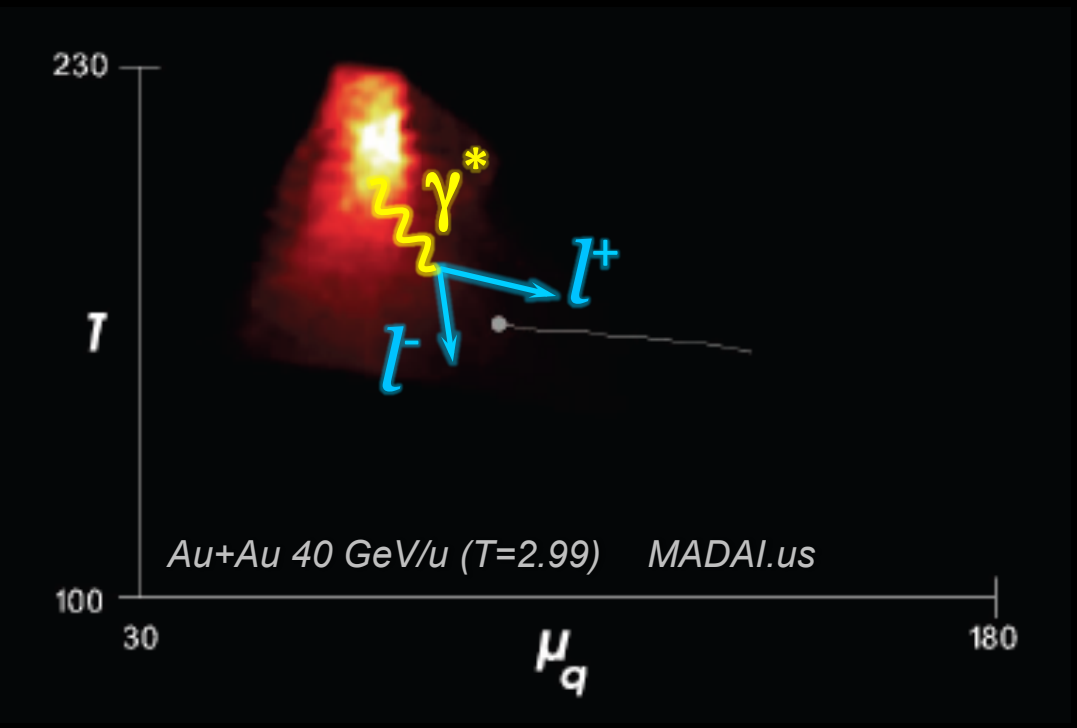
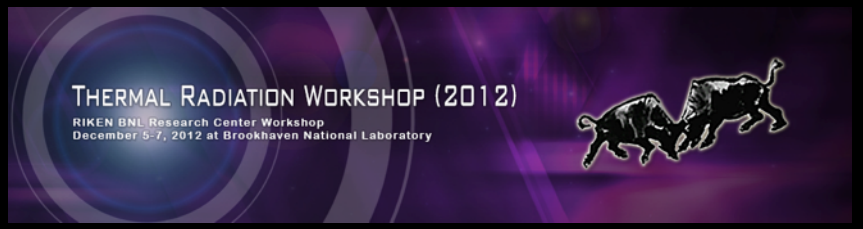




Results on virtual-photon production at SIS: resume and prospects

Tetyana Galatyuk
TU Darmstadt / GSI
for the HADES and CBM Collaborations

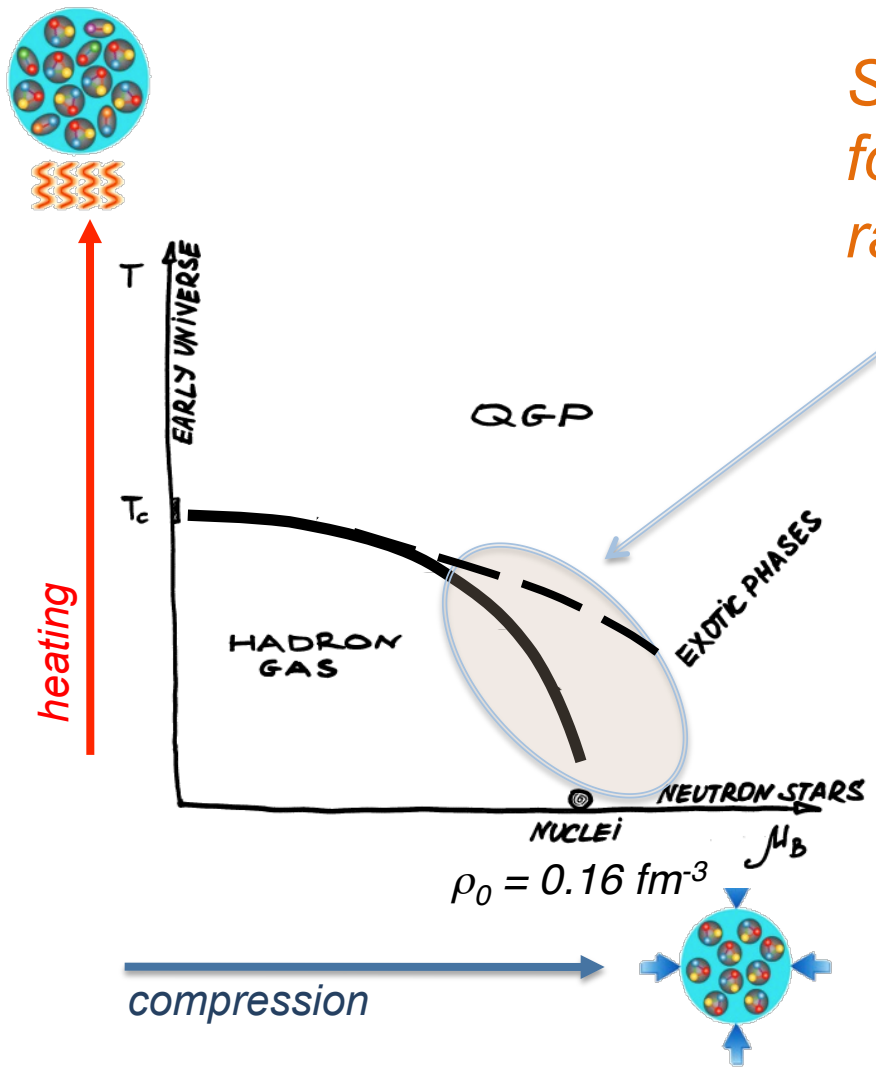
TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

EMMI

High Acceptance DiElectron Spectrometer

The HADES mission



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

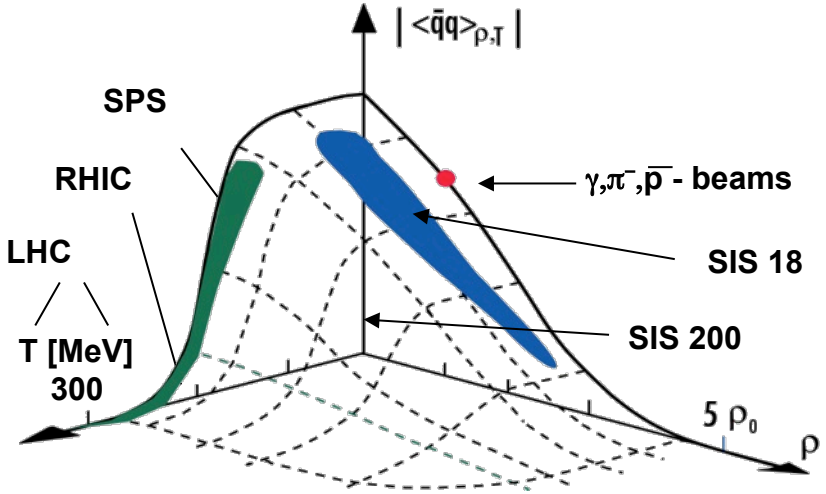
- Stage I (2002 - 2008)
  - Limited granularity of time-of-flight system → light collision systems
- Stage II (2012 - 2015)
  - Heavy collision-systems
  - π-induced reactions
- Stage III (2018 - …)
  - Lepton pair excitation function up to 8 GeV/u (medium-heavy systems) and (multi-)strange particle

+ Various aspects of baryon-resonances physics

Dileptons and the phase diagram of matter

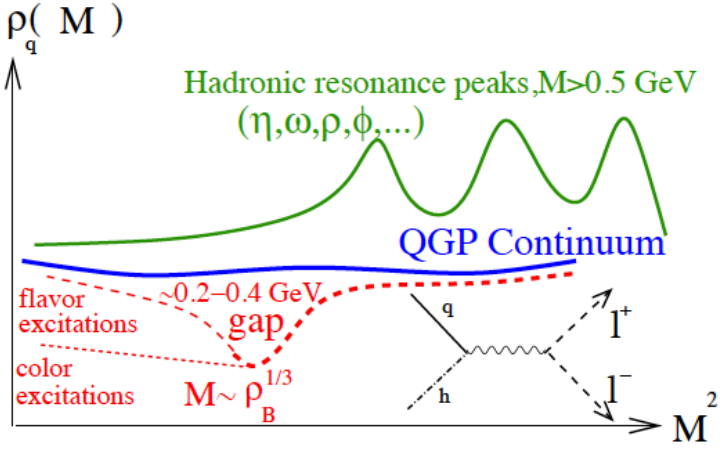
„I wonder if it finally will turn into a bluff...“

Use ρ as a probe for the restoration of χ symmetry



Robert D. Pisarski, PLB 110 (1982),
…

Dileptons from exotic phases…



*S. Lottini and G. Torrieri, **PRL 107**, 152301 (2011)*
S. Lottini and G. Torrieri, arXiv:1204.3272v1 [nucl-th]
…

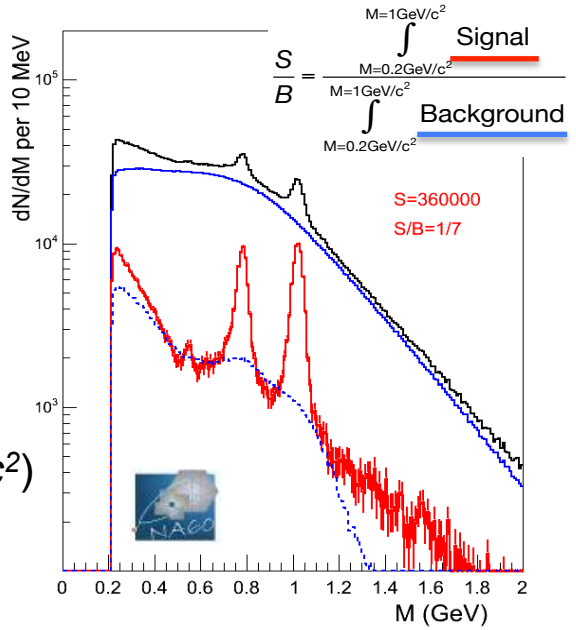
→ *Experimental test*

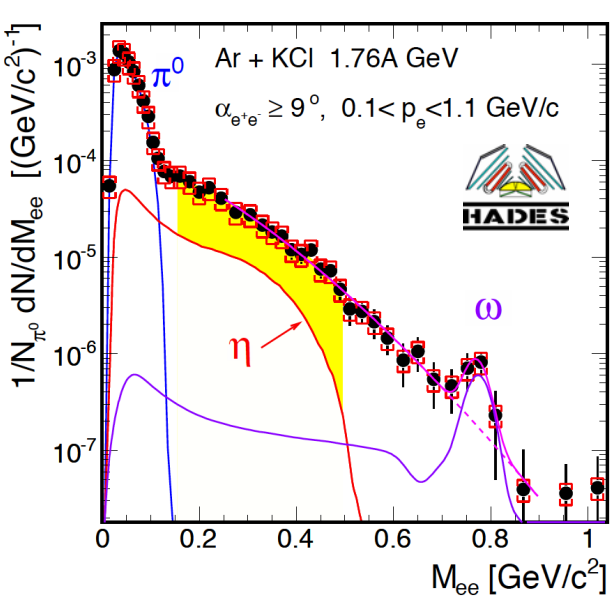
The experimental challenge…

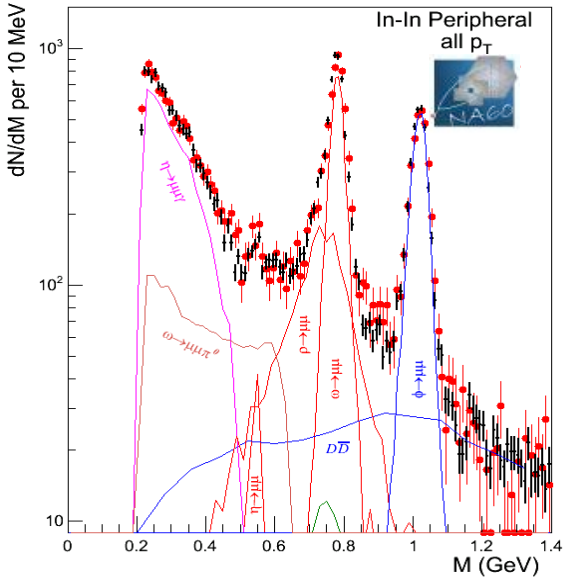
- Lepton pairs are rare probes (branching ratio O(10^{-4}))
- at SIS18 energies vector mesons are produced sub-threshold (NN)

- Large combinatorial background from:
  - **e^+e^-:** Dalitz decays (π^0) and conversion pairs
  - **$\mu^+\mu^-$:** weak π, K decays

- Isolate the contribution to the spectrum from the dense stage (***X Factor*** = *excess yield above hadronic cocktail in $0.2<M_{ll}<0.6$ GeV/c^2*)

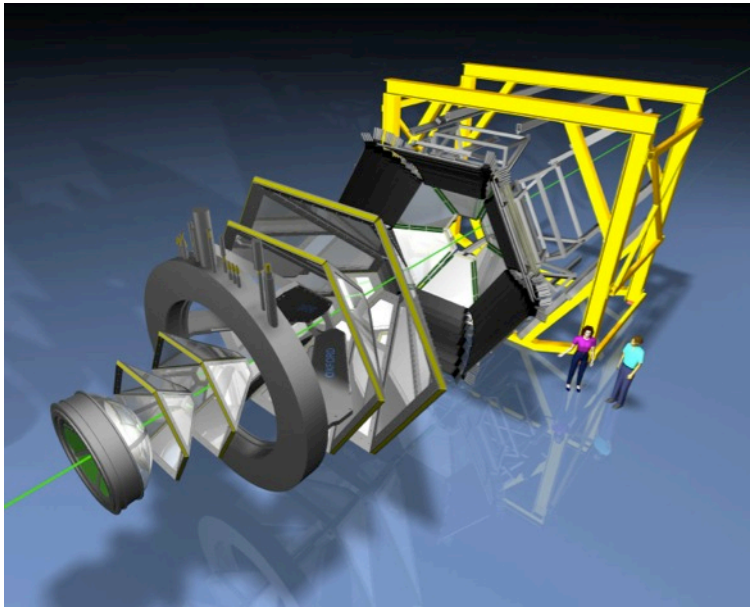






High Acceptance Di-Electron Spectrometer

HADES



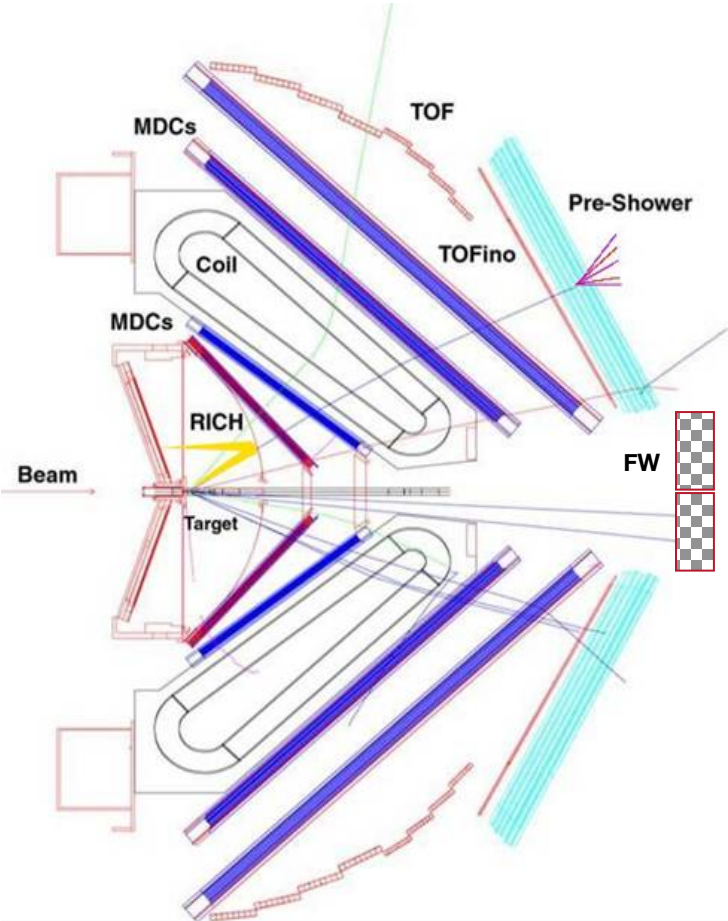
HADES strategy:
Systematic di-electron and strangeness measurements in NN, AA, pA, πN and πA collisions

- Beams provided by SIS18: π, p, ions

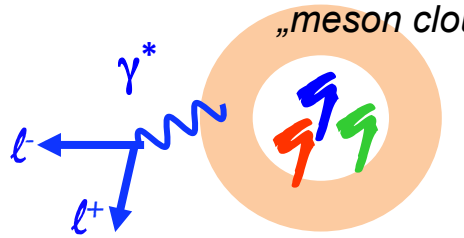
- Full azimuthal coverage
- Hadron and lepton identification

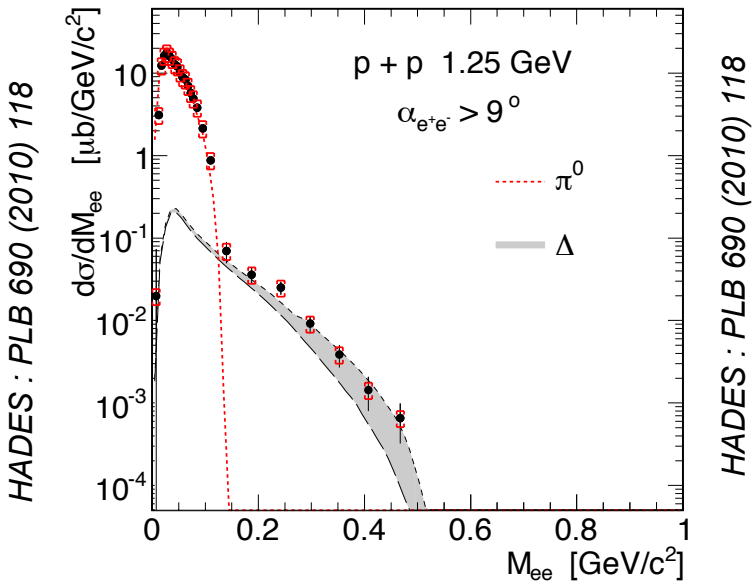
- e^+e^- pair acceptance 0.35
- **Mass resolution 2 % (ρ/ω region)**

- ~ 80.000 channels
- now: **up to 50 kHz event rate (400 Mbyte/s peak data rate)**



NN Reference: e^+e^- in p+p collisions at 1.25 GeV





HADES : PLB 690 (2010) 118

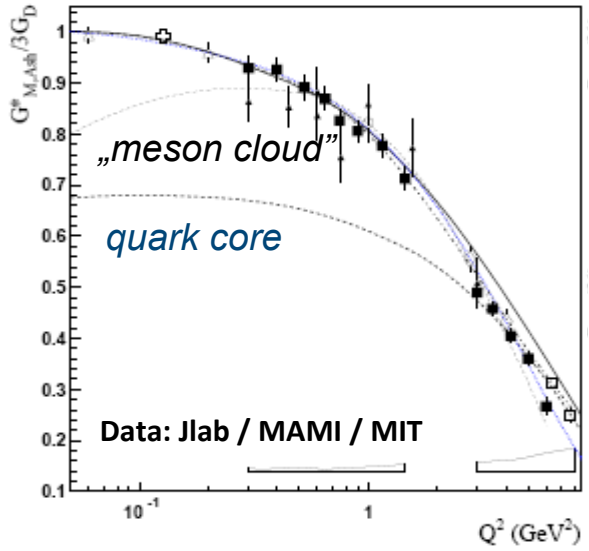
time-like region $q^2 > 0$

Goal

- Understand Δ → N γ* transition
  - **Known from γN → Δ → πN**
    (exact QED calculation, Krivoruchenko et al. PRD 65 (2001) 017502)
  - **Unknown at q^2 >0!**

→ use models fitted to the space-like data

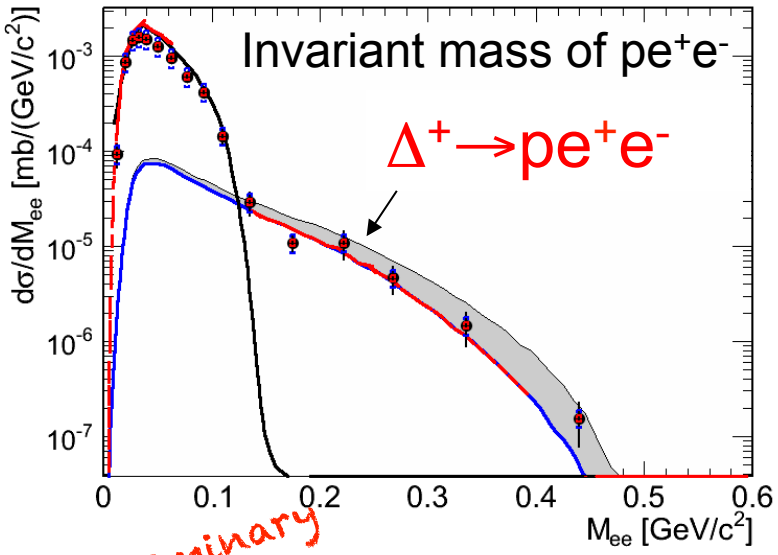
G. Ramalho and T. Pena arxiv: 1205.2575v1 (2012)
Wan and Iachello, int. J. Mod. Phys. A20 (2005) 1846

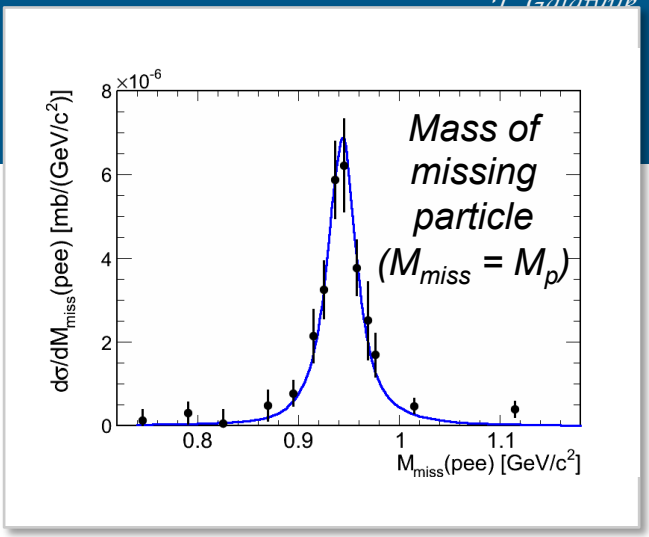


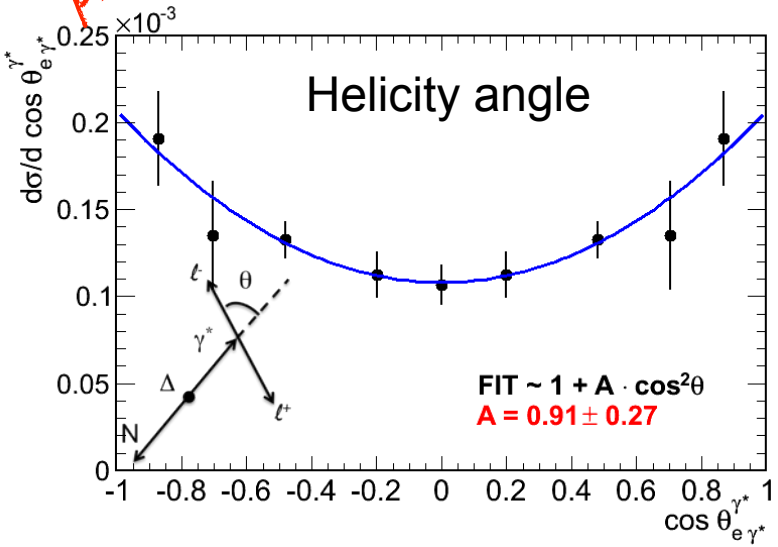
space-like region $q^2 < 0$

- Excitation of a baryon can be carried by the meson cloud
  - Precise data from Jlab / MAMI / MIT
  - **Strong hint for dominant contribution to the $G_M(Q^2)$ from the meson cloud (30% at $G_M(0)$)**
    I.G. Aznauryan, V.D. Burkert Prog. Part. Nucl. Phys. 67, 1 (2012)

NN Reference: exclusive analysis pp→ppe⁺e⁻

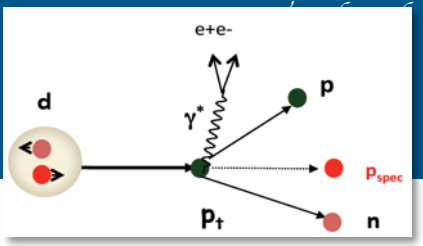


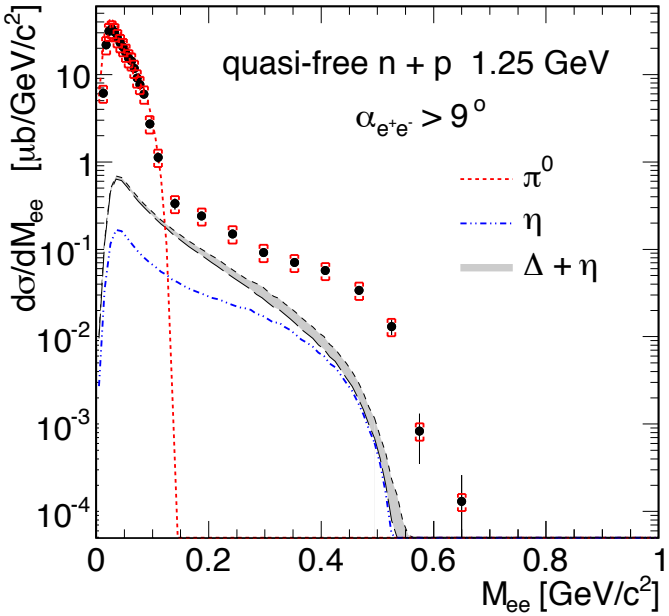




- **First direct access to the Δ transition form factor in the time-like region**
  - Data agree with QED calculation!
  - Branching ratio (Δ⁺→pe⁺e⁻) = 4.2×10⁻⁵

NN Reference: e^+e^- in QF n+p collisions $\sqrt{s} - 2m_N \approx m_\eta$

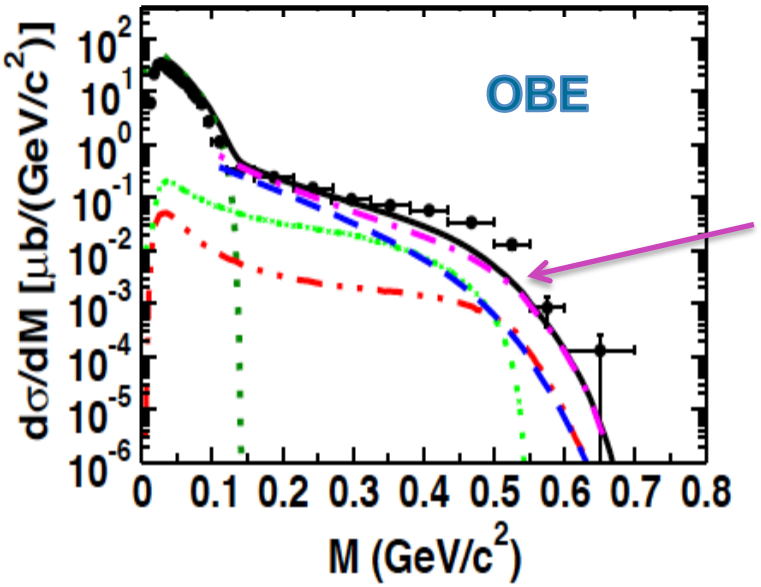


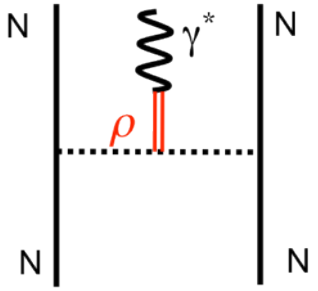


HADES : PLB 690 (2010) 118

- Large isospin dependence in dilepton production!
  - Role of the momentum distribution of the neutron inside the deuteron?
  - NN bremsstrahlung?

→ Check with One Boson Exchange effective Lagrangian based approach





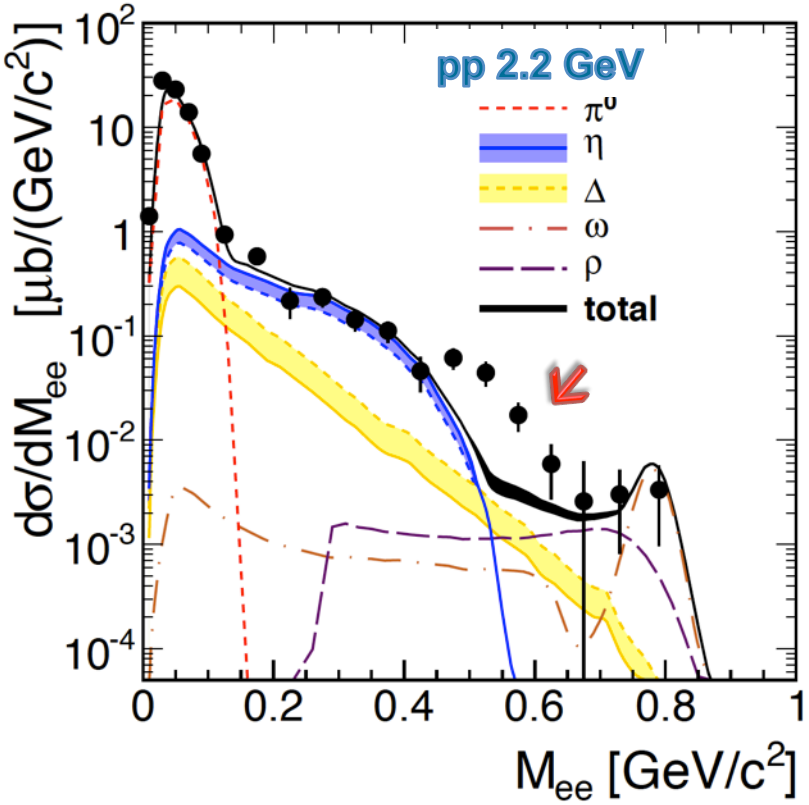
Much better agreement with data when including π em form factor

→

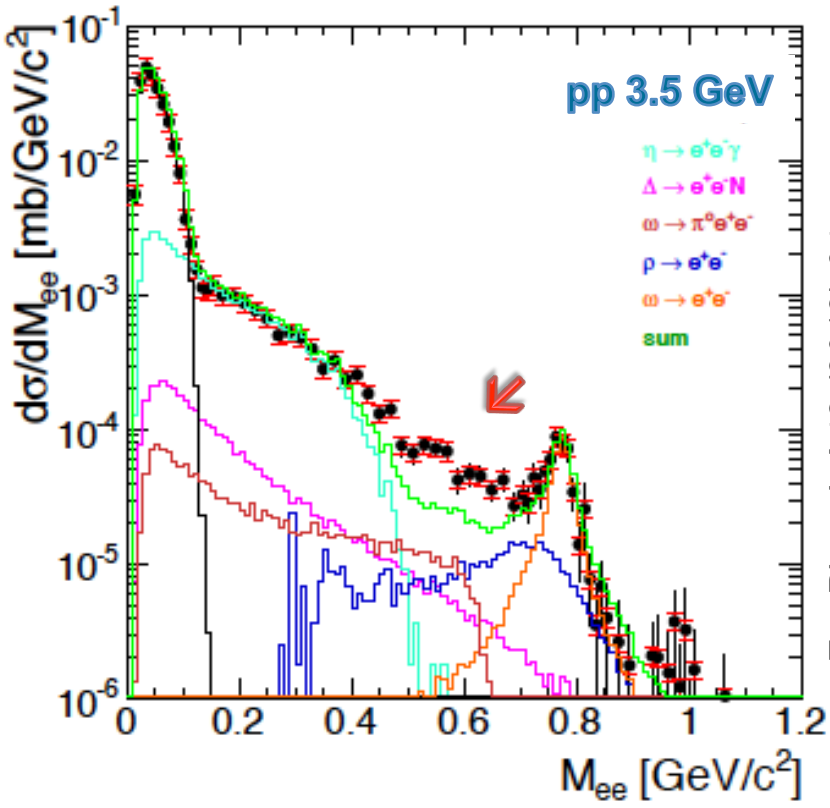
Sensitivity to hadronic electromagnetic structure

R. Shyam and U. Mosel, PRC 82:062201, 2010

NN Reference: e^+e^- in p+p collisions at 2.2 GeV and 3.5 GeV



Phys.Rev. C85 (2012) 054005



Eur.Phys.J. A48 (2012) 64

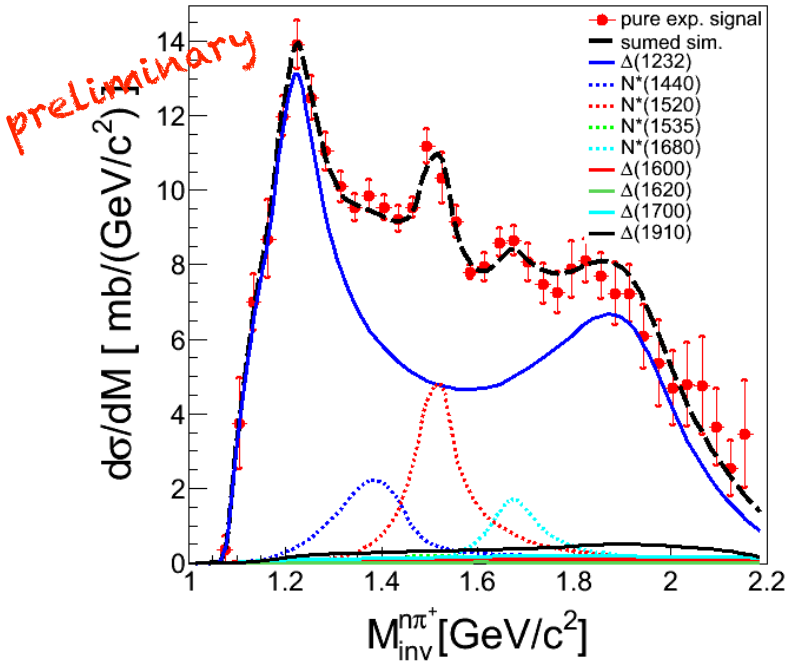
PDG Enrty 2012
BR(η→e+e-) < 5.6x10^{-6} (90% CL)

- Effect of electromagnetic form factor?
  → Dalitz decays of broad resonances is not well understood theoretically

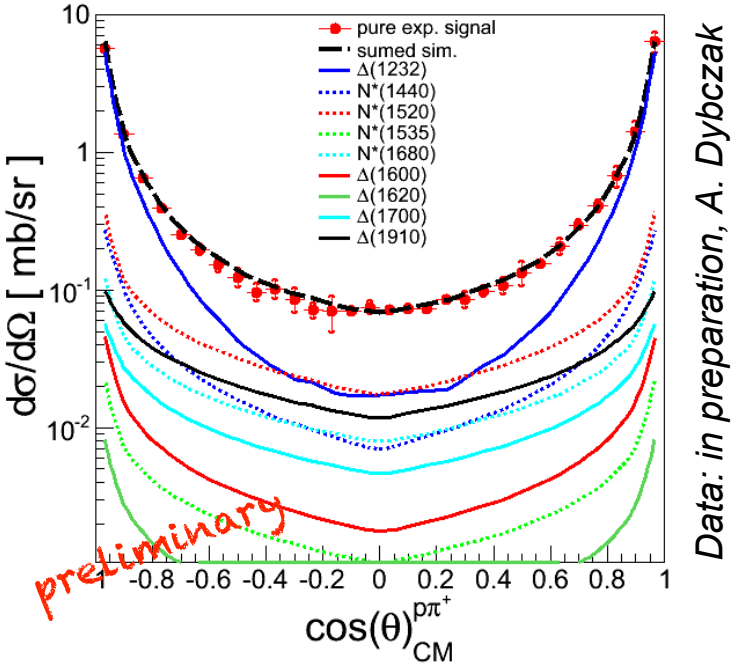
- Coupling of ρ to baryonic resonances
  → Cross check with hadronic final states needed!

Reconstruction of contributing baryonic resonances: exclusive analysis of pp → pnπ⁺ ans pp → ppπ⁰

$n\pi^+$ invariant mass



$p\pi^+$ angular distribution



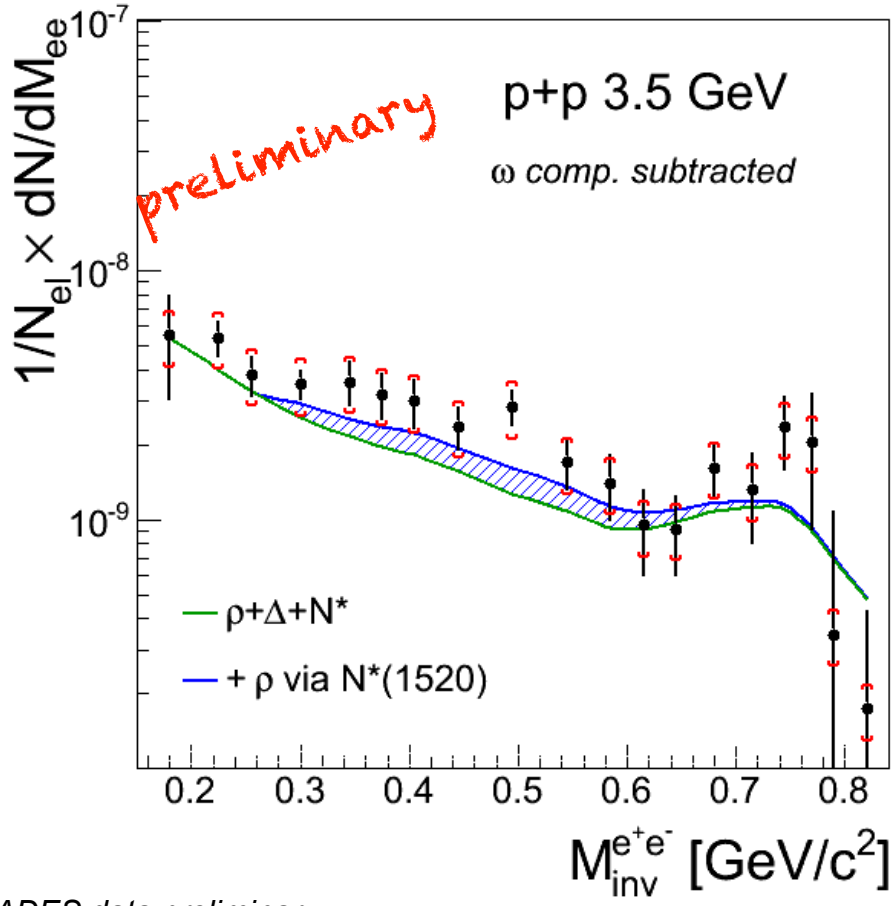
- 14 baryonic resonances are included in the analysis (N*1535 constrained by pp → ppη channel)
  K. Teilab Int.J.Mod.Phys.A26:694-696,2011

→ $pp \rightarrow ppe^+e^-$

- Cross section for resonance production via exclusive analysis of pp → pnπ⁺ and pp → ppπ⁰

Exclusive dilepton production

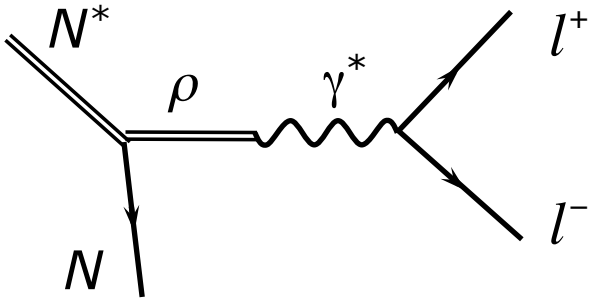
Exclusive analysis: pp → ppe⁺e⁻



HADES data preliminary
Model: M. Zetenyi and Gy. Wolf
Phys. Rev. C 67, 044002 (2003).

- Relative contribution is fixed through exclusive pion production
- ω contribution subtracted, η contribution suppressed by kinematics

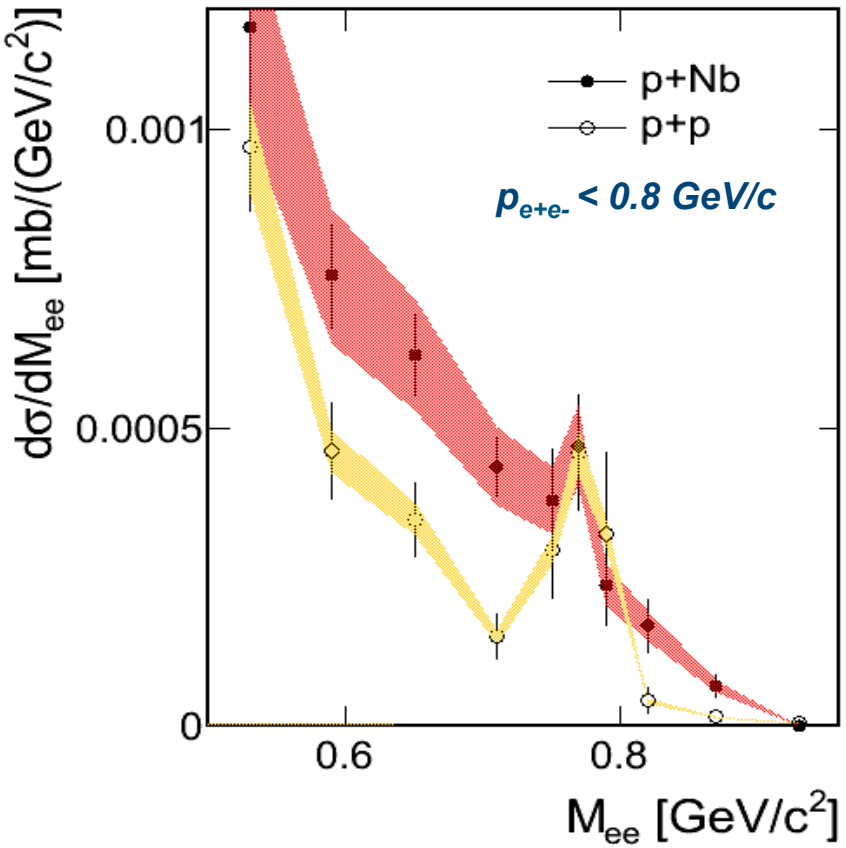
Dalitz decays of baryonic resonances – are the dominant source at low beam energies.



Electron pairs from cold nuclear matter

"if you are out to describe the truth, leave elegance to the tailor" (A. Einstein)

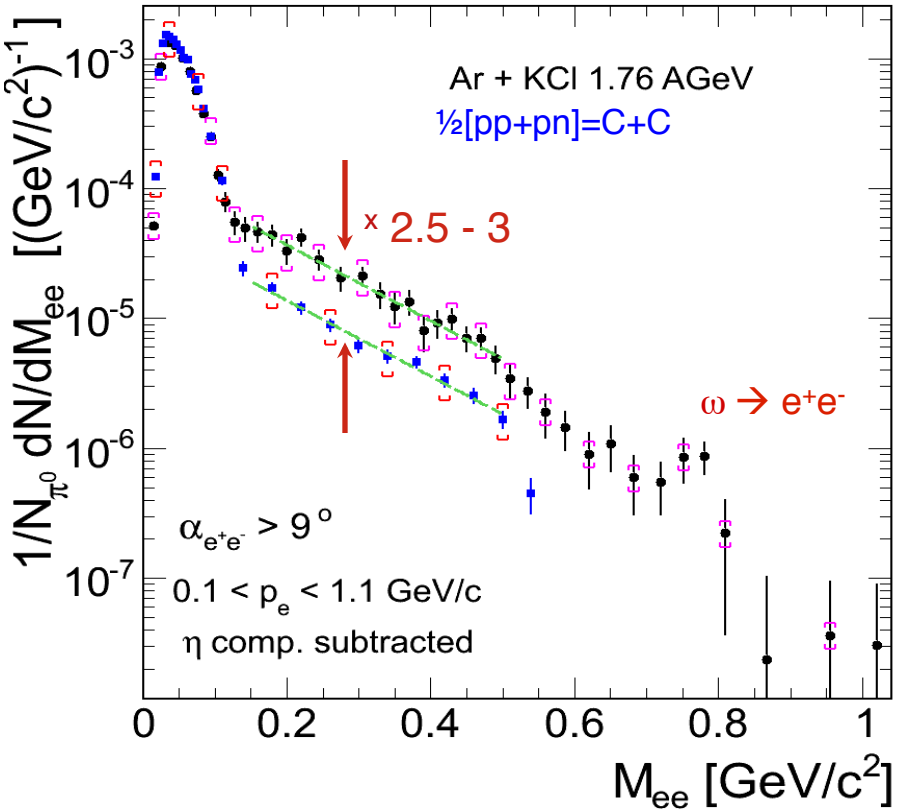
HADES: Phys.Lett. B715 (2012) 304-309



- **First measurement of lepton pairs with p_{e+e-} < 0.8 GeV/c radiated from cold matter**
  → not measured in this region by CLAS, KEK-E325
- Mass resolution: $\sigma_{M\omega}$ **= 16 MeV/c^2**
- Clear **excess over p+p**
  → role of the secondary ρ from N(1520), Δ (1700)…?
- **Reduced ω yield** → strong broadening?

Virtual photon emission in A+A collisions

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



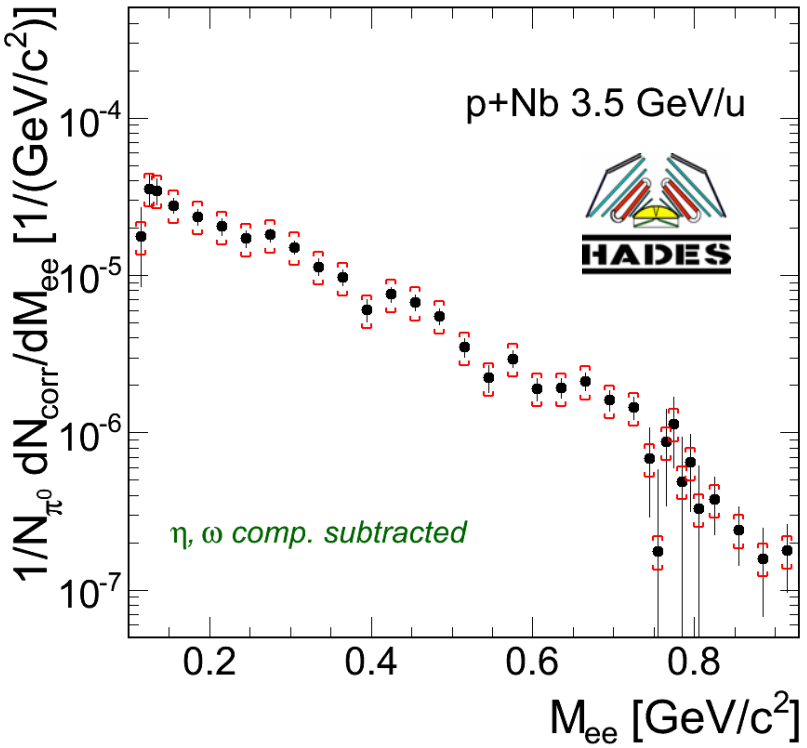
- **First evidence for radiation from the "medium"!**
- Excess yield scales with system size like $A_{part}^{1.4}$

Quest for heavier systems!

HADES: Phys.Rev.C84:014902,2011

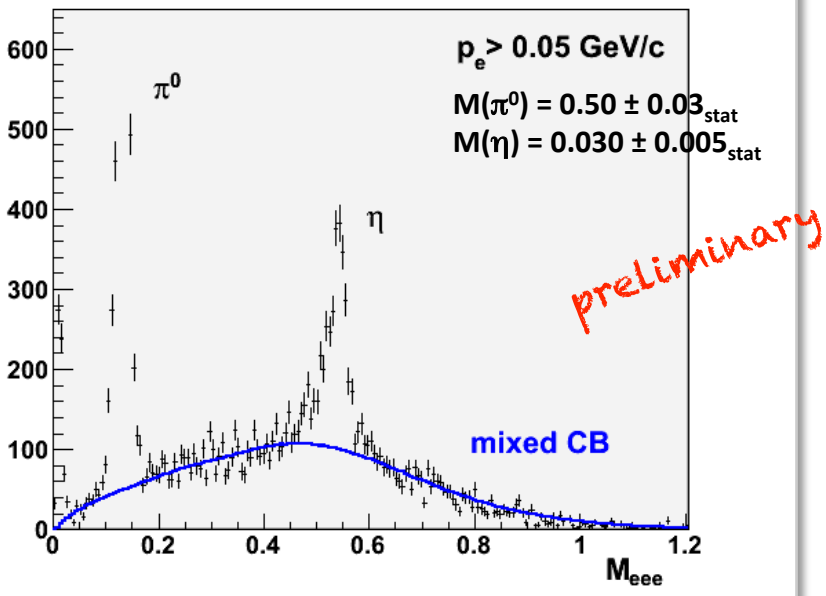
Isolation of excess by a comparison with a **measured** decay cocktail

Excess e^+e^- yield in p+Nb 3.5 GeV



In medium ρ modification?
→ will be answered only after pp reference is understood!

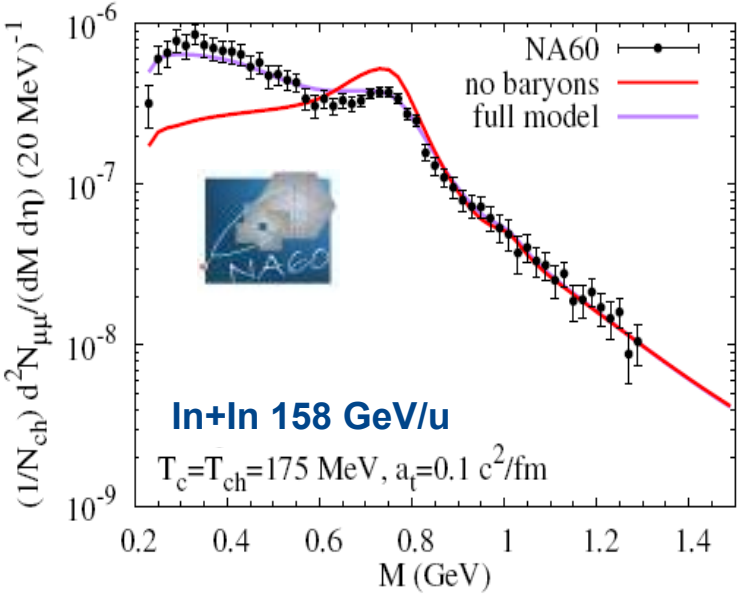
- Full reconstruction of π^0 and η decays (meson → $e^+e^-e^+e^-$)



- HADES η cross section provides constraint on Δ and N* contributions!
- Critical test for theoretical input!

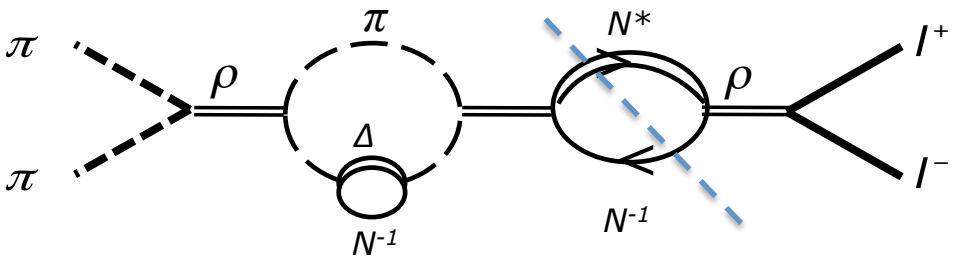
The ρ meson in a hot and/or dense fireballs: from SIS18 to SPS

Acc.-corrected $\mu^+\mu^-$ excess spectrum

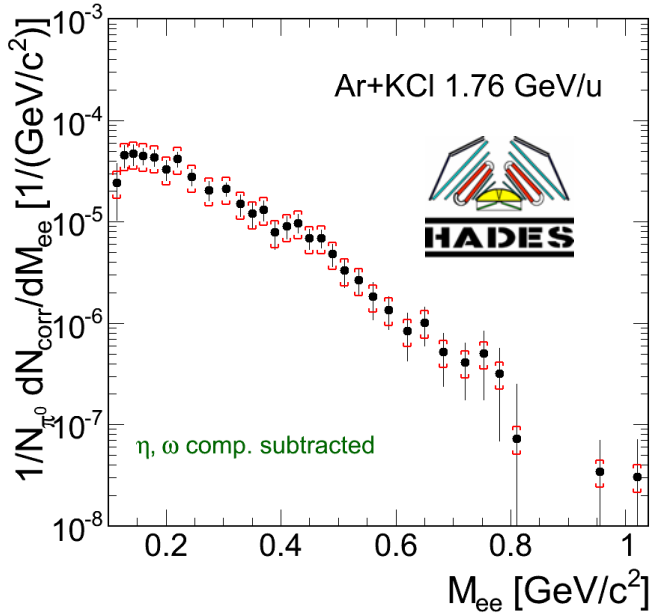


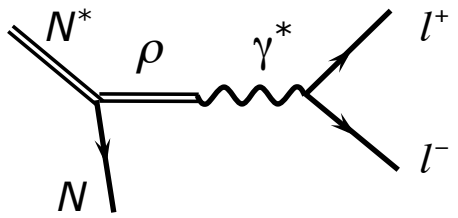
Data: EPJC 59 (2009) 607
R.Rapp: NPA806 (2008) 339

- Main source: $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$
- Low mass enhancement is **due to coupling of the VM to baryons**!



Excess e^+e^- yield, Ar+KCl 1.76 GeV/u

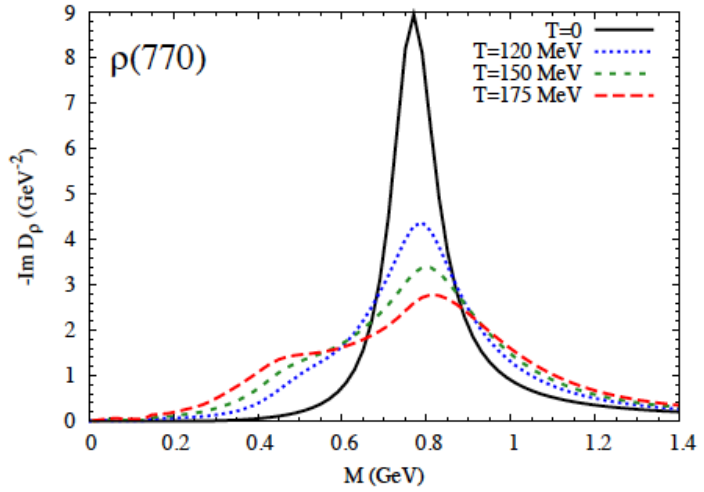




Dalitz decays of baryonic resonances – dominant source at SIS18!

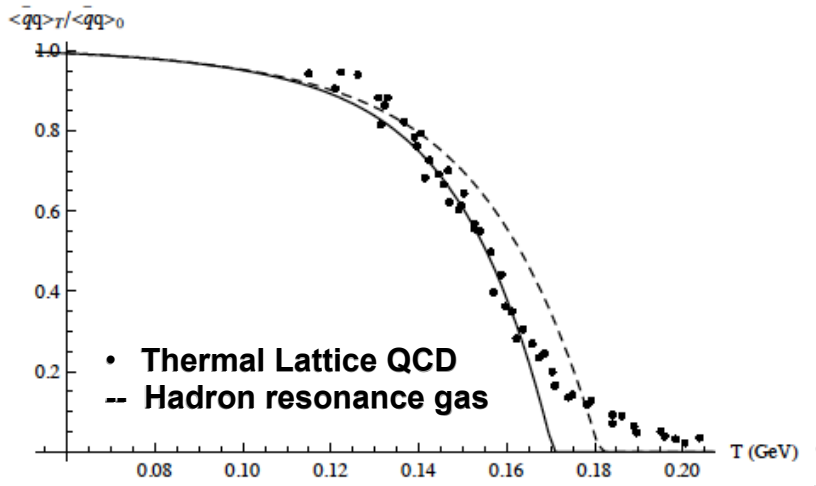
Dileptons, baryonic resonances and the phase diagram of matter

In-medium ρ spectral function



R. Rapp, Acta Phys. Polon. B 42, 2823, 2011

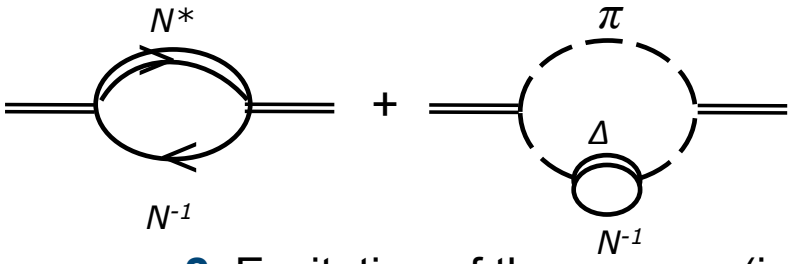
Temperature dependence of the chiral quark condensate



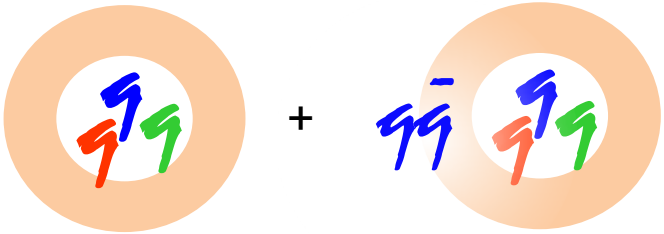
S. Borsanyi et al., JHEP 1009, 073 (2010)

effective hadronic theory ⟺ $\frac{\langle\bar{q}q\rangle(T,\mu_B)}{\langle\bar{q}q\rangle_0} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$

1. $\Sigma_h = m_q \langle h|q\bar{q}|h\rangle > 0$ contains ***quark core + "pion cloud"***



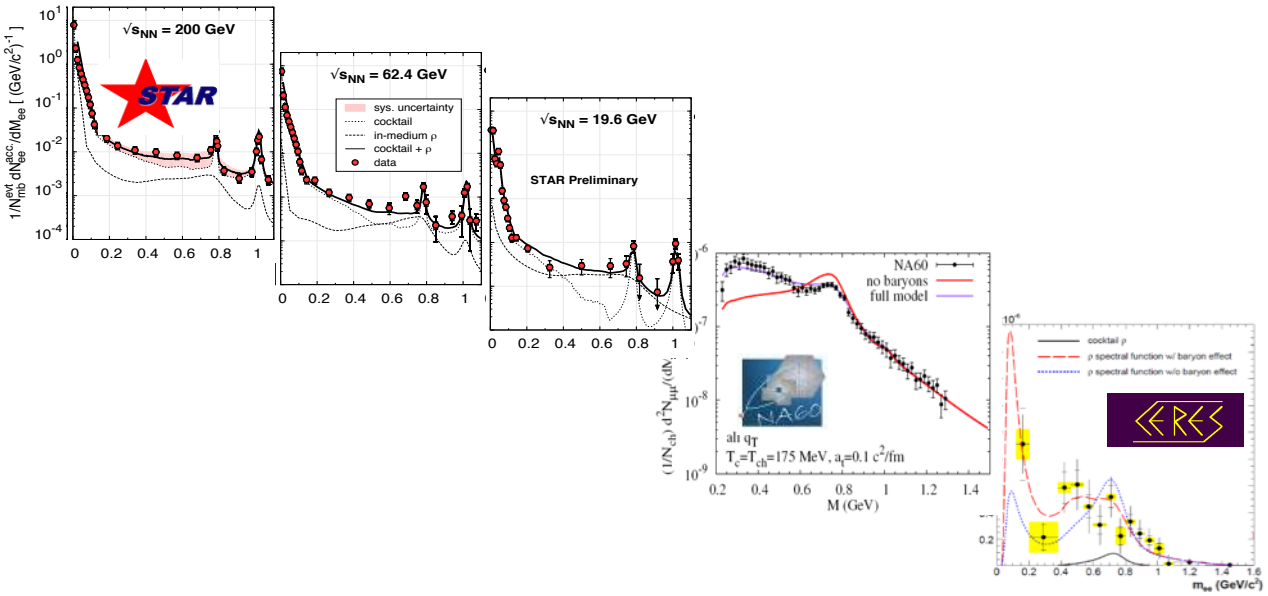
⟺



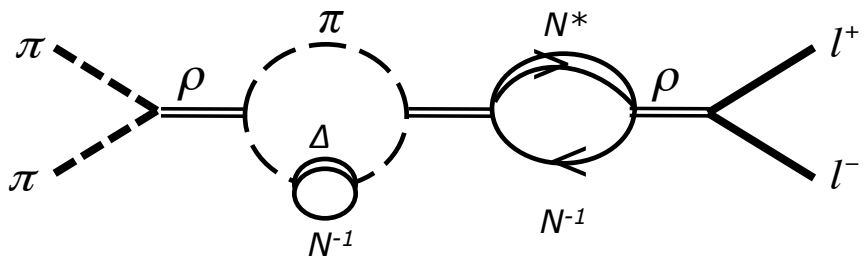
2. Excitation of the vacuum (i.e. melting of the condensate) influences the modification of the spectral properties

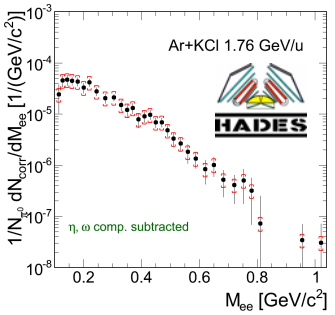
Virtual photon radiation from hot and/or dense QCD matter

T



Model: Ralf Rapp
STAR: QM2012,
NA60: EPJC 59 (2009) 607,
CERES: Phys. Lett. B 666 (2006) 425,
HADES: Phys.Rev.C84 (2011) 014902

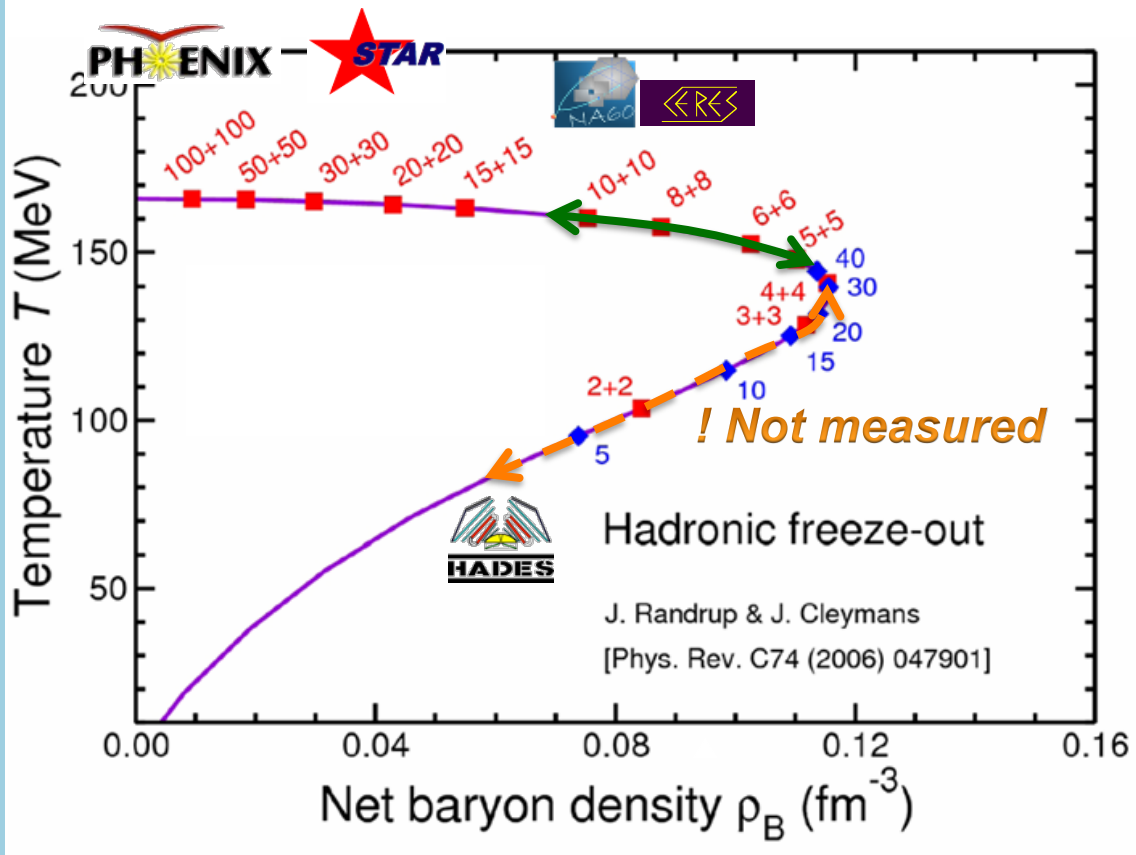




Highly interesting results from RHIC, SPS, SIS18 → importance of baryons!

μ_B

Quest: explore the regime of baryon dominated matter

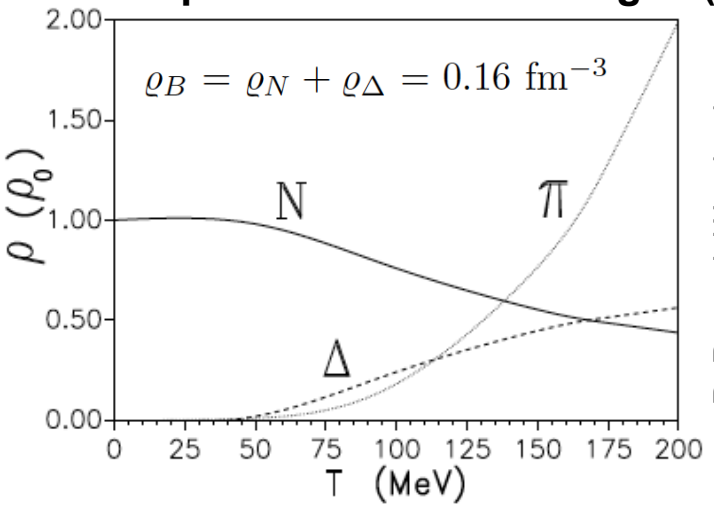


No measurement for beam energies of 2-40 GeV/u

→ **HADES/CBM at SIS100**

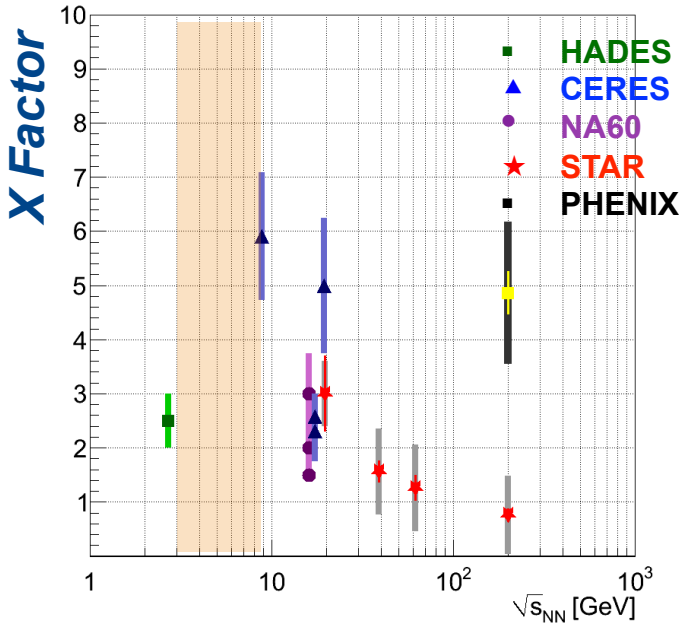
→ **CBM at SIS300**

Composition of a hot πΔN gas (T)



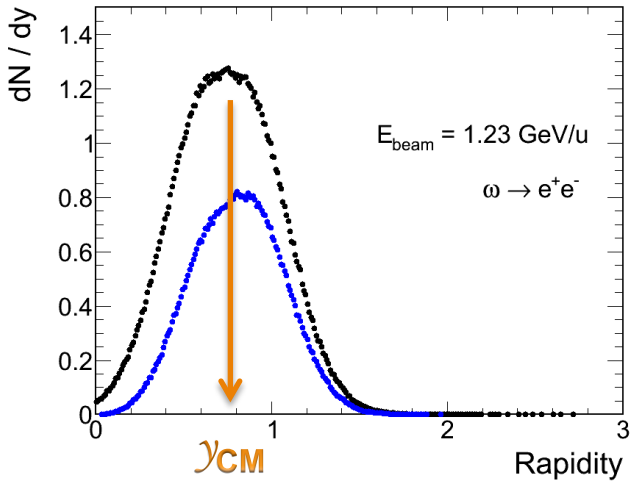
R. Rapp, J. Wambach, Adv.Nucl.Phys. 25 (2000) 1

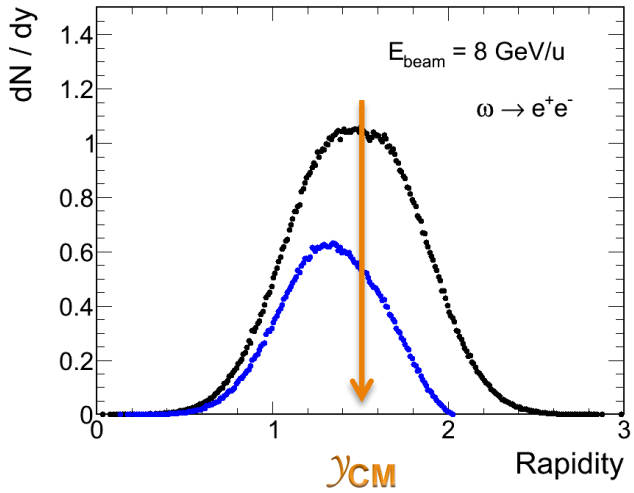
Published low-mass enhancement factors

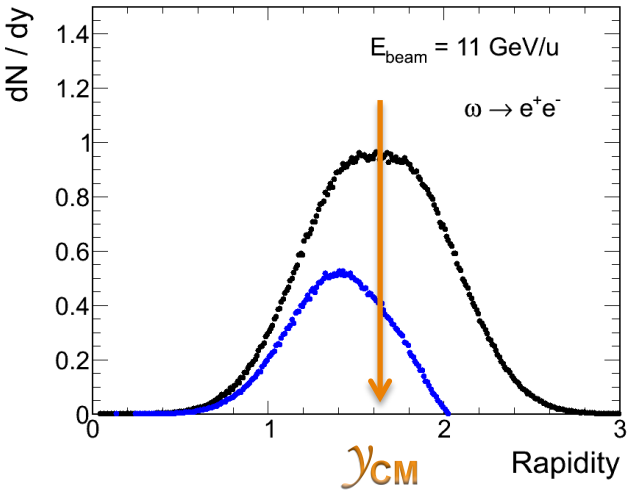


HADES at SIS100: phase space coverage for e^+e^-

The "sweet spot" is at mid-rapidity and low p_t!







E_{beam} = 1 GeV/u

- overall acceptance for di-electron pairs Acc ≈ 35%
- with nice mid-rapidity coverage

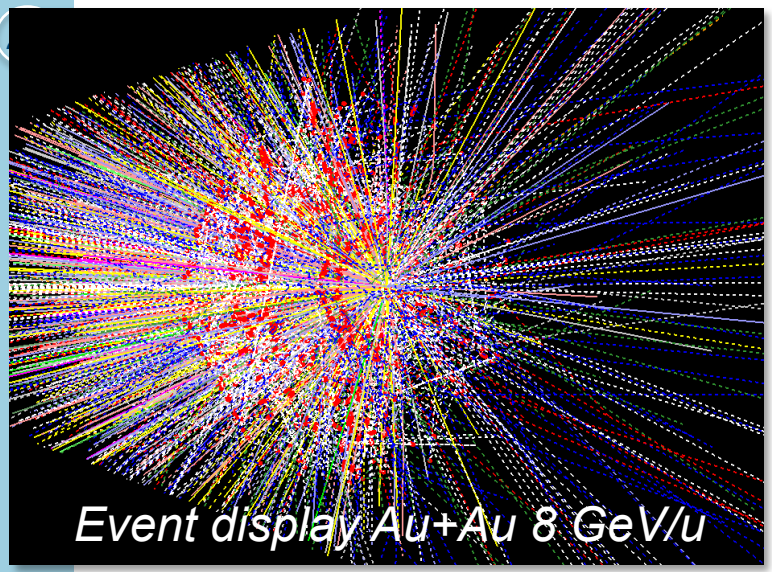
E_{beam} = 8 GeV/u

- Acc ≈ 20%
- (natural) shift towards backward rapidity

E_{beam} = 11 GeV/u

- … still HADES → Acc ≈ 20%
- **but…**

HADES at SIS100: problems, challenges, opportunities



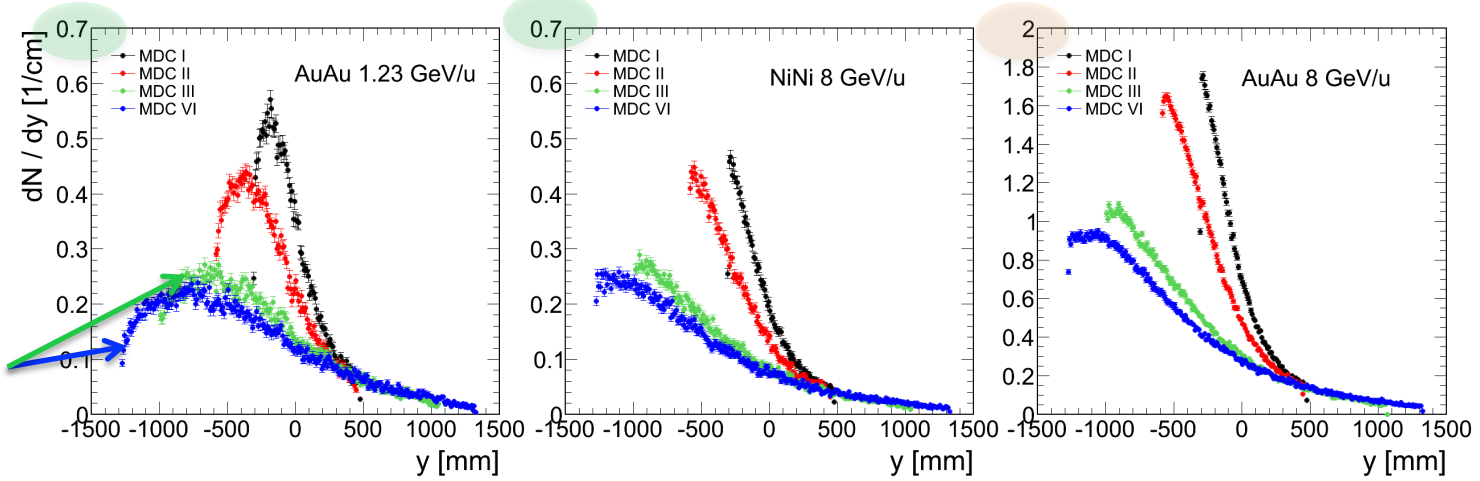
- **Challenge:** limited granularity →
  - sophisticated tracking algorithm

- Au+Au 1.23 GeV/u successfully measured in May 2012
- Ni+Ni 8 GeV/u ≈ Au+Au at 1.23 GeV/u
- Au+Au 8 GeV/u occupancy increases by factor of 4-5!

→ **CBM kicks in**

Occupancy in tracking chambers (b_{max} = 1 fm)

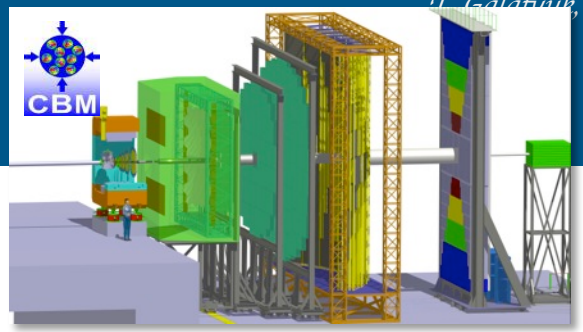
Cell size is factor of 2 larger

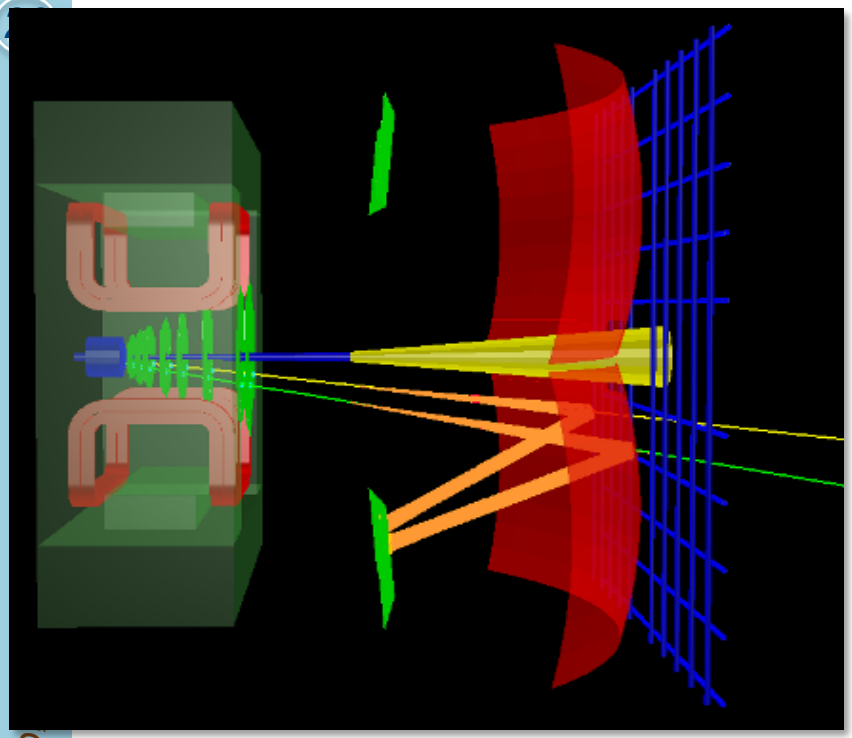


y – radial coordinate in drift chamber

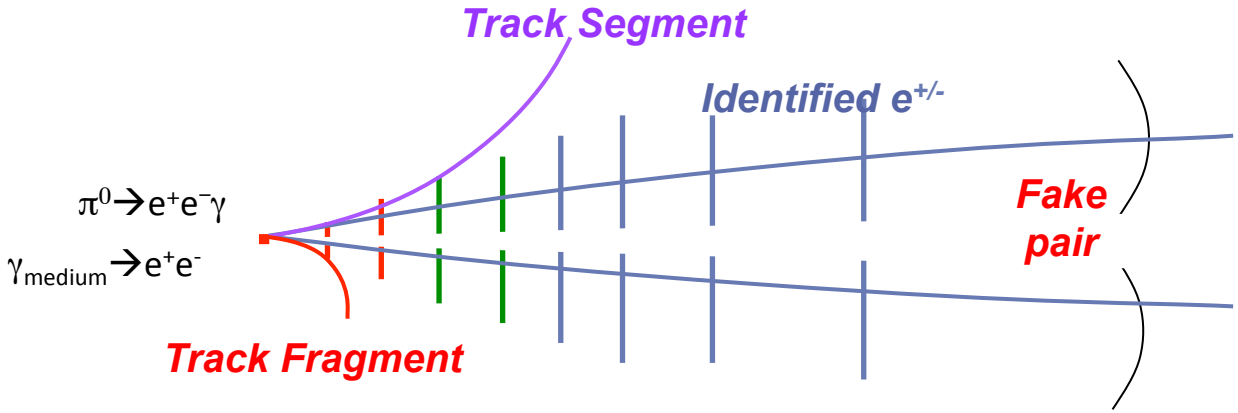
Di-electron reconstruction in CBM

T. Galatyuk,



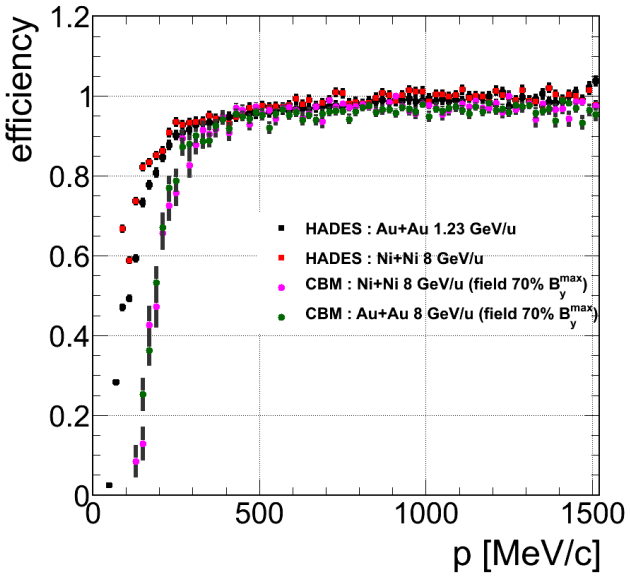


- **Challenge:**
  - No electron identification before tracking
  - Background due to material budget of the STS
  - Sufficient π discrimination (600 $\pi^{+/-}$/event, misidentification 10^{-4})
- **Strategy:**
  - Reduction of background by reconstructing pairs from γ-conversion (~3 γ) and π^0 Dalitz decay (8 π^0/event)
  - Excellent double-hit resolution in MAPS (<100μm) provides substantial close pair rejection capability



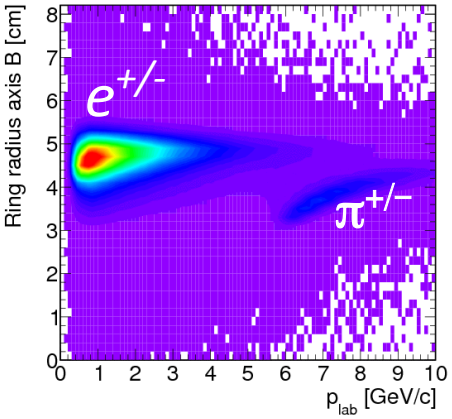
Electron identification

Track reconstruction efficiency

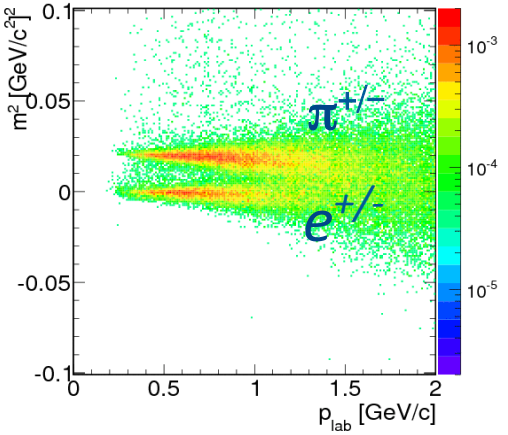


- Momentum distribution of conversion pairs are very soft
- High reconstruction efficiency is required for rejection of conversion pairs

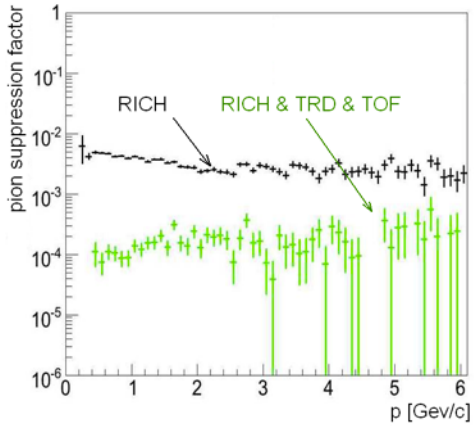
Ring radius vs. momentum



RICH identified $e^{+/-}$ in TOF



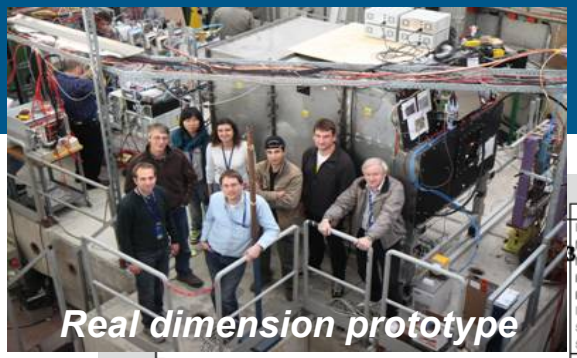
π suppression factor of 10^4 (for p < 1 GeV/c) is in reach with RICH and ToF

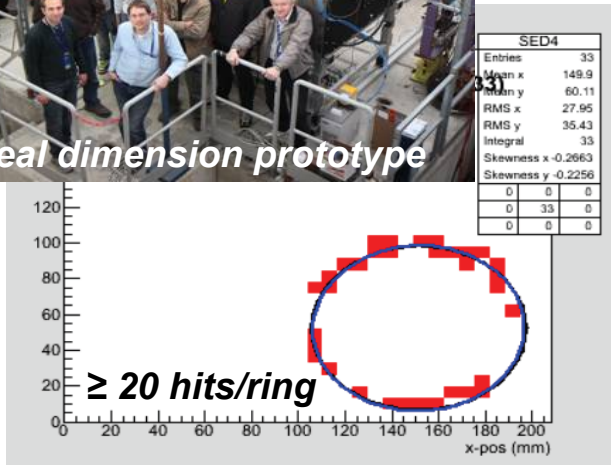


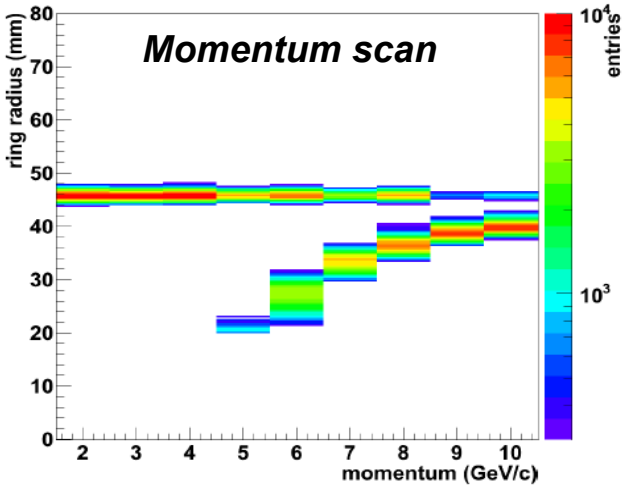
Detector R&D

RICH

- Conventional design based on commercial products (Germany, Russia, Korea)
  - Float glass mirror (carbon as backup)
  - Multi-anode PMT photo detector



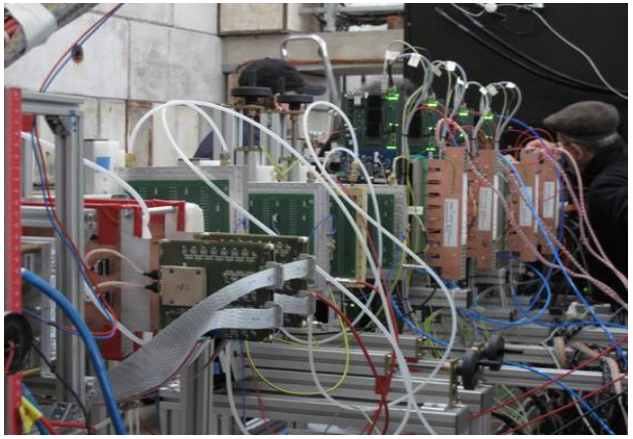


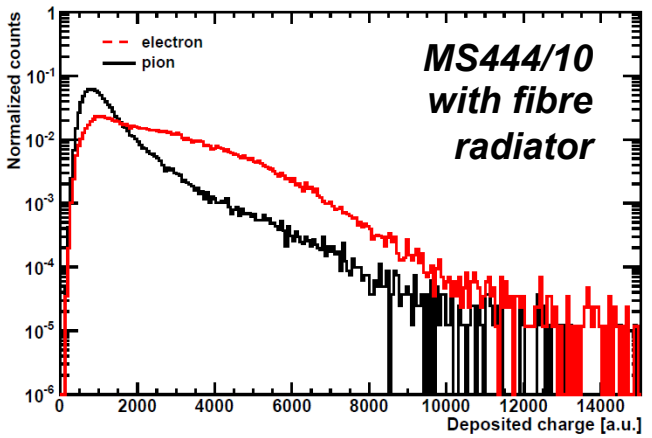


- Test Beam at CERN T9, October 2011
- Mixed electron / pion beam of 2 – 10 GeV/c

TRD

- Thin gap design based on ALICE TRD (Germany, Russia, Romania)

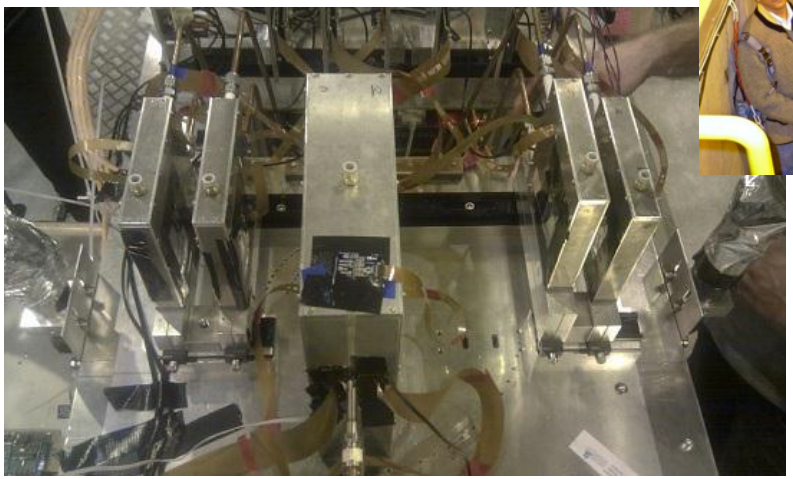




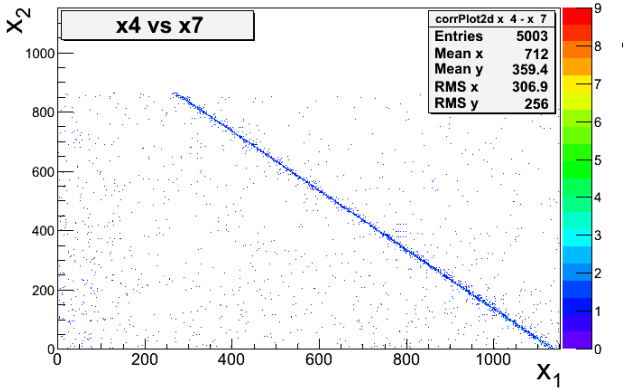
Detector R&D : Micro-Vertex Detector

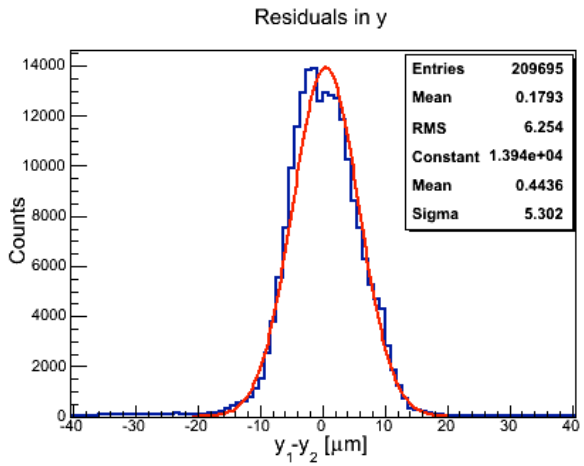
Detector module:

- Two thinned (50 μm) sensors mounted to either side of a 200 μm CVD diamond carrierer.
- ***Total thickness = 0.3% x/X0***



- **Test Beam at CERN T9, 26-30 November 2012**
- **Pion beam of 20, 60, 120 GeV/c**





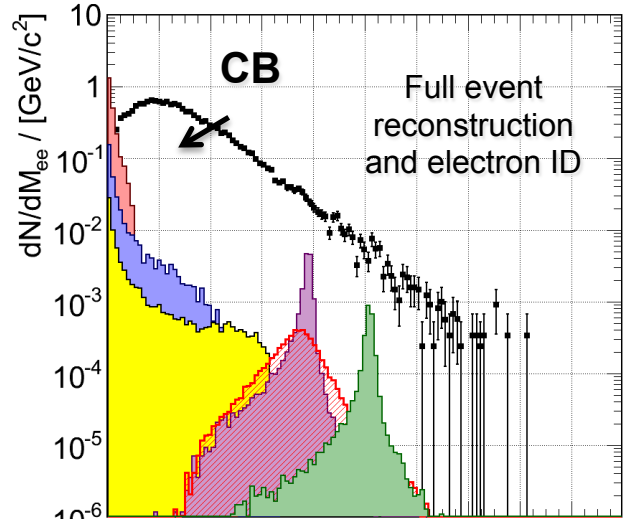
Spatial Resolution

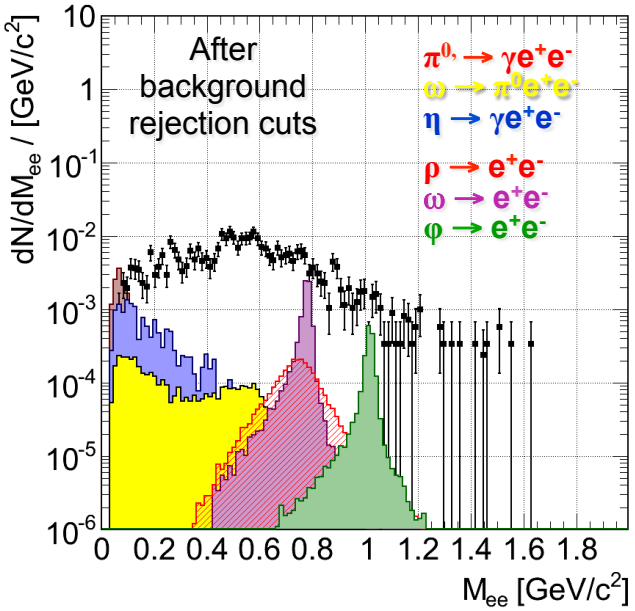
σ_x = 3.3 μm

σ_y = 3.7 μm

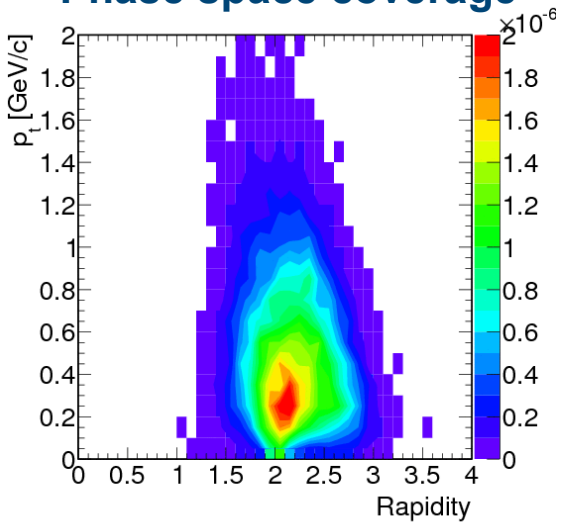
Low mass electron pairs reconstruction

Au+Au 25 GeV/u, b = 0 fm!



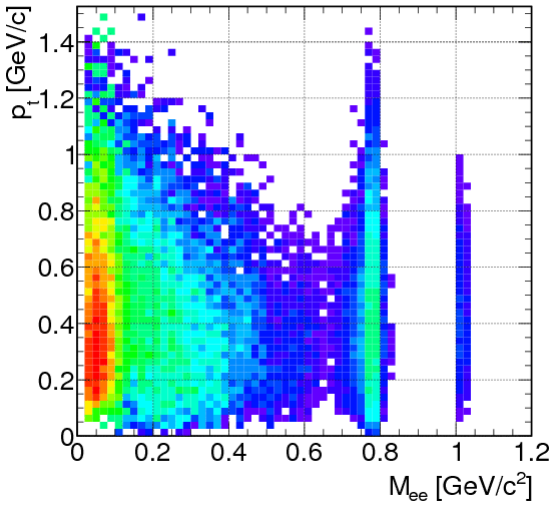


Phase space coverage



after all cuts

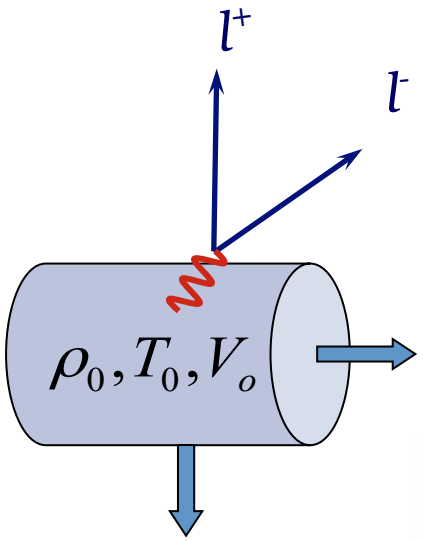
Coverage in pair p_t-m_{inv} plane



after all cuts
excluding single leg p_t cut

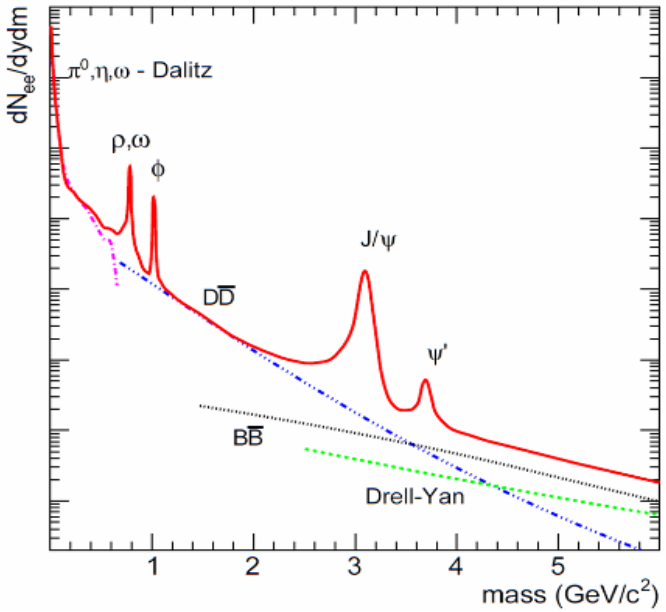
Dilepton emission rates in theory

Thermal emission...

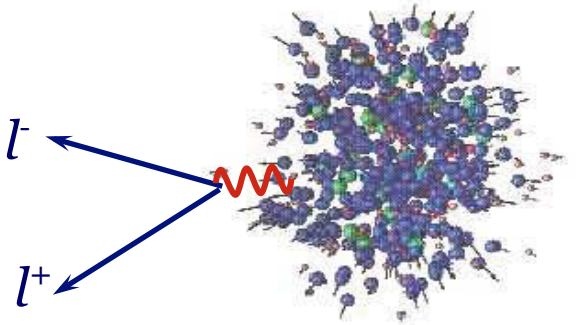


$$\frac{d^3N}{dMdydp_t} \equiv \int_{t=0}^{\infty} \frac{d^4\varepsilon}{d\mathbf{p}} \left[T(\mathbf{x}), \mu_B(\mathbf{x}), \vec{v}_{coll}(\mathbf{x}), ..\right] d\mathbf{x}$$

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

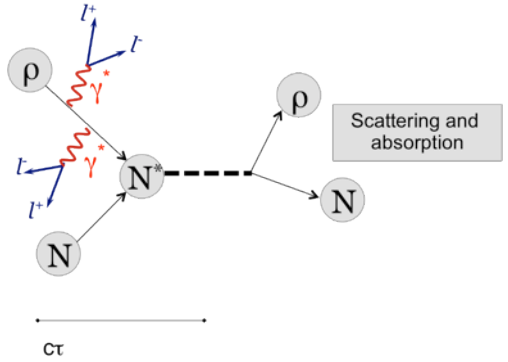


...or from transport

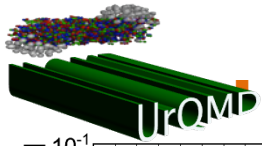


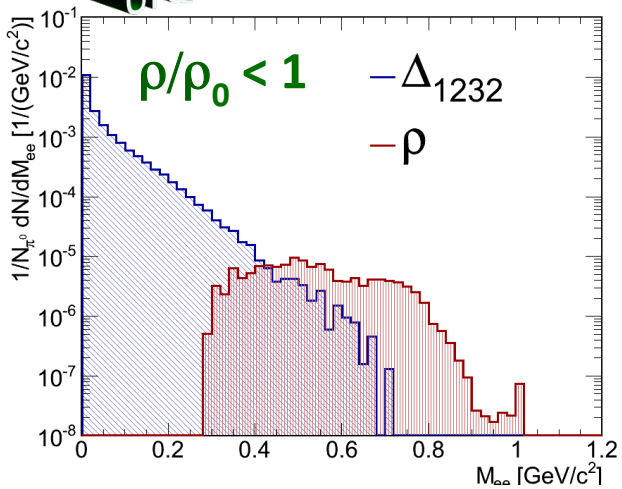
Radiation from dense matter

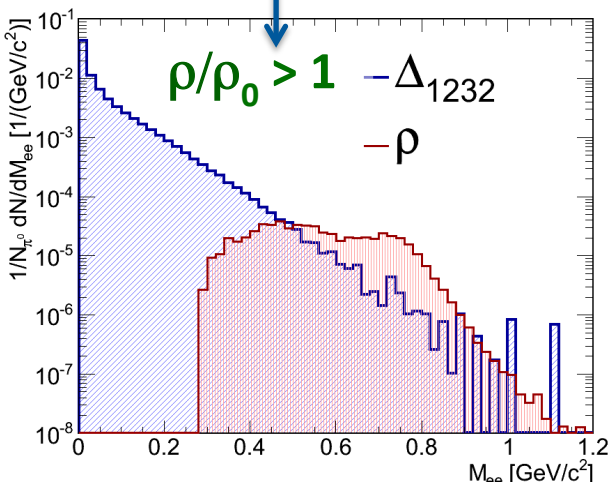
- Schematic illustration of ρ meson propagation within "shining" approach.
- Resonance can continuously emit dileptons over its whole lifetime.



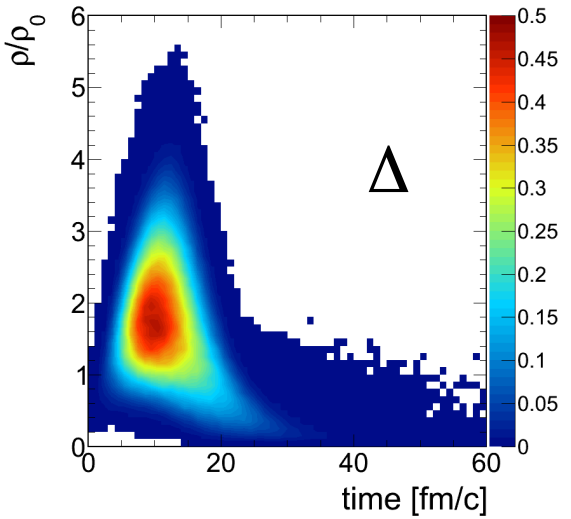
- Isolate the contribution to the spectrum from the dense stage
- Couple transport and a **thermal model**

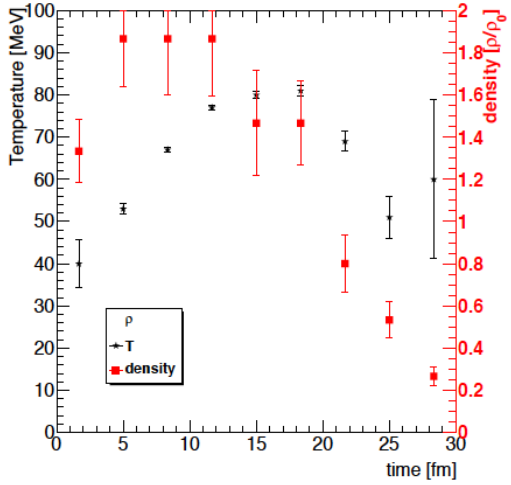






Emission density evolution





- First (points) and second (errors) moment of the density profile at a given τ.
- T – Boltzmann fit to the particle m_T spectra

π beam experiments with HADES

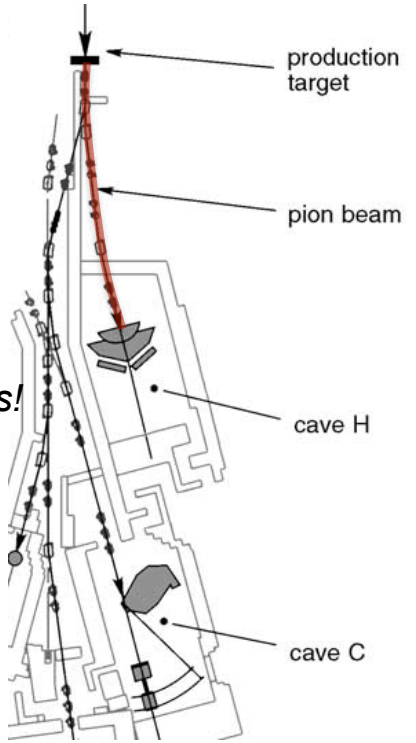
- **Physics with πN experiments:**
  - New precision data are of enormous importance for understanding of baryon resonance physics
  - Special interest to sub-threshold production
- **Challenges:**
  - Determine π momentum with Δp/p ~1-5%
  - Beam spot of 6x6 cm^2 at dispersive plane
    → detector with sufficient active area
  - Beam intensity ~10^8 part./s
    → radiation hard detector
    → fast readout electronics

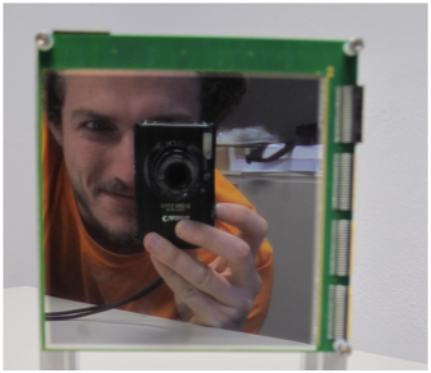
Primary beam:
10^{11} N (2 AGeV) /spill

SIS fast ramping

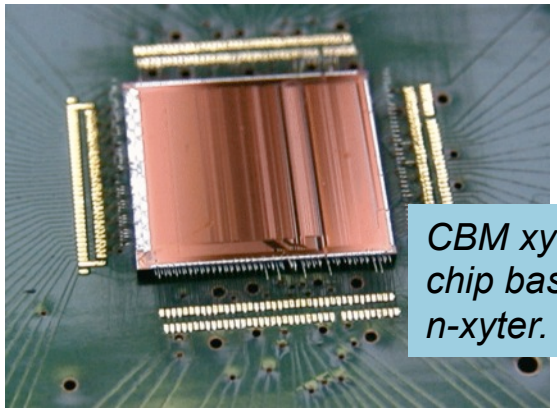
Spill: 4s cycle

Stable run for 3 weeks!





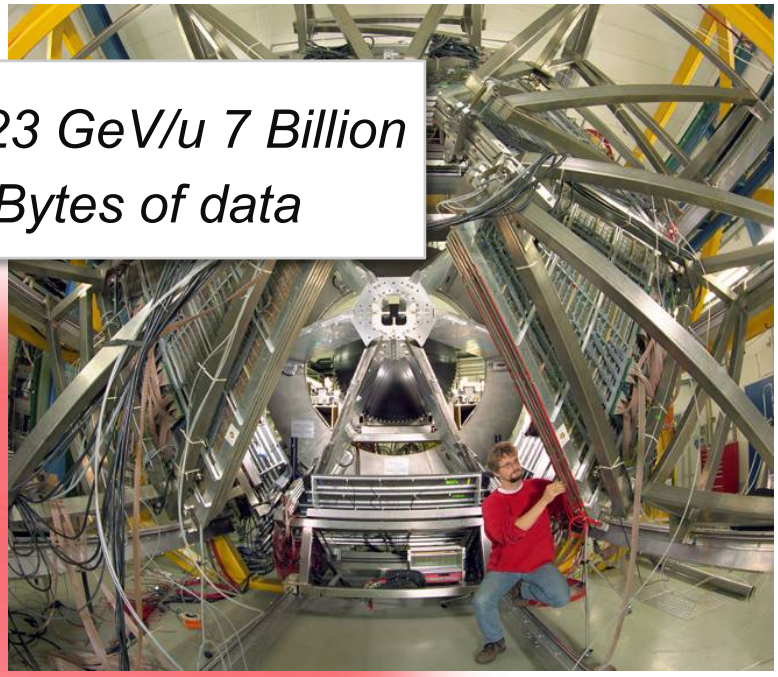
- **Strategy:**
  - Use 10×10cm^2 silicon strip detector
  - 2×128 channels - double sided
  - Radiation hard
  - Profit from n-xyter developments for CBM
    - ✓ Self-triggered architecture
    - ✓ 128 channels
    - ✓ Average hit per channel rate 160 kHz

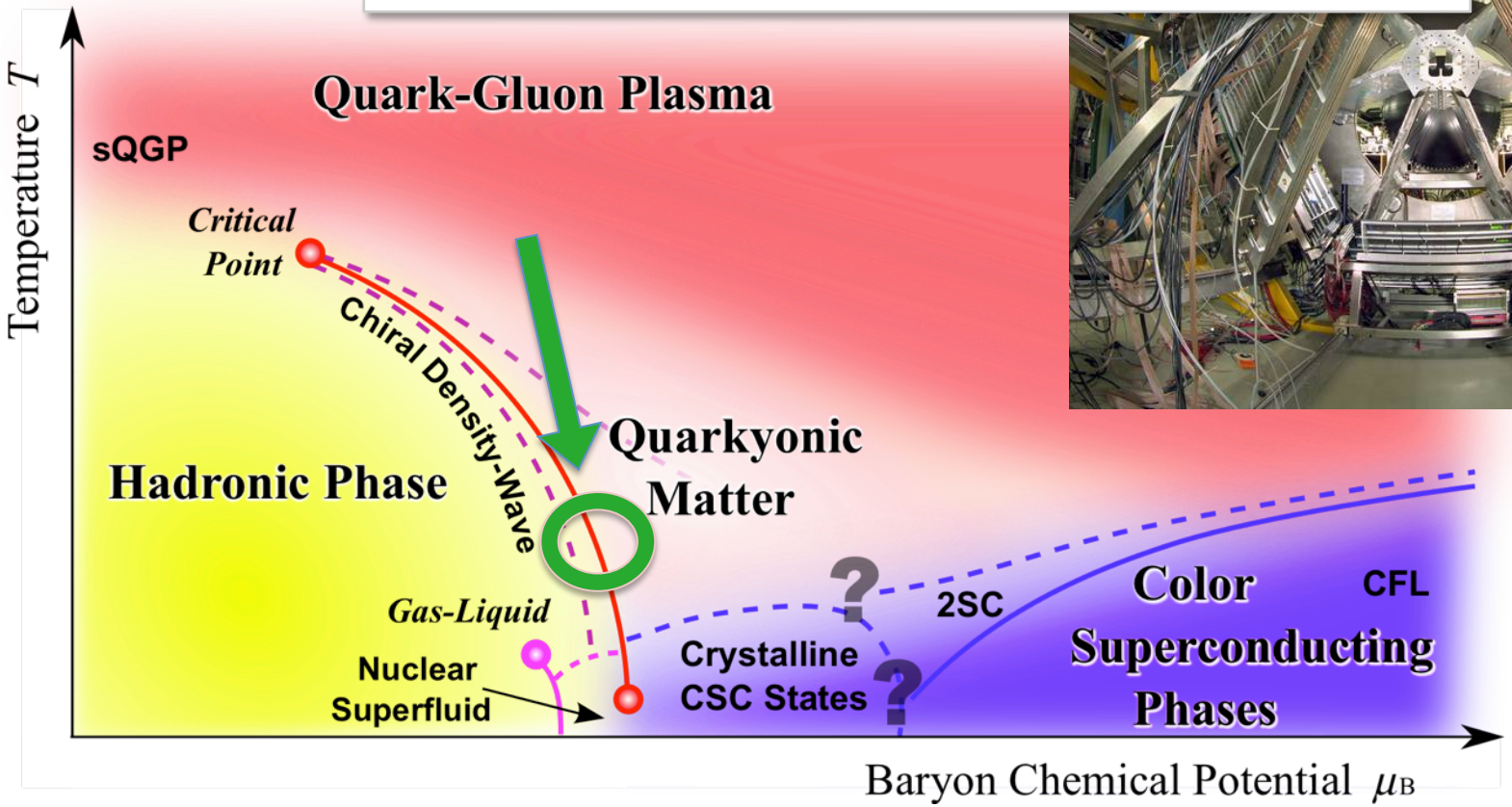


CBM xyter FE chip based on n-xyter.

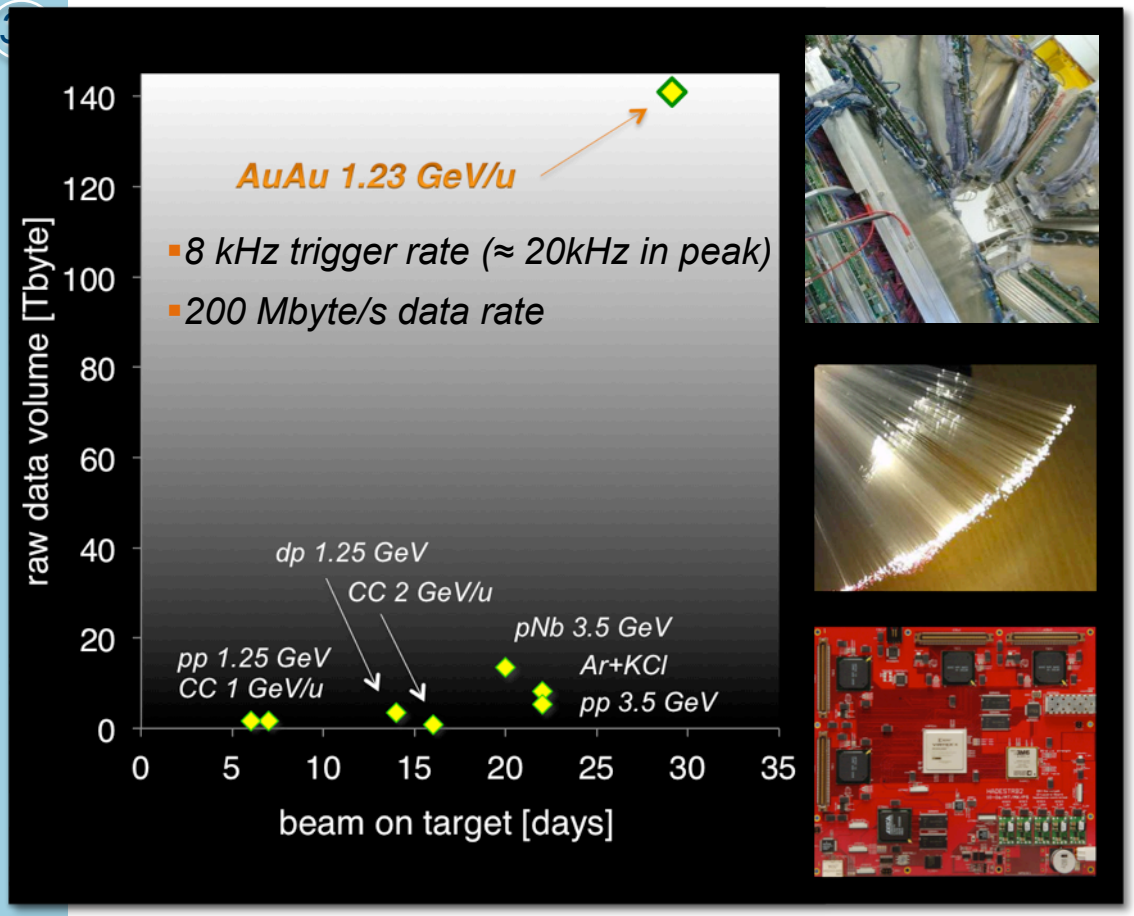
HADES explores Quarkyonic matter

April-May 2012 Au+Au run,1.23 GeV/u 7 Billion events in 4 weeks,140 T Bytes of data

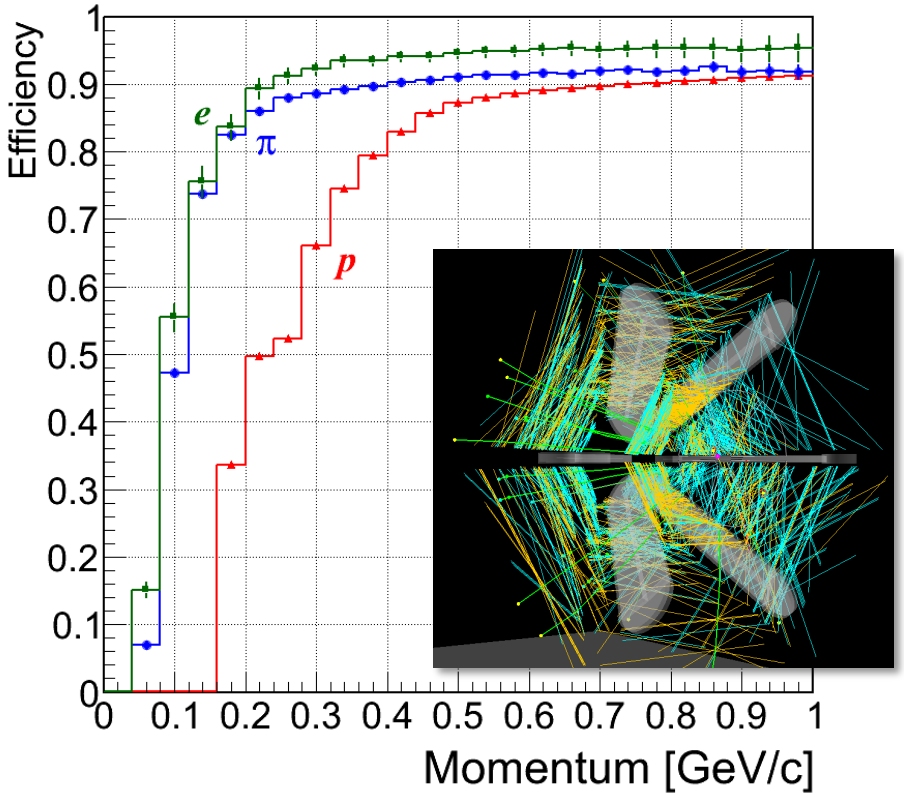




Au+Au at 1.23 GeV/u (beam time April – May '2012)



Track reconstruction efficiency in high track density environment

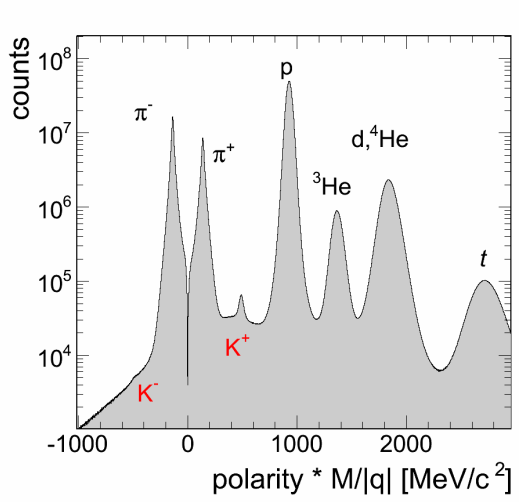


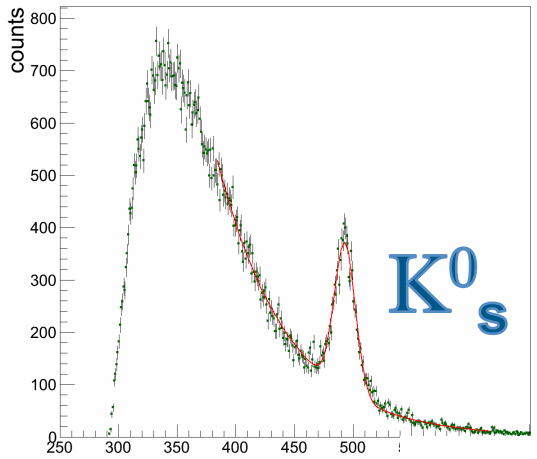
HADES DAQ:

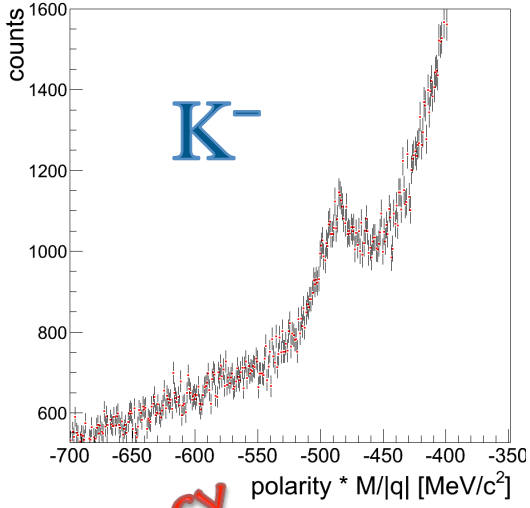
Versatile, FPGA board based system using dedicated add-on boards and data/trigger/slow-control transport via serial optical links (TRBnet)

Strangeness

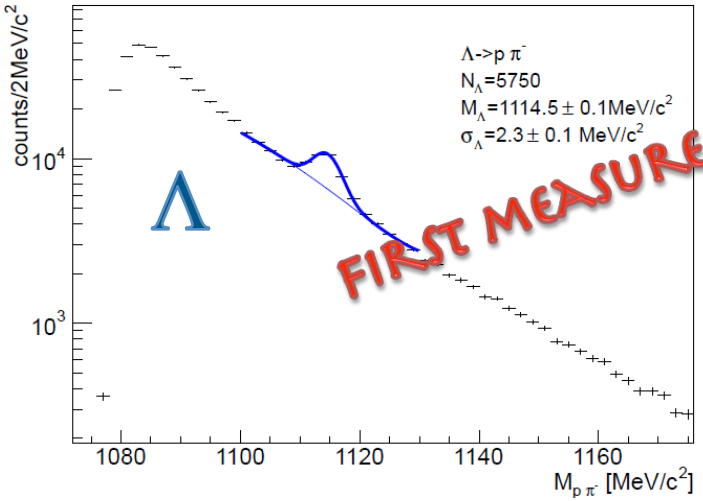
NN excess energy 0.44 GeV only!
Strong constraints on production mechanism

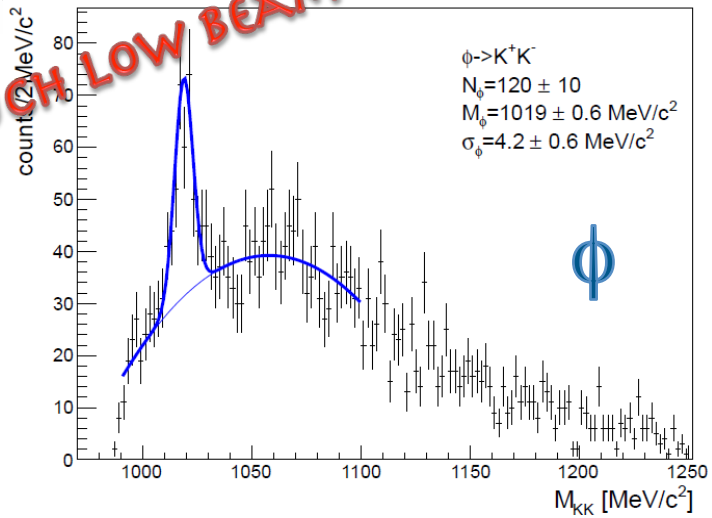




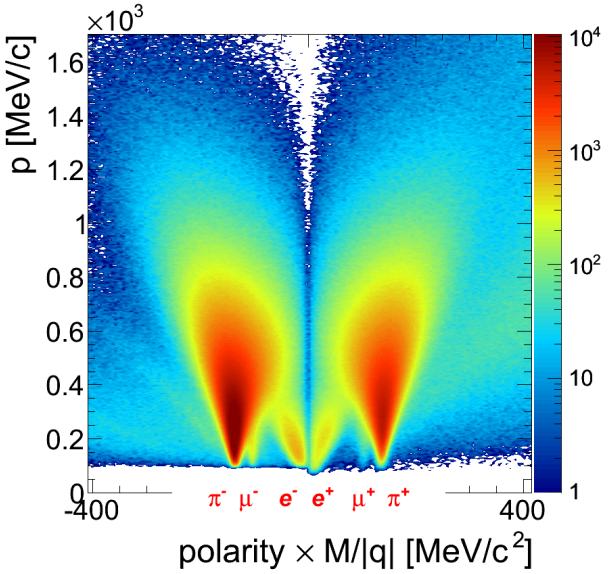


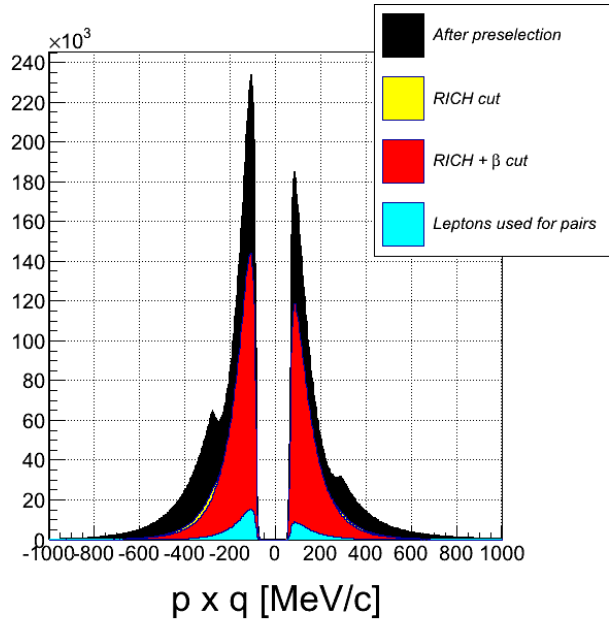
FIRST MEASUREMENT AT SUCH LOW BEAM ENERGY

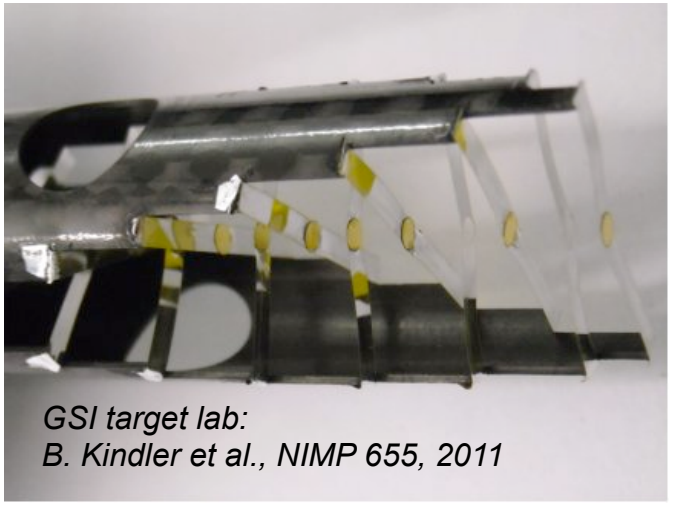




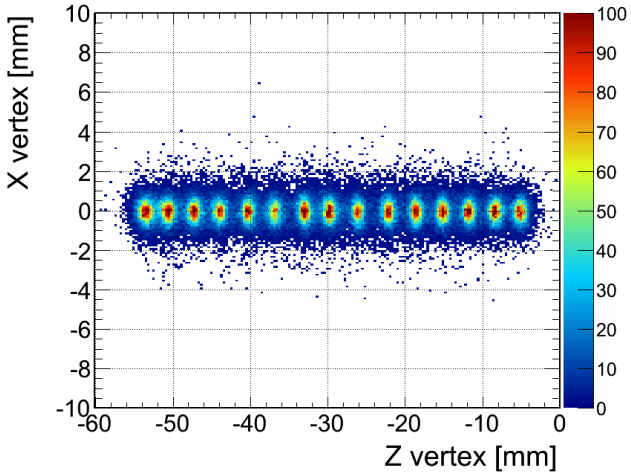
Leptons







GSI target lab:
B. Kindler et al., NIMP 655, 2011



Summary

Encouraging prospects for studying QCD matter in the region of compressed baryonic matter (finite μ_B)

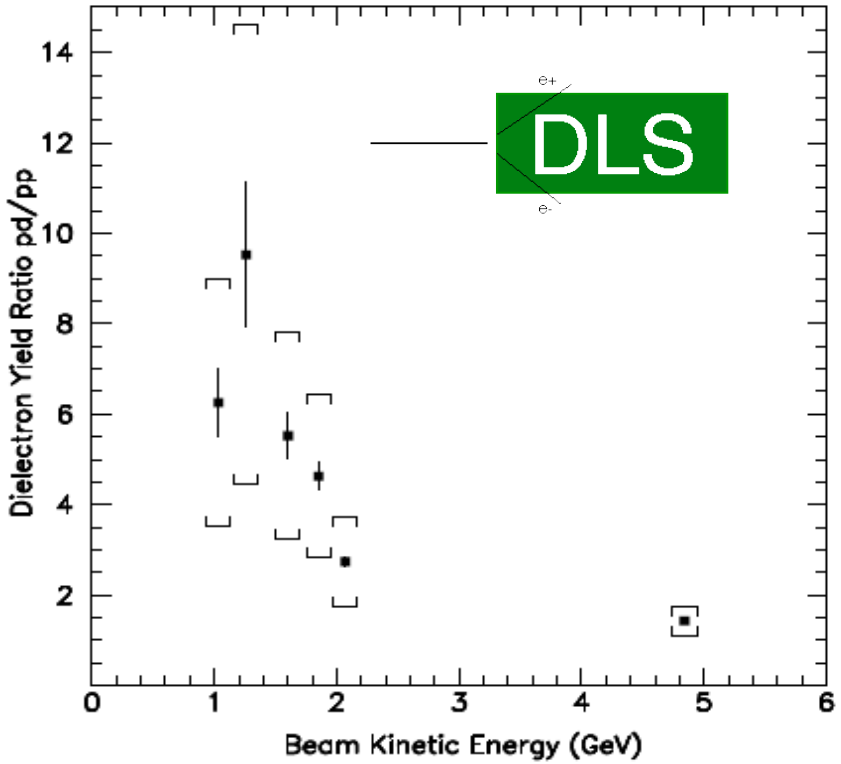
- Explore “unknown” territory of the nuclear matter phase diagram with HADES and CBM :
  - **Unique possibility of characterizing properties of baryon dominated matter with rare probes:**
    - long-lived states of compressed nuclear matter are produced in heavy-ion collisions at few GeV energy regime
    - this state of matter might be much more exotic than a hadron gas (Quarkyonic metter?)
  - **Establish a complete excitation function of dilepton production up to energies of 40 GeV/u:**
    - baryon dominated to meson dominated fireballs!
    - from "transport" to "thermal expansion" models!
    - from "no QGP" to "QGP”?

The results presented is the work of many …

… THE HADES AND CBM COLLABORATIONS

BONUS SLIDES

NN Reference : e^+e^- in QF n+p collisions

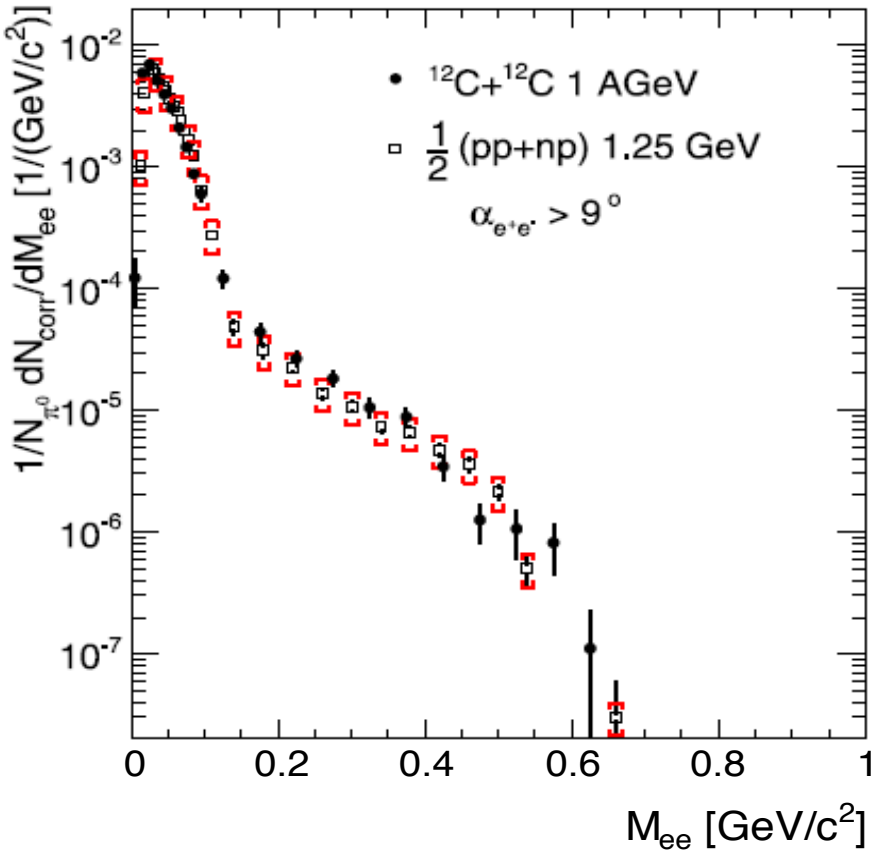


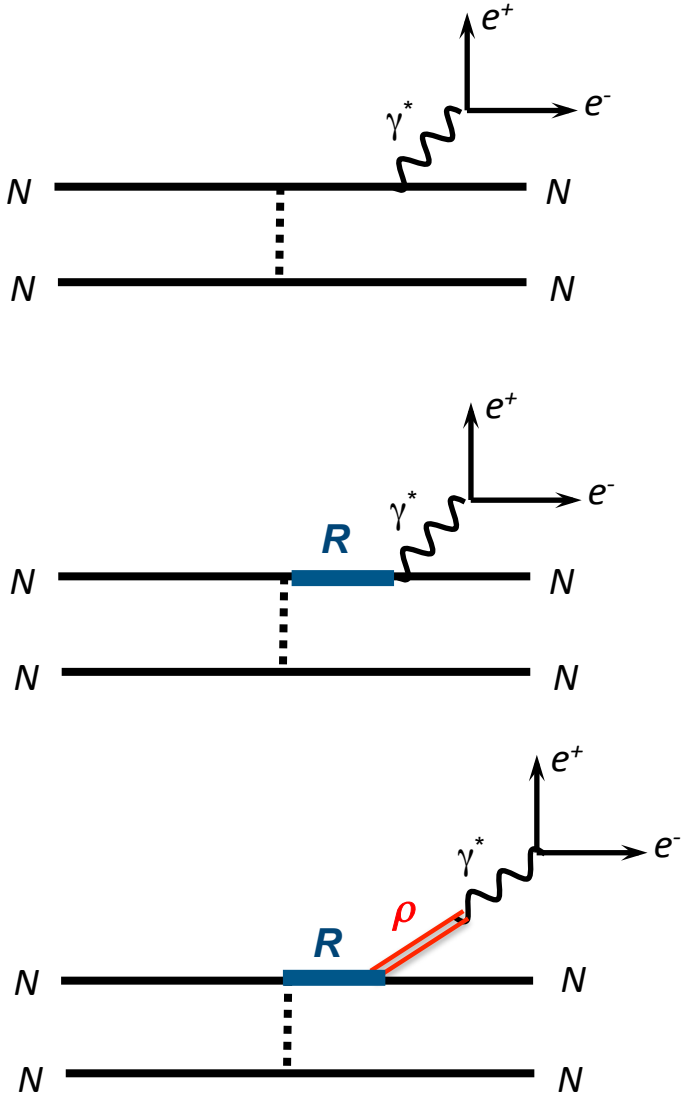
W. Wilson et al., Phys. Rev. C 57 (1998)

- Large isospin effects in dilepton production!
  - Role of the momentum distribution of the neutron inside the deuteron?
  - NN bremsstrahlung?

Virtual photon emission in A+A collisions

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

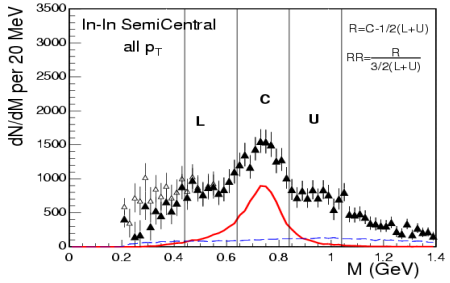




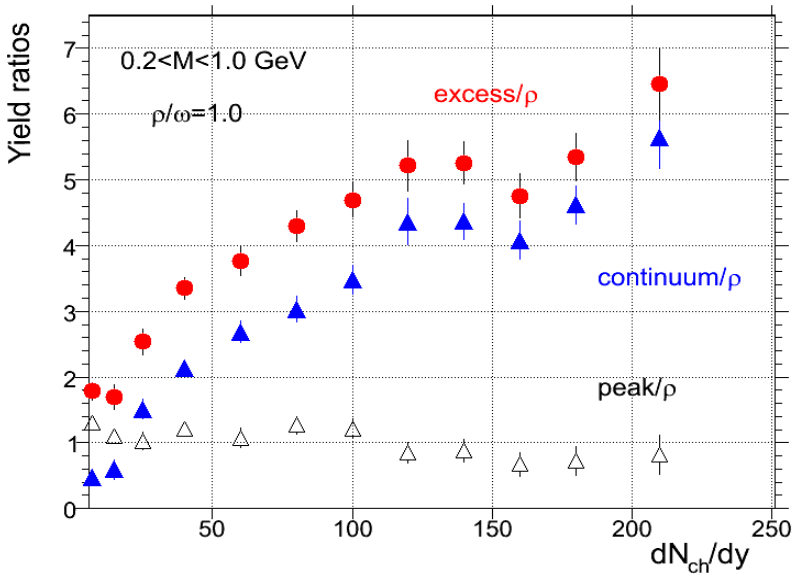
Baryonic contributions from NN "reference"

R = Δ, N*

Centrality dependence of spectral shape



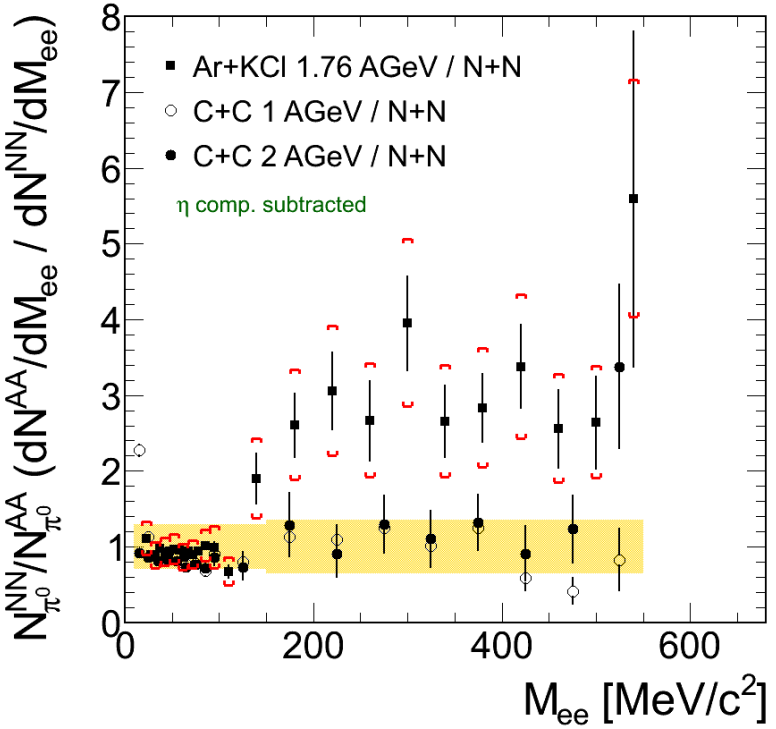
"ρ clock"



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

Na60 data: EPJC 61 (2009) 711

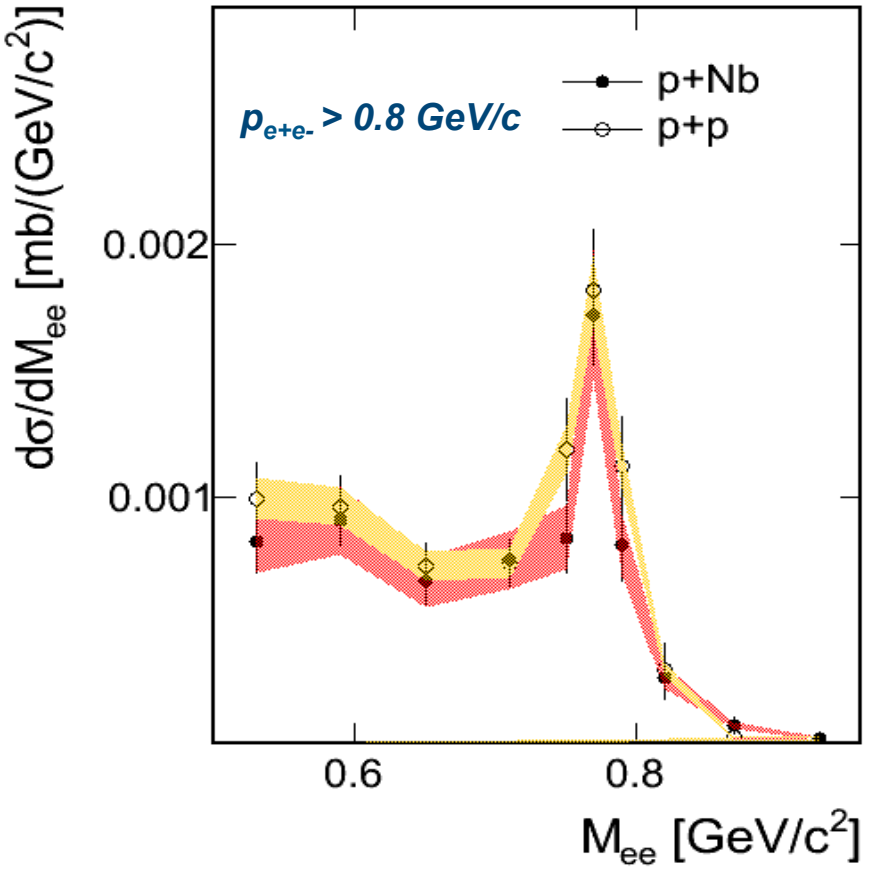
"Δ clock"

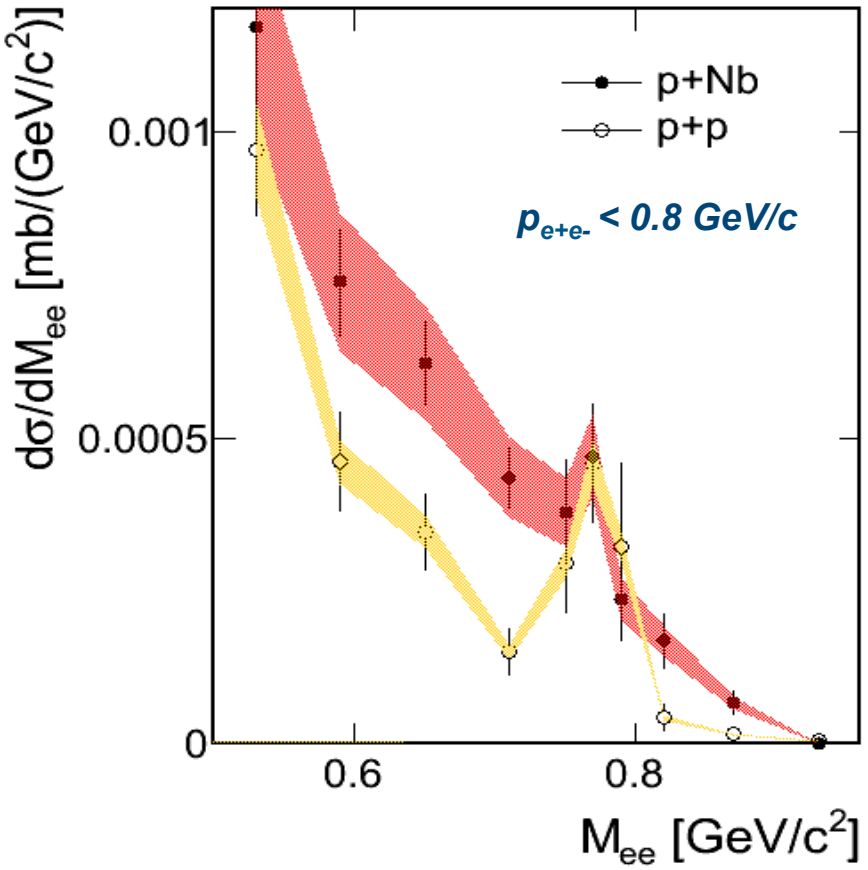


HADES: Phys.Rev.C84:014902,2011

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

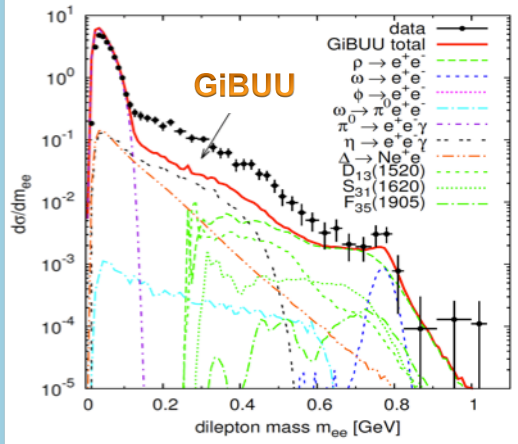
Electron pairs from cold nuclear matter



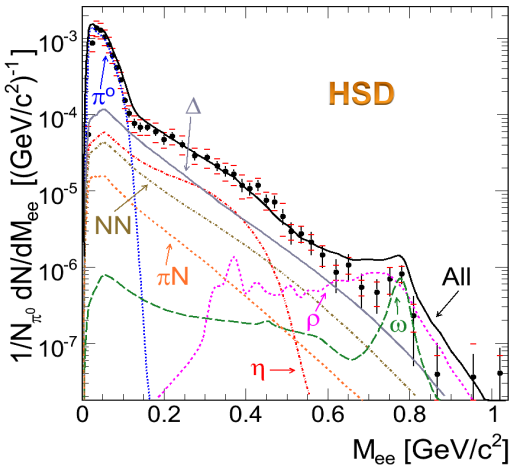


Virtual photon emission in A+A collisions - transport

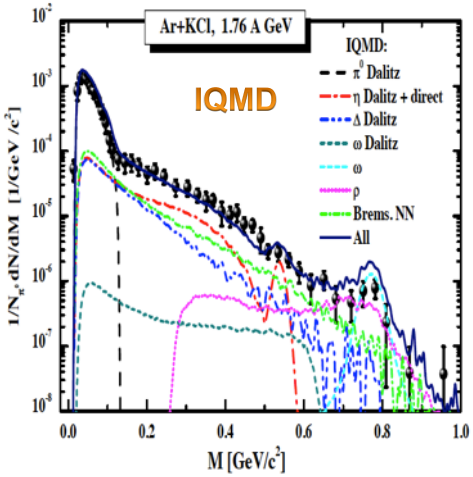
J. Weil at al., arXiv:1106.1344v1

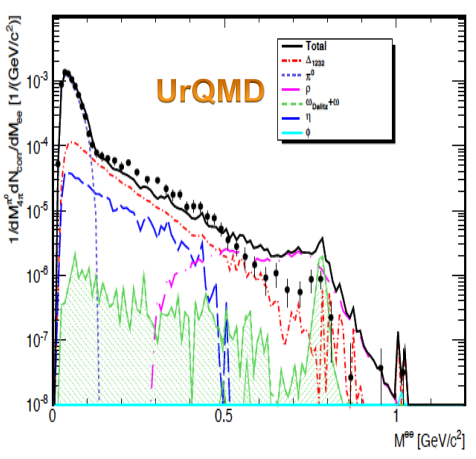


E.L. Bratkovskaya, NPA 807 (2008) 214



J. Aichelin et al, in preparation



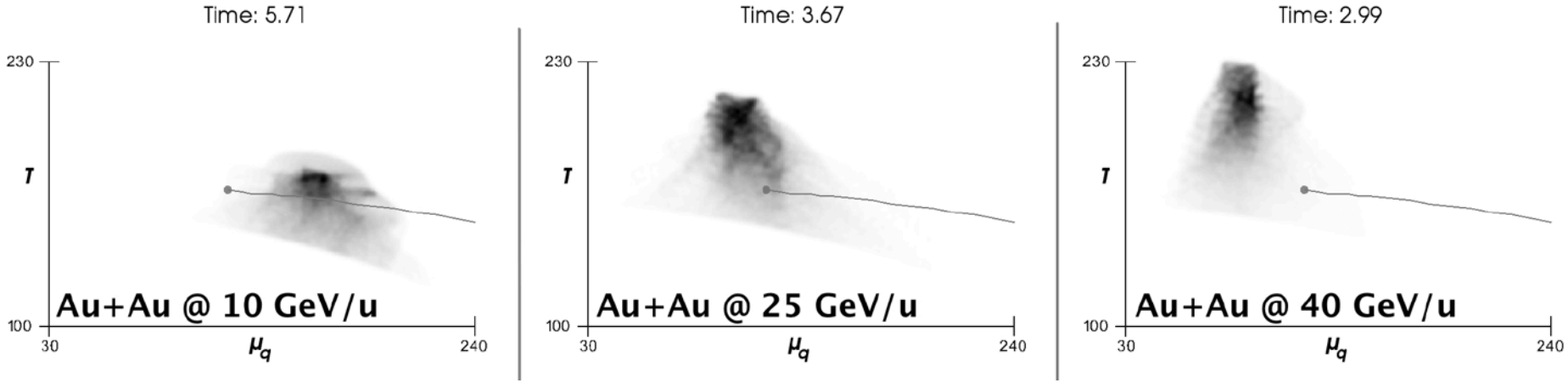


No consistent picture yet:

- don't describe (yet) QF n+p data
- „excess" region dominated by Δ but with different contributions
- Treatment of NN, πN bremsstrahlung?
- M_{e+e-}>0.6 GeV/c² dominates by ρ with complicated vacuum structure

Hot and dense matter

Time-evolution of the hot and dense QCD medium in T - μ space from model calculation



MADAI WORKBENCH

an incident beam energy of 25 GeV/u seems to provide the best opportunity for creating and probing QCD matter in the vicinity of the CEP.

H. Petersen et al. , arXiv:1202.0076v1 [nucl-th]