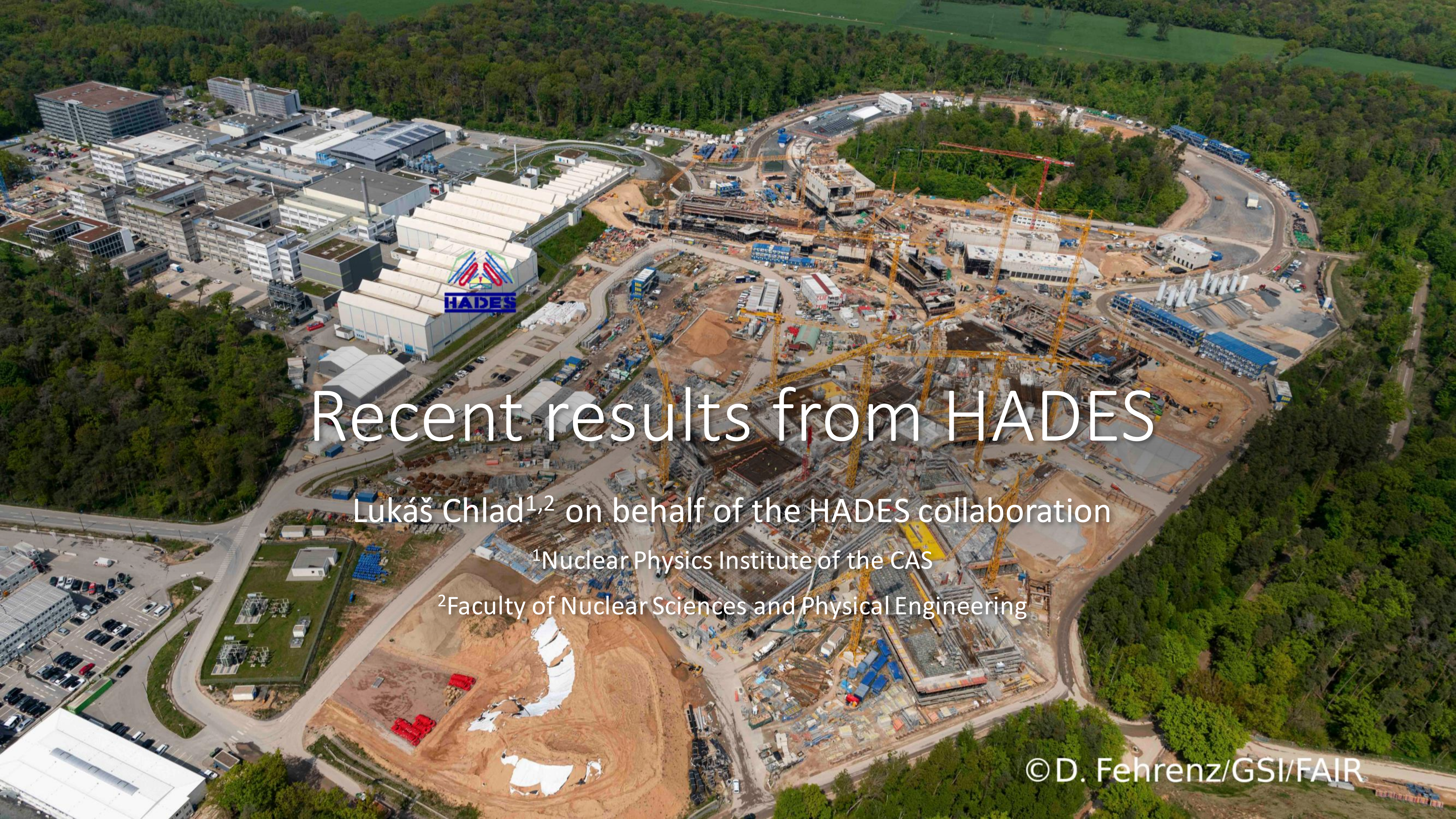
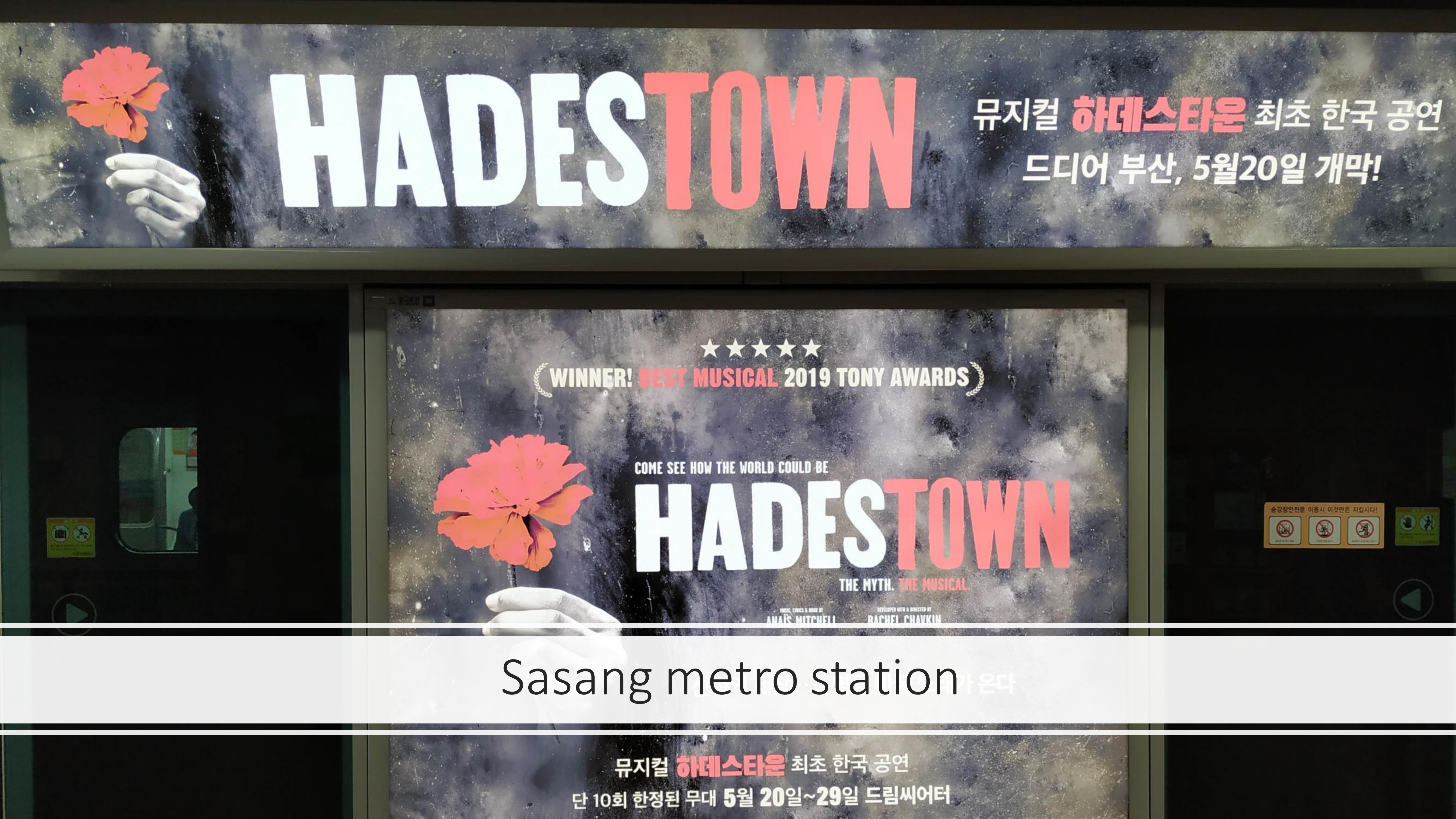
Recent results from HADES

Lukáš Chlad[1,2] on behalf of the HADES collaboration

[1]Nuclear Physics Institute of the CAS

[2]Faculty of Nuclear Sciences and Physical Engineering

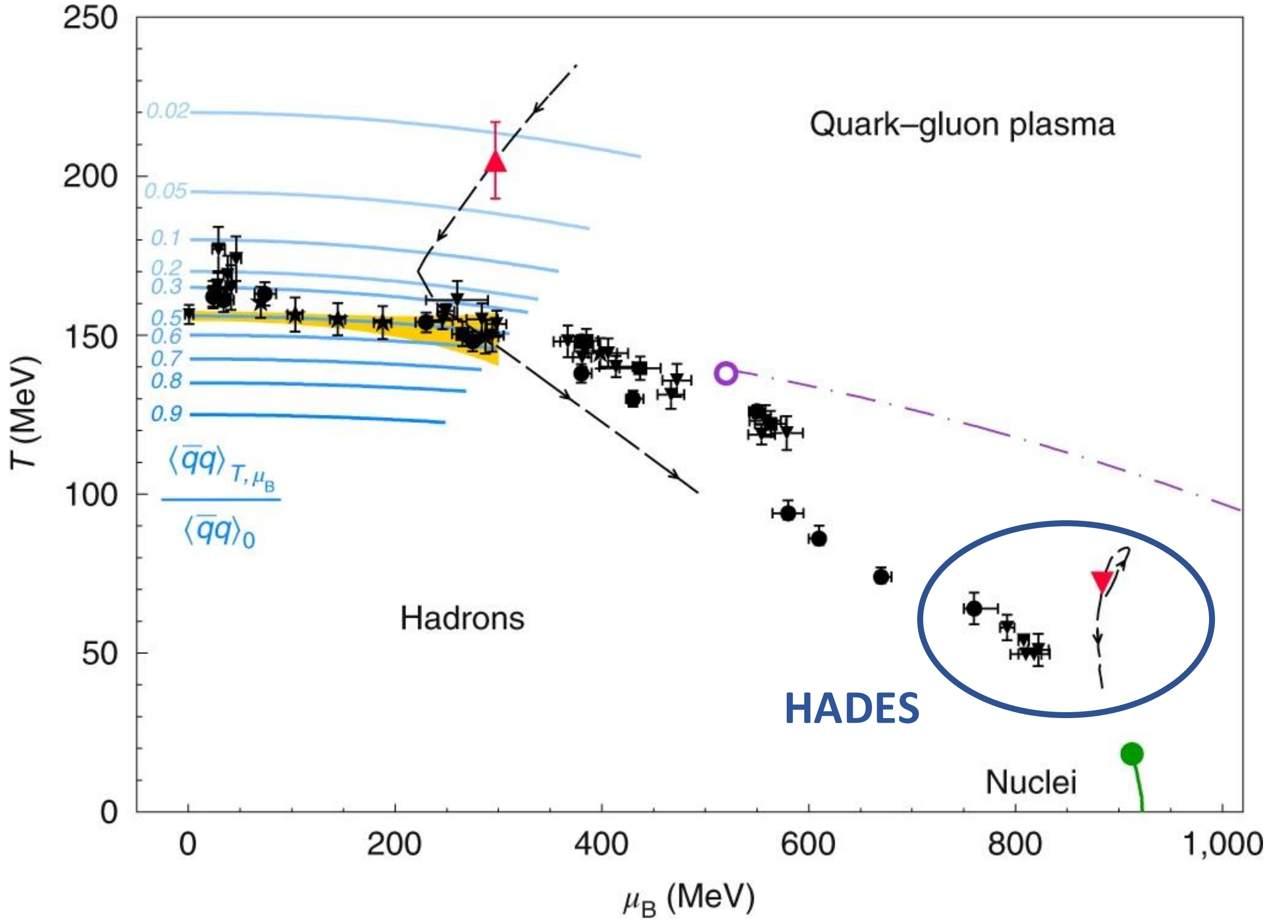




Sasang metro station

Central heavy-ion collisions at SIS18

- High μ_B and moderate T
- System under study:
  - Free nucleons ~ 200
  - Bound nucleons ~ 100
  - Pions ~ 50
  - K^+ ~ 10^{-2}
  - K^- ~ 10^{-4}

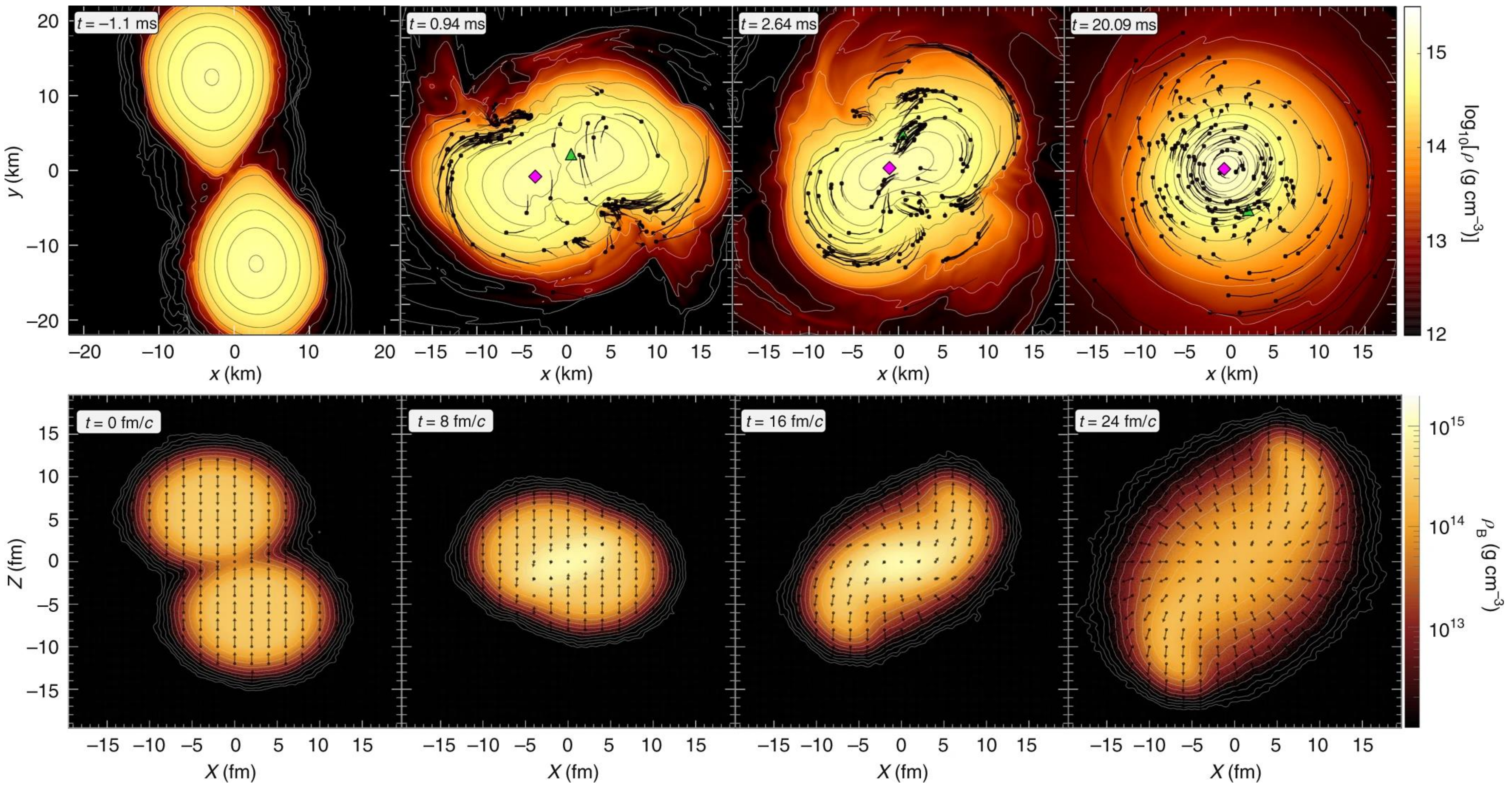


Nature Phys. 15, 1040-1045 (2019)

Link to astrophysical observations

Merging Neutron Stars

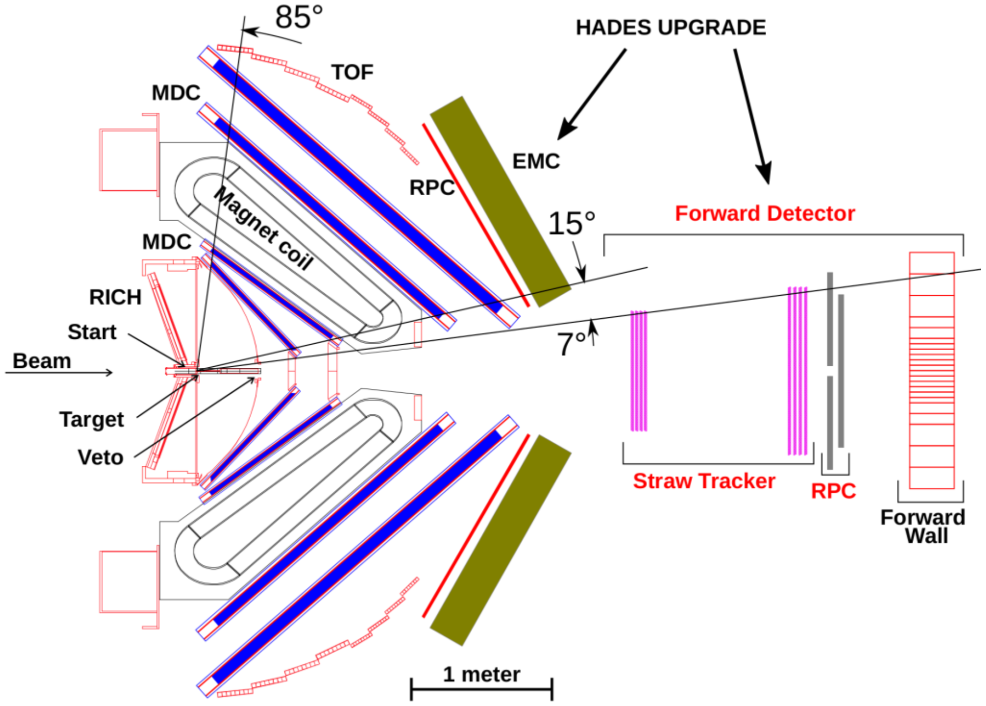
UrQMD Au+Au $\sqrt{s_{NN}}$ =2.4 GeV



Nature Phys. 15, 1040-1045 (2019)

High Acceptance Di-Electron Spectrometer

- fixed target – pion/proton/deuteron/nuclei induced collisions on p/A targets
- large acceptance – full azimuthal and large polar angle acc.
- high rate capability – A+A up to 16kHz, p+p up to 40kHz

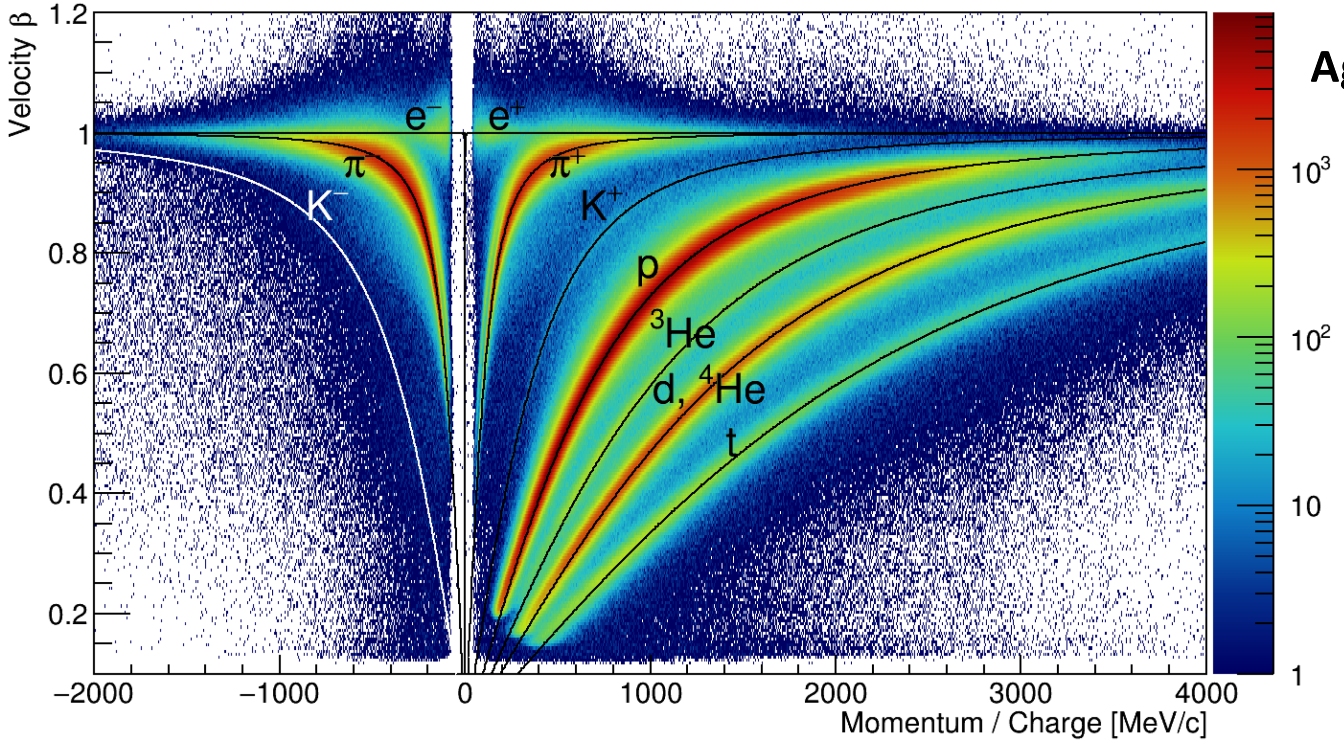


Experiments

- 2002 – 2008
  Light collision systems (p+p, d+p, p+Nb, Ar+KCl)
- 2012 – 2015
  Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV 7x10^9 events (April 2012)
  π-induced reactions 1.5x10^9 events (summer 2014)
- since 2019 as FAIR Phase-0
  Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV 14x10^9 events (March 2019)
  p+p at $\sqrt{s_{NN}}$ = 3.46 GeV 40x10^9 events (February 2022)

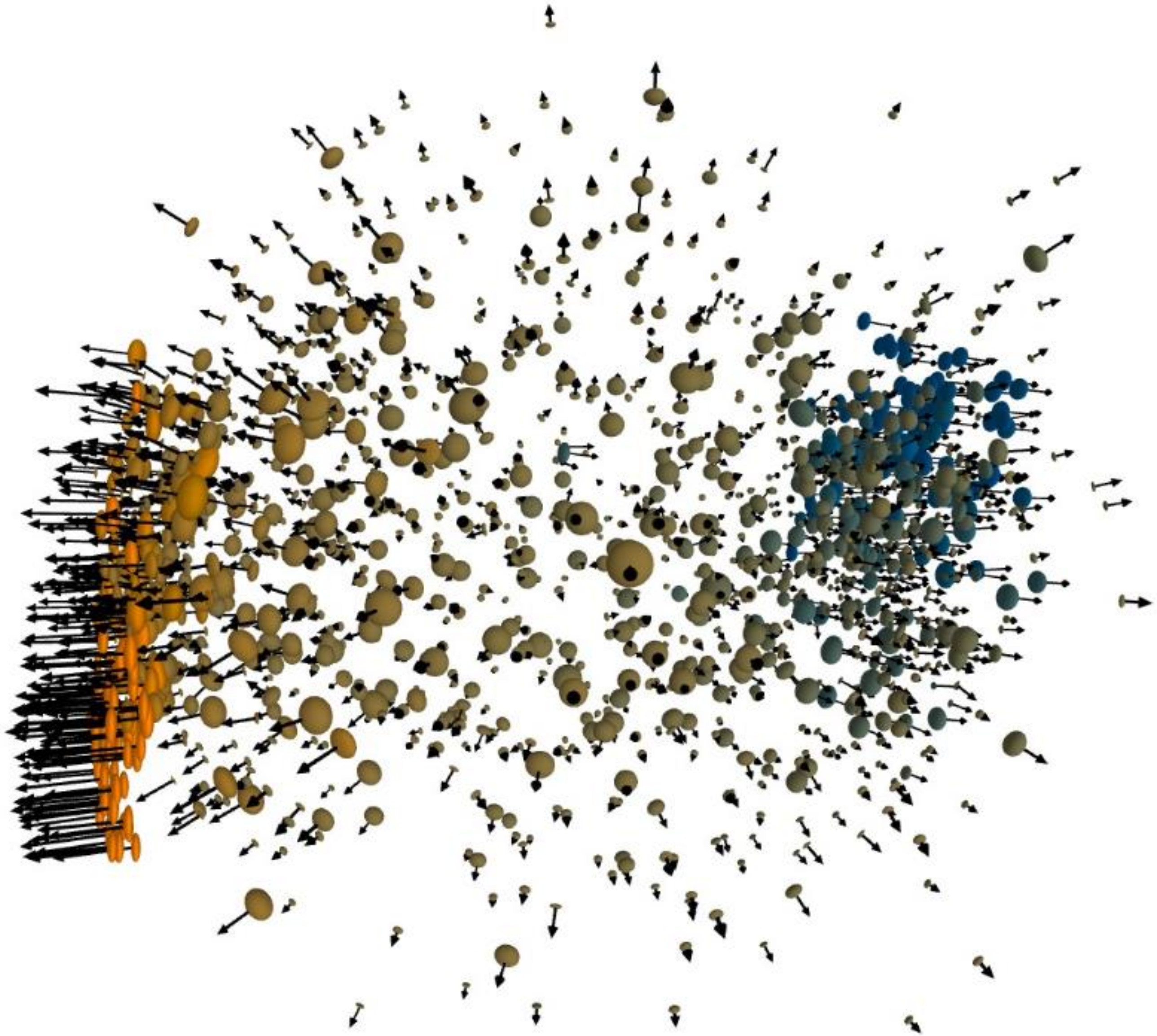
Observables at baryon dominated hot and dense matter

- Bulk observables – protons (many bound in light nuclei), pions (N_p/N_π ~ 10)
- Virtual photons – vector meson spectral function modification
- Strange hadrons – subthreshold production effects



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

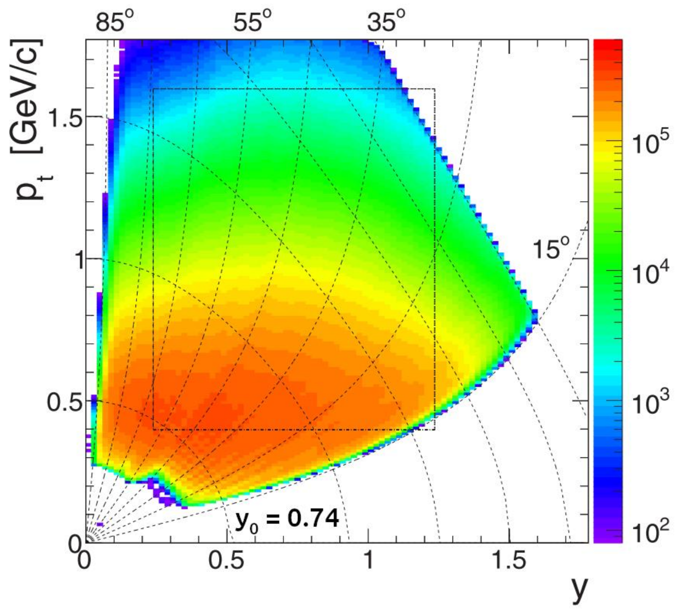
Bulk



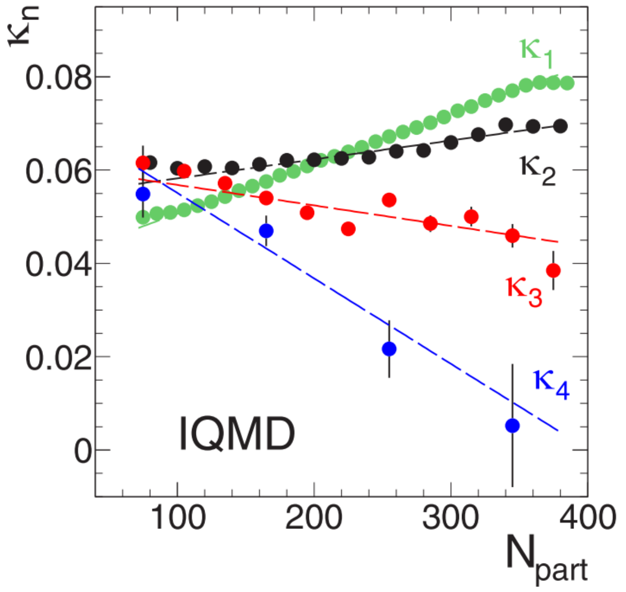
Proton-number fluctuations

Phys. Rev. C 102, 024914 (2020)

- Proton dominated at SIS18 energies
- Very large coverage by HADES
- Background effects – event-wise, track-wise
- Detection efficiency – phase-space & occupancy dependent
- Centrality selection & Volume fluctuation corrections



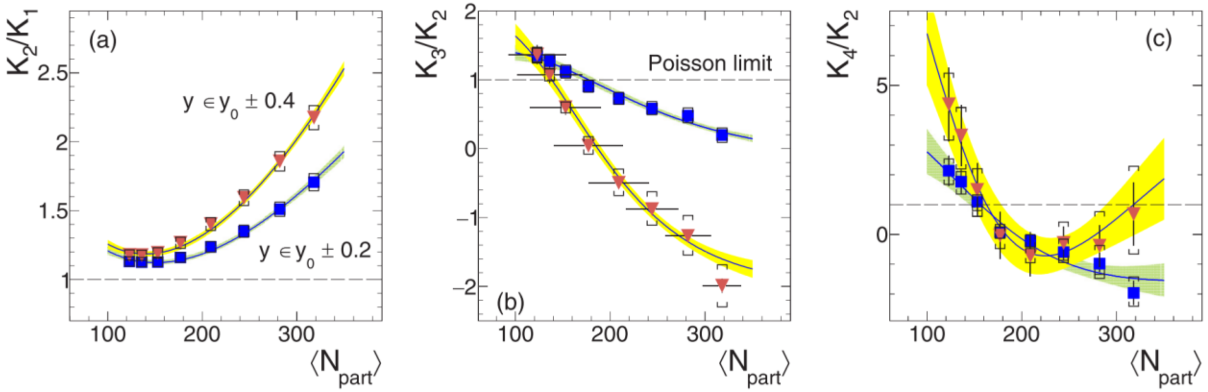
Nuisance effect	Relative contribution
Event pileup	$\leqslant 3 \times 10^{-5}$
Au+C reactions	$\leqslant 2.5 \times 10^{-5}$
PID impurities	$\leqslant 10^{-3}$
Knockout reactions	$\leqslant 3 \times 10^{-3}$
Hyperon decays	$\leqslant 6.5 \times 10^{-4}$
Antiprotons (model fit)	$\simeq 2 \times 10^{-8}$/evt



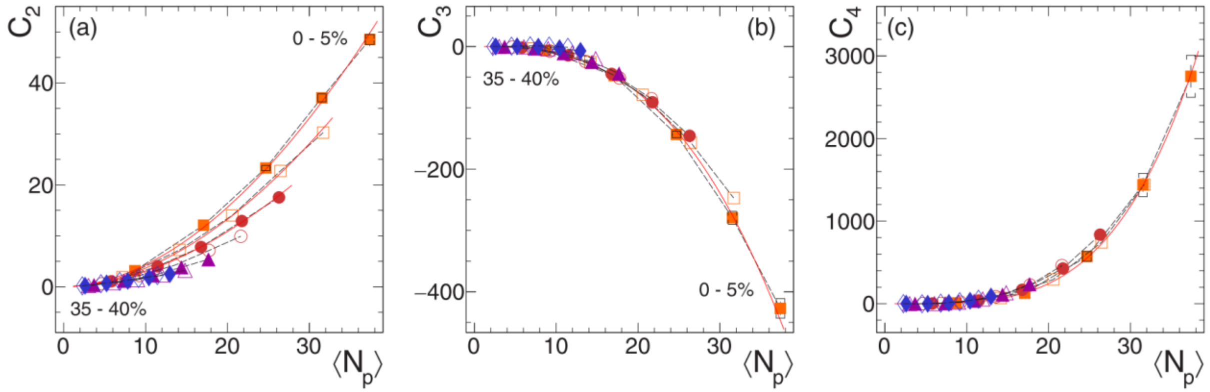
Proton-number fluctuations

Phys. Rev. C 102, 024914 (2020)

- Proton-number cumulants ratios compared for 2 rapidity width and Poisson limit



- *n*-particle correlators fitted with power-law $C_n(N)=C_0N^{\alpha}$ suggest a dominant long-range correlations (α~n)

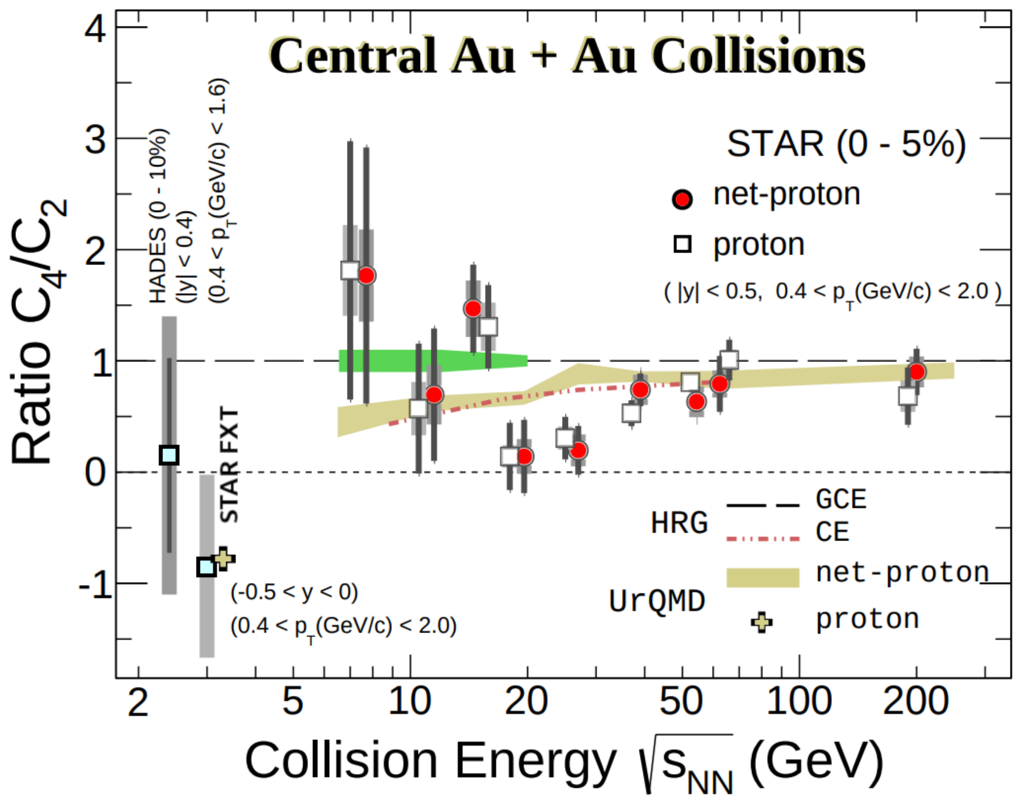


Δy = 0.1, 0.2, .., 0.5

Proton-number fluctuations

Phys. Rev. C 102, 024914 (2020) & arXiv:2112.00240v3 [nucl-ex]

- Collision energy dependence of $C_4/C_2 = \kappa\sigma^2$ - interesting for potential critical end point search



Charged pions – Coulomb effect

arXiv:2202.12750v2 [nucl-ex]

- Positive charge of fireball => influence kinetic energy of different charges (long range effect!)
- Faster particles do not contribute, assuming common freeze-out of pions => effective potential $V_C\left(\mathrm{erf}(x) - (2/\sqrt{\pi})\,x\,e^{-x^2}\right)$ where $x = \sqrt{(E_\pi/m_\pi - 1)\,m_p/T_p}$
- Two contributions in differential yield (Δ decay vs. thermal/broad resonances, details in EPJA 56, 259 (2020))

$$J = \frac{E_i\,p_i}{E_f\,p_f} = \frac{(E_f \mp V_{\mathrm{eff}})\sqrt{(E_f \mp V_{\mathrm{eff}})^2 - m_\pi^2}}{E_f\sqrt{E_f^2 - m_\pi^2}}$$

$$\frac{d^2N^\pm}{dm_t dy} = A\,m_t^2\left(f\,e^{-(E_f \mp V_{\mathrm{eff}})/T_1} + (1-f)\,e^{-(E_f \mp V_{\mathrm{eff}})/T_2}\right) \times J \times J_{\mathrm{eff}}$$

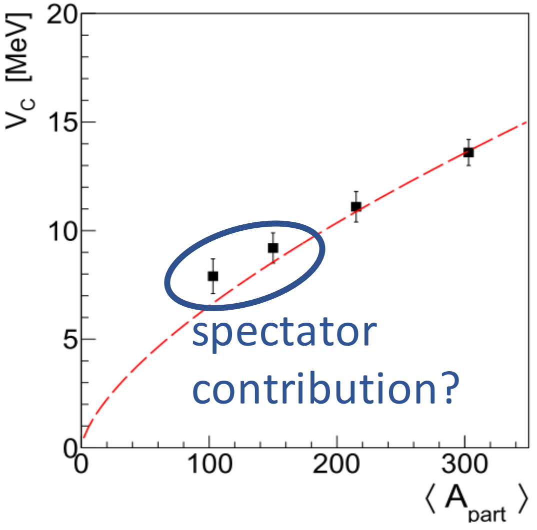
NEW term

$$1 \mp \frac{2}{\sqrt{\pi}}\,\frac{V_C\,m_p}{m_\pi\,T_p}\,x\,e^{-x^2}$$

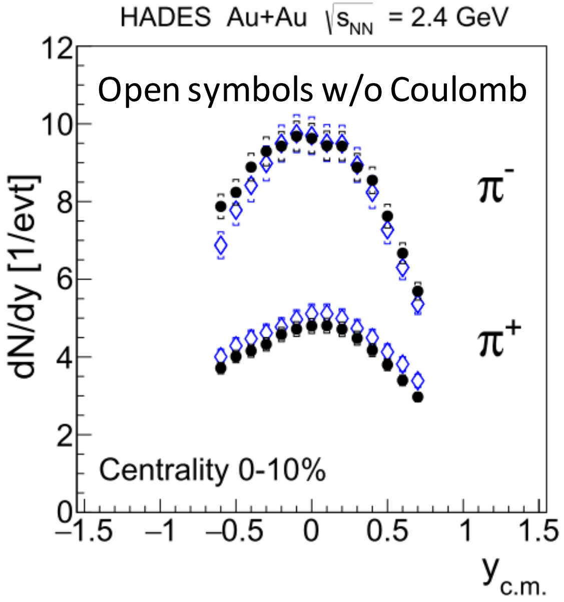
Charged pions – Coulomb effect

arXiv:2202.12750v2 [nucl-ex]

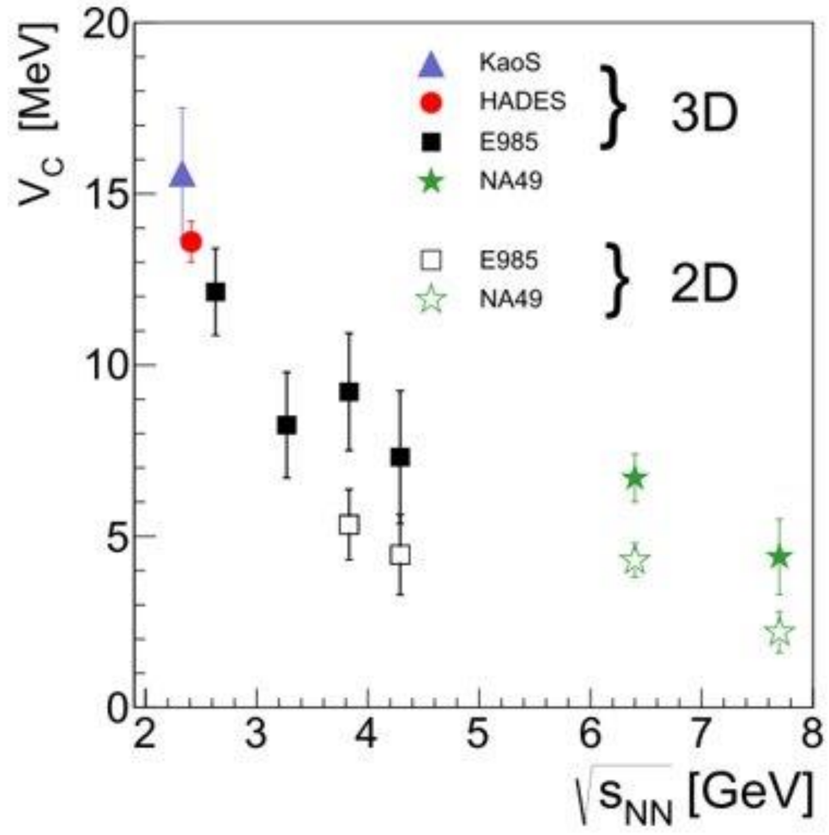
- Centrality dependence for mid-rapidity region ($|y_{c.m.}| < 0.05$)



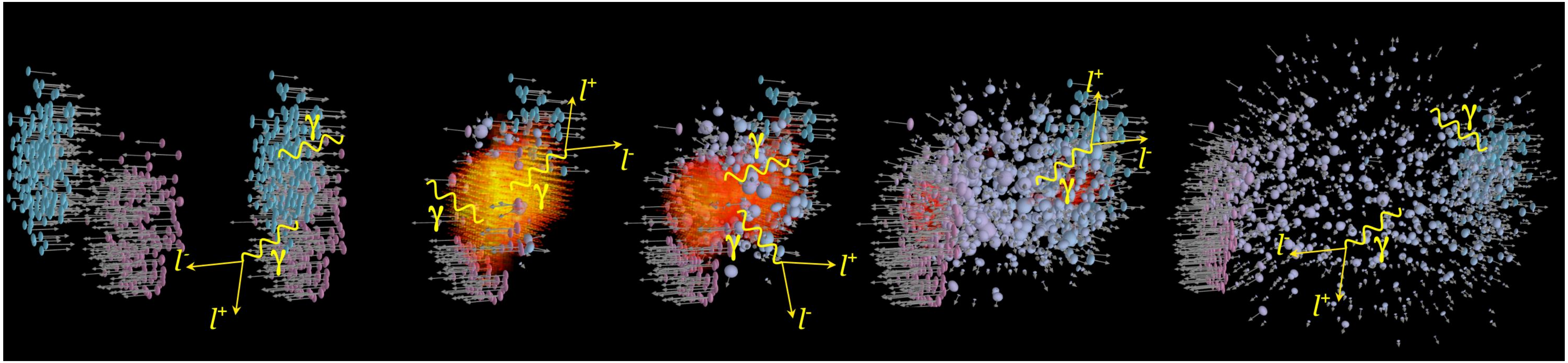
- Rapidity dependence for central collisions (0-10%)



- Energy dependence

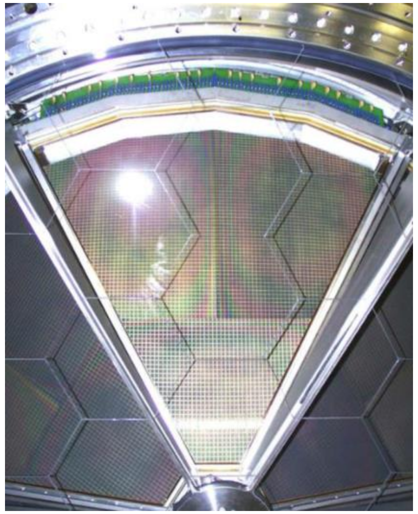


Virtual photons

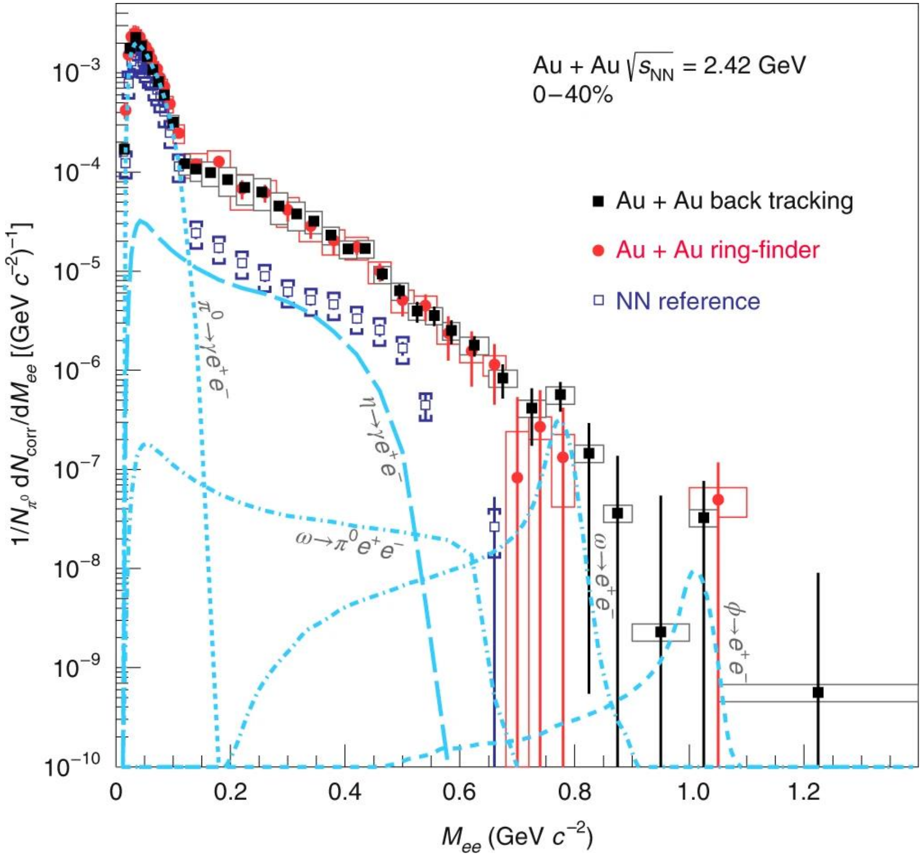


Heavy-ion collisions

Nature Phys. 15, 1040-1045 (2019)

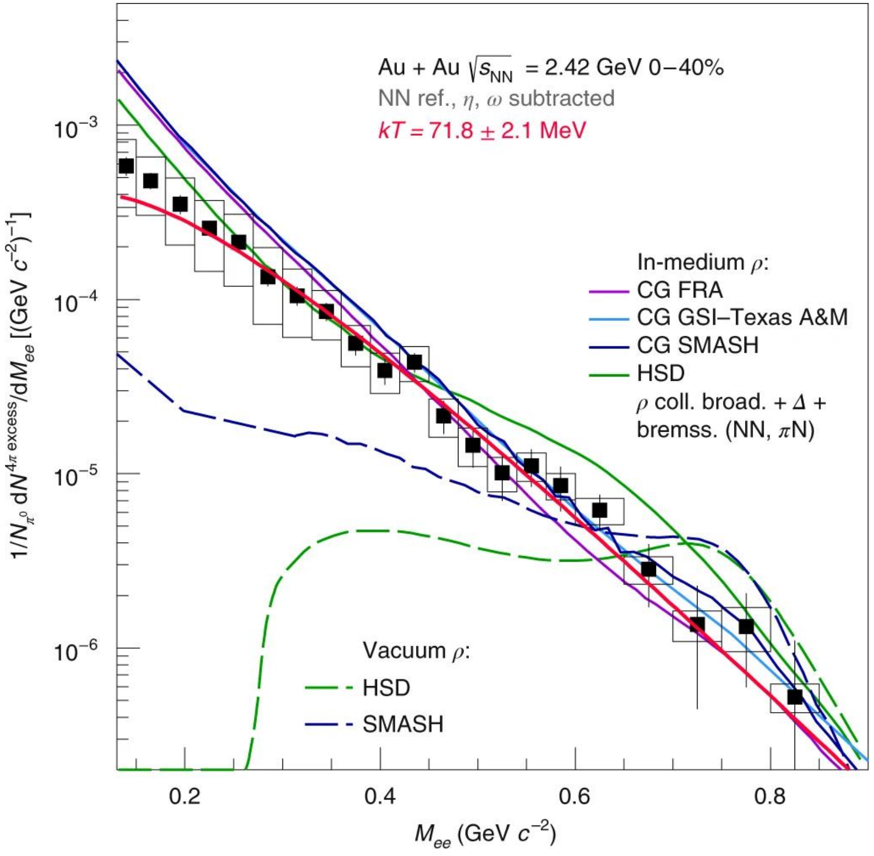


- $e^{\pm}$ mostly via RICH detector (original photon detector ~ 5000 pads)

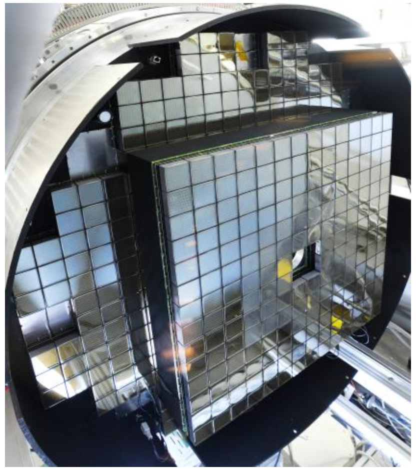


subtract measured NN ref. and simulated η, ω contributions

$$dN/dM_{ee} \propto (M_{ee})^{3/2} \exp(-M_{ee}/T)$$



Medium heavy-ion collisions

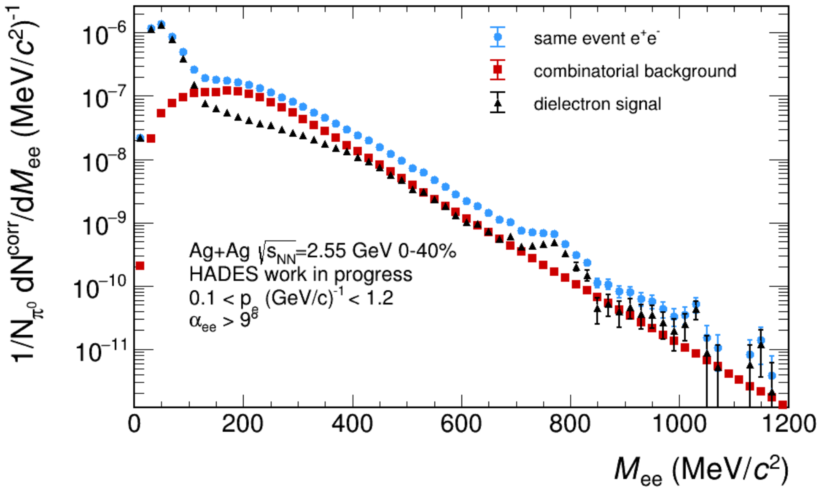


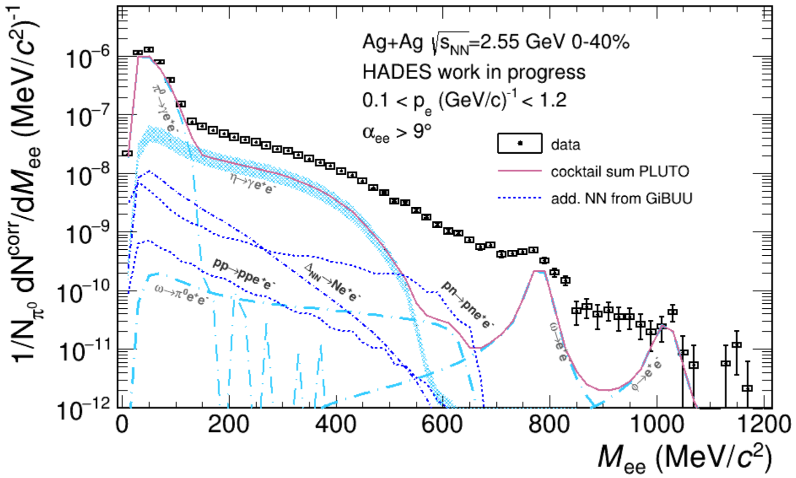
- Upgraded RICH photon detector (using FAIR-CBM technology, ~27000 pixels)

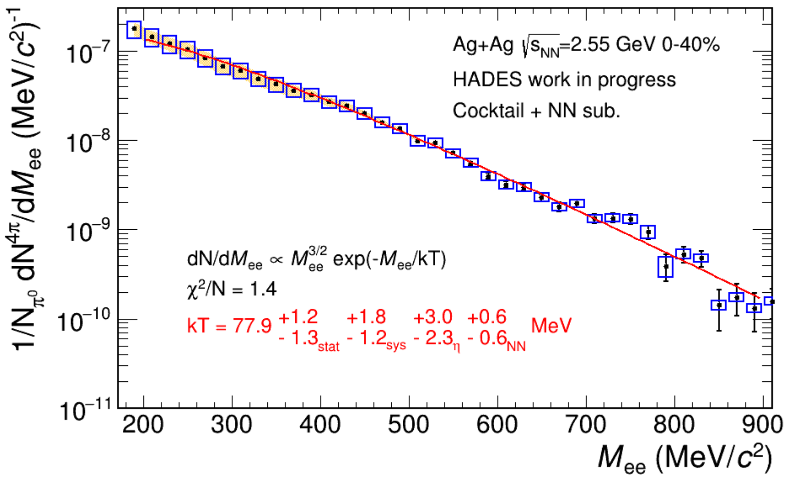
- Efficiency corr. via single $e^{\pm}$ embedding
- Combinatorial background
  - <+-> = 2k sqrt(<++><-->)
  - for M_{ee}>400MeV/c^2 mixed-event technique

NN ref. measured just very recently (Feb22) => using GiBUU

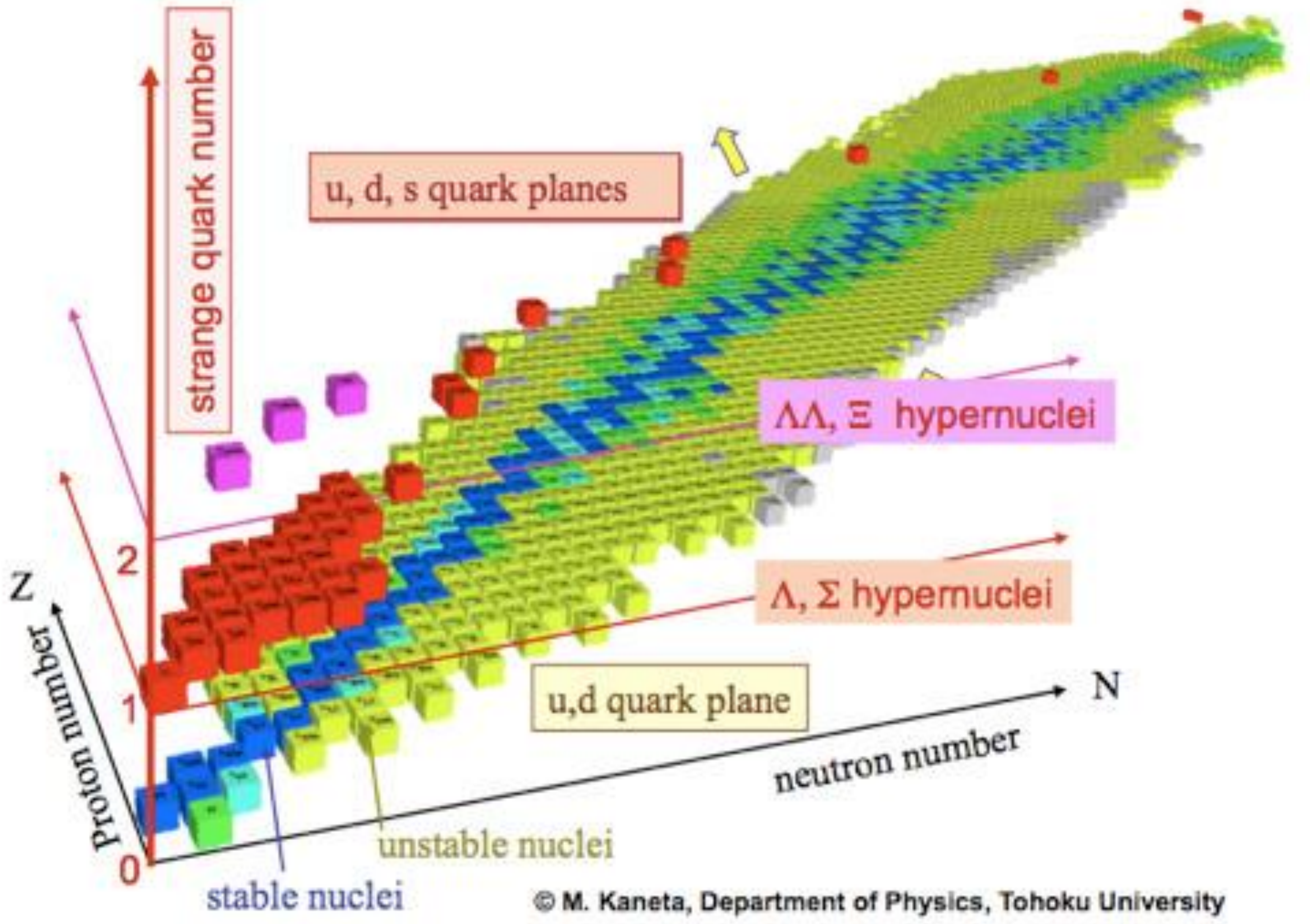
Only minor temperature dependence on centrality







Strangeness



Subthreshold production

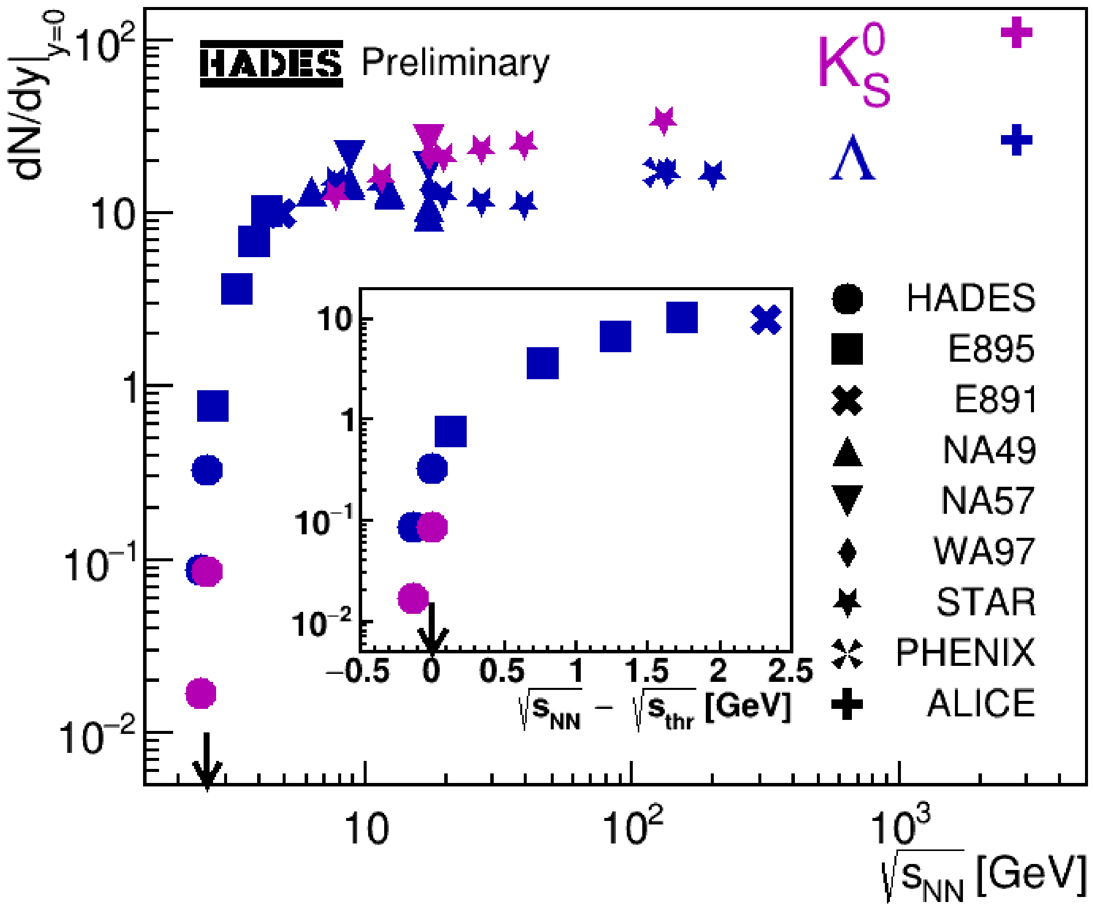
- Final state / Threshold $\sqrt{s_{NN}}$

Final state	Threshold $\sqrt{s_{NN}}$
NKΛ	2.55 GeV
$NNK\bar{K}$	2.86 GeV
NNφ	2.90 GeV

- Measurements

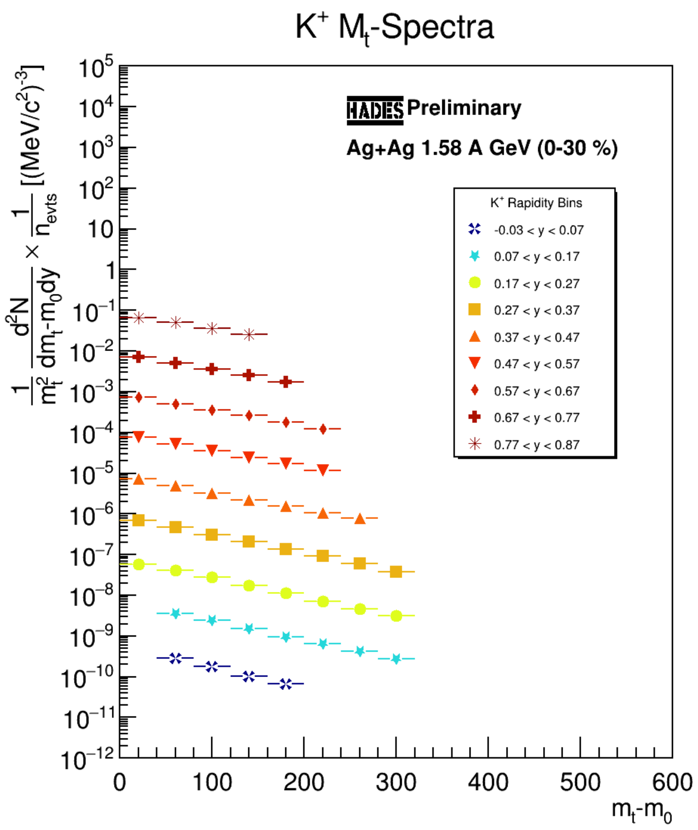
system	$\sqrt{s_{NN}}$ [GeV]	#events
Au+Au	2.42	$7x10^9$
Ag+Ag	2.55	$14x10^9$

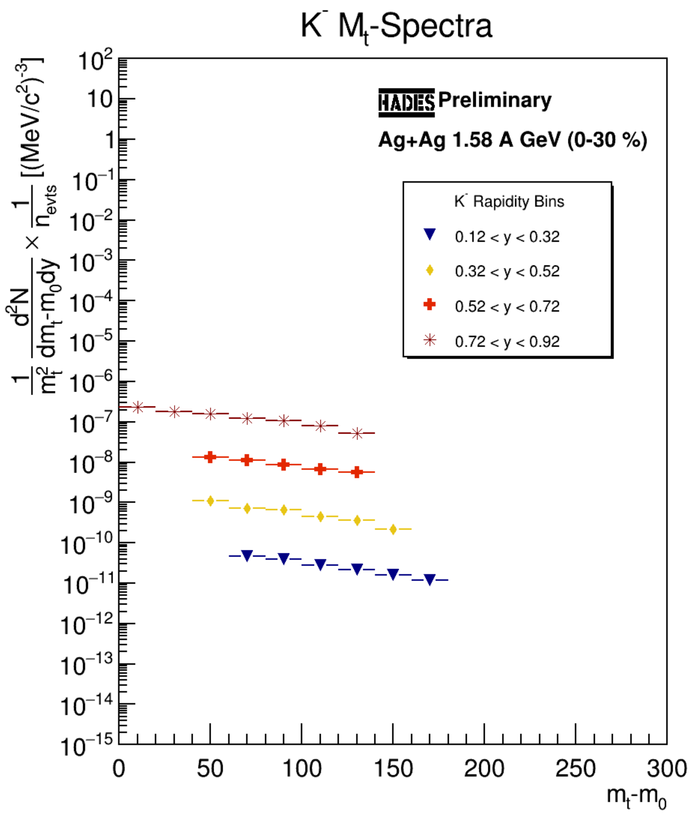
- e.g. effects allowing subthreshold production
  - Fermi momentum
  - Multistep process (resonance excitation)
  - In medium effect (V_{KN} or V_{YN} potentials, EOS)

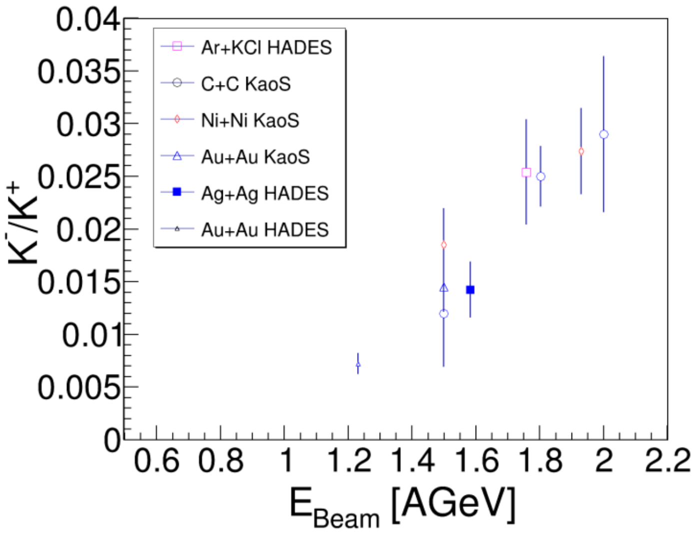


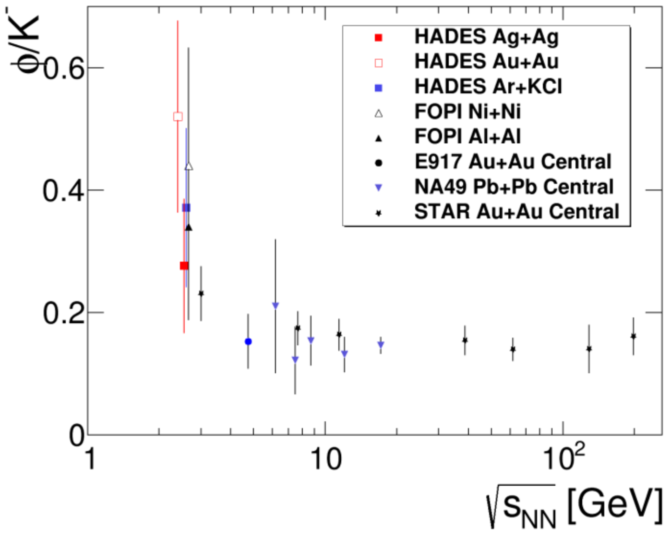
Charged kaons and phi meson

- M. Kohls talk on Wednesday 11:10 AM (GBR2)



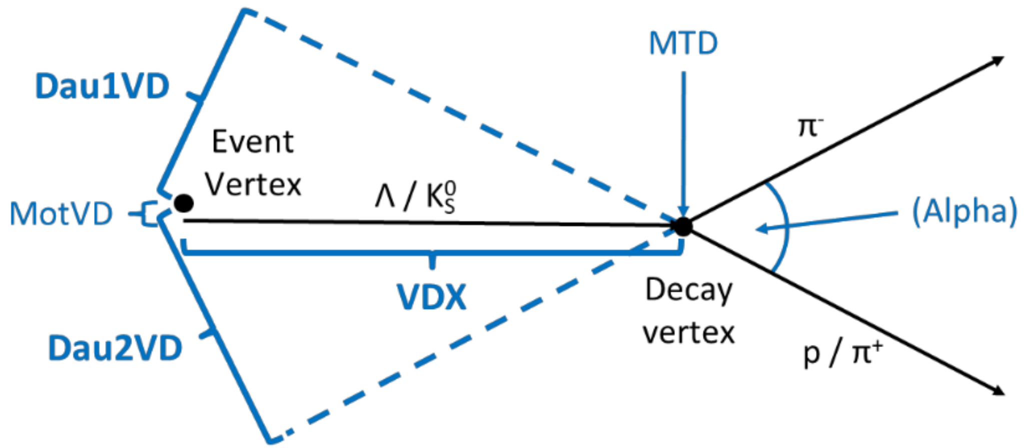


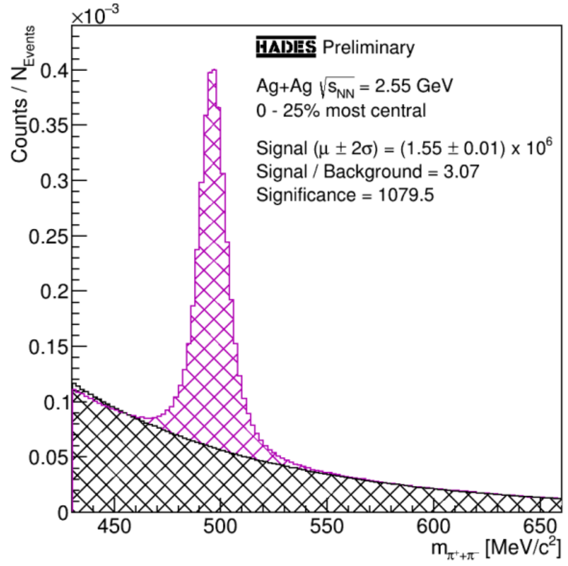


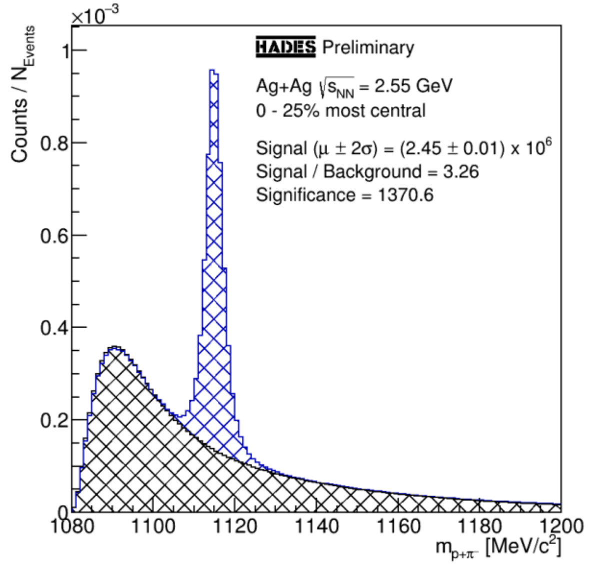


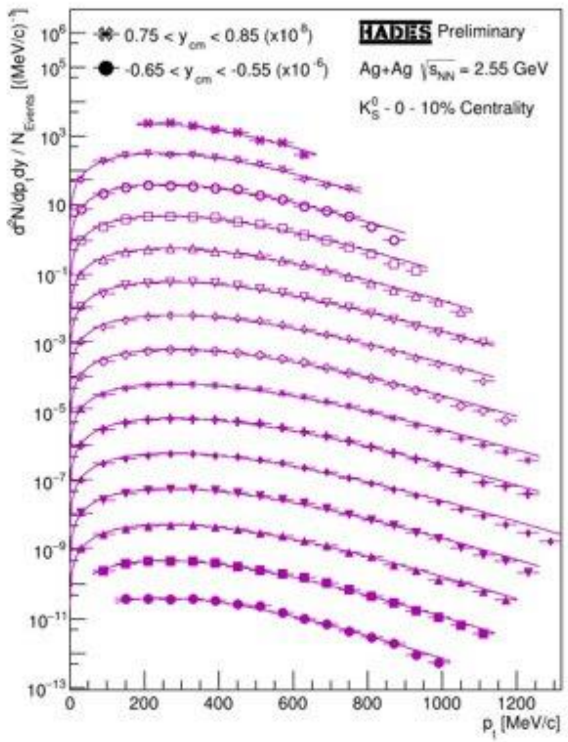
Neutral strange hadrons

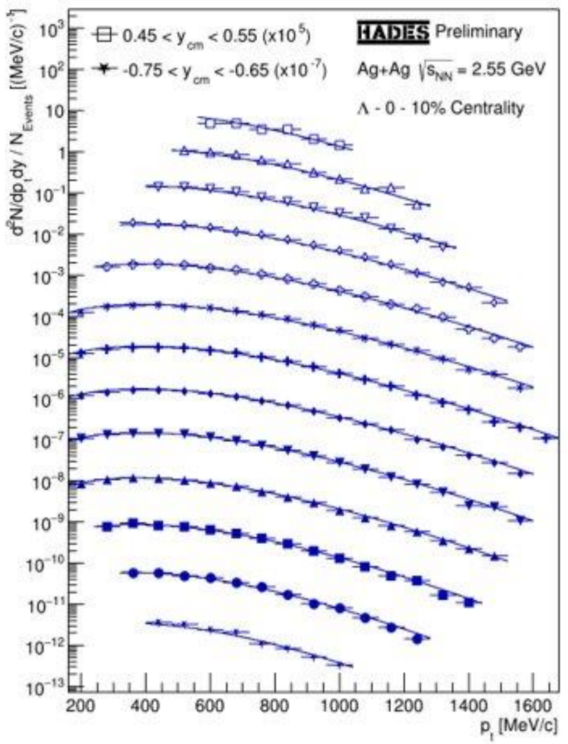
- Weak decay topology
- Selection criteria optimized with TMVA framework







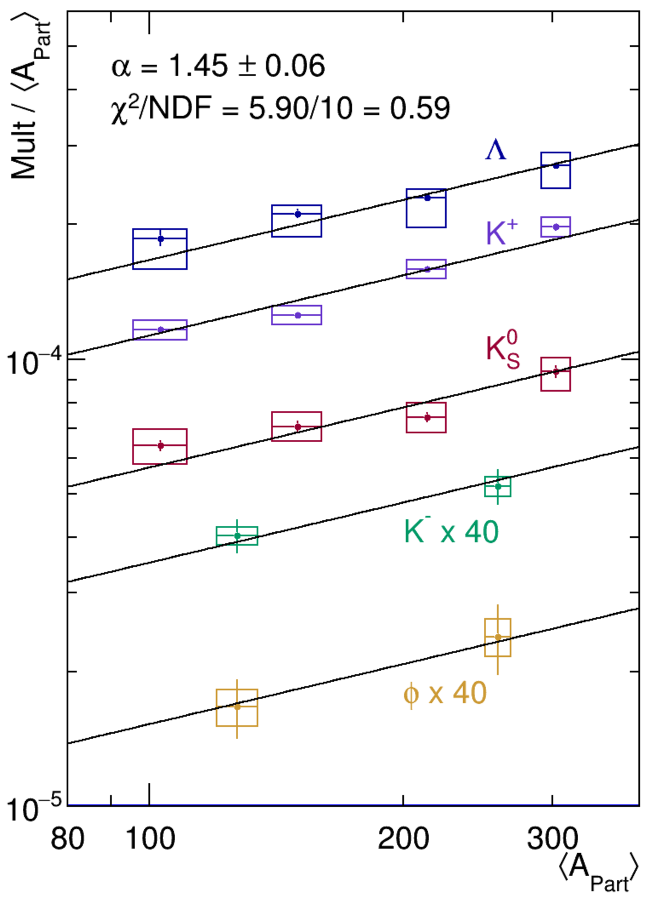


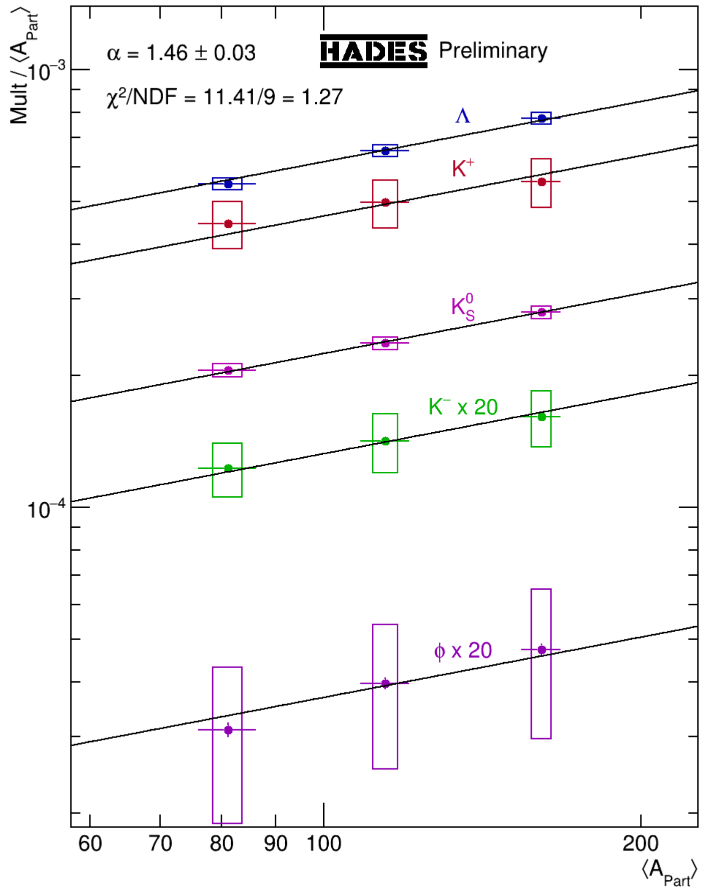


Yields as <A$_{part}$>

- Strange hadrons yields with $M \sim \langle A_{part} \rangle^{\alpha}$
  => not reflected hierarchy in production threshold (significant difference: 2.55 vs 2.90 GeV)
- Scaling with absolute amount of $s\bar{s}$

- Quantum percolation at $\rho \sim 1.8\rho_0$
  [PRD 102, 096017 (2020)]

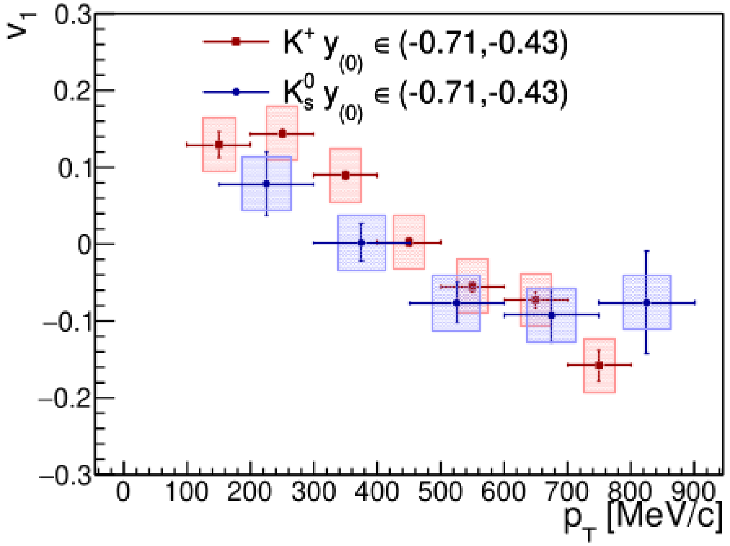


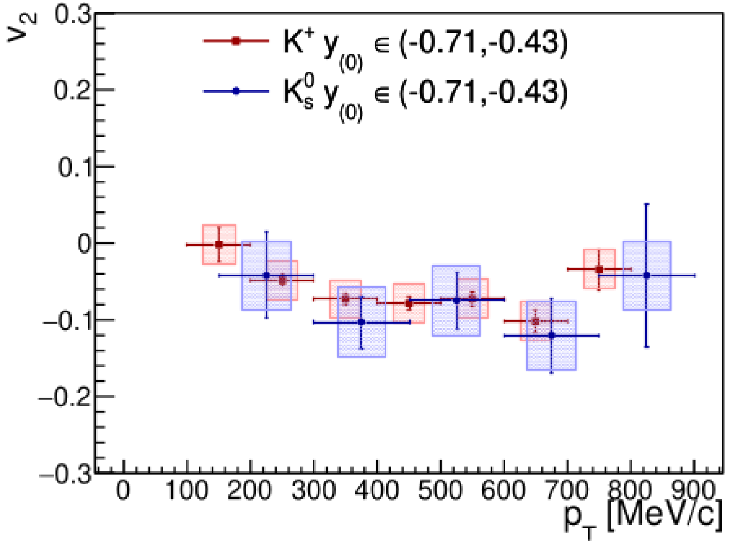


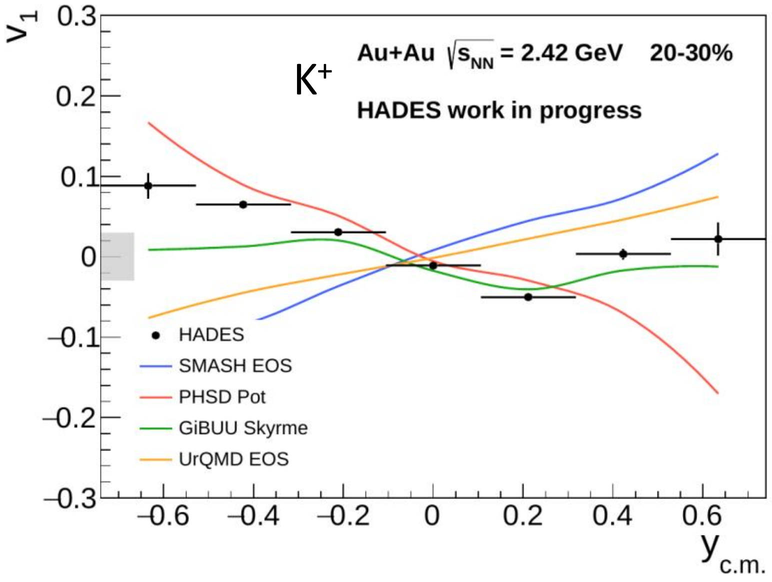
Phys. Lett. B 793, 457-463 (2019)

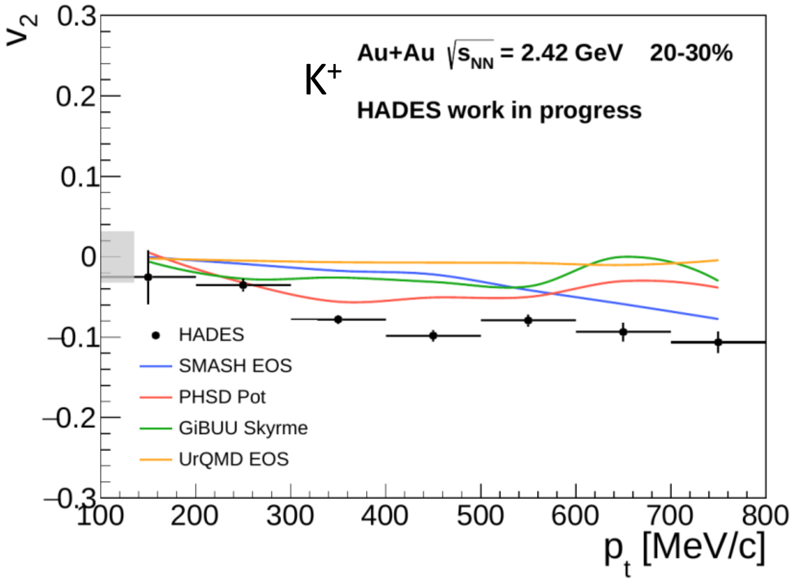
Kaon flow

- No significant difference in flow of charged and neutral kaons
- Good statistics to constrain models
    - Observed differences with selected transport models







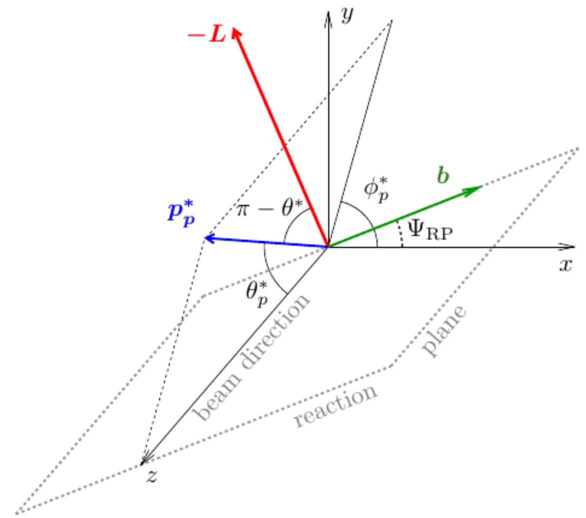


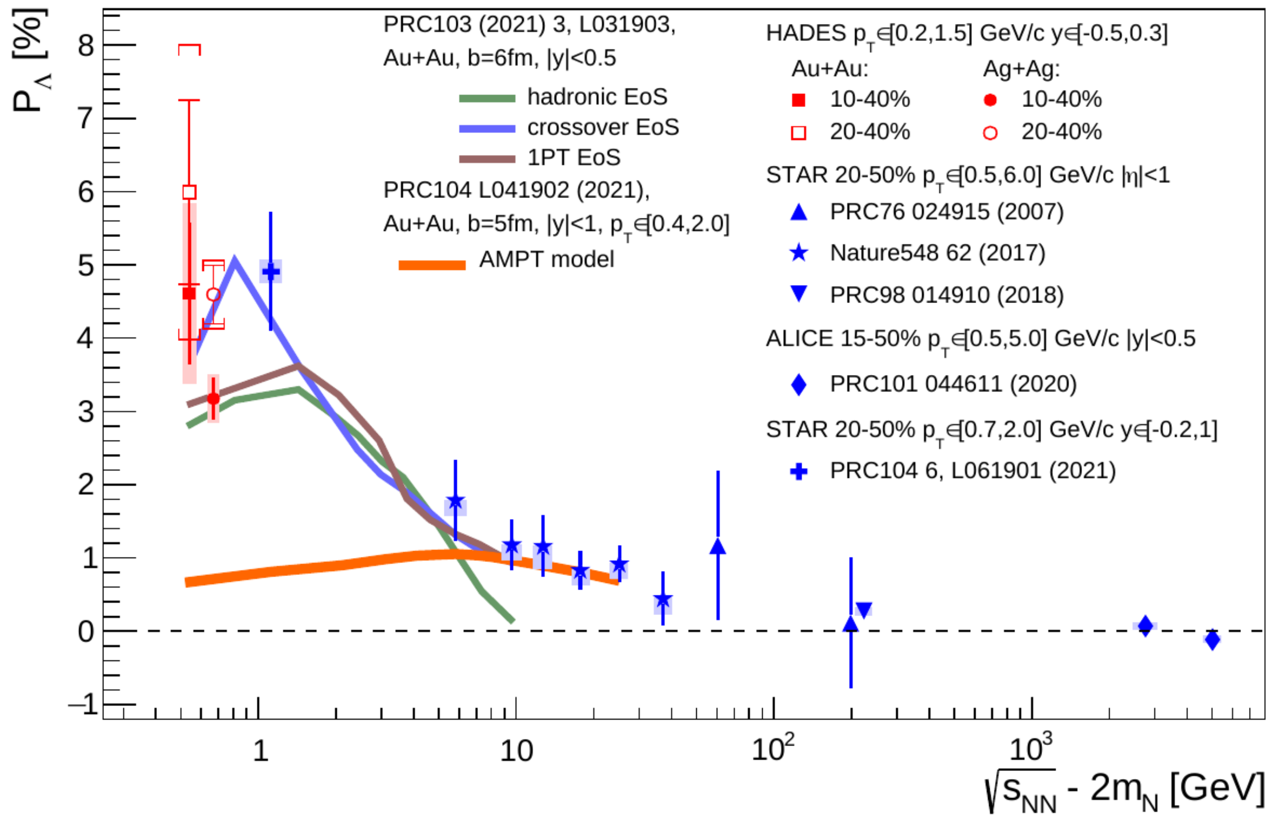
Lambda polarization

- Global polarization of Lambdas

$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{\langle \sin(\Psi_{\mathrm{EP}} - \phi_{\mathrm{p}}^{*})\rangle}{R_{\mathrm{EP}}}$$

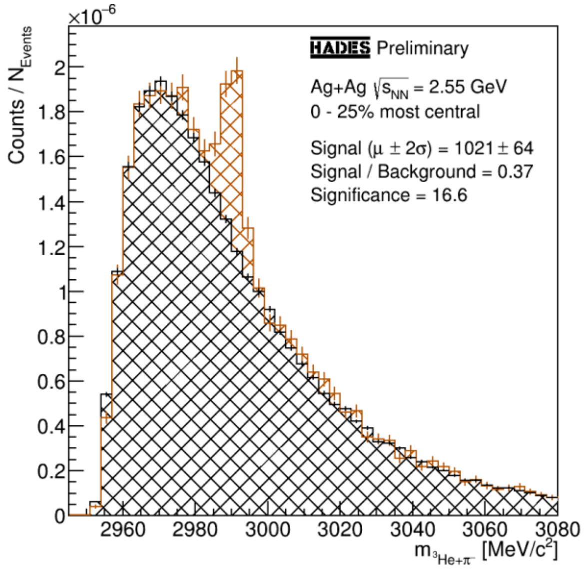
- Collision energies at SIS18 are at maximum polarization
  - vanishing at $2m_N$
  - matching prediction from 3D-fluid-dynamics
- Strong centrality dependence
- Remarkable agreement with UrQMD + thermal vorticity
- Origin of polarization? Not only QGP, baryon-dominated hadronic matter as well

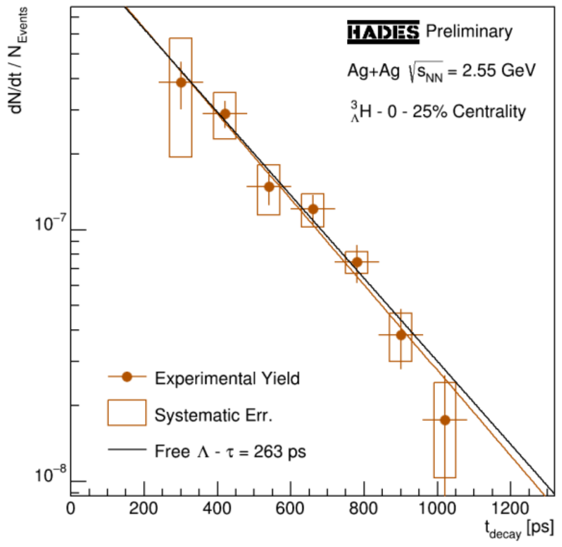


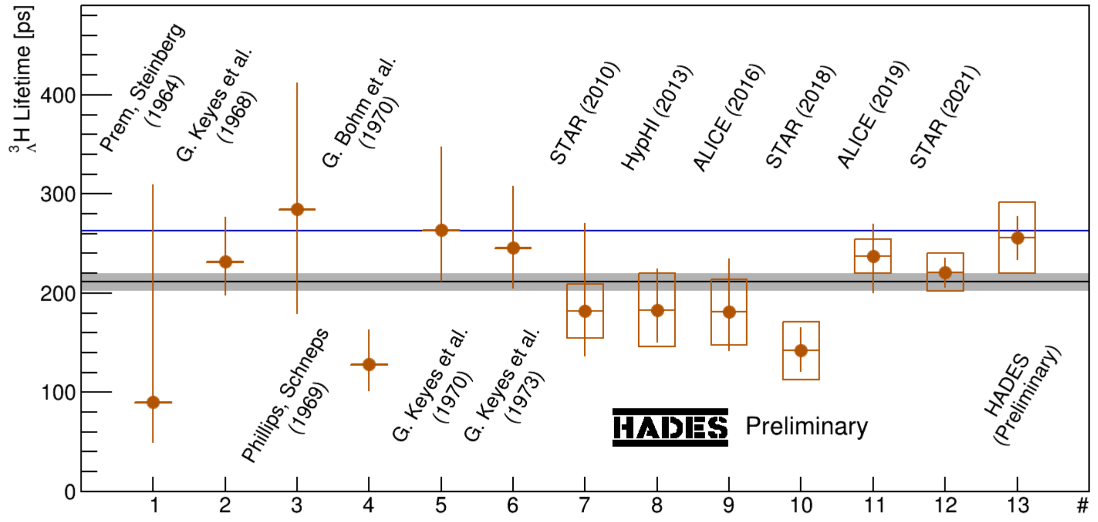


Hypernuclei - $^{3}_{\Lambda}H$

- Similar approach as for neutral strange hadrons (decay into $^{3}He+\pi^{-}$)
- First measurement with mid-rapidity coverage
- Observed lifetime (256 ± 22 ± 36) ps compatible with free Λ

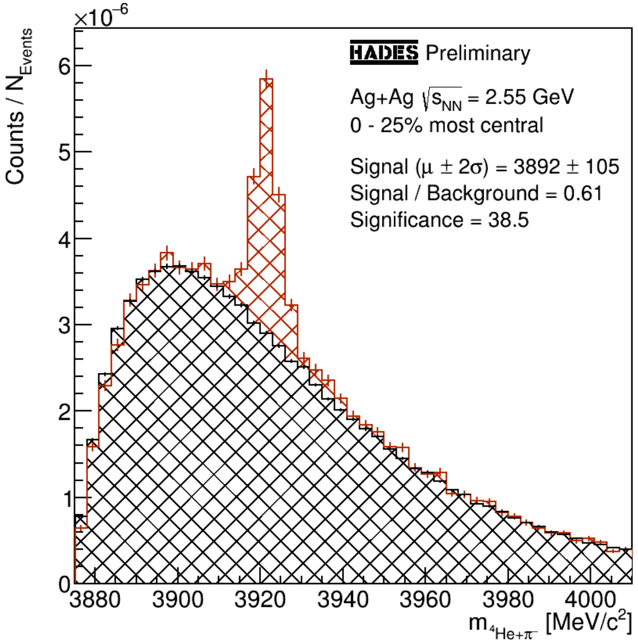


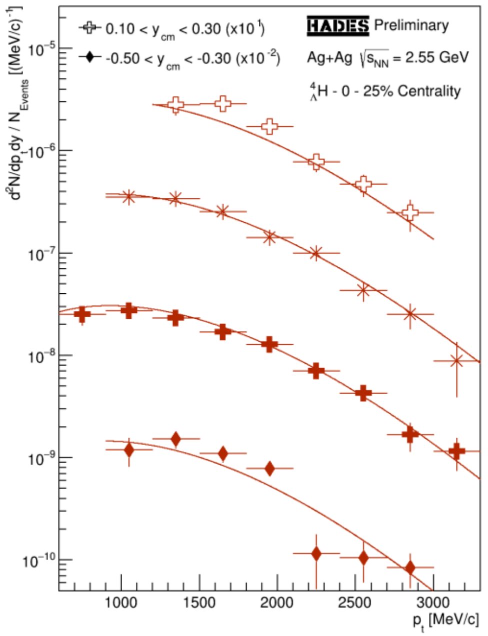


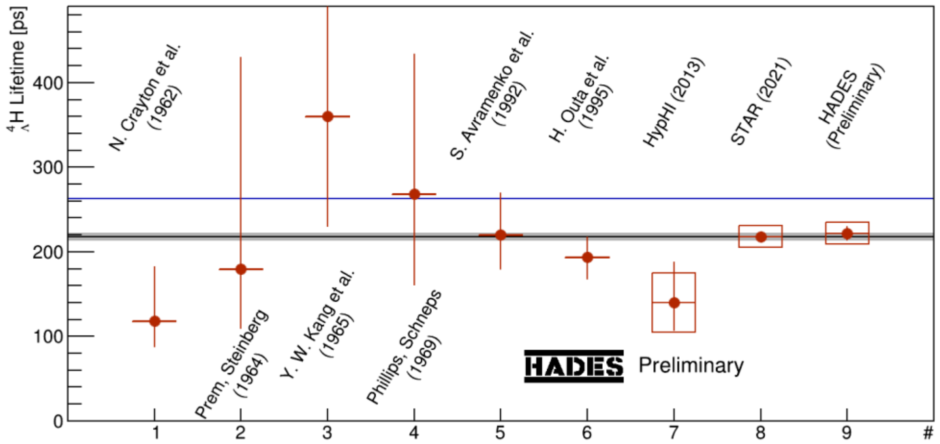


Hypernuclei - ${}^{4}_{\Lambda}H$

- Higher binding energy and BR (decay into ${}^{4}He+\pi^{-}$) than hypertriton
- Observed lifetime (222 ± 8 ± 13) ps compatible with other measurement (significantly lower than free Λ)







Summary &Outlook

- Many interesting published/upcoming results
  - Global Λ polarization
  - $e^{\pm}$ in Ag+Ag extracting omega peak
  - Strangeness & Hypernuclei production in Ag+Ag
  - Flow measurements in Au+Au (p/d/t, pions and kaons)
- First real photon measurements in Ag+Ag with ECAL
- Publications on charged pions [Phys.Rev.C 102, 024001 (2020)], and e± from π^-+p [arXiv:2205.15914] at $\sqrt{s}$=1.49 GeV => ρ meson in vacuum

Thank you for your attention!

BACKUP

Proton-number fluctuations

Phys. Rev. C 102, 024914 (2020)

- Proton dominated at SIS18 energies
- Very large coverage by HADES
- Background effects – event-wise, track-wise

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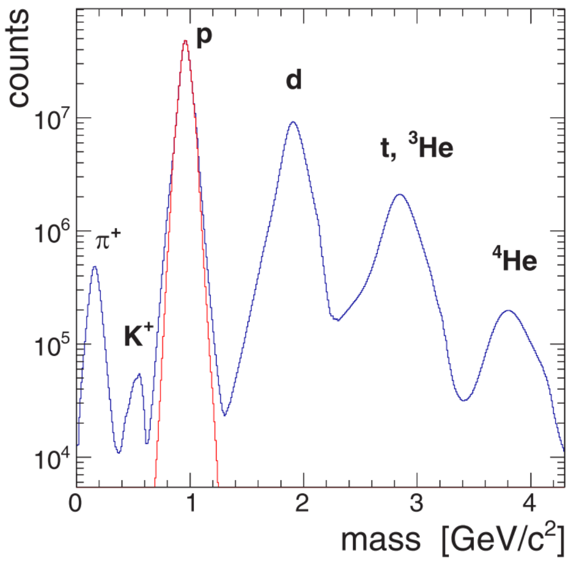
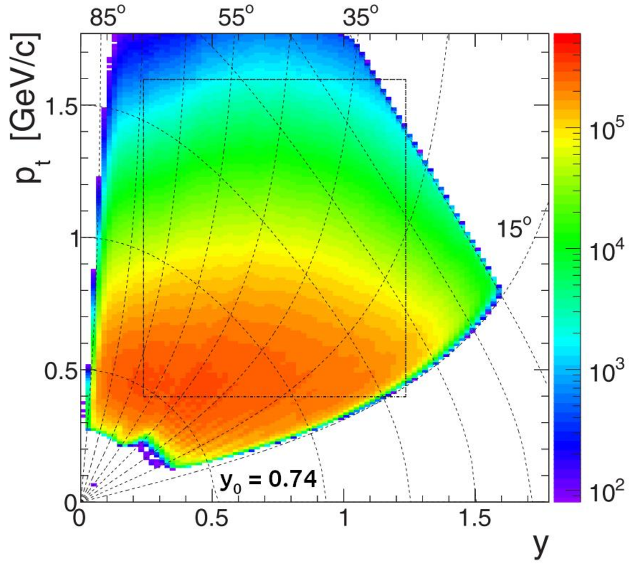
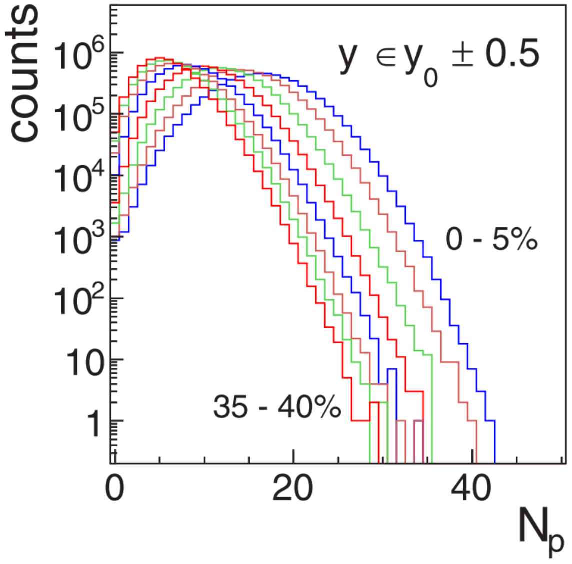




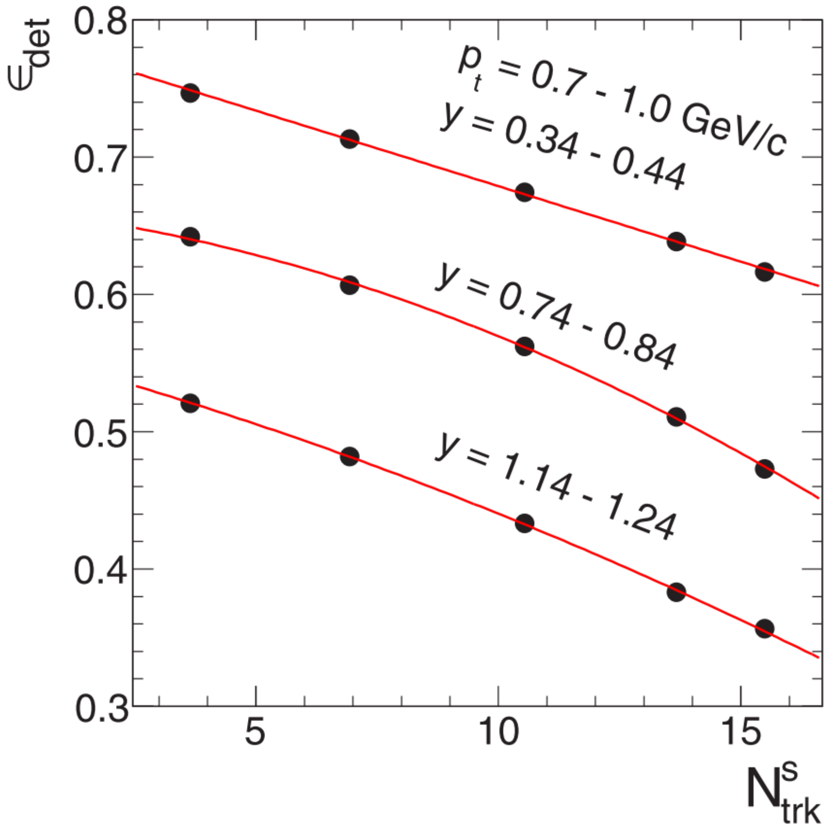
Raw multiplicities

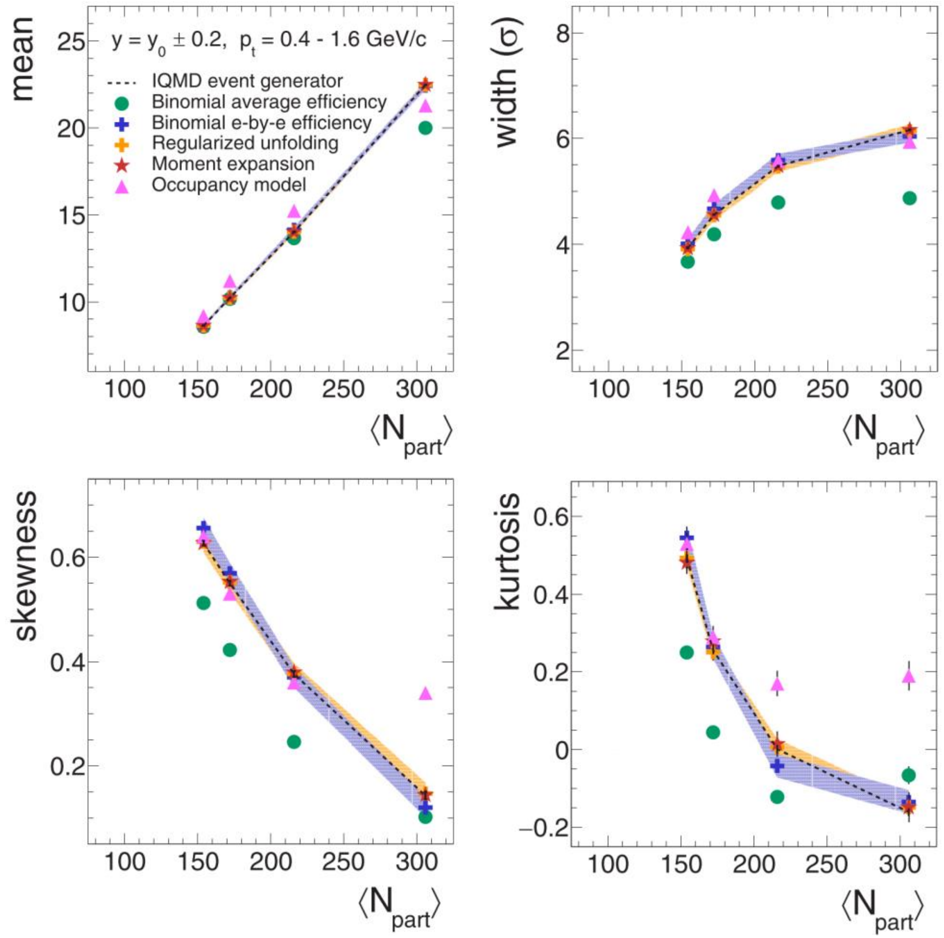


Proton-number fluctuations

Phys. Rev. C 102, 024914 (2020)

- Detection efficiency – phase-space & occupancy dependent

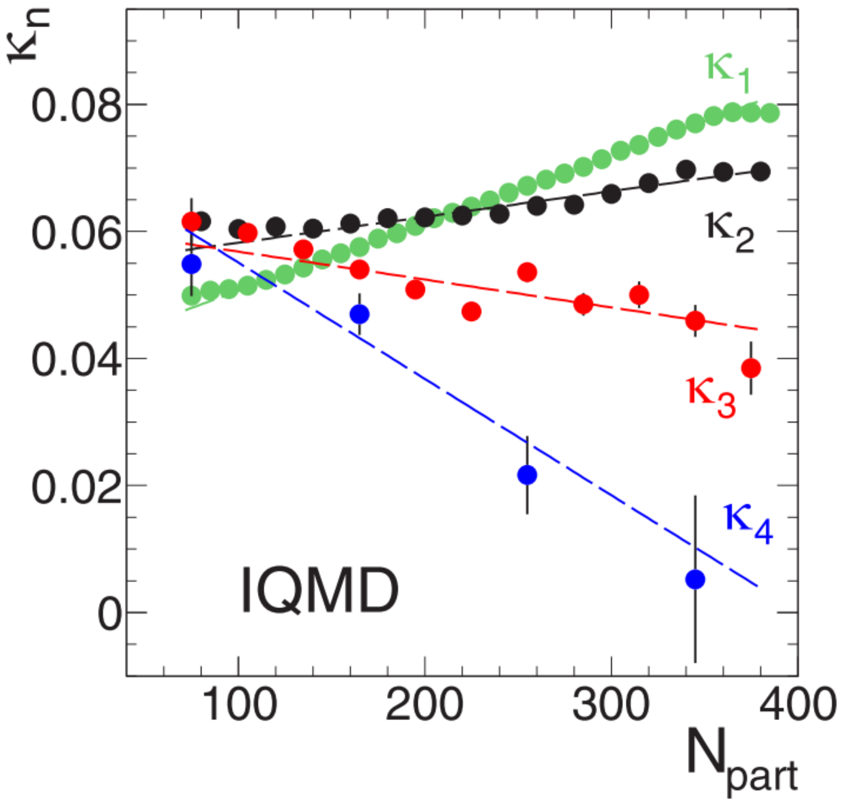




Proton-number fluctuations

Phys. Rev. C 102, 024914 (2020)

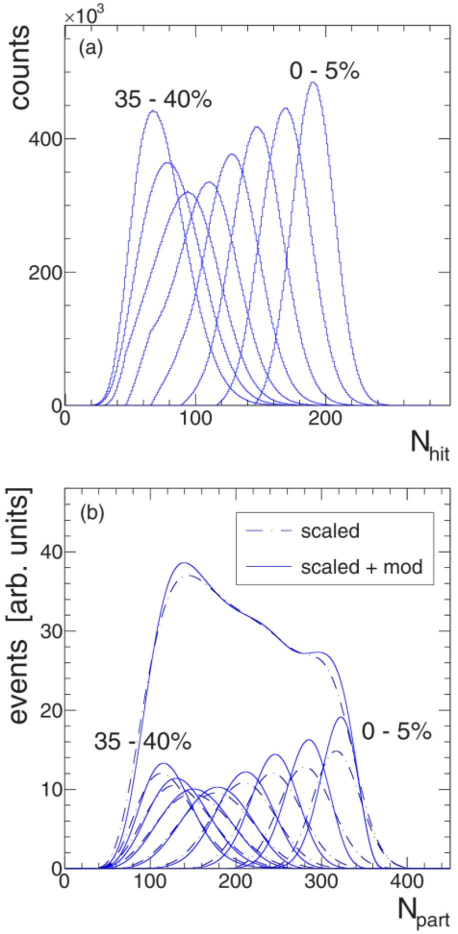
- Volume correction – quadratic dependence $\kappa_n(V) = \kappa_n + \kappa_n'(V - \langle V \rangle) + \kappa_n''(V - \langle V \rangle)^2$



Proton-number fluctuations

Phys. Rev. C 102, 024914 (2020)

- Volume correction – quadratic dependence $\kappa_n(V) = \kappa_n + \kappa_n'(V - \langle V\rangle) + \kappa_n''(V - \langle V\rangle)^2$
- Centrality selection – influence on volume cumulants (non-zero correlation coefficient $\rho(N_{prot},\Sigma Q_{FW})$)



efficiency corr. reduced cumulants $\tilde{\kappa}_1$

sim. based modified reduced volume cumulants

$$v_l^{\rm mod} = f_l^{\rm sim} \times v_l + d_l^{\rm sim}$$

system of equations $\tilde{\kappa}_1 = \kappa_1 + v_2\kappa_1' + (V_2 + v_3)\kappa_1''$

=> $\kappa_n = K_n/V$

Charged pions – Coulomb effect

arXiv:2202.12750v2 [nucl-ex]

- Positive charge of fireball => influence kinetic energy of different charges (long range effect!)
- Faster particles do not contribute, assuming common freeze-out of pions => effective potential

$$V_{\text{eff}} = \begin{cases} V_C\left(1-e^{-x^2}\right) & \text{Cylindrical sym. (higher energies)} \\ V_C\left(\text{erf}(x)-(2/\sqrt{\pi})\,x\,e^{-x^2}\right) & \text{Spherical sym. (below 8AGeV)} \end{cases}$$

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

- Two contributions in differential yield (Δ decay vs. thermal/broad resonances, details in EPJA 56, 259 (2020))

$$\frac{d^2N^{\pm}}{dm_t dy} = A m_t^2\left(f\,e^{-(E_f\mp V_{\text{eff}})/T_1}+(1-f)\,e^{-(E_f\mp V_{\text{eff}})/T_2}\right)\times J\times J_{\text{eff}}$$

- Up to now omitted term (factor ≤2)

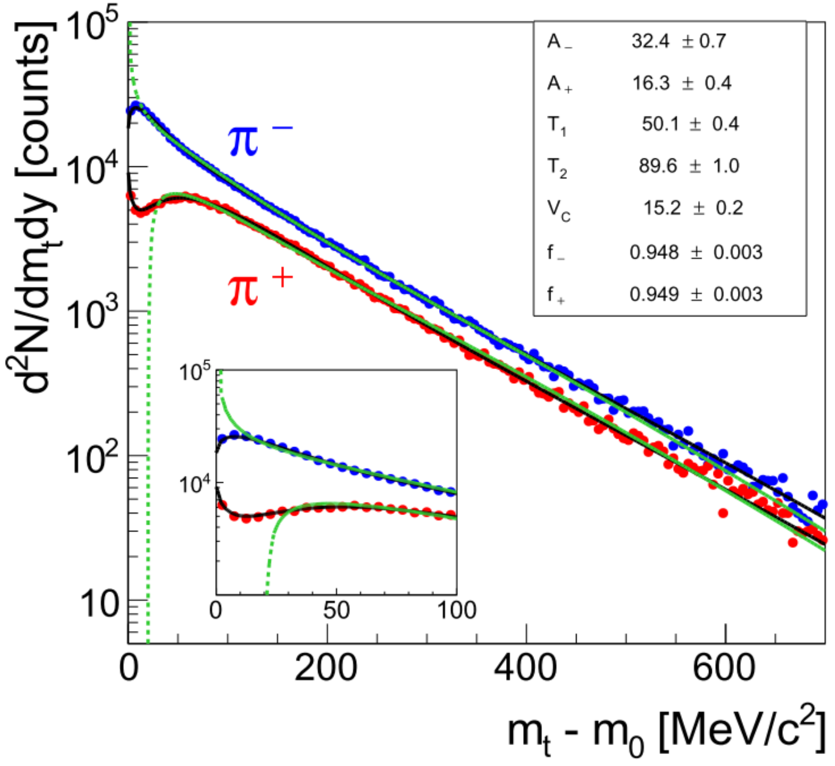
$$J=\frac{E_i\,p_i}{E_f\,p_f}=\frac{(E_f\mp V_{\text{eff}})\sqrt{(E_f\mp V_{\text{eff}})^2-m_\pi^2}}{E_f\sqrt{E_f^2-m_\pi^2}}$$

$$J_{\text{eff}} = \begin{cases} 1\mp\frac{V_C\,m_p}{m_\pi\,T_p}\,e^{-x^2} \\ 1\mp\frac{2}{\sqrt{\pi}}\,\frac{V_C\,m_p}{m_\pi\,T_p}\,x\,e^{-x^2} \end{cases}$$

Charged pions – Coulomb effect

arXiv:2202.12750v2 [nucl-ex]

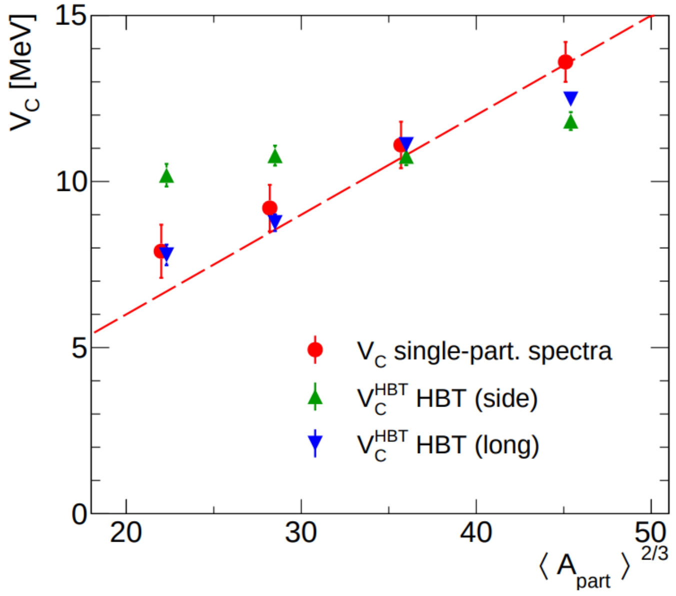
- Prove of principle with simulations
  (input values T_1=50MeV, T_2=90MeV, f=0.95, V_C=15MeV, T_p=130MeV)

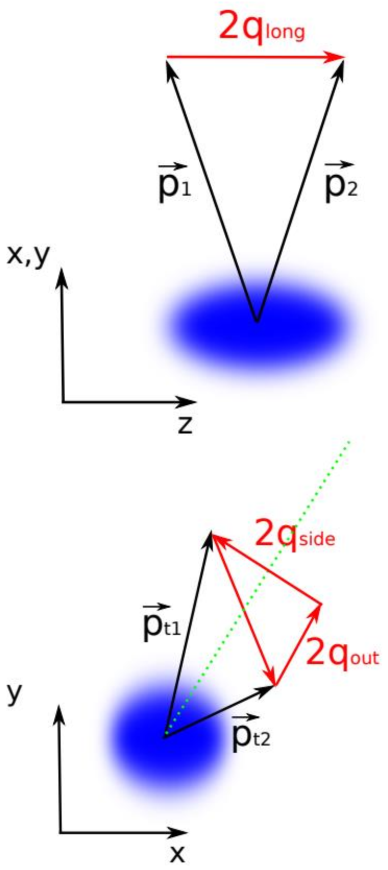


Charged pions – Coulomb effect

arXiv:2202.12750v2 [nucl-ex]

- Comparison with HBT pion pairs of the same sign

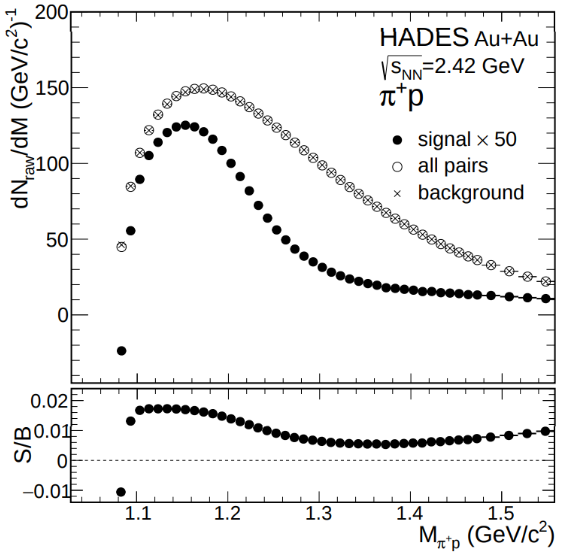


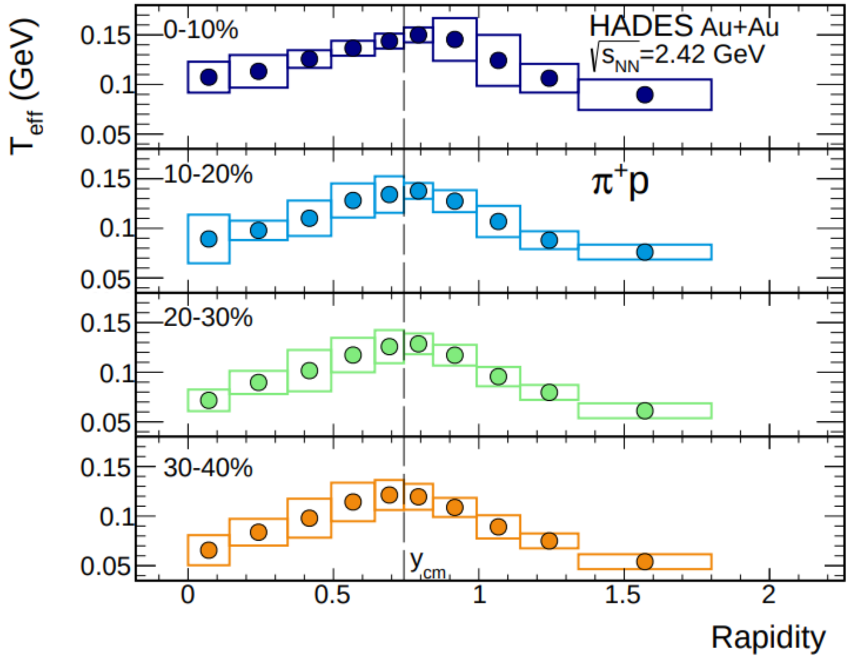


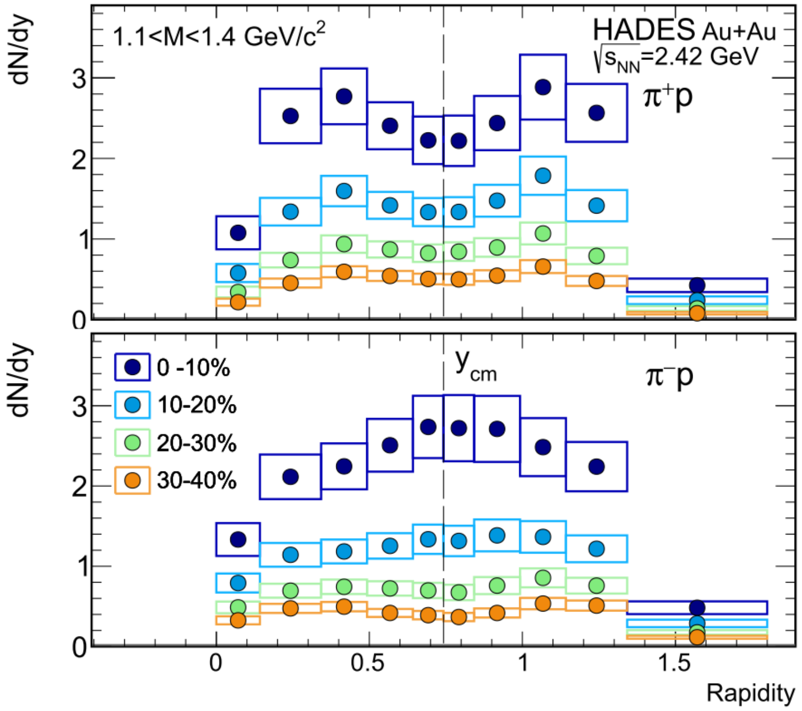
Pion freeze-out region
<==>
Homogeneity of two-pion correlations

Proton-pions correlated pairs

Phys. Lett. B 819, 136421 (2021)





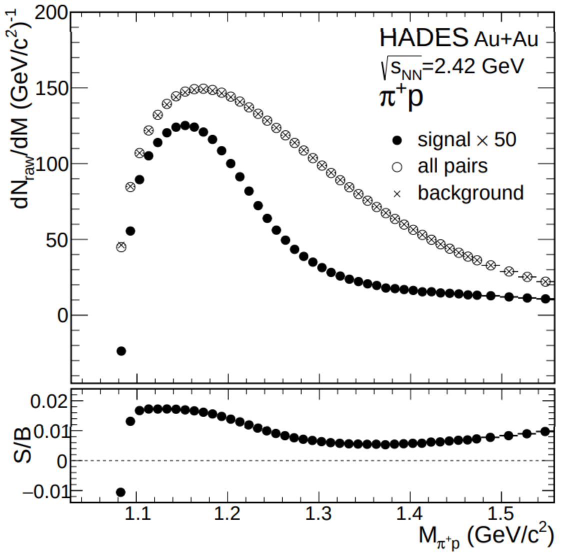


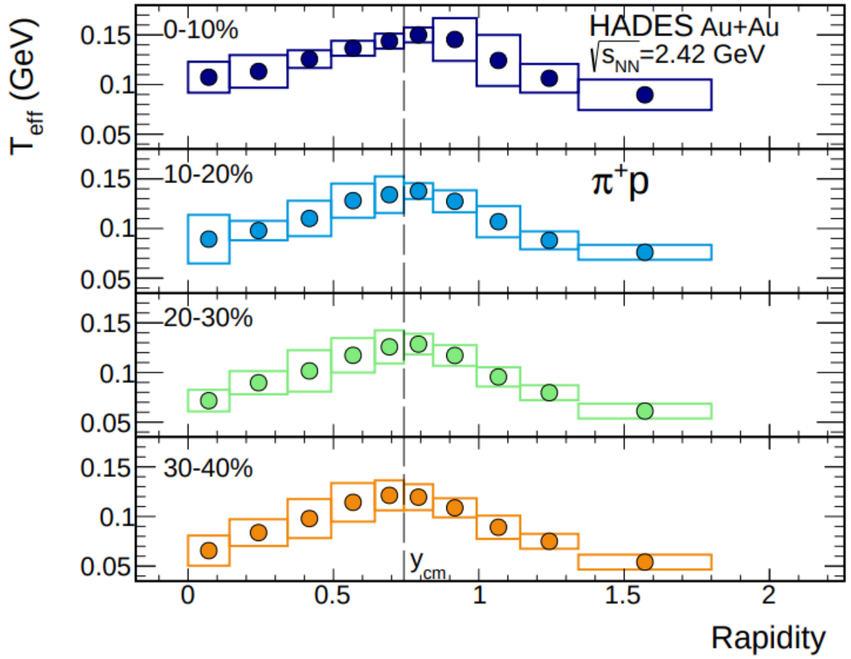
- Novel iterative bckg subtraction technique EPJA 55, 204 (2019)
- Dominant Δ(1232) signal (significant line shape modification)

- Expected Δ^{++} freeze-out T_{fo}~50 MeV (from radial-blast expansion) shows late decoupling
- In accordance with values deduced in Coulomb effect analysis

Proton-pions correlated pairs

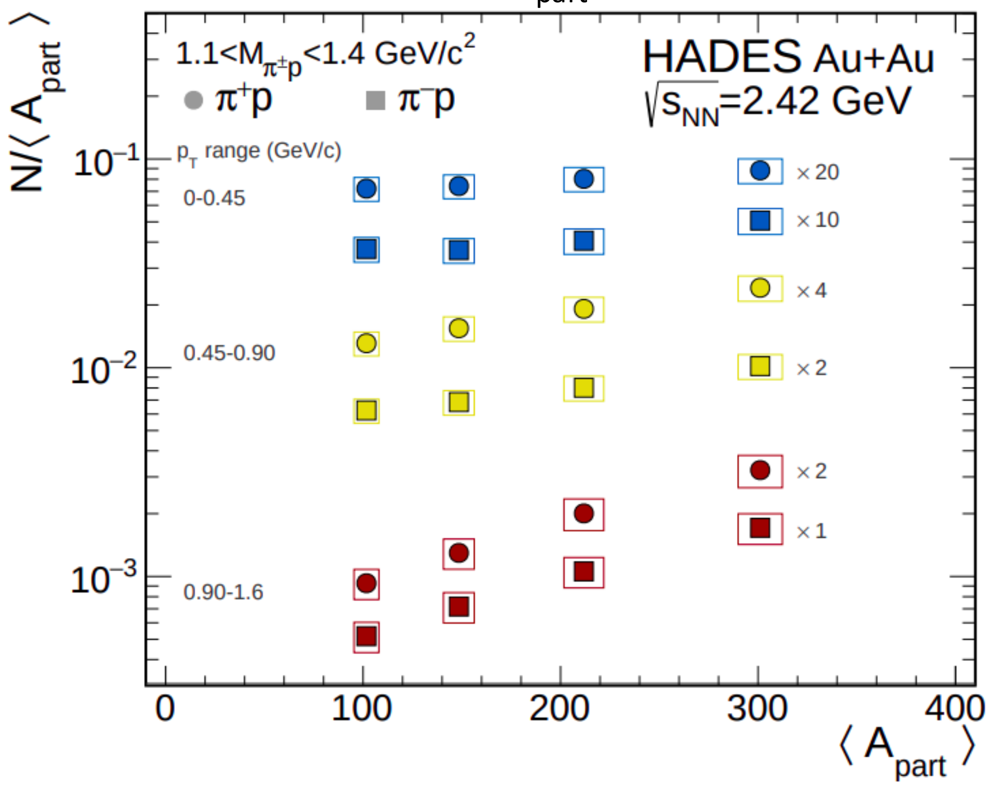
Phys. Lett. B 819, 136421 (2021)





Yield scaling follows power-law

$N \propto \langle A_{part} \rangle^{\alpha}$



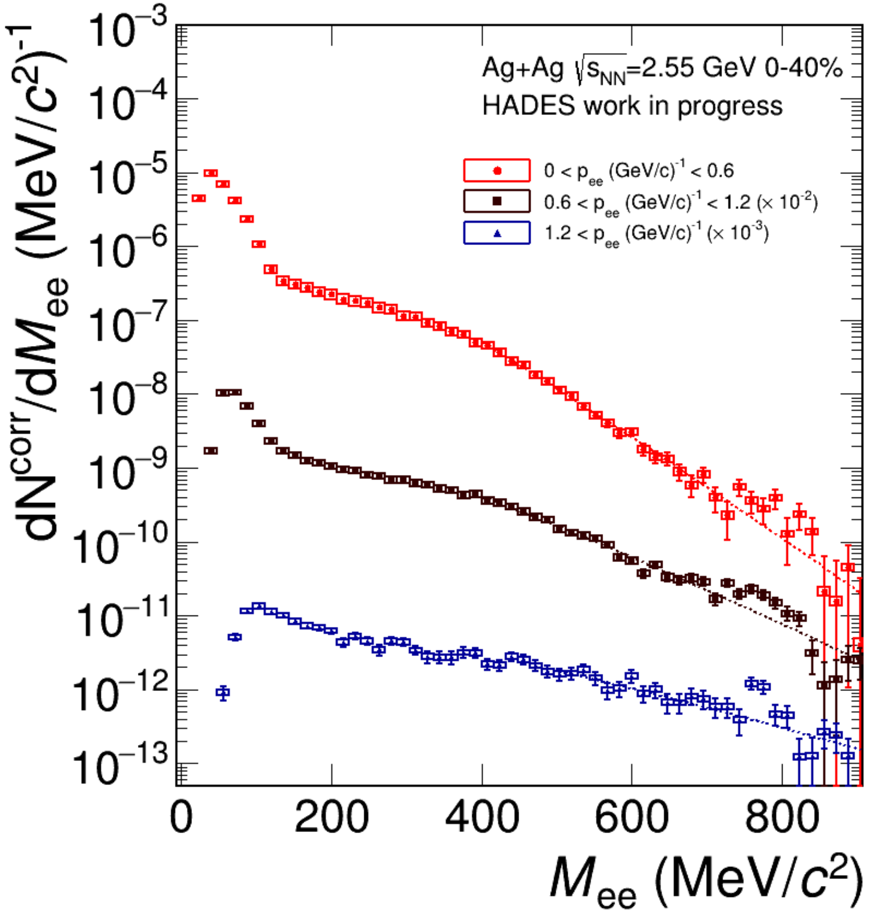
- Novel iterative bckg subtraction technique EPJA 55, 204 (2019)
- Dominant Δ(1232) signal (significant line shape modification)

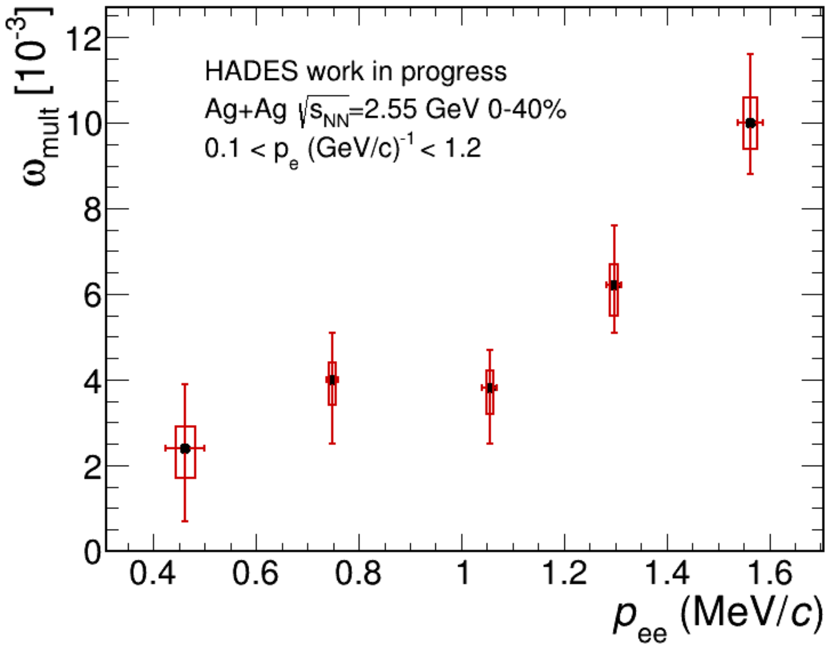
Expected Δ^{++} freeze-out T_{fo}~50 MeV (from radial-blast expansion) shows late decoupling

p_T (GeV/c)	$\alpha_{\Delta^{++}}$	α_{Δ^0}
0 – 1.6	$1.49 \pm 0.08^{st} \pm 0.21^{sy}$	$1.48 \pm 0.09^{st} \pm 0.20^{sy}$
0 – 0.45	$1.20 \pm 0.09^{st} \pm 0.19^{sy}$	$1.33 \pm 0.09^{st} \pm 0.21^{sy}$
0.45 – 0.9	$1.58 \pm 0.11^{st} \pm 0.20^{sy}$	$1.47 \pm 0.10^{st} \pm 0.20^{sy}$
0.9 – 1.6	$2.18 \pm 0.14^{st} \pm 0.26^{sy}$	$2.13 \pm 0.14^{st} \pm 0.25^{sy}$

Medium heavy-ion collisions

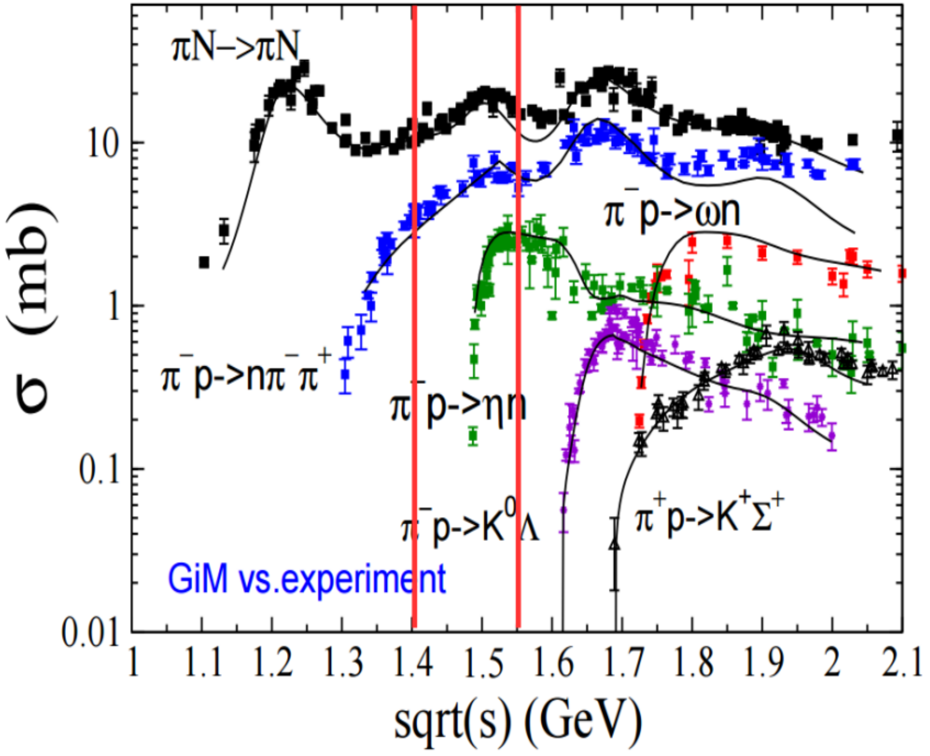
- Dilepton pair momentum dependent analysis
- Excess over continuum at M_{ee}~770MeV/c^2 develops with higher momentum
- Scenarios:
  - Omega hidden under broad excess for low p_{ee}
  - Omega is broadened if coming from later HIC stage (lower p_{ee})



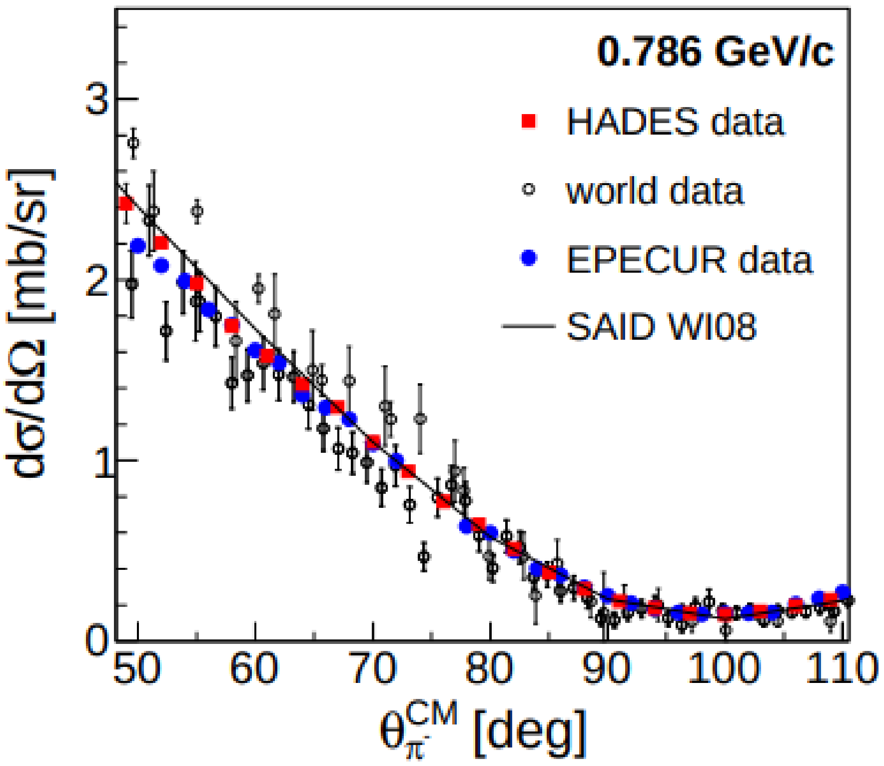


Pion induced collisions

Pion beam energy scan



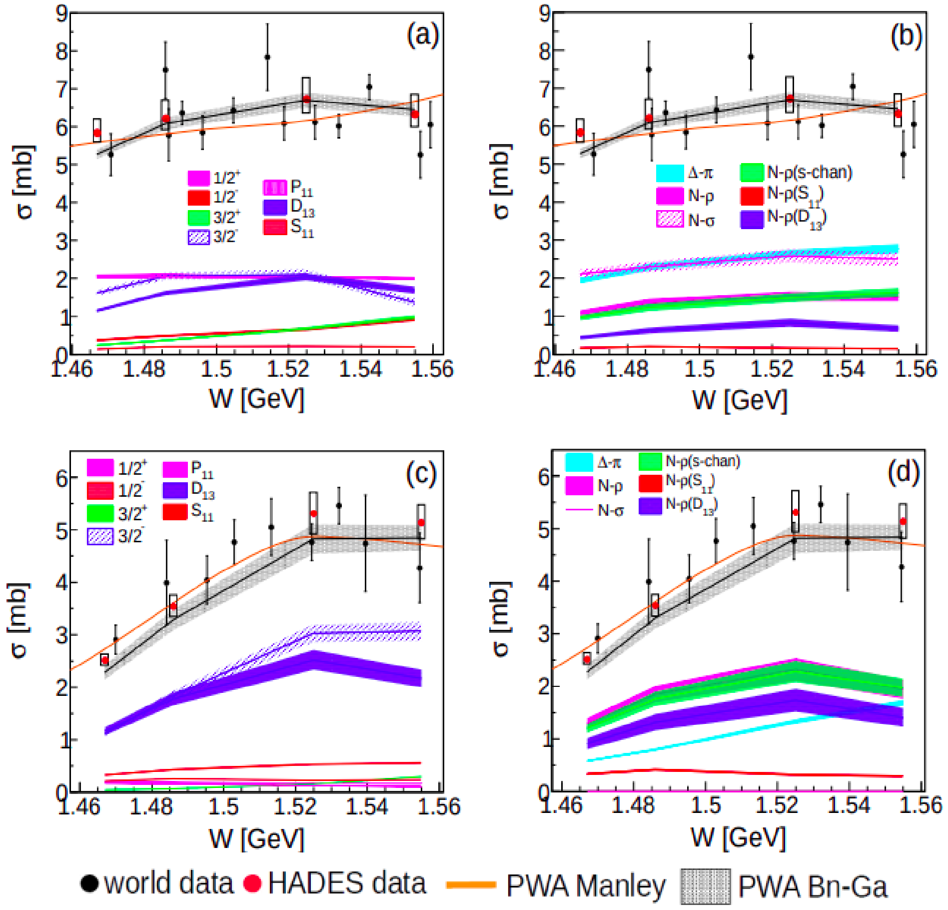
Absolute normalization based on elastic scattering



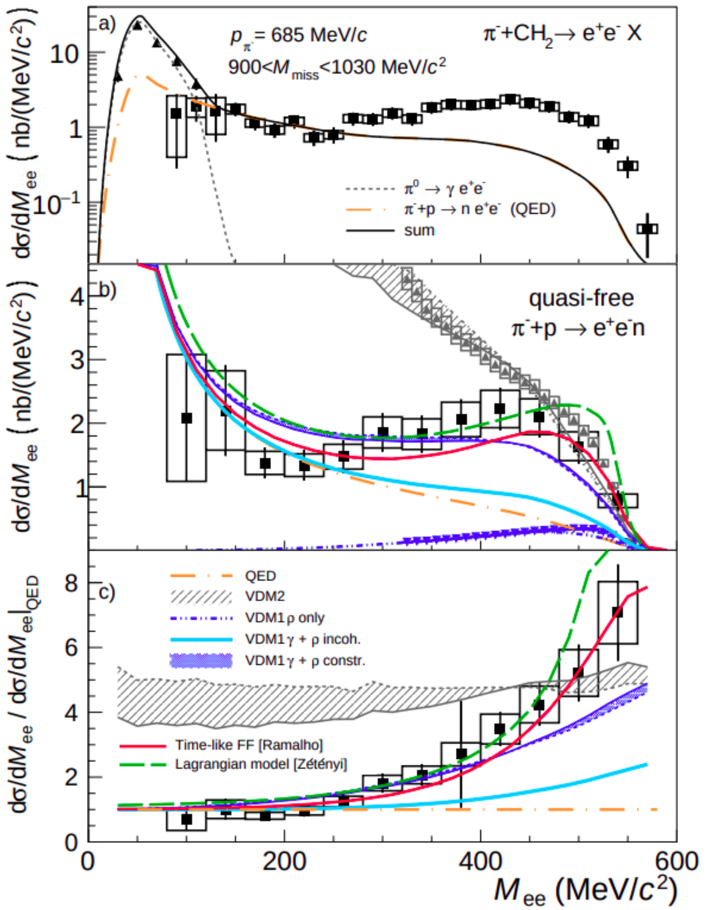
Pion induced collisions

PWA with 2 pion channels

$\pi^- p \rightarrow n\pi^+\pi^-$ $\pi^- p \rightarrow p\pi^0\pi^-$

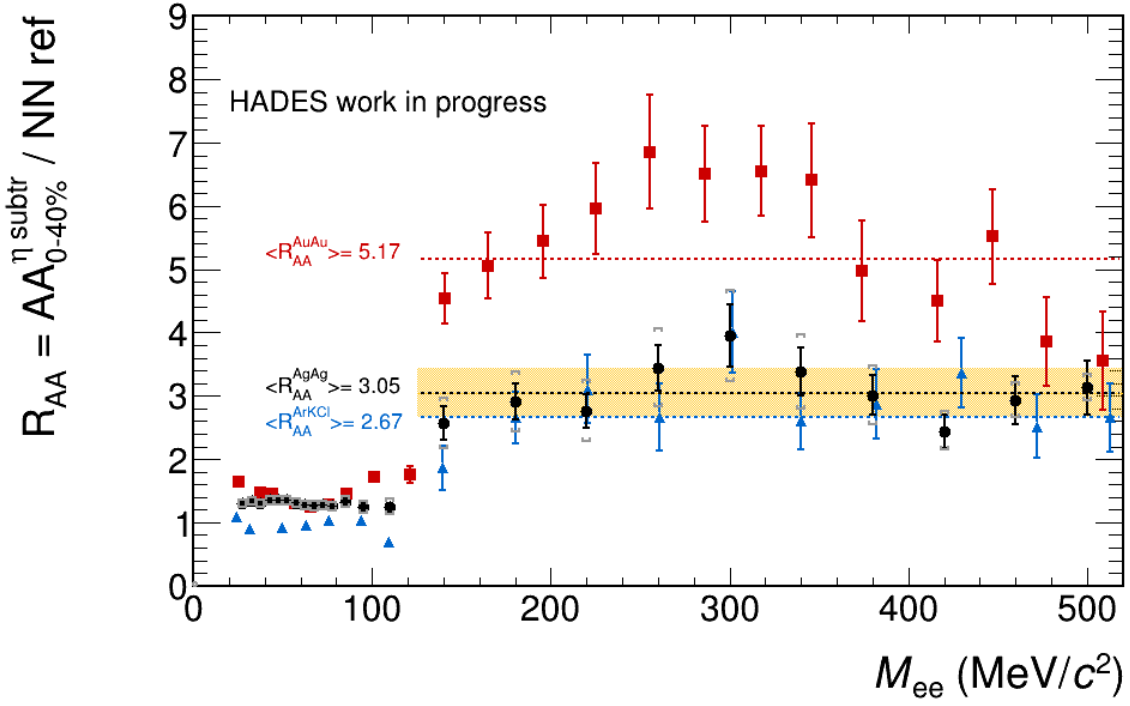


Dilepton spectral function of rho meson



Heavy ion collisions

- Small Mee dominated by pi0 Dalitz contribution
- Systematic uncertainties dominated by eta meson multilicity (subtracted)



Kaon flow

- From Au+Au $\sqrt{s_{NN}}$ =2.42 GeV
- Extend measurements to lower p_T where large differences are observed
- No differences between K^+ and K^0_s and rather small differences between K^+ and K^-

STAR [PLB 827, 137003 (2022)]