Measurement of virtual photons radiated from Au+Au collisions at E_{beam} = 1.23 AGeV in HADES

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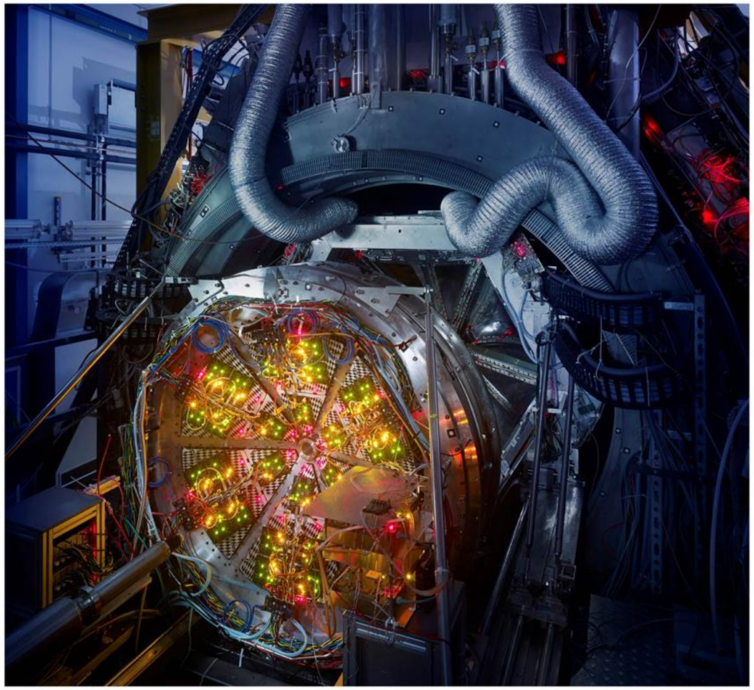
Szymon Harabasz for the HADES collaboration



Motivation

Lepton identification

Combinatorial background subtraction

Excess yield extraction

Comparison to models

Summary

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Electromagnetic Probes of Strongly Interacting Matter

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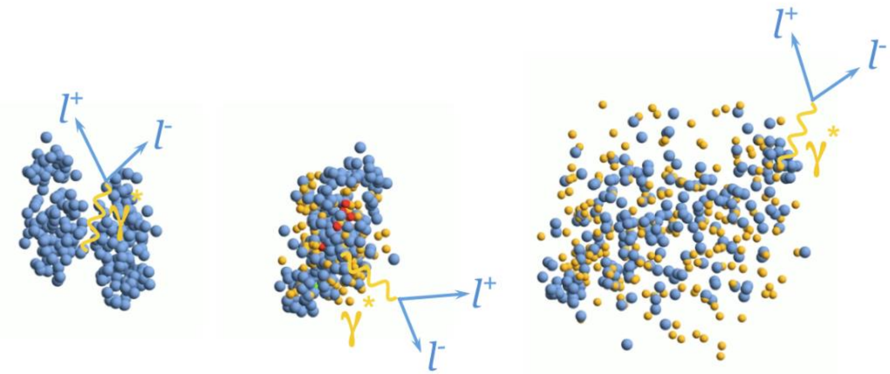
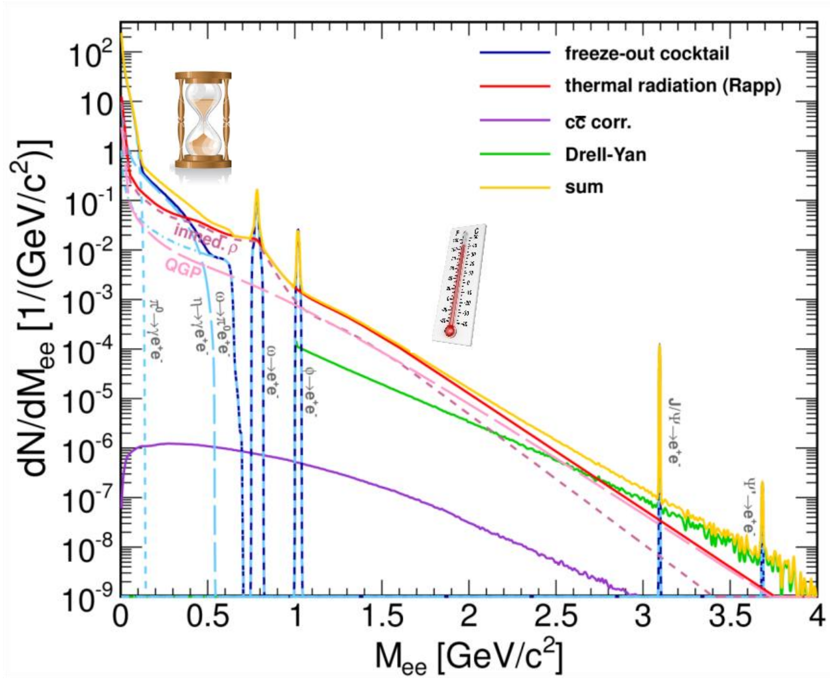
- γ, $\gamma*$: No strong final state interactions
  → **leave reaction volume undisturbed**

- Reflect whole "history" of collision:
  - From pre-equilibrium phase
  - From QGP and hot hadronic gas
  - From meson decays after thermal freeze-out



PHSD: Nucl. Phys. A 831 (2009)

Schematic spectral distribution of lepton pairs emitted in ultra-relativistic heavy ion collisions



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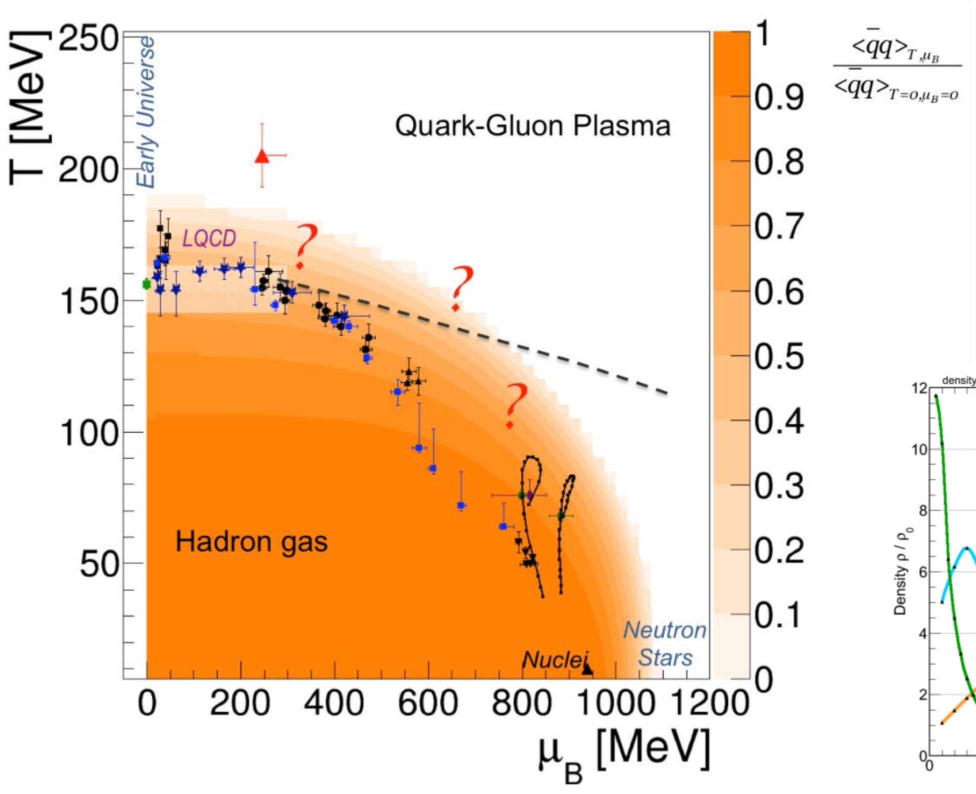
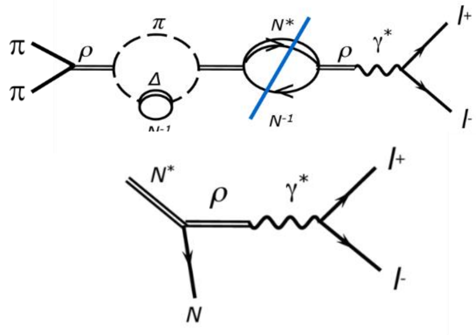
Low Energy ≠ Little Excitement

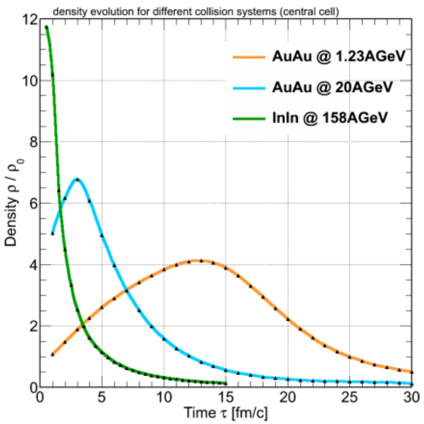


SPS, RHIC, LHC

Decrease $\sqrt{s_{NN}}$

SIS18





Central cell, UrQMD

- Dilepton yield dominated by resonance decays, but underlying physics the same as the dressing of vector meson propagator
- Dense phase "lives" by far much longer than at higher energies, penalty → lower T
- Does (at least) most central part of fireball probe exotic regions of QCD phase diagram?

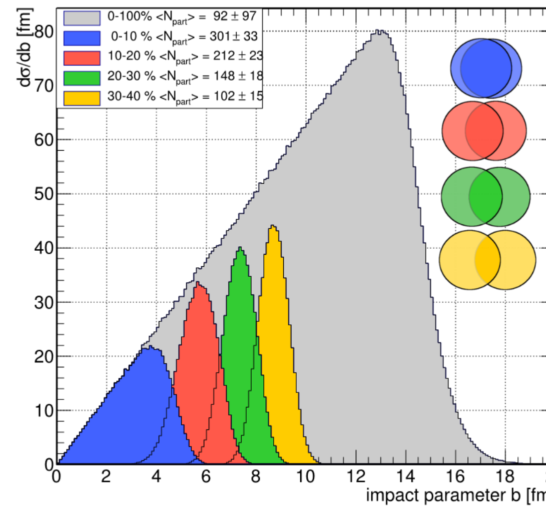
NA60 (μ+μ-) : H.J.Specht: AIP Conf.Proc. 1322 (2010)

See talk by F. Seck

Meet the HADES

Photograph by A. Rost

Glauber Monte Carlo



4.3×10^9 of 40% most central Au+Au events recorded

Beams from SIS18: protons, nuclei, secondary pion beams, E_{kin}=1-2 GeV/u

Search for very rare probes

-Di-lepton production governed by the factor α^2

-Branching ratio to e^+e^- ~7.14×10^{-5}

-Vector meson production sub-threshold

→**Fast detector** → interaction rate of 8 kHz

→**Large acceptance** → full azimuth, θ from 18º to 85º

→**Mass resolution** → of the order of few %

→**Good particle identification**

→**Efficient track reconstruction**

Track multiplicity as large as 300 per event (incl. fakes & secondaries)

→ **combinatorial background**

See talk by M. Lorentz

Electron Identification

Track quality selection

Energy loss

Particle velocity

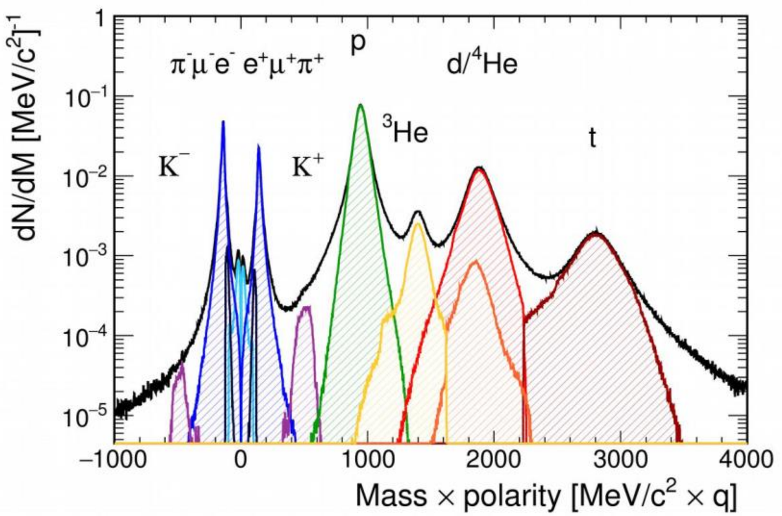
Electromagnetic shower

Correlated with momentum

Cherenkov radiation

→ two independent analyses:

- Ring Finder
- Backtracking



All combined in a multivariate analysis (neural networks)

Purity of single lepton identification at least 98 %

Electron Identification
Two Approaches to Detect Cherenkov Signal

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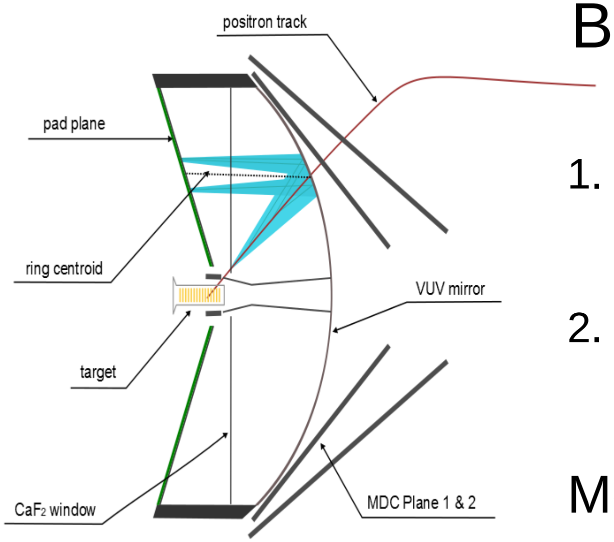
Ring finder

1. Search for rings in the photodetection plane using **pattern matrix** or **Hough transform**

2. Use **angular correlations** to match rings with tracks in drift chambers



Side view of the RICH detector

Backtracking algorithm

P. Sellheim, J.Phys.Conf.Ser. 599 (2015)

1. Identify lepton candidates using **velocity** and **energy loss**

2. Check the **ring hypothesis** around the expected ring enter

Motivation and advantages

- Ability to resolve overlapping rings
- Removal of close pairs (γ-conversion, combinatorial background)

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Background Subtraction

1. Combinatorial background is estimated by:

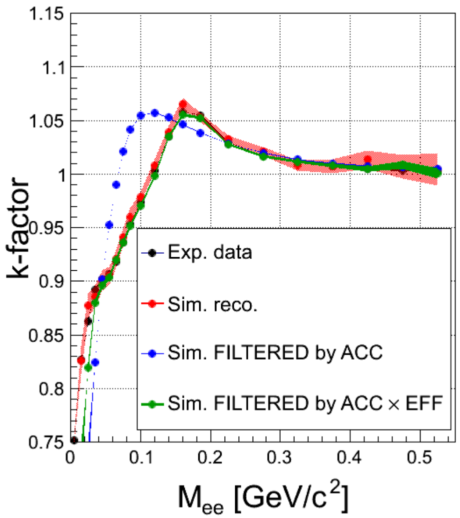
$$\langle BG_{+-}\rangle = k \cdot 2\sqrt{\langle FG_{++}\rangle\langle FG_{--}\rangle}$$

2. With the *k-factor*:

$$k = \frac{[\epsilon_{+-} + \epsilon_{+}(1-\epsilon_{+-})][\epsilon_{+-} + \epsilon_{-}(1-\epsilon_{+-})]}{[\epsilon_{++} + \epsilon_{+}(1-\epsilon_{++})][\epsilon_{--} + \epsilon_{-}(1-\epsilon_{--})]} = \frac{\langle FG_{+-}^{\mathrm{MIX}}\rangle}{2\sqrt{\langle FG_{++}^{\mathrm{MIX}}\rangle\langle FG_{--}^{\mathrm{MIX}}\rangle}}$$

3. This tells us that **not only geometry but also reconstruction** efficiency is important.

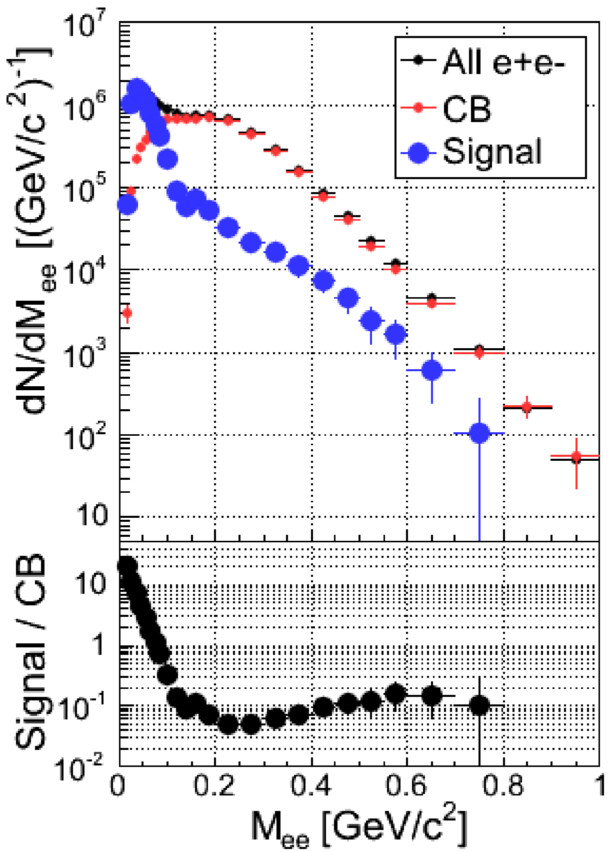
4. It is valid for **any event-by-event distribution of leptons** produced in the event.



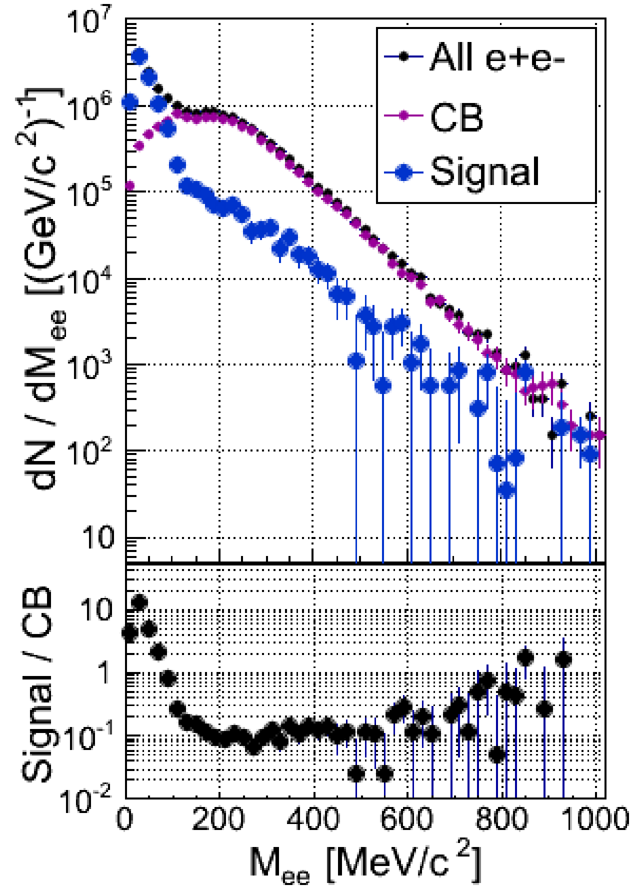
Take home: k-factor from event mixing is well-founded mathematically and necessary in case of charge asymmetry of the detection!

Signal Determination

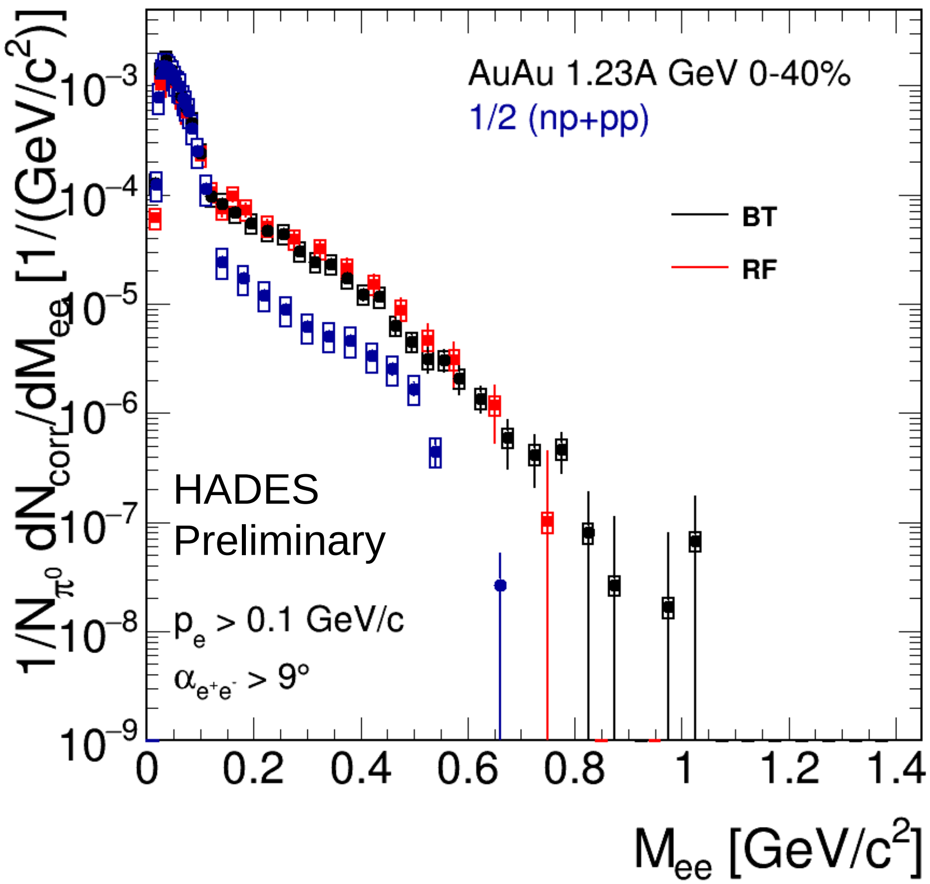
RICH Ring Finder (RF)



Backtracking (BT)



Invariant Mass Distribution



Results obtained with the **two analysis methods agree**

Agreement in the π^0-Dalitz region with the prevoiusly measured 1/2(np+pp) reference confirms the **constistency of the reconstruction**.

Above 0.15 GeV/c² clear enhancement compared to the reference
→ **Medium radiation**

Constraining the Cocktail
by the Measurements in the Same Experiment

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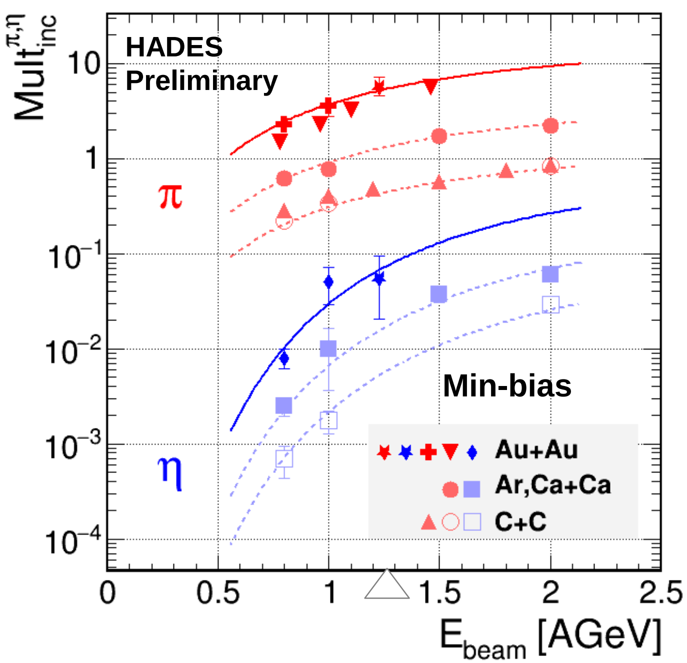
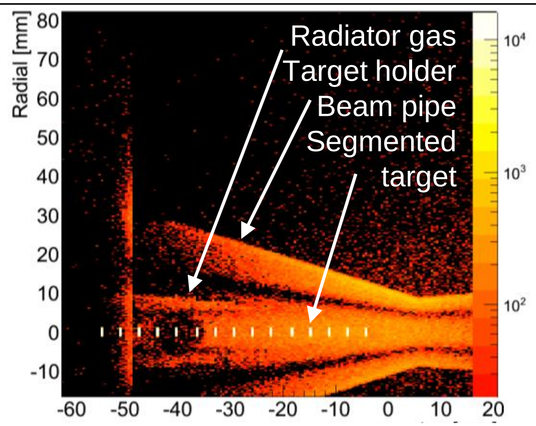
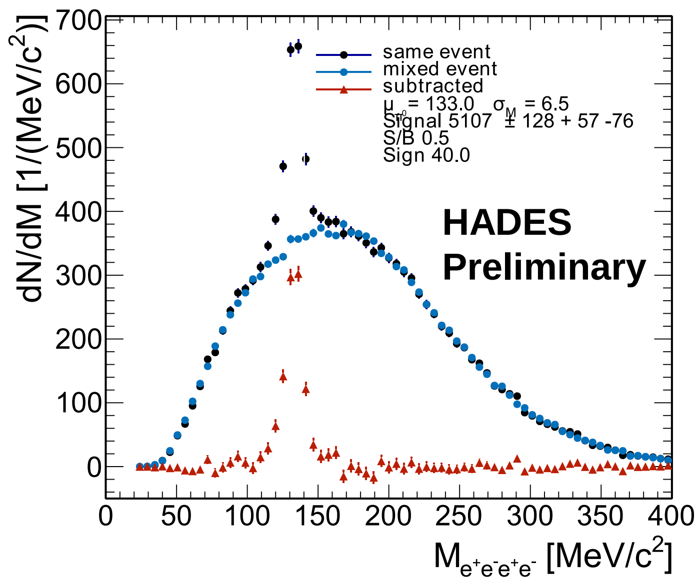
π^0 and η reconstruction

C. Behnke, J.Phys.Conf.Ser. 599 (2015)

- Conversion method
- Challenge: Low mass spectrometer!
- Conversion probability: **≈1%**







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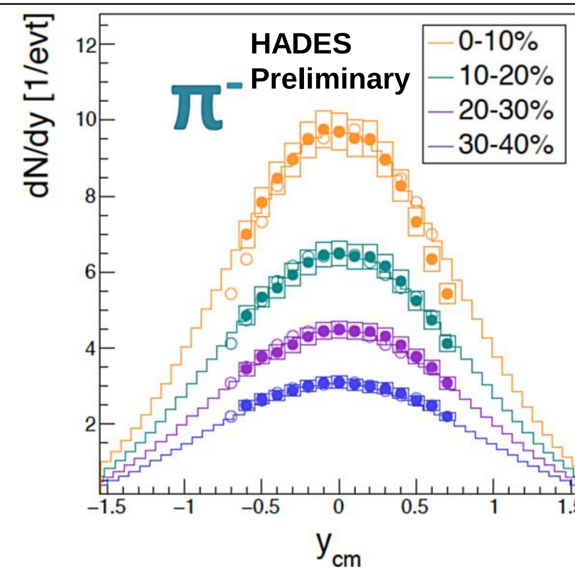
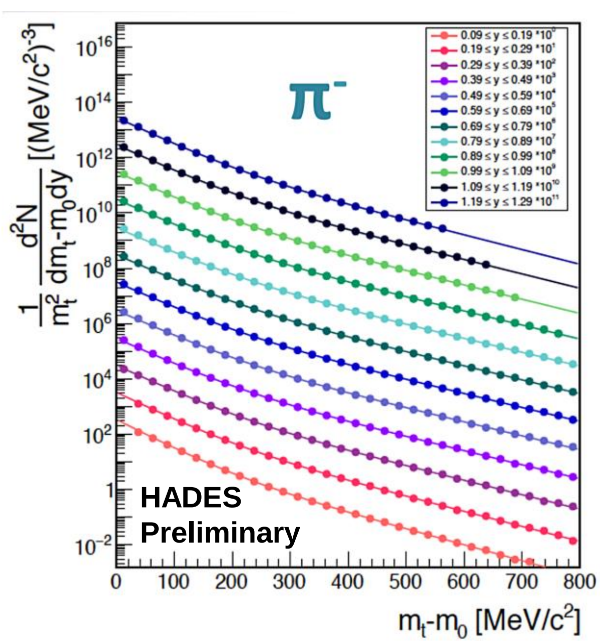
Constraining the Cocktail
by the Measurements in the Same Experiment

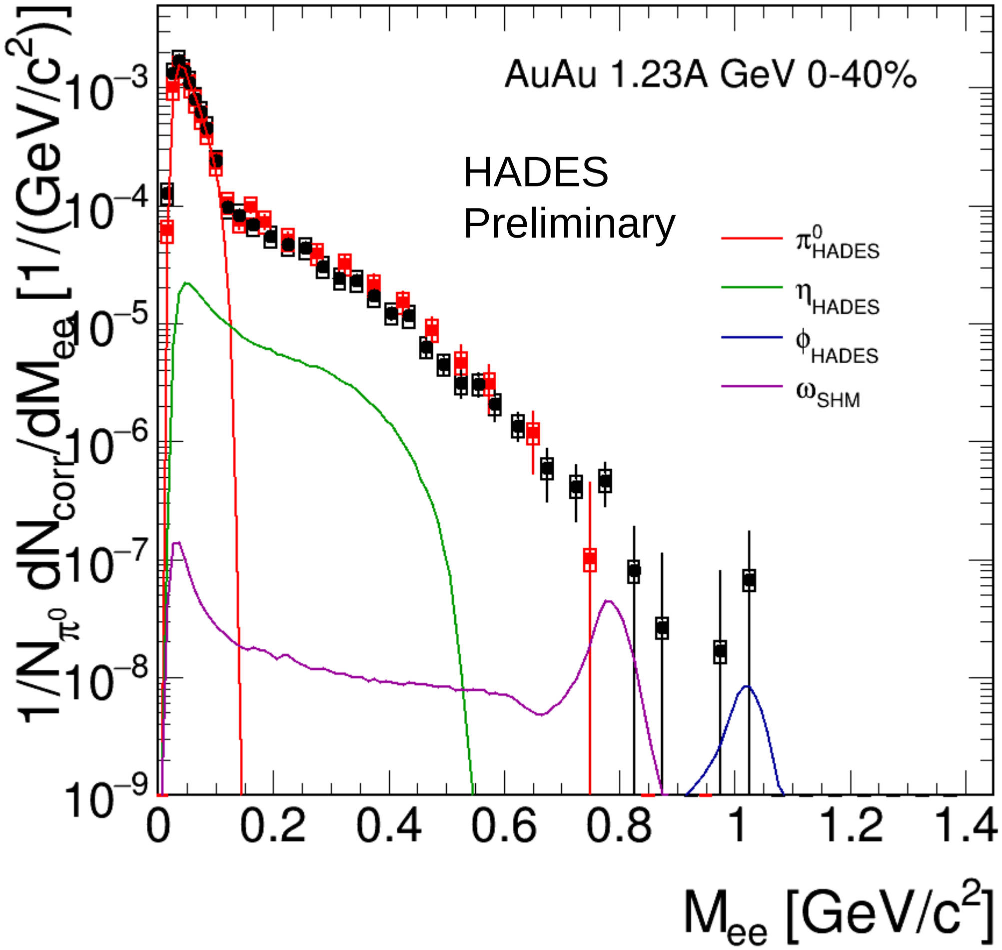
- Measurement of π^+ and π^- yields, thus giving π^0
- In addition:Extraction of slope parameters of $\pi^{+/-}$





Centrality	A_{Part}	M $(\pi^+ + \pi^-)/2$
0-10%	303	13.4
10-20%	215	9.5
20-30%	150	6.8
30-40%	103	4.9
0 -40 %	191	9.4

Constraining the Cocktail
by the Measurements in the Same Experiment

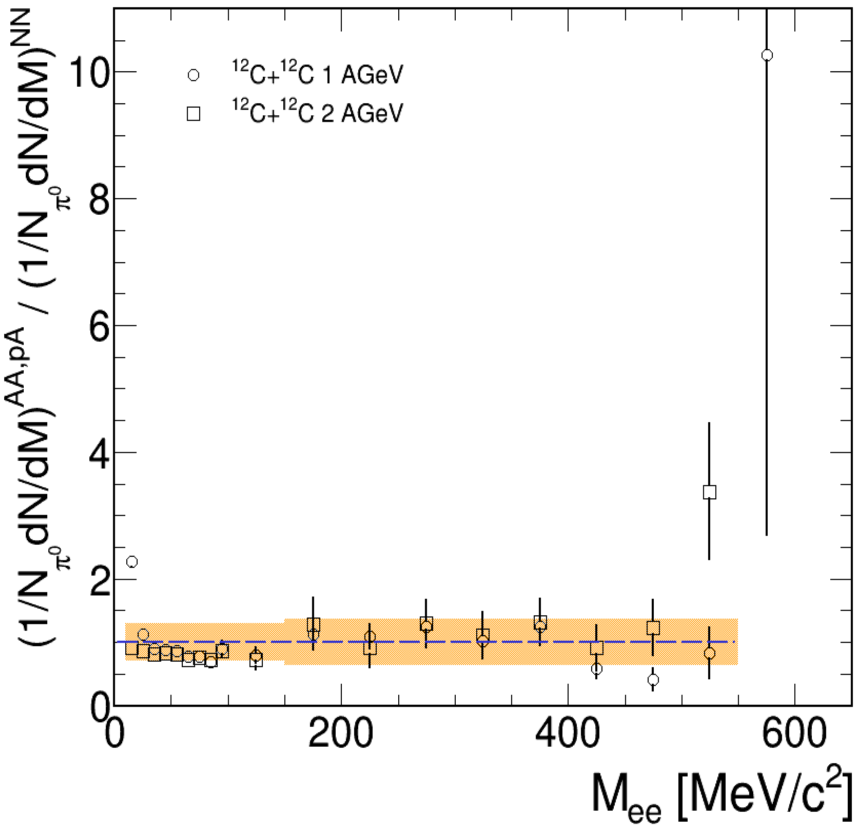


- π^0 from charged pions multiplicity, cross-checked with the conversion method
- η from the γ conversion
- ϕ from the K^+K^- channel
- ω from the Statistical Hadronization Model

Quantifying the Excess
What is "Non-trivial" Physics?

HADES performed a thourogh study of various collision systems in the same energy regime.

- Freeze-out contributions removed (π^0 by normalization, η by subtraction)
- The remaining radiation in C+C is already present in N+N



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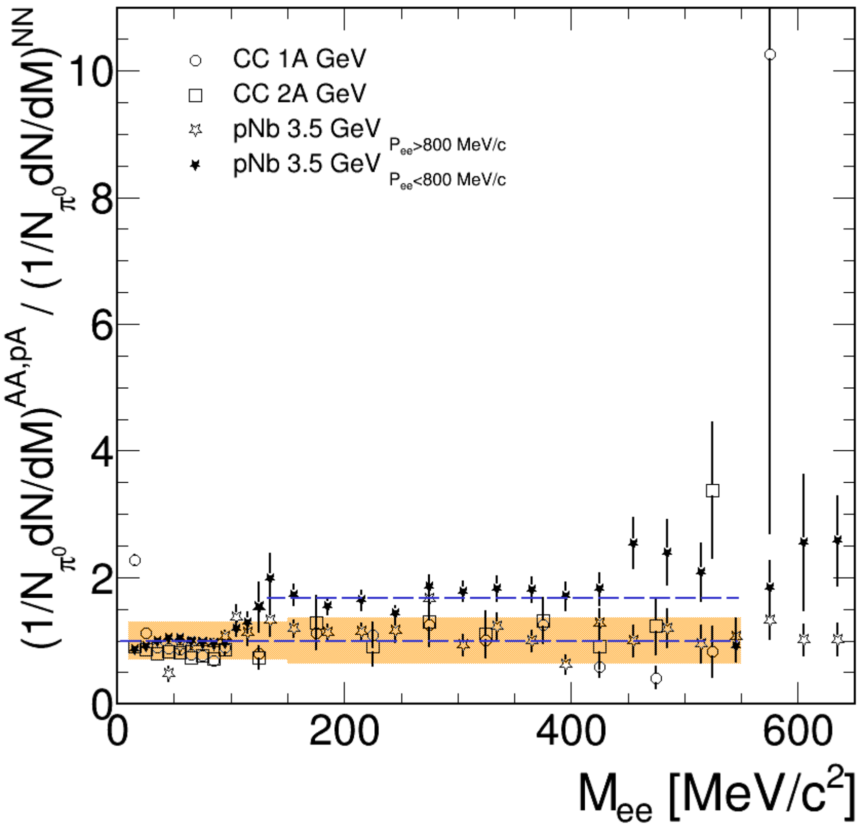

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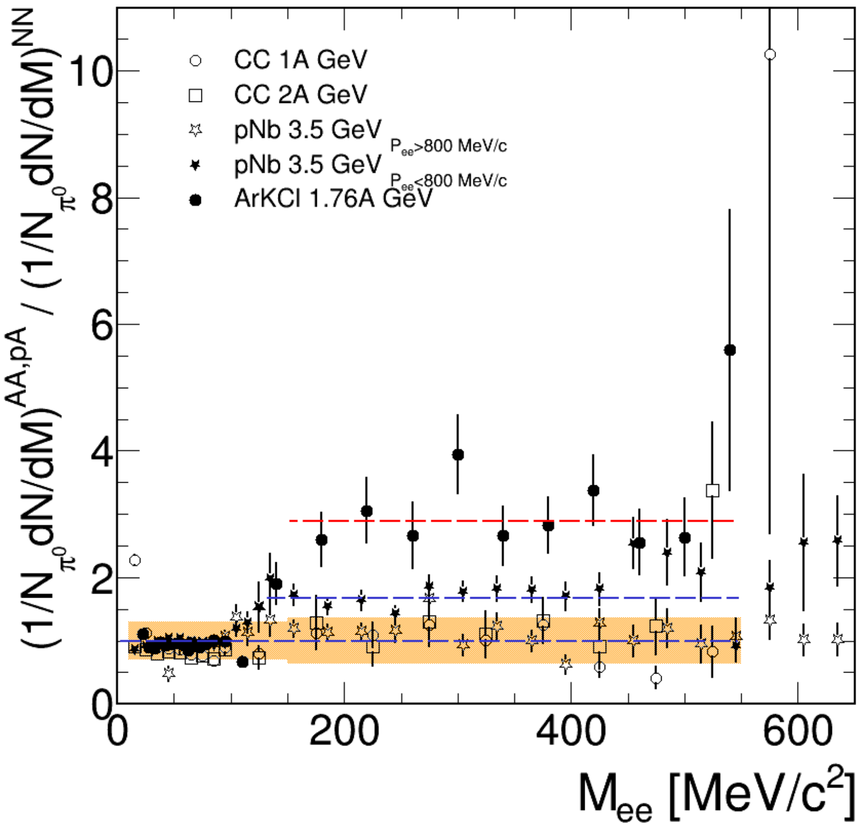
- Much stronger excess in Ar+KCl



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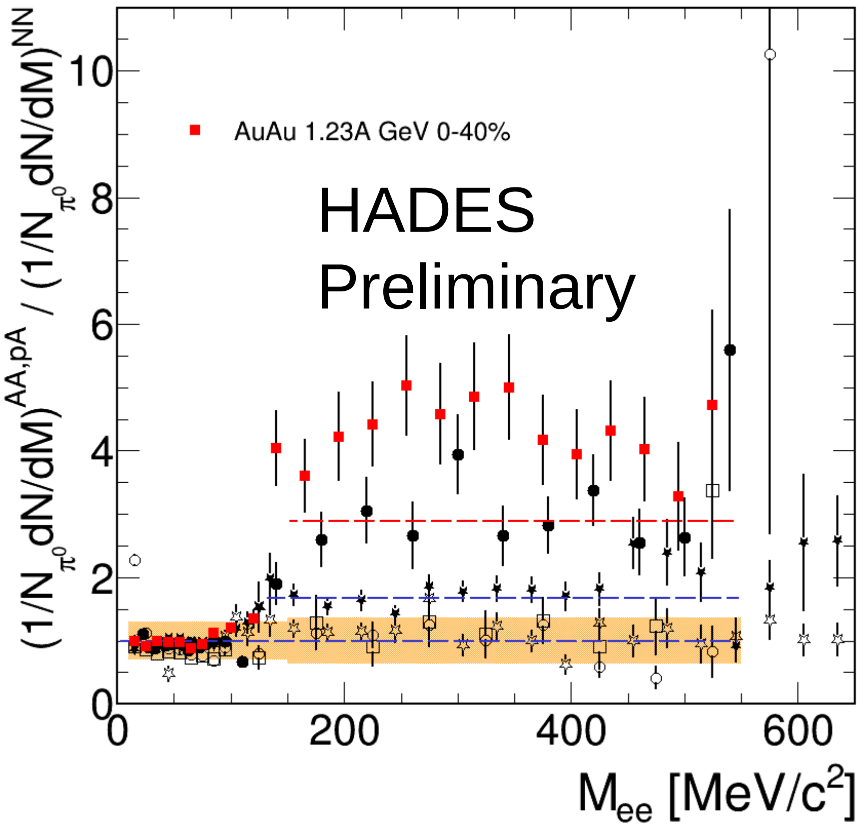
- Even stronger excess in Au+Au



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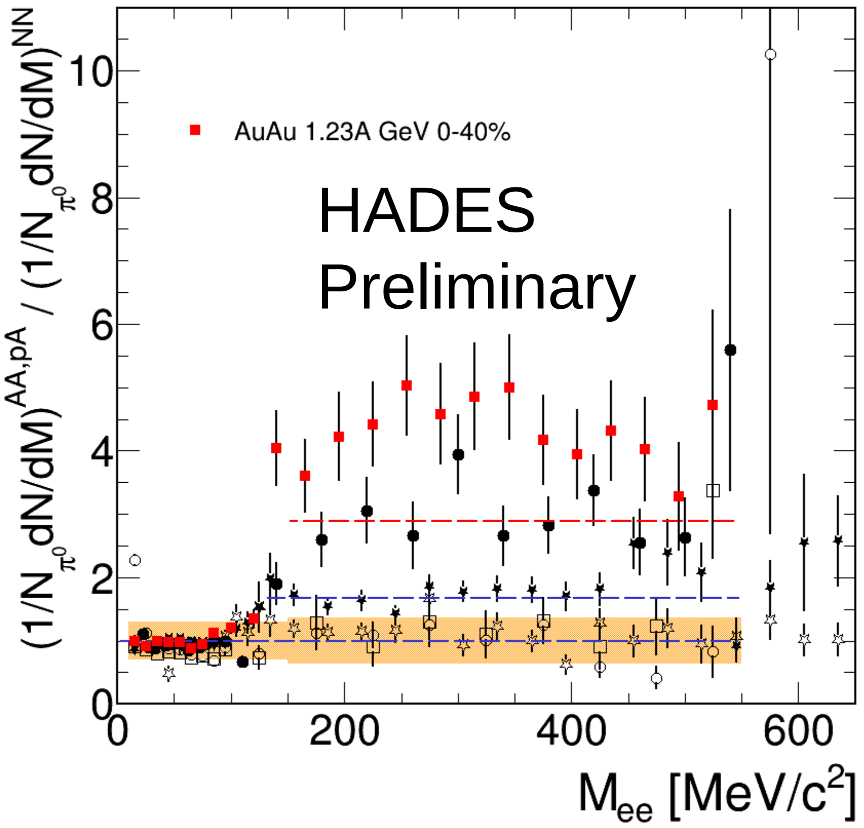
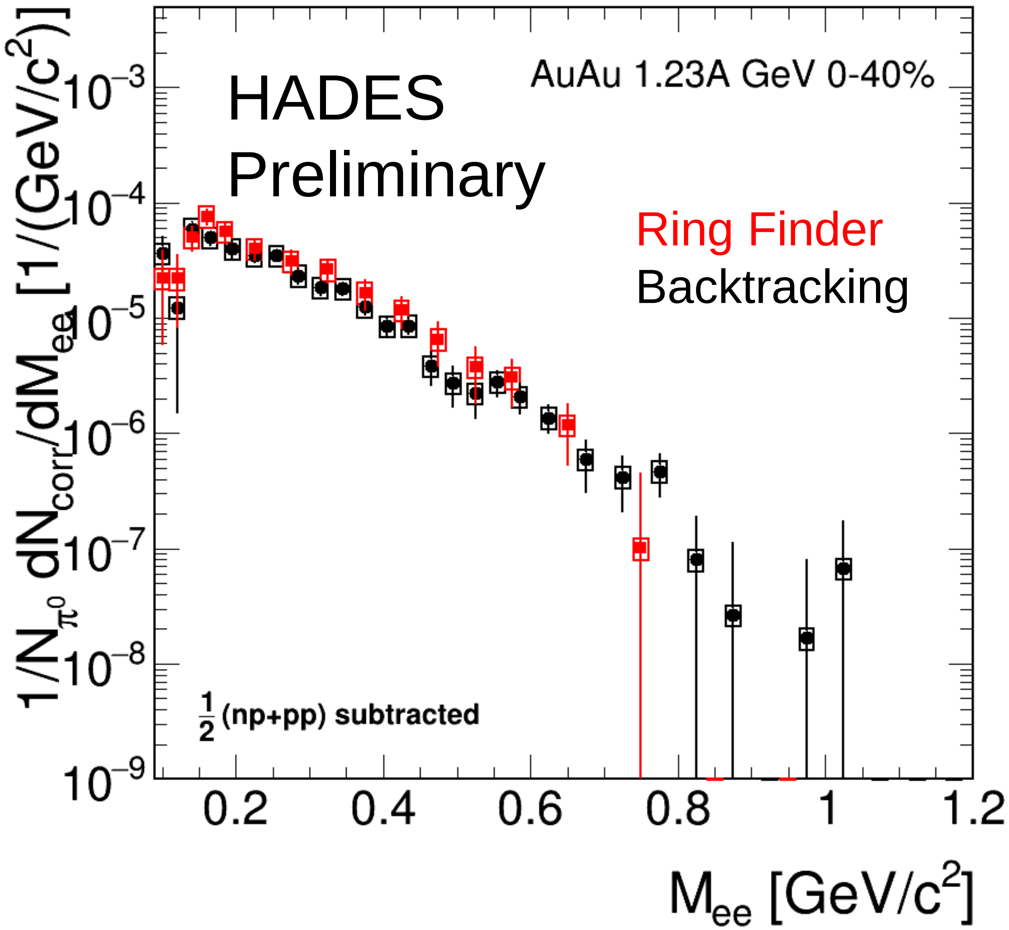
- On the other hand, enhancement is visible in p+Nb (for slow dileptons)
- Much stronger excess in Ar+KCl
- Even stronger excess in Au+Au
- Question of "medium" is about the effects beyond simple superposition of NN collisions

  → Regeneration of baryonic resonances



Subtracting the Reference

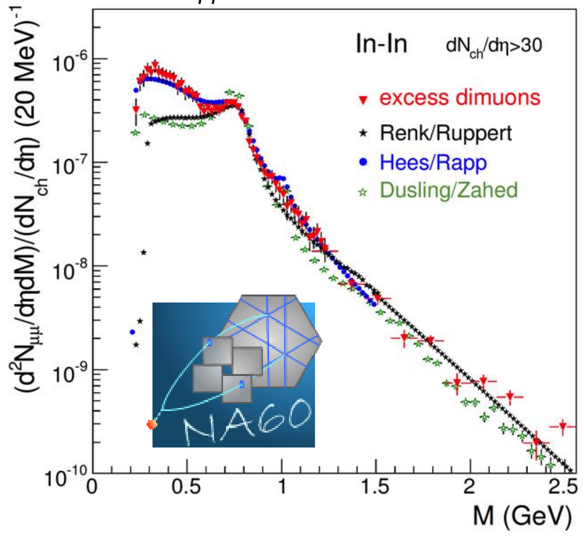


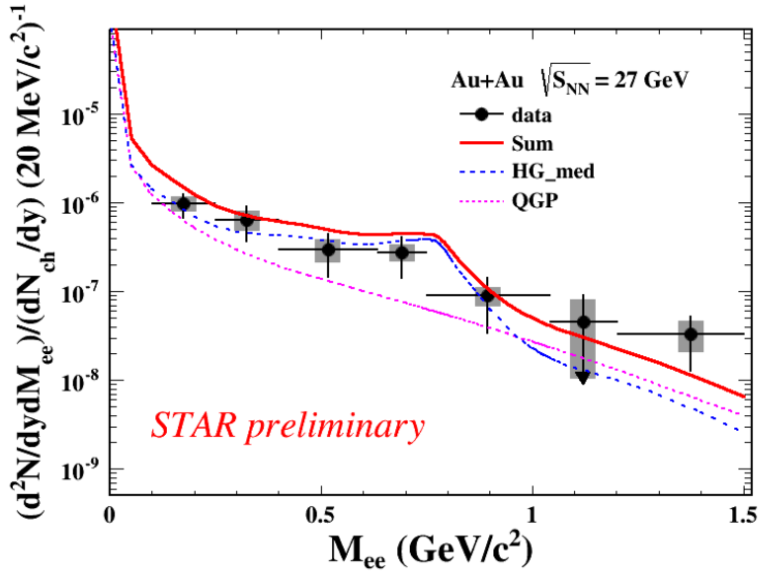
- Isolation of the excess by subtracting the experimentally measured reference
- How to describe the excess radiation theoretically?

Low-mass e^+e^- Excitation Function

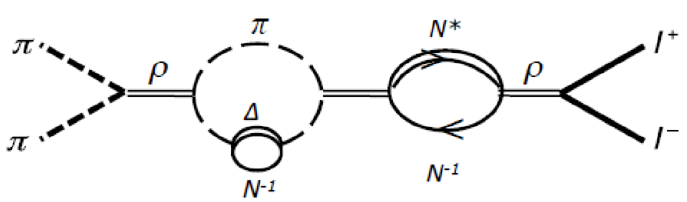
$\sqrt{s_{NN}} = 2.42, 17.3, 19.6\text{-}200$ GeV

NA60: H.J.Specht, AIP Conf.Proc. 1322 (2010)
Model: Rapp/Wambach/Hees



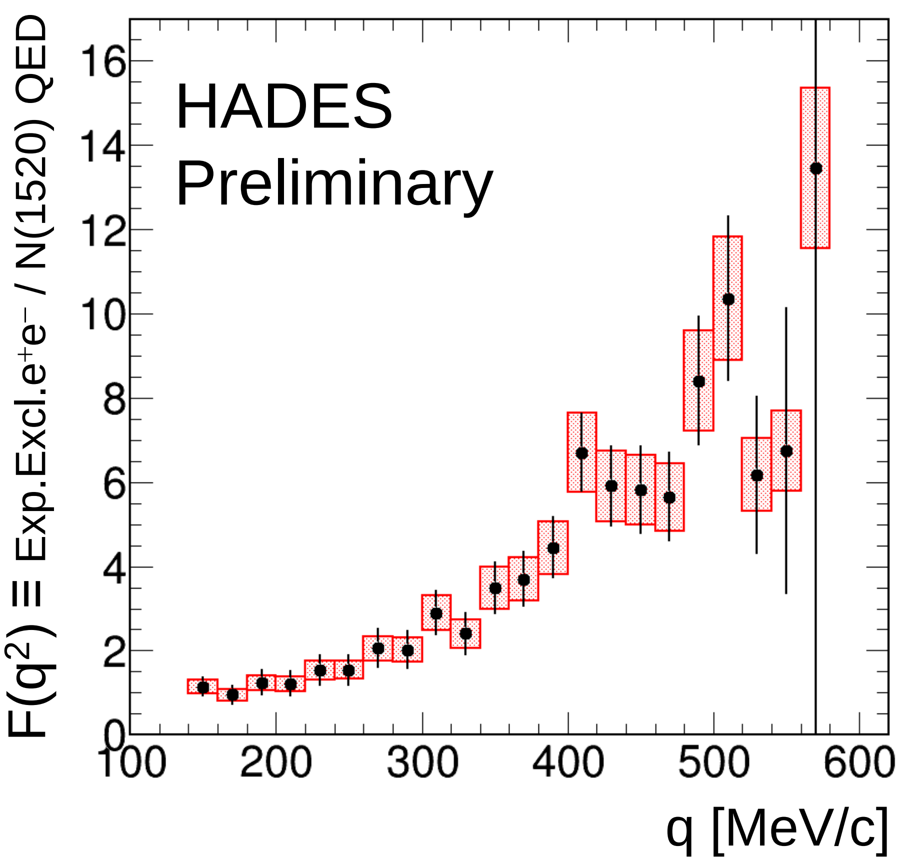


ρ - Δ/N^* couplings play substantial role in ρ melting observed in UrHIC

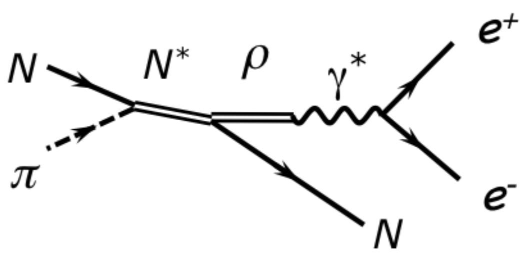


At low energies the same couplings govern off-shell ρ production by resonance decay
→ HADES Au+Au with ρ spectral function within the coarse graining framework

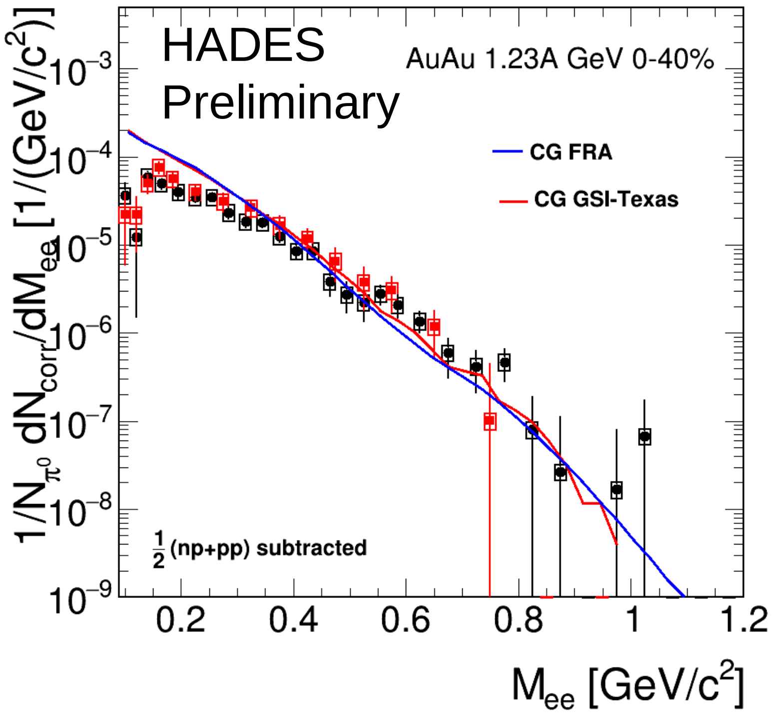
Vector Meson Dominance

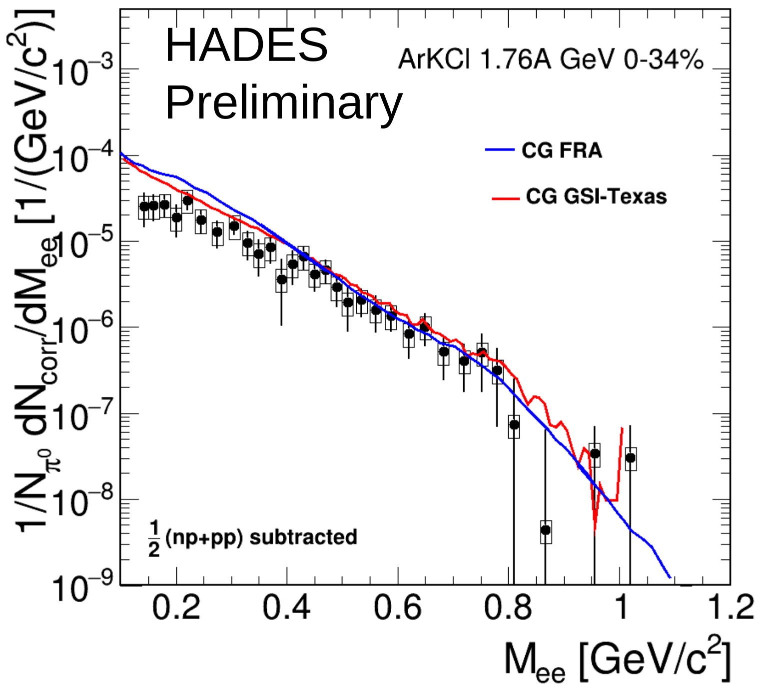


- Data measured by HADES in exclusive π^-p (secondary beam) reactions with $\sqrt{s} = 0.55$ GeV
- Strong deviation from unity show the time-like contribution to the resonance decay and confirm the validity of the VMD



Coarse Graining & Data



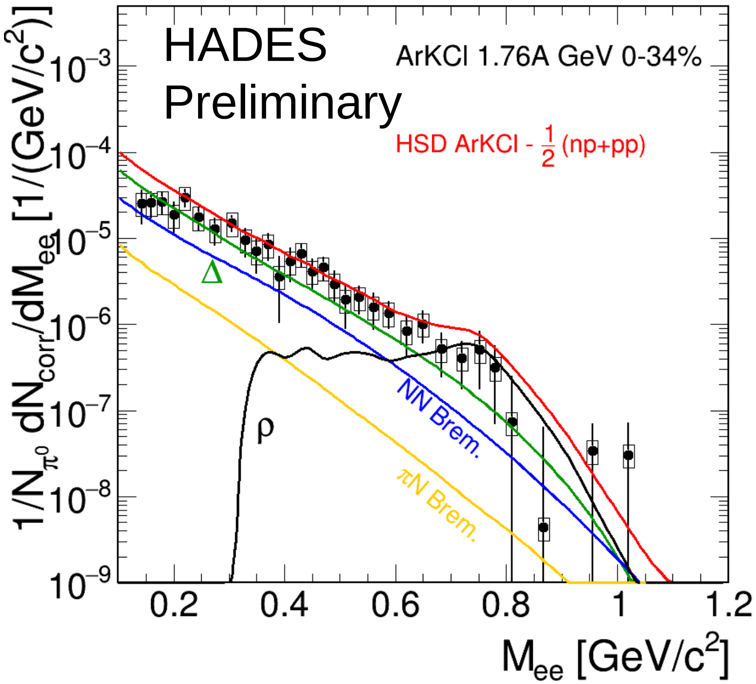


- Medium contribution calculated through ρ in-medium spectral function with thermodynamic parameters obtained from UrQMD ambient
- Both calculations are consistent and in good agreement with measured data

CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-TAMU: Eur. Phys. J. A, 52 5 (2016) 131

Comparison to Transport

- HSD analysed in the same way as data:
  - constrain reference
  - subtracted from Ar+KCl (component-by-component)
- Incoherent sum of NN and πN Bremsstrahlung, Δ, ρ

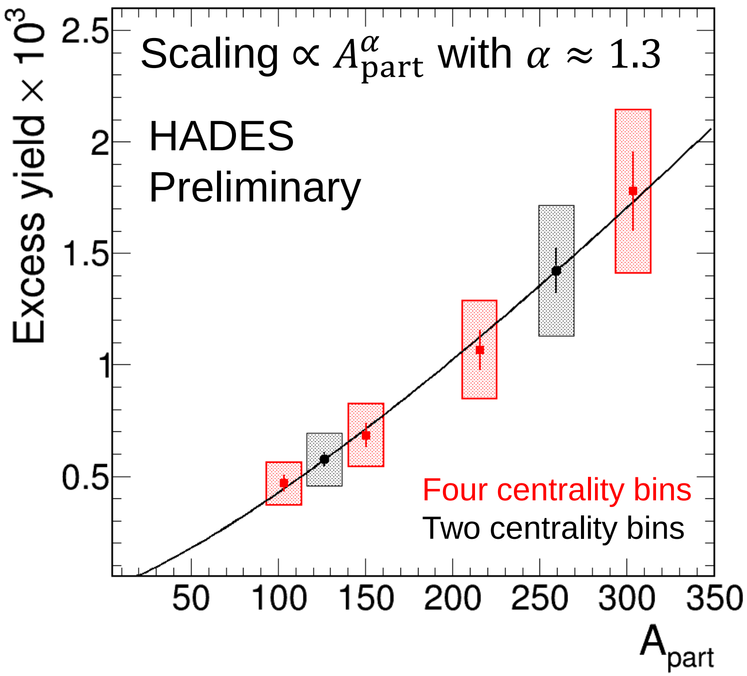


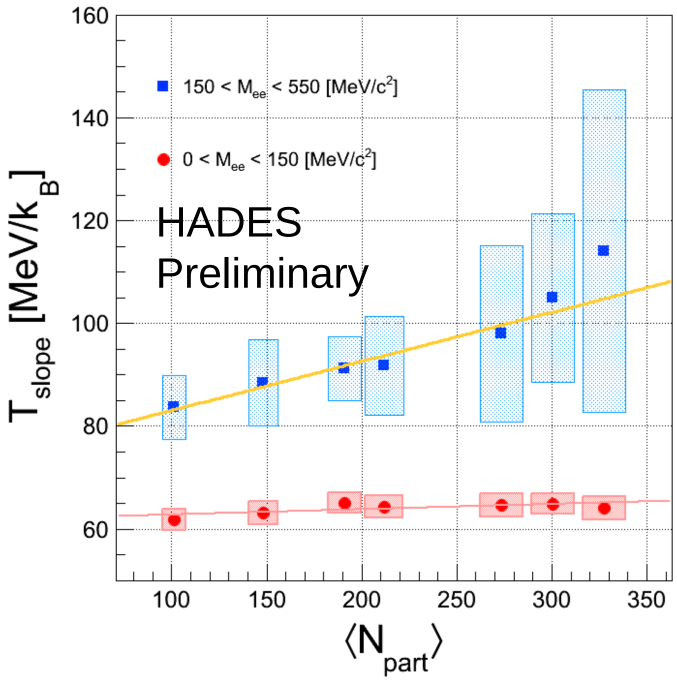
- Both approaches agree well with the data → go for multi-differential analysis

HSD: Phys. Rev. C 87, 064907 (2013)

Centrality dependence

$300 < M_{ee} < 700$ [MeV/c^2]





- Two observables indicate the formation of longer-lived and hotter medium in the most central collisions

Summary and Perspectives

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Conclusions

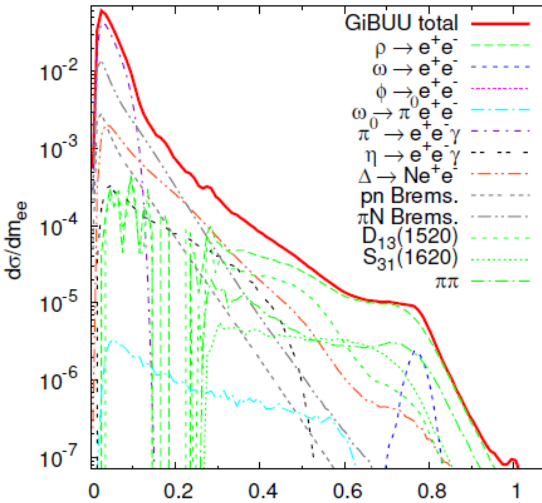
- HADES explores baryon rich matter at SIS 18
- Heavy-ion and elementary collisions are measured simultaneously
- Properly extracted dilepton excess yield agrees well with theory predictions

Coming soon from dilepton analysis

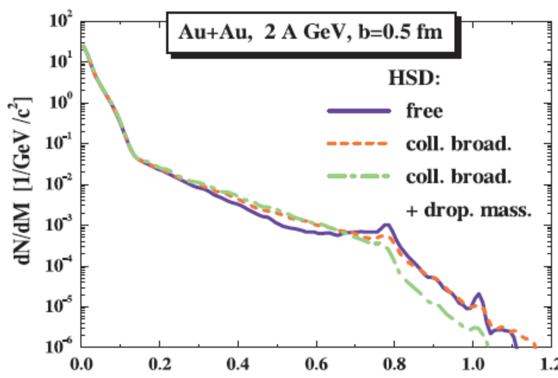
- Completion of the e^+e^- excitation function
- Extraction of a fireball lifetime
  → centrality dependence of the excess yield
- Extraction of an emitting source temperature?
  - Mass above 1 GeV/c^2 → statistics!
  - From mt spectra → when β is known

Outlook

- **Now:** HADES Upgrade
- **FAIR phase 0:** Ag+Ag at 1.65 GeV/u and pion induced reactions
- **FAIR phase 1:** SIS 100 → Ag+Ag at 3.5 GeV/u



[J. Weil, Fairness 2012]



[O. Linnyk et al. Progr.Part.Nucl.Phys. **87** (2016) 50-115]

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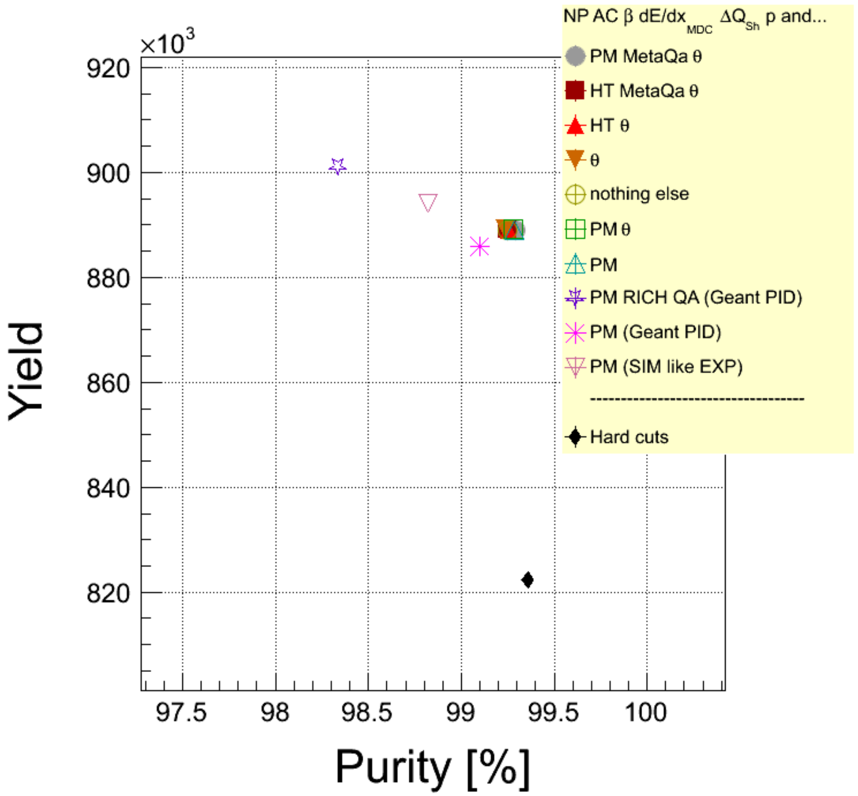
Thank You for Your Attention

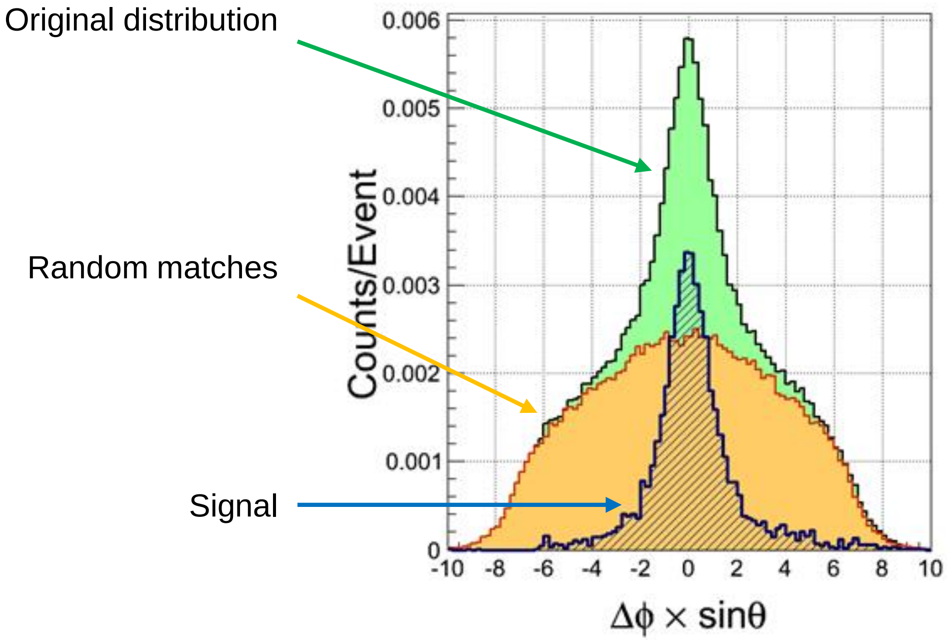
BACKUP SLIDES

Efficiency and Purity

Ring Finder Case



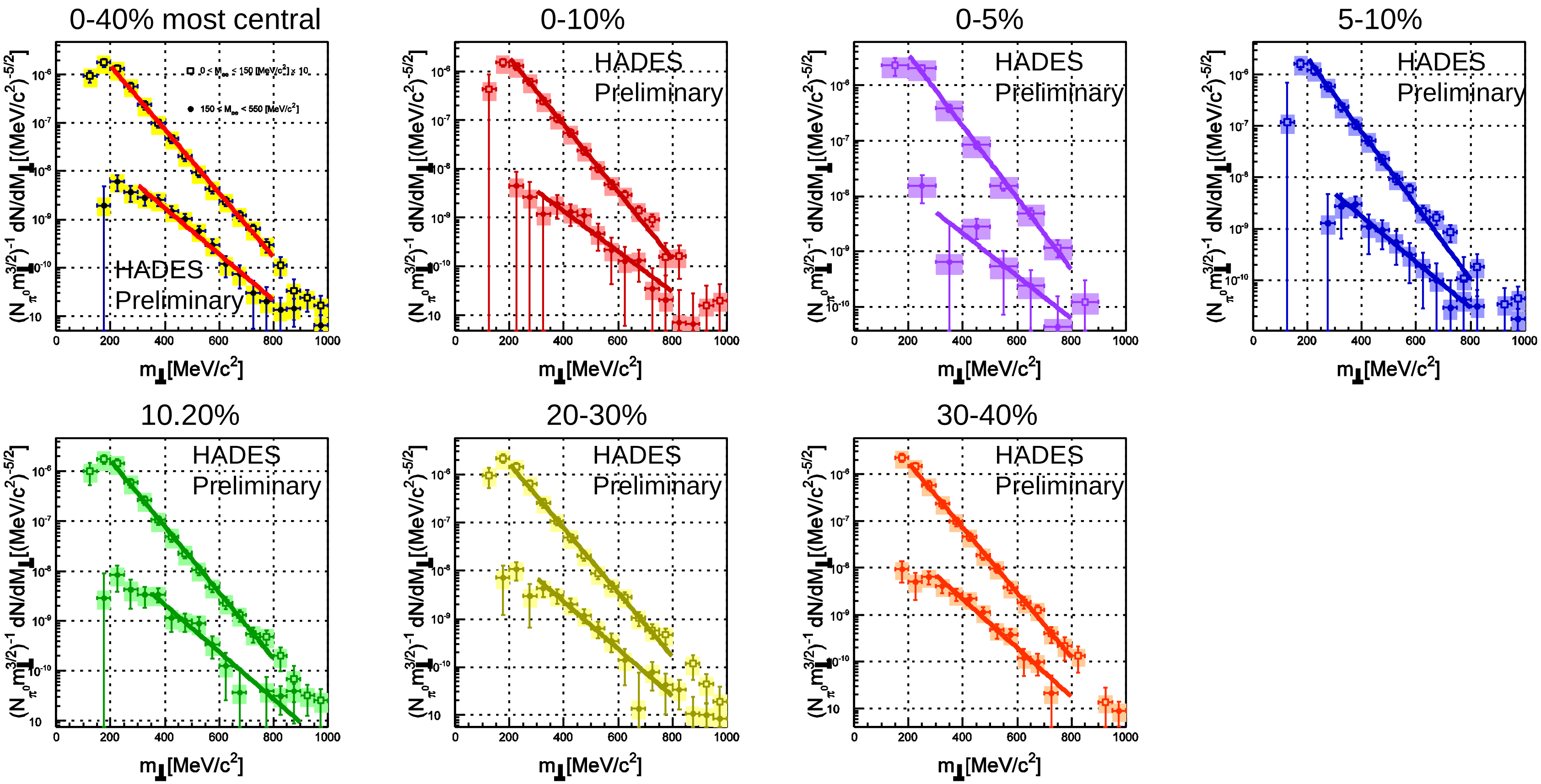
Purity is estimated based on measured data by reproducing random RICH ring-MDC track matches (matching tracks and rings from different HADES sectors)



- Efficiency of different methods can be confronted by comparing total yields of identified leptons
- Most points lie in the same place – this indicates the stability of the "training" procedure

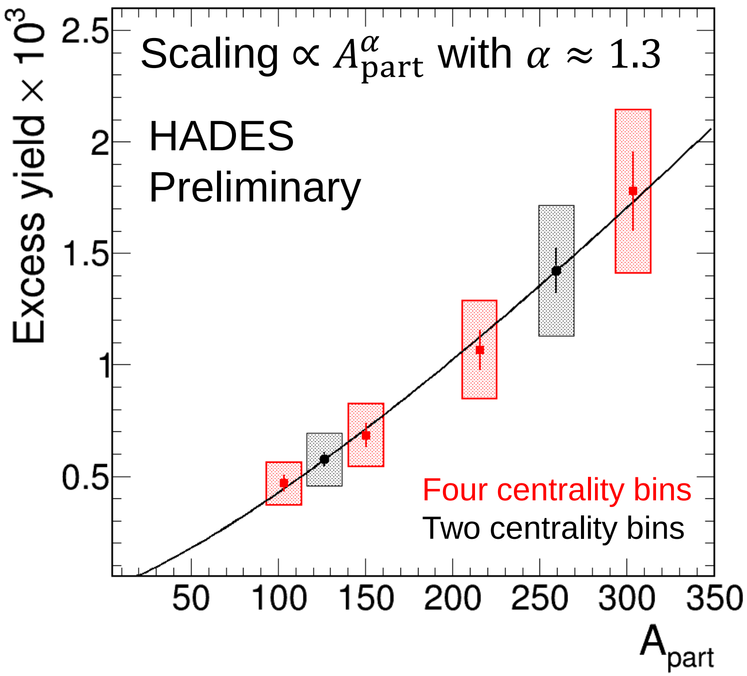
(for illustration of the method all pre-selected lepton candidates, without strict PID cuts, are shown)

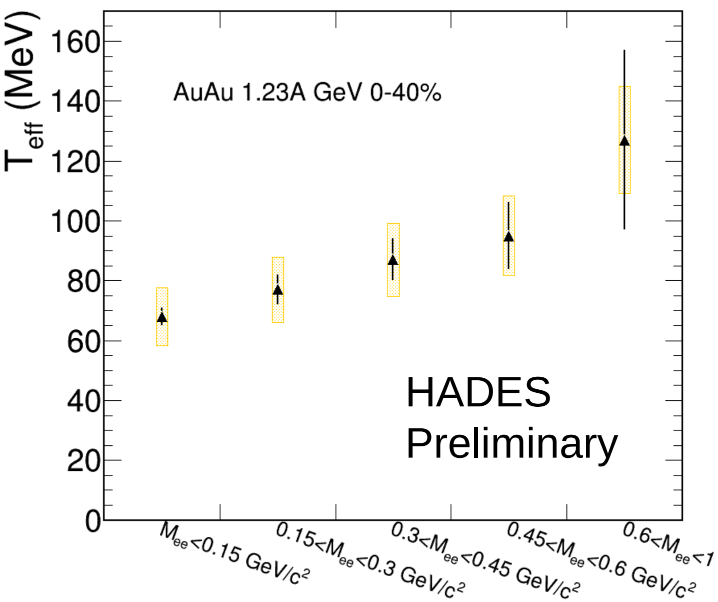
Multi-differential Analysis



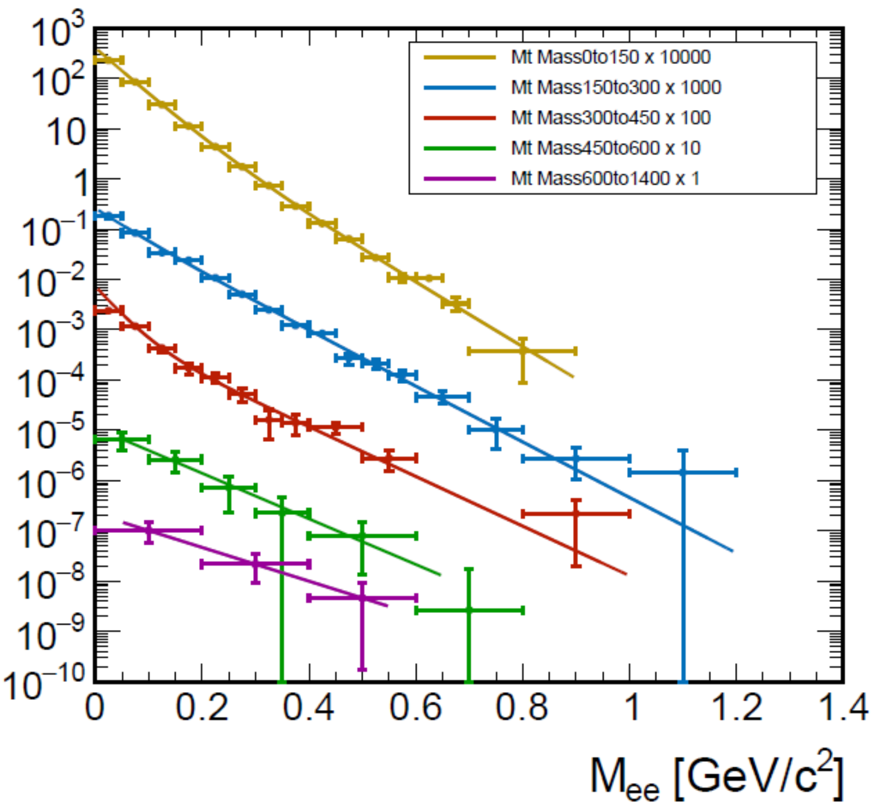
Centrality dependence

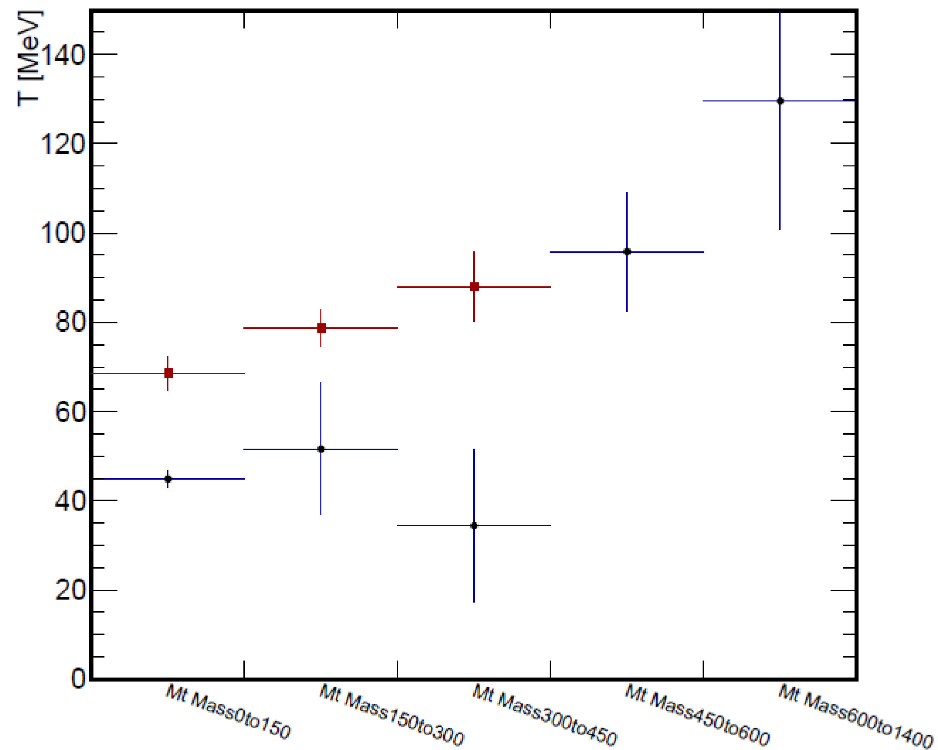
300 < M_{ee} < 700 [MeV/c^2]



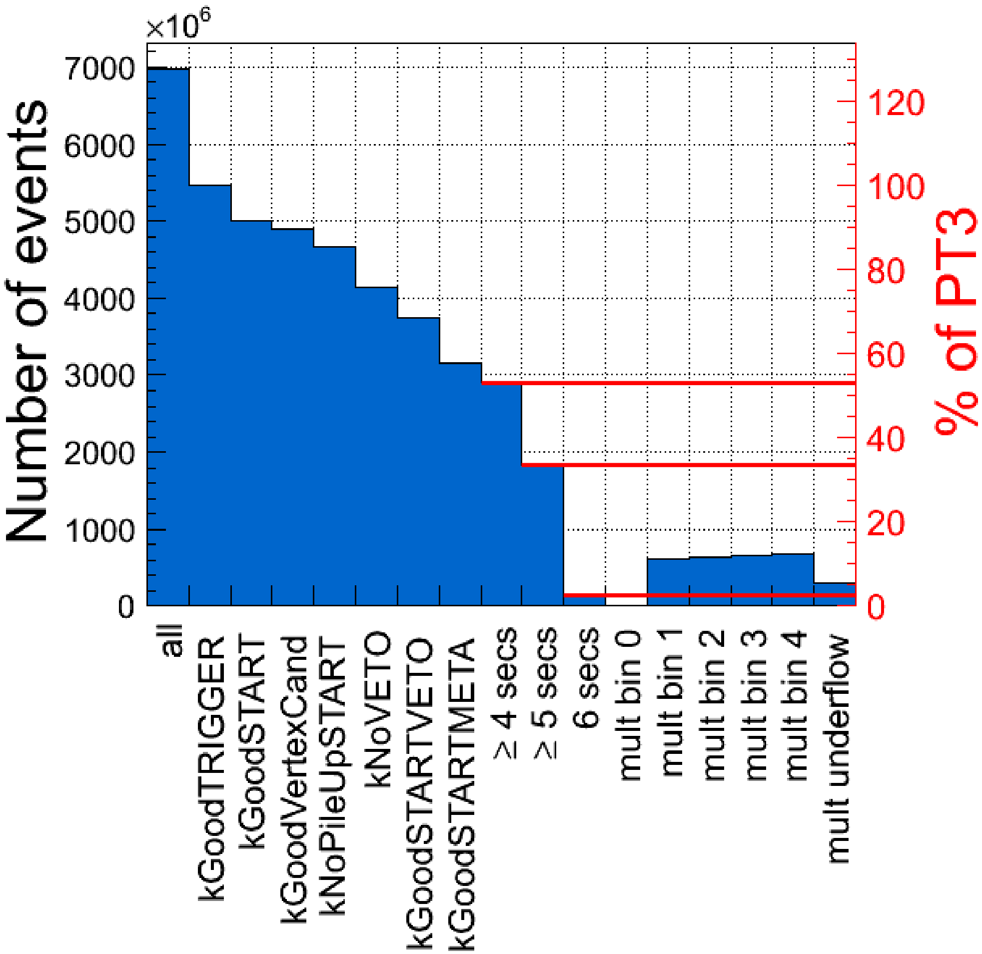


- Two observables indicate the formation of longer-lived and hotter medium in the most central collisions


Mt Mass0to150 x 10000
Mt Mass150to300 x 1000
Mt Mass300to450 x 100
Mt Mass450to600 x 10
Mt Mass600to1400 x 1
M_{ee} [GeV/c^2]


T [MeV]
Mt Mass0to150
Mt Mass150to300
Mt Mass300to450
Mt Mass450to600
Mt Mass600to1400

Event Selection



- DST **gen 8**
- New standard event flags
- File lists of good sectors
- Track selection and sorting also standard
- Lepton identification:
  - Neural networks trained on data with two sets of input variables
  - Neural network trained on SIM like on data
  - Neural network trained on Geant PID
  - Hard cuts
  - **All based on RICH ring finder, no usage of backtracking**

Bin	Centrality	$N_{\text{META hit, cut}}$ >	$N_{\text{META hit,cut}}$ ≤
0	Multiplicity overflow		
1	0-10 %	160	240
2	10-20 %	121	160
3	20-30 %	88	121
4	30-40 %	58	88
5	Multiplicity underflow		

Why We Need the k-Factor

[A. Adare et al. Phys. Rev. C **81** 034911]

1. Assume that **e^+e^- are always produced in pairs** (charge conservation)
2. The probability to register n_p out of N pairs is given by the **binomial distribution** $B(n_p,N,\varepsilon_p)$
3. **Out of the remaining pairs** there are three possibilities:
   a) No track is detected
   b) One e^+ is detected
   c) One e^- is detected
4. They are described by the **multinomial distribution** $\omega(n_+,n_-)=M(n_+,n_-;N-n_p;\varepsilon_+,\varepsilon_-)$

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5. Number of all like-sign combinatoins of reconstructed leptons is:

$$\langle n_{+-}\rangle = n_p^2 + n_p \sum_{n_+=1}^{N-n_p} n_+ \boxed{\omega(n_+)} + n_p \sum_{n_-=1}^{N-n_p} n_- \boxed{\omega(n_-)} + \sum_{n_+=1}^{N-n_p} \sum_{n_-=1}^{N-n_p} n_+ n_- \omega(n_+, n_-)$$

Sum from $\omega(n_+,n_-)$ over all possible n_-

Sum from $\omega(n_+,n_-)$ over all possible n_+

6. Similar formula is for unlike-sign pairs:

$$\langle n_{++}\rangle = \sum_{n_+=1}^{N-n_p} \frac{(n_p + n_+)(n_p + n_+ - 1)}{2} \omega(n_+)$$

7. To get the expected number of reconstructed pairs we average also over n_p:

$$\langle N_{+-}\rangle = \sum_{n_p} \langle n_{+-}\rangle B(n_p, N, \epsilon_p)$$

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8. Next, averaging over N producd pairs yields the foreground pairs:

$$\langle FG_{+-}\rangle = \sum_N \langle N_{+-}\rangle P(N) = [\epsilon_p+\epsilon_+(1-\epsilon_p)][\epsilon_p+\epsilon_-(1-\epsilon_p)](\langle N^2\rangle-\langle N\rangle)+\epsilon_p\langle N\rangle = \langle BG_{+-}\rangle+\langle S\rangle$$

Some boring algebra

9. And similarly for ulike-sign…

$$\langle FG_{++}\rangle = \sum_N \langle N_{++}\rangle P(N) = \frac{1}{2}[\epsilon_p + \epsilon_+(1-\epsilon_p)]^2(\langle N^2\rangle - \langle N\rangle) = \langle BG_{++}\rangle$$

$$\langle FG_{--}\rangle = \sum_N \langle N_{--}\rangle P(N) = \frac{1}{2}[\epsilon_p + \epsilon_-(1-\epsilon_p)]^2(\langle N^2\rangle - \langle N\rangle) = \langle BG_{--}\rangle$$

10. And in the end the paper says, that **when** $\boldsymbol{\varepsilon_{+-}=\varepsilon_{++}=\varepsilon_{--}=\varepsilon_p}$, then:

$$\langle BG_{+-}\rangle = 2\sqrt{\langle BG_{++}\rangle\langle BG_{--}\rangle} = 2\sqrt{\langle FG_{++}\rangle\langle FG_{--}\rangle}$$

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Well, but if efficiencies are different, we are left with some ugly thing:

$$\langle BG_{+-}\rangle = \frac{[\epsilon_{+-} + \epsilon_{+}(1-\epsilon_{+-})][\epsilon_{+-} + \epsilon_{-}(1-\epsilon_{+-})]}{[\epsilon_{++} + \epsilon_{+}(1-\epsilon_{++})][\epsilon_{--} + \epsilon_{-}(1-\epsilon_{--})]} 2\sqrt{\langle FG_{++}\rangle\langle FG_{--}\rangle}$$

Fortunately, the same formula **stays valid in the event mixing**, with the exception, that there is no signal there, and the unlike-sign foreground = like-sign background.

So, we can juggle and replace the factor with epsilons by:

(lower-case denotes the spectra from event mixing)

$$\langle BG_{+-}\rangle = \frac{\langle fg_{+-}\rangle}{2\sqrt{\langle fg_{++}\rangle\langle fg_{--}\rangle}} 2\sqrt{\langle FG_{++}\rangle\langle FG_{--}\rangle} \equiv k 2\sqrt{\langle FG_{++}\rangle\langle FG_{--}\rangle}$$

Take home: k-factor from event mixing is well-founded mathematically and necessary unless you are getting it =1

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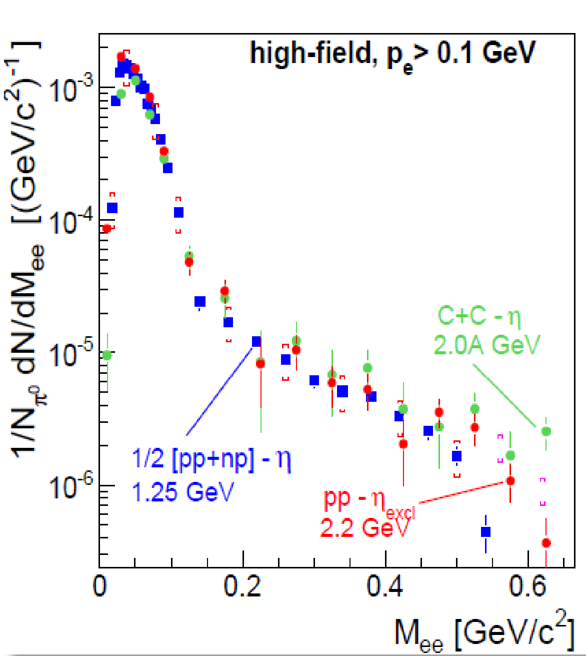
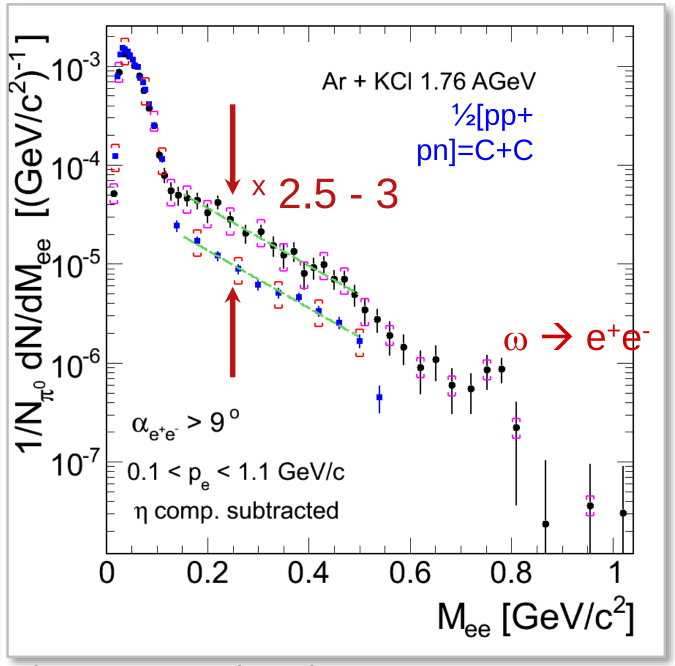
Low-mass Dileptons at 1 – 2A GeV

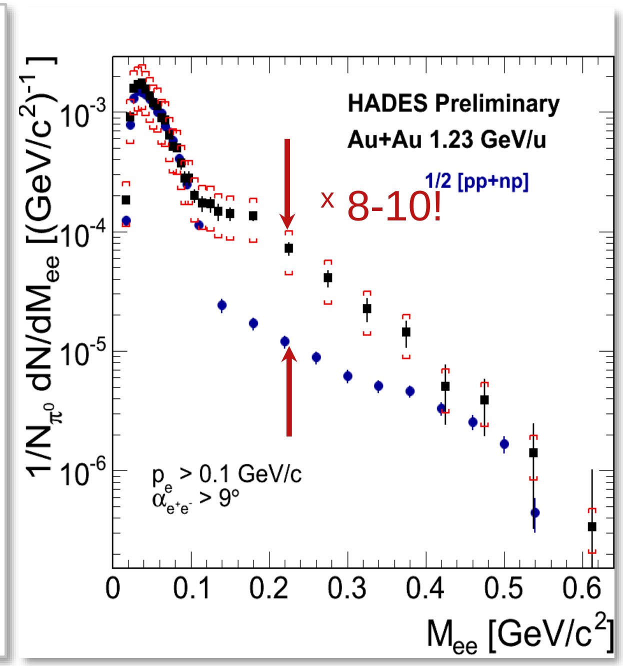
HADES "Resonance clock"



Phys.Lett. B 690 (2010) 118



Phys.Rev.C 84 (2011) 014902



S. Harabasz, P. Sellheim (PhD)

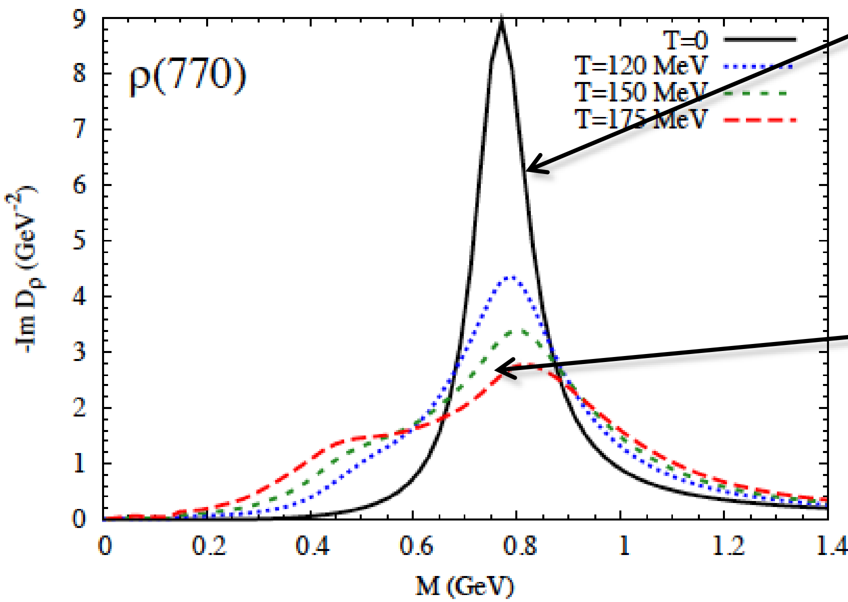
- C+C: After η subtraction, coincides with (pp+np)
- Ar+KCl: First evidence for radiation from the "medium" in this energy regime!
- Rapid increase of relative yield reflects the number of Δ's/ N*'s regenerated in fireball

Observables: light vector mesons

Vector Meson Dominance

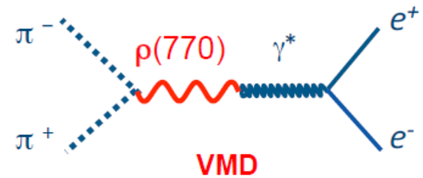
In low mass region (M_{ll} < 1.1 GeV):

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

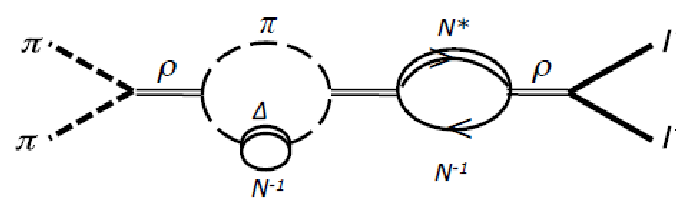


Vacuum

Both ρ and γ* have $J^P=1^-$



Medium



ππ interactions and baryonic excitations

Additional contributions to self-energy of the ρ meson:

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