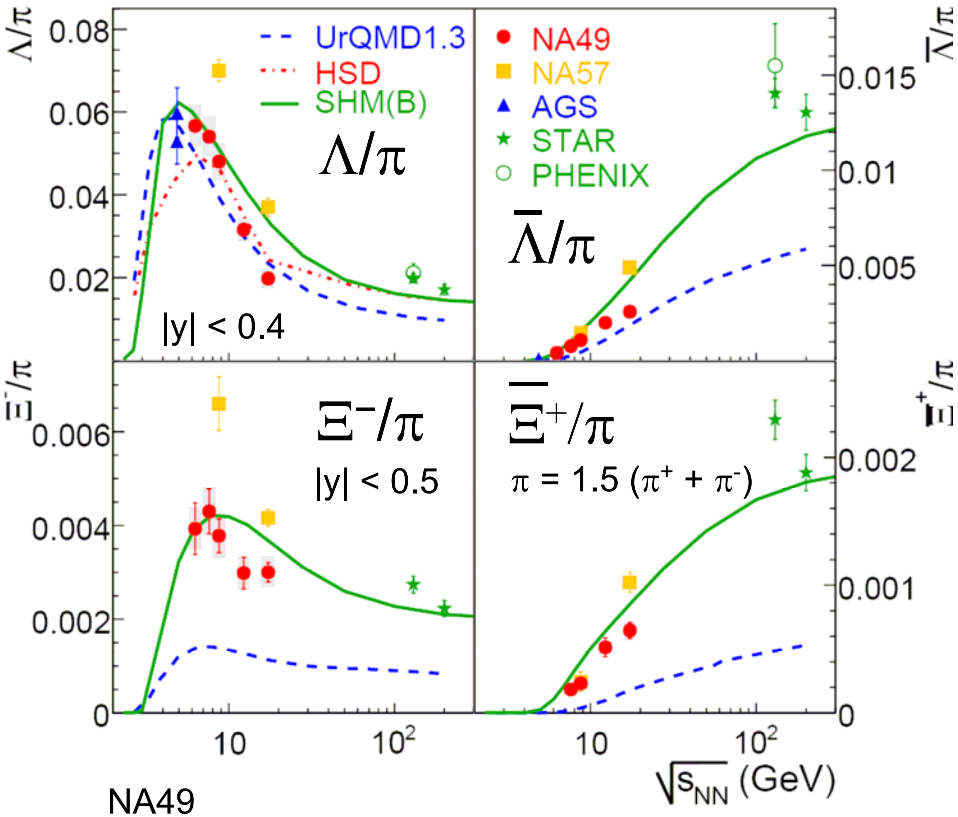
Parameterization of freeze-out parameters T_{ch} and μ_B vs $\sqrt{s_{NN}}$



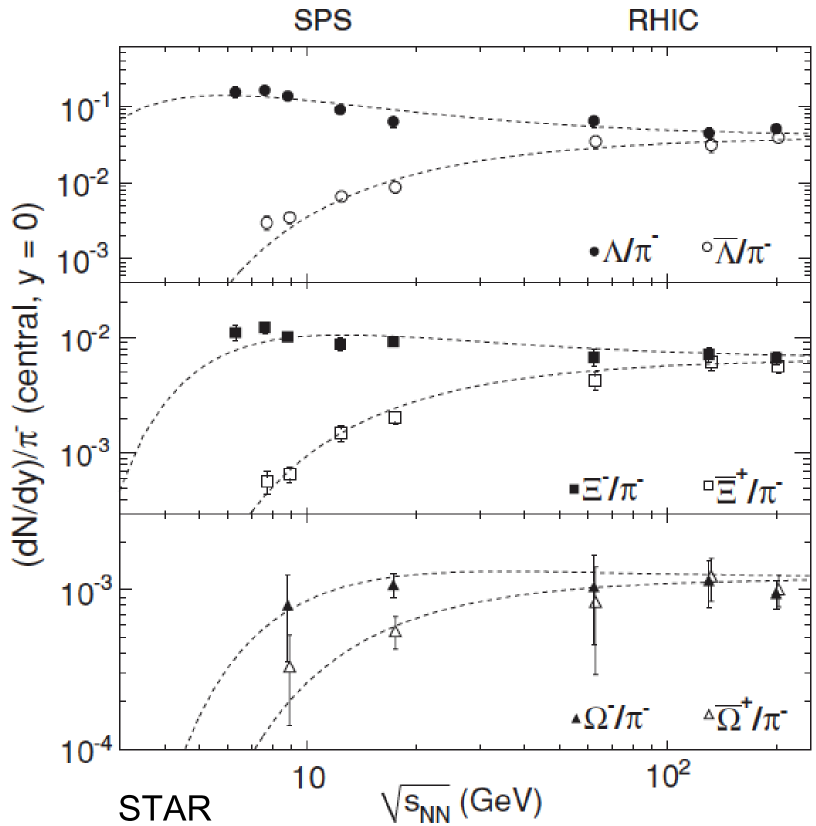


Strangeness Enhancement

Statistical Model Comparison in A+A



NA49
PRC78, 034918 (2008)
SHM: A. Andronic et al.
NPA772, 167 (2006)



STAR
PRC83, 024901 (2011)
SHM: S. Wheaton et al.
CPC180, 84 (2009)

Strangeness close to statistical model expectation in A+A

Already at lowest SPS energies (some exceptions ⇒ ϕ)

Strangeness Enhancement

K⁺ and Λ Towards Low Energies

|S| = 1 Particles

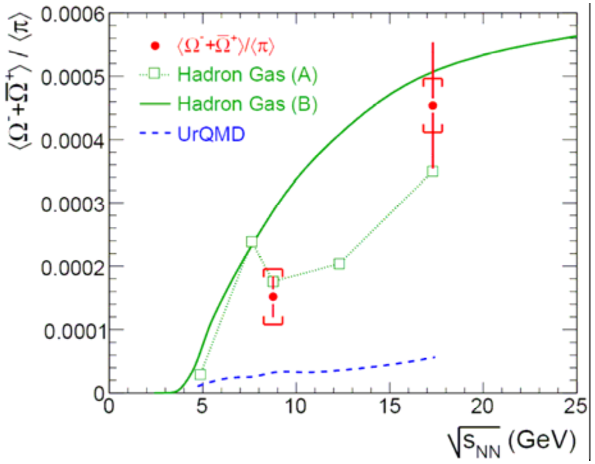
Continuous decrease with increasing $\sqrt{s_{NN}}$

Most dramatic change at lower energies
Threshold effects

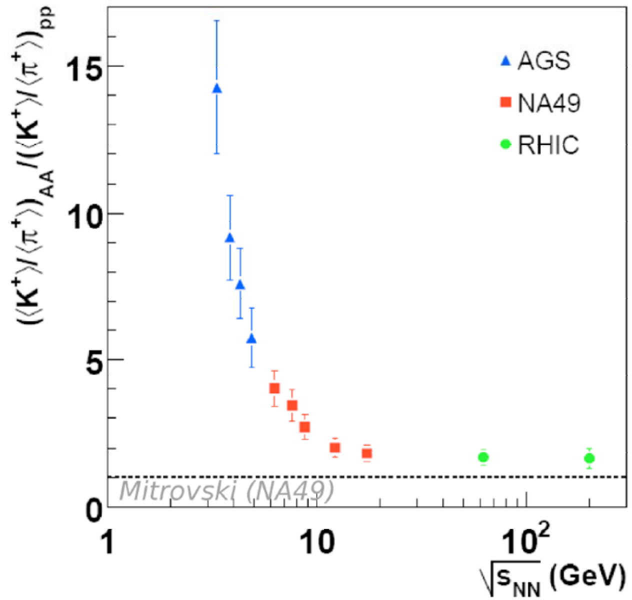
Reasonably described by
transport models

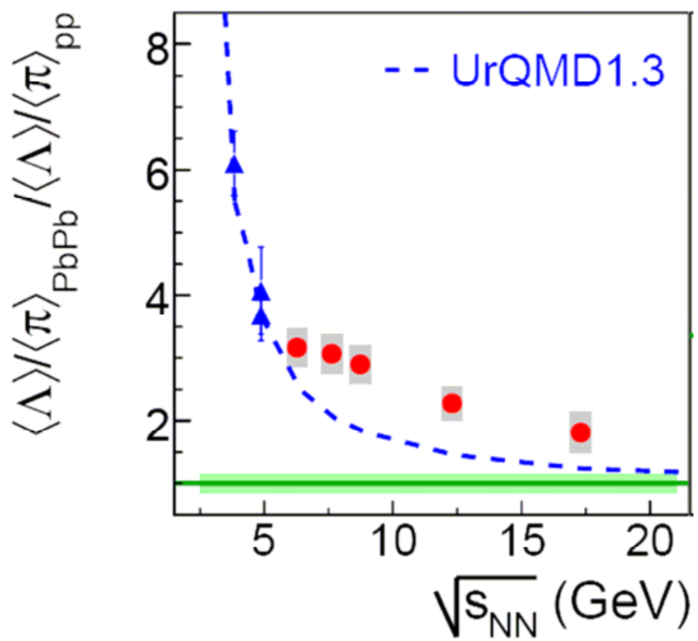
Multistrange particles

Scarce data, pp reference missing



NA49
PRL94, 192301 (2005)





Strangeness Enhancement

Cascades at Low Energies

Sub-Threshold

Threshold in N+N: E_{thr} = 3.74 GeV

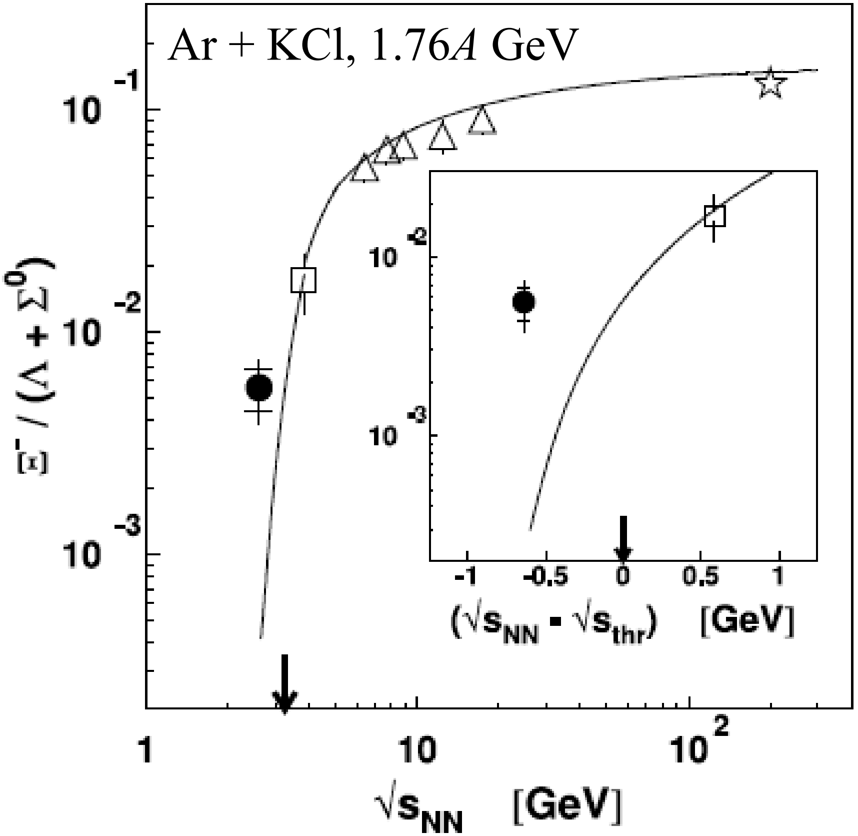
Surprisingly high Ξ^- yield

Statistical model comparison

Data much above model expectation

Similar for transport models

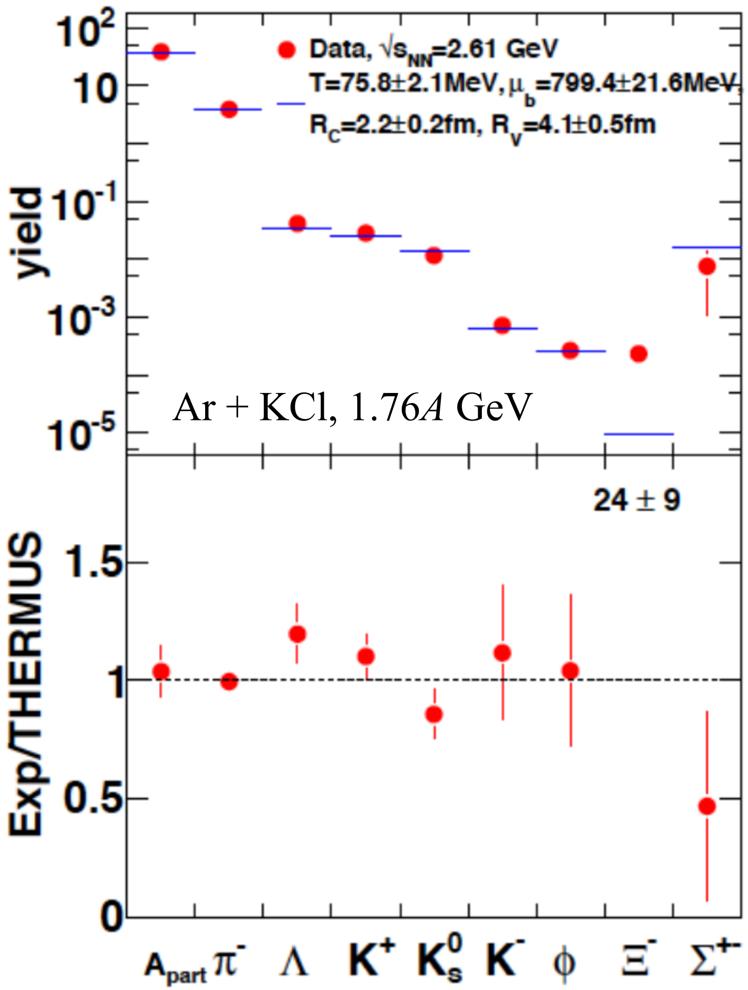
New mechanisms?



HADES
PRL103, 132301 (2009)

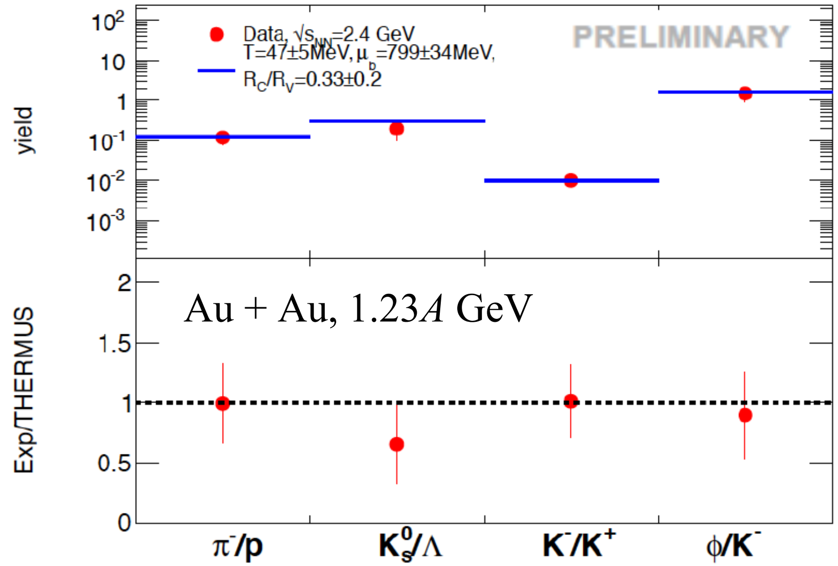
Strangeness Enhancement

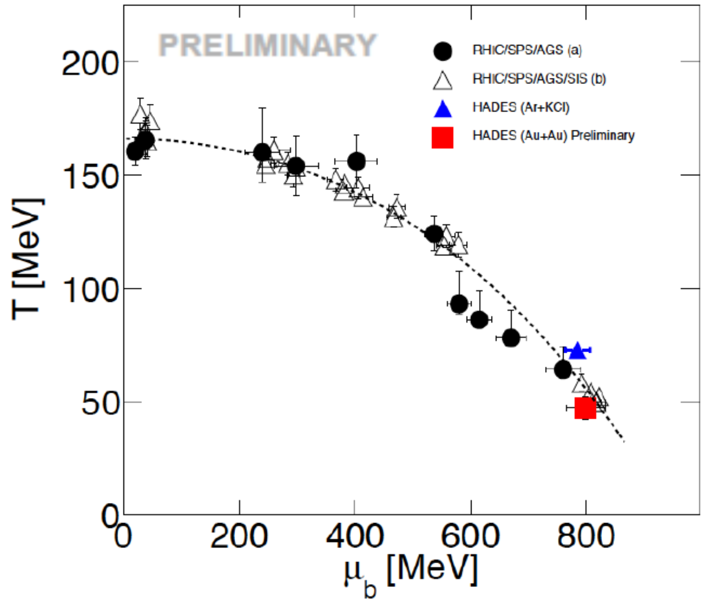
SIS-18: HADES Data Compared to Statistical Model



M. Lorenz
SQM2015

SHM: S. Wheaton et al.
CPC180, 84 (2009)





Strangeness Enhancement
Conclusions

Strangeness enhancement decreases with increasing energy

E.g. Ω-enhancement reduces from ~20 to ~6 from SPS to LHC

Centrality dependence fits core-corona picture

Central A+A data well described by statistical model at higher energies

Strong rise of enhancement towards low energies

Sub-threshold multistrange particles above statistical model expectation!

Experimental situation

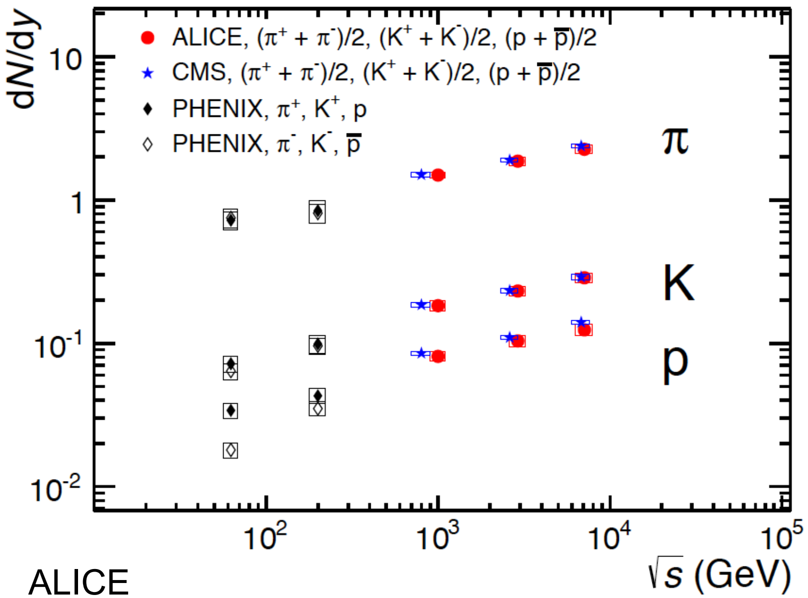
All particles species between top-SPS and LHC

Very good coverage of energy dependence

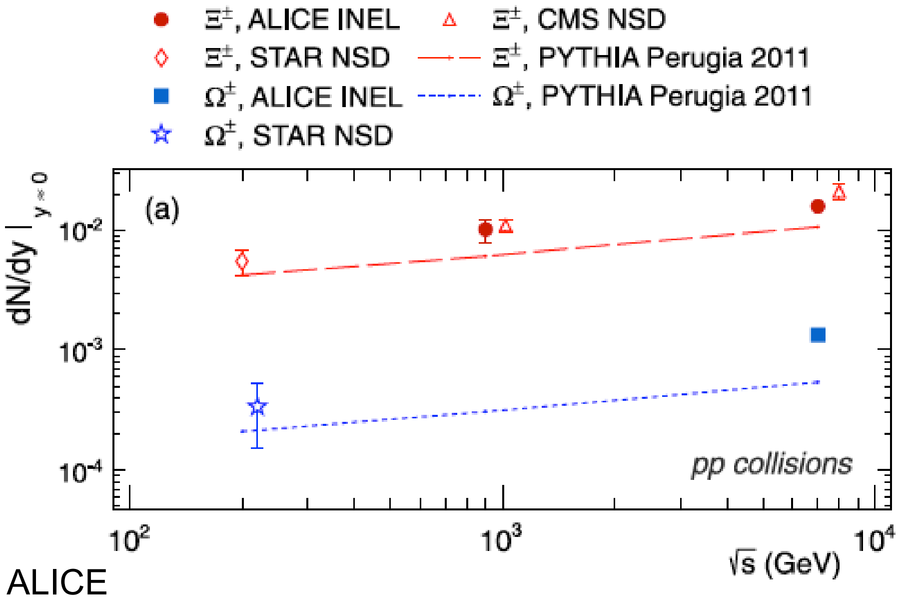
Data on rare particles (Ξ, Ω) scarce at energies below top-SPS

Small Systems

Energy Dependence of pp Data (RHIC and LHC)



ALICE
EPJC75,226 (2015)



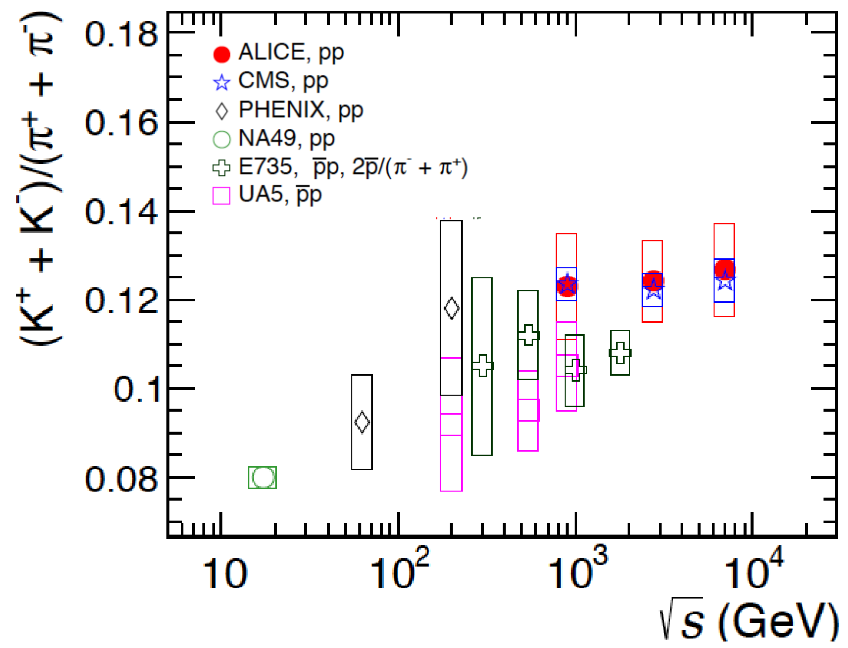
ALICE
PLB712, 309 (2012)

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

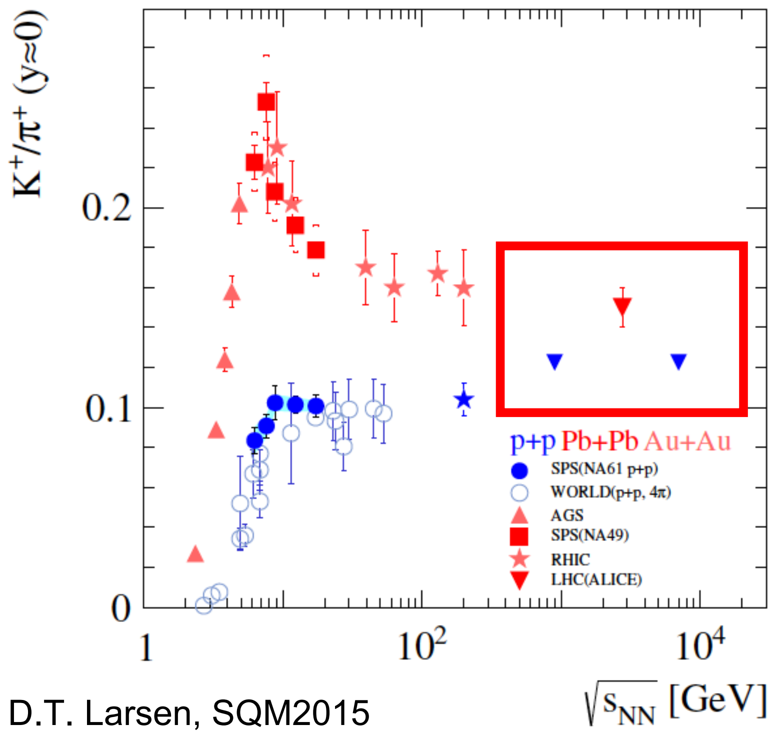
Stronger than model expectation for multistrange particles

Small Systems

Energy Dependence of pp Data



ALICE
EPJC75,226 (2015)



D.T. Larsen, SQM2015

Strange / non-strange ratio: K^+/π^+

Continuous increase with √s in pp (not in A+A, though)

Ratio converges to approx. same value at high energies

Small Systems

Energy Dependence of pp Data

Ratio strange/non-strange

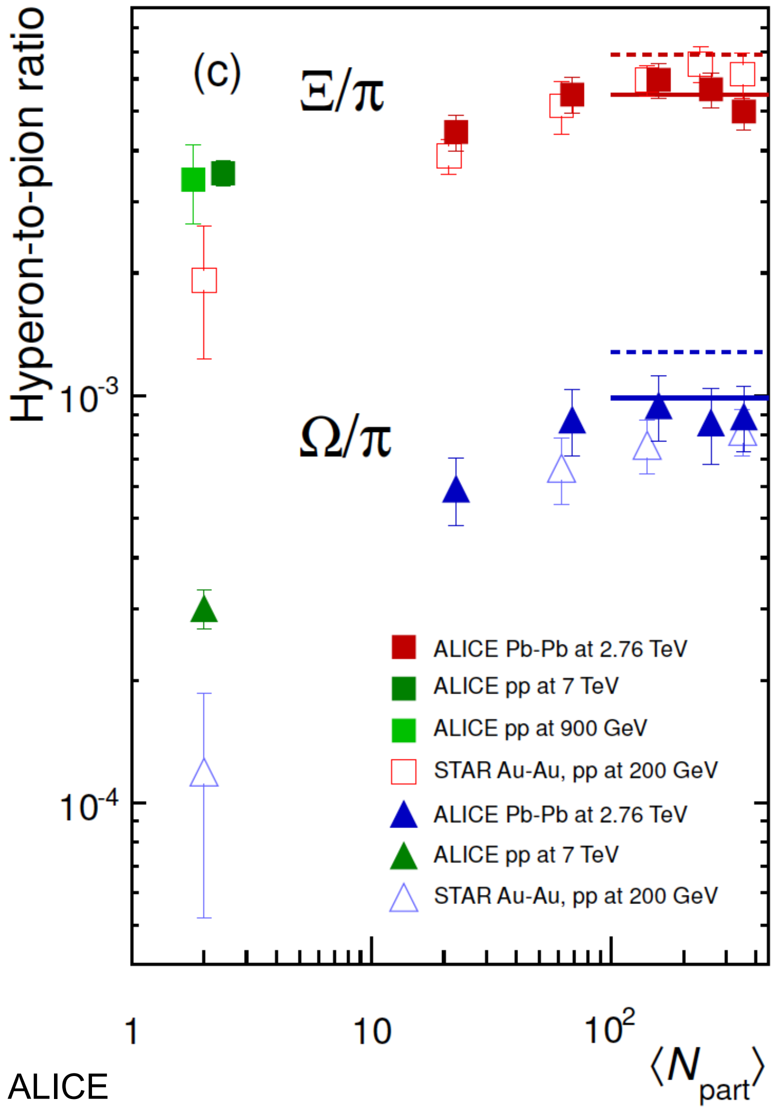
Hyperon-to-pion ratios

Increase with $\sqrt{s}$ 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)

Strangeness-suppression in pp released at high energies



ALICE
PLB728, 216 (2014)

Small Systems

Statistical Model Comparison in pp

Statistical model analysis of pp

Existing for lower energies and
older Tevatron data at higher energies

Based on canonical ensemble

Predictions for pp

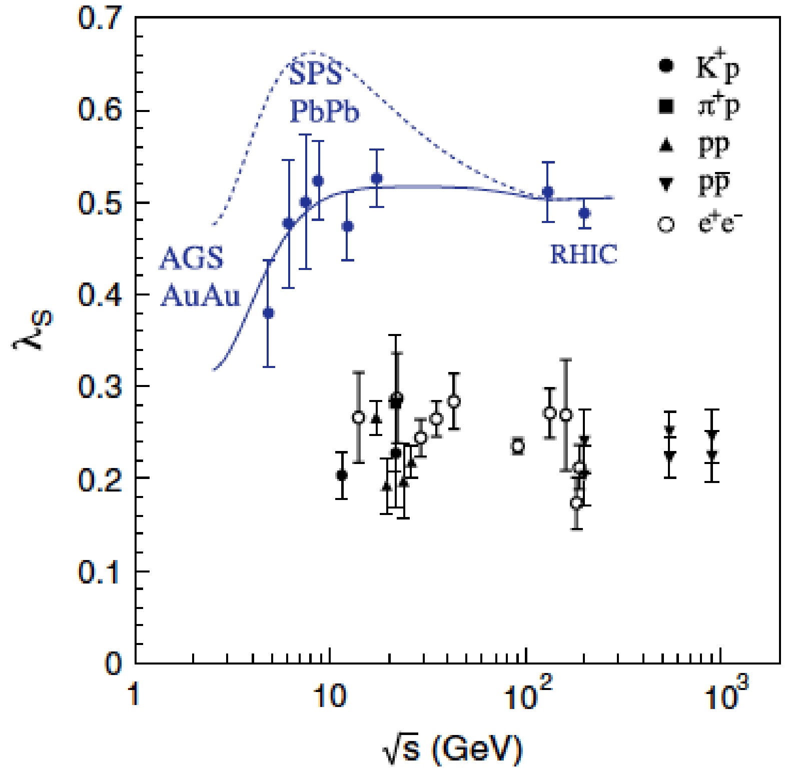
Table 2. Predictions of the midrapidity density of hadrons relative to that of all charged hadrons at $\sqrt{s}$ = 10 TeV in the grand-canonical limit. The temperature value is assumed as T = 170 MeV, and the numbers *do not* include weak decay products.

Particle	$(dn/dy)/(dn/dy_{ch})$ $\gamma_S = 0.6$	$(dn/dy)/(dn/dy_{ch})$ $\gamma_S = 1$
…		
$\Lambda = \bar{\Lambda}$	0.0112	0.0162
$\Xi^+ = \Xi^-$	0.001 05	0.002 54
$\Omega^+ = \Omega^-$	0.000 121	0.000 488

F. Becattini et al.,
JPG38, 025002 (2011)

Measurement (pp, $\sqrt{s}$ = 7
$\Xi^-/(dN_{ch}/d\eta)$: 0.00131
$\Omega^-/(dN_{ch}/d\eta)$: 0.000112

ALICE
PLB728, 216 (2014)



F. Becattini and J. Manninen,
JPG35, 104013 (2008)

Wroblewski-factor:

$$\lambda_s = \frac{2\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

Small Systems

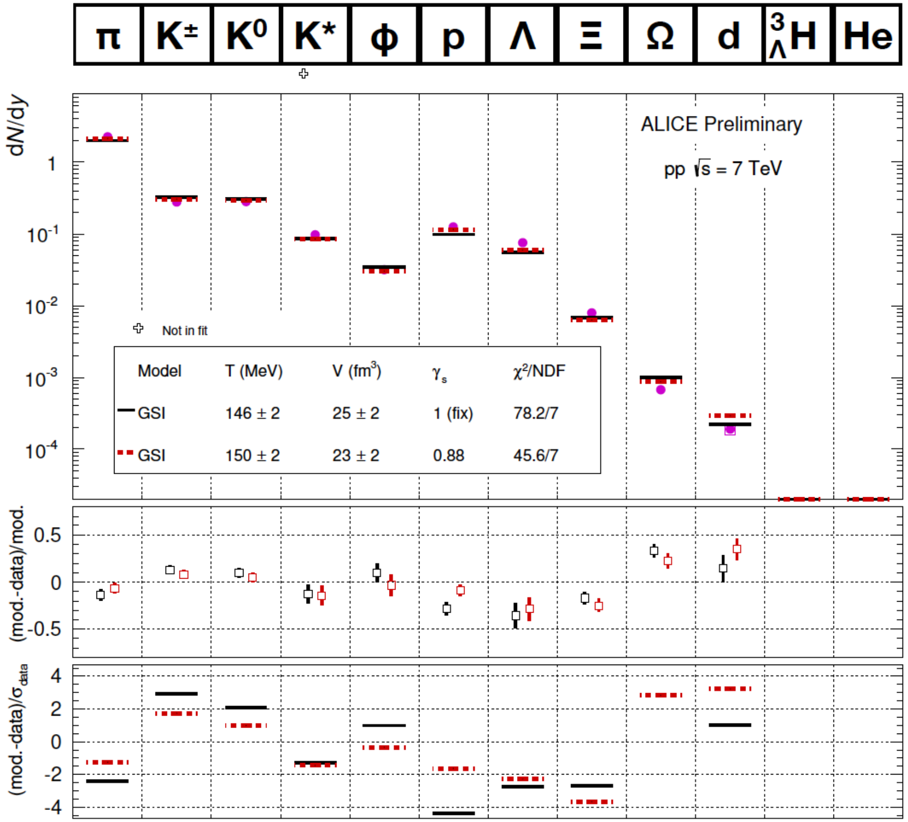
Statistical Model Comparison in pp

Statistical model fit

Grand canonical ensemble

χ^2/NDF not too impressive

Lower temperature than in extrapolation by Becattini et al.



M. Floris, QM2014

Small Systems

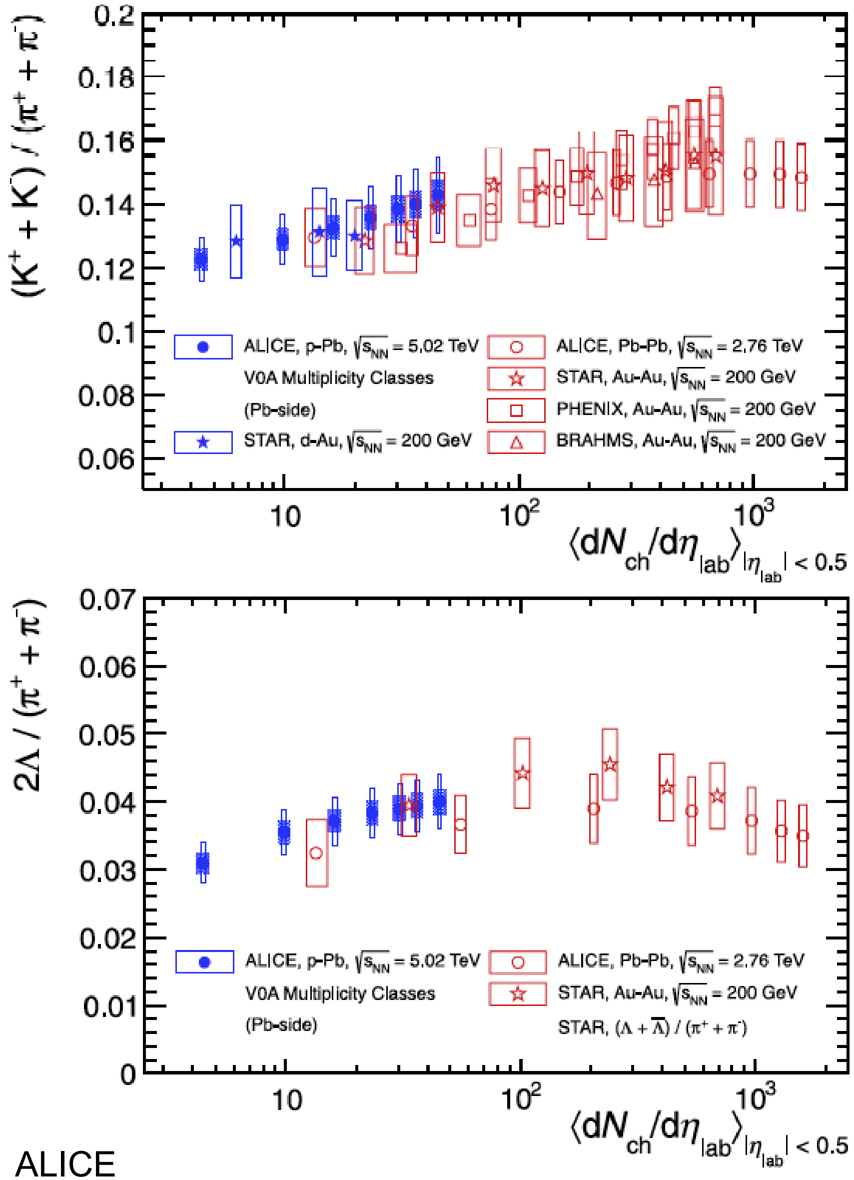
Particle Ratios: K/π and Λ/K^0_s in Proton-Nucleus Collisions

Multiplicity Dependence

Similar increase of strange/non-strange ratios in p-Pb and Pb-Pb

Connection between pp and AA?

How about multistrange particles?



ALICE
PLB728, 25 (2014)

Small Systems

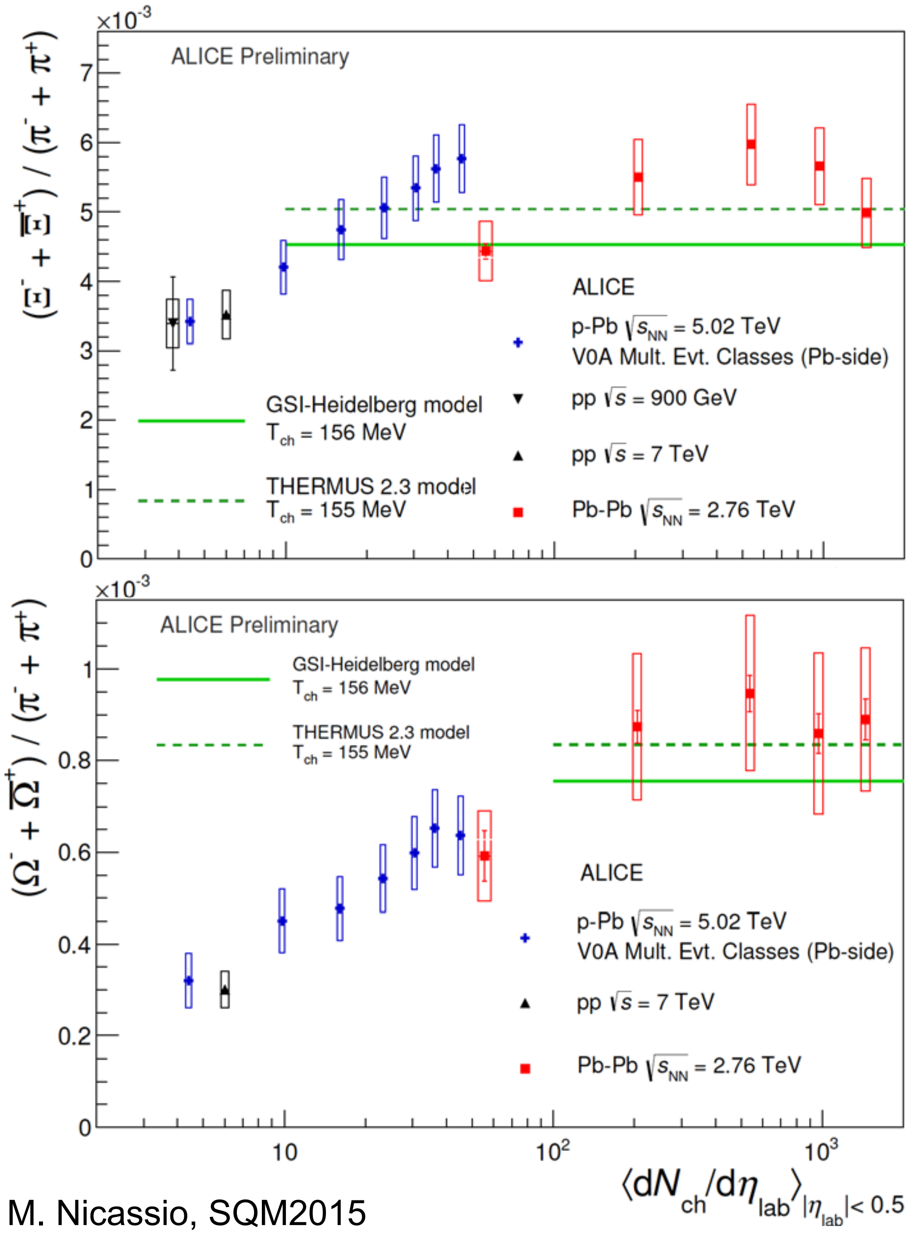
Particle Ratios in Proton-Nucleus: Ξ/π and Ω/π

Multiplicity Dependence

p-Pb provides qualitative connection between pp and Pb-Pb also for multistrange particles

Better scaling with multiplicity density?

Reaches level of statistical model (GC) expectation



M. Nicassio, SQM2015

Small Systems

Statistical Model for p-Pb

Statistical model fits

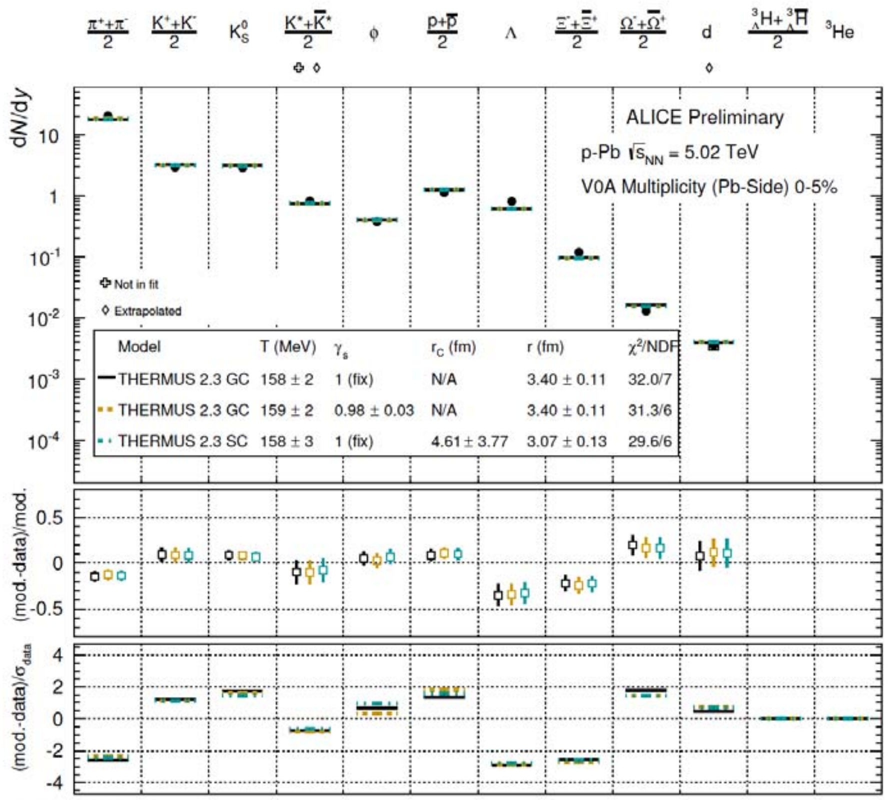
Grand-canonical (GC) and strangeness-canonical (SC)

Most central p-Pb collisions

χ^2/NDF not too impressive

γ_s compatible with unity.

$R_c \approx R_V \Rightarrow$ no canonical strangeness suppression



M. Floris, QM2014

Small Systems

Conclusions

Proton-proton collisions

Ratios of strange/non-strange particles rise faster in pp than in AA
Reach almost same level for |*S*| = 1 particles at LHC (e.g. K^+/π^+)

Strangeness suppression in pp get released
Grand-canonical limit reached?
⇒Systematic studies with statistical models

Proton-nucleus collisions

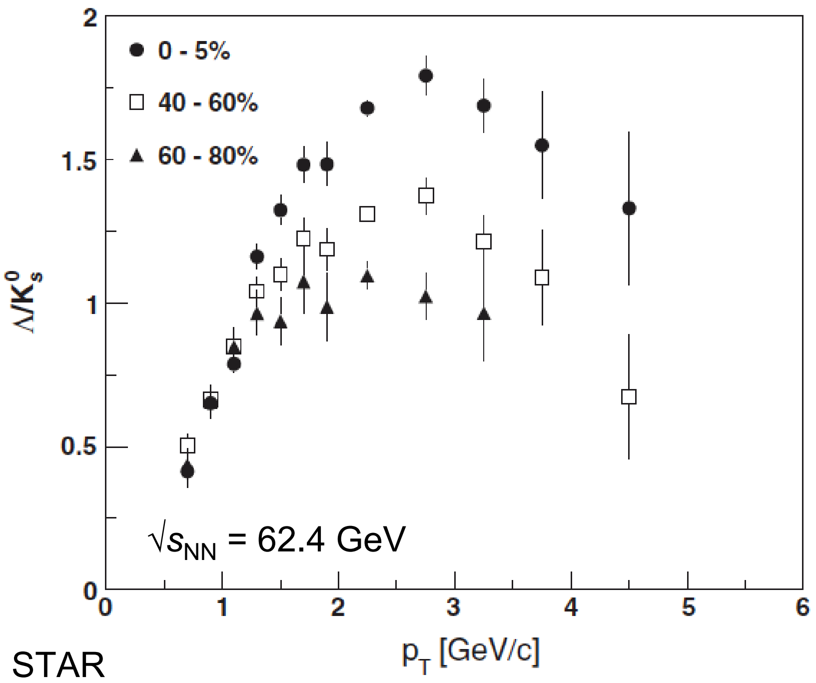
Can qualitatively bridge gap between pp and peripheral AA
Use of $dN_{ch}/d\eta$ to quantify centrality

Always exact overlap between pA and AA?

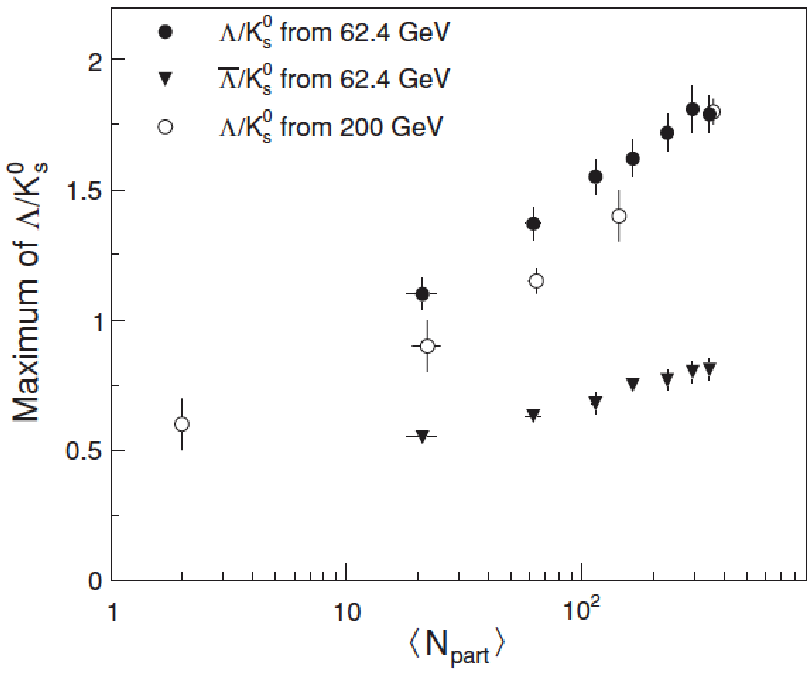
Statistical model comparisons inconclusive

Baryon-Meson Ratios

Λ/K^0_s-Ratio vs p_T at RHIC



STAR
PRC83, 024901 (2011)



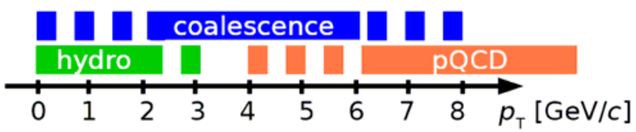
Physics of intermediate p_T region

Dominance of baryon production ⇒ $\Lambda/K^0_s > 1$ for $1.5 < p_T < 4$ GeV/c

Recombination

Hydro flow

Other (baryons as color singlet, transparent to final state interactions)



S. Brodsky and A. Sickles, PLB668, 111 (2008)

Baryon-Meson Ratios

Λ/K^0_s-Ratio vs p_T at SPS

Stronger baryon dominance

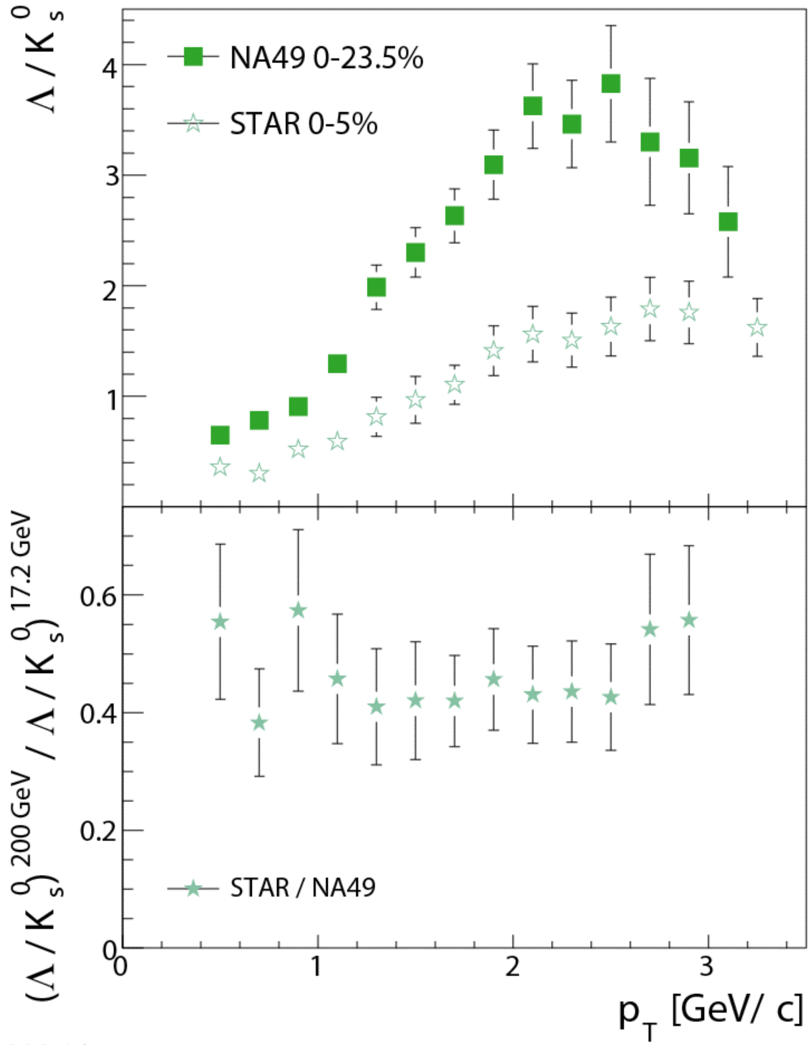
Height of maximum larger than RHIC

SPS: $(\Lambda/K^0_s)_{max} \approx 3.5$

RHIC: $(\Lambda/K^0_s)_{max} \approx 1.5$

Similar p_T dependence

Maximum maybe at slightly smaller p_T



NA49
JPG32, S479 (2006)

Baryon-Meson Ratios

Λ/K^0_s-Ratio vs p_T at LHC

Same baryon dominance

Height of maximum similar to RHIC
$(\Lambda/K^0_s)_{max} \approx 1.5$

Position of maximum
shifted to slightly higher p_T

Strong centrality dependence
pp: $(\Lambda/K^0_s)_{max} \approx 0.5$

High p_T (> 7 GeV/c)

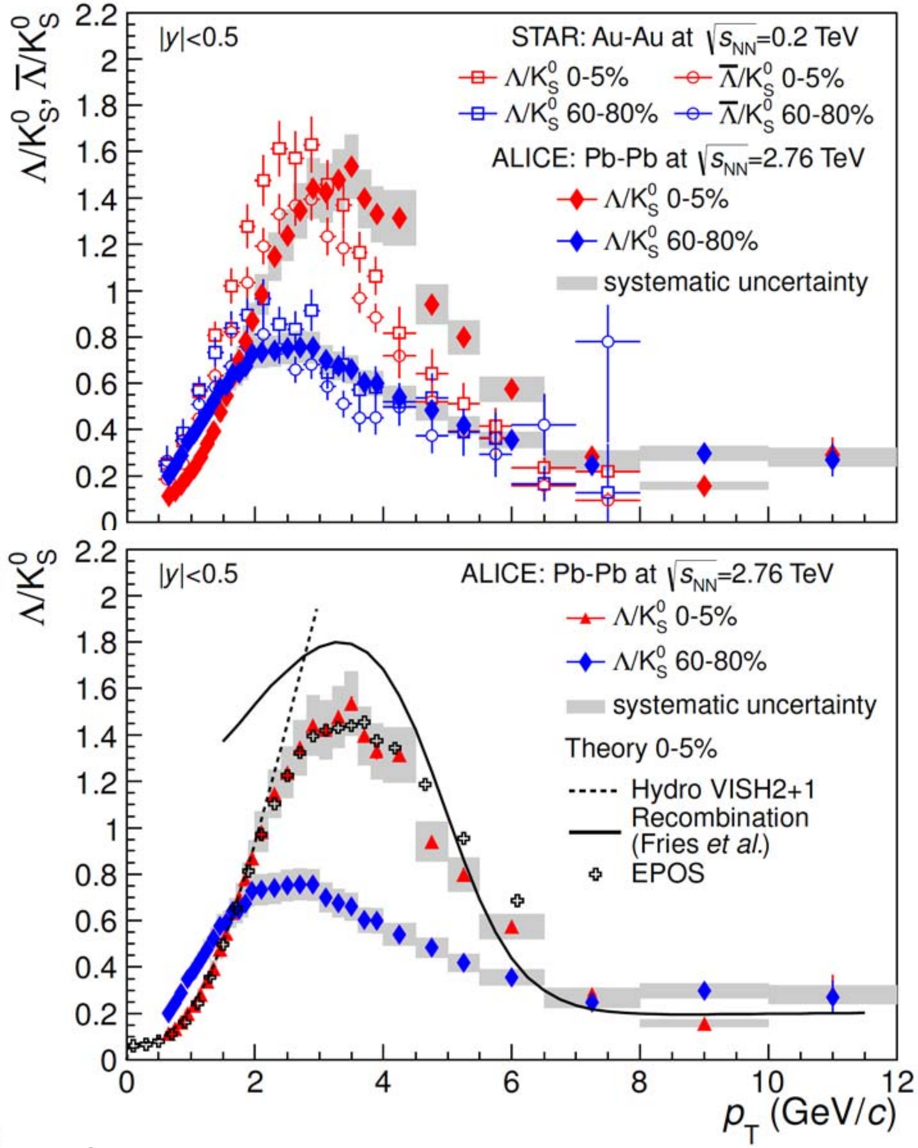
Ratio the same in pp and A+A (~ 0.3)

Model comparisons

Hydro works up to $p_T \approx 2$ GeV/c

Recombination model describes shape, but overestimates ratio

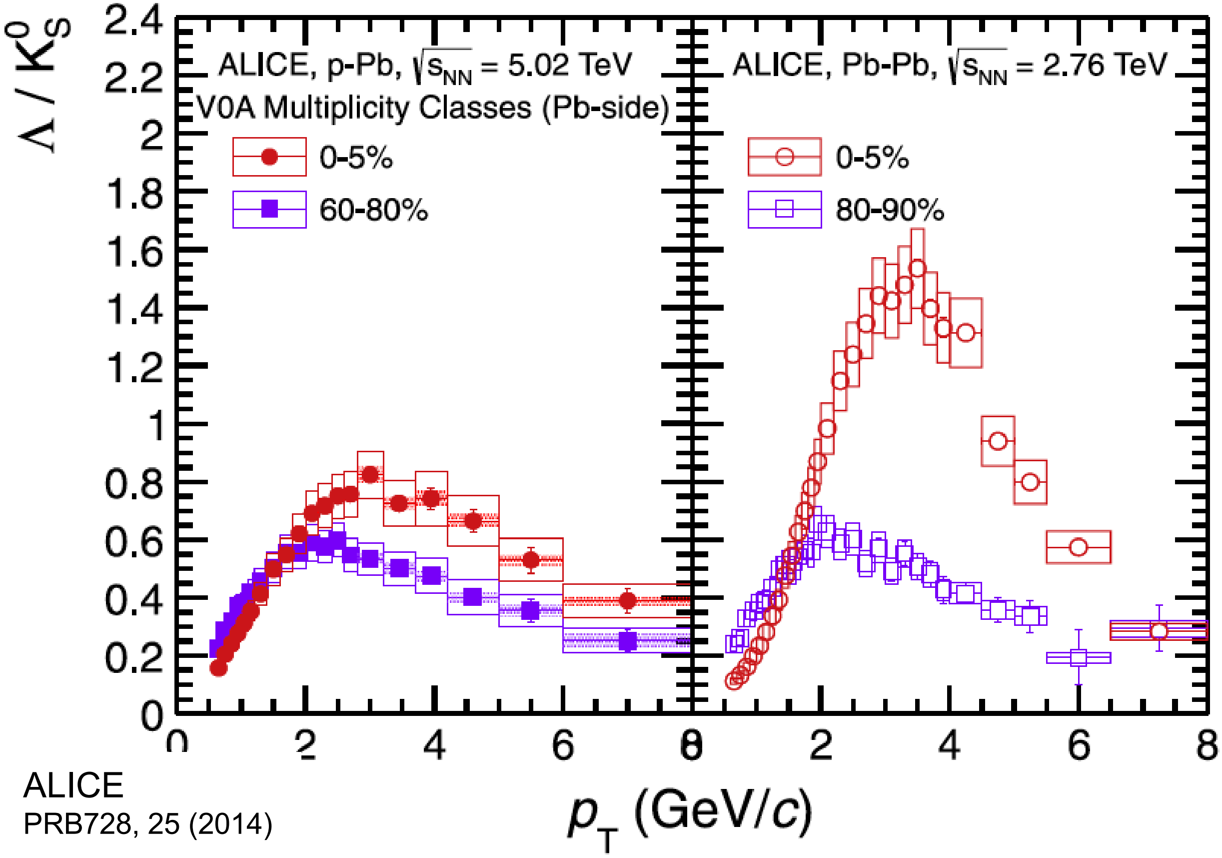
Good description by EPOS



ALICE
PRL111, 222301 (2013)

Baryon-Meson Ratios

Λ/K^0_s-Ratio vs p_T at LHC: p-Pb vs Pb-Pb



ALICE
PRB728, 25 (2014)

No enhancement above unity in p-Pb

But higher than in pp, with maximum at similar position than Pb-Pb

Multiplicity dependence in p-Pb seen

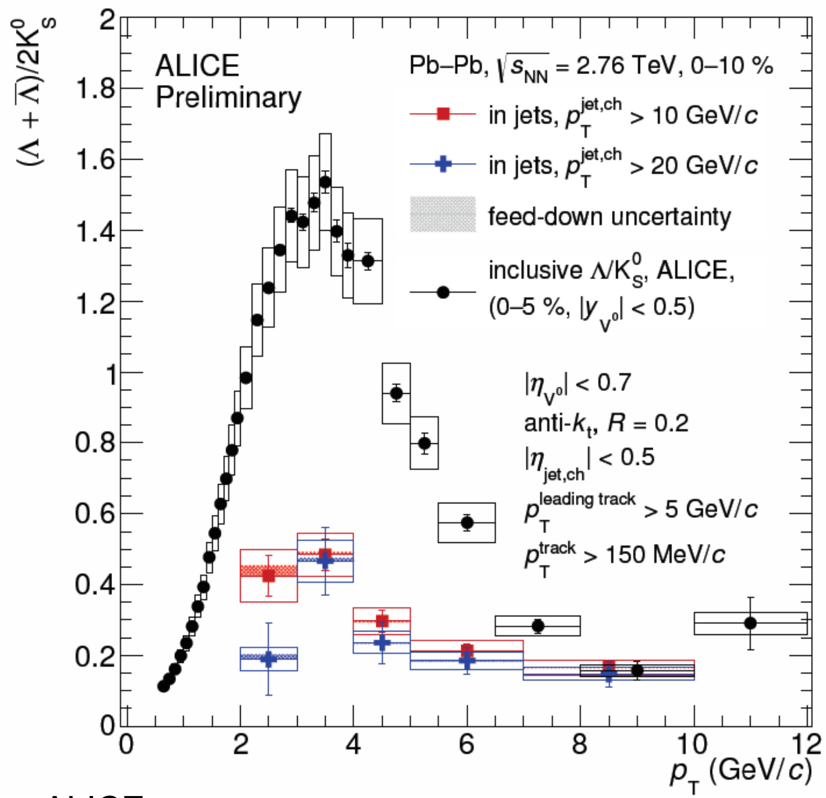
Baryon-Meson Ratios

Λ / K^0_s-Ratio vs p_T at LHC

Bulk vs jet

Enhancement seen only in inclusive Λ/K^0_s-ratio

Not seen for particles in jet cone
⇒ fragmentation dominates there



ALICE
M. Floris, SQM15

Baryon-Meson Ratios

Λ/K^0_s-Ratio vs p_T at LHC

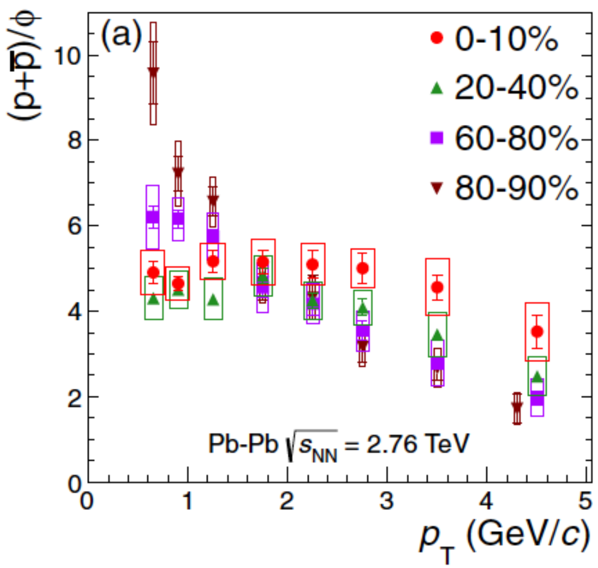
Baryon/meson or mass?

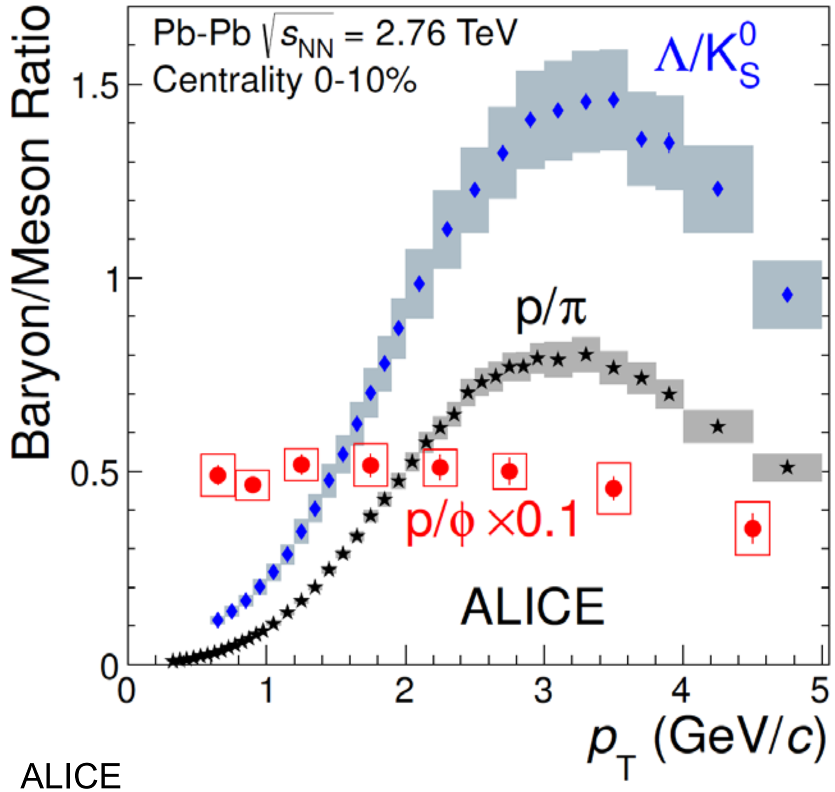
Comparison of Λ/K^0_s and p/ϕ

p/ϕ-ratio is flat as function of p_T (central collisions)

$\Rightarrow$ Mass difference the driving factor

Strong centrality dependence of p/ϕ
Role of rescattering?





ALICE
PRC91, 024609 (2015)

Baryon-Meson Ratios

Early Decoupling of Ω

Particles with low hadronic cross section

E.g. multi-strange baryons (Ξ, Ω)

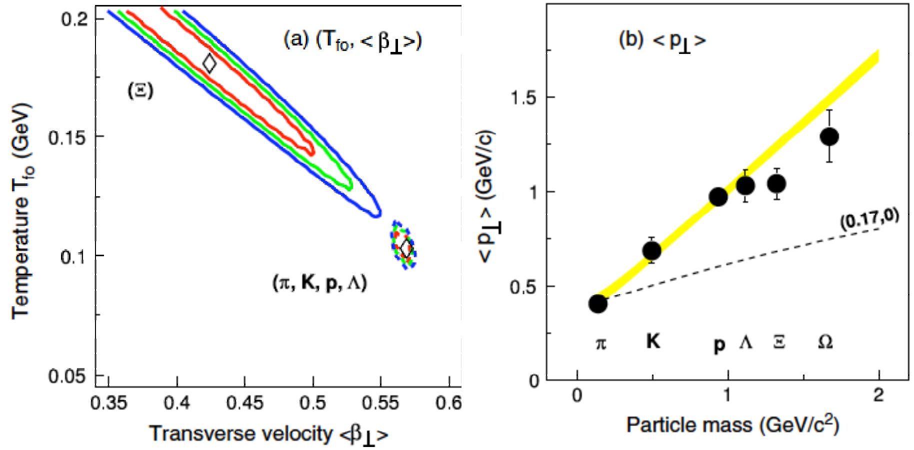
Should decouple earlier

Less affected by transverse expansion of hadronic phase

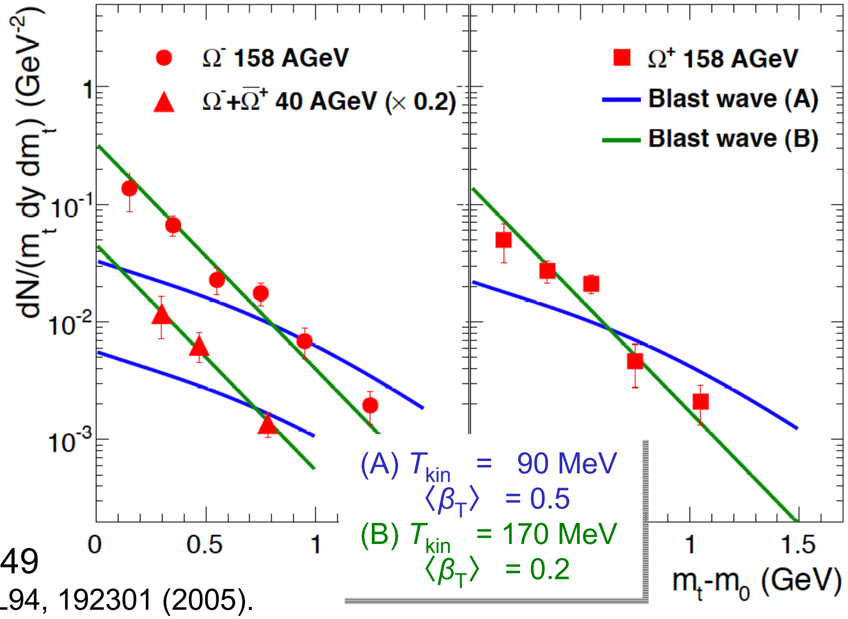
N. Xu and M. Kaneta, NPA**698**, 306 (2002).

Effect visible in BW fits at RHIC and LHC

Higher T_{kin} and lower $\langle \beta_T \rangle$ for Ξ and Ω than for lighter hadrons (π, K, p)



STAR
PRL92, 182301 (2004).



NA49
PRL94, 192301 (2005).

Baryon-Meson Ratios

Ω /ϕ-Ratio vs p_T at RHIC and LHC

Only strange quarks

Baryon (sss) and meson ($s\bar{s}$)

Small hadronic cross section
⇒ partonic phase

Ratio Ω/ϕ

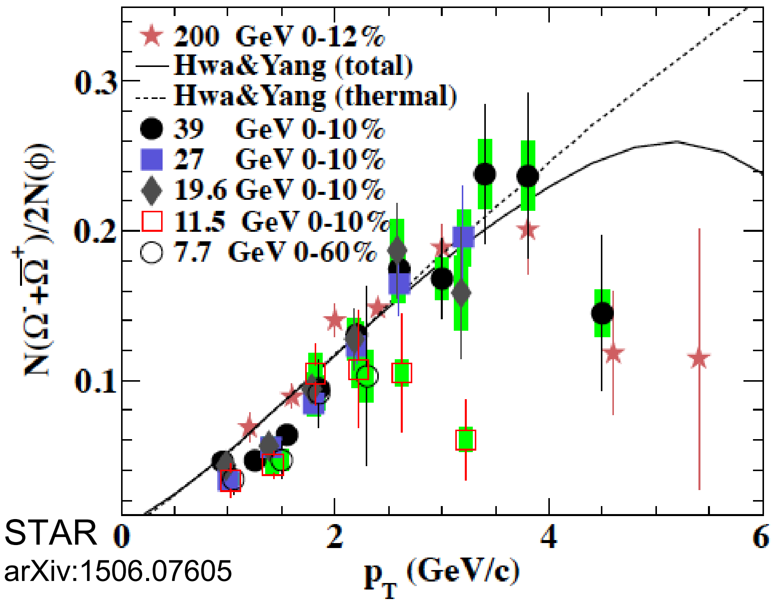
Rising up to $p_T \approx 4$ GeV/c

Consistent with quark coalescence model up to $p_T \approx 4$ GeV/c
Maximum at different position

p_T dependence not described by any model

Ω/ϕ(LHC) > Ω/ϕ(RHIC, 200 GeV) for p_T > 3 GeV/c

Also deviation at $\sqrt{s_{NN}}$ = 11.5 GeV



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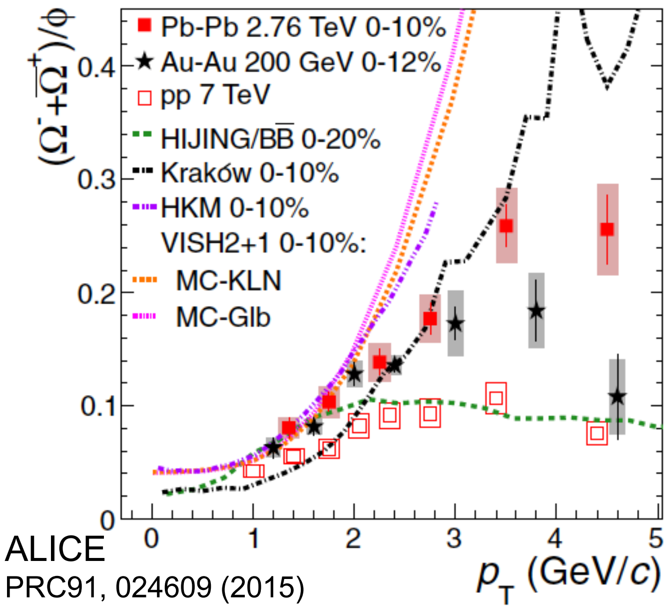
arXiv:1506.07605



ALICE
PRC91, 024609 (2015)

Baryon-Meson Ratios

Ω/ϕ-Ratio vs p_T at RHIC

NCQ-scaled Ω/ϕ-ratio

Might reflect strange quark distribution $f_s(p^s{}_T)$ at hadronization

$$\frac{N(\Omega^- + \bar{\Omega}^+)|_{p_T^\Omega = 3p_T^s}}{N(\phi)|_{p_T^\phi = 2p_T^s}}$$

J.H. Chen et al., PRC78, 034907 (2008)

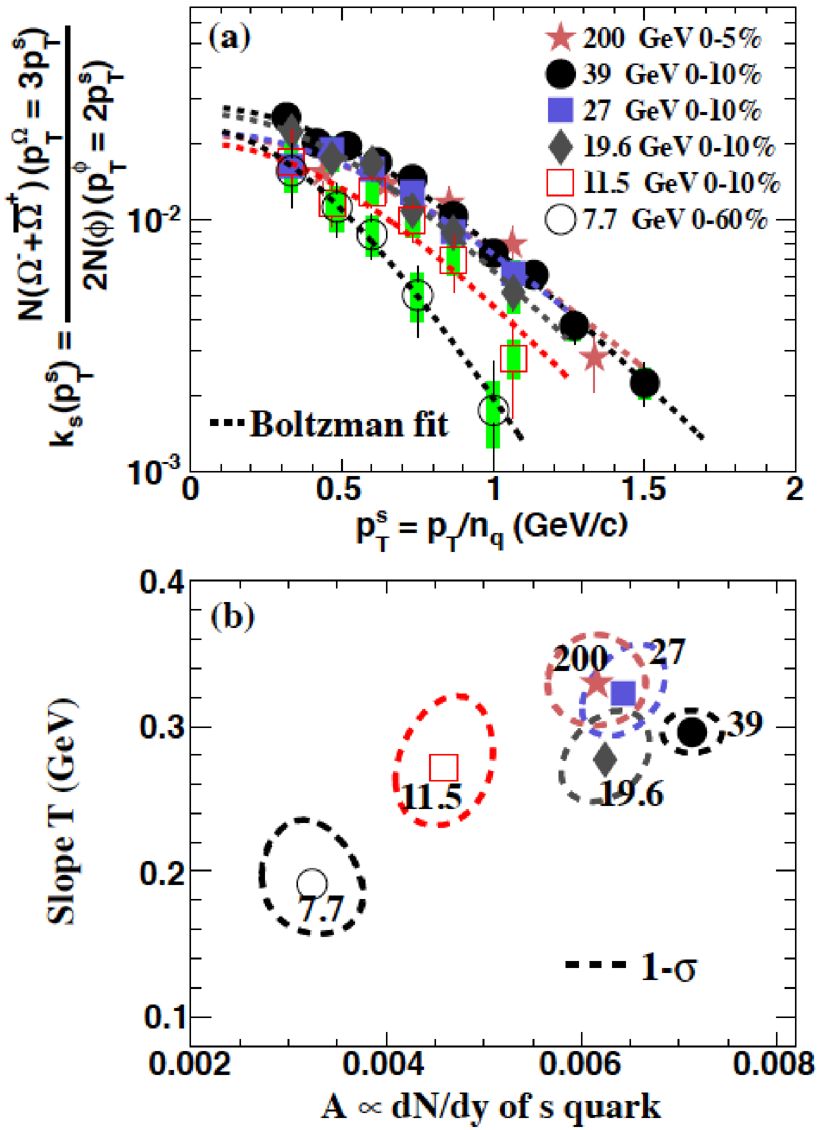
Fit to ratios with Boltzmann

$$g_s\ A\ \frac{m_T}{T\ (m_s + T)}\ e^{-(m_T - m_s)/T}$$

(m_s = 0.46 GeV/c^2, g_s takes $\sqrt{s_{NN}}$-dependent yield ratio $\bar{s}/s$ into account)

Similar fit results for $\sqrt{s_{NN}} \geq$ 19.6 GeV deviations below
(note: centrality selection different at 7.7 GeV)

Transition from partonic to hadronic matter below $\sqrt{s_{NN}}$ = 19.6 GeV ?



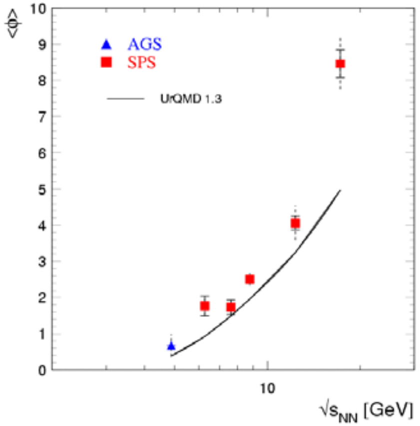
STAR
arXiv:1506.07605

The ϕ Meson

Total Yields

At SPS yields not fully described by models

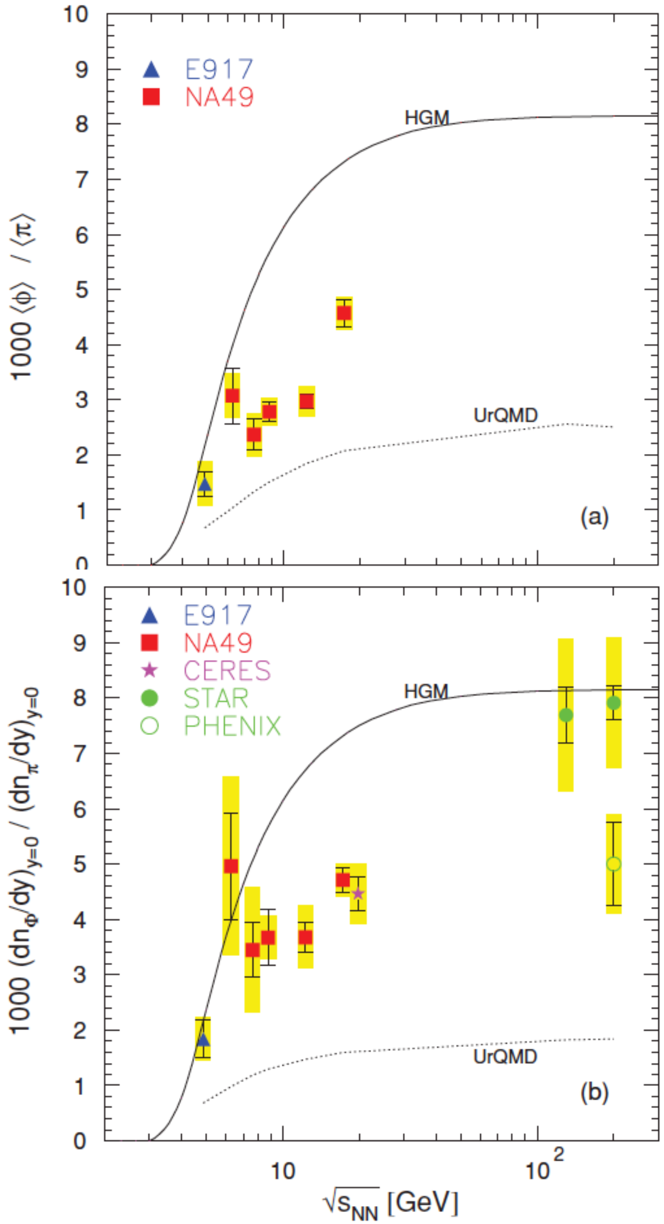
UrQMD1.3 underestimates ϕ/π-ratio but good description of ϕ yield at lower energies



Statistical model (γ_s = 1) above ϕ/π-ratio

NA49
PRC78, 044907 (2008)

HGM: P. Braun-Munzinger et al.,
NPA687, 902 (2002).



The ϕ Meson

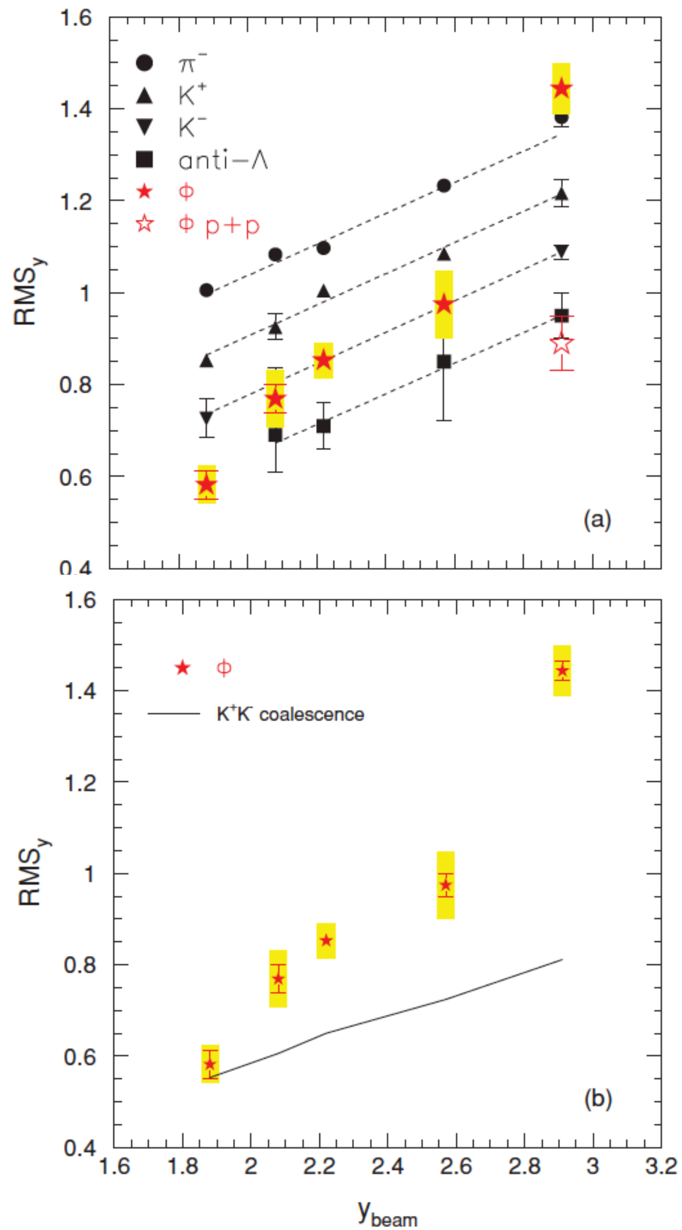
Rapidity Dependence (SPS)

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
PRC78, 044907 (2008)



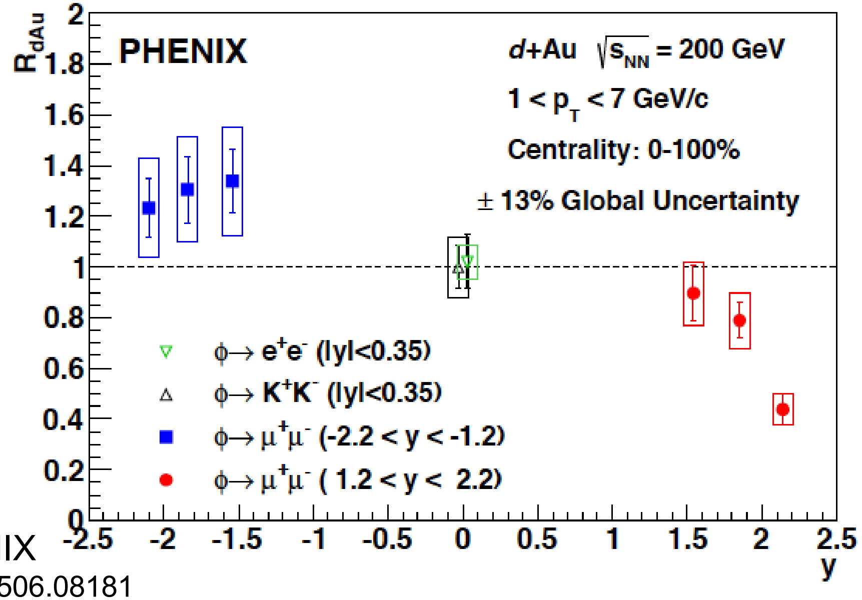
The ϕ Meson

Rapidity Dependence (RHIC and LHC)

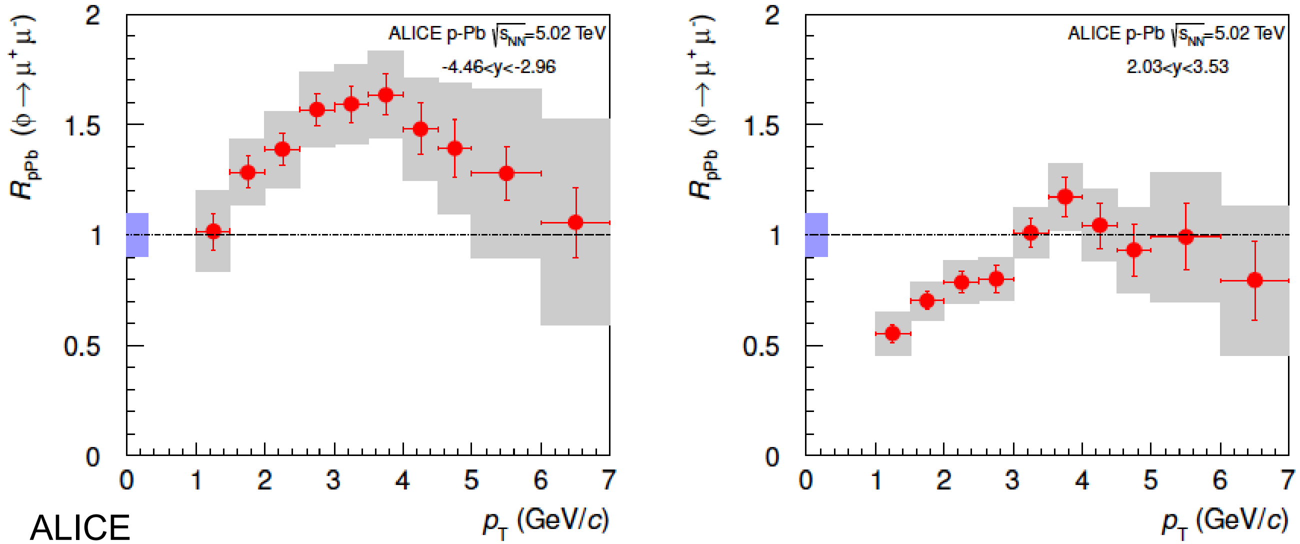
Rapidity distributions

Accessible at RHIC and LHC
via di-muon channel

Strong Cronin-like enhancement in
the backward region in p-Pb



PHENIX
arXiv:1506.08181



ALICE
arXiv:1506.09206

The ϕ Meson

ϕ/K⁻-Ratios as Function of $\sqrt{s_{NN}}$

No strong $\sqrt{s_{NN}}$ dependence

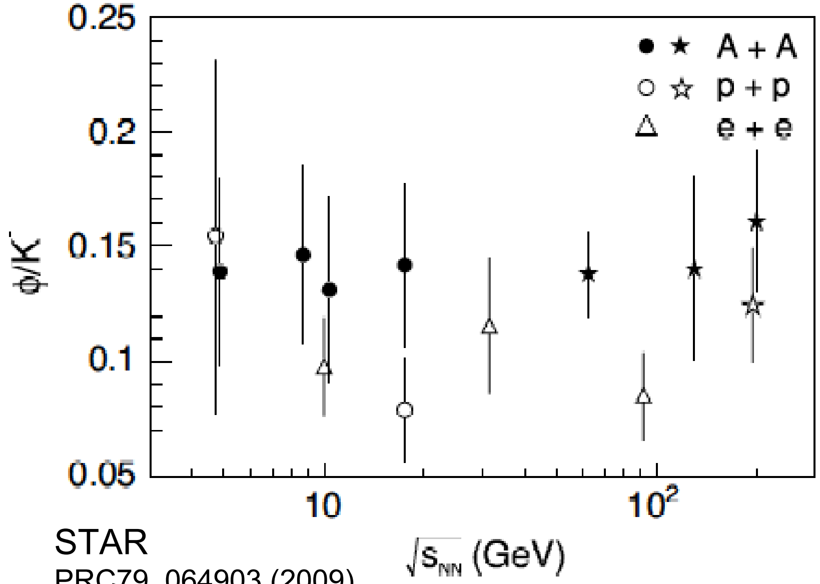
Ratio constant for A+A up to RHIC

Indication for slight drop towards LHC

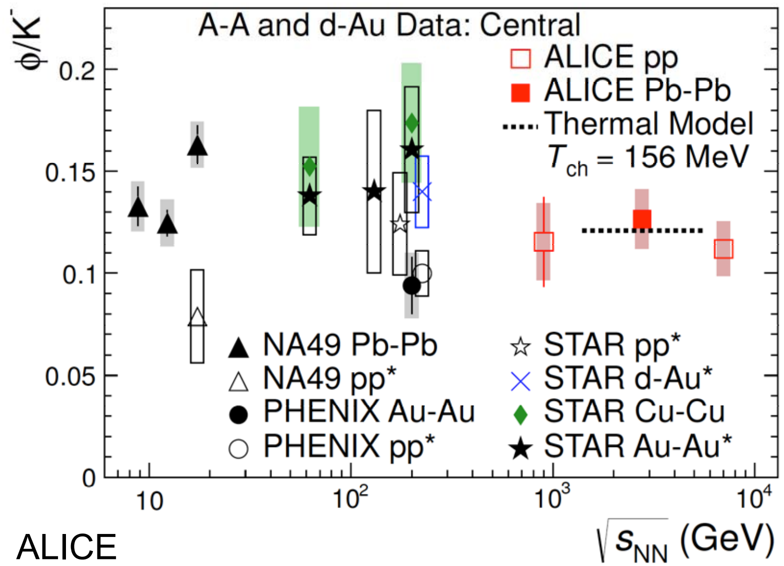
LHC data agrees with thermal model

Comp. to small systems

$\phi/K^-(AA) > \phi/K^-(pp)$ at lower $\sqrt{s_{NN}}$, but the same at LHC



STAR
PRC79, 064903 (2009)



ALICE
PRC91, 024609 (2015)

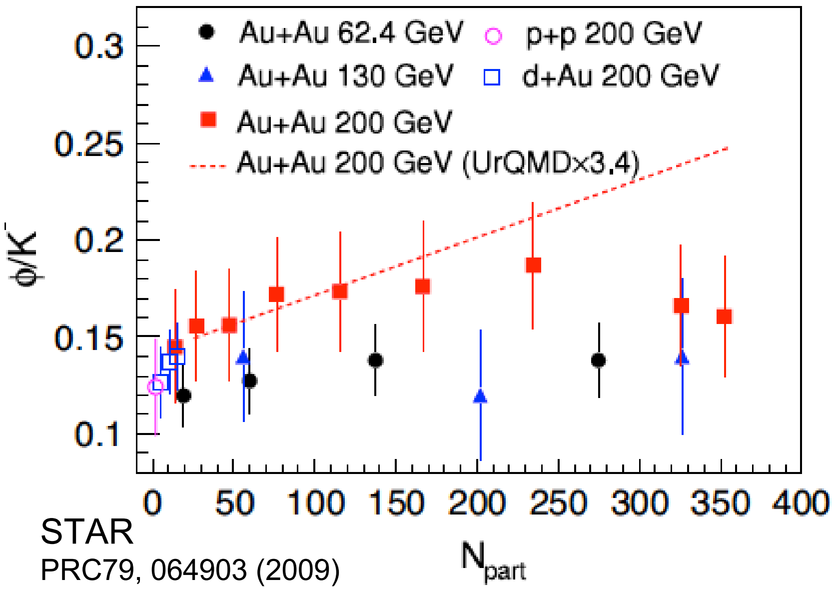
The ϕ Meson

ϕ/K⁻-Ratios vs System Size

No strong system size dep.

Indications for a maximum for mid-central collisions

Universal dependence as function of $(dN_{ch}/d\eta)^{1/3}$ for all systems (?)



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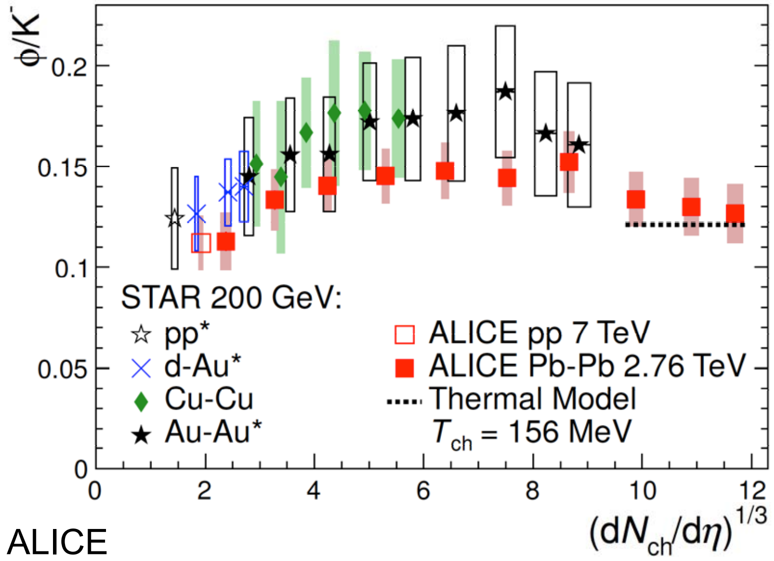
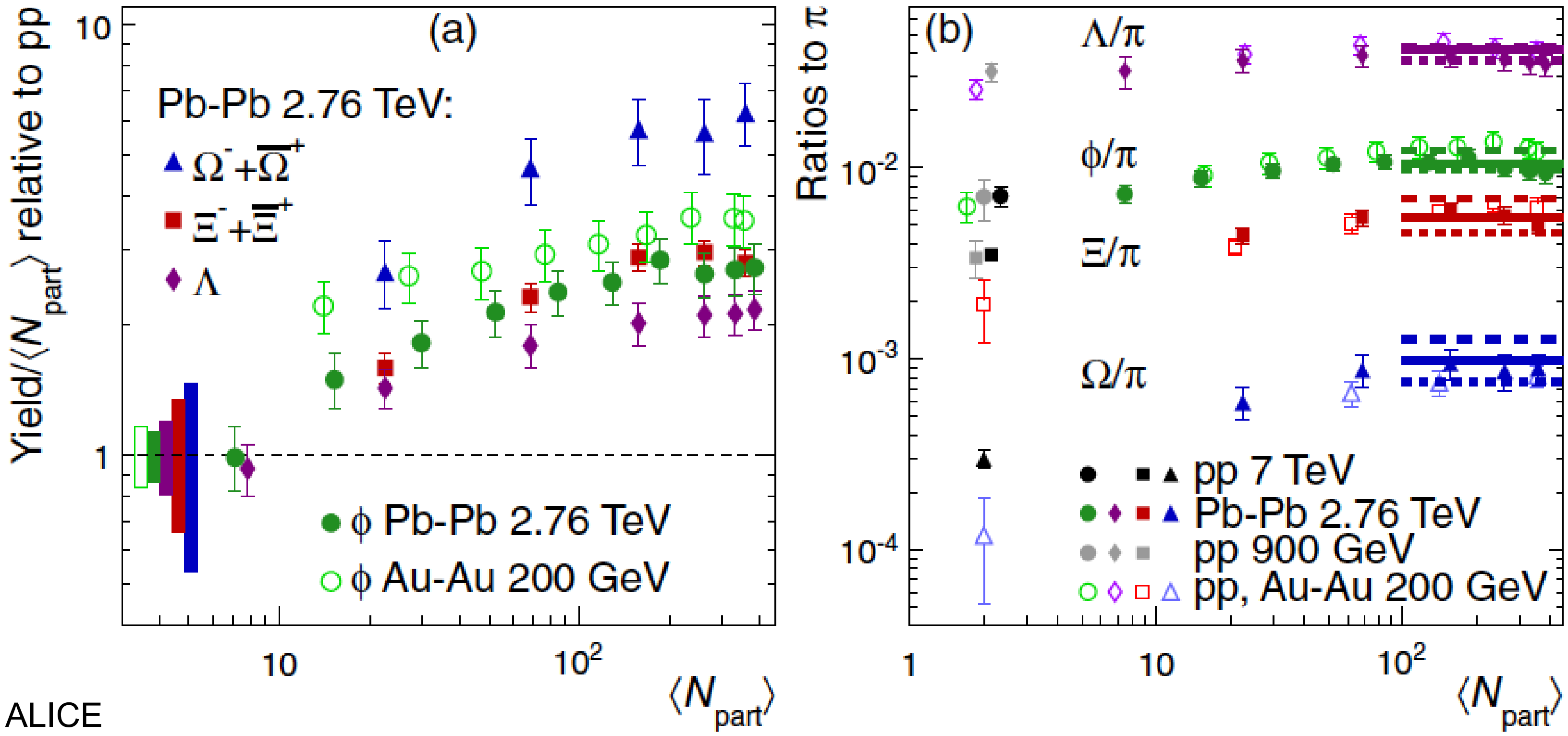
PRC79, 064903 (2009)



ALICE
PRC91, 024609 (2015)

The ϕ Meson

Comparison of Enhancements



ALICE
PRC91, 024609 (2015)

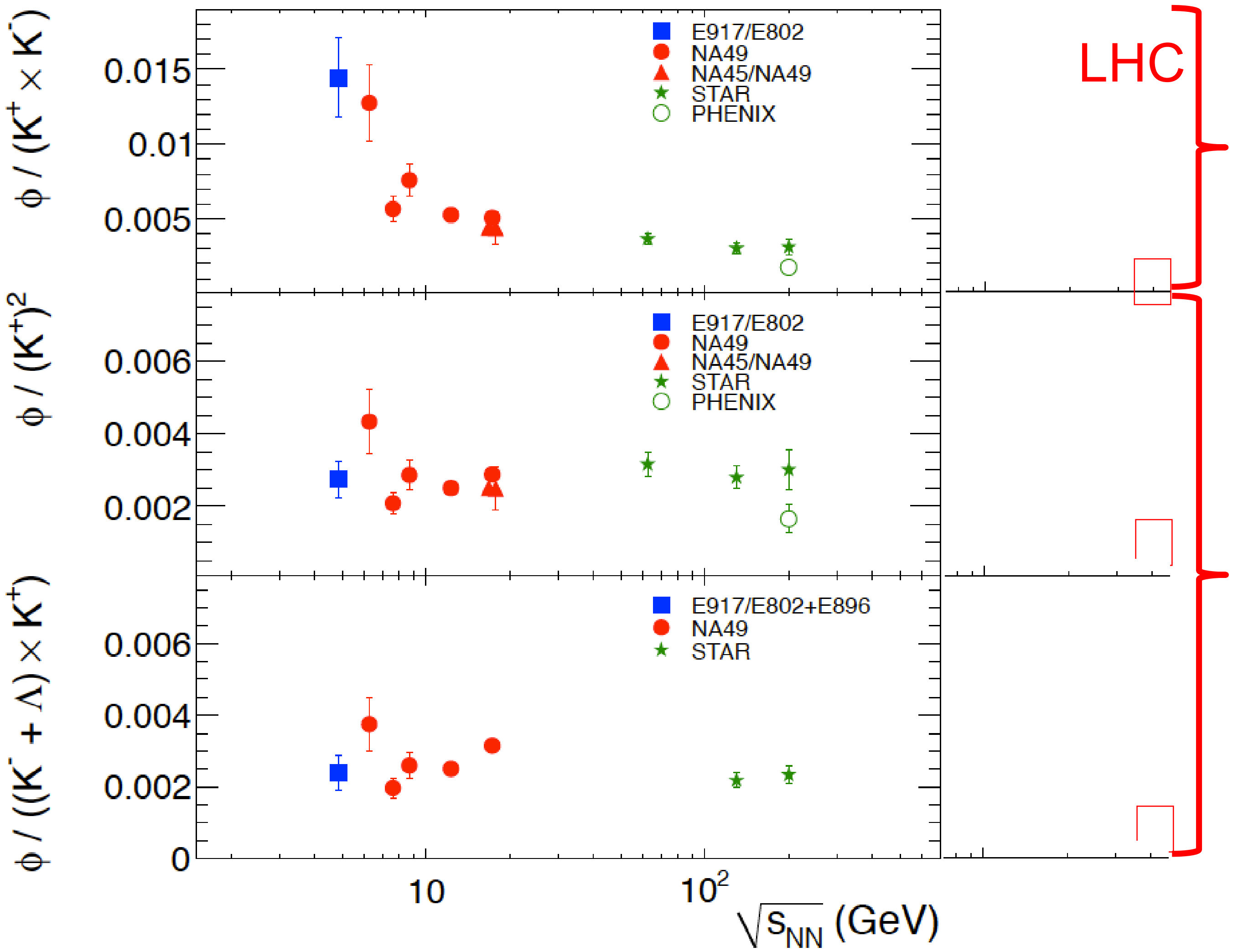
Enhancement of ϕ between Λ and Ξ

Effective strangeness between 1 and 2

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

The ϕ Meson

Some More Ratios …



No scaling with $K^+ \times K^-$
(coalescence picture)

Scaling with (s-Quarks)^2
$\Phi = s\bar{s}$

$K^+ \propto \bar{s}$-Quarks
$K^- + \Lambda \propto$ s-Quarks

Works up to
RHIC energies

CB and C. Markert,
PPNP66, 834 (2011).

The φ Meson

Low Energies (SIS)

Φ /K⁻-ratio

Rapid rise towards low energies

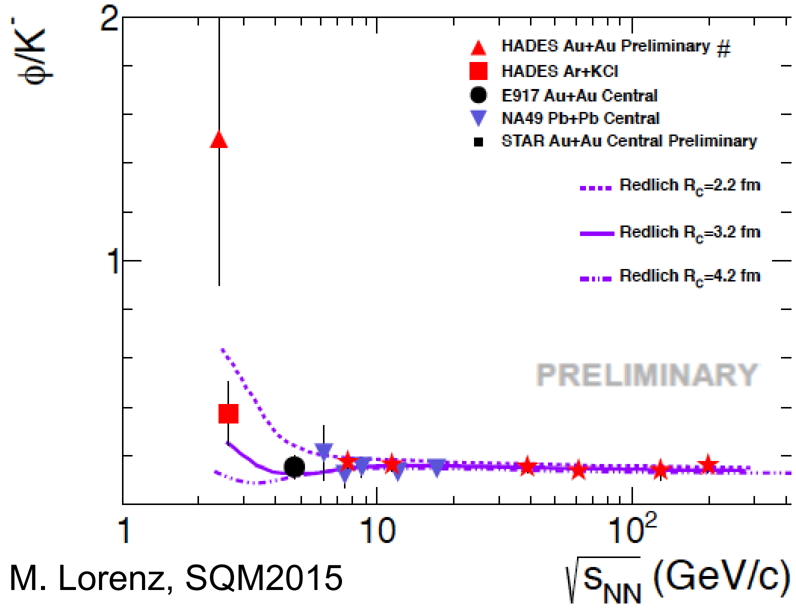
Qualitatively predicted by statistical model

But might be higher than expected in Au+Au collisions

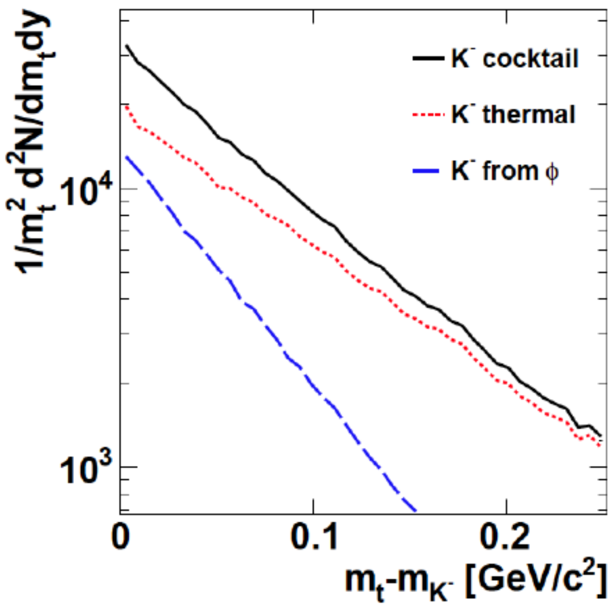
Feeddown into kaons

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

Important role of φ at low energies



M. Lorenz, SQM2015



Baryon-Meson-Ratios and the ϕ Meson

Conclusions

Baryon-Meson-Ratios

Strong enhancement of Λ/K^0_s and Ω/ϕ ratios above unity at intermediate p_T

Same level of Λ/K^0_s-enhancement at RHIC and LHC, Ω/ϕ is higher at LHC
Strong increase of Λ/K^0_s-ratio towards SPS energies!

Slight increase of position of maximum with $\sqrt{s_{NN}}$

p/ϕ-ratio not p_T dependent at LHC

Sign of recombination or hydrodynamic flow?
Depends on which side of the Atlantic you live … ☺

The ϕ meson

Many interesting features

How does ϕ production scale?

Does not behave like a strangeness neutral particle
(effective strangeness between 1 and 2)

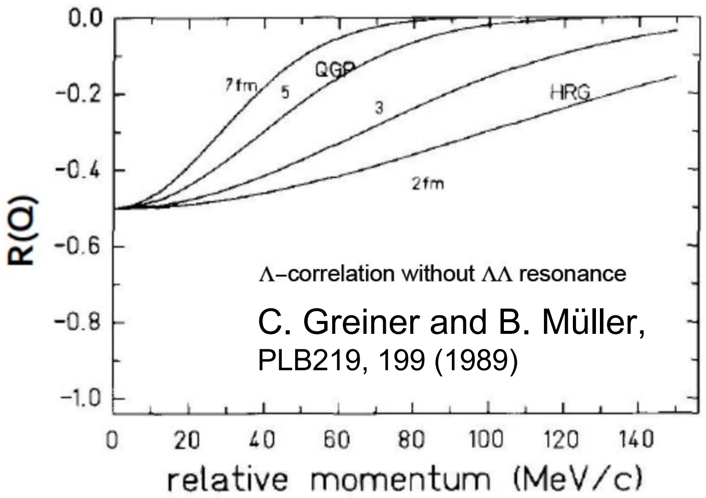
Systematic study could provide valuable information on onset partonic matter

Hyperon Interaction

Λ Λ Correlations

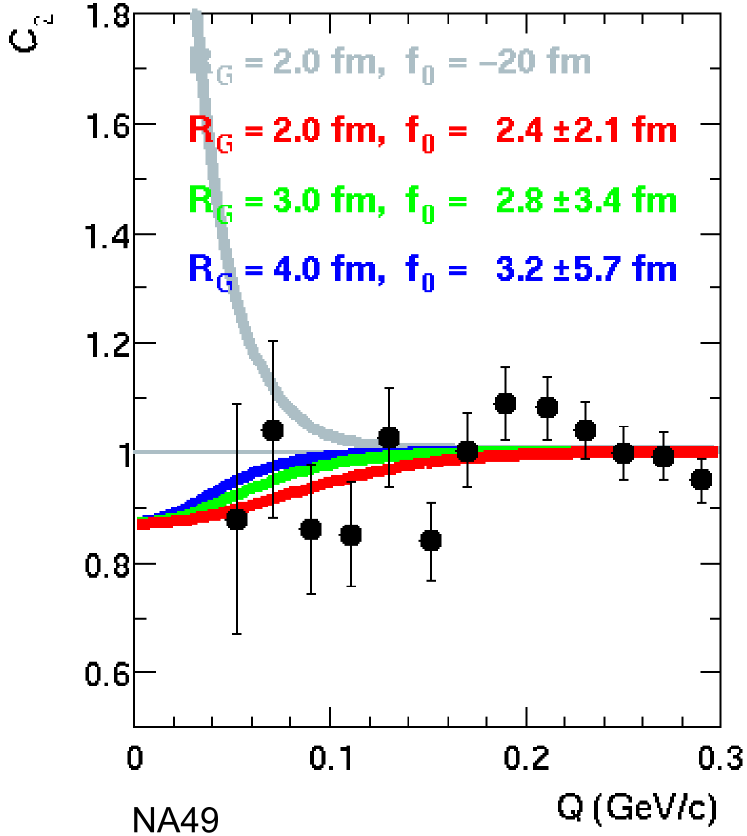
ΛΛ correlation function

Information on ΛΛ interaction can be extracted from two-particle c.f.



Experimental challenge

High statistics on low-*Q* pairs needed



NA49
NPA715, 55c (2003)

Hyperon Interaction

Λ Λ Correlations

High statistics measurement

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

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

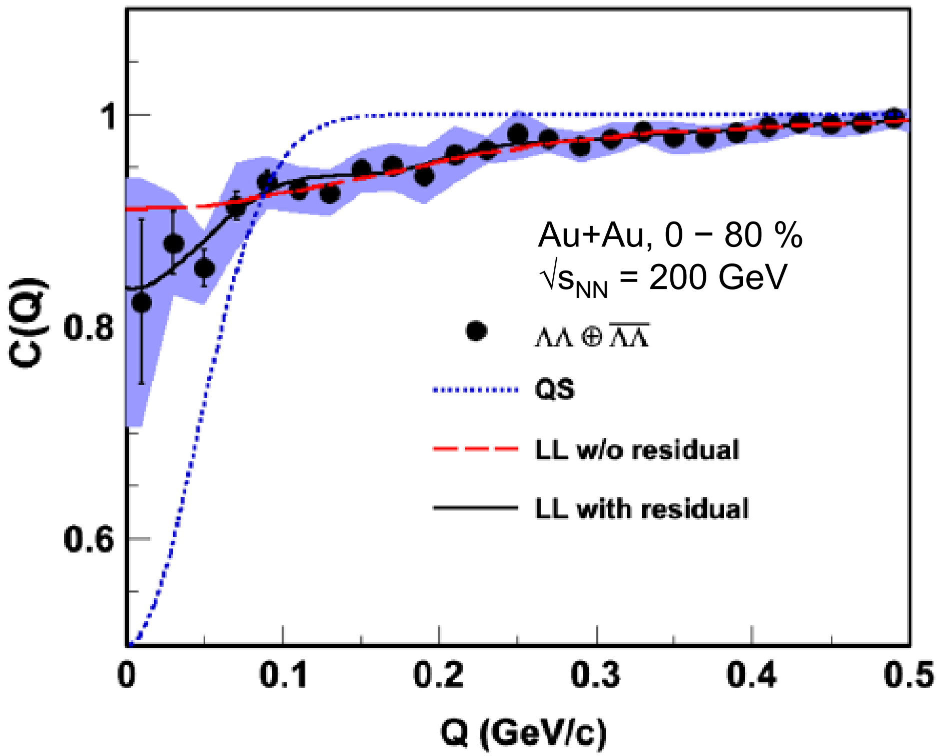
Corrections: Λ purity ($P(Q)$)

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
PRL114, 022301 (2015)

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. λ)

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

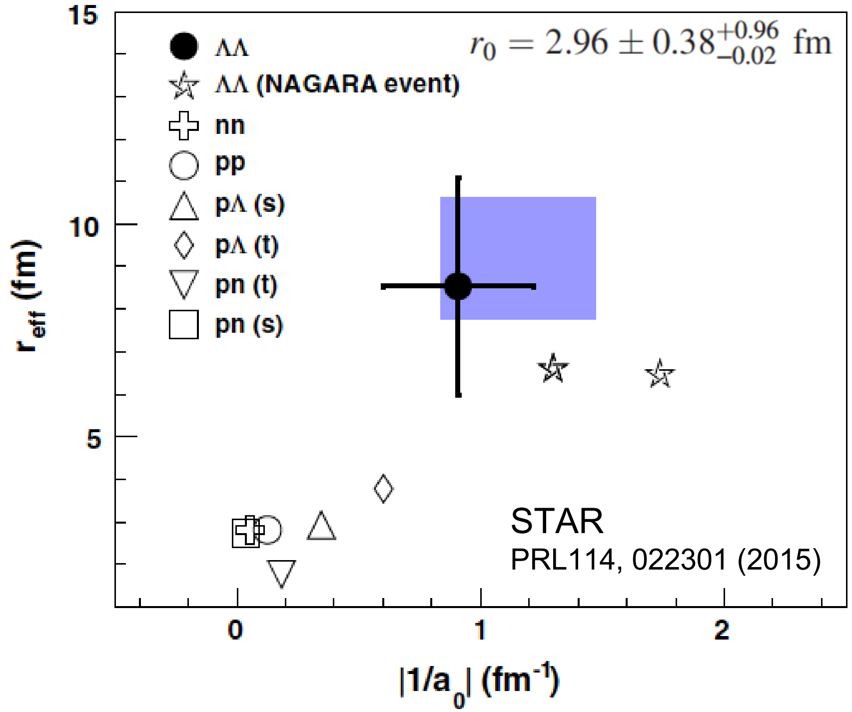
Interaction is weak

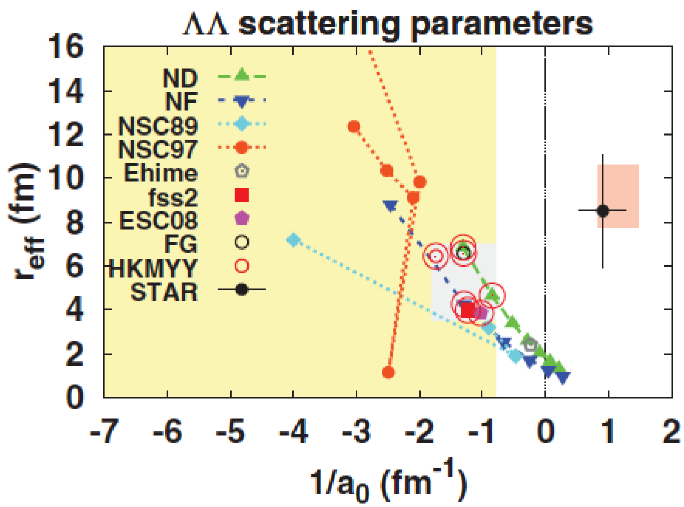
$|a_{\Lambda\Lambda}| < |a_{p\Lambda}| < |a_{NN}|$

Sign not yet conclusive

Fit suggests weak repulsive interaction

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





K. Morita et al. PRC91, 024916 (2015)

Hyperon Interaction

Implications for Bound States (H-Dibaryon)

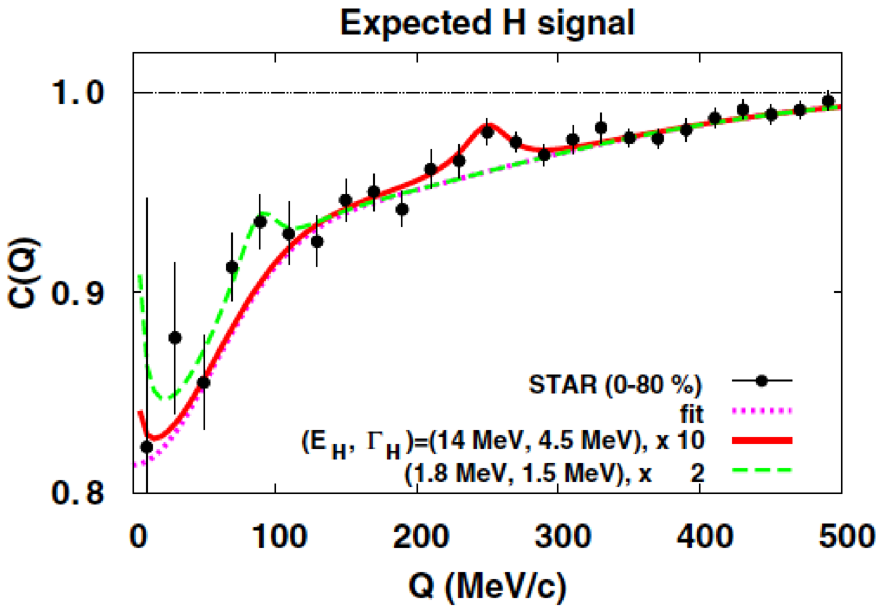
ΛΛ bound state

Disfavored, since it would imply a depletion below 0.5 of c.f. at *Q* = 0

Resonance above ΛΛ thres.

Very small signal expected

More statistics needed



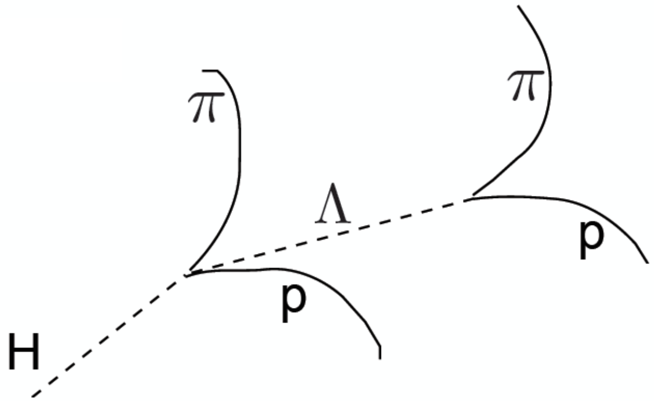
K. Morita et al.
PRC91, 024916 (2015)

Hyperon Interaction

Direct Searches for H-Dibaryon

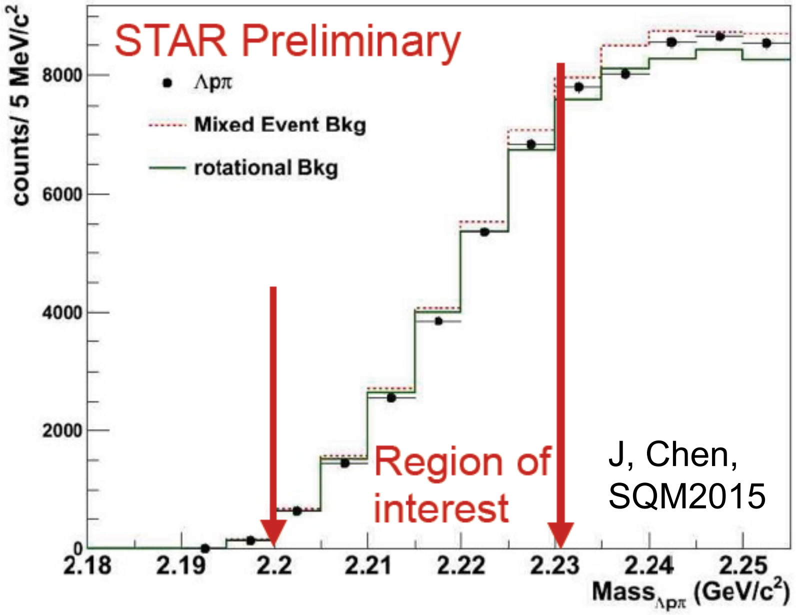
Invariant mass studies

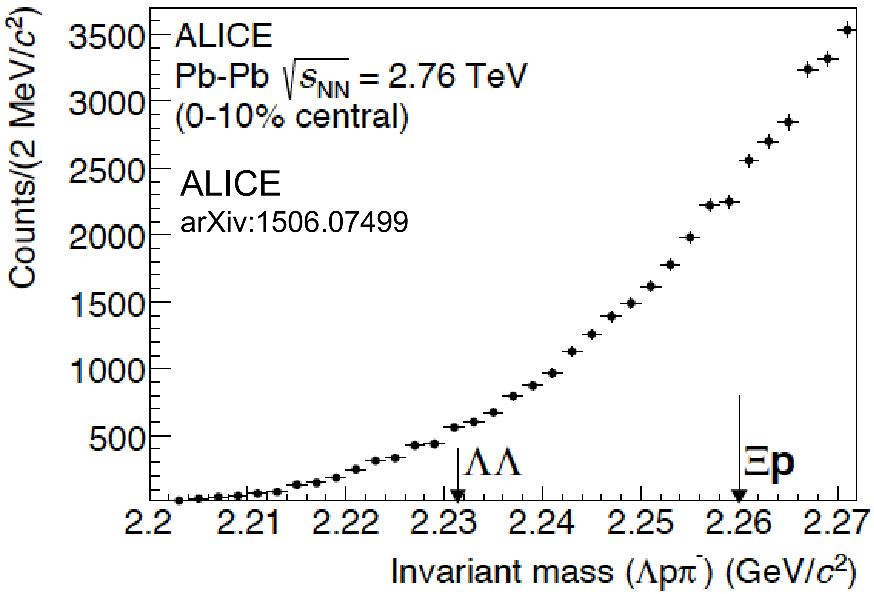
Topological reconstruction of πpΛ



No signals observed

STAR and ALICE data





Hyperon Interaction

Direct Searches for H-Dibaryon

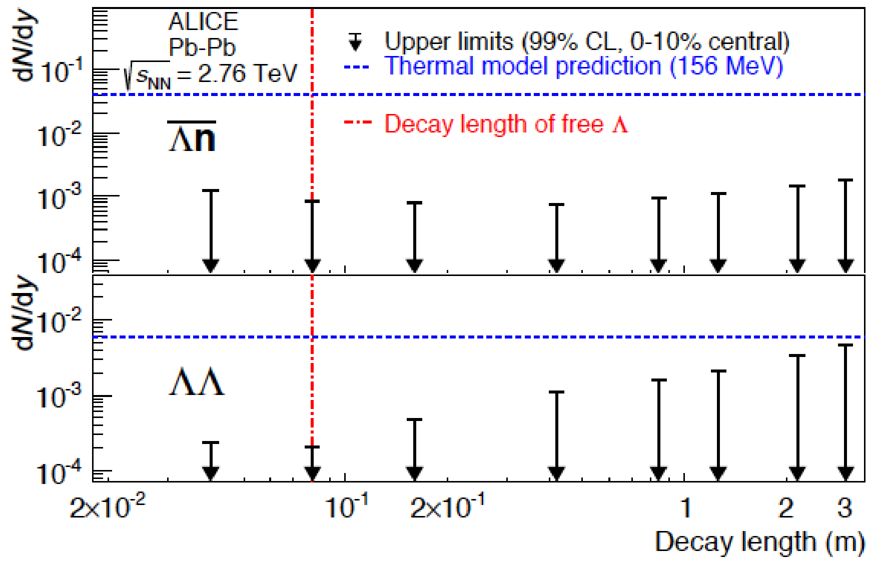
Extraction of upper limits

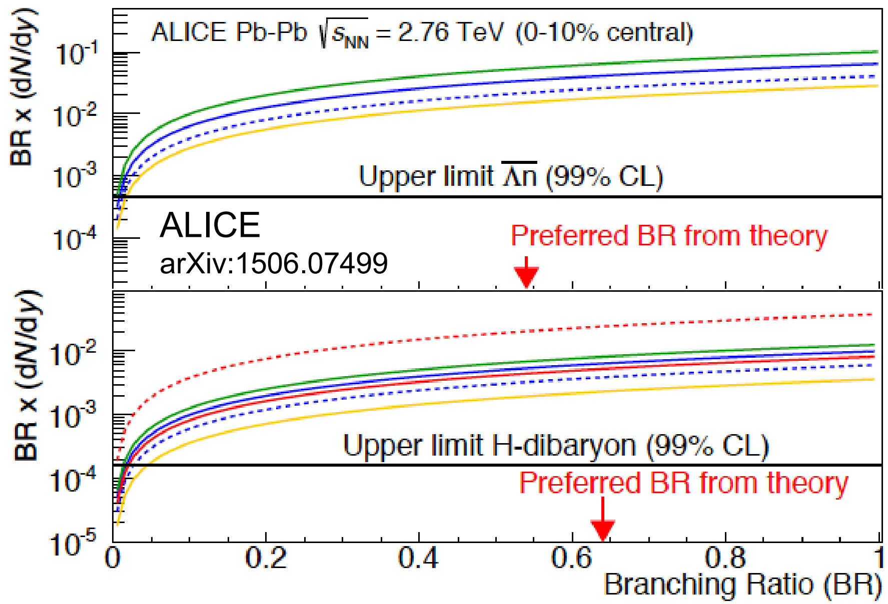
Λ-bound states: $\Lambda\Lambda$ and $\overline{\Lambda n}$

$H \rightarrow \Lambda\, p\, \pi^-$
$\overline{\Lambda}n \rightarrow \overline{d}\, \pi^+$

Upper limits as function of lifetime and branching ratios

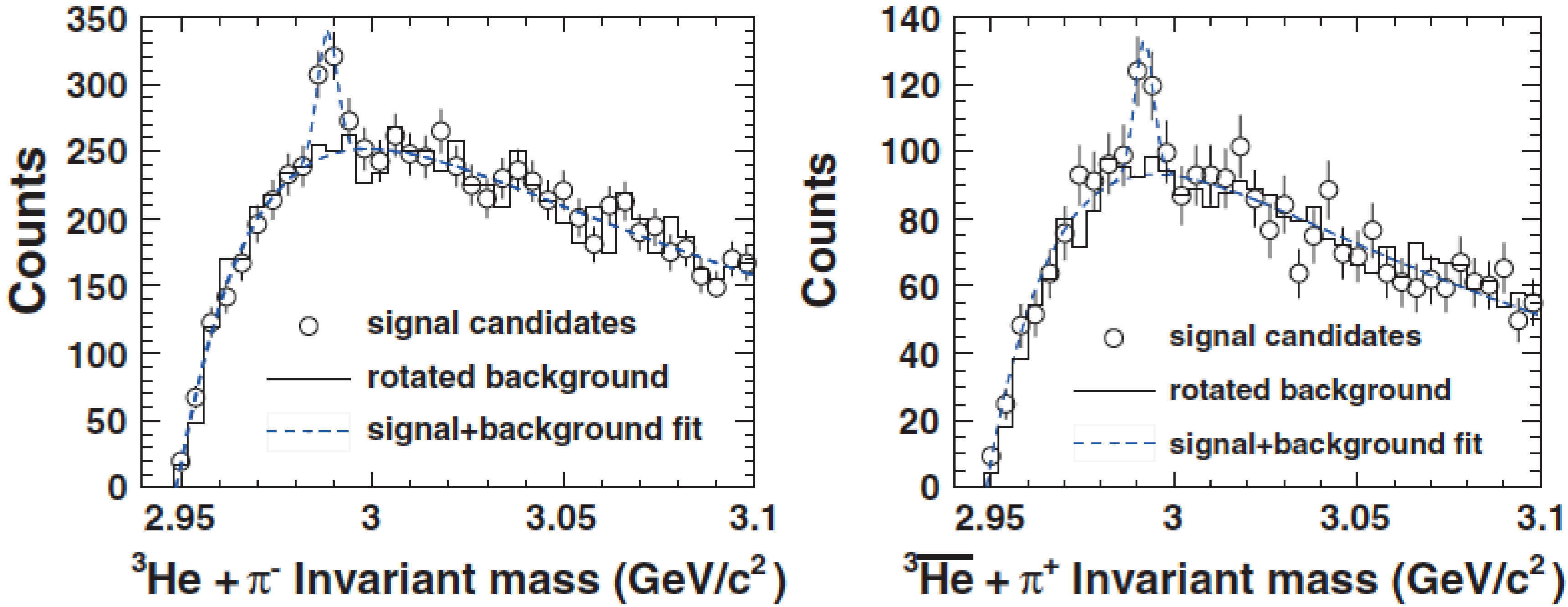
Theory expectations from thermal model (eq. and non-eq.), hybrid UrQMD, and coalescence model (for H-dibaryon)





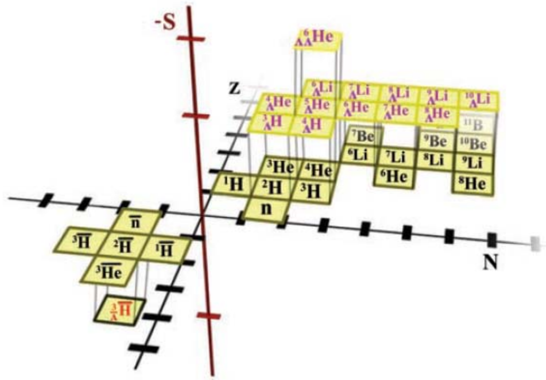
Hypernuclei

Hypertriton Measurement by STAR



STAR
Science vol.328, 58 (2010)

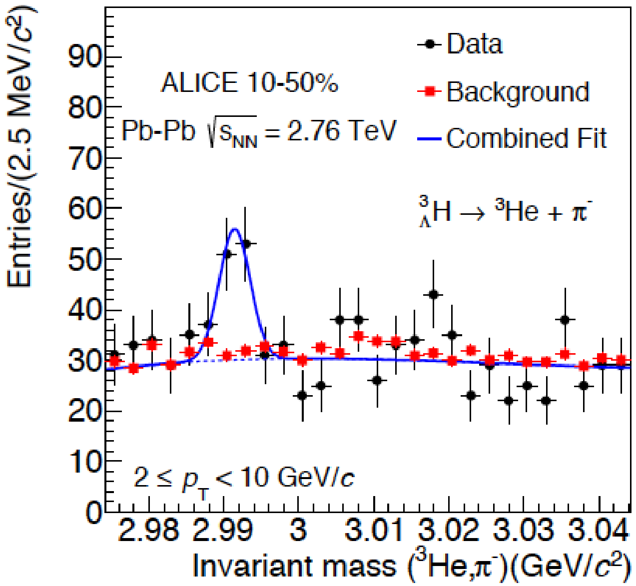
First observation of an anti-hypernucleus
Extends chart of nuclei



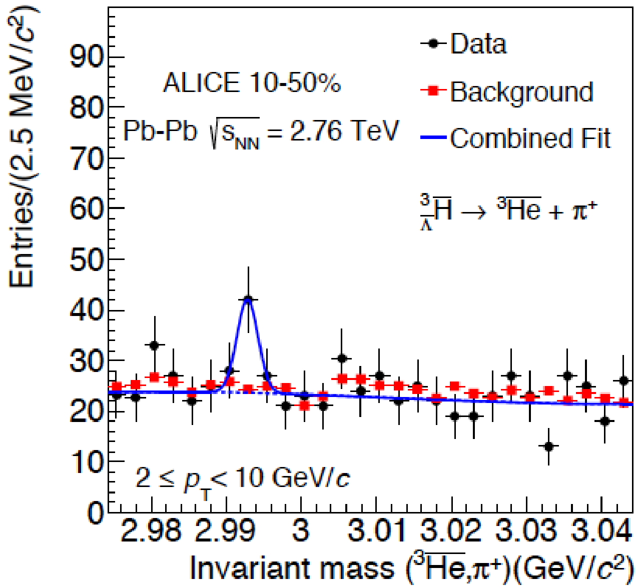
Bound Λ-nucleon states
Good agreement with thermal model expectation
in contrast to ΛΛ and $\overline{\Lambda}$n

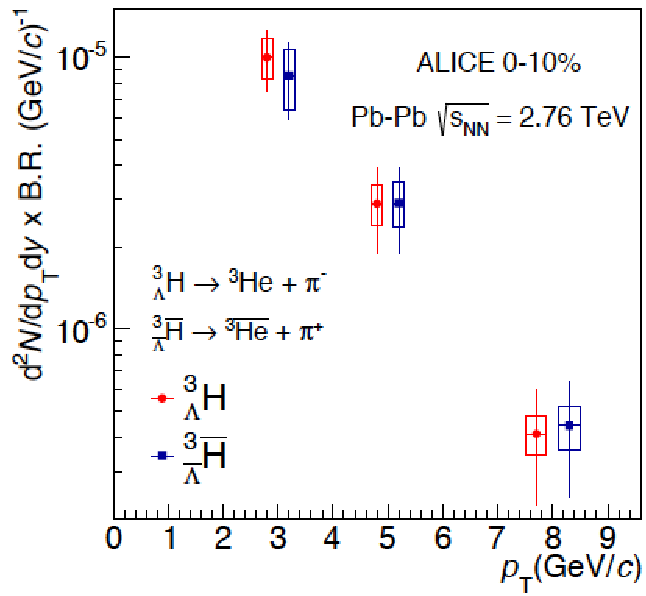
Hypernuclei

Hypertriton Measurement by ALICE



ALICE
arXiv:1506.08453



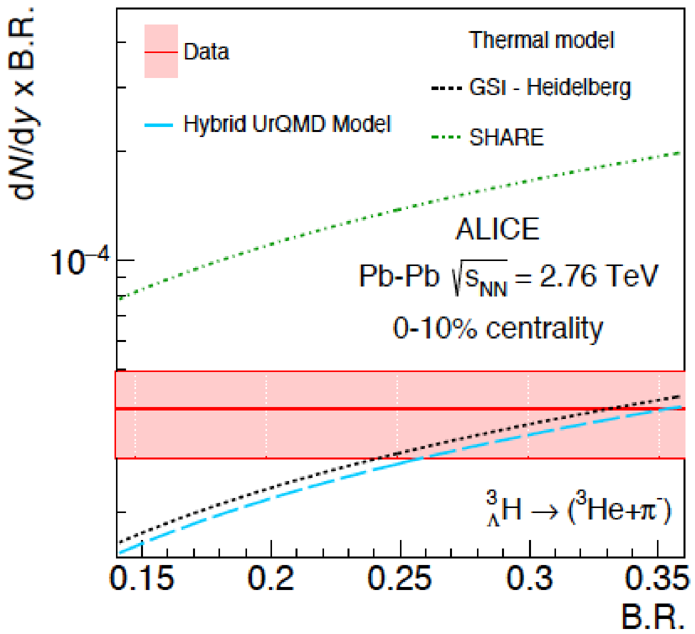


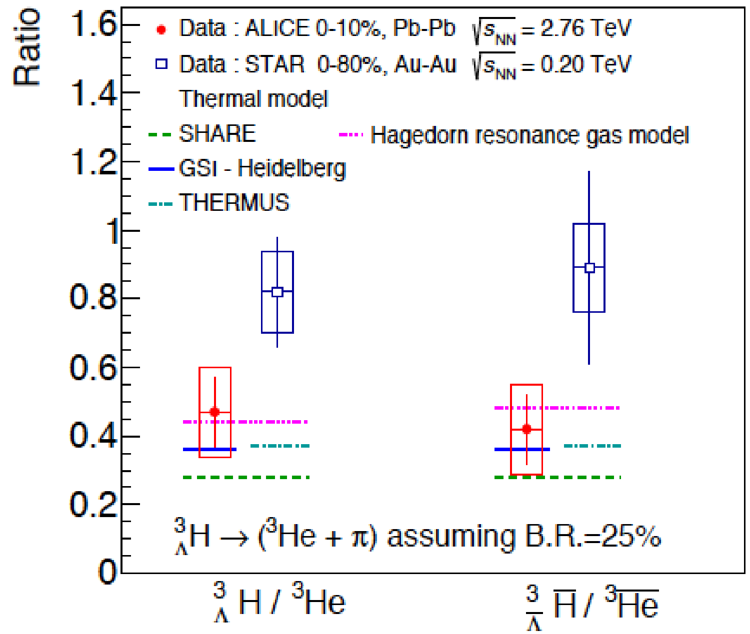
Same yield of hypertriton and anti-hypertriton

p_T dependence measured

Hypernuclei

Hypertriton Measurement by ALICE





ALICE
arXiv:1506.08453

Yield of hypertriton

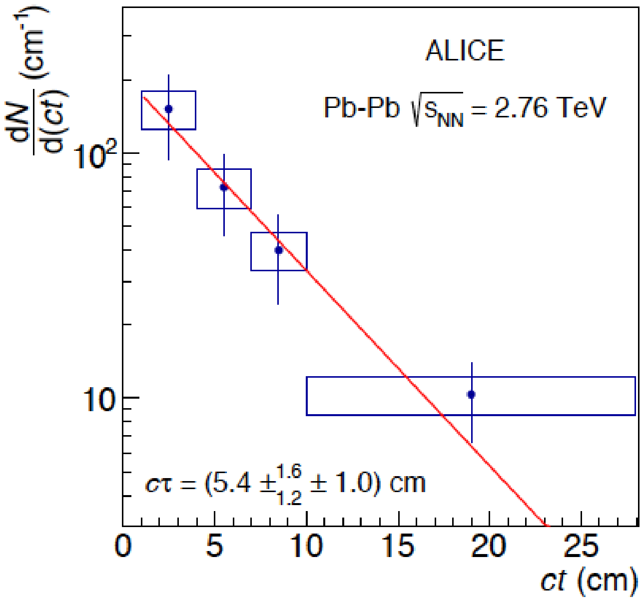
Good agreement with equilibrium thermal models and hybrid UrQMD

Ratio hypertriton/^{3}He

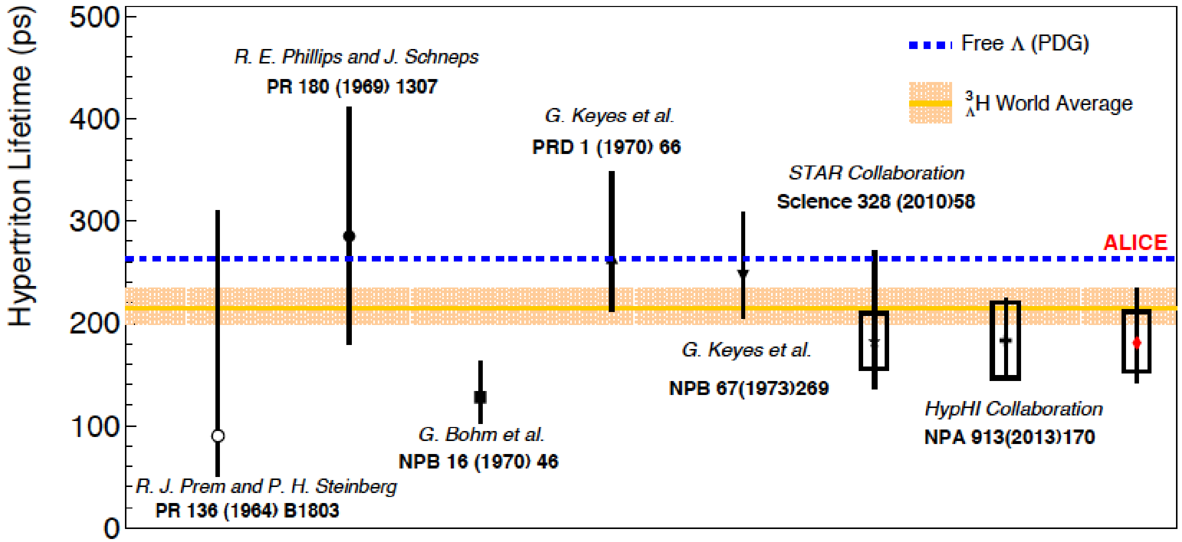
Good agreement with thermal model expectations

Hypernuclei

Lifetime of Hypertriton



ALICE
arXiv:1506.08453



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

Good agreement with STAR and ALICE measurement

Slightly below expectation for free Λ

Hyperon Interaction and Hypernuclei

Conclusions

Hyperon interaction

First useful information from ΛΛ correlations

ΛΛ is clearly weaker than between pΛ or NN

Not finally clear whether it is attractive

No evidence for a Λ-bound state (e.g. H-dibaryon)

Hypernuclei

Anti-Hypertriton discovery by STAR, also measured at LHC
Extension of chart of nuclei into a new direction

Good agreement of yields with statistical model expectation

Hypertriton lifetime below free Λ-decay

(Personal) Conclusion on Strangeness

Lots of new and precise data in the last few years

No big surprises in AA, though

Small systems get interesting at high energies

New topics appear (e.g. anti-hypernuclei)

More unexpected things might happen at low energies

Femtoscopy

Correlations of Strange Particles

Role of strange particles

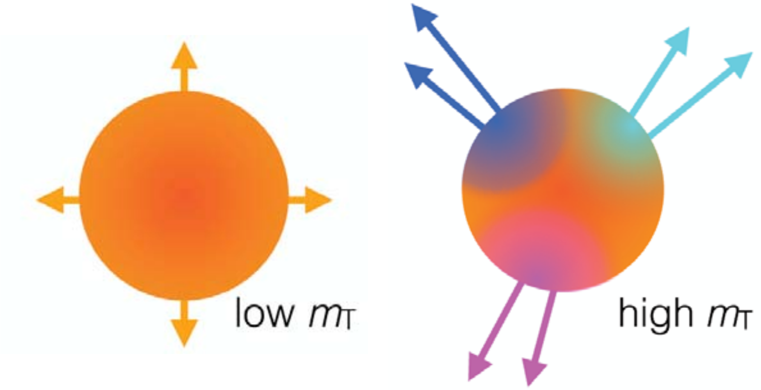
Higher masses than pions
⇒ Higher reach in m_T

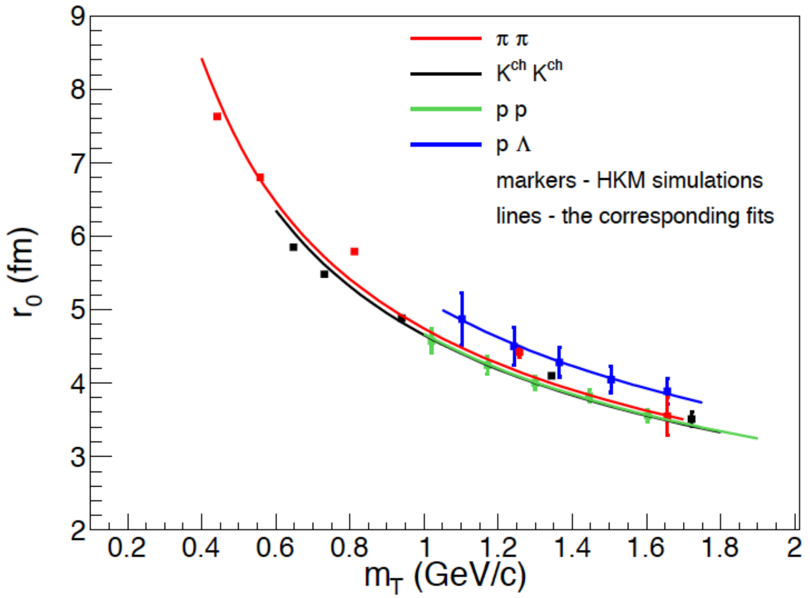
Hadronic interactions
⇒ Different sensitivity to possible effects of hadronic rescattering phase

m_T-Scaling

Can be broken due to rescattering

Correlations of strange particles can provide useful information





Y. Sinyukov et al.,
arXiv:1508.01812

Femtoscopy
Correlations of Kaon-Pairs at LHC

Charged and neutral kaons

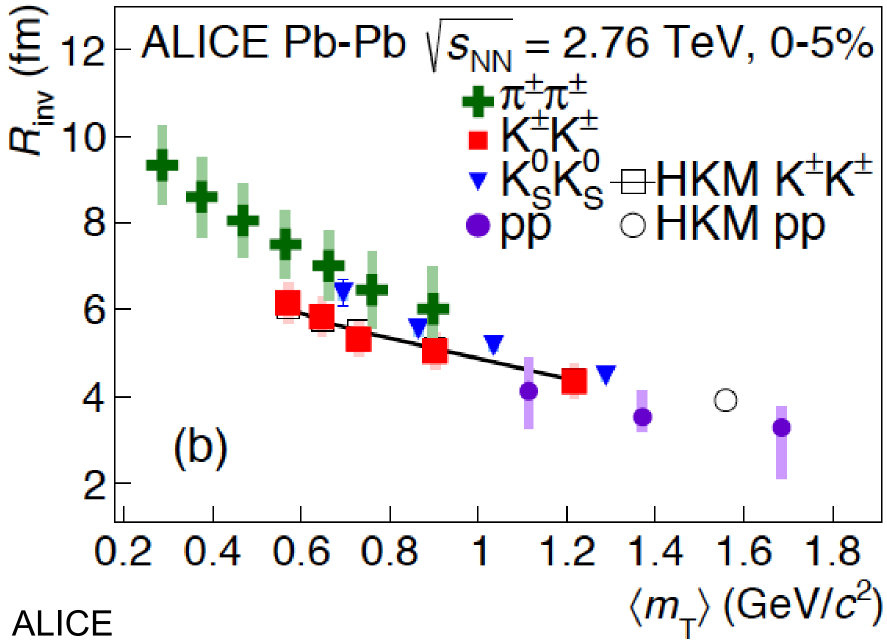
1-d Radius parameter R_{inv} compared to $\pi^{\pm}\pi^{\pm}$ and pp correlation results

Roughly consistent with m_T-scaling expectation

Slight deviation for charged kaons

Described by hydrokinetic model HKM

V. Shapoval et al., arXiv:1404.4501



ALICE arXiv:1506.07884

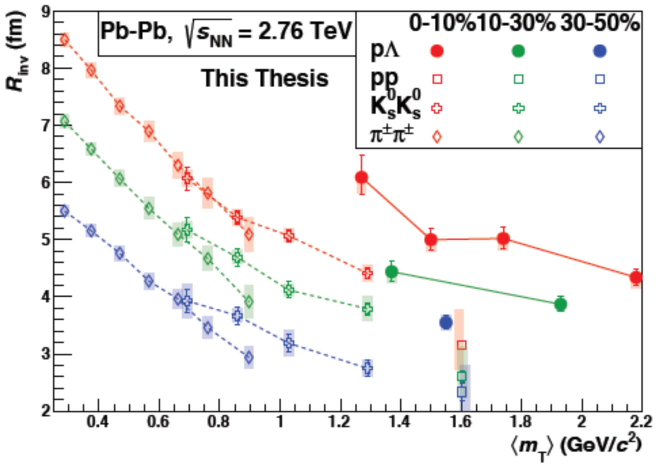
Femtoscopy

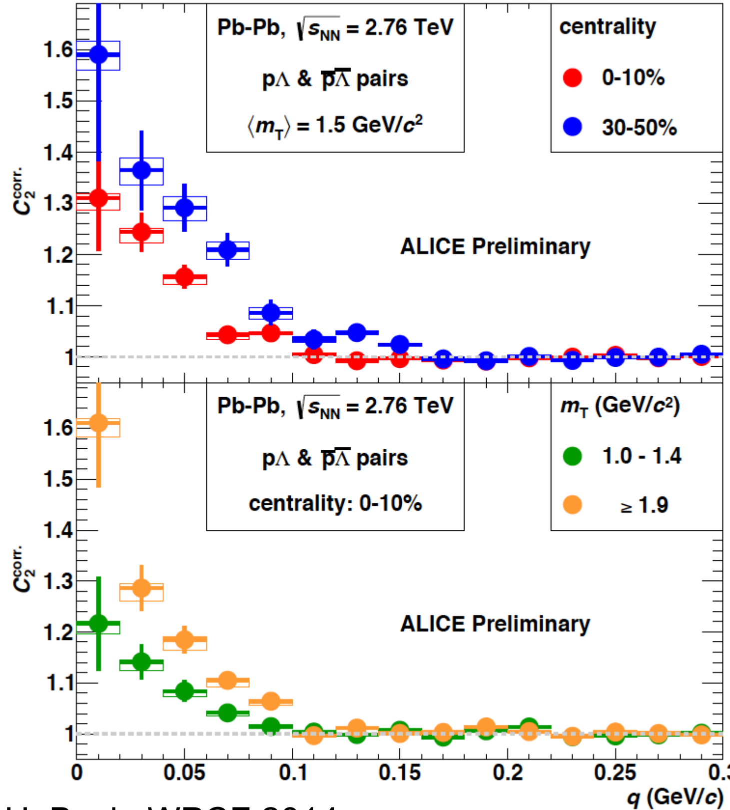
Correlations of p-Λ-Pairs at LHC

Proton-Lambda-Correlations

Differential study vs m_T and centrality

Indication for a violation of m_T-scaling

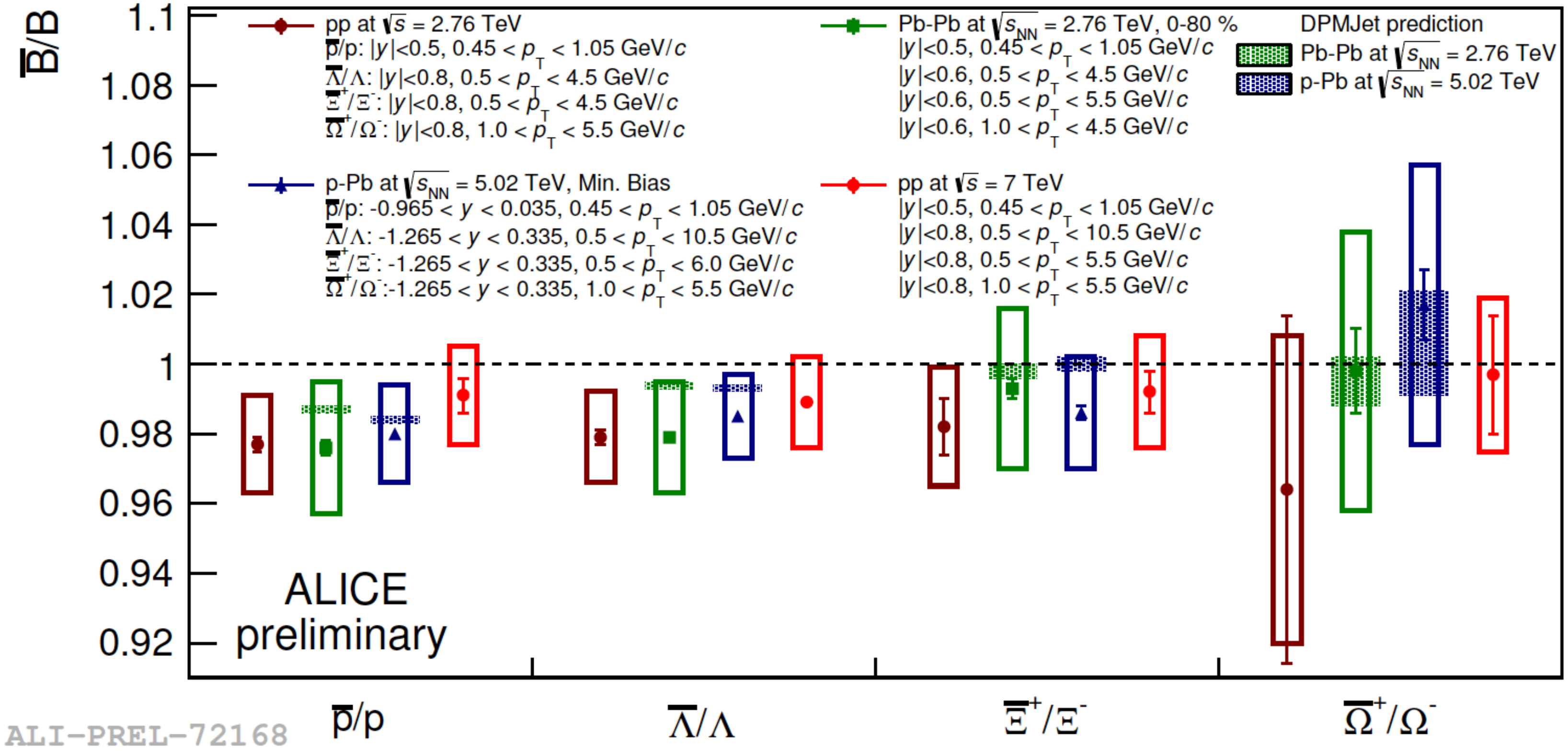




H. Beck, WPCF 2014

Small Systems

Antibaryon-Baryon Ratios at LHC



Antibaryon-baryon ratios same for all systems at LHC

Comparison pp, p-Pb, Pb-Pb

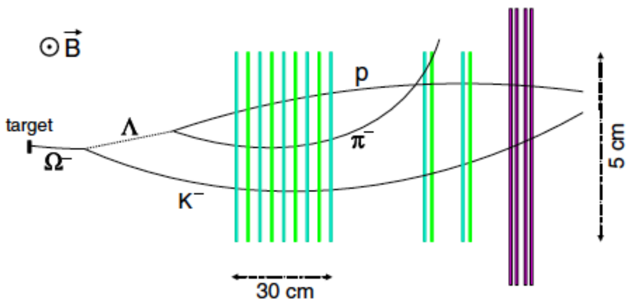
Experiments

CERN-SPS: NA57

Energy scan program

Pb+Pb at 40 and 158 AGeV

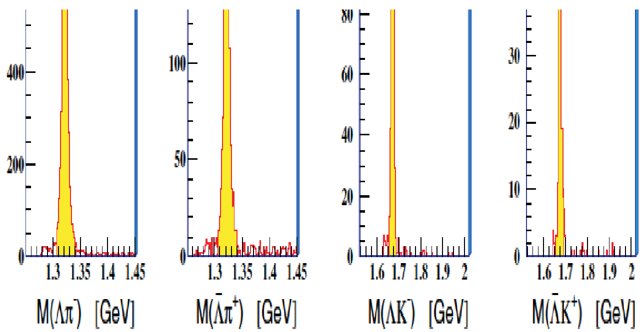
Silicon tracker



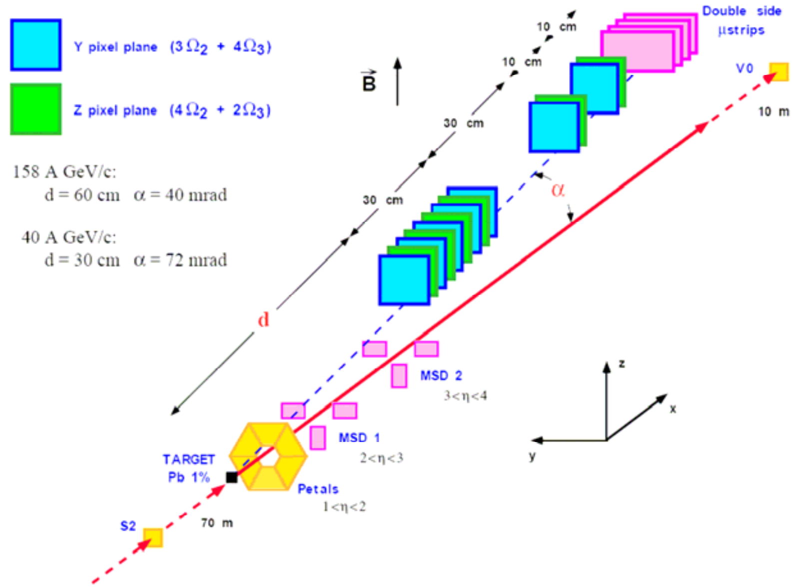
Strange particles:

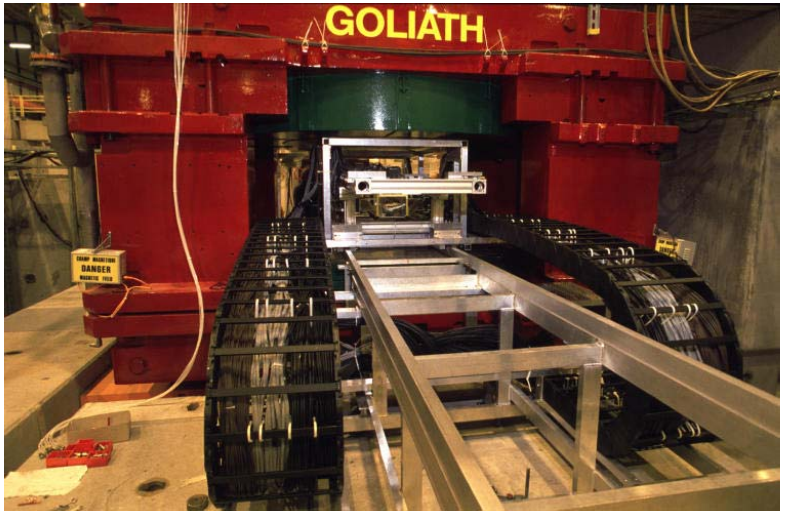
K^0_s, Λ, Ξ, Ω

Around mid-rapidity (Δy ~ 0.5):



NA57
JPG30, 823 (2004)





Experiments

CERN-SPS: NA49

Energy scan program

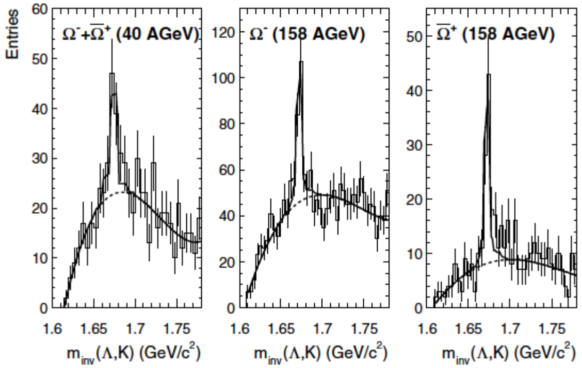
Pb+Pb reactions

Year	1998 1999	2000	2002
$\sqrt{s_{NN}}$ (GeV)	8.8	12.3 17.3	6.3 7.6
E_{beam} (AGeV)	40	80 158	20 30

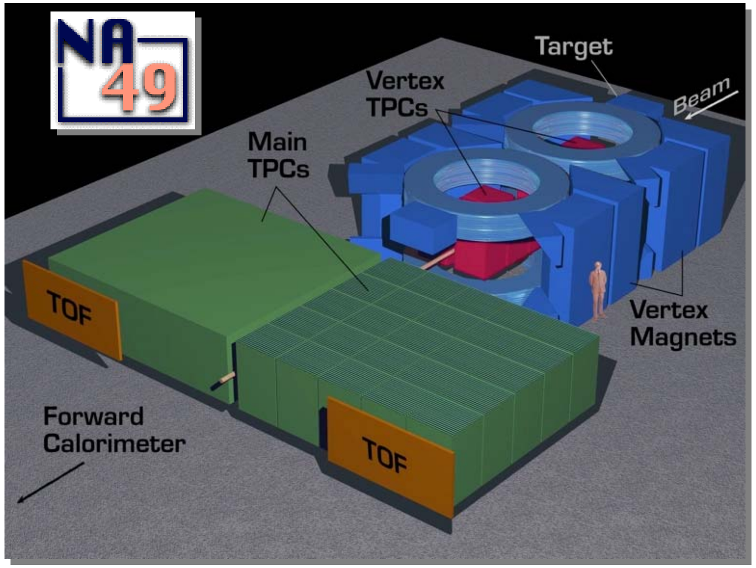
Covers ~250 MeV < μ_B < ~470 MeV

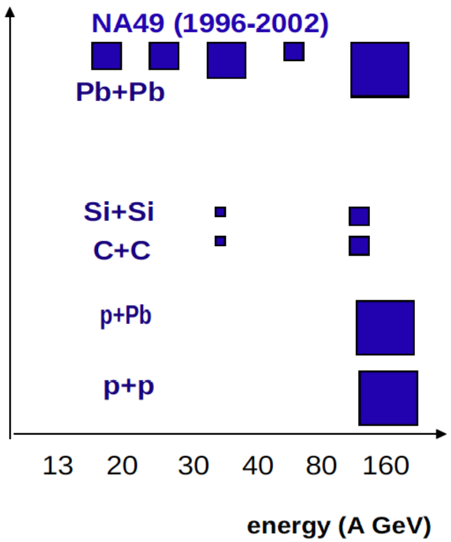
Strange particles:

Kaons, Λ, Ξ, Ω, ϕ, resonances (4π)



NA49
PRL94,
192301
(2005)





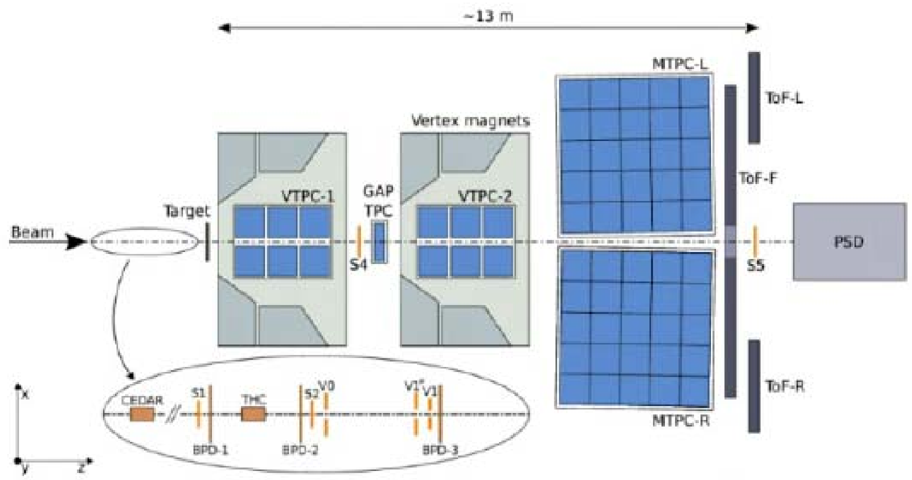
Experiments
CERN-SPS: NA61 / SHINE

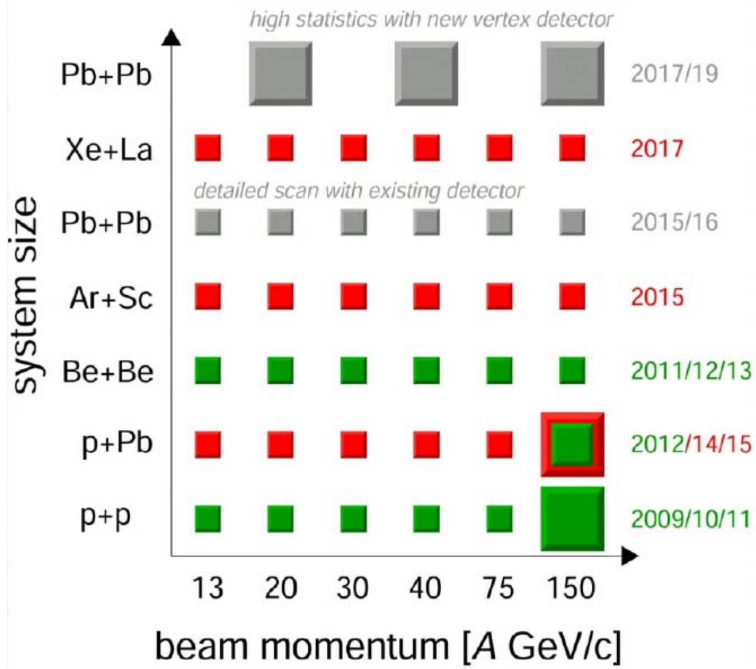
Upgrade of NA49 setup
Faster readout
Projectile Spectator Detector (PSD)
Secondary ion beam line
(fragment separator)

Strange particles:
Kaons, Λ, Ξ, Ω, ϕ, resonances
~ 4π acceptance

Program
2D scan: energy + system size

Recorded: p+p, Be+Be, Ar+Sc
Approved: Xe+La, p+Pb
Considered: Pb+Pb





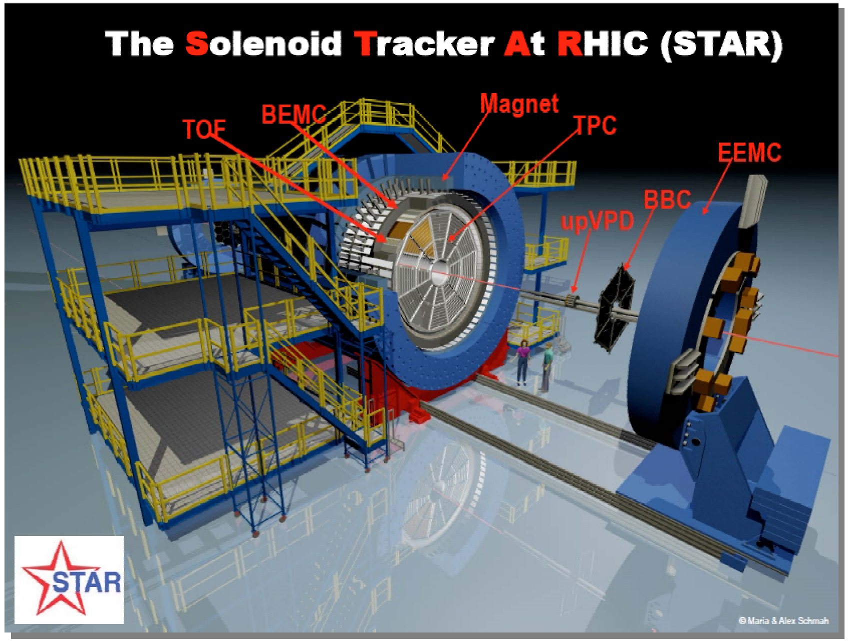
Experiments
RHIC: STAR

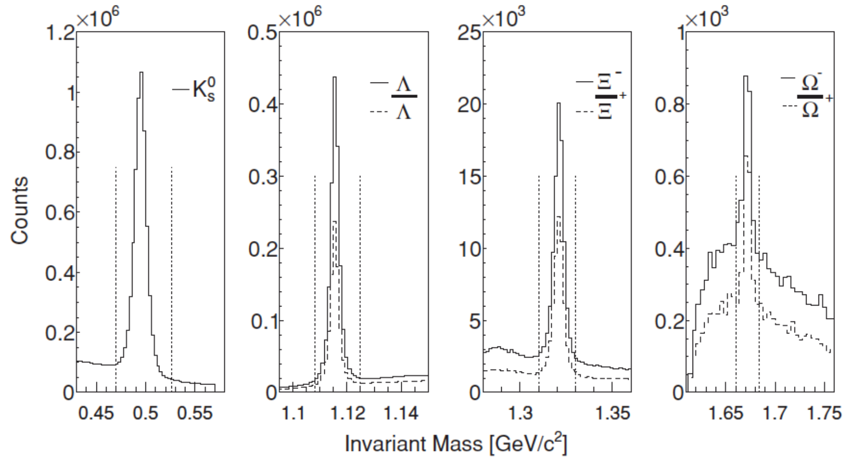
BES program of STAR
Au+Au reactions

Year	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Events (10^6)
2010	200	20	350
2010	62.4	70	67
2010	39	115	130
2011	27	155	70
2011	19.6	205	36
2014	14.5	260	20
2010	11.5	315	12
2010	7.7	420	4

Covers ~20 MeV < μ_B < ~420 MeV

Strange particles:
Kaons, Λ, Ξ, Ω, ϕ, resonances
Mid-rapidity: |y| < 1.0





STAR
PRC83, 024901 (2011)

Experiments

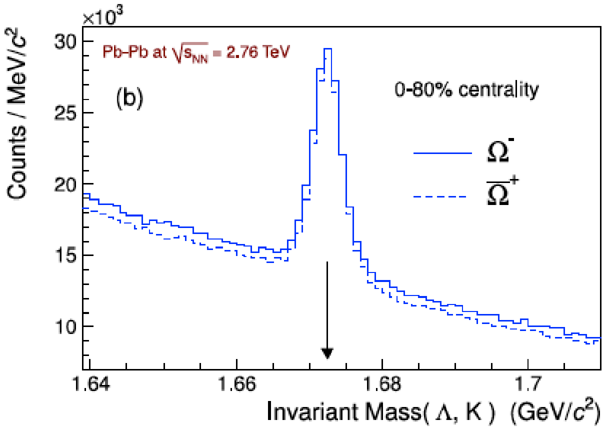
LHC: ALICE

Central barrel

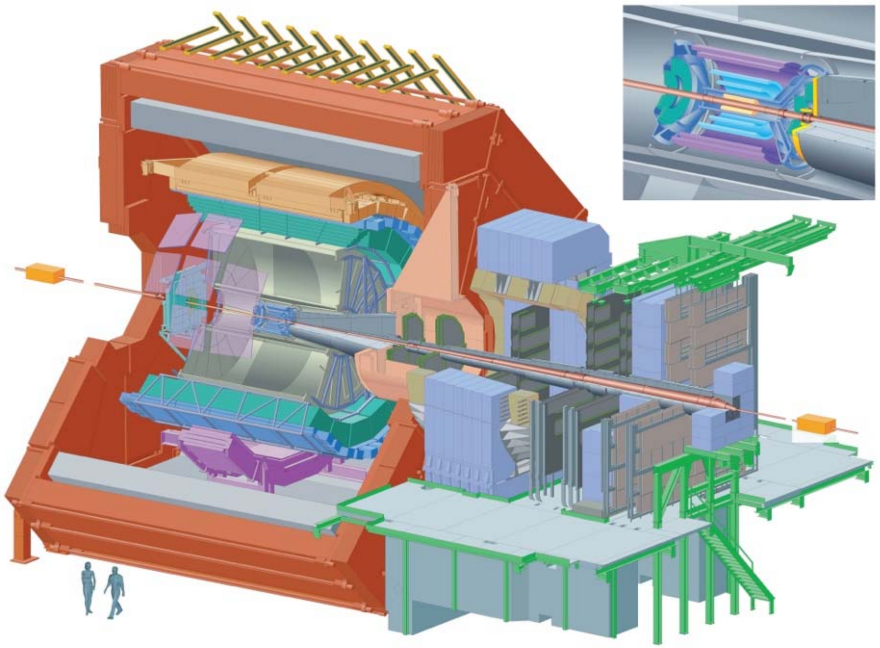
Tracking: ITS + TPC + TRD
PID: TPC + TRD + TOF
Secondary vertex: ITS

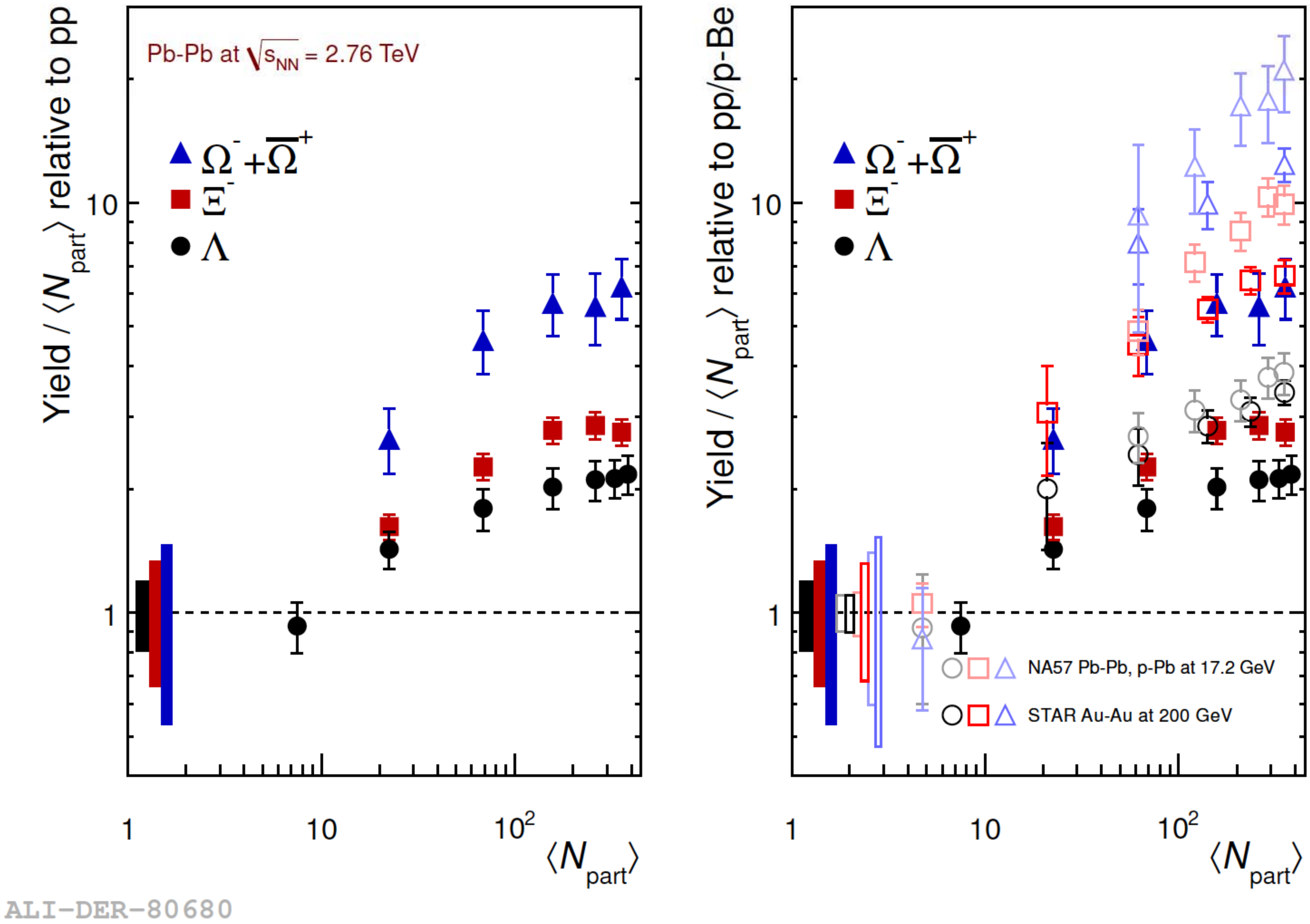
Strange particles:

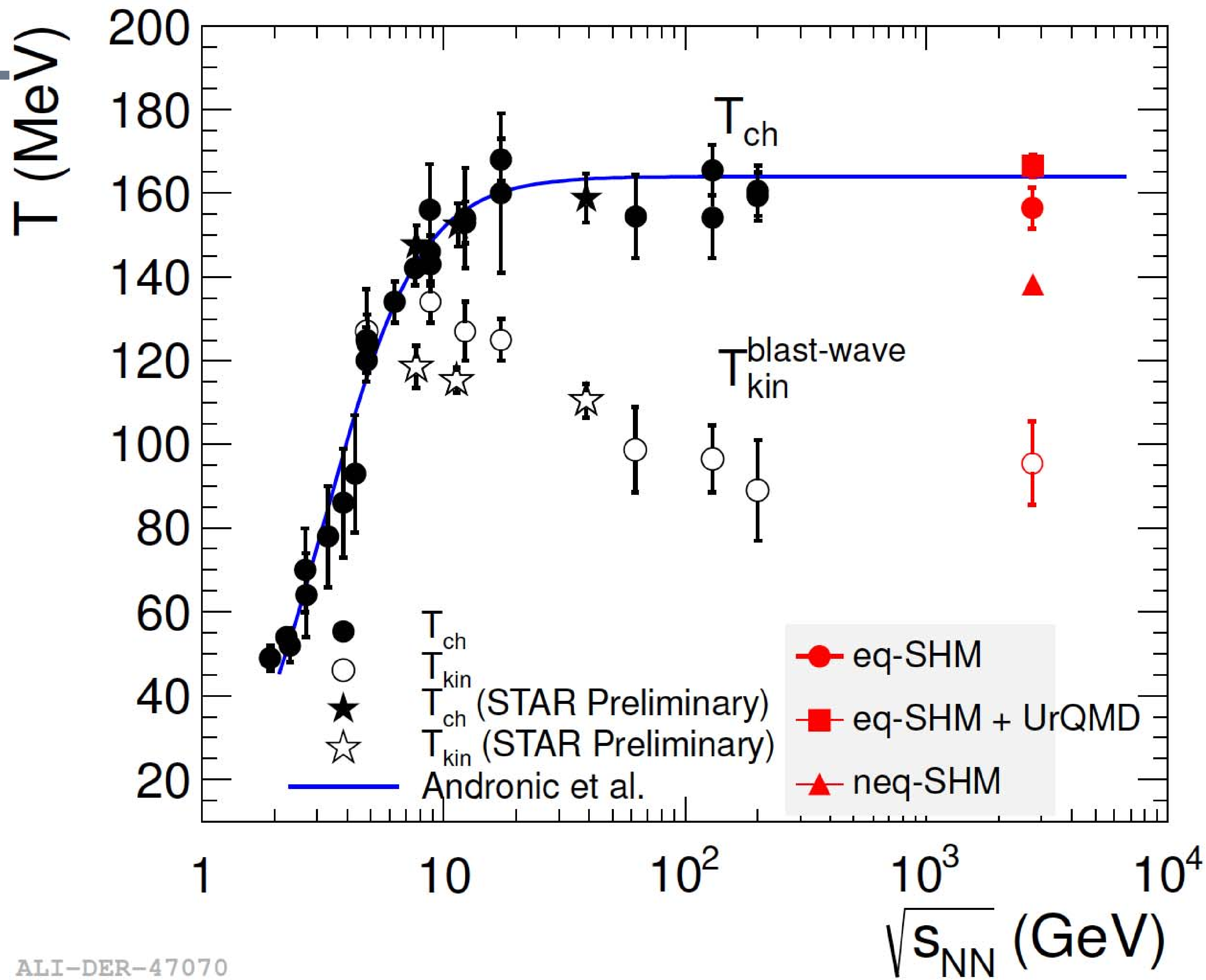
Kaons, Λ, Ξ, Ω, ϕ, resonances
Mid-rapidity: |y| < 0.5

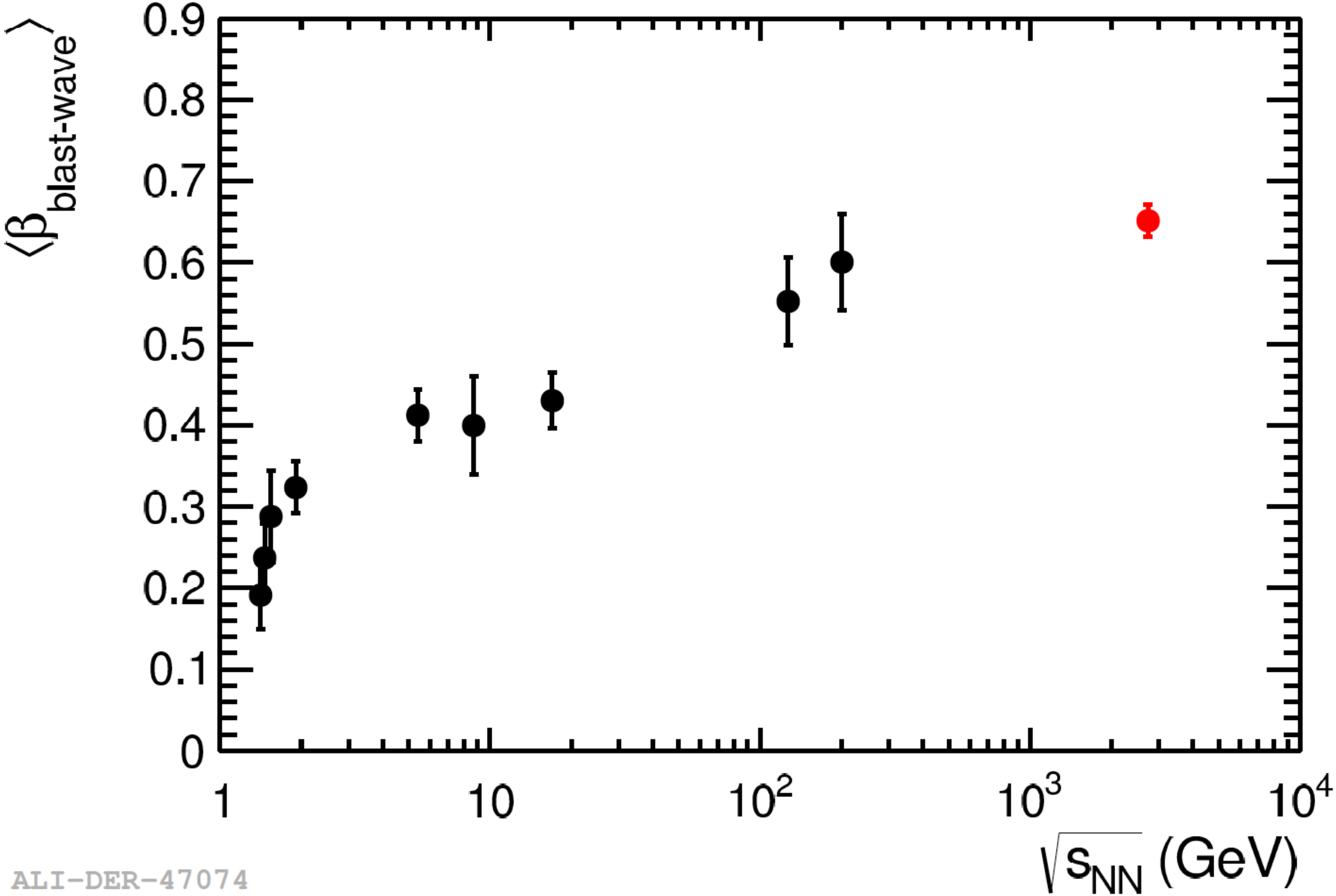


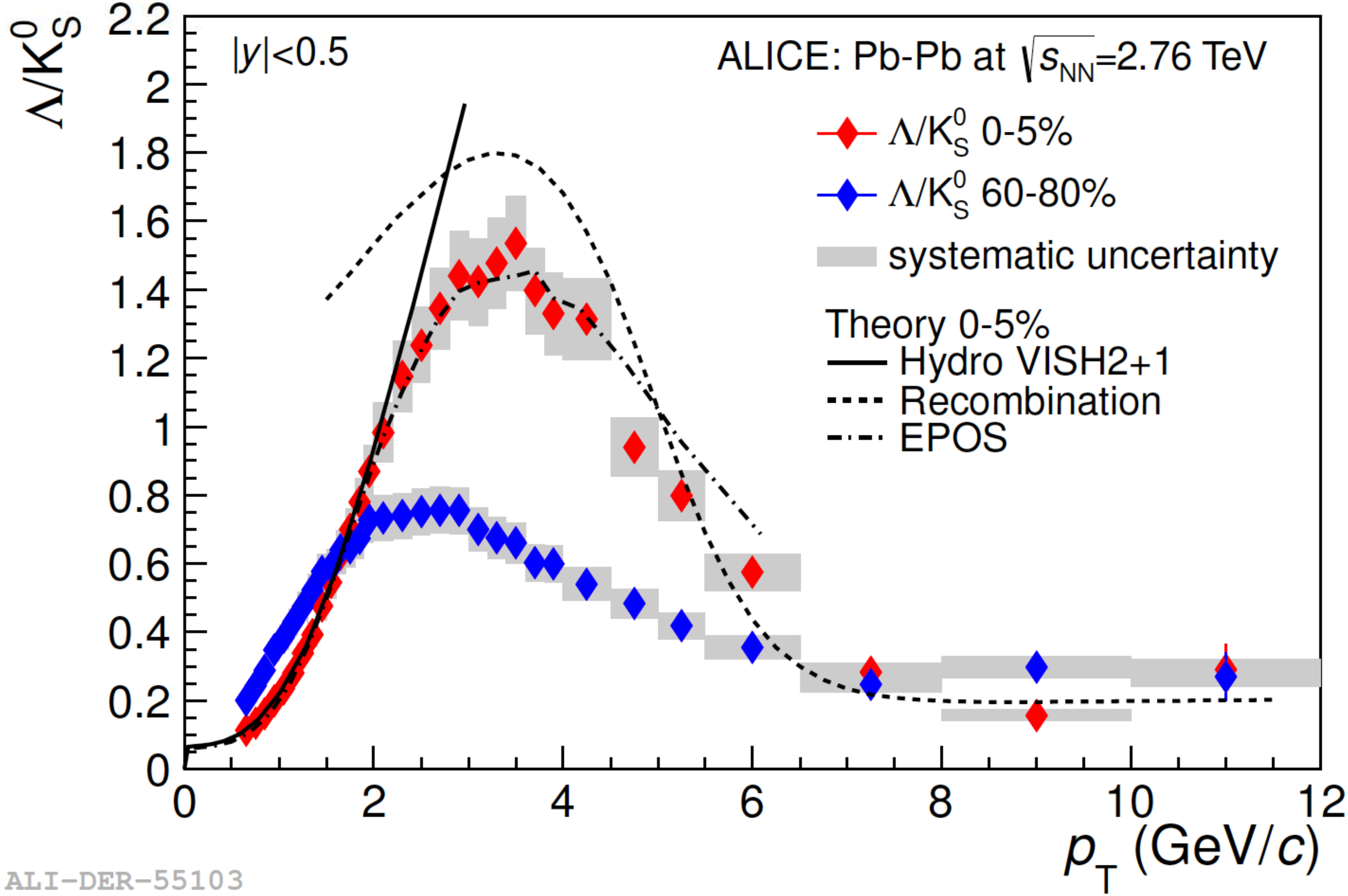
ALICE
PLB728,
216 (2014)

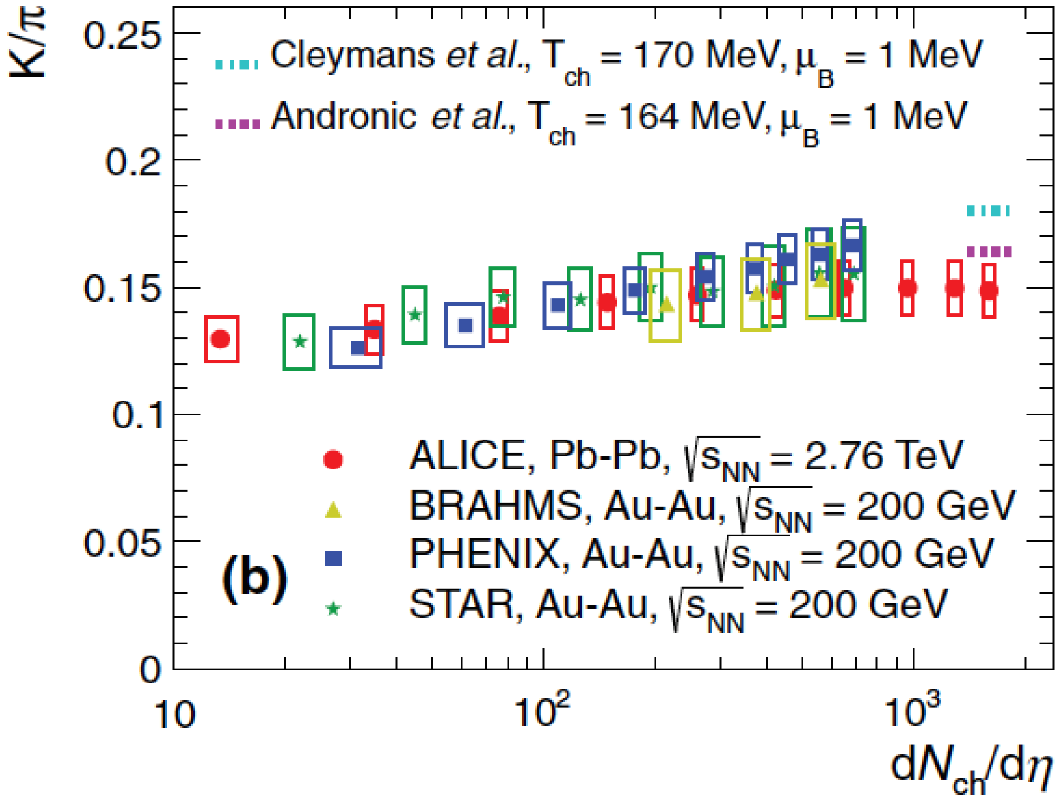



Pb-Pb at √s_NN = 2.76 TeV
Yield / ⟨N_part⟩ relative to pp
Yield / ⟨N_part⟩ relative to pp/p-Be
Ω⁻+Ω̄⁺
Ξ⁻
Λ
NA57 Pb-Pb, p-Pb at 17.2 GeV
STAR Au-Au at 200 GeV
⟨N_part⟩
ALI-DER-80680

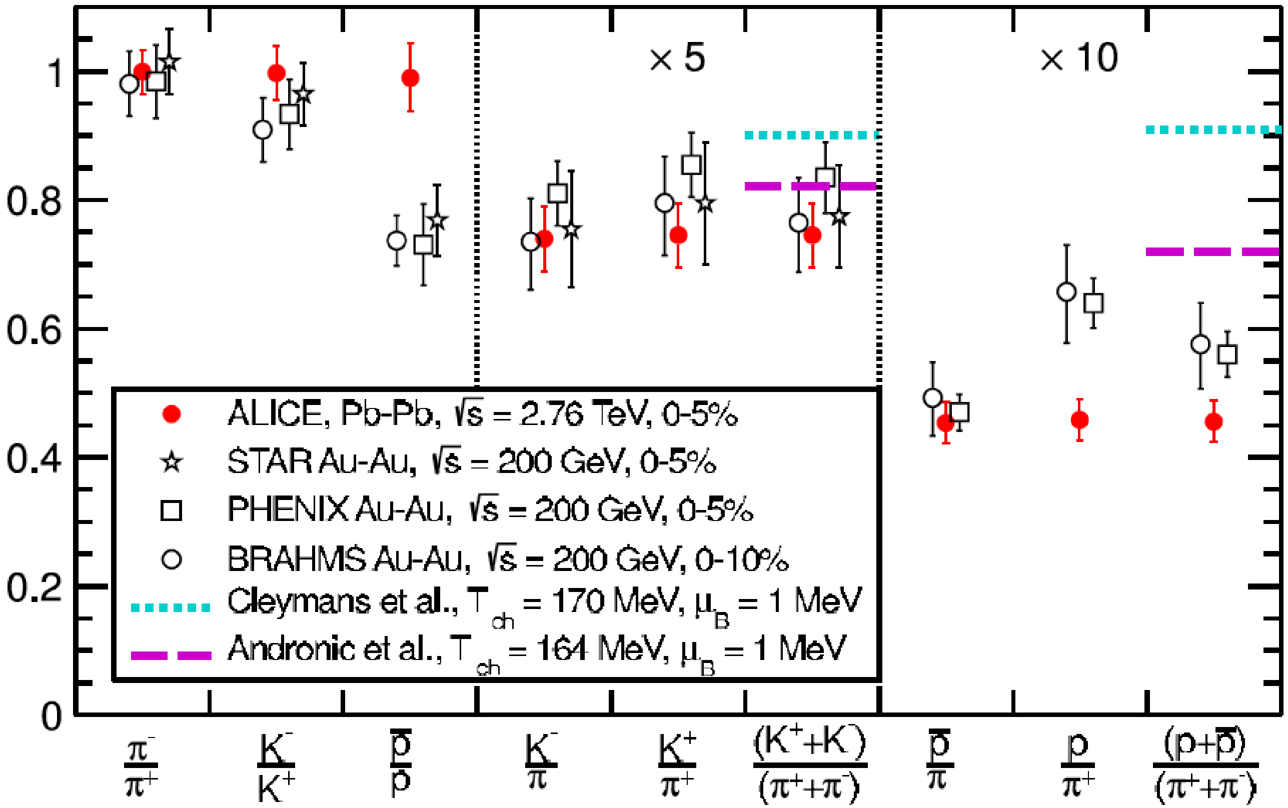

T (MeV)
200
180
160
140
120
100
80
60
40
20
1
10
10^2
10^3
10^4
√s_NN (GeV)
T_ch
T_kin^blast-wave
T_ch
T_kin
T_ch (STAR Preliminary)
T_kin (STAR Preliminary)
Andronic et al.
eq-SHM
eq-SHM + UrQMD
neq-SHM
ALI-DER-47070


⟨β_blast-wave⟩
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
10^2
10^3
10^4
√s_NN (GeV)
ALI-DER-47074

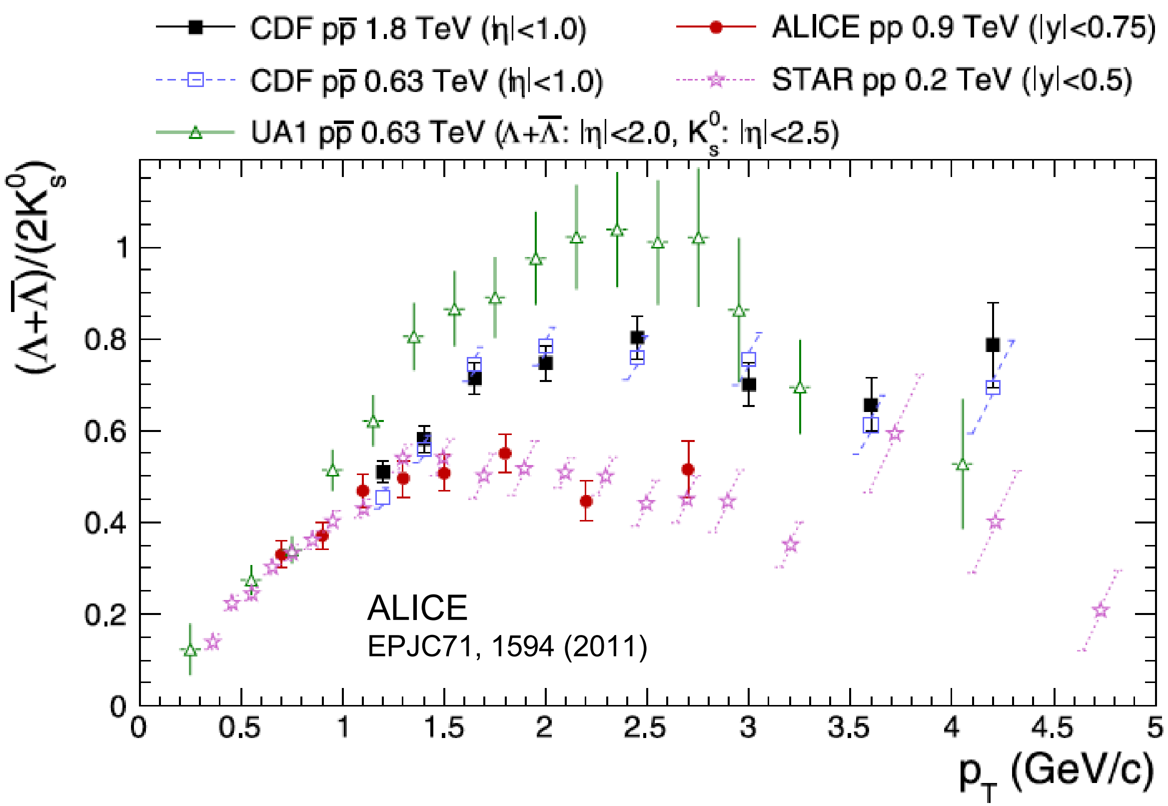

Λ/K^0_S
|y|<0.5
ALICE: Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
Λ/K^0_S 0-5%
Λ/K^0_S 60-80%
systematic uncertainty
Theory 0-5%
Hydro VISH2+1
Recombination
EPOS
p_T (GeV/c)
ALI-DER-55103



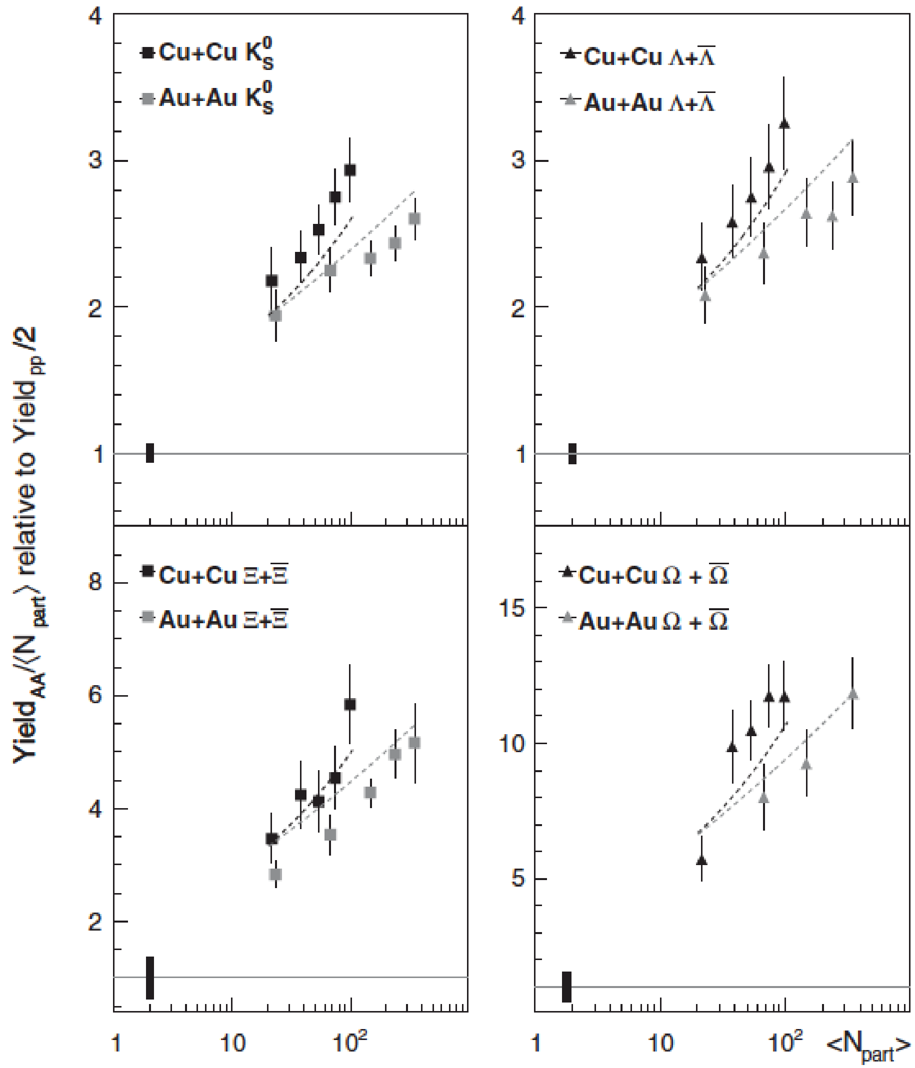
ALICE
PRC88, 044910 (2013)



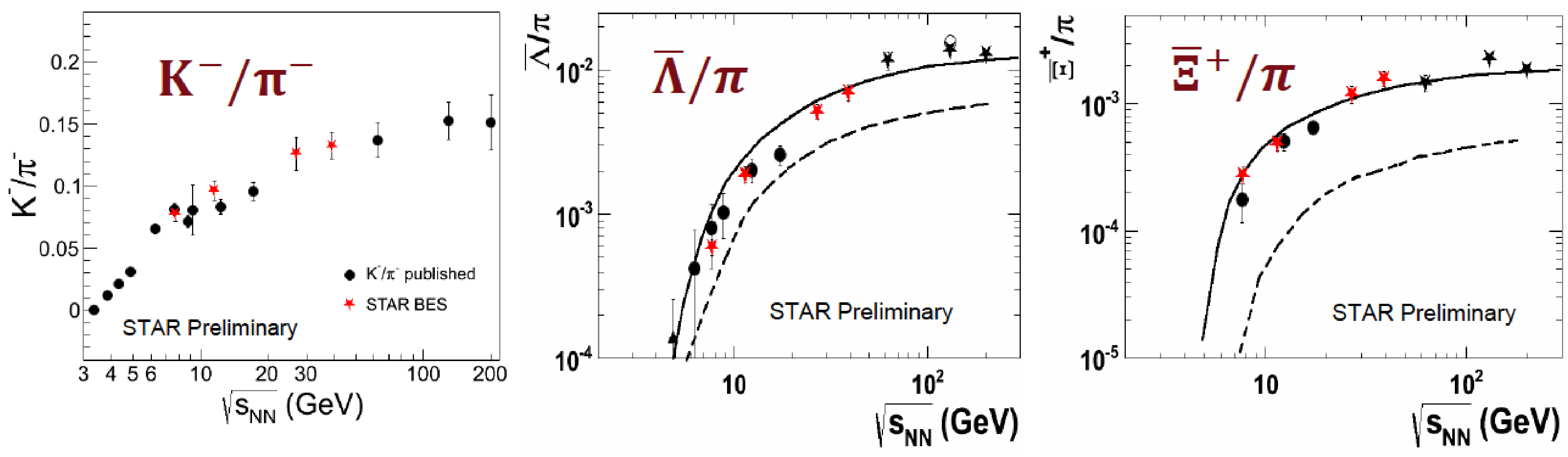
ALICE
PRL109, 252301 (2012)



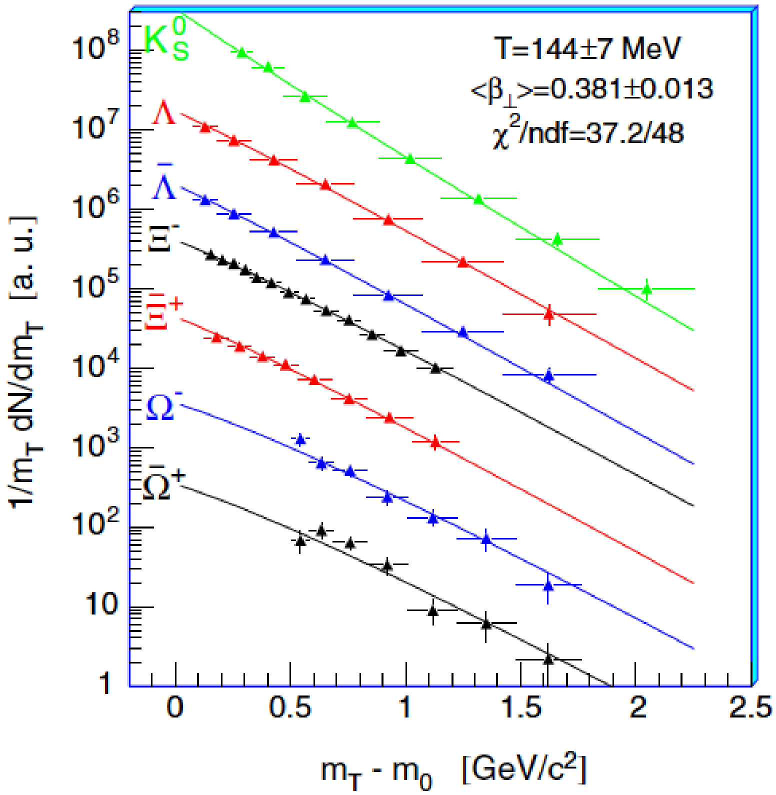
CDF $p\bar{p}$ 1.8 TeV (|η|<1.0)
CDF $p\bar{p}$ 0.63 TeV (|η|<1.0)
UA1 $p\bar{p}$ 0.63 TeV ($\Lambda+\bar{\Lambda}$: |η|<2.0, K^0_s: |η|<2.5)
ALICE pp 0.9 TeV (|y|<0.75)
STAR pp 0.2 TeV (|y|<0.5)
$(\Lambda+\bar{\Lambda})/(2K^0_s)$
p_T (GeV/c)
ALICE
EPJC71, 1594 (2011)



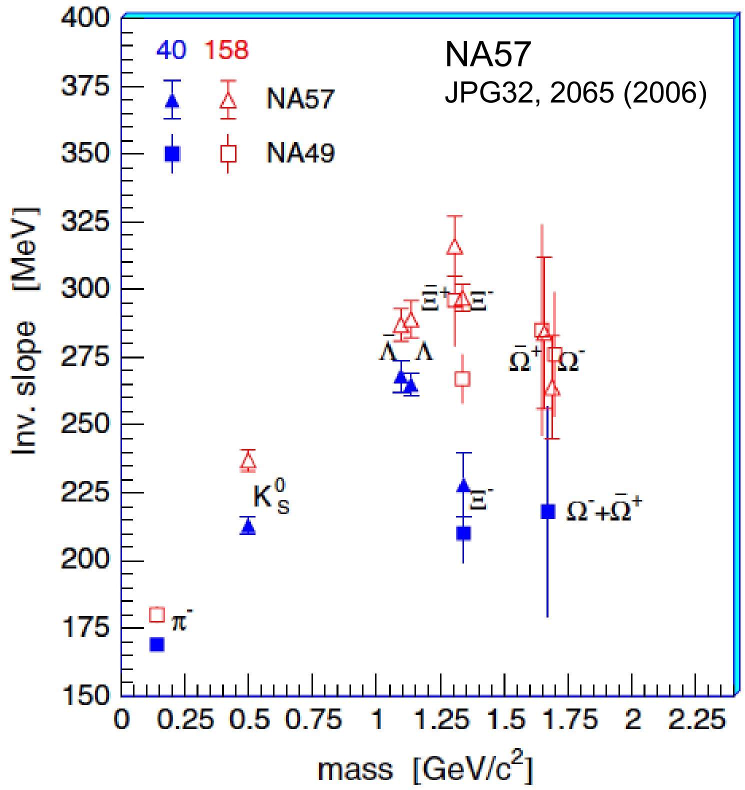
STAR
PRL108, 072301 (2012)



X. Zhang, SQM 2015



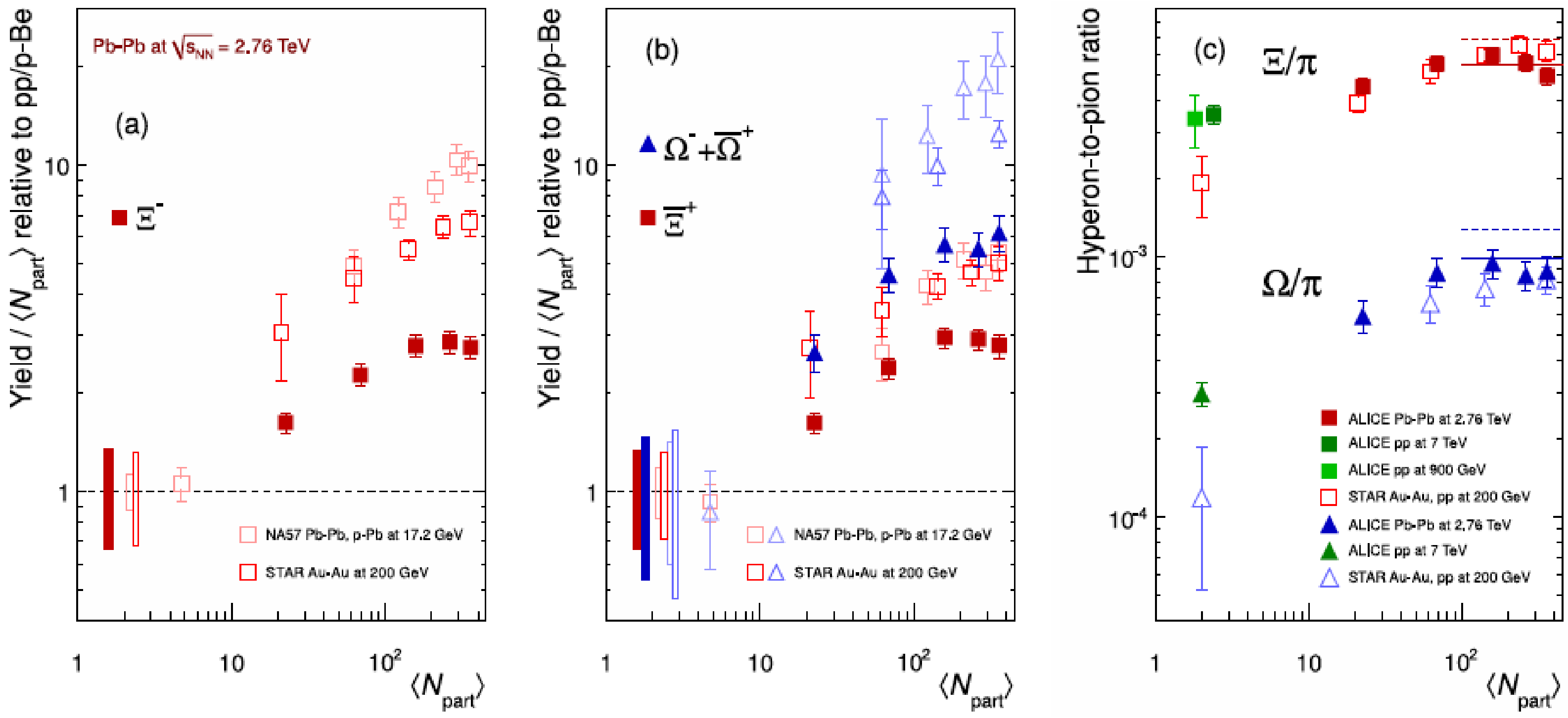
T=144±7 MeV
<β⊥>=0.381±0.013
χ2/ndf=37.2/48
1/mT dN/dmT [a. u.]
mT - m0 [GeV/c2]



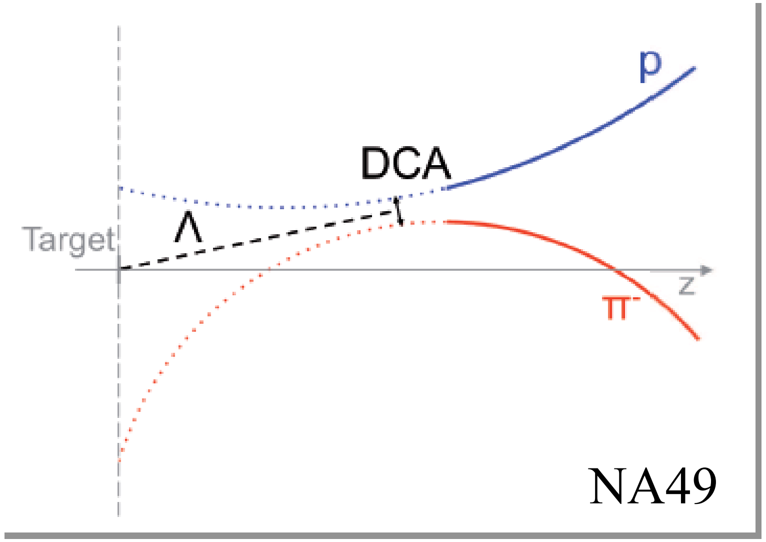
NA57
JPG32, 2065 (2006)
40 158
NA57
NA49
Inv. slope [MeV]
mass [GeV/c2]

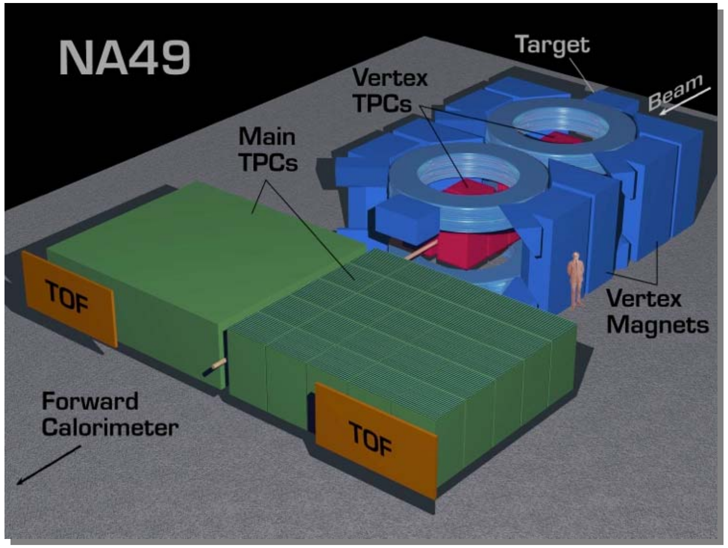
Strangeness Enhancement

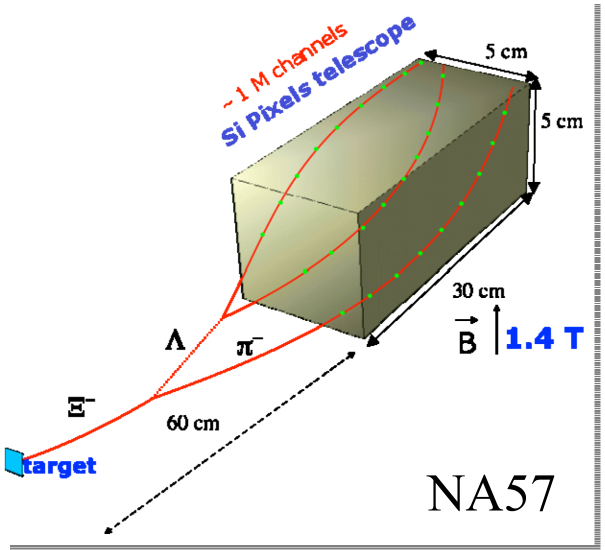
LHC Data (ALICE)

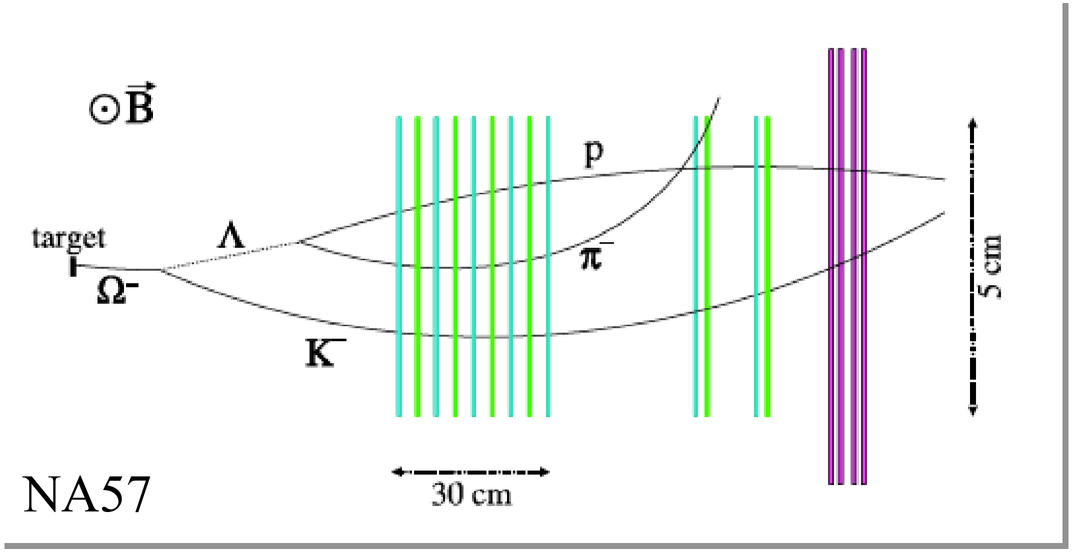


ALICE
PLB728, 216 (2014)


p
DCA
Target
Λ
z
π⁻
NA49

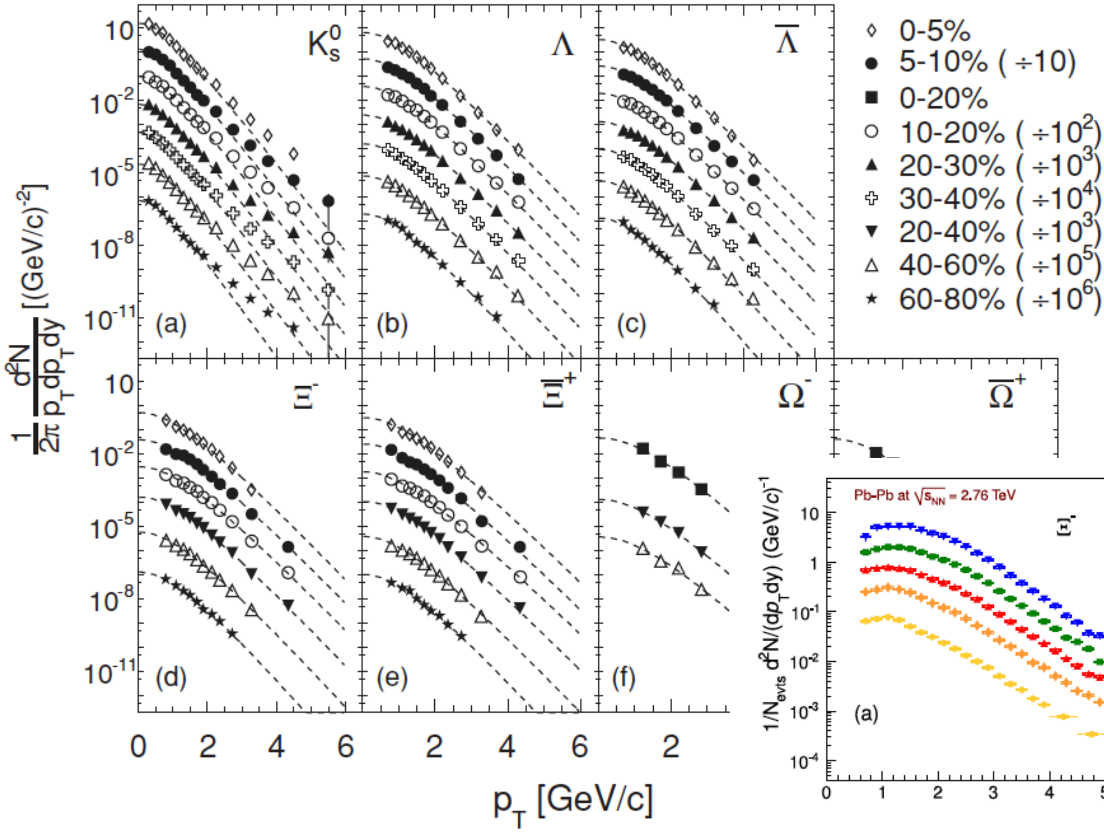

NA49
Target
Beam
Vertex
TPCs
Main
TPCs
TOF
Vertex
Magnets
Forward
Calorimeter
TOF


~1 M channels
Si Pixels telescope
5 cm
5 cm
30 cm
B 1.4 T
Λ
π⁻
Ξ⁻
60 cm
target
NA57

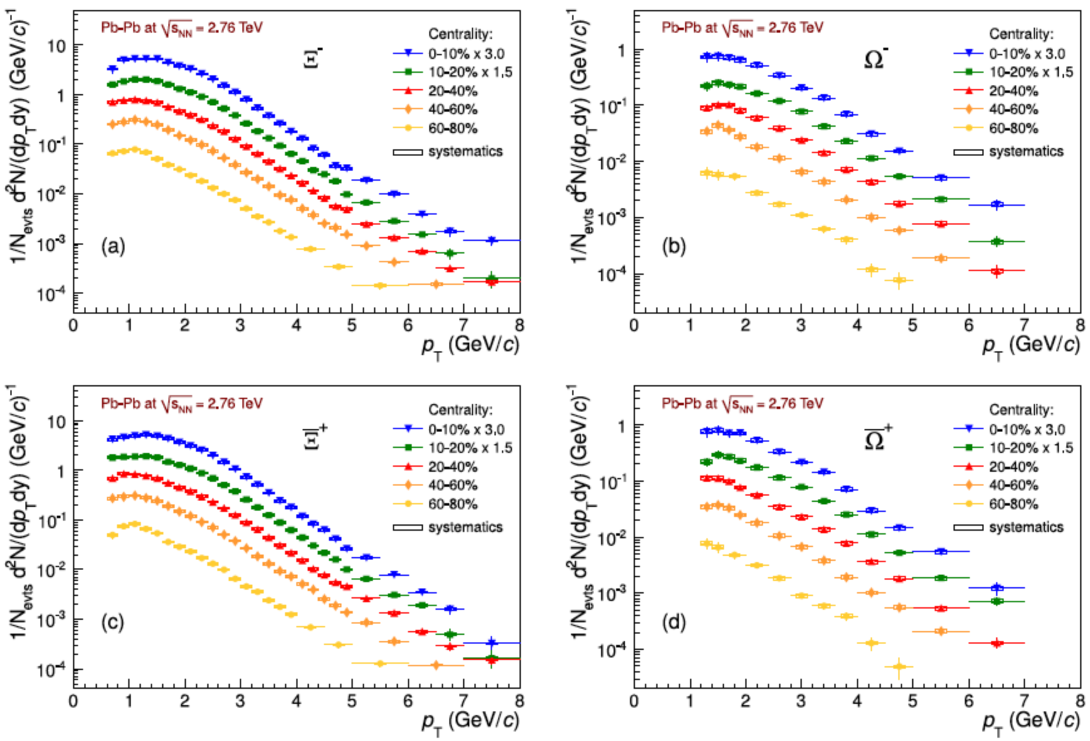

⊙B
p
target
Λ
π⁻
Ω⁻
K⁻
5 cm
30 cm
NA57

Overview on Existing Data

RHIC and LHC



STAR
PRC83, 024901 (2011)
$\sqrt{s_{NN}}$ = 62.4 GeV



ALICE
PLB728, 216 (2014)
$\sqrt{s_{NN}}$ = 2.76 TeV

System Size Dependence

Total Yields of Λ and Λ

Transport models

OK for Λ

Slightly below $\bar{\Lambda}$ but similar $\langle N_W \rangle$-dependence

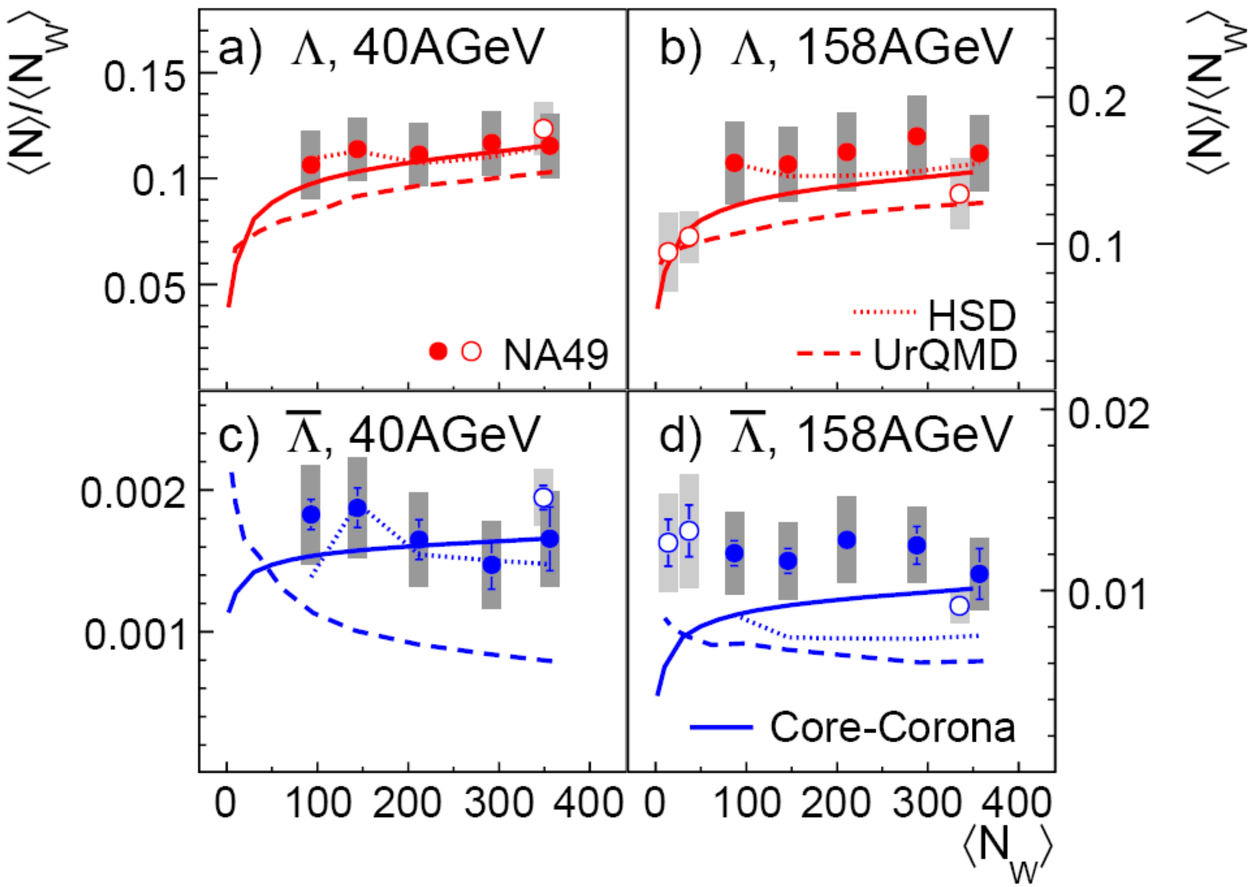
Core Corona model

OK for Λ

$\langle N_W \rangle$-dependence of $\bar{\Lambda}$ not described

$\bar{\Lambda}$ absorption ?

NA49 data:
arXiv:0906.0469



Open symbols: central C+C, Si+Si, Pb+Pb

UrQMD: H. Petersen et al. arXiv: 0903.0396

HSD: W. Cassing and E. Bratkovskaya, Phys. Rep. **308**, 65 (1999) and private communication

Core-corona: F. Becattini and J. Manninen, Phys. Lett. **B673**, 19 (2009) J. Aichelin and K. Werner, arXiv:0810.4465

Energy Dependence

Total yields of Λ and Ξ

NA49 data
Phys. Rev. **C78**,
034918 (2008)

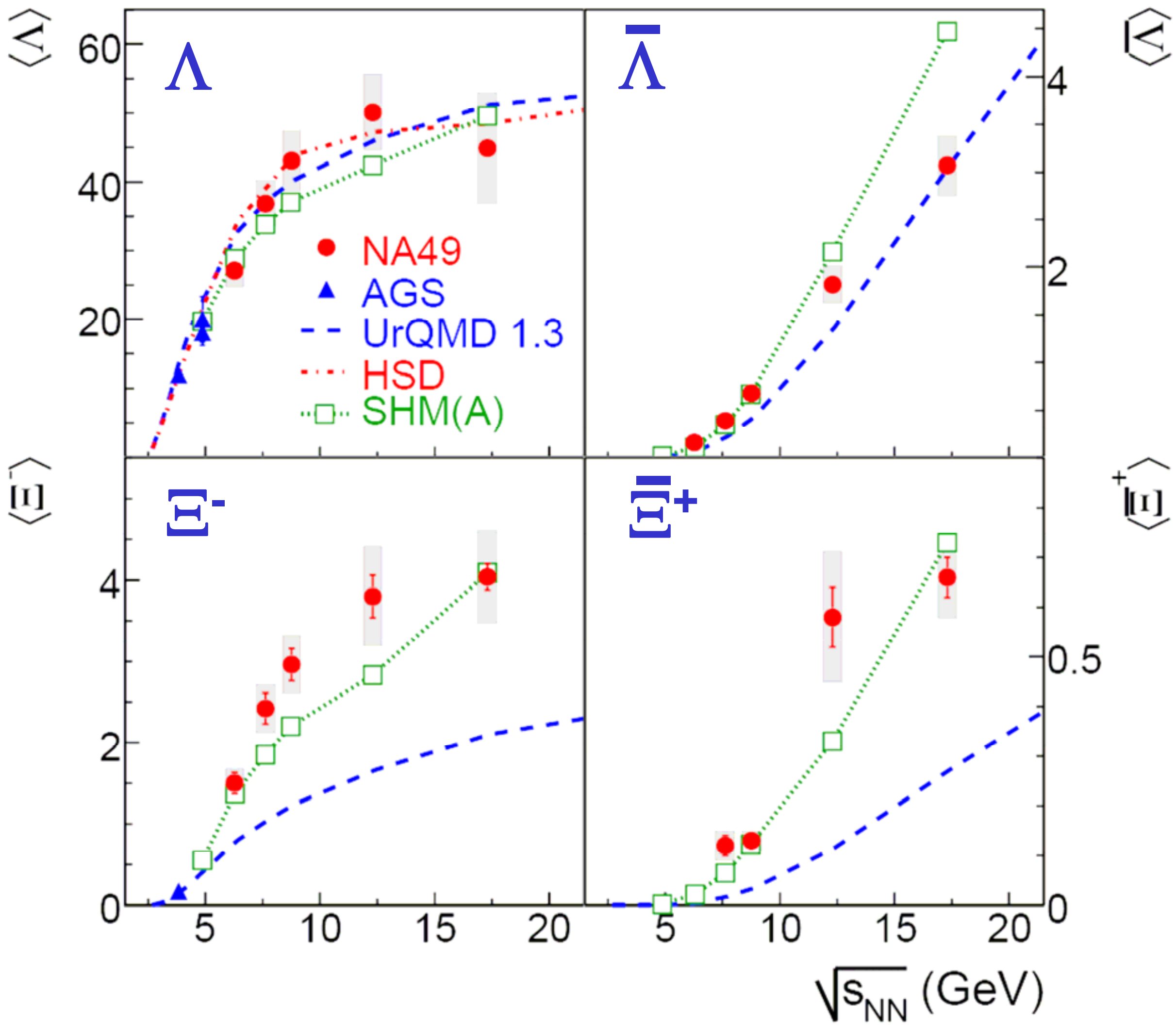
Transport models

OK for Λ
Too low for Ξ

Statistical Models

Generally good description at all energies

SHM(A): F. Becattini et al., Phys Rev. **C69**, 024905 (2004).
UrQMD: M. Bleicher et al., J. Phys. **G 25**, 1856 (1999) and private communication
HSD: E. Bratkovskaya et al., Phys. Rev. **C69**, 054907 (2004)



Energy Dependence

K^+/π^+ and Λ/π^--Ratios

Extended statistical model

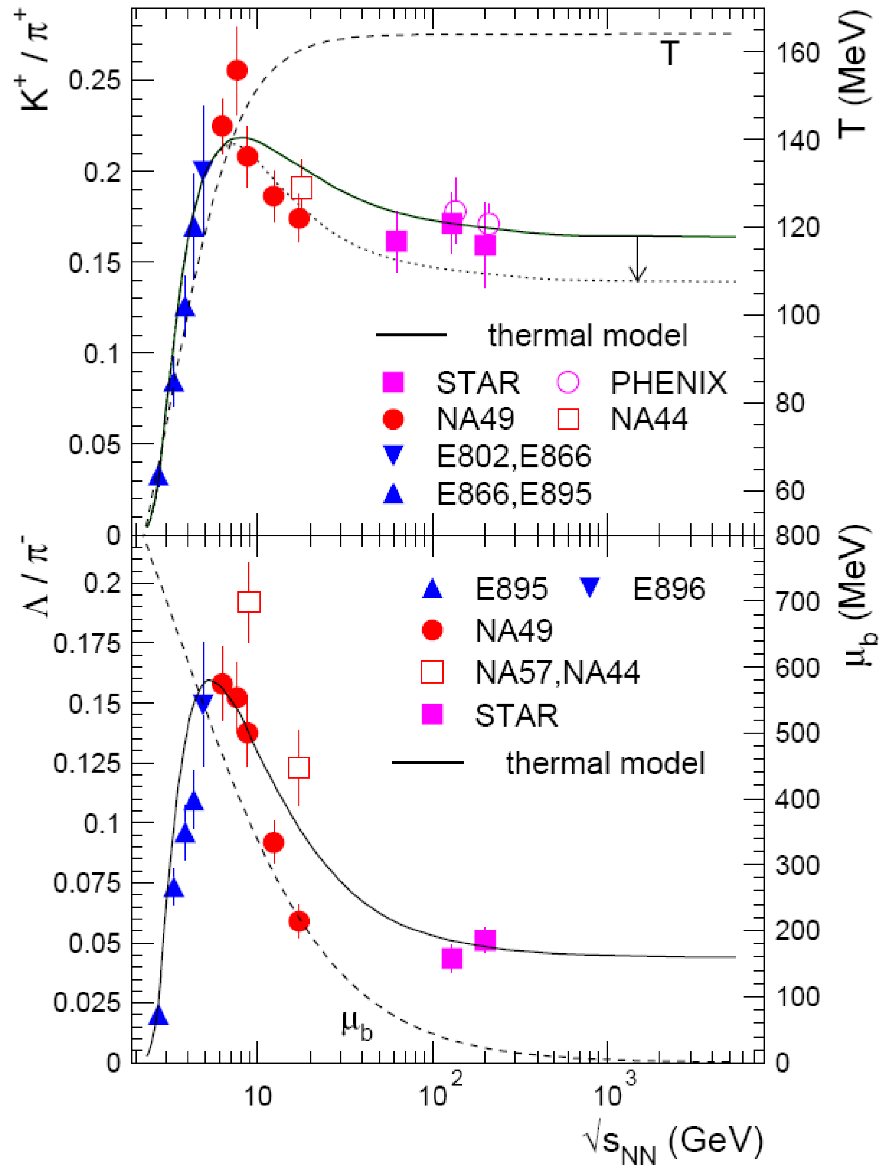
Higher mass resonances included (up to 3 GeV)

$\Rightarrow$ Improved description of pions and thus of the K^+/π^+-ratio

Limiting temperature reached in SPS energy region

Equilibration due to proximity of phase boundary?

A. Andronic et al., arXiv:0812.1186.



Energy Dependence

Λ/π - and Ξ/π -Ratios

NA49 data
Phys. Rev. **C78**, 034918 (2008)

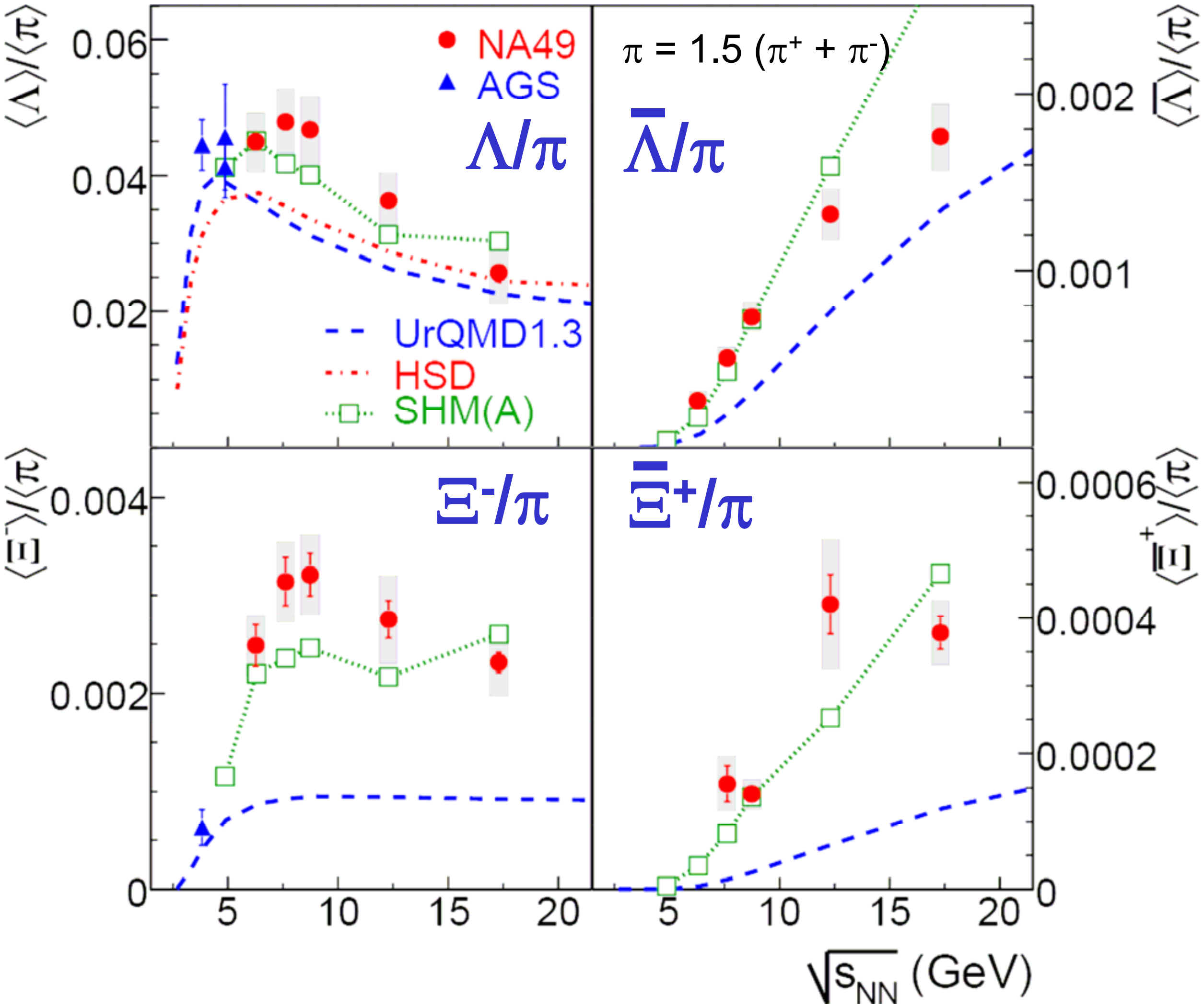
Transport models

OK for Λ
Too low for Ξ

Statistical models

Generally good description at all energies

SHM(A): F. Becattini et al., Phys Rev. **C69**, 024905 (2004).
UrQMD: M. Bleicher et al., J. Phys. **G 25**, 1856 (1999) and private communication
HSD: E. Bratkovskaya et al., Phys. Rev. **C69**, 054907 (2004)



Energy Dependence

Λ/π - and Ξ/π -Ratios

NA49 data
Phys. Rev. **C78**, 034918 (2008)

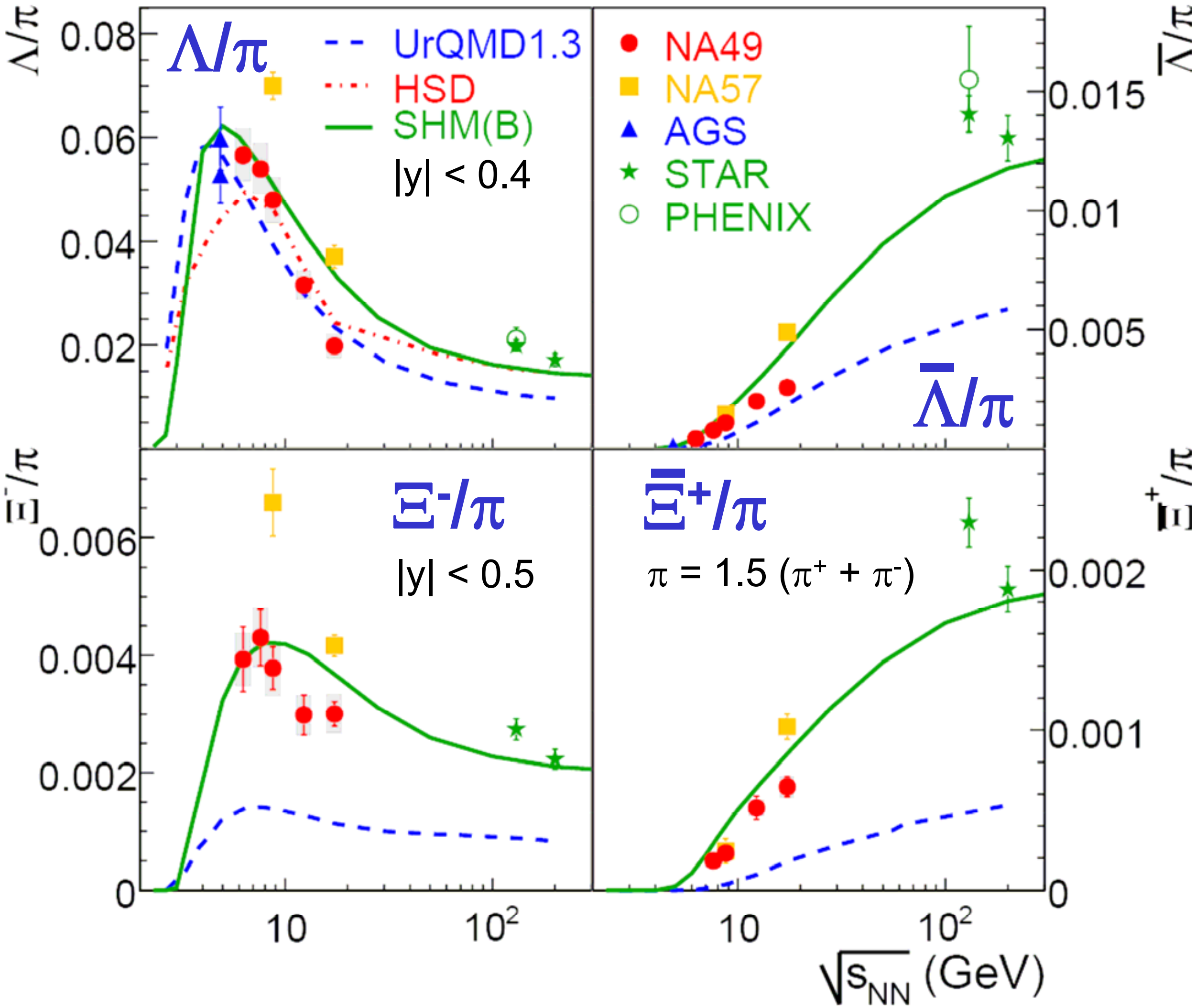
Transport models

OK for Λ
Too low for Ξ

Statistical models

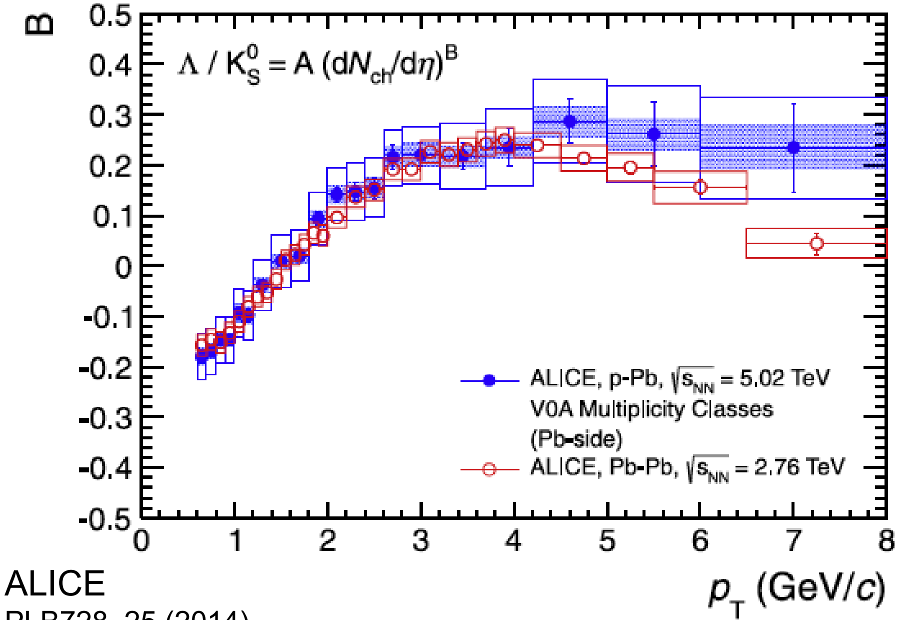
Generally good description at all energies

SHM(B): A. Andronic et al., Nucl. Phys. A **772**, 167 (2006).
UrQMD: M. Bleicher et al., J. Phys. **G 25**, 1856 (1999) and private communication
HSD: E. Bratkovskaya et al., Phys. Rev. **C69**, 054907 (2004)

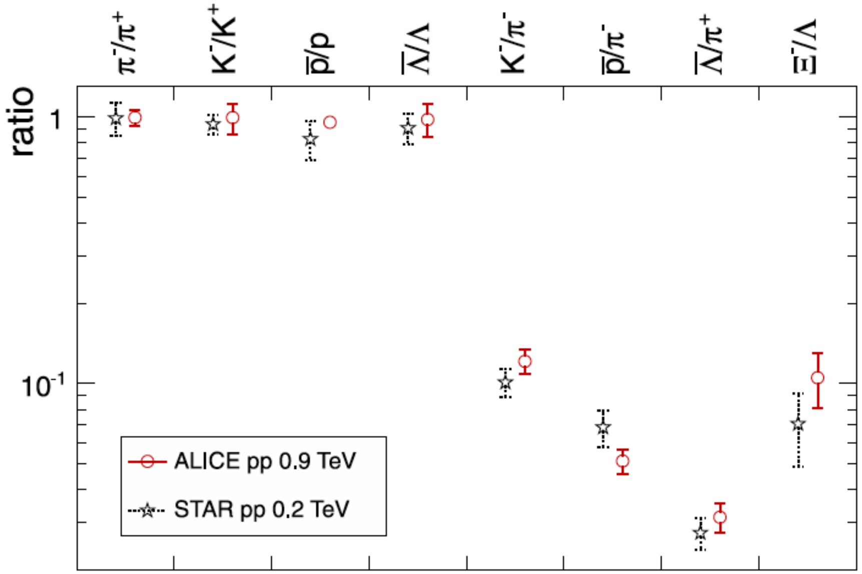


Proton-Nucleus Data

Λ/K^0_s-Ratios at LHC



ALICE
PLB728, 25 (2014)


π⁻/π⁺
K⁻/K⁺
p̄/p
Λ̄/Λ
K⁻/π⁻
p̄/π⁻
Λ̄/π⁺
Ξ⁻/Λ
ratio
1
10⁻¹
ALICE pp 0.9 TeV
STAR pp 0.2 TeV