Spheroidal expansion and freeze-out geometry of heavy-ion collisions in the few-GeV energy regime

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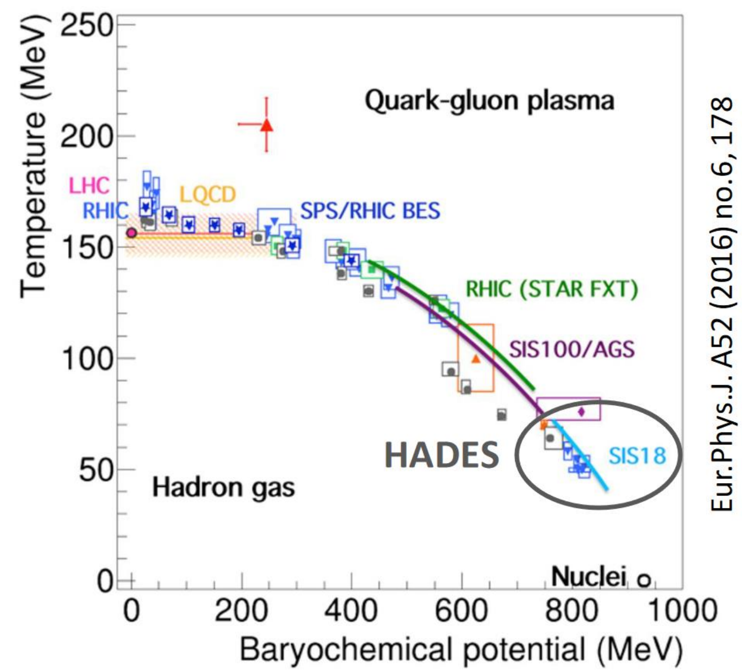
The Area of Study

- Low collision energy
- High baryochemical potential
- Experiment of choice: HADES
- System:
  - Au+Au
  - $\sqrt{s_{NN}} = 2.4$ GeV
  - 0-10% centrality



THERMal heavy-IoN generATOR 2

- SHM-based model (Cooper-Frye)
- Single freeze-out
- Decay list: standard SHARE package + excited states of nuclei
- Femtoscopic afterburner (Adam Kisiel's weights algorithm)

HADES
- Experimental particle yields

Cooper-Frye formula
- Thermodynamic paramaters

THERMINATOR 2
- Event generation

HADES
- Transverse momentum spectra

The Siemens-Rasmussen Spheroidal Model

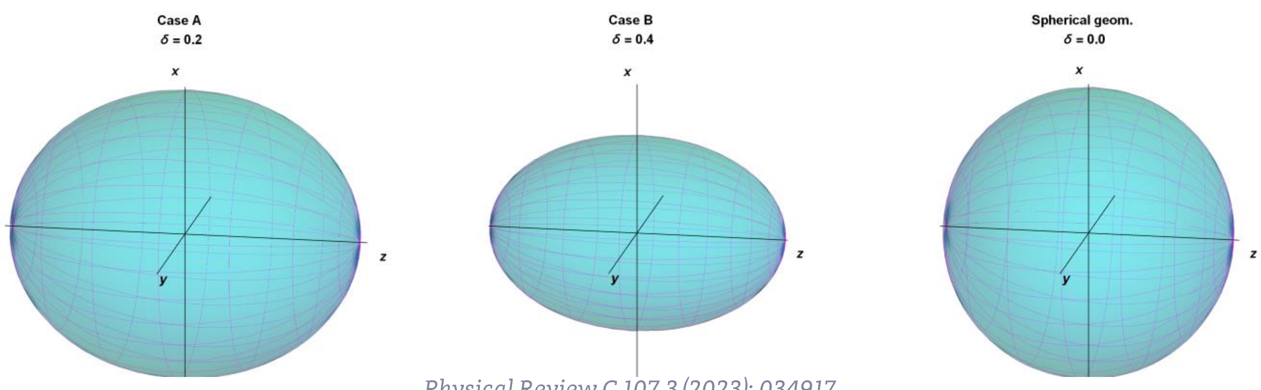
- Based on the blast wave model of Siemens and Rasmussen (*Physical Review Letters 42.14 (1979): 880*)
- Includes following changes:
  - Radial flow profile:

    $$v(r) = \tanh(\boldsymbol{H}\, r)$$

  - Spheroidal symmetry:

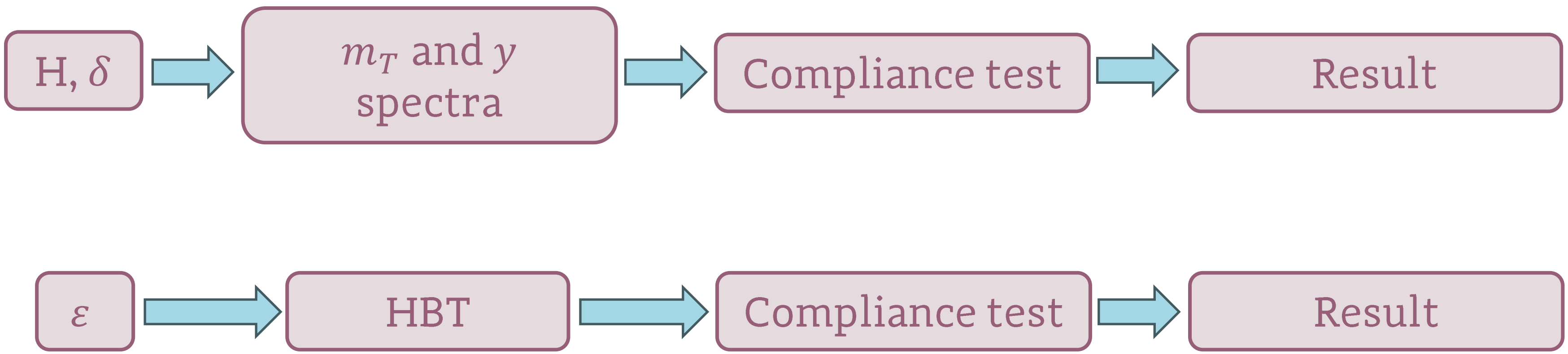
    $$x^{\mu} = \left(t, r\sqrt{1-\boldsymbol{\varepsilon}}\cos\phi\sin\theta\,, r\sqrt{1-\boldsymbol{\varepsilon}}\sin\phi\sin\theta\,, r\sqrt{1+\boldsymbol{\varepsilon}}\cos\theta\right)$$

    $$u^{\mu} = \gamma(\xi)(t, v(\xi)\sqrt{1-\boldsymbol{\delta}}\cos\phi\sin\theta\,, v(\xi)\sqrt{1-\boldsymbol{\delta}}\sin\phi\sin\theta\,, v(\xi)\sqrt{1+\boldsymbol{\delta}}\cos\theta)$$



Physical Review C 107.3 (2023): 034917

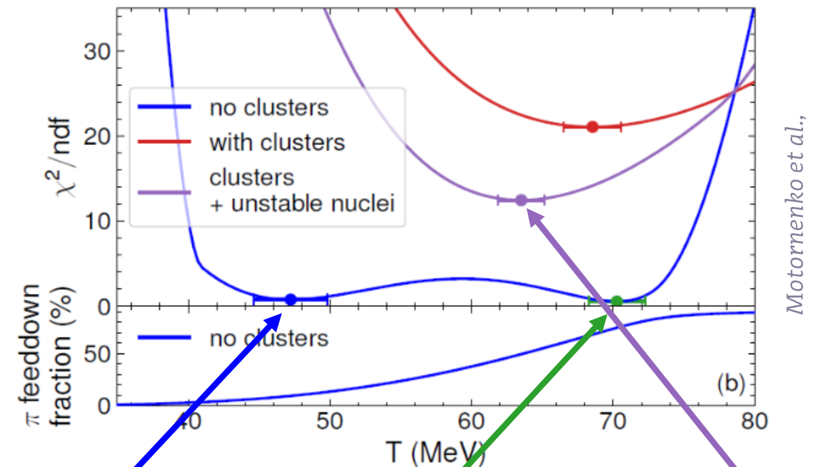
„Kinematic" Parameters Estimation



Compliance test ⟷ $$Q^2 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{\left(Y_{i,model} - Y_{i,exp}\right)^2}{{Y_{i,exp}}^2}}$$

Thermodynamic Landscape of HADES

- Our model was tested with results from *Motornenko et al.*
- Later denoted as:
  - Case A
  - Case B
  - Case C
- Different approach to light nuclei production:
  - Cases A and B – coalescence
  - Case C - thermal



Parameter	Harabasz *et al.* [1]	no clusters low T minimum	no clusters high T minimum	with clusters	with clusters + unstable nuclei
T (MeV)	49.6 ± 1.1	47.2 ± 2.6	70.3 ± 2.0	68.6 ± 2.0	63.5 ± 1.6
R (fm)	16.0	18.9 ± 2.2	6.8 ± 0.9	[illegible]	10.4 ± 0.3
μ_B (MeV)	776 ± 3	780.1 ± 3.8	872.1 ± 24.3	786.7 ± 2.9	781.1 ± 3.3
γ_S	0.16 ± 0.02	0.19 ± 0.07	0.05 ± 0.01	0.03 ± 0.01	0.04 ± 0.01
χ^2/N_{df}	$N_{df} = 0$	1.58/2	1.13/2	105.30/5	62.30/5

Motornenko et al., Physics Letters B 822 (2021): 136703

Spherical vs Spheroidal

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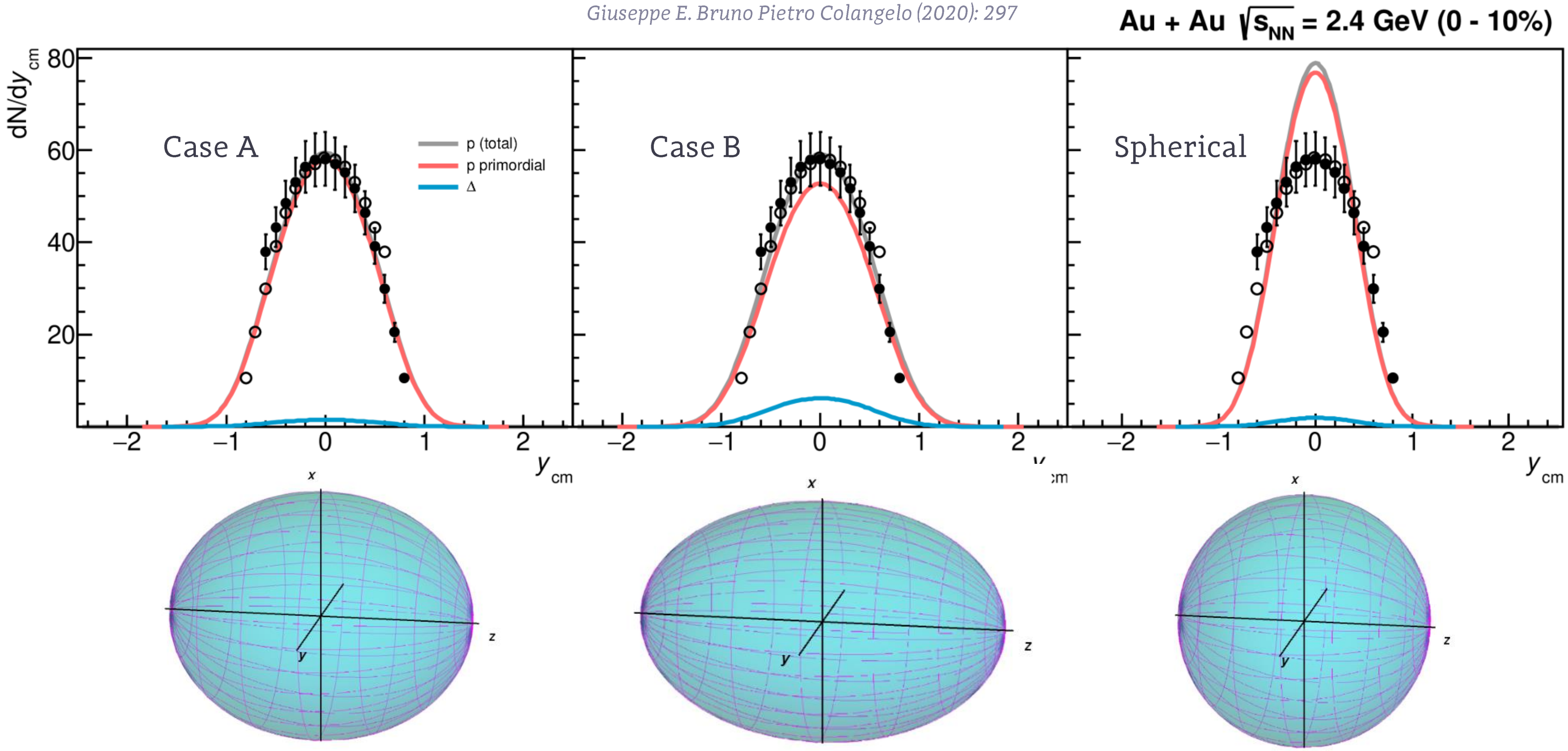
Rapidity Distribution (proton)

Physical Review C 107.3 (2023): 034917
Szala, Melanie. "Proton and Light Nuclei from Au+ Au Collisions at." Domenico Elia Giuseppe E. Bruno Pietro Colangelo (2020): 297



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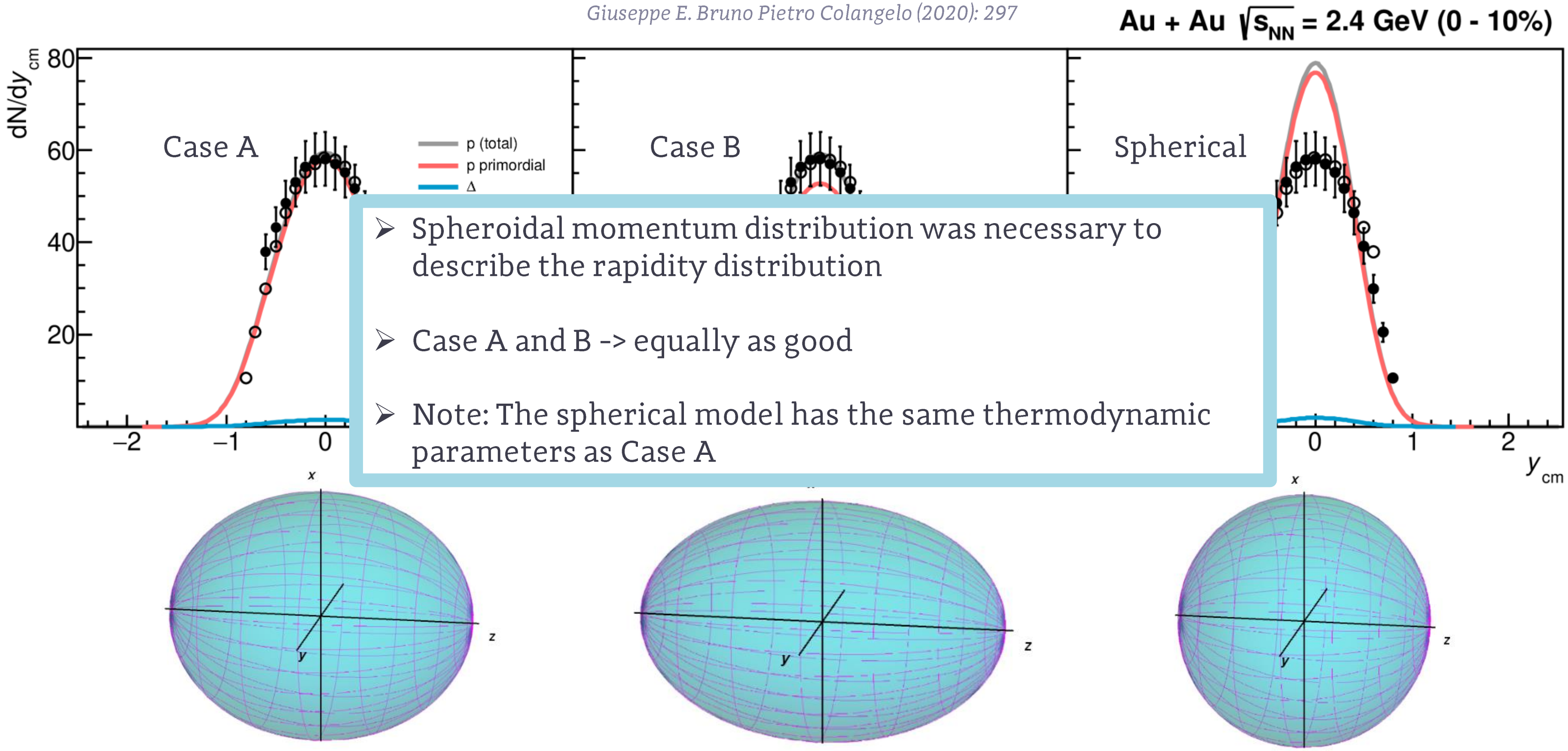

- ➢ Spheroidal momentum distribution was necessary to describe the rapidity distribution
- ➢ Case A and B -> equally as good
- ➢ Note: The spherical model has the same thermodynamic parameters as Case A

Transverse Momentum Spectra (proton)

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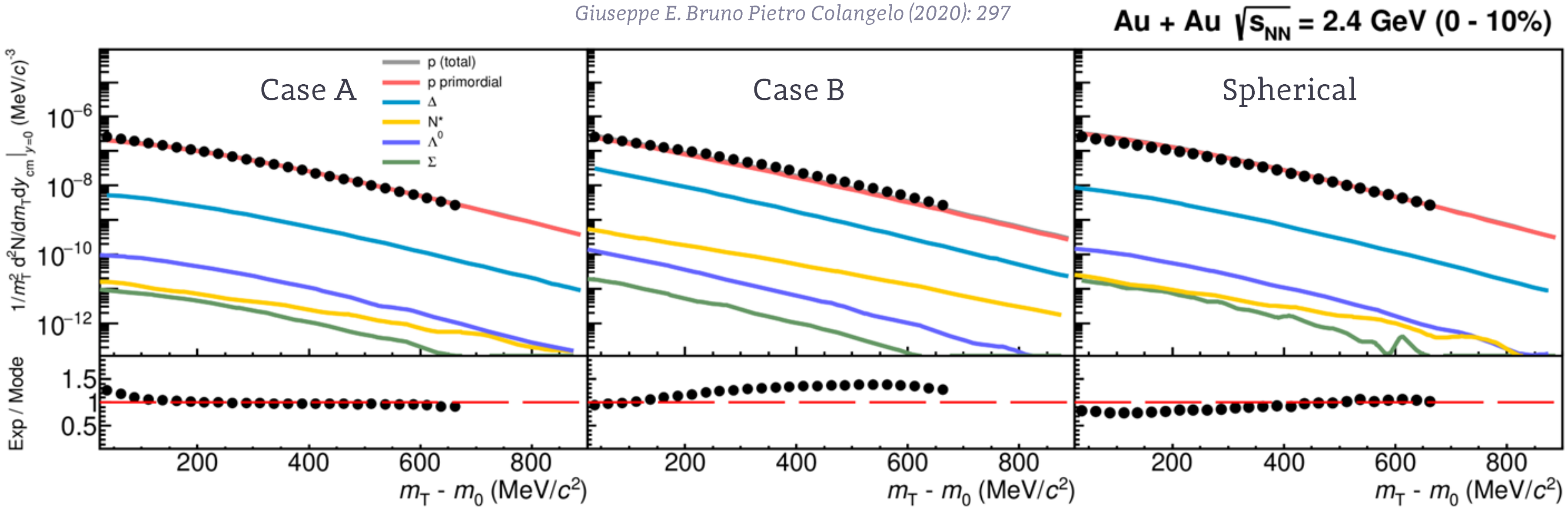
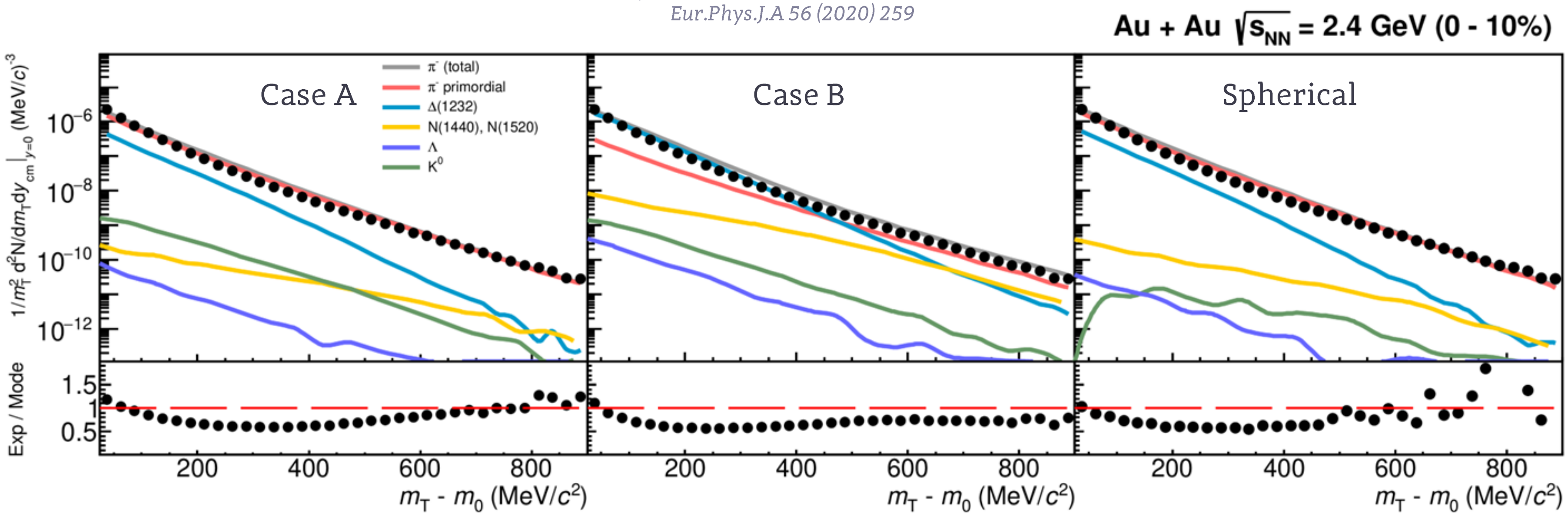


- Similarly good agreement
- Thermal protons -> dominant contribution
- Spherical is just as good as spheroidal -> no noticeable difference without looking at the rapidity

Transverse Momentum Spectra (negative pion)

Physical Review C 107.3 (2023): 034917
Eur.Phys.J.A 56 (2020) 259



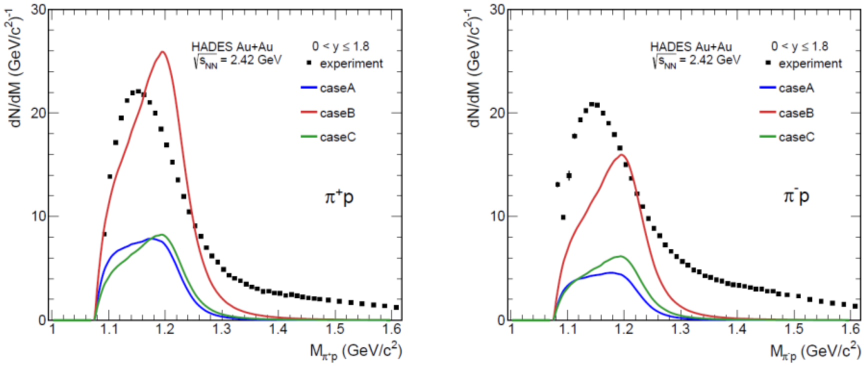
- Similarly good agreement
- Case B shows a „double slope" (Δ(1232) + primordial decay)
- Δ(1232) decay becomes a dominant contribution below 500 MeV for Case B
- Coulomb effect is visible (< 100 MeV)

Coalescence vs Thermal

The Delta(1232) and Other Resonances

- Originally, resonance mass = fixed PDG value
- Idea: use finite width for all resonances
- For Δ(1232), derivative of the scattering phase shift was used (Phys. Rev. C 96, 015207 (2017))
- For other resonances, Breit-Wigner parametrisation with mass-dependent width was used (*arXiv:0708.2382* (2007))

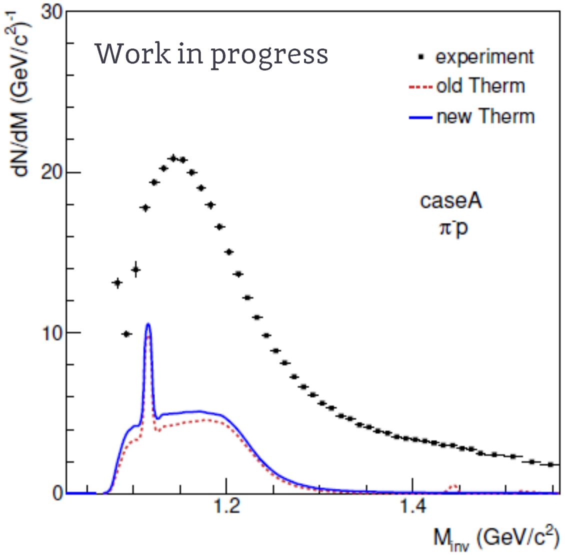
True MC Δ(1232) vs correlated pairs of protons and pions:



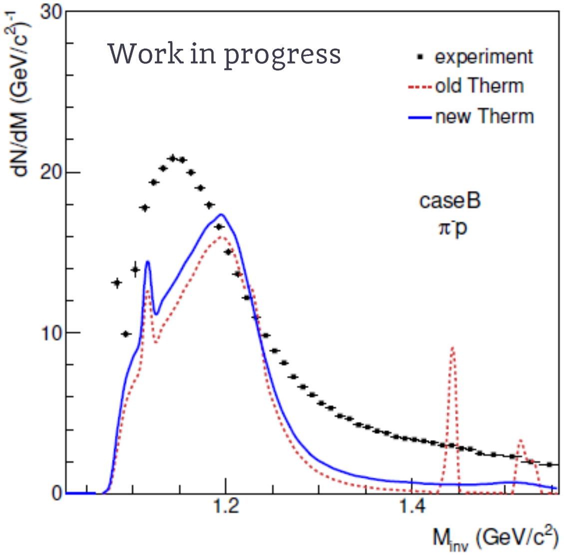
M. Kurach „Phase-space distributions of Delta resonances reconstructed from Therminator events ”, Get_Involved internship

The Delta(1232) and Other Resonances

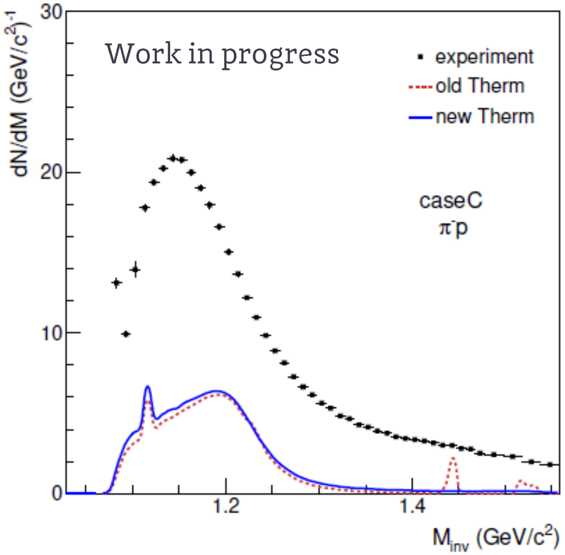
M. Kurach „Study of resonance production Au+Au collisions at HADES with Therminator ", Get_Involved internship



(a) Case A.



(b) Case B.



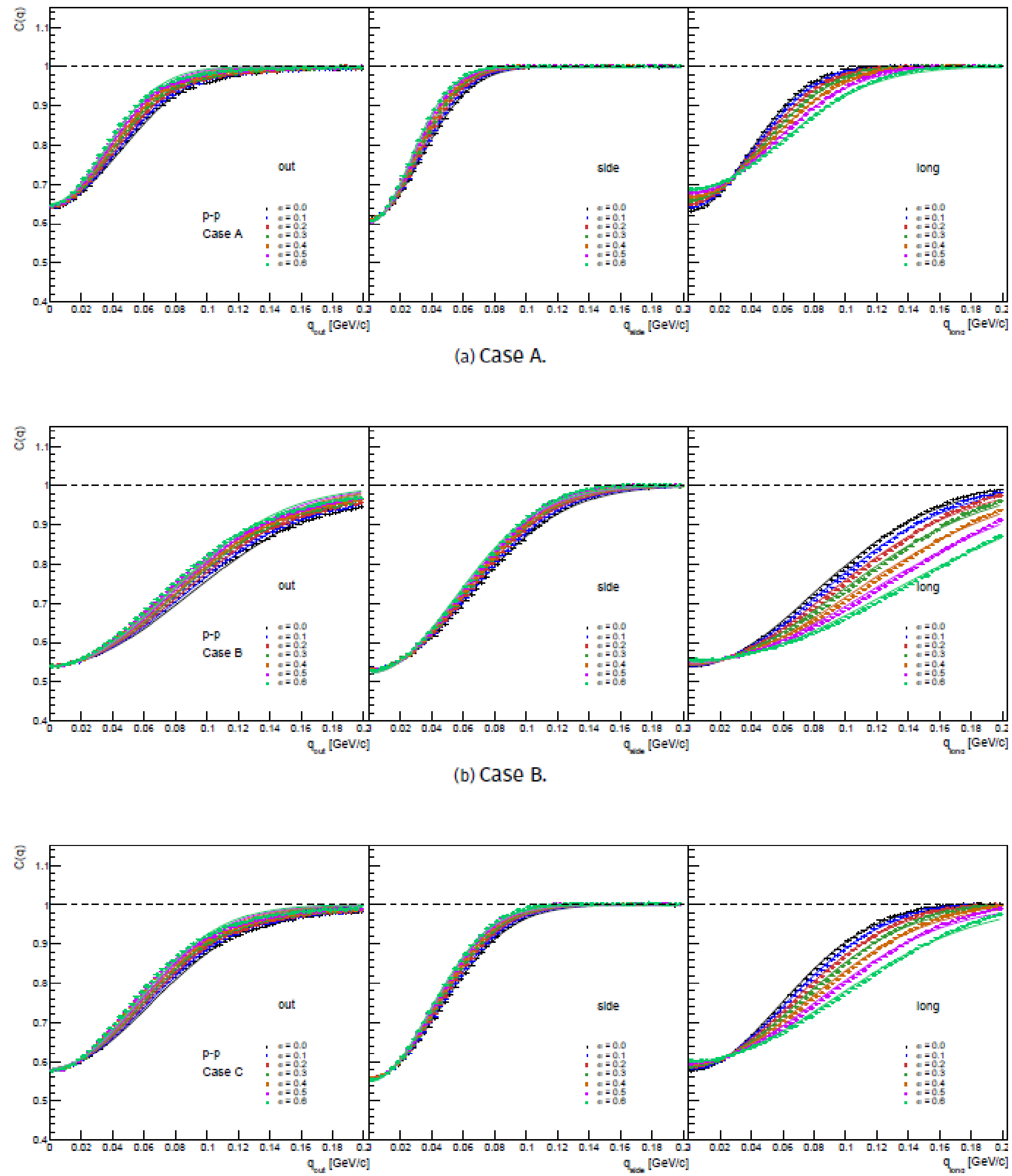
(c) Case C.

- Smeared peaks of heavy resonances
- Work in progress

Position Deformation Sensitivity of Correlation Functions

- No final-state interactions included
- Long direction -> the most sensitive to the eccentricity parameter
- Negligible sensitivity of H and δ

M. Kurach, Eng. Thesis (2022), Faculty of Physics, WUT



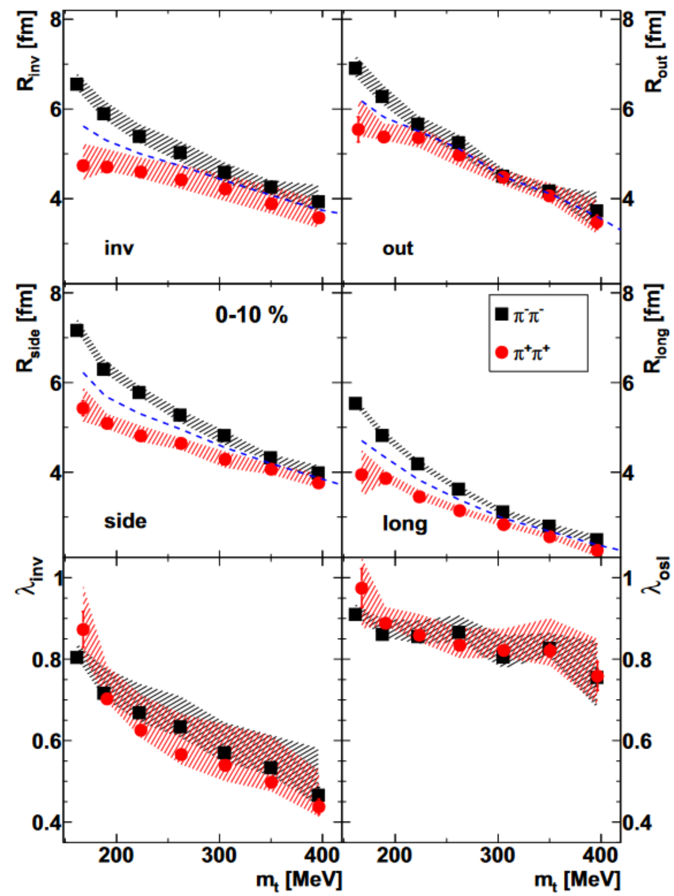
(a) Case A.

(b) Case B.

(c) Case C.

Pion HBT @ HADES

- Original work from R. Griefenhagen, PhD Thesis (2020), Dresen Technical University, published in Eur.Phys.J.A 56 (2020) 4, 140 and Phys.Lett.B 795 (2019) 446-451
- Noticeable radii separation at low mT -> Coulomb effect
- Pion correlation -> „simplest” of correlations -> best for my study



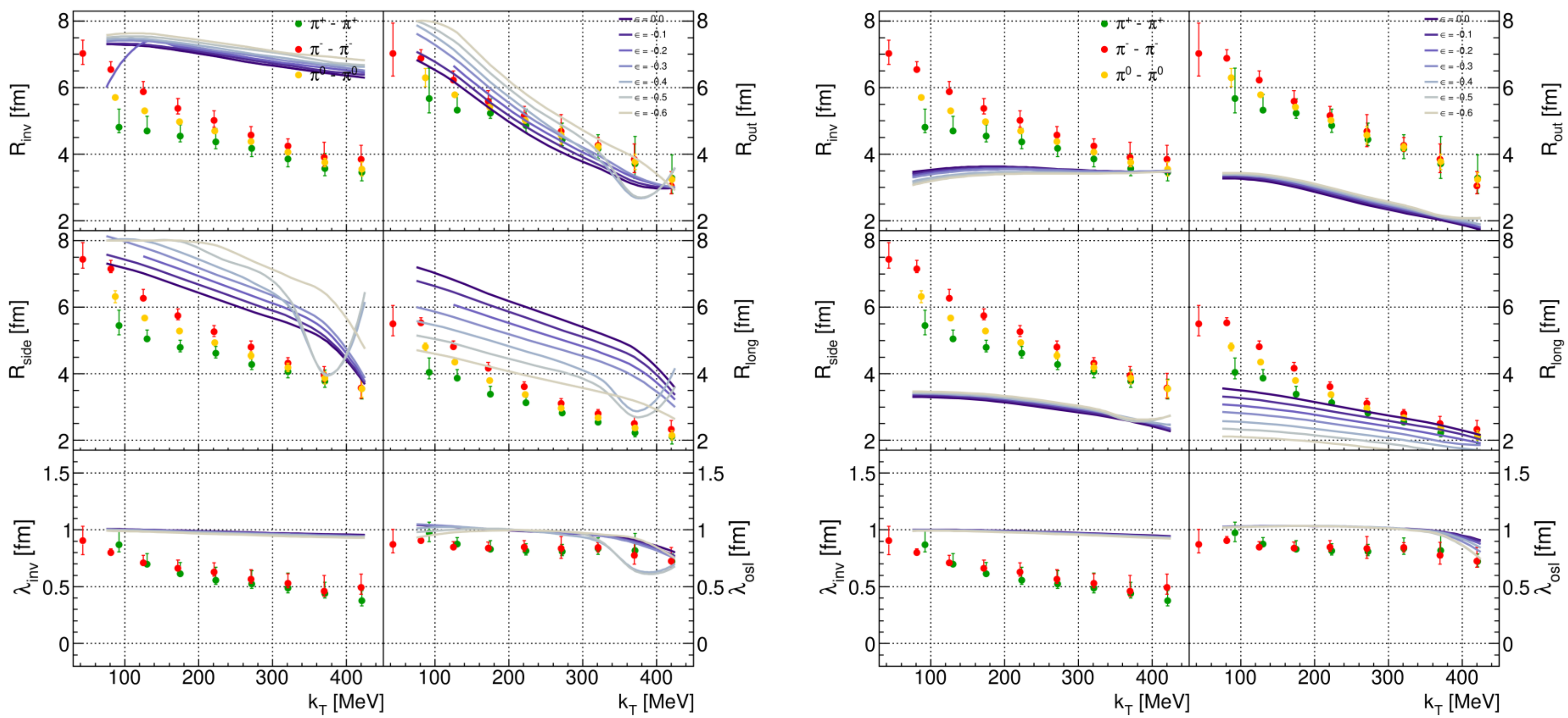
Eur.Phys.J.A 56 (2020) 5, 140
Phys.Lett.B 795 (2019) 446-451

Femtoscopy in Coalescence Approach

J. Kołaś, MSc Thesis (2022), Faculty of Physics, WUT
Eur.Phys.J.A 56 (2020) 5, 140
Phys.Lett.B 795 (2019) 446-451

Case A

Case B



Femtoscopy in Coalescence Approach

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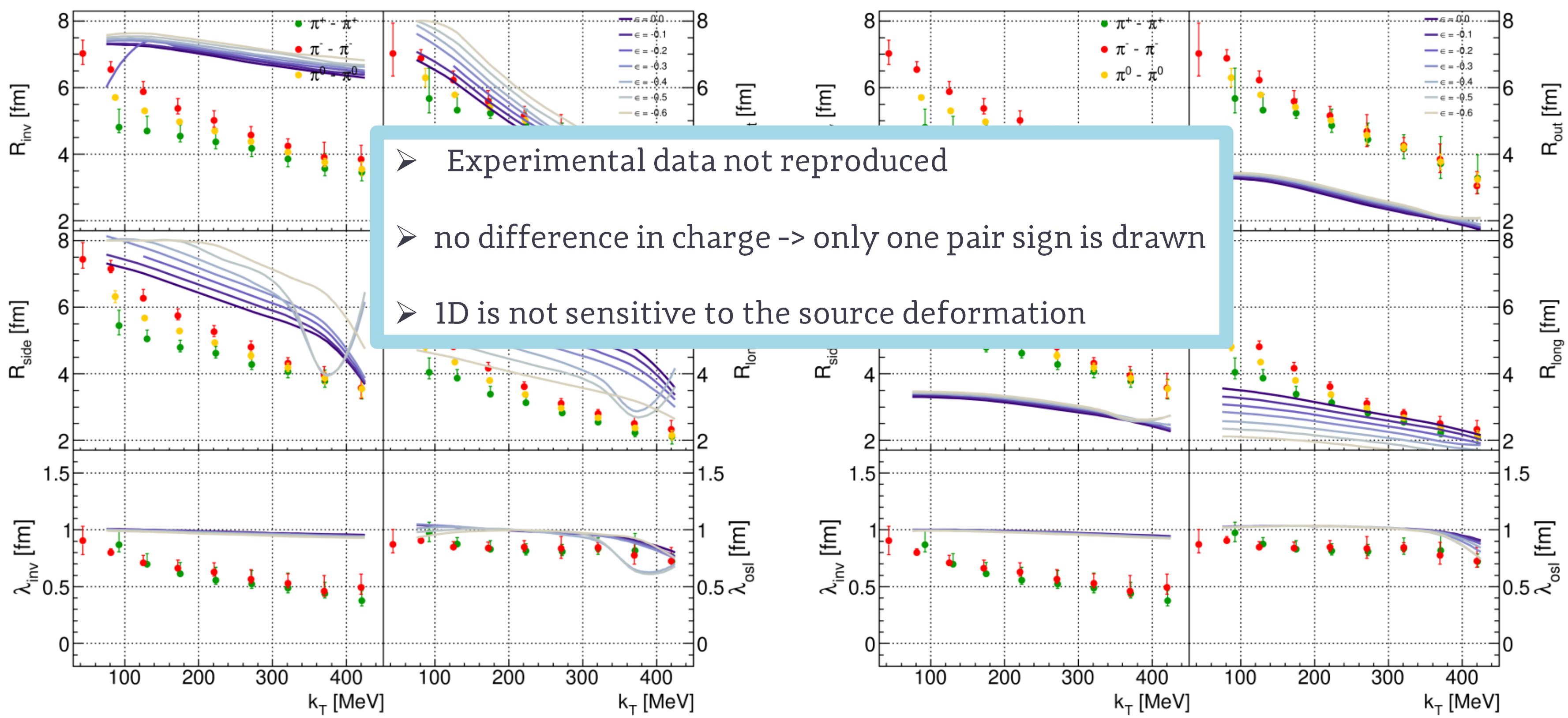
Case A

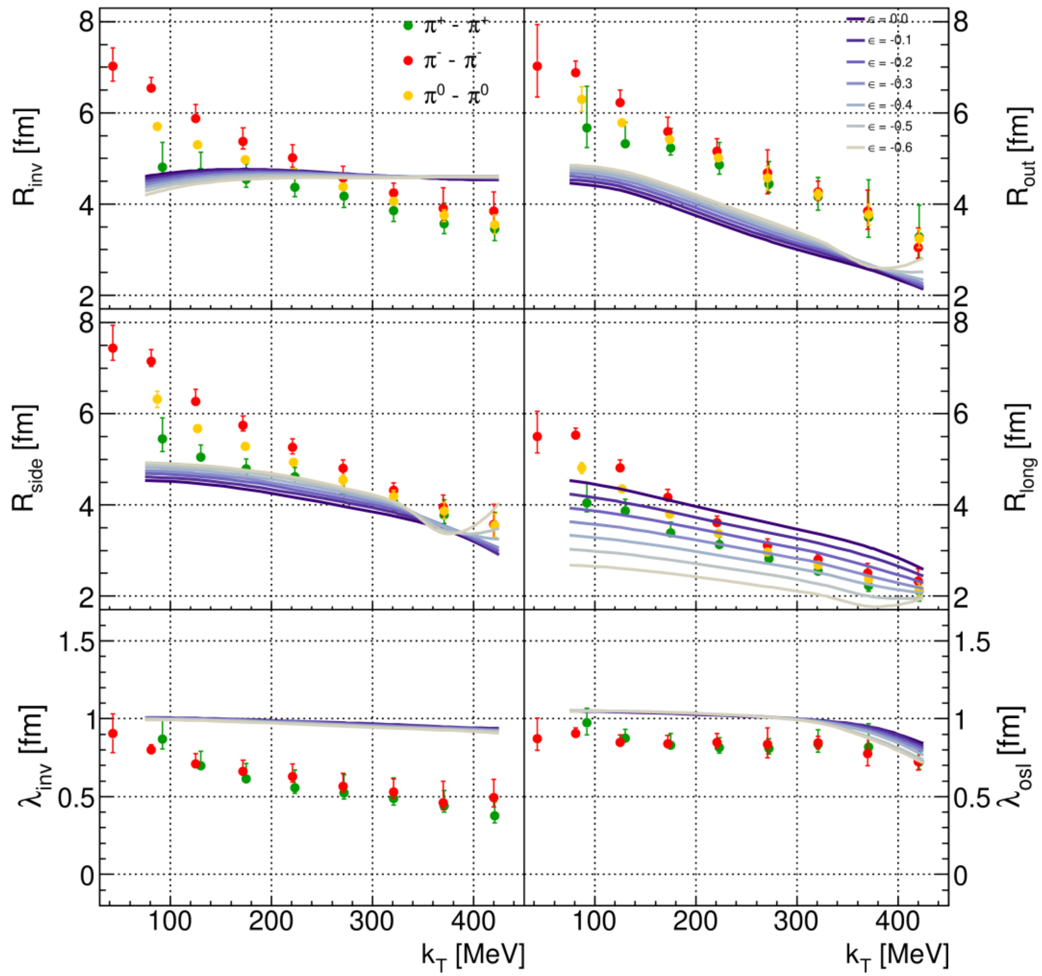
Case B



- Experimental data not reproduced
- no difference in charge -> only one pair sign is drawn
- 1D is not sensitive to the source deformation

Femtoscopy in Thermal Approach

- Closest reproduction (of all three) of the invariant radius
- Strong position eccentricity dependence in the *long* direction
- Simple afterburner, only QS included



J. Kołaś, MSc Thesis (2022), Faculty of Physics, WUT
Eur.Phys.J.A 56 (2020) 5, 140
Phys.Lett.B 795 (2019) 446-451

Summary

Spherical vs Spheroidal

- The spheroidal model is necessary to reproduce spectra
- It works well for abundant particles (protons and charged pions)

Coalescence vs Thermal

- Resonances play a significant role (for momentum distribution)
- R_{inv} and R_{long} HBT radii are best reproduced in the thermal approach (Case C)
- Proton and pion m_T and y spectra are well reproduced by both Case A and Case B
- Delta resonance favours Case B

Thank You For Your Attention

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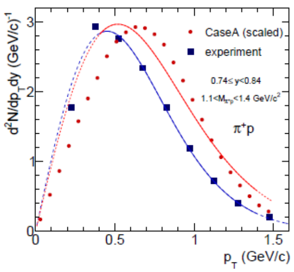
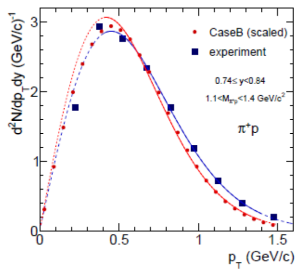
Backup

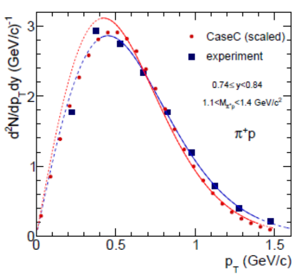
The Delta(1232) and Other Resonances



(a) Case A.



(b) Case B.



(c) Case C.

Case A is not as good...