Investigating dense nuclear matter
Recent results from HADES

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for the
HADES Collaboration

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

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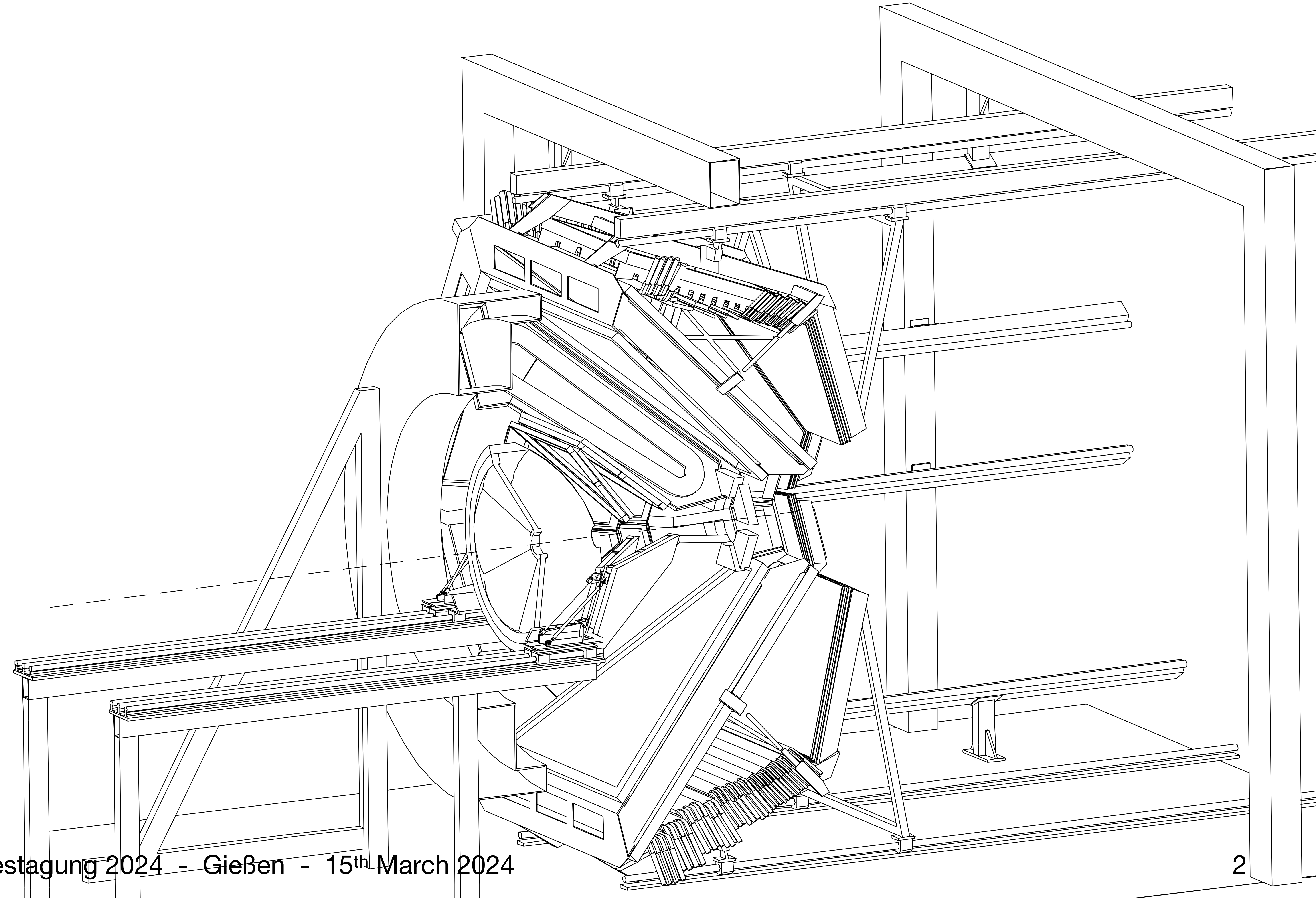
15th March, 2024

Outline

- Dense nuclear matter and astrophysics
- The HADES experiment
- Recent results:
  - Emissivity
  - Collectivity
  - Vorticity
  - Strangeness and hypernuclei
- Outlook

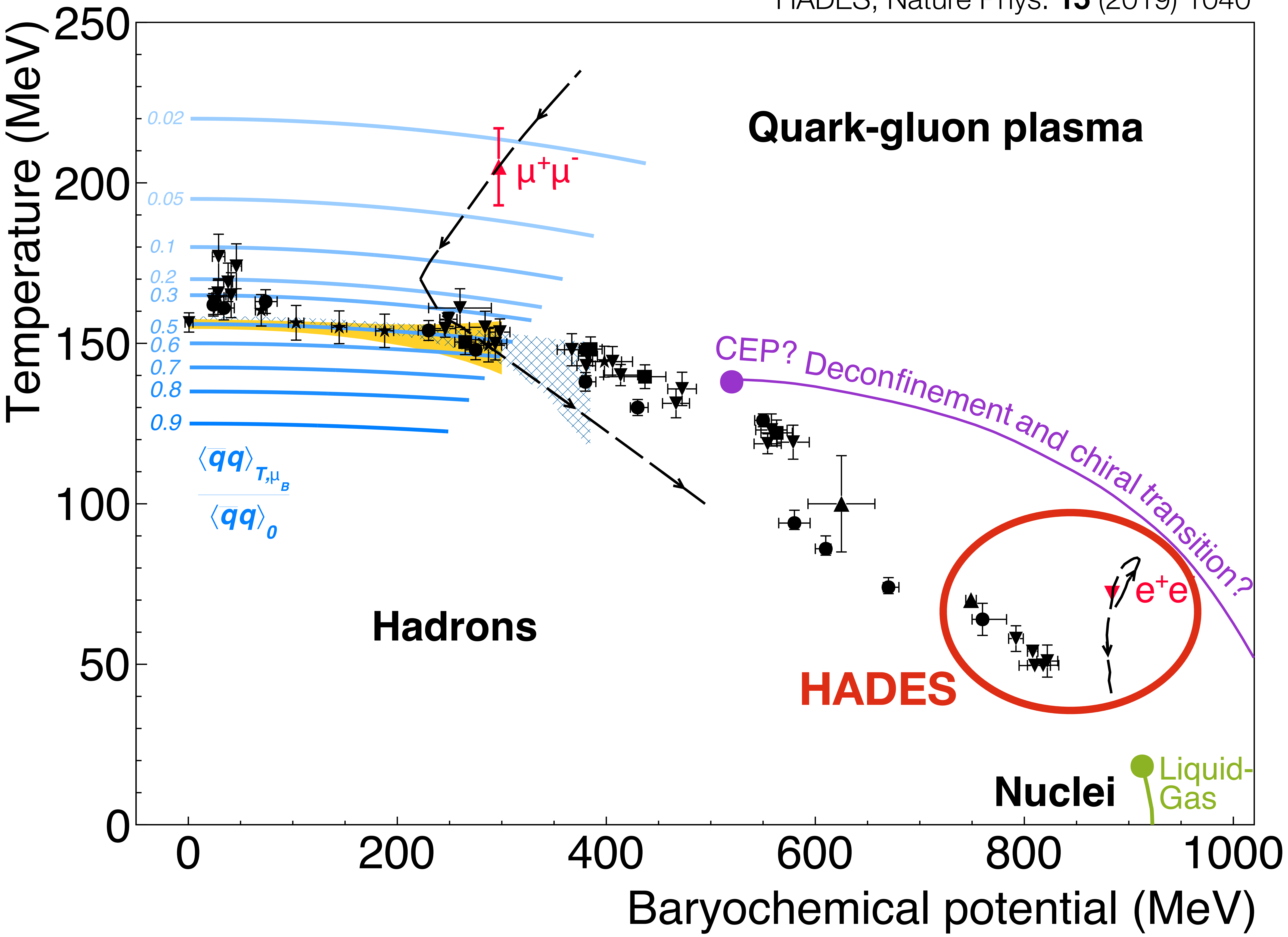


Dense nuclear matter and astrophysics

Phase diagram of QCD Matter

- Deconfinement phase transition
  - Indications for crossover transition at high energies corresponding to vanishing μ_B (e.g. LHC)
  - Conjecture of 1. order phase transition at low energies corresponding to high μ_B (e.g. SIS100/FAIR, SIS18/GSI)
  - Critical End Point (CEP)
- HADES at SIS18
  - Nucleons essentially stopped in collision zone
  - Baryon dominated fireball ⇒ μ_B ~ 800 MeV

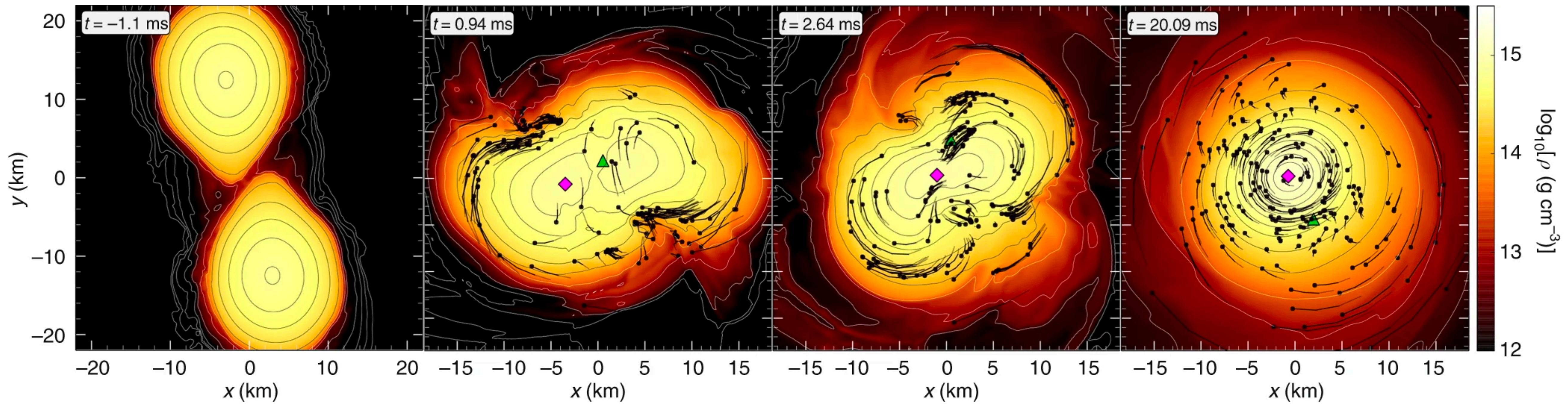
HADES, Nature Phys. **15** (2019) 1040



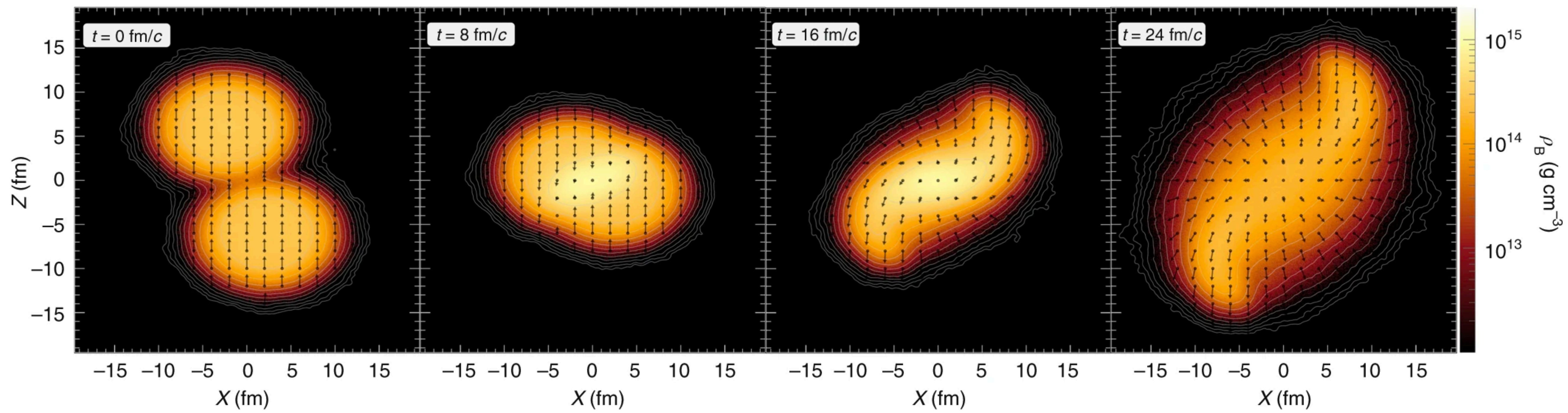
Dense nuclear matter and astrophysics

- Properties of neutron star and its Equation-Of-State (EOS)
- Similar conditions in heavy-ion collisions at SIS18 energies than in merging neutron stars

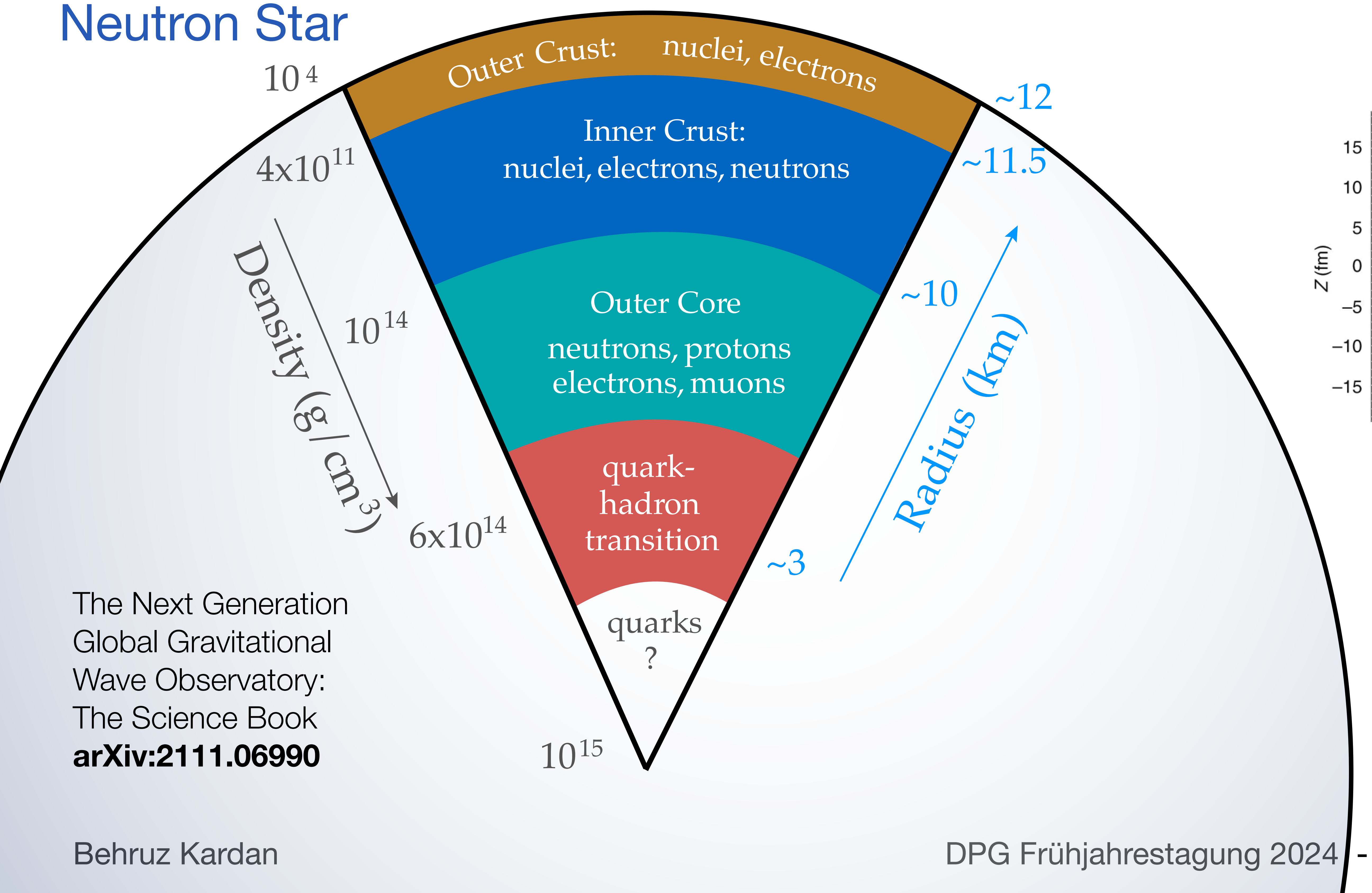
Neutron Star Merger



Heavy-ion Collision



Neutron Star

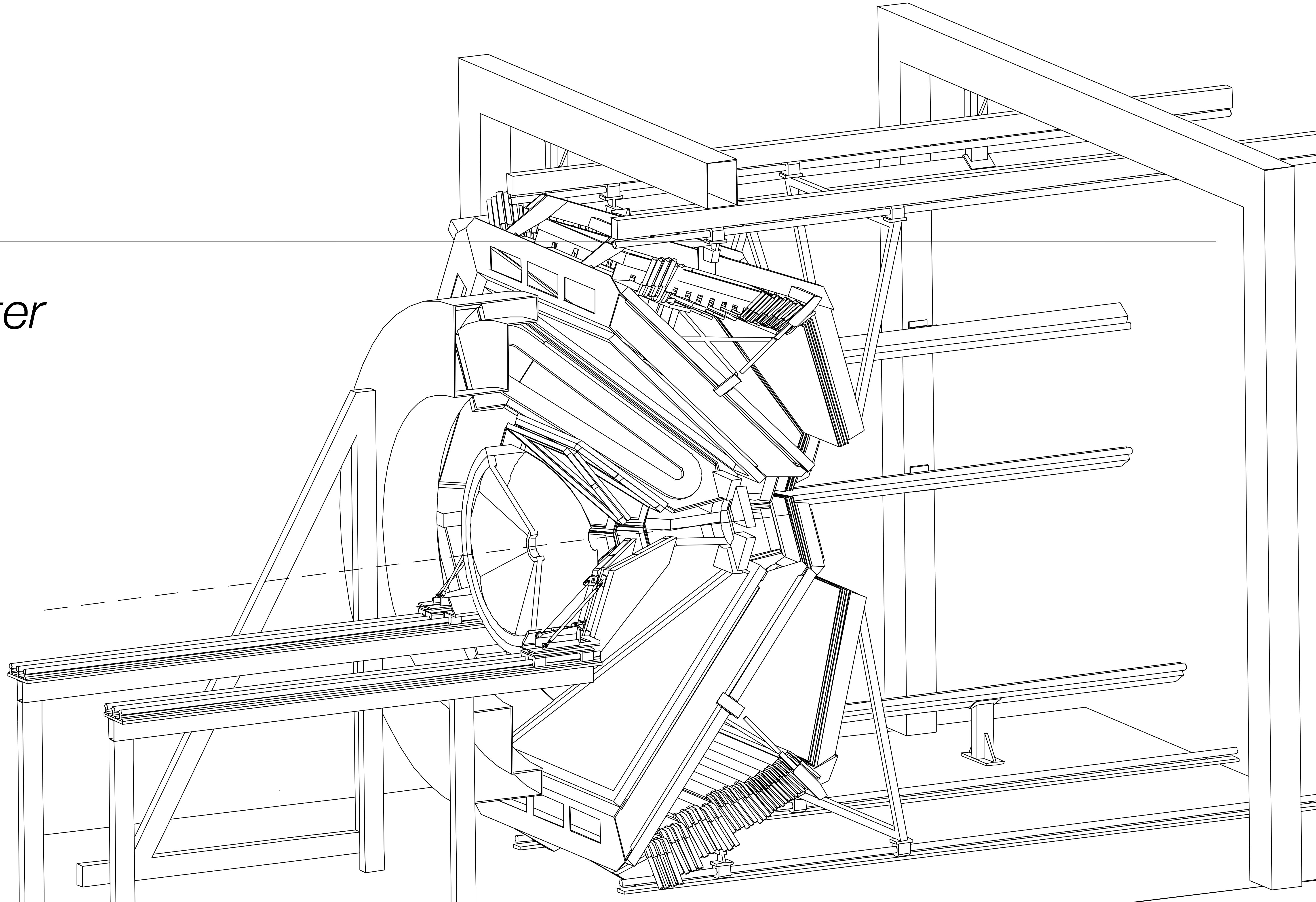


The Next Generation Global Gravitational Wave Observatory: The Science Book
arXiv:2111.06990

⇒ Heavy-ion collisions can provide access to equation-of-state of neutron star matter

The HADES experiment

High-Acceptance Dielectron Spectrometer



The HADES experiment

Fixed-target experiment at SIS18(GSI, Germany)

Large acceptance in 6 identical sectors

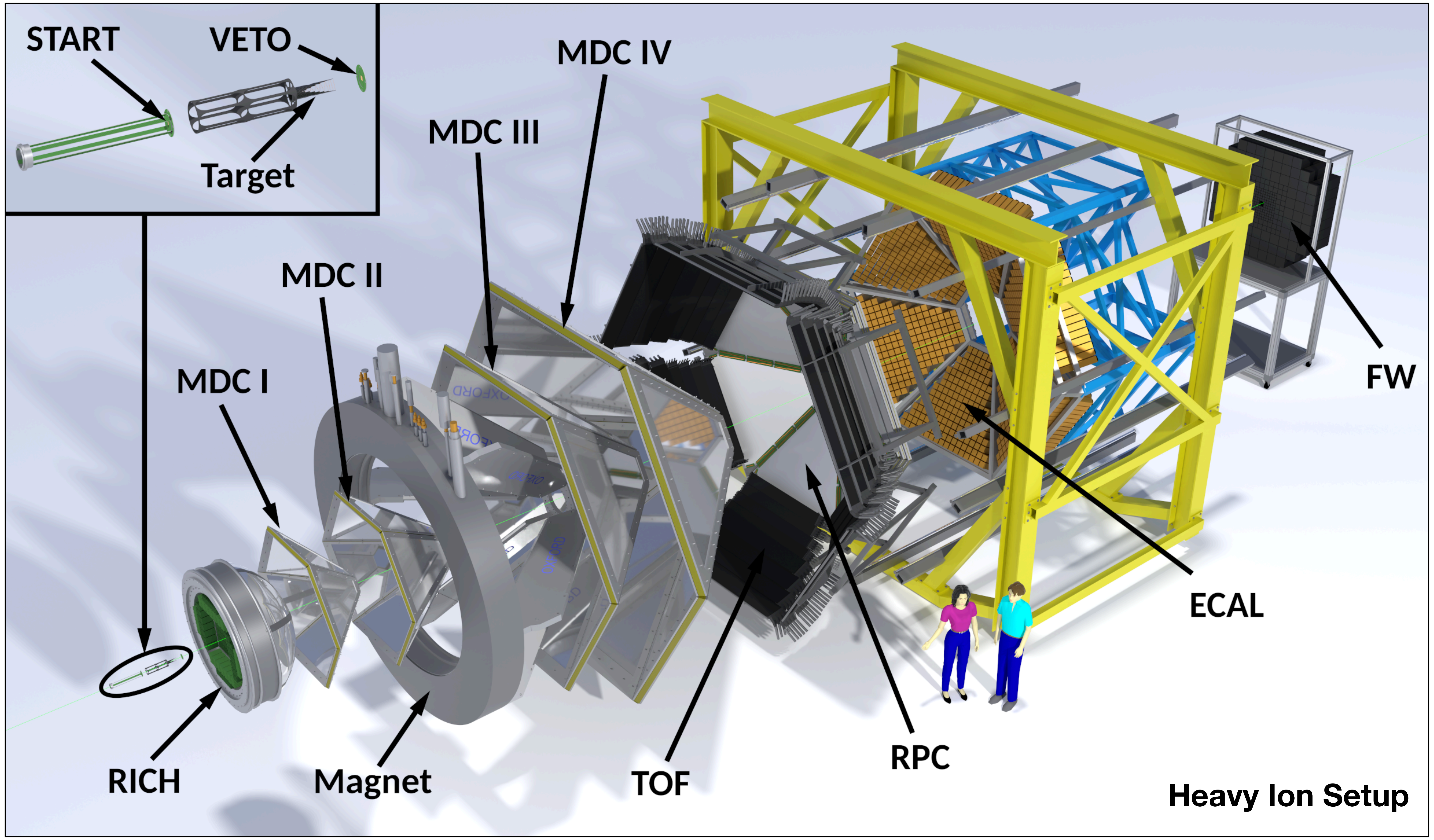
- Symmetric azimuthal coverage
- Superconducting toroidal magnets
- Low-mass Drift Chambers (MDC)

Particle identification

- Time-of-Flight walls (TOF and RPC)
- Energy loss (MDC and TOF)
- e^+/e^- and photon identification (RICH and ECAL)

Forward Wall

- Reaction plane reconstruction



The HADES experiment

(*) *center-of-mass energy in the nucleon-nucleon frame* $\sqrt{s_{NN}}$

Physics Program

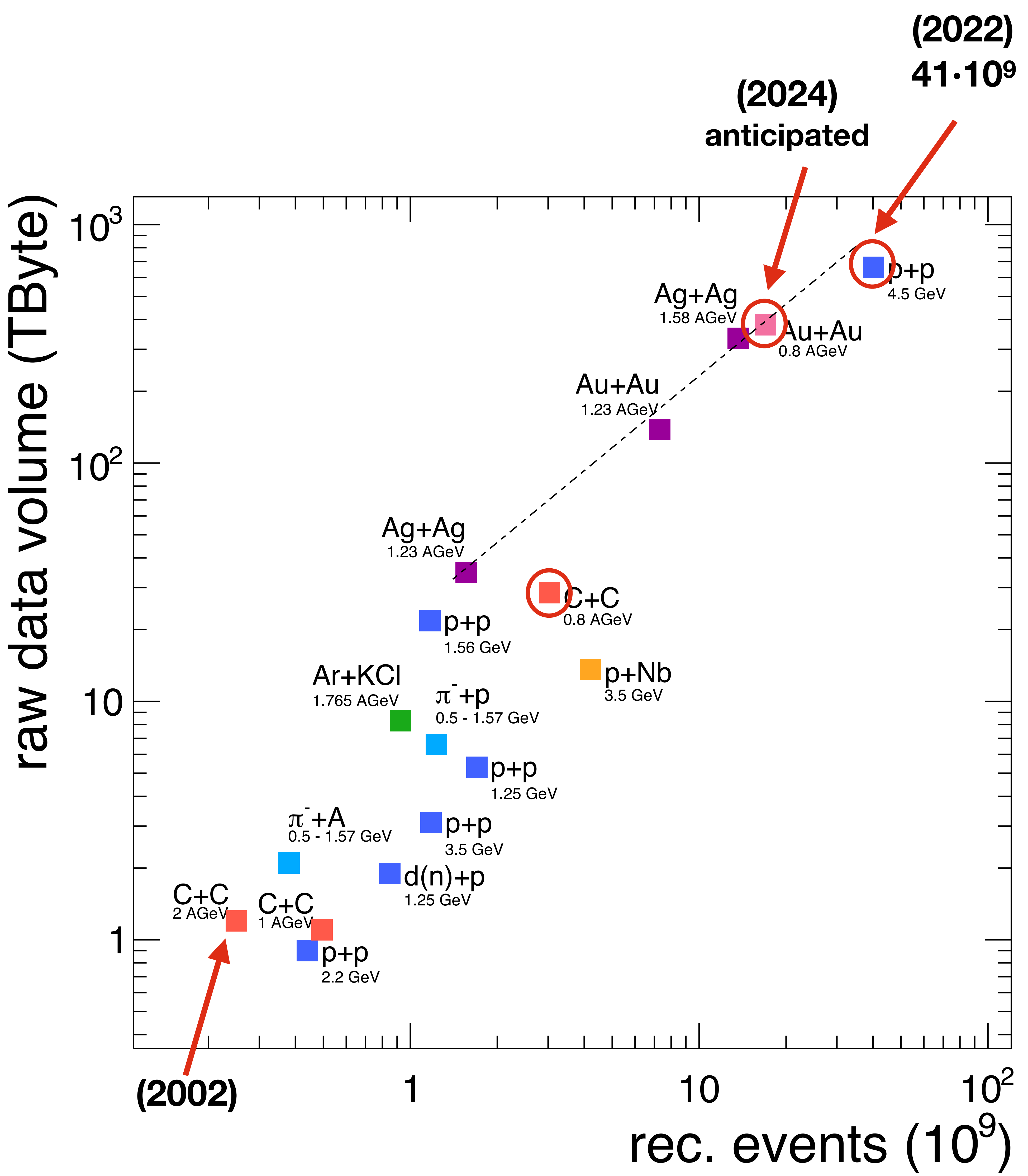
- Heavy ion collisions
  - Equation-of-State
  - Microscopic properties of baryon dominated matter
- Proton and pion beam
  - Reference measurement (vacuum, cold nuclear matter)
  - In-medium modifications
  - *em* structure of baryons/hyperons in time-like region

Heavy ion collisions:
Ar+KCl (2005) 2.61 GeV
Au+Au (2012) 2.42 GeV
Ag+Ag (2019) 2.55 / 2.42 GeV
Au+Au (2024) 2.23 - 1.96 GeV

Light ion collisions:
C+C (2002) 2.7 GeV
C+C (2004) 2.32 GeV
C+C (2024) 2.23 GeV

Proton/deuteron beams:
p+p (2004) 2.7 GeV
d(n)+p (2006) 2.42 GeV
p+p (2007) 3.18 GeV
p+p (2022) 3.46 / 2.55 GeV
p+Nb (2008) 3.1 GeV

Pion beams:
π^- + W / C / PE (2014) 1.5 GeV



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HK9.1	N. Schild - Virtual photons
HK9.4	M. Kohls - Thermal model
HK33.1	M. Nabroth - Fluctuation
HK33.3	S. Spies - Centrality
HK46.3	S. Kim - Dilepton flow
HK55.2	C. Udrea - Low-mass dileptons
HK56.3	T. Povar - Neutral mesons
HK72.24	C. Grimm - Collective flow

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Pion beams:
π^- **+ W / C / PE** (2014) 1.5 GeV

HK11.2	V. Kladov - Analysis pp→ppKK
HK11.5	R. Yassine - Dilepton production
HK33.5	L. Albohn - Neutral pion production
HK35.3	S. Pattnaik - Hyperon-production
HK46.1	K. Scharmann - Dilepton
HK47.4	G. Perez-Andrade - Luminosity
HK71.2	A.Foda - Partial Wave Analysis

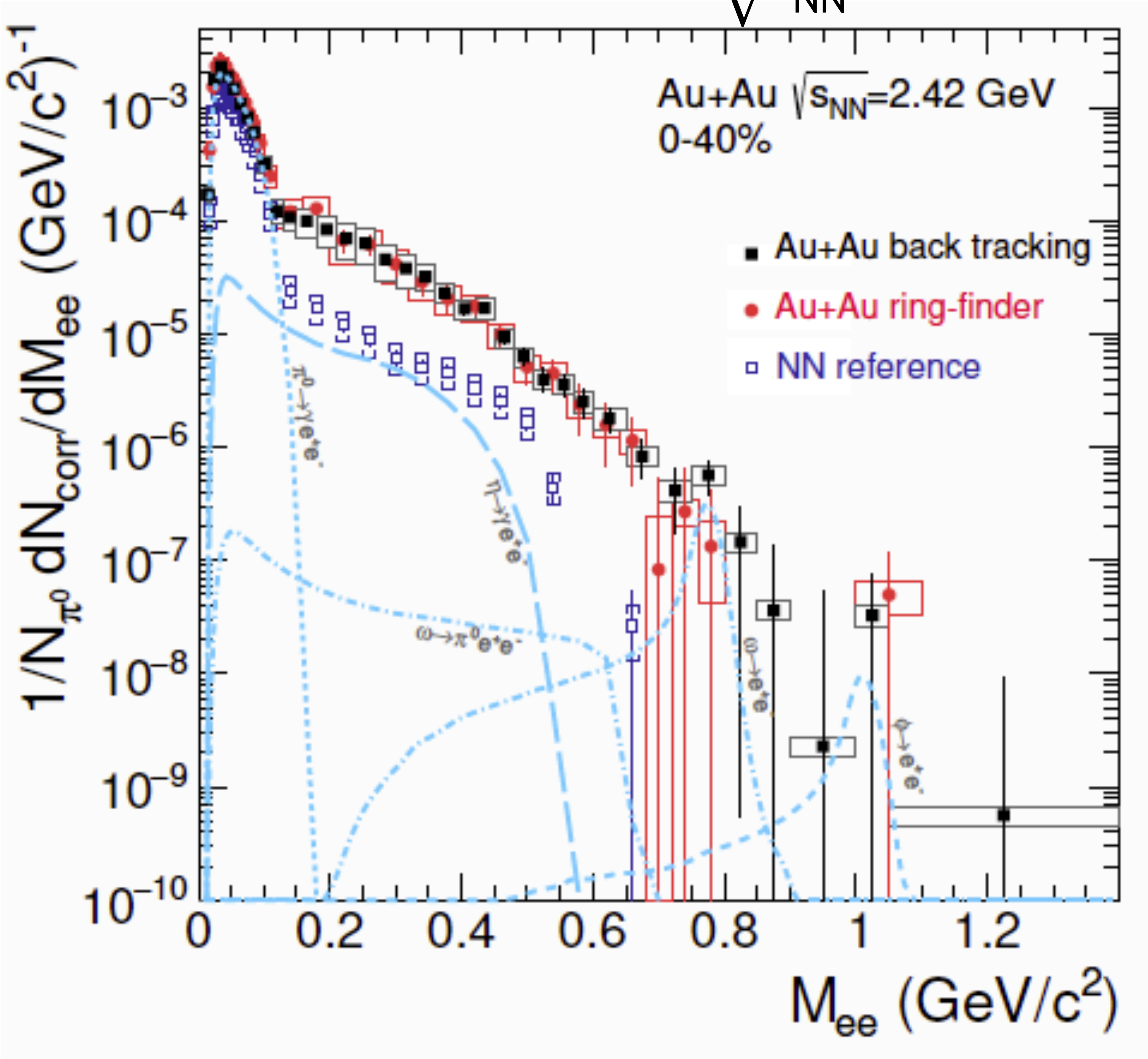
Emissivity

Electromagnetic Radiation

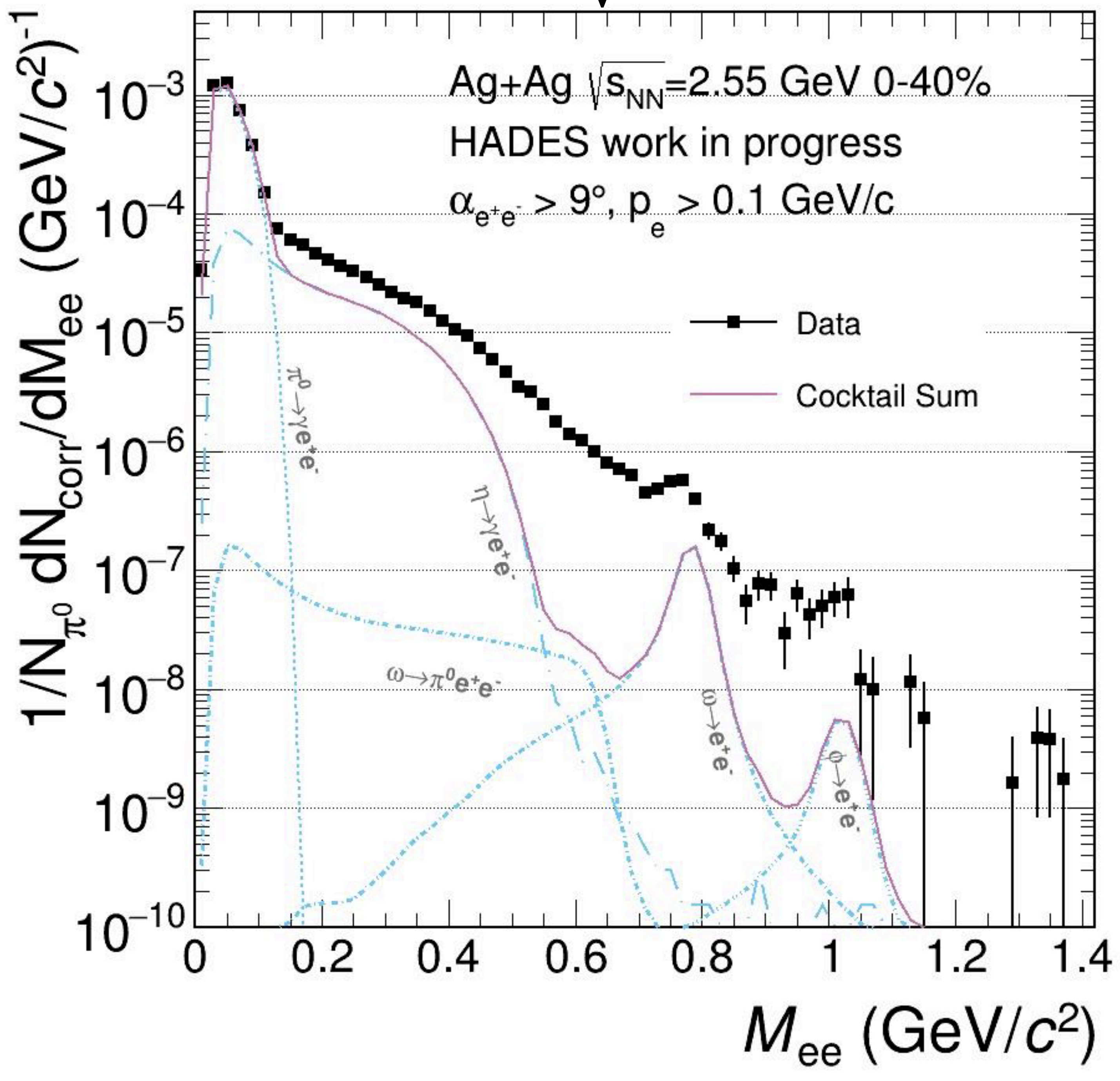
Emissivity

- Inclusive dilepton spectrum in heavy ion collisions
- Isolation of thermal radiation by subtraction of measured decay cocktail from elementary reactions
- NN reference done with p+p and d(n)+p collisions

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



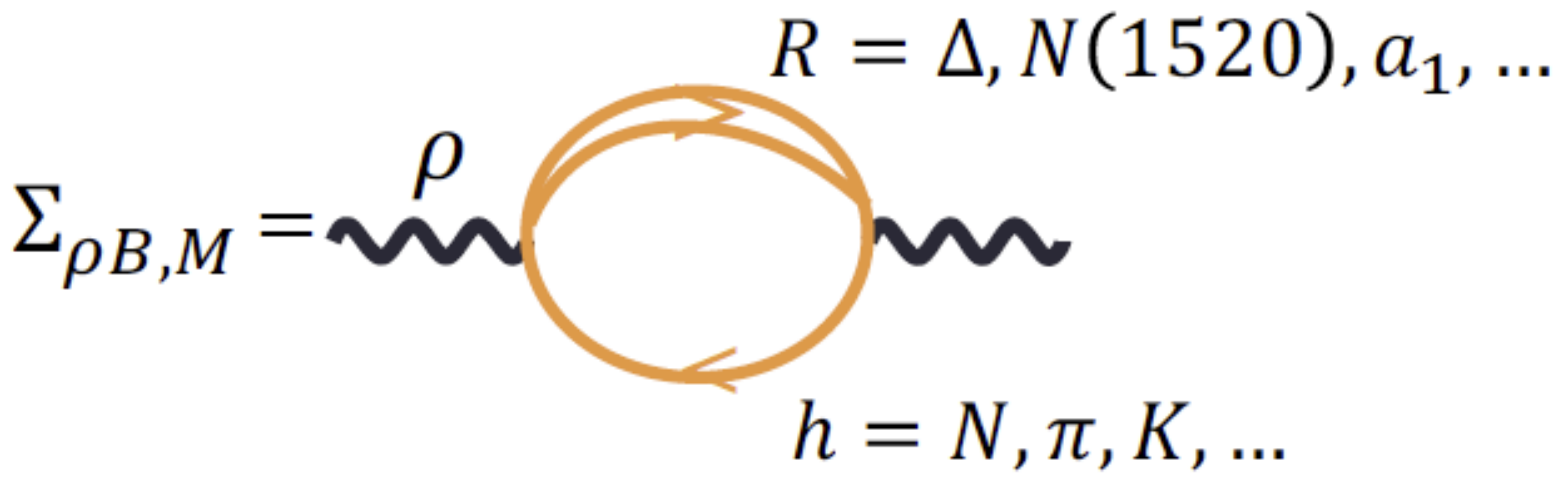
Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV

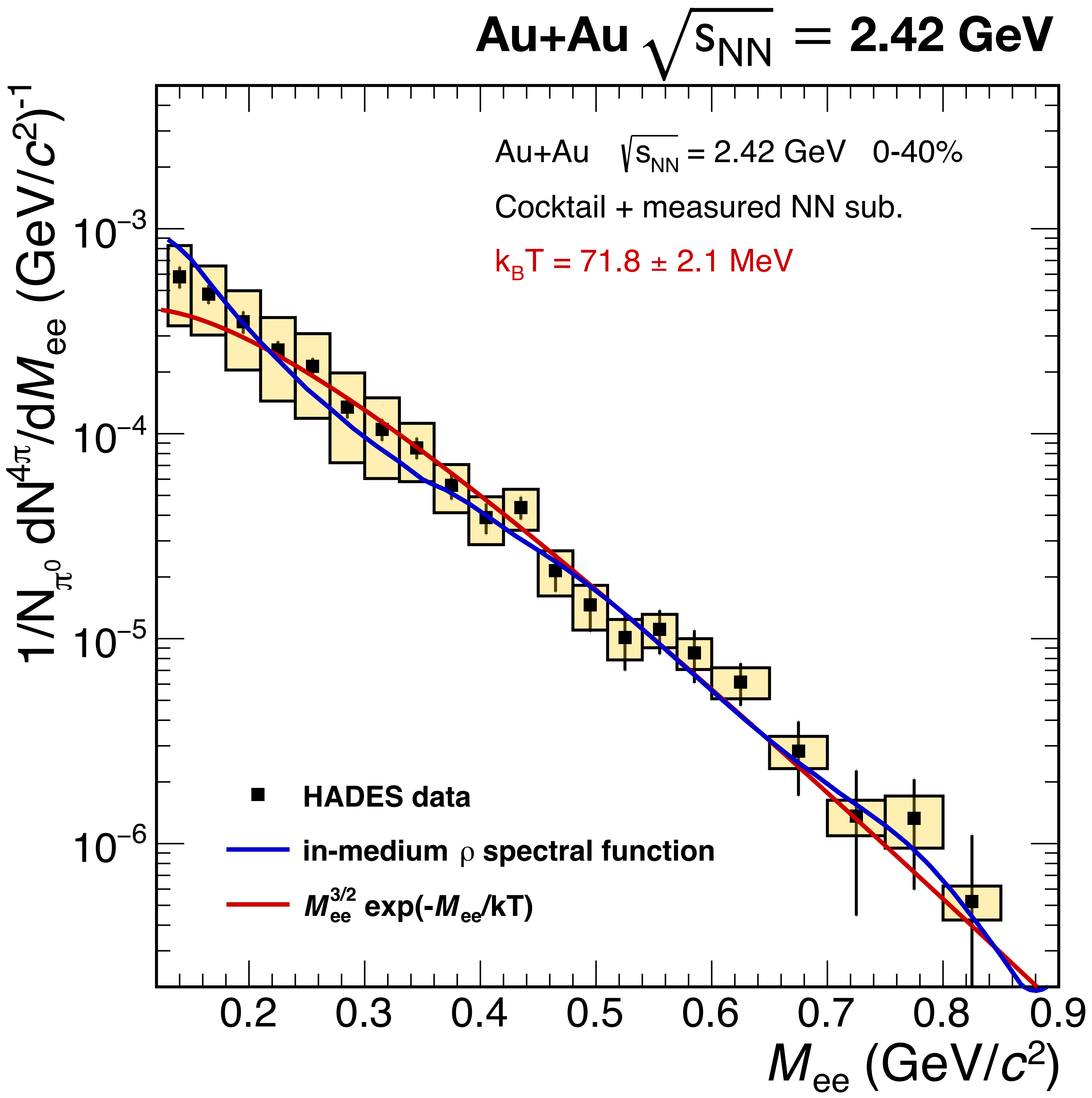


HADES, Nature Phys. **15** (2019) 1040

Emissivity

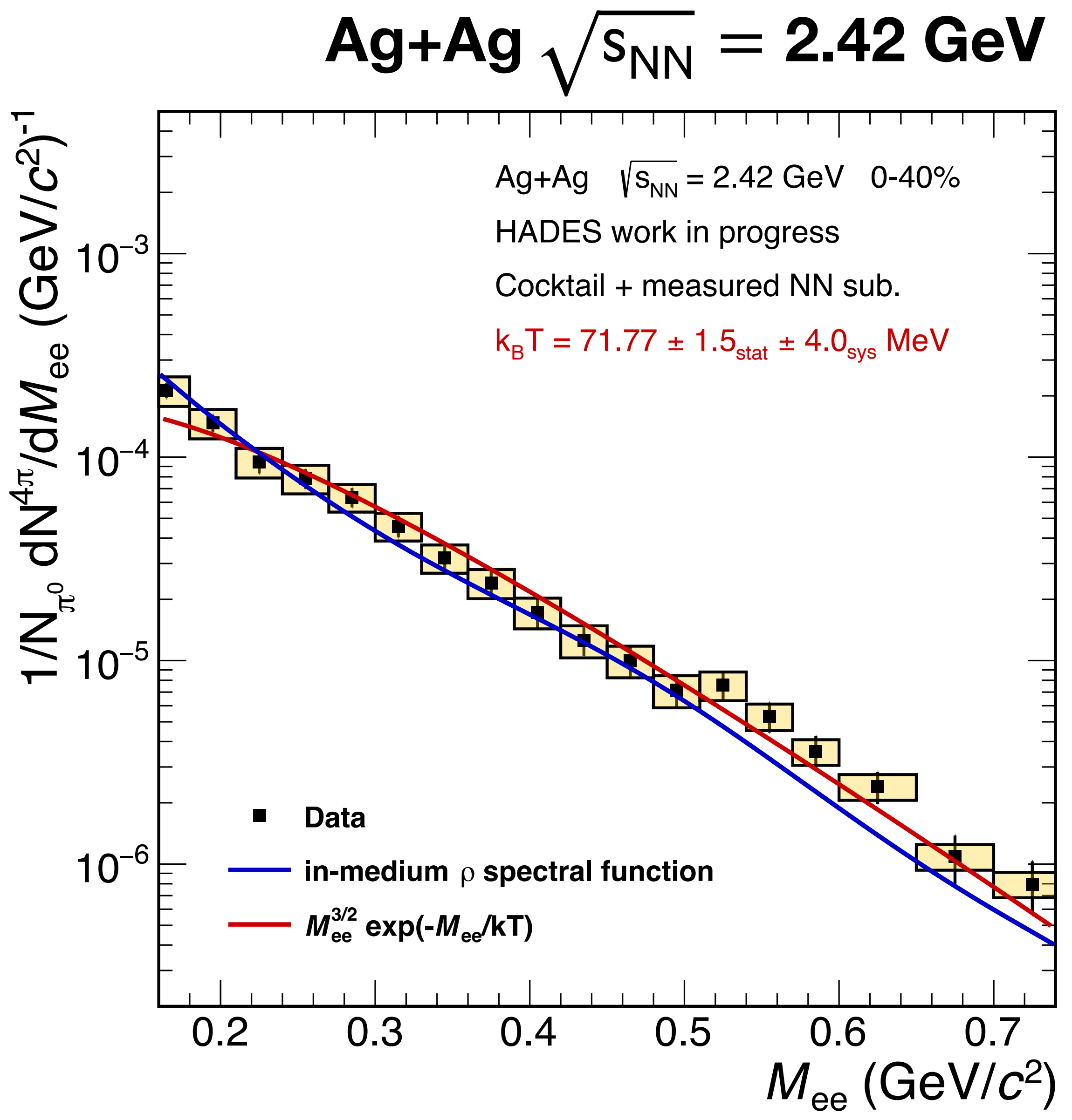
- Dilepton excess radiation established at HADES (Au+Au, Ag+Ag) and gives access to thermal properties including early stage of reaction
- Boltzmann-Formel $\sim M_{ee}^{3/2} \exp(-M_{ee}/kT)$
- ρ-meson peak undergoes a strong broadening in medium
- Radiation explained by decays of medium-modified vector mesons (VMD, "radiation of the cloud")

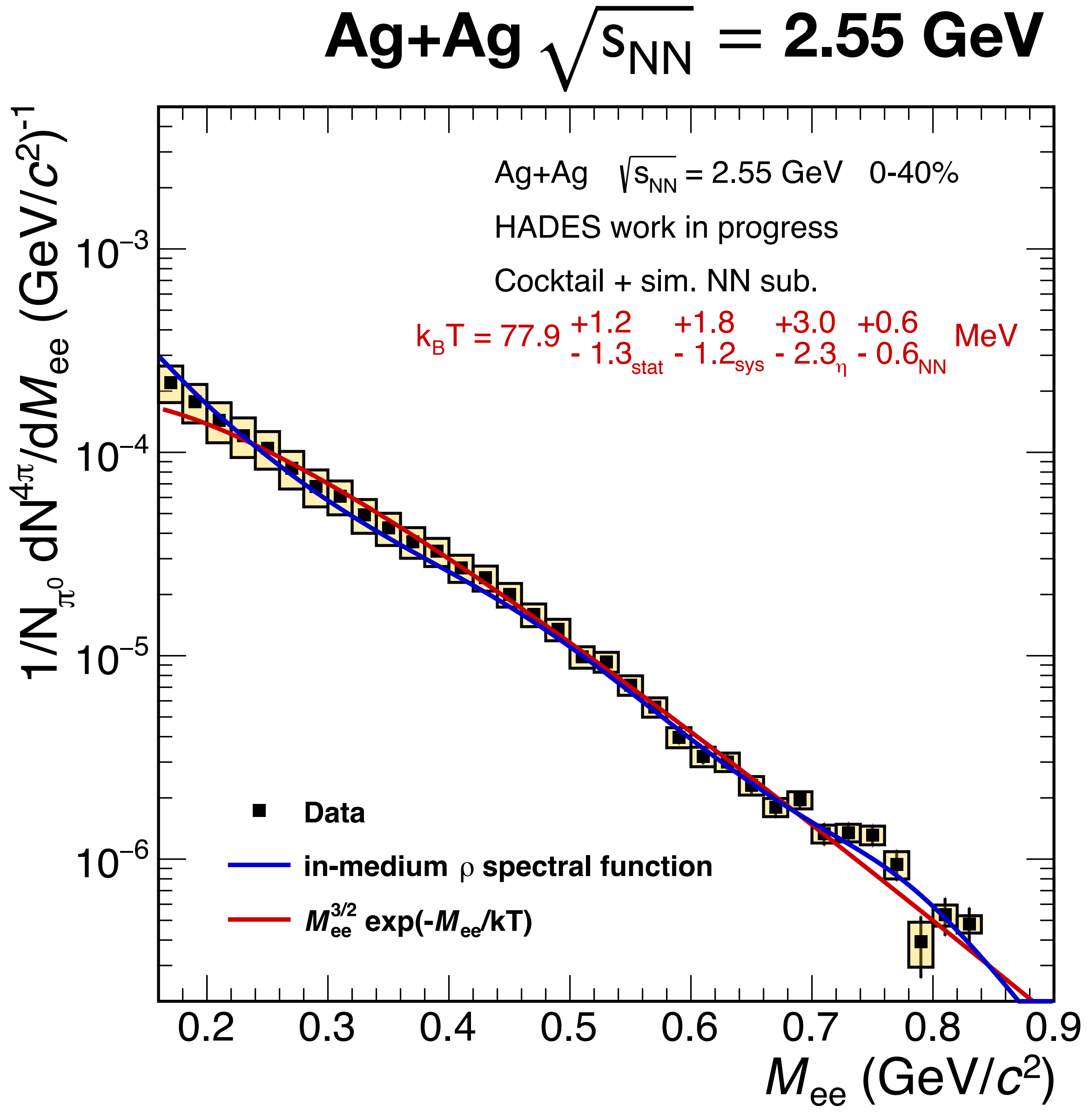




Data:
HADES, Nature Phys. **15** (2019) 1040
Ag+Ag in preparation

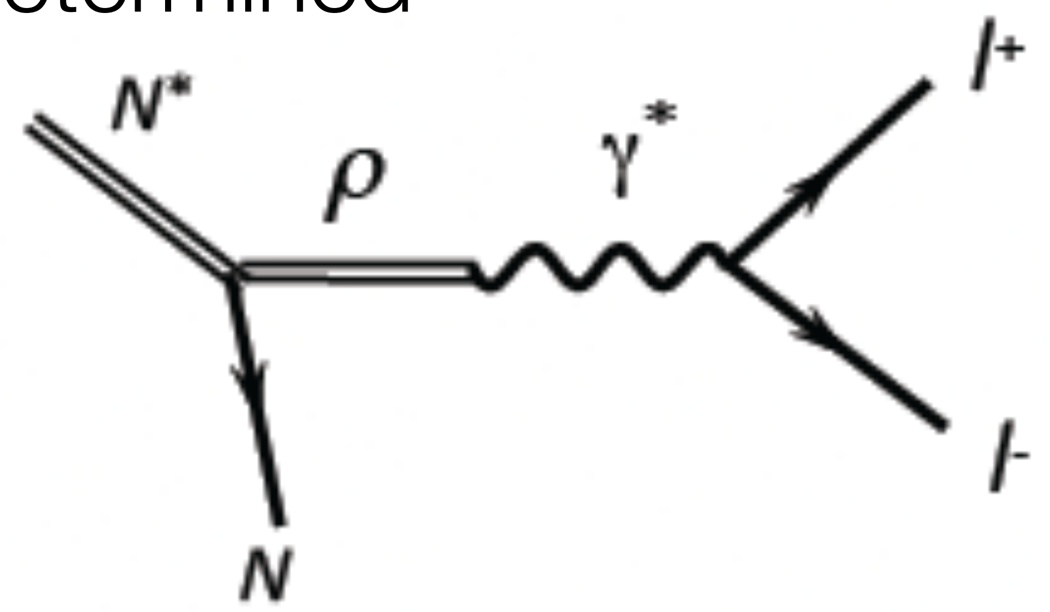
Model:
Galatyuk, Hohler, Rapp, Seck, Stroth, Eur.Phys.J.A 52 (2016) 5, 131



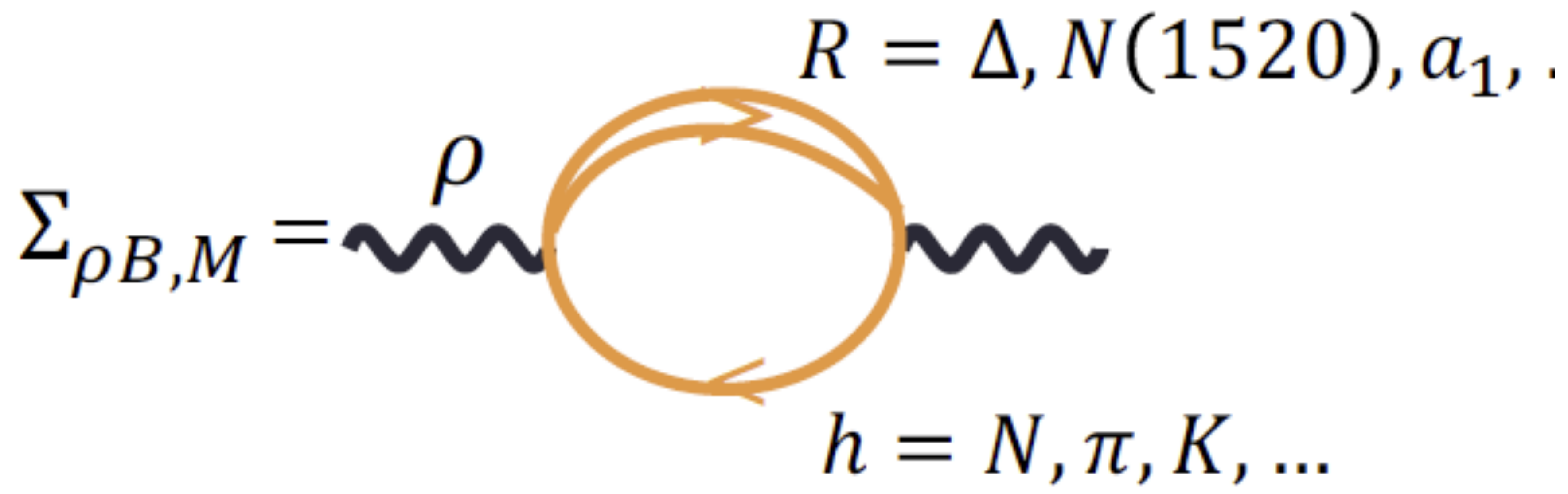


Emissivity

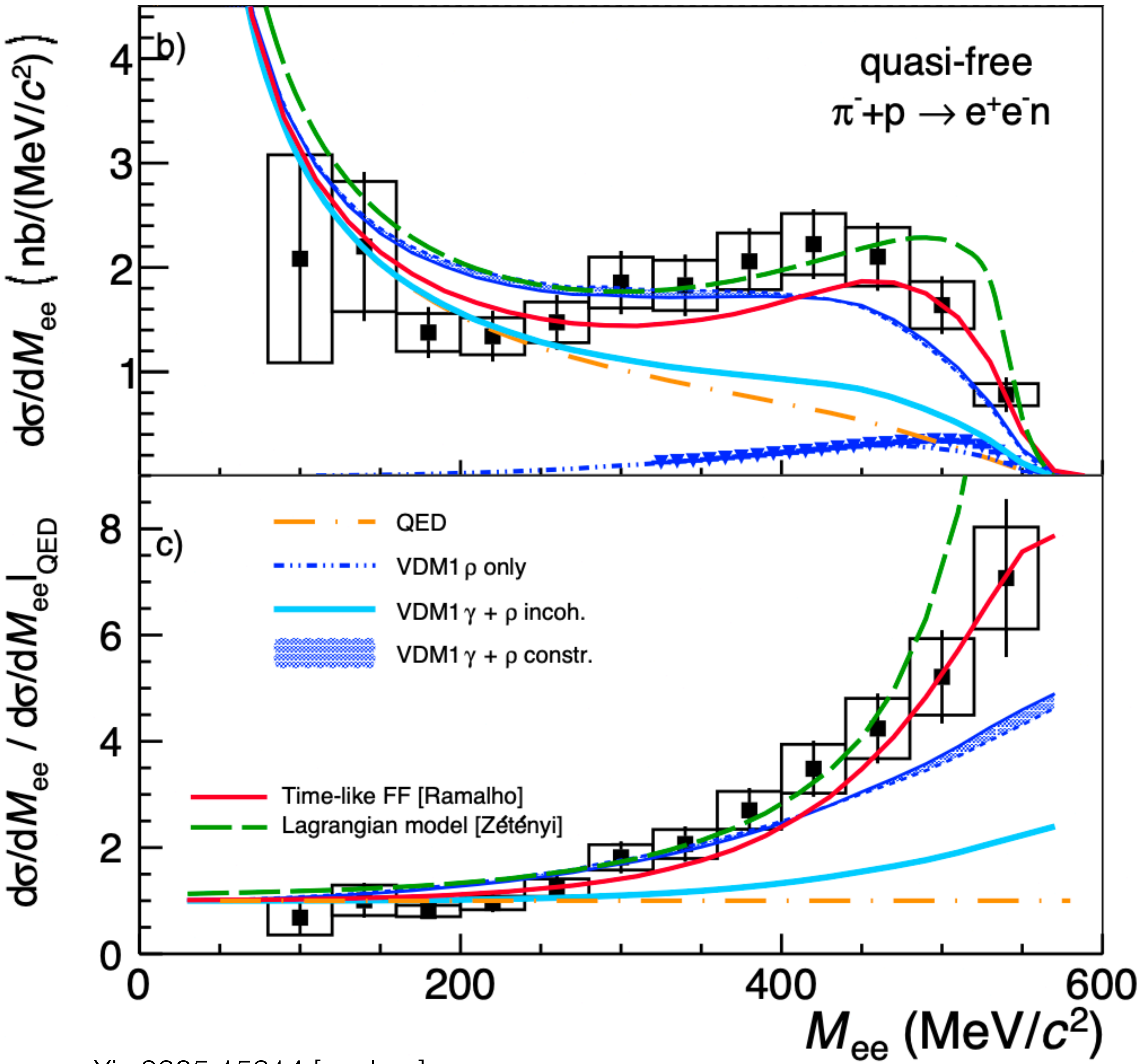
- Crucial baryonic effects determined via pion beam
  $\pi^- + p \rightarrow e^+ + e^- + n$



- Modification of vector mesons in a baryon-rich environment



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

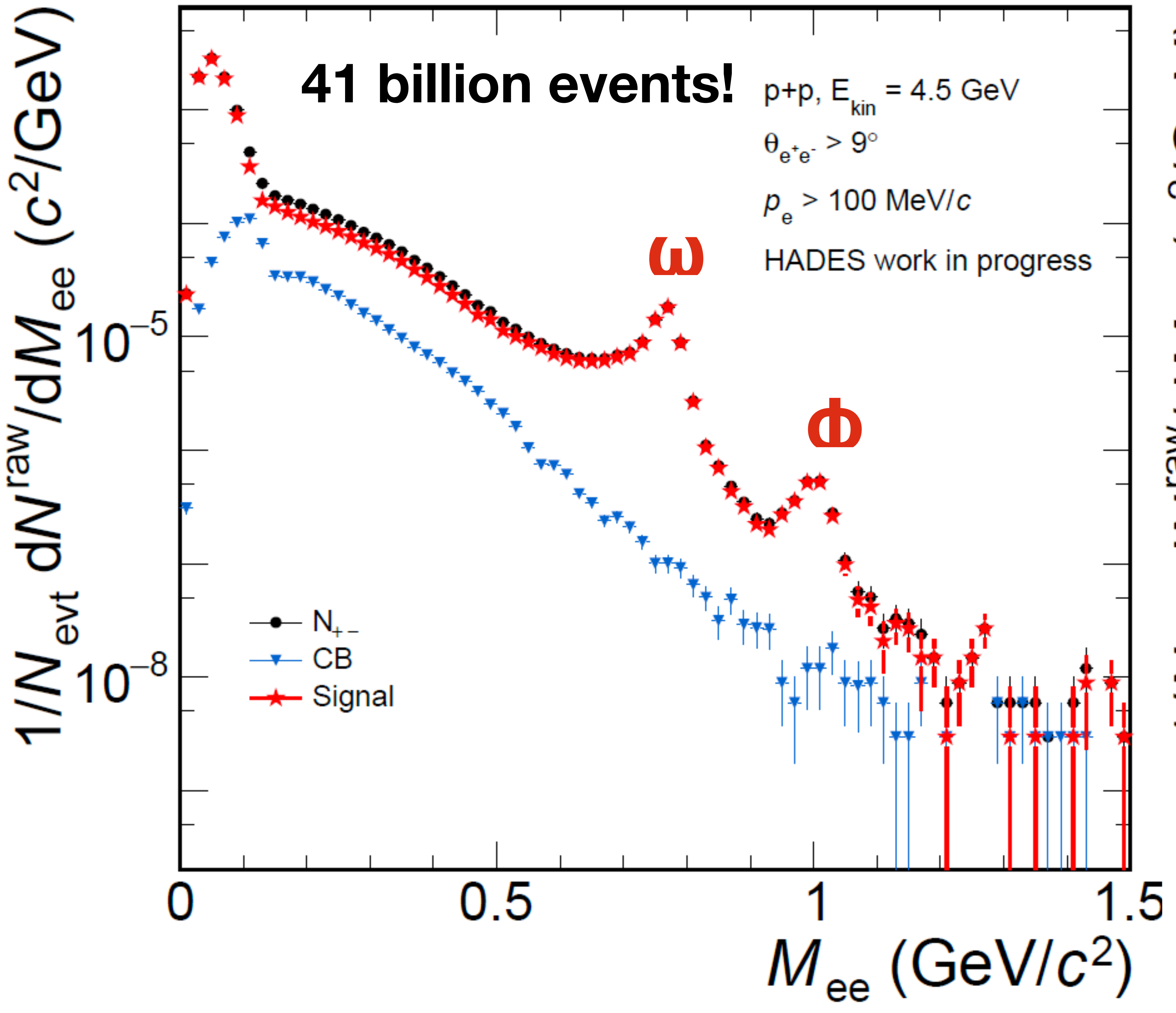


arXiv:2205.15914 [nucl-ex]

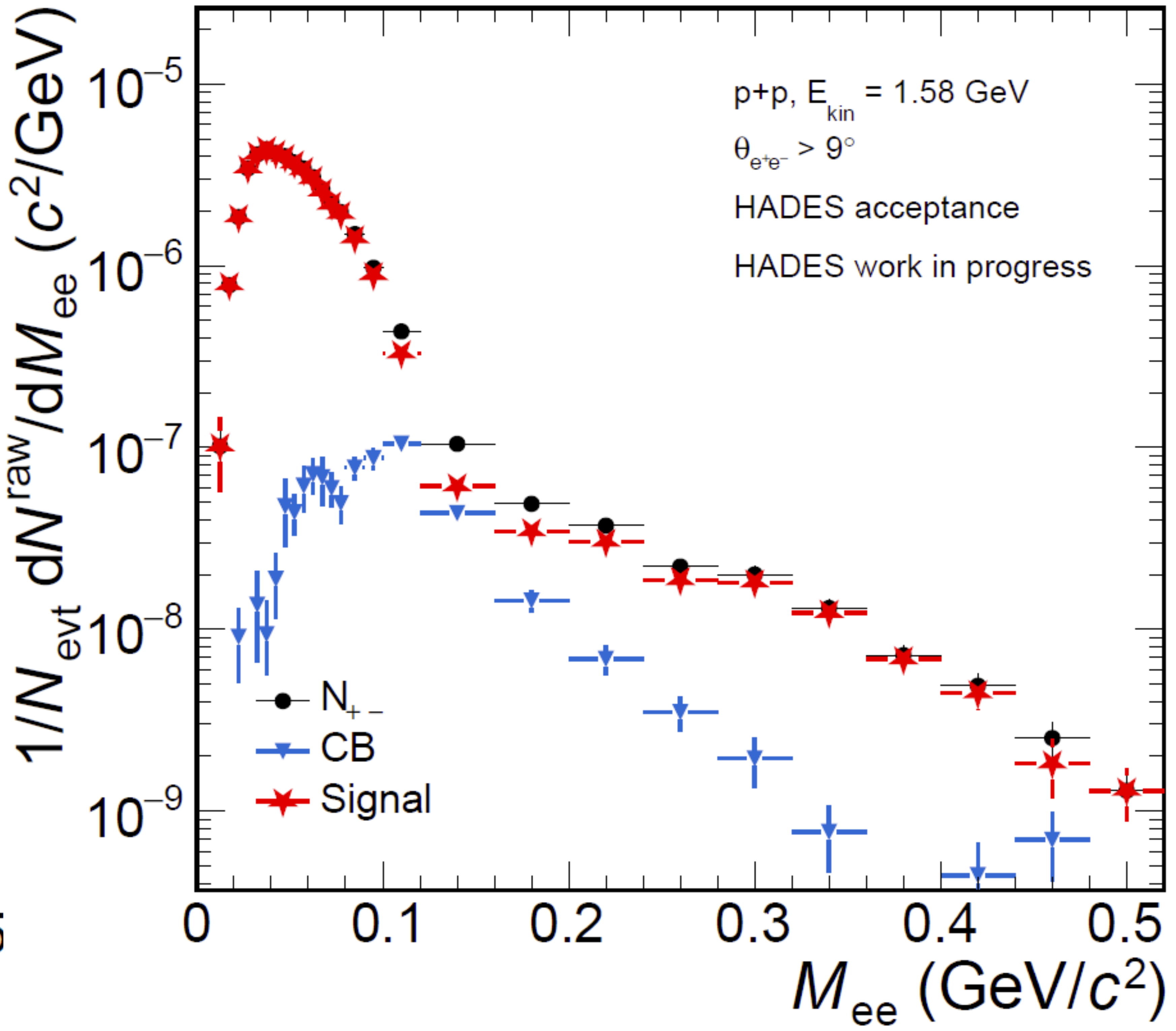
Emissivity

- Reference dilepton spectrum
  - High statistics p+p $\sqrt{s_{NN}}$ = 3.5 GeV (February 2022)
  - Clear signals for ω(782)and ϕ(1020)

p+p $\sqrt{s_{NN}}$ = 3.5 GeV



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



Collectivity

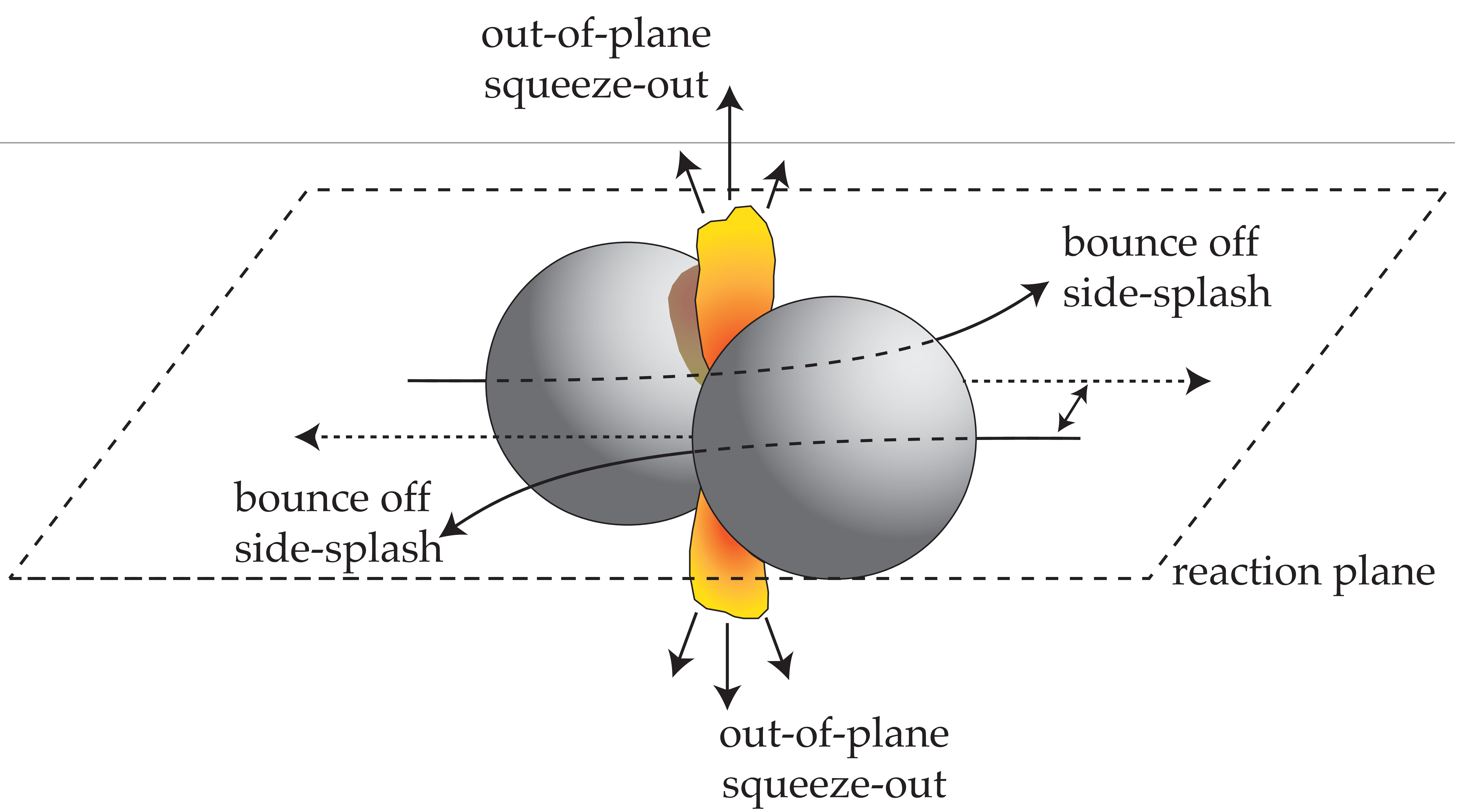
Flow Phenomena

Collectivity

Emission relative to event plane

In-medium interactions and nuclear stopping
$\Longrightarrow$ buildup of non-uniform pressure gradients provides accelerating forces in different directions

Access to medium properties, e.g. viscosity, equation-of-state



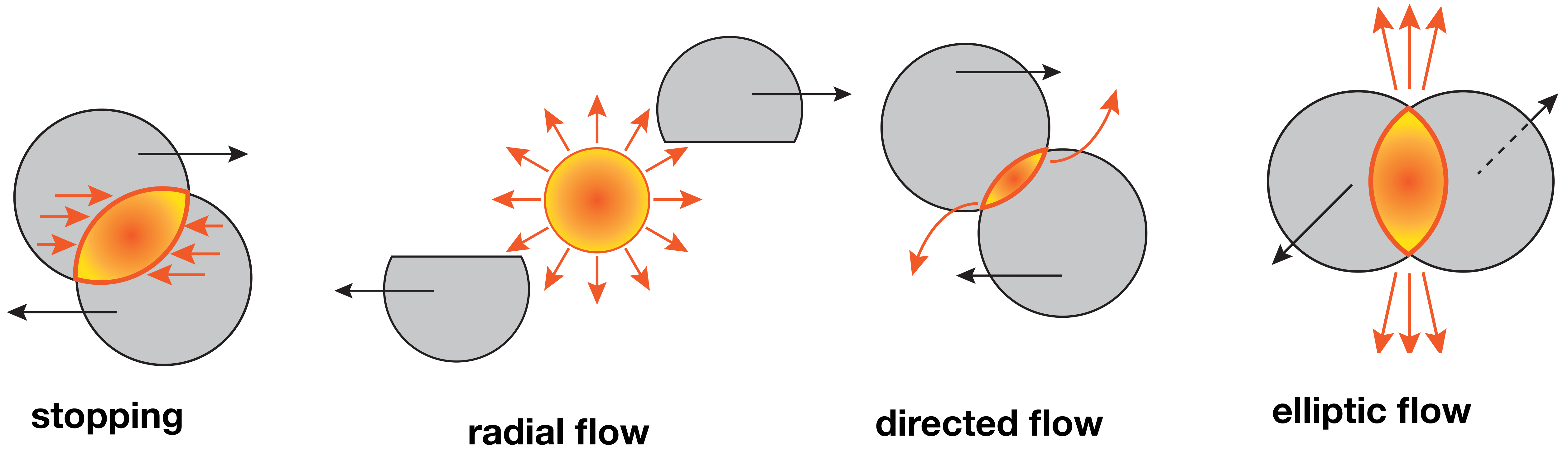
Fourier-decomposition
of the triple differential invariant cross section

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\,\frac{d^2N}{p_t\,dp_t\,dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_t, y)\cos(n\phi)\right)$$

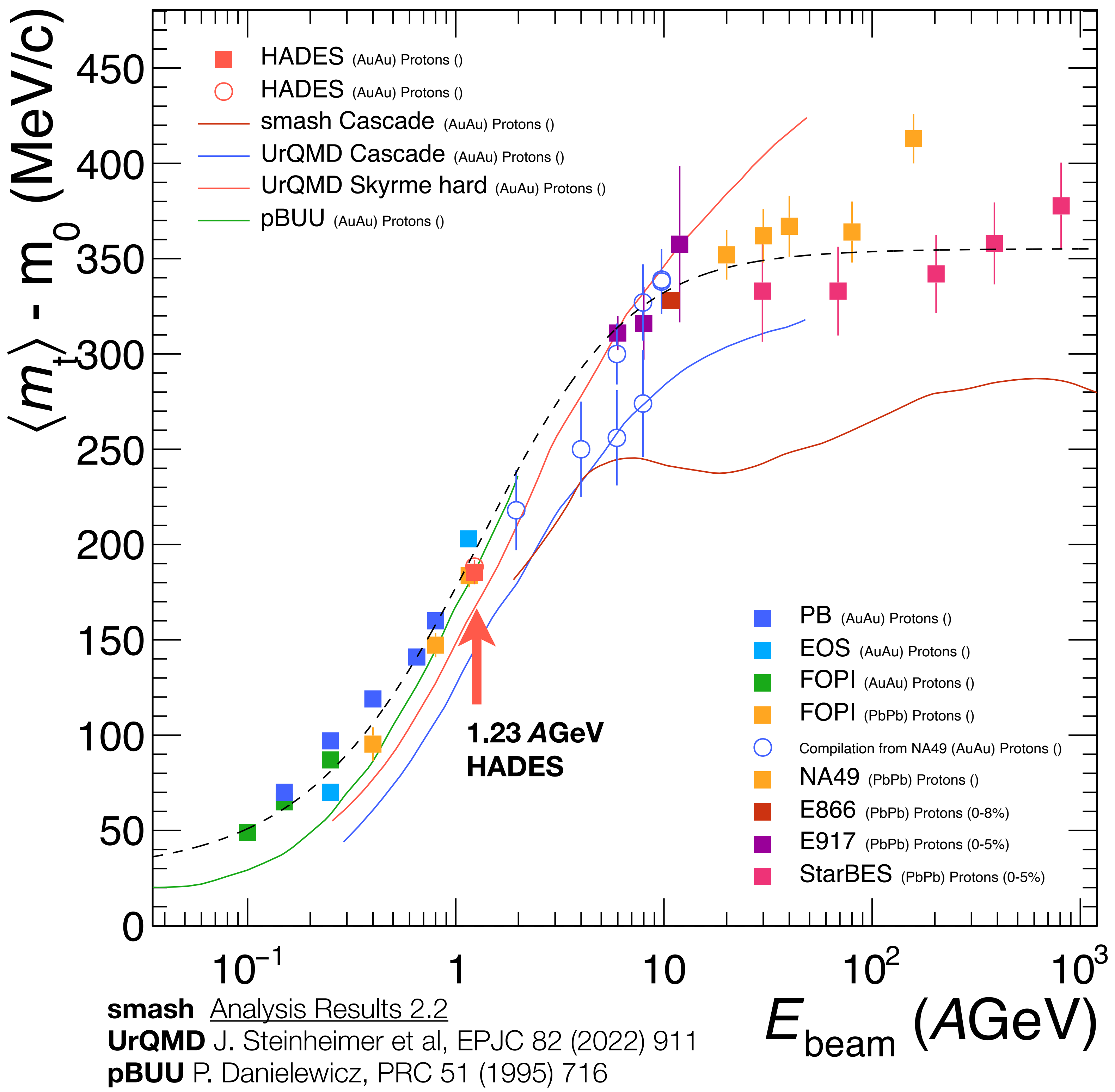
$$\phi = (\varphi - \Psi_{RP})$$

Extraction of azimuthal moments v_n

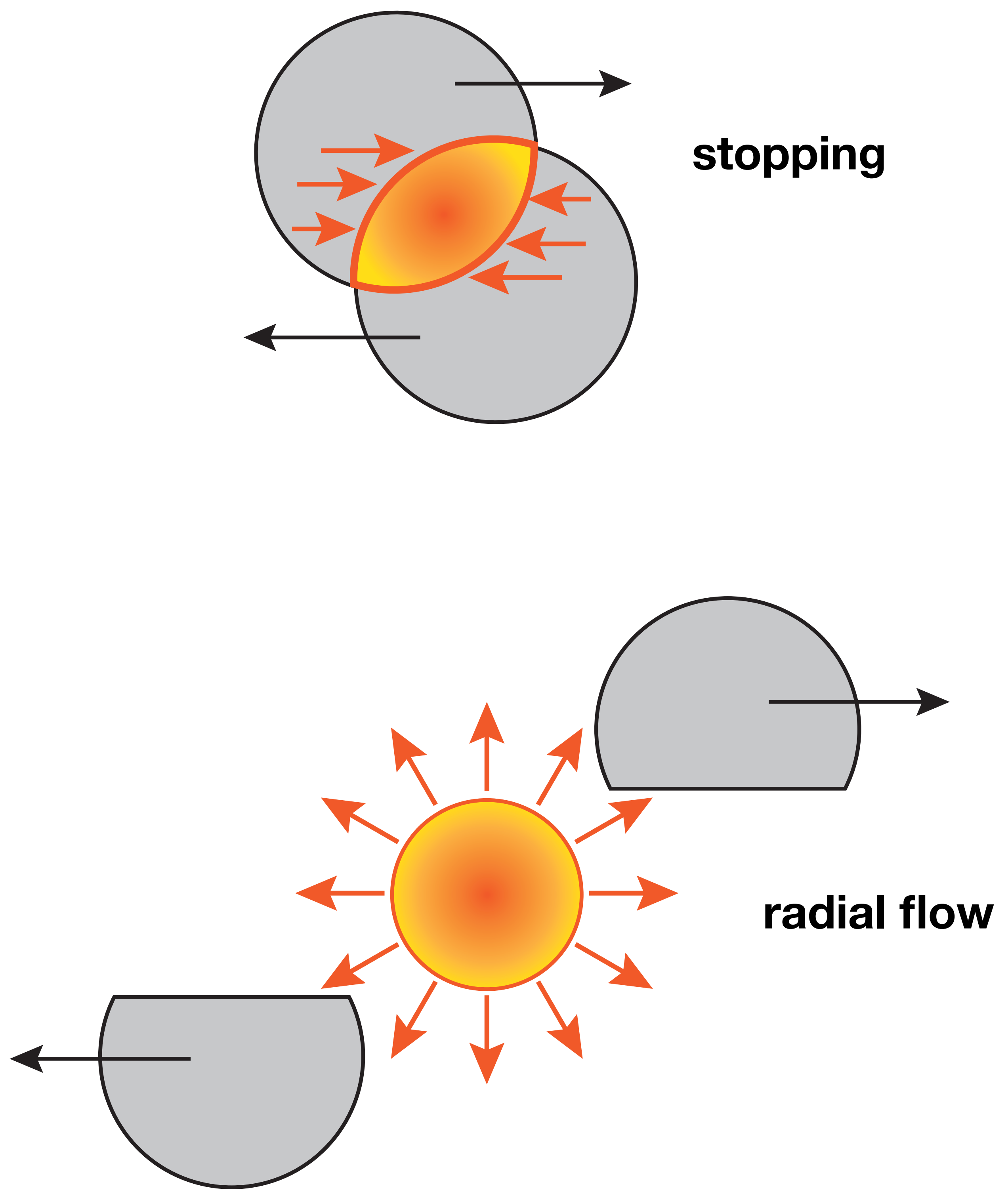
$$v_n(p_t, y) = \langle \cos(n\phi) \rangle$$



Collectivity



smash Analysis Results 2.2
UrQMD J. Steinheimer et al, EPJC 82 (2022) 911
pBUU P. Danielewicz, PRC 51 (1995) 716



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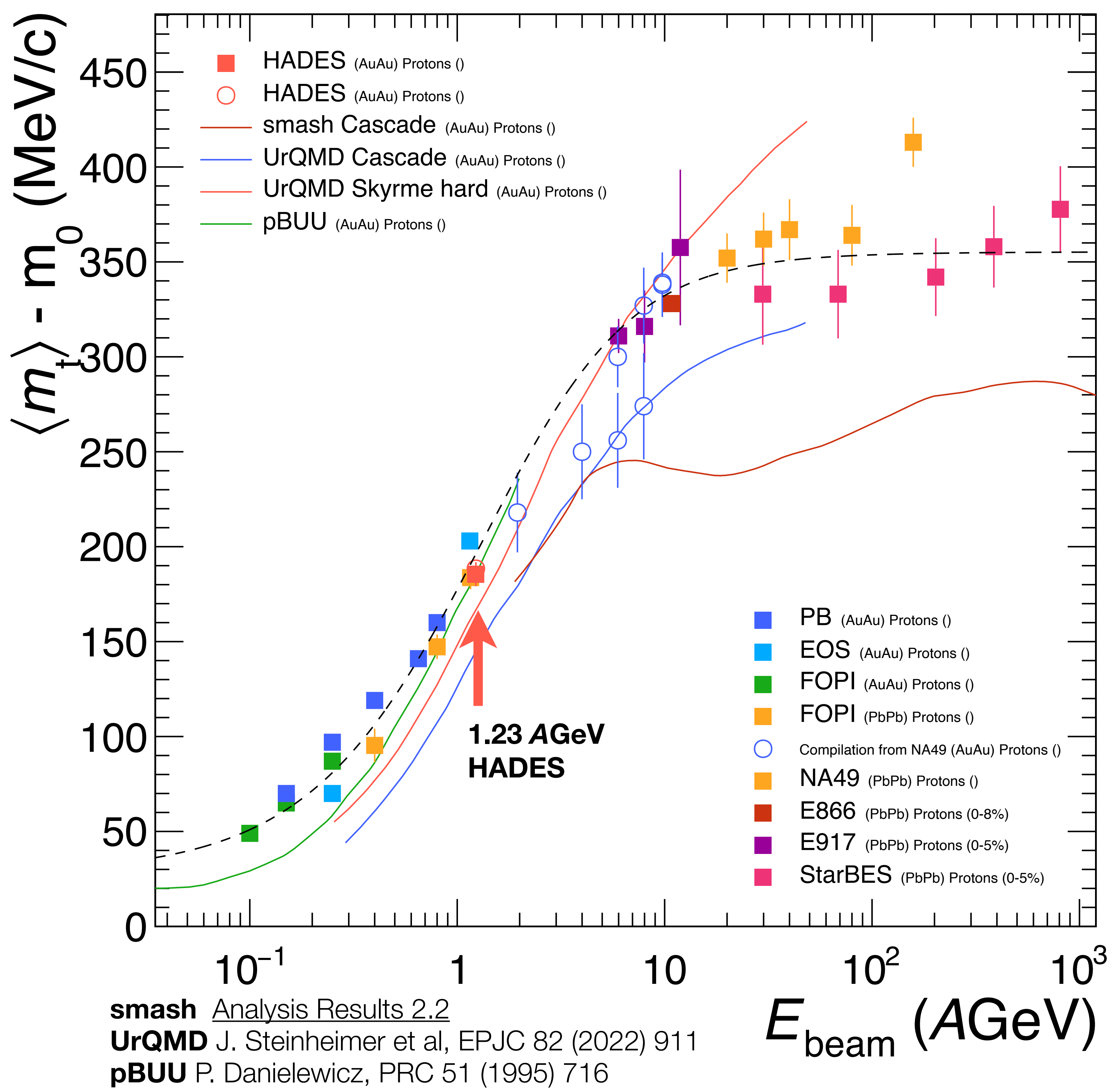

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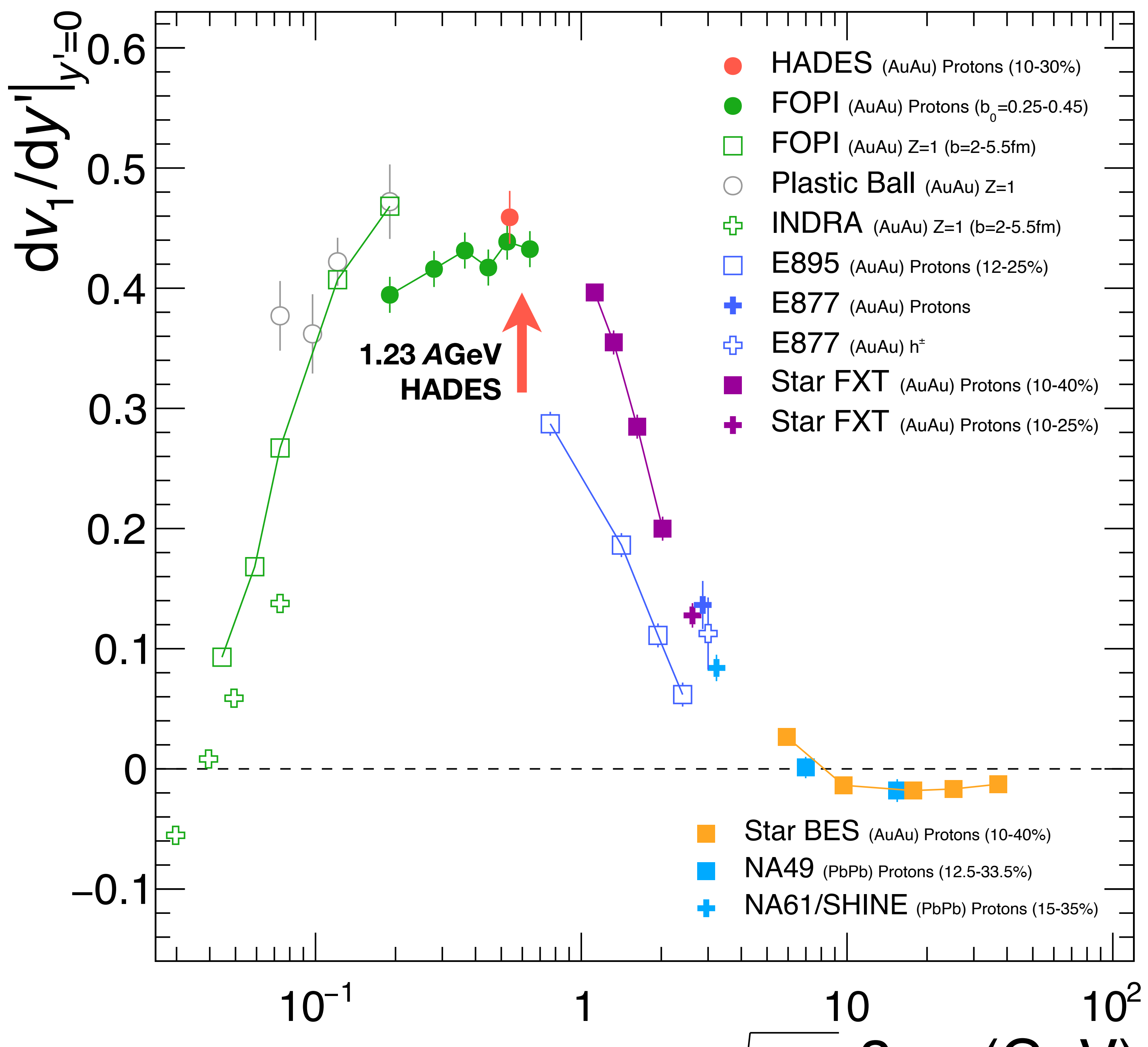
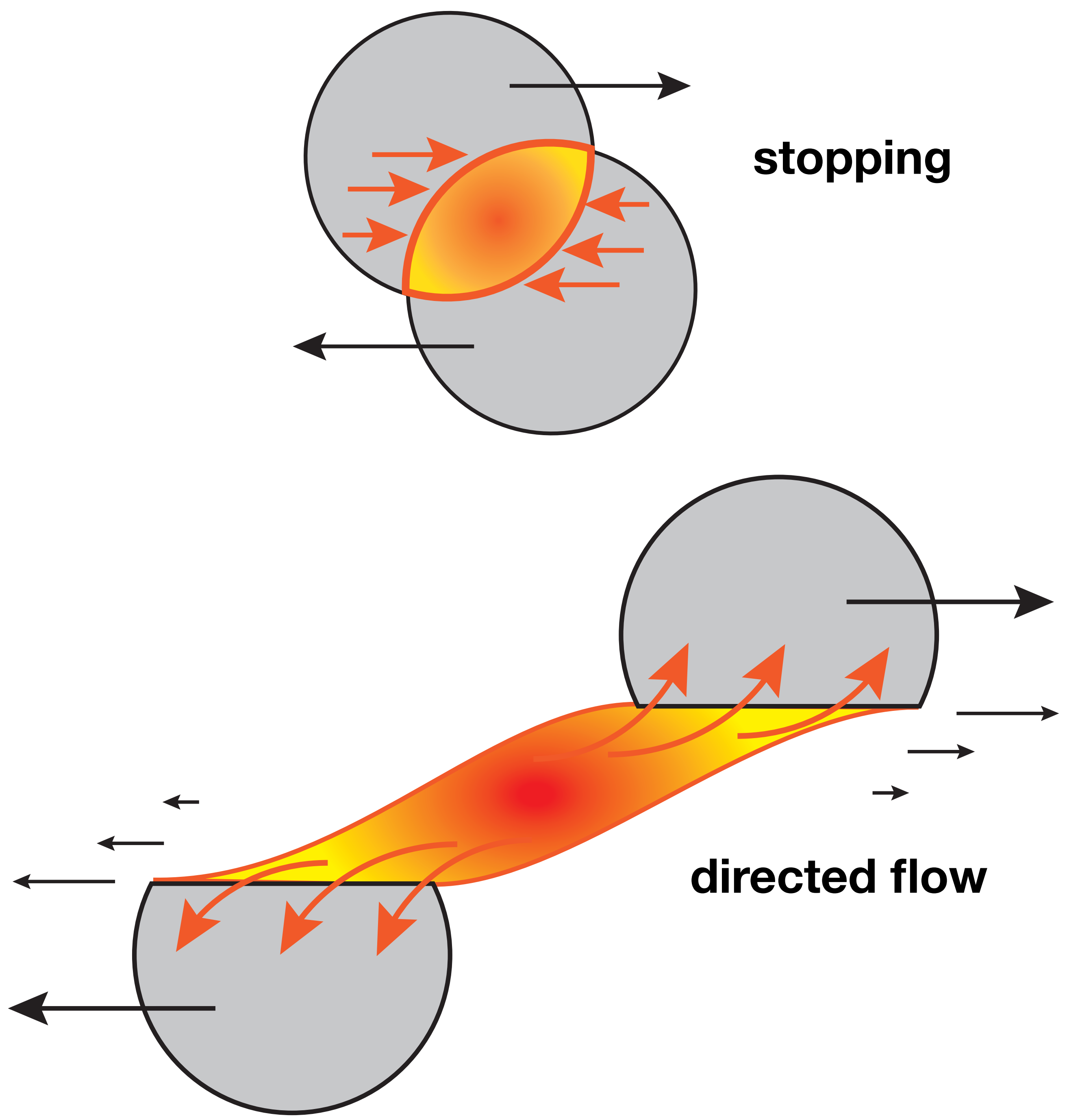
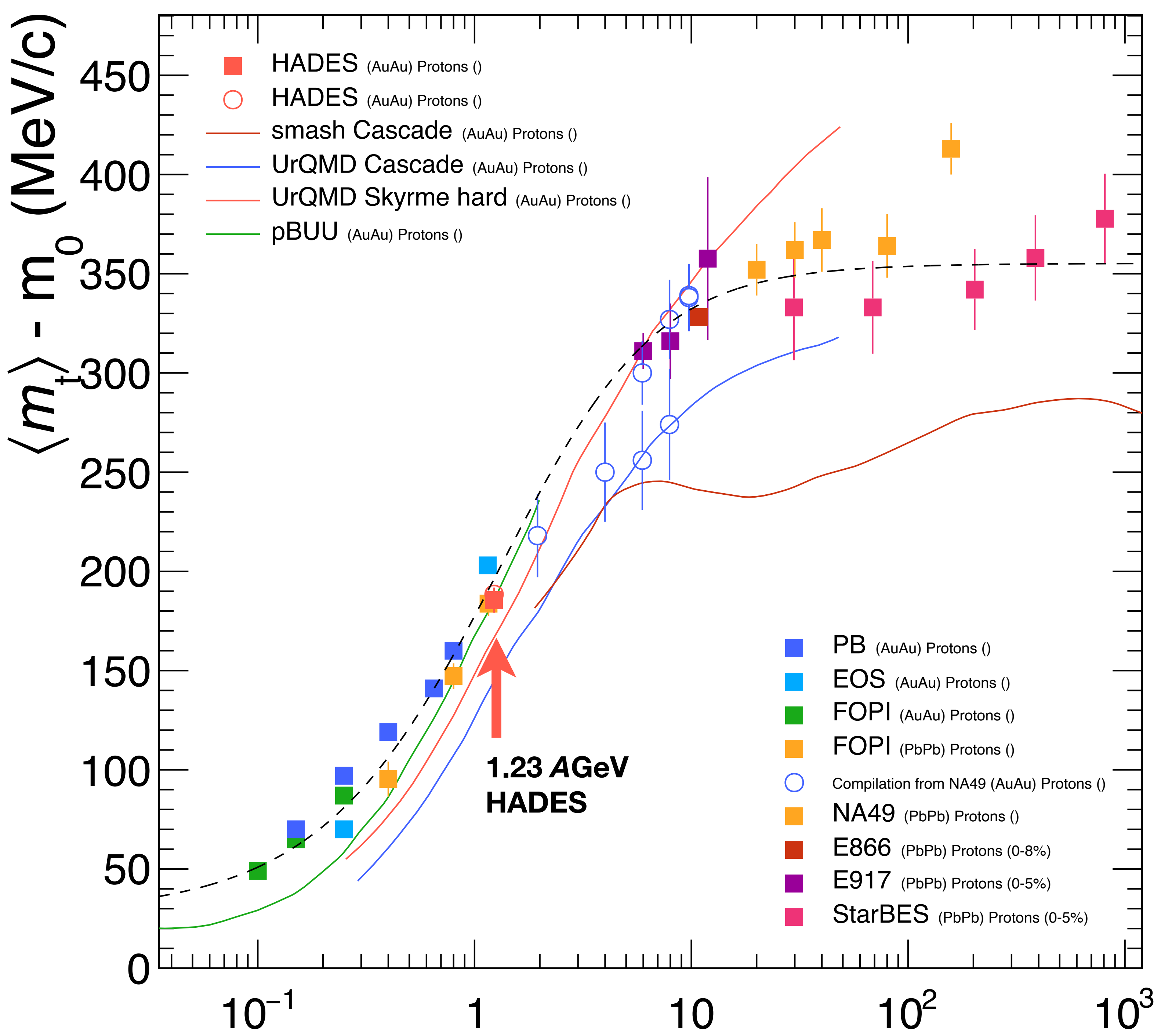


HADES, EPJ A 59 (2023) 80
Update Star FXT QM2023



Collectivity



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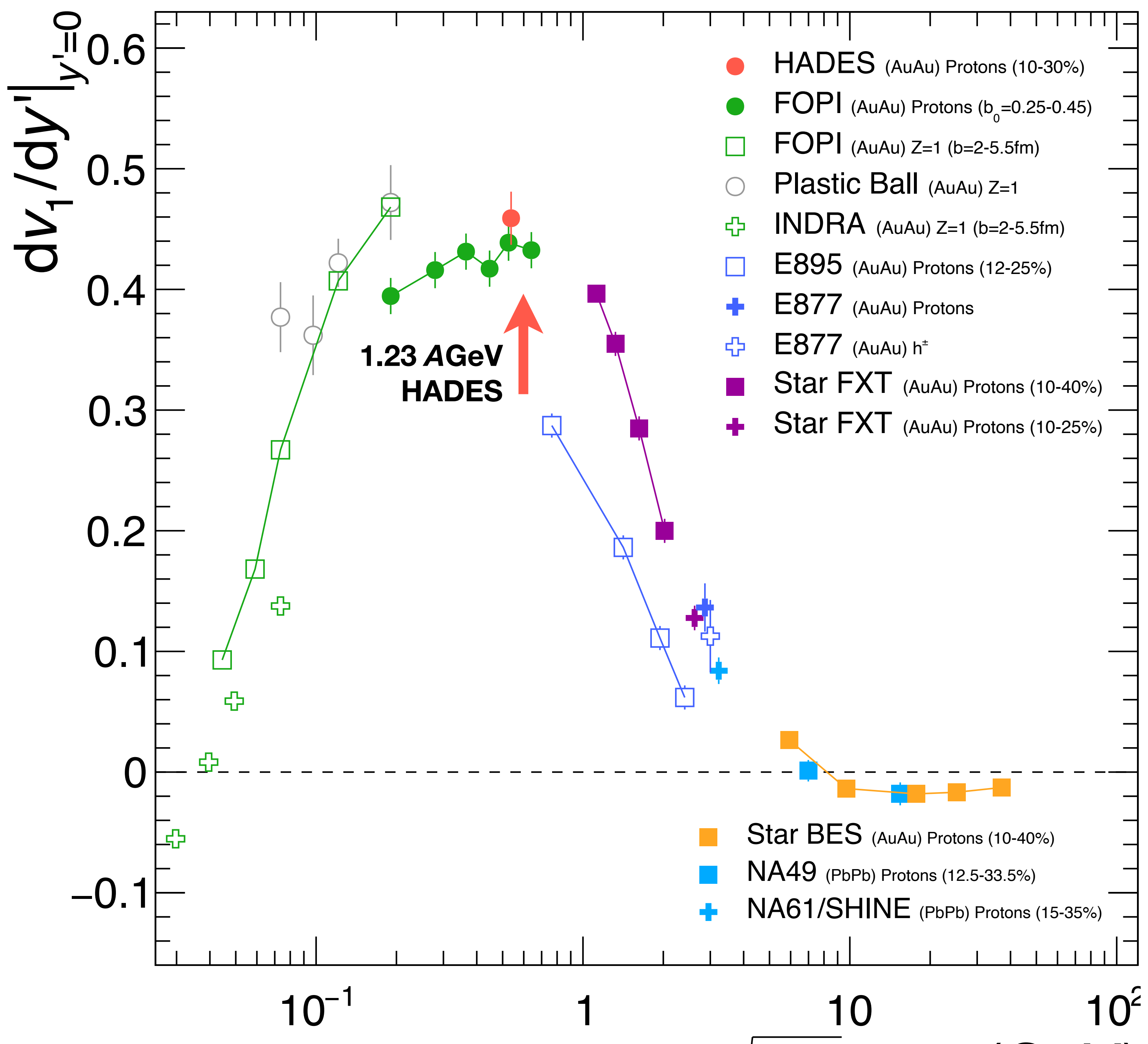
UrQMD J. Steinheimer et al, EPJC 82 (2022) 911
pBUU P. Danielewicz, PRC 51 (1995) 716



HADES, EPJ A 59 (2023) 80
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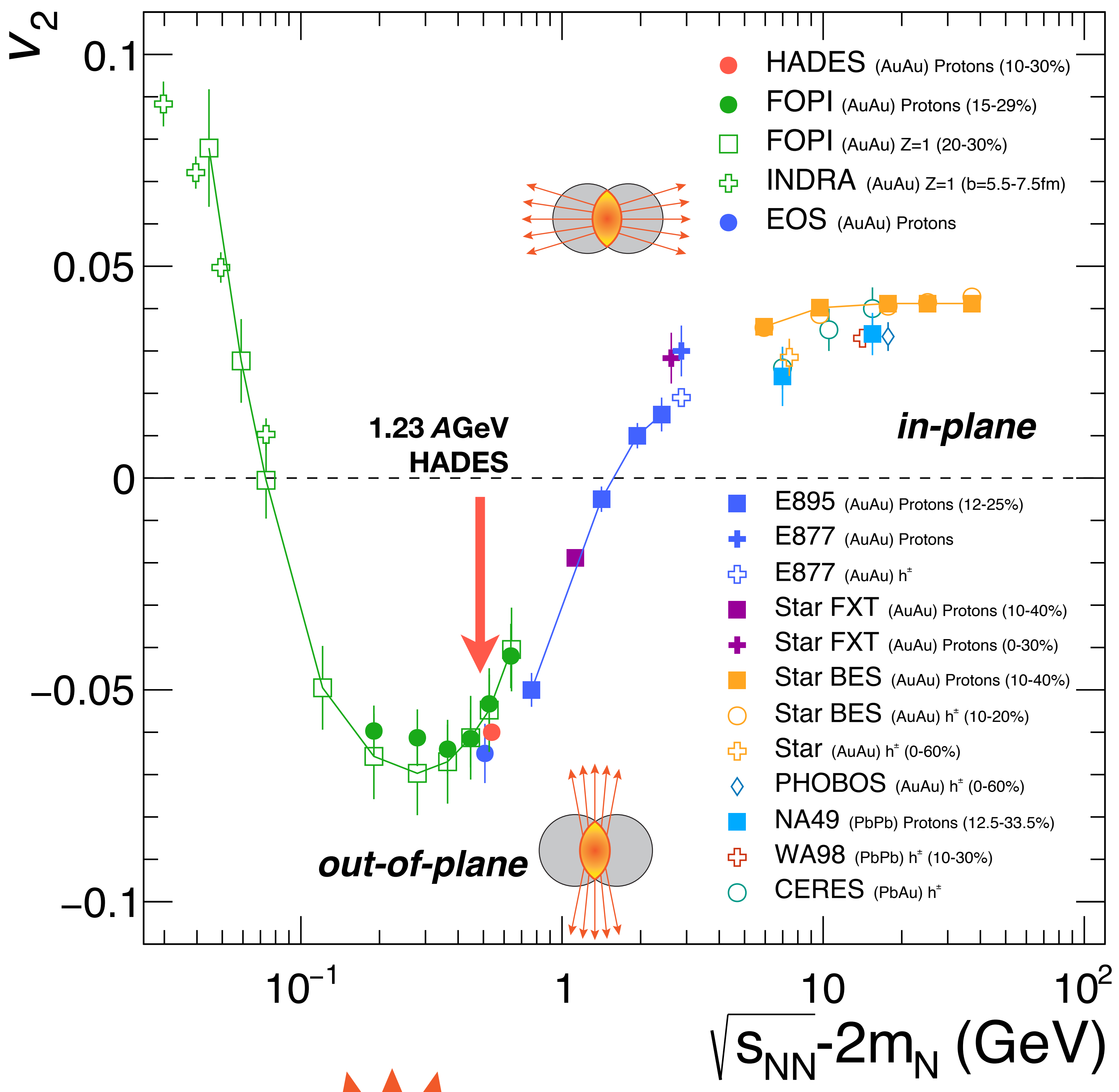
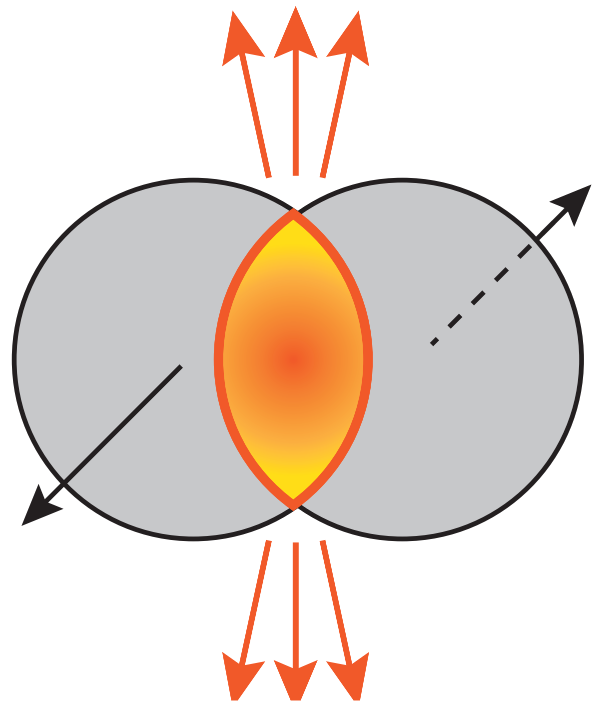


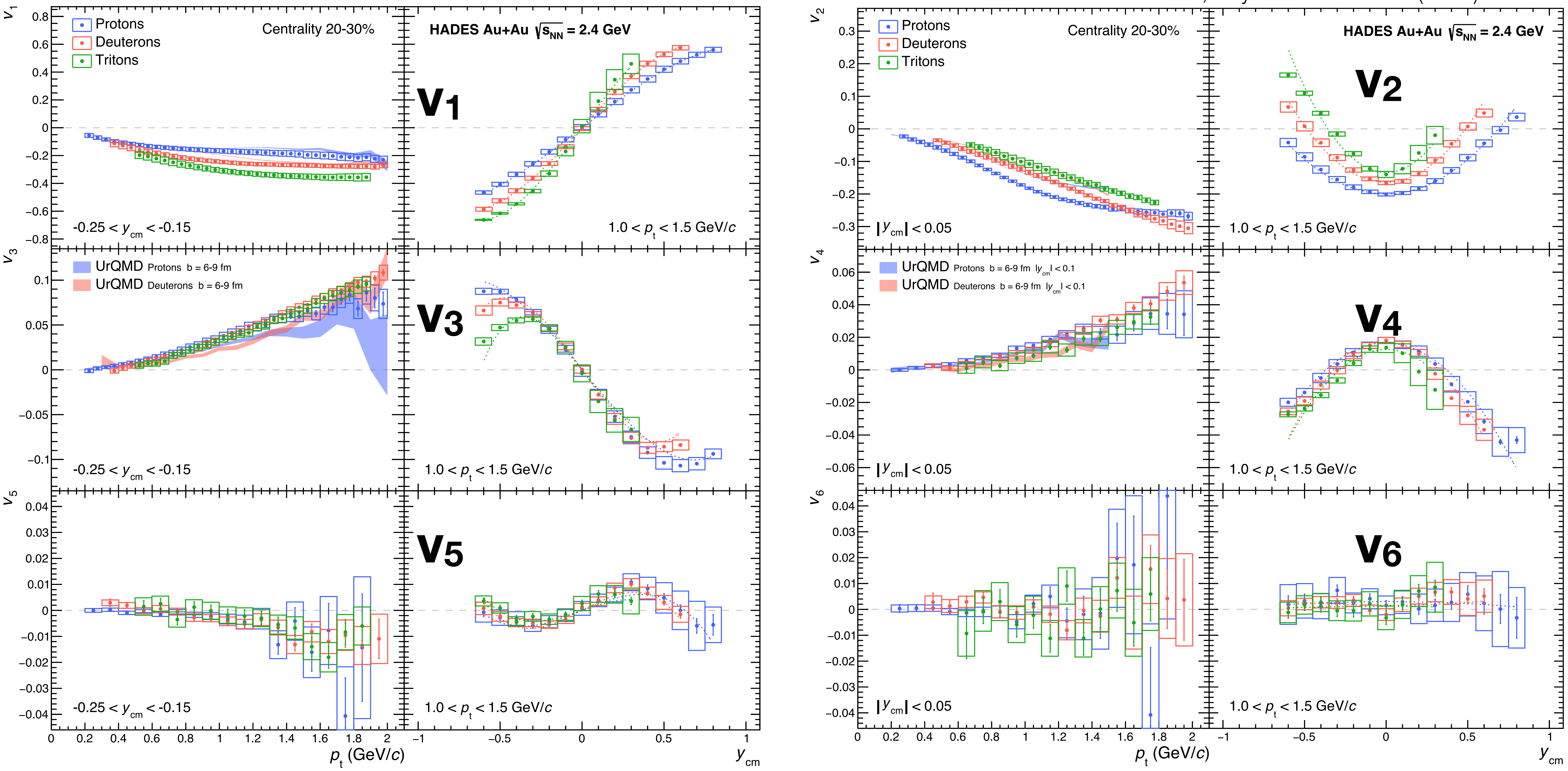


elliptic flow

Good agreement with world data

Collectivity

HADES, Phys. Rev. Lett. **125** (2020) 262301



Collectivity

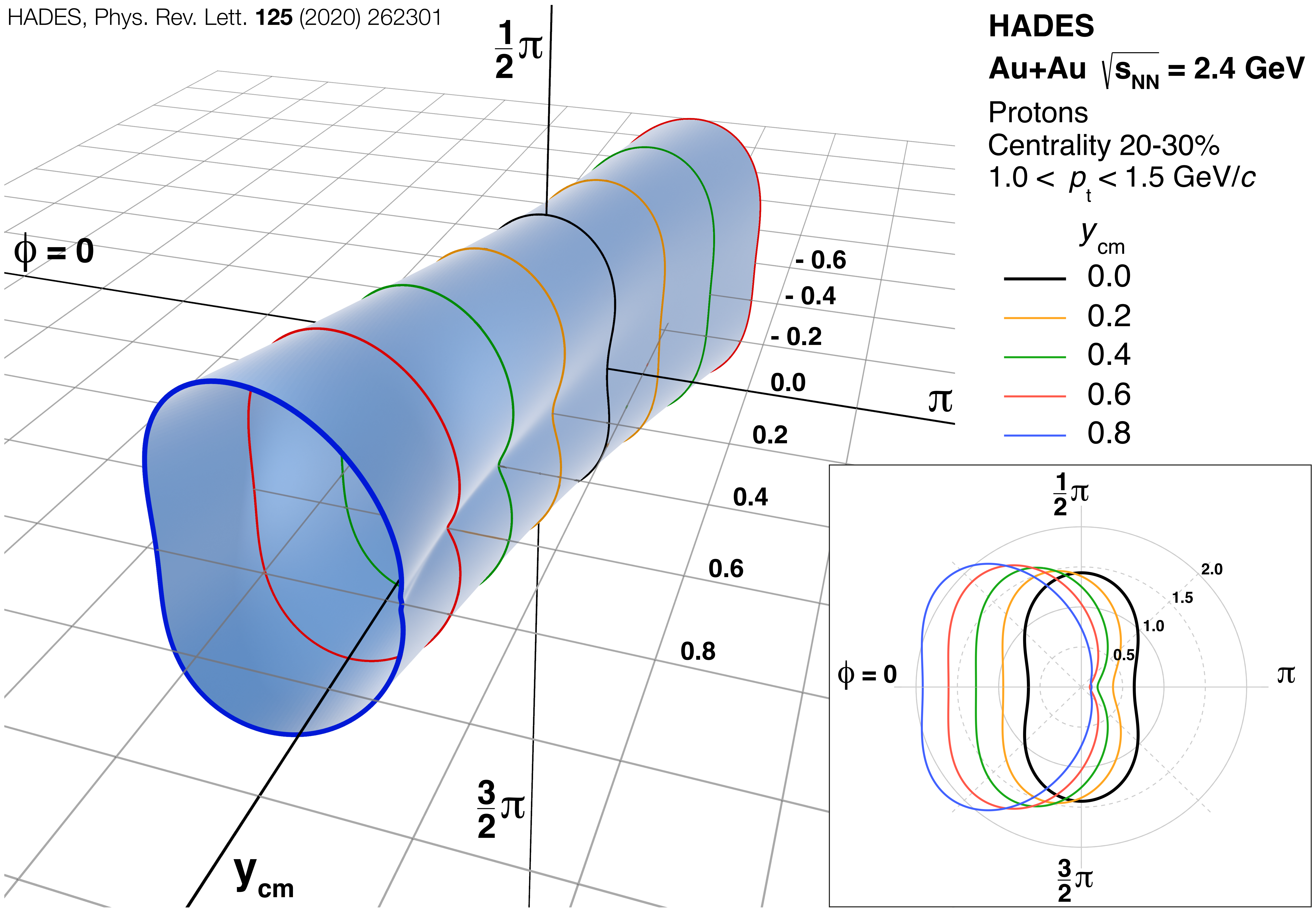
Allows to reconstruct a full 3D-picture of the emission pattern in momentum space

Complex evolution of shape as function of rapidity determined by flow coefficients v_1 — v_6

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

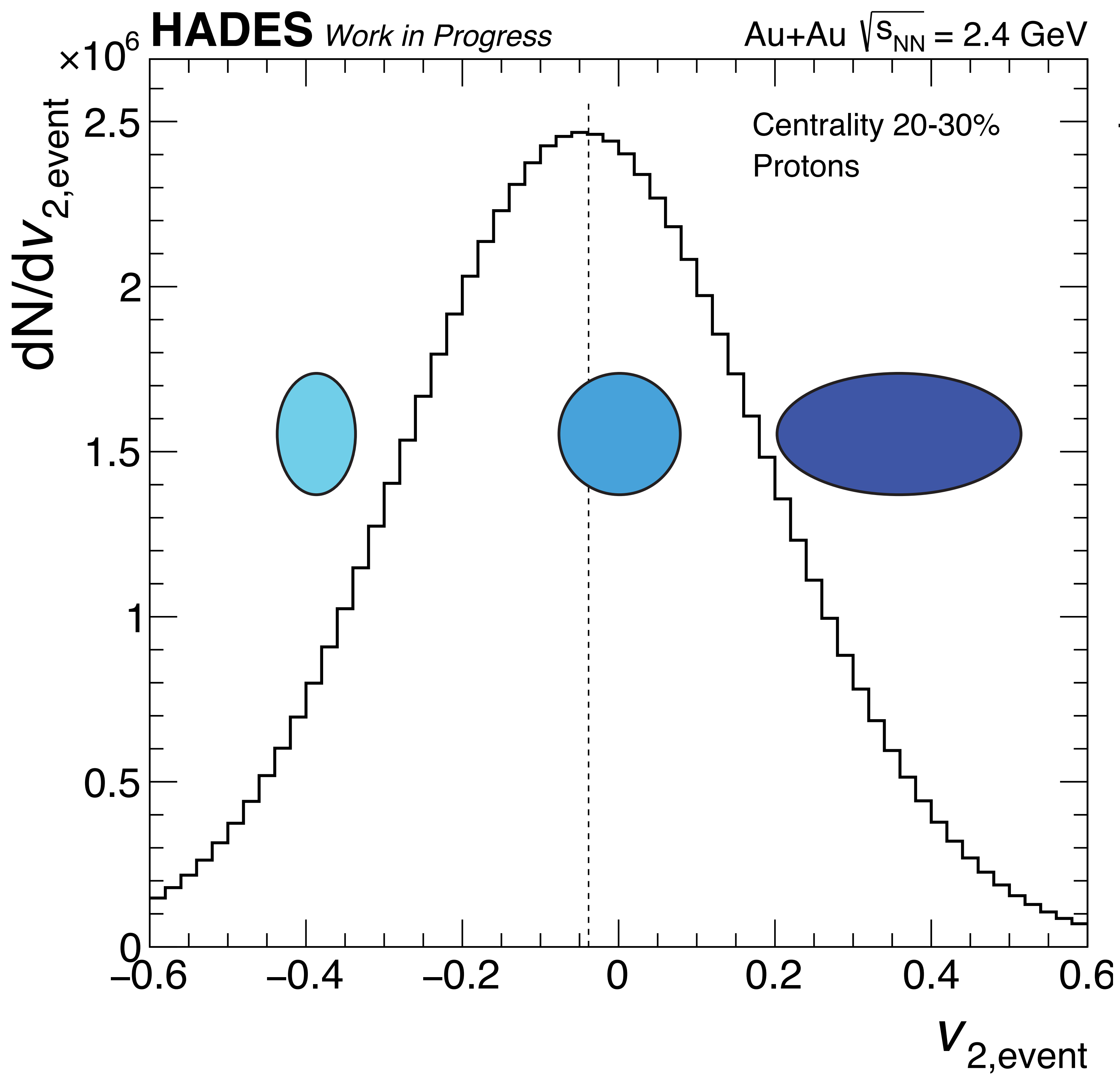
First Proposed in S. Voloshin and Y. Zhang
Z.Phys. C70 (1996) 665-672

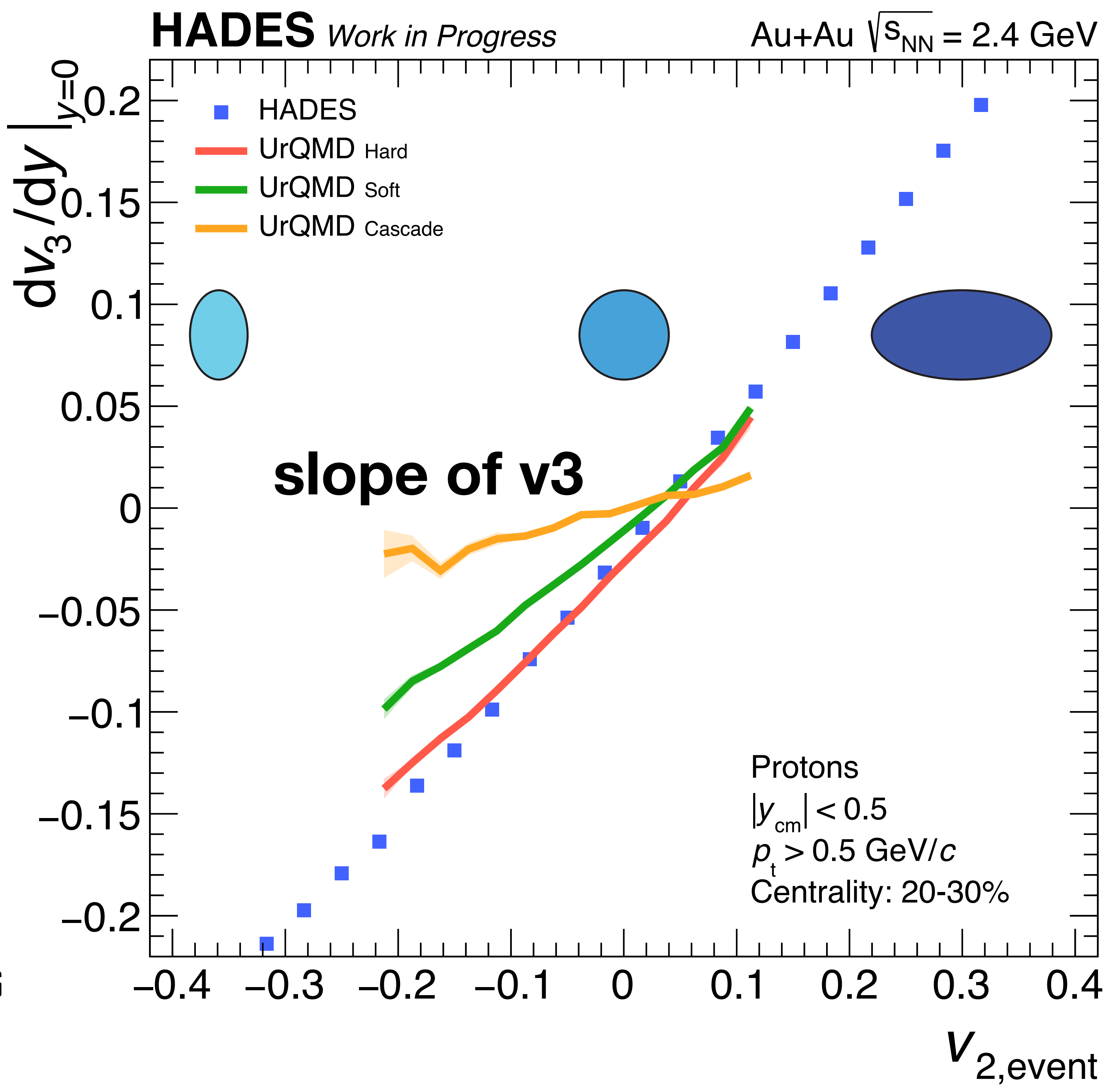
HADES, Phys. Rev. Lett. **125** (2020) 262301



Collectivity

- Events can characterised according to event-wise magnitude of elliptic flow $v_{2,event}$
- Slope of triangular flow $dv_3/dy|_{y=0}$ as function of $v_{2,event}$
- A strong sensitivity to the EoS is seen as predicted by transport model





UrQMD Model Simulations:
T. Reichert et al. EPJ C 82 (2022) 510

Vorticity

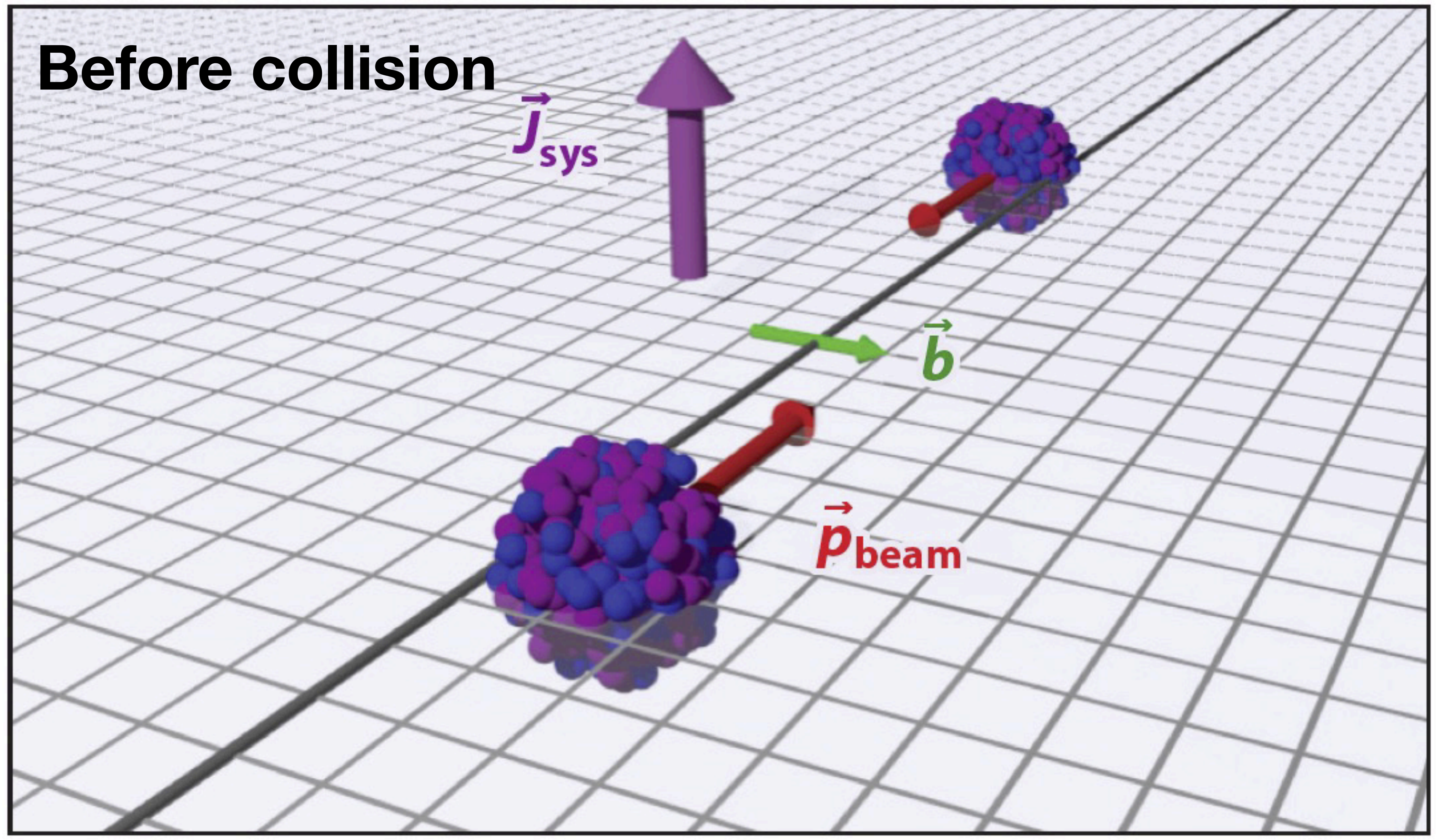
Global Polarisation of Λ

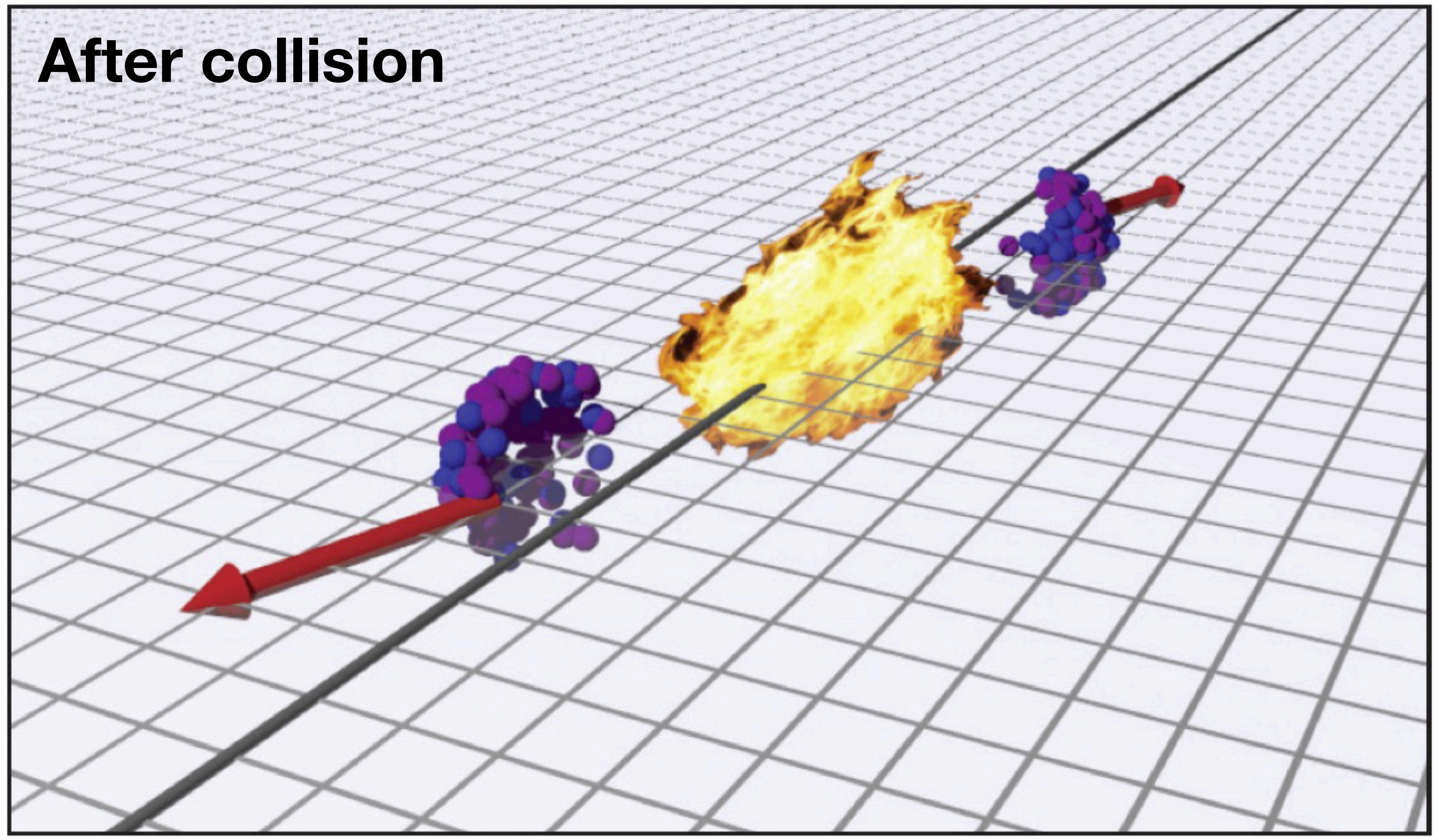
Vorticity

- Global polarisation
- Large angular momenta |L| ~ $10^5\,\hbar$
- Extreme vorticities possible ($\omega \approx 10^{21}\ s^{-1}$)
- Observable via polarisation of spins relative to event plane (spin-orbit coupling, e.m.-coupling)
- $\Lambda \rightarrow p+\pi^-$ decay self-analysing
  ⇒ decay-proton emitted preferentially in Λ spin direction

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

Λ decay parameter: $\alpha_\Lambda = 0.732 \pm 0.014$
Ψ_{EP} = event plane angle
R_{EP} = EP-resolution
Φ^*_p = proton azimuth angle relative to EP



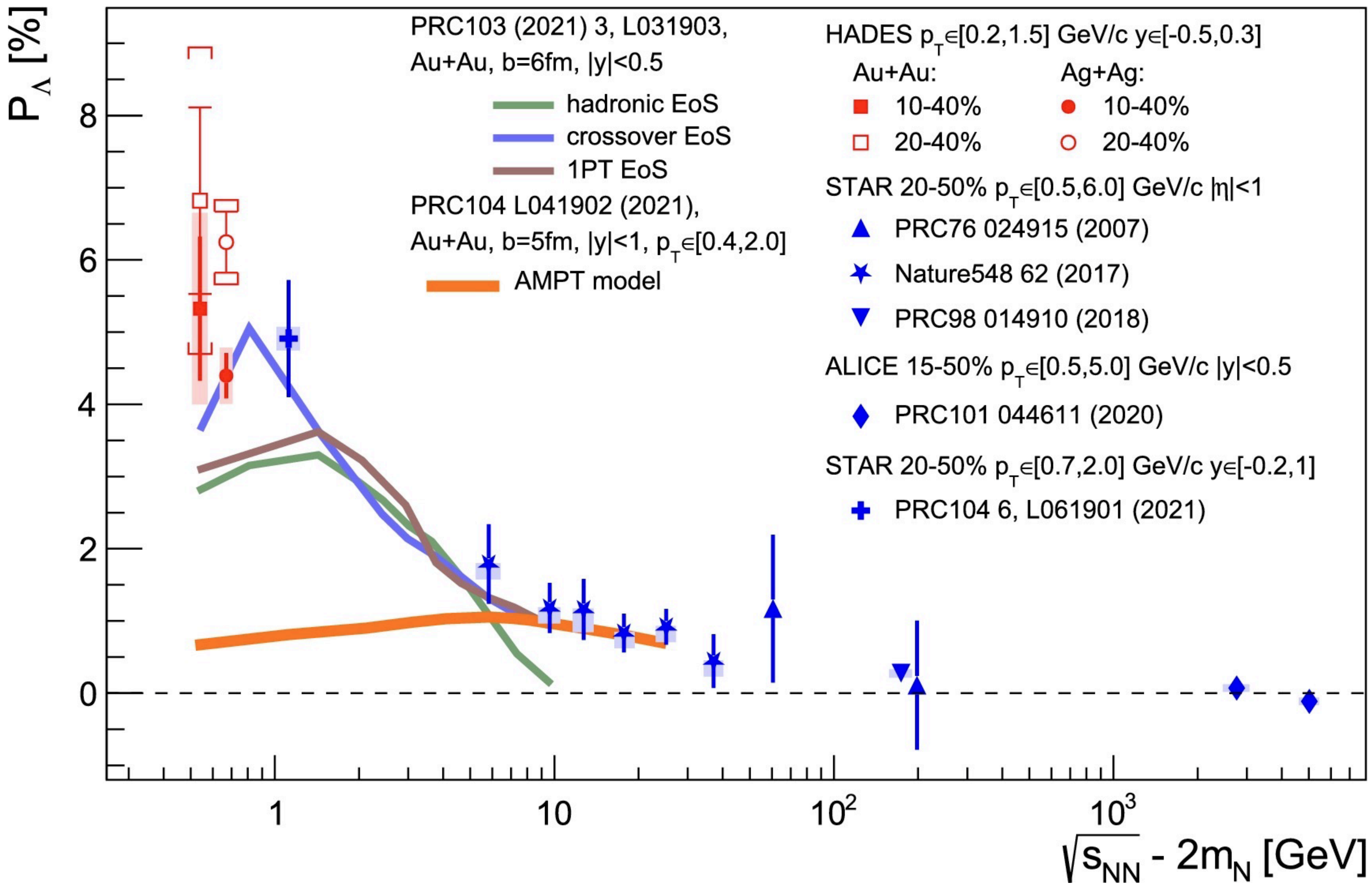


F. Becattini and M. Lisa, Ann. Rev. Nucl. Part. Sci. 70 (2020) 395

Vorticity

- Strong increase of P_Λ towards lower energies with highest polarisation measured by HADES
- Rough agreement with 3 fluid-hydro
- AMPT model disfavoured
- Further constraints for the EoS of compressed baryonic matter

HADES, Phys.Lett.B 835 (2022) 137506

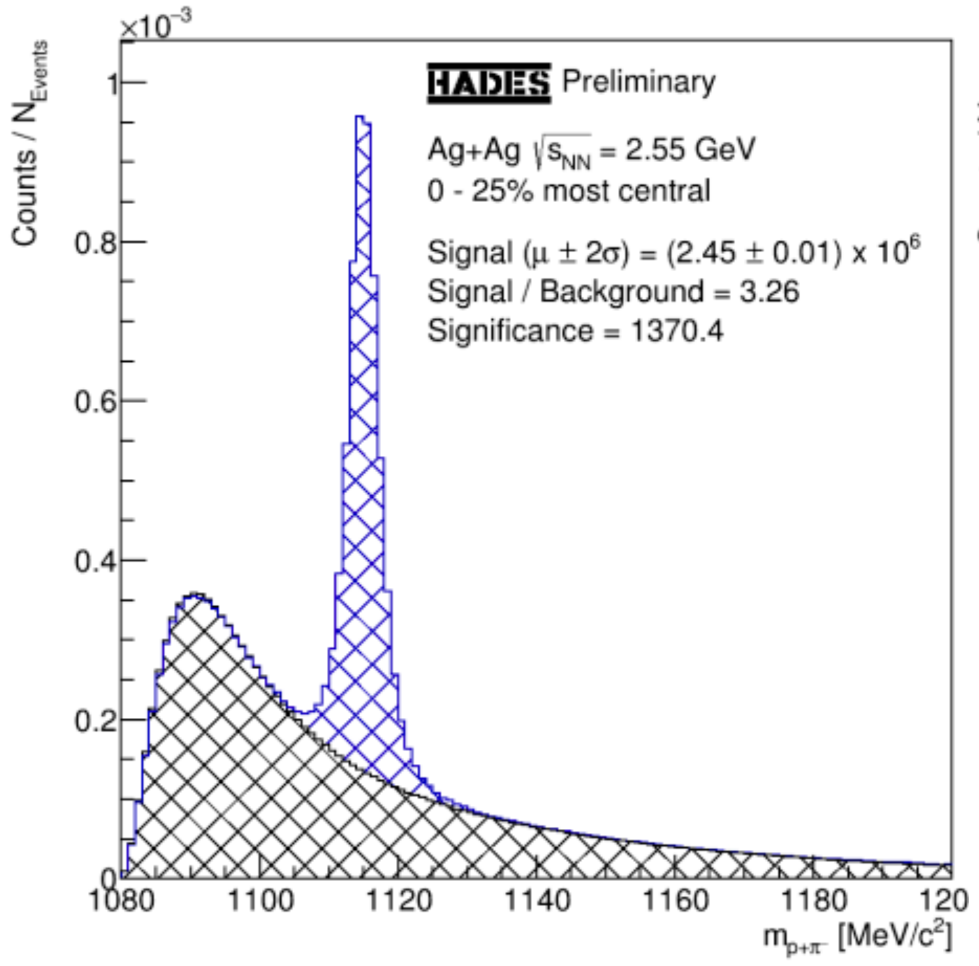


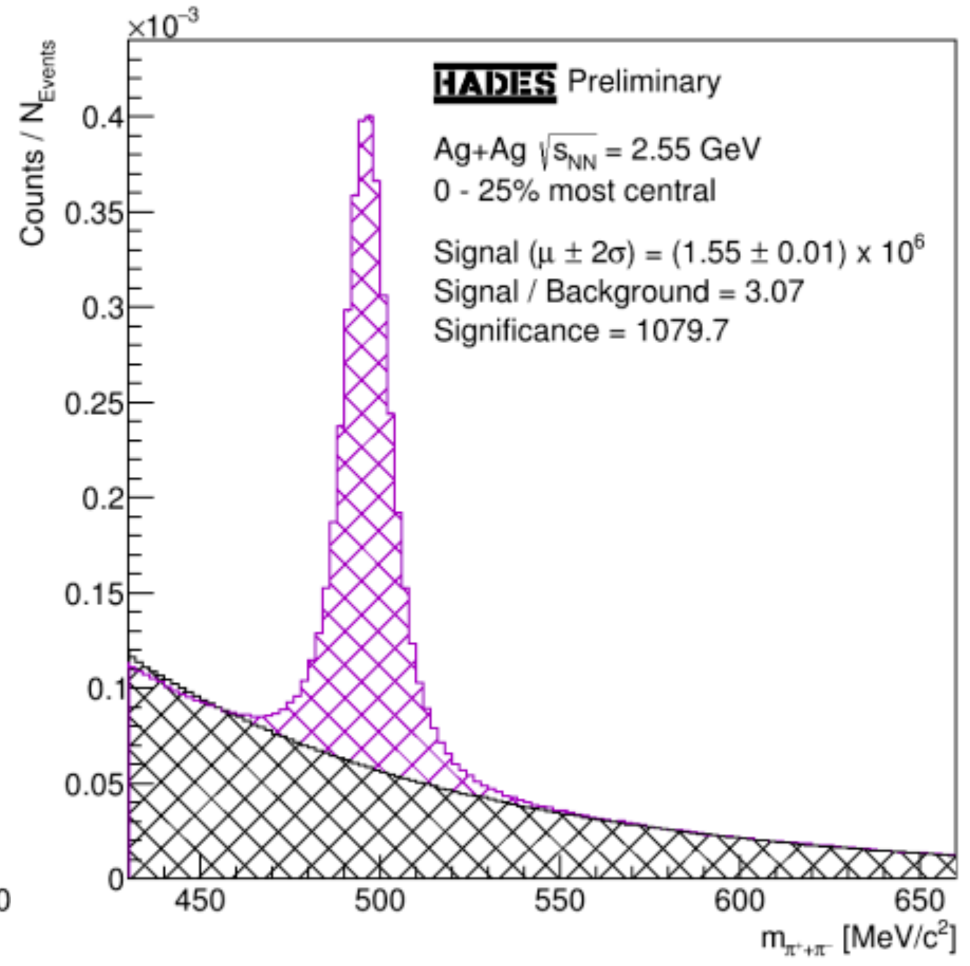
Strangeness and Hypernuclei

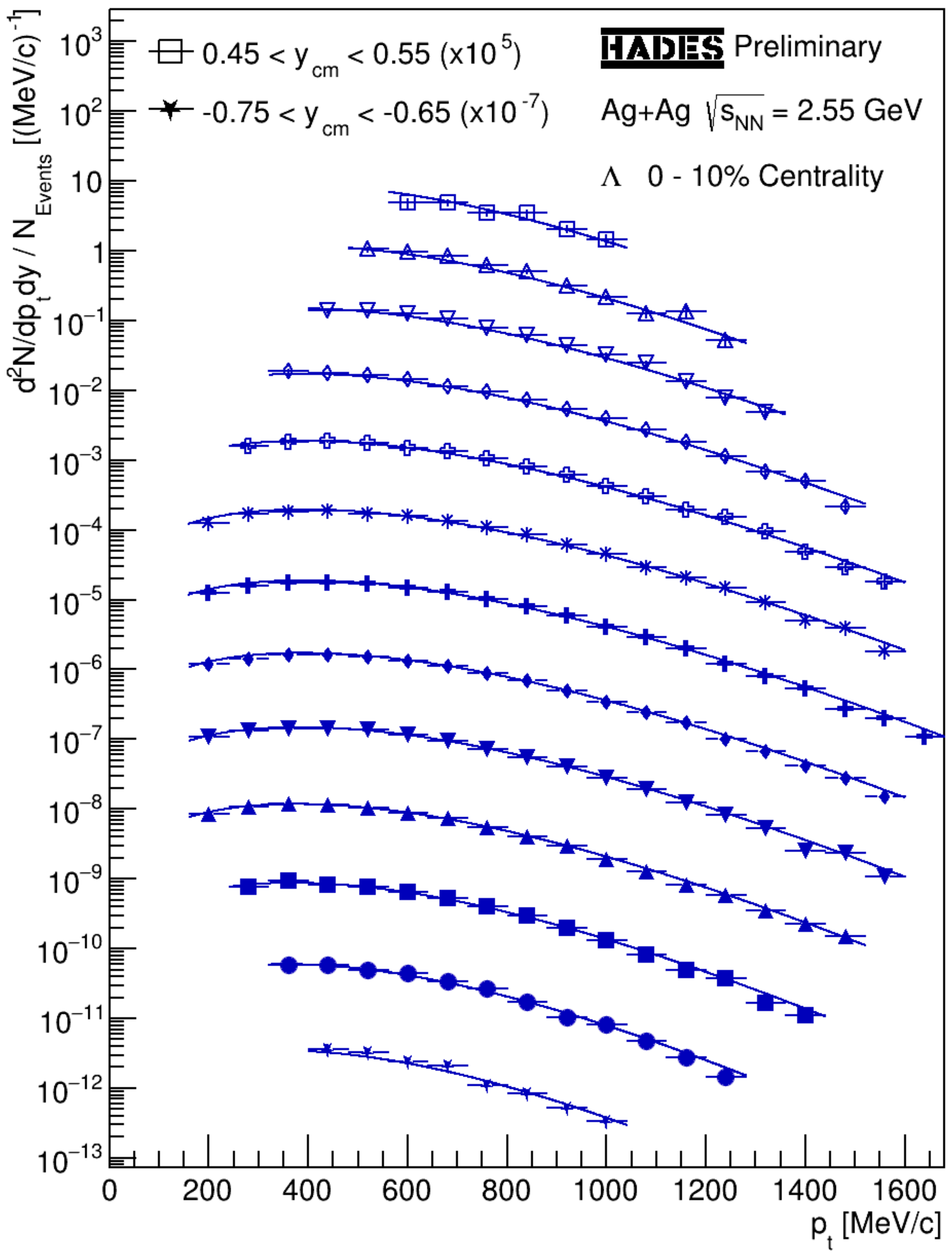
Systematics of strangeness production

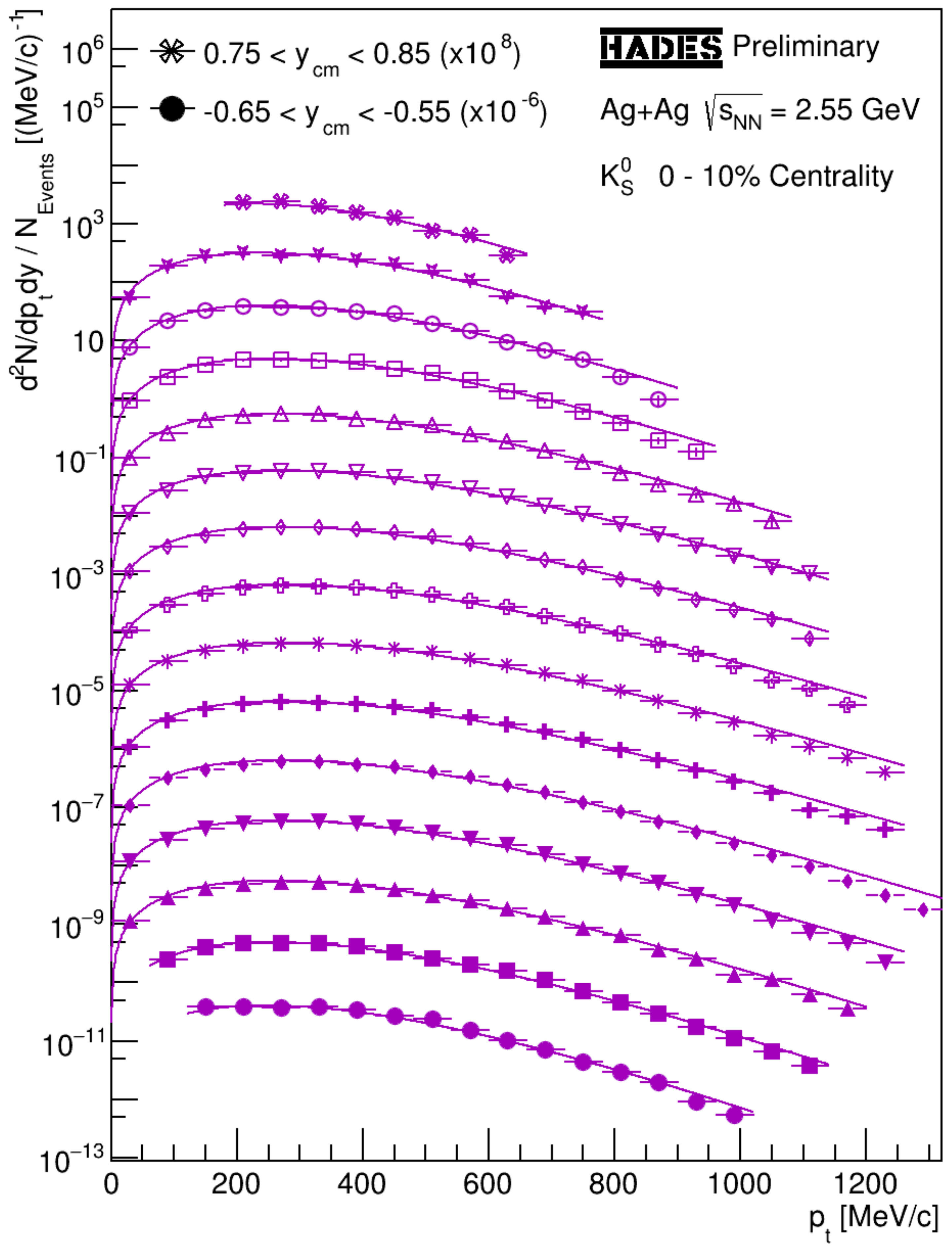
Strangeness and Hypernuclei

- Large phase space coverage with small statistical errors
- Phase space distribution well described by Boltzmann functions
    - used for extrapolation to 4π
- Weak decay topology recognition with Artificial Neural Network (ANN)







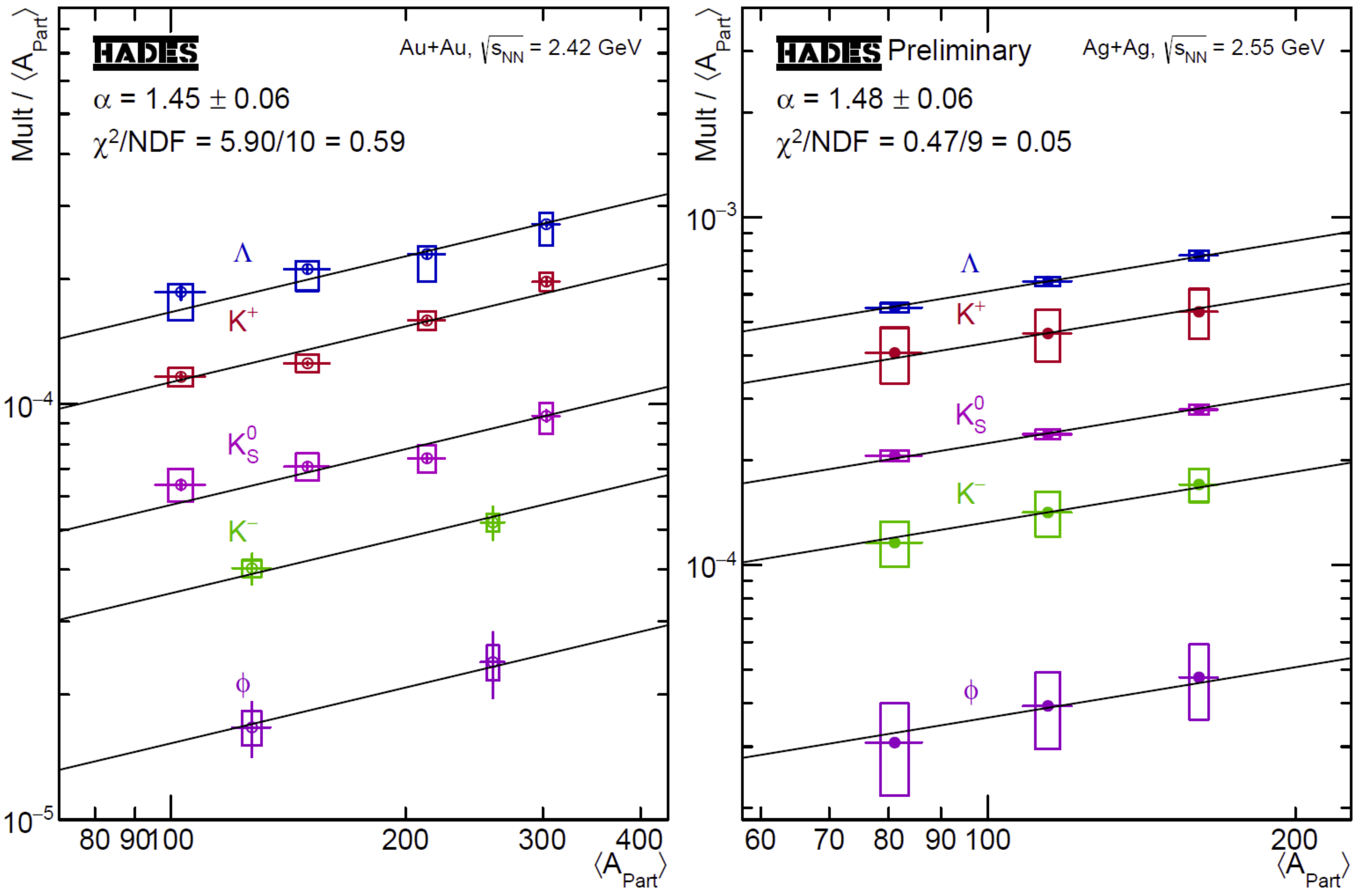


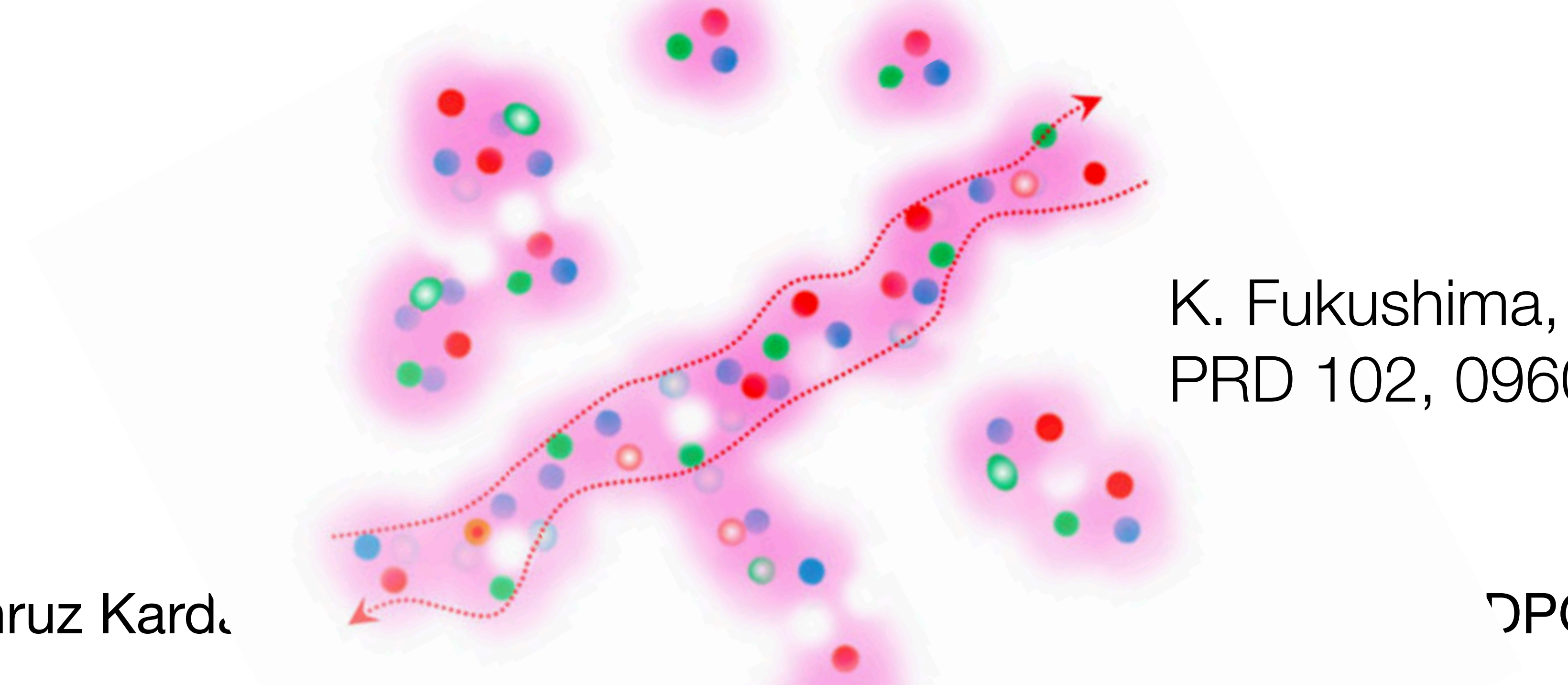
Strangeness and Hypernuclei

- Production below (at) free NN-threshold
  - Missing energy provided by the system
- Centrality dependence compatible with universal scaling assumption:

$$\text{Mult} \propto \langle A_{part} \rangle^{\alpha}$$

  - Au+Au: $\alpha_{Au+Au} = 1.45 \pm 0.06$
    Ag+Ag: $\alpha_{Ag+Ag} = 1.48 \pm 0.06$
  - Hierarchy in production thresholds not reflected
  - Suggests scaling with primary $s\bar{s}$ creation
    ⇒ Hint for quark percolation

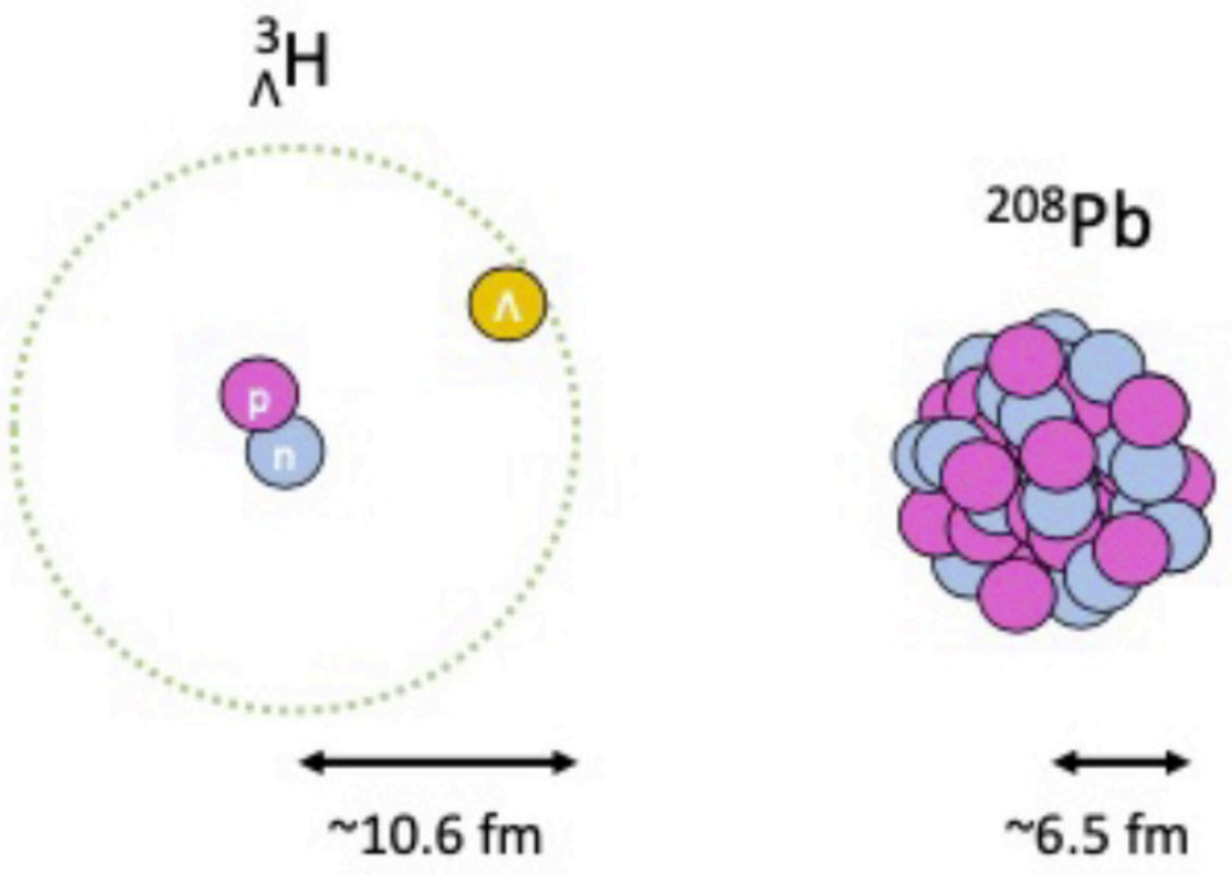




K. Fukushima, T. Kojo, W. Weise, PRD 102, 096017 (2020)

Strangeness and Hypernuclei

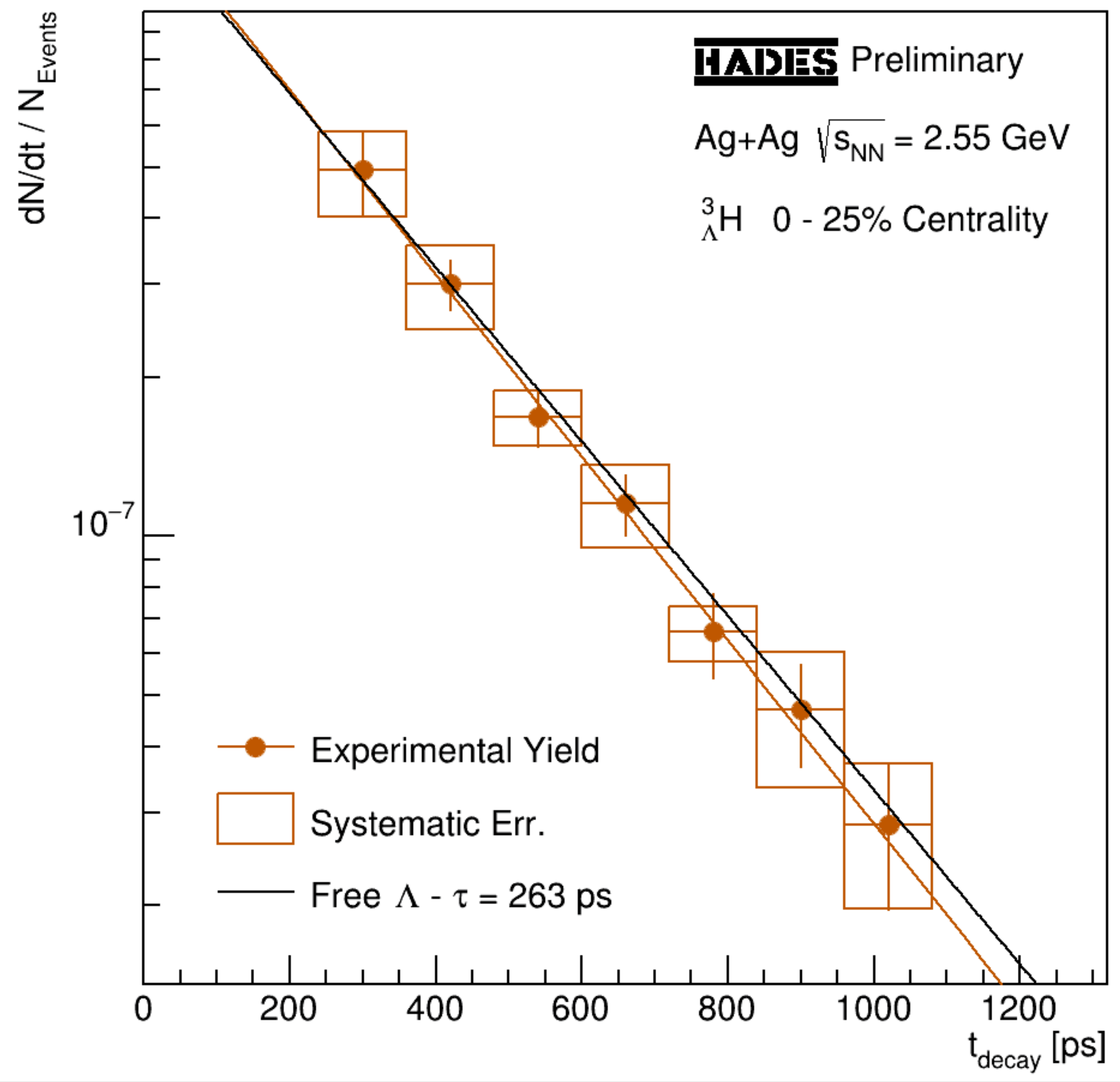
- Loosely bound object
  - Λ binding energy: $B_\Lambda \approx 400$ keV (compare $B_d = 2.2$ MeV)
  - Wavefunction larger than Pb-nucleus

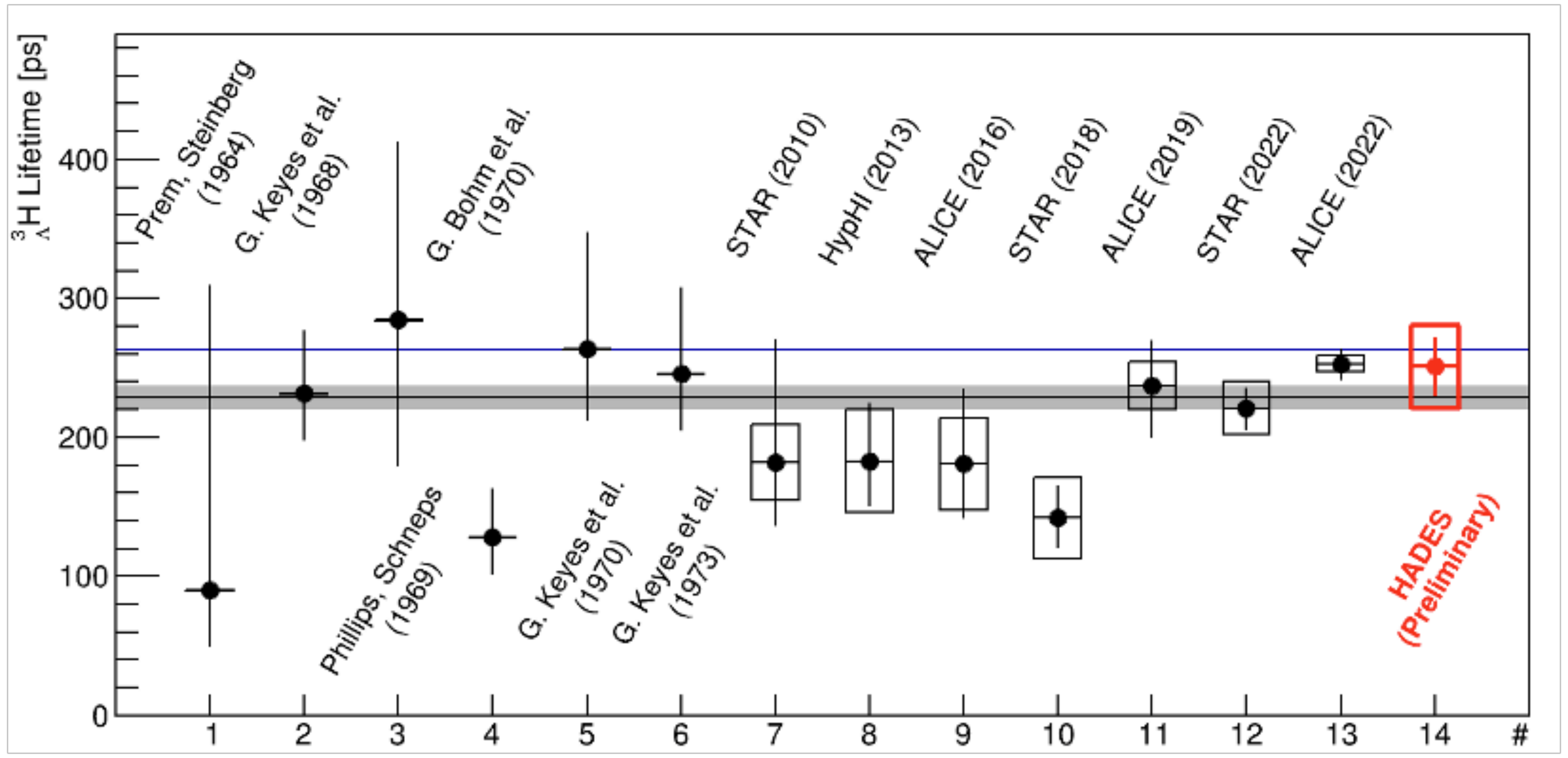


- Decay mode: $^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$
- $^3_\Lambda$H lifetime of $(251 \pm 21_{stat} \pm 30_{sys})$ ps compatible with free Λ lifetime and other measurements (e.g. ALICE)

ALICE, Phys.Rev.Lett. 131 (2023) 102302

$$^3_\Lambda\mathrm{H}$$

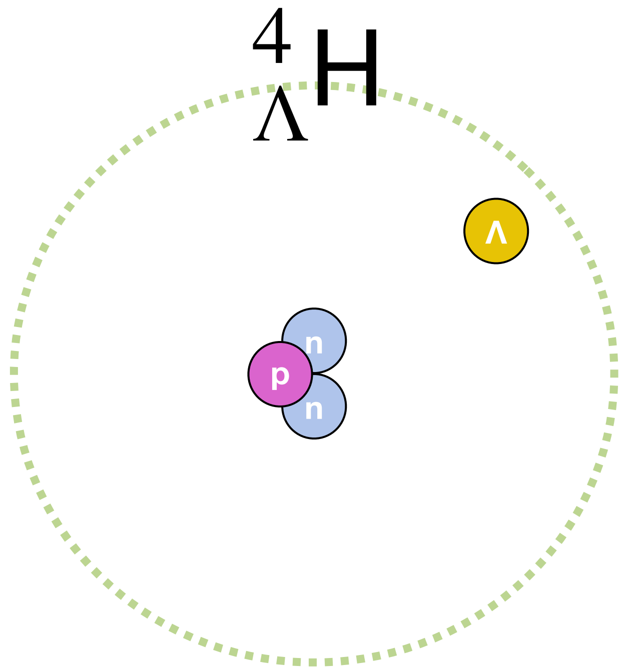


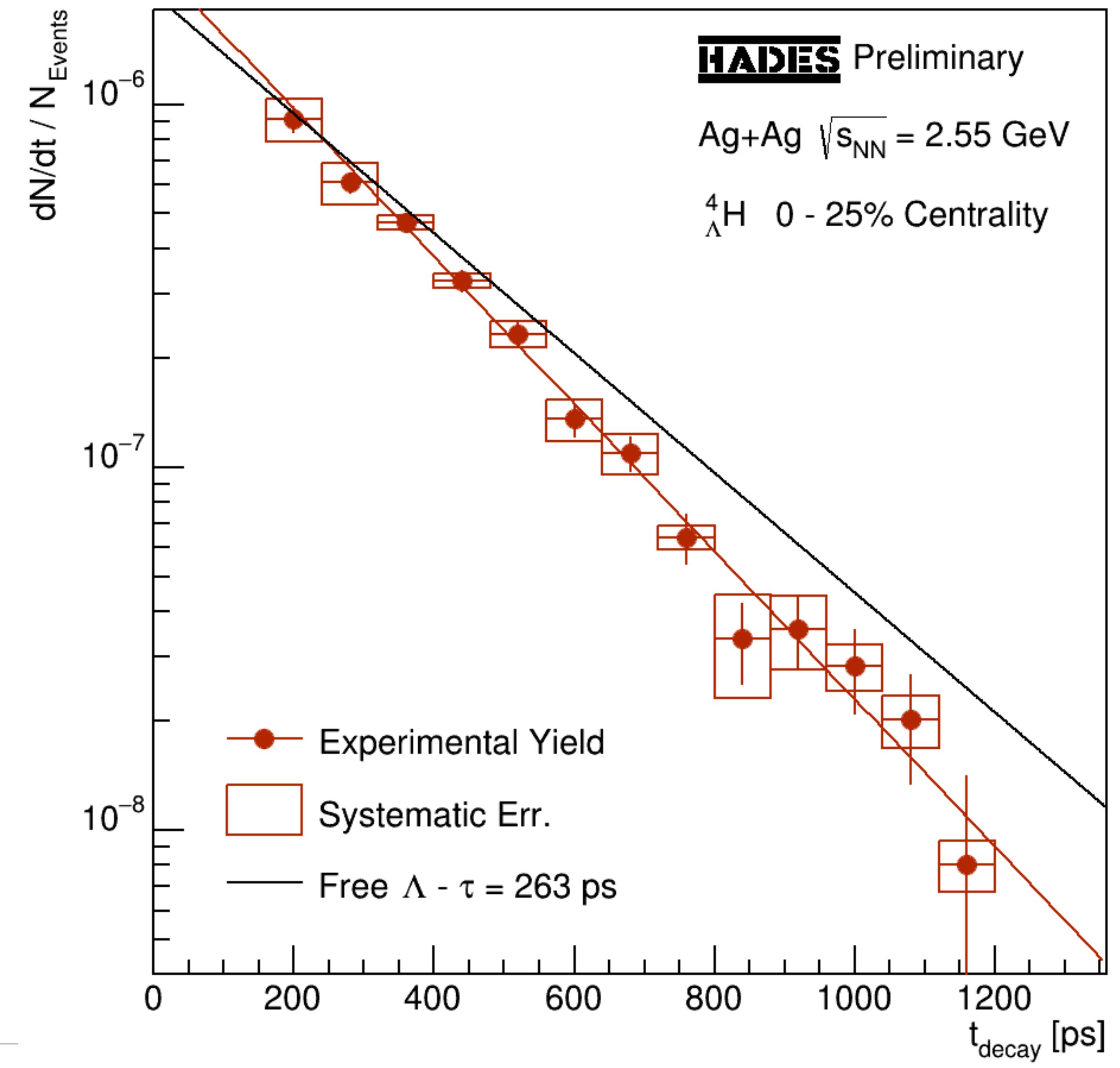


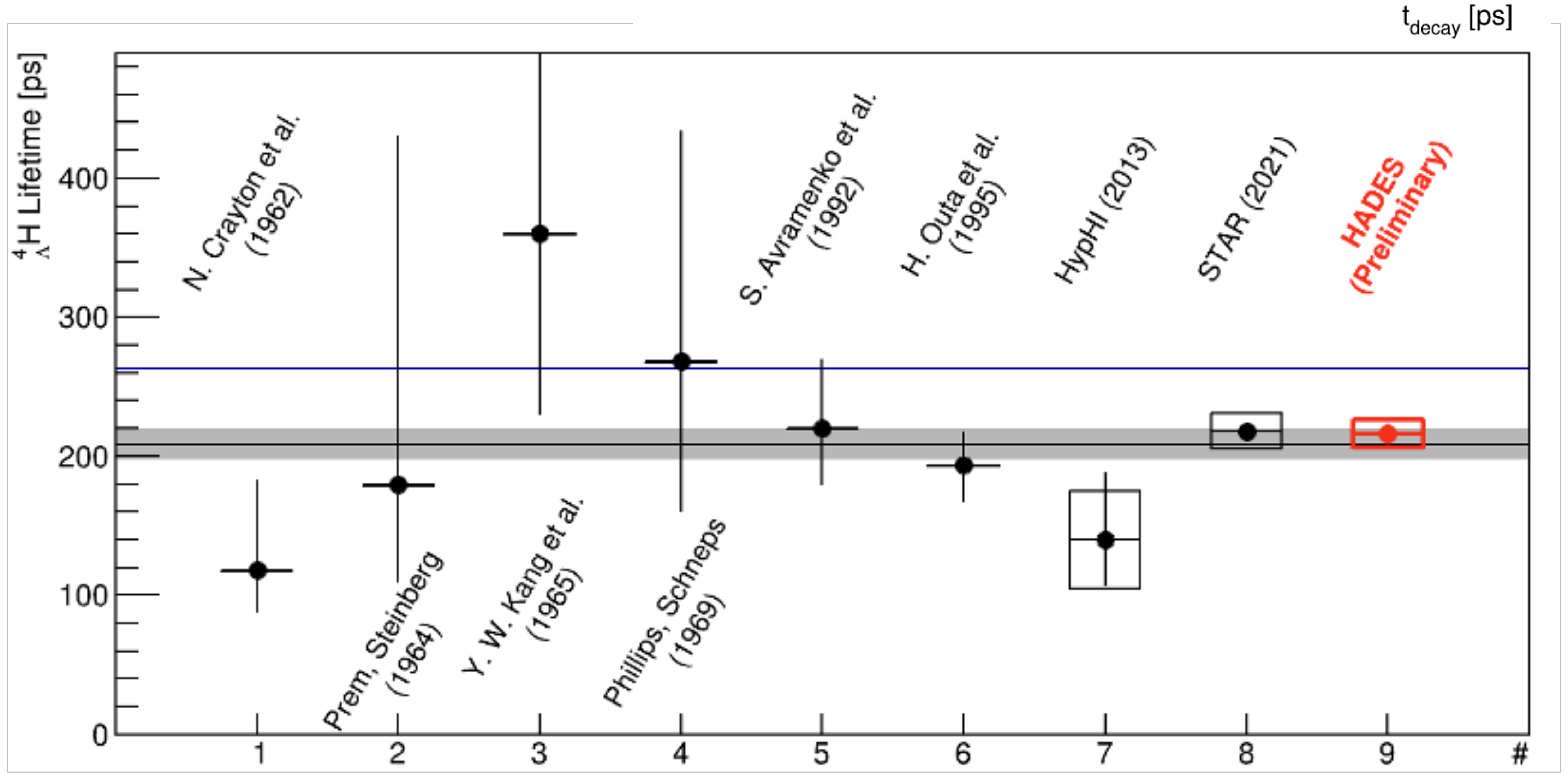
Strangeness and Hypernuclei

$^{4}_{\Lambda}\mathrm{H}$

- Decay mode: $^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$
- $^{4}_{\Lambda}\mathrm{H}$ lifetime of $(216 \pm 7_{stat} \pm 10_{sys})$ ps measured
  - 4.85σ deviation to free Λ lifetime



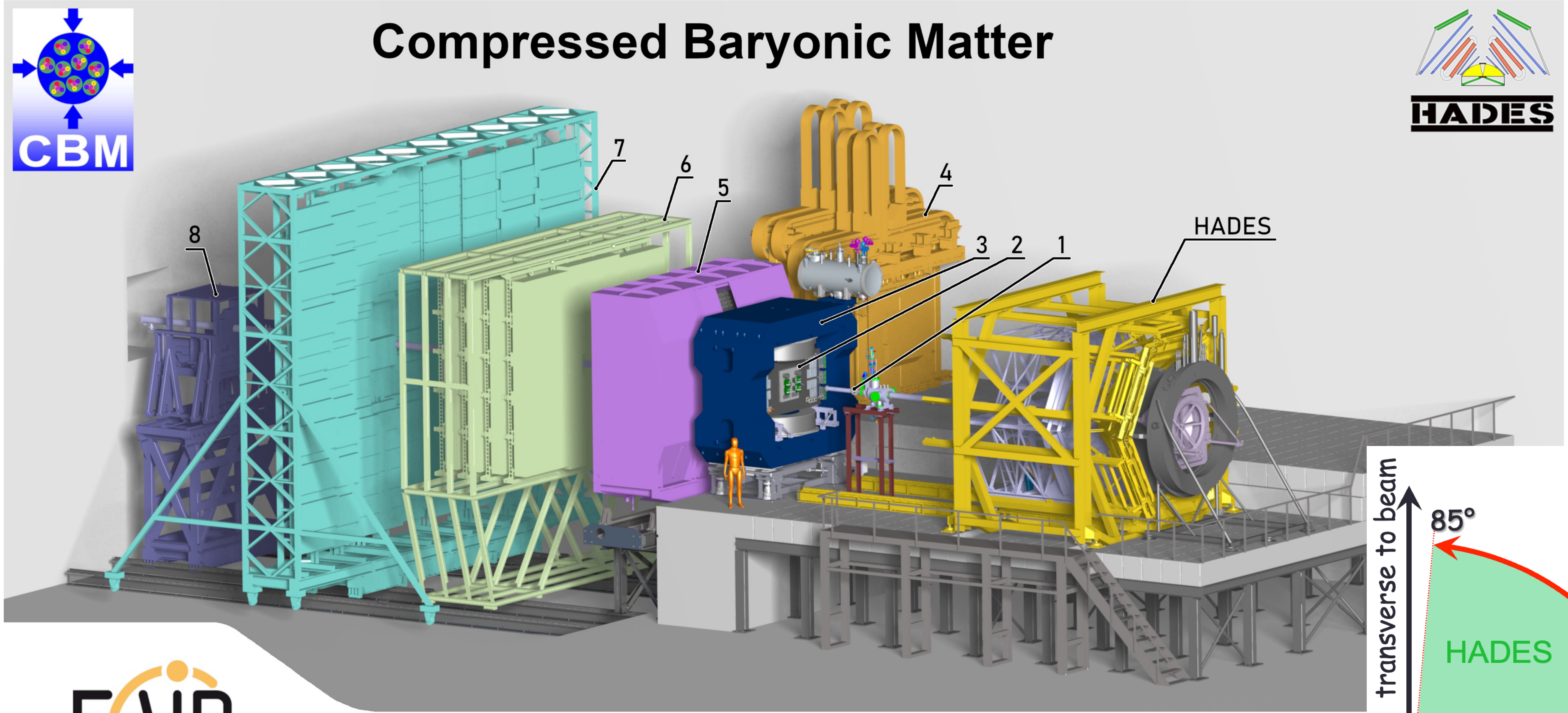


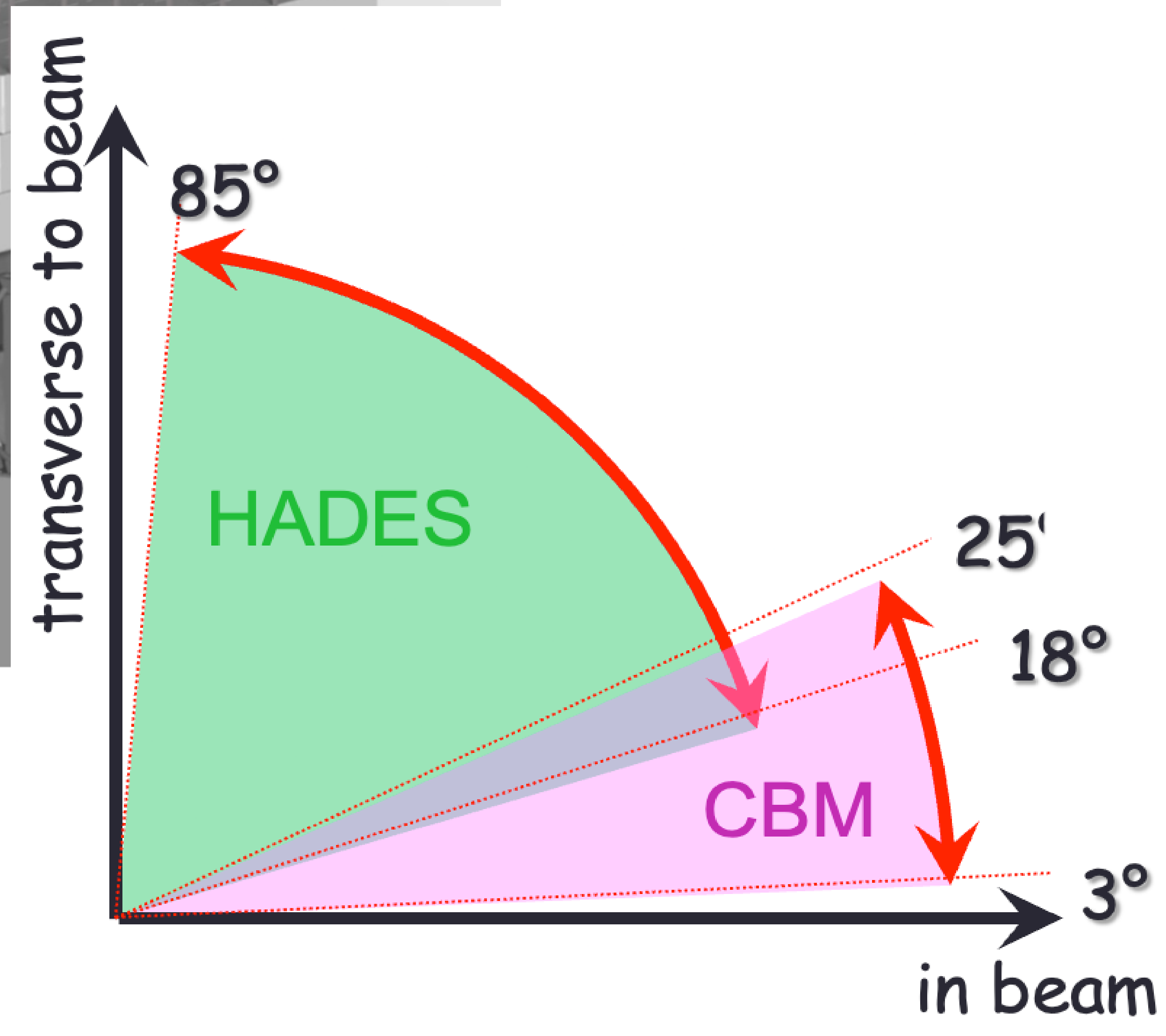


Outlook

HADES and CBM at SIS100

Outlook: HADES and CBM



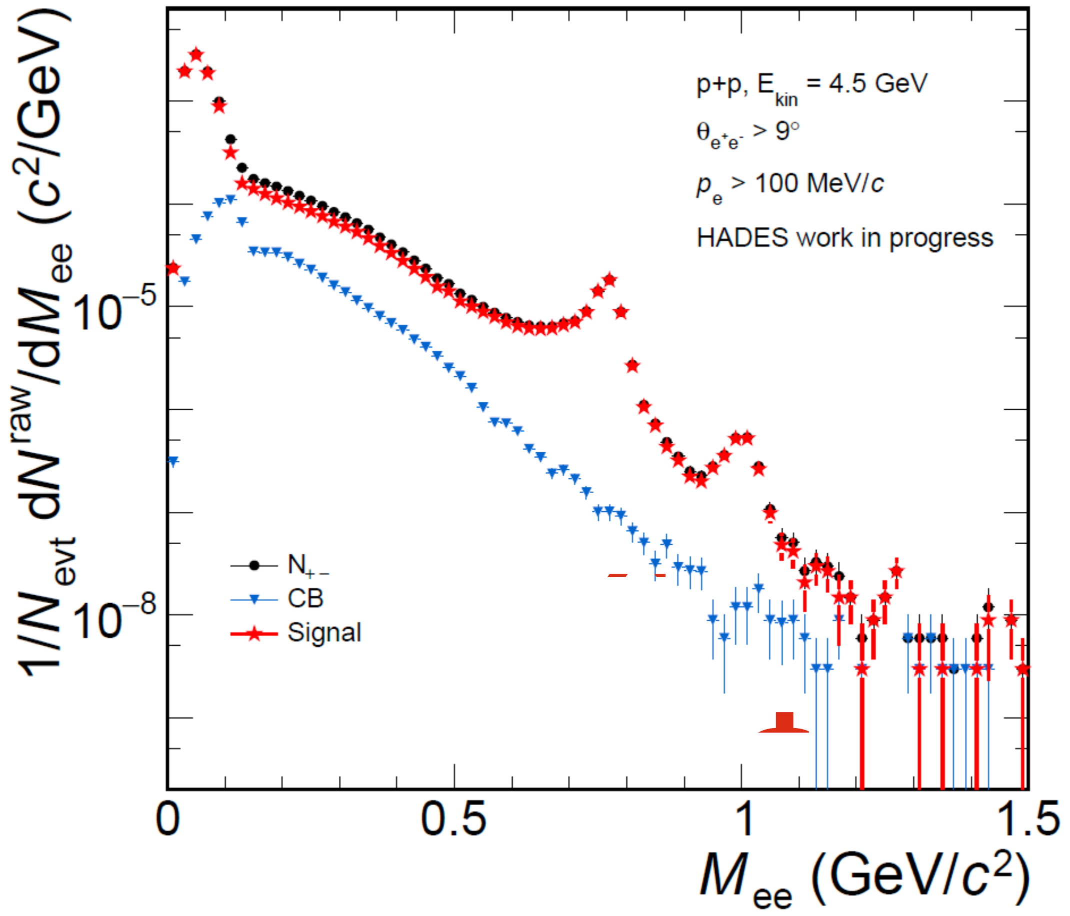


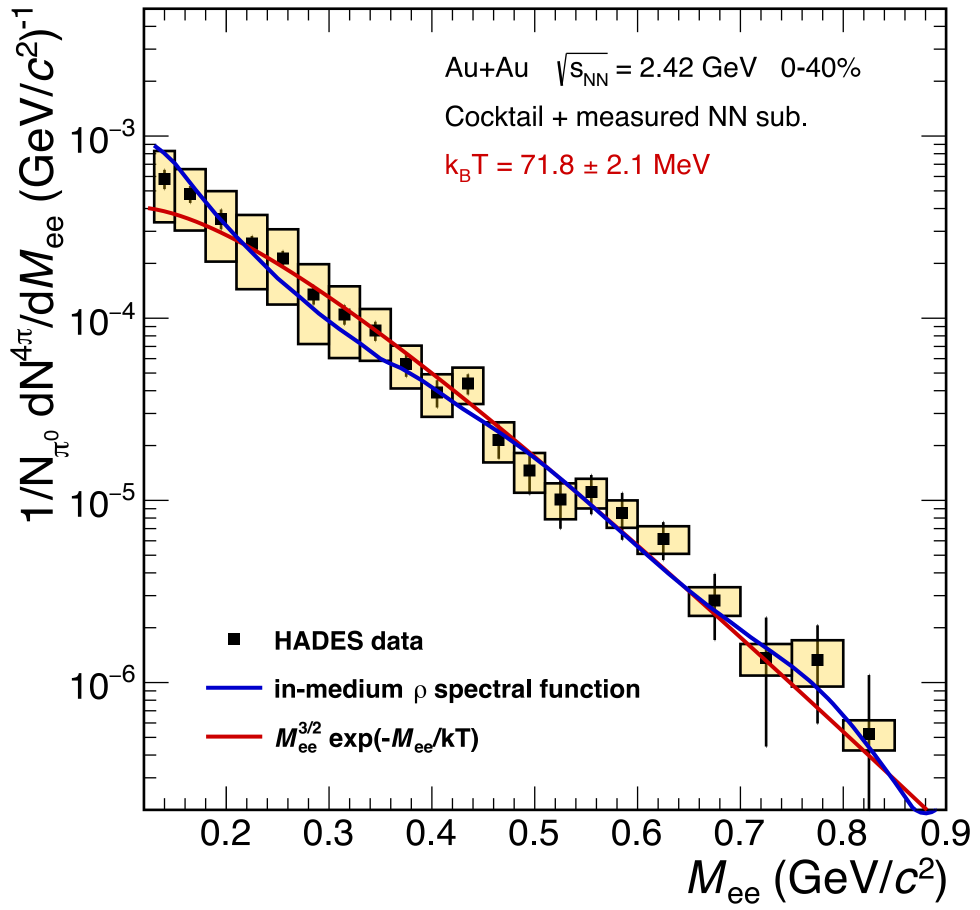
HADES and CBM will be operated at the SIS100

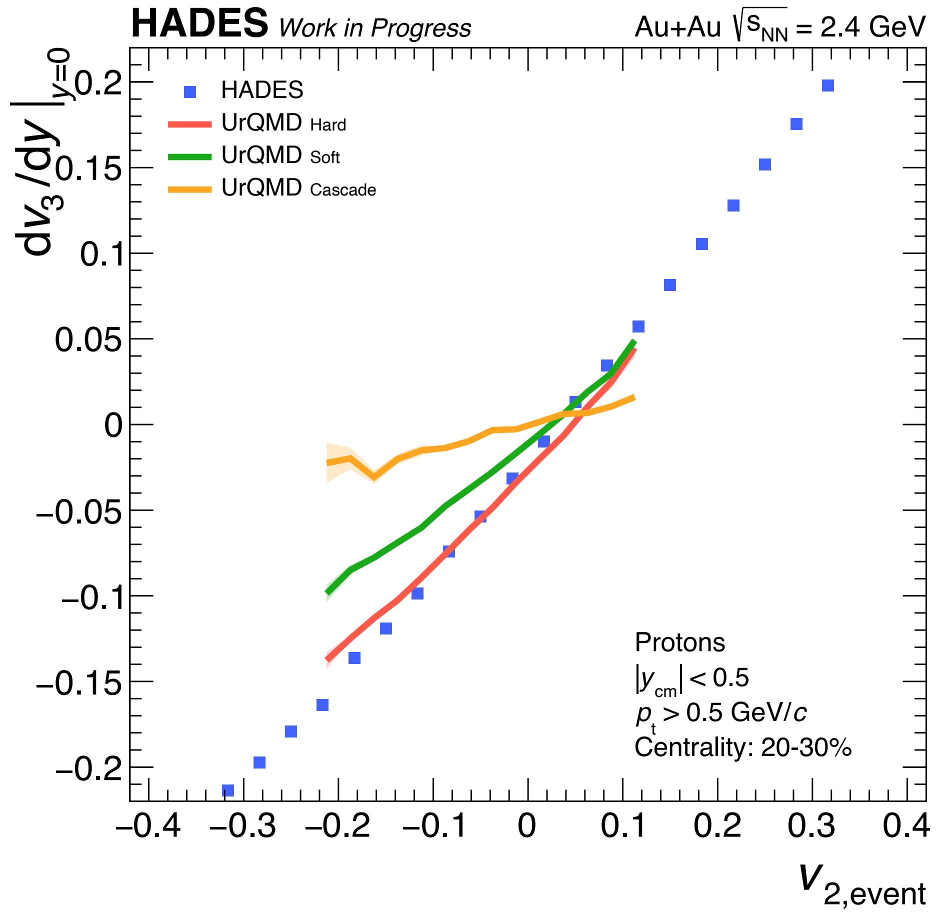
Angular coverage of both detectors complementary

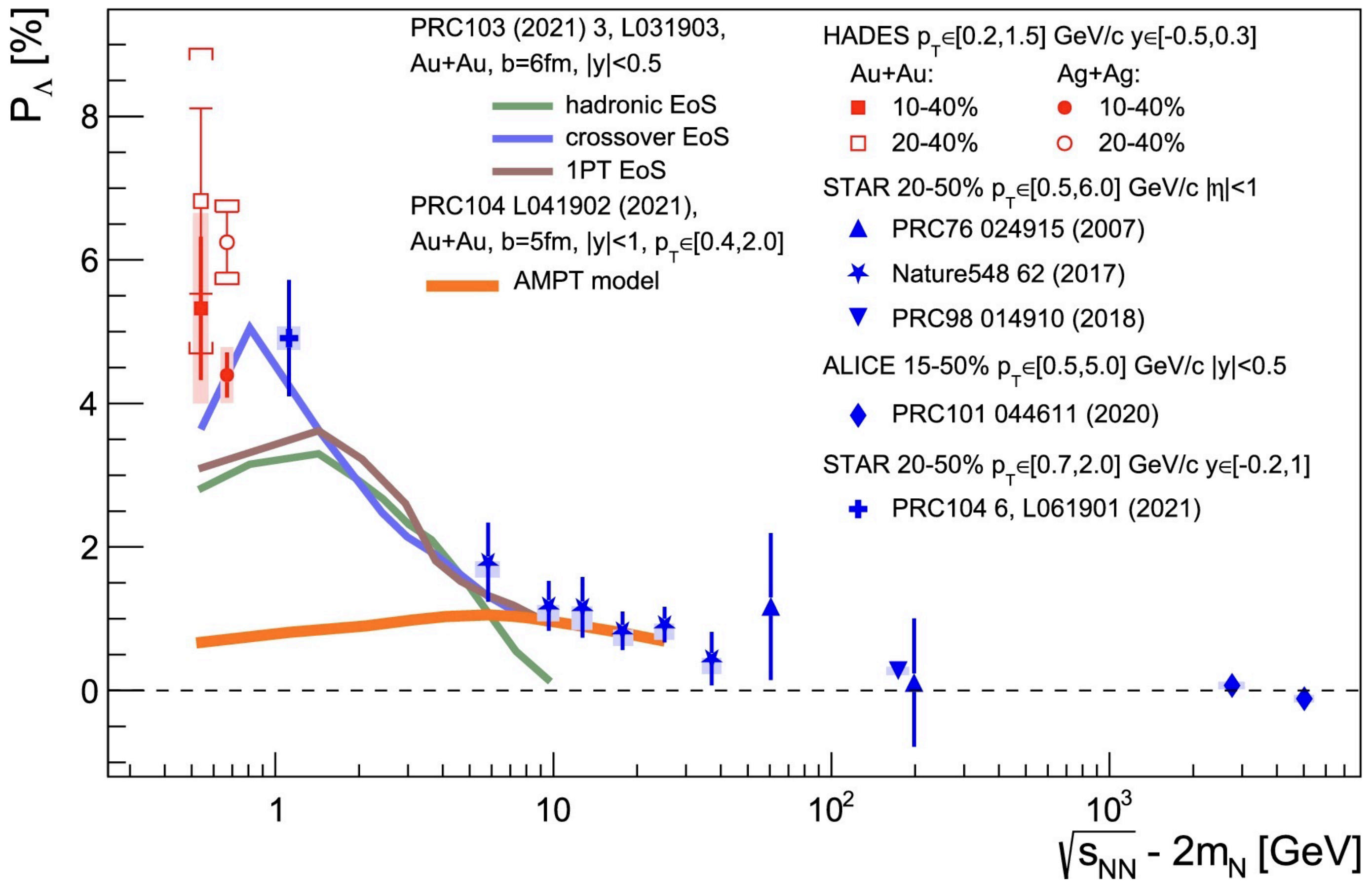
Summary

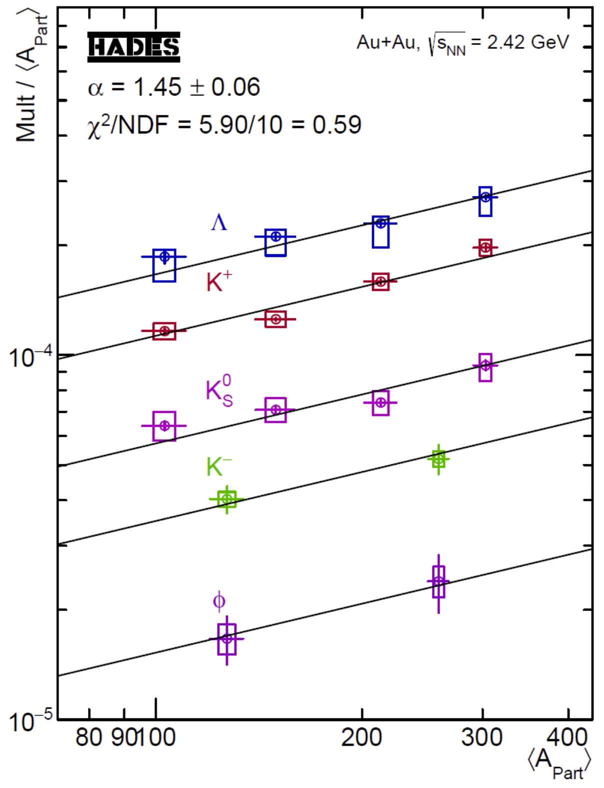
- HADES - systematic study of dense nuclear matter
- Emissivity:
  - Access to thermal radiation
- Collectivity:
  - Reconstruction of full 3D-emission
  - Constraints on EOS
- Vorticity:
  - Highest global Λ polarisation at HADES energies
- Strangeness and hypernuclei
  - Universal strangeness scaling
  - ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H lifetime compatible to previous measurements

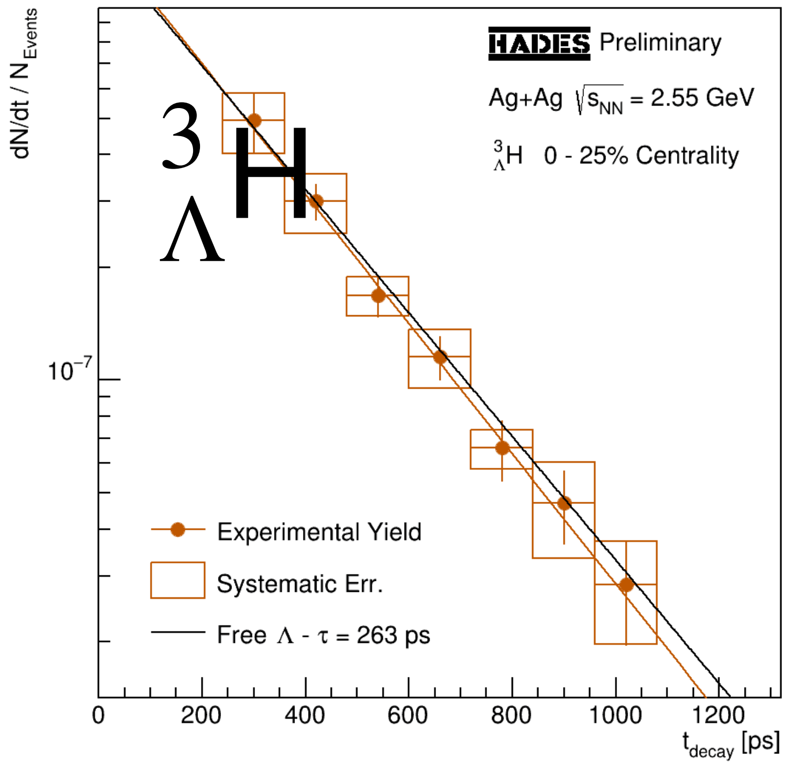


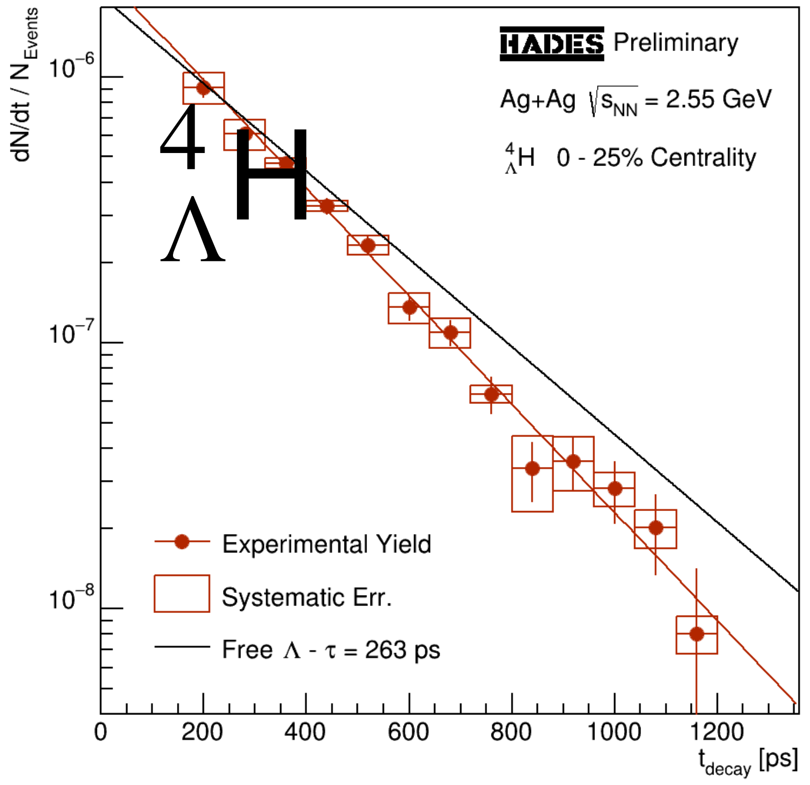












HADES Collaboration

Thank you for your attention!