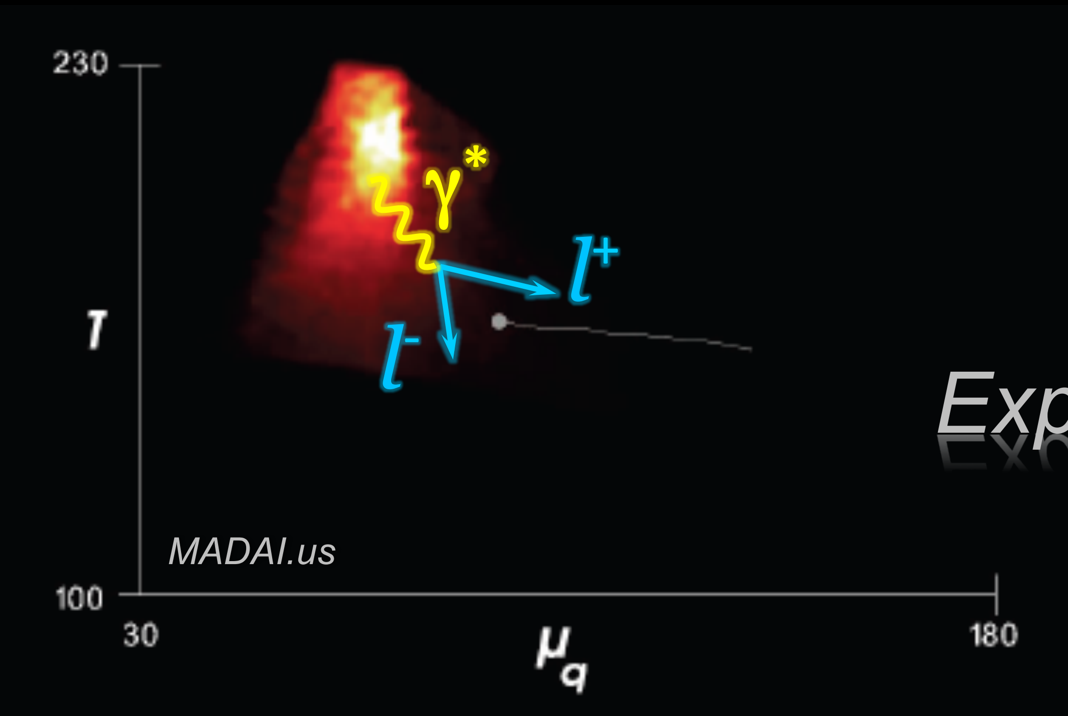
ExtreMe Matter Institute EMMI
EMMI Physics Days 2012
GSI, Darmstadt, Germany
November 13 - 14, 2012



Exploring the phase diagram of matter with virtual photons

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

TECHNISCHE UNIVERSITÄT DARMSTADT

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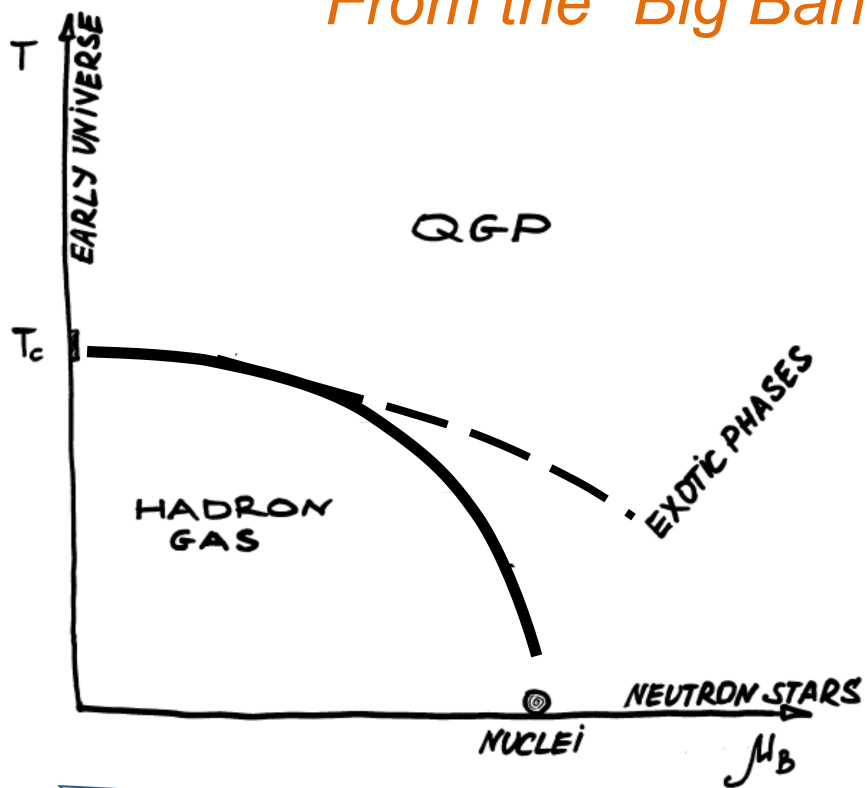
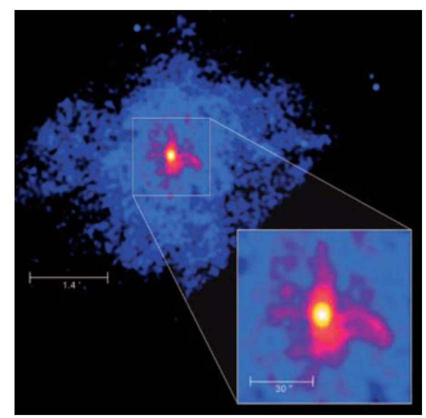
EMMI

Nuclear matter in the universe

From the "Big Bang" to neutron stars



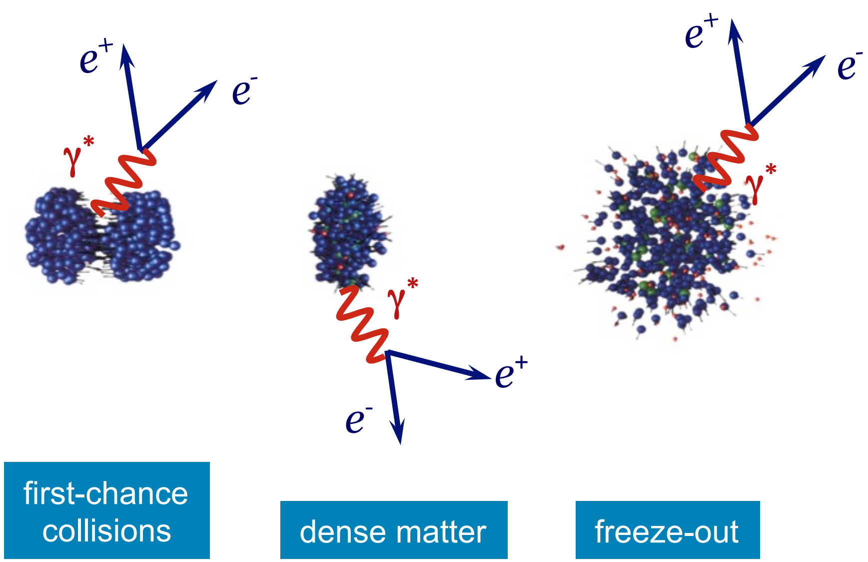


Accessible through heavy-ion collisions

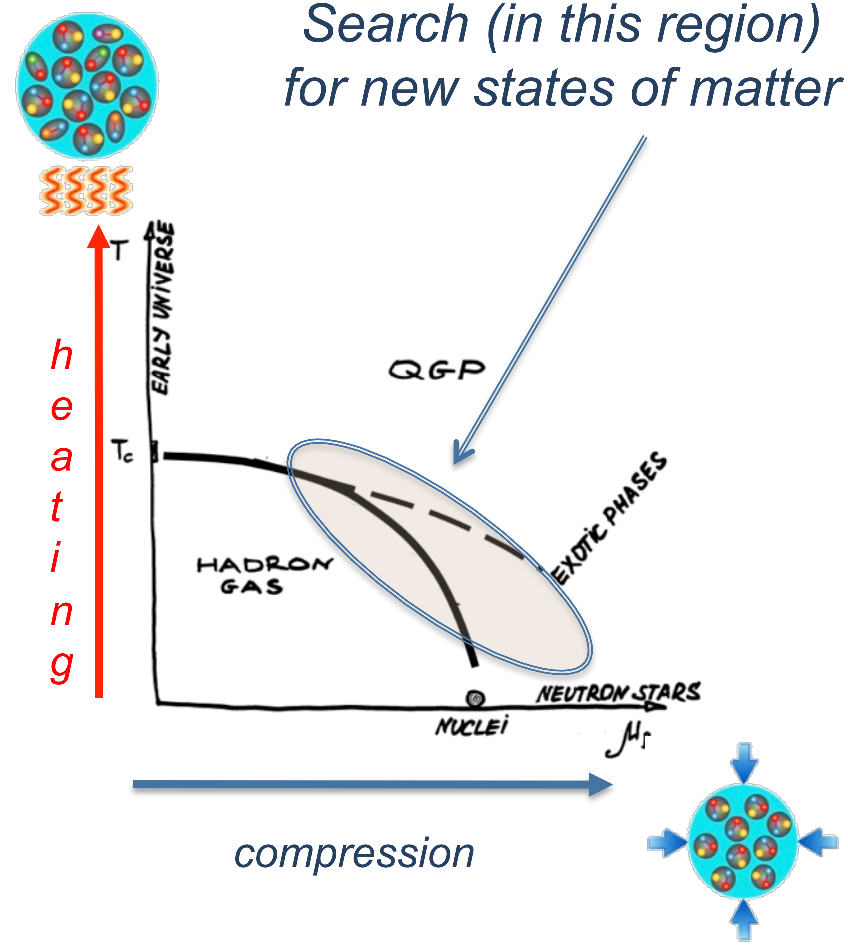
Electromagnetic structure of dense/hot matter

Electromagnetic radiation
is one of the probes of the interior of compressed matter

The three stages of a heavy-ion collision

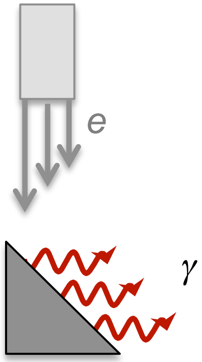


Search (in this region) for new states of matter

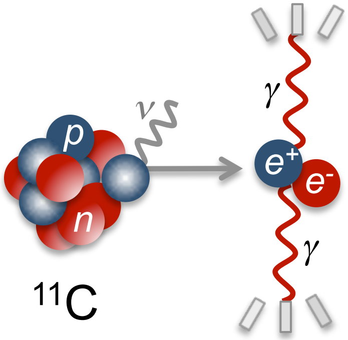


Photons and medical science (an old story)

Electromagnetic radiation as a tool to study properties of "matter"



X-ray technology has allowed us to see inside the human body since 1895



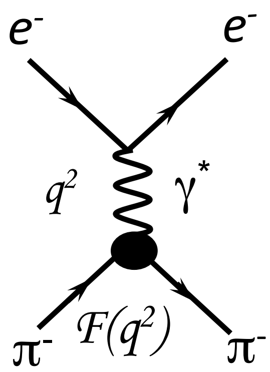
Positron Emission Tomography (3D imaging of the human body)

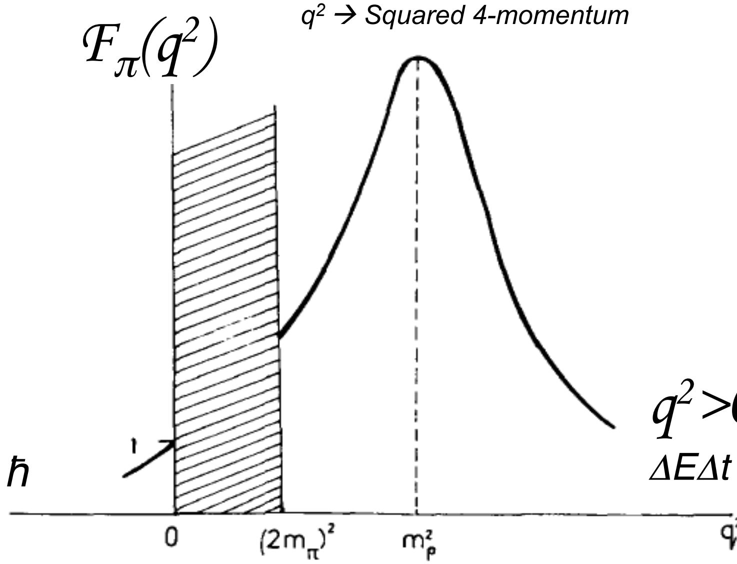
How do photons couple to hadrons?

$F(q^2) \rightarrow$ Form Factor

$q^2 \rightarrow$ Squared 4-momentum

space-like photons





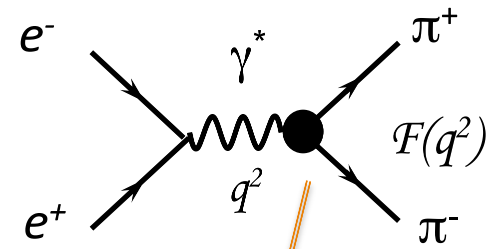
$q^2<0$

$\Delta p \Delta x \geq \hbar$

$q^2>0$

$\Delta E \Delta t \geq \hbar$

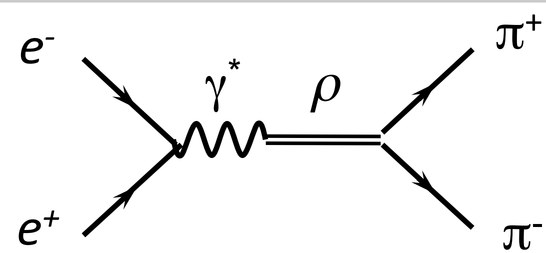
time-like photons



Low mass region, *$M_{ll} \leq 1.1$ GeV/c²*

$$\mathrm{Im}\,\Pi_{EM} \sim \left[\mathrm{Im}\ D_\rho + \frac{1}{9}\mathrm{Im}\ D_\omega + \frac{2}{9}\mathrm{Im}\ D_\phi\right]$$

ρ – meson dominated



$J^P = 1^-$ for both γ^* and Vector Meson

Vector Meson Dominance model

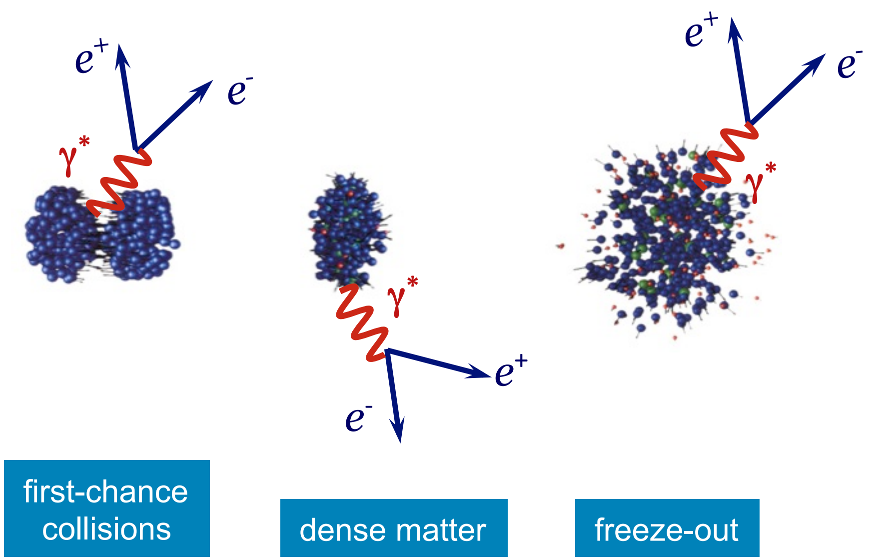
Observable: vector mesons (ρ, ω, ϕ)

Emissivity of strongly interacting matter

Invariant mass spectrum directly reflects thermal emission rate

$$\boxed{\frac{dN_{ll}}{d^4x d^4q}} = -\frac{\alpha_{EM}^2}{\pi^3}\frac{L(M)}{M^2} f^B(q_0;T) \boxed{\mathrm{Im}\,\Pi_{EM}^{\mu\nu}(M,q;\mu_B,T)}$$

- Vector current coupling to photons (and dileptons)
  - **Emissivity of hadronic matter**
  - **In-medium spectral functions**



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

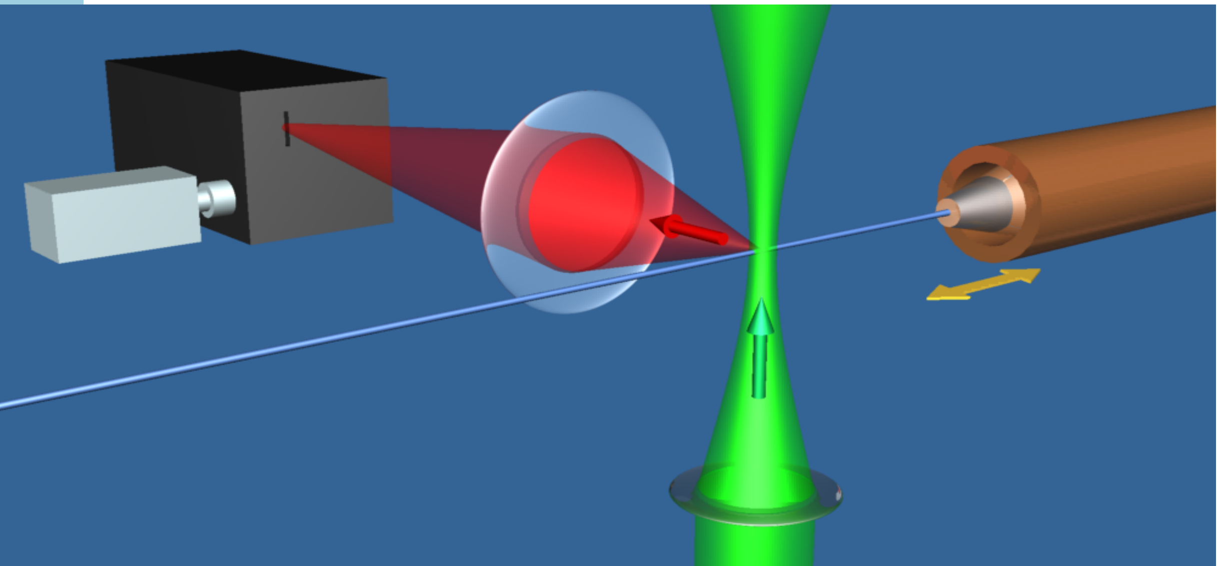
EXAMPLE FROM ATOMIC PHYSICS

Example from atomic physics

Exotic states in supercooled hydrogen

Raman spectroscopy of vibrational states in freezing H_2.

- Liquid cools due to expansion into vacuum.
- Storage ring internal target technology.



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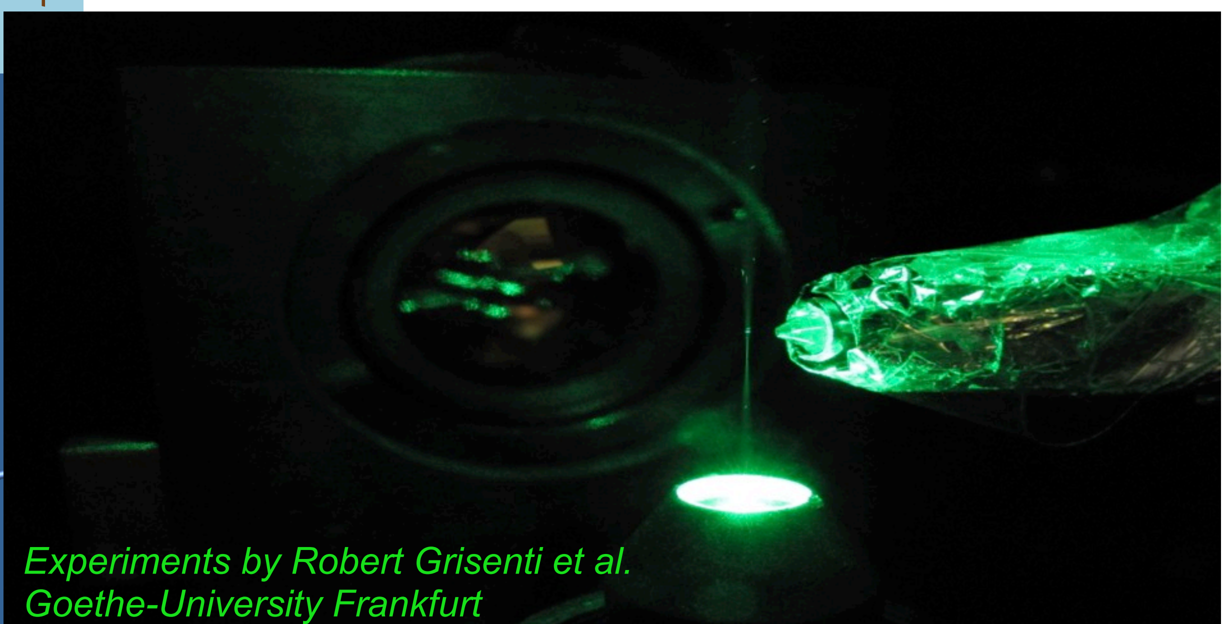
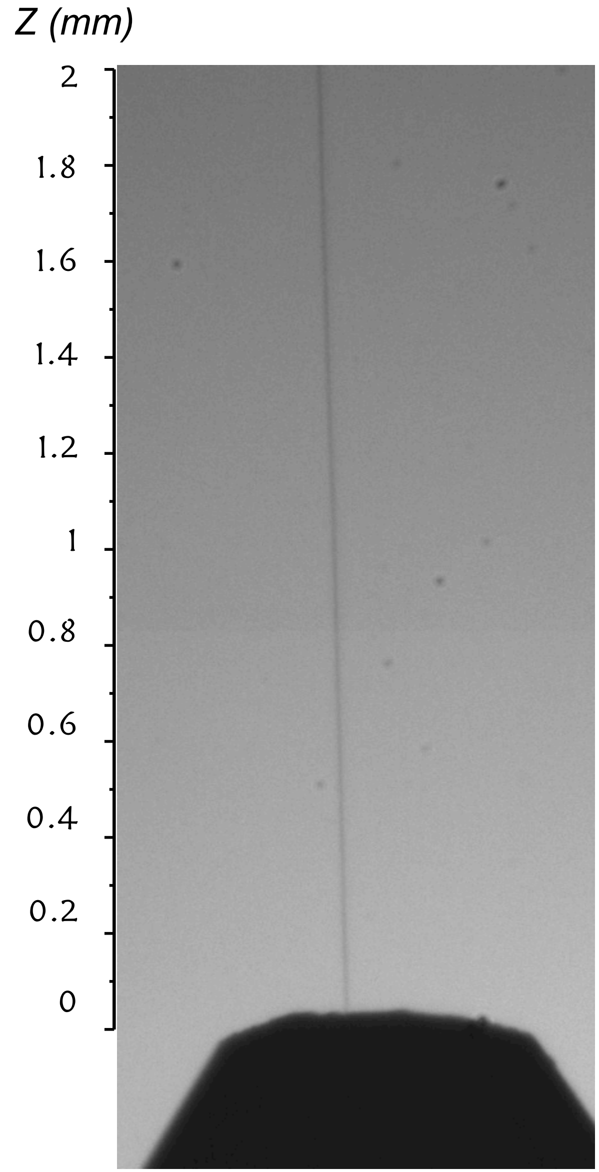
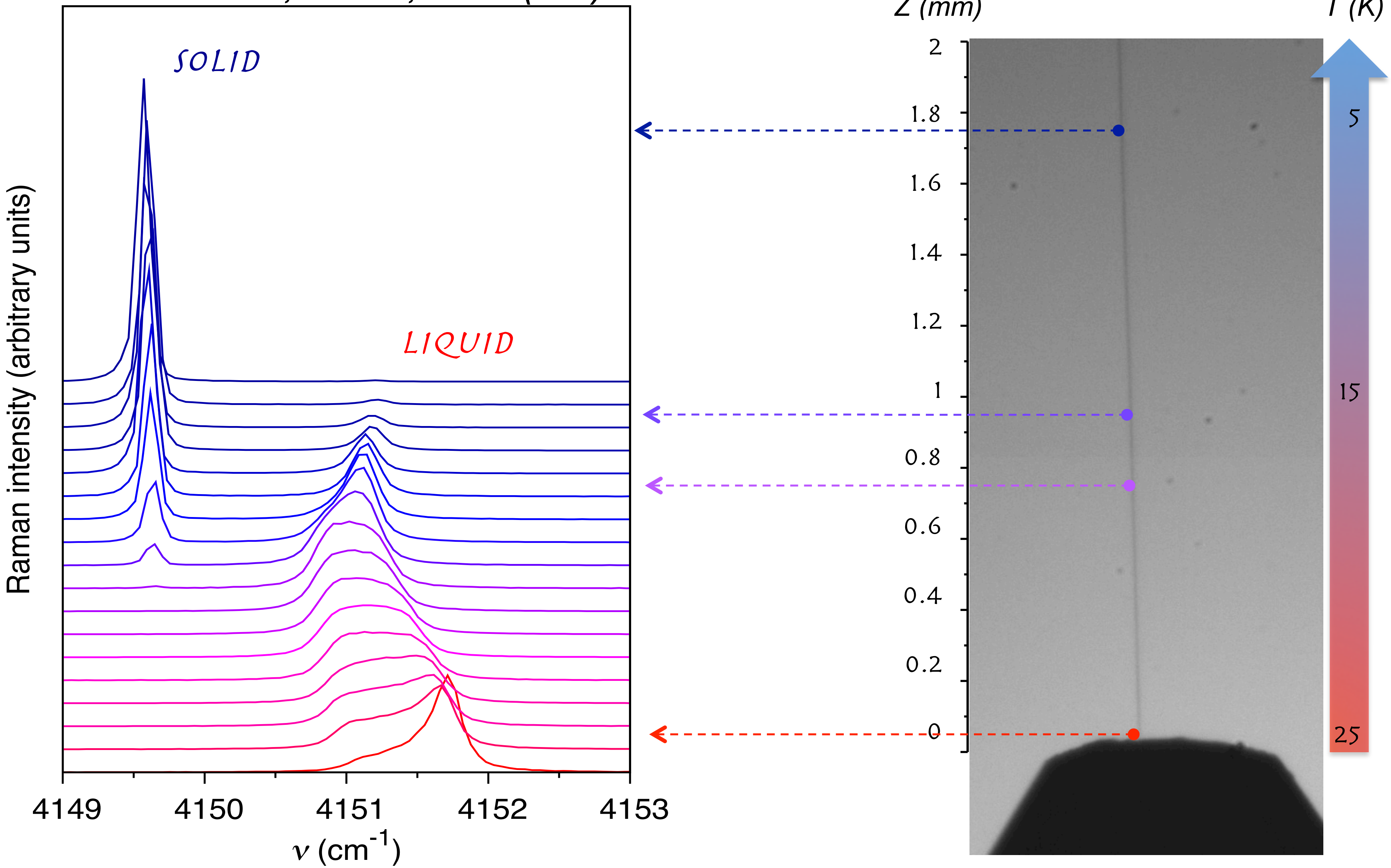




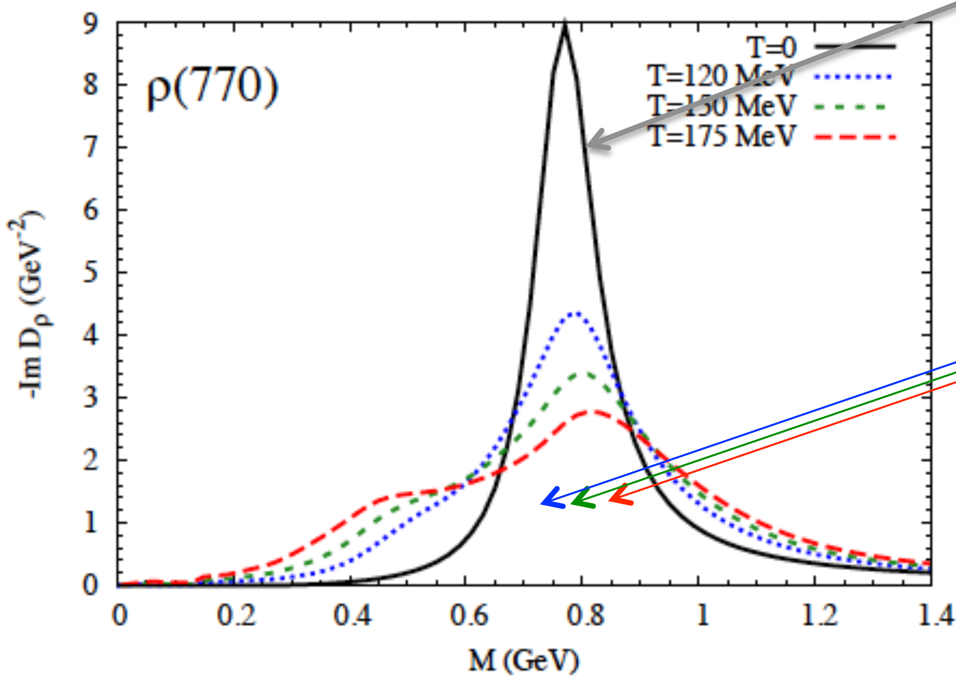
Example from atomic physics

R. Grisenti et al., PRL 106, 245301 (2011)



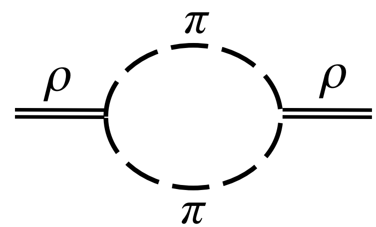
Going back to sub- atomic physics

The ρ meson in nuclear matter



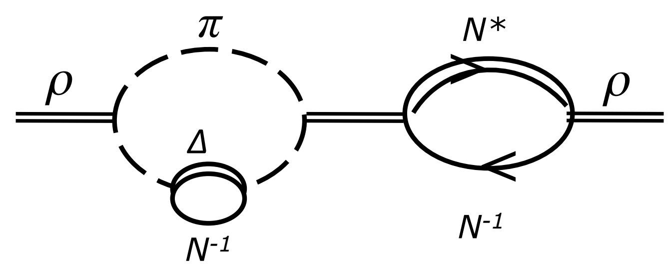
The ρ spectral function **strongly broadens** in the medium because **it couples to baryons!**

Vacuum



Medium

$$D_\rho(M,q;\mu_B,T) = \frac{1}{\left[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}\right]}$$



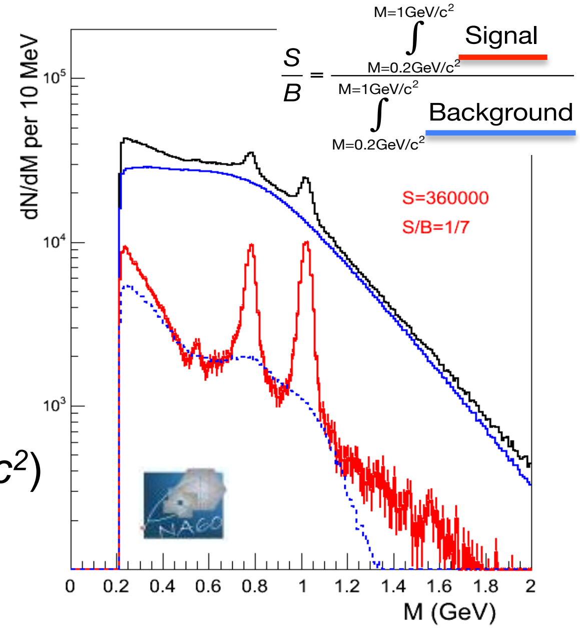
Additional contributions to the ρ-meson self-energy in the medium

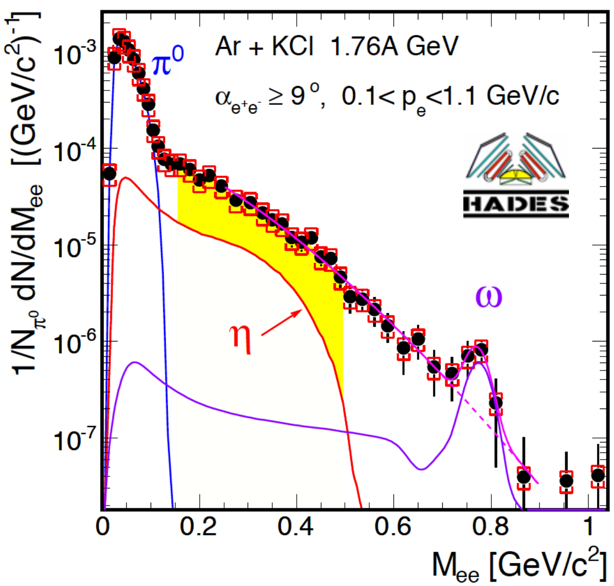
The experimental challenge…

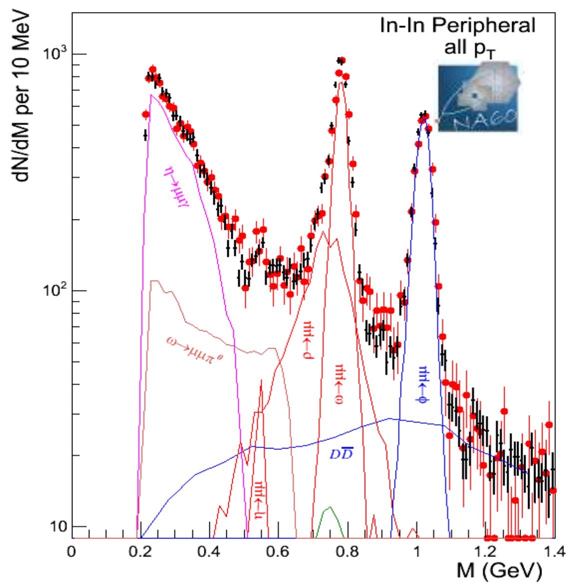
- Lepton pairs are rare probes (branching ratio O(10^{-4}))
- At SIS energies vector mesons are produced sub-threshold

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

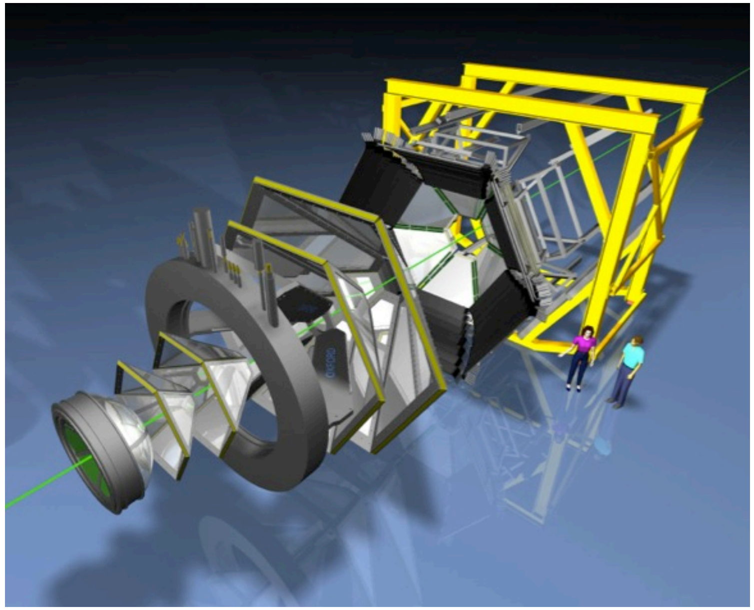






High Acceptance Di-Electron Spectrometer

HADES



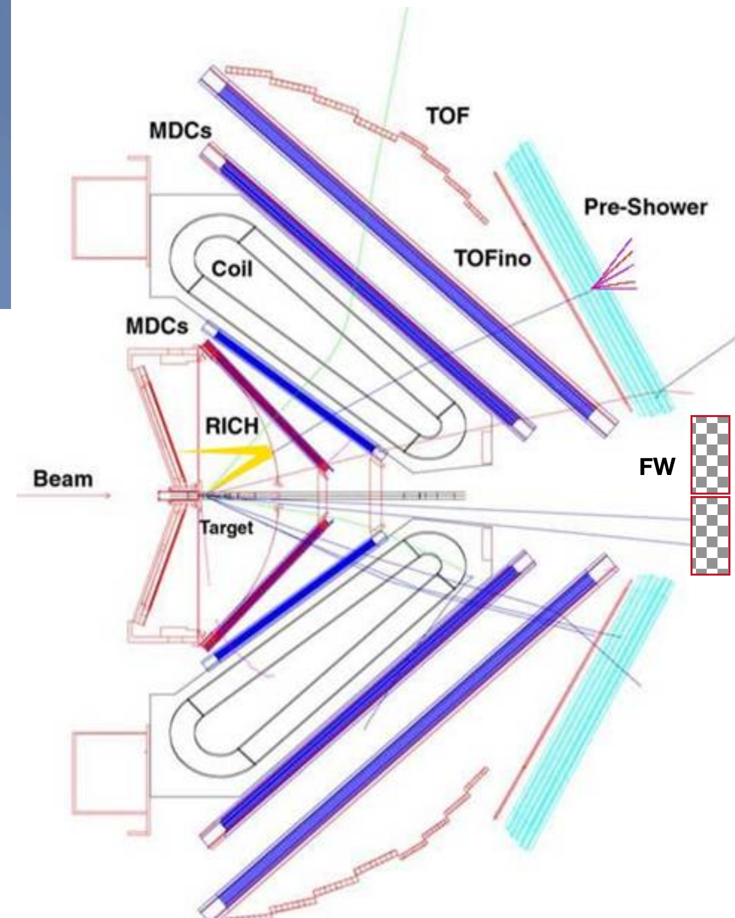
HADES strategy:
Systematic di-electron and strangeness measurements in NN, AA, pA, πN and πA collisions

- Beams provided by SIS18: π, p, nuclei

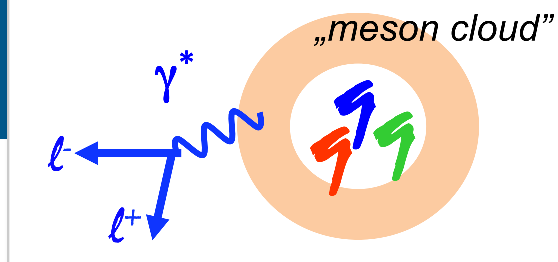
- Full azimuthal coverage
- Hadron and lepton identification

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

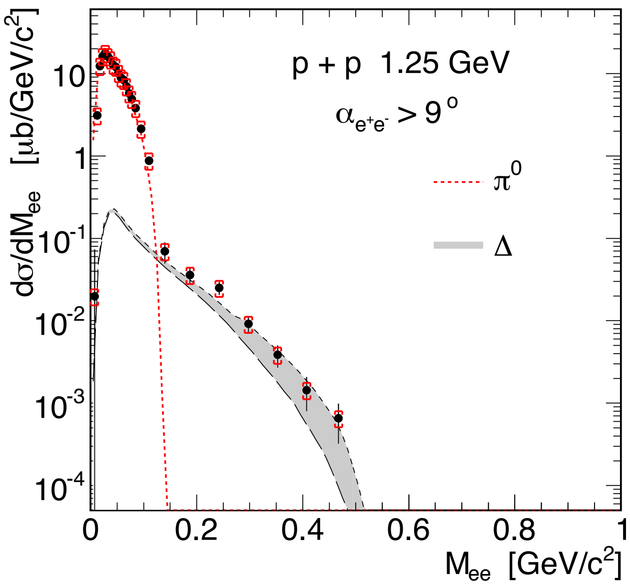
- ~ 80.000 channels
- now: **50 kHz event rate (400 Mbyte/s peak data rate)**



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



HADES : PLB 690 (2010) 118



HADES : PLB 690 (2010) 118

time-like region $q^2 > 0$

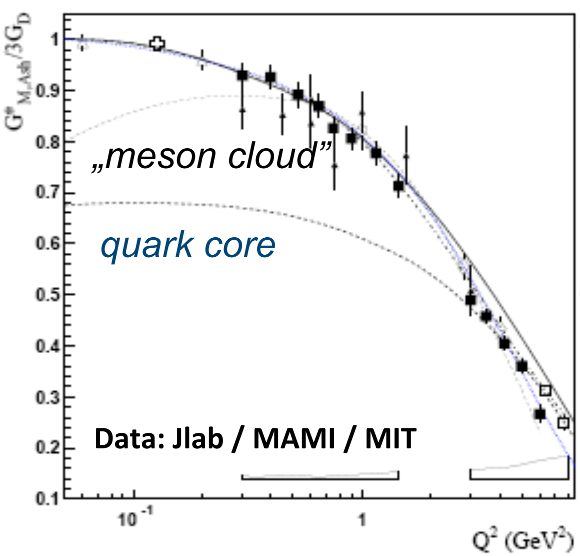
Goal

- Understand Δ (J=3/2) → N (J=1/2) 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

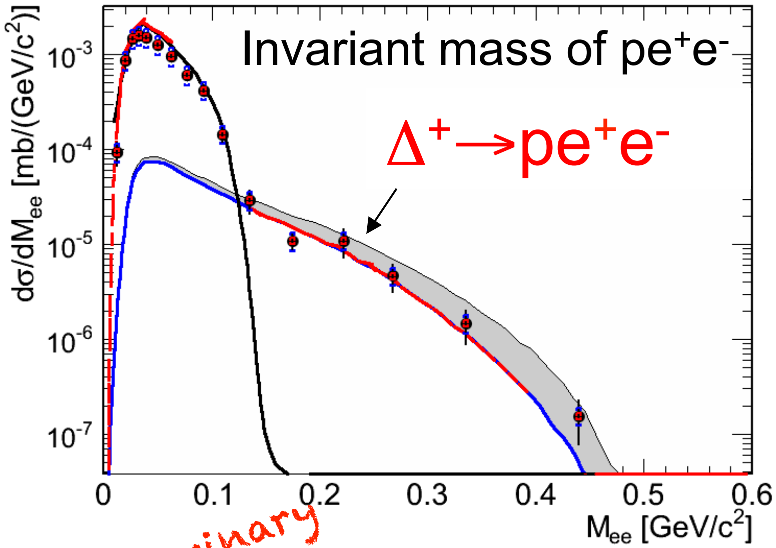


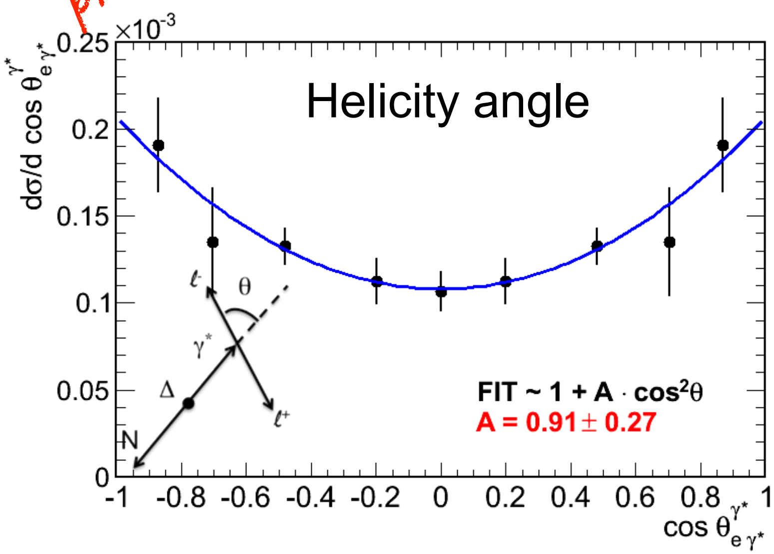
space-like region $q^2 < 0$

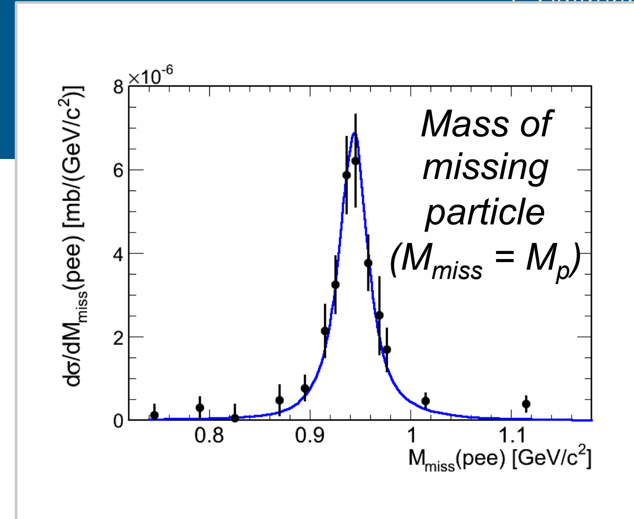
- Excitation of a baryon can be carried by the meson cloud
  - Precise data from Jlab / MAMI / MIT
  - **Strong hint for dominant contribution to the $G_M(Q^2)$ from the meson cloud (30% at $G_M(0)$)**

    I.G. Aznauryan, V.D. Burkert Prog. Part. Nucl. Phys. 67, 1 (2012)

NN Reference: exclusive analysis pp→ppe$^+$e$^-$

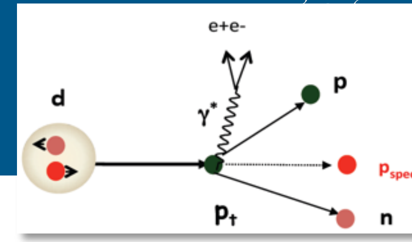


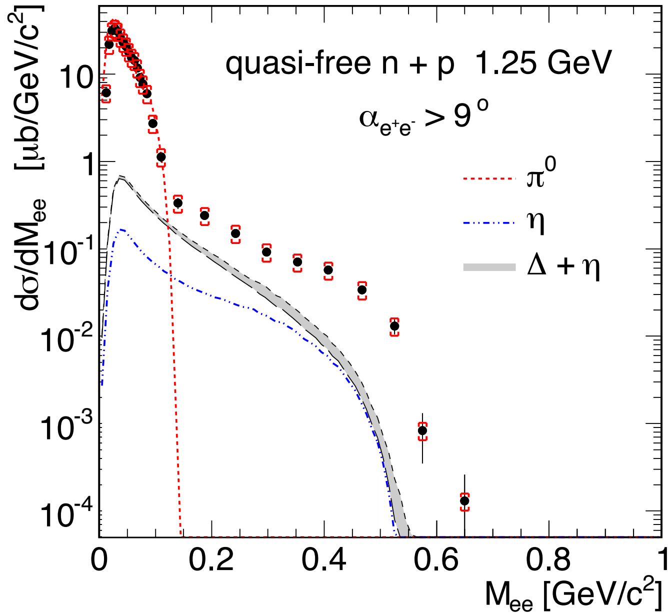




- **First direct access to the Δ transition form factor in the time-like region**
  - Data agree with QED calculations!
  - Branching ratio (Δ$^+$→pe$^+$e$^-$) = 4.2×10^{-5}

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

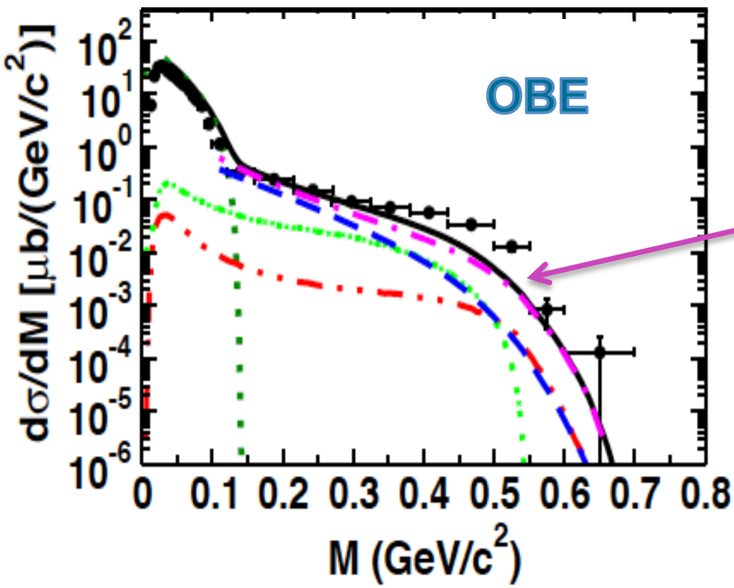


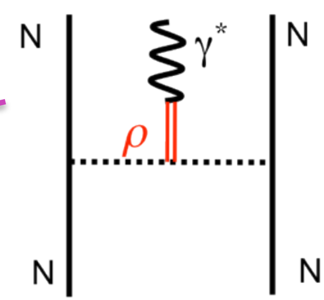


HADES : PLB 690 (2010) 118

- 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



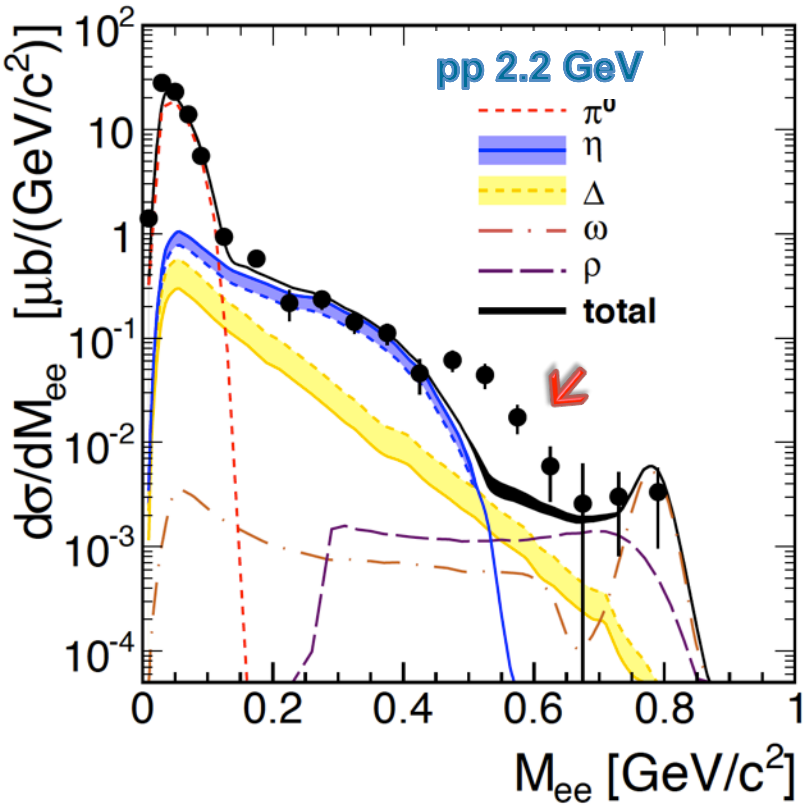


Much better agreement with data when including π EM form factor →

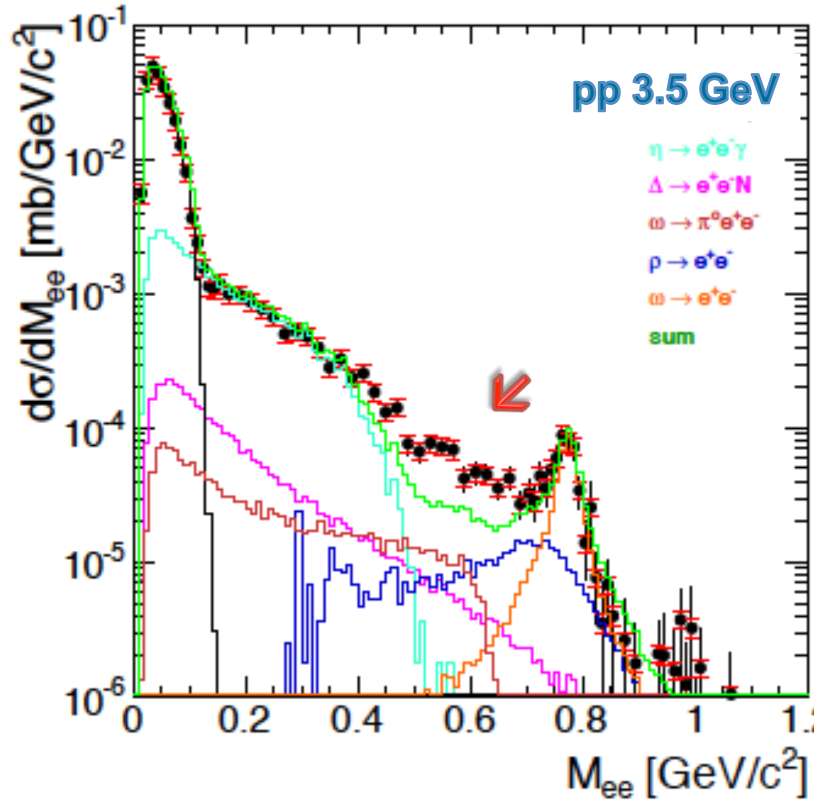
Sensitivity to hadronic electromagnetic structure

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



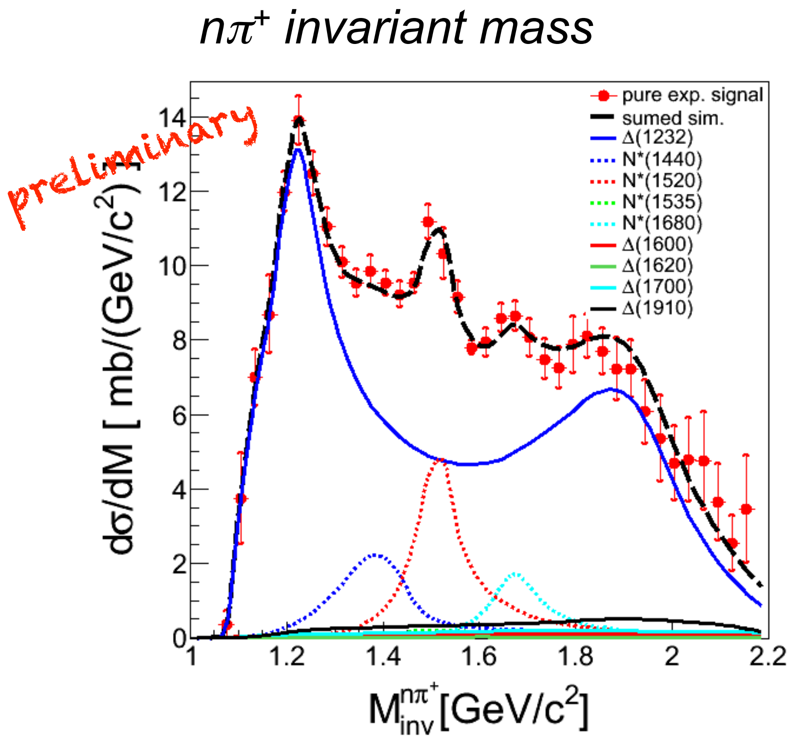
Phys.Rev. C85 (2012) 054005

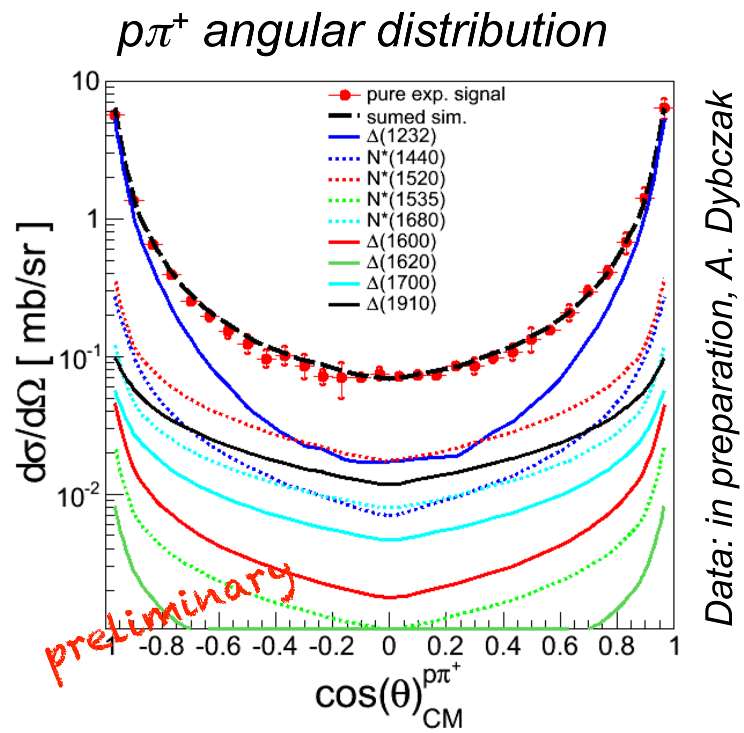


Eur.Phys.J. A48 (2012) 64

- Effect of electromagnetic form factors
  → Treatment of Dalitz decays of broad resonances is not well understood
- Coupling of ρ to baryonic resonances
  → Cross check from πN mass spectra needed!

Reconstruction of contributing baryonic resonances: exclusive analysis of pp → pnπ^+ ans pp → ppπ^0





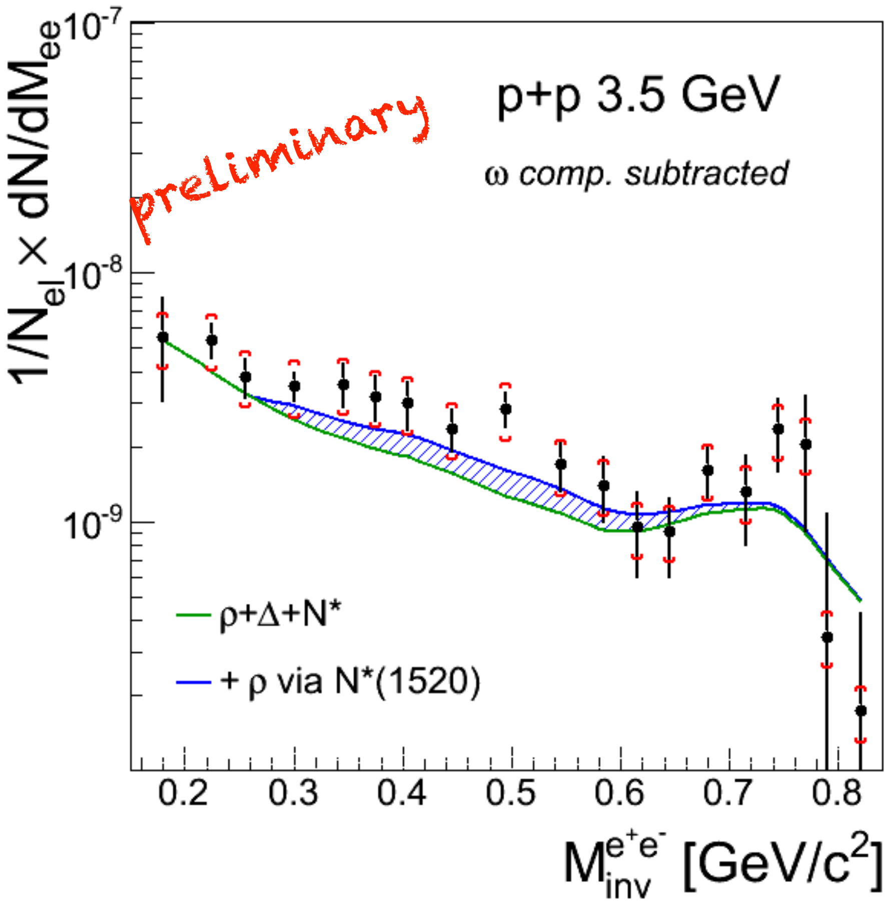
- 14 baryonic resonances are included in the analysis (N*1535 constrained by pp → ppη channel)
  K. Teilab Int.J.Mod.Phys.A26:694-696,2011

- Cross section for resonance production via exclusive analysis of pp → pnπ^+ and pp → ppπ^0

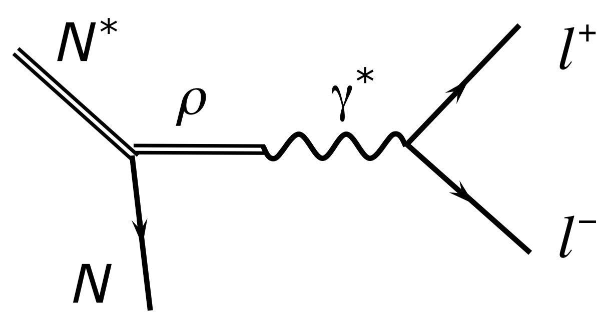
→ *pp → ppe$^+$e$^-$*

Dileptons: from SIS to SPS...

Exclusive analysis: pp → ppe⁺e⁻



- Relative contribution is fixed through exclusive pion production
- ω contribution subtracted, η contribution suppressed by kinematics
- Dalitz decays of baryonic resonances - dominant source at low beam energies.

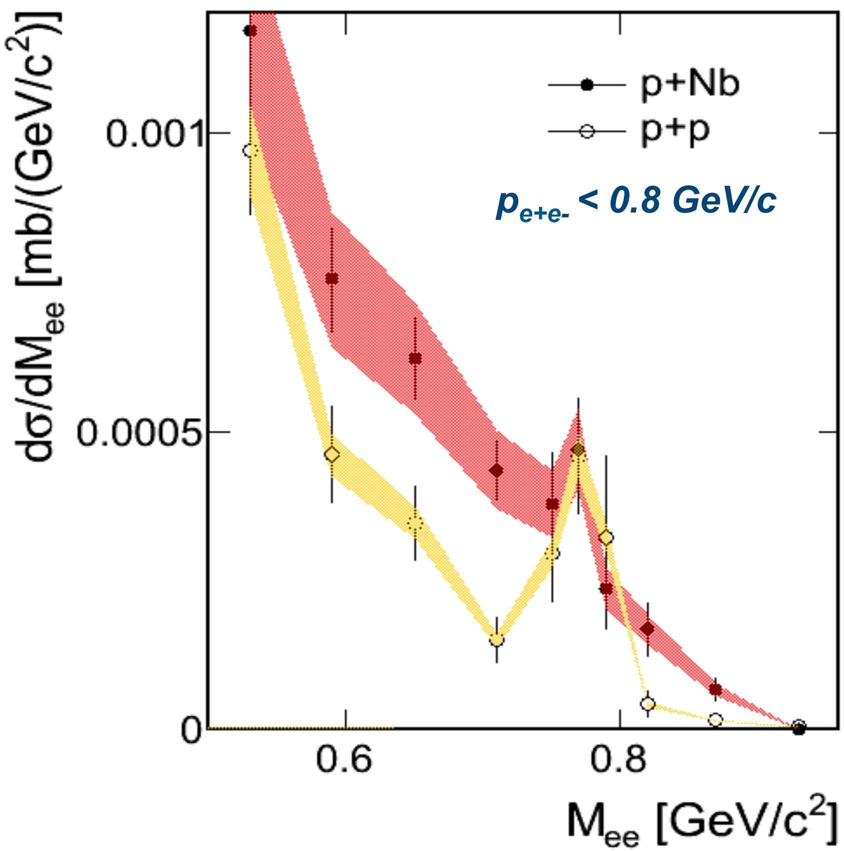


HADES data preliminary
Model: M. Zetenyi and Gy. Wolf
Phys. Rev. C 67, 044002 (2003).

Electron pairs from cold nuclear matter

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

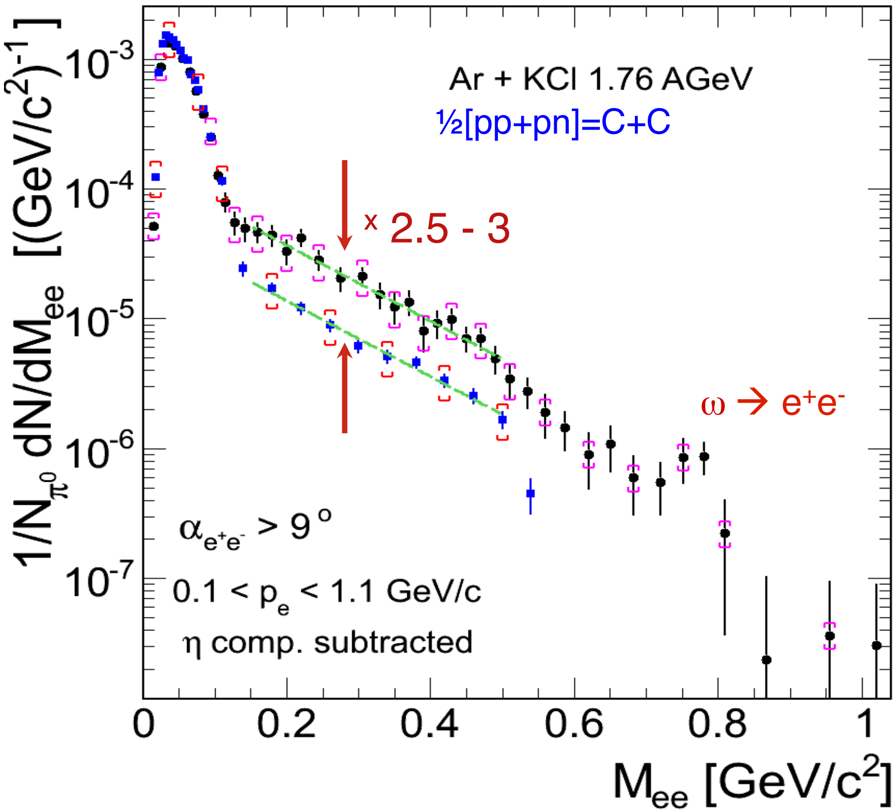
HADES: Phys.Lett. B715 (2012) 304-309



- **First measurement of lepton pairs with p_{e+e-} < 0.8 GeV/c radiated from cold matter**
  → not measured by CLAS, KEK-E325
- Mass resolution: $\sigma_{M\omega}$ **= 16 MeV/c²**
- No ω line shape modification is observed
- 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



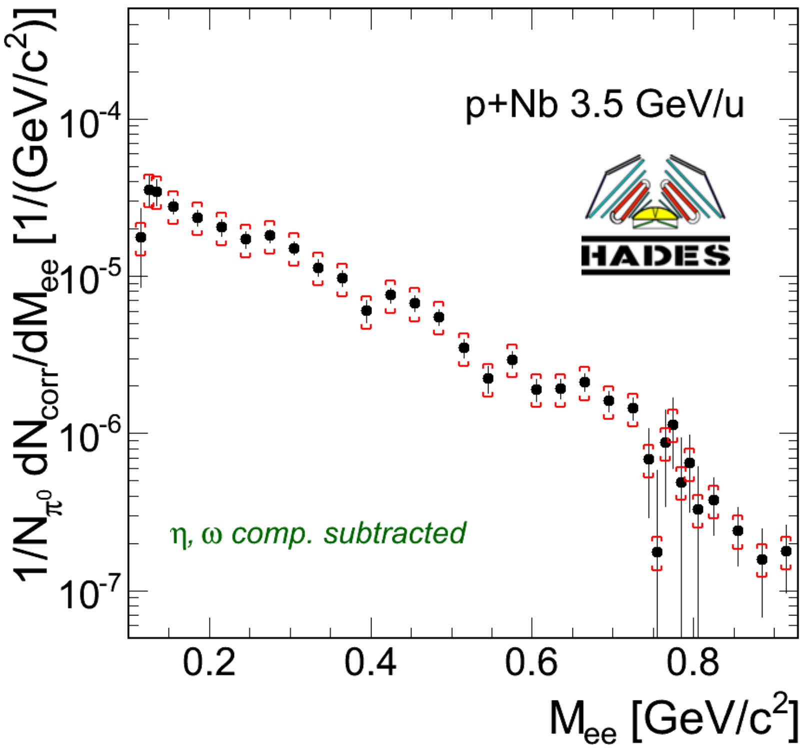
- Isolation of excess by a comparison with a **measured** "reference" spectrum
- **First evidence for radiation from the "medium"!**
- Excess yield scales with system size like $A_{part}^{1.4}$

Quest for heavier systems!

HADES: Phys.Rev.C84:014902,2011

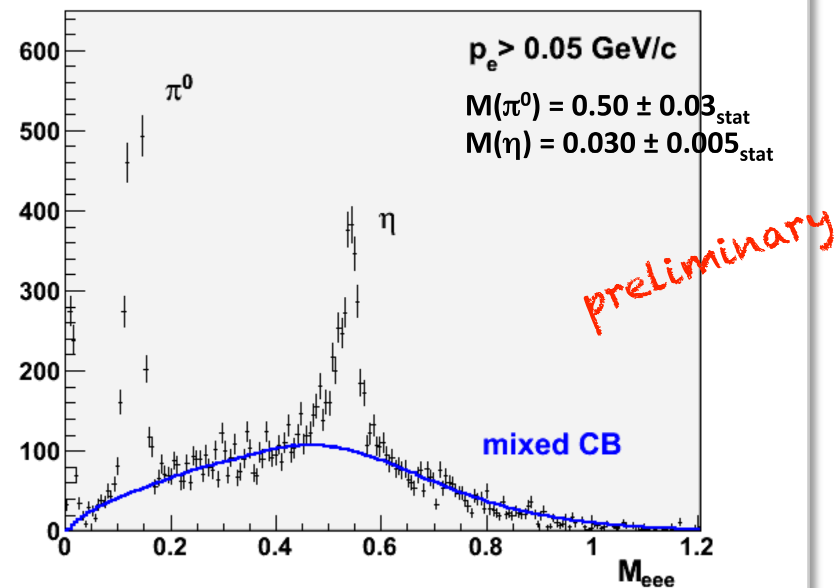
Isolation of excess by a comparison with a **measured** decay cocktail

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



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

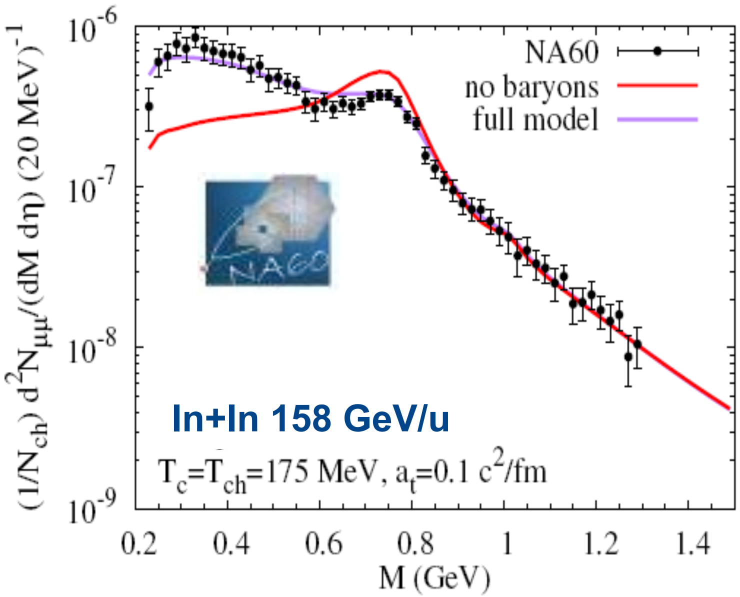
- Full reconstruction of π^0 and η decays (meson → $e^+e^-e^+e^-$)



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

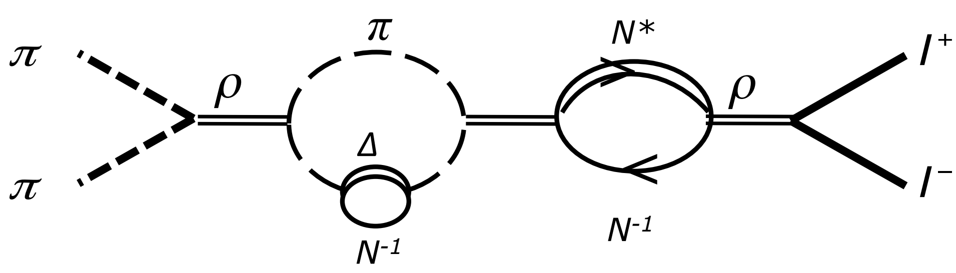
The ρ meson in hot and/or dense fireball: from SIS18 to SPS

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



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

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



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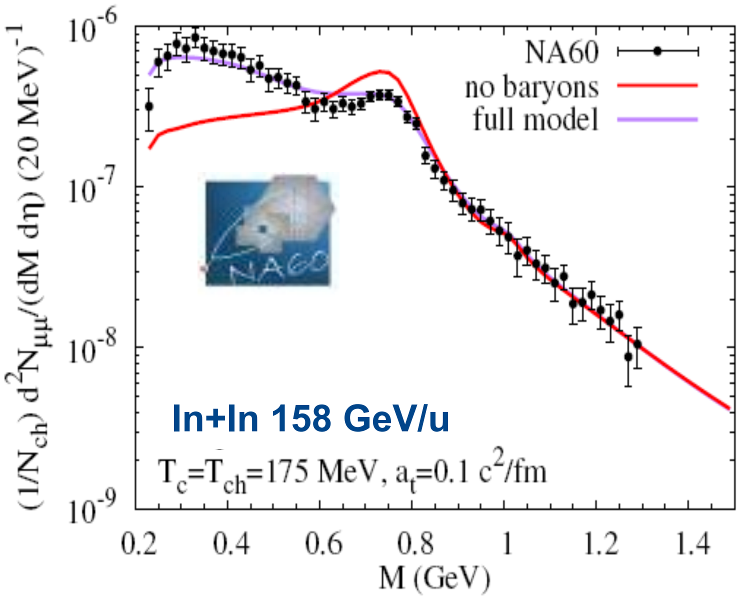

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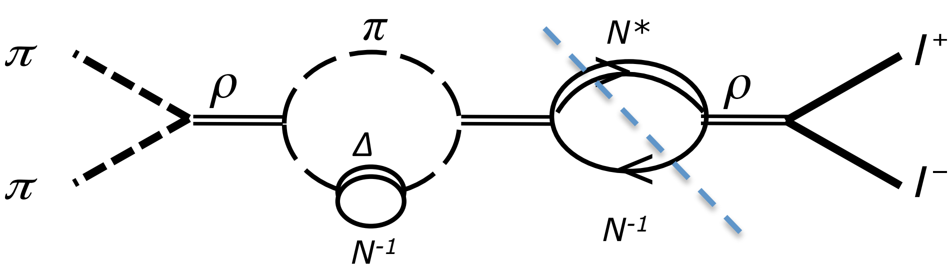
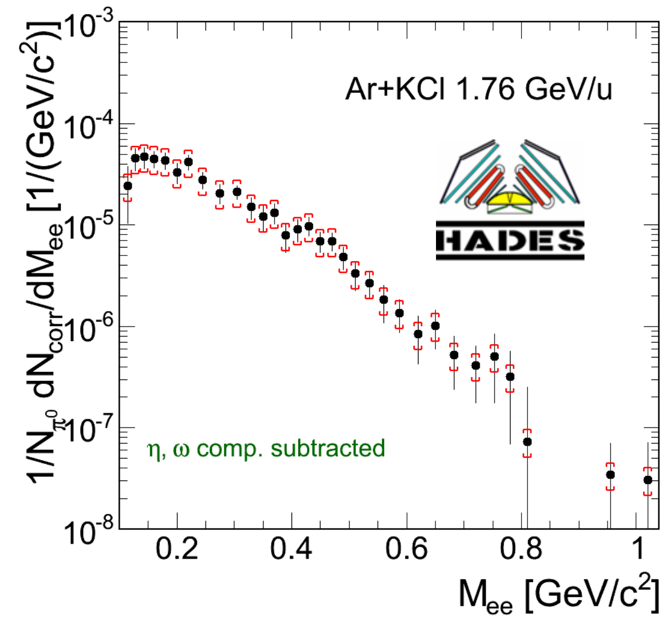
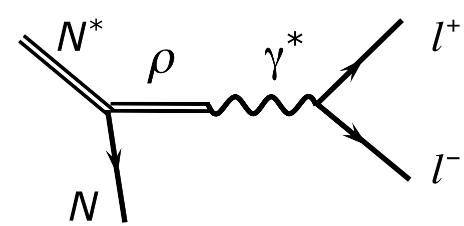


Excess e^+e^- yield, Ar+KCl 1.76 GeV/u

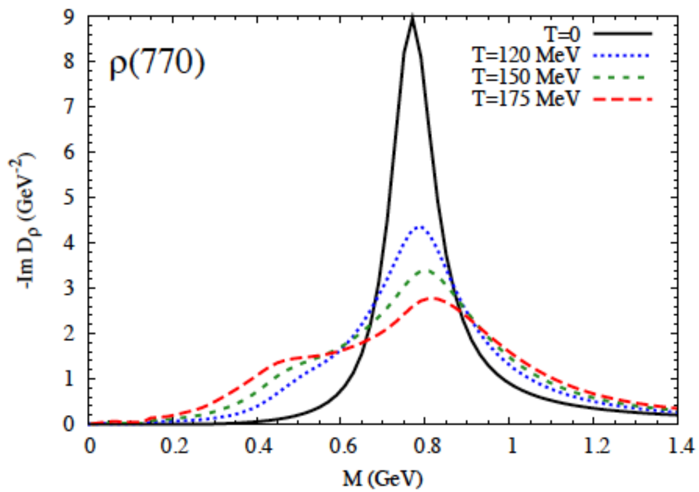




Dalitz decays of baryonic resonances – dominant source at SIS18!

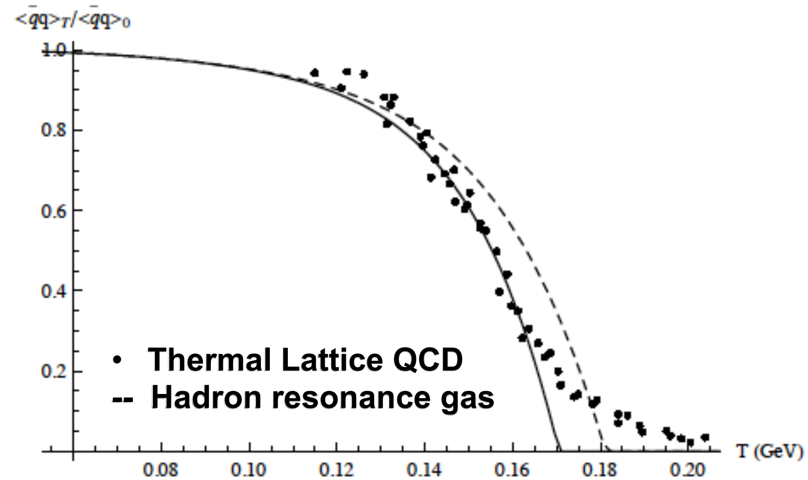
Dileptons, hadronic resonances and phase diagram of matter

In-medium ρ spectral function



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

Temperature dependence of the chiral quark condensate

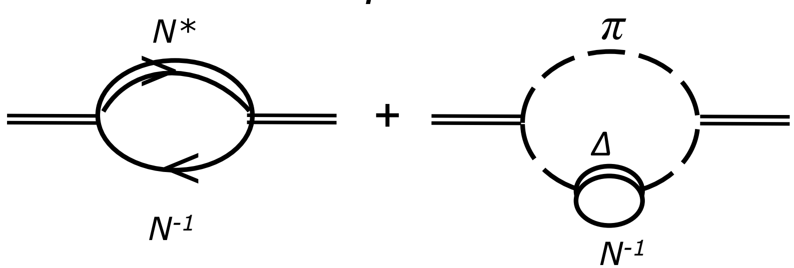


S. Borsanyi et al., JHEP 1009, 073 (2010)

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"***



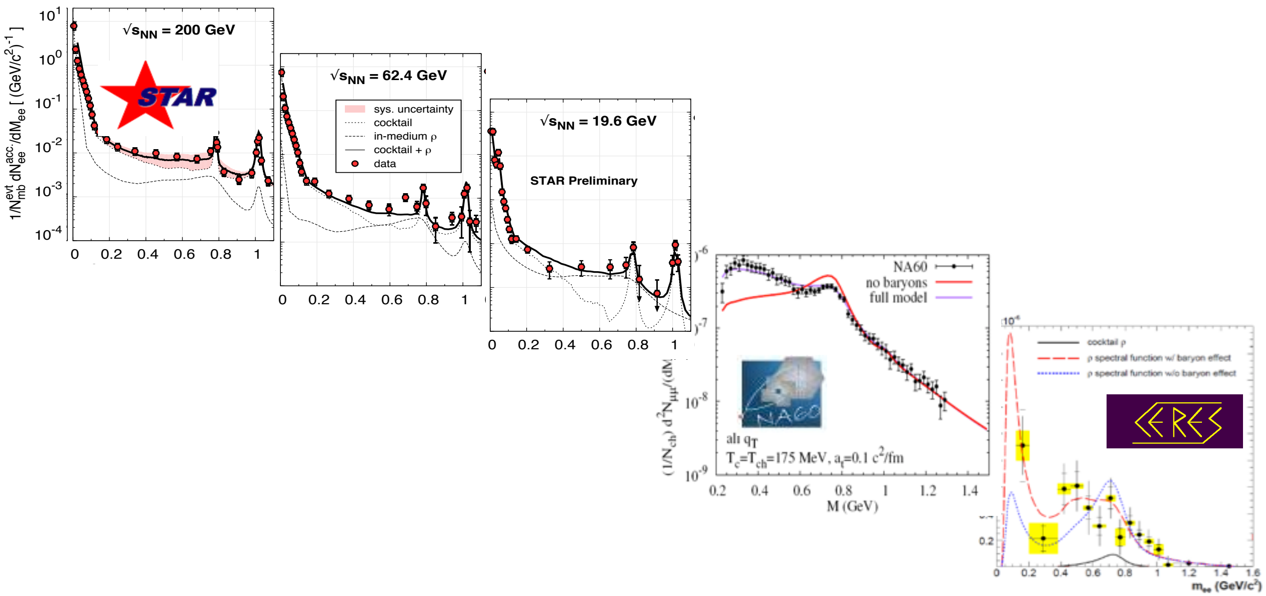
⟺

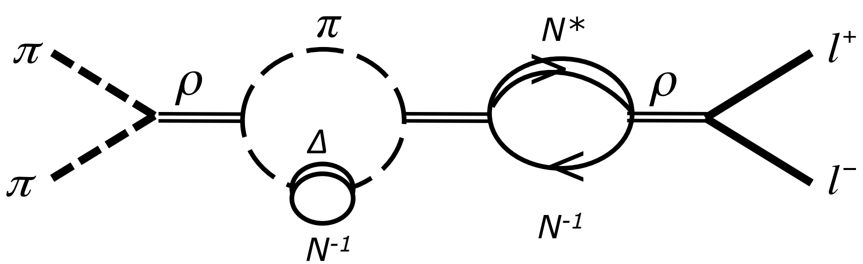
2. Excitation of the vacuum (melting of condensate) matches spectral medium effects

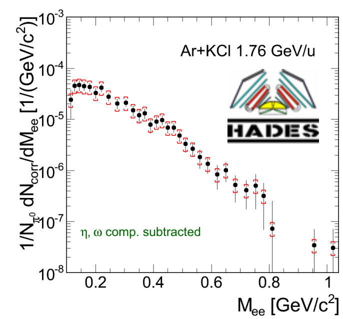
Virtual photon radiation from hot and/or dense QCD matter

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

T



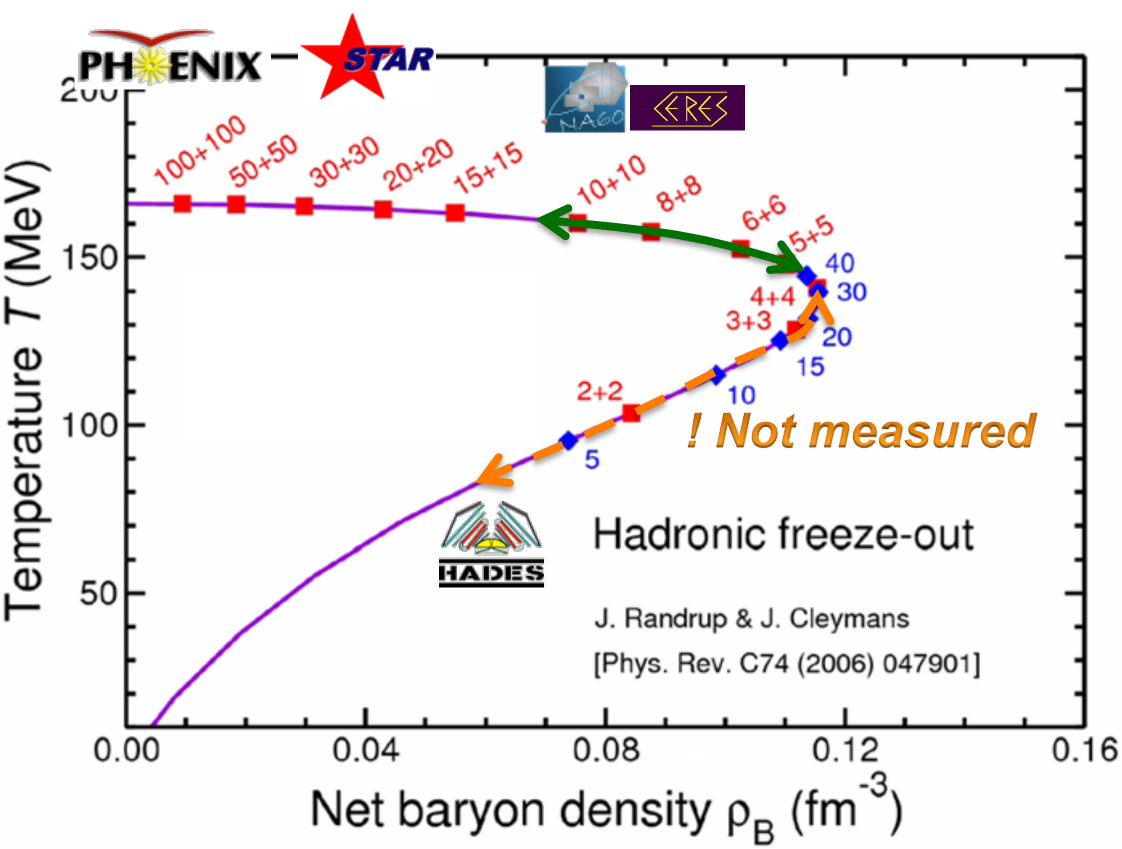




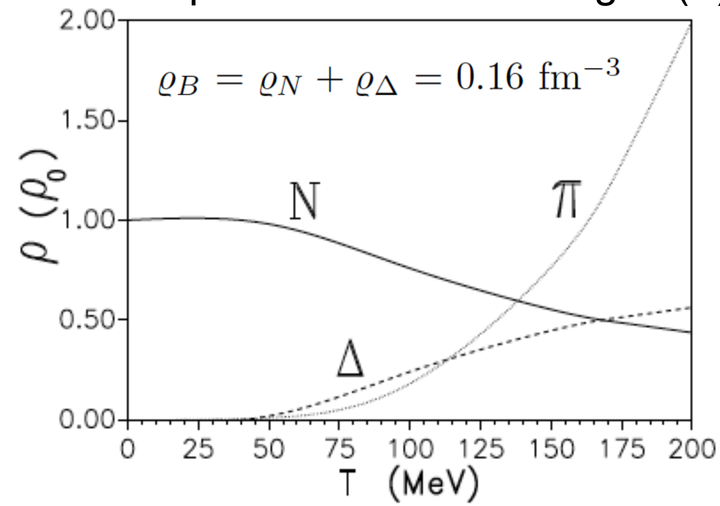
Highly interesting results from RHIC, SPS, SIS18 → importance of baryons!

μ_B

Quest: explore the regime of maximal baryon density

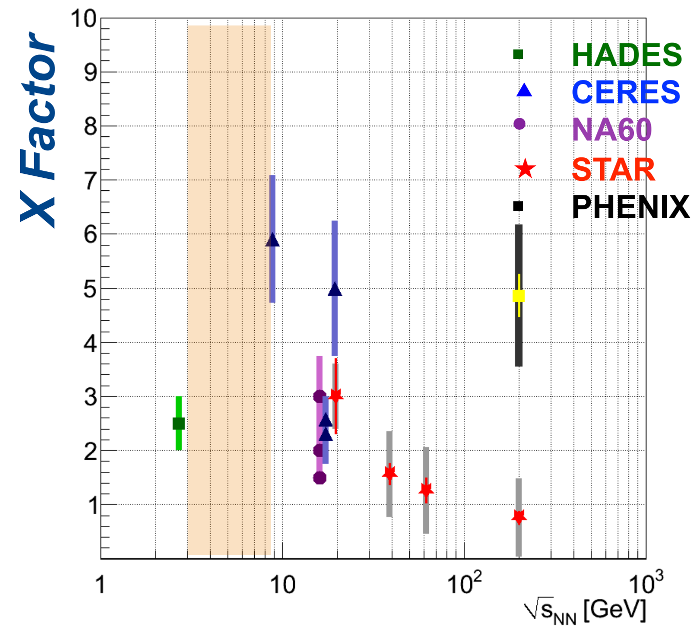


Composition of a hot πΔN gas (T)



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

Published low-mass enhancement factors

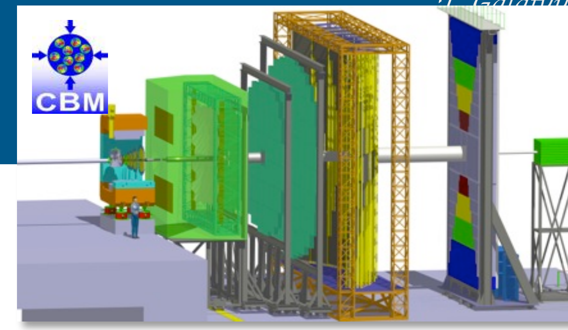


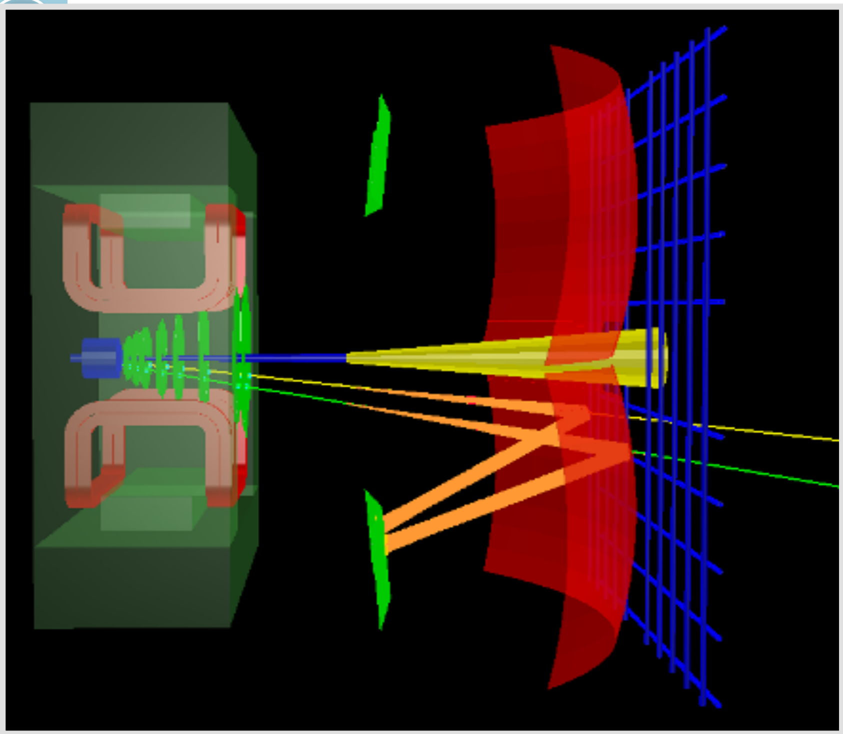
No measurement for beam energies of 2-40 GeV/u

→ HADES/CBM at SIS100

→ CBM at SIS300

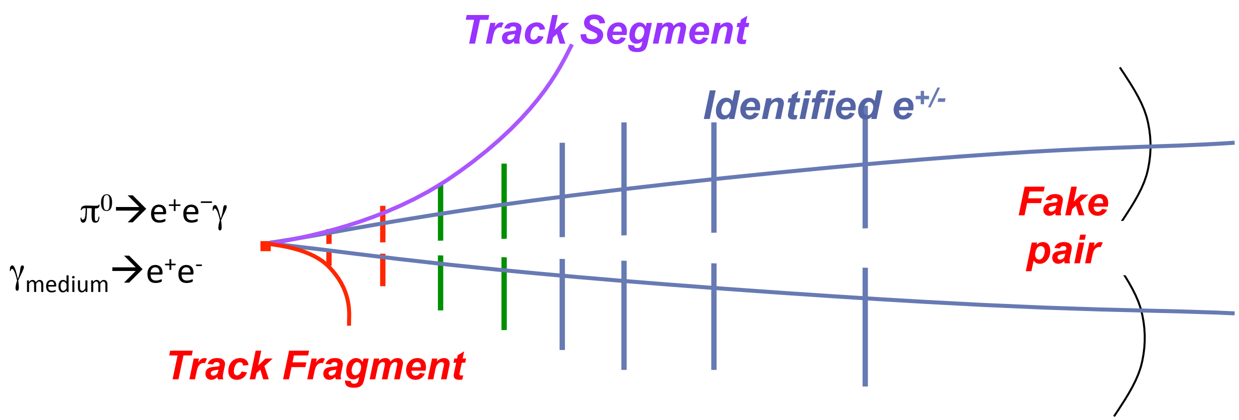
Di-electron reconstruction in CBM





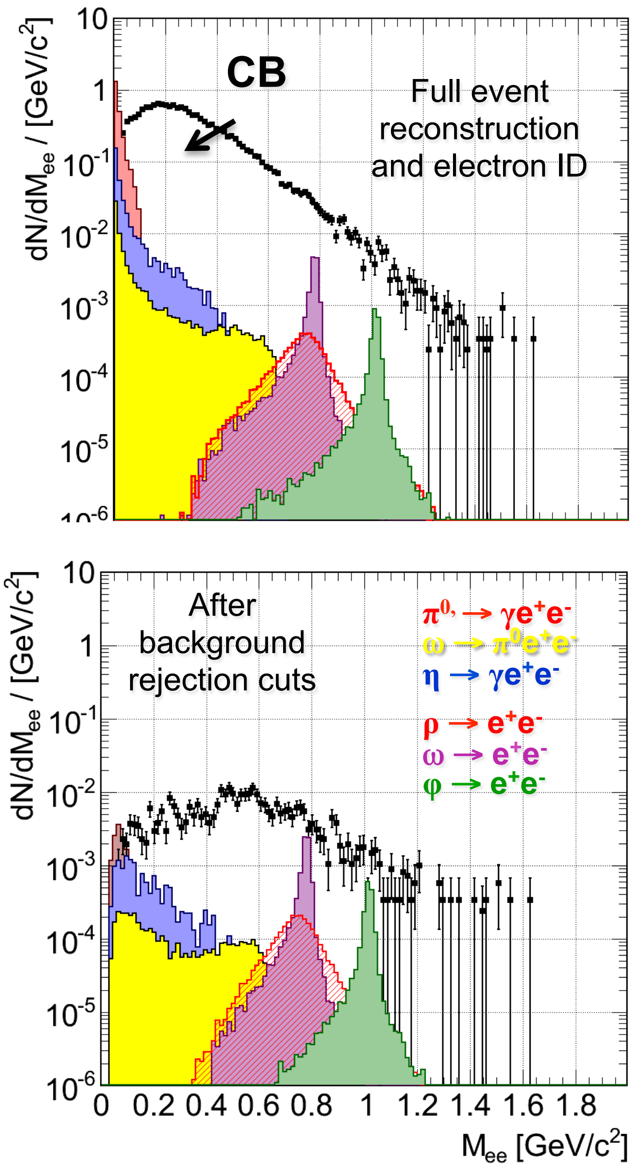
- **Challenge:**
  - No electron identification before tracking
  - Background due to material budget of the STS
  - Sufficient π discrimination (600 $\pi^{+/-}$/event, misidentification 10^{-4})

- **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

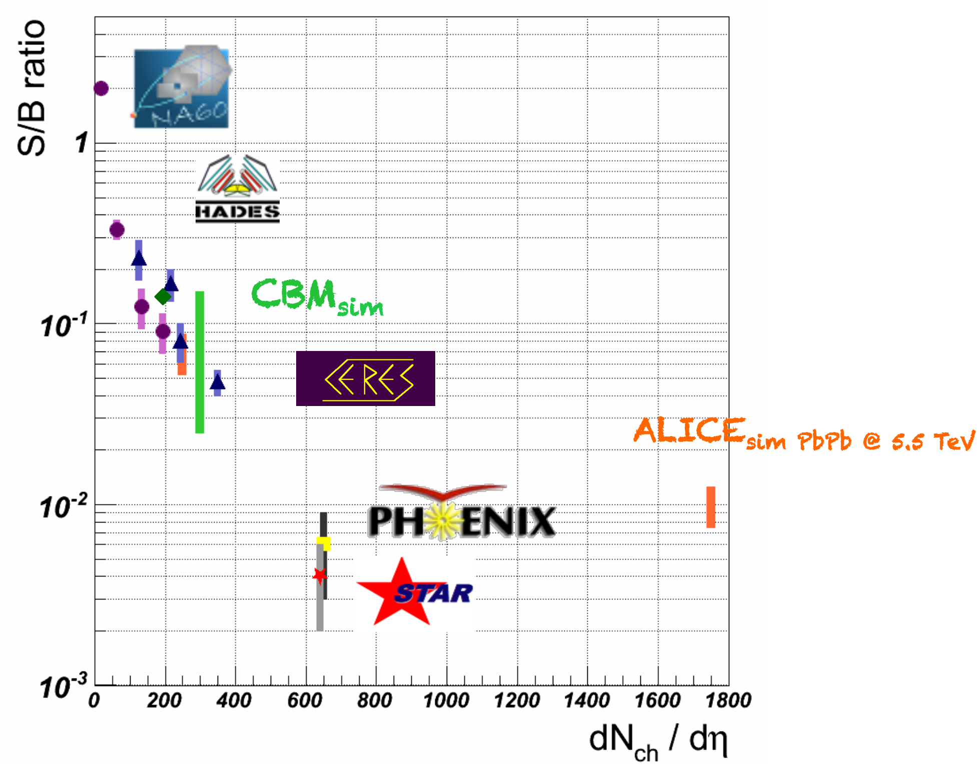


Low mass electron pairs reconstruction

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



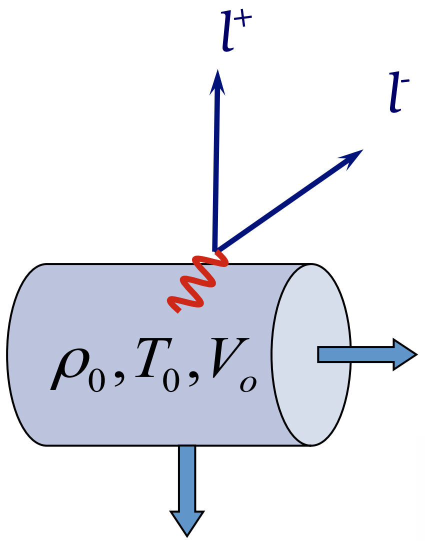
Expected signal-to-background ratio for CBM (di-electrons) compared to the existing experiments



- CBM_{sim} : Au+Au 25 GeV/u, **zero impact parameter**
- Lower edge - free cocktail, upper edge – assuming factor of 6 for medium contribution
- $ALICE_{sim}$: Pb+Pb 5 TeV, R. Rapp in.medium SF

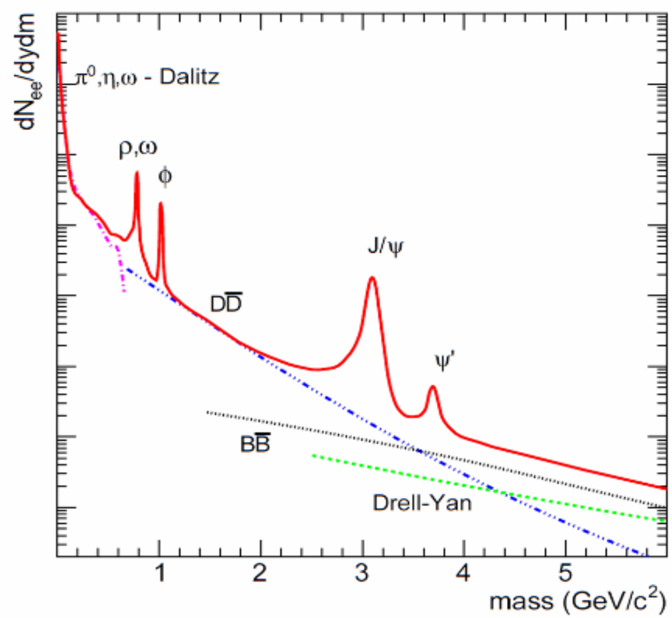
Dilepton emission rates in theory

Thermal emission...

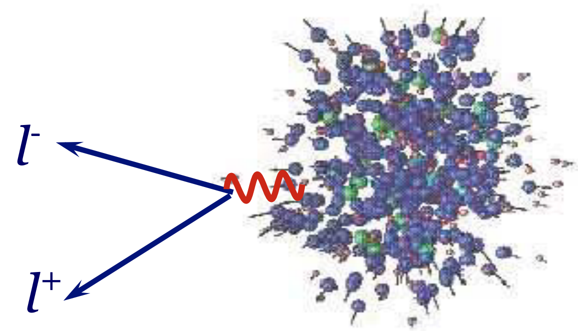


$$\frac{d^3N}{dMdydp_t} \equiv \int_{t=0}^{\infty} \frac{d^4\varepsilon}{d\mathbf{p}} \left[T(\mathbf{x}), \mu_B(\mathbf{x}), \vec{v}_{coll}(\mathbf{x}), ..\right] d\mathbf{x}$$

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

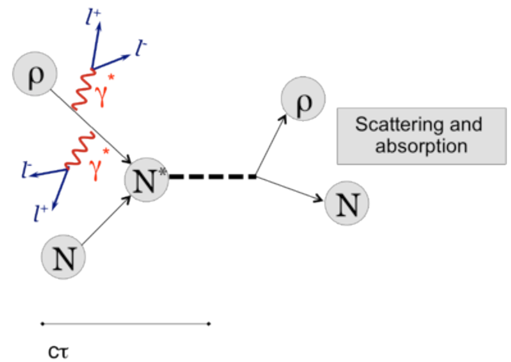


...or from transport

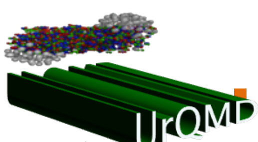


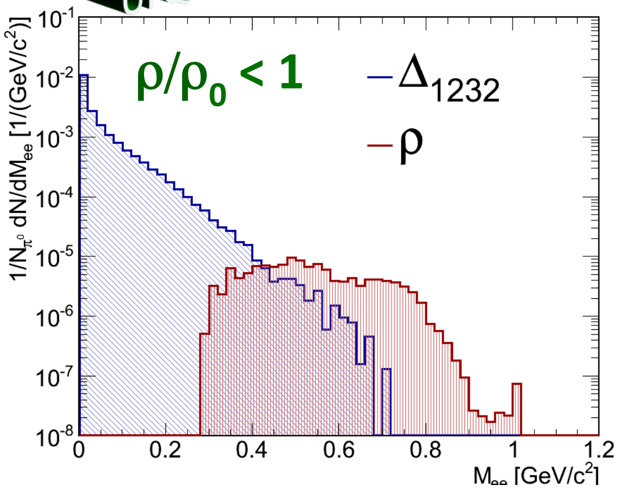
Radiation from dense matter

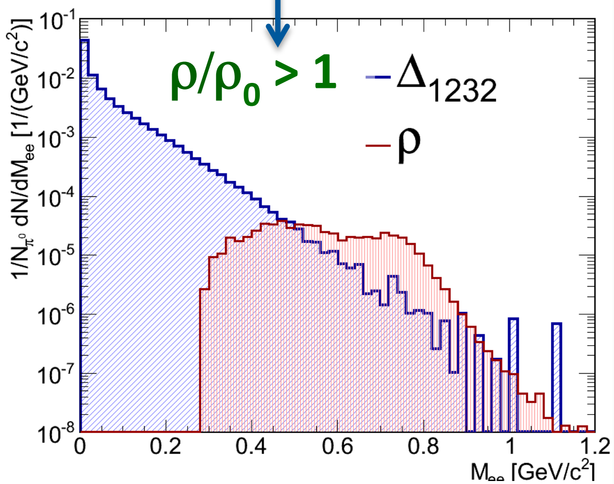
- Schematic illustration of ρ meson propagation within "shining" approach.
- Resonance can continuously emit dileptons over its whole lifetime.



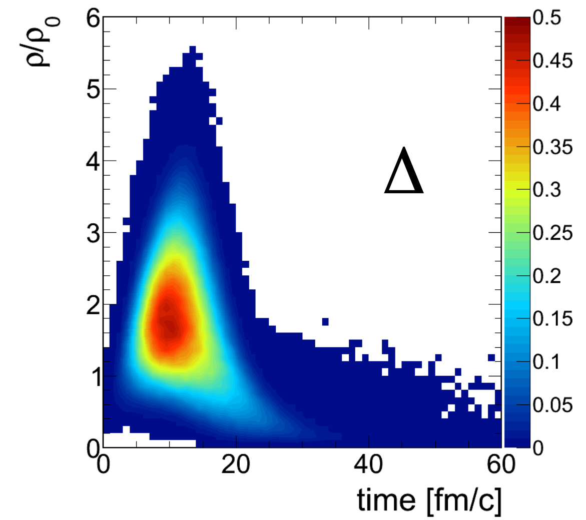
- Isolate the contribution to the spectrum from the dense stage
- Couple transport and a **thermal model**

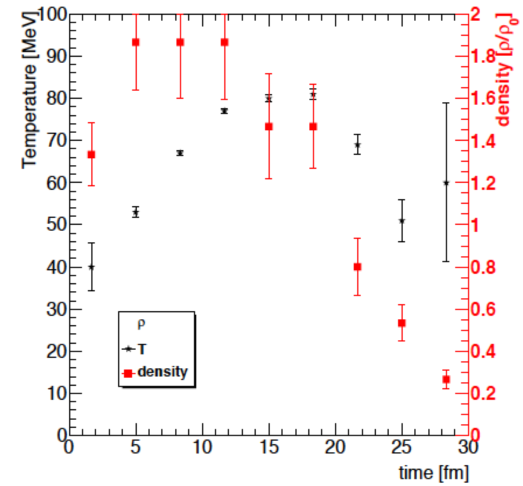






Emission density evolution

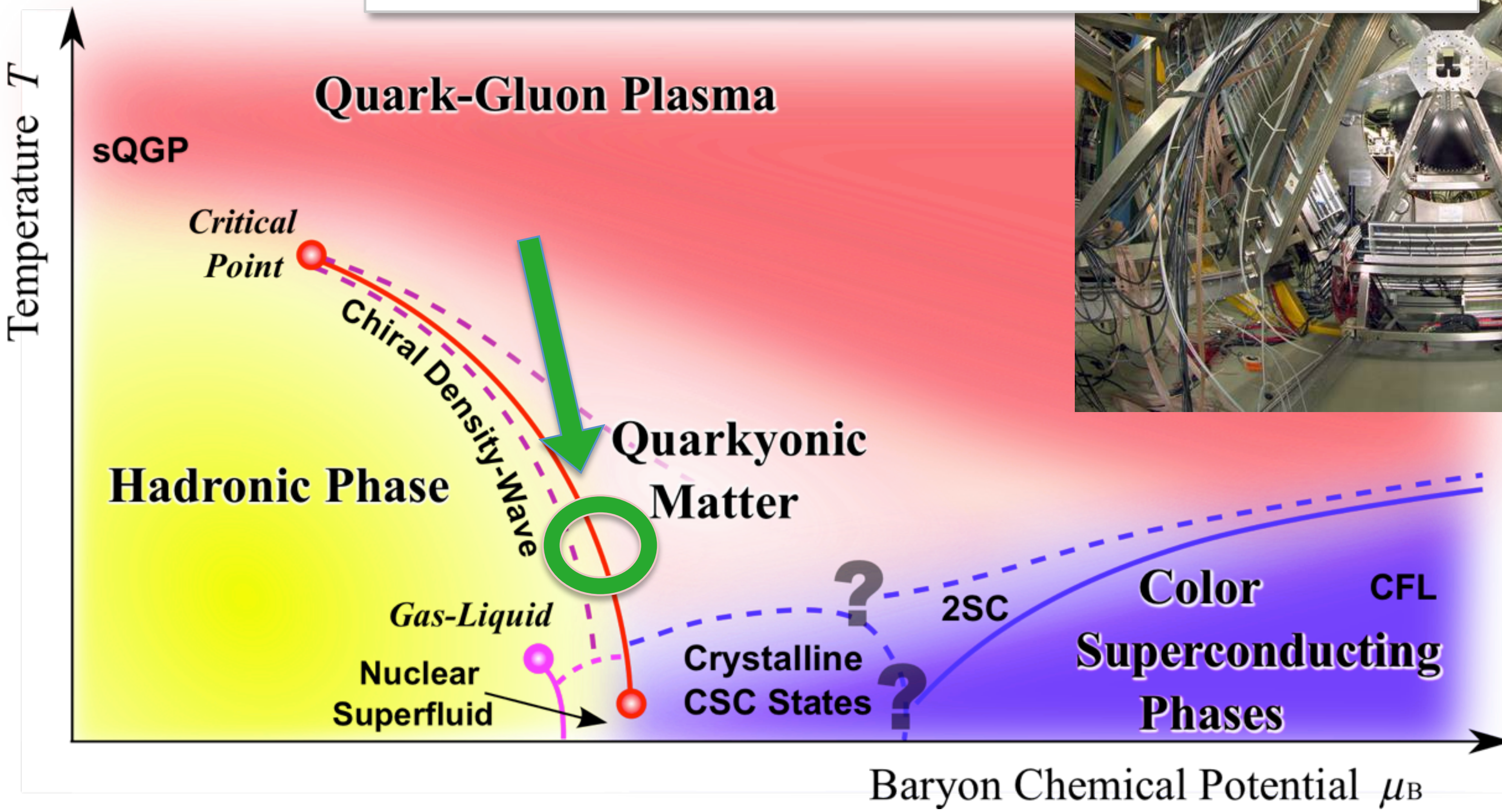


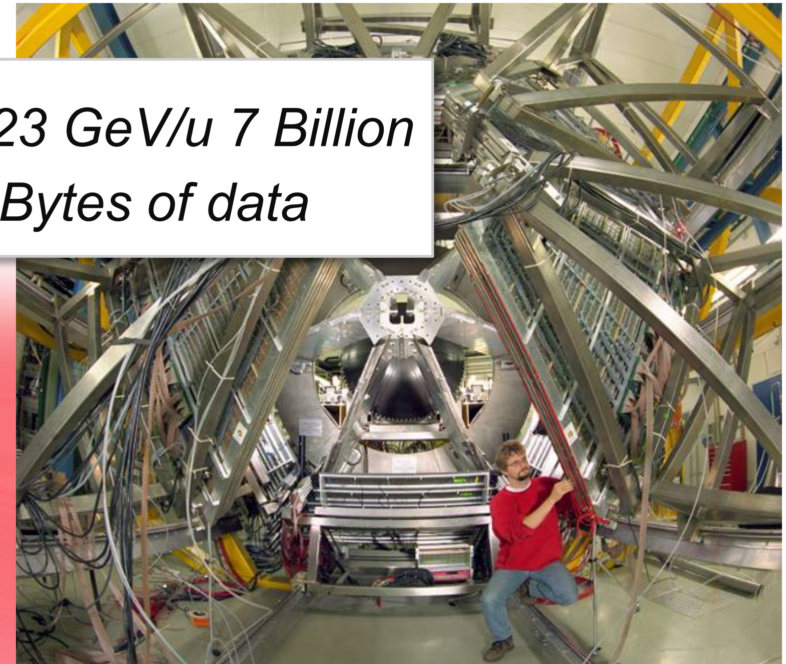


- First (points) and second (errors) moment of the density profile at a given τ.
- T – Boltzmann fit to the particle m_T spectra

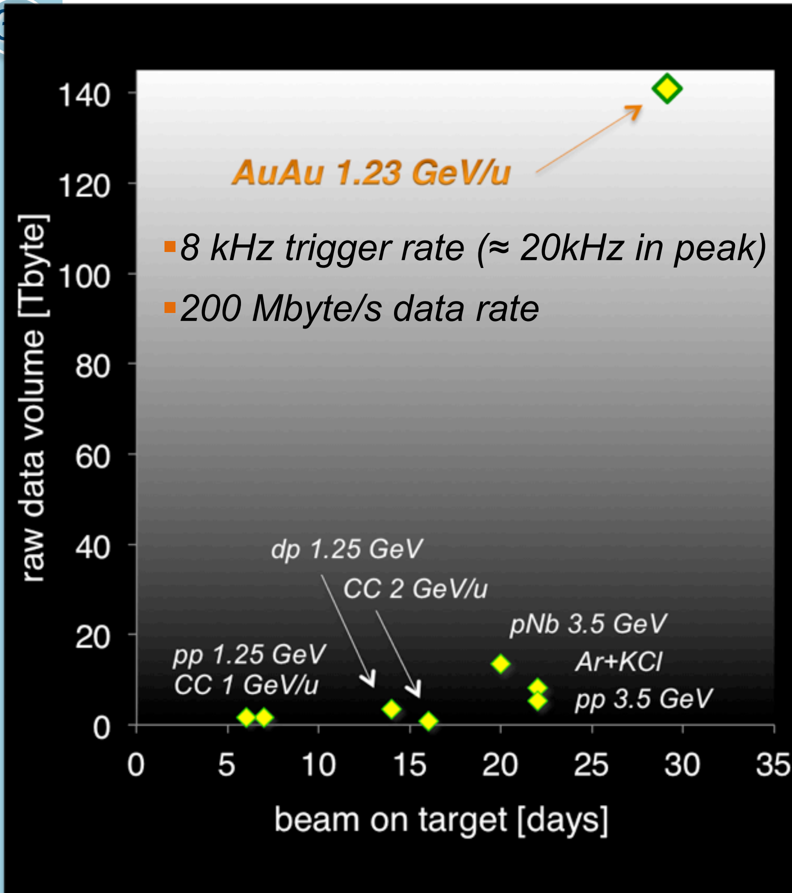
HADES explores Quarkyonic matter

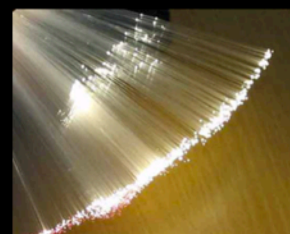
April-May 2012 Au+Au run, 1.23 GeV/u 7 Billion events in 4 weeks, 140 T Bytes of data



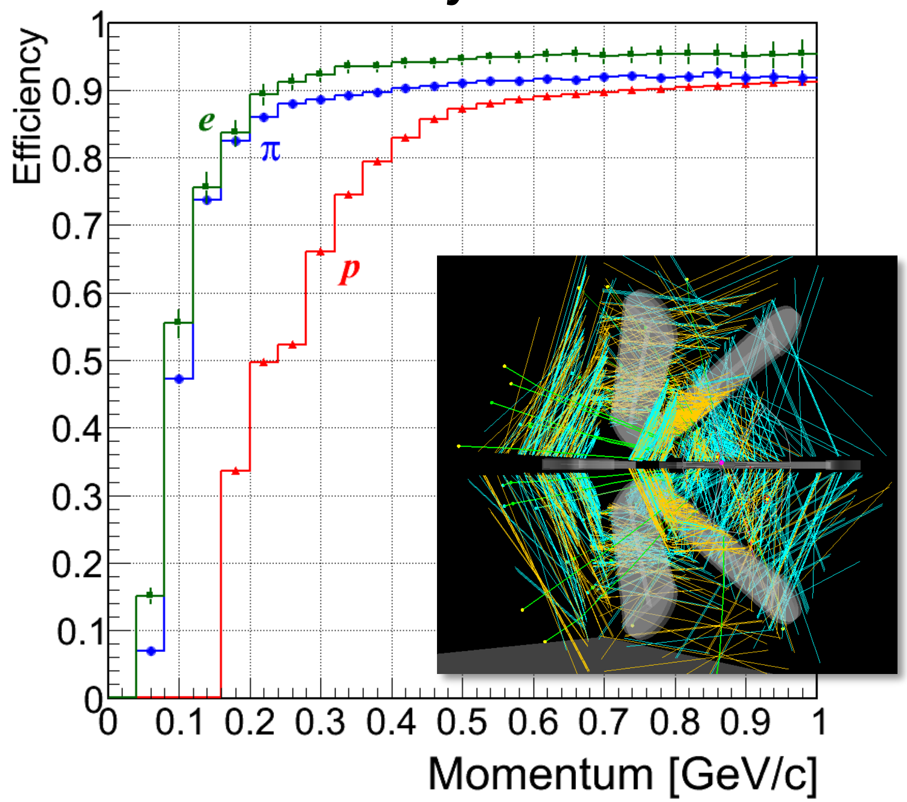


Au+Au at 1.23 GeV/u (beam time April – May '2012)





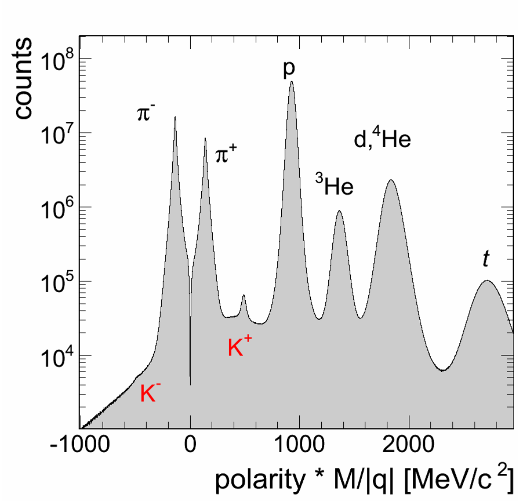
Track reconstruction efficiency in high track density environment

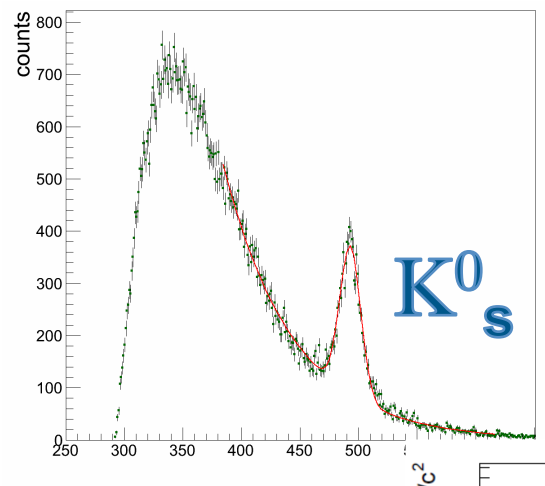


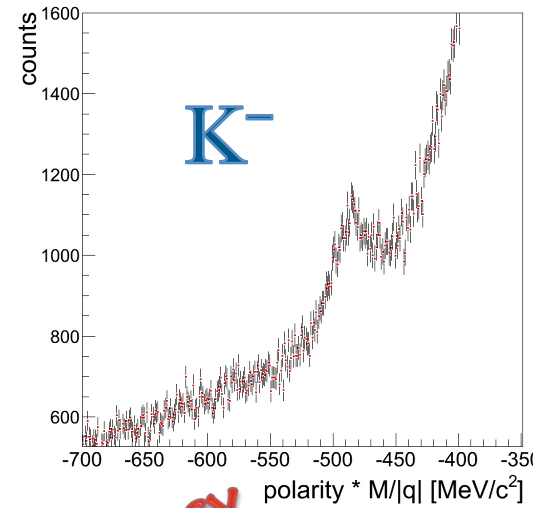
HADES DAQ:
Versatile, FPGA board based system using dedicated add-on boards and data/trigger/slow-control transport via serial optical links (TRBnet)

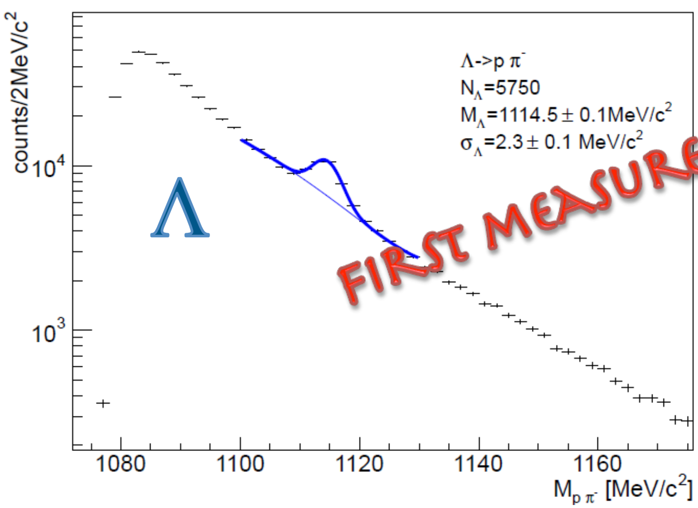
Strangeness

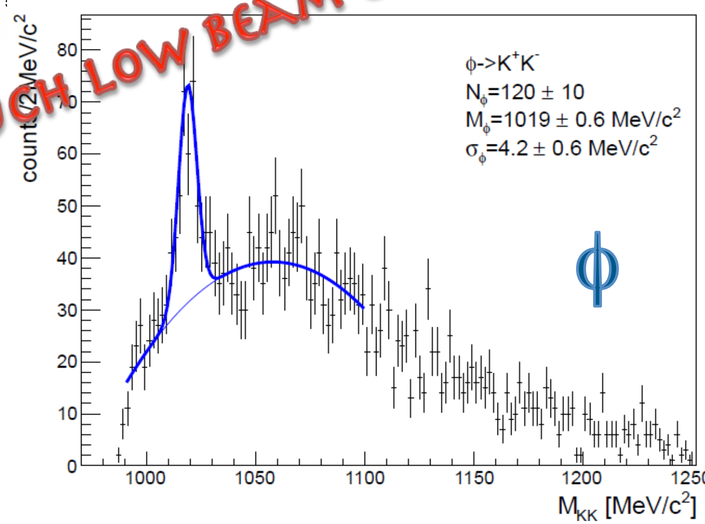
NN excess energy 0.44 GeV only!
Strong constraints on production mechanism





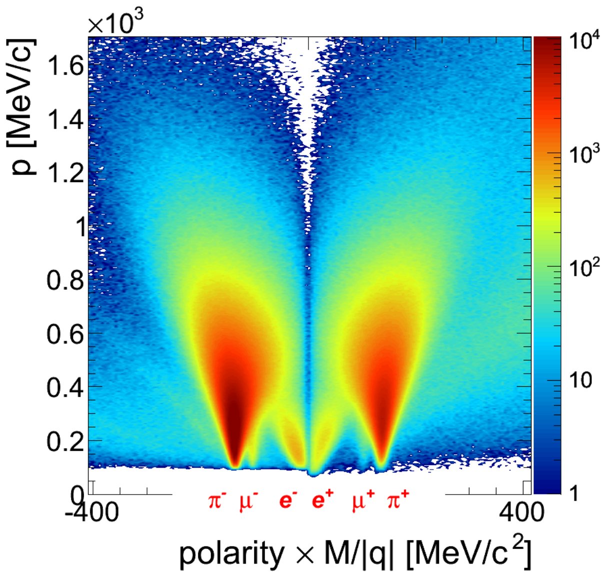




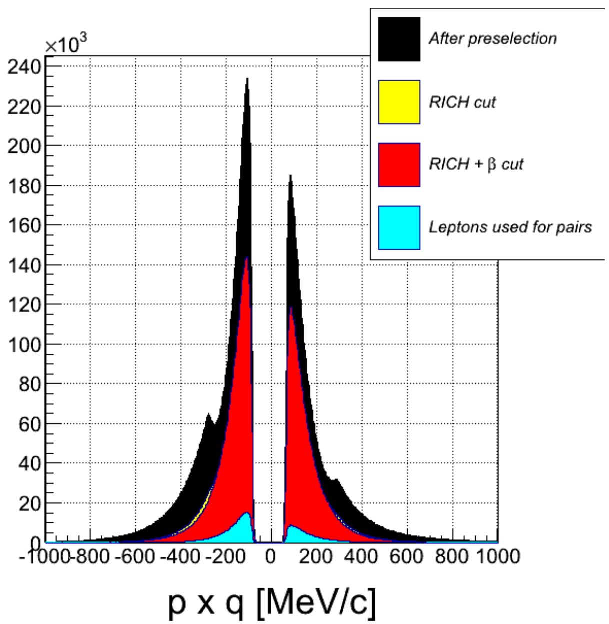


FIRST MEASUREMENT AT SUCH LOW BEAM ENERGY

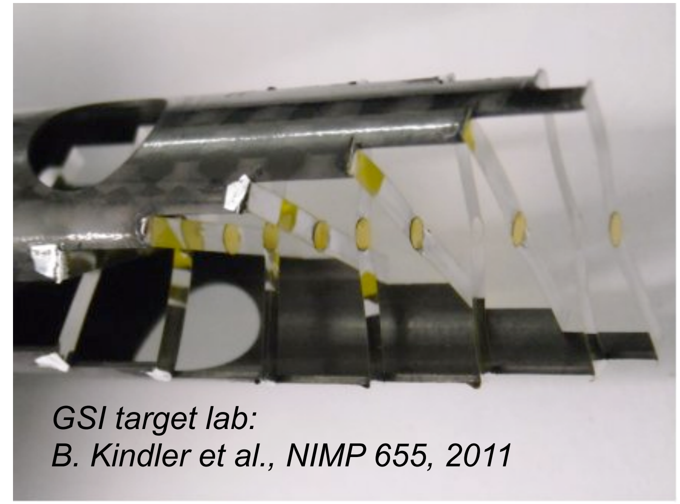
Leptons



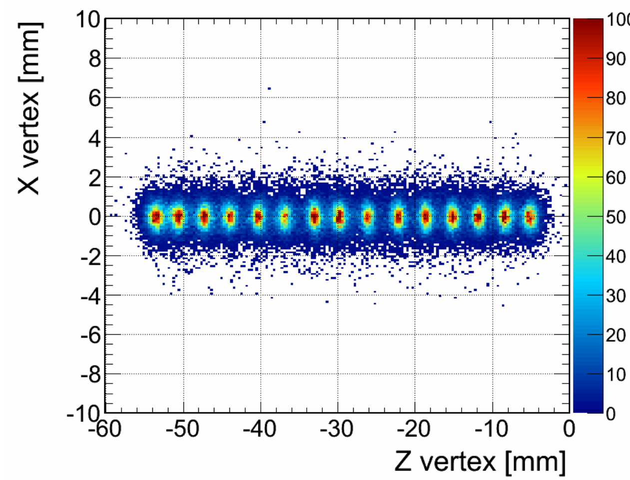
×10^3
p [MeV/c]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-400
400
π⁻ μ⁻ e⁻ e⁺ μ⁺ π⁺
polarity × M/|q| [MeV/c²]
10^4
10^3
10^2
10
1



After preselection
RICH cut
RICH + β cut
Leptons used for pairs
×10^3
240
220
200
180
160
140
120
100
80
60
40
20
0
-1000 -800 -600 -400 -200 0 200 400 600 800 1000
p x q [MeV/c]



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



X vertex [mm]
10
8
6
4
2
0
-2
-4
-6
-8
-10
-60 -50 -40 -30 -20 -10 0
Z vertex [mm]
100
90
80
70
60
50
40
30
20
10
0

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

π beam experiments with HADES

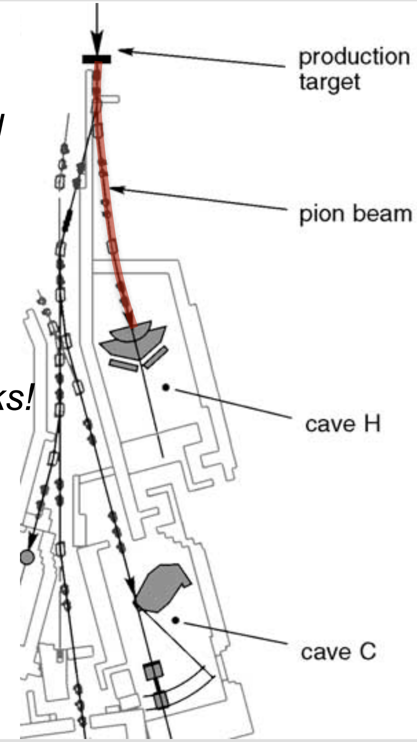
- **Physics with πN experiments:**
  - New precision data are of enormous importance for understanding of baryon resonance physics
  - Special interest to sub-threshold production
- **Challenges:**
  - Determine π momentum with $\Delta p/p$ ~1-5%
  - Beam spot of 6x6 cm^2 at dispersive plane
    → detector 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

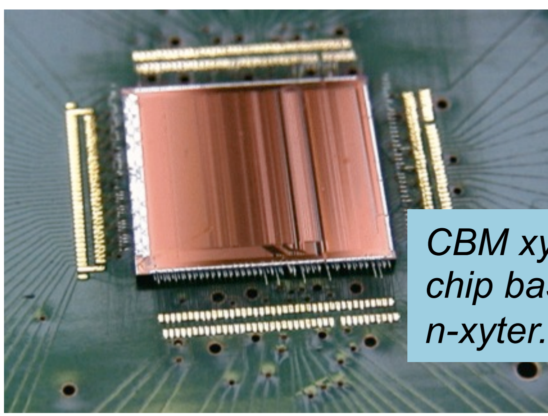
Spill: 4s cycle

Stable run for 3 weeks!



ZEUS at DESY

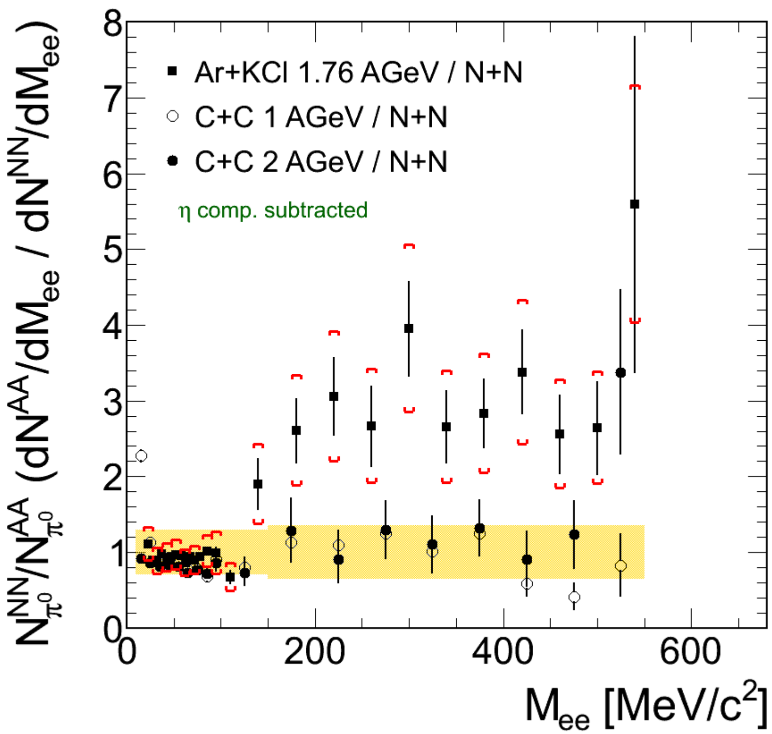
- **Strategy:**
  - Use 10×10cm^2 silicon strip detector
  - 2×128 channels - double sided
  - Radiation hard
  - Profit from n-xyter developments for CBM
    - ✓ Self-triggered architecture
    - ✓ 128 channels
    - ✓ Average hit per channel rate 160 kHz



CBM xyter FE chip based on n-xyter.

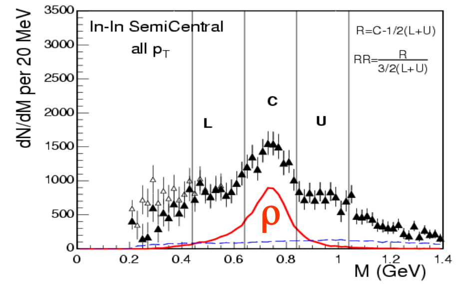
Centrality dependence of spectral shape

HADES "Δ clock"

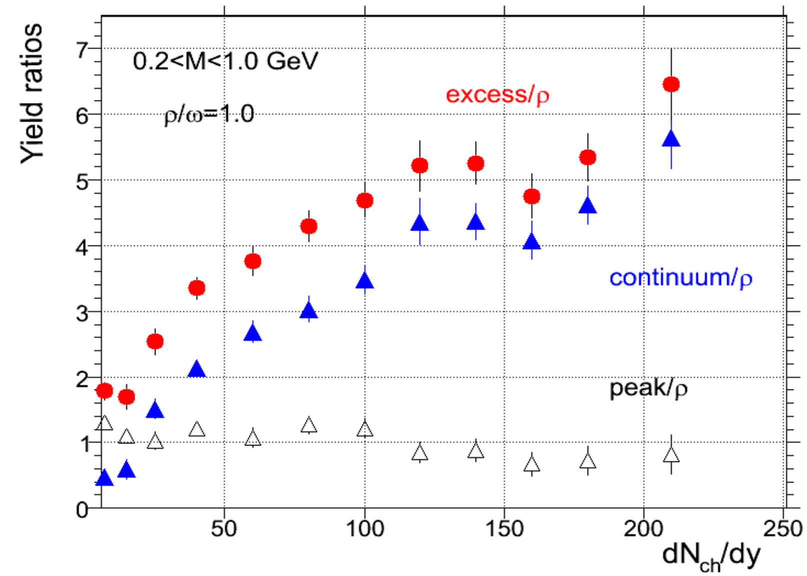


HADES: Phys.Rev.C84:014902,2011

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



NA60's "ρ clock"



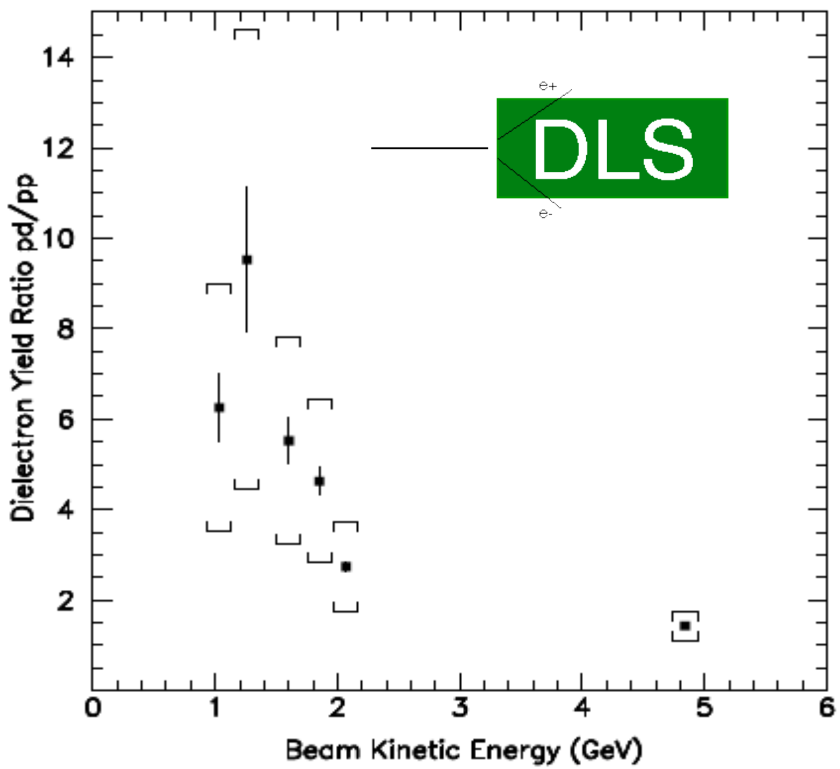
- Rapid increase of relative yield reflects the number of ρ's regenerated in fireball

Na60 data: EPJC 61 (2009) 711

Overview of existing dilepton experiments (summary)

Experiment	System	$\sqrt{s}$	$dN_{ch}/d\eta$	E	S/B	Sys error (%)
CERES	Pb+Au	8.86	216	**5.9**	1/6	20
CERES (σ/σ_{tot} = 28%)	Pb+Au	17.2	245	**2.31**	1/13	24
CERES (σ/σ_{tot} = 7%)	Pb+Au	17.2	350	**2.58**	1/21	16
NA60(central)	In+In	17.2	193	**3**	1/11	25
NA60(semi-central)	In+In	17.2	133	**2**	1/8	25
NA60(semi-peripheral)	In+In	17.2	63	**2**	1/3	12
NA60(peripheral)	In+In	17.2	17	**1.5**	2	3
CERES	S+Au	19.5	125	**5**	1/4.3	25
PHENIX(0-10% centrality)	Au+Au	200	650		1/200	PRC 2010
STAR	Au+Au	200	650	**2**	1/250	QM2012
SIMULATION						
CBM (sim) (b=0fm) (free SF)	Au+Au	8	300		0.025 0.025 * 6	
ALICE (sim) (R.Rapp in-medium SF)	Pb+Pb	5.5 TeV	248		7e-2	25 LOI
ALICE (sim) (R.Rapp in-medium SF)	Pb+Pb	5.5 TeV	1750		1e-2	25 LOI

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

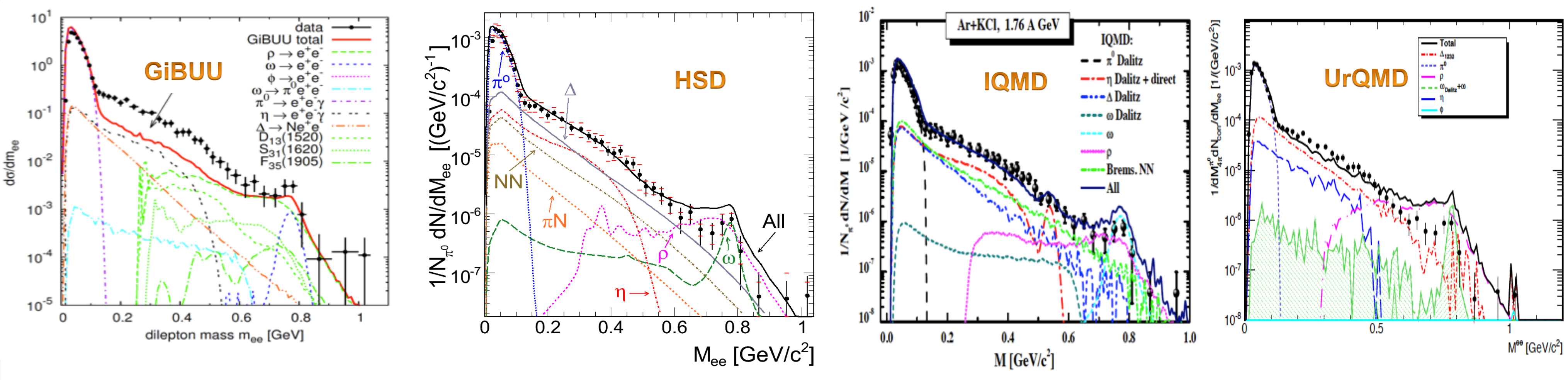


W. Wilson et al., Phys. Rev. C 57 (1998)

- 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 - transport

J. Weil at al., arXiv:1106.1344v1 | *E.L. Bratkovskaya, NPA 807 (2008) 214* | *J. Aichelin et al, in preparation*

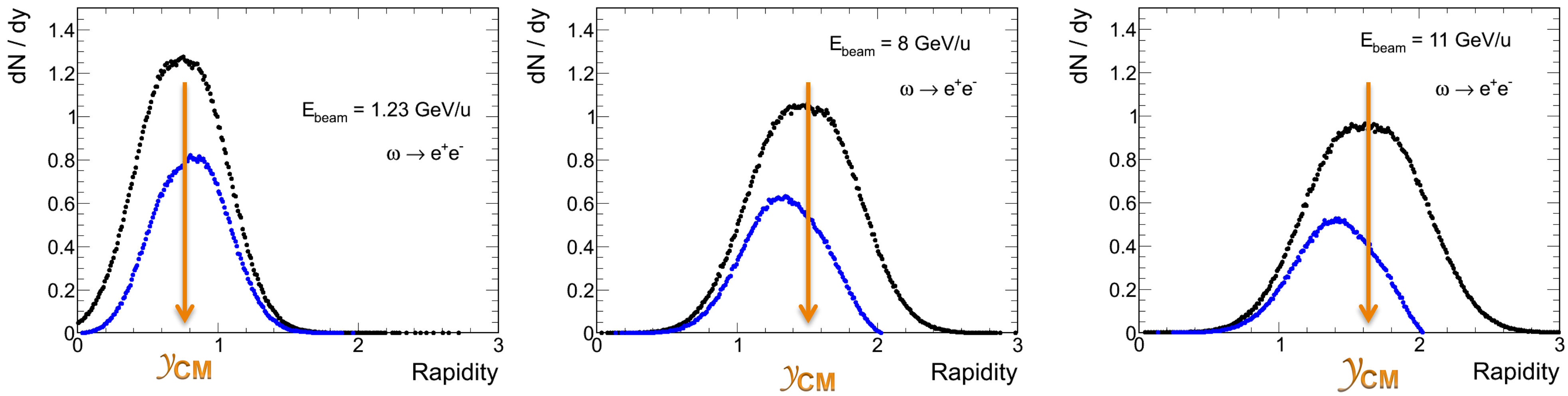


No consistent picture yet:

- 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/c^2 dominates by ρ with complicated vacuum structure

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

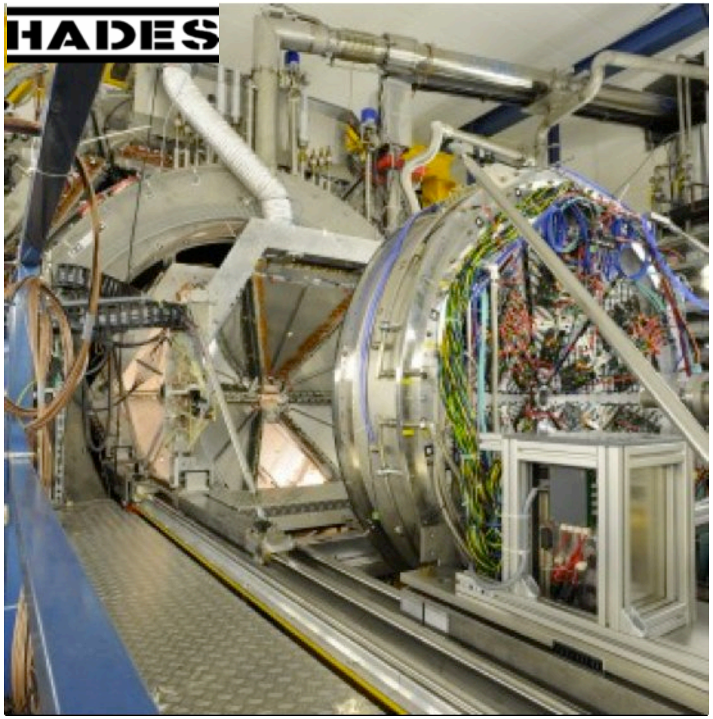
E_{beam} = 8 GeV/u

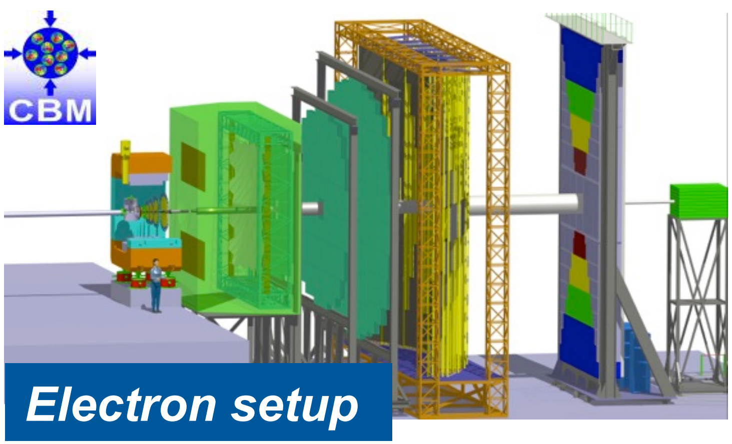
- Acc ≈ 20%
- (natural) shift towards backward rapidity

E_{beam} = 11 GeV/u

- … still High Acceptance DiElectron Spectrometer → Acc ≈ 20%
- **but…**

2016: HADES goes underground





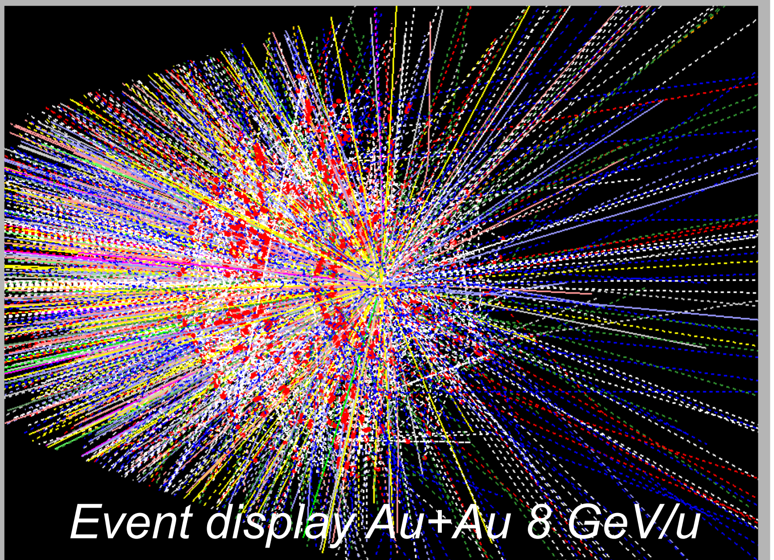
SIS100:

- HADES and CBM:
  - Emissivity of hot/dense nuclear matter
    - In-medium spectral functions of ρ in dense (**baryon dominated**) hadronic matter
  - Multi-strange particle excitation functions
  - Charm production in proton induced reactions
  - Bulk observables

SIS300 :

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

HADES at SIS100: problems, challenges, opportunities



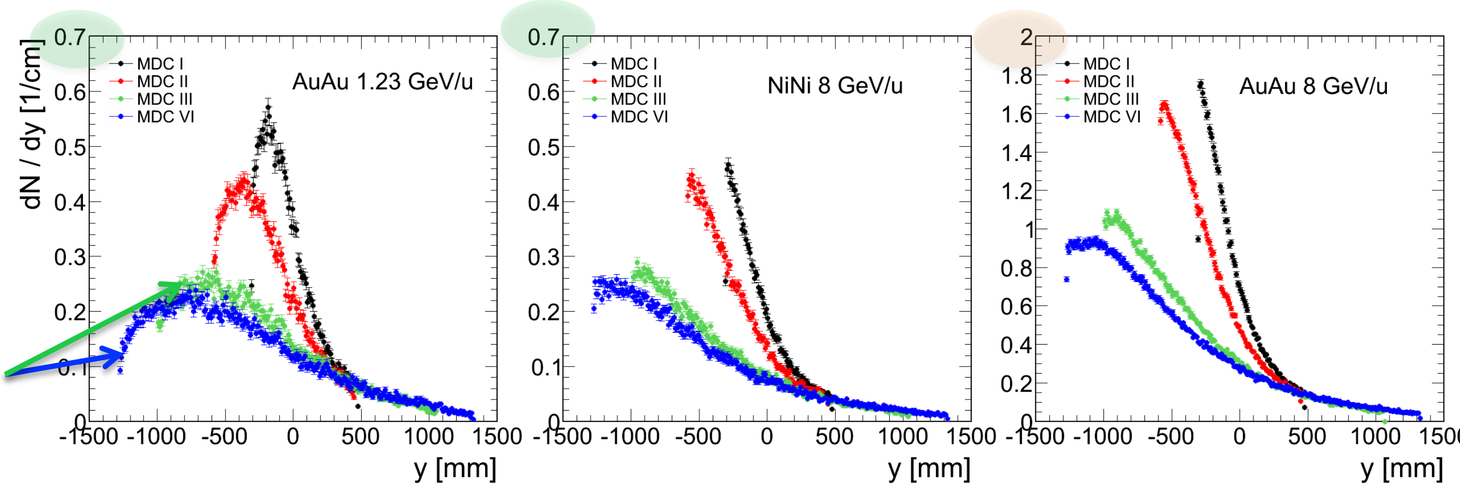
- **Challenge:** tracking issue →
  - wires introduce long range correlations between particle tracks

- 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)

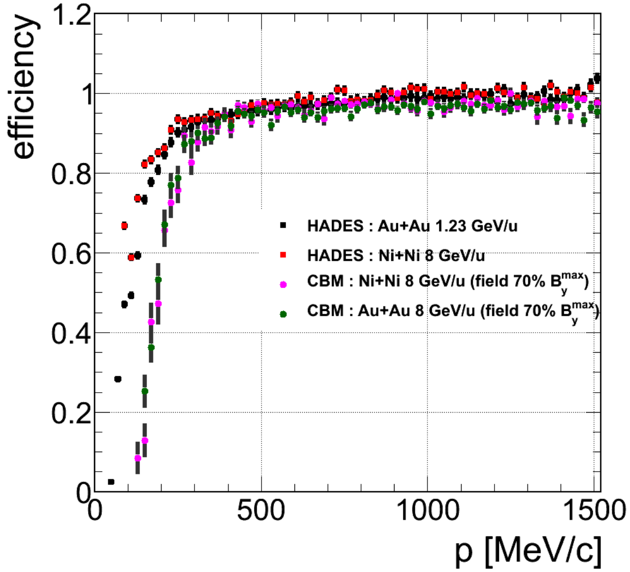
Cell size is factor of 2 larger



y – radial coordinate in drift chamber

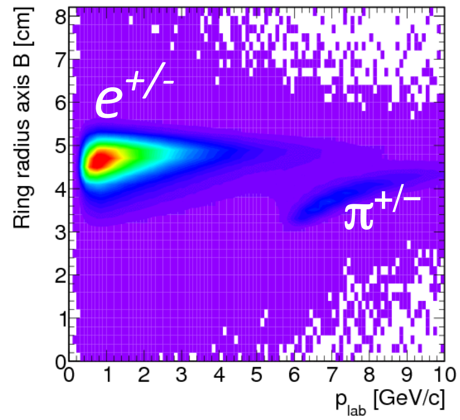
Electron identification

Track reconstruction efficiency

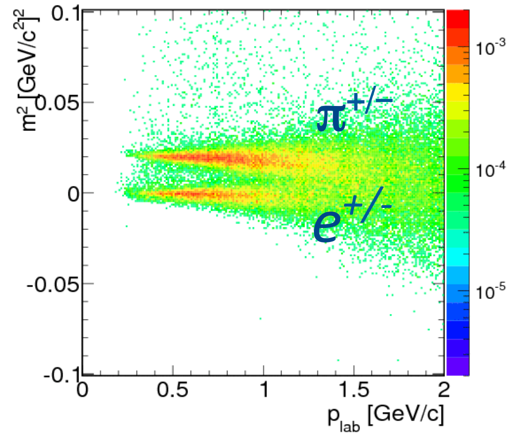


- Momentum distribution of conversion pairs are very soft
- High reconstruction efficiency is required for rejection of conversion pairs

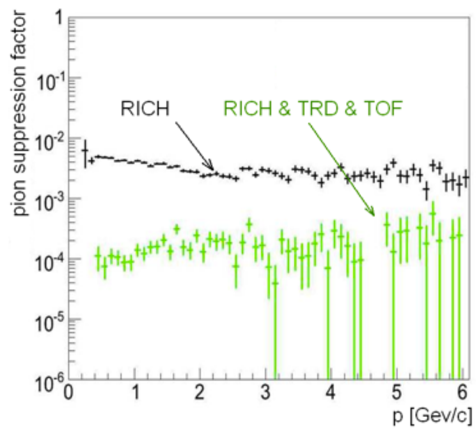
Ring radius vs. momentum



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



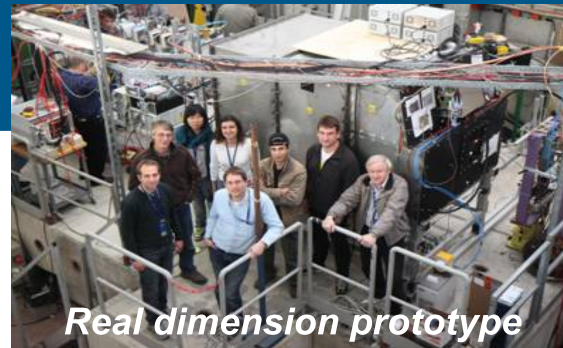
π suppression factor of 10^4 (for p < 1 GeV/c) is in reach with RICH and ToF

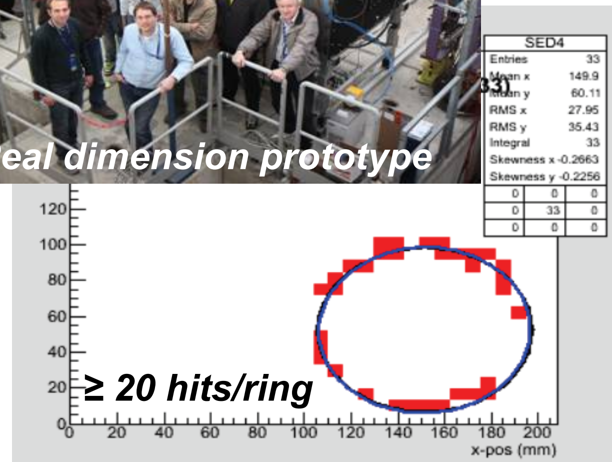


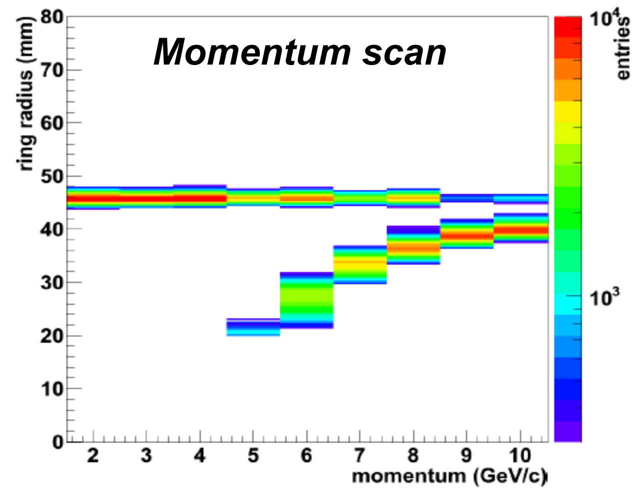
Detector R&D

RICH

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



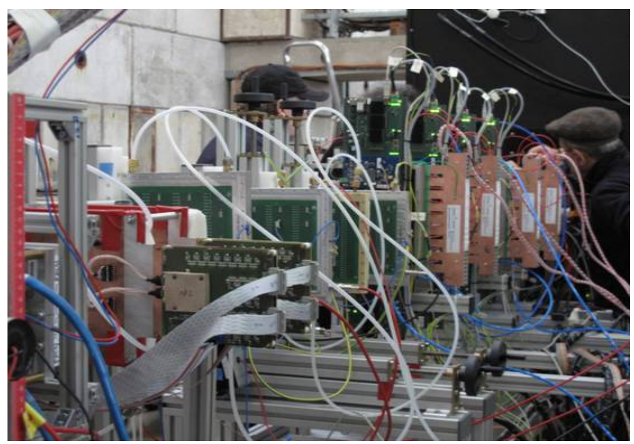


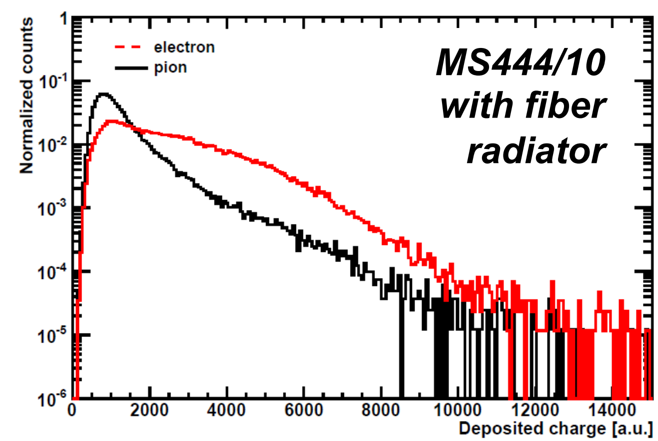


- **Test Beam at CERN T9, October 2011**
- **Mixed electron / pion beam of 2 – 10 GeV/c**

TRD

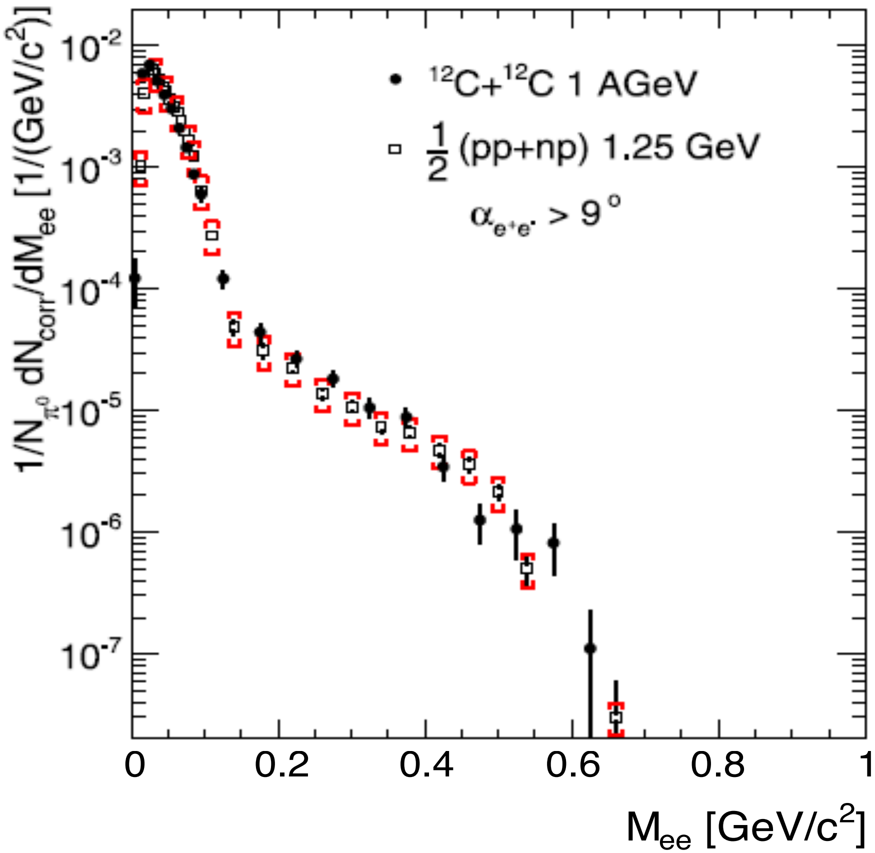
- Thin gap design based on ALICE TRD (Germany, Russia, Romania)





Virtual photon emission in A+A collisions

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



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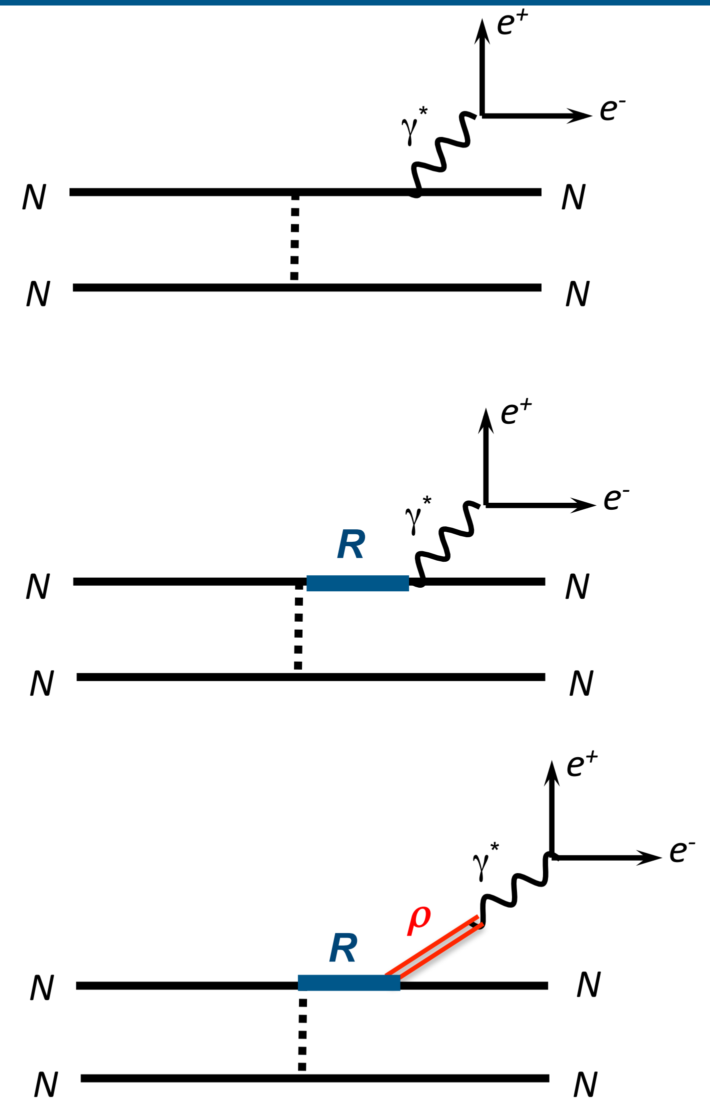

Baryonic contributions from NN "reference"

$R = \Delta, N^*$