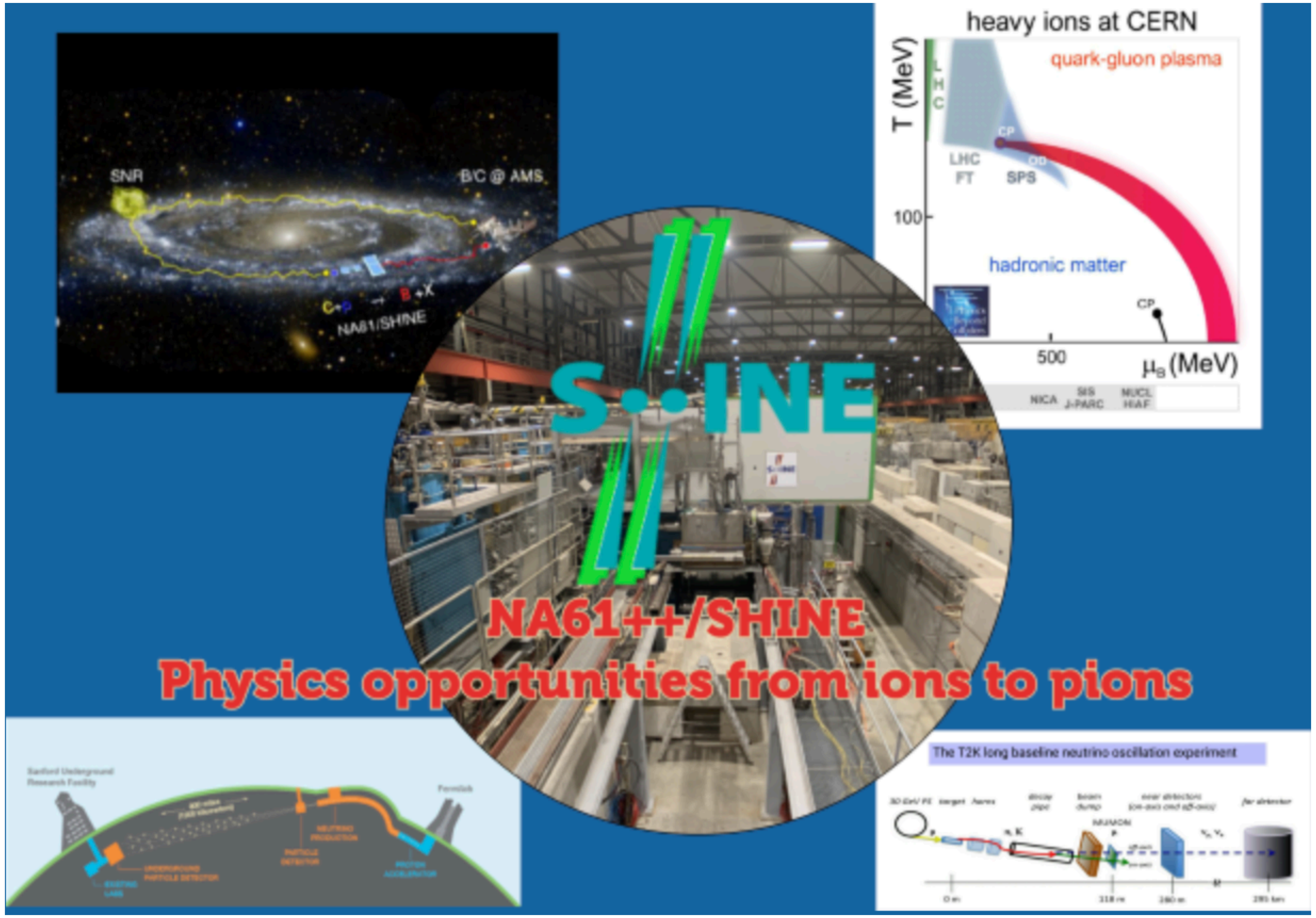
The HADES experiment at GSI
current status and future prospects



Anar Rustamov

for the HADES Collaboration

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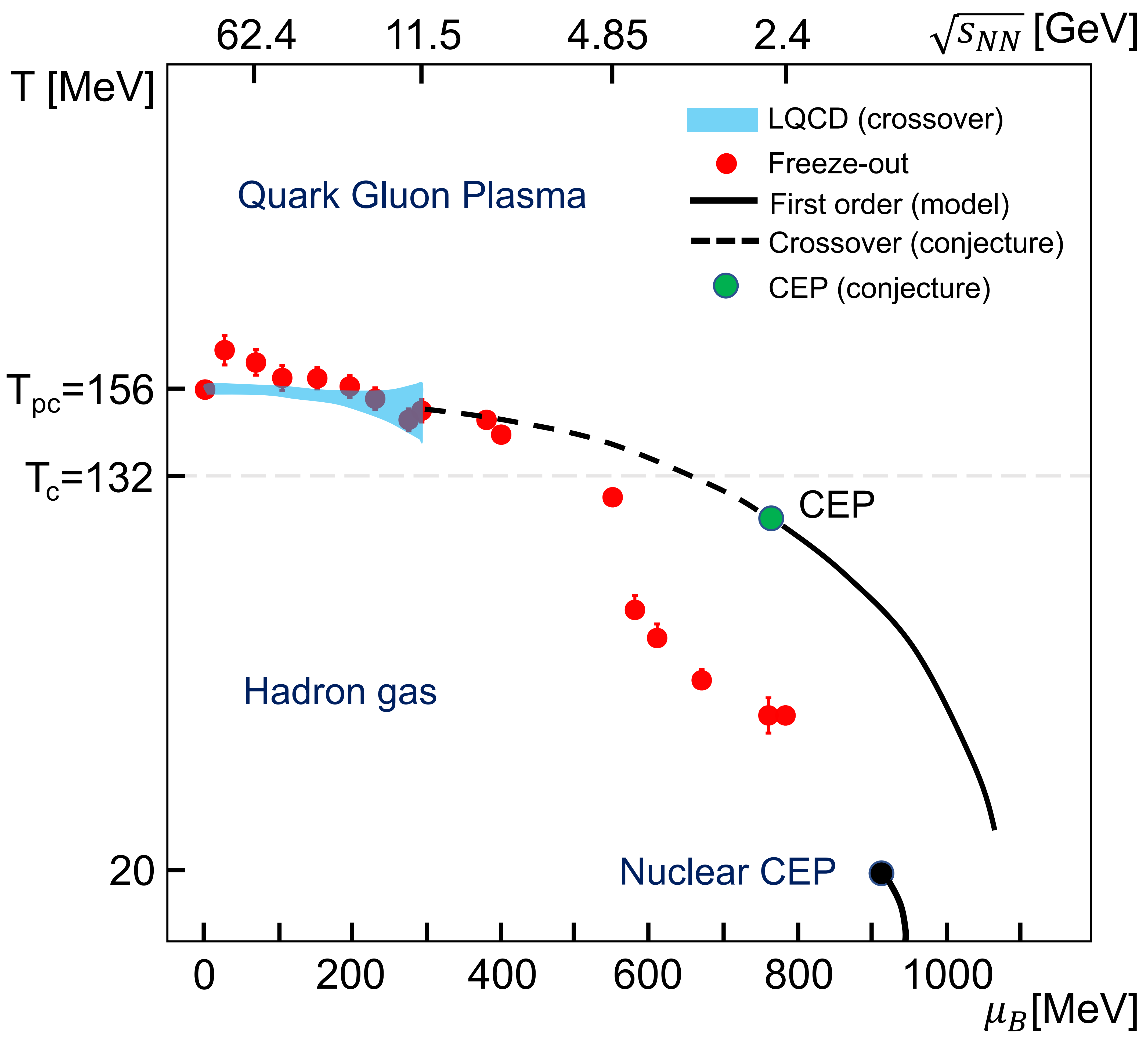
Phase structure of strongly interacting matter



A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature 561, 321–330 (2018)
H. T. Ding et al [HotQCD], arXiv:1903.04801, A. Bazavov et al [HotQCD], arXiv:1812.08235

- **The ultimate goal**
  - deciphering the phase structure of QCD matter
- **Promising observables (covered in this talk)**
  - fluctuations of conserved charges
  - penetrating probes
  - strangeness production phenomenology

experimentally neither crossover transition

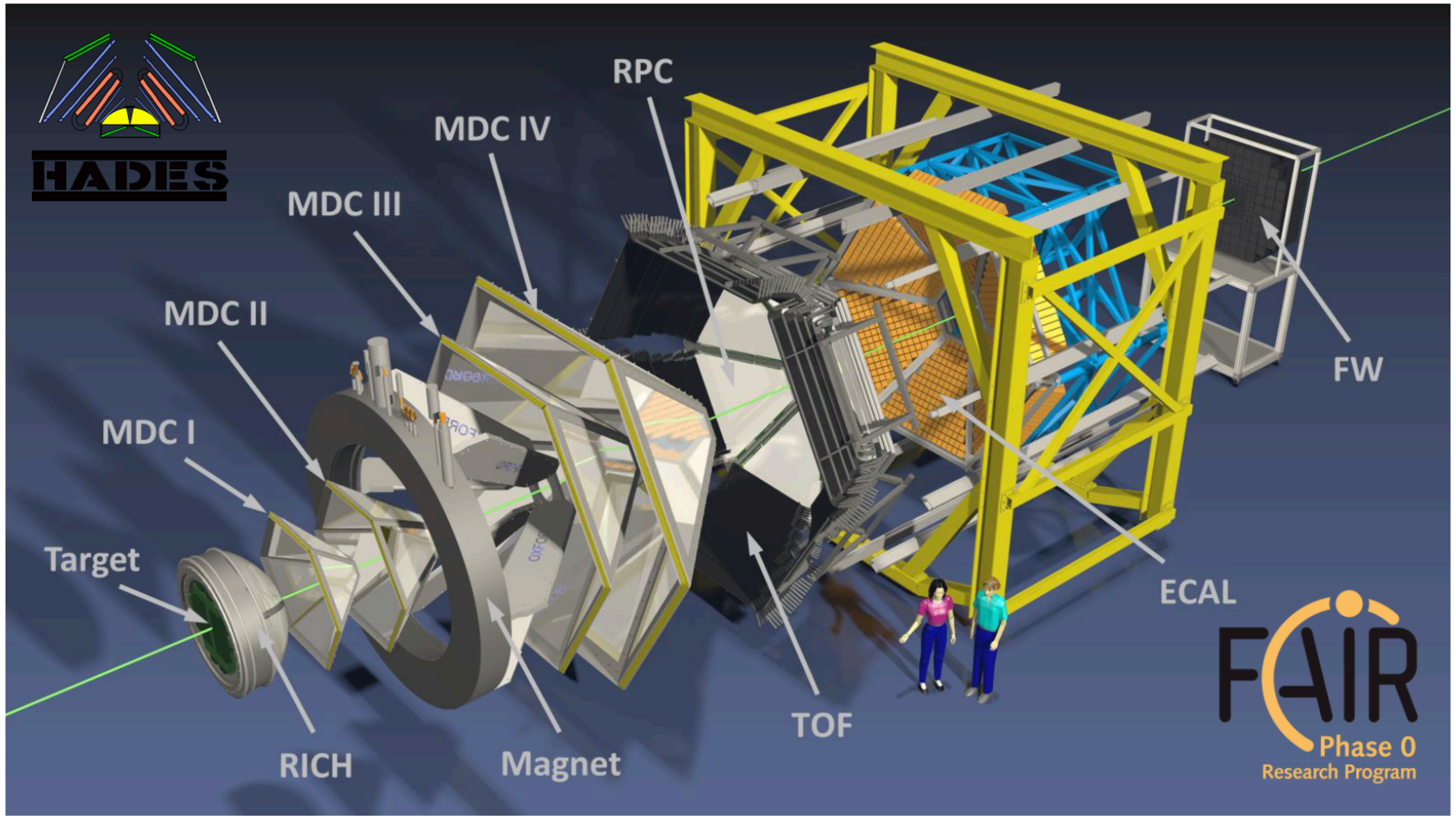
no critical point are discovered to date

(more efforts are needed)

P. Braun-Munzinger, AR, J. Stachel, 2211.08819 [hep-ph]

The HADES apparatus

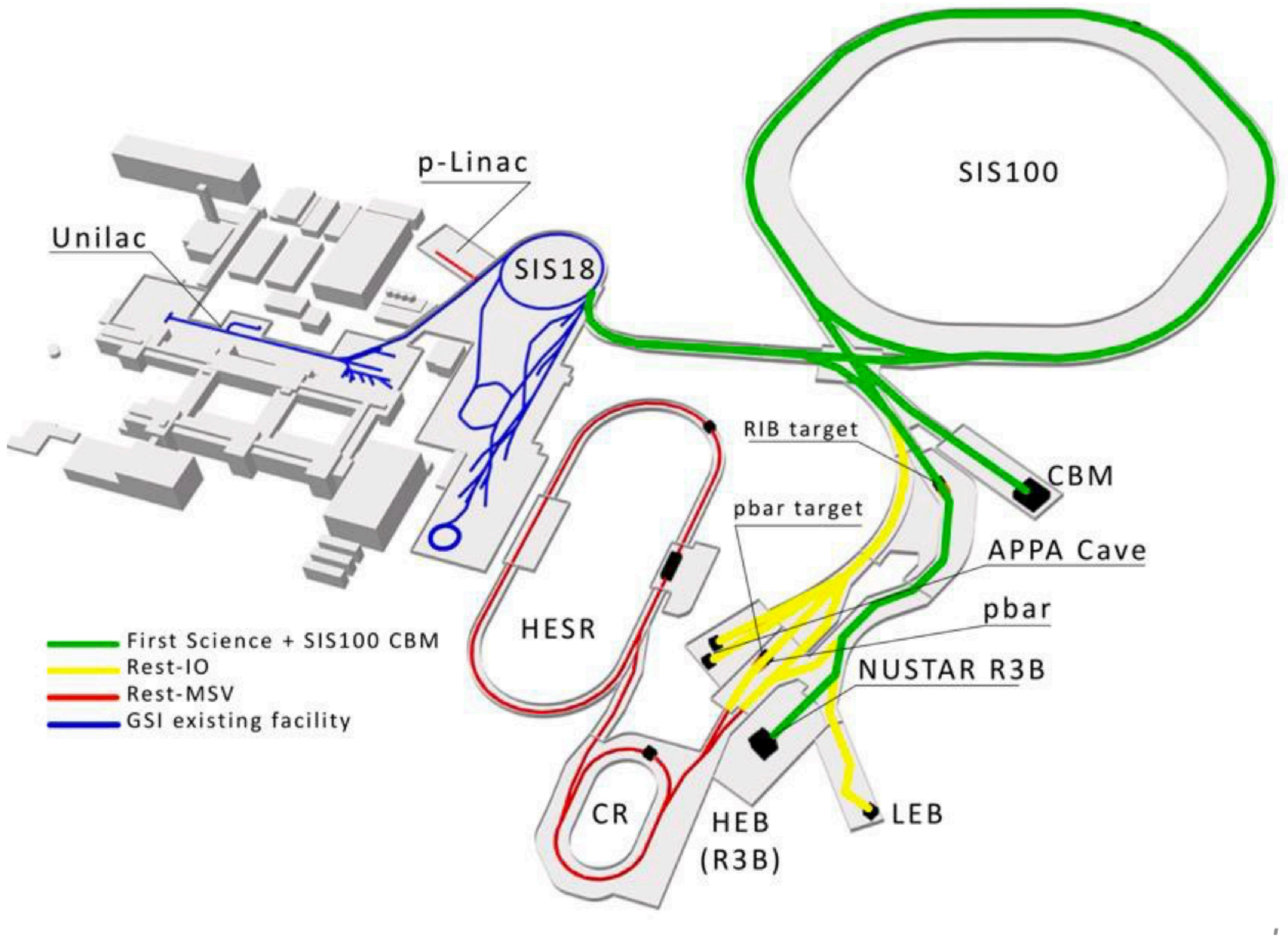
High **A**cceptance **D**i-**E**lectron **S**pectrometer



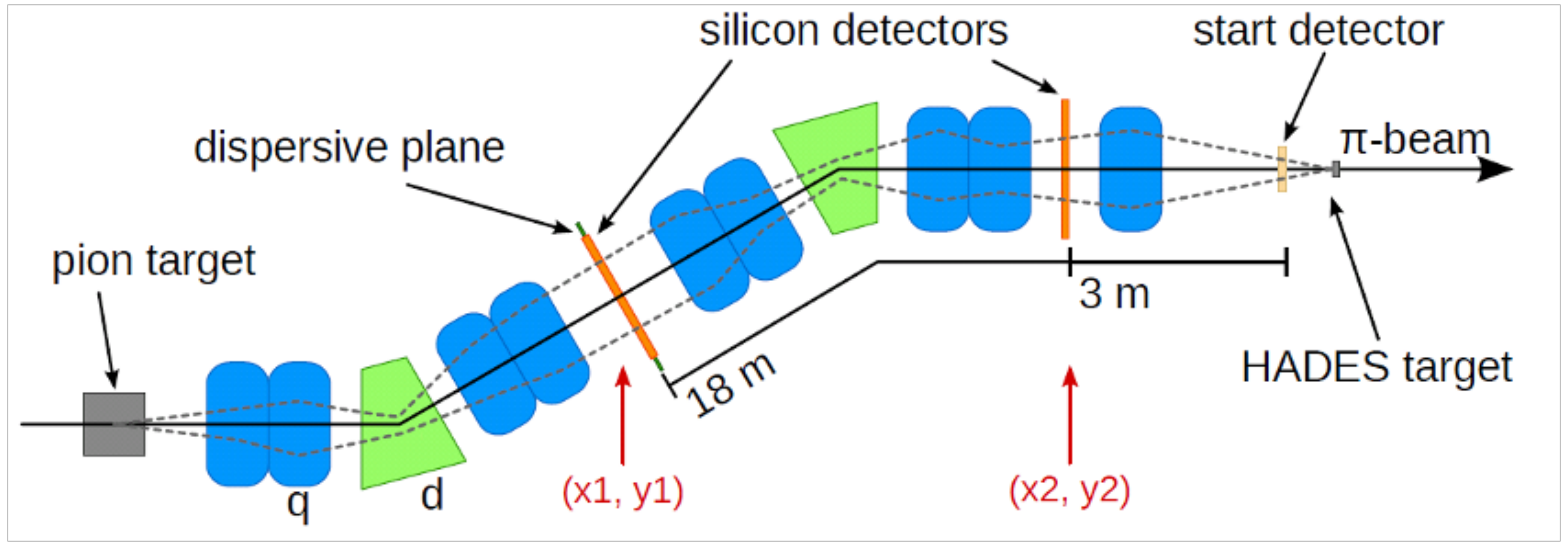
Specifications

- **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



HADES 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**

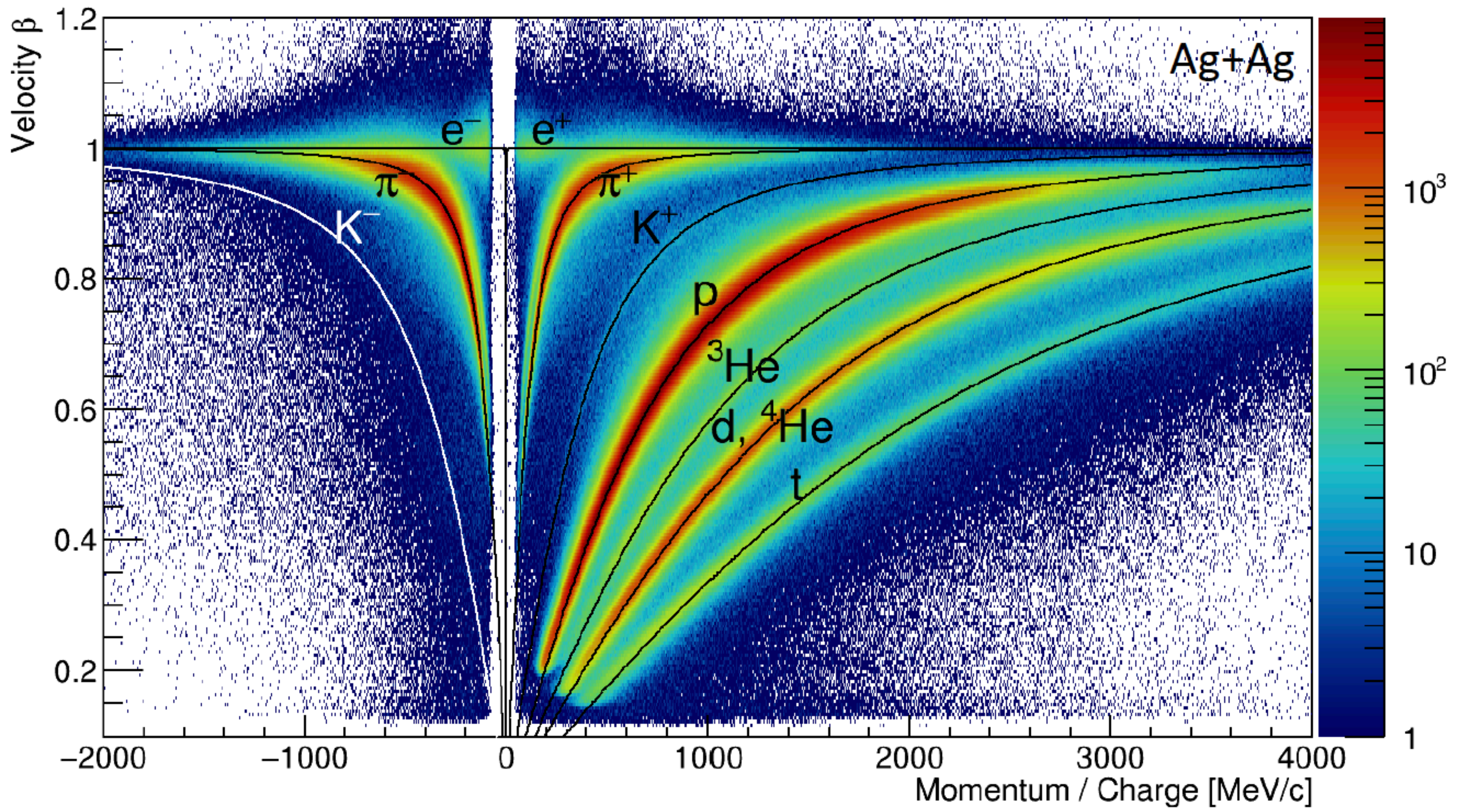
Proton (deuteron) beam

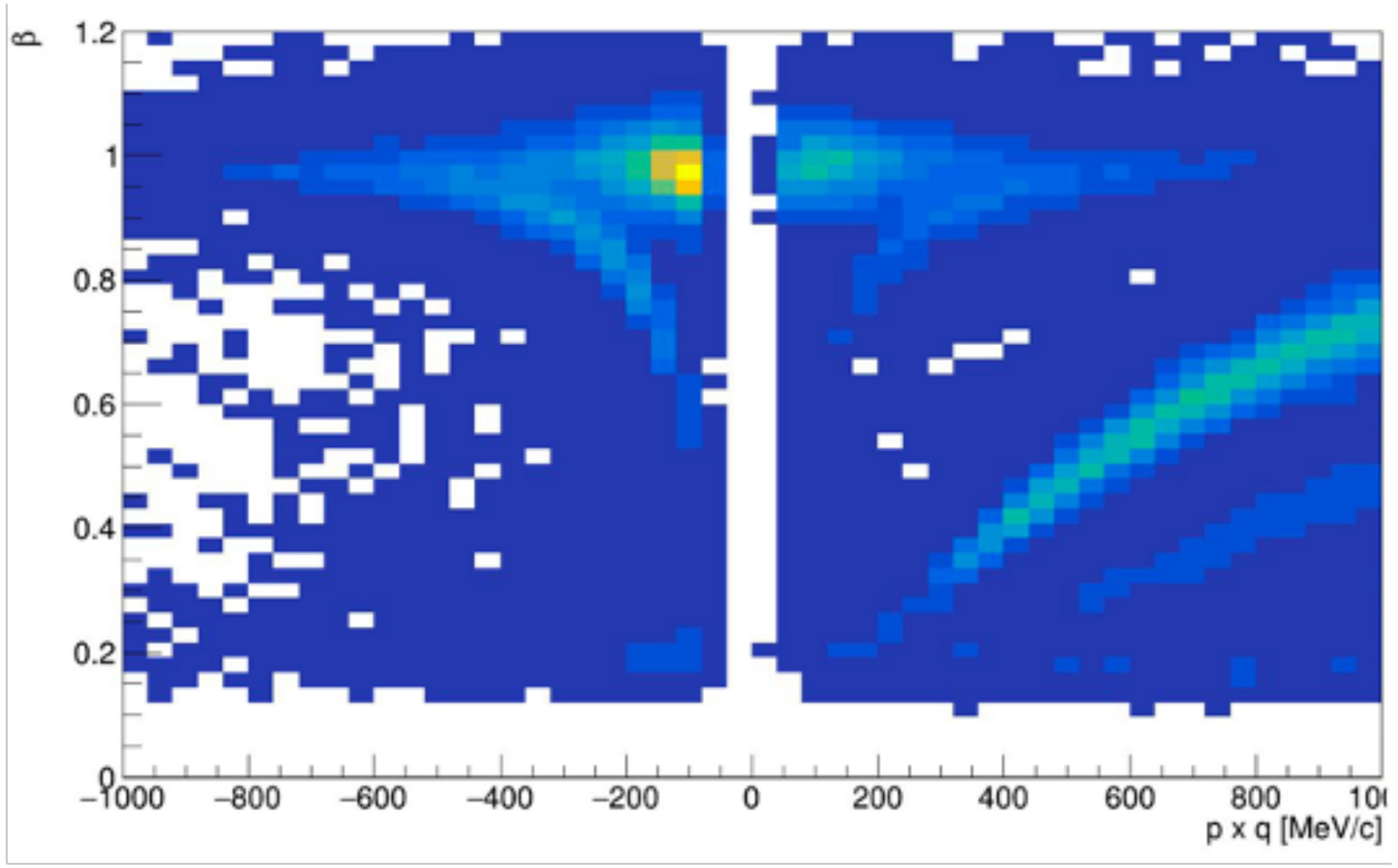
Date	Reaction	$\sqrt{s_{NN}}$ [GeV]
Jan 2004	p+p	2.77
Apr 2006	p+p	2.42
Apr 2007	p+p	3.18
Apr 2007	d+p	2.42
Sep 2008	p+Nb	3.18
Feb 2022	p+p	3.46

Pion beam

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

Particle identification capabilities





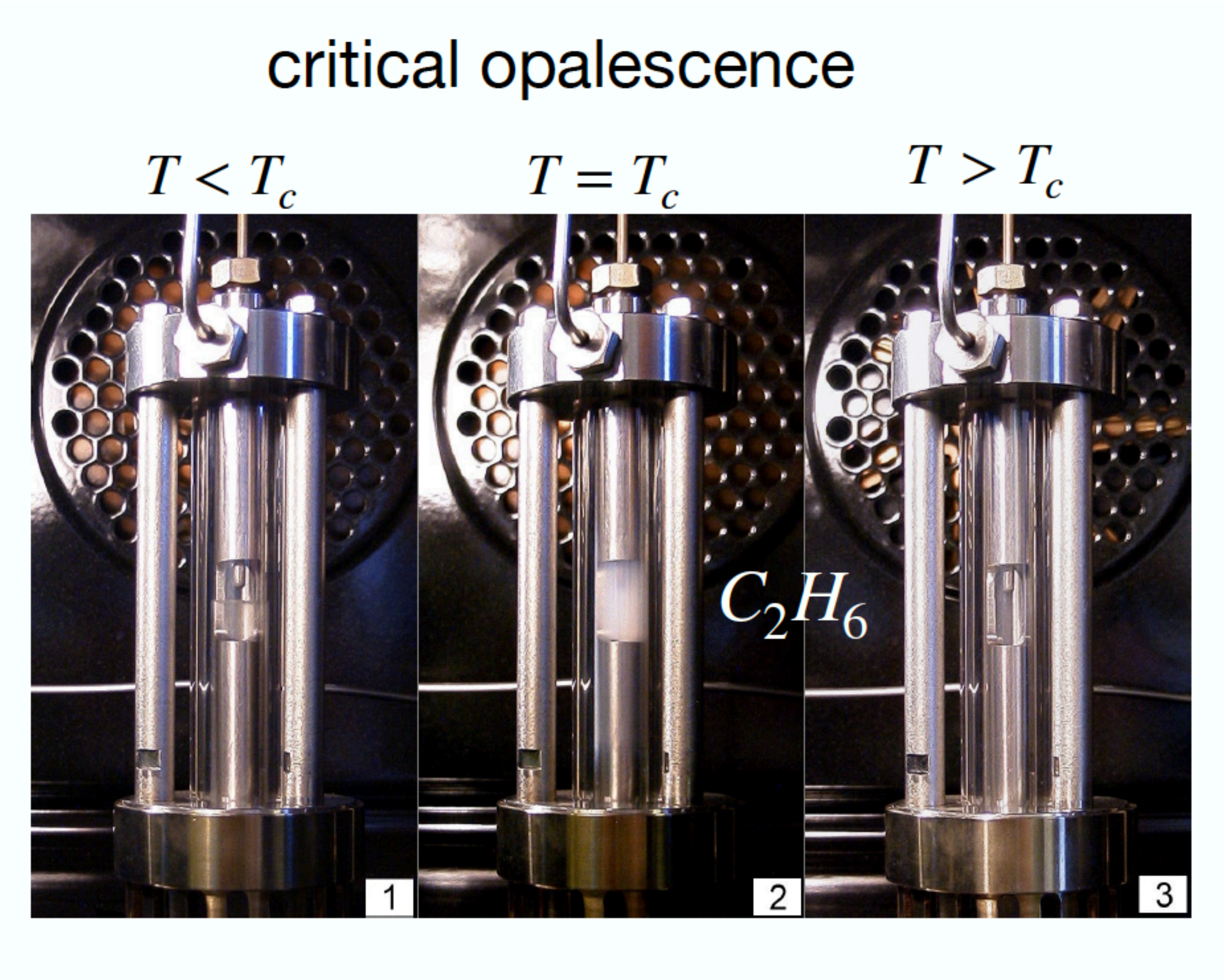
with ring matching + time cut

- Excellent particle identification by correlating measured momenta and velocities of different particle species

- Upgraded RICH photo-detection plane (with CBM)
  - significantly improved lepton identification
  - excellent timing precision

E-by-E Fluctuations

E-by-E fluctuations



caused by enhanced density fluctuations

A. Einstein, Annalen der Physik, Volume 338, Issue 16, 1910: $h \sim \frac{1}{\lambda^4}\chi_T$

E-by-E fluctuations are direct probes of critical phenomena

predicted within Grand Canonical Ensemble

direct link to EoS

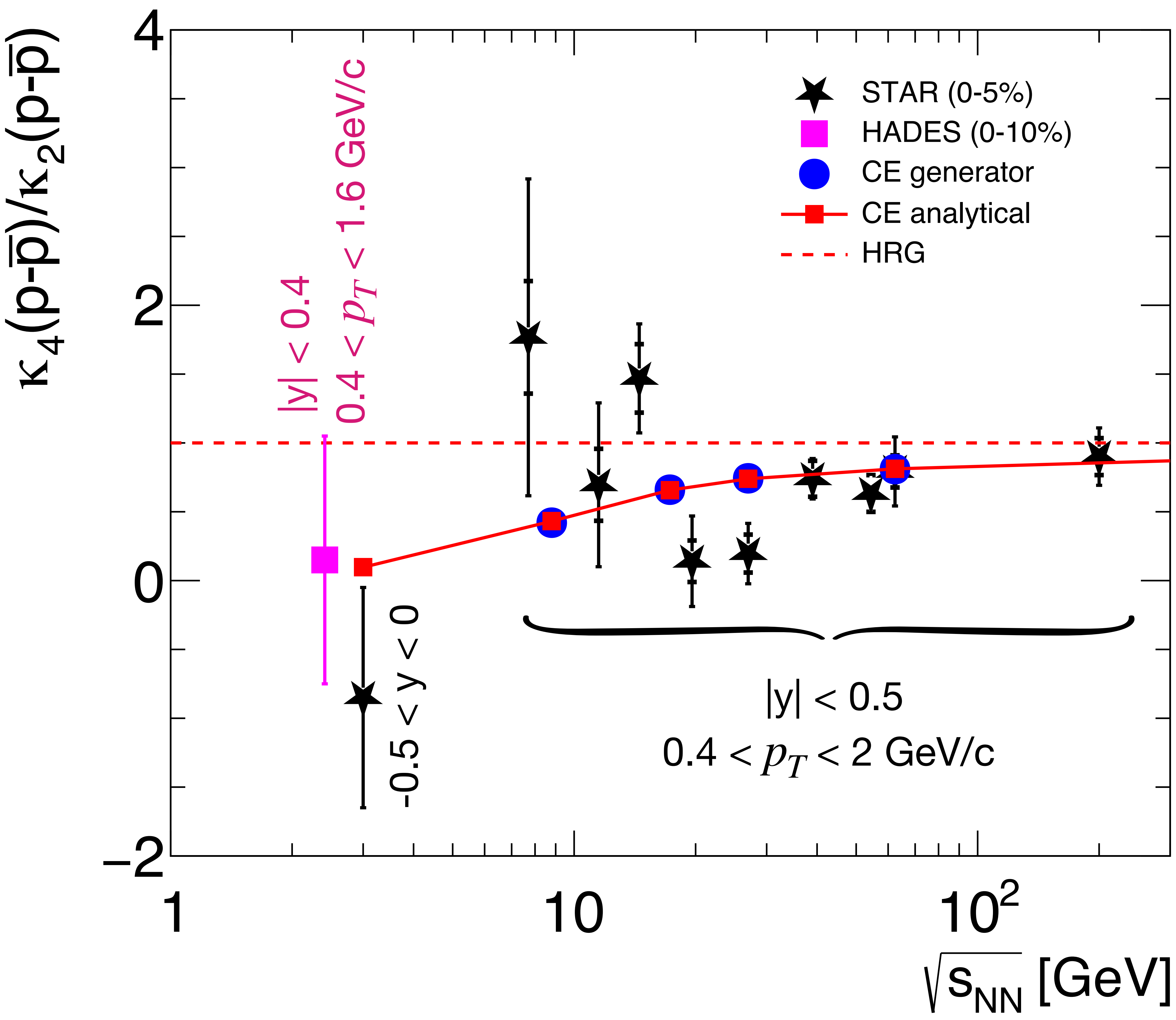
$$\frac{\kappa_n(N_B - N_{\bar{B}})}{VT^3} = \frac{1}{VT^3}\frac{\partial^n lnZ(V,T,\mu_B)}{\partial\left(\mu_B/T\right)^n} \equiv \hat{\chi}_n^B$$

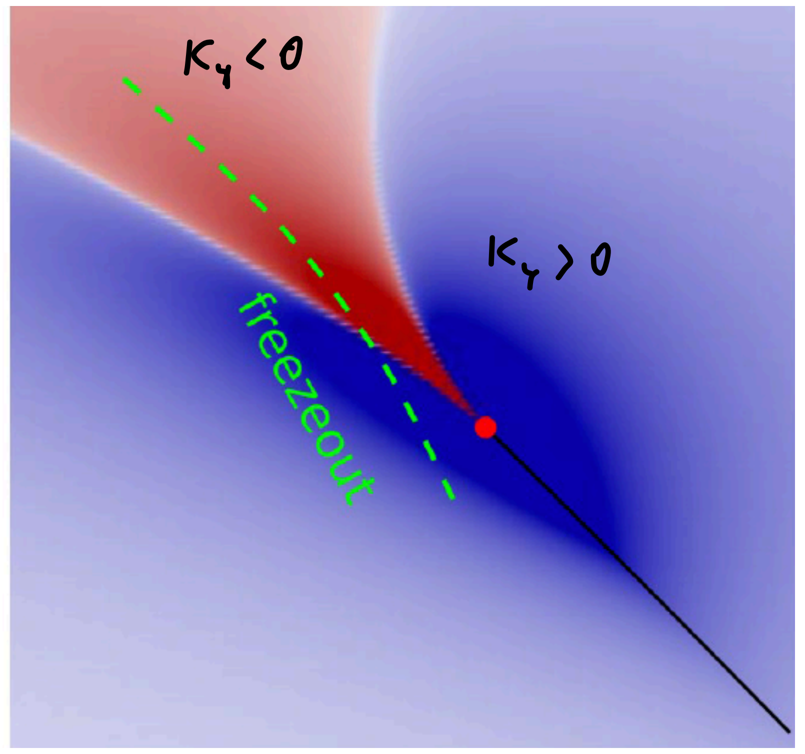
κ_n - cumulants (measurable in experiment)

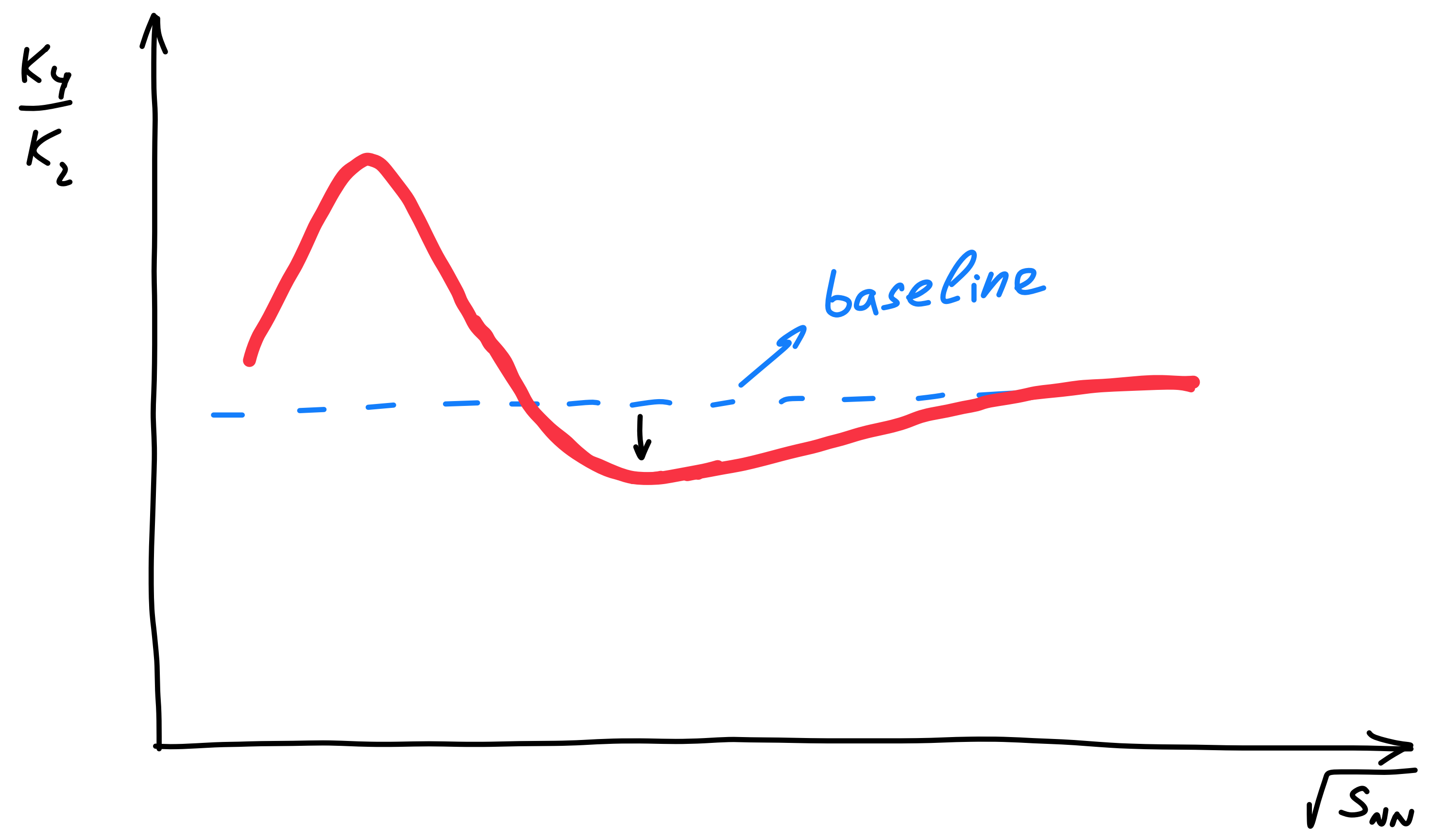
$\hat{\chi}_n^B$ - susceptibilities (e.g. from lQCD)

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

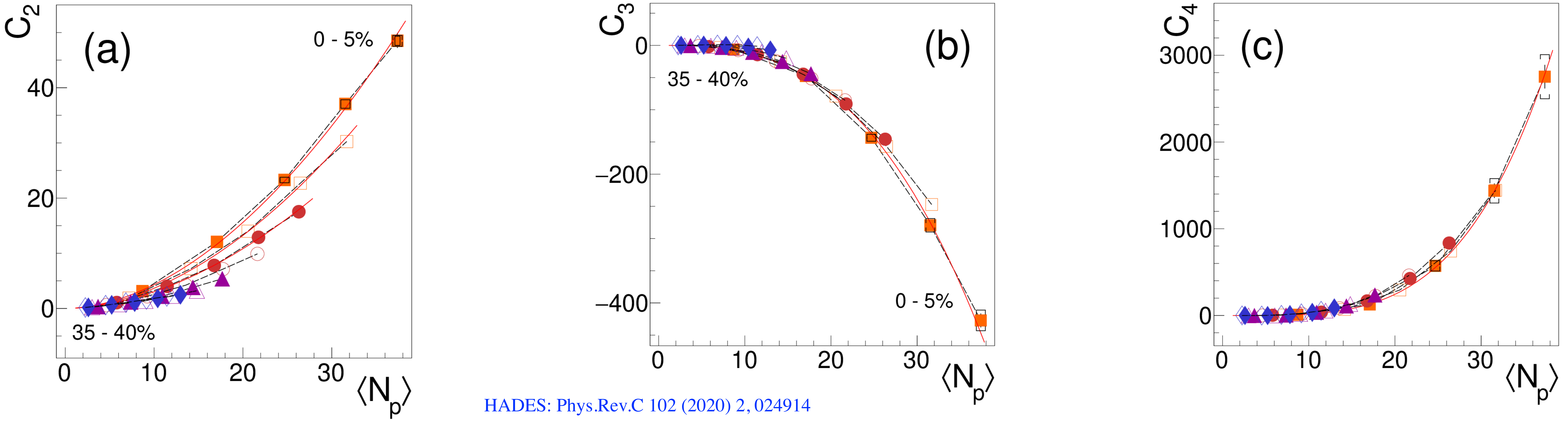
non-monotonic behaviour with a significance of 3.1σ relative to Skellam expectation

CE Baseline: P. Braun-Munzinger, B. Friman, K. Redlich, AR, 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)

see also: V. Vovchenko, V. Koch, Ch. Shen, Phys.Rev.C 105 (2022) 1, 014904

higher statistics is needed for unambiguous conclusions



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

$\kappa_2 = \kappa_1 + C_2$ $\kappa_3 = \kappa_1 + 3C_2 + C_3$ $\kappa_4 = \kappa_1 + 7C_2 + 6C_3 + C_4$

$$\rho_2(y_1, y_2) = \rho(y_1)\rho(y_2) + C_2(y_1, y_2)$$

$$\langle n^2 \rangle - \langle n \rangle^2 = \langle n \rangle + \boxed{\int C_2(y_1 y_2) dy_1 dy_2}$$

integrated correlation function: C_n

B. Ling, M. Stephanov, PRC 93 (2016) 034915
A. Bzdak, V. Koch, N. Strodthoff, PRC 95 (2017) 054906
V. Vovchenko, V. Koch, *Phys.Lett.B* 833 (2022) 137368

- $\langle N_p \rangle$ - mean number of protons in selected $y_0 \pm \Delta y$
- Δy = 0.1, 0.2, 0.3, 0.4, 0,5

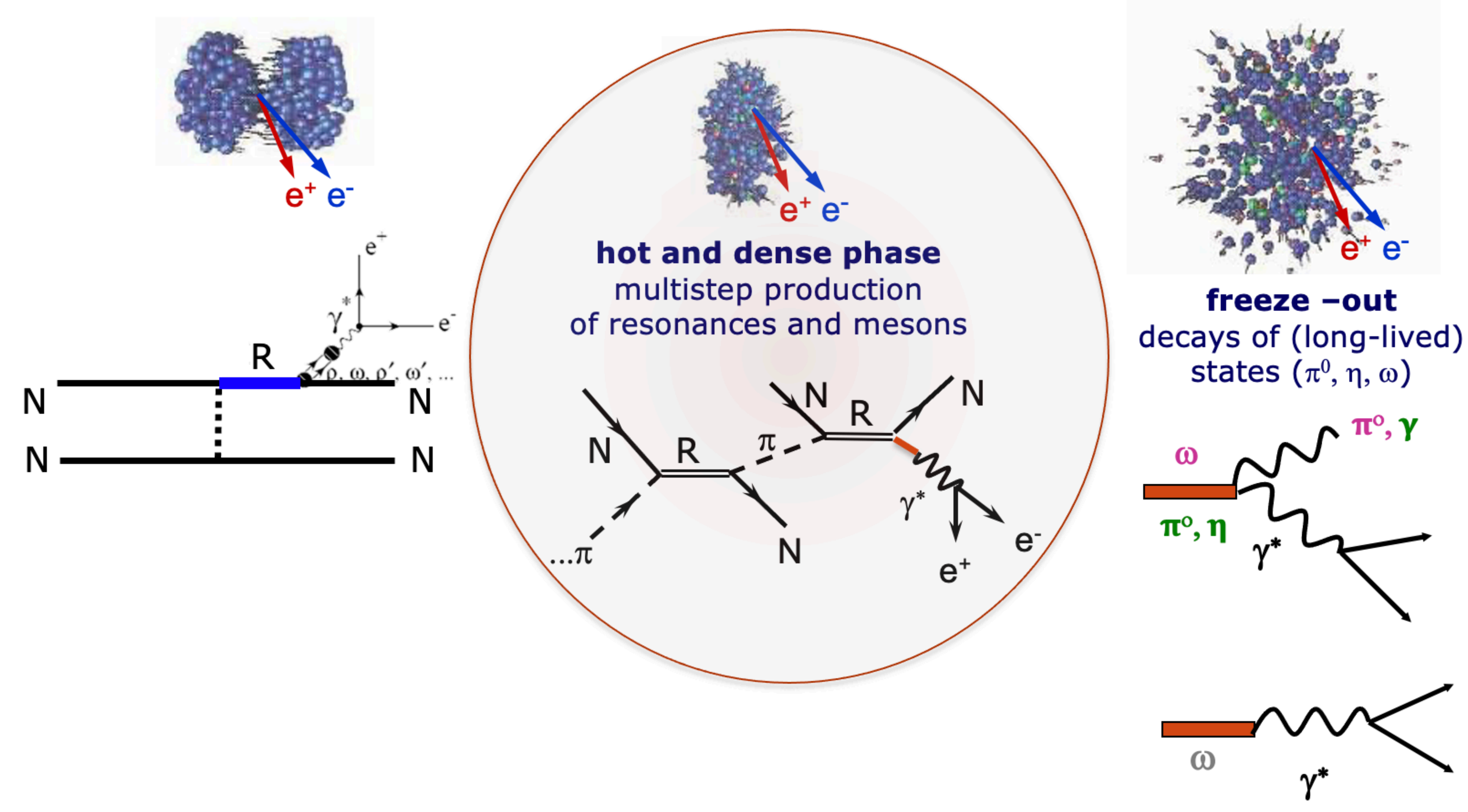
large values for integrated correlation functions

- do data imply multi-cluster formation?
- what is the mechanism behind?

Electromagnetic radiation

Electromagnetic radiation

Dilepton sources at E_{kin} = 1-3 A GeV

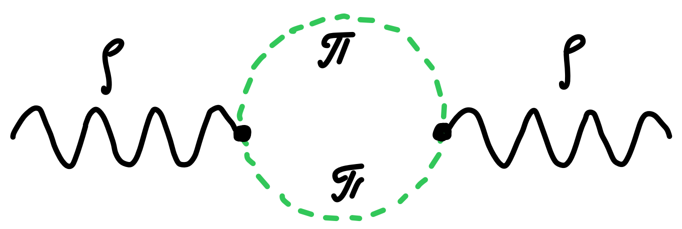


form factors in time-like domain are essential for all 3 stages

- **source:** vector mesons embedded into matter
  - promising candidate: ρ(770) meson, $c\tau$=1.3 fm/c
- access via **penetrating probes** (dileptons)

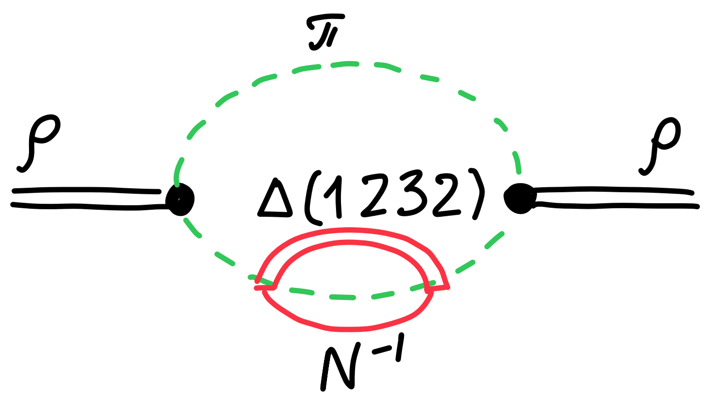
$$m_{h->e^-(p_1)e^+(p_2)} = \sqrt{(p_1+p_2)^2} \qquad \frac{dN_{h\to e^+e^-}}{dm} \sim \rho(m)\frac{\Gamma_{h\to e^+e^-}(m)}{\Gamma_{total}(m)}$$

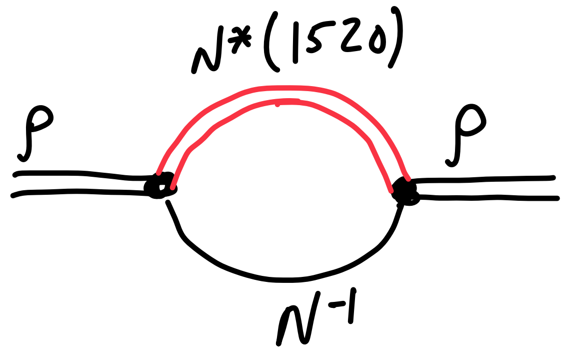
Vacuum properties of ρ spectral function



$$\rho(m) = A\frac{m^2\Gamma}{(m^2-M_R^2)^2+m^2\Gamma^2}$$

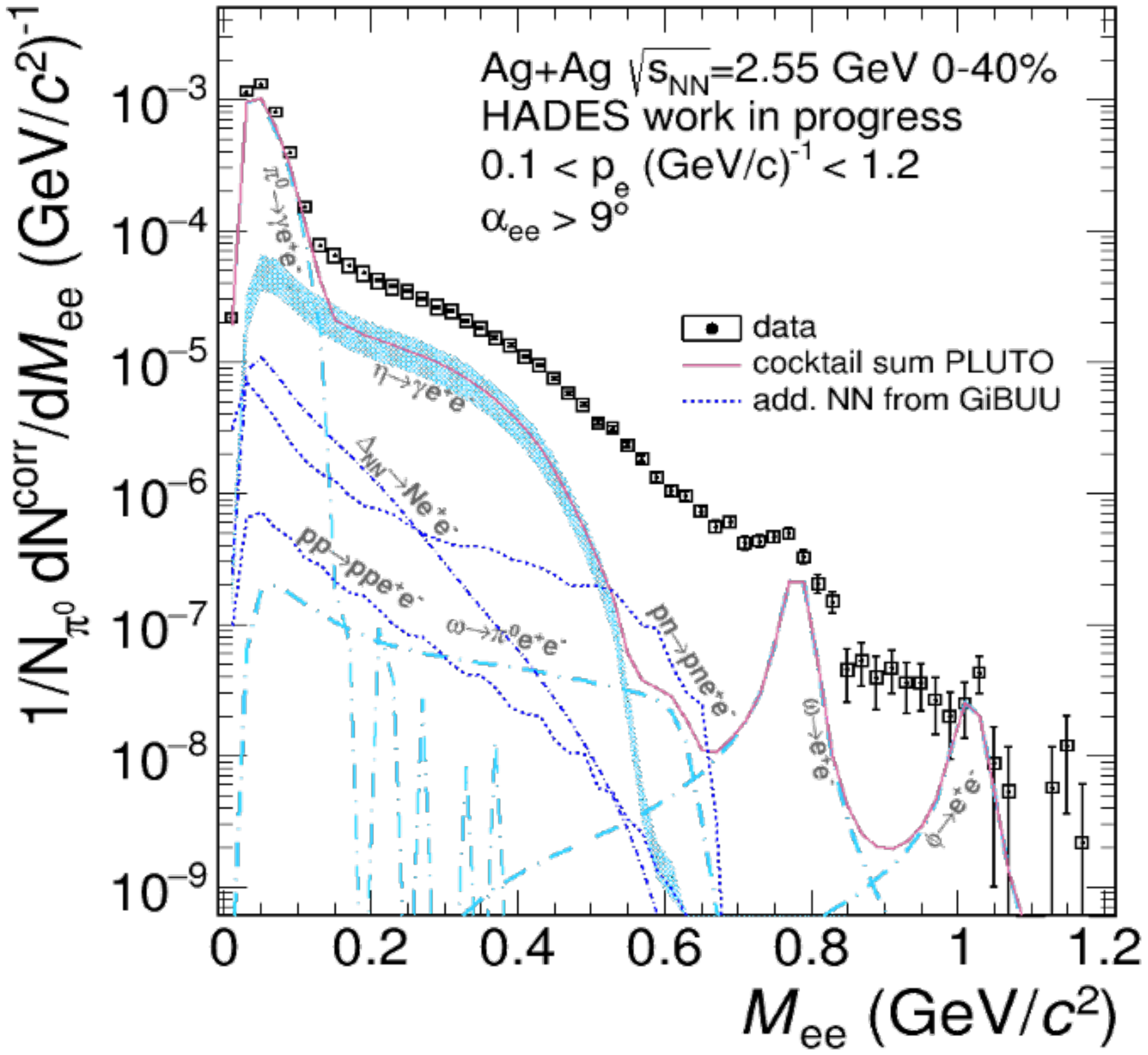
In-medium properties, additional self-energies

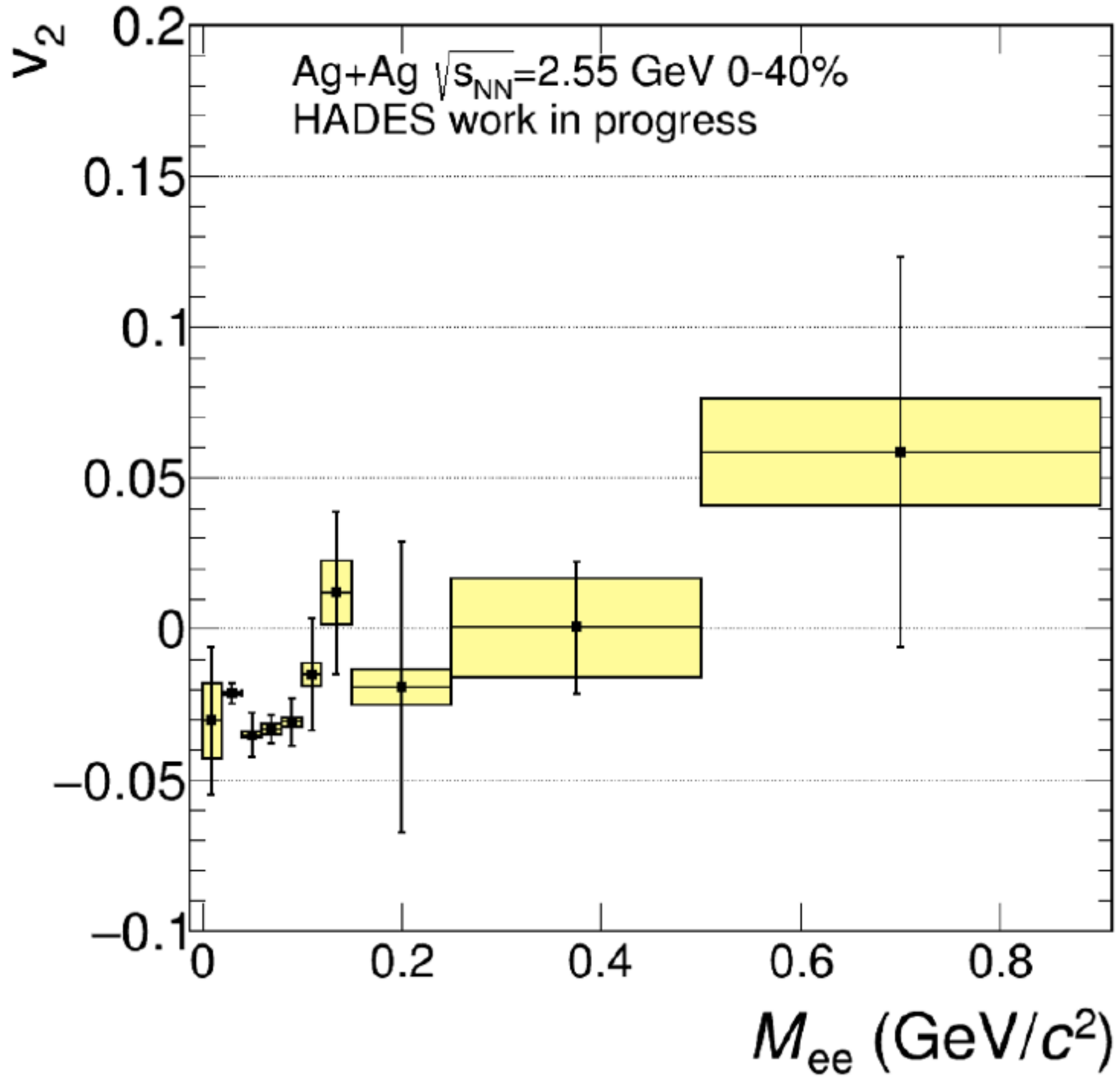




W. Peters et al. NPA 632 (1998) 109

Invariant mass of dielectorns





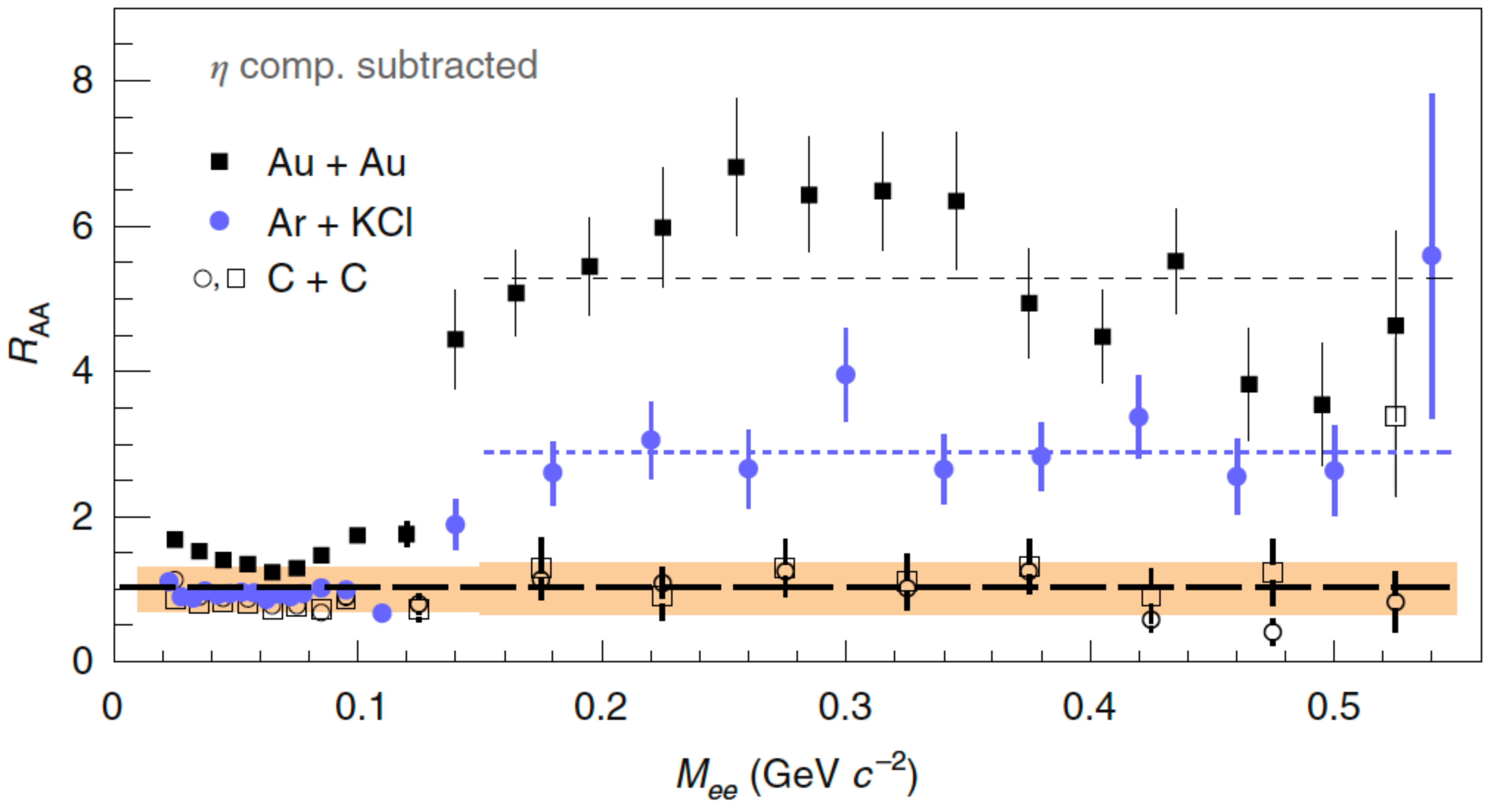
- Large statistics data
- Clearly visible vector mesons (ω, ϕ)

S. Spies, CPOD 2022

- Vanishing v_2 of dielectrons for high-mass region
  - Penetrating probes!

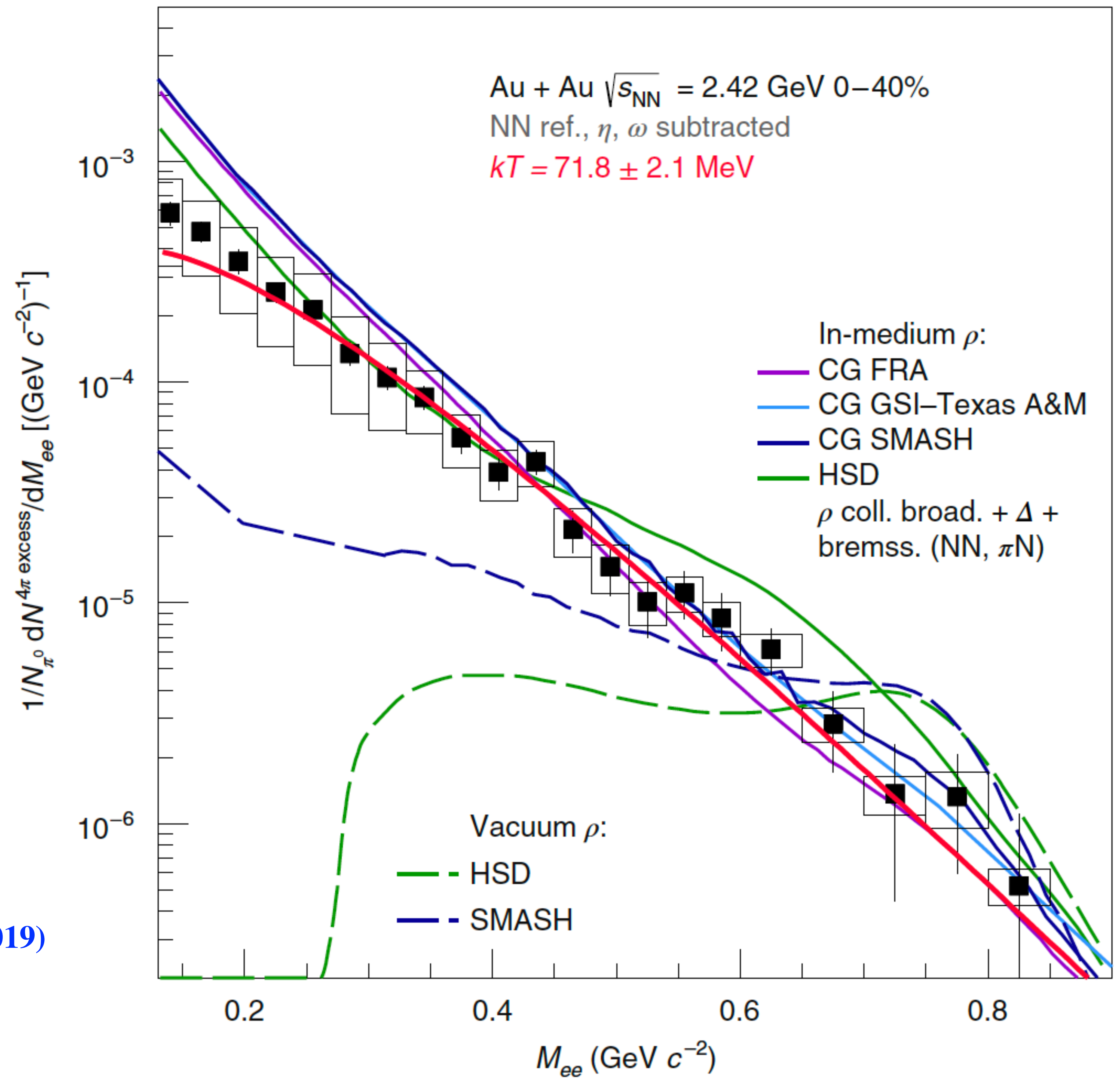
N. Schild, CPOD 2022

Emissivity of nuclear matter



$$R_{AA} = \frac{1}{\langle N_{part}^{AA} \rangle} \frac{dN^{AA}}{dM_{ee}} \left(\frac{dN^{NN}}{dM_{ee}} \right)^{-1}$$

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



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

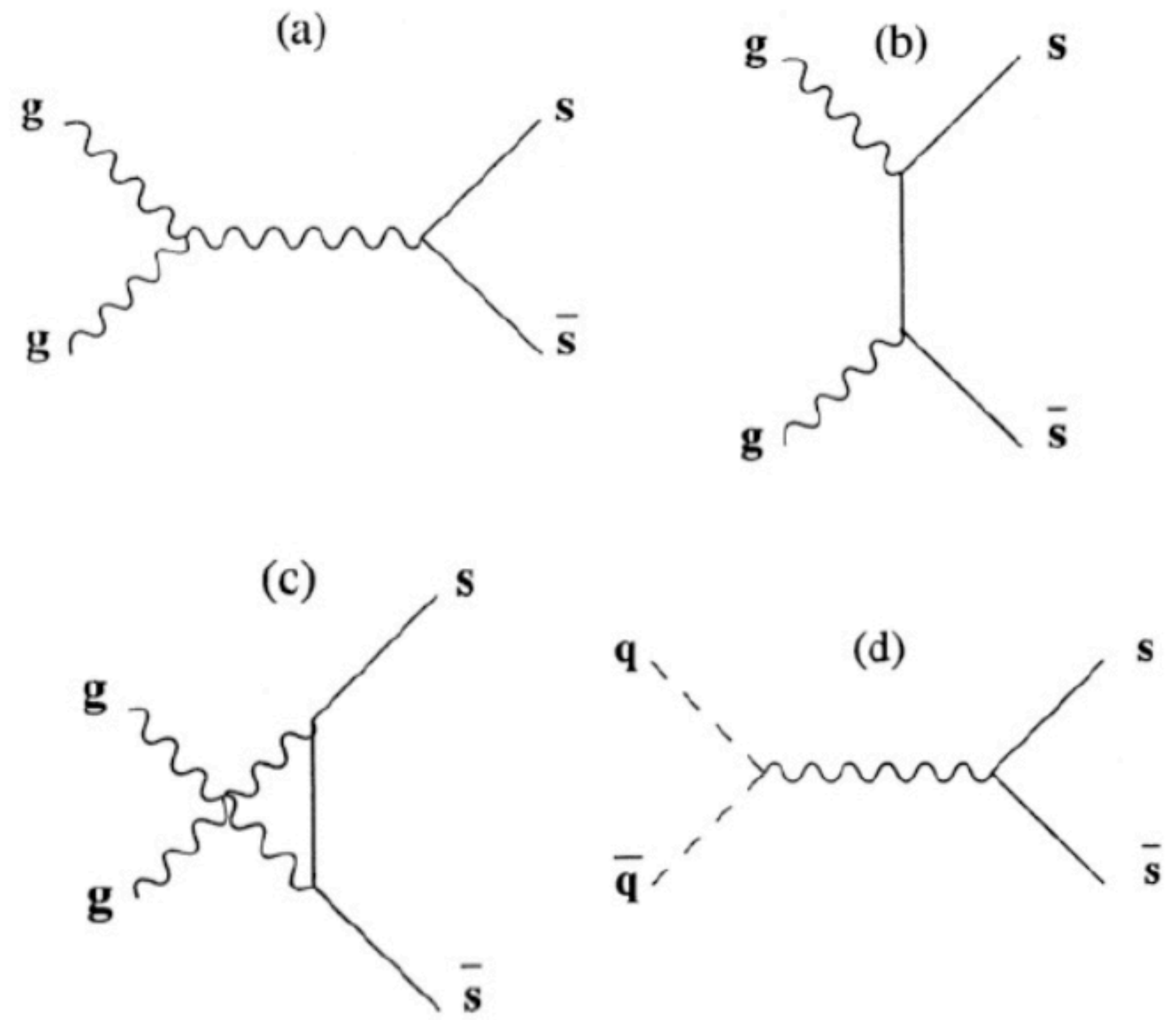
$$dN/dM_{ee} \sim M_{ee}^{3/2} exp(-M_{ee}/T)$$

the data suggests a strong ρ broadening, which may be induced by partial restoration of the chiral symmetry

Strangeness Production Phenomenology

Strangeness production phenomenology

Enhancement



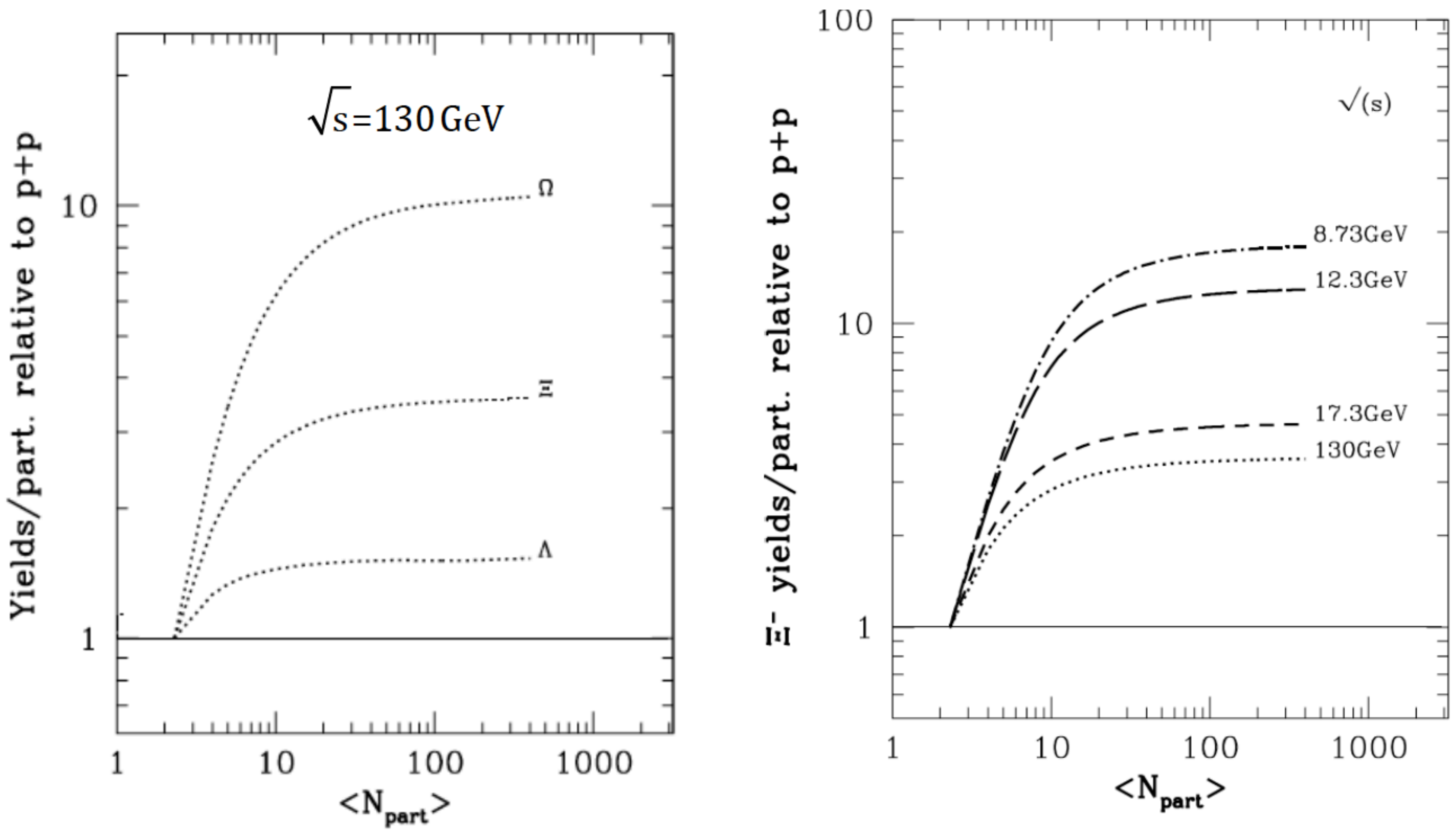
Energy needed:

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)

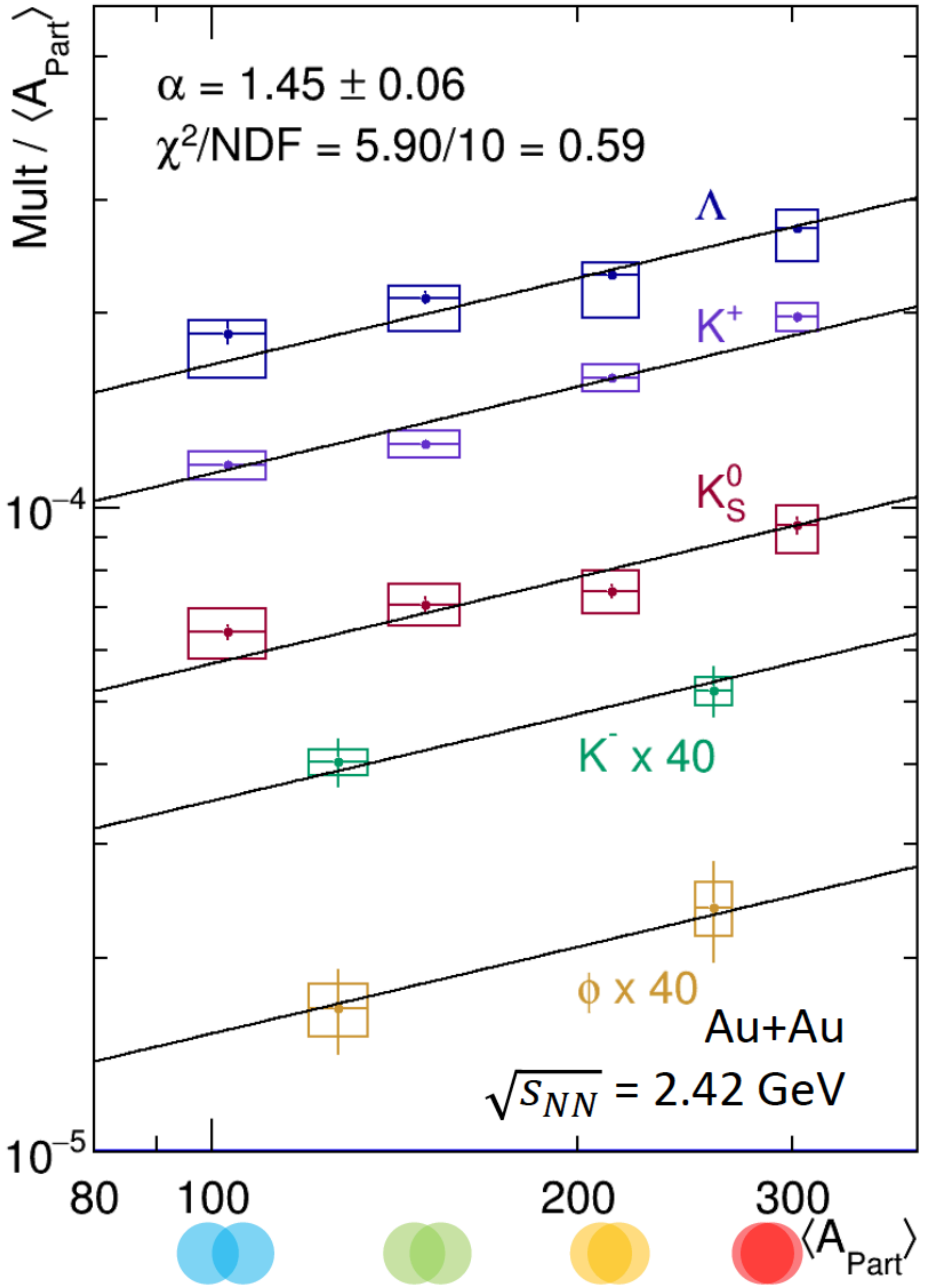
Strangeness centrality dependence

Universal scaling with centrality

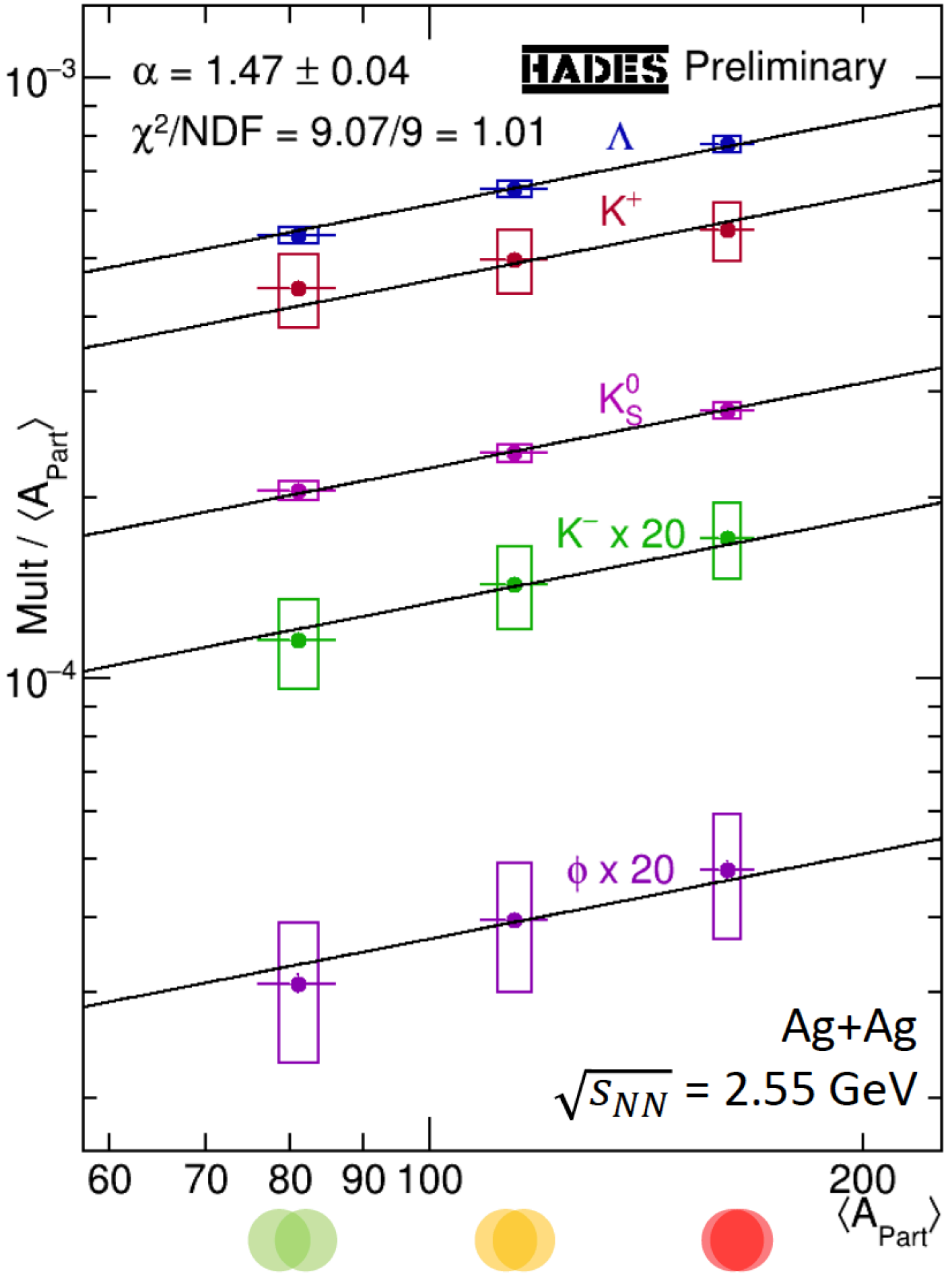
$$\text{Mult} \sim \langle A_{part} \rangle^{\alpha}$$

α_{Au-Au} = 1.45 ± 0.06

α_{Ag-Ag} = 1.47 ± 0.04



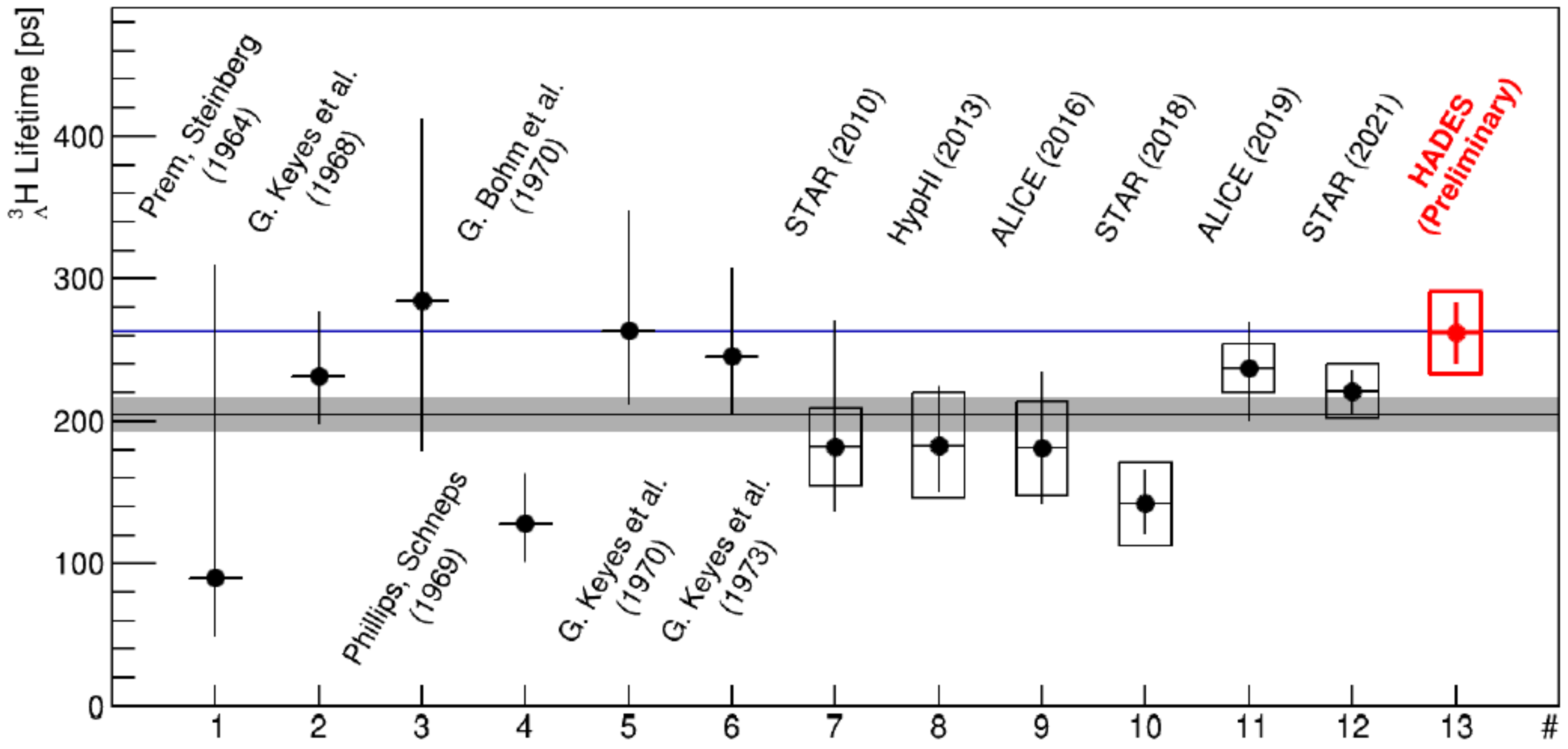
HADES: PLB 793 (2019) 457-463



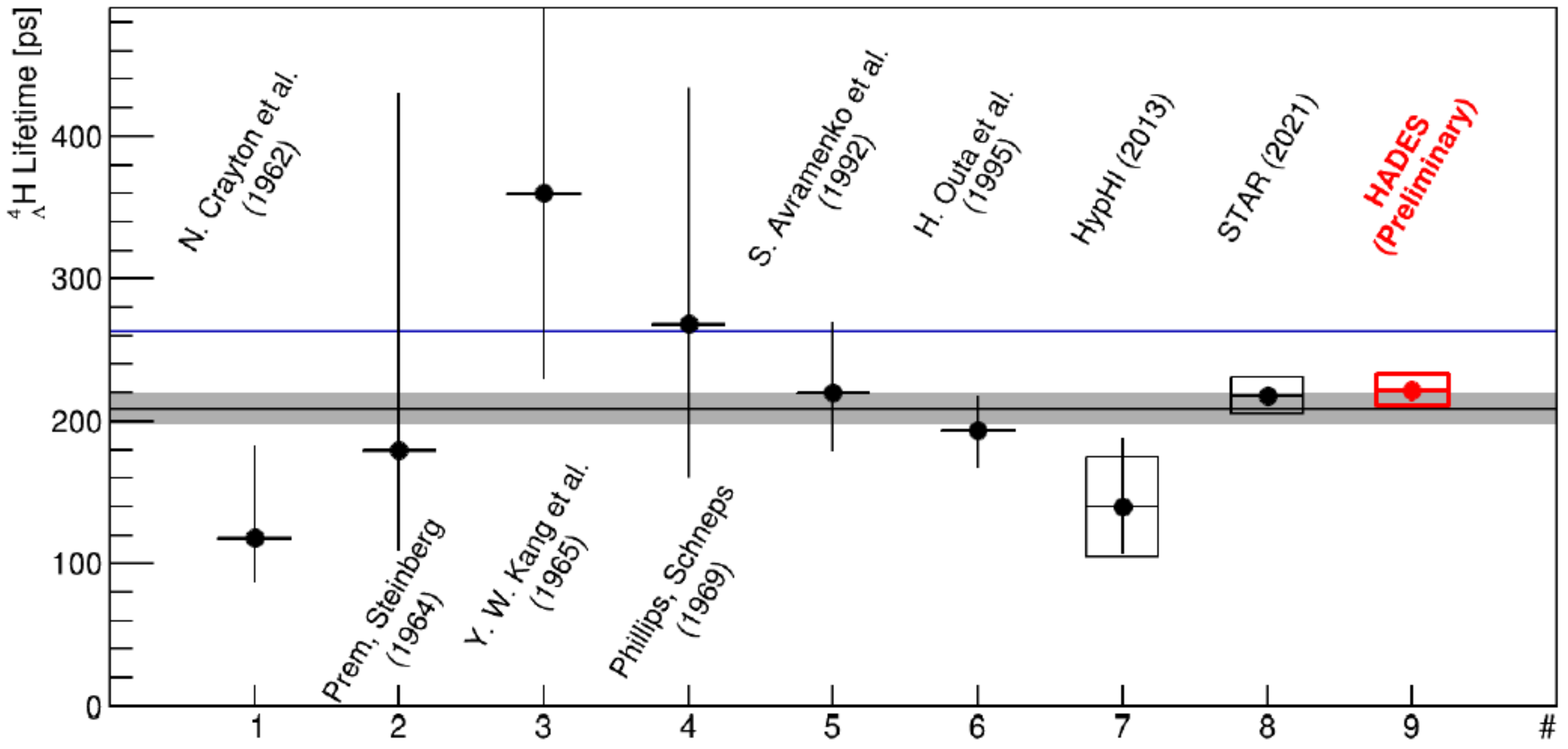
HADES: Preliminary

Hypernuclei measurements

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



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



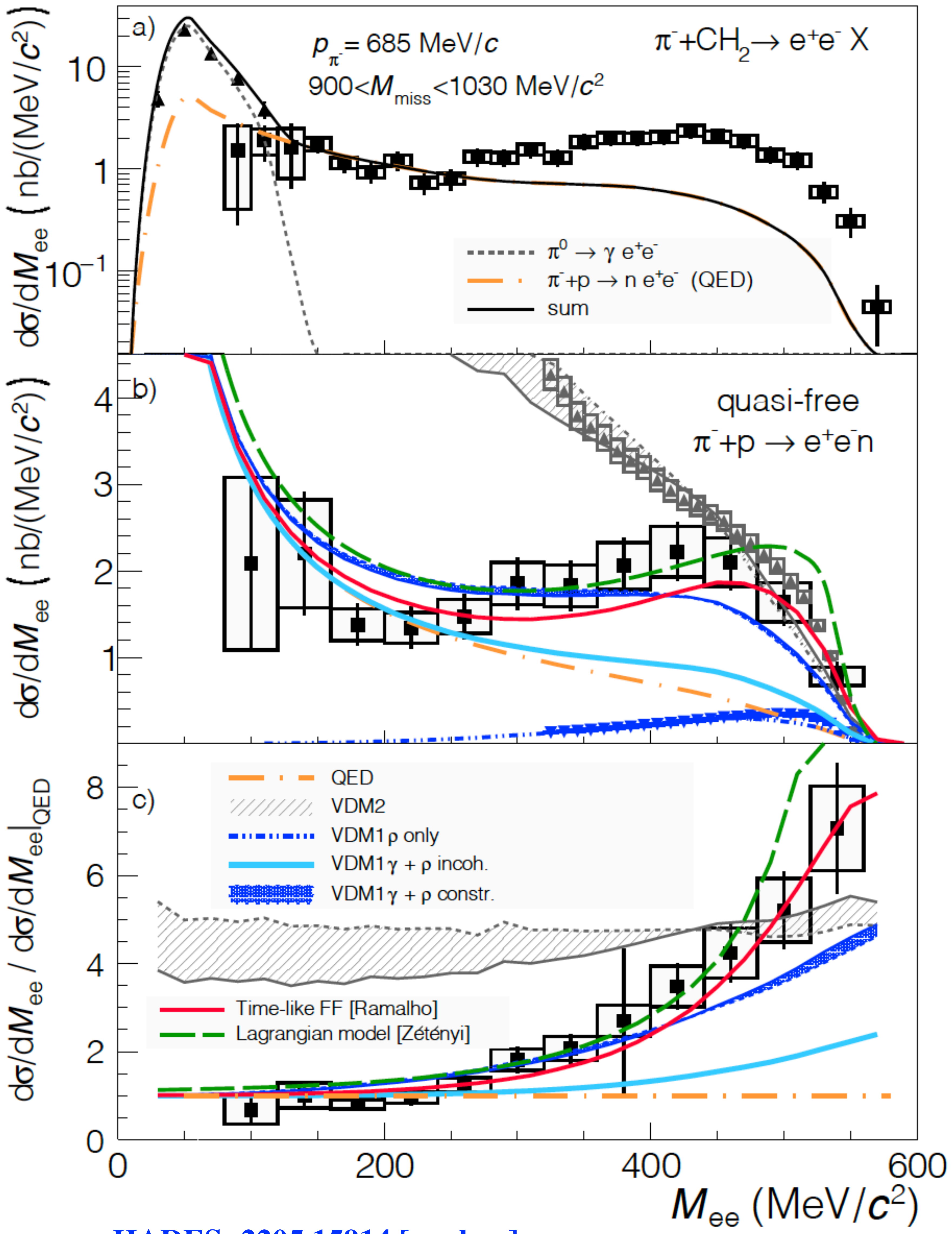
measured lifetime (262 ± 22_{stat} ± 28_{sys} ps) is comparable with that of free Λ (263 ps)

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

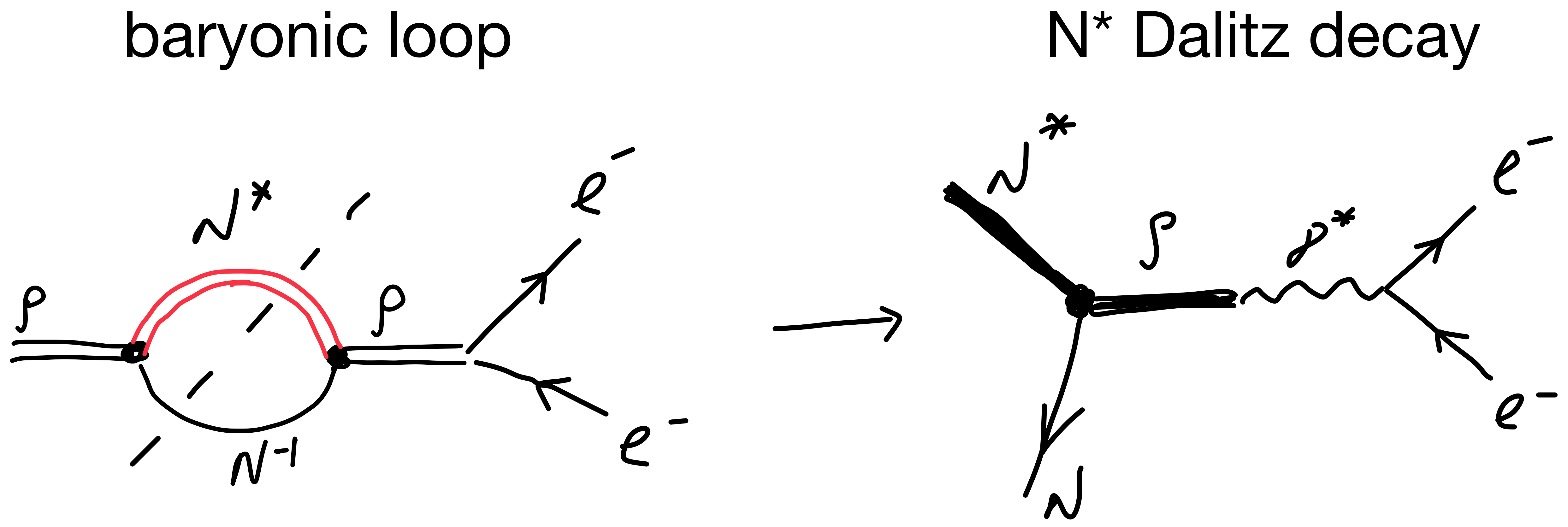
S. Spies, CPOD 2022

Pion induced reactions

Transition form-factors for baryon resonances

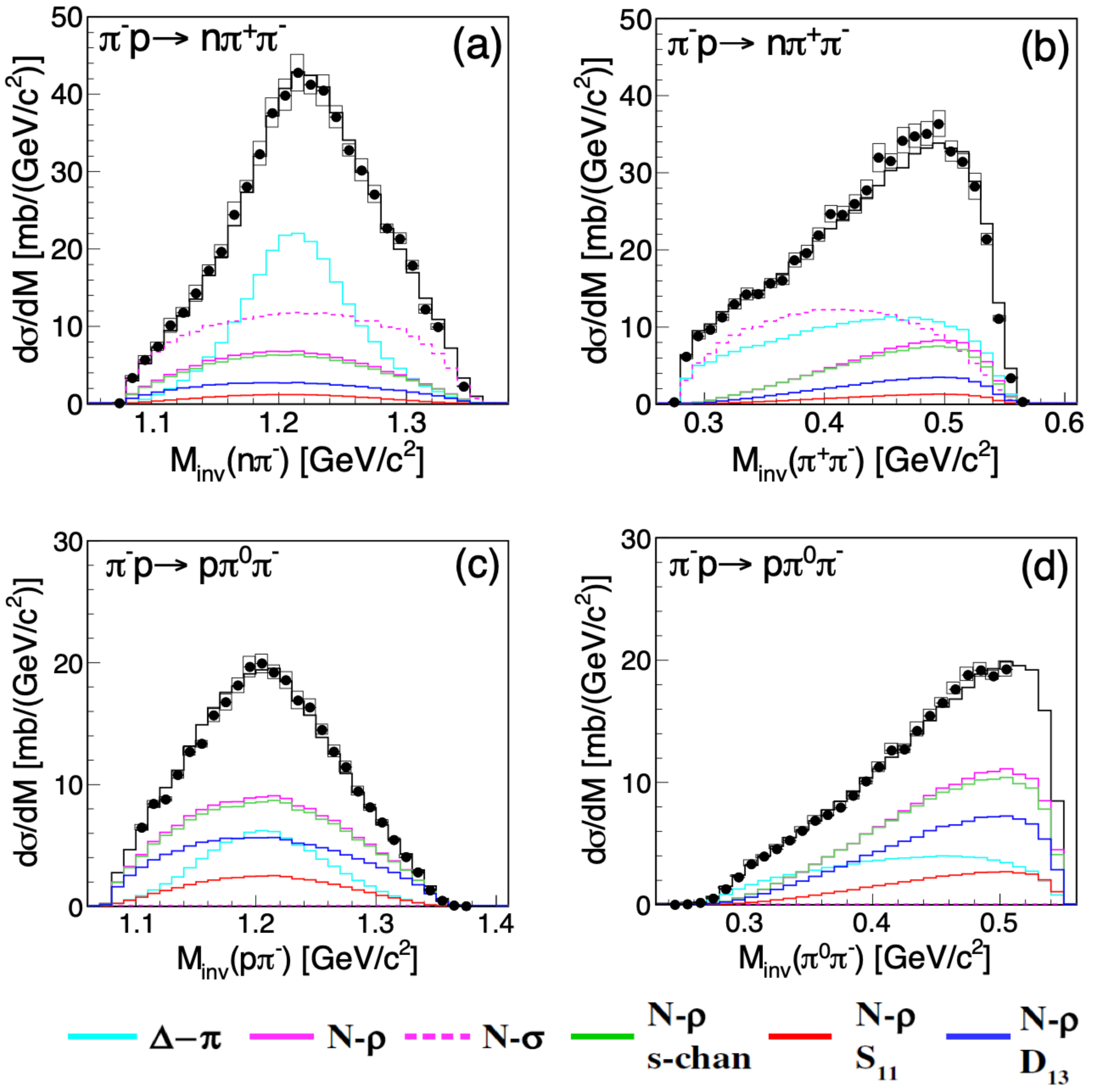


HADES: 2205.15914 [nucl-ex]



- Contribution from the ρ meson is clearly visible
- Strong support for inclusion of time-like transition from-factors
- Input for interpretation of dielectron data

Extracting ρ production amplitudes



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

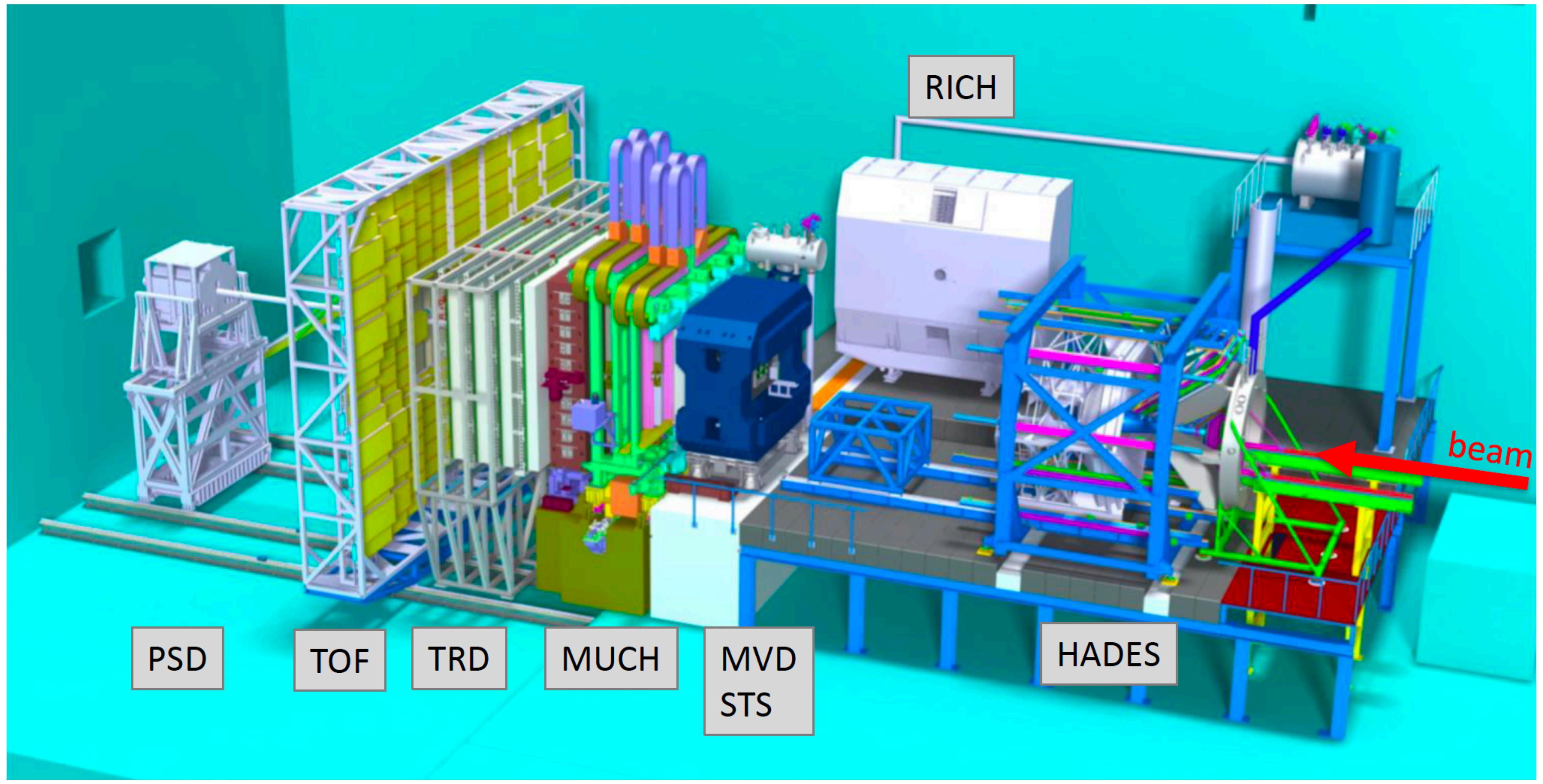
Constraining ρ production amplitudes

$\pi^- p \rightarrow n\pi^+\pi^-$, $p_\pi = 0.685$ GeV/c

Bonn-Gatchina Partial Wave Analysis (PWA)

Future Prospects

- **February 2022: p+p @4.5 GeV (done)**
  - baseline for FAIR experiments (and beyond)
- **Beam energy scan**
  - Au-Au collisions, with projectile kinetic energies: 0.8*A*, 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
    - studying contributions of stopped protons to multi-particle correlations
- …



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 as well as pion induced collisions
- Measured multi-particle correlation functions of protons demonstrate non-trivial multiplicity dependencies
  - Further studies are needed to clarify this observation
- High statistics dielectron measurements indicate strong in-medium broadening of the ρ meson
  - Possible hint for partial restoration of chiral symmetry
- Universal scaling of strangeness production with centrality is observed in Au-Au and Ag-Ag collisions
- Measured lifetime of ${}^{3}_{\Lambda}H$ is consistent with that of free Λ
  - Contrary to that, the lifetime of ${}^{4}_{\Lambda}H$ deviates by 4.7σ from that of free Λ

The HADES Collaboration


THANKS FOR YOUR
ATTENTION