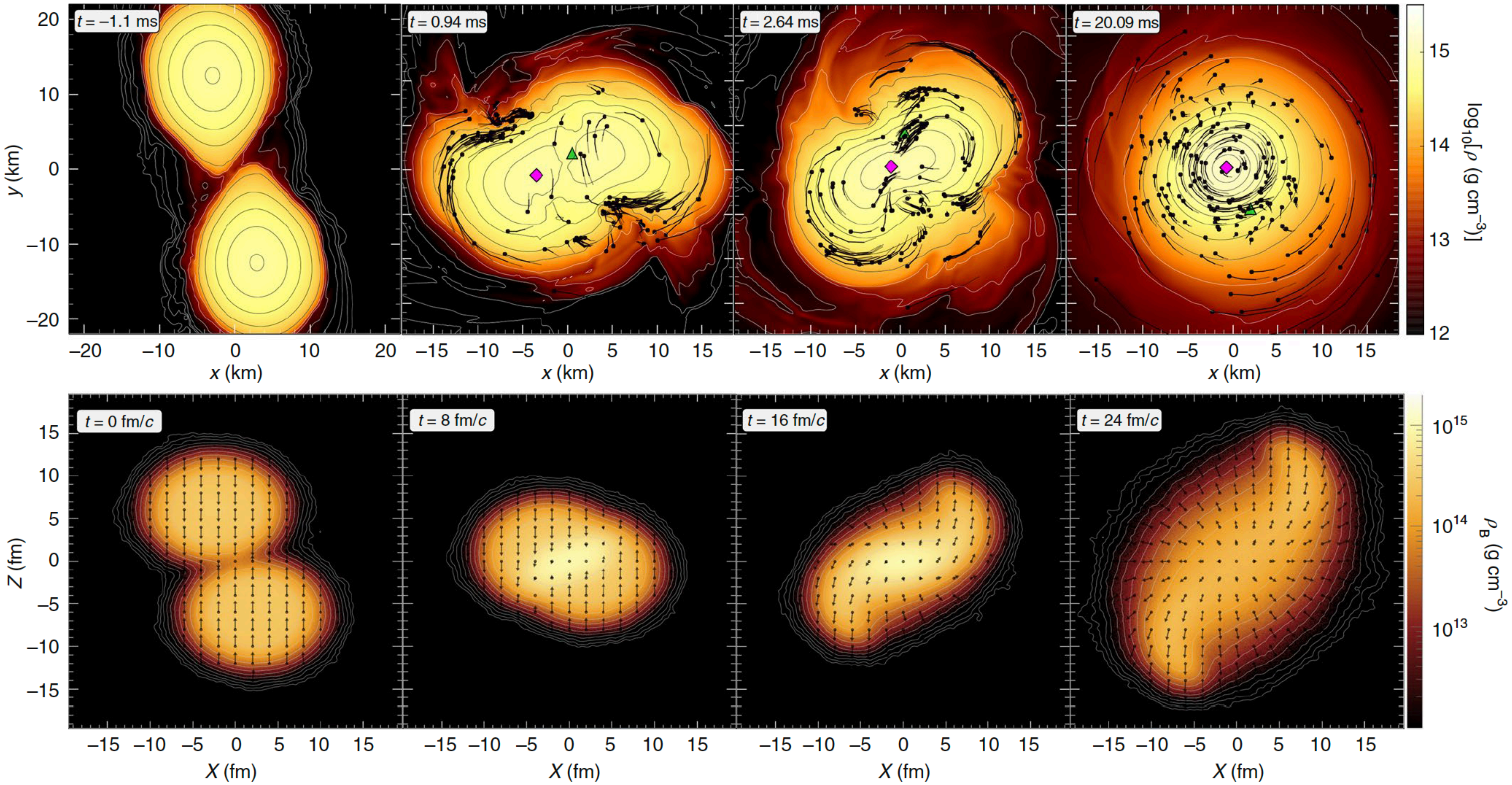
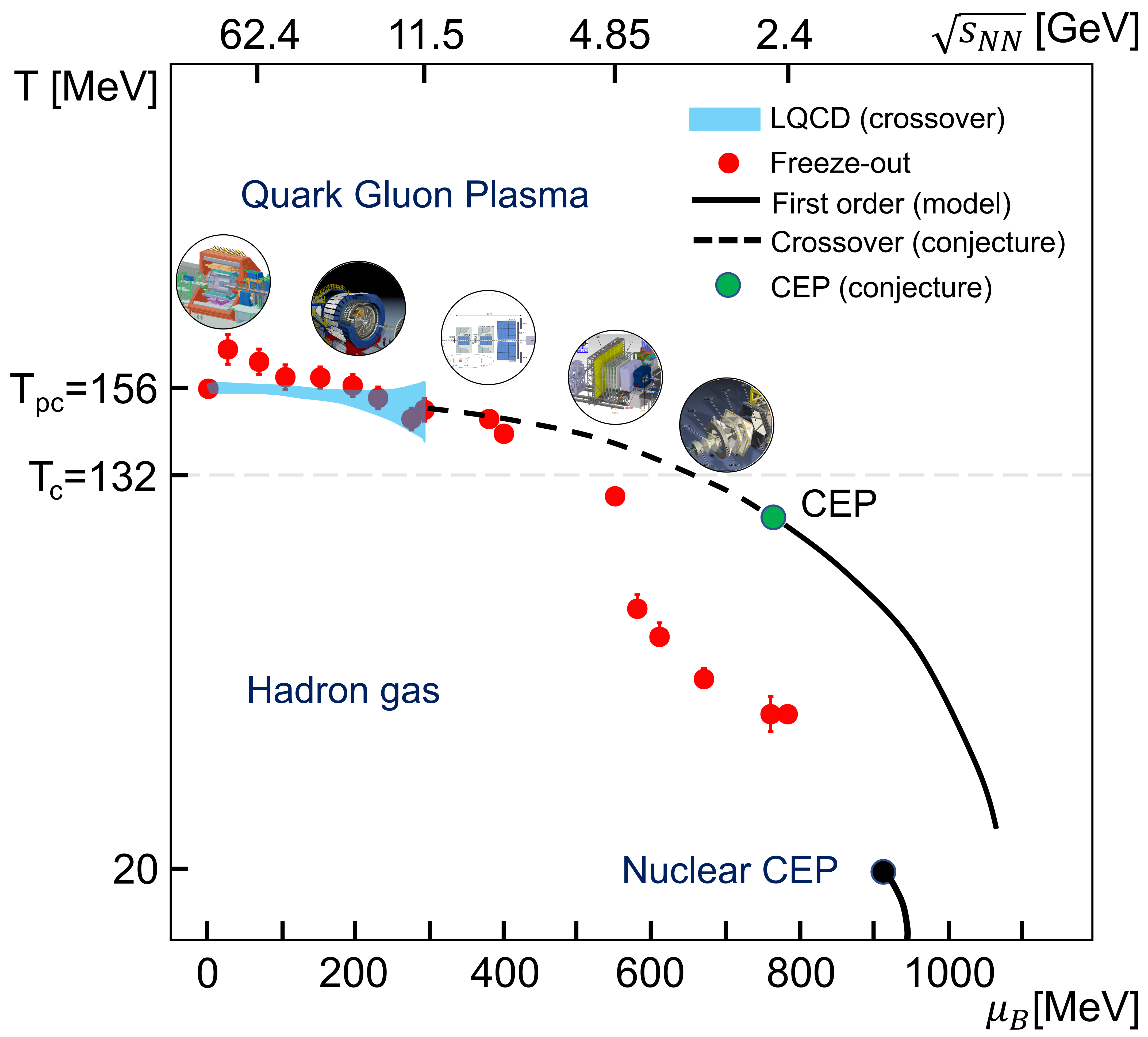
Results from the HADES experiment

Anar Rustamov for the HADES Collaboration



15th Workshop on Critical Point and Onset of Deconfinement, May 20-24, LBNL, Berkeley

Phases of strongly interacting matter



P. Braun-Munzinger, A.R., J. Stachel, arXiv:2211.08819

F. Gross et al., arXiv:2212.11107

What do we know about the QCD phase diagram?

Mainly theory based predictions!

- **Experimentally measured**
  - Precise energy dependence of freeze-out parameters

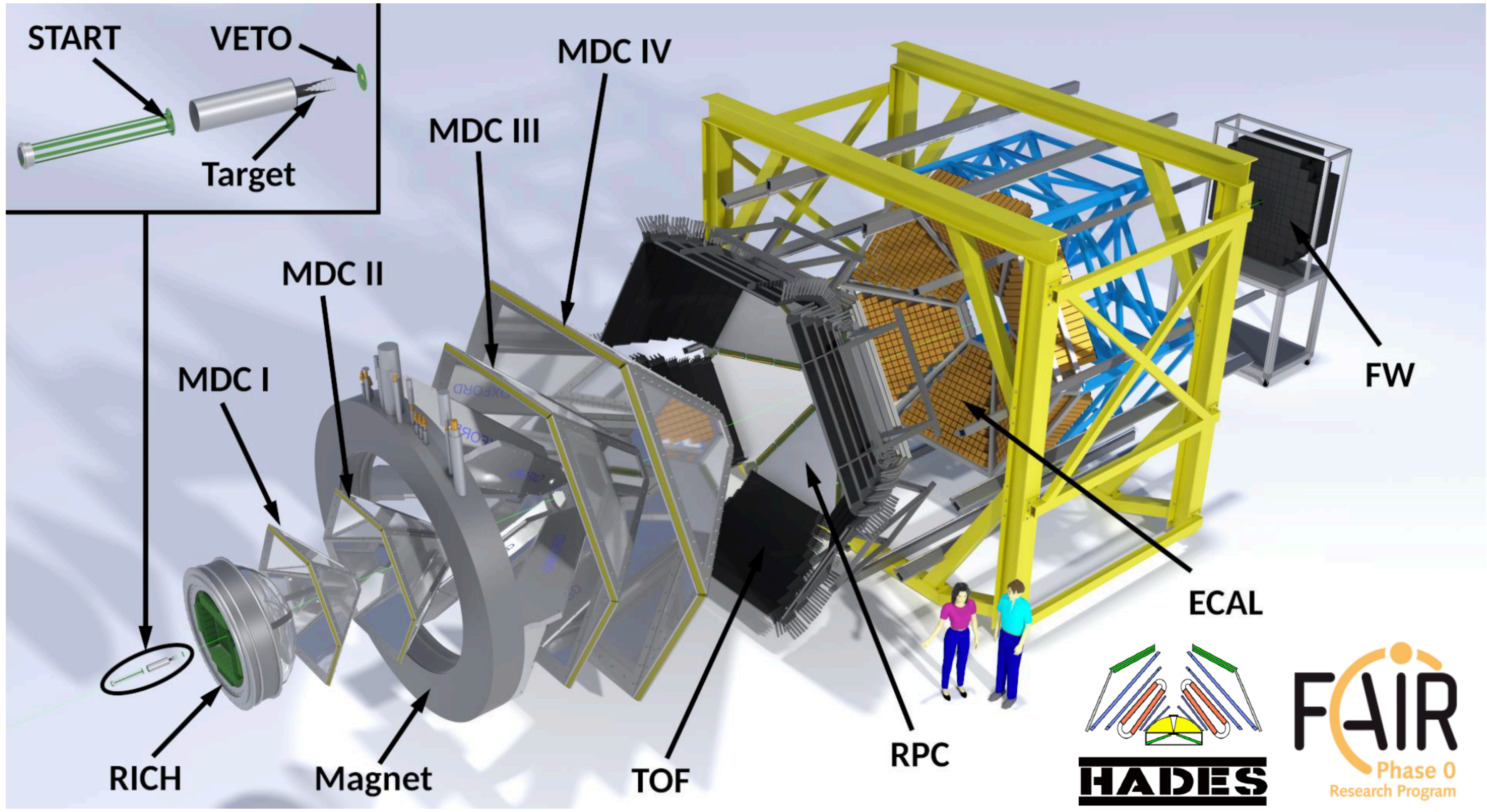
- **To be confirmed in experiments**
  - Existence of a crossover transition
  - Existence of a first order phase transition line
  - Existence of a critical point

Outline

- The HADES apparatus
- Penetrating signals
  - Dileptons
- Direct probes of EoS
  - E-by-E fluctuations of proton number
  - Flow measurements
- Detector upgrades
- Summary
- Outlook

The HADES apparatus

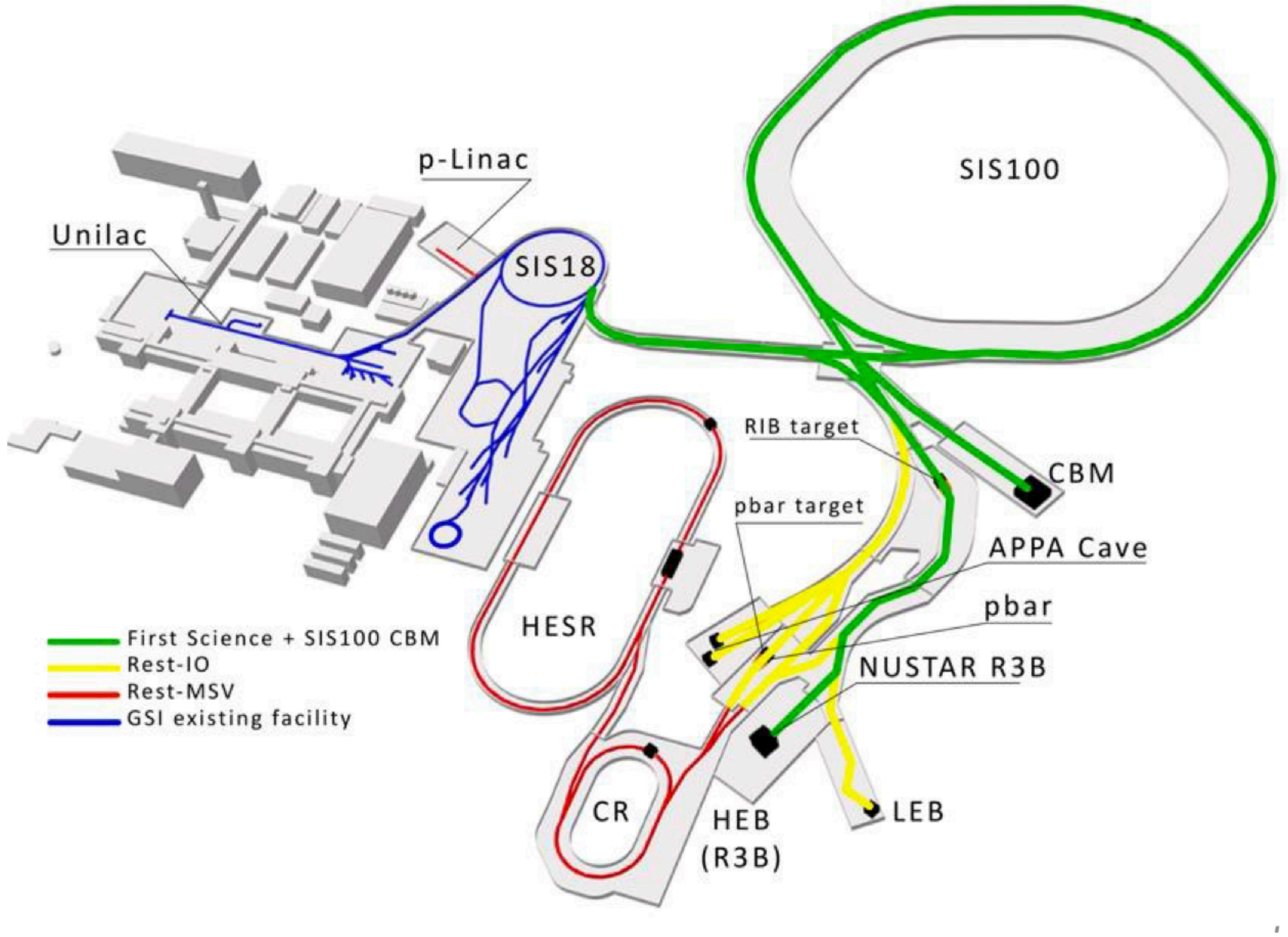
High **A**cceptance **D**i-**E**lectron **S**pectrometer



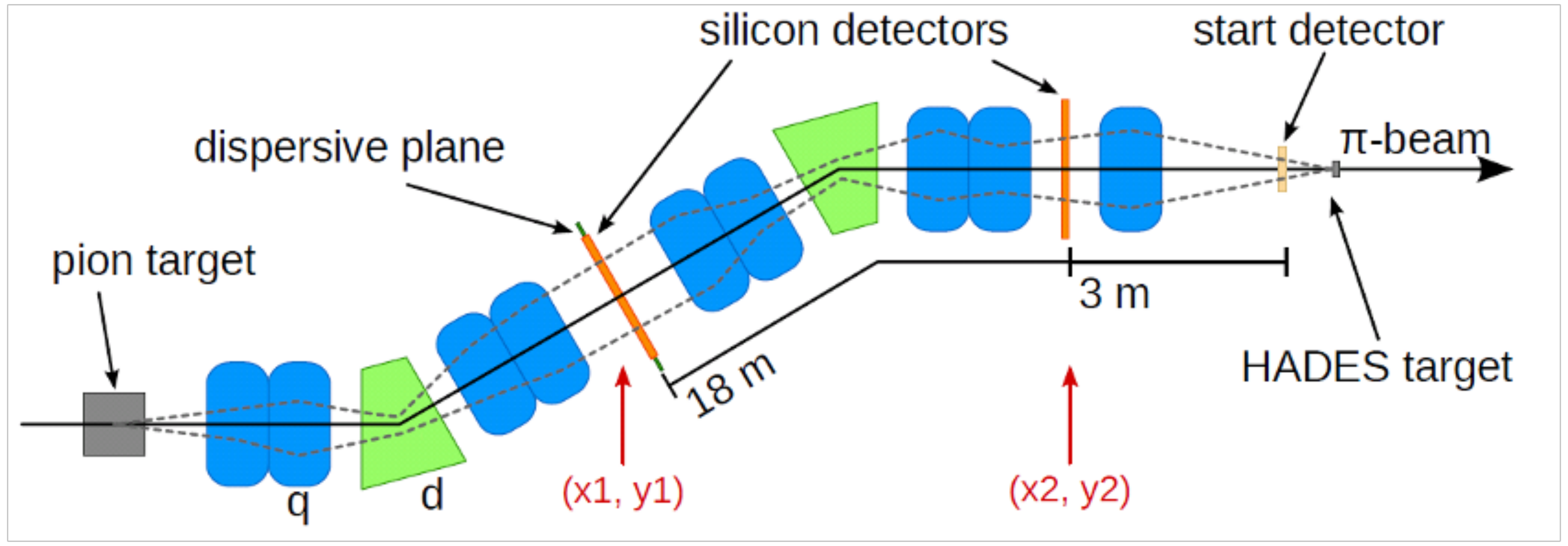
Specifications

- **Acceptance**
  - nearly full azimuthal coverage
  - polar angle between 18^0 - 85^0
    - 0.5^0-7^0 with forward Wall
- **PID**
  - primarily by correlating momentum with velocity
    - also by using dE/dx in ToF and drift chambers
  - RICH for electron identification
- **Accepted trigger rates**
  - 16 kHz for Ag-Ag collisions
  - 50 kHz for proton beams
- **Upgrades**
  - RICH photon detection plane (with CBM)
  - Forward detector (with PANDA)
  - ECal

Data Campaigns



Unique Pion Beam Facility



Ion beam

Date	Reaction	$\sqrt{s_{NN}}$ [GeV]
Nov 2002	C+C	2.7
Aug 2004	C+C	2.32
Sep 2005	Ar+KCl (~Ca+Ca)	2.61
Apr 2012	**Au+Au**	**2.42**
Mar 2019	**Ag+Ag**	**2.55, 2.42**
Mar 2024	**Au+Au**	**2.24**

Proton (deuteron) beam

Date	Reaction	$\sqrt{s_{NN}}$ [GeV]
Jan 2004	p+p	2.77
Apr 2006	p+p	2.42
Apr 2007	p+p	3.18
Apr 2007	d+p	2.42
Sep 2008	p+Nb	3.18
Feb 2022	p+p	3.46

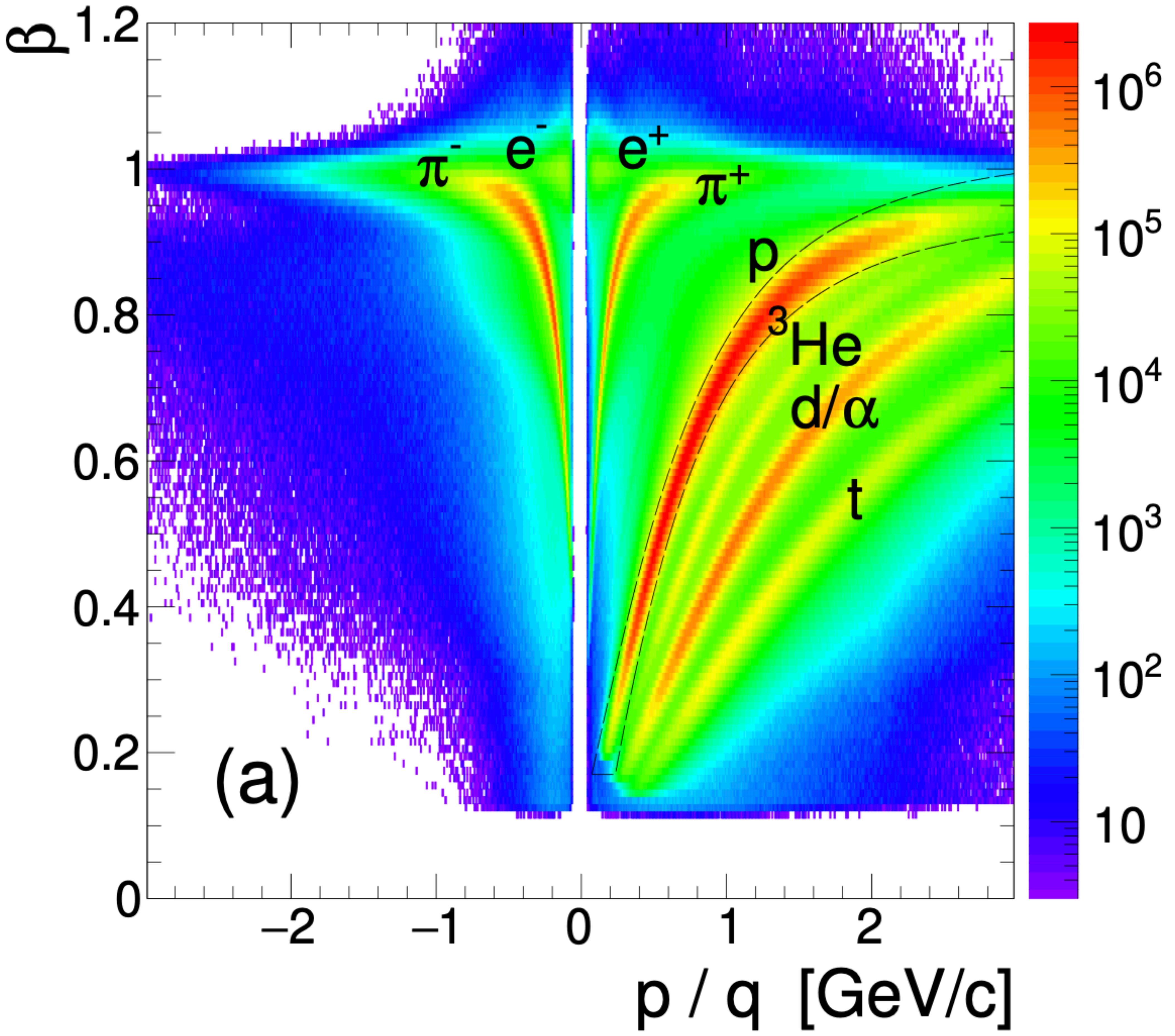
Pion beam

Date	Reaction	p_π [GeV/c]
Jul-Sep 2014	π^- + C/PE	0.66, 0.69, 0.75, 0.8

Principal Particle Identification methods

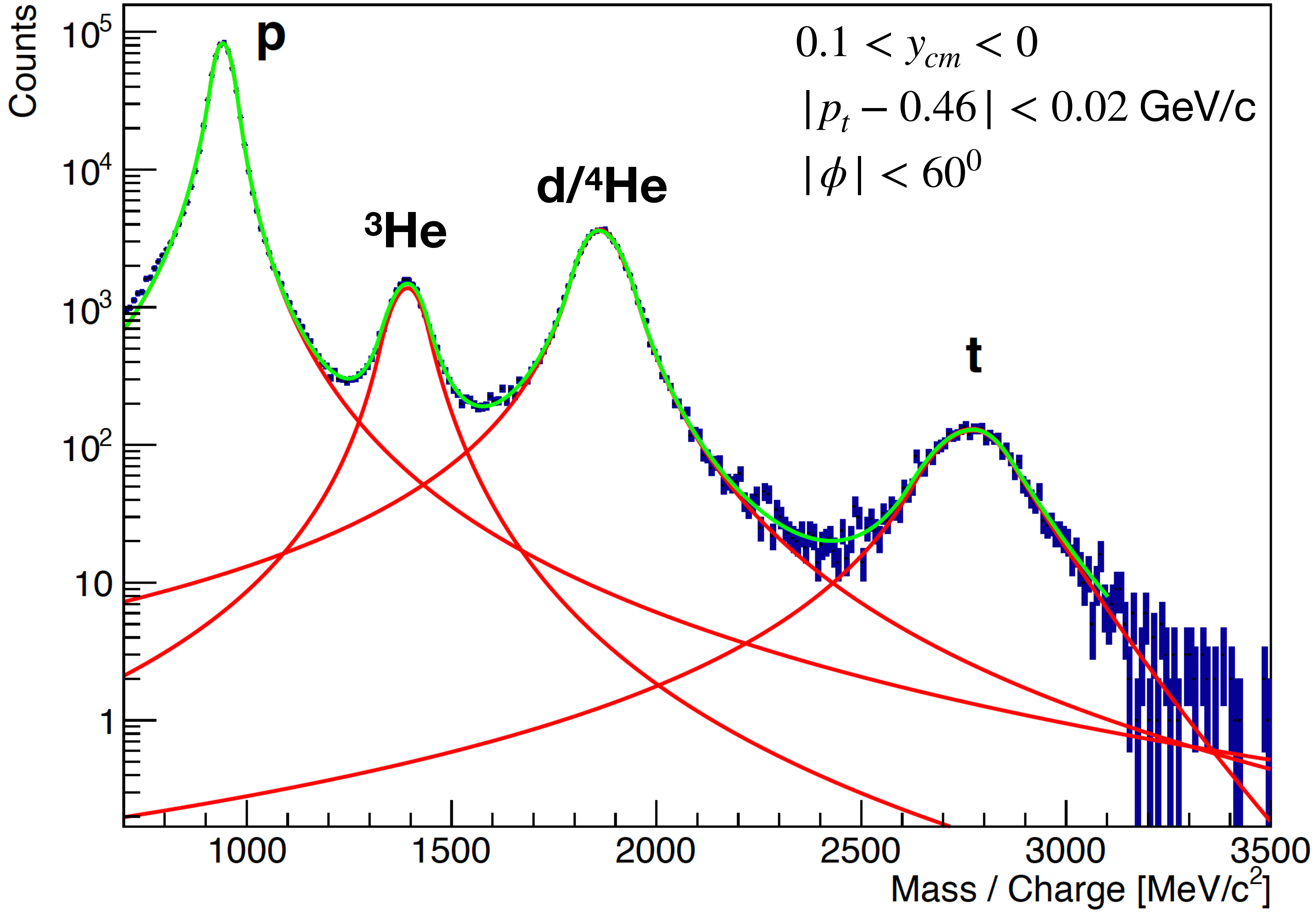
HADES: Phys.Rev.C 102 (2020) 2, 024914

Cut-based approach



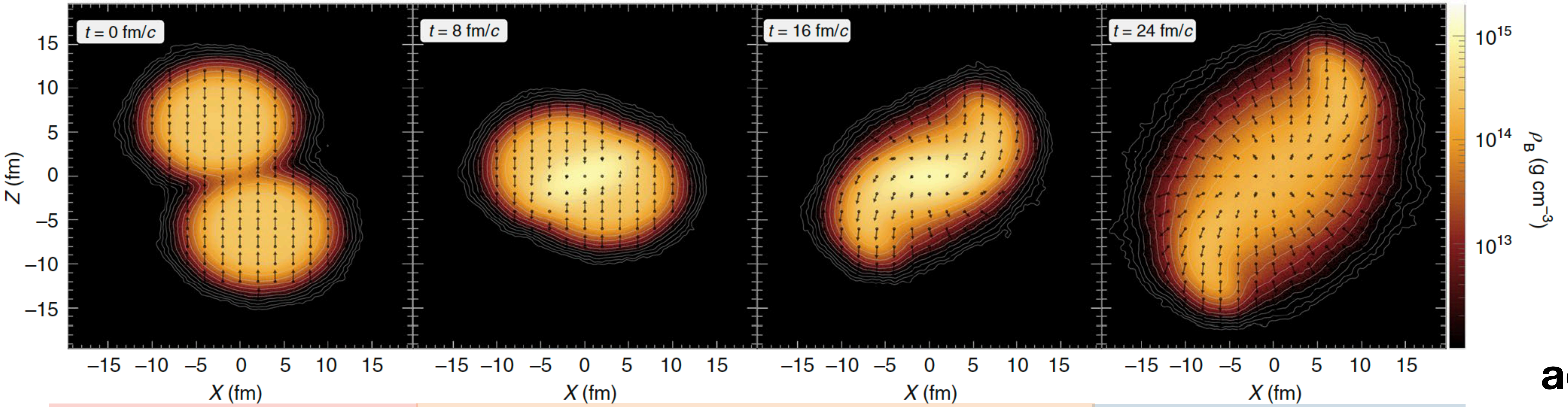
correlation between momentum ($|\vec{p}|$) and velocity ($|\vec{\beta}|$)

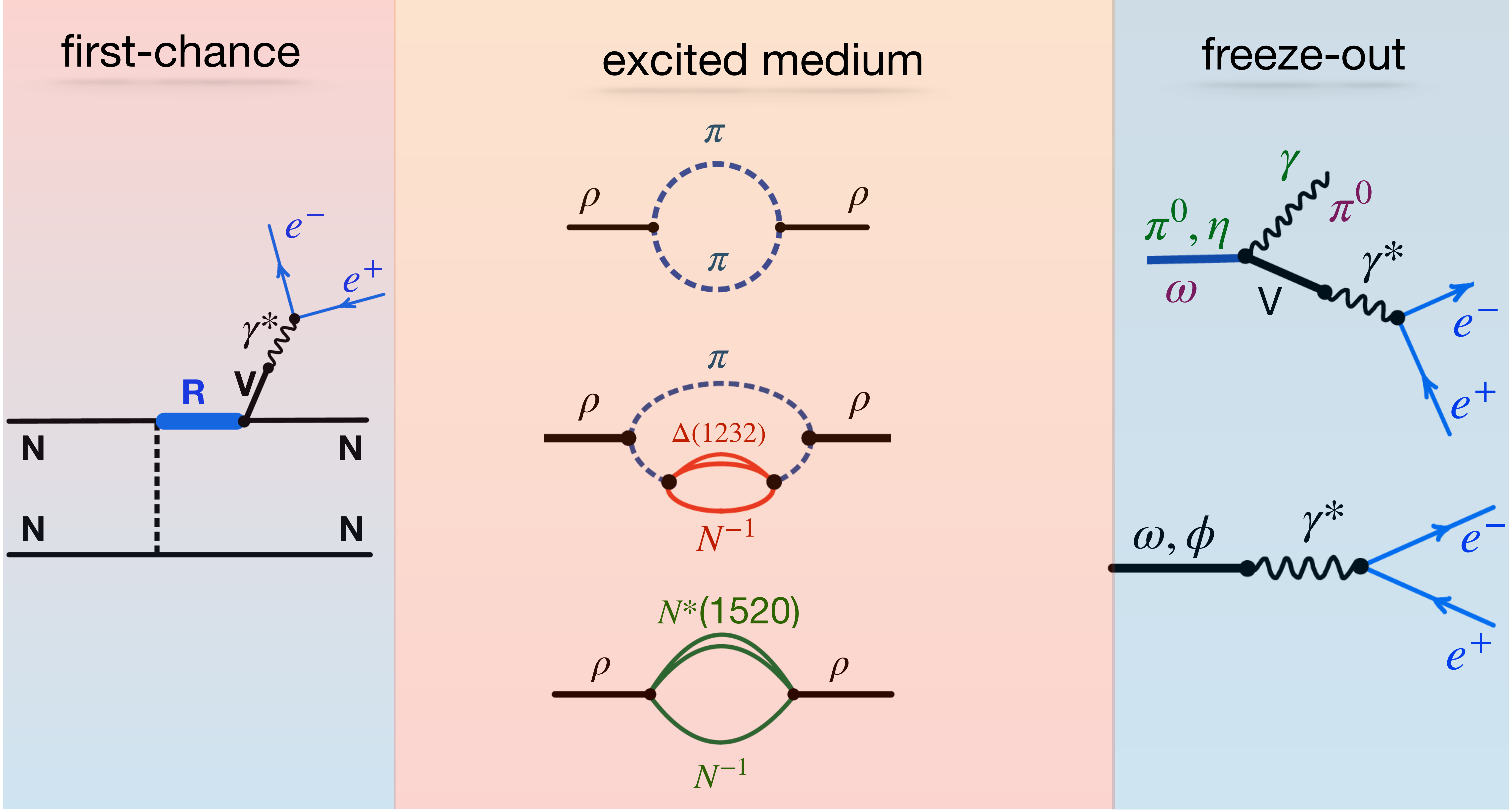
Probabilistic approach (New)



$$m = |\vec{p}|\sqrt{1/|\vec{\beta}|^2 - 1}$$

Dilepton sources in a few GeV nuclear interactions





changes in medium

changes in hadron properties

accessing spectral functions of hadrons

cross section **spectral function**

$$\frac{d\sigma_{h \to e^+e^-}}{dM} = \int \frac{d\sigma_h(\rho_h, \mu)}{d\mu} \frac{d\Gamma_{h \to ee}(\mu)}{dM_{ee}} \frac{d\mu}{\Gamma_{total}(\mu)}$$

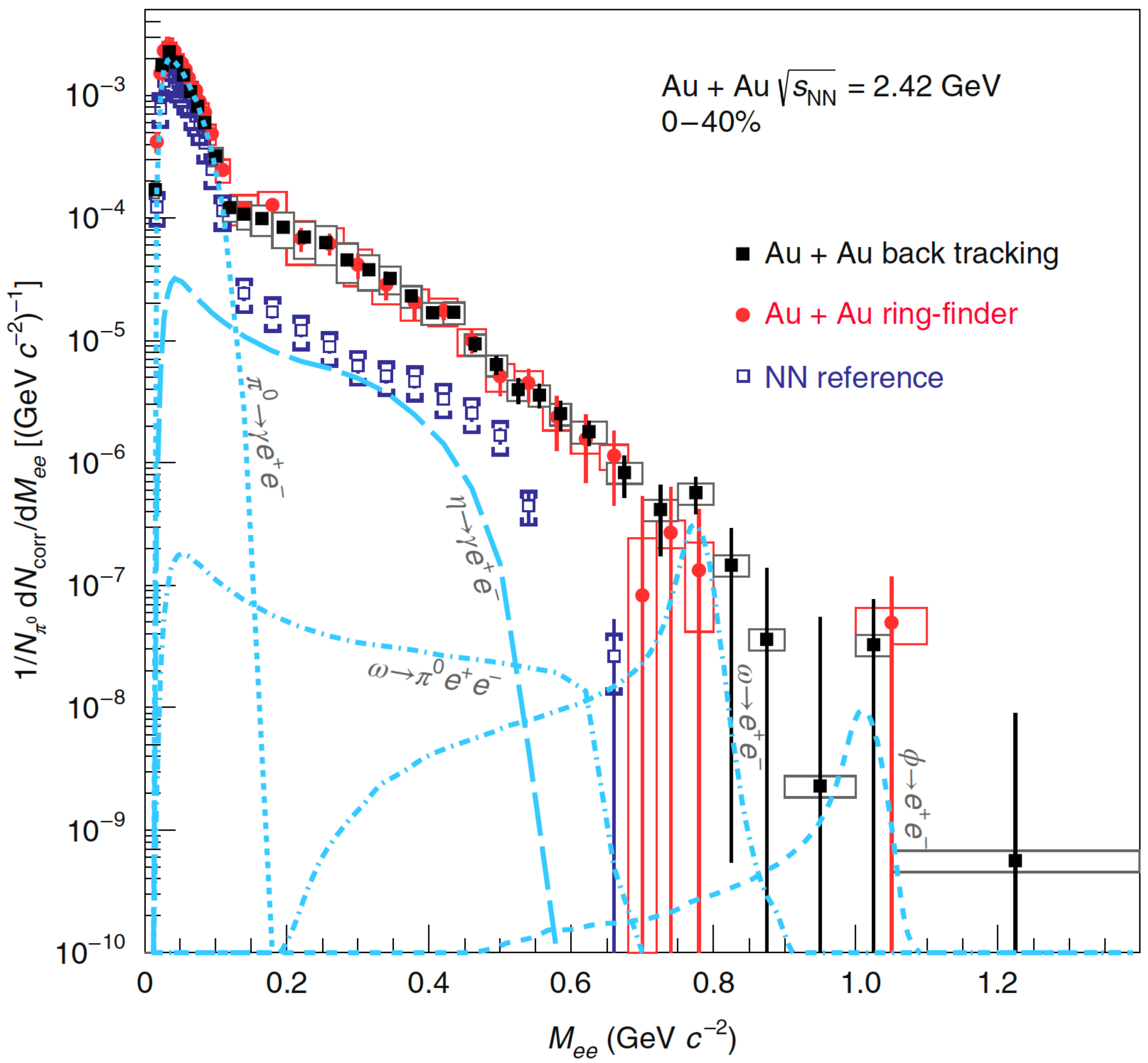
decay width (QED + models for form factor)

$$M_{h \to e^+e^-} = \sqrt{\left(p_{e^+} + p_{e^-}\right)^2}$$

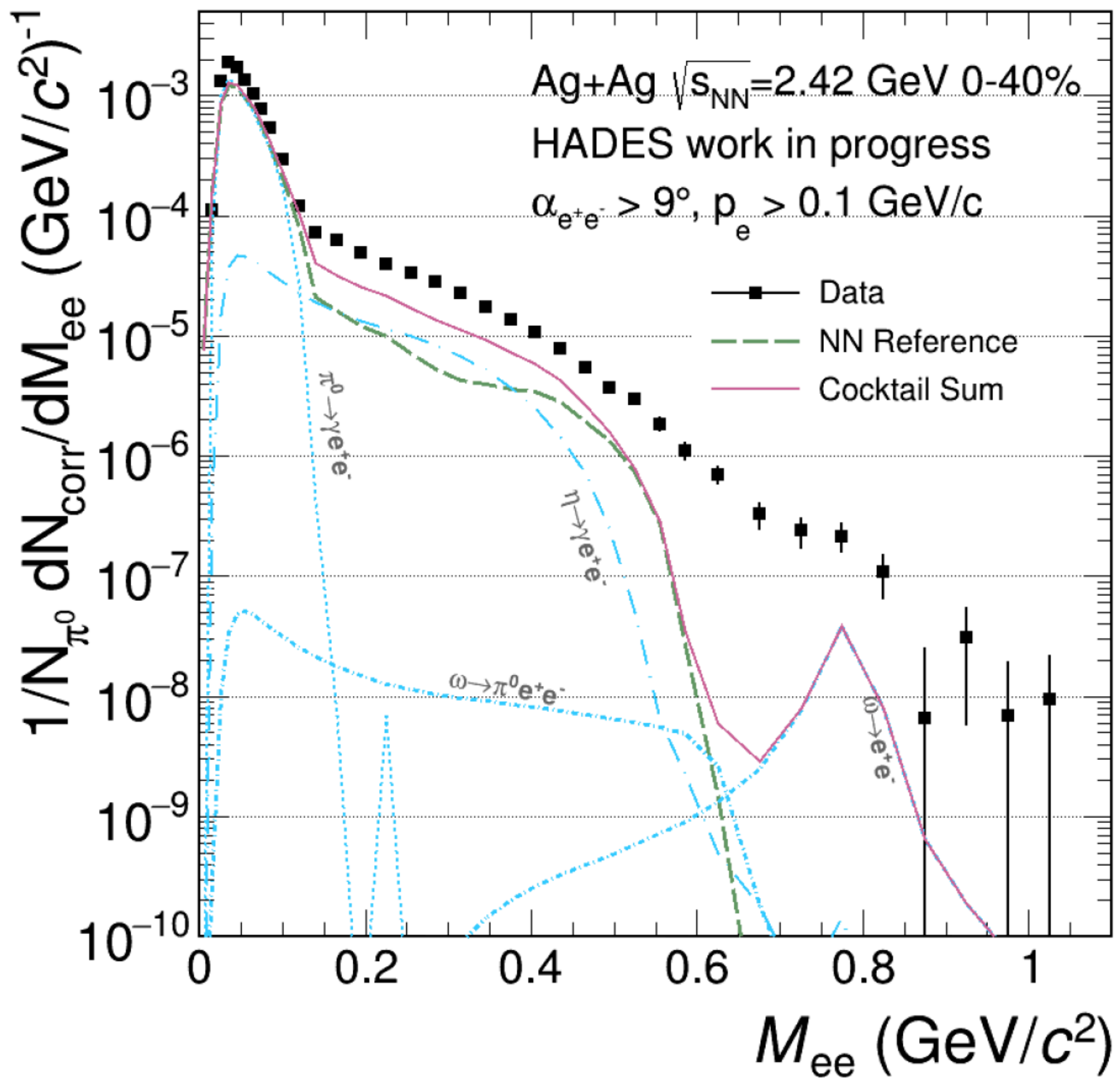
p_{e^+}, p_{e^-} - four momenta of leptons

Measured invariant mass distributions

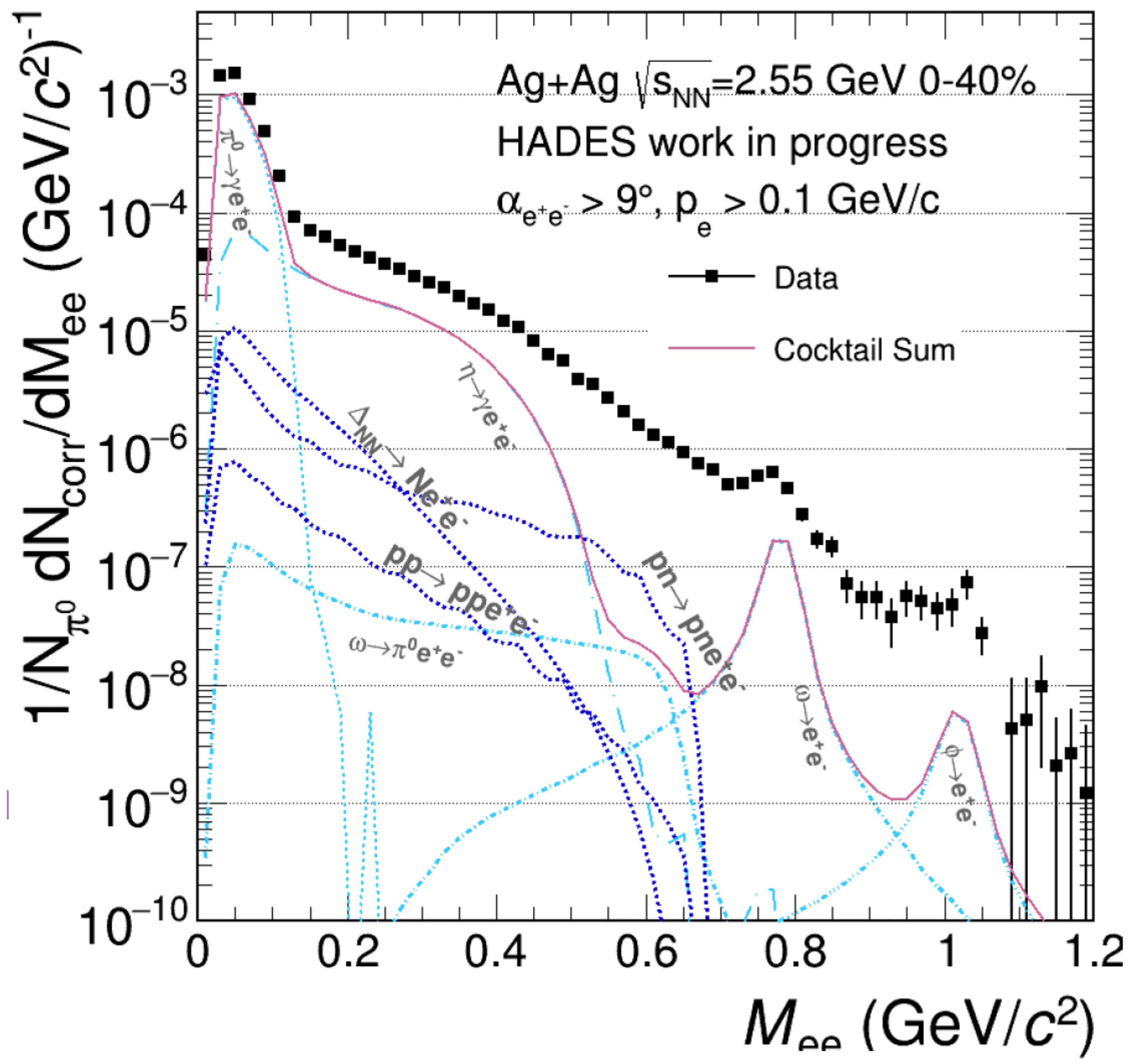
$Au + Au, \sqrt{s_{NN}}$ = 2.42 GeV



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



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



$$\frac{d\sigma_{h\to e^+e^-X}}{dM_{ee}} = \sigma_h(\mu)\frac{d\Gamma_{h\to e^+e^-X}(\mu)}{dM_{ee}}\frac{1}{\Gamma_{total}}$$

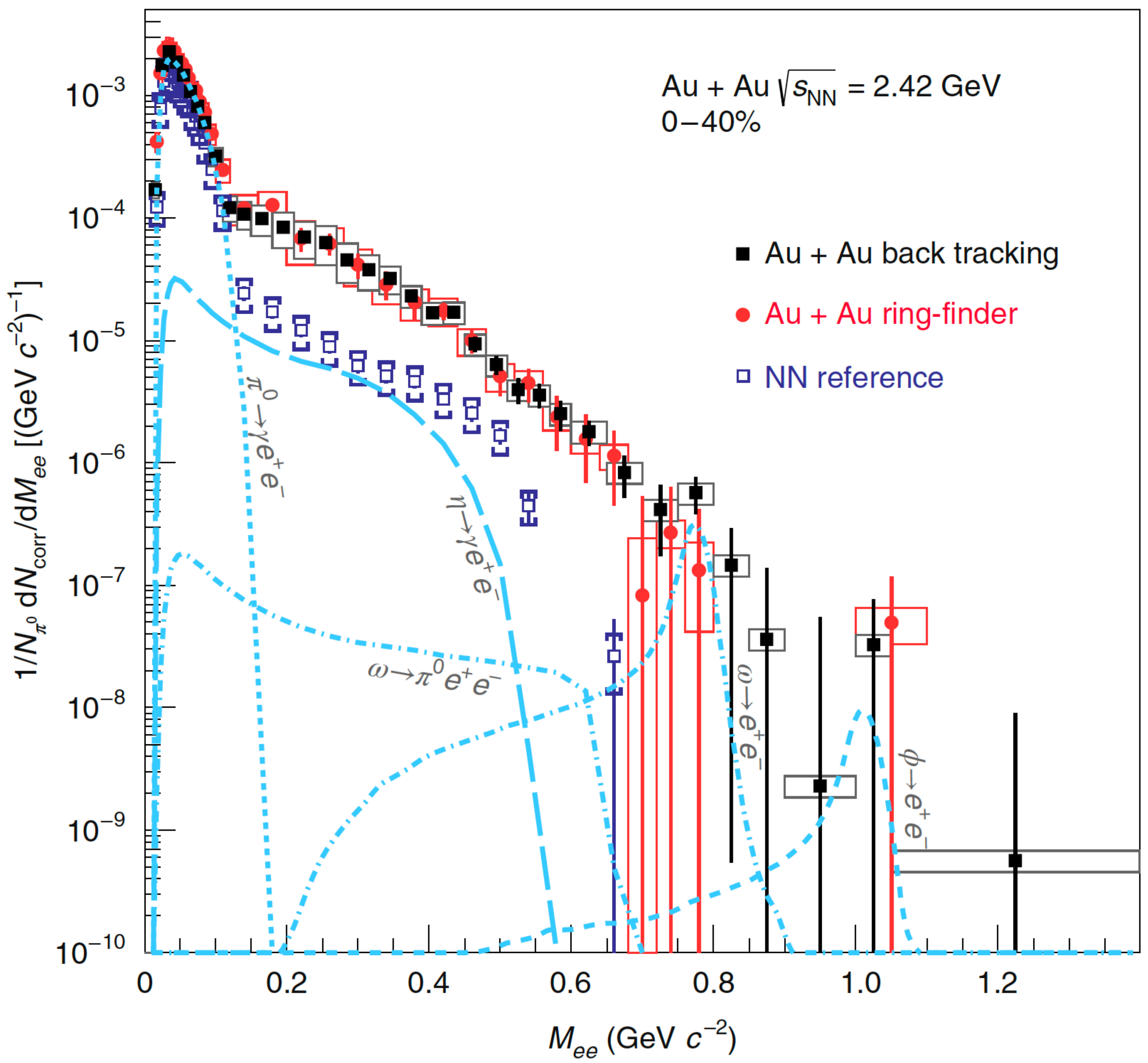
narrow state

$$\frac{d\sigma_{h\to e^+e^-X}}{dM} = \int \frac{d\sigma_h(\rho_h,\mu)}{d\mu}\frac{d\Gamma_{h\to eeX}(\mu)}{dM_{ee}}\frac{d\mu}{\Gamma_{total}(\mu)}$$

broad state

The HADES data show clear excess radiation over the hadronic cocktail (without ρ)

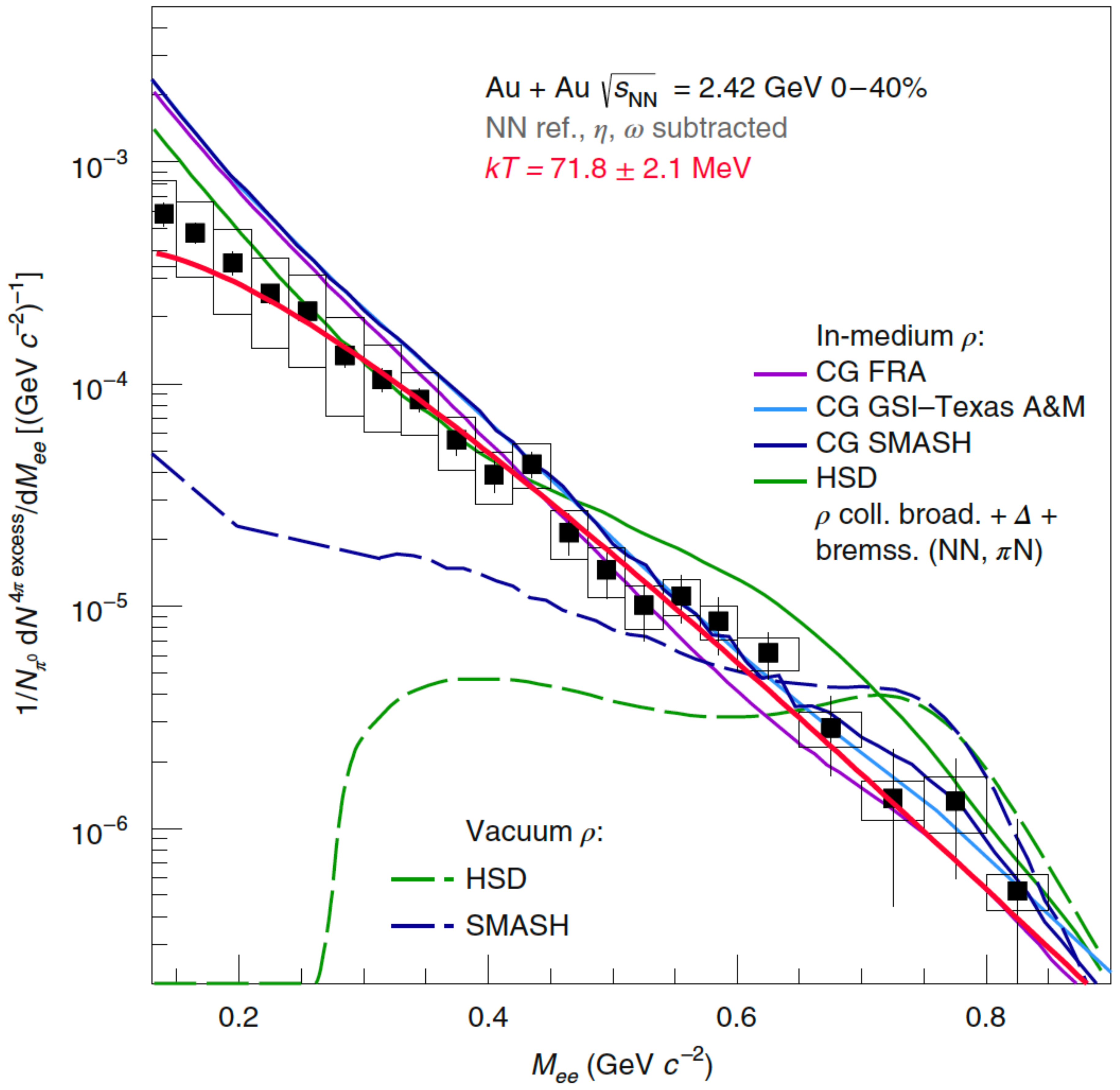
Isolating the excess radiation



Subtracting contributions from

- reference spectra (without η)
- η, ω, ϕ contributions

in-medium ρ



$$\frac{1}{N_{\pi^o}}\frac{dN^{NN}_{ref}}{dM_{ee}} = \left(\frac{0.54}{N_{\pi^o}}\frac{dN^{pp}}{dM_{ee}} + \frac{0.46}{N_{\pi^o}}\frac{dN^{np}}{dM_{ee}}\right)$$

ρ meson is completely melted away
Indicative of Chiral Symmetry restoration?
(technically yes, via QCD sum rules)

HADES: Nature Physics 15, 1040-1045 (2019)

Excess radiation, interpretation

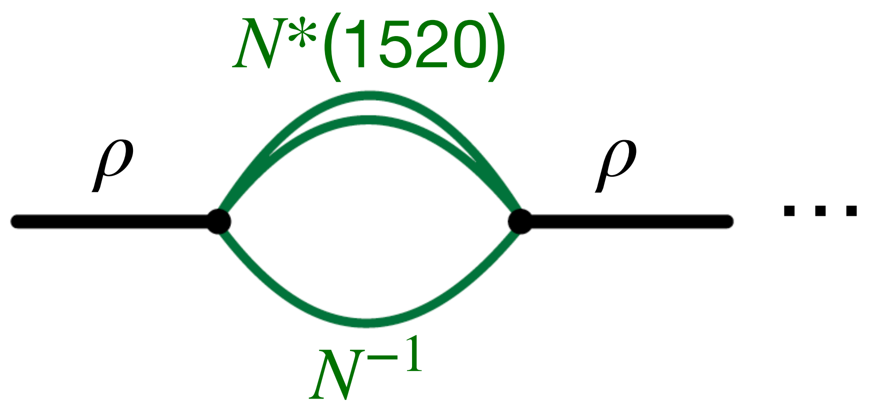
Coarse-Grained Transport Simulations

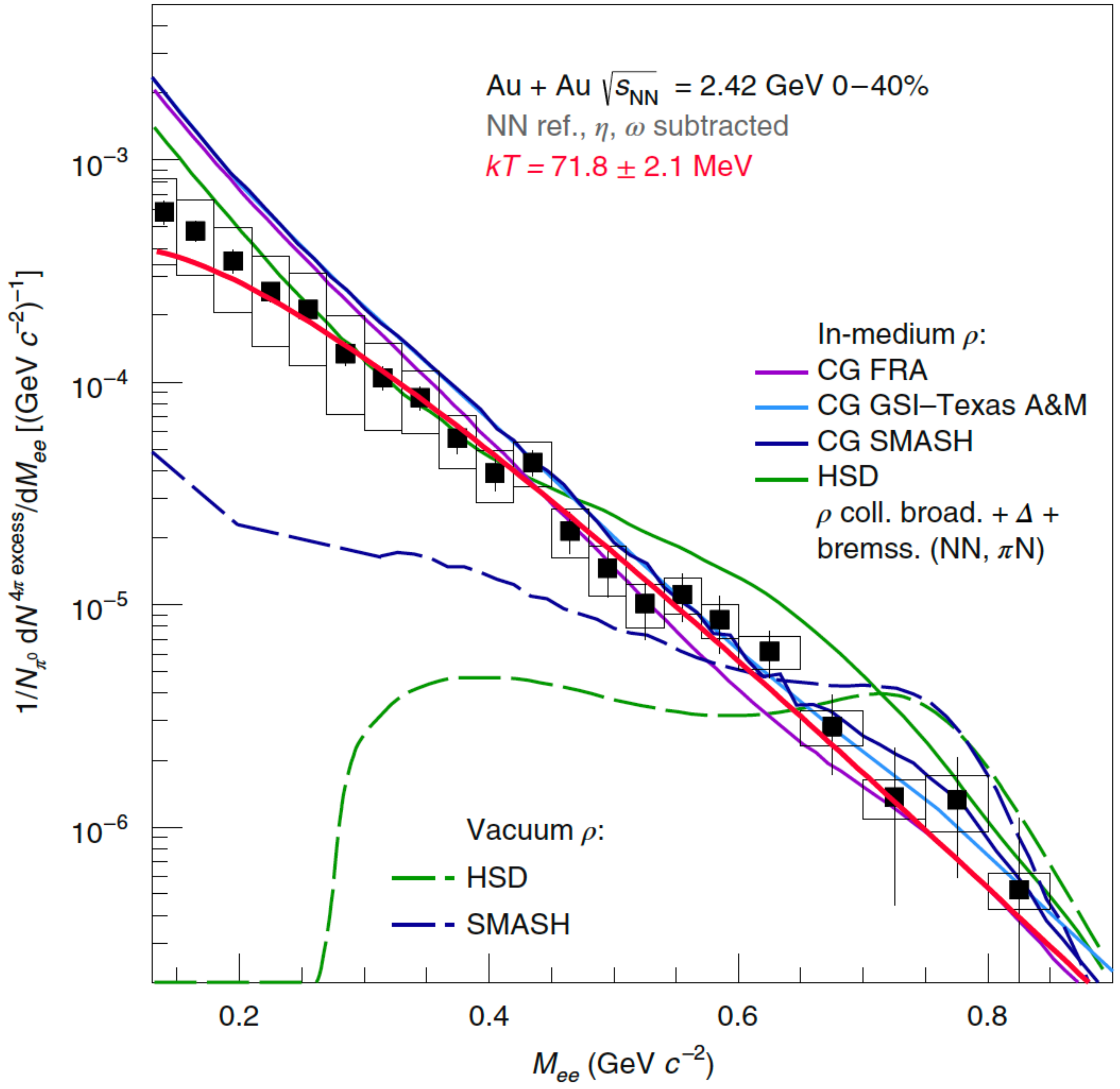
- setup a 4D space-time cells ($\Delta x, \Delta y, \Delta z, \Delta t$)
- calculate T and μ_B for each cell
- assume that cells are in full equilibrium
- compute the dilepton rate from each cell

$$\frac{d^8N}{d^4qd^4x} = -\frac{\alpha^2 L(M)}{3\pi^3 M_{ee}^2} f^{BE}(q_0, T) Im\Pi_{em}(M_{ee}, q; T, \mu_B)$$

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

- use VDM to setup a contact with e.g., ρ meson
- use in-medium spectral functions …





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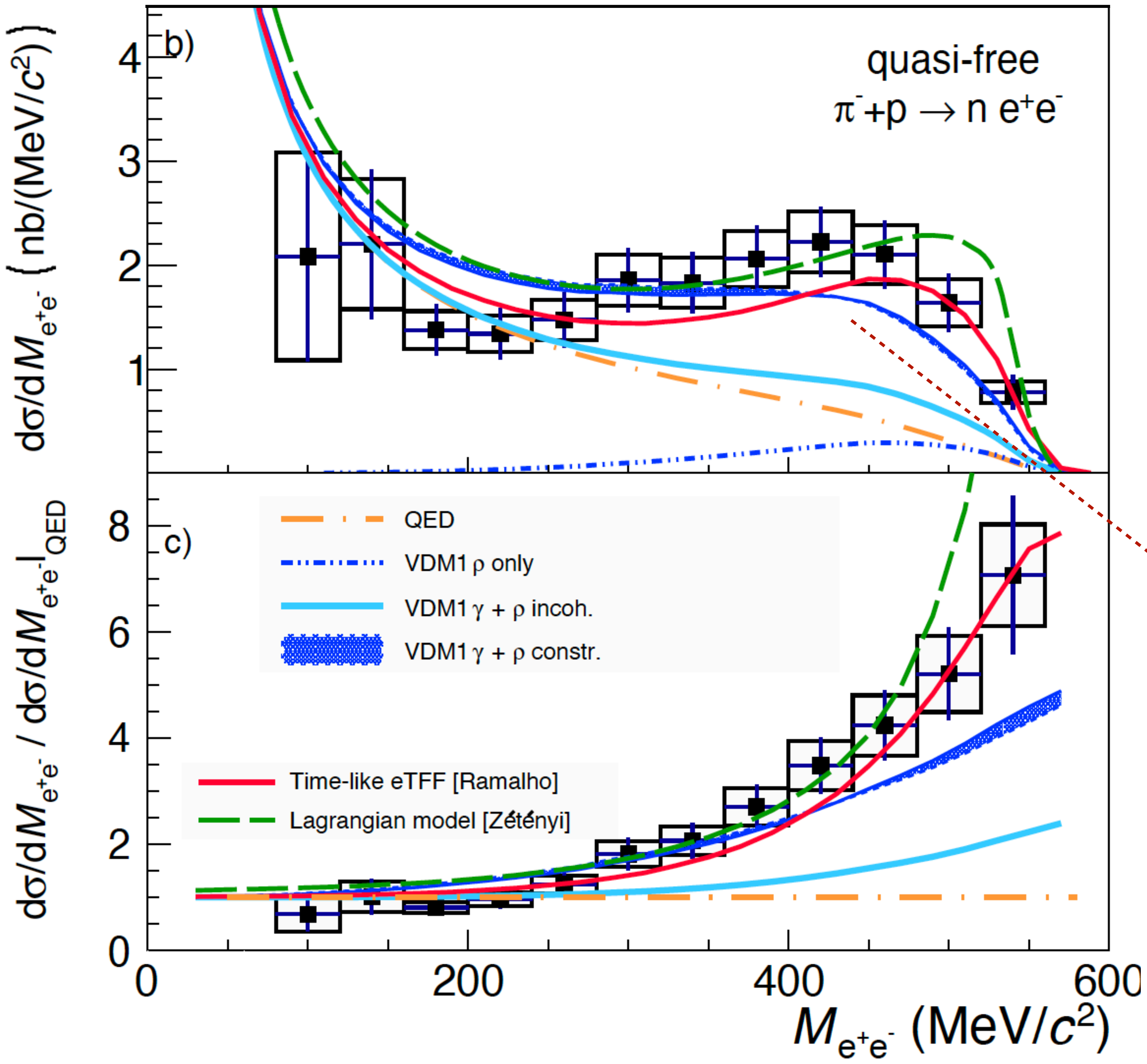
HADES: Nature Physics 15, 1040-1045 (2019)
S. Endres et al., Phys.Rev.C 92 (2015) 1, 014911
T. Galatyuk et al., Eur.Phys.J.A 52 (2016) 5, 131
Including in-medium spectral functions:
R. Rapp, J. Wambach, H. van Hees, Landolt-Bornstein 23 (2010) 134

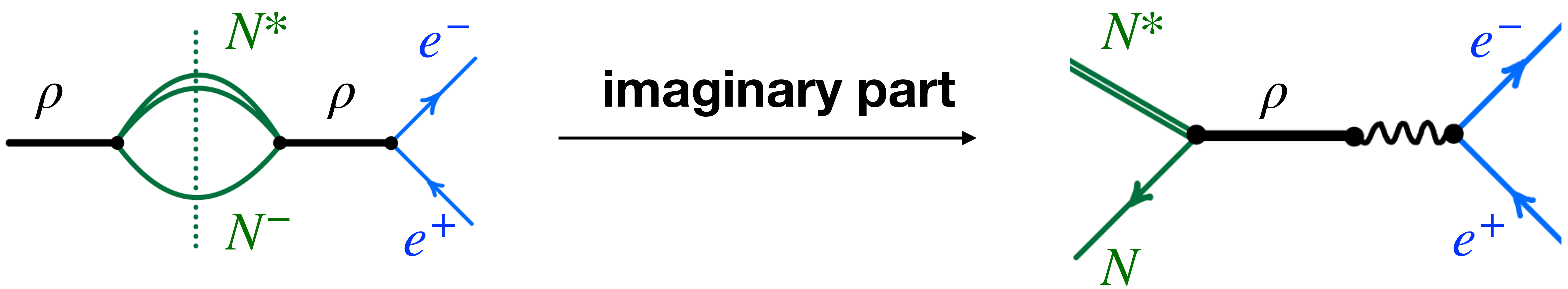
Talk by Florian Seck, Fri 24.05

First verification of the VDM assumption with pion beams



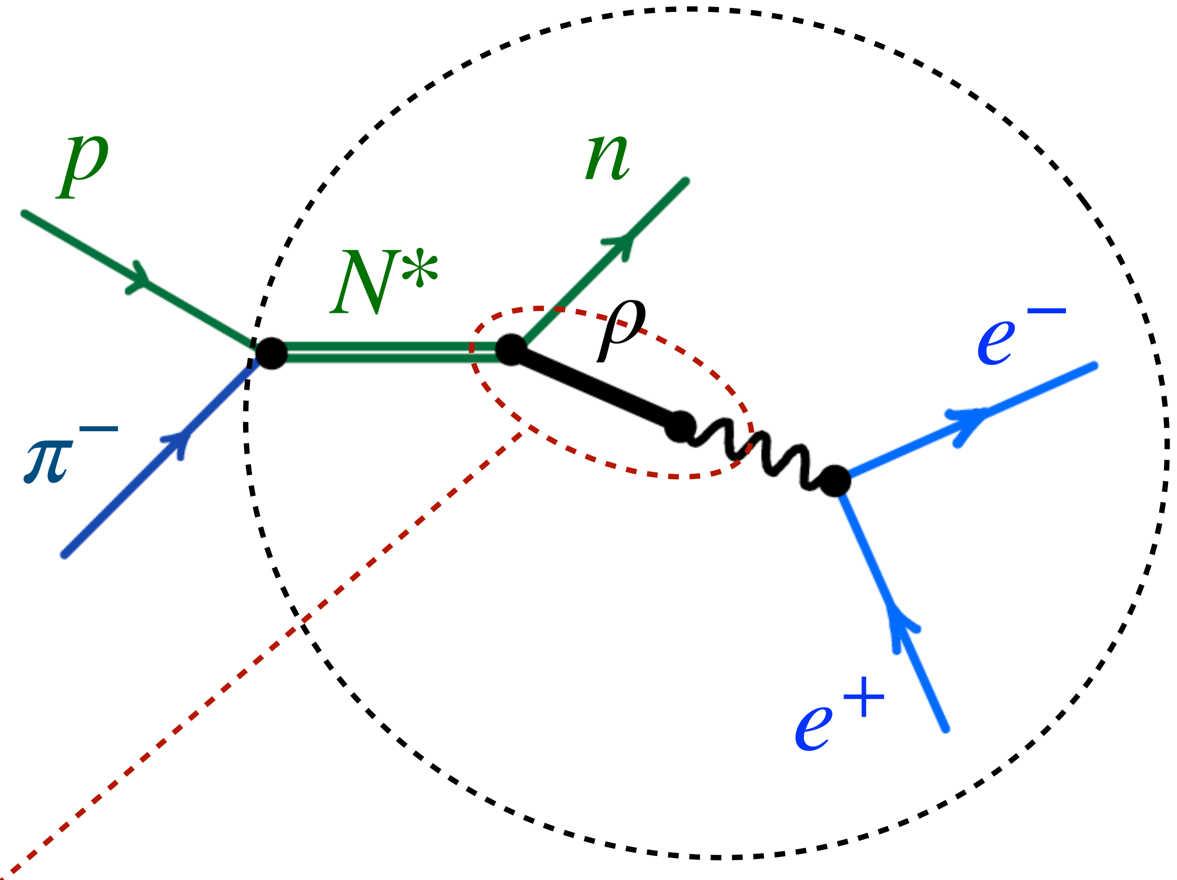
HADES: 2205.15914 [nucl-ex], submitted to PRL
2309.13357 [nucl-ex], submitted to PRC

in-medium ρ meson **N^* Dalitz decay**



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

$p_\pi = 0.685$ GeV/c, $\sqrt{s_{\pi p}} \sim 1.49$ GeV

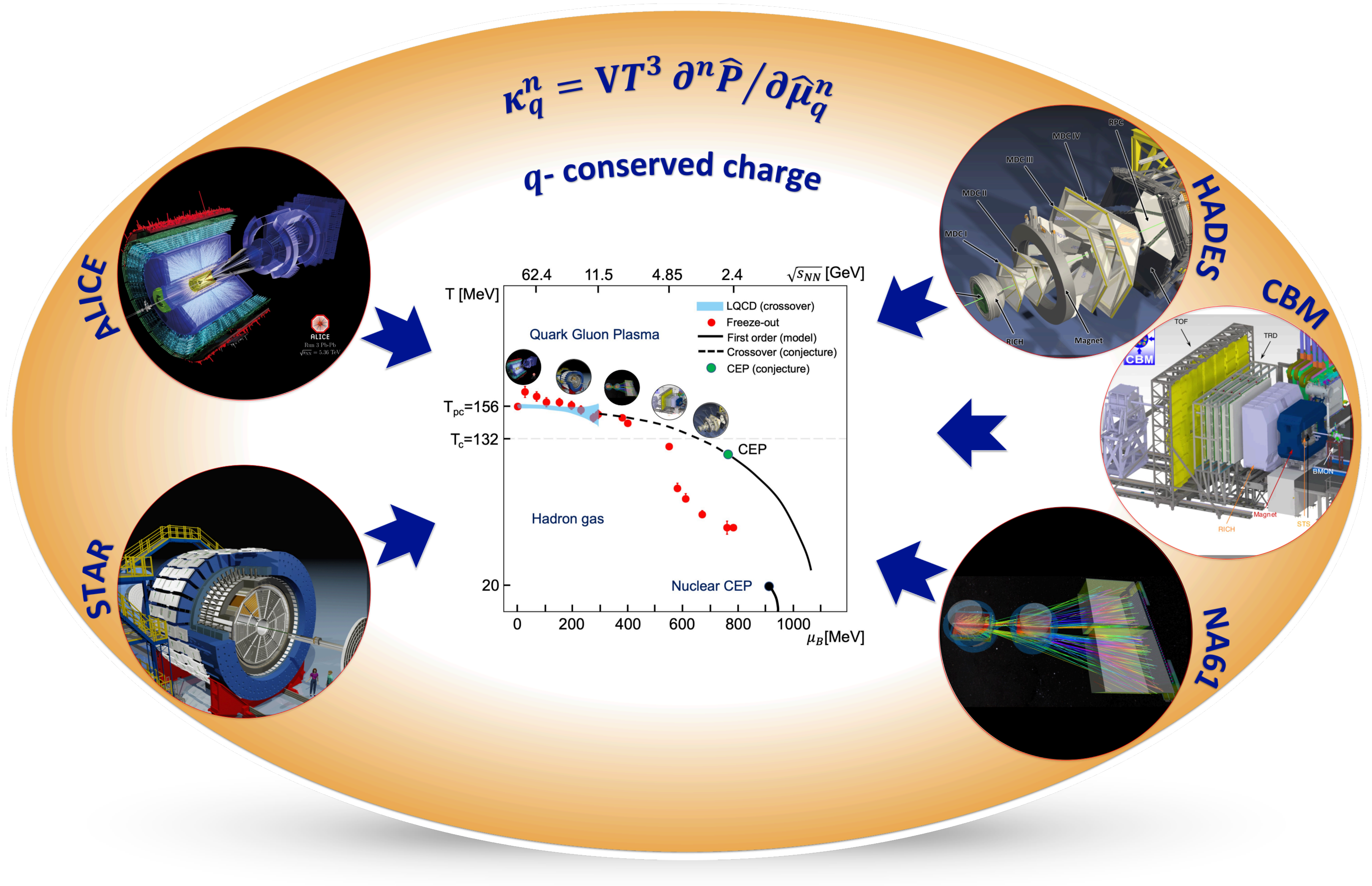


Holy grail

- **First measurement of electromagnetic time-structure of baryons**
- Contribution from ρ meson is clearly visible
- Essential input for interpretation of A-A and p-p dilepton data

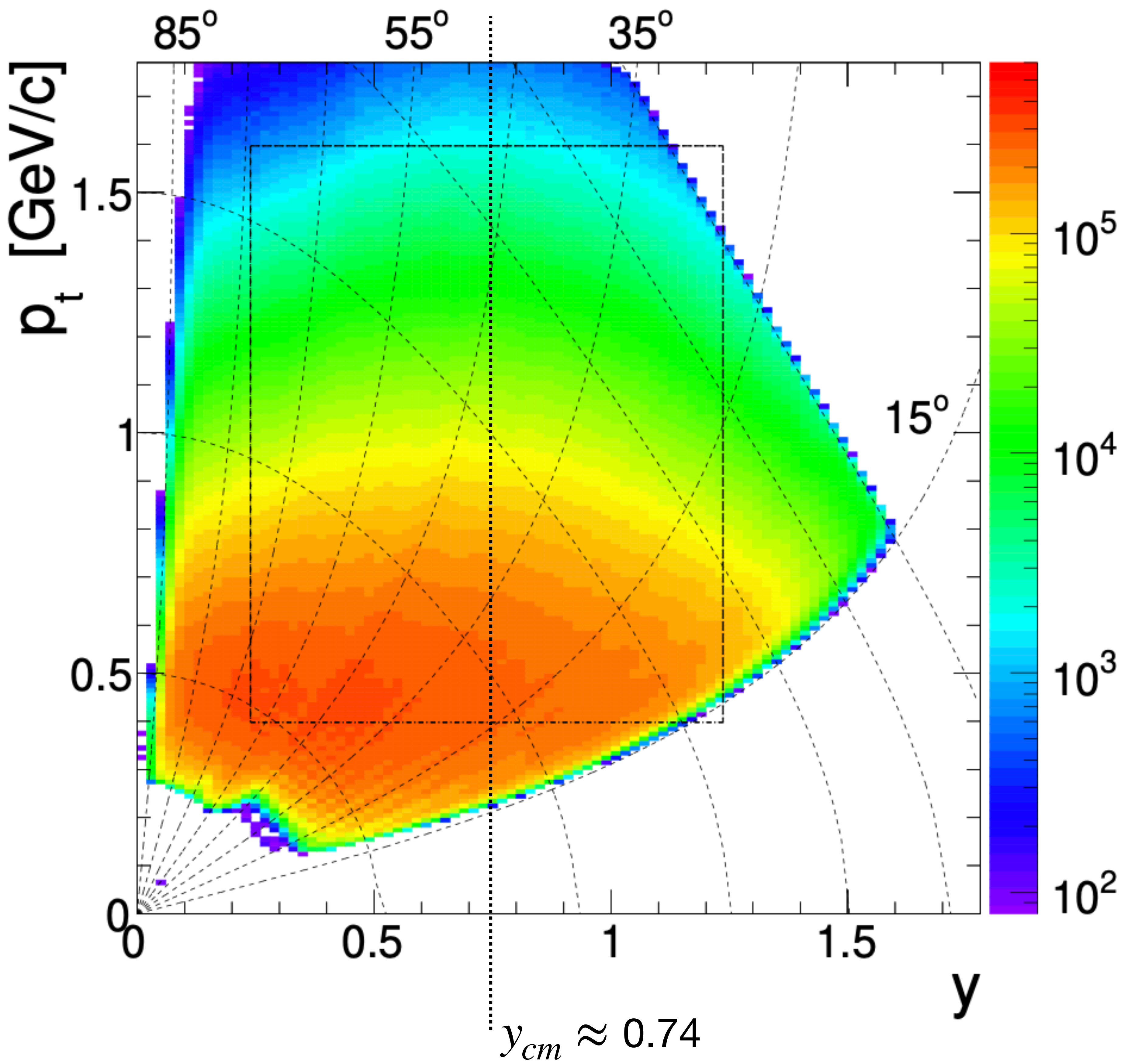
Fluctuations of conserved charges from event-to-event

fundamental/direct tools to study phase transitions



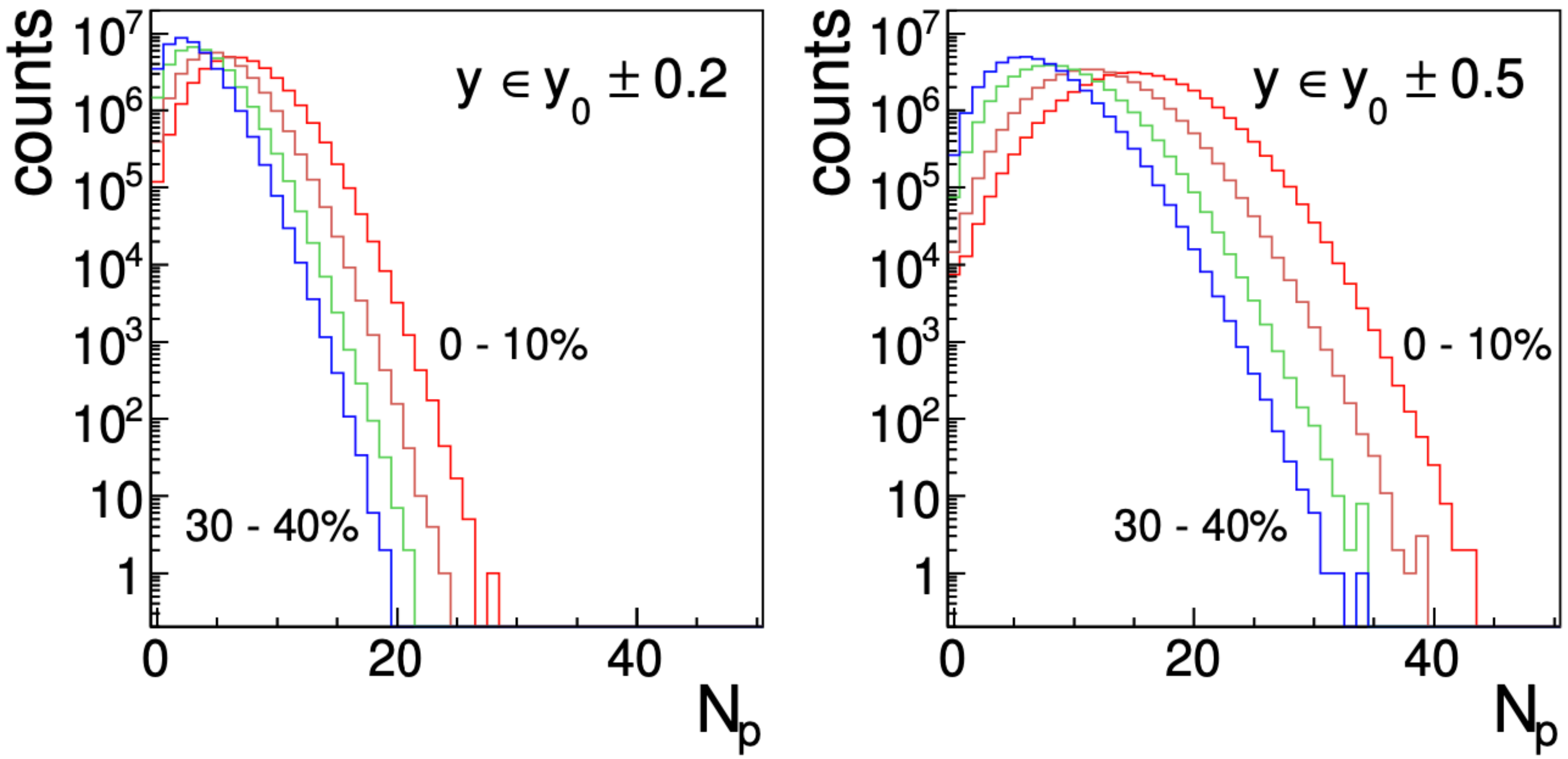
Proton multiplicity distributions

HADES Au+Au, $\sqrt{s_{NN}} \approx 2.4$ GeV



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

eff. uncorrected Proton number distributions

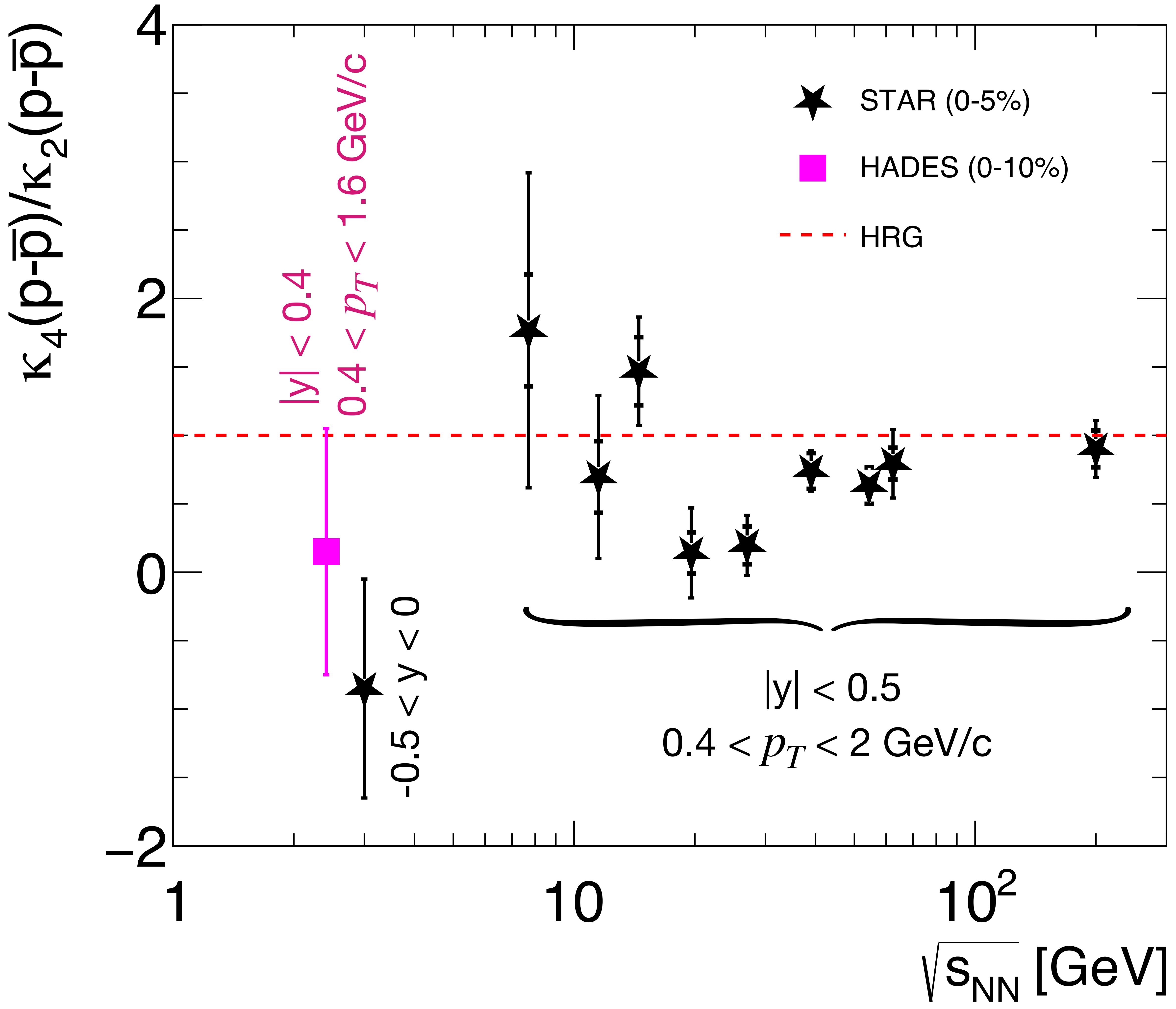


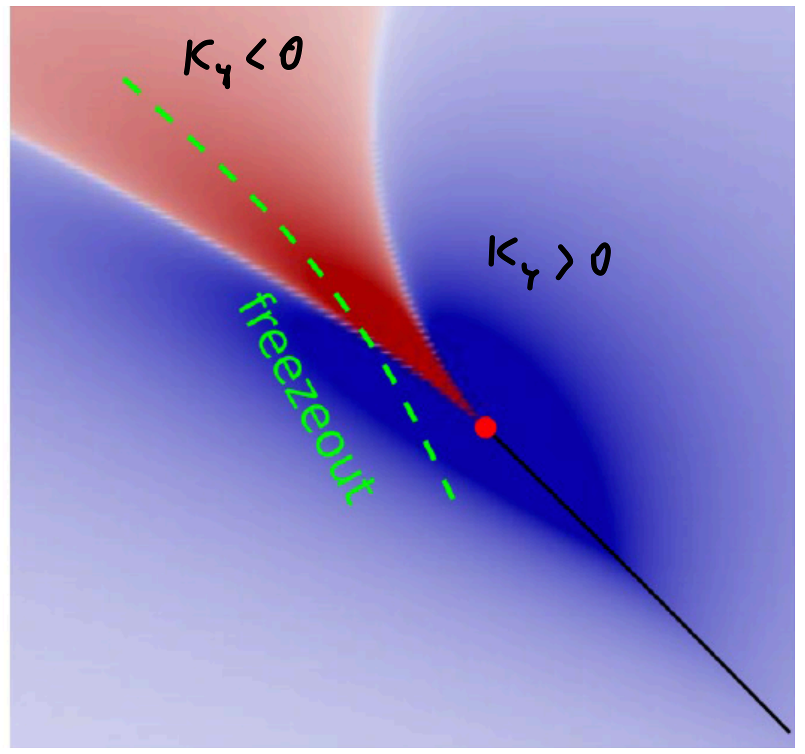
quantifying fluctuations with cumulants, κ_r

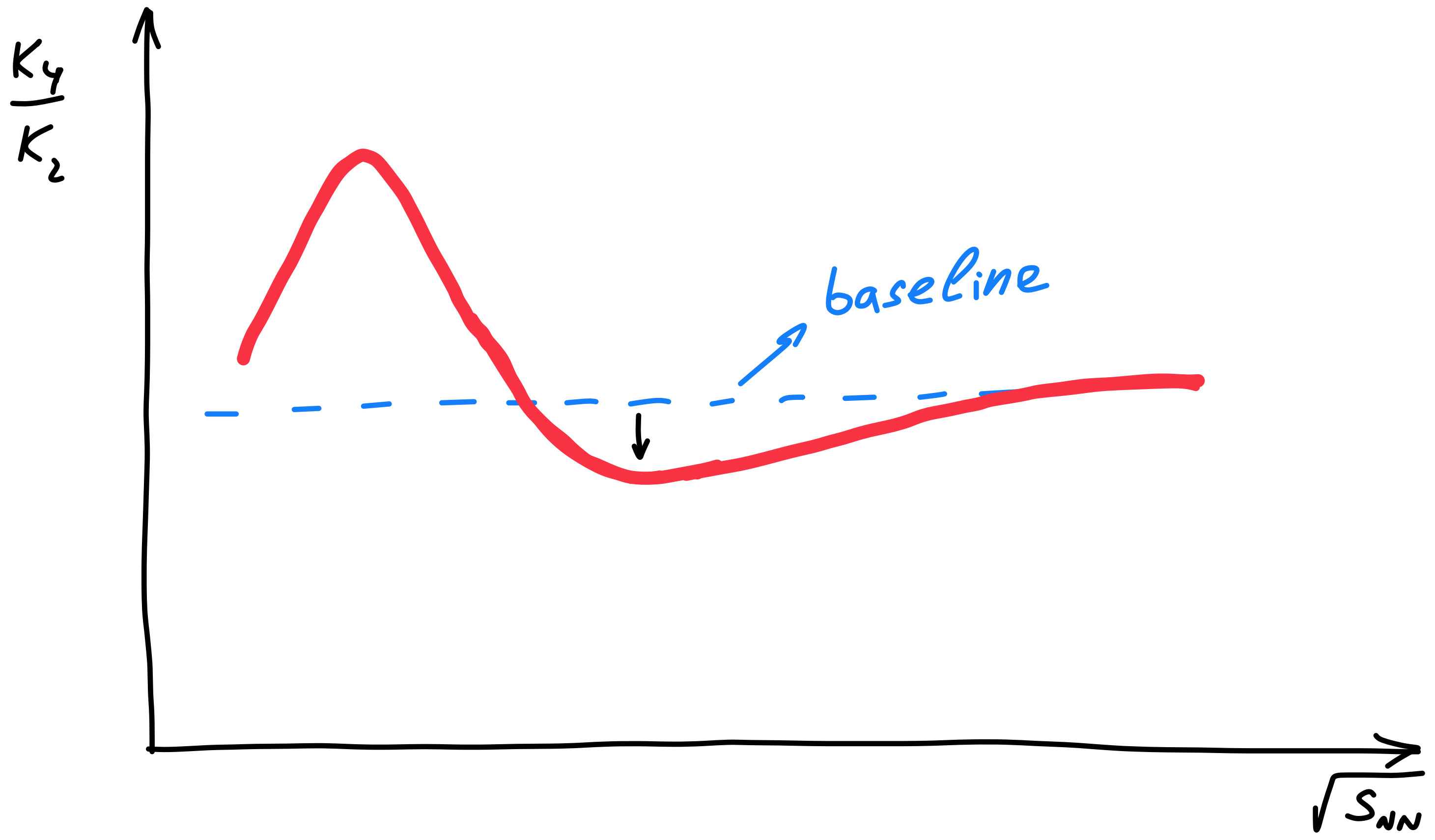
- N occurs with probability $p(N)$ (measured)
- r^{th} order central moment: $\mu_r = \sum_N (N - \langle N \rangle)^r p(N)$
- $\kappa_1 = \langle N \rangle, \ \kappa_2 = \mu_2 = \sigma^2, \quad \kappa_3 = \mu_3, \ \kappa_4 = \mu_4 - 3\mu_2^2, \ldots$

Energy excitation function of κ_4/κ_2 in central Au-Au collisions

HADES: Phys.Rev.C 102 (2020) 2, 024914
STAR: Phys.Rev.Lett. 126 (2021) 9, 092301







a dip in the excitation function is generic

M. Stephanov, PRL102.032301(2009), PRL107.052301(2011)
M.Cheng et al, PRD79.074505(2009)

STAR: Phys.Rev.Lett. 126 (2021) 9, 092301

non-monotonic behaviour with a significance of 3.1σ relative to Skellam expectation

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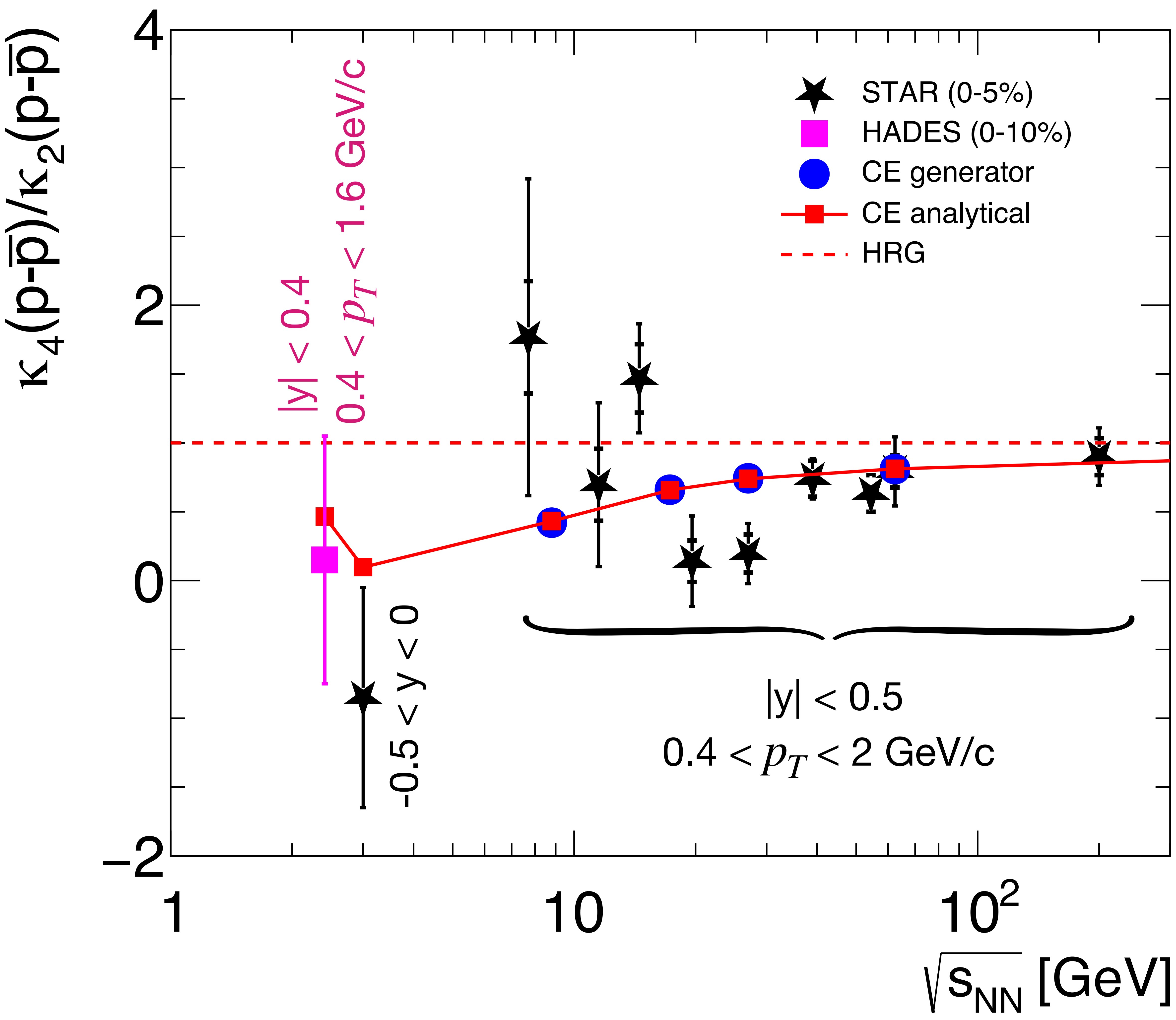

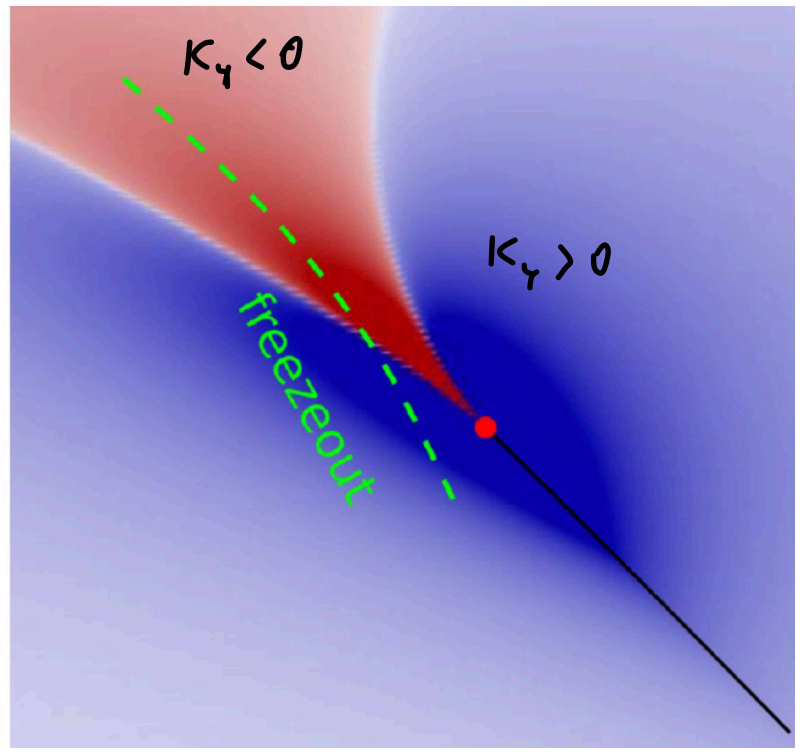

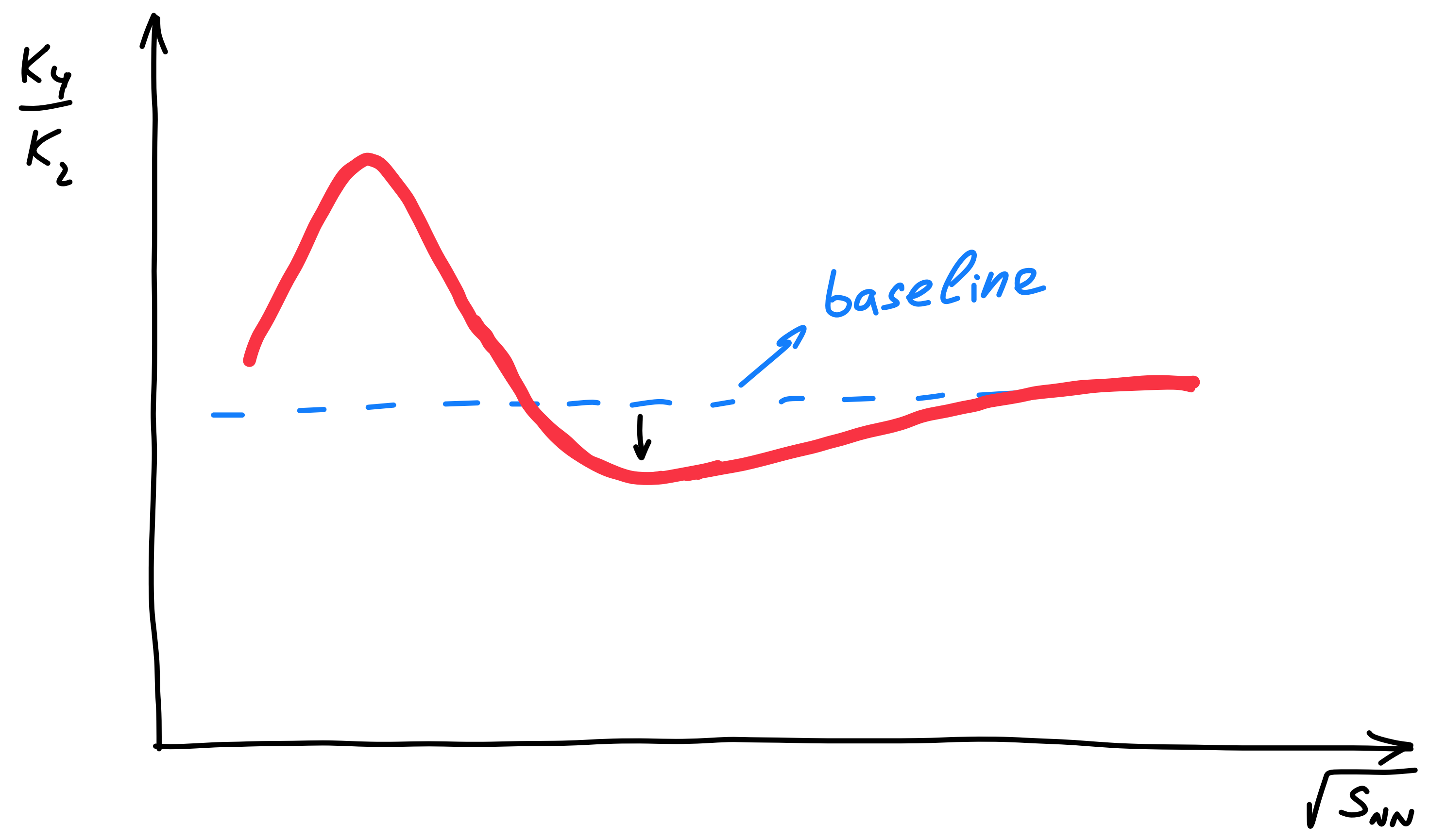

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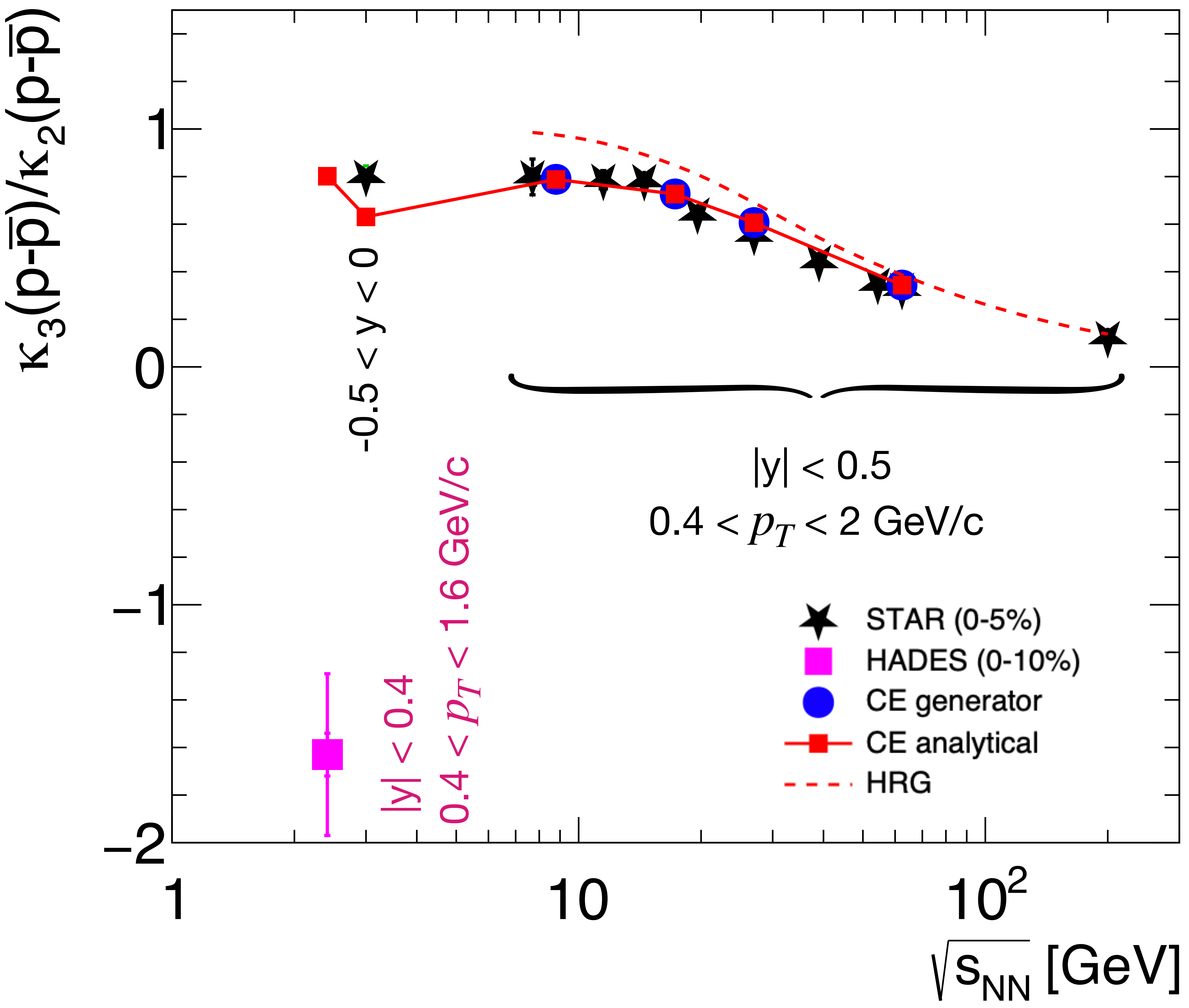
CE Baseline: P. Braun-Munzinger, B. Friman, K. Redlich, A.R., J. Stachel, NPA 1008 (2021) 122141

no statistically significant difference between the data and the canonical baseline (KS test: 1.2σ, χ^2 test: 1.5σ)

Energy excitation function of κ_3/κ_2 in central Au-Au collisions

HADES: Phys.Rev.C 102 (2020) 2, 024914
STAR: Phys.Rev.Lett. 126 (2021) 9, 092301

CE Baseline: P. Braun-Munzinger, B. Friman, K. Redlich, A.R., J. Stachel, NPA 1008 (2021) 122141



- no statistically significant difference between the data and the canonical baseline for $\sqrt{s_{NN}} > 3\text{GeV}$
- large difference between the CE baseline and HADES
  - remnants from volume fluctuations?

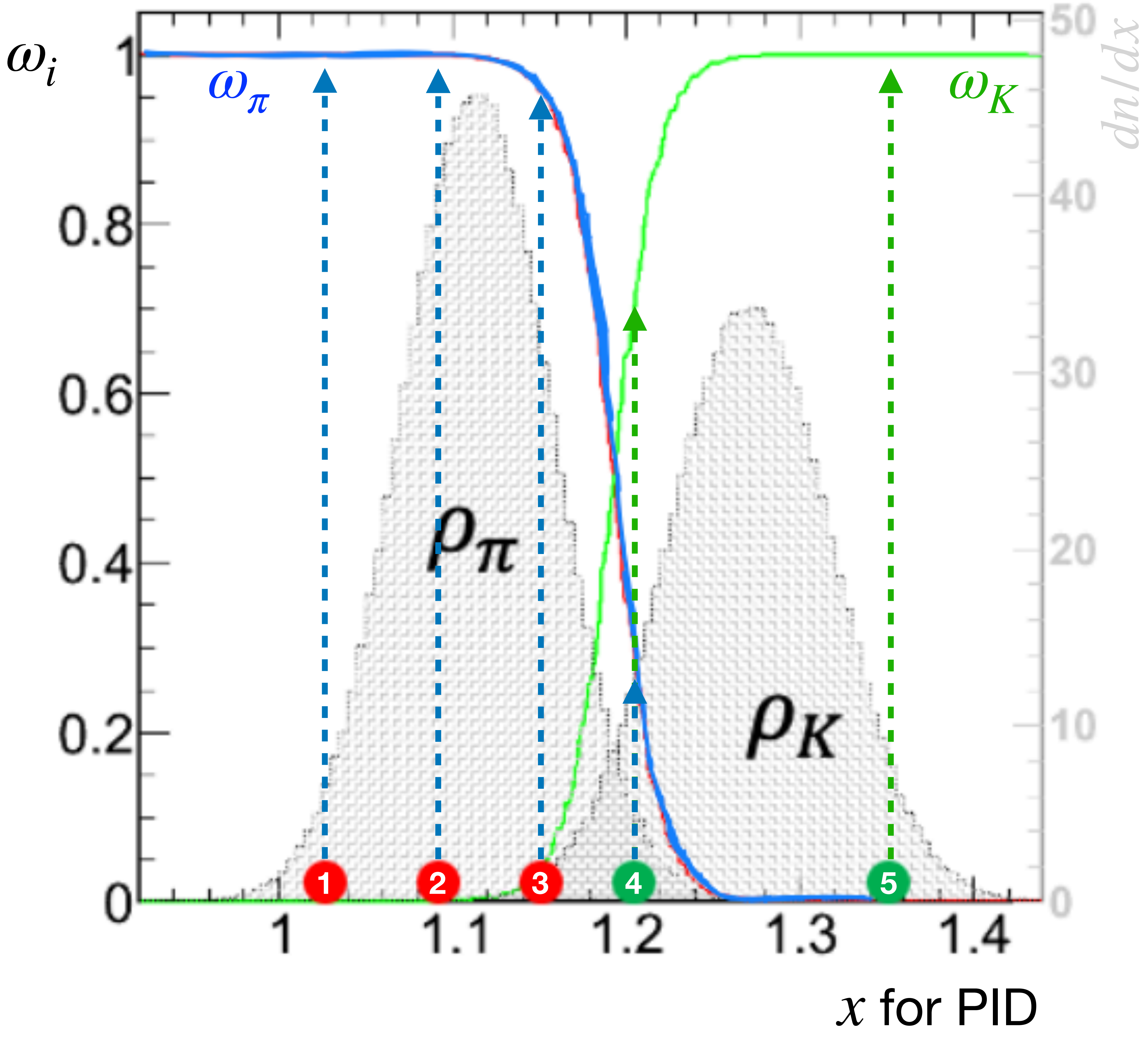
New methods to account for volume fluctuations

A.R., R. Holzmann, J. Stroth, NPA 1034 (2023) 122641
R. Holzmann, V. Koch, A. R., J. Stroth, 2403.03598 [nucl-th] (submitted to NPA)

Talk by Marvin Nabroth, Tue 21.05

Innovative idea: Identity Method

single event



- Input for this event: 3 pions ❶ ❷ ❸, 2 kaons ❹ ❺
- Probabilities that a given measurement x_i is pion or Kaon

$$\omega_\pi^i = \frac{\rho_\pi(x_i)}{\rho_\pi(x_i) + \rho_K(x_i)} \qquad \omega_K^i = \frac{\rho_K(x_i)}{\rho_\pi(x_i) + \rho_K(x_i)}$$

New Idea (Identity method): using proxies for particle numbers

$$W_\pi = \sum_{i=1}^{i=5} \omega_\pi(x_i) \qquad W_K = \sum_{i=1}^{i=5} \omega_K(x_i)$$

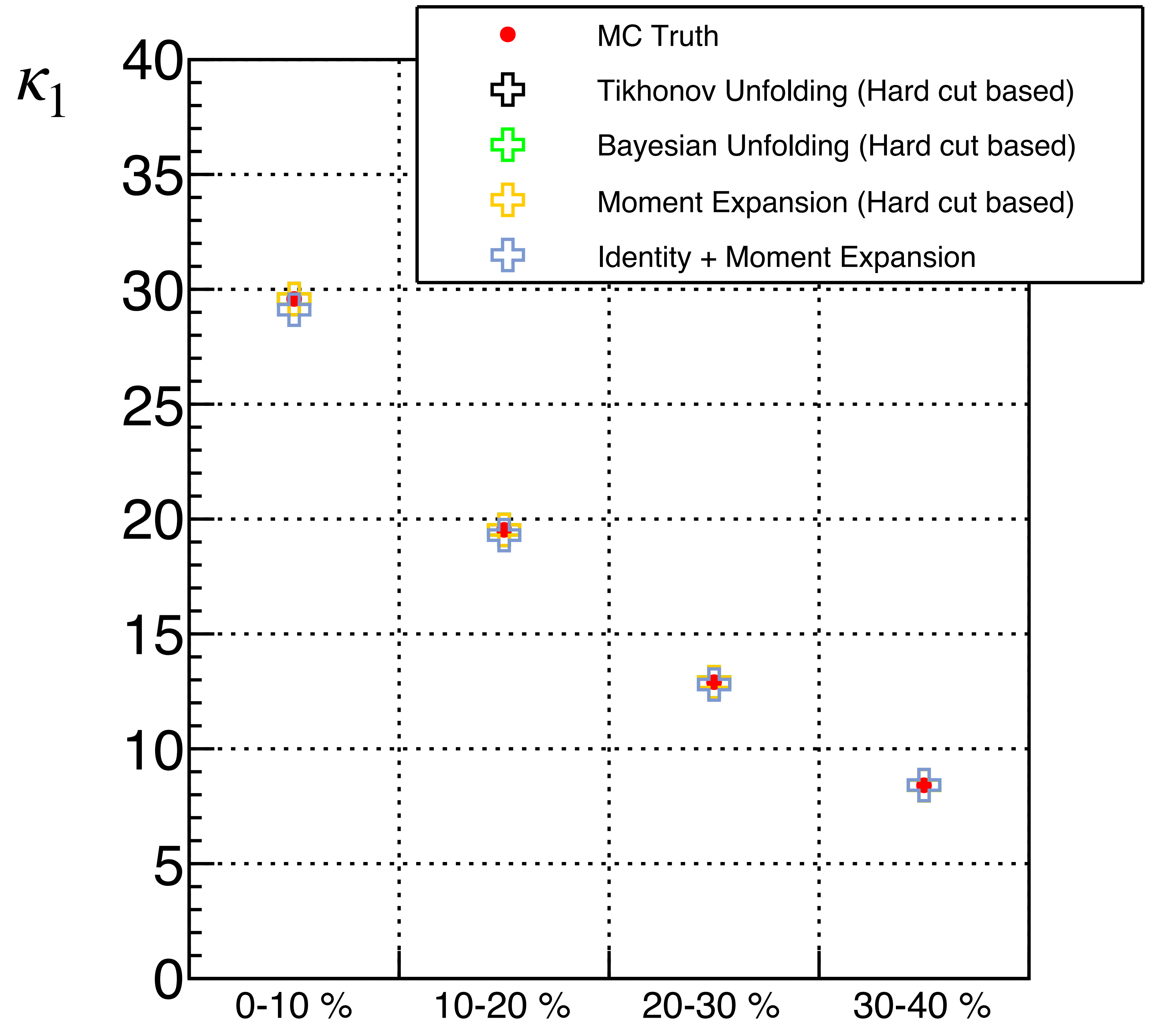
$$\begin{pmatrix} \langle N_K^2 \rangle \\ \langle N_\pi^2 \rangle \\ \langle N_\pi N_K \rangle \end{pmatrix} = A^{-1} \text{ defined by } \rho_i(x) \times \begin{pmatrix} \langle W_K^2 \rangle - f_1(\rho_i) \\ \langle W_\pi^2 \rangle - f_2(\rho_i) \\ \langle W_\pi W_K \rangle - f_3(\rho_i) \end{pmatrix}$$

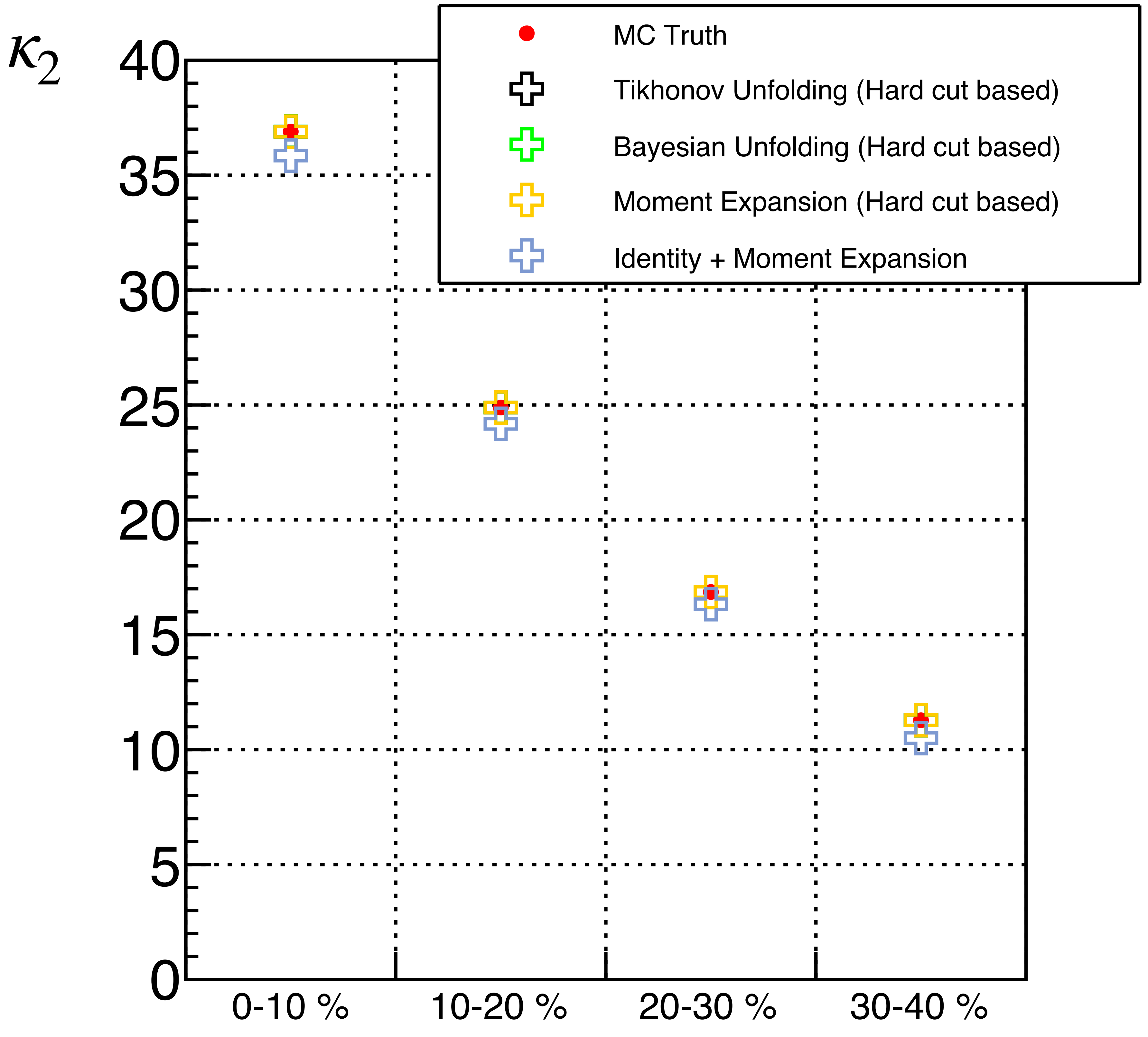
- provides unique solutions
- works for any number of particles
- works for higher order pure and mixed moments

M. Gazdzicki et al., Phys.Rev.C 83 (2011) 054907
M. I. Gorenstein, PRC 84, 024902 (2011)
AR, M. I. Gorenstein, PRC 86, 044906 (2012)
M. Arslandok, AR, NIM A946, 162622 (2019)

Identity vs cut-based results

UrQMD Ag+Ag, $\sqrt{s_{NN}}$ = 2.55 GeV, $|y_{cm}|$ < 0.4, 0.4 < p_T < 1.6 GeV/c

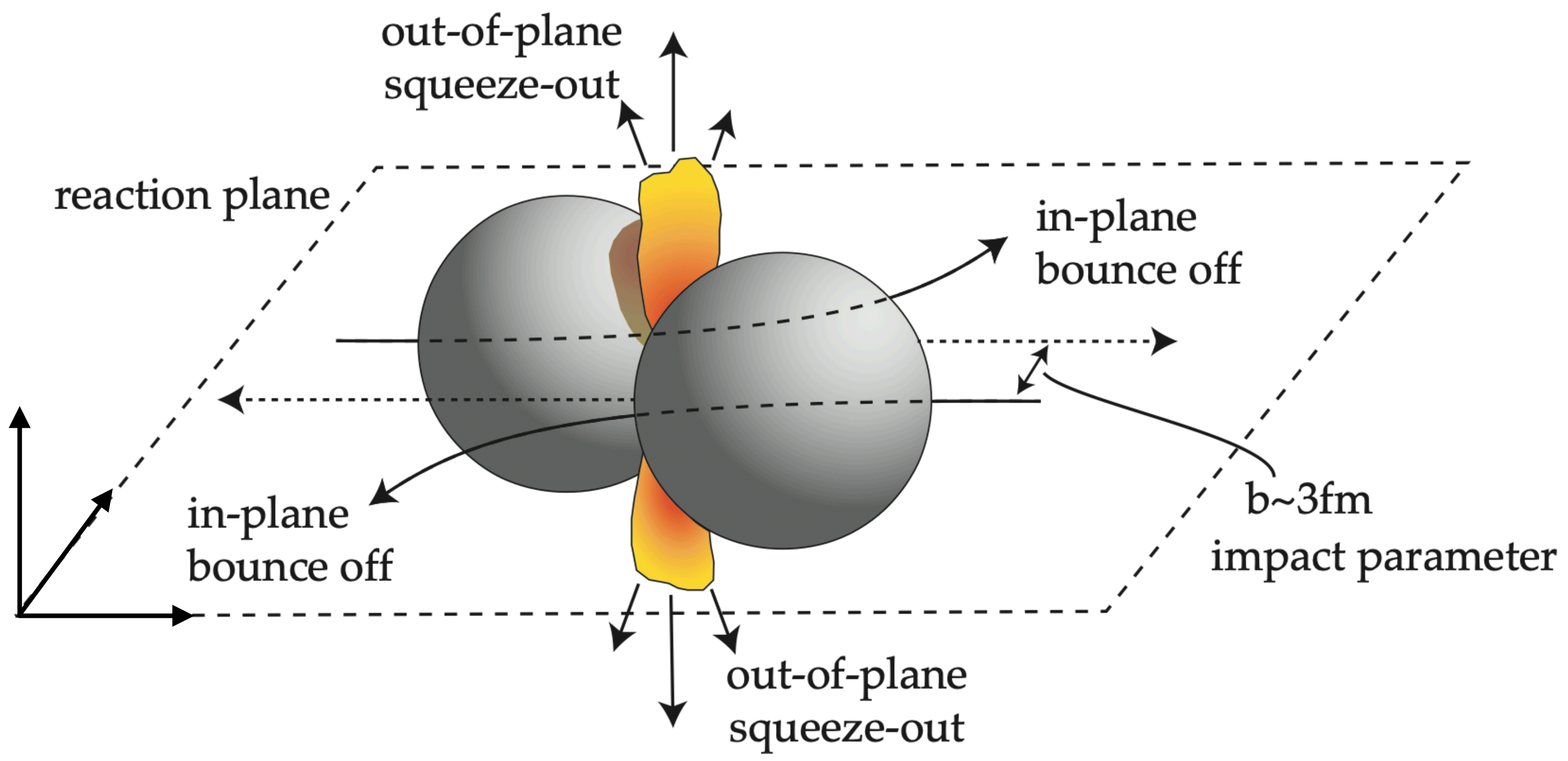




- **consistent results for different efficiency correction methods**
- **reasonable agreement between the Identity and cut-based methods**

Collective effects

For a phase transition to happen, interactions are necessary



delicate balance between transverse expansion and passage time

Cheuk-Yin Wong, PLB 88, 12, 1979
S. Voloshin, Y. Zhang, Z.Phys.C 70 (1996) 665-672

Fourier series of invariant cross section

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

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

$$v_n = \langle cos(n\phi)\rangle$$

$$v_1 = \langle cos\phi\rangle = \langle p_x/p_t\rangle$$

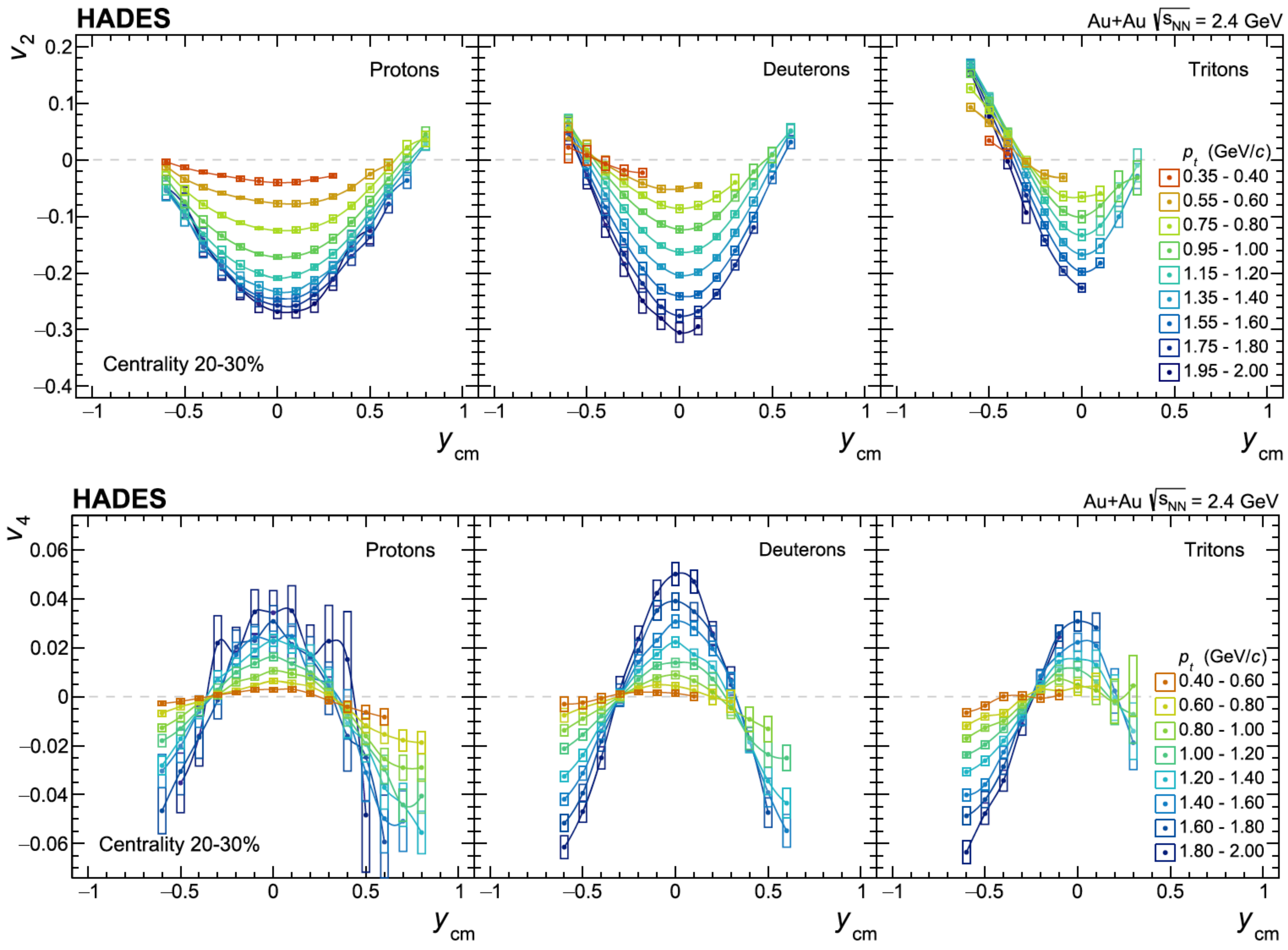
$$v_2 = \langle cos2\phi\rangle = \langle (p_x^2 - p_y^2)/p_t^2\rangle = \langle (p_x^2 - p_y^2)/(p_x^2 + p_y^2)\rangle$$

$$v_3 = \langle cos(2\phi)\rangle = \langle (p_x^3 - 3p_x p_y^2)/p_t^3\rangle$$

$$v_4 = \langle cos(4\phi)\rangle = \langle (p_x^4 - 6p_x^2 p_y^2 + p_y^4)/p_t^4\rangle$$

…

Flow measurements of different particle species

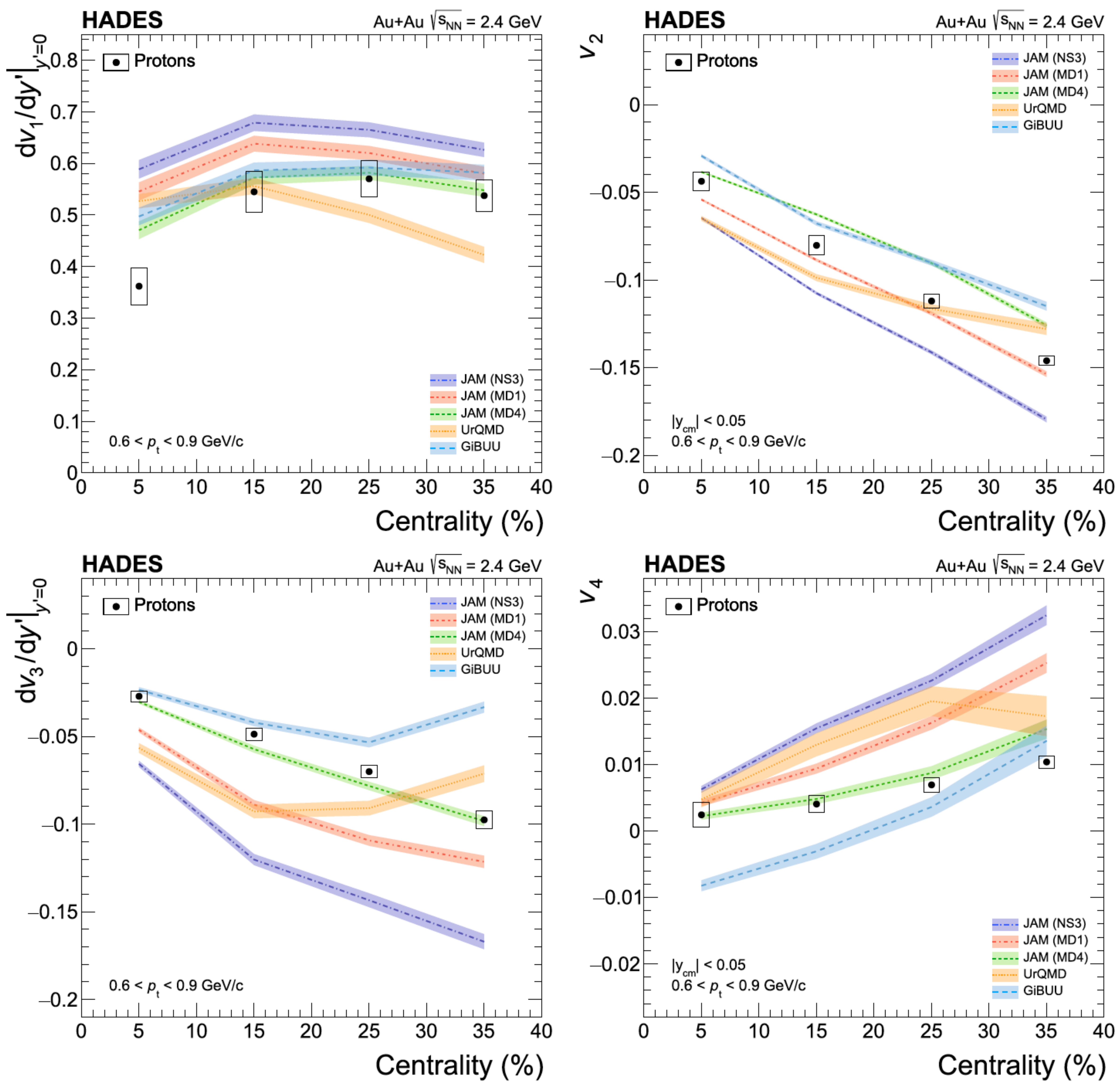


HADES: Eur. Phys.J.A 59 (2023) 4, 80

Systematic measurements of flow coefficients up to v_4

Can be used to constrain EoS

Sensitivity of flow coefficients to EoS



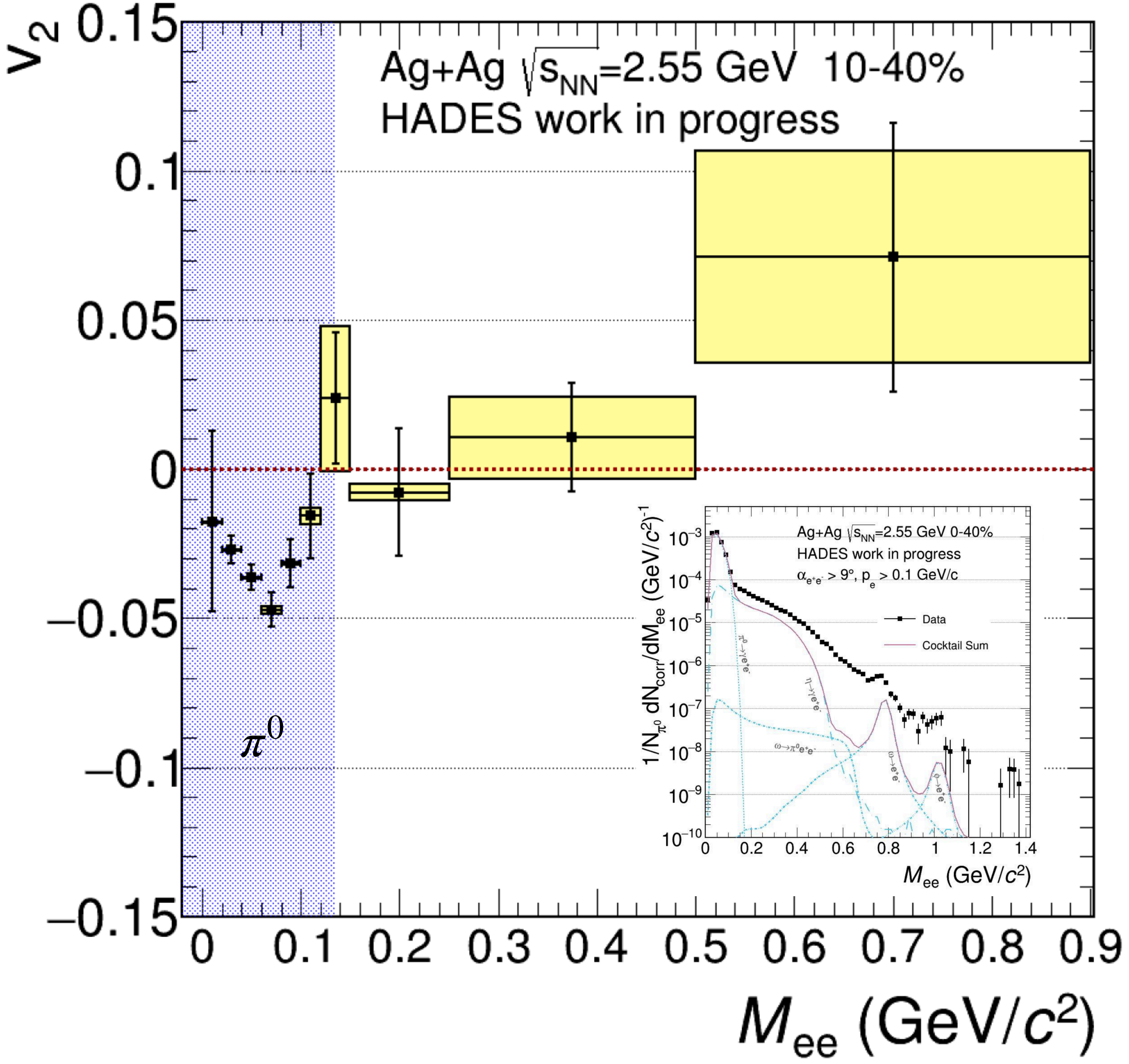
HADES: Eur. Phys.J.A 59 (2023) 4, 80

Constraining EoS

- **JAM (NS3)** - hard EoS, momentum independent
- **JAM (MD1)** - hard EoS, momentum dependent
- **JAM (MD4)** - soft EoS, momentum dependent
- **UrQMD** - hard EoS, momentum independent
- **GiBUU** - soft EoS

- **Overall trend is reasonably described**
- **Quantitatively all models fail to describe the data**
  - Most consistent is **JAM (MD4)**

Elliptic flow of dileptons

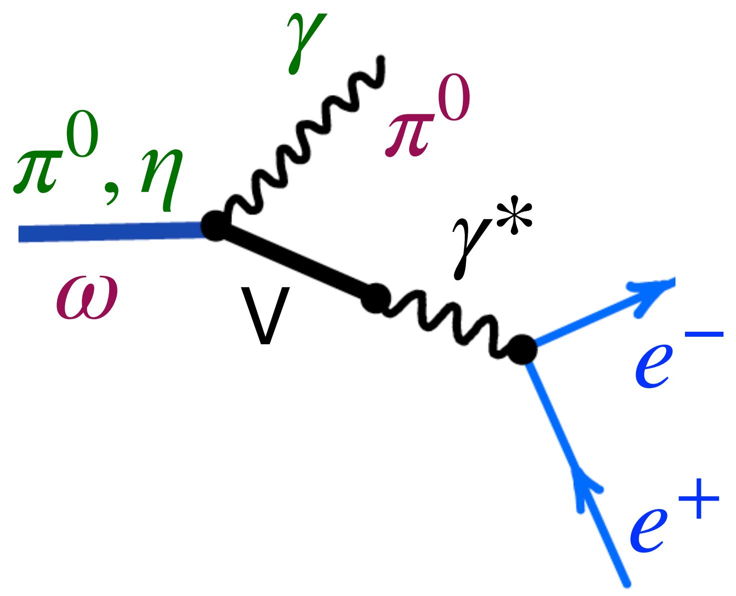


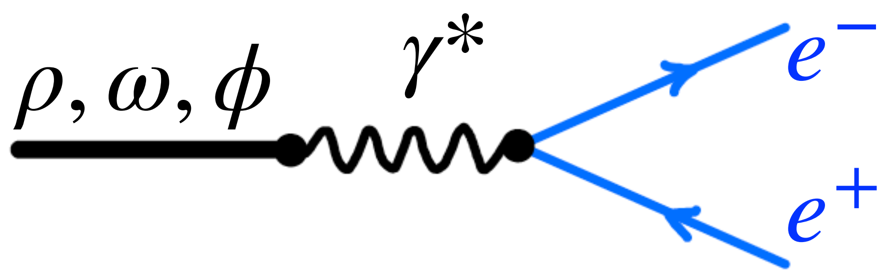
Penetrating probes, dileptons should not "flow"!

- $M_{ee} < 0.12$ GeV/c² - dominated by pions
  - negative v_2, constant with negative v_2 for pions
- $M_{ee} \geq 0.12$ GeV/c²
  - contributions from thermal medium?
    - vanishing values v_2 within uncertainties

Ongoing

isolating the flow of a parent hadron

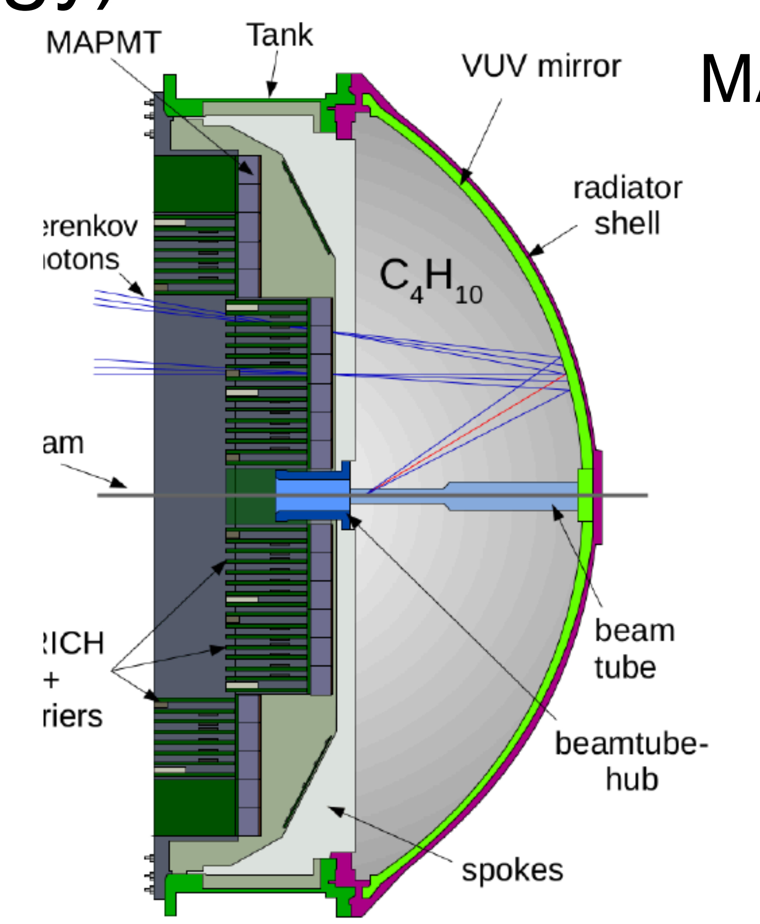




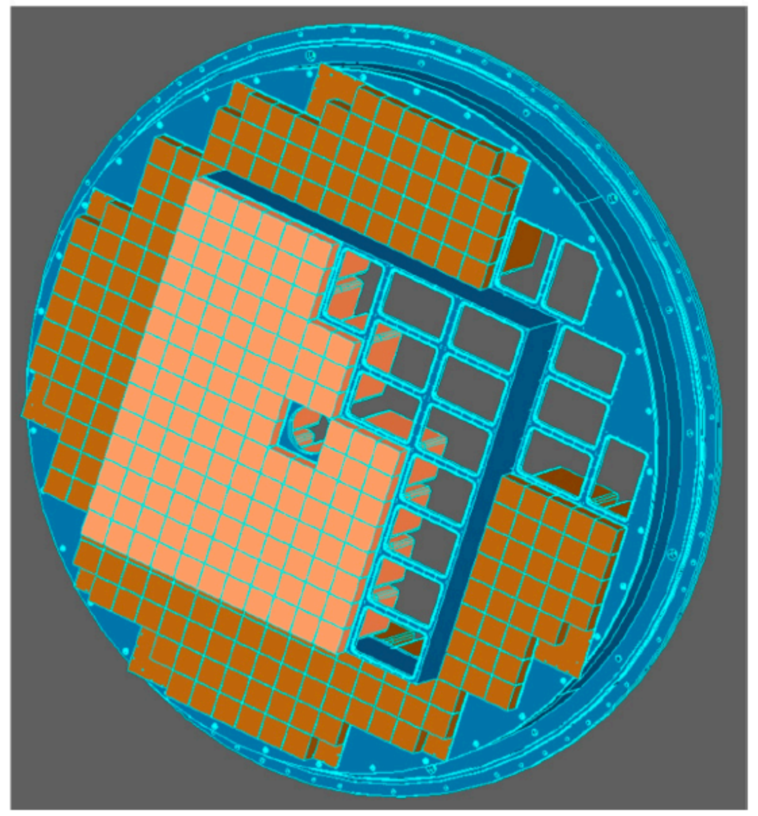
Detector upgrades (in cooperation with CBM)

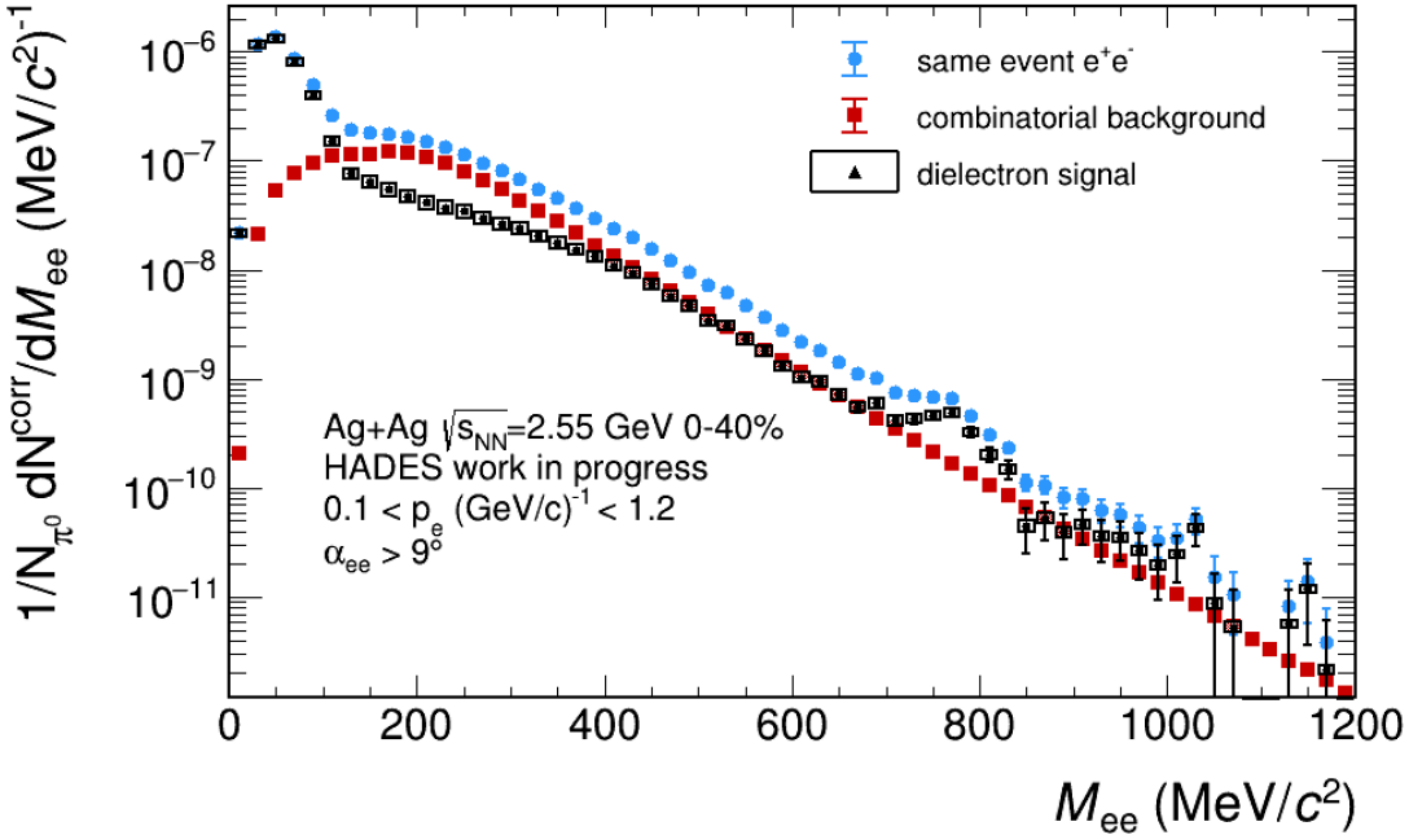
Upgrade of old RICH photon detector with MAPMT based camera (CBM technology)

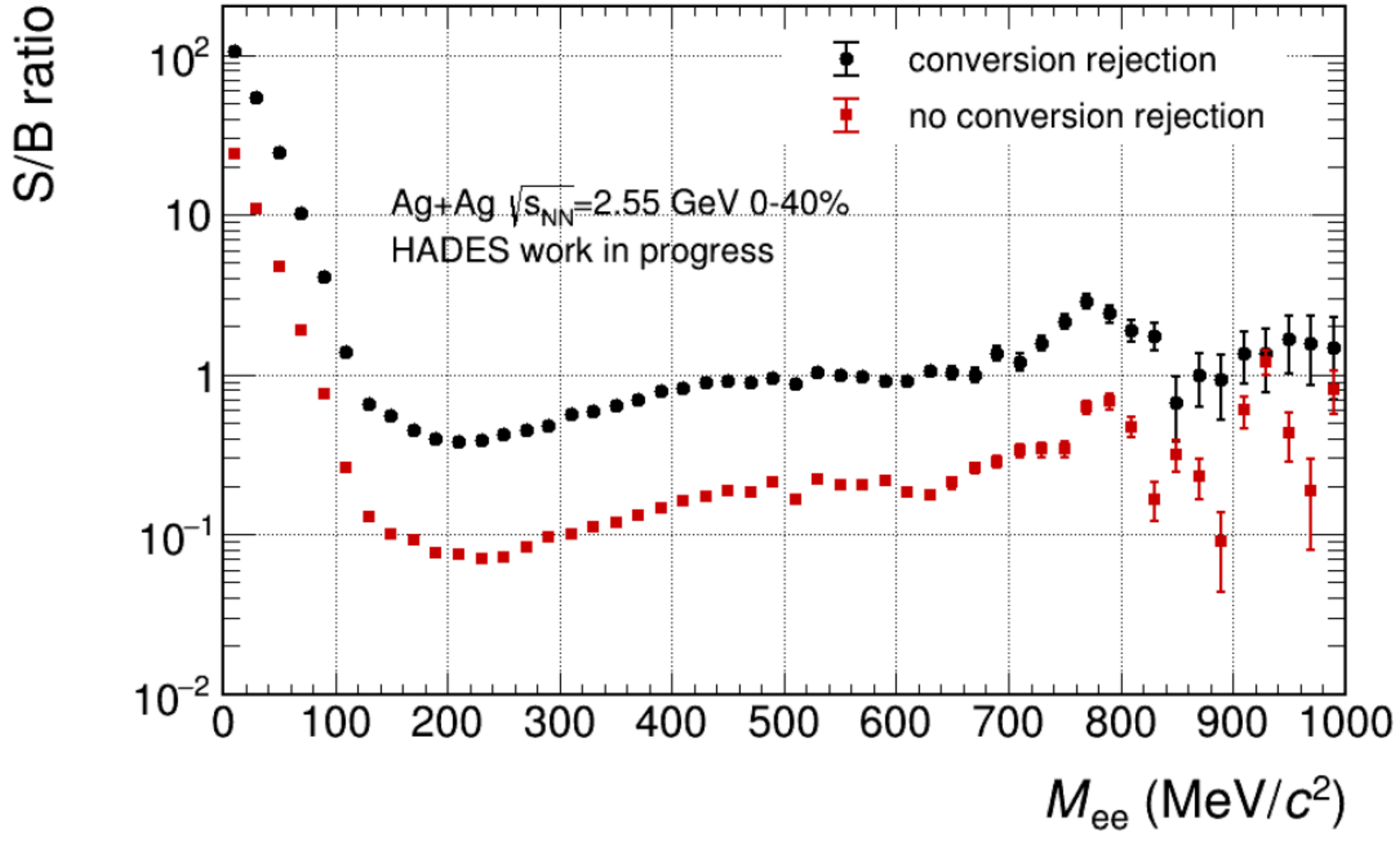
- Large number of fired pads per ring
  - Significantly improved lepton identification
  - Excellent conversion rejection
- Noise rejection owing to high precision timing information



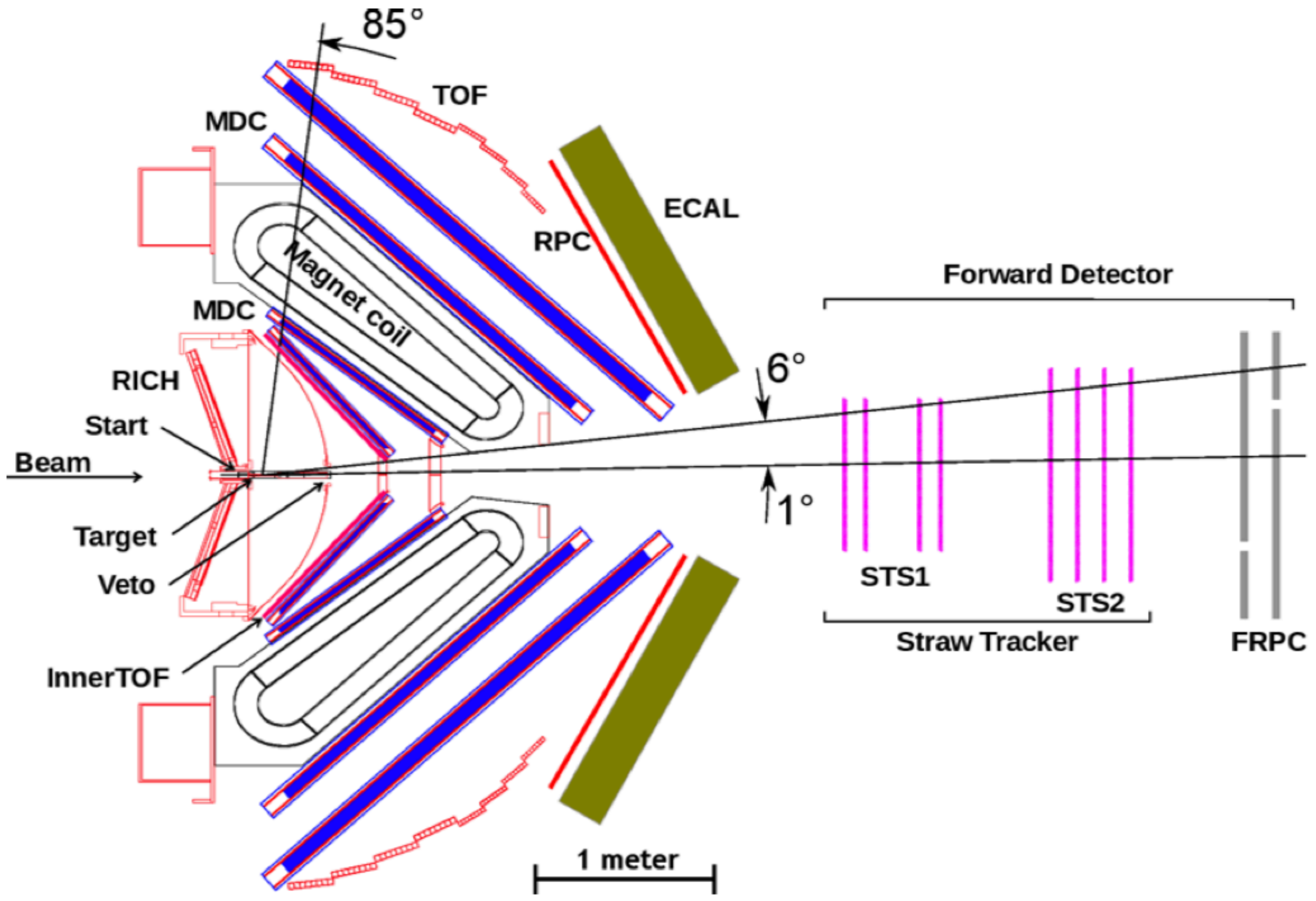
MAPMT plane of the HADES RICH







Detector upgrades (in cooperation with PANDA)



New detector systems

- **T0 detector based on LGAD technology**
  - precise T_0 determination, beam monitoring
  - used in p+p @ T = 4.5 GeV and Au+Au @ T = 0.8 GeV

J. Pietraszko, et al., Eur. Phys. J. A 56, 183 (2020)

Extending the physics performance towards forward hemisphere (for elementary collisions)

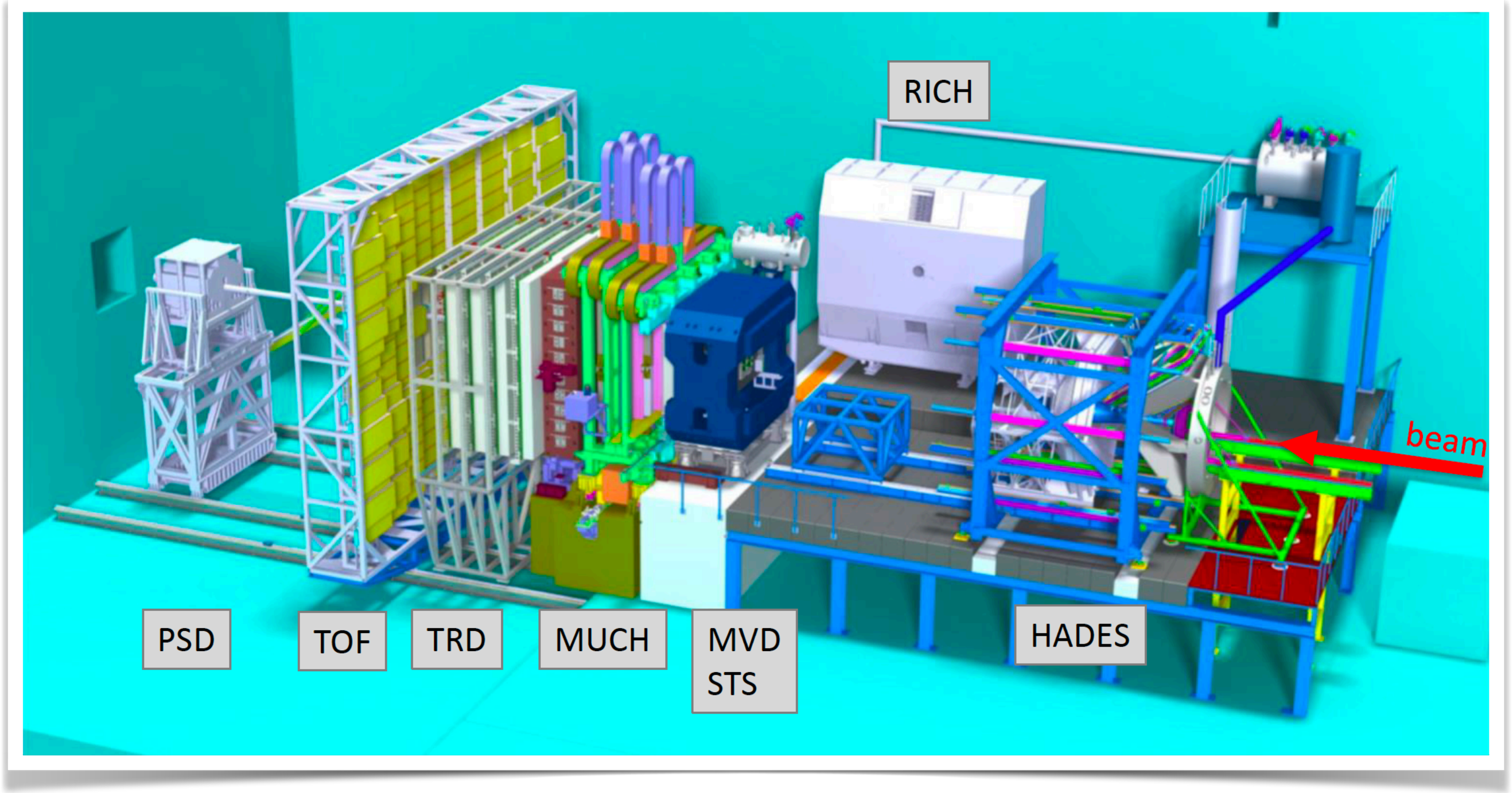
PoS FAIRness2022 (2023) 043

- **Forward detector to track charged particles at $1^0 < \theta < 6^0$**
  - **two** straw trackers and **one** RPC
  - used in p+p @ T = 4.5 GeV
- **Inner TOF**
  - three plastic scintillators per sector
    - improvement of trigger selectivity
    - used in p+p @ T = 4.5 GeV

Future Prospects

- **February 2022: p+p, T = 4.5 GeV (done)**
  - baseline for FAIR experiments (and beyond)
  - **March 2024: Au+Au, T = 0.8A GeV (done)**
- **Beam energy scan (2025)**
  - Au-Au collisions, with projectile kinetic energies: 0.6*A*, 0.4*A*, 0.2*A* GeV

    (~ 10^9 events for each energy)
    - systematic study of fluctuations and correlation functions at the high values of μ_B
    - probing the vicinity of nuclear liquid-gas phase transition
- **Pion beams for third resonance region (2025)**
- **…**

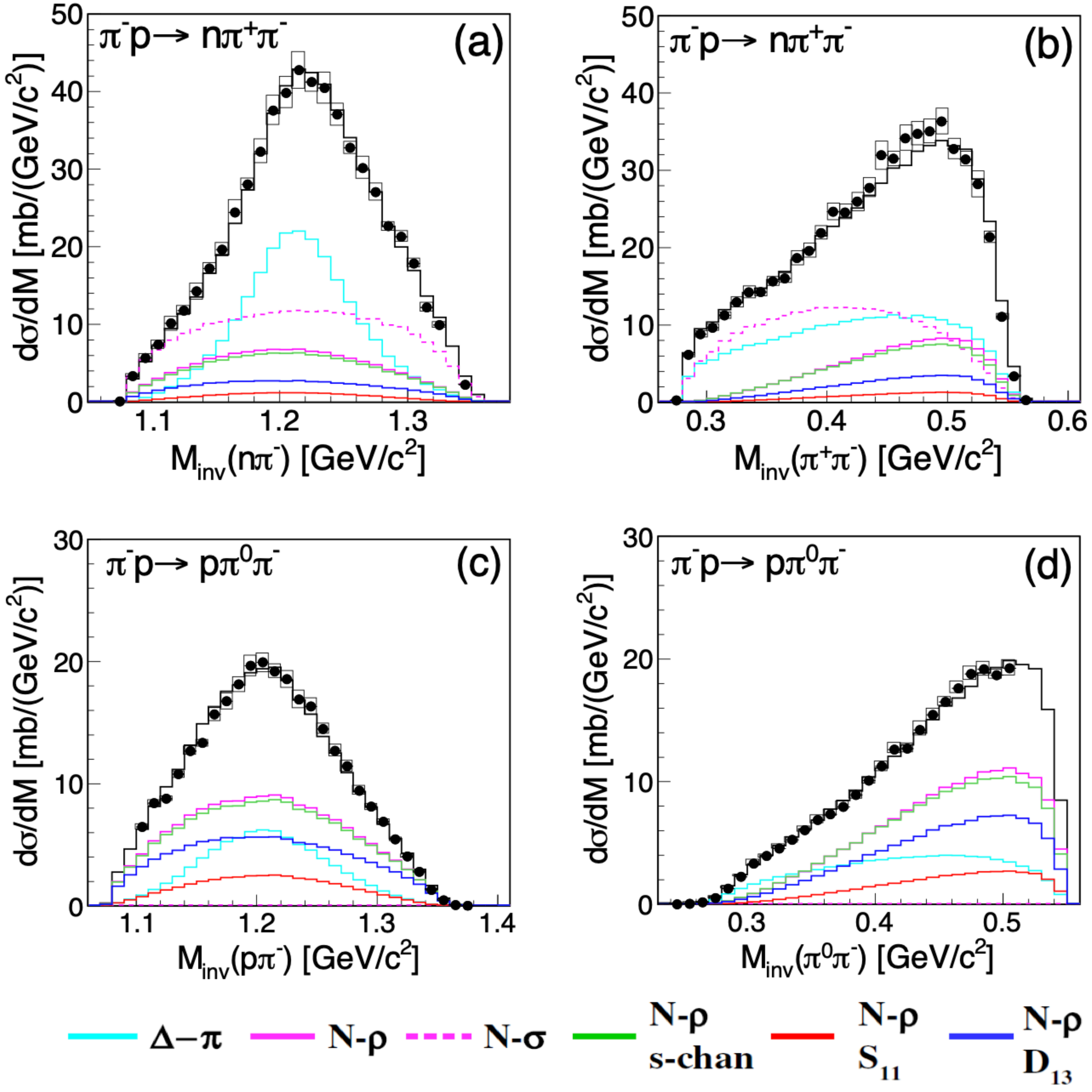


Summary

- The HADES experiment at GSI/SIS provides unique opportunities to unravel the QCD phase structure
- High statistics data are recorded for A-A, p-A, p-p as well as pion induced collisions
- High precision dielectron measurements indicate strong in-medium broadening of the ρ meson
  - Possible hint for partial restoration of chiral symmetry
- κ_4 of proton number is consistent with the canonical baseline
- κ_3 of proton number is significantly below the canonical baseline
  - Application of the Identity method and accounting for volume fluctuations are ongoing
- Systematic and differential measurements of flow coefficients for different particles are performed
  - Important for constraining EoS of matter at large μ_B
- Several new detector systems are installed and already used during data taking


XLVI HADES Collaboration Meeting, Darmstadt, Germany (16 – 19 April 2024)


THANKS FOR YOUR ATTENTION



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

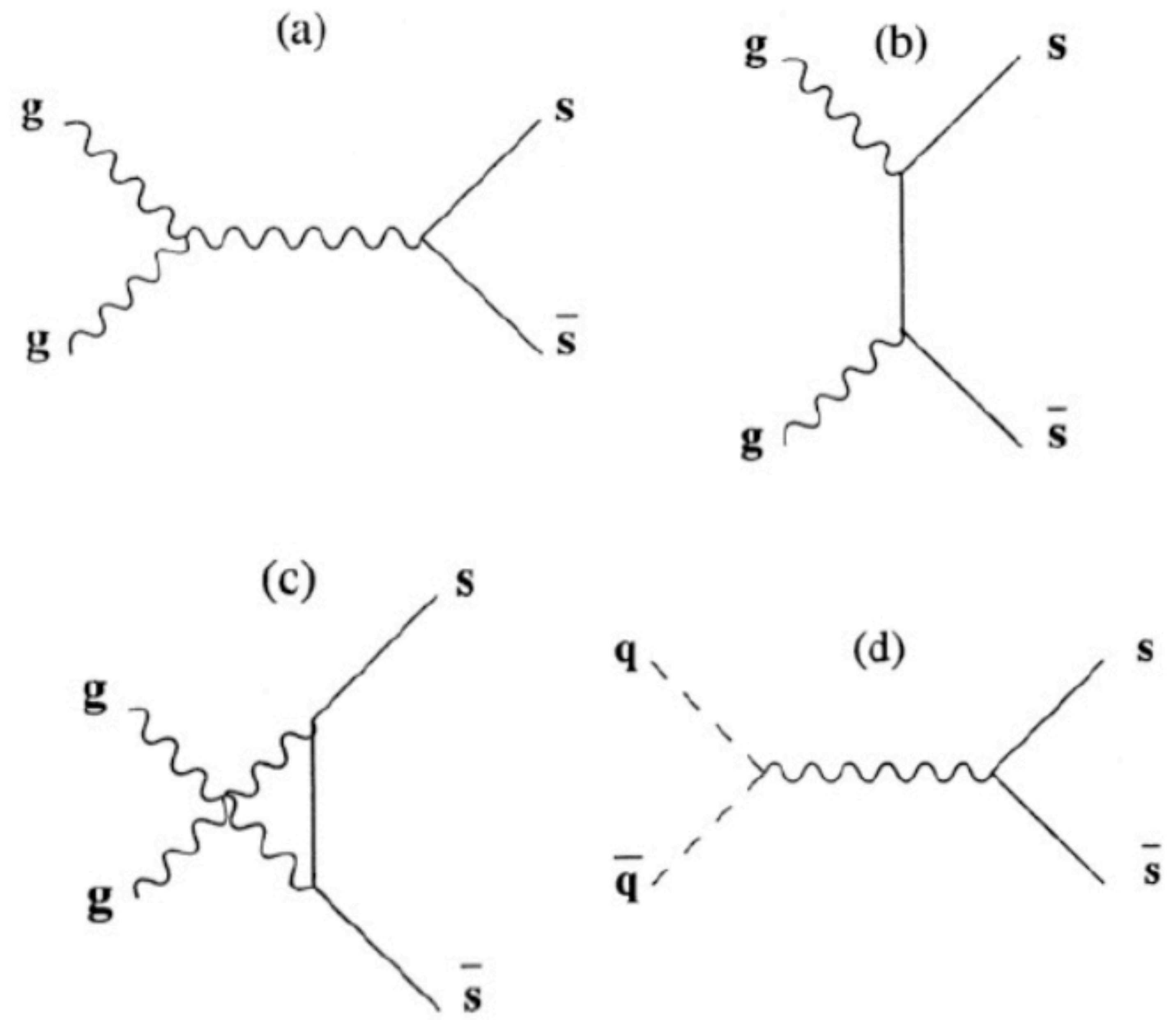
Constraining ρ production amplitudes

$\pi^- p \rightarrow n\pi^+\pi^-$, p_π = 0.685 GeV/c, $\sqrt{s_{\pi p}}$ ~ 1.49 GeV

Bonn-Gatchina Partial Wave Analysis (PWA)

Strangeness production phenomenology

Enhancement



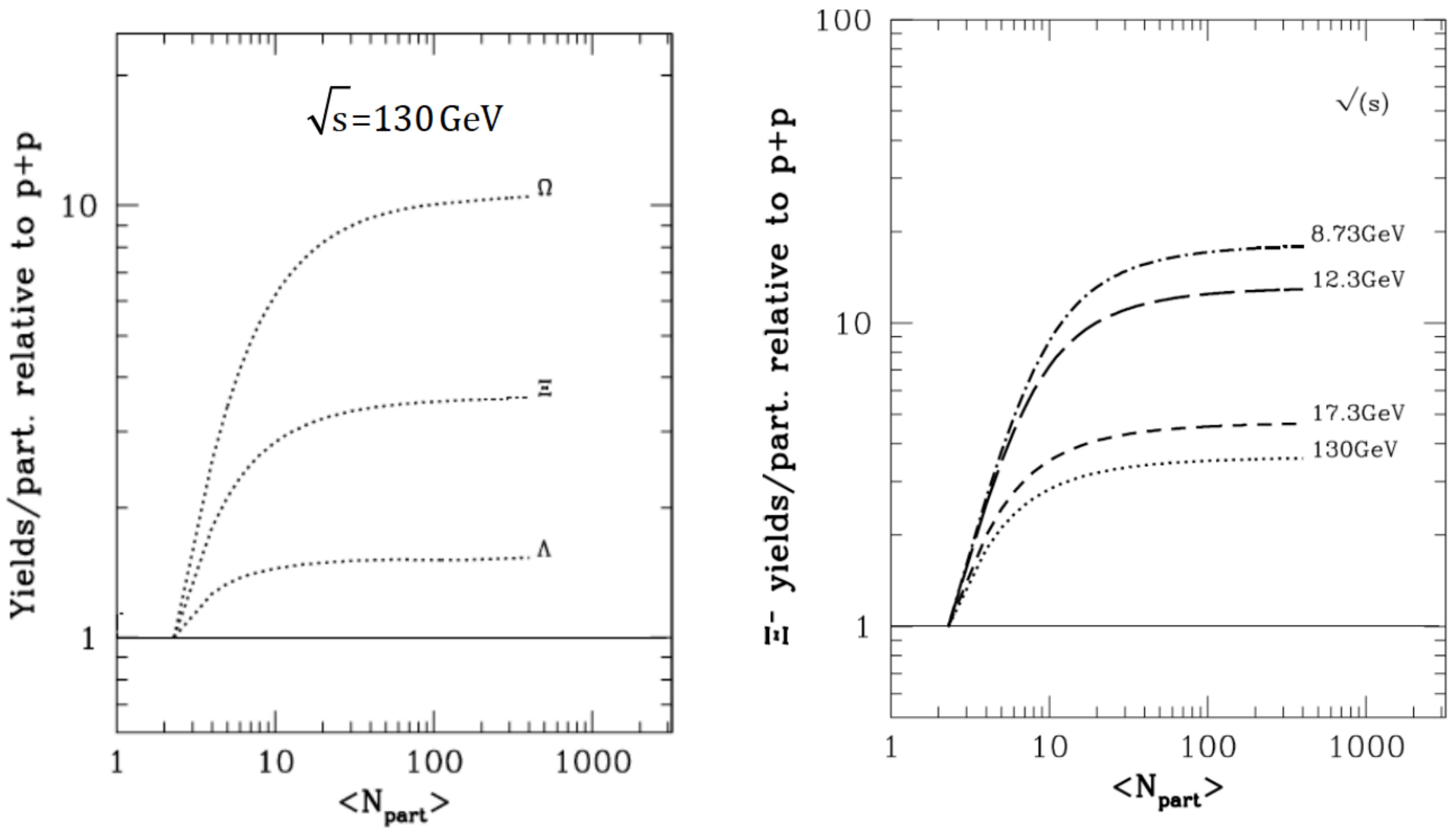
Energy needed:

QGP: $2m_s \approx 200$ MeV

Hadron gas: e.g., NN -> NΛK $\approx$ 670 MeV

J. Rafelski, B. Müller, PRL 48, 1066 (1982)
P. Koch, B. Müller, J. Refelski, Phys. Rep. 142, 167 (1986)

Suppression as apparent enhancement



Canonical suppression factor $F_s = I_s(x)/I_0(x)$

I_s - modified Bessel function, $x \sim V$

<Mult>$_{CE}$ = F_s<Mult>$_{GCE}$

Hierarchy follows the strangeness content

Enhancement decreases with increasing energy

S. Hamieh, K. Redlich, A. Tounsi, PLB 486, 61 (2000)

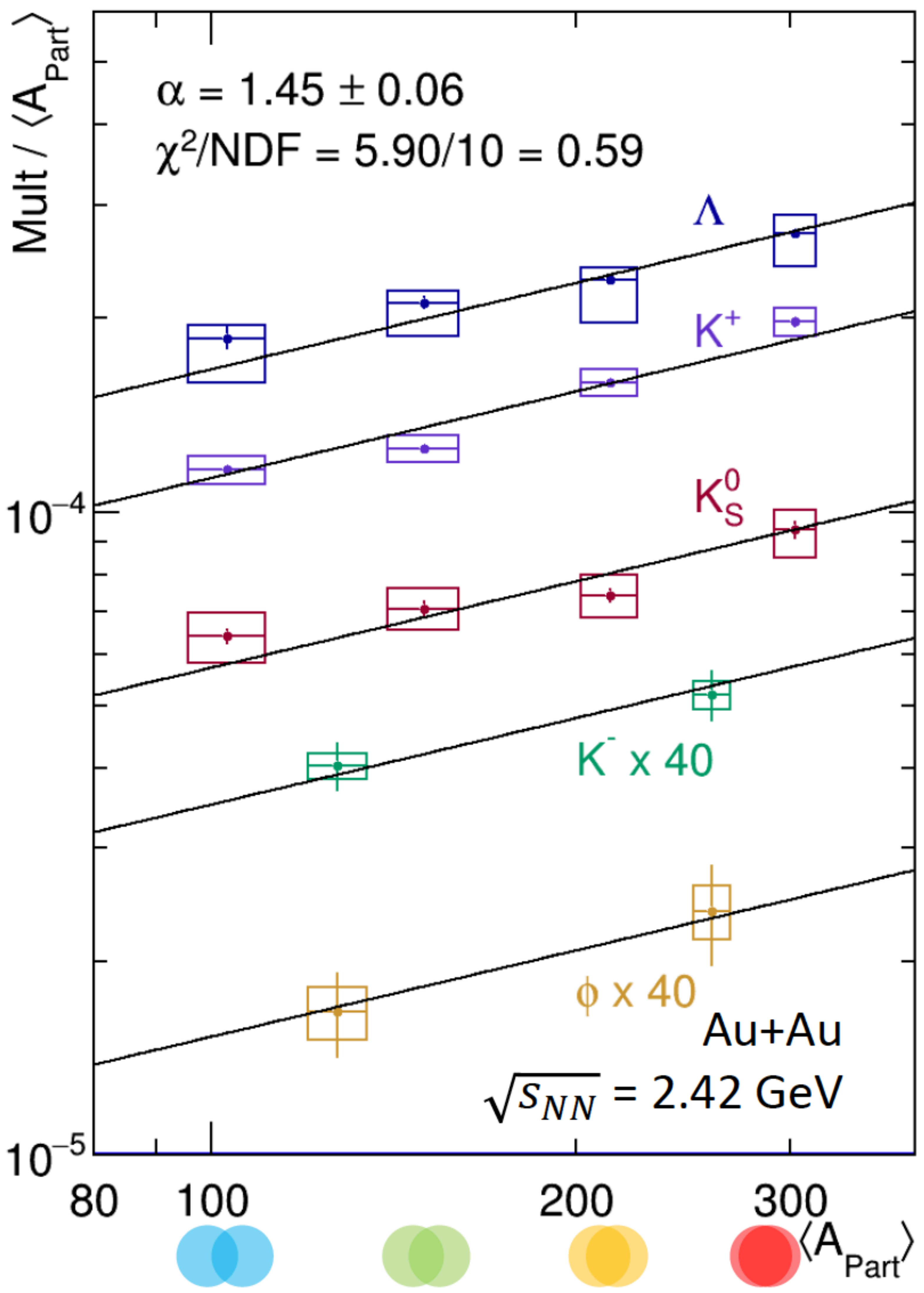
Strangeness centrality dependence

Universal scaling with centrality

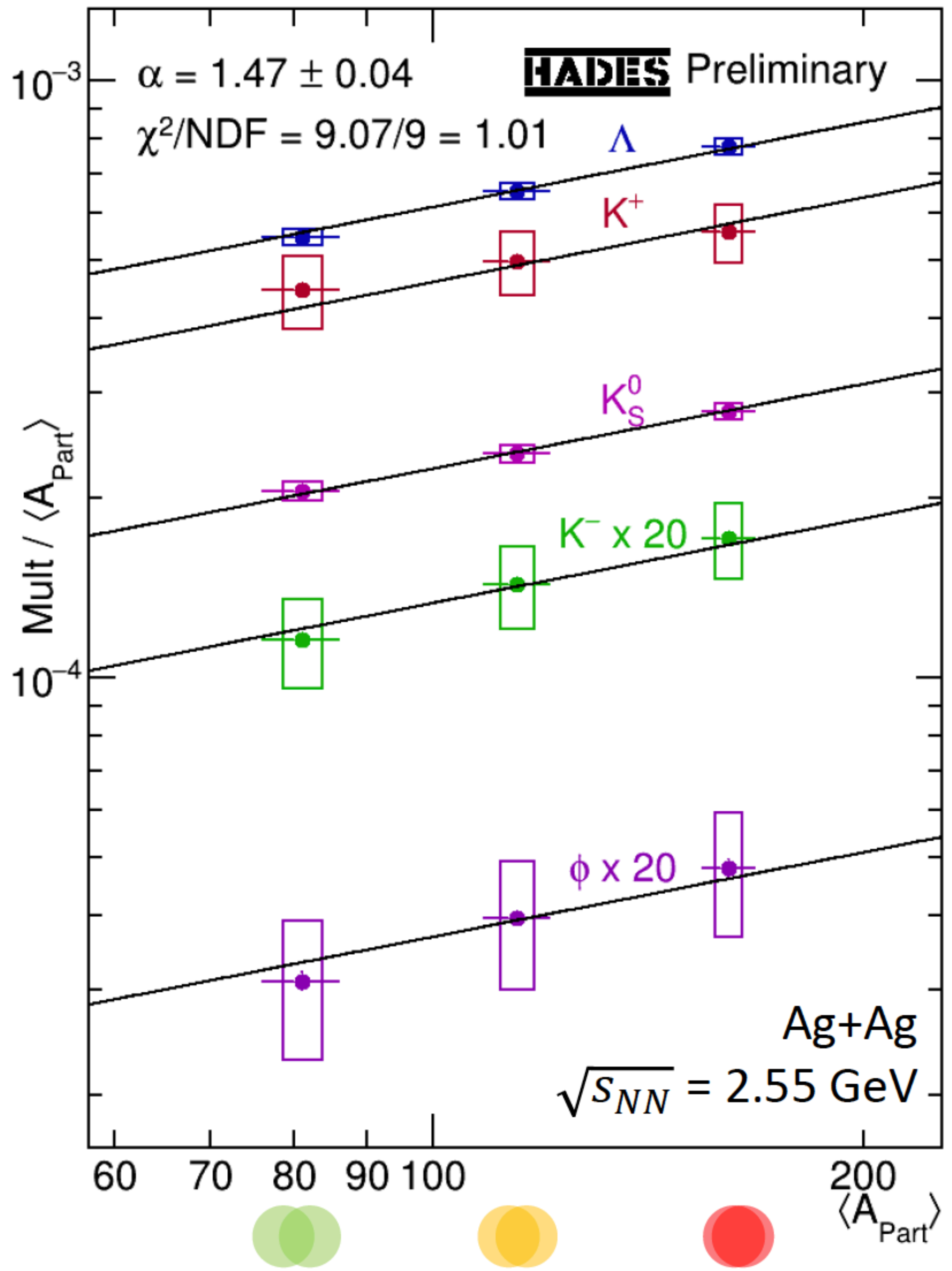
$$\text{Mult} \sim \left\langle A_{part} \right\rangle^{\alpha}$$

α_{Au-Au} = 1.45 ± 0.06

α_{Ag-Ag} = 1.47 ± 0.04



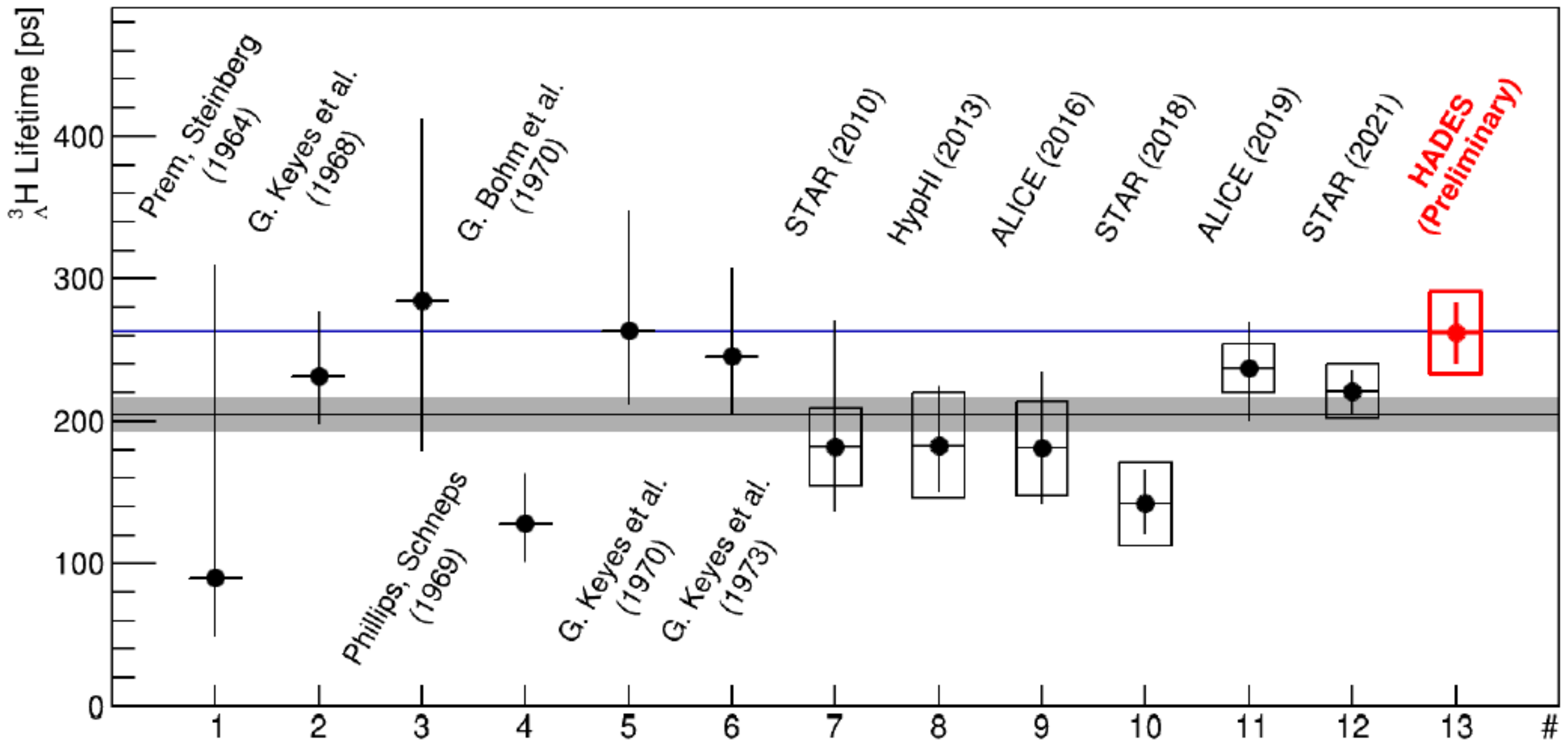
HADES: PLB 793 (2019) 457-463



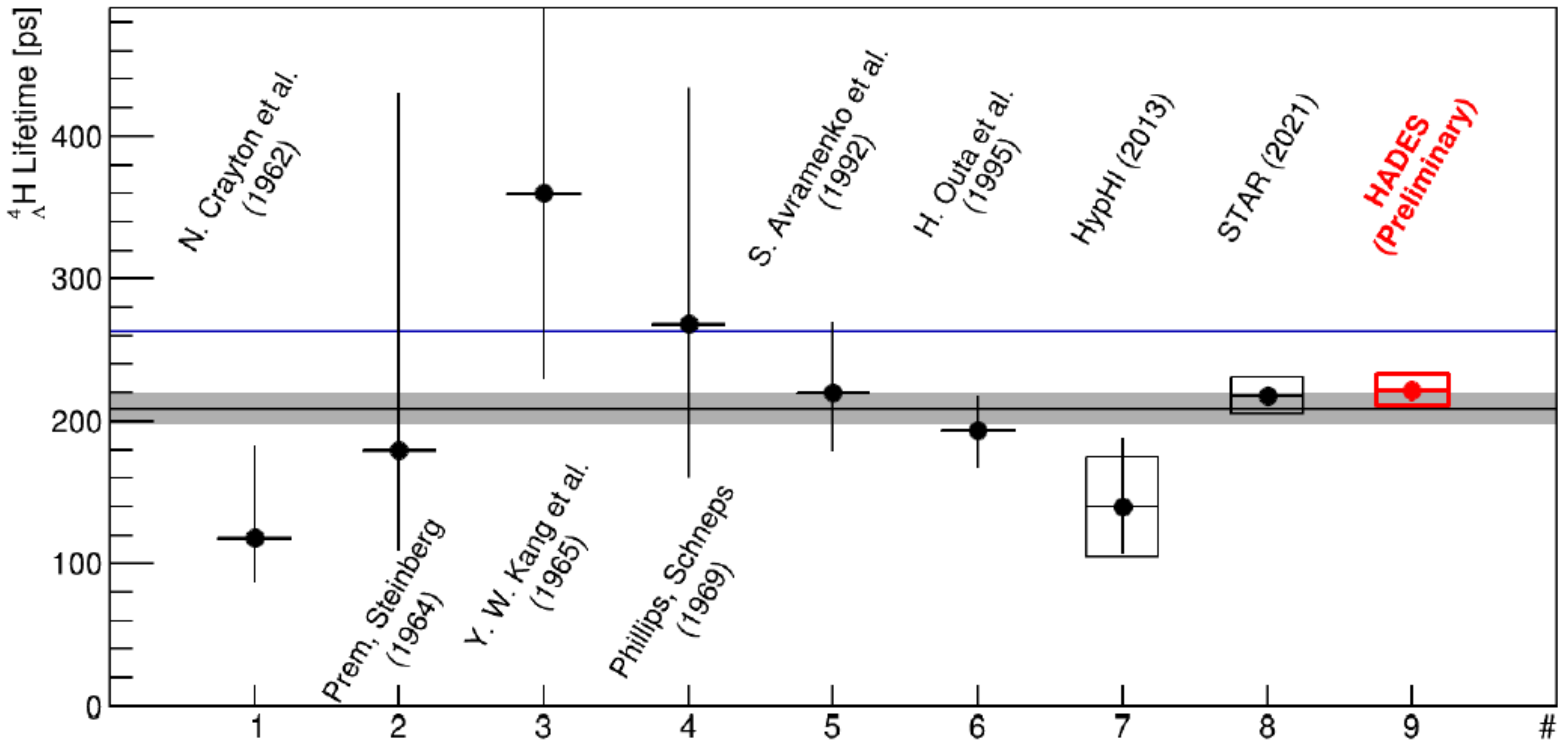
HADES: Preliminary

Hypernuclei measurements

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$



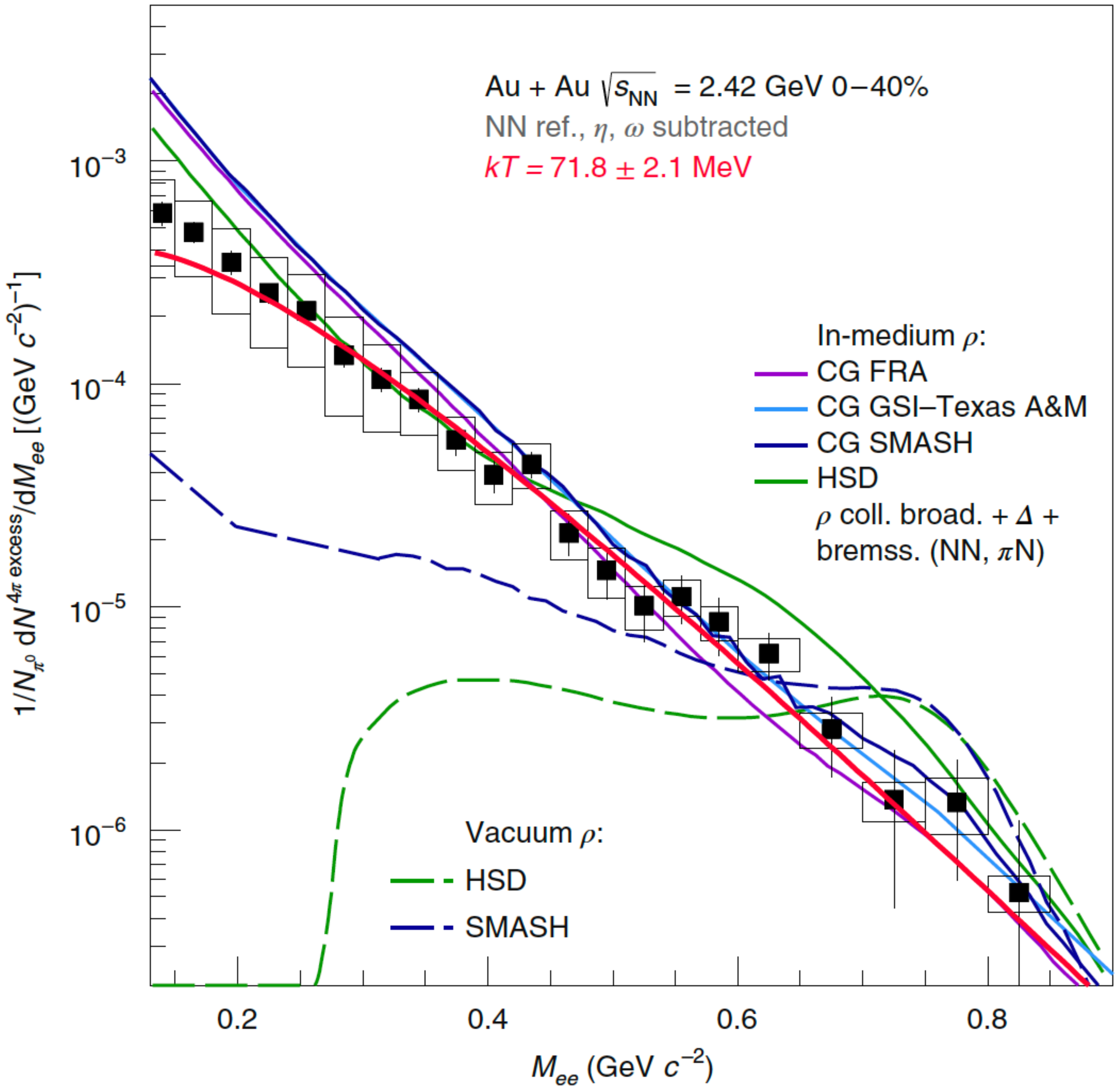
$$^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$$



measured lifetime ($262 \pm 22_{stat} \pm 28_{sys}$ ps) is comparable with that of free Λ (263 ps)

measured lifetime ($222 \pm 7_{stat} \pm 12_{sys}$ ps) is 4.7 σ below compared to free Λ lifetime (263 ps)

Understanding excess radiation



HADES: Nature Physics 15, 1040-1045 (2019)

Coarse-grained transport simulations, thermal ρ emission

dilepton rate from a thermlized source (rho meson) at T and

$dN/dM_{ee} \sim M_{ee}^{3/2} exp(-M_{ee}/T)$ ⟶ T = 71.8 ± 2.1 MeV

The HADES data suggests a strong ρ broadening

(may) evidence partial restoration of chiral symmetry

S. Endres et al., Phys.Rev.C 92 (2015) 1, 014911
T. Galatyuk et al., Eur.Phys.J.A 52 (2016) 5, 131
Including in-medium spectral functions:
R. Rapp,J. Wambach, H. van Hees, Landolt-Bornstein 23 (2010) 134

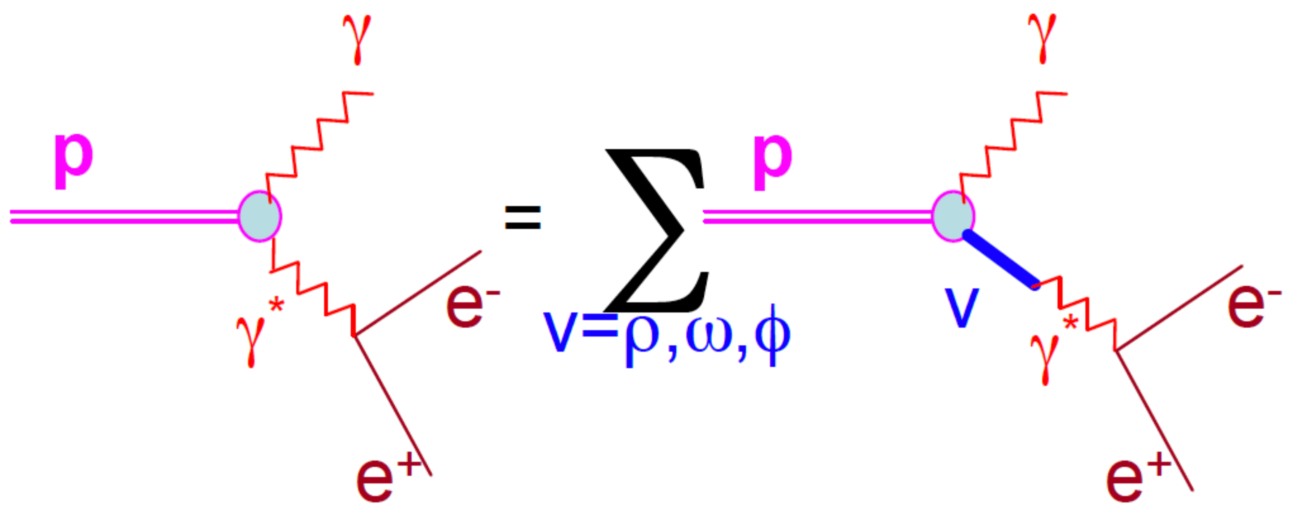
Is this measurement connected to Chiral Symmetry Restoration?

technically yes, via e.g., QCD sum rules

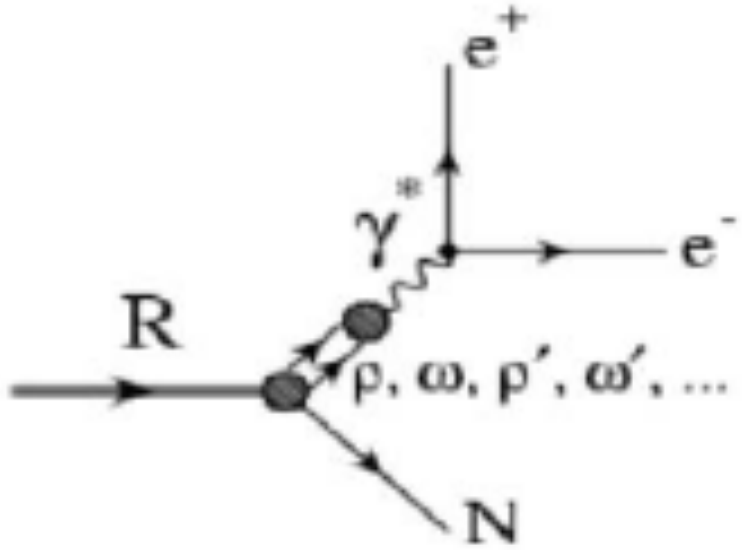
$$\frac{1}{\pi}\int_0^\infty ds \frac{\rho(s)}{s-q^2} = \sum_i C_i(q^2)\langle O_i \rangle$$

Electromagnetic transition form factors

ELECTROMAGNETIC TRANSITION FORMFACTORS

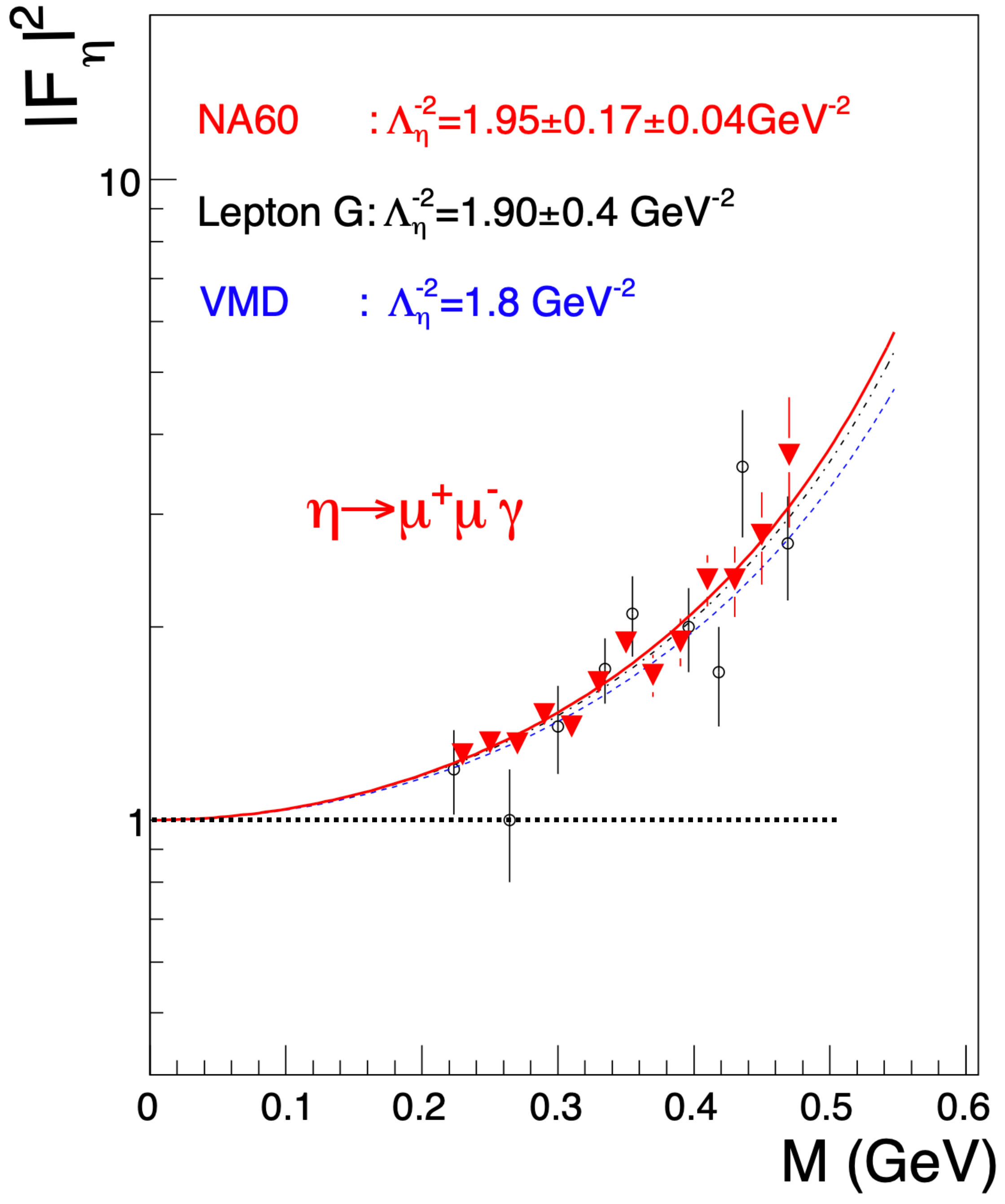


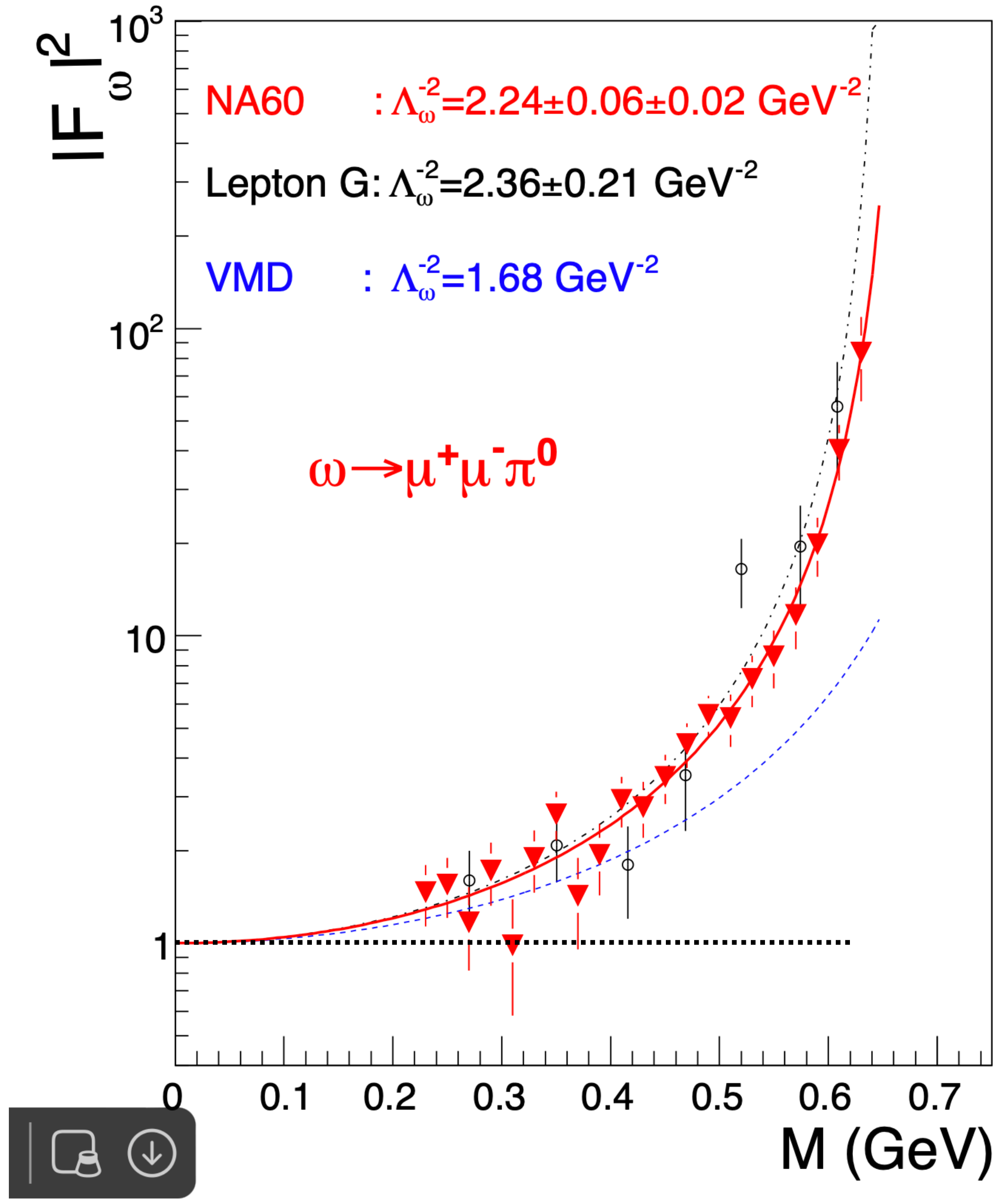
$$\left[\frac{d\Gamma}{dM_{ee}}\right]_{exp} = \left[\frac{d\Gamma}{dM_{ee}}\right]_{QED} \left|F(M_{ee})\right|^2$$

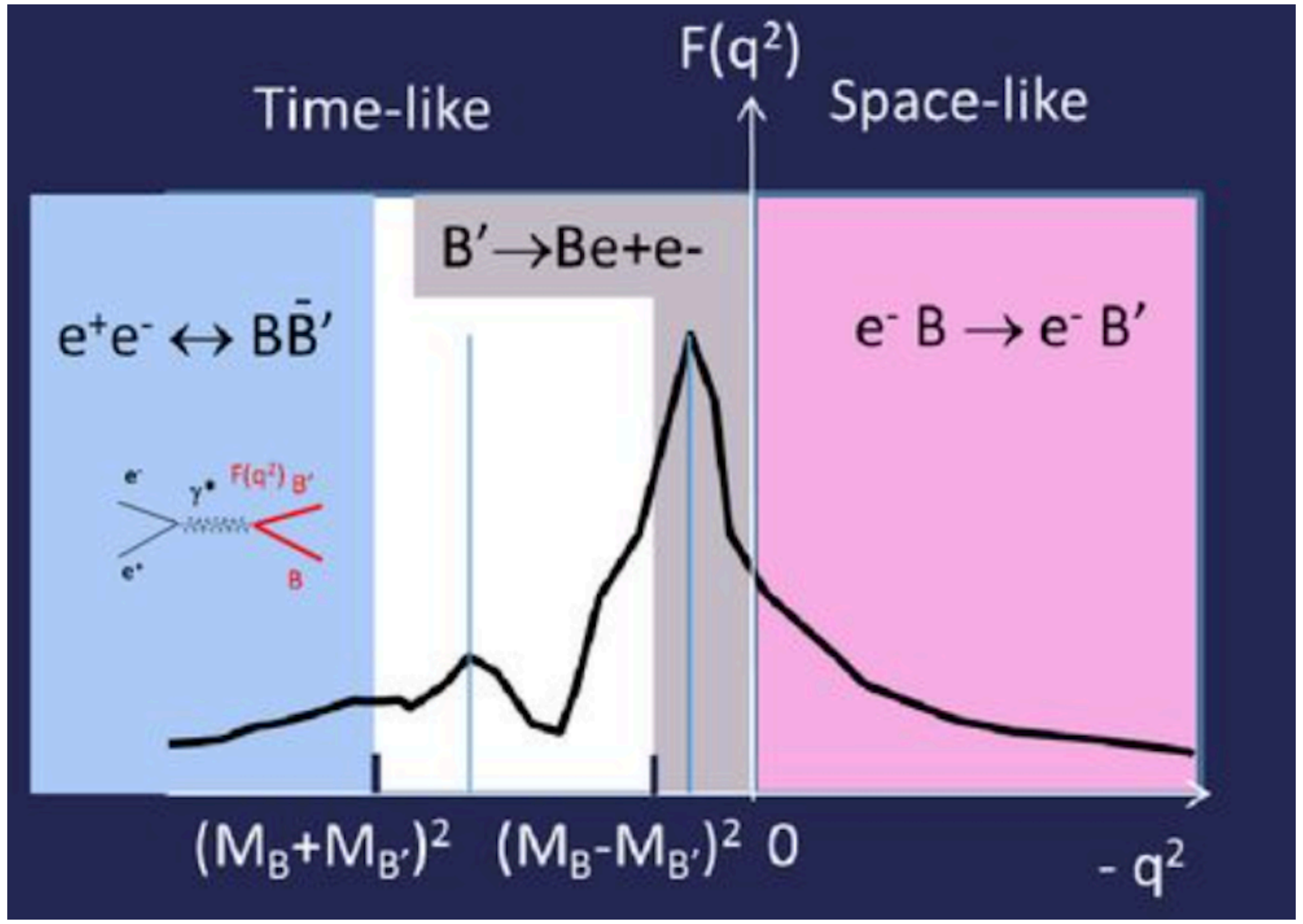


$$\left|F_\eta\right|^2 = \left(1 - \frac{M^2}{\Lambda_\eta^2}\right)^{-2}$$

$$\left|F_\omega\right|^2 = \frac{\Lambda_\omega^4}{\left(\Lambda_\omega^2 - M^2\right)^2 + \Lambda_\omega^2\Gamma_\omega^2}$$







first measurement from HADES

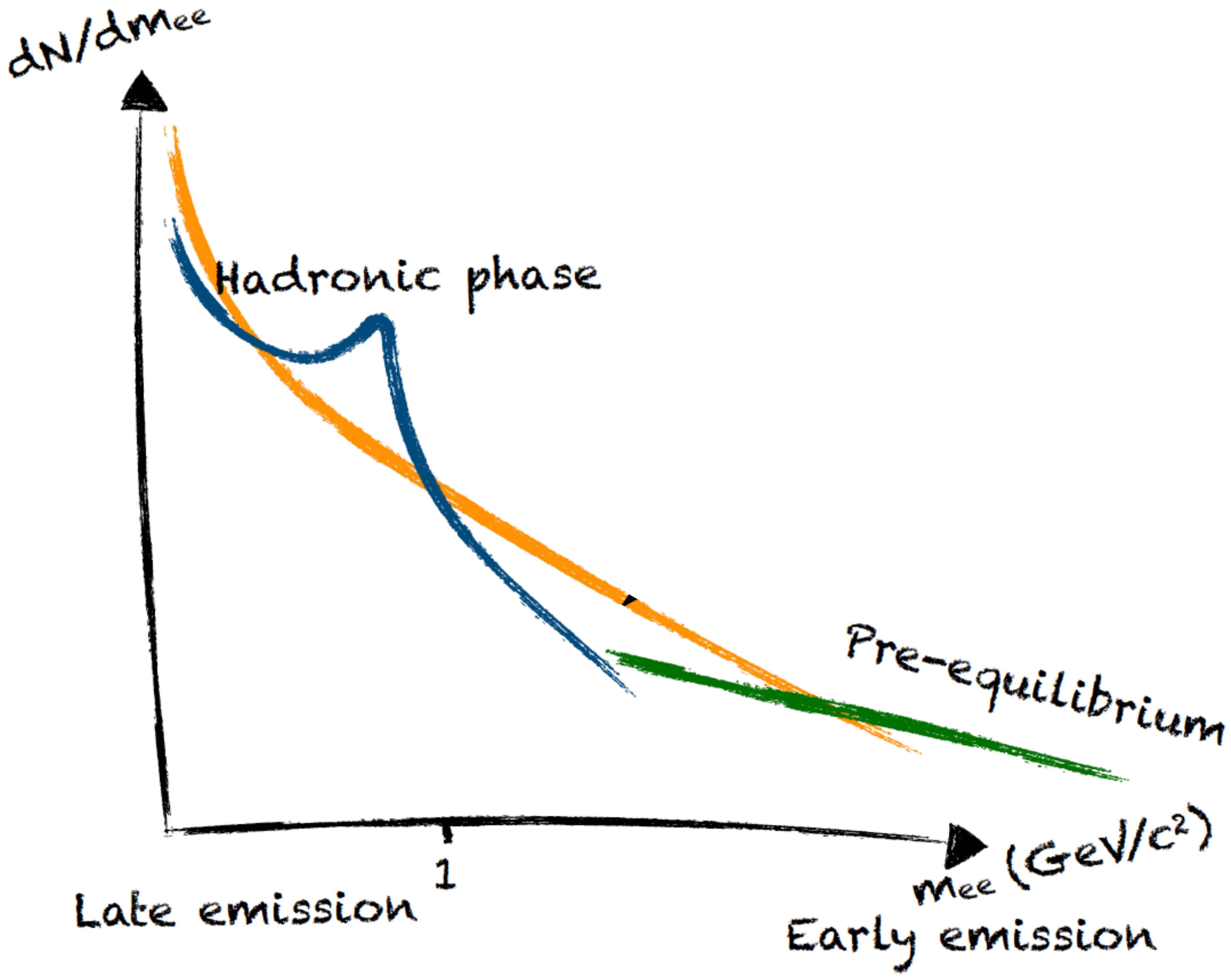
HADES: 2205.15914 [nucl-ex]

NA60: Phys.Lett.B 677 (2009) 260-266

C. Terschlusen, S. Leupold, Phys.Lett.B 691 (2010) 191-201

Probing a matter with dileptons

changes in medium ⟷ modification in hadron properties

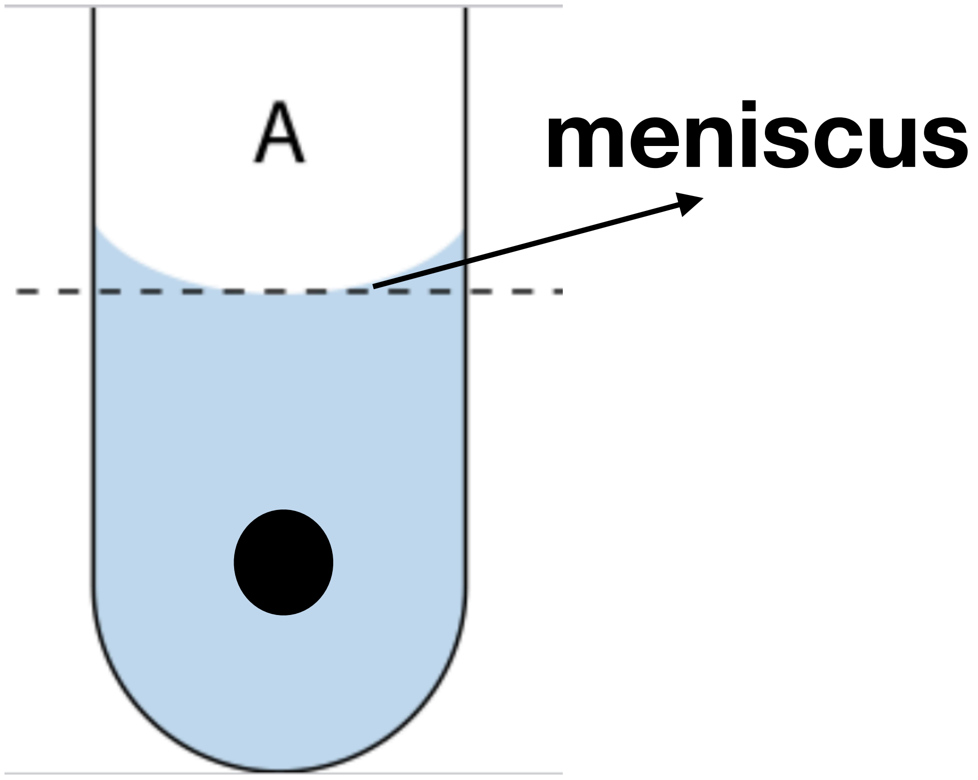


Probing hadron properties through their dilepton decays

- Advantage
  - penetrating probe (no strong interaction)
    - encodes the properties of medium
      - probes Chiral Symmetry Restoration
- Disadvantage
  - penetrating probe (no strong interaction)
    - measures only time integrated signals
    - small branching ratios (rare probes)

Critical point discoveries

discovered ~ 200 years ago



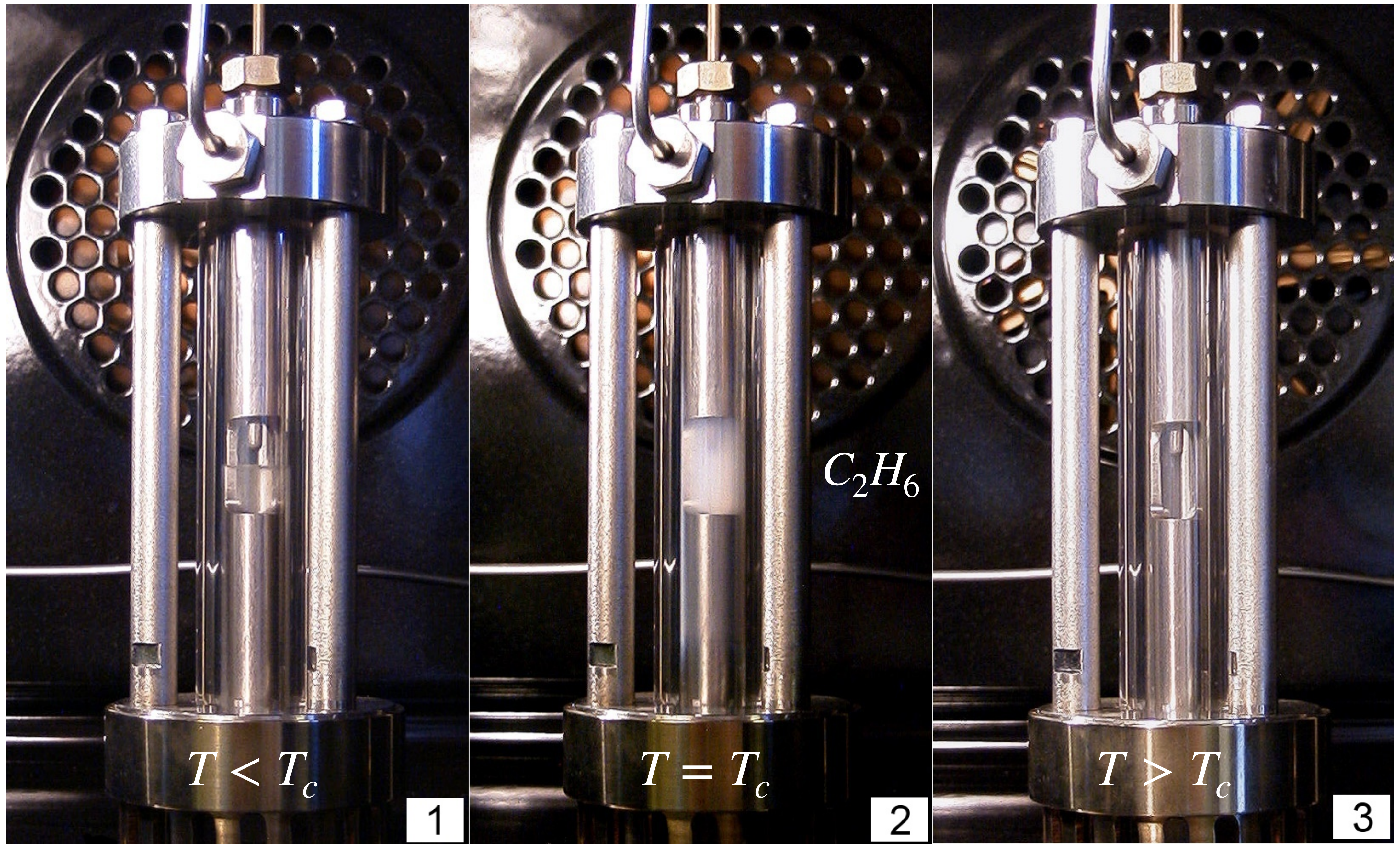
Cagniard de la Tour (1777-1859)

Ann. Chim. Phys., 21 (1822) 127-132

using steam digester
invented by Denis Papin in 1679

T_{cp}^{water} = **362 °C (today: 374 °C)**

critical opalescence



in statistical mechanics (GCE)

$$\frac{\langle \rho^2 \rangle - \langle \rho \rangle^2}{\langle \rho \rangle^2} = \frac{T\chi_T}{V}$$

density fluctuations

A. Einstein, Annalen der Physik, Volume 338, Issue 16, 1910:

$$h \sim \frac{1}{\lambda^4}\chi_T$$

By listening to the system ⟵ **discovering critical point** ⟶ **By watching the system**