Dense Matter Research with HADES

International School of Nuclear Physics
34th Course
Probing Extreme States of Matter
Erice/Sicily, September 16-24, 2012

Joachim Stroth, Goethe-University Frankfurt / GSI
and the HADES collaboration

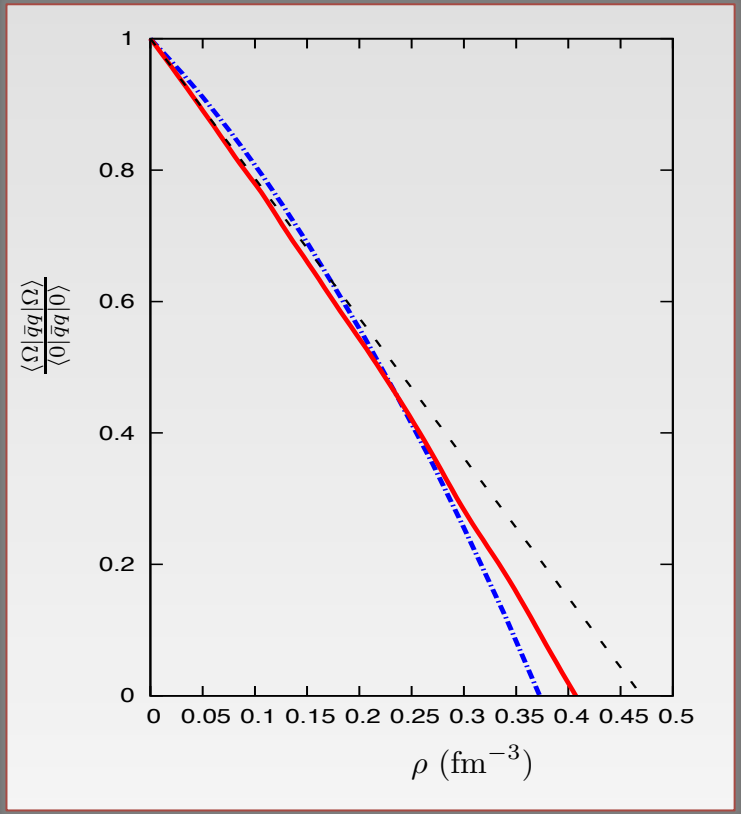
Motivation came from theory!

- R. Pisarski (1982): connection of phase-transition to modification of the ρ mass (dileptons) (PLB 110, 1982).
- G.E. Brown / M. Rho: Scaling of masses with χ-condensate (PRL 1989, 1991)

$$m^* \approx m\left[\langle \bar{q}q^* \rangle / \langle \bar{q}q \rangle\right]^u$$

- T. Hatsuda / S. Lee: operator product expansion PRC46(1992)R34

$$m^* = m\left(1 - \alpha\rho/\rho_0\right)$$



$\bar{q}q$ expectation in chiral power counting by U. Meissner et al. arXiv:1007.2574v1

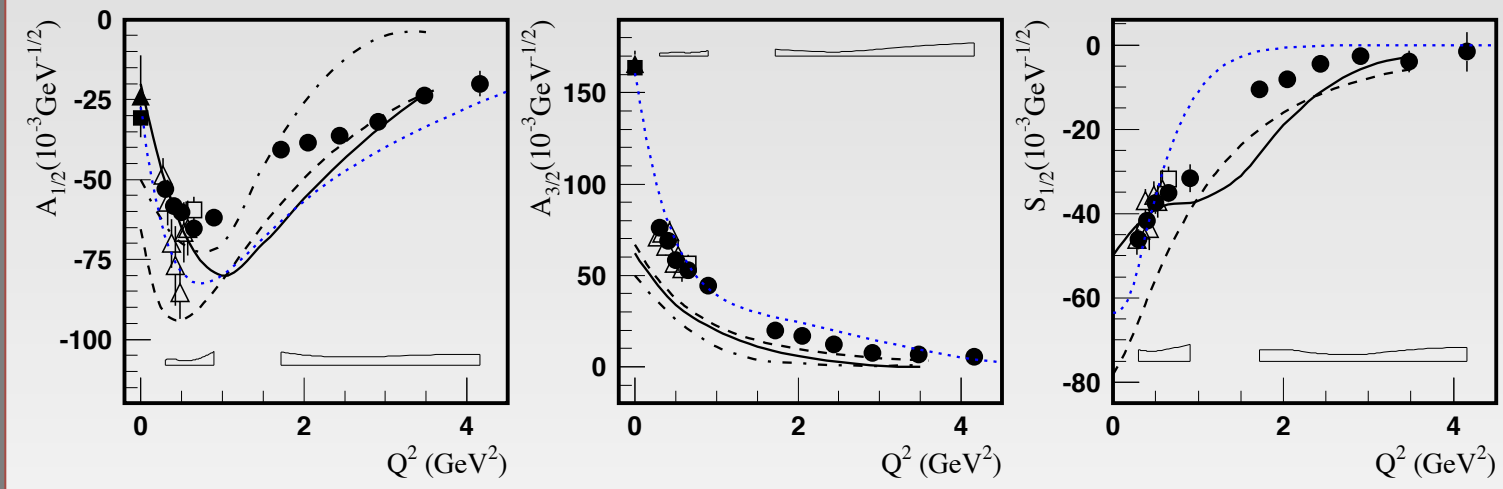
The masses of hadrons in QCD

- Energy needed to confine a color-neutral object (qqq, $q\bar{q}$) in the non-perturbative vacuum

- The meson cloud is important for their structure

CLAS-JLAB results on baryonic resonances

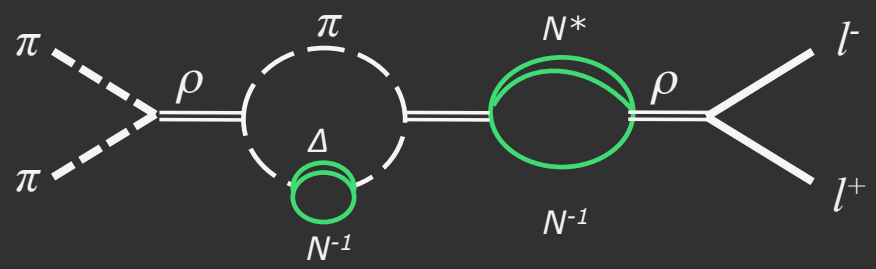
- Excitation of a baryon can be carried by the meson cloud
  - ✘ Pion electro-production: γ^* p -> N(1520)D13 -> π N



I.G. Aznauryan and J.V. Burkert, Progr. in Part. Nucl. Phys. 67/1, 2012, p. 1–54
CLAS data

- Strong hint for dominant contribution to the helicity amplitude $A_{3/2}$ from the meson cloud near the photo point.

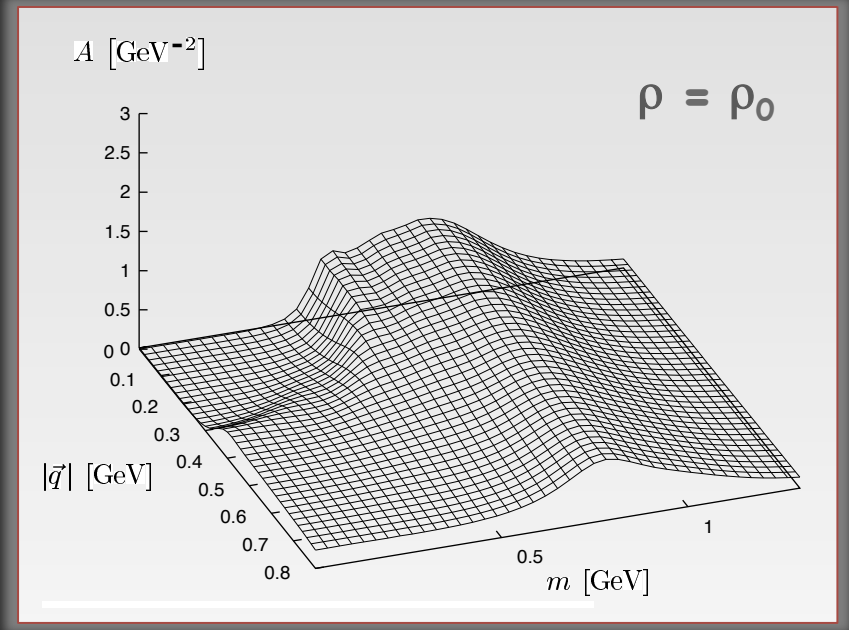
In-medium self energy of the ρ

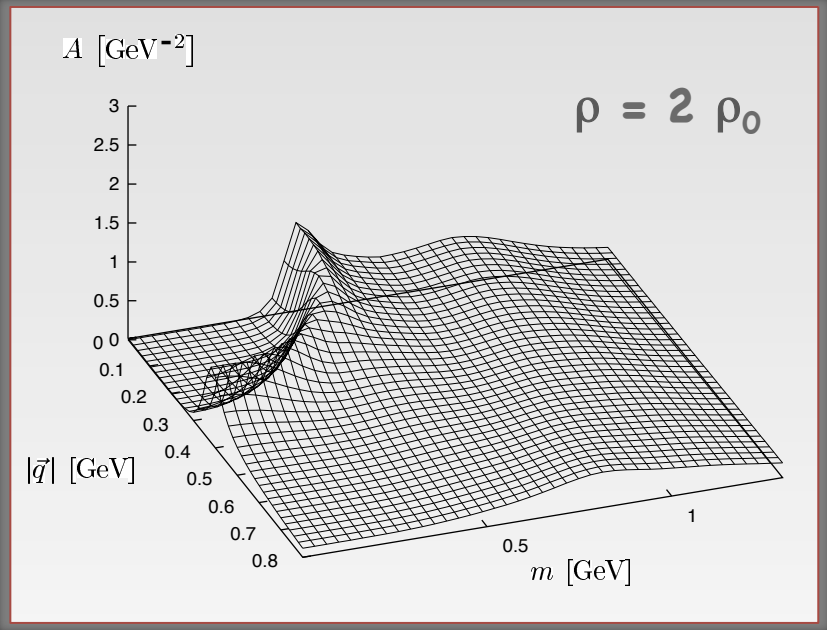


- For details see e.g. (reviews):
  - ✘ arXiv:9909.229, R. Rapp and J. Wambach
  - ✘ arXiv:0907.2388: S.Leupold, V. Metag, U. Mosel

In-medium spectral functions from hadronic models

- Coupling of the ρ to resonance hole excitations provoke a modification of the spectral distribution
- Strong dependence on relative momentum and baryon density





W. Peters, M. Post, H. Lenske, S. Leupold, U. Mosel: Nucl.Phys. A632 (1998) 109-127

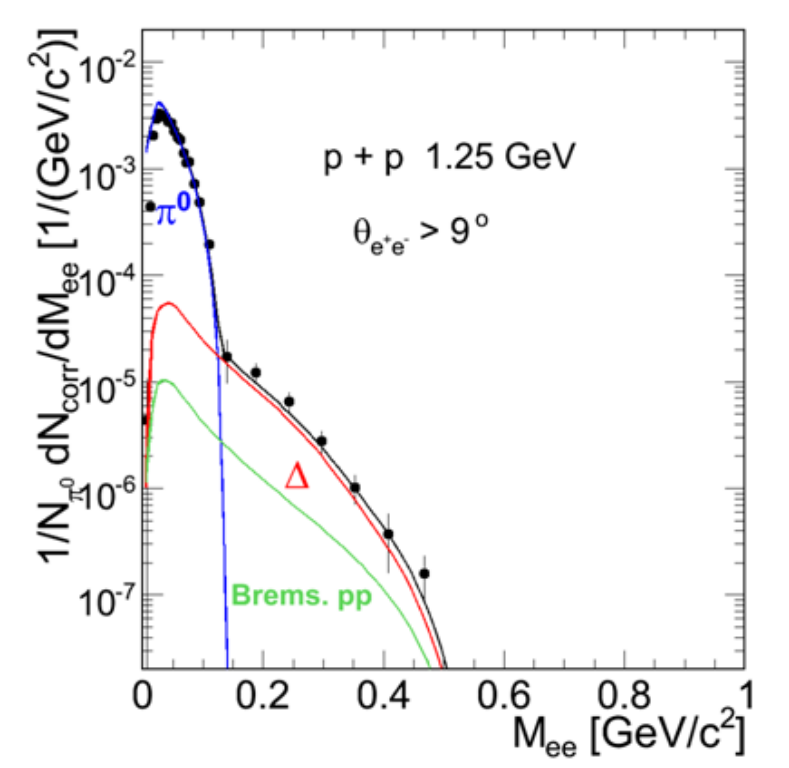
Agenda

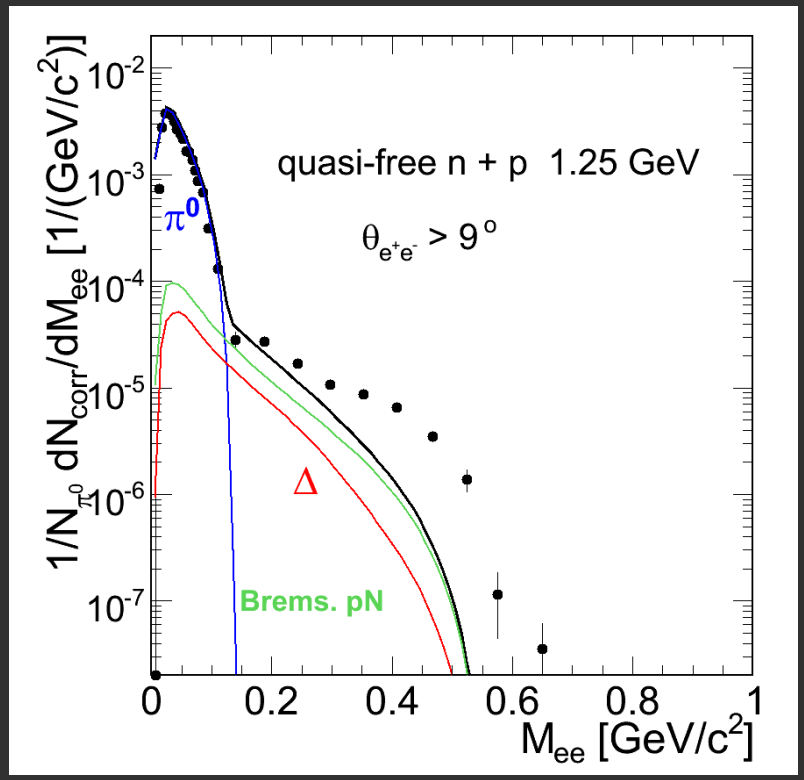
- Virtual photons from NN bremsstrahlung
- Vector meson production in p (3.5 GeV) induced reactions
- Virtual photons from Ar+KCl (1.76 AGeV) reactions
- Towards high baryon densities

Virtual photons from NN Bremsstrahlung

e^+e^- pairs from pp and np reactions (HADES)

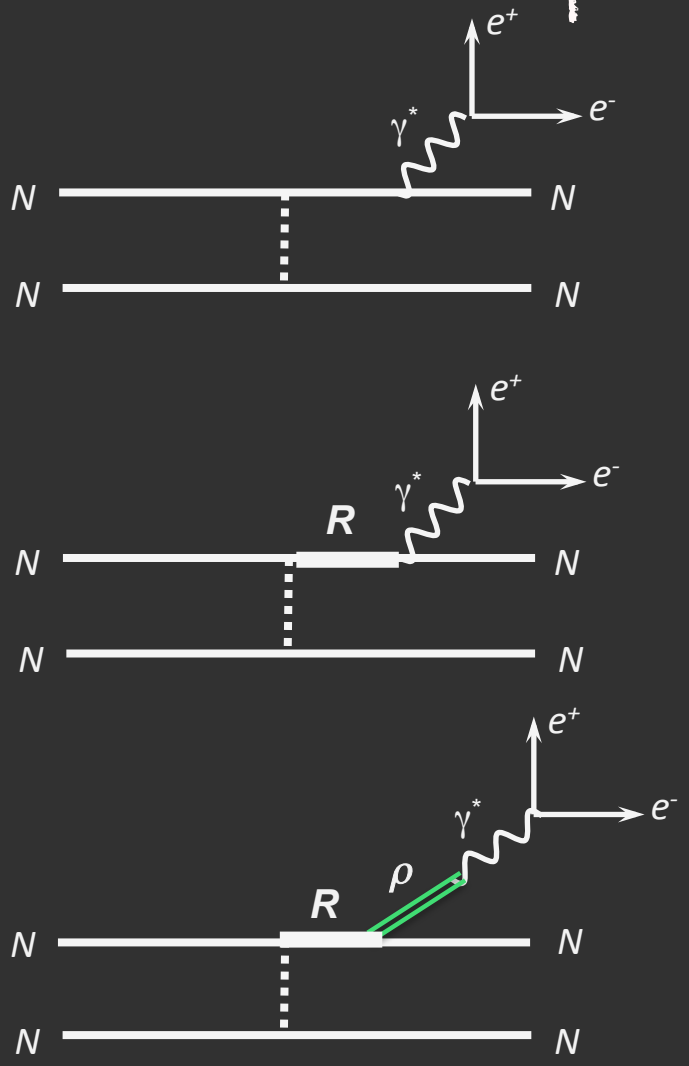
Data from HADES pp and dp (tagged n) at 1.25 GeV/u
Cocktail from HSD calculation 2008 with revised description of Bremsstrahlung

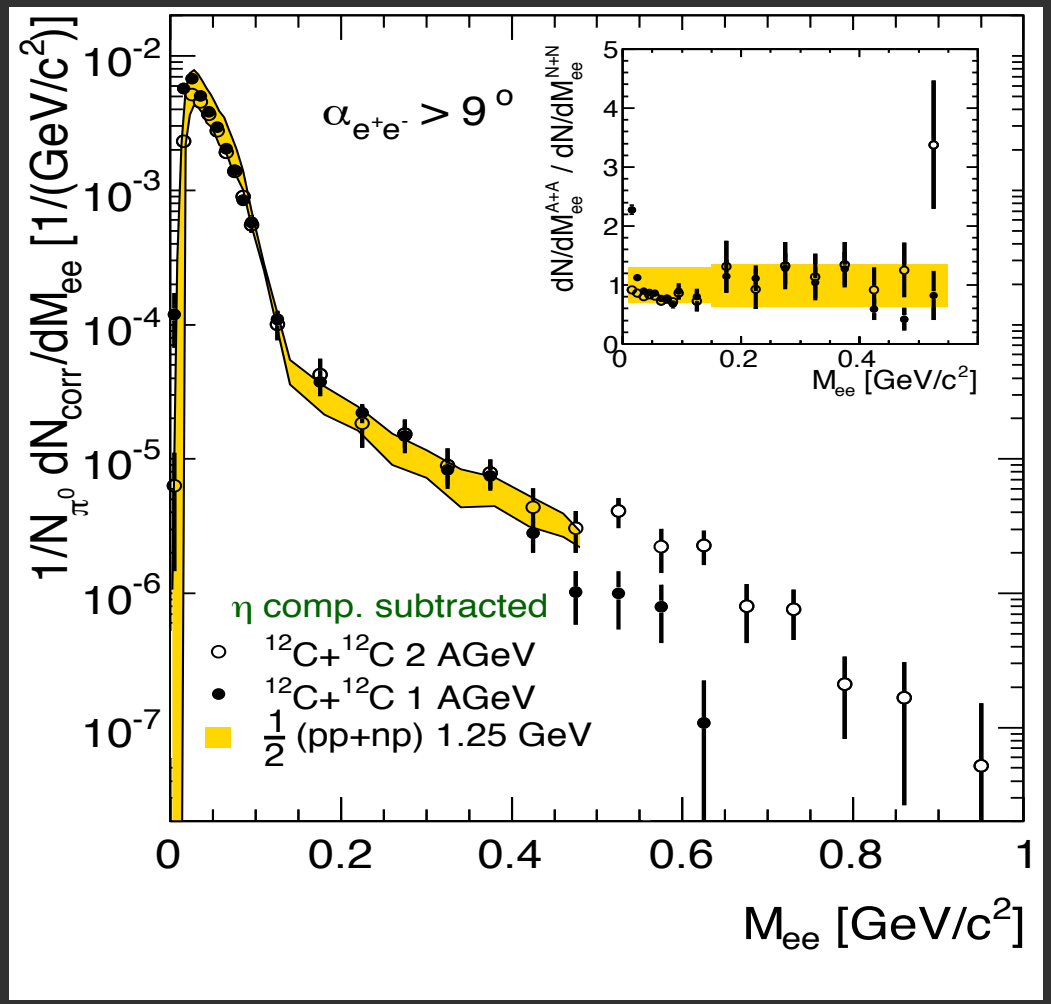




HADES collaboration, PLB 690 (2010) 118

Electron pairs from C+C collisions compared to NN reference

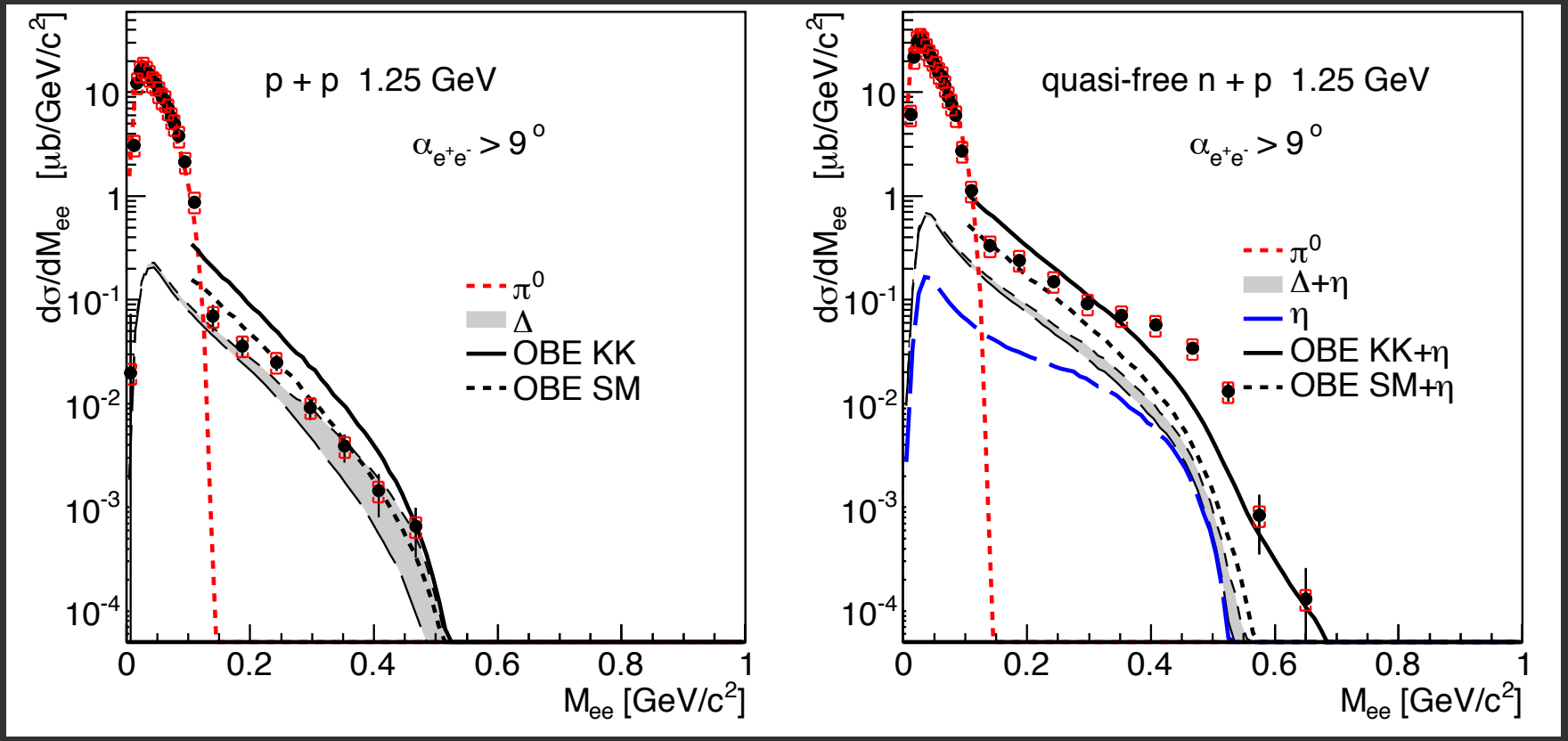




HADES collaboration, PLB 690 (2010) 118

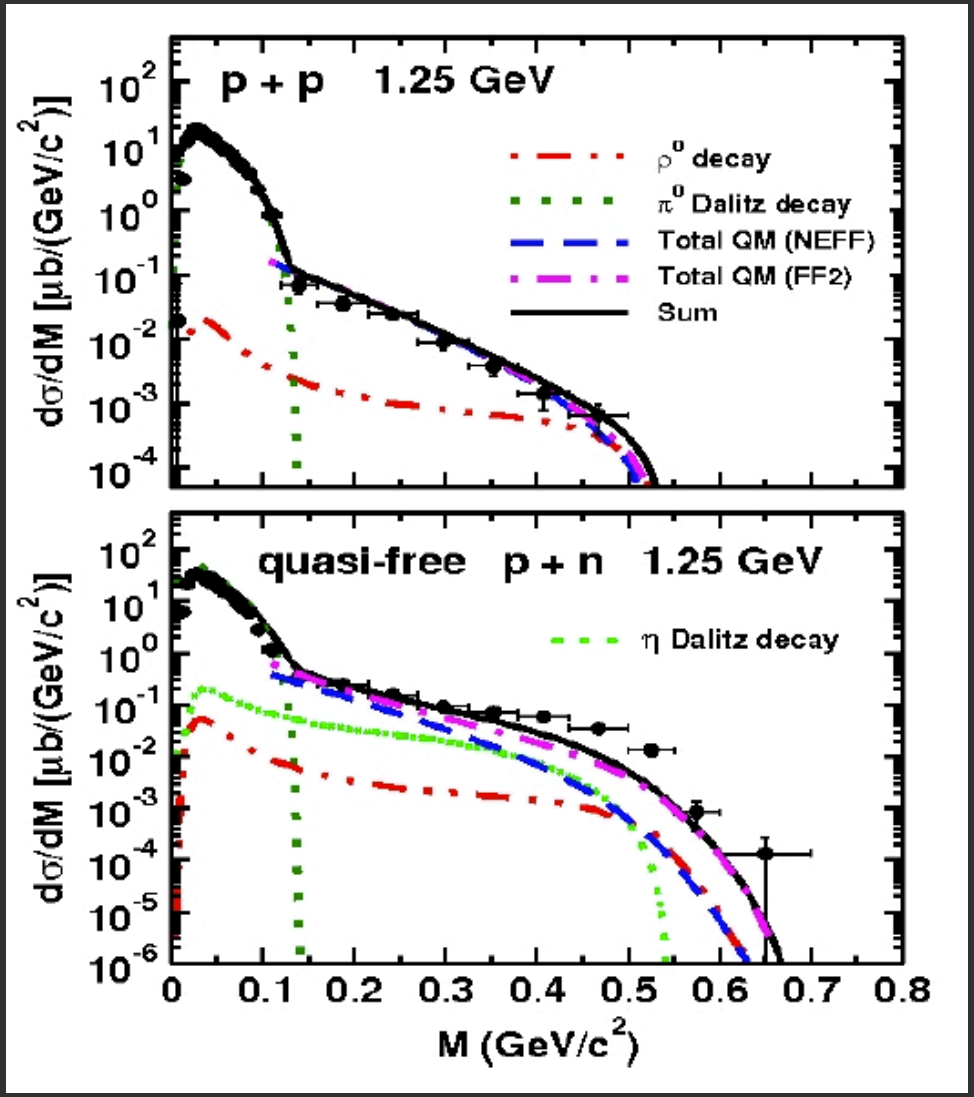
Comparison with One Boson Exchange calculations

Data from HADES pp and dp (tagged n) at 1.25 GeV/u ($\sqrt{s} - 2m_N \approx m_\eta$)
OBE calculations, different schemes for implementing gauge invariance.

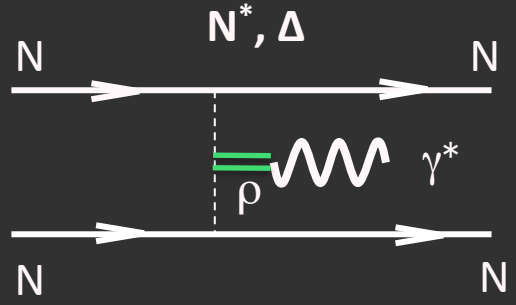


One Boson Exchange calculations reproduce p+p, but not (yet) fully n+p !

Close to a theoretical explanation!



OBE calculation including pion electromagnetic form factor for the internal pion line.

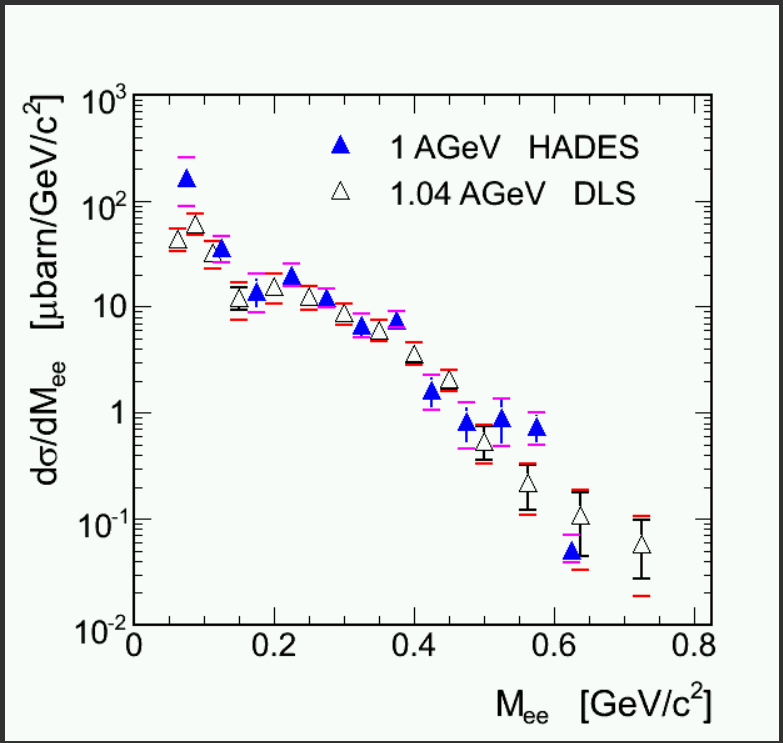


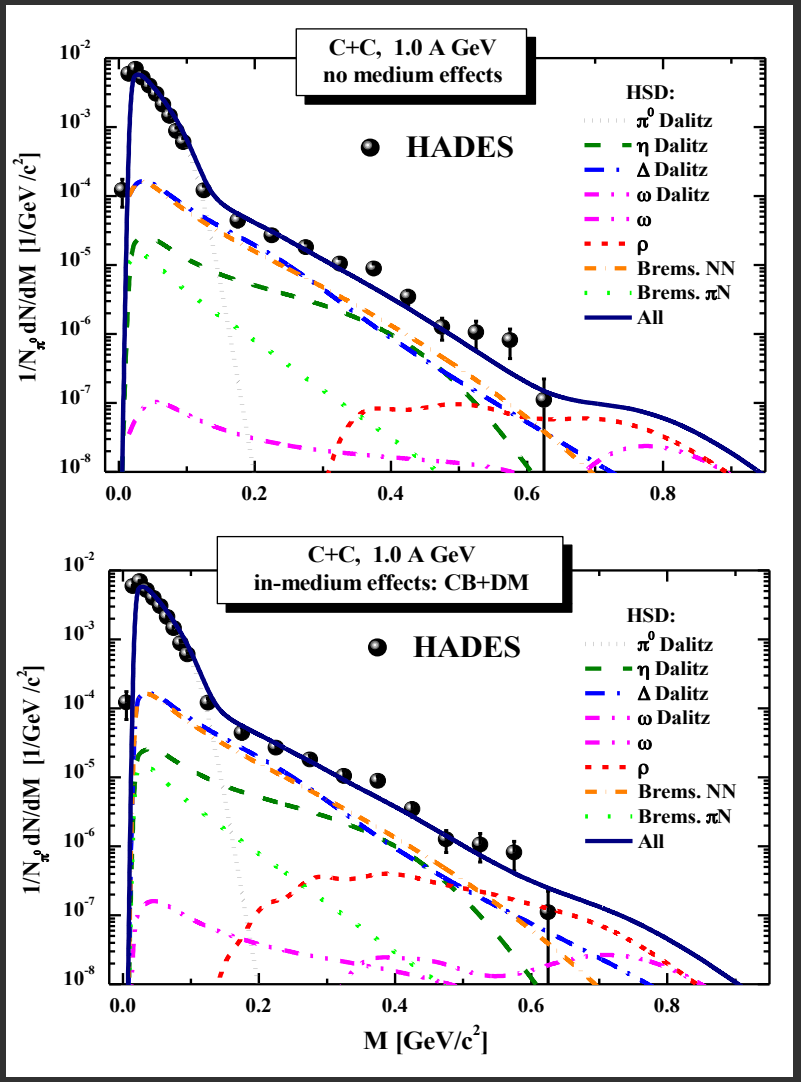
R. Shyam and U. Mosel
arXiv 1006.3873

The solution to the DLS puzzle

HADES data in the acceptance of DLS, compared to DLS data.

HADES collaboration, PLB 663 (2008)



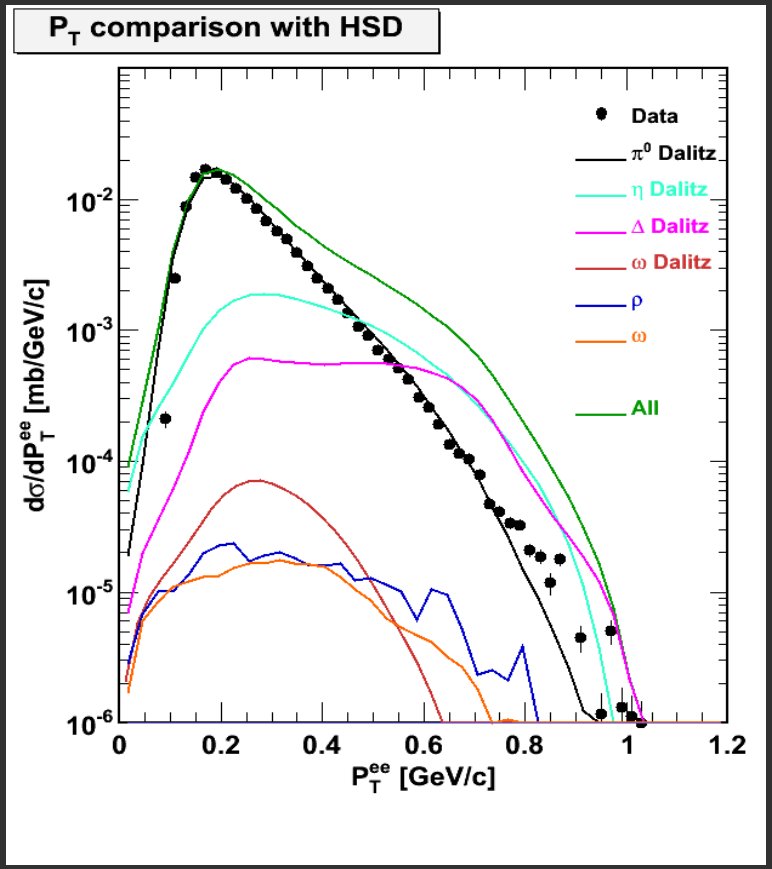


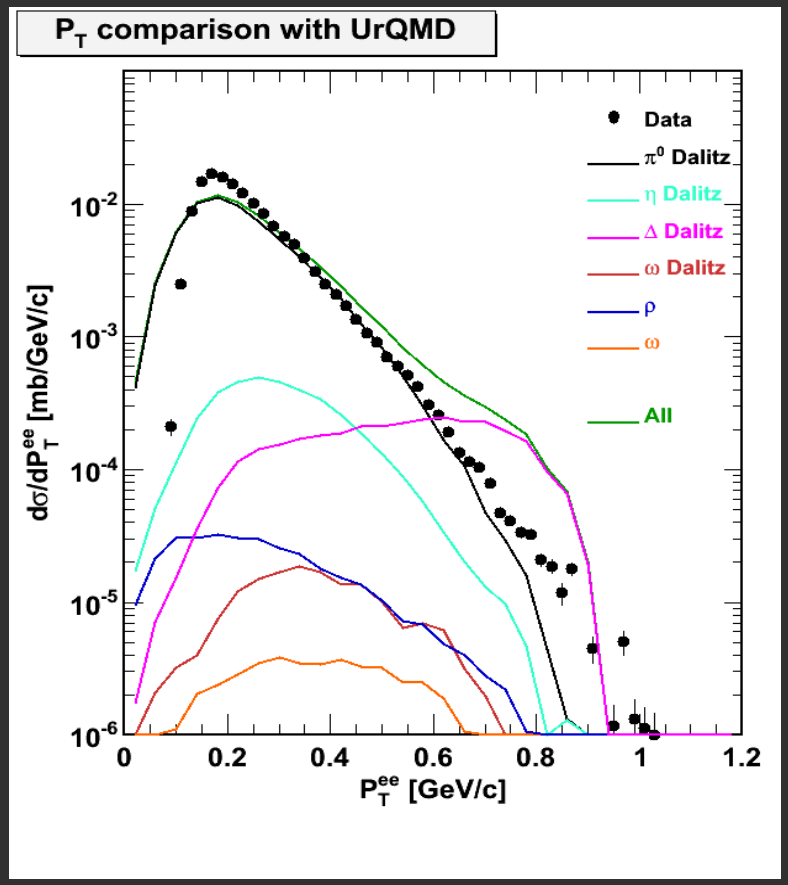
E. Bratkovskaya et al., PLB 2008.

Modified description of bremsstrahlung in HSD inspired by Kaptari et al.

Proton (3.5 GeV) induced reactions

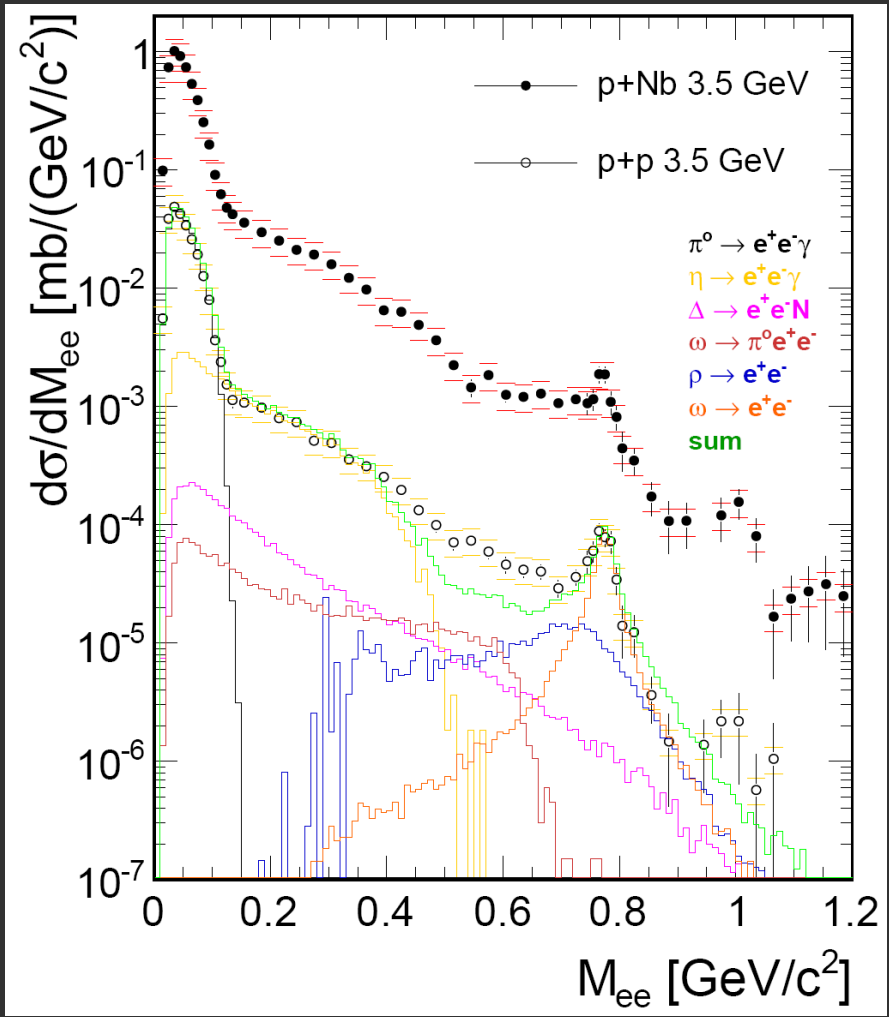
p_t Distributions from transport





p+p 3.5 GeV HADES data

e^+e^- Pairs from p+p and p+Nb reactions (HADES, 3.5 GeV/c)

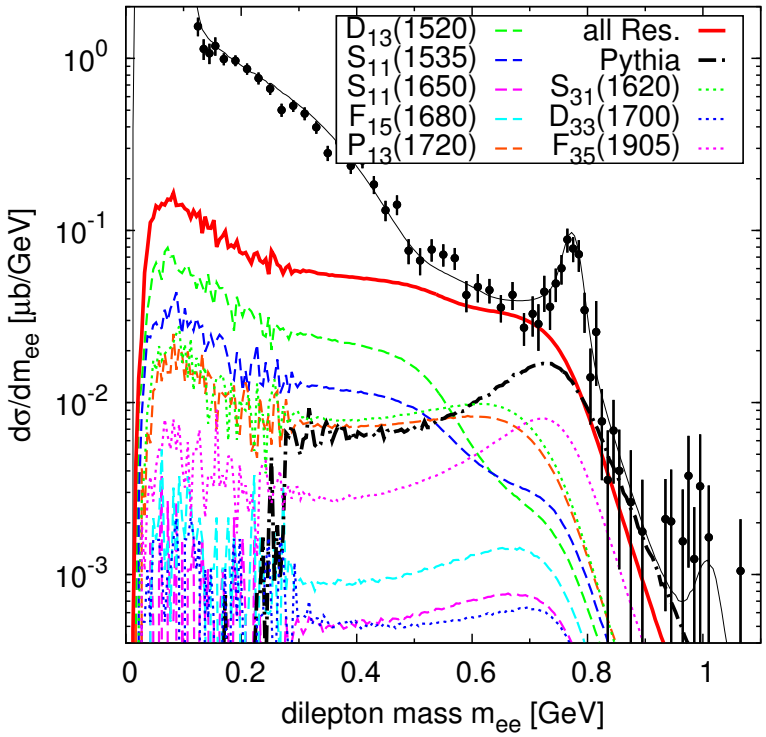


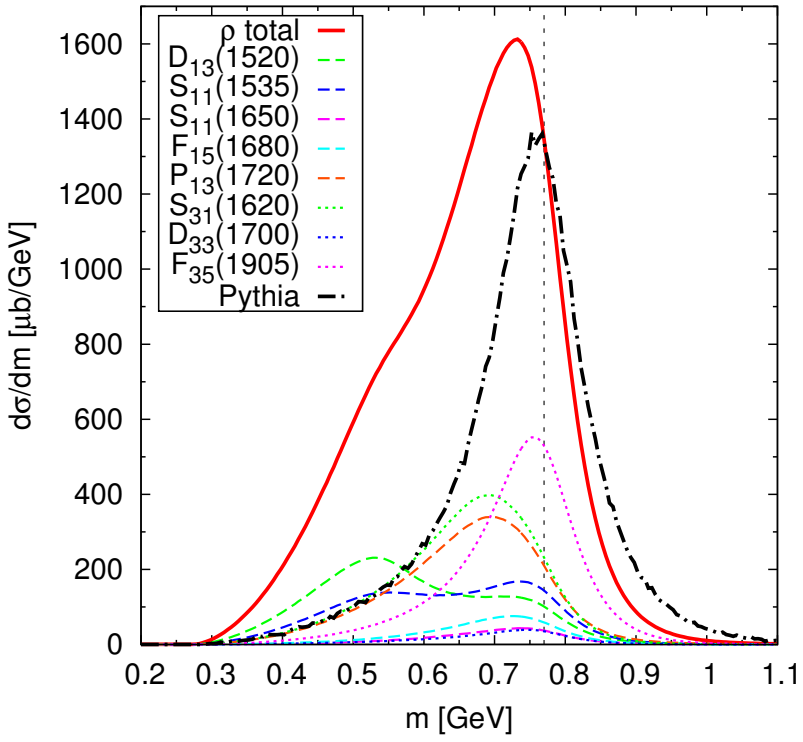
p+p:
extraction of inclusive cross sections by fitting conventional sources to the experimental spectrum:

π^o:	17 ± 2.7 ± 1 mb
Δ:	7.5 ± 1.7 mb
η:	1.14 ± 0.2 mb
ω:	0.273 ± 0.07 mb
ρ:	0.223 ± 0.06 mb

p+Nb:
ω production suppressed

HADES pp 3.5 GeV with GiBUU





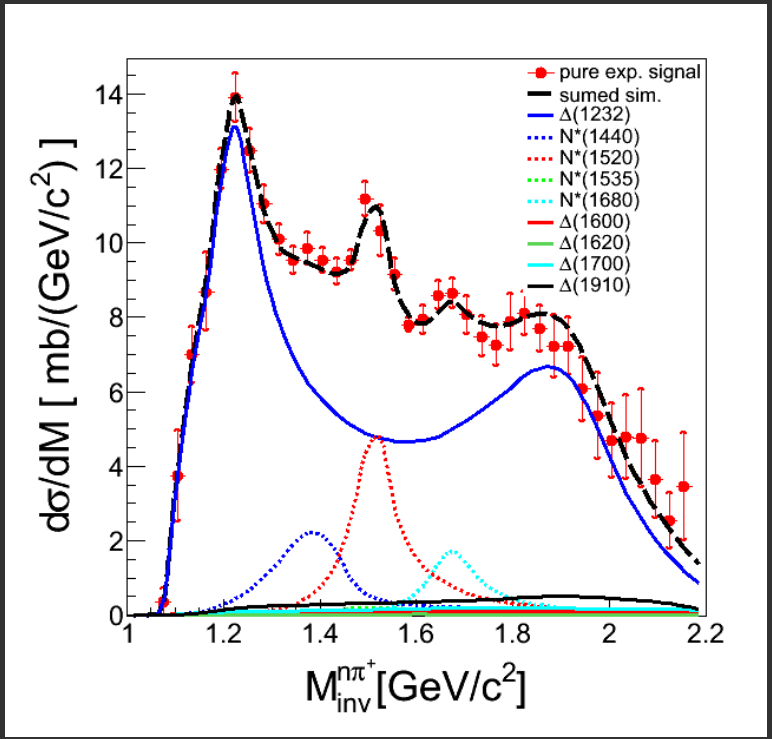
Resonance production cross sections from resonance model (based on Teis et al.)

Giessen group, J. Weil, U. Mosel and colleagues: arXiv:1203.3557v2

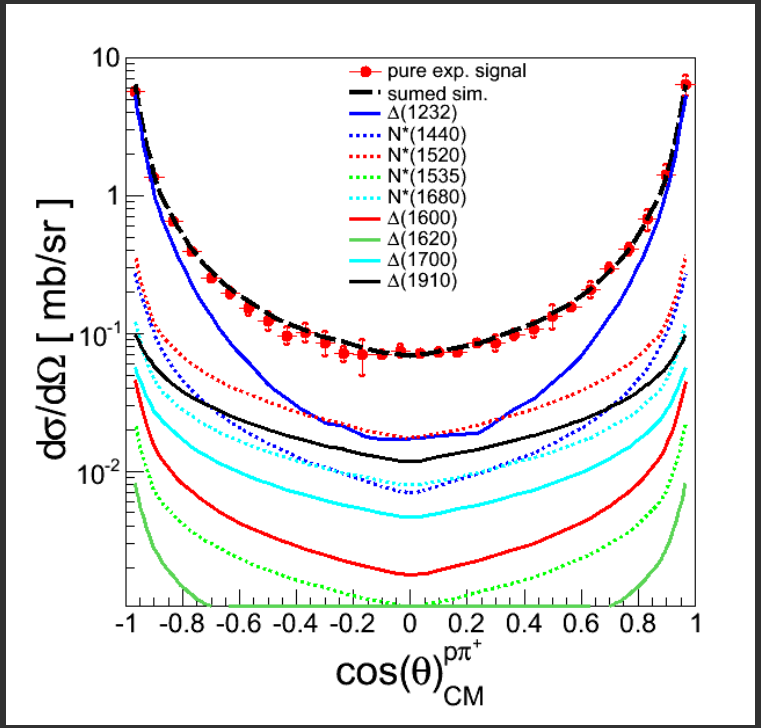
Exclusive channels in p+p 3.5 GeV

- pp → pnπ^+ and pp → ppπ^0 (missing mass analysis)

nπ^+ invariant mass



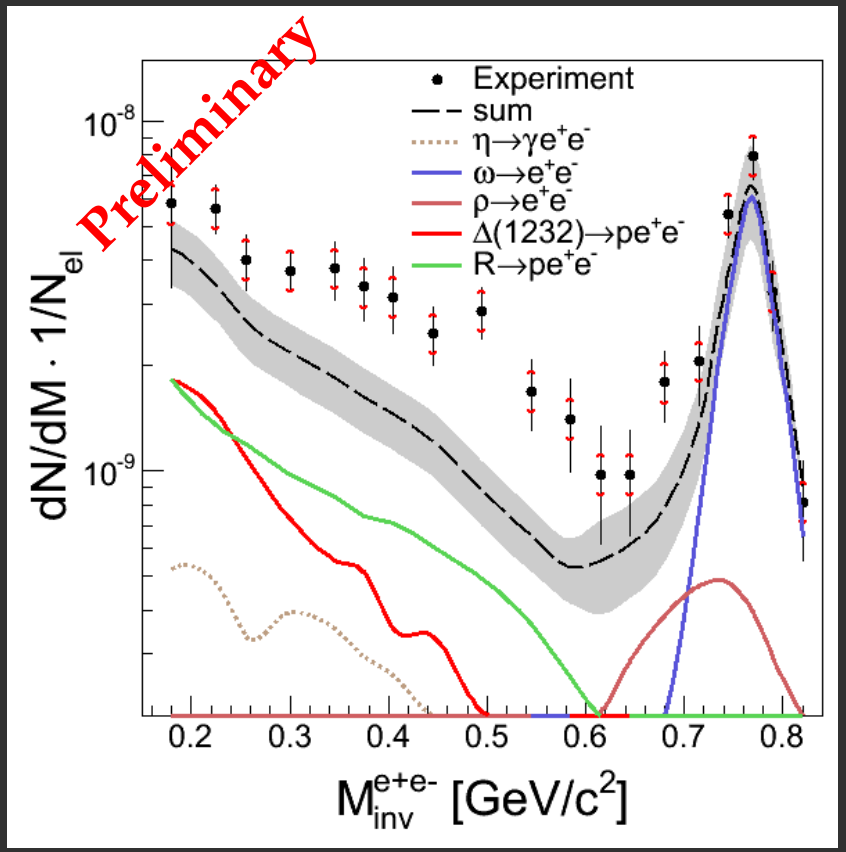
pπ^+ angular distribution



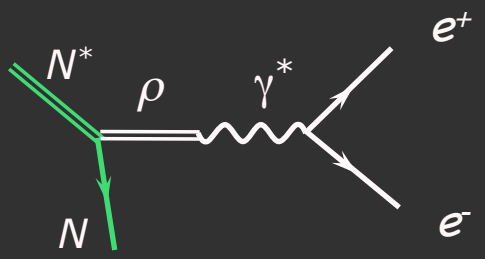
- Hadronic observables to fix the resonance contributions, analysis inspired by S. Teis et al. (Z. Phys. A356, 421 (1997))

Exclusive dilepton spectrum

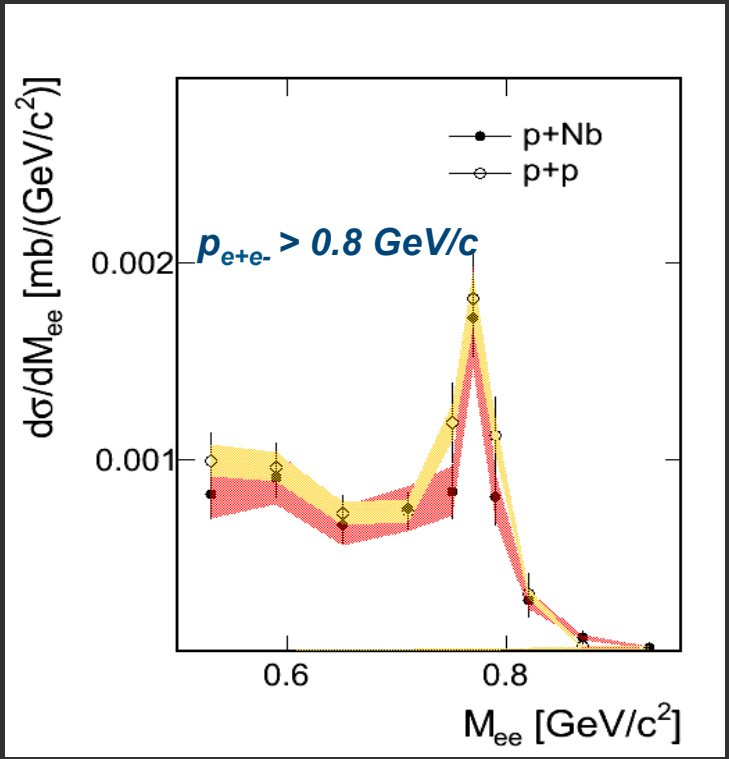
- pp → ppe⁺e⁻

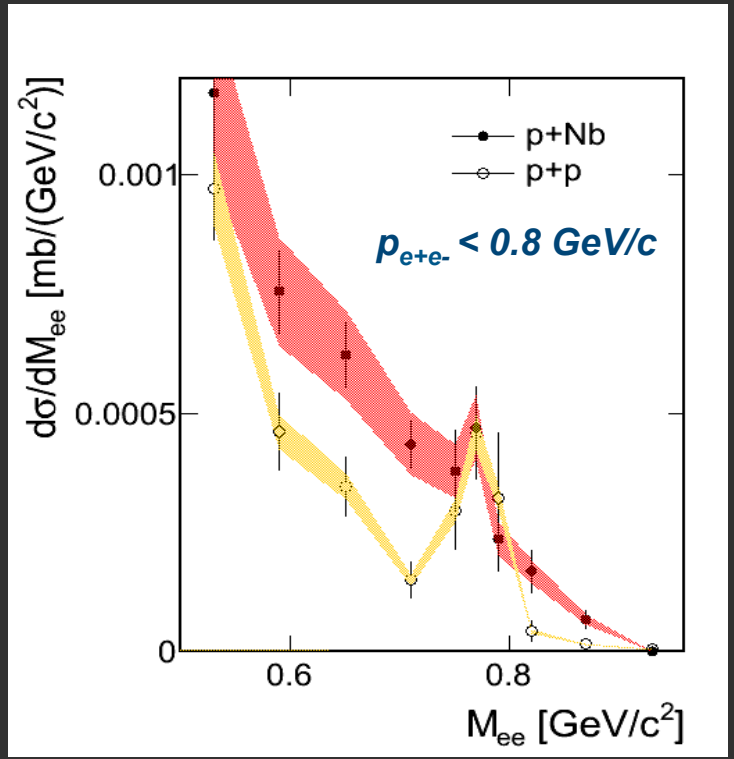


- Resonance contributions as fixed through exclusive pion production
- Pure QED transitions (no form factors for N-γ* vertex)
- ➢ Baryonic resonances contribute substantially to the dilepton yield in the few GeV energy regime



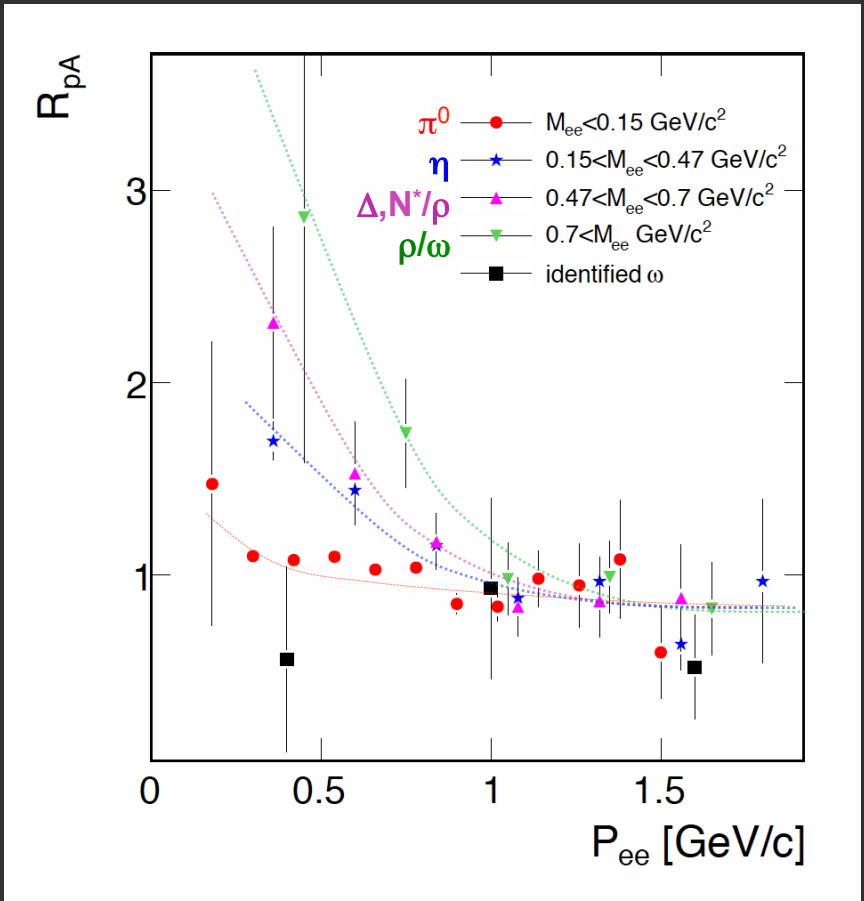
Momentum binned invariant mass spectra





- First measurement of in-medium vector mesons in the relevant momentum region
- ω suppressed, in-medium decays buried under ρ-like contribution

Momentum dependence of R_{pA}



$$R_{pA} = \frac{d\sigma/dp^{pNb}}{d\sigma/dp^{pp}} \cdot \frac{A^{pp}_{part}}{A^{pNb}_{part}} \cdot \frac{\sigma^{pp}_{reaction}}{\sigma^{pNb}_{reaction}}$$

- The modification cannot be interpreted in terms of absorption only!
- Different production processes in p+A reaction
- Low P_{ee} enhancement seems to go with virtual photon mass
- No P_{ee} dependence of identified ω

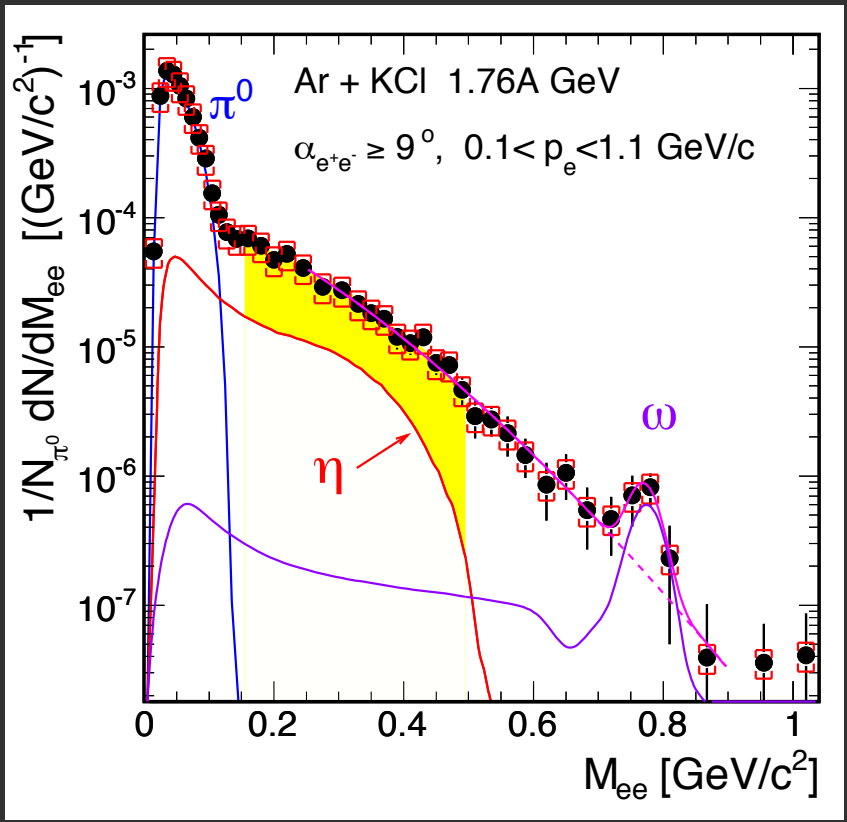
Ar+KCl 1.76 AGeV

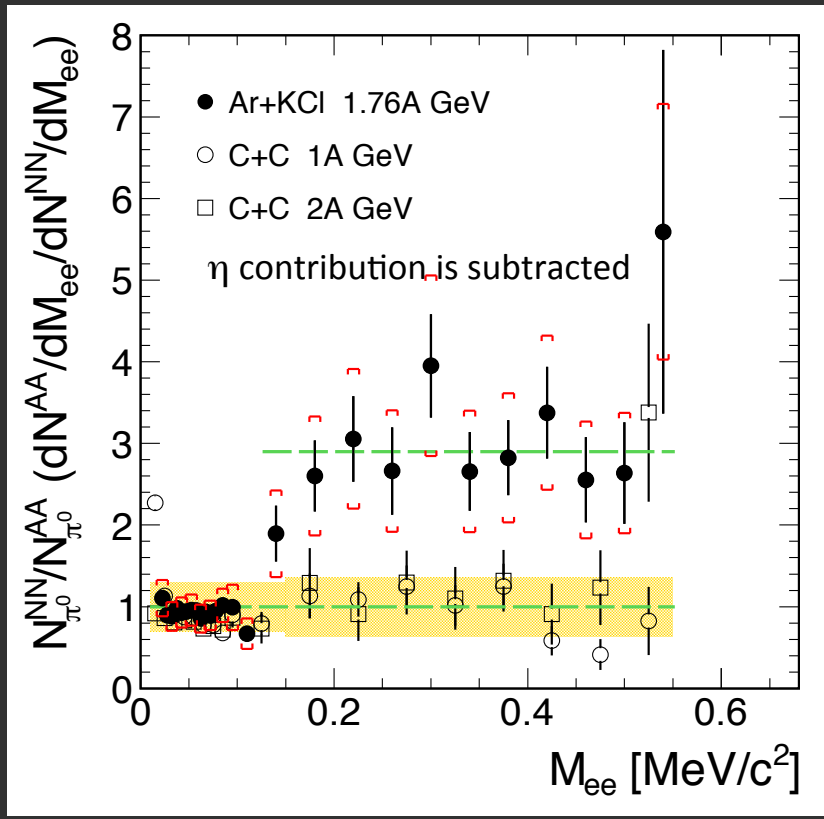
e^+e^- pairs from Ar+KCl at 1.76 GeV/u

First observation of ω mesons in HI collisions at these energies.

„True" excess (~factor 3)

➢ The HADES „Delta" clock





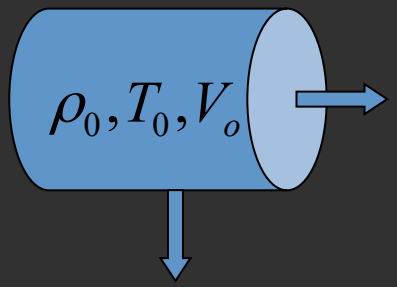
HADES collaboration, Nucl.Phys.A830:483C-486C,2009

Towards high baryon density

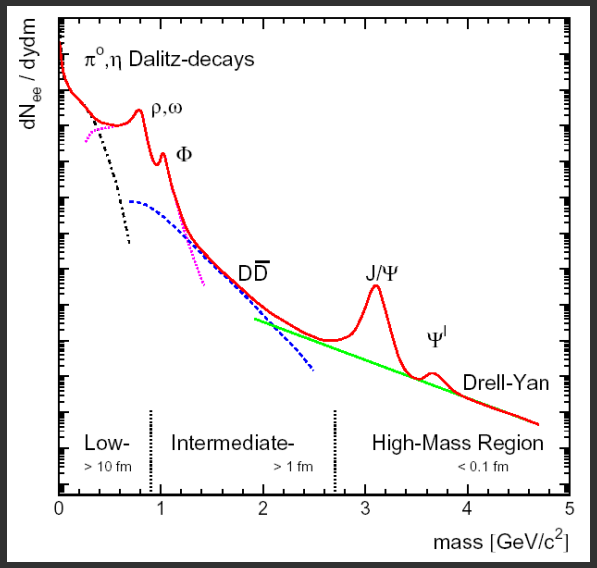
Dilepton rates from theory

- Thermal dilepton rates …

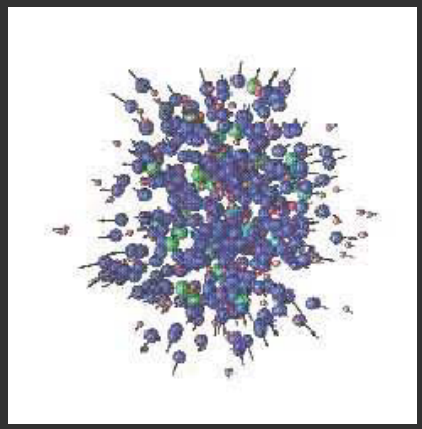
$$\frac{d^3N}{dMdydp_t} \equiv \int_{t=0}^{\infty} \frac{d^4\varepsilon}{d\mathbf{p}} \left[T(\mathbf{x}), \mu_B(\mathbf{x}), \vec{v}_{coll}(\mathbf{x}), ..\right] d\mathbf{x}$$



isentropic expansion

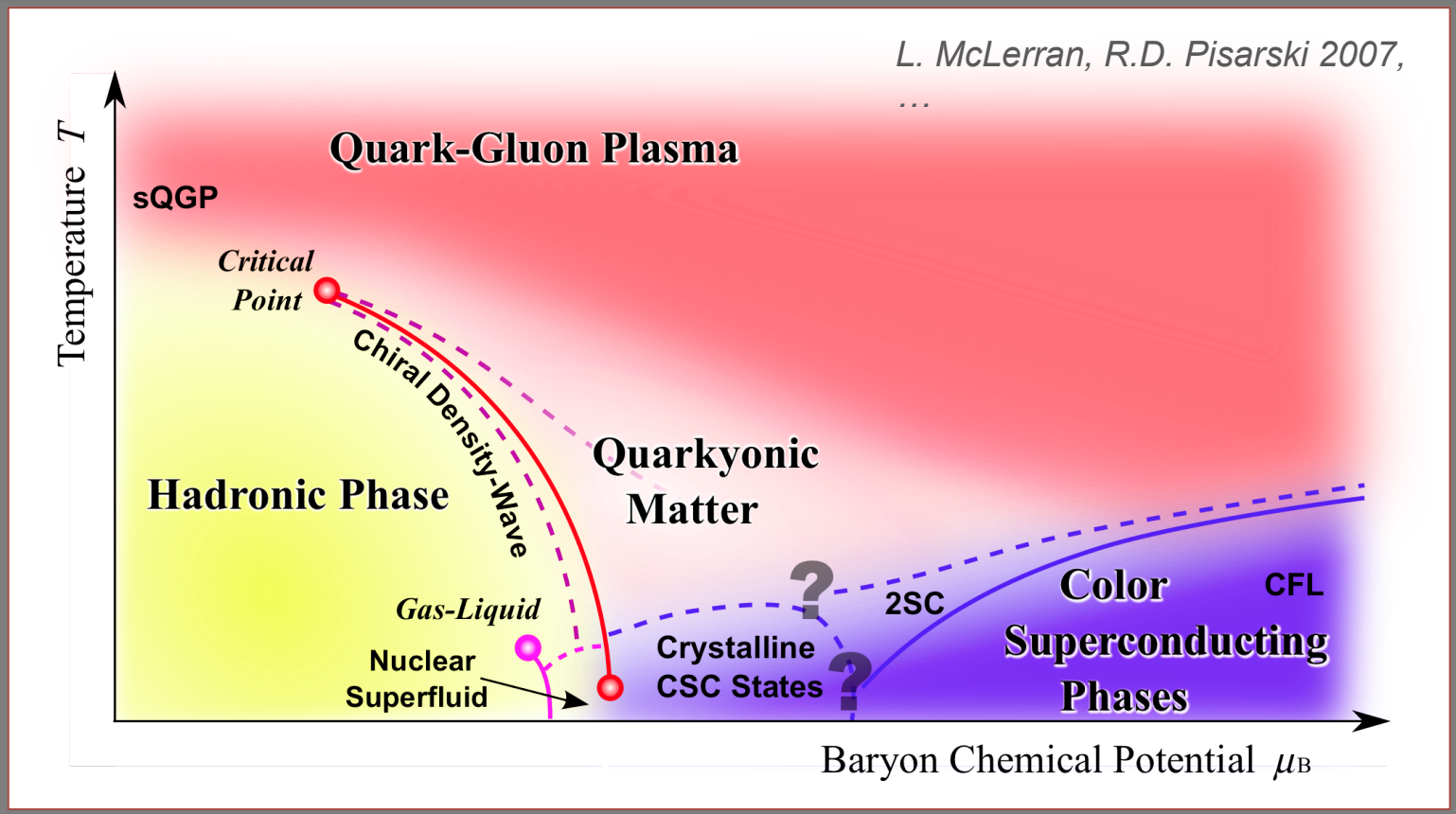


- … or from (hybrid) transport



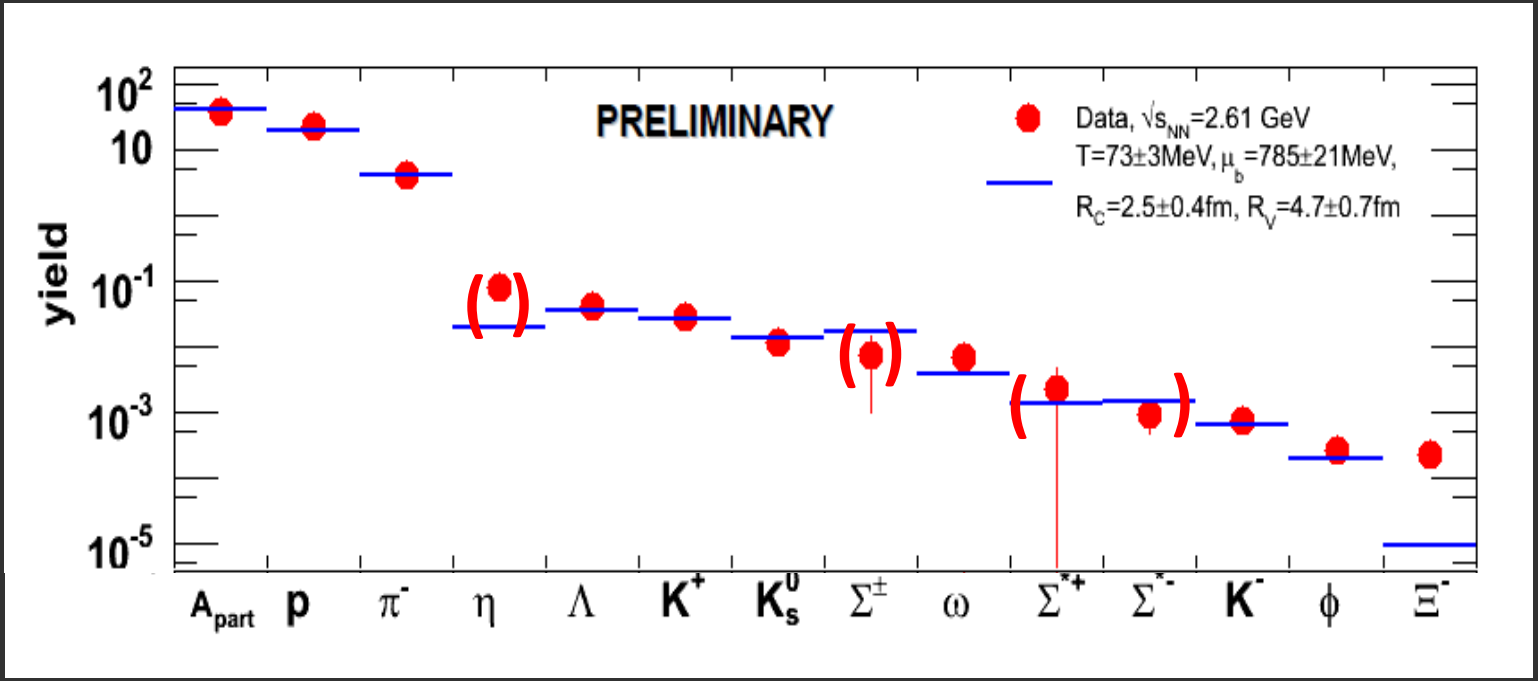
The QCD Phase Diagram

- Tremendous interest: RHIC-BES, NA61, NICA, and CBM/HADES!

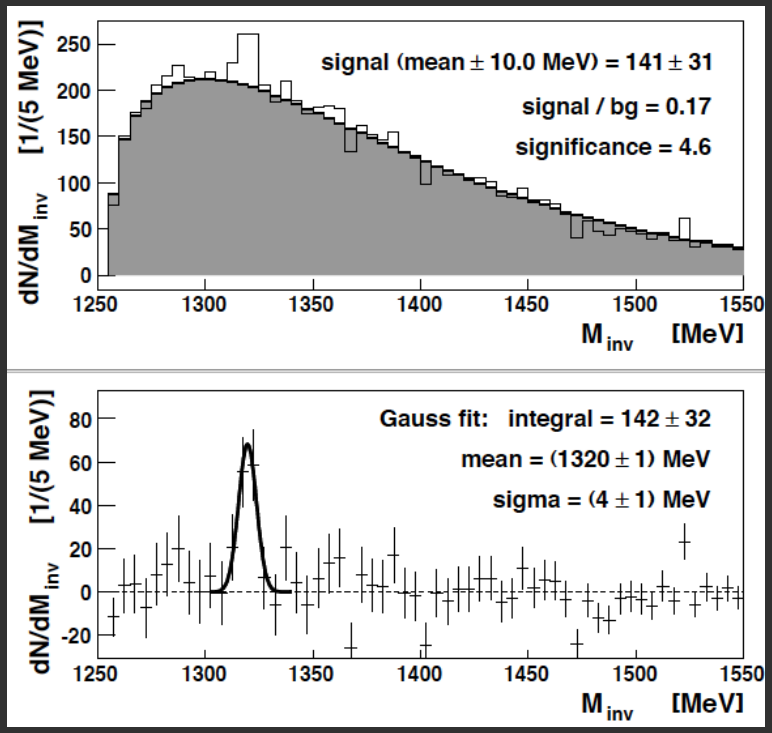


Hadron multiplicities in Ar+KCl

- Particle yields surprisingly well described by a Statistical Hadronization Model (here THERMUS)
  - ✘ ϕ not suppressed
  - ✘ What about the Cascade?

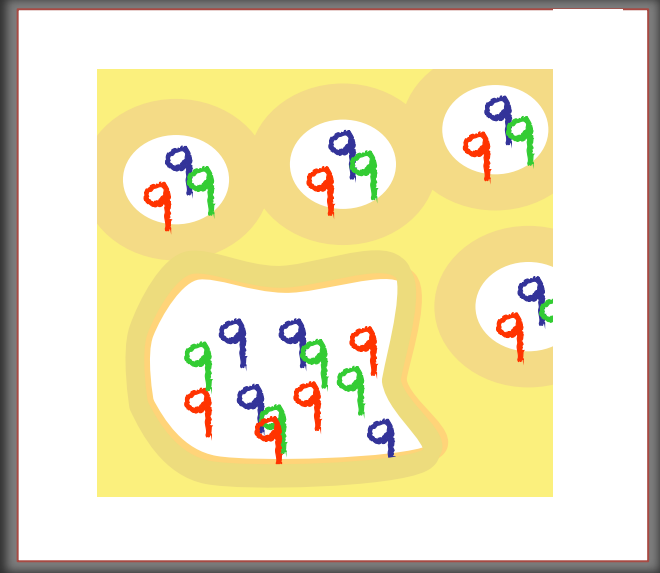


Unexpectedly High Cascade Yield



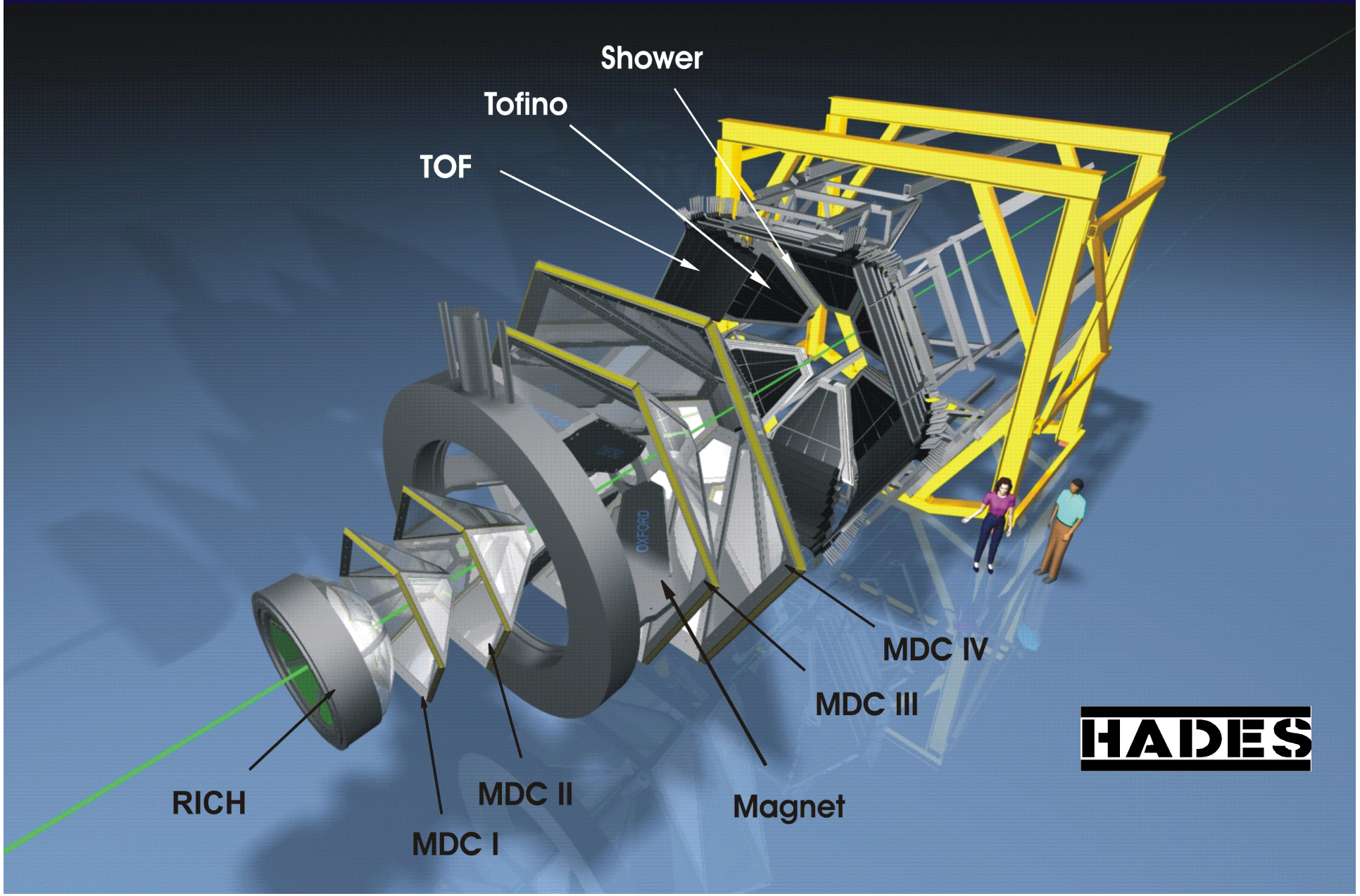
Probability (M_{ss}) to produce in an Ar+KCl collisions a strange quark pair was found to be 5×10^{-2}

The multiplicity for Ξ is:
$M_{\Xi} \approx 0.1\ M^2_{ss}$

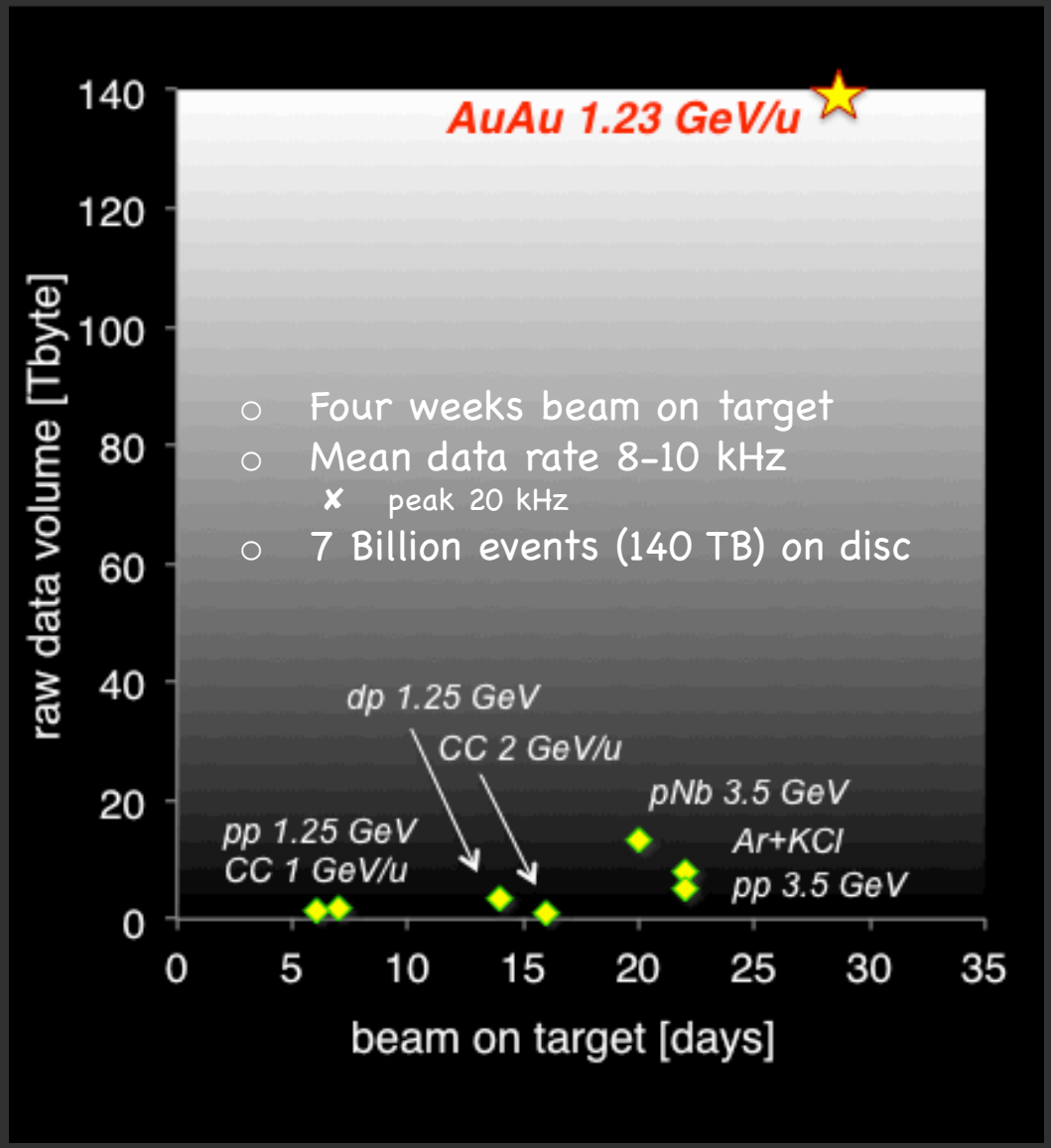


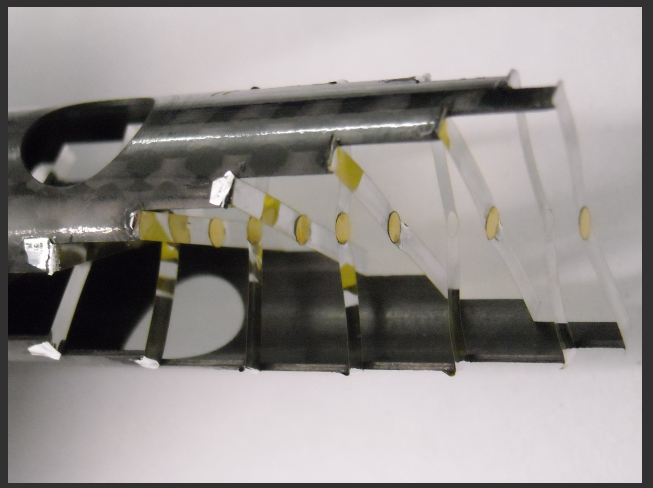
Are the strange quarks trapped in bubbles?

The HADES experiment @ GSI

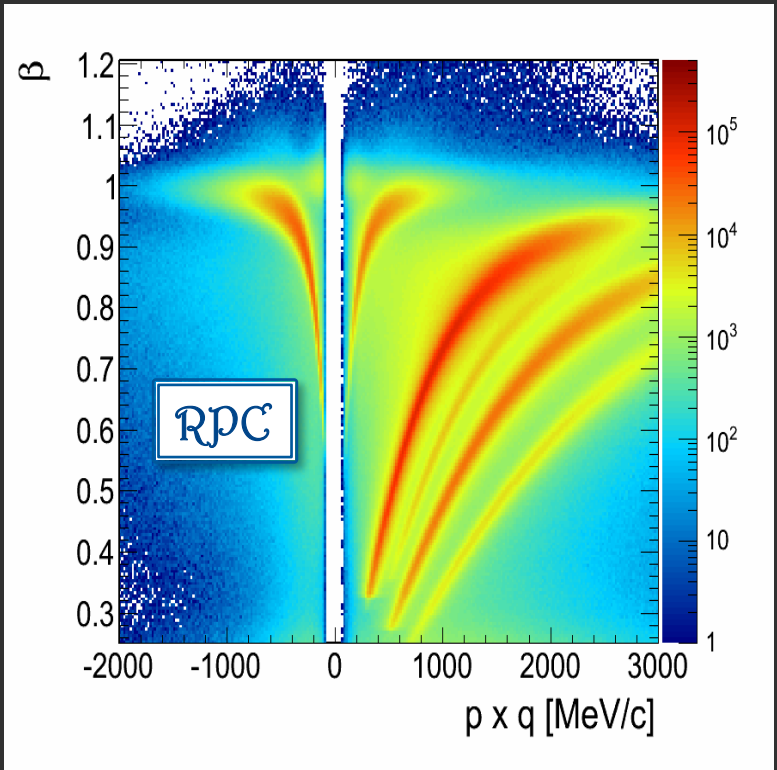


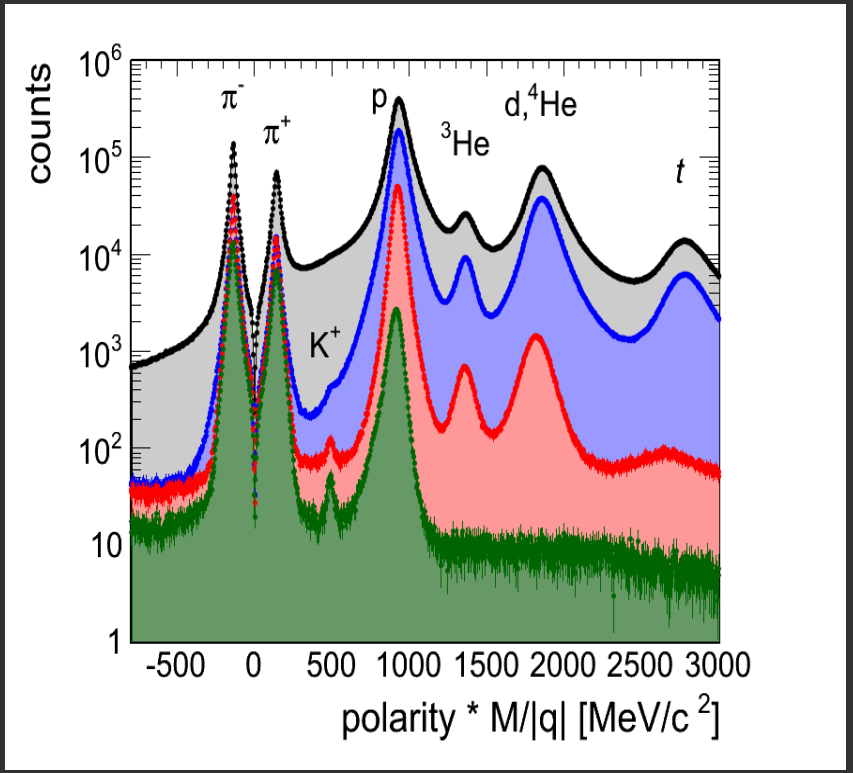
Au+Au run in April 2012





Performance of the new RPC time-of-flight system





RPC detector built by the Coimbra team (P. Fonte et al.)

NIM A602:687-690,2009, NIM A602:775-779,2009

The HADES collaboration

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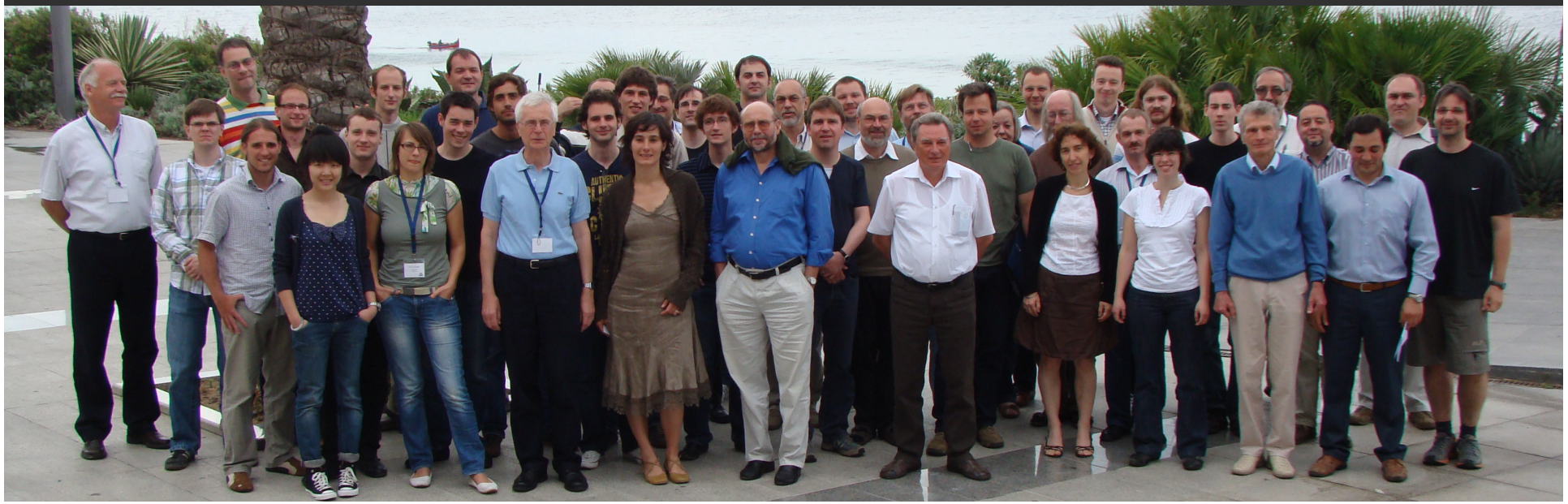
Departamento de Física de Partículas, University of Santiago de Compostela, 15782 Santiago de C.a, Spain



Summary and Outlook

- HADES has collected a collected a high-quality data on dilepton emission from A+A and elementary collisions, including exclusive analysis.
- No evidence for mass shifts of ρ/ω
- Contributions from the dense/early phase a quite featureless -> strong broadening of in-medium states!(?)
- Interesting observations in strangeness production
- Missing: heavy collision systems and pion induced reactions (time is running)
- Bright future for the investigation of Compressed Baryonic Matter at FAIR

Thank You!