HADRONS from HADES

Manuel Lorenz for the Collaboration

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GSI

HIC for FAIR Helmholtz International Center

Outline

So far so good:

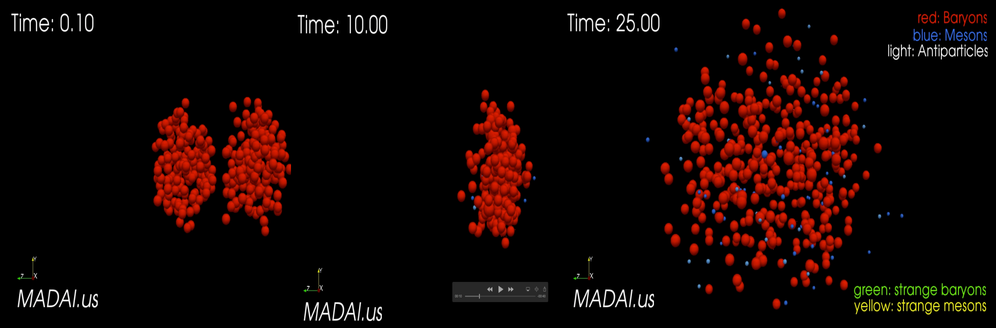
- ϕ/K^- and K^- freeze-out
- Hadron yields vs. SHM

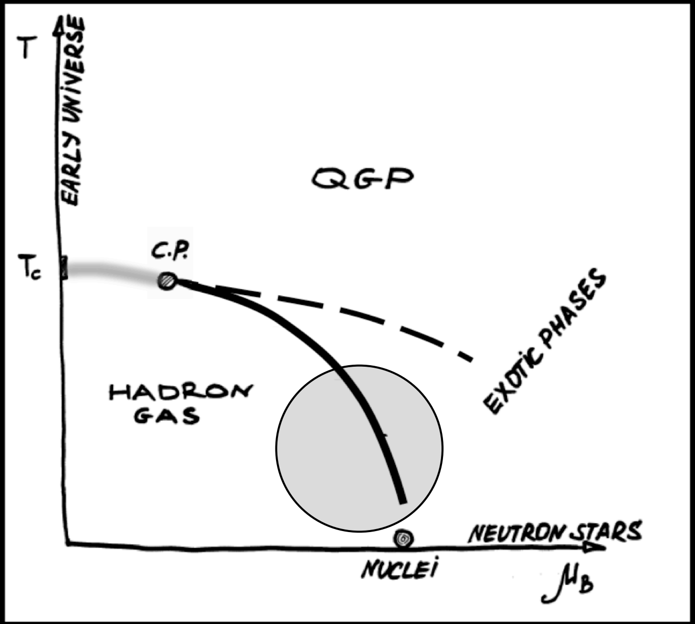
What's the deal? A closer look:

- Macroscopic description
  - Systematic comparison of yields vs. SHM
  - Kinetic vs. chemical freeze-out
- Microscopic description
  - Strangeness
  - Light nuclei

Summary and Outlook

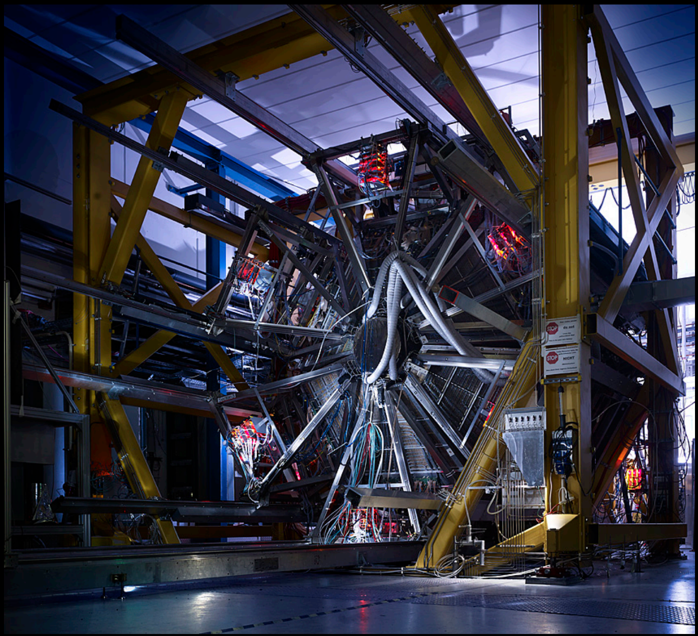
Au+Au collisions at $\sqrt{s_{NN}}$=2.4 GeV





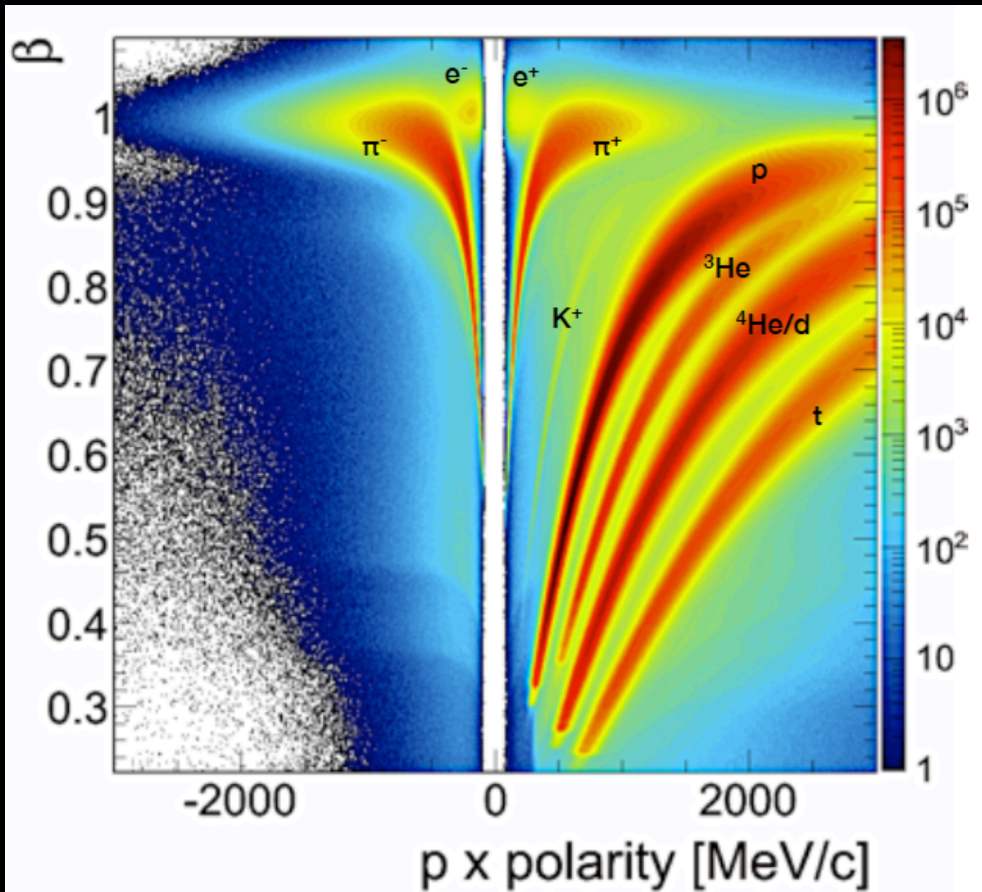
Long interpenetration times
Baryon stopping in the collision zone

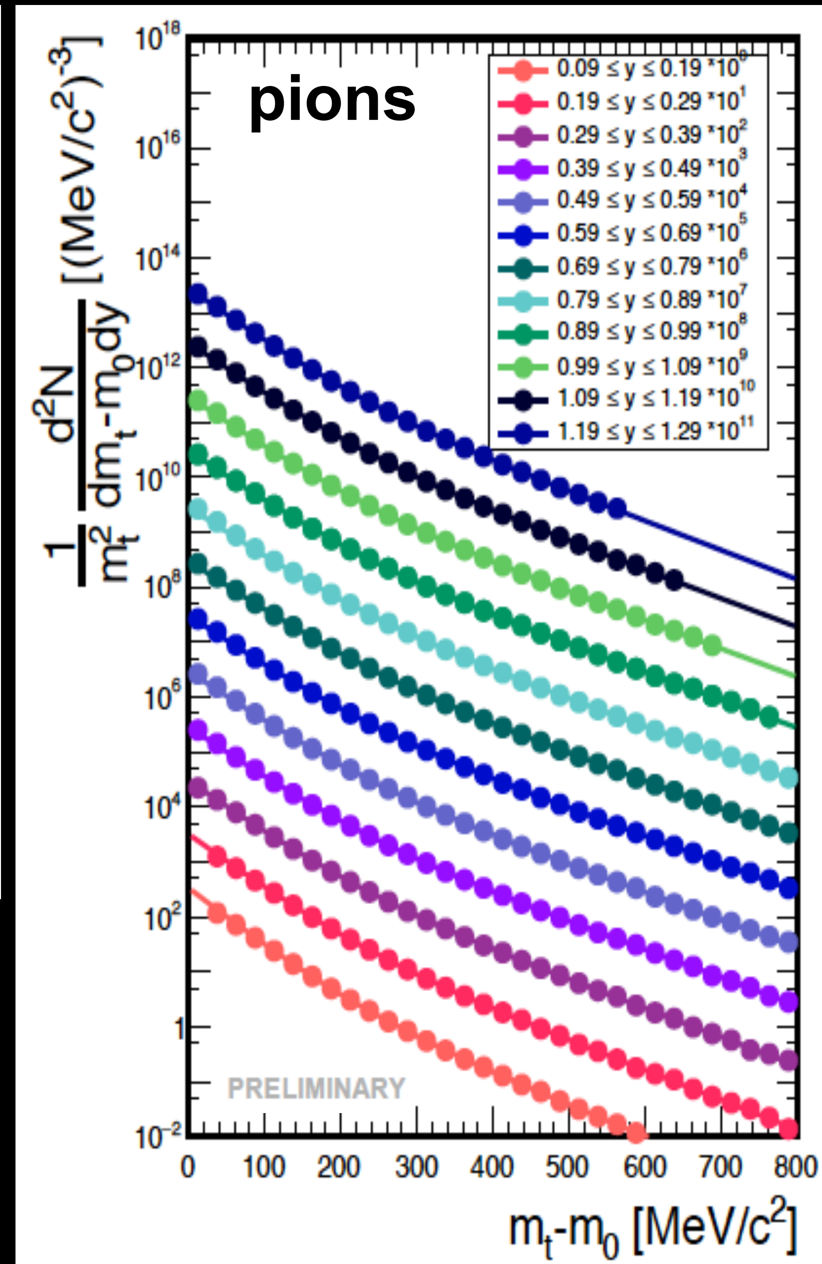
→ Baryon dominated system



→ Fast detectors with high acceptance
7×10^9 events collected in 4 weeks

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





→ Baryon dominated system
clear hierarchy in hadron yields:
p ≈ 100, π ≈ 10, $K^+ \approx 10^{-2}$, $K^- \approx 10^{-4}$
and ≈ 50 p bound in light nuclei!

→ Fast detectors with high acceptance
7×10^9 events collected in 4 weeks

So far so good

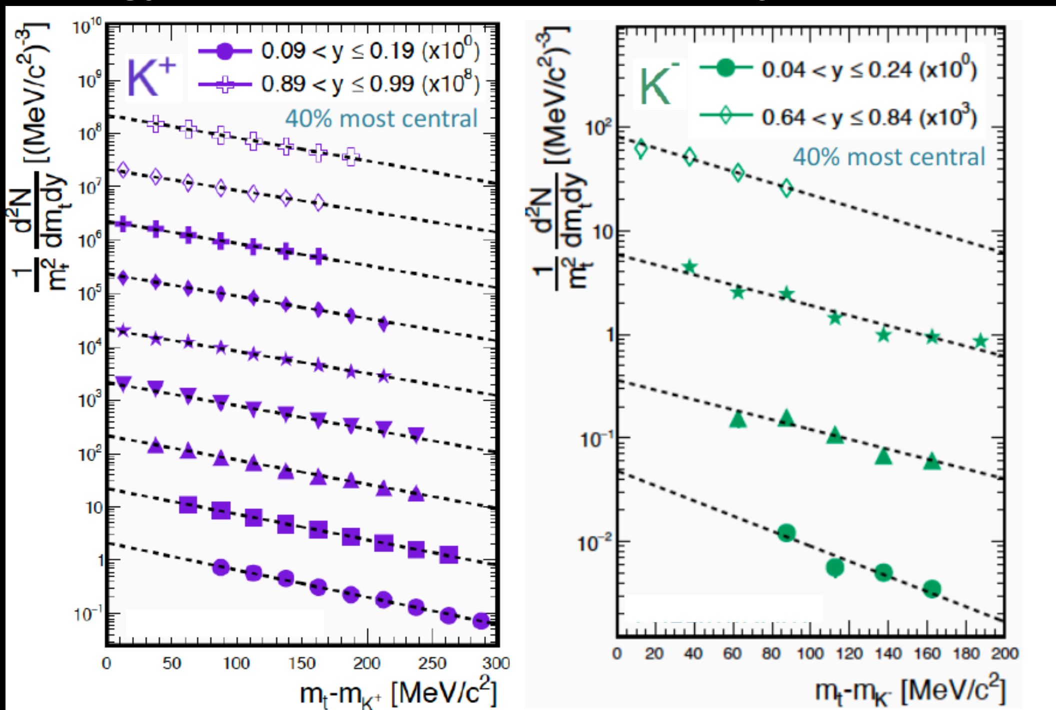
(Sub-Threshold) Strangeness Production

Unique observable:
Not produced in binary NN collisions at $\sqrt{s_{NN}}$= 2.4 GeV, micro-canonical ensemble Z(E,N,V).

NN→NYK^+: $\sqrt{s_{NN}}$= 2.55 GeV, NN→NNK^+K^-: $\sqrt{s_{NN}}$= 2.86 GeV (strong K^- suppression).

Energy must be provided from the system.

KaoS: Phys.Rev. C75 (2007) 024906

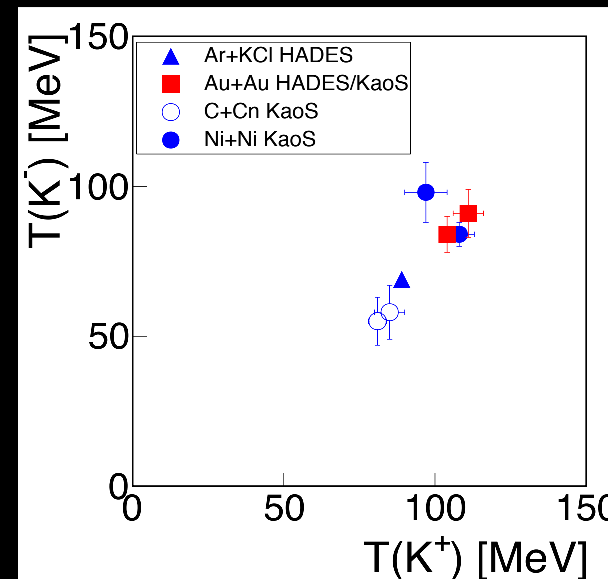


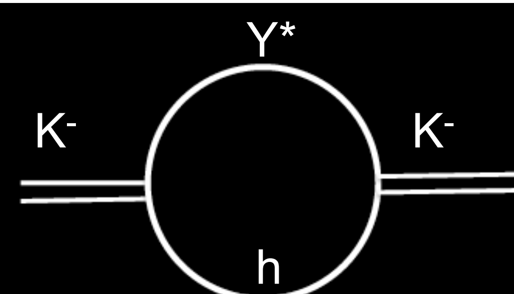
$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = C(y)\exp\frac{-(m_t - m_0)c^2}{T_B(y)}$$

$T_B^{K+}(y_{mid})$ = 104 ± 2 MeV

$T_B^{K-}(y_{mid})$ = 84 ± 6 MeV

Kaons and antikaons show different slopes

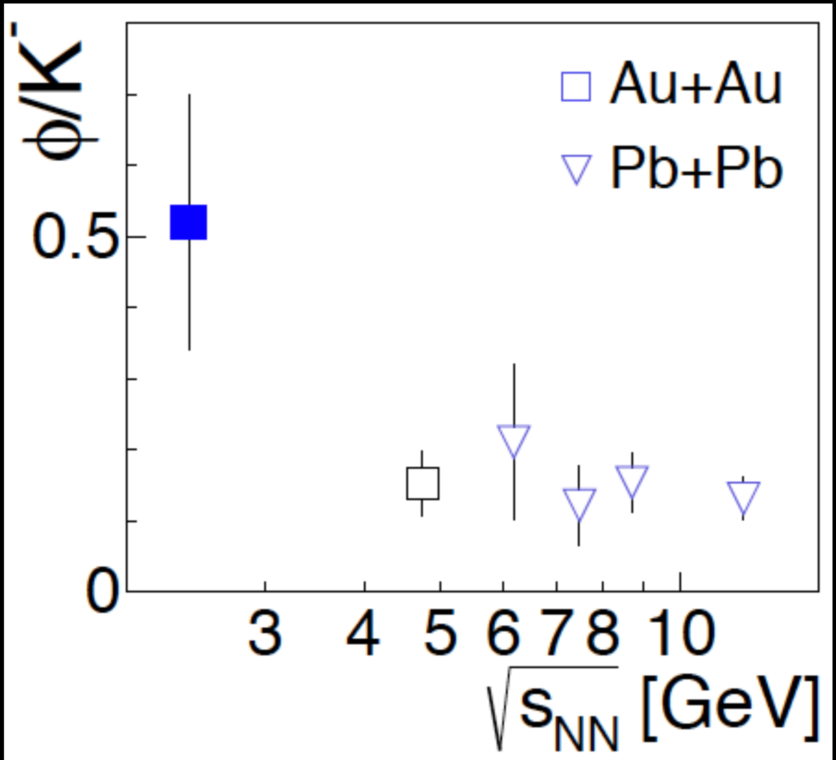


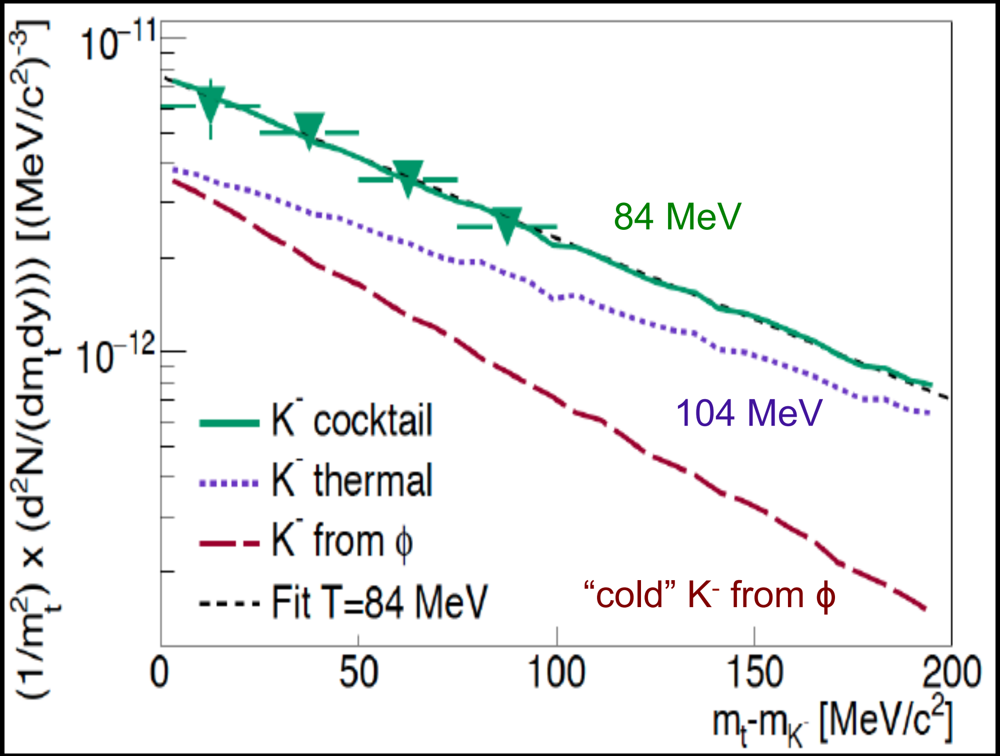


"Later freeze-out of K^- compared to K^+, due to coupling to baryons and strangeness exchange reactions ??"

(Sub-threshold) Strangeness Production

Phys.Lett. B778 (2018) 403-407





Increased in Au+Au collisions at low energies
→ 25% of K^- result from Φ decays!

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)

(Sub-threshold) Strangeness Production

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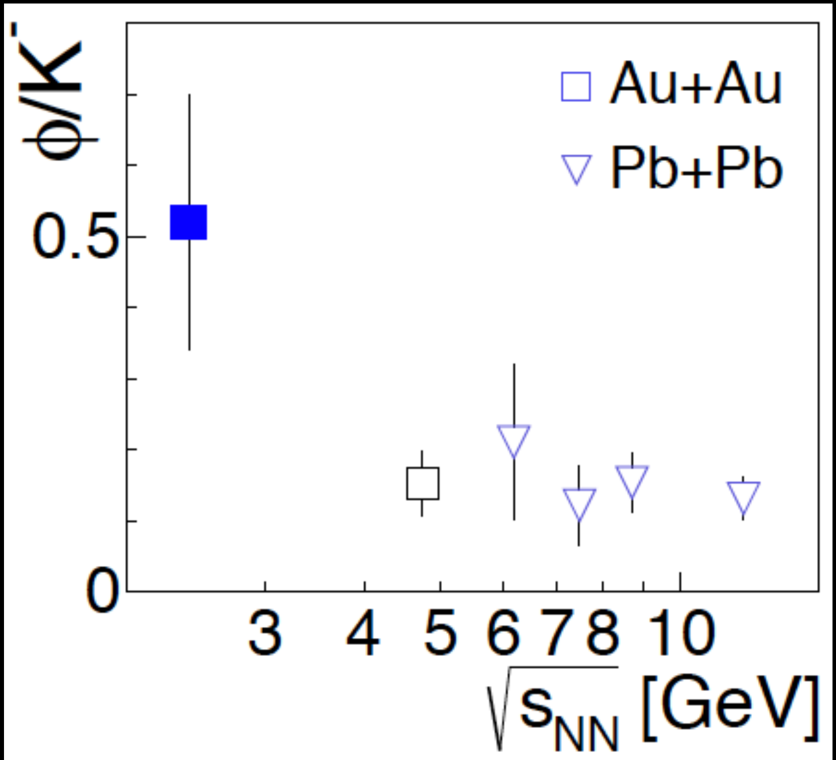
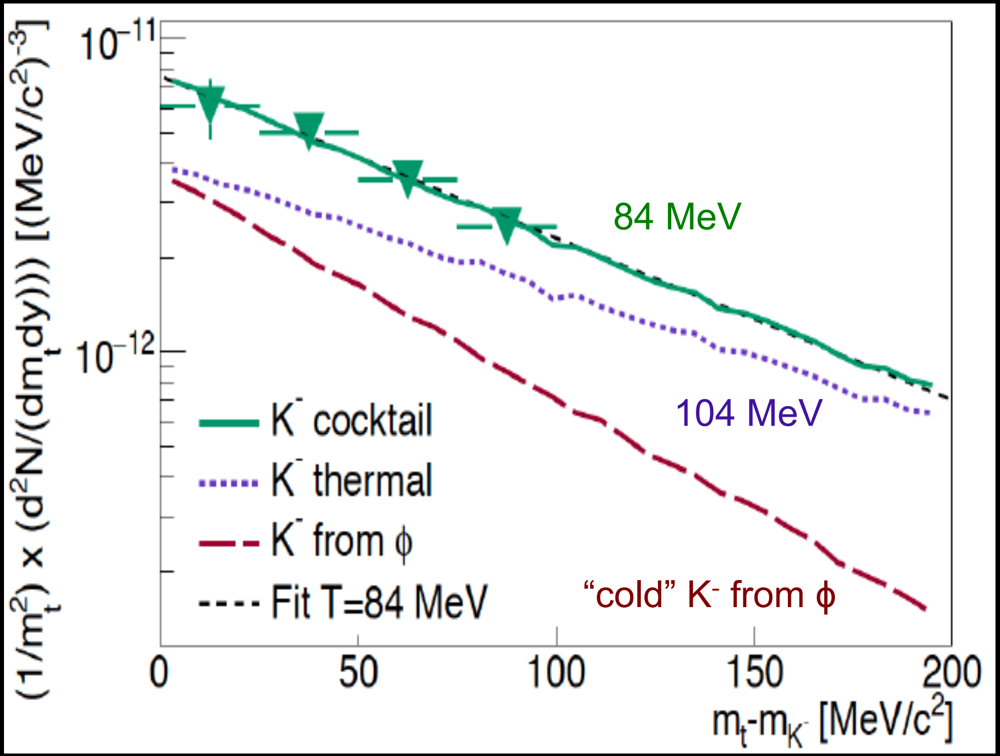


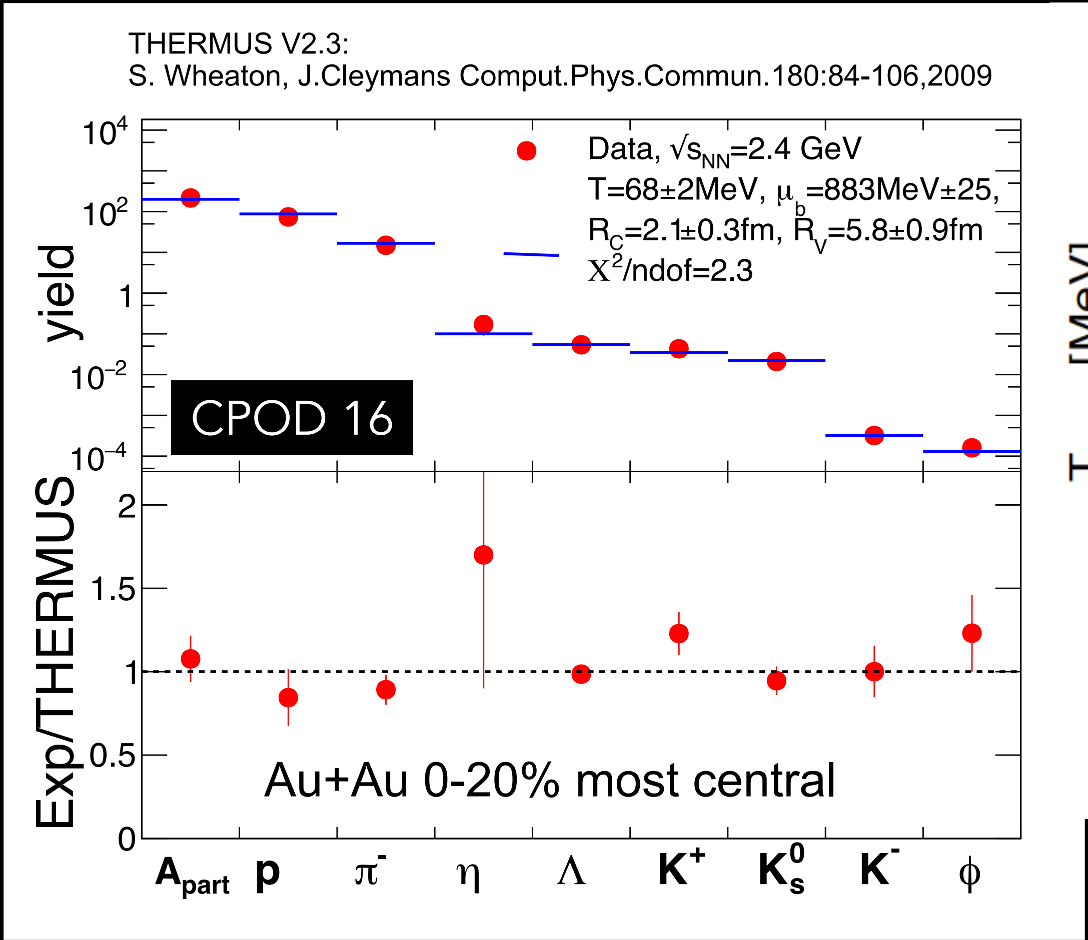


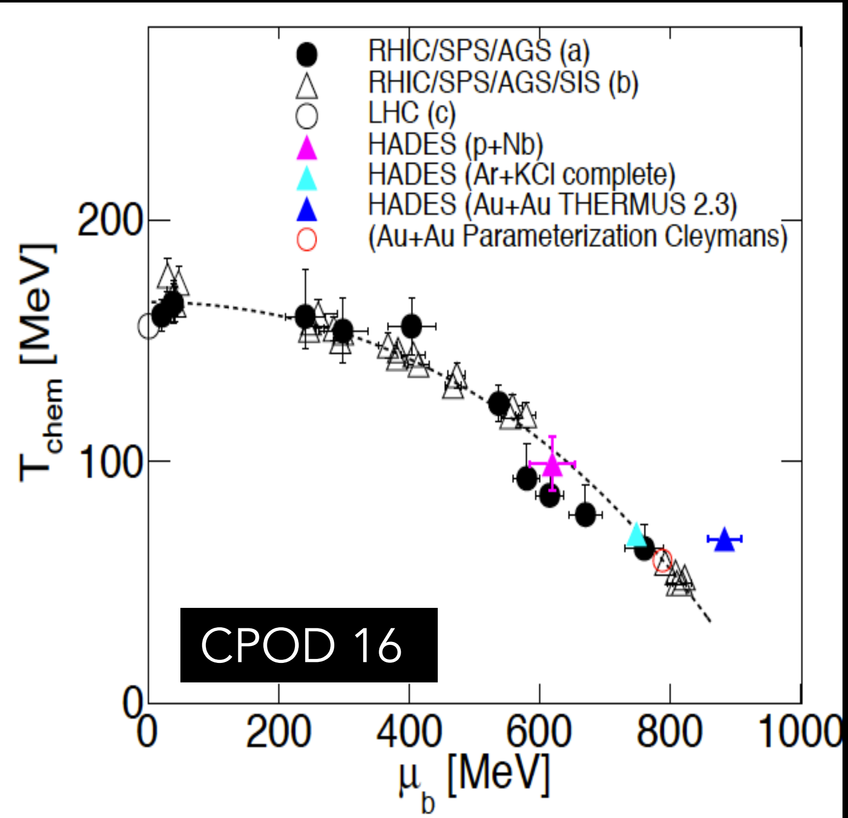
Increased in Au+Au collisions at low energies
→ 25% of K^- result from Φ decays!

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 if K^- spectrum is corrected for feed-down.

Hadron yields vs. SHM





Freeze-out point at higher T and μ_B than expected from parameterization and previous fits.

Hadron yields described by 4 parameters (T, μ_B, R, R_c)

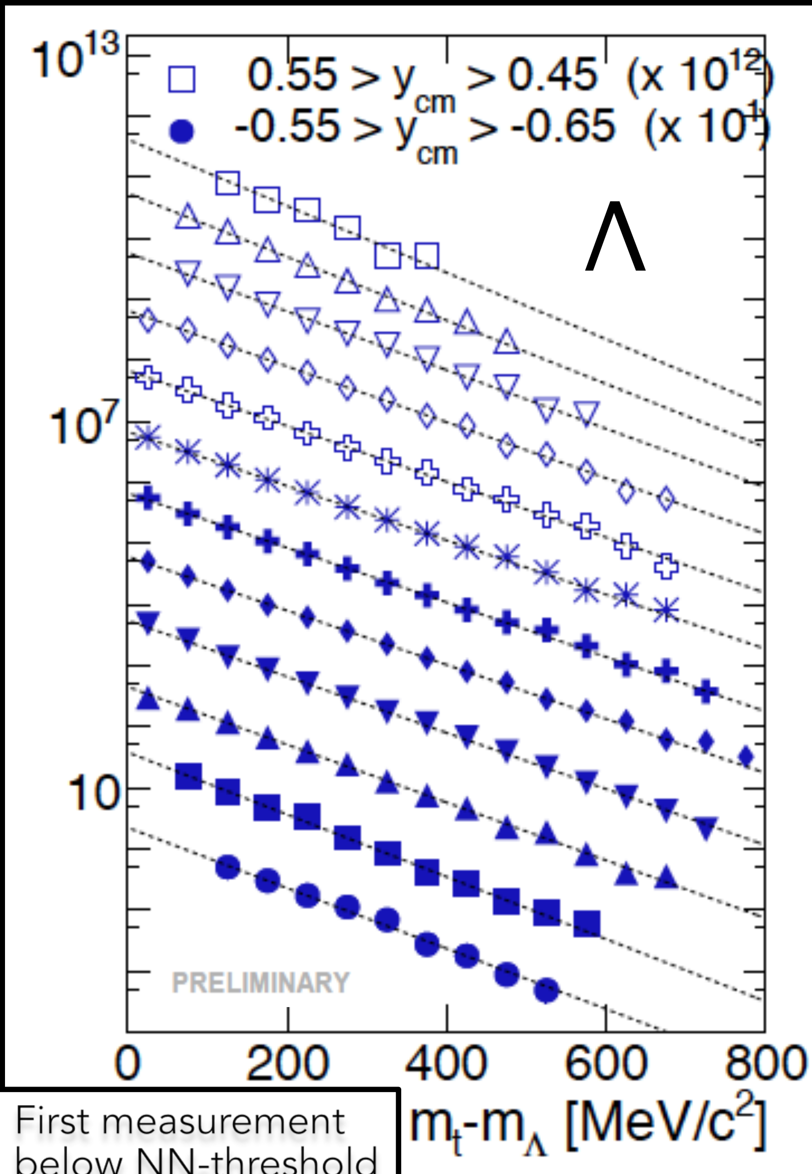
Freeze-out points:
A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature 561 (2018) no.7723, 321
A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl.Phys. A 772, 167 (2006).
J. Cleymans, H. Oeschler, K. Redlich and S. Wheaton, Phys. Rev. C 73, 034905 (2006).
Parameterization: Cleymans, Oeschler et al, Phys.Rev.C73:034905, (2006).

[1]R. Hagedorn, K. Redlich Z.Phys. C27 (1985) 541

What’s the deal?
A closer look.

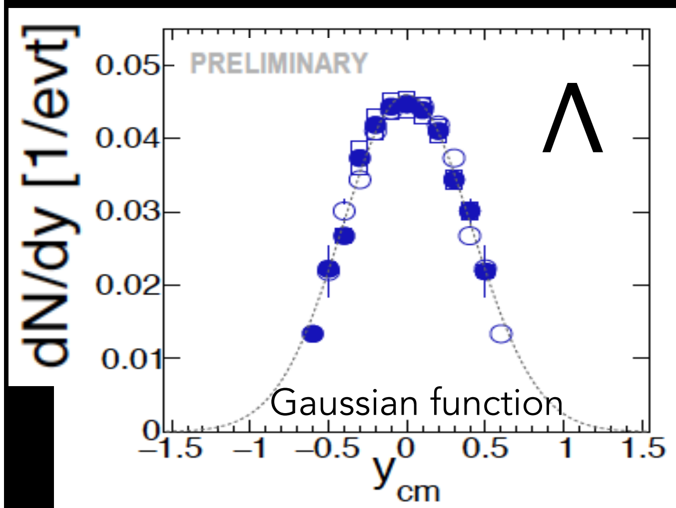
Sub-threshold strangeness production

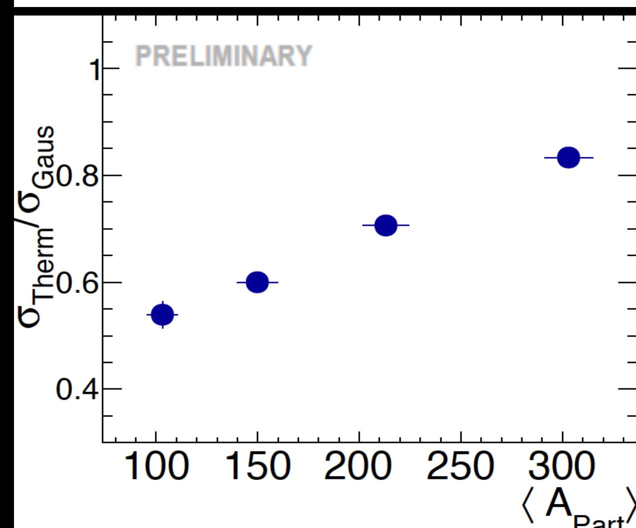
Not produced in binary NN collisions at $\sqrt{s_{NN}}$= 2.4 GeV. NN→NΛK⁺: $\sqrt{s_{NN}}$= 2.55 GeV.



First measurement below NN-threshold

Transverse mass spectra can be described by single slope Boltzmann distribution.





Wide range of the rapidity distribution measured.

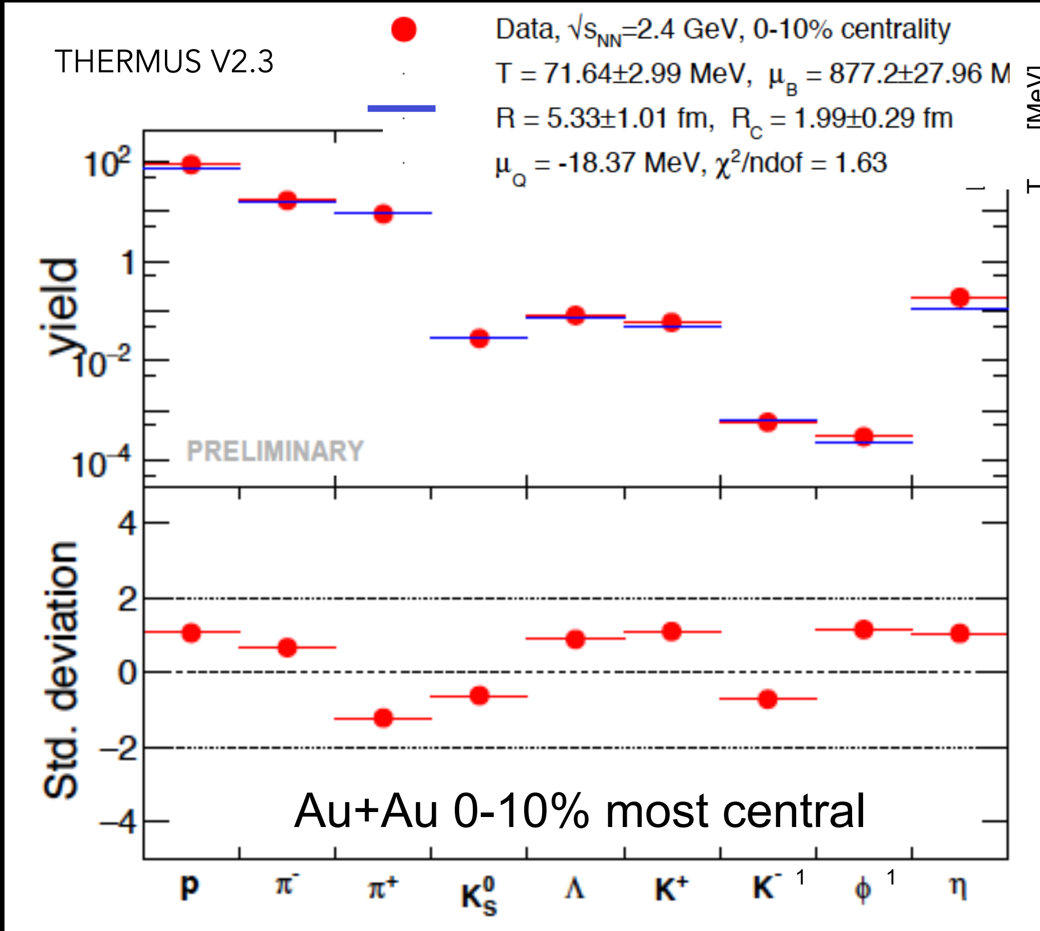
For thermal source:

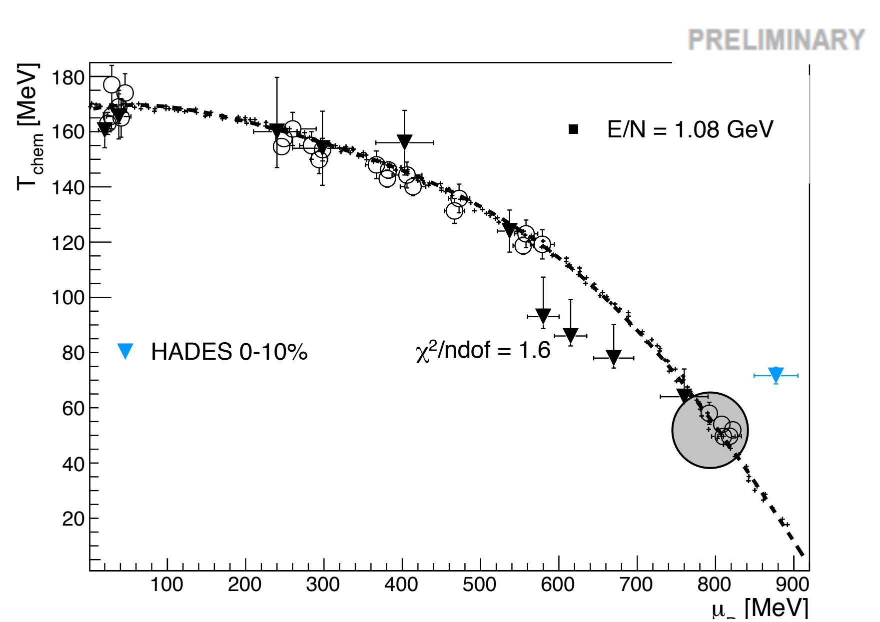
$$\sigma_{Therm} = \sqrt{\frac{T_{eff}}{m_0 c^2}},$$

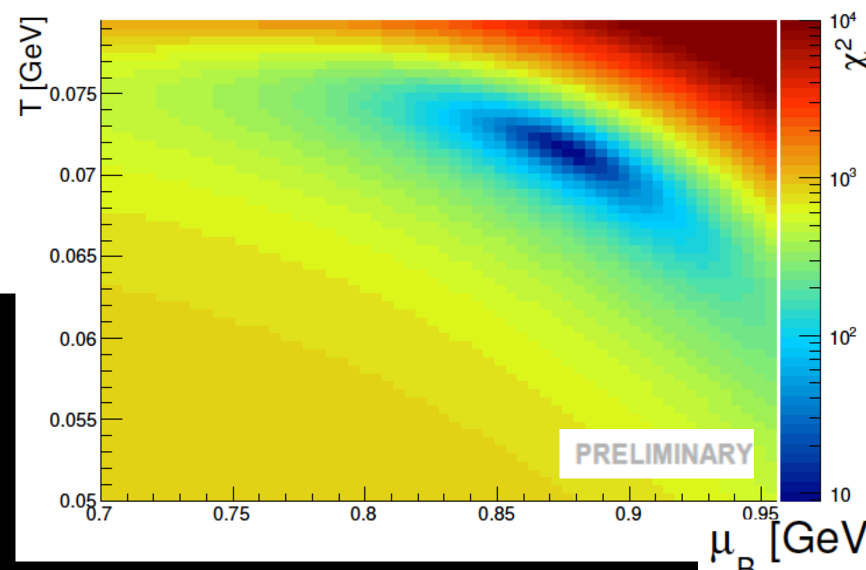
Momentum distribution not isotropic even in most central events

MA S. Spies

Macroscopic Description



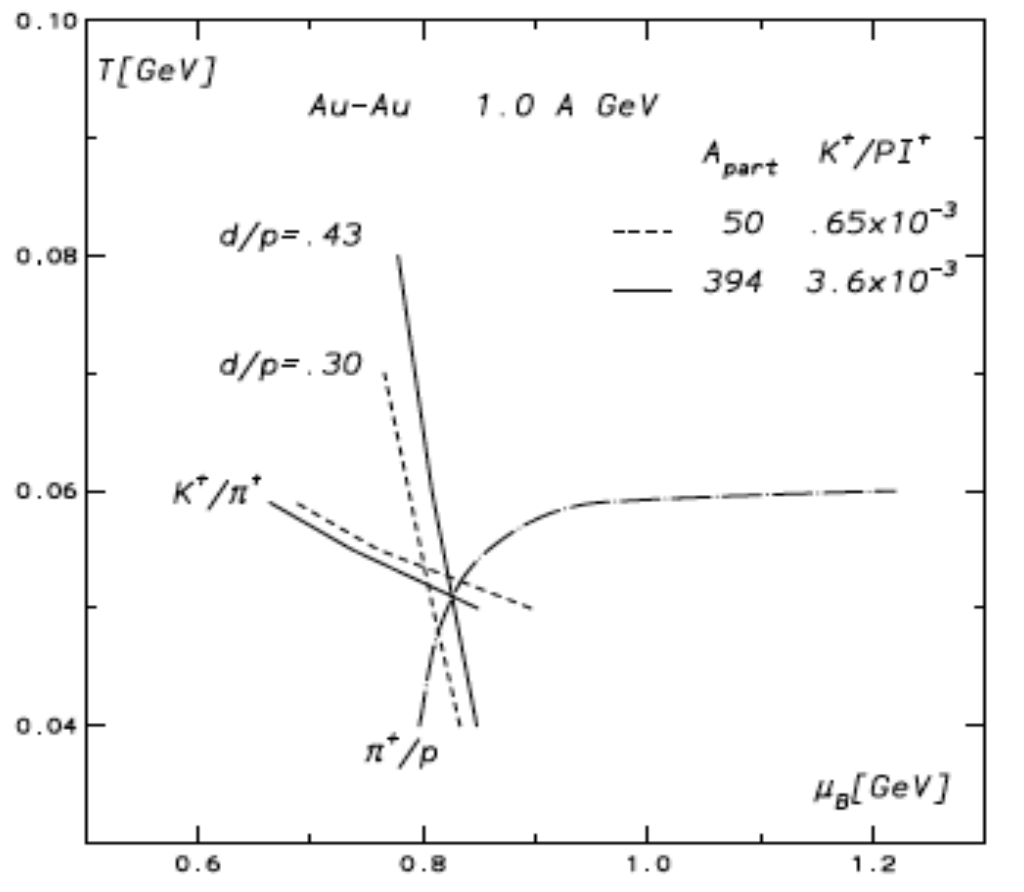


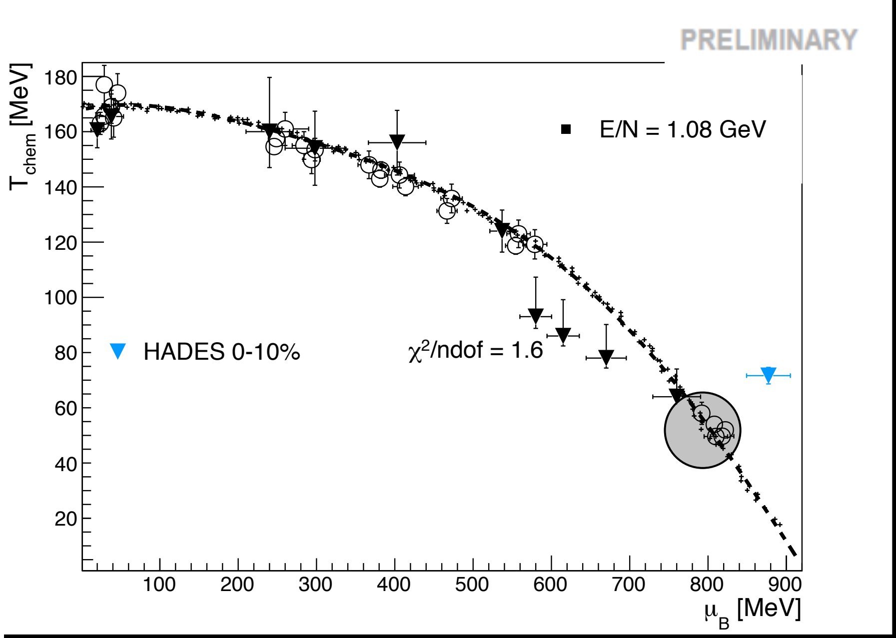


- Freeze-out point stays at higher T and μ_B also for 0-10% most central events
- X^2 scan: no minimum near expected freeze-out
- Which hadron yields drive the fit away?

[1] scaled from 0-20% most central

Macroscopic Description

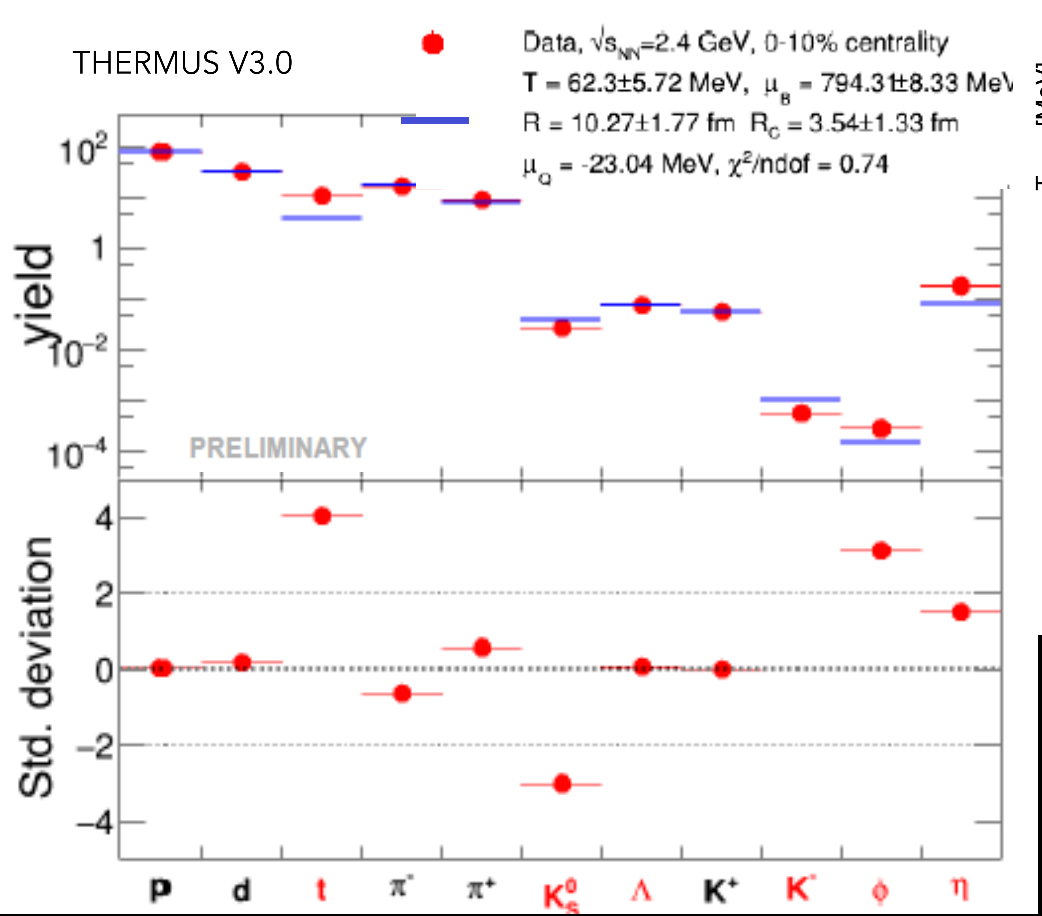


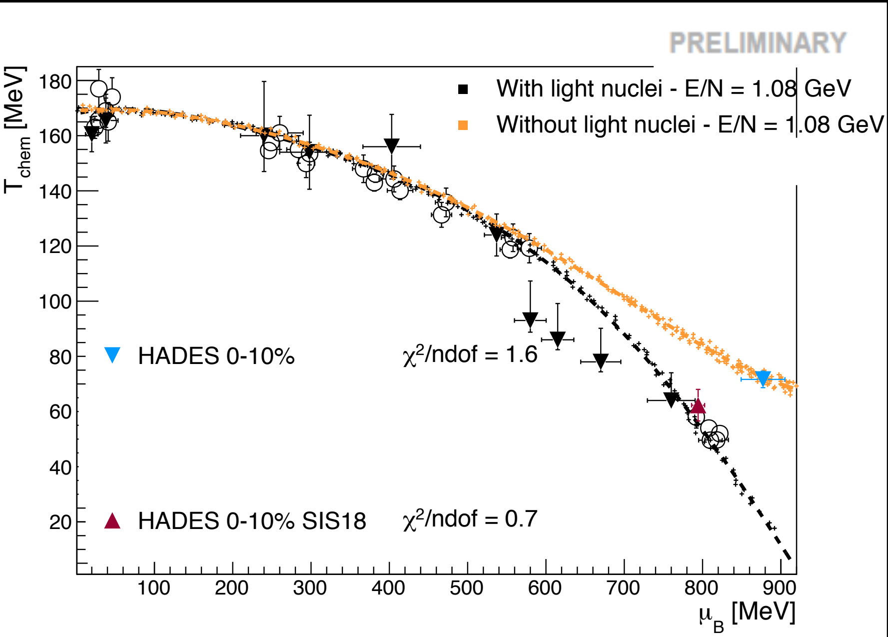


J. Cleymans, H. Oeschler, K. Redlich, Phys.Rev. C59 (1999)

- Freeze-out points previously estimated based on ratios of p, d, K^+, π^+
- Light nuclei are not included in Thermus V2.3
  Switch to Thermus V3.0 or Thermal-Fist https://github.com/vlvovch/Thermal-FIST

Macroscopic Description





J. Cleymans, H. Oeschler, K. Redlich, Phys.Rev. C59 (1999)

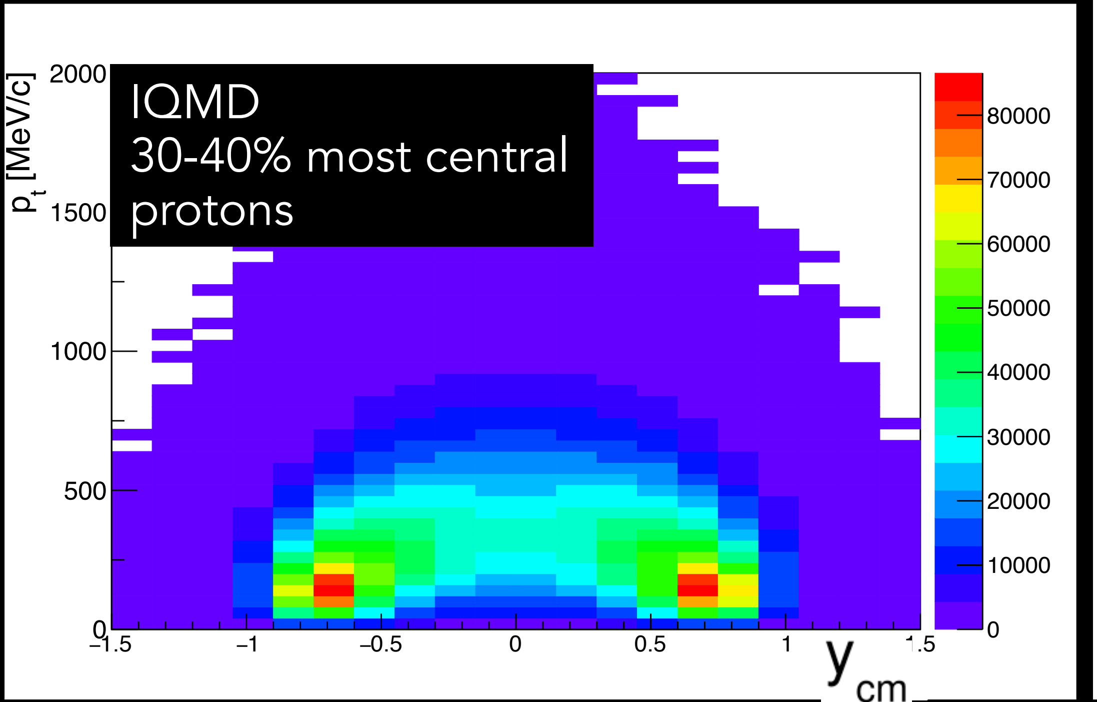
- Fit to HADES data consistent with previous works when same hadron yields are used
- E/N=1.08 GeV with or without light nuclei?
- Light nuclei are important to define chemical freeze-out line at high μ_B.

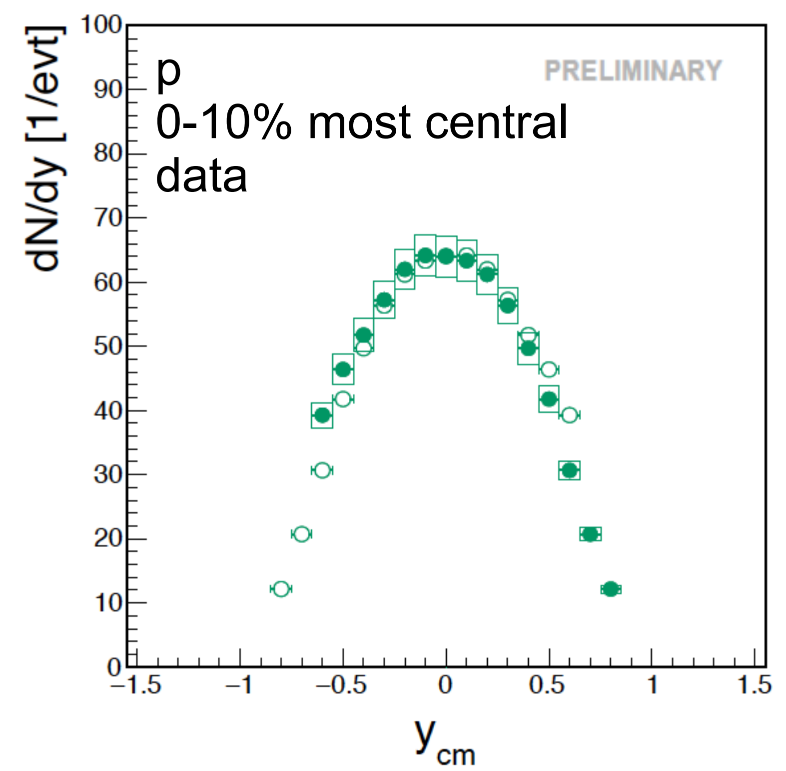
- Freeze-out points previously estimated based on ratios of p, d, K^+, π^+

- Light nuclei are not included in Thermus V2.3 Switch to Thermus V3.0 or Thermal-Fist https://github.com/vlvovch/Thermal-FIST

Experimental Excurse: Baryons at $\sqrt{s_{NN}}$= 2.4 GeV

Spectator and fireball regions not well separated.





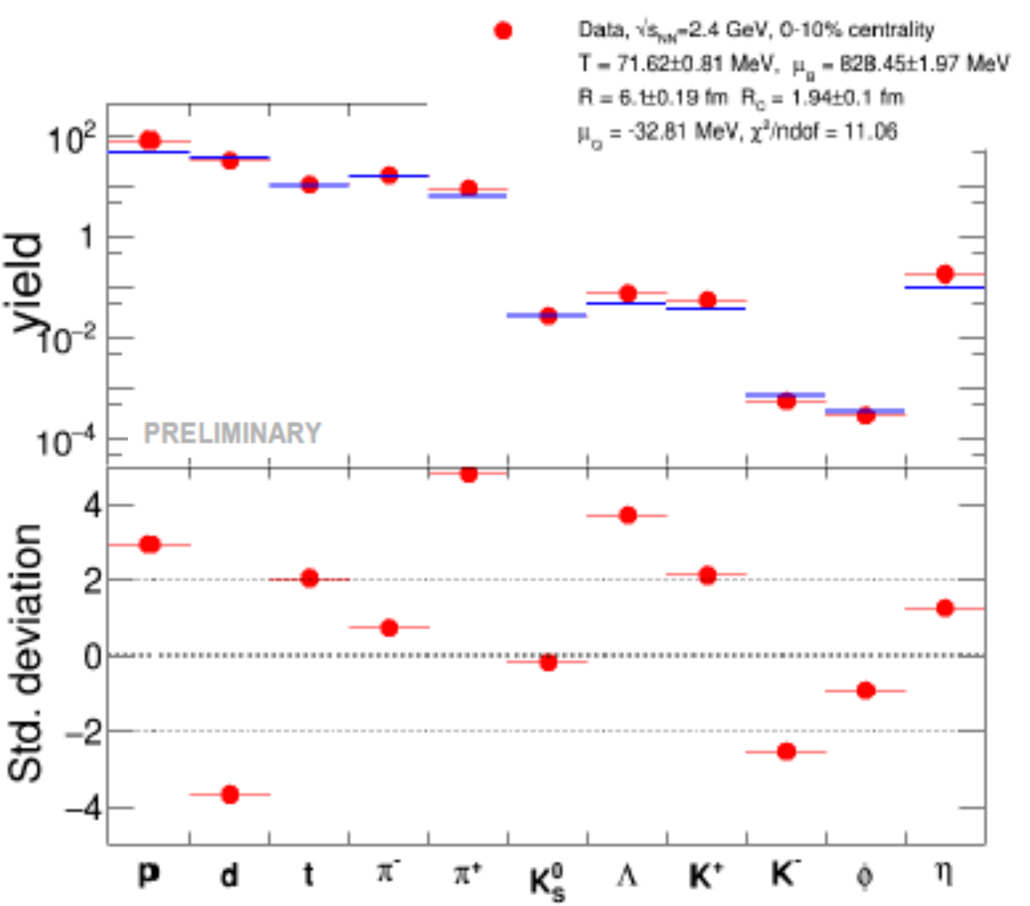
Careful analysis of protons:

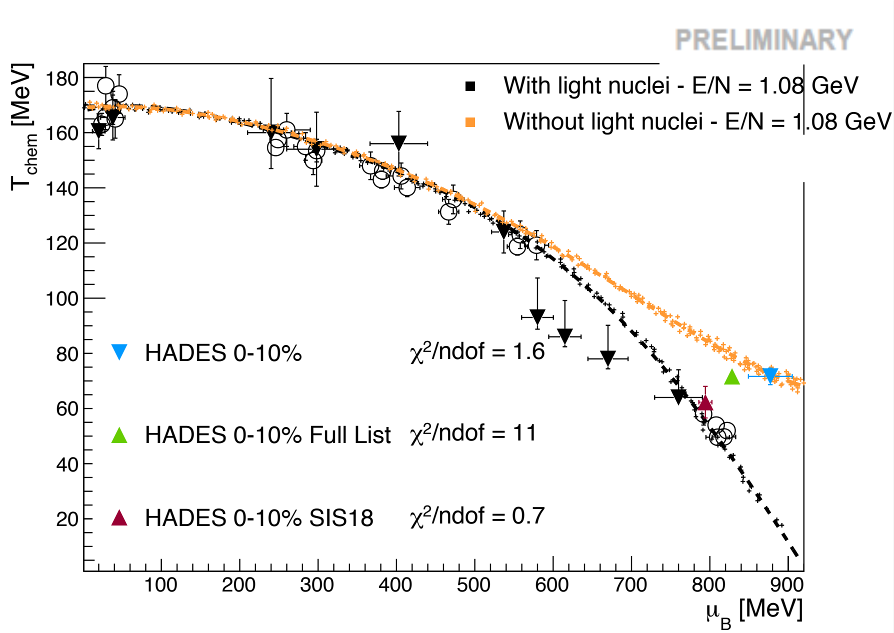
→ Extension to high lab. momenta in order to cover forward hemisphere (no acceptance at low p_t)
→ Minimize uncertainty due to extrapolation in y
→ Estimate spectator contamination by symmetry of the distribution

Similar checks for d and t are ongoing.

PhD M. Szala

Macroscopic Description





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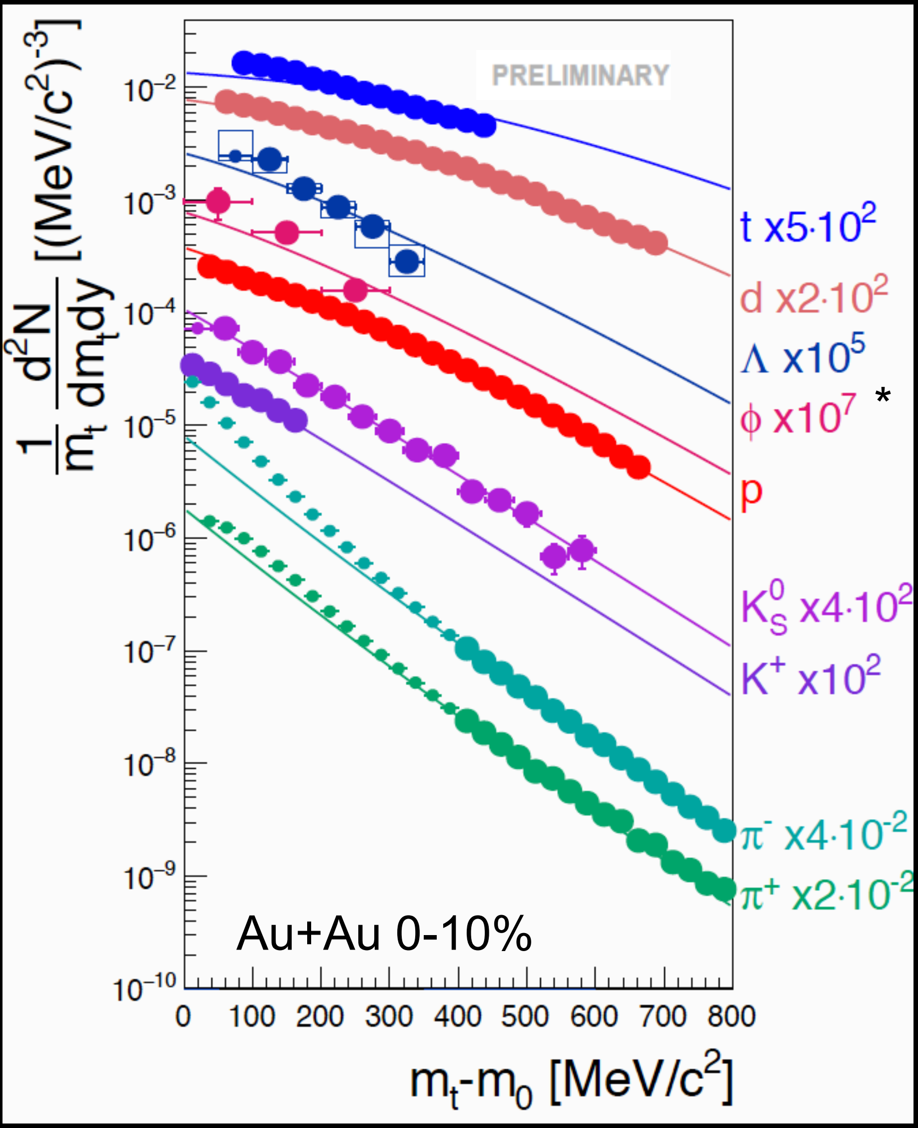
- Fit to HADES data consistent with previous works when same hadron yields are used
- E/N=1.08 GeV with or without light nuclei?
- Light nuclei are important to define chemical freeze-out line at high μ_B.
- Fit to complete hadron set gives bad χ^2 (very preliminary triton yield)
- Inclusion of repulsive interactions[1] needed?

[1] V. Vovchenko ,H. Stöcker J.Phys. G44 (2017) no.5, 055103
A. Andronic et al. arXiv:1808.03102

Further constraints



Kinetic freeze-out:
T_{kin}=66±8 MeV and $<\beta_r>$=0.34±0.02
extracted from blast wave fit to HADES data
Φ and Λ are not described.

Virtual photons:
T_{ee}=72±2 MeV
(see Tetyana's talk tomorrow)

Expected hierarchy in freeze-out temperature:

$$T_{kin} \leq T_{chem} \leq T_{ee}$$

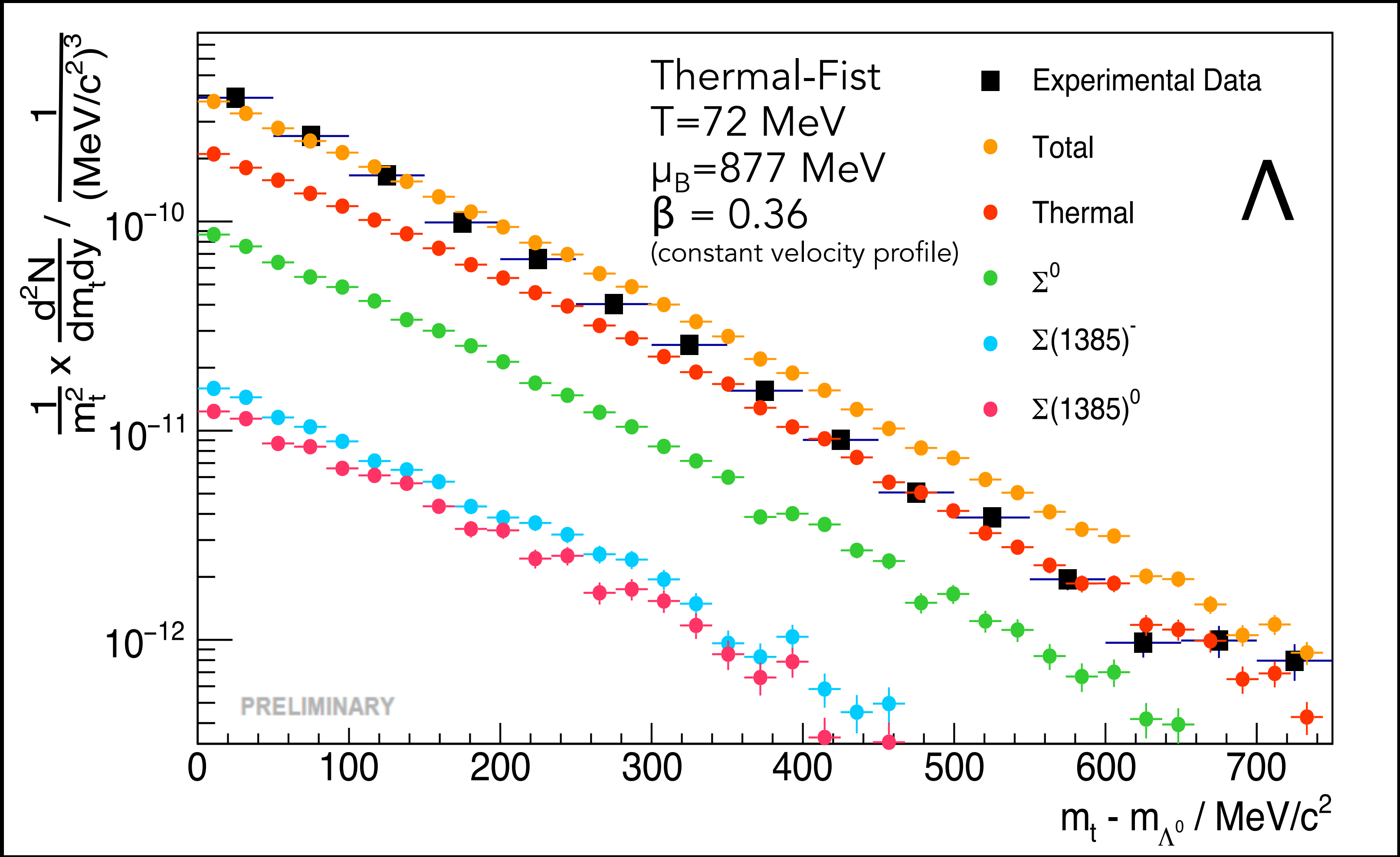
→ 58 MeV < T_{chem} < 74 MeV

Extracted higher value T_{chem} = 72 MeV
lower value T_{chem} = 62 MeV

Kaons sensitive to hypernuclei yields due to exact strangeness conservation.

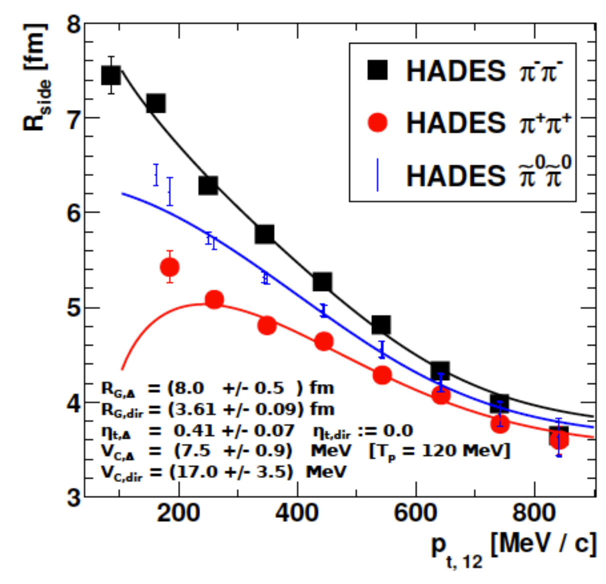
*0-20%

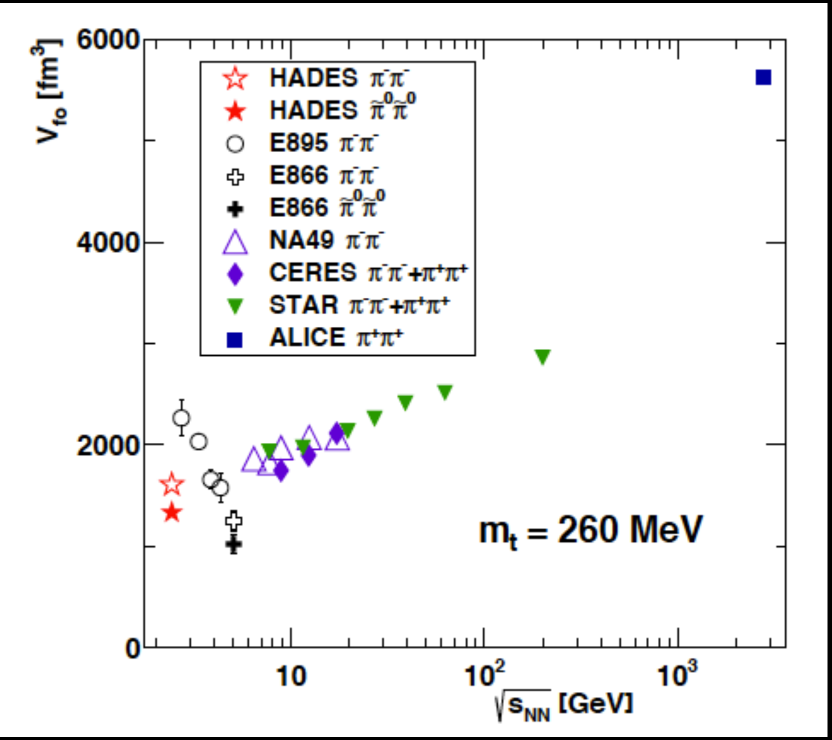
Event generator



Coupling of statistical particle production with a blast wave model:
Compare directly spectra including effects of blast and resonance decays.
Slope of Λ not described.

Comparison of extracted freeze-out radius





Direct pions (HBT) $R_{HBT} \approx 6.5 \pm 0.5$ fm
(see Robert's talk)
(Gaussian radius to hard sphere radius: $R_H = R_G * \text{sqrt}(2) *5 \approx R_G*1.8$)

Extracted higher value R_{chem}= 10.3 fm
lower value R_{chem}= 5.3 fm

Both without inclusion of repulsive interactions.

$R_{chem} \leq R_{HBT}$

Summary macroscopic description

Created system not isotropic.

Light nuclei determine the freeze-out line.

No simultaneous description of light nuclei and rare mesons:

- Very preliminary triton yield.
- Additional parameters needed?

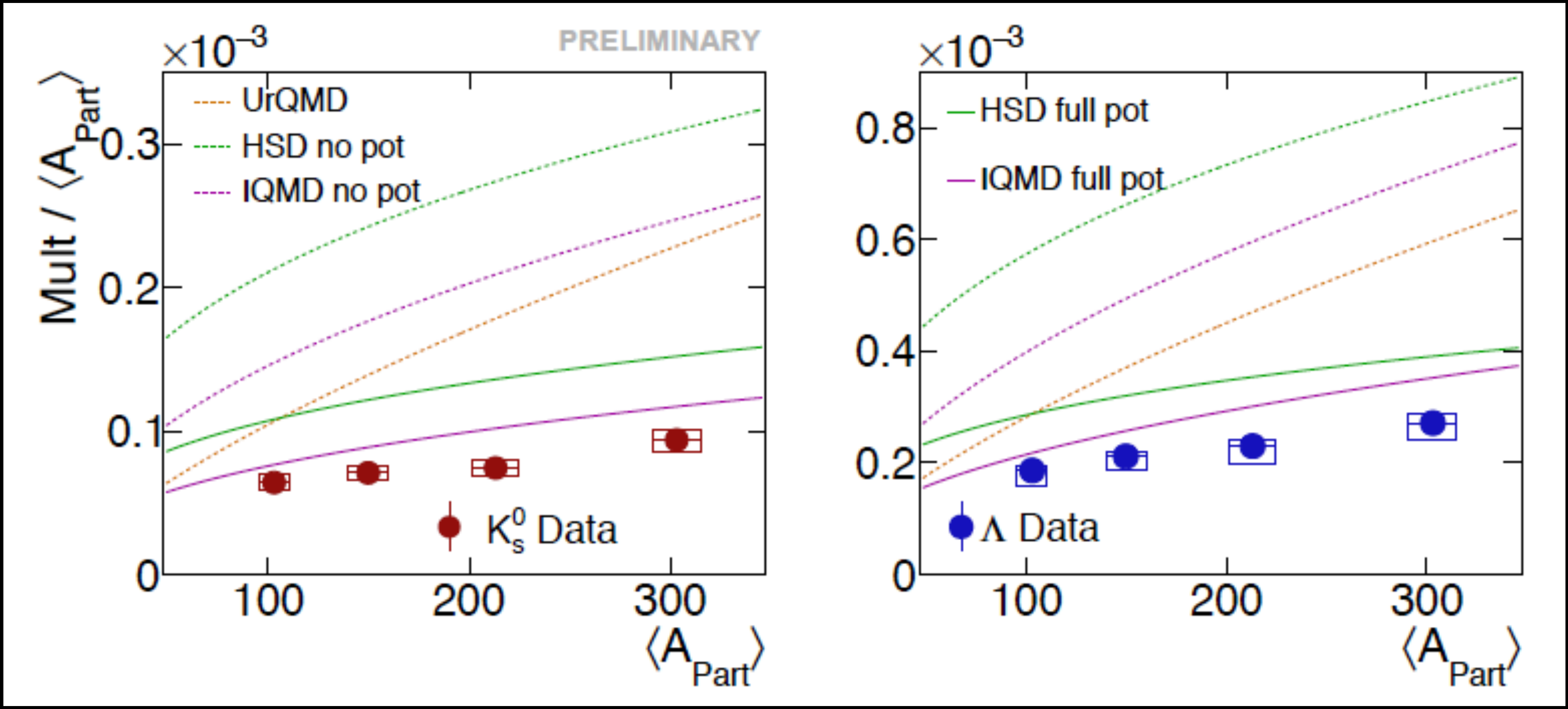
Further constraints for freeze out:

- $T_{kin} \leq T_{chem} \leq T_{ee}$
- HBT volume

Event generators:

- slopes of spectra not fully described
  (modeling of broad resonances and their decay).

Microscopic description of strangeness production

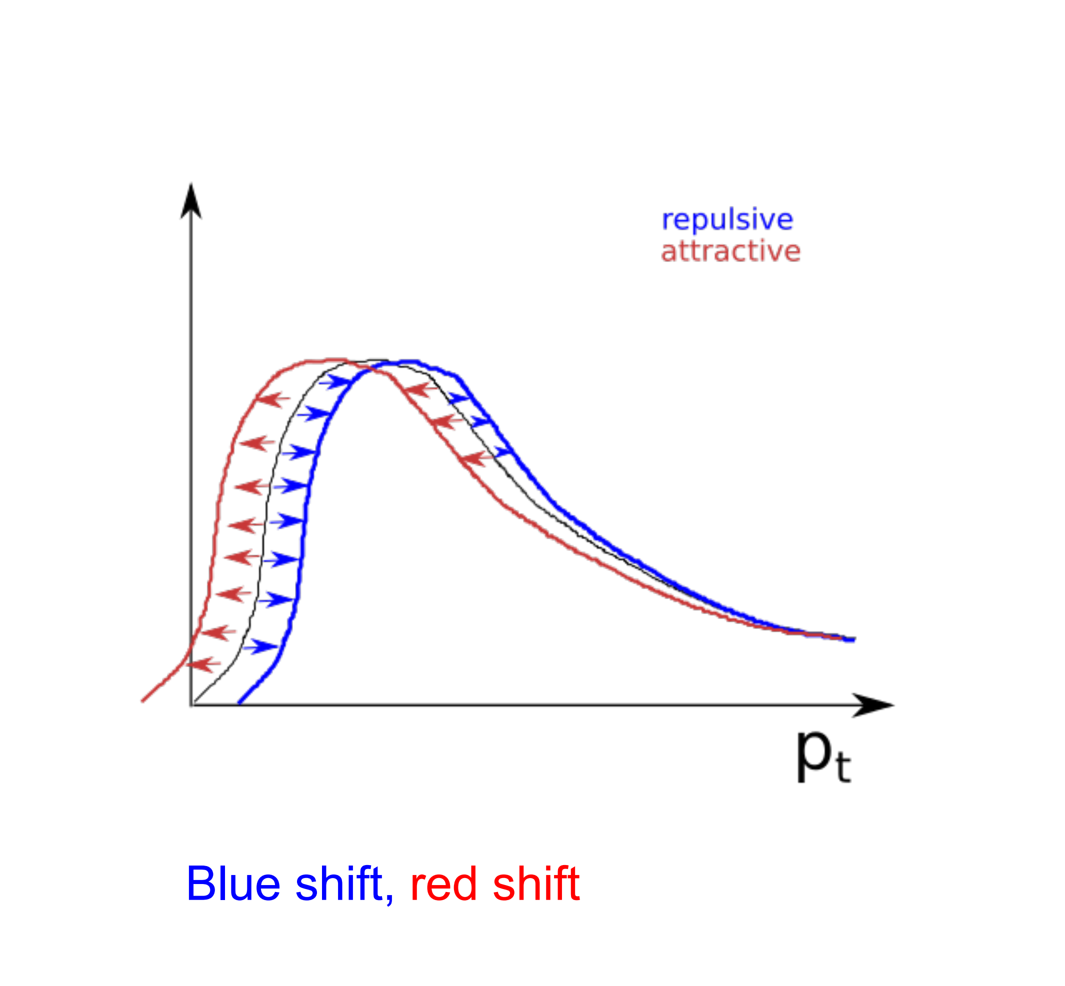


Model predictions: UrQMD 3.4, HSD 711n, IQMD c8, (full pot.= 40 MeV)

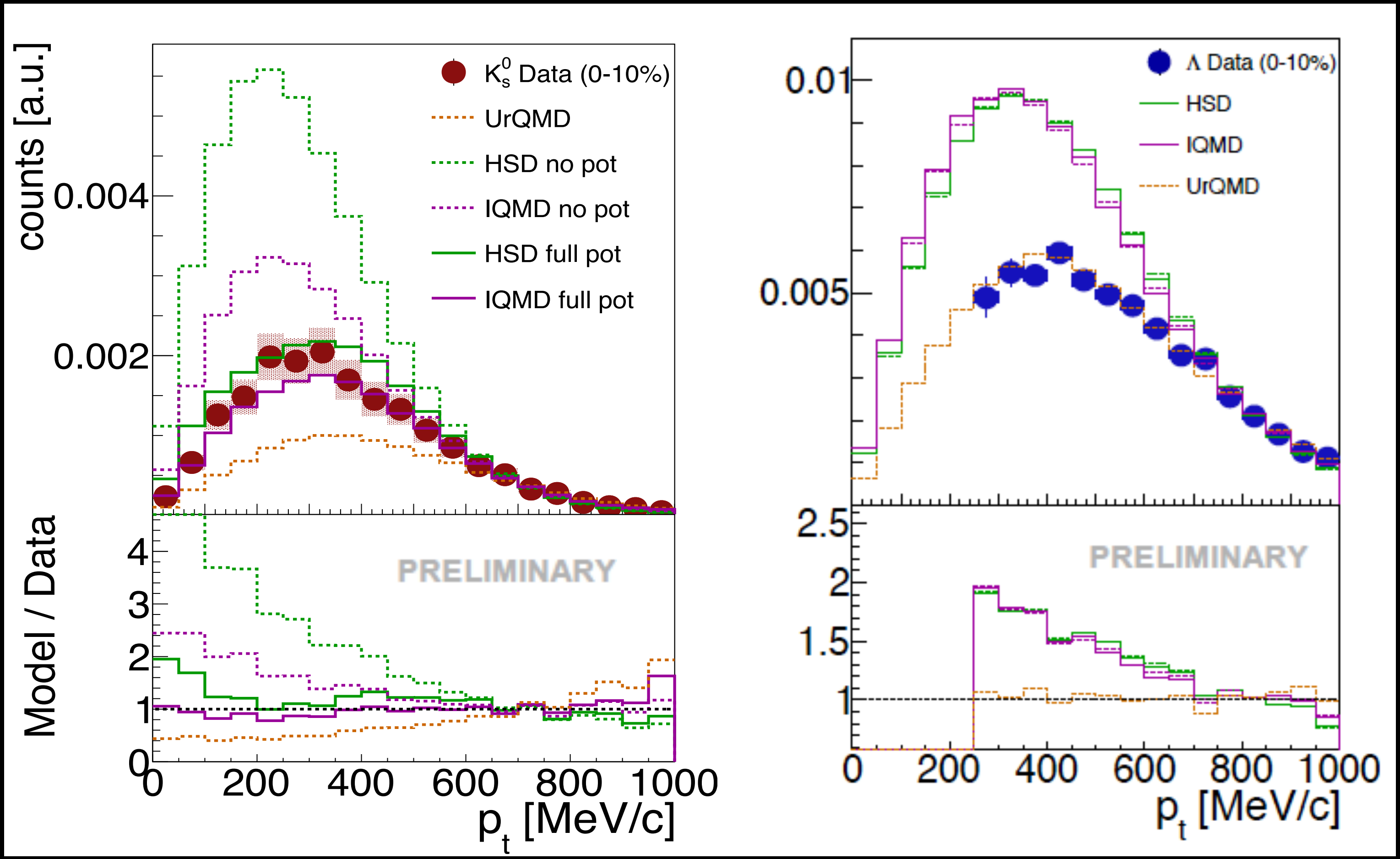
General trend to overshoot data → uncertainty in overall yield
Repulsive KN potential reduces the yield → compare shape of p_t spectra

Thanks to Y. Leifels, E. Bratkovskaya, C. Hartnack, J. Aichelin, J. Steinheimer and M. Bleicher

KN Potential revisited: comparison of the p_t shape



KN Potential revisited: comparison of the p_t shape



KN-Potential affects mostly low p_t → spectra normalized in high p_t region
Inclusion of potential: Similar trend in HSD and IQMD, reduction of low p_t clear improvement of description (IQMD perfect).
UrQMD: without any potential even lower yield at low p_t, shape of spectra also modified by production via different baryonic resonances, best description of Λ

Summary of this comparison

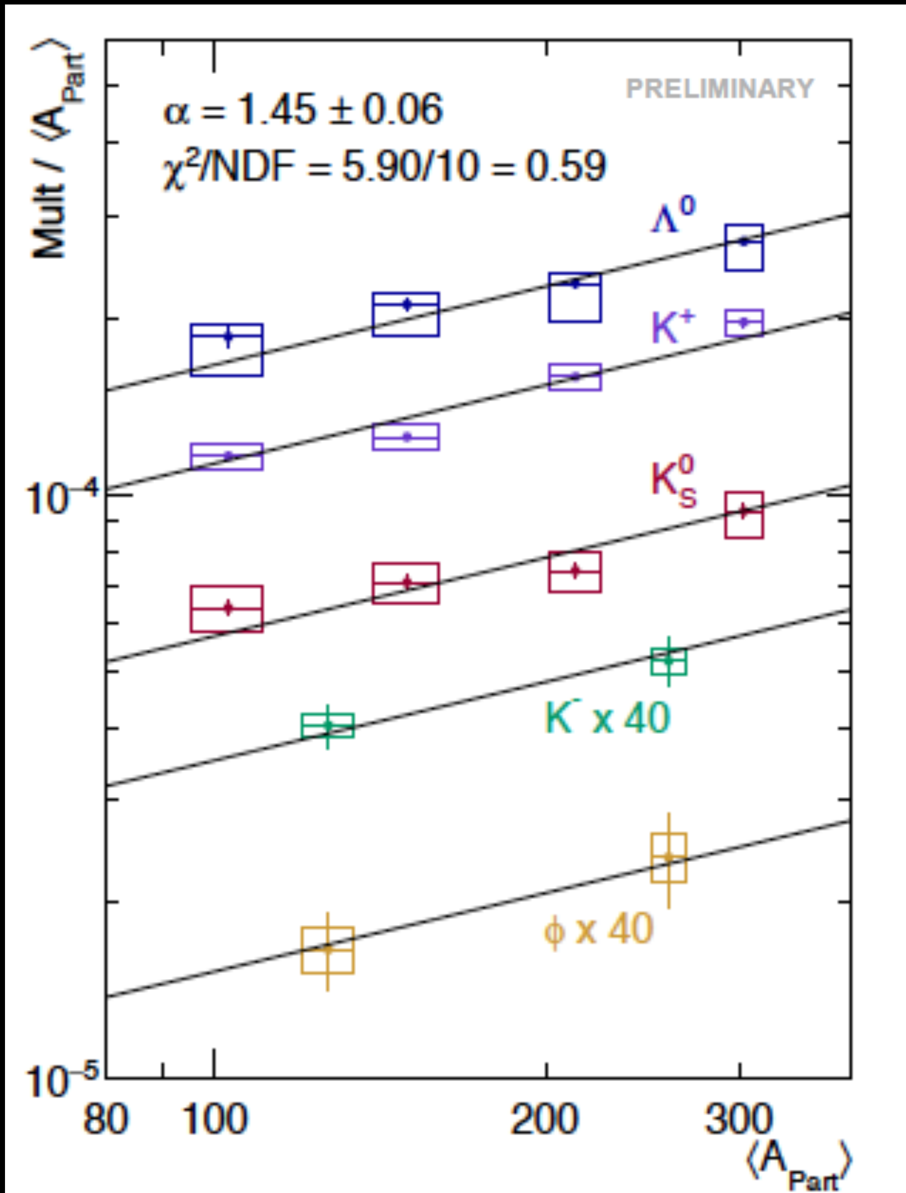
		K0S			Lambda			
Model	K-N Potential	pt	y	Mult	pt	y	Mult	α
UrQMD	0	-	(+)	-	+	(+)	-	-
HSD	yes	-	+	-	-	-	-	-
IQMD	yes	(+)	+	-	-	-	-	+

Neither UrQMD, HSD, IQMD calculations can simultaneously describe the presented K^0_s and Λ observables.

Notation: "+" = X^2/Ndata < 3.5
"(+)"= X^2/Ndata < 5
"(-)" = X^2/Ndata > 5

Draft will appear in November on the arXiv.

(Sub-Threshold) Strangeness Production: the Complete Picture



- Strange particle yields rise stronger than linear with $<A_{part}>$ ($M \sim <A_{part}>^{\alpha}$)

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

→ Hierarchy in production threshold not reflected

N→NYK⁺ $\sqrt{s_{NN}}$= 2.55 GeV
NN→NNK⁺K⁻ $\sqrt{s_{NN}}$= 2.86 GeV

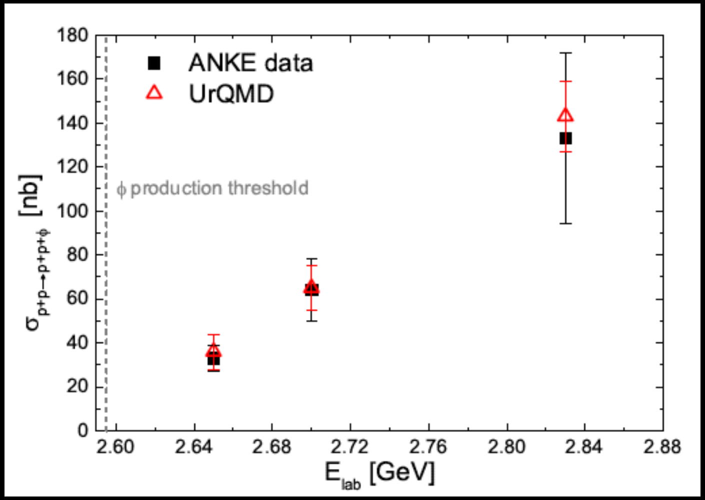
Scaling with absolute amount of strangeness not with individual hadron states .. → Outlook

Draft will appear in November on the arXiv.

Φ/K⁻ in transport

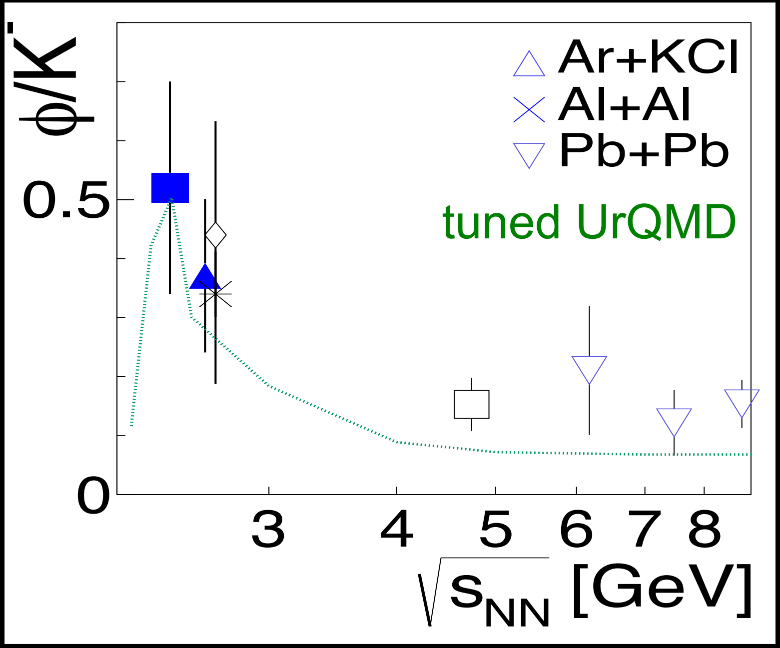
PHSD/PQMD: on going project to include ϕ spectral function

D. Cabrera et al. Phys.Rev. C95 (2017) no.1, 015201



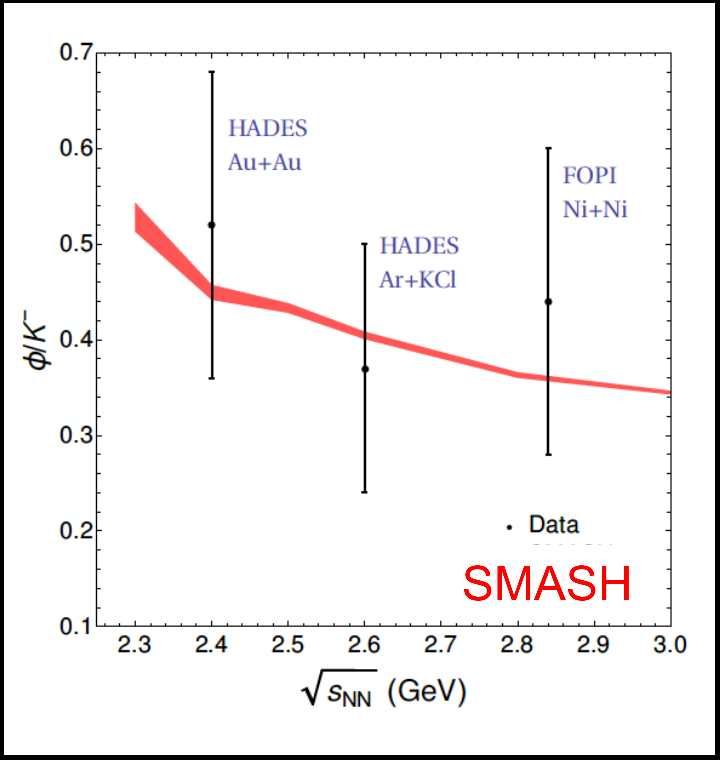
UrQMD tuned to cross section in p+p collisions gives good prediction for Φ/K⁻ ratio at low energies

J. Steinheimer, M. Bleicher J.Phys. G43 (2016) no.1, 015104



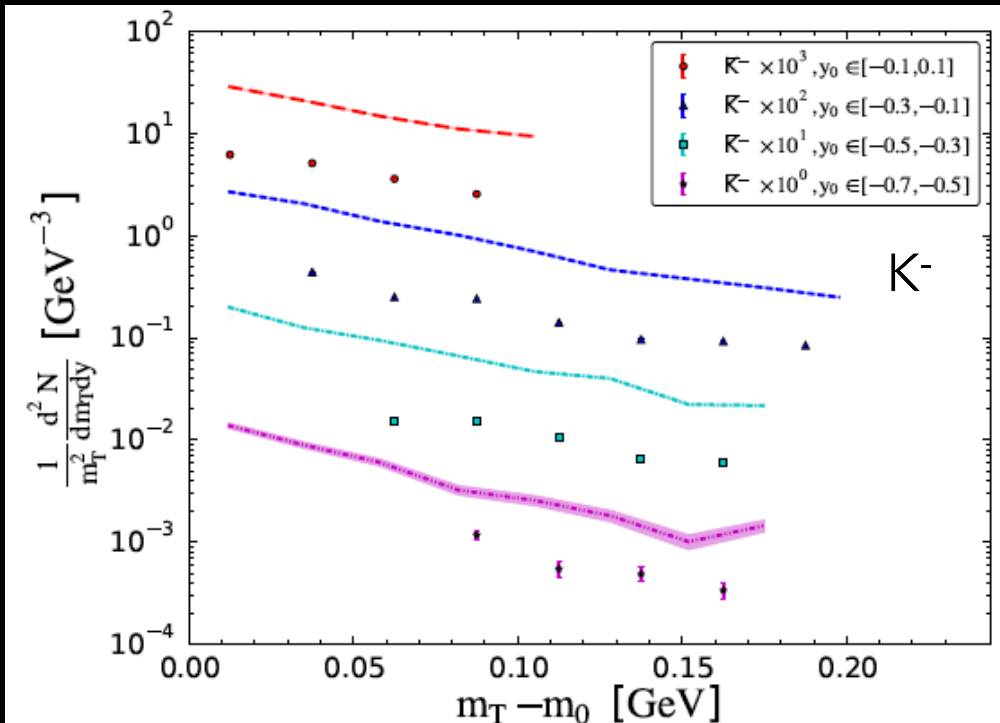
Very similar in SMASH

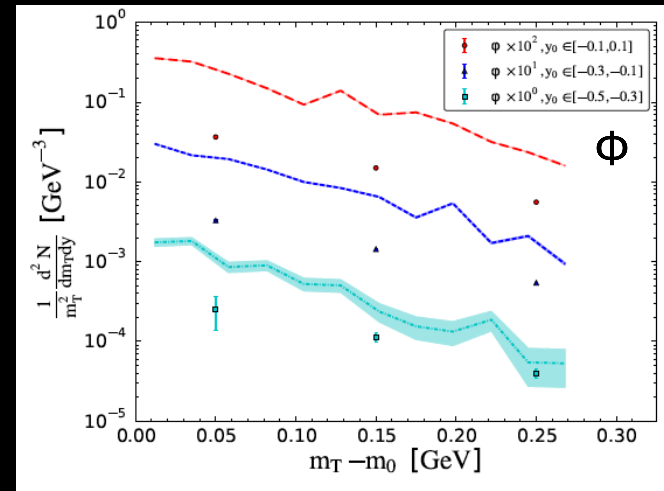
V. Steinberg, J. Staudenmaier, D. Oliinychenko, F. Li, Ö. Erkiner, H. Elfner. arXiv:1809.03828

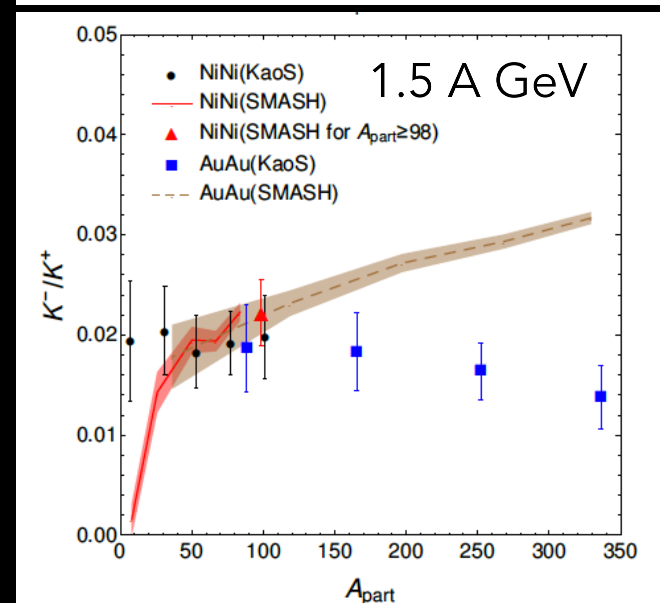


Φ/K$^-$ in transport

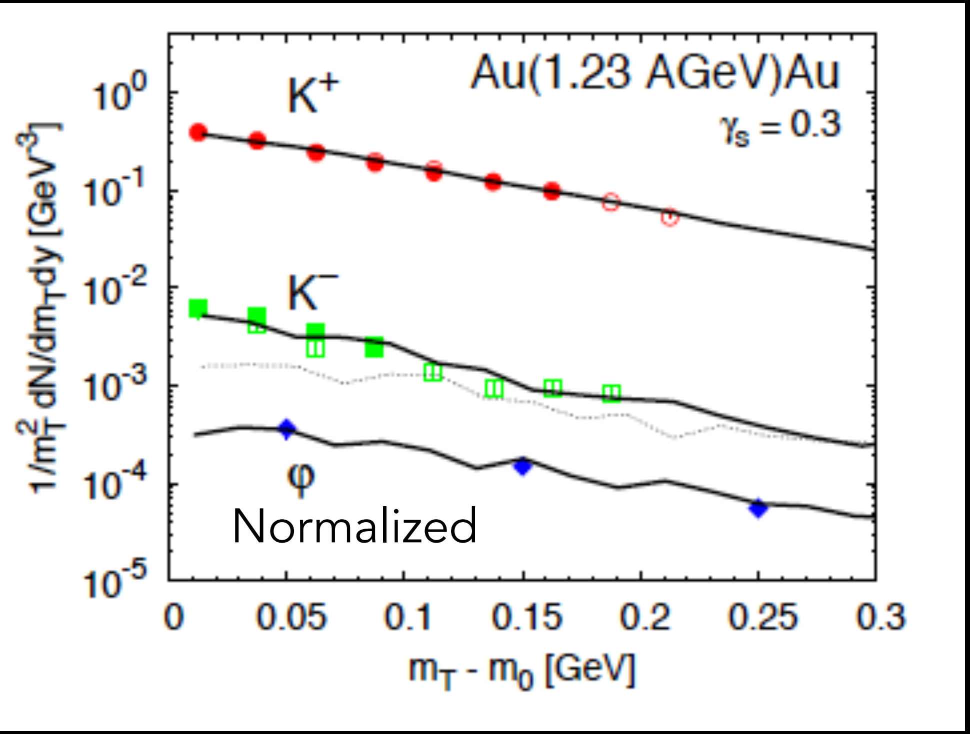
Both UrQMD and SMASH fail to reproduce absolute yields and A_{part} dependence







GiBUU plus Hagedorn Resonances



Adding of Hagedorn resonances improves description of slopes.

K. Gallmeister, M. Beitel, C. Greiner Phys.Rev. C98 (2018) no.2, 024915

What about light nuclei?

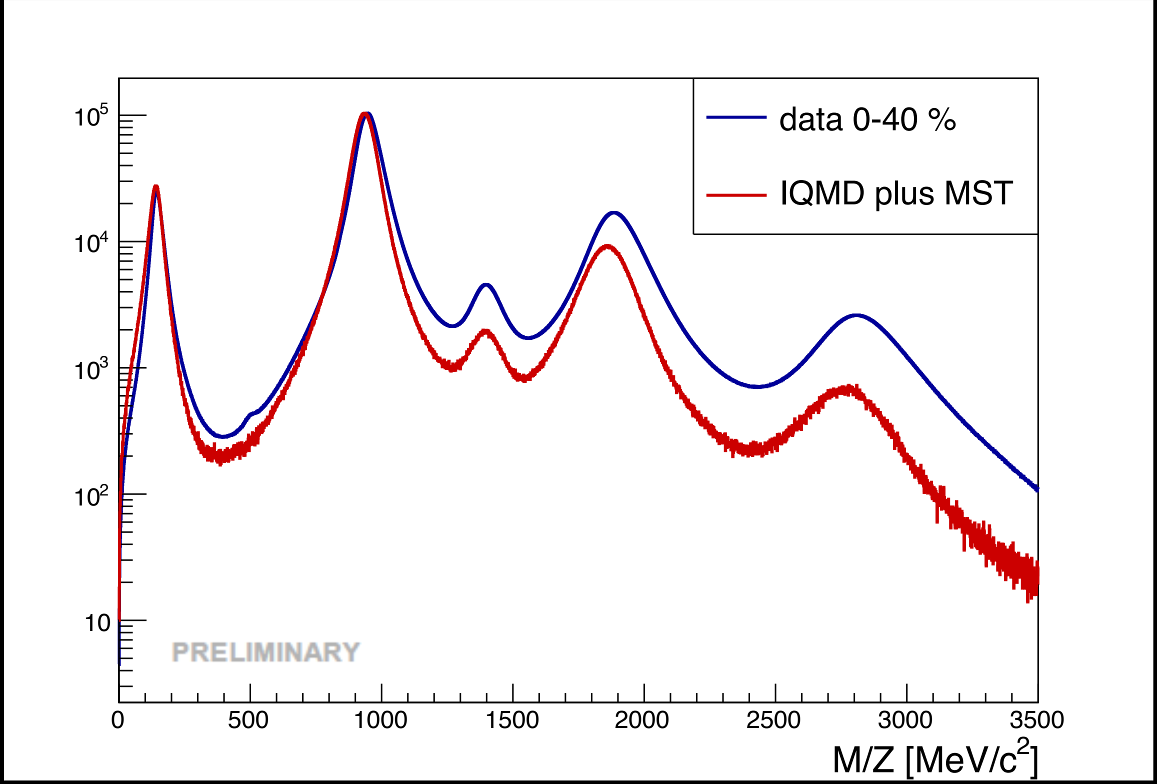
Except for FRIGA[1] light nuclei are "clustered" with the help of some coalescence type "afterburner".

* Thanks to Y. Leifels

Example: IQMD plus minimal spanning tree (MST) *

r = 5 fm in position space and t<140 fm/c

tracked through full HADES Geant Simulation



→ Challenge to reproduce light nuclei yields at mid-rapidity.

[1] Le Févre, Y. Leifels, J. Aichelin, Ch. Hartnack, V. Kireyev, E. Bratkovskaya. J.Phys.Conf.Ser. 668 (2016) no.1, 012021

Summary microscopic description

Neither UrQMD, HSD, IQMD calculations can simultaneously describe the presented K^0_s and Λ observables.

UrQMD and SMASH predict the ratio of deep-subthreshold K^- and Φ but no absolute yields.

Light nuclei yields at mid-rapidity are underestimated by coalescence afterburners.

Activity and new approaches.

None of the models is able to describe the universal $\langle A_{part} \rangle$ dependence of strange hadrons.

Personal Summary

A lot of phenomenological understanding.

Neither microscopic nor macroscopic models are yet able to describe all observables (light nuclei 30% of all baryons).

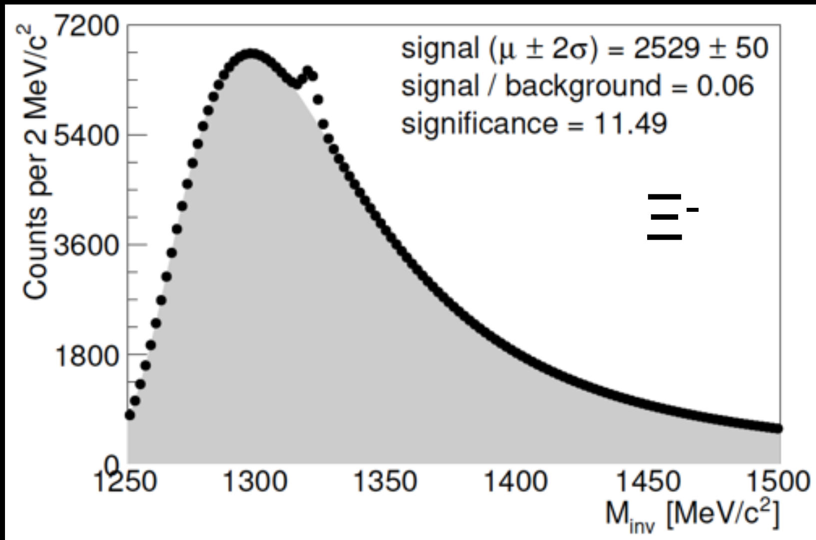
Only effective approaches to QCD as guidance.

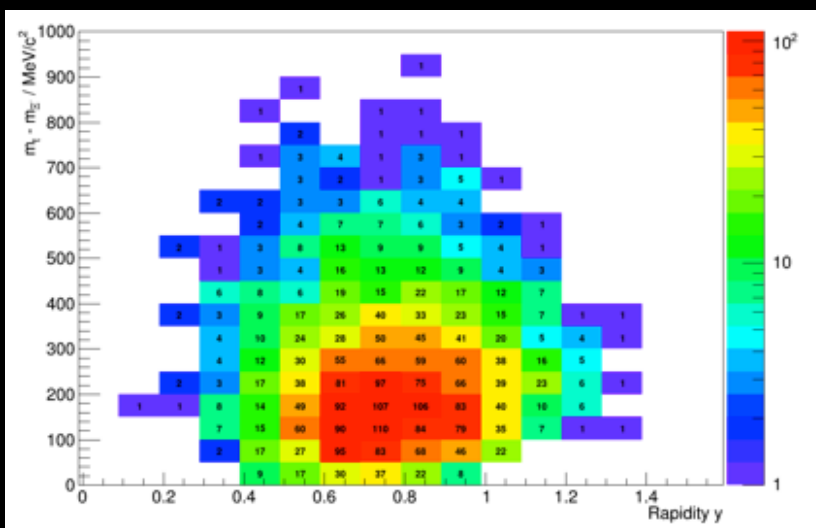
→ Very difficult to characterize matter in this region of the phase diagram

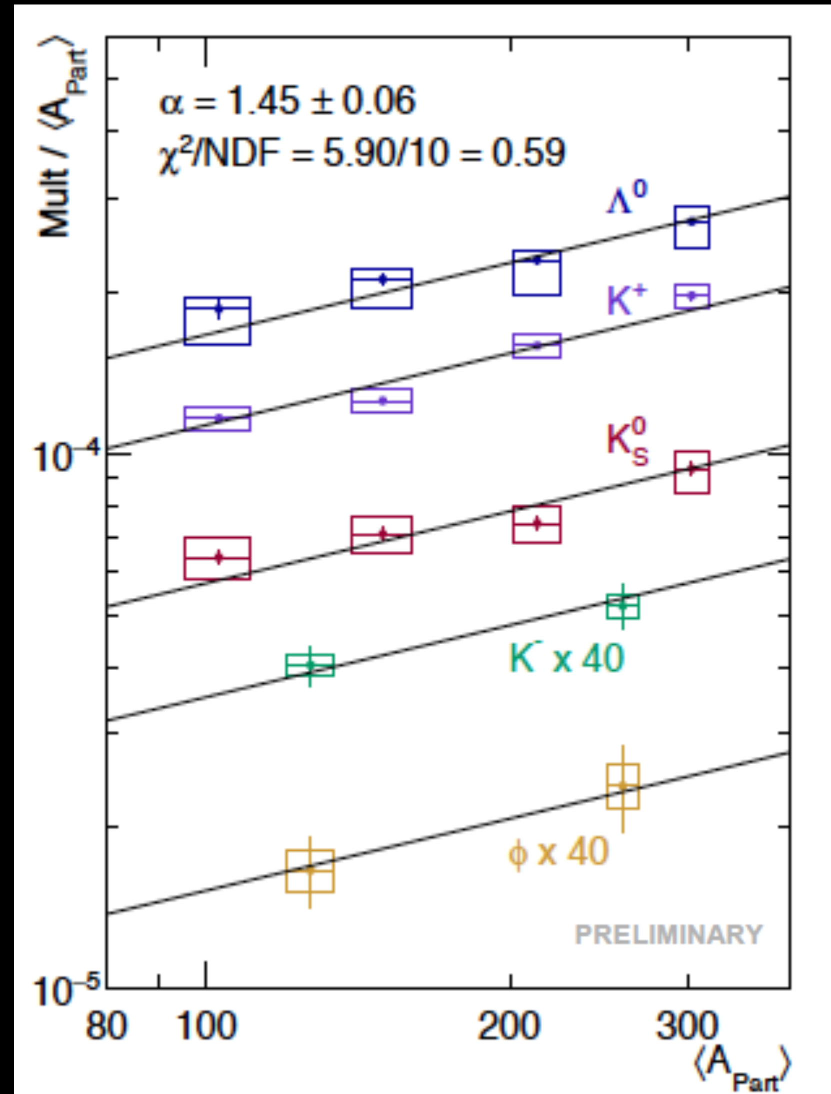
but ..

lots of activity, new ideas and upcoming experiments.

Outlook: Ag+Ag $\sqrt{s_{NN}}$= 2.55 GeV







Test of universal <A_{part}> dependence of strange hadrons.

The HADES collaboration

Thank you for your attention!