Exploring compressed nuclear matter with HADES

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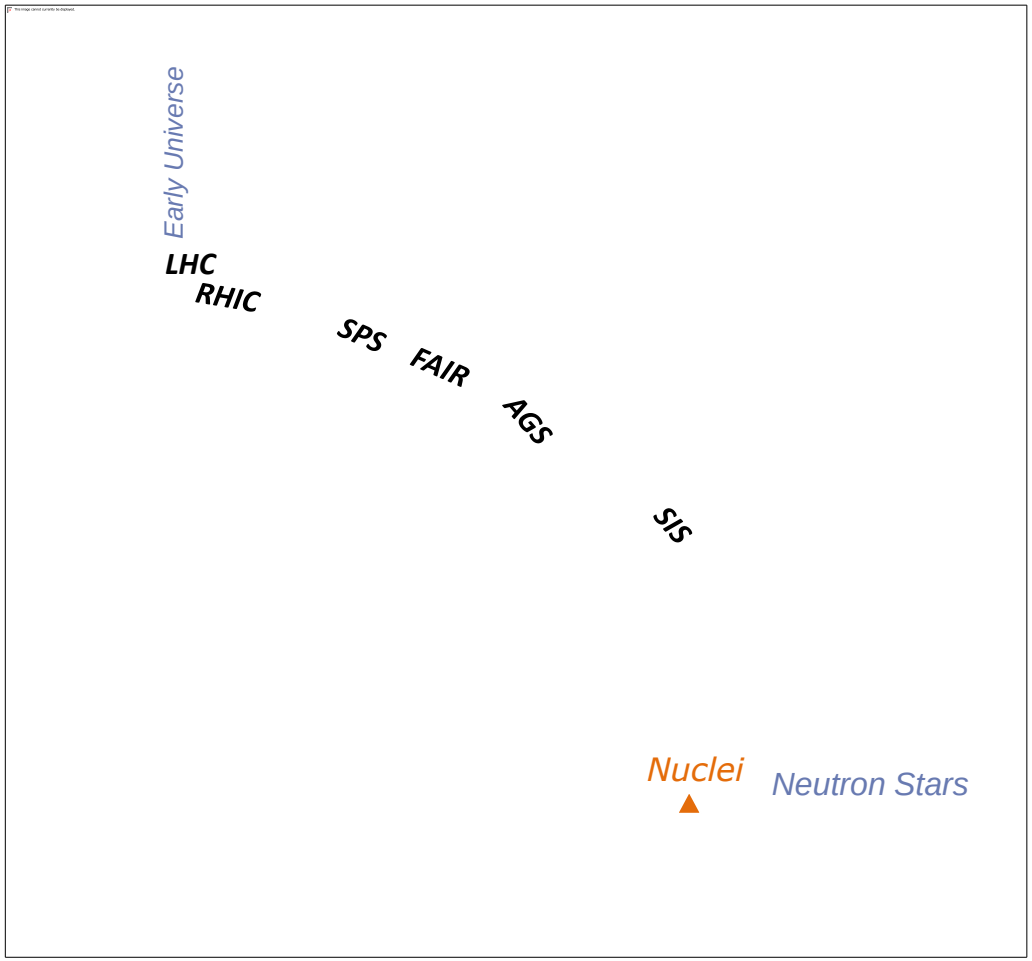
Goethe-Universität Frankfurt / EMMI

Outline:

- Exploring compressed nuclear matter with HADES:
  - dileptons and strangeness
- HADES and the Phase Diagram of Matter
- The perspectives and challenges at FAIR

Searching for landmarks of the phase diagram of matter



- Chemical „freeze-out“ points from measured particle yields analyzed with Statistical Hadronization Model
  - Universal conditions for freeze-out (?)
  - Why is it working at low beam energies?

SHM : J. Cleymans, K. Redlich, PRC 60 054908

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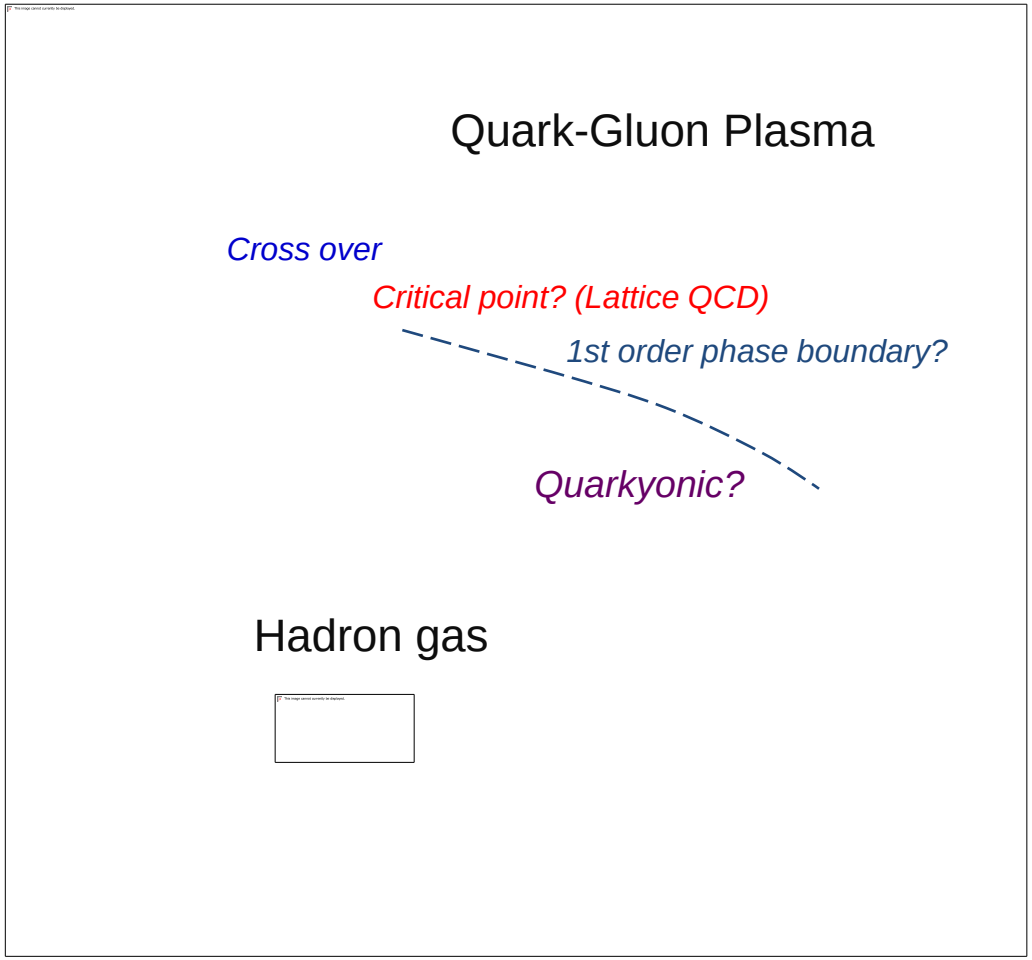

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- Possible 1st order phase transition and critical point at large μ_B
- Phase diagram at large N_c limit
  → ***Quarkyonic Matter?*** Confined gas of perturbative quarks
- QCD inspired effective models predict the melting of the condensate

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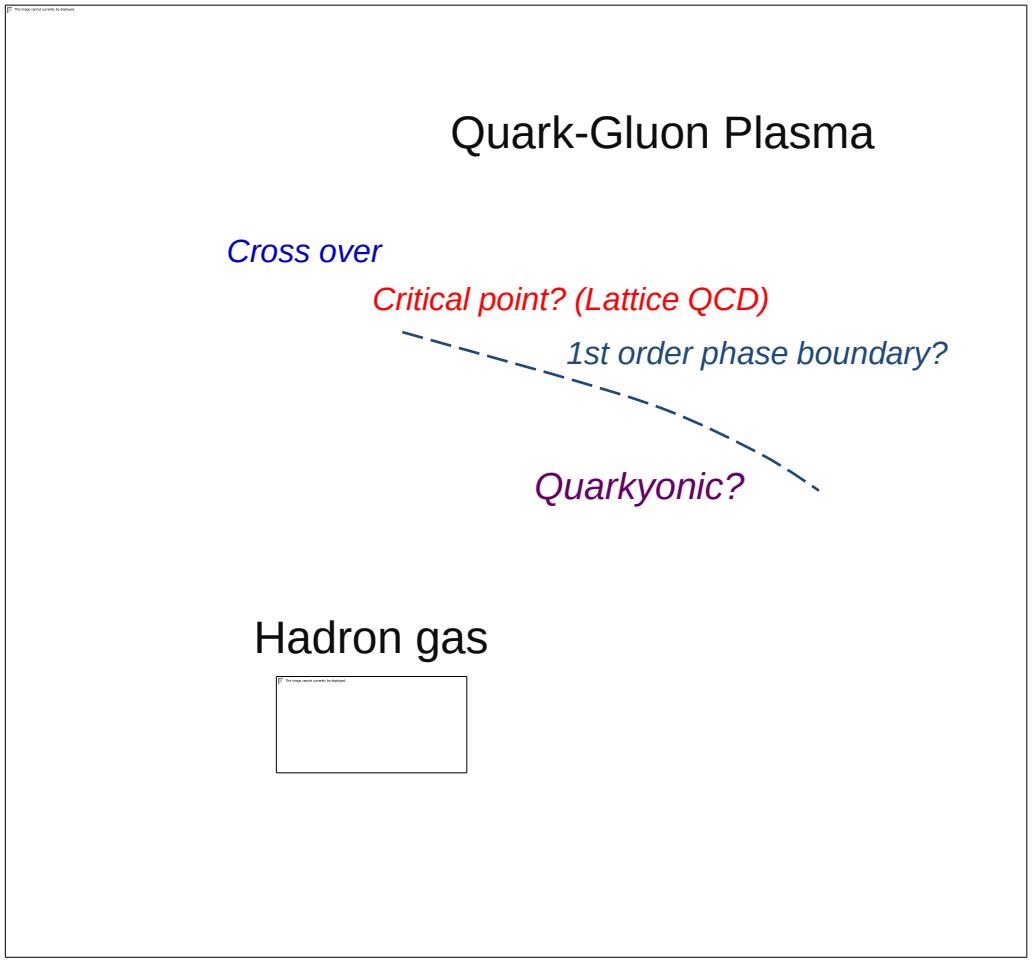

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<(qqbar)^2>: S. Leupold (private comunication)

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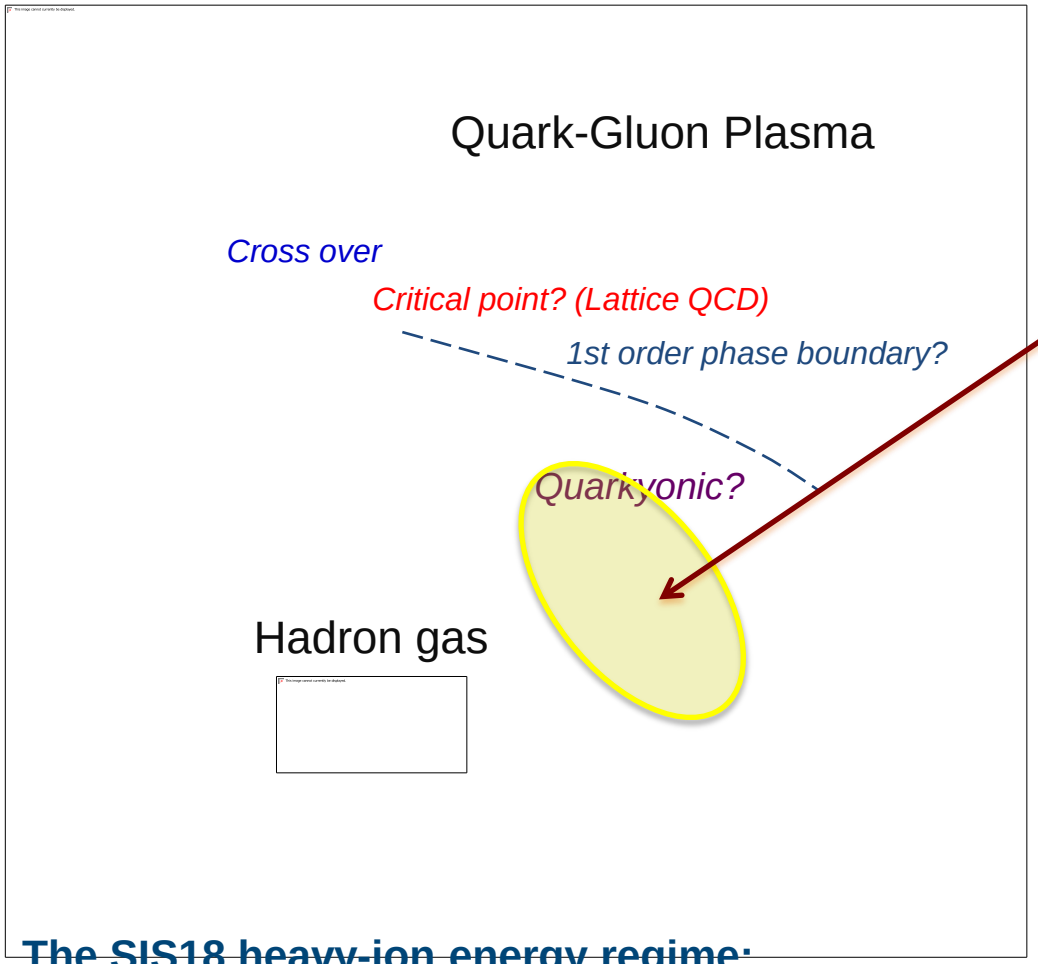
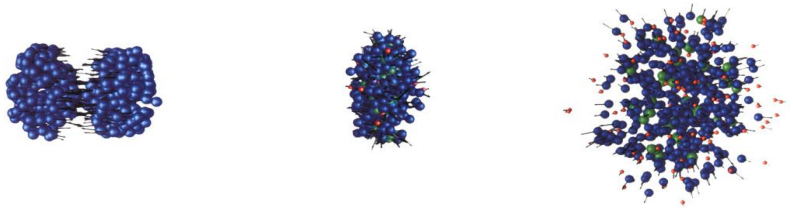


Search (in this region) for new states of matter with rare and penetrating probes

Is a true "phase" realized in the course of the collision?

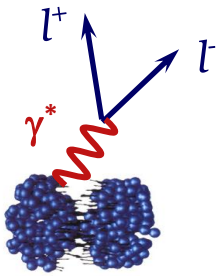


first-chance collisions | dense matter | freeze-out

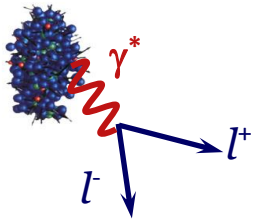
The SIS18 heavy-ion energy regime:

- T < 100 MeV
- ρ_{max}/ρ_0 = 2 – 3
- τ ~ 15 fm/c

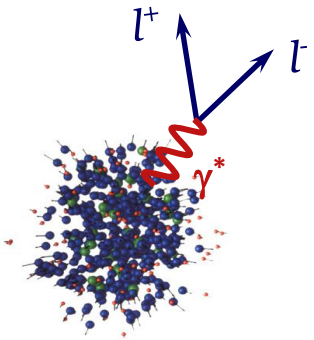
Radiation from hot and dense matter



first-chance collisions



dense matter



freeze-out

- The dilepton signal contains **contributions from throughout the collision**
- No strong final state interactions
  → **leave reaction volume undisturbed**
- Probes the **electromagnetic structure of dense/hot hadronic matter**

- **Emissivity of hadronic matter**
- **In-medium spectral functions**

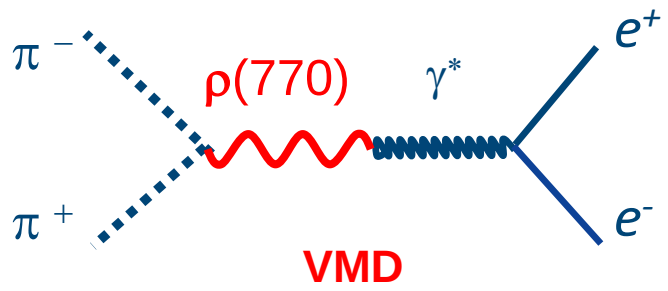
Emissivity of strongly interacting matter

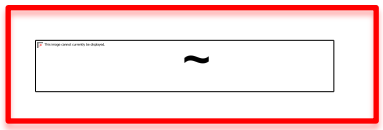
Electromagnetic Current-Current Correlation Function:

Thermal Dilepton Production Rates:

Low mass region, $M_{ll} \leq 1.1$ GeV/c^2

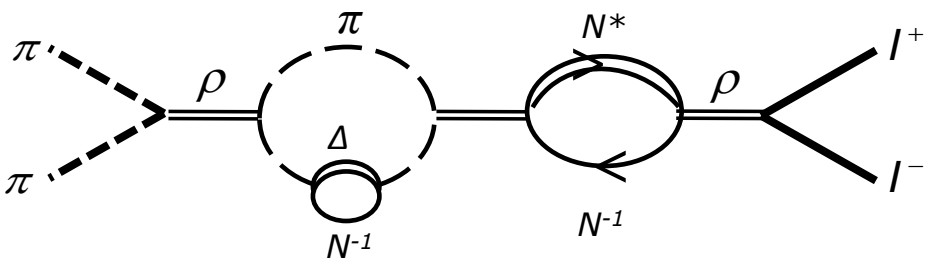
CBM Physics Book





ρ – meson dominated

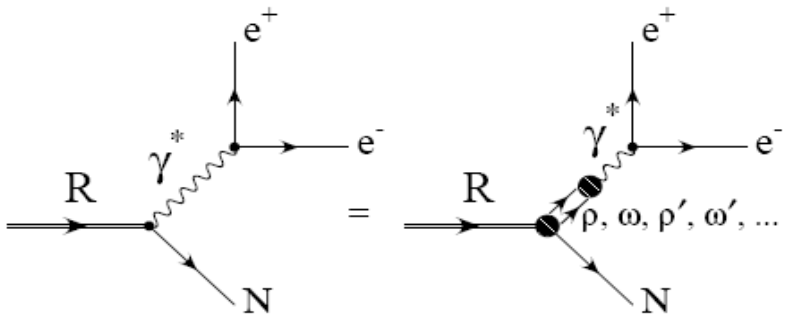
The ρ meson in nuclear matter

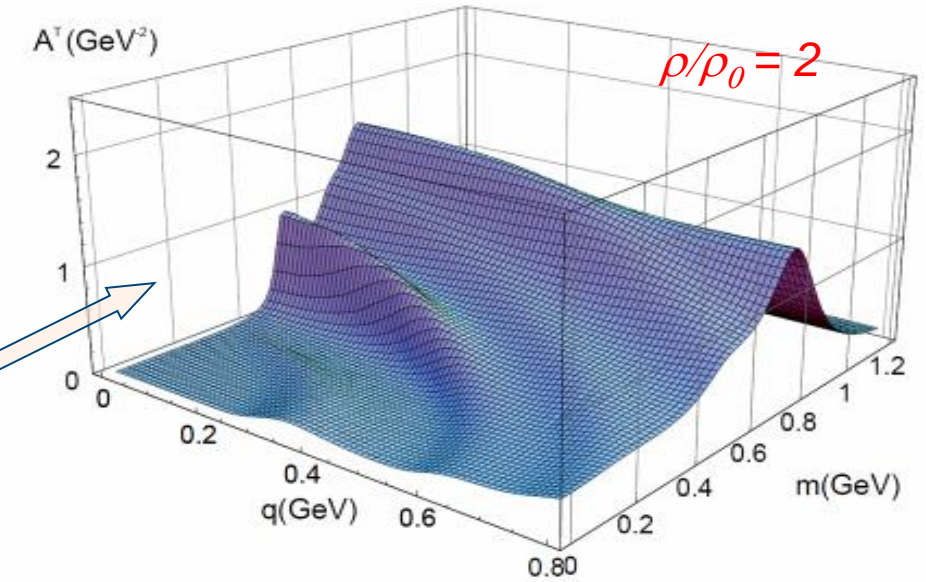


Additional contributions to the ρ-meson self-energy in the medium

S. Leupold, U. Mosel, Post et al.
NPA 741 (2004) 81, NPA 780 (2006) 187

Dalitz decay of resonances





Meson nucleon molecules

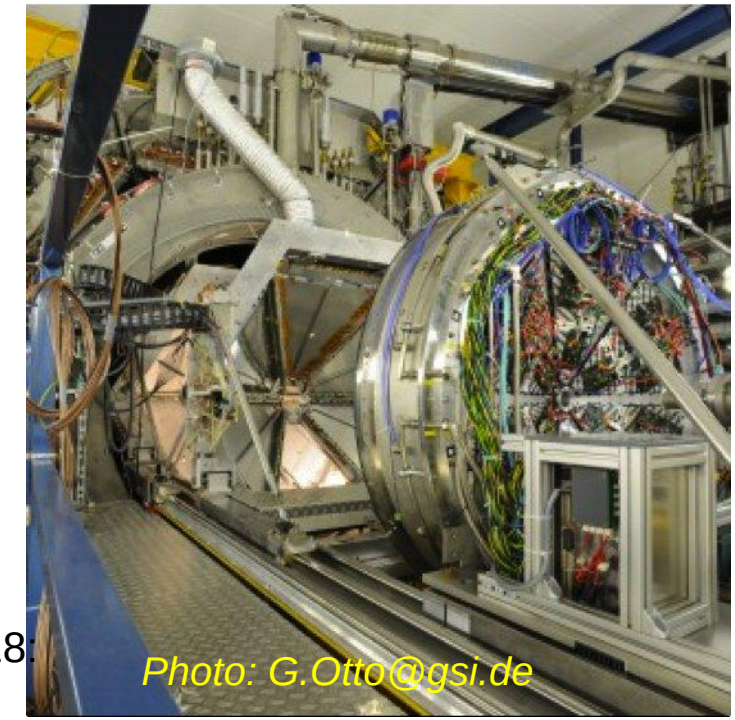
The experimental challenge...

- Lepton pairs are rare probes (branching ratio < 10^{-4})
- at SIS energies sub-threshold vector meson production

- Large combinatorial background in e^+e^- from:
  - Dalitz decays (π^0)
  - Conversion pairs

- Isolate the contribution to the spectrum from the dense stage

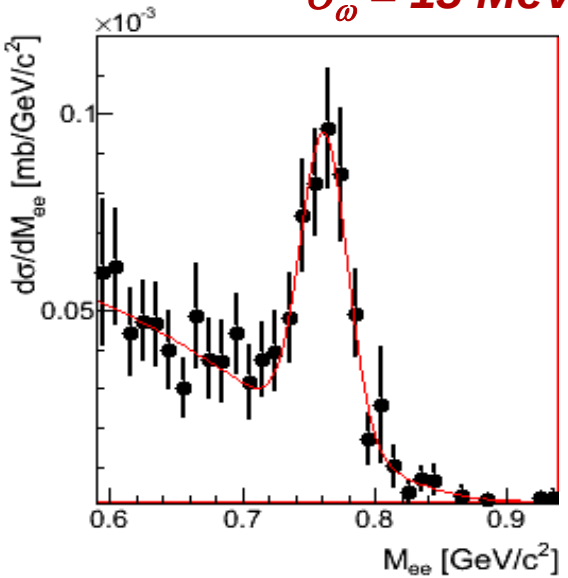
High Acceptance Di-Electron Spectrometer



HADES strategy:
Systematic di-electron and strangeness measurements in NN, AA, pA, πN and πA collisions

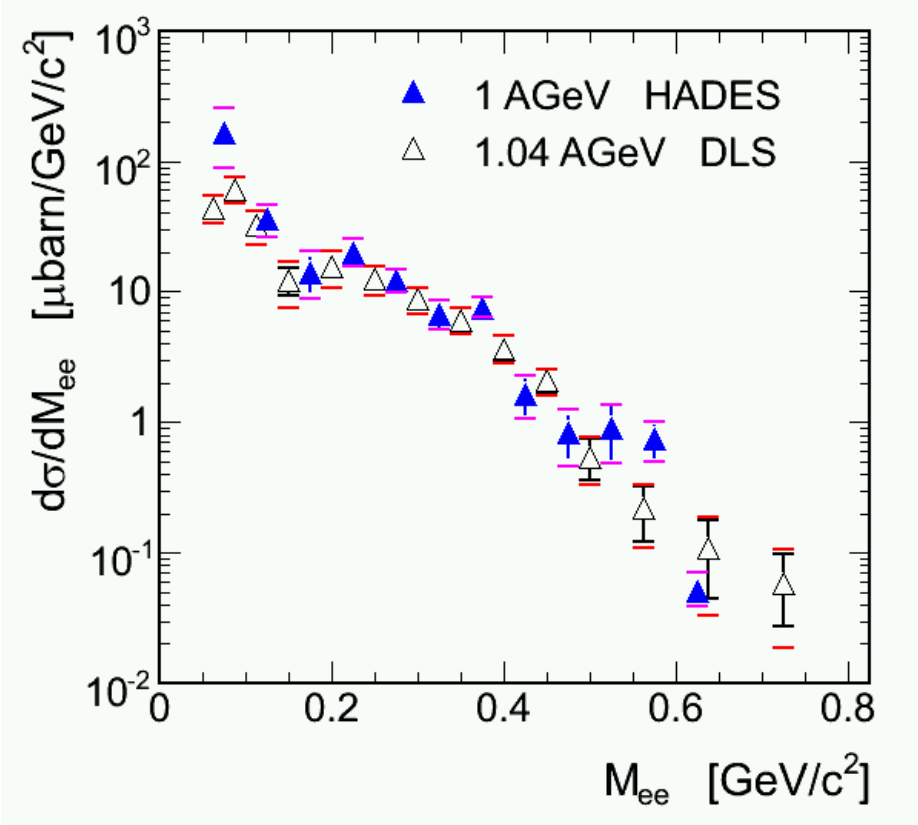
- Beams provided by SIS18: π, p, nuclei
- Full azimuthal coverage
- Hadron and lepton identification
- e^+e^- pair acceptance 0.35
- **Mass resolution 2 % (ρ/ω region)**
- ~ 80.000 channels
- now: **50 kHz event rate (400 Mbyte/s peak data rate)**

σ_ω = 15 MeV/c²

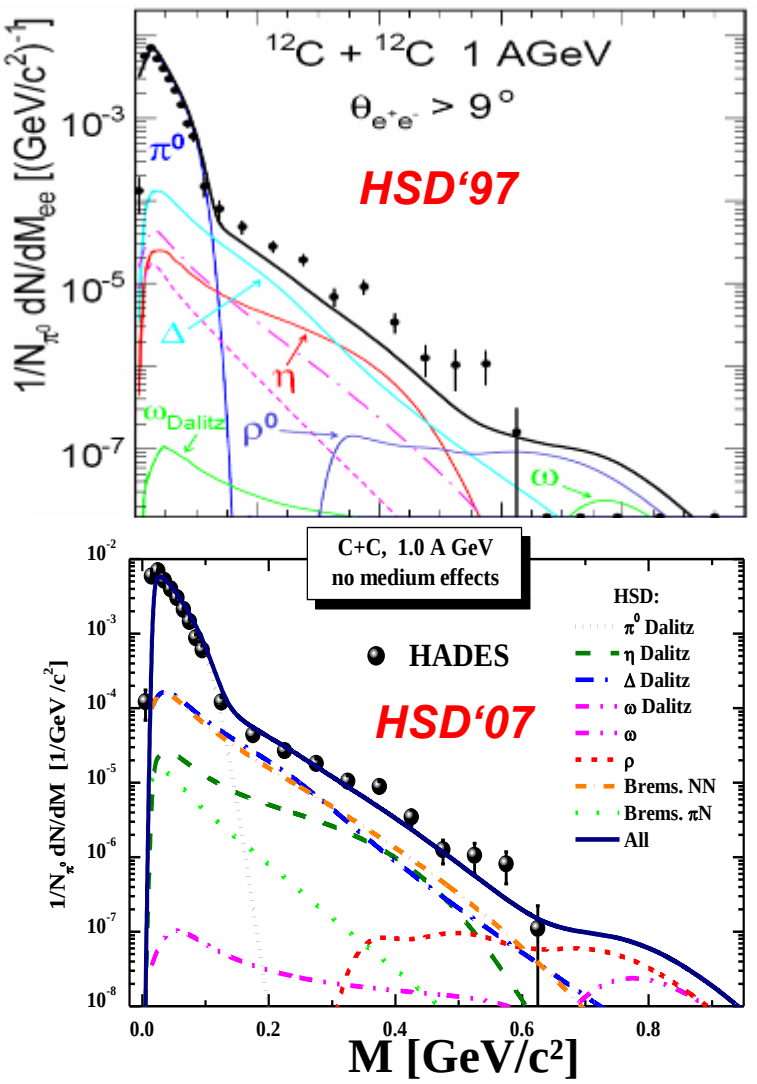


The solution to the DLS puzzle?

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



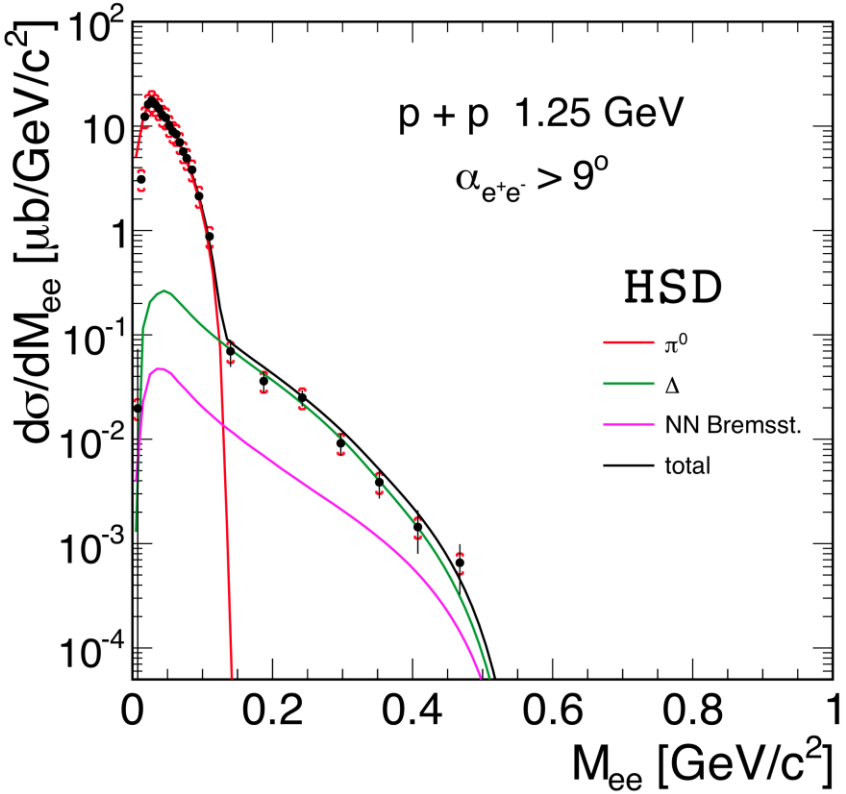
HADES: Phys. Lett. B 663 (2007)

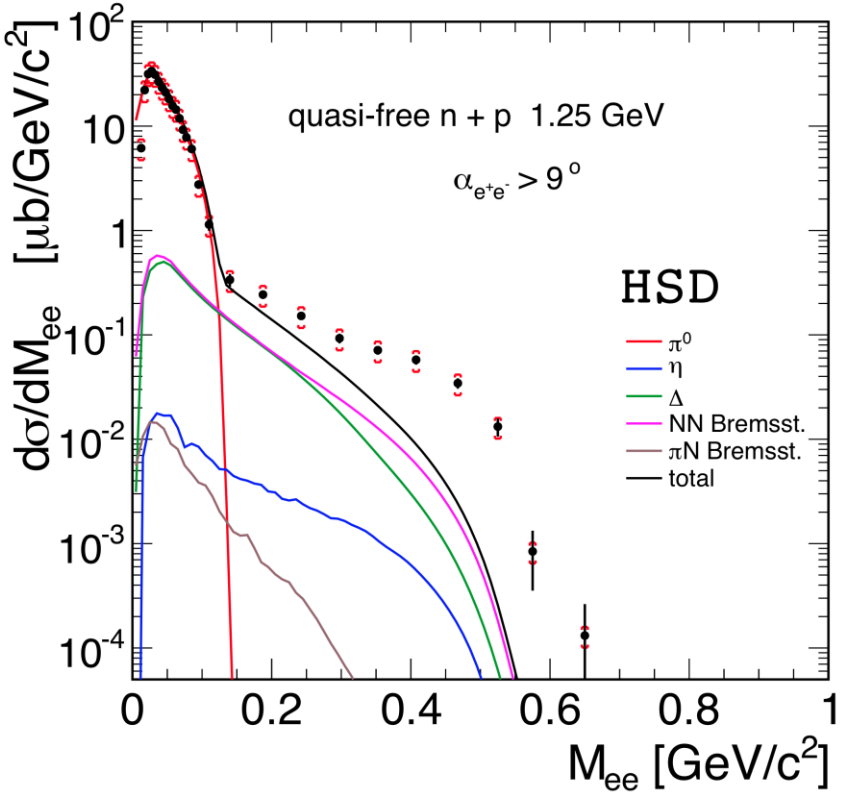


"DLS puzzle" may be solved when incorporating a stronger Bremsstrahlung contribution???

Dileptons from pp and dp (tagged n) reactions at 1.25 GeV: comparison with HSD

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

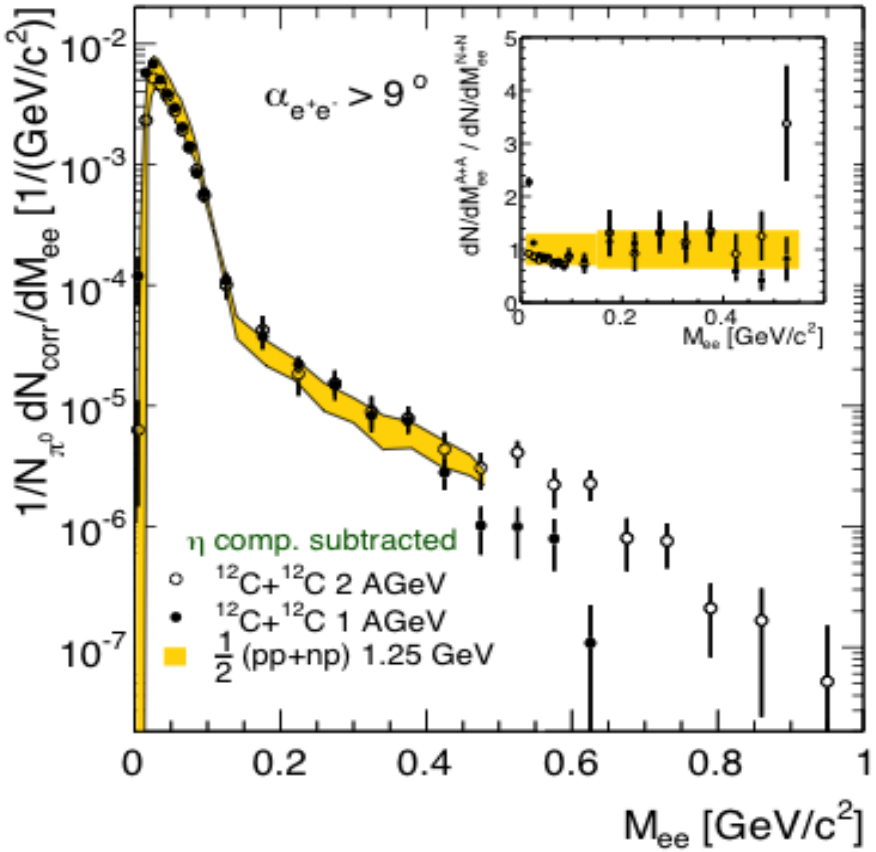




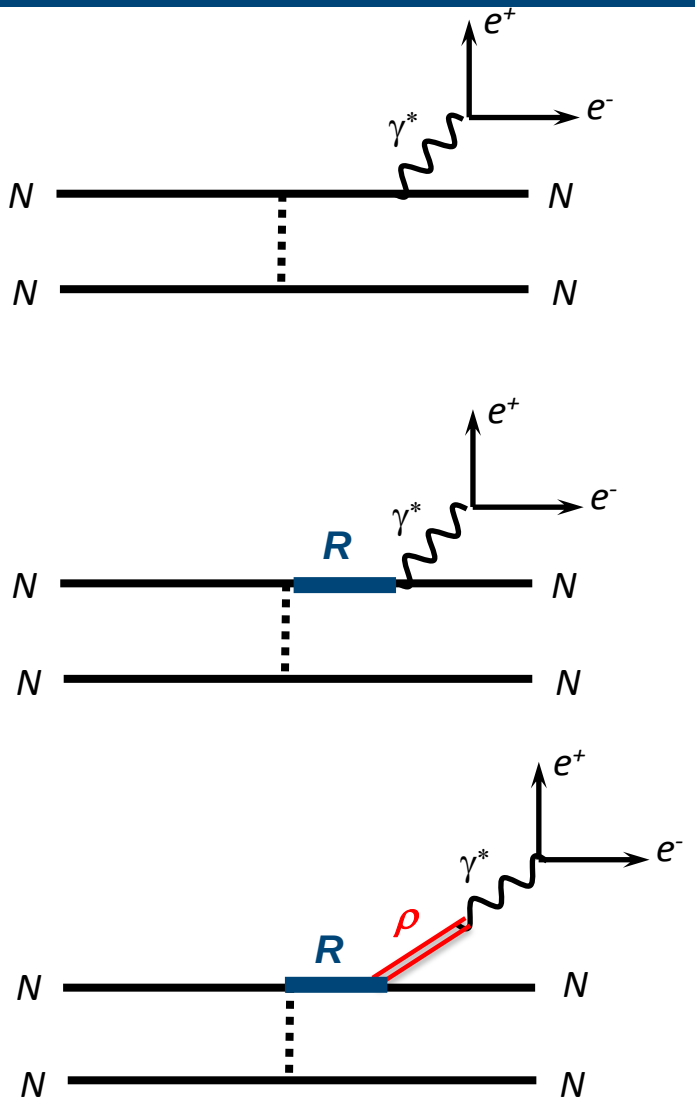
HADES: Phys. Lett. B 690 (2010) 118
HSD: Nucl.Phys A 807, 214 (2008)
Bremsstrahlung: Nucl.Phys. A 764 (2006) 338

Origin of the low-mass pair excess in C+C collisions

Definition of the "Reference data"



HADES: Phys. Lett. B 690 (2010) 118

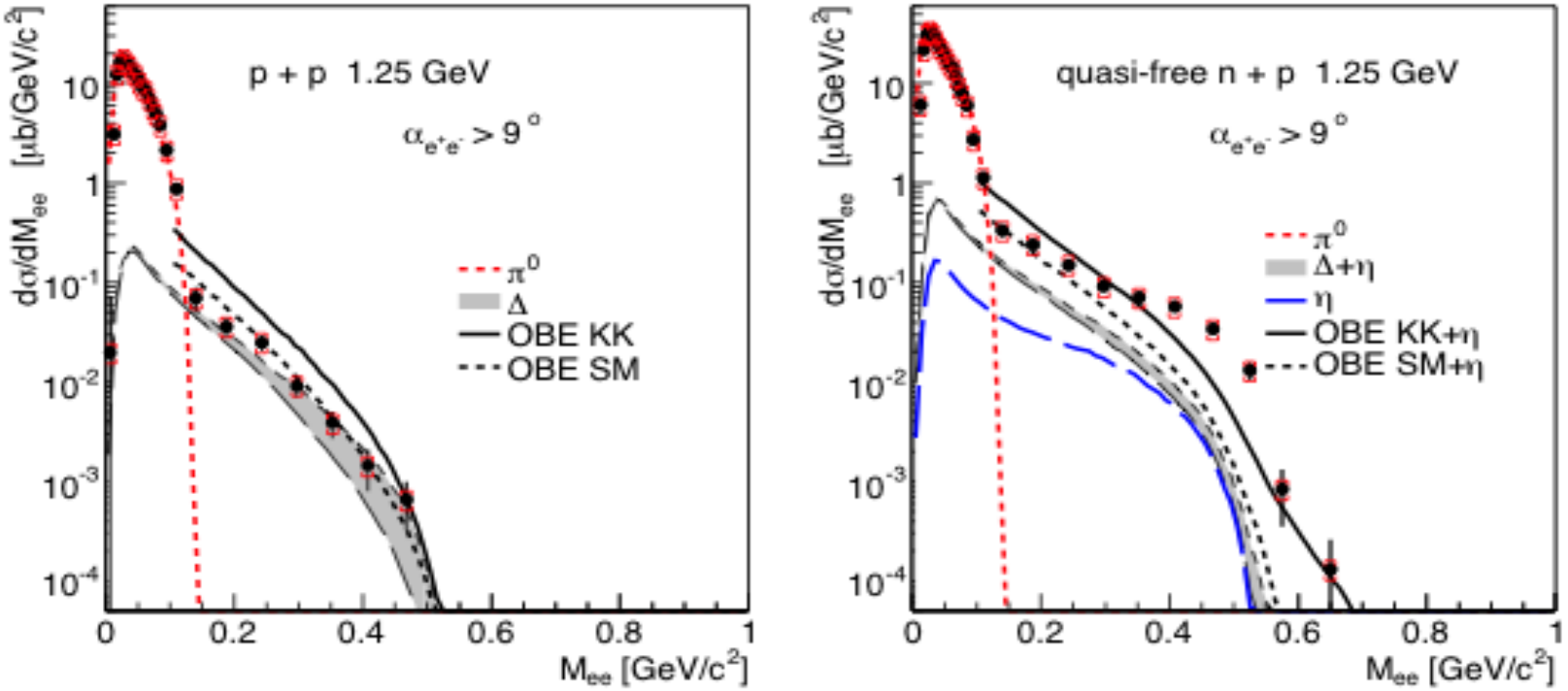


Dilepton "excess" scales with beam energy like π production

R = Δ, N*

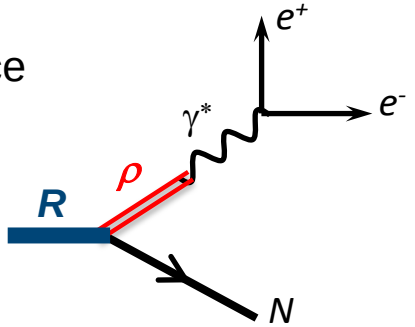
HADES pp and dp (tagged n) data vs. models

"If you are out to describe the truth, leave elegance to the tailor"+ + *A. Einstein*

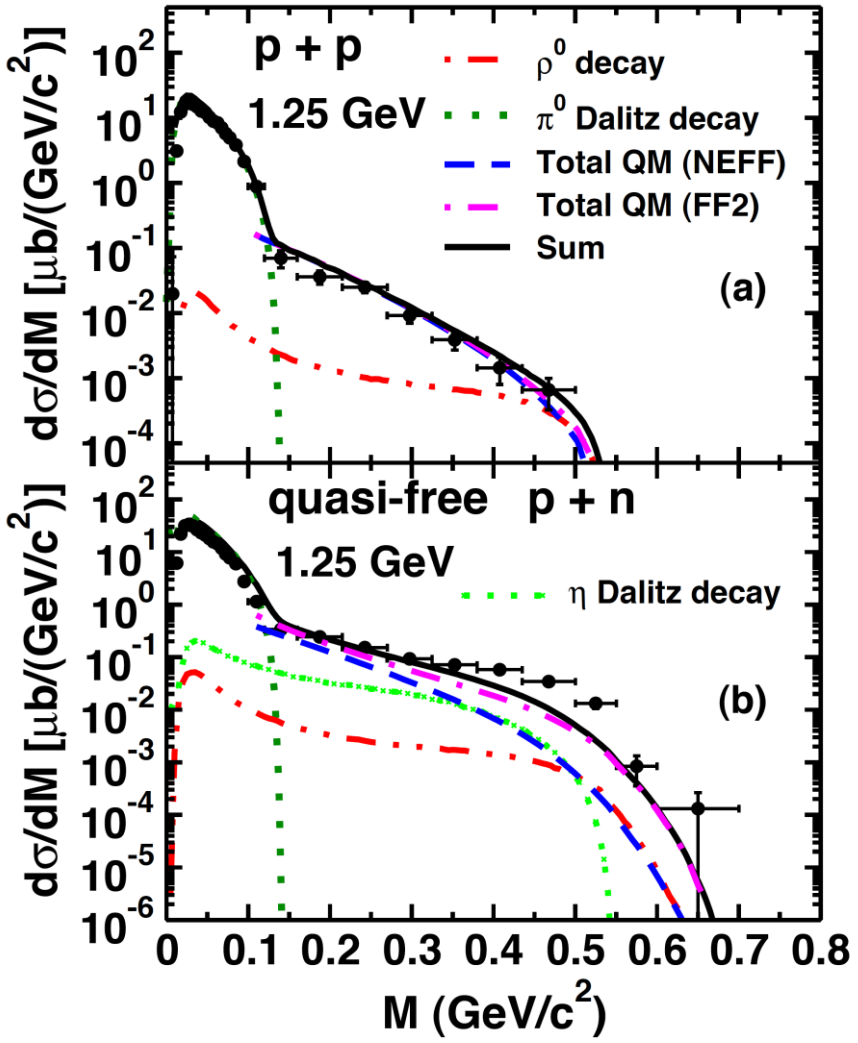


HADES: Phys. Lett. B 690 (2010) 118
Model: Pluto - ROOT based event generator

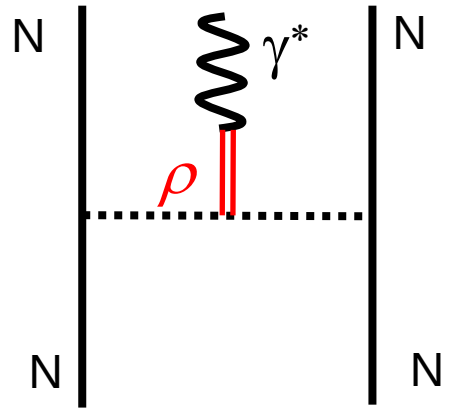
- n+p case: Different schemes for implementing gauge invariance
- OBE effective models reproduce p+p, but not (yet) n+p
- Coupling of the γ^* to Δ via intermediate ρ might play a role



Close to a theoretical explanation



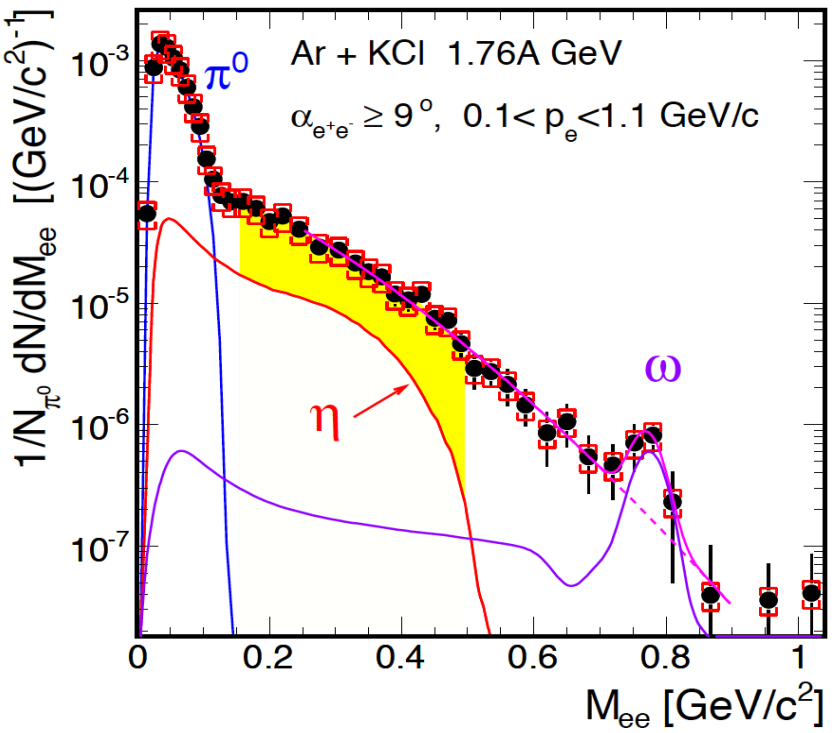
- One Boson Exchange effective Lagrangian based approach including pion electromagnetic form factor



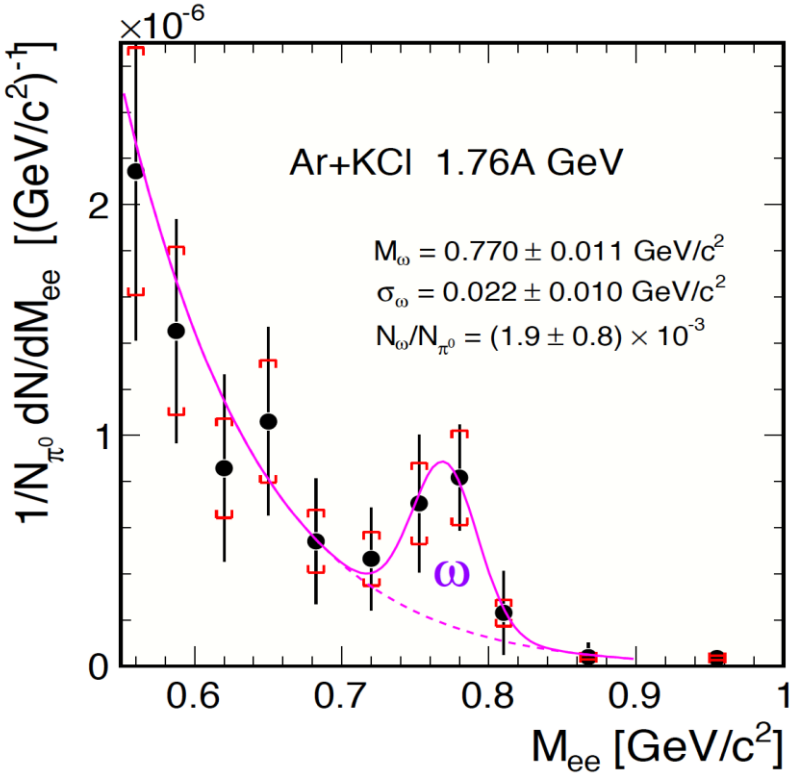
R. Shyam and U. Mosel,
Phys. Rev. C 82:062201, 2010

Electron pairs from Ar+KCl collisions at 1.76 GeV/u

First observation of ω→e⁺e⁻ peak in heavy-ion collisions at SIS energies



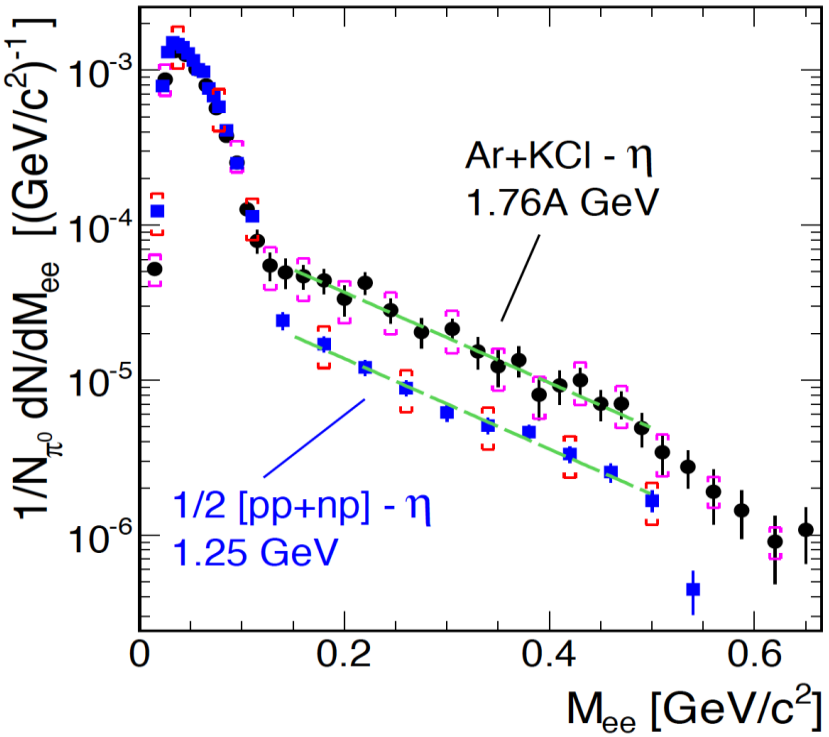
Fit: sum of a Gauss function and an exponential background



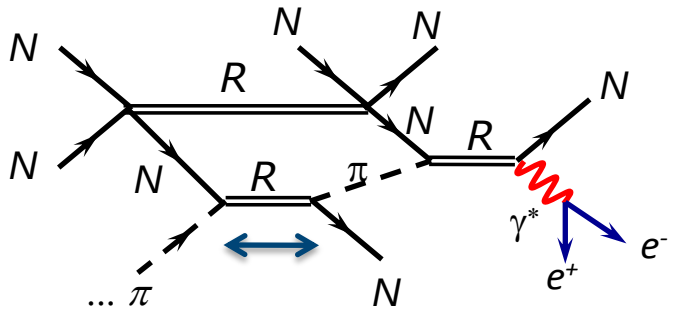
HADES: Phys.Rev.C84:014902,2011.

Isolating "true" excess

Ar+KCl compared to reference
after subtraction of contributions from η



- **First evidence for radiation from the medium**
- Excess yield scales with system size ~ $A_{part}^{1.4}$
- → multi-step processes or multi-particle correlation

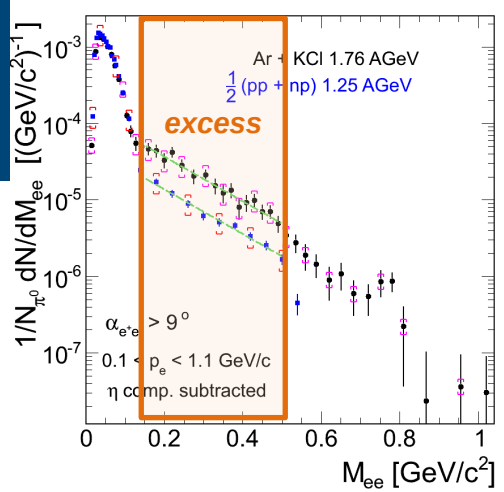


$\tau_{coll.} \leq 1$ fm/c (200 MeV)

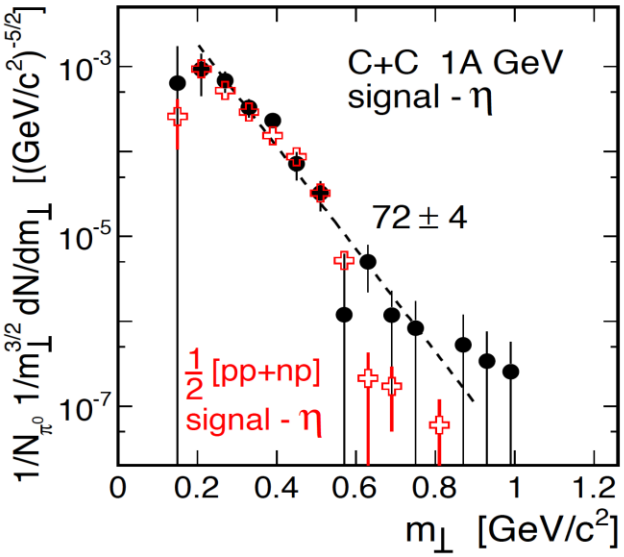
HADES: Phys.Rev.C84:014902,2011.

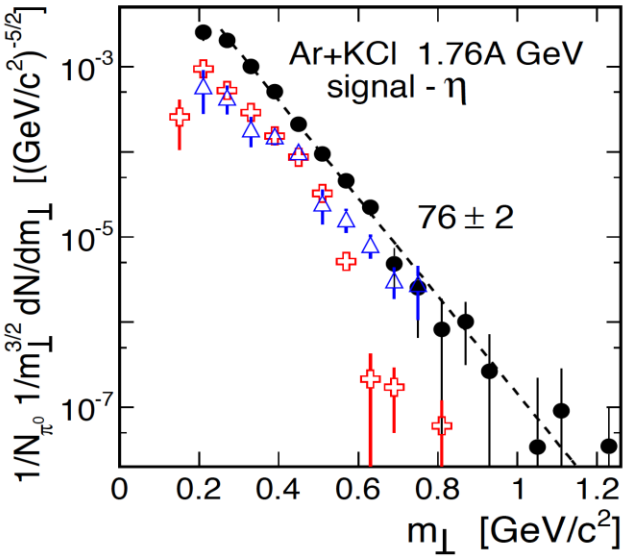
Characterizing the pair excess

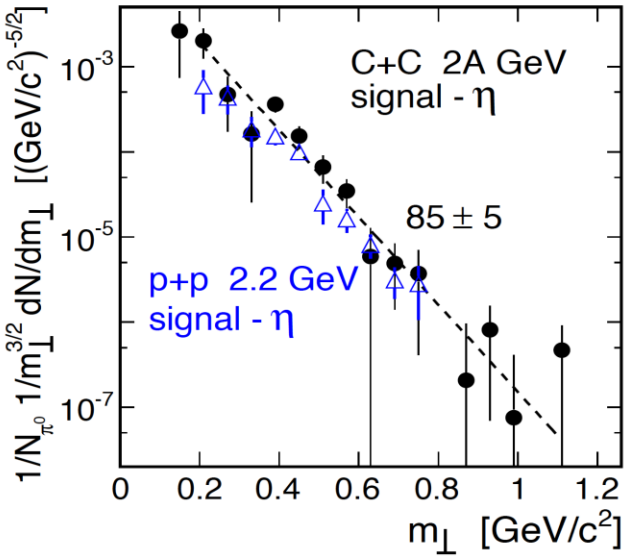
Excess e^+e^- transverse mass distributions compared to NN reference after subtraction of respective contributions from η



$0.15 < M_{ee} < 0.50$ GeV/c^2





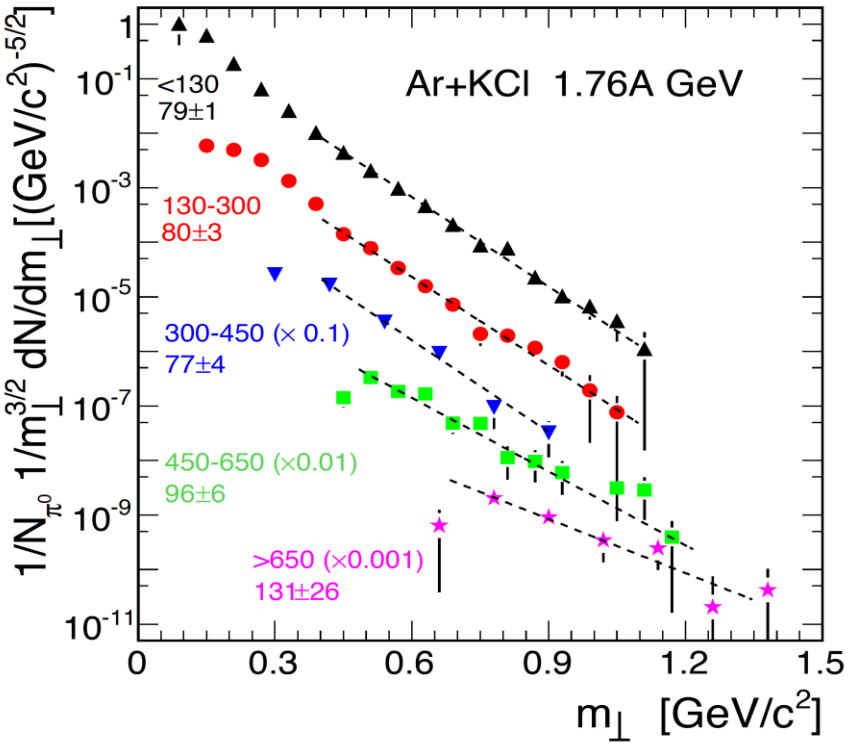


N+N reference overlaps with C+C, but misses Ar+KCl by large factor!

HADES: Phys.Rev.C84:014902,2011.

Systematics of e^+e^- dN/dm_T distributions

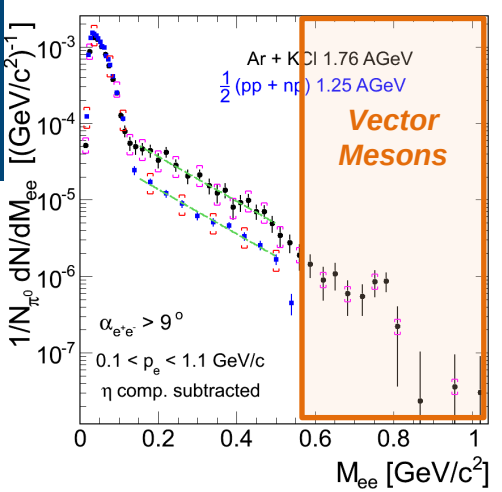
Transverse mass spectra in invariant mass bins



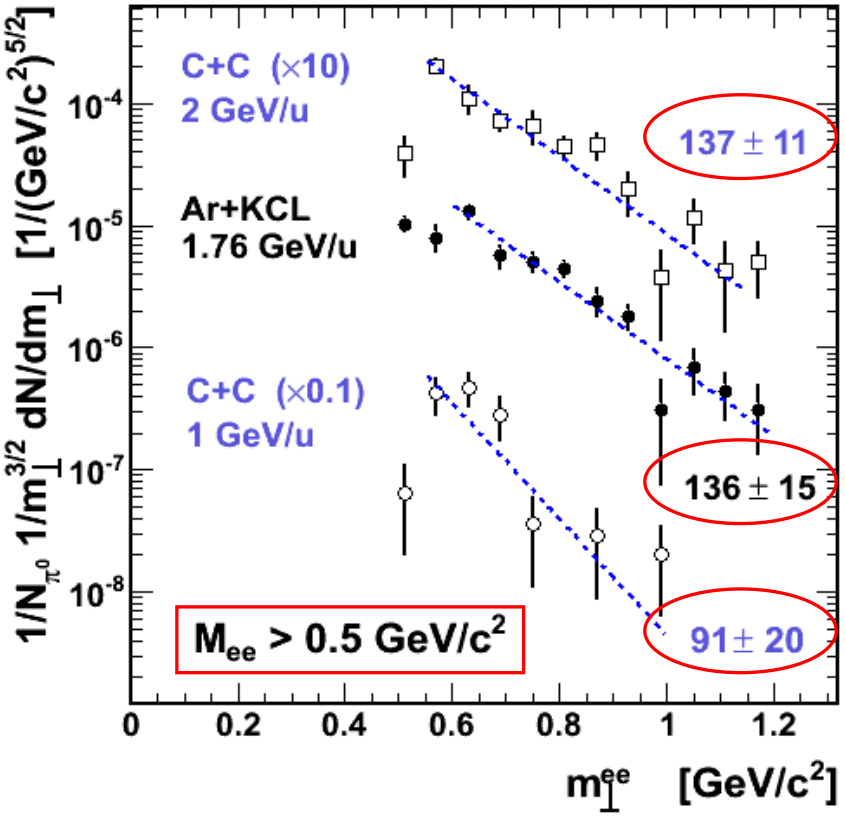
- **Significant change in slope when invariant mass grows!**
- **Explanation remains challenging:**
  - Final-state interaction
    → ω re-absorption
  - Collective effects
    → radial flow
  - Spectral functions

HADES: Phys.Rev.C84:014902,2011.

Systematics of e^+e^- dN/dm_T distributions



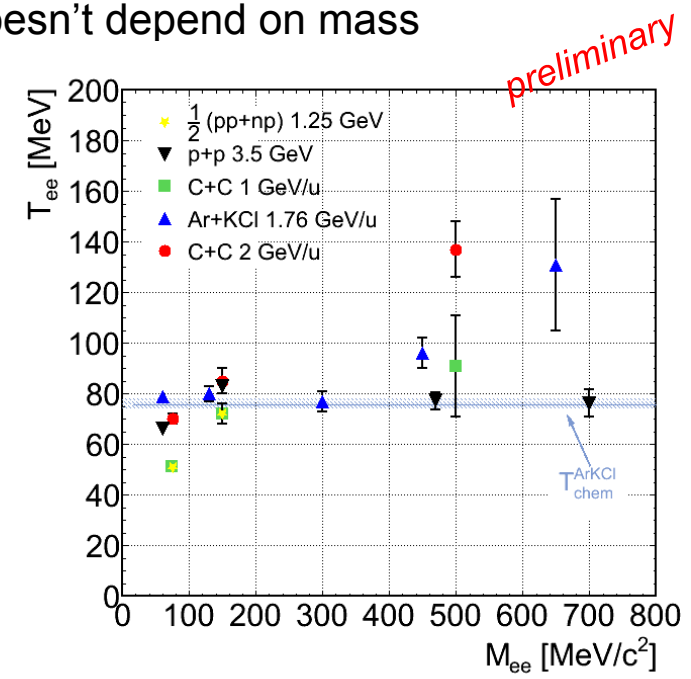
Transverse mass spectra for the invariant mass bin $M_{ee} > 0.5$ GeV/c^2



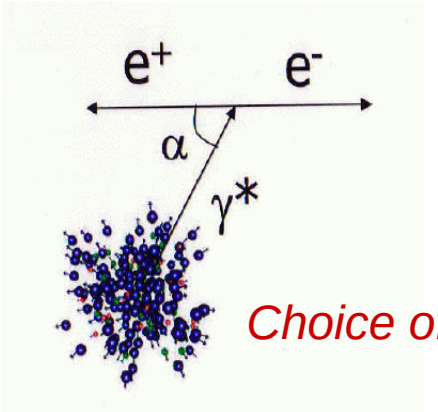
HADES: Phys.Rev.C84:014902,2011.

- Large T_{e+e-} seen in C+C collisions as well !

- $T_{e+e-} < 80$ MeV in p+p reactions and doesn't depend on mass

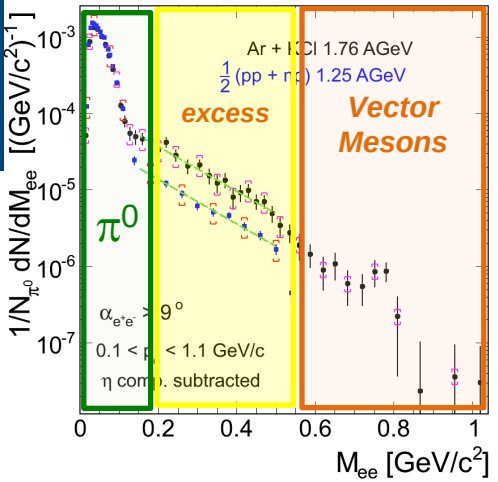


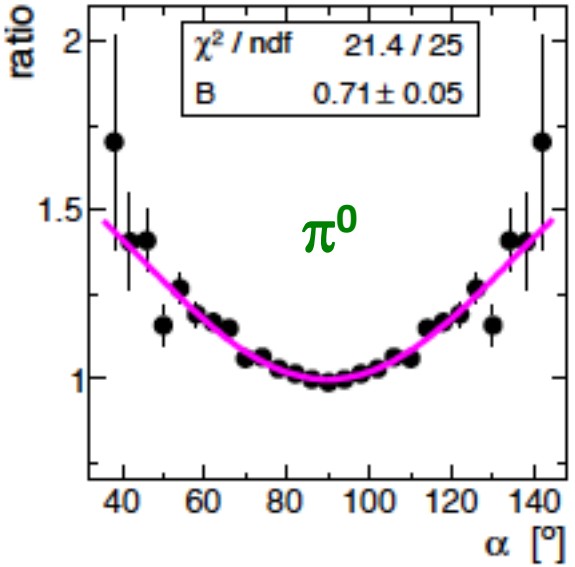
e^+e^- angular distributions in Ar+KCl

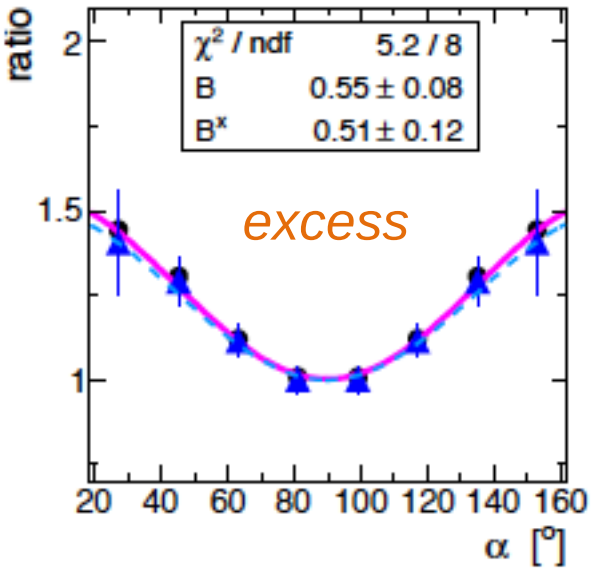


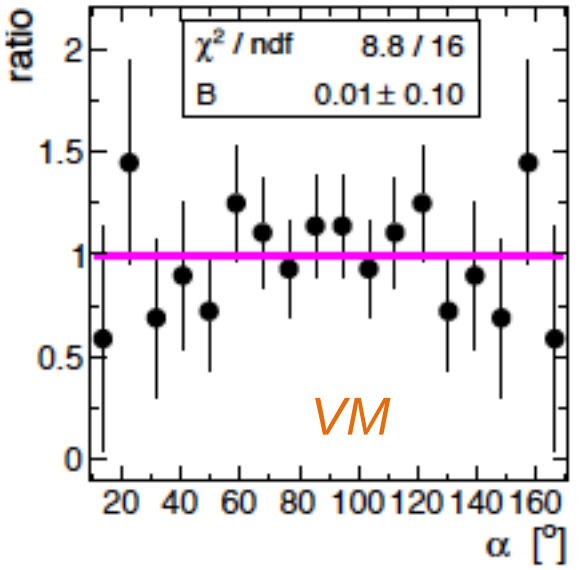
$$\frac{dN}{d\alpha} = A(1 + B\cos^2\alpha)$$

Choice of reference frame: AA frame







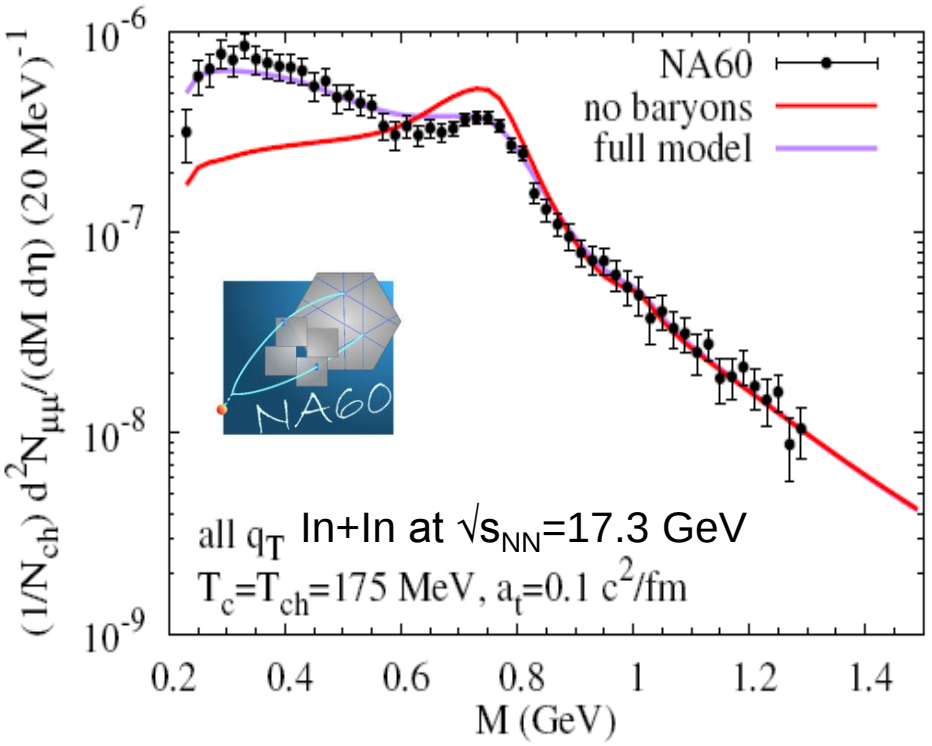


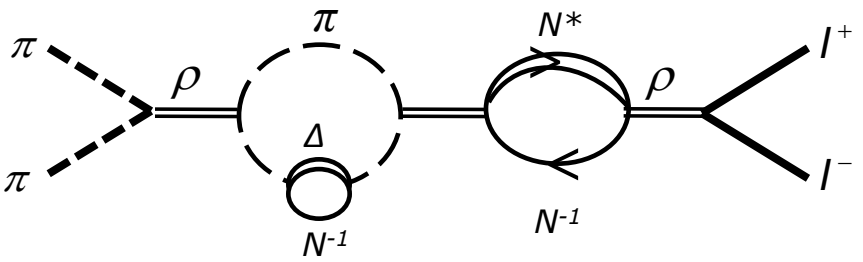
Excess has polarization consistent with Δ

Not clear → need more statistic *(B = 0 at SPS)*

Dilepton pair excess: from SPS to SIS...

Isolation of excess by subtraction of measured decay cocktail (without ρ)





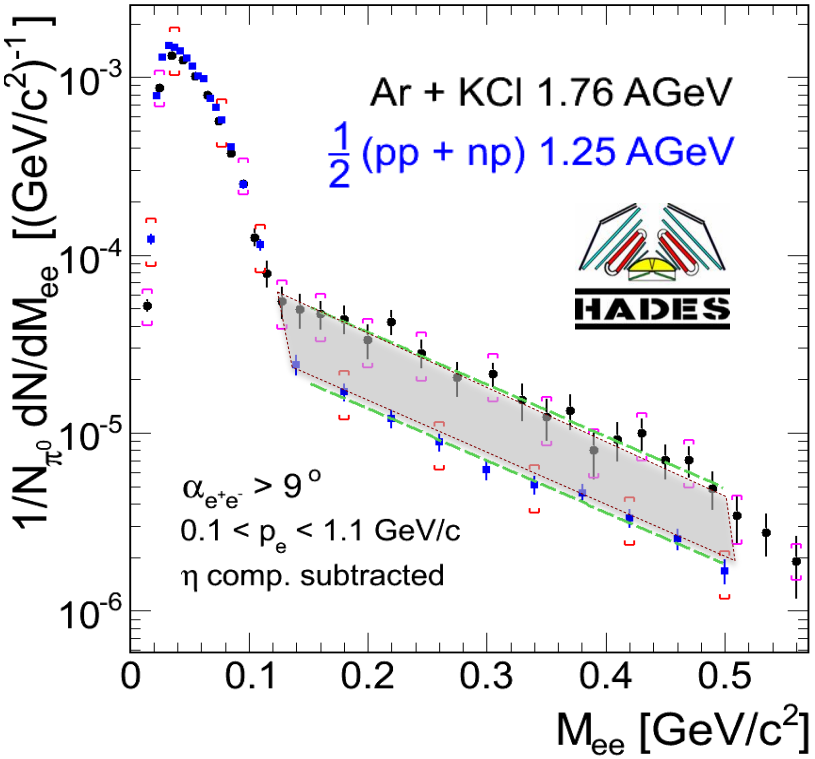
- Main source: $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$
- Strength of dilepton yield at low masses is **due to coupling to baryons**!

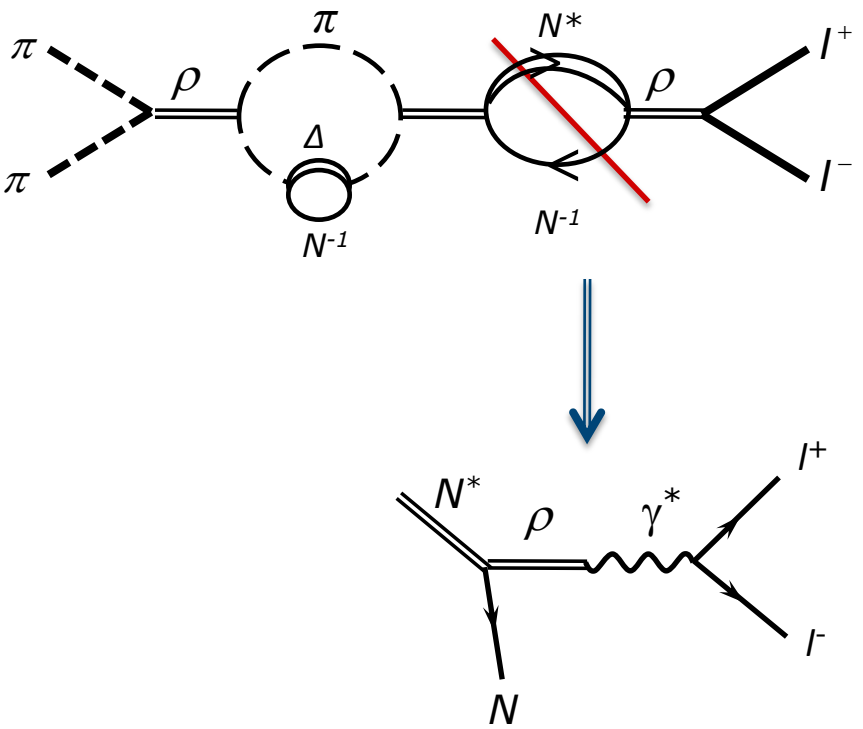
Data : Na60 acceptance corrected, EPJC 59 (2009) 607
Model: R. Rapp and H. van Hees NPA806 (2008) 339.

How these effects contribute to the e^+e^- production at low beam energies?

Dilepton pair excess: from SPS to SIS...

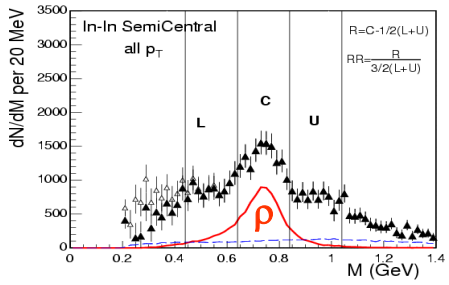
Isolation of excess by comparing with measured "reference" spectrum



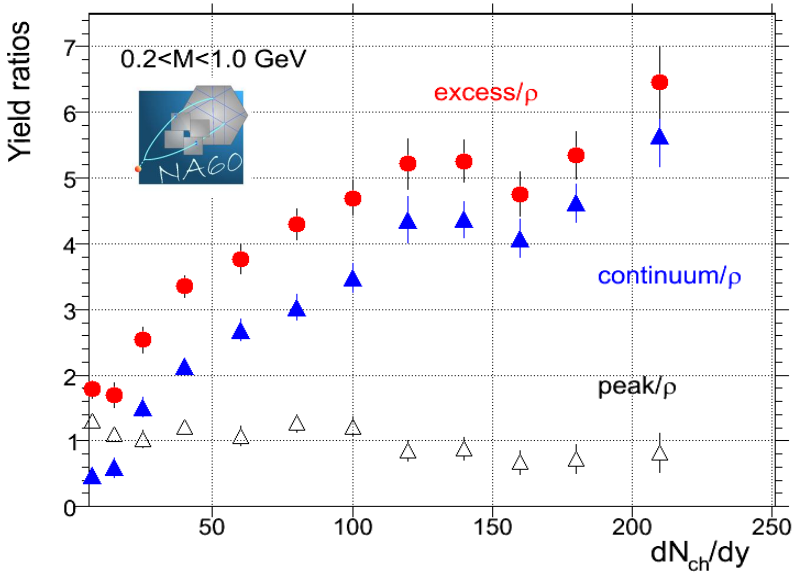


Dalitz decays of baryonic resonances - dominant source at low beam energies.

Centrality dependence of spectral shape



NA60's "ρ clock"

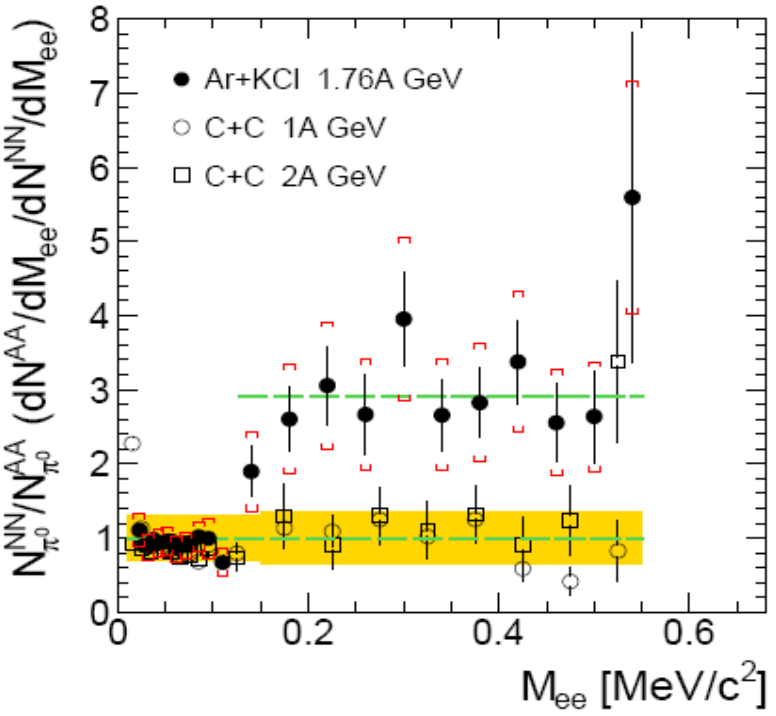


- Rapid increase of relative yield reflects the number of ρ's regenerated in fireball

Na60 data: EPJC 61 (2009) 711

"Δ clock"

HADES data

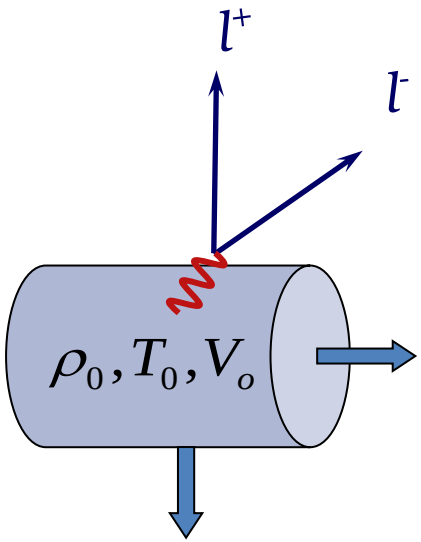


- 34% most central collisions (A_{part}=38)
- Δ regeneration

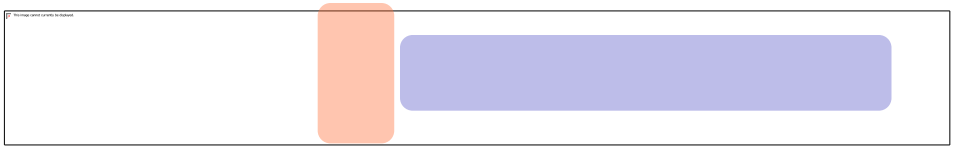
HADES: PRC 84 (2011) 014902

Modeling of the experimental results

Thermal emission...

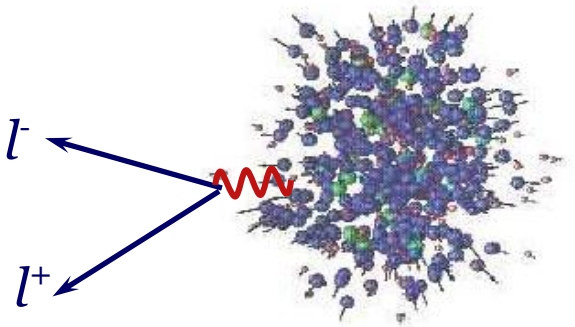


isentropic expansion



R. Rapp, J. Wambach and H. Hees : arXiv:0901.3289

...or from transport



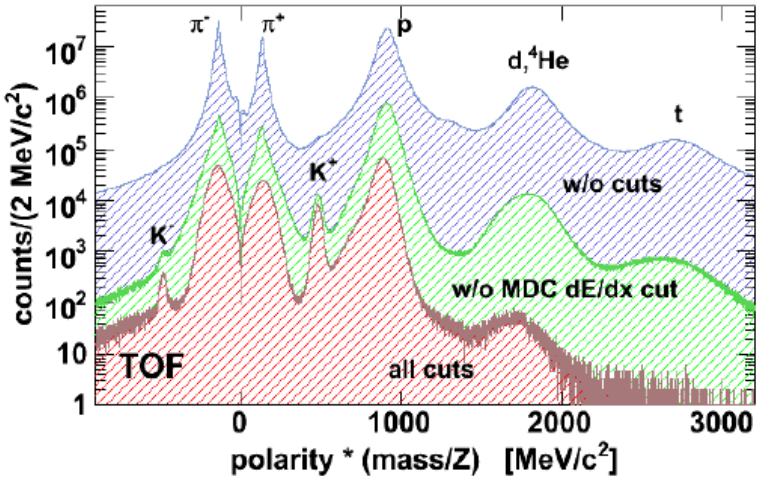
... or new approach will combine the advantages of a transport and a thermal model

Strangeness production at SIS energies

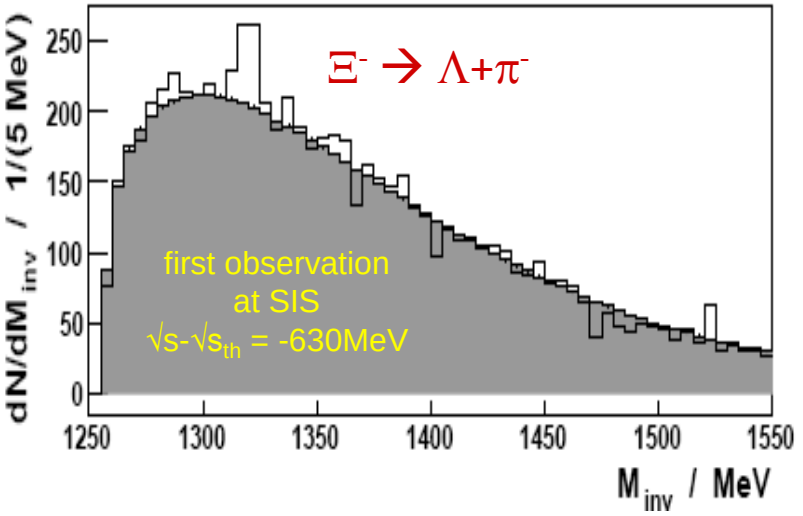
Experimental challenge: at SIS energies strangeness produced sub-threshold

- **Elementary collisions**
  - K^+ production
    NN→ $NK^+\Lambda$
  - K^- production
    NN→ NNK^+K^-
- **Heavy-ion collisions**
  → production below free NN threshold:
  - Secondary collisions of exited baryons
  - Reduced in-medium K^- mass?

Ar+KCl at E_{kin}=1.76 GeV/u
PID based on dE/dx and TOF



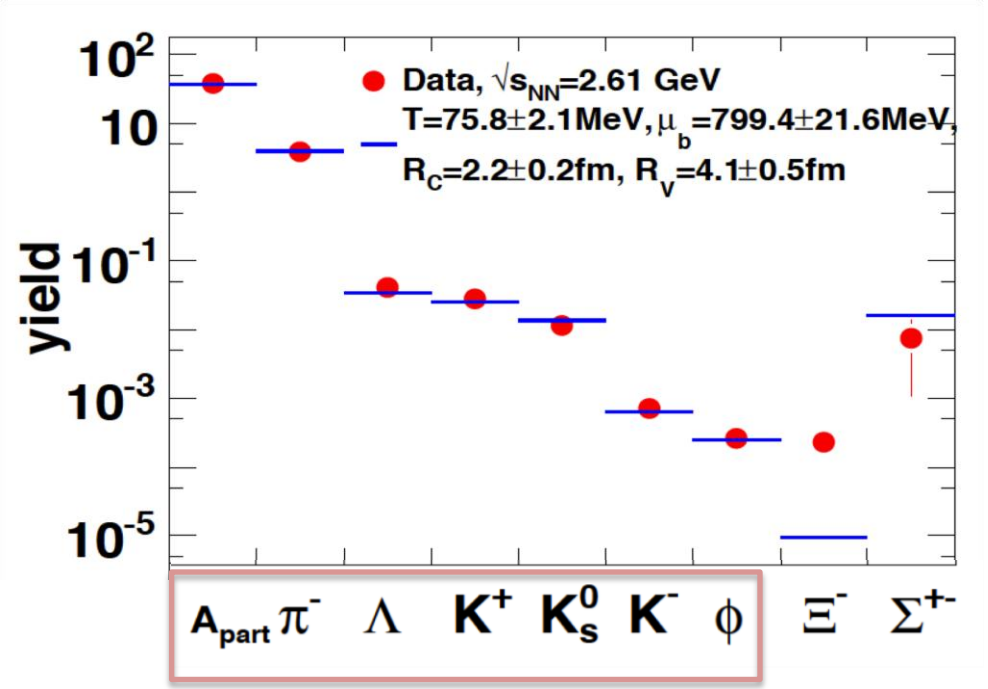
HADES: Phys. Rev. C80:025209



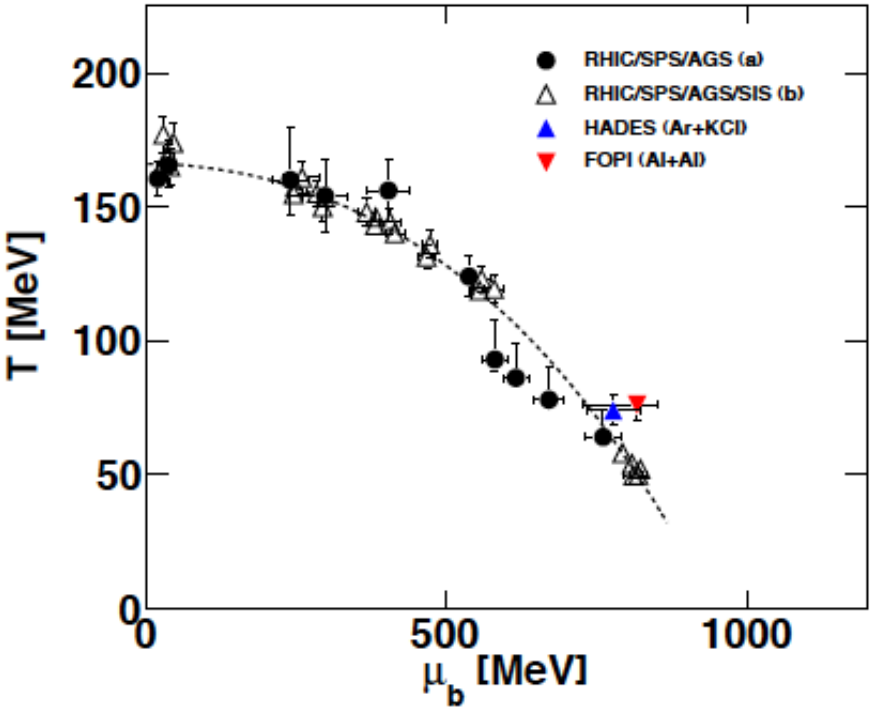
Phys. Rev. Lett. 103, 132301, (2009)

HADES and the Phase Diagram of Matter

— THERMUS calculation: T, μ_b and R_C fit to
● HADES Ar+KCl (1.76 GeV/u) data



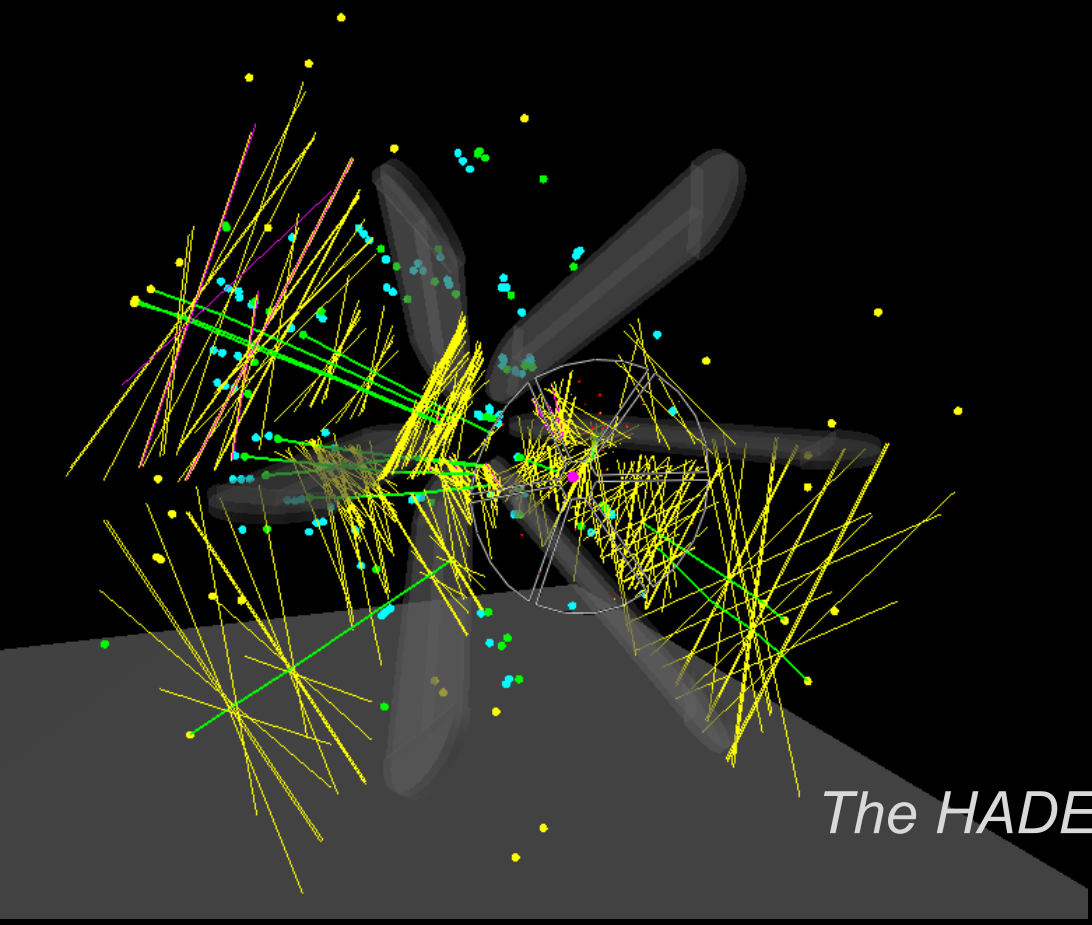
Extracted (T, μ_b) fit in the systematics of the SHM



THERMUS fit: J.Cleymans, J.Phys.G31(2005)S1069
HADES: Eur. Phys. J. A 47:21, 2011.

Statistical Hadronization Model describes hadron abundances accept in case of large Ξ^- (s=-2) yield

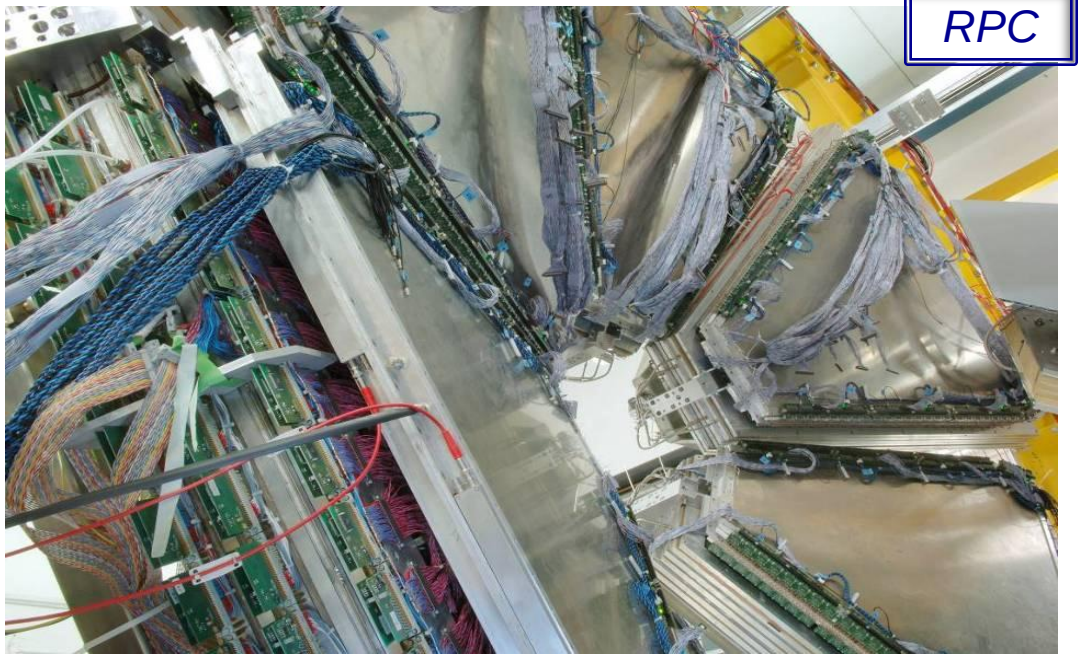
Thermal equilibration also at low energies (high μ_B) in particular concerning multi-strange hadrons ?



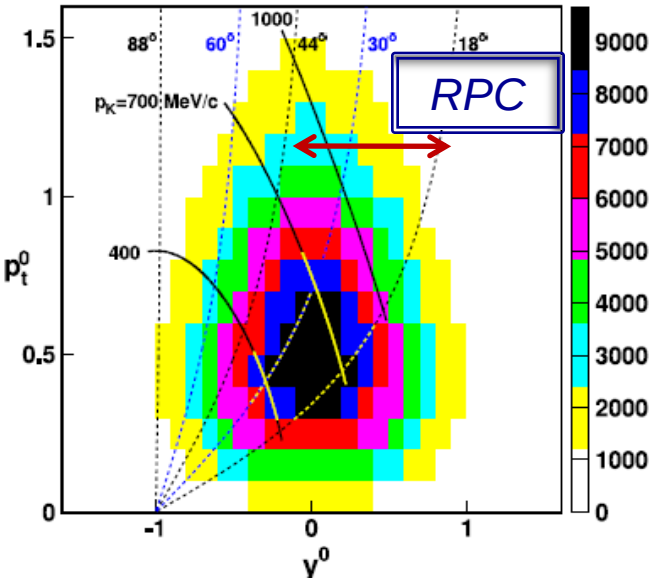
The HADES upgrade …

… from 8 Ξ/day (Ar+KCl) to 170 Ξ/day (Ag+Ag) and dilepton statistics like NA60

HADES upgrade: The RPC time-of-flight

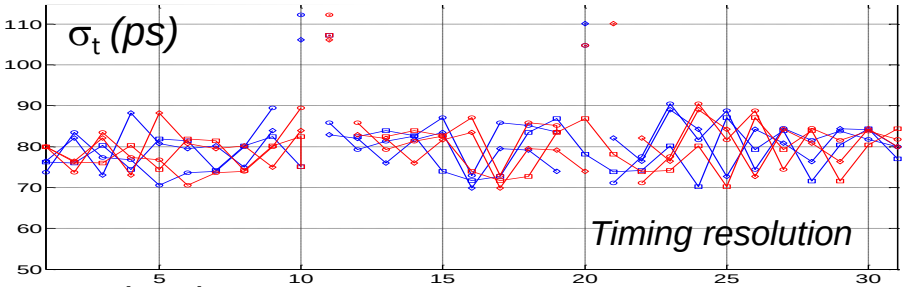


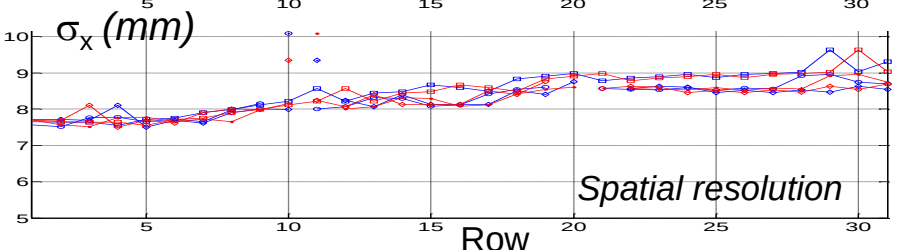
K^- acceptance (nice y_{CM} coverage!)



Full-system test results:

- $\sigma_t \leq 100$ ps
- $\sigma_x \leq 8$ mm
- $\varepsilon \sim 97\%$

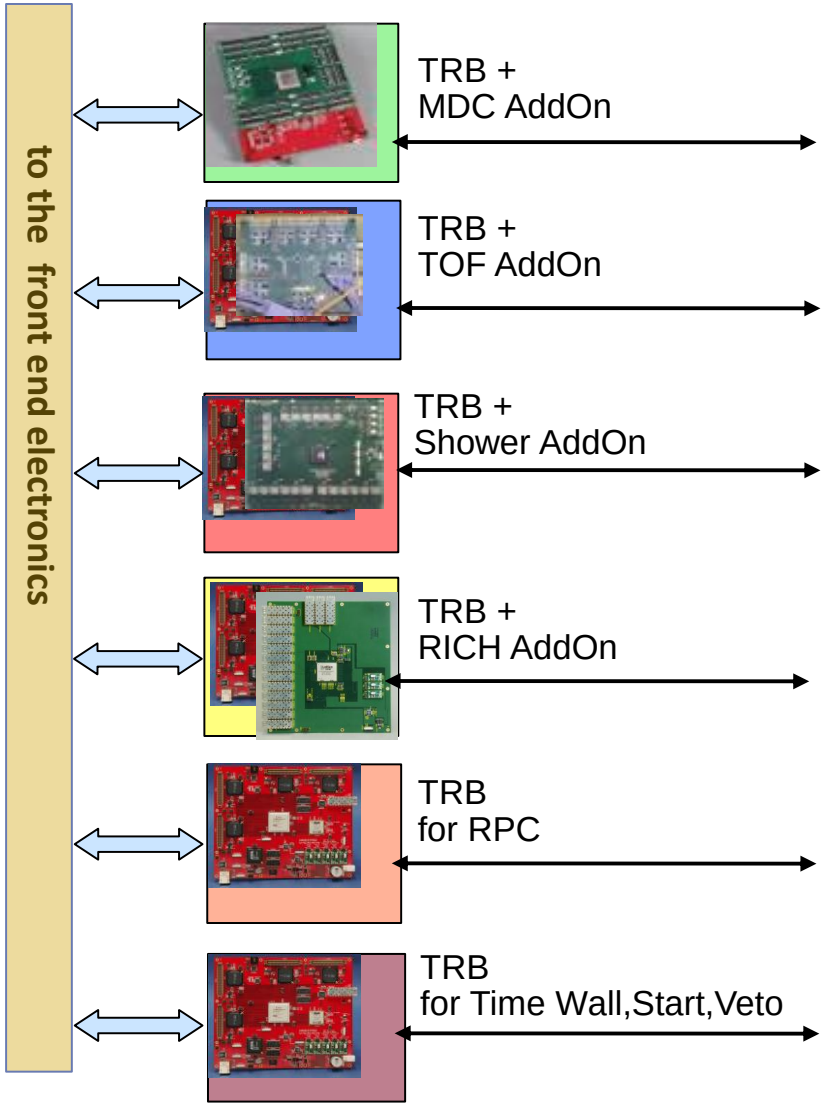




Leading institute:
Coimbra, Portugal

D. Belver et al . NIM A602(2008) 687, 788
E. Blanco et al. NIM A602(2008) 691

HADES DAQ upgrade

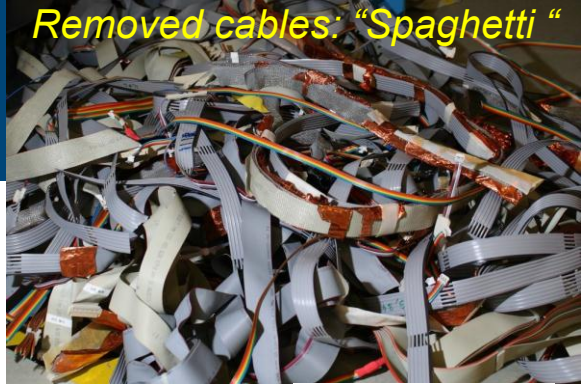


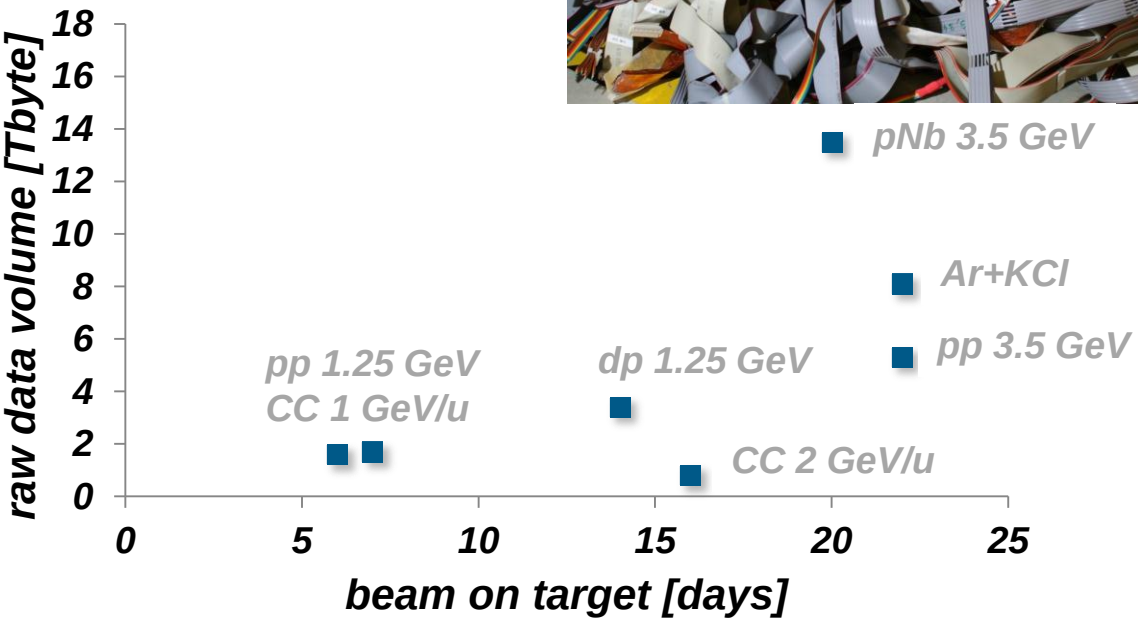
Quest: Heavier Systems + Higher Statistics

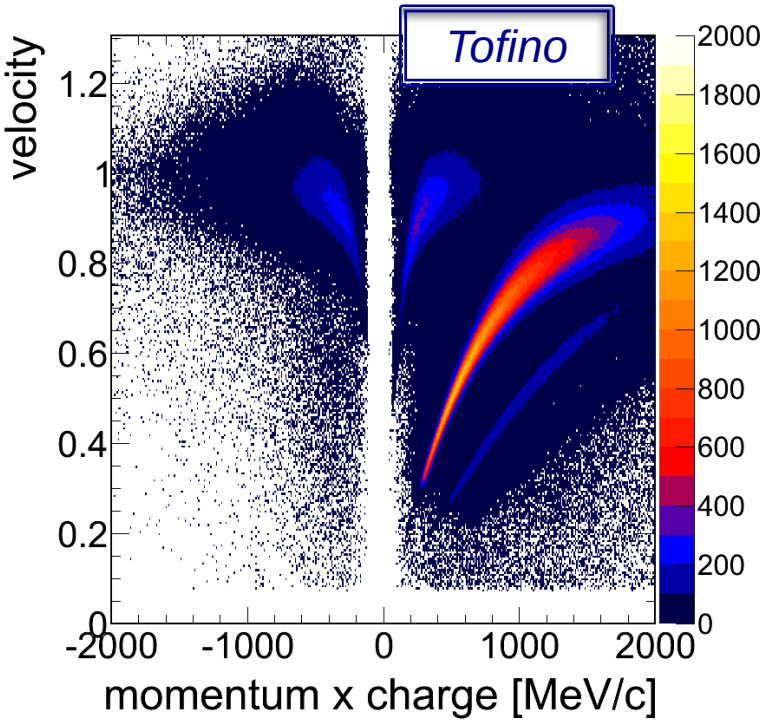
- Event rate up to 100 kHz (p + p), 20 kHz (Au + Au)
- Data rate up to 400 Mbyte/s (peak), 250 Mbyte/s (avg)

System performance before the HADES upgrade

- The HADES electronics are already more than 10 years old
  - Data for Ar+KCl was taken at 3 kHz event rate
  - → For Au + Au we would expect 700 Hz

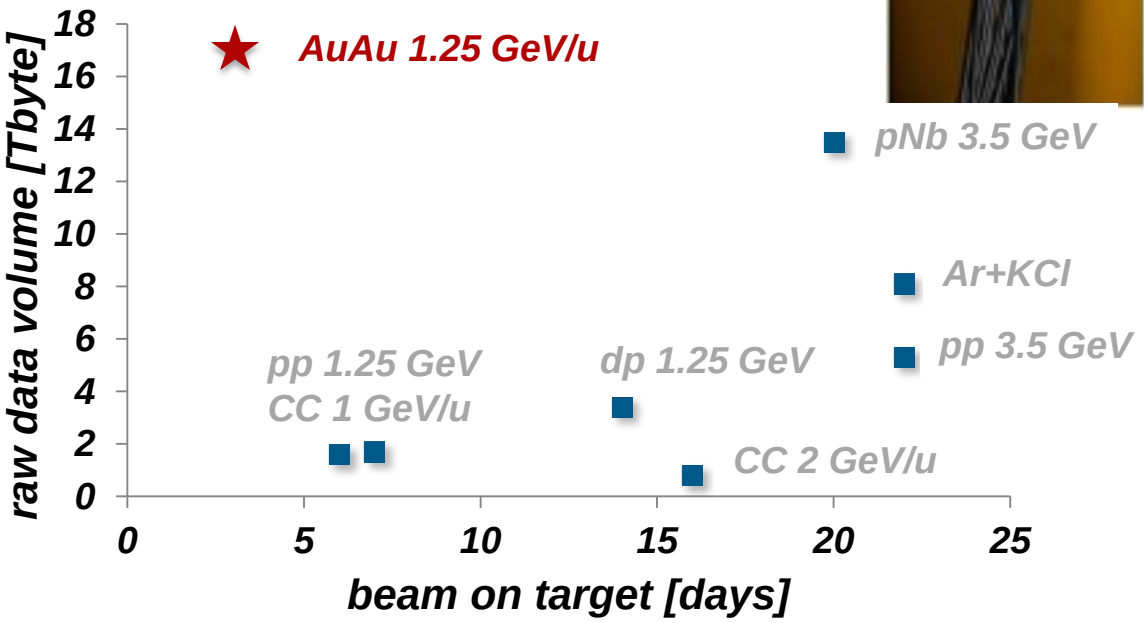


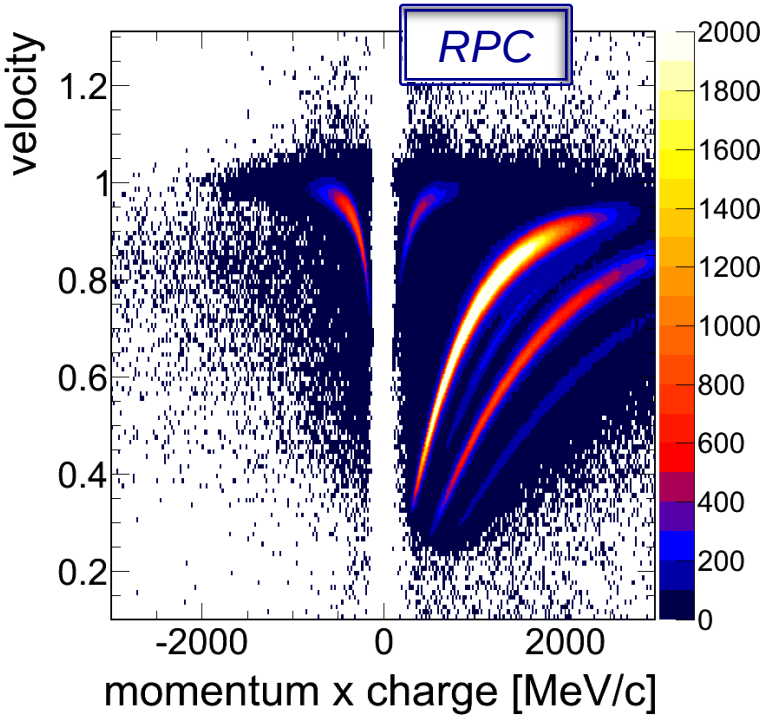


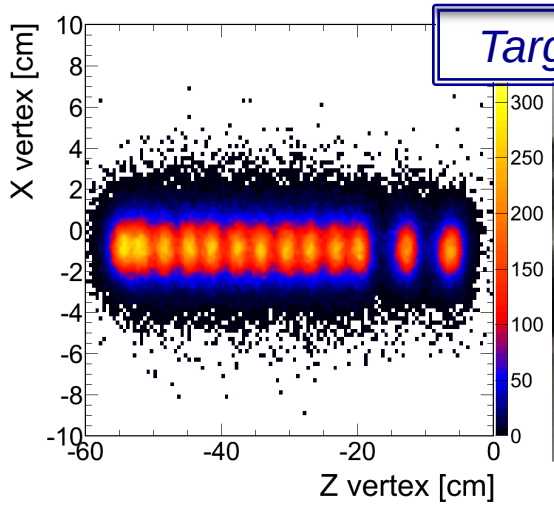


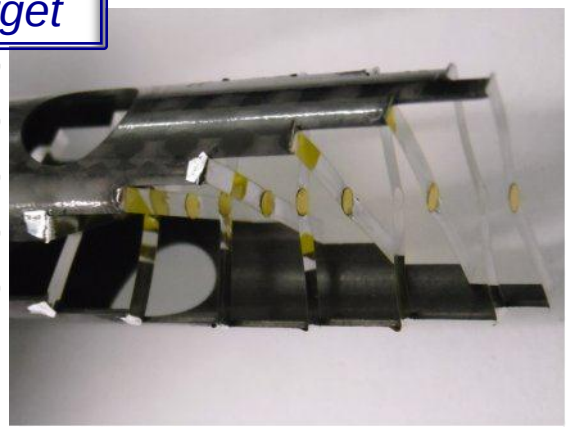
Au+Au at 1.25 GeV/u (commissioning beam time Aug'2011)

- 64 hours beam Au on Au target
- 1.3 x 10^7 ions per second
- 8 kHz trigger rate
- 200 Mbyte/s data rate
- 0.84 x 10^9 events
- 17 x 10^{12} Byte of data









Summary

HADES provides high-quality data for understanding di-electron and strangeness production in elementary and heavy-ion collisions at SIS energy regime.

- Long-lived states of compressed nuclear matter are produced in heavy-ion collisiobs at few GeV energy regime
- This state of matter might be much more exotic as a hadron gas
- Observations:
  - “Thermal” hadron production (with some exceptions)
  - Strong broadening of in-medium states

Summary

HADES provides high-quality data for understanding di-electron and strangeness production in elementary and heavy-ion collisions at SIS energy regime.

- Long-lived states of compressed nuclear matter are produced in heavy-ion collisiobs at few GeV energy regime
- This state of matter might be much more exotic as a hadron gas
- Observations:
  - “Thermal” hadron production (with some exceptions)
  - Strong broadening of in-medium states

Au+Au at 1.25 GeV/u commissioning beam time

- HADES took off!
  Performance is good or better than expected

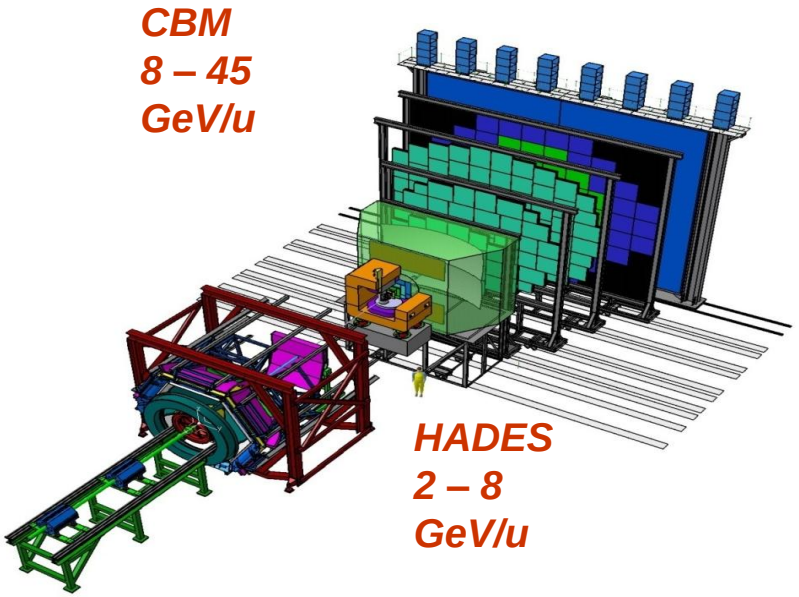
From GSI to FAIR

SIS100:

- HADES and CBM:
  - Emissivity of hot/dense nuclear matter
  - Spectral functions of ρ/ω in dense (baryon dominated) hadronic matter
  - Multi-strange particle and lepton pair excitation functions
  - Charm production in proton induced reactions

SIS300 :

- CBM:
  - Full exploitation of rare probes a highest μ_B; fluctuations, flow



The HADES Collaboration

Cyprus:
Department of Physics, University of Cyprus

Czech Republic:
Nuclear Physics Institute, Academy of Sciences of Czech Republic

France:
IPN (UMR 8608), Université Paris Sud

Germany:
GSI, Darmstadt
FZ Dresden-Rossendorf
IKF, Goethe-Universität Frankfurt
II.PI, Justus Liebig Universität Giessen
PD E12, Technische Universität München

Italy:
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud
Istituto Nazionale di Fisica Nucleare, Sezione di Milano

Poland:
Smoluchowski Institute of Physics, Jagiellonian University of Cracow

Portugal:
LIP-Laboratório de Instrumentação e Física Experimental de Partículas

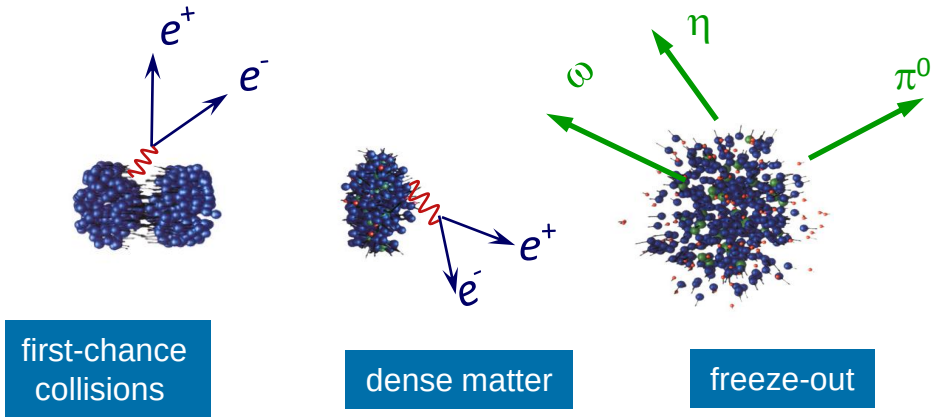
Russia:
INR, Russian Academy of Science
Joint Institute of Nuclear Research
ITEP

Spain:
Departamento de Física de Partículas, University of Santiago de Compostela
Instituto de Física Corpuscular, Universidad de Valencia-CSIC

17 institutions
> 150 members

BONUS

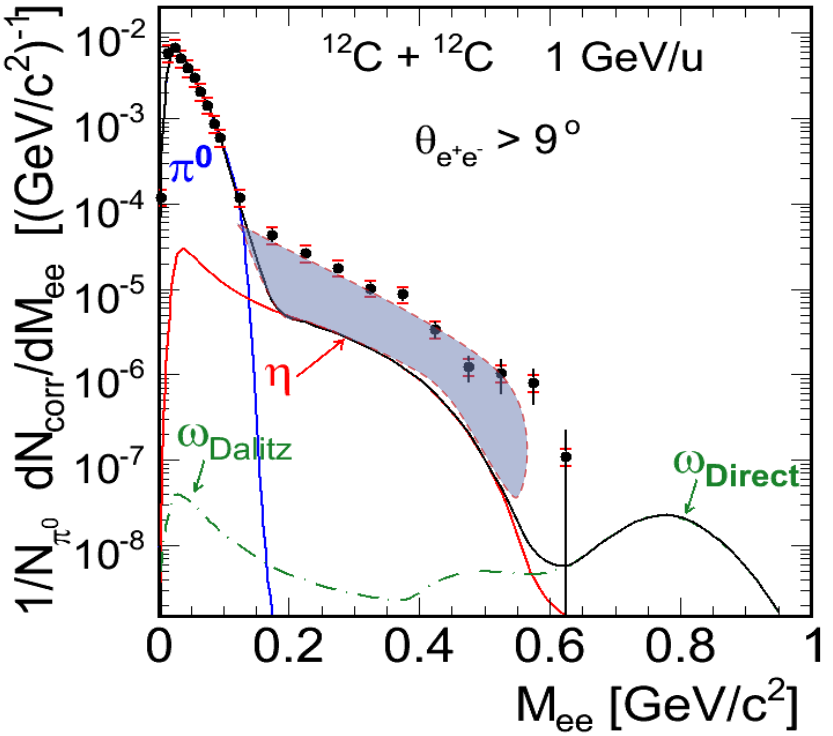
Is there any medium radiation?



- **First chance NN collisions**
  - Baryonic sources:
    - NN bremsstrahlung
    - Resonances (Δ, N^*) $\rightarrow$ Ne^+e^-
- **Freeze-out: long lived mesons**
  - π^0 / η - fixed by TAPS data

R. Averbeck et al., 1997 Z. Phys. A 359 65

Efficiency corrected di-electron spectra normalized to the number of neutral pions



Phys. Lett. B 663 (2008) 43

Enhanced pair yield above η-contribution established!

„True" excess from dense phase?

Contribution from the initial phase?

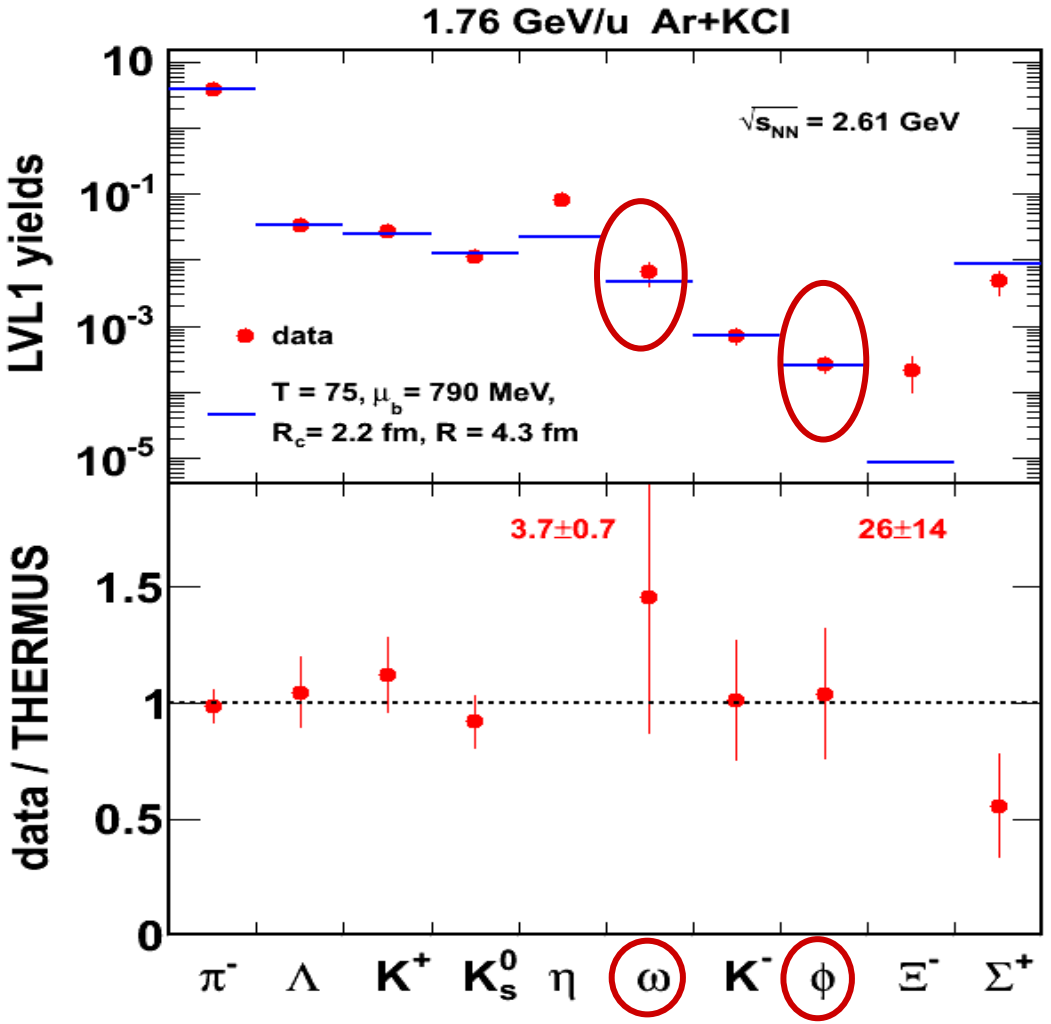
Comparison with statistical model

THERMUS
statistical model

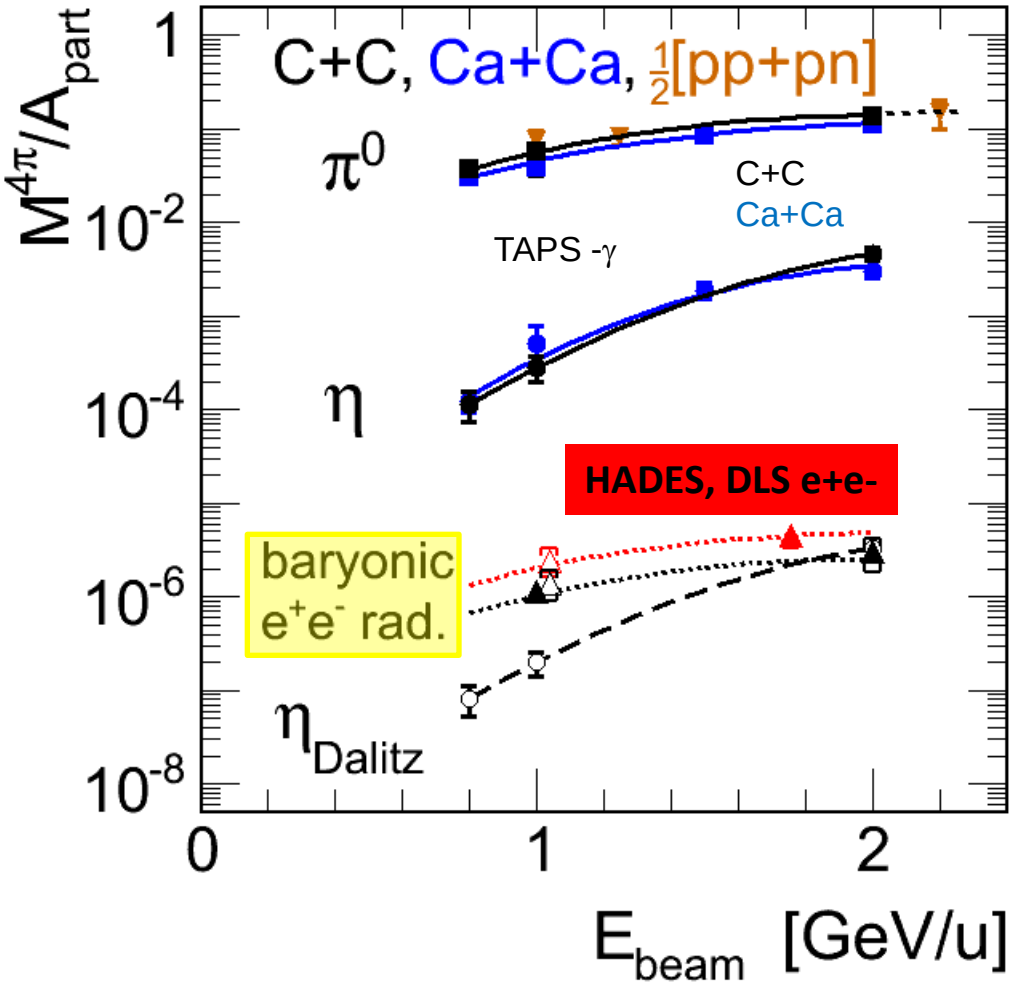
T, μ_B and R_C
fitted to HADES yields

in particular from

$\omega \rightarrow e^+e^-$
$\phi \rightarrow K^+K^-$

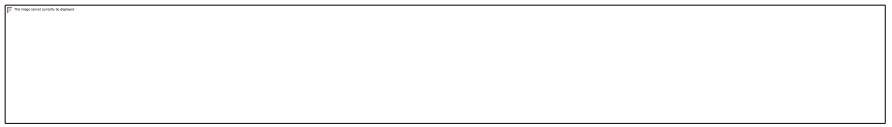


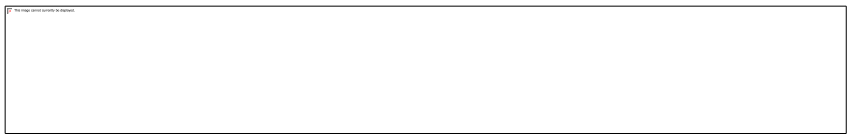
Baryonic sources at SIS



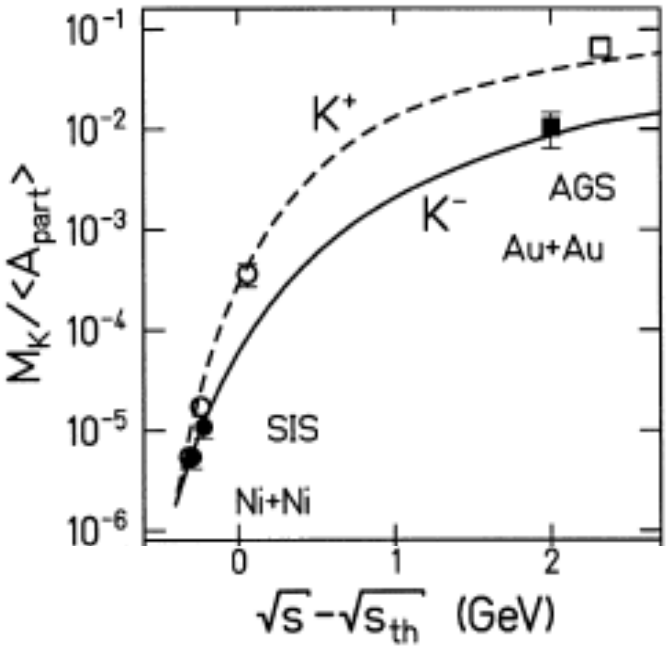
Statistical approach and K^-, K^+

Statistical approach (canonical ensemble for the strangeness) : **common freeze-out parameters** using **free masses for kaons**





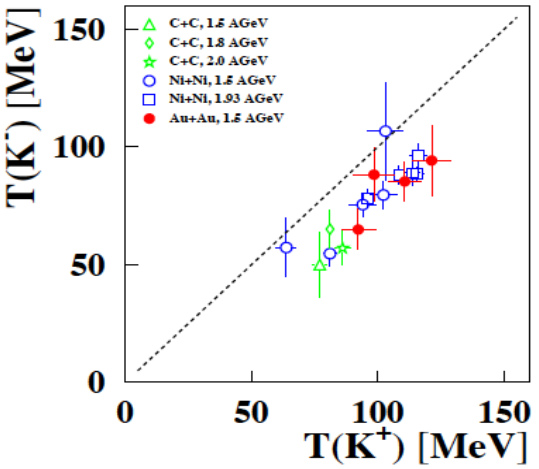
H. Oeschler, Proc. 20th Winter Workshop on Nuclear Dynamics (2003) 000–000



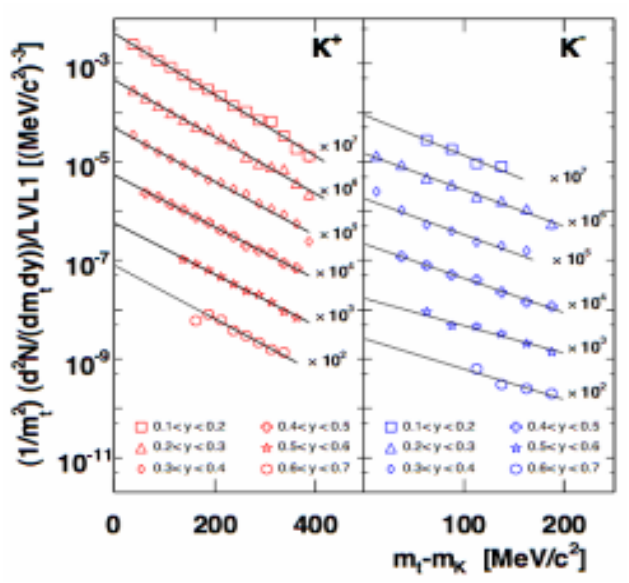
KAOS

Contradiction with these results:
Slopes of K^- systematically
10-20 MeV lower compared to K^+

A. Forster et al. Phys.Rev.C75:024906,2007

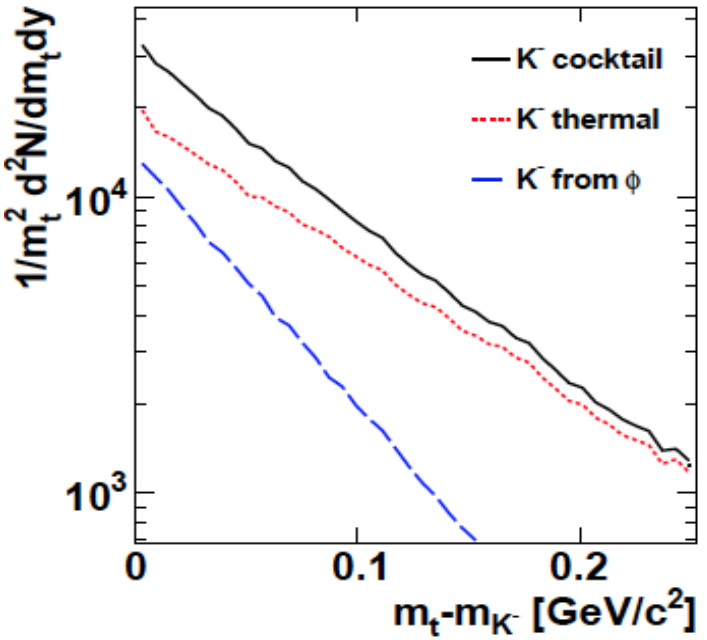


ϕ decay: an relevant source for K^- production at SIS energies



different freeze-out conditions?

- $\phi/K^- = 0.37\pm0.13$
  → 18% of K^- originate from ϕ decays



M. Lorenz et al, PoS BORMIO2010:038,2010

→ **Unique freeze-out criteria when ϕ decay kinematics is taken into account**

→ **Support for statistical model**