Coulomb effects on pion spectra and HBT correlations at few GeV/A beam energies

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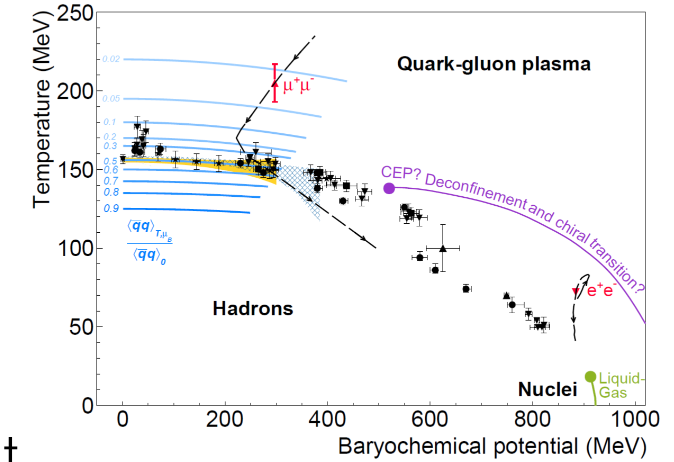
Nuclear collisions at SIS18/HADES energies

<u>HADES program:</u>
- EOS of hot and dense matter
- Medium modifications of hadrons
- Various aspects of baryon-resonance physics in cold matter and vacuum



Nature Phys. **15** (2019) 10, 1040-1045 (update 2023 T. Galatyuk)

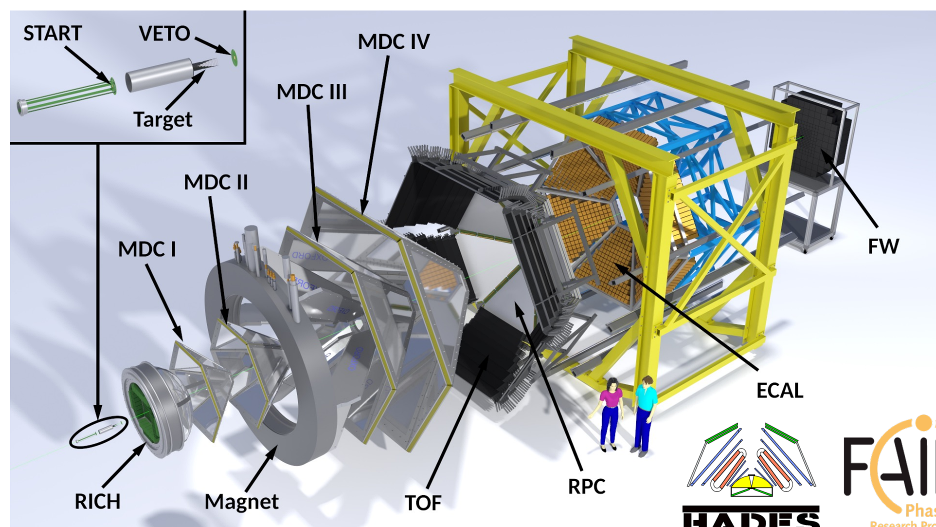
Similar conditions as expected in merging neutron stars (Nature Physics **15**, 1040–1045 (2019), J. Phys.: Conf. Ser. **878** 012031, Phys. Rev. Lett. **122**, 061101)

Measurements at SIS18 : Fixed target experiment
Interaction rate capability : up to 50kHz trigger rate
Large acceptance : full azimuthal coverage, 18°-85° polar one

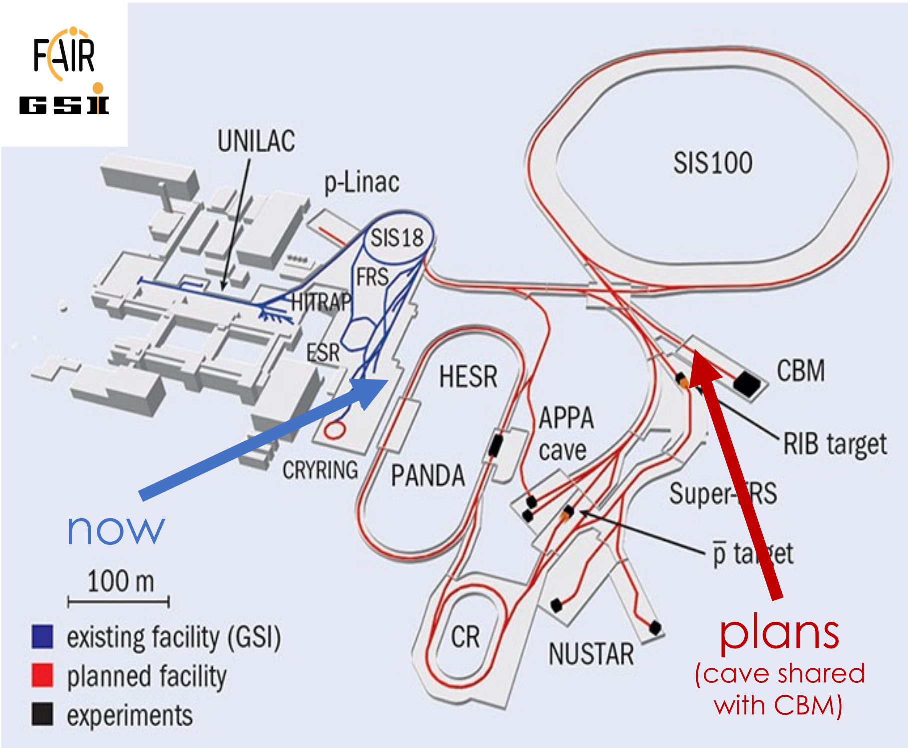
Tracking with low-mass Mini Drift Chambers (MDC)

Hadron Identification
Time-of-flight (TOF, RPC) and/or dE/dx (MDC, TOF)

Centrality selection based on N_{hits} and Glauber Monte Carlo



HADES space-time coordinates



- **Nov 2002** C+C at $\sqrt{s_{NN}} = 2.7$ GeV
- **Jan 2004** p+p at $\sqrt{s} = 2.77$ GeV
- **Aug 2004** C+C at $\sqrt{s_{NN}} = 2.32$ GeV
- **Sep 2005** Ar+KCl at $\sqrt{s_{NN}} = 2.61$ GeV
- **Apr 2006** p+p at $\sqrt{s} = 2.42$ GeV
- **Apr 2007** p+p at $\sqrt{s} = 3.18$ GeV,
  d+p at $\sqrt{s_{NN}} = 2.42$ GeV
- **Sep 2008** p+Nb at $\sqrt{s_{NN}} = 2.7$ GeV
- **Apr 2012** Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV
- **Jul-Aug-Sep 2014** π^- + W/C/polyethylene
- **Mar 2019** Ag+Ag at $\sqrt{s_{NN}} = 2.55$ and 2.42 GeV
- **Feb 2022** p+p at $\sqrt{s} = 3.46$ GeV

Presentation based on pion production from AuAu@1.23AGeV collisions

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

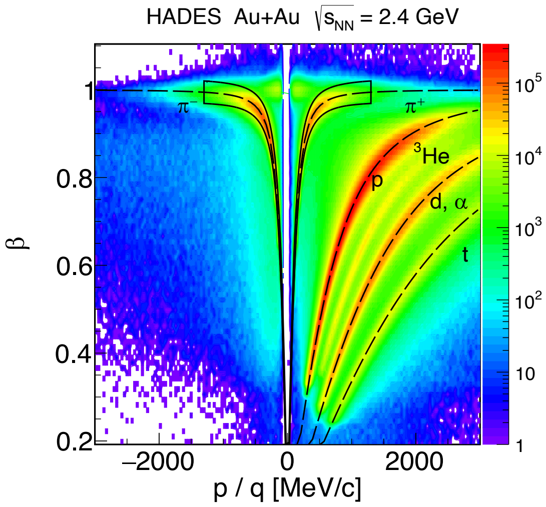
Eur.Phys.J.A 58 (2022) 166

Charged pion production in Au+Au collisions at 1.23AGeV

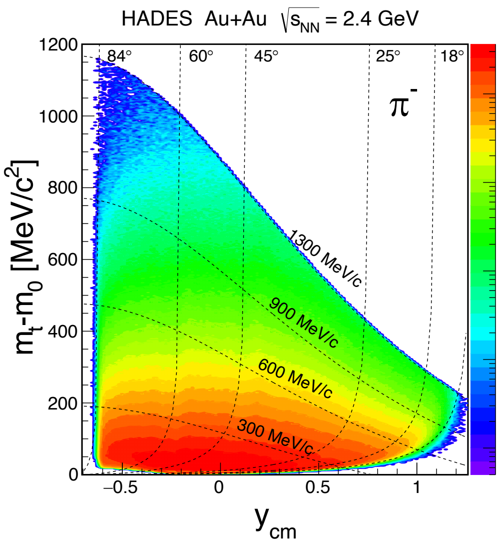
- Pions are most aboundantly produced particles
- Sensitive to bulk properties of hot and dense matter
- Huge data sample → detailed multi-differential analysis possible

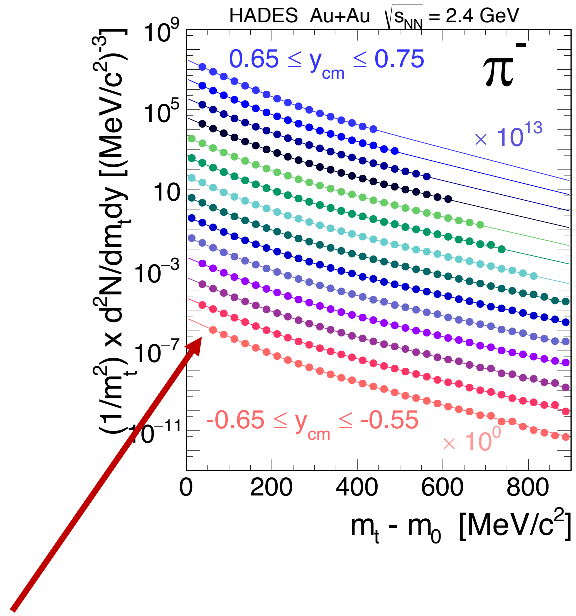
- Particle ID based on velocity vs. momentum

Particle identification



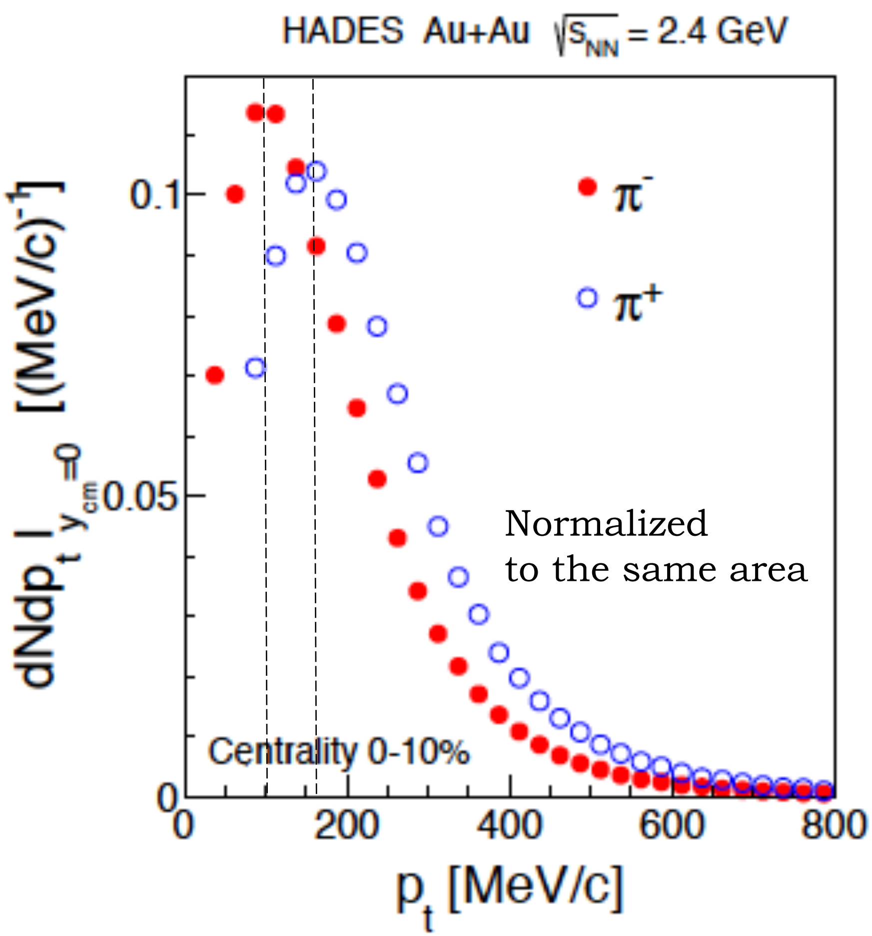
Phase-space





Curves corresponds to two-slope Boltzmann fits commonly used for extrapolation outside of the detector acceptance at low and high transverse mass

Coulomb effects on the pion spectra



→ Split between peak positions:
100 MeV/c for π^- vs. 160MeV/c for π^+

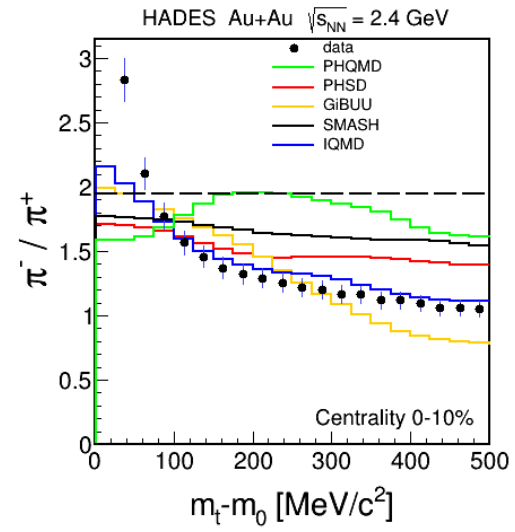
→ Can be attributed to the Coulomb interaction of the pions with the positive charge of the fireball.

- ➢ π^- are decelerated
- ➢ π^+ are accelerated

$$E_f(p_f) = E_i(p_i) \pm V_C$$

How to acount for the Coulomb effect ?

Full dynamic evolution (e.g. transport model) would be the best
→ Only IQMD and GiBUU include "Coulomb effect"
→ Only as a mean field



Simple parametrization: *PRC57, 2536 (1998), arXiv:1408.1369*
Phys. Lett.B420,20 (1998) , Nucl.Phys.A 610,286c (1996)

→ Shift of energy : $E_f(p_f) = E_i(p_i) \pm V_{\text{eff}}$,

→ One needs Jacobian of variable transformation

→ Expanding source (spherically symmetric) : *Barz et al. PRC57 (1998)*

$$V_{\text{eff}} = \begin{cases} V_C\left(1 - e^{-x^2}\right) & \text{for a 2D expansion ,} \\ V_C\left(\text{erf}(x) - (2/\sqrt{\pi})\, x e^{-x^2}\right) & \text{for a 3D expansion ,} \end{cases}$$

$$x = \sqrt{(E_\pi/m_\pi - 1)\, m_p/T_p},$$

For low-energy

→ Original fit function: $$\frac{1}{m_t^2}\frac{d^2N}{dm_t d_y} = A\left(f e^{-m_t/T_1} + (1-f)e^{-m_t/T_2}\right)$$

(double-Bolzmann)

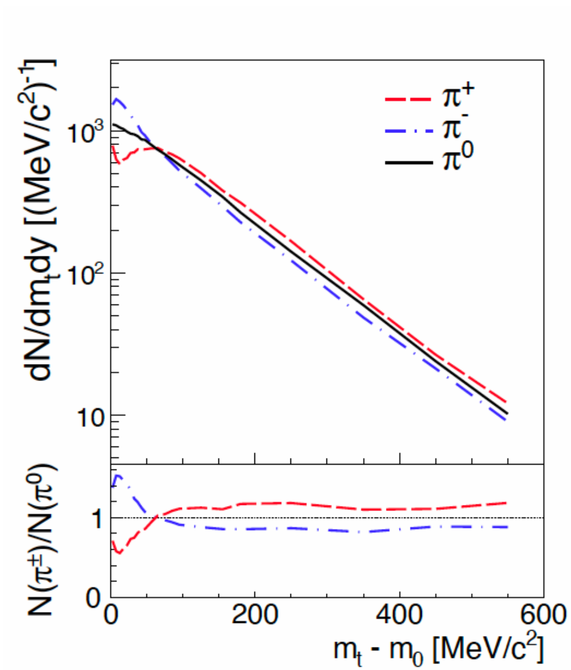
$$Jac = \frac{E_i\, p_i}{E_f\, p_f}$$

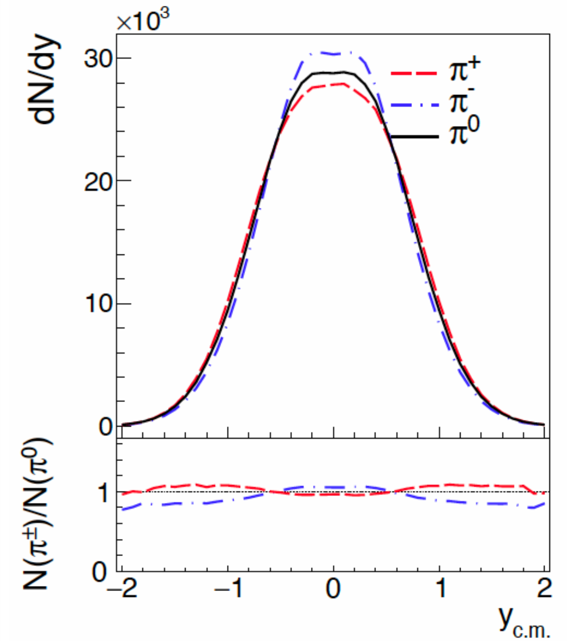
→ Transformed one : $$\frac{1}{m_t^2}\frac{d^2N}{dm_t d_y} = A\left(f e^{-E_i/T_1} + (1-f)e^{-E_i/T_2}\right) \cdot Jac \cdot JacEff$$

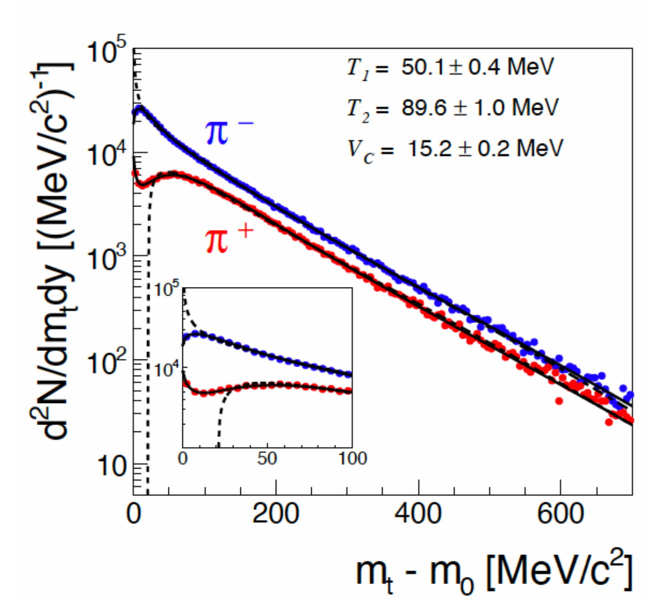
Toy simulations with thermal source

Coulomb-modified thermal source implemented in Pluto event generator with parameters:

→ T1 = 5eV, T2 = 90MeV, frac = 0.95 and Vc=15 MeV

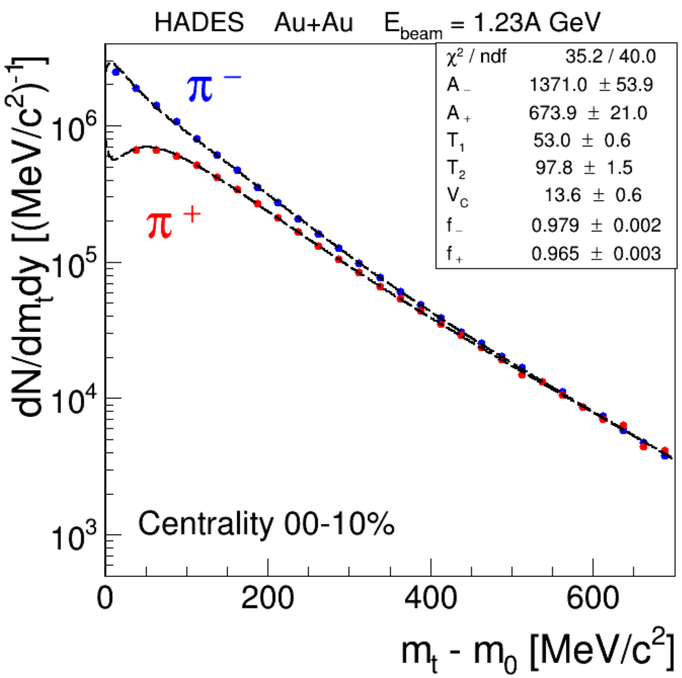


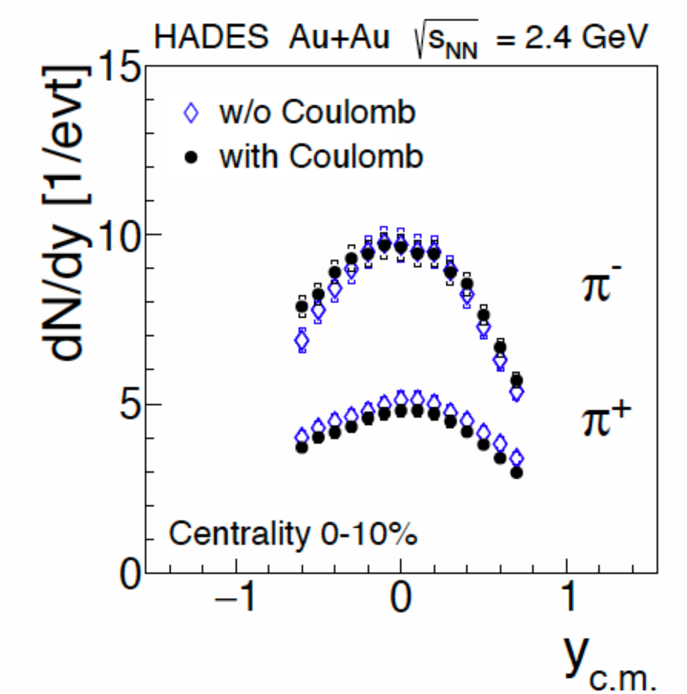




Fit parameters agree with the input

Extracting Coulomb potential. Rapidity dependence

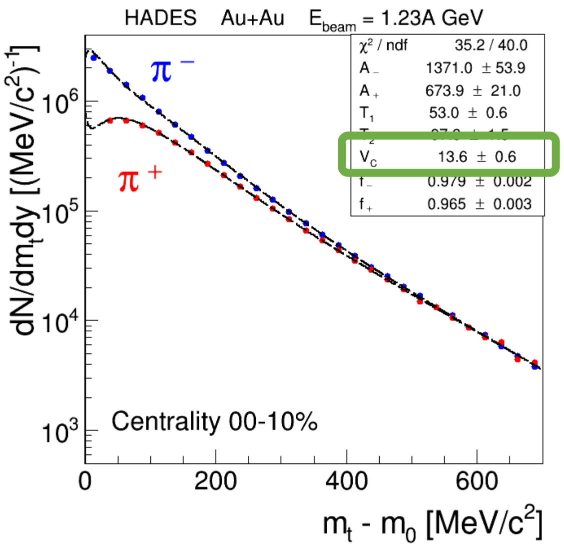


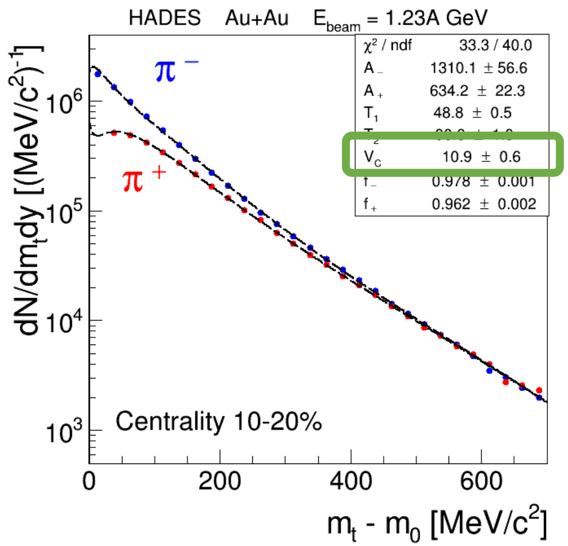


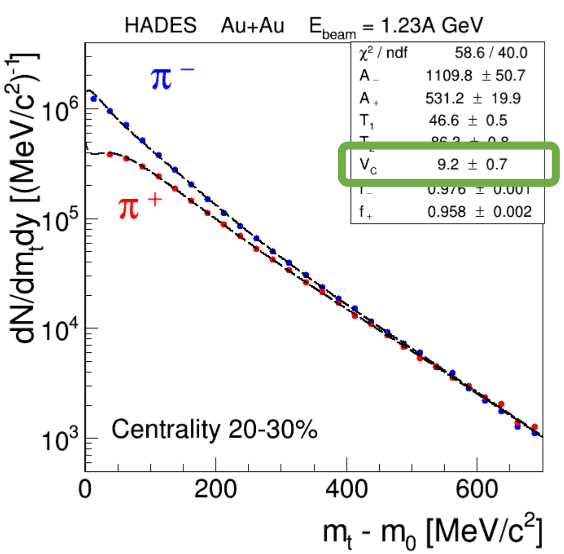
- Combined fit to both charges
  - most central events
  - mid-rapidity
- All parameters in the fit are free

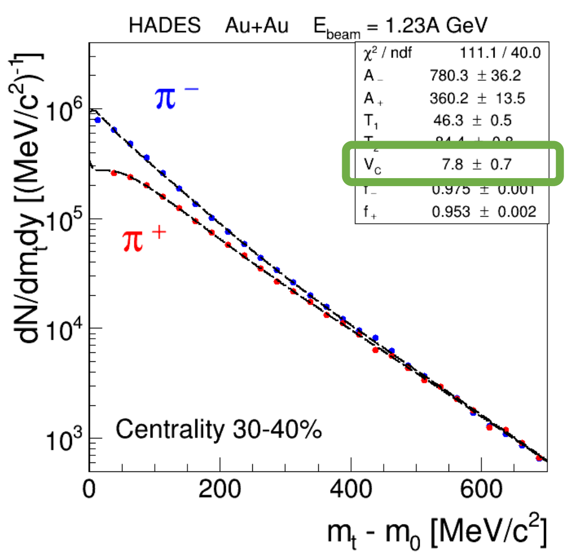
Including Coulomb effects gives more reliable fit, to use for extrapolation

Centrality dependence



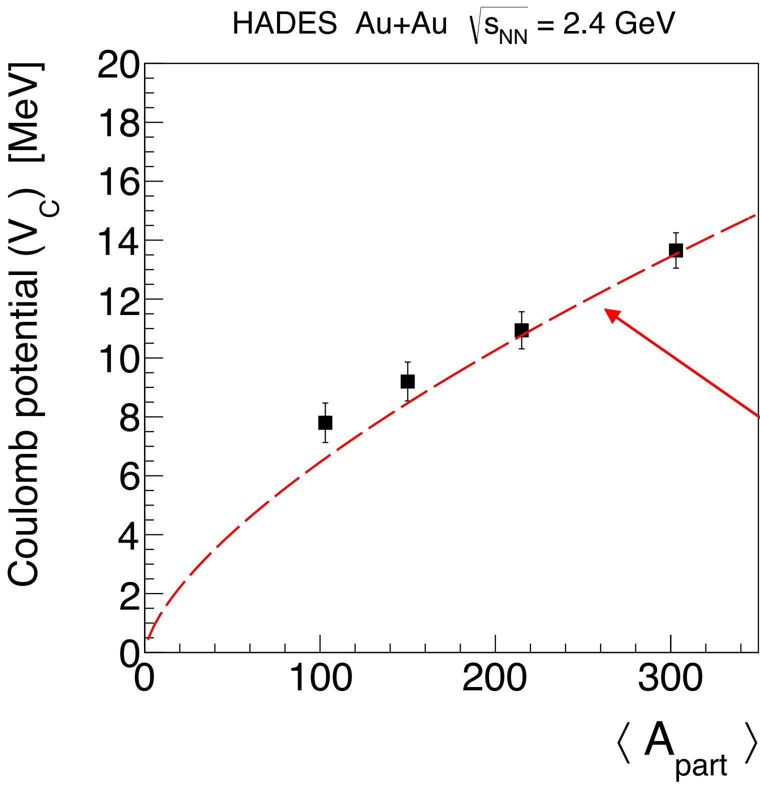






- Combined fit
- to both charges
  - 4 centralities
  - mid-rapidity spectra
- All fit parameters free

Centrality dependence



Pions decoupling from fireball at freeze-out

$$\langle V_c \rangle = \frac{6}{5}\frac{Ze^2}{R}$$

Hard-sphere model

for constant freeze-out density

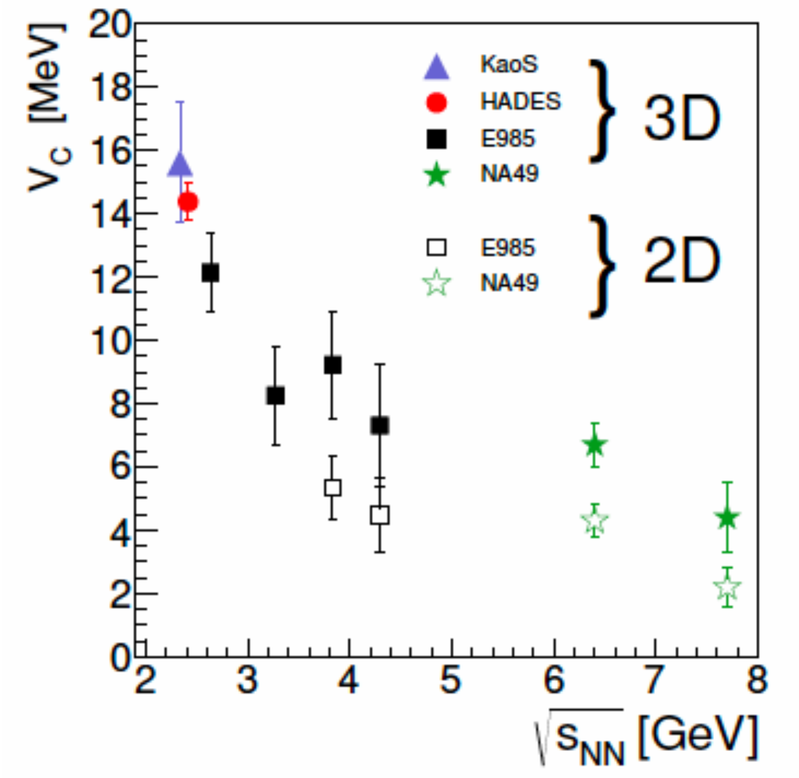
$$R \propto A^{1/3}$$
$$Z \propto A$$

Normalized to 0-10%

$$V_C \propto A^{2/3}$$

- Coulomb potential scales with A_{part} roughly like $A^{2/3}$
- Deviations can be caused by spectator charges which are not taken into account in the parametrization

Beam energy dependence of Vc

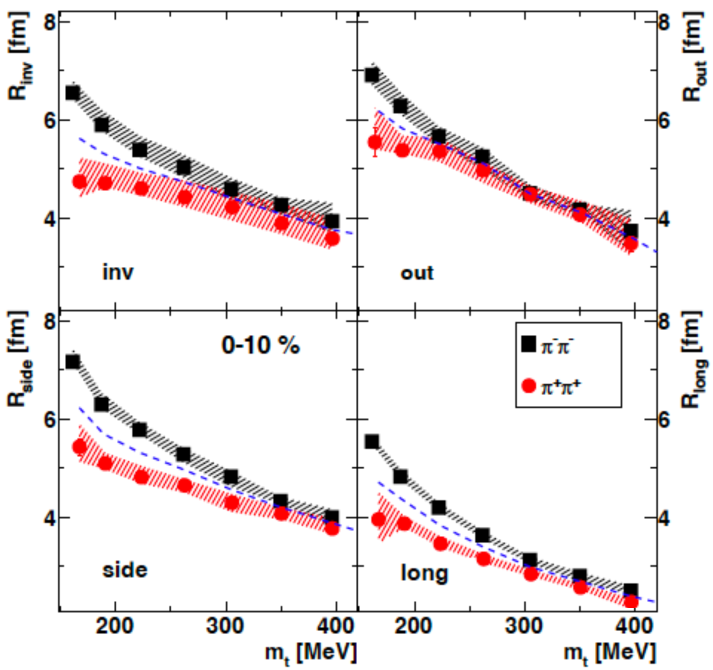


Potential is decreasing with increasing beam energy

- stronger expansion → larger radii → lower Vc=Z/R
- 3D → 2D
- Less stopping? Is this true at AGS energies already or does that set in at SPS only

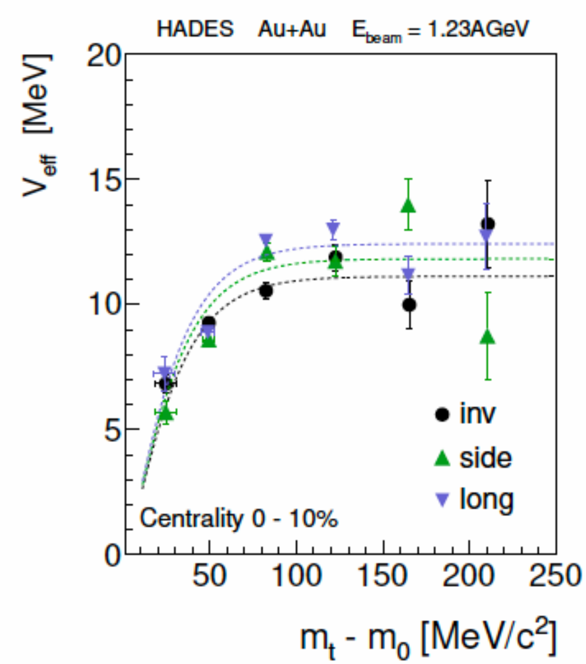
Coulomb potential from HBT radii

- Coulomb potential acts on the relative momentum of charged-pion pairs, affecting the extracted HBT radii.
- V_{eff} (mt) can be extracted using : $$V_{\rm eff}(m_t) = \frac{m_t^2 - m_\pi^2}{4m_t} \, \frac{R^2_{\pi^-\pi^-} - R^2_{\pi^+\pi^+}}{R^2_{\pi^0\pi^0}} \, .$$
- V_C can be extracted from V_{eff} (mt) considering an 3D expanding source (along to the single particle consideration)

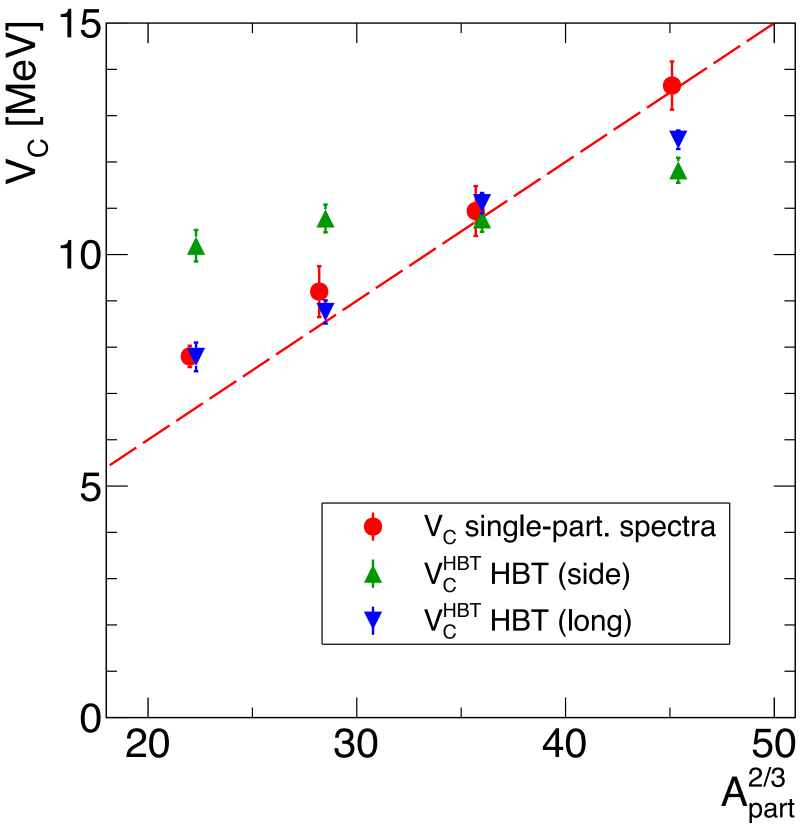


HBT published in:
Phys.Lett.B 795 (2019) 446-451
Eur.Phys.J.A 56 (2020) 5, 140

- HBT analysis provides various radii: R^{inv}, R^{side}, R^{out}, R^{long}
- R^{out} not considered here



Extracted Vc, single spectra vs HBT

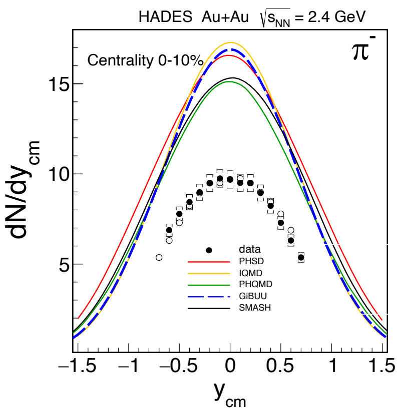


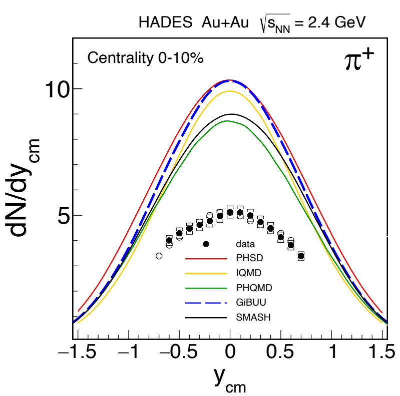
Reasonable agreement between HBT and single particles spectra results.

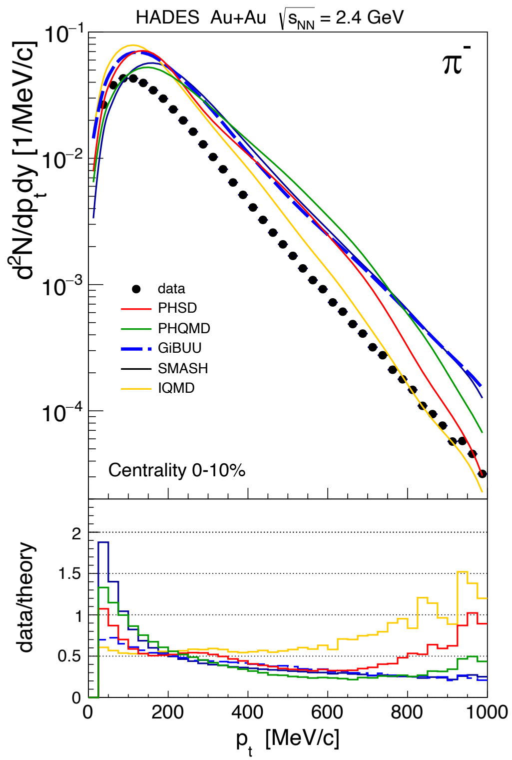
We do have a fair/reasonable agreement but close inspection shows systematic differences:

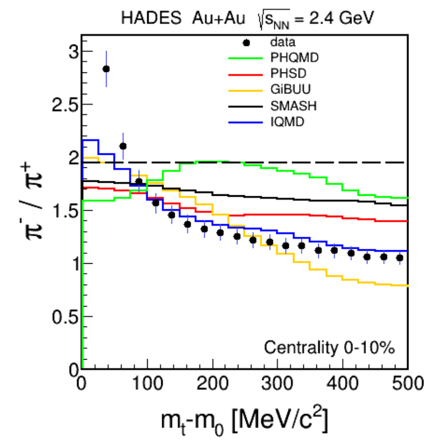
- Do we compare the same volumes ?
- HBT measures a homogeneity radius !

Comparison to transport models (status from 2020)

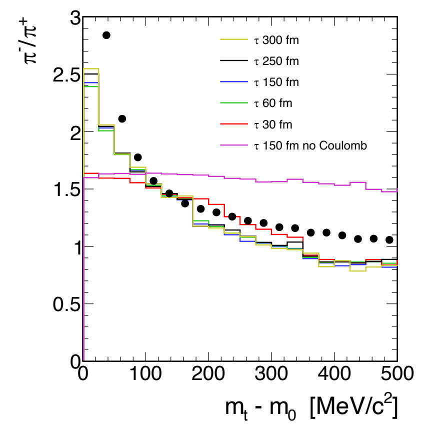








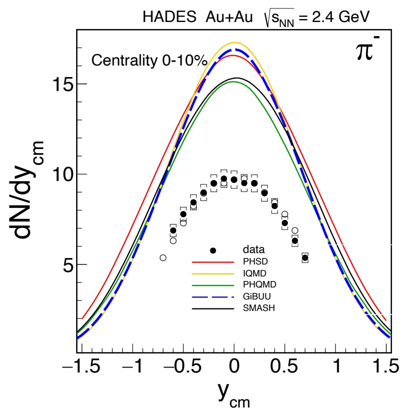
GiBUU

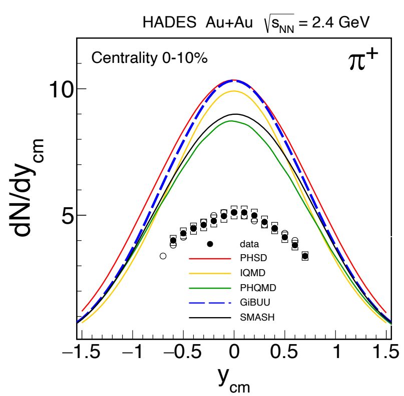


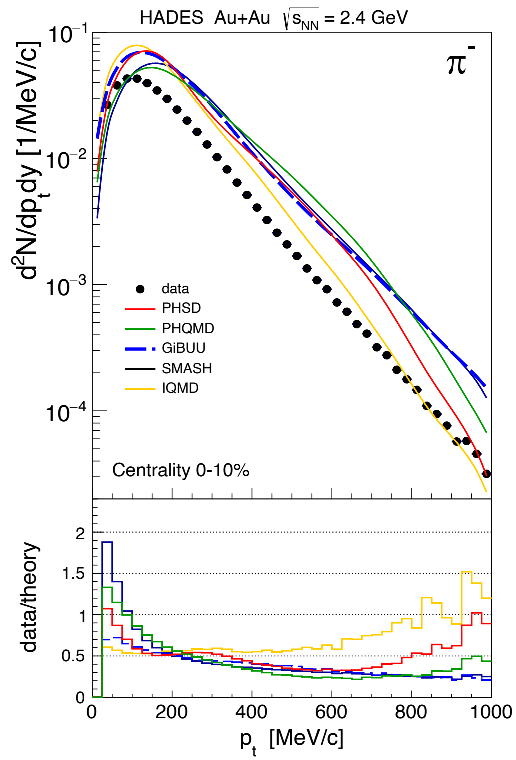
Measured pion yields are compared with various transport model calculation.
All models overshoot our data by nearly a factor 2!

→ This triggered new efforts on the theory side to improve the agreement

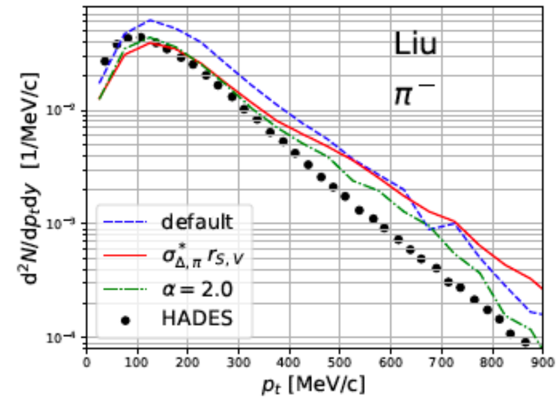
Comparison to transport models (status from 2020)

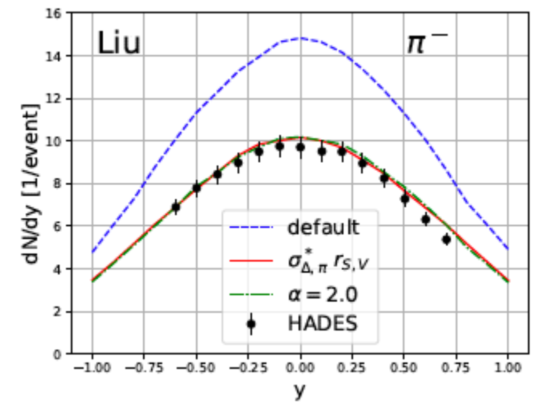






Pesent GiBUU 2023





C.Kummer et al. arXiv:2309.09042v1

Measured pion yields are compared with various transport model calculation.
All models overshoot our data by nearly a factor 2!

- Improvement in EOS
- In-medium modification of
    - Cross sections
    - Delta resonance

Summary

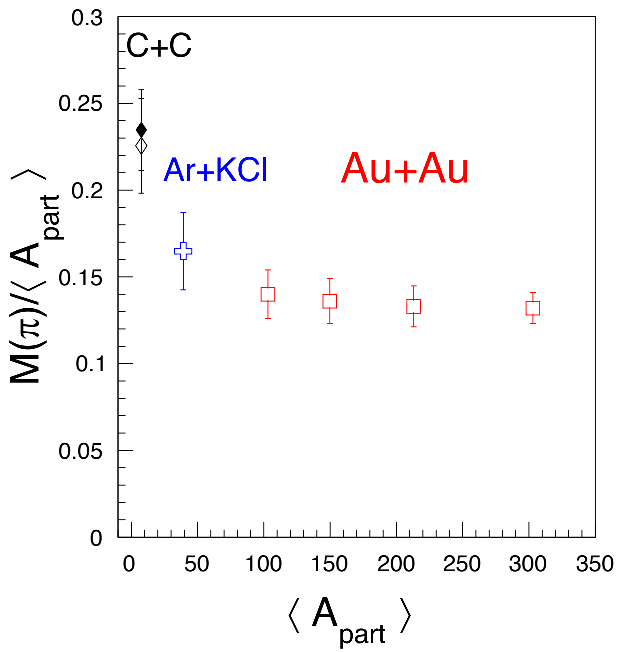
- HADES measured charged pion production with unprecedented statistics in Au+Au collisions.
- A detailed multi-differential analysis has been done, including Coulomb modifications of the pion spectra.
- The evolution of the Coulomb potential with collision centrality and beam energy has been presented.
- Effects of the Coulomb potential on 2-pion interferometry have been presented as well, consistent with the potentials obtained from the single-pion spectra.

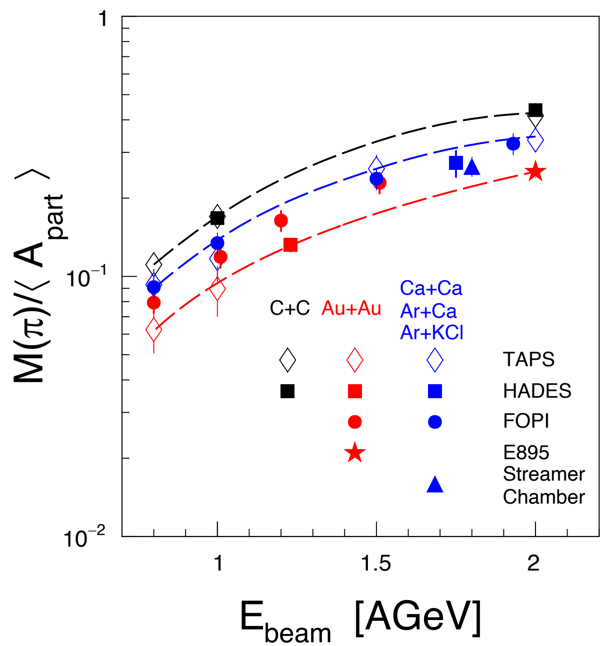
Outlook

- Agreement with transport calculations is expected to improve in the near future.
- HADES will continue these studies with new data to be gathered in a beam-energy scan (0.2 - 0.8 AGeV) scheduled for March 2024.

Back-up slides

Pion systematic : A_{part} and E_{beam} dependence



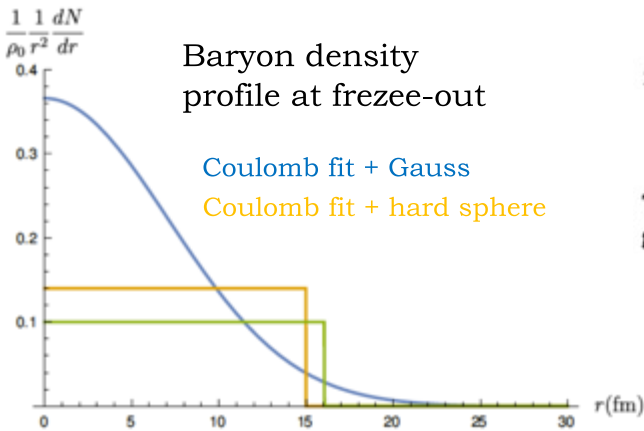


Strong system size and energy dependence

Hadron resonance gas

Vc → charge radius → Baryon density distribution

assuming charge radius = matter radius



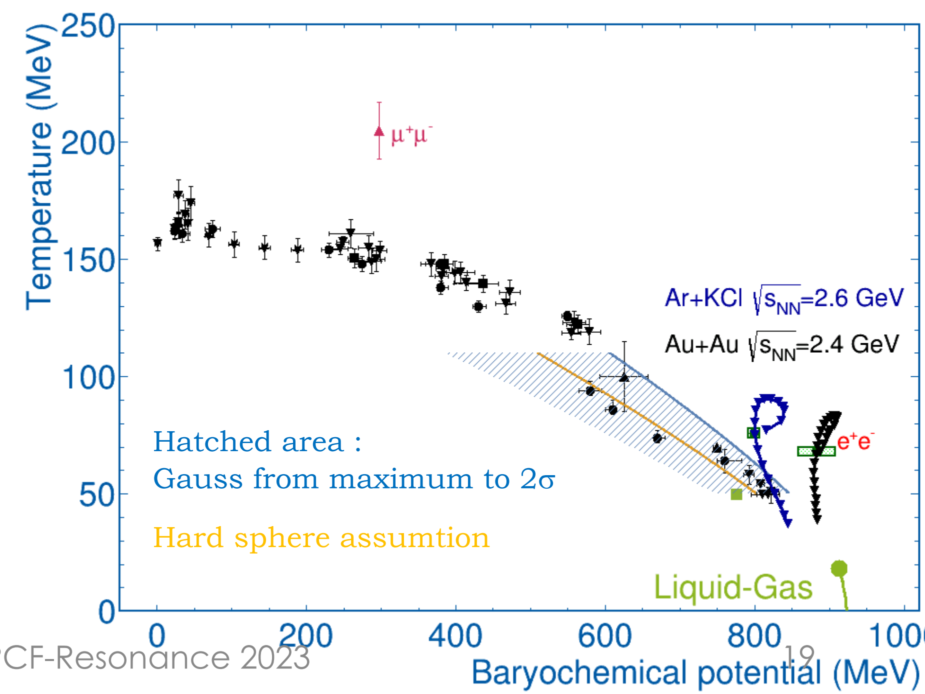
† We may write out for reference the formula for the chemical potential of a monatomic ideal gas with statistical weight (degree of degeneracy) of the ground state g:

$$\mu = T \log \left[\frac{P}{gT^{5/2}}\left(\frac{2\pi\hbar^2}{m}\right)^{3/2}\right] = T \log \left[\frac{N}{gV}\left(\frac{2\pi\hbar^2}{mT}\right)^{3/2}\right]. \quad (46.1a)$$

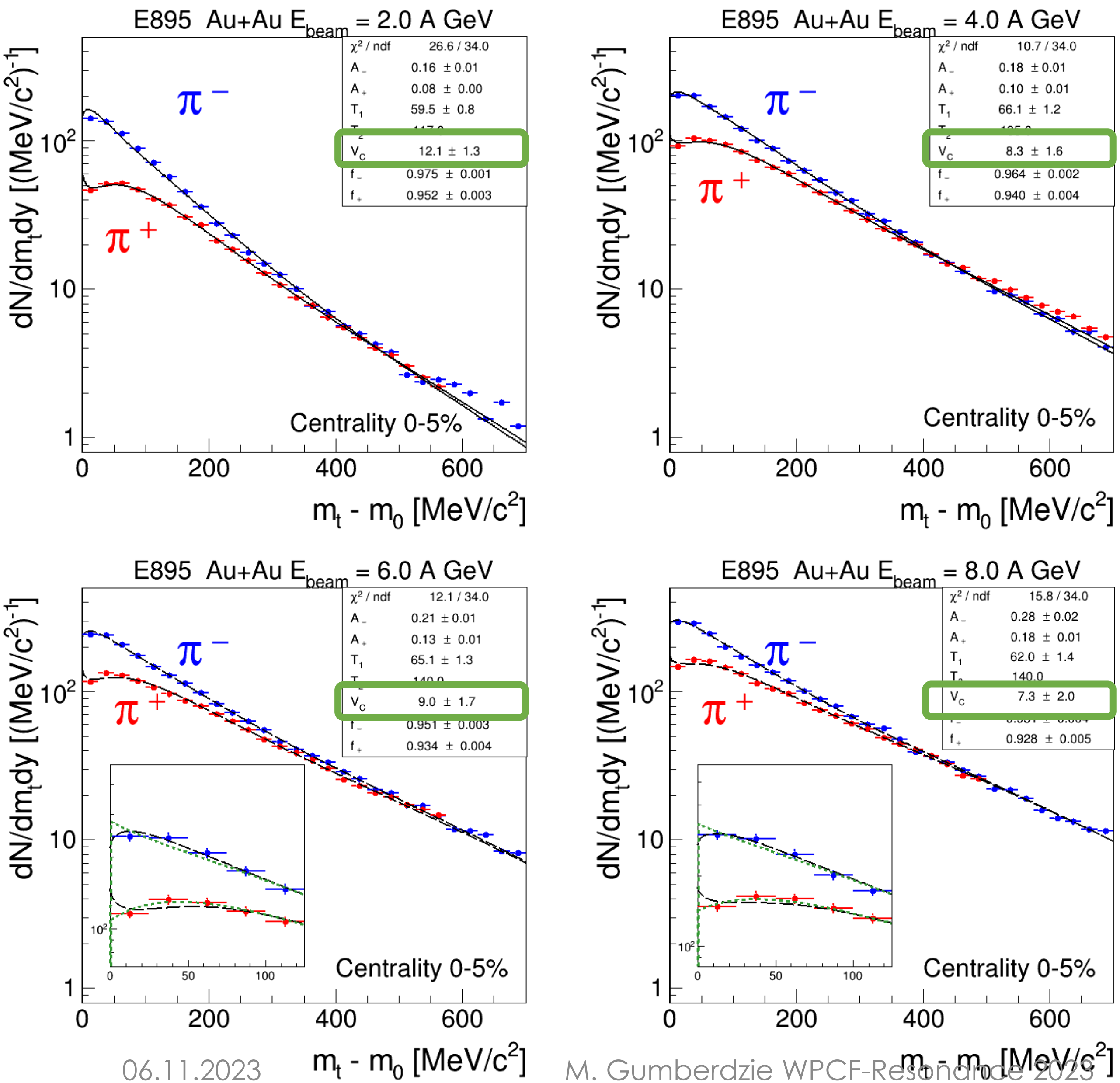
This applies also to a Boltzmann gas of elementary particles; for instance, in an electron gas $g = 2$.

L. D. Landau and E. M. Lifshitz,
Statistical Physics 2nd ed. Course of Theoretical Physics,
Vol. 5 (Pergamon Press Ltd., 1969).

- Independent way of estimating freeze-out point/region in phase diagram
- Result consistent with the fits to particle yields



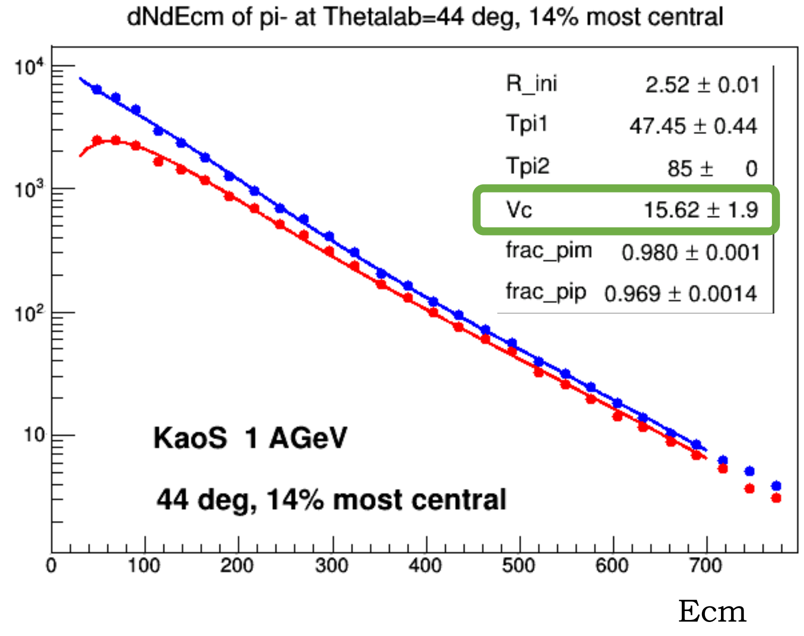
Beam energy dependence: E895 experiment at AGS



- in our fits T2 is fixed to published values
- other parameters set to be free,

data taken from : http://nuclear.ucdavis.edu/~e895/published_spectra.html

Beam energy dependence : Kaos and Fopi



Phys. Lett. B420, 20 (1998)