Multi-differential analysis of dileptons in $\sqrt{s_{\mathrm{NN}}} = 2.4$ GeV Au+Au collisions

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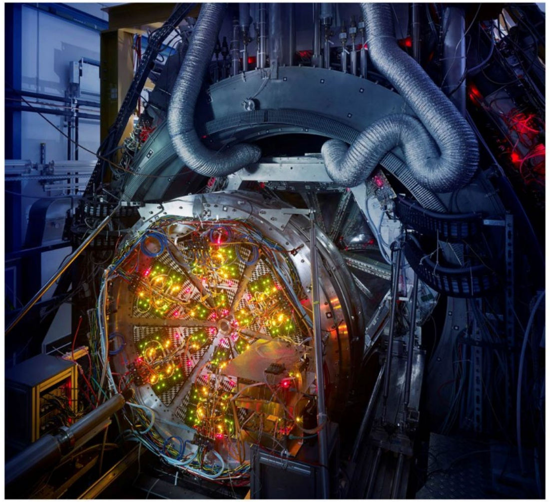
Szymon Harabasz for the HADES Collaboration



Introduction

Data Analysis

Differential Spectra

Summary

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INTRODUCTION

Meet the HADES

(High Acceptance Di-Electron Spectrometer)

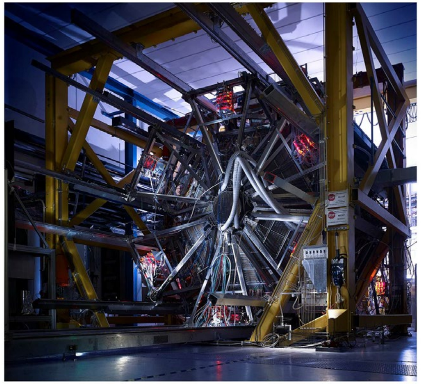
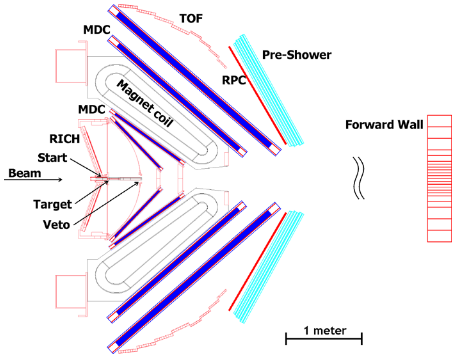
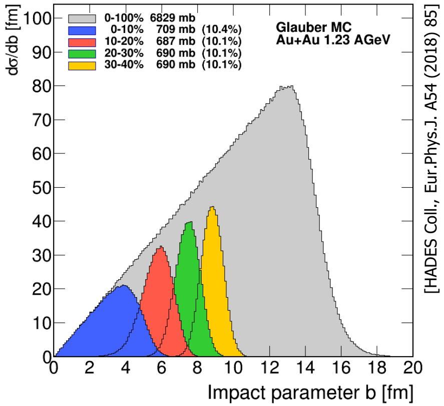


Photo: Jan Michael Hosan/HA Hessen Agentur GmbH





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 rare penetrating probes

- Di-lepton production suppressed by the factor α^2
- Vector meson production sub-threshold

- ✓ **Fast detector** → interaction rate: 8 kHz in AuAu, 200 kHz at SIS100
- ✓ **Large acceptance** → full azimuth, θ from 18° to 85°
- ✓ **Mass resolution** → of the order of few %
- ✓ **Good particle identification** → single $e^{+/-}$ purity > 98 %
- ✓ **Efficient track reconstruction**

Dilepton excess yield

QM 2017

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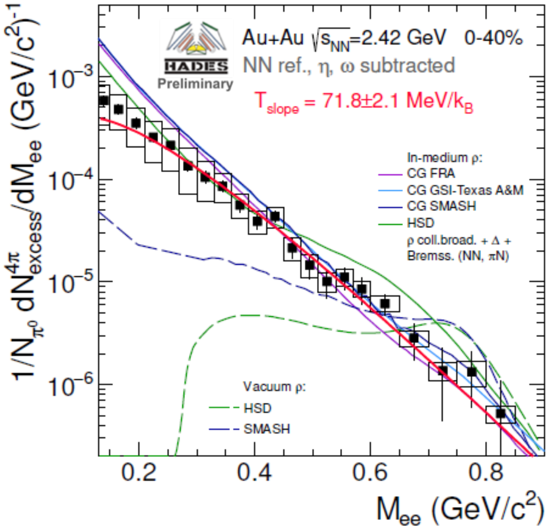
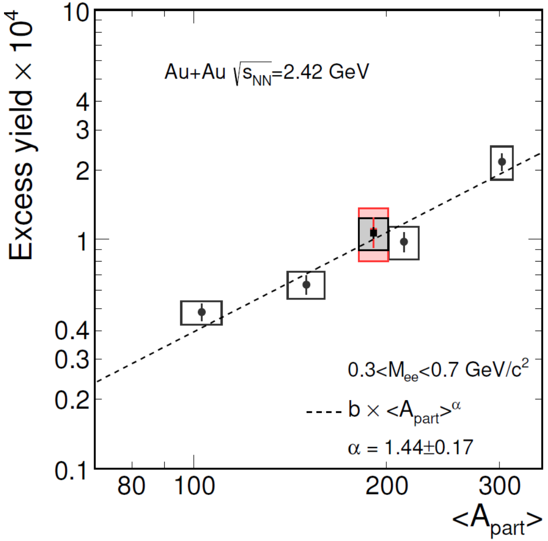




Coarse Graining (CG): ρ in-medium spectral function with thermodynamic parameters from transport

Medium radiation goes beyond incoherent superposition of NN collisions (like $A_{\rm part}^{4/3}$)

→ **Dilepton chronometer** of the collision time:

$$N_{\rm ee} \sim A_{\rm part} \cdot A_{\rm part}^{1/3} \sim V \cdot \boldsymbol{\tau}_{\bf fireball}$$

CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur. Phys. J. A, 52 5 (2016) 131
CG SMASH: arXiv:1711.10297 [nucl-th]
HSD: Phys. Rev. C 87, 064907 (2013)

DATA ANALYSIS

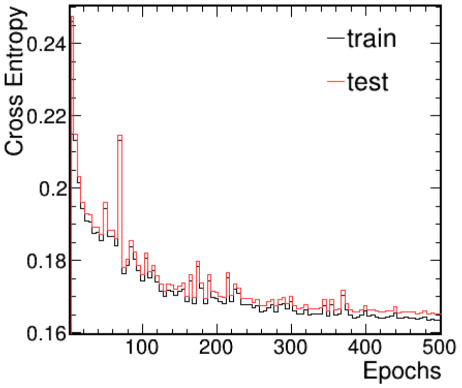
Electron Identification

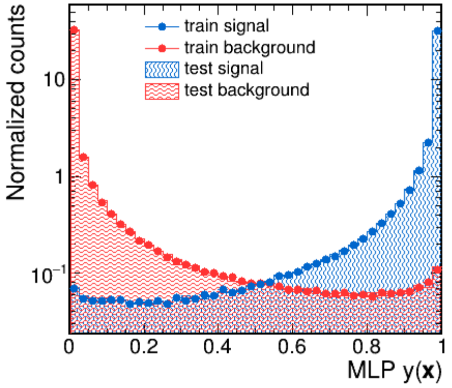
- Track quality selection
- Energy loss
- Particle velocity
- Electromagnetic shower

} 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 %

PID with multi-layer perceptron (MLP)

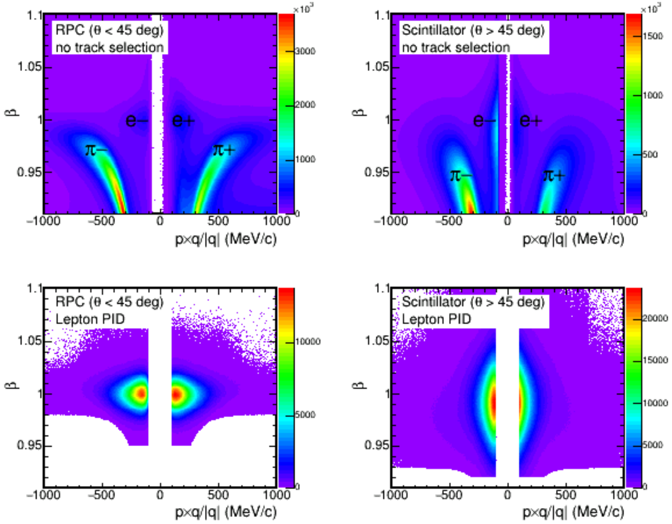




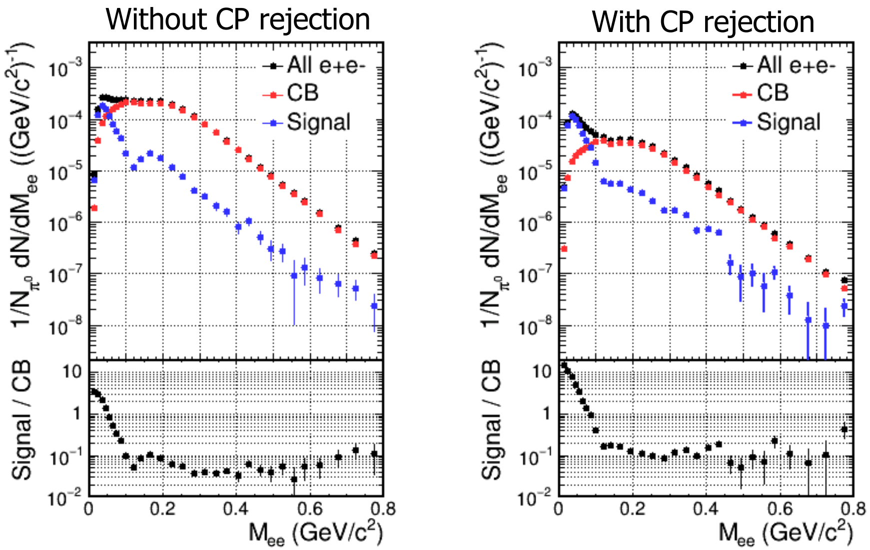
- Train and test do no split
  → No signal of overtraining
- Plateau reached
  → Sufficient number of training epochs

- Distributions drop rapidly
  → Good discrimination power
- Train and test overlap
  → Ability of the model to generalize for unseen data

Selection of Signal Leptons

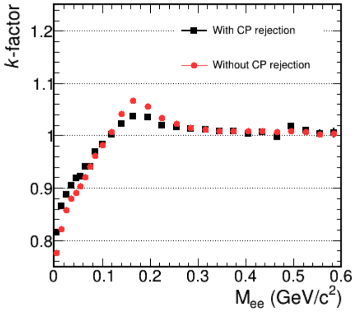


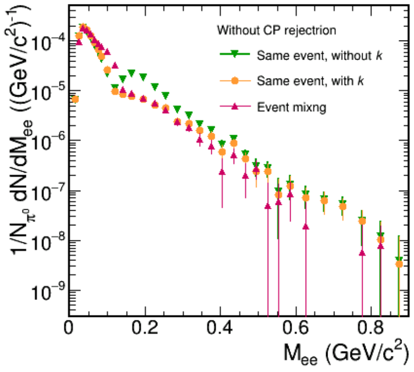
Close pair (CP) rejection: identify second lepton by loose cuts → find the nearest to the reference lepton → if opening angle smaller than given condition, remove reference lepton from the sample

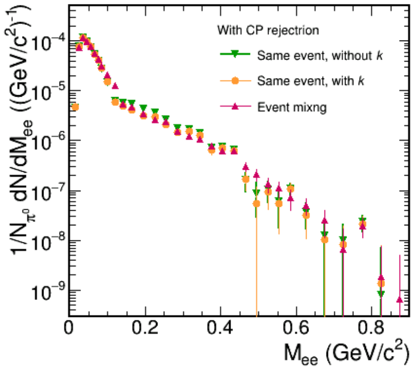


Combinatorial Background

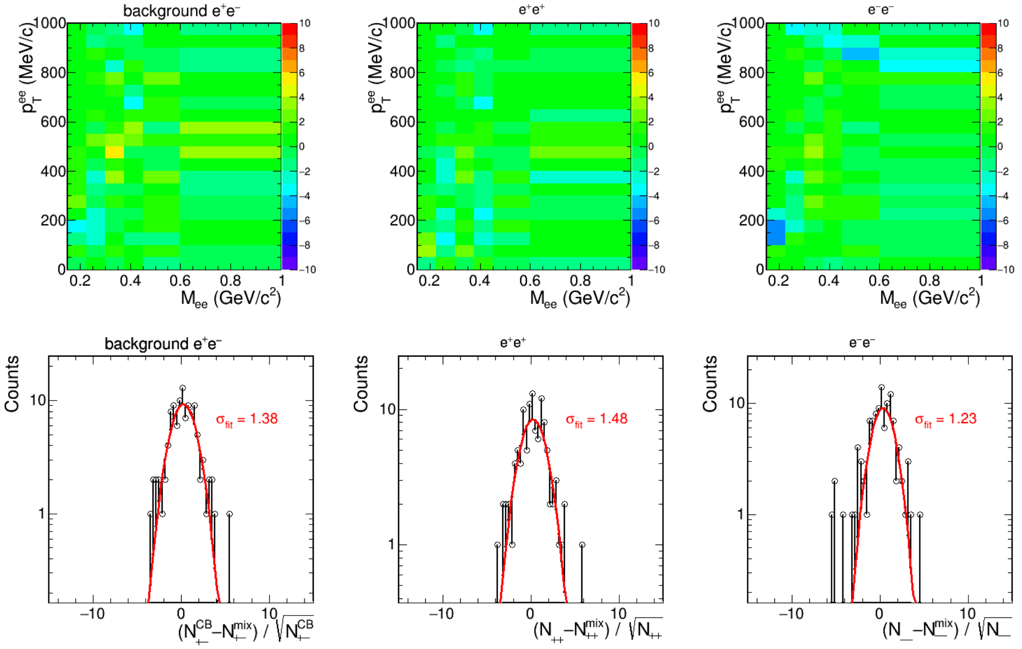
Correction for asymmetry in reconstruction of like and unlike sign pairs



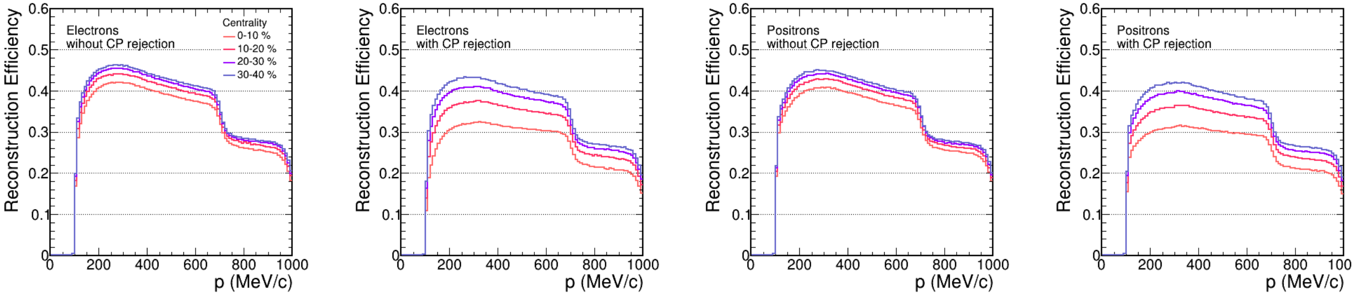




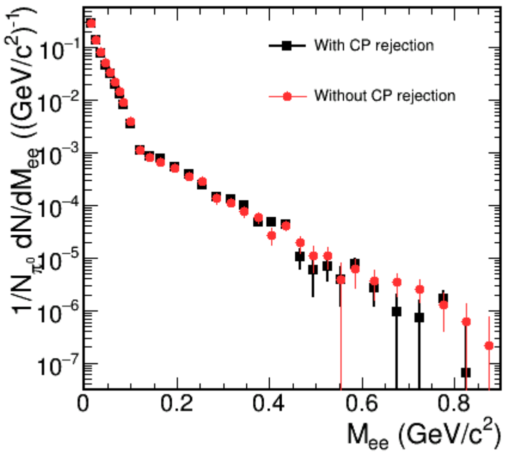
Same event like-sign to event mixing residuals



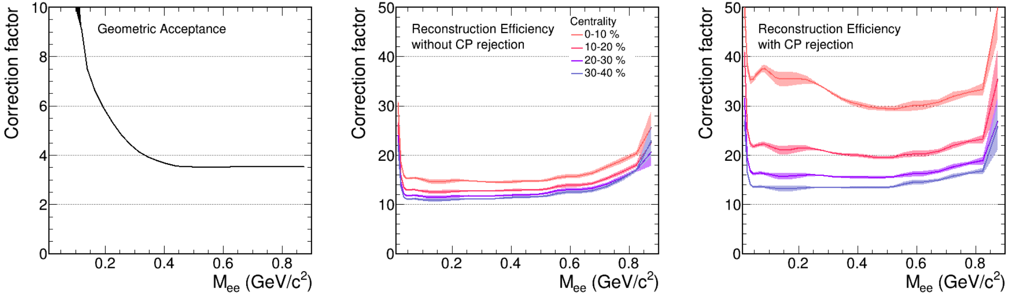
Efficiency and Acceptance Corrections



After corrections



- Translate to pair observables by MC cocktails
- Error bands: variance from different models



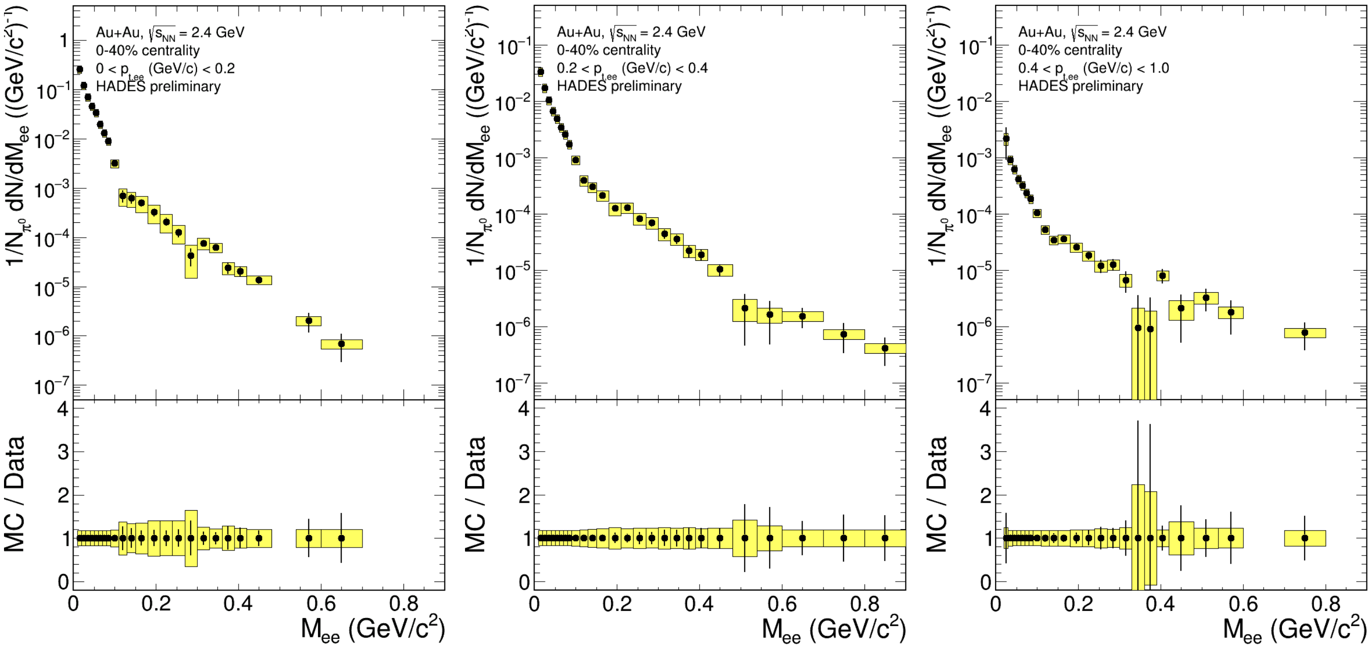
- Perfect agreement
- Final version: "with CP" used above 0.3 MeV/c2, below – mean of the two

DIFFERENTIAL SPECTRA

Invariant mass

p_t-dependent

$0 < p_{t,ee}$ (GeV/c) < 0.2 | $0.2 < p_{t,ee}$ (GeV/c) < 0.4 | $0.4 < p_{t,ee}$ (GeV/c) < 1.0



- Invariant mass spectra – not affected by the blue shift
- Less steep at higher p_t
- Similar observation as for IMR dimuons at SPS NA60
  [S. Damjanowic, Trento 2010]

Invariant mass

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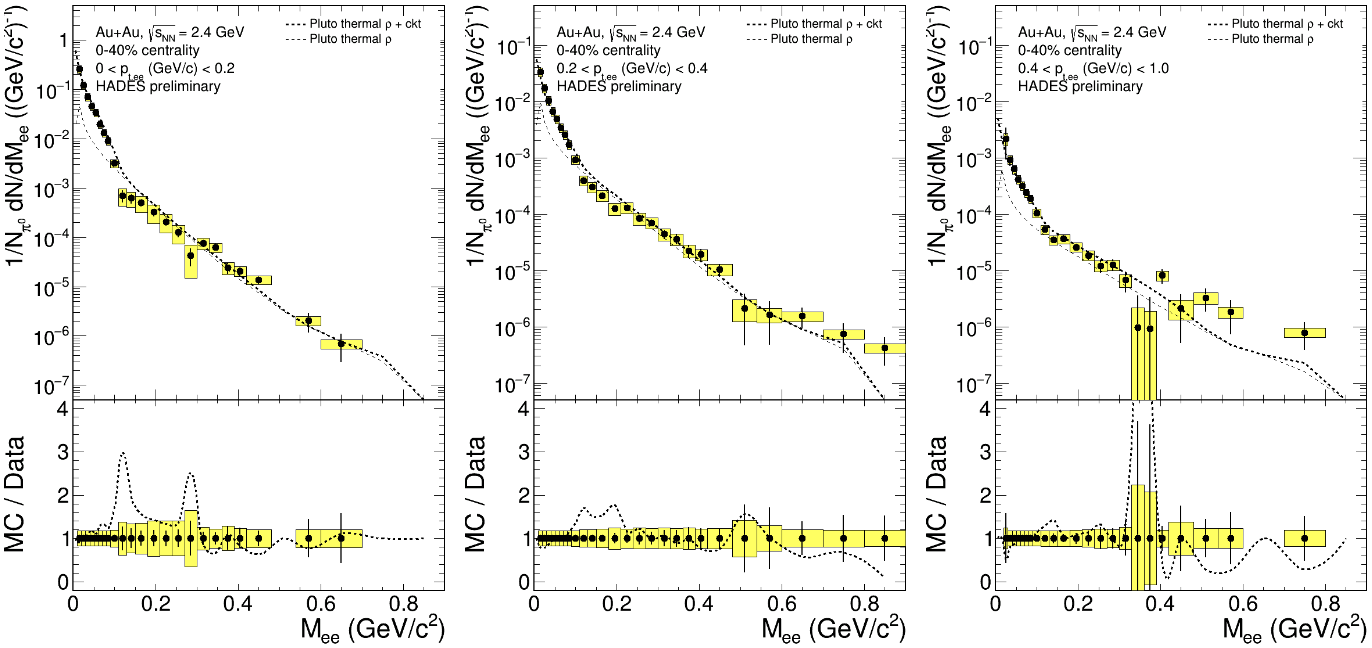

Cocktail:

- 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 m_t scaling

Pluto thermal ρ:

- Breit-Wigner + Boltzmann
- Weighted with $1/M^3$ factor (from VMD)
- No $2m_\pi$ cutoff

Invariant mass

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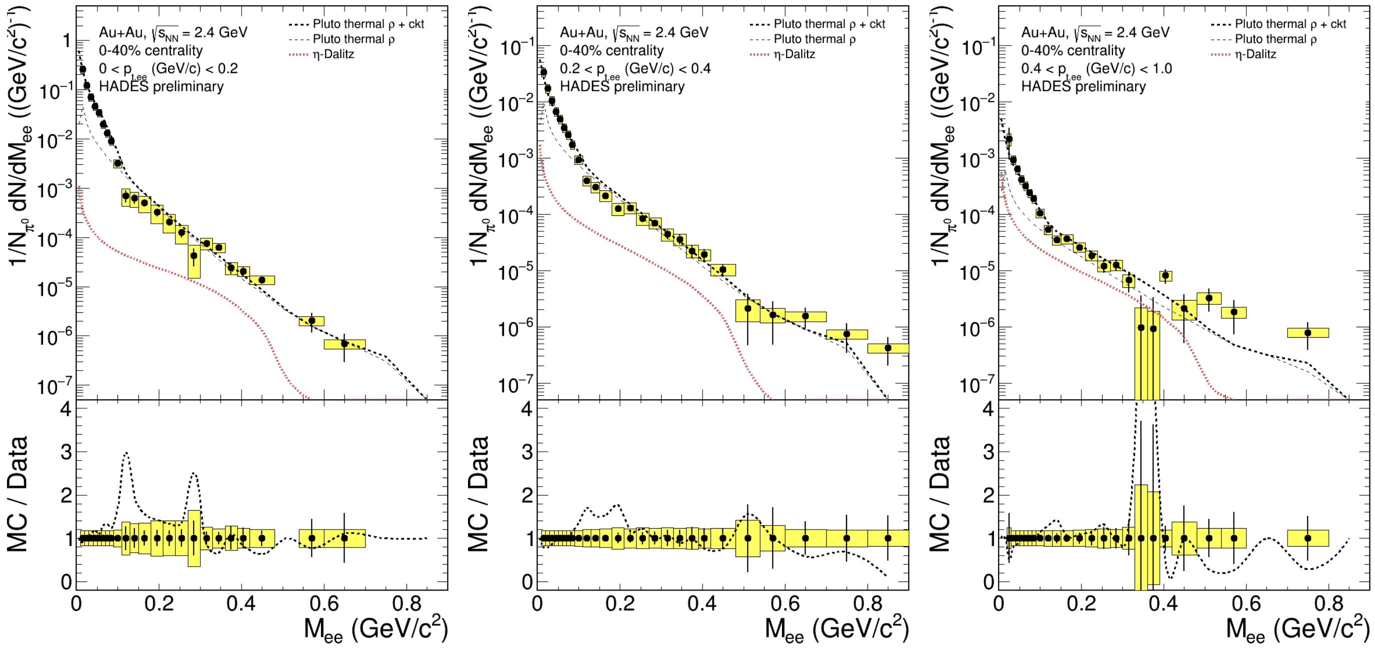
$0 < p_{t,ee}$ (GeV/c) < 0.2 $\quad$ $0.2 < p_{t,ee}$ (GeV/c) < 0.4 $\quad$ $0.4 < p_{t,ee}$ (GeV/c) < 1.0



Cocktail:

- π^0 from charged pions multiplicity, cross-checked with the conversion method
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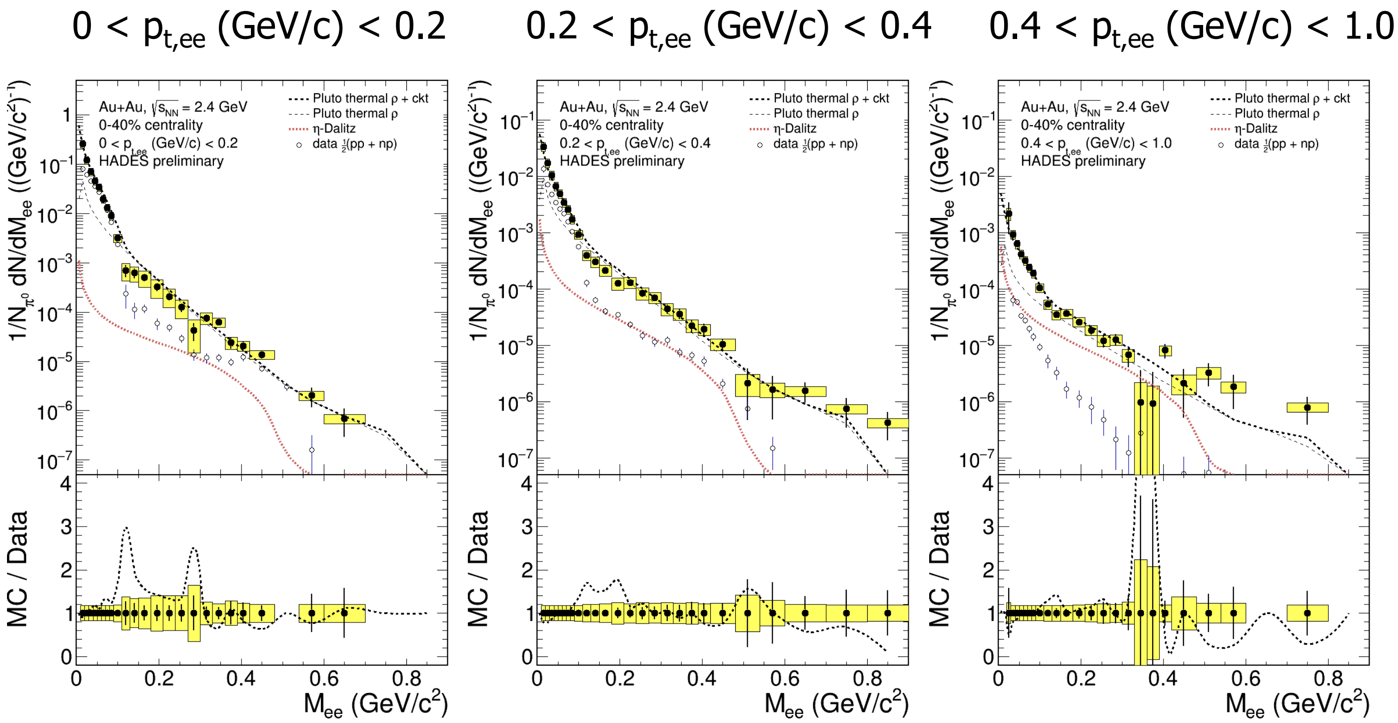
Invariant mass

p_t-dependent

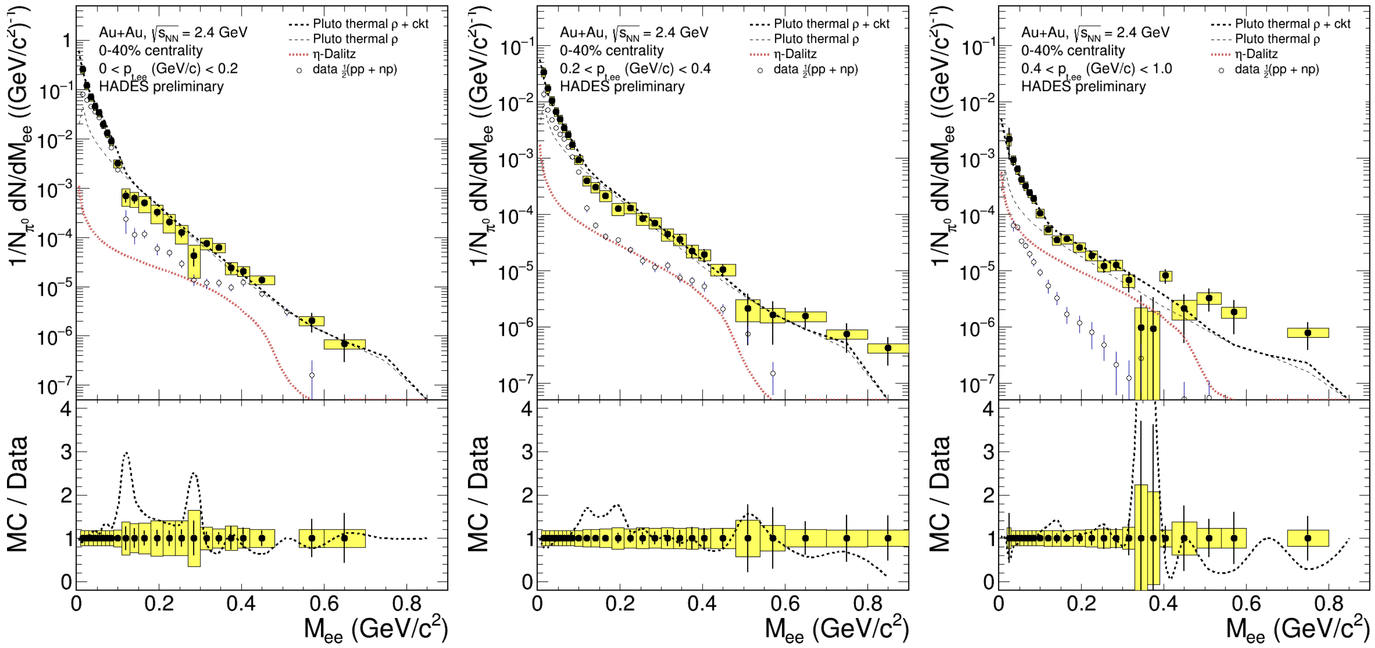


- $\frac{1}{2}$(pp + np) – dileptons from elementary collisions at the same energy as Au+Au
- Respective η contribution subtracted
- "Reference spectra"

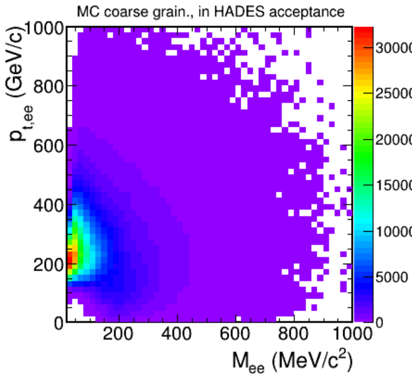
Invariant mass

p_t-dependent

$0 < p_{t,ee}$ (GeV/c) < 0.2 — $0.2 < p_{t,ee}$ (GeV/c) < 0.4 — $0.4 < p_{t,ee}$ (GeV/c) < 1.0

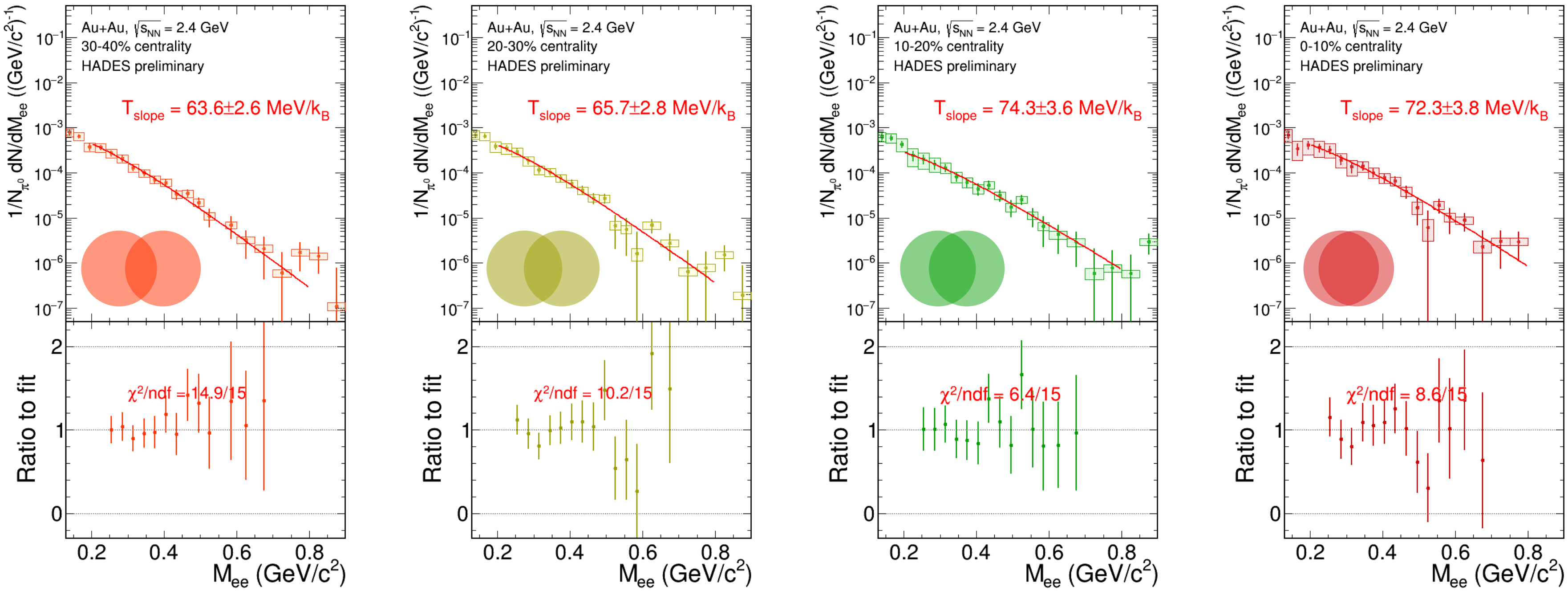


- Highest sensitivity to the excess below $M_{ee} \sim 500$ MeV/c^2 and $p_{t,ee} \sim 400$ MeV/c
- Crucial to cover this region with experimental acceptance



Fit to the invariant mass in centrality bins

Total e+e– yield



Hotter radiation source in more central collisions

Fit to the invariant mass in centrality bins

Total e+e– yield

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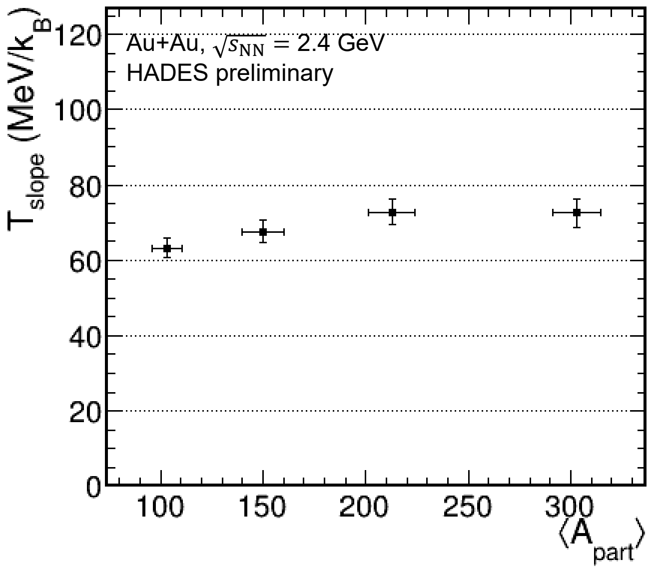
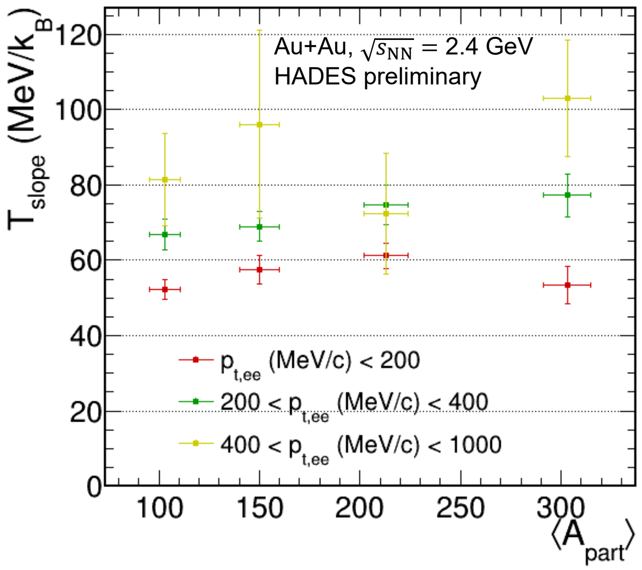
Integrated over p_t



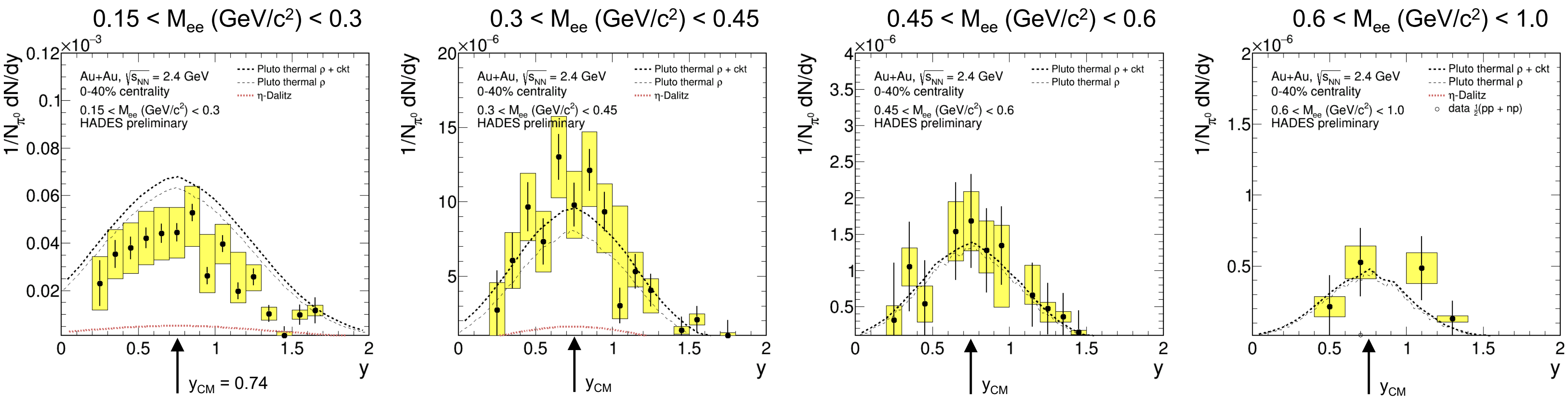
p_t-dependent



Hotter source of radiation at higher p_t

Rapidity distributions of dileptons

Total e+e– yield

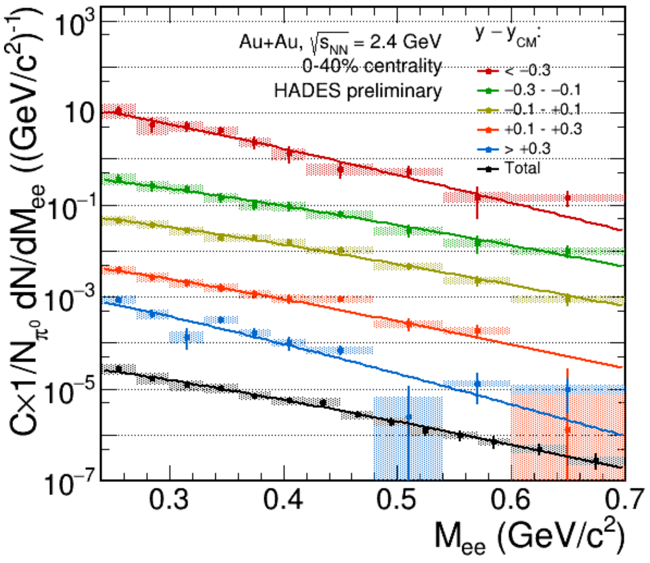


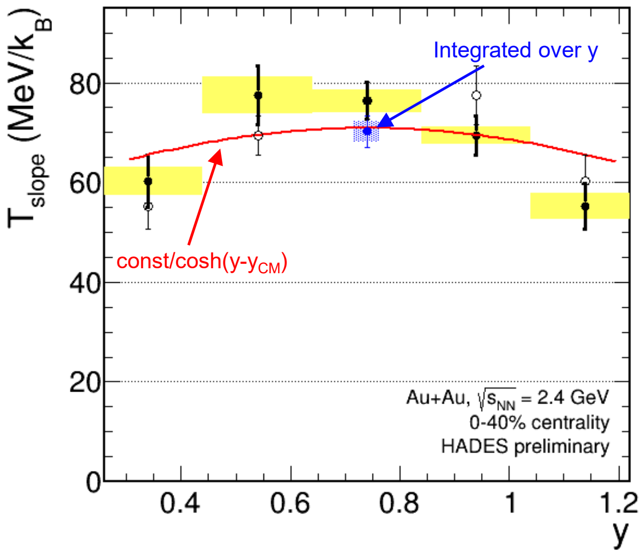
Most of dileptons inside the rapidity region, where HADES do have acceptance coverage

→ Validity of the thermal fits

Fit to invariant mass as a function of rapidity

Total e+e– yield

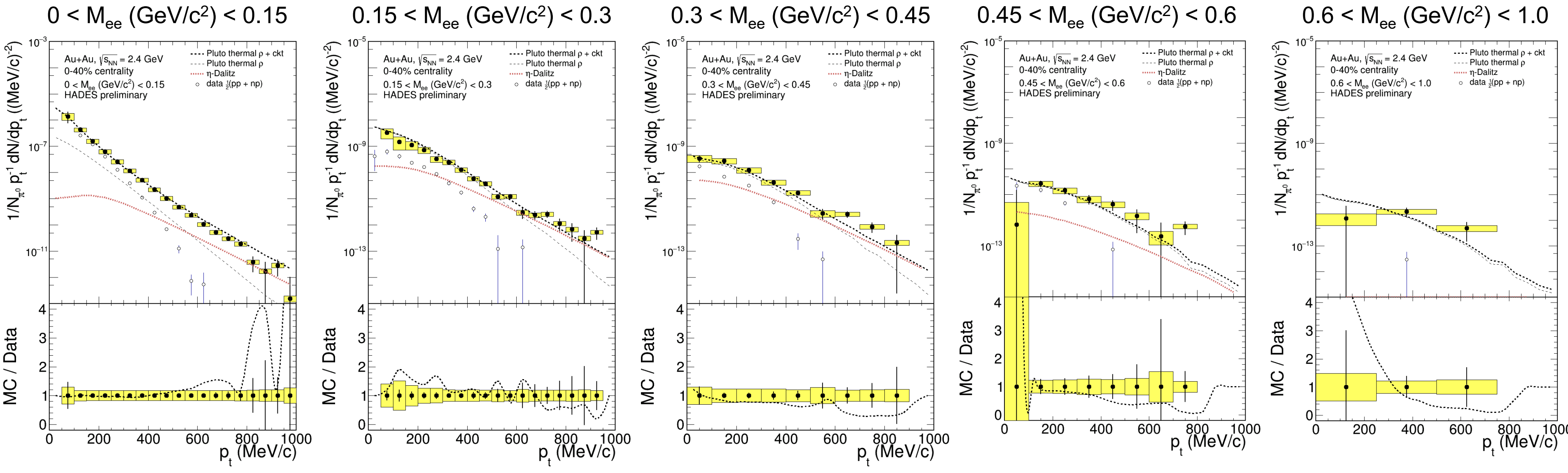




Consistent with thermal ansatz
$T_{slope} \propto 1/\cosh(y-y_{CM})$

Transverse momentum and model calculations

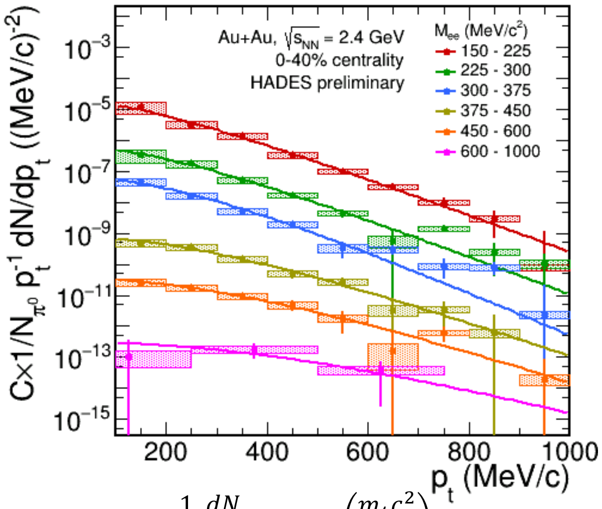
Total e+e– yield



Spectra consistent with the models

Transverse momentum with fits

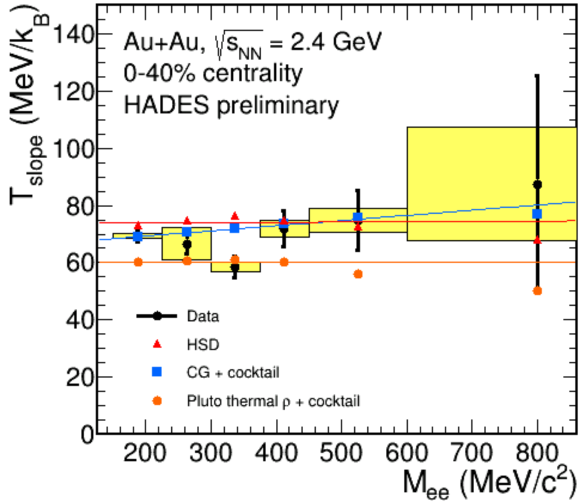
Total e+e– yield



$$\frac{1}{p_t}\frac{dN}{dp_t} \propto m_t K_1\left(\frac{m_t c^2}{k_B T}\right)$$

Assumes pure Boltzmann nature of the source:

$$\frac{d^3N}{d\vec{p}} \propto \exp\left(-\frac{E}{k_B T}\right)$$

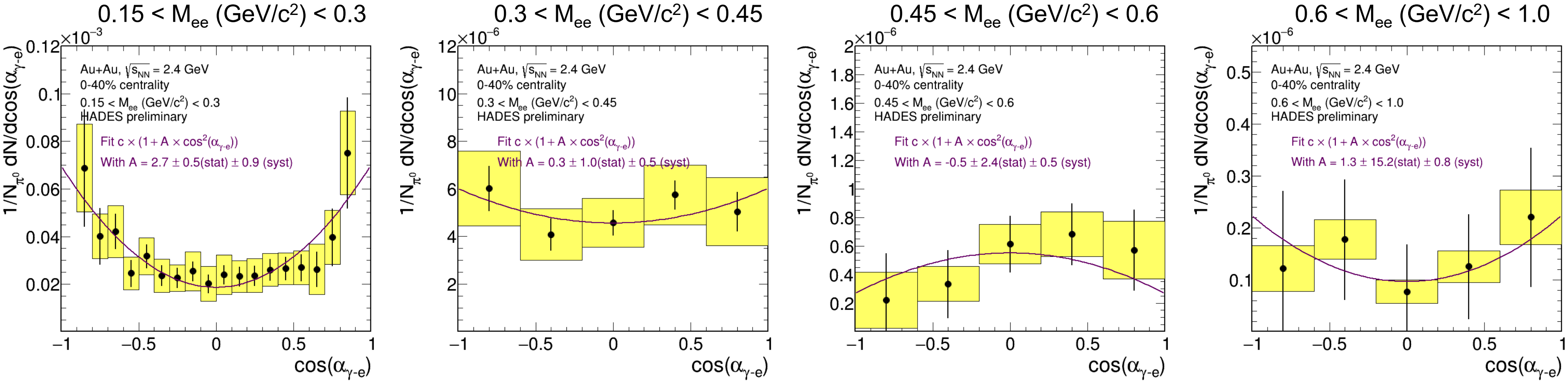


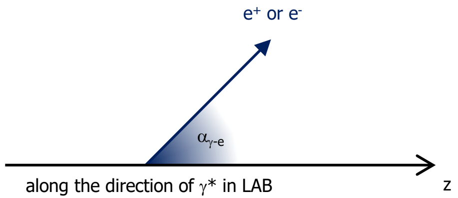
$$k_B T_{\text{slope}} = k_B T_{\text{kin}} + \tfrac{1}{2} M_{ee} c^2 \langle\beta\rangle^2$$

- Fit to the model points:
  - CG: $T_{\text{kin}} = 65\ \text{MeV}/k_B, \langle\beta\rangle = 0.19$
  - HSD: $T_{\text{kin}} = 74\ \text{MeV}/k_B, \langle\beta\rangle = 0.05$
- Blast-wave fit to hadrons spectra: $T_{\text{kin}} = 60\ \text{MeV}/k_B, \langle\beta\rangle = 0.36$

Angular distributions

Total e+e– yield





- So called "helicity" angle, related to photon polatization
- Lack of anisotropy may be interpreted as hint for thermalized source
- Pseudoscalar Dalitz decays are self-polarizing

Azimuthal anisotropy at intermediate energies

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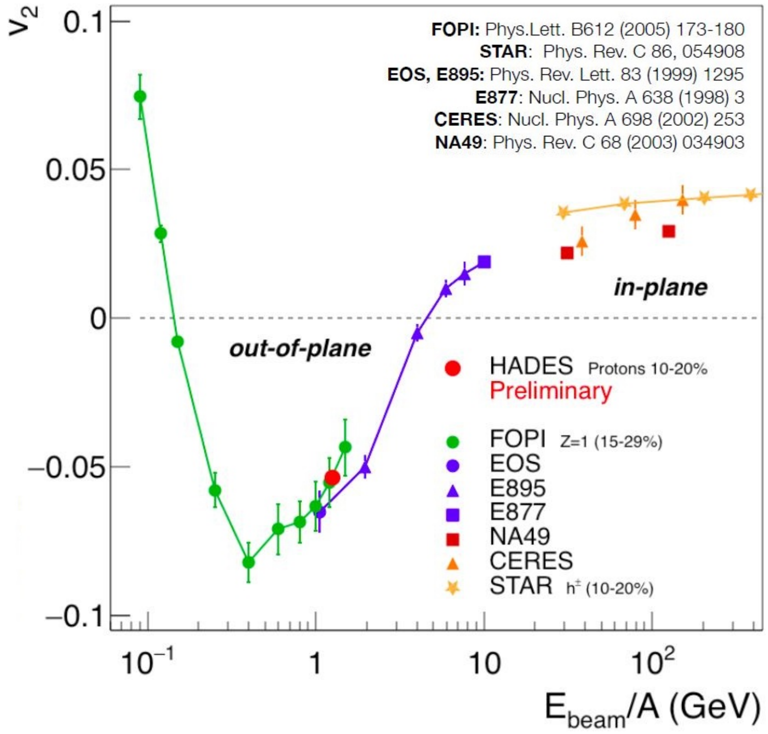
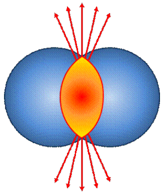
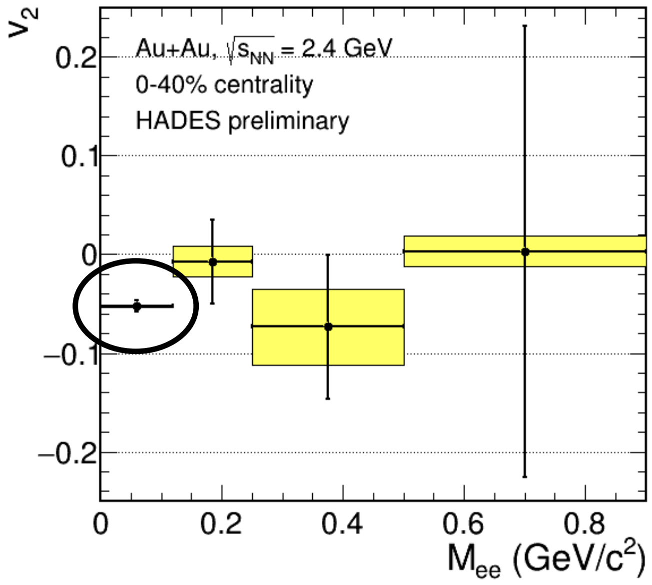


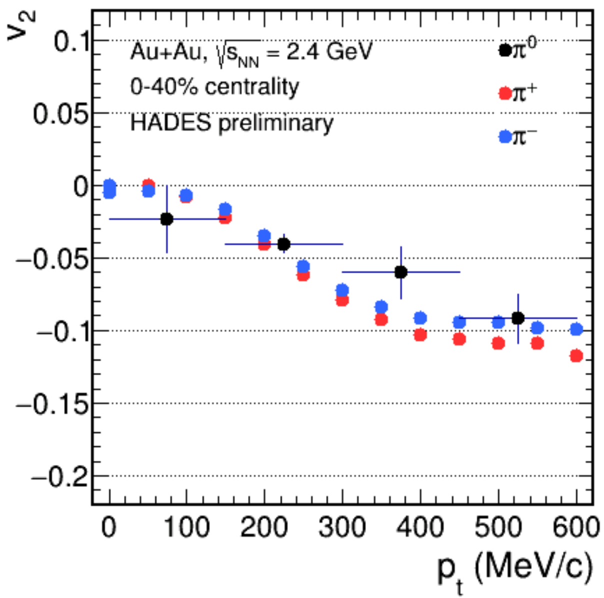
Recall, at SIS18 energies:

- Long passing times
- Moderate temperatures
- Negative v_2: preferred emission of hadrons perpendicular to reaction plane
- Shadowing by spectators



Dilepton azimuthal anisotropy





- HADES is capable of extracting v_2 of dileptons
- For more conclusive results larger statistics is needed

Summary and Perspectives

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Conclusions

- HADES explores baryon rich matter at SIS 18
- Properly extracted dilepton excess yield agrees well with theory predictions
- Differential spectra of p_t, rapidity and angular distributions have been presented
- Azimuthal anisotropy coefficient v_2 has been extracted

Outlook

- Analysis of more peripheral events and Au+C
- Look forward to the peaks in Ag+Ag at 1.65A GeV

Thank you for you attention

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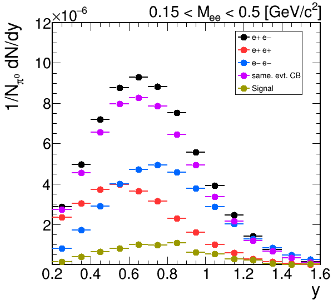
HADES Collaboration, Feb 22nd 20018

EXTRA SLIDES

Overview of data analysis

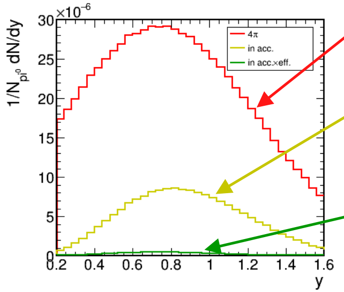
(Rapidity distribution as an example)

Combinatorial background

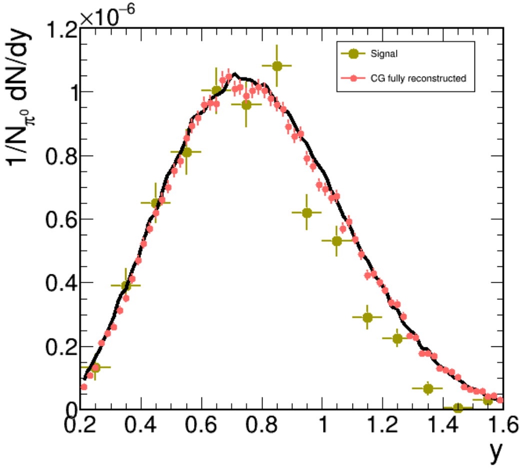


- Combinatorial background estimated from geometric mean of like-sign spectra
- Note very different acceptances for e^+e^+ and e^-e^-

Efficiency and acceptance corrections



- Simulated cocktail of dilepton sources in 4π
- Use of single-lepton matrices $acc_+(p_+,\theta_+,\phi_+)*acc_-(p_-,\theta_-,\phi_-)$ to get cocktail spectra inside HADES acceptance
- Use of single-lepton matrices $eff_+(p_+,\theta_+,\phi_+)*eff_-(p_-,\theta_-,\phi_-)$ to get cocktail spectra "after reconstruction"
- Correction factors for data are ratios of these spectra: ε = acc/eff, α = 4π/acc



- Excellent agreement
- Systematics at forward rapidity is going to be understood and reduced

Combinatorial background estimation

Two formalisms

Single leptons are produced independently, with Poisson statistics.
[*PHENIX analysis note*]

Suitable for:
- semileptonic decays
- ...

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

Leptons are always produced in pairs, no assumption about the statistics.
[*Adare et al. (STAR) PRC* ***81*** *034911*]

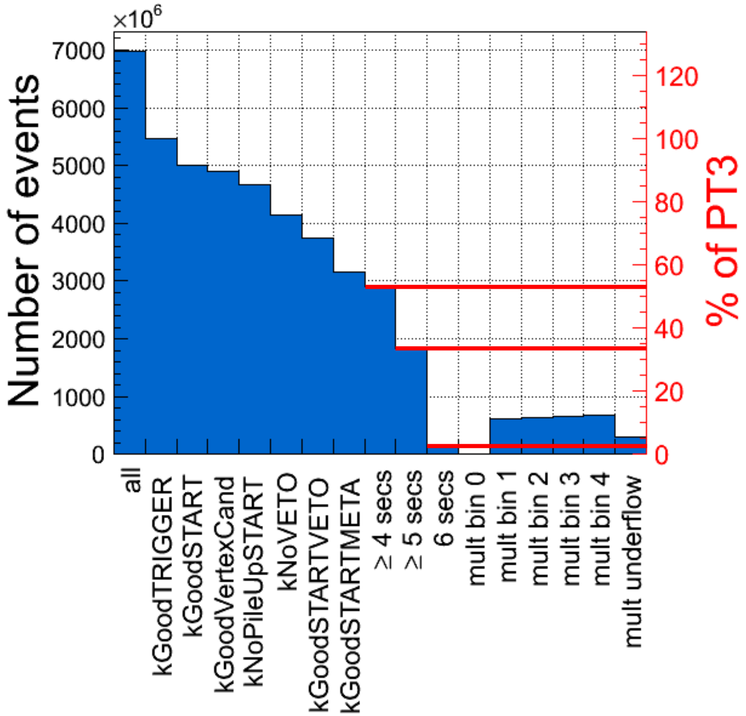
Suitable for:
- virtual photons

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

Reality is somewhere between the two sets of assumptions
Fortunately, "factors with epsilons" can be replaced with ratios of spectra from event mixing:

$$k = \frac{\langle FG^{\mathrm{mix}}_{+-}\rangle}{2\sqrt{\langle FG^{\mathrm{mix}}_{++}\rangle\langle FG^{\mathrm{mix}}_{--}\rangle}}$$

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	$N_{META\ hit,\ cut}$ >	$N_{META\ hit,cut}$ ≤
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		

Low-mass Dileptons at 1 – 2A GeV

HADES "Resonance clock"

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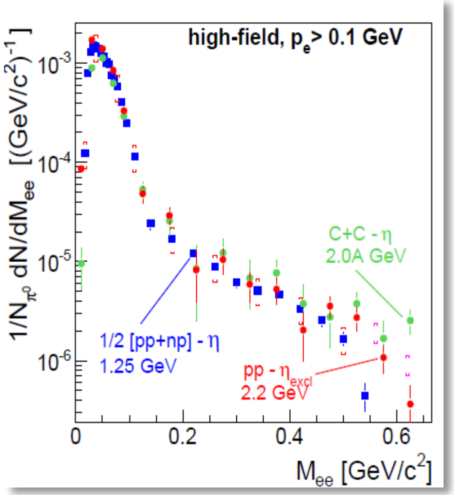
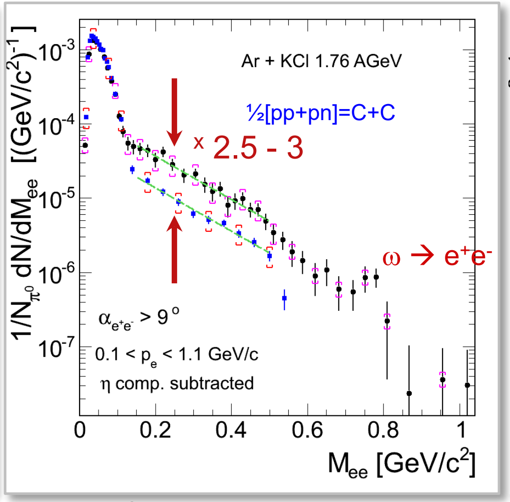
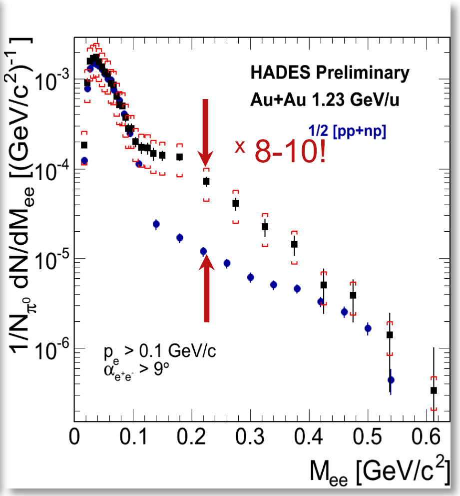


Phys.Lett. B 690 (2010) 118



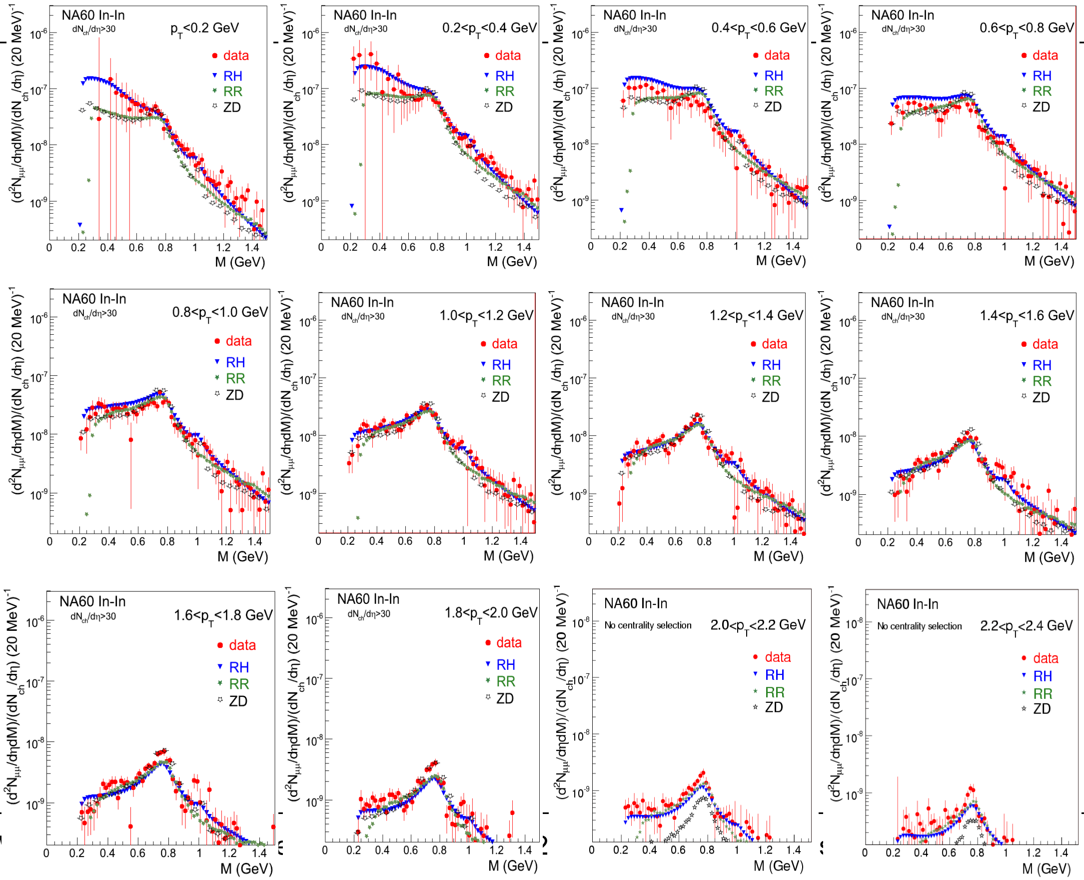
Phys.Rev.C 84 (2011) 014902



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

NA60 excess p_t dependent



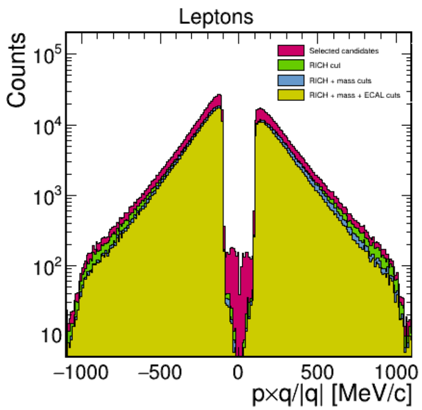
TOWARDS DILEPTON EXCITATION FUNCTION

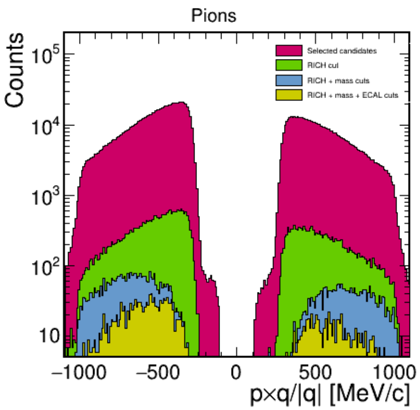
Ag+Ag at $\sqrt{s_{NN}} = 2.6$ GeV

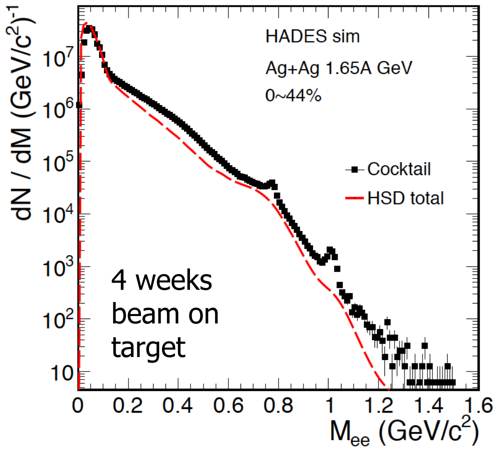
- Upgrade of RICH detector
- Installation of electromagnetic calorimeter

→ Higher efficiency for dileptons

- First measurement of the IMR slope at SIS18 energy regime

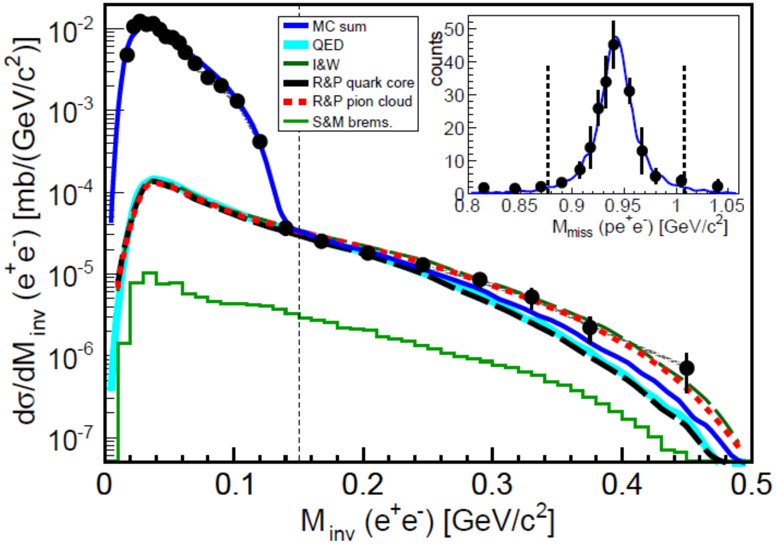






Exclusive analysis of pp→ppe⁺e⁻

Exclusive analysis of pp→ppe⁺e⁻
[PRC **95**, 065205 (2017)]



QED: point like γ*NR, Heavy Ion Phys. 17, 27 (2003)

I&W: two component quark model, PRC 69, 055204 (2004)

R&P: covariant constituent quark model, PRD 93, 033004 (2016)

S&M brems.: PRC 82, 062201 (2010)

Δ(1232) BRANCHING RATIOS

$\Gamma(N\pi)/\Gamma_{total}$ Γ_1/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
0.994 OUR ESTIMATE				
1.00	ARNDT	06	DPWA	$\pi N \to \pi N, \eta N$
1.0	CUTKOSKY	80	IPWA	$\pi N \to \pi N$
1.0	HOEHLER	79	IPWA	$\pi N \to \pi N$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.994	SHRESTHA	12A	DPWA	Multichannel
1.0	ANISOVICH	10	DPWA	Multichannel
1.000	ARNDT	04	DPWA	$\pi N \to \pi N, \eta N$
1.00	PENNER	02C	DPWA	Multichannel

$\Gamma(pe^+e^-)/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-5})	DOCUMENT ID
4.19±0.34±0.62	[1] ADAMCZEW...17

[1] The systematic uncertainty includes the model dependence.

PDG 2018

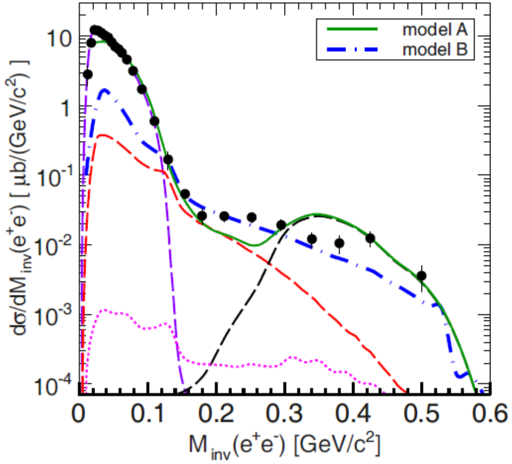
First measurement of

BR(Δ→pe⁺e⁻) = 4.19 ± 0.42(model) ± 0.46(syst.) ± 0.34(stat.)

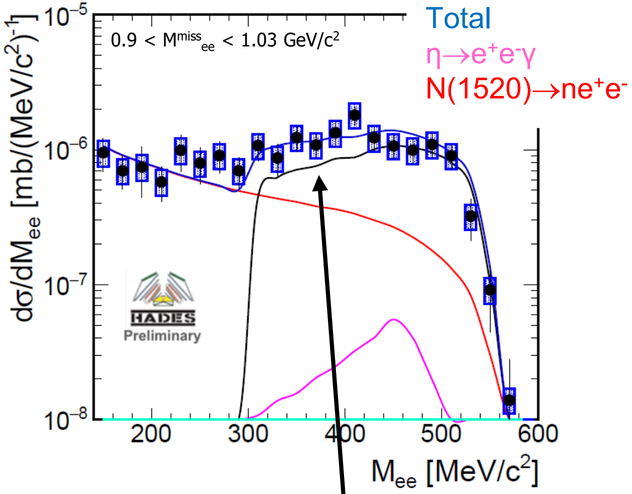
Role of the ρ meson

Exclusive $np \rightarrow npe^+e^-, \sqrt{s} = 2{,}4$ GeV

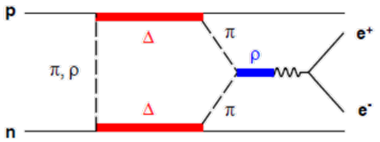
HADES, EPJA 53, 149 (2017)



Exclusive $\pi^- + p \rightarrow ne^+e^-, \sqrt{s} = 1.49$ GeV



Model A [EPJA 50, 107 (2014)], e.g.:



Model B [PRC 82, 062201 (2010)], e.g.: