ExtreMe Matter Institute
Strongly Coupled Systems
GSI, Darmstadt, Germany
November 15-17, 2010

Exploring compressed nuclear matter with HADES

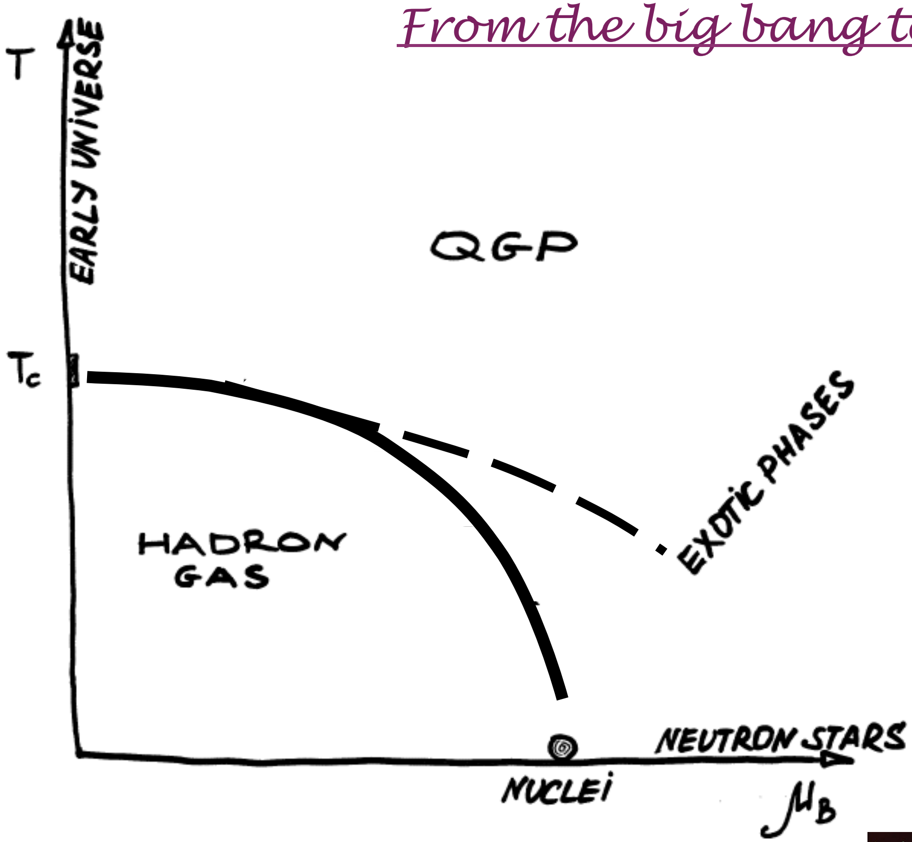
Tatyana Galatyuk for the HADES Collaboration
Goethe-Universität Frankfurt / EMMI

Outline:

- Probing resonance matter with HADES:
  dileptons and strangeness
- e^+e^- pairs: from elementary to heavy-ion collisions
- HADES and the Phase Diagram of Matter
- The perspectives and challenges at FAIR

Nuclear matter in the universe

From the big bang to the galaxies



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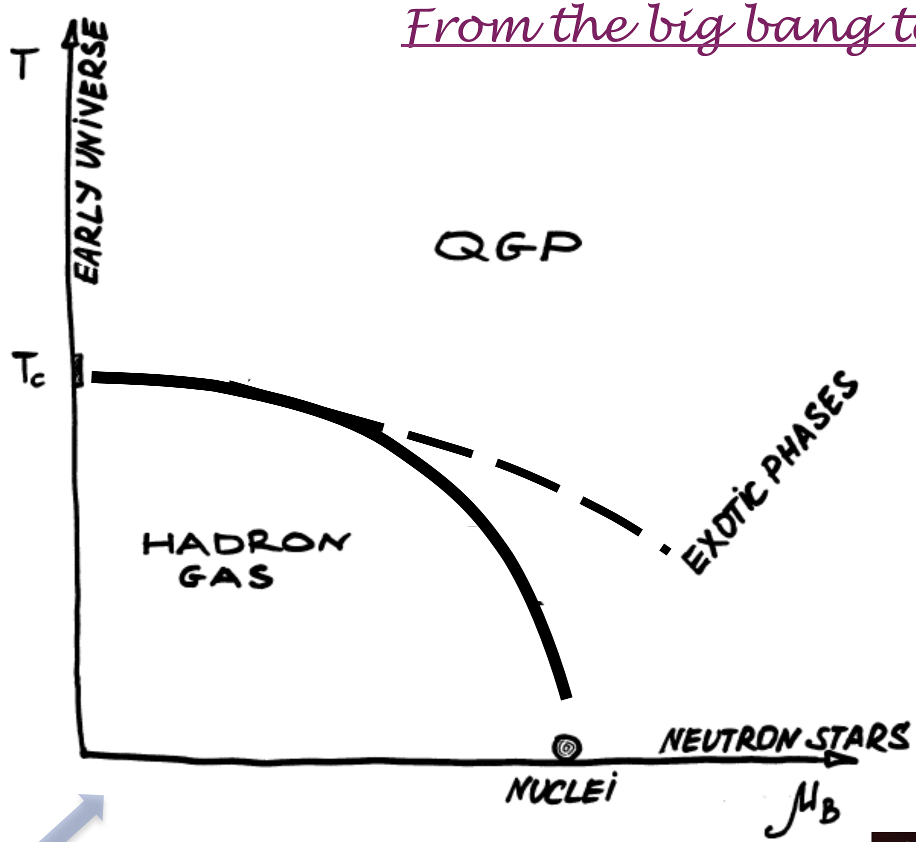
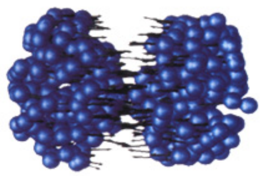
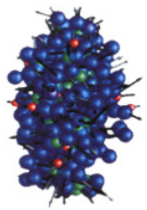


Accessible through HI collisions

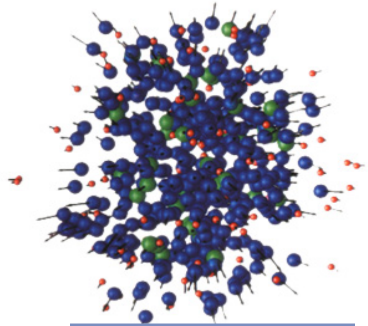
Transient existence of a dense/hot phase



first-chance collisions



dense phase: $\tau < 10$ fm/c

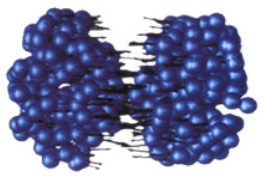


freeze-out

Challenge

Extract information on the high density phase

Transient existence of a dense/hot phase



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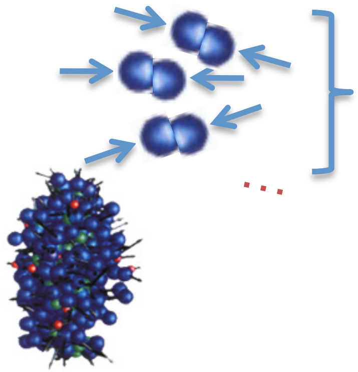

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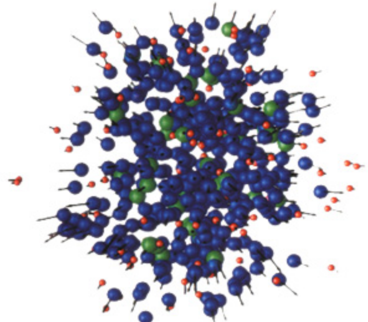


freeze-out

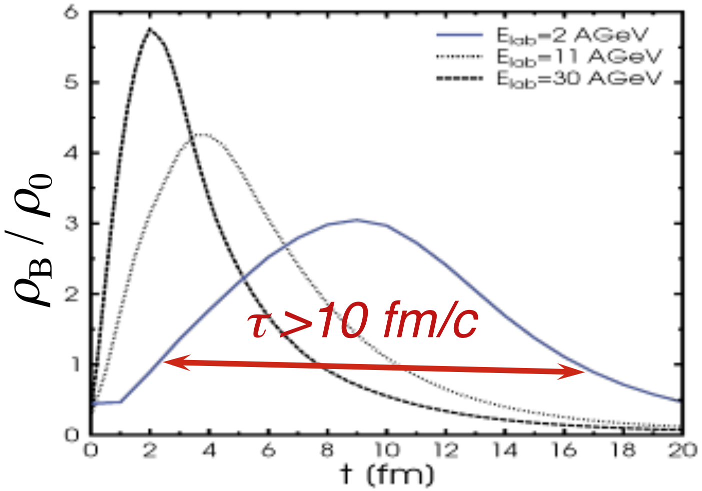
Challenge

Extract information on the high density phase

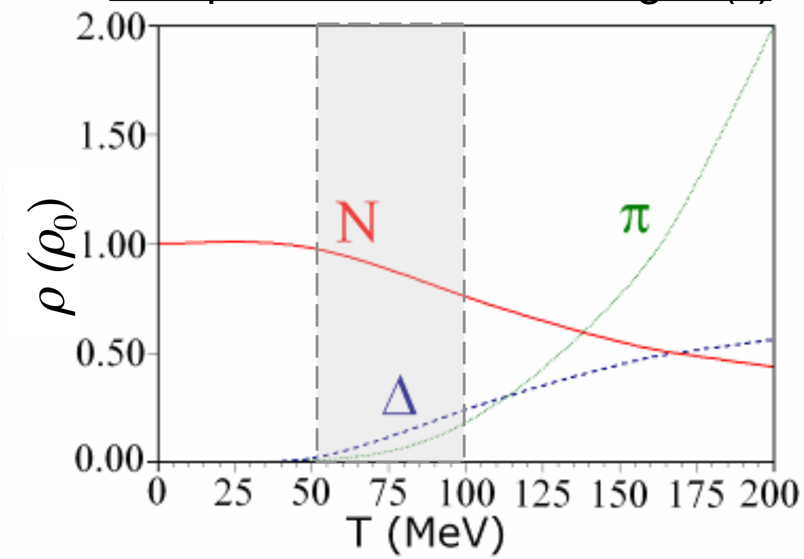
- Is extreme matter created at SIS?
- Same in the whole volume or <*dense and “corona” like*>

The SIS heavy-ion energy regime

Evolution of average $\rho_B\ (\tau_{system})$



Composition of a hot $\pi\Delta N$ gas (T)



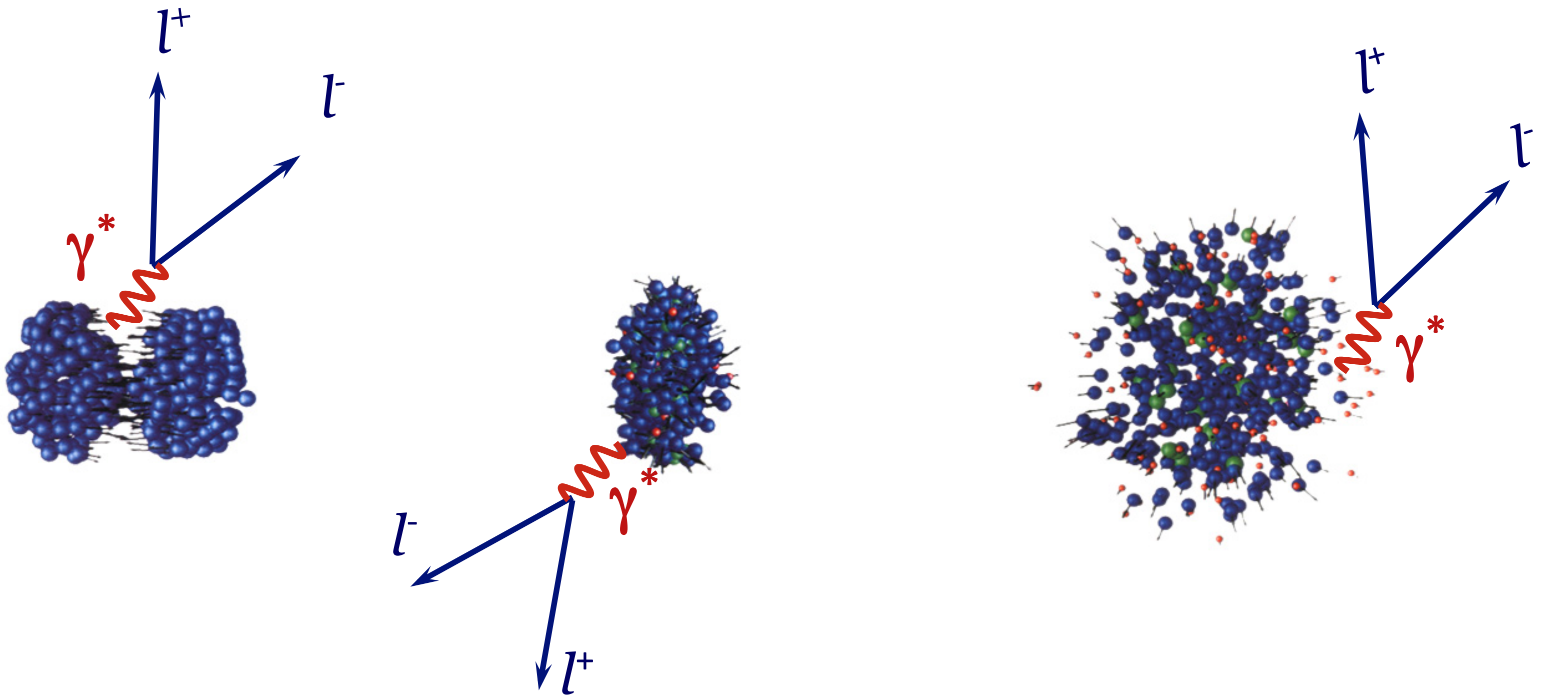
- Long lifetime of the high density phase:
  - *System stays above ground state density for > 10 fm/c*
  - densities: $\rho_{max}/\rho_{0} = 2\text{-}3$
  - temperature: T < 100 MeV

- Baryon dominated:
  - π densities a factor ~100 lower as compared to SPS regime!
  - matter dominated by baryonic resonances (~30%), $N_\pi/A_{part} \approx 10\%$

I prefer penetrating probes

S. Vogel et al., Phys. Rev. C 78 (2008) 044909
R. Rapp and J. Wambach, ArXiv:hep-ph/9909229v1

Electromagnetic structure of dense/hot matter

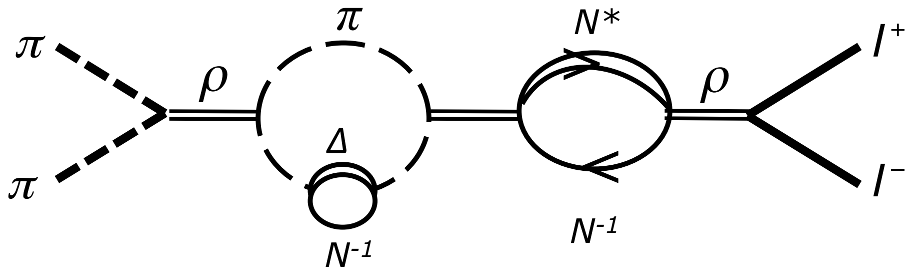


- Lepton pairs couple to hadrons through time-like virtual photons.
- The reconstruction of virtual photons via dileptons gives access to the electromagnetic properties of nuclear matter under extreme conditions.

- *Observable:* short-lived vector mesons (ρ, ω, ϕ)

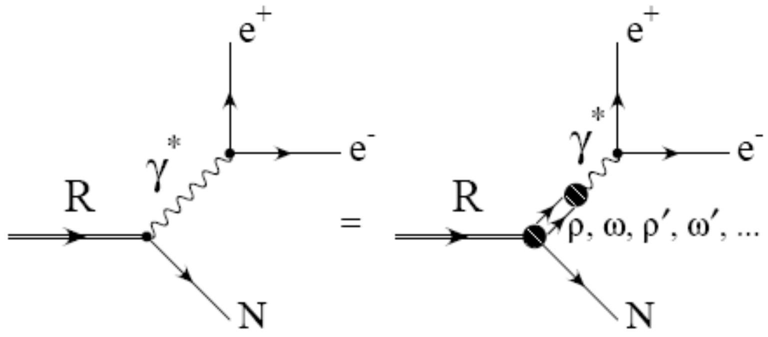
  Strong coupling of γ^* to Vector Meson → VMD model

The ρ meson in nuclear matter

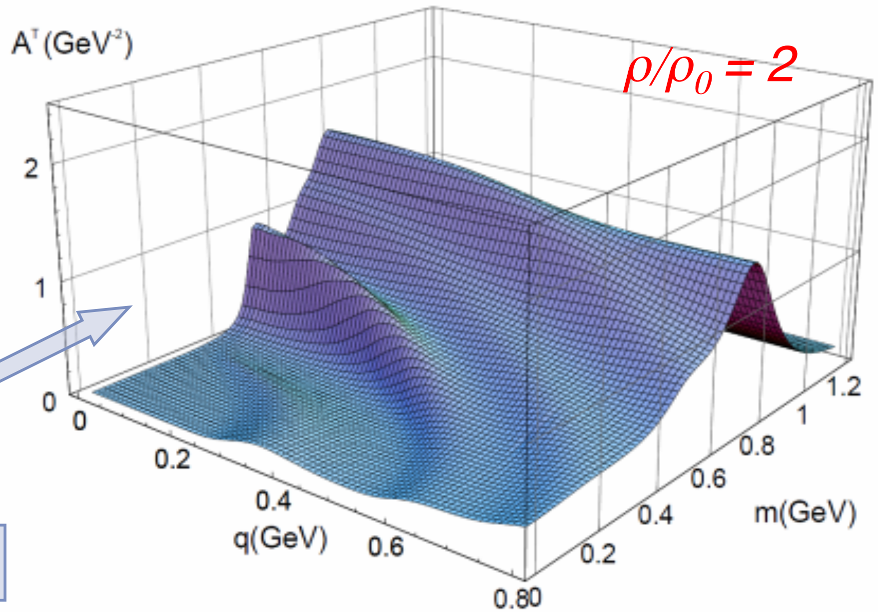


Additional contributions to the ρ-meson self-energy in the medium

Dalitz decay of resonances



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



Meson nucleon molecules?

The experimental challenge...

"There's no such thing as a free lunch"+

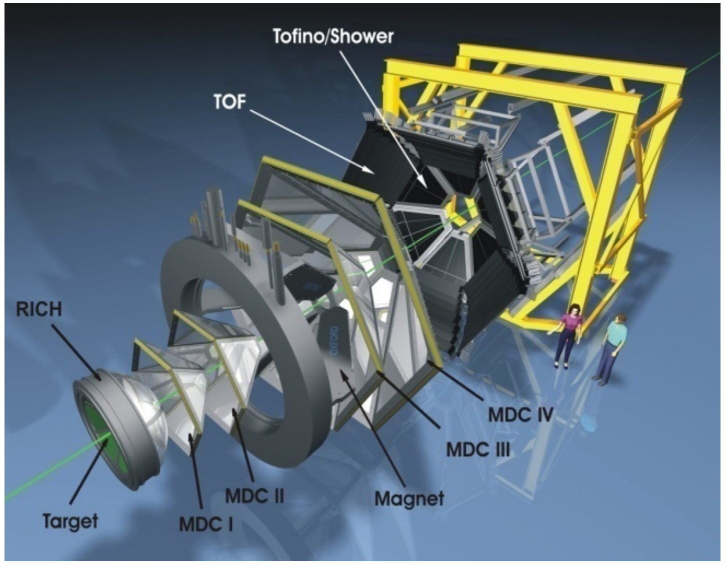
- Lepton pairs are rare probes (Branching Ratio < 10^{-4})
- at SIS energies sub-threshold Vector Meson production

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

\+ H.Wallace, 1943

High Acceptance Di-Electron Spectrometer

HADES



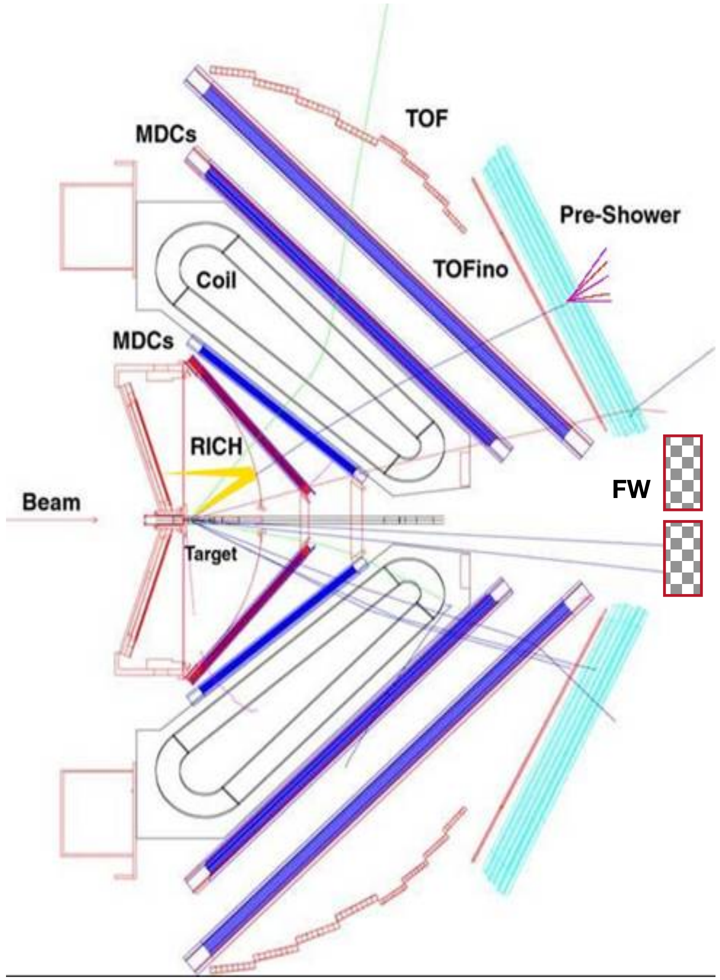
HADES strategy:
Systematic di-electron spectroscopy in NN, AA, pA, πN and πA collisions

- Beams provided by SIS18: π, p, nuclei

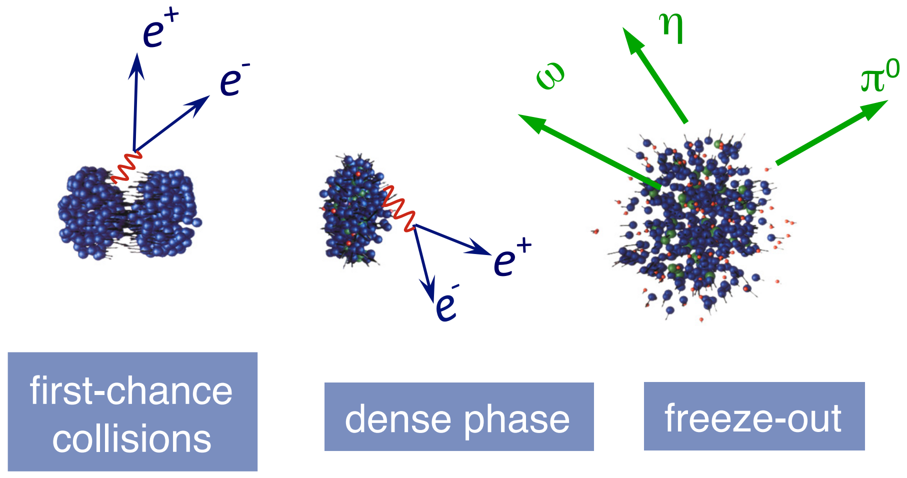
- Full azimuthal coverage
- Hadron and lepton PID

- e^+e^- pair acceptance 0.35
- Mass resolution 2 % (ρ/ω region)

- ~ 80.000 channels
- now: 20 kHz event rate (500 Mbyte/s peak data rate)



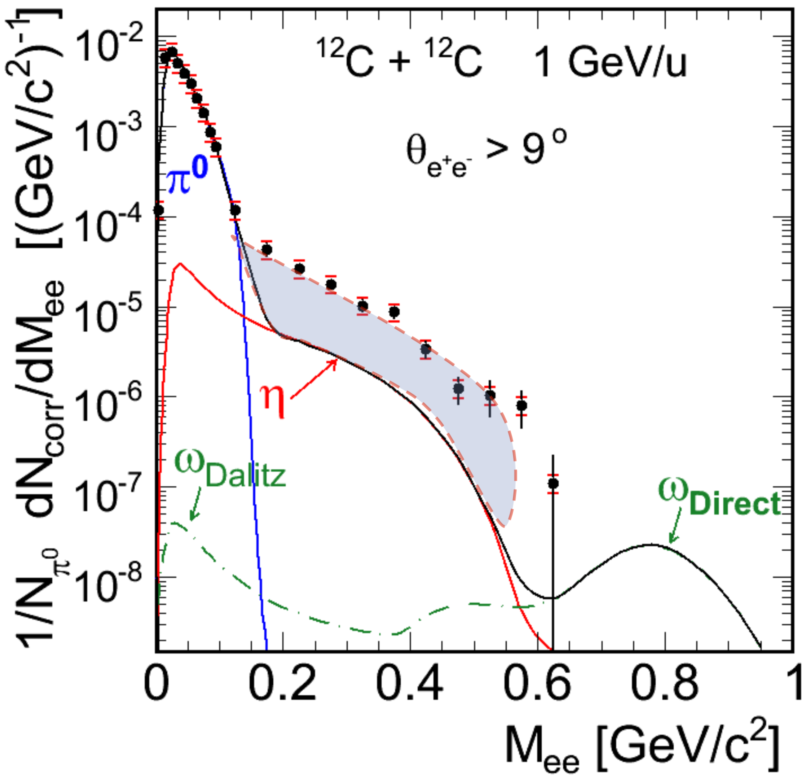
Is there any medium radiation?



- **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?

Elementary reactions with HADES

"If you are out to describe the truth, leave elegance to the tailor"+

+ A. Einstein

- *Goal:*
  - Understand baryonic lepton pair production
  - Establish cocktail of „free“ hadron decays → reference for pA and AA collisions

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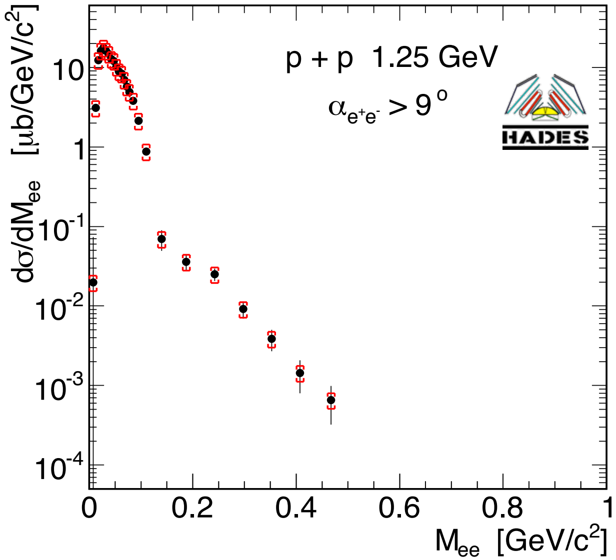
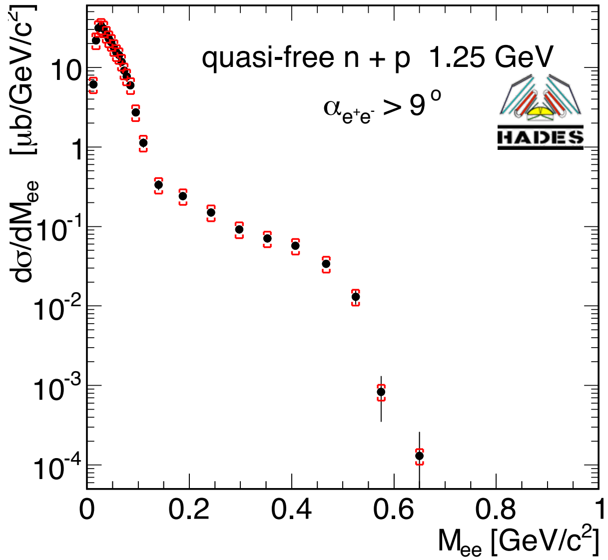
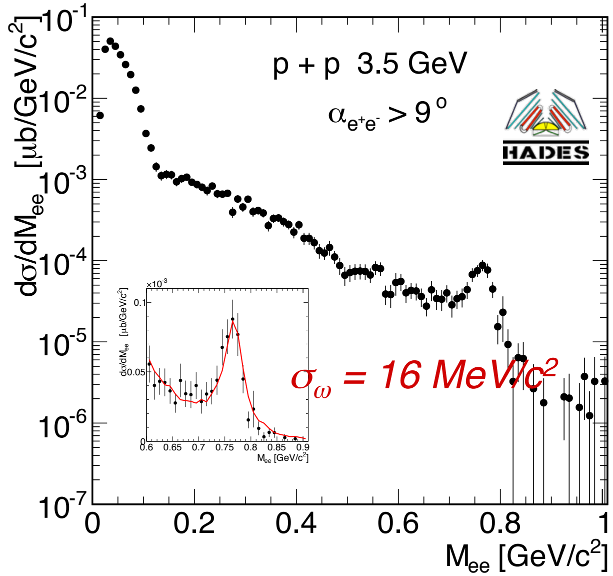
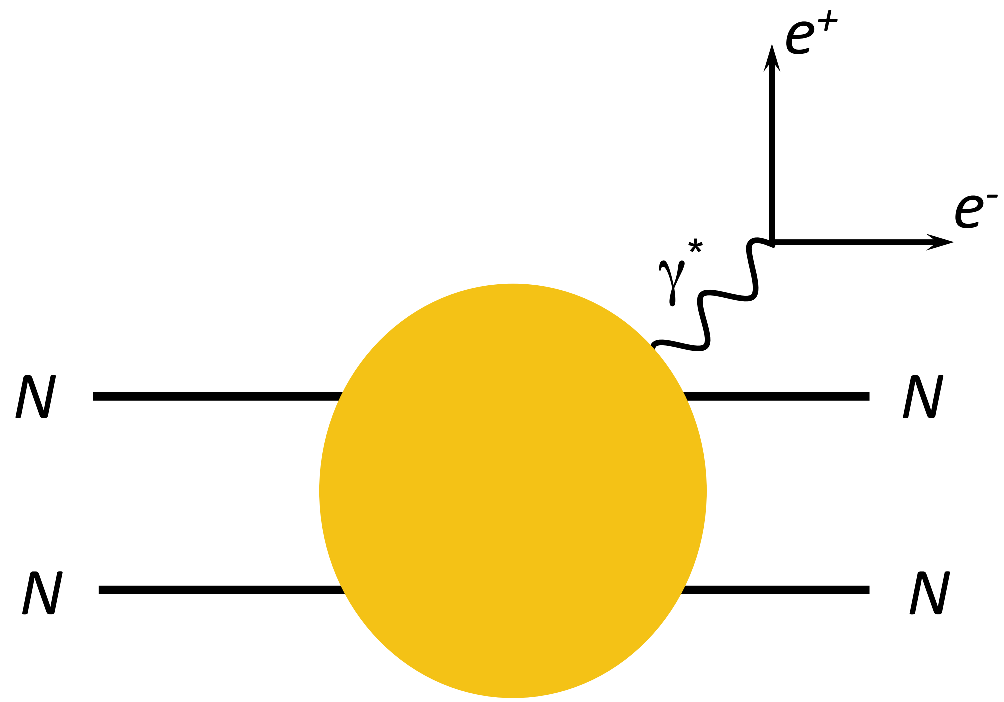






Virtual photon production in NN collisions



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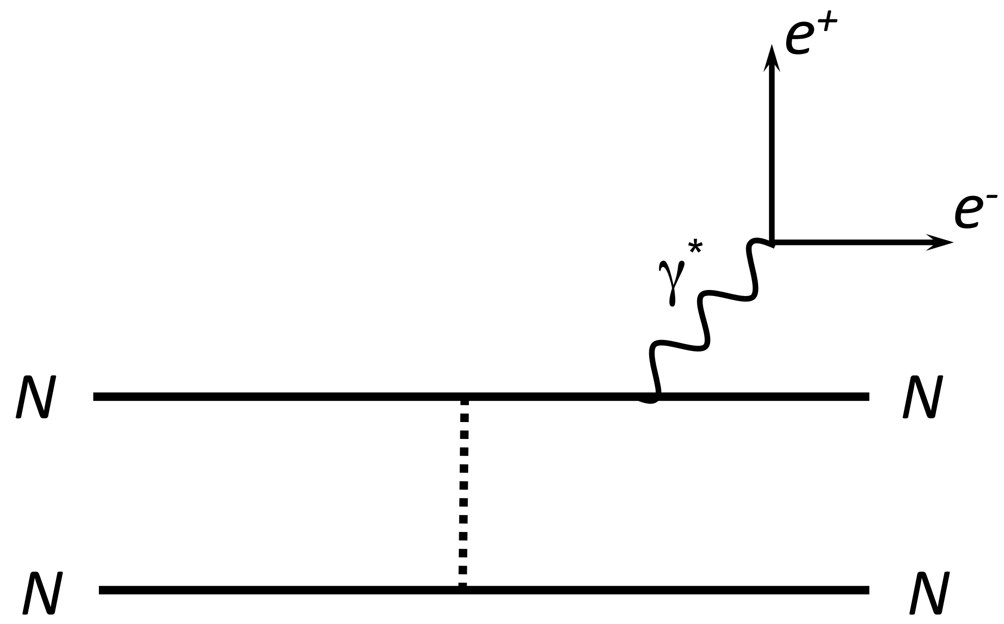

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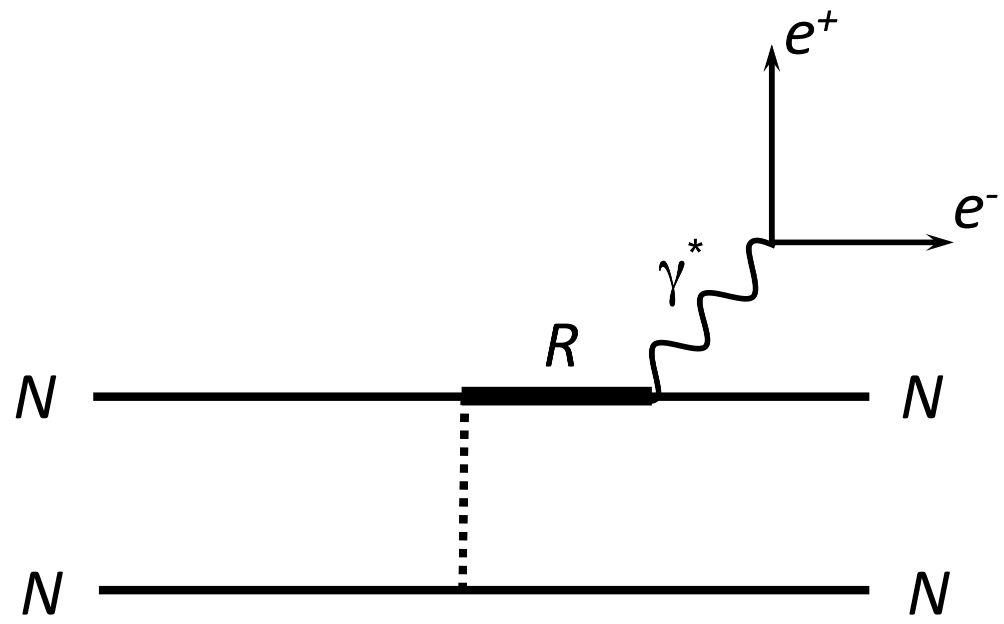

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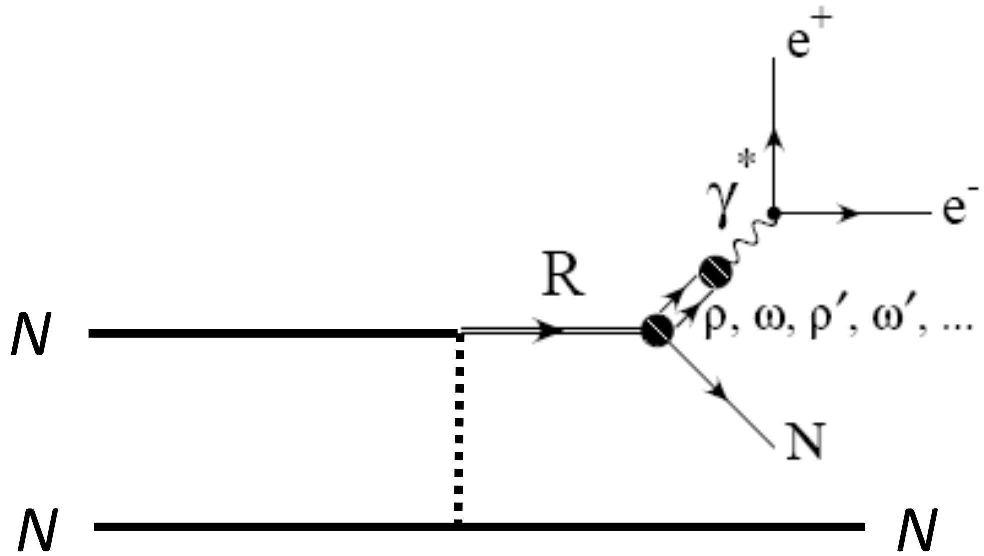
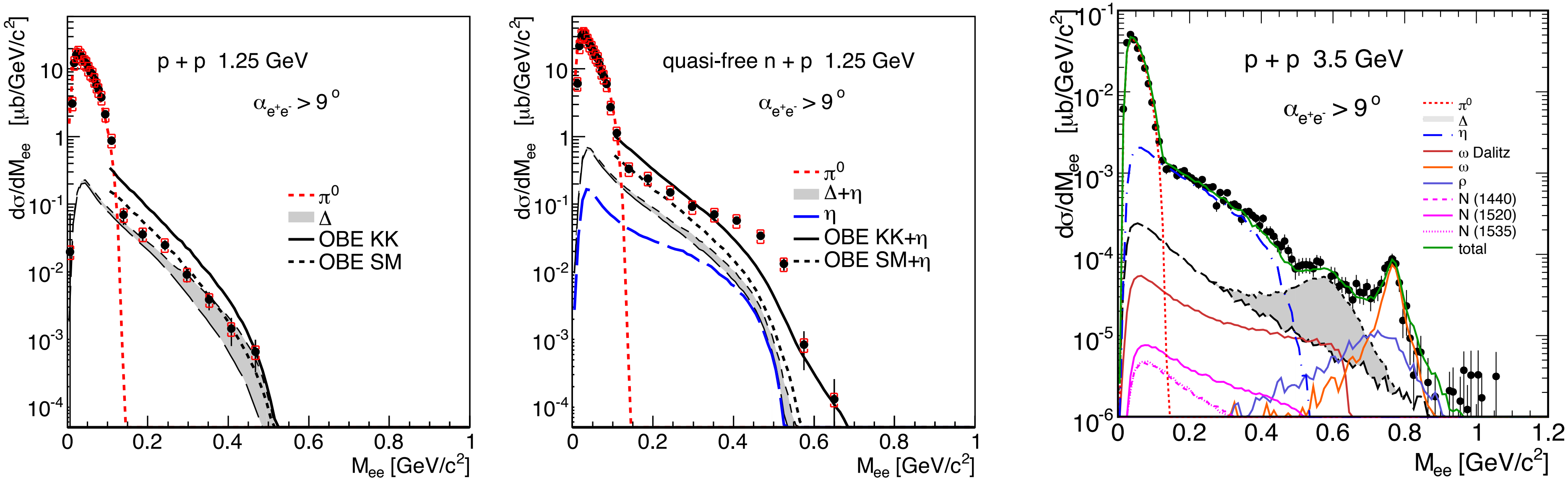


C. Fuchs, PRC 68, 014904 (2003)

HADES data vs. models



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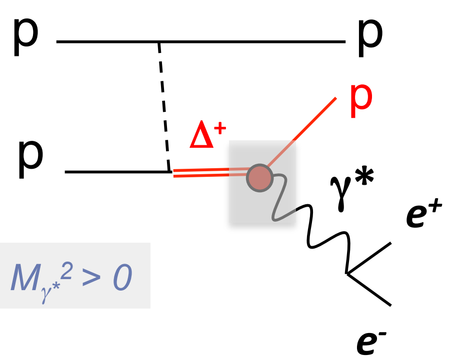
- OBE effective models reproduce p+p, but not (yet) n+p !
- Better agreement with data when pion form-factor is included

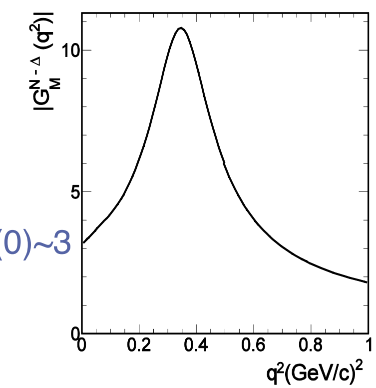
  R. Shyam and U. Mosel arXiv:1006.3873

- N-Δ transition electromagnetic form factors

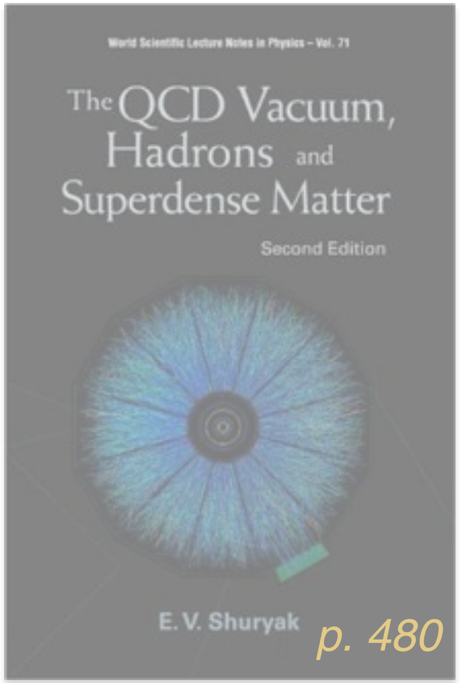
  Wan and Iachello, int. J. Mod. Phys. A20 (2005) 1846
  Krivoruchenko et al. Phys. Rev. D 65 (2001) 017502
  Model: Pluto ROOT based event generator



$G_M(0)\sim 3$



$q^2 = M^2_{inv}(e^+e^-) = M_{\gamma^*}^2 > 0$

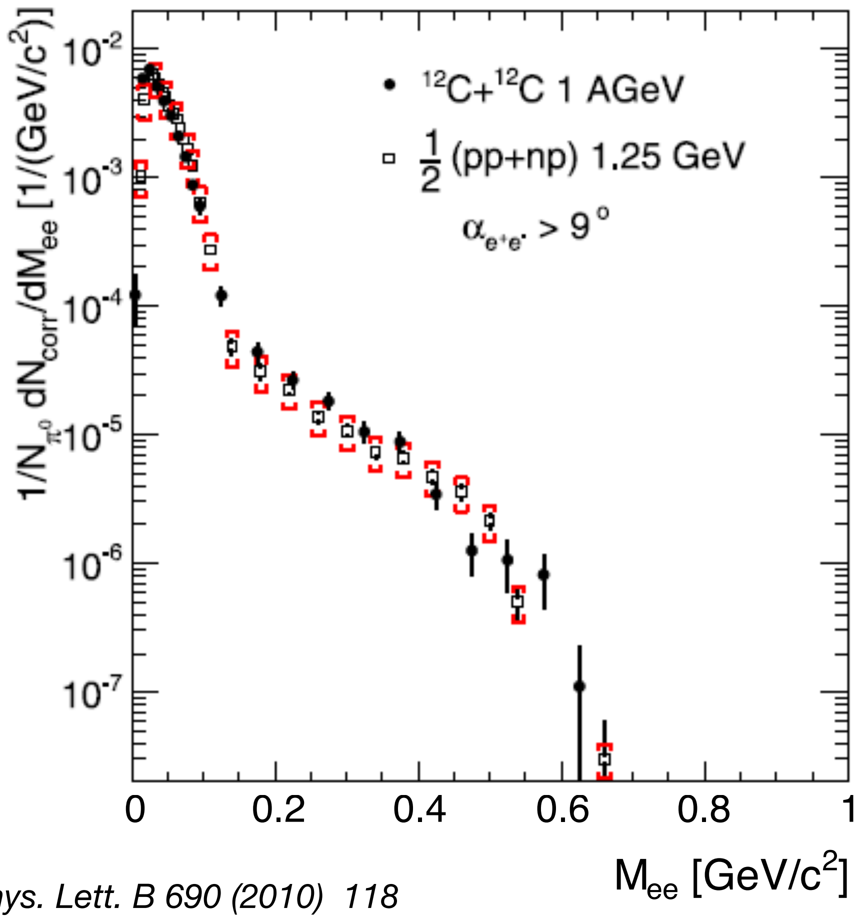


„At Berkeley BEVALAC the DLS spectrometer was built to study dileptons... A striking dilepton signal was found, but my guess is its reality will probably never be understood, although this mass/energy region will be soon tested by the HADES experiment at GSI“

E. Shuryak

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

Comparison of C+C to N+N collisions



Phys. Lett. B 690 (2010) 118

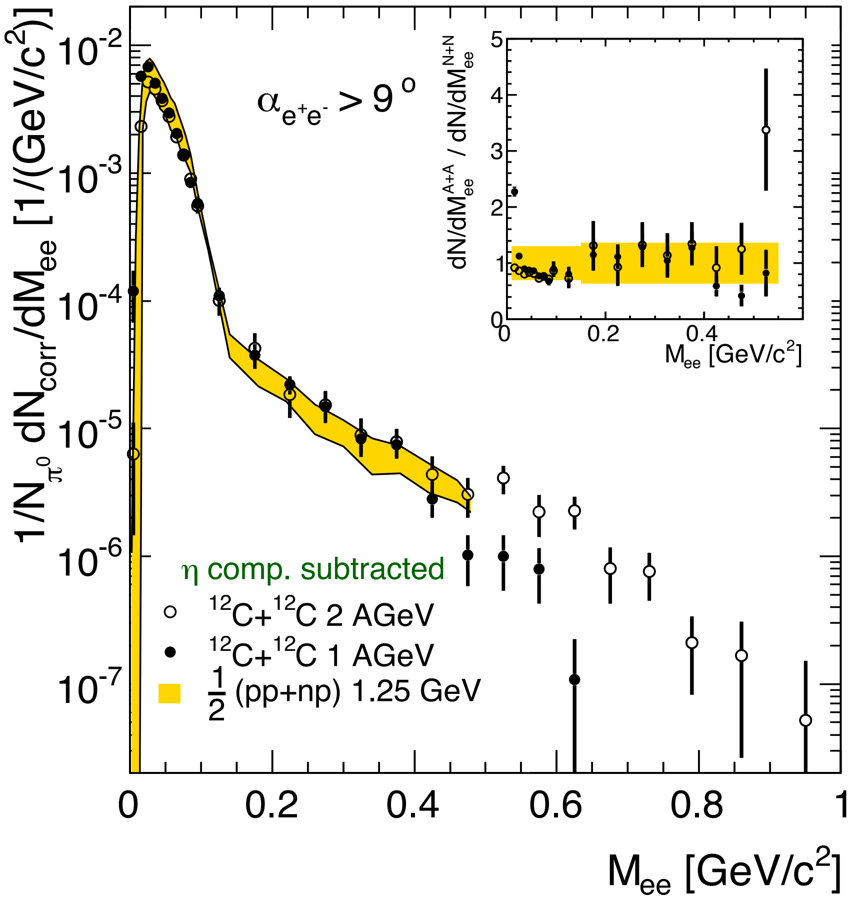
- C+C data reproduced (within 20%) by superposition of N+N interactions
- Pair excess observed in C+C data has been traced back to anomalous pair production in n+p collisions

How does the excess evolves with beam energy?

IMPORTANT: know your reference!

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

Definition of the "Reference data"



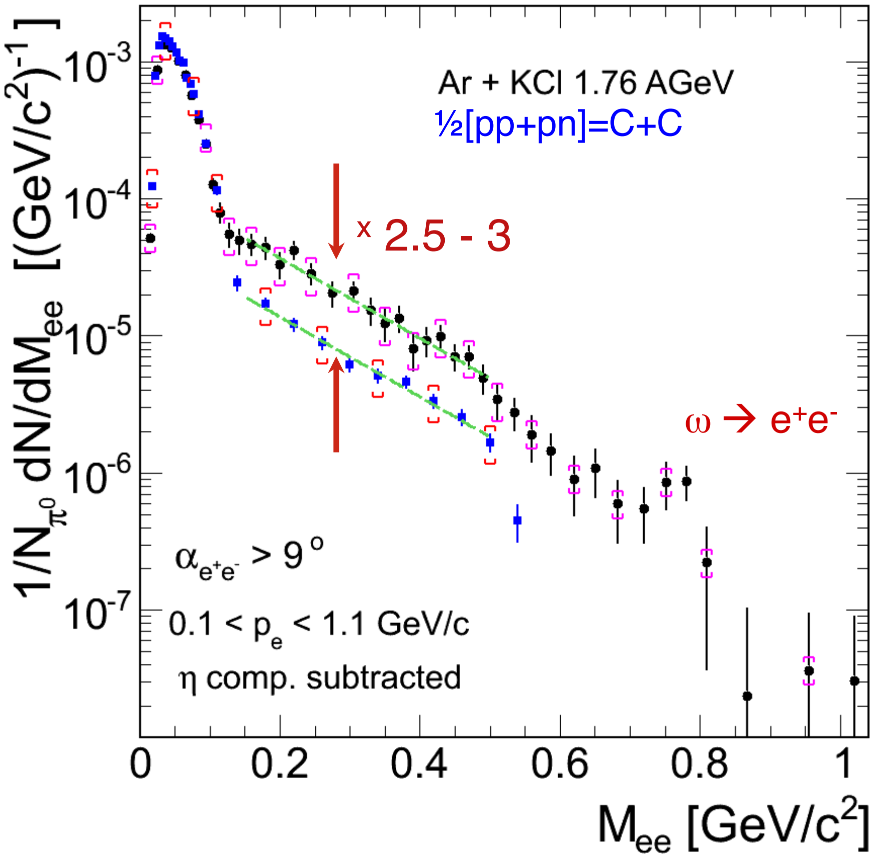
HADES: Phys. Lett. B 690 (2010) 118

- Beam energy doesn't matter doesn't matter for invariant masses below 0.5 GeV/c^2
- Baryonic source scales as pion production
- No true medium effects observed, at least not for *C+C* data

How does the excess evolves with system size?

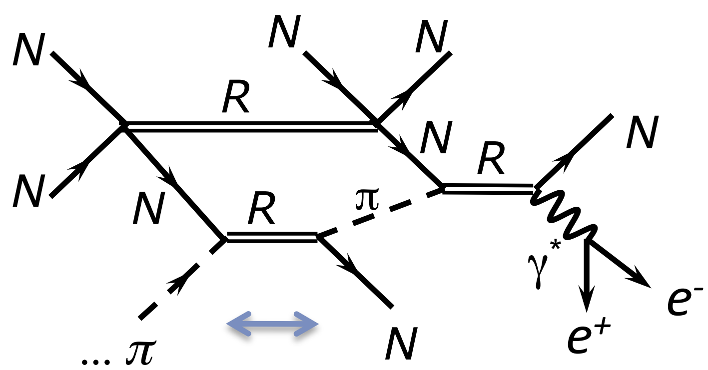
Is there physics beyond free N+N?

Efficiency corrected dielectron spectra
from Ar+KCl at E_{kin} = 1.76 GeV/u



HADES: Nuclear Physics, A 830 (2009)

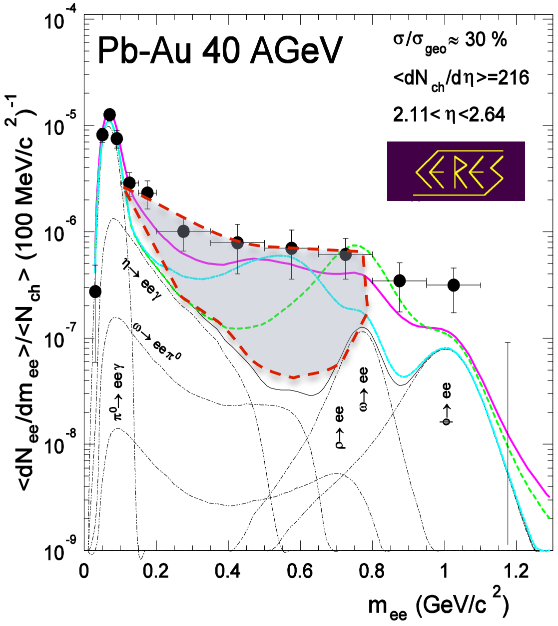
- First observation of $\omega \rightarrow e^+e^-$ peak in heavy-ion collisions at SIS energies
- First evidence for „true“ excess (strong excess above the “reference cocktail”)
- Excess yield scales with system size ~ $A_{part}^{1.4}$ (“multi step” processes)

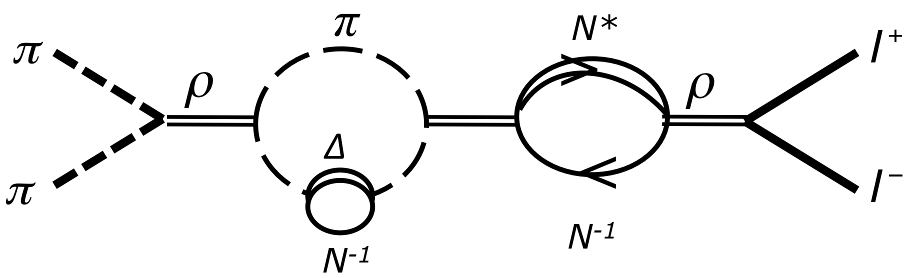


$\tau_{coll.} \leq 1$ fm/c (200 MeV)

Dilepton pair excess: from SPS to SIS...

CERES: Phys. Rev. Lett. 91 (2003) 042301

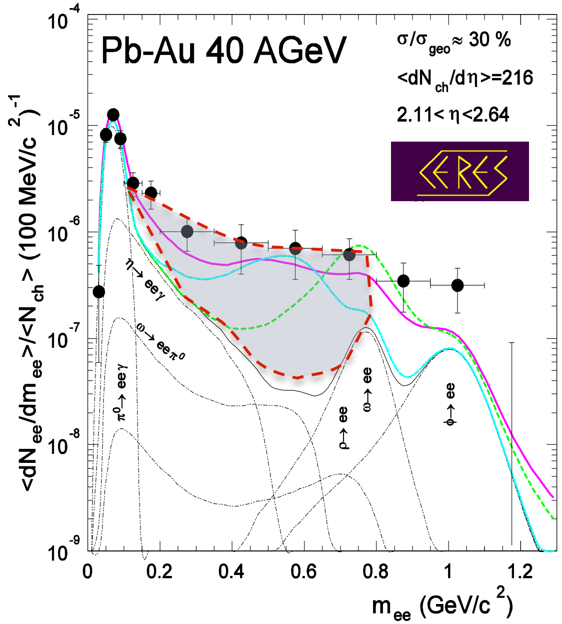


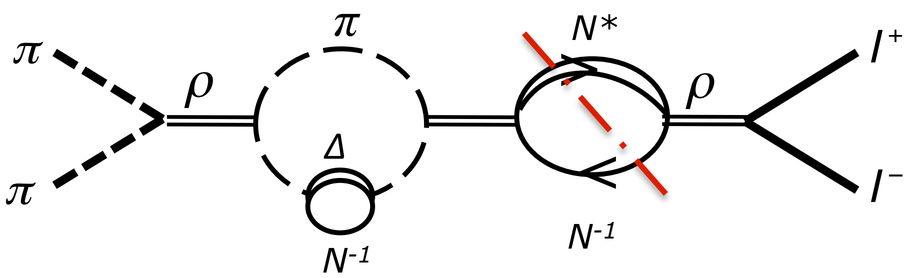


- Main source: $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$
- Strength of dilepton yield at low masses is due to coupling to baryons!

Dilepton pair excess: from SPS to SIS...

CERES: Phys. Rev. Lett. 91 (2003) 042301





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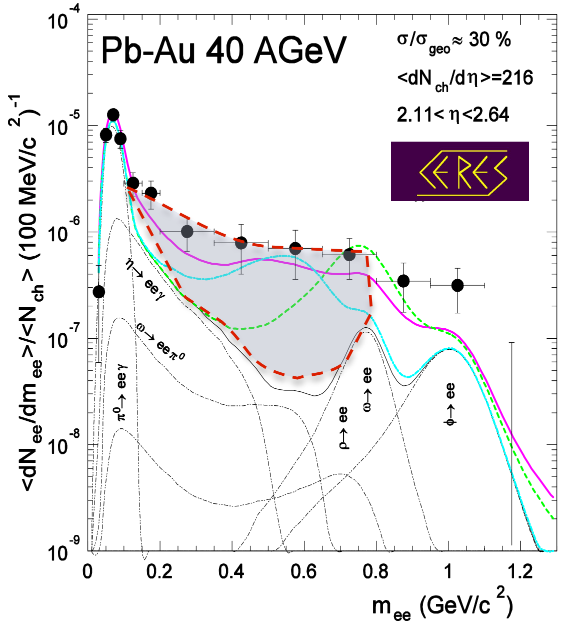

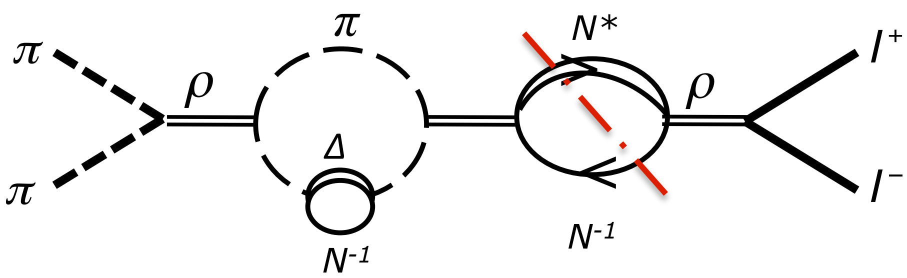

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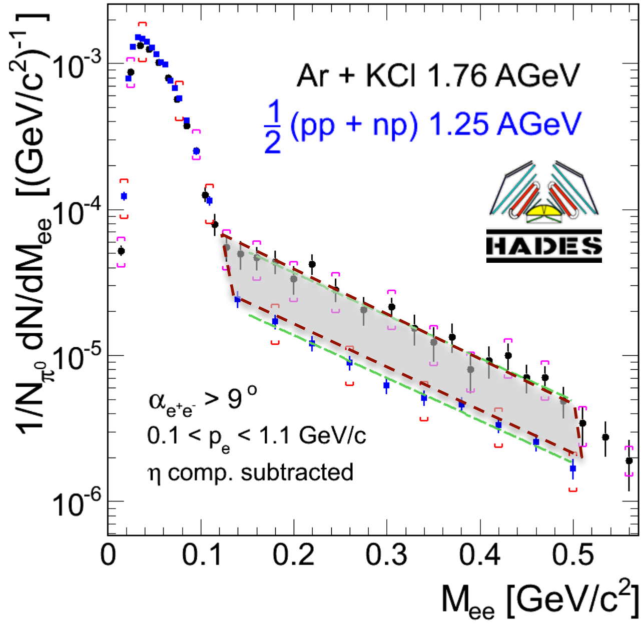
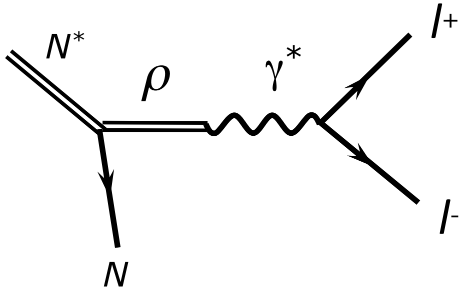
<u>e^+e^- pair yield Ar+KCl 1.76 GeV/u</u>





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

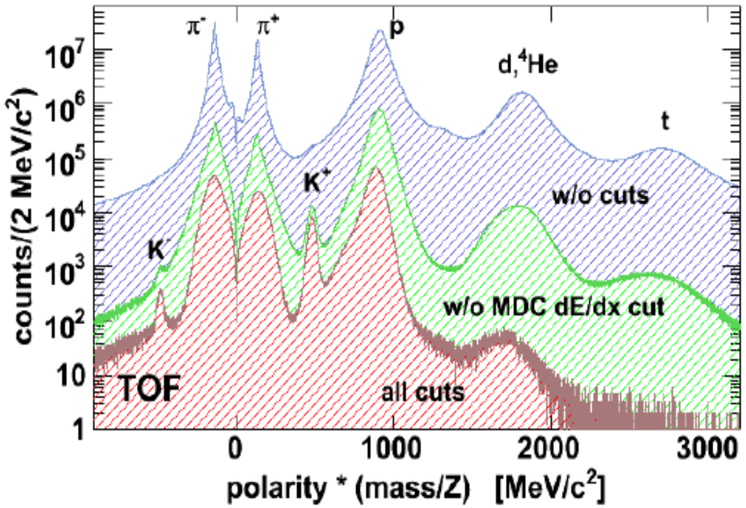
Strangeness production in 1.76 GeV/u Ar+KCl

HADES has

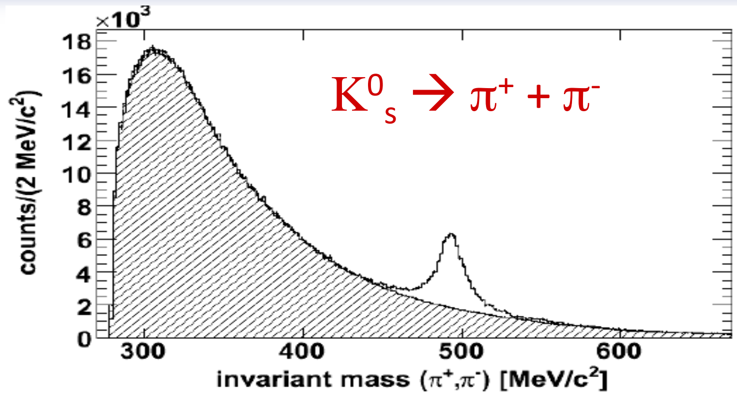
high momentum resolution, high acceptance, good particle identification, vertexing

→ high-statistics measurement of π^+, π^-, K^+ and K^-, but also: K^0_s, Λ, ϕ, Ξ^-

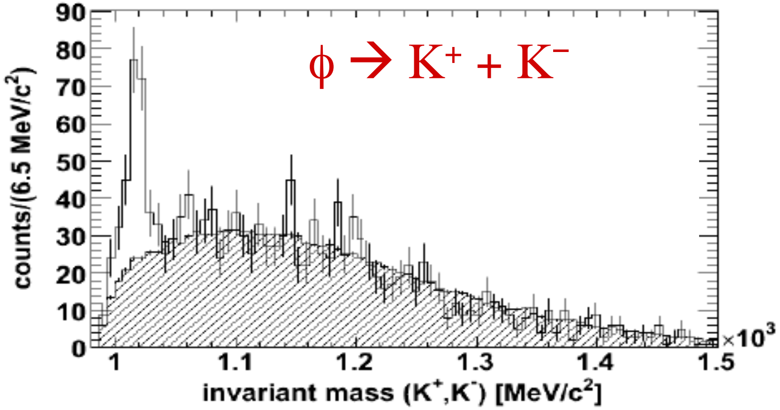
<u>Ar+KCl 1.76 GeV/u</u>
<u>PID based on dE/dx and TOF</u>



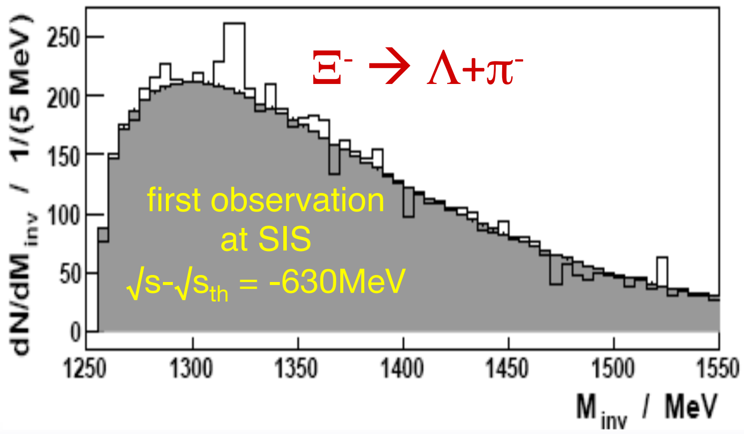
HADES: Phys. Rev. C80:025209



arXiv:1004.3881v1 [nucl-ex]



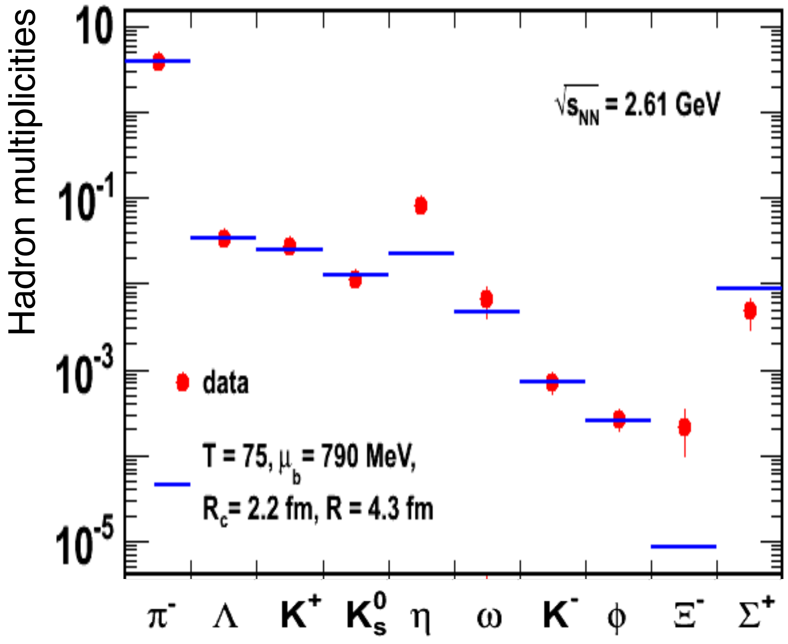
arXiv:0902.3487v1 [nucl-ex]



PRL103, 132301, (2009)]

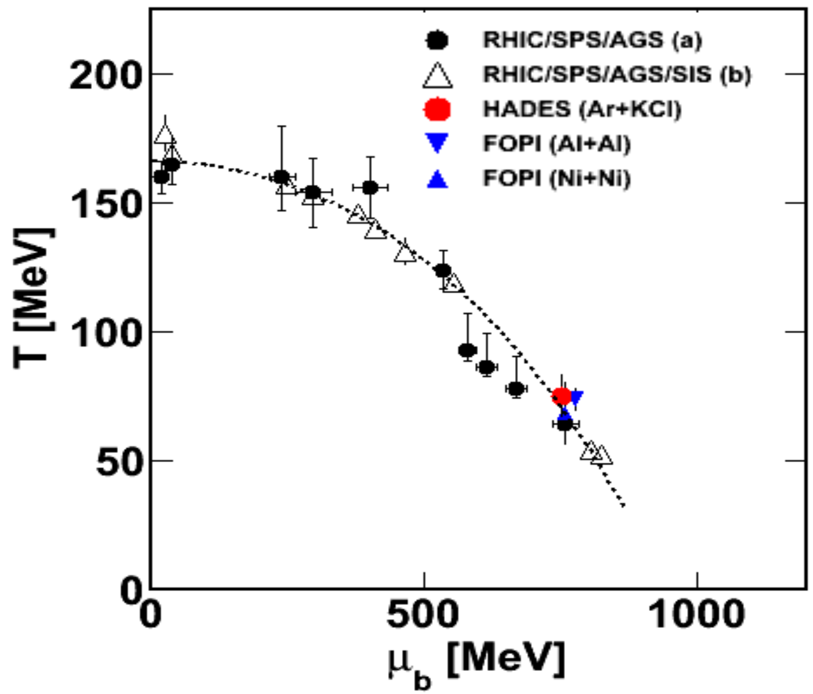
Hadron multiplicities at SIS and Statistical Hadronization Model

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



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

Extracted (T, μ_b) fit in the systematics of the Statistical Hadronization Model

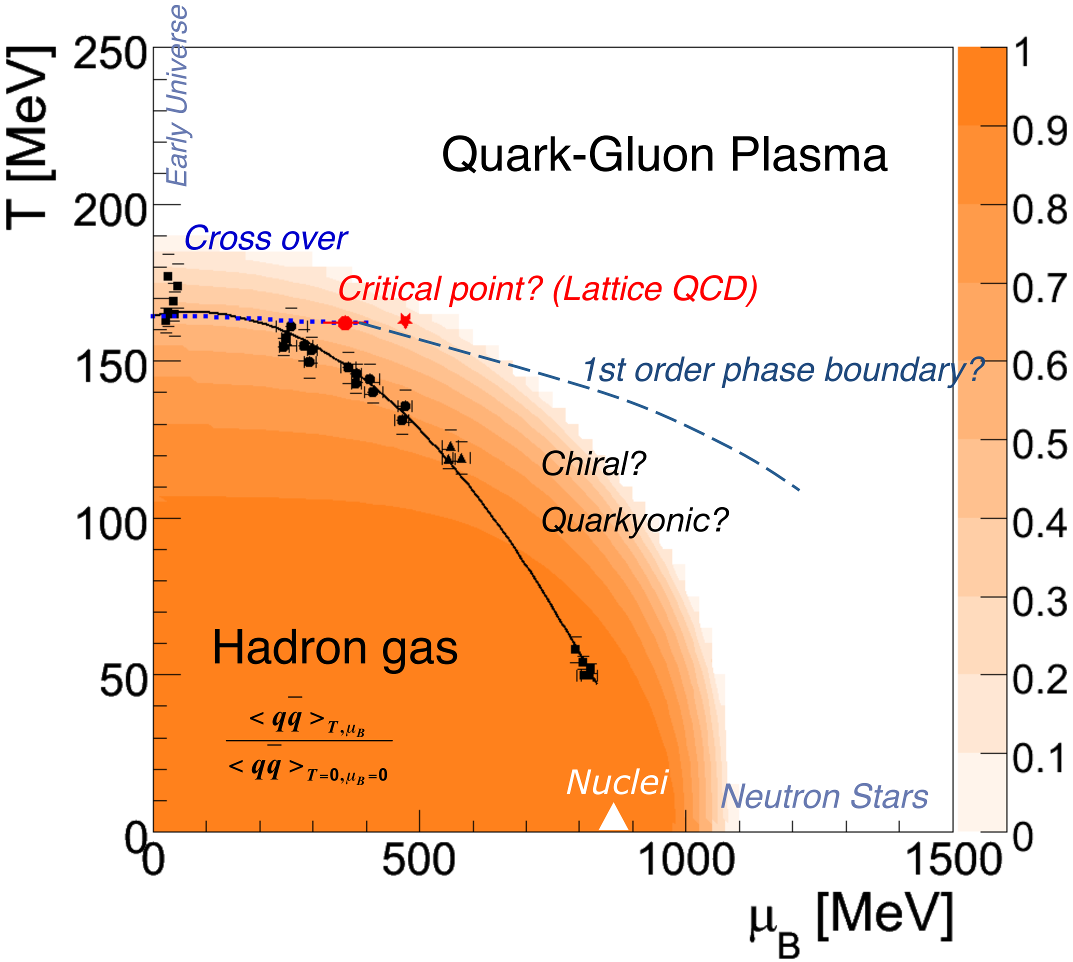


Statistical Hadronization Model describes hadron abundances accept in case of:

- large Ξ^- (s=-2) yield
- large η yield (η from TAPS)

S. Wheaton, J. Cleymans, Phys.Commun.180:84-106,2009
η from TAPS: R. Averbeck et. al. PRC 67 (2003) 024903

Searching for landmarks of the phase diagram of matter at high μ_B



SHM : P. Braun-Munzinger, K. Redlich, J. Stachel, nucl-th/0304013
J. Cleymans, K. Redlich, PRC 60 054908

lQCD : Z. Fodor et al., hep-lat/0402006, F. Karsch, QM04

<qqbar> : Schäfer, Wambach (priv. communication)

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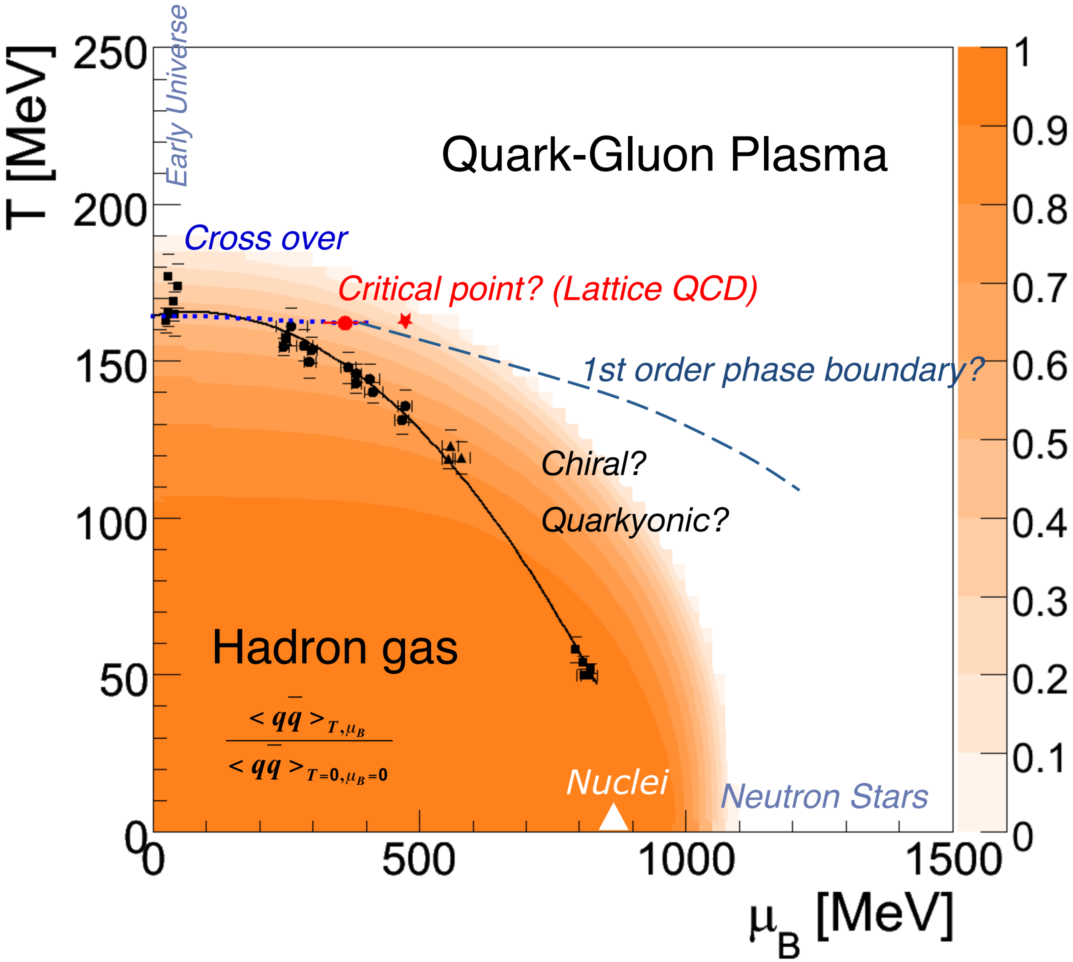

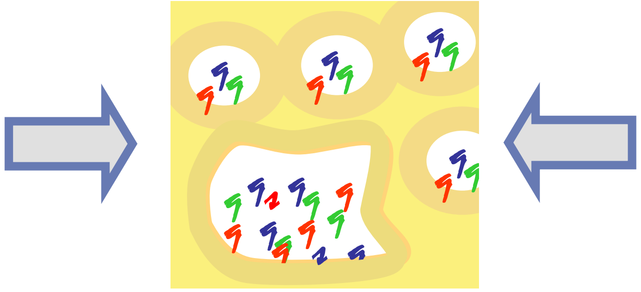

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The future at SIS18

Runs in	p,d,π induced	AA	Status
2002		$^{12}C+^{12}C$ 2 GeV/u	*Phys.Rev.Lett.98:052302,2007*
2004	p+p 2.2 GeV		Analysis finished
2004		$^{12}C+^{12}C$ 1 GeV/u	*Phys.Lett.B663:43-48,2008*
2005		$^{40}Ar+^{39}KCl$ 1.76 GeV/u	Analysis finished
2006	p+p 1.25 GeV		*Phys. Lett. B 690 (2010) 118*
2007	d+p 1.25 GeV/u		*Phys. Lett. B 690 (2010) 118*
	p+p 3.5 GeV		Analysis finished
2008	p+^{93}Nb 3.5 GeV/u		Analysis ongoing
2008-2010	Upgrade RPC, DAQ, MDC I		
2011		Au+Au, Ag+Ag	
	π + N, A		

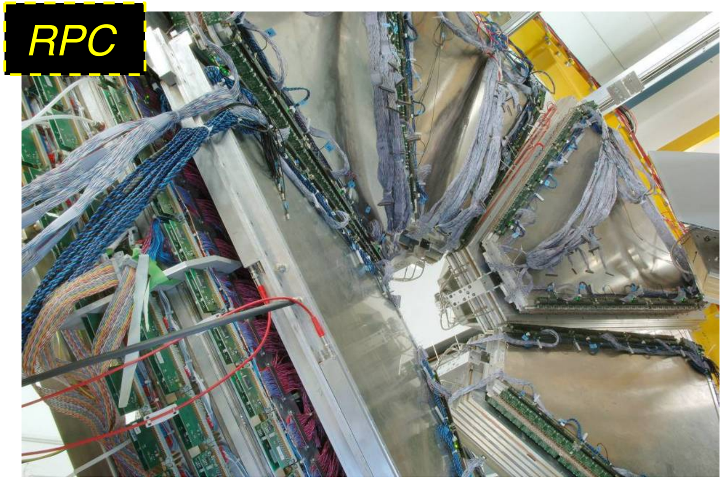
"The most beautiful sea hasn't been crossed yet.
And the most beautiful words I wanted to tell you
I haven't said yet ..."

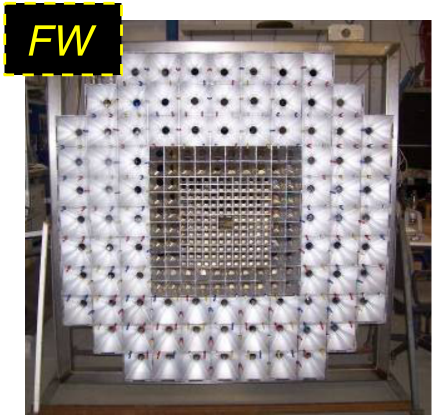
Nazim Hikmet

- Scaling of the excess pairs with <A_{part}> need more studies (planed):
  - *Ni+Ni*: highest collision energies
  - *Au+Au:* highest densities
- *π+N, π+A* to study resonance production and coupling to virtual photons

HADES upgrade

- *Quest:*
  - Heavier systems
  - Much higher statistics
- *Objective:*
  - Cope with multiplicities of Au+Au collisions
  - Accept up to 20 kHz event for heaviest systems
- *Measures:*
  - RPC replaces TOFino
  - Add forward hodoscope
  - New DAQ

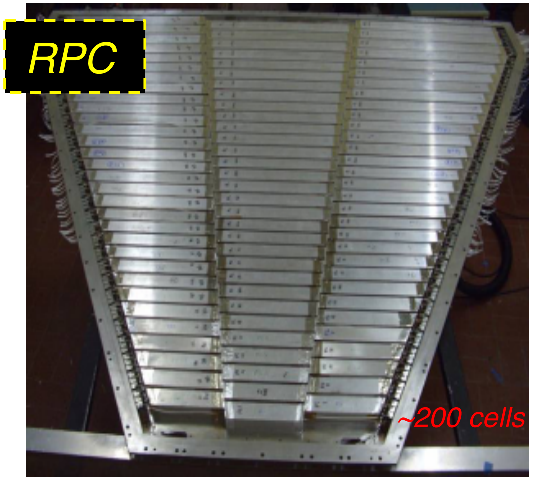


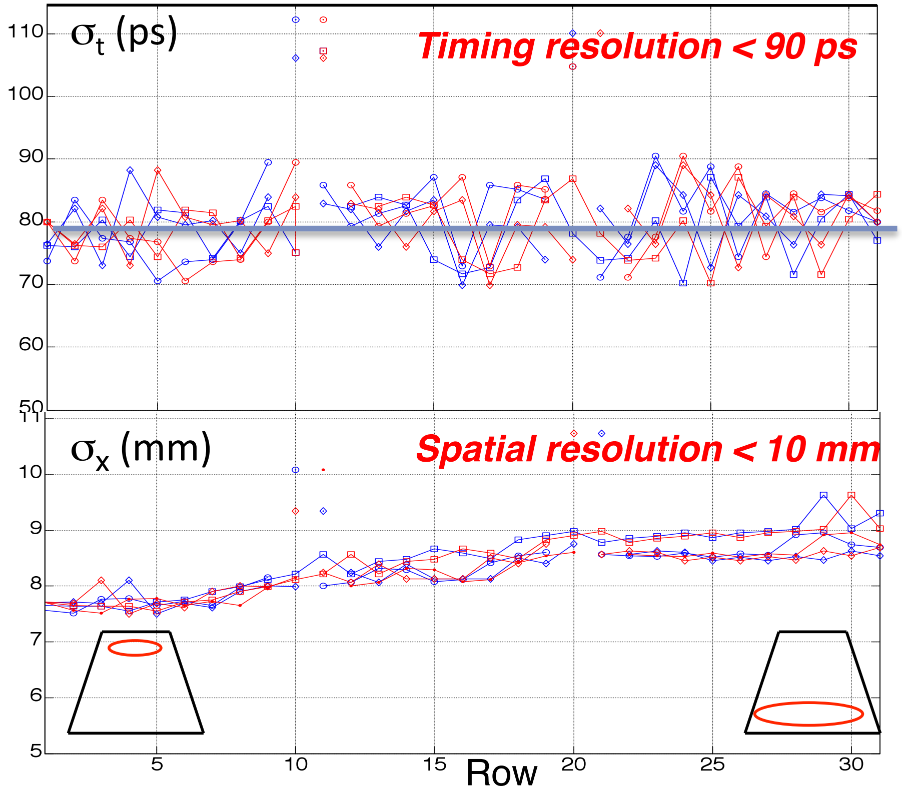


HADES upgrade: Resistive Plate Chambers

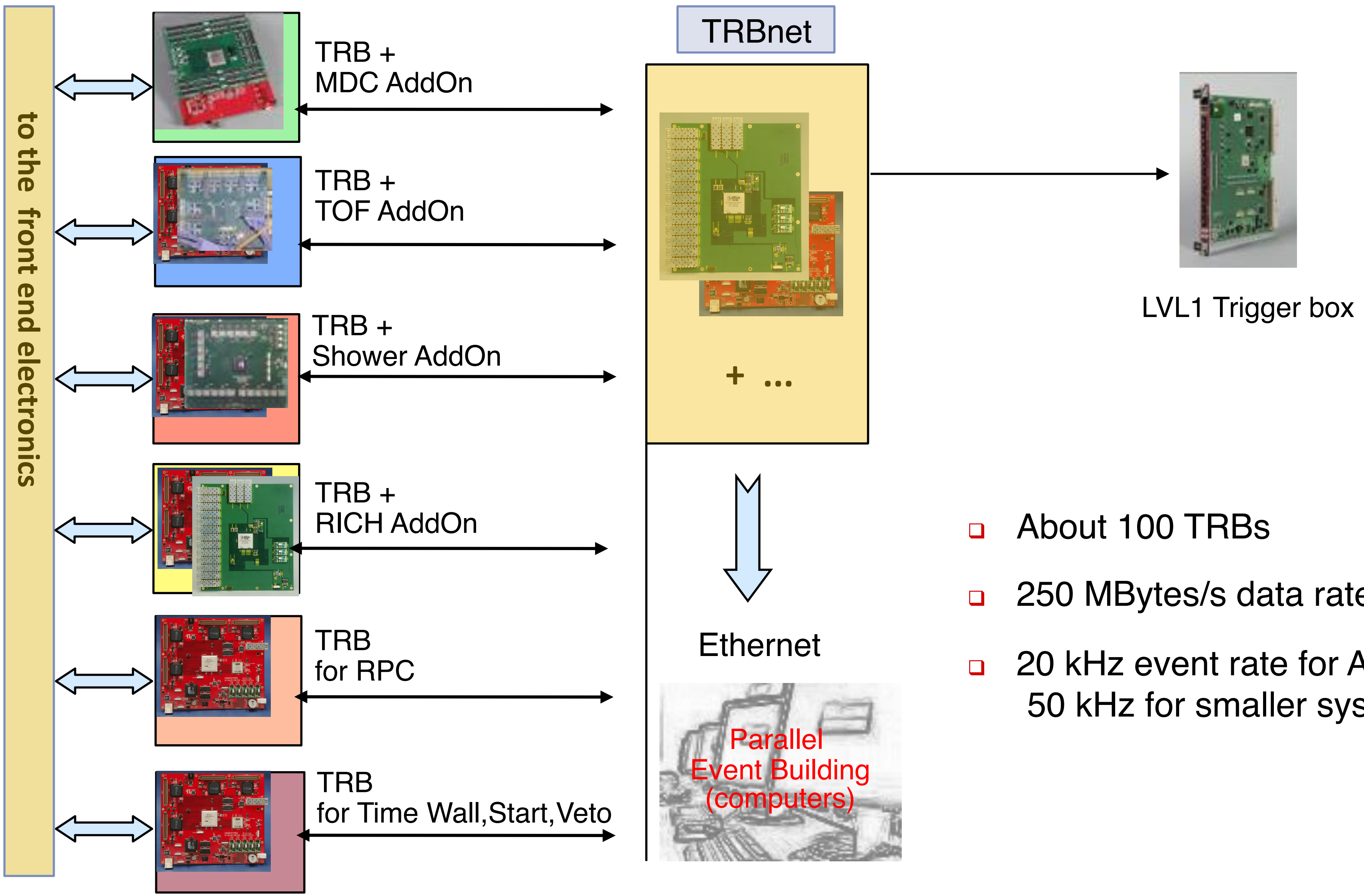
Technology

- 1116 individually shielded RPC-cells
  - Robust performance
- Novel Charge-to-Width FEE for 2232 channels
  - Encodes time and charge information into one signal
- General Purpose Trigger and Readout-Board (TRB) for DAQ
  - Combines FEE and DAQ on one PCB
  - Very flexible add-on board concept
  - Finally is used for all HADES subsystems





HADES DAQ upgrade

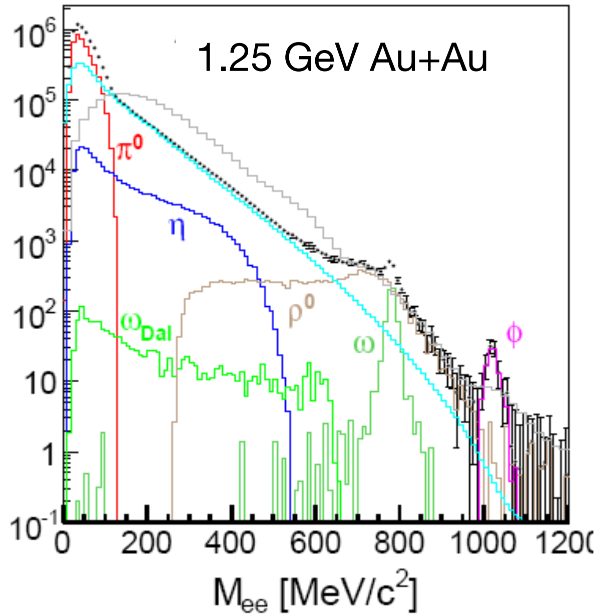


- About 100 TRBs
- 250 MBytes/s data rate (DC)
- 20 kHz event rate for Au+Au
  50 kHz for smaller systems

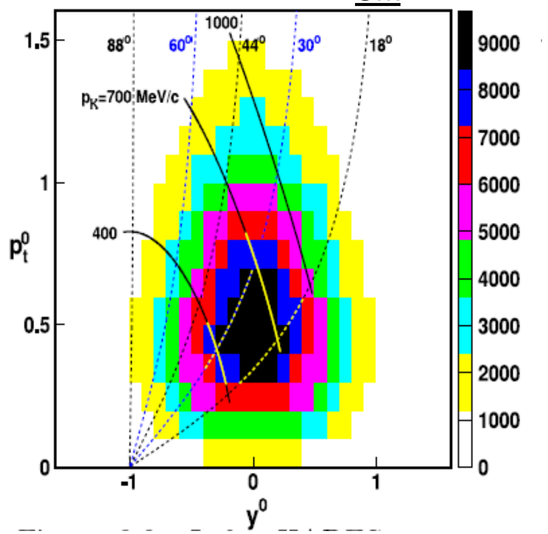
Getting ready for Au beam

- Beam: ^{197}Au
- Beam intensity ~2x10^{7}/spill (spill = 5s)
- 1% interaction target (12 segments)
  - DAQ is operating stably
  - Event rate up to 25 kHz
  - Data rate up to 250 Mbyte/s
- Expected pair rates/day:
  - 20 ω, 480 ρ, 3 ϕ, 32k η, 28k „excess" pairs
  - And plenty of strangeness!
- Production beam Au+Au at 1.25 GeV/u is scheduled for the beginning of next year

Simulated counts for 4 weeks beam



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



„The show must go on ...“

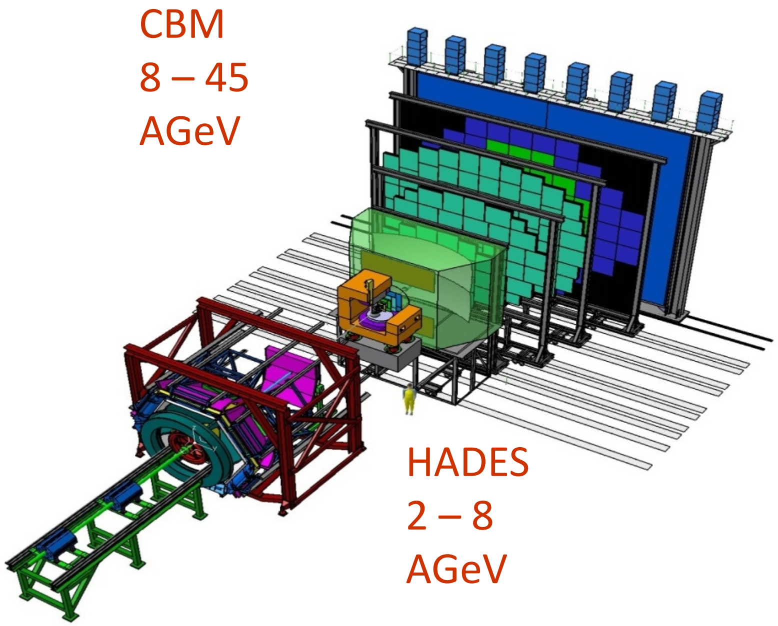
The future at FAIR

SIS100:

- Joint running of HADES and preCBM:
  - 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:

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



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 HIC 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

Thanks

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:
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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

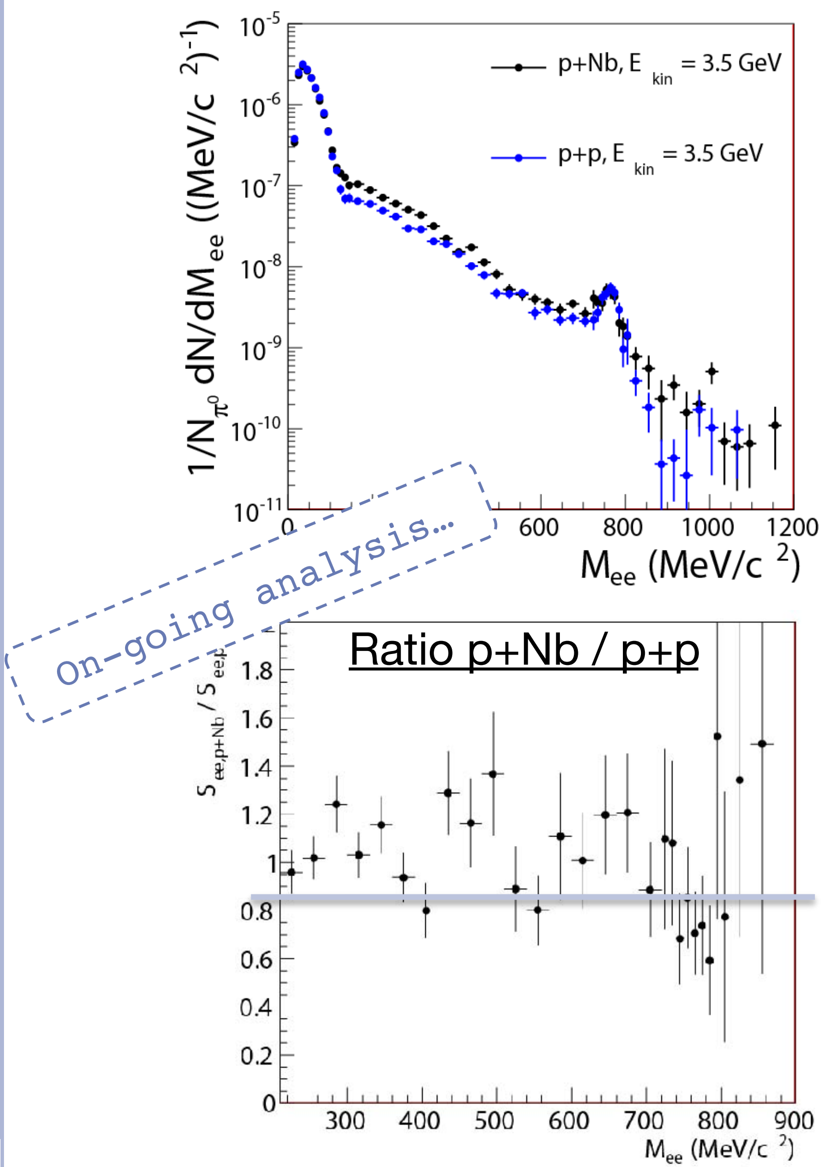
17 institutions

> 150 members

Bonus slides

ω in cold nuclear matter: p+Nb vs. p+p

Spectra normalized to π^0 yield



Analysis: M. Weber, M. Lorenz

p+Nb vs. p+p: no change in the ω width, position

- From photoproduction data, ω is known to be broadened in the medium by factor of 16:
  - additional inelastic channels for removing ω-mesons, e.g. $\omega N \rightarrow \pi N$
    - shortening of ω-lifetime
    - increase in width

- in-medium ω inelastic width proportional to ω absorption:

$$\Gamma(\rho,|\vec{p}_\omega|) \propto \rho v \sigma_{abs}$$

- use transparency ratio (probability for leaving the nucleus) :

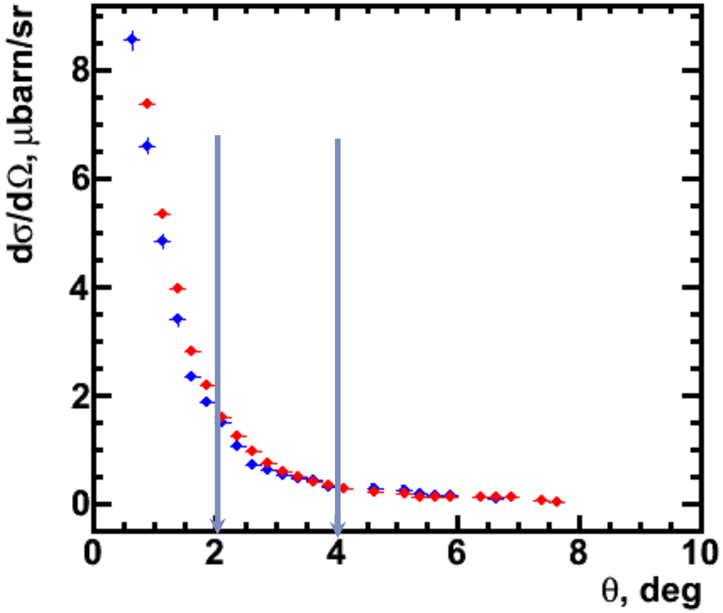
$$T_A = \frac{\sigma_{\gamma A \rightarrow \omega X}}{A \cdot \sigma_{\gamma N \rightarrow \omega X}}$$

Is a validity of the spectator model guaranteed?

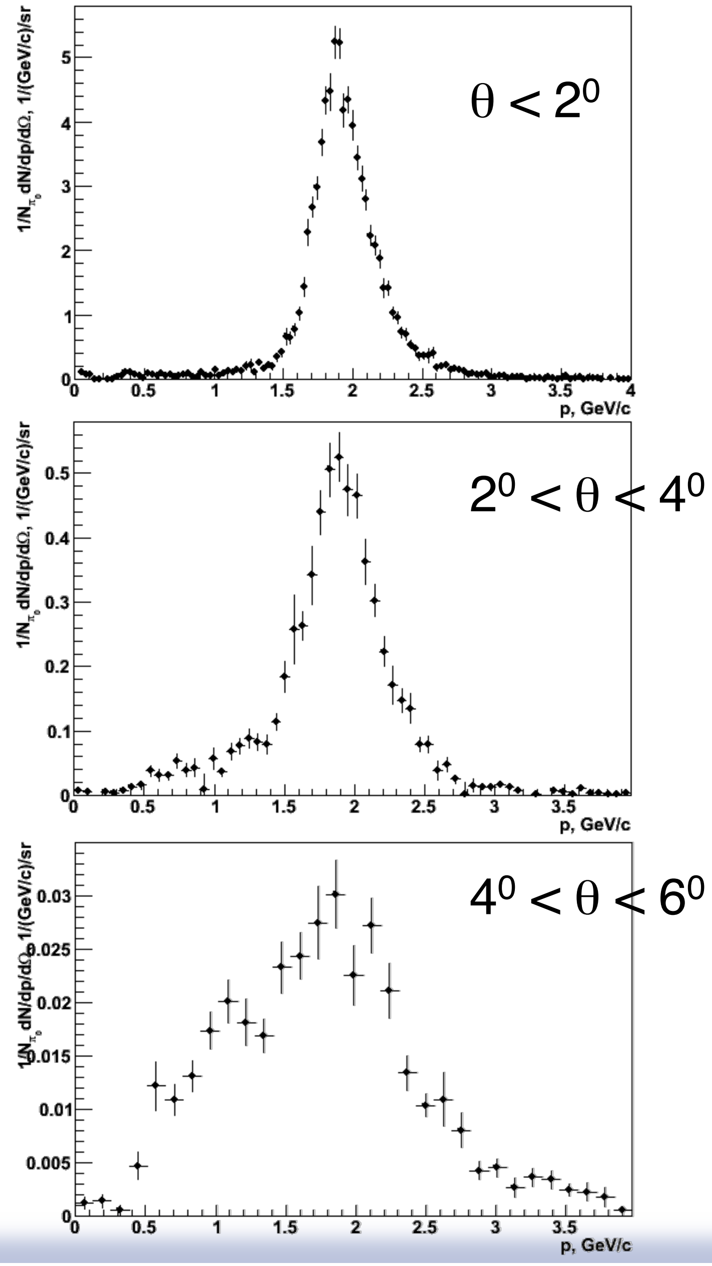
Spectator proton:
small angles, momentum ~ $p_d/2$

$$p_{beam} = \sqrt{E_{beam}^2 - m_p^2} = 1.976\,\mathrm{GeV}$$

Laboratory scattering angle

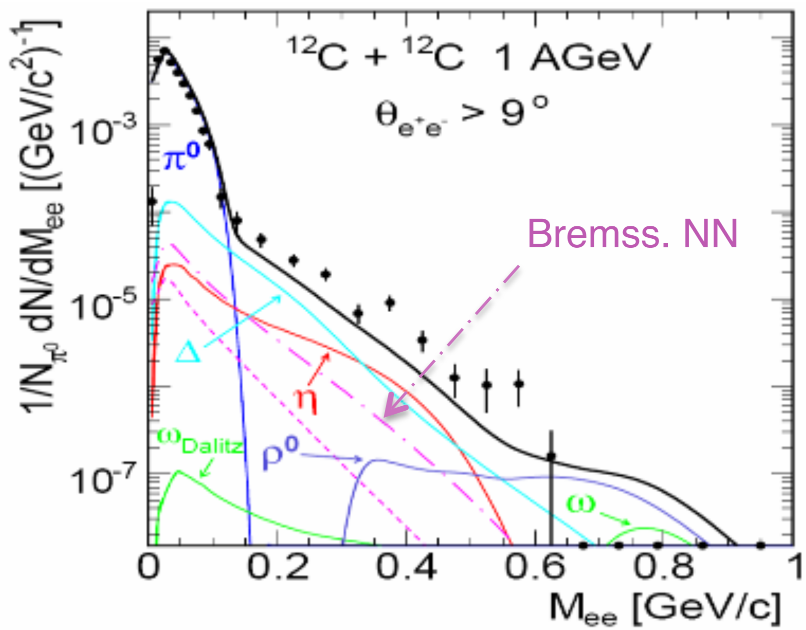


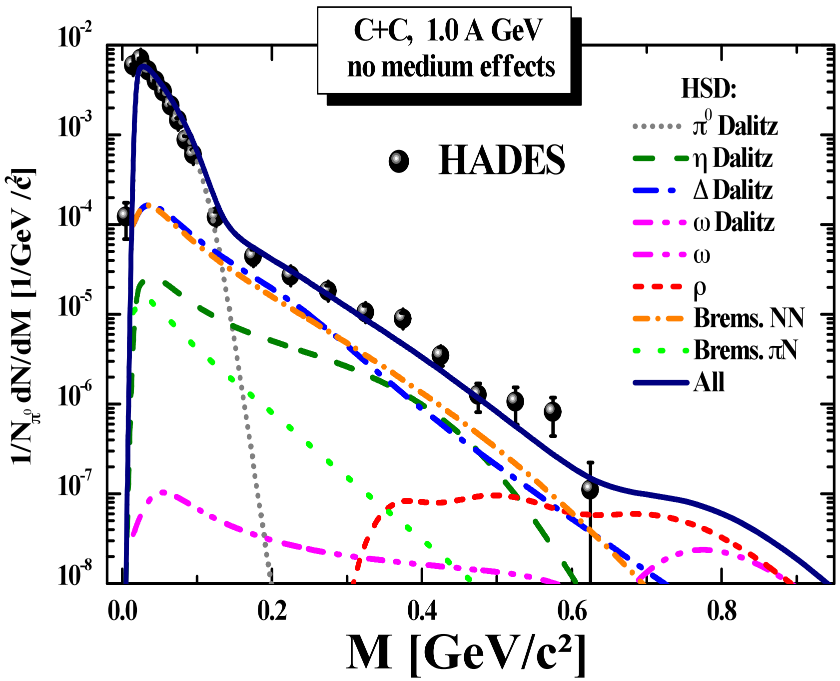
p_{sp} momentum distributions



„DLS puzzle“ solved by Bremstrahlung?

Efficiency corrected di-electron spectra and HSD transport



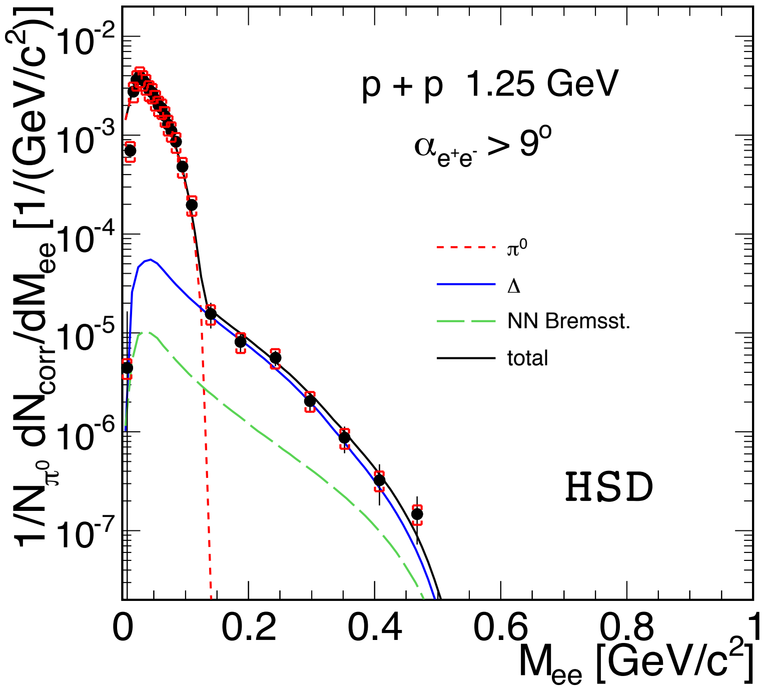


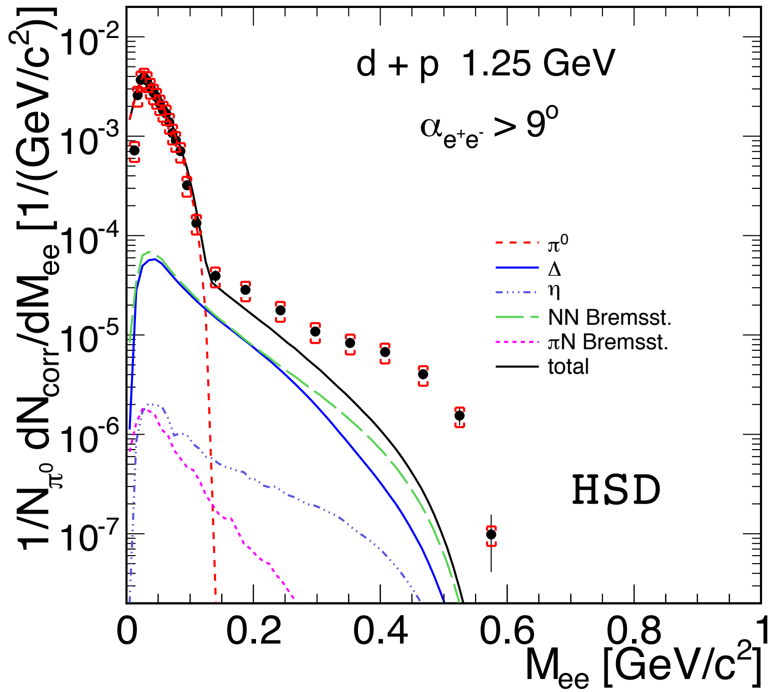
- ✗ 1997: Bremsstrahlung contribution was found to be small
- ✗ 2007: “DLS puzzle” may be solved when incorporating a stronger Bremsstrahlung contribution???

→ experimental test!

HSD: E.L. Bratkovskaya and W. Cassing Nucl.Phys A 807 (2008) 214
New treatment of bremsstrahlung: L.P. Kaptari and B. Kämpfer, Nucl.Phys. A 764 (2006) 338

Elementary reactions in transport models

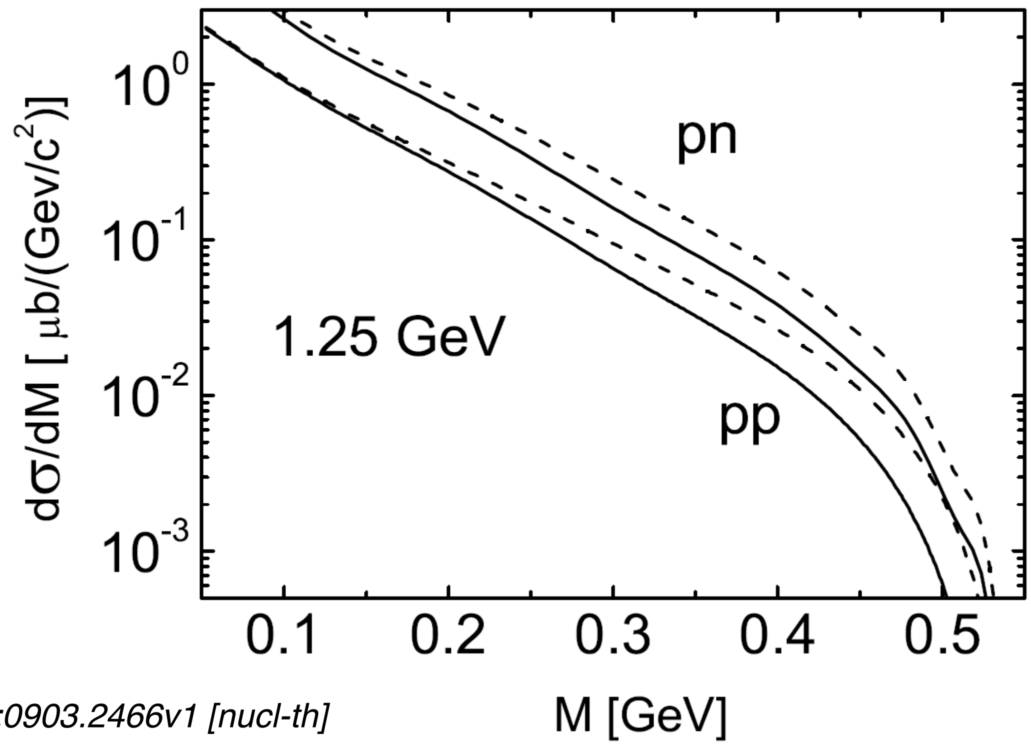




- NN bremsstrahlung are calculated within the SPA model, restricting the emission process to elastic NN collisions
- Δ contribution is treated explicitly by producing and decaying the resonance within a Dalitz-decay model in inelastic collisions
- The interference of elastic and inelastic channels is neglected.

The interference effects

M_{inv} distribution of e^+e^- in pp and pn collisions as a coherent sum (solid lines) vs. an incoherent summation (dashed lines)

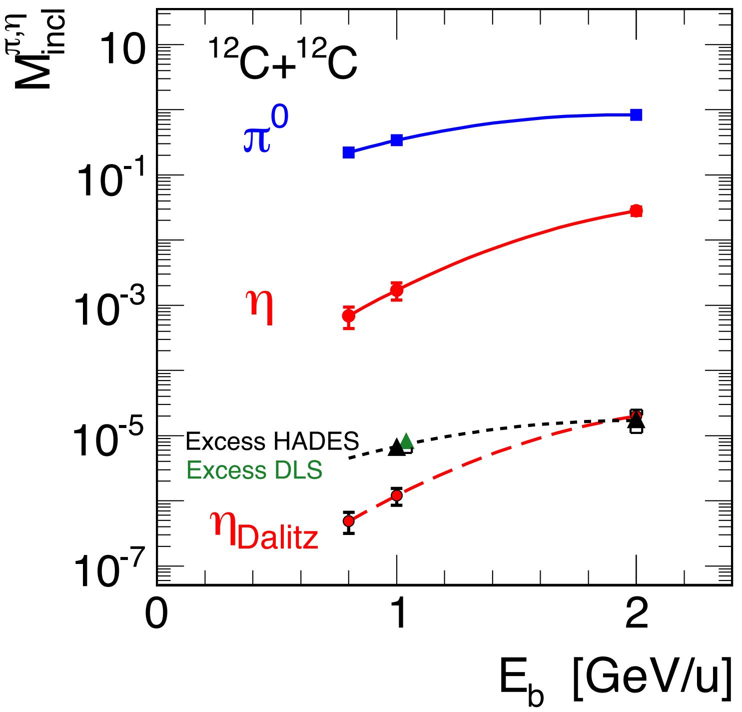


L. Kaptari et al. arXiv:0903.2466v1 [nucl-th]

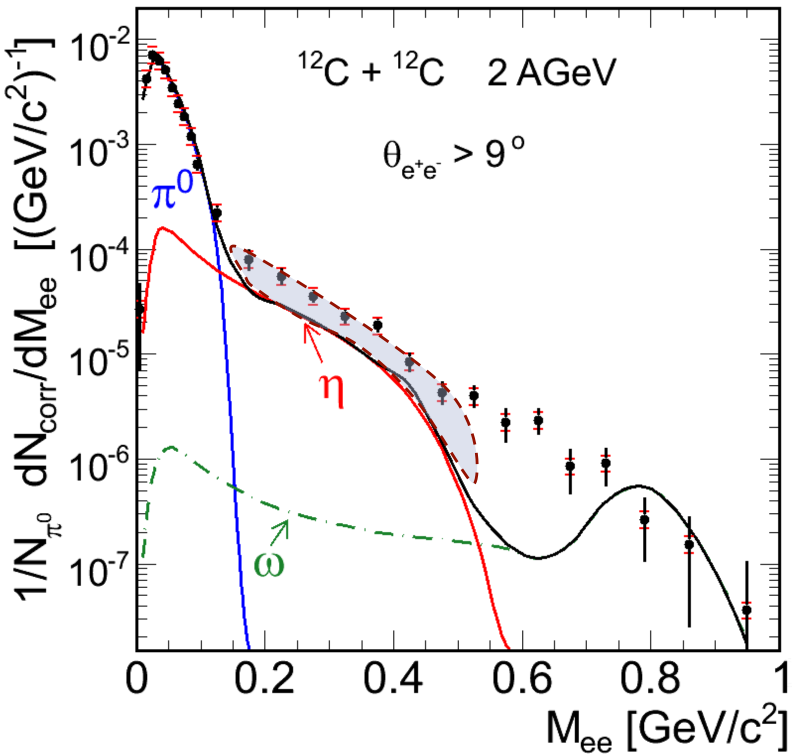
The interference effects become significant at higher values of the di-electron invariant mass and reduce the cross section by a factor of about 2 – 2.5!

The pair „excess" in CC quantified

Excess pair yield over cocktail of long-lived sources vs. E_{beam}



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



Phys. Rev. Lett 98 (2007) 052302

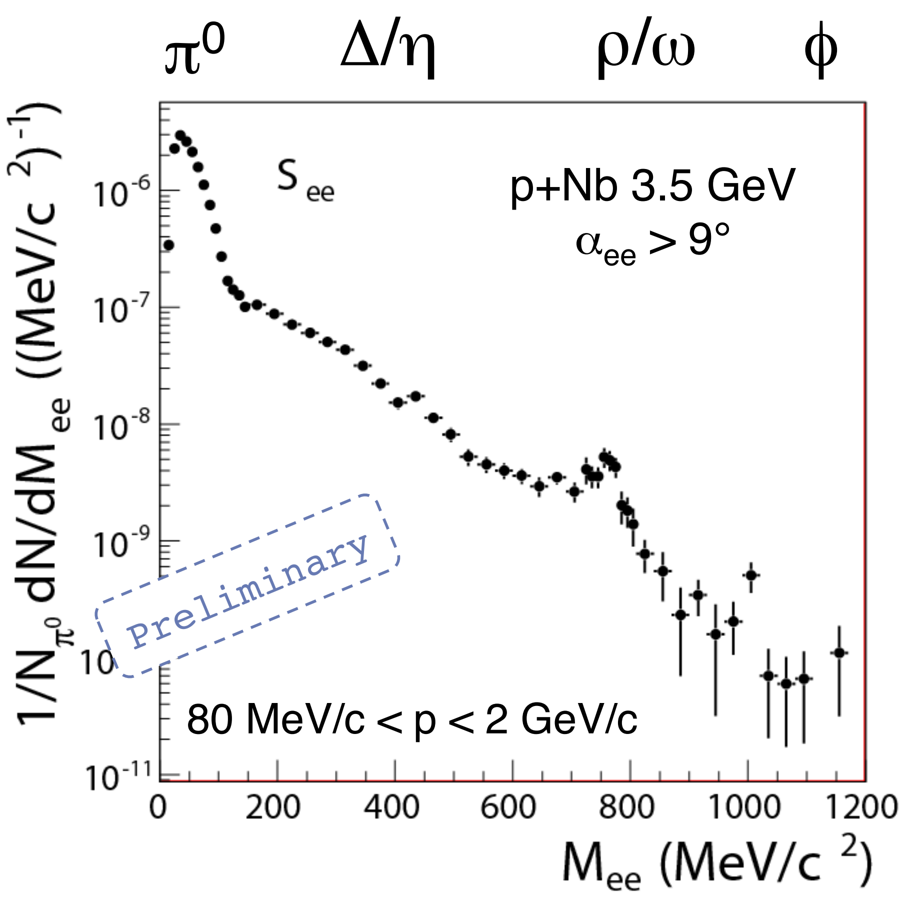
Hadron data:

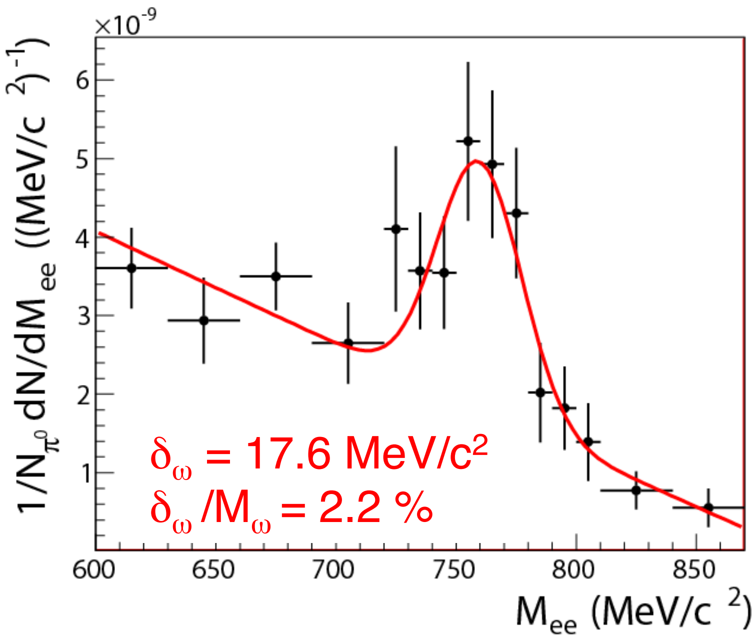
[1] R. Averbeck et al., TAPS coll., Z. Phys. A 359, 65 (1997)
[2] R. Holzmann et al., TAPS coll., Phys. Rev. C 56, R2920 (1997)

- Measured pair excess in CC scales with beam energy as M_π
- Hinting at Δ resonance decays and/ or NN bremsstrahlung

e^+e^- pairs from p+Nb at E_{beam} = 3.5 GeV

Efficiency corrected data, normalized to π^0 yield (via measured $\pi^{\pm}$)

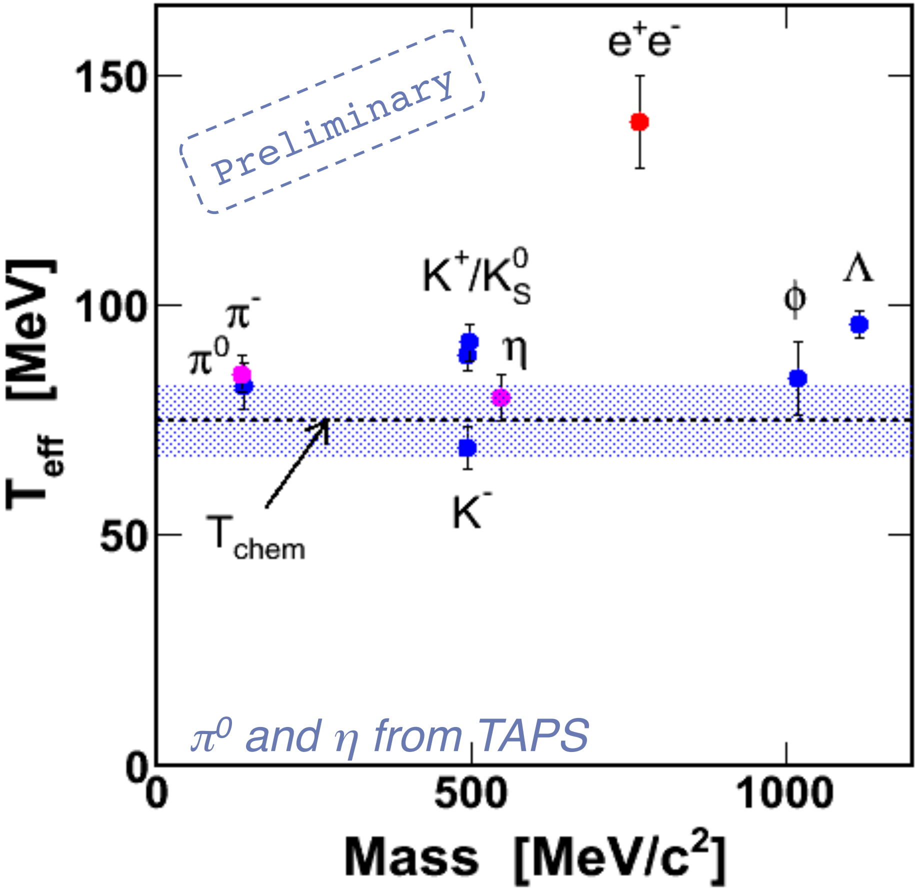




signal pairs	$6.5 \cdot 10^5$
π^0 region	$5.5 \cdot 10^5$
ω/ρ region	463
ϕ region	36

Analysis: M. Weber

Systematic on slopes at 1.76 GeV/u: Hadrons vs Dileptons



- No strong deviation between kinematical and chemical freeze out
- Slope for $\rho/\omega > T_{chem}$ and other hadrons
- Different slopes for $\phi \rightarrow K^+K^-$ and ρ/ω