HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

REVIEW OF THE HADES EXPERIMENT

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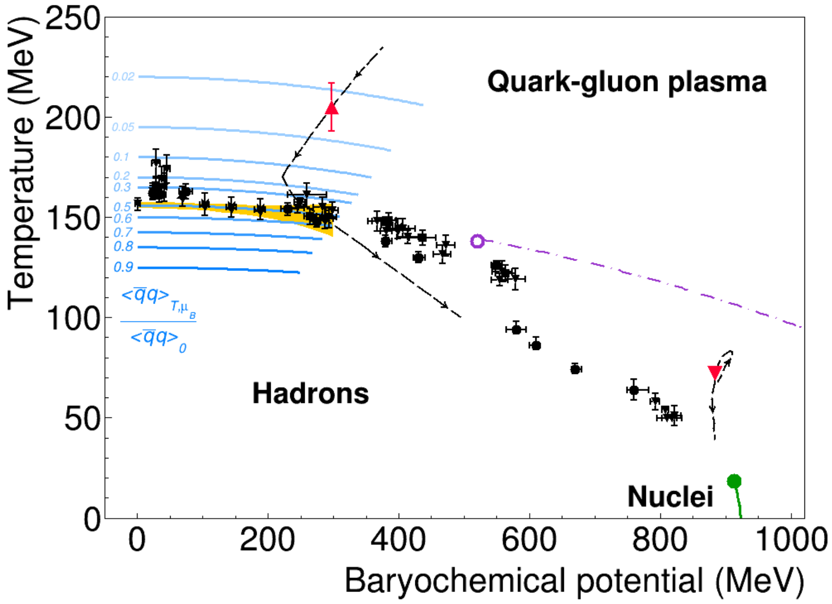
GSI / TU Darmstadt

RFBR Grants for NICA | 20 - 23 Oct 2020

HADES GSI FAIR Phase 0 Research Program TECHNISCHE UNIVERSITÄT DARMSTADT

THE HADES PHYSICS CASE



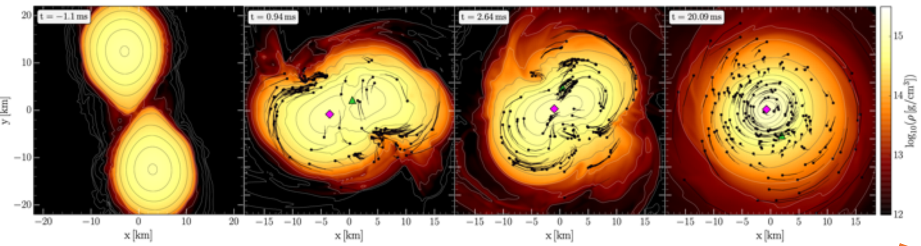
- Explore high-μ_B region of the QCD phase diagram
- Focus on rare and penetrating probes
- Address various aspects of baryon-meson coupling

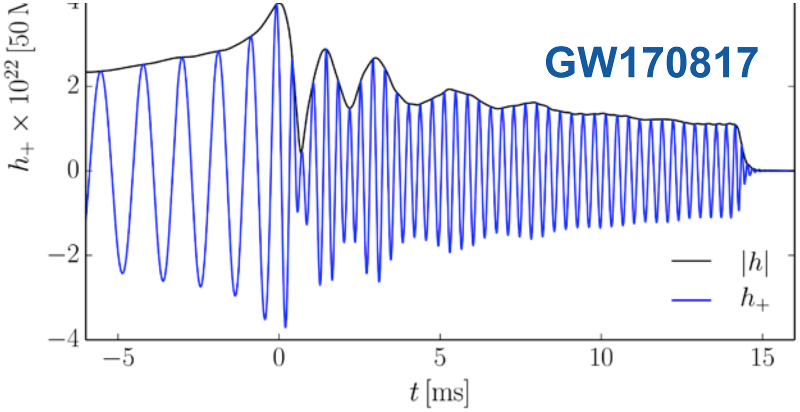
- **π and p beams:**
  - Reference measurement (vacuum, cold nuclear matter)
  - em structure of baryons/hyperons in time-like region
- **Heavy-ion collisions $\sqrt{s_{NN}} = 2 - 2.4\ GeV$:**
  - Microscopic properties of baryon dominated matter
  - Equation-of-State:
    - E-b-e correlations and fluctuations
    - Flavour production and collective effects
    - Dileptons

HADES, Nature Phys. 15 (2019) 10, 1040-1045
A. Andronic *et al.*, Nature 561 (2018) no.7723
LQCD: S. Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
LQCD: A. Bazavov *et al.*, Phys.Lett.B 795 (2019) 15-21

LABORATORY STUDIES OF THE MATTER PROPERTIES (EoS) IN COMPACT STELLAR OBJECTS

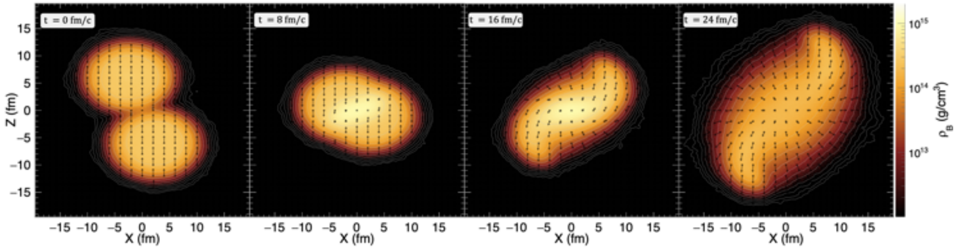
Neutron Star merger (model calculations)





M. Hanauske, Journal of Phys.: Conf. Series 878 (2017) 012031
L. Rezzolla *et al.*, Phys. Rev. Lett. 122, no. 6, 061101 (2019)

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

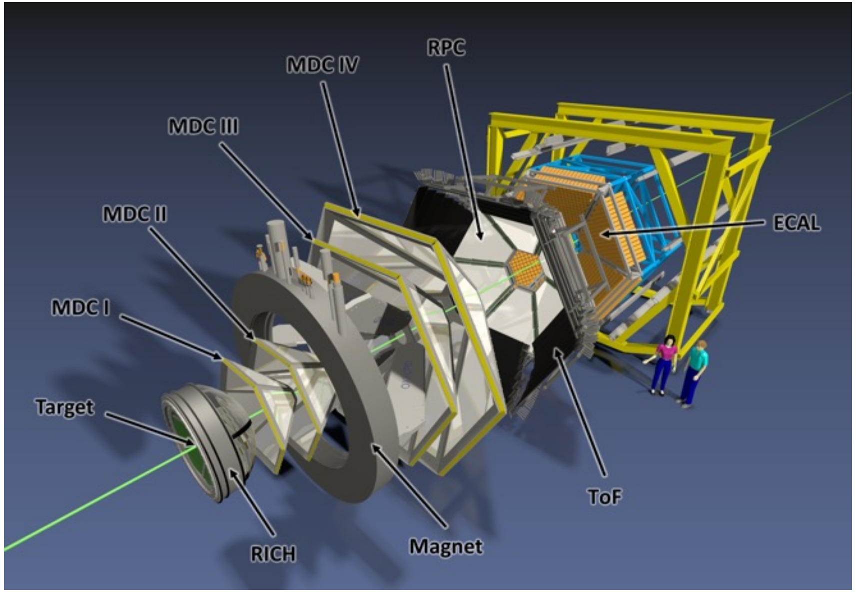


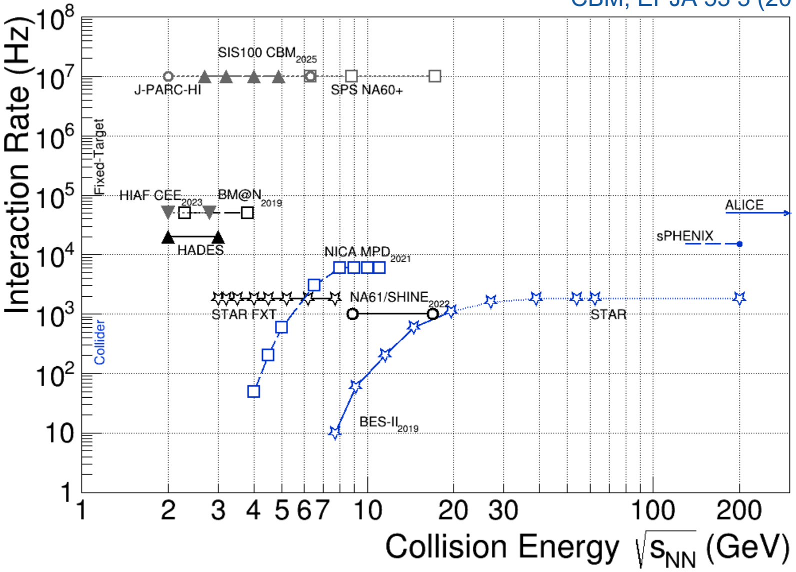
- ☐ T < 70 MeV, $\rho < 3\rho_0$ for both (note the different isospin)
- ☐ Role of YN, YY phase shifts in EOS!
  HADES, Phys.Rev. C94 (2016) 025201
  ALICE, Phys.Rev.C 99 (2019) 2, 024001

Strong connections between the fields

SOME BASIC FACTS ON HADES

TG, Nucl.Phys. A982 (2019)
CBM, EPJA 53 3 (2017) 60





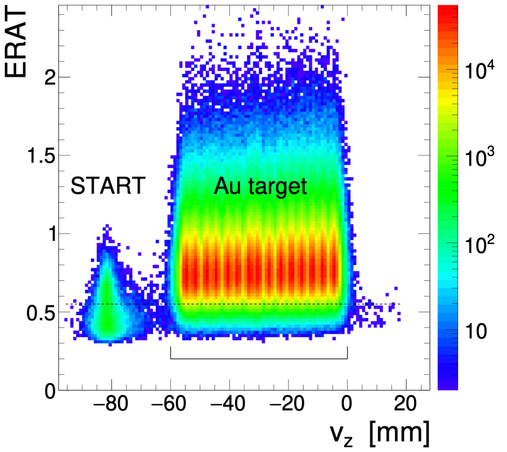
- New since 2019 RICH photo camera, ECAL (5 sectors)
- In 2020 forward detector system Sraw Tracker, RPC
- For 2022 new MDC FEE and 100 kHz DAQ upgrade

- Accepted trigger rates:
  - 8 kHz in Apr 2012 Au+Au $\sqrt{s_{NN}} = 2.42\ GeV$
  - 16 kHz in Mar 2019 Ag+Ag $\sqrt{s_{NN}} = 2.55\ GeV$ and $\sqrt{s_{NN}} = 2.42\ GeV$
  - 50 kHz for hadron beams

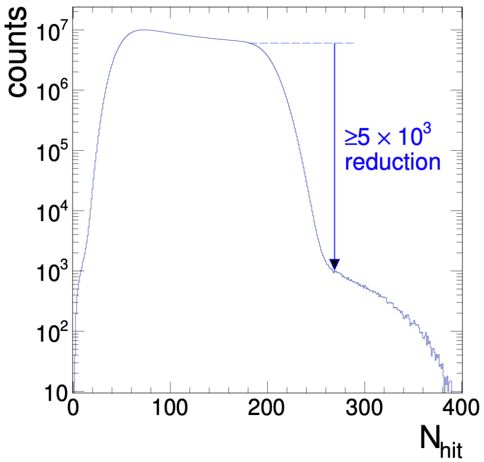
EVENT SELECTION and PARTICLE IDENTIFICATION

- Au beam on 15-fold segmented Au target
- 7×10^9 events recorded
  - LVL1 trigger on 43% most central collisions
  - Min. bias events scaled down (factor 8)

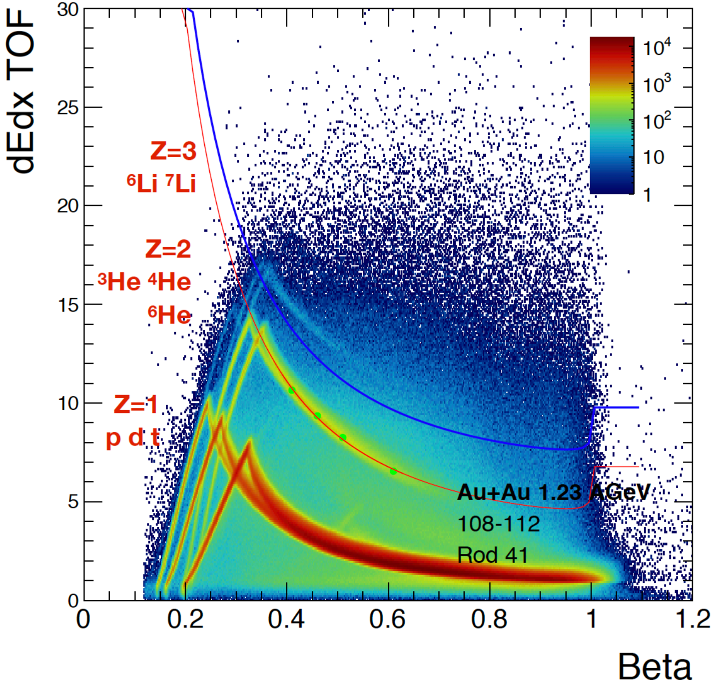
- Velocity, Momentum
- dE/dx in MDC and ToF
- RICH information



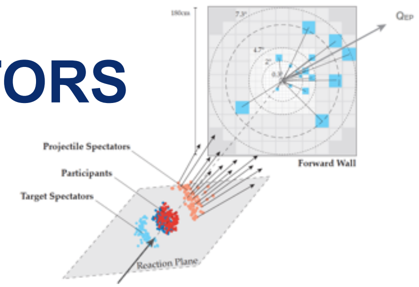
$$ERAT = \frac{E_\perp^{tot}}{E_\parallel^{tot}} = \frac{\sum_i E_{\perp,i}}{\sum_i E_{\parallel,i}} = \frac{\sum_i E_i sin\theta_i}{\sum_i E_i cos\theta_i}$$



Event pile-up $\leq 2\times10^{-4}$
Segmented target + Start + VETO



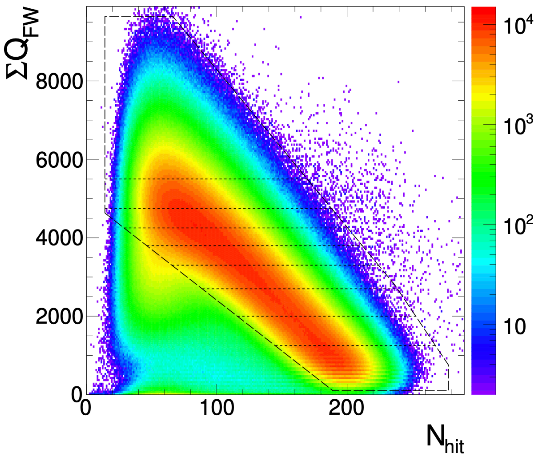
EVENT CHARACTERIZATION ENTRALITY ESTIMATORS



Centrality estimator

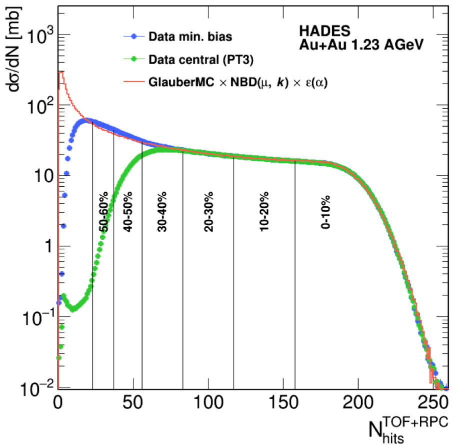
Off-line centrality selection based on hit or track multiplicity and/or Forward Wall (FW) integral charge

Centrality determination based on FW avoids bias on e-b-e fluctuation observables



HADES, Phys.Rev.C 102 (2020) 2, 024914

Using Glauber MC - distributions agree with transport model calculations (processed by GEANT and filtered with standard analysis code)



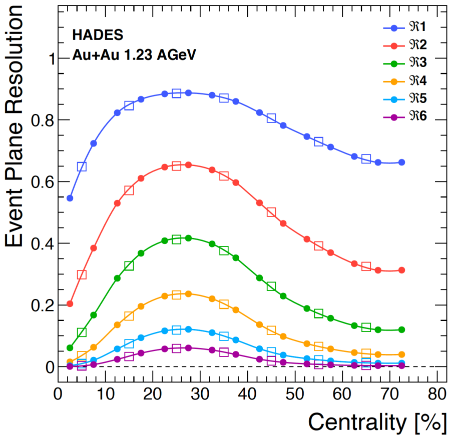
HADES, Eur.Phys.J.A 54 (2018) 5, 85

Event plane reconstruction

Based on hits of charged projectile spectators in the FW

Resolution determined from sub-event resolution
Based on method by J.-Y. Ollitrault, arXiv:nucl-ex/9711003

$$v_n = v_n^{obs} / \Re_n \qquad \Re_n = \langle \cos [n(\Psi_n - \Psi_{RP})] \rangle$$

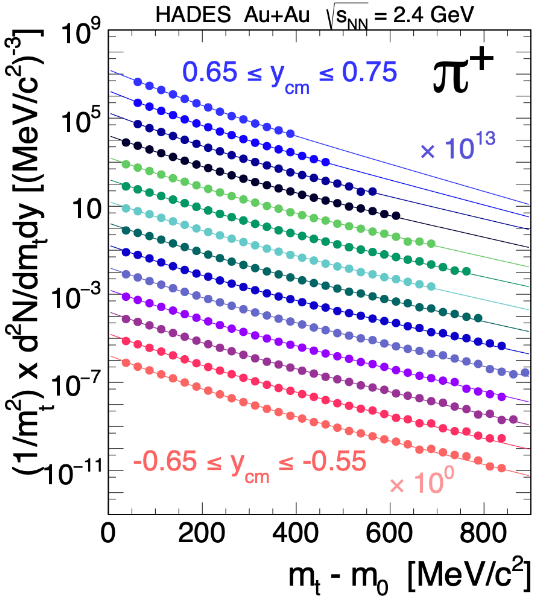


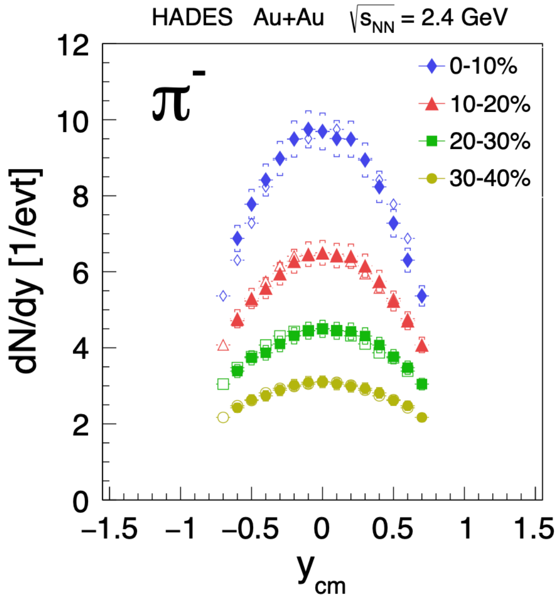
HADES Collab., arXiv:2005.12217 [nucl-ex]

BULK PROPERTIES OF THE MATTER

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

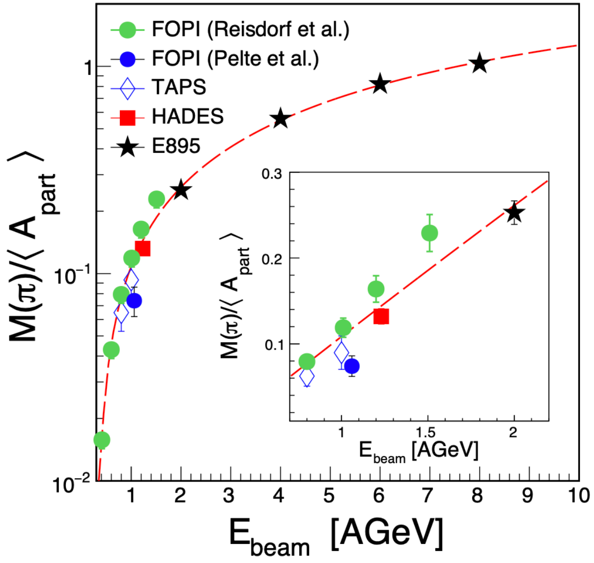
- ~ 1 pion per 10 baryons
- High statistics sample
- Large phase-space coverage





HADES, Eur.Phys.J.A 56 (2020) 10, 259

World data



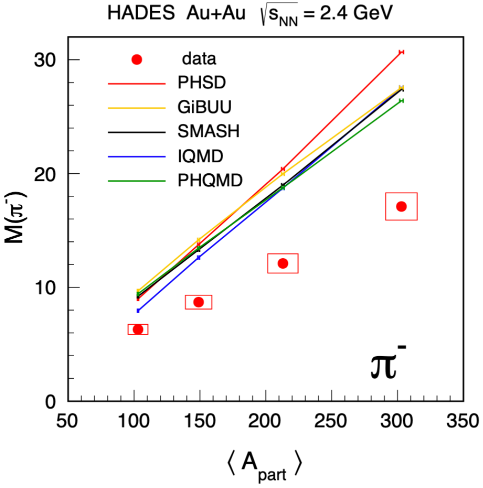
J. W. Harris et al. , Phys. Rev. Lett. 58 (1987) 463
R. Averbeck et al. Phys. Rev. C 67 (2003), 024903
E895, J. L. Klay et al., Phys. Rev. C 68 (2003) 054905

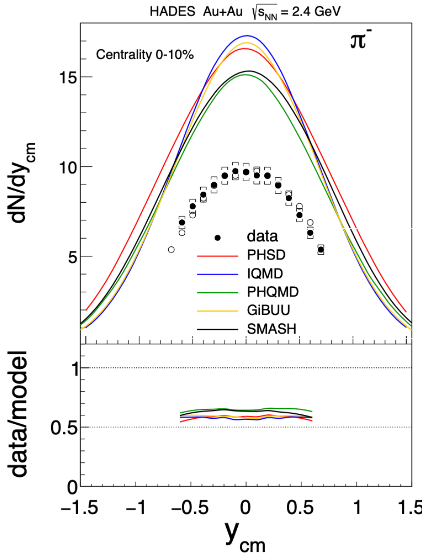
FOPI, W.Reisdorf et al., Phys. A 781, 459 (2007)
FOPI data $2.5\ \sigma$ above world data

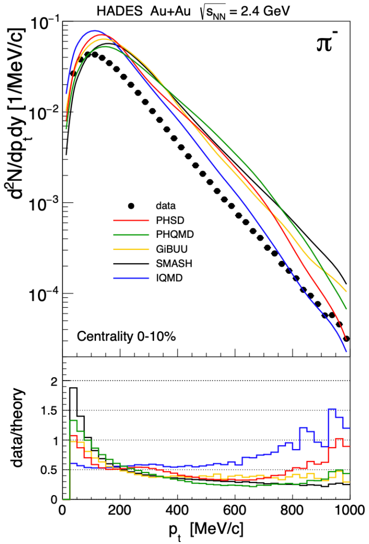
MICROSCOPIC DESCRIPTION

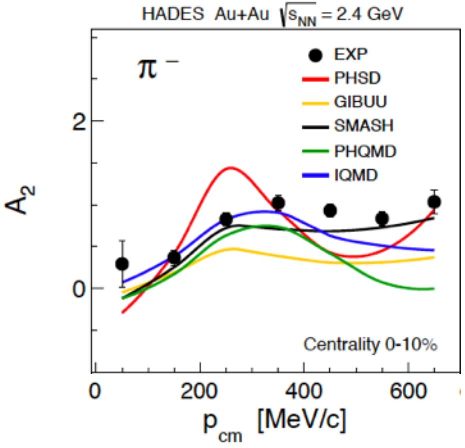
Example for π^-, same holds for π^+

Pion and Proton “Temperatures” in HIC
R. Stock et al., Phys.Rev.Lett 1984









$$\frac{dN}{d(\cos\theta_{cm})} = C(1 + A_2 \cos^2\theta_{cm})$$

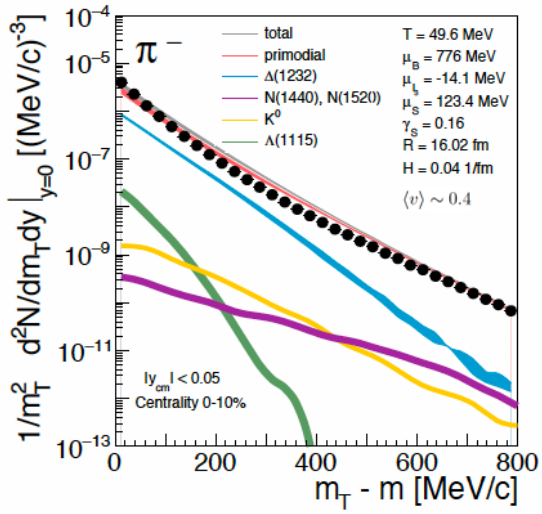
- Microscopic transport models consistently fail to describe the data
- Main source of pions - baryonic resonances propagating in hot and dense fireball

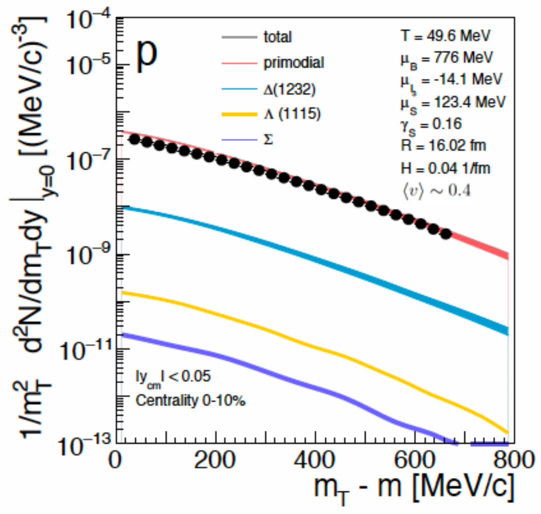
THERMAL EVENT GENERATOR (THERMINATOR 2)

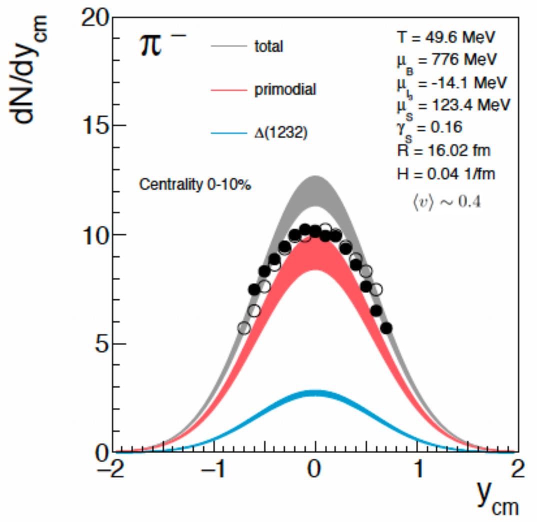
Extension of the model to not boost invariant systems

S. Harabasz et al., arXiv:2003.12992 [nucl-th] (accepted by PRC)

- Freeze-out model: Siemens-Rasmussen
- Hubble-like expansion velocity profile $\beta = \tanh(Hr)$
- Δ spectral function from πN phase shift P.M. Lo et al., PRC 96 (2017) 015207





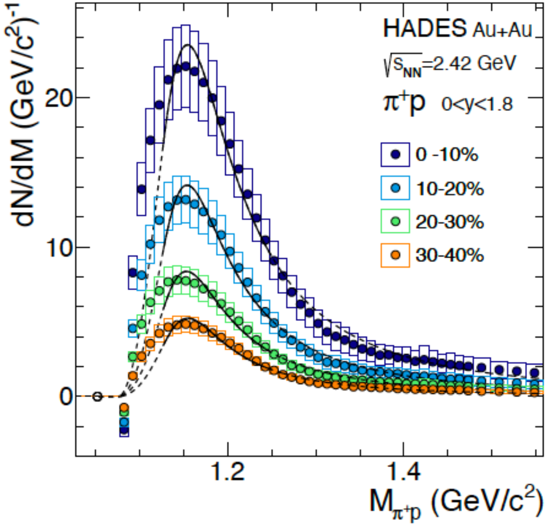


Good description of most abundant particles using a thermal model with only few simple assumptions!

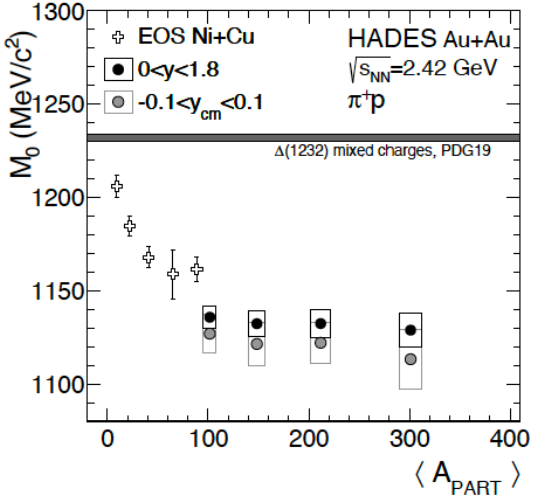
CORRELATED PION-PROTON PAIR EMISSION

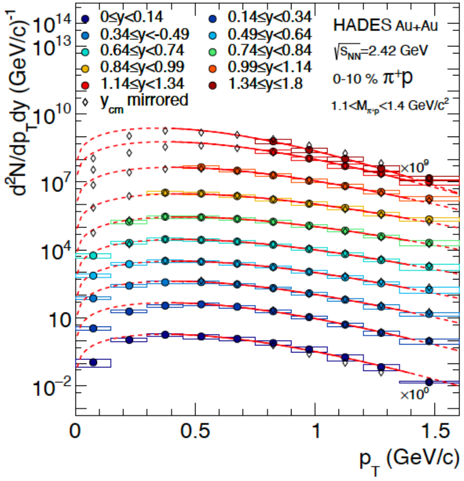
π^+p and π^-p analysis

$$\sigma_{BW}(M_{\pi p}) = \frac{q^3}{q^3+\mu^3}\frac{\sigma_0}{1+4[(M_{\pi p}-M_0)/\Gamma_0]^2}$$



HADES, in collab. review





- High statistics allows multi-differential analysis
- Next: Understanding of “kinematical” mass shift with S-matrix formalism
- Comparison to microscopic transport

UrQMD, T. Reichert et al., 2004.10539 [nucl-th];
Astron.Nachr. 340 (2019) 9-10, 1018-1022

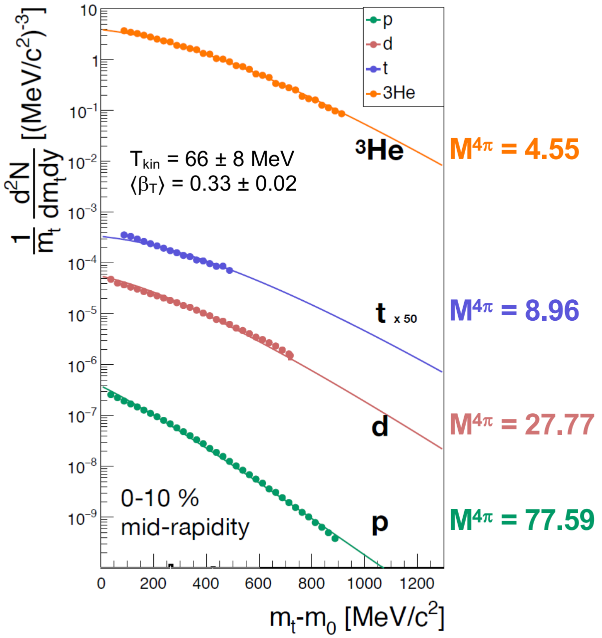
Pok Man Lo, Eur. Phys.J. C77 (2017) no.8, 533
R. Dashen etal., Phys. Rev. 187 (1969) 345
R.Venugopalan et al., Nucl. Phys. A 546 (1992) 718
W. Weinhold, B. Friman, Phys. Lett. B 433 (1998) 236

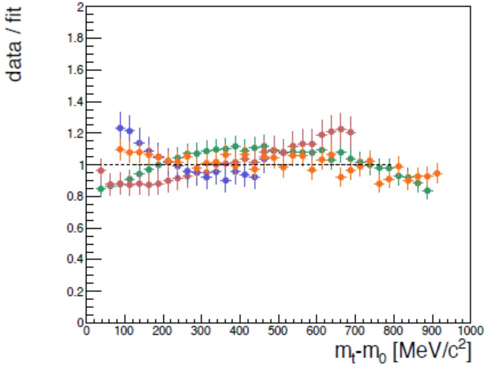
PROTONS AND LIGHT NUCLEI

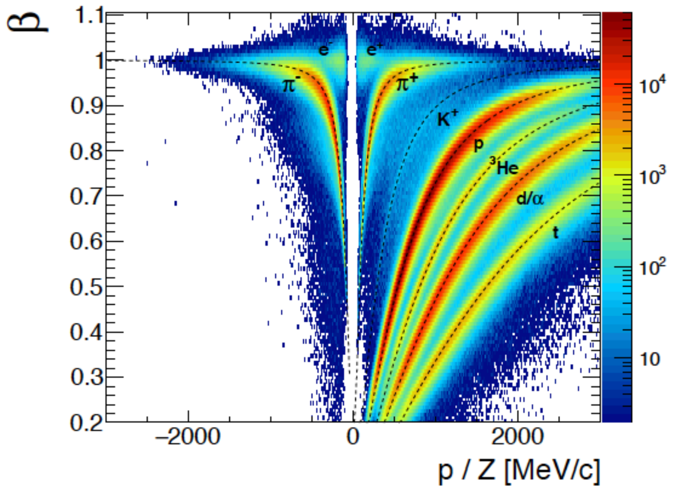
High statistic multi-differential data

Blast-Wave fit at mid-rapidity

E. Schnedermann et al., Phys. Rev. C 48, 2462







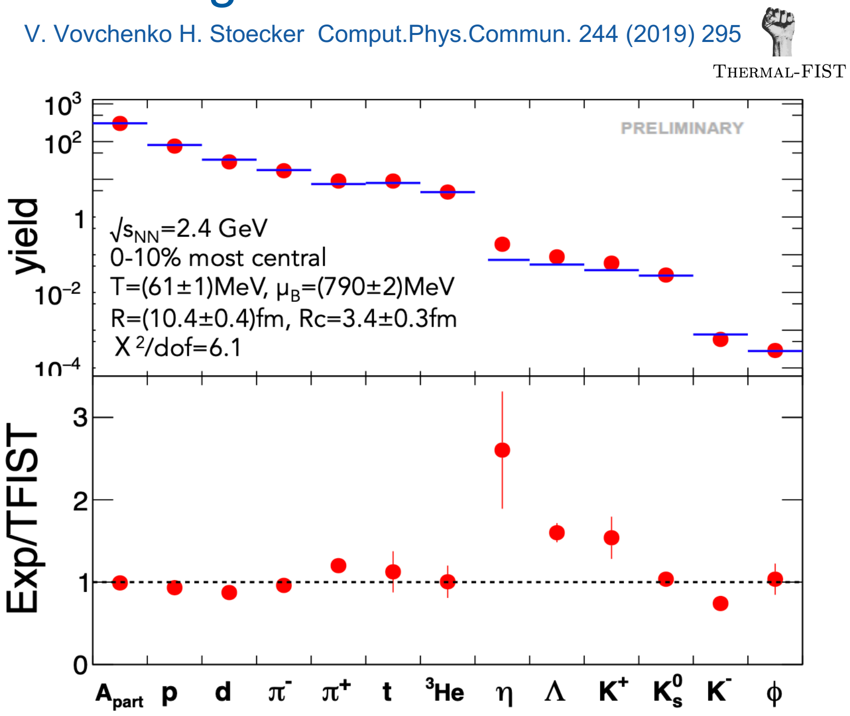
- ☐ Fit works reasonably well
- ☐ Consistency of the analysis:
  - ☐ $p + n + 2\times d + 3\times t + 3\times\, ^3He = 290$
  - ☐ $\langle Apart\rangle = 303 \pm 11$

→ 37% of p are bound in nuclei

MACROSCOPIC DESCRIPTION OF YIELDS

Including excited nuclei

V. Vovchenko H. Stoecker Comput.Phys.Commun. 244 (2019) 295



- Grand canonical ensemble (T, μ_B, V)
- Strangeness canonically suppressed at low T using a correlation radius $R_c < RV$
- Include feed-down from ^4He, ^4H, ^4Li

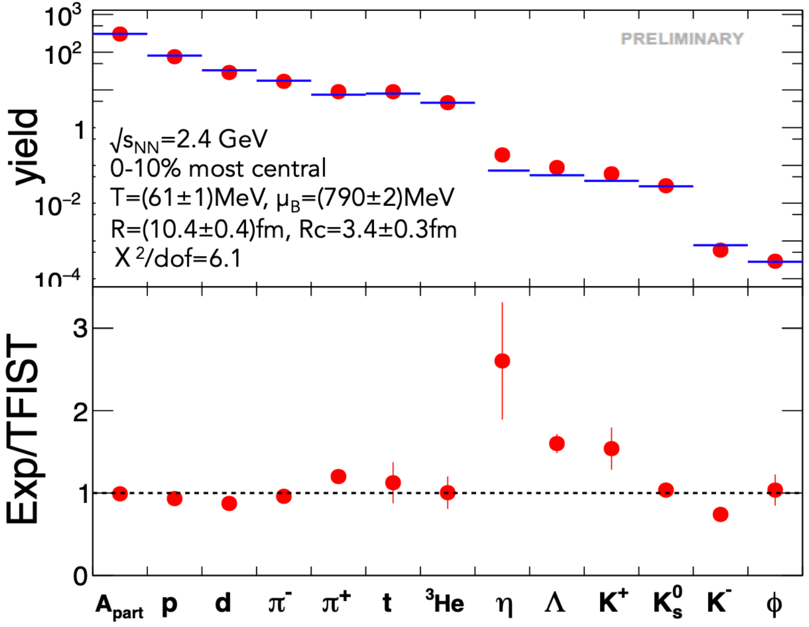
  D. Hahn, H. Stöcker, Nucl.Phys.A 476 (1988) 718-772
  E. Shuryak, J. M. Torres-Rincon Phys.Rev.C 101 (2020) 3, 034914

MACROSCOPIC DESCRIPTION OF YIELDS

Including excited nuclei

V. Vovchenko H. Stoecker Comput.Phys.Commun. 244 (2019) 295

THERMAL-FIST



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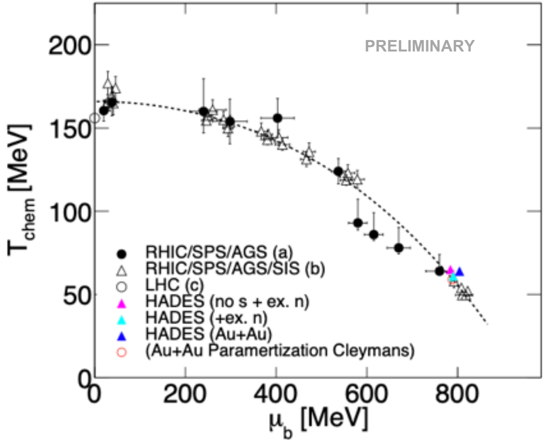
  D. Hahn, H. Stöcker, Nucl.Phys.A 476 (1988) 718-772
  E. Shuryak, J. M. Torres-Rincon Phys.Rev.C 101 (2020) 3, 034914
- Hadron abundances described by T, μ_B, R_c, R_V
  ⤳ But resulting in a large $\chi^2 = 6$
  ⤳ $\chi^2 = 1.6$, when strangeness excluded

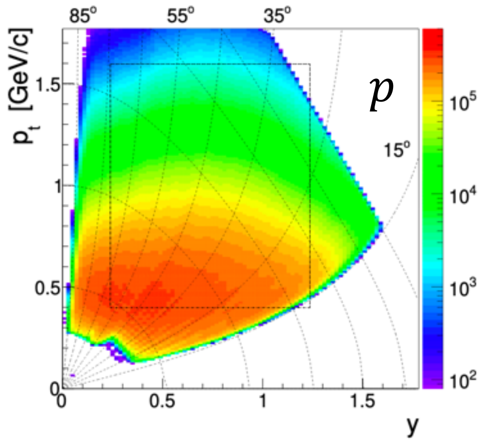


- Coupling of statistical particle production with a blast wave model
- Compare directly spectra including effects of blast and resonance decays

PROTON NUMBER FLUCTUATIONS

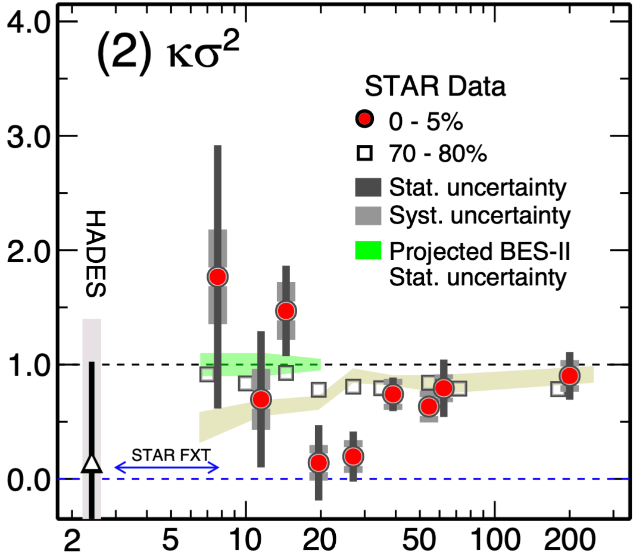
1[st] time this kind of analysis in fixed-target experiment at $\sqrt{s_{NN}} = 2.42\ GeV$

Detailed systematic study of experimental and instrumental effects



CRITICAL FLUCTUATIONS

STAR, arXiv: 2001.02852 (resubmitted)



cf. B. Friman *et al.*, EPJC 71 (2011) 1694
M. Stephanov, Phys.Rev.Lett.107 (2011) 052301

- High moments $S\sigma = \frac{\kappa_3}{\kappa_2}$ $k\sigma^2 = \frac{\kappa_4}{\kappa_2}$ $\kappa_2, \kappa_3, \kappa_4$ cumulants
  of proton multiplicity distributions probe the structure of strong interaction matter

Direct link to EoS $\frac{1}{VT^3} k_n = \frac{\partial^n \hat{p}}{\partial \hat{\mu}^n}$

$\hat{p} = \frac{p}{T^4}$ reduced pressure

$\hat{\mu} = \frac{\mu}{T}$ reduced chemical potential

Ling, Stephanov, PRC 93, 034915 (2016)

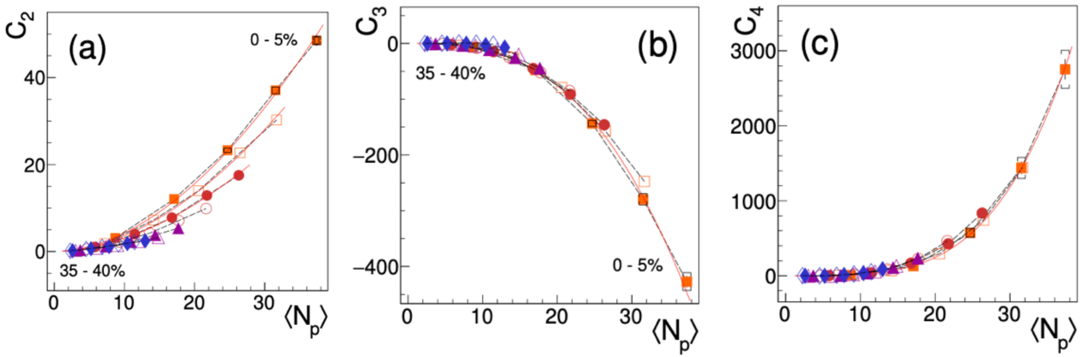
Cumulants k_n hold information on multi-particle correlators C_n

Bzdak, Koch, Strodthoff, PRC 95, 054906 (2017)

Investigate C_n vs. $\langle N_p \rangle$ to isolate relevant physics, $C_n \propto \langle N_p \rangle^{\alpha}$

$\langle N_P \rangle$ SCALING OF CORRELATORS C_n

HADES, Phys.Rev.C 102 (2020) 2, 024914



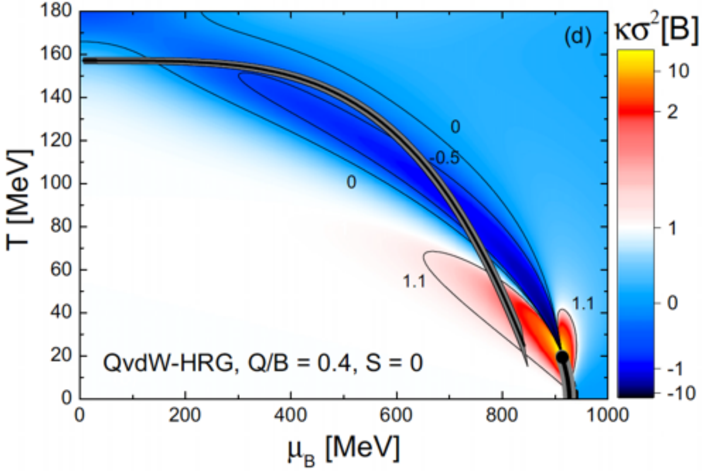
$C_2 \propto \langle N_p \rangle^{\alpha}$
$\alpha = 1.86 \pm 0.04$

$C_3 \propto \langle N_p \rangle^{\alpha}$
$\alpha = 2.84 \pm 0.05$

$C_4 \propto \langle N_p \rangle^{\alpha}$
$\alpha = 3.89 \pm 0.14$

$\alpha \simeq n$ → signature of multi-particle correlations ($\Delta y_{corr} > 1$)

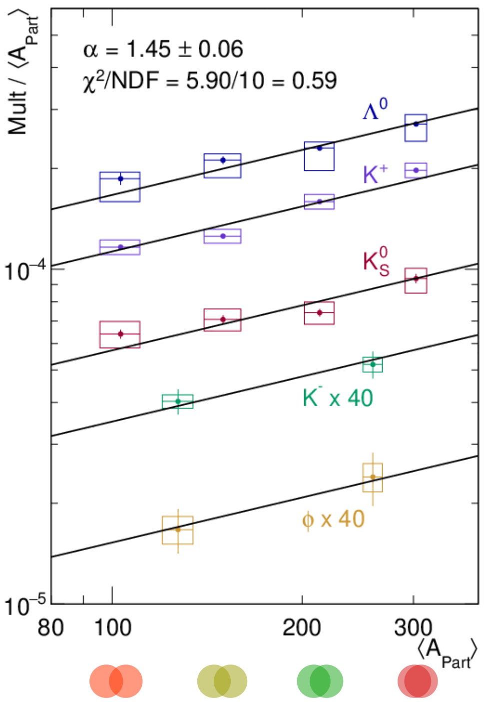
- ☐ Stopping of nucleons may produce multi-particle “clusters”
- ☐ Quarkyonic matter?
- ☐ Remnants of nuclear liquid-gas phase transition?



Bzdak, Koch, Skokov, EPJC (2017) 288
Shuryak, Torres-Rincon Phys.Rev.C 101 (2020) 3, 034914
Kojo, Hidaka, McLerran, Pisarski, Nucl. Phys. A843 (2010), 37
R. Poberezhnyuk et al., Phys.Rev. C100 (2019) no.5, 054904

SYSTEM WITH LONG-RANGE CORRELATIONS?

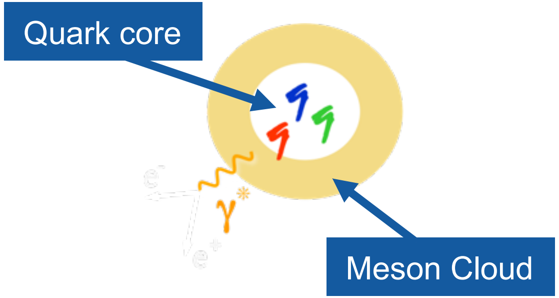
HADES, Phys.Lett.B 793 (2019) 457



- Universal scaling with participant number
- Does not reflect the hierarchy of NN production thresholds
  - $K^+\Lambda$: $-160\ MeV$
  - K^+K^-: $-470\ MeV$
- Not expected if strangeness produced in *isolated* NN collisions

Scaling with absolute amount of strangeness not with individual hadron states

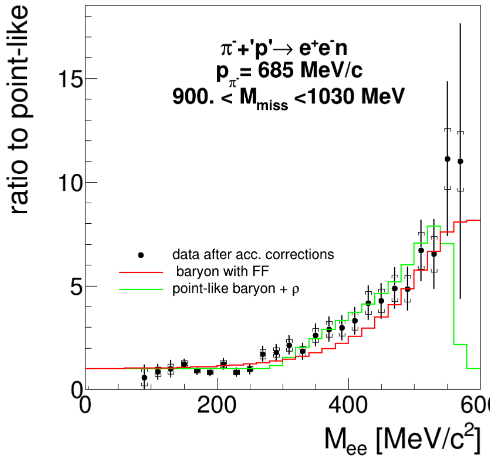
MESON CLOUD



Exclusive analysis, e^+e^- invariant mass distribution ratio to point-like contributions

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

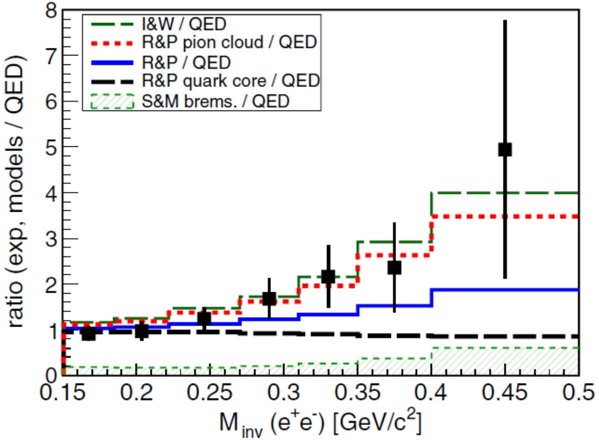
HADES, ms. in prep.



4 first entries (Nρ)
4 additional entries

HADES, Phys.Rev.C 102 (2020) 2, 024001

$pp \rightarrow ppe^+e^-$



first entry BR $\Delta \rightarrow pe^+e^-$

HADES, Phys.Rev.C 95 (2017) 065205

- Studying the structure of the nucleon as an extended object
- Dominance of the N*(1520) resonance
  - Contribution fixed by analysis of $\pi^+\pi^-$ channel with PWA

Excitation of a baryon can be carried by the meson cloud

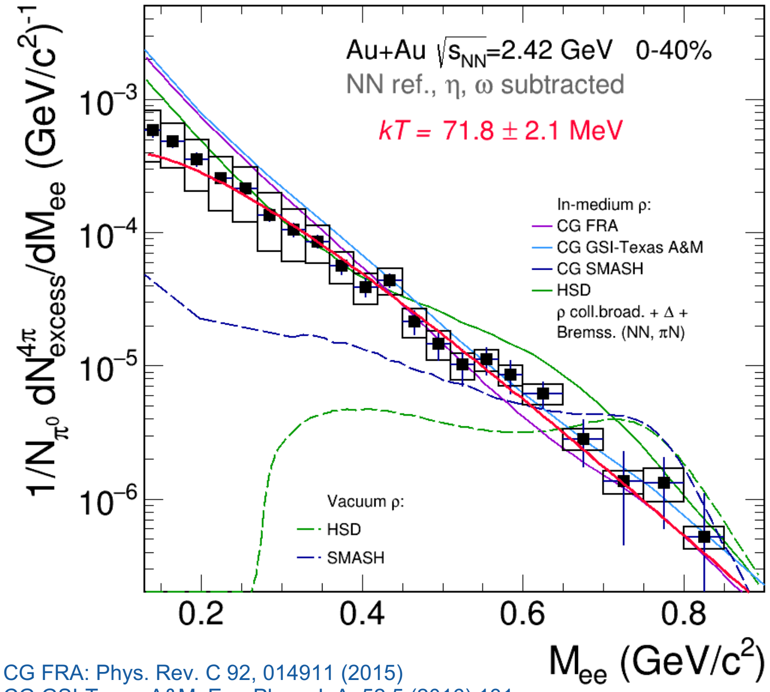
VDM form factor models

DILEPTON EXCESS YIELD

$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T) Im\Pi_{em}(M,q,T,\mu_B)$$

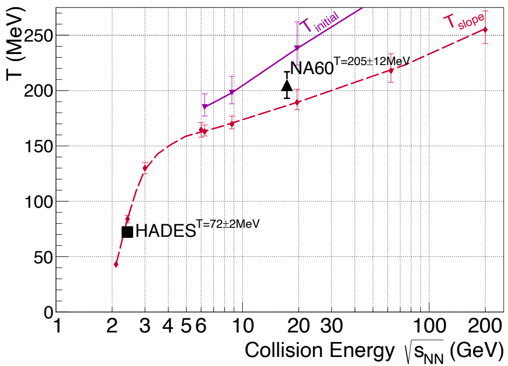
McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

HADES Collab., Nature Physics 15 (2019) 1040



CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur. Phys. J. A, 52 5 (2016) 131
CG SMASH: Phys.Rev.C 98 (2018) 5, 054908
HSD: Phys. Rev. C 87, 064907 (2013)

- Thermal rates folded over coarse-grained medium evolution from transport works at low energies
- Radiation from a long-lived source ($\tau \approx 13\, fm$) in local thermal equilibrium
- ρ melts - mass spectrum falls exponentially → slope measures radiating source T (no blue shift)



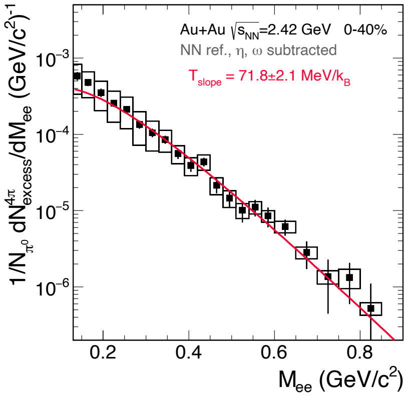
Mapping QCD caloric curve (T vs ε)

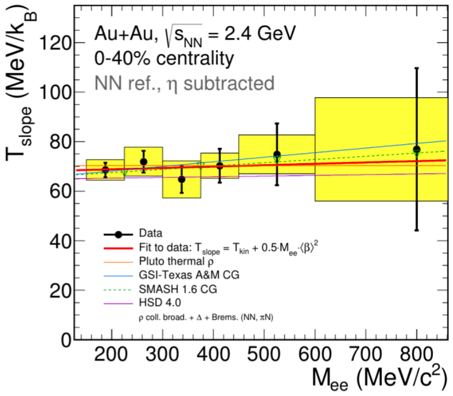
NA60: AIP Conf.Proc. (2010) 1322
HADES: Nature Physics 15 (2019) 1040
Rapp&Hess, PLB 753 (2016) 586
TG *et al.*: EPJA 52 (2016) 131

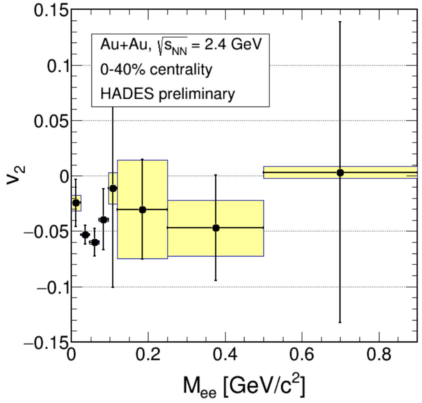
MULTI-DIFFERENTIAL PATTERN OF DILEPTON RADIATION

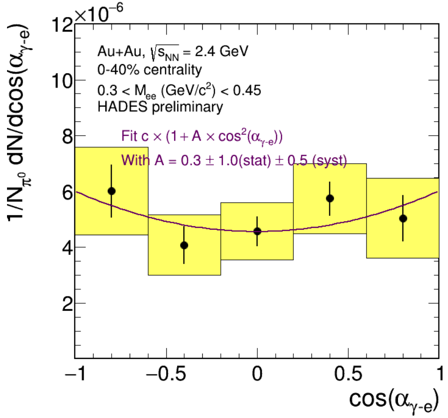
Dileptons carry invaluable information in terms of their four-momentum

- **Spectrometer**
- **Chronometer**
  $$\int_{0.3\,GeV}^{0.7\,GeV} \frac{dN}{dM} \sim \tau$$
- **Thermometer**
  $$if\ \frac{Im\Pi^{\mu\nu}_{EM}}{M^2} \sim const.$$
- **Barometer**
  - $T_{slope}\ vs.\ M$
  - $v_2\ vs.\ M$
- **Polarimeter**
  - γ^* polarization via lepton angular distribution









CG: $T = 65\ MeV;\ \langle\beta_{ee}\rangle = 0.19$
HSD: $T = 74\ MeV;\ \langle\beta_{ee}\rangle = 0.05$

v_2 consistent with zero for $M_{ee} > 0.12\ MeV/c^2$

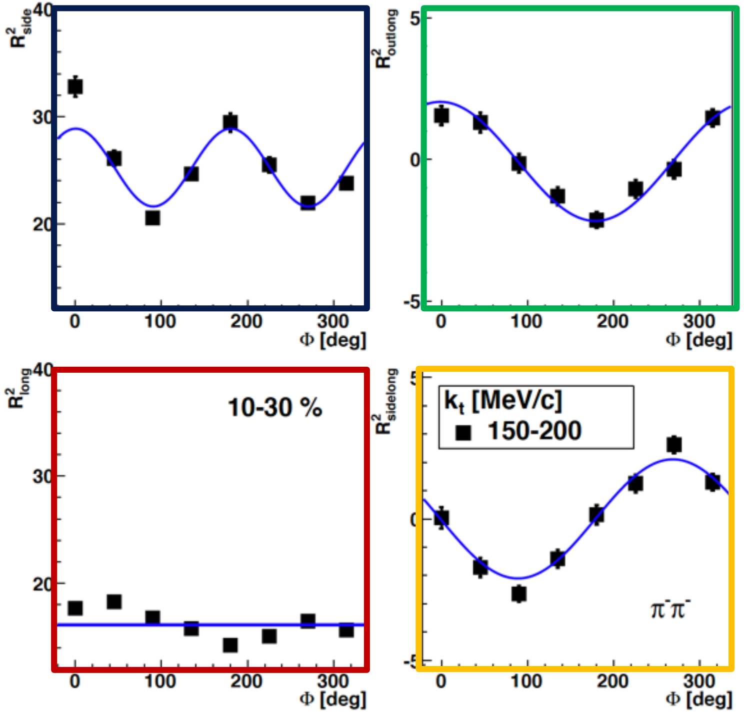
NA60 Collab., PRL 96 (2009) 222301
HADES Collab., PRC 84 (2011) 014902
E. Speranza et al., PLB 782 (2018)

HADES, ms. in prep.

AZIMUTHAL ANISOTROPY

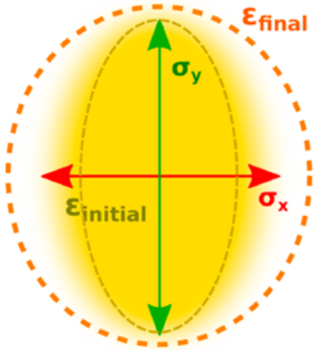
TWO-PION INTENSITY INTERFEROMETRY

3D HBT ($\pi^-\pi^-$) image of Au+Au collision zone



$\Phi = \angle yb$ *(long axis and impact parameter)*

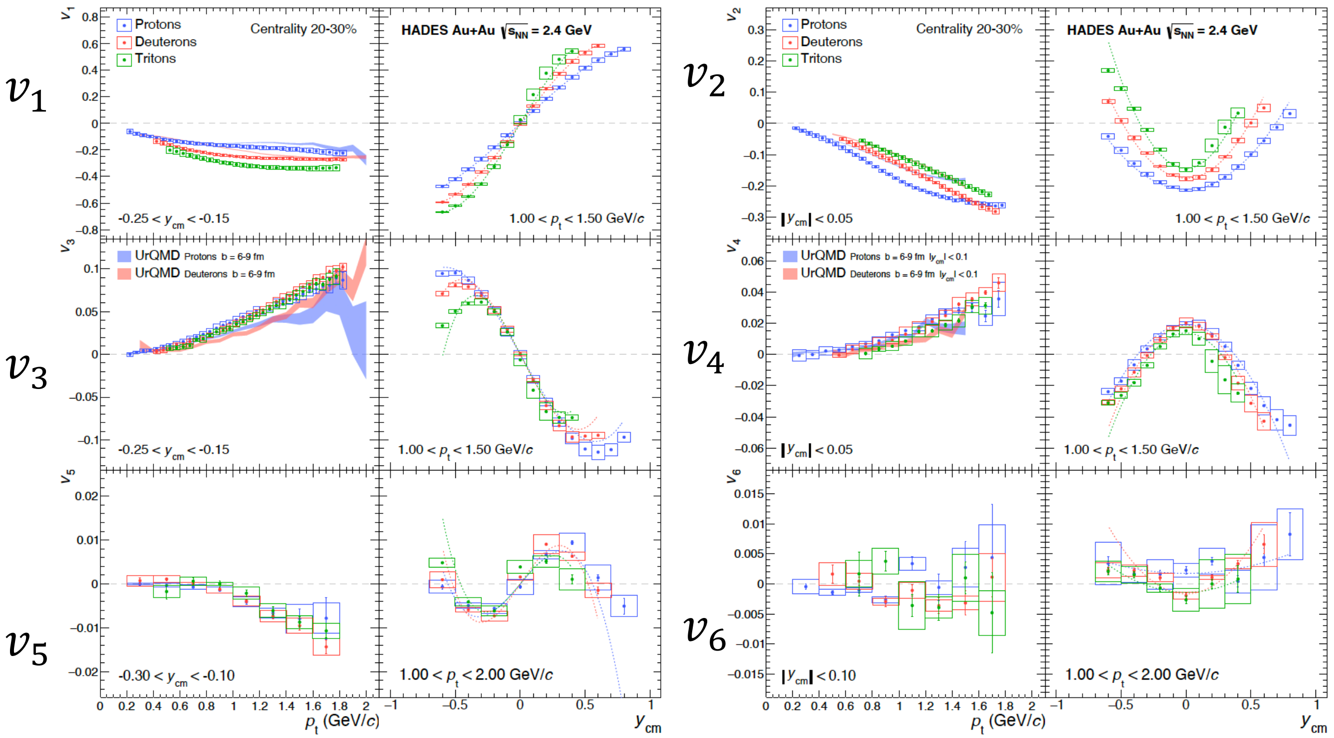
- Identical particle correlations from Au-Au collisions, a.f.o. relative event-plane angle Φ and pair momentum
- Size modulations available for 6 bins in pair momentum
- Initial (nuclear overlap) eccentricity is relaxed at freeze-out $\epsilon_{\text{initial}} > \epsilon_{\text{final}}$.



$$R^2_{ij} = \begin{pmatrix} R^2_{o} & R^2_{os} & R^2_{ol} \\ R^2_{os} & R^2_{s} & R^2_{sl} \\ R^2_{ol} & R^2_{sl} & R^2_{l} \end{pmatrix}$$

HADES, Phys.Lett.B 795 (2019) 446-45
HADES, Eur.Phys.J.A 56 (2020) 5, 140

PROTONS and LIGHT NUCLEI $v_n, n = 1 - 6$



- Sensitivity to the EoS: $\boldsymbol{p, d\ v_{2,3,4}\{\psi_{RP}\}}$

$$V_{sk} = -124\left(\frac{\rho_{int}}{\rho_0}\right) + 71\left(\frac{\rho_{int}}{\rho_0}\right)^2$$

UrQMD: P. Hillmann et al., J. Phys. G47 (2020) 055101

- Rapidity dependense paramerized with

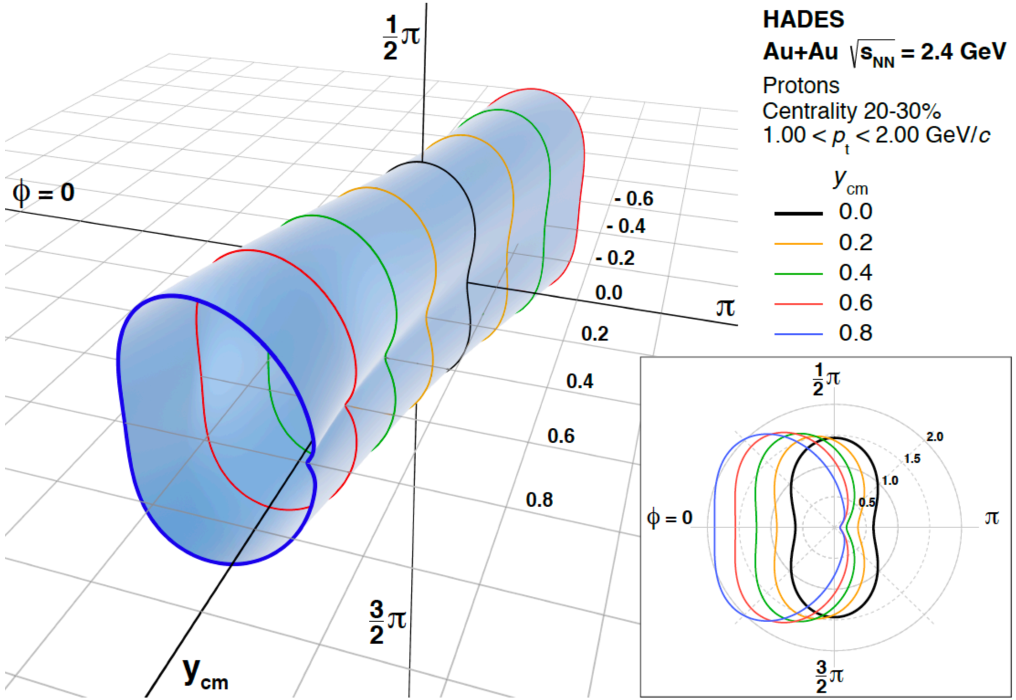
$$v_{1,3,5}(y_{cm}) = a y_{cm} + b y_{cm}^3$$

$$v_{2,4,6}(y_{cm}) = c + d y_{cm}^2$$

HADES, arXiv:2005.12217 [nucl-ex]

3D PICTURE OF THE PARTICLE EMISSION PATTERN

In momentum space



HADES, arXiv:2005.12217 [nucl-ex]

$$1 + 2\sum_{n=1}^{\infty} v_n\,(y_{cm})\cos n\,(\phi - \psi_{RP})$$

With rapidity depend parameterisation $n = 1 - 6$ (see previous slide)

- At mid-rapidity
  - Almost elliptical shape
  - Odd coefficients consistent with zero
- Very forward/backward rapidities
  - Triangular shape
  - Interplay: central fireball pressure – interaction with spectator matter

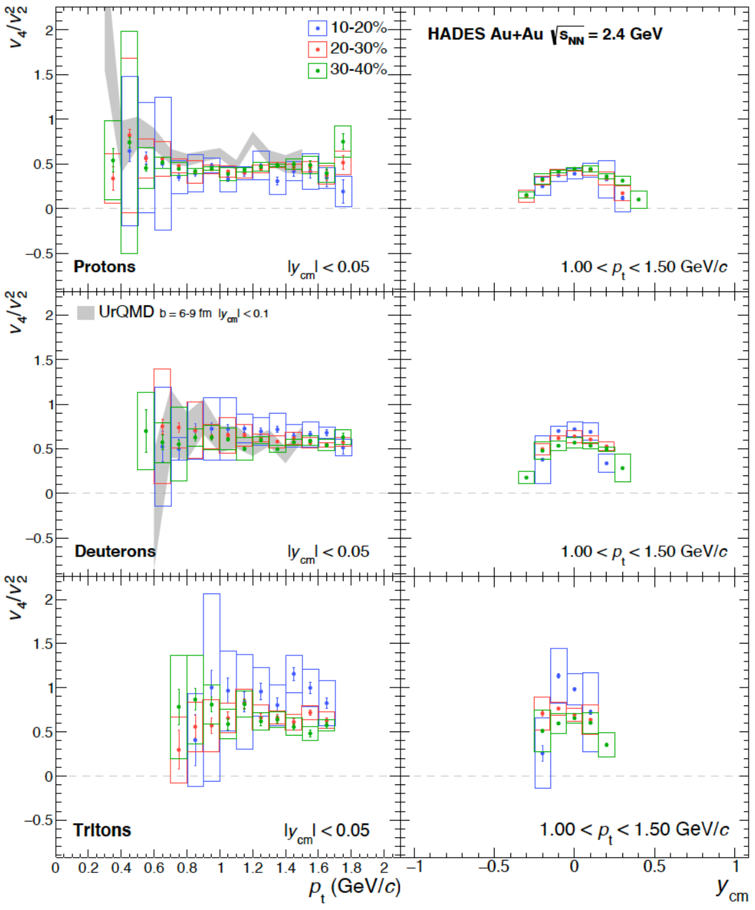
“IDEAL FLUID SCALING”

Protons and light nuclei

- Ideal fluid dynamics predicts contribution to v_4 from v_2 at large p_t by $v_4 = 0.5\, {v_2}^2$
- Realistic hydro calculation at RHIC ${v_4}/{v_2}^2 \sim 0.63$

N. Borghini and J.-Y. Ollitrault
Phys.Lett. B642 (2006) 227-231

At **mid-rapidity** $\boldsymbol{v_4/v_2^2}$ for p, d, t are remarkably close to **0.5**

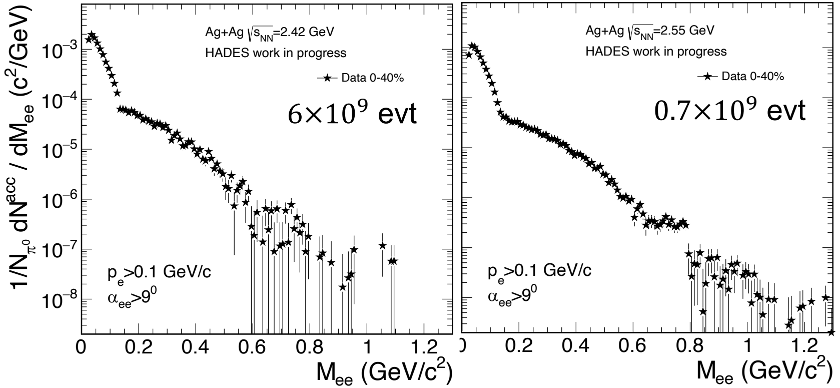


NOW and THEN

Ag+Ag COLLISIONS AT $\sqrt{s_{NN}} = 2.55\ GeV$ (+3 DAYS RUN AT $\sqrt{s_{NN}} = 2.42\ GeV$)

4 weeks run in Mar 2019, $14{\times}10^9$ events on disk, 43% most central + downscaled min.bias

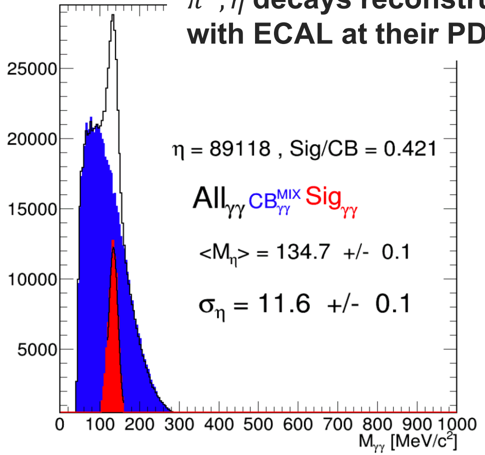
Efficiency corrected dielectron spectra



$187{\times}10^3$ in case of $\sqrt{s_{NN}} = 2.55\ GeV, M_{ee} > 0.12\ GeV/c^2$

$18.4{\times}10^3$ in case of $\sqrt{s_{NN}} = 2.42\ GeV, M_{ee} > 0.12 GeV/c^2$

π^0, η decays reconstructed with ECAL at their PDG mass

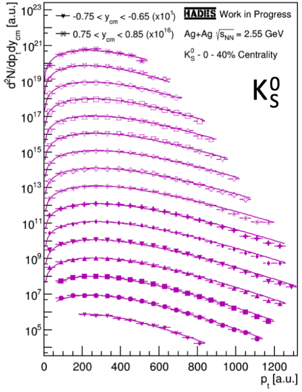


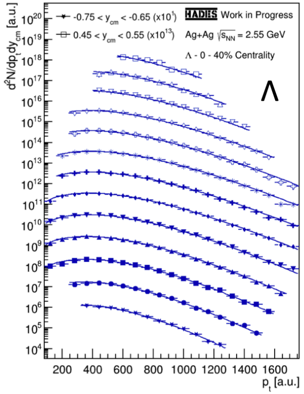
Phase 0
Research Program

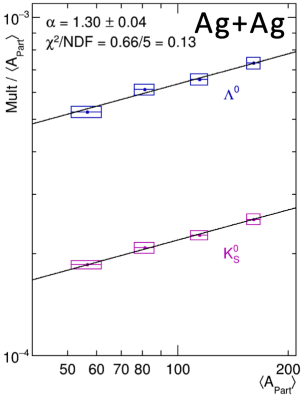
- Calibrations ongoing and full Monte-Carlo for efficiency corrections running.
- Performance of new RICH photo detector (with CBM) and ECAL at design value.

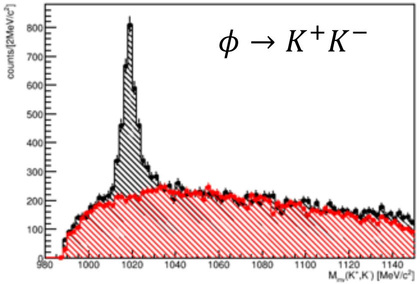
Ag+Ag COLLISIONS AT $\sqrt{s_{NN}} = 2.55\ GeV$ (+3 DAYS RUN AT $\sqrt{s_{NN}} = 2.42\ GeV$)

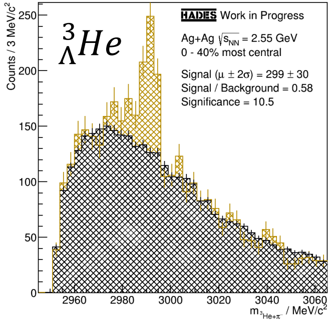
4 weeks run in Mar 2019, 14×10^9 events on disk, 43% most central + downscaled min.bias



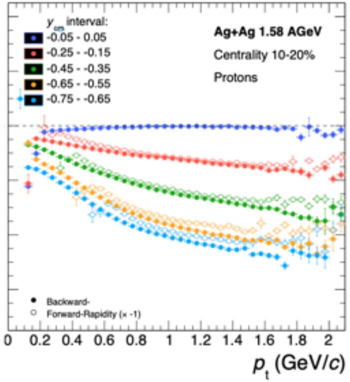






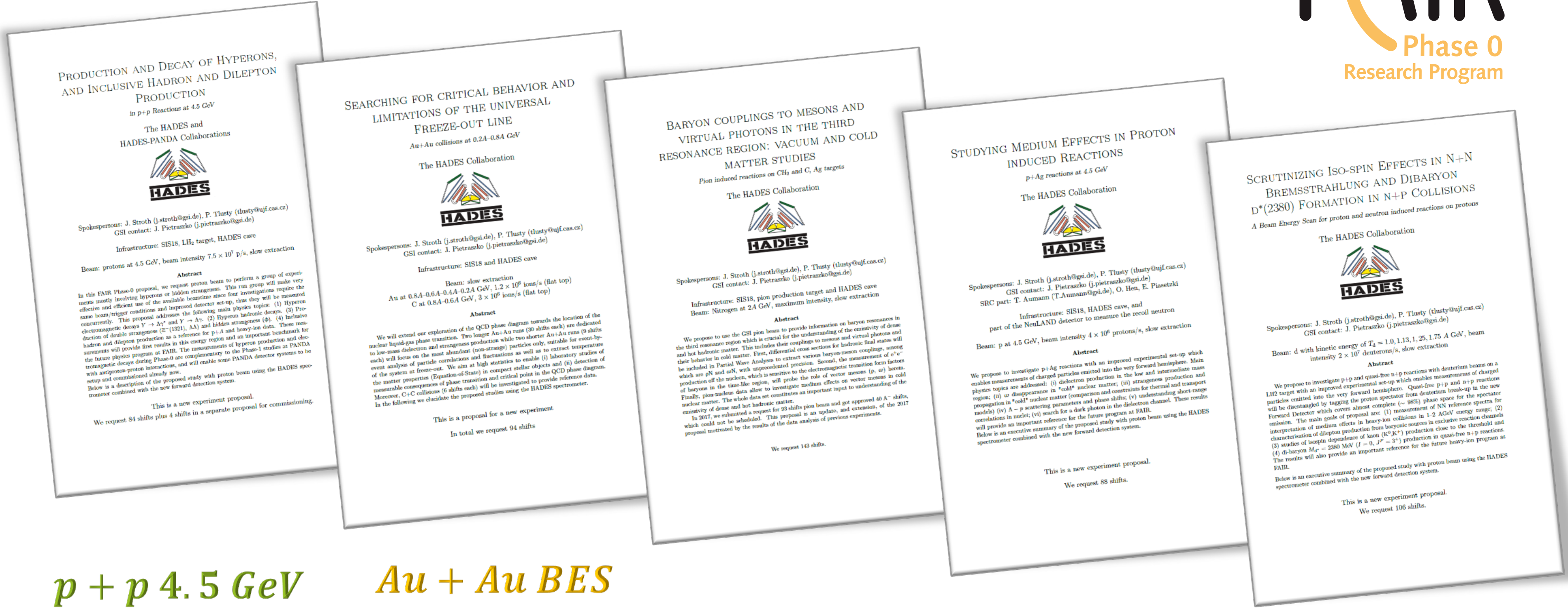


- $K^+ (26\ \text{M}), K^- \ (231\ \text{k}), K^0 (1.6\ \text{M}), \phi\ (7\ \text{k})$ and $\Lambda\ (2.7\ \text{M})$, significant (10σ) $^3_\Lambda H\ (290)$ signal reconstructed
- Multi-differential analyses are possible and ongoing



Flow of the protons (multi-differential)

HADES PROPOSALS FOR G-PAC



PRODUCTION AND DECAY OF HYPERONS, AND INCLUSIVE HADRON AND DILEPTON PRODUCTION

in p+p Reactions at 4.5 GeV

The HADES and HADES-PANDA Collaborations

Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tlusty (tlusty@ujf.cas.cz)
GSI contact: J. Pietraszko (j.pietraszko@gsi.de)

Infrastructure: SIS18, LH$_2$ target, HADES cave

Beam: protons at 4.5 GeV, beam intensity 7.5×10^7 p/s, slow extraction

This is a new experiment proposal.

We request 84 shifts plus 4 shifts in a separate proposal for commissioning.

SEARCHING FOR CRITICAL BEHAVIOR AND LIMITATIONS OF THE UNIVERSAL FREEZE-OUT LINE

Au+Au collisions at 0.2A–0.8A GeV

The HADES Collaboration

Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tlusty (tlusty@ujf.cas.cz)
GSI contact: J. Pietraszko (j.pietraszko@gsi.de)

Infrastructure: SIS18 and HADES cave

Beam: slow extraction
Au at 0.8A-0.6A-0.4A-0.2A GeV, 1.2×10^6 ions/s (flat top)
C at 0.8A-0.6A GeV, 3×10^6 ions/s (flat top)

This is a proposal for a new experiment

In total we request 94 shifts

BARYON COUPLINGS TO MESONS AND VIRTUAL PHOTONS IN THE THIRD RESONANCE REGION: VACUUM AND COLD MATTER STUDIES

Pion induced reactions on CH$_2$ and C, Ag targets

The HADES Collaboration

Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tlusty (tlusty@ujf.cas.cz)
GSI contact: J. Pietraszko (j.pietraszko@gsi.de)

Infrastructure: SIS18, pion production target and HADES cave

Beam: Nitrogen at 2A GeV, maximum intensity, slow extraction

We request 143 shifts.

STUDYING MEDIUM EFFECTS IN PROTON INDUCED REACTIONS

p+Ag reactions at 4.5 GeV

The HADES Collaboration

Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tlusty (tlusty@ujf.cas.cz)
GSI contact: J. Pietraszko (j.pietraszko@gsi.de), O. Hen, E. Piasetzki
SRC part: T. Aumann (T.Aumann@gsi.de)

Infrastructure: SIS18, HADES cave, and part of the NeuLAND detector to measure the recoil neutron

Beam: p at 4.5 GeV, beam intensity 4×10^6 protons/s, slow extraction

This is a new experiment proposal.

We request 88 shifts.

SCRUTINIZING ISO-SPIN EFFECTS IN N+N BREMSSTRAHLUNG AND DIBARYON D*(2380) FORMATION IN N+P COLLISIONS

A Beam Energy Scan for proton and neutron induced reactions on protons

The HADES Collaboration

Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tlusty (tlusty@ujf.cas.cz)
GSI contact: J. Pietraszko (j.pietraszko@gsi.de)

Beam: d with kinetic energy of $T_d = 1.0, 1.13, 1.25, 1.75$ A GeV, beam intensity 2×10^7 deuterons/s, slow extraction

This is a new experiment proposal.

We request 106 shifts.

$p + p$ 4.5 GeV
2021/22

Au + Au BES
2022

RÉSUMÉ AND PROSPECTS

Encouraging prospects for studying baryon dominated QCD matter with HADES

- Results from Au+Au collisions suggest a thermalized strongly interacting medium created at $\sqrt{s_{NN}} = 2.42\ GeV$
  - Thermal models fit yield and spectra
  - Data sensitive to the EoS (hydro description works)
  - Thermal origin of dilepton excess spectrum
  - System with long-range correlations (?)
- Complementary program on exclusive measurements in π, p induced reactions
- Strong scientific program for FAIR Phase-0
- … and for FAIR Phase-1

movie FAIR status Apr 2020

THE HADES COLLABORATION