GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HADES

Strangeness Production at Low Energies

Heidi Schuldes

GSI

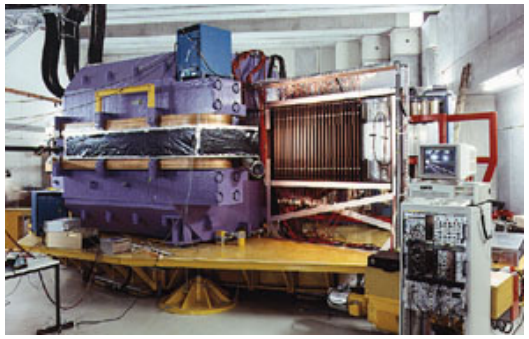
Outline

- **Introduction**
- **Microscopic description of sub-threshold strangeness production** (K^0 and Λ)
- **Deep sub-threshold strangeness production** (K^- and ϕ)
- **The global picture**
- **Summary**

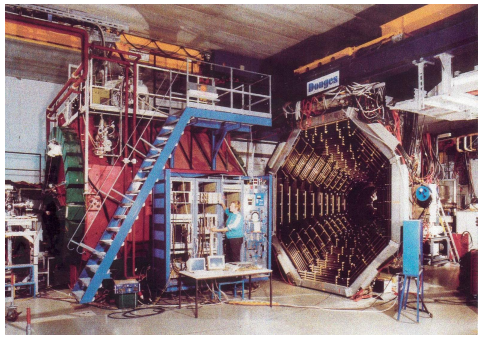
Experiments at SIS18

Detailed Study of Matter Properties at Highest μ_B

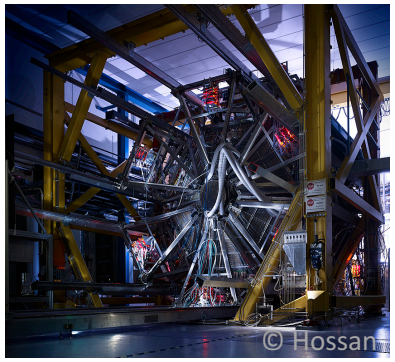
KaoS



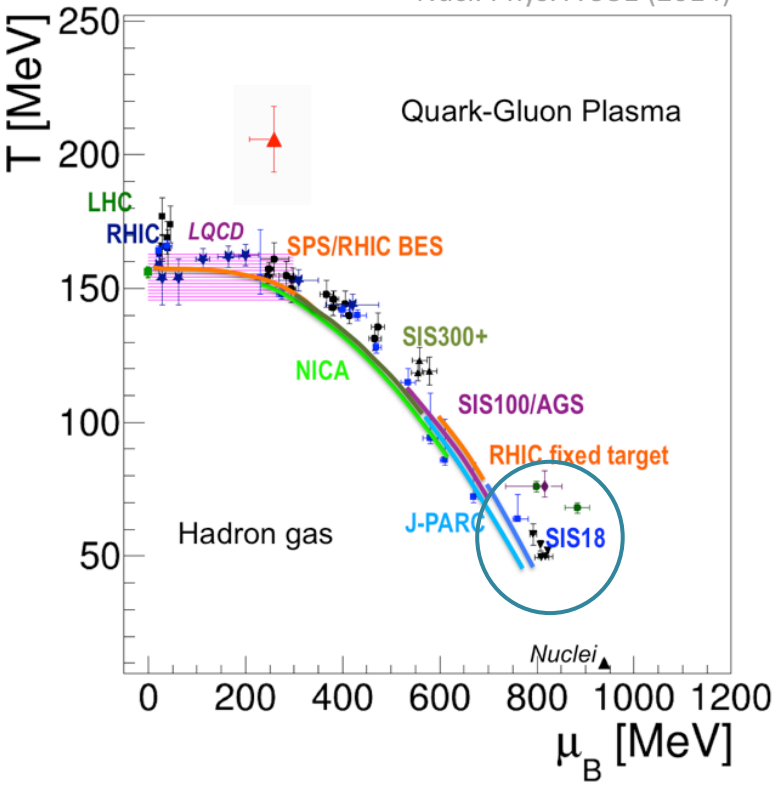
FOPI



HADES



Nucl. Phys. A 931 (2014)

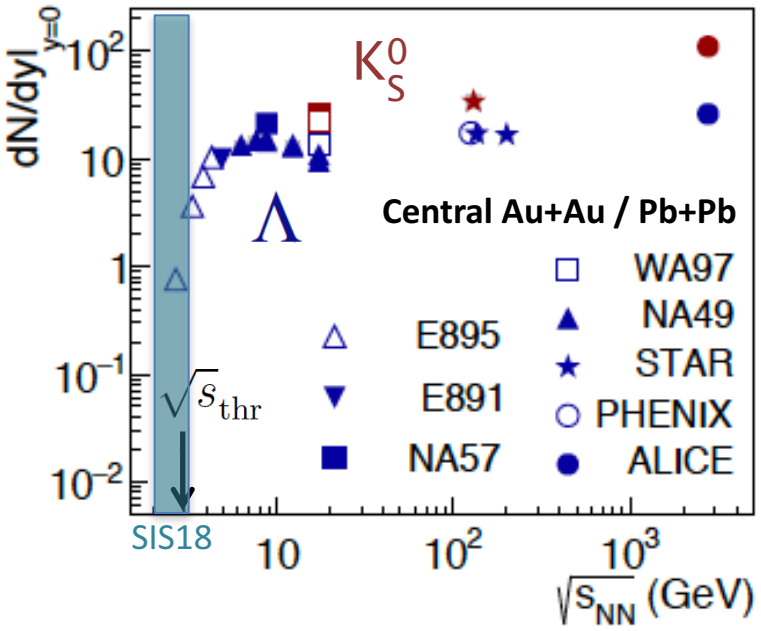


- Heavy-ion beams from SIS18: E_{kin} = 1-2*A* GeV
- Large stopping and long penetration times ➢ Baryon dominated system
- High densities and moderate temperatures at freeze-out
- *Produced matter characterized by global properties?*

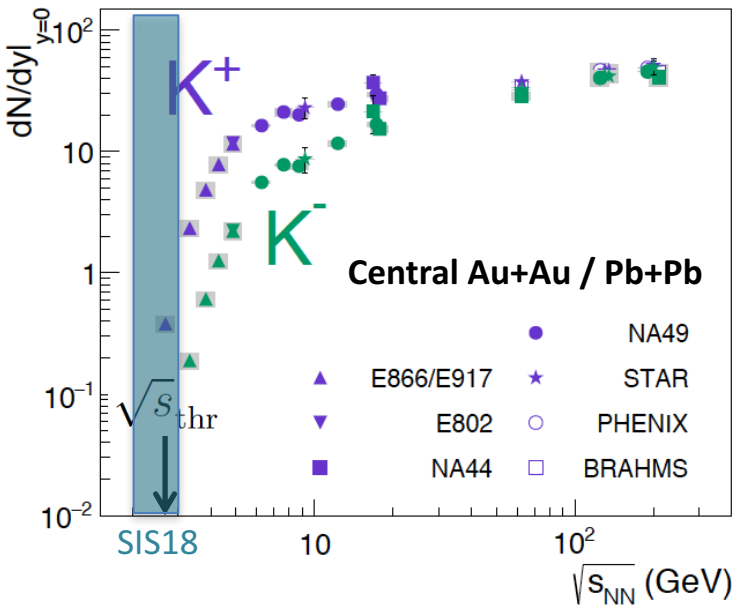
Strangeness Production at SIS Energies

Sub-threshold Strangeness Production

$$NN \rightarrow NK^+\Lambda$$
$$\sqrt{s_{\mathrm{thr}}} = 2.55\ \mathrm{GeV}$$



$$NN \rightarrow NNK^+K^-$$
$$\sqrt{s_{\mathrm{thr}}} = 2.86\ \mathrm{GeV}$$



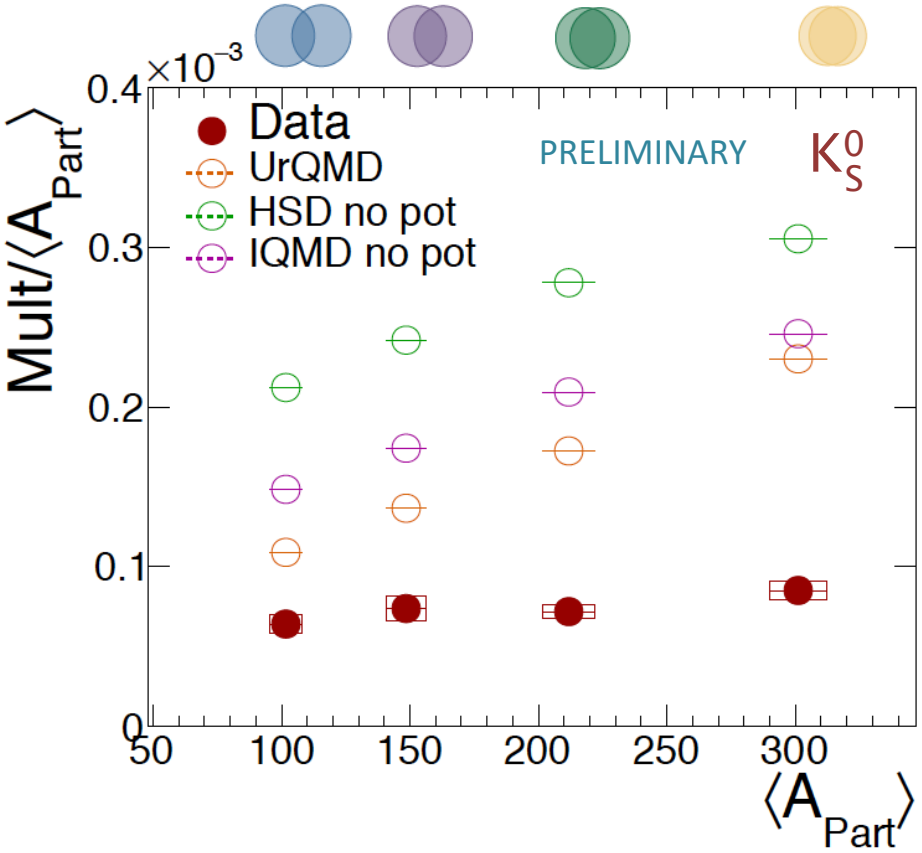
Data compilation: Prog.Part.Nucl.Phys. 66 (2011) 834-879

- All strange hadrons produced below/close to NN-thresholds
- Steep excitation function at low energies
- Lower production yield of K^- (two orders of magnitude w.r.t. K^+)

Microscopic Description

K^0_S Production Compared to Transport Model Calculations

Au+Au@1.23*A* GeV



- State-of-the-art transport model calculations overestimate yield and $<A_{part}>$ dependence is not reproduced

HSD v711n: Phys rep, 308:65–233, January 1999
IQMD c8: Eur.Phys.J.,A1:151–169, 1998
UrQMD 3.4: Prog.Part.Nucl.Phys., 41:255–369, 1998

Microscopic Description

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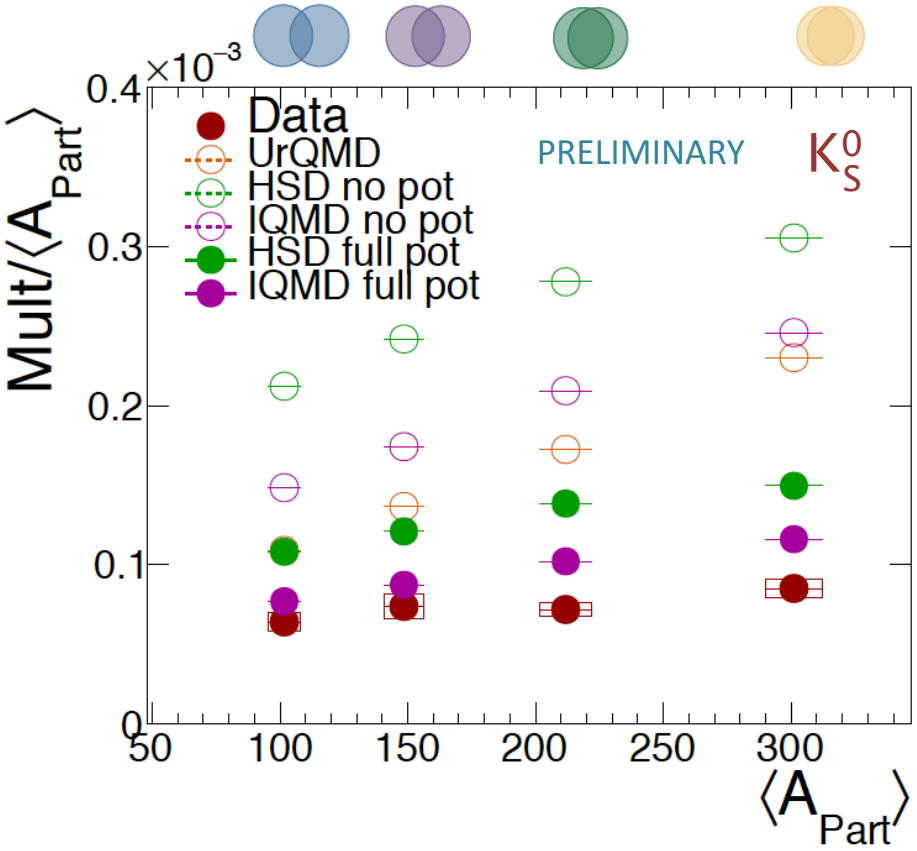


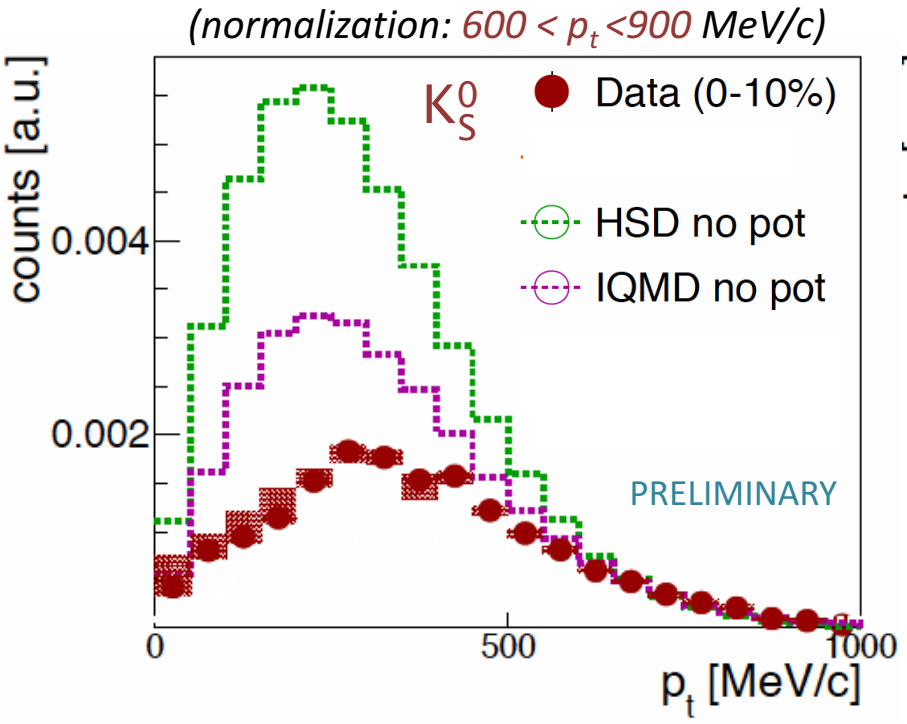
- Inclusion of repulsive KN potential reduces yield and $<A_{part}>$ dependence

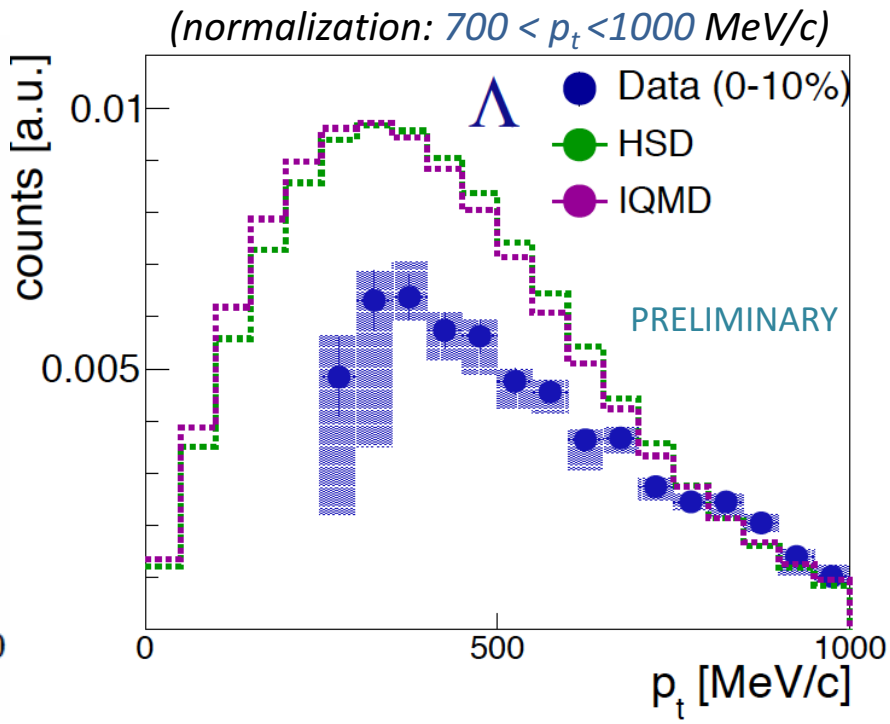
HSD v711n: Phys rep, 308:65–233, January 1999
IQMD c8: Eur.Phys.J.,A1:151–169, 1998
UrQMD 3.4: Prog.Part.Nucl.Phys., 41:255–369, 1998

Microscopic Description

P_t Distribution of K^0_S and Λ Compared to Transport Model Calculations

Au+Au@1.23*A* GeV





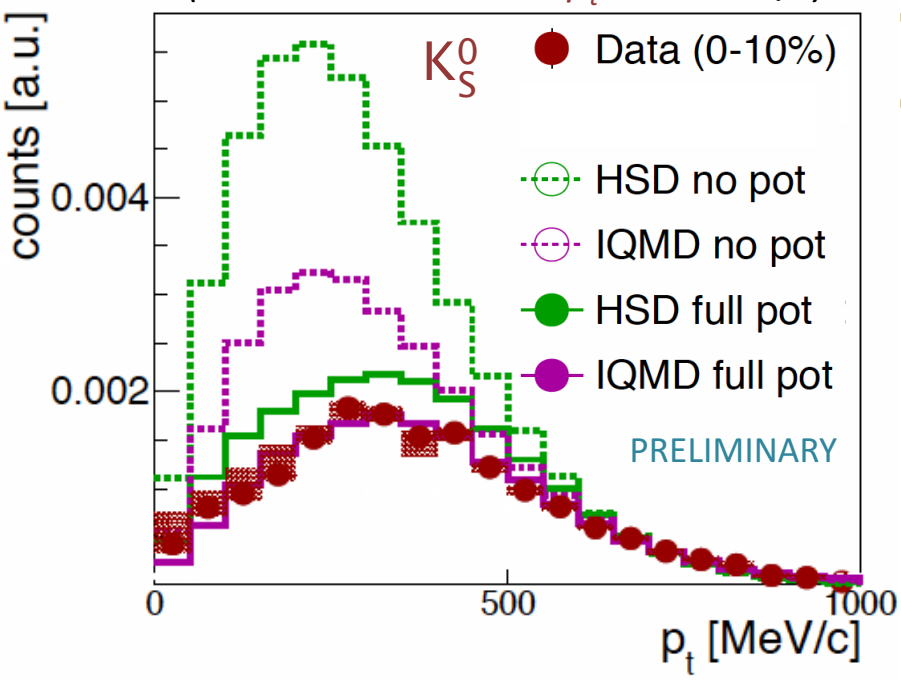
- Models w/o potential do not match low p_t

Microscopic Description

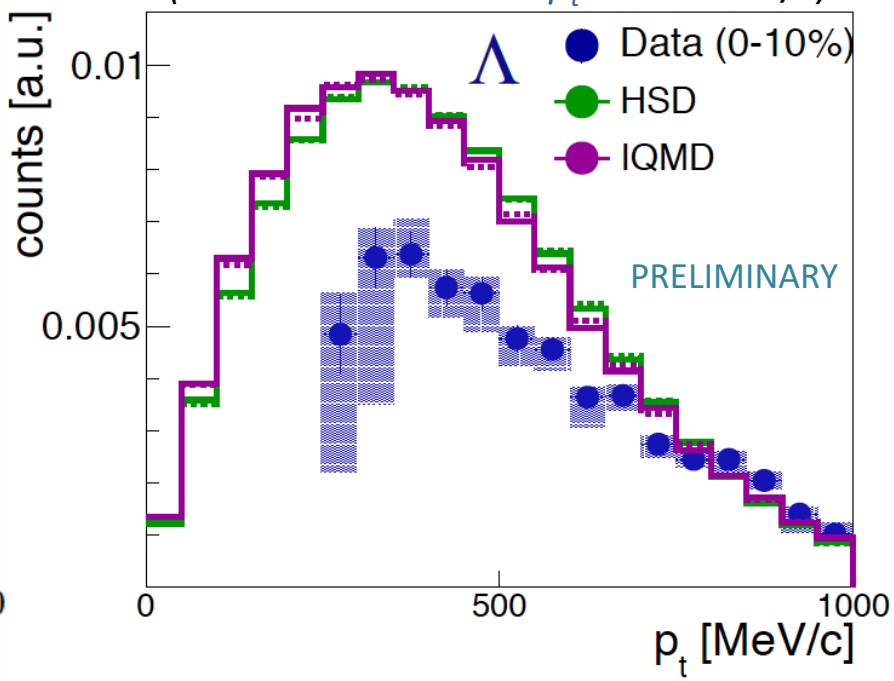
P_t Distribution of K^0_S and Λ Compared to Transport Model Calculations

Au+Au@1.23*A* GeV

(normalization: 600 < p_t <900 MeV/c)



(normalization: 700 < p_t <1000 MeV/c)



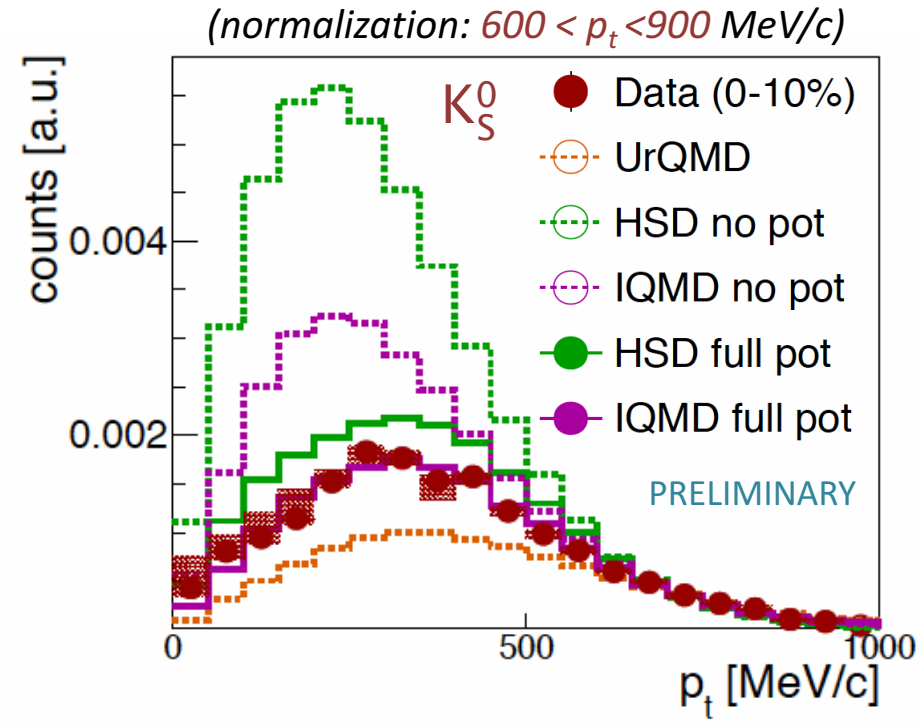
- Models w/o potential do not match low p_t
- Better description of kaon spectra with KN potential (no effect for Λ)

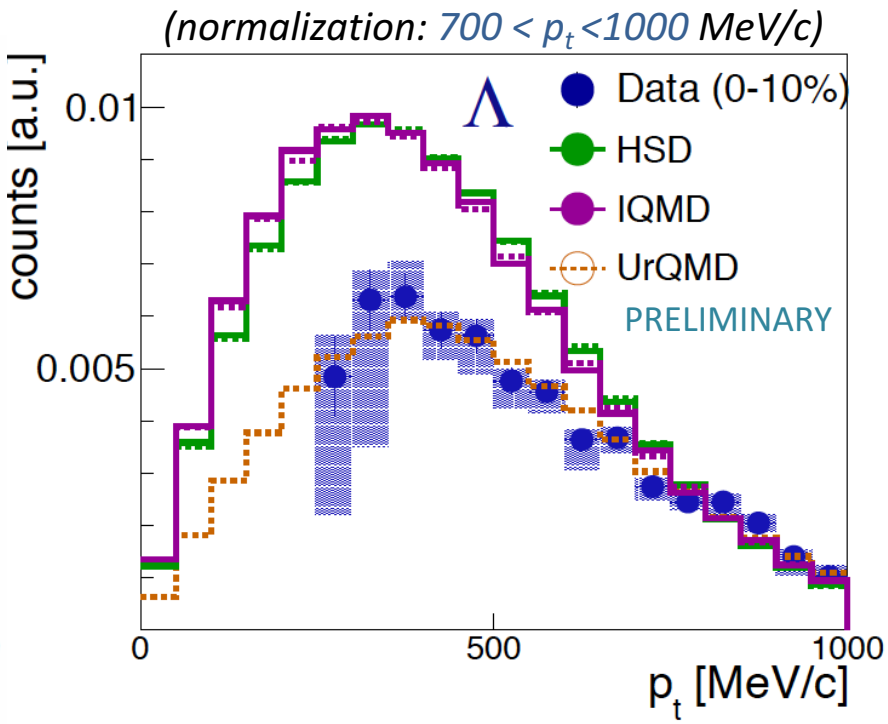
Microscopic Description

P_t Distribution of K^0_S and Λ Compared to Transport Model Calculations

HADES

Au+Au@1.23*A* GeV

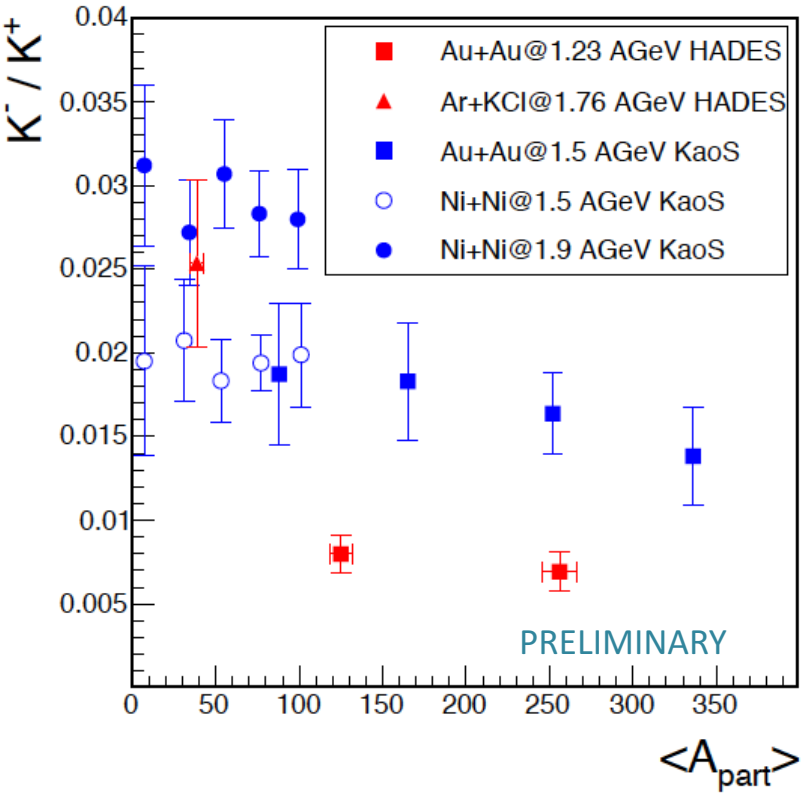




- Models w/o potential do not match low p_t
- Better description of kaon spectra with KN potential (no effect for Λ)
- Λ p_t spectrum best described by UrQMD
- ➢ **No model describes simultaneously kaon and Λ results**

Deep Sub-threshold Strangeness Production

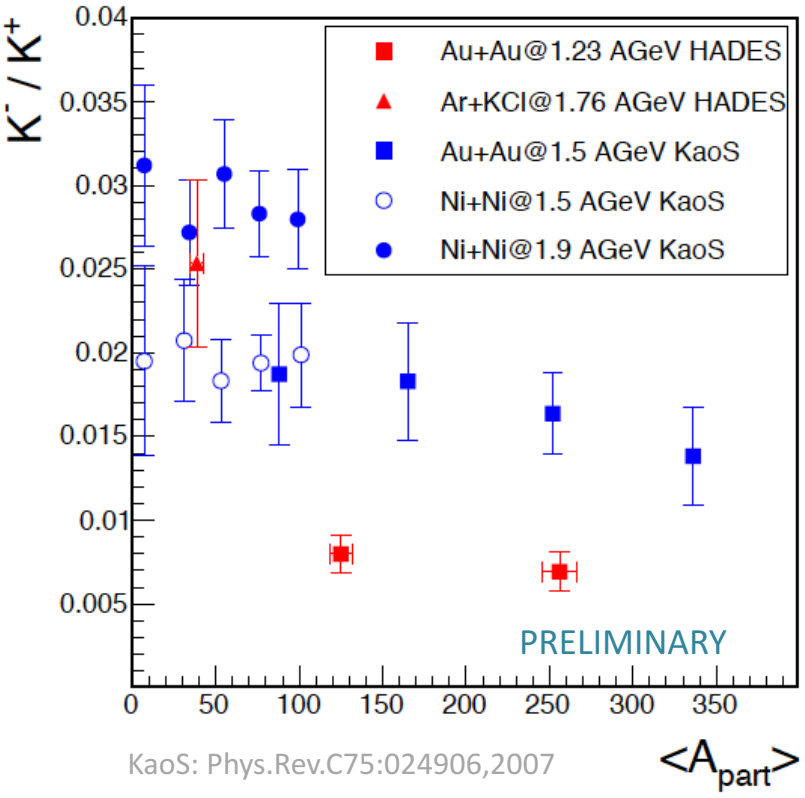
K^- / K^+ Production - Comparison to KaoS



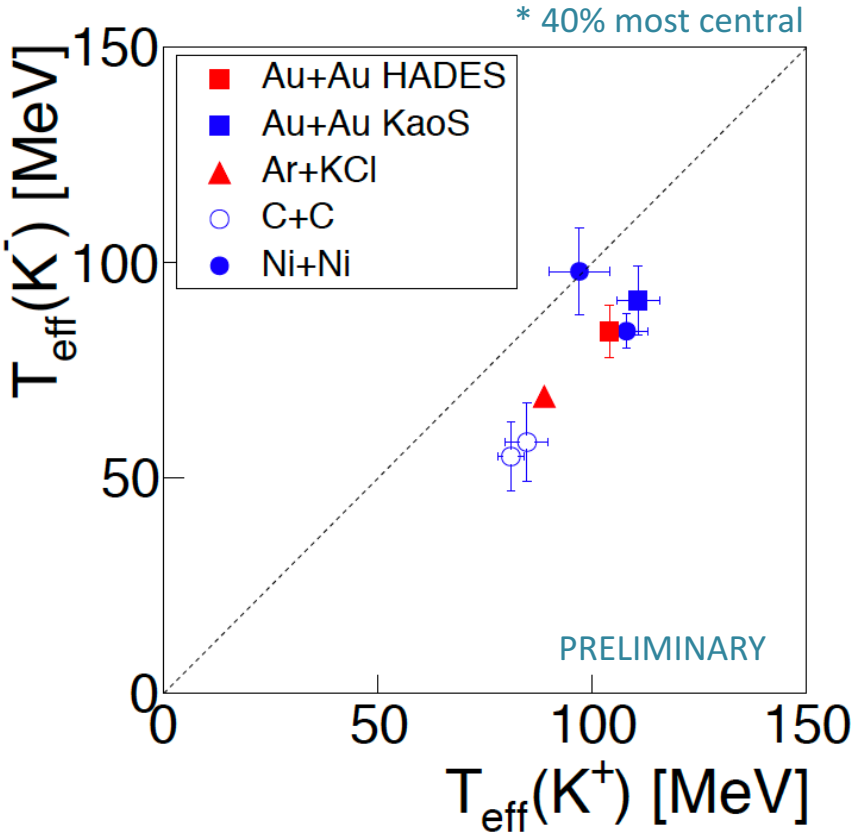
- No strong centrality dependence of K^- / K^+ ratio

Deep Sub-threshold Strangeness Production

K^- / K^+ Production - Comparison to KaoS



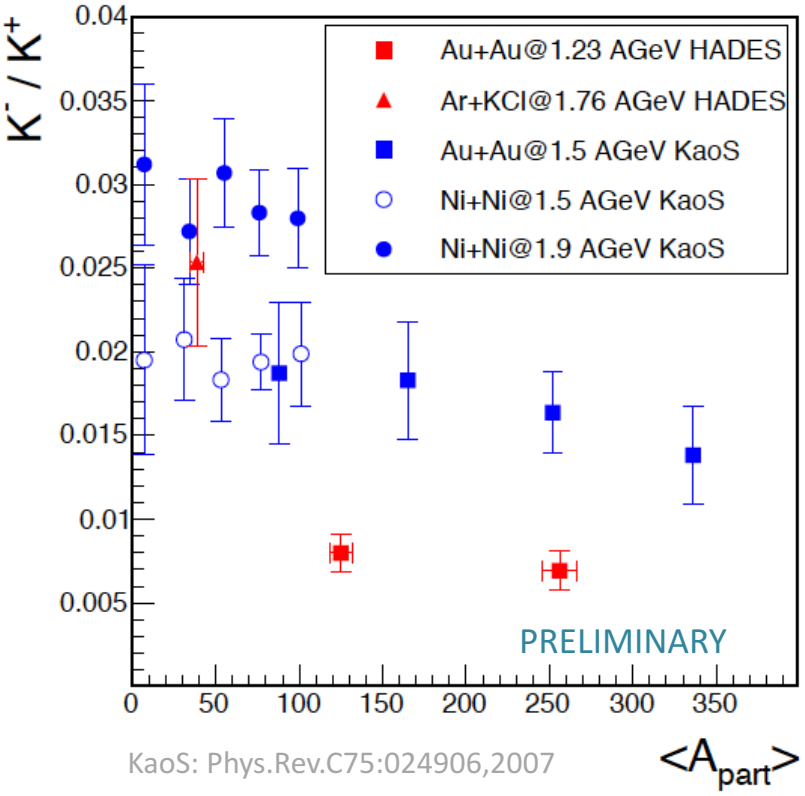
KaoS: Phys.Rev.C75:024906,2007



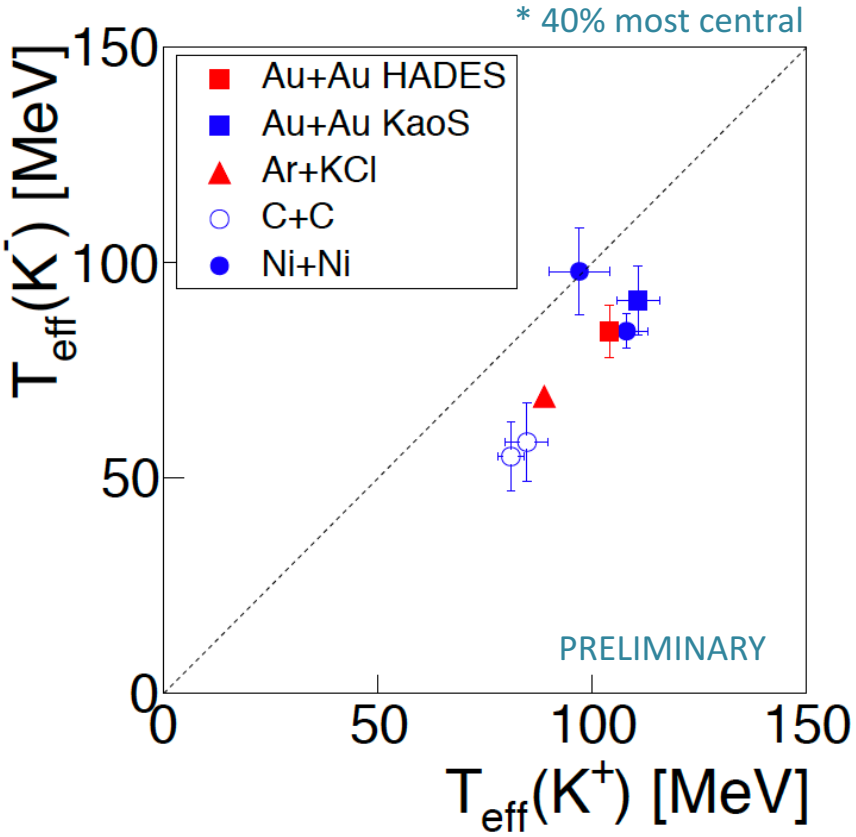
- No strong centrality dependence of K^- / K^+ ratio
- Effective temperature of K^- systematically below K^+

Deep Sub-threshold Strangeness Production

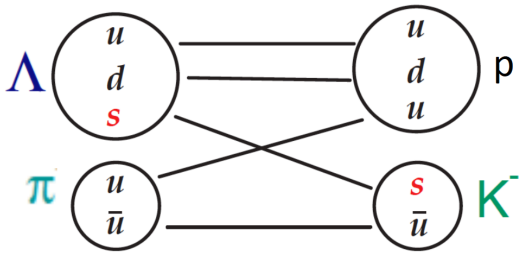
K^- / K^+ Production - Comparison to KaoS



KaoS: Phys.Rev.C75:024906,2007



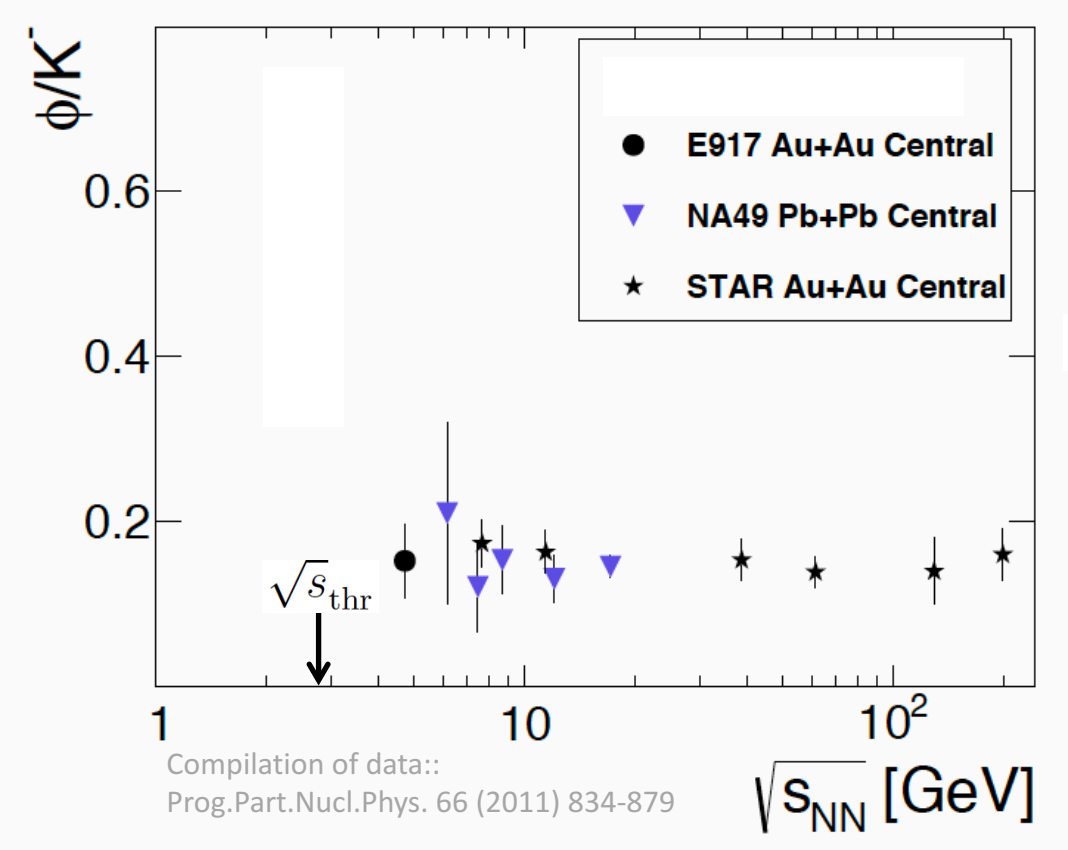
- No strong centrality dependence of K^- / K^+ ratio
- Effective temperature of K^- systematically below K^+
- ➢ *Interpretation: Production coupled via strangeness exchange reaction + later freeze-out of K^-*



Phys.Rept. 510 (2012) 119-200

Deep Sub-threshold Strangeness Production

ϕ Meson as the Game Changer

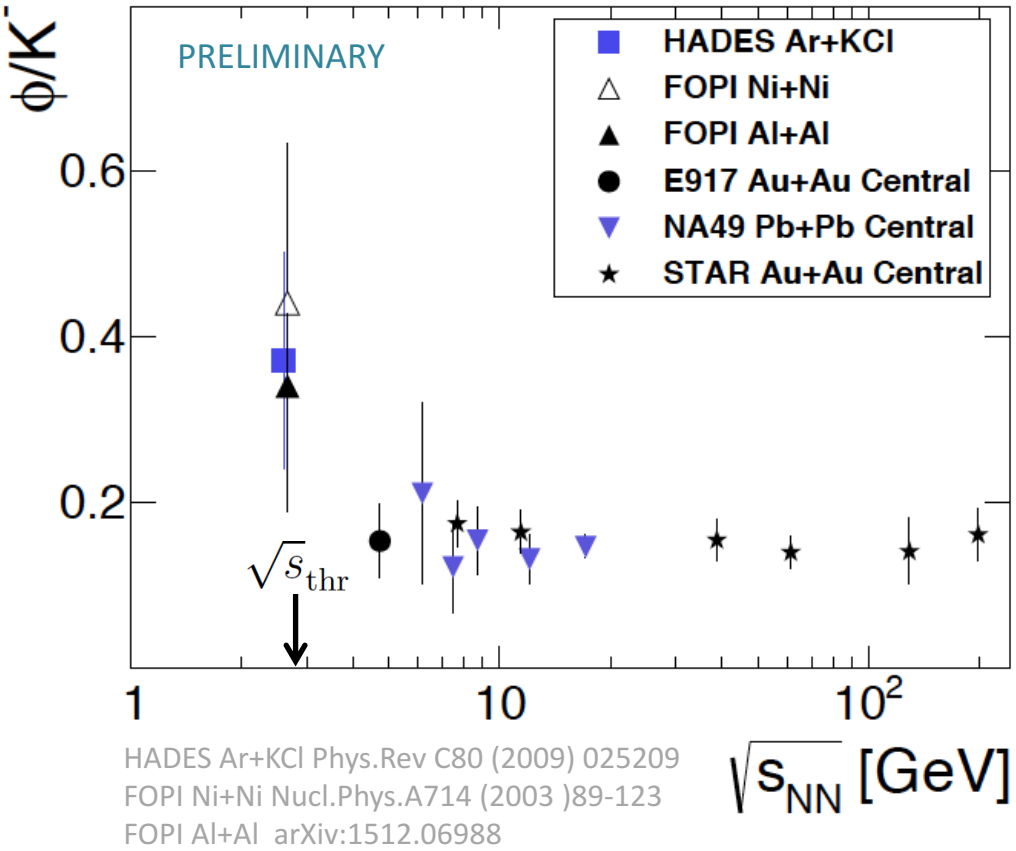


$$NN \rightarrow NN\phi$$
$$\sqrt{s}_{thr} = 2.91 \text{ GeV}$$

- Constant ϕ / K^- ratio at high energies

Deep Sub-threshold Strangeness Production

ϕ Meson as the Game Changer



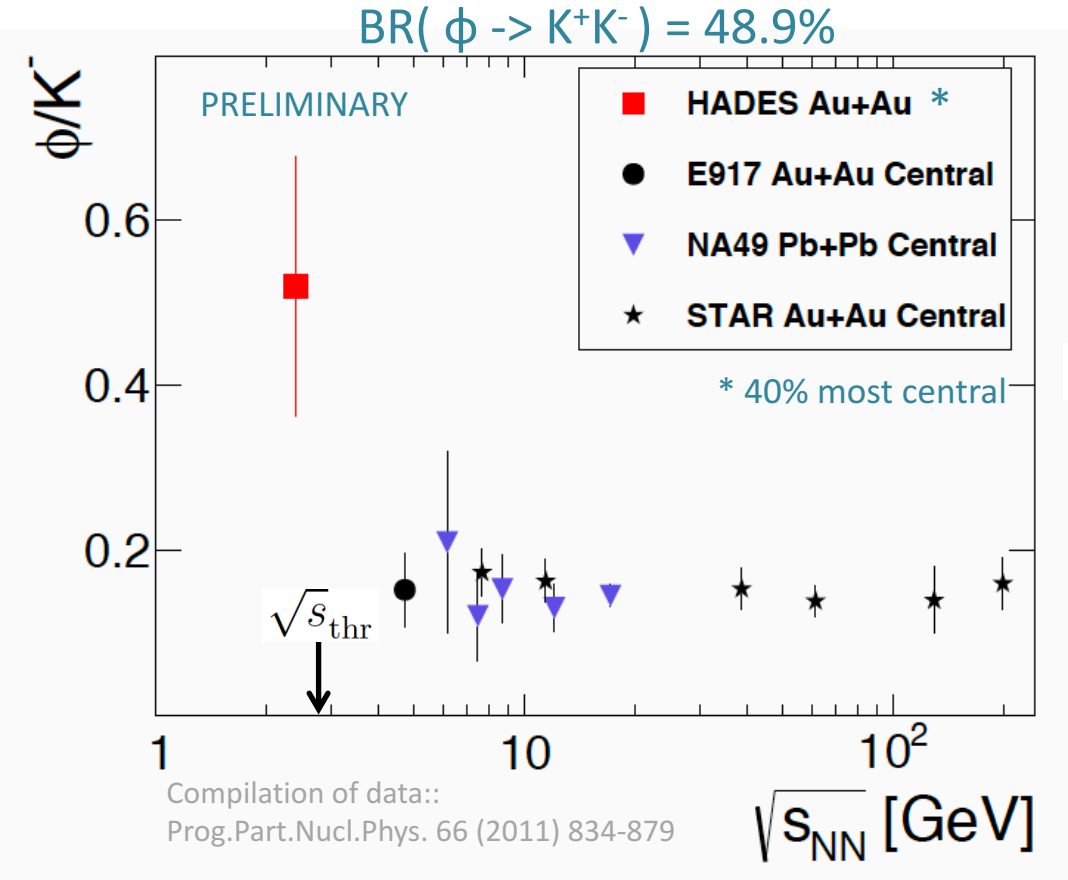
HADES Ar+KCl Phys.Rev C80 (2009) 025209
FOPI Ni+Ni Nucl.Phys.A714 (2003)89-123
FOPI Al+Al arXiv:1512.06988

$$NN \rightarrow NN\phi$$
$$\sqrt{s}_{thr} = 2.91 \text{ GeV}$$

- Enhanced ϕ / K^- ratio at energies below NN-threshold in small systems

Deep Sub-threshold Strangeness Production

ϕ Meson as the Game Changer



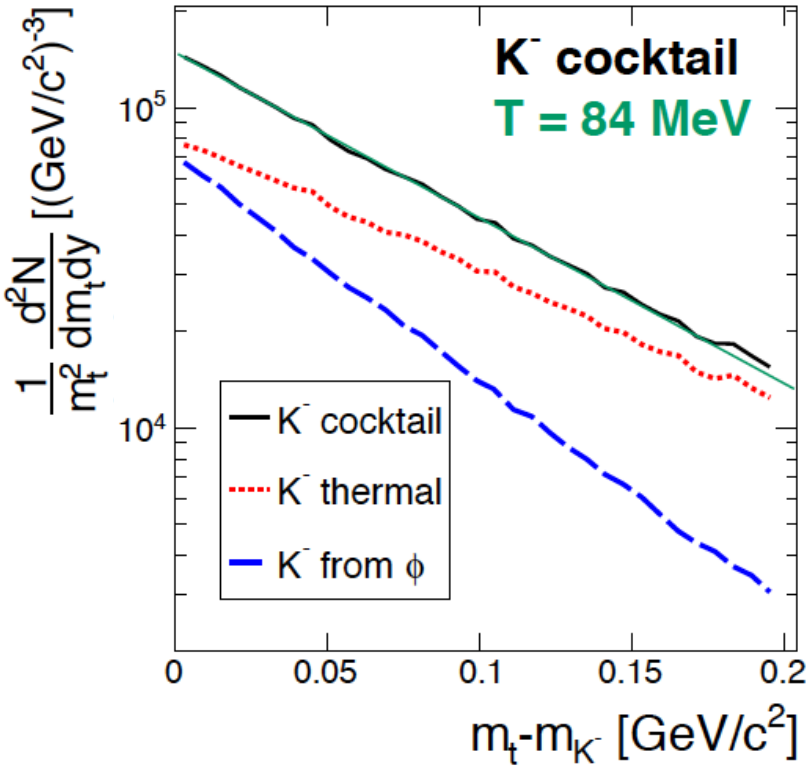
$$NN \rightarrow NN\phi$$
$$\sqrt{s}_{thr} = 2.91 \text{ GeV}$$

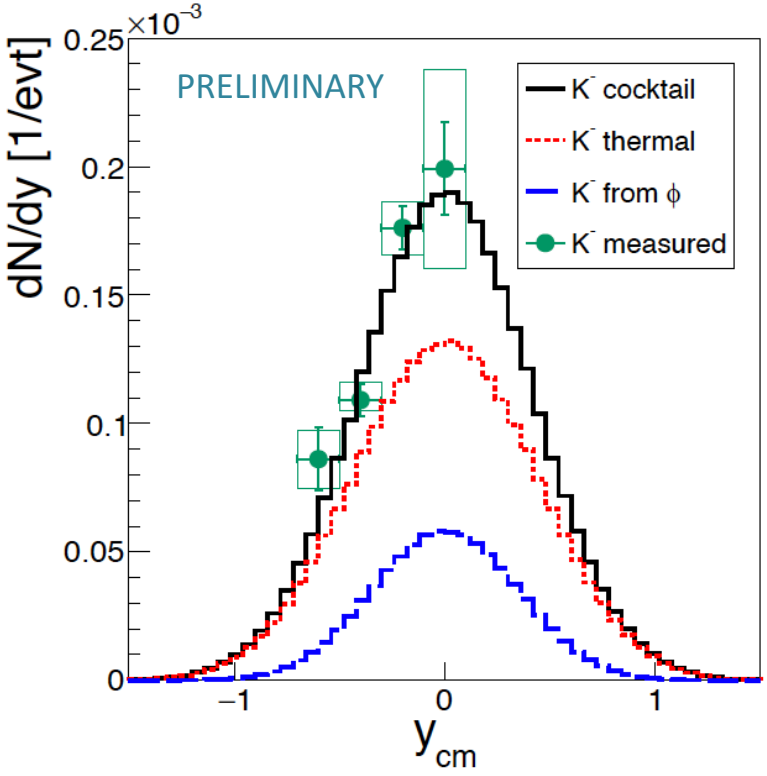
- Au+Au @ $\sqrt{s}$ = 2.41 GeV: **ϕ/K⁻ = 0.52 ± 0.16**
  - ~25% of all measured K⁻ from ϕ feed-down *(and not from s-exchange)*
  - ϕ important source for K⁻ production below NN-threshold

Deep Sub-threshold Strangeness Production

ϕ Mesons as Source of K⁻

Au+Au@1.23*A* GeV



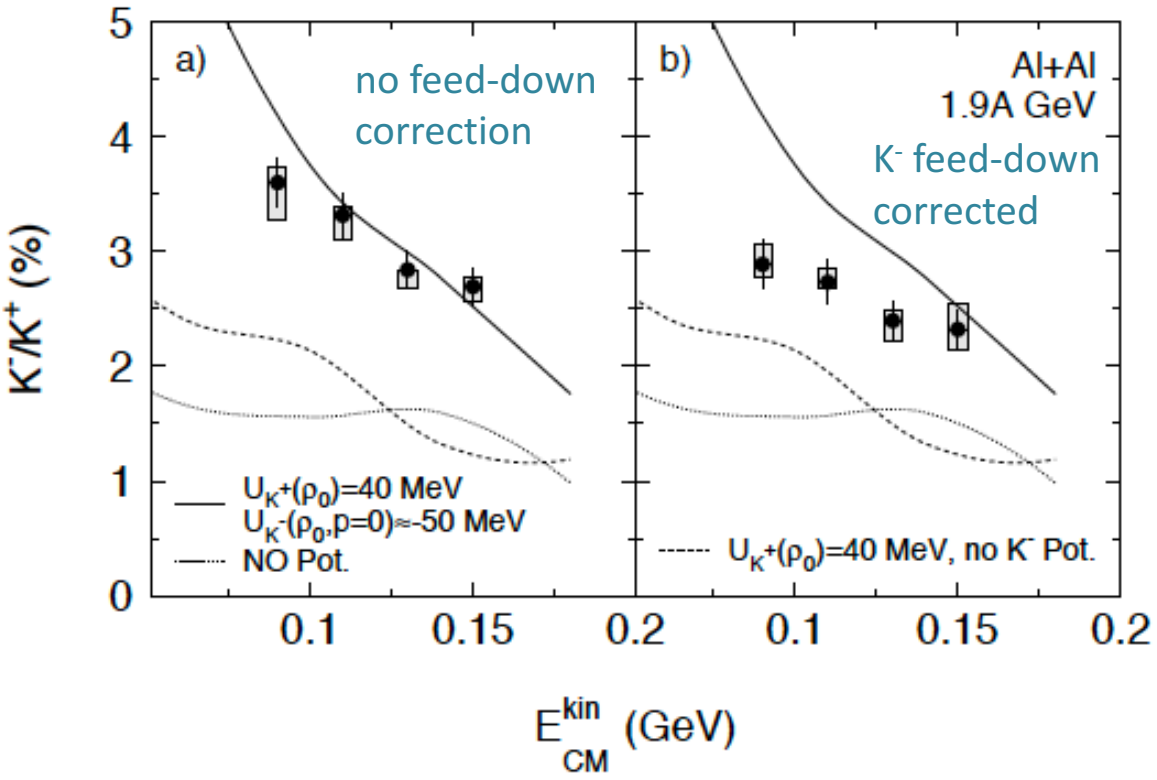


- Feed-down contribution from **ϕ decays** can explain lower inverse slope parameter of K^- *T(K^-) = 84 ± 6 MeV* in comparison to K^+ *T(K+)= 104 ± 2 MeV*
- Measured rapidity distribution reproduced by cocktail
- **No indication for sequential kaon freeze-out**

Deep Sub-threshold Strangeness Production

ϕ Mesons as Source of K^-

FOPI: Eur.Phys.J. A52 (2016) no.6, 177

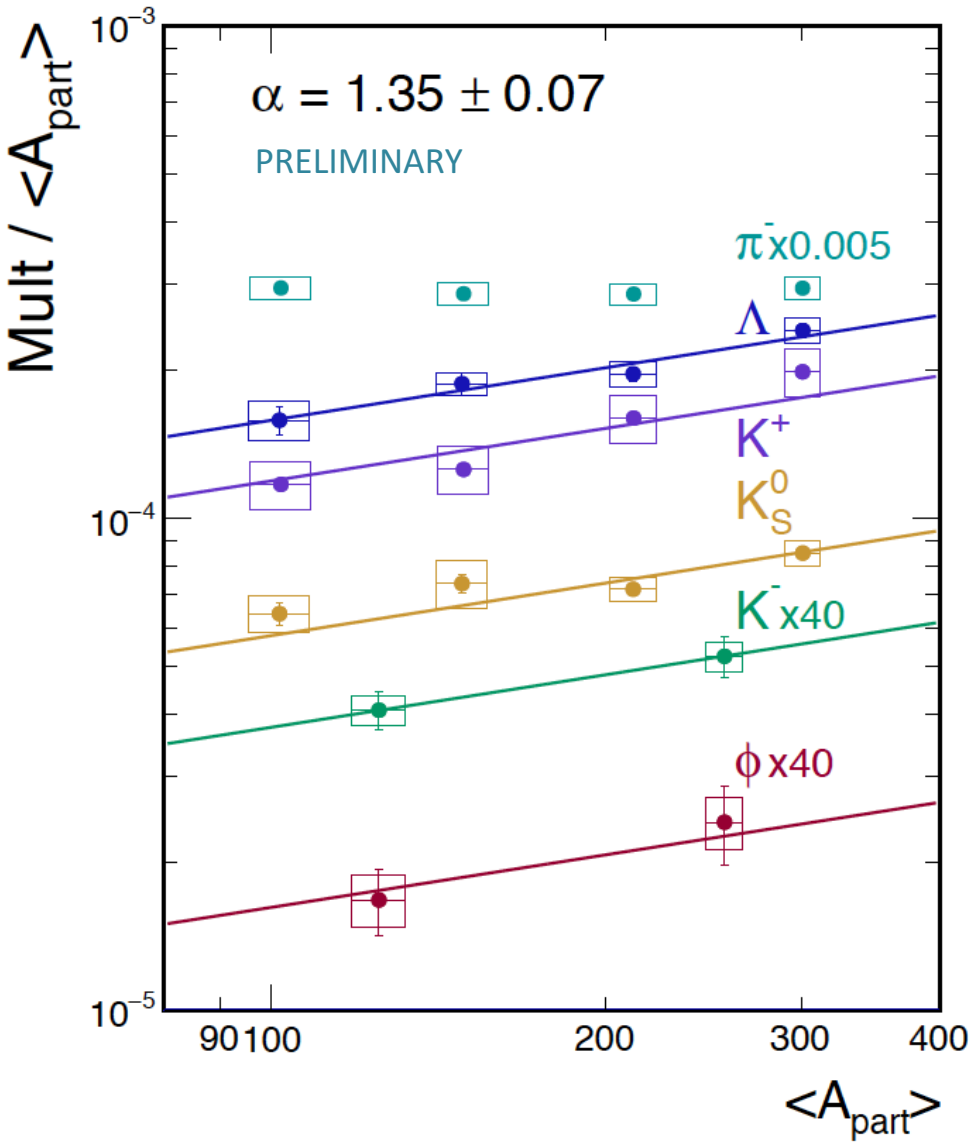


- Feed-down contribution from ϕ decays changes conclusion on kaon potential

Strangeness Production: The Global Picture

<A_{part}> Dependence of Multiplicities

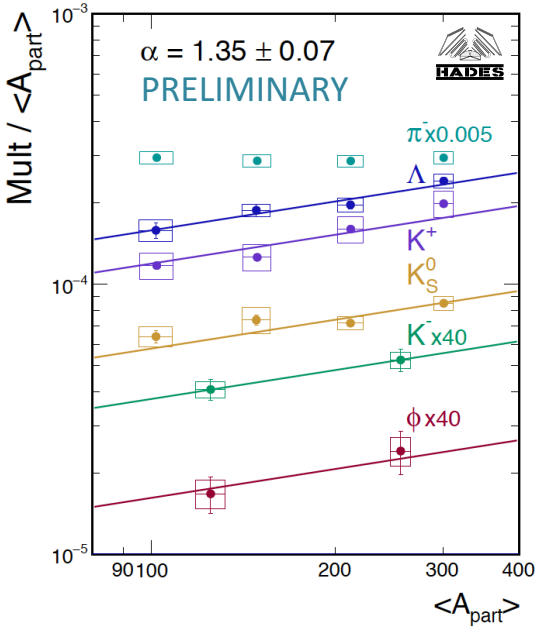
HADES
Au+Au@1.23*A* GeV

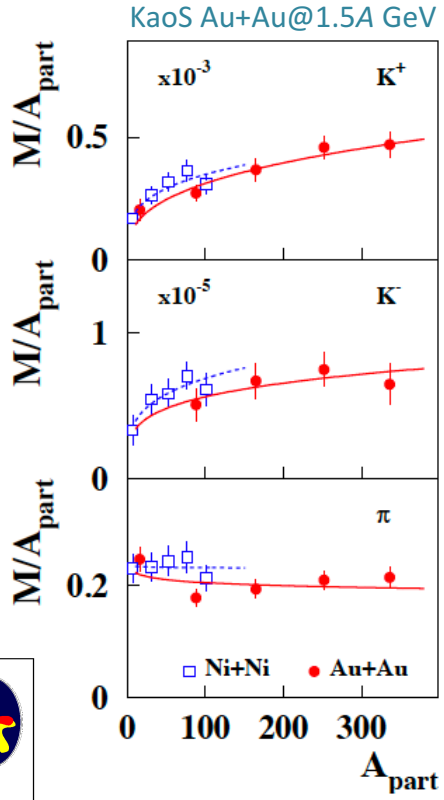


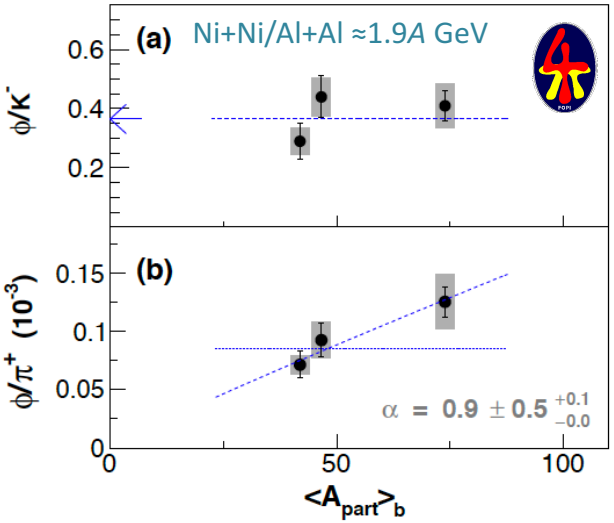
- Same dependence on number of participating nucleons: $Mult \sim \langle A_{part} \rangle^{\alpha}$: $\alpha = 1.35 \pm 0.07$
- Not expected from different NN-thresholds

Strangeness Production: The Global Picture

<A_{part}> Dependence of Multiplicities







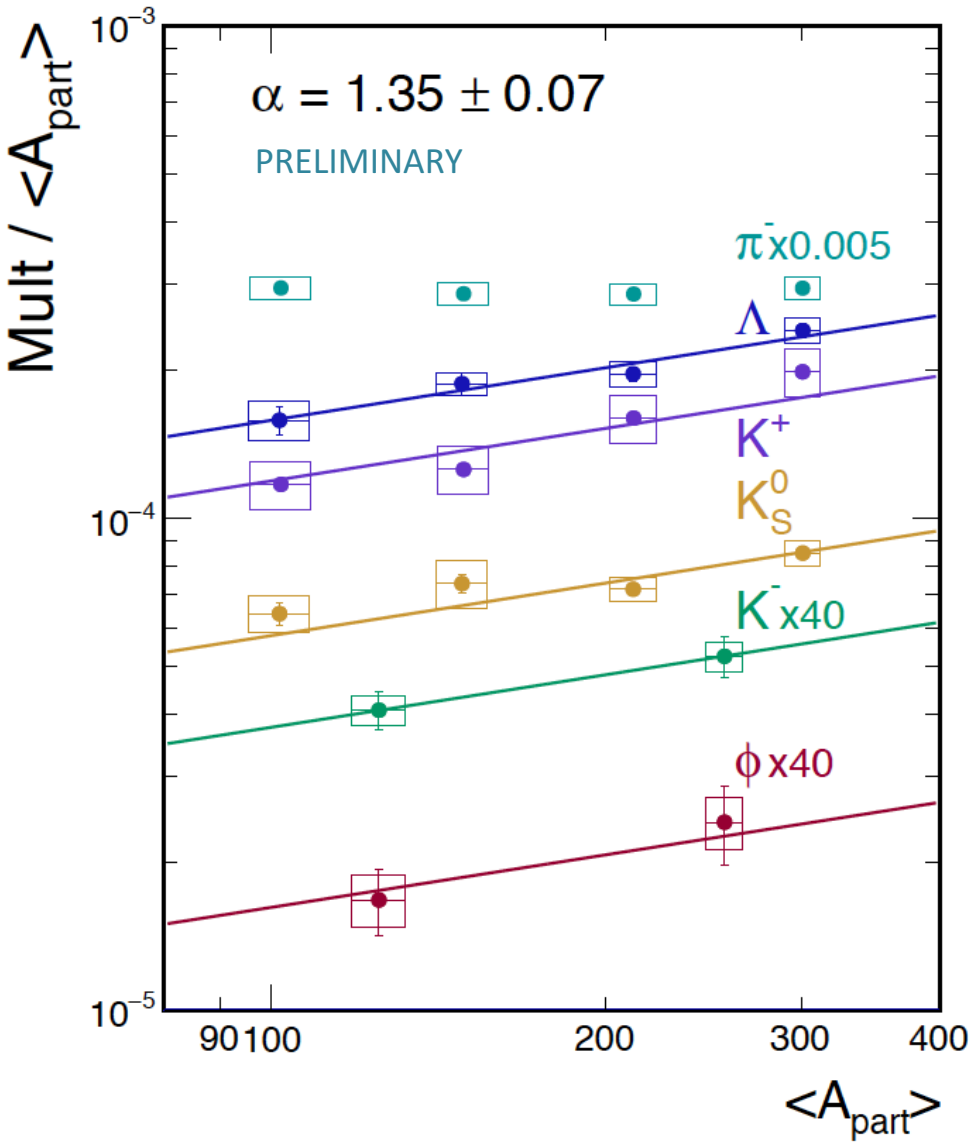
- Same dependence on number of participating nucleons: $Mult \sim \langle A_{part} \rangle^{\alpha}$: $\alpha = 1.35 \pm 0.07$
- Not expected from different NN-thresholds
- Same observation at higher energies and smaller collision systems (α_{K+}=1.34 ± 0.16, α_{K-}=1.22 ± 0.27, constant ϕ/K^-)

KaoS: Phys.Rev.C75:024906,2007
FOPI: Phys.Rev.C94 (2016) no.1, 014901

Strangeness Production: The Global Picture

<A_{part}> Dependence of Multiplicities

HADES
Au+Au@1.23*A* GeV

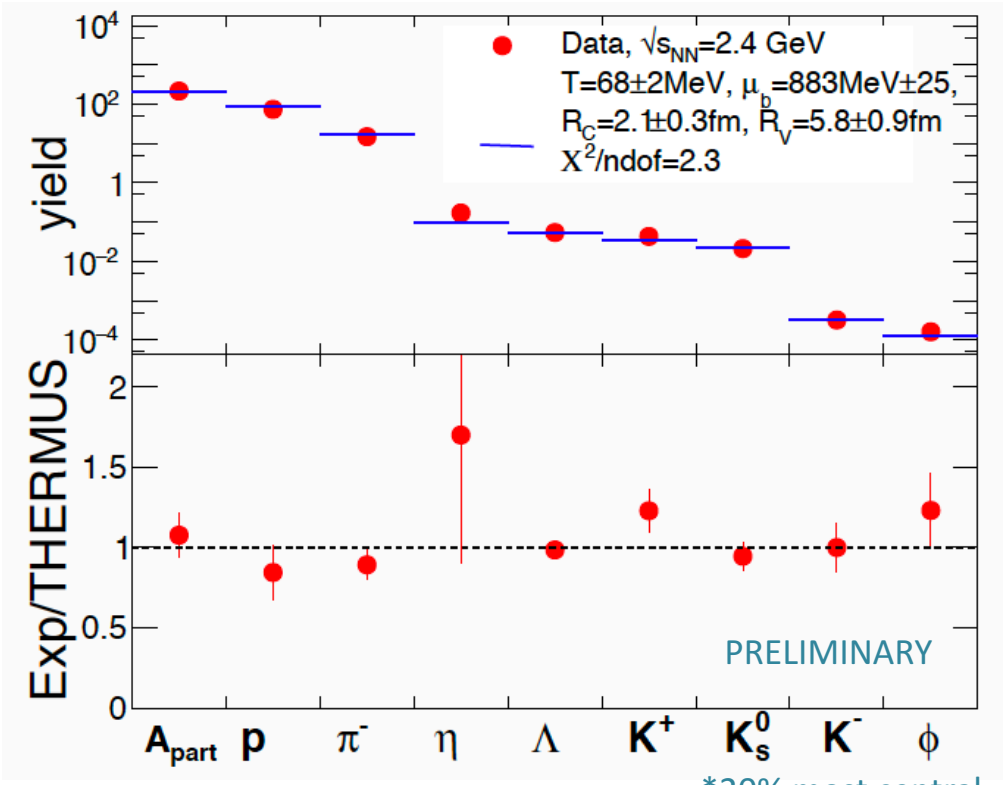


- Same dependence on number of participating nucleons: *$Mult \sim \langle A_{part} \rangle^{\alpha}$: $\alpha = 1.35 \pm 0.07$*
- Not expected from different NN-thresholds
- ➢ Universal centrality dependence of strangeness production
- *Can system be treated macroscopically?*

Chemical Freeze-Out

Statistical Hadronization Model

Au+Au@1.23*A* GeV



*20% most central

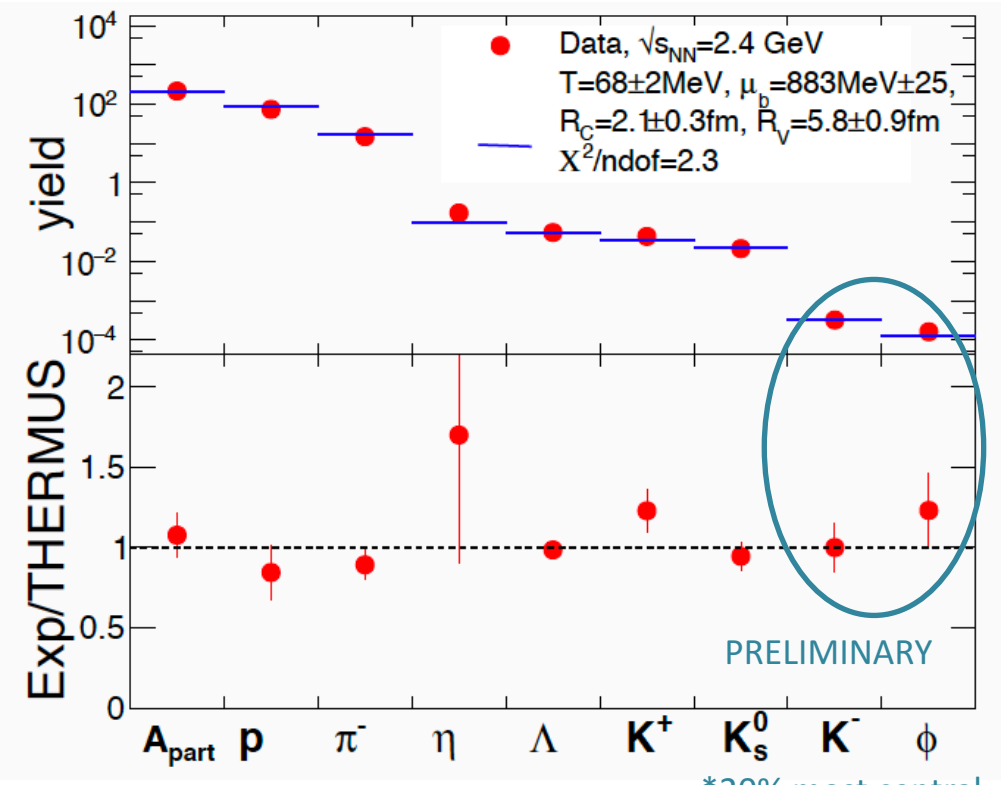
- Hadron yields well described by SHM with global parameters: T, μ_B, R_V, R_C

THERMUS v2.3
Comput. Phys.Commun.180:84-106, 2009

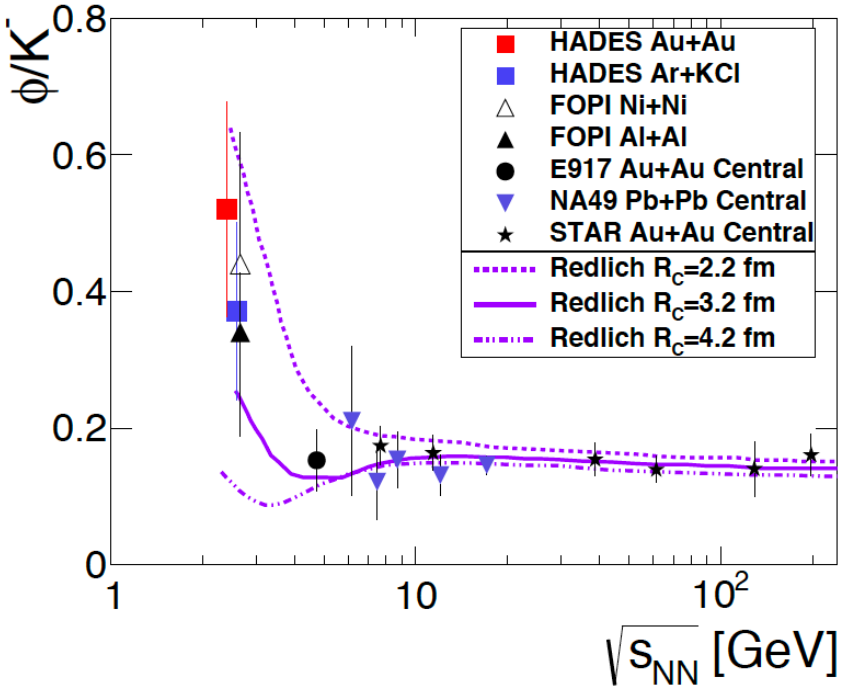
Chemical Freeze-Out

Statistical Hadronization Model

Au+Au@1.23*A* GeV



*20% most central



* 40% most central

- Hadron yields well described by SHM with global parameters: T, μ_B, R_V, R_C
- Strangeness canonically suppressed ➤ ϕ / K^- ratio

THERMUS v2.3
Comput. Phys.Commun.180:84-106, 2009

Chemical Freeze-Out

Statistical Hadronization Model

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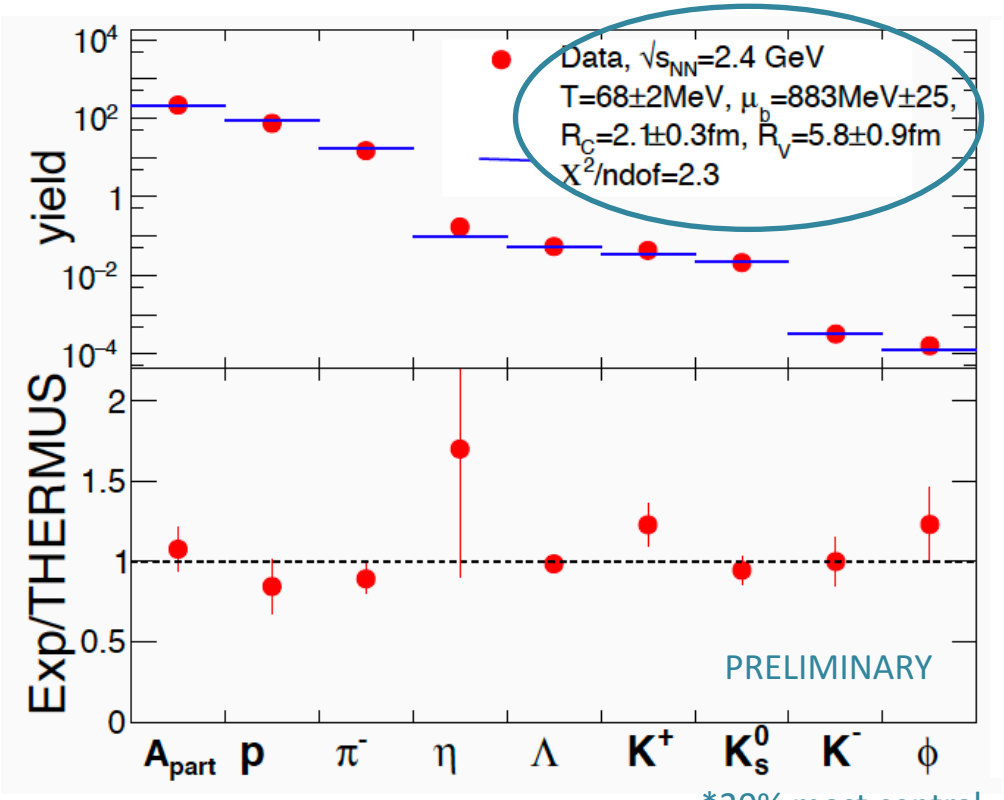
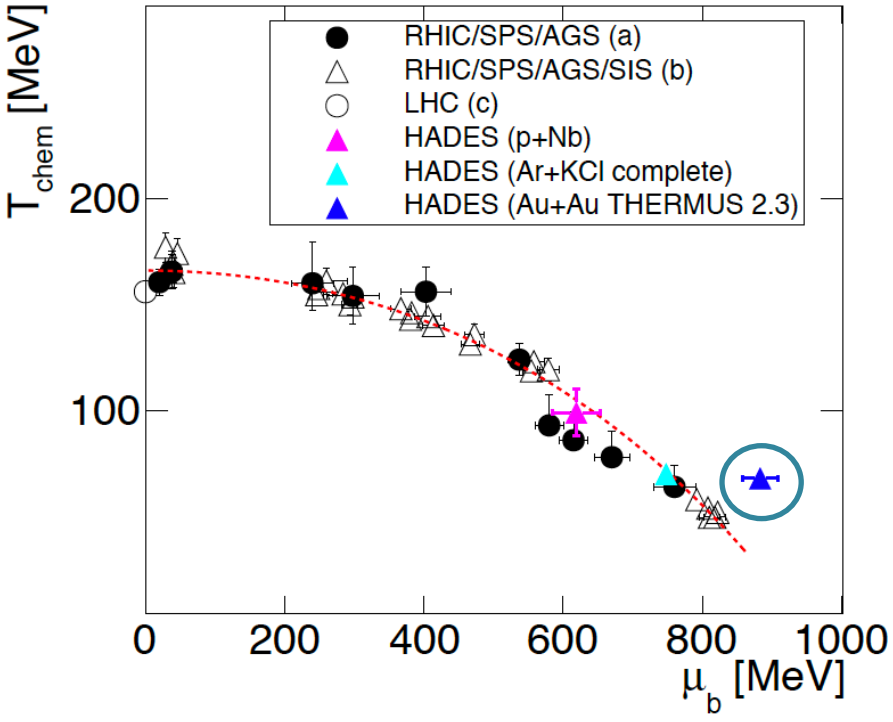
Au+Au@1.23*A* GeV



*20% most central

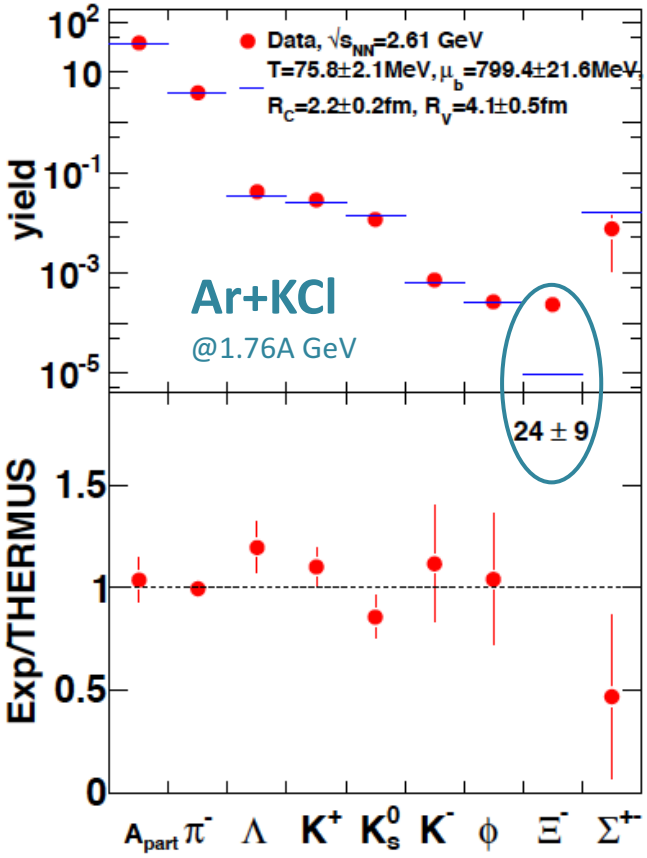


- Hadron yields well described by SHM with global parameters: T, μ_B, R, R_C
- Strangeness canonically suppressed
  - ϕ / K^- ratio
- T, μ_B higher than expected
  - More particle species included
- Radius lower than expected
  - Eigenvolumes

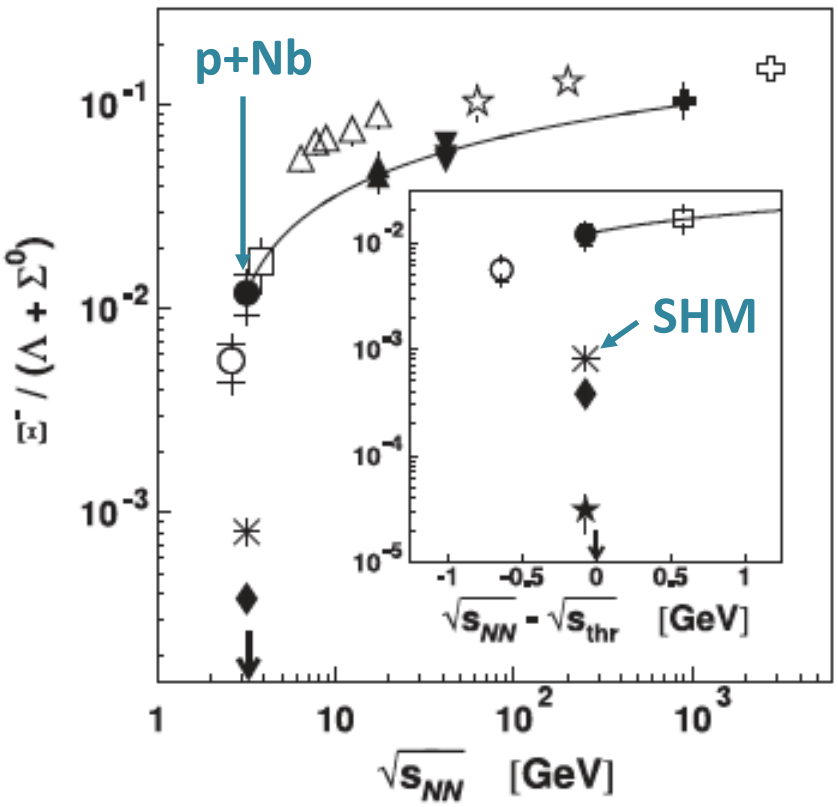
Cascade Production Puzzle

Xi⁻ Enhancement

Eur.Phys.J. A47 (2011) 21



PRL 114 (2015) 212301



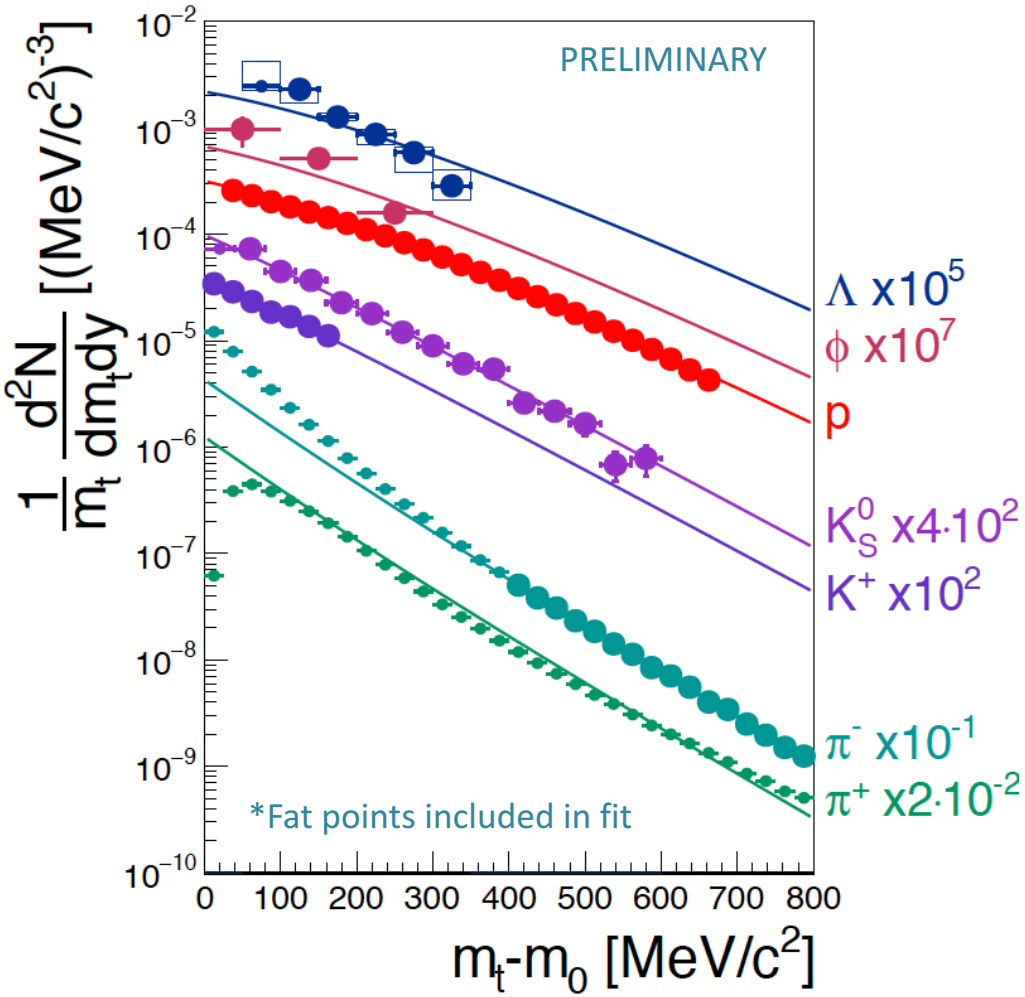
- Strong excess of Ξ^-
- Already present in cold nuclear matter

Kinetic Freeze-Out

Simultaneous Blast Wave Fit

HADES

Au+Au@1.23*A* GeV



*0-10% most central, sys err on diff count rate 5%

φ: 0-20% most central, sys err on diff. count rate 10%

Phys.Rev. C 48, 2462

- Blast wave model:

$$\frac{dN}{p_T\,dp_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{\rm kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{\rm kin}}\right)$$

Linear flow velocity profile:

$$\beta = \beta_S (r/R)^n$$
$$n = 1$$

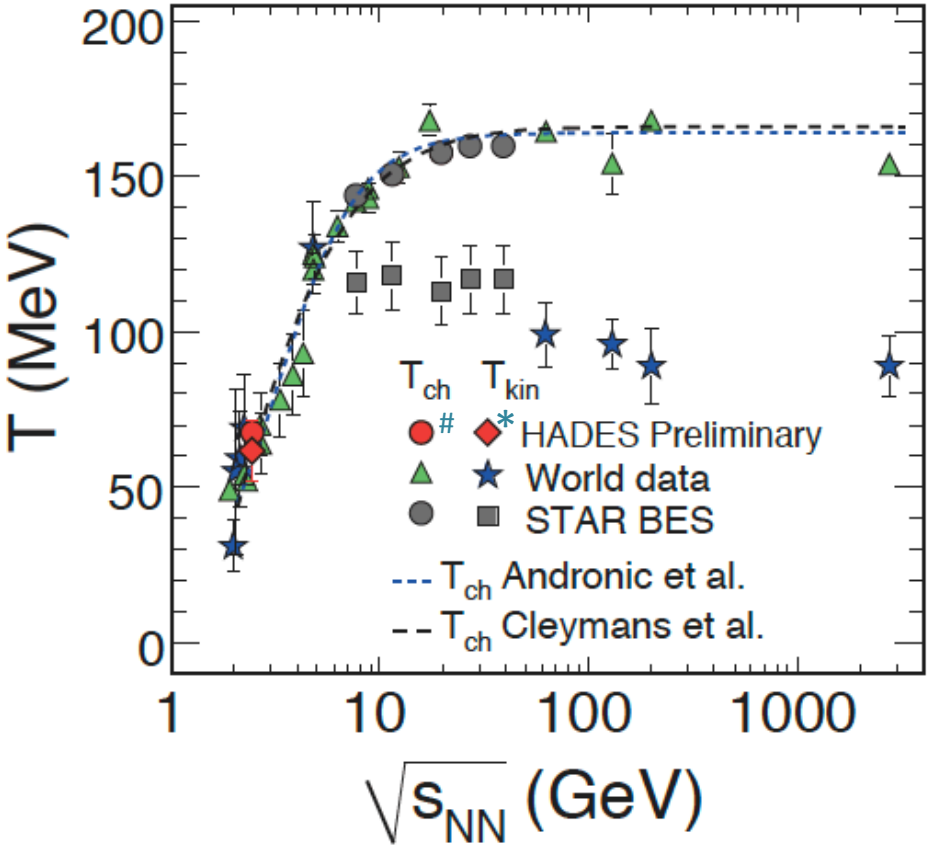
- Proton, Kaon and Pion spectra well described by simultaneous blast wave fit with global parameters:

$$T_{kin} = 62 \pm 10 \text{ MeV}$$
$$\langle \beta_r \rangle = 0.36 \pm 0.04$$

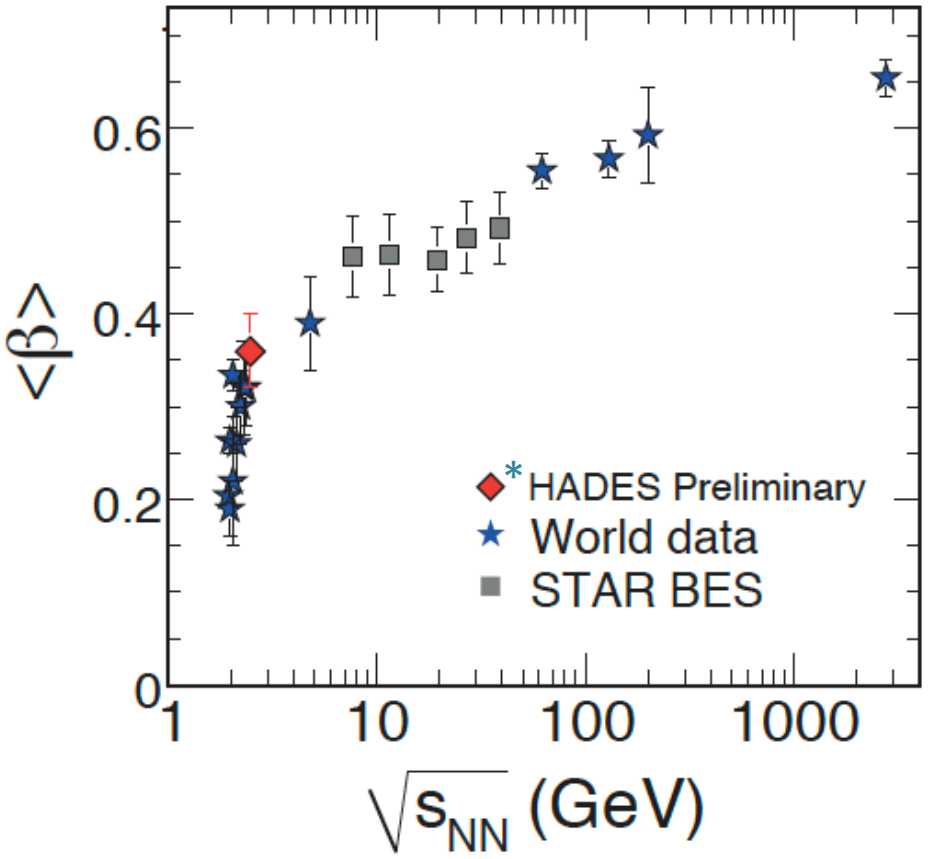
Freeze-Out Parameter

Comparison to World Data

#0-20% most central
*0-10% most central



STAR arXiv:1701.07065, 2016



- Global freeze-out parameters fit well into trend of world data

Summary

Microscopic description:

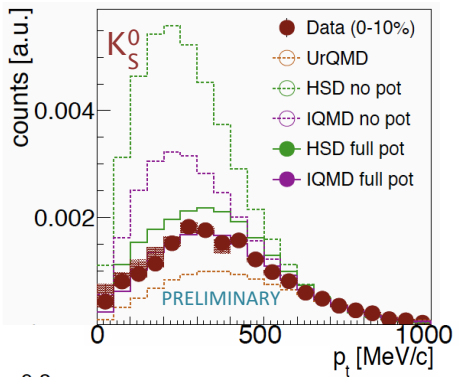
- Kaon spectra best described by IQMD with potential, however, does not describe Λ spectra
- ➢ No model describes all particle species simultaneously

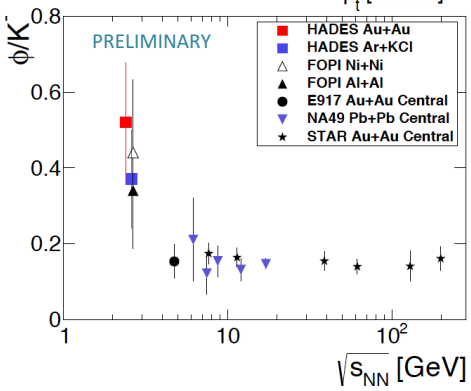
Deep sub-threshold strangeness production:

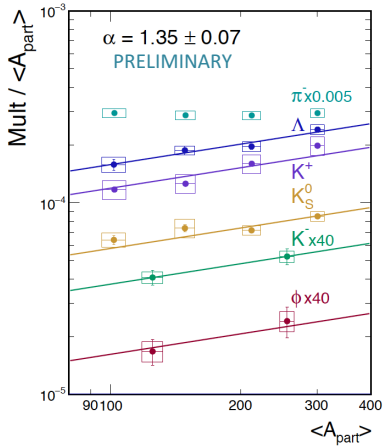
- ϕ sizeable source for K^- production
- Feed-down can explain lower effective temperature and rapidity spectrum of K^-
- ➢ No indication for sequential freeze-out of K^+/K^-

The global picture:

- Universal centrality dependence of strangeness production
- SHM describes particle yields *(except Ξ^-)*



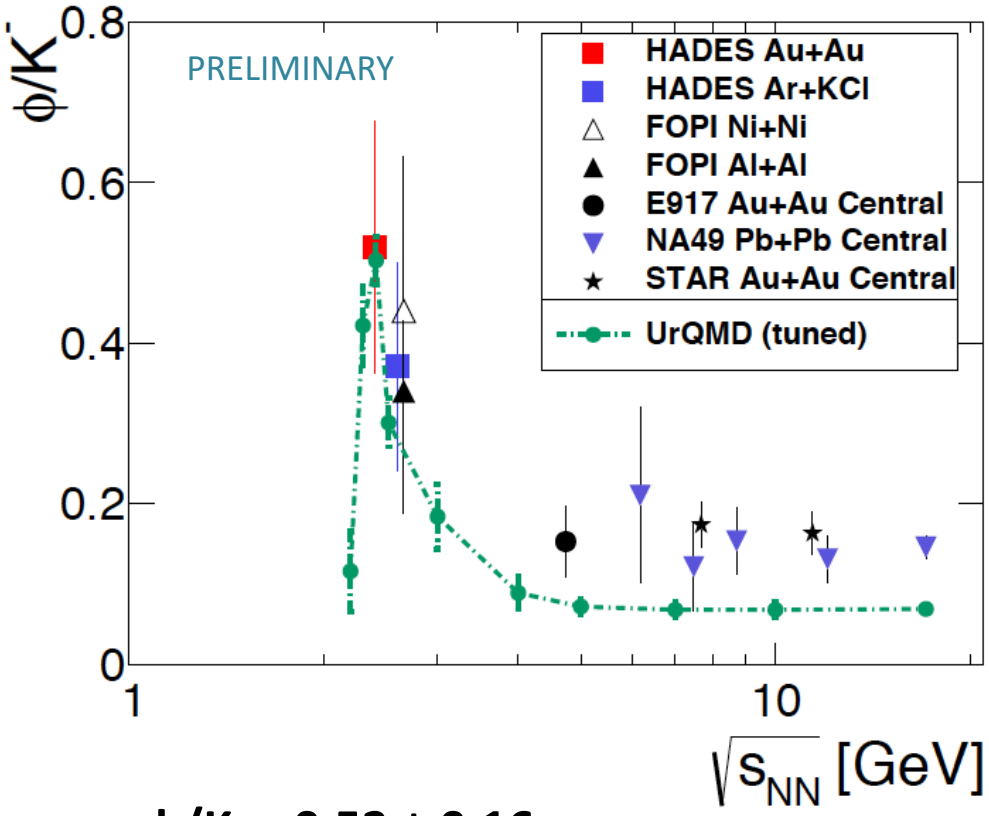


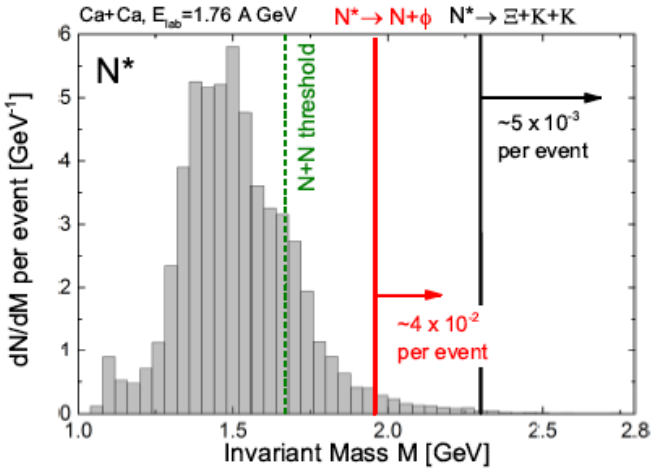


BACKUP

ϕ / K⁻ ratio

Excitation function

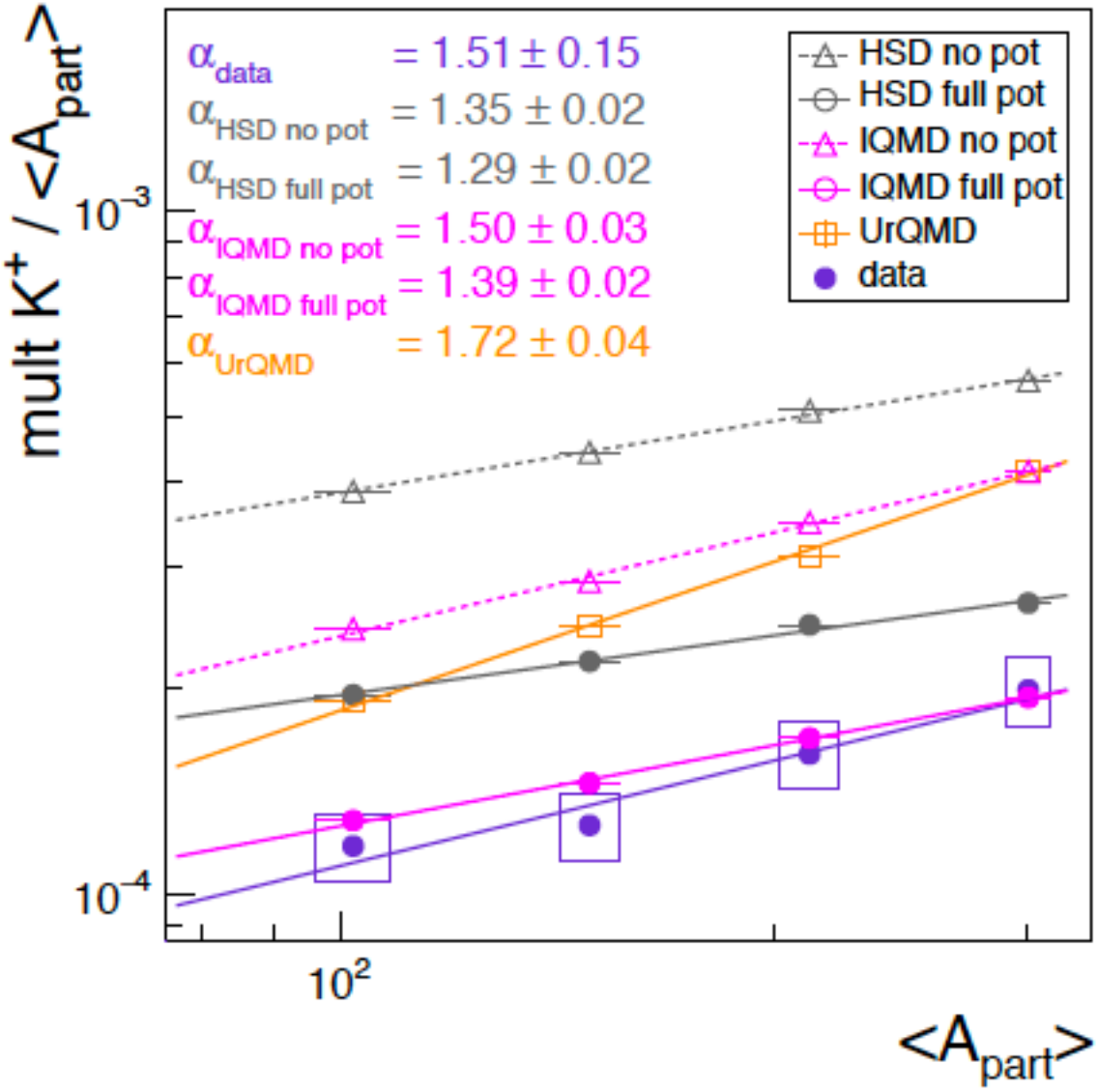




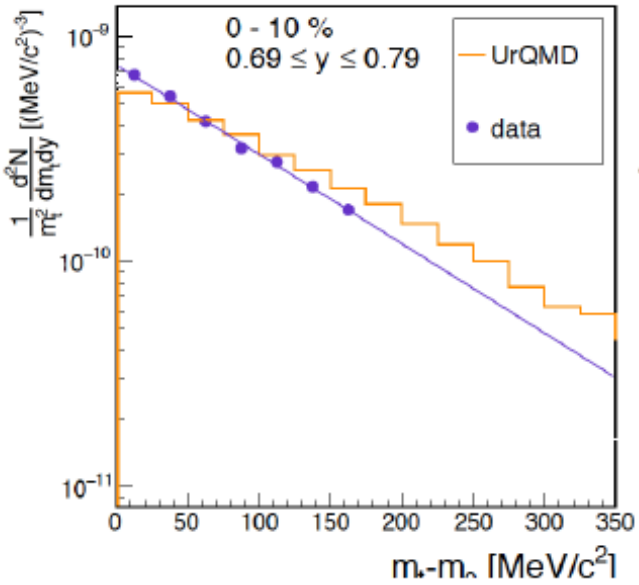
UrQMD tuned: J.Phys. G43 (2016) 1, 015104
HADES Ar+KCl Phys.Rev C80 (2009) 025209
FOPI Ni+Ni Nucl.Phys.A714 (2003)89-123
FOPI Al+Al arXiv:1512.06988
Compilation data higher energies:
Prog.Part.Nucl.Phys. 66 (2011) 834-879

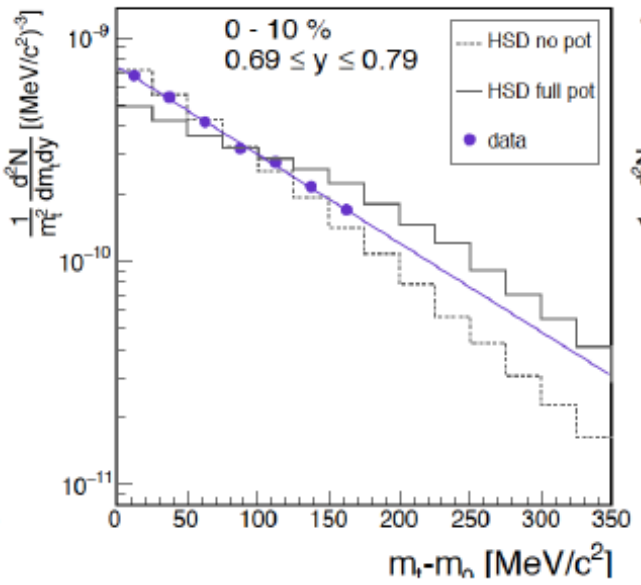
- **ϕ/K⁻ = 0.52 ± 0.16**
- ~26% of all measured K⁻ from ϕ feed-down
- Trend expected from SHM when open strangeness suppressed by R_C
- First transport model to describe data: UrQMD (tuned)when including new decay channels from high mass baryonic resonances

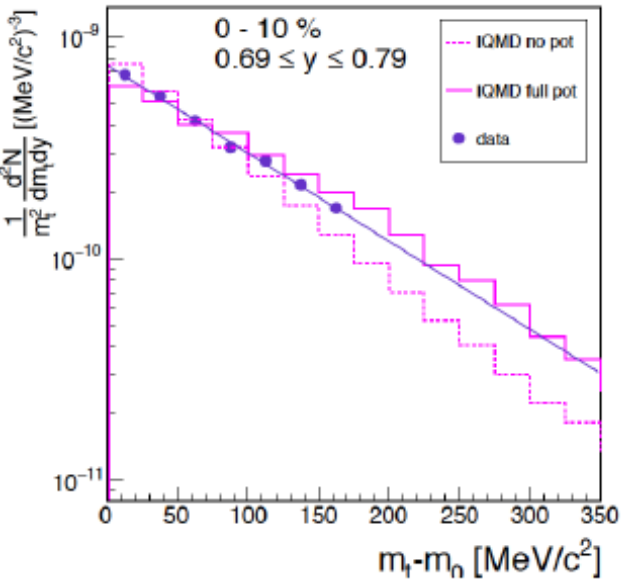
K^+ vs. Transport

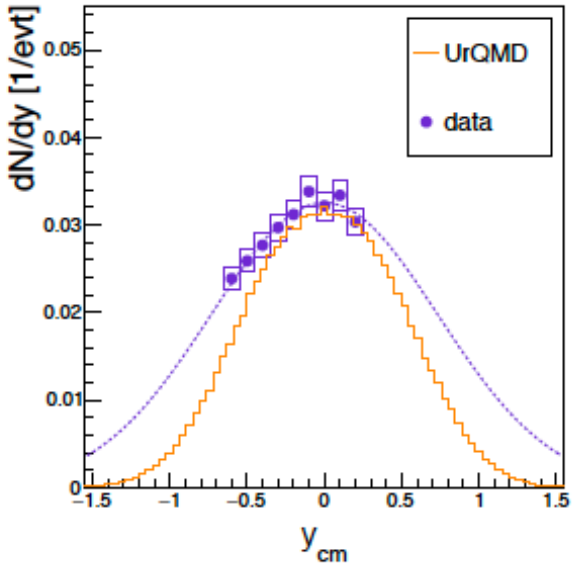


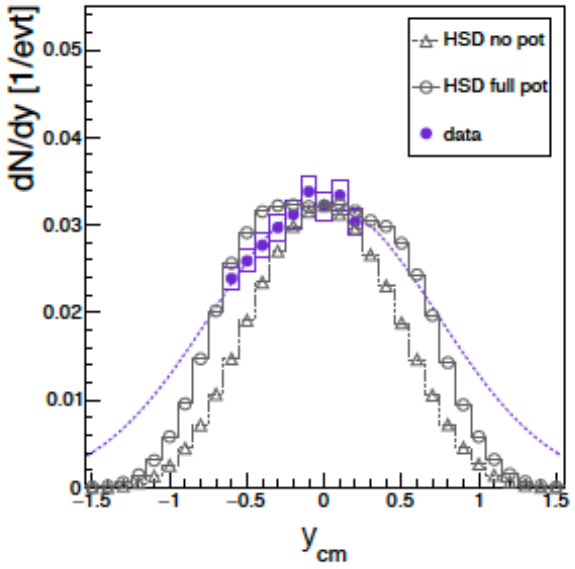
K^+ vs. Transport

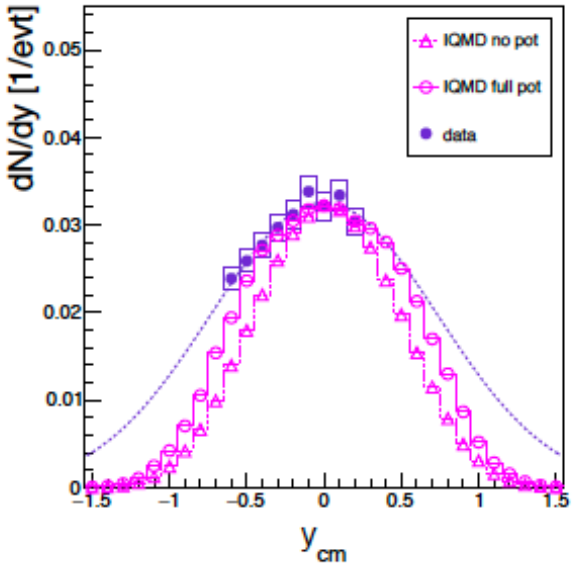






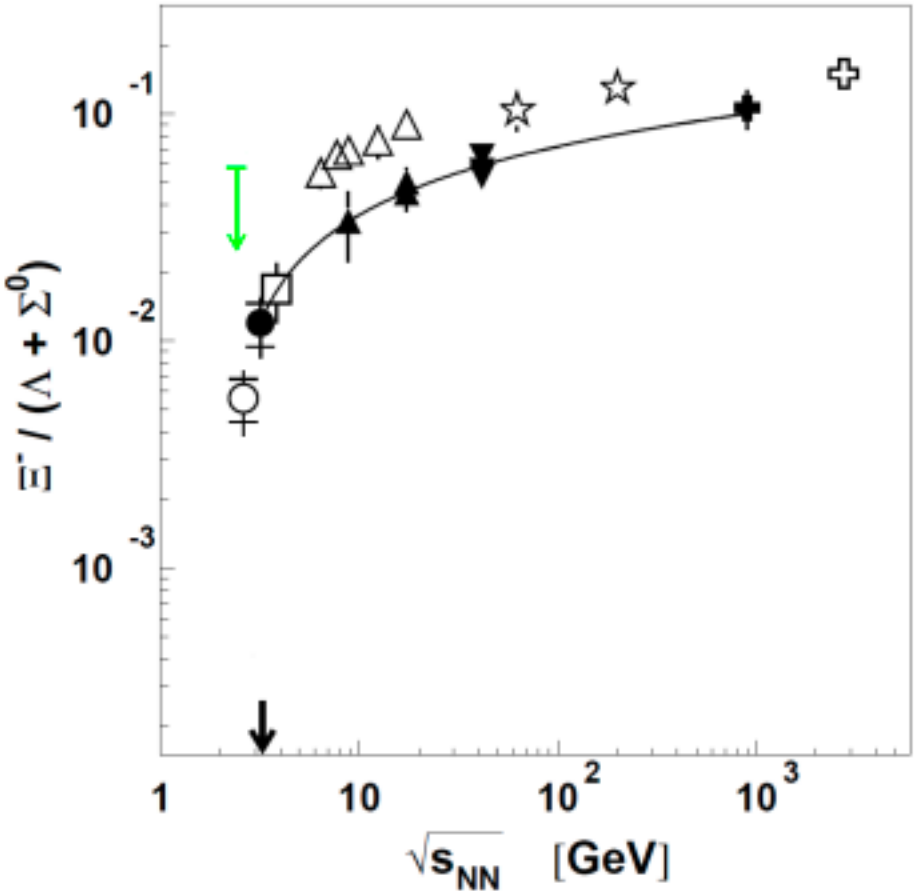






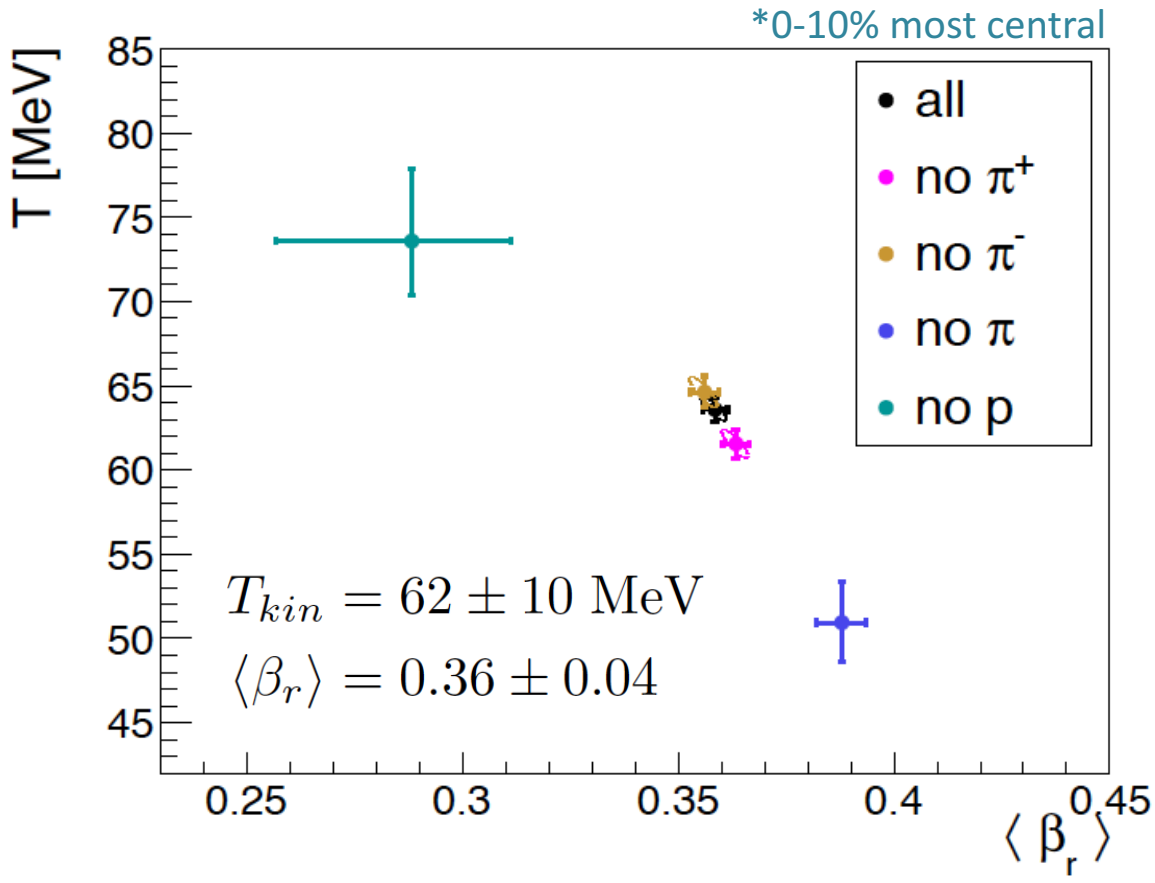
Strangeness Production at SIS Energies

Xi upper limit



Blast Wave Fit

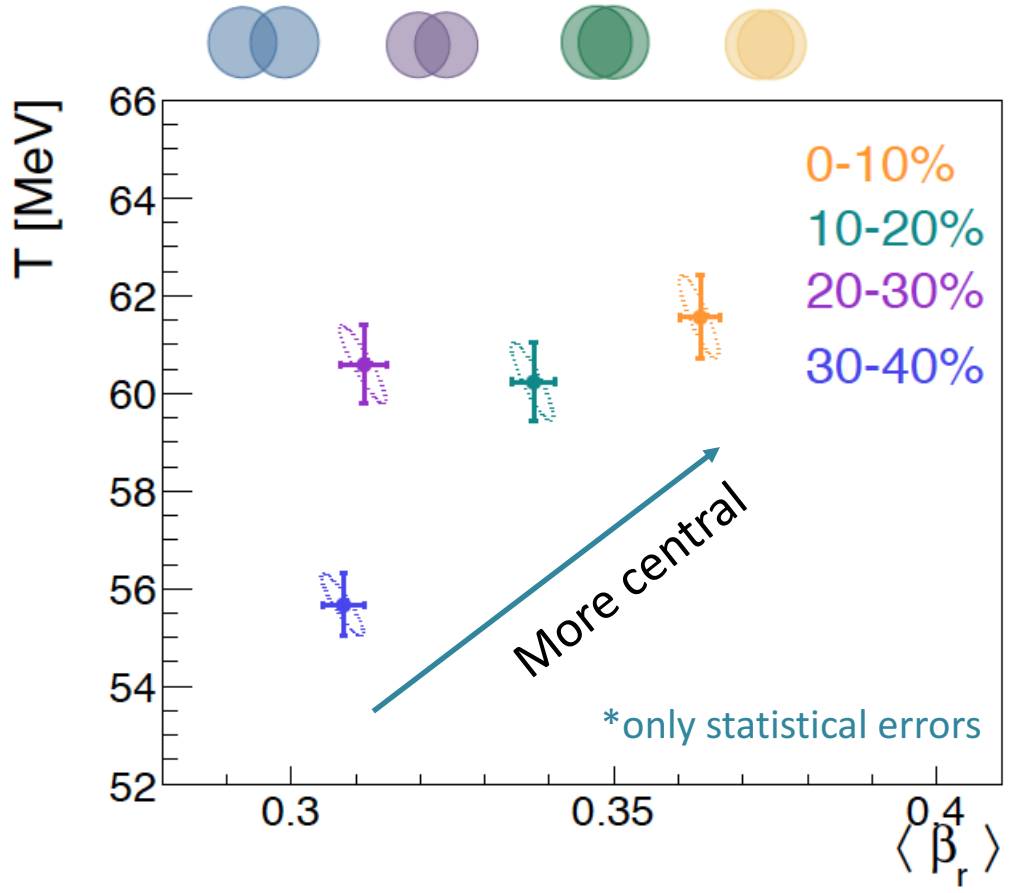
Systematic error investigation



- Variation of particle species included in simultaneous fit
- Strongest effect if protons or both, π^+ and π^-, are excluded from fit
- ➢ Conservative errors till spectra published

Blast Wave Fit

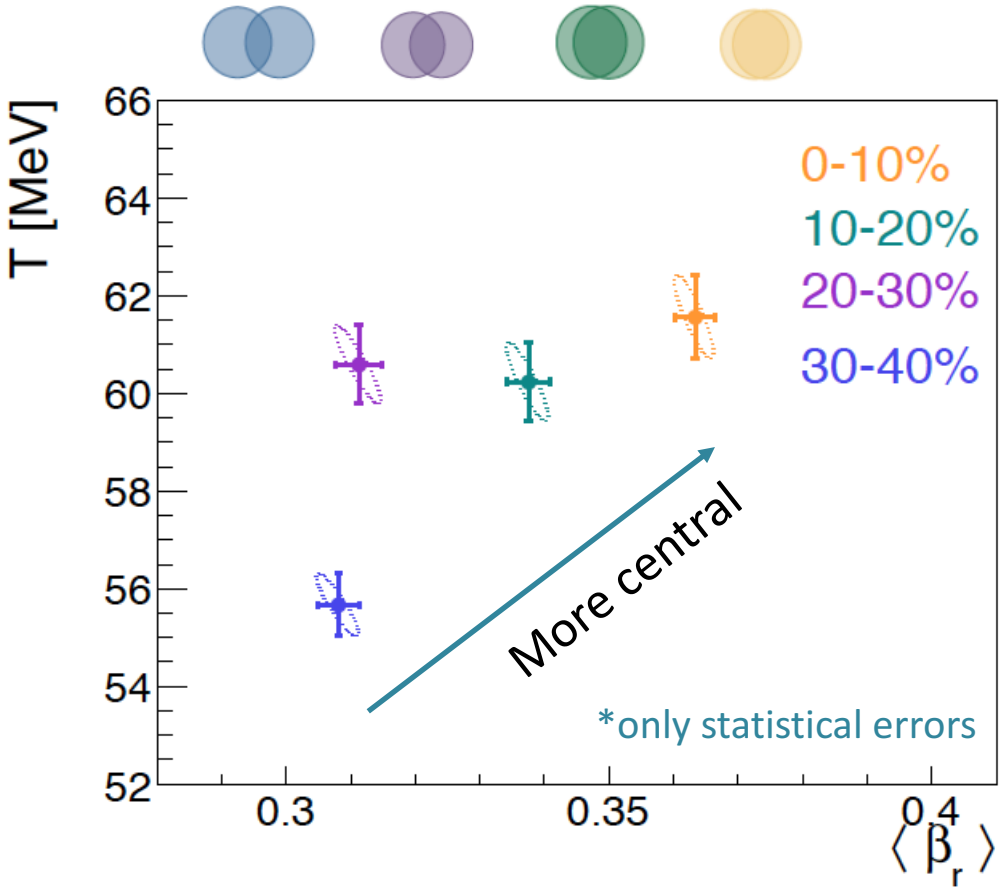
Centrality dependence



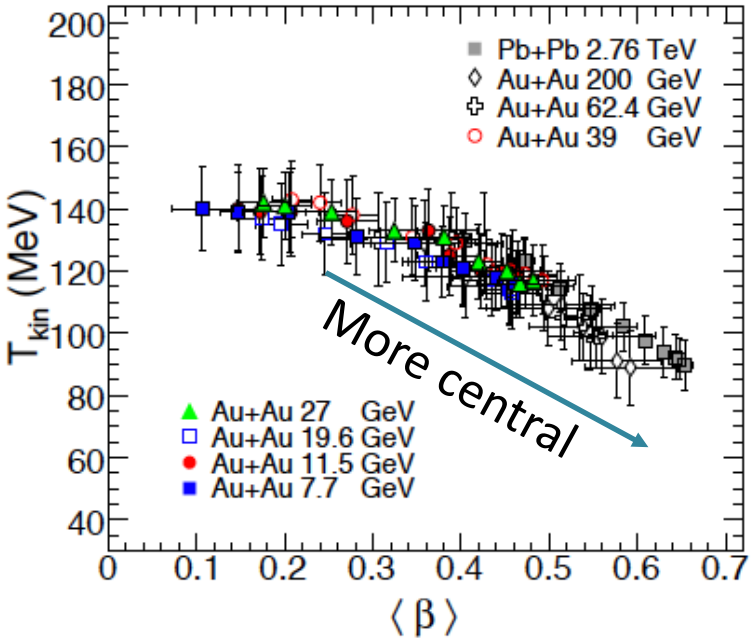
- Slightly lower kinetic freeze-out parameters for more peripheral collisions

Blast Wave Fit

Centrality dependence

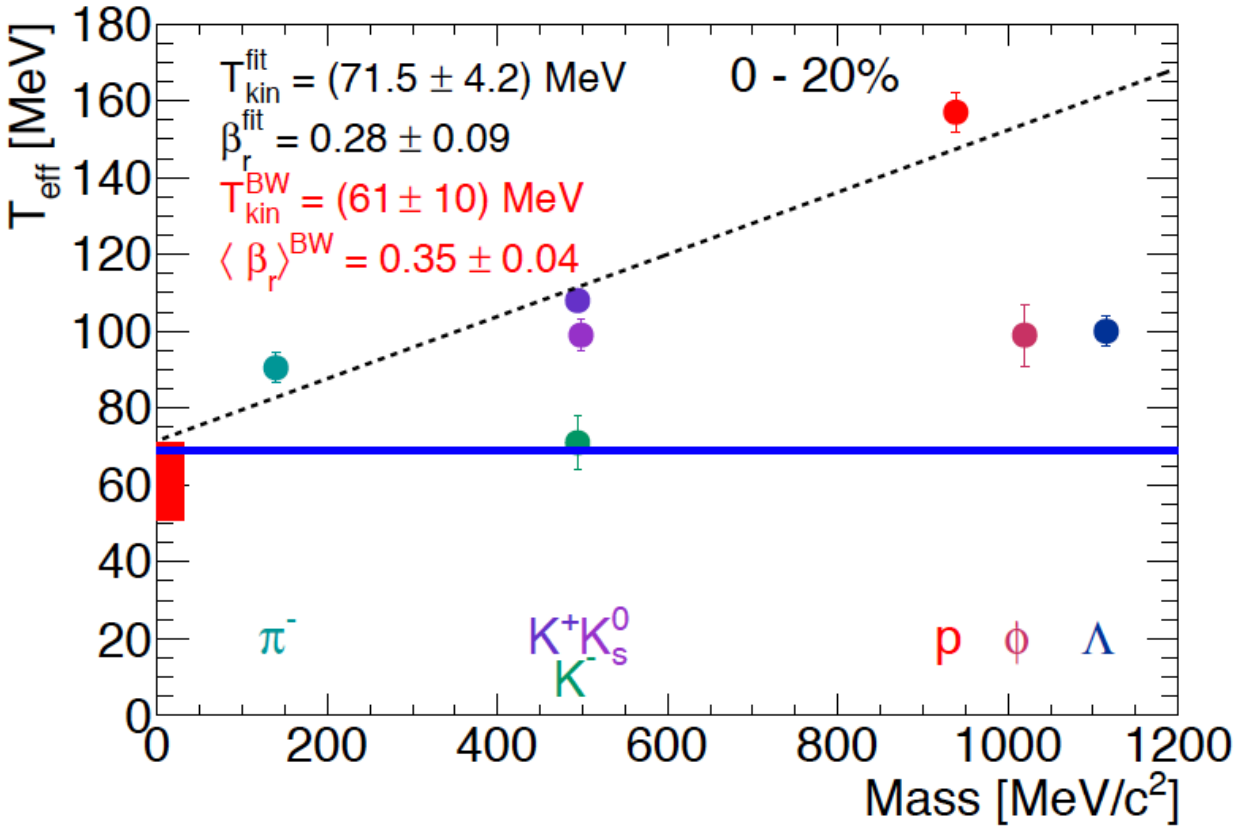


STAR arXiv:1701.07065, 2016



- Slightly lower kinetic freeze-out parameters for more peripheral collisions
- Different behavior at higher energies

Chemical vs. Kinetic Freeze-out



- T_{chem} consistent with T_{kin} obtained from blast wave fit to transverse mass spectra of hadrons and from extrapolation of mass dependence of effective temperatures

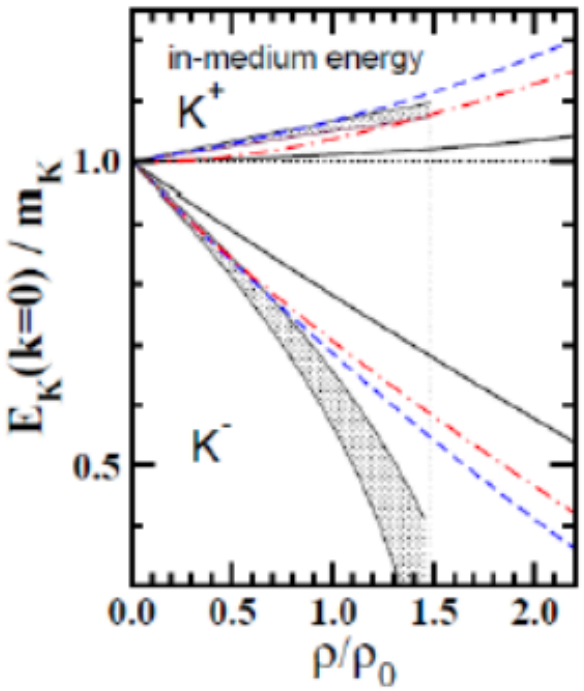
Seltsamkeitsproduktion bei SIS Energien

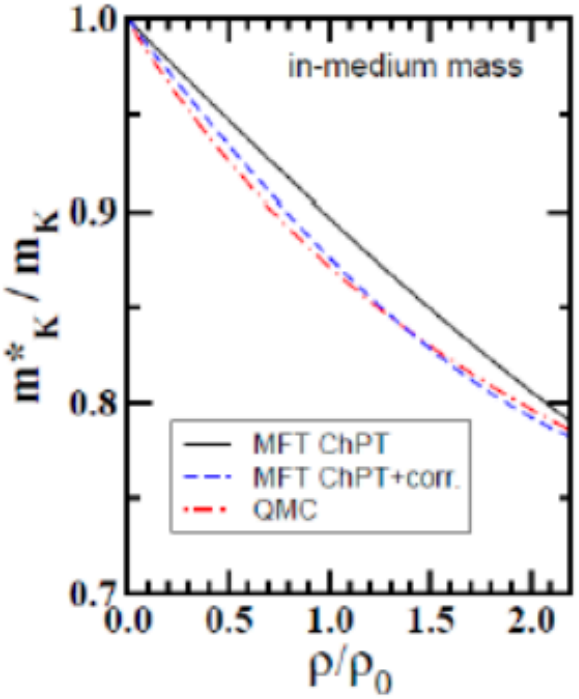
Theoretische Beschreibung von Kaonen

- Effektiver Chiraler Lagrangian:

$$\mathcal{L} = \bar{N}(i\gamma^\mu\partial_\mu - m_N)N + \partial^\mu\bar{K}\partial_\mu K - (m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\bar{N}N)\bar{K}K - \frac{3i}{8f_\pi^2}\bar{N}\gamma^\mu N\bar{K}\overleftrightarrow{\partial_\mu}K,$$

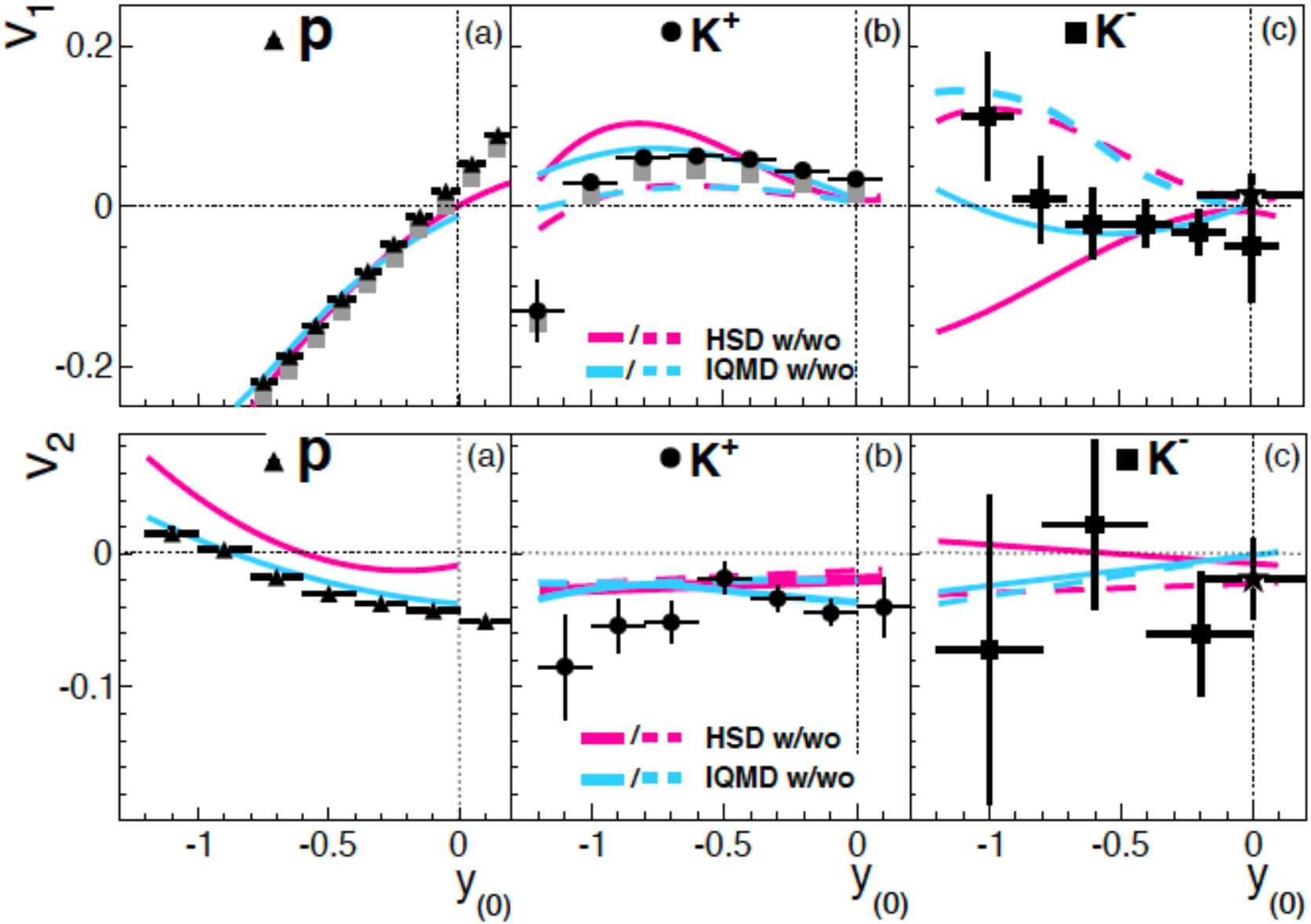
  - Skalare Interaktion (Kaplan und Nelson Term): Gleich für Kaon und Antikaon
  - Vektor Interaktion (Weinberg-Tomozawa): Repulsiv für Kaon – Attraktiv für Antikaon





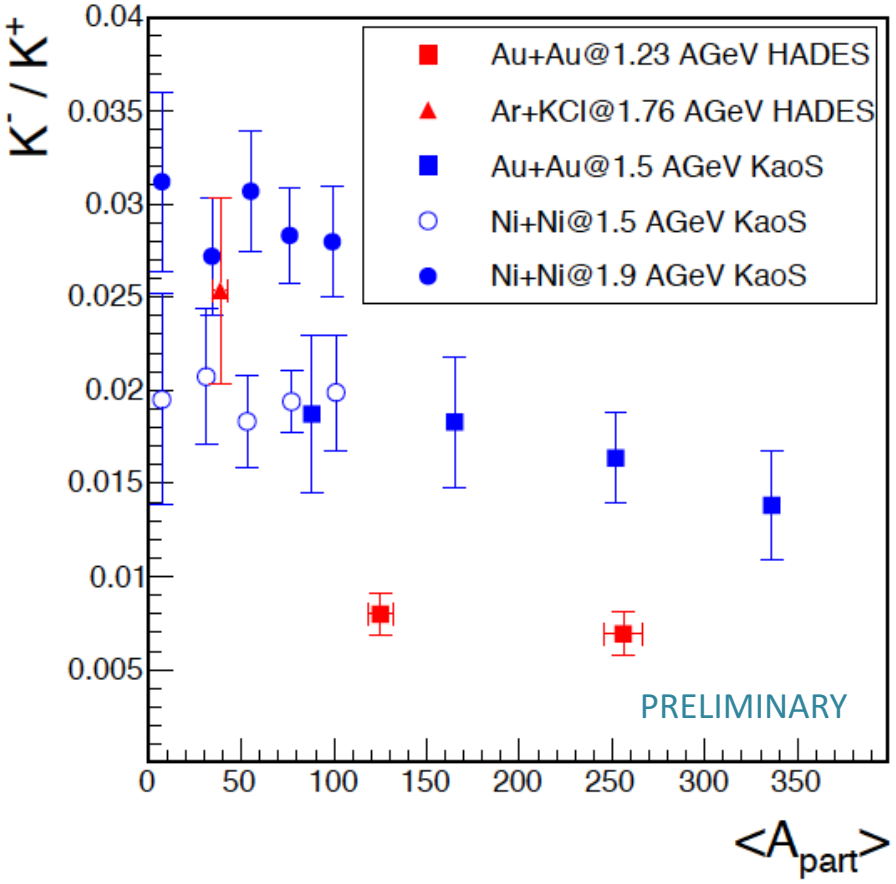
Strangeness Production at SIS Energies

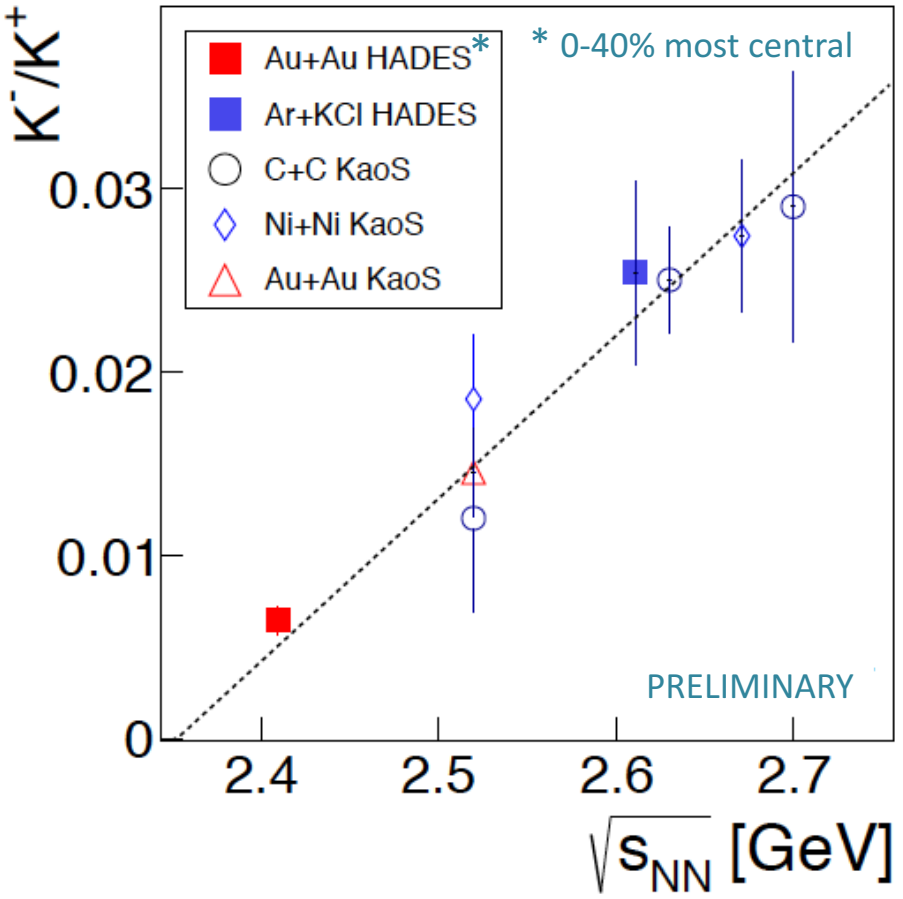
Kaon flow



K^- / K^+ ratio

Centrality dependence and comparison to KaoS

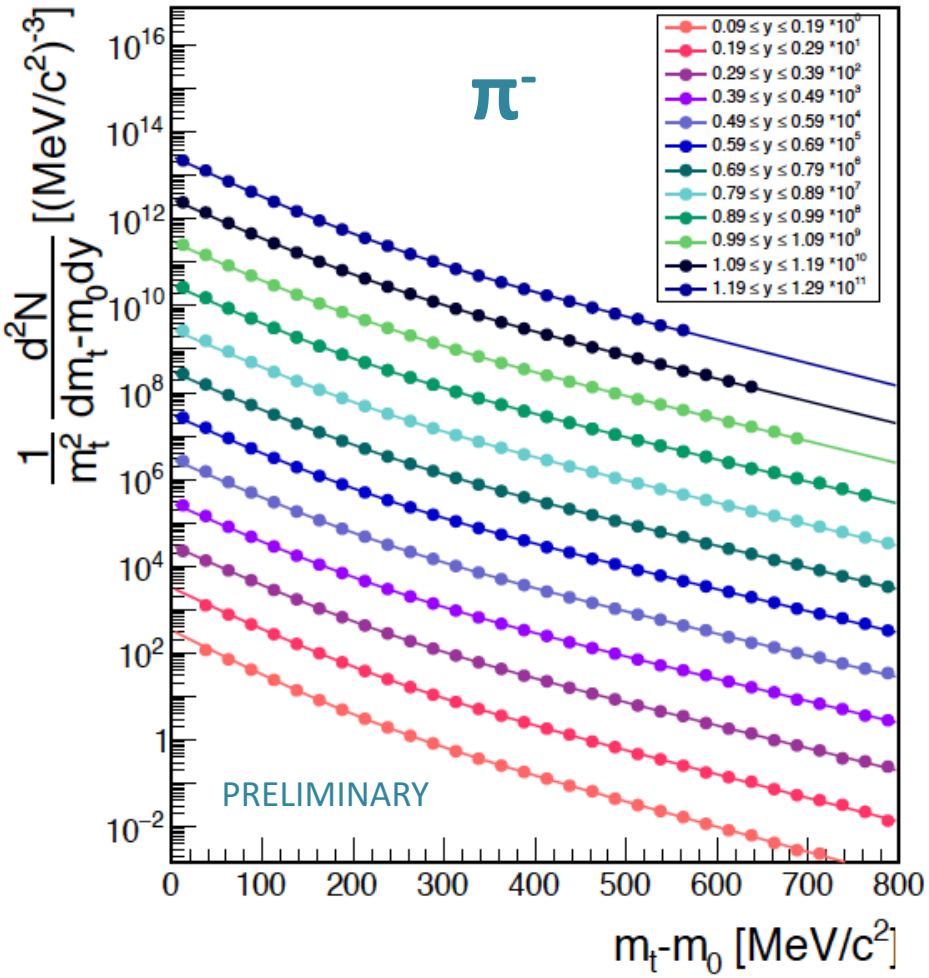


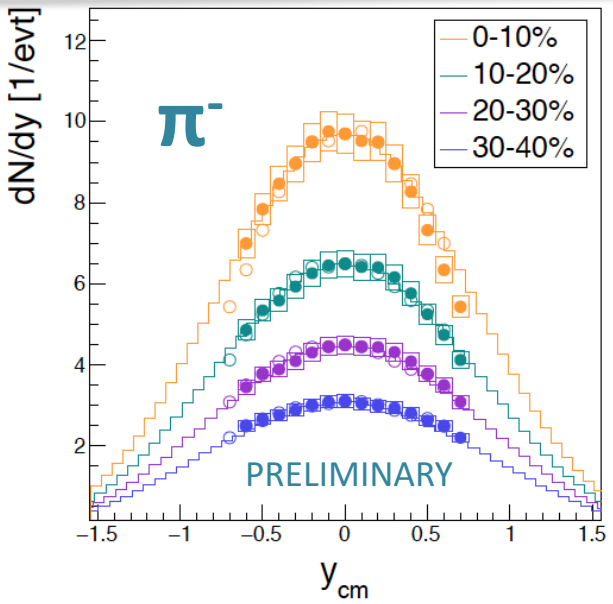


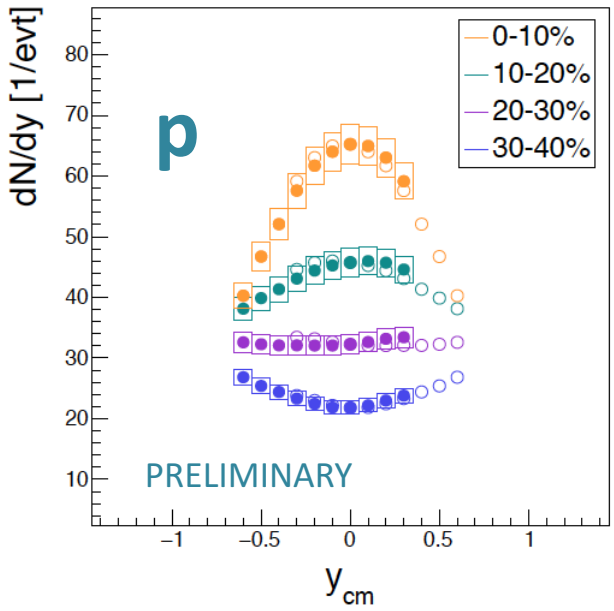
- No strong centrality dependence of K^- / K^+ ratio observed
- K^- / K^+ ratio fits energy dependence of KaoS data

Multi differential analysis of pions and protons

High statistics (1 out of 30 days)

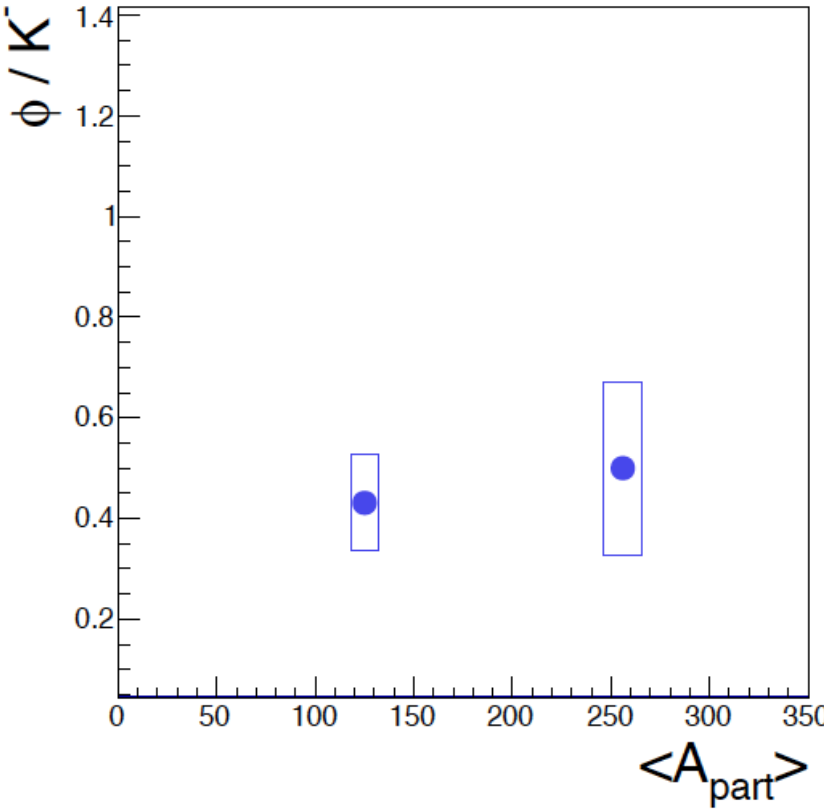


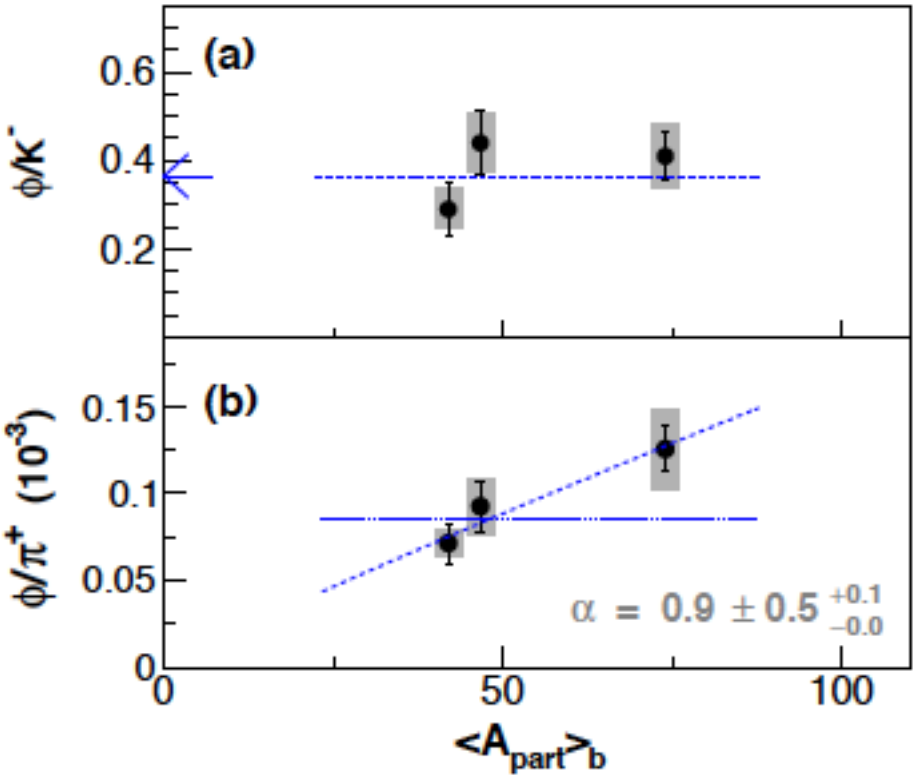




ϕ / K⁻ ratio

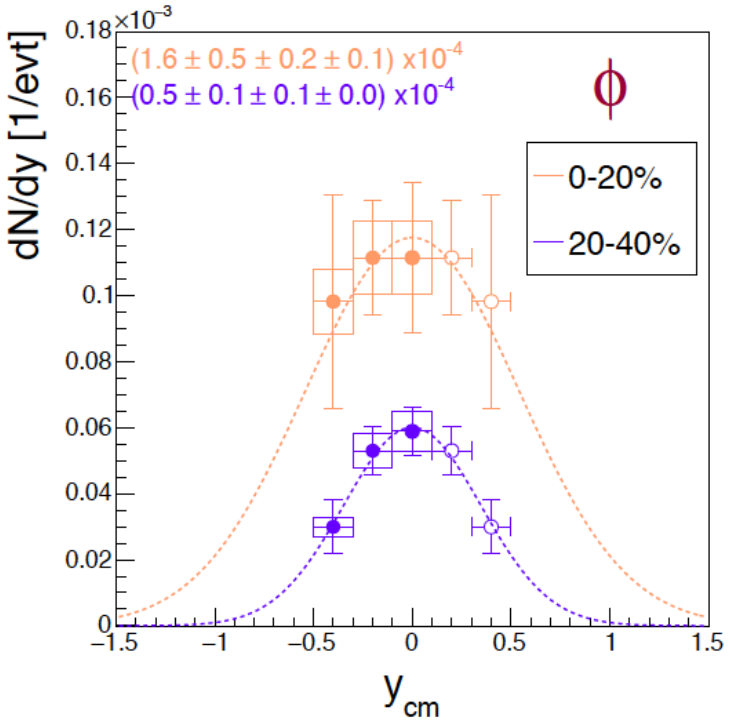
Centrality dependence

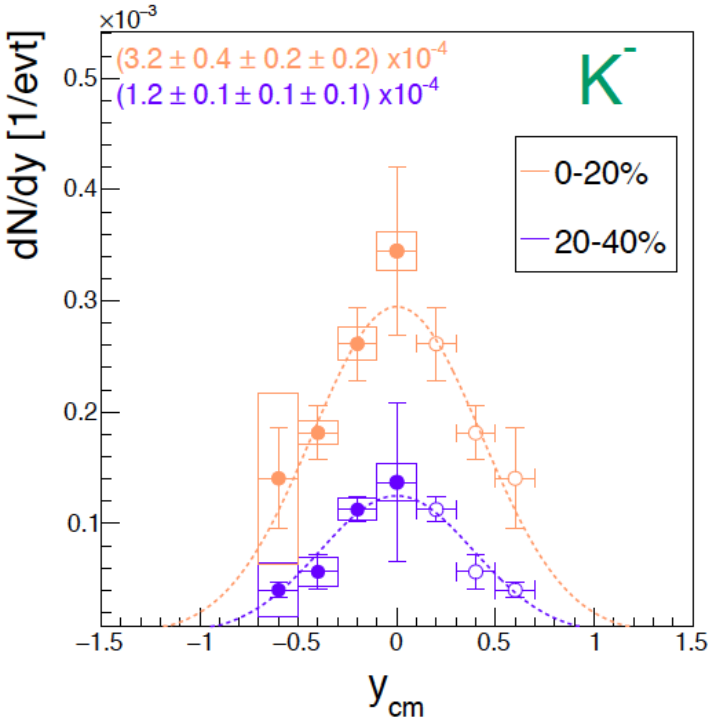




- ϕ/K⁻ ratio almost constant as function of centrality
- Similar trend observed from FOPI for Ni+Ni @ 1.9 AGeV

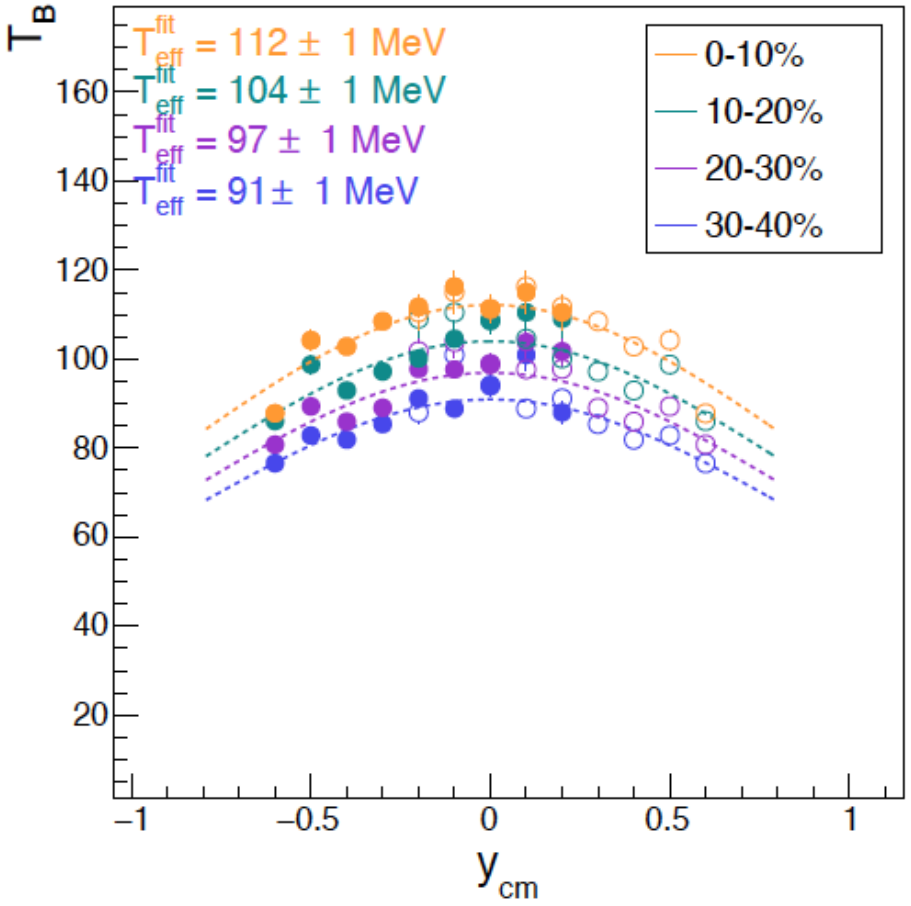
Centrality

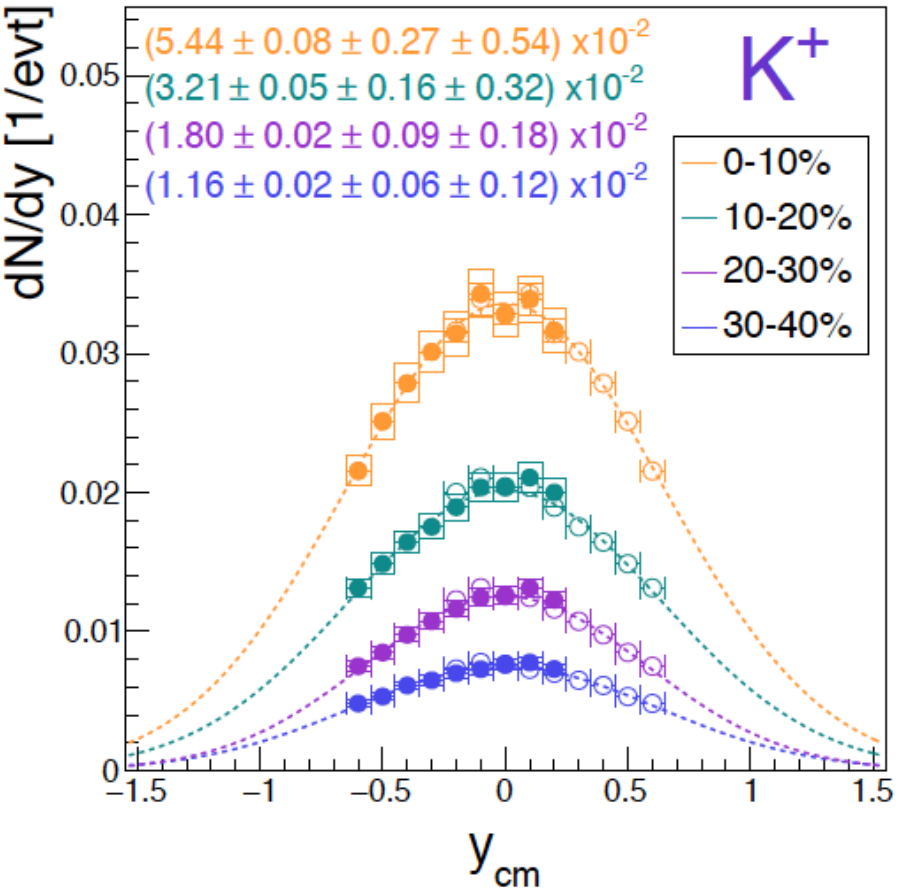

×10⁻³
(1.6 ± 0.5 ± 0.2 ± 0.1) x10⁻⁴
(0.5 ± 0.1 ± 0.1 ± 0.0) x10⁻⁴
ϕ
0-20%
20-40%
dN/dy [1/evt]
y_cm


×10⁻³
(3.2 ± 0.4 ± 0.2 ± 0.2) x10⁻⁴
(1.2 ± 0.1 ± 0.1 ± 0.1) x10⁻⁴
K⁻
0-20%
20-40%
dN/dy [1/evt]
y_cm

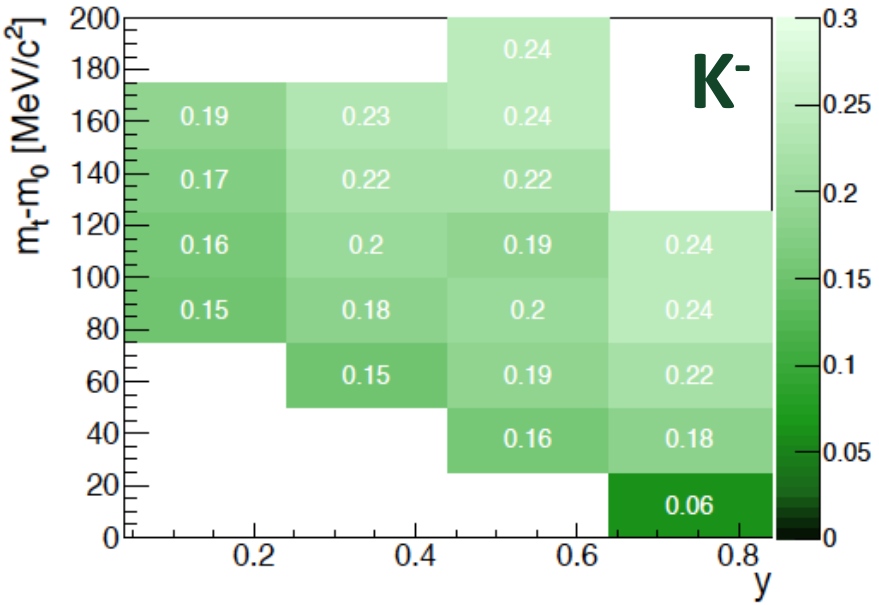
K^+ Production

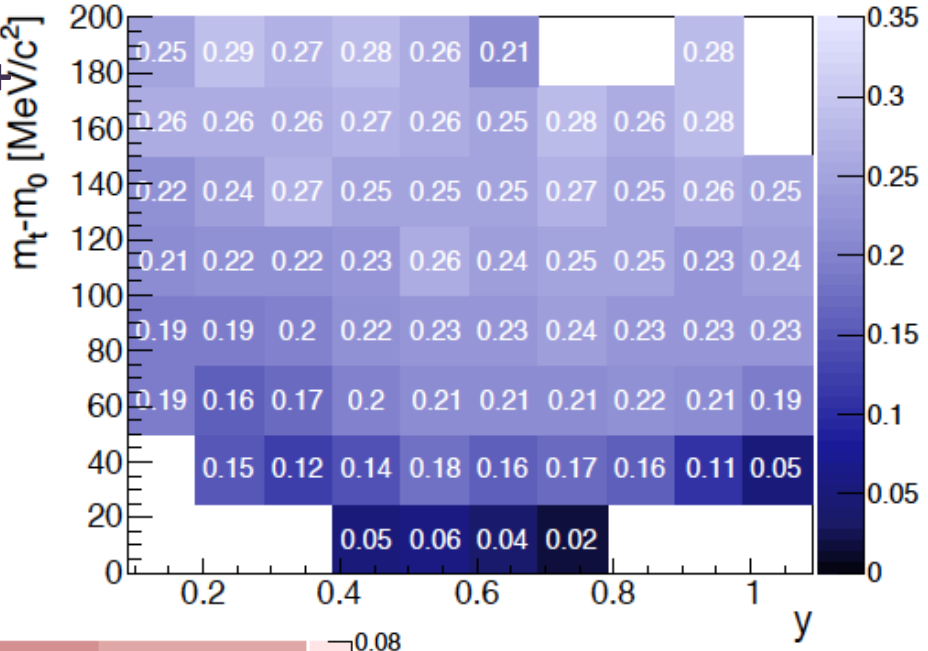
Centrality dependent

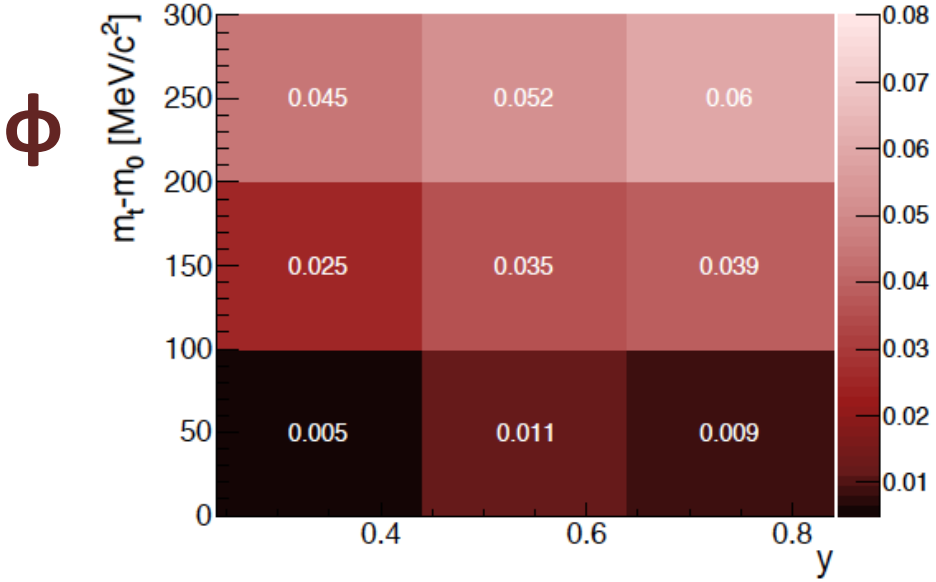




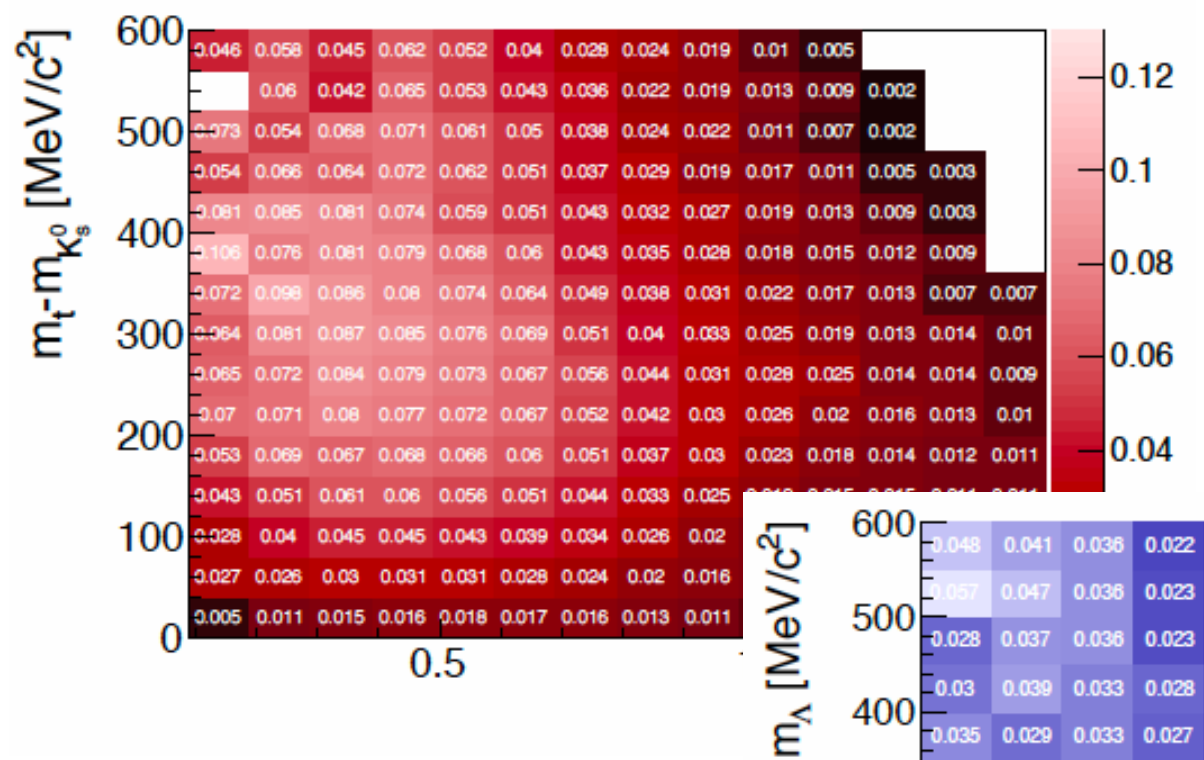
Efficiency * acceptance

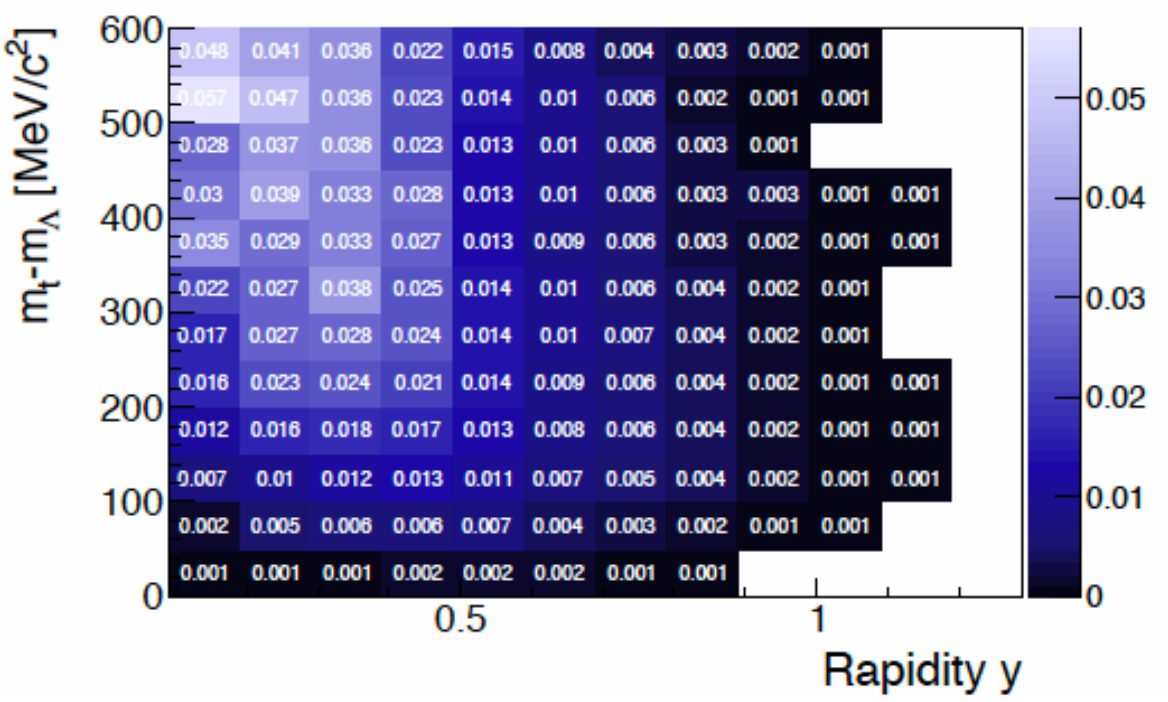




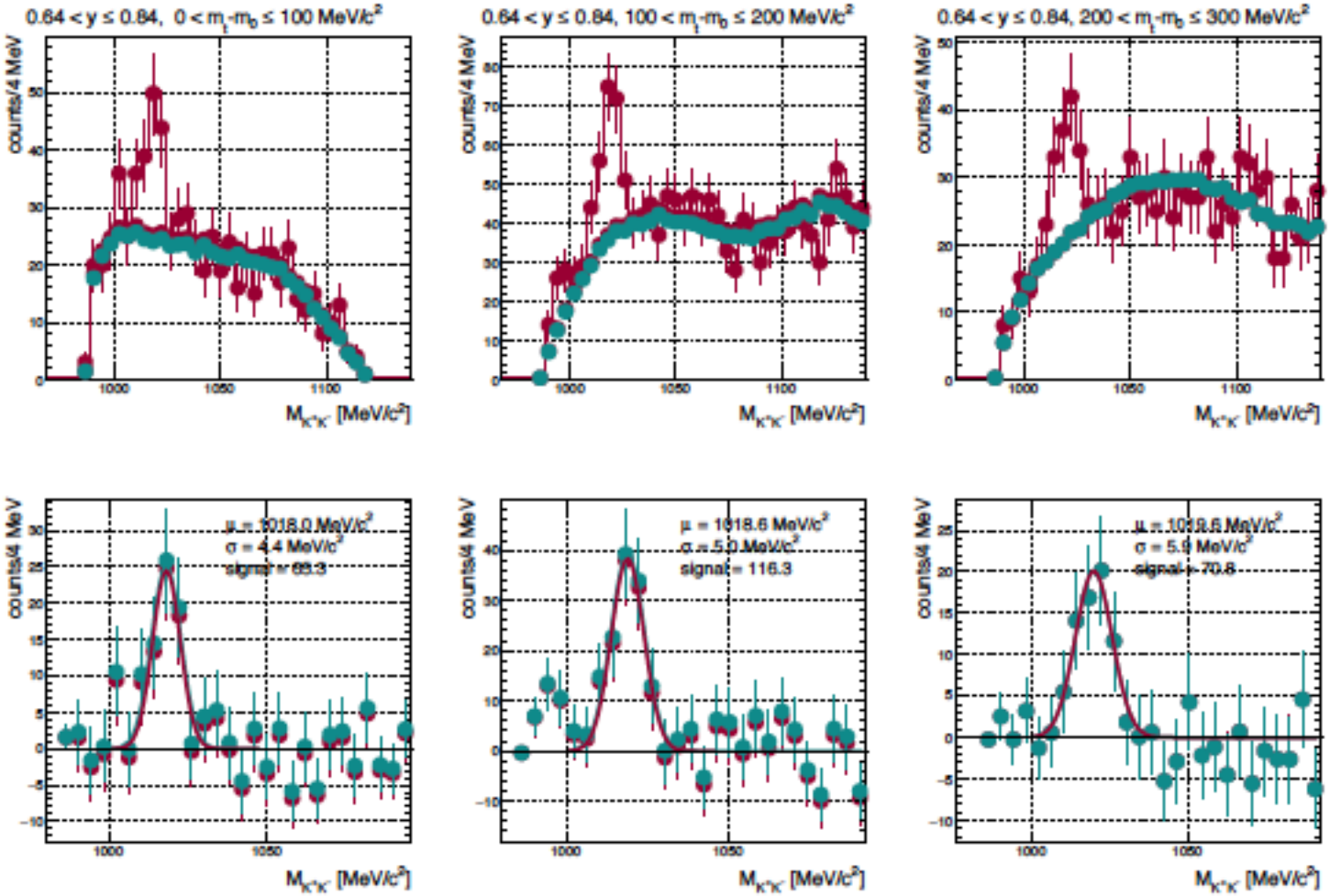


Efficiency * acceptance





Invariant mass ϕ

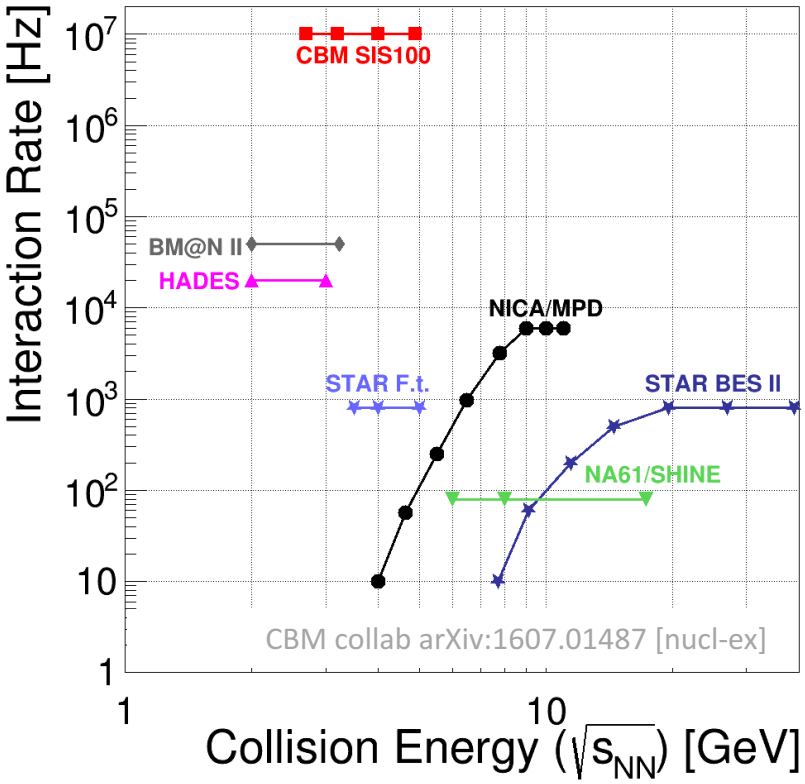


HADES Performance

Au+Au at $\sqrt{s}$ = 2.41 GeV

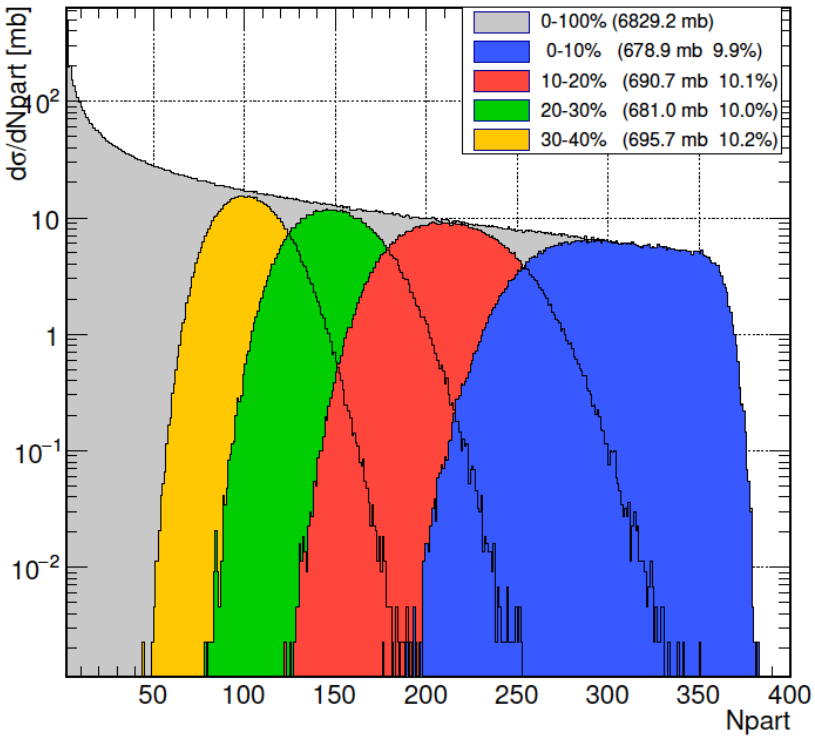
High interaction rates

- Beam: 1.5 x 10^6 Au ions /s
- Trigger rates up to 8 kHz



Centrality dependence

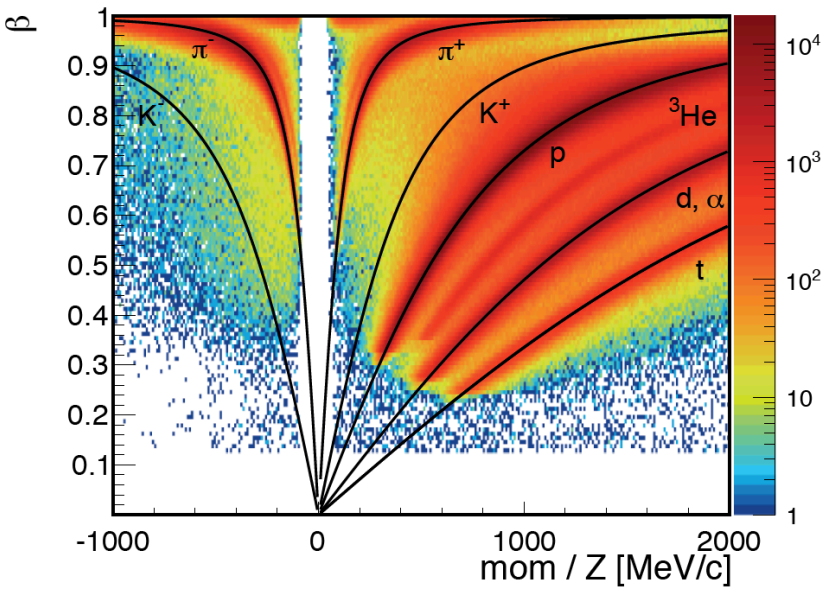
- 40% most central collisions
- 2.1 x 10^9 events analyzed

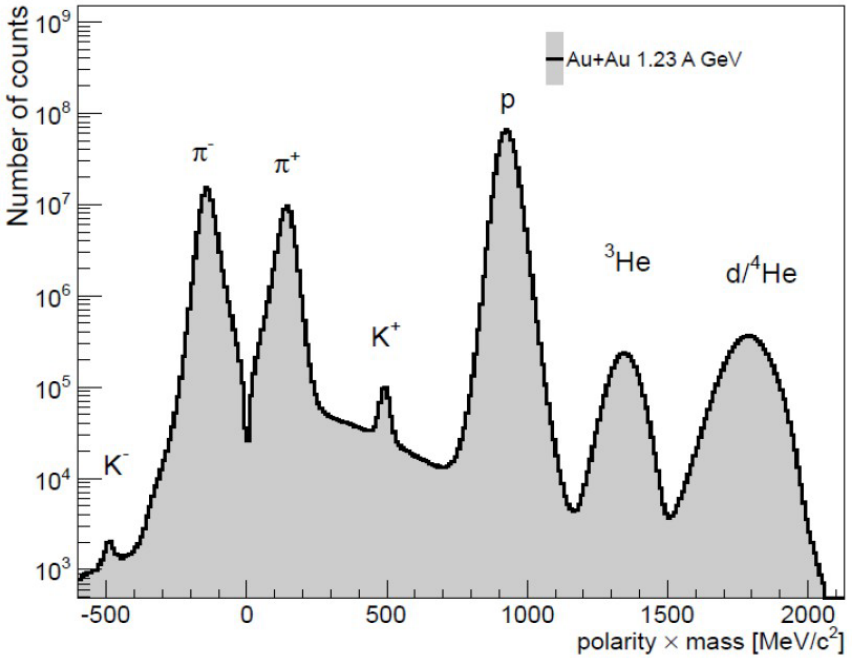


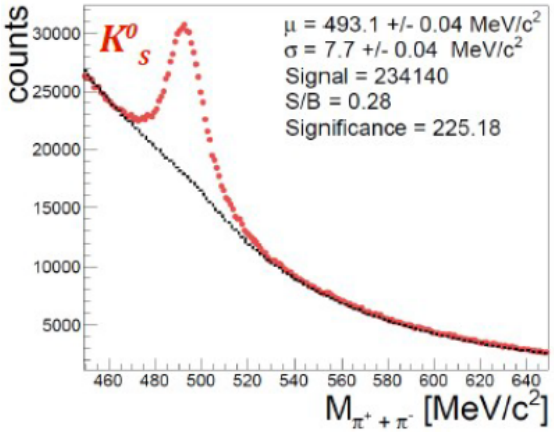
HADES Performance

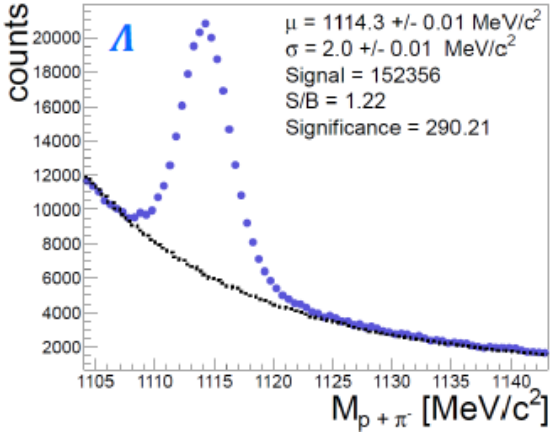
Au+Au at 1.23A GeV

Excellent Particle Identification







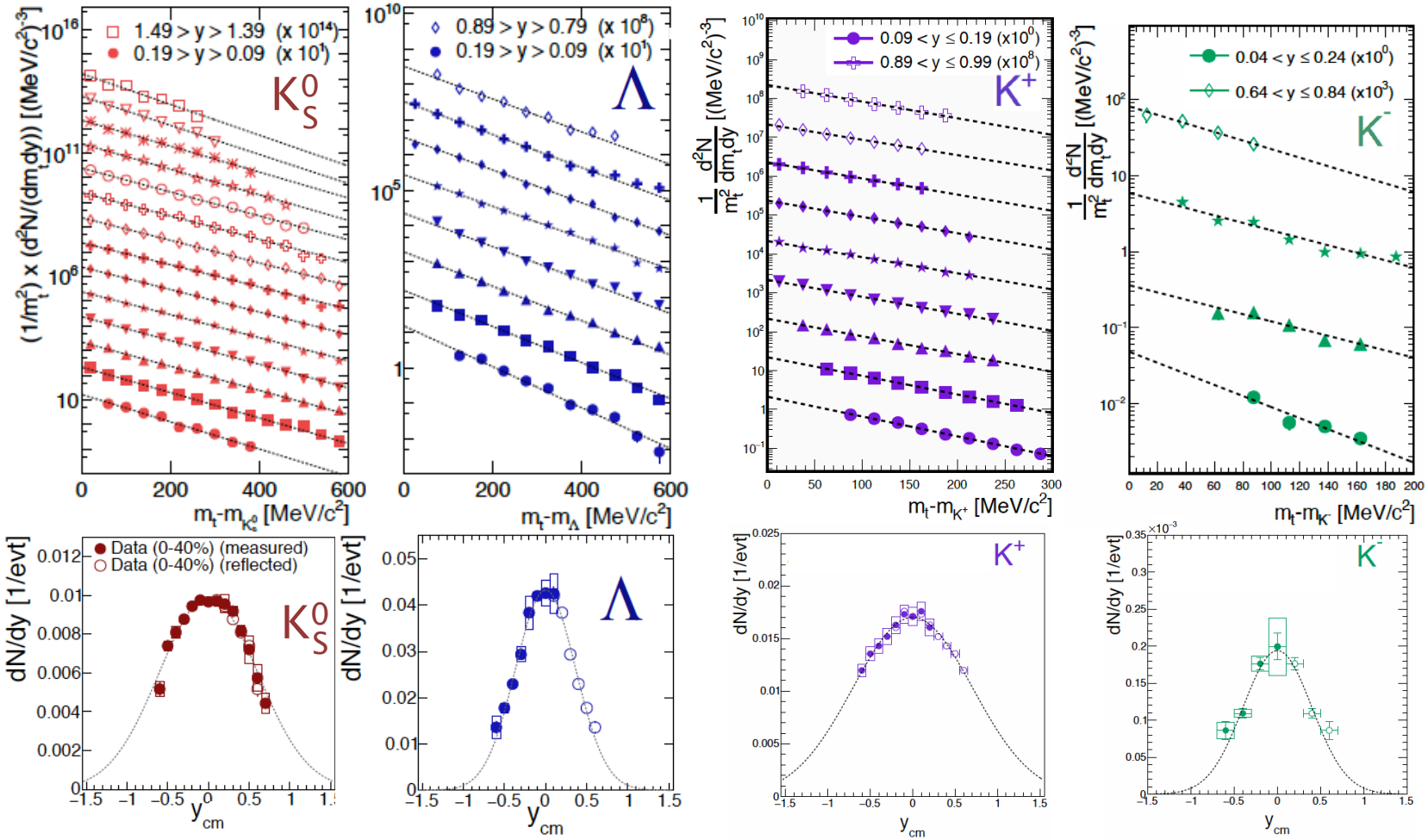


HADES Performance

Reconstruction of Strange Hadrons in Au+Au at $\sqrt{s}$ = 2.41 GeV

Large Acceptance

* 40% most central



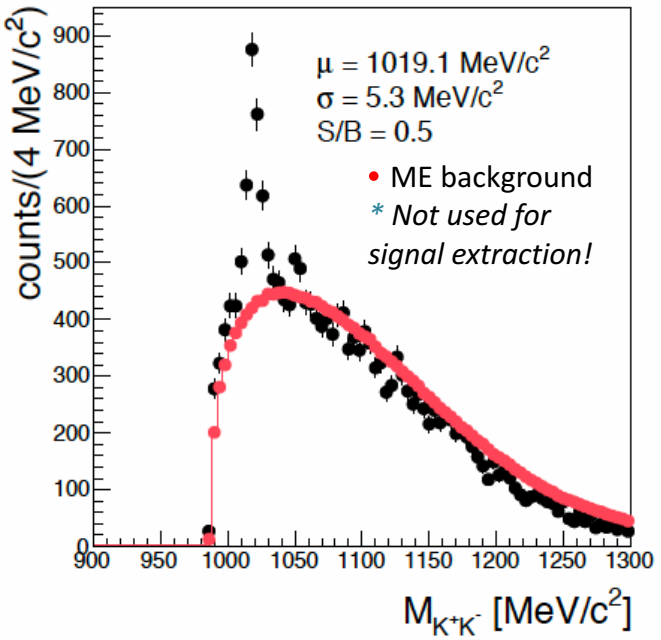
- 4π Multiplicities

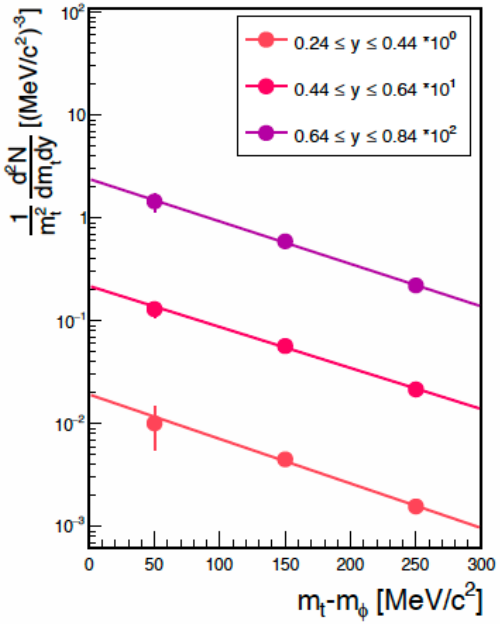
Extrapolation in m_t:

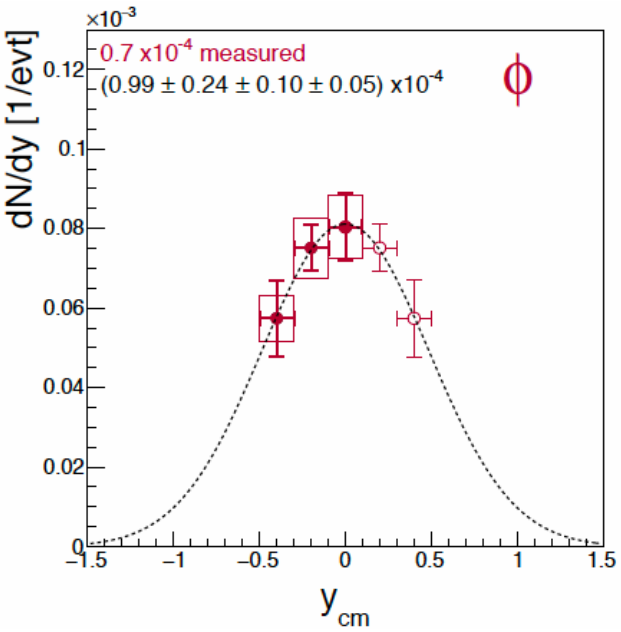
$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = C(y)\exp\frac{-(m_t - m_0)c^2}{T_B(y)}$$

Reconstruction of ϕ Mesons

BR(ϕ -> K^+K^-) = 48.9%







* 40% most central

- First measurement of ϕ mesons so far below NN-threshold
- In total about 1000 ϕ reconstructed
- ➢ Multi-differential analysis possible