Puzzles, facts, lessons from dileptons in few GeV energy regime

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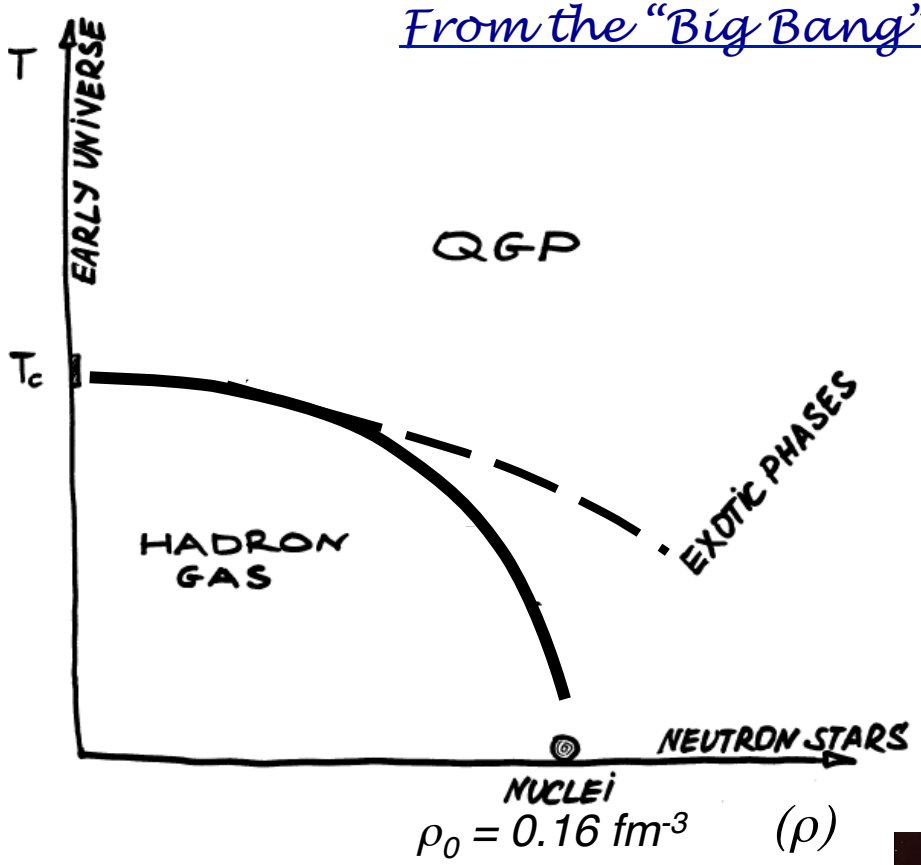
Goethe-Universität Frankfurt / EMMI

Outline:

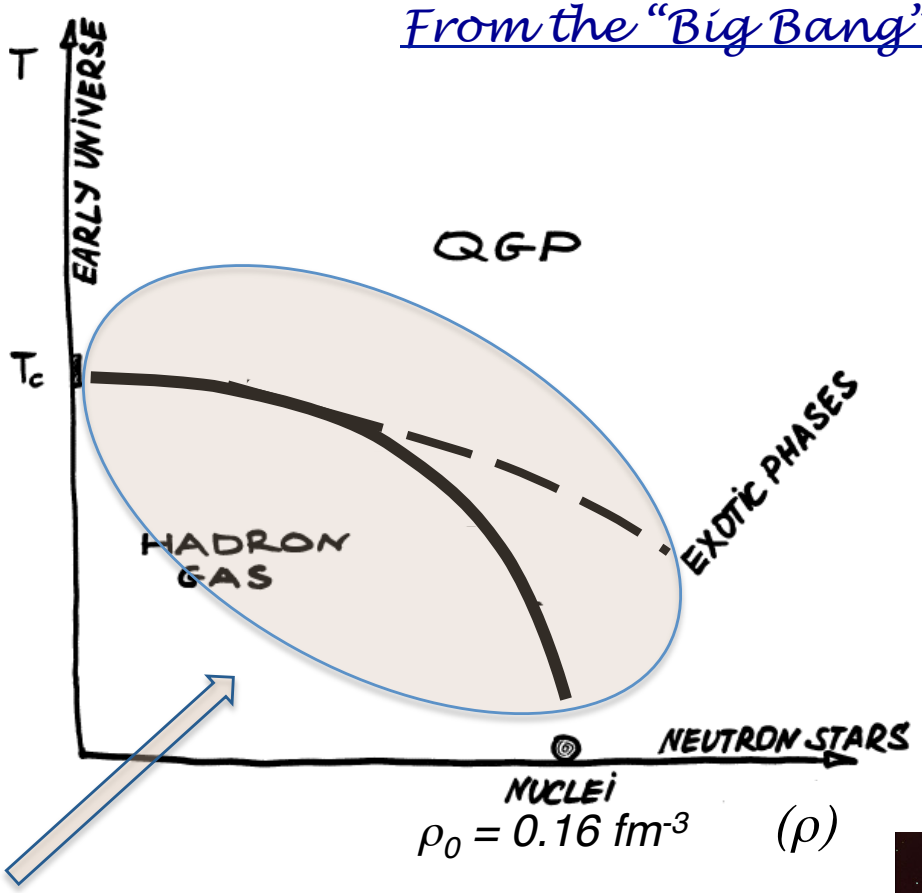
- Probing resonance matter with HADES:
  dileptons and strangeness
- e^+e^- pairs: from elementary to heavy-ion collisions
- HADES and the Phase Diagram of Matter
- The perspectives and challenges at FAIR

Nuclear matter in the universe



From the "Big Bang" to the galaxies

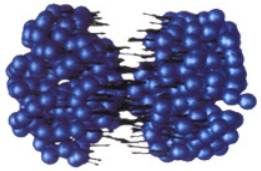
Nuclear matter in the universe



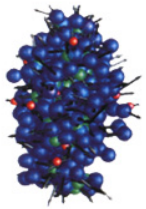
From the "Big Bang" to the galaxies

Accessible through heavy-ion collisions

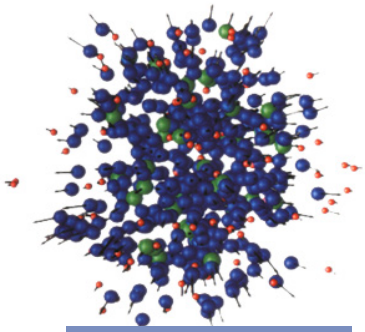
Transient existence of a dense/hot phase



first-chance collisions



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

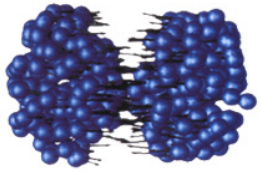


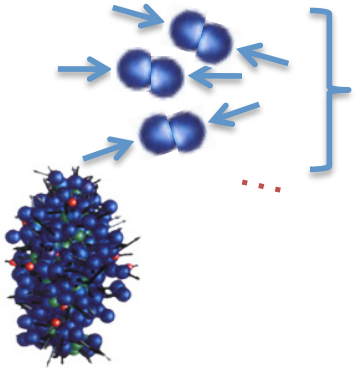
freeze-out

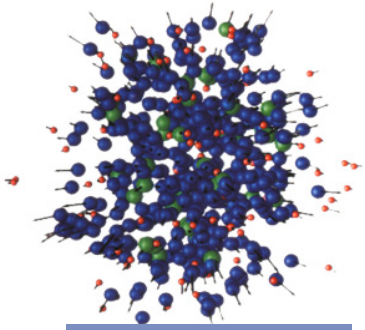
Challenge

Extract information on the high density phase

Transient existence of a dense/hot phase







first-chance collisions

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

freeze-out

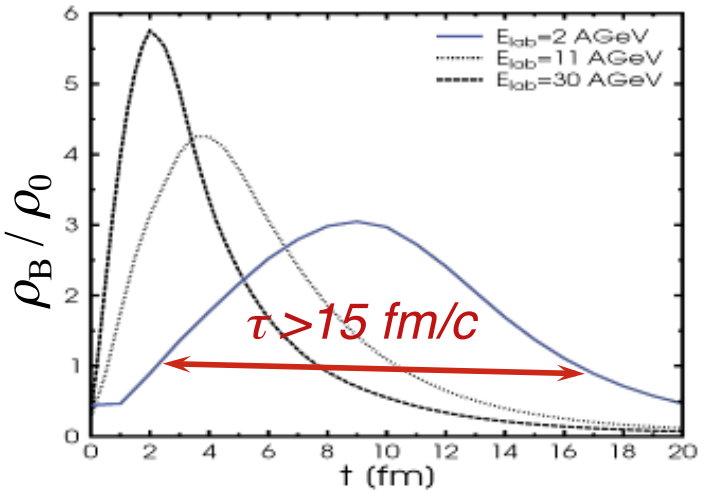
Challenge

Extract information on the high density phase

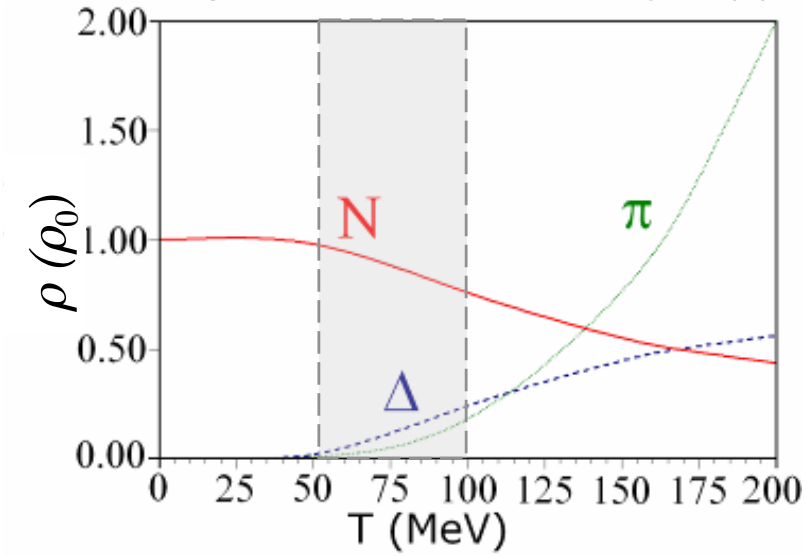
- Is extreme matter created at SIS?
- Same in the whole volume or *<dense and "corona" like>*

The SIS heavy-ion energy regime – baryon dominated!

Evolution of average ρ_B (τ_{system})



Composition of a hot πΔN gas (T)



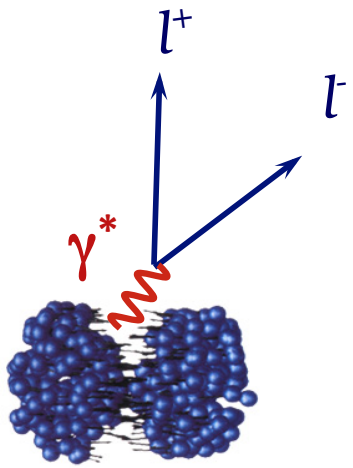
S. Vogel et al., Phys. Rev. C 78 (2008) 044909
R. Rapp and J. Wambach, ArXiv:hep-ph/9909229v1

- Long lifetime of the high density phase:
  - → *System stays above ground state density for > 15 fm/c*
  - densities: ρ_{max}/ρ_0 = 2-3
  - temperature: T < 100 MeV

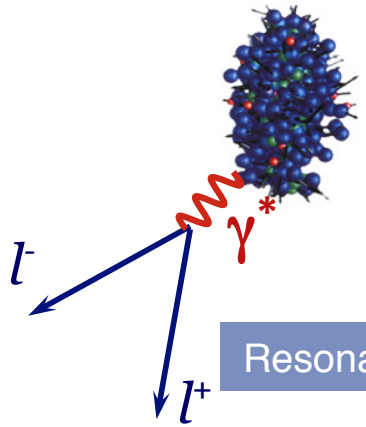
- Baryon dominated:
  - π densities a factor ~100 lower as compared to SPS regime!
  - matter dominated by baryonic resonances (~30%), N_π/A_{part} ≈ 10%

I prefer penetrating probes

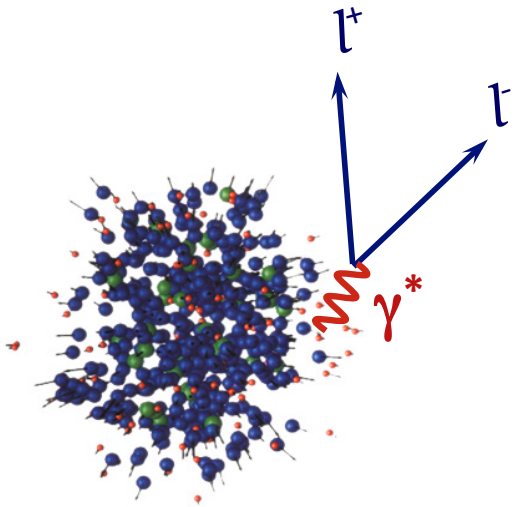
Electromagnetic structure of dense/hot matter



Bremsstrahlung



Resonance decay



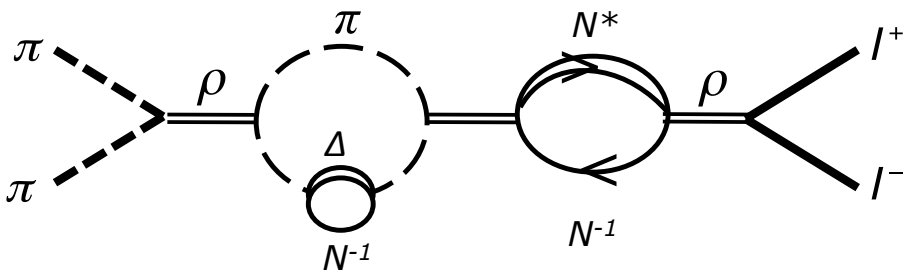
Decays of (long-lived) neutral mesons (π^0, η, ω)

- 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)

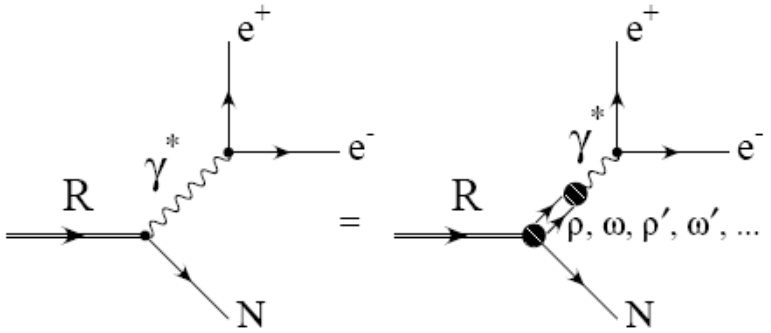
  Strong coupling of γ^* to Vector Meson → VMD model

The ρ meson in nuclear matter

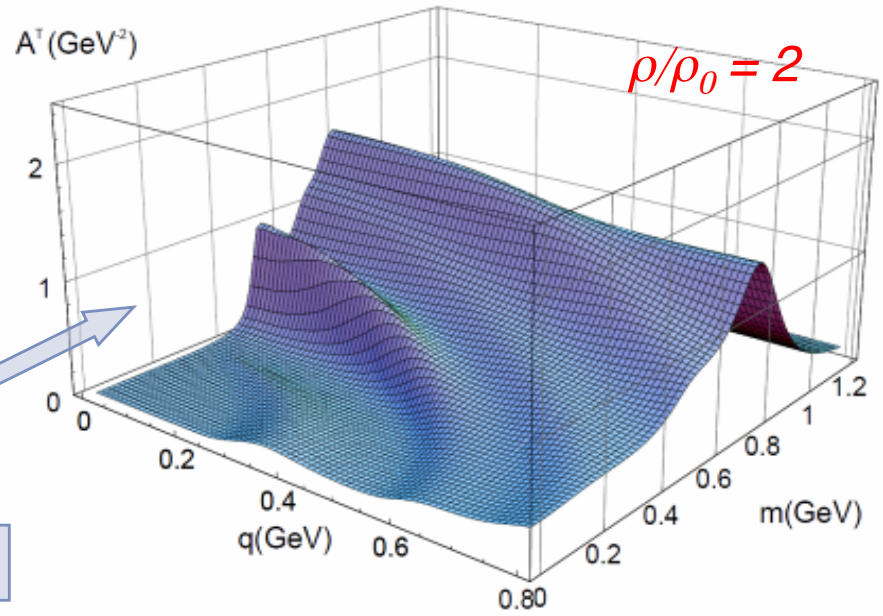


Additional contributions to the ρ-meson self-energy in the medium

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

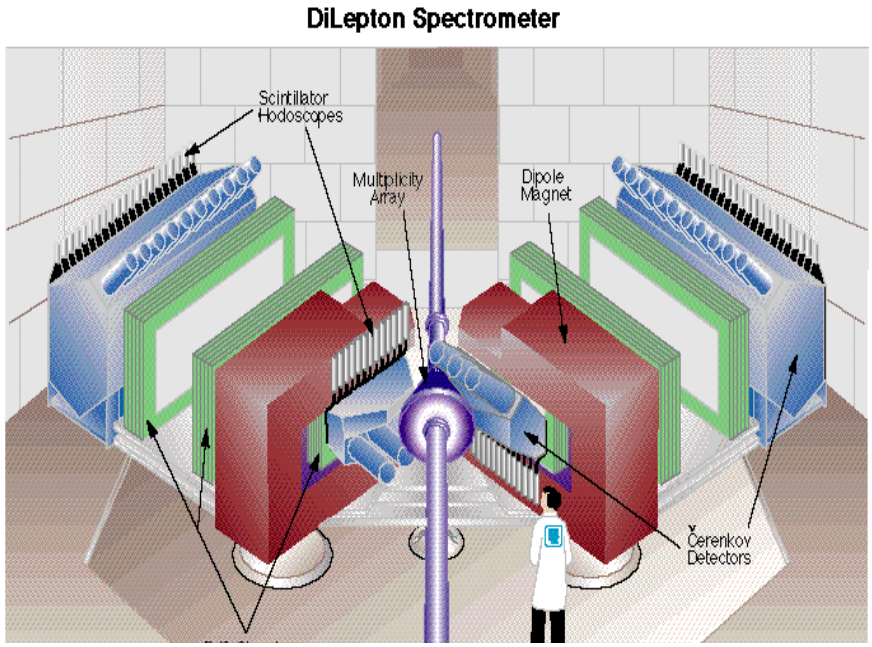
- Large combinatorial background in e^+e^- from:
  - Dalitz decays (π^0)
  - Conversion pairs

[+] *H.Wallace, 1943*

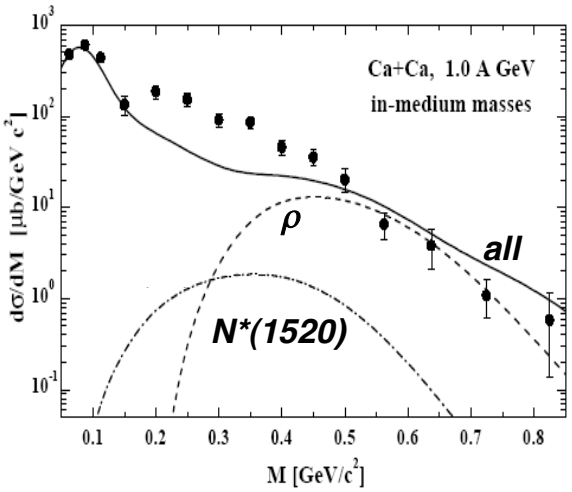
The DLS at LBNL

The DLS puzzle !

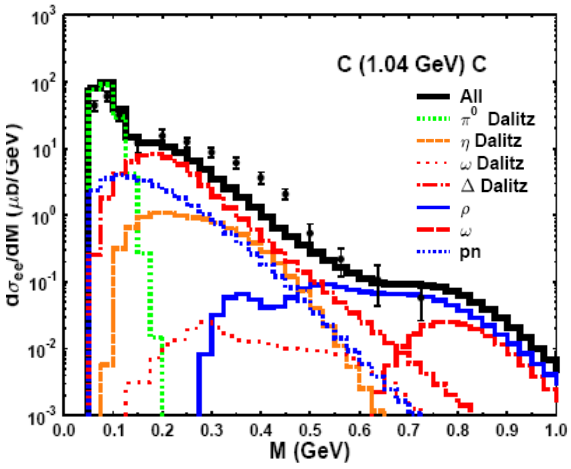
Observed excess remained unexplained over years



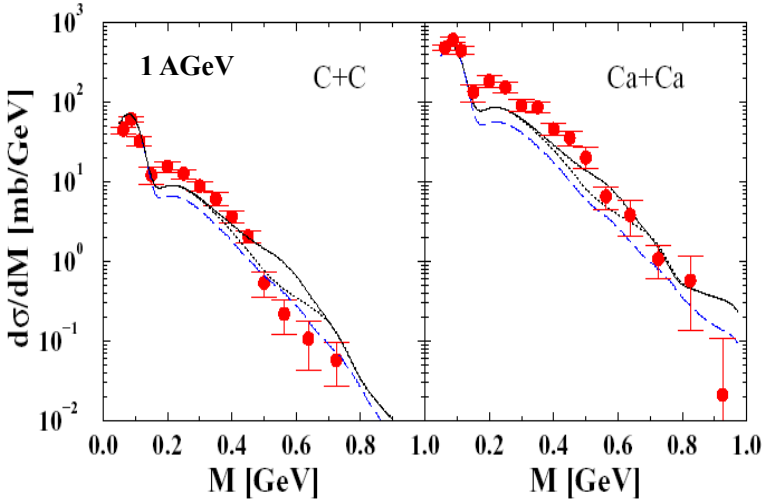
Calculation: ***E.L.Bratkovskaya et al.***
Phys. Lett. B445 (1999) 265



Calculation: ***Ernst et al.***
Phys. Rev. C58 (1998) 447

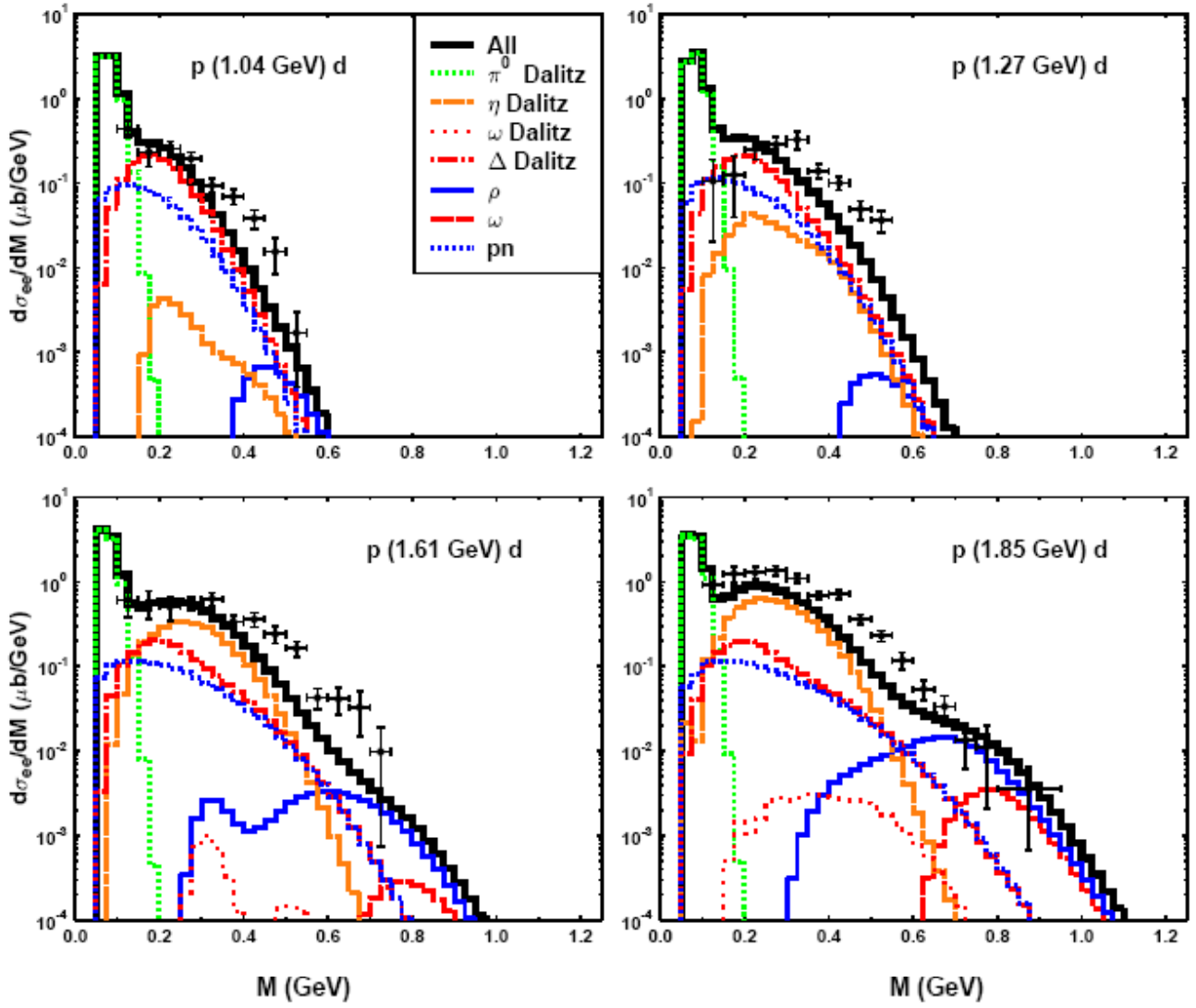


Calculation: ***C. Fuchs et al.***
Phys. Rev. C68 (2003) 014904



Even more puzzling

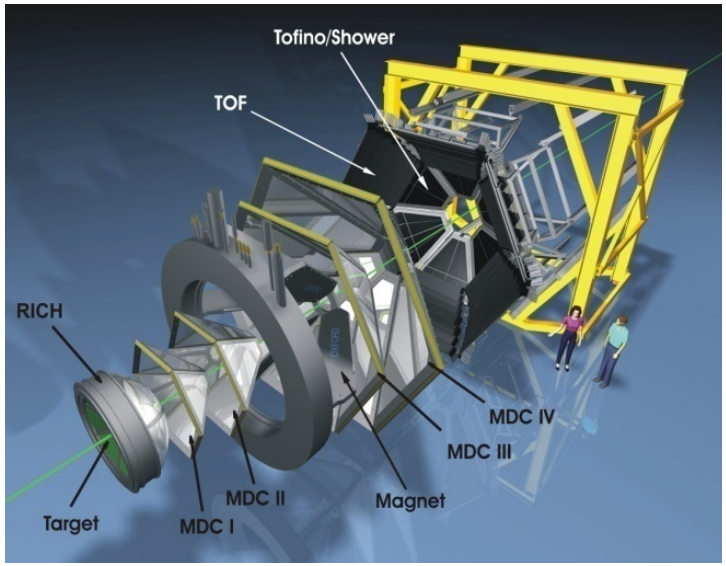
No consistent explanation of pair production in elementary reactions



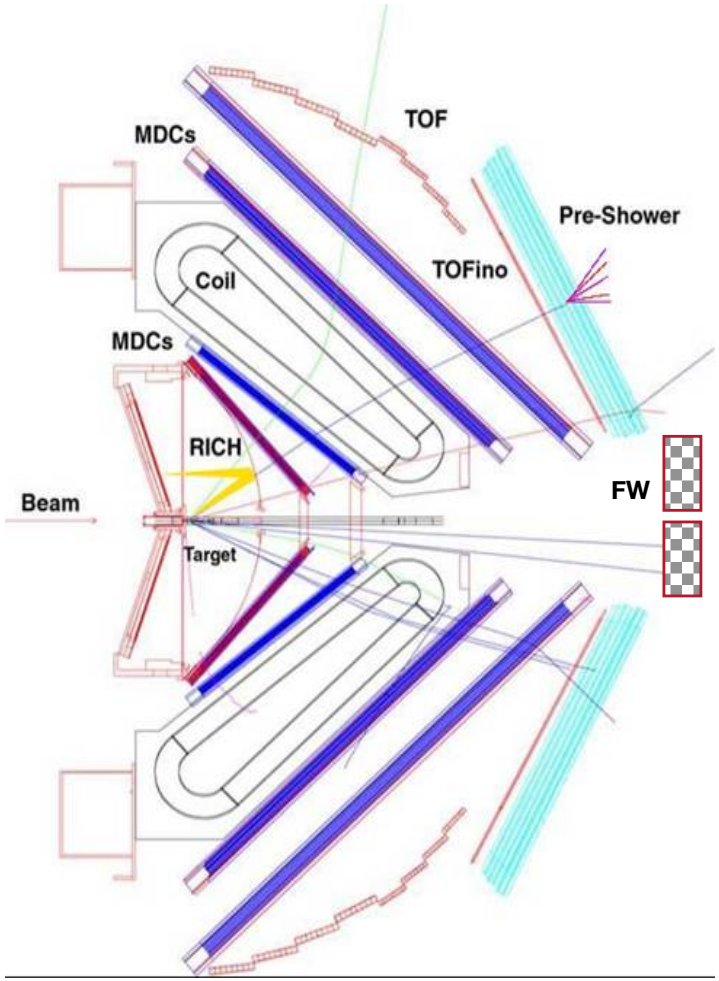
UrQMD C. Ernst et al. PRC 58 (1997) 447

High Acceptance Di-Electron Spectrometer

HADES

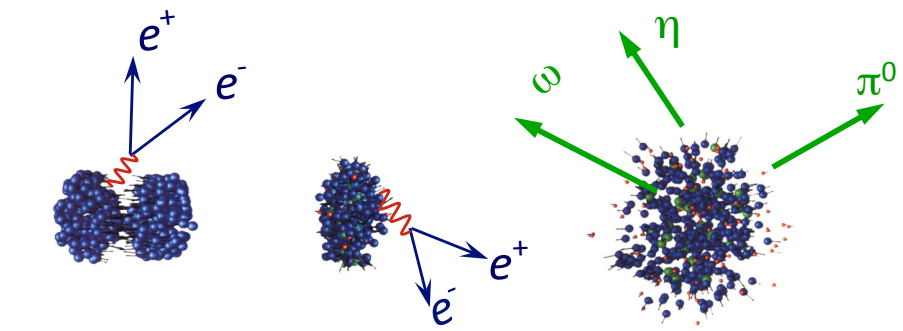


HADES strategy:
Systematic di-electron spectroscopy in NN, AA, pA, πN and πA collisions



- 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?

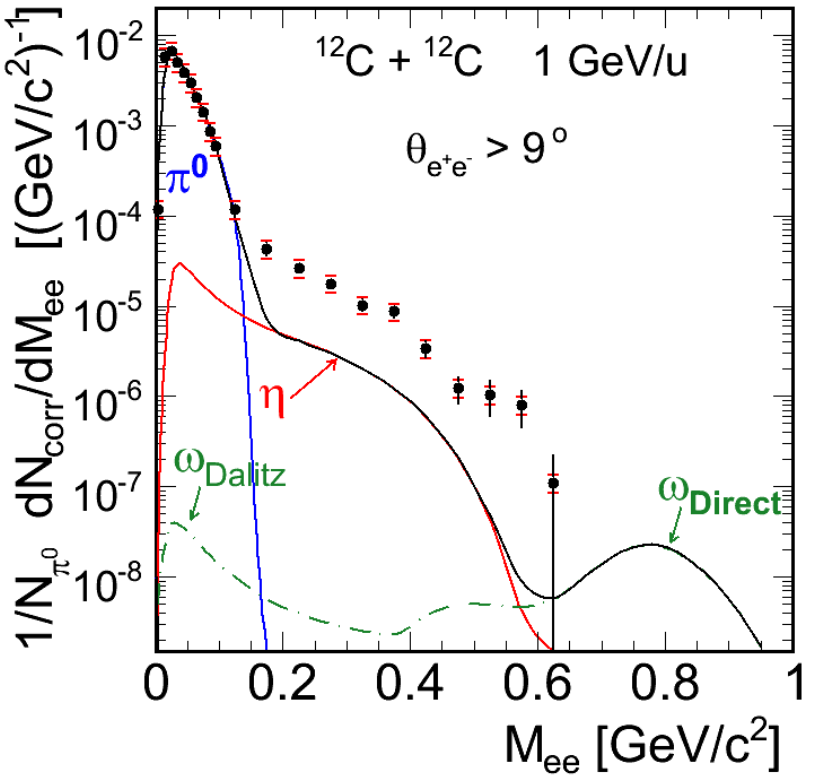


first-chance collisions | dense phase | freeze-out

- **First chance NN collisions**
  - Baryonic sources:
    - NN bremsstrahlung
    - Resonances (Δ, N^*) → 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!

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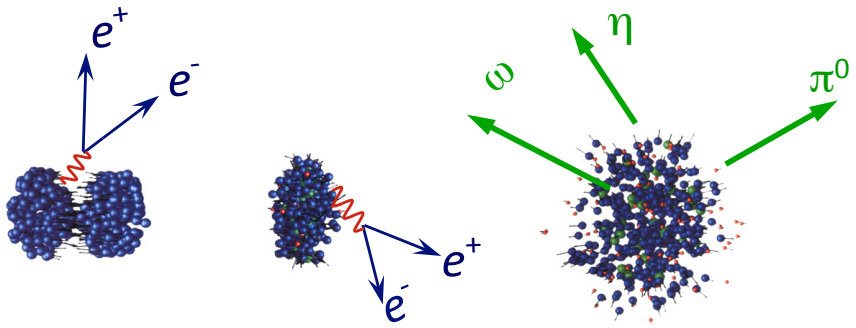

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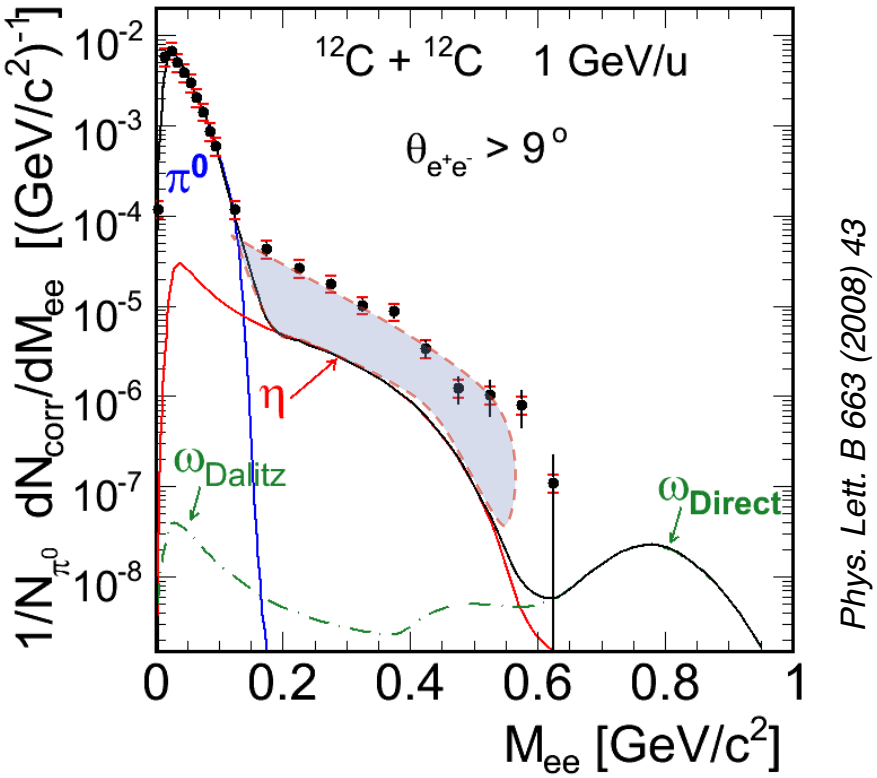
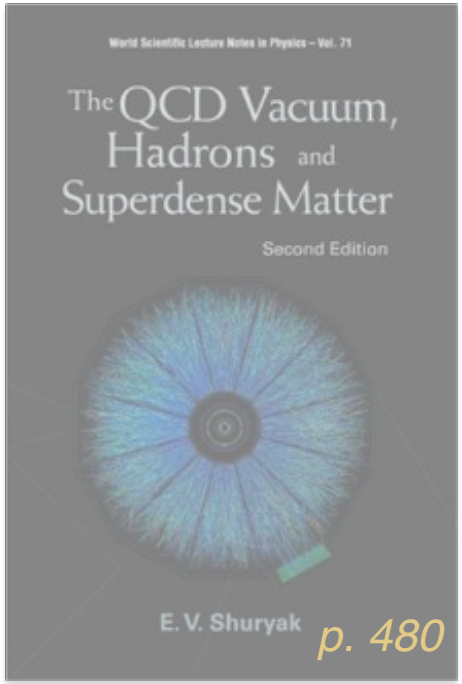


Phys. Lett. B 663 (2008) 43

Enhanced pair yield above η-contribution established!

„True" excess from dense phase?

Contribution from the initial phase?

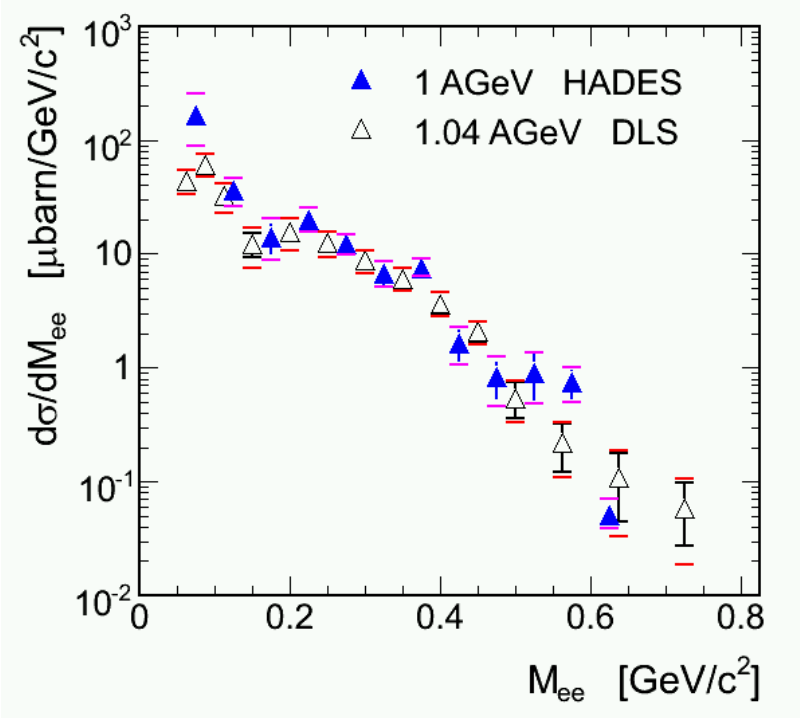


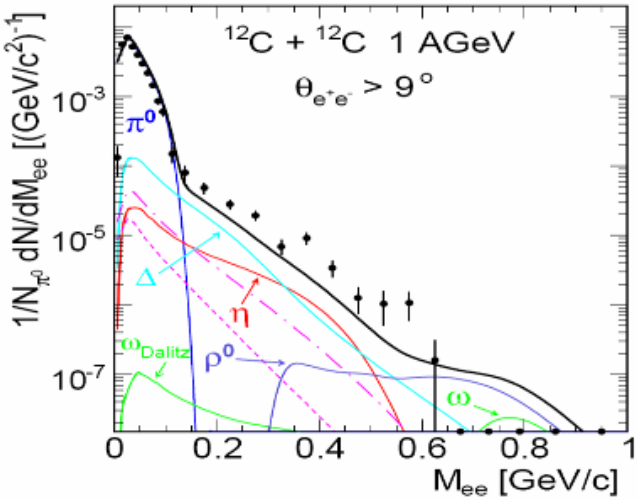
„At Berkeley BEVALAC the DLS spectrometer was built to study dileptons... A striking dilepton signal was found, but my guess is its reality will probably never be understood, although this mass/energy region will be soon tested by the HADES experiment at GSI“

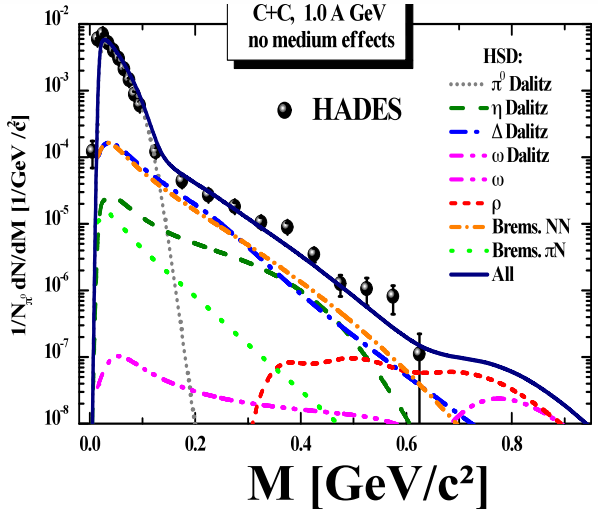
E. Shuryak

„DLS“ puzzle solved by Bremsstrahlung?

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







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

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 HI collisions

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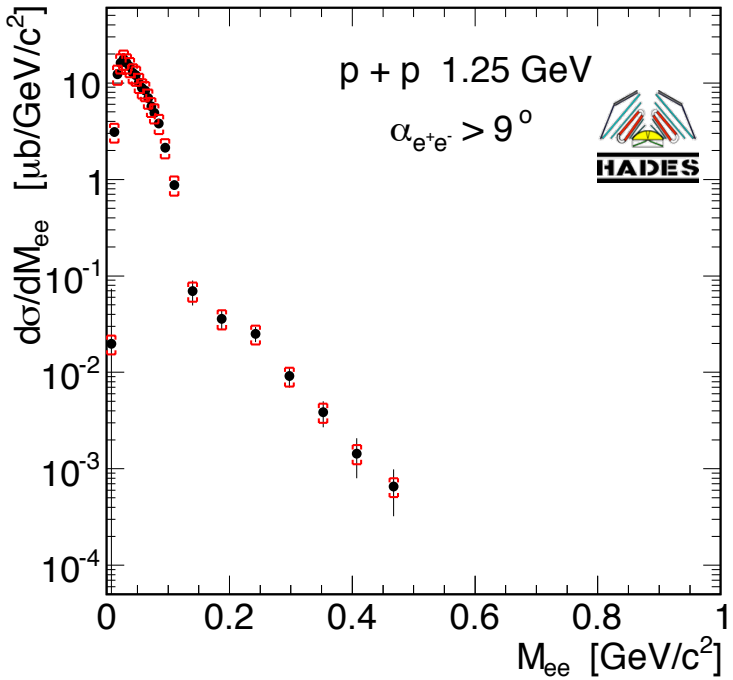
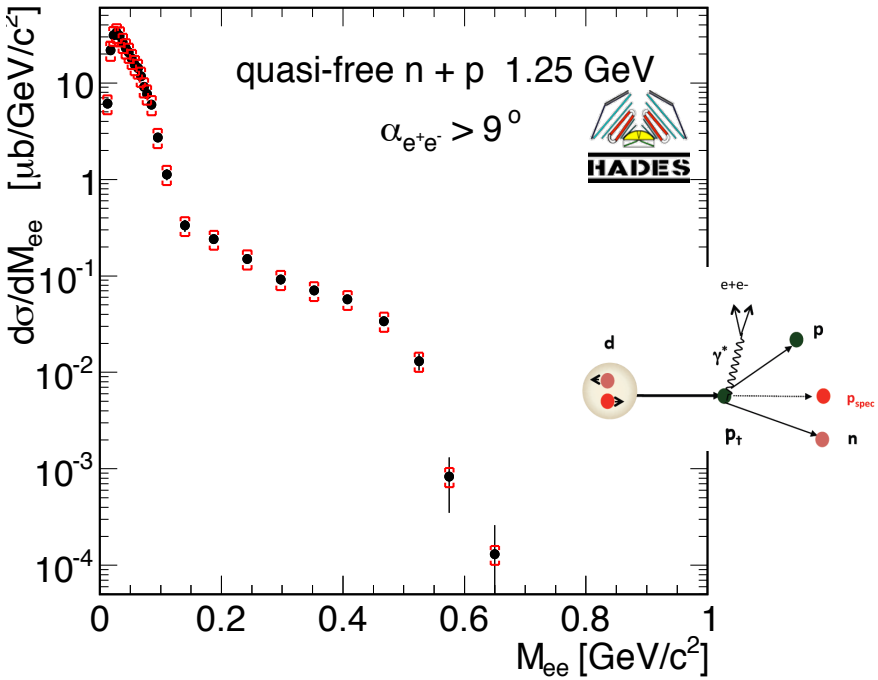
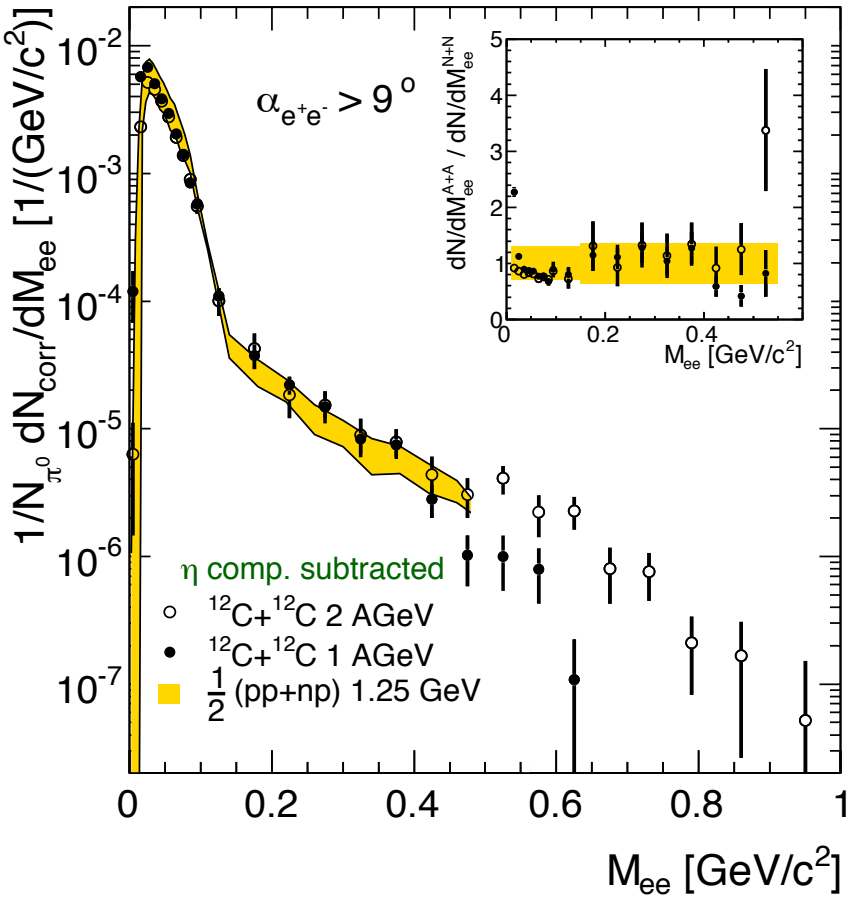


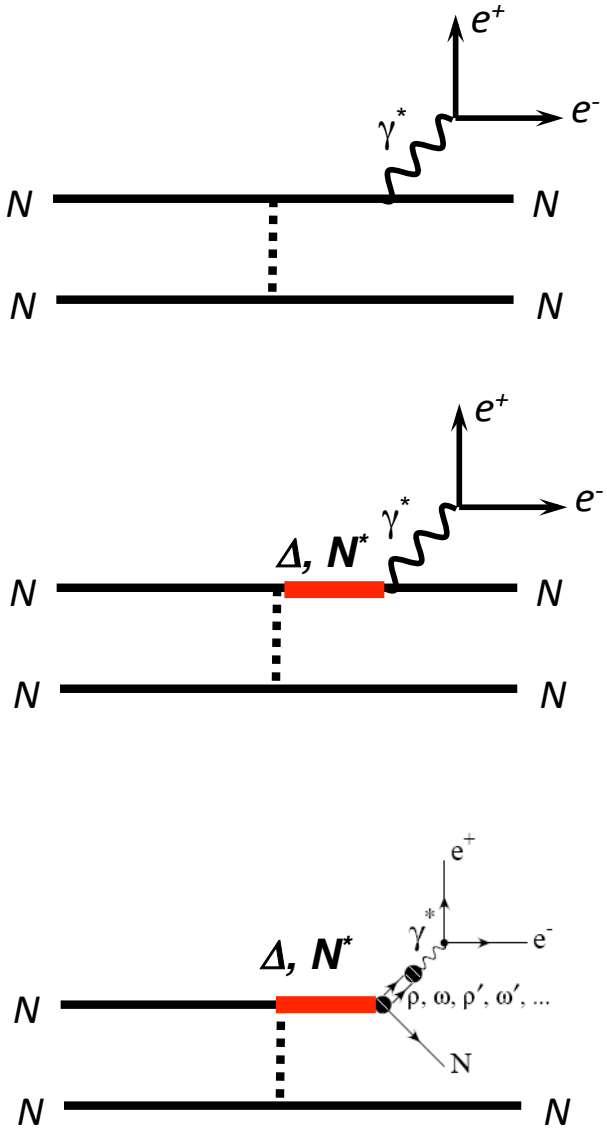


Origen of the low-mass pair excess in C+C collisions

Definition of the "Reference data"



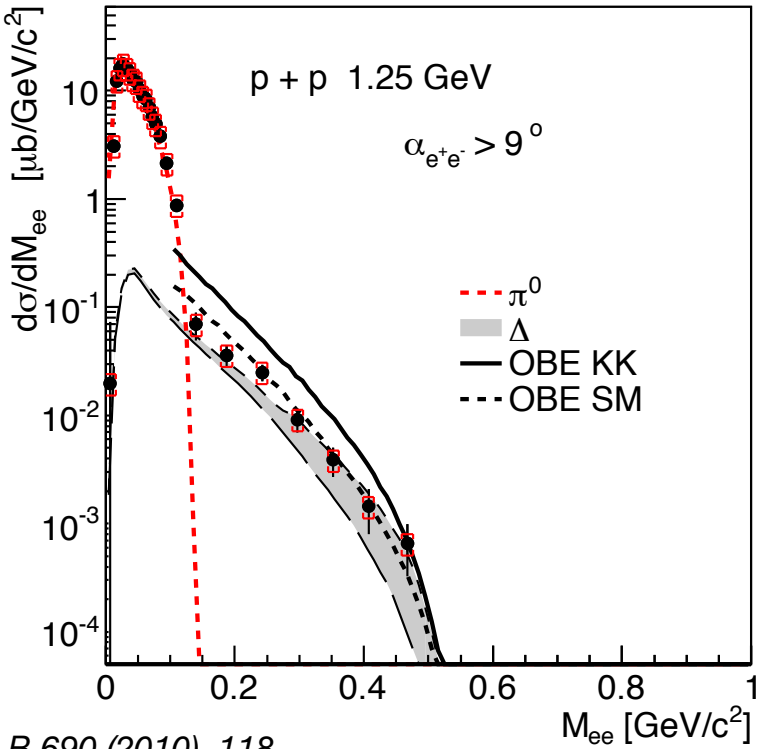
HADES: Phys. Lett. B 690 (2010) 118

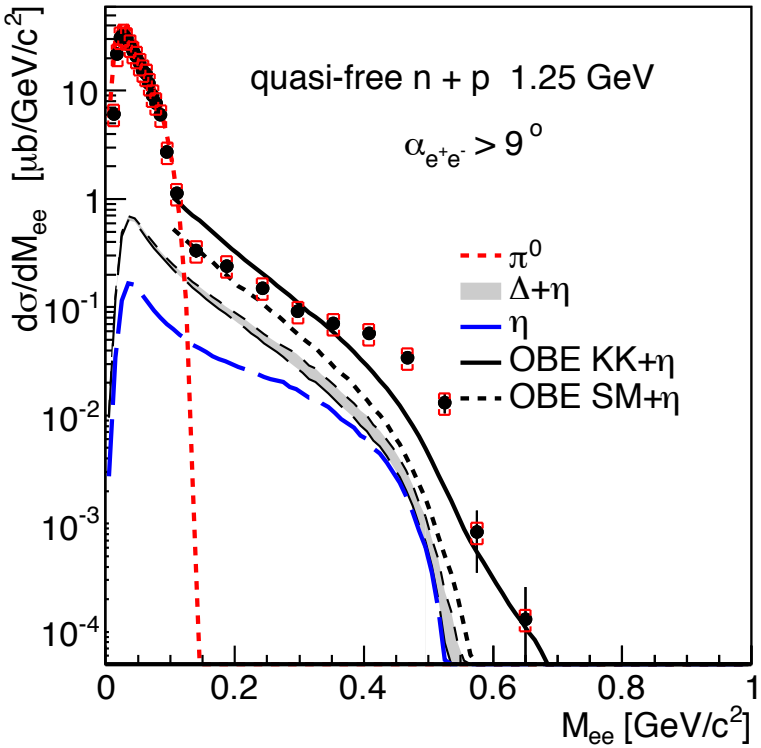


C. Fuchs, PRC 68, 014904 (2003)

Lesson: know your reference!

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



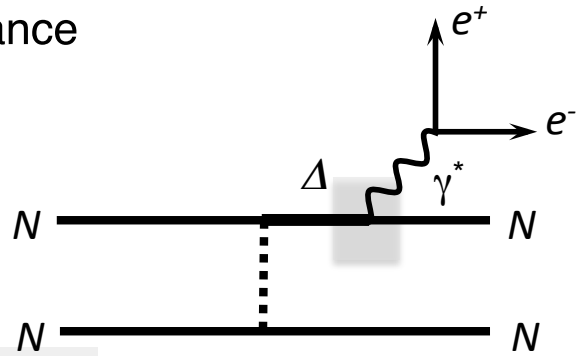


Phys. Lett. B 690 (2010) 118

- n+p case: Different schemes for implementing gauge invariance
- OBE effective models reproduce p+p, but not (yet) n+p !

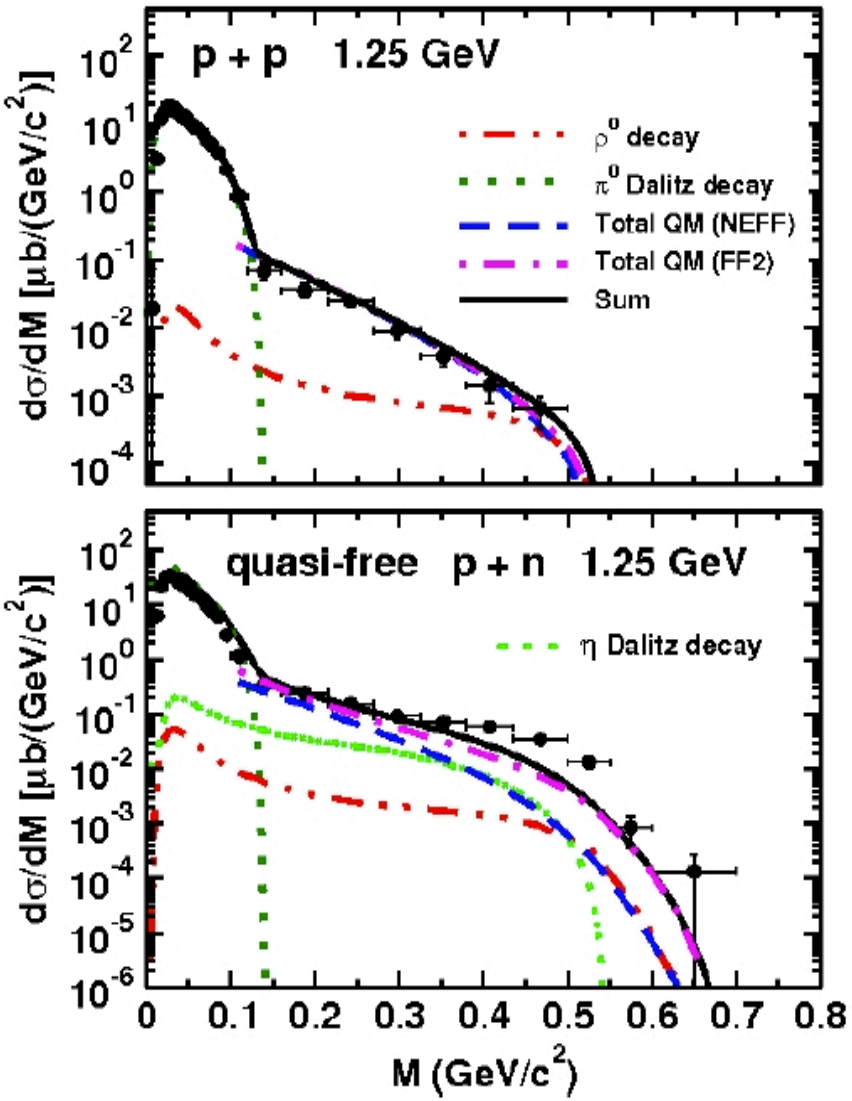
- N-Δ transition electromagnetic form factors

  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

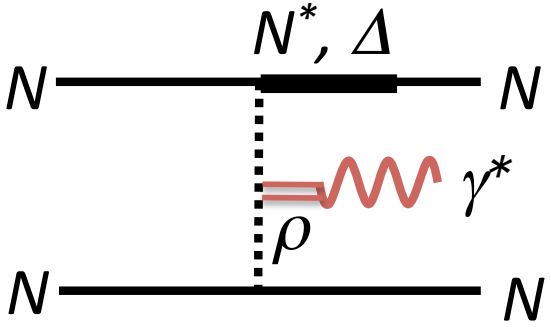


$q^2 = M^2_{inv}(e^+e^-) = M_{\gamma^*}{}^2 > 0$

Close to a theoretical explanation

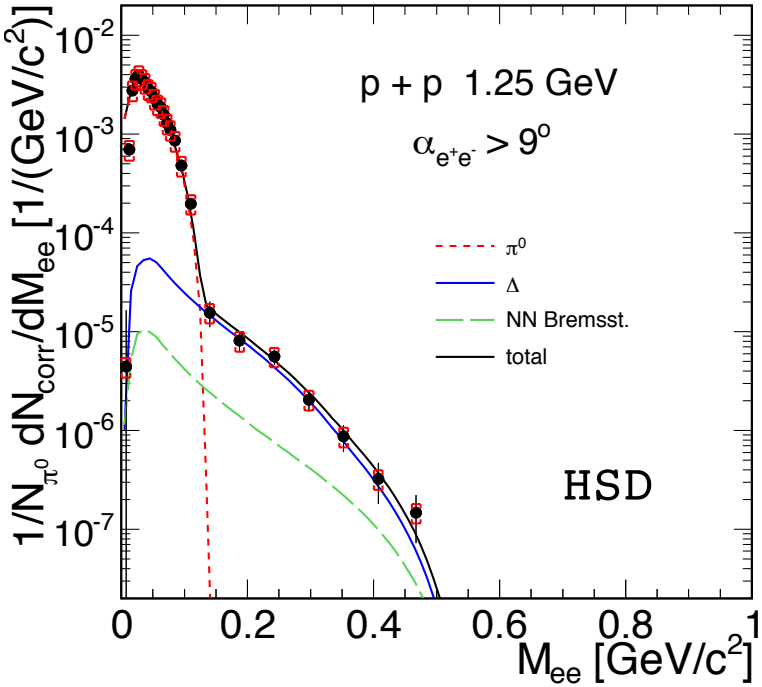


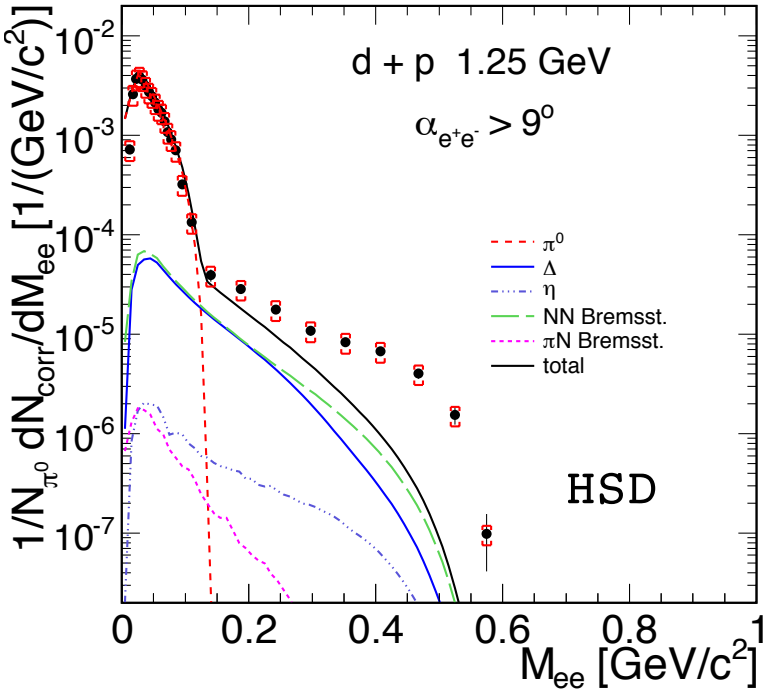
- One Boson Exchange effective Lagrangian based approach including pion electromagnetic form factor



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

Elementary reactions in transport models

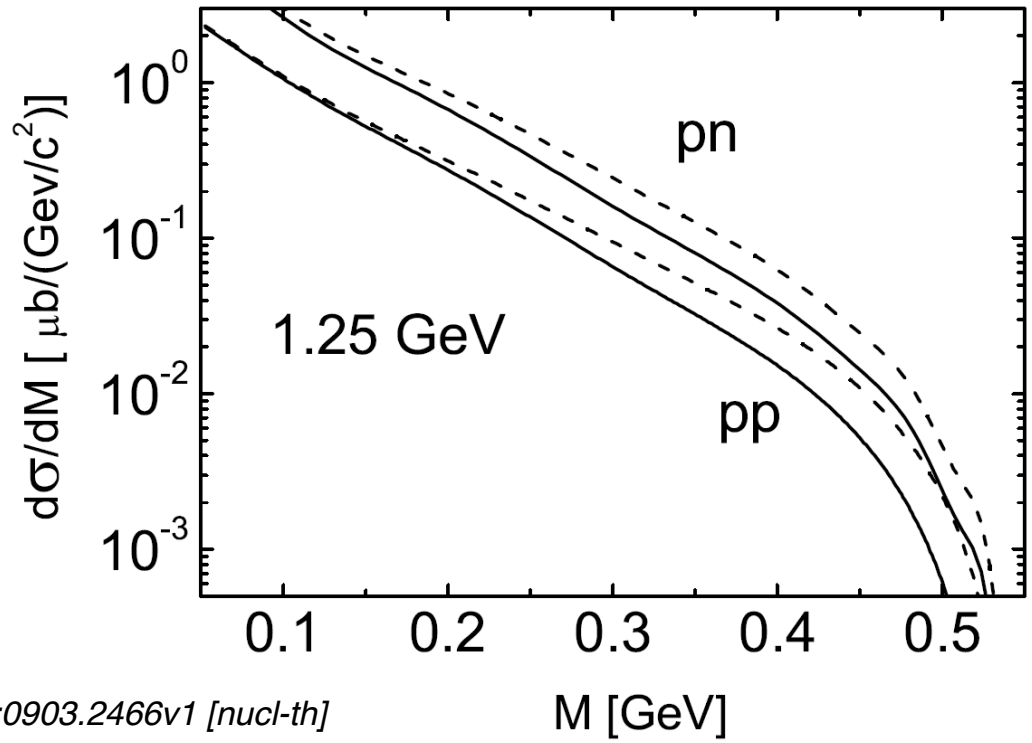




- NN bremsstrahlung are calculated within the SPA model, restricting the emission process to elastic NN collisions
- Δ contribution is treated explicitly by producing and decaying the resonance within a Dalitz-decay model in inelastic collisions
- The interference of elastic and inelastic channels is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

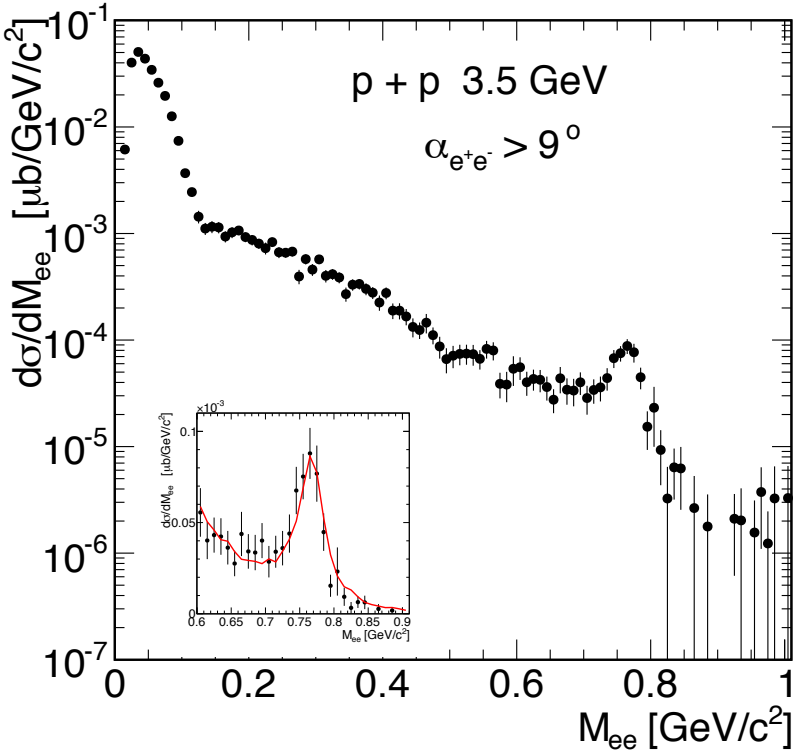


L. Kaptari et al. arXiv:0903.2466v1 [nucl-th]

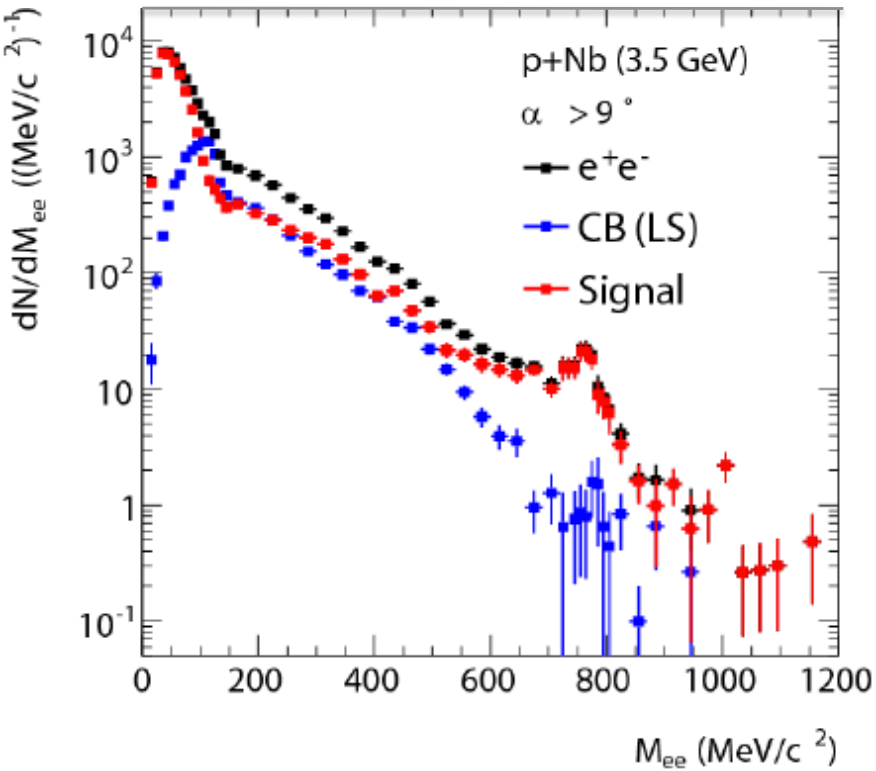
The interference effects become significant at higher values of the di-electron invariant mass and reduce the cross section by a factor of about 2 – 2.5!

Investigation of ω meson modifications at nuclear ground state density

Efficiency corrected data, normalized to the number of pp elastic events



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



Results:

- Mass resolution: σ_ω = 16 MeV/c^2
- VM region practically background free: S/B ratio > 10

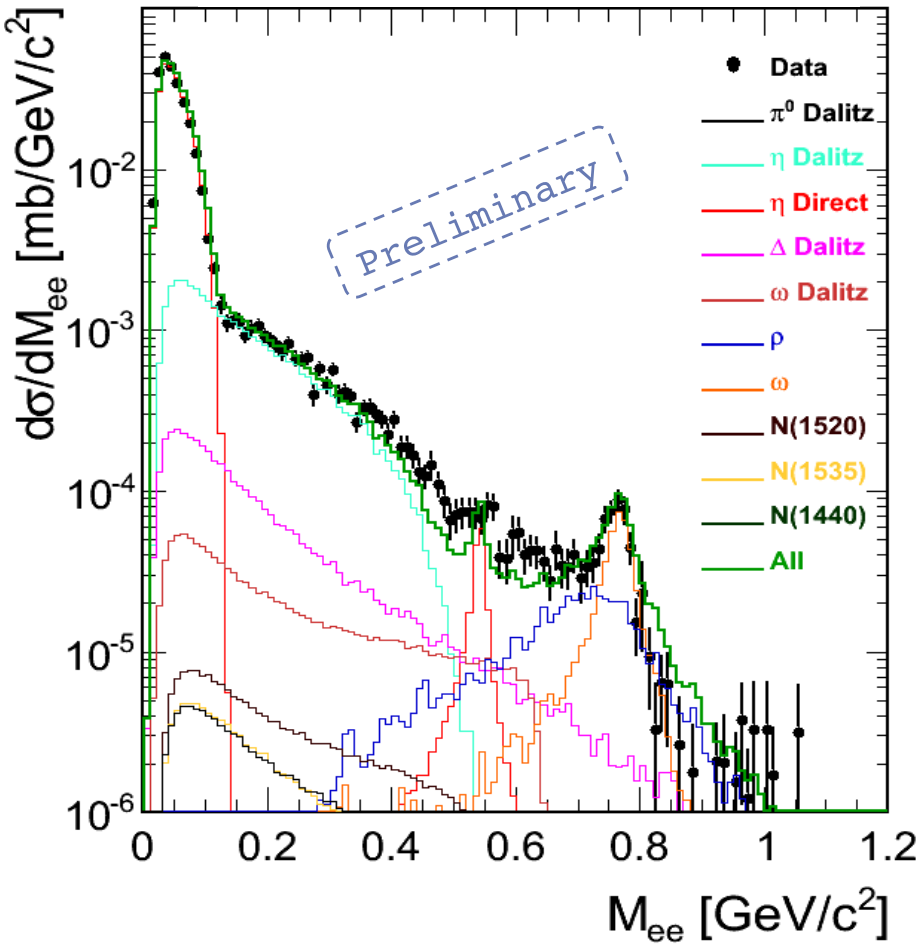
Electron pairs from pp collisions at 3.5 GeV

Extraction of inclusive cross sections by fitting conventional sources to the experimental spectrum (PLUTO event generator):

- π^o: 15 mb
- Δ: fixed to π^o
- η: 1.04 mb
- ω: 0.28 mb
- ρ: 0.36 mb

The PDG 2010 value for $\eta \rightarrow e^+e^-$ BR has to be scaled down by a factor of at least 3.

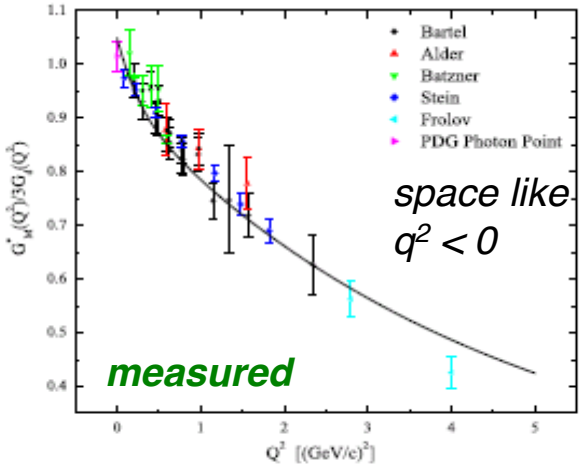
Comparison with Pluto cocktail

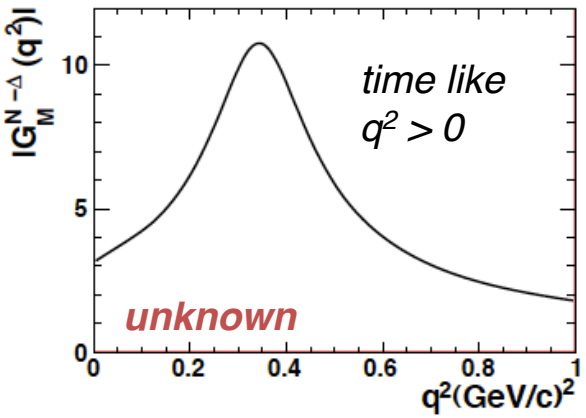


Electron pairs from pp collisions at 3.5 GeV

Δ-N transition EM form factor
Two–component VDM type model

- only ρ is relevant in case of Δ
- reproduces simultaneously nucleon space-like and time-like as well as N-Δ





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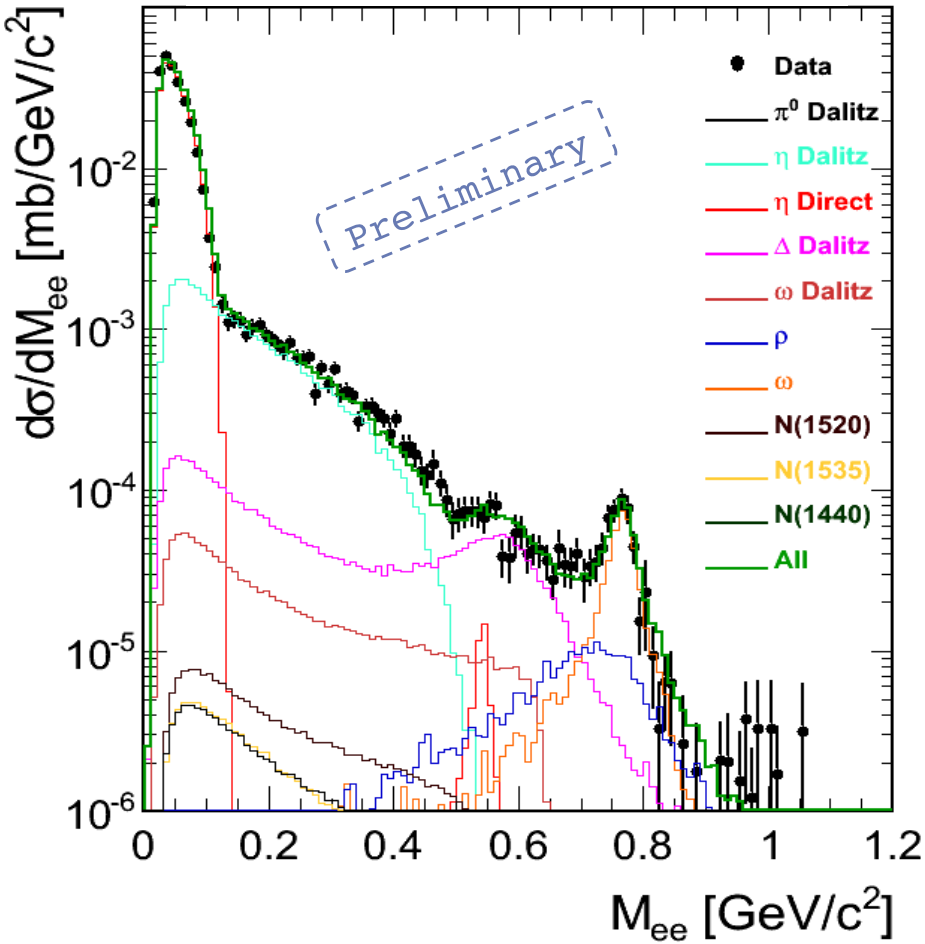
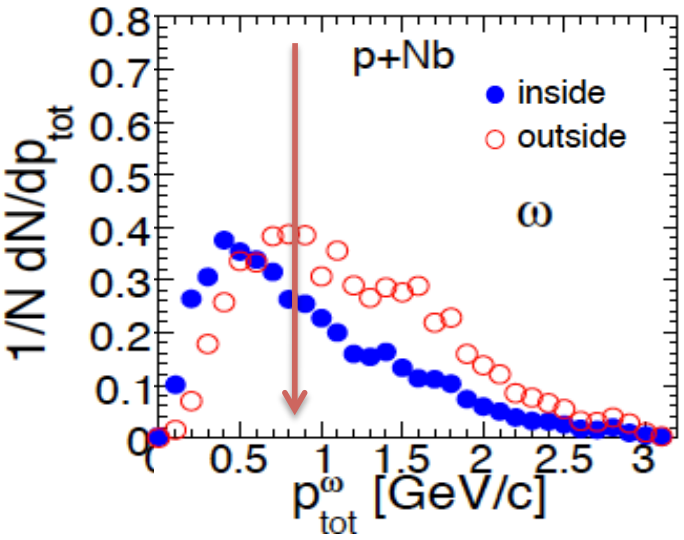
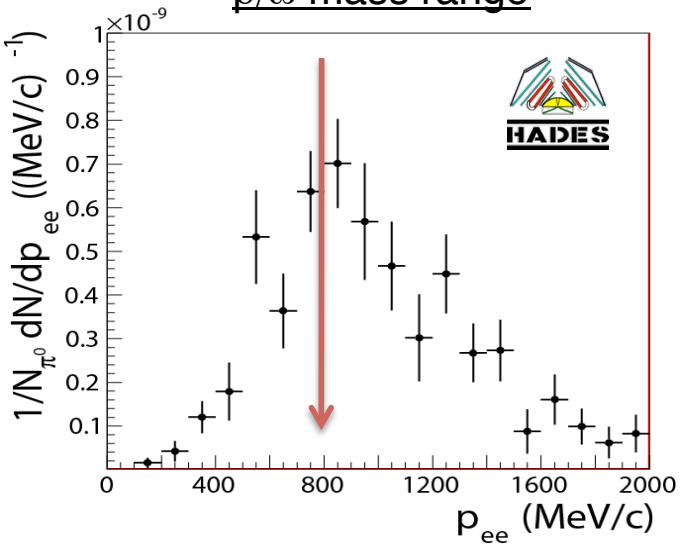


In-medium (cold nuclear matter) effects

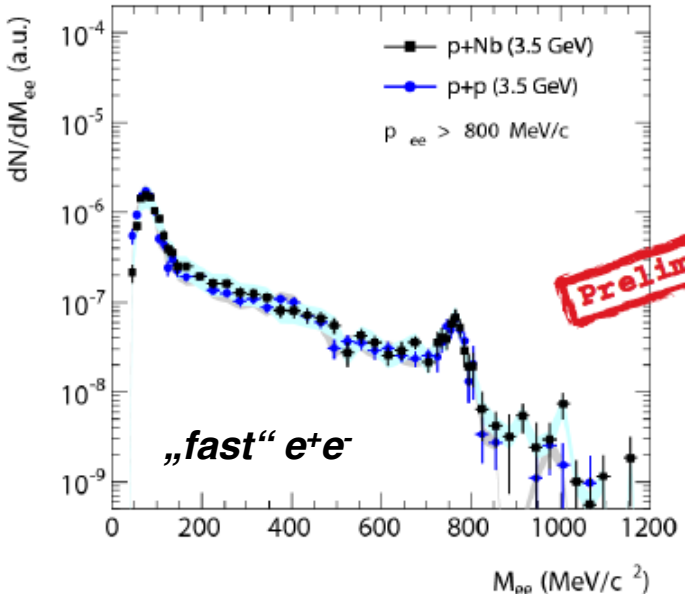
Laboratory momentum distributions for inside and outside decay of ω

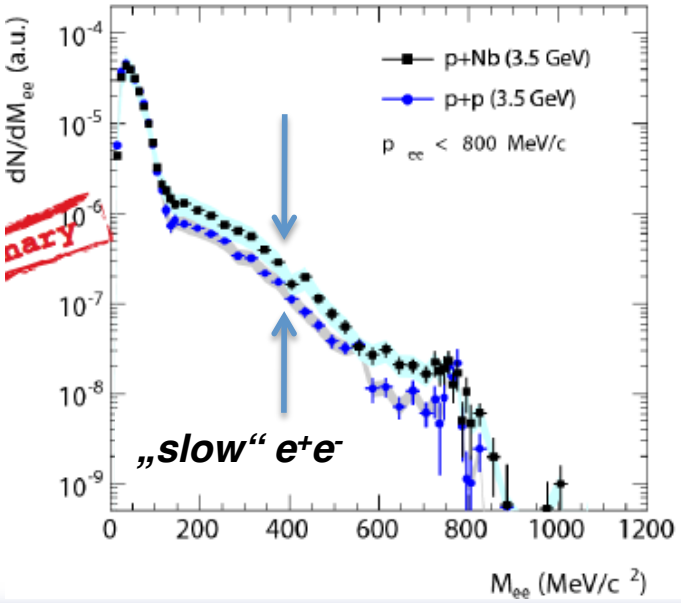


35% of pairs with p < 800 MeV/c in ρ/ω mass range



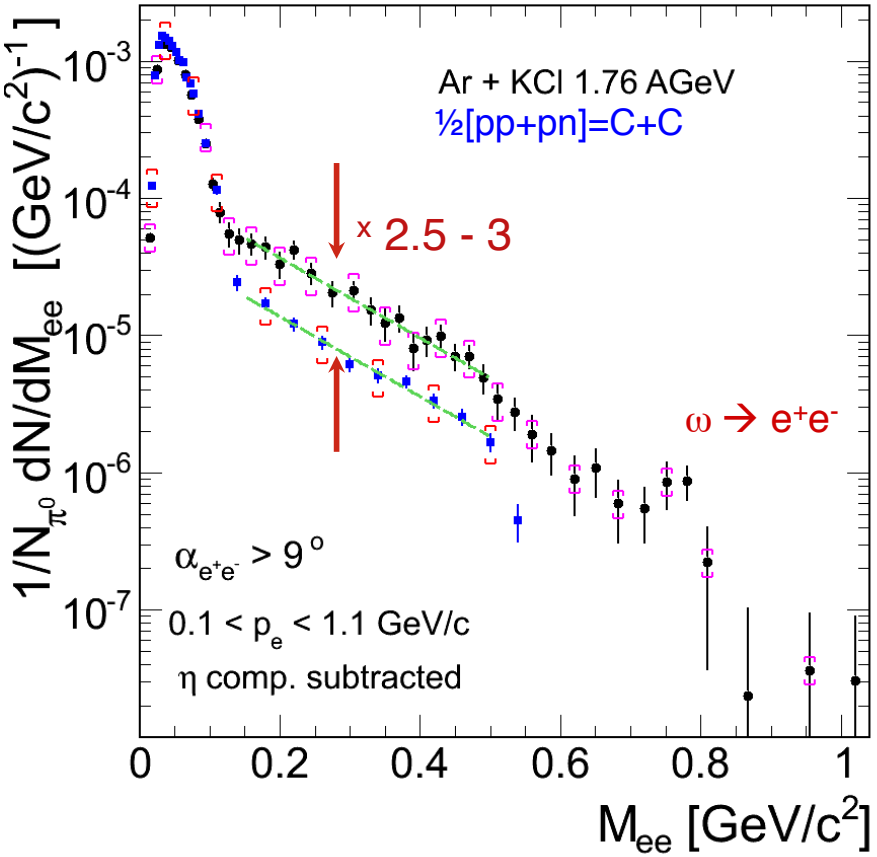
Fast and slow e^+e^- sources





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)

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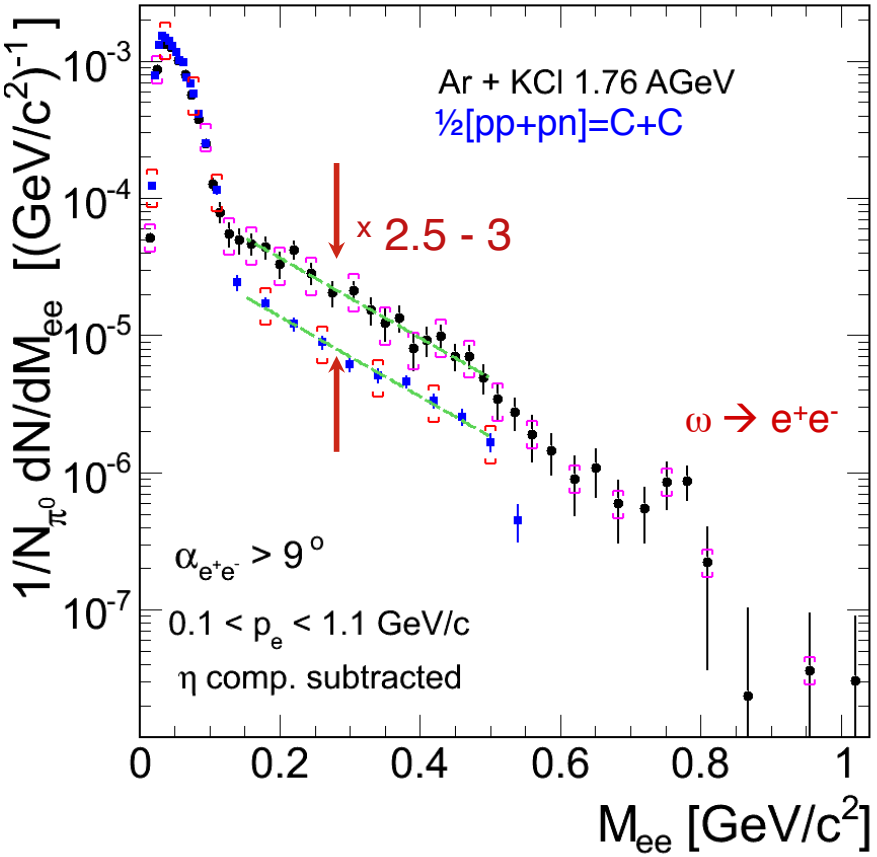

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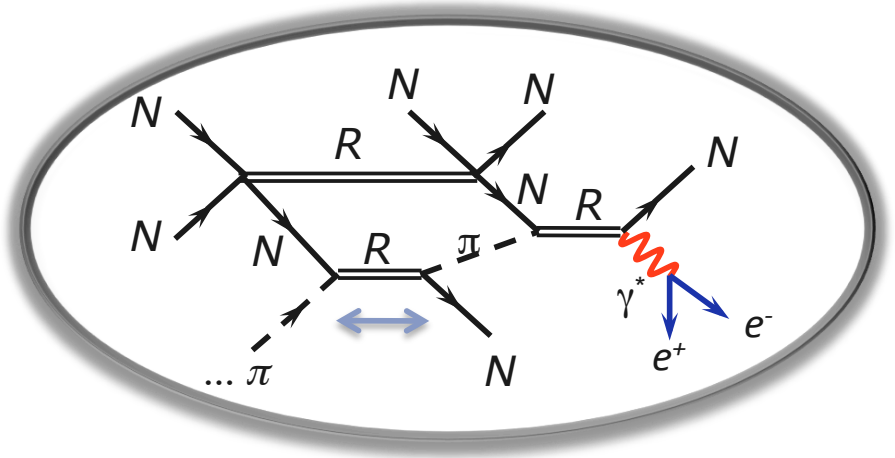
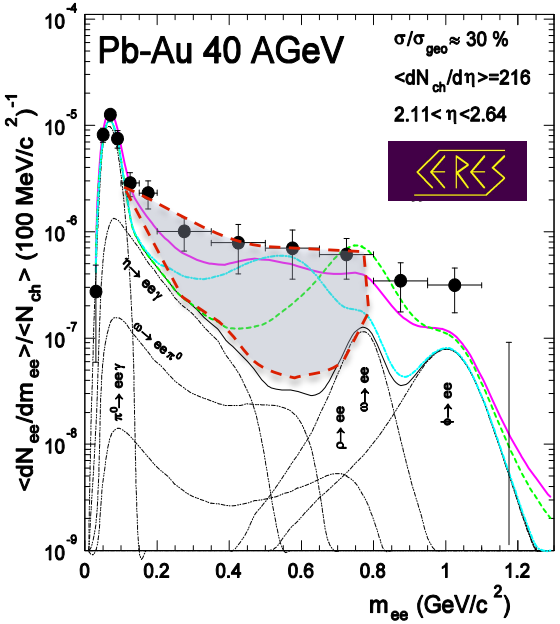
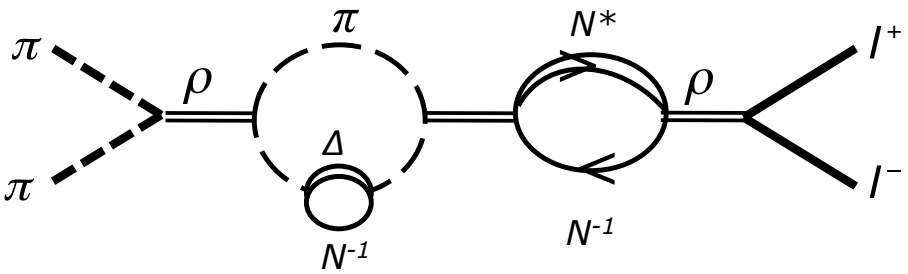


$\tau_{coll.} \leq 1$ fm/c (200 MeV)

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!

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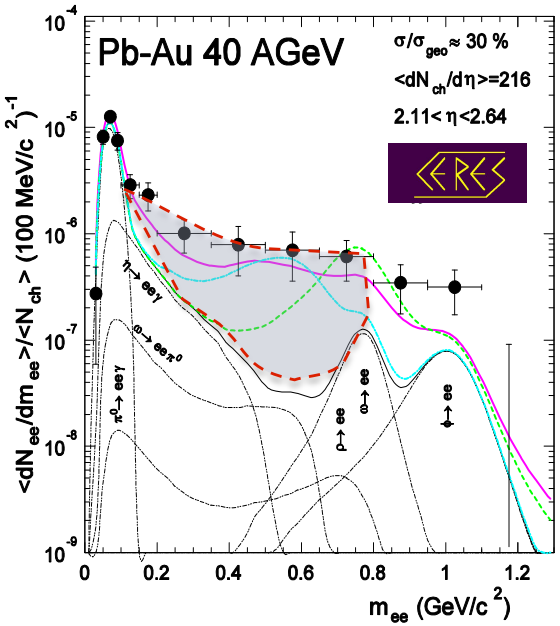

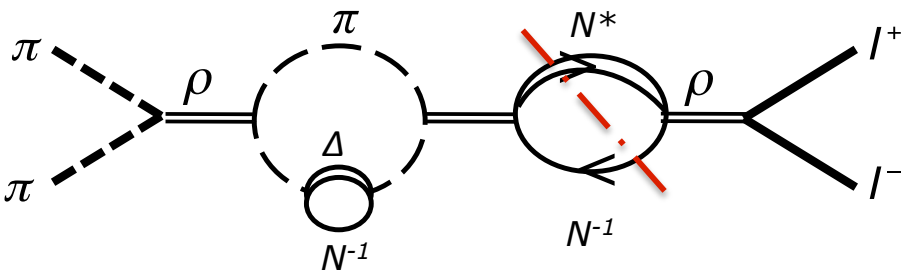

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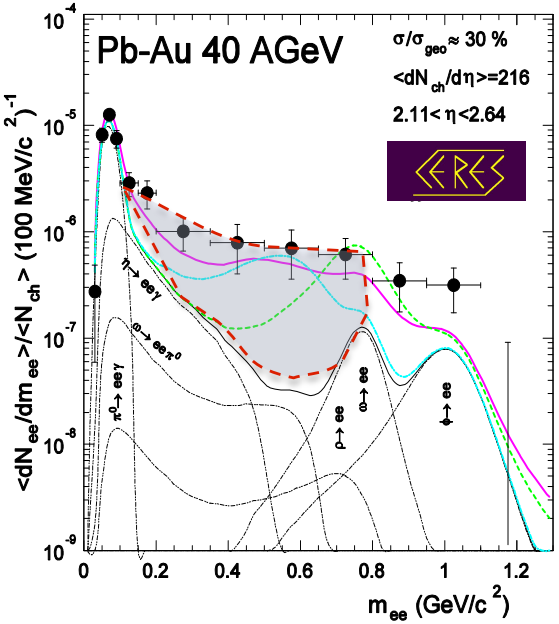

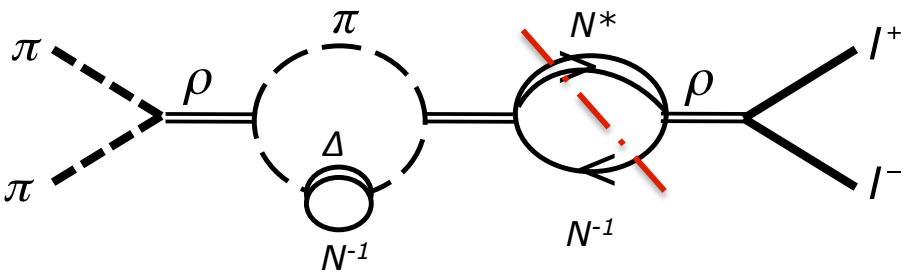

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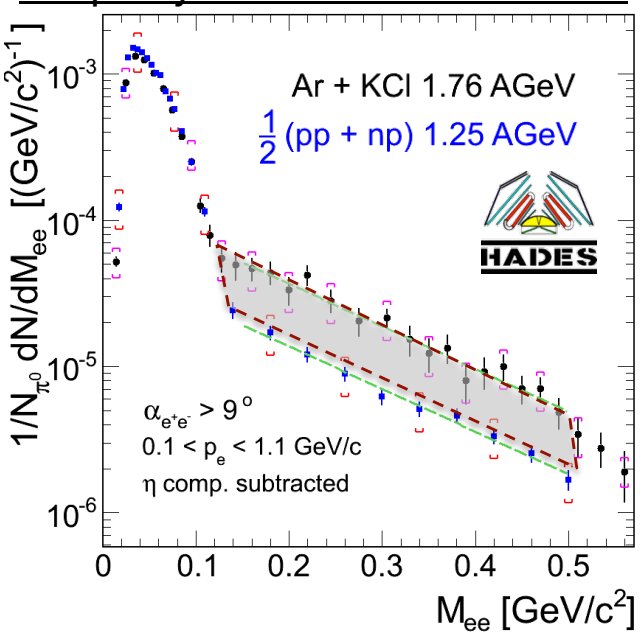
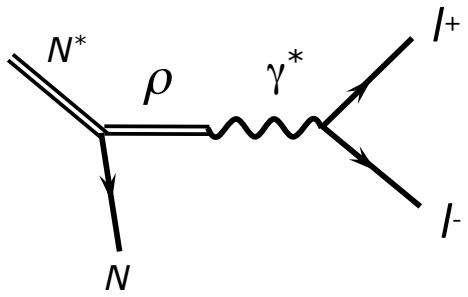
e^+e^- pair yield Ar+KCl 1.76 GeV/u

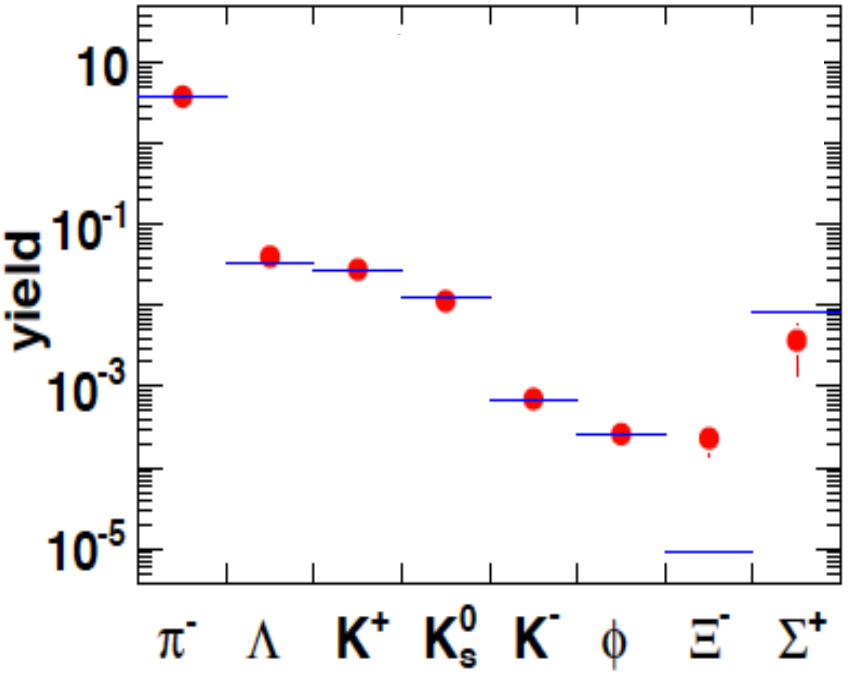




- Dalitz decays of baryonic resonances - dominant source at low beam energies.

Hadron multiplicities at SIS and Statistical Hadronization Model

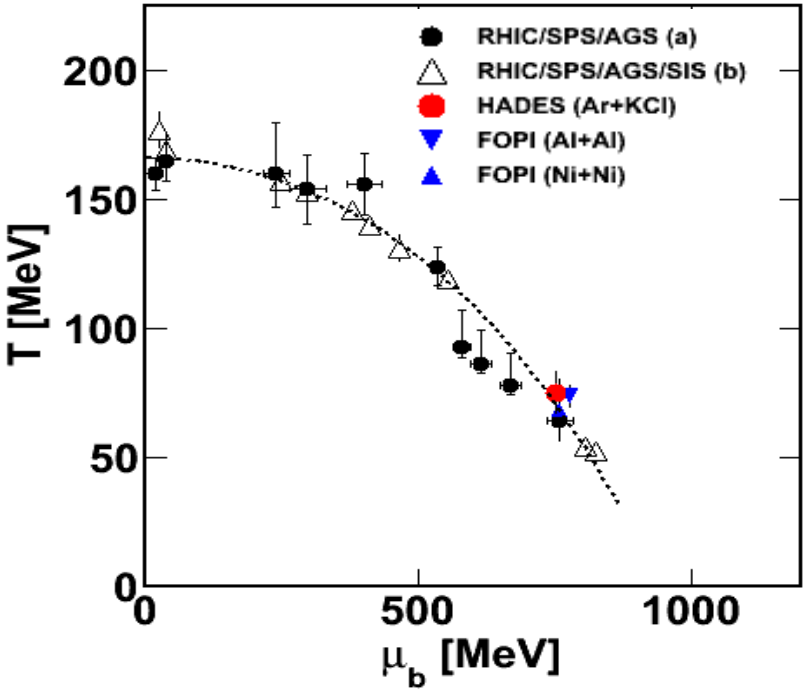
— THERMUS calculation: T, μ_b and R_C fit to
● HADES Ar+KCl (1.76 GeV/u) data



THERMUS fit: S.Wheaton and J.Cleymans, J.Phys.G31(2005)S1069

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

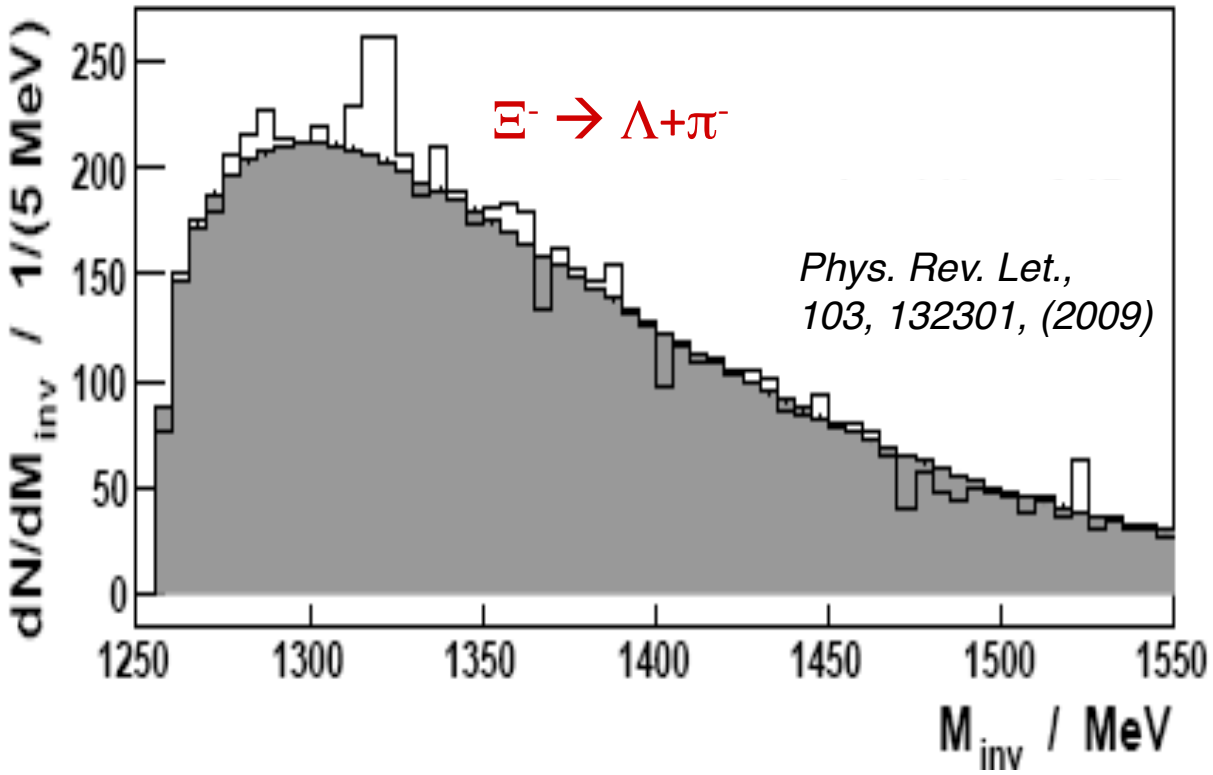


Statistical Hadronization Model describes hadron abundances accept in case of:

- large Ξ^- (s=-2) yield

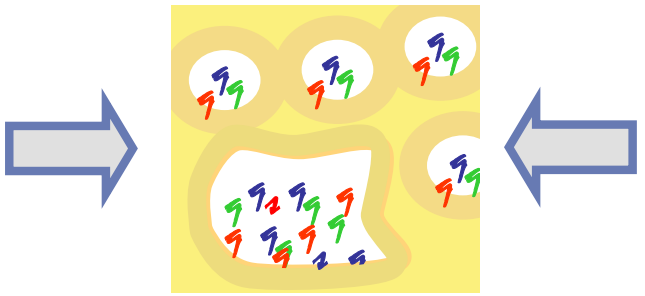
Strangeness production in 1.76 GeV/u Ar+KCl

HADES



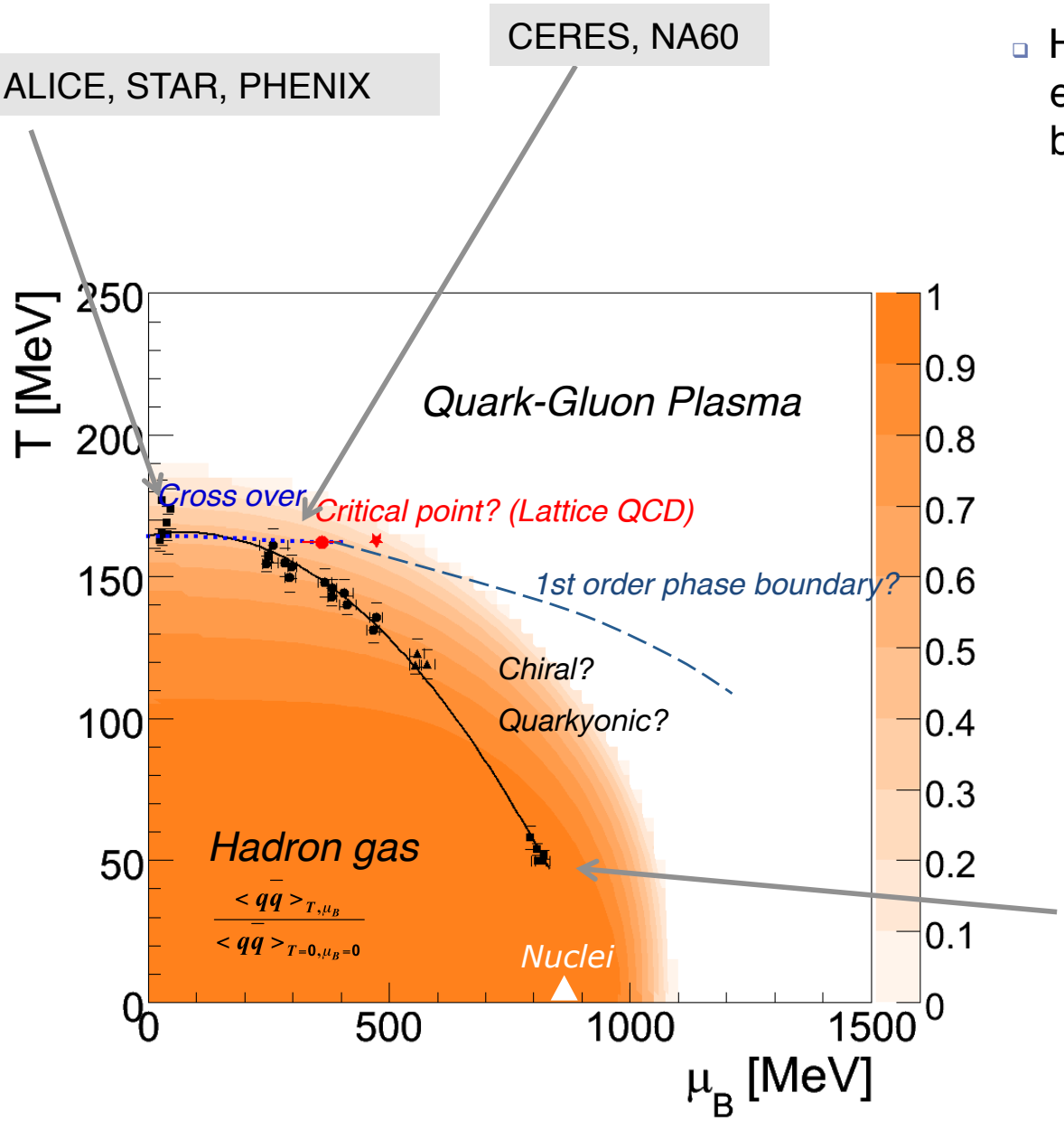
- Double strange baryon
- First observation at SIS
  $\sqrt{s}-\sqrt{s_{th}}$ = -630MeV

→ *Extreme and exotic phase of Nuclear Matter at SIS*



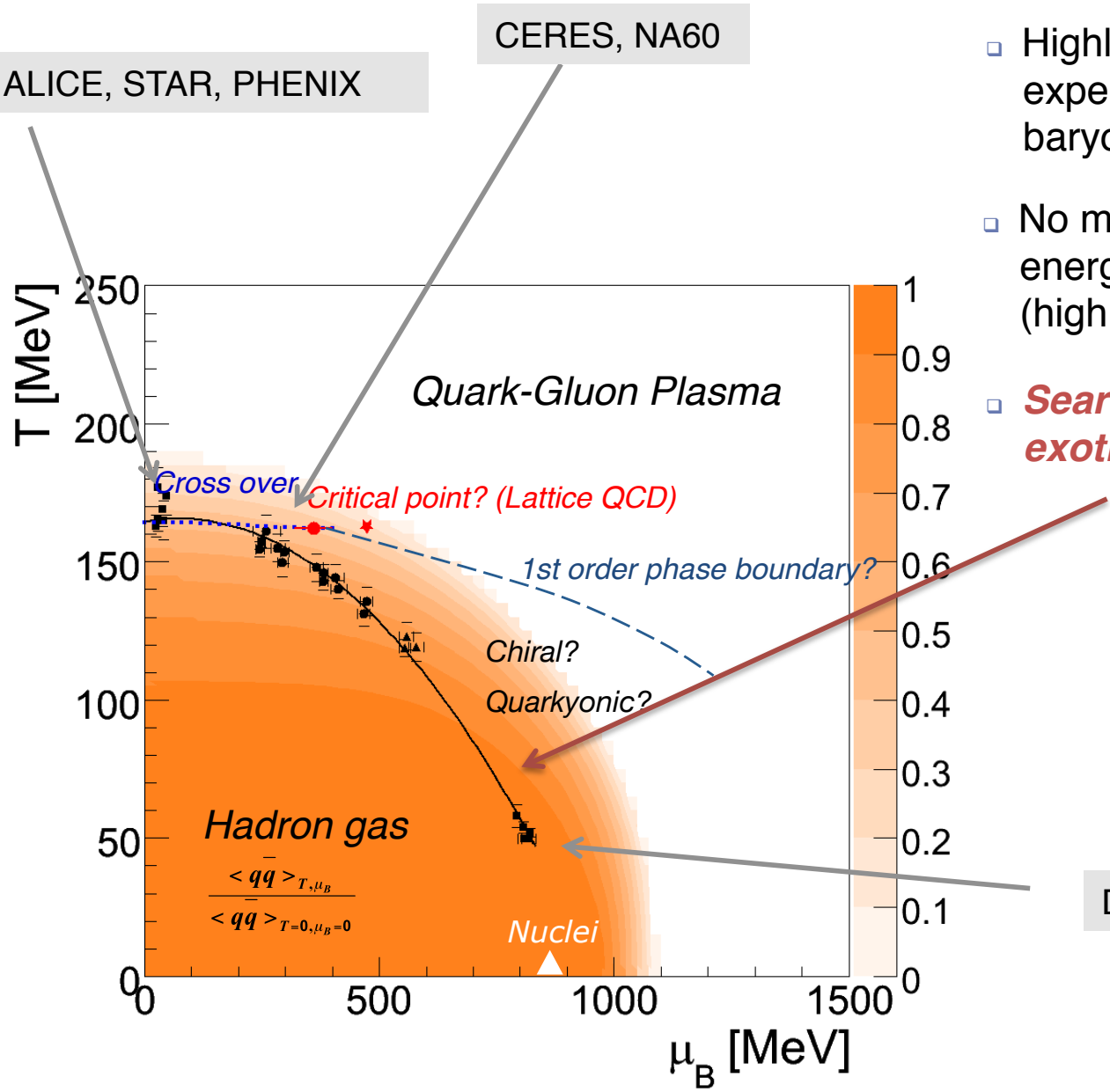
Strange quarks "trapped" in bubbles?

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



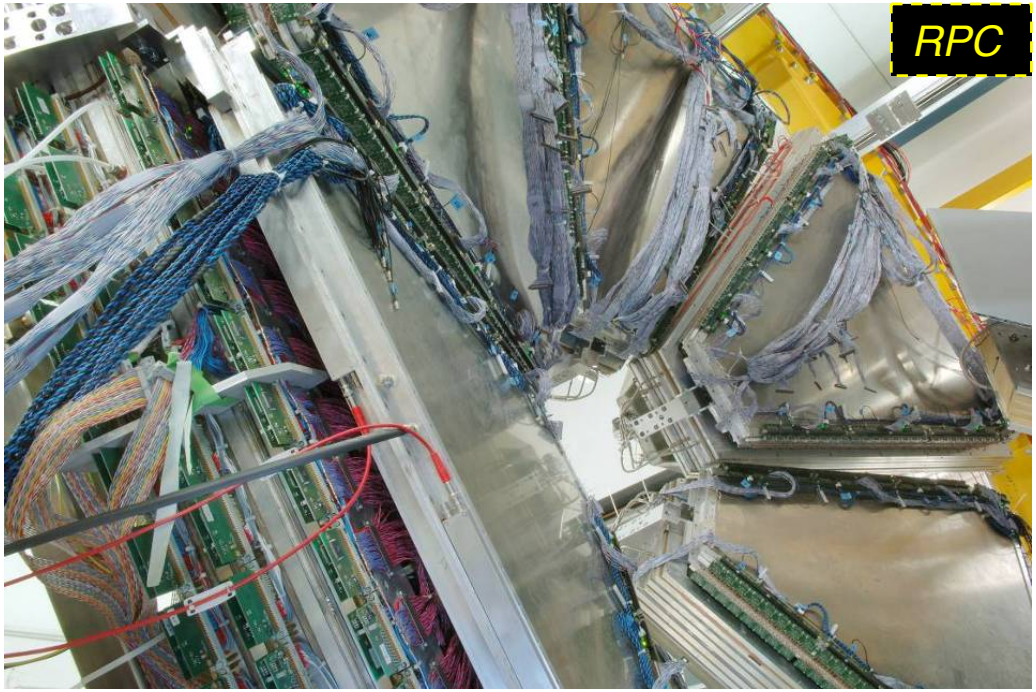
- Highly interesting results from experiments → importance of baryons

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

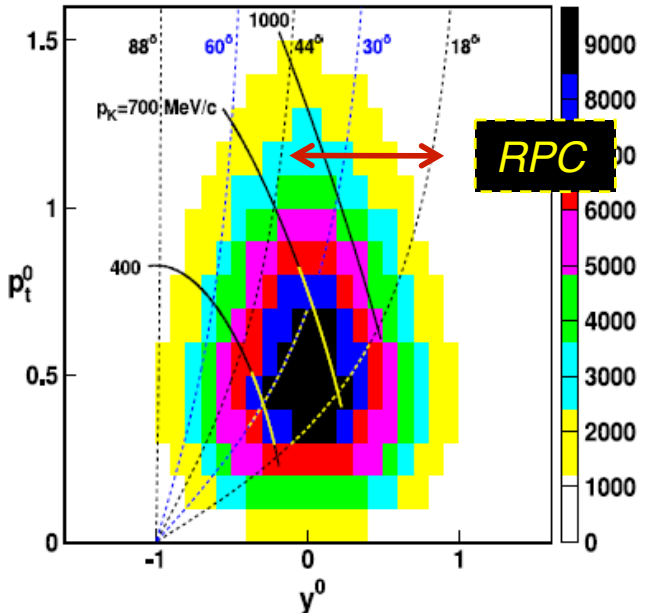


- Highly interesting results from experiments → importance of baryons
- No measurements for beam energies of 2 – 40 GeV/u (high baryon densities)
- ***Search (in this region) for exotic phases***

HADES upgrade: The RPC time-of-flight

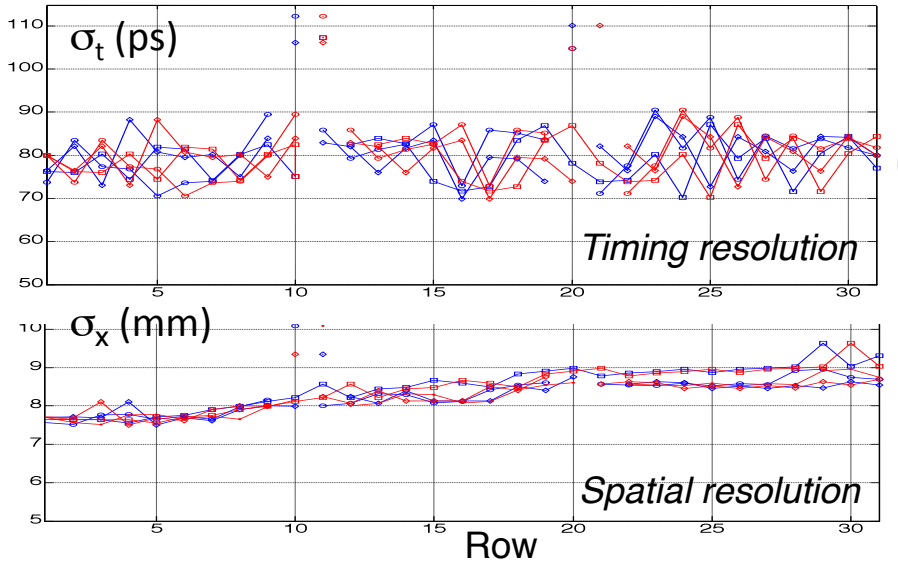


K⁻ acceptance (nice y_{CM} coverage!)



Full-system test results:

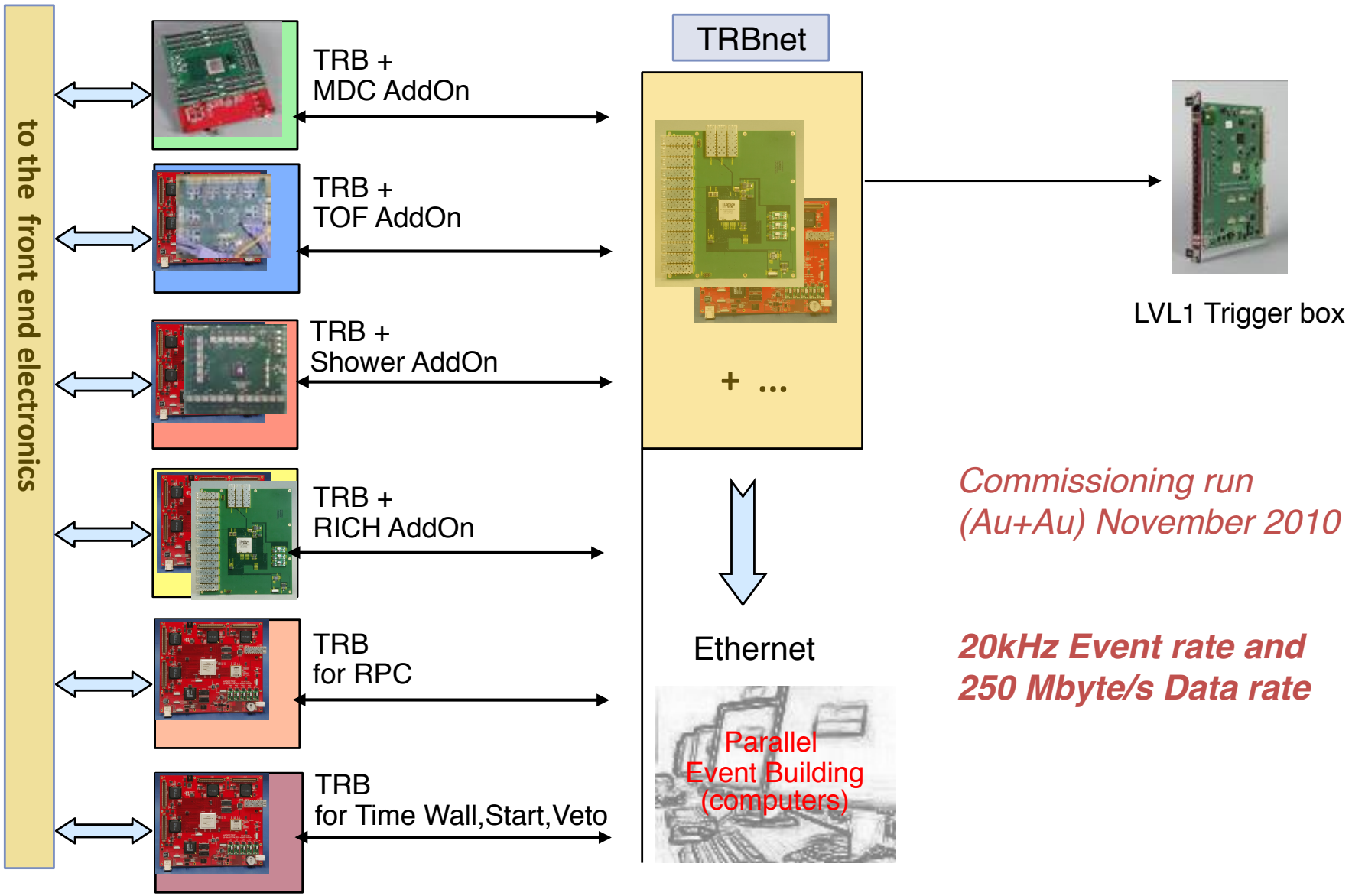
- $\sigma_t \leq 78$ ps
- $\sigma_x \leq 8$ mm
- $\varepsilon \sim 97\%$



Leading institute:
Coimbra, Portugal

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

HADES DAQ upgrade



Commissioning run
(Au+Au) November 2010

20kHz Event rate and
250 Mbyte/s Data rate

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

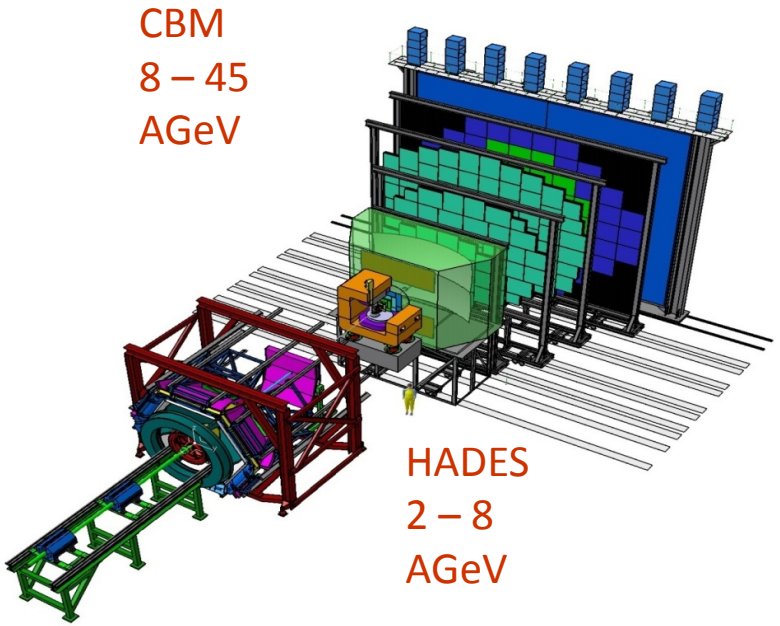
The future at FAIR

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



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

Thanks for the dilepton workshop in 1991…

Bonus slides

Exclusive $\Delta \rightarrow pe^+e^-$ in p+p collisions at E_{kin} = 1.25 GeV

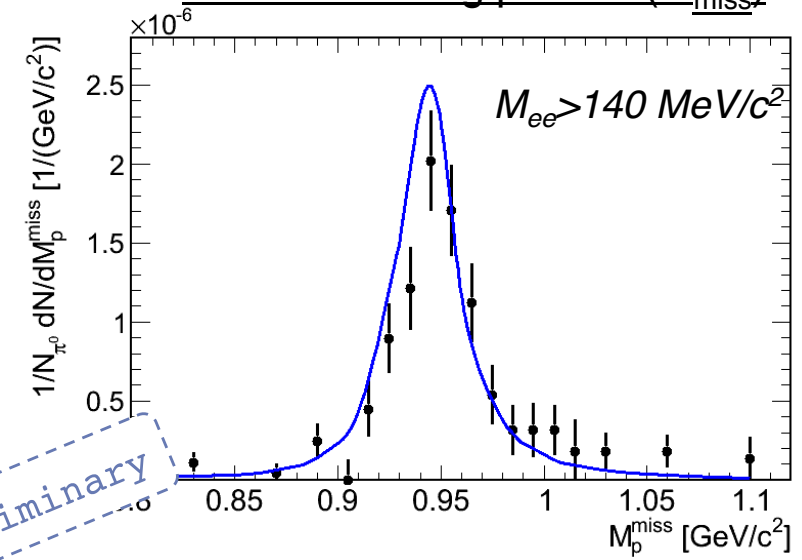
Do we really measure $pp \rightarrow p\Delta^+ \rightarrow pp e^+e^-$?

→

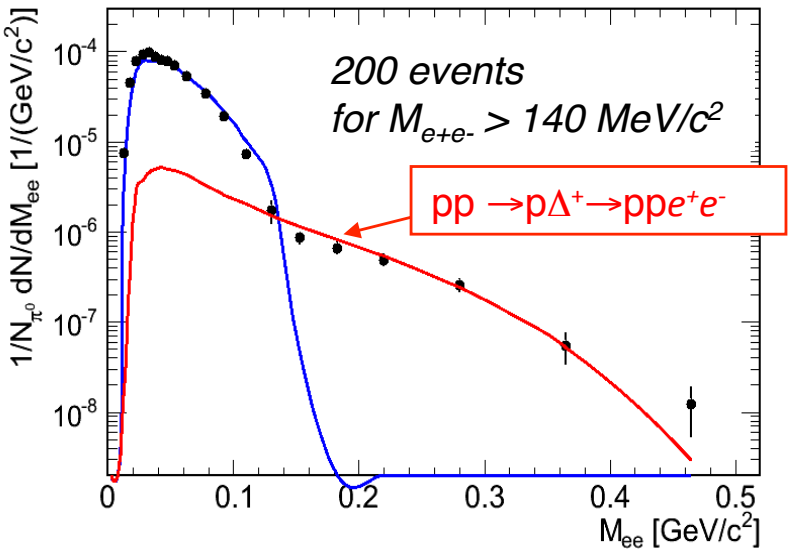
Check by detecting three particles in the final state, i.e. p, e^+, e^-

- Identification of the final state vs. less acceptance
- Much lower background
- Allows determination of the:
  - $\Delta \rightarrow pe^+e^-$ branching ratio
  - Electromagnetic transition form factor?

Mass of missing particle (M_{miss})



Invariant mass distribution of pe^+e^-

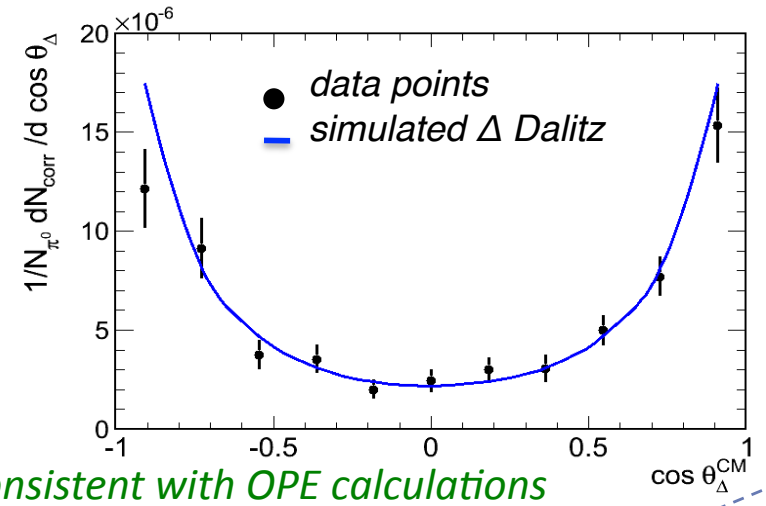


Exclusive Δ → pe^+e^-: angular distributions

- pp data at high e^+e^- masses is dominated by Δ Dalitz decay
- First measurement of Δ Dalitz decays branching ratio → in agreement within 20% with QED value of 4.2×10^{-5}

Helicity angle: angle between a lepton in the γ rest frame, and a γ* in the Δ rest frame.*

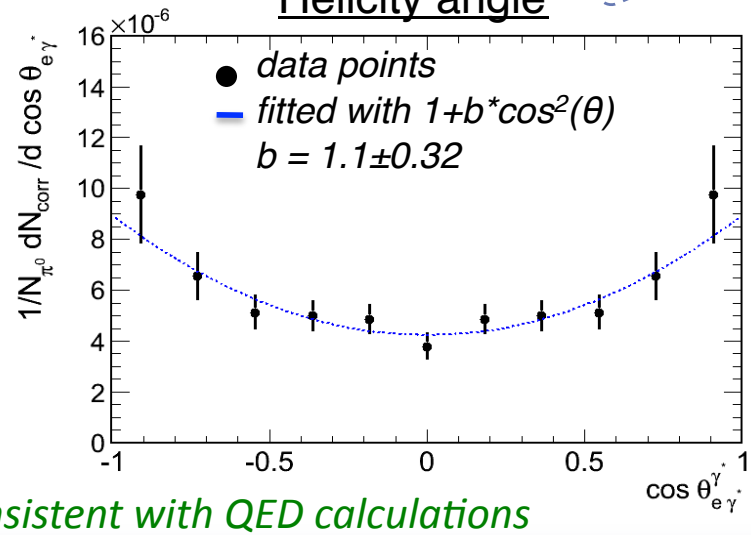
cm. angular distribution of pe^+e^-



consistent with OPE calculations

Preliminary

Helicity angle



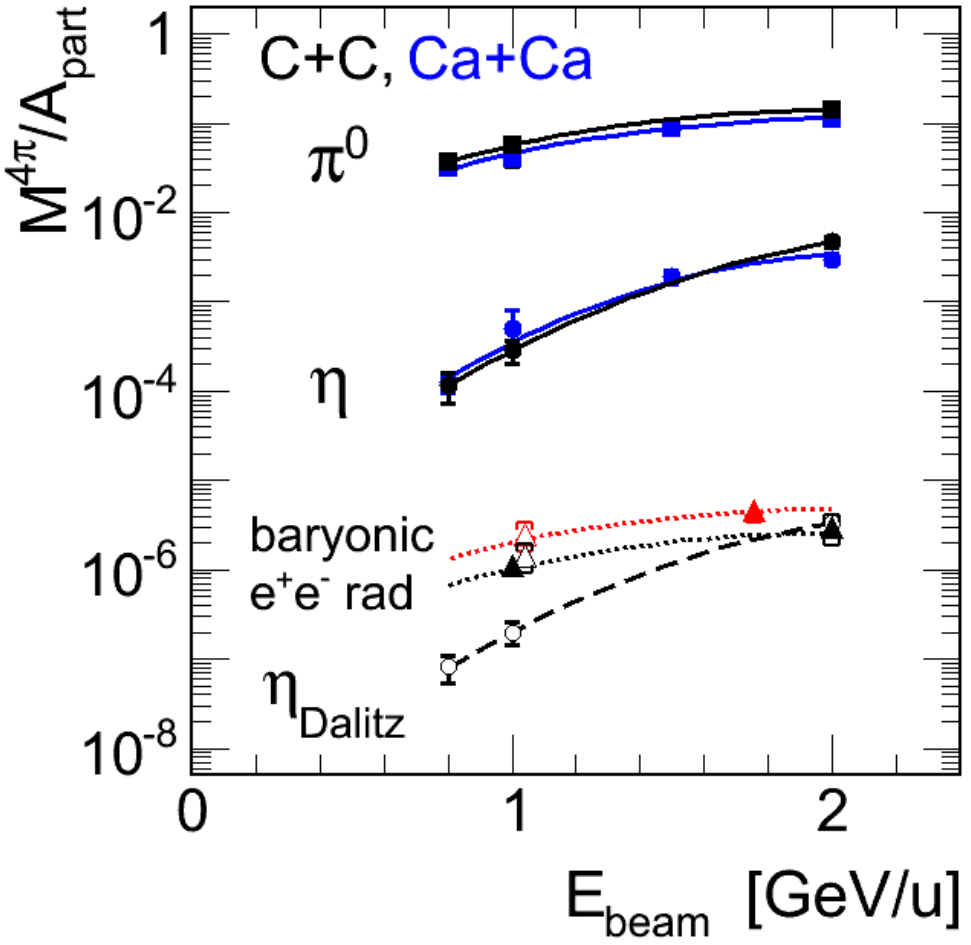
consistent with QED calculations

Systematic of the excess yield

Data for π^0 and η from TAPS collaboration

Dilepton excess scales with beam energy like π production

C+C (DLS)
C+C (HADES)
Ca+Ca (DLS)
Ar+KCl (HADES)



Excess yield scales stronger than linear with A_{part}