Light Nuclei Production in Au+Au Collisions

Melanie Szala for the HADES Collaboration

ECT* workshop

Light cluster in nuclei and nuclear matter

2 - 6 September 2019, Villa Tambosi, Trento

Outline

Introduction

Experimental details

- HADES detector
- Particle identification

Results and discussion

- Transverse mass spectra
- Yields
- Statistical description
- Coalescence Parameter B_A

Summary and Outlook

Motivation

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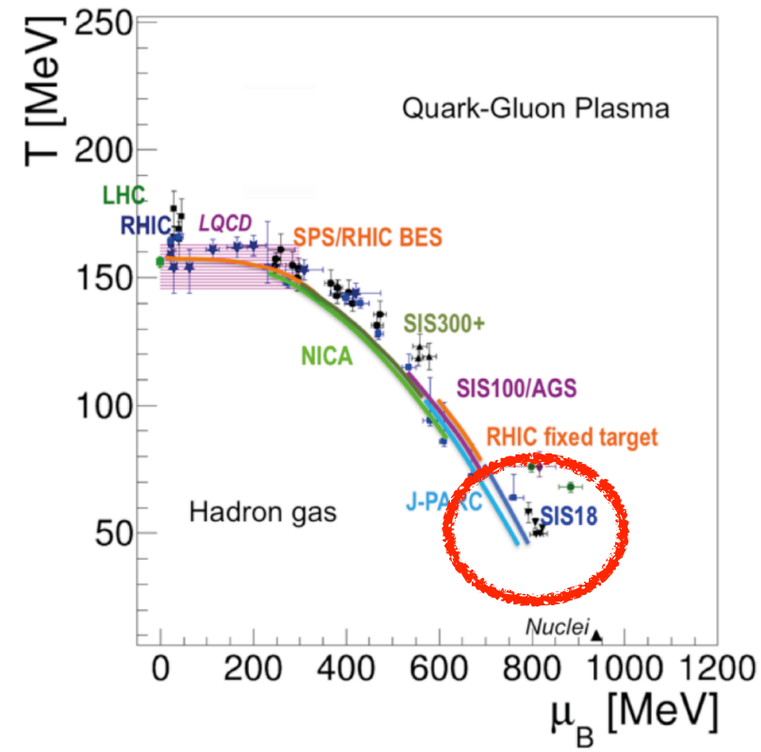
- HADES located at SIS18, GSI (energy regime up to $\sqrt{s_{NN}} \approx$ 2-3 GeV)



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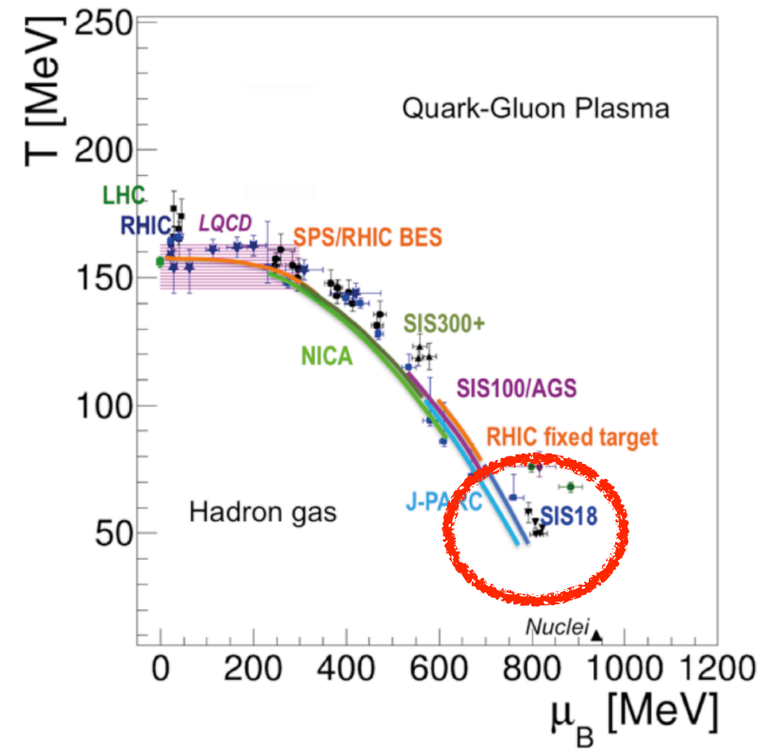
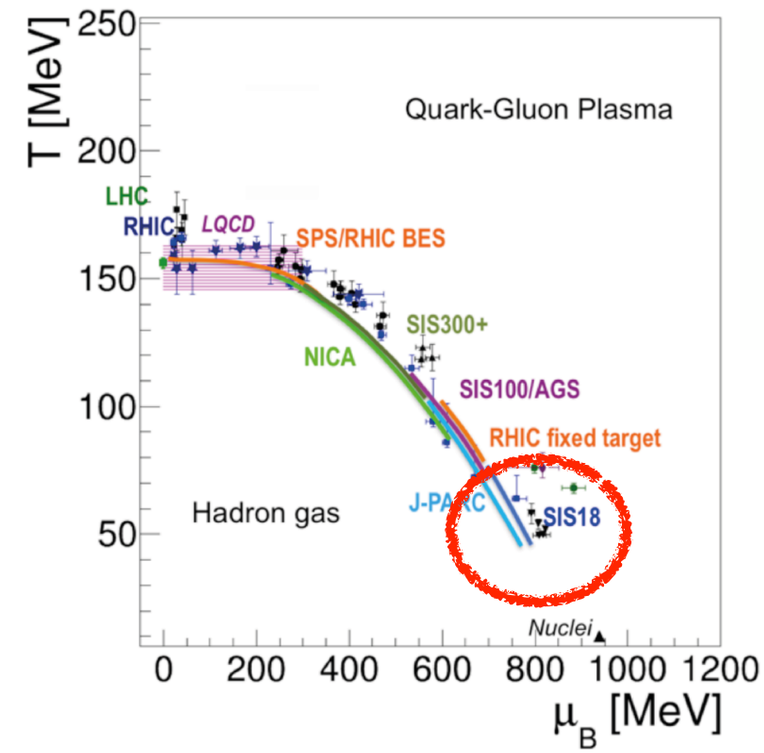
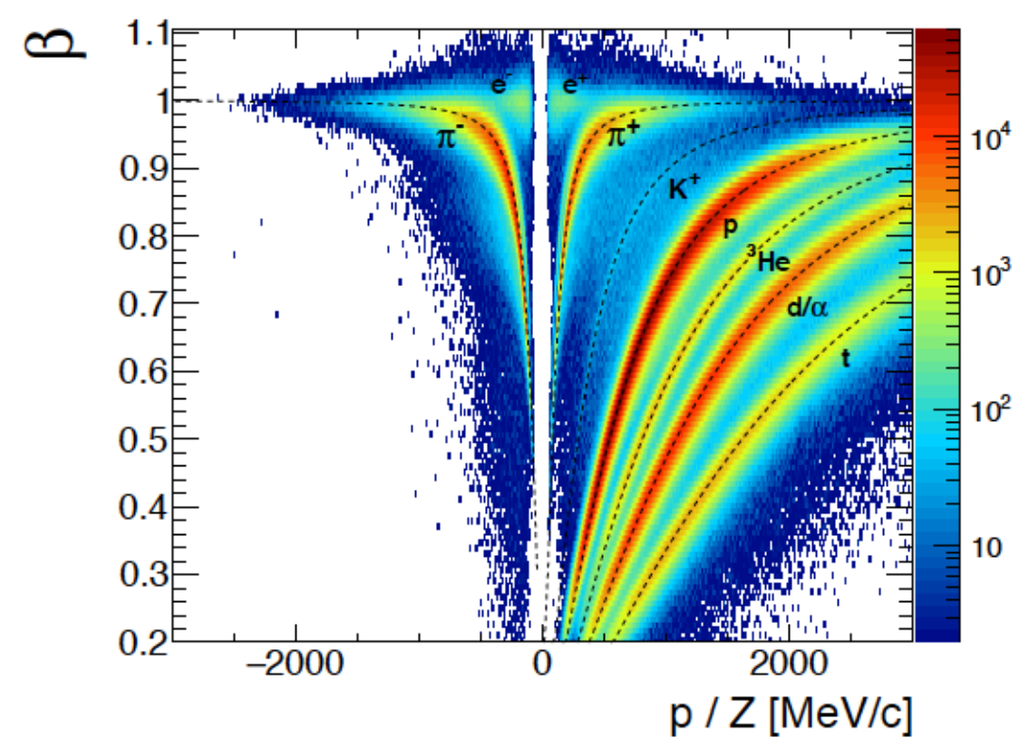
- Large stopping and interpenetration times



Motivation

- HADES located at SIS18, GSI (energy regime up to $\sqrt{s_{NN}} \approx$ 2-3 GeV)
- Large stopping and interpenetration times
- Clear hierarchy in particle multiplicities (M):
  - $M_p \approx 100$
  - $M_\pi \approx 10$
  - $M_{K+} \approx 10^{-2}$, $M_{K-} \approx 10^{-4}$
  - $M_{bound\ p} \approx 50$





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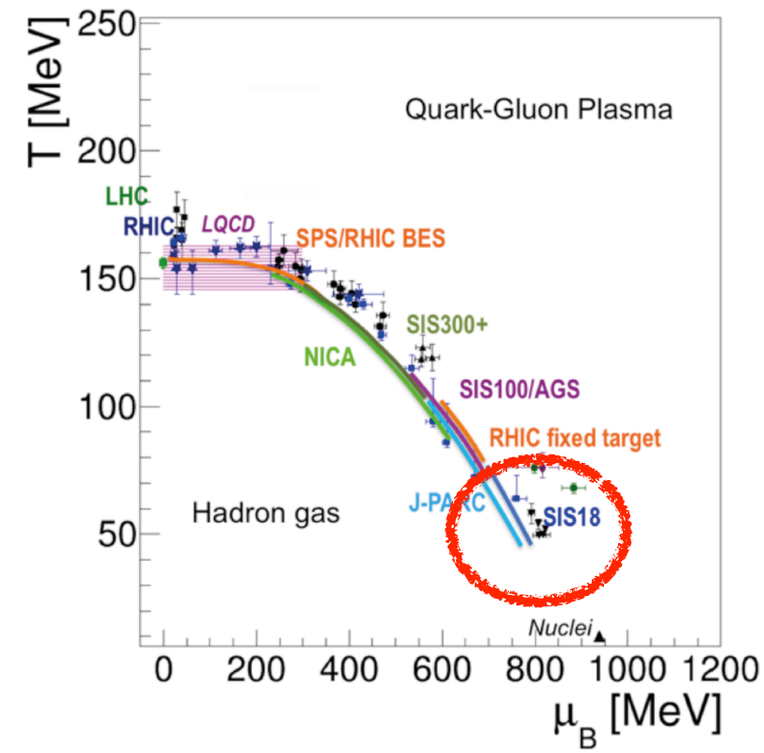
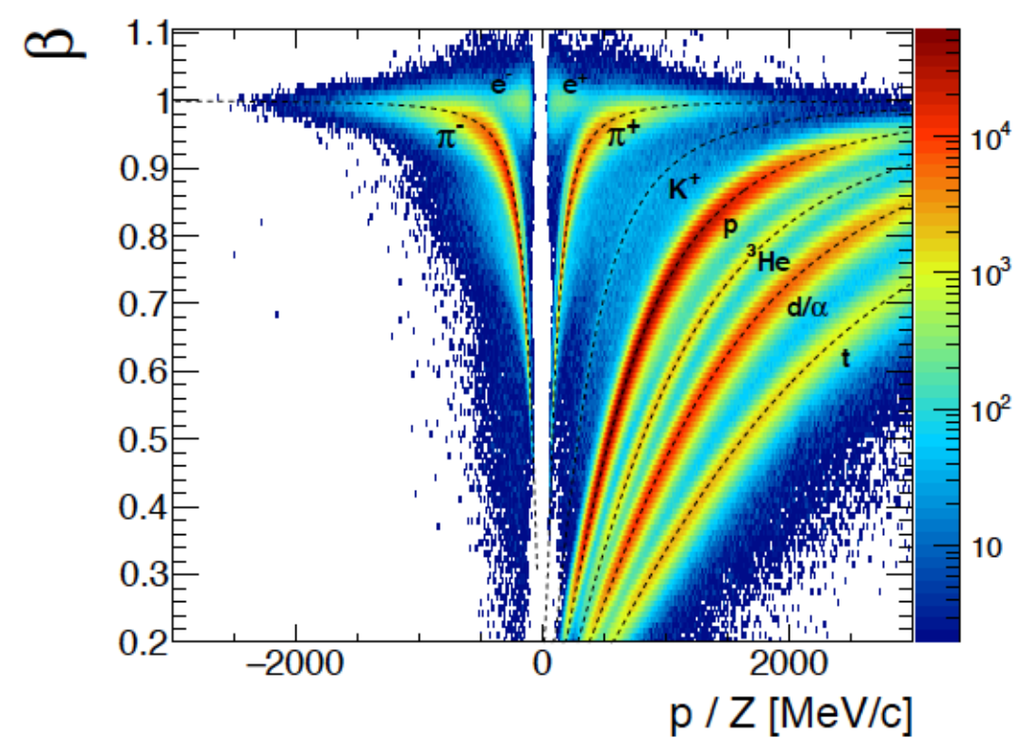
- Light nuclei not a rare probe, contribute to the bulk
- Detailed investigations needed to understand created medium





Formation of Light Nuclei

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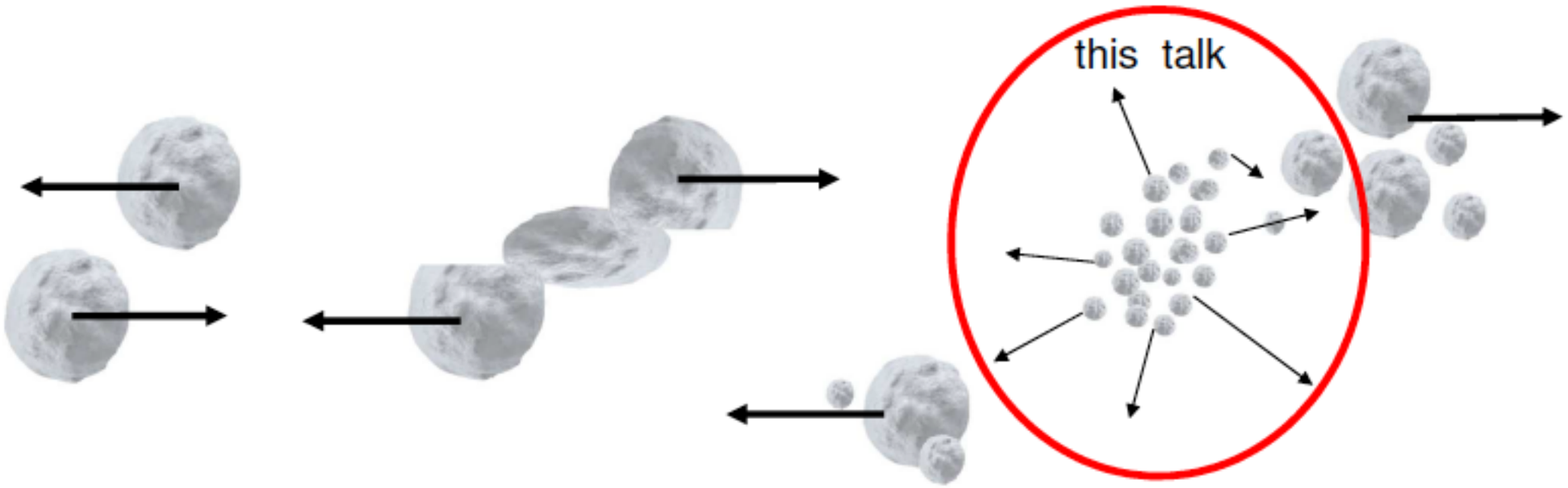

Two distinguished regions

- mid-rap. participants
- spectator break-up regions
- no clear separation between projectile/target spectators and participants at HADES energies

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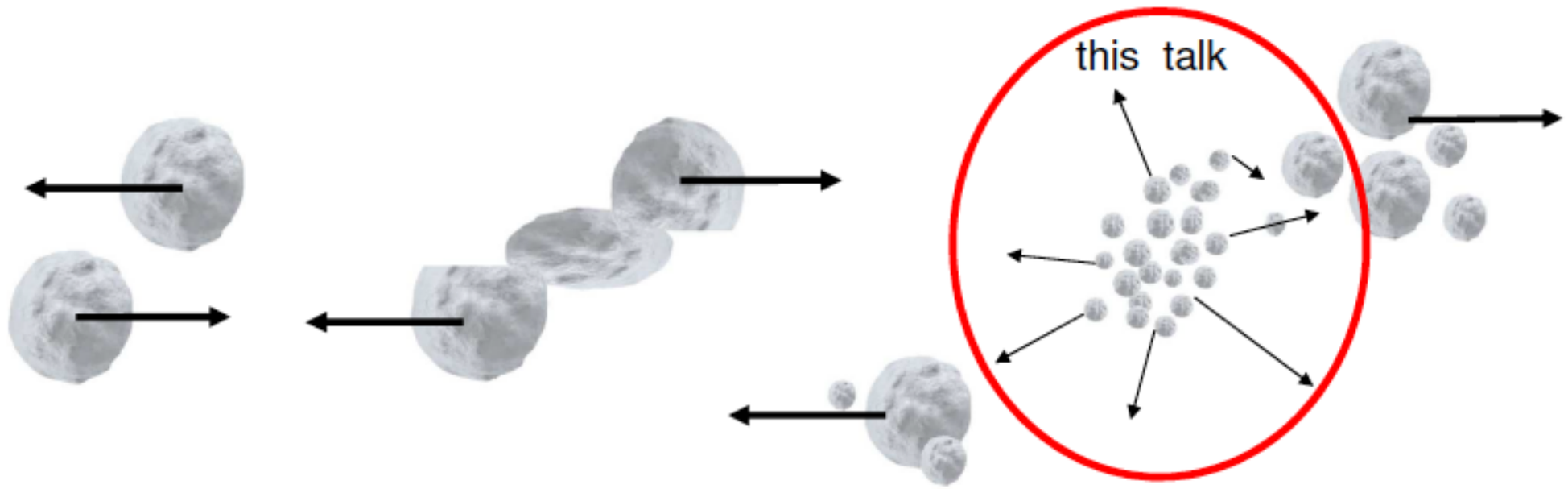

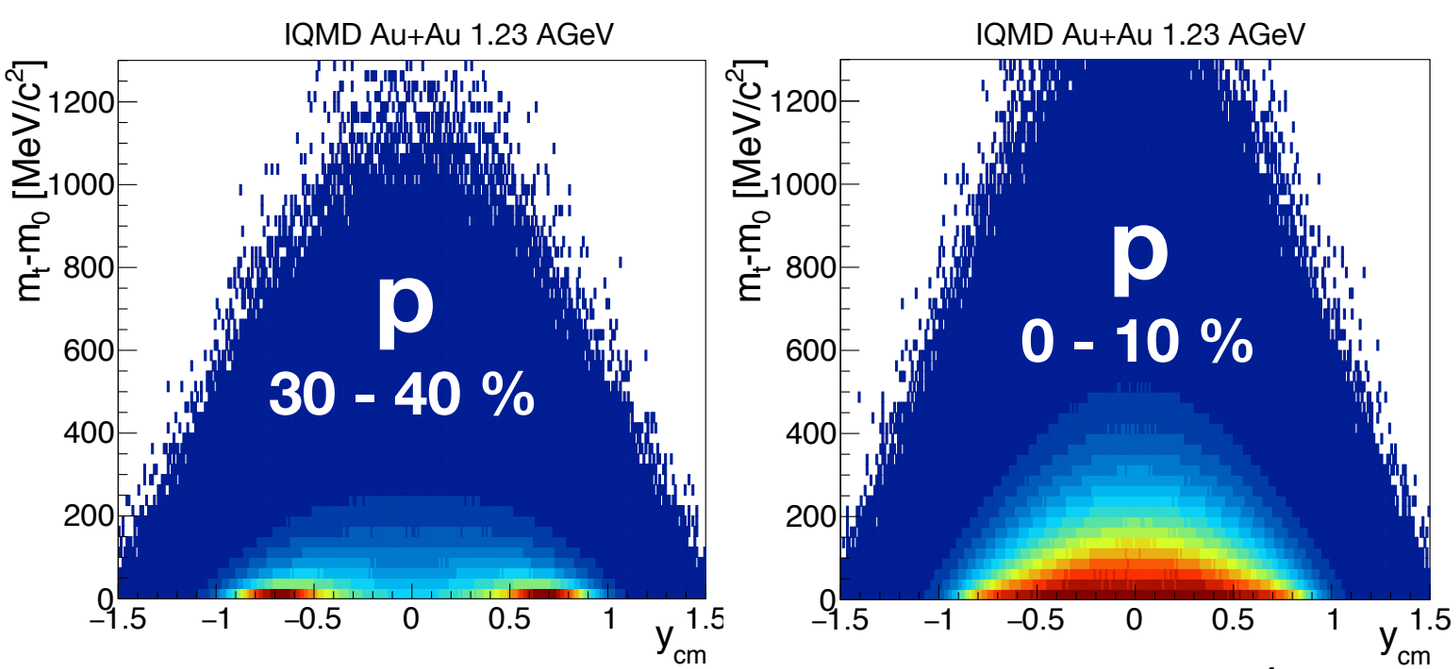

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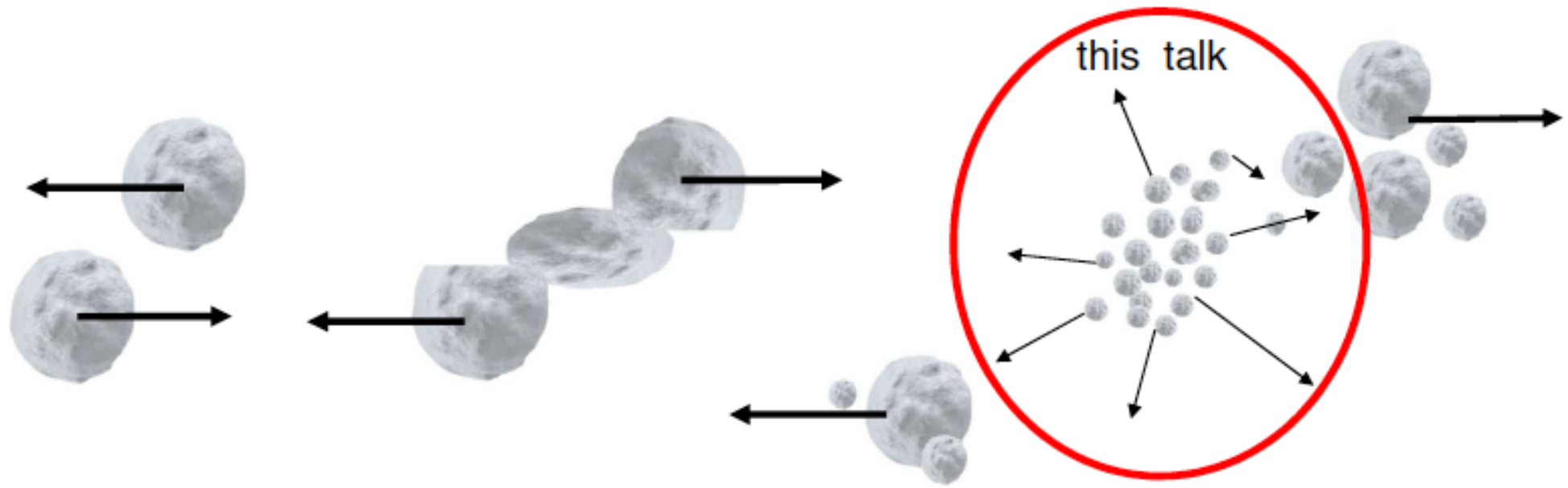
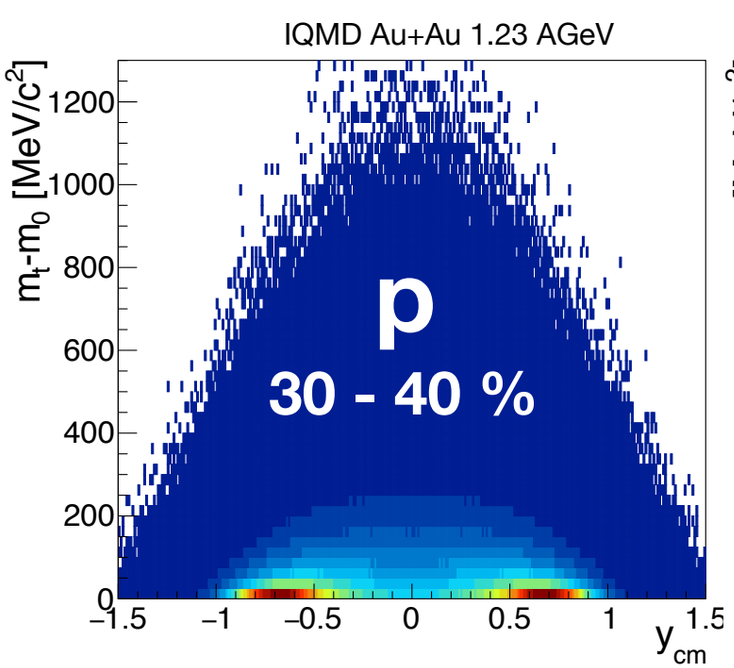
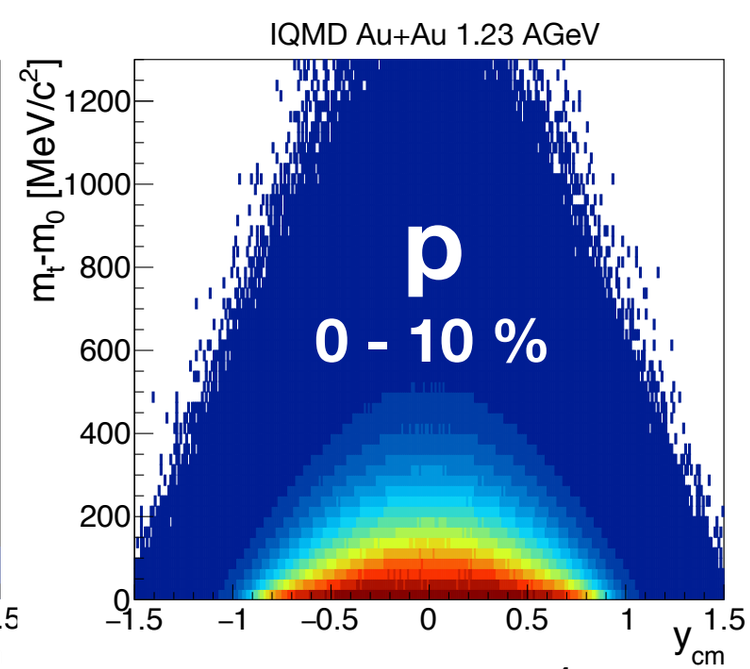






Two distinguished regions

- mid-rap. participants
- spectator break-up regions
- no clear separation between projectile/target spectators and participants at HADES energies
- mid-rap. source observed best in **central collisions**

HADES spectrometer

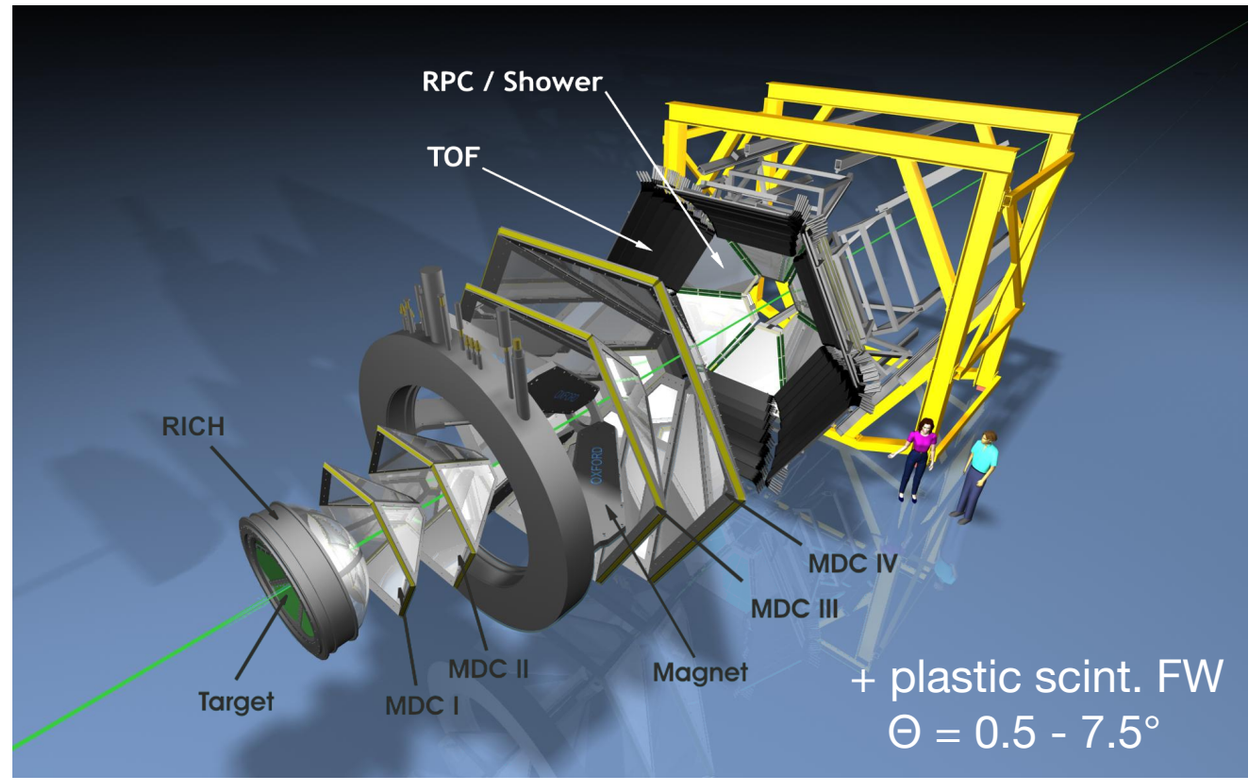
Located at SIS18, GSI, fixed target experiment

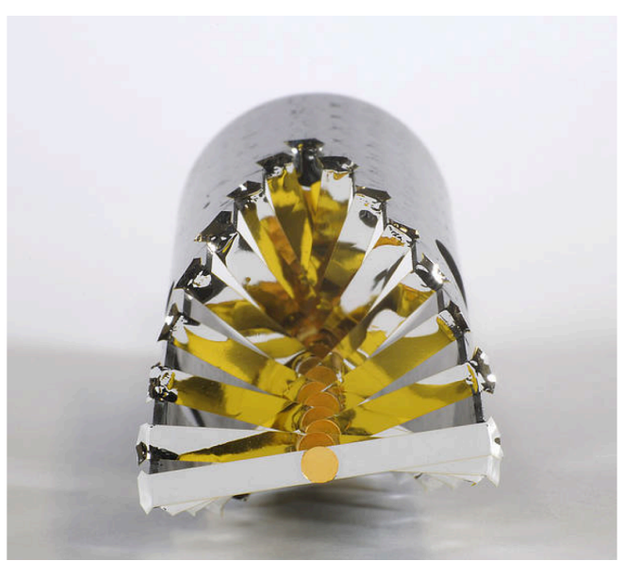
Large acceptance

- Symmetric azimuthal coverage
- 18°-85° in polar angle

Fast detector

- Trigger rate 8 kHz (16 kHz in Ag+Ag)
- Large statistics

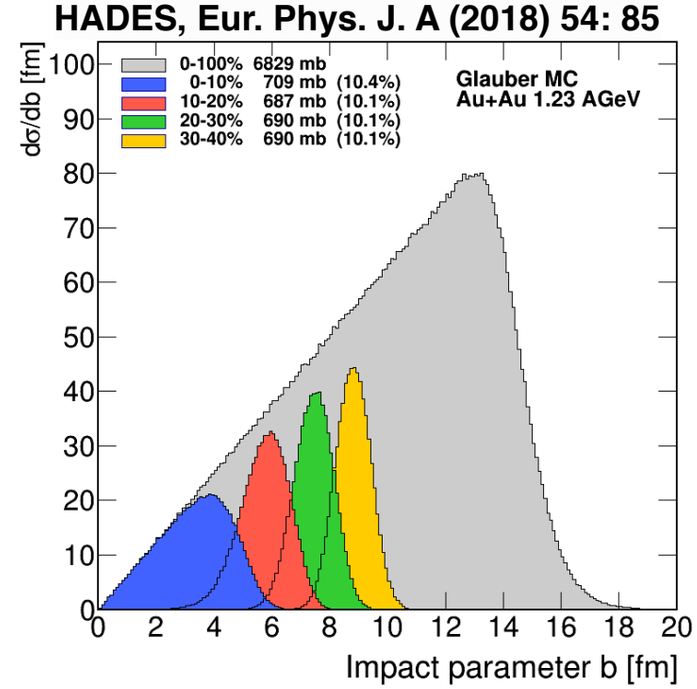




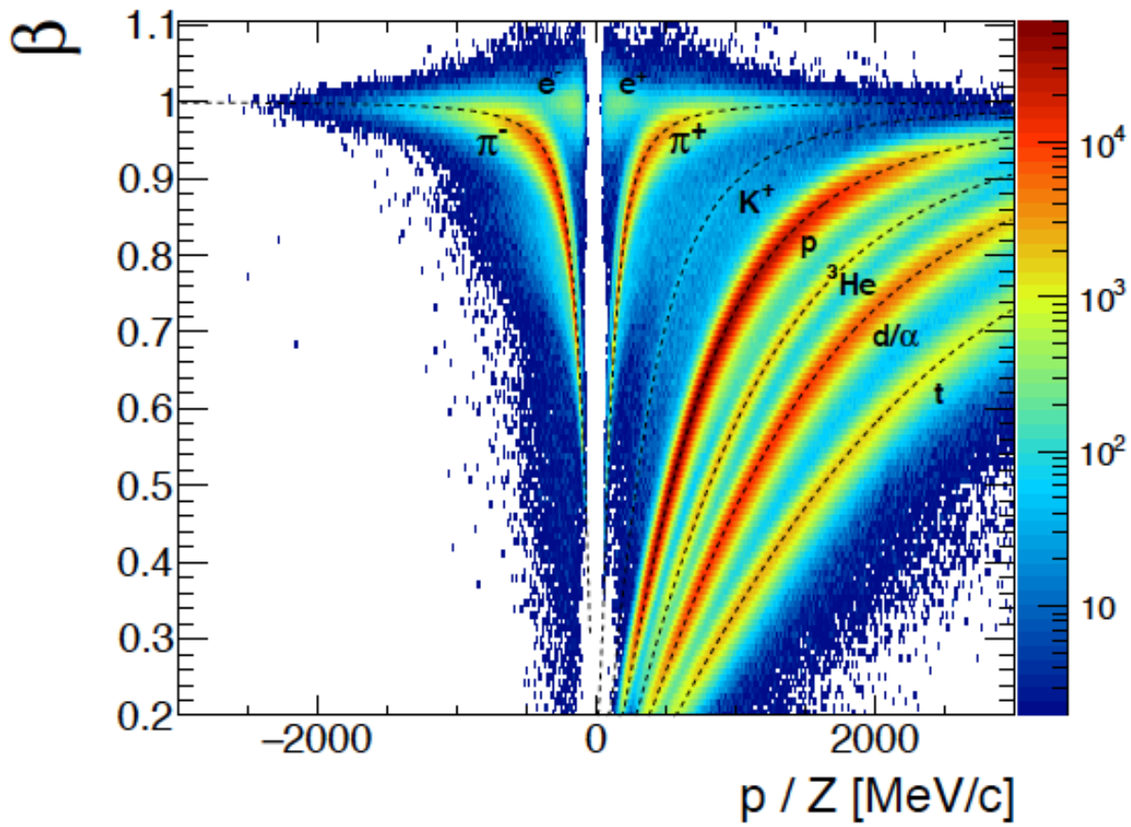
Au + Au @1.23 AGeV, $\sqrt{s_{NN}}$=2.4 GeV

- 15 fold segmented Au target
- 2.2 x 10^9 events analysed
- Trigger on 40% most central collisions

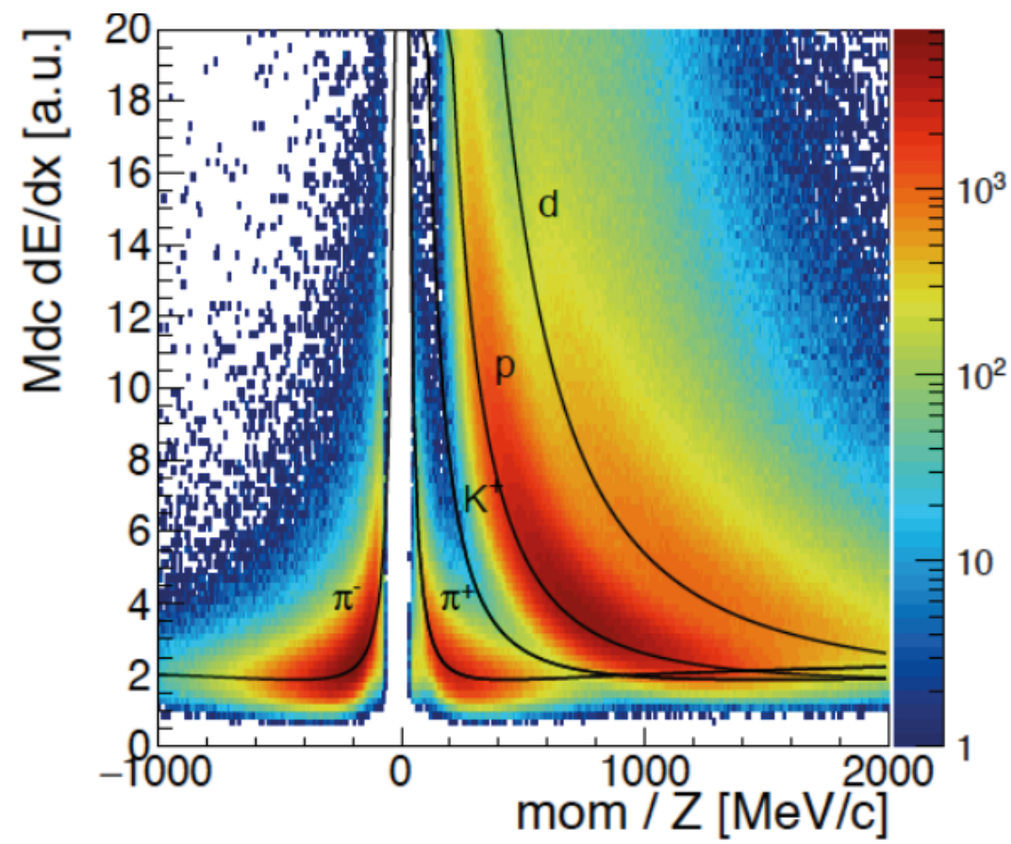
HADES, Eur. Phys. J. A (2018) 54: 85



Particle Identification



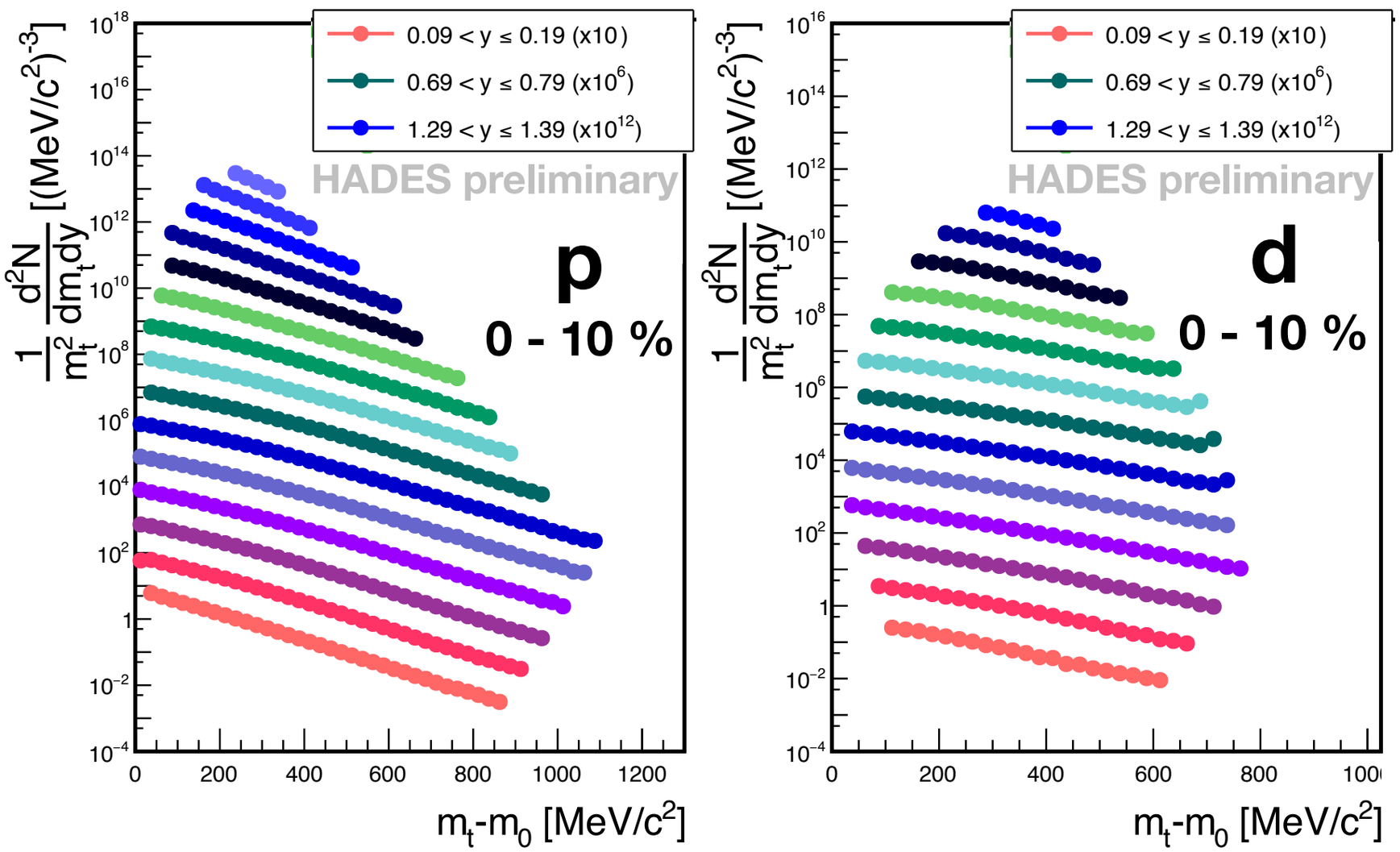
Time-of-Flight



Energy loss

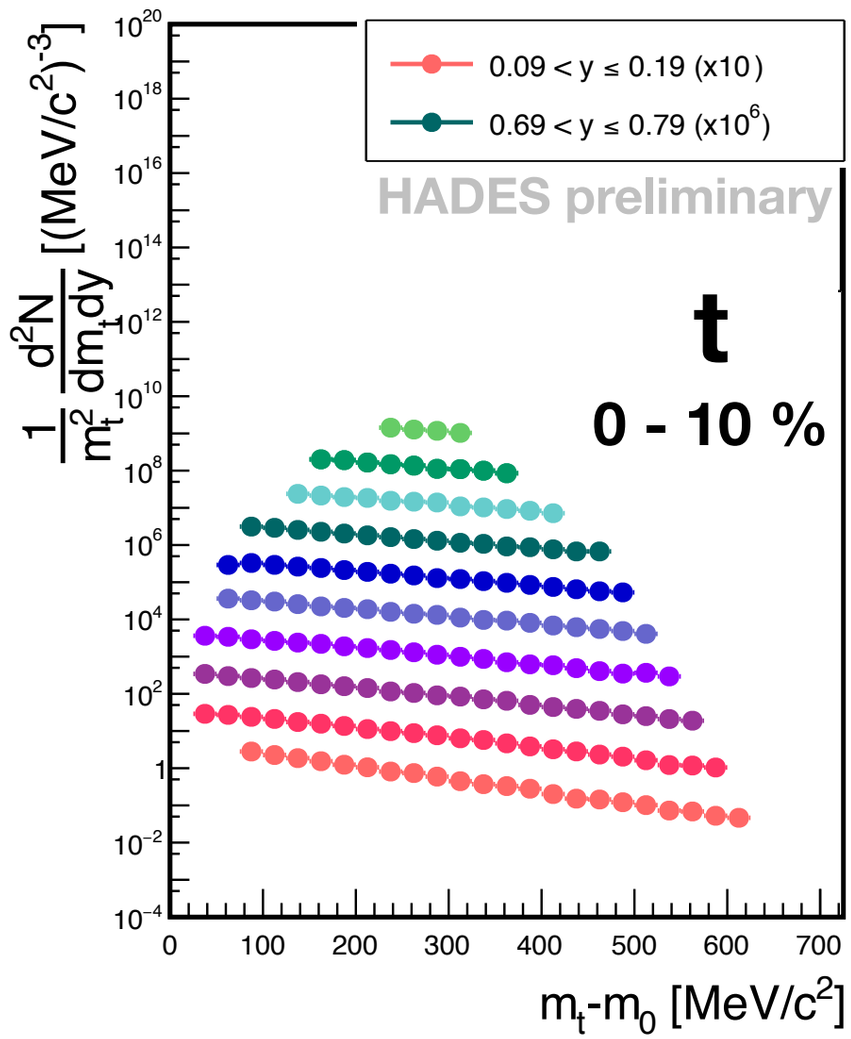
- drift chambers
- TOF detector

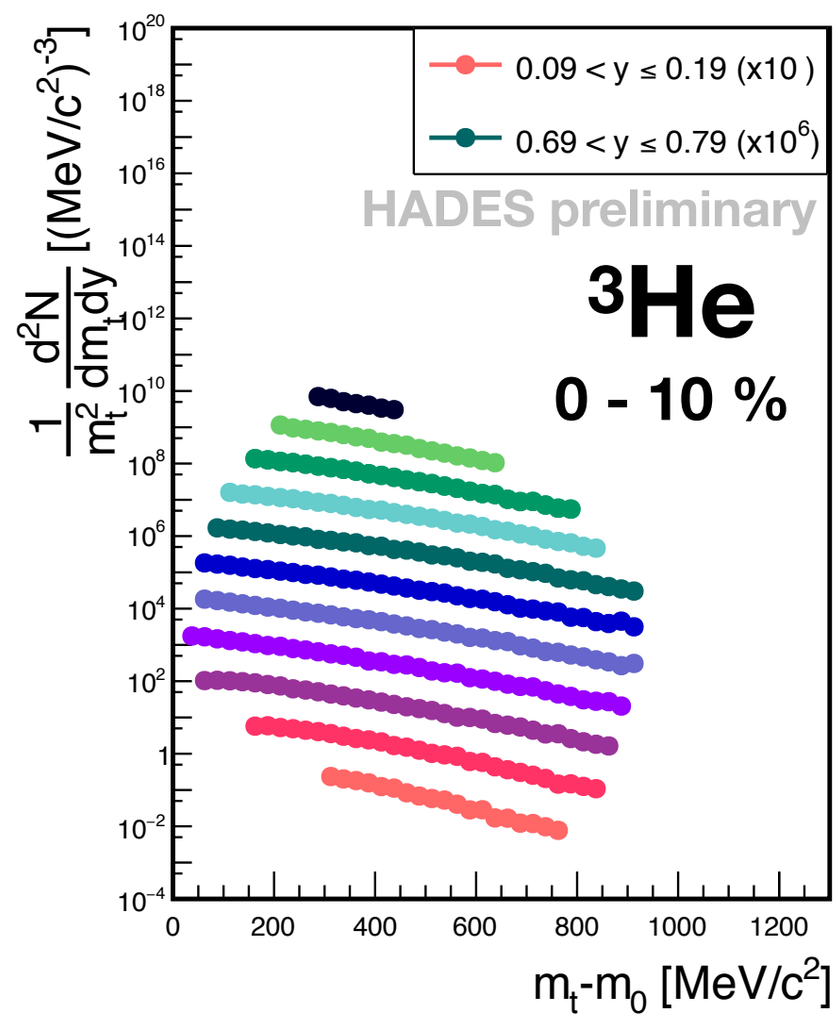
Particle spectra



High statistic multi-differential data

Particle spectra





High statistic multi-differential data

Blast Wave Model

High collisions energies or Midrap. yield

- Cylindrically symmetric blast wave model
  - The momentum distribution in the cylindrically symmetric blast wave model is given by

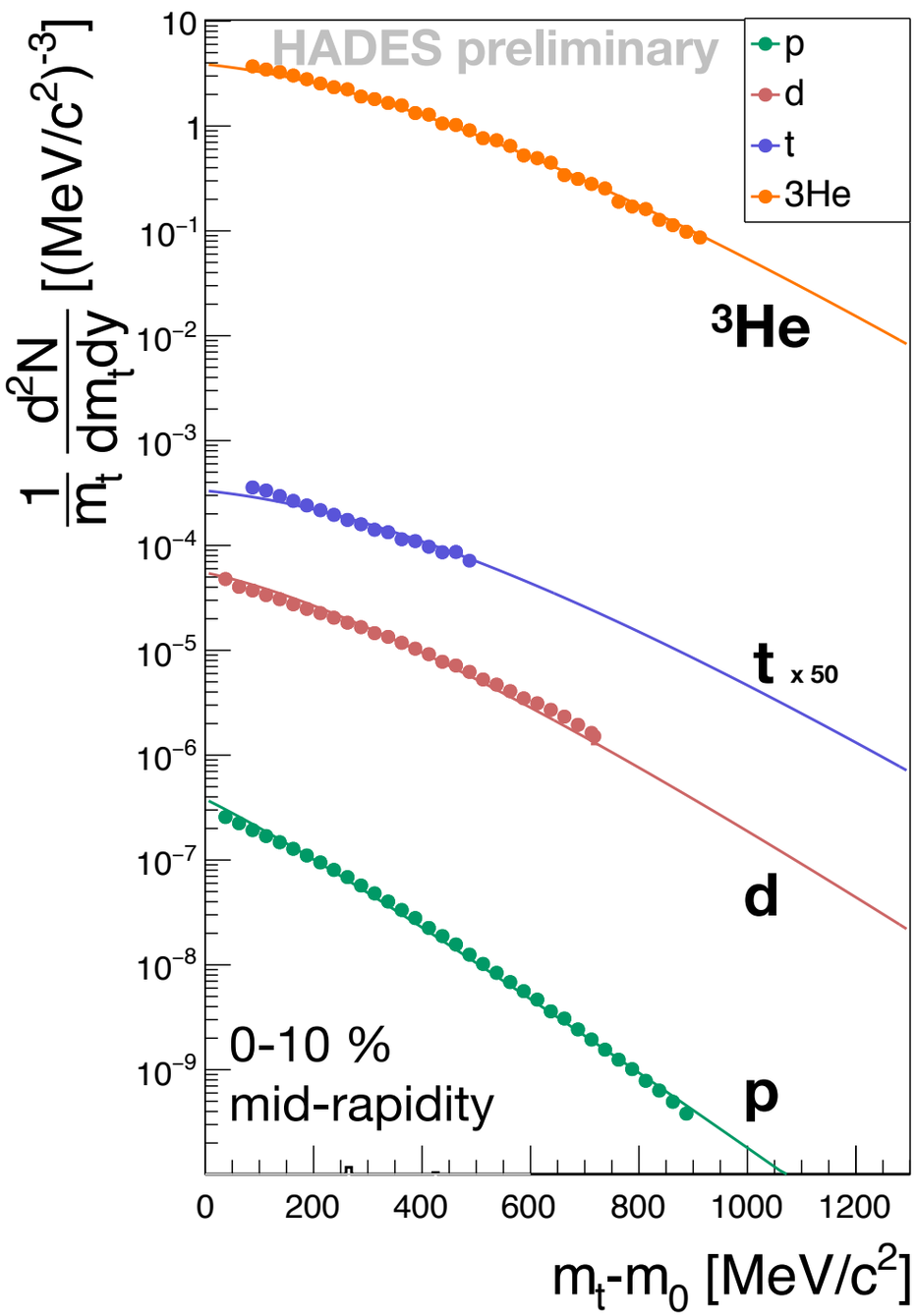
$$\frac{dN}{p_T\,dp_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{\rm kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{\rm kin}}\right)$$

with linear flow velocity profile

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

$n = 1$

Blast Wave Fit



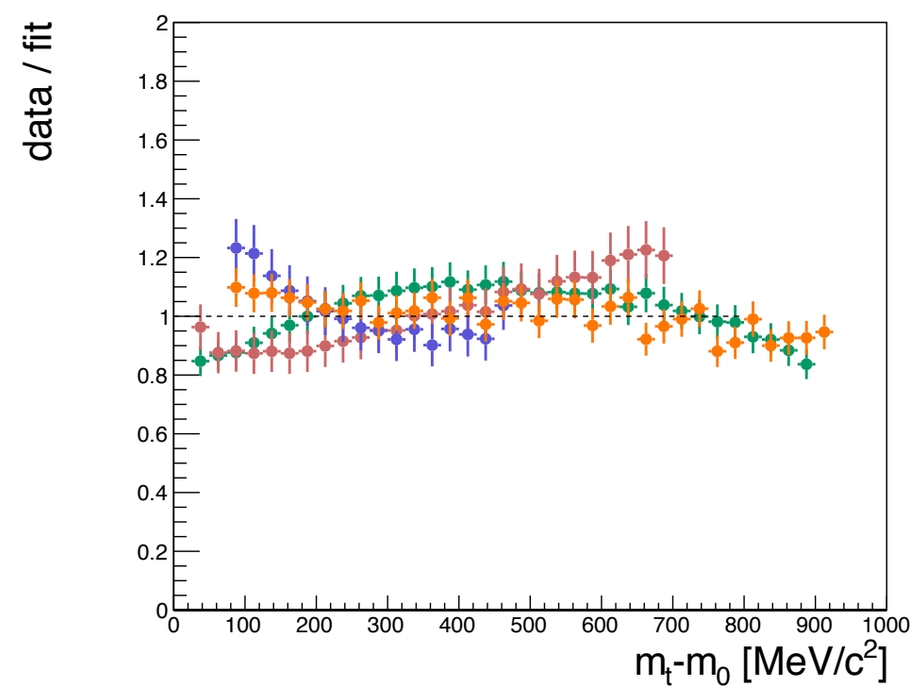
Blast Wave Model: Phys.Rev.C48:2462-2475,1993

$$\frac{dn}{m_T\, dm_T} \propto \int_0^R r\, dr\, m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

Linear velocity profile

T_{kin} = 71 ± 8 MeV

< β_r> = 0.30 ± 0.02



- **p, d, t, ^{3}He described with simple BW model**
- **20 % deviations from fit for all particles**

Blast Wave Model

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with linear flow velocity profile

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$$n = 1$$

Intermediate collisions energies

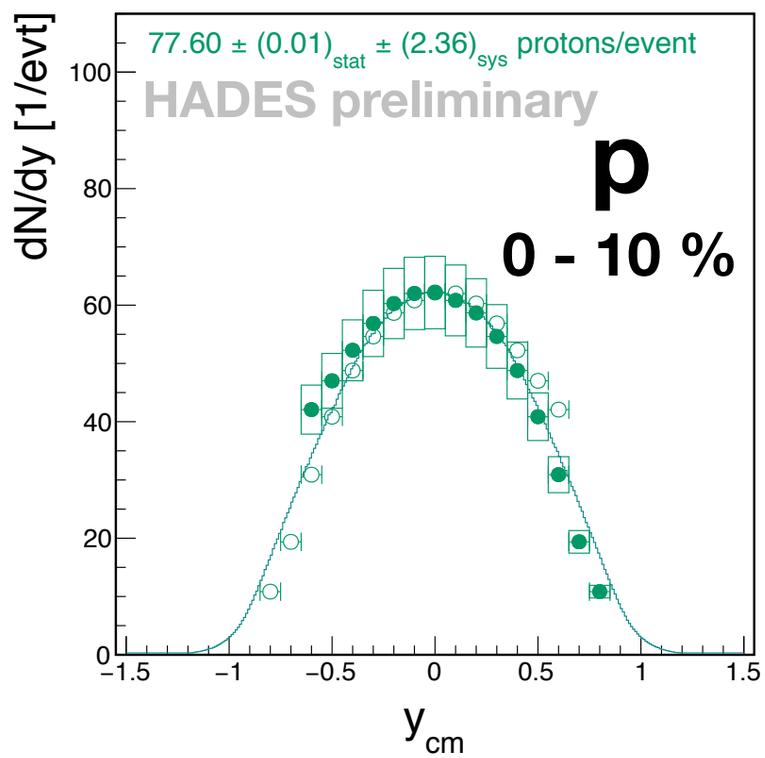
- Spherically symmetric blast wave model
  - In the spherically symmetric blast wave model the momentum distribution is given by the **Siemens-Rasmussen formula**

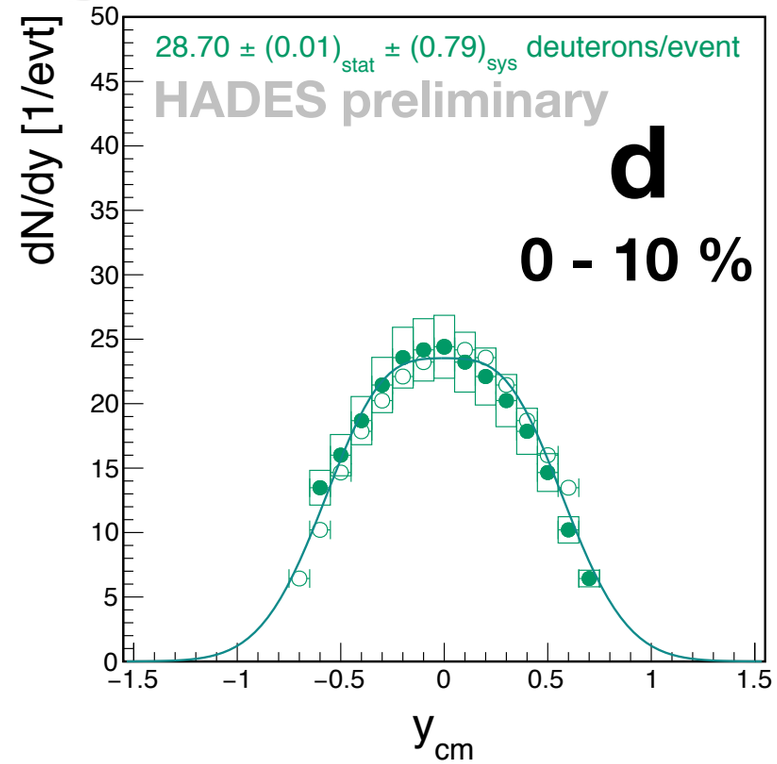
$$\frac{d^2N}{2\pi p_t dp_t y_0} = CEe^{-\gamma_r \frac{E}{T}}\left[\left(\gamma_r + \frac{T}{E}\right)\frac{sinh(\alpha)}{\alpha} - \frac{Tcosh(\alpha)}{E}\right]$$

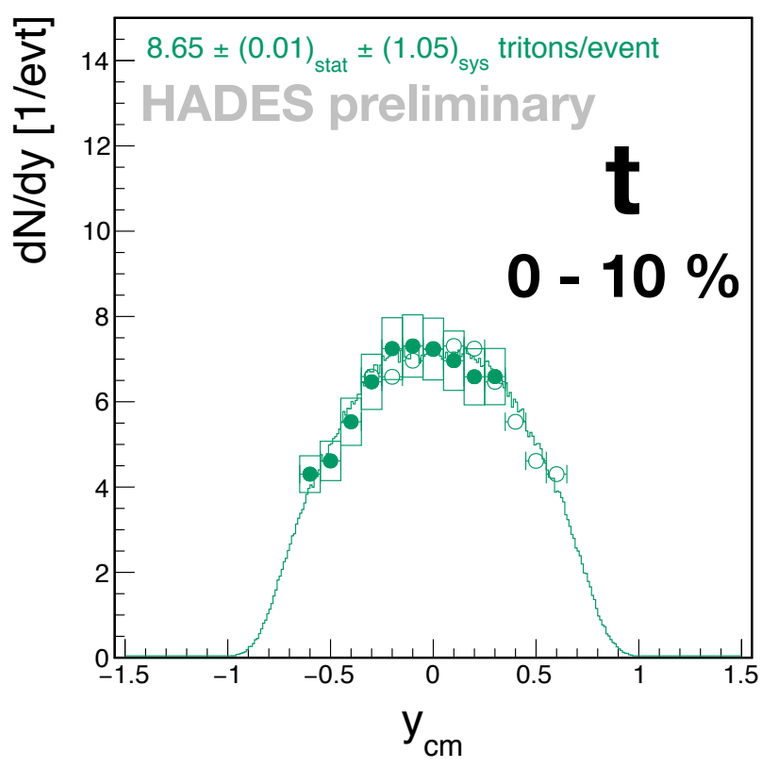
$$\alpha = (\gamma\beta_r p) \text{ and } \gamma = \frac{1}{\sqrt{1-\beta_r^2}}$$

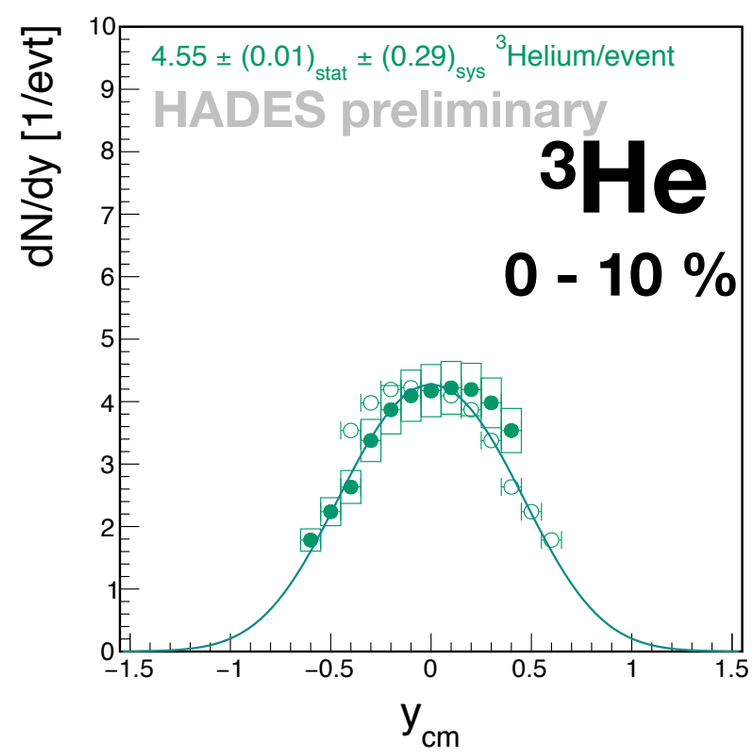
$$E = m_t cosh(y)$$

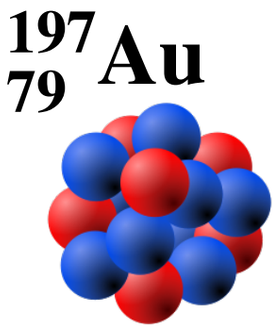
Particle yields



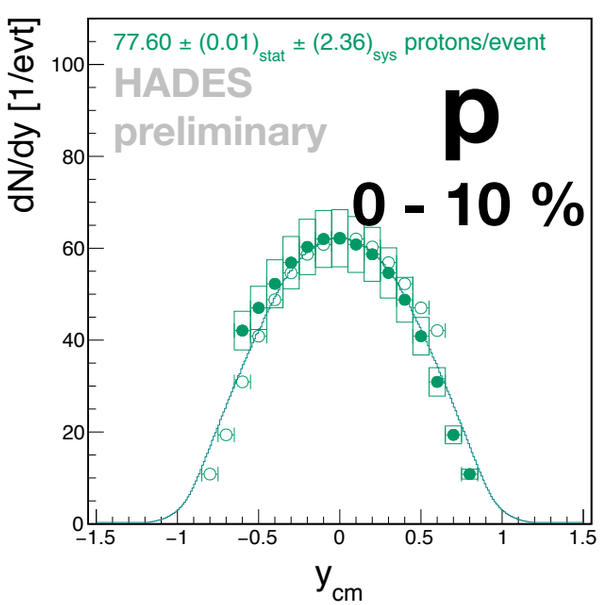


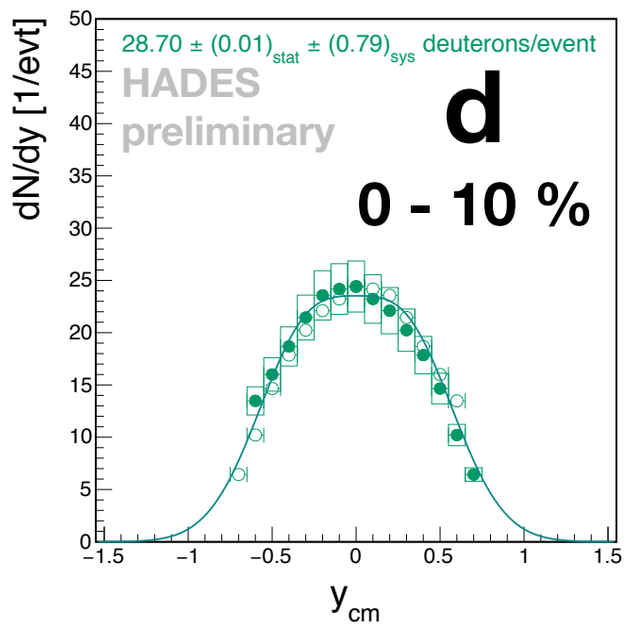


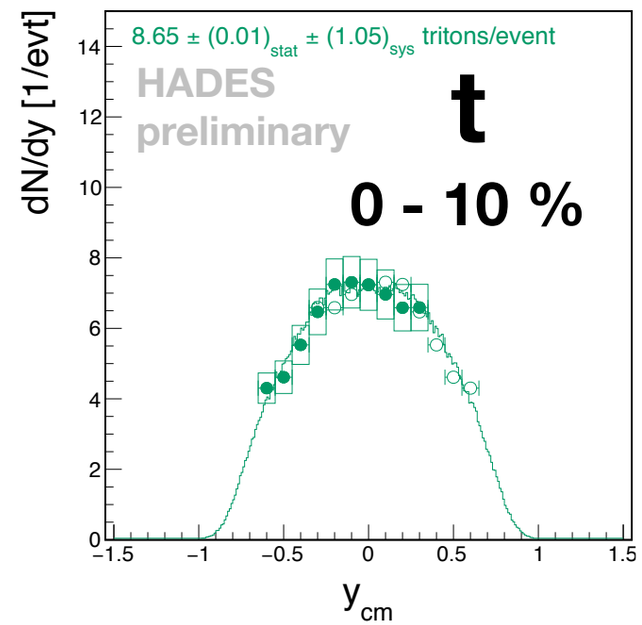


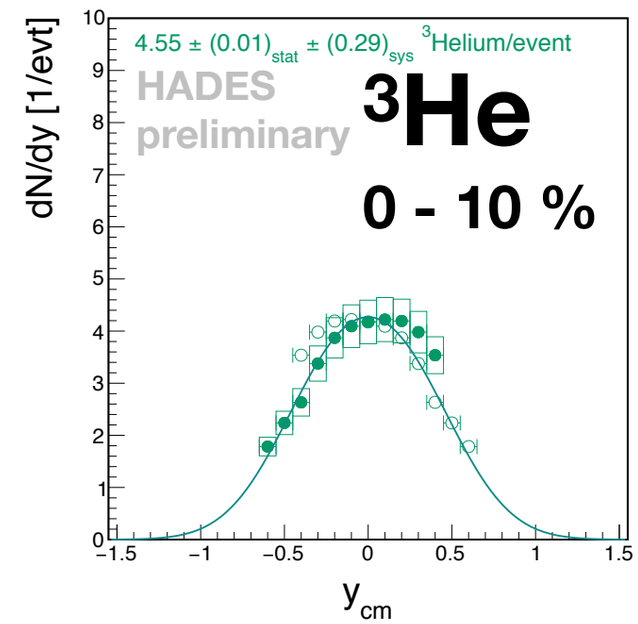


Baryon Number Conservation









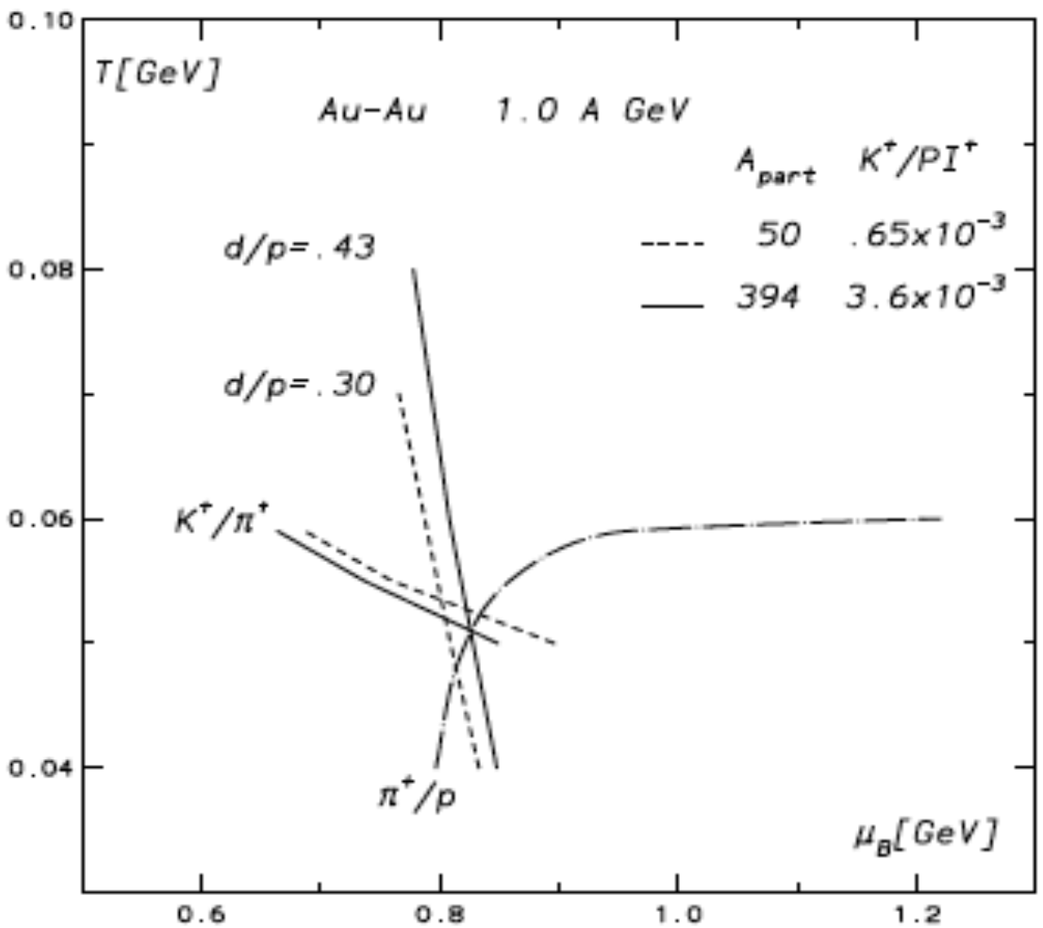
$$\langle A_{part} \rangle = p + n + d + t + {}^{3}He + x({}^{4}He, \ldots)$$
$$= 77.6 + 1.5 * 77.6 + 2*28.7 + 3*8.65 + 3*4.55 + x({}^{4}He, \ldots)$$
$$= 291 + x({}^{4}He, \ldots)$$

$\langle A_{part} \rangle = 303 \pm 11$

Glauber Fit to nb. of tracks in detector

HADES, Eur. Phys. J. A (2018) 54: 85

Statistical Model



J. Cleymans, H. Oeschler, K. Redlich, Phys.Rev. C59 (1999)
Thermus 3.0

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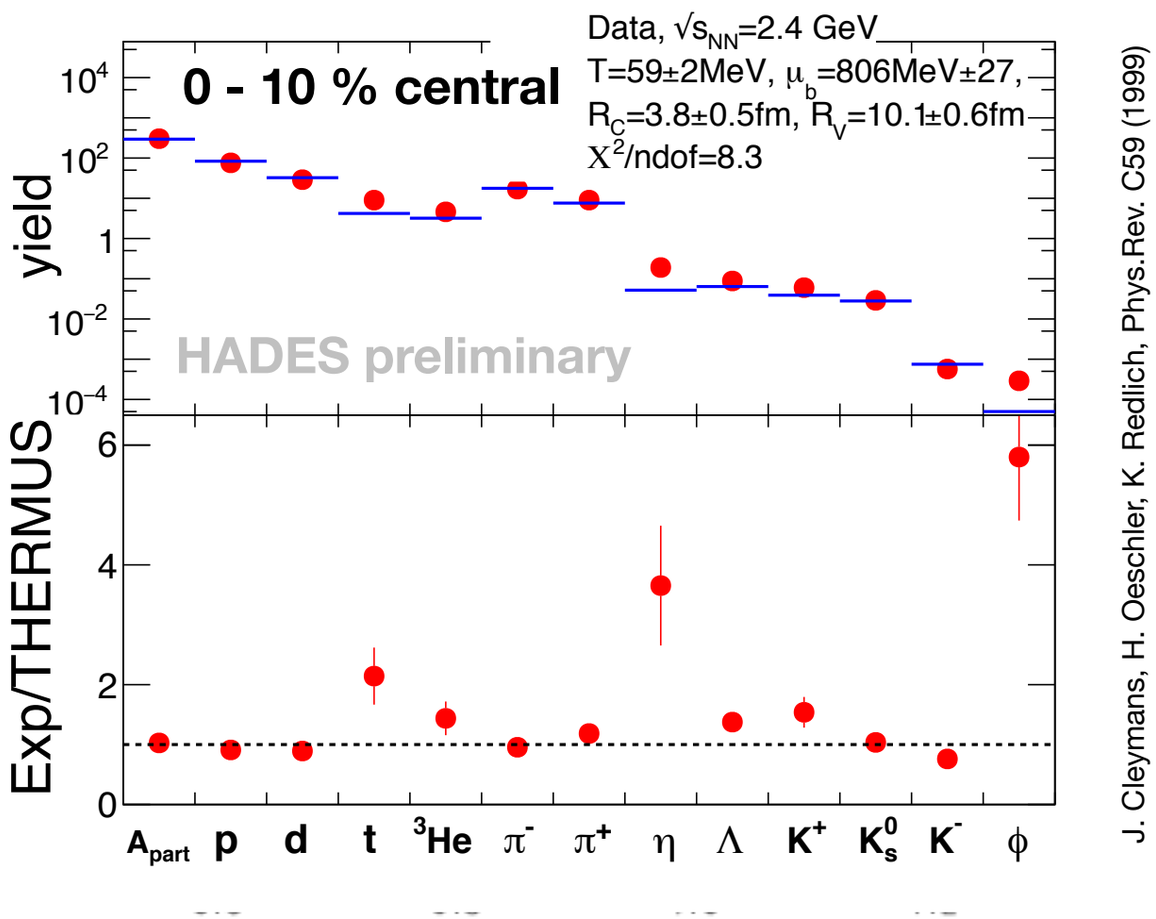

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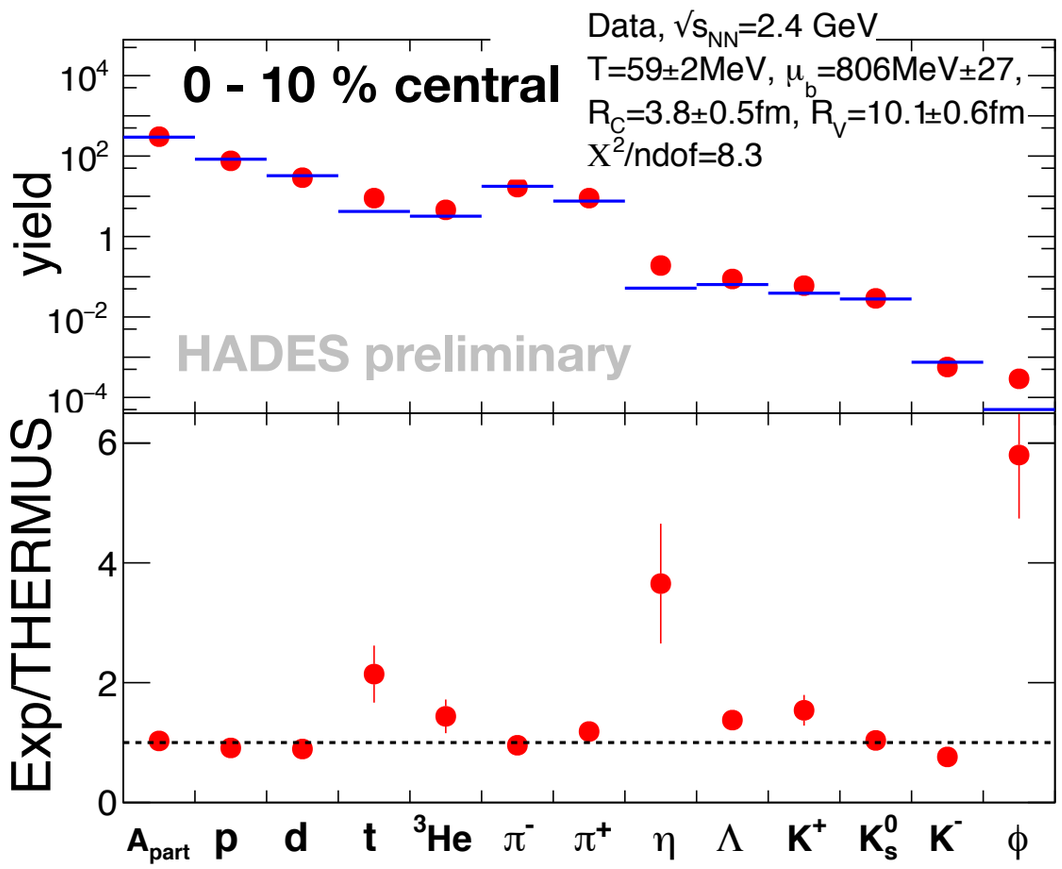

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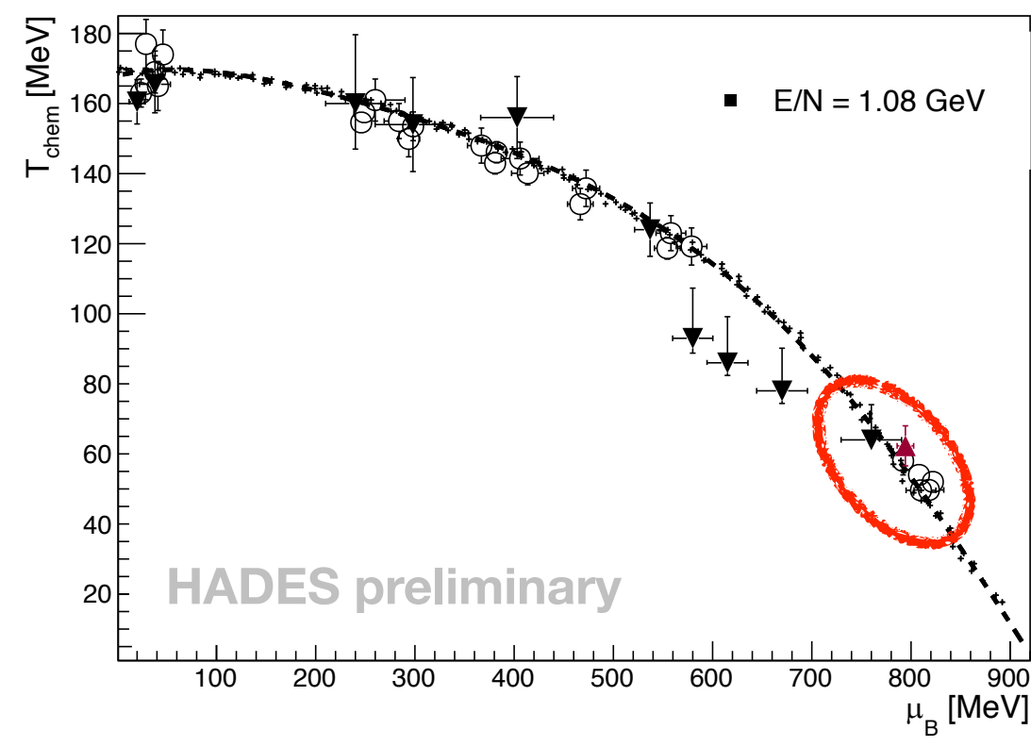

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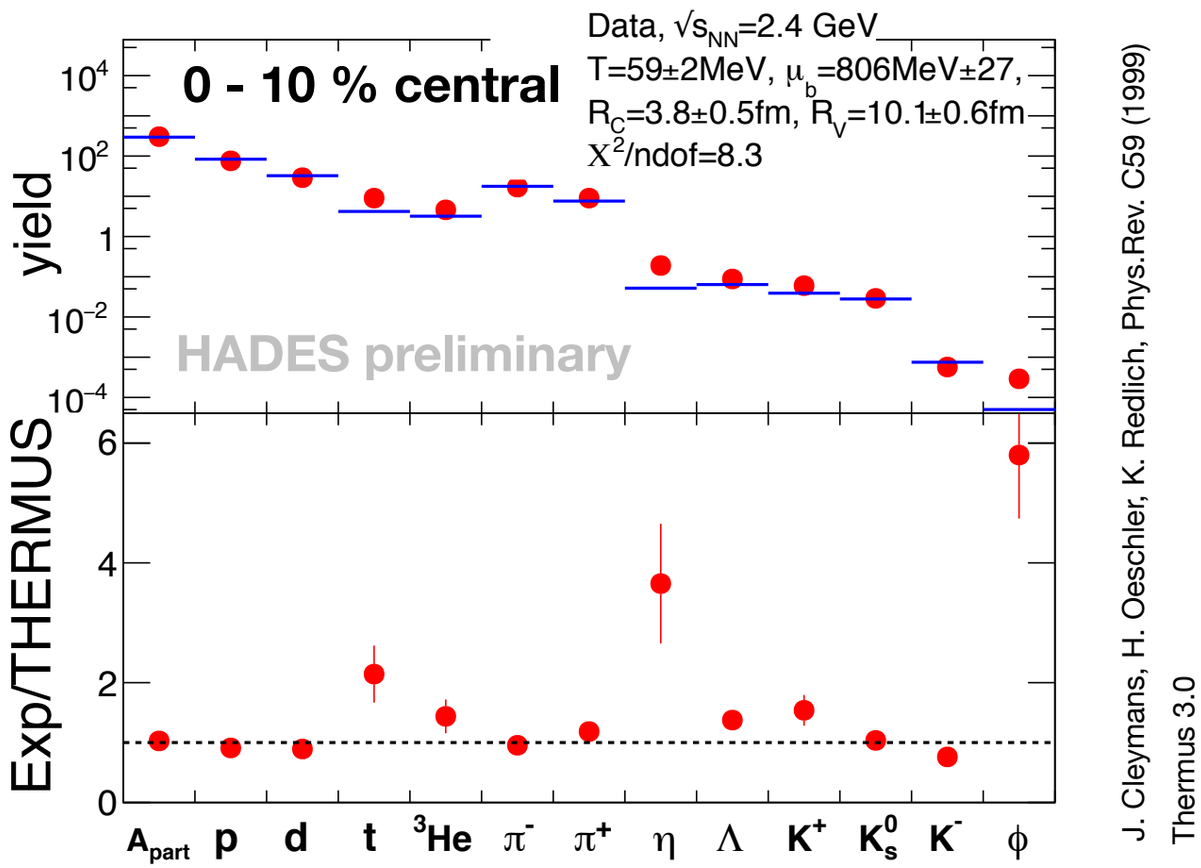

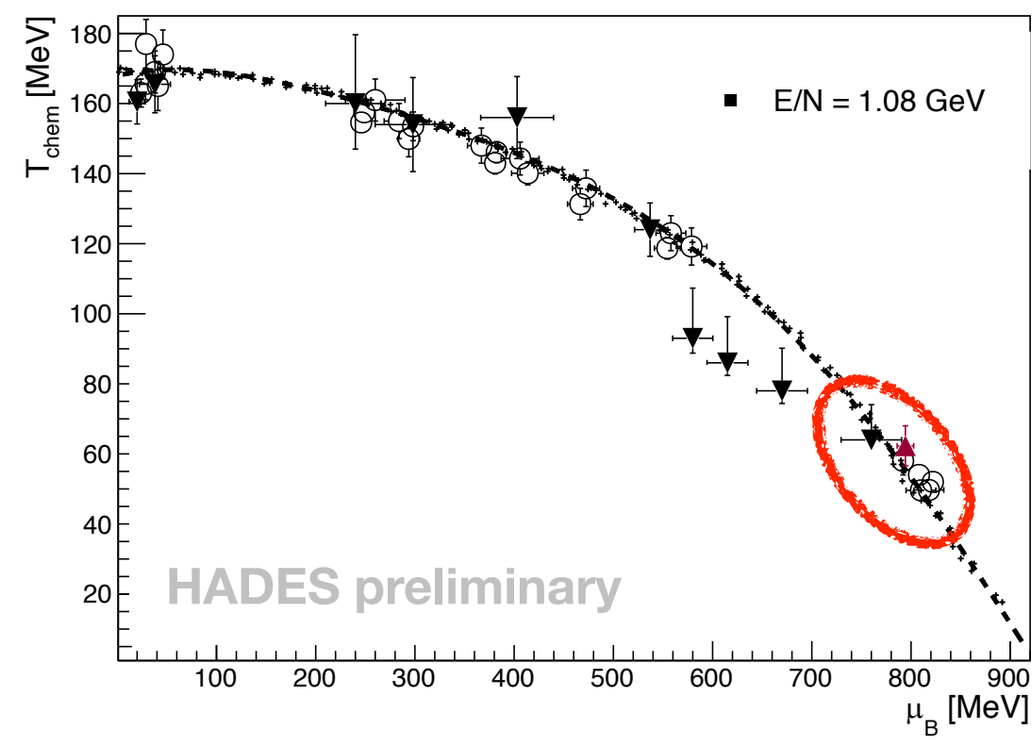

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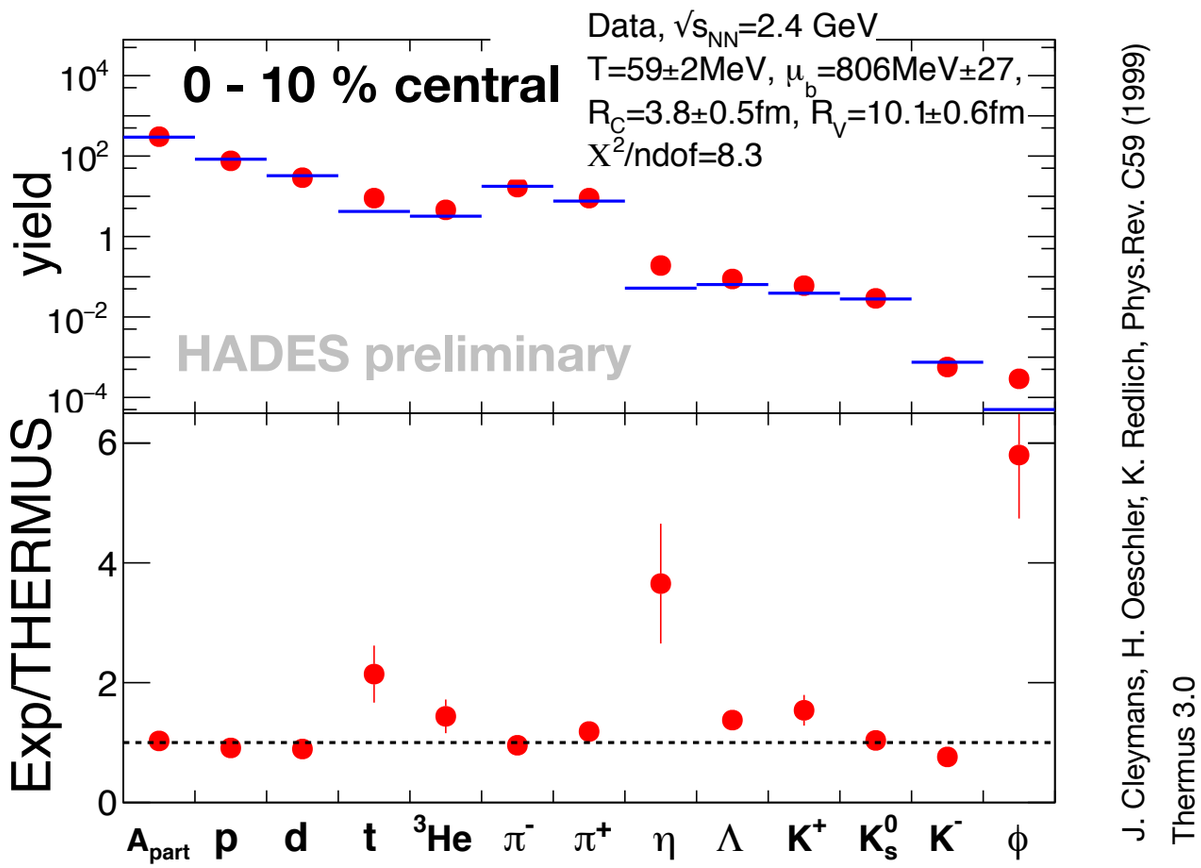

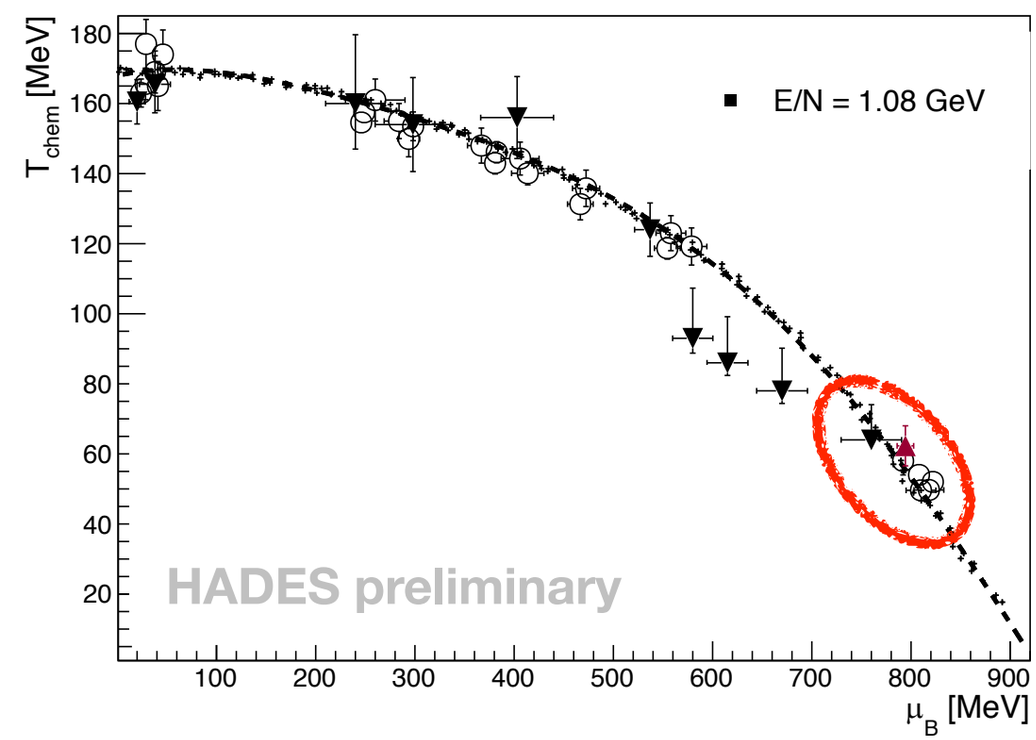

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- Fit to HADES data consistent with previous works
- Fit to full hadron spectra results in large χ^2

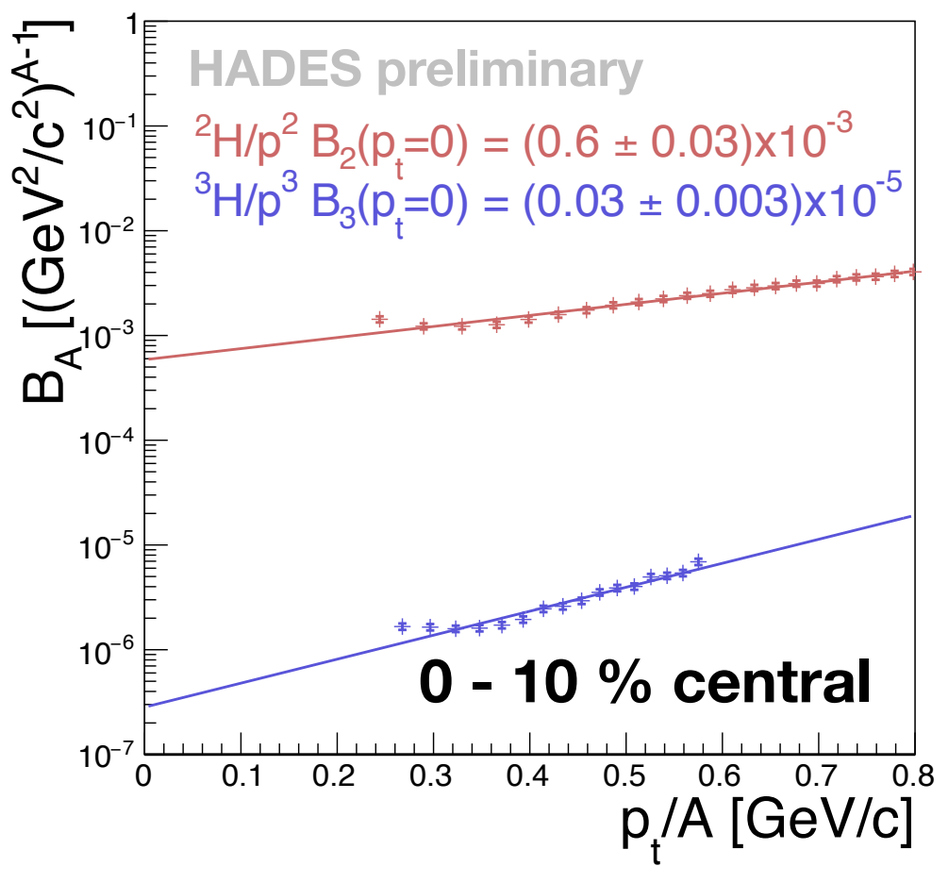
Nucleon Coalescence

- Nuclei are formed at late stages of collision, at kinetic freeze-out
- Nucleons bind into nuclei if they are close in phase space

$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_p \frac{dN_p}{d^3P_p}\right)^Z \left(E_n \frac{dN_n}{d^3P_n}\right)^N \Bigg|_{P_p=P_n=P_A/A}$$

- Coalescence parameter B_A: probability that number of A nucleon coalesce
- Expectations:
  - $B_A \propto \left(\frac{1}{V}\right)^{(A-1)}$ -> $B_2 \sim 1/V_{HBT}$, $B_3 \sim 1/V_{HBT}^2$

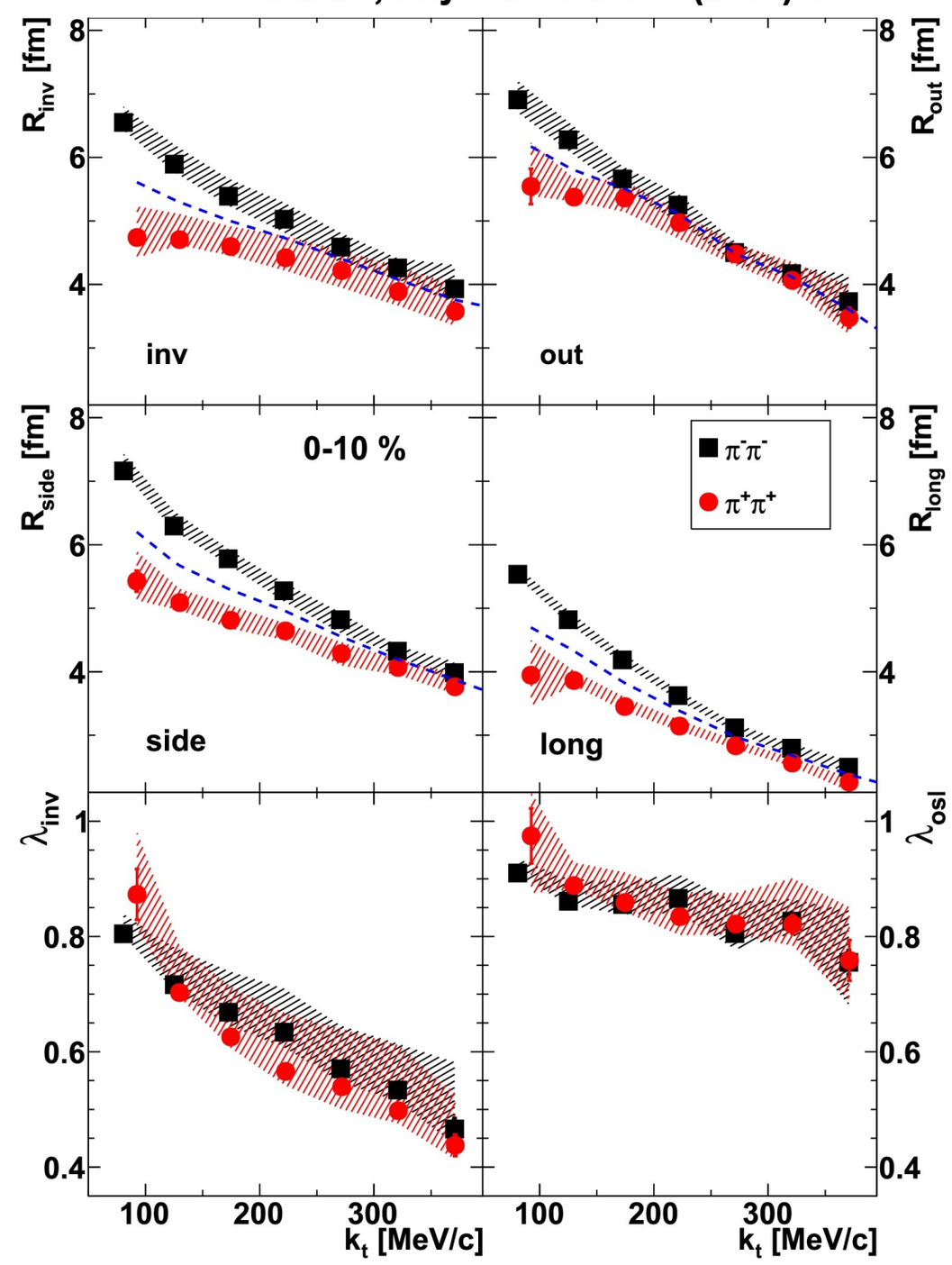
Nucleon Coalescence



Compatible with coalescence

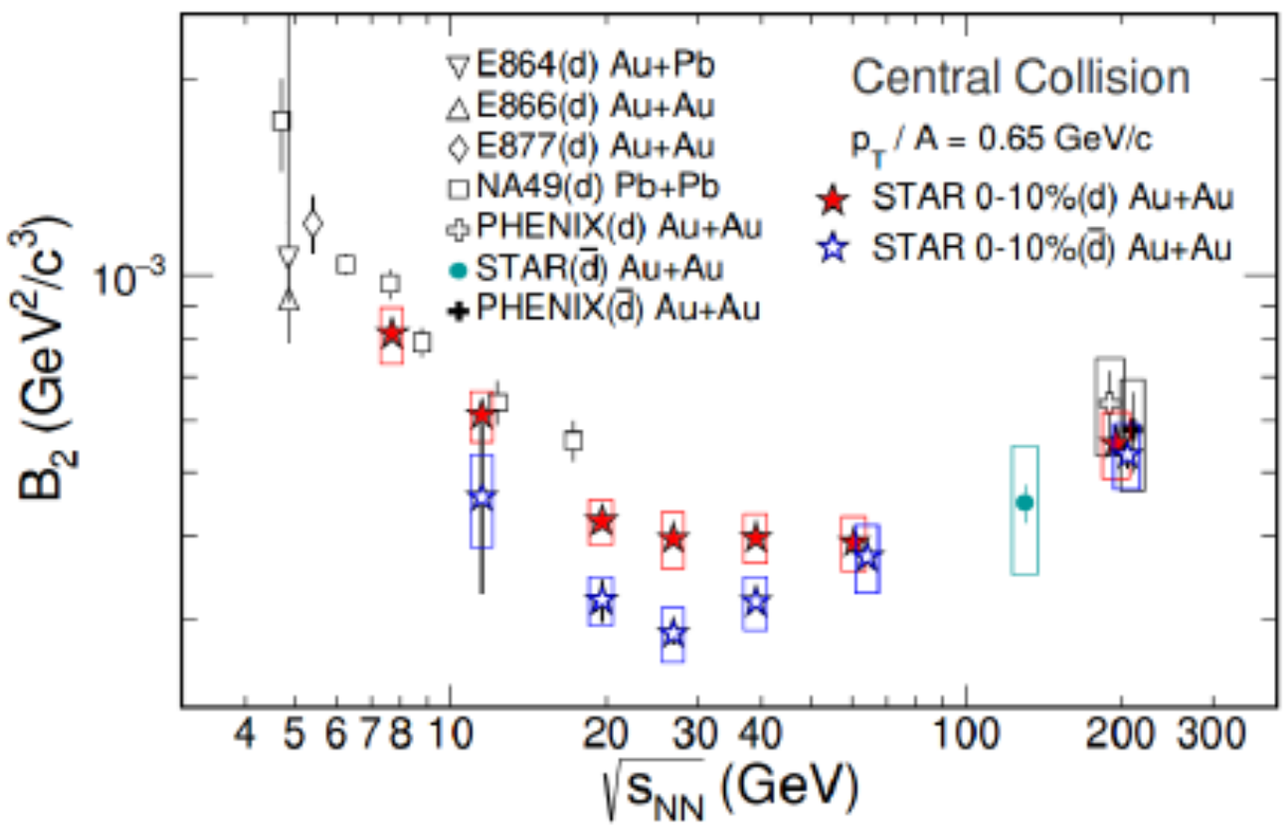
$B_2(m_T)$ ↑ , $v_{HBT}(m_T)$ ↓

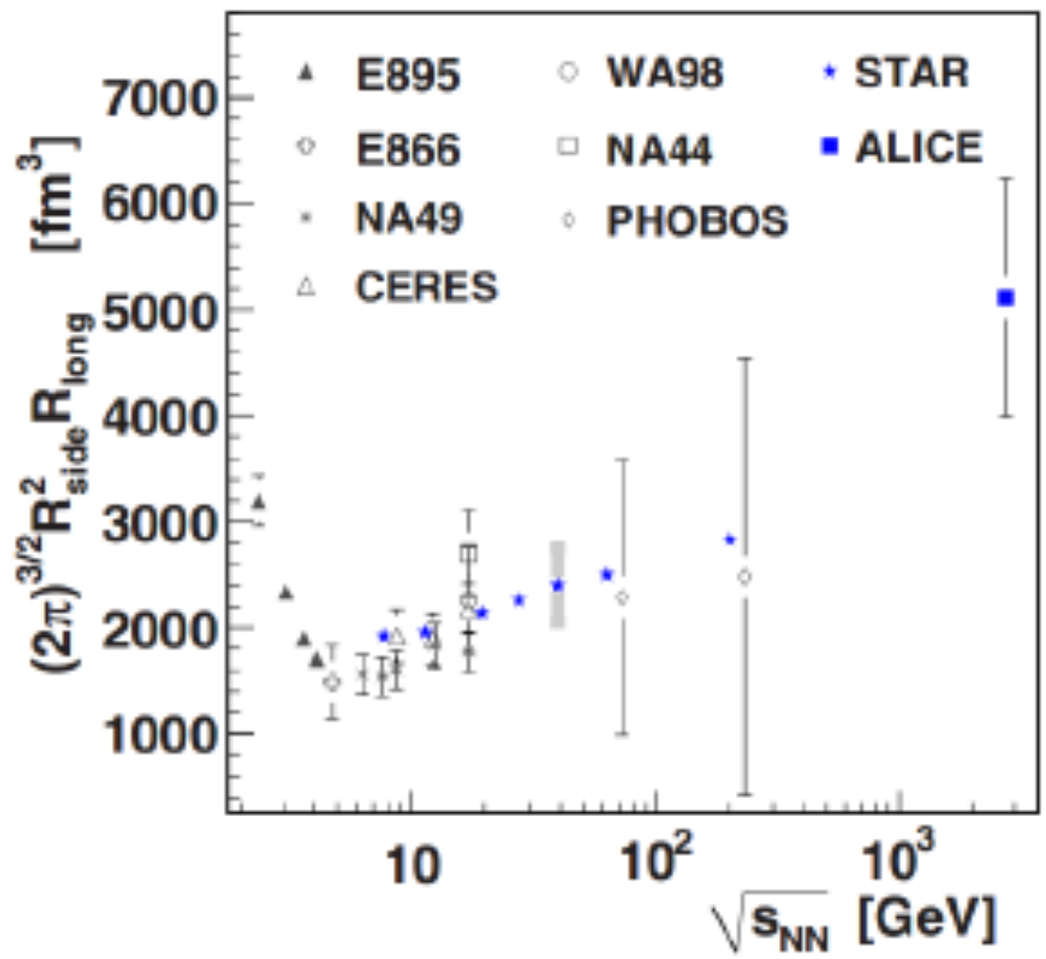
HADES, Phys. Lett. B 795 (2019) 446



Nucleon Coalescence

STAR, Phys.Rev. C99 (2019) no.6, 064905

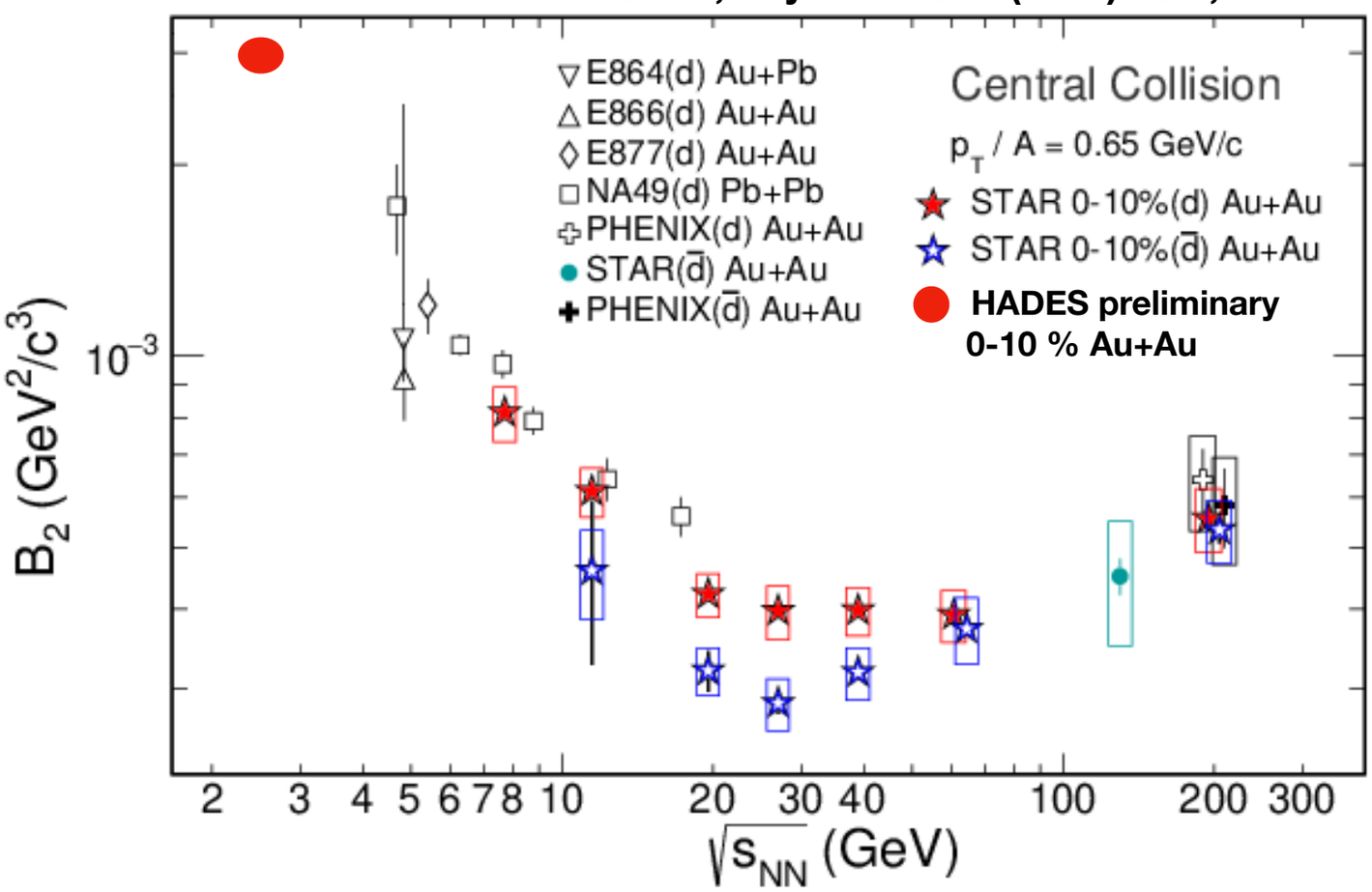


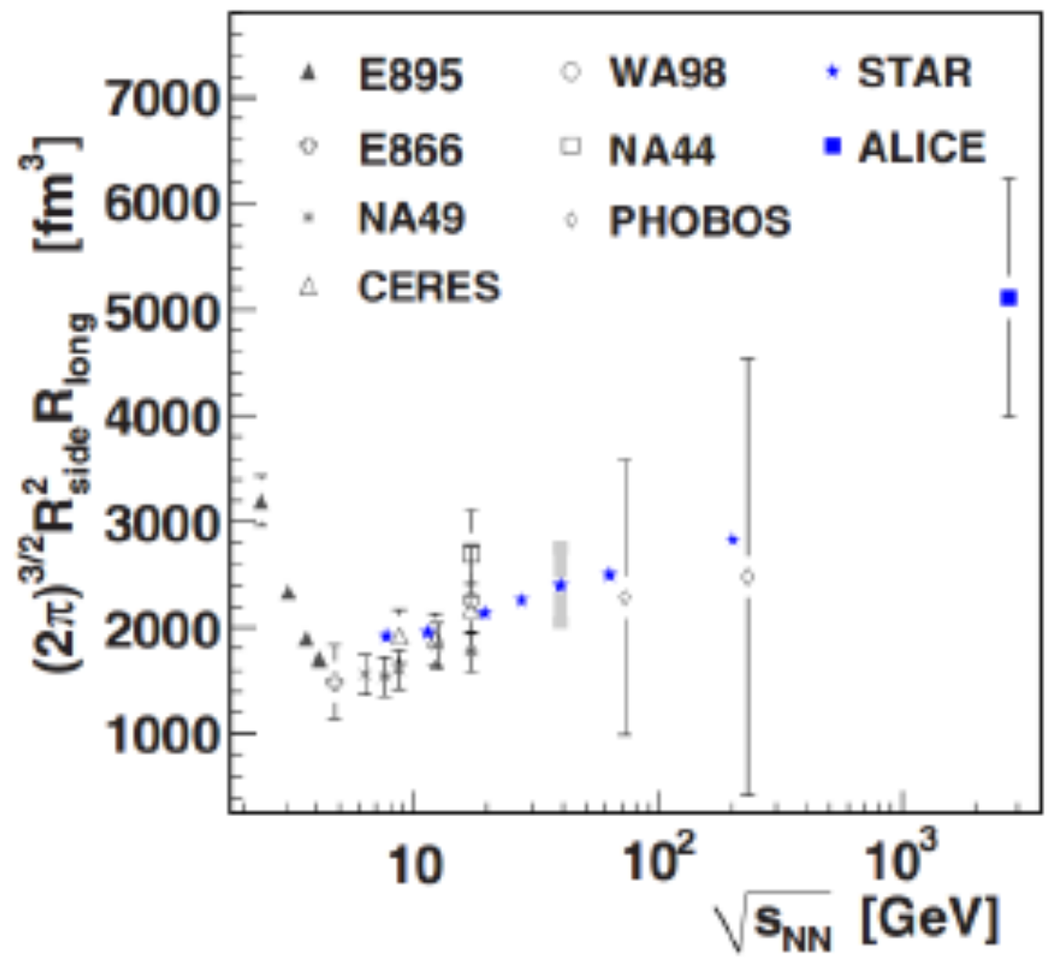


- Deviations from expectations $B_A \sim V_{HBT}^{-(A-1)}$
- **v_{HBT}** ↘↗ **=> coalescence B_2** ↗↘

Nucleon Coalescence

STAR, Phys. Rev. C 92 (2015) no.1, 014904
STAR, Phys.Rev. C99 (2019) no.6, 064905

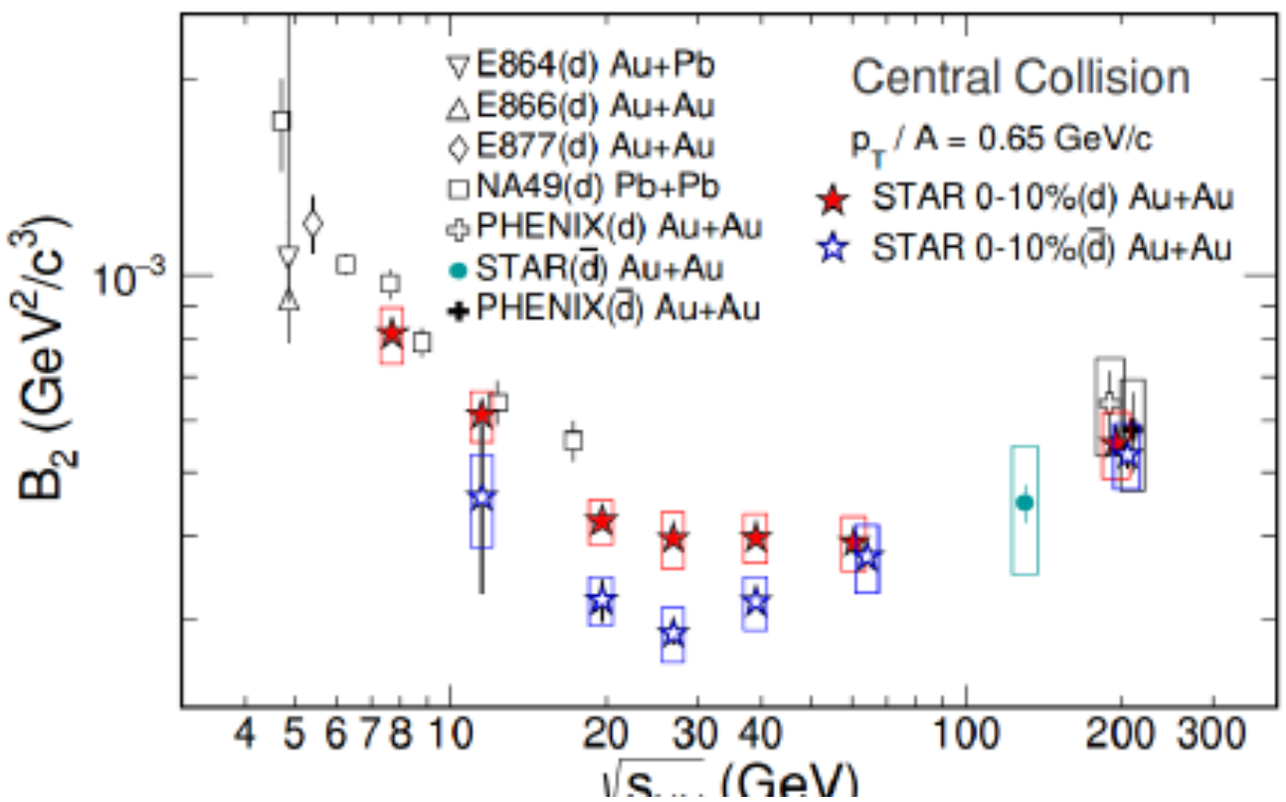




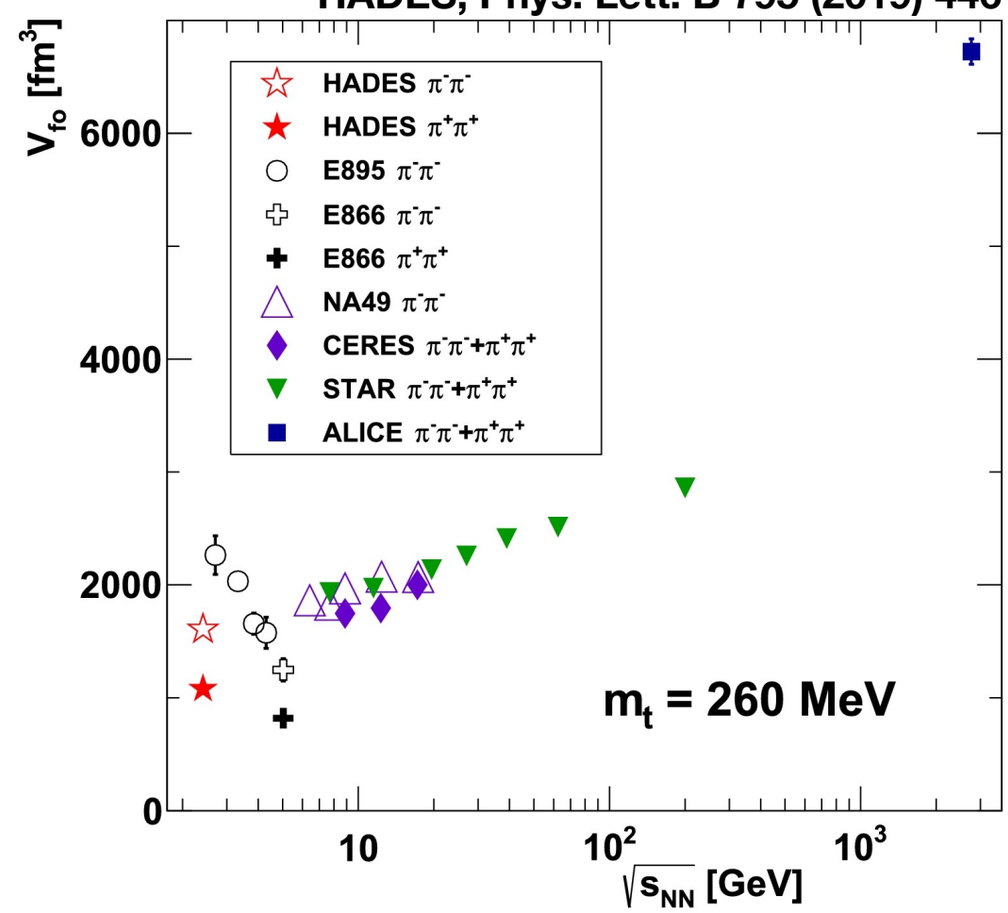
- Deviations from expectations $B_A \sim V_{HBT}^{-(A-1)}$
- **v_{HBT}** ↘↗ **=> coalescence B_2** ↗↘

Nucleon Coalescence

STAR, Phys.Rev. C99 (2019) no.6, 064905



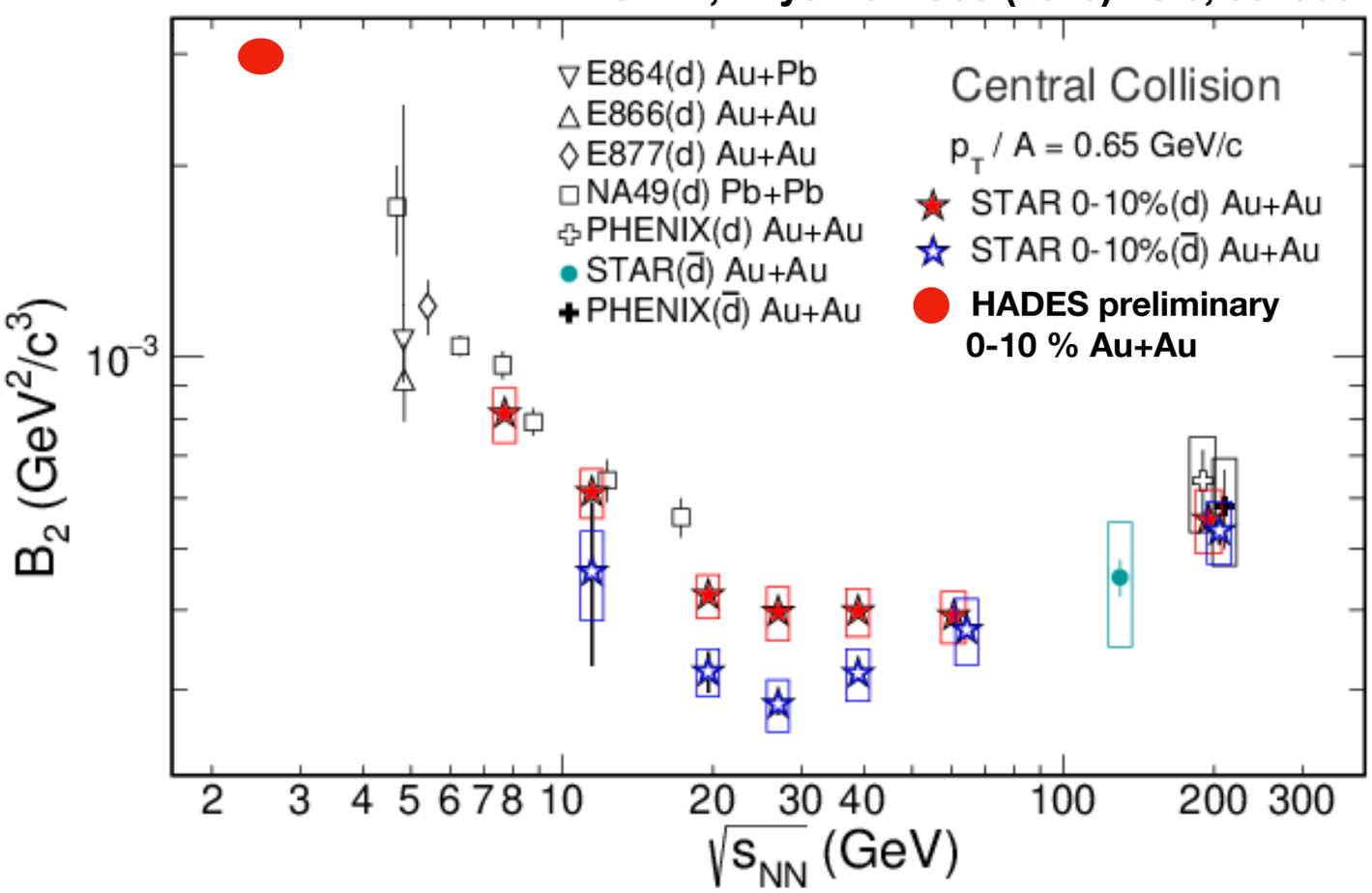
HADES, Phys. Lett. B 795 (2019) 446



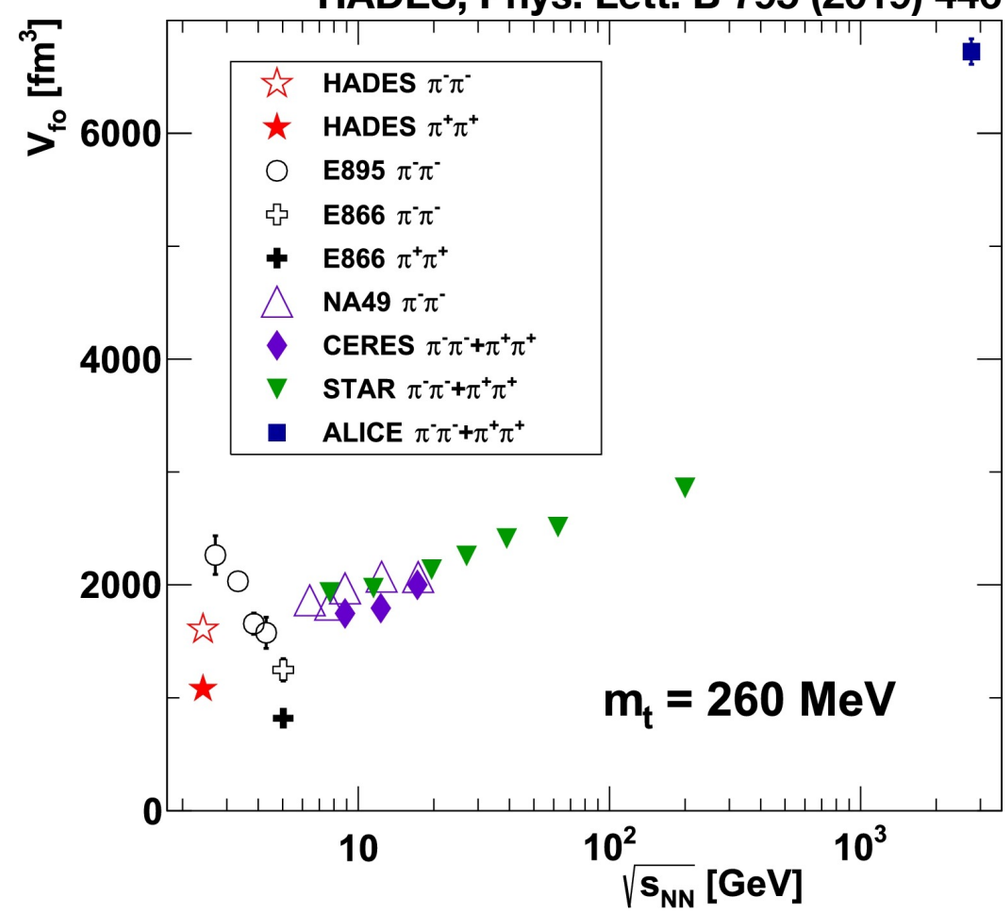
- **Compatible with coalescence**
- **V_{HBT} ↗ => coalescence B_2 ↘**

Nucleon Coalescence

STAR, Phys.Rev. C99 (2019) no.6, 064905



HADES, Phys. Lett. B 795 (2019) 446



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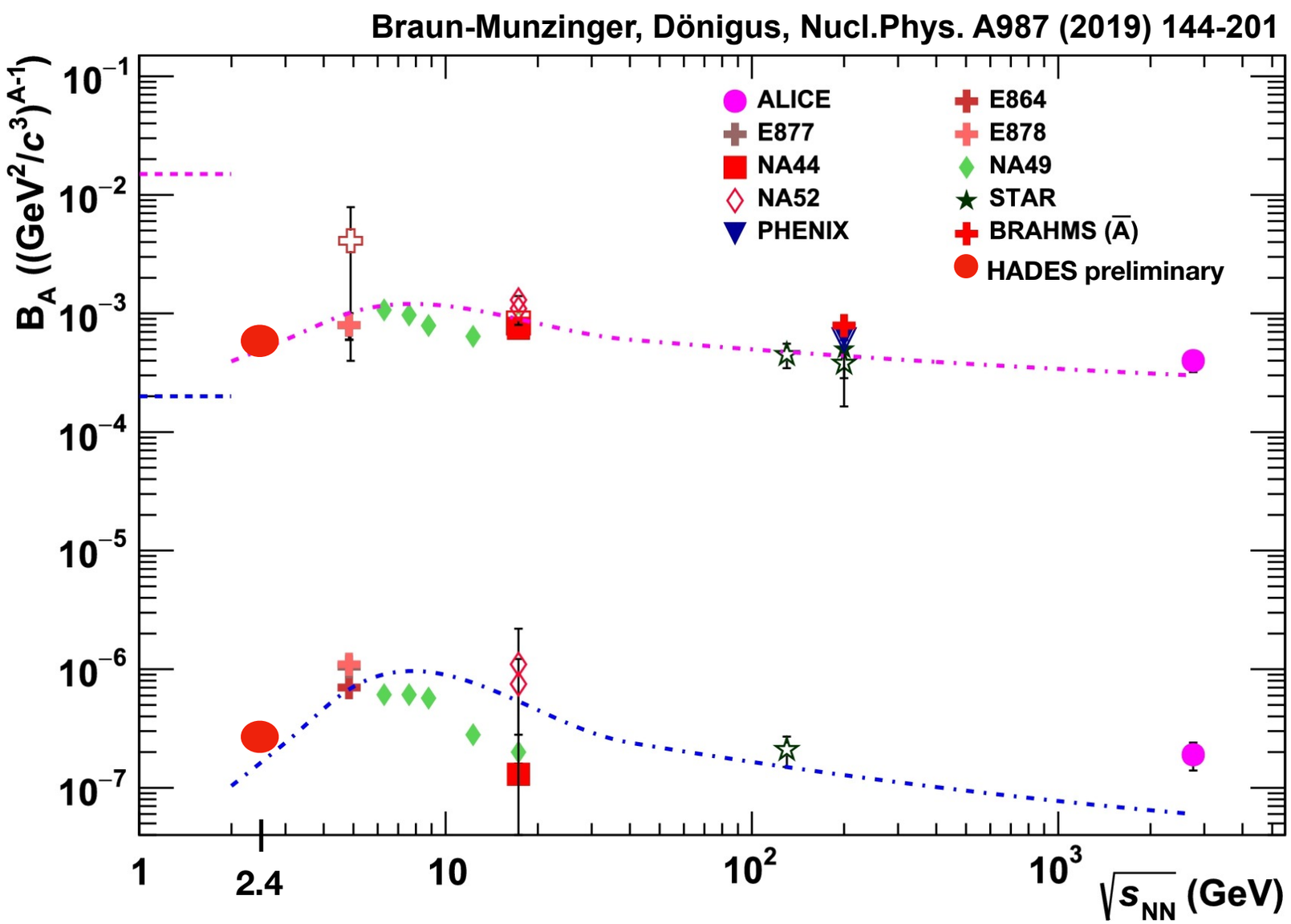
Nucleon Coalescence



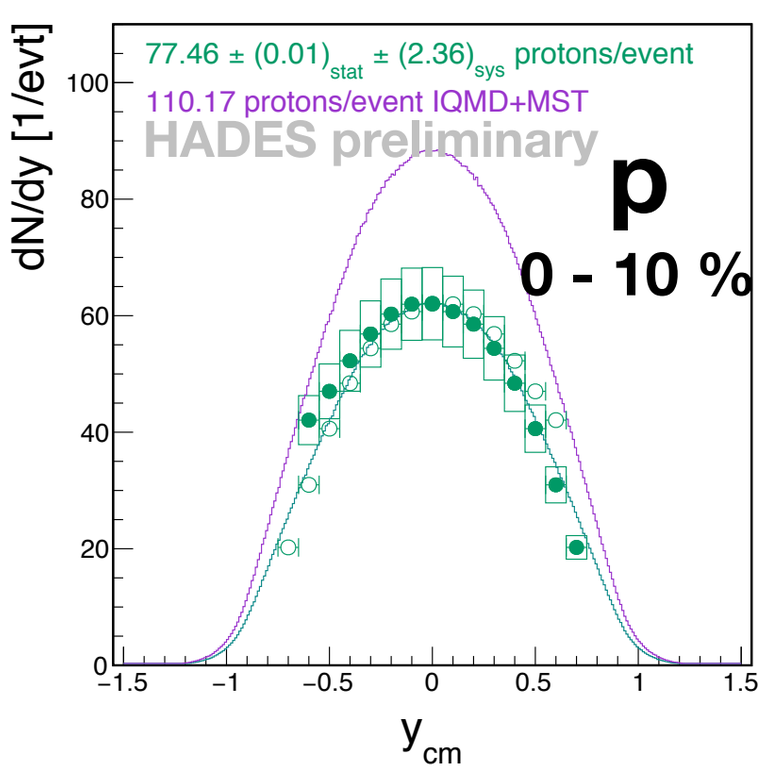
- Deviations from expectations
- Order of magnitude is still right

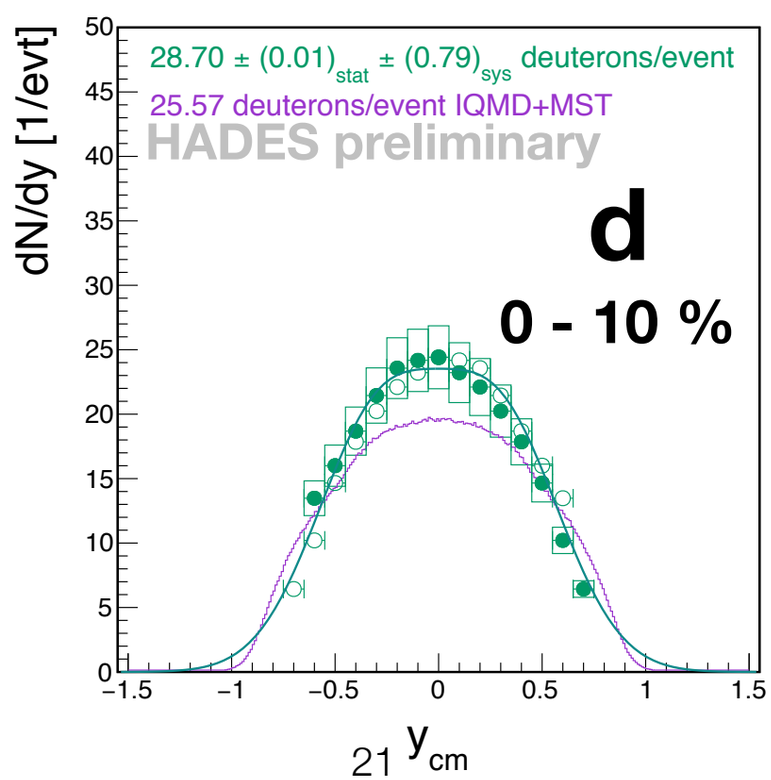
Comparison to model

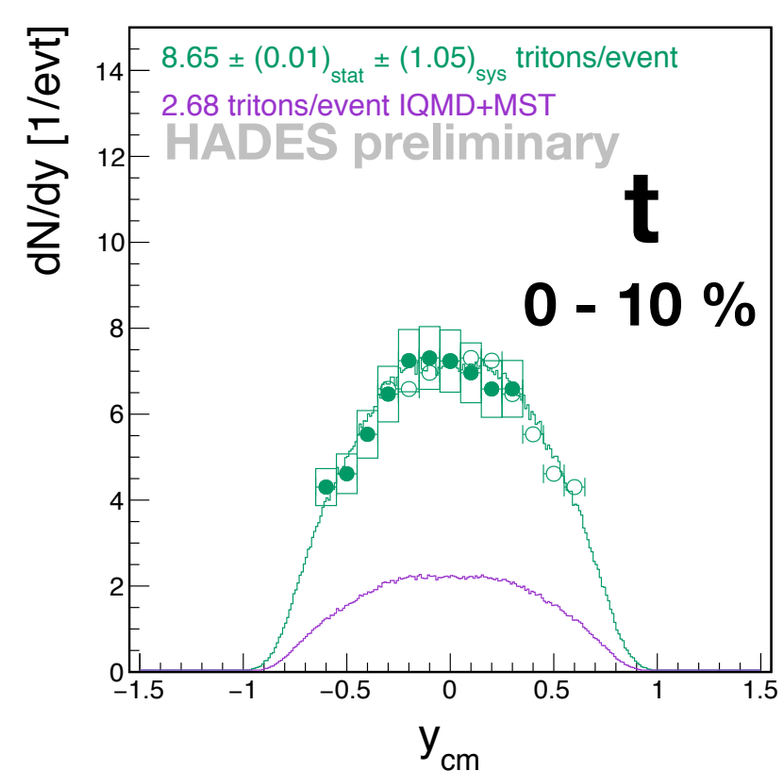
IQMD + MST model

- Light nuclei are clustered with the help of some coalescence afterburner
  - IQMD plus minimal spanning tree (MST):
  - r = 4 fm in position space and t = 200 fm/c
- fractions of light nuclei not reproduced by IQMD

➡ **Light nuclei yields are underestimated by coalescence afterburners around mid-rapidity**



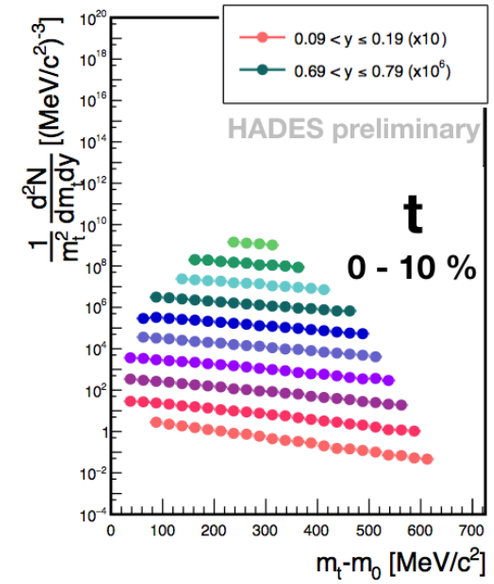


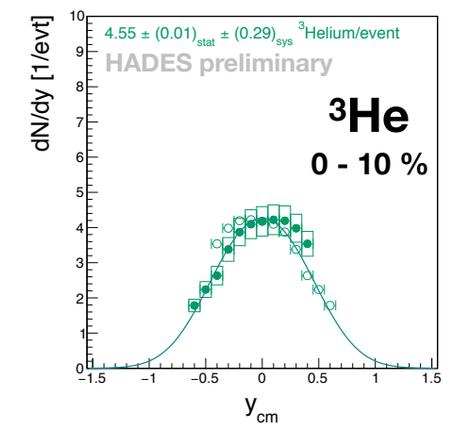


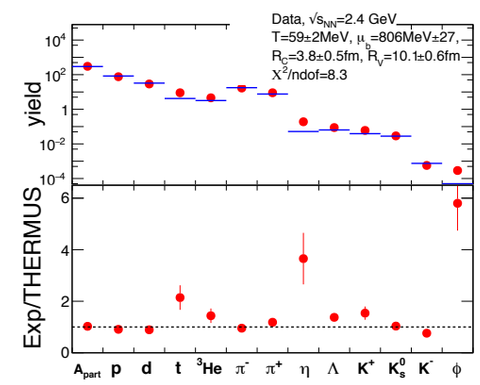
Thanks to Y. Leifels

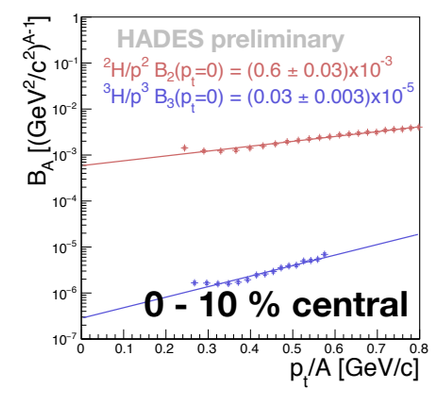
Summary

- High statistic data sample
- Differential analysis of p, d, t, ^{3}He performed
- High degree of cluster formation even in most central collisions
- Light nuclei production cannot be described consistently in simple statistical models
- Simple coalescence model does not reproduce light nuclei yields in the participant region
- B_A parameters as function of $p_T(y)$ provided









Outlook

- Transport models
  - major difficulty in formation of clusters
  - is often oversimplified or not omitted

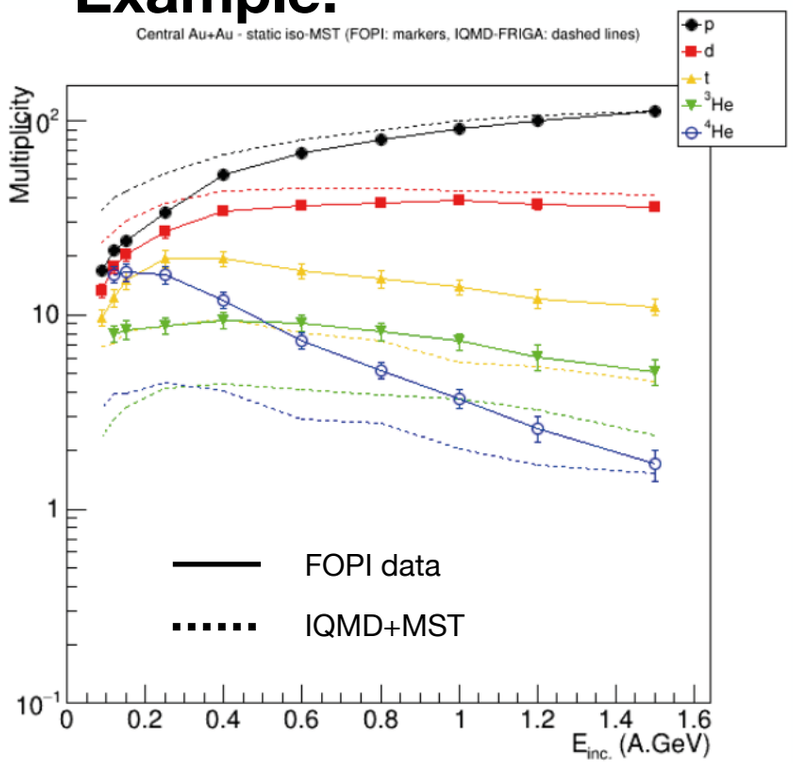
- Nucleon Coalescence model
  - simple coalescence model could not explain behaviour

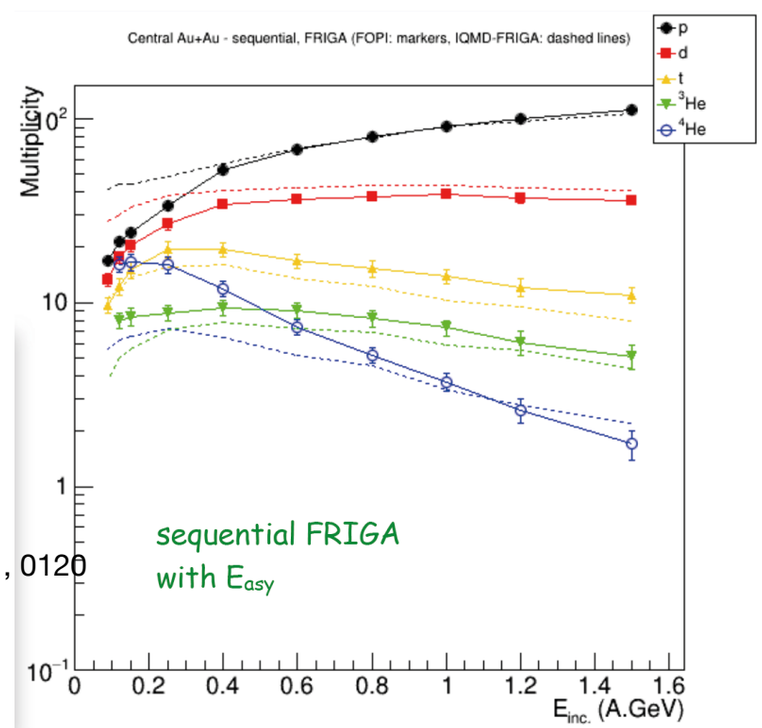
- Light nuclei are formed in multitude of processes but not generally by simple coalescence

- More advanced models for light nuclei production are needed, e.g FRIGA, PHQMD

P. Danielewicz and Q. Pan, Phys. Rev. C 46, 2002 (1992).
C. Kuhrts, M. Beyer, P. Danielewicz, and G. Ropke, Phys.Rev. C 63, 034605 (2001).
Akira Ono, EPJ Web of Conferences 122, 11001 (2016).
Le Févre, Y. Leifels, J. Aichelin, Ch. Hartnack, V. Kireyev, E. Bratkovskaya. J.Phys.Conf.Ser. 668 (2016) no.1, 0120

Example:





Arnaud Le Fèvre, EMMI Workshop, 11.02.-13.02.2019, GSI
FOPI Collaboration, Nuclear Physics A 848 (2010) 366–427