Studying baryonic matter with HADES at GSI/FAIR

✓ GSI/FAIR facility and HADES detector

✓ Motivation (driven by obtained results) and new measurements:

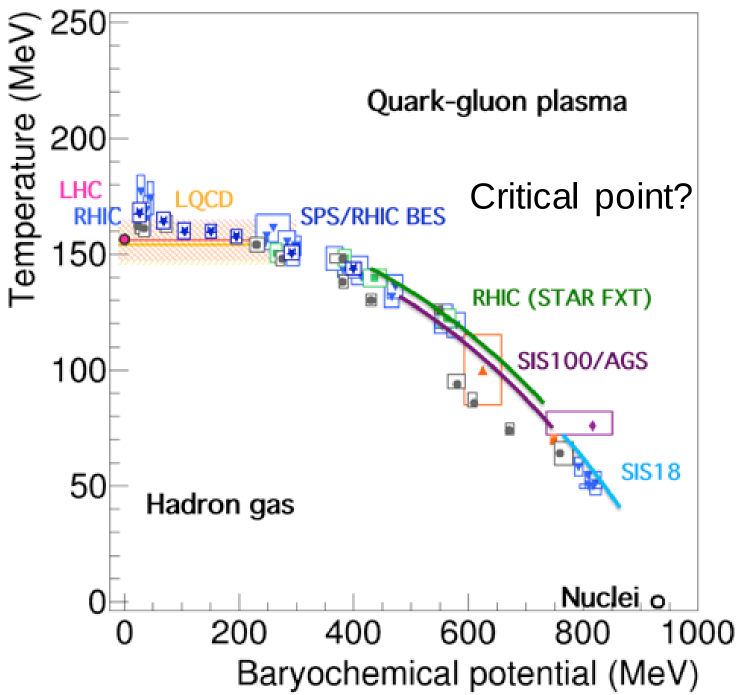
focus on

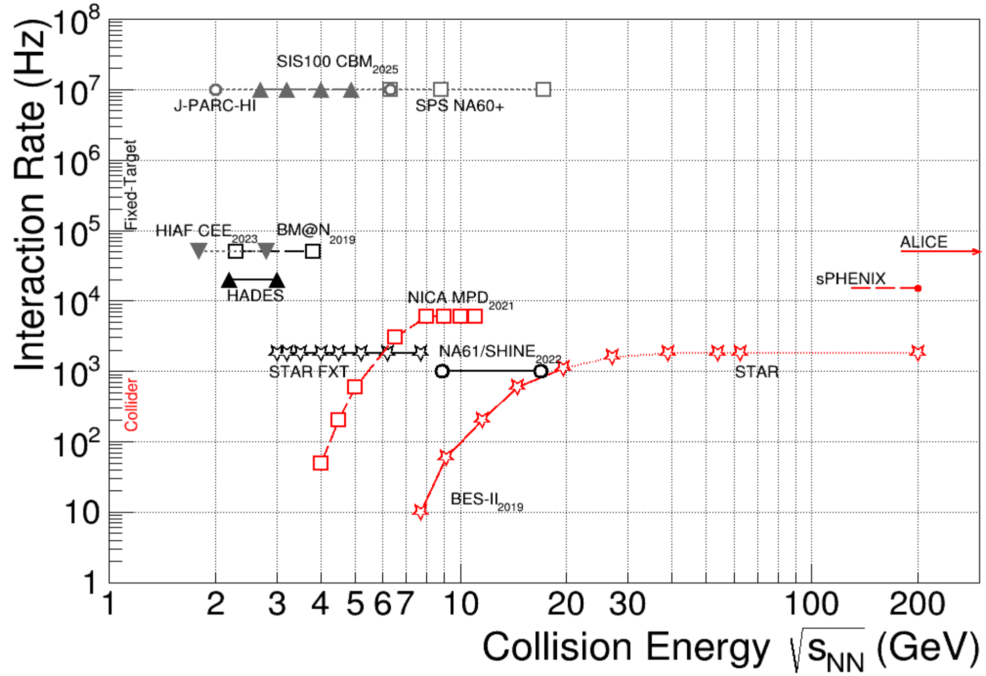
- dileptons,
- strangeness

✓ Summary

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

Detectors: present and Future ..





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

- HADES @ GSI/FAIR (SIS18-SIS100) covers high μ_B region -> import region to cover in QCD phase diagrame- EOS, exotic QCD faces, neutron star merges,…
- Focus on penetrating (dilectrons) and rare (strangeness) probes – first complete measurements at low energies!
- Reference measurements with proton/pion beams (radiative decays of baryons, baryon resonance excitation and decays)

GSI- FAIR

from 2022

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 $2.8x10^{13}$/s
Secondary pion beam ! 0.5-2 GeV/c

SIS 100 2T (4T/s) magnets

Au 8-10 GeV/u 10^{12} ions/s
protons 30 GeV $2.8x10^{13}$/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

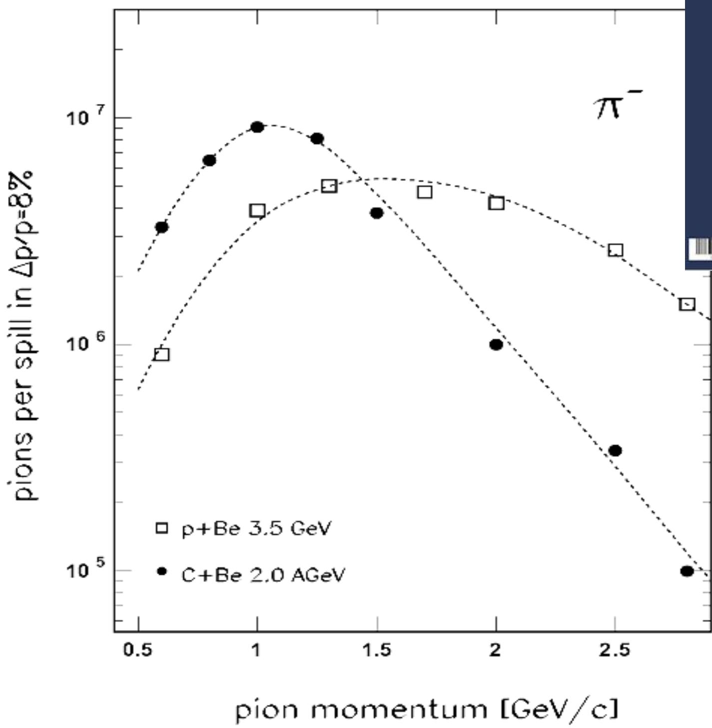
Phase0: 2018-2022 at SIS18 !

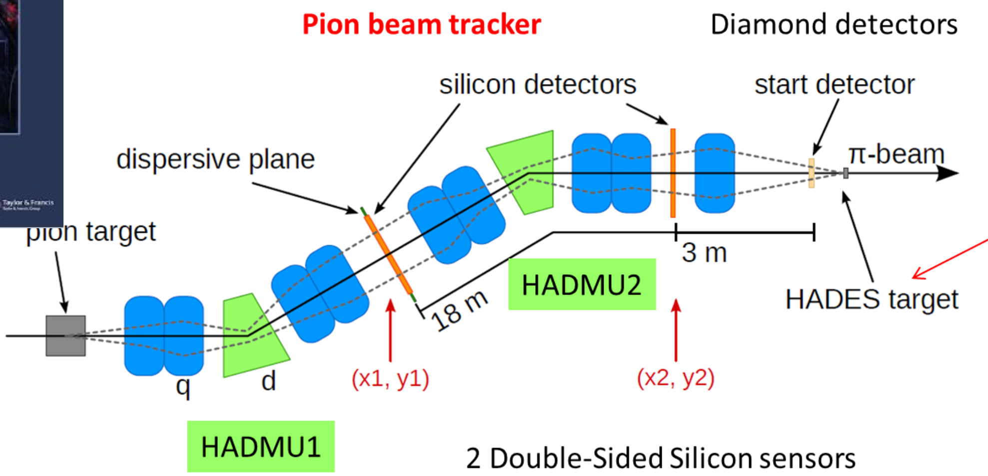
HADES: Ag+Ag @1.65 AGeV(2019)
π+p, π+A, p+p, p+A

Phase1: > 2022 at SIS100

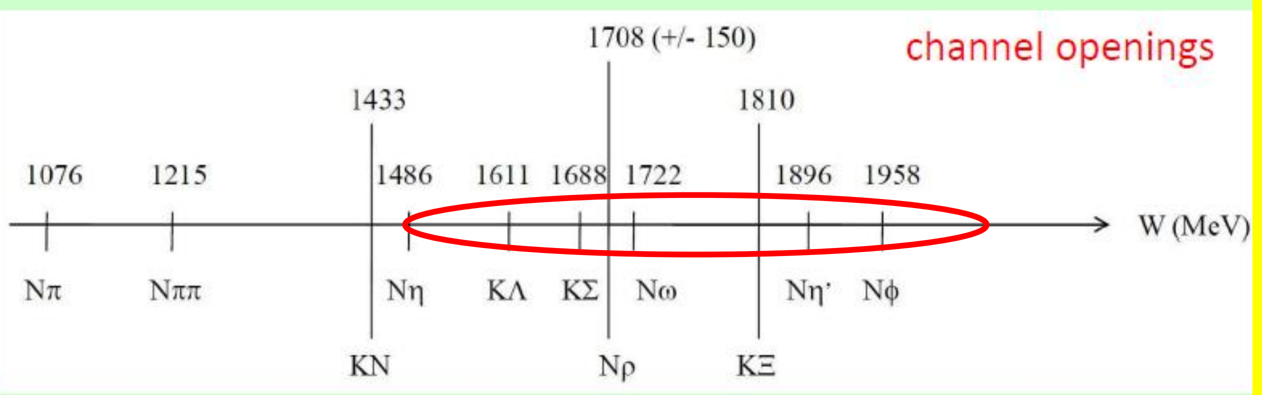
pp,pA, AA (Ag+Ag@4.5 AGeV

pion beams & HADES - unique in world





2 Double-Sided Silicon sensors
100 x100mm^2, 300µm thick
2 x128 channels

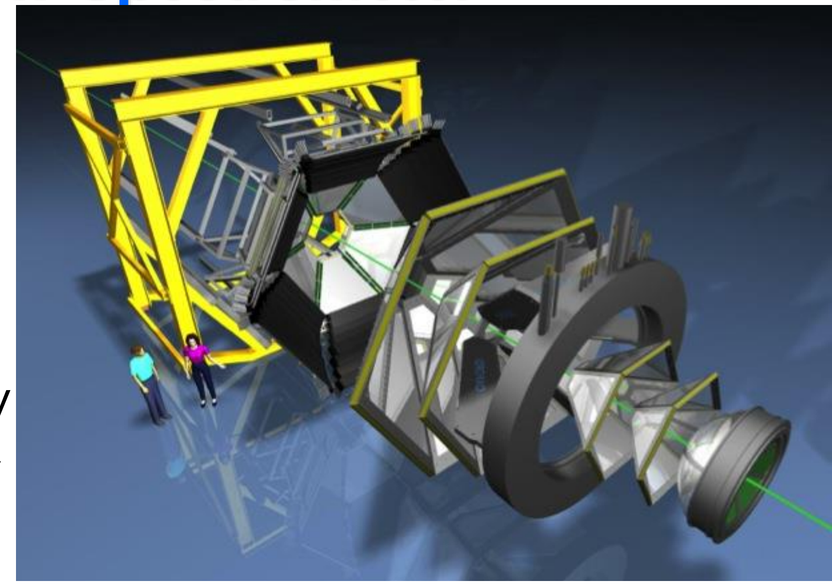


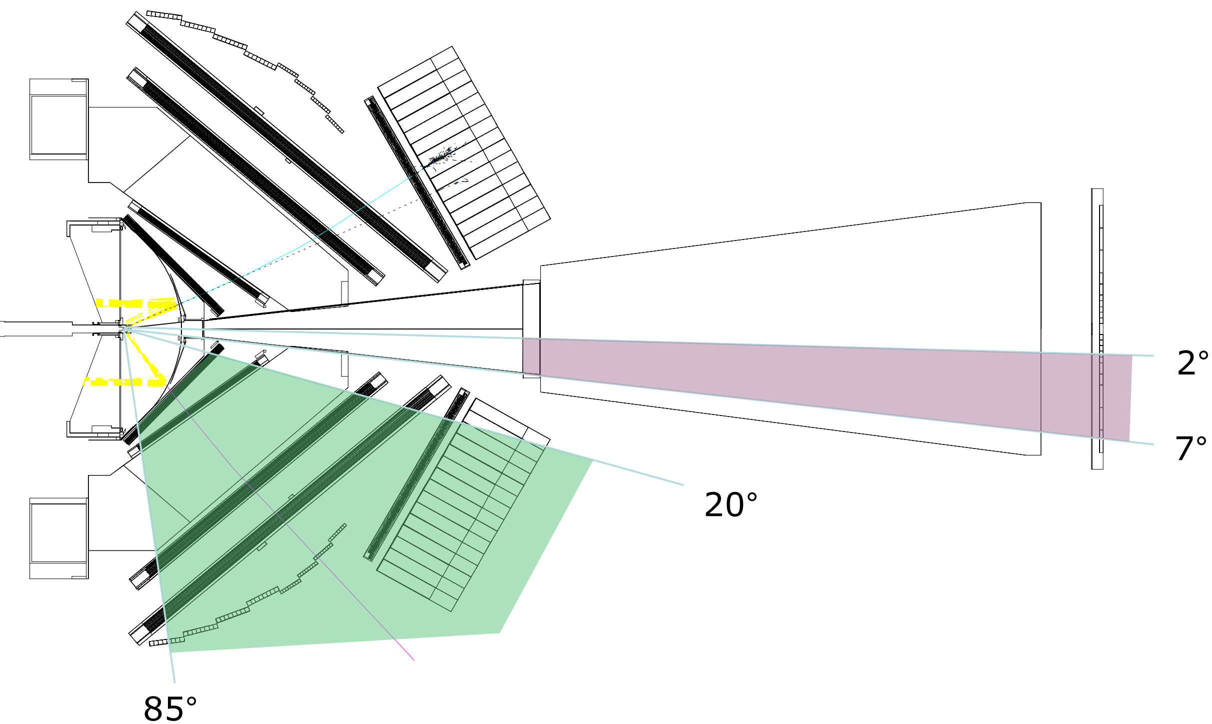
- Mean focus: radiative decays of baryons → microscopic input to emissivity calculations
- Cold matter physics (Vector mesons, kaons, hyperons)
- ππ, KΛ/Σ , ρ/ω/φ/N -> impact on baryon spectroscopy PWA

High Acceptance Di-Electron Spectrometer

- ✓ Spectrometer with ΔM/M - 2% at ρ/ω
- ✓ electrons : RICH (hadron blind)
- ✓ hadrons: TOF & dE/dx vs p
- ✓ Flow and correlation measurements
- ✓ Centrality from track mult. (Glauber Model)
- ✓ 2004-2104: HI (C+C, Ar+KCl, Au+Au √s~2.4-2.6 GeV

p+p, d+p, p+N √s =2.4-3.0 π+p √s ~2.4-3.0 √s= 1.5 GeV

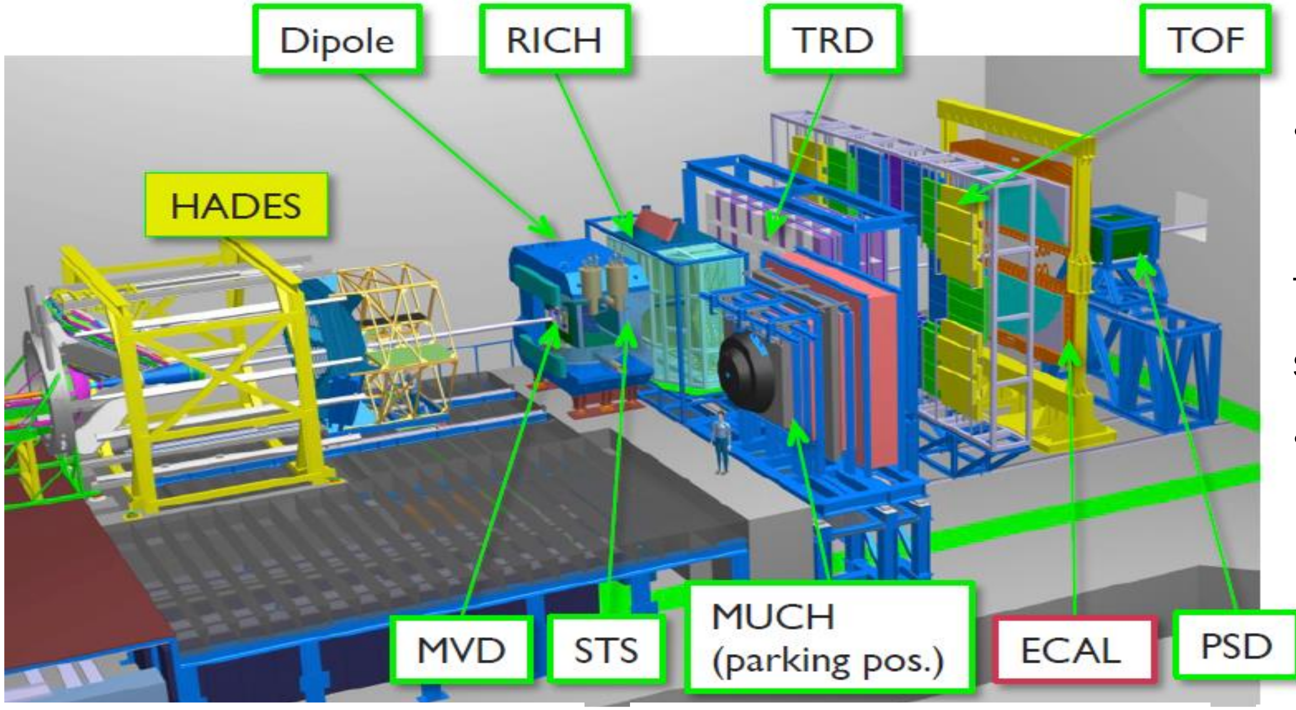




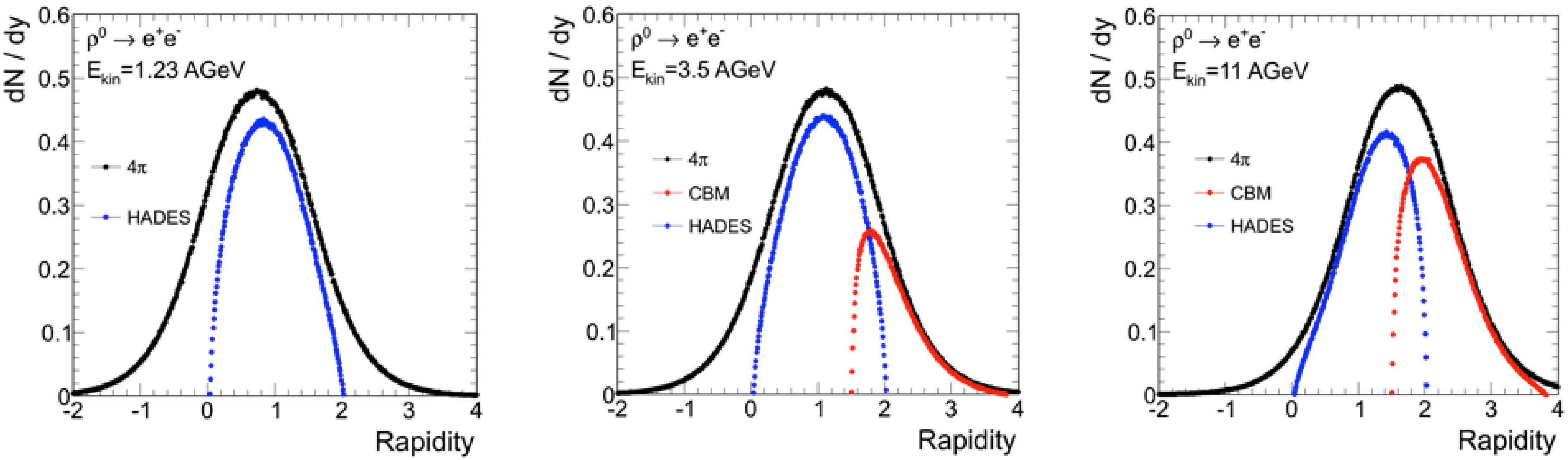
Upgrade 2018/2019

- New RICH photon det (HADES/CBM) – 2-3 ⊗ e_{eff}
- Forward tracking straws +RPC – Λ/Ξrec. in pp/pA (HADES/PANDA)
- el. Calorimiter (lead glass)- neutrals
- Planned: 200 kHz DAQ , 10⊗ count rate increase

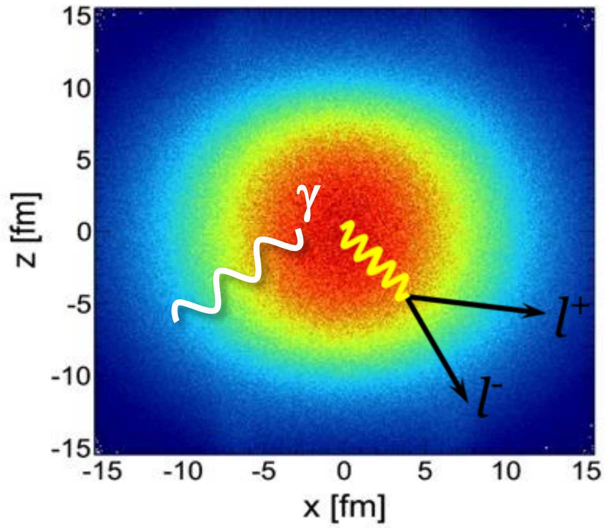
HADES & CBM at SIS100



- Complementary covarage HADES more backward –better for p+A (cold matter physics studies @ highest E_{beam})
- Limited granularity → Max Ag+Ag @ 4.5 GeV

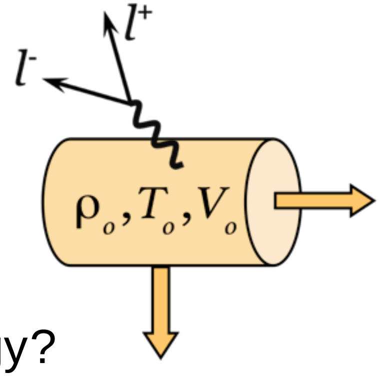


Dielepton radiation



Emissivity of QCD matter

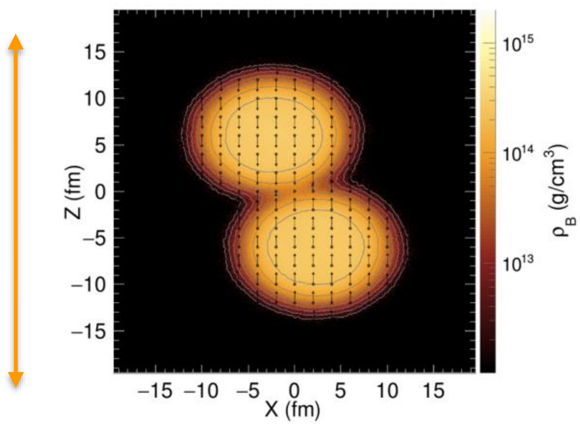
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

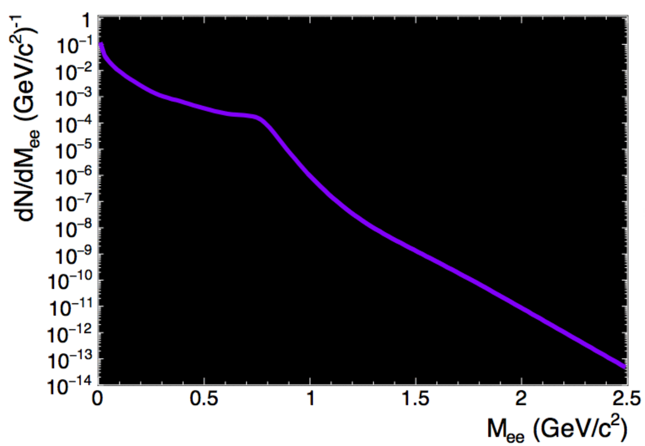


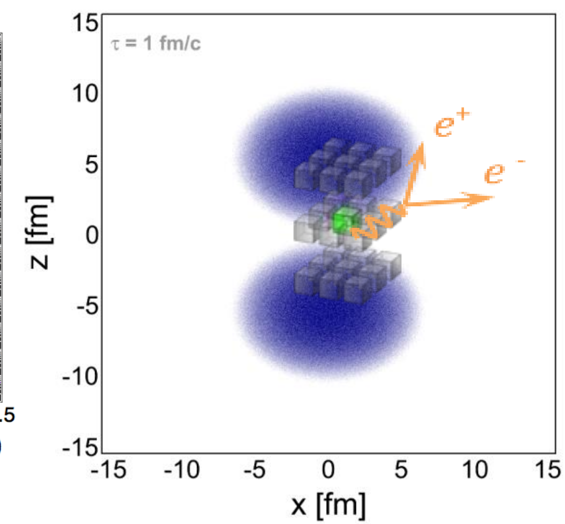
McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

Successful 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}



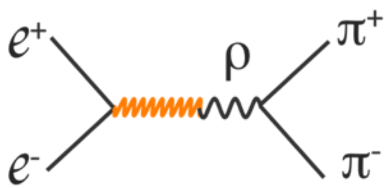




Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131

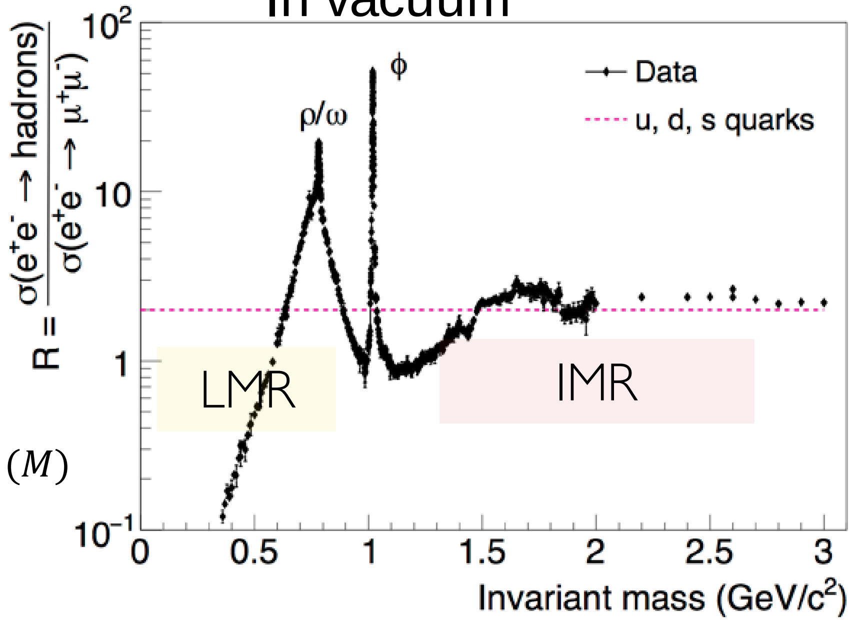
Electromagnetic current-current correlator

Low mass: ρ meson



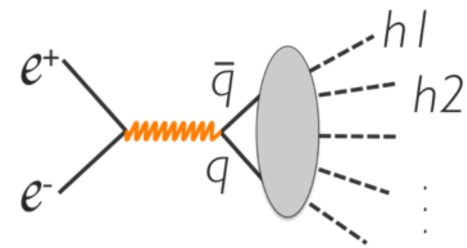
$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

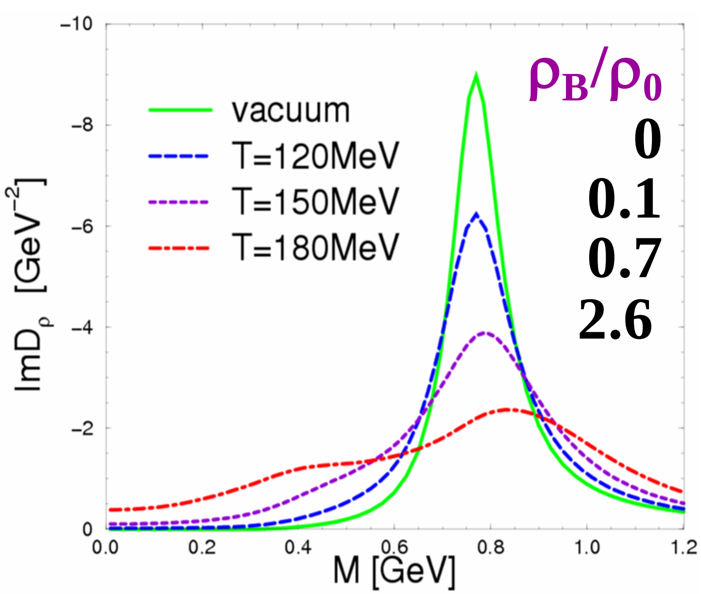
In vacuum



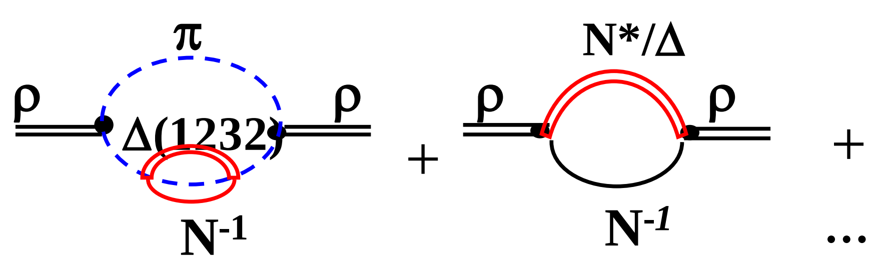
Intermediate mass (M>1.5 GeV/c²)

Perturbative QCD continuum





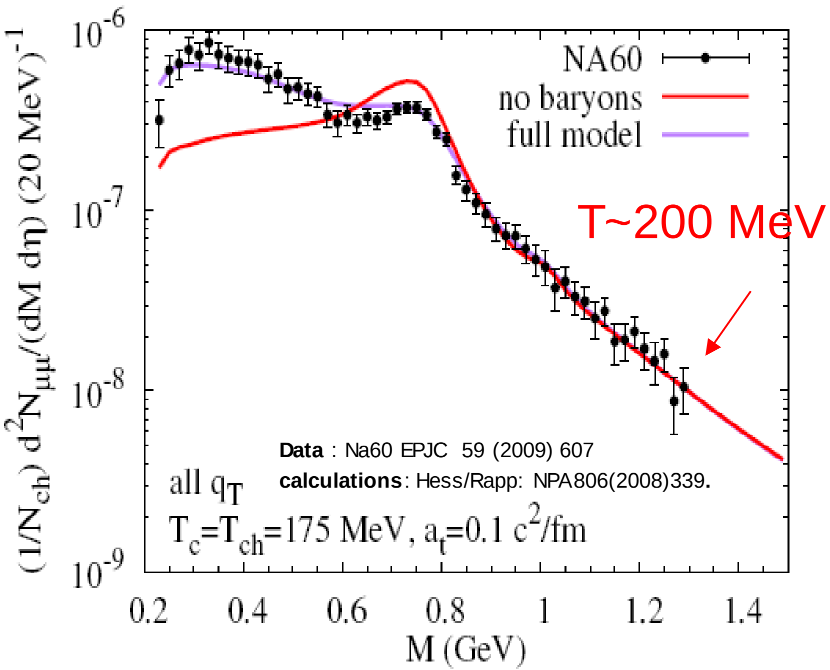
- In –medium: strong modification of ρ due to meson-baryon couplings

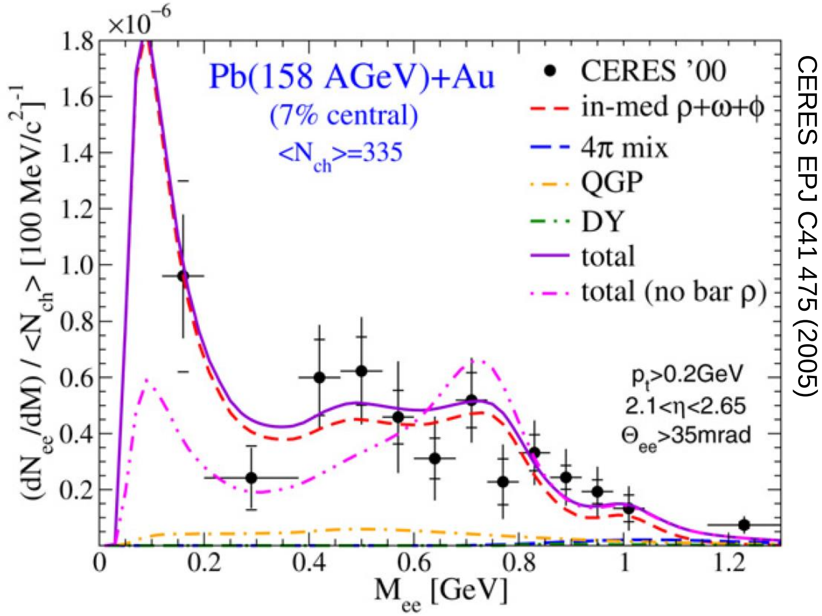


Microscopic model R. Rapp, J. Wambach, Adv. Nucl. Phys.25 (2000) 1.

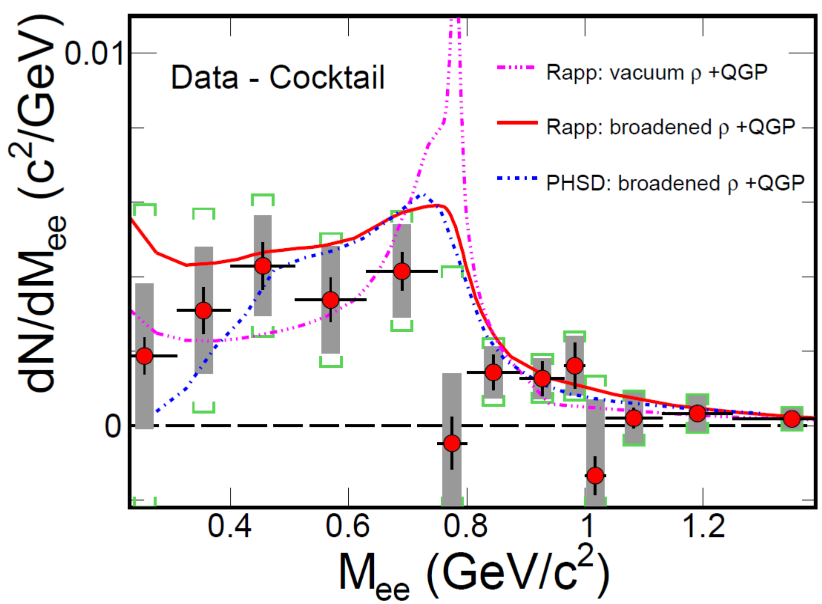
Dielepton excess from UrHIC SPS/RHIC

Na60 @ SPS In+In (μ+μ-) $\sqrt{s}$=17.3 GeV





STAR $\sqrt{s}$=200 GeV PRC92 (2015)



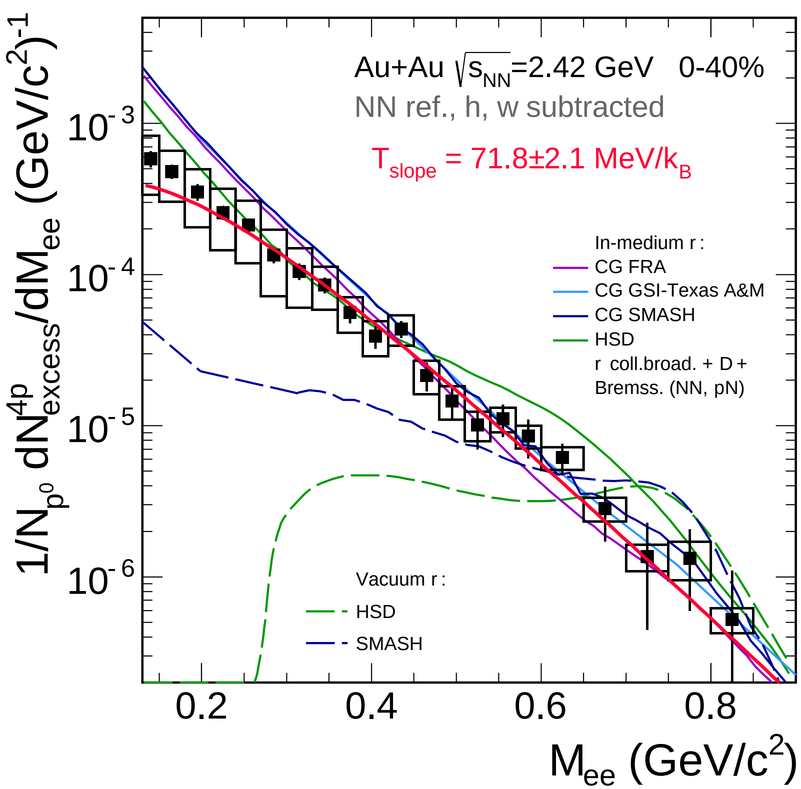
- LMR dominated by thermal radiation from ρ
- Broadenning „melting" of ρ :

baryon-ρ interactions are driving force for the observed effect (model of Rapp/Wambach)

- IMR – T measurement ! T > $T_{c.f.o}$ (Na60)

Thermal dileptons from Au+Au

Excess yield fully corrected for acceptance



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 Coarse-Grained (CG)) approach + 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/c²
- $<T>_{\text{emitting source}} = 72 \pm 2$ MeV/k_B

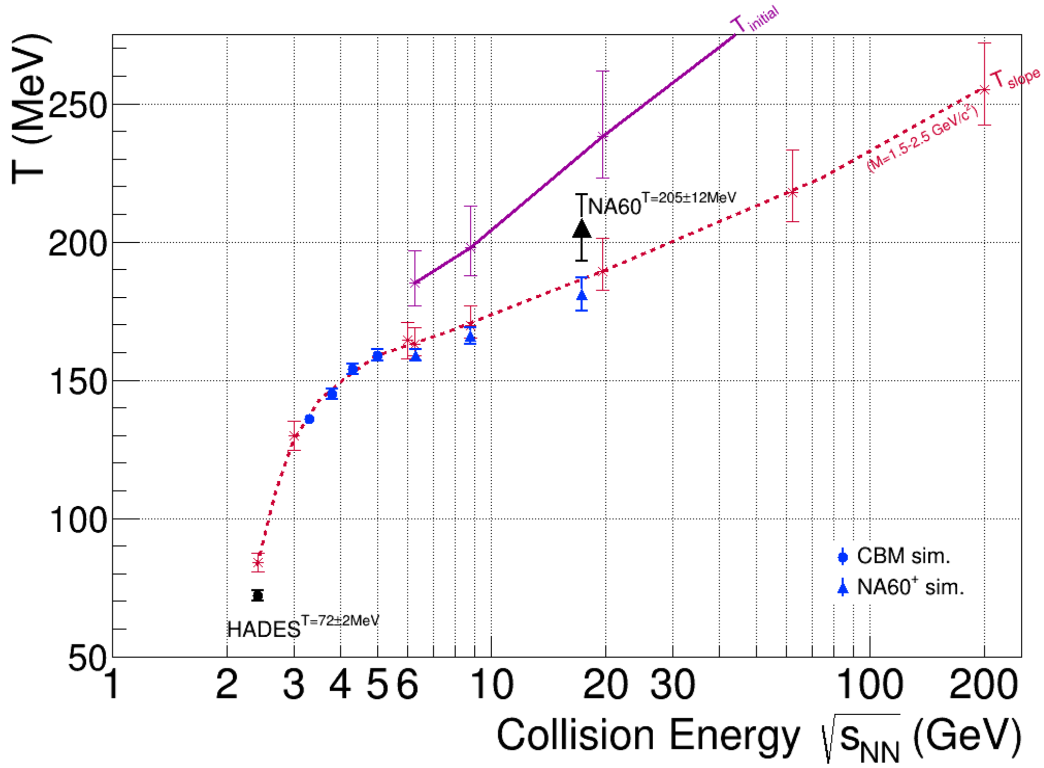
- Strong melting of ρ meson
- In agreement with microscopic model of Rapp & Wambach (interactions with baryons !)
- Same model describe also RHIC(STAR), SPS (CERES, Na60 data)

Robust understanding across QCD phase diagram

Standard candle of HI?

Dileptons- thermomether of HI collisions?

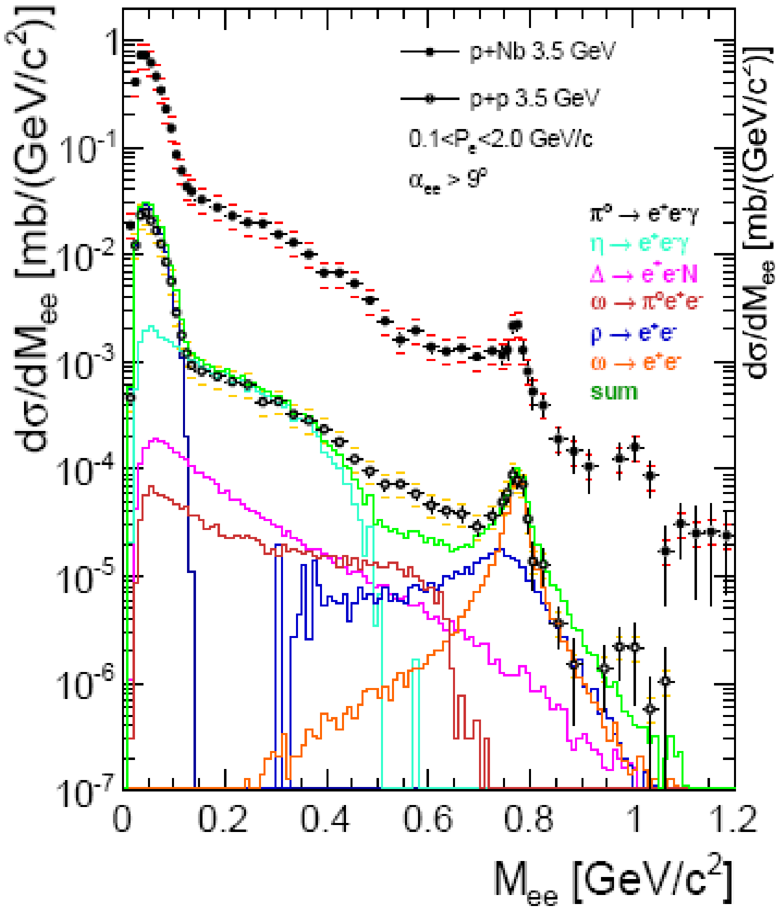
R. Rapp, H. van Hees, PLB 753 (2016) 586
T.Galatyuk et al.: EPJA 52 (2016) 131



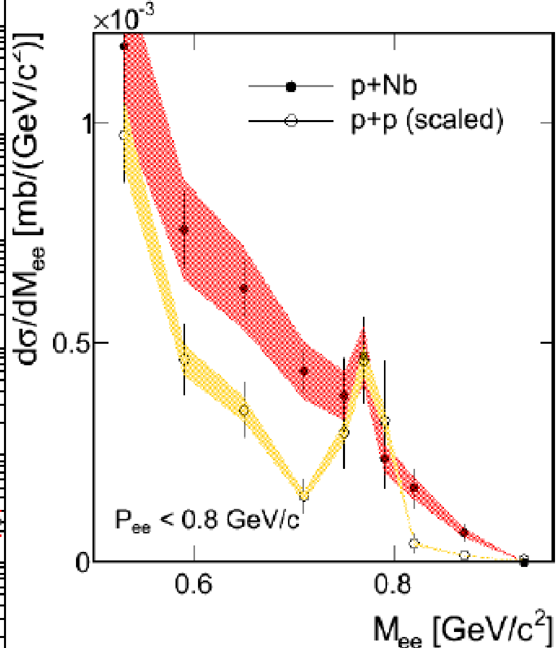
- Model calculations with in-medium ρ describing LMR and IMR of RHIC/SPS/SIS18
- Look for deviations , platou (phase transition.),..

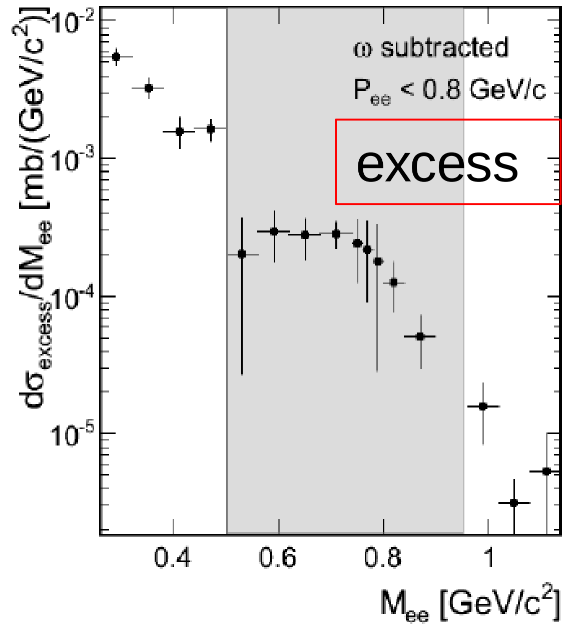
Medium effects present also in cold matter..

data: HADES PLB715 (2012) 304



„slow sources" p_{e+e-}< 0.8 GeV/c





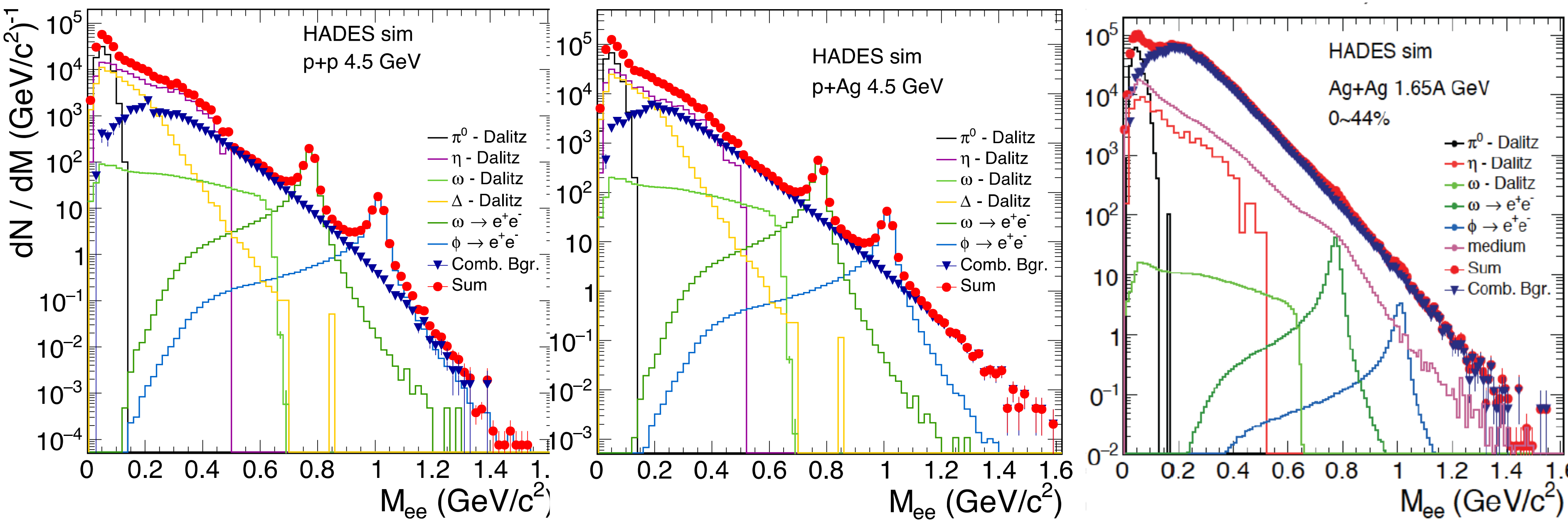
pp data scaled by
„A_{part}" scaling

$$R_{pA} = \frac{d\sigma^{pNb}/dp}{d\sigma^{pp}/dp} \times \frac{\langle A^{pp}_{part} \rangle}{\langle A^{pNb}_{part} \rangle} \times \frac{\sigma^{pp}_{reaction}}{\sigma^{pNb}_{reaction}}.$$

Nuclear modification factor

- remarkable difference between p+p, p+A : reduction of ω yield (absorption), broadenning of ρ

Expected performance p+p, p+A, A+A @ 4.5 GeV



10 – fold increase in statistics
M>m_π w.r.t p+ Nb/p+p

6-fold increase in stat
M>m_π w.r.t Au+Au

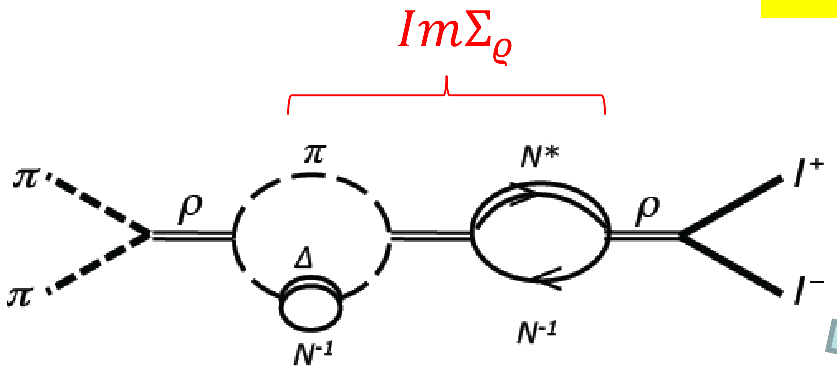
- Programme in FAIR/Phase0 (4 weeks running)
- prominent ω/φ signals expected -
- first measurement beyond 1 GeV (small partonic contribution)→look for $\rho - a_1$ *chiral mixing*

$\int ds(A_\rho - A_{a1}) = m_q < q\bar{q} >$ (Weinberg sum rules)

Scrutinizing baryon-vitrual photon couplings

ρ meson spectral function :

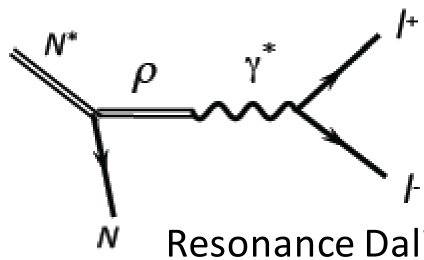
$$A_\rho(M) = -\frac{2 Im\Sigma_\rho(M)}{[M^2 - m_\rho^2 - \mathrm{Re}\Sigma_\rho(M)]^2 + [Im\Sigma_\rho(M)]^2}$$



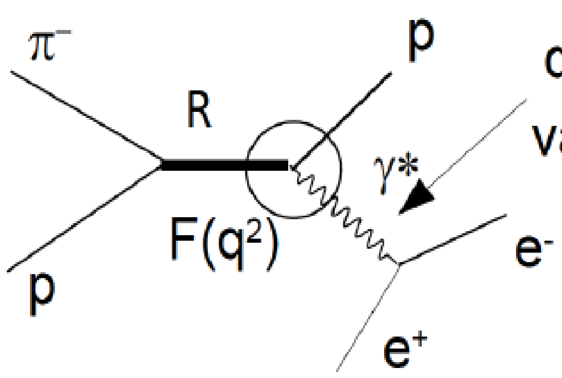
pion loop

„Baryonic loops ”

direct ρ - N^*/Δ



Resonance Dalitz decays !



$q^2 = (M_{ee})^2 > 0$ variable

Pion beams & HADES

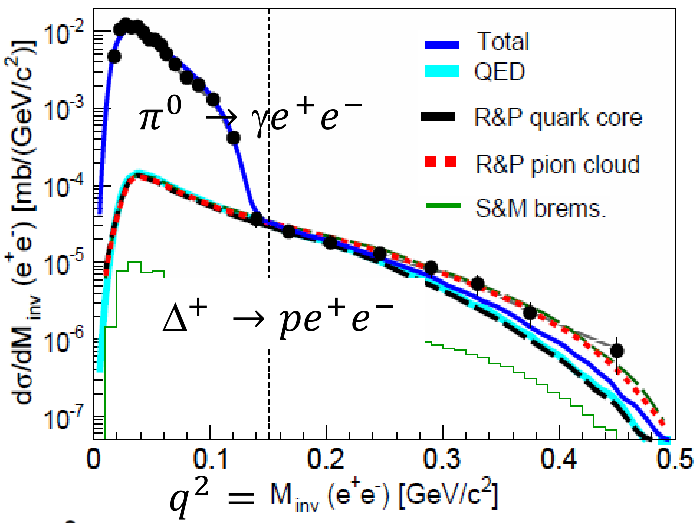
- π-N$\rightarrow N^*$ direct formation (fixed mass of resonance !)
- No $N\gamma^* \rightarrow e^+e^-$ transition measured

note no BR $N^* \rightarrow N\rho \rightarrow N\pi\pi$ in PDG

- Related to inverse proces $e^- N \rightarrow N\pi$

(CLAS@JLAB, MAMI, Bonn)

Δ(1232)→Nγ* Transitions

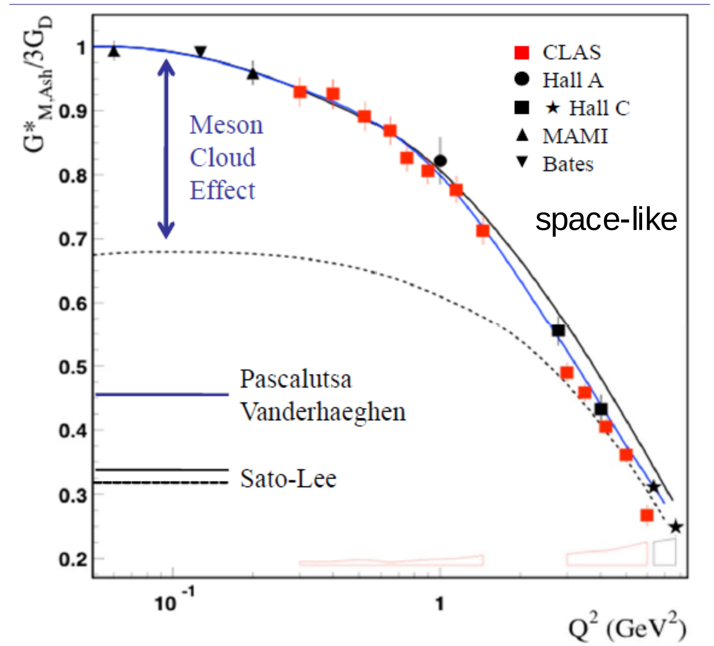


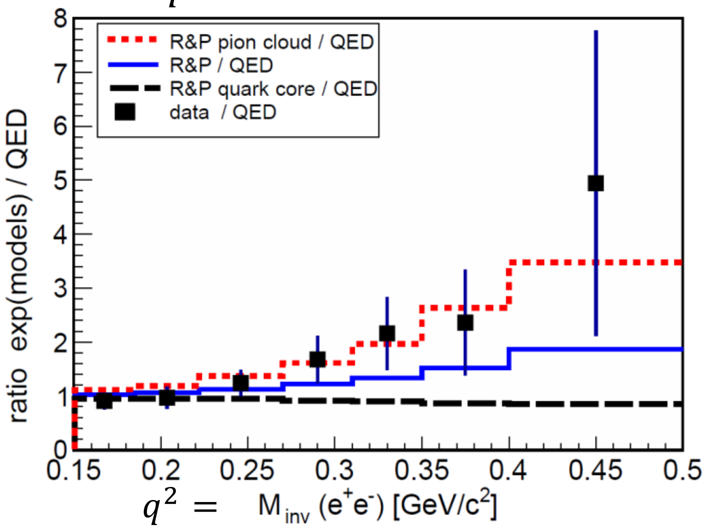
Phys. Rev. C95 (2017) no.6, 065205)

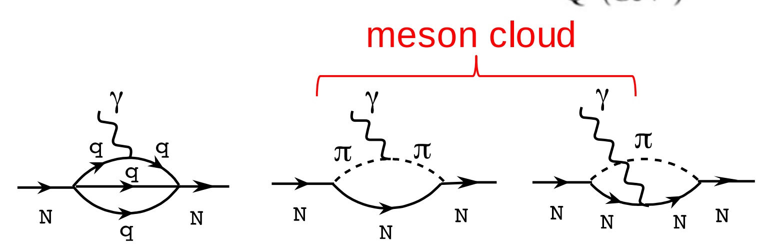
$$BR(\Delta \to p\gamma^*) = 4.2 \cdot 10^{-5}$$

electro-scattering

Transition form factor $G_M(Q^2)$







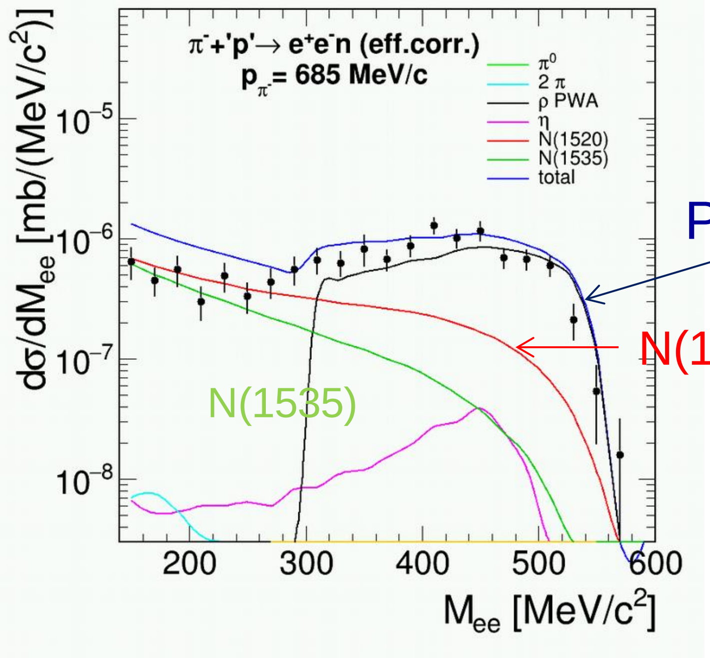
- Baryon structure described by interplay between quark core and meson cloud

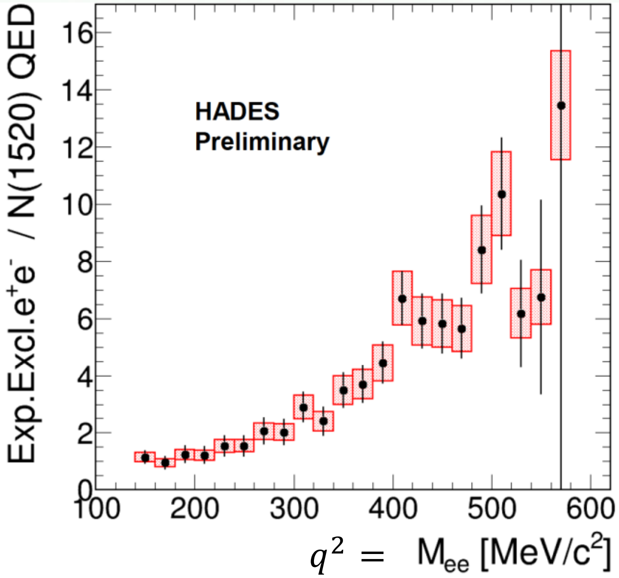
- Rise due to pion cloud

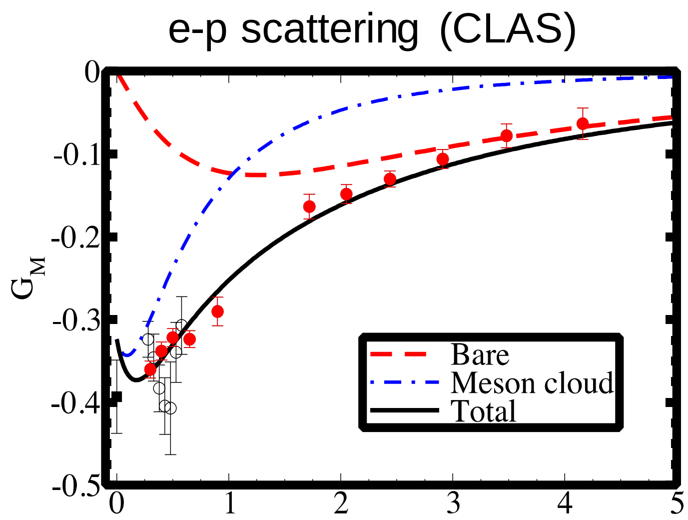
I.G. Aznauryan & V. D. Burkert, NSTAR-2017

G. Ramalho & T. Pena, et al PRD 93 014003 (2017),

$N^*(1520)/N^*(1535) \rightarrow N\gamma^*$ Transitions







- Dominant role of $N^*(1520)$ and off-shell ρ in decay
- Dominnat role of pion cloud

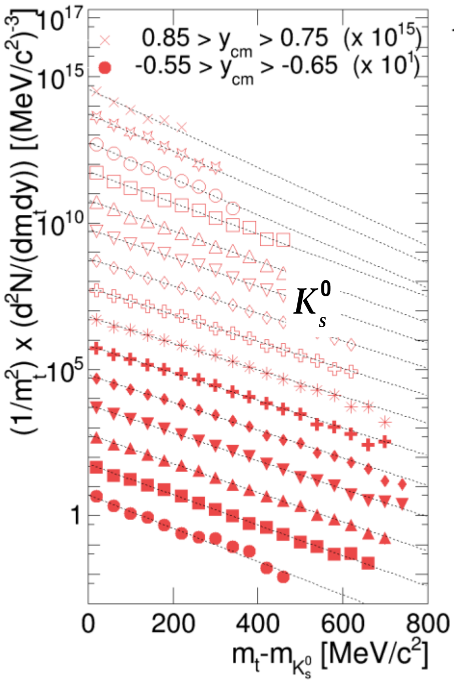
G. Ramalho and M. T. Pena, PRD95, 014003 (2017)

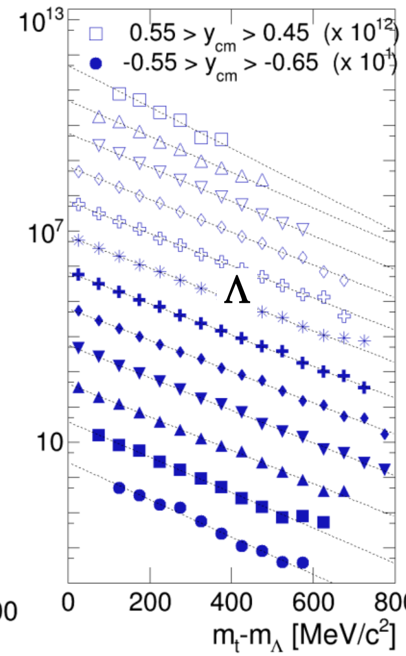
- 2019-2022

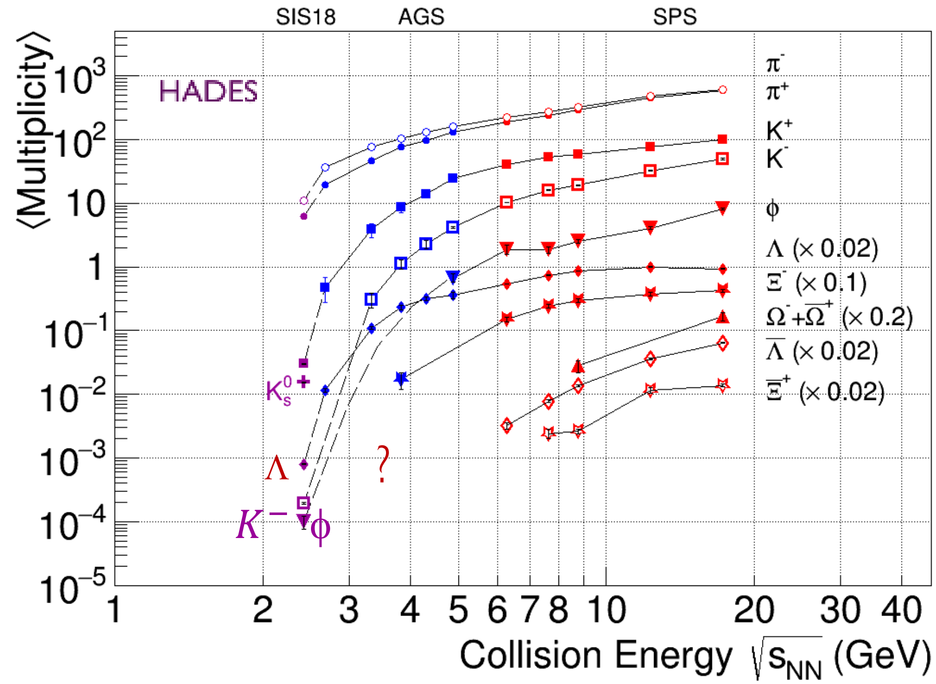
continuation of the programme in 1.7<√s<2.0 GeV

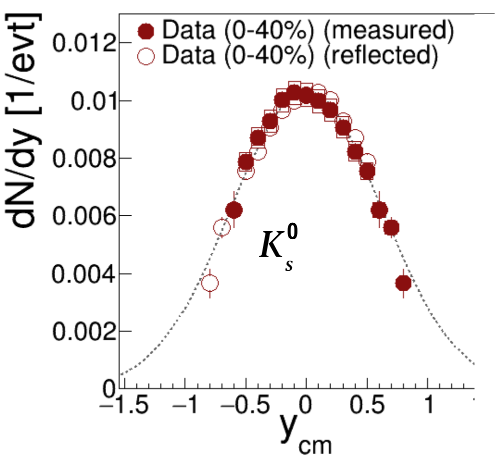
Strangeness

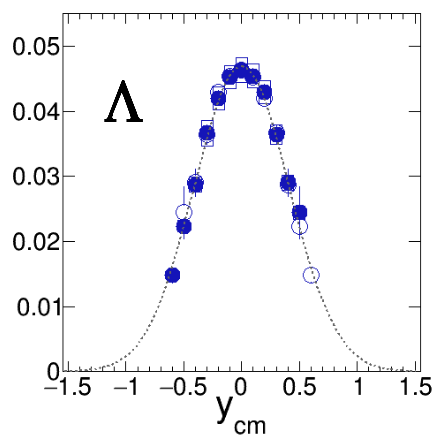
Strangeness production: Au+Au @√s=2.4 GeV









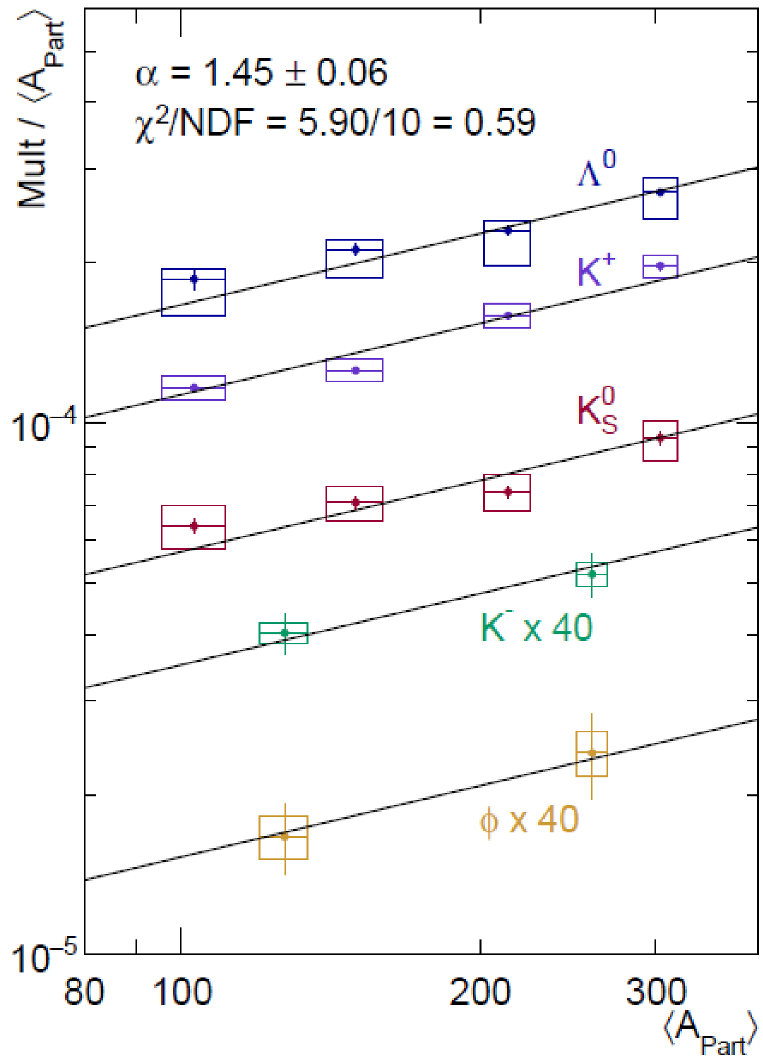


$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = C(y)\exp\frac{-(m_t - m_0)c^2}{T_B(y)}$$

- Subthreshold production
  $Q^{K+,\Lambda} = -0.15\ GeV$ $Q^{\phi,K-} = -0.5$ GeV
- First high statistics measurements of Λ and K_s^0 at high μ_B
- Strong constraints on strangeness production and propagation mechanism
- ϕ/K^- (~0.6 !) strong contribution to K^- *production* !

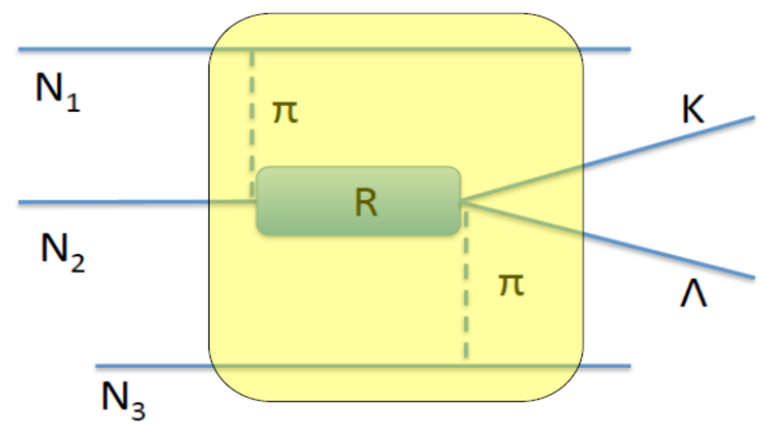
Strangeness production - A_{part}

Au+Au @ 1.23 AGeV



- Despite different production threshold in N-N collisions for K^+, K^-, ϕ.. similar non linear rise with A_{part} ! (linear for pions)

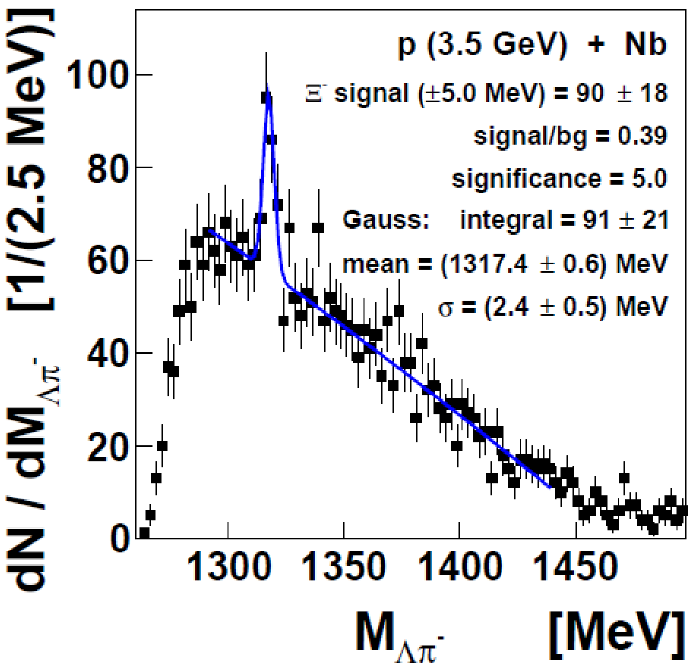
- multi-step collisions ?



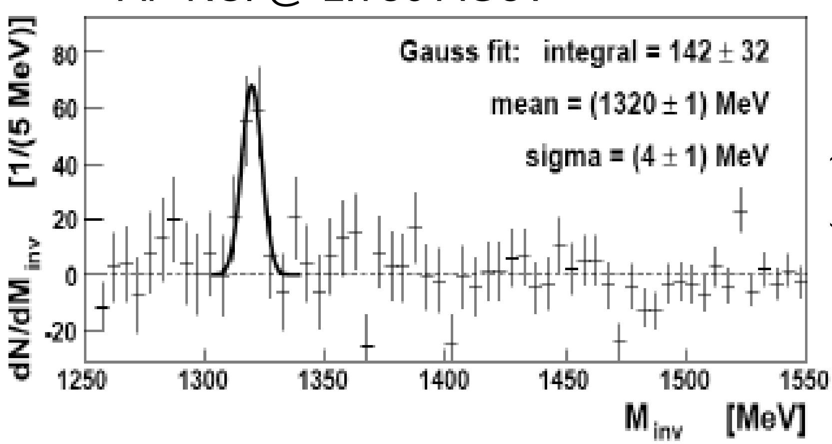
- Decay of heavy (M≥ 2 GeV) N* resonances ? – reference measurements with π,p beams

Enhanced Ξ^- (1321) production

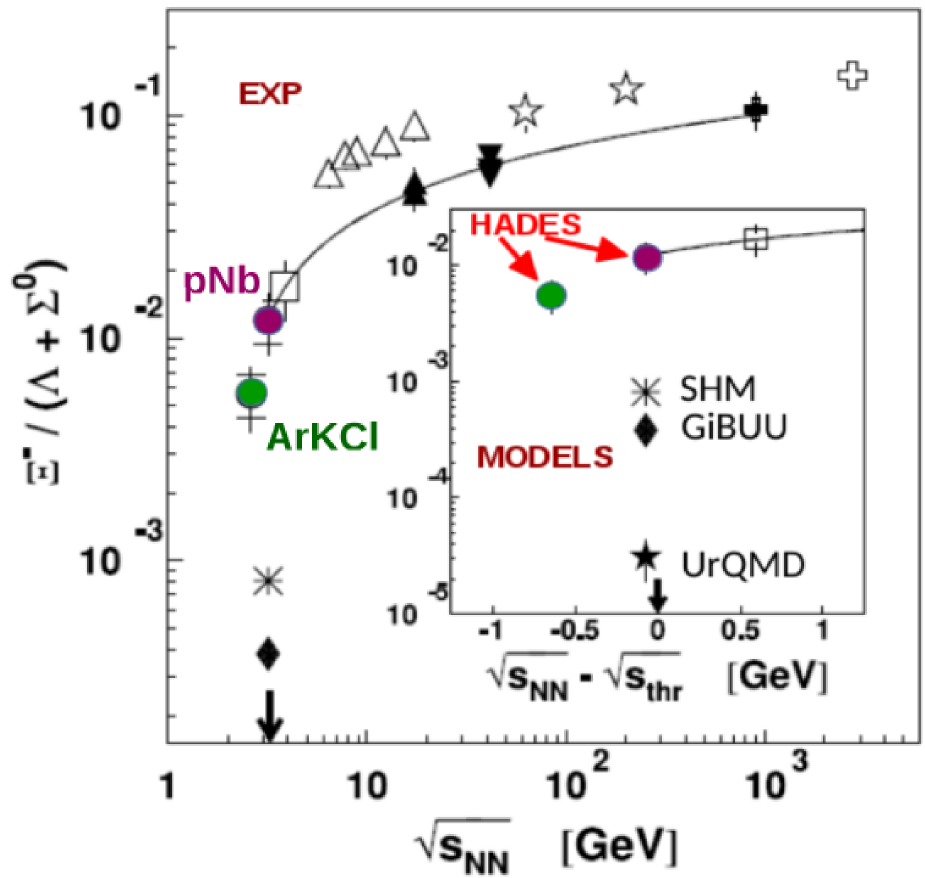
PRL. 114 (2015) no.21, 212301



Ar+KCl @ 1.756 AGeV



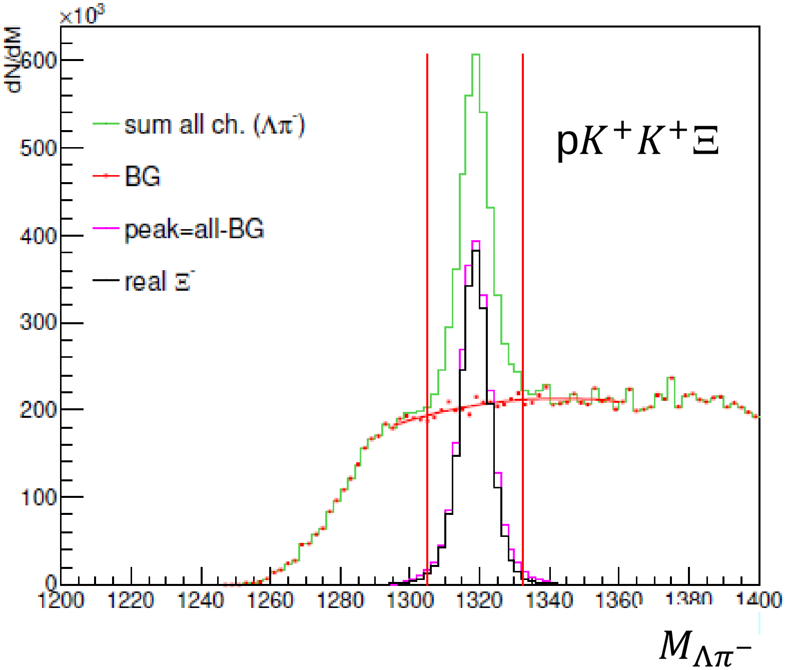
PRL 103 (2009) 132310



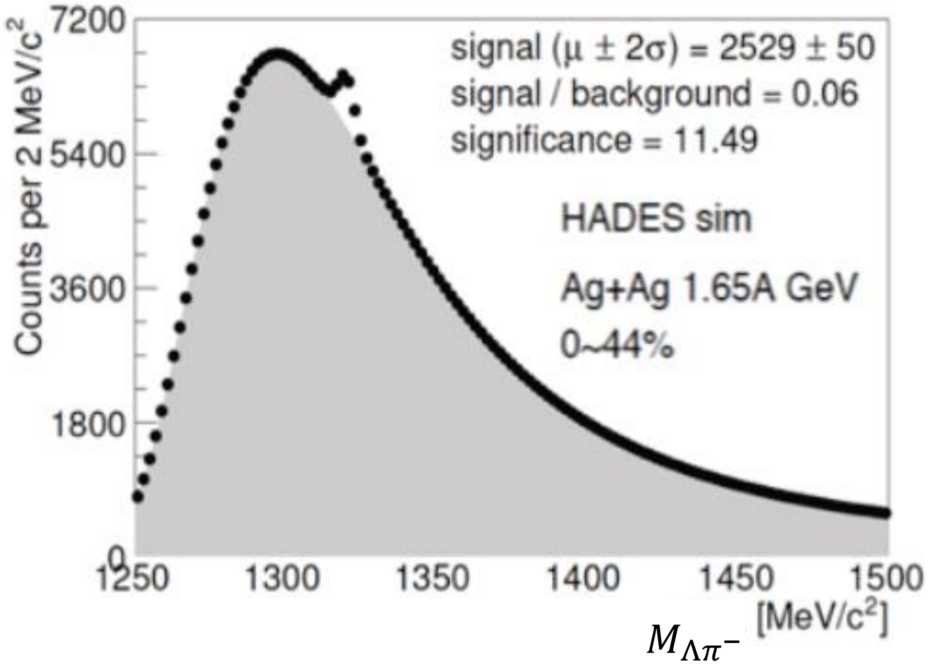
- ❑ Strong enhacement above models (Statistical Hadron Model (SHM), UrQMD, GiBUU
- ❑ YY Fusion?, $N^* \rightarrow \Xi K K$?, ..
- ❑ Reference measurements in p+p badly needed (no data!)

Cascade & Hyperon production

p+p @ 4.5 GeV



Ag+Ag @ 1.65 AGeV



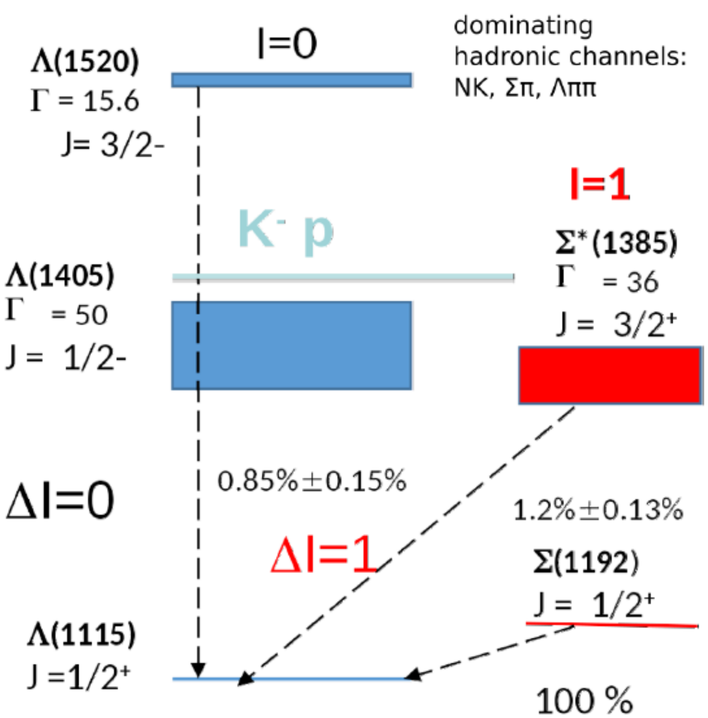
- 4 weeks $\mathcal{L} = 2 * 10^{31} \frac{}{cm^2 s} \sim \frac{10^4}{day}$ expected
- Spectroscopy of Ξ states (only 3 ground states known!) role of N* in production?

- Large sample of Λp, Σp pairs for correlations studies (pA,pp) → details of Λ-N potential

- ~2.5 10^3 Ξ in 4 weeks expected

- differential distributions

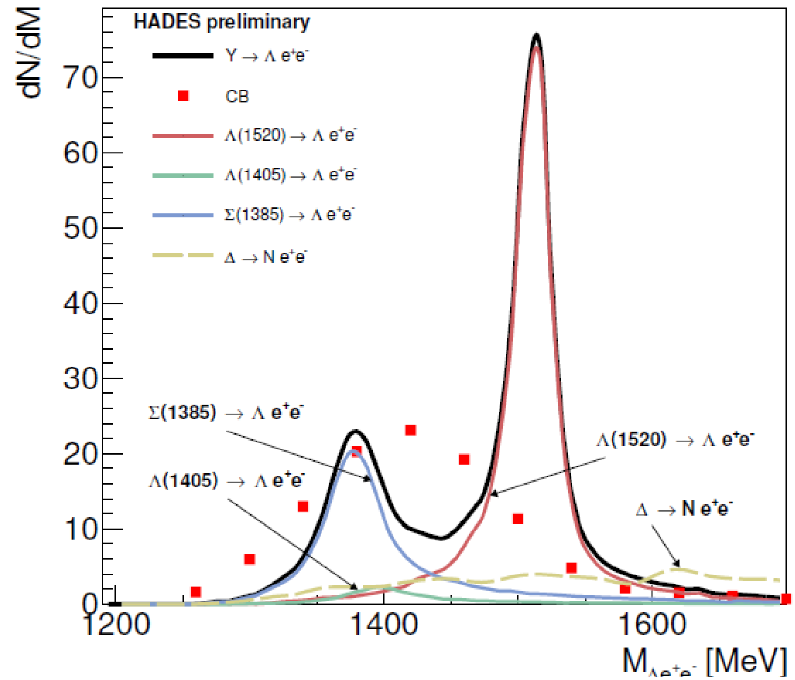
Hyperon Electromagnetic decays

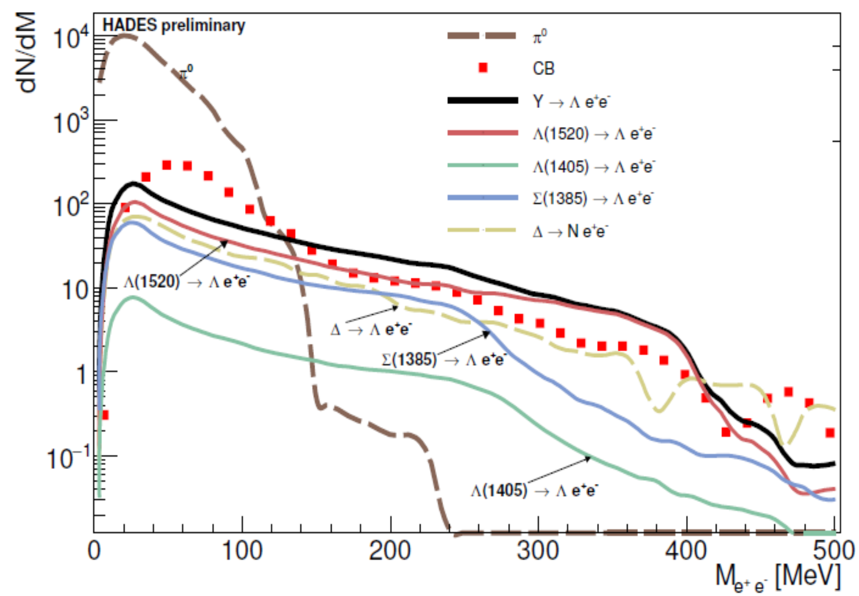


data CLAS *PRL114(2015)212301*

- sever constraints for structure models (bag,QM,..)
- SU(3) symmetry– comparisons $\Delta(1232)/\Sigma^*(1385)$ $N^*(1520)/\Lambda(1520)$ Dalitz decays (VDM?)

Λe^+e^- invariant mass





Summary

- Combination of HI and hadron beams with HADES allows for comprehensive studies of virtual photon radiation from baryon rich matter (em. structure of baryons –role of pion cloud.)
- Big impact on understanding of emissivity of strongly interacting matter over full QCD phase diagramme$\rightarrow$extraction of T, evolution of in-medium ρ spectral function
- Complete measurements of strangeness with unprcedented statistics->challange for modesl (Ξ , ϕ) production need reference measurements

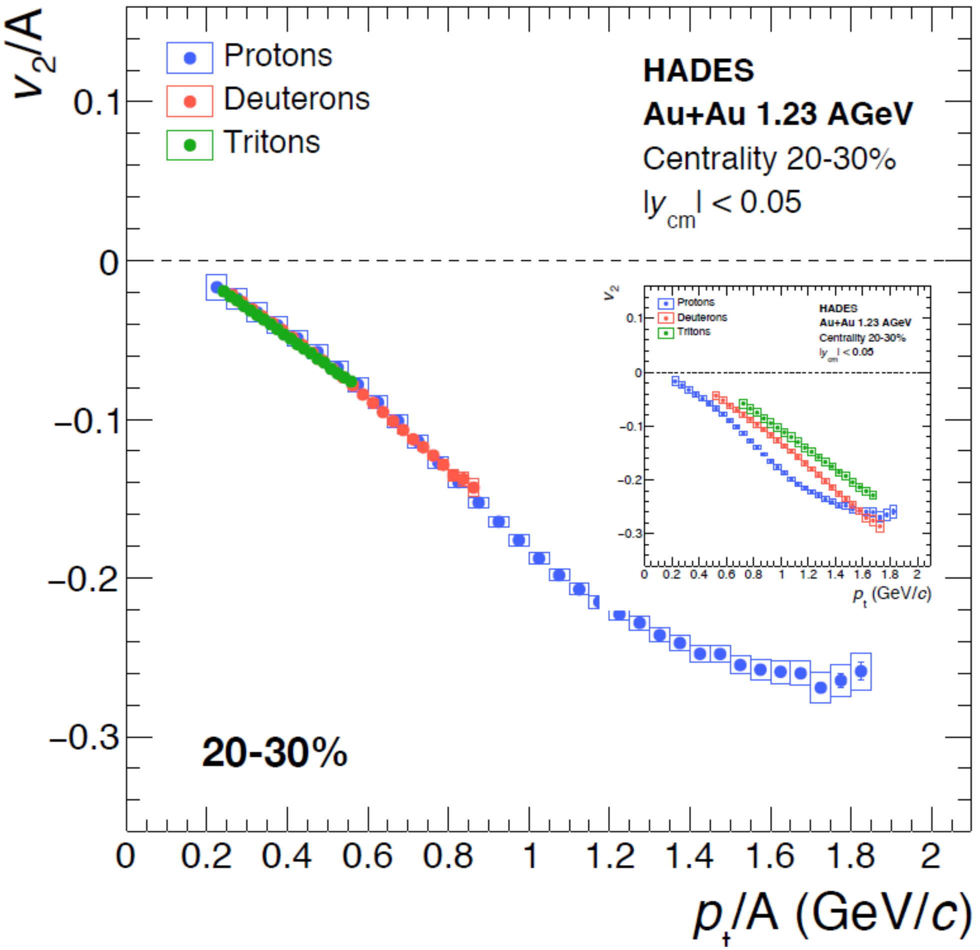
- **Outlook** : continuation of experimental programe (HI and pion beam experiments) at SIS18 till 2022 and later at SIS100 (excitation functions of dilepton production , complementing measurements o Compressed Baryonic Matter experiment)

Bulk properties: v_1, v_2, v_3 for p /d/t

Example: Elliptic flow (v_2) of Protons, Deuterons and Tritons

- Comparison of p, d, t v_2 at mid-rapidity
- Scaling of v_2 and p_t with nuclear mass number A
- As expected for nucleon coalescence

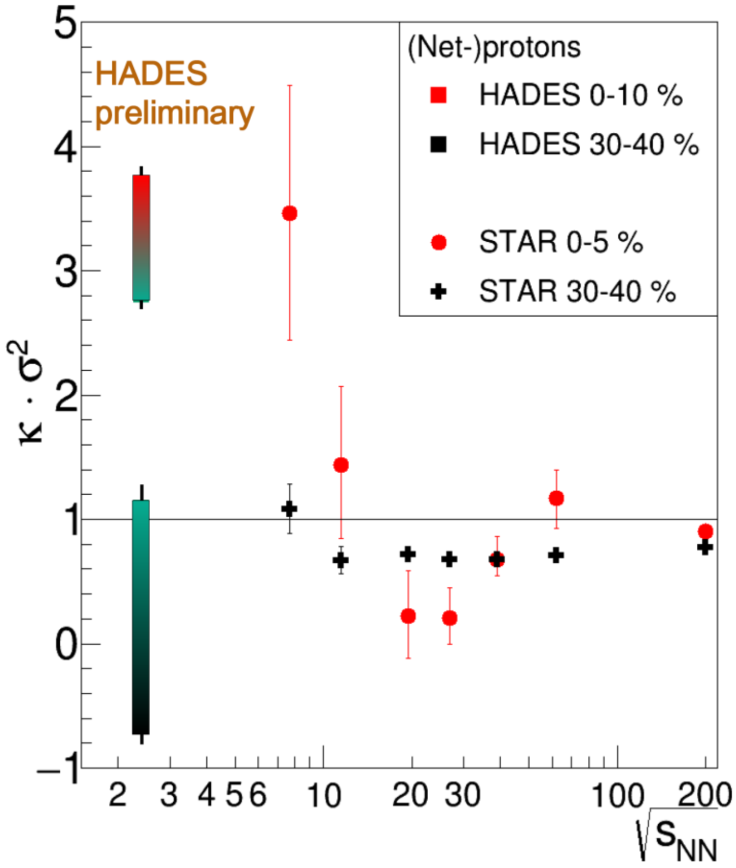
- Meson flow : on going



QM17, Nucl.Phys.A967 (2017)

Proton number fluctuations

R. Holzman CPOD2017



Unfolding + vol. flucs. corr.

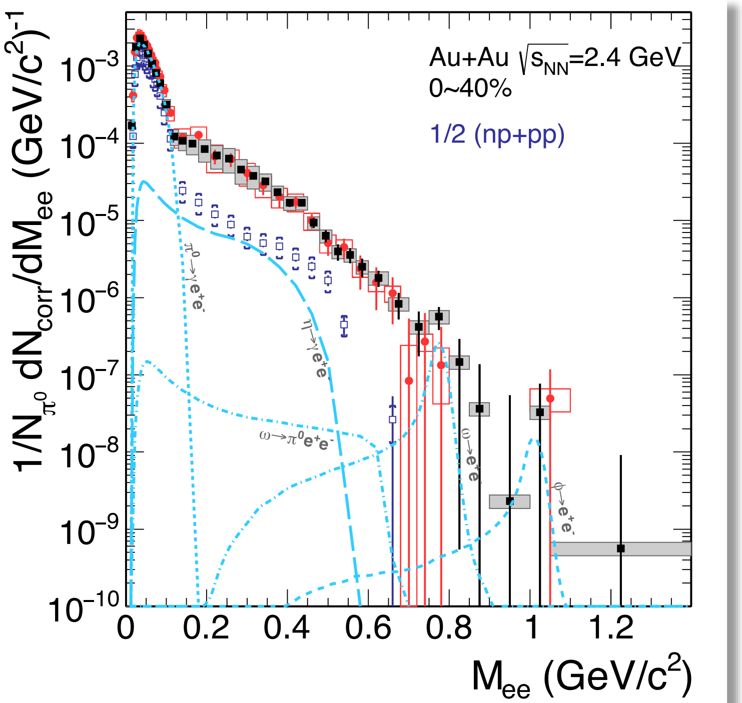
E-b-e eff corr. of factorial moments + vol. flucs. corr.

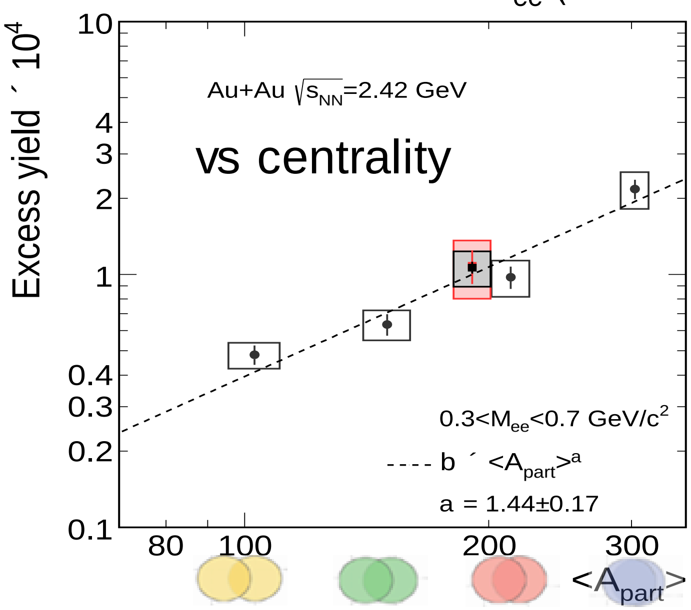
- 1[st] time this kind of analysis in fixed-target experiment at $\sqrt{s_{NN}}$ = 2.42 GeV
- Detailed systematic study of experimental and instrumental effects:
  - E-b-e changes of efficiency
  - Corrections for volume fluctuations
  - Proper selection of p_t-y bite
  - Protons bound to nuclei

NOT YET completed..
volume corrections .. on-going

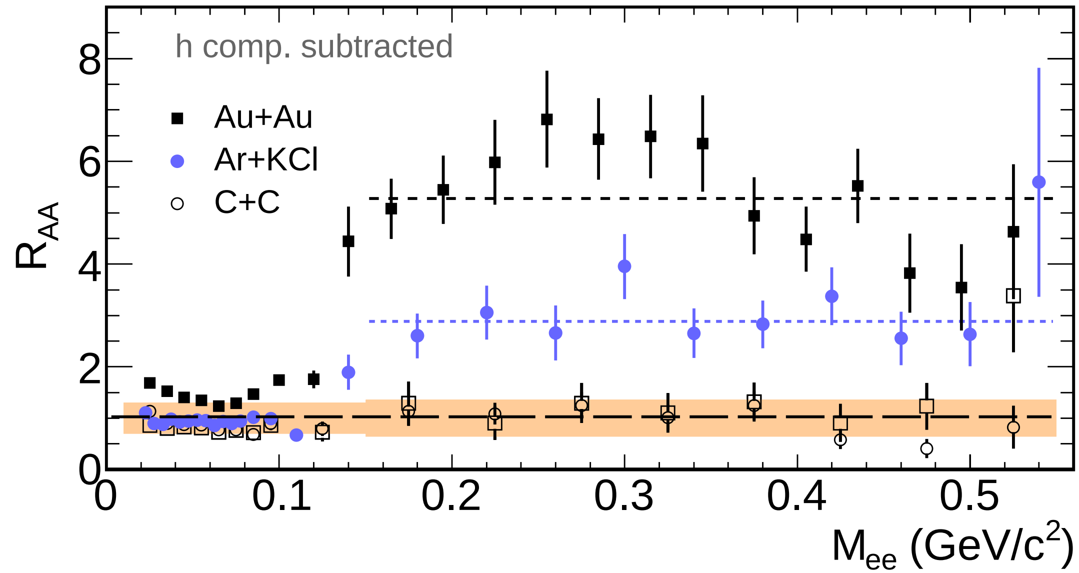
Garg et al., J. Phys. G: Nucl. Part. Phys. 40 (2013)
A. Bzdak, V. Koch, PRC 86 (2012); X. Luo, PRC 91 (2015); M. Kitasawa, PRC 93 (2016
V. Skokov *et al.*, PRC 88 (2013) 034911; A. Rustamov *et al.*, NPA 960 (2017) 114

HADES: Dilectron excess vs sys. size and centrality



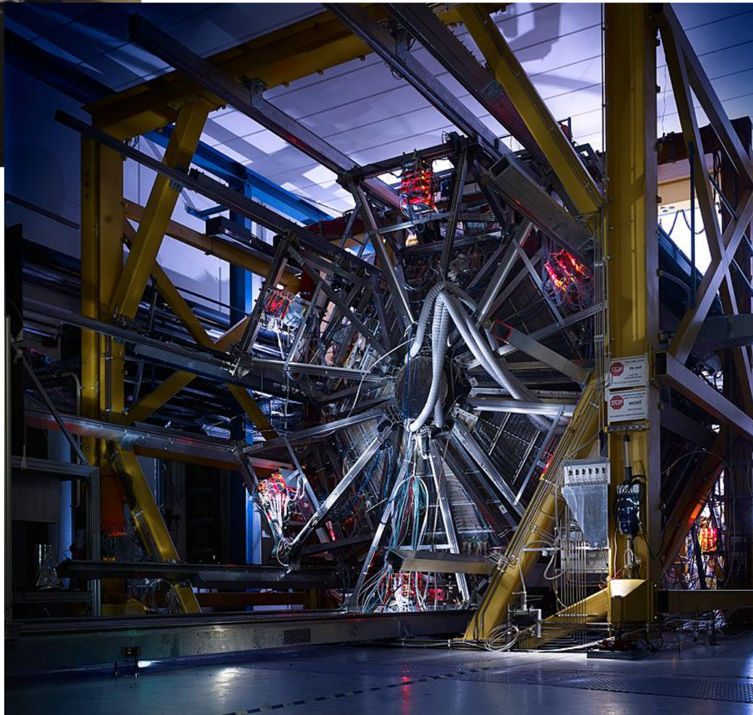


Excess above „hadronic cocktail” vs system size

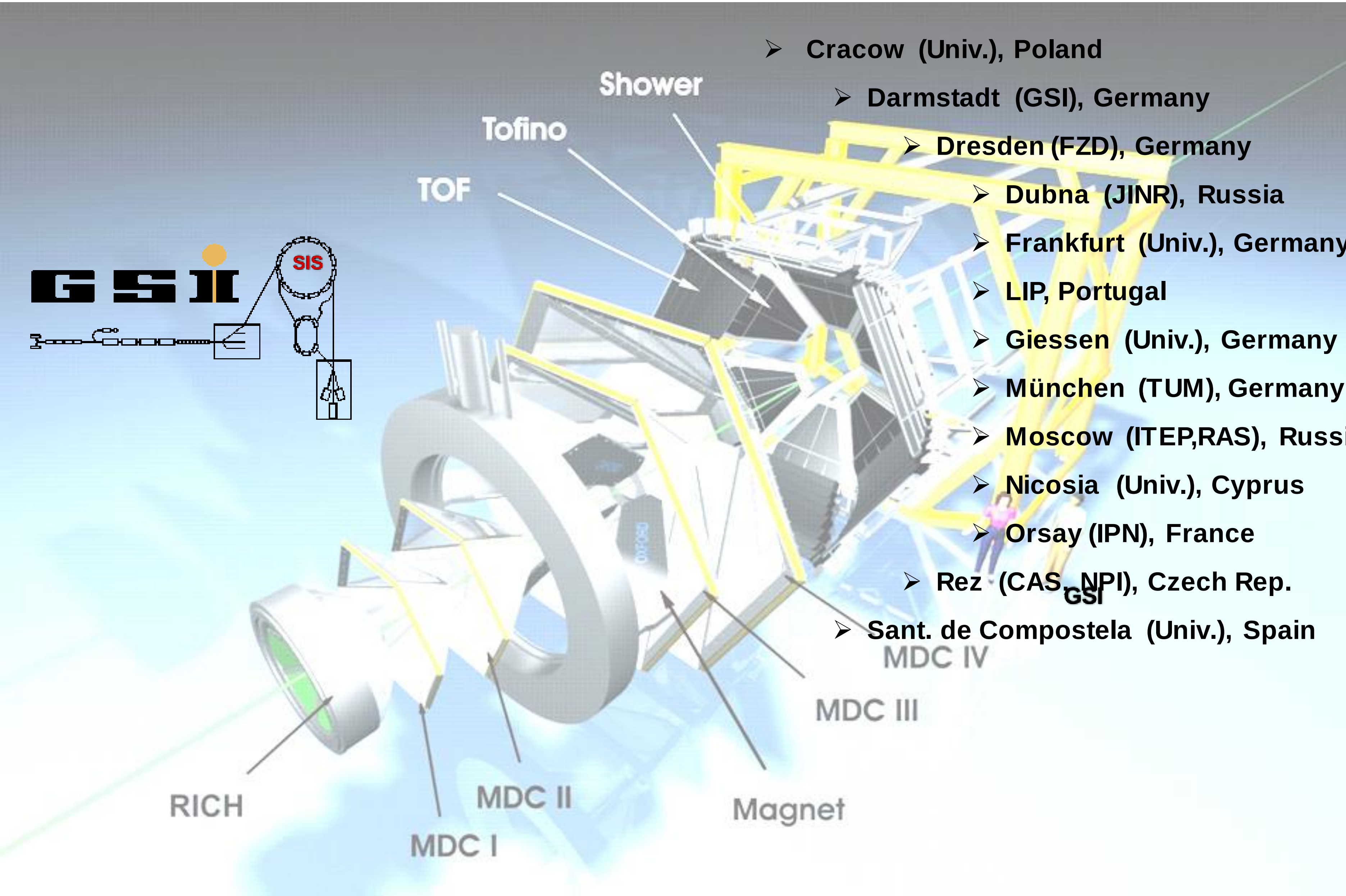


- Additional radiation from hot and dense phase of collision identified for the first time at such low energy

HADES @ GSI

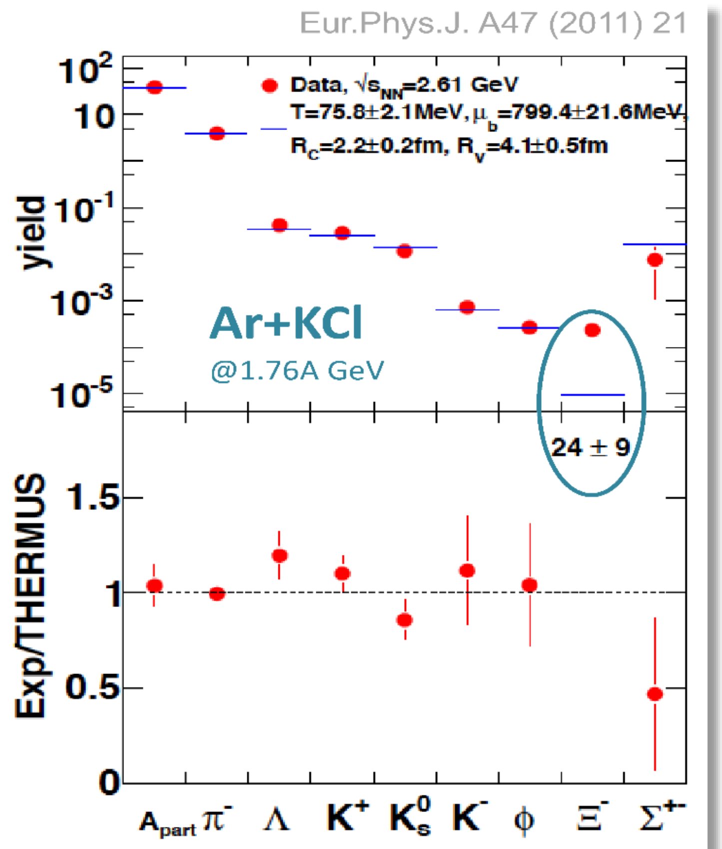


The HADES collaboration



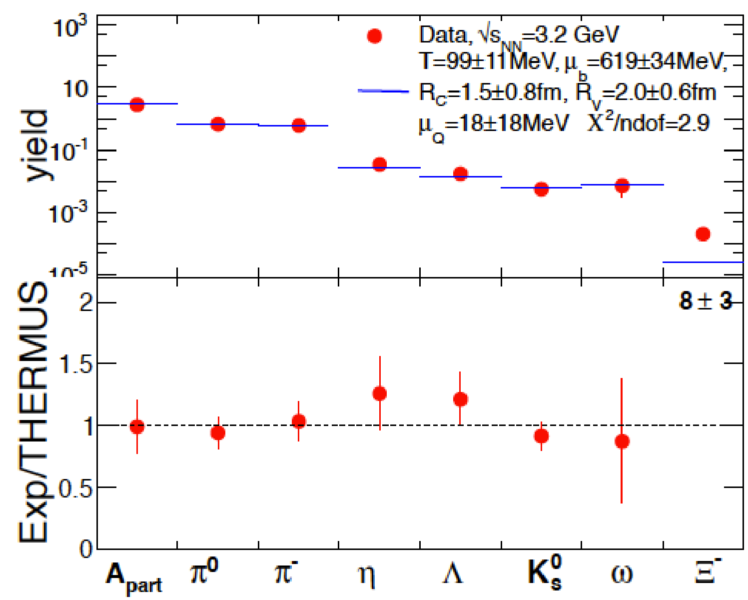
- Cracow (Univ.), Poland
- Darmstadt (GSI), Germany
- Dresden (FZD), Germany
- Dubna (JINR), Russia
- Frankfurt (Univ.), Germany
- LIP, Portugal
- Giessen (Univ.), Germany
- München (TUM), Germany
- Moscow (ITEP,RAS), Russia
- Nicosia (Univ.), Cyprus
- Orsay (IPN), France
- Rez (CAS, NPI), Czech Rep.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

Statistical production of hadrons at SIS18 ?



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

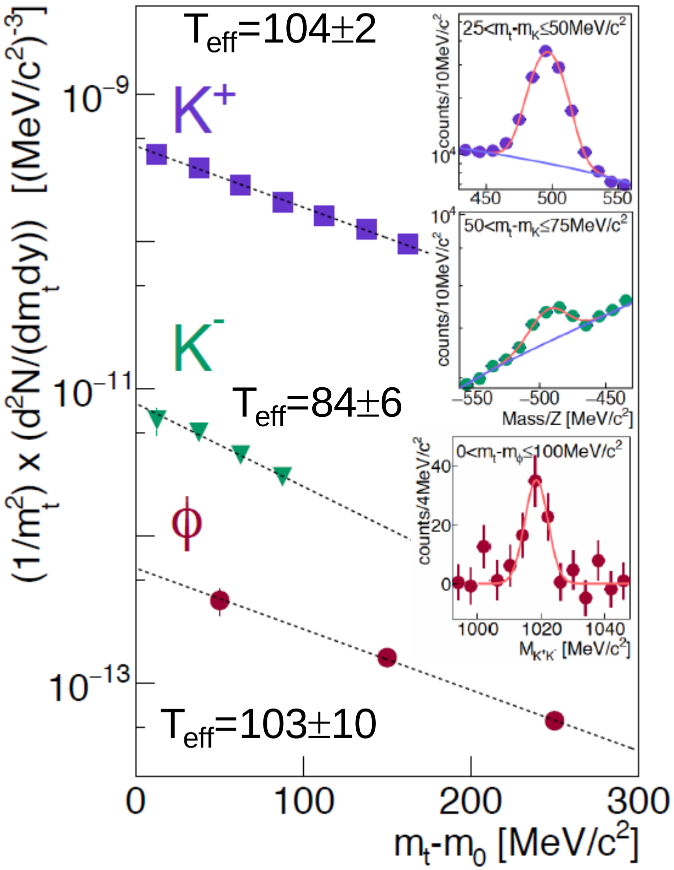
…works also well for p+Nb@ 3.5 GeV except Ξ !

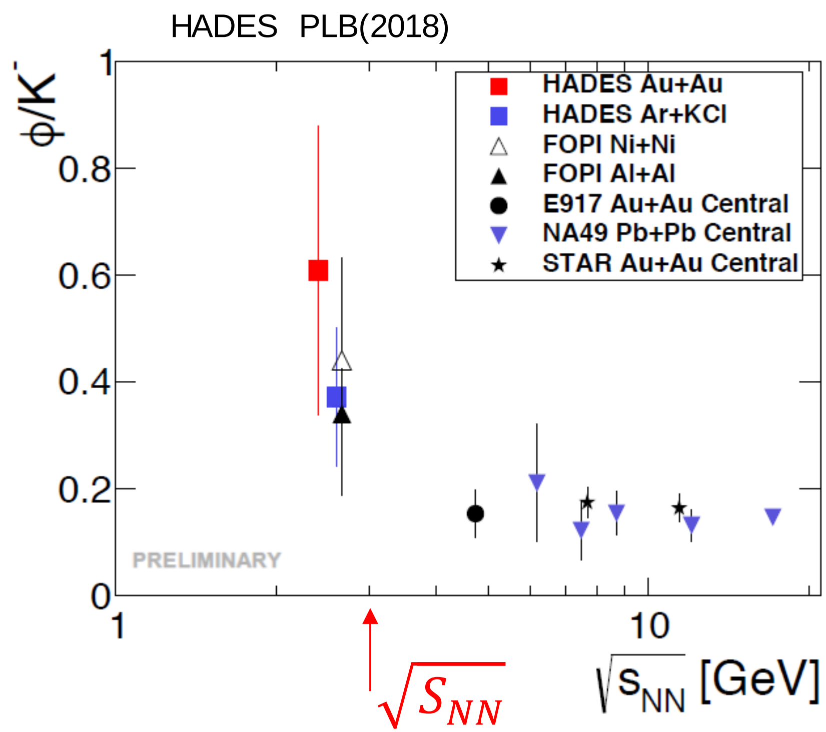


Eur.Phys.J. A52 (2016) no.6, 178

- Satisfactory description with Stat.Hadr. Model
- But not for Au+Au when light ions are inlcuded !

ϕ production at subthresold energies: important source of K^-

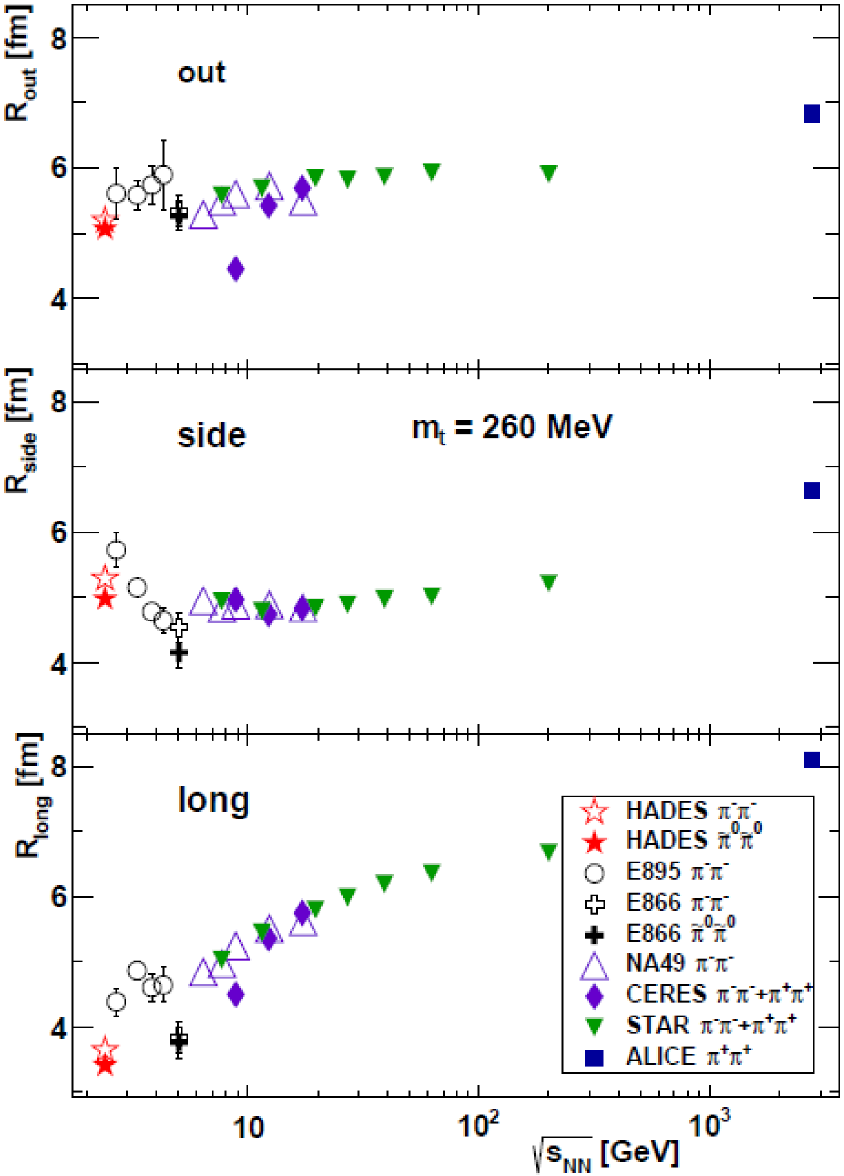


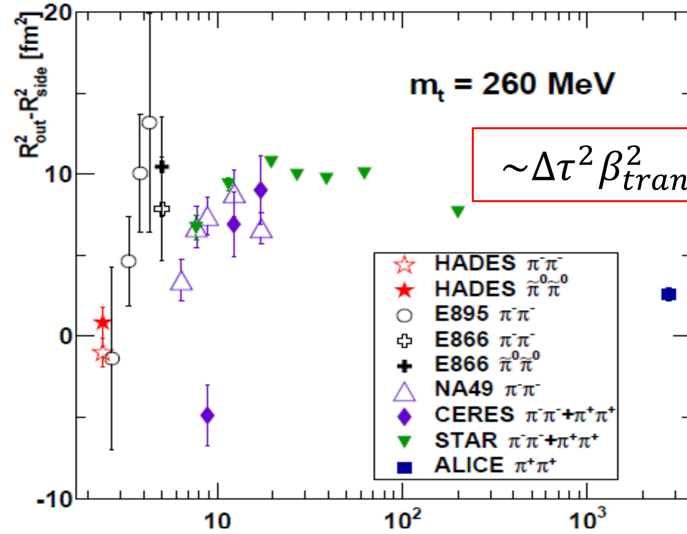


- ϕ/ K^- ratio strongly increases below threshold !

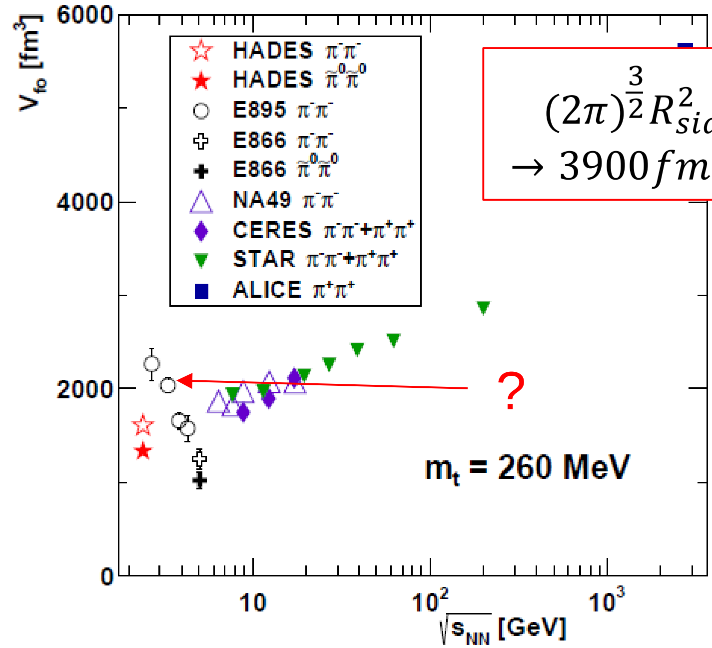
  so far strangeness exchange $\pi Y \rightarrow K^- N$ was suggested as the main source of K^-
- T_{therm} (K^-) $=T_{K+}$ if decay from ϕ included in the K^- production
- ϕ, K^- rates consistent with Statistical Hadronization Models, but NOT explained consistently by any transport model

HBT results- exc. functions





$\sim\Delta\tau^2\beta^2_{trans}$



$$(2\pi)^{\frac{3}{2}}R^2_{side}R_{long}$$
$$\rightarrow 3900\,fm^3\,(k=0)$$

- Hades follows more trend from STAR/NA49

HBT correlations

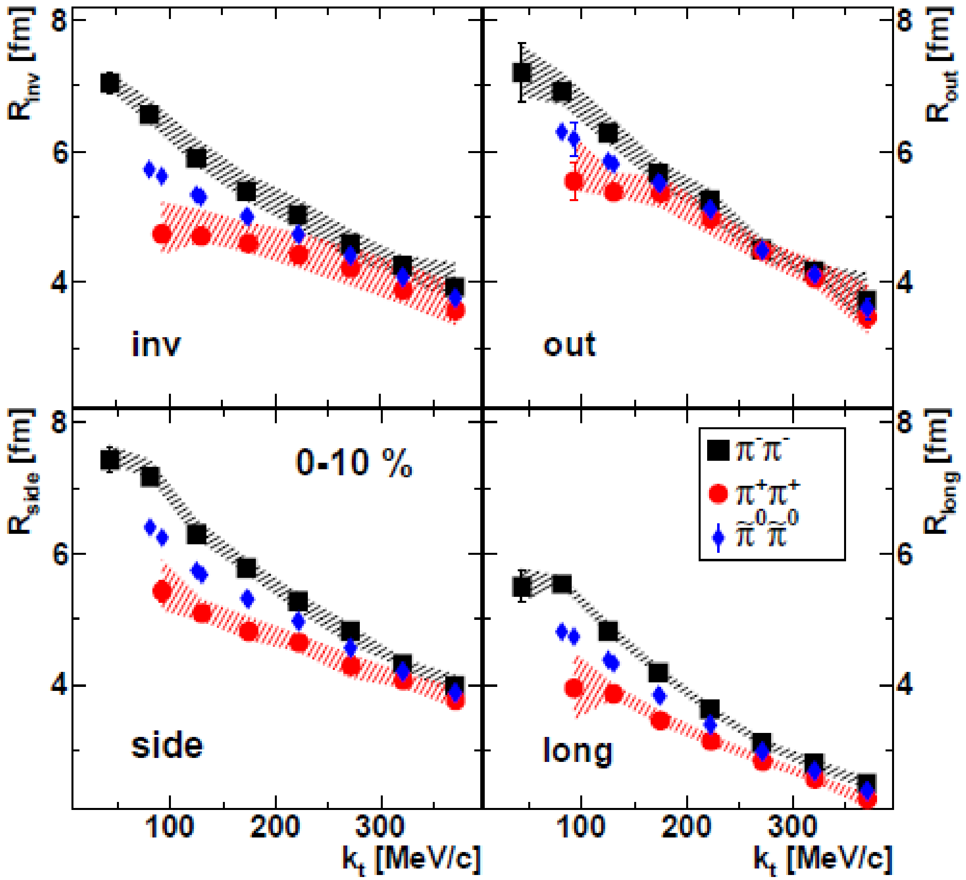
- Fit 3'd

Bertsch-Pratt parametrisation: $\vec{q} \to (q_o, q_s, q_l)$
Integration over azimuth. ang. $\phi \Rightarrow R_{os}, R_{sl} \to 0$
boost into longitudinal co-moving system (LCMS), $p_{1z} = -p_{2z}$

$$C(\vec{q}) = C_0[(1-\lambda) + \lambda \cdot K_{\mathrm{Coul}}(\hat{q}, R_{\mathrm{inv}}) \cdot \underbrace{(1 + e^{-(2q_o R_o)^2 - (2q_s R_s)^2 - (2q_l R_l)^2})}_{\text{Bose-Einstein(BE) part}}]$$

- Coulomb effect clearly visible

$$R^2_{\tilde{\pi}^0\tilde{\pi}^0} = \frac{1}{2}(R^2_{\pi^+\pi^+} + R^2_{\pi^-\pi^-}),$$



Submitted to PRL

arXiv:1811.06213

ρ -meson : the main player

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

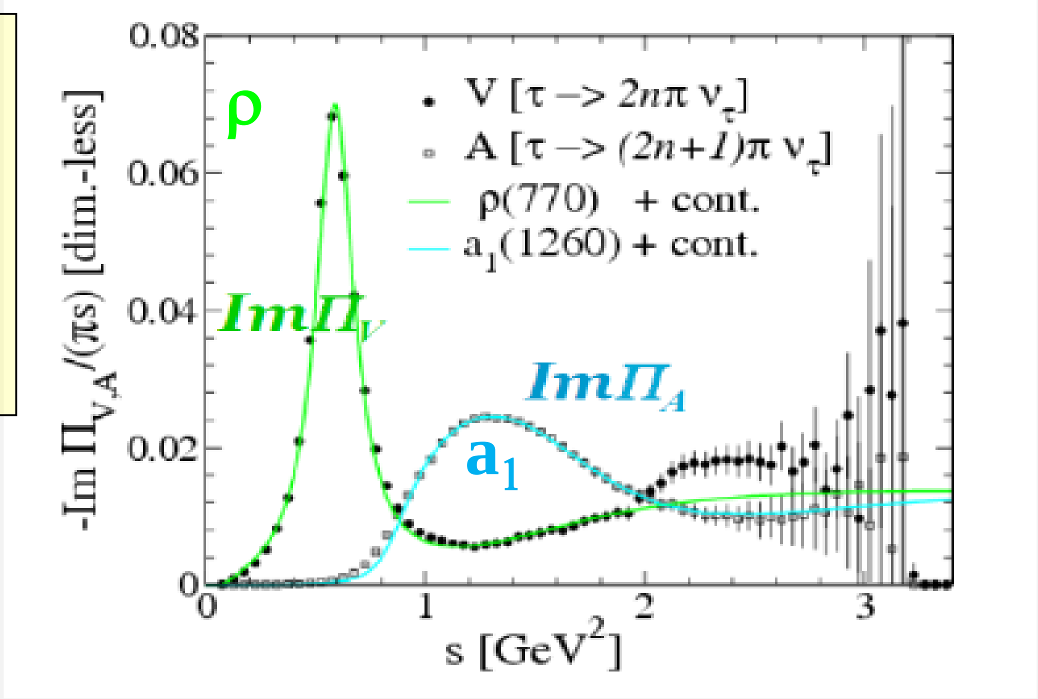
[Hatsuda+Lee '91, Asakawa+Ko '93, Leupold et al '98, …]

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

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

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

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



- in vacuum ρ-a_1 mass splitting

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

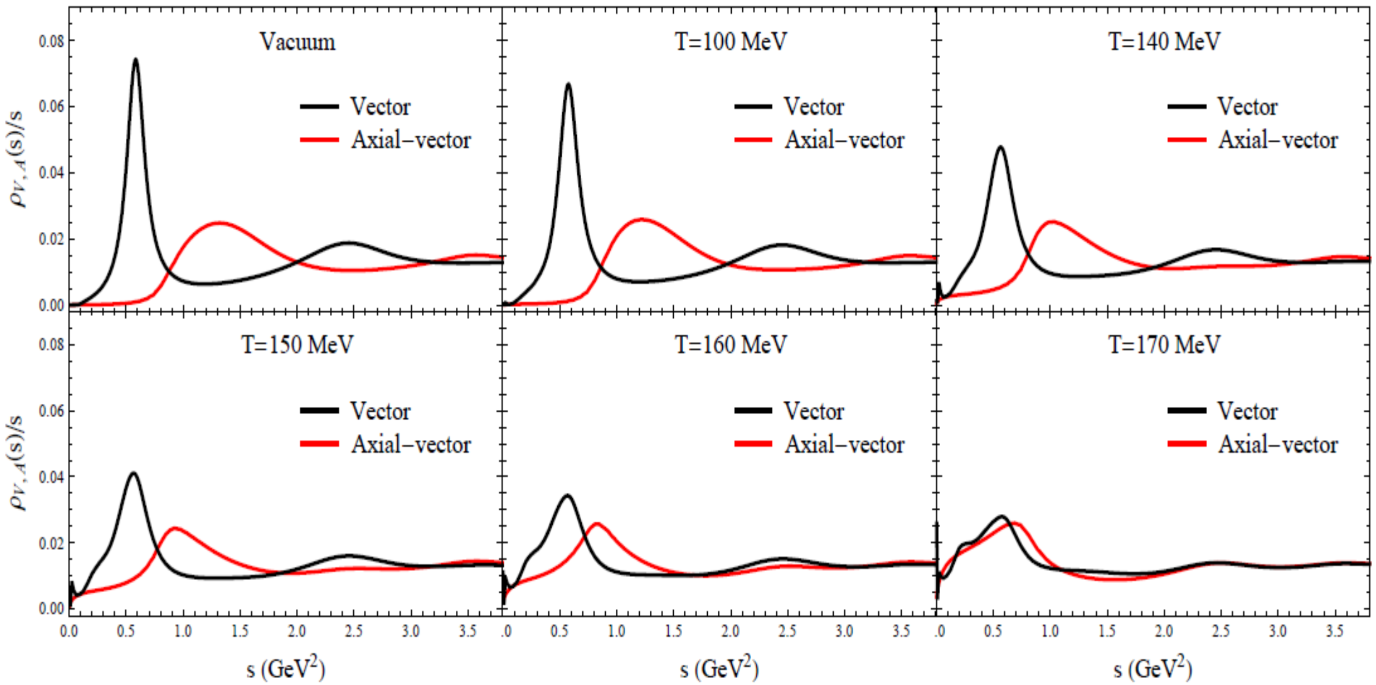
- χSR – both spectra functions overlap
- Thermal emission dominated by in-medium ρ-spectral function

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

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 !

Dalitz decays and em. Transition Form Factors

- HADES: Resonance production with pion and proton beams

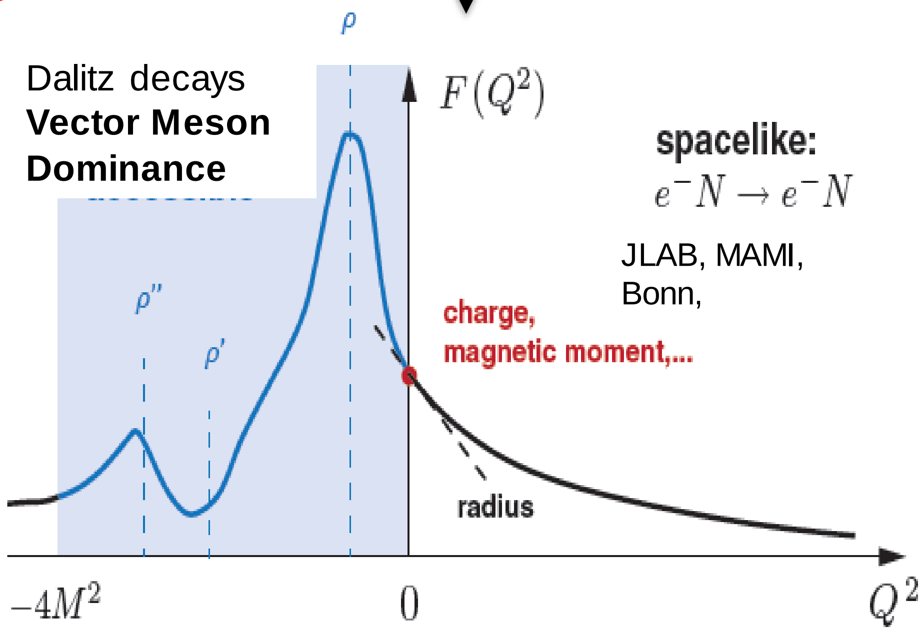
example Dalitz decay $\Delta^{\frac{3}{2}} \rightarrow N^{\frac{1}{2}} \gamma^*$ $\quad M_{\gamma*} = M_\Delta - M_N$

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

„QED ” point-like

QCD

Transition Form Factors



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