Studying baryonic matter with HADES at GSI/FAIR

- ✓ HADES experiment at GSI/FAIR
- ✓ Properties of baryon rich matter from HI collisions: bulk properties, vector meson (dileptons), strangeness production (some highlights)
- ✓ Connection of emissivity to em. structure of baryon resonances
- ✓ Outlook

P. Salabura
M. Smoluchowski Institute of Physcis
Jagiellonian University, Kraków
Poland

GSI - NOW

SIS 18 18Tm (1.8 T magnets)

U^{73+} 1.0 GeV/u 10^9 ions/s
Ni^{26+} 2.0 GeV/u 10^{10}
protons 4.5 GeV 2.8×10^{13}/s
pions ! 0.5-2 GeV/c

POLAND is one of funding members of FAIR

GSI-FAIR (> 2022)

SIS 100 2T (4T/s) magnets

Au do 8-10 GeV/u 10^{12} ions/s
protons do 30 GeV 2.8×10^{13}/s

Secondary beams

Radioctive beams 1.5 GeV/u (Super FRS)
anty-protons

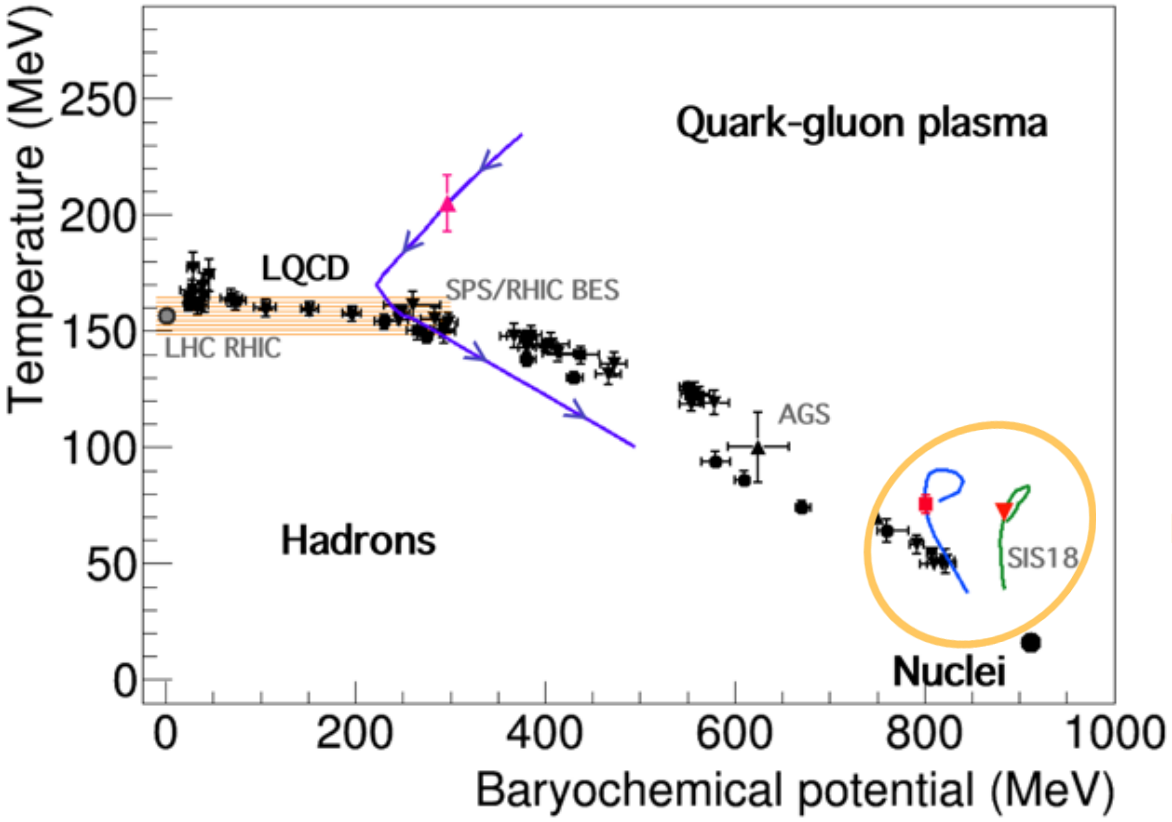
Storage rings

Precision experiments in Atomic Physics
HESR: Anty-protons 1.5- 15 GeV/c – exp PANDA

Phase0: 2018-2022 at SIS18 !

HADES, PANDA, CBM

Various faces of QCD: phase diagram

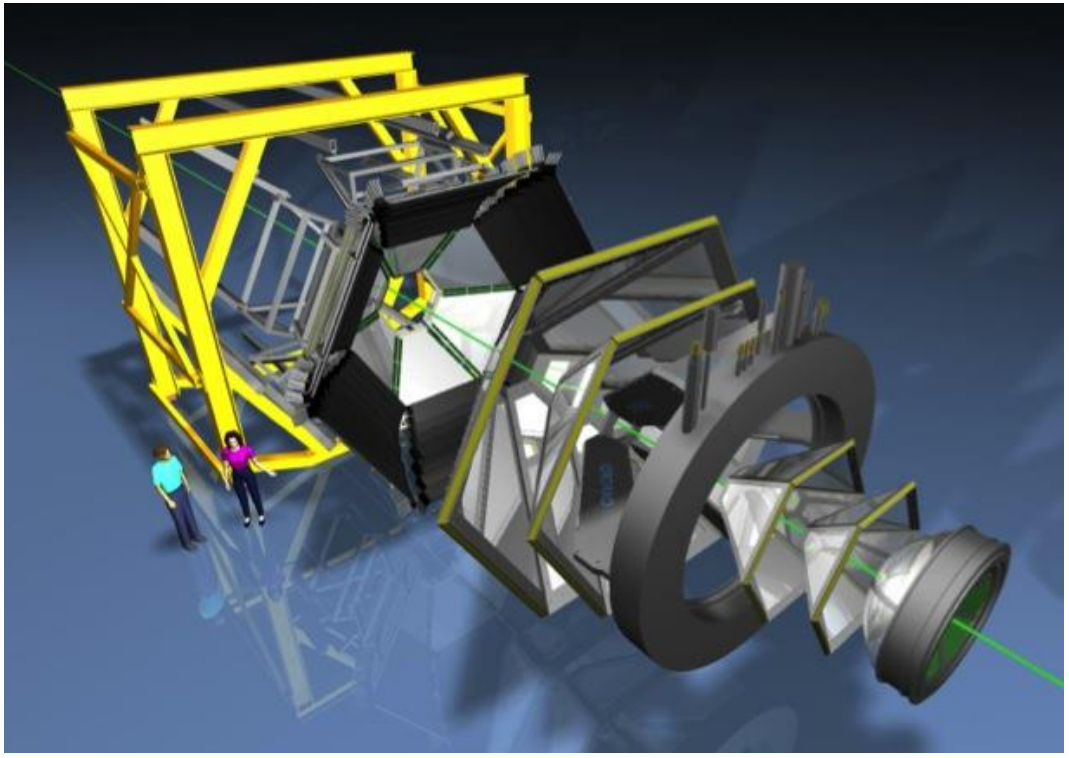


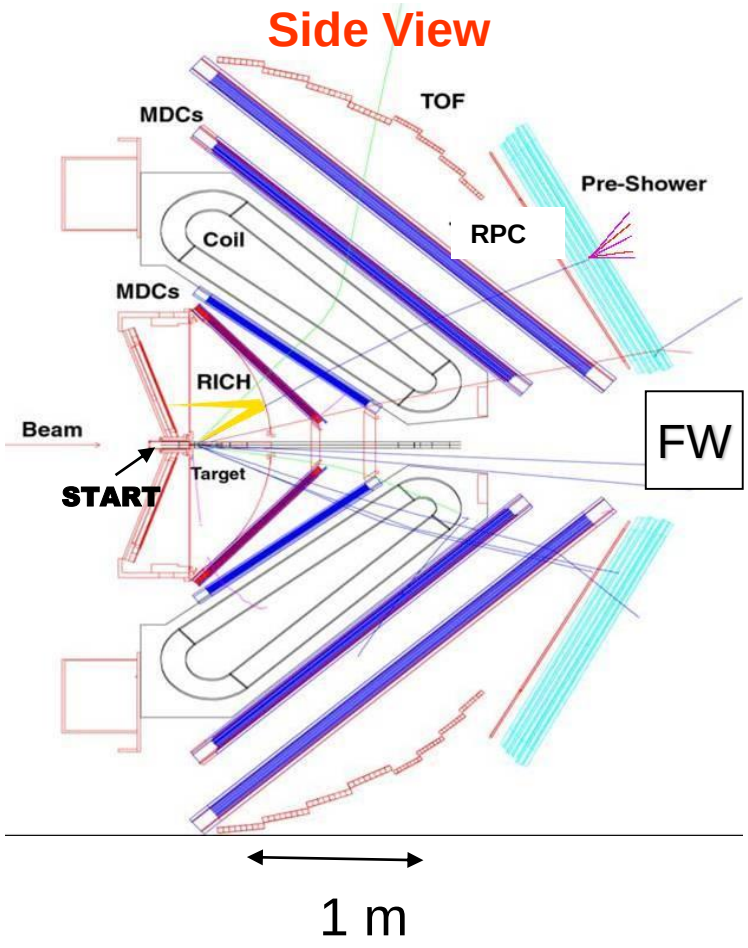
HADES

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

High Acceptance Di-Electron Spectrometer

- ✓ Spectrometer with $\Delta M/M$ - 2% at ρ/ω
- ✓ π/p/K separation with TOF/tracking
- ✓ electrons : RICH (hadron blind), TOF/Pre-Shower
- ✓ FW – event plane reconstruction
- ✓ Centrality from track mult. (Glauber Model)
- ✓ DAQ ~20 KHz with Au+Au collisions

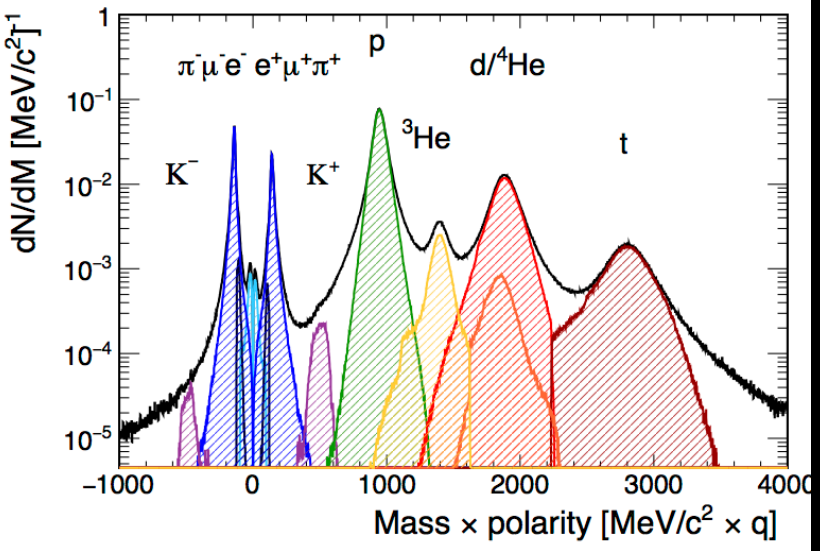


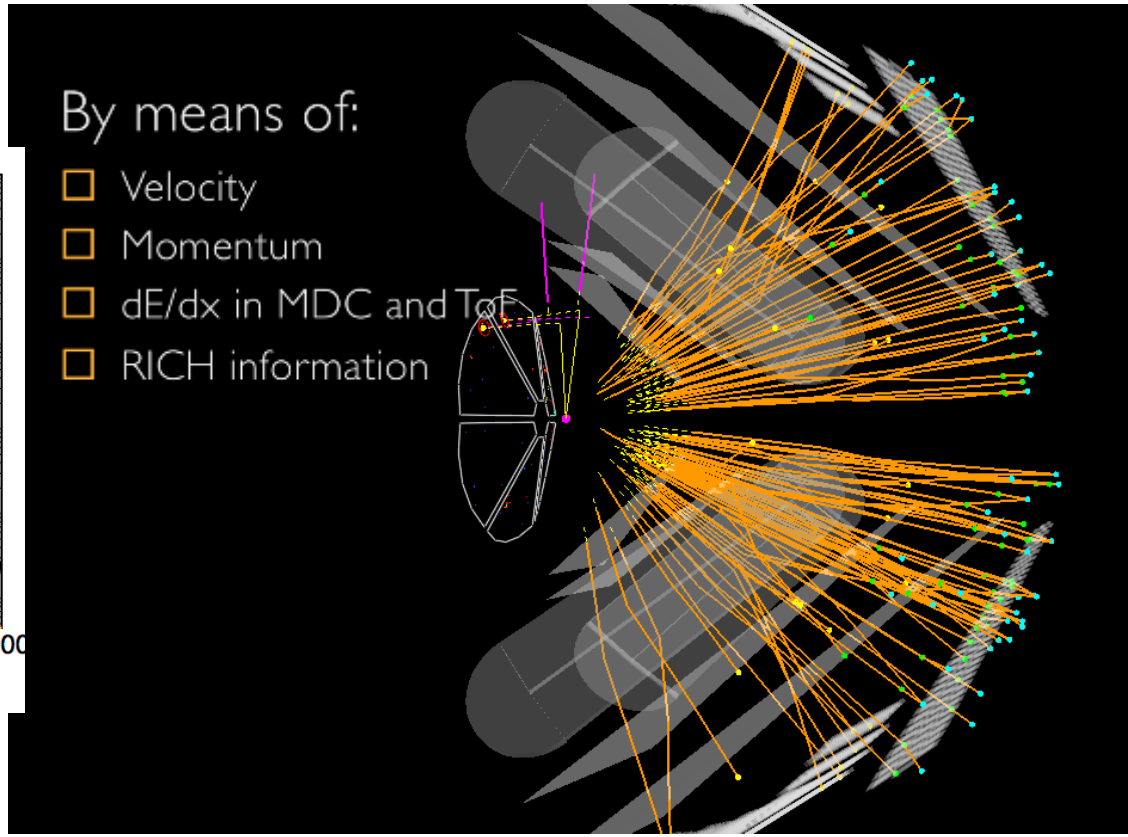


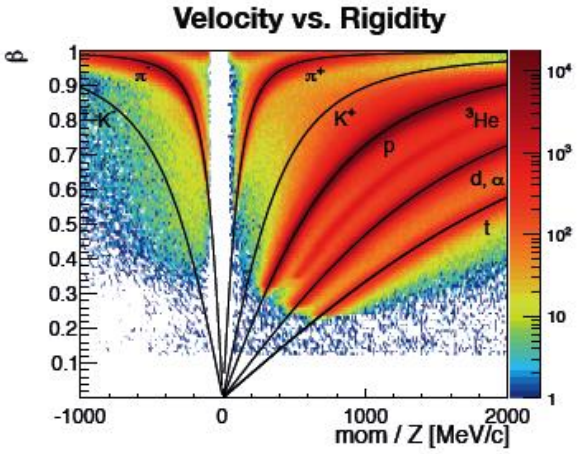
Geometry

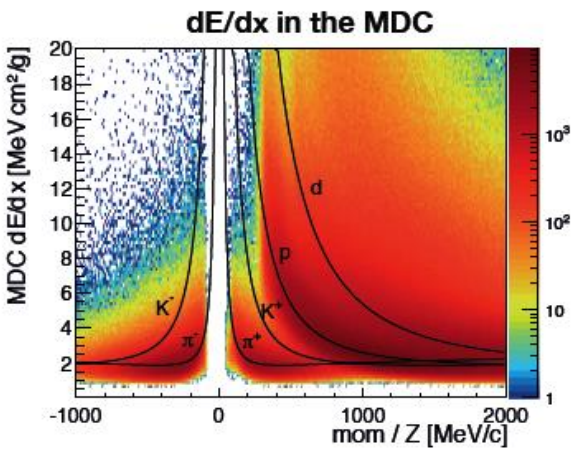
Full azimuth, polar angles 18° - 85°
e+e- pair acceptance ≈ 0.35

Particle identification

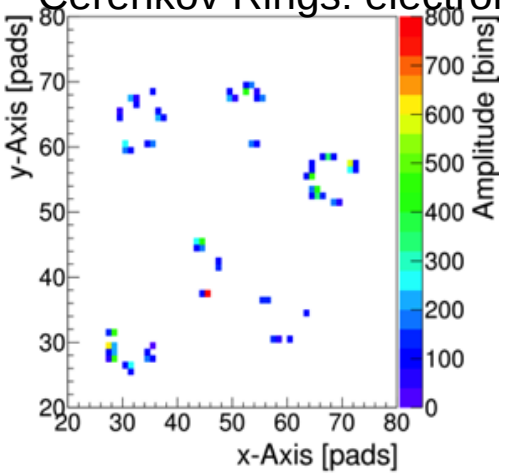




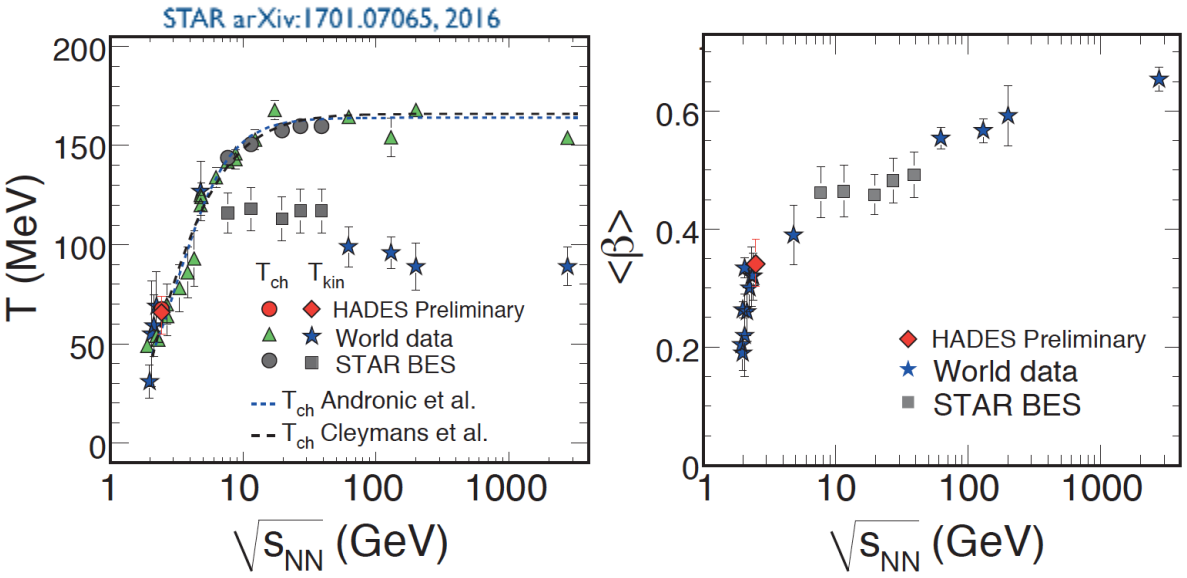


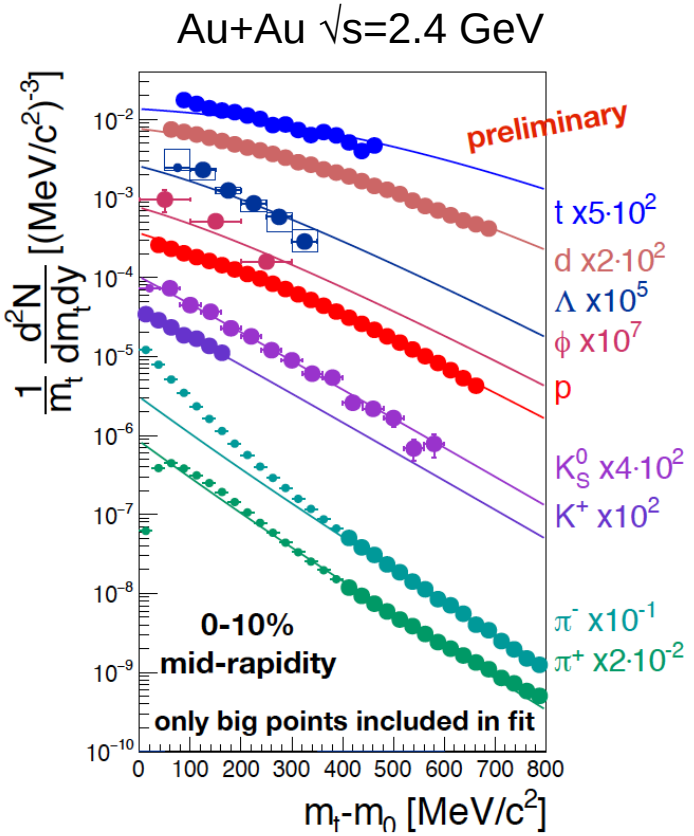


Cerenkov Rings: electron



Radial Flow



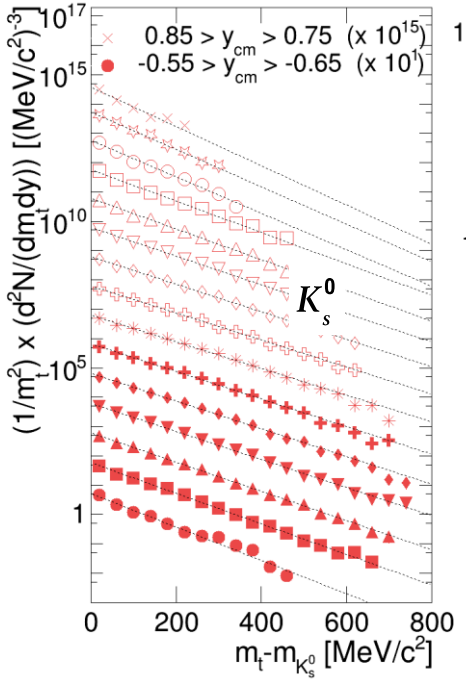


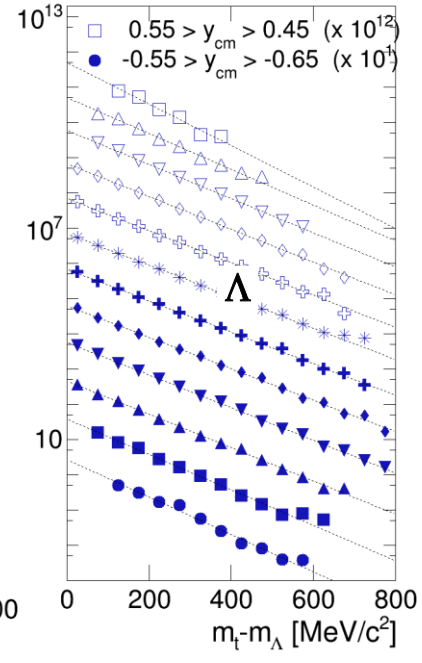
- Global freeze-out parameters fit well into trend of world data
- $T_{kin} < T_{chem}$ also at low energies

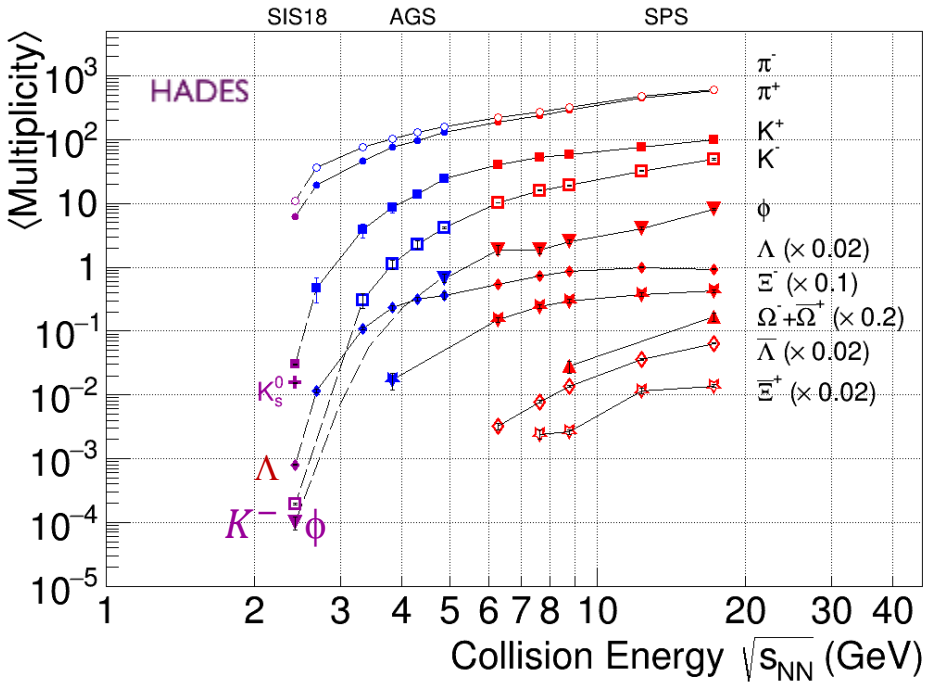
- Fit: Blast wave model with linear radial flow velocity profile
- T_{kin}=66±8 MeV, $<\beta_r>$=0.34±0.04

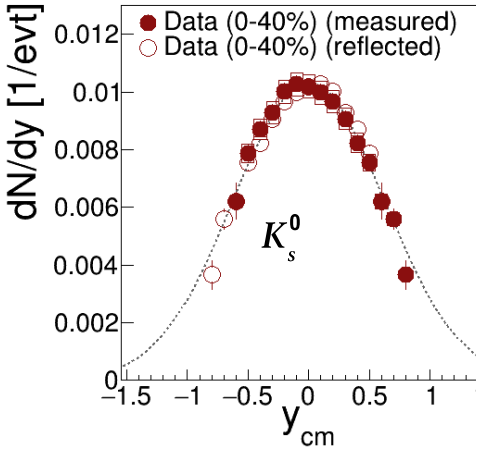
- Bad for ϕ, Λ
- pions at low m_t affected by $\Delta \rightarrow N\pi$

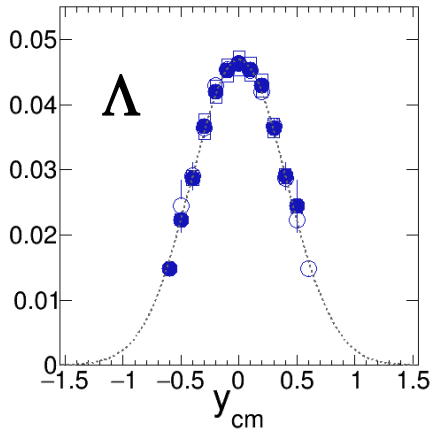
Strangeness production: Au+Au @√s=2.4 GeV











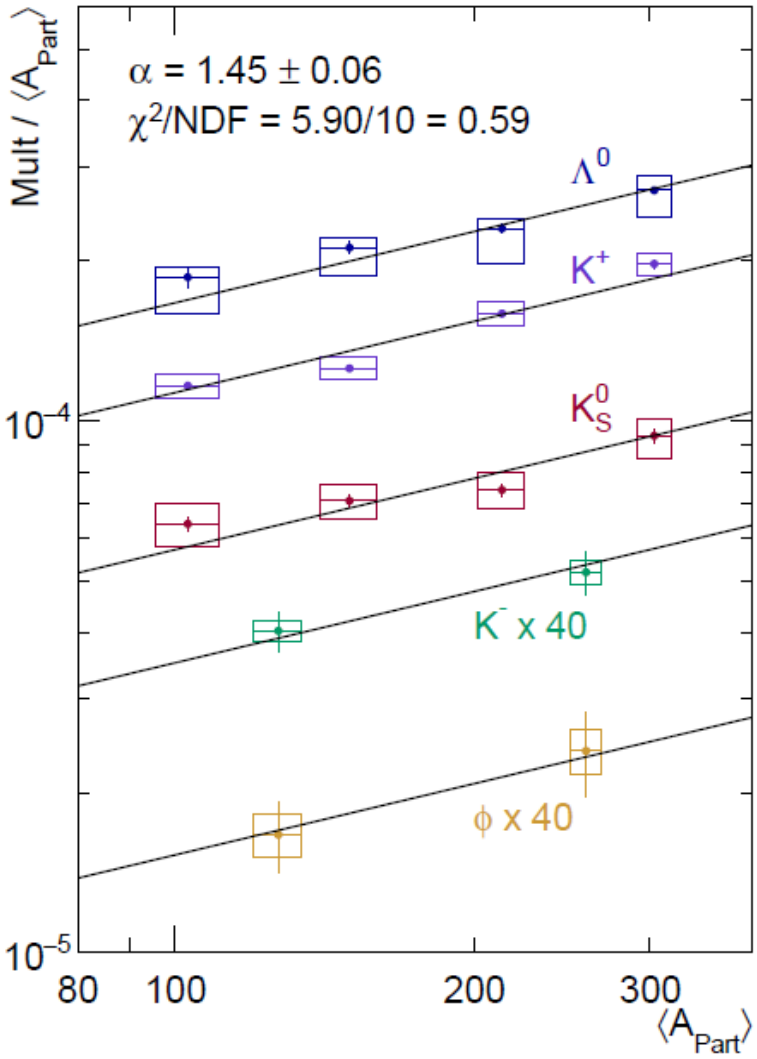
- Subthreshold production

  $Q^{K+,\Lambda} = -0.15\ GeV$ $\quad$ $Q^{\phi,K-} = -0.5$ GeV

- First high statistics measurements of Λ and K_s^0 at high μ_B
- Strong constraints on strangeness production and propagation mechanism

Centrality dependence

Au+Au @ 1.23 AGeV



- Despite different production threshold

in N-N collisions for $K^+, K^-, \phi..$ similar non linear rise with A_{part} ! (linear for pions)

surprising in view of multi-step scenario assumed in many models

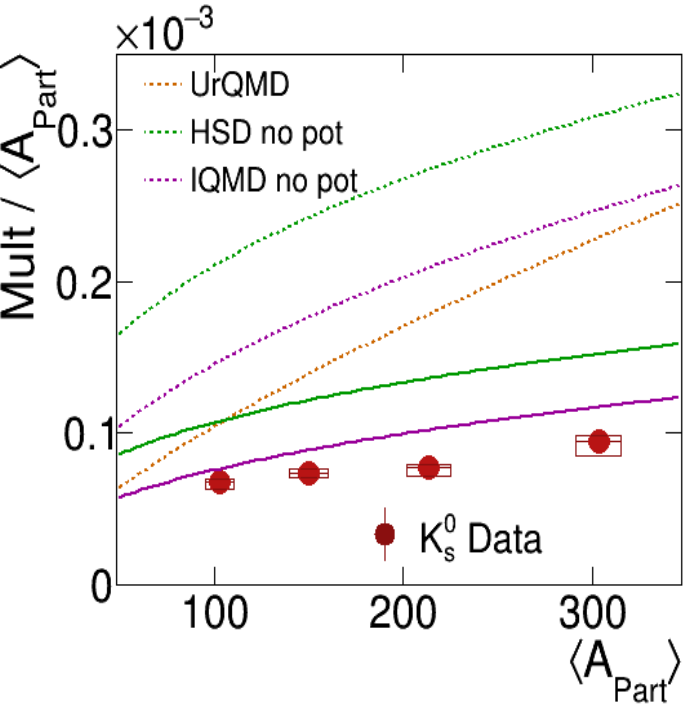
N+N→N+N+ π, πY→ K^-N

N+N,N+Δ,..→RN R→YK^-, R→Nϕ

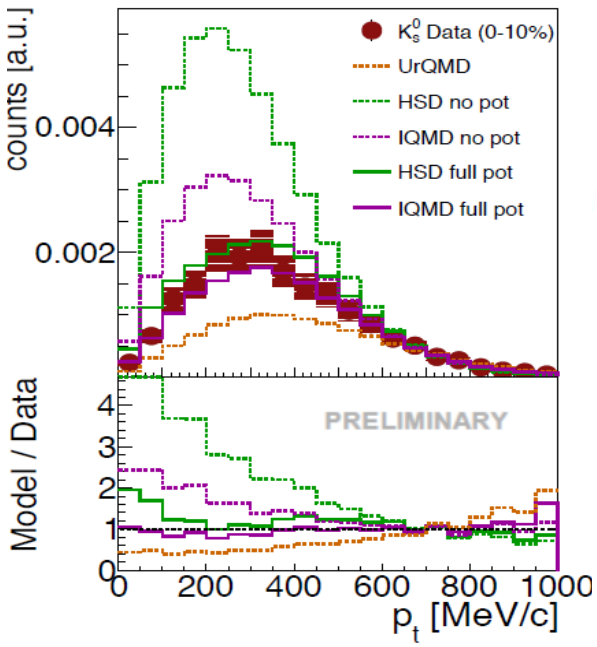
- Real challenge to models !

Microscopic description: K in- medium potential

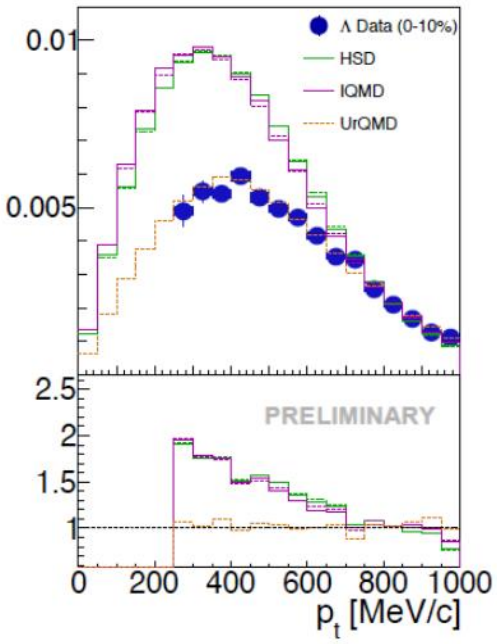
Centrality and p_t dependence vs transport models



K^0



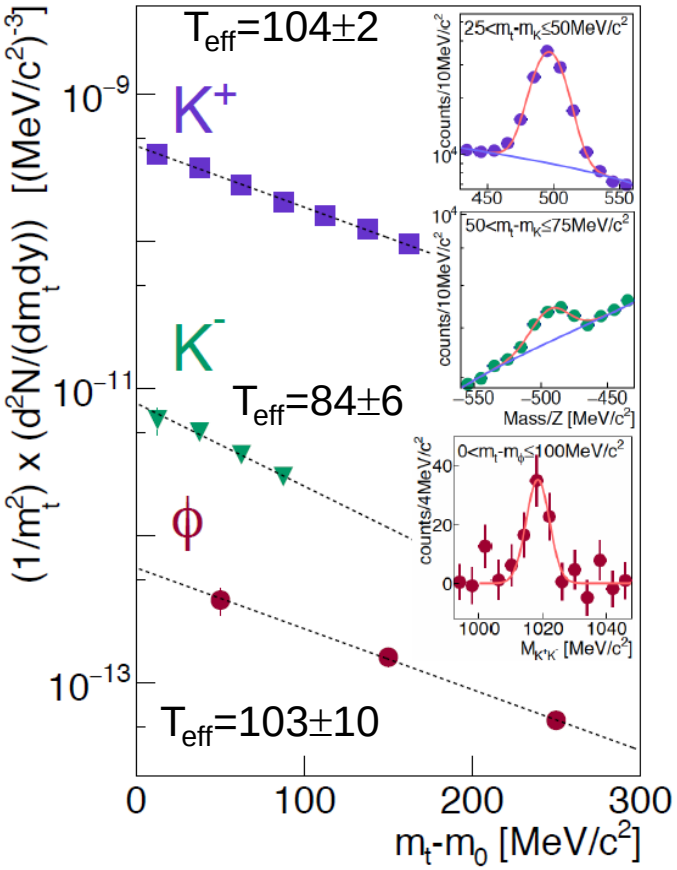
Λ

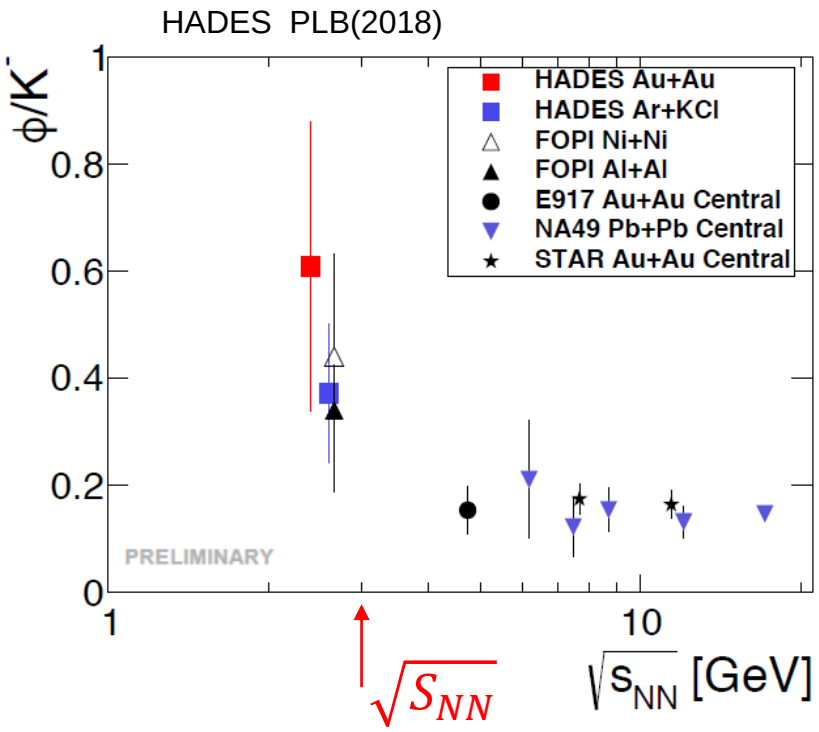


- Inclusion of repulsive Kaon –medium potential brings models to better agreement with data $U_{opt} = +40\ MeV \cdot \rho/\rho_0$

but still fails to describe simultaneously p_t of K^0 *and* Λ

ϕ production at subthresold energies: source of K⁻ ?



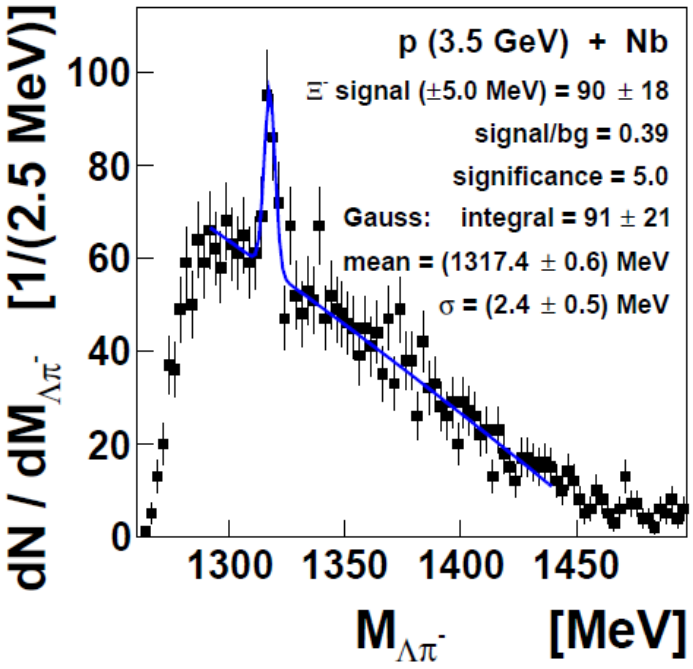


- ϕ/ K⁻ ratio strongly increases below threshold !

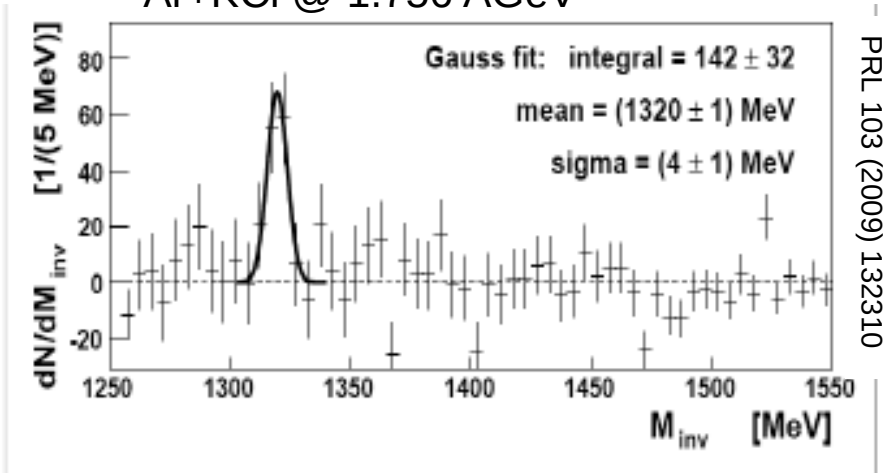
  so far strangeness exchange πY→K⁻ N was suggested as the main source of K⁻
- T_{therm} (K⁻) =T_{K+} if decay from ϕ included in the K^- production
- ϕ rates consistent with Statistical Hadronization Models but with NO suppression

Enhanced Ξ^- (1321) production

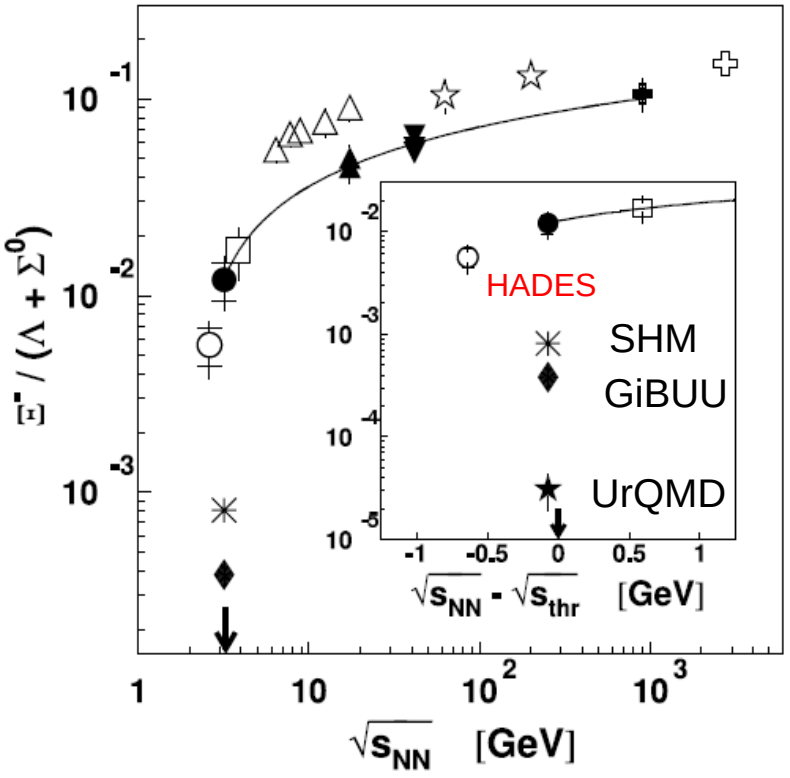
Phys.Rev.Lett. 114 (2015) no.21, 212301



Ar+KCl @ 1.756 AGeV

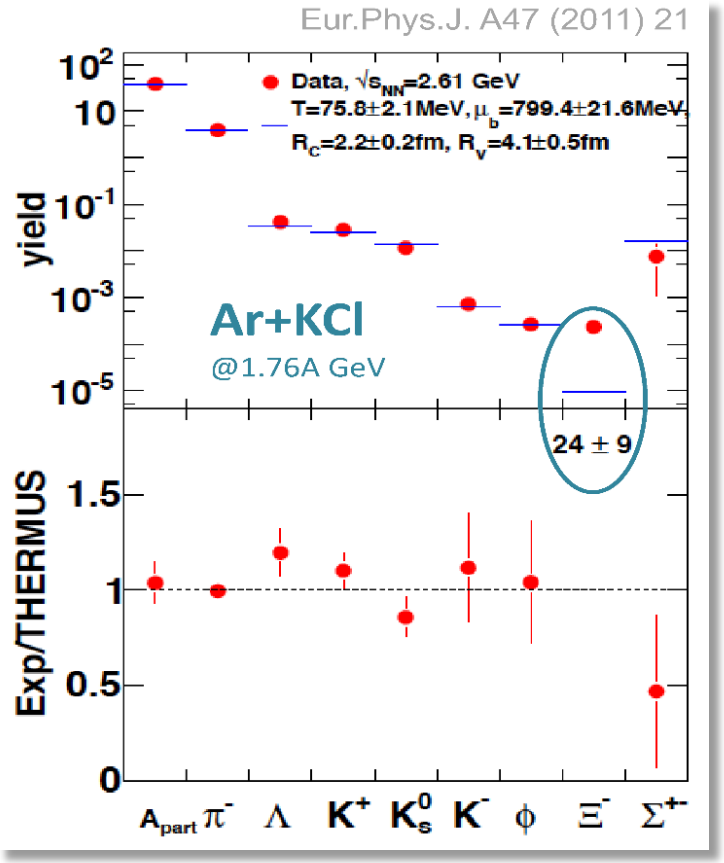


PRL 103 (2009) 132310



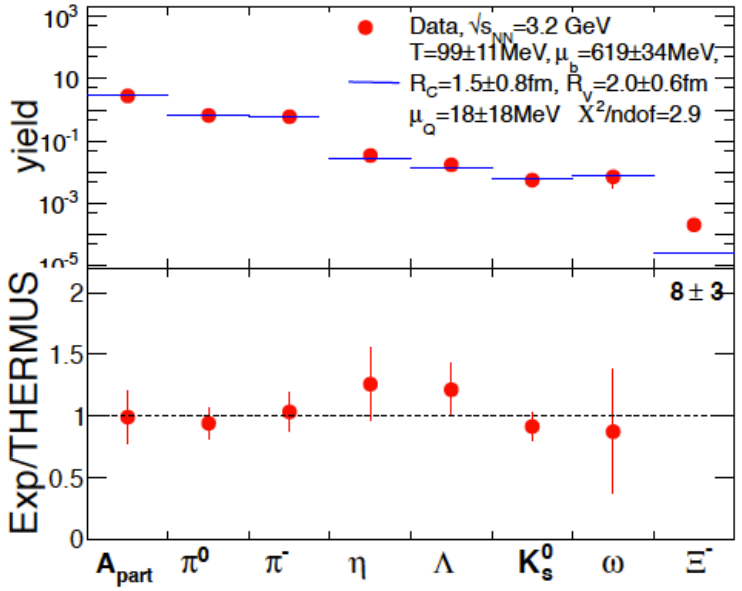
- Strong enhacement above models (Statistical Hadron Model (SHM), UrQMD, GiBUU

Statistical production of hadrons at SIS18 ?



- Grand canonical ensamble (T, μ_b , V)
- Strangeness: canonical suppression + strangeness conservation inside volume with R_c

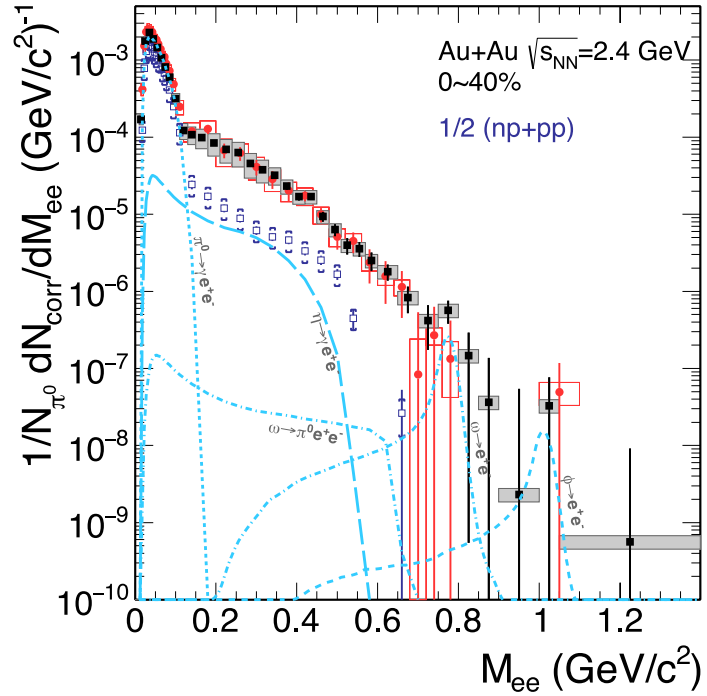
…works also well for p+Nb@ 3.5 GeV except Ξ !

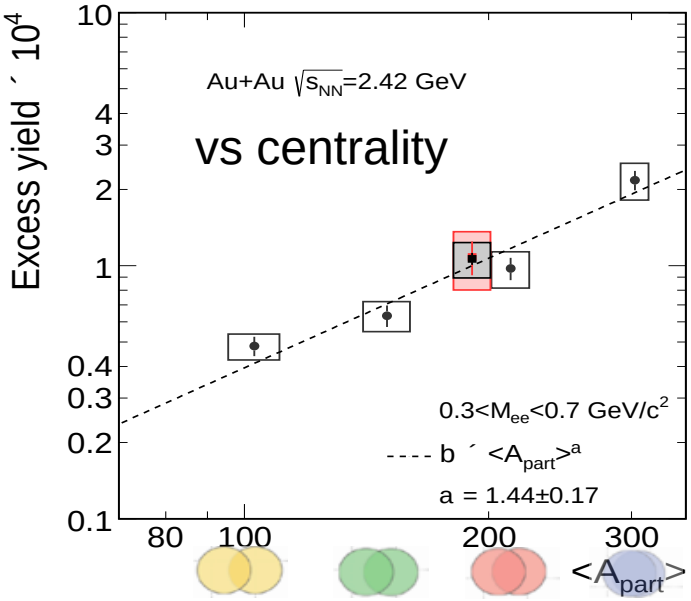


Eur.Phys.J. A52 (2016) no.6, 178

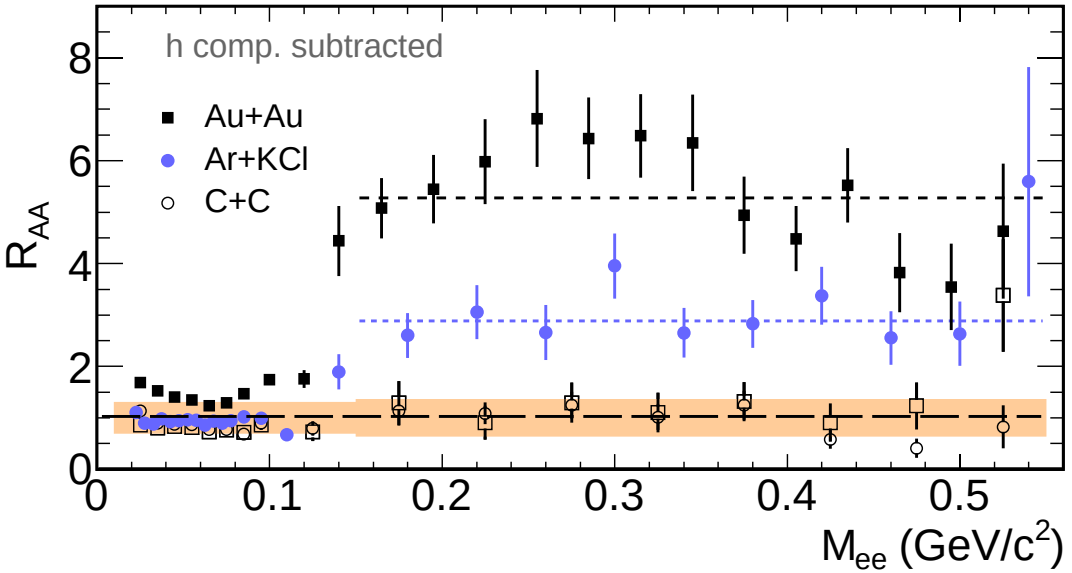
- Satisfactory description with Stat.Hadr. Model

Dilectron radiation vs sys. Size and Centrality





Excess above „hadronic cocktail" vs system size

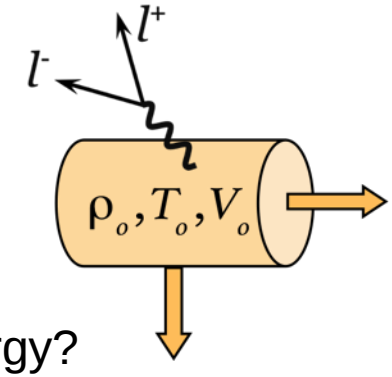


- Additional radiation from hot and dense phase of collision identified for the first time at such low energy

Emissivity of QCD matter

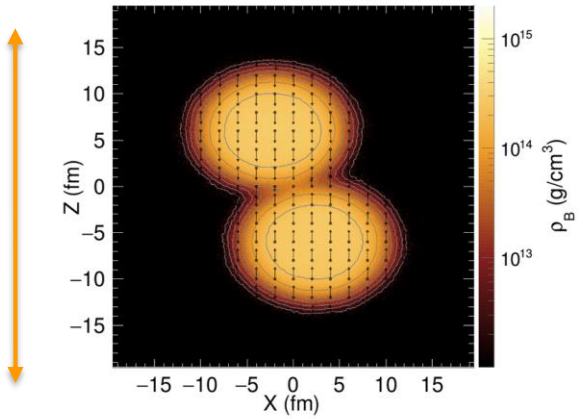
$$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

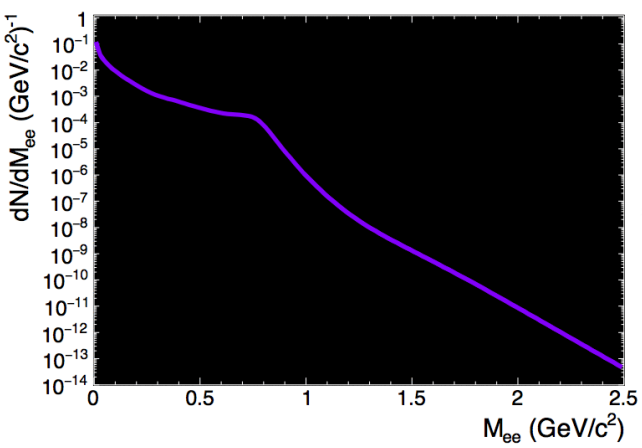
McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

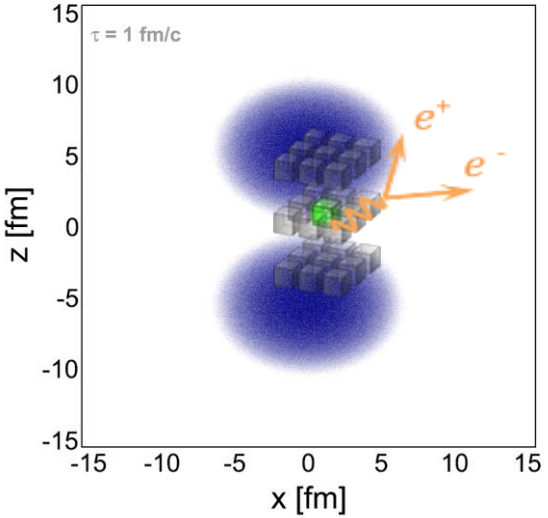


Successfull approach at SPS/RHIC. Does it work at low energy?

- Bulk evolution from transport →determine (T, ϱ_B) locally
- Apply emissivity formula with in medium Π_{em}



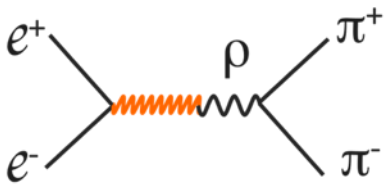




Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131

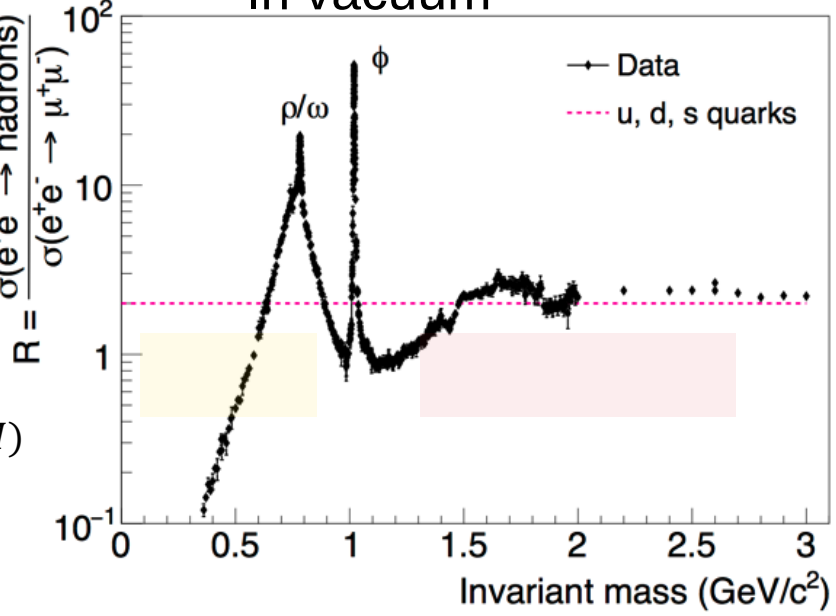
Electromagnetic current-current correlator

Low mass: ρ meson



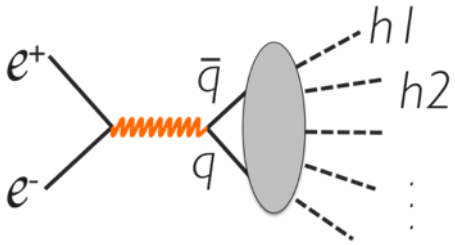
$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

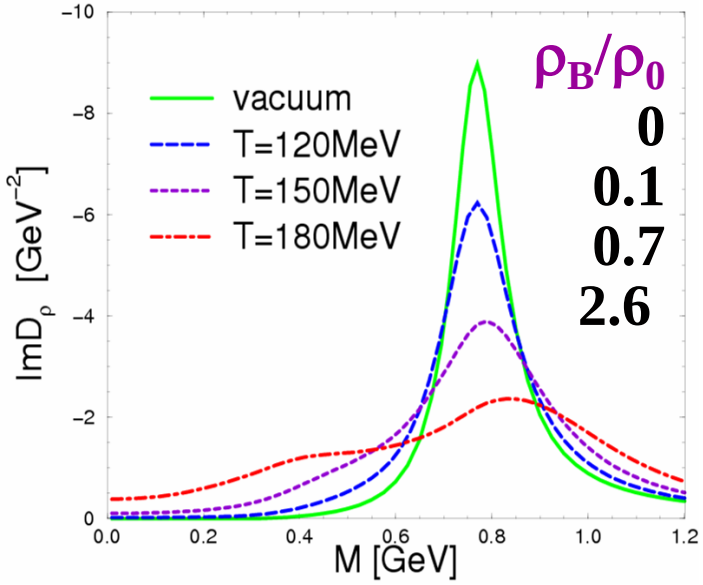
In vacuum



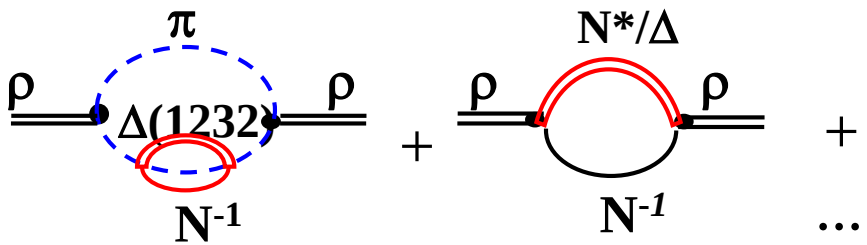
Intermediate mass ($M > 1.5$ GeV/c^2)

Perturbative QCD continuum



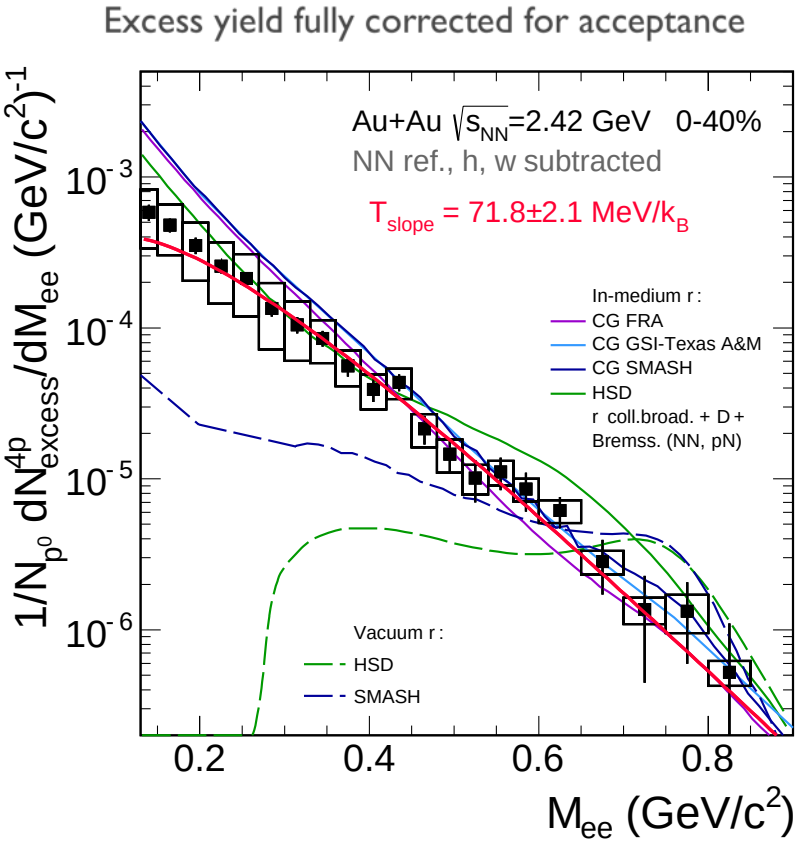


- In –medium: strong modification of ρ due to meson-baryon couplings



Microscopic model R. Rapp, J. Wambach, Adv. Nucl. Phys.25 (2000) 1.

Thermal dileptons from Au+Au



HADES Collab., submitted
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1
HSD: Phys. Rev. C 87, 064907 (2013)

- Successfull description with emissivity formula

Dileptons as thermometer

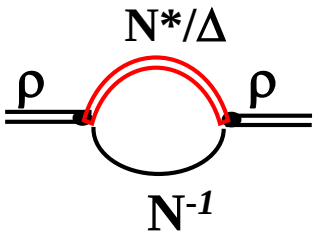
- Mass spectrum falls exponentially → "Planck-like"
- Fit $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$ in range M=0.2-0.8 GeV/c^2
- $\langle T \rangle_{\text{emitting source}}$ = 72 ± 2 MeV/k_B

- Strong melting of ρ meson
- In agreement with microscopic model of Rapp & Wambach (interactions with baryons !)
- Same model describe also RHIC(STAR), SPS (CERES, Na60 data)

Robust understanding across QCD phase diagram

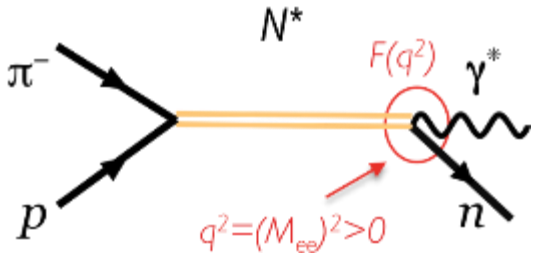
Scrutinizing baryon-vitrual photon couplings

- In –medium: strong modification of ρ are due to meson-baryon couplings



related to elementary process

„Dalitz decays"
- not measured before !



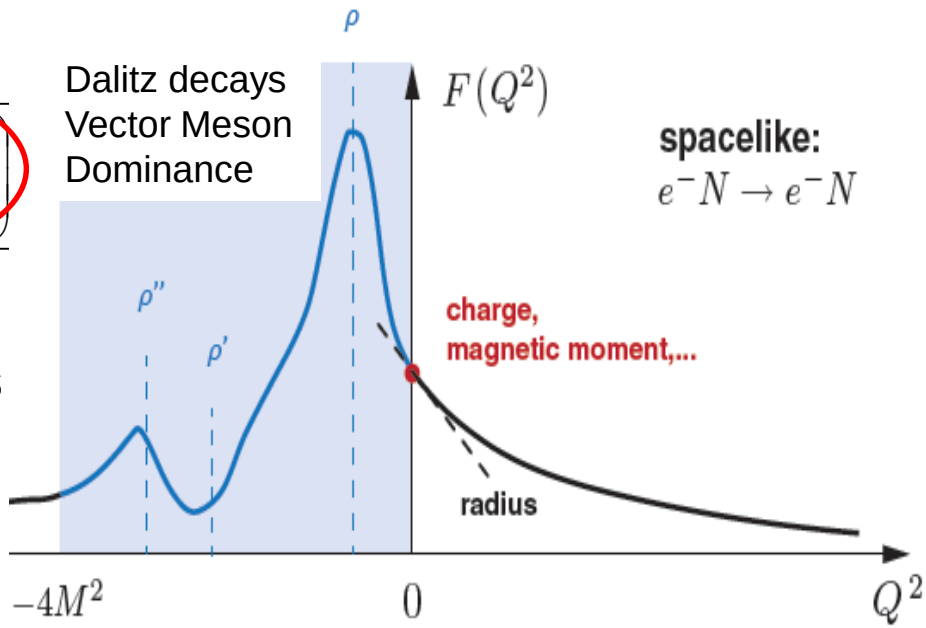
- HADES: Resonance production with pion and proton beams

for example Dalitz decay $\Delta^{\frac{3}{2}} \rightarrow N\gamma^*$

$$\frac{d\Gamma(\Delta \rightarrow Ne^+e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$

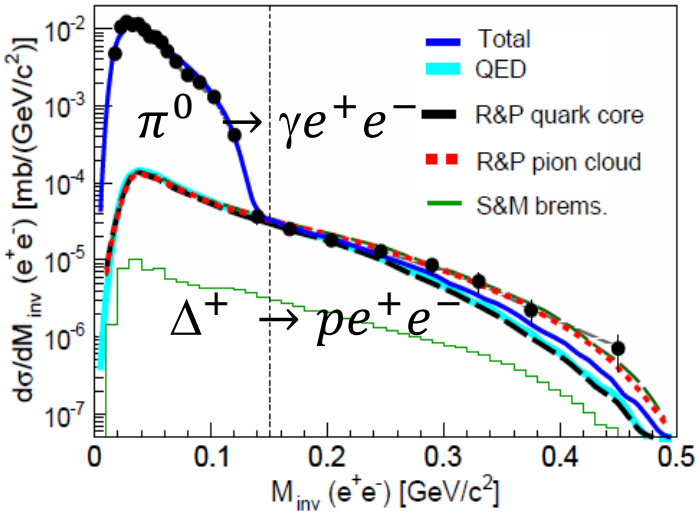
„QED "
point-like

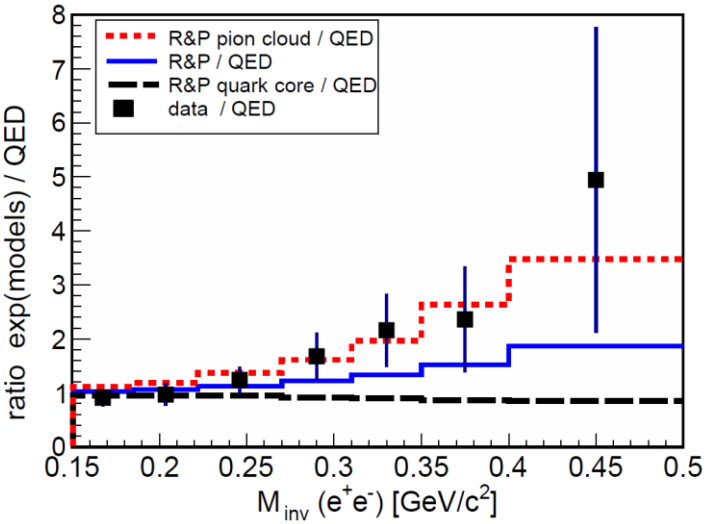
QCD
Transition Form Factors



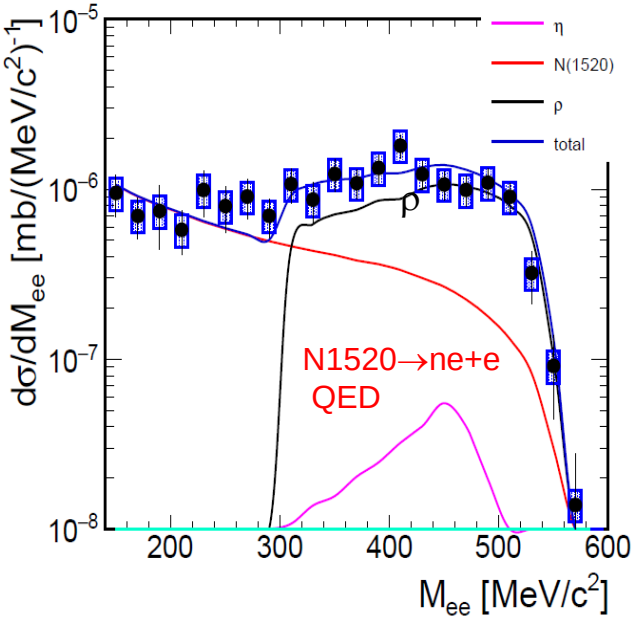
- Carry information about baryon structure : mesonic (cloud) (low q^2), quark d.o.f

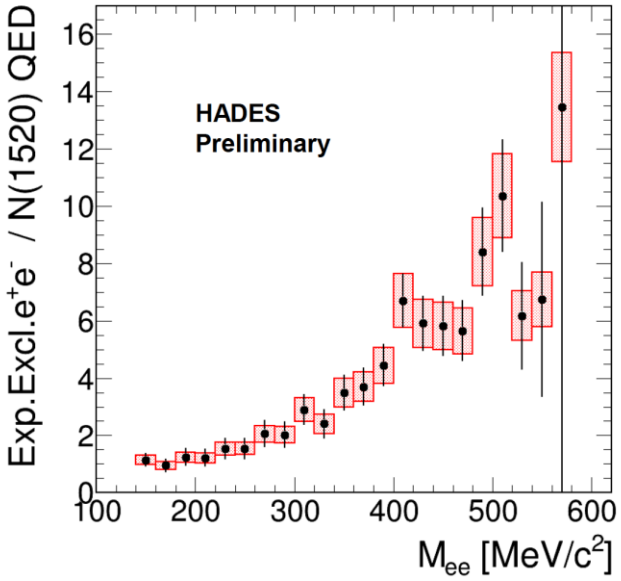
Δ(1232), $N^*(1520)\rightarrow N\gamma^*$ Transitions





$$BR(\Delta \rightarrow p\gamma^*) = 4.2 \cdot 10^{-5}$$





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

- Strong rise of „VDM type”

Summary

- HADES provides complete (kaons, hiperons, ϕ) data on strangeness production at subthreshold energy that calls for comprehensive explanation (real challenge for models):

non linear A_{part} dependence , strong ϕ and Ξ production

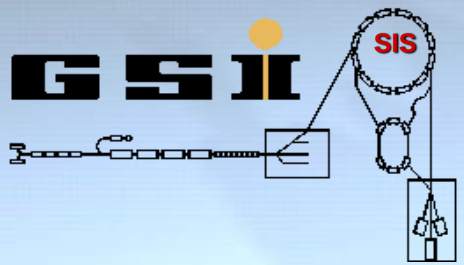
- dilepton radiation in Low Mass Region at low energy consistent with a global picture of emissivity established in UrHIC (not really expected before ..)!

excess radiation is dominated in Low Mass Region by a thermal radiation from strongly modified ρ meson according to hadronic many body theories

- Strong baryon - ρ coupling along VDM found in measurements of Baryon Dalitz decays

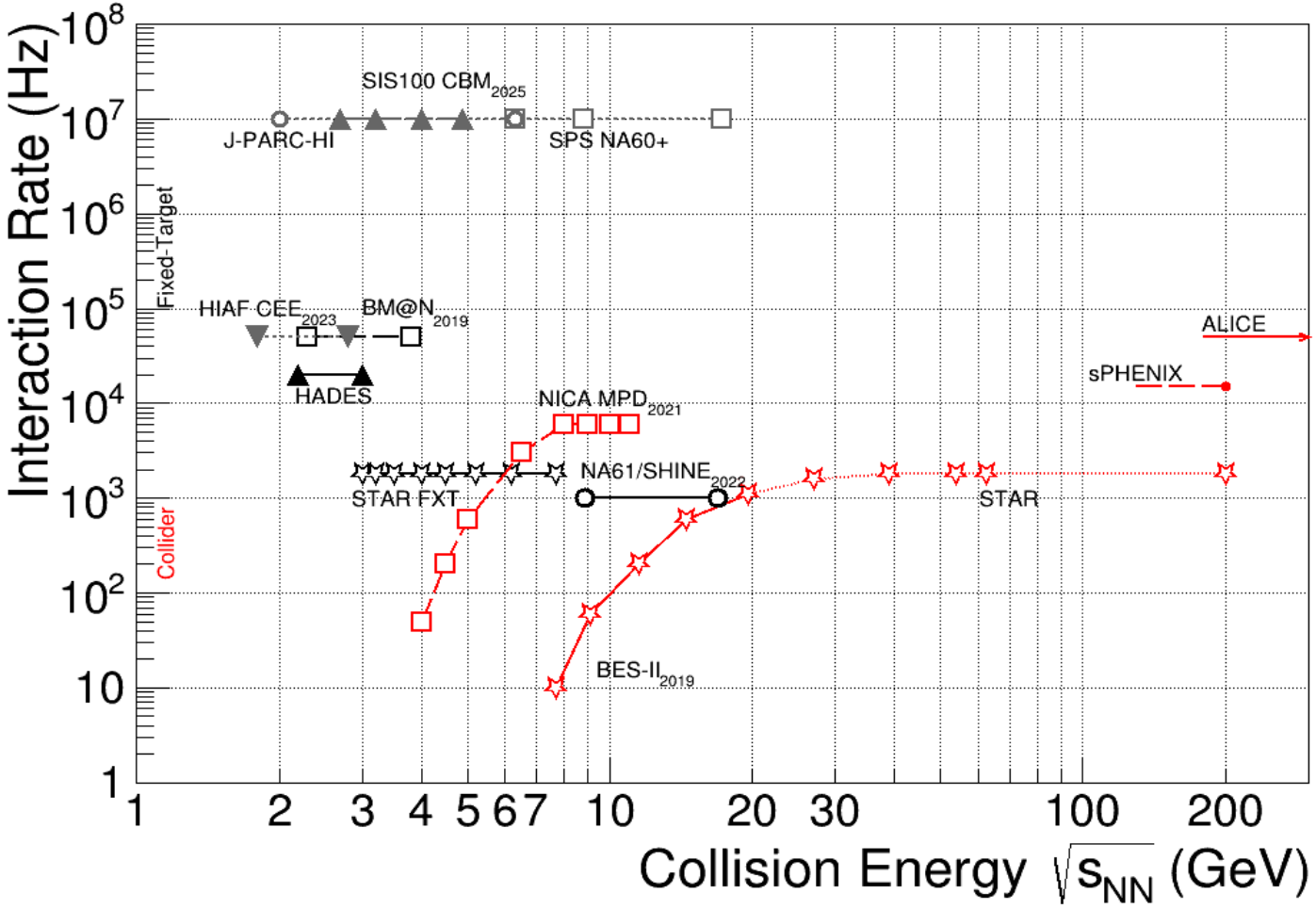
- **Outlook** : continuation of experimental programe (HI and pion beam experiments) at SIS18 til 2022 and later at SIS100 (excitation functions of dilepton production , complementing measurements o Compressed Baryonic Matter experiment)

The HADES collaboration



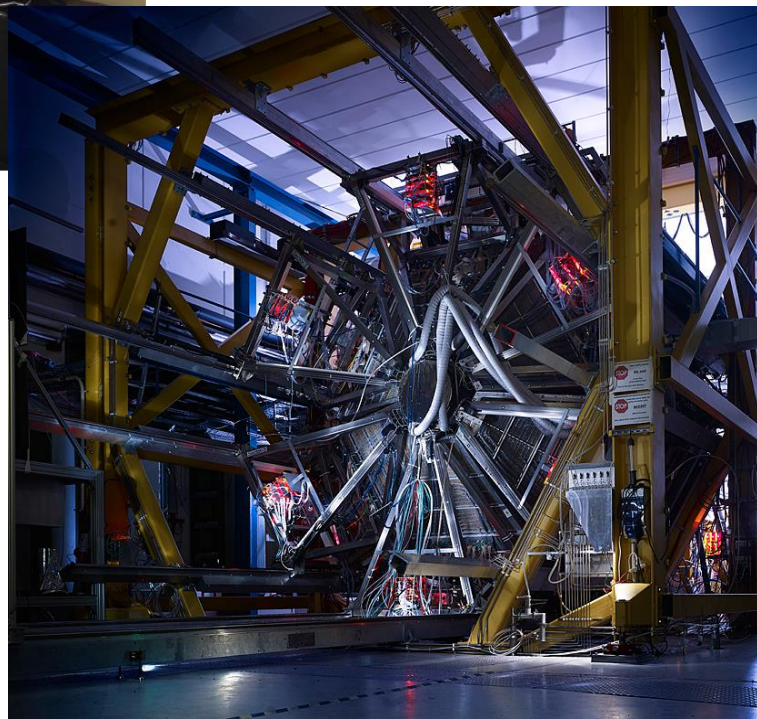
- Cracow (Univ.), Poland
- Darmstadt (GSI), Germany
- Dresden (FZD), Germany
- Dubna (JINR), Russia
- Frankfurt (Univ.), Germany
- LIP, Portugal
- Giessen (Univ.), Germany
- München (TUM), Germany
- Moscow (ITEP,RAS), Russia
- Nicosia (Univ.), Cyprus
- Orsay (IPN), France
- Rez (CAS, NPI), Czech Rep.
- Sant. de Compostela (Univ.), Spain

Detectors: present and Future ..



CBM Collab., EPJA 53 3 (2017) 60
TG, NPA-D-18-00411 (2018)

HADES @ GSI

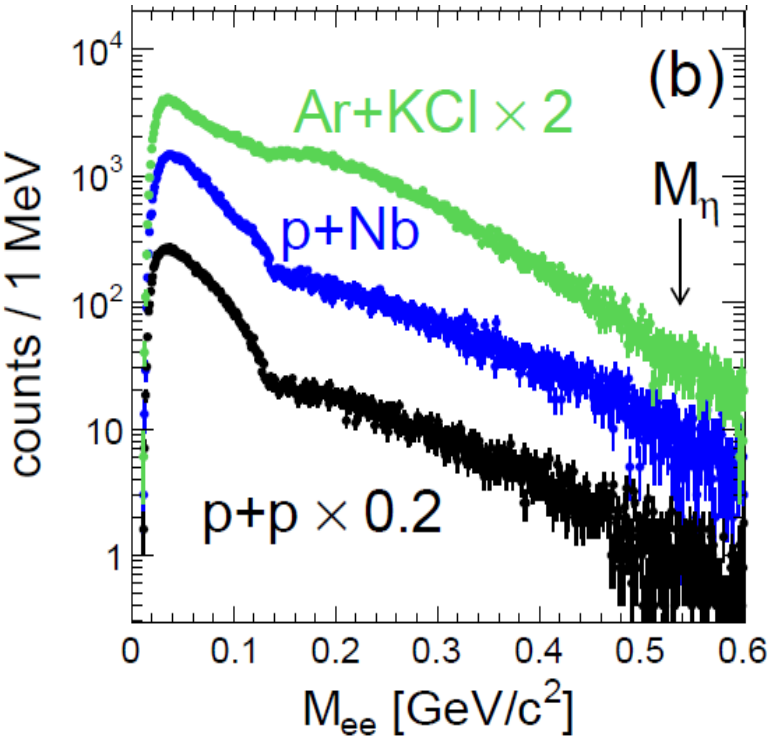


Search for U(1)$'$ -boson „dark photon”

- Extension of SM via U(1)$'$ gauge symmetry

$\rightarrow$ dark photon: coupling of dark matter to SM photon with coupling α' ; $\varepsilon^2 = \alpha'/\alpha$

- can appear in any el. decay via coupling to photon
- could explain $(g-2)_{muon}$ discrepency (~2.6 σ) between data and theory , anomaluous e+/e- ratio (E>10 GeV) observed from Universe,…

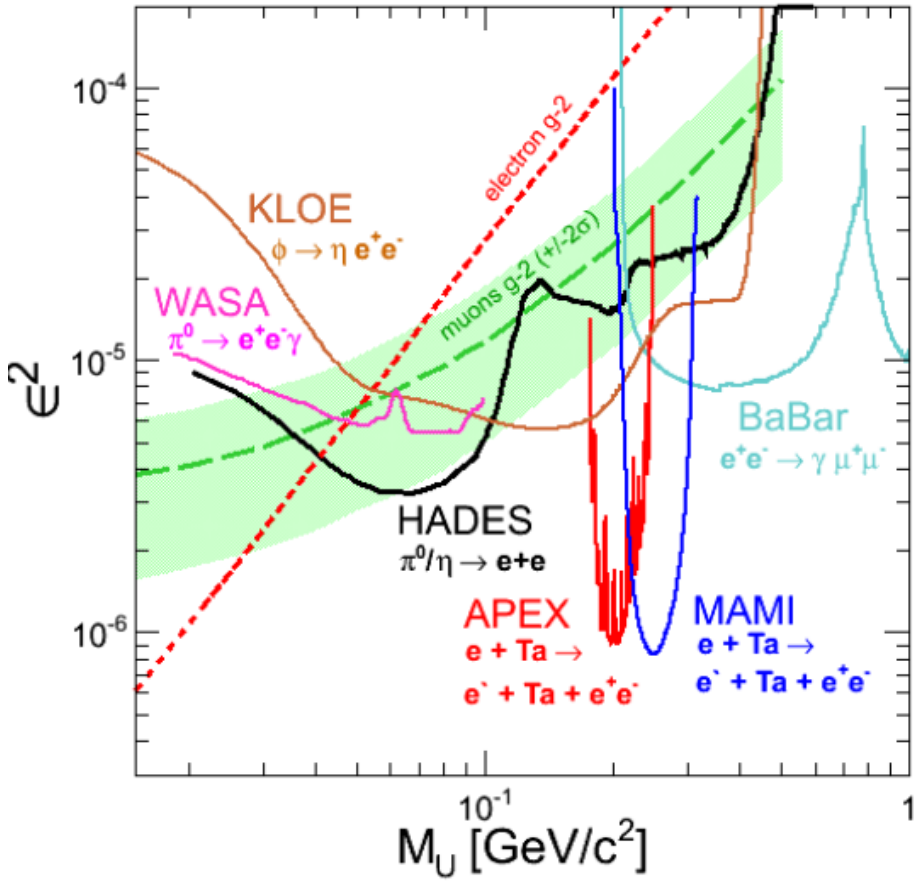


Use large sample of e+e- collected by HADES on

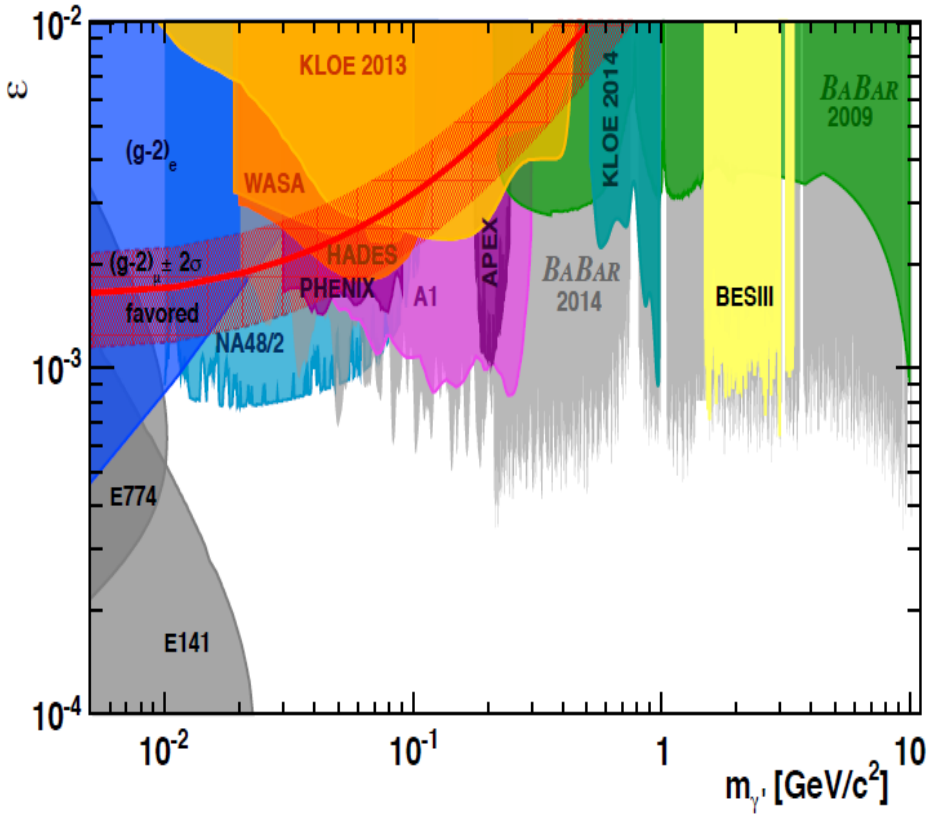
π^0 (η)$\rightarrow$e+e-γ and $\Delta\rightarrow$Ne+e- (Dalitz decays) and search for narrow peak !
If absent give 90% confidence level upper limit on $\in$

Upper limits for Dark Photon

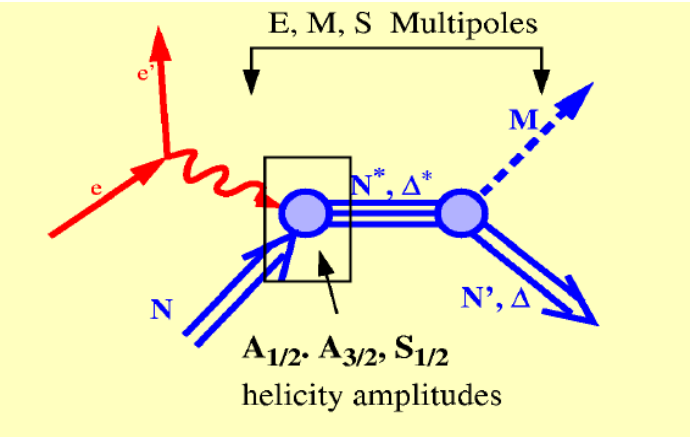
Phys. Lett. B 731 (2014), pp. 265-271



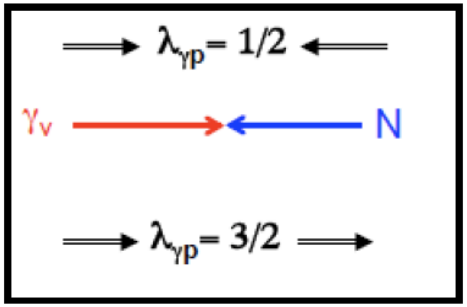
dark photon Status : 2017



Role of meson cloud in baryons

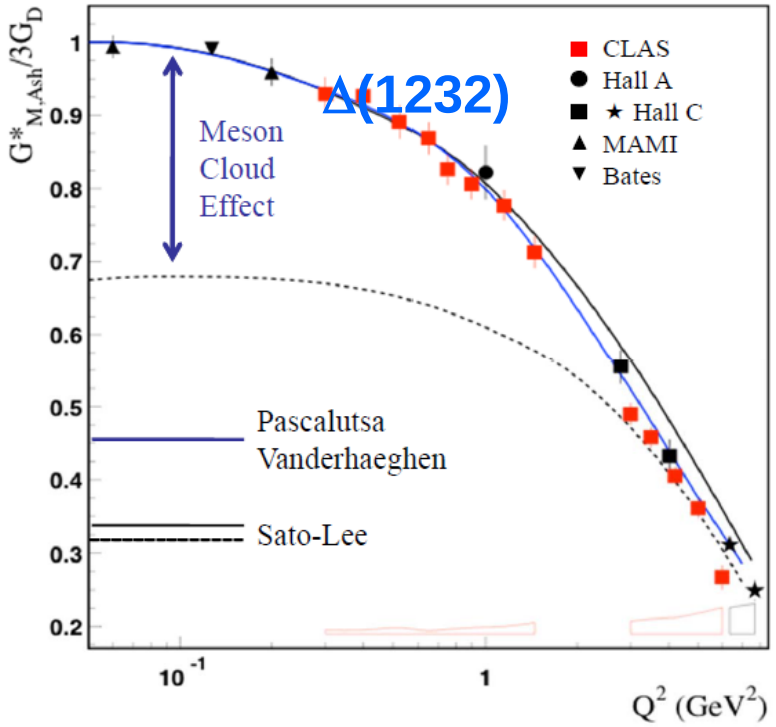


Helicity amplitudes: or Form-Factors

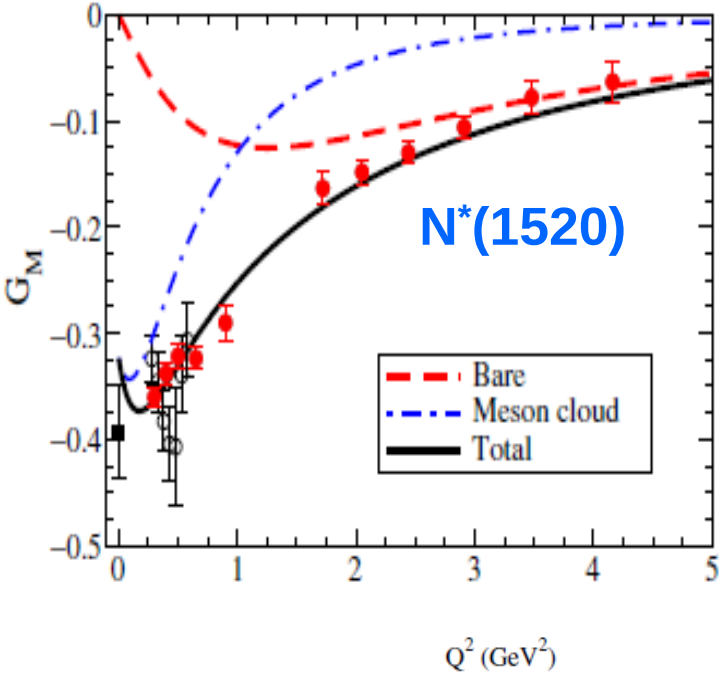


Magnetic G_M
Electric G_E
Coulomb G_C

Data CLAS, MAMI

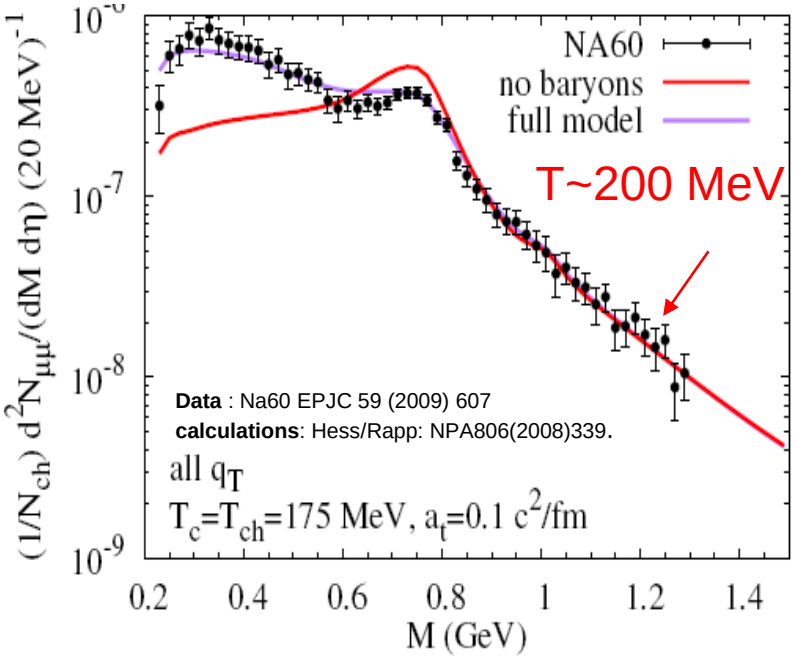


Data CLAS : theory T. Pena et al. PRD93(2017)

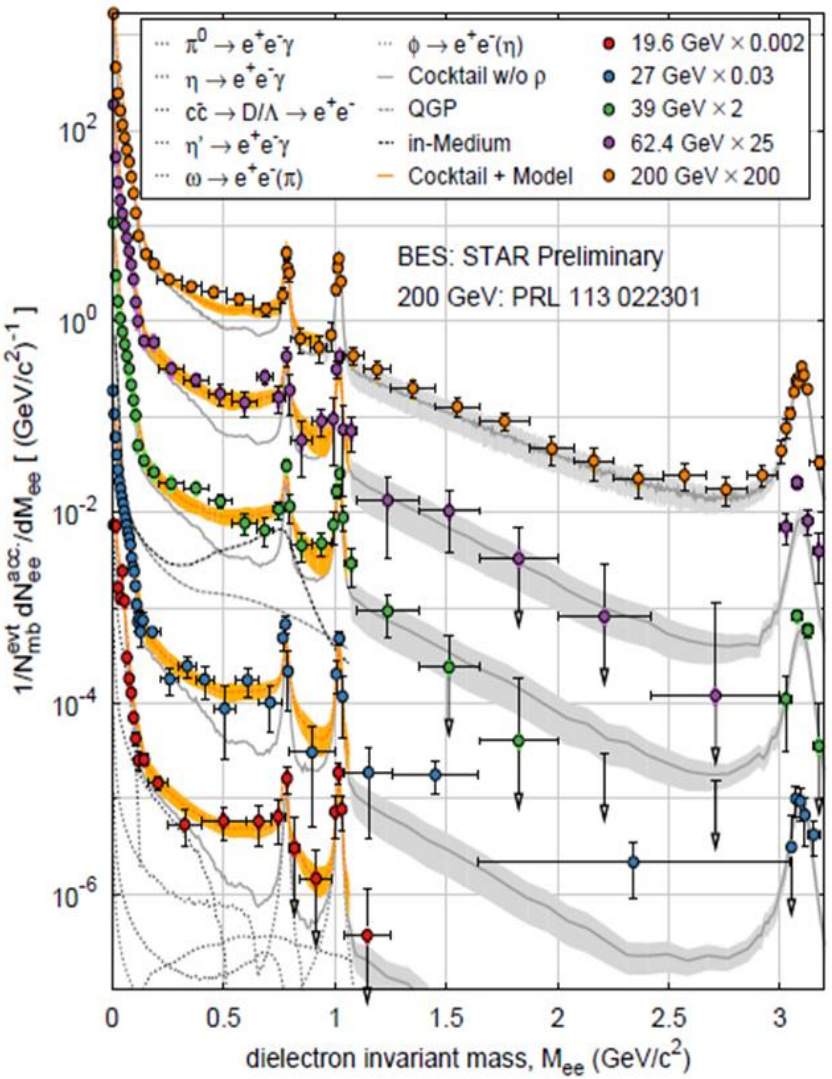


Low Mass Region from UrHIC SPS/RHIC

Na60 @ SPS In+In
Thermal radiation ($\mu^+\mu^-$)



RHIC



☝General conclusion from UrHIC:

- LMR dominated by thermal radiation from modium modified ρ
- baryons are driving force for observed melting of the ρ meson over all energy

ρ -meson : the main player

$$\frac{1}{M^2}\int_0^\infty ds \frac{\rho_V(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) + \frac{m_q\langle\bar{q}q\rangle}{M^4} + \frac{1}{24M^4}\langle\frac{\alpha_s}{\pi}G^2_{\mu\nu}\rangle - \frac{56\pi\alpha_s}{81M^6}\langle\mathcal{O}_4^V\rangle\ldots$$

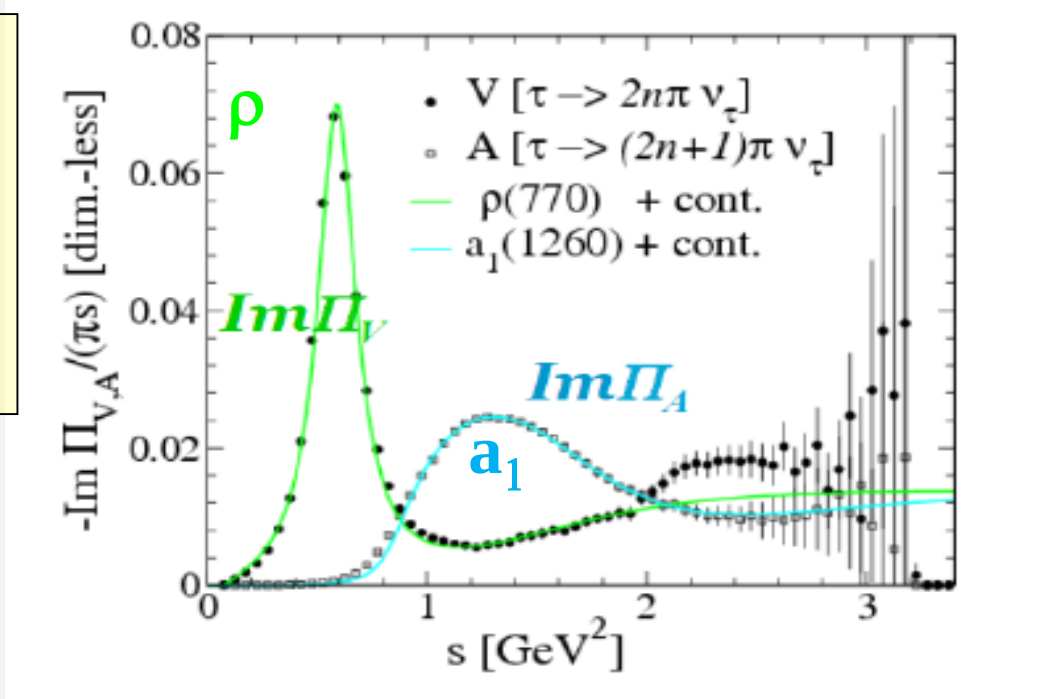
[Hatsuda+Lee '91, Asakawa+Ko '93, Leupold et al '98, …]

$$\int ds \frac{1}{s}(\rho_V - \rho_A) = f_\pi^2$$

$$\int ds\,(\rho_V - \rho_A) = -m_q\langle\bar{q}q\rangle$$

$$\int ds\, s\,(\rho_V - \rho_A) = c\alpha_s\langle(\bar{q}q)^2\rangle$$

[Weinberg '67, Das et al '67; Kapusta+Shuryak '94]



- in vacuum ρ-a_1 mass splitting

due to χS breaking (~ f_π , $\langle\bar{q}q\rangle$, …)

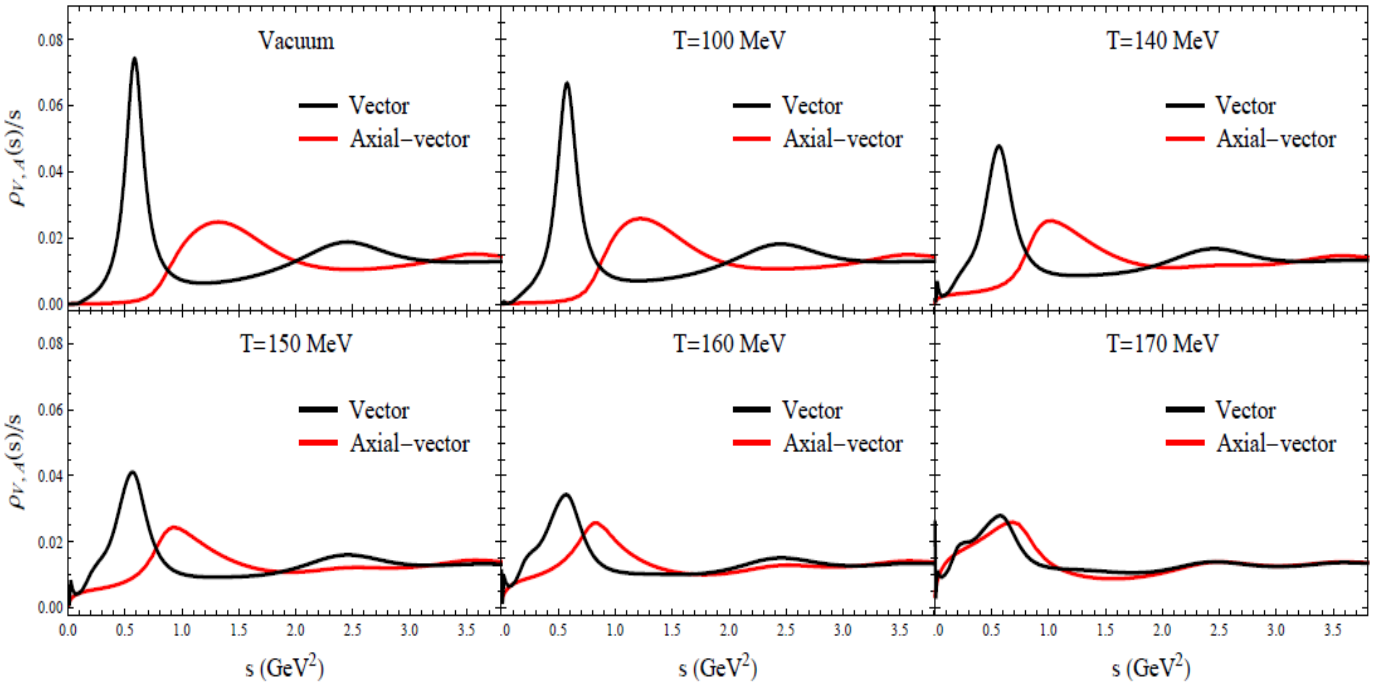
- χSR – both spectra functions overlap
- Thermal emission dominated by in-medium ρ-spectral function

$$\frac{dN_{ee}}{d^4x\,d^4q} \sim \frac{\alpha_{\rm em}^2}{\pi^3 M^2} f^B(q_0,T)\,\mathrm{Im}\,D_\rho$$

Consistency of hadronic description of Chiral Symmetry Restoration – removal of ρ/a_1 mass splitting

M. Holher & R.Rapp

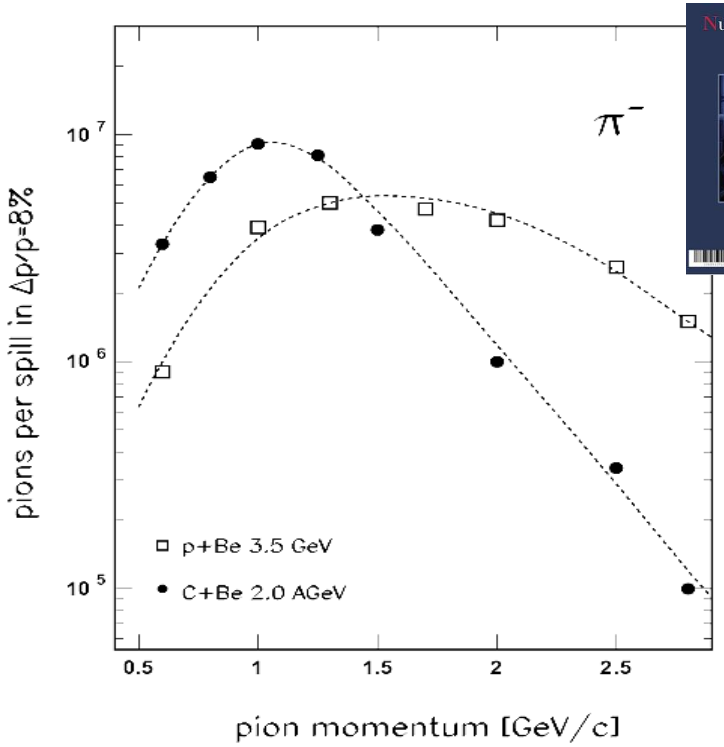
- Use spectral functions of ρ constrained by e+e- data
- Use (μ_b=0) results on evolution of quark/gluon condensates with T from lattice QCD
- Use QCD sum rules (spectral functions $\leftrightarrow$ quark and gluon condensates) and Weinberg sum rules (spectra functions of Vector (ρ) $\leftrightarrow$ Axial vector (a_1) states)
- Predict evolution of a_1 spectral function in T up to T_c

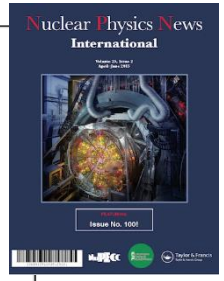


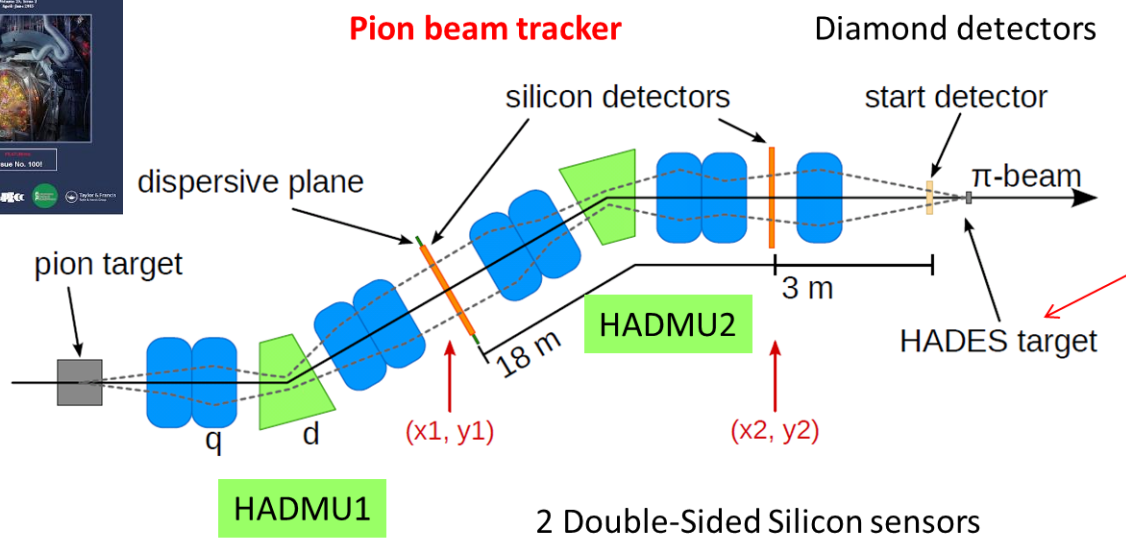
- Compatible with chiral restoration scenario for μ_B =0:

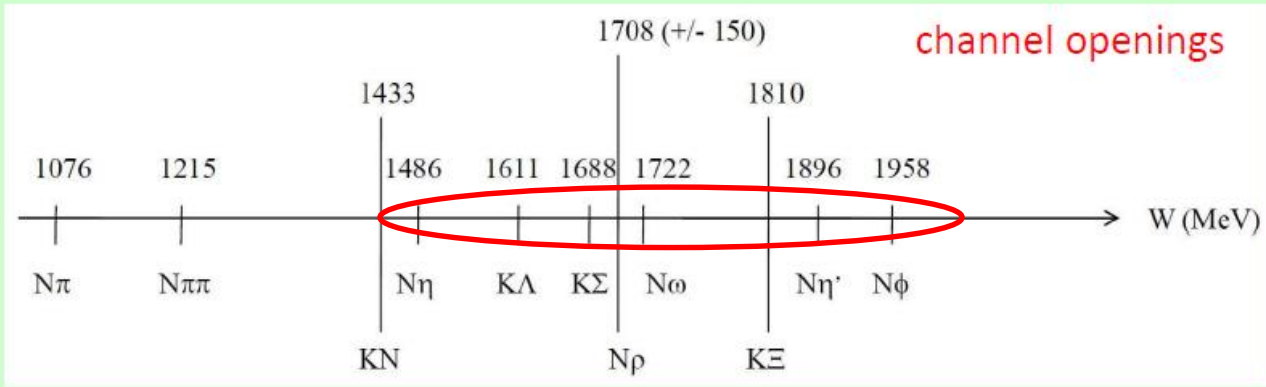
ρ and a_1 becomes degenerate around T_c !

pion beams & HADES - unique in world



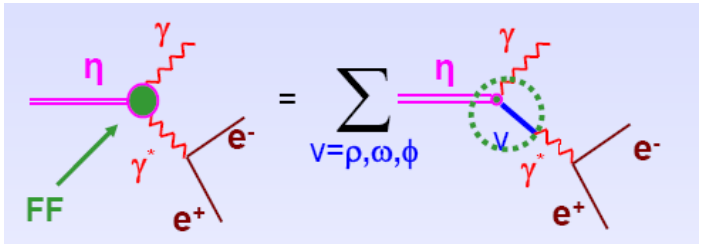






- π-p studied in 80'es – since then no new data
- Precision data needed - big impact on baryon spectroscopy

Dalitz (3 body:e^+e^-X) decays - Mesons



Vector Meson Dominance (VMD) :

$F(q^2)$ determined by ρ mesons

$$F(q^2) = \frac{d\Gamma/dm_{exp}}{(d\Gamma/dm)_{point-like}}$$

F (q^2) influences dielectron inv. mass spectrum