Φ Meson Production and Propagation in Cold and Dense Nuclear Matter

Manuel Lorenz for the HADES Collaboration
Goethe-University Frankfurt

Deep sub-threshold ϕ production in Au+Au collisions

J. Adamczewski-Musch[4], O. Arnold[10,9], C. Behnke[8], A. Belounnas[15], A. Belyaev[7], J.C. Berger-Chen[10,9], J. Biernat[3], A. Blanco[2], C. Blume[8], M. Böhmer[10], P. Bordalo[2], S. Chernenko[7,†], L. Chlad[16], C. Deveaux[11], J. Dreyer[6], A. Dybczak[3], E. Epple[10,9], L. Fabbietti[10,9], O. Fateev[7], P. Filip[1], P. Fonte[2,a], C. Franco[2], J. Friese[10], I. Fröhlich[8], T. Galatyuk[5,4], J. A. Garzón[17], R. Gernhäuser[10], M. Golubeva[12], R. Greifenhagen[6,c], F. Guber[12], M. Gumberidze[5,b], S. Harabasz[5,3], T. Heinz[4], T. Hennino[15], S. Hlavac[1], C. Höhne[11], R. Holzmann[4], A. Ierusalimov[7], A. Ivashkin[12], B. Kämpfer[6,c], T. Karavicheva[12], B. Kardan[8], I. Koenig[4], W. Koenig[4], B. W. Kolb[4], G. Korcyl[3], G. Kornakov[5], R. Kotte[6], W. Kühn[11], A. Kugler[16], T. Kunz[10], A. Kurepin[12], A. Kurilkin[7], P. Kurilkin[7], V. Ladygin[7], R. Lalik[10,9], K. Lapidus[10,9], A. Lebedev[13], L. Lopes[2], M. Lorenz[8], T. Mahmoud[11], L. Maier[10], A. Mangiarotti[2], J. Markert[4], S. Maurus[10], V. Metag[11], J. Michel[8], D.M. Mihaylov[10,9], S. Morozov[12,d], C. Müntz[8], R. Münzer[10,9], L. Naumann[6], K. N. Nowakowski[3], M. Palka[3], Y. Parpottas[14,e], V. Pechenov[4], O. Pechenova[8], O. Petukhov[12,d], J. Pietraszko[4], W. Przygoda[3], S. Ramos[2], B. Ramstein[15], A. Reshetin[12], P. Rodriguez-Ramos[16], P. Rosier[15], A. Rost[5], A. Sadovsky[12], P. Salabura[3], T. Scheib[8], H. Schuldes[8], E. Schwab[4], F. Scozzi[5,15], F. Seck[5], P. Sellheim[8], J. Siebenson[10], L. Silva[2], Yu.G. Sobolev[16], S. Spataro[f], H. Ströbele[8], J. Stroth[4,8], P. Strzempek[3], C. Sturm[4], O. Svoboda[16], M. Szala[8], P. Tlusty[16], M. Traxler[4], H. Tsertos[14], E. Usenko[12], V. Wagner[16], C. Wendisch[4], M.G. Wiebusch[8], J. Wirth[10,9], Y. Zanevsky[7,†], P. Zumbruch[4]

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(Dated: November 7, 2018)

We present data on charged kaons ($K^{\pm}$) and ϕ mesons in Au(1.23A GeV)+Au collisions. It is the first simultaneous measurement of K^- and ϕ mesons in central heavy-ion collisions below a kinetic beam energy of 10A GeV. The ϕ/K^- multiplicity ratio is found to be surprisingly high with a value of 0.52 ± 0.16 and shows no dependence on the centrality of the collision. Consequently, the different slopes of the K^+ and K^- transverse-mass spectra can be explained solely by feed-down, which substantially softens the spectra of K^- mesons. Hence, in contrast to the commonly adapted argumentation in literature, the different slopes do not necessarily imply diverging freeze-out temperatures of K^+ and K^- mesons caused by different couplings to baryons.

PACS numbers:

Until now, hadron properties and interactions at high baryon densities - as reached in relativistic heavy-ion collisions (HICs) - cannot be addressed directly by ab-initio QCD calculations and thus have to be modeled using effective Lagrangians. Both the equation of state and the kinetic description of the HIC dynamics provide severe challenges with far reaching implications for astrophysical objects, e.g. for neutron star structure and merger

Strong absorption of hadrons with hidden and open strangeness in nuclear matter

J. Adamczewski-Musch[4], O. Arnold[10,9], E.T. Atomssa[16], C. Behnke[8], A. Belounnas[16], A. Belyaev[7], J.C. Berger-Chen[10,9], J. Biernat[3], A. Blanco[1], C. Blume[8], M. Böhmer[10], S. Chernenko[7,†], L. Chlad[17], P. Chudoba[17], I. Ciepał[2], C. Deveaux[11], D. Dittert[5], J. Dreyer[6], A. Dybczak[3], E. Epple[10,9], L. Fabbietti[10,9], O. Fateev[7], P. Fonte[1,a], C. Franco[1], J. Friese[10], I. Fröhlich[8], T. Galatyuk[5,4], J. A. Garzón[18], R. Gernhäuser[10], M. Golubeva[12], R. Greifenhagen[6,c], F. Guber[12], M. Gumberidze[4,b], S. Harabasz[5,3], T. Heinz[4], T. Hennino[16], C. Höhne[11,4], R. Holzmann[4], A. Ierusalimov[7], A. Ivashkin[12], B. Kämpfer[6,c], B. Kardan[8], I. Koenig[4], W. Koenig[4], B. W. Kolb[4], G. Korcyl[3], G. Kornakov[5], F. Kornas[5], R. Kotte[6], J. Kubos[2], A. Kugler[17], T. Kunz[10], A. Kurepin[12], A. Kurilkin[7], P. Kurilkin[7], V. Ladygin[7], R. Lalik[3], K. Lapidus[10,9], A. Lebedev[13], S. Linev[4], L. Lopes[1], M. Lorenz[8], T. Mahmoud[11], L. Maier[10], A. Malige[3], J. Markert[4], S. Maurus[10], V. Metag[11], J. Michel[8], D.M. Mihaylov[10,9], V. Mikhaylov[17], S. Morozov[12,14], C. Müntz[8], R. Münzer[10,9], L. Naumann[6], K. Nowakowski[3], Y. Parpottas[15,d], V. Pechenov[4], O. Pechenova[4], O. Petukhov[12], J. Pietraszko[4], A.P. Prozorov[17], W. Przygoda[3], B. Ramstein[16], A. Reshetin[12], P. Rodriguez-Ramos[17], A. Rost[5], A. Sadovsky[12], P. Salabura[3], T. Scheib[8], K. Schmidt-Sommerfeld[10], H. Schuldes[8], E. Schwab[4], F. Scozzi[5,16], F. Seck[5], P. Sellheim[8], J. Siebenson[10], L. Silva[1], J. Smyrski[3], S. Spataro[e], S. Spies[8], H. Ströbele[8], J. Stroth[8,4], P. Strzempek[3], C. Sturm[4], O. Svoboda[17], M. Szala[8], P. Tlusty[17], M. Traxler[4], H. Tsertos[15], C. Ungethüm[5], O. Vázquez Doce[9,8], V. Wagner[17], C. Wendisch[4], M.G. Wiebusch[8], J. Wirth[10,9], Y. Zanevsky[7,†], P. Zumbruch[4]

(HADES collaboration)

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(Dated: December 11, 2018)

We present the first observation of K^- and ϕ absorption within nuclear matter by means of π^--induced reactions on C and W targets at an incident beam momentum of 1.7 GeV/c studied with HADES at SIS18/GSI. The double ratio $(K^-/K^+)_W/(K^-/K^+)_C$ is found to be $0.319 \pm 0.009(\mathrm{stat})^{+0.014}_{-0.012}(\mathrm{syst})$ indicating a larger absorption of K^- in heavier targets as compared to lighter ones. The measured ϕ/K^- ratios in $\pi^- + \mathrm{C}$ and $\pi^- + \mathrm{W}$ reactions within the HADES acceptance are found to be equal to $0.55 \pm 0.04(\mathrm{stat})^{+0.06}_{-0.07}(\mathrm{syst})$ and to $0.63 \pm 0.06(\mathrm{stat})^{+0.11}_{-0.11}(\mathrm{syst})$, respectively. The similar ratios measured in the two different reactions demonstrate for the first time experimentally that the dynamics of the ϕ meson in nuclear medium is strongly coupled to the K^- dynamics. The large difference in the ϕ production off C and W nuclei is discussed in terms of a strong ϕN in-medium coupling.

Introduction:

Experimental Access to Medium Effects
HADES Setup and Performance

Part 1: Heavy-ion Collisions at HADES

Charged Kaon Yields and Spectra
$\boldsymbol{\Phi}$ Meson Yield and Spectra
Excitation Functions

Part 2: Pion Induced Reactions in Cold Nuclear Matter

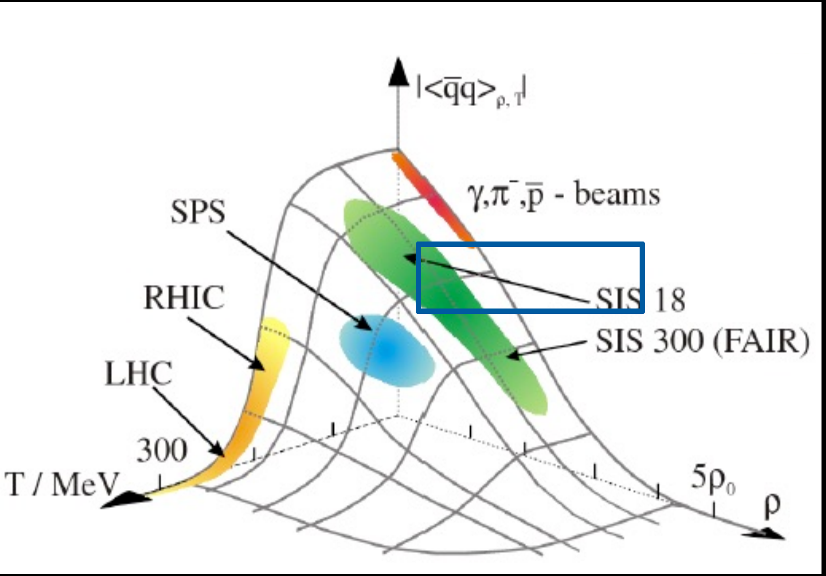
K^- Suppression Relative to K^+
$\boldsymbol{\Phi}$ Meson Suppression Relative to K^-

Summary and Outlook

Experimental Access to Medium Effects

"Observed hadron masses are nature's compromise between distortion of the vacuum and localization!" F. Wilczek

→ *Change vacuum, change hadron properties!*



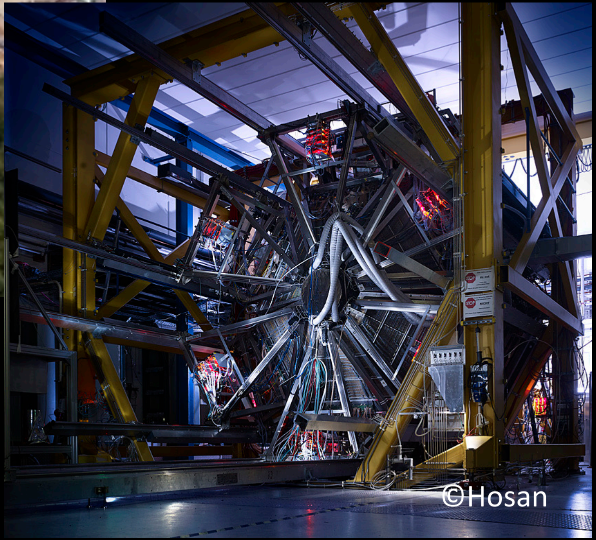
Cold nuclear matter:

The easiest way to distort the QCD vacuum, controlled conditions (static medium).

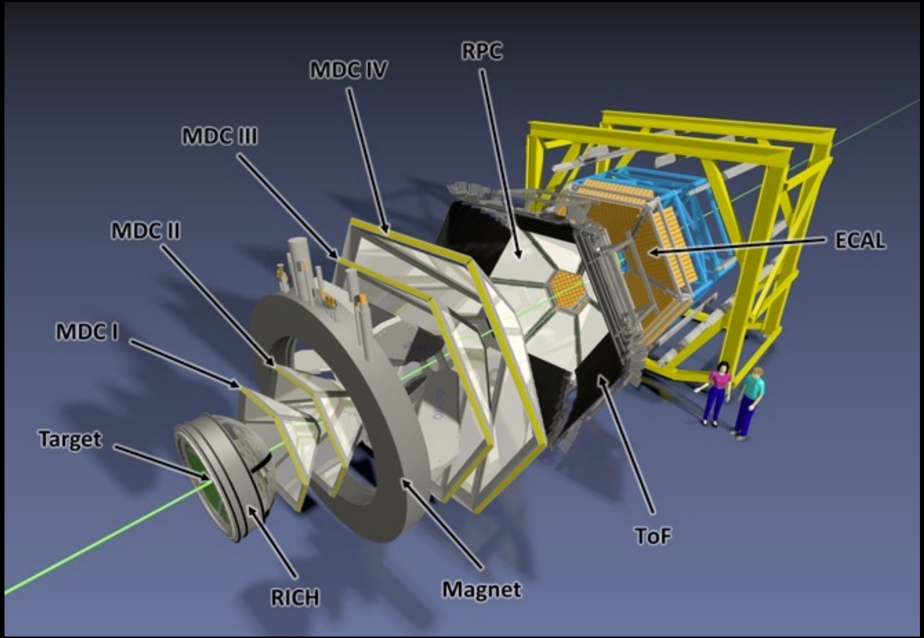
Heavy-ion collisions:

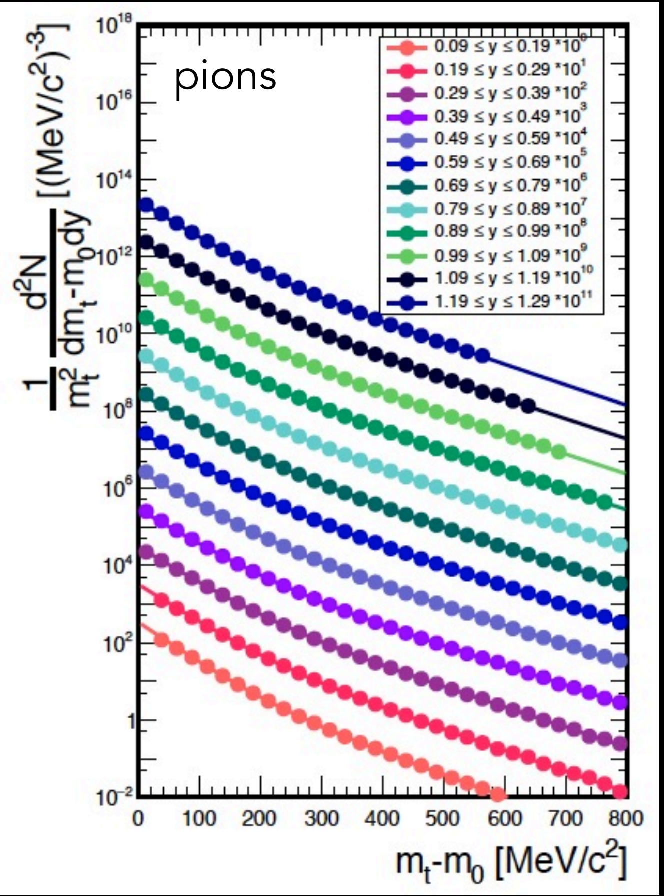
Larger effects compared compared to cold matter.

HADES at GSI/FAIR in Darmstadt, Germany



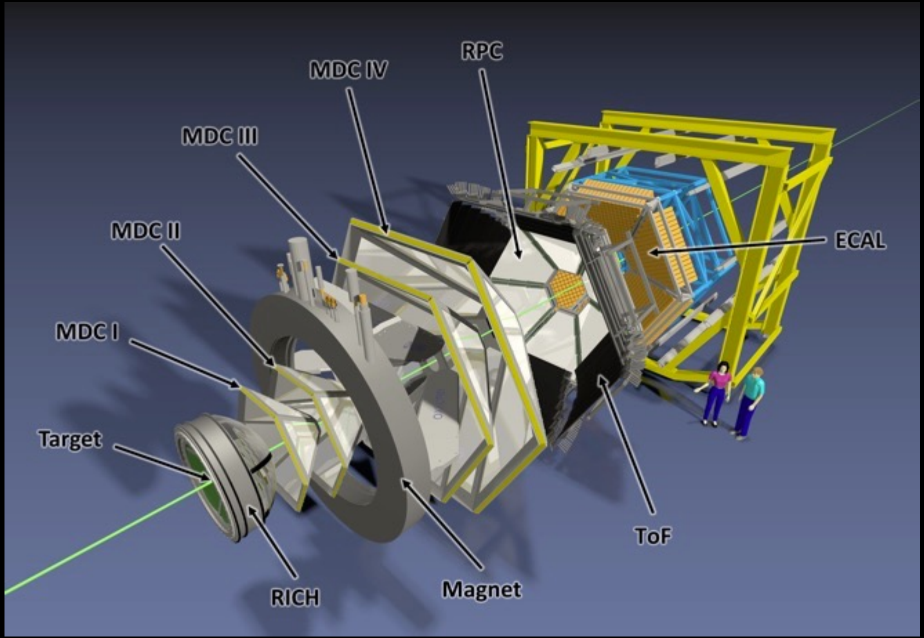
HADES: Setup and Performance

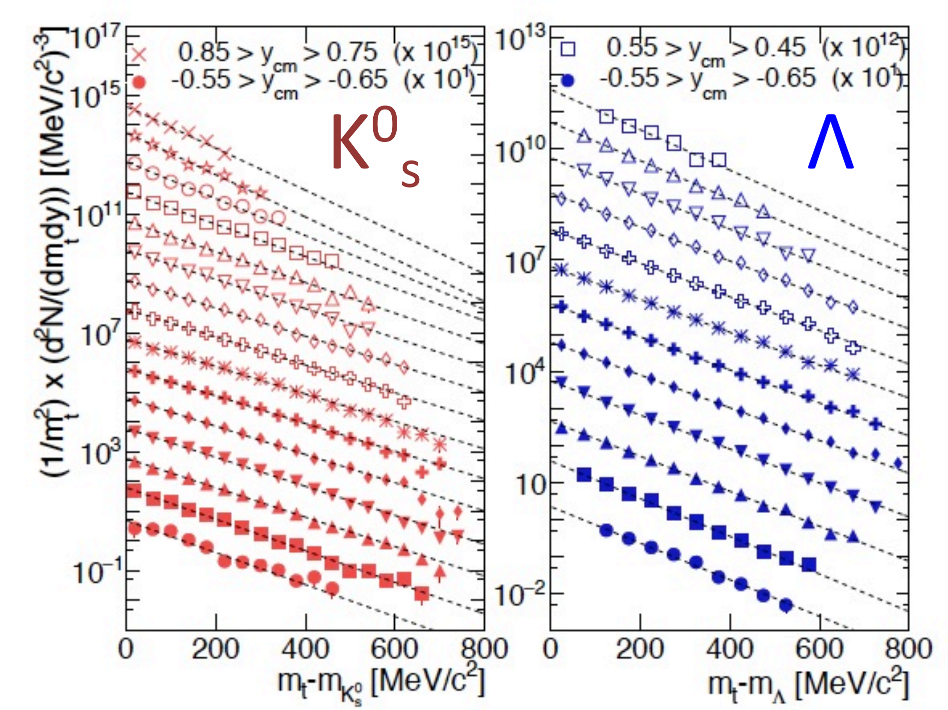




Fast detector: 16 kHz Ag+Ag, 50 kHz p+p
Large acceptance: full azimuthal and
polar angle coverage of ϴ = 18° – 85°
Hadron PID: **β**, dE/dx
additional PID for leptons: RICH, SHOWER

HADES: Setup and Performance





Fast detector: 16 kHz Ag+Ag, 50 kHz p+p
Large acceptance: full azimuthal and polar angle coverage of ϴ = 18° – 85°
Hadron PID: **β**, dE/dx
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Data and Observable

Heavy-Ion Collisions

Au+Au @$\sqrt{s_{NN}}$=2.4 GeV
4.0×10^9 events collected in 2012

Ag+Ag @$\sqrt{s_{NN}}$=2.55 GeV
1.4×10^{10} events collected in 2019

direct line shape modifications → see Tetyana's talk

Production yields and phase space distributions.
Steep excitation function, sensitive to conditions reached (strange hadrons).
Important to compare also various hadrons relatively to each other.

Cold Nuclear Matter

π^- + C @ p_{π^-} = 1.7 GeV/c
1.3×10^8 events collected in 2014

π^- + W @ p_{π^-} = 1.7 GeV/c
1.7×10^8 events collected in 2014

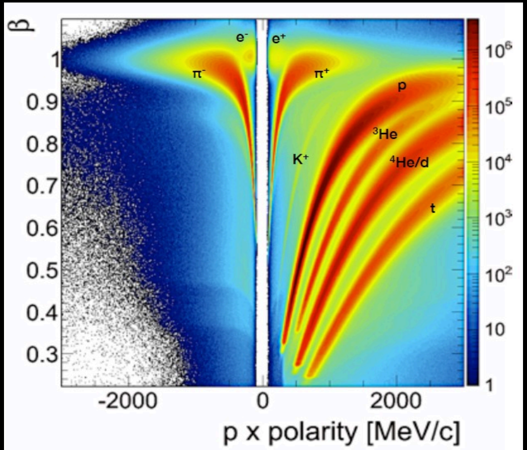
Partial decay branch might be suppressed by collisional broadening:

$$N_{e^+e^-} \propto \Gamma_{e^+e^-}\tau_{meson} \propto \frac{\Gamma_{e^+e^-}}{\Gamma_{tot}}$$

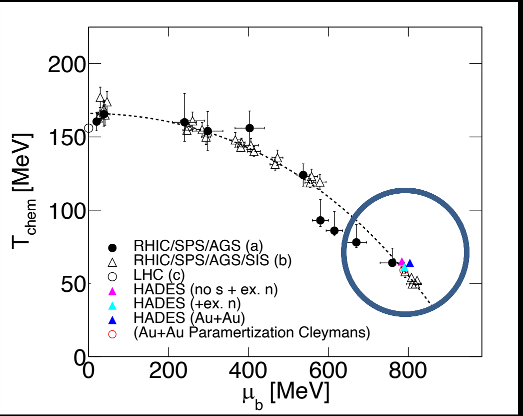
$$\Gamma_{tot} = \Gamma_{vac} + \Gamma_{coll}$$

→ nuclear suppression sensitive to in-medium width (indirect measurement) → see also Volker's talk

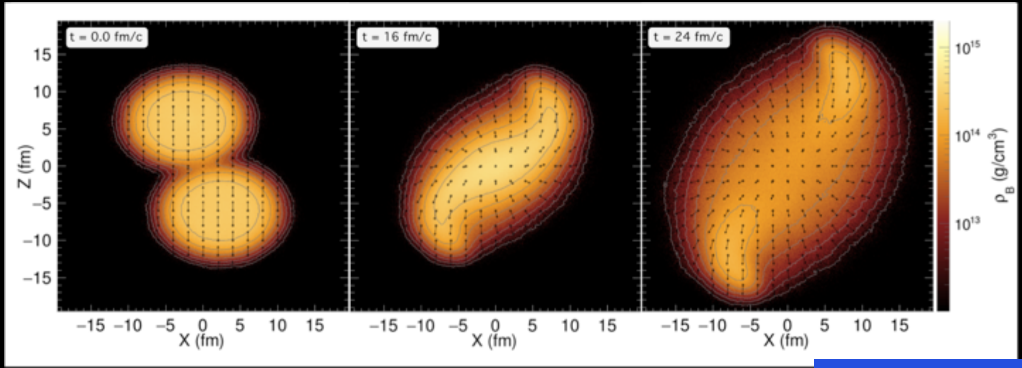
Part 1: Heavy-ion Collisions at HADES



Baryon dominated system

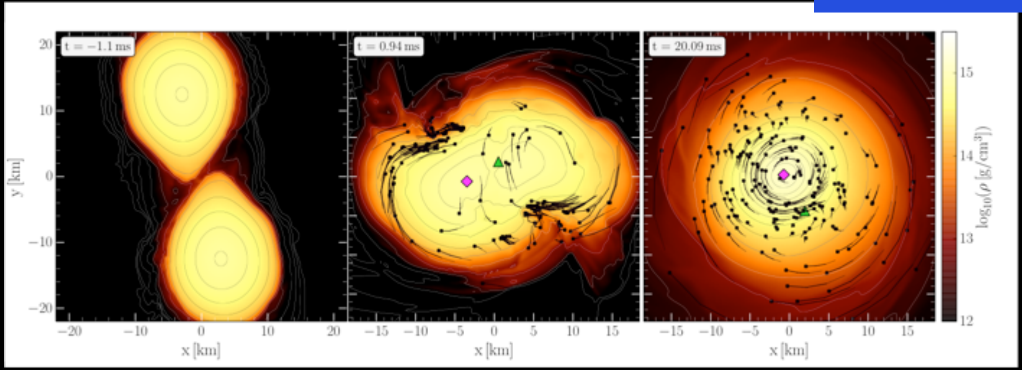


Central Au+Au $\sqrt{s_{NN}}$=2.4 GeV



T < 70 MeV,
$\rho \approx 3\rho_0$

Merging Neutron Stars

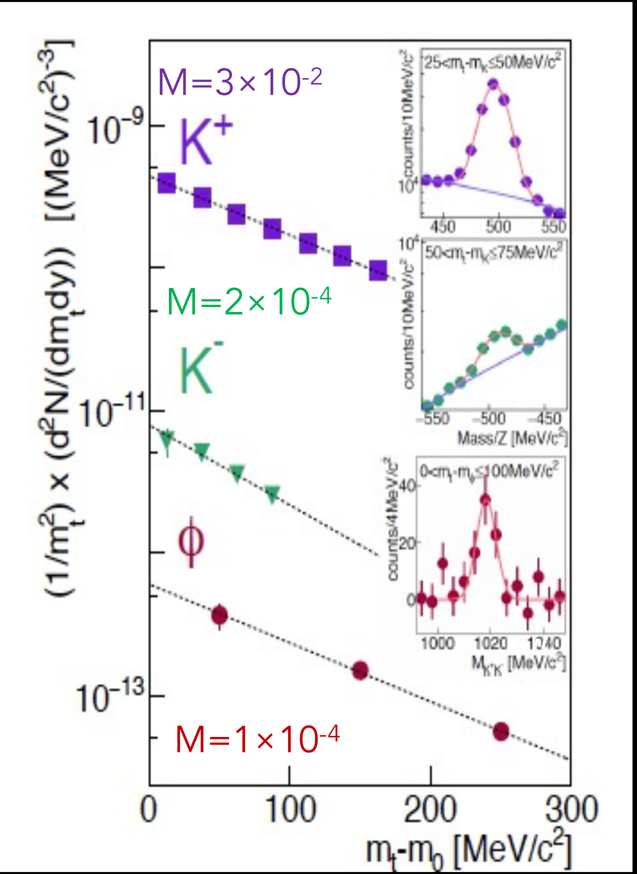


M. Hanauske, J.Phys.: Conf. Series878 012031 (2017)
L. Rezzolla et. al. PRL 122, n0.6, 061101 (2019)

Nature Phys. 15 (2019) 10, 1040-1045

(Sub)-Threshold Strangeness Production

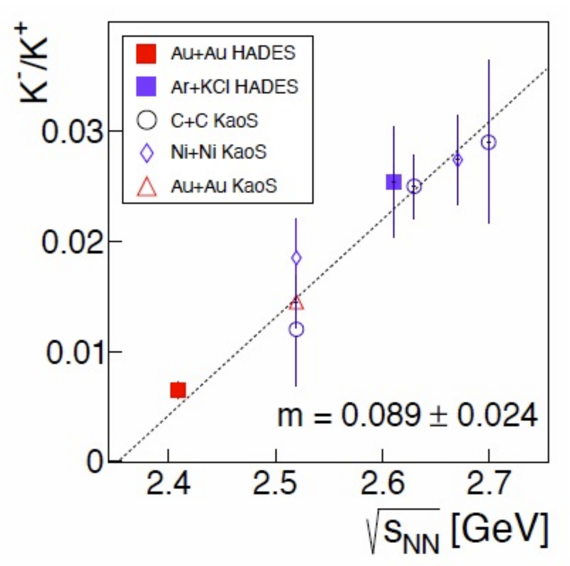
NN→NYK$^+$	$\sqrt{s_{NN}}$= 2.55 GeV
NN→NNK$^+$K$^-$	$\sqrt{s_{NN}}$= 2.86 GeV
NN→NNϕ	$\sqrt{s_{NN}}$= 2.9 GeV



Phys.Lett. B778 (2018) 403-407

K$^+$ yield 2 orders of magnitude higher than K$^-$ and **Φ** yields

Lower inverse slope parameter of K$^-$ compared to K$^+$



KaoS: Phys.Rev. C75 (2007) 024906

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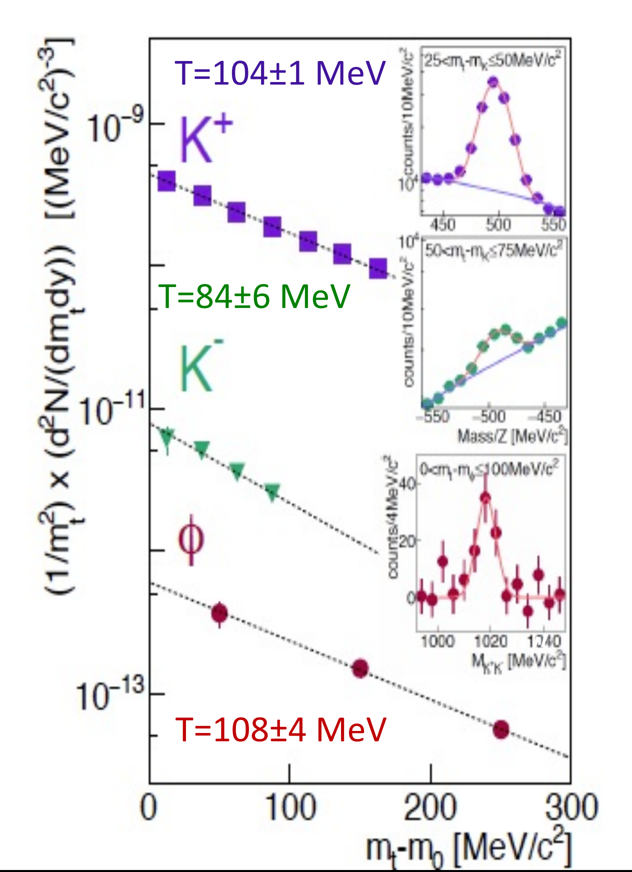
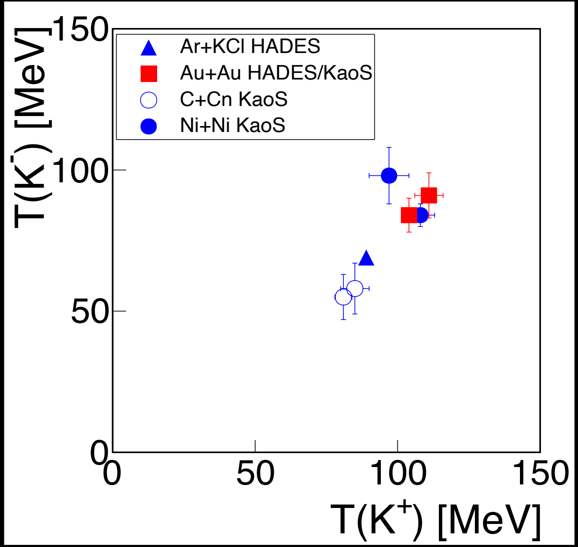


"Later freeze-out of K^- compared to K^+, due to coupling to baryons and strangeness exchange reactions."

Still true if **Φ** is taken into account?

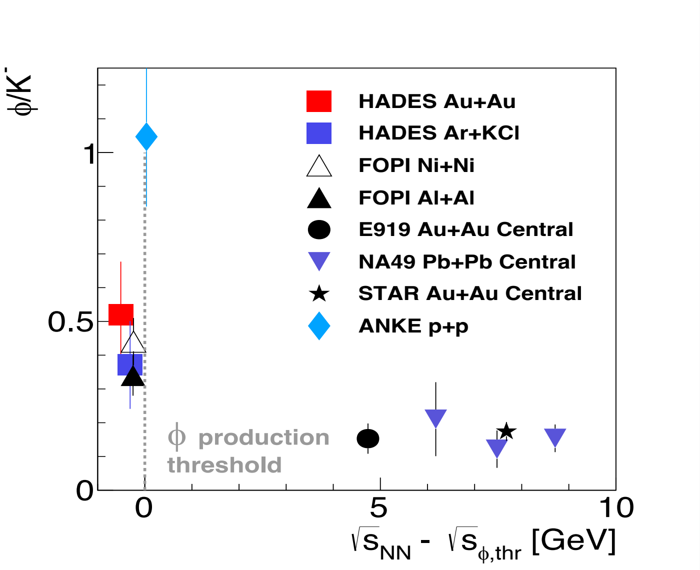
K^+ yield 2 orders of magnitude higher than K^- and **Φ** yields

Lower inverse slope parameter of K^- compared to K^+

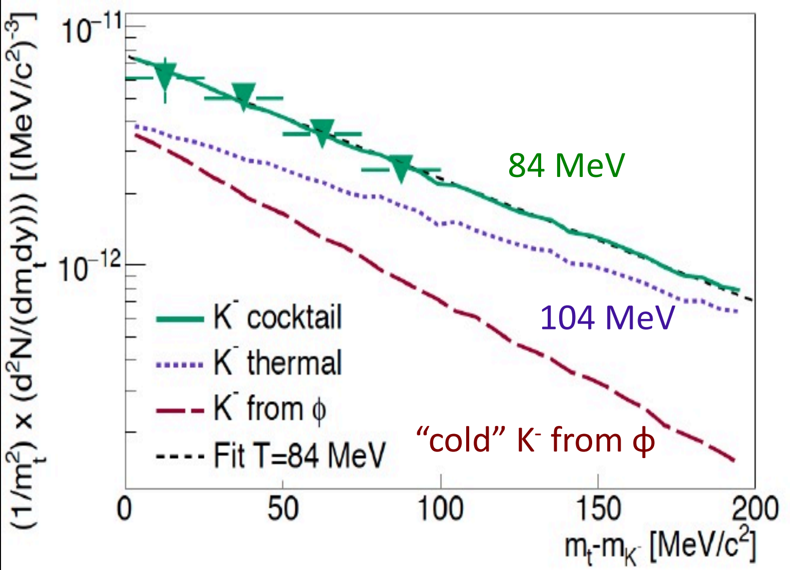


KaoS: Phys.Rev. C75 (2007) 024906

Φ-AntiKaon Interplay in HIC



Increased in HIC at low $\sqrt{s_{NN}}$:
→ 25% of K^- result from **Φ** decays!



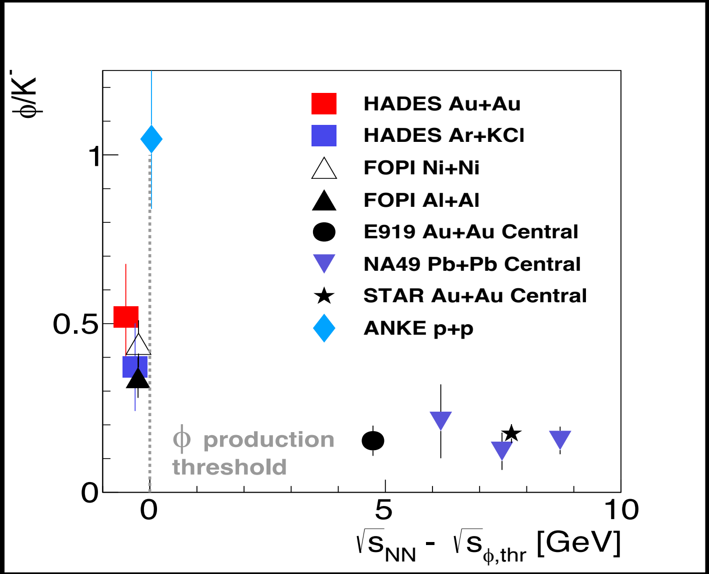
Phys.Lett. B778 (2018) 403-407

Φ feed-down can explain lower inverse slope parameter of K^- spectrum (T_{eff} = 84 ± 6 MeV) in comparison to the one of K^+ (T_{eff} = 104 ± 1 MeV)

→ No indication for sequential K^+K^- freeze-out from K^- spectrum if corrected for feed-down.

M. Lorenz et al. PoS BORMIO2010 (2010) 038

Φ-AntiKaon Interplay in HIC



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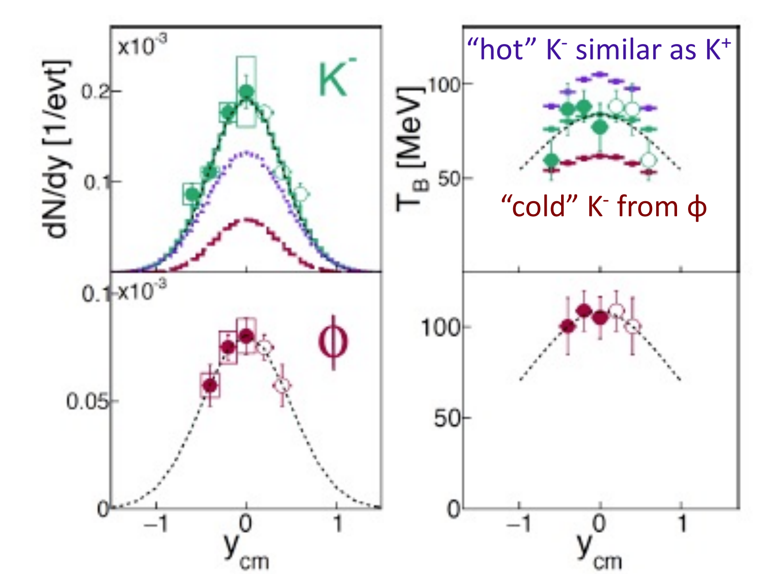

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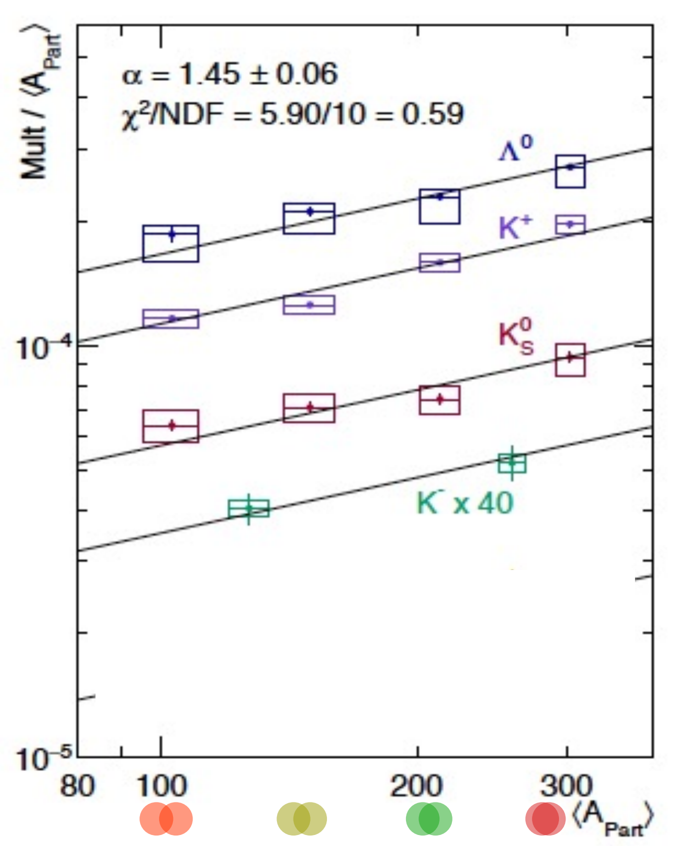
M. Lorenz et al. PoS BORMIO2010 (2010) 038

Centrality Dependence in Au+Au @ $\sqrt{s_{NN}}$=2.4 GeV

Phys.Lett. B793 (2019) 457-463



Complete set of strange hadrons produced below NN-threshold:

NN→NYK$^+$	$\sqrt{s_{NN}}$= 2.55 GeV
NN→NNK$^+$K$^-$	$\sqrt{s_{NN}}$= 2.86 GeV
NN→NNϕ	$\sqrt{s_{NN}}$= 2.9 GeV

→ unique observable:

Energy must be provided by the system.

Strange particle yields rise stronger than linear with

$<A_{part}>$ (M ~ $<A_{part}>^{\alpha}$)

Universal $<A_{part}>$ dependence of strangeness production

→ Hierarchy in production threshold
not reflected in scaling

Scaling with absolute amount of ssbar, not with individual hadron states.

Centrality Dependence in Au+Au @ $\sqrt{s_{NN}}$=2.4 GeV

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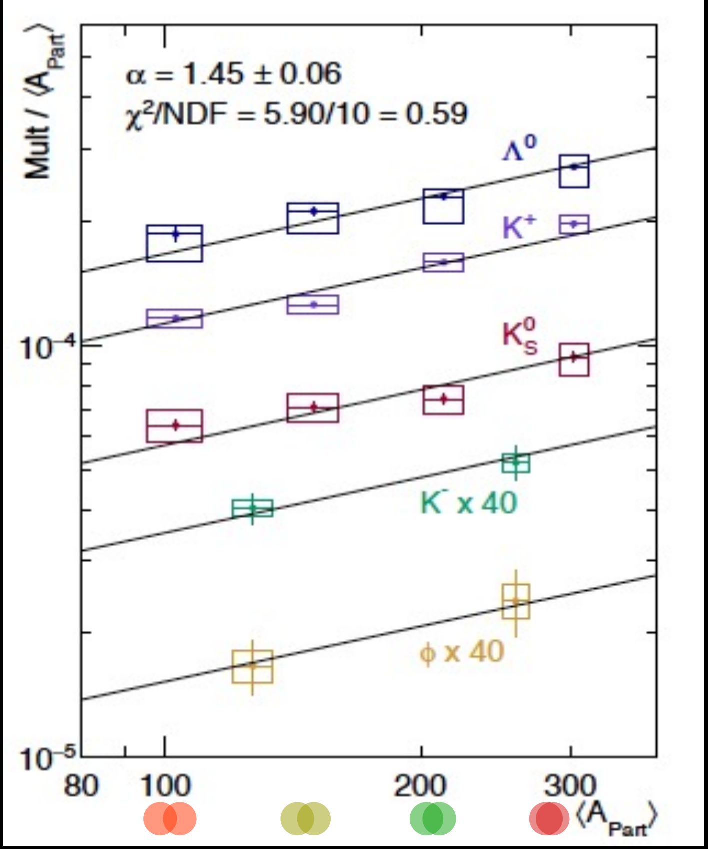

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Universal $<A_{part}>$ dependence of strangeness production

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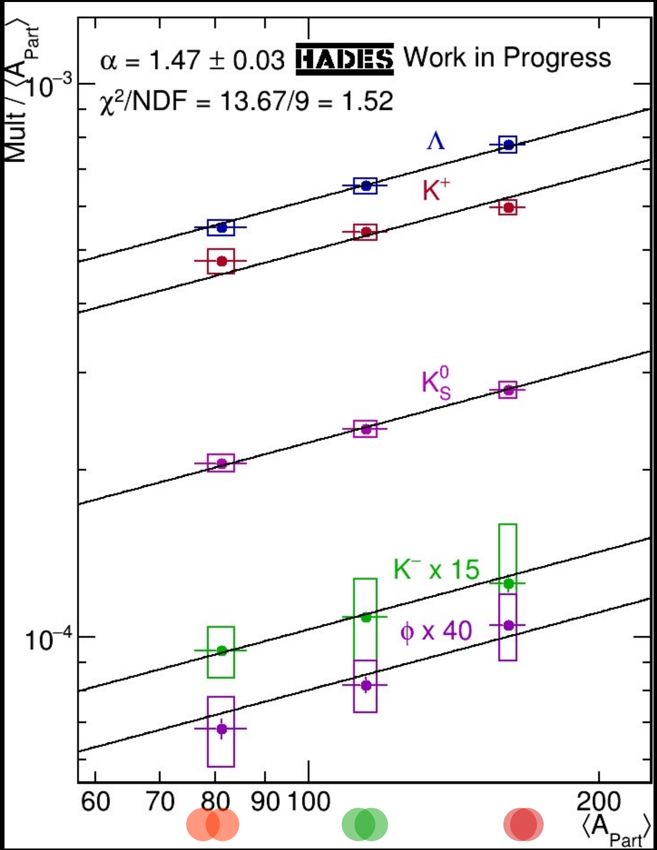
Scaling with absolute amount of ssbar, not with individual hadron states.

Centrality Dependence in Ag+Ag @ $\sqrt{s_{NN}}$=2.55 GeV

Phys.Lett. B793 (2019) 457-463



Complete set of strange hadrons produced at or below NN-threshold:

$NN \rightarrow NYK^+$	$\sqrt{s_{NN}}$= 2.55 GeV
$NN \rightarrow NNK^+K^-$	$\sqrt{s_{NN}}$= 2.86 GeV
$NN \rightarrow NN\phi$	$\sqrt{s_{NN}}$= 2.9 GeV

→ unique observable:

Energy must be provided by the system.

Strange particle yields rise stronger than linear with

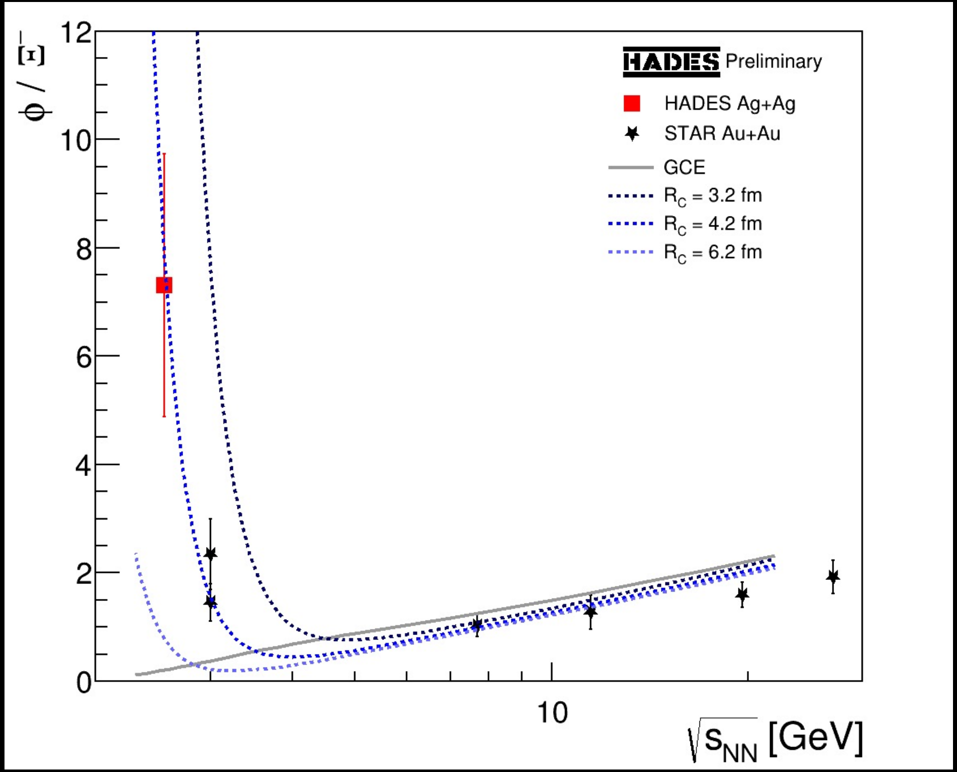
$\langle A_{part} \rangle$ ($M \sim \langle A_{part} \rangle^{\alpha}$)

Universal $\langle A_{part} \rangle$ dependence of strangeness production

→ Hierarchy in production threshold
not reflected in scaling

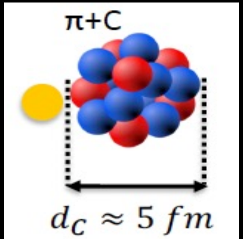
Scaling with absolute amount of ssbar, not with individual hadron states.

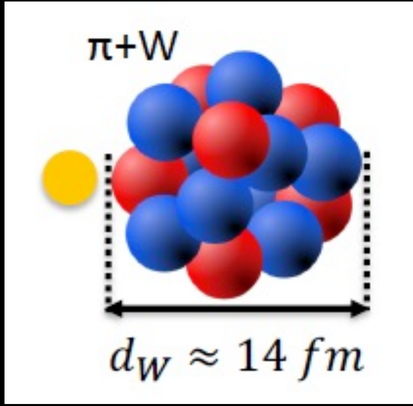
Φ/Ξ^- the yield excitation function in HICs



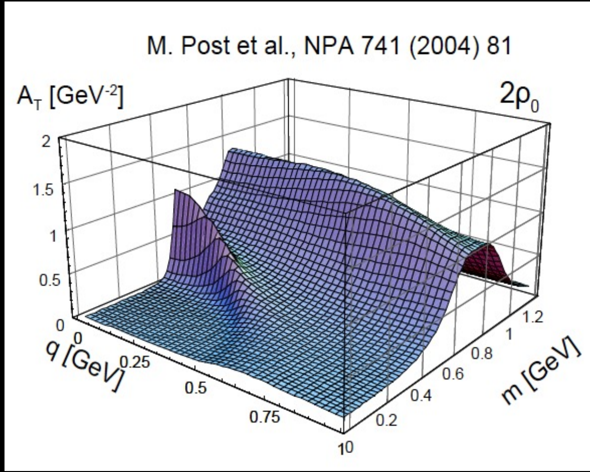
STAR data and model curves: https://arxiv.org/abs/2108.00924

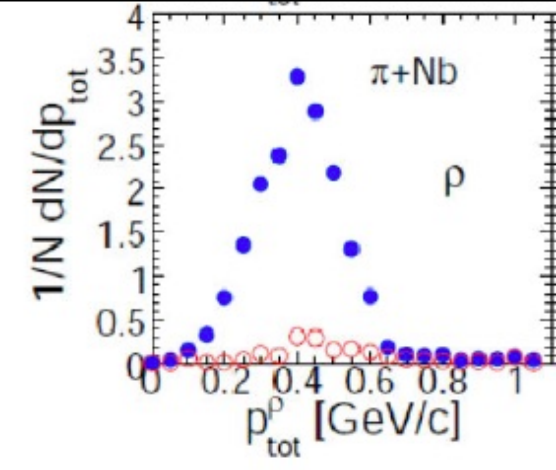
Part 2: Pion Induced Reactions in Cold Nuclear Matter





→ Mean free path $\lambda_\pi = 1.5\ fm$
$(p_\pi = 1.7\ GeV/c\ , \rho_B \approx \rho_0)$



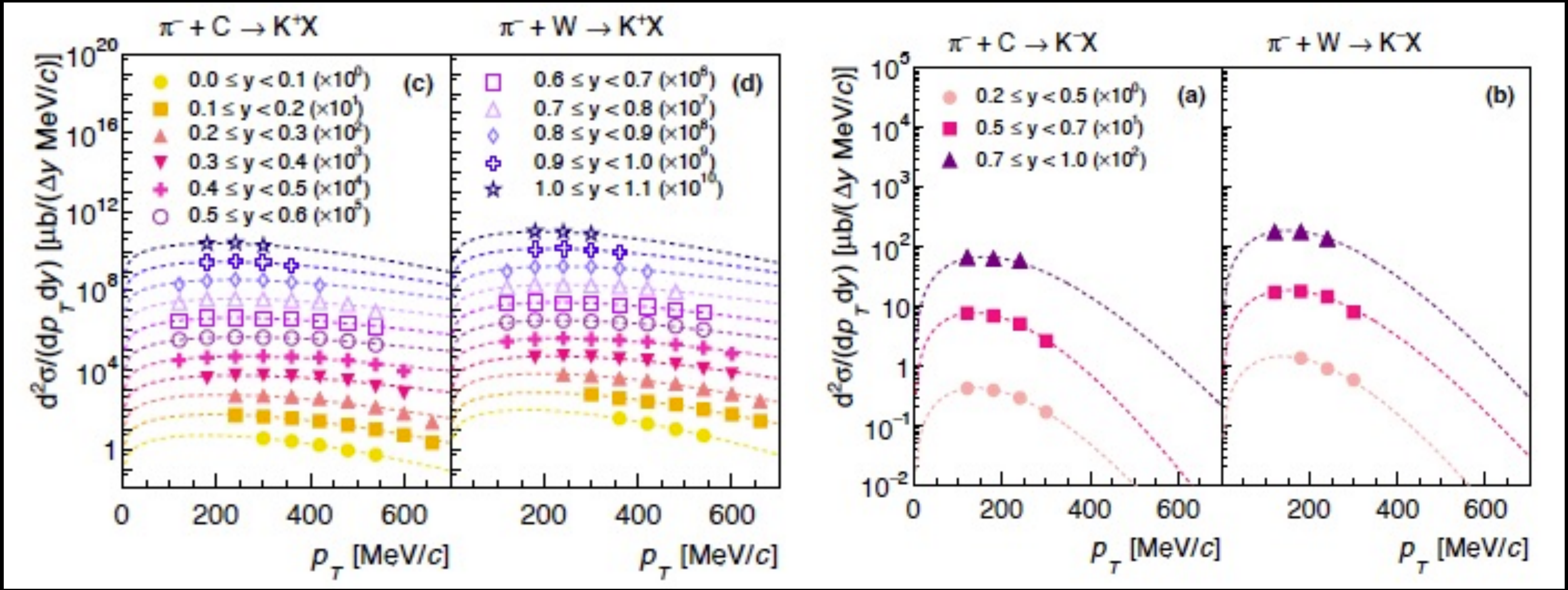


Effects mainly at small momenta
→ Advantage of pion induced compared to p induced reactions

π^- + C @ p_{π^-} = 1.7 GeV/c
1.3×10^8 events collected in 2014

π^- + W @ p_{π^-} = 1.7 GeV/c
1.7×10^8 events collected in 2014

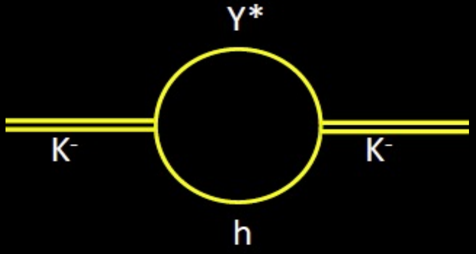
Charged Kaons in Cold Nuclear Matter



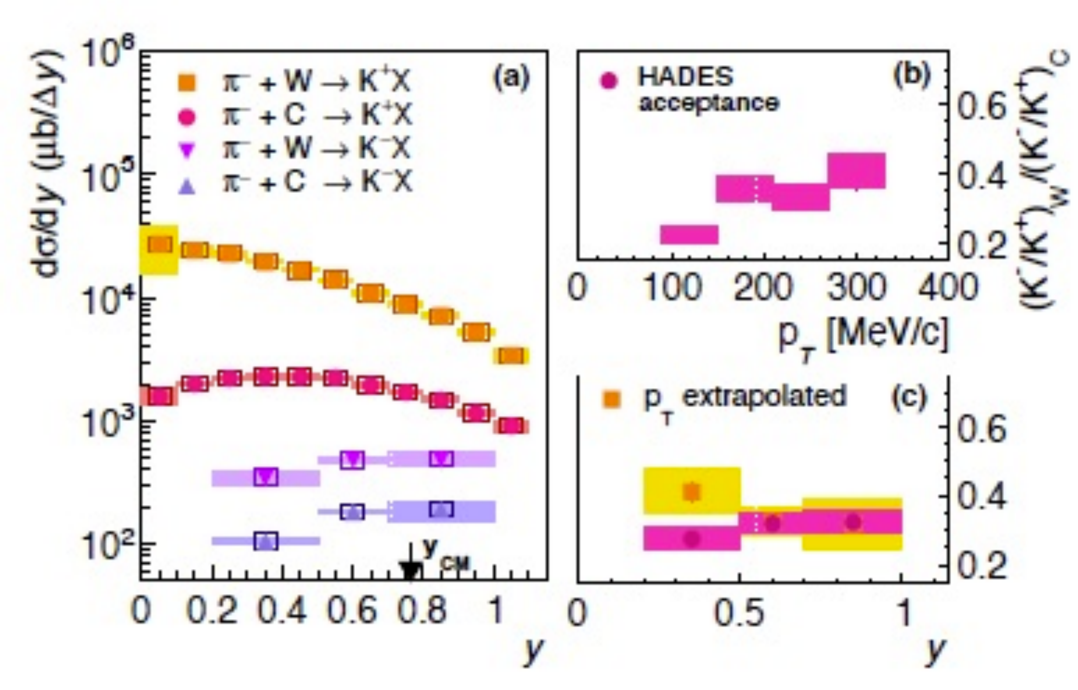
Phys.Rev.Lett. 123 (2019) 2, 022002

K^- production relative to K^+

K^- -baryon coupling



not possible for K^+



Phys.Rev.Lett. 123 (2019) 2, 022002

→ Suppression of K^- relative to K^+

ϕ production relative to K^-

Phys.Rev.Lett. 123 (2019) 2, 022002

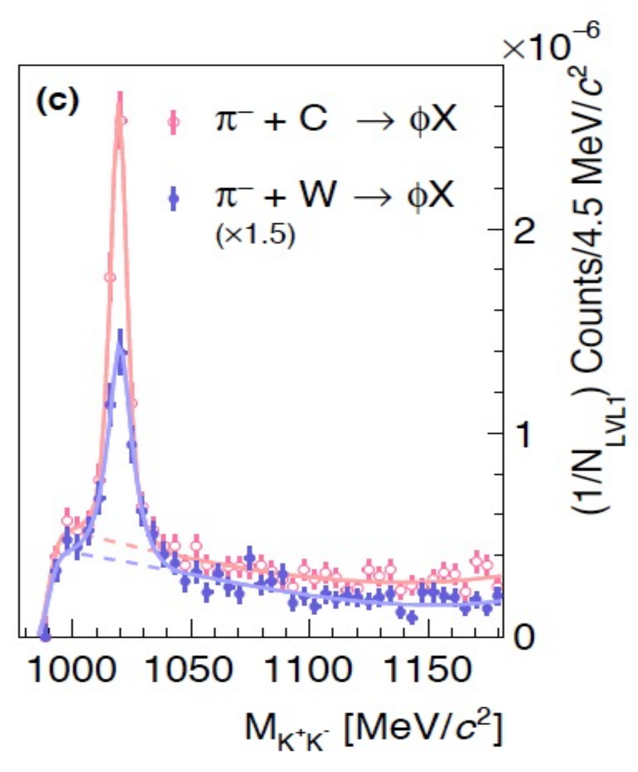


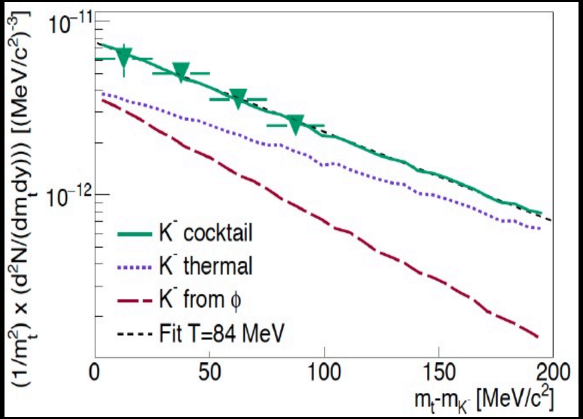
TABLE II. Particle ratios inside the HADES acceptance. Error values shown are statistic (first), systematic (second) and normalization (third).

Ratios	
$(K^-/K^+)_W/(K^-/K^+)_C$	$0.319 \pm 0.009^{+0.014}_{-0.012}$
$(\phi/K^-)_C$	$0.55 \pm 0.03^{+0.06}_{-0.07}$
$(\phi/K^-)_W$	$0.63 \pm 0.05 \pm 0.11$
$T = \frac{12}{184}\frac{\Delta\sigma^{\phi}_{W}}{\Delta\sigma^{\phi}_{C}}$	$0.18 \pm 0.02 \pm 0.01^{+0.04}_{-0.03}$

→ Similar suppression for ϕ like for K^-

→ see Volker's talk

Summary

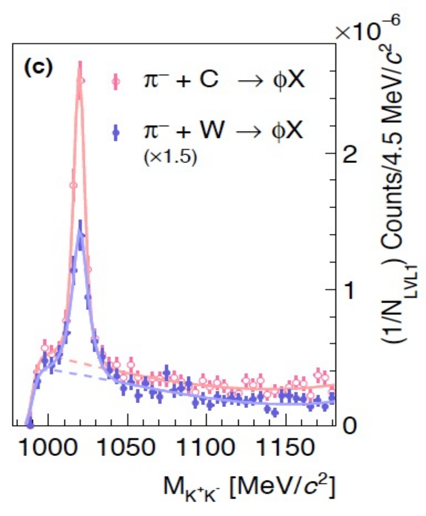


Part 1: Heavy-ion Collisions

Φ yield increases relative to K^- with decreasing $\sqrt{s_{NN}}$.

Universal $\langle A_{part} \rangle$ dependence of strangeness production.

No indication for sequential K^+K^- freeze-out from K^- spectrum if corrected for feed-down.

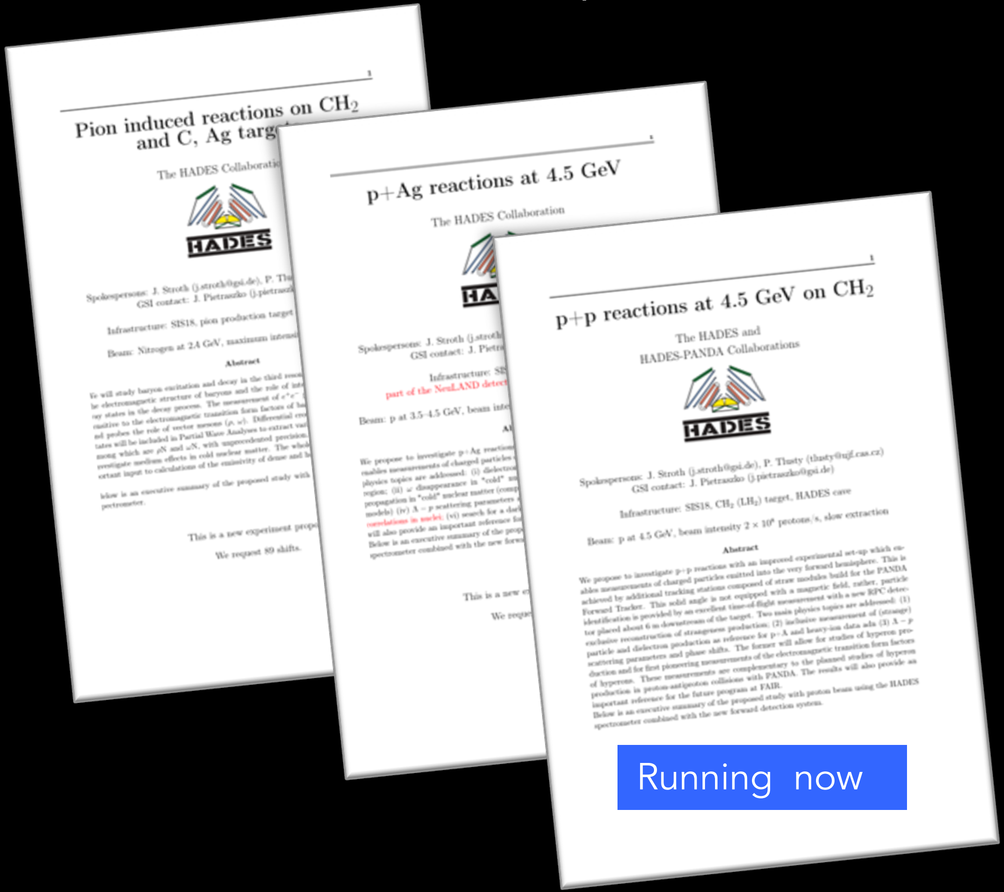


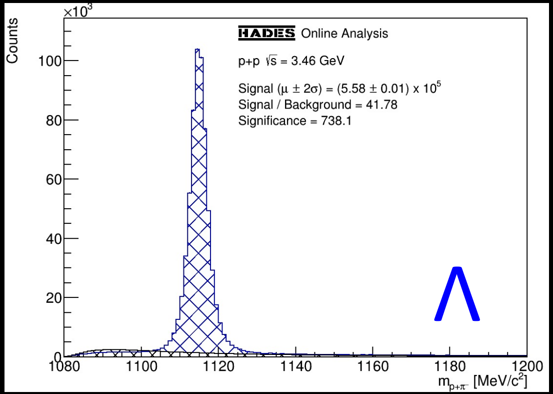
Part 2: Pion Induced Reactions in Cold Nuclear Matter

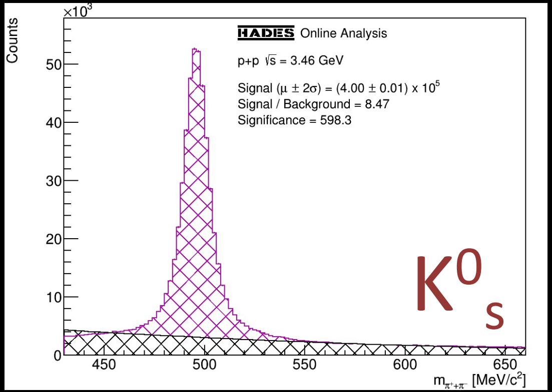
K^- are suppressed relative to K^+.
Similar suppression as for ***Φ*** mesons as for K^-.

Thank you!

Proposals for beam time at SIS18: 2021 - 2025



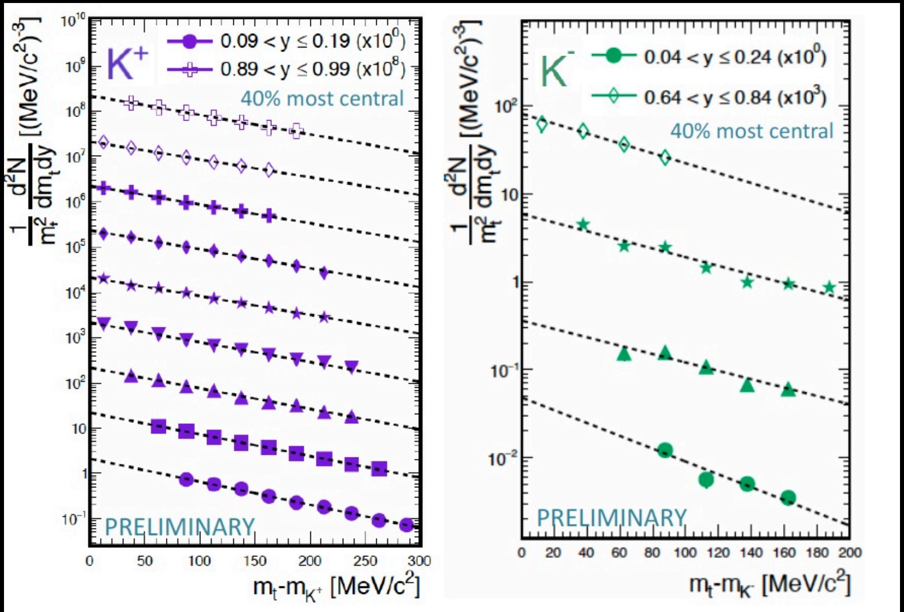




The Team

Back Up

(Sub-threshold) Strangeess Production

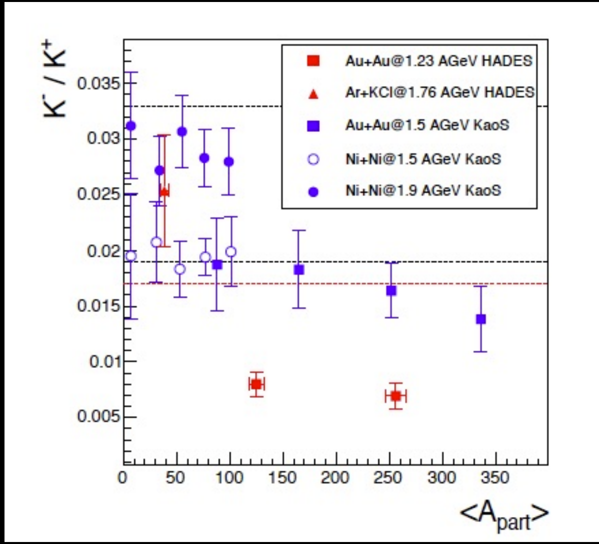


$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = C(y)\exp\frac{-(m_t - m_0)c^2}{T_B(y)}$$

$T_B^{K+}(y_{mid}) = 104 \pm 2$ MeV

$T_B^{K-}(y_{mid}) = 84 \pm 6$ MeV

KaoS: Phys.Rev. C75 (2007) 024906



Kaons and antikaons show different slopes