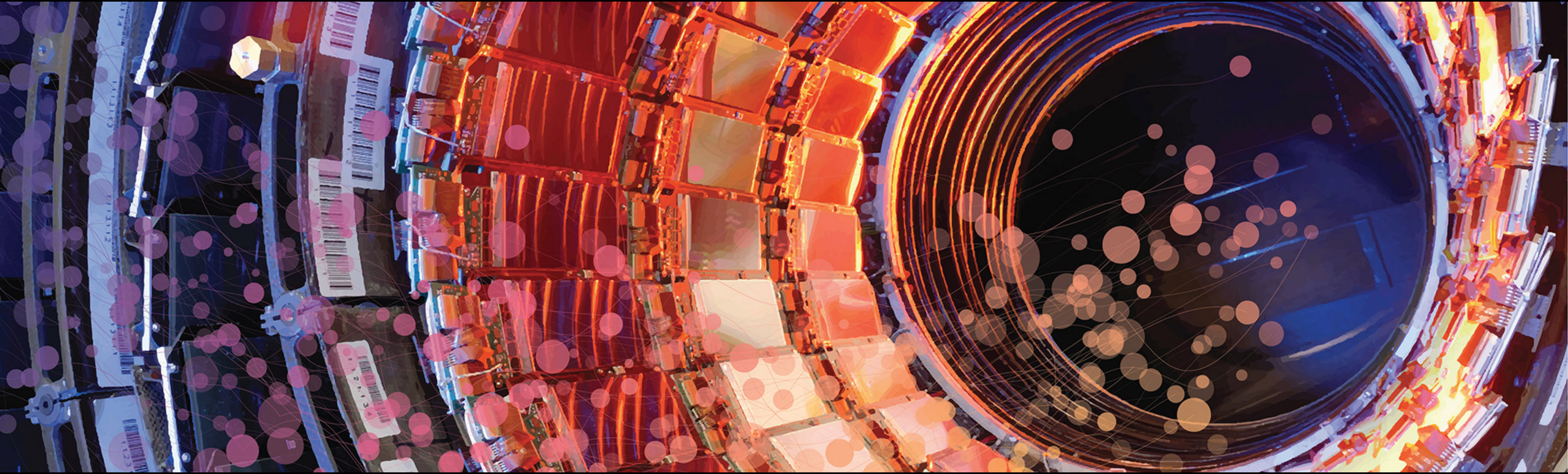
Exploring the QCD phase diagram in the region of highest μ_B with HADES



Manuel Lorenz

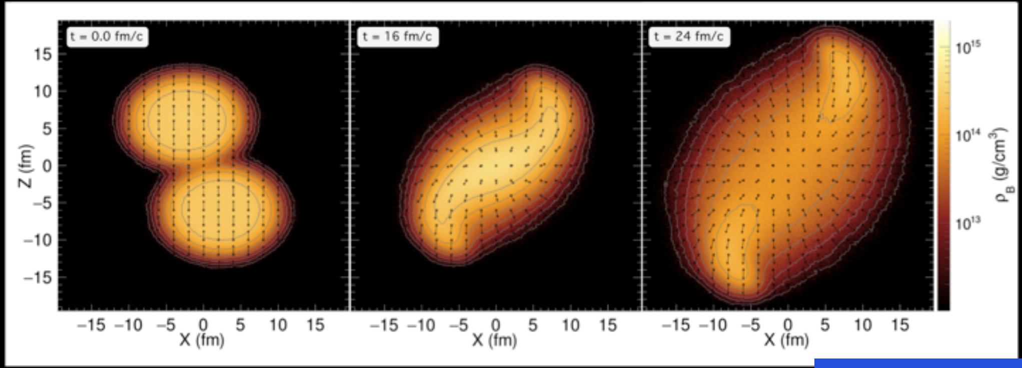
for the collaboration

Goethe-University Frankfurt

The high μ_B Side of the Phase Diagram

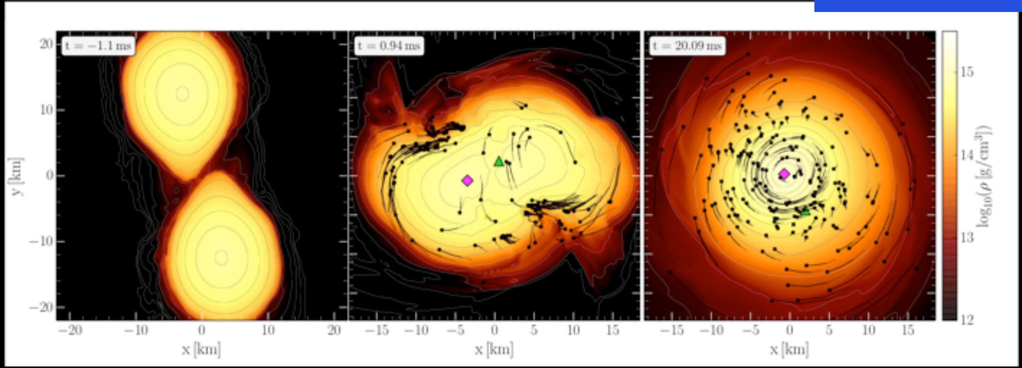
Nature Phys. 15 (2019) 10, 1040-1045

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

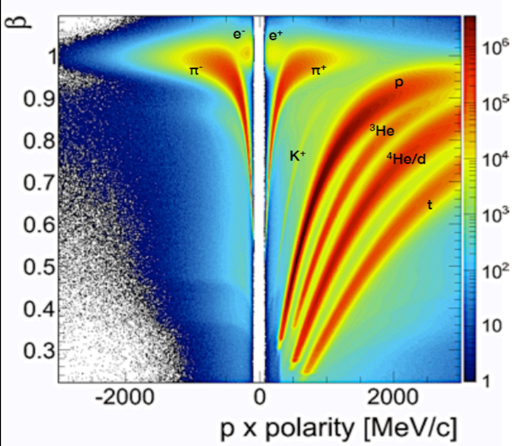


T < 70 MeV,
$\rho \approx 3\rho_0$

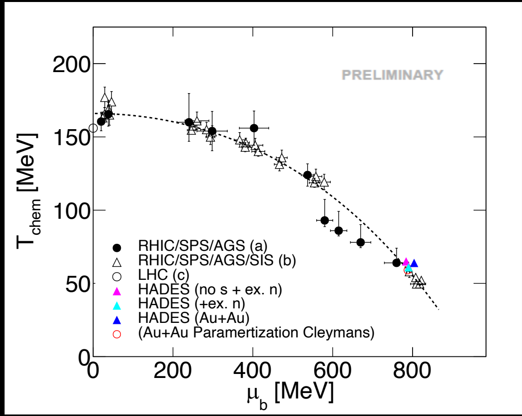
Merging Neutron Stars



M. Hanauske, J.Phys.: Conf. Series878 012031 (2017)
L. Rezzolla et. al. PRL 122, n0.6, 061101 (2019)

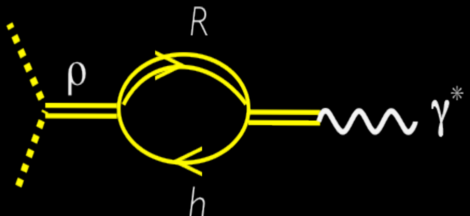


Hierarchy in hadron yields:
$p \approx 100$, $p_{bound} \approx 50$, $\pi \approx 10$, $K^+ \approx 10^{-2}$, $K^- \approx 10^{-4}$



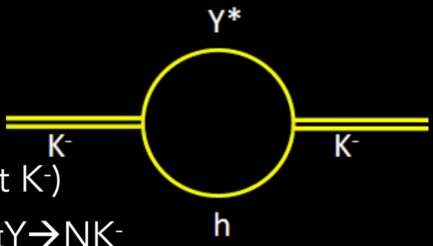
Outline of this Talk

Au+Au $\sqrt{s_{NN}}$=2.4 GeV, 2.2x10^9 events analyzed



1. Virtual Photons:

Vector meson spectral functions modified by coupling to baryons



2. Subthreshold Strangeness Production:

NN→NYK^+ $\sqrt{s_{NN}}$= 2.55 GeV

NN→NNK^+K^- $\sqrt{s_{NN}}$= 2.86 GeV (Kinematical suppression of direct K^-)

Coupling of K^- to baryons via strangeness exchange reactions e.g πY→NK^-

Aspects of medium emission

3. Bulk Properties:

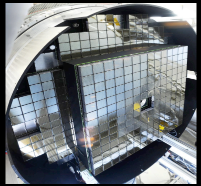
p , light nuclei and ***π***

proton number fluctuations, flow anisotropies and ***π π*** intensity interferometry

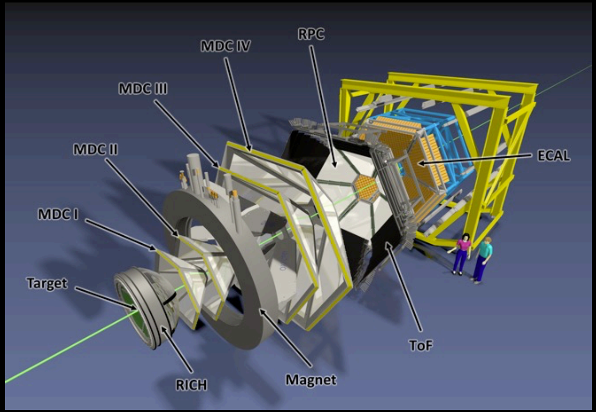
Characterizing the collision

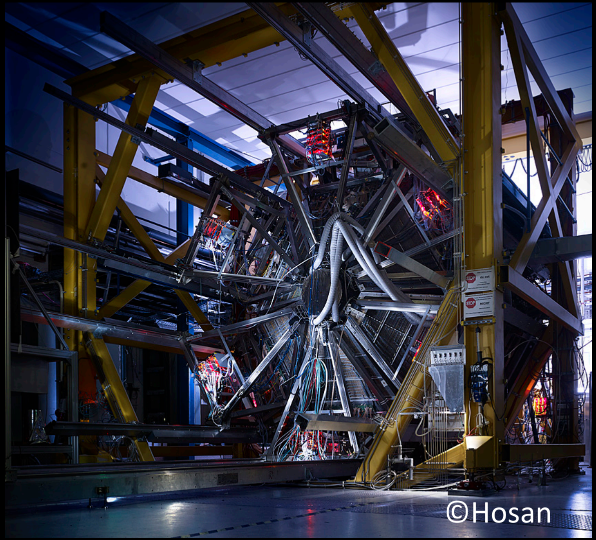
4. FAIR-Phase 0:

new Ag+Ag data and the future



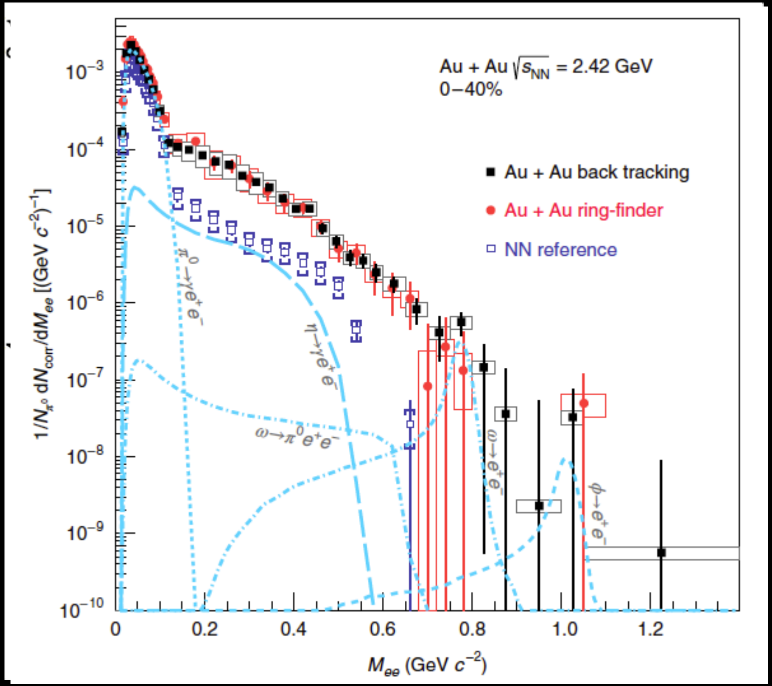
HADES at GSI/FAIR in Darmstadt, Germany





Virtual Photons

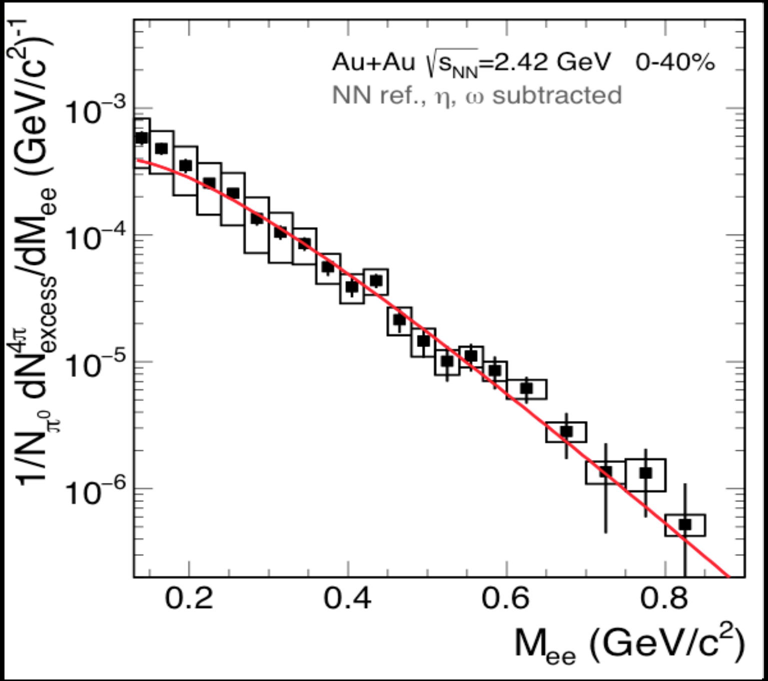
Virtual Photon Radiation from Dense Baryon Matter



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

- First measurement for a heavy system at low $\sqrt{s_{NN}}$.
- Strong excess ($0.15<M<0.7$ GeV/c^2) above components of meson decays at freeze-out and NN-reference.
- Isolation of excess by subtracting the NN-reference.

Virtual Photon Radiation from Dense Baryon Matter



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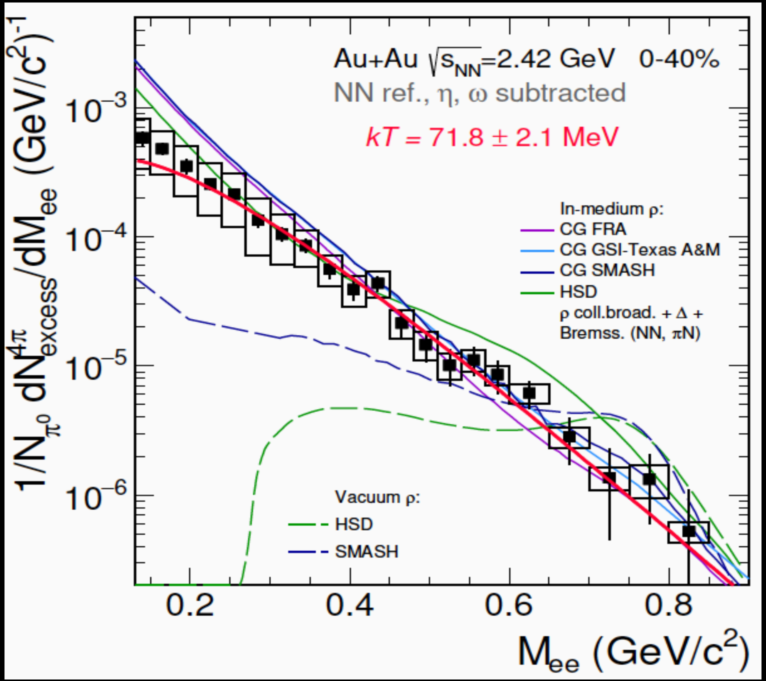
- Exponentially falling spectrum,
  → extraction of temperature $<T_{ee}>$ = 72 MeV

Virtual Photon Radiation from Dense Baryon Matter



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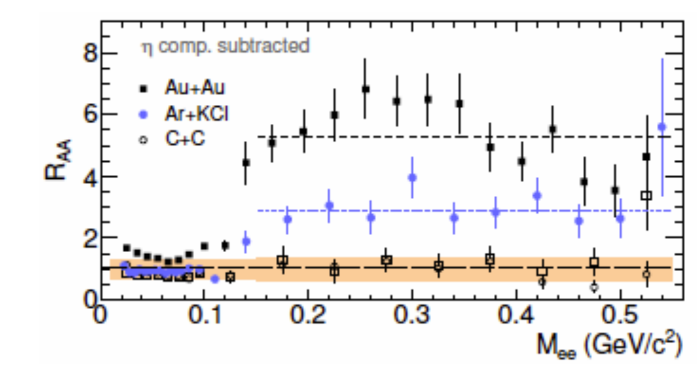
- Medium radiation: Strong broadening of the ρ due to direct ρ-baryon scattering
- Exponentially falling spectrum,
  → extraction of temperature $\langle T_{ee} \rangle$ = 72 MeV
- Thermal rates folded over coarse-grained transport medium evolution works at low energies
- Supports baryon-driven medium effects at SPS, RHIC (LHC)!

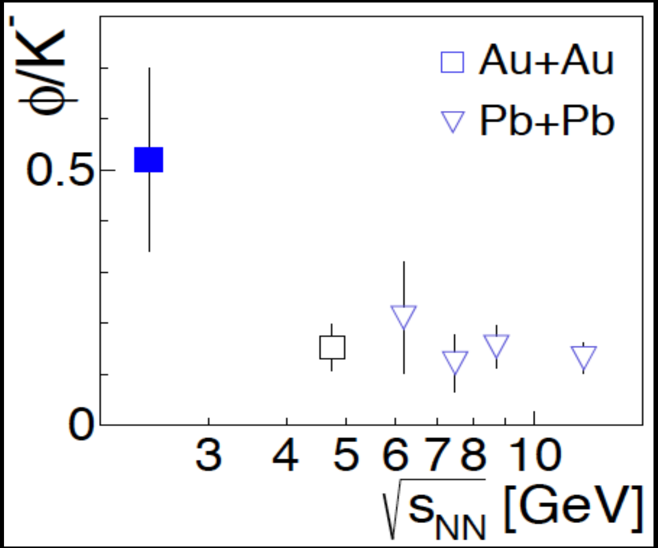


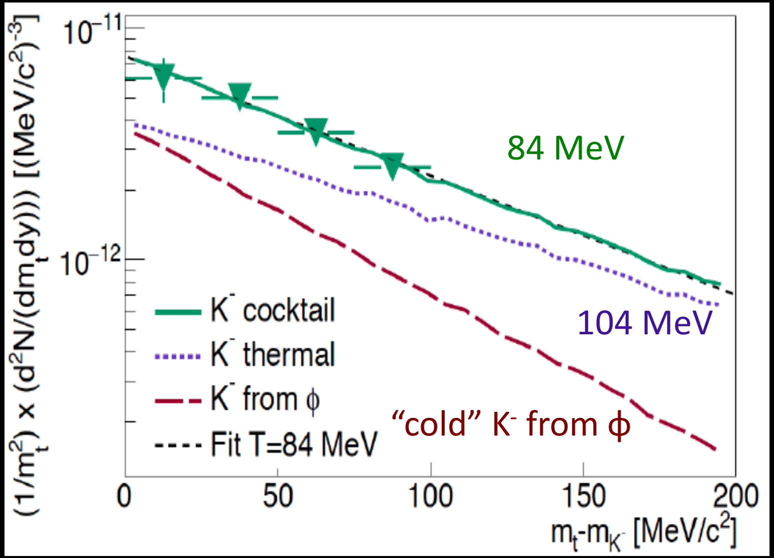
- Onset of medium radiation in Ar+KCl collisions

Strangeness

ϕ-AntiKaon Interplay in HIC

Reminder





Increased in HIC at low $\sqrt{s_{NN}}$:
→ 25% of K^- result from Φ decays!

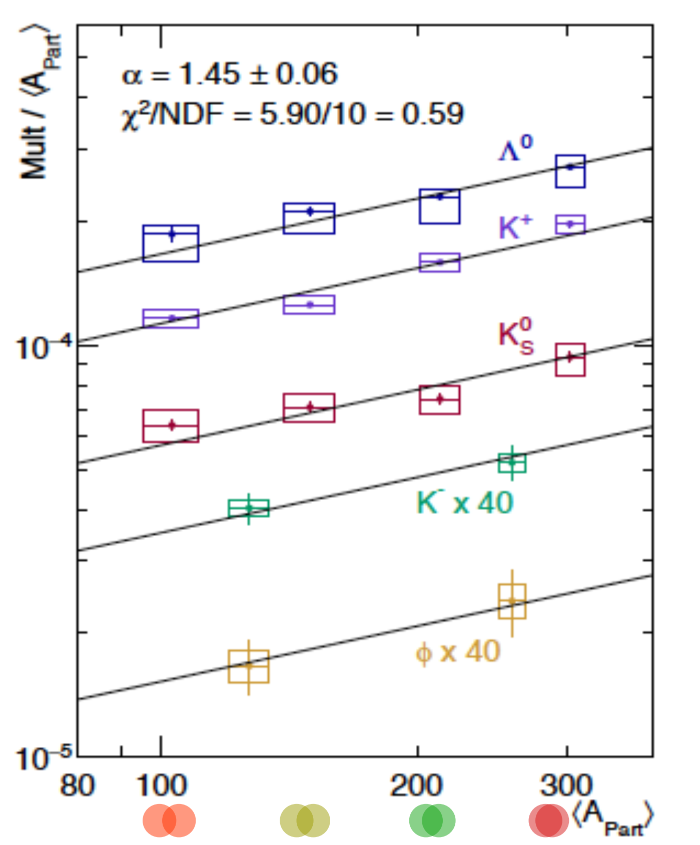
→ No indication from K^- spectrum for sequential K^+K^- freeze-out if corrected for feed-down.

Phys.Lett. B778 (2018) 403-407

Sub-threshold Strangeness Production in Au+Au @ $\sqrt{s_{NN}}$= 2.4 GeV

Complete set of strange hadrons produced below NN-threshold: NN→NYK$^+$: $\sqrt{s_{NN}}$= 2.55 GeV
NN→NNK$^+$K$^-$: $\sqrt{s_{NN}}$= 2.86 GeV

Phys.Lett. B793 (2019) 457-463



→ unique observable:

Energy must be provided from the system.

Strange particle yields rise stronger than linear with

$<A_{part}>$ $(M \sim <A_{part}>^{\alpha})$

Universal $<A_{part}>$ dependence of strangeness production

→ Hierarchy in production threshold not reflected.
Scaling with absolute amount of strangeness,
not with individual hadron states.

Bulk Properties

Proton Number Fluctuations

arXiv:2002.08701v1 [nucl-ex] 20 Feb 2020

Proton number fluctuations in $\sqrt{s_{NN}} = 2.4$ GeV Au+Au collisions studied with HADES

J. Adamczewski-Musch[4], O. Arnold[10,9], C. Behnke[8], A. Belounnas[16], A. Belyaev[7], J.C. Berger-Chen[10,9], J. Biernat[3], A. Blanco[2], C. Blume[8], M. Böhmer[10], P. Bordalo[2], S. Chernenko[7,†], L. Chlad[17], C. Deveaux[11], J. Dreyer[6], A. Dybczak[3], E. Epple[10,9], L. Fabbietti[10,9], O. Fateev[7], P. Filip[1], P. Fonte[2,a], C. Franco[2], J. Friese[10], I. Fröhlich[8], T. Galatyuk[5,4], J. A. Garzón[18], R. Gernhäuser[10], M. Golubeva[12], R. Greifenhagen[6,b], F. Guber[12], M. Gumberidze[4,5], S. Harabasz[5,3], T. Heinz[4], T. Hennino[16], S. Hlavac[1], C. Höhne[11,4], R. Holzmann[4], A. Ierusalimov[7], A. Ivashkin[12], B. Kämpfer[6,b], T. Karavicheva[12], B. Kardan[8], I. Koenig[4], W. Koenig[4], M. Kohls[8], B. W. Kolb[4], G. Korcyl[3], G. Kornakov[5], F. Kornas[5], R. Kotte[6], A. Kugler[17], T. Kunz[10], A. Kurepin[12], A. Kurilkin[7], P. Kurilkin[7], V. Ladygin[7], R. Lalik[3], K. Lapidus[10,9], A. Lebedev[13], L. Lopes[2], M. Lorenz[8], T. Mahmoud[11], L. Maier[10], A. Mangiarotti[2], J. Markert[4], T. Matulewicz[19], S. Maurus[10], V. Metag[11], J. Michel[8], D.M. Mihaylov[10,9], S. Morozov[12,14], C. Müntz[8], R. Münzer[10,9], L. Naumann[6], K. Nowakowski[3], M. Palka[3], Y. Parpottas[15,c], V. Pechenov[4], O. Pechenova[4], O. Petukhov[12], K. Piasecki[19], J. Pietraszko[4], W. Przygoda[3], S. Ramos[2], B. Ramstein[16], A. Reshetin[12], P. Rodriguez-Ramos[17], P. Rosier[16], A. Rost[5], A. Rustamov[4], A. Sadovsky[12], P. Salabura[3], T. Scheib[8], H. Schuldes[8], E. Schwab[4], F. Scozzi[5,16], F. Seck[5], P. Sellheim[8], I. Selyuzhenkov[4,14], J. Siebenson[10], L. Silva[2], Yu.G. Sobolev[17], S. Spataro[d], S. Spies[8], H. Ströbele[8], J. Stroth[8,4], P. Strzempek[3], C. Sturm[4], O. Svoboda[17], M. Szala[8], P. Tlusty[17], M. Traxler[4], H. Tsertos[15], E. Usenko[12], V. Wagner[17], C. Wendisch[4], M.G. Wiebusch[8], J. Wirth[10,9], Y. Zanevsky[7,†], P. Zumbruch[4]

(HADES Collaboration*)

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[19] *Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland*

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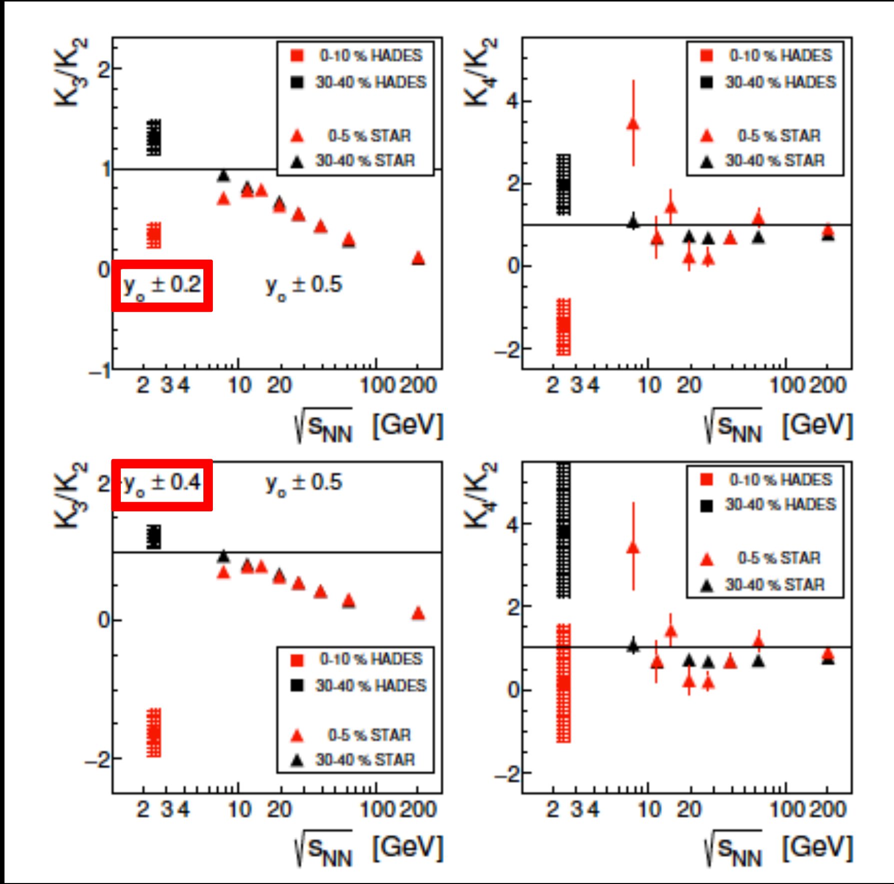
[b] *also at Technische Universität Dresden, 01062 Dresden, Germany*
[c] *also at Frederick University, 1036 Nicosia, Cyprus*
[d] *also at Dipartimento di Fisica and INFN, Università di Torino, 10125 Torino, Italy*
* *e-mail: hades-info@gsi.de (J. Stroth)*
† *deceased*

(Dated: February 21, 2020)

We present an analysis of proton number fluctuations in $\sqrt{s_{NN}} = 2.4$ GeV ^{197}Au+^{197}Au collisions measured with the High-Acceptance DIElectron Spectrometer (HADES) at GSI. With the help of extensive detector simulations done with IQMD transport model events including nuclear clusters, various nuisance effects influencing the observed proton cumulants have been investigated. Acceptance and efficiency corrections have been applied as a function of fine grained rapidity and transverse momentum bins, as well as considering local track density dependencies. Next, the effects of volume changes within particular centrality selections have been considered and beyond-leading-order corrections have been applied to the data. The efficiency and volume corrected proton number moments and cumulants K_n of orders $n = 1, \ldots, 4$ have been obtained as a function of centrality and phase-space bin, as well as the corresponding correlators C_n. We find that the observed correlators show a power-law scaling with the mean number of protons, i.e. $C_n \propto \langle N \rangle^n$, indicative of mostly long-range multi-particle correlations in momentum space. We also present a comparison of our

CONTENTS

First analysis at Au+Au @ √s_{NN}= 2.4 GeV.
Detailed study of experimental effects.



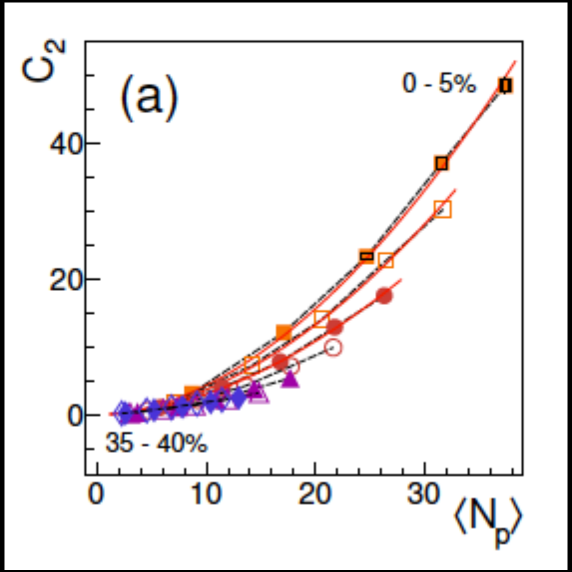
Comparison to data from STAR for different rapidity bins.

J. Adam et al. (STAR), (2020), arXiv:2001.02852 [nuclex].

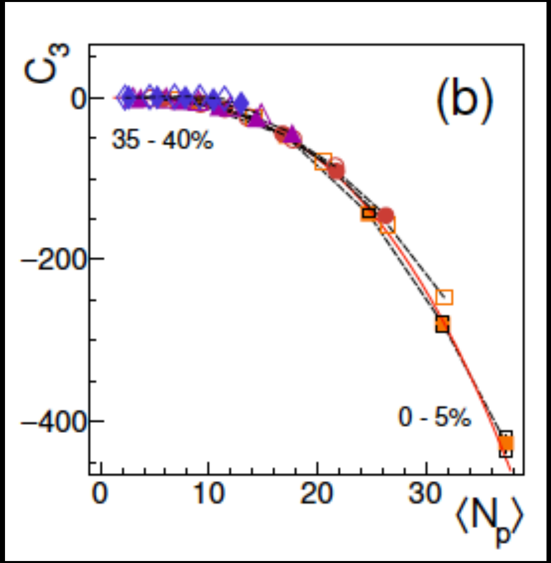
$\langle N_p \rangle$ scaling of Correlators C_n

Cumulants K_n hold information on multi-particle correlators C_n
Ling & Stephanov, PRC 93, 034915 (2016)

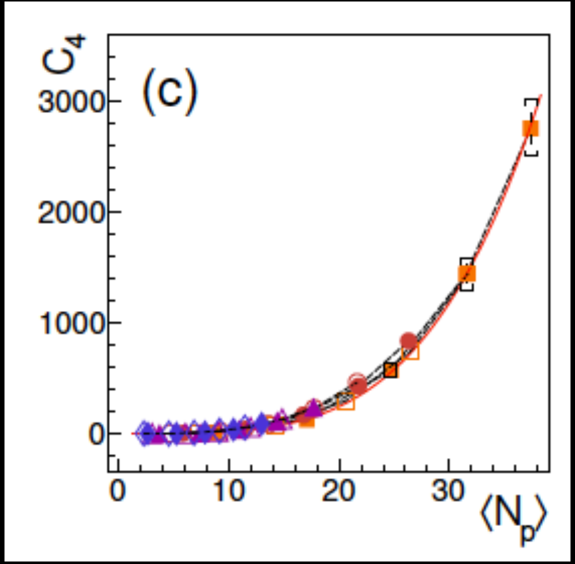
Investigate C_n vs. $\langle N_p \rangle$ to isolate relevant physics
Bzdak, Koch & Strodthoff, PRC 95, 054906 (2017)



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



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



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

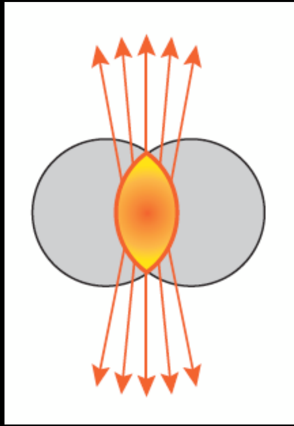
$\alpha \simeq n$ $\rightarrow$ signature of long-range correlations ($\Delta y_{corr} > 1$)

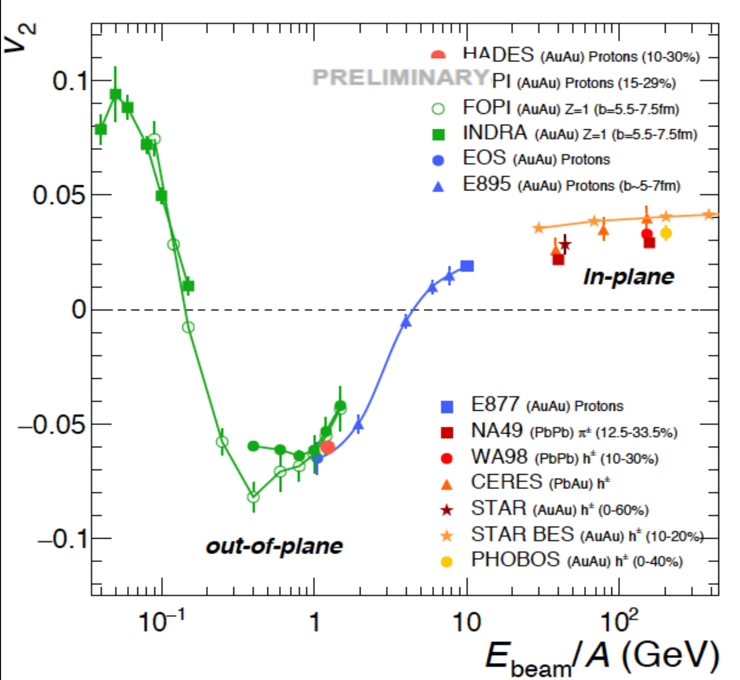
Due to the proximity of the liquid/gas phase transition?

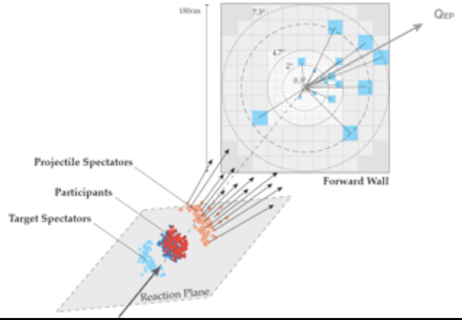
Flow Anisotropies

Out-of-plane v_2

- Long spectator passing time
  $\tau_{passing} \approx \tau_{expansion}$
- Squeeze-out



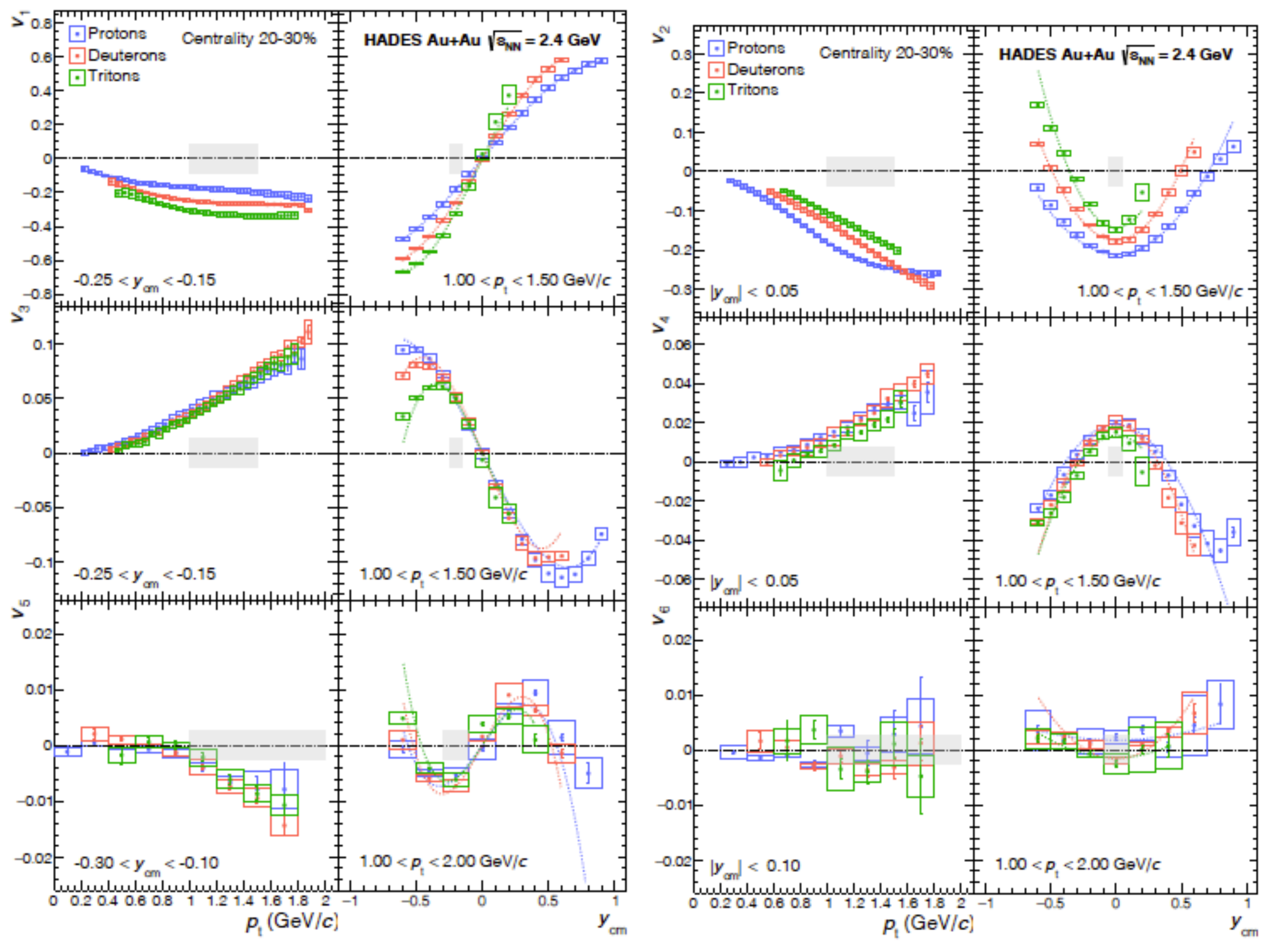




Event plane reconstruction
Based on hits of charged projectile spectators in the FW

p, d, t : v_1 - v_6

First analysis up to v_6 in this energy regime

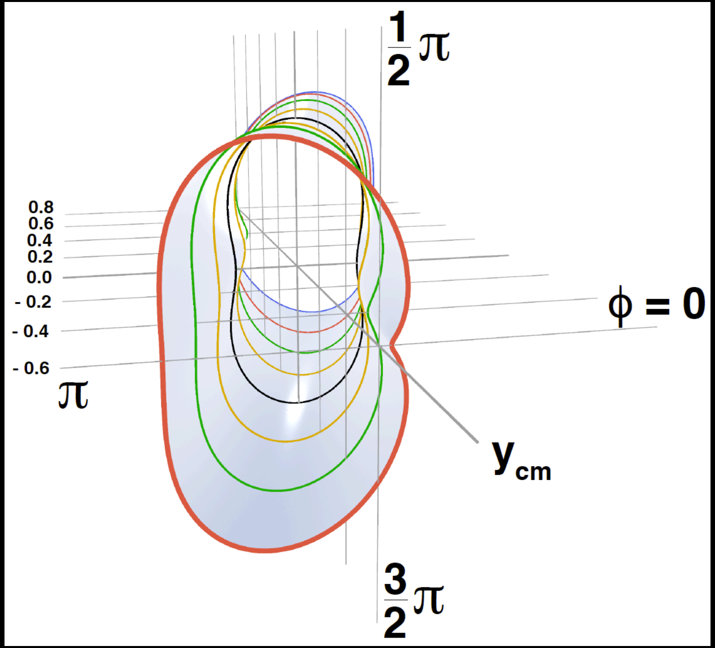


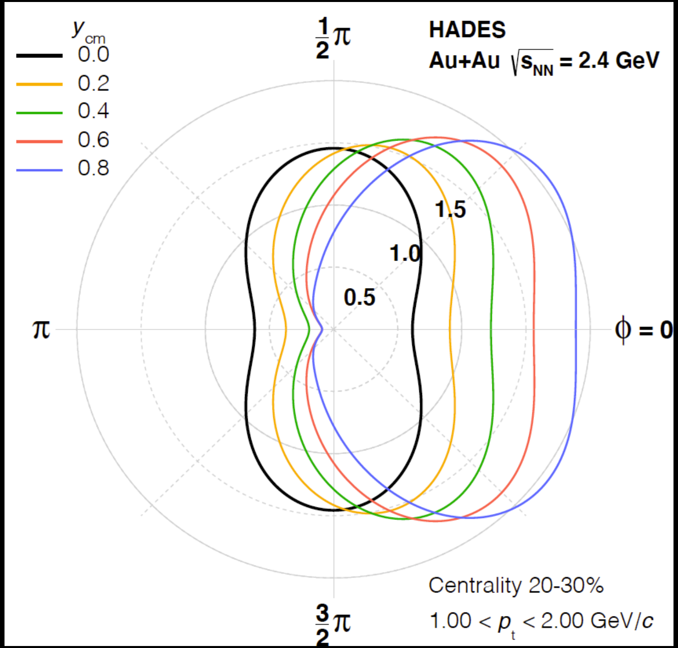
arxiv.org/abs/2005.12217

Parameterization of y dependence:

$$v_{1,3,5}(y_{cm}) = a y_{cm} + b y_{cm}^3$$
$$v_{2,4,6}(y_{cm}) = c + d y_{cm}^2$$

3D Visualization of Particle Flow





Mid-rapidity:
Almost elliptical shape
odd coefficients consistent with zero

Forward/backward rapidities:
Triangular shape
Interplay: central fireball pressure and interaction with spectator matter?

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

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

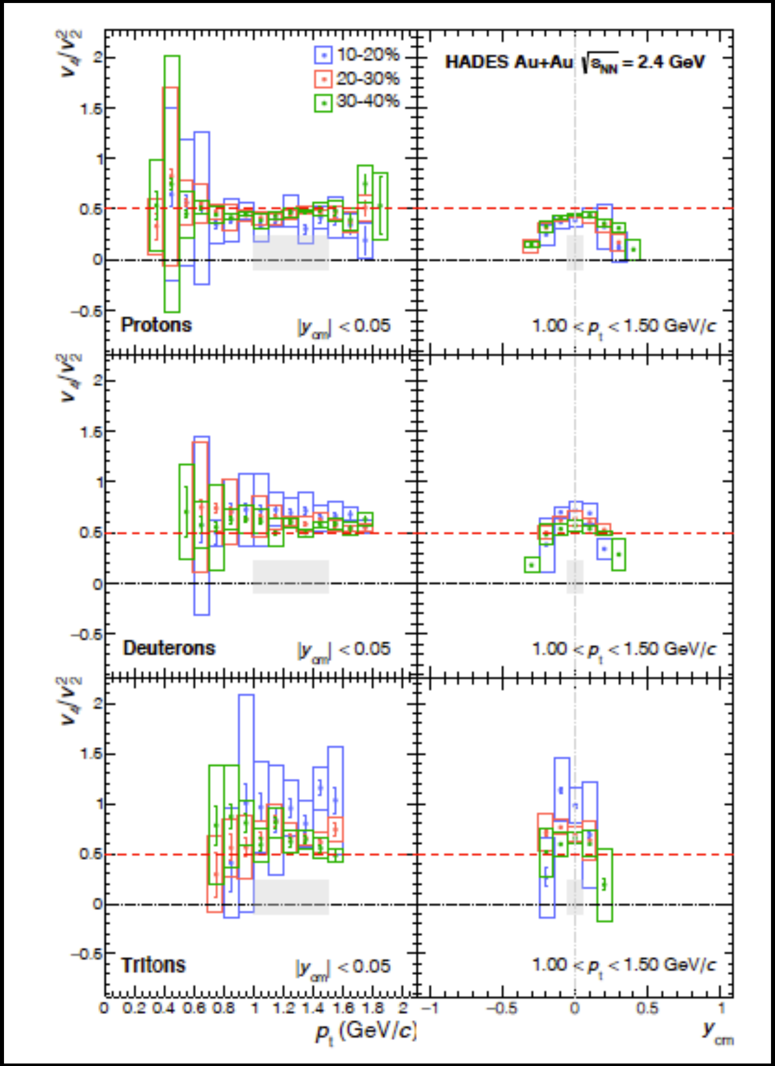
arxiv.org/abs/2005.12217

p, d, t : Scaling Behavior

- Ideal fluid dynamics prediction: 0.5

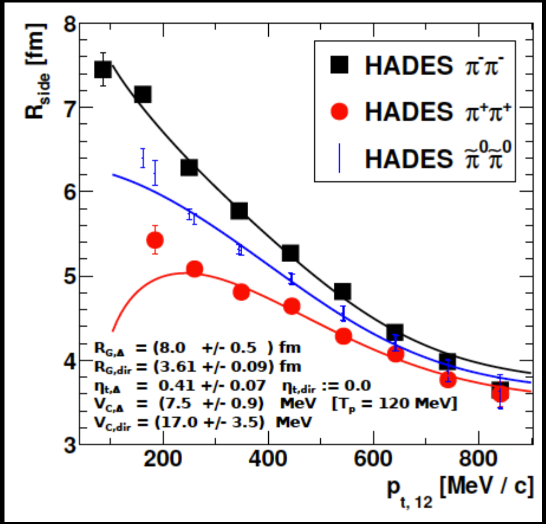
  N. Borghini and J.-Y. Ollitrault, Phys. Lett. B642, 227 (2006).

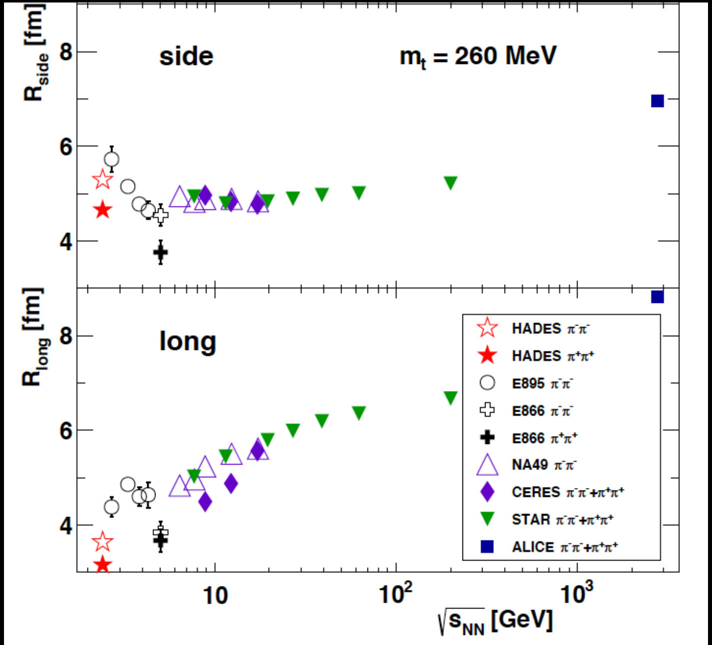
- At mid-rapidity p, d, t data are remarkably close.

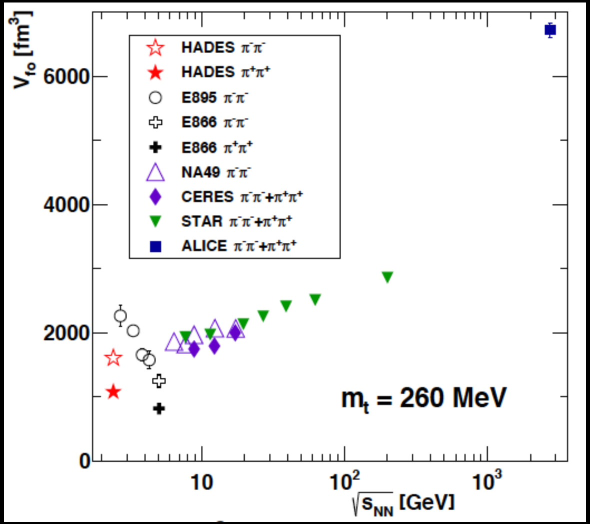


arxiv.org/abs/2005.12217

Identical π Intensity Interferometry







Indications for charge-sign differences reported previously:

E866 R. A. Soltz, M. Baker, J. H. Lee, Nucl. Phys. A 661, 439c (1999)
E877 D. Miskowiec et al., Nucl. Phys. A590, 473c (1995)
NA44 I.G. Bearden et al., Nucl. Phys. A638, 103c (1998)

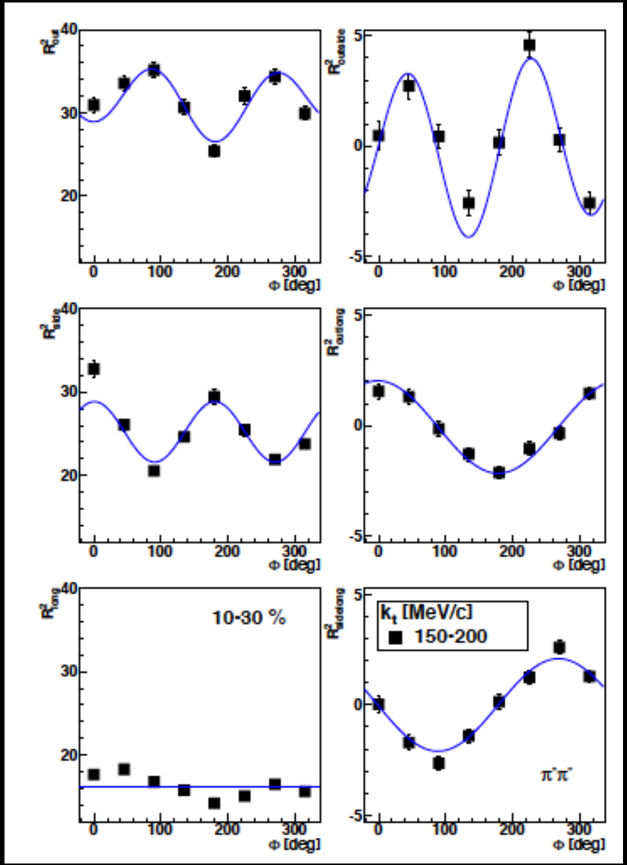
First time observation of substantial differences!

HADES follows trend from STAR/NA49 more than trend from E895
→ room for structures?

Phys.Lett.B 795 (2019) 446-451

Identical π Intensity Interferometry

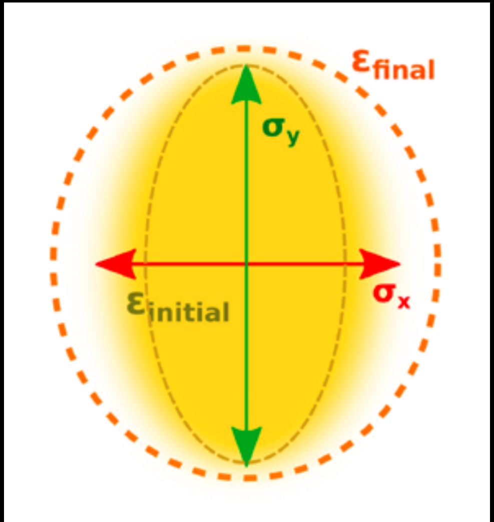
Eur.Phys.J.A 56 (2020) 5, 140



ϕ-dependent HBT parameter

Identical pion correlations as function of the event-plane angle **Φ** and pair momentum (5 bins)

Initial (nuclear overlap) eccentricity
is relaxed at freeze-out
$\epsilon_{\text{initial}} > \epsilon_{\text{final}}$.

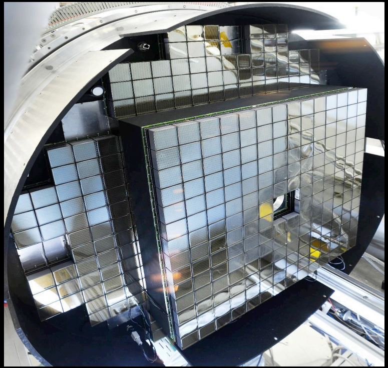


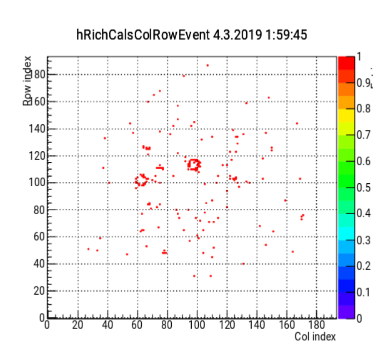
$$R^2_{ij} = \begin{pmatrix} R^2_o & R^2_{os} & R^2_{ol} \\ R^2_{os} & R^2_s & R^2_{sl} \\ R^2_{ol} & R^2_{sl} & R^2_l \end{pmatrix}$$

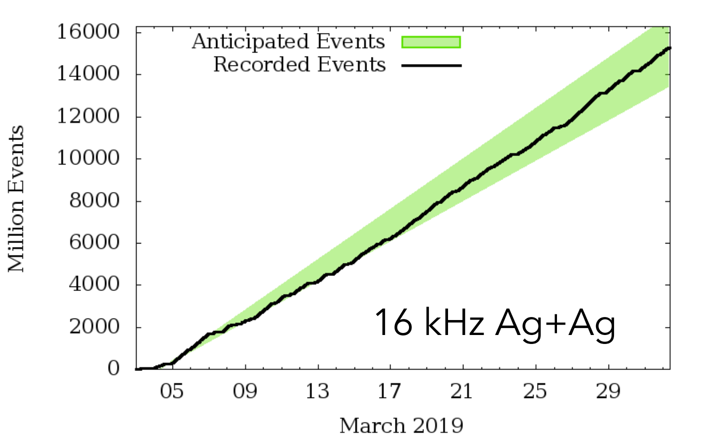
$$\varepsilon_{xy} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2},$$

FAIR-Phase 0

Ag+Ag $\sqrt{s_{NN}}$= 2.6 GeV: Virtual Photons

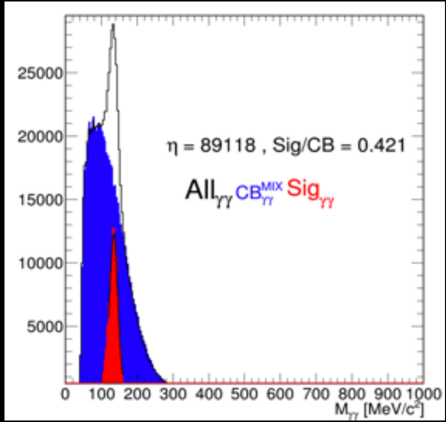




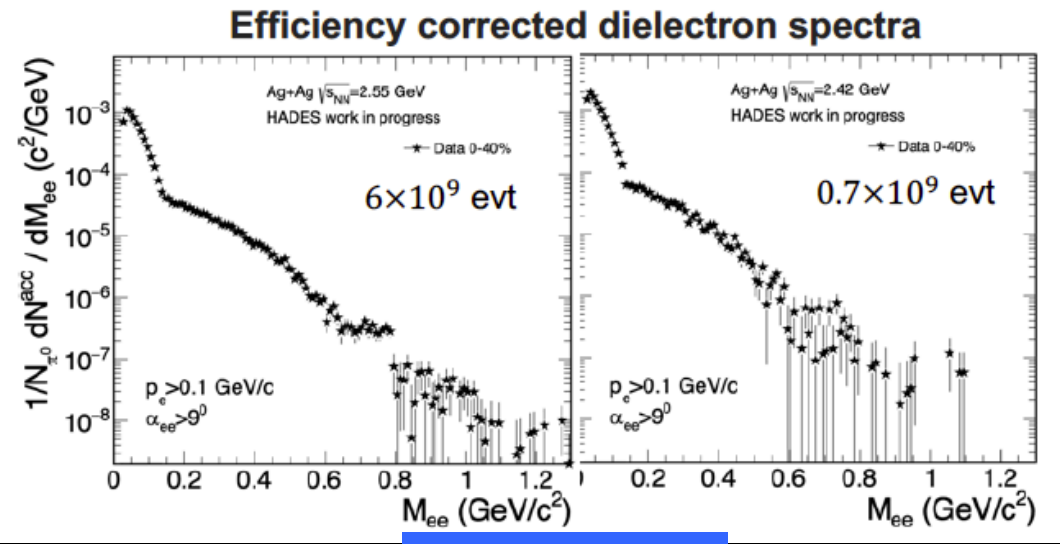


½ of the CBM RICH photon detector

Stable operation during 4 weeks of beamtime

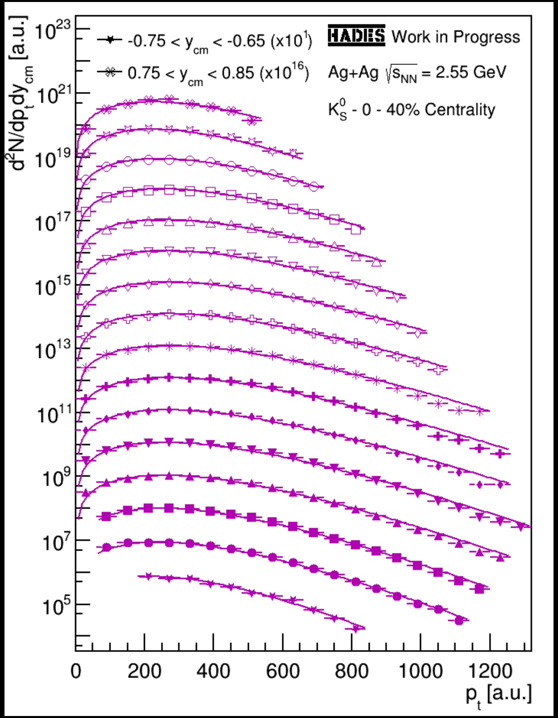


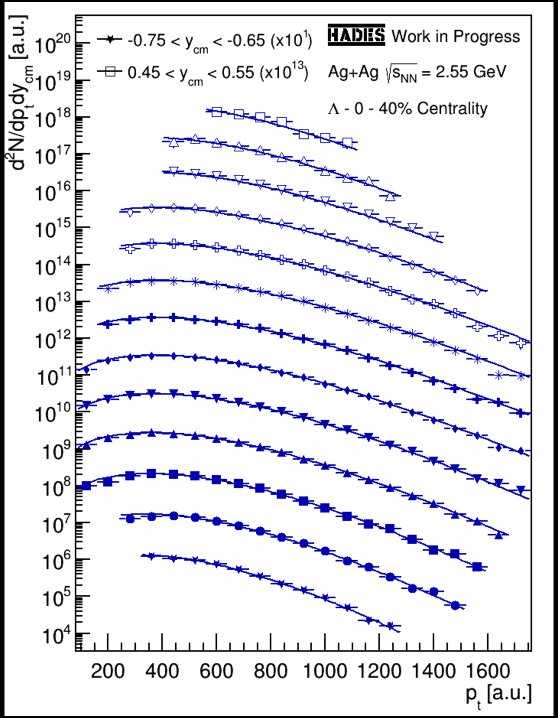
← Supplemented by new ECAL detector

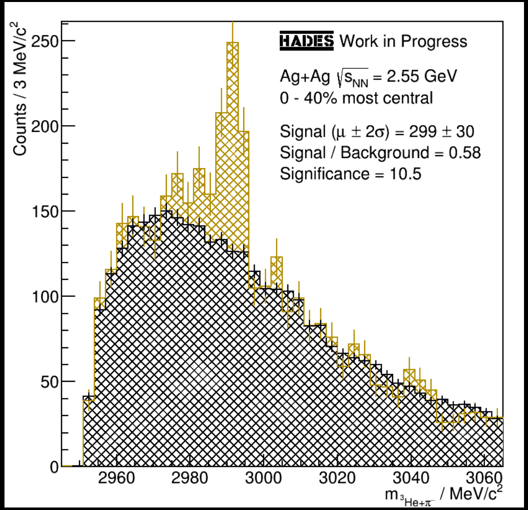


Resulting spectra

Ag+Ag $\sqrt{s_{NN}}$= 2.6 GeV: Strangeness



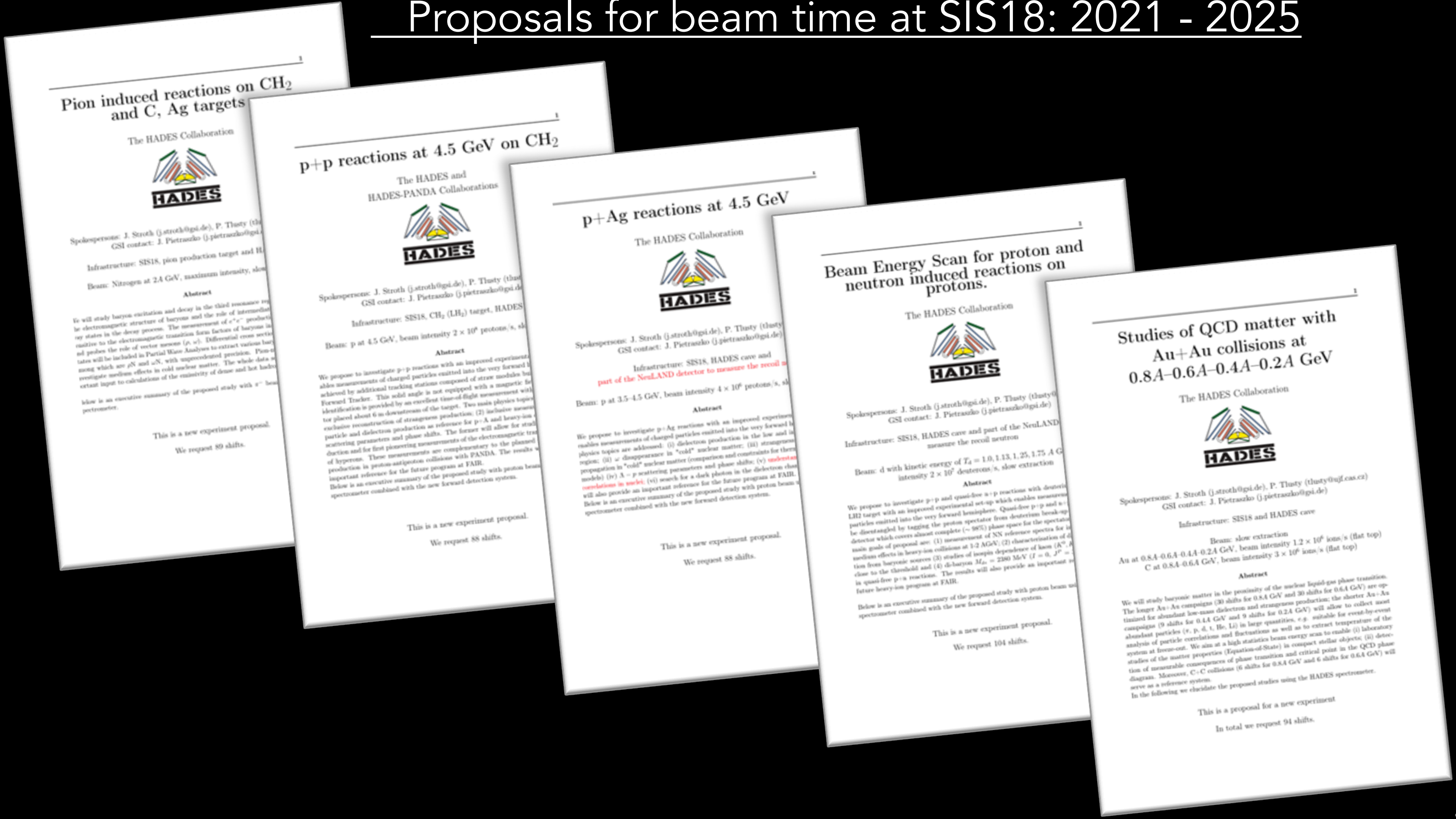




Hint for a signal

K^0_s and Λ production at the NN-threshold

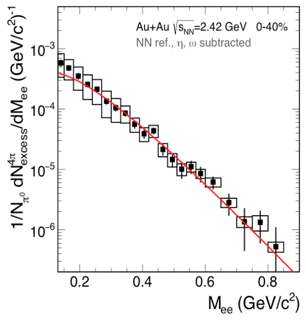
Proposals for beam time at SIS18: 2021 - 2025



Summary

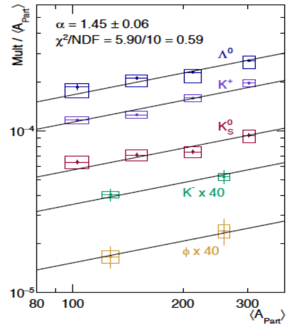
Virtual Photons:

Strong broadening of the ρ, exponentially falling spectrum,
→ extraction of temperature $\langle T_{ee} \rangle$ = 72 MeV
Onset of medium radiation in Ar+KCl collisions.



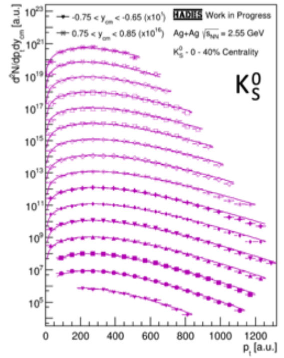
Strangeness:

No indication for sequential K^+K^- freeze-out if p_t spectra corrected for feed-down.
Universal $\langle A_{part} \rangle$ dependence of strangeness production.



The Bulk:

First data on: proton number fluctuations.
flow anisotropies up to v_6.
identical pion HBT as function Φ and k_t.



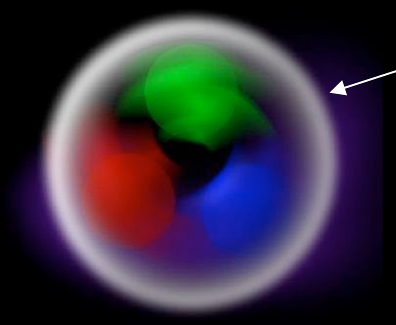
FAIR-Phase0:

High quality data ~~to come~~ are here
A lot to come in the next years.

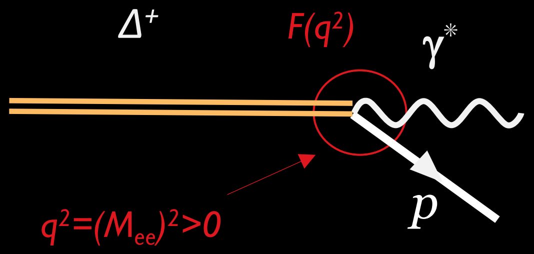
The Team

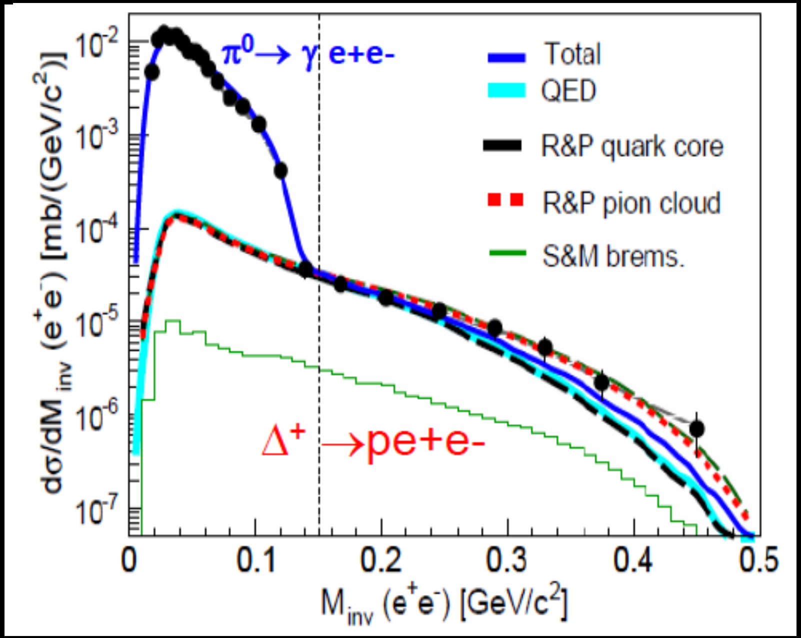
Back Up

EM Formfactors of Baryonic Resonances



p+p(1.25 GeV) → p+p+e⁻+e⁺

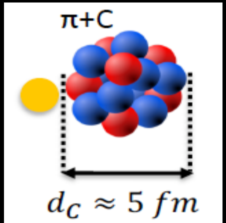


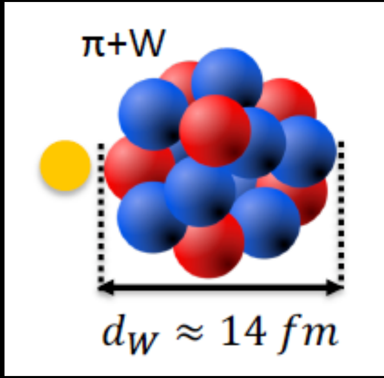


Phys. Rev. C95 (2017) no.6 065205

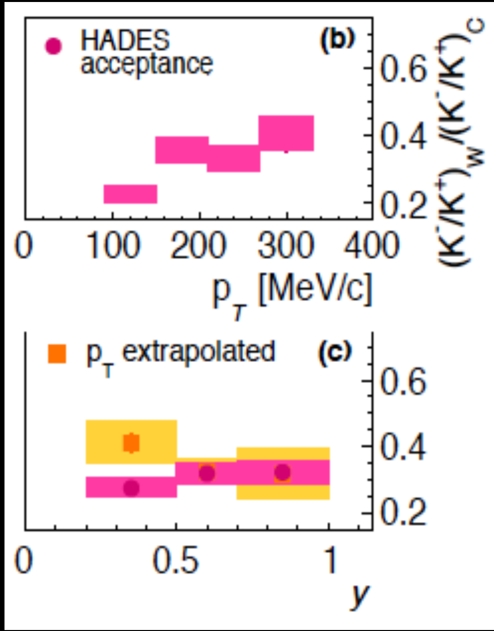
Good agreement with model of Ramahlo & Pena if pion cloud is taken into account

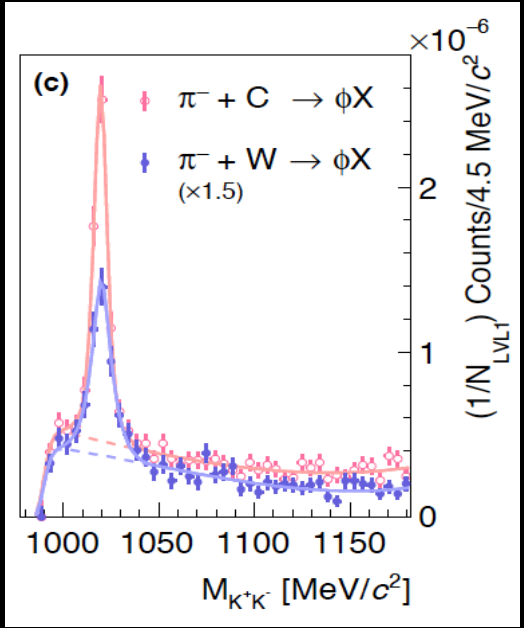
ϕ-AntiKaon Interplay in Cold Nuclear Matter





→ Mean free path $\lambda_\pi = 1.5\ fm$
$(p_\pi = 1.7\ GeV/c\ , \rho_B \approx \rho_0)$





→ Suppression of K^- relative to K^+

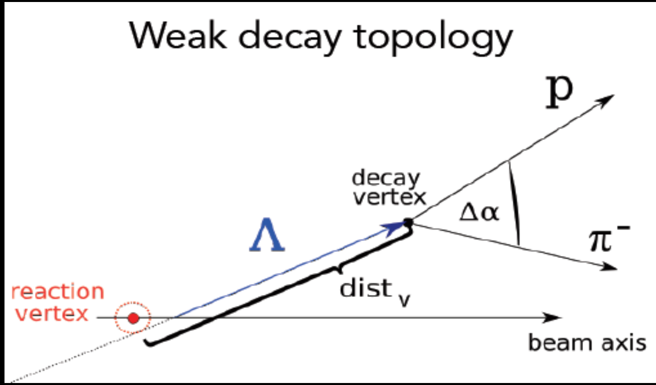
→ Similar suppression for ϕ like for K^-

In HADES acceptance:

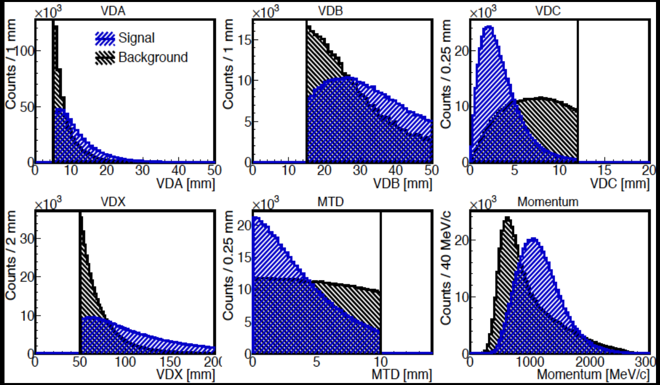
$$(\phi/K^-)_C = 0.55 \pm 0.04(stat)^{+0.06}_{-0.07}(sys)$$

$$(\phi/K^-)_W = 0.63 \pm 0.06(stat) \pm 0.11(sys)$$

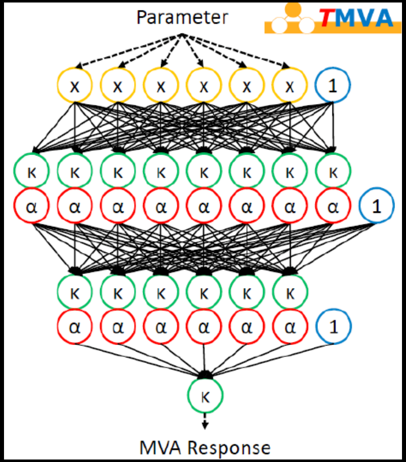
Weak Decay Topology Recognition with Neural Networks



Results in several parameters

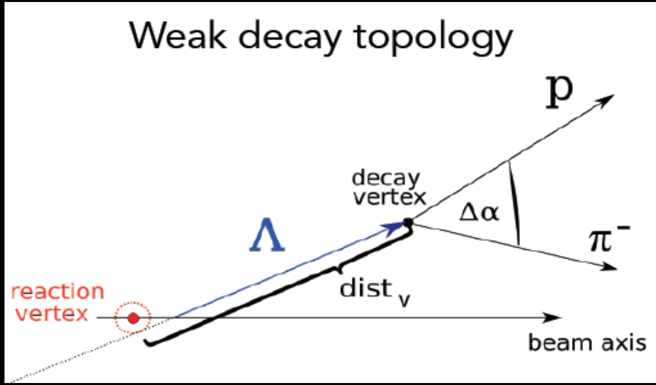


Which can be feed into an ANN

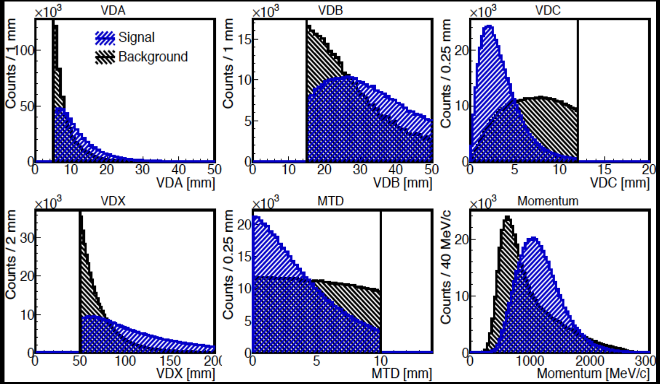


MA S. Spies, PhD F. Kornas, Phys.Lett. B793 (2019) 457-463

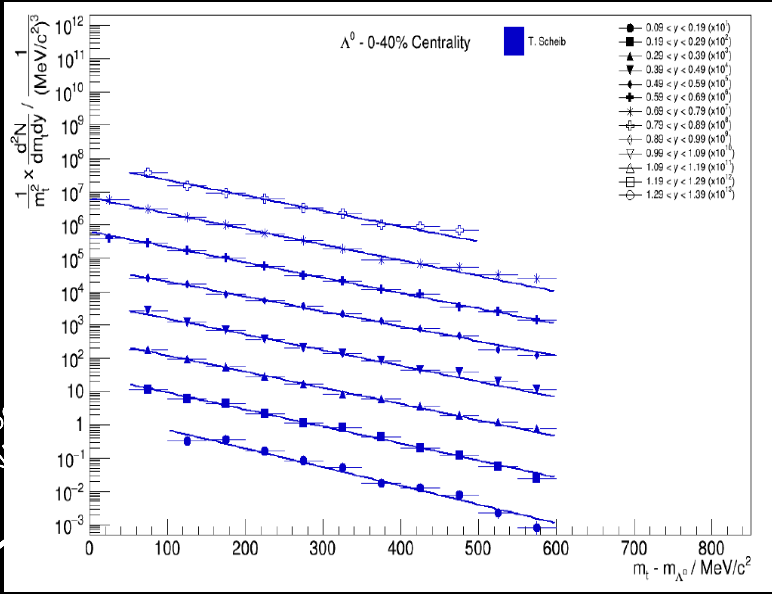
Weak Decay Topology Recognition with Neural Networks



↓ Results in several parameters

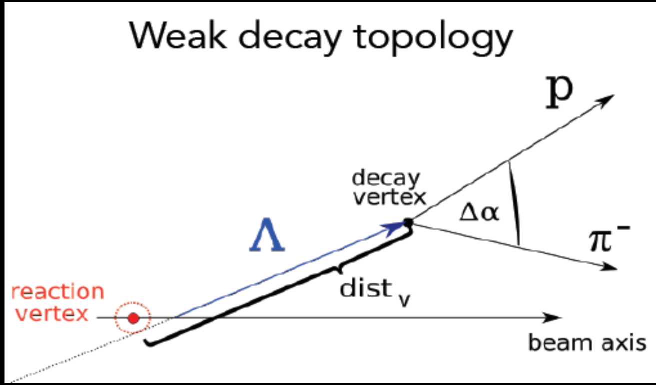


Which can b
into an AN

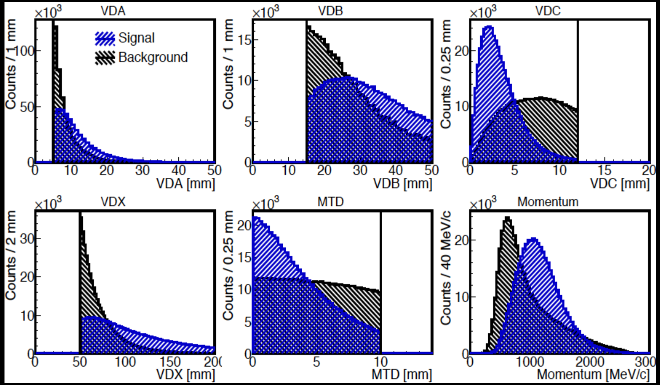


MA S. Spies, PhD F. Kornas, Phys.Lett. B793 (2019) 457-463

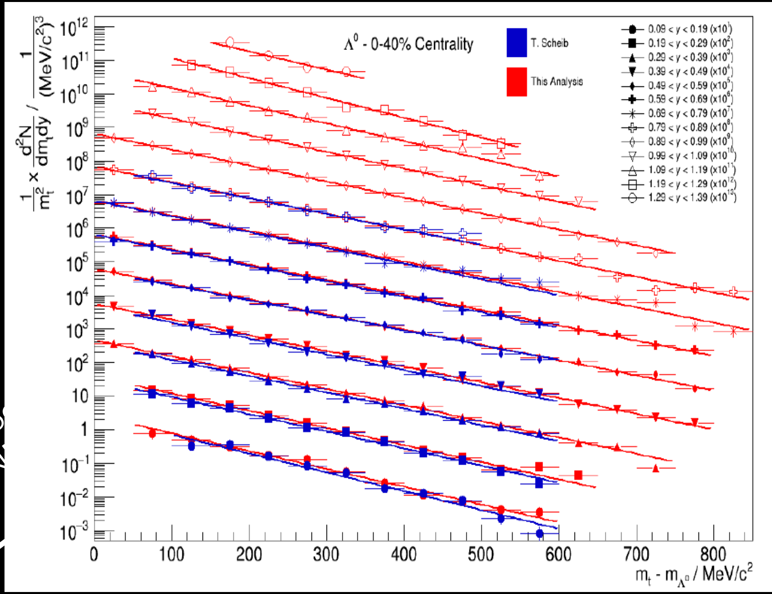
Weak Decay Topology Recognition with Neural Networks



↓ Results in several parameters

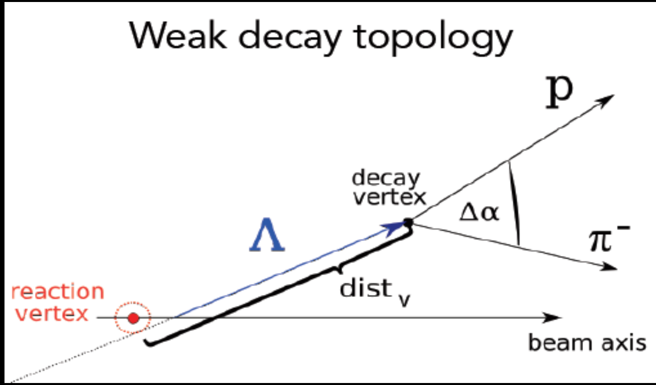


Which can b
into an AN

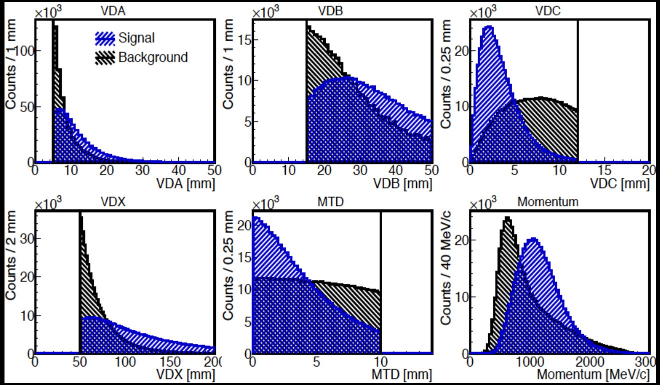


MA S. Spies, PhD F. Kornas, Phys.Lett. B793 (2019) 457-463

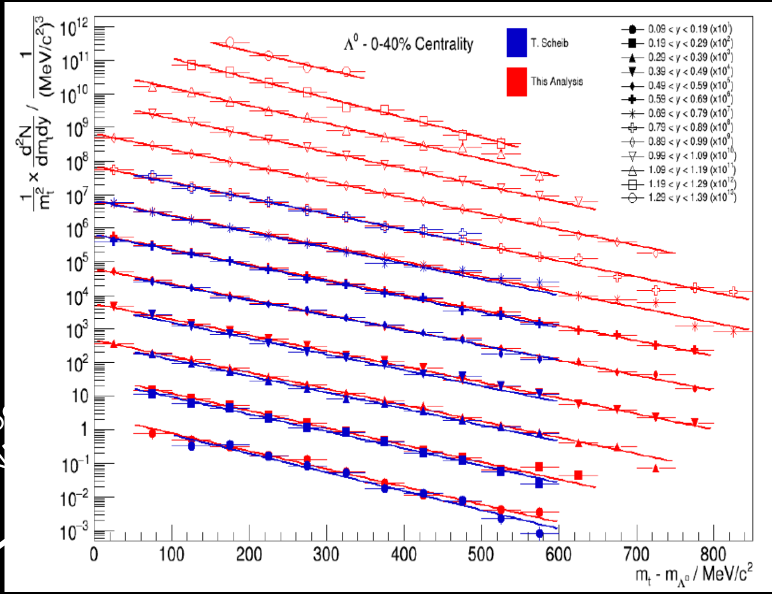
Weak Decay Topology Recognition with Neural Networks



↓ Results in several parameters



Which can be ... into an AN...

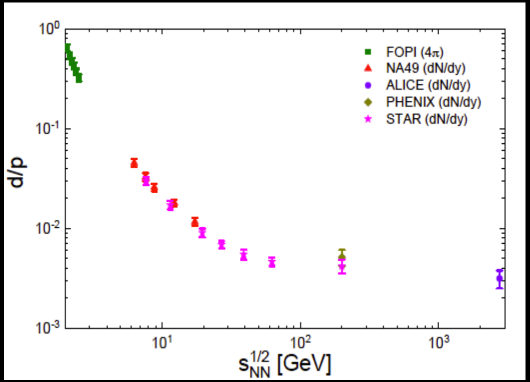


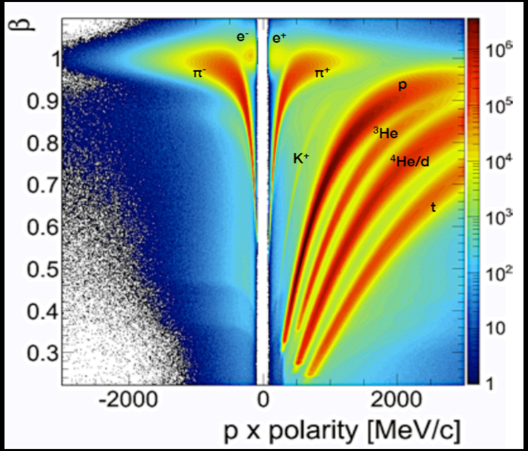
ANN in combination with pre-selection on topology parameters improves performance → reduction of uncertainty for 4π yield extraction.

MA S. Spies, PhD F. Kornas, Phys.Lett. B793 (2019) 457-463

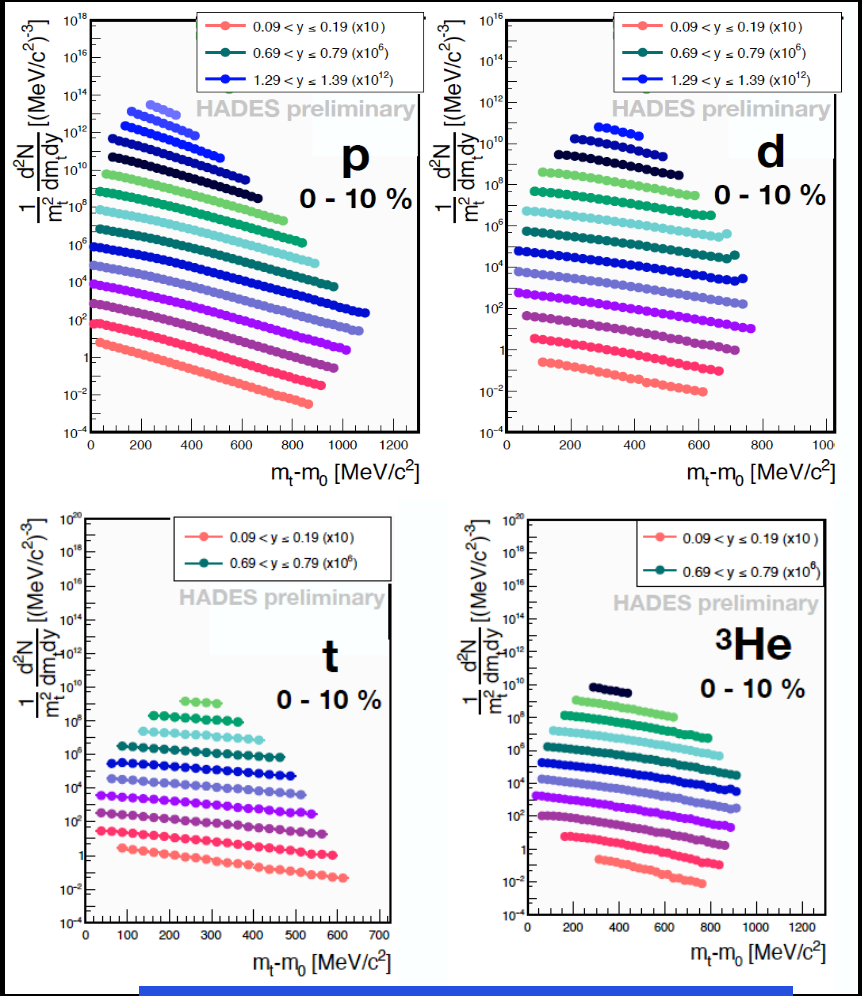
Light Nuclei

Data collection:
https://arxiv.org/abs/2004.04411



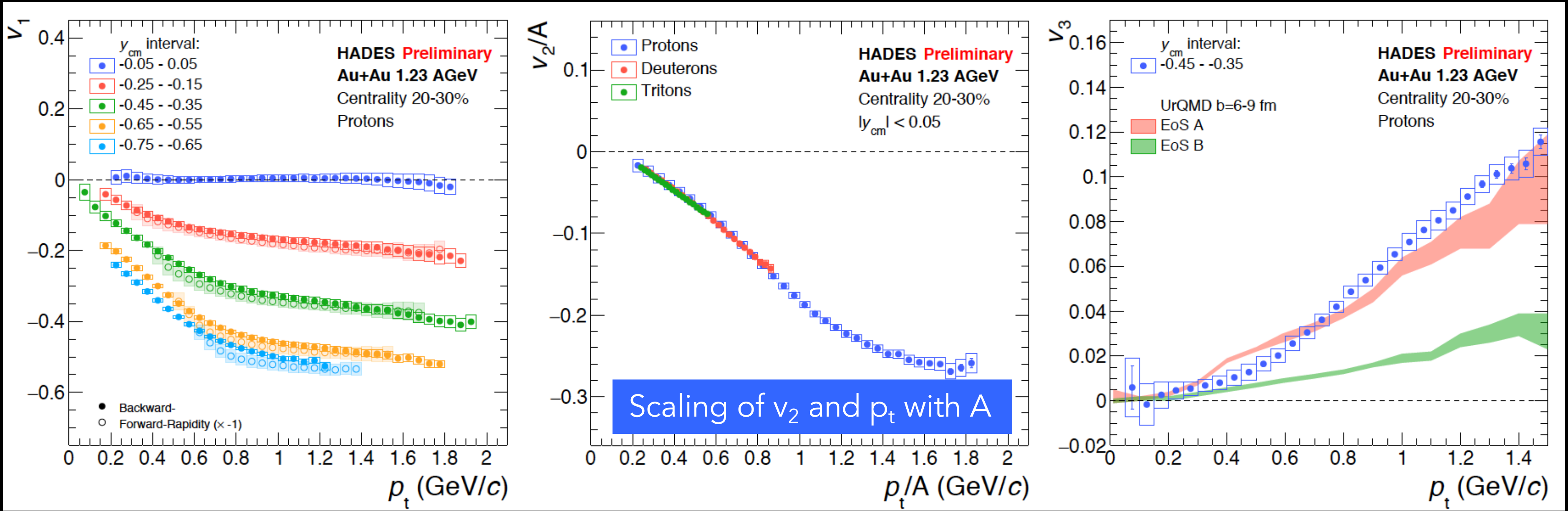


Hierarchy in hadron yields:
p ≈ 100, p_{bound} ≈ 50, π ≈ 10,



High statistic multi-differential data

p, d, t v_1, v_2, v_3, v_4



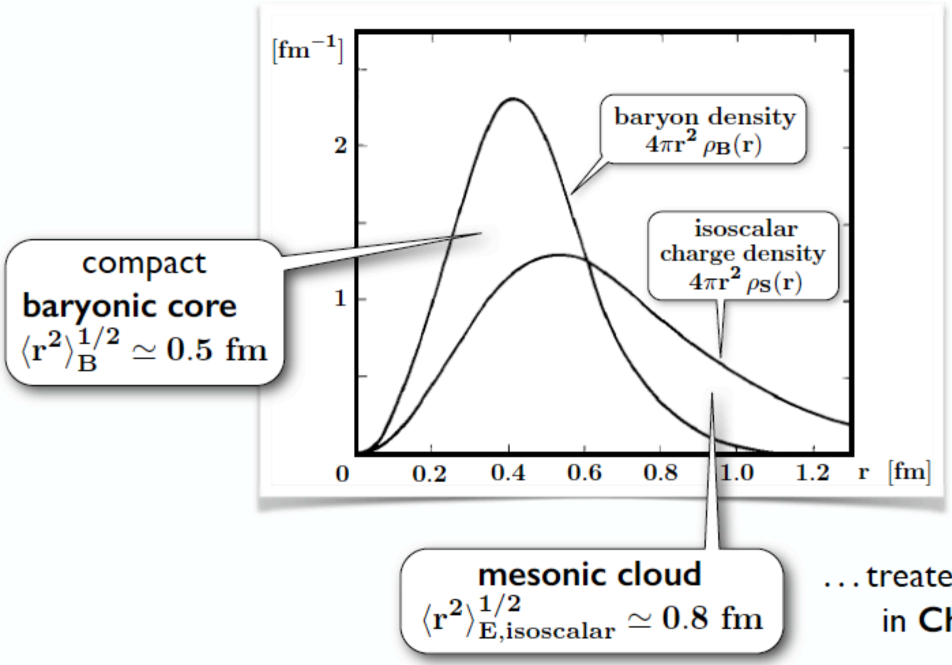
High statistic multi-differential data

Comparison p,d,t at mid-rapidity

Sensitivity to EOS

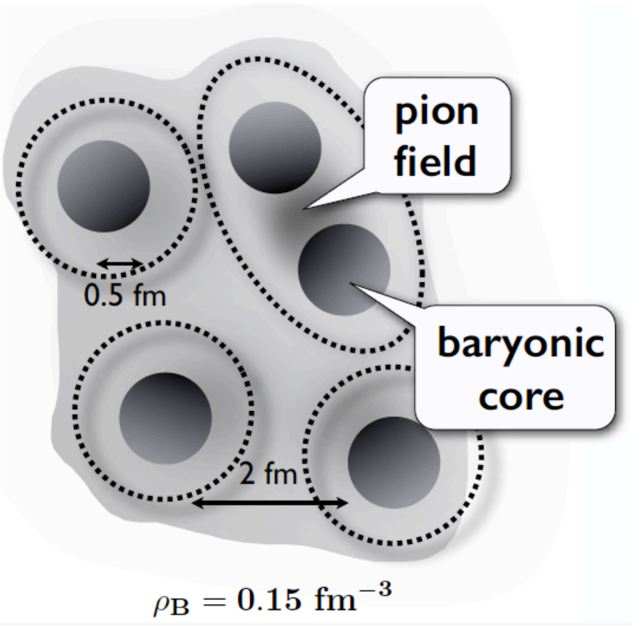
UrQMD prediction: P. Hillmann et al. J.Phys. G45 (2018) no.8, 085101

Consequences for the created system?



N. Kaiser,
U.-G. Meißner,
W.W.
Nucl. Phys.
A466 (1987) 685

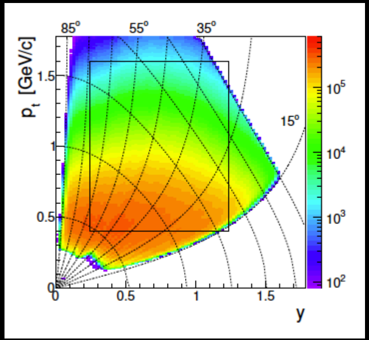
...treated properly
in **Chiral EFT**

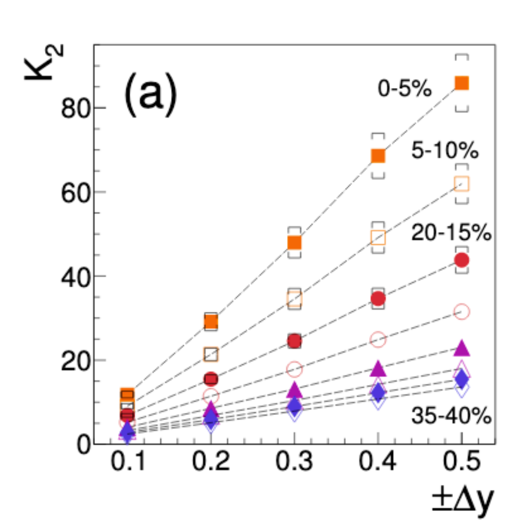


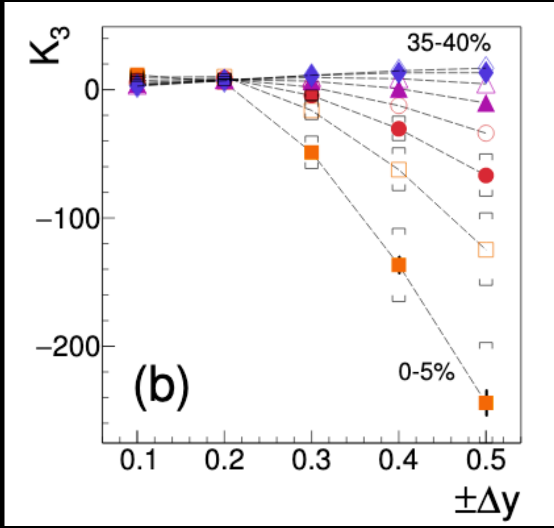
Can we connect this to an observable?

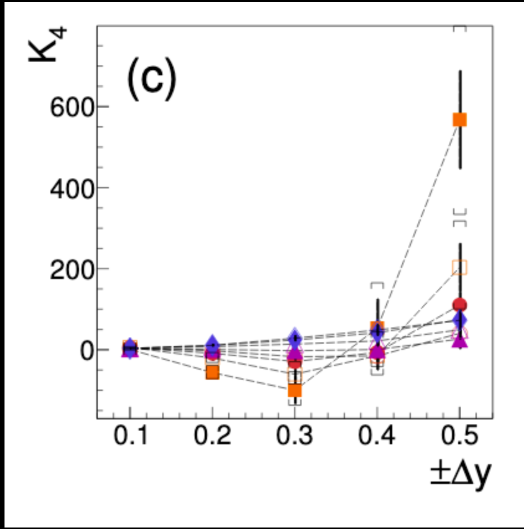
Figures from W. Weise

Volume-corrected proton cumulants vs Δy









Ling & Stephanov, PRC 93, 034915 (2016)

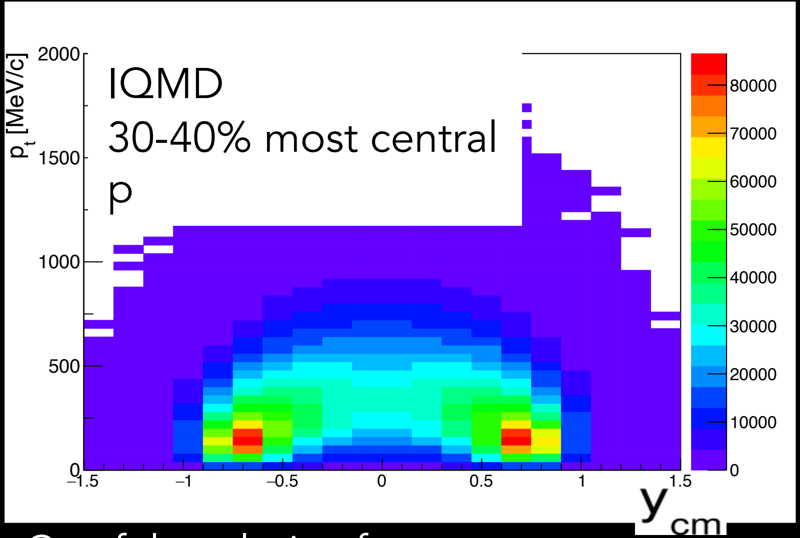
Bzdak, Koch & Strodthoff, PRC 95, 054906 (2017)

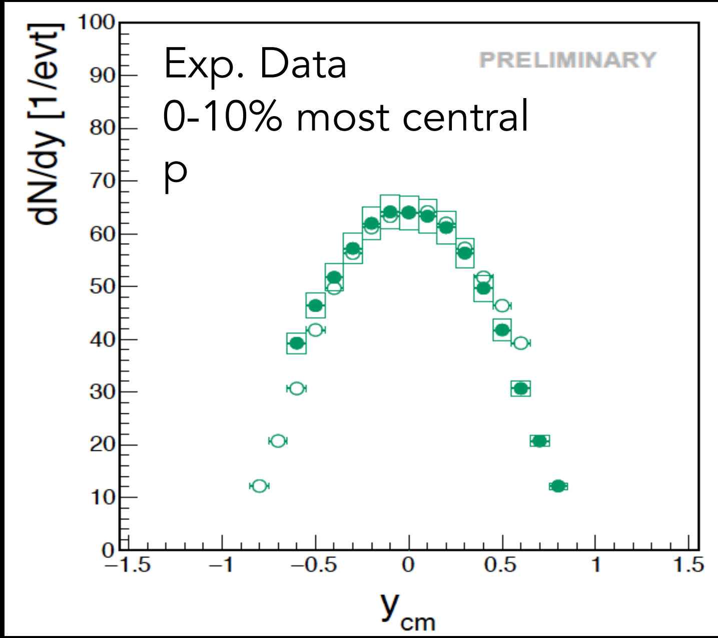
Cumulants K_n hold information on multi-particle correlators C_n

Investigate C_n vs. $\langle N_p \rangle$ to isolate relevant physics

Protons and light nuclei at Au+Au $\sqrt{s_{NN}}$= 2.4 GeV

Spectator and fireball regions not well separated.





Careful analysis of protons:

Extension to high lab. momenta in order to cover forward hemisphere (no acceptance at low p_t)

→ Estimate spectator contamination by symmetry of the distribution

→ Minimize uncertainty due to extrapolation in y

Similar investigations for d and t are ongoing.