Equation of state studies with HADES (perspectives)

Manuel Lorenz

Goethe-University Frankfurt

Outline:

1. HADES

   experimental runs, apparatus, performance

2. Experimental highlights

   dilepton radiation, HBT, Coulomb potential, strangeness,
   flow (see Behruz's talk)

3. Caveats (Devil's advocate)

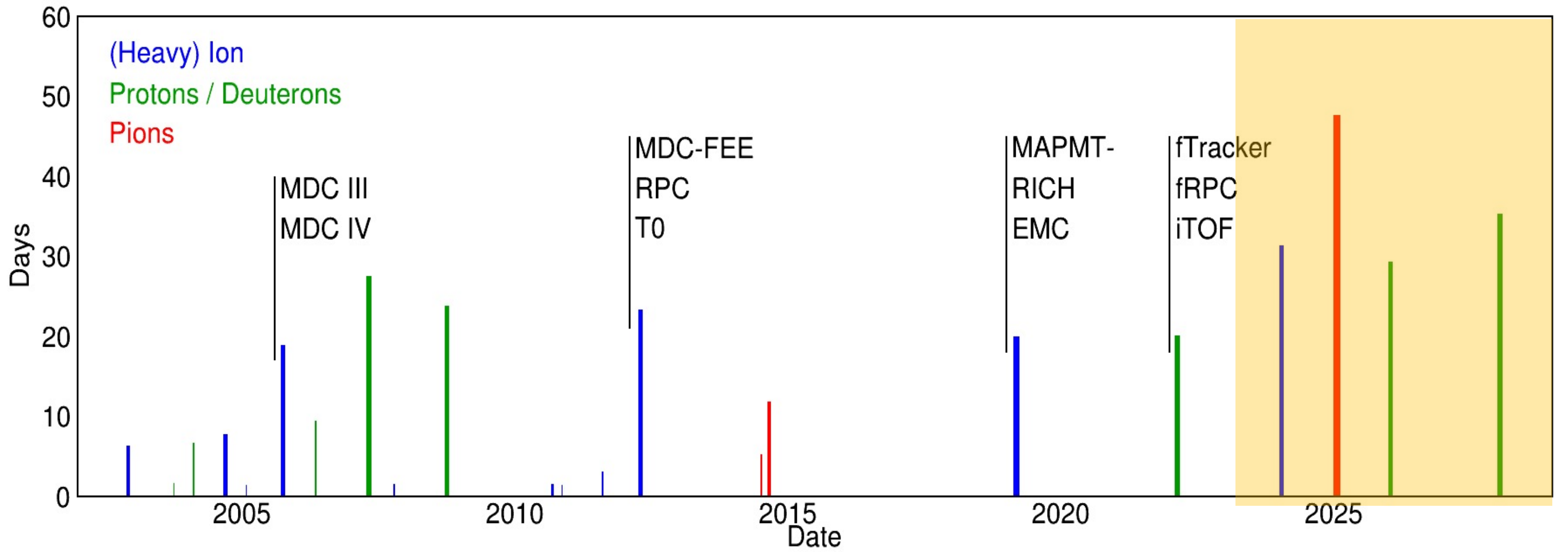
   world data on pion-, bound and free proton-yields

4. Perspectives

   Au+Au energy scan at 0.8-0.2 A GeV 2024, HADES @SIS100 ..

1. HADES

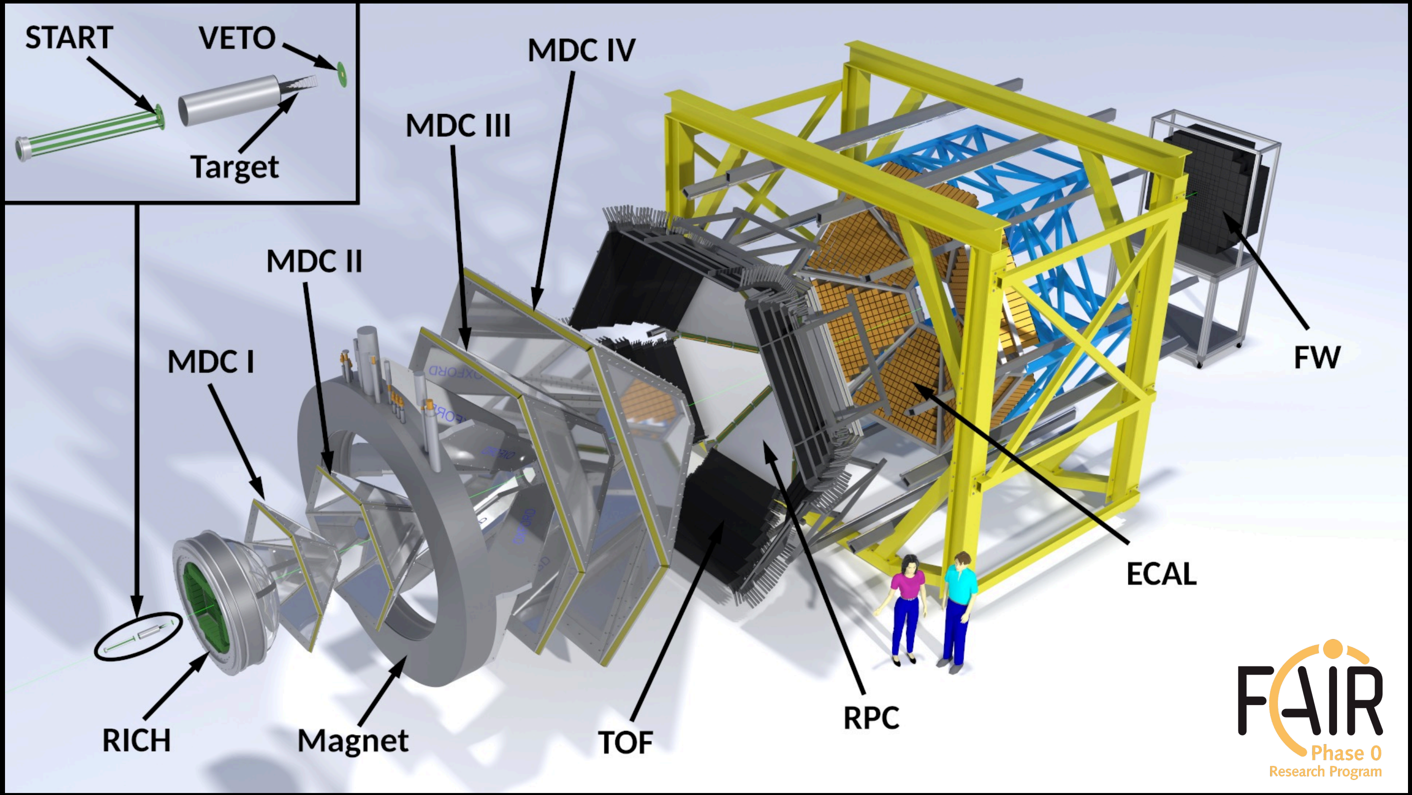
Overview: experimental runs



Future runs

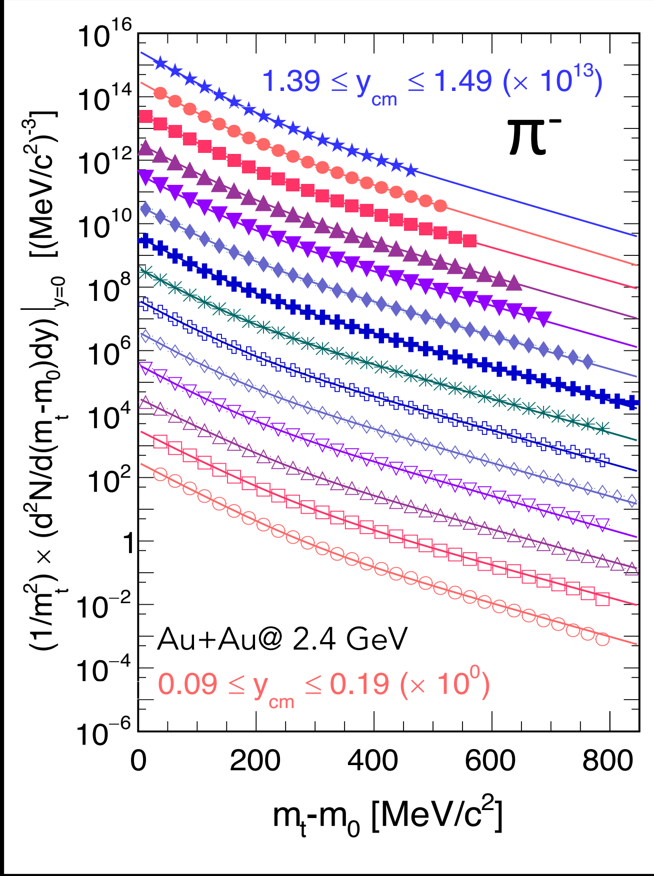
- Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV, 7.2 bil. evts. (2012)
- Ag+Ag $\sqrt{s_{NN}}$ = 2.55 / 2.42 GeV 15.2 billion events (2019)

Apparatus:

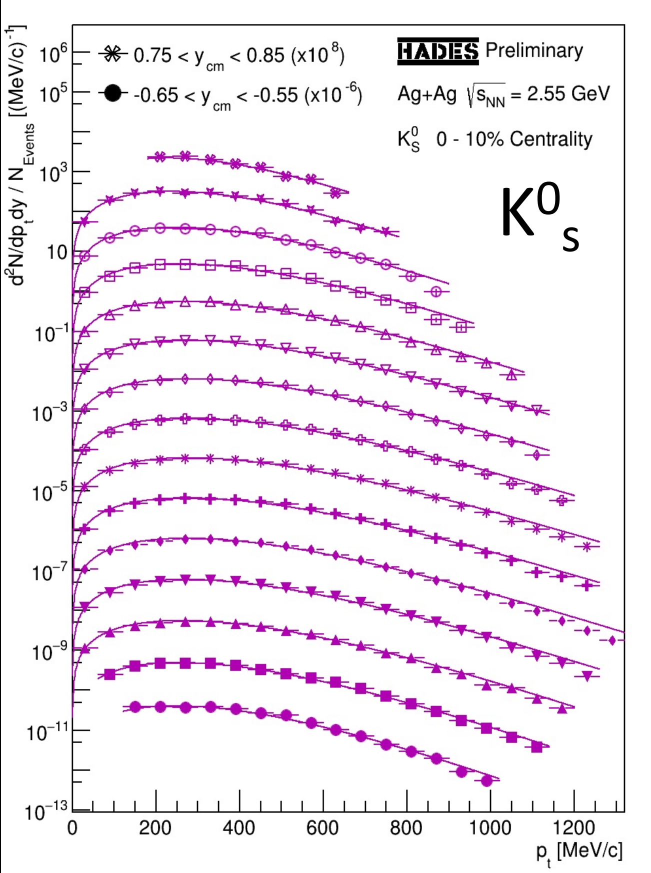


Fast detector: 16 kHz Ag+Ag
Large acceptance: full azimuthal and polar angle coverage of ϴ = 18° – 85°

Performance:



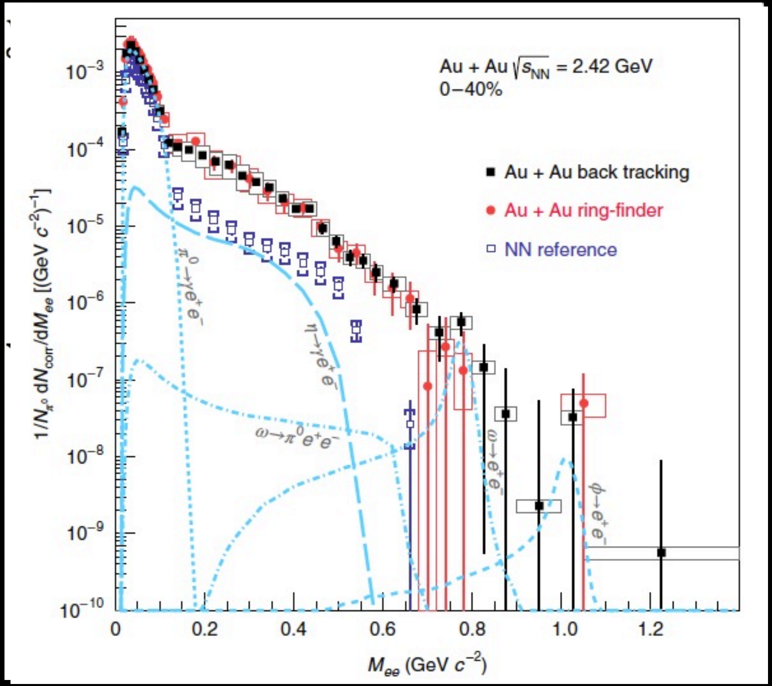
Eur.Phys.J.A 56 (2020) 259.



Weak decay topology recognition enforced by aNN.

2. Experimental highlights

Dilepton radiation from dense baryon matter



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

- First measurement for a heavy system at low $\sqrt{s_{NN}}$.
- Strong excess (0.15<M<0.7 GeV/c²) above components of meson decays at freeze-out and NN-reference.
- Isolation of excess by subtracting the NN-reference.

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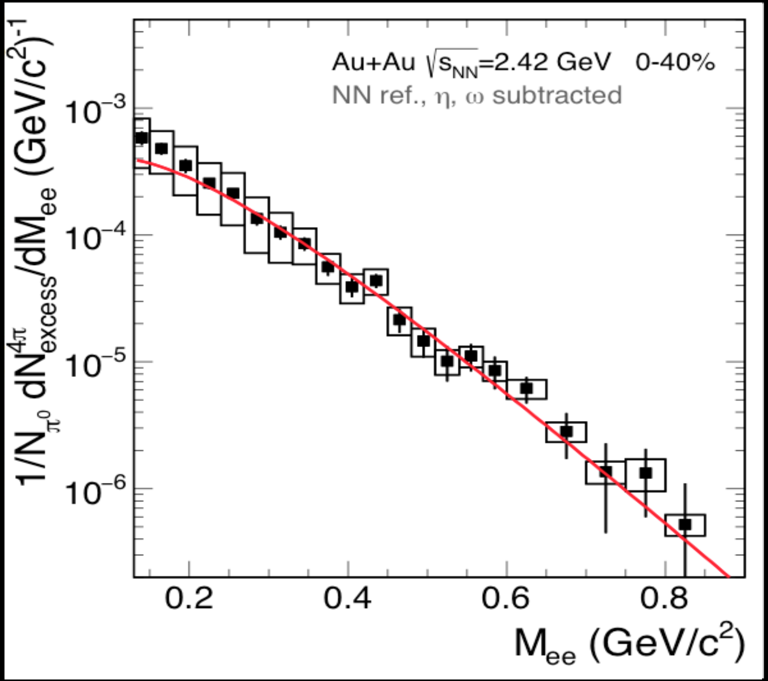

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- Medium radiation: Strong broadening of the ρ due to direct ρ-baryon scattering
- Exponentially falling spectrum,
  → extraction of source temperature $\langle T_{ee} \rangle$ = 72 MeV
- Predicted factor 2 - 3 larger yield in low-mass region near first-order phase transition e-Print: 2209.05267 [nucl-th]

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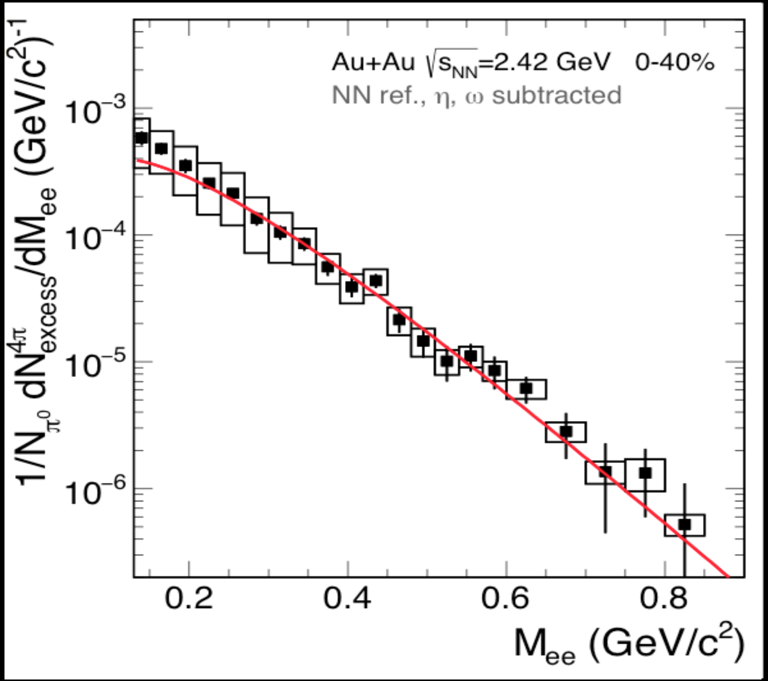

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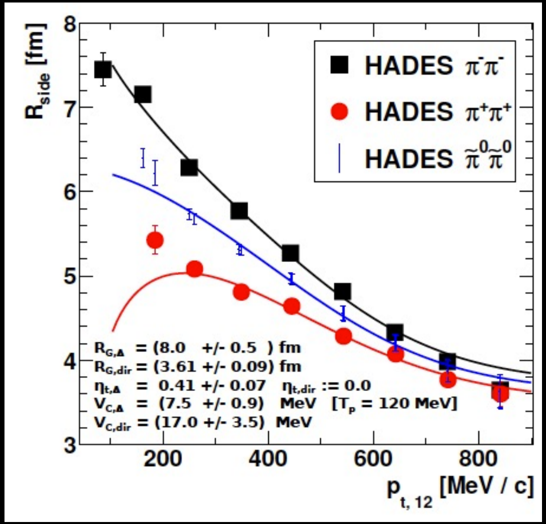
Ideal observable for energy scan.

Identical π Intensity Interferometry



Indications for charge-sign differences reported previously:

E866 R. A. Soltz, M. Baker, J. H. Lee, Nucl. Phys. A 661, 439c (1999)
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First time observation of substantial differences!

Phys.Lett.B 795 (2019) 446-451

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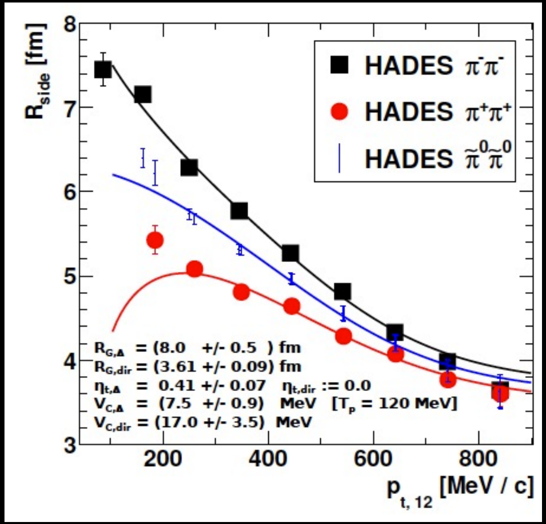

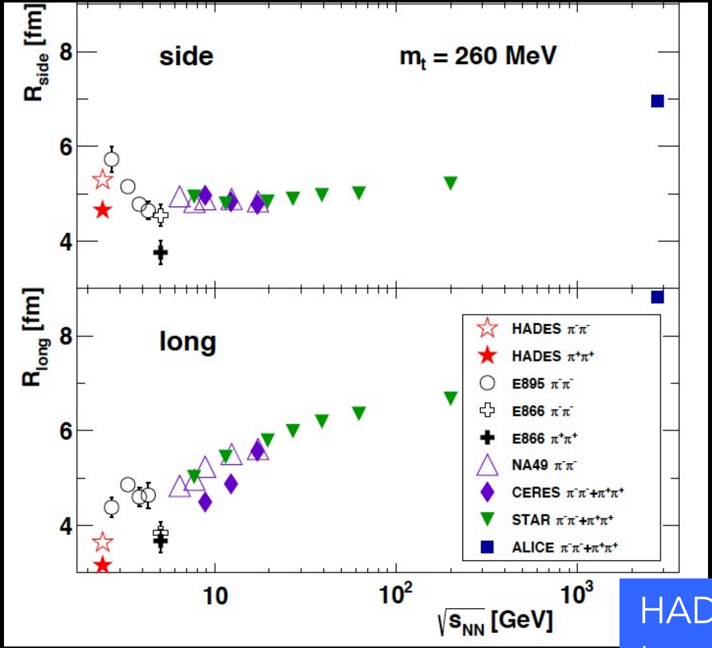

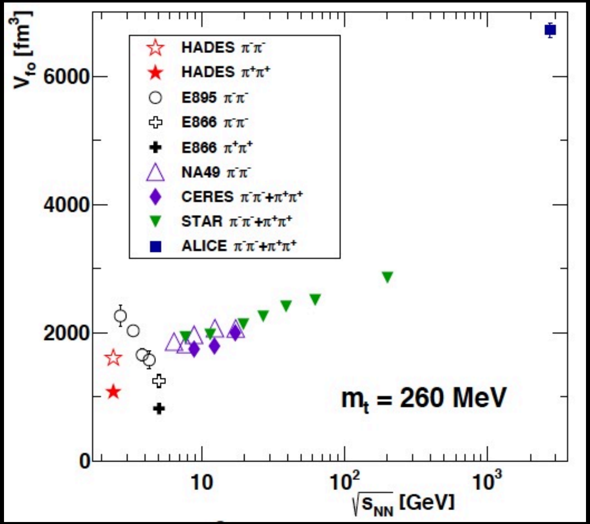

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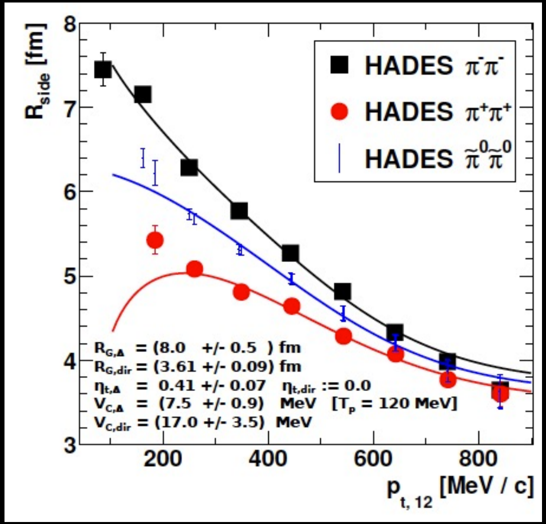

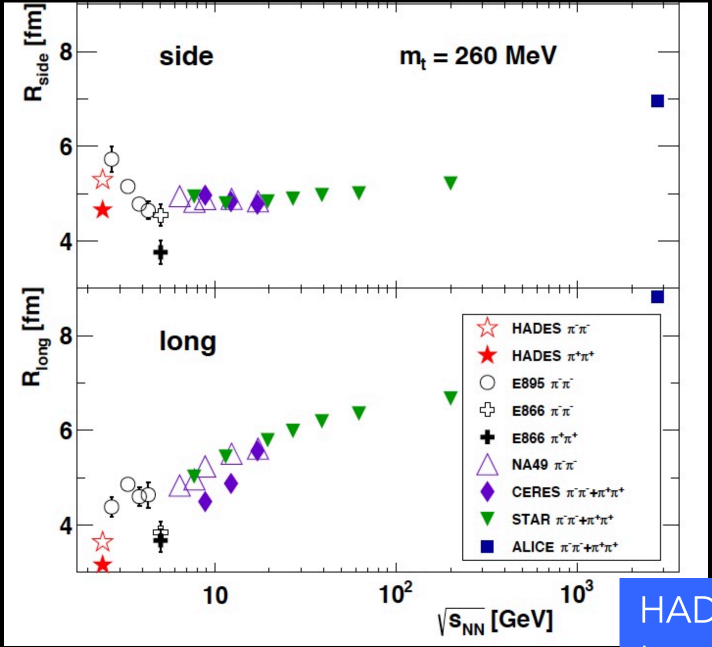

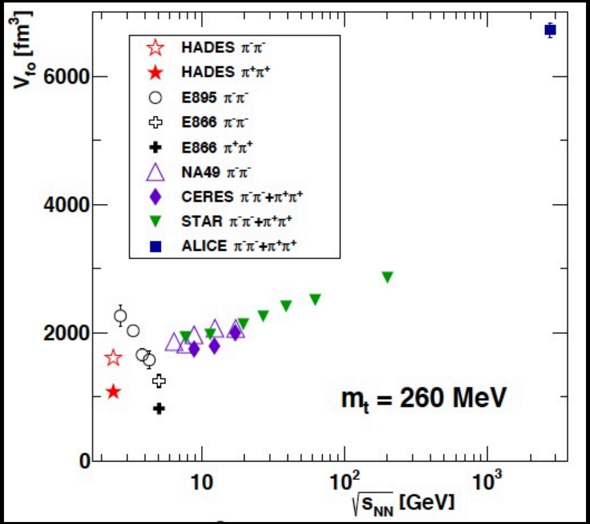

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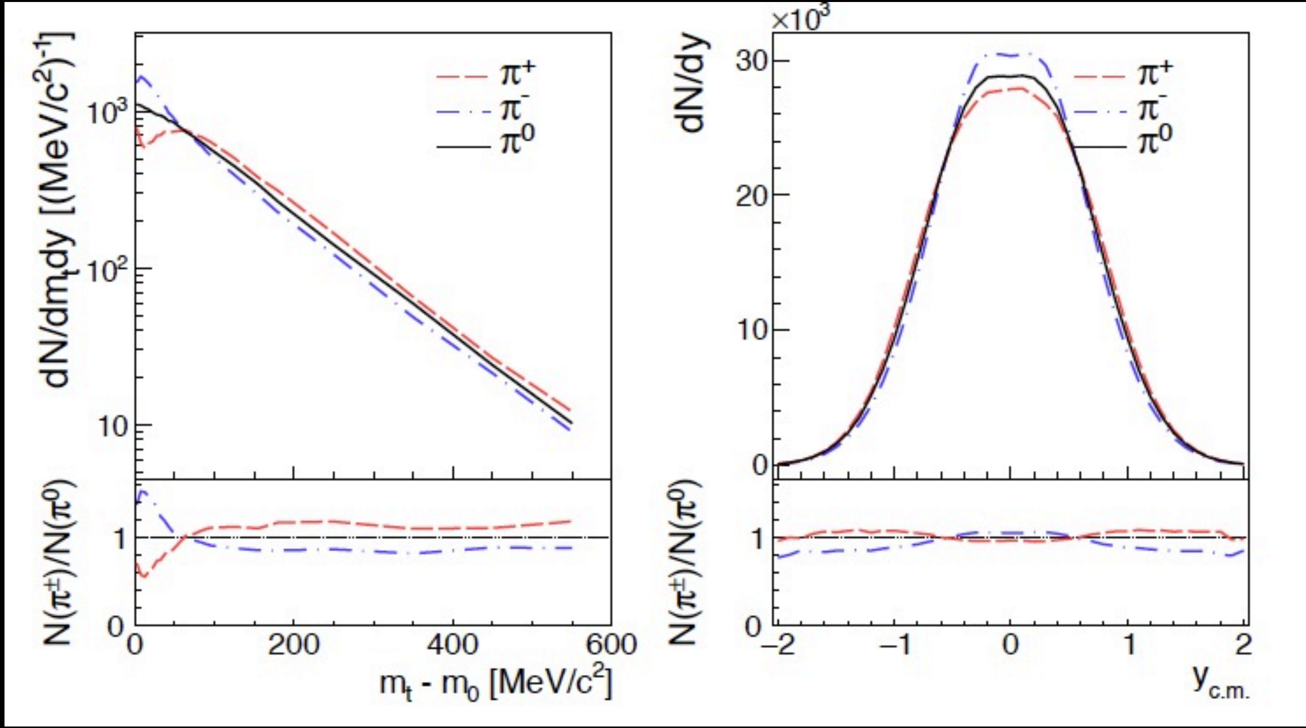
How does the trend continue at lower energy?

Phys.Lett.B 795 (2019) 446-451

Influence of Coulombpotential on π yields

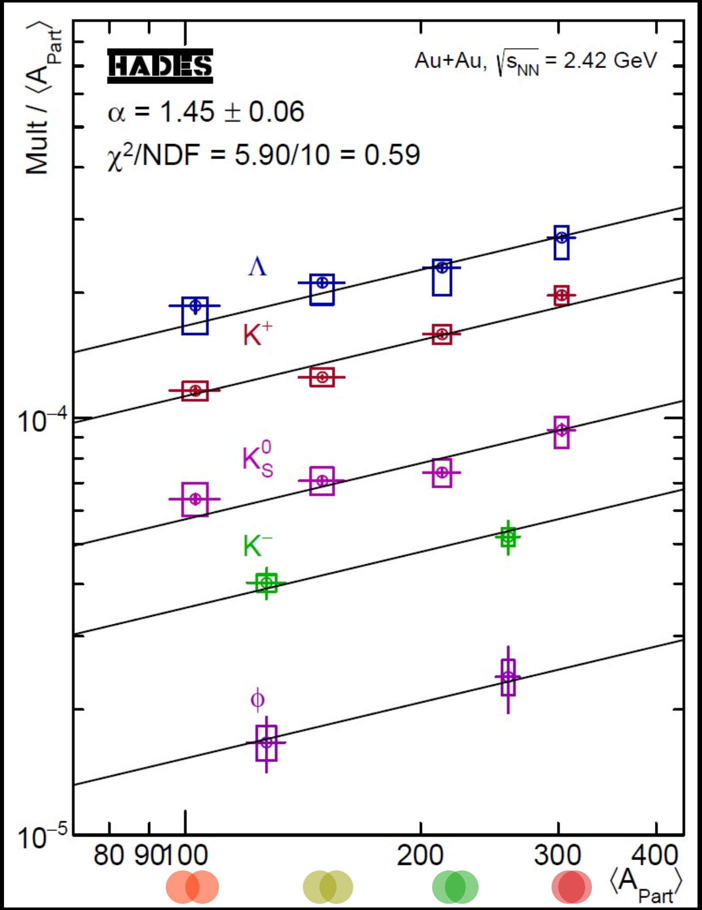


Eur.Phys.J.A 58 (2022) 9, 166

Take Coulomb interaction via potential into account.
Difference in extrapolated 4pi yields: 3% for pi- and 8% for pi+ in case of HADES.

Important to take into account for symmetry energies studies based pions.

Strangeness



Phys.Lett. B793 (2019) 457-463

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

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

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

Excitation functions: Centrality

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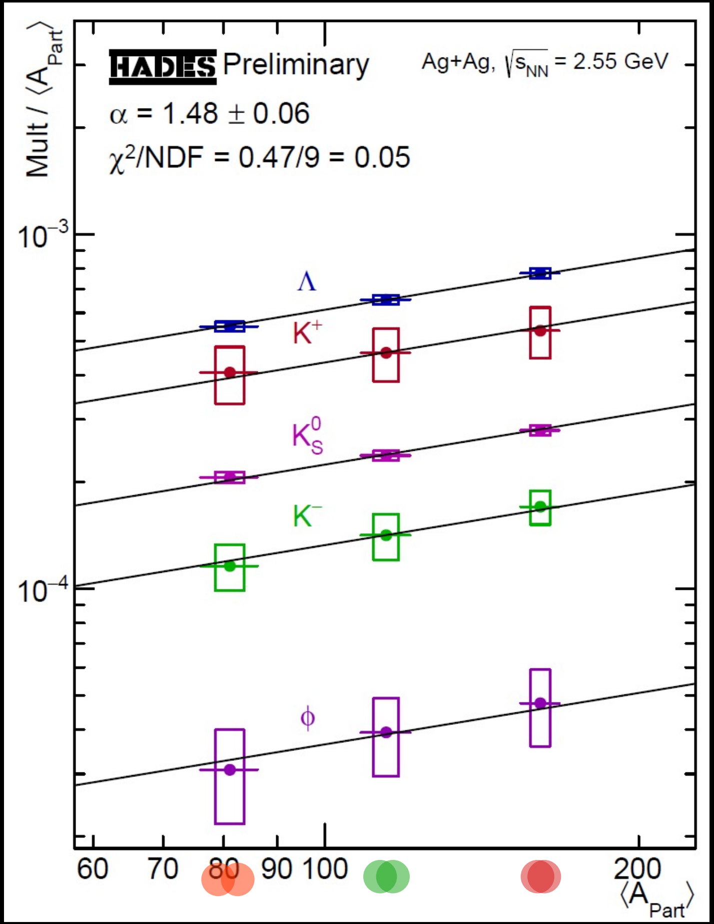

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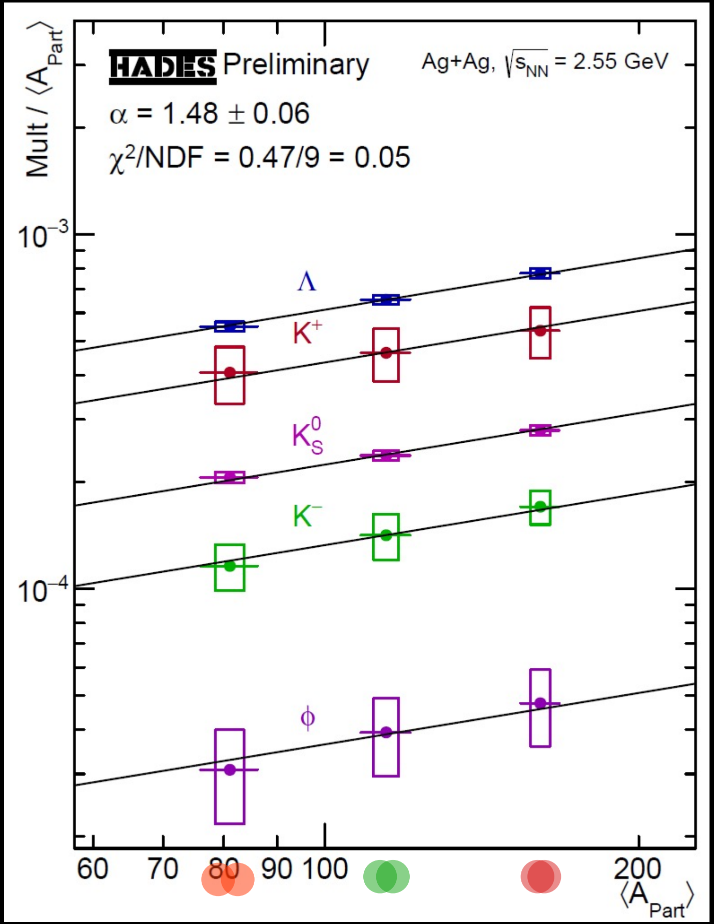

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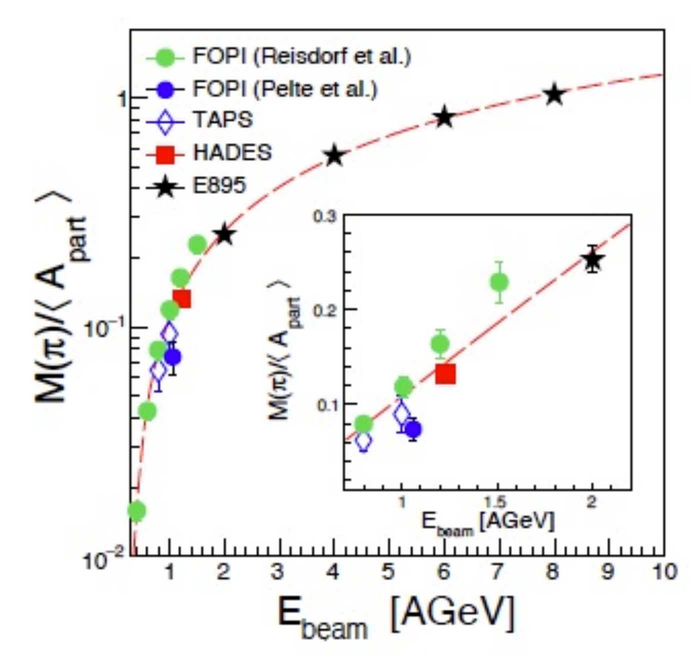
Scaling with absolute amount of ssbar, not with individual hadron states.

EOS properties based on strangeness assume fast formation of hadrons relative to the in-medium propagation time.

How does the trend continue at lower energy?

3. Caveats (Devil's Advocat)

Pion yields @ $\sqrt{s_{NN}}$ = 2.42 GeV



Discrepancy between HADES and FOPI data (factor ≈ 1.35).

Eur.Phys.J.A 56 (2020) 259.

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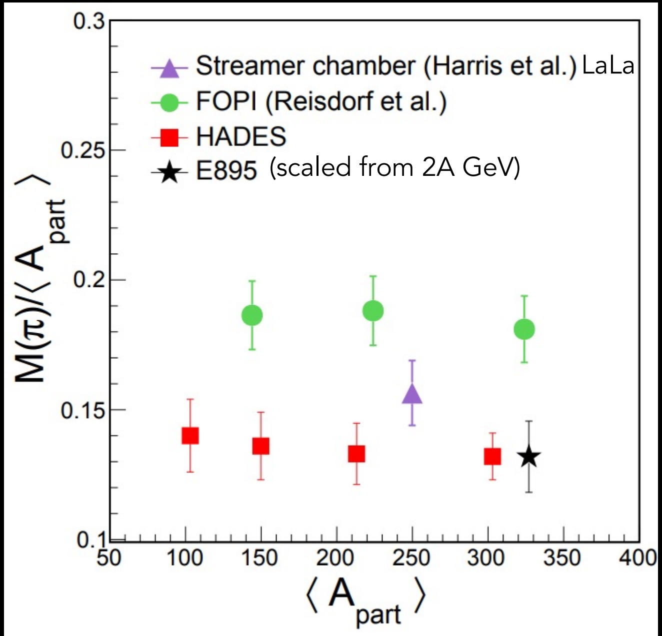

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Eur.Phys.J.A 56 (2020) 259, private communication W.Reisdorf

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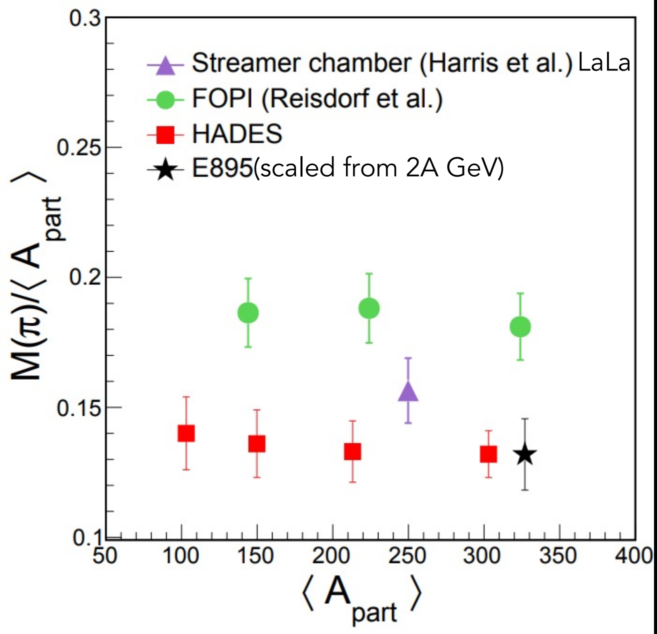

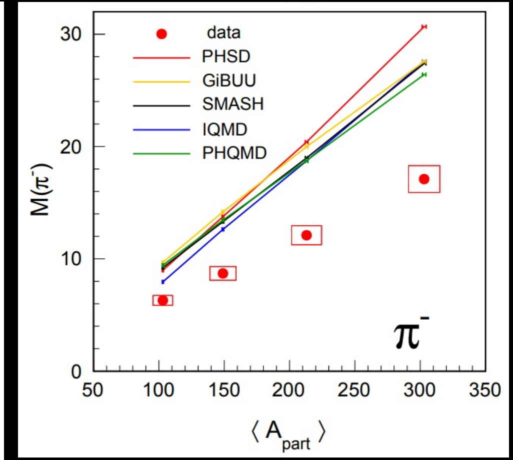

Large overshoot of transport models.

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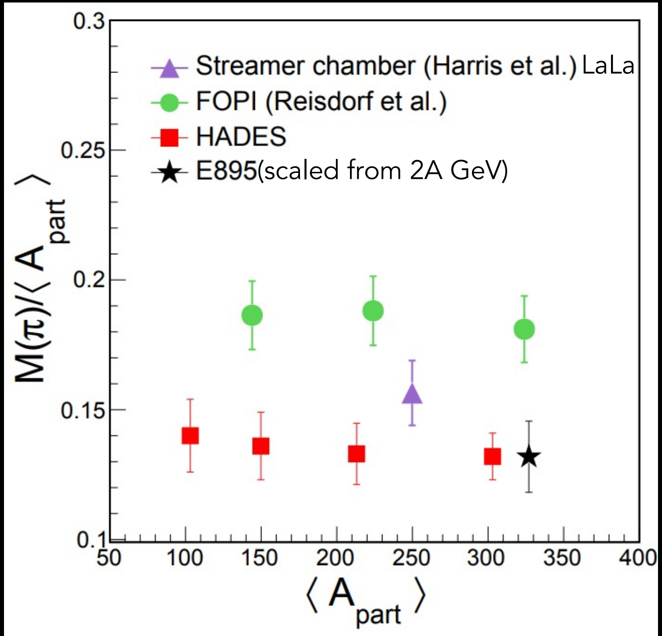

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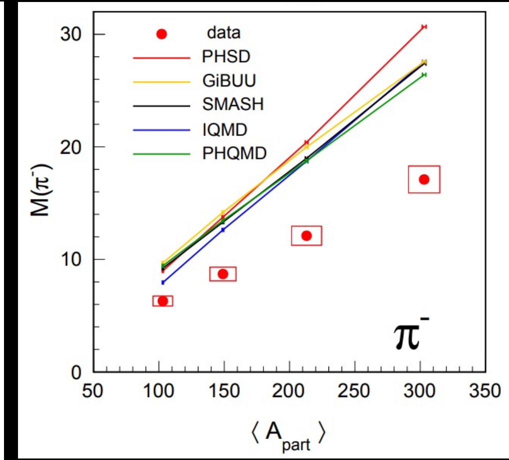
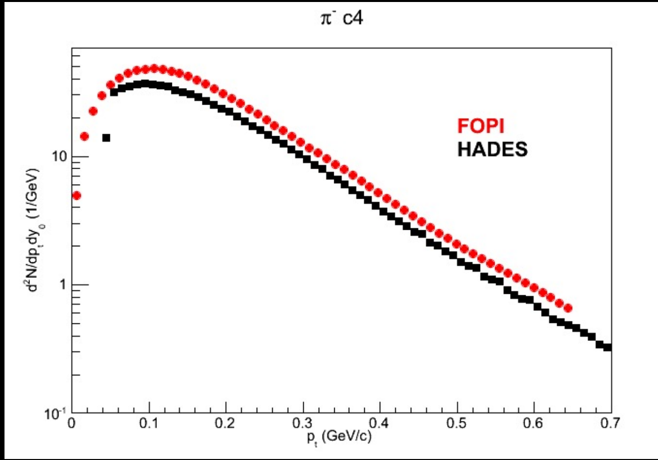


Large overshoot of transport models.

A closer look at the FOPI and HADES data:



Very similar shape of p_t spectra, factor ≈ 1.35).

Eur.Phys.J.A 56 (2020) 259, private communication W.Reisdorf

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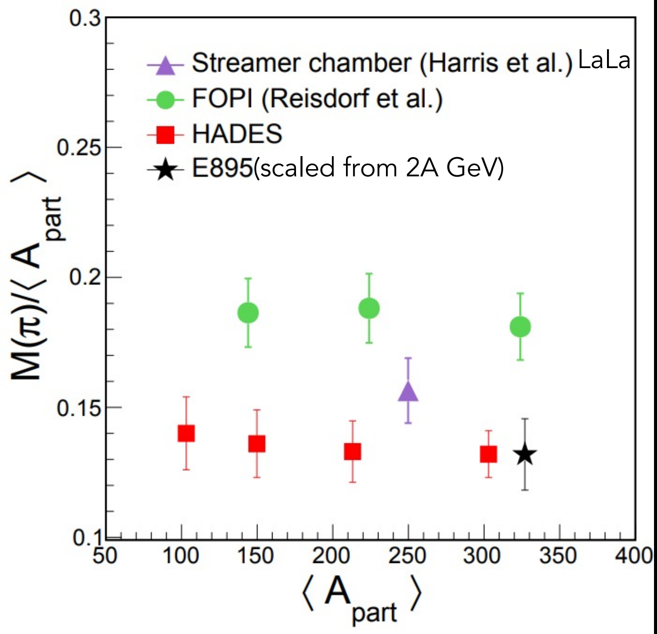

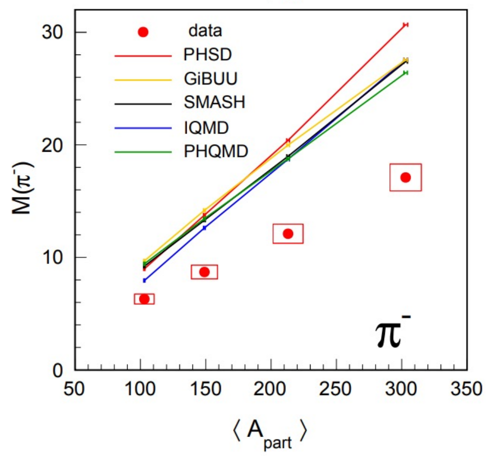

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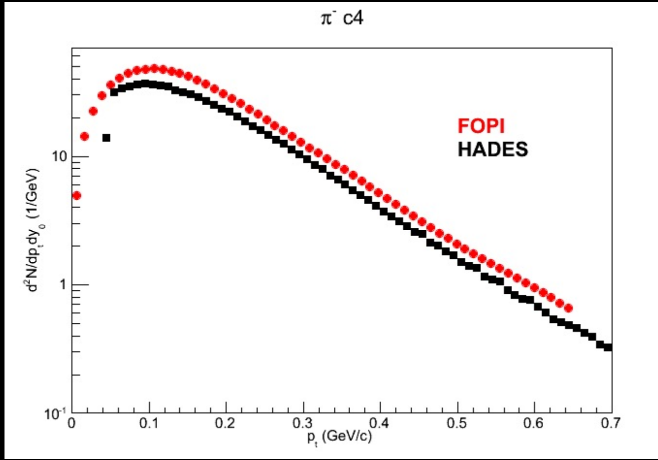

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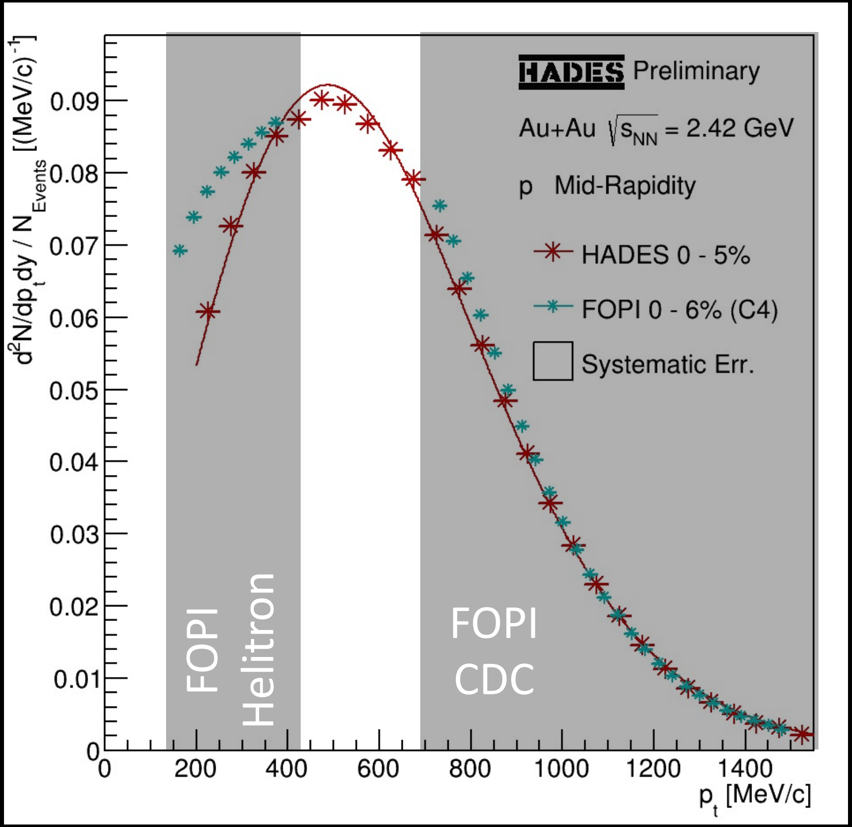
What about protons?

Eur.Phys.J.A 56 (2020) 259, private communication W.Reisdorf

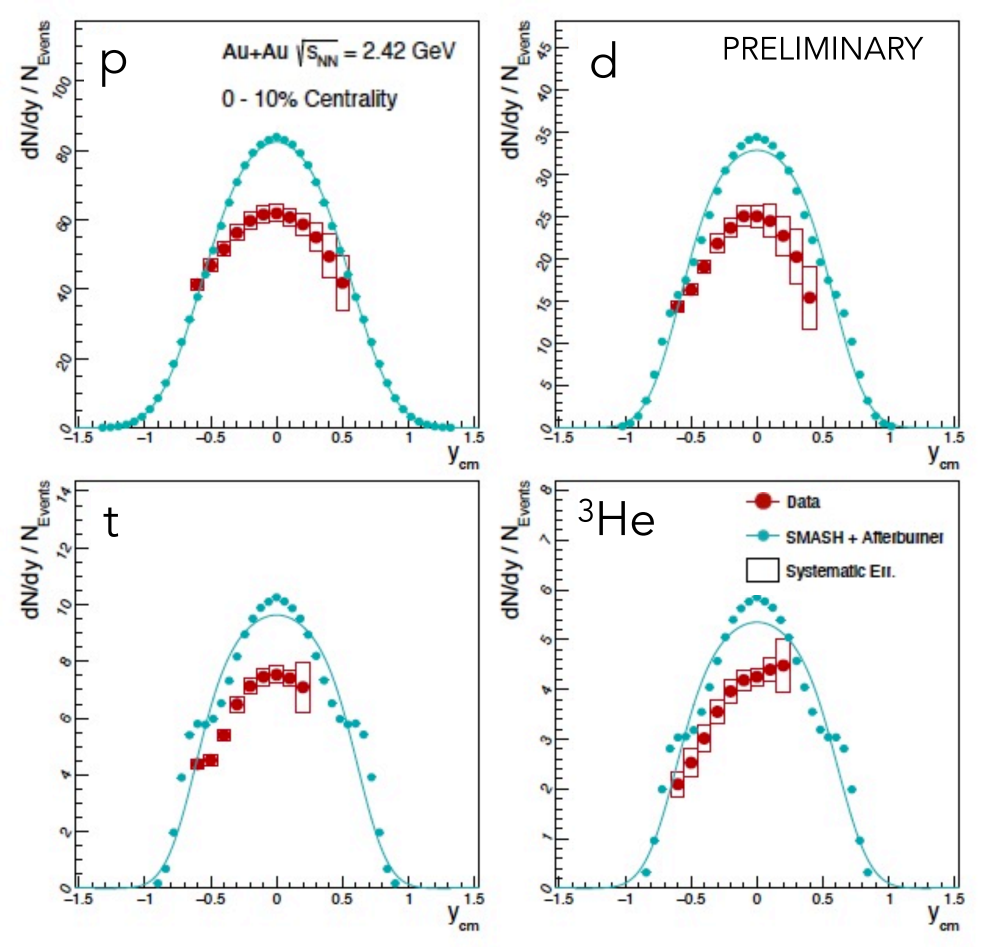
Proton yields and spectra @ $\sqrt{s_{NN}}$ = 2.42 GeV



- Comparison of HADES 1.23A GeV Au+Au 0-5% results to FOPI 1.20A GeV C4 (≈ 0-6%) results
- FOPI "Mid-Rapidity" spectrum actually y_{cm} ∈ [0, 0.072] vs. HADES y_{cm} ∈ [-0.05, 0.05]
- Almost perfect agreement in the high transverse momentum region covered by CDC of FOPI and some tension in the low transverse momentum region covered by Helitron of FOPI
- dN/dy distributions agree with ≲ 10% differences
- Overall fair agreement between HADES and FOPI data → Not 30%+ difference like for **Pions**

private communication W.Reisdorf

Proton and light nuclei vs. transport @ $\sqrt{s_{NN}}$ = 2.42 GeV



To much baryons stopped and emitted around mid-rapidity in transport for 0-10% most central events.

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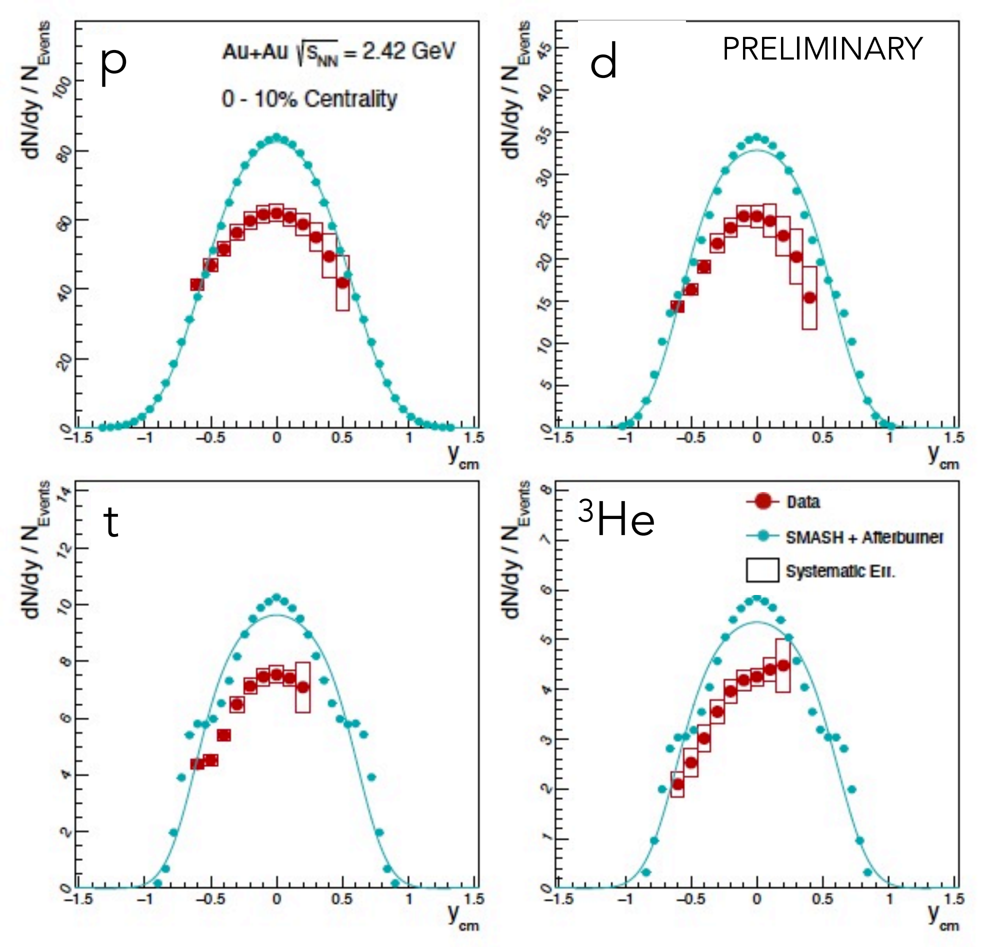

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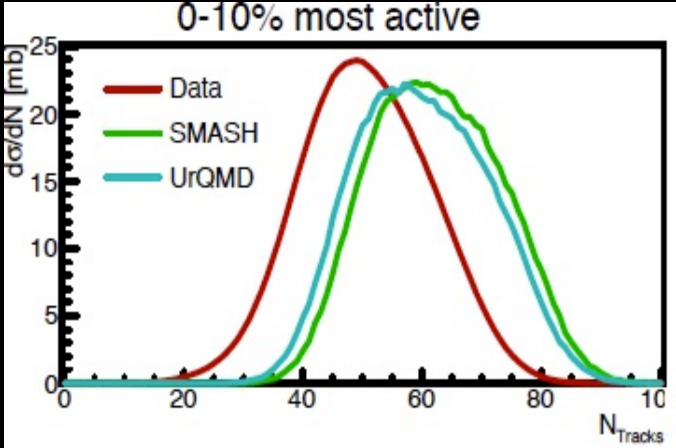
More direct observable:
Number of charged tracks in HADES



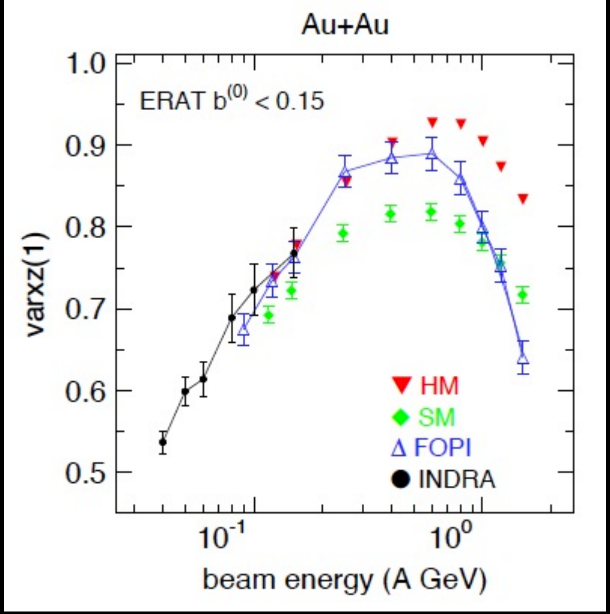
Similar picture and conclusion.

Proton and light nuclei vs. transport @ $\sqrt{s_{NN}}$ = 2.42 GeV

Systematics of central heavy ion collisions in the 1A GeV regime

W. Reisdorf,[a,1], A. Andronic[a], R. Averbeck[a], M.L. Benabderrahmane[f], O.N. Hartmann[a], N. Herrmann[f], K.D. Hildenbrand[a], T.I. Kang[a,j], Y.J. Kim[a], M. Kiš[a,m], P. Koczoń[a], T. Kress[a], Y. Leifels[a], M. Merschmeyer[f], K. Piasecki[f,ℓ], A. Schüttauf[a], M. Stockmeier[f], V. Barret[d], Z. Basrak[m], N. Bastid[d], R. Čaplar[m], P. Crochet[d], P. Dupieux[d], M. Dželalija[m], Z. Fodor[c], P. Gasik[ℓ], Y. Grishkin[g], B. Hong[j], J. Kecskemeti[c], M. Kirejczyk[ℓ], M. Korolija[m], R. Kotte[e], A. Lebedev[g], X. Lopez[d], T. Matulewicz[ℓ], W. Neubert[e], M. Petrovici[b], F. Rami[k], M.S. Ryu[j], Z. Seres[c], B. Sikora[ℓ], K.S. Sim[j], V. Simion[b], K. Siwek-Wilczyńska[ℓ], V. Smolyankin[g], G. Stoicea[b], Z. Tymiński[ℓ], K. Wiśniewski[ℓ], D. Wohlfarth[e], Z.G. Xiao[a,i], H.S. Xu[i], I. Yushmanov[h], A. Zhilin[g]

(FOPI Collaboration)

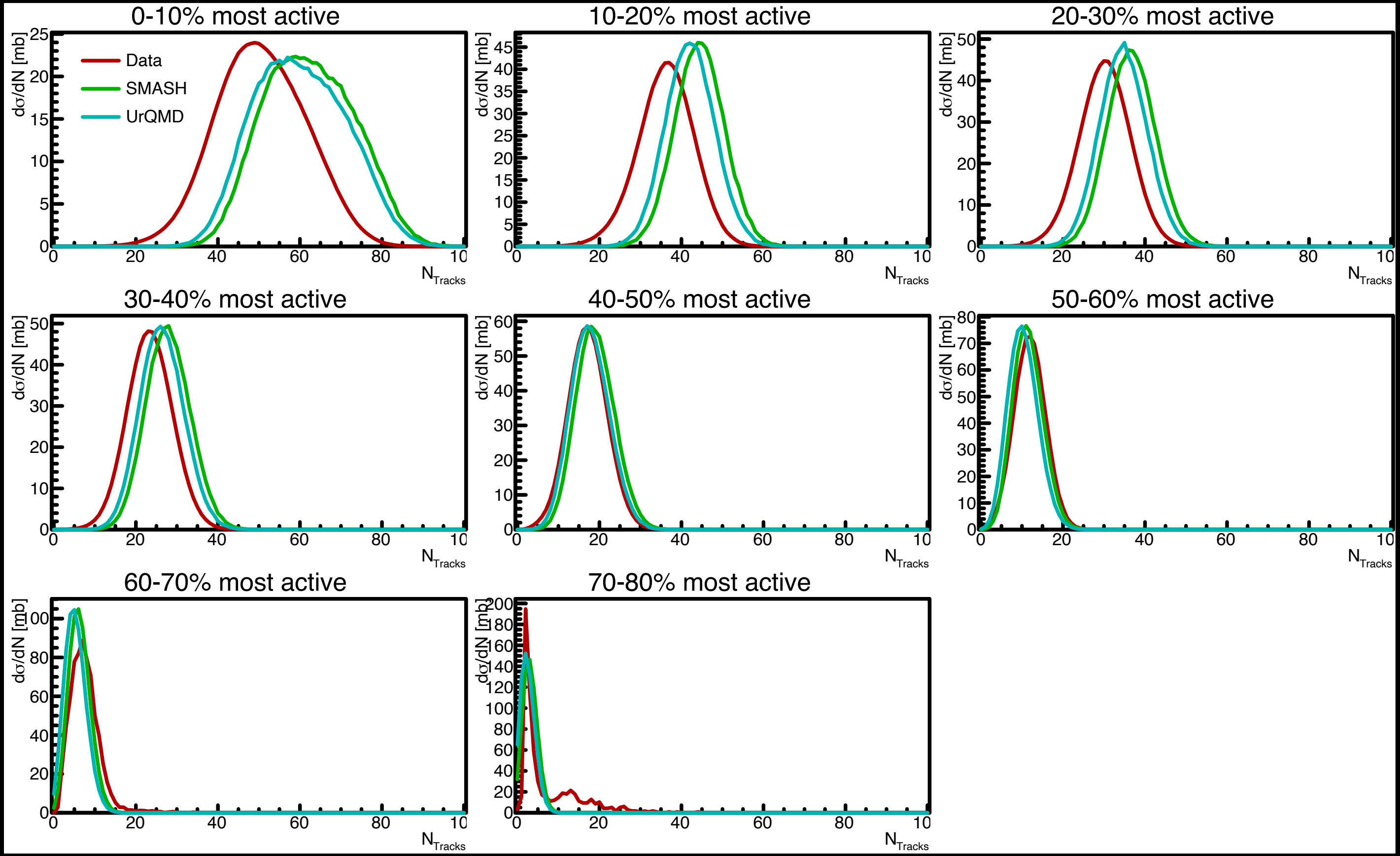


also clear that the 'residual' interaction, i.e. the explicit collision term, influences the outcome. The present parameterization of IQMD as used here is obviously not able to reproduce the data, in particular the rapid drop of *varxz(1)* beyond 0.8A GeV is not reproduced. A fair reproduction of a portion (0.25A to 1.0A GeV) of the excitation function was achieved in [50].

Similar conclusion as FOPI.

[50] T. Gaitanos, C. Fuchs, H. H. Wolter, Phys. Lett. B 609 (2005) 241.

Proton and light nuclei vs. transport @ $\sqrt{s_{NN}}$ = 2.42 GeV



4. Perspectives

Proposals for beam time at SIS18: 2021 - 2025

Pion induced reactions on CH_2 and C, Ag targets

The HADES Collaboration

HADES

This is a new experiment proposal.

We request 89 shifts.

p+p reactions at 4.5 GeV on CH_2

The HADES and HADES-PANDA Collaborations

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This is a new experiment proposal.

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p+Ag reactions at 4.5 GeV

The HADES Collaboration

HADES

This is a new experiment proposal.

We request 88 shifts.

Beam Energy Scan for proton and neutron induced reactions on protons.

The HADES Collaboration

HADES

This is a new experiment proposal.

We request 104 shifts.

Studies of QCD matter with Au+Au collisions at 0.8A–0.6A–0.4A–0.2A GeV

The HADES Collaboration

HADES

Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tlusty (tlusty@ujf.cas.cz)

GSI contact: J. Pietraszko (j.pietraszko@gsi.de)

Infrastructure: SIS18 and HADES cave

This is a proposal for a new experiment

In total we request 94 shifts.

HADES energy scan 2024

System	Energy (*A* GeV)	Requested shifts	DAQ rate (kHz)	Estimated #events
Au+Au	0.8	30	10	3×10^9
Au+Au	0.6	30	10	3×10^9
Au+Au	0.4	9	10	1×10^9
Au+Au	0.2	9	10	1×10^9
C+C	0.8	6	30	2×10^9
C+C	0.6	6	30	2×10^9

- Beam intensity (flat top) 1.2×10^6 Au ions/s, 3×10^6 C ions/s
- 1.5% interaction length gold target
- 2% interaction length carbon target
- Count rate estimate includes 0.66 (lifetime) x 0.56 (duty cycle)

Estimated count rates and requested beam time based solely on experimental results and known spectrometer performance

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3 weeks instead of 4 weeks.

- Beam intensity (flat top) 1.2×10^6 Au ions/s, 3×10^6 C ions/s
- 1.5% interaction length gold target
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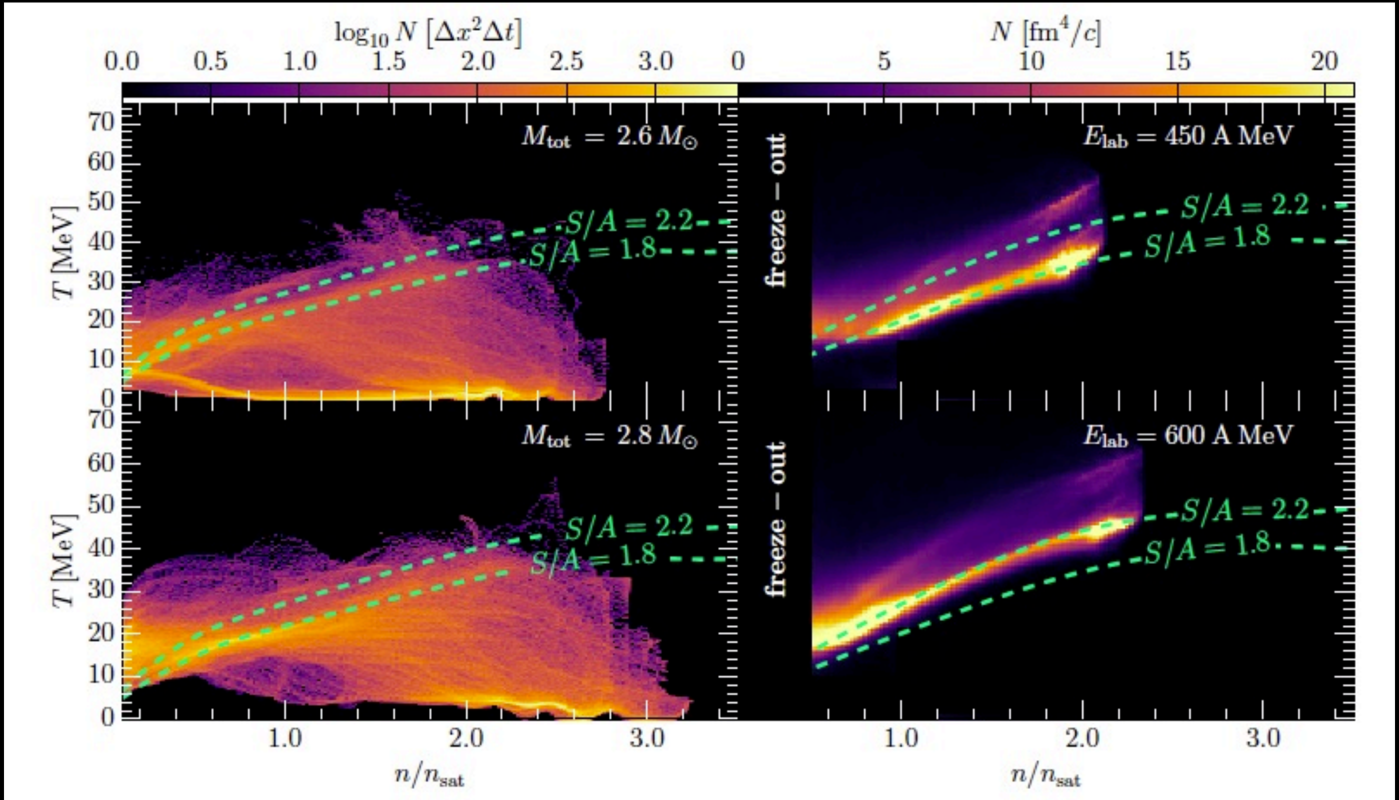
Estimated count rates and requested beam time based solely on experimental results and known spectrometer performance

Probing similar density and temperature profiles like merging neutron stars

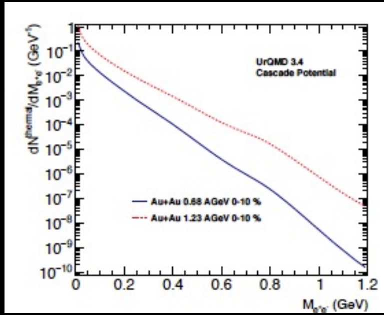


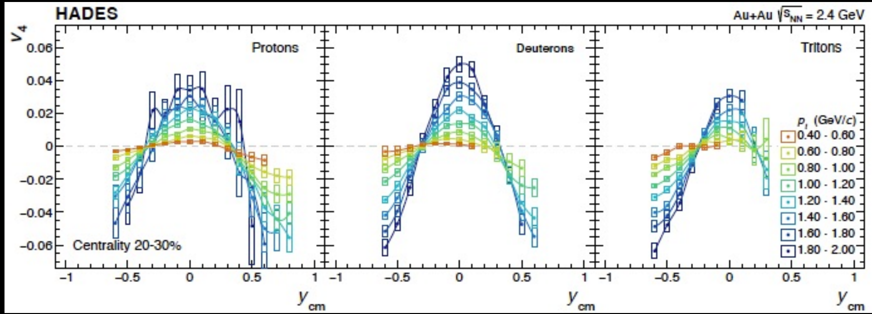
Phys.Rev.D 107 (2023) 4, 043034

HADES energy scan 2024

Multi messenger: new observables not accessible by previous experiments

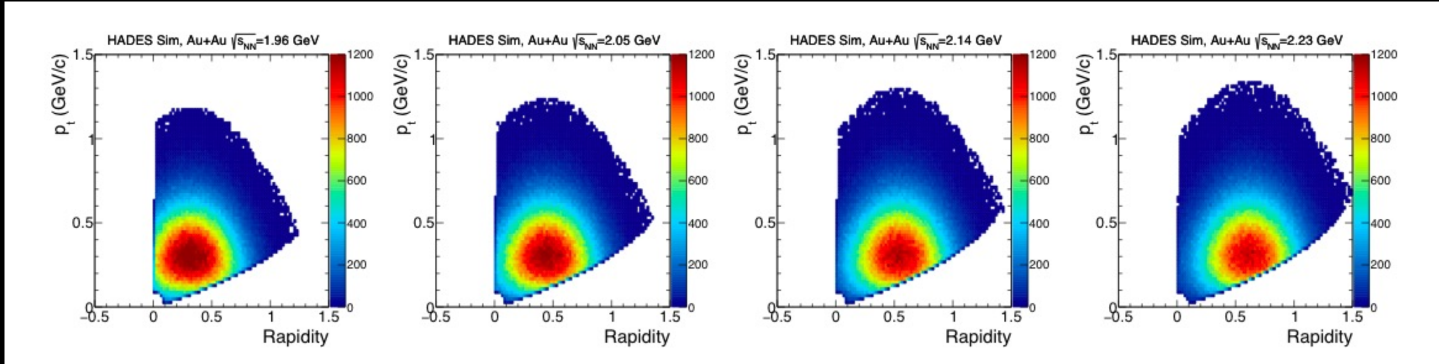
dileptons, higher o. flow c., strangeness, e-b-e-fluctuations



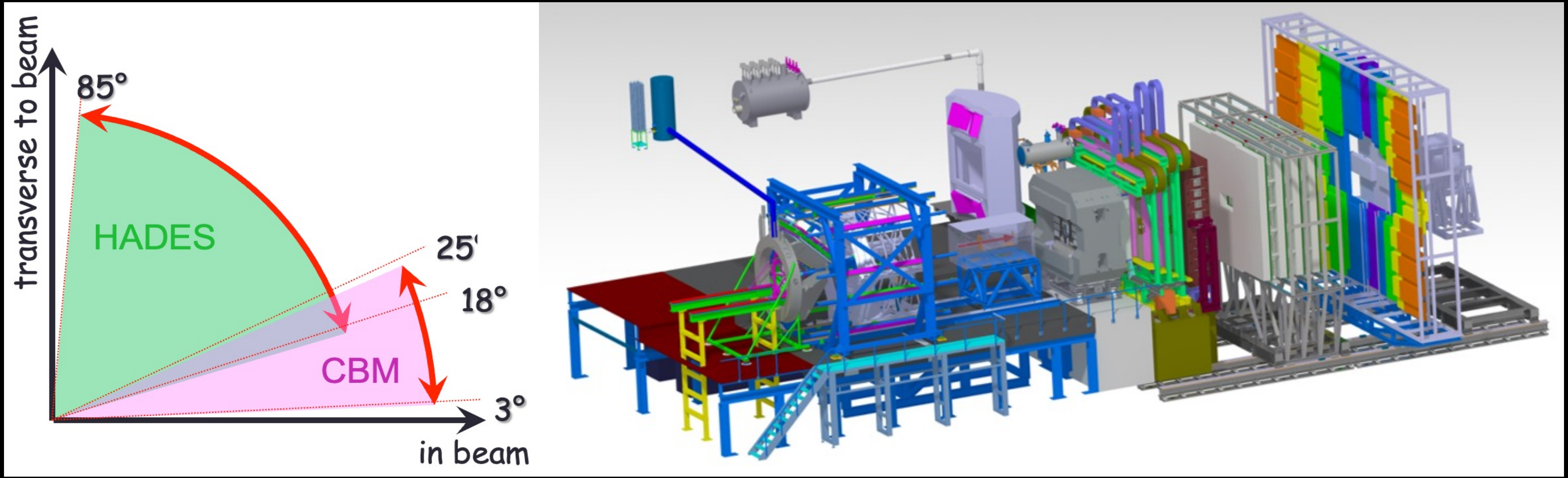


+systematic comparison to previously measured ones

pion, proton and light nuclei yields and spectra, lower order flow c.

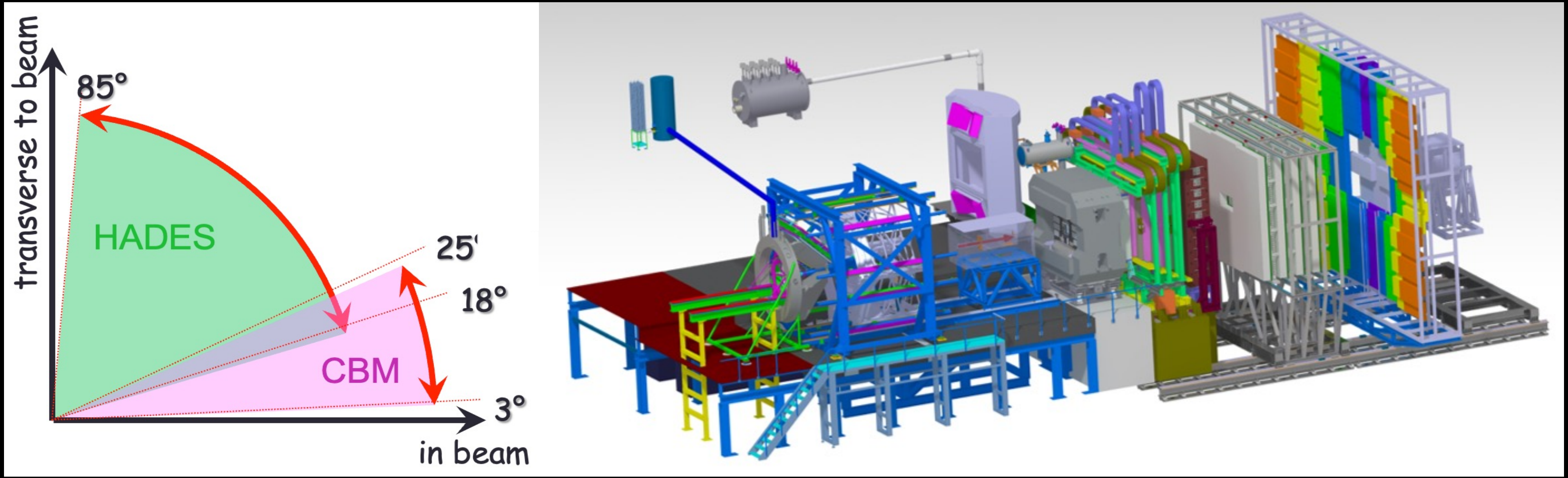


HADES @ SIS 100



- HADES and CBM will be operated at the SIS100
- Angular coverage of both detectors complementary, very important for measuring pion, kaon, proton (..) 4pi yields at energies below 4 A GeV!

HADES @ SIS 100



- HADES and CBM will be operated at the SIS100
- Angular coverage of both detectors complementary, very important for measuring pion, kaon, proton (..) 4pi yields at energies below 4 A GeV!

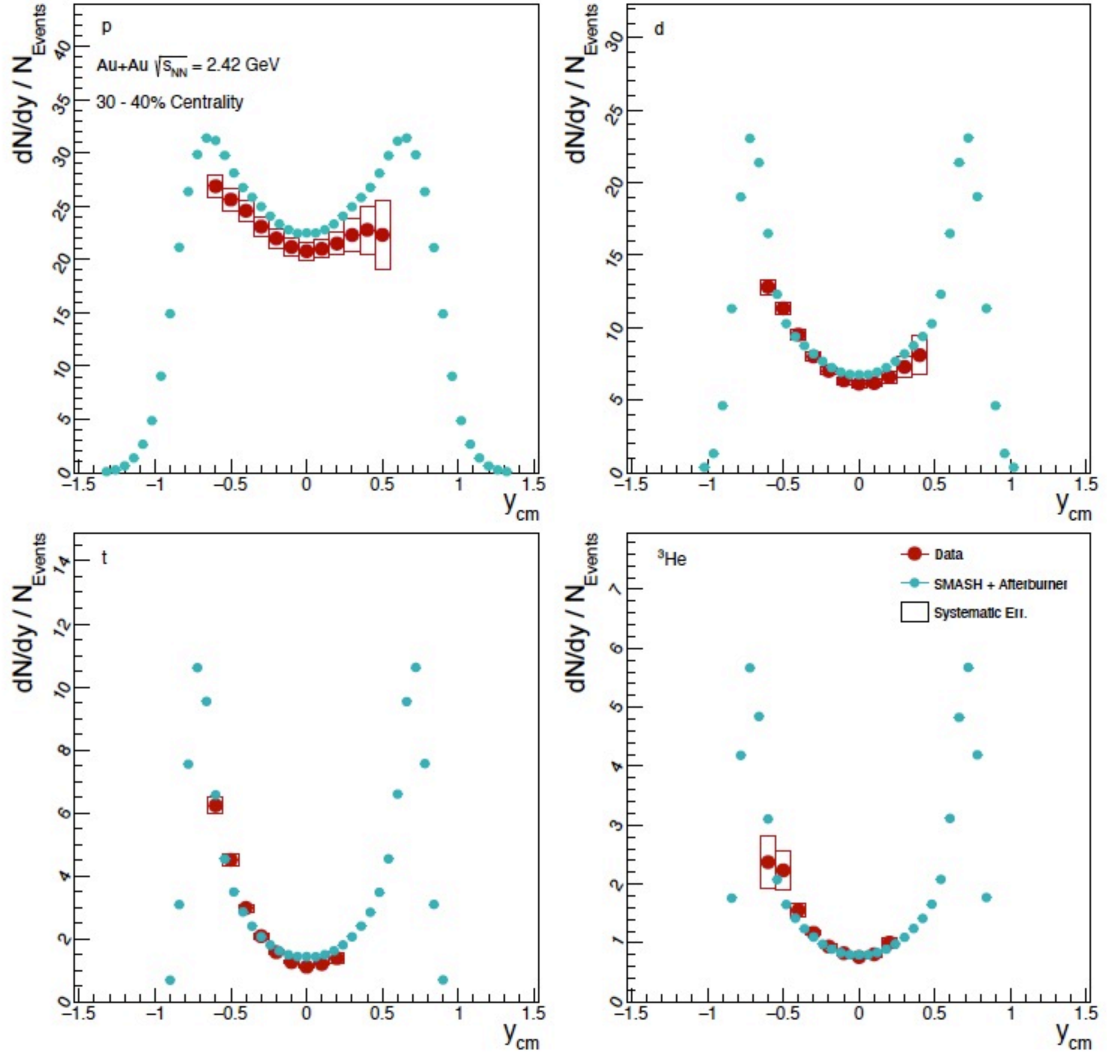
Systematic uncertainties vs. statistical errors!

Summary

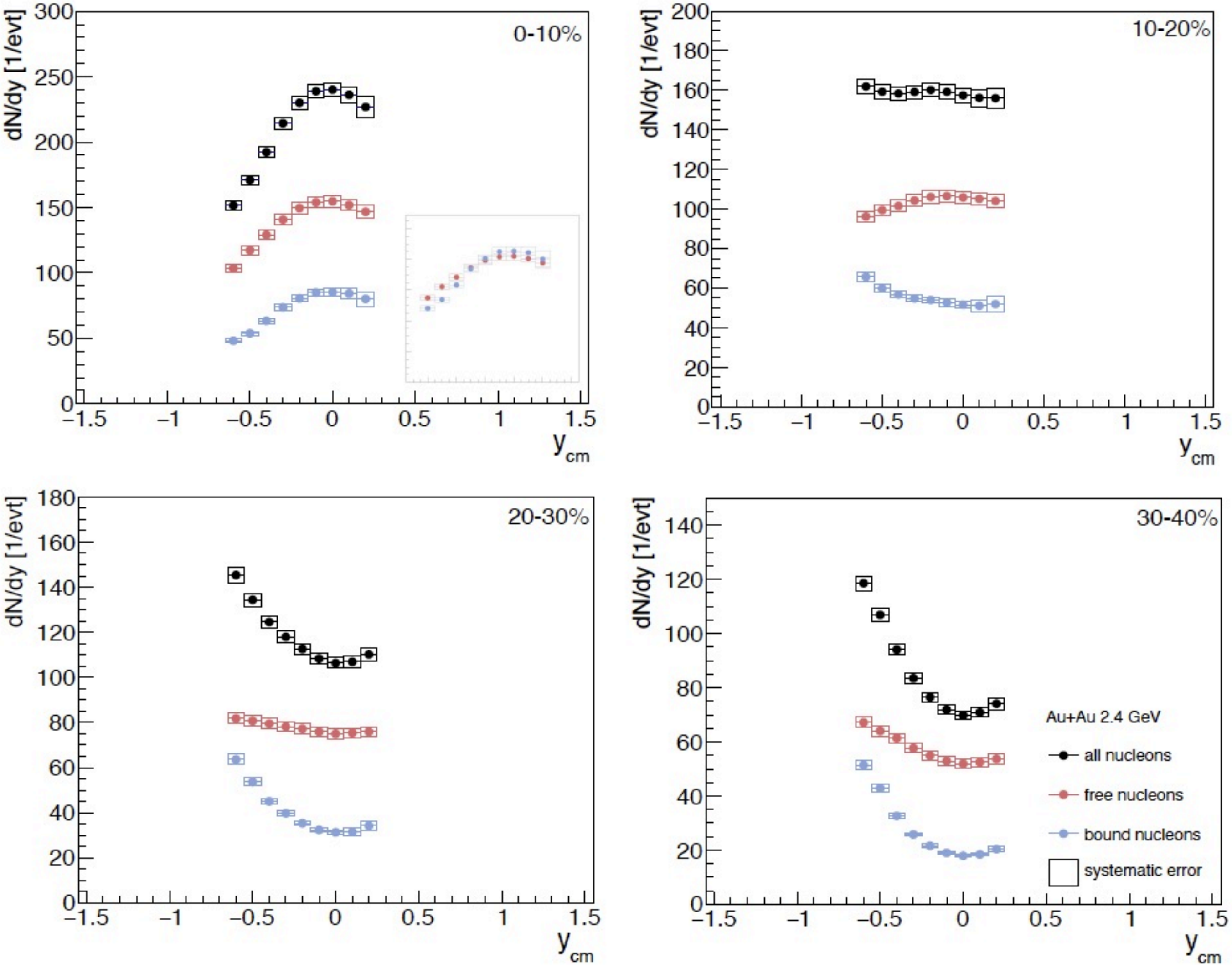
Dilepton radiation: temperature measurement and sensitive to rapid changes in the EOS.
HBT: extracted radii follow trend from SPS and LHC.
Strangeness: universal Apart scaling with number of ssbar quarks.

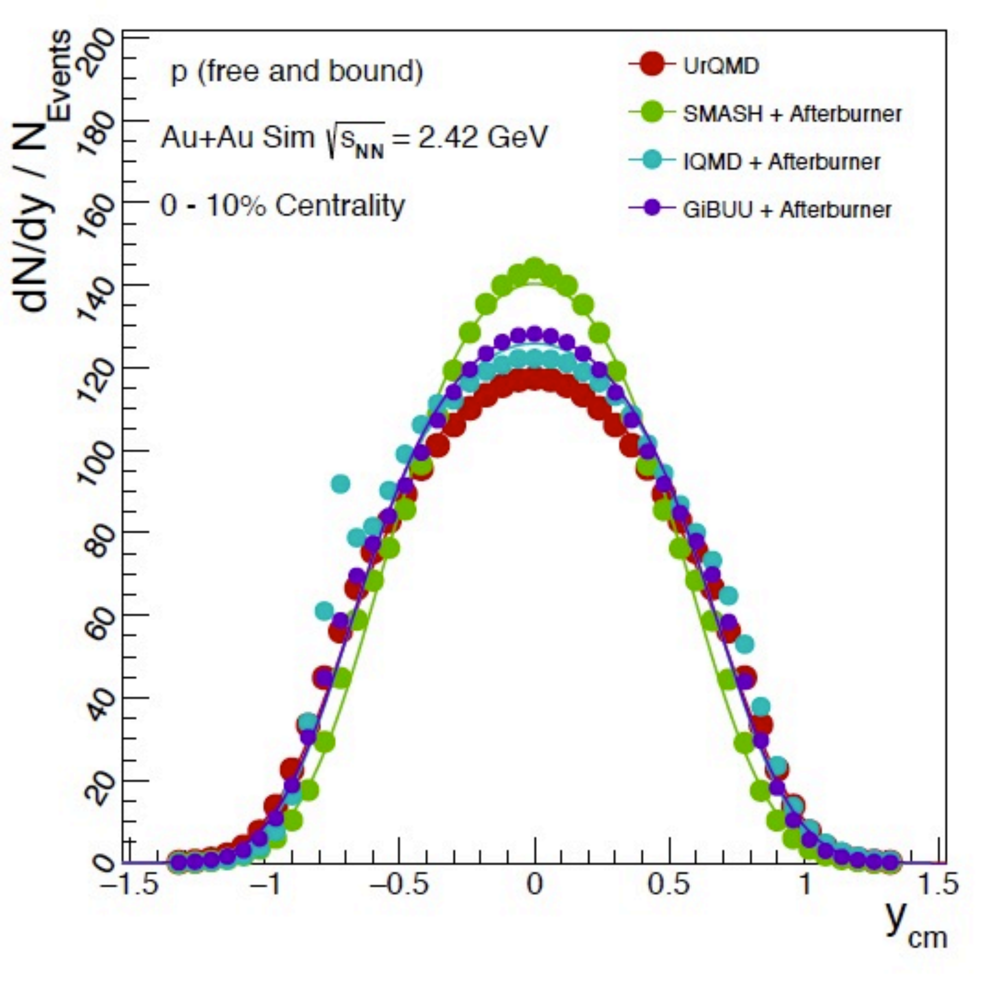
Pion and proton yields: discrepancy on pions between HADES and FOPI,
agreement on protons,
to much baryons stopped and emitted around mid-rapidity in 0-10% most active events in transport codes for beam energies 1-2 A GeV.

Perspectives: HADES Au+Au energy scan at 0.8, 0.6, 0.4 and 0.2 A GeV 2024:
new observables and systematic comparison to previous measurements.
HADES @SIS100 important for beam energies below 4 A GeV.



p
Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV
30 - 40% Centrality
d
t
^{3}He
Data
SMASH + Afterburner
Systematic Err.
dN/dy / N_{Events}
y_{cm}

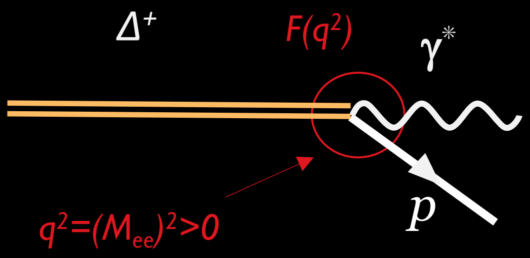

0-10%
10-20%
20-30%
30-40%
dN/dy [1/evt]
y_{cm}
Au+Au 2.4 GeV
all nucleons
free nucleons
bound nucleons
systematic error

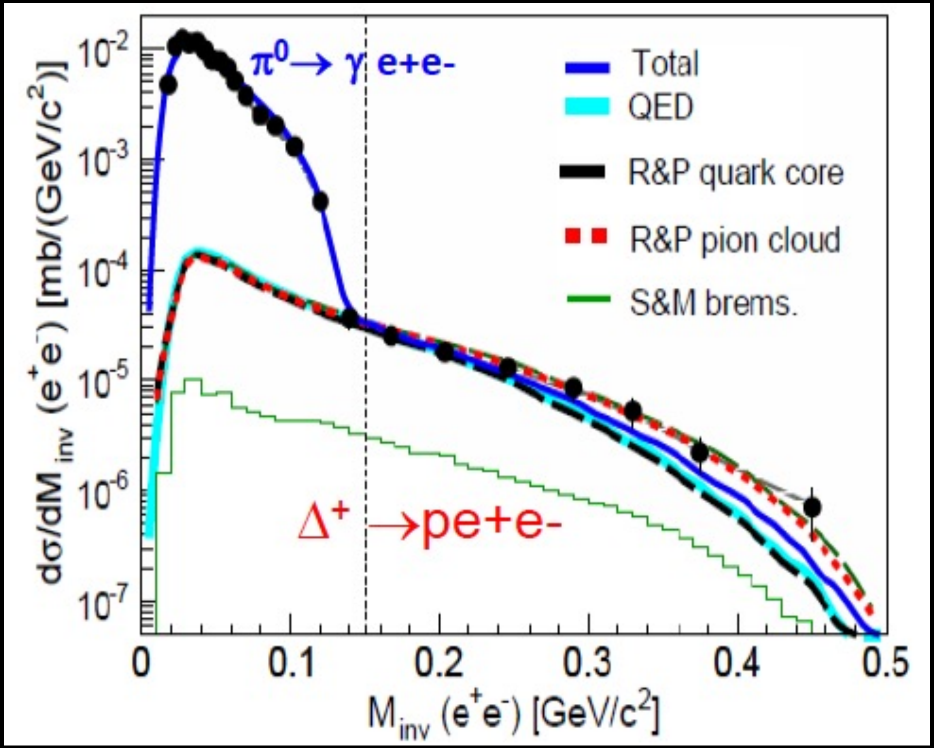


p (free and bound)
Au+Au Sim $\sqrt{s_{NN}}$ = 2.42 GeV
0 - 10% Centrality
UrQMD
SMASH + Afterburner
IQMD + Afterburner
GiBUU + Afterburner
dN/dy / N_{Events}
y_{cm}
0
20
40
60
80
100
120
140
160
180
200
−1.5
−1
−0.5
0
0.5
1
1.5

EM Formfactors of baryonic resonances

$p+p(1.25\ \text{GeV}) \rightarrow p+p+e^-+e^+$

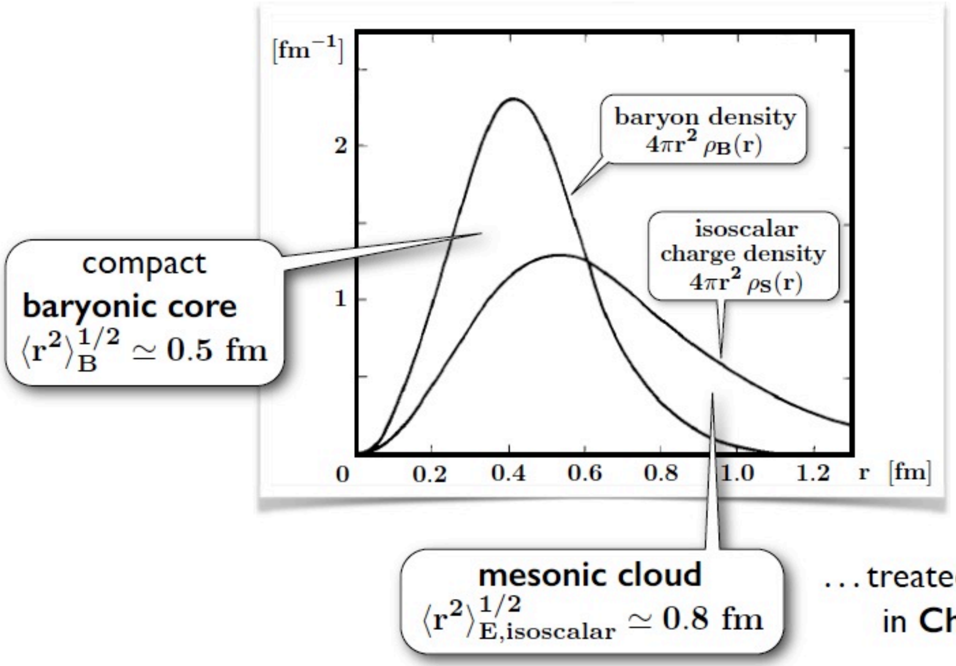




Phys. Rev. C95 (2017) no.6 065205

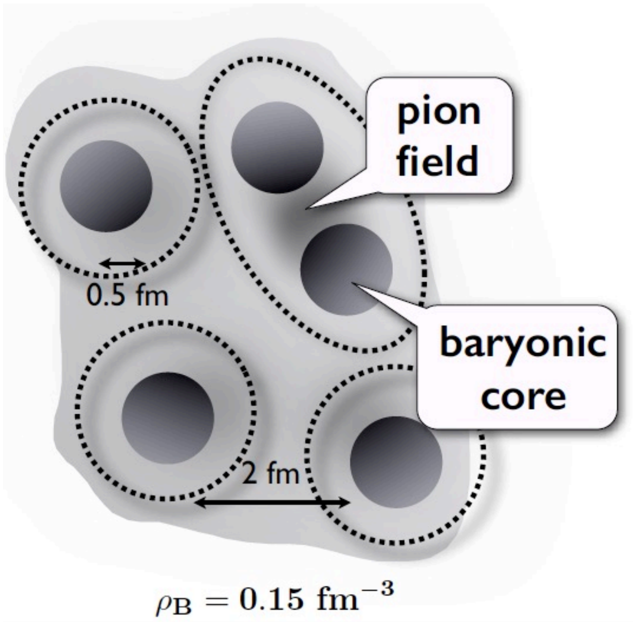
Good agreement with model of Ramahlo & Pehna
if pion cloud is taken into account

Consequences of the created system?



N. Kaiser,
U.-G. Meißner,
W.W.
Nucl. Phys.
A466 (1987) 685

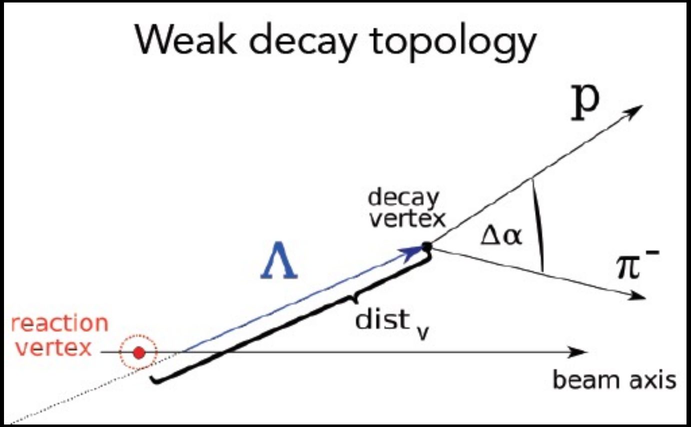
. . . treated properly
in **Chiral EFT**



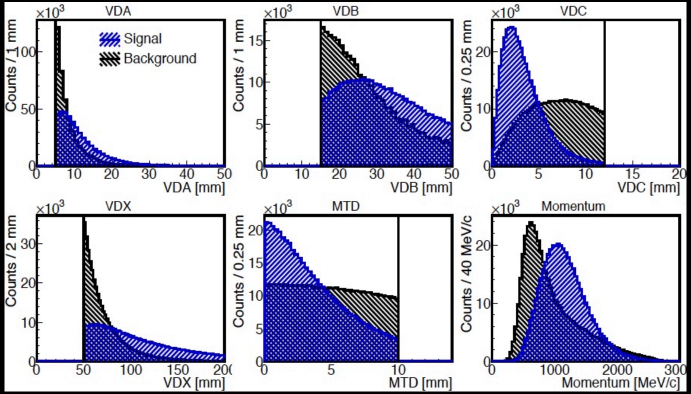
Can we connect this to an observable?

Figures from W. Weise

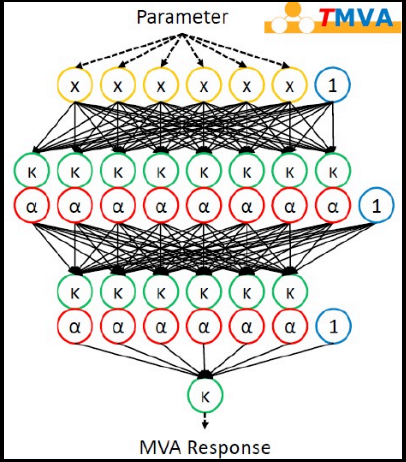
Weak decay topology recognition with neural networks



↓ Results in several parameters

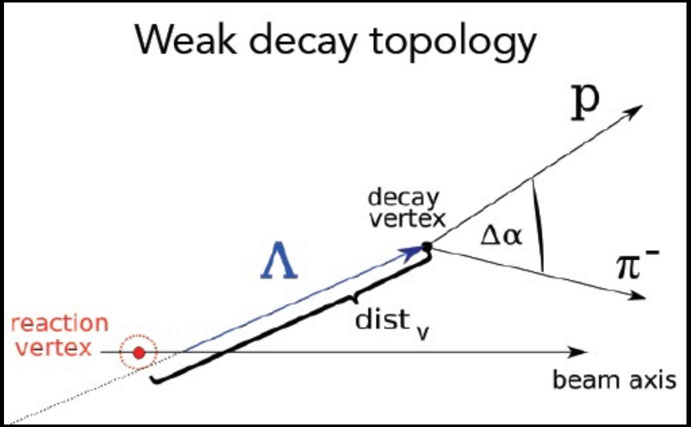


Which can be fed into an ANN



MA S. Spies, PhD F. Kornas, Phys.Lett. B793 (2019) 457-463

Weak decay topology recognition with neural networks



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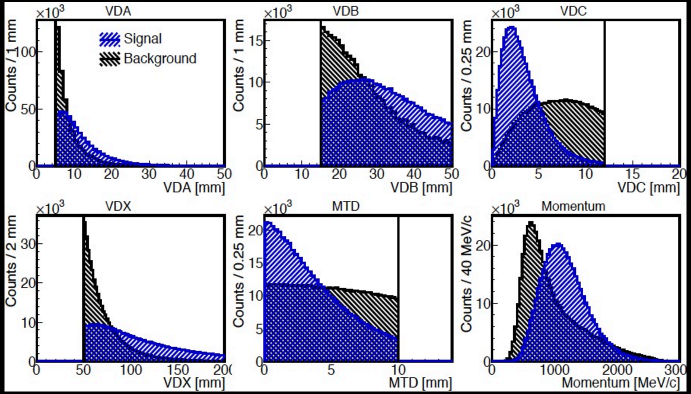
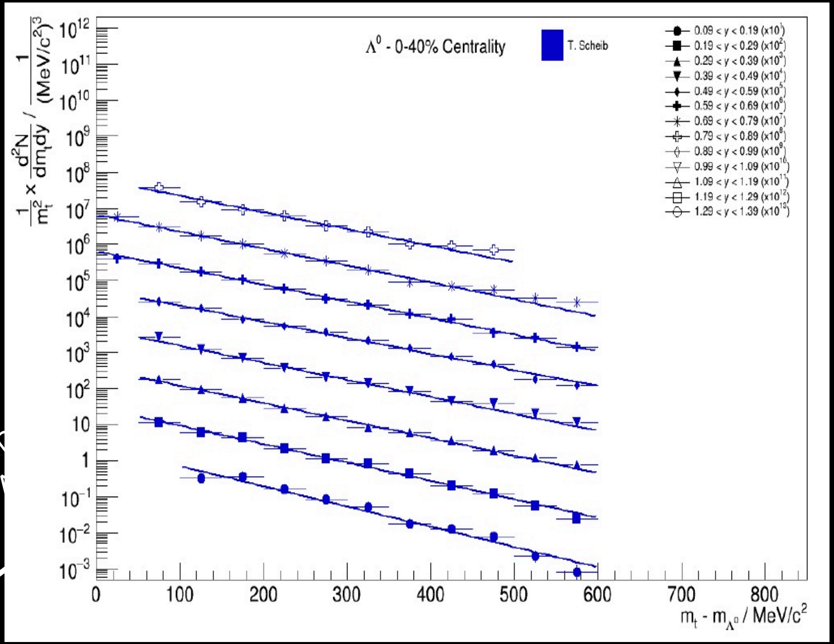
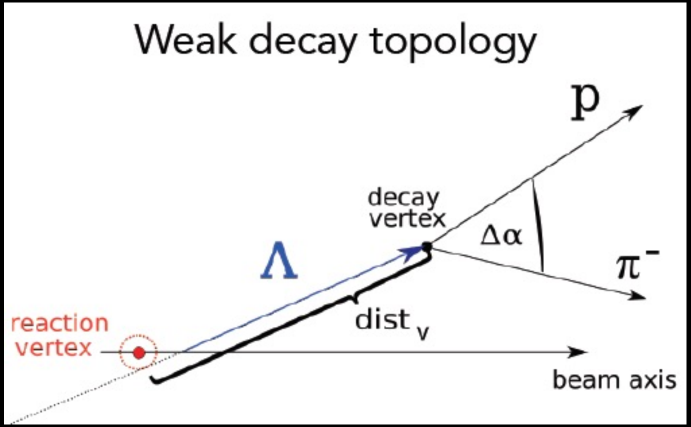


Which ca
into an

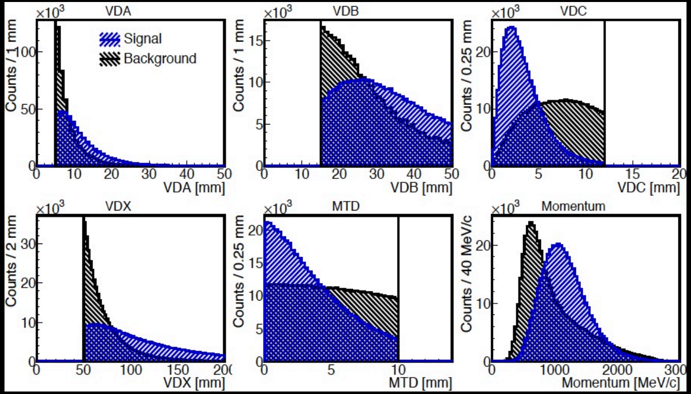


MA S. Spies, PhD F. Kornas, Phys.Lett. B793 (2019) 457-463

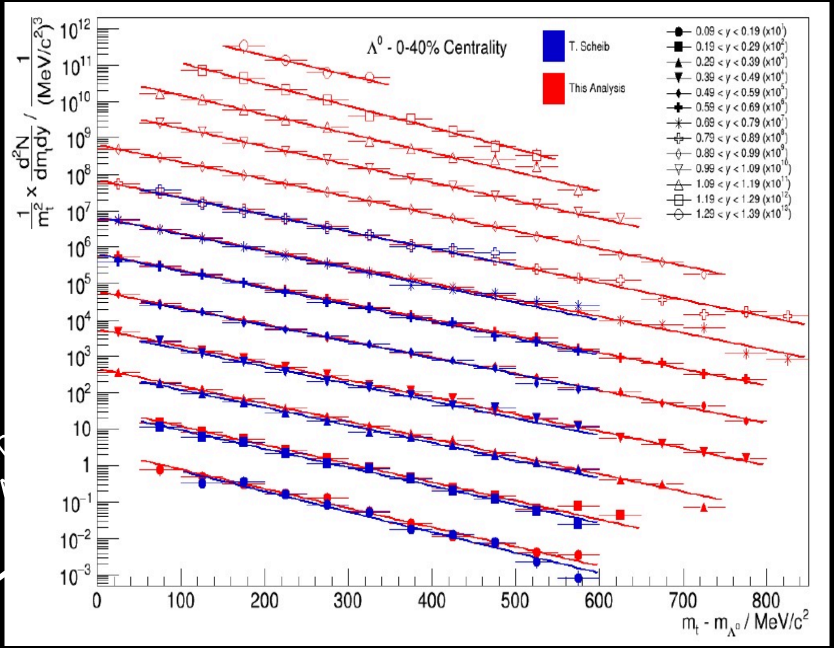
Weak decay topology recognition with neural networks



↓ Results in several parameters

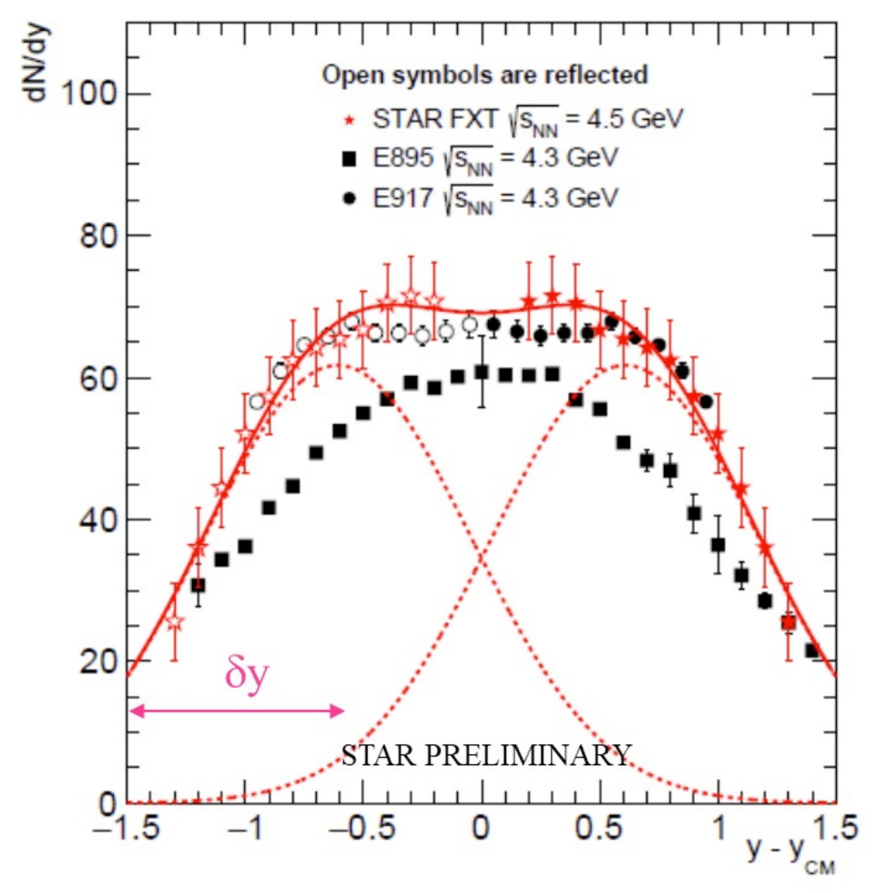


Which ca…
into an …



ANN in combination with pre-selection on topology parameters improves performance → reduction of uncertainty for 4π yield extraction.

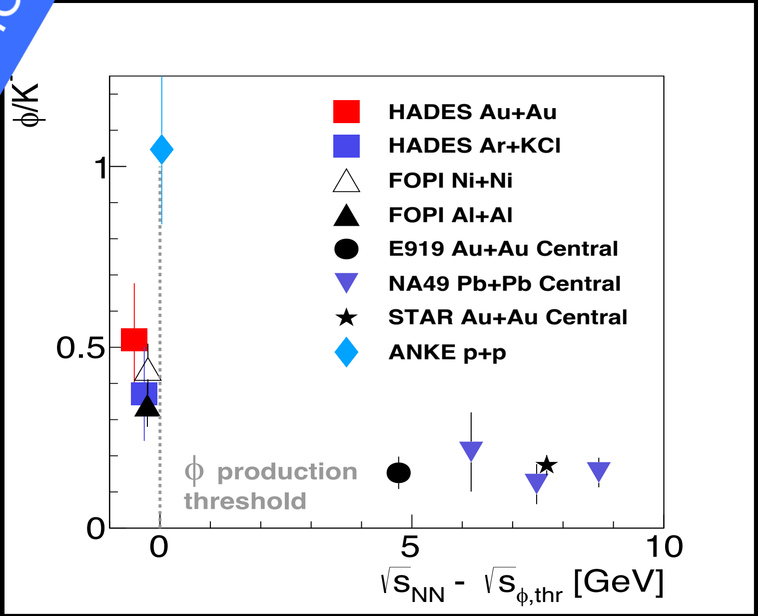
MA S. Spies, PhD F. Kornas, Phys.Lett. B793 (2019) 457-463

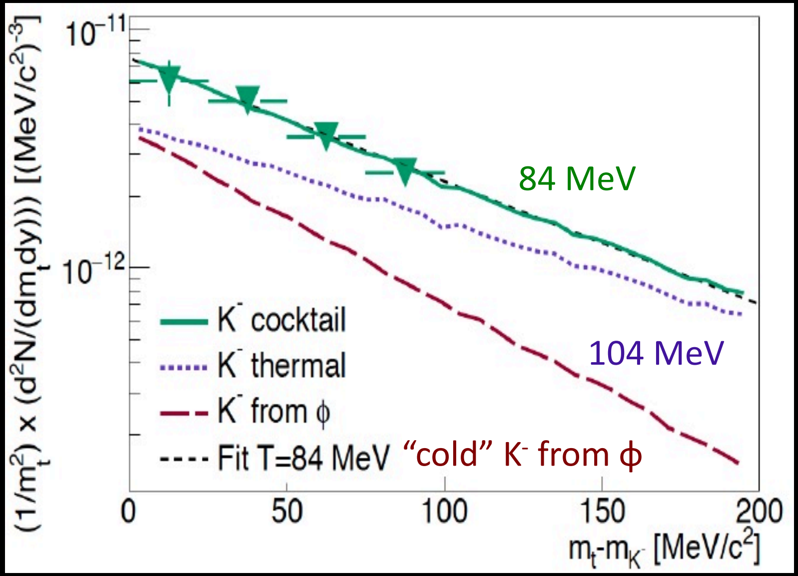


D. Cebra, INT Workshop 22-84W: Dense Nuclear Matter Equation of State 2022

Reminder

Φ-AntiKaon Interplay in HIC





Phys.Lett. B778 (2018) 403-407

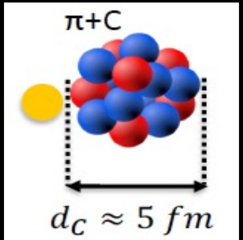
Increased in HIC at low $\sqrt{s_{NN}}$:
→ 25% of K^- result from **Φ** decays!

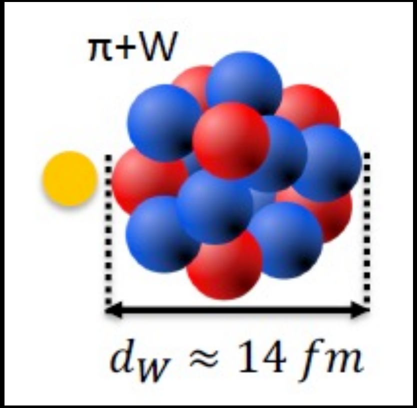
Φ feed-down can explain lower inverse slope parameter of K^- spectrum (T_{eff} = 84 ± 6 MeV) in comparison to the one of K^+(T_{eff} = 104 ± 1 MeV)

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

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

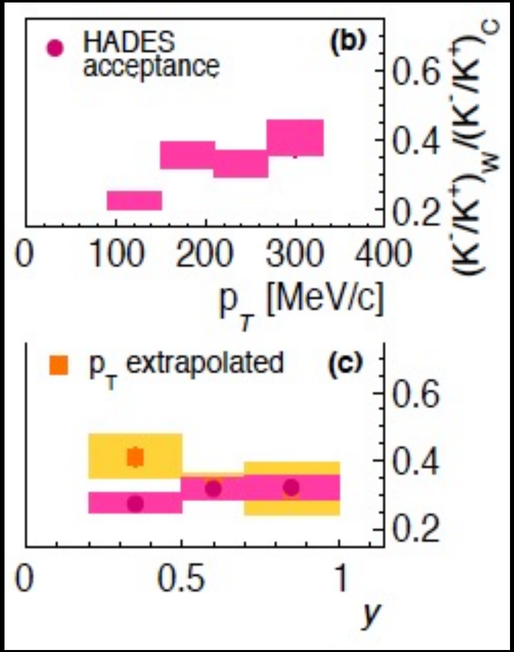
Φ-AntiKaon Interplay in Cold Matter

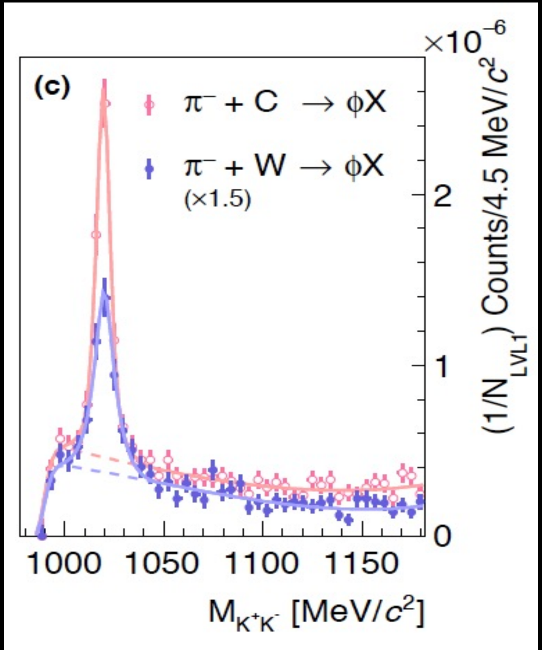




→ Mean free path $\lambda_\pi = 1.5\,fm$

$(p_\pi = 1.7\,GeV/c\,, \rho_B \approx \rho_0)$





→ Suppression of K^- relative to K^+

→ Similar suppression for ϕ like for K^-

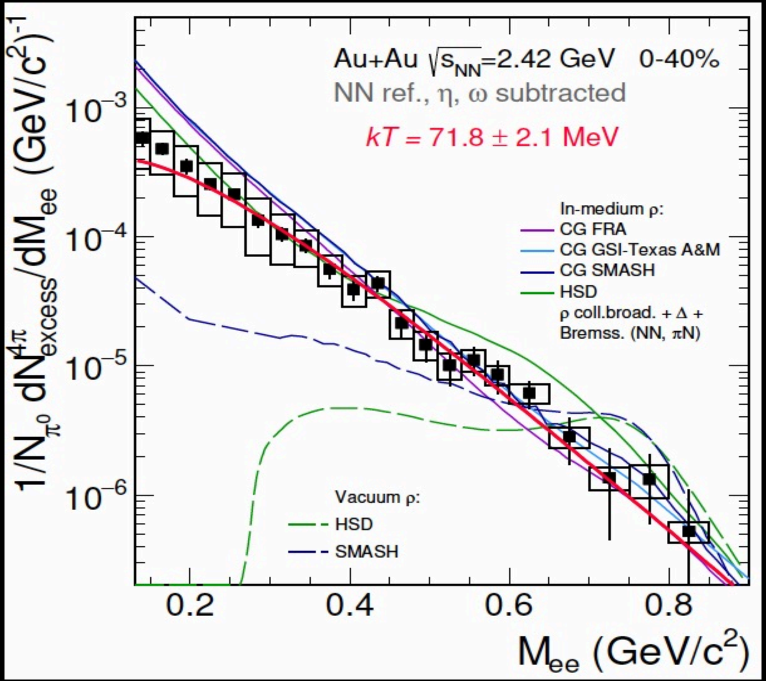
In HADES acceptance:

$$(\phi/K^-)_C = 0.55 \pm 0.04(stat)^{+0.06}_{-0.07}(sys)$$

$$(\phi/K^-)_W = 0.63 \pm 0.06(stat) \pm 0.11(sys)$$

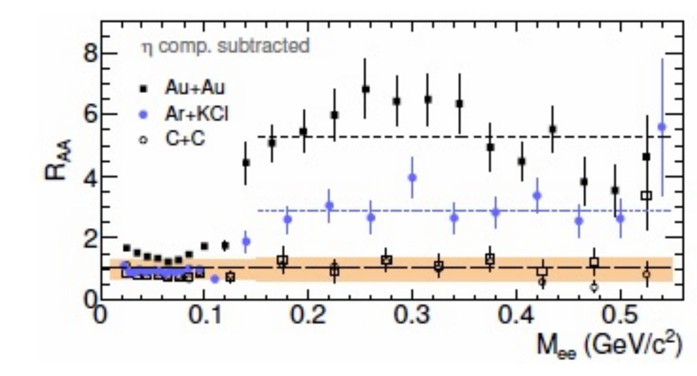
Phys.Rev.Lett. 123 (2019) 2, 022002

Virtual Photon Radiation from Dense Baryon Matter



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

- First measurement for a heavy system at low $\sqrt{s_{NN}}$.
- Strong excess (0.15<M<0.7 GeV/c^2) above components of meson decays at freeze-out and NN-reference.
- Isolation of excess by subtracting the NN-reference.
- Medium radiation: Strong broadening of the ρ due to direct ρ-baryon scattering
- Exponentially falling spectrum,
  → extraction of temperature $\langle T_{ee} \rangle$ = 72 MeV
- Thermal rates folded over coarse-grained transport medium evolution works at low energies
- Supports baryon-driven medium effects at SPS, RHIC (LHC)!



- Onset of medium radiation in Ar+KCl collisions