HADES Overview

Recent results from measurements probing the high μ_B / high net-baryon density region of the QCD phase diagram

Simon Spies for the HADES Collaboration

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FAIR Phase 0 Research Program

EL EM EN TS

HADES

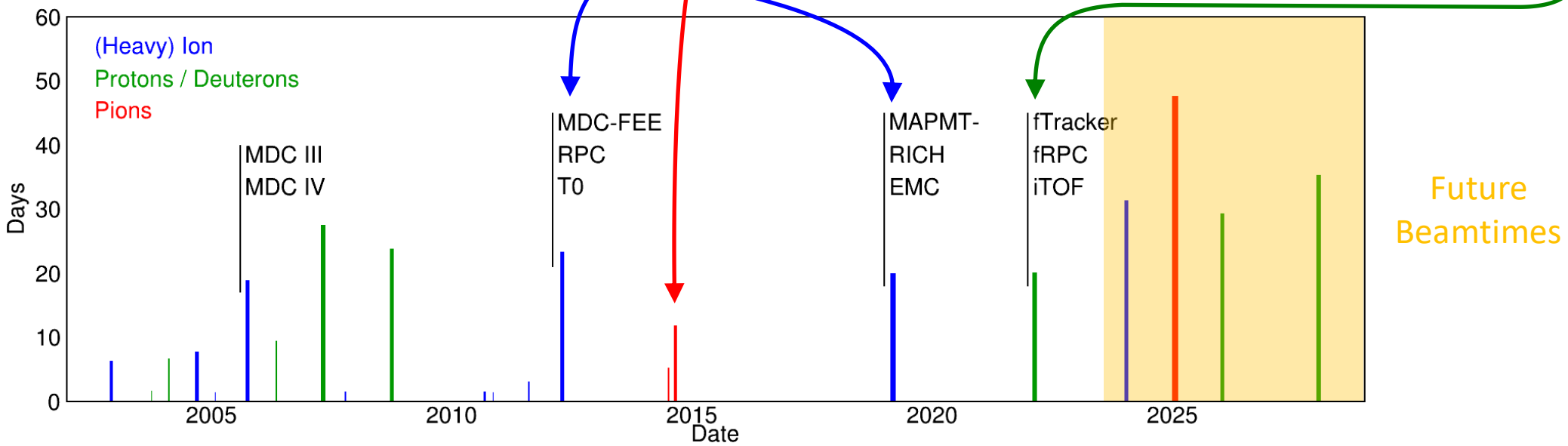
The HADES Physics Program

(Heavy-)Ion Collisions

- Ar+KCl $\sqrt{s_{NN}}$ = 2.61 GeV, 0.9 bil. evts. (2005)
- 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)

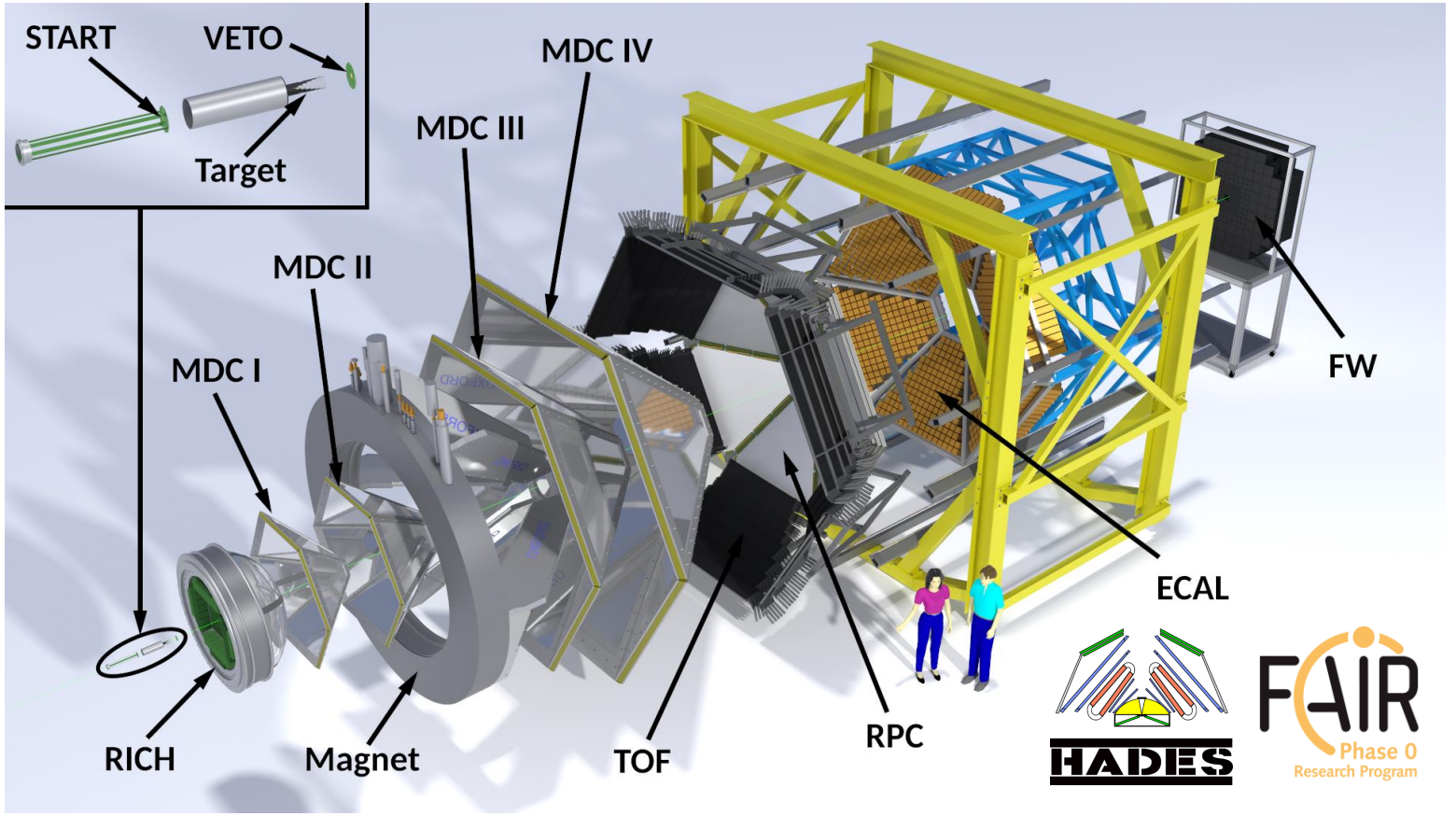
Proton / Pion Beam Experiments

- p+Nb $\sqrt{s_{NN}}$ = 3.2 GeV, 4.2 bil. evts. (2008)
- π+W / π+C / π+PE $\sqrt{s}$ = 1.5 GeV
  1.8 billion events (2014)
- p+p $\sqrt{s}$ = 3.5 GeV, 41.0 billion events (2022)



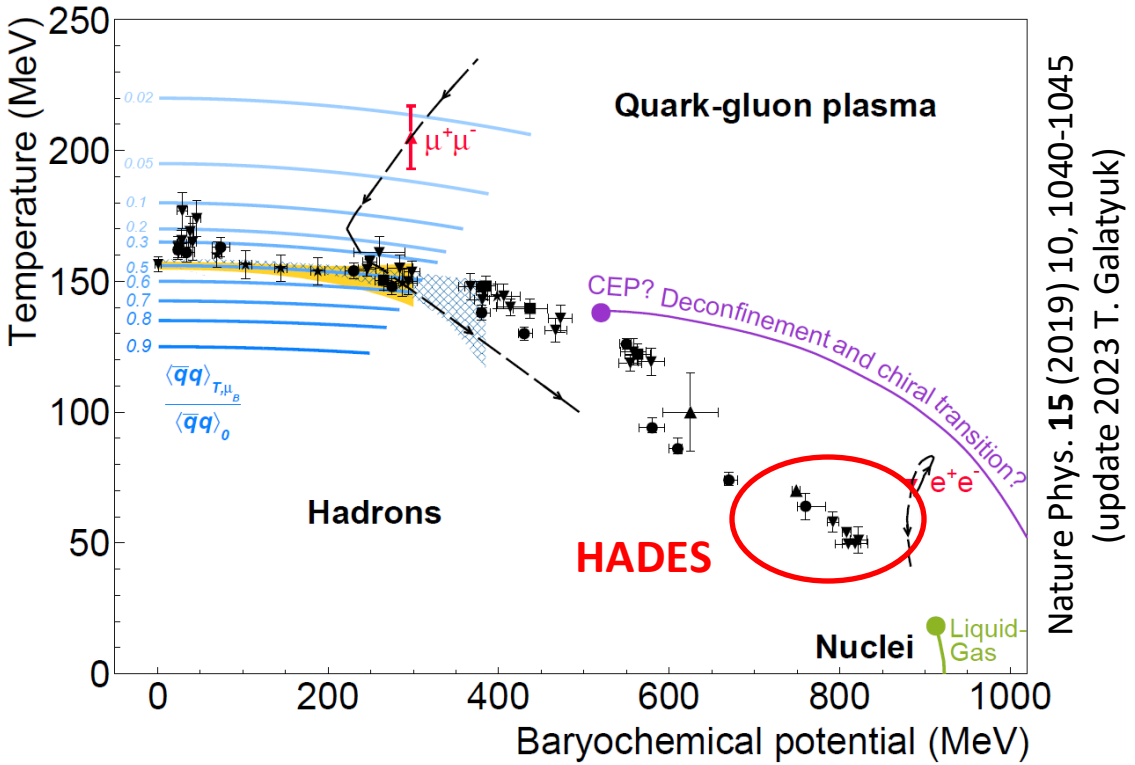
The HADES Experiment (Heavy-Ion Setup)

- Fixed target experiment at SIS18 (GSI, Germany)
- Magnet spectrometer
- Low mass Mini-Drift-Chambers (MDCs)
- Time of flight walls RPC and TOF
- RICH and ECAL for e^+/e^- and photon identification
- Forward hodoscope (FW) for spectator detection



- Almost full azimuthal angle and polar angles between 18° and 85° covered

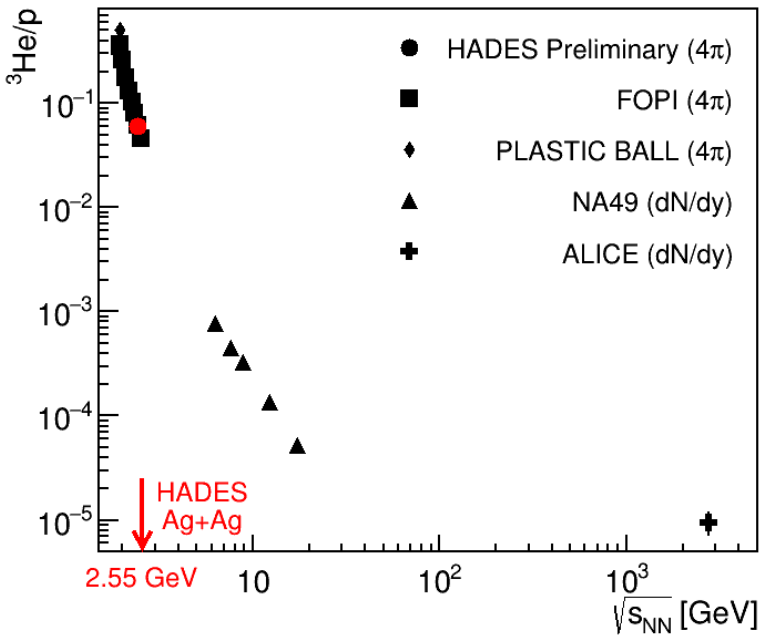
Nuclear Collisions at SIS18/HADES Energies



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)

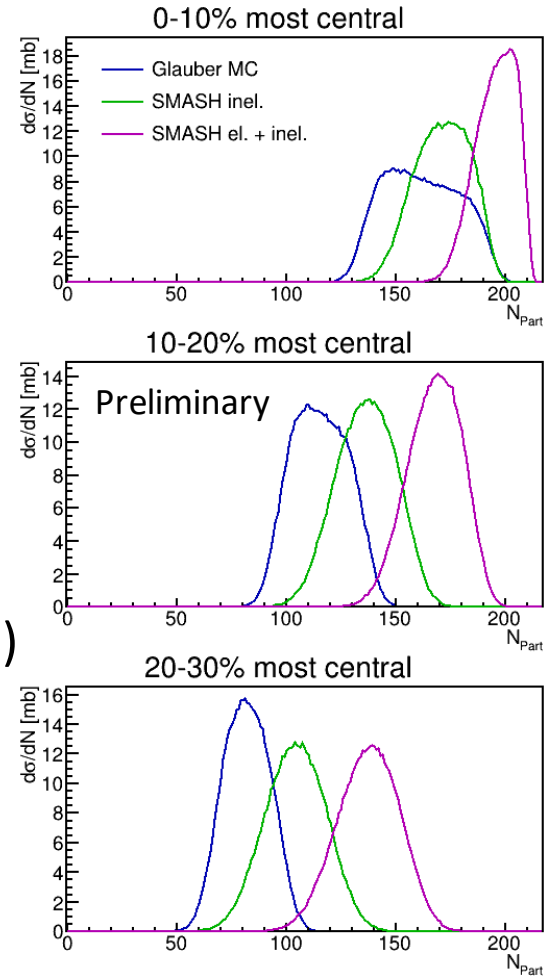
- Nucleons essentially stopped in collision zone
  - ➢ Baryon dominated fireball N(B) ≈ 10 N(π)
- About 50% of protons clustered in light nuclei

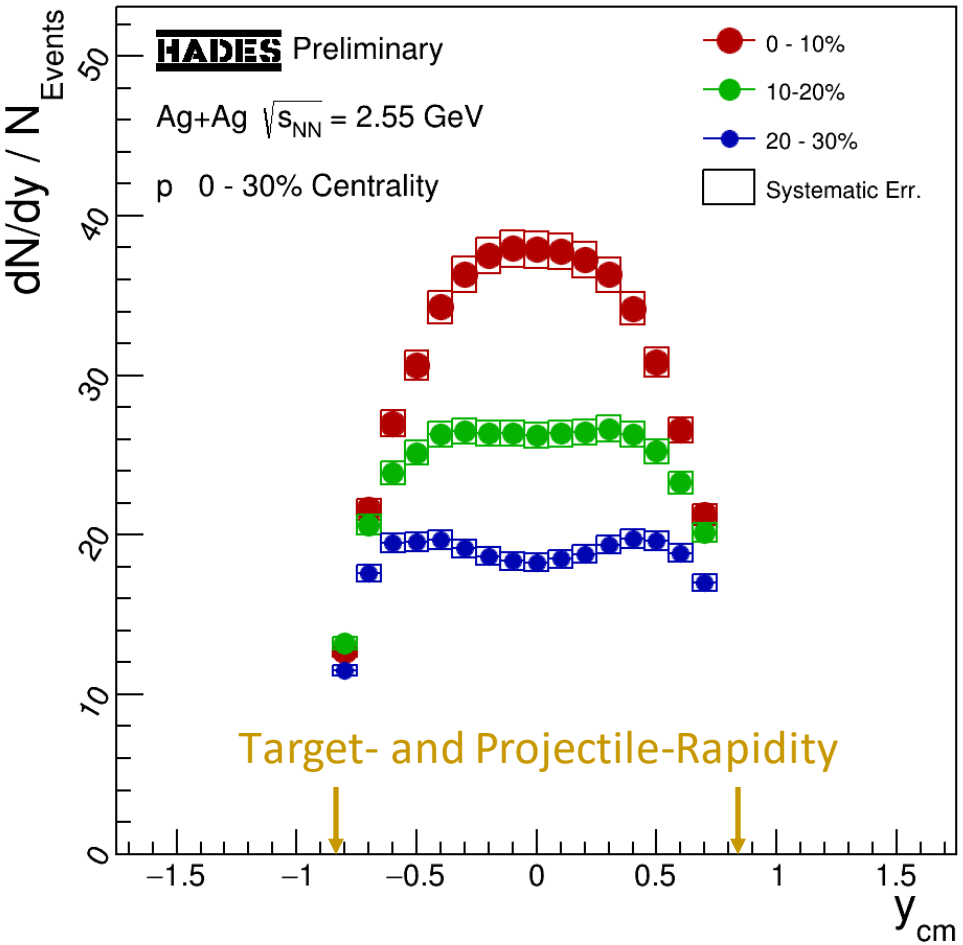


Data Collection:
Phys.Lett.B **809** (2020) 135746
STAR 3 GeV data upcoming

Nuclear Collisions at SIS18/HADES Energies

- Nucleons essentially stopped in collision zone
  - ➢ Detected particles pre-dominantly rescattered nucleons
- Slow spectators – $\beta_{CM} \approx 2/3c$
  - ➢ Secondary interactions in spectator regions (pole caps)
- Centrality estimation more challenging than at high collision energies

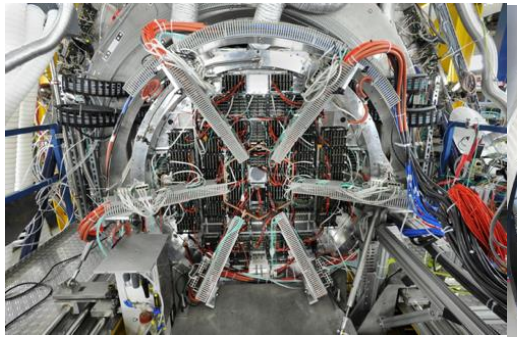


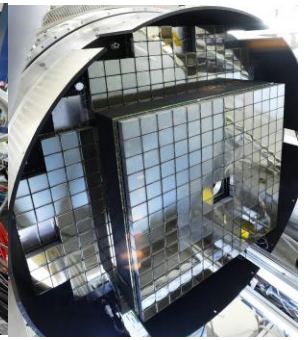


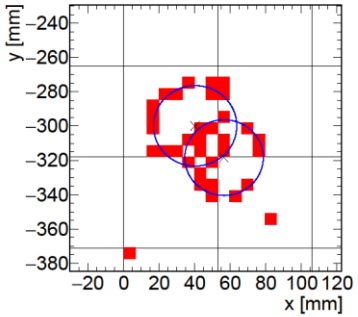
Electromagnetic Probes

Reconstruction and analysis of virtual and real photons

Dilepton Reconstruction Performance

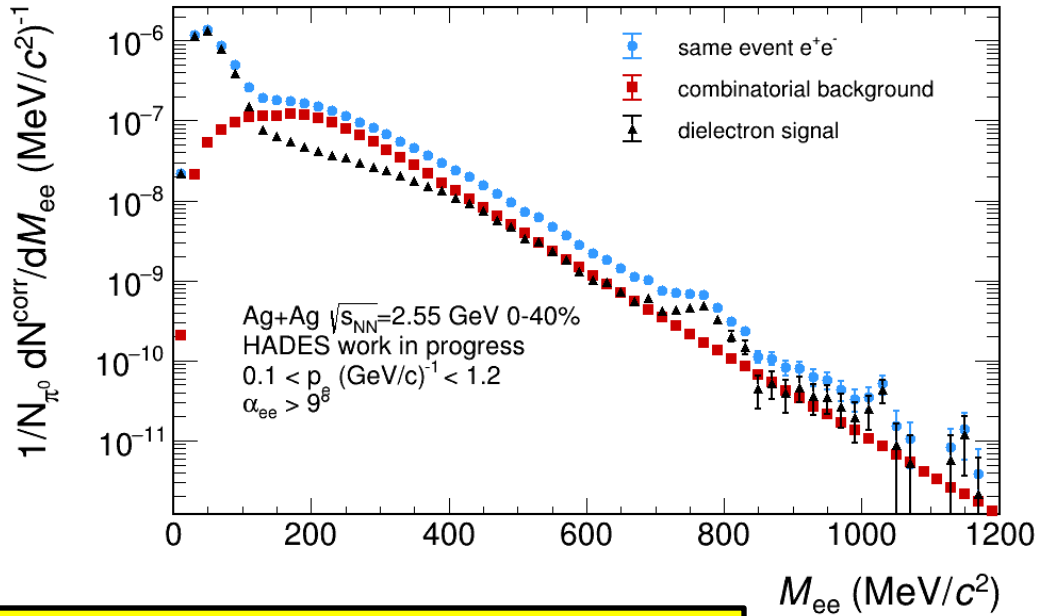






- Upgraded RICH photodetection plane involving future CBM @ FAIR technology
- Good time resolution and increased sensitivity
- Significantly improved lepton identification and double-ring detection → On average 16 hits per ring detected

- Significant statistics up to high invariant mass ≈ 1000 MeV/c^2
- ω(782) and ϕ(1020) signals visible

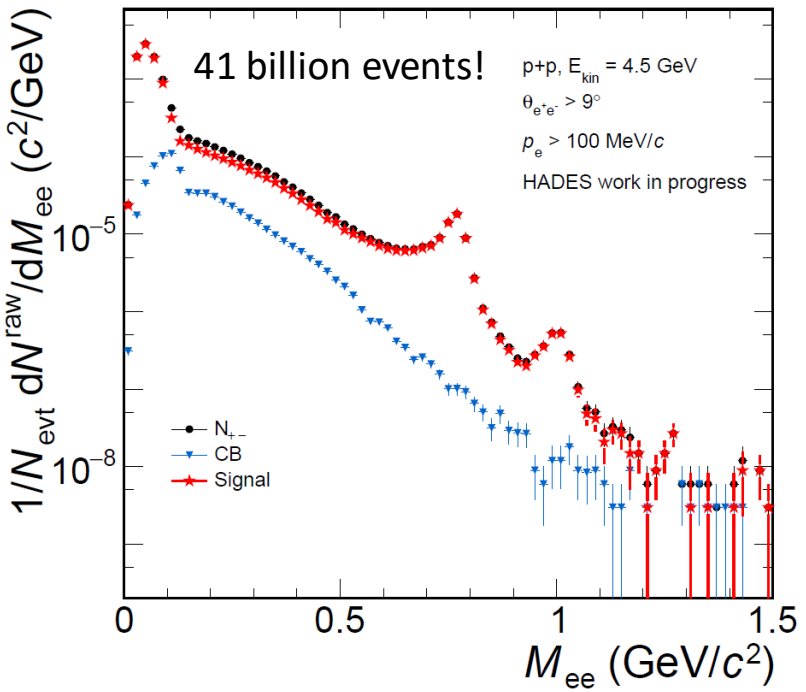


Poster by Karina Scharmann: Contribution 201

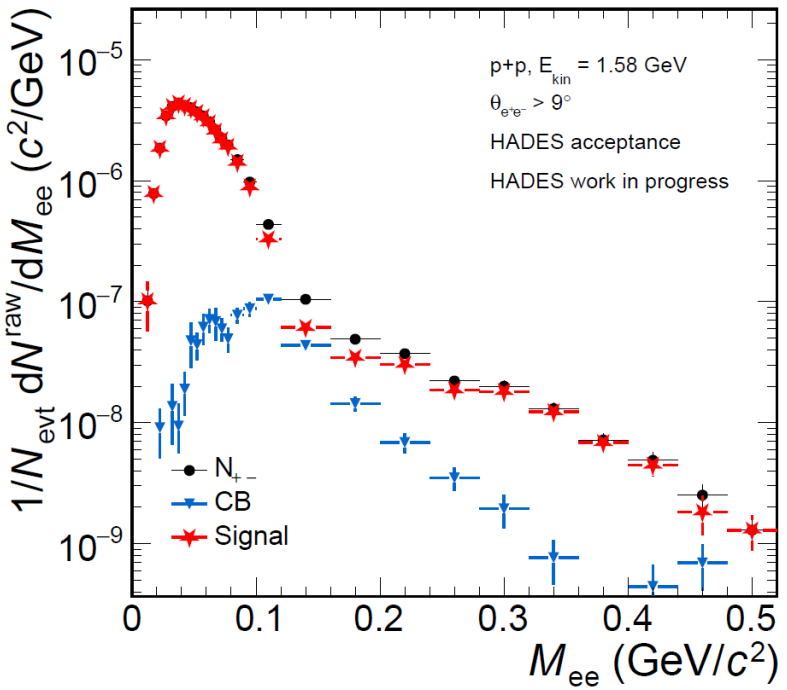
February 2022: p+p $\sqrt{s}$ = 3.5 / 2.55 GeV

- Scientific goals
  - ➢ Decays of excited hyperons
  - ➢ Electromagnetic transition form factors of hyperons
- Inclusive dilepton spectrum
  - ➢ High statistics in the ϕ(1020) invariant mass region and above
  - ➢ Clear signals for ω(782)and ϕ(1020)

p+p $\sqrt{s}$ = 3.5 GeV

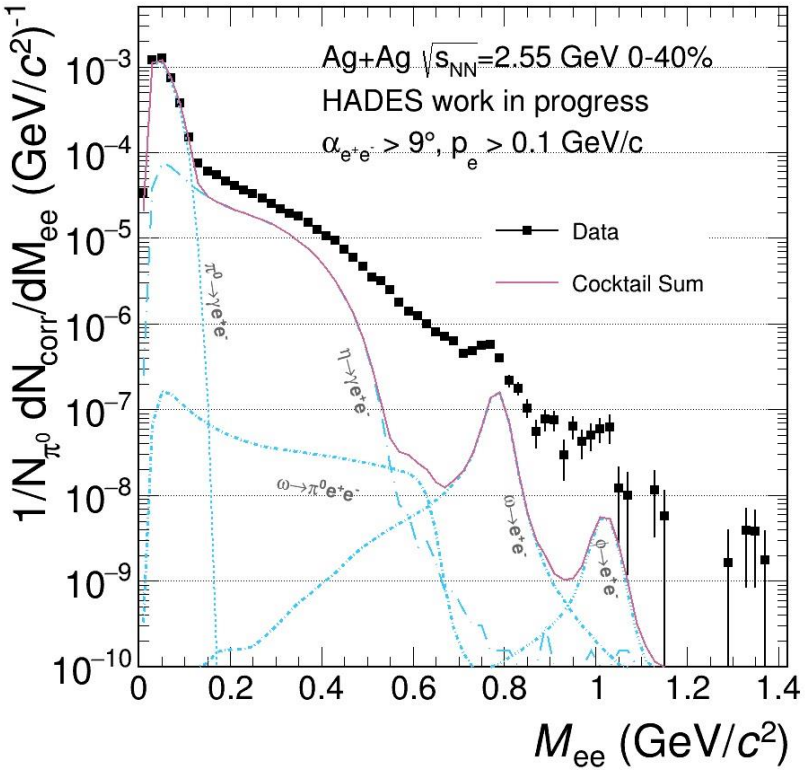


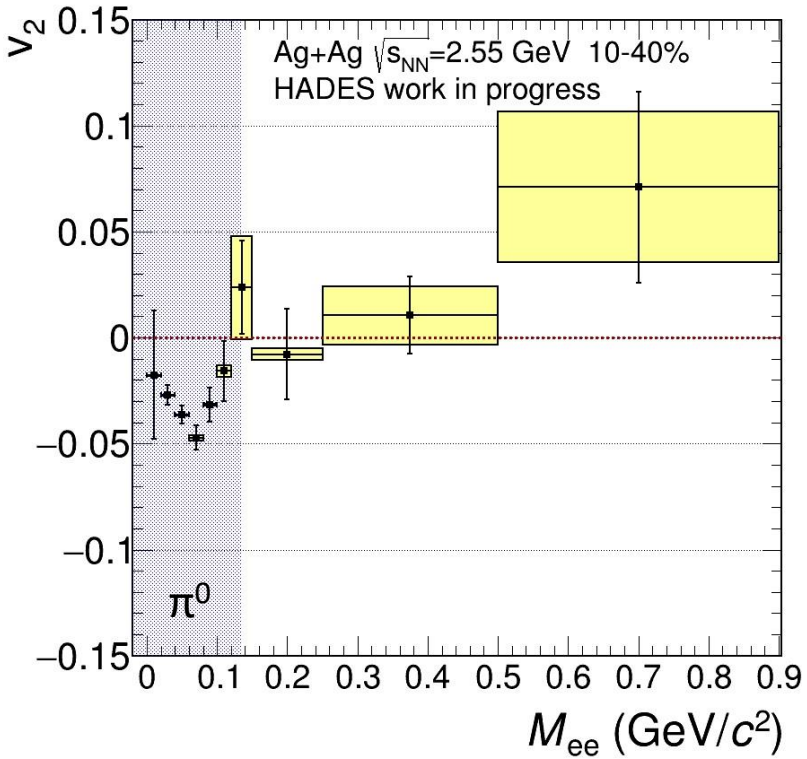
p+p $\sqrt{s}$ = 2.55 GeV

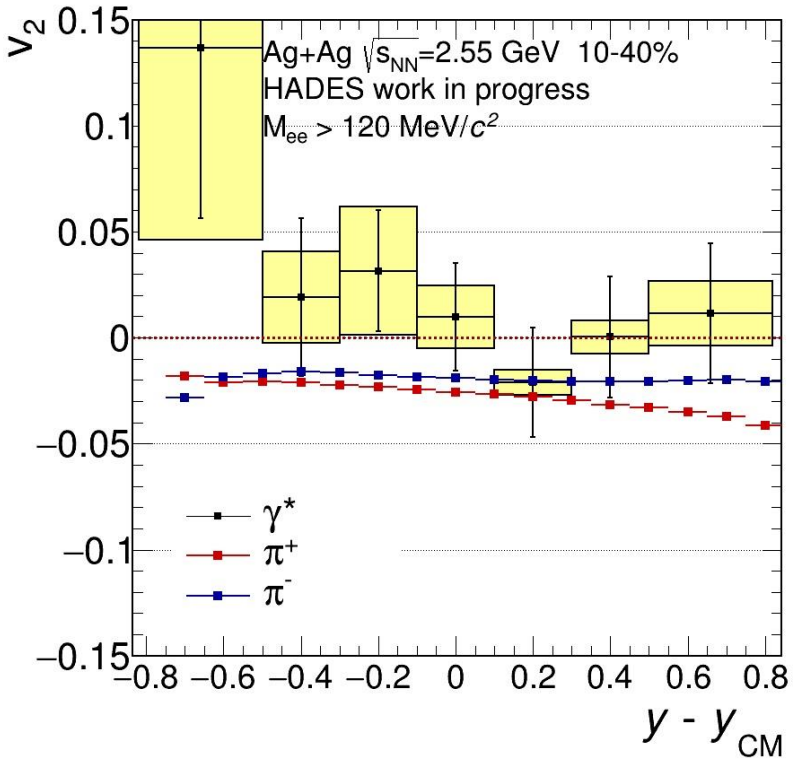


Poster by Karina Scharmann: Contribution 201

Dilepton Spectra and Flow from Ag+Ag







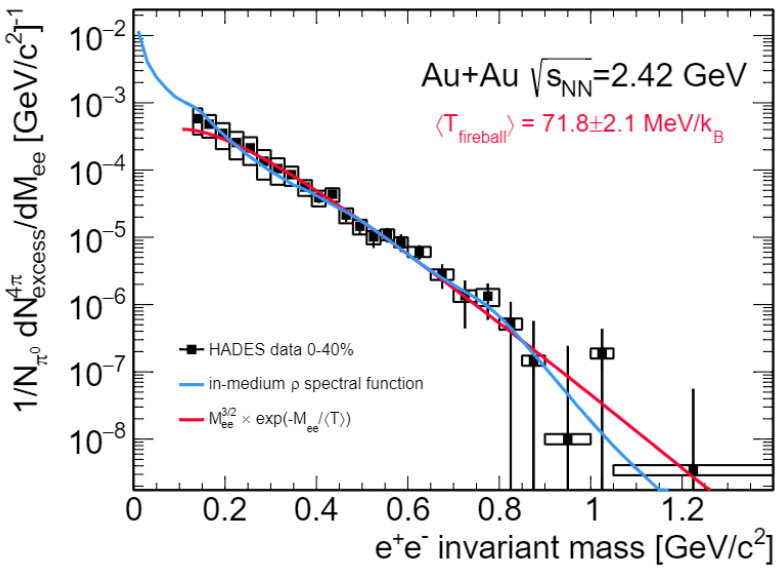
- Negative π^0 flow observed at $M_{ee} < 120$ MeV
- v_2 becomes 0 at $M_{ee} > 120$ MeV → Dileptons are penetrating probes

Poster by Niklas Schild:
Contribution 683

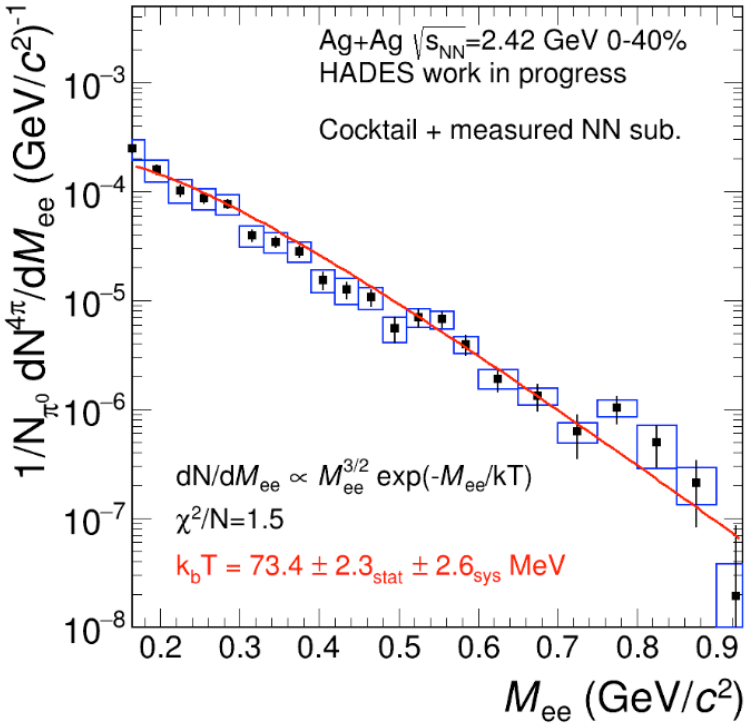
Dilepton Excess Radiation

Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV

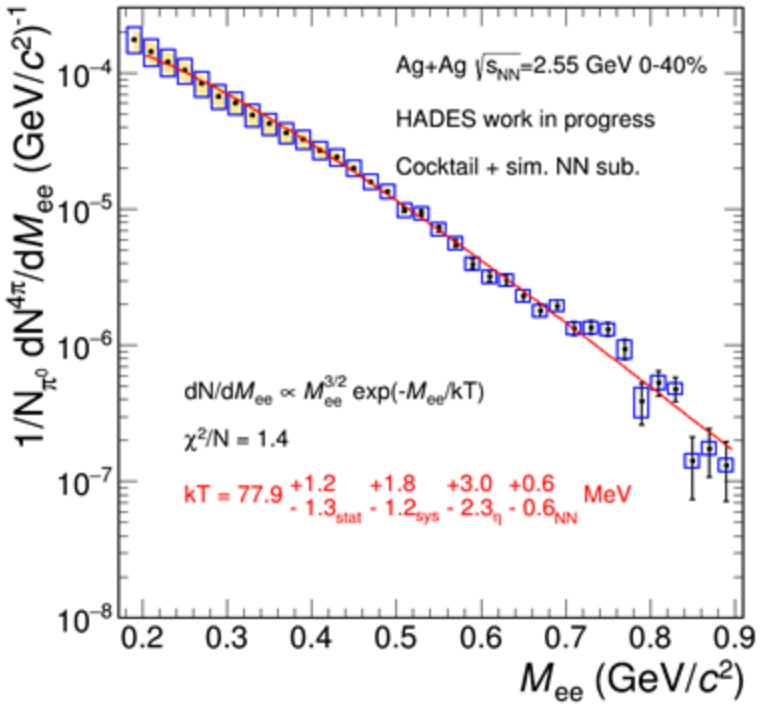
Nature Phys. **15** (2019) 10, 1040-1045



Ag+Ag $\sqrt{s_{NN}}$ = 2.42 GeV



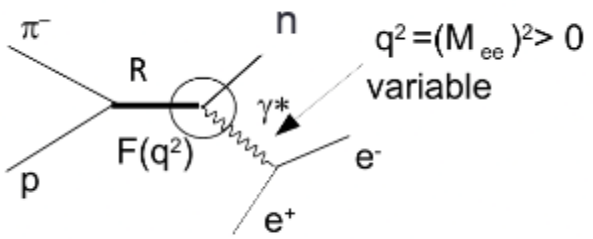
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV

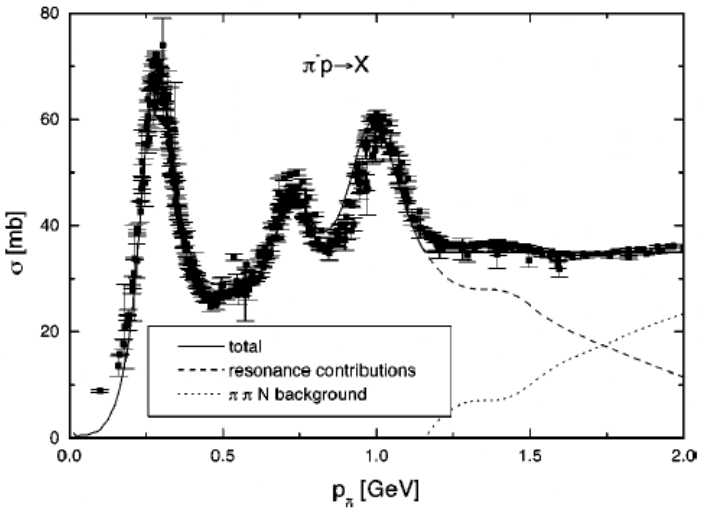


- VDM describes excess radiation in heavy-ion reactions properly using coarse graining approach!

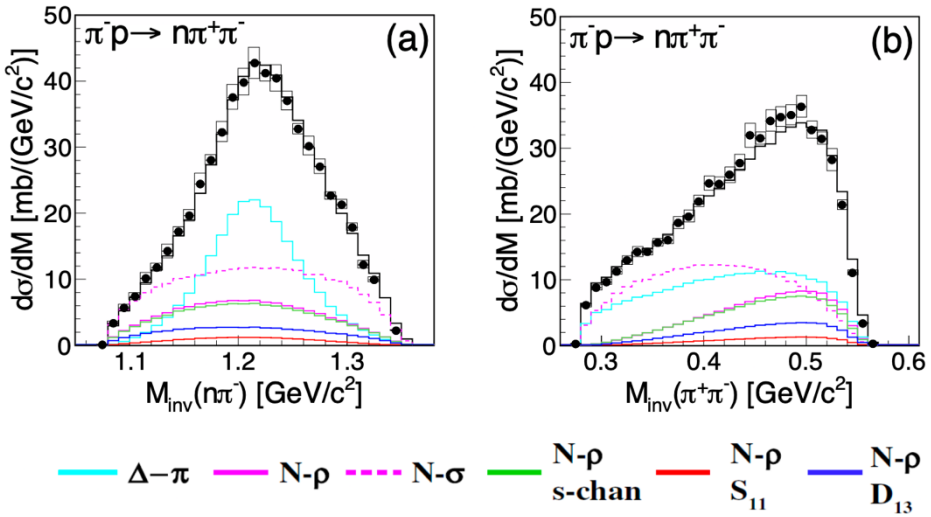
First direct evidence that VDM works for baryons

- Studying Baryon-ρ coupling using Pion-induced reactions
- p_π = [0.66, 0.69, 0.75, 0.80] GeV/c
  - ➢ Second resonance region





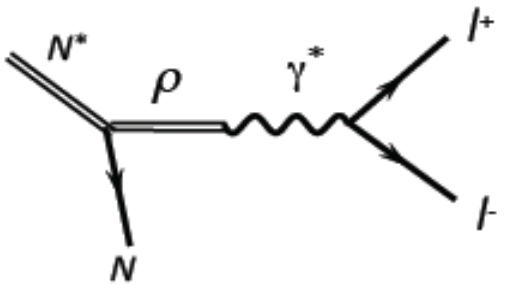
- Partial wave analysis of exclusive $\pi^- + p \rightarrow n + \pi^+ + \pi^-$ channel



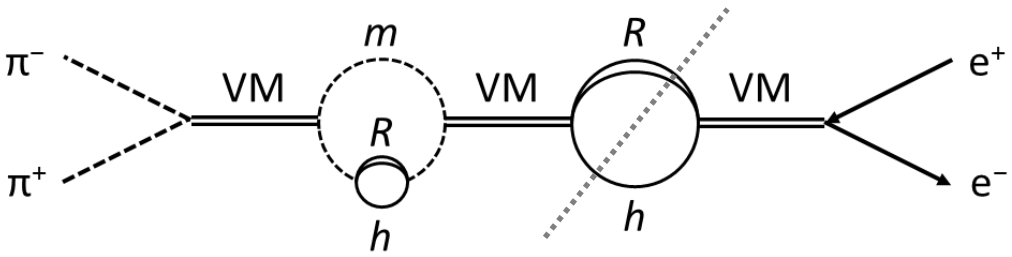
- $\pi^- + p \rightarrow n + \pi^+ + \pi^-$
  - ➢ PWA using Bonn/Gatchina code with invariant masses and angular distribution (not shown)
- $\pi^- + p \rightarrow n + e^+ + e^-$
  - ➢ Predict dilepton emission using strict VDM
  - ➢ Comparison to different approaches and models

First direct evidence that VDM works for baryons

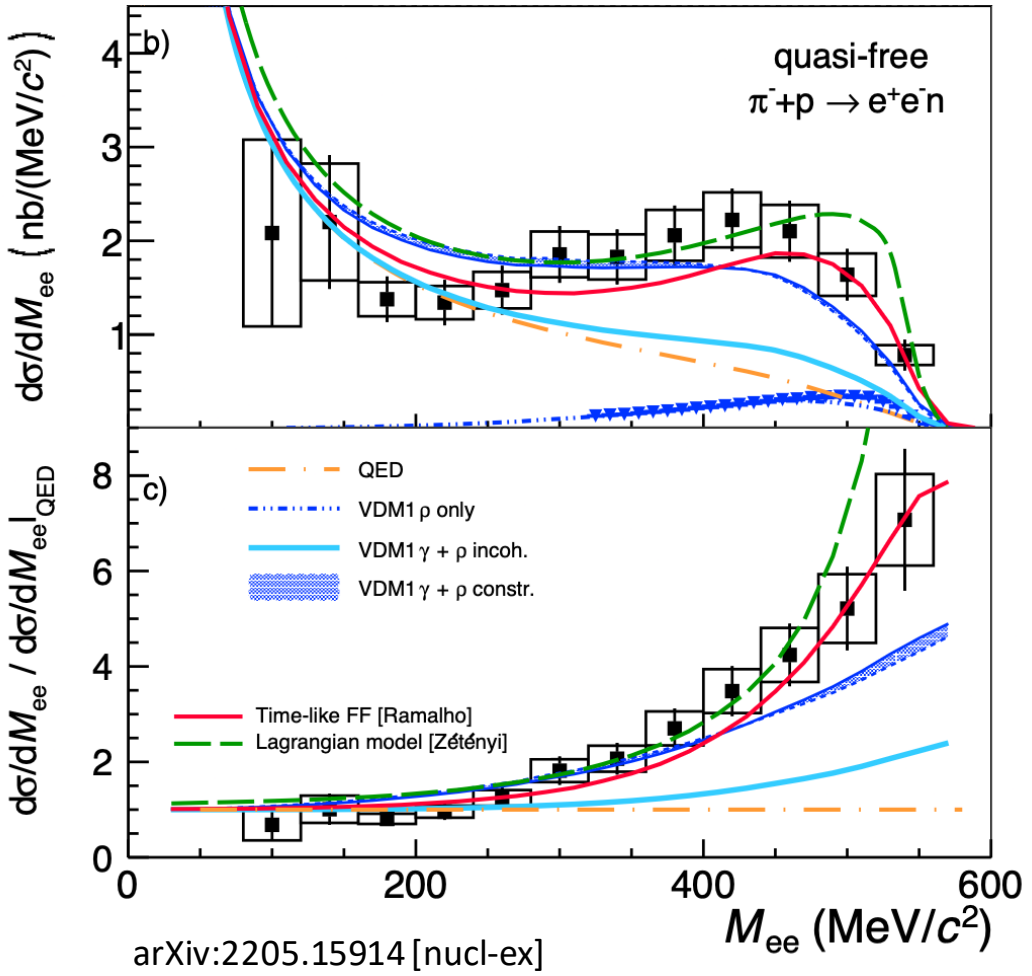
- $\pi^- + p \rightarrow n + e^+ + e^-$



- Modification of vector mesons in a baryon-rich environment (VDM: Medium-Emissivity)



- Effective **transition form factor** (time-like) extracted by subtracting QED expectation from exclusive invariant mass distribution



arXiv:2205.15914 [nucl-ex]

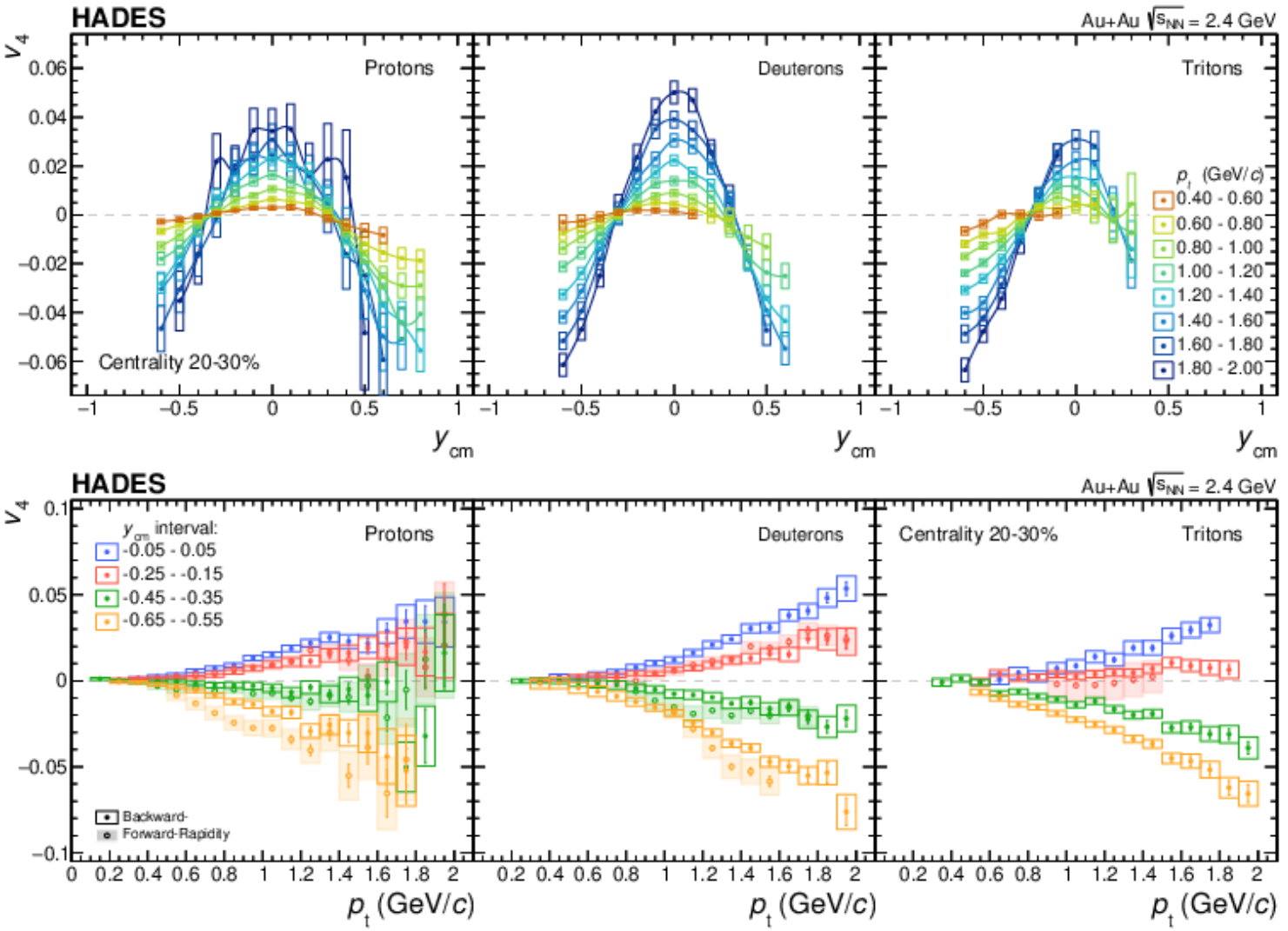
Collective Phenomena

Flow, Correlations, Fluctuations of (abundant) particles

Flow (Au+Au)

- High precision measurement of Proton, Deuteron and Triton flow coefficients up to v_4
  Eur.Phys.J.A **59** (2023) 4, 80
- Important input to model calculations to constrain of EoS of compressed baryonic matter
- Correlations of flow coefficients can be studied event-wise

Poster by Behruz Kardan, (Christoph Blume): Contribution 304



Eur.Phys.J.A **59** (2023) 4, 80

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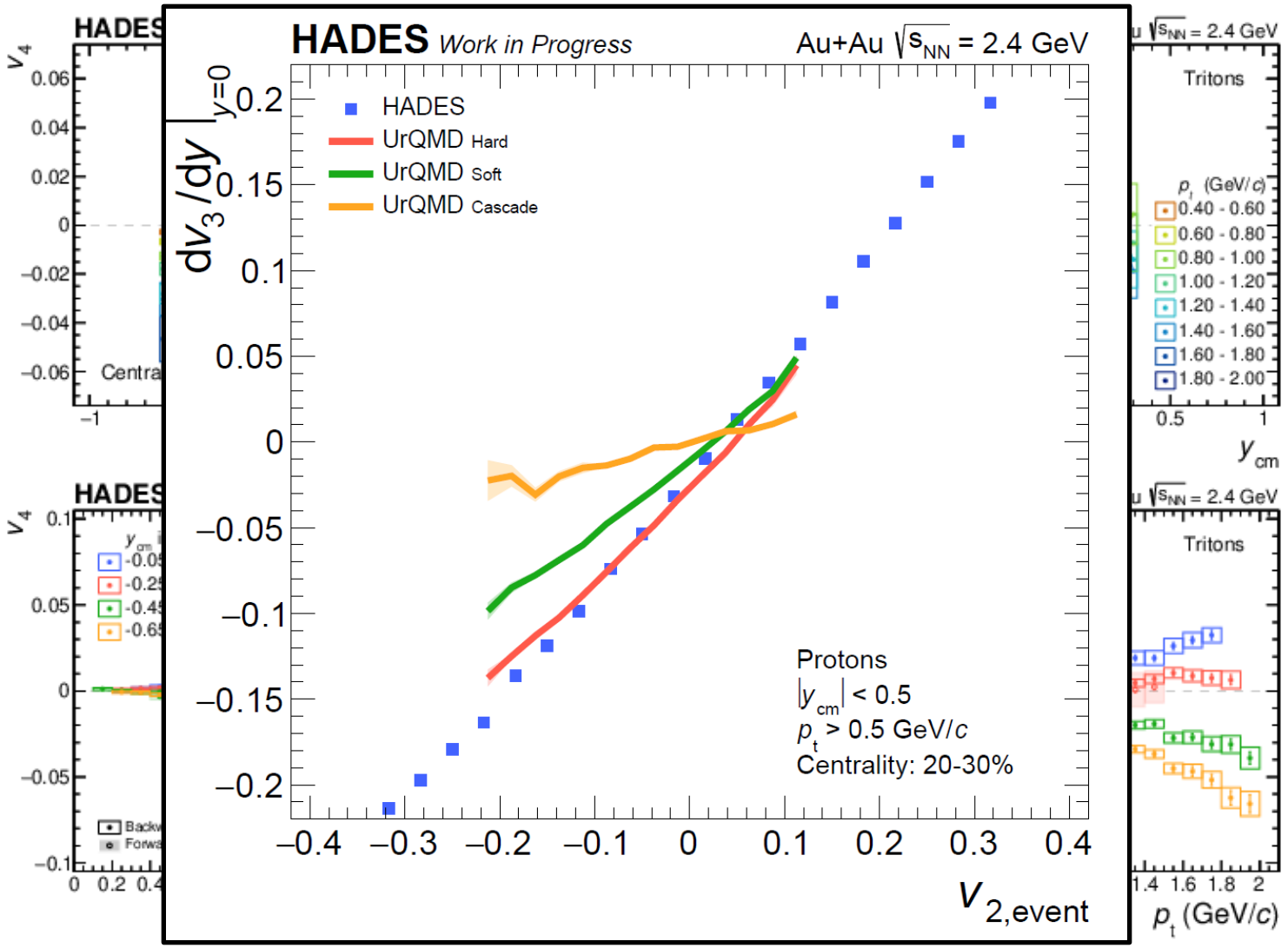


UrQMD Simulations: EPJ C **82** (2022) 510

Two-Particle Femtoscopy Correlations

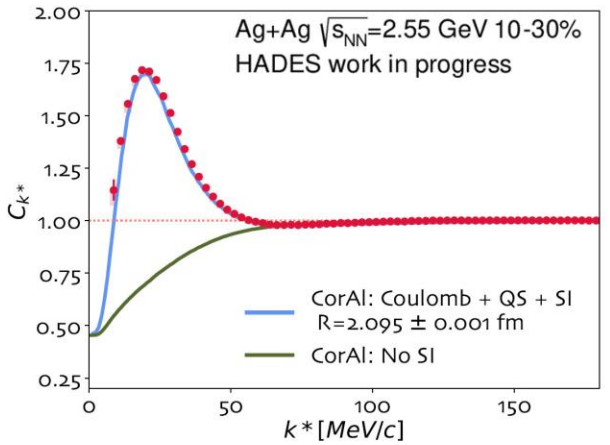
- High precision measurement of correlation functions of Protons, Deuterons, Tritons and Helium3, as well as Proton - Λ and γ - γ

- Direct access to study the interactions determining the EoS of compressed baryonic matter including Hyperons

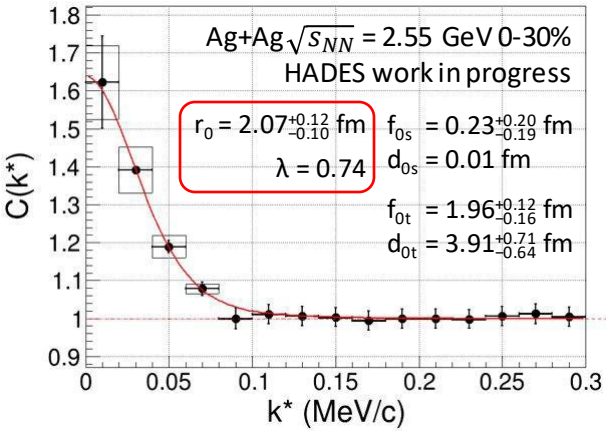
Talk by Mateusz Grunwald
Wednesday 06.09.2023 16:30

Poster by Maria Stefaniak:
Contribution 682

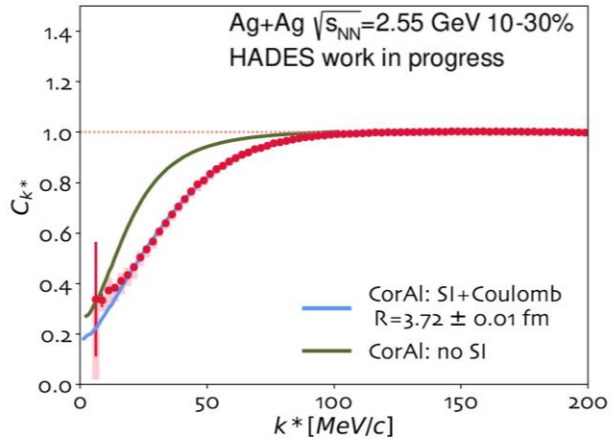
Proton - Proton



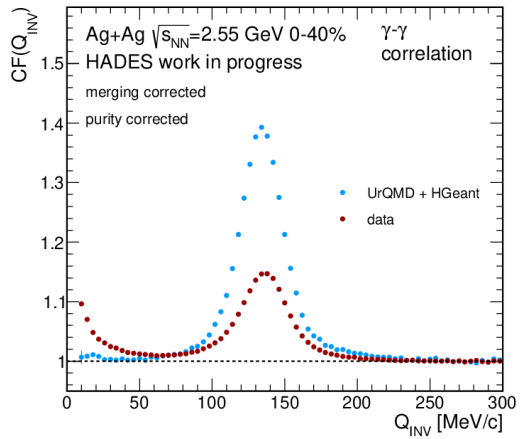
Proton - Λ



Proton - Deuteron

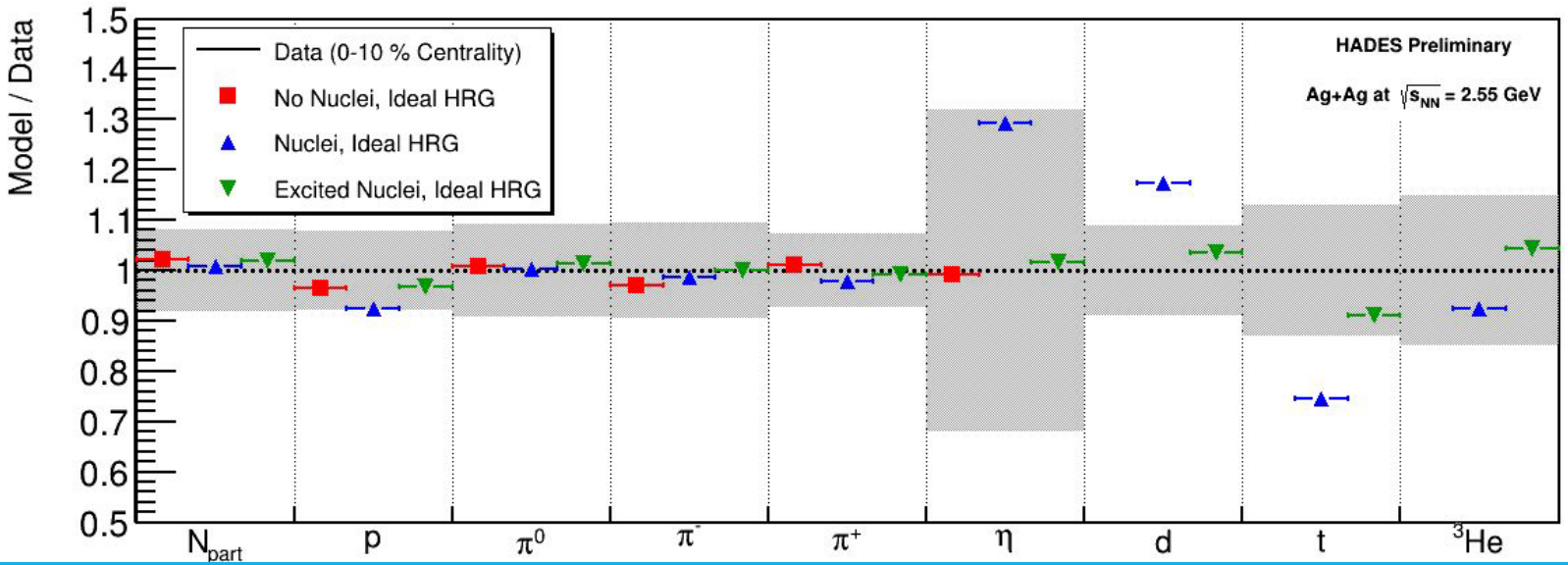


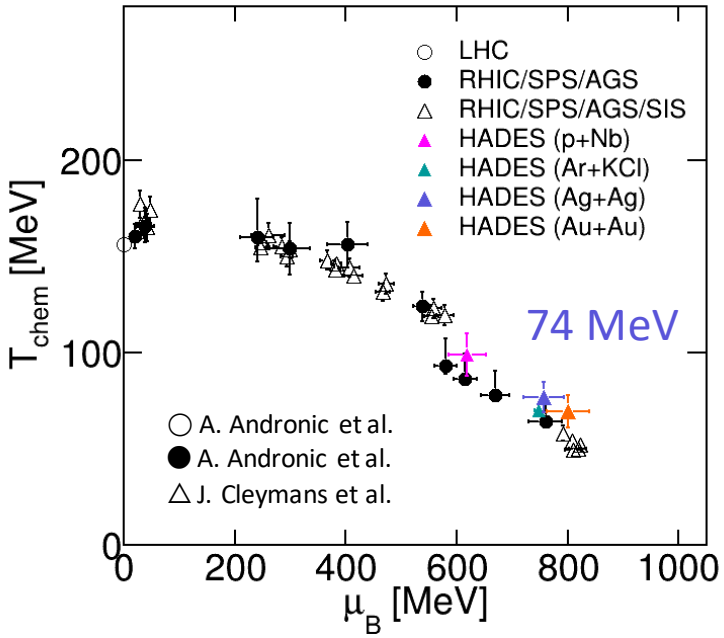
γ - γ



Statistical Hadronization Model

- Production rates of non-strange hadrons reproduced by SHM
  - ➢ Ideal hadron resonance gas model sufficient
  - ➢ Feed-down from excited nuclei states needs to be considered
- Chemical freeze-out point aligns well with world data



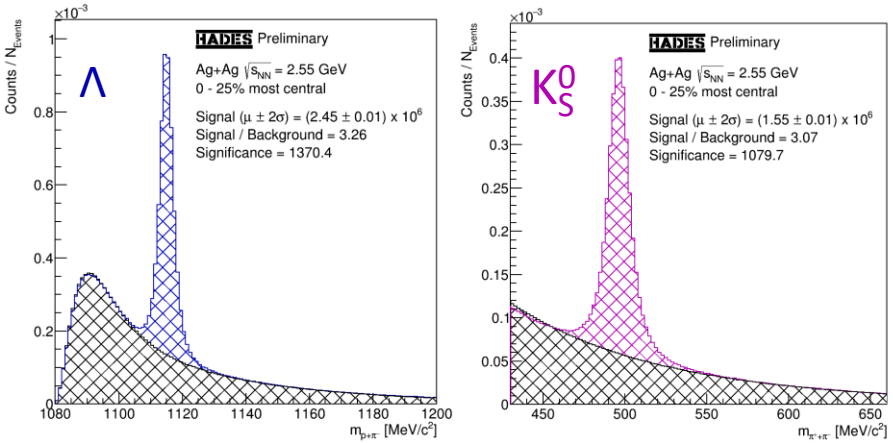


Poster by Marvin Kohls: Contribution 622

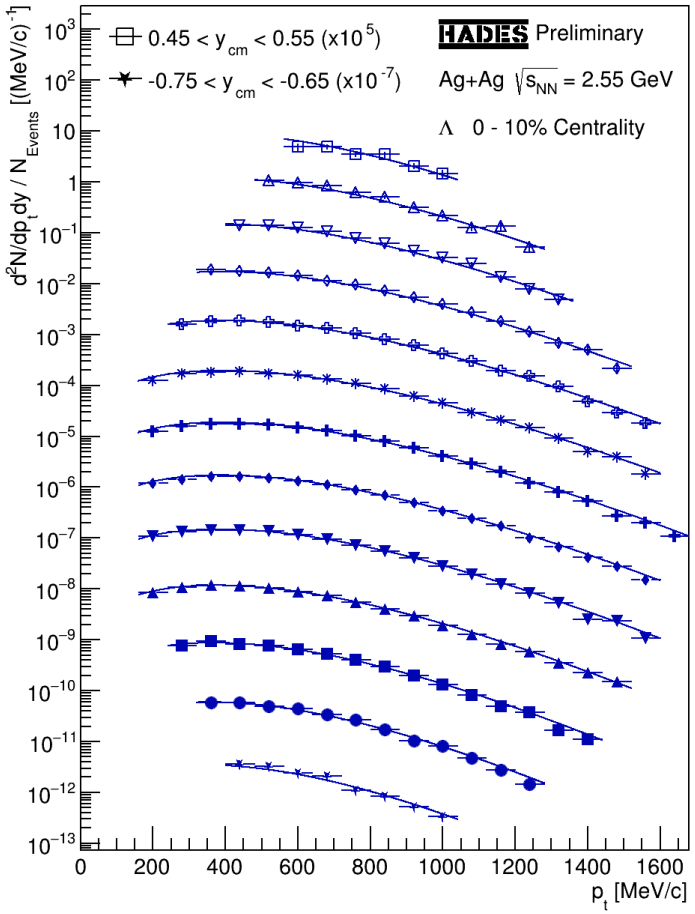
Strange Hadrons

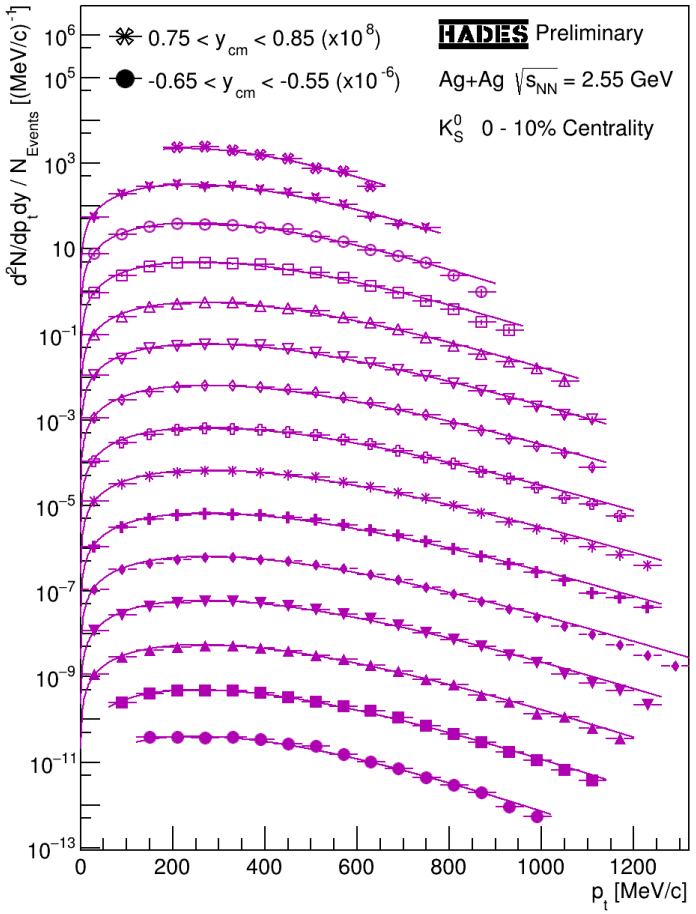
Reconstruction and analysis of hadrons containing strangeness

Weak Decay Reconstruction Performance



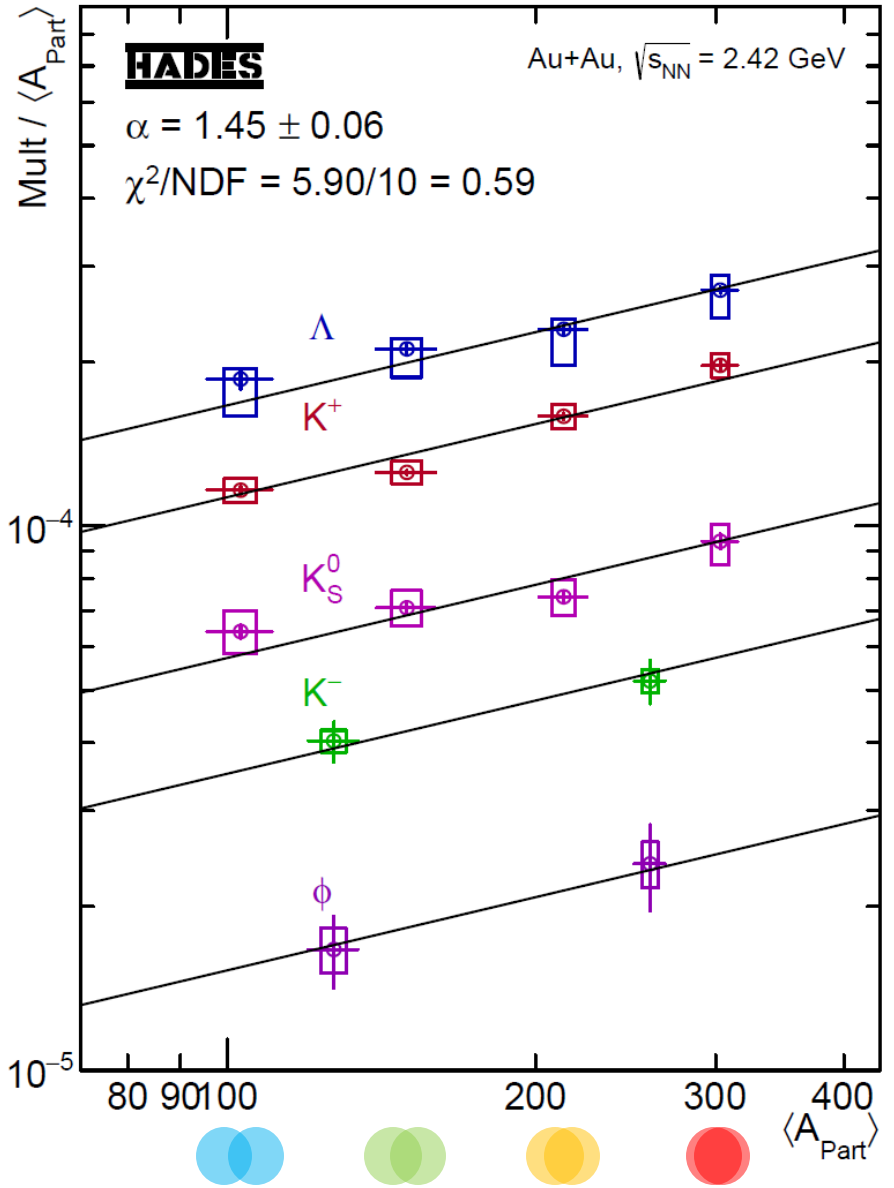
- Large phase space coverage with low statistical errors
- Data points well described by Boltzmann functions
  - ➢ Extrapolation to 4π





Strange Yields vs. $\langle A_{Part} \rangle$

- Production below (at) free NN-threshold
  - Missing energy provided by the system
- Centrality dependence compatible with universal scaling assumption:
  Mult $\propto \langle A_{Part} \rangle^{\alpha}$ with $\alpha_{Au+Au} = 1.45 \pm 0.06$
  - Hierarchy in production thresholds not reflected
  - Suggests scaling with primary $s\bar{s}$ creation
  - Hint for quark percolation
    K. Fukushima, T. Kojo, W. Weise, PRD **102**, 096017 (2020)



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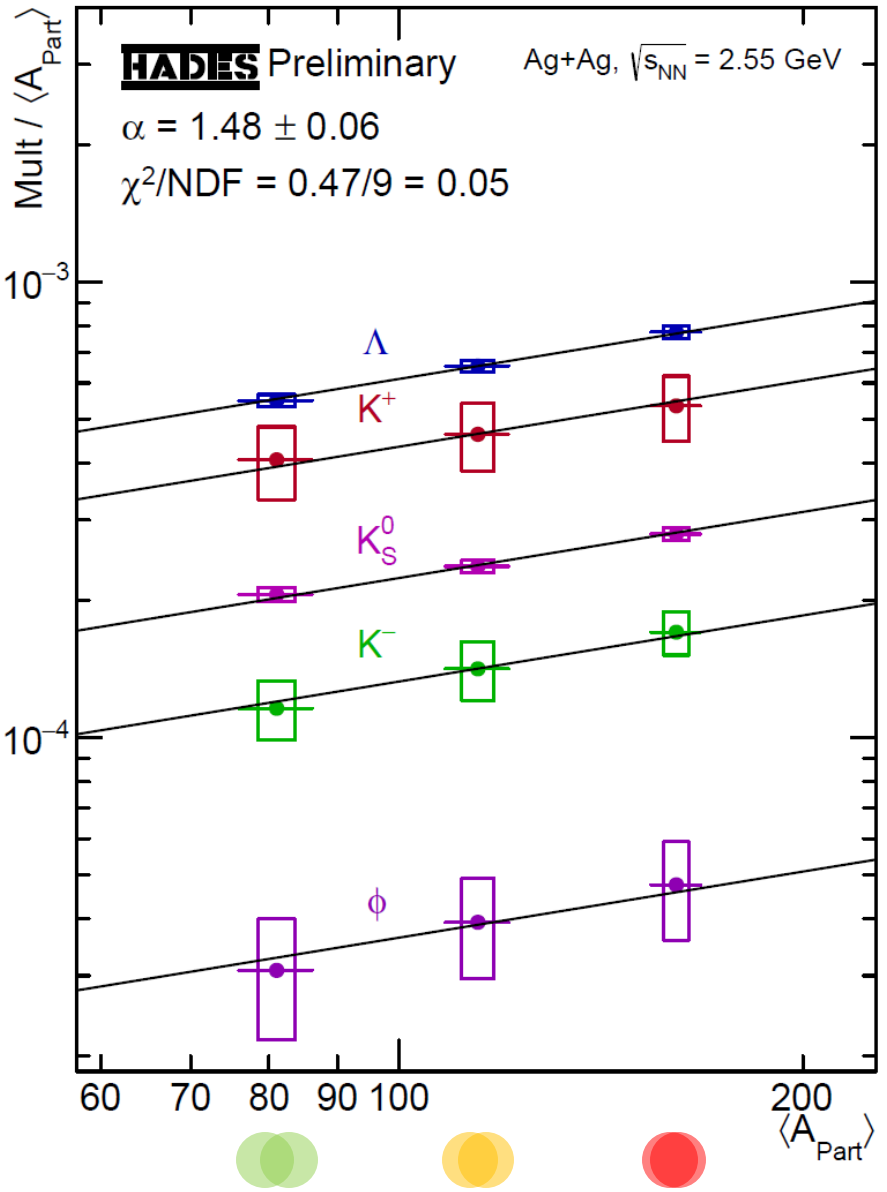
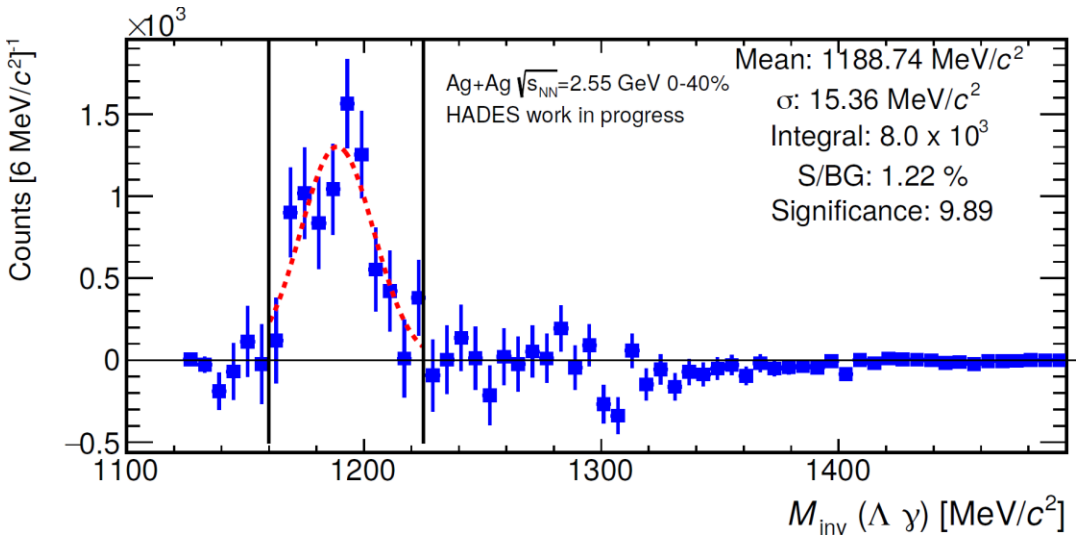
  - ➢ Hint for quark percolation
    K. Fukushima, T. Kojo, W. Weise, PRD **102**, 096017 (2020)
- Ag+Ag: identical slope within errors $\alpha_{Ag+Ag} = 1.48 \pm 0.06$

Poster by Marvin Kohls: Contribution 622

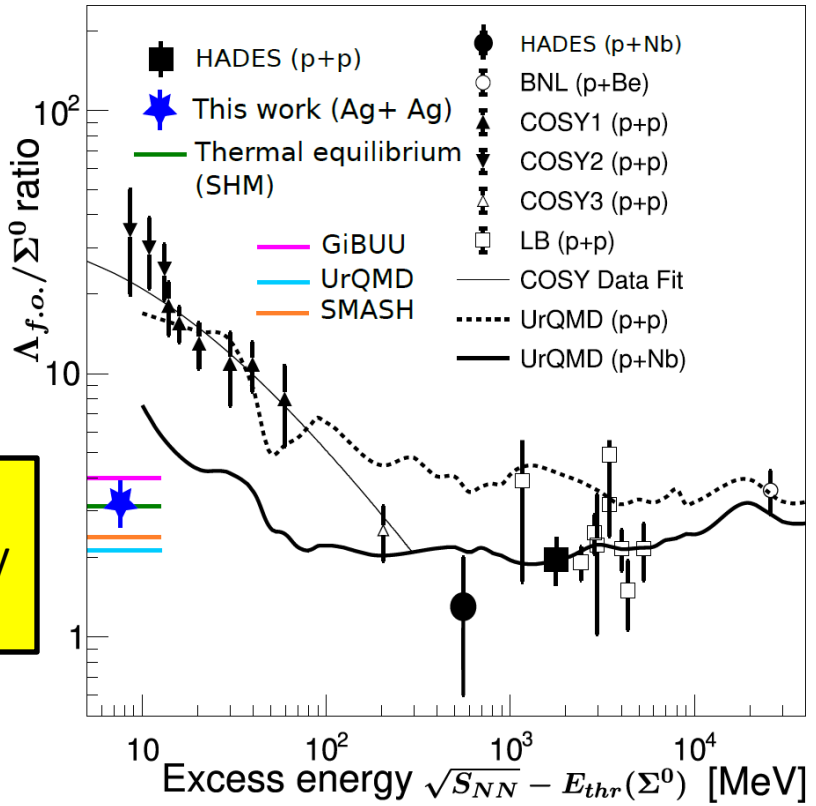


Reconstruction of Σ^0 Hyperons

- Σ^0 Hyperons measured via their two-step electro-weak decay chain: $\Sigma^0 \rightarrow \Lambda + \gamma \rightarrow p + \pi^- + \gamma$
- SHM capable of describing Λ / Σ^0 ratio almost perfectly
- Λ / Σ^0 ratio sensitive to differences between transport models



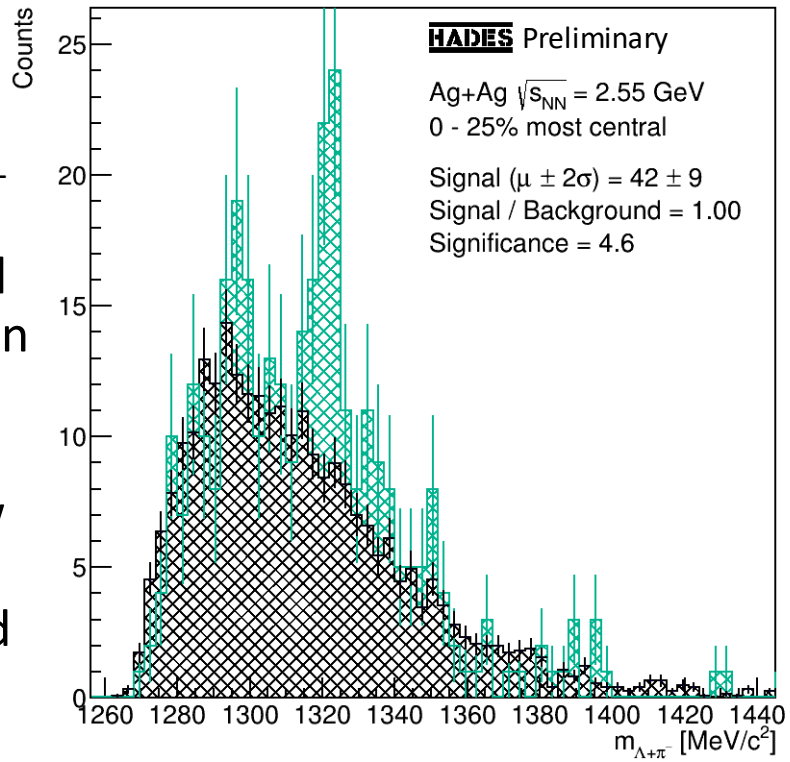
Talk by Marten Becker Wednesday 06.09.2023 10:10

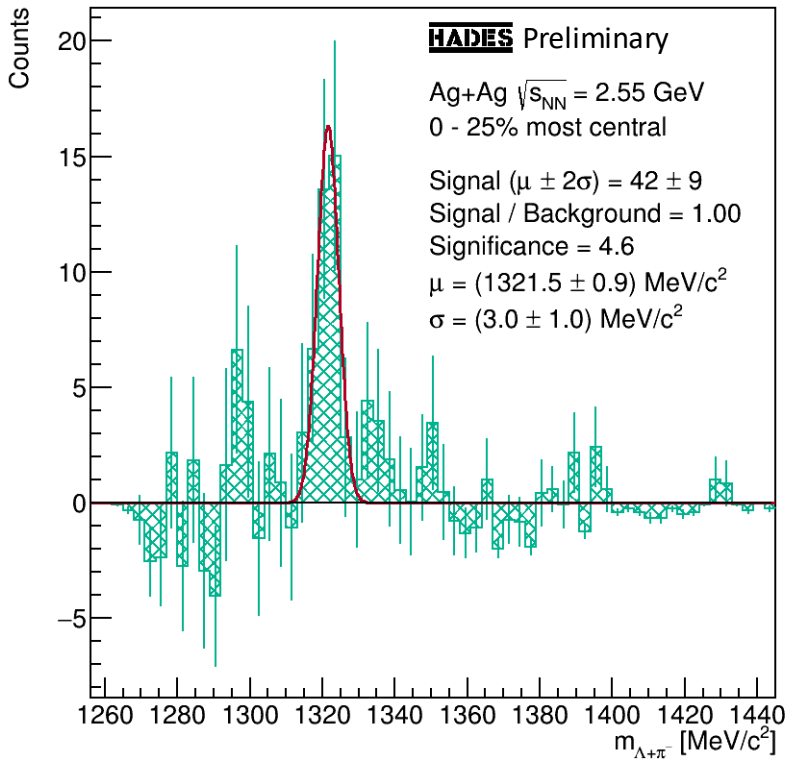


➢ Possibility to investigate differences between various SHM fits and transport models

Reconstruction of double-strange Ξ^- Hyperons

- Ξ^- Hyperons measured via their double-weak decay chain:
  $\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^- + \pi^-$
  - ➢ Excellent combinatorial background suppression enabled by two aNN
- Significance slightly below 5σ yet clear signal above combinatorial background observable



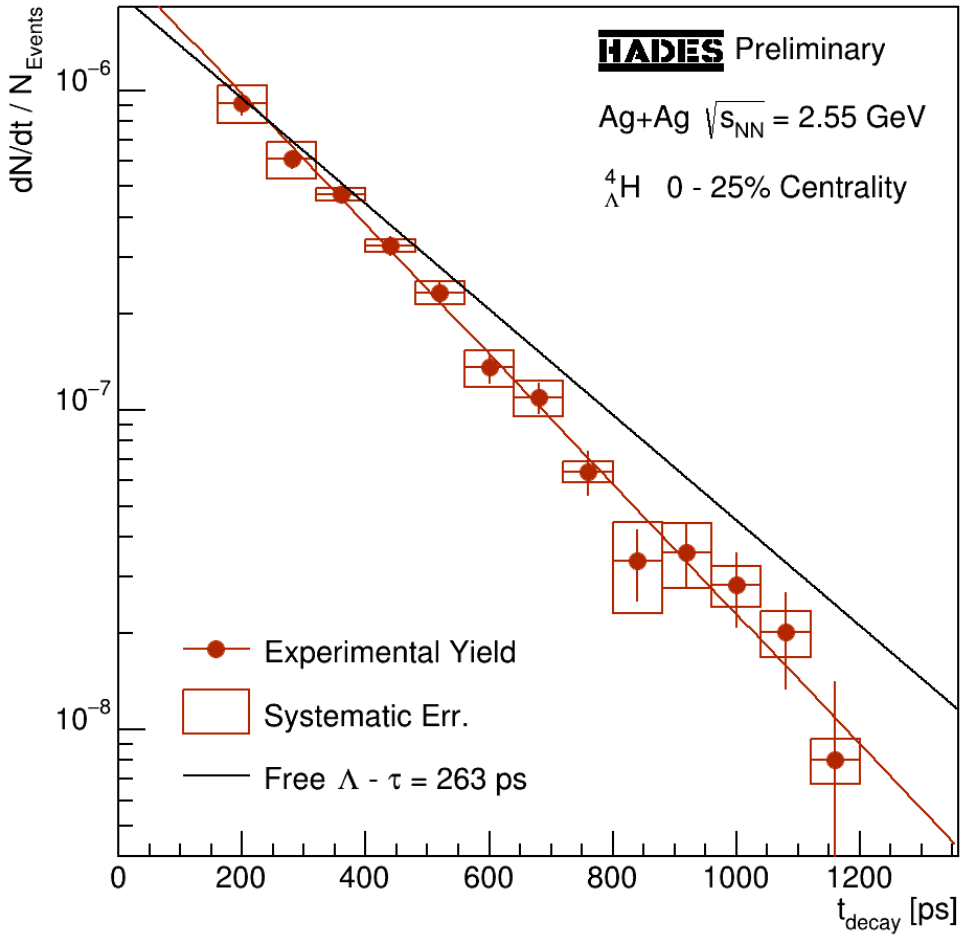


- First measurement of double-strange Ξ^- Hyperons in few GeV heavy-ion collisions
- Outlook: Improved reconstruction efficiencies using KFParticle package

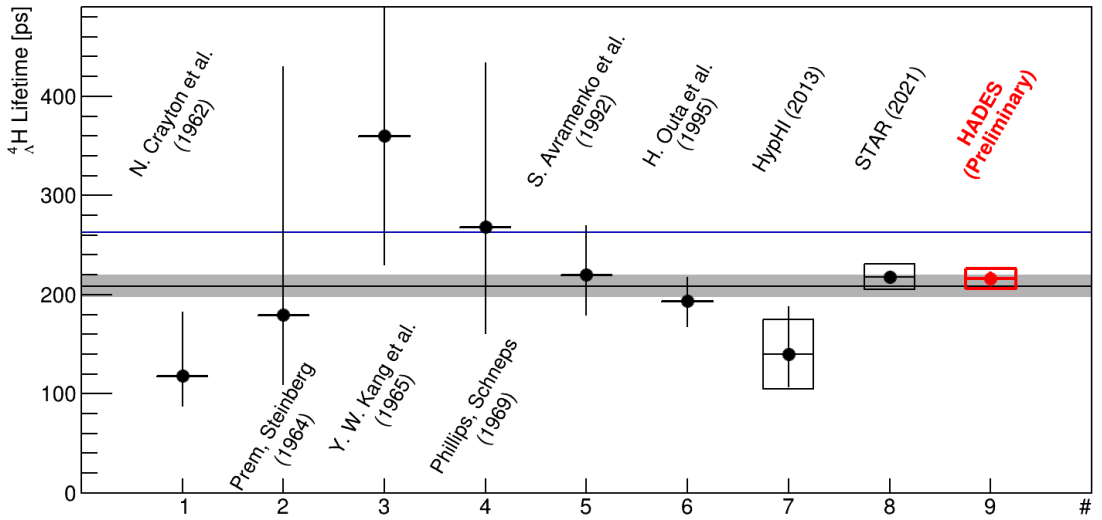
Hypernuclei

Reconstruction and analysis of Hypernuclei

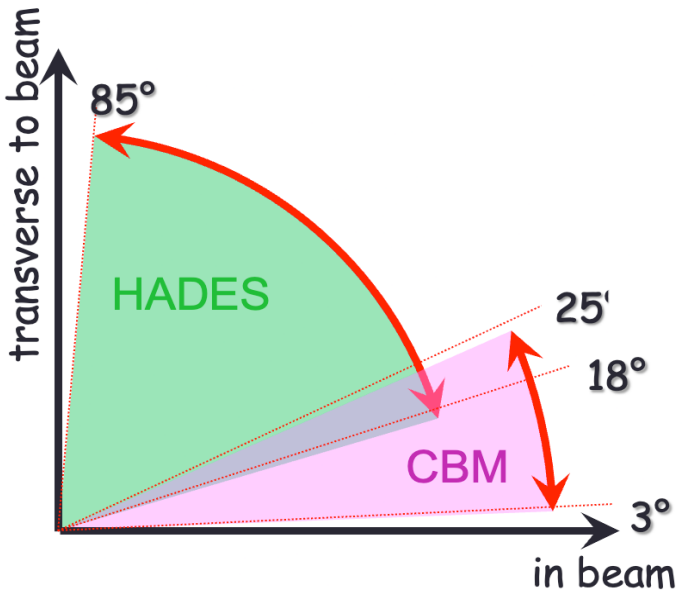
Hypernuclei Lifetime Measurements

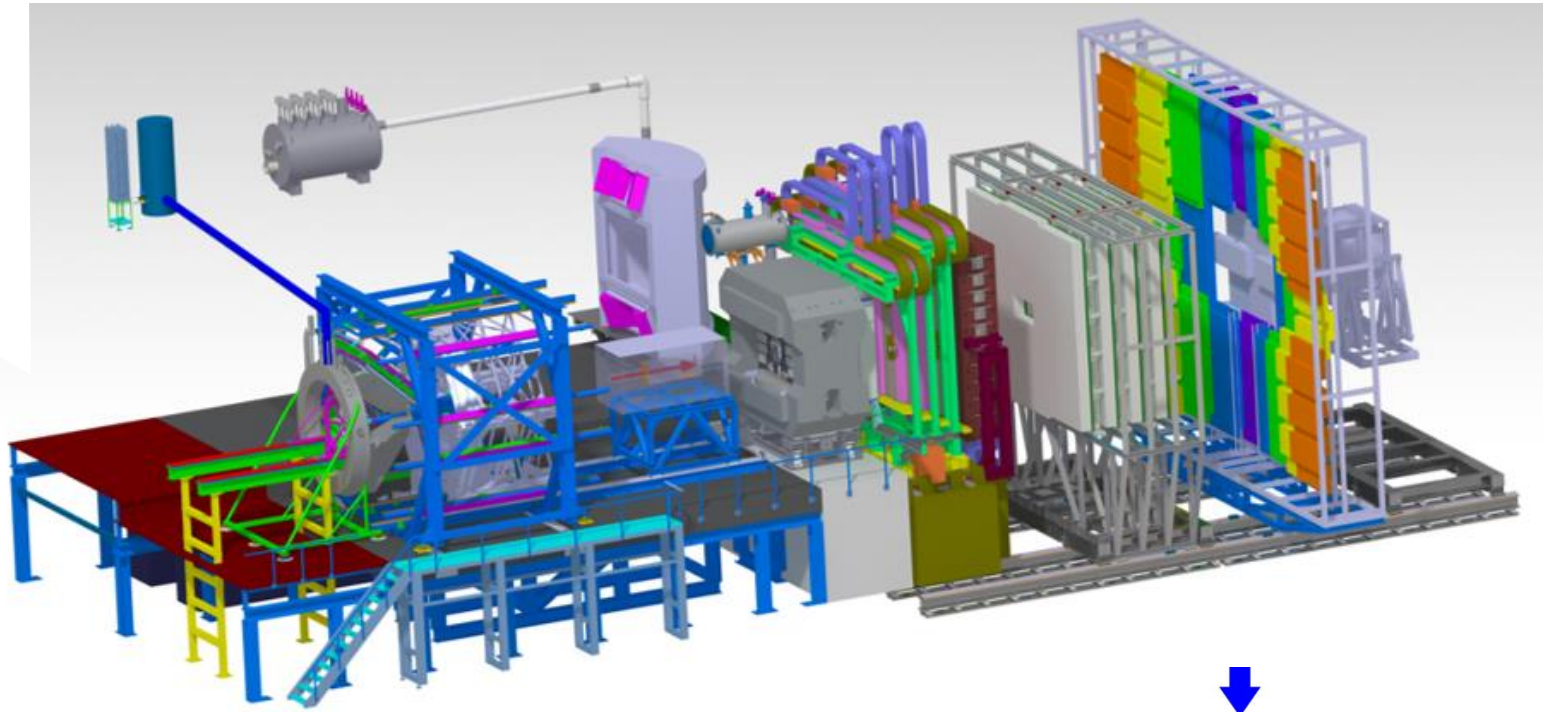


- $^3_\Lambda$H lifetime of $(251 \pm 21_{stat} \pm 30_{sys})$ ps compatible with free Λ lifetime and earlier measurements measured
- $^4_\Lambda$H lifetime of $(216 \pm 7_{stat} \pm 10_{sys})$ ps measured
  - ➢ 4.85σ deviation to free Λ lifetime
- Interaction cross-section within first 40cm of HADES detector material $\lesssim$ 0.5%



Outlook: HADES and CBM @ SIS100





- HADES and CBM will be operated at the SIS100
- Angular coverage of both detectors complementary

HADES

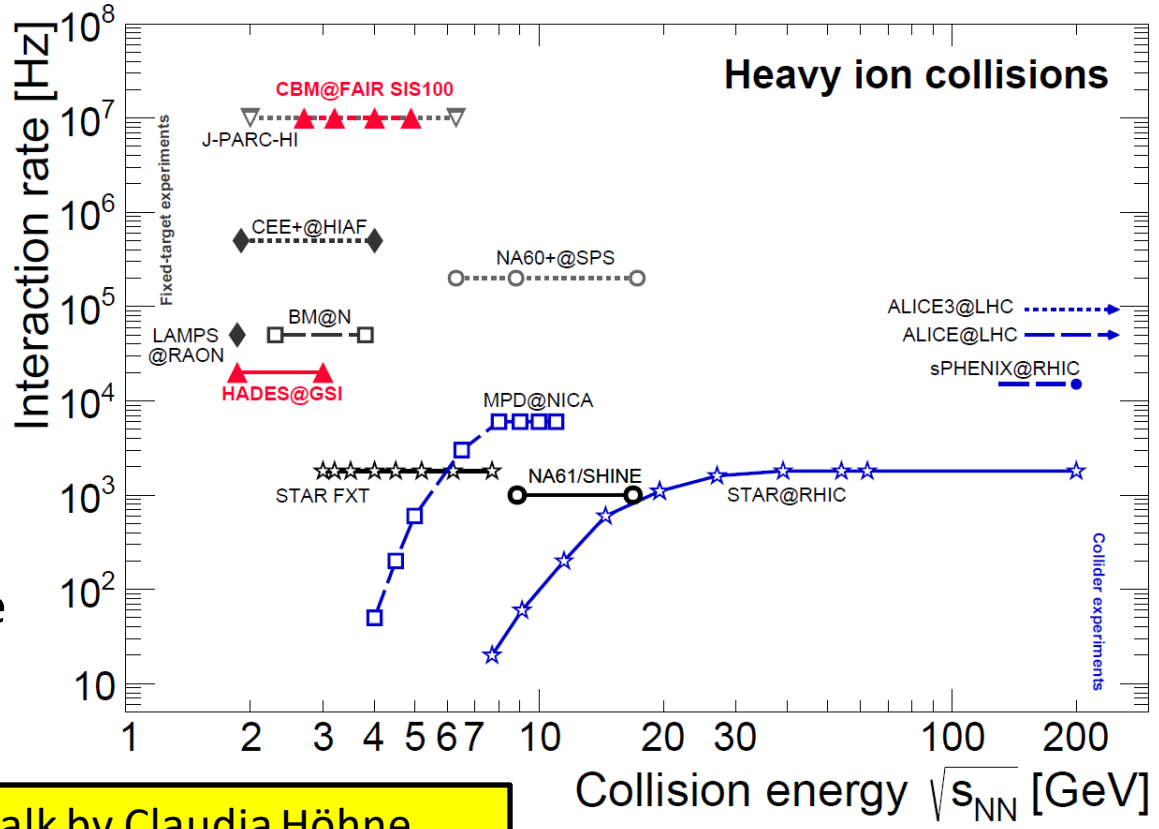
Talk by Claudia Höhne
Wednesday
06.09.2023 12:00

CBM

Outlook: HADES and CBM @ SIS100

- Investigation of the QCD phase-diagram in the 2.7-4.9 GeV energy regime
- Interaction rates of up to 10 MHz with CBM using free streaming data collection
  - ➢ Rare probes can be studied in detail
- Di-electron and di-muon setup available
- Micro-Vertex-Detector / Tracker
  - ➢ Reconstruction of further particles possible e.g. $\Sigma^{\pm}$, $D^{\pm}$, etc.
- CBM physics program:
  Lect.Notes Phys. **814** (2011) pp.1-980

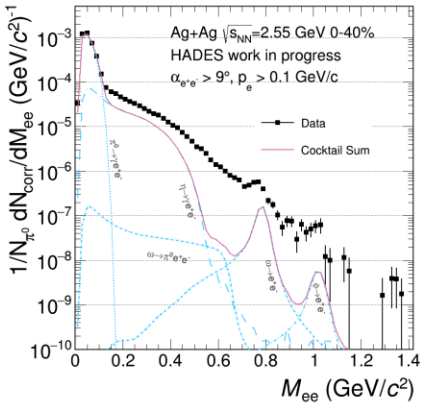
https://github.com/tgalatyuk/interaction_rate_facilities

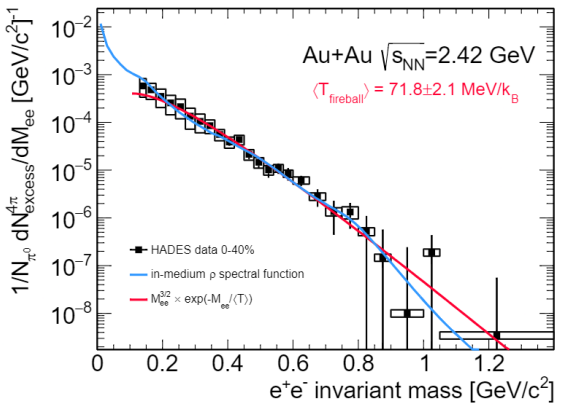


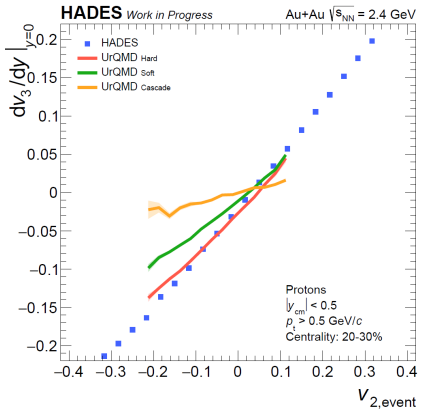
Talk by Claudia Höhne
Wednesday 06.09.2023 12:00

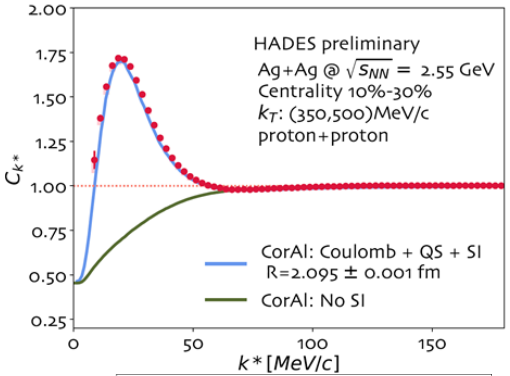
Summary

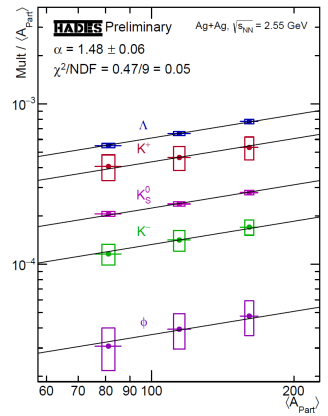
- HADES detector is upgraded with FAIR technology (ECAL, RICH, iTOF, STS1,2 and fRPC)
- High statistics in dilepton invariant mass spectrum
  - ➢ ϕ(1020) signal visible in heavy-ion collisions
- First direct evidence that VDM works for baryons
- Detailed analyses of Protons, Light Nuclei and Pions
  - ➢ Multi-differential flow measurement up to v_4
  - ➢ p+p, p+A, A+A, p+Λ, γ+γ Femtoscopy measurements
- Universal strangeness scaling holds in Ag+Ag
- ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ lifetime compatible to previous measurements
  - ➢ 4.85σ deviation of ${}^{4}_{\Lambda}\mathrm{H}$ lifetime to free Λ

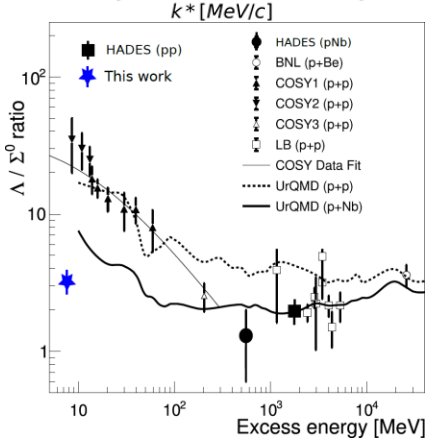








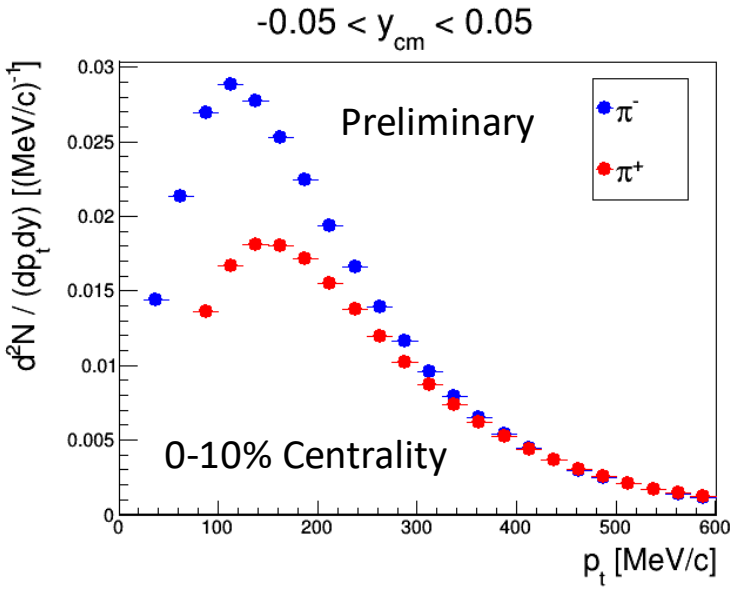




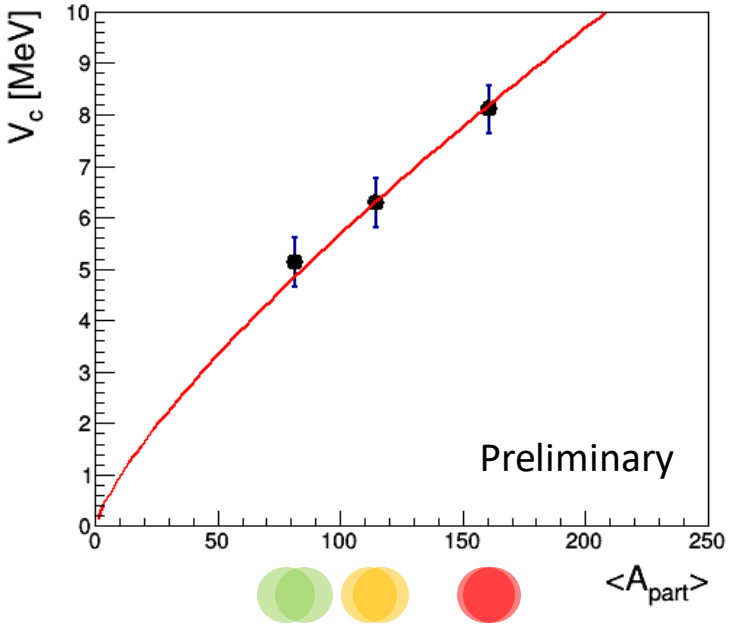
The HADES Collaboration

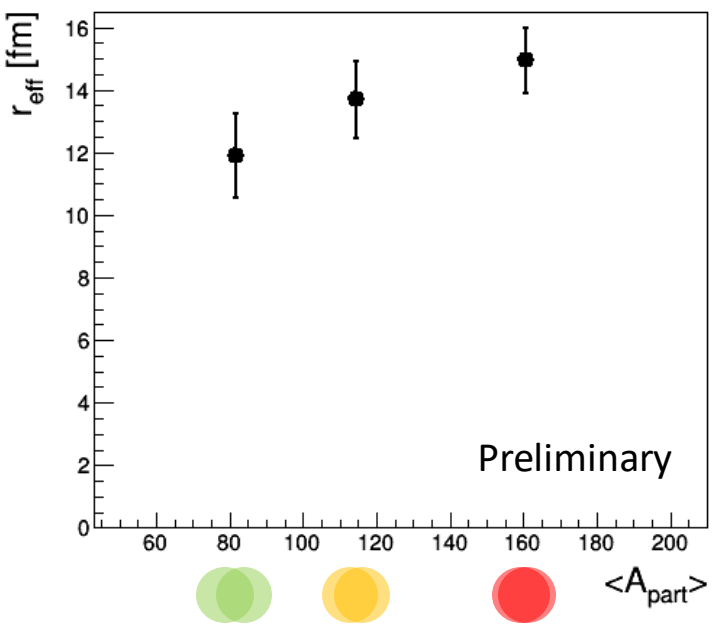
Coulomb Potential

All Plots: Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV



HADES allows to measure
Pions down to $p_{lab} \approx 60$ MeV/c





- Coulomb potential V_c and effective charge radius r_{eff} extracted from π^+ and π^- transverse momentum spectra
- $V_c(\langle A_{Part} \rangle)$ well described by $V_c \propto \langle A_{Part} \rangle^{\alpha}$; r_{eff} in peripheral events error-prone due to spectator contributions