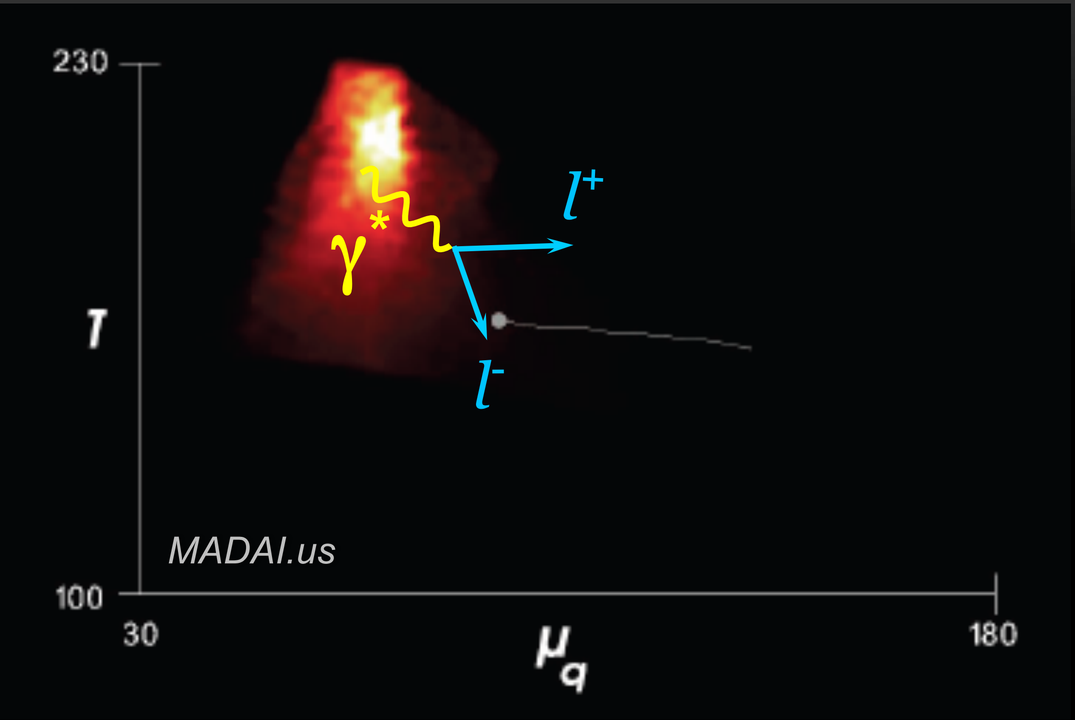
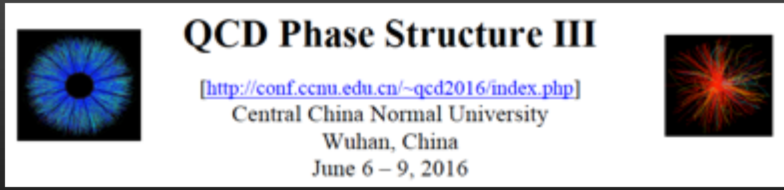




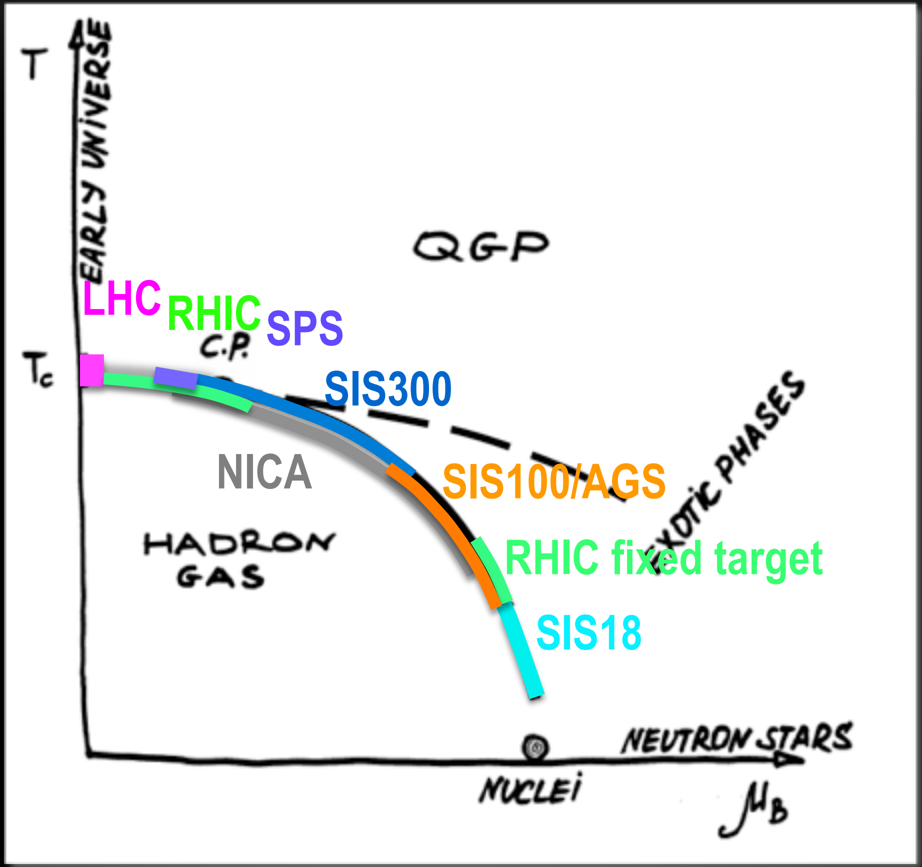
DI-LEPTON PRODUCTION AT HIGH BARYON DENSITY REGION

Tetyana Galatyuk
Technische Universität Darmstadt / GSI

PHASE DIAGRAM OF MATTER

From the "Big Bang" to Neutron stars

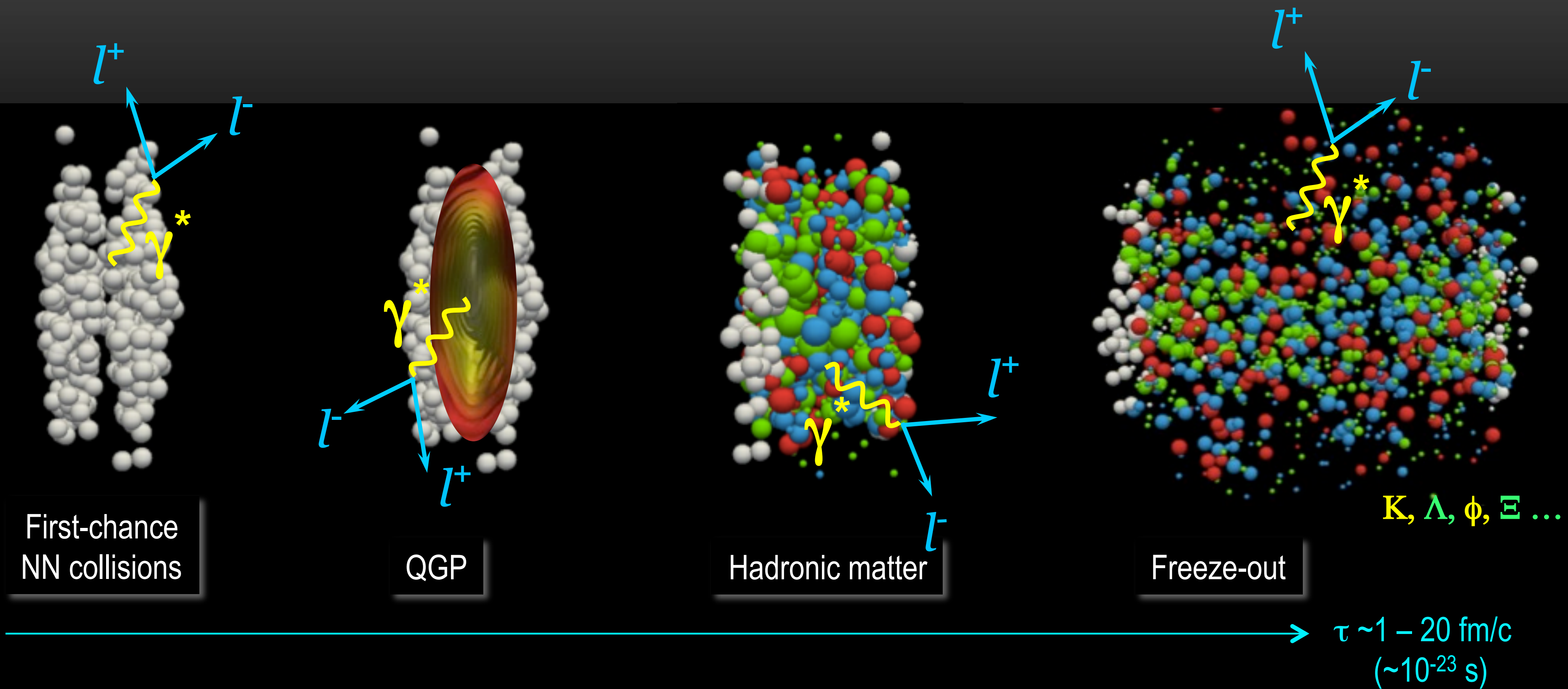
O. Dolinskyy, GSI



Accessible through heavy-ion collisions

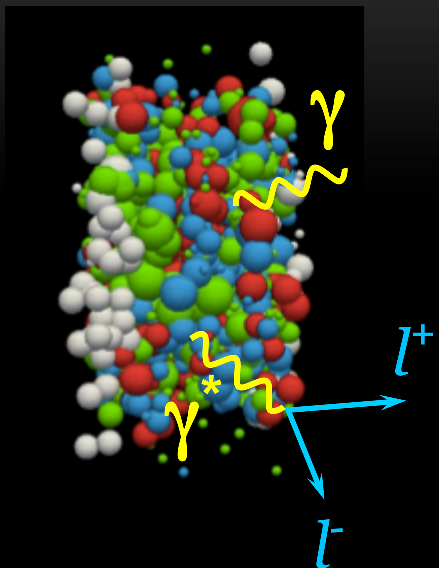
O. Dolinskyy, GSI

COURSES OF THE HEAVY-ION COLLISION



- Bulk properties: Equation of State, Transport Coefficients, Hadron-chemistry
- Microscopic properties: Degrees of Freedom, Spectral Functions
- Phase transitions: Condensate Structure

ELECTROMAGNETIC PROBES: DILEPTONS vs. REAL PHOTONS



Electromagnetic radiation (photons and lepton pairs) probes the interior of fireballs

- The dilepton signal contains contributions from throughout the collision
- No strong final state interactions → leave reaction volume undisturbed

Photons (γ) : 1 variable: p_T
Lepton pairs (γ^*) : 2 variables: M, p_T

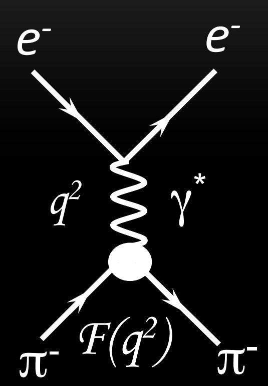
Dileptons more rich and more rigorous than photons

- p_T sensitive to temperature and expansion velocity
- M is the only Lorenz-invariant thermometer the field[1]

[1] *H. J. Specht*

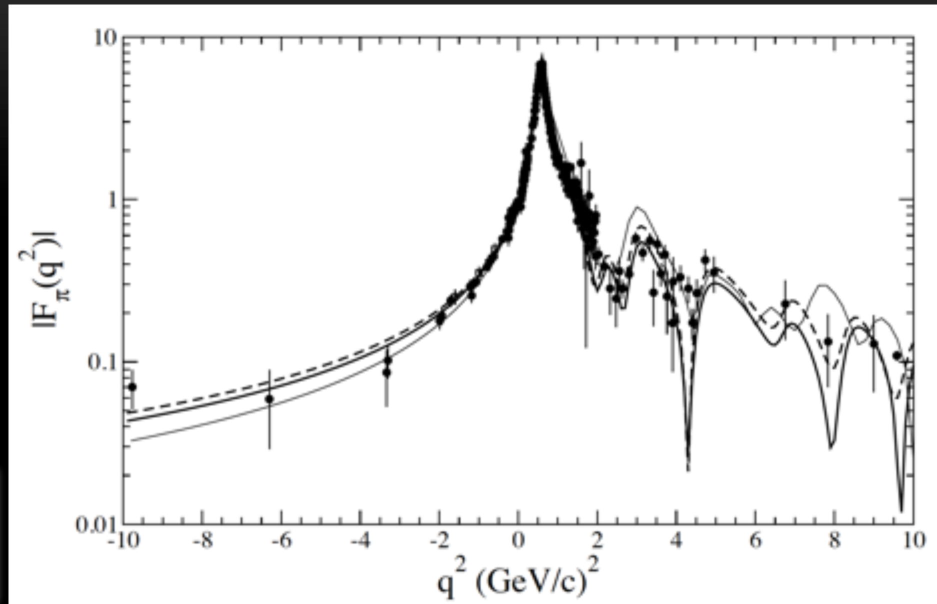
HOW DO PHOTONS COUPLE TO HADRONS?

space-like photons



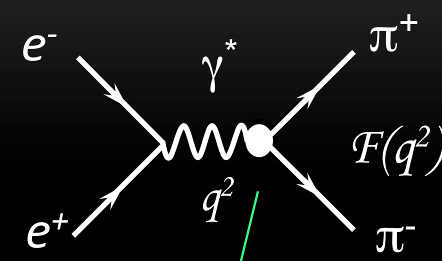
$q^2<0$

$\Delta p \Delta x \geq \hbar/2$



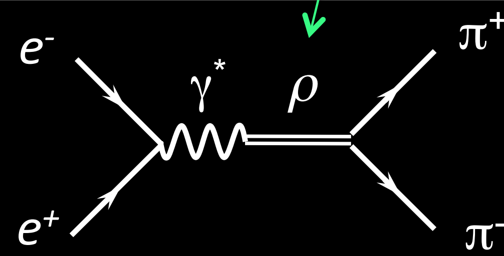
De Melo et al., Phys. Rev. D73 (2006) 070413

time-like photons



$q^2>0$

$\Delta E \Delta t \geq \hbar/2$

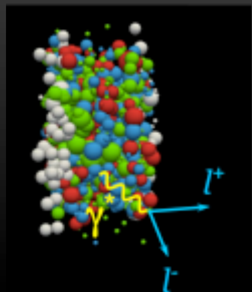


$$F(q^2) = \frac{d\sigma/dq^2}{\left(d\sigma/dq^2\right)_{\text{point like}}}$$ → *Form factor*

$$q^2 = (\Delta E)^2 - (\Delta p)^2$$ → *Squared 4-momentum*

- $J^P = 1^-$ for both γ^* and Vector Meson
- Strong coupling of γ^* to Vector Meson
  → Vector Meson Dominance model
- Observable: vector mesons (ρ, ω, ϕ)

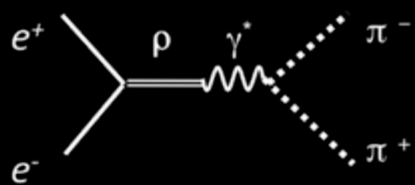
DILEPTON RATE IN A STRONGLY INTERACTING MEDIUM



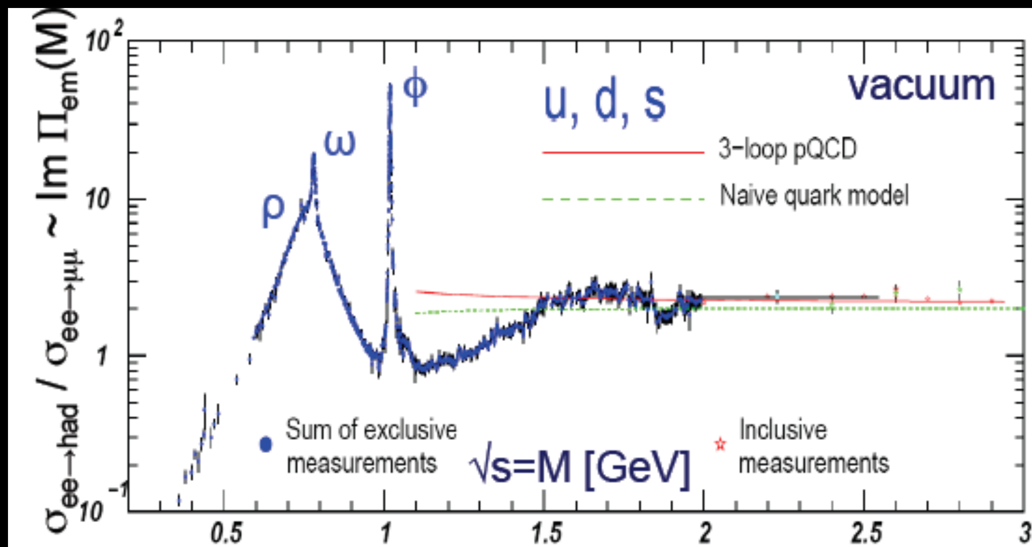
Unique direct access to in-medium spectral function

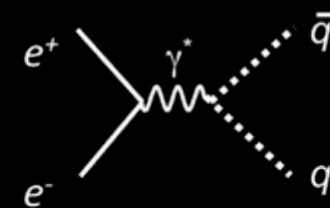
$$\frac{dN_{ll}}{d^4xd^4q} = -\frac{\alpha_{EM}^2}{\pi^3}\frac{L(M)}{M^2} f^B(q_0;T) \, \mathrm{Im}\, \Pi_{EM}^{\mu\nu}(M,q;\mu_B,T)$$

Photon self-energy



Strong coupling of γ* to ρ → VMD

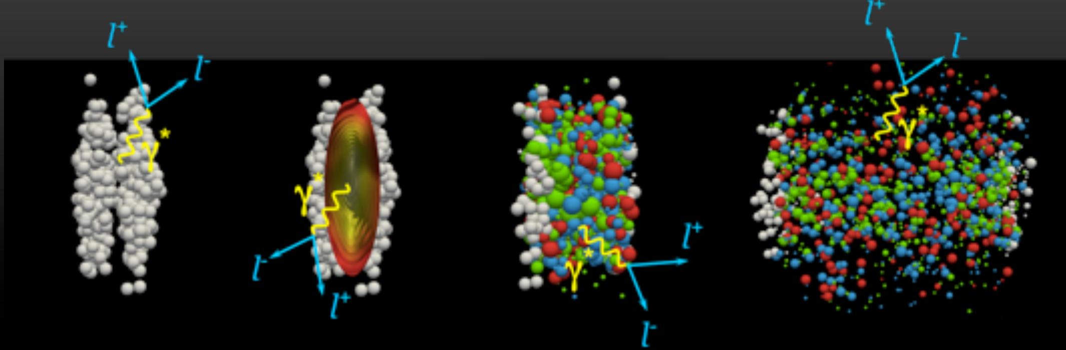




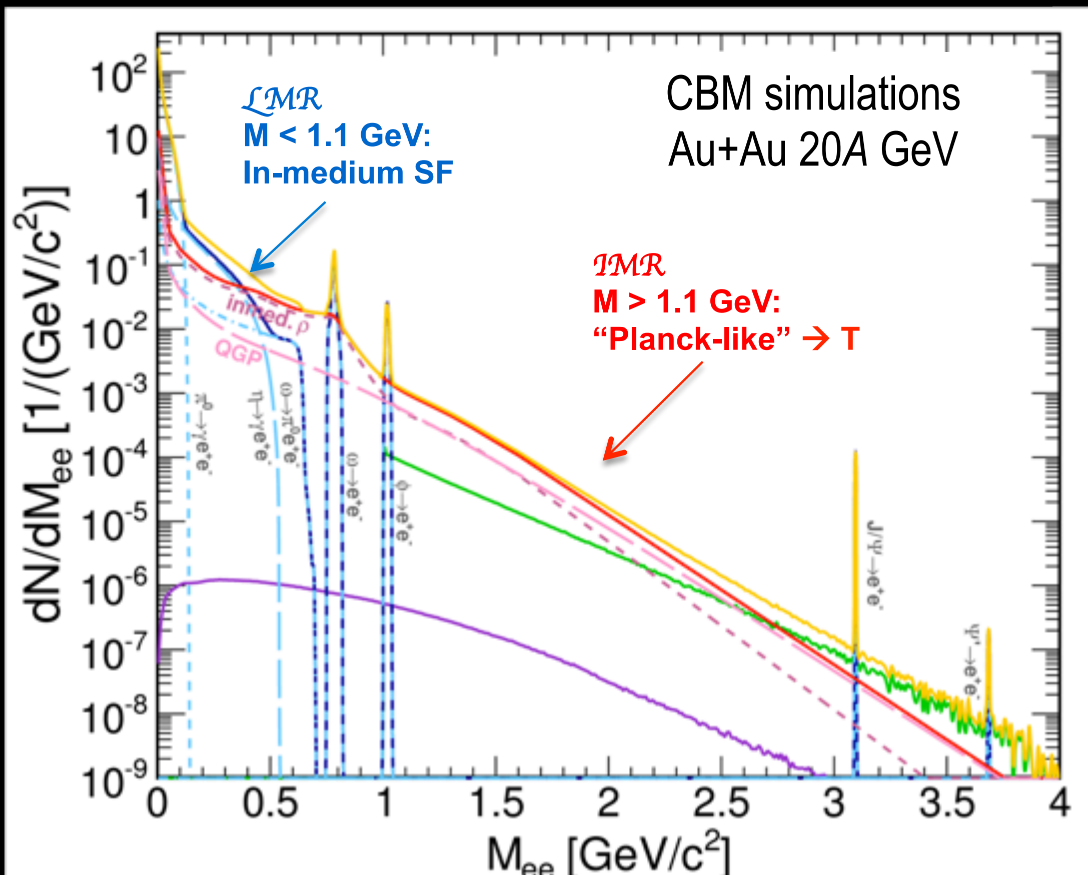
“Planck-like” → thermometer

- Hadrons: $Im\ D_{\rho,\omega,\phi}$
  - Change in degrees of freedom?
  - Restoration of chiral symmetry?
- $\bar{q}q$ Continuum
  - Emitting source temperature?

CHARACTERISTIC FEATURES OF DILEPTON INVARIANT MASS SPECTRA



- Dilepton spectra represent the space-time integral of EM radiation
- Mass dependence allows separation of collision stages



F. Seck (M. Sc.)

- *Drell-Yan* (NN → l^+l^-X)
- Heavy-flavor: $c\bar{c}$ → l^+l^-
- Medium radiation (R. Rapp):
  - QGP: $q\bar{q}$ → l^+l^-
  - In-medium ρ, ω → l^+l^-
  - "4π annihilation": πa_1 → l^+l^-
- Final state decays (hadron cocktail): π^0, η → γe^+e^-

„IF YOU WANT TO DETECT SOMETHING NEW,
BUILD A DILEPTON SPECTROMETER“
S. TING

THE EXPERIMENTAL CHALLENGE …

- Lepton pairs are rare probes (BR < 10^{-4})
- at SIS energies sub-threshold vector meson production
  → $M_\rho \times \Gamma_{ee}/\Gamma_{tot}$ decay per 10 mio events

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

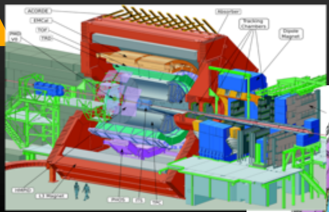
- Isolate the contribution to the spectrum from the dense stage
- Low-momentum coverage!

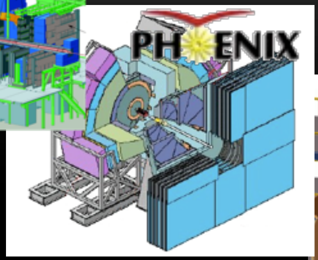
DATA QUALITY

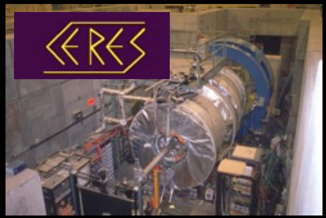
- The decisive parameters: Number of Interactions and Signal/Background
  - Range of $\mathcal{B}/\mathcal{S}$: 20 - 100 → $\mathcal{B}/\mathcal{S} >> 1$;
    - Effective sample size: $\mathcal{S}_{eff} \sim \mathrm{I} \times \mathcal{S}/\mathcal{B}$ reduction by factors of 20-100
    - Systematics: $\delta\mathcal{S}_{eff}/\mathcal{S}_{eff} = \delta\mathcal{B}/\mathcal{B} \times \mathcal{B}/\mathcal{S}$ $\delta\mathcal{B}/\mathcal{B} = 2\ldots5\times10^{-2}$

VIRTUAL PHOTON RADIATION FROM HOT AND DENSE QCD MATTER

T







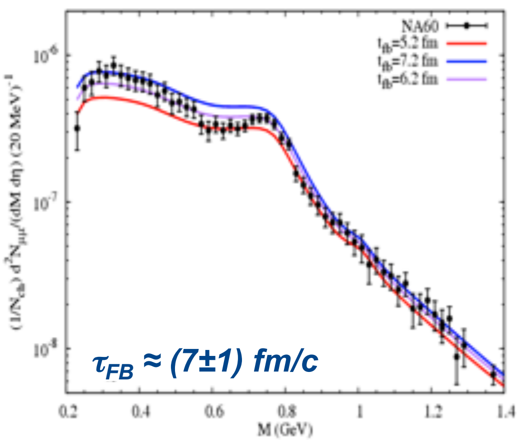
Highly interesting results from RHIC, SPS, SIS18

→ lepton pairs as true messengers of the dense phase

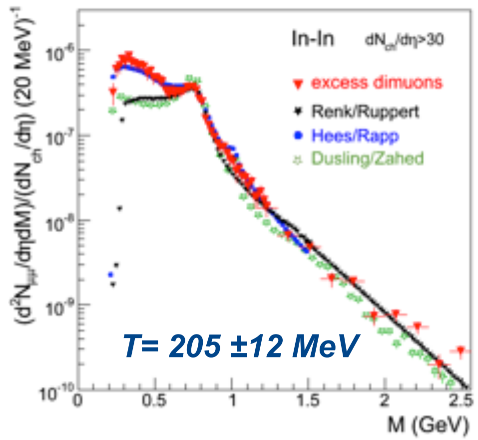
μ_B

IT'S JUST ONE SPECTRUM… BUT

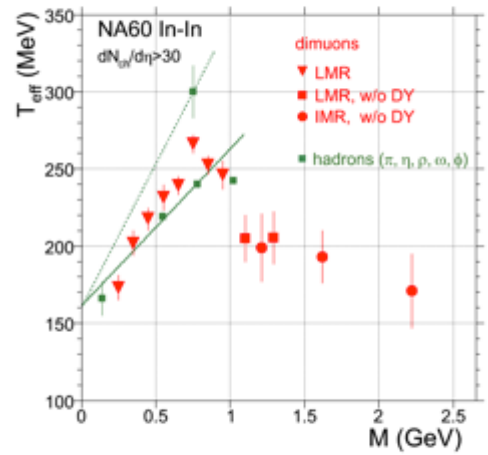
WHAT DID WE LEARNT FROM SPS DILEPTONS?



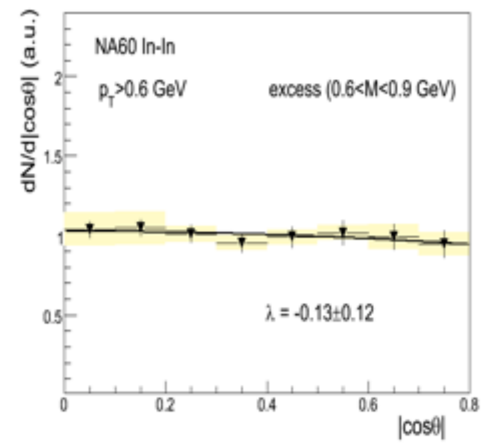
NA60: PRL 96 (2006) 162302
R.Rapp and H. van Hees, 2008



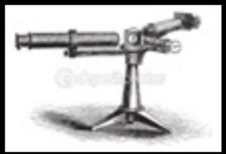
H.J. Specht,
AIP Conf.Proc. 1322 (2010) 1



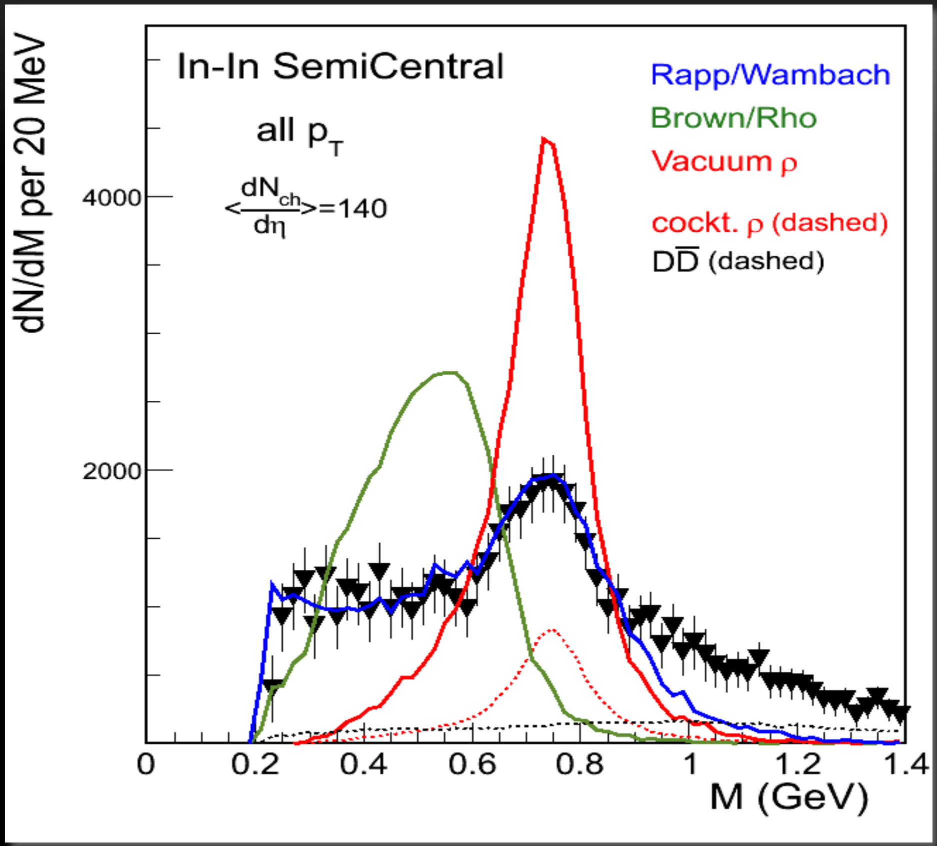
NA60 Coll.
PRL 100 (2008) 022302



NA60 Coll.
PRL 102 (2009) 222301

- LMR: First “explicit” measurement of interacting-fireball lifetime 
- IMR: First measurement of emitting source temperature (true T, no blue shift) 
- LMR+IMR inverse-slope analysis → fireball acceleration 
- LMR: Lack of any polarization in excess supports emission from thermalized source
- LMR+IMR shape and yield 

ARE NARROW IN-MEDIUM VECTOR MESON STATES WITH SUBSTANTIALLY SHIFTED POLE MASS OBSERVED?



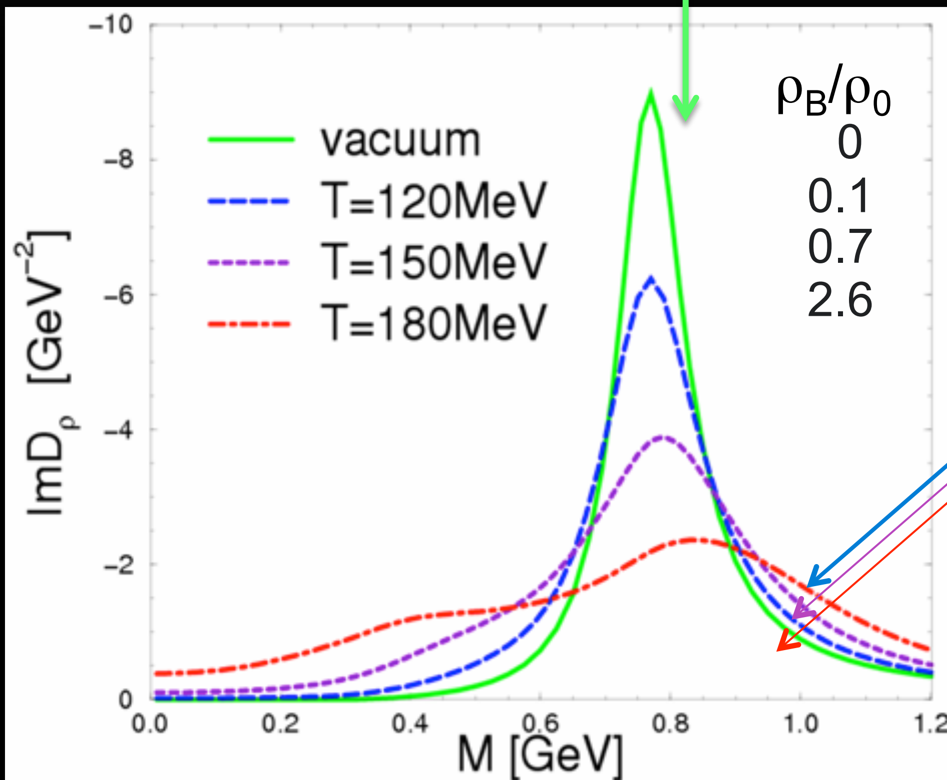
NA60:

- Disfavors "dropping mass" scenario
- Strongly supports in-medium broadening

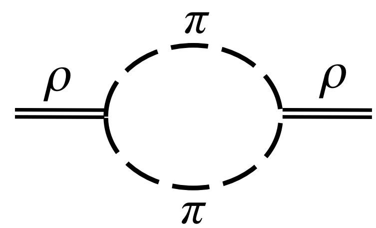
Data: Phys. Rev. Lett. 96 (2006) 162302
Calculations: R.Rapp and H. van Hees, 2008

THE ρ MESON IN-MEDIUM SPECTRAL FUNCTION

R. Rapp and J. Wambach, Eur.Phys.J. A6 (1999)

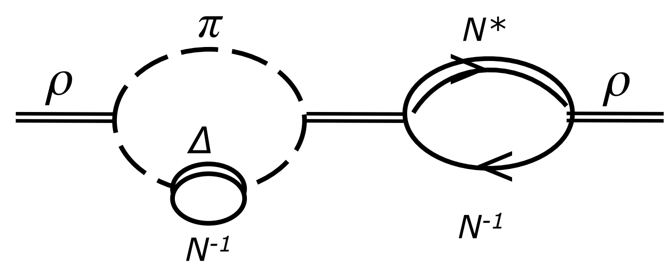


Vacuum



Medium

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

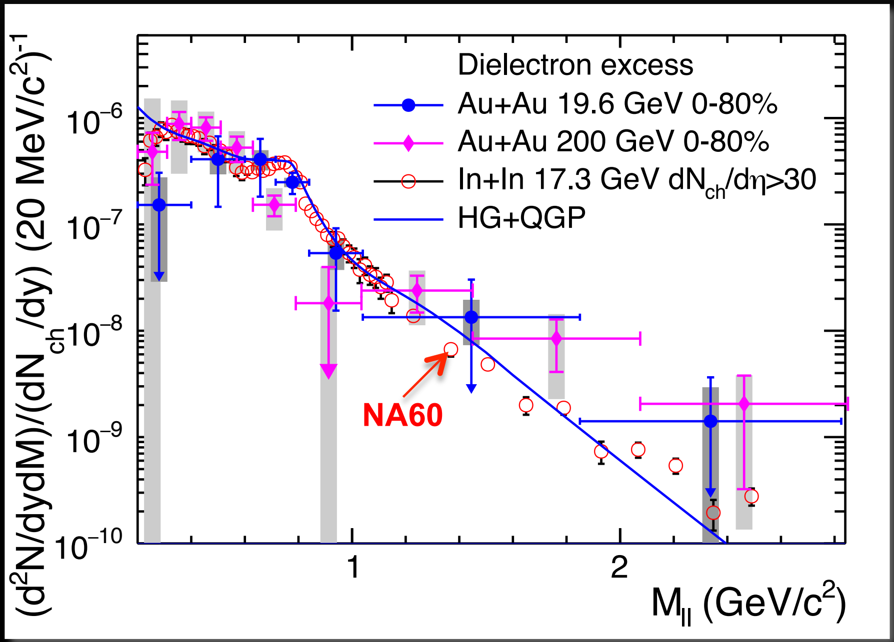


Additional contributions to the ρ-meson self-energy in the medium

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

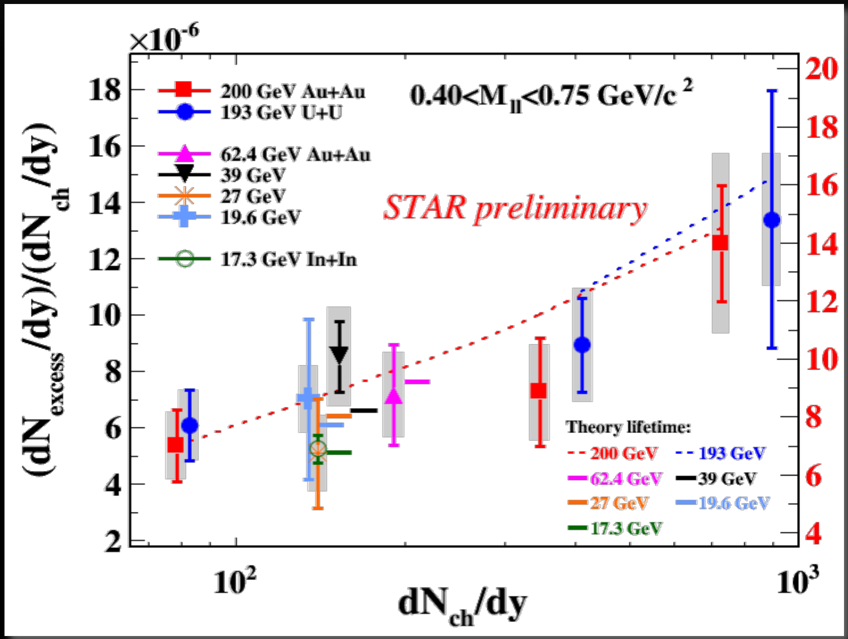
LOW-MASS e^+e^- EXCITATION FUNCTION: 19.6-200 GeV

Acceptance corrected invariant-mass excess spectrum STAR and NA60, independent absolute scales



STAR: PLB 750 (2015) 64
NA60: AIP Conf. Proc. 1322 (2010) 1

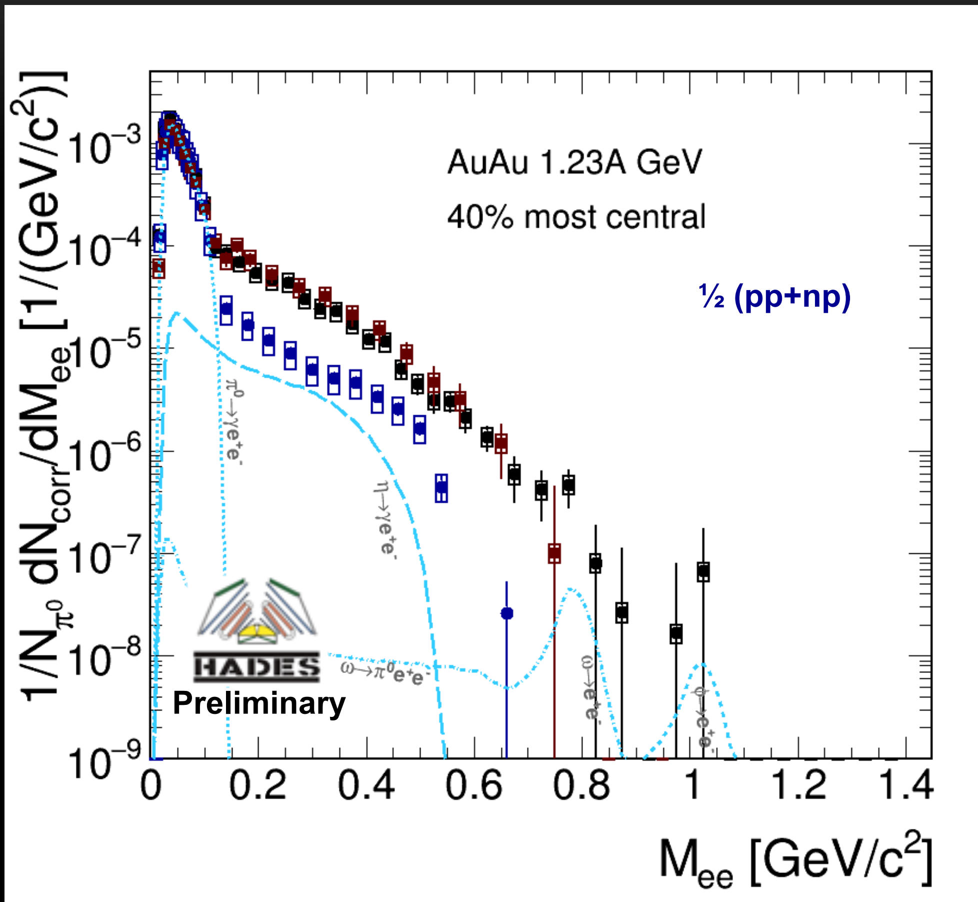
Normalized excess yields for the mass region 0.4<M<0.75 GeV vs. dN_{ch}/dy
Correlation with the fireball life-times



*Model: R. Rapp, H. van Hees, Phys. Lett. B **753** (2016) 586*

- Nearly constant total baryon density
- Indications of longer medium lifetime in central collisions
- Compatible with predictions from melting ρ meson
- "Universal" source around T_{pc}

VIRTUAL PHOTON EMISSION IN Au+Au COLLISIONS AT 1.25 *A*GeV



HADES, in preparation

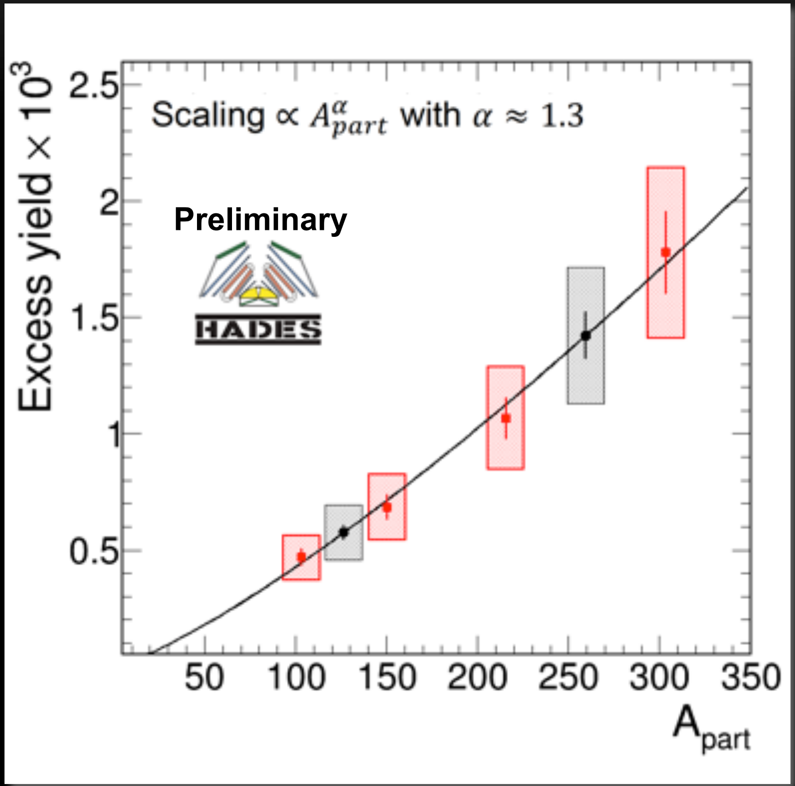
- Corrected for efficiency, not (yet) for acceptance
- Normalized to the number of produced π^0
- Strong enhancement above π^0
- Almost exponential spectrum up to vector meson region!

Experimentally defined hadronic cocktail:

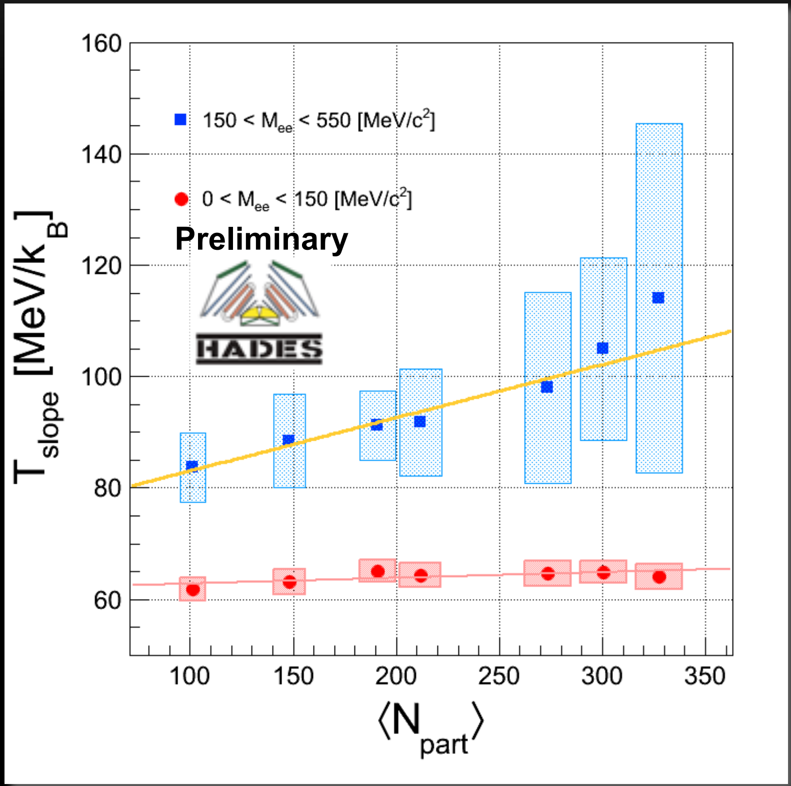
π^0 → charged pions or conversion method
η → conversion method
ϕ → K+K- channel
ω → Statistical hadronization model

CENTRALITY DEPENDENCE

Excess radiation 0.3 < M < 0.7 GeV/c^2

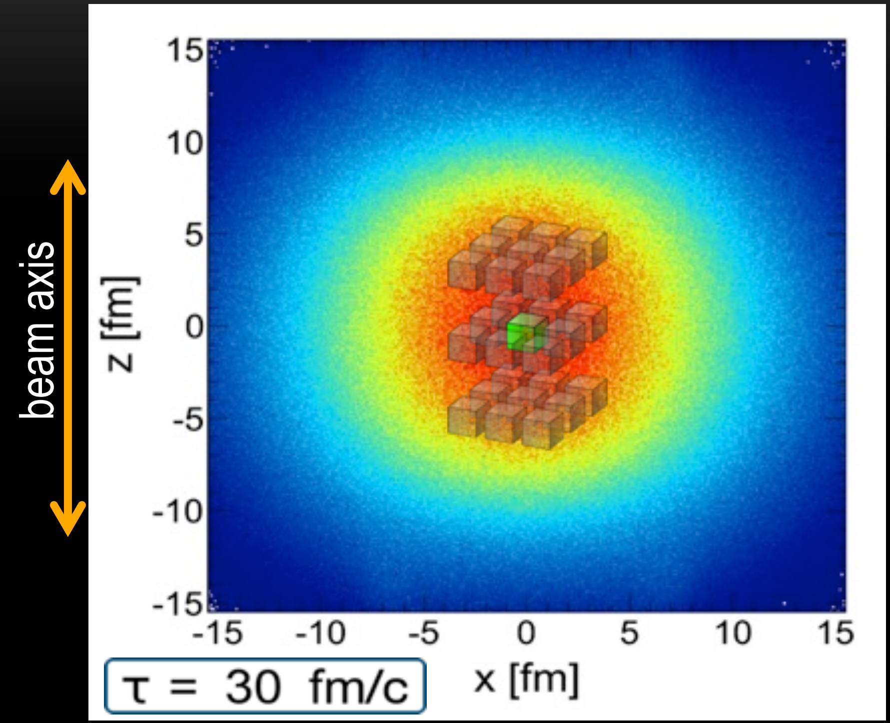


Effective Temperature

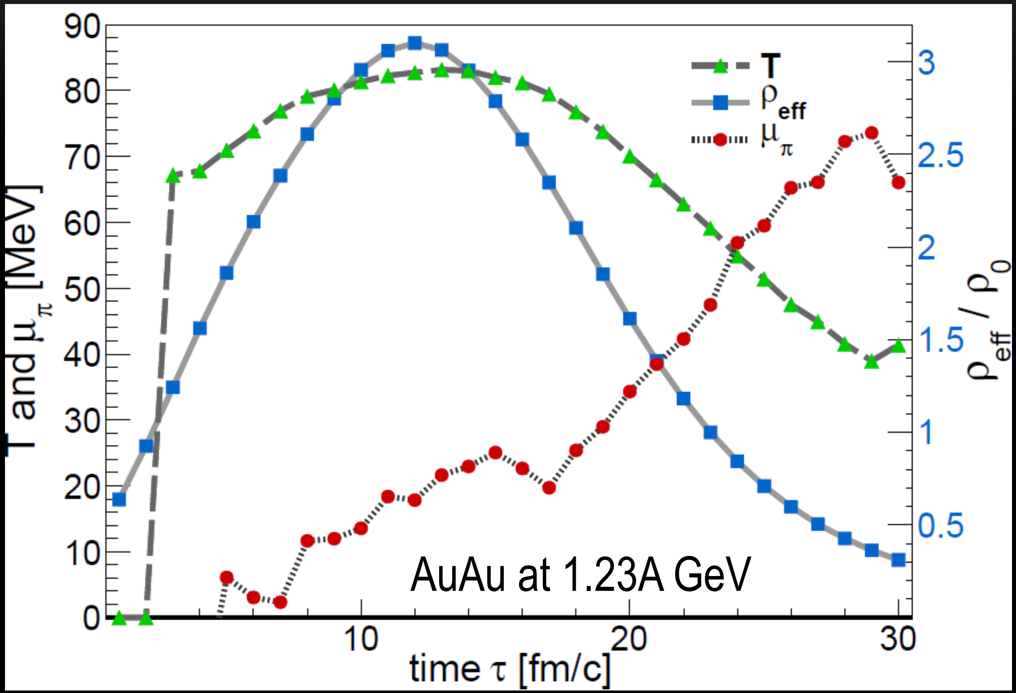


- Both observables indicate formation of longer-lived and hotter medium in the most central collisions

COARSE-GRAINED TRANSPORT APPROACH



"CENTRAL-CELL TRAJECTORY" FROM UrQMD

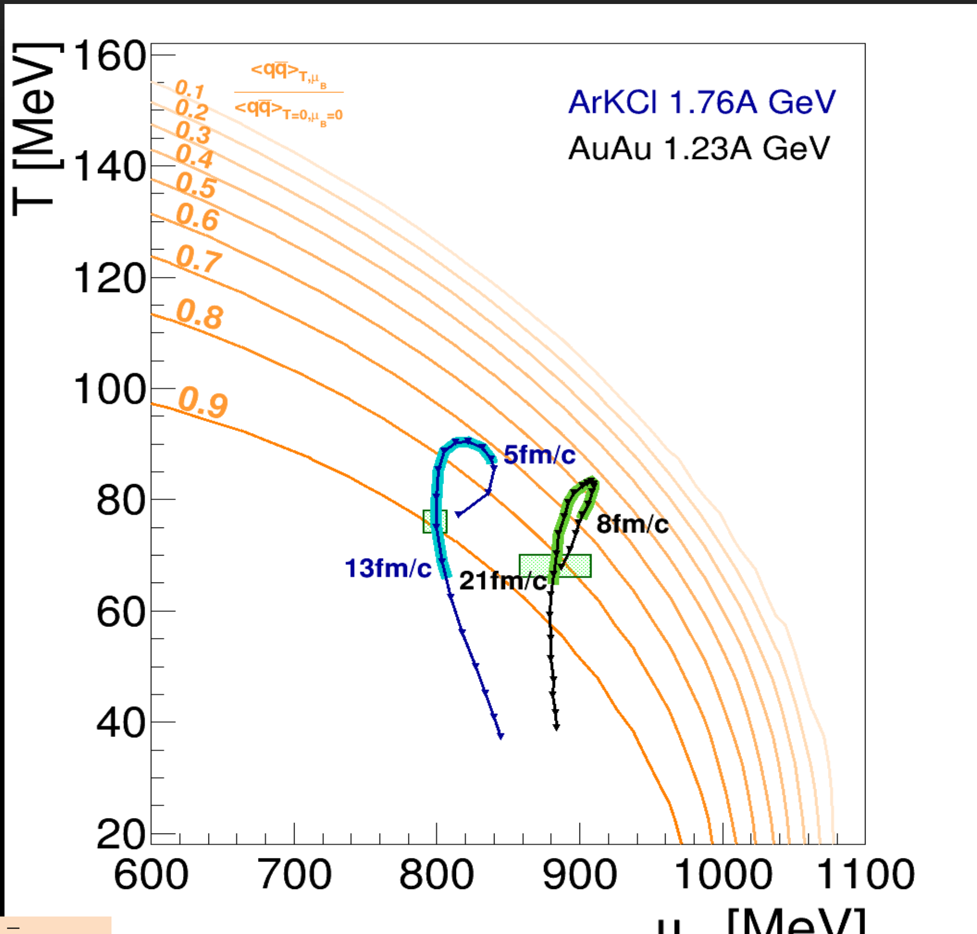


TG, Hohler, Rapp, Seck, Stroth, Eur. Phys. J. A 52 (2016) 131

- Bulk evolution from microscopic transport
  - Coarse graining in space-time cells → extract *T*, μ_B , μ_π, collective velocity...
- Apply equilibrium rates locally

Similar approaches by
*Huovinen et al.: PRC **66** (2002) 014903*
E. Santini et al., Phys.Rev. C84 (2011) 014901
*Endres et al.: PRC **91** (2015) 054911, PRC **92** (2015) 014911, PRC **93** (2016) 054901, arXiv:1604.06414*

DILEPTONS AT HADES
AND QCD PHASE DIAGRAM



$\frac{\langle q\bar{q} \rangle_{T,\mu_B}}{\langle q\bar{q} \rangle_{T=0,\mu_B=0}}$: *B.J. Schaefer and J. Wambach*

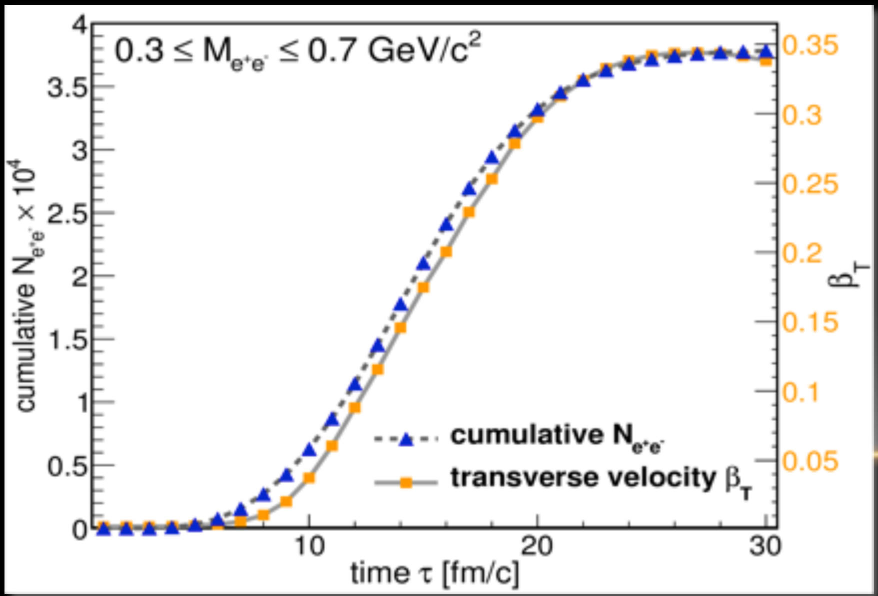
- Chemical freeze-out from measured particle yields analyzed with SHM
  HADES data: Nucl. Phys. ***A931*** *(2014) c785.*

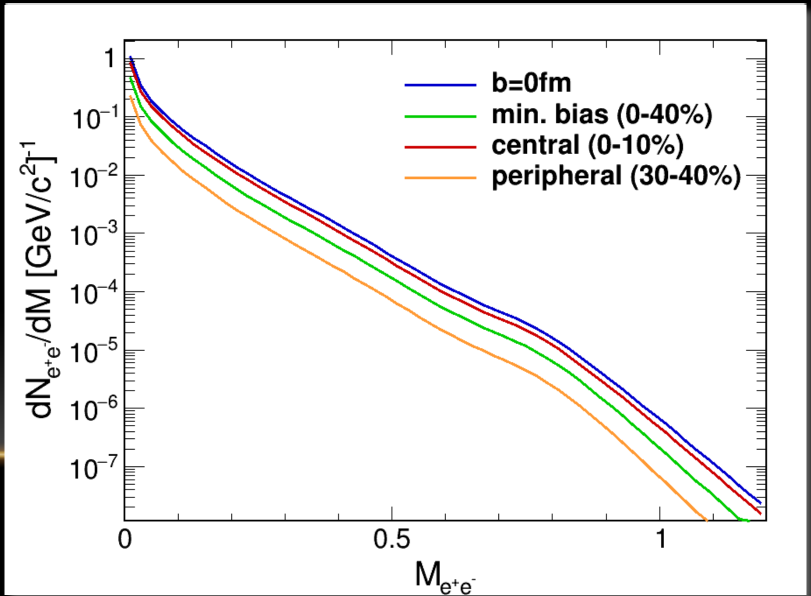
- Trajectories extracted from inner cube of cells with coarse-grained UrQMD

- Time-window of dilepton emission
  - Radiation stops shortly after chemical freeze-out
  - Access to hot and dense stage of the heavy-ion collision

DILEPTONS AS FIREBALL PROBES

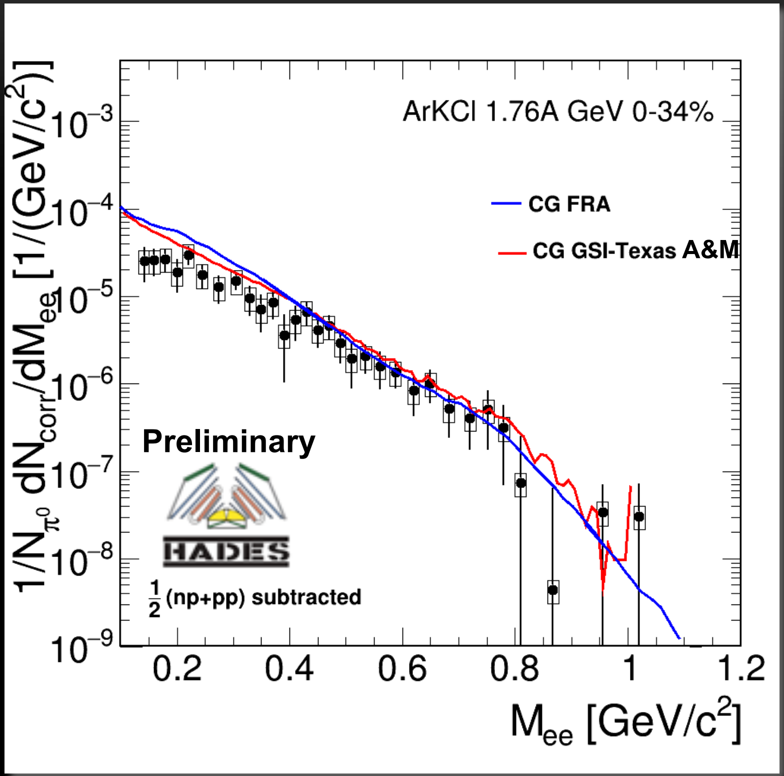
- Time evolution of cumulative dilepton yield in mass window M = 0.3-0.7 GeV/c2
- Active radiation window ~13 fm/c follows build-up of collective medium flow ⇒ fireball lifetime
- Strong medium effects on ρ-meson ⇒ remarkably structure-less low-mass spectrum
- $$\mathrm{d}R_{ll}/\mathrm{d}M \propto (MT)^{3/2} \exp(-M/T)$$
- Inverse slope parameter: T_S = 88 ± 5 MeV in IMR, T_S = 64 ± 5 MeV in LMR
- Thermal excess radiation scales with $(A_{part})^{1.4}$

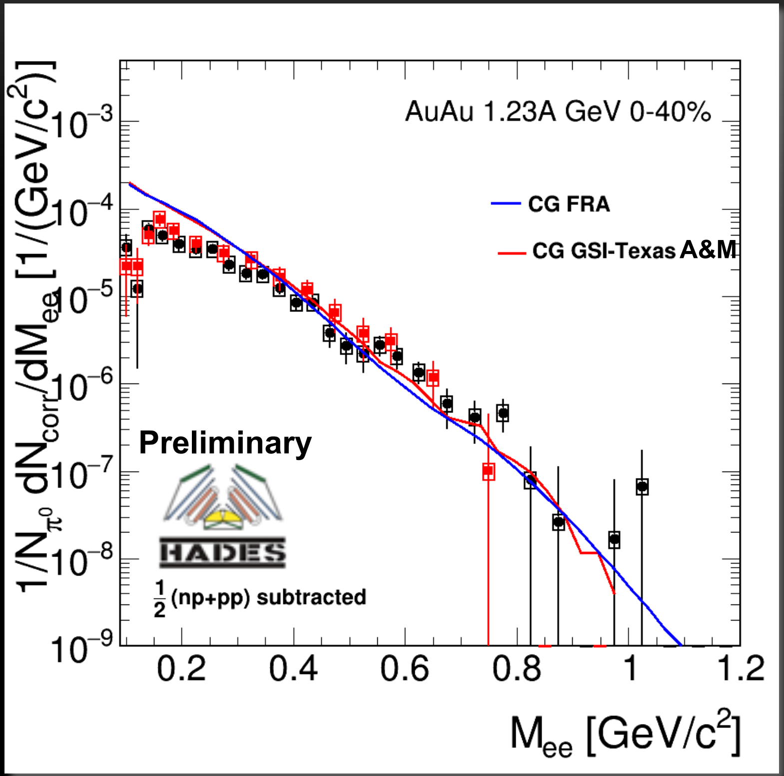




EXCESS RADIATION AT HADES
URQMD-MEDIUM EVOLUTION + RAPP/WAMBACH RATES

CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas: Eur.Phys.J. A52 (2016) no.5, 131
HADES ArKCl data: Phys.Rev.C 84 (2011) 014902

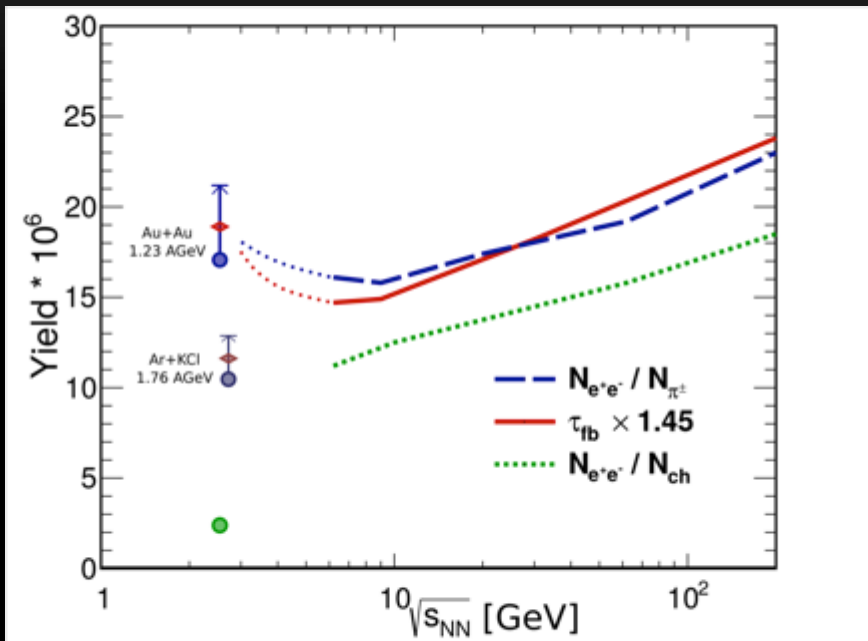




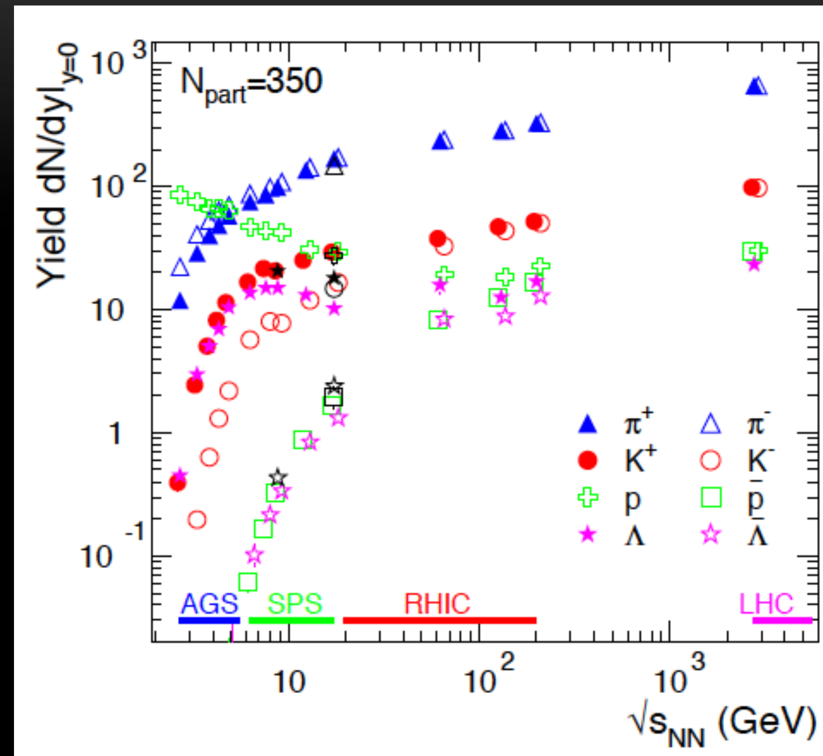
- Isolation of excess by a comparison with a measured “reference” spectrum
- Coarse-graining method works at low energies!
- Supports baryon-driven medium effects at SPS and RHIC!

EXCITATION FUNCTION OF DILEPTON PRODUCTION

Yield in low-mass window fireball tracks lifetime



R. Rapp, H. van Hees: Phys. Lett. B ***753*** *(2016) 586*
TG, Hohler, Rapp, Seck, Stroth, Eur. Phys. J. A 52 (2016) 131



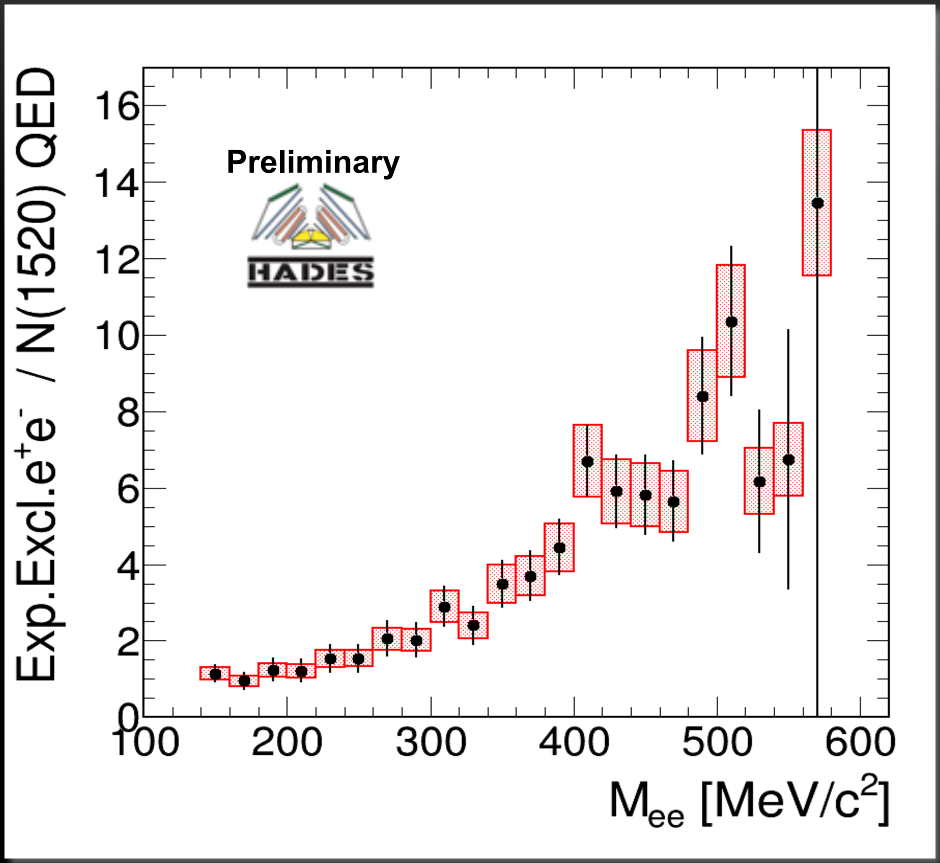
A. Andronic, arXiv:1407.5003

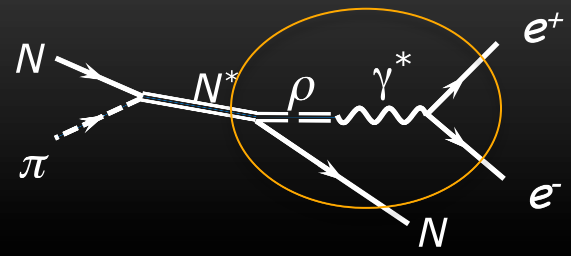
- Fireball dominated by incoming nucleons at lower energies
- Number of charged particles N_{ch} not a good proxy for thermal excitation energy
- Normalization to number of charged pions N_π

”IF YOU ARE OUT TO DESCRIBE THE TRUTH, LEAVE ELEGANCE TO THE TAILOR”

A. EINSTEIN

VERIFY THE ρ-BARYON COUPLING MECHANISM



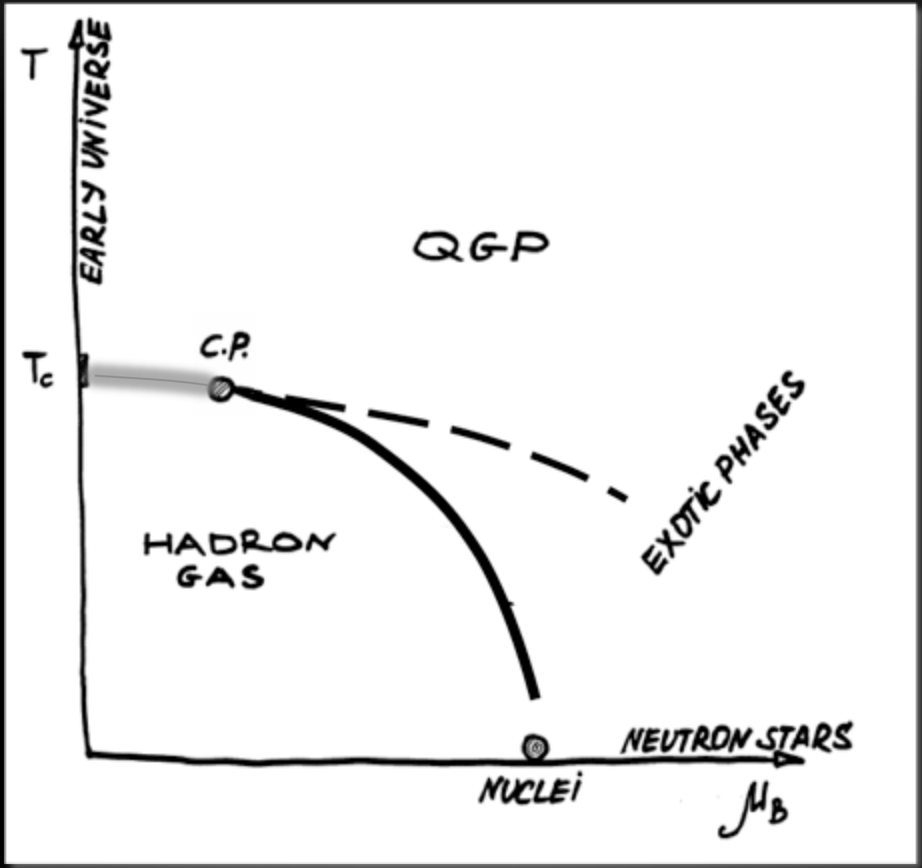


- **Vector Meson Dominance:** the basis of emissivity calculations for QCD matter.
- Crucial to support the validity of the model by elementary reactions

HADES π (secondary) beam run in 2014

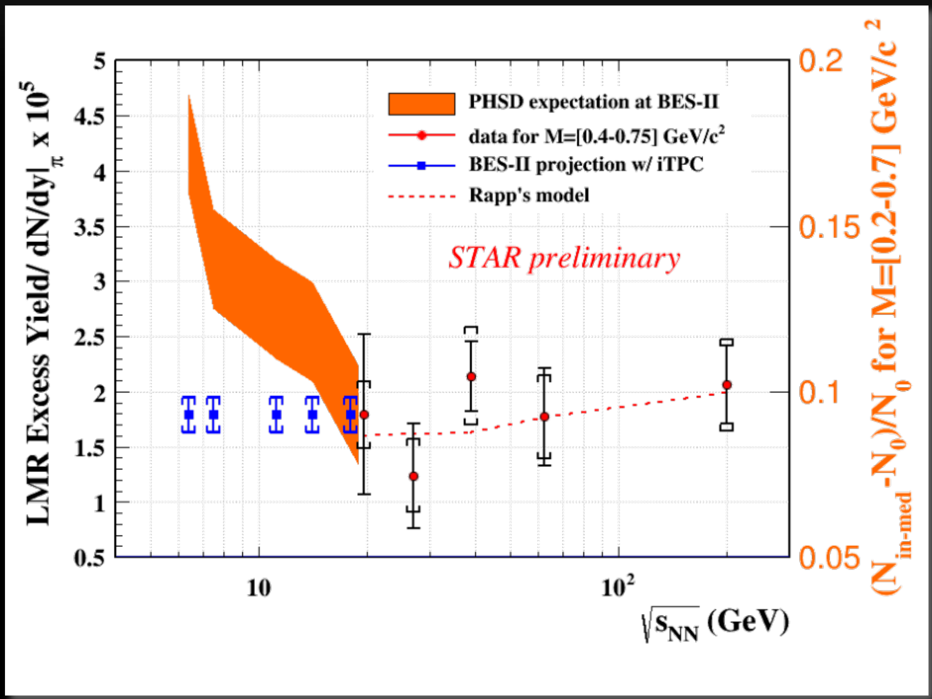
- Exclusive $\pi^- p$ reactions at $\sqrt{s}$ = 1.49 GeV
- Strong deviation from unity show the time-like contribution to the resonance decay and confirm the validity of the VMD!

MAPPING QCD PHASE DIAGRAM WITH DILEPTONS



DILEPTON EXCITATION FUNCTIONS

LOW-MASS EXCESS (0.45 < $\mathcal{M}$ < 0.7 GeV/c^2)



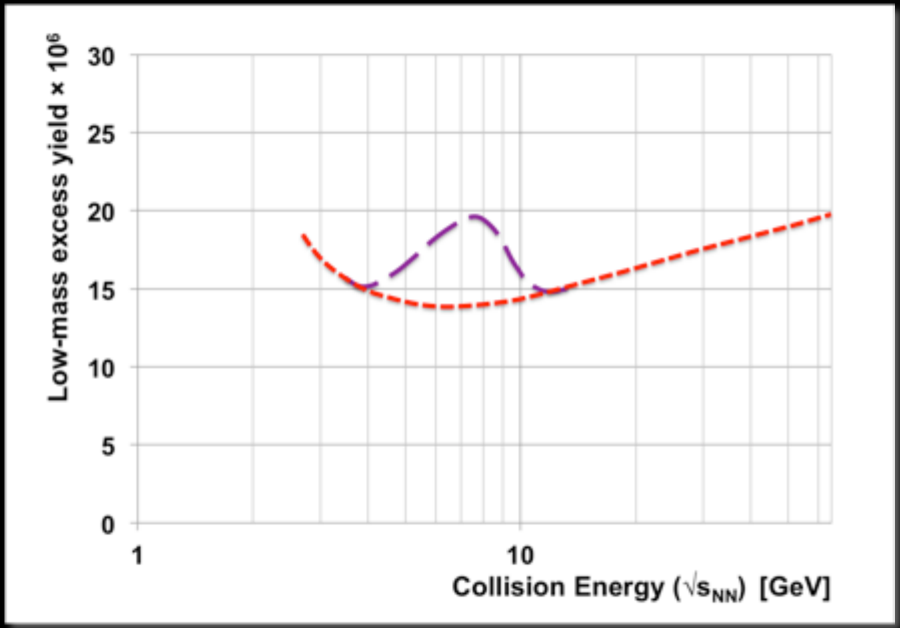
STAR Note 619

See also STAR: PLB 750 (2015) 64

- In-medium modifications to ρ spectral function is driven by the total baryon density
- Tracks fireball lifetime well
- Should get maximal at low energy?

DILEPTON EXCITATION FUNCTIONS

LOW-MASS EXCESS ($0.45 < \mathcal{M} < 0.7$ GeV/c^2)



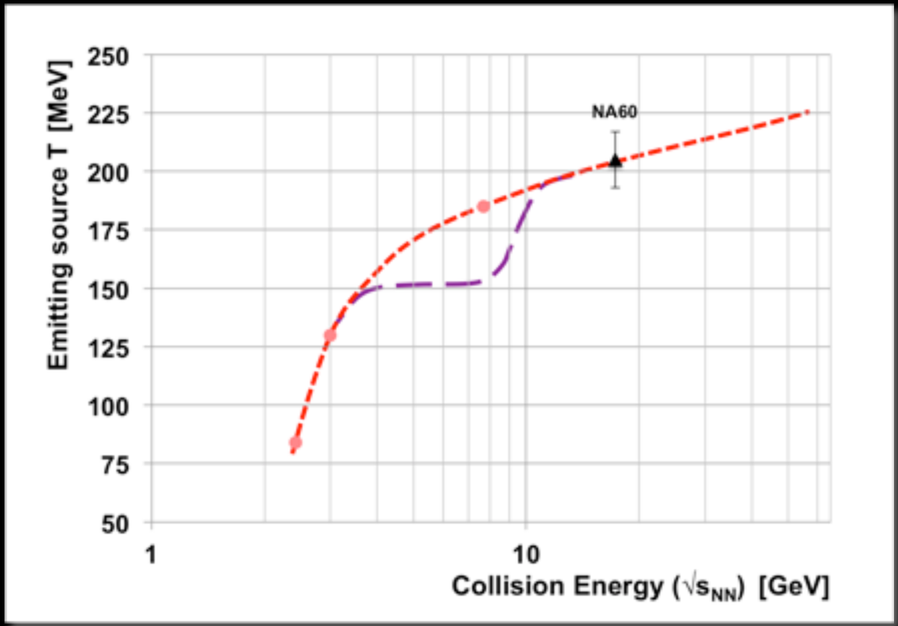
- Measure ρ spectral function and… expect the unexpected!
  → Search for anomalous fireball lifetime around phase transition & CP

Red curve; scenario w/o phase transition

Dashed violet curve corresponds to a speculated shape with phase transition

DILEPTON EXCITATION FUNCTIONS

INTERMEDIATE-MASS SLOPE (1.5 < $\mathcal{M}$ < 2.5 GeV/c^2)



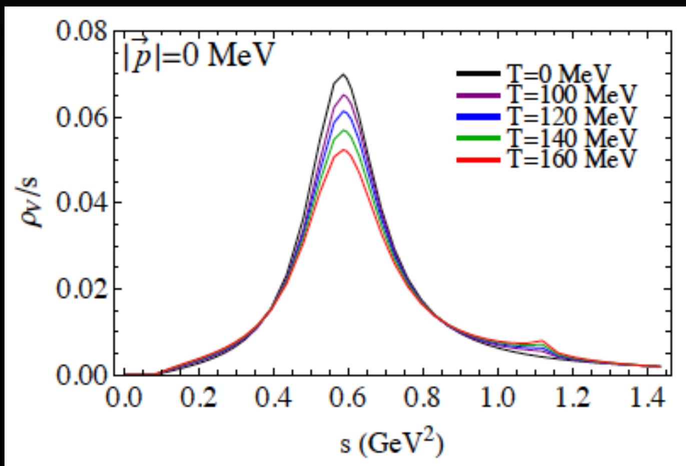
- Measure T_{slope} (note, $T_{slope} < T_{initia}$)
  "caloric curve"
  → Plateau around onset of deconfinement?
  (see e.g. M. D'Agostino et al. NPA 749 (2005) 5533)

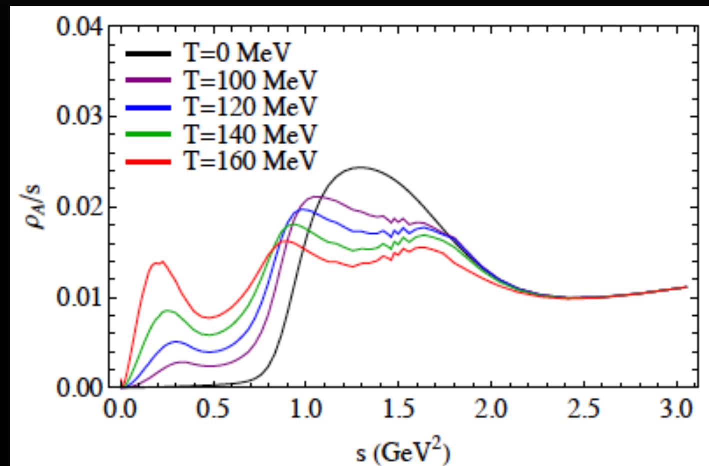
R. Rapp, H. van Hees: PLB 753 (2016) 586
F. Seck et al., Eur. Phys. J. A 52 (2016) 131

Dashed violet curve corresponds to a speculated shape with phase transition

DILEPTON EXCITATION FUNCTIONS

INTERMEDIATE-MASS SPECTRAL SHAPE, YIELD (1.5 < $\mathcal{M}$ < 2.5 GeV/c^2)





P. Hohler, R.Rapp, arXiv:1510.00454v1 [hep-ph] 2 Oct 2015

- Vector and axial-vector spectral functions in a pion gas
- No baryon effects accounted for yet

- 4π processes: $\pi + a_1 \rightarrow \gamma^* \rightarrow$ *l+l-* (chiral mixing) is a dominant hadronic source in IMR
  - *No correlated charm contribution!*
  - *No Drell-Yan!*
  - *No QGP!*

→ Access to chiral symmetry restoration? (thought in model dependent way!)

FUTURE

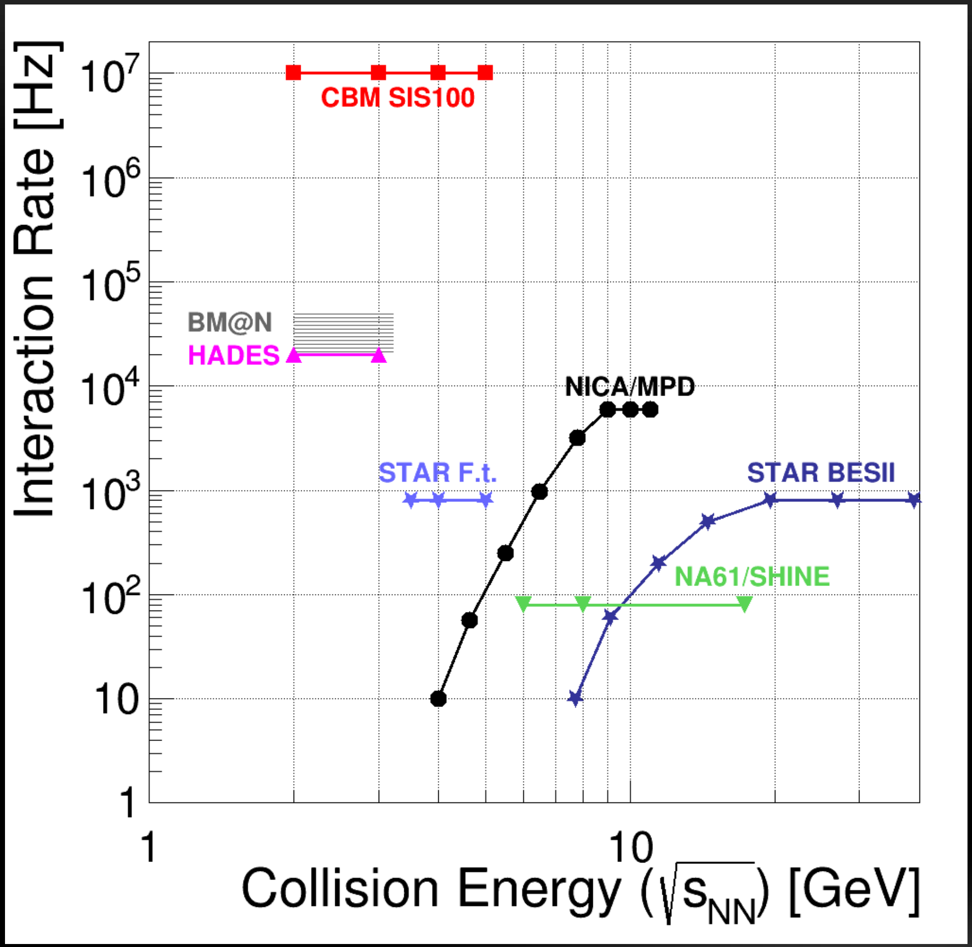
EXPERIMENTS AIMING FOR DILEPTONS, ECT* DEC. 2015

		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
HADES	SIS18			2.5 GeV + pA, πA							
STAR BES	RHIC				8 – 20 GeV			200GeV			
MPD	NICA				4 – 11 GeV						
CBM	SIS100							2 – 5 GeV			
ALICE*	LHC	5.5 TeV					5.5 TeV				
	J-PARC**			pA 8 GeV							2 –5GeV
NA60+	SPS		LOI						6 – 17 GeV		
PHENIX	RHIC	200 GeV									
STAR	RHIC	200 GeV	pp(500)								
sPHENIX								200 GeV			
BM@N	Nuclotron		2 – 3 GeV								

* - ITS, 50kHz, lower field

** - Proposal to J-PARC in 2016, If approved, construction of HI injector and detectors in 10 years ?

THE PRESENT AND FUTURE ION EXPERIMENTS



Program needs high quality data!

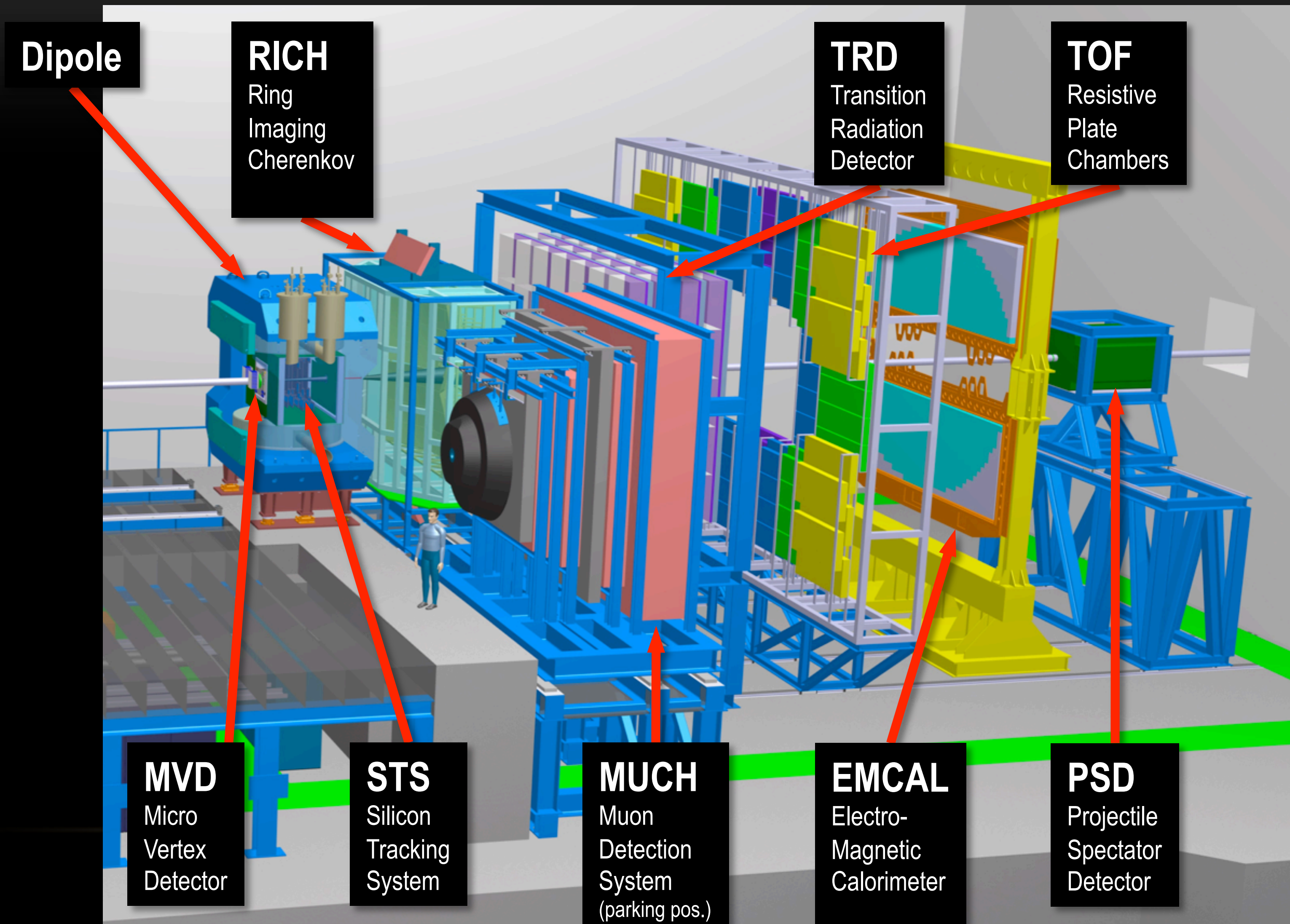
Systematic measurements from SIS18 – SIS100 energies of T, T_{eff} vs M_{ll}, yield, shape with high precision (few MeV) needed!

Colliders not competitive to fixed-target experiments in terms of interaction rate
→ Rare probes difficult to access

Numbers are from:

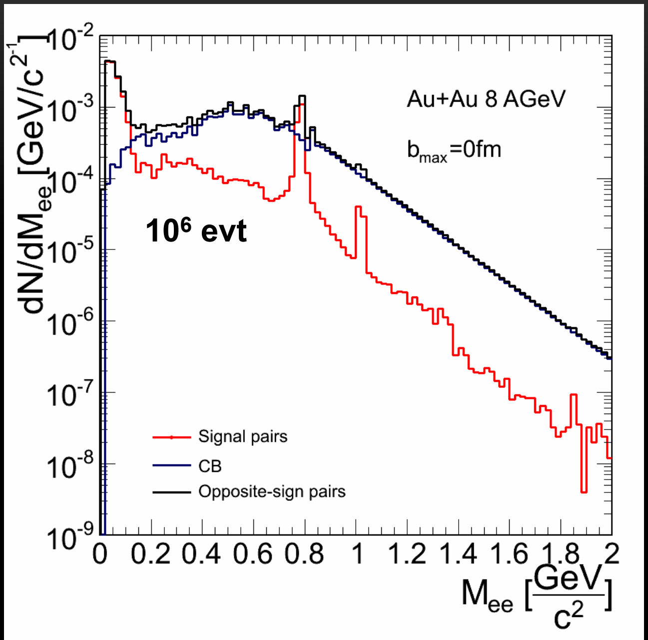
- NICA: A. Sorin, CPOD 2014
- RHIC: C. Montag, D. Cebra, CPOD 2014
- STAR Fixed Target: G. Odyniec, CPOD 2013
- SPS: G. Usai TPD workshop’14
- NA61: M. Gazdzicki, CBM Symposium 2014
- HADES: J. Michel et al., IEEE Trans.Nucl.Sci. 58 (2011)

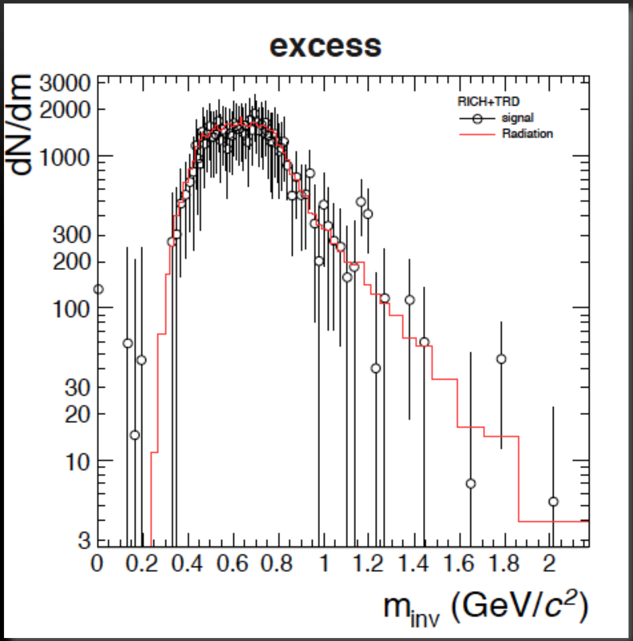
EXPERIMENTAL SETUP
CBM DETECTOR COMPONENTS

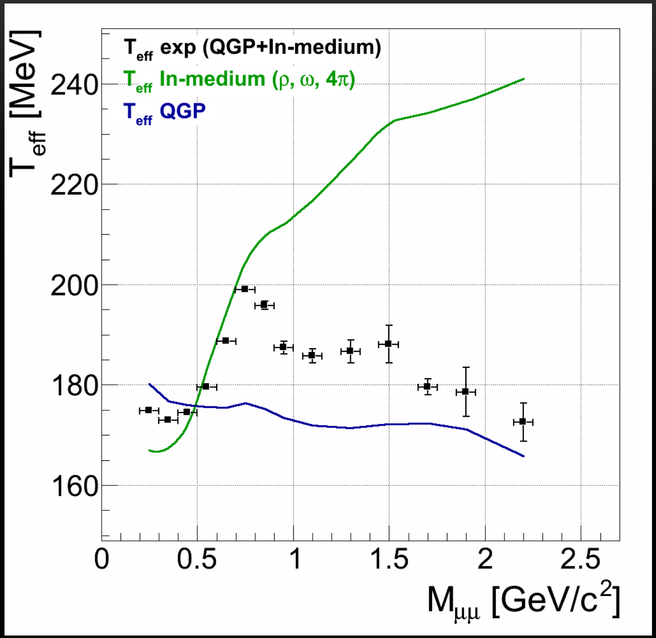


CBM AT SIS100/300
SIMULATION RESULTS

Dilepton signal: detected







Aim:

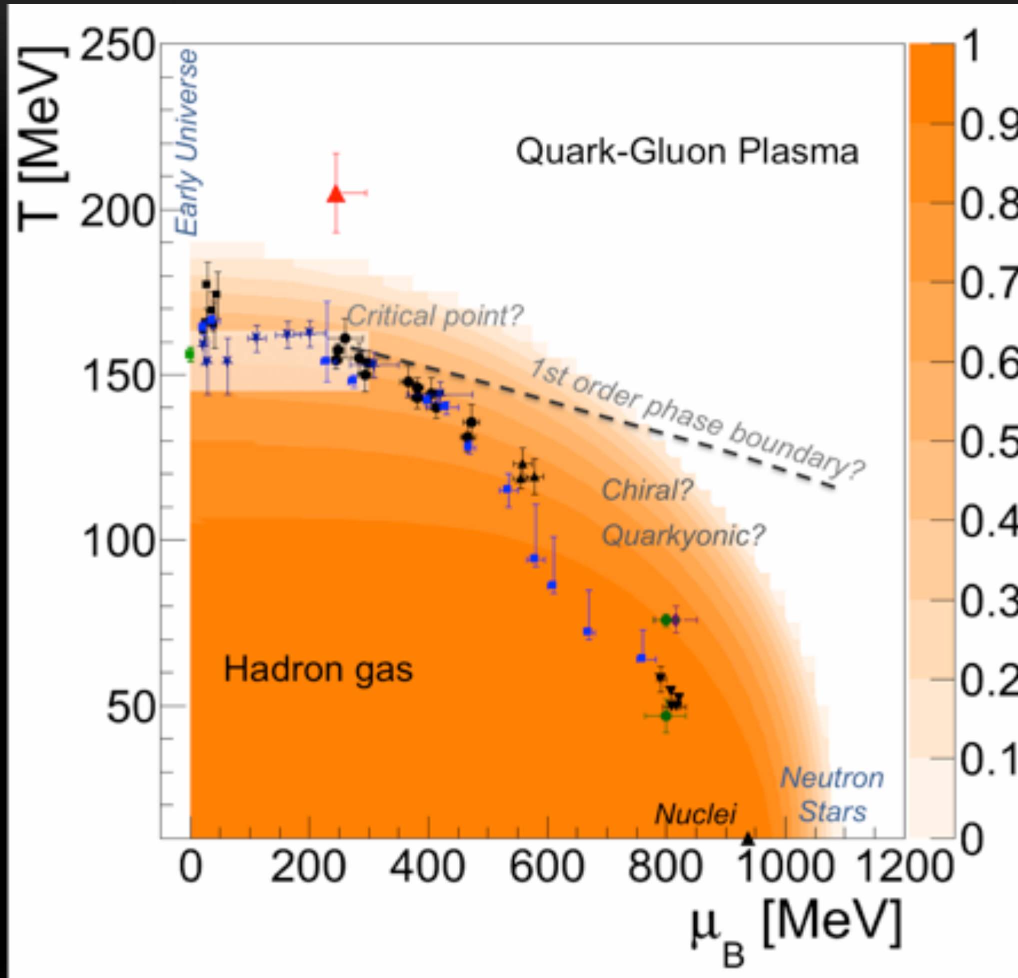
- Systematic measurement of EM radiation over the full energy range from SIS18 to SIS100
- Energy scan, Au and p beams

Performance:

- Simulations with realistic detector geometries, material budget, and response
- Mass resolution: $\sigma_M(\omega)$= 14 MeV/c^2
- Pair detection probability ≈ 8%

EXPLORING QCD PHASE STRUCTURE USING RARE PROBES

Direct γ
ALICE: JPCS 446 (2013) 012028
PHENIX: PRL 104 (2010) 132301



$\frac{<\bar{q}q>_{T,\mu_B}}{<\bar{q}q>_{T=0,\mu_B=0}}$: B.J. Schaefer and J. Wambach

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

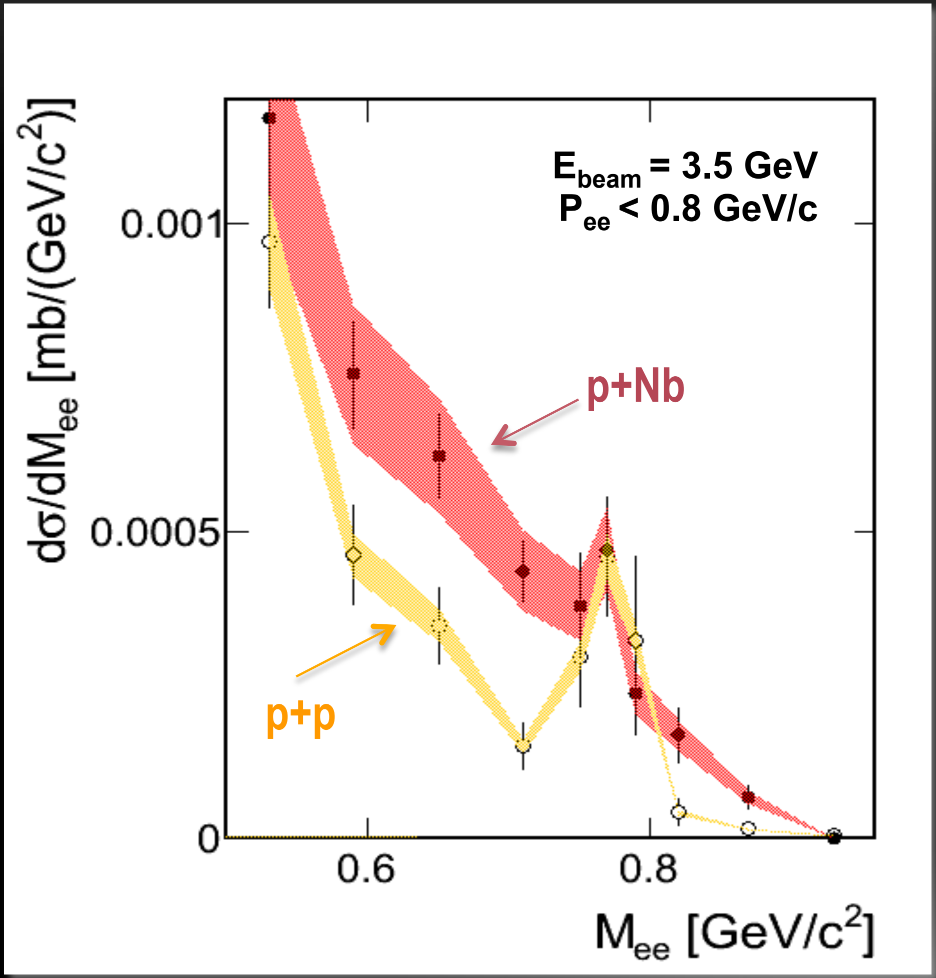
Encouraging prospects for studying QCD matter in the region of finite μ_B with dileptons

- Explore unknown territory of the nuclear matter phase diagram
  - Aim: establish a complete excitation function of dilepton production from SIS18 up to LHC
    - Change in degrees of freedom
    - Chiral symmetry restoration
    - Emitting source temperature

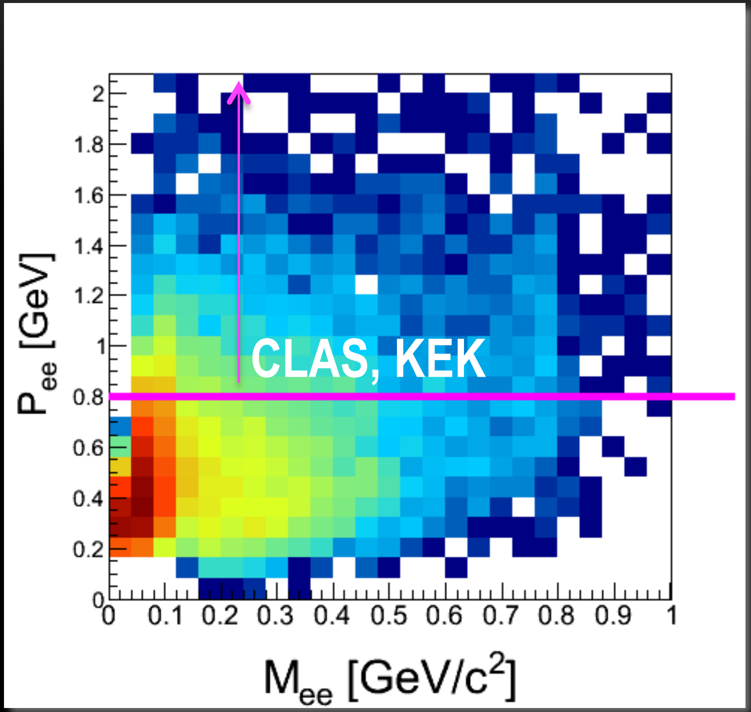
- Much more emphasis are put on running at energies optimal for the study of the QCD phase transitions and high baryon densities
- Future experiments allows for overlap and independent confirmation of results

THANK YOU!

VECTOR MESON MODIFICATIONS IN p+A REACTIONS



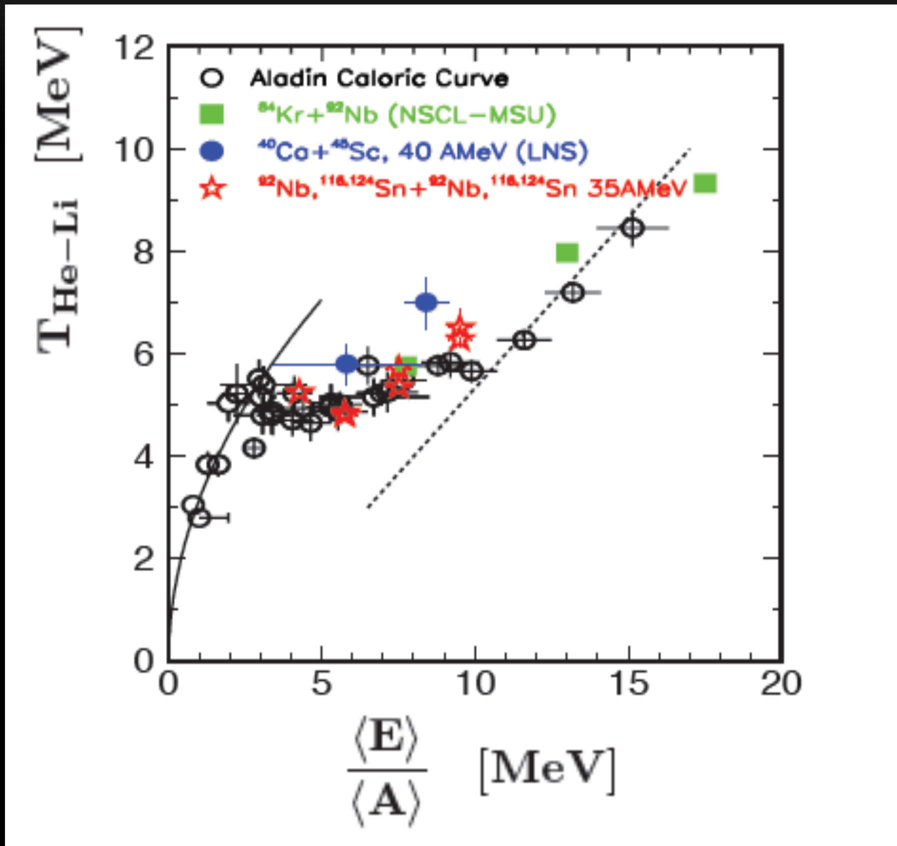
HADES: Phys.Lett. B715 (2012)

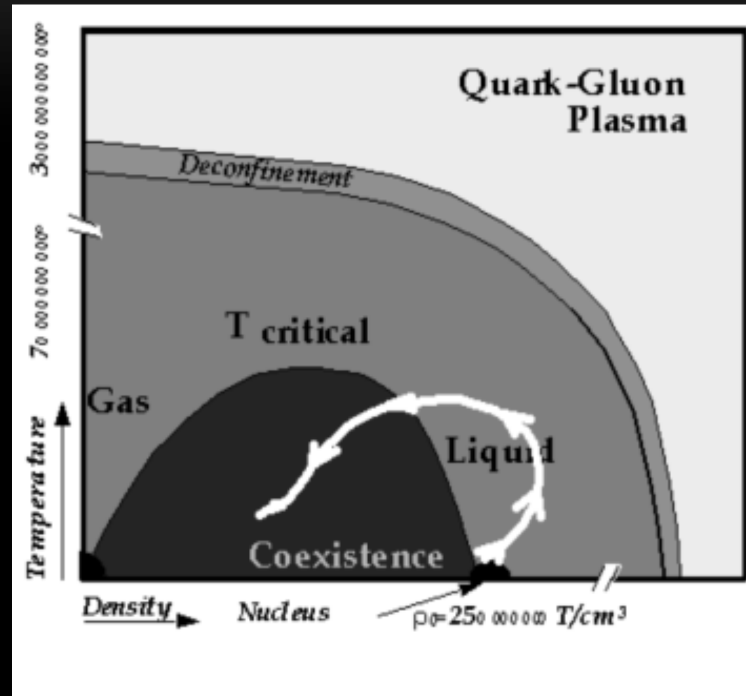


- First measurement of in-medium vector meson decays in the relevant momentum region (P_{ee} down to 0.2 GeV/c)
- HADES sees rather a melting than a shift

NUCLEAR LIQUID-GAS TRANSITION

FROM MULTI-FRAGMENTATION MEASUREMENTS IN HEAVY-ION COLLISIONS

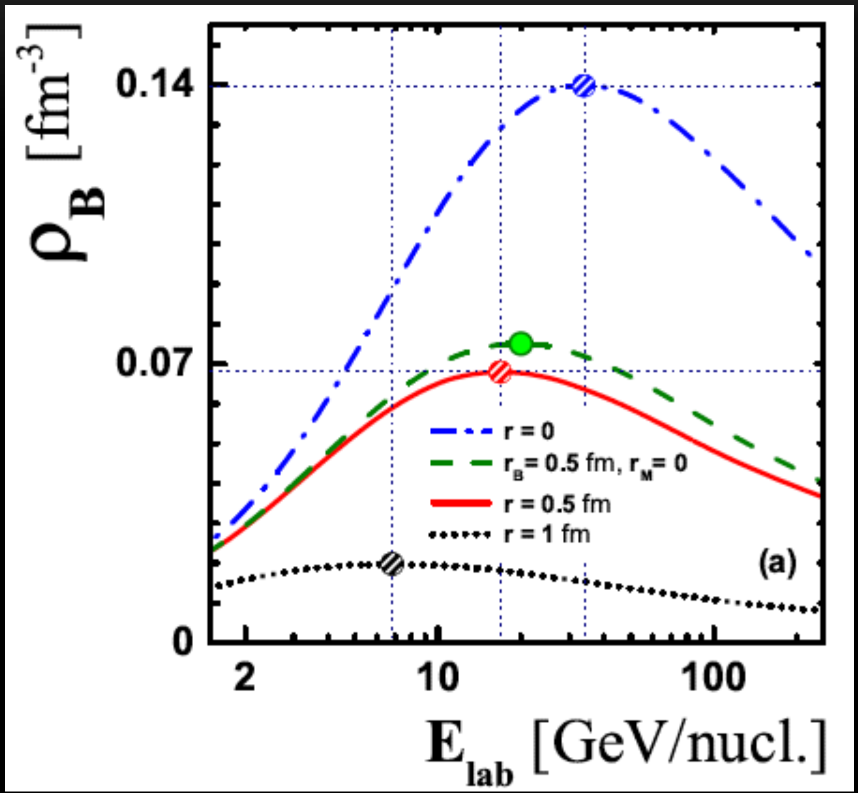




J. Pochodzalla et al. Phys. Rev. Lett. 75 (1995) 1040
M. D'Agostino et al. Nucl. Phys. A 749 (2005) 5533
P. Chomaz Nucl. Phys. A 685 (2001) 274

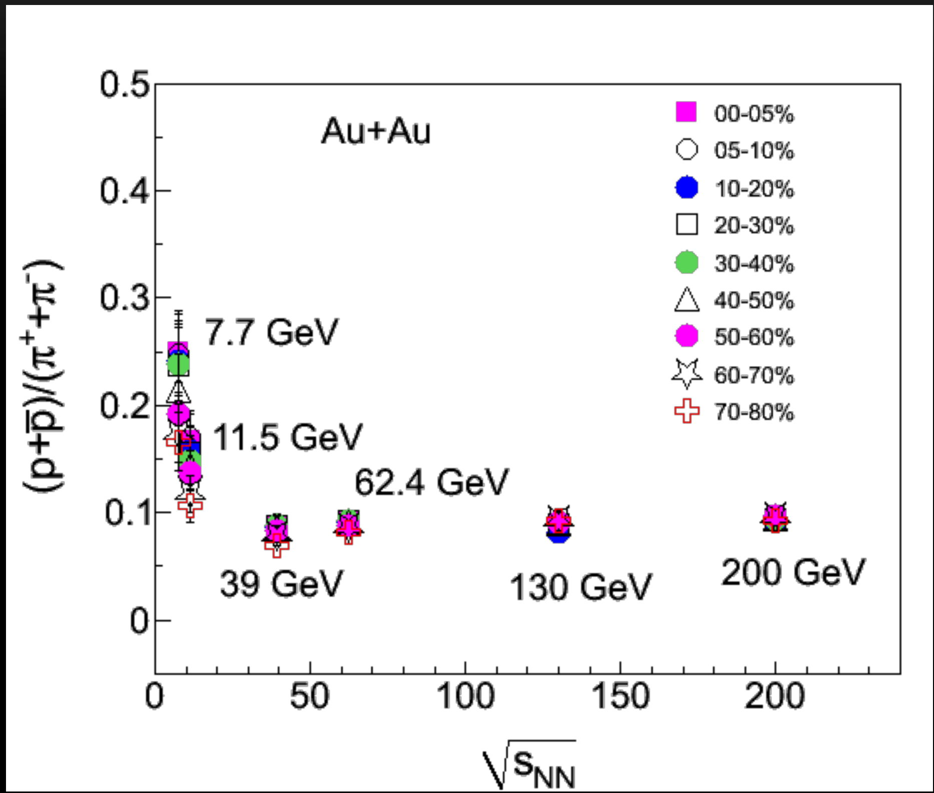
QUEST: EXPLORE THE REGIME OF BARYON DOMINATED MATTER

Hadron-Resonance Gas at freeze-out

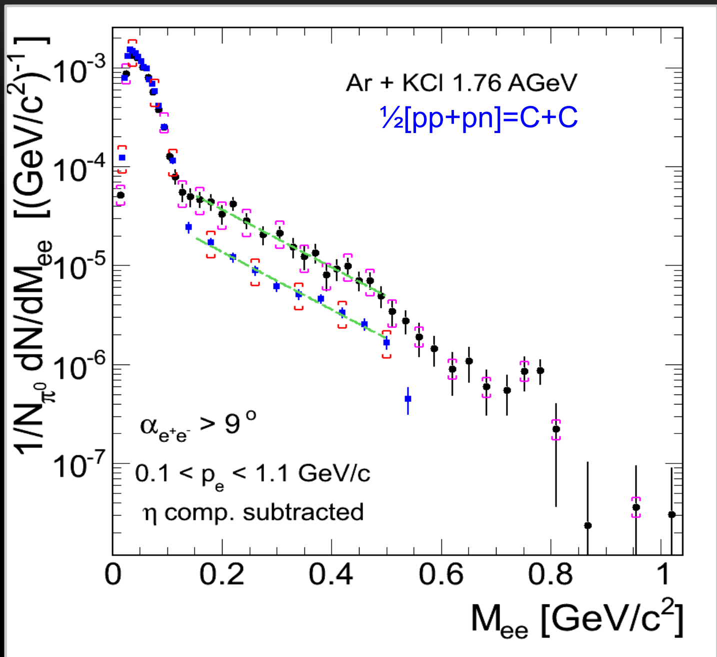


V.V. Begun et al., PRC PhysRevC.88.024902

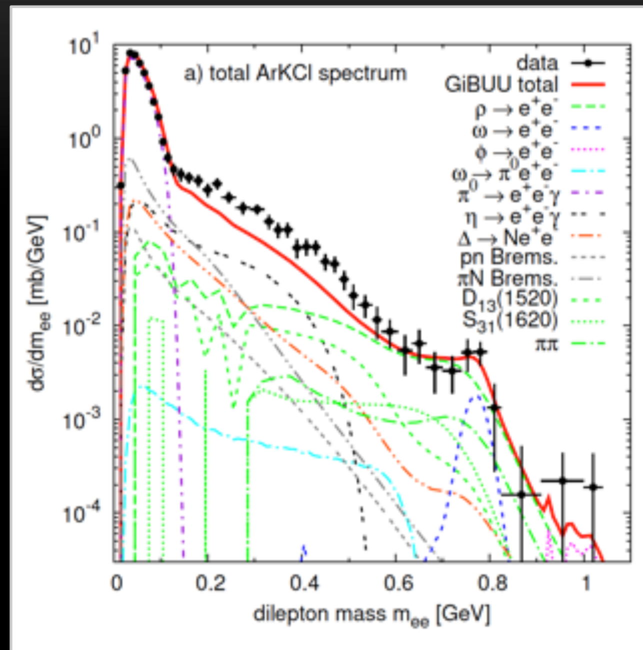
Baryon – to – pion ratio, STAR data



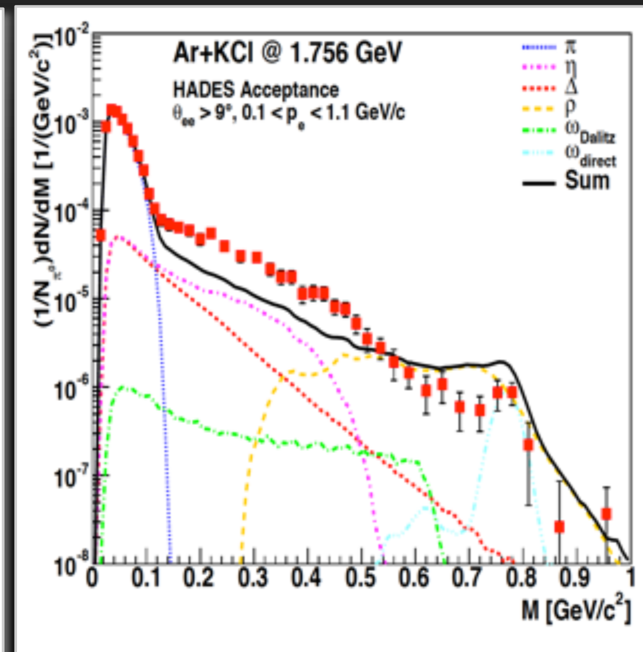
- Baryon density is factor of ~2 larger at SPS compared to SIS18
- π densities a factor ~50 higher at SPS (~ 7.5 pions / baryon)
- No dilepton measurements for beam energies of 2 - 40 GeV/nucl.



HADES: Phys.Rev.C 84 (2011) 014902



J. Weil
J.Phys.Conf.Ser. 426 (2013) 012035



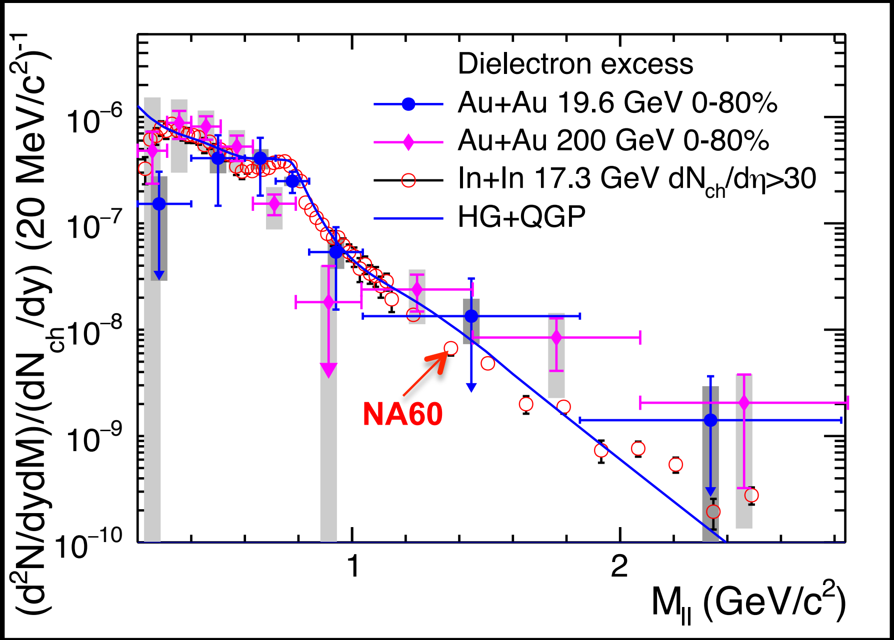
S. Endres
J.Phys.Conf.Ser. 503 (2014) 012039

- First evidence for radiation from the "medium" in this energy regime!

- Models with vac. SF misses data → room for medium modifications!
  See also [Bratkovskaya et al , Kämpfer et al, Weil et al,…]

THE HIGH ENERGY FRONTIER: STAR (NOW) & ALICE (RUN 3)

Acceptance corrected invariant-mass excess spectrum

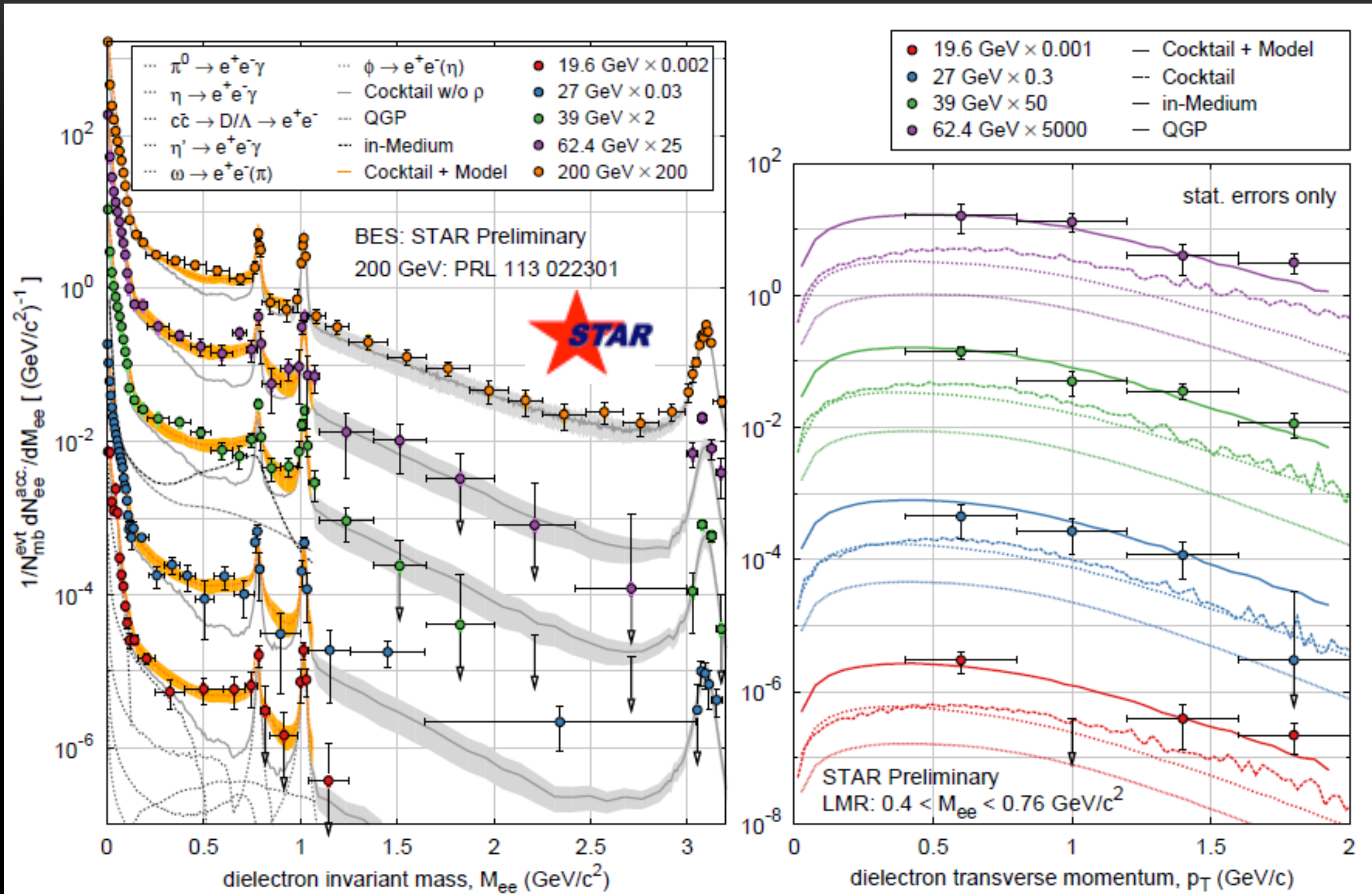


STAR: PLB 750 (2015) 64
NAN60: AIP Conf. Proc. 1322 (2010) 1

- RHIC $\sqrt{s_{NN}}$ = 200 GeV and LHC
  - μ_B<<T, i.e. vanishing net-baryon density
  - **Lattice QCD computations are most powerful!**
- Precision measurement from $\sqrt{s_{NN}}$ = 200GeV is needed to "calibrate" EM rates
- Wish: excess mass spectrum a-la NA60, i.e. subtracting all know sources, at $\sqrt{s_{NN}}$ = 200GeV
  - High precision measurements of charm
  - Statistic!

→ Use 4 × 10^9 events with HFT

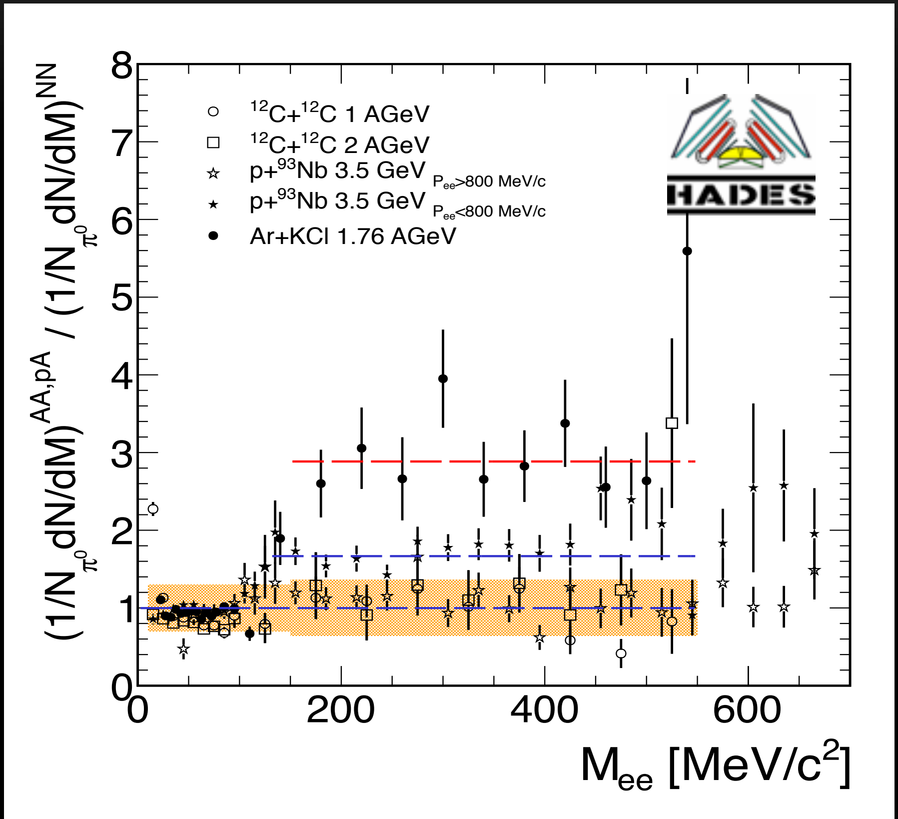
LOW-MASS e^+e^- EXCITATION FUNCTION: 19.6-200 GeV



STAR data: P. Huck et al., Nucl.Phys. A931 (2014)
Model: Rapp/Wambach/Hees

- Compatible with predictions from melting ρ meson
- "Universal" source around T_{pc}

LOW-MASS DILEPTONS AT 1 – 2A GeV, LIGHT SYSTEMS

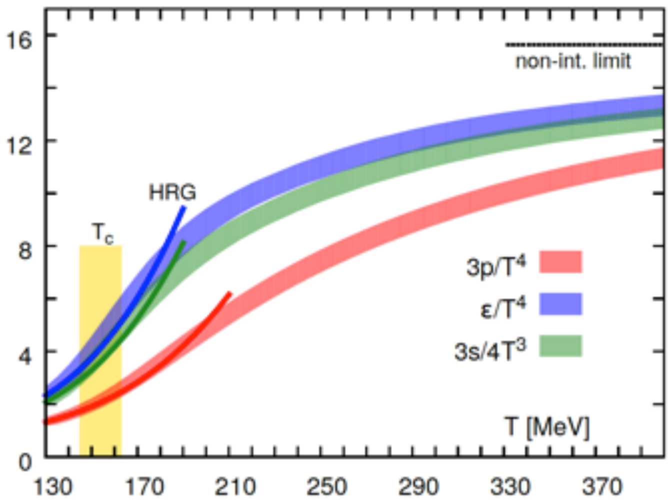


- Freeze-out contributions removed (π^0 by normalization, η by subtraction)
- pNb: First measurement of in-medium vector meson decays in the relevant momentum region (P_{ee} down to 0.2 GeV/c)
- Ar+KCl: First evidence for radiation from the "medium" in this energy regime
- It scales with the system size stronger then linearly and "counts" number of Δ/N^* regenerations!

HADES Coll.:
Phys.Rev. Lett 98 (2007) 052302
Phys.Lett. B 663 (2008) 43
Phys.Lett. B 690 (2010) 118
Phys.Rev. C 84 (2011) 014902
Phys.Lett. B 715 (2012)

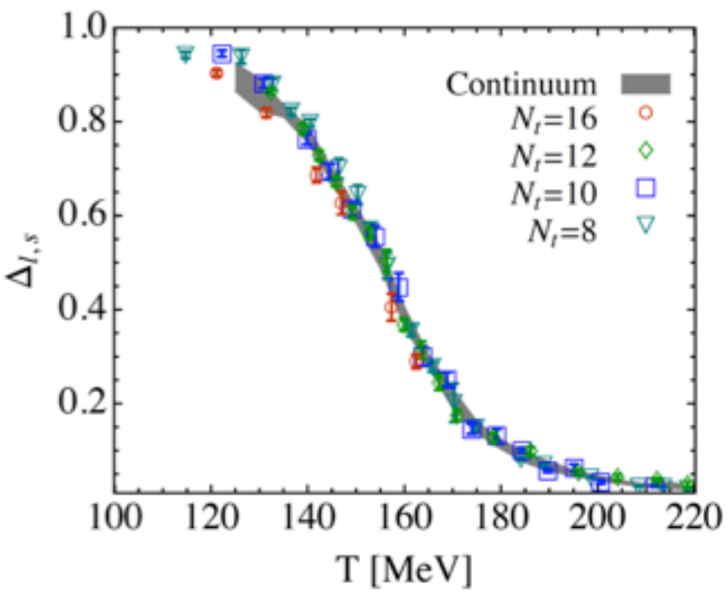
HADES "Resonance clock"

Deconfinement transition



Hot QCD Coll., arXiv:1407.6387 (2014)

Chiral symmetry restoration



S. Borsanyi et al. [Wuppertal-Budapest Coll.], JHEP 1009 (2010) 073

MOTIVATION

Mass degeneration and deconfinement are closely related to the fate of the QCD condensates in the medium!

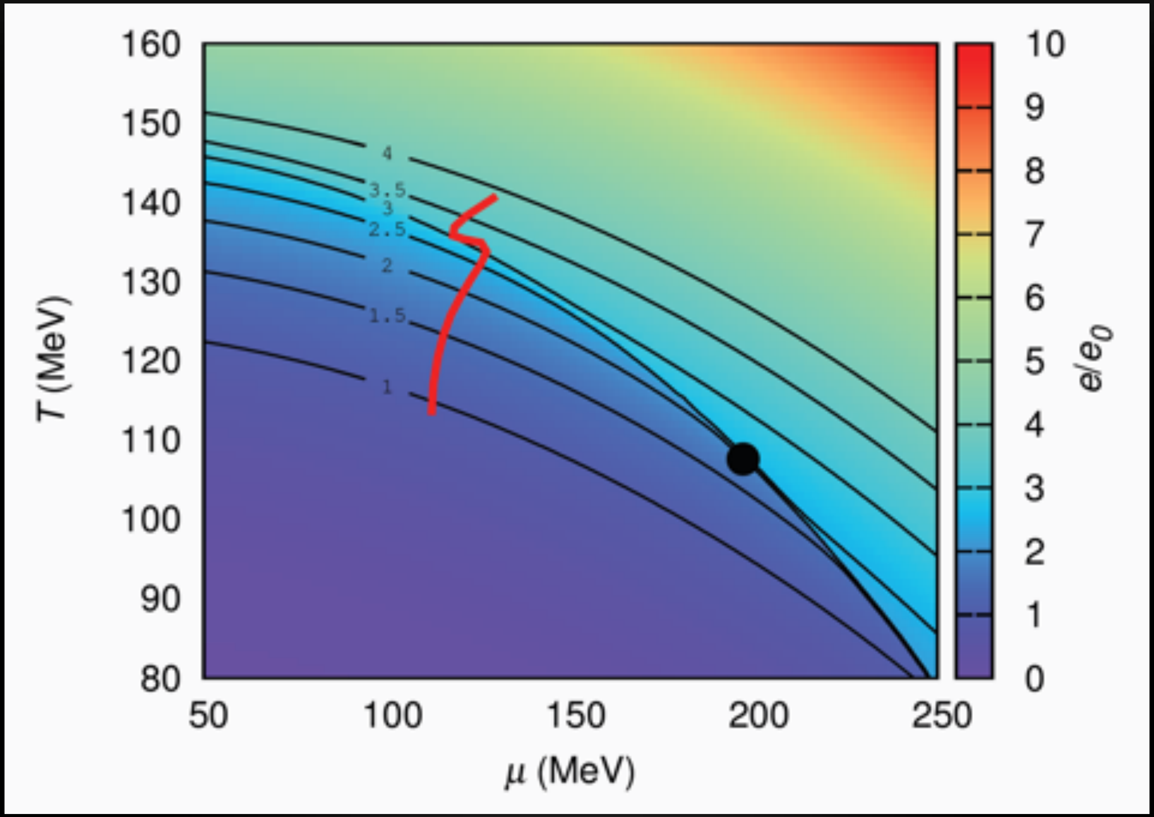
Under which temperature and pressure does matter deconfine and/or restore symmetry?

- Establish the nature of QCD phase transitions
- Understand the generation of mass in strong interactions

→ *Experimental test!*

MAPPING QCD PHASE DIAGRAM WITH DILEPTONS

Event-averaged trajectory near the critical point (black dot)



C. Herold, M. Nahrgang, Y. Yan and C. Kobdaj, PRC93 (2016) no.2