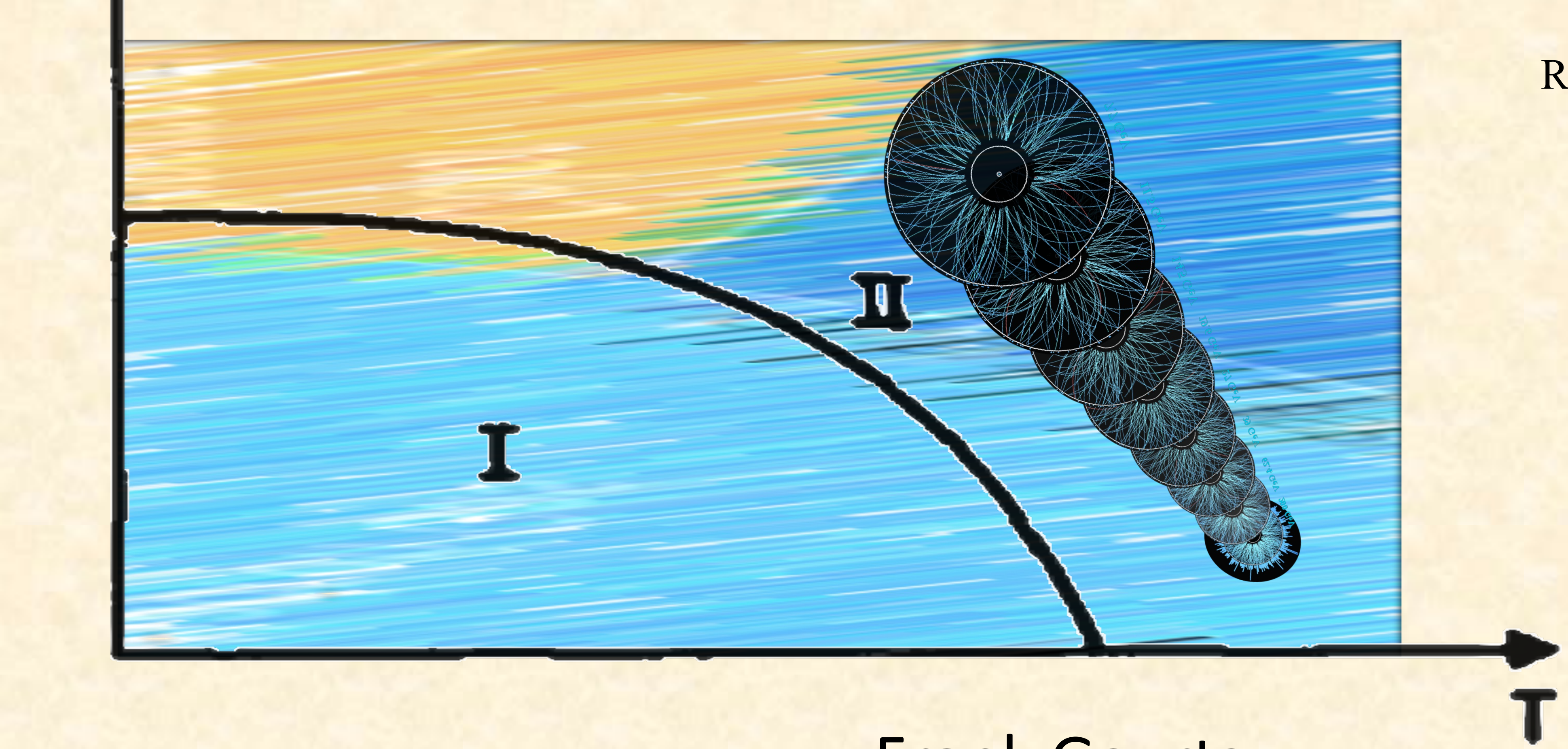
Dileptons and BES Physics



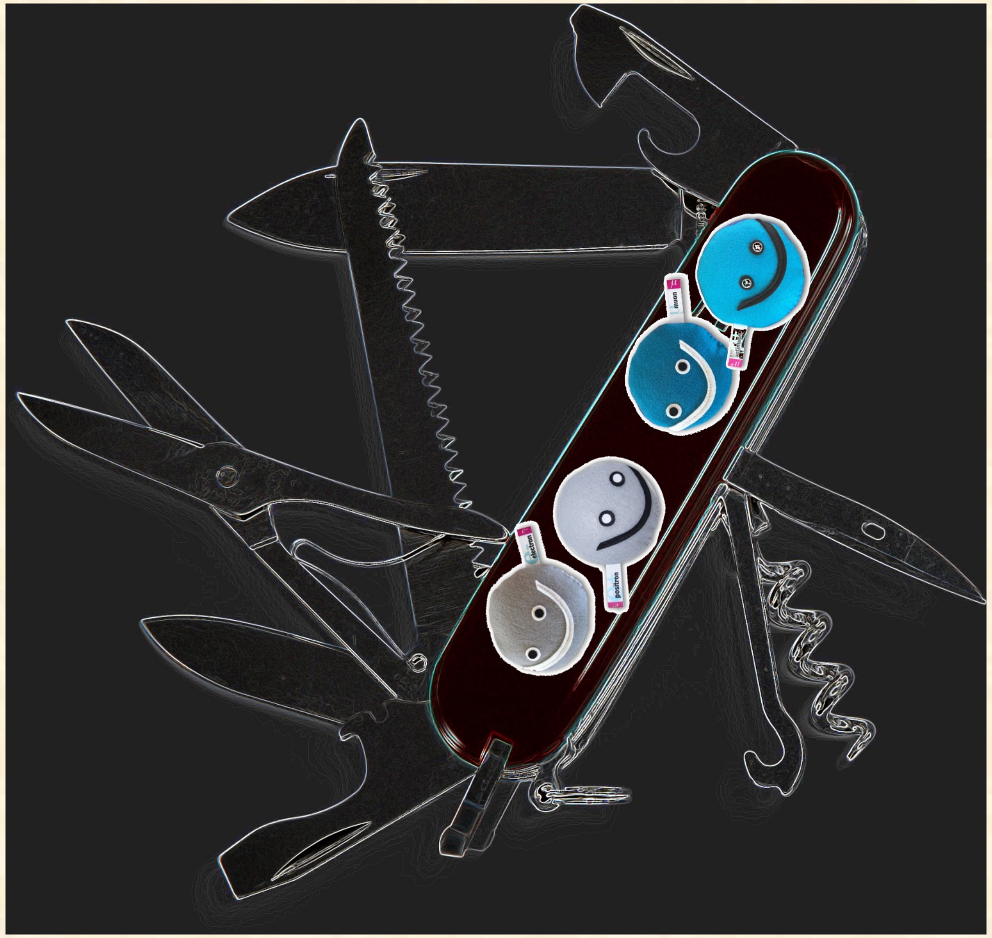
RHIC-BES Seminar
April 25, 2023

Frank Geurts
Rice University

Outline

- QCD Phase Diagram
- What role can dileptons play?
- Some theoretical considerations
- Some experimental considerations
- The Dilepton Multitool

  spectrometer, chronometer, thermometer,
  barometer, polarimeter, multimeter
- Future prospects



QCD phase diagram

Experimentally, one can access different regions of phase diagram by varying centre-of-mass energy

- experimental data over 3-4 orders of magnitude in $\sqrt{s_{NN}}$

LHC, RHIC, and FAIR provide access to low μ_B region

– cross-over region

Several experiments/facilities give access to μ_B regions that both cover cross-over, possible 1st order PT and a conjectured CP

- AGS, SPS (NA61/SHINE)
- SIS18/FAIR (Hades)
- RHIC beam energy scan (BES)

Cabbibo & Parisi, PLB58 (1975) 67

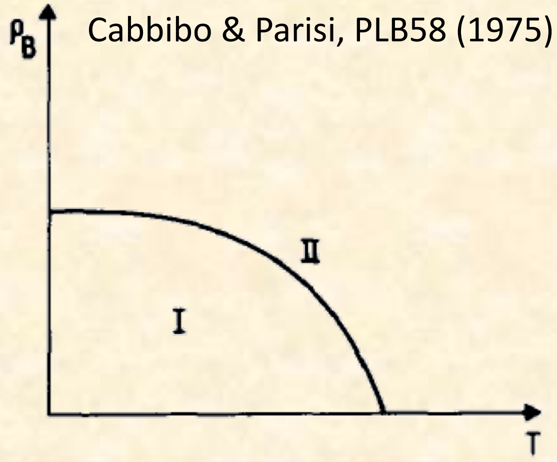
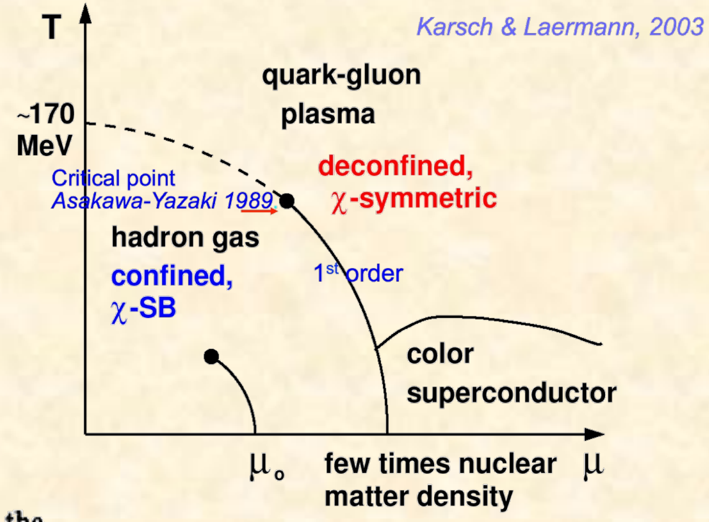
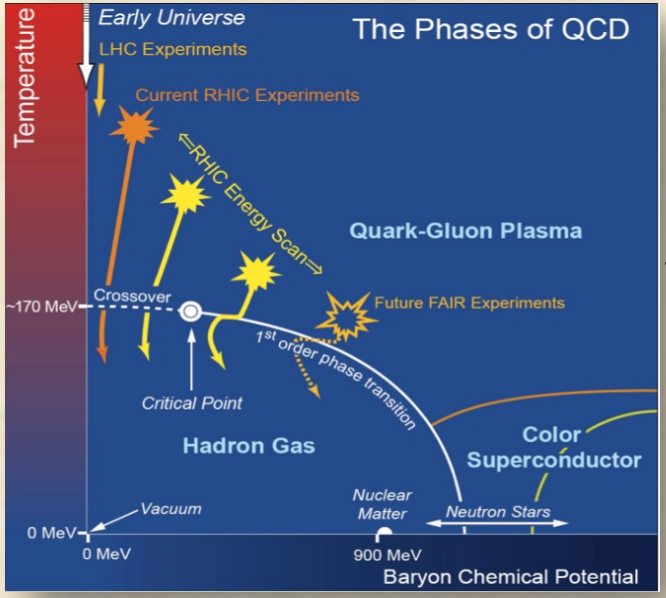


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

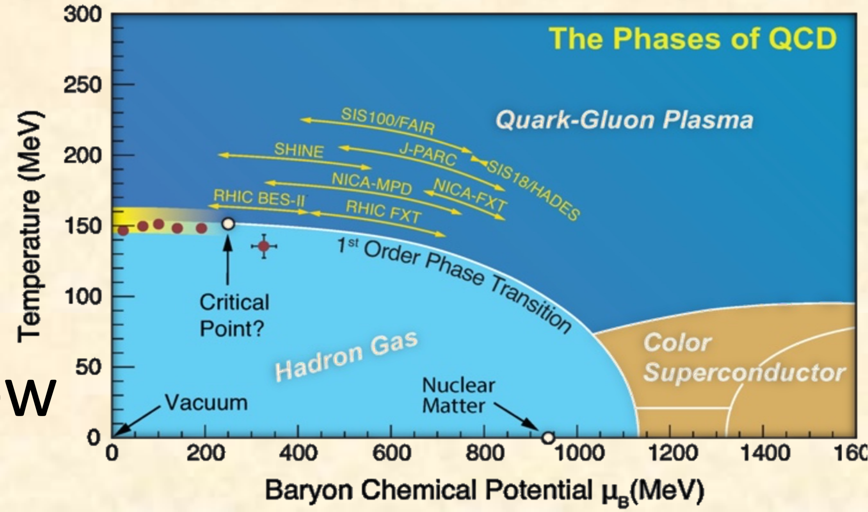
Karsch & Laermann, 2003





BES-2 White Paper – STAR Note 598

Charting the QCD phase diagram



- Turn-off of QGP signatures - suppression, elliptic flow

- First-order phase transition - changes in EoS due to attractive force (softest point)
  - ➢ "step" in mean transverse mass of identified particles
  - ➢ non-monotonic behavior of directed flow slope at mid-rapidity $(dv_1/dy|_{y=0})$

- Critical point - divergence of the correlation length ⇒ non-monotonic behavior of higher moments of conserved quantities
  - ➢ experimentally, skewness S, and kurtosis κ of event-by-event net-particle distributions

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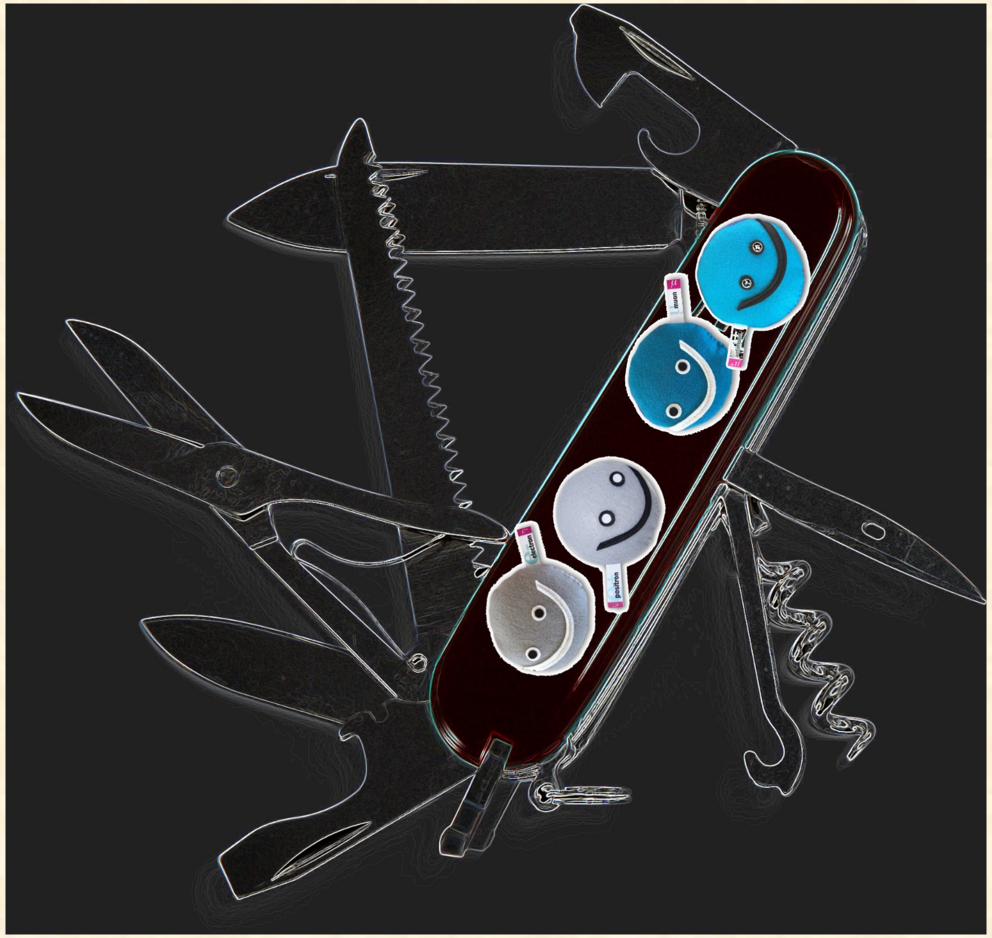
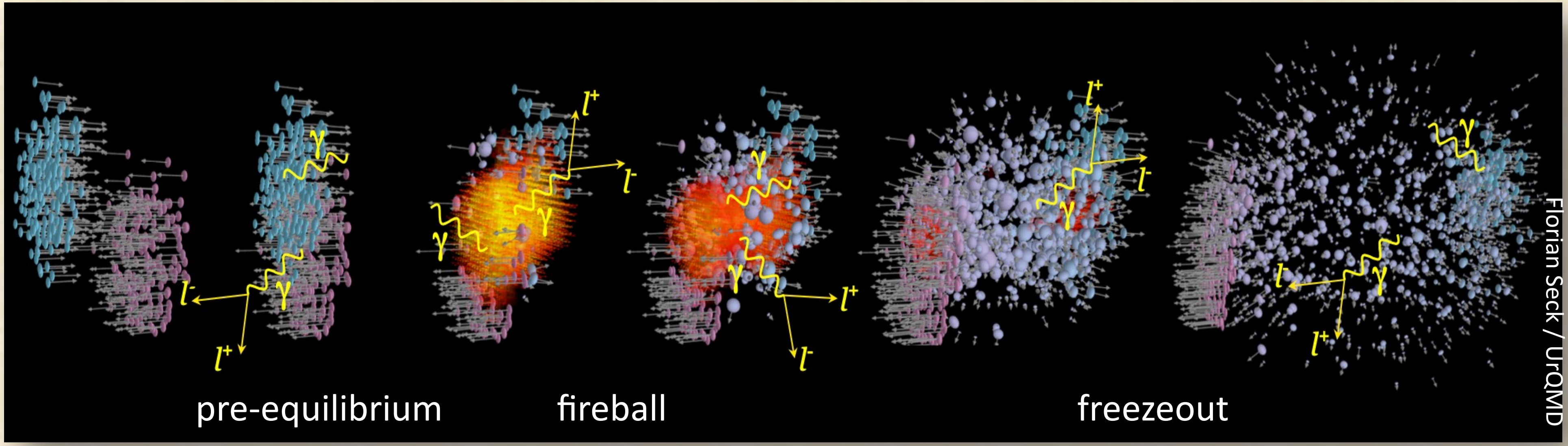


What can dileptons do?

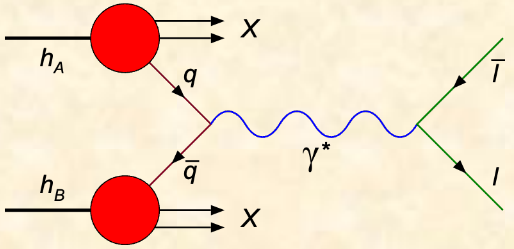


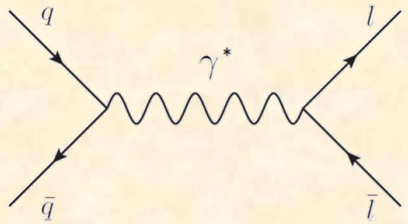
Dileptons are excellent penetrating probes

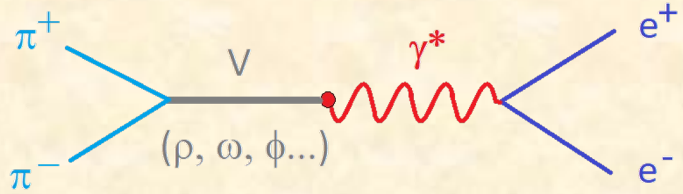
- colorless objects ∴ no coupling to strongly interacting matter
- produced in various ways throughout the system's evolution
- long mean free paths
- experimentally provide an additional "knob": invariant mass

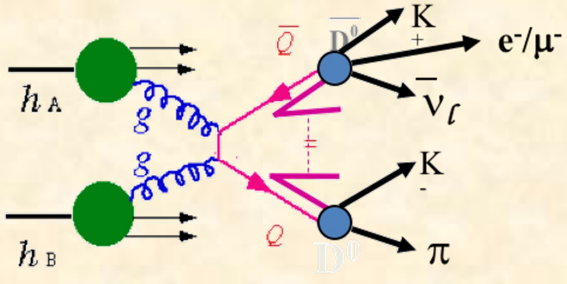
Dilepton invariant mass spectrum

- Primordial emissions, pre-equilibrium
  - Drell-Yan, $NN \rightarrow e^+e^- X$
  - heavy flavor production $(c\bar{c}, b\bar{b})$, quarkonia & open charm
- Thermal radiation from QGP/hadronic matter
  - QGP thermal radiation $q\bar{q} \rightarrow e^+e^-$
  - HG thermal radiation $\pi^+\pi^- \rightarrow e^+e^-$
  - in-medium ρ
  - other 4π, multi-meson interactions, incl. $\rho - a_1$mixing
- Long-lived hadron and resonance decays
  - decays of light mesons of π^0, η, ω, φ (incl. Dalitz decays)
    - in-medium modification of vector mesons
  - decays of quarkonia J/Ψ, Ψ' and correlated $D\bar{D}$ *pairs*
    - nuclear modification effects

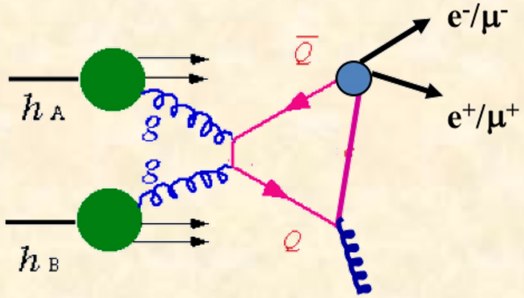








open heavy flavor



heavy quarkonia

Dilepton invariant mass spectrum

- High Mass Range (HMR)

  $M_{ee} > 3$ GeV/c^2

  – primordial emission, Drell-Yan
  – Heavy quarkonia: J/ψ and ϒ suppression

- Intermediate Mass Range (IMR)

  $1.1 < M_{ee} < 3$ GeV/c^2

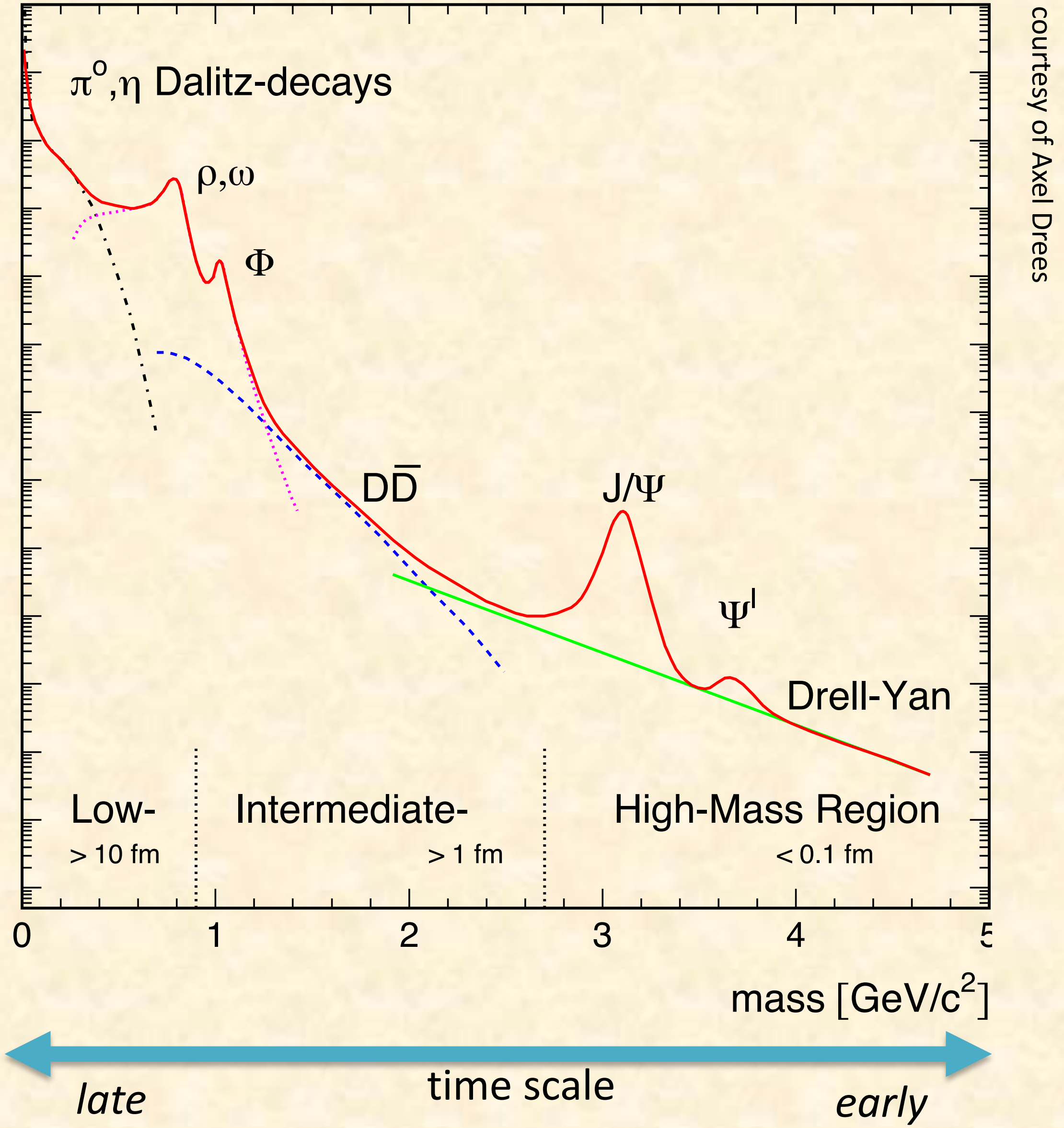
  – QGP thermal radiation
  – Semi-leptonic decay of correlated charm

    heavy-flavor modification

- Low Mass Range (LMR)

  $M_{ee} < 1.1$ GeV/c^2

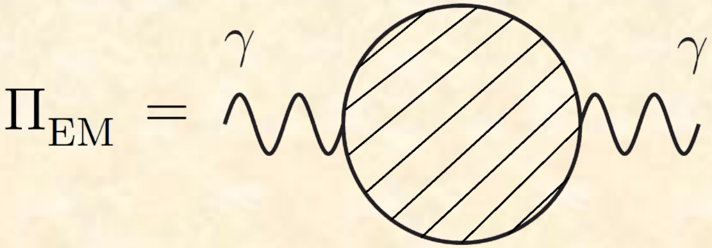
  – in-medium modification of vector mesons
  – fireball lifetime measurement
  – transport coefficients (electrical conductivity)



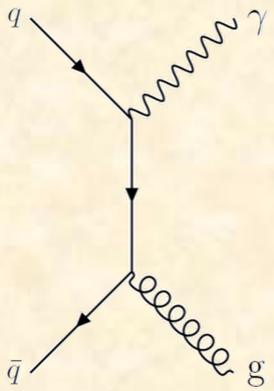
EM production rates

From thermal field theory†, using EM current-current correlation function:

$$\Pi^{\mu\nu}_{em}(q_0, q) = -i \int d^{4x}\, e^{iqx}\Theta(x^0)\, \langle\langle [j^\mu(x), j^\nu(0)] \rangle\rangle$$



$$j^\mu = \sum\nolimits_q e_q \bar{q}\gamma^\mu q = \tfrac{2}{3}\bar{u}\gamma^\mu u - \tfrac{1}{3}\bar{d}\gamma^\mu d \; - \tfrac{1}{3}\bar{s}\gamma^\mu s$$



with the thermal emission rates

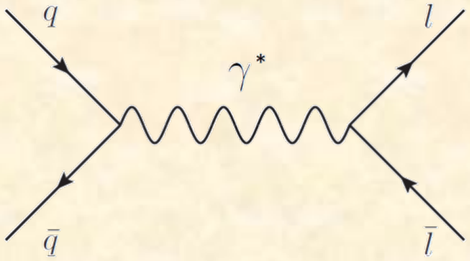
- photons:

$$p_0 \frac{dN_\gamma}{d^4x\, d^3p} = -\frac{\alpha_{em}}{\pi^2} f^B(p_0;T)\ \frac{1}{2} g_{\mu\nu}\ \mathrm{Im}\Pi^{\mu\nu}_{\mathrm{em}}(M=0, p; \mu_B, T)$$

- dileptons:

$$\frac{dN_{ll}}{d^4x\, d^4p} = -\frac{\alpha_{em}^2}{\pi^3 M^2} L(M) f^B(p_0;T)\ \frac{1}{3} g_{\mu\nu}\ \mathrm{Im}\Pi^{\mu\nu}_{\mathrm{em}}(M, p; \mu_B, T)$$

$L(M)$ is lepton space factor and $f^B(p;T)$ is the thermal Bose distribution



- both governed by same underlying spectral functions
  - but different kinematic regimes (lightlike and timelike)

† see e.g. Friman, et al., Lecture Notes in Phys. 814 (2011) 1

Connection with vector mesons

For lightest quarks

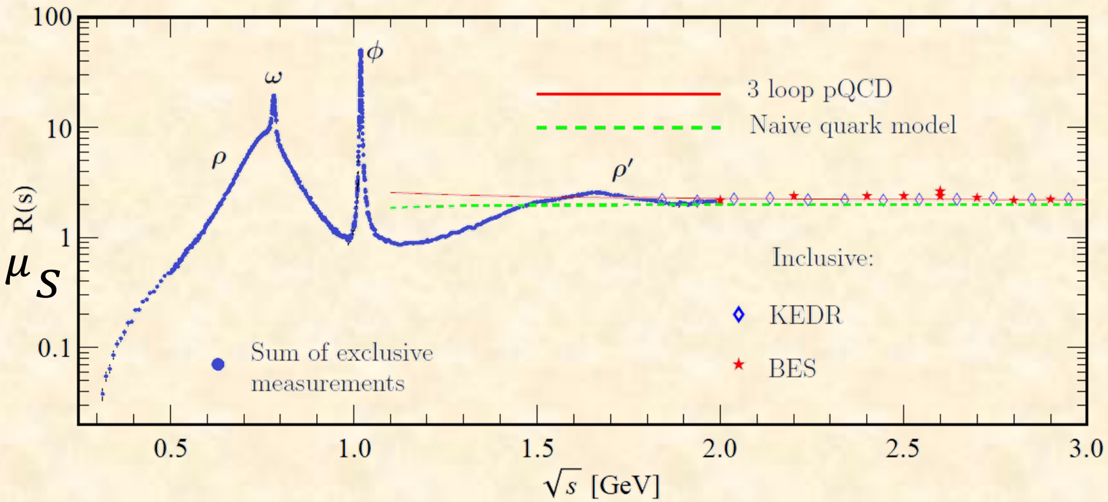
$$j^\mu = \sum_q e_q \bar{q}\gamma^\mu q = \tfrac{2}{3}\bar{u}\gamma^\mu u - \tfrac{1}{3}\bar{d}\gamma^\mu d - \tfrac{1}{3}\bar{s}\gamma^\mu s$$

or grouping into isospin states $I = 1(\rho), 0\ (\omega, \varphi)$:

$$j^\mu = \tfrac{1}{2}\left(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d\right) + \tfrac{1}{6}\bar{d}\gamma^\mu d\left(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d\right) - \tfrac{1}{3}\bar{s}\gamma^\mu s$$

$$= \frac{1}{\sqrt{2}} j_\rho^\mu + \frac{1}{3\sqrt{2}} j_\omega^\mu + \frac{1}{3} j_\phi^\mu$$

Im Π_{em} is well understand in vacuum:

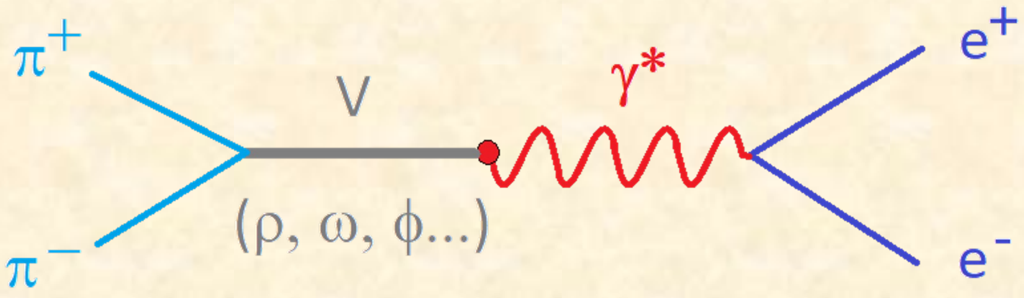


which leads at low M :

$$\mathrm{Im}\,\Pi_{\mathrm{em}} \sim D_\rho + \frac{1}{9} D_\omega + \frac{2}{9} D_\phi$$

vector meson dominance

- carry same quantum numbers as photons
- can directly decay into dileptons
- ρ(770) dominant source



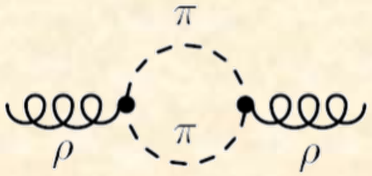
In-medium vector mesons (1)

ρ meson will interact with hadrons in the medium

propagator will have various contributions to the self-energy

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

$\Sigma_{\rho\pi\pi}$ =

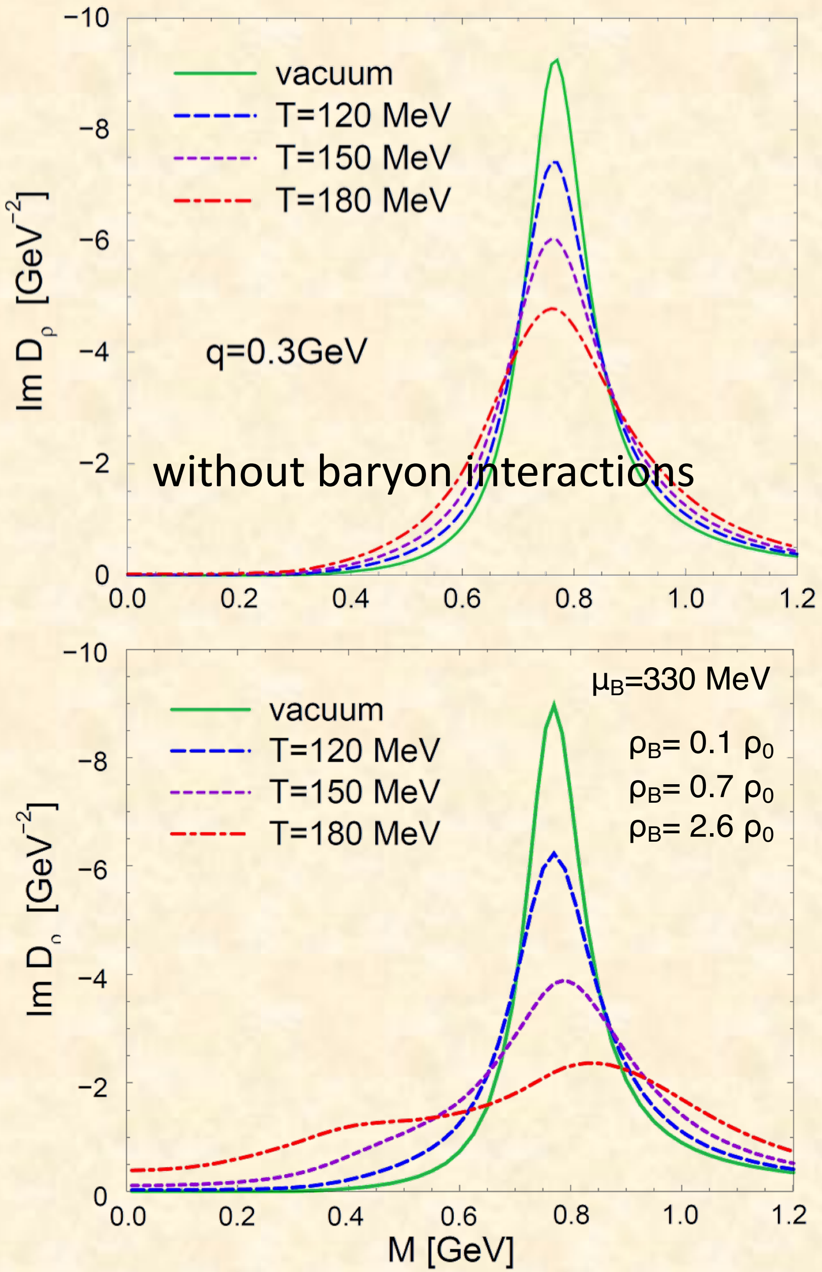


in-medium pion cloud

$\Sigma_{\rho B,M}$ =

direct ρ-hadron scattering

strong broadening of ρ spectral function
→ baryons are important



Rapp, Acta Phys. Polon. B42 (2011) 2823

In-medium vector mesons (2)

QCD langrangian contains subgroup $SU_L(n_f)\times SU_R(n_f)$

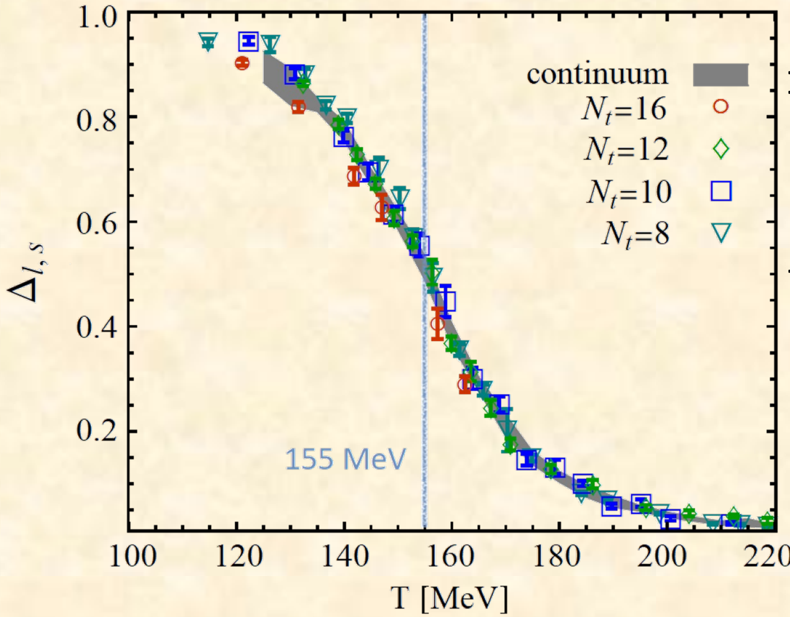
- chiral symmetric in limit of vanishing quark masses
  - lattice QCD: dynamical formation of $\langle q\bar{q}\rangle \sim \Delta_{l,s}$
    breaks chiral symmetry
  - profound effect on chiral partners

$$\langle q\bar{q}\rangle = \langle q_L\bar{q}_R + q_R\bar{q}_L\rangle$$

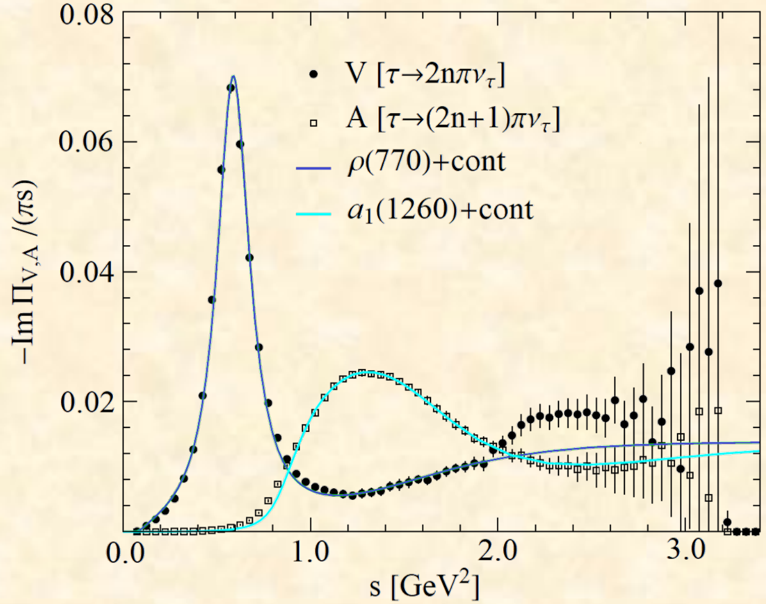
    significant mass splitting between chiral partners
    ρ(770) - a_1(1260), nucleon(940) - N(1535), σ – π

- Weinberg (chiral) sum rules connect SFs to condensates:

$$\int_0^\infty \frac{ds}{\pi}\left(\Pi_V(s) - \Pi_A(s)\right) = m_\pi^2 f_\pi^2 = -2\, m_q\langle q\bar{q}\rangle$$



Wuppertal-Budapest collaboration

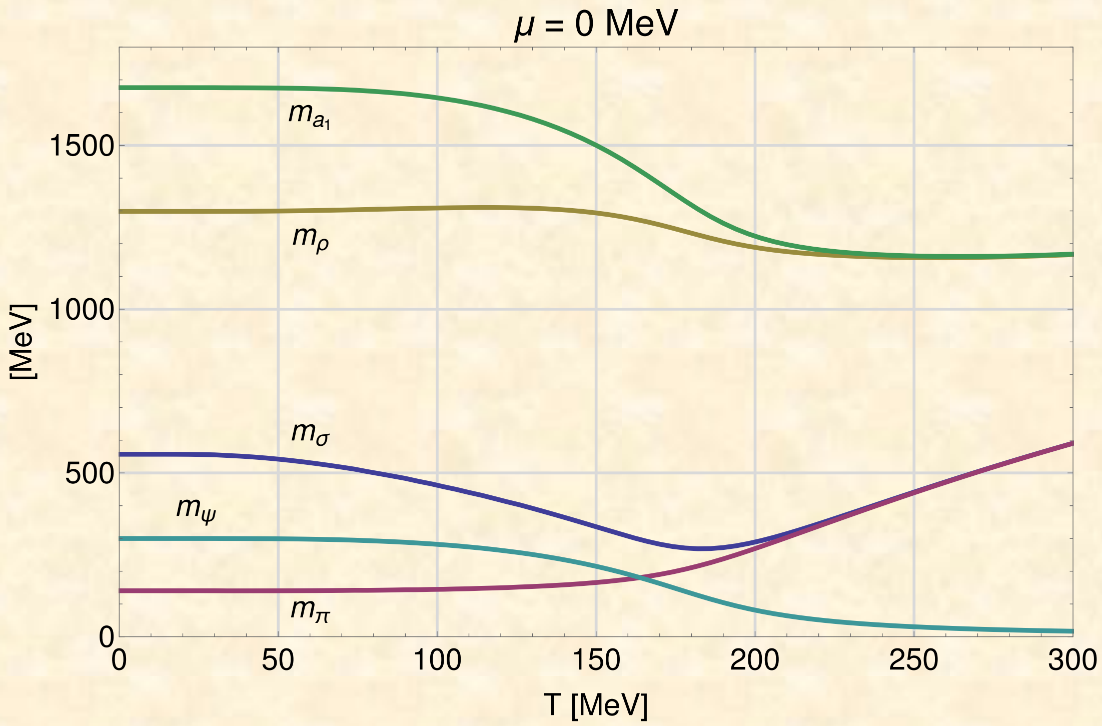


Rapp, Pramana 60 (2003) 675

Chiral symmetry restoration

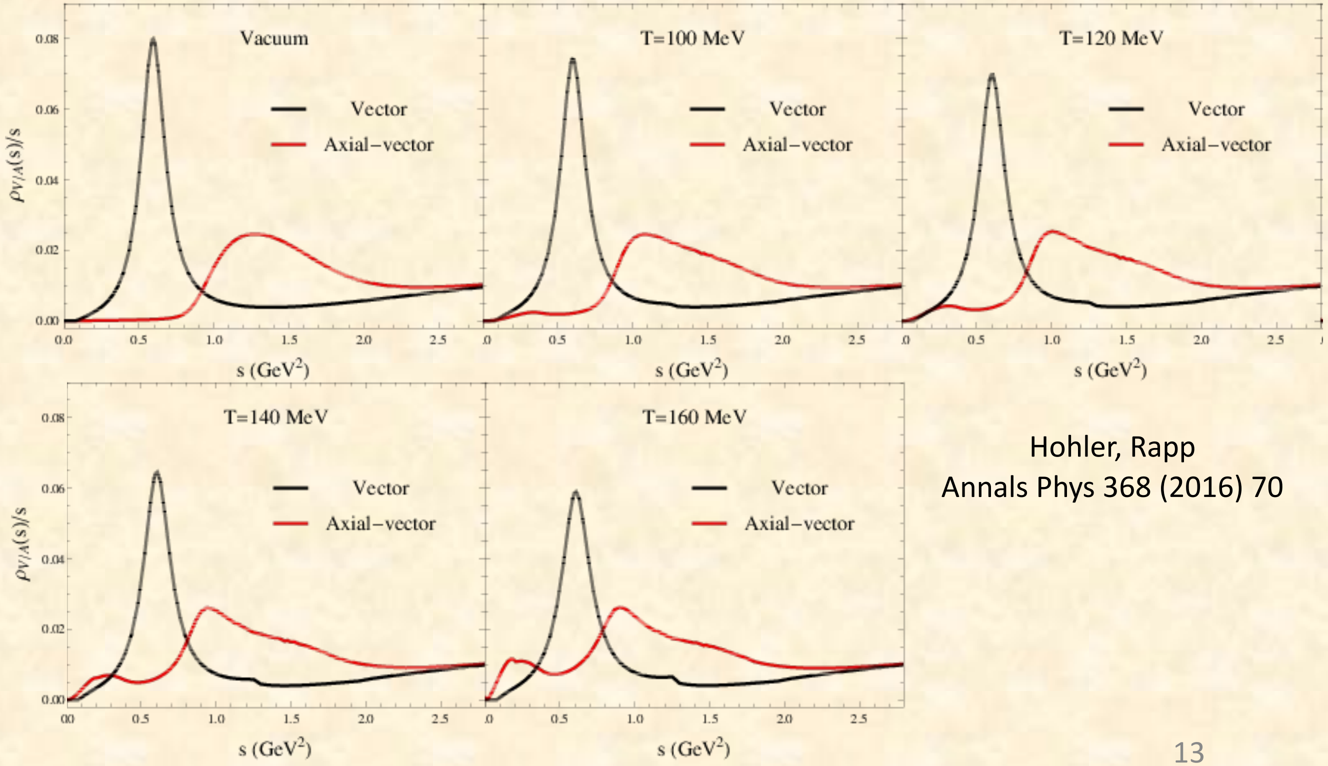
- restoration of chiral symmetry manifests itself in mixing of V and A correlators
- ρ mesons melts in hot matter while a_1 decreases and degenerates

➢ chiral mass splitting ”burns off”



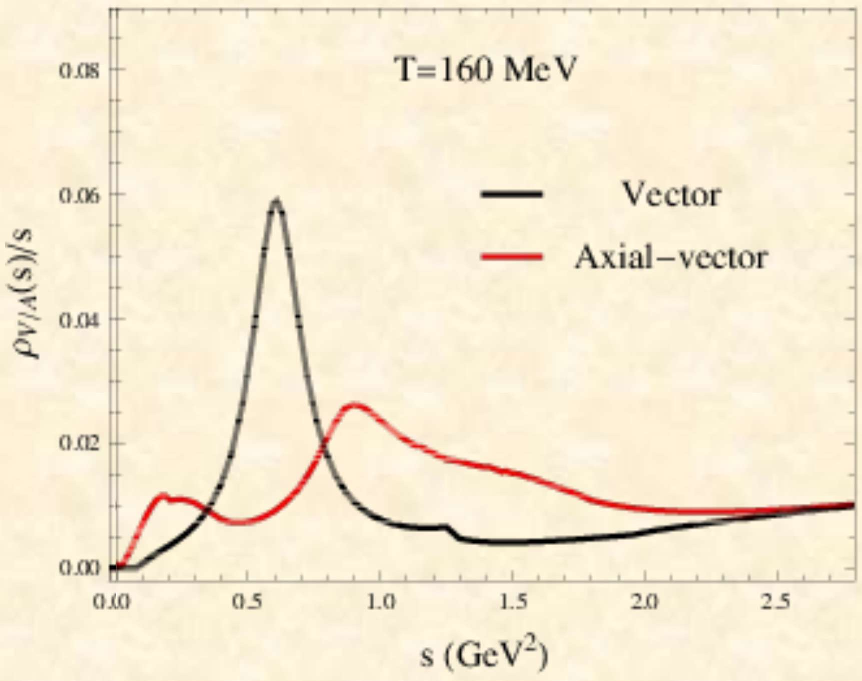
Jung, et al. PRD 95 (2017) 036020

Massive Yang-Mills in hot pion gas

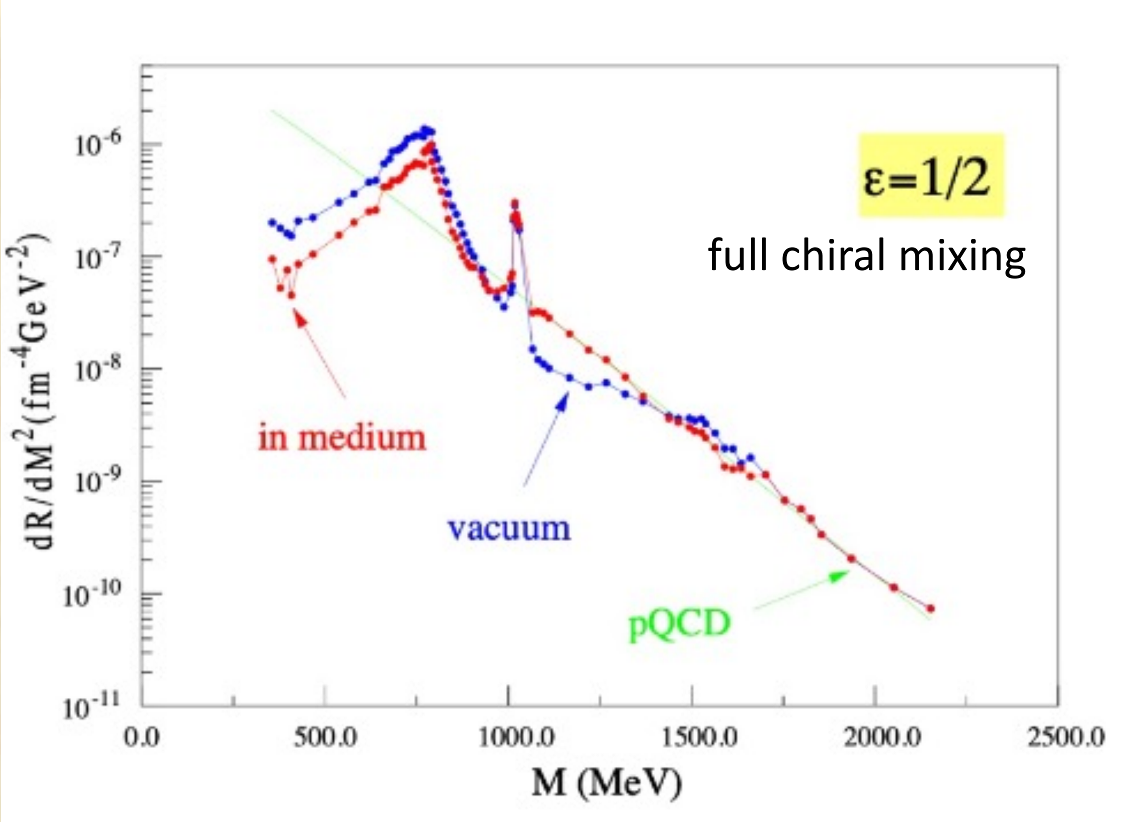


Hohler, Rapp
Annals Phys 368 (2016) 70

Chiral symmetry restoration: ρ-a_1 mixing



Hohler, Rapp, Annals Phys 368 (2016) 70



Stroth, ECT* Trento 2021

$$\pi a_1 \rightarrow \rho' \rightarrow l^+ l^-$$

- mixing "moves strength from the axialvector to the vector channel" Rapp, Wambach, Adv. Nucl.Phys. 25 (2000) 1

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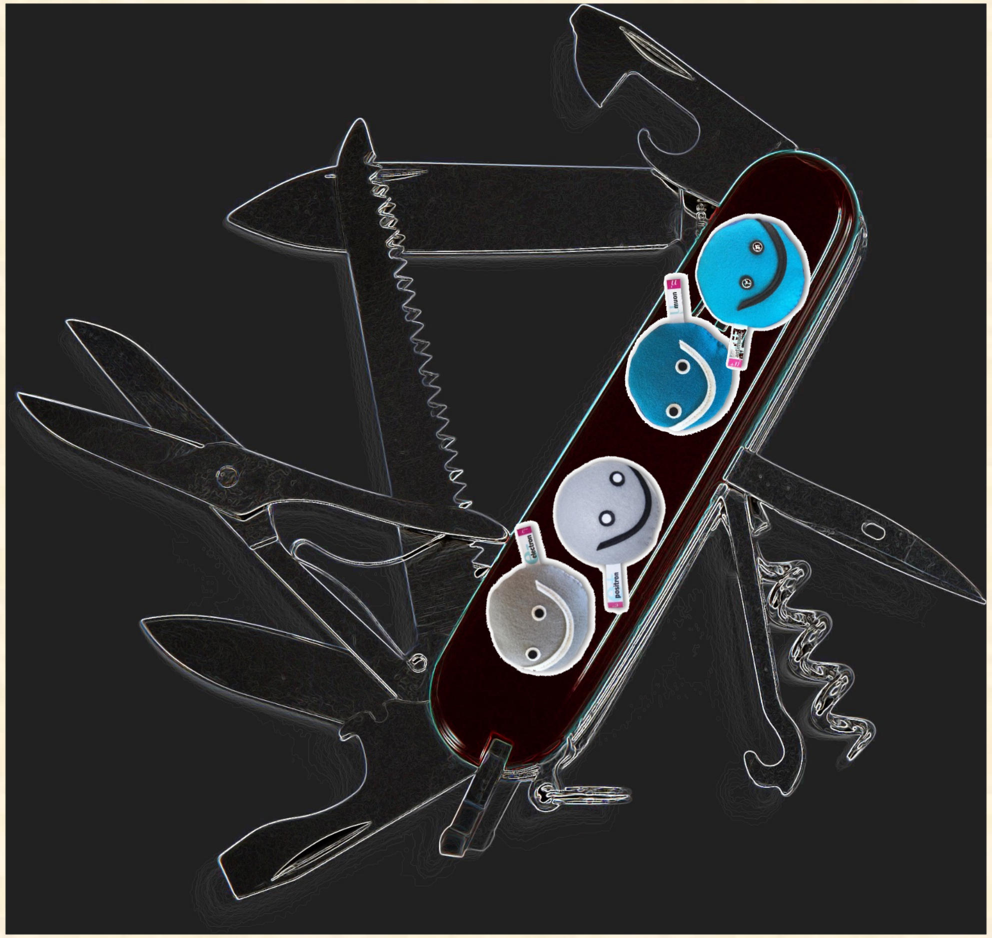


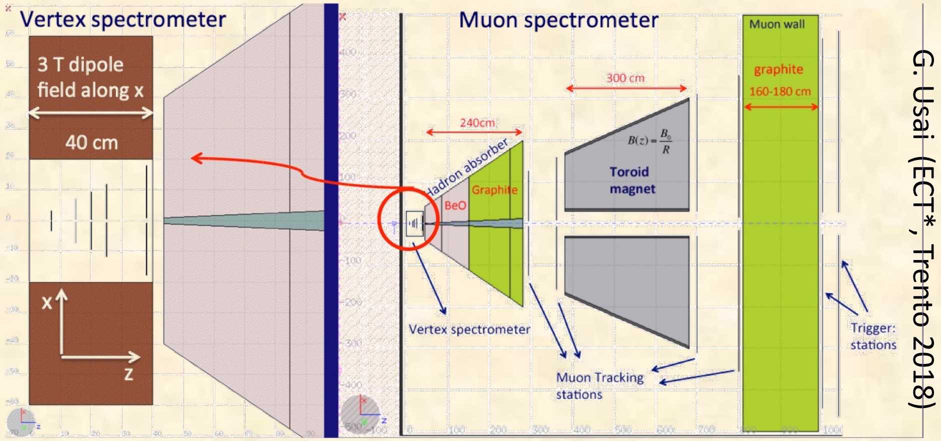
The experimental challenge

- di-leptons need large acceptance + high purity PID
  - good momentum resolution
- electron PID from a combination of a tracker with time-of-flight (velocity), energy loss measurements (dE/dx), or RICH (very high γ thresholds) information.
- muon PID from employing hadron absorber with tracking before and after the absorber

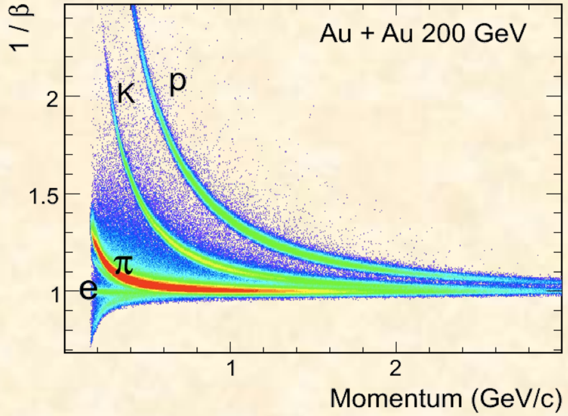
- dileptons are rare probes: production rate is very low

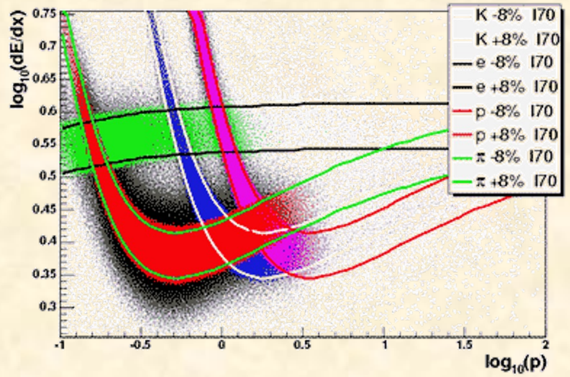
  for example: $\frac{\rho \rightarrow e^+e^-}{\rho \rightarrow \pi^+\pi^-} \sim 5\times10^{-5}$
- large combinatorial background
  - photon conversions from detector materials
  - Dalitz decays from light mesons
  - purity of muons, “fake” muons from weak decays
  - signal/background can be as low as 1%

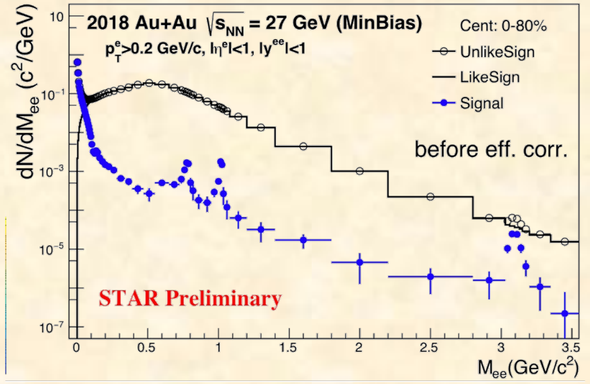
NA60+

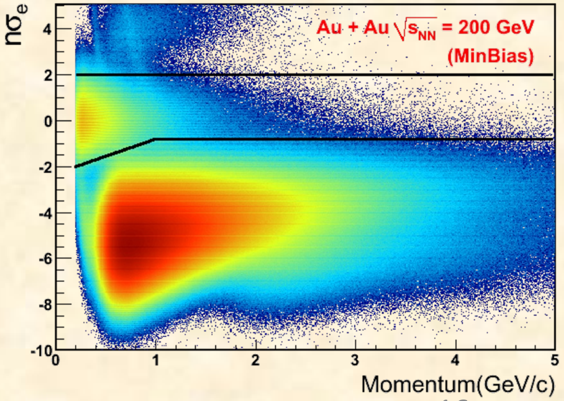


G. Usai (ECT*, Trento 2018)









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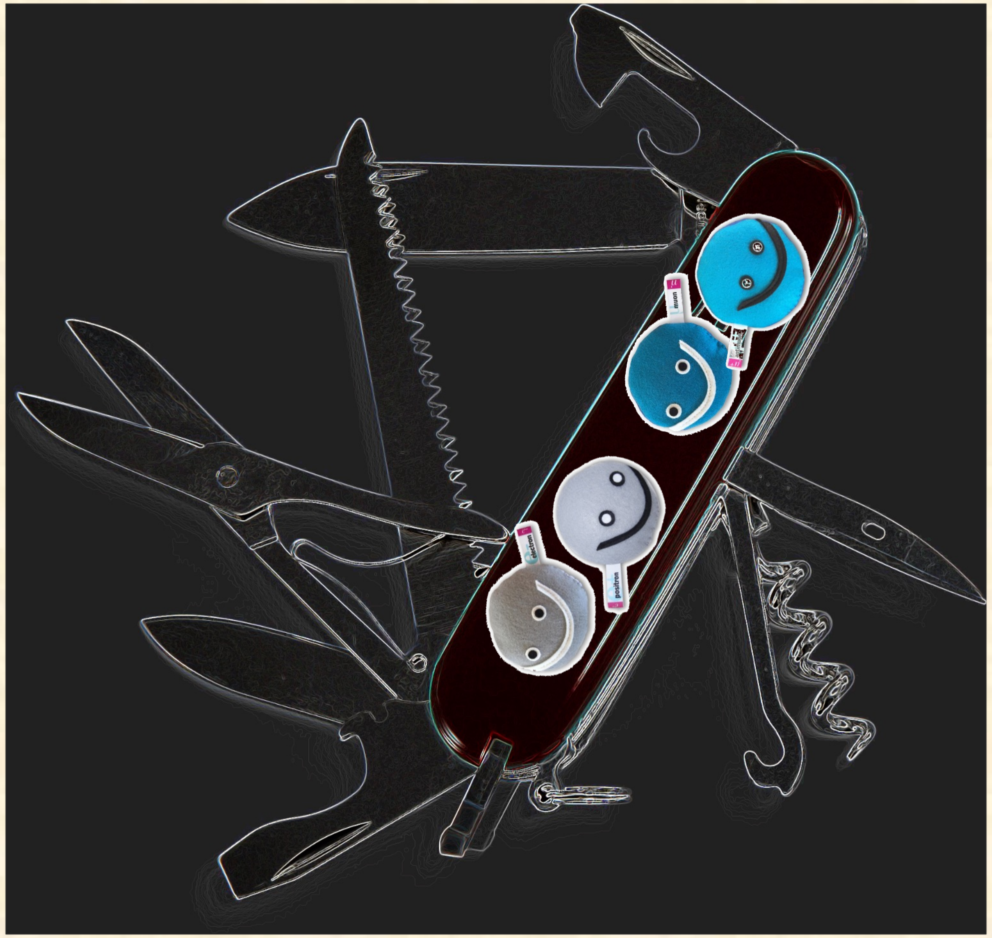
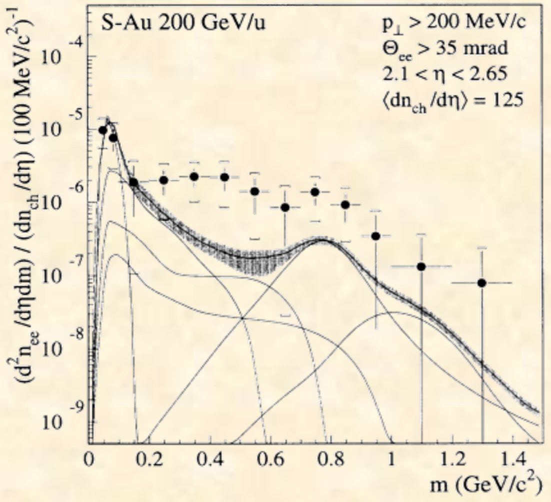
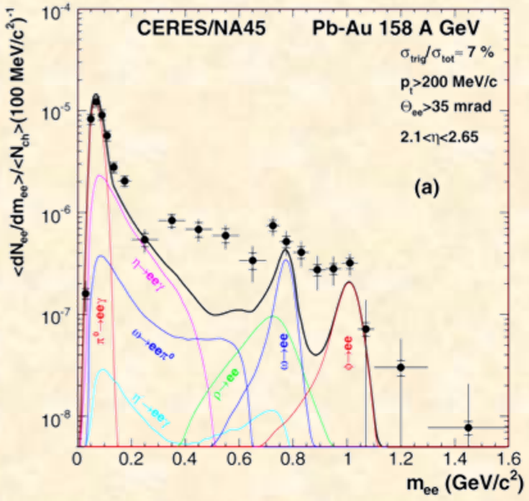


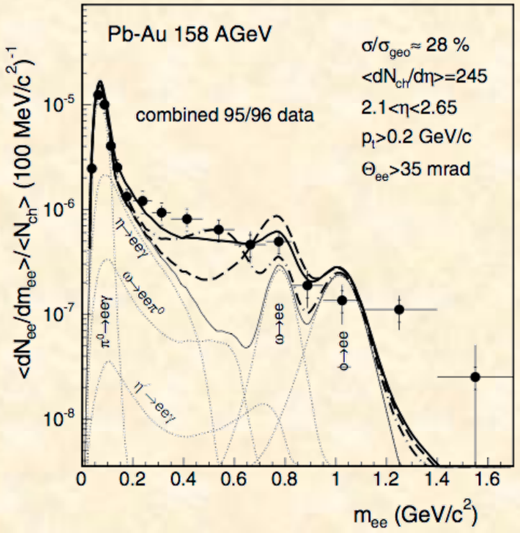
SPS dielectrons spectra (CERES)

First observation of a significant LMR enhancement – PRL 75 (1995) 1272





PLB 666 (2008) 425



EPJ C41 (2005) 475

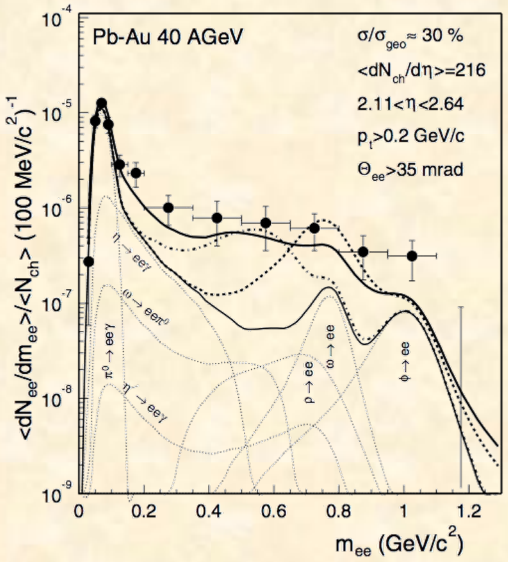
Vacuum ρ unable to describe this data

dashed = vacuum ρ; dash-dotted = DM; solid = RB

- ➢ Introduce in-medium modifications
- decrease of ρ mass (Brown-Rho)
  - mass expected to scale with q-qbar condensate
- broadening of ρ spectral function (Rapp-Wambach)
  - hadronic (baryons) scattering

Both rely on high baryon densities

Both showed good agreement with 158 and 40 AGeV

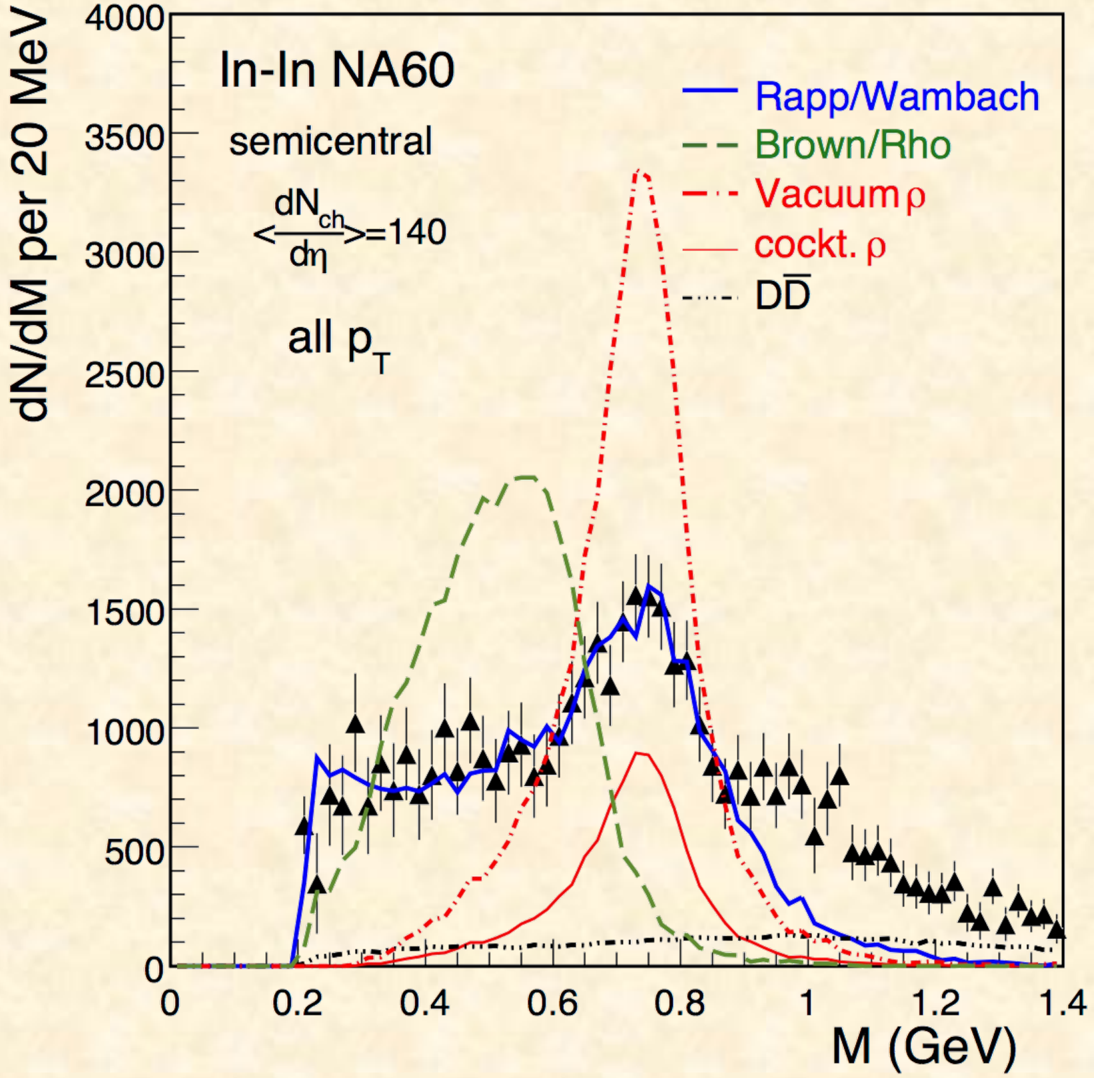


PRL 91 (2003) 042301

SPS dimuons spectra (NA60)

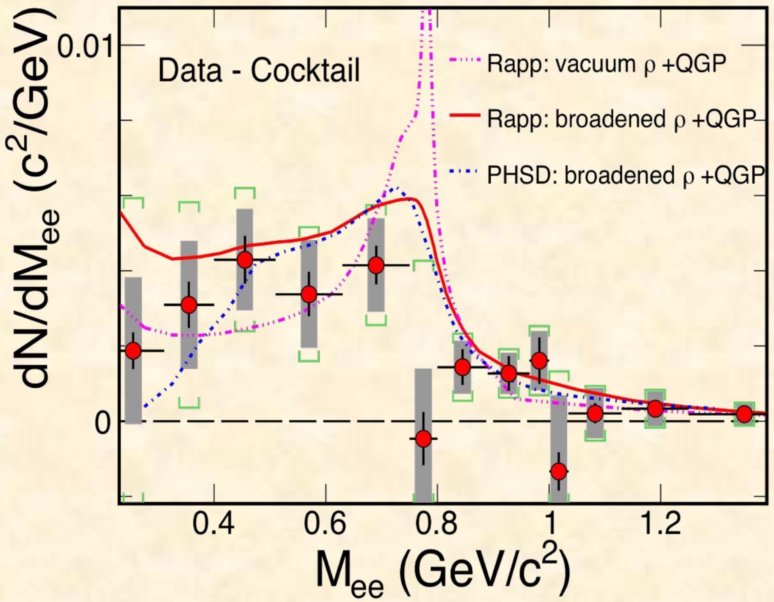
Excess in LMR $\mu^+\mu^-$ – EPJ C61 (2009) 711

- rules out: dropping-mass scenario
- very good agreement with Resonance Width Broadening for $M_{\mu\mu} < 0.9$ GeV/c^2



RHIC dielectron spectra at 200GeV

✓STAR



PRC 92 (2015) 024912

R. Rapp,PRC 63 (2001) 054907
O. Linnyk et al., PRC 85 024910 (2012)

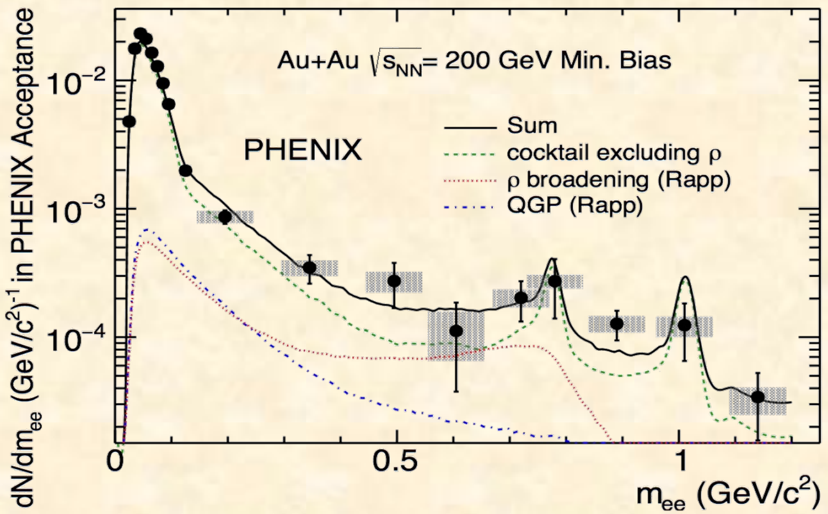
➢ Data does not support vacuum ρ

➢ Within uncertainties agreement between experiment and theory

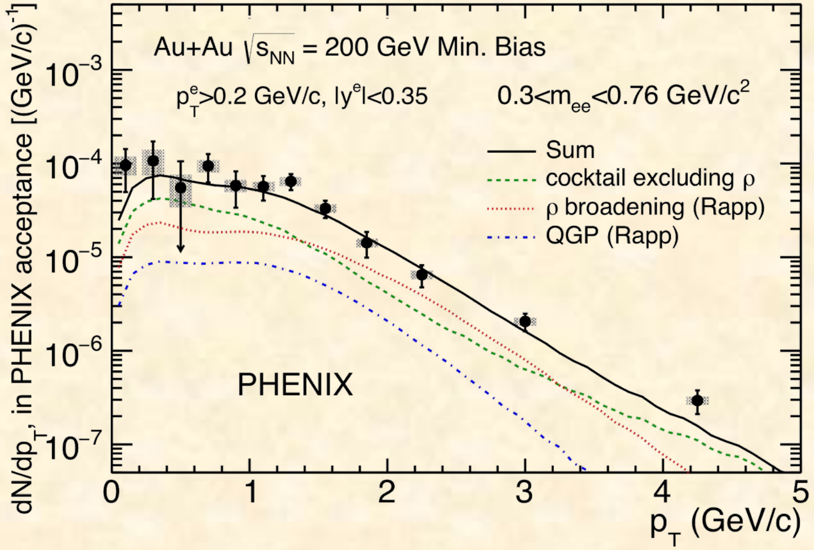
TABLE VIII. Reduced χ^2 for model calculations compared to the excess data in the invariant-mass region of 0.3–1.0 GeV/c^2.

Model	χ^2/ndf	p value
Rapp: vacuum ρ + QGP	41.3/8	2.4×10^{-7}
Rapp: broadened ρ + QGP	8.0/8	0.32
PHSD: broadened ρ + QGP	16.5/8	0.040

✓PHENIX

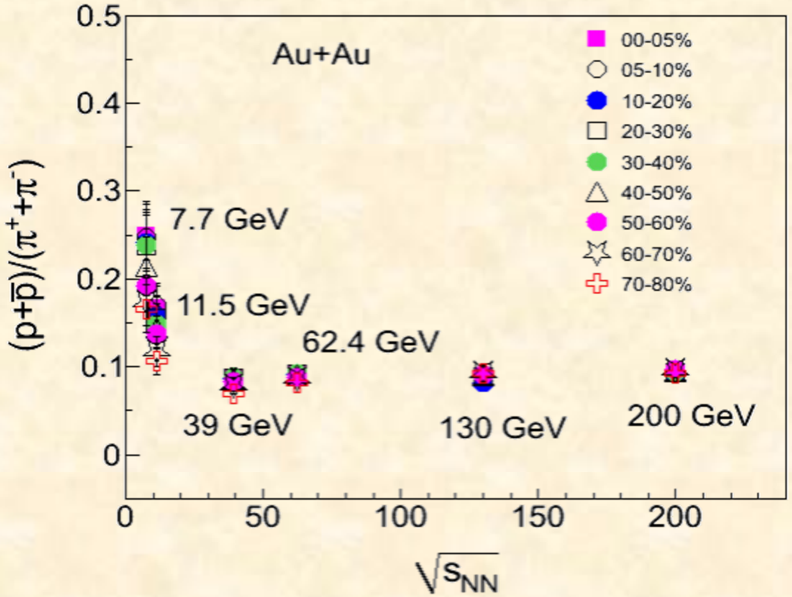


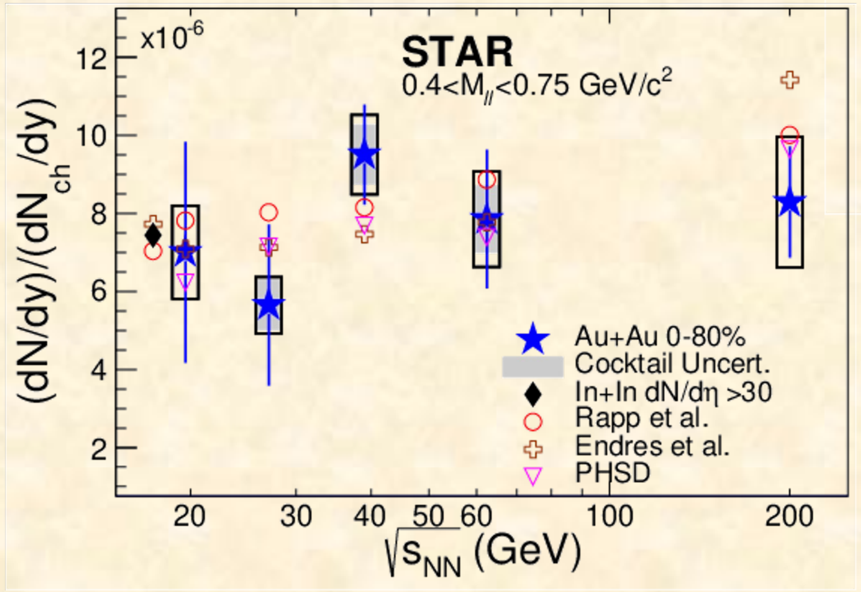
PRC 93 (2016) 014904

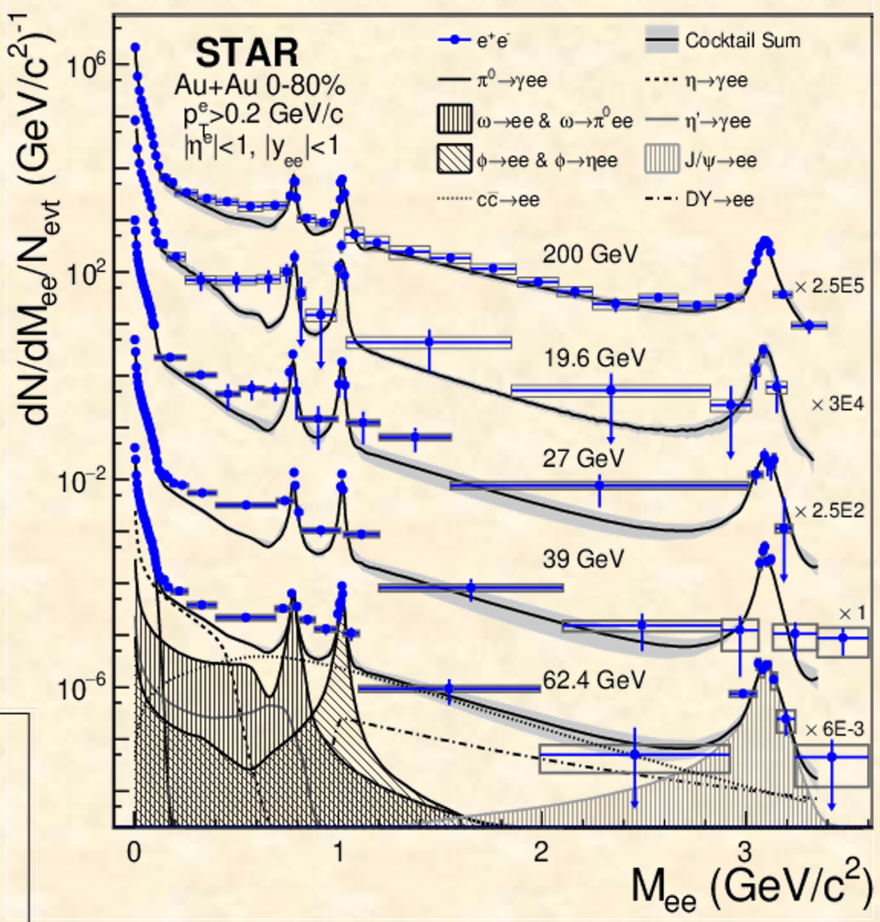


RHIC dielectron production from BES

- Excess established at RHIC by PHENIX & STAR
  - in-medium modification?
  - indications of chiral symmetry restoration?
- RHIC Beam Energy Scan
  - explore low-mass range down to SPS energies
  - opportunity to determine excitation function
    - dependence on temperature, total baryon density, and medium lifetime
  - normalized excess yield shows no significant $\sqrt{s_{NN}}$ dependence
    - nor does the total baryon density
- BES Phase 1: limited precision to constrain model assumptions
  - especially for $\sqrt{s_{NN}}$ < 19 GeV







STAR, arXiv:1810.10159

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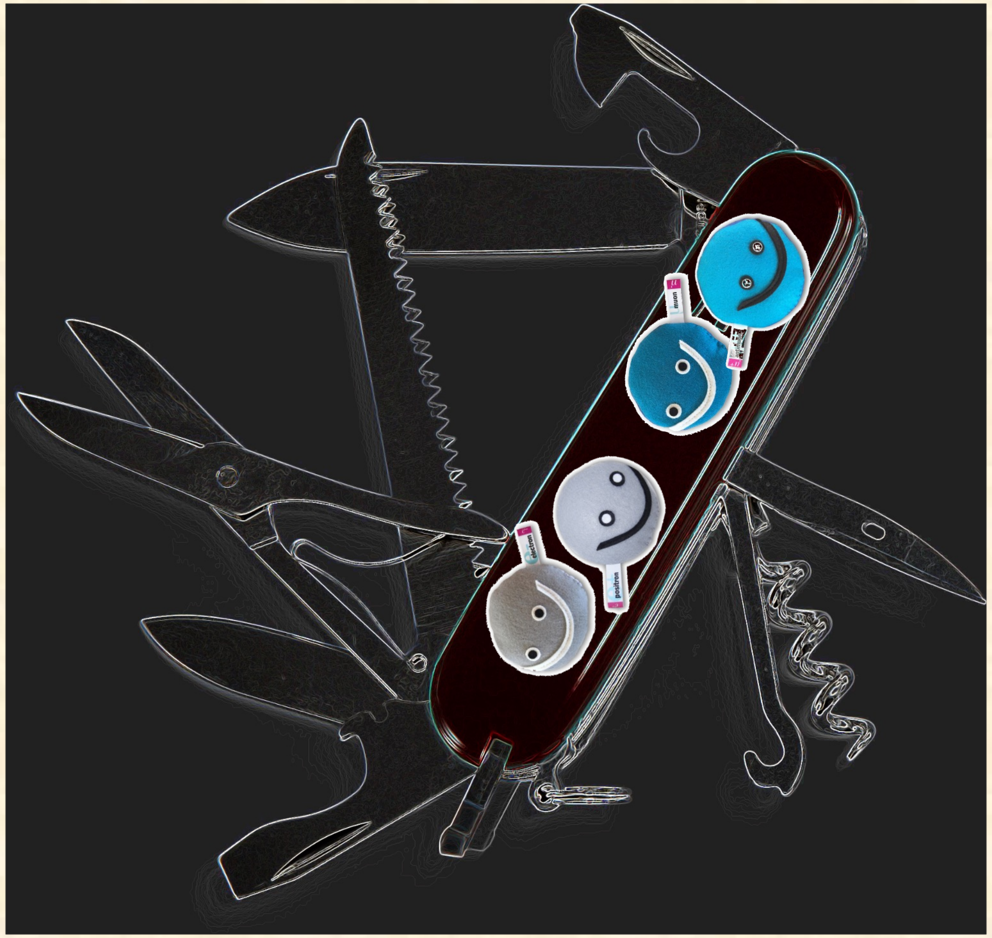
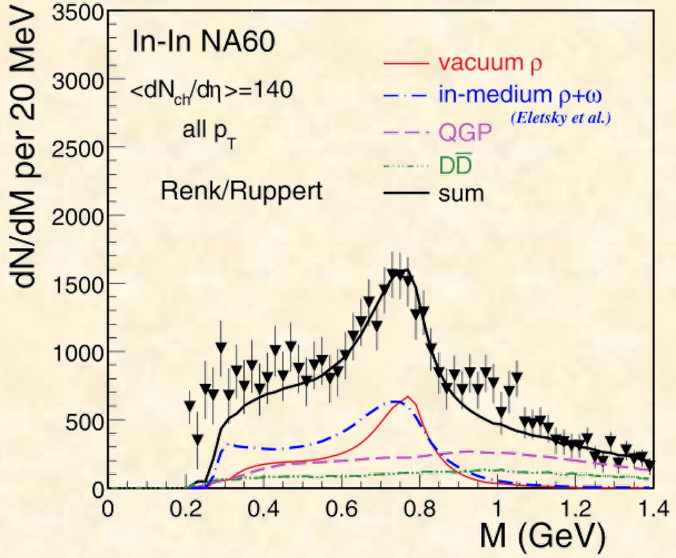
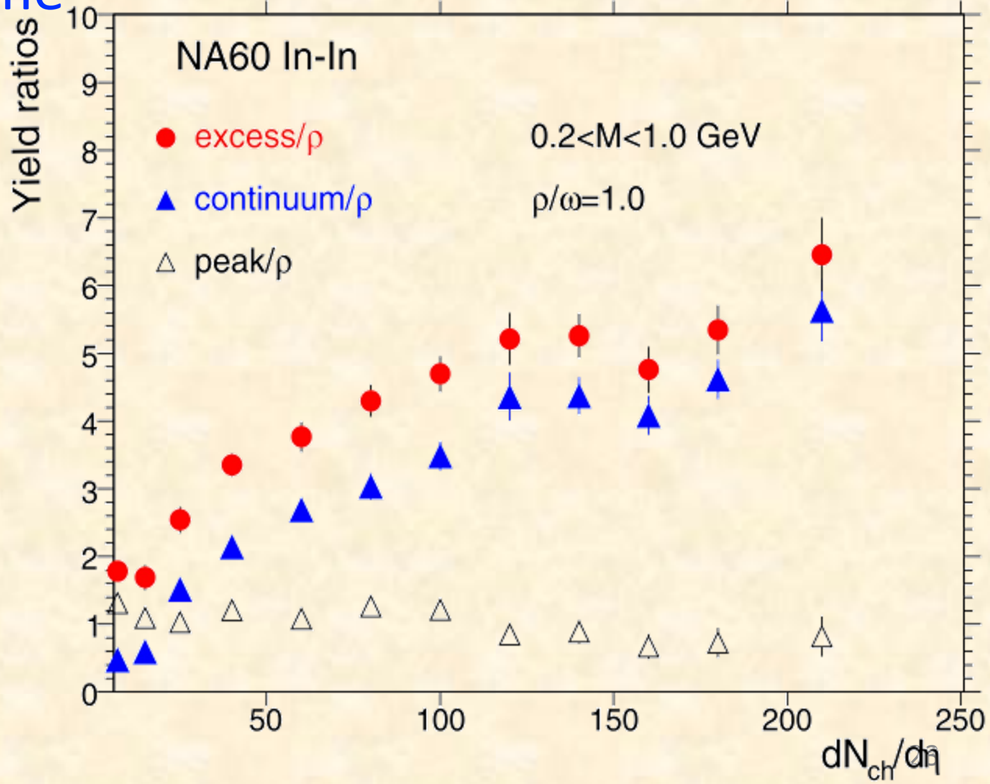


Dileptons as chronometer

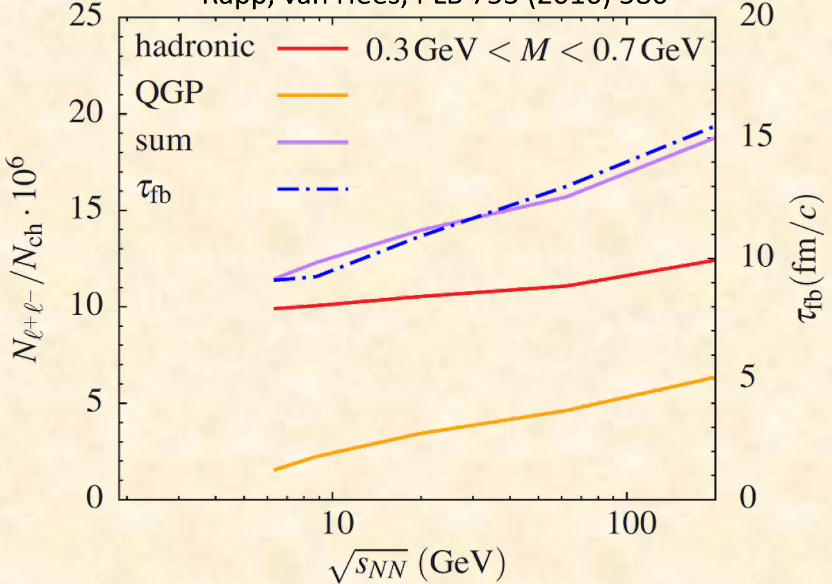
- ρ peak as a clock for fireball lifetimes
  - see e.g., U.Heinz, KS.Lee, PLB 259 (1991) 162
- NA60: "ρ clock"
  - centrality dependence of excess yield
  - reaches up to 6 generations
- Normalized excess yields in LMR track medium lifetime
  - sensitive to onset of 1st order phase transition?
  - sensitive to anomalous variations in lifetime in vicinity of CP?





NA60, EPJC 61 (2009) 711

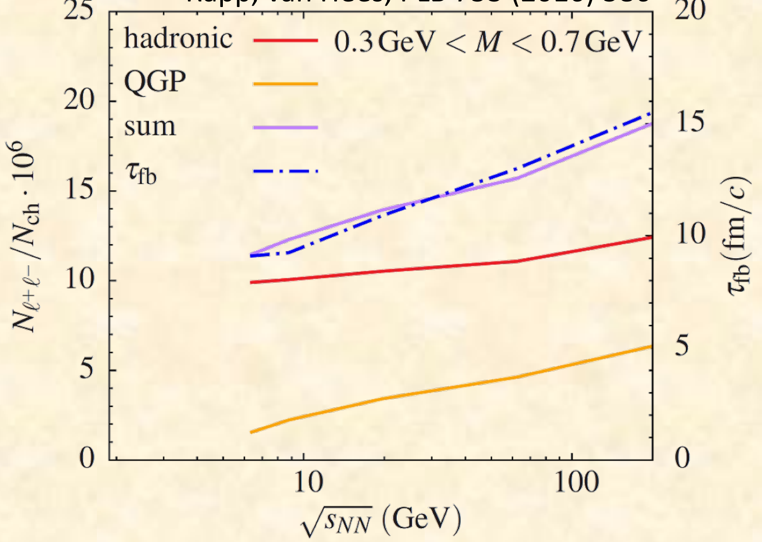
Rapp, van Hees, PLB 753 (2016) 586

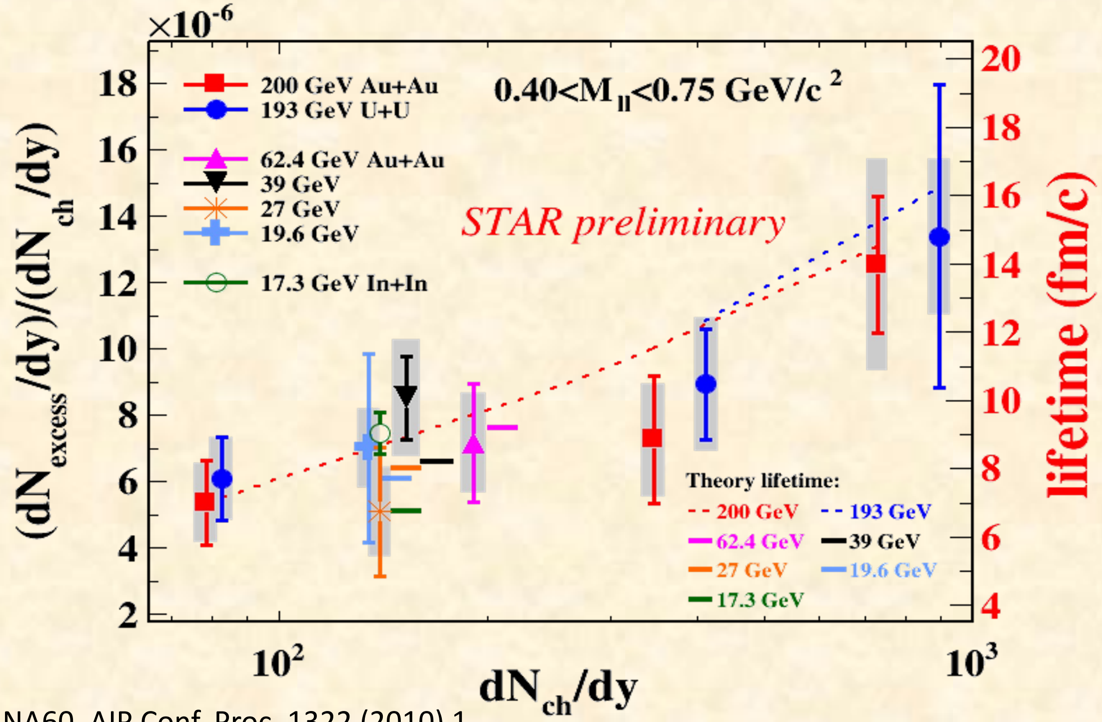


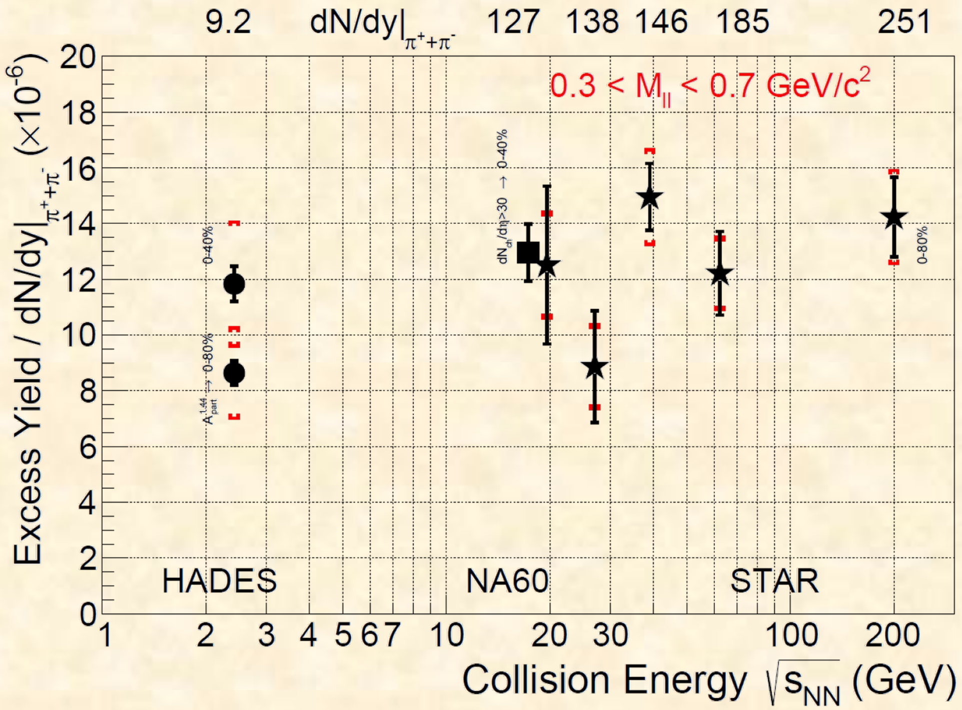
Dileptons as chronometer

- Integrated excess radiation
  - measured below free ρ/ω mass
  - results from HADES, NA60, STAR look promising
- Experimental uncertainties are large
  - high statistics measurements needed

Rapp, van Hees, PLB 753 (2016) 586







Galatyuk, JPC Conf.32 (2020) 010079

NA60, AIP Conf. Proc. 1322 (2010) 1
STAR, PLB 750 (2015) 64
STAR, arXiv 1810.10159

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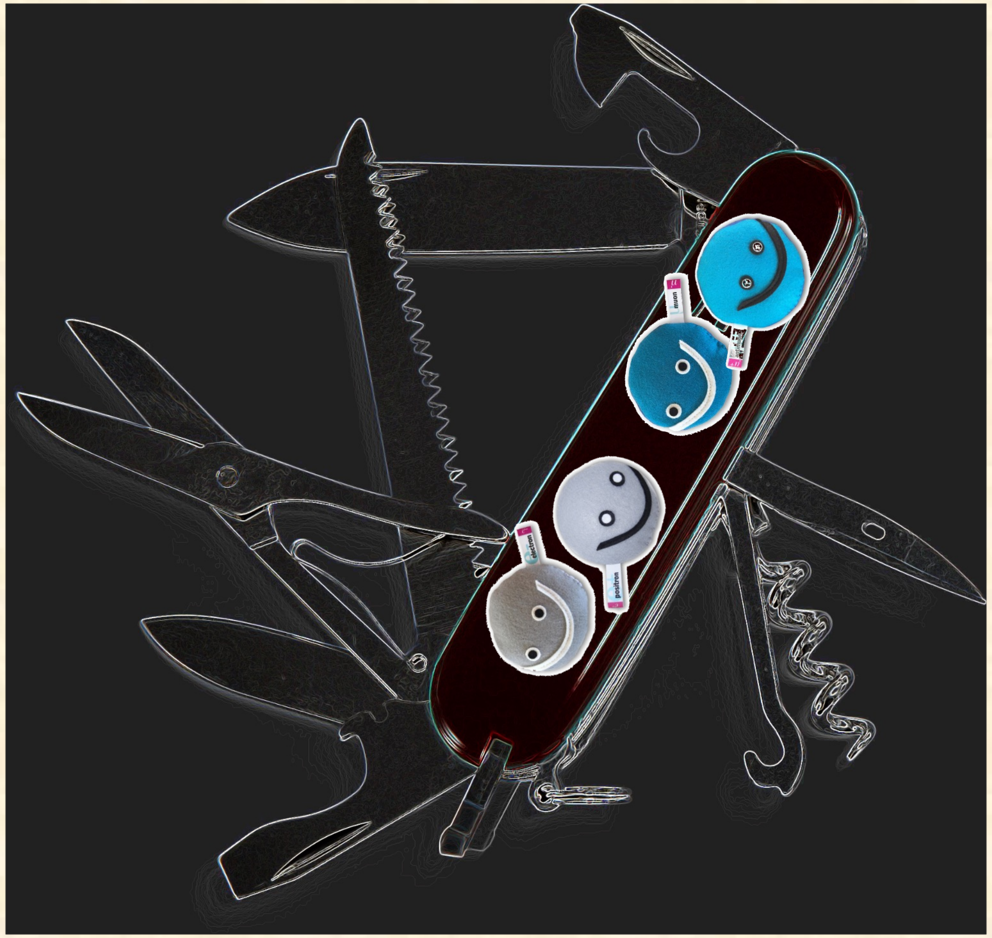


Dileptons as thermometer

Reall thermal dilepton radiation:

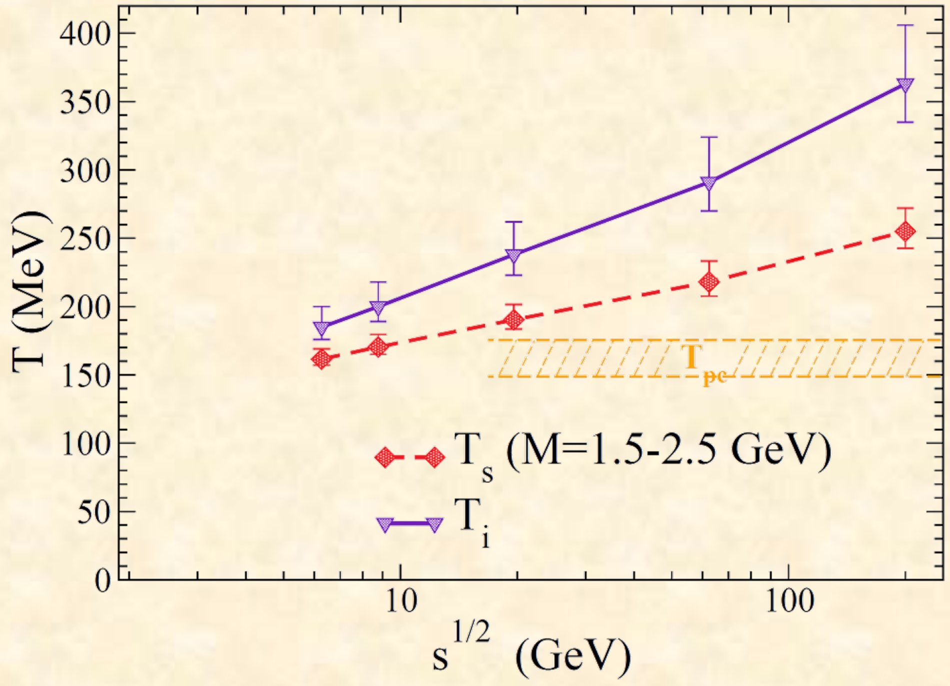
- LMR - dilepton spectra saturated by light vector mesons
- IMR - quark-antiquark continuum

IMR dilepton rate

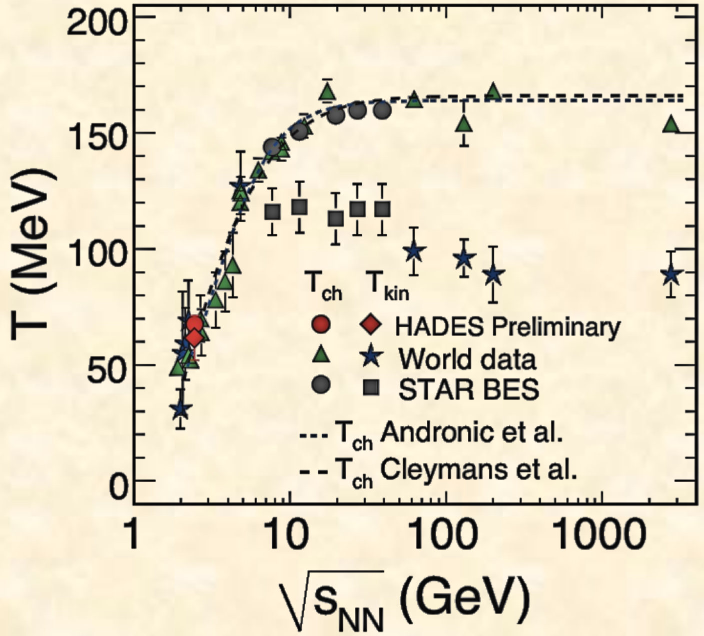
$$\frac{dR_{ll}}{dM} \propto \left(\frac{M}{T}\right)^{\frac{3}{2}} \exp(-\frac{M}{T})$$

- *M* by construction Lorentz-invariant
- independent of flow → no blue-shift effects
- average over the system evolution

- Other bulk temperature measurements rely on hadron yields and spectra
  - chemical and kinetic freezout
  - separation between T_{chem} and T_{kin} grows with $\sqrt{s_{NN}}$



Rapp, van Hees, PLB753 (2016) 586

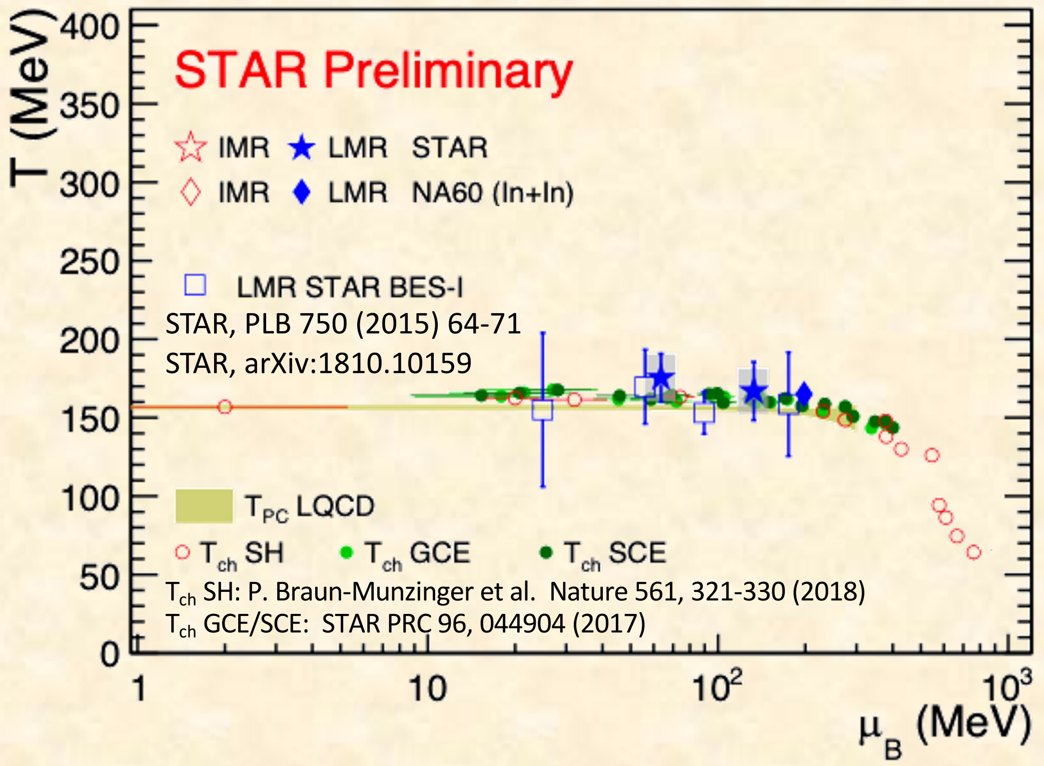


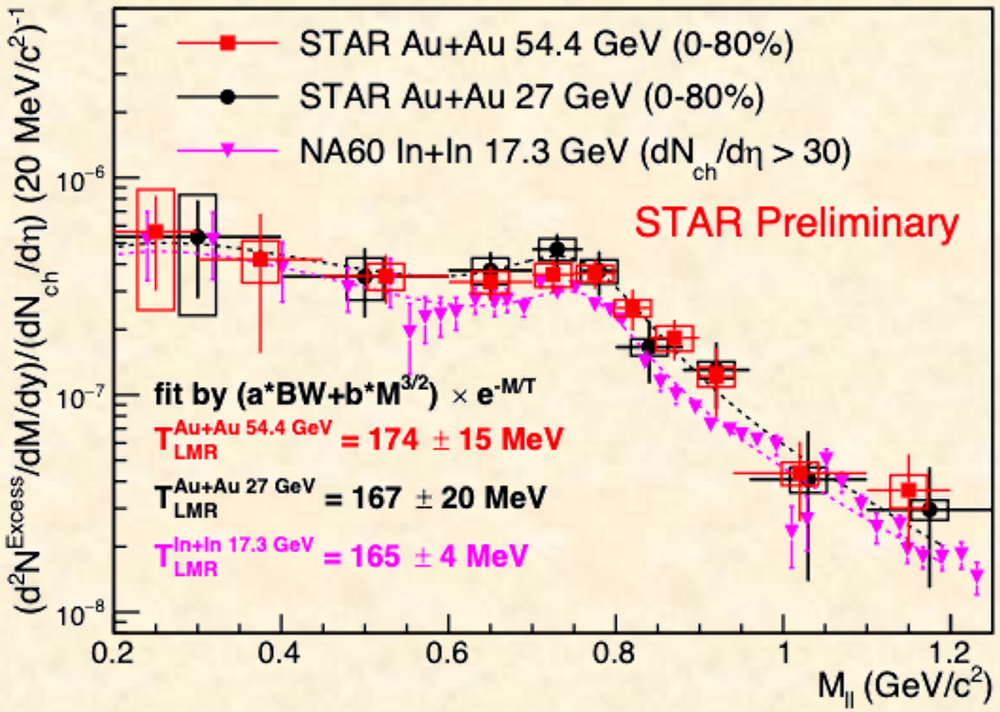
World Data:
SIS: HADES, (FOPI)
AGS: E802,E866, E877,E895, E917
SPS: NA49
RHIC: STAR
LHC: ALICE

LMR temperature measurements

At SPS/RHIC energies

- predominantly thermal dileptons from in-medium ρ
- include Breit-Wigner in T_{LMR} fit
- recent STAR results at $\sqrt{s_{NN}}$ = 27 and 54 GeV show similar mass spectra and extracted T_{LMR}
  - ➢ compared with NA60 at 17.3GeV





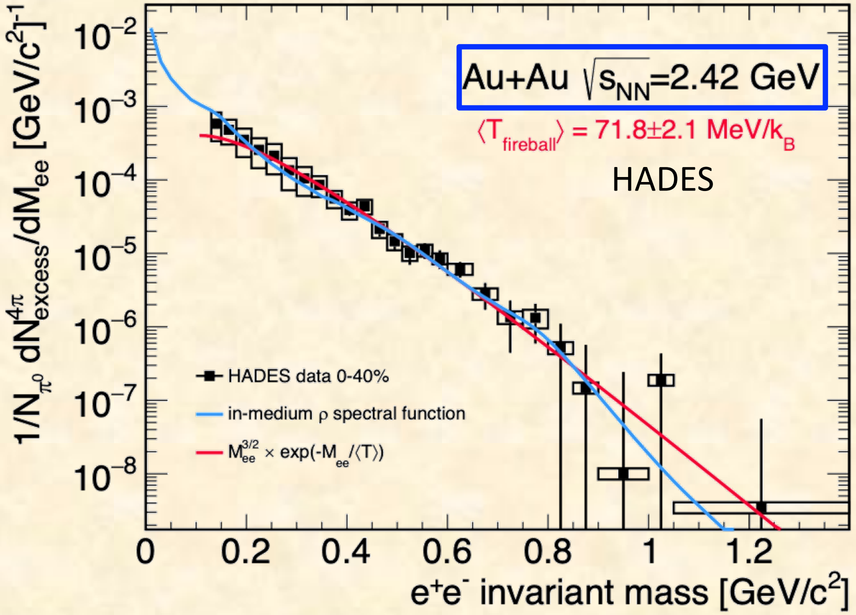
Zaochen Ye (SQM2022)

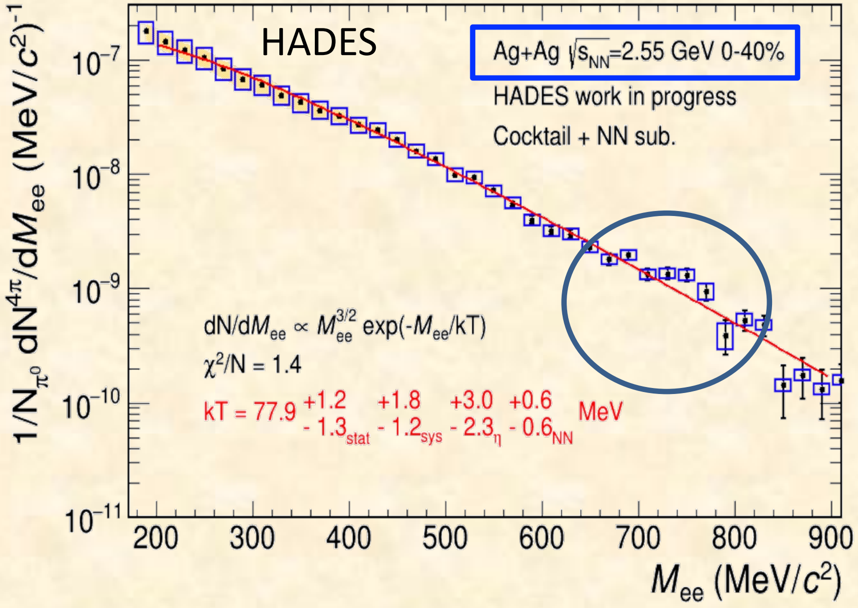
➢ temperatures close to T_{ch} and T_{pc}

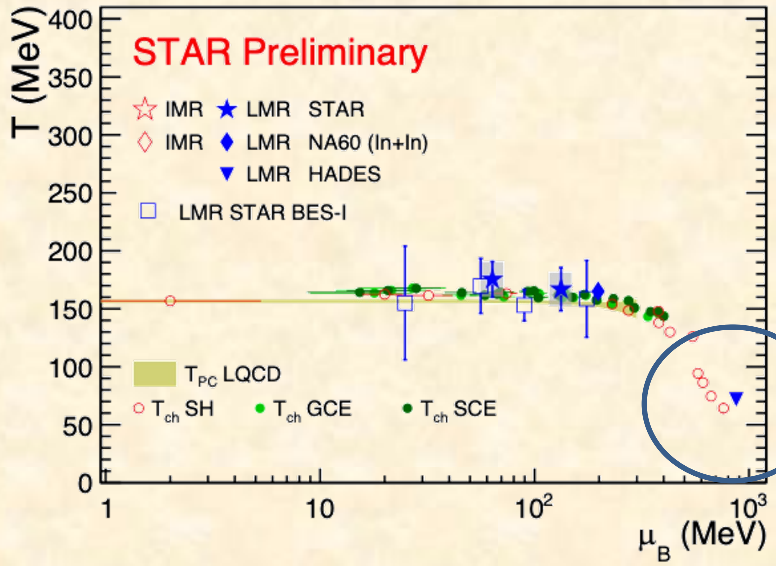
- emitted from hadronic phase
- predominantly around phase transition

LMR temperature measurements at higher μ_B

Nat.Phys.15 (2019) 1040







Zaochen Ye (SQM2022)

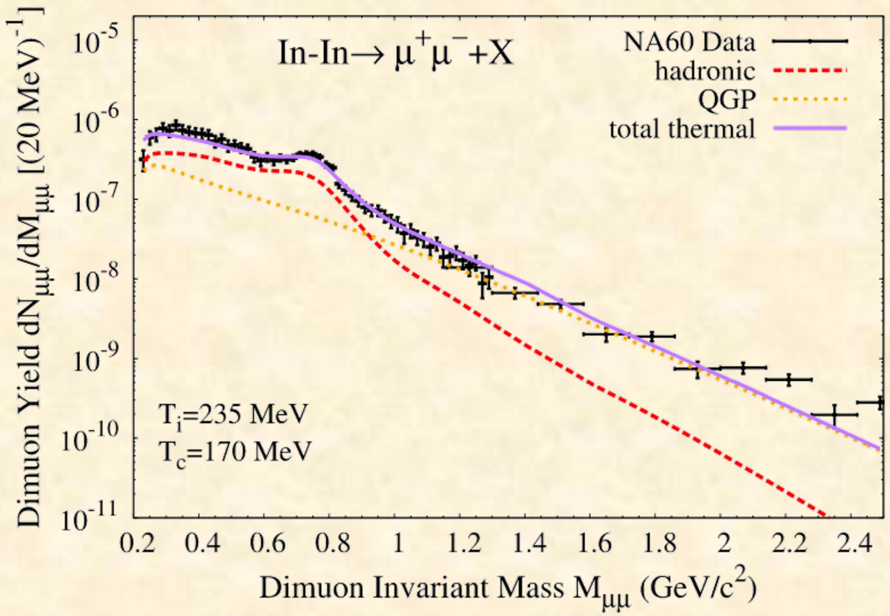
At lower energies

- higher baryon density (μ_B~ 700 - 900MeV)
- in-medium ρ substantially modified through frequent scattering with baryons
  - almost structureless exponential distribution

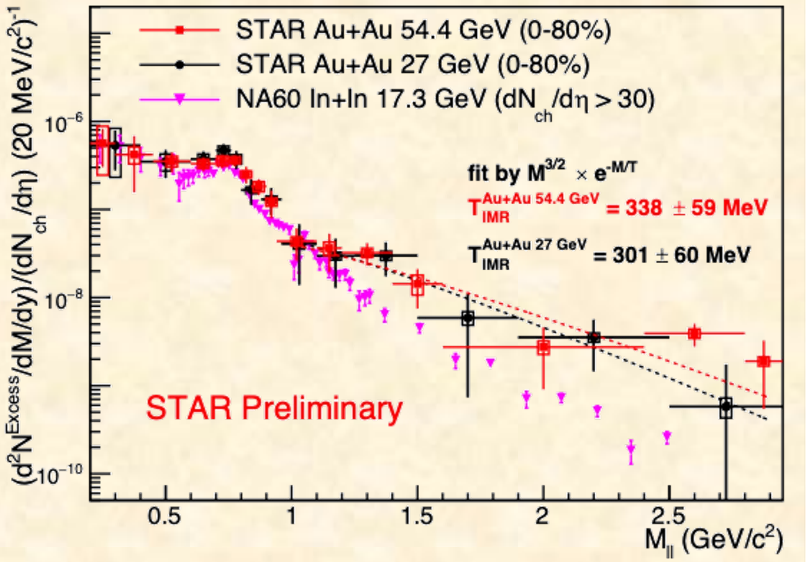
➢ HADES: T_{LMR}= 70-80 MeV
  - Au+Au @ 2.42GeV and Ag+Ag @ 2.55GeV

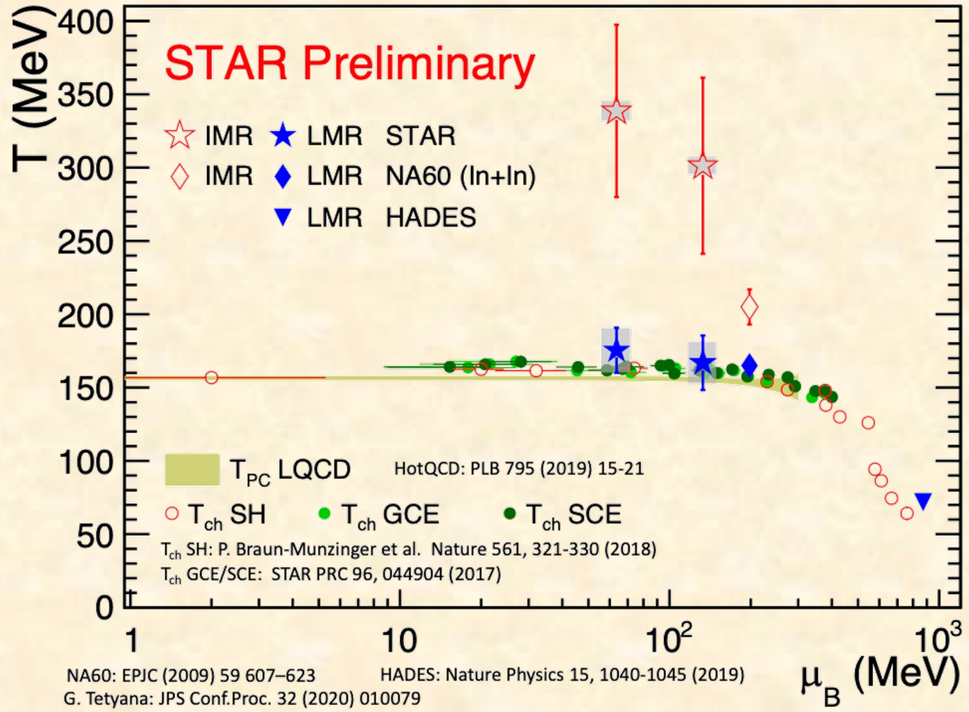
IMR temperature measurements

- ➢ Access to $q\bar{q}$ radiation
- NA60[†] first $\mu^+\mu^-$ measurement: T_{IMR}=205 ± 12MeV
  - range 1.2 < M < 2.0 GeV/c²
- Recent STAR IMR e^+e^- results: T_{IMR}~320 MeV
  - compare with T_{IMR}(NA60) [† †] = 246 ± 15 MeV
  - range 1.2 < M < 2.5 GeV/c²
  - – average T_{IMR} higher due to longer lifetime?
  - – supported by generally higher yields
- ✓ Average T_{IMR} well above T_{pc}



Rapp, van Hees, PLB 753 (2016) 586





Zaochen Ye, QM 2022

†NA60, AIP Conf. Proc.1322 (2010) 1
† † B.Mueller/Z.Ye, priv. comm

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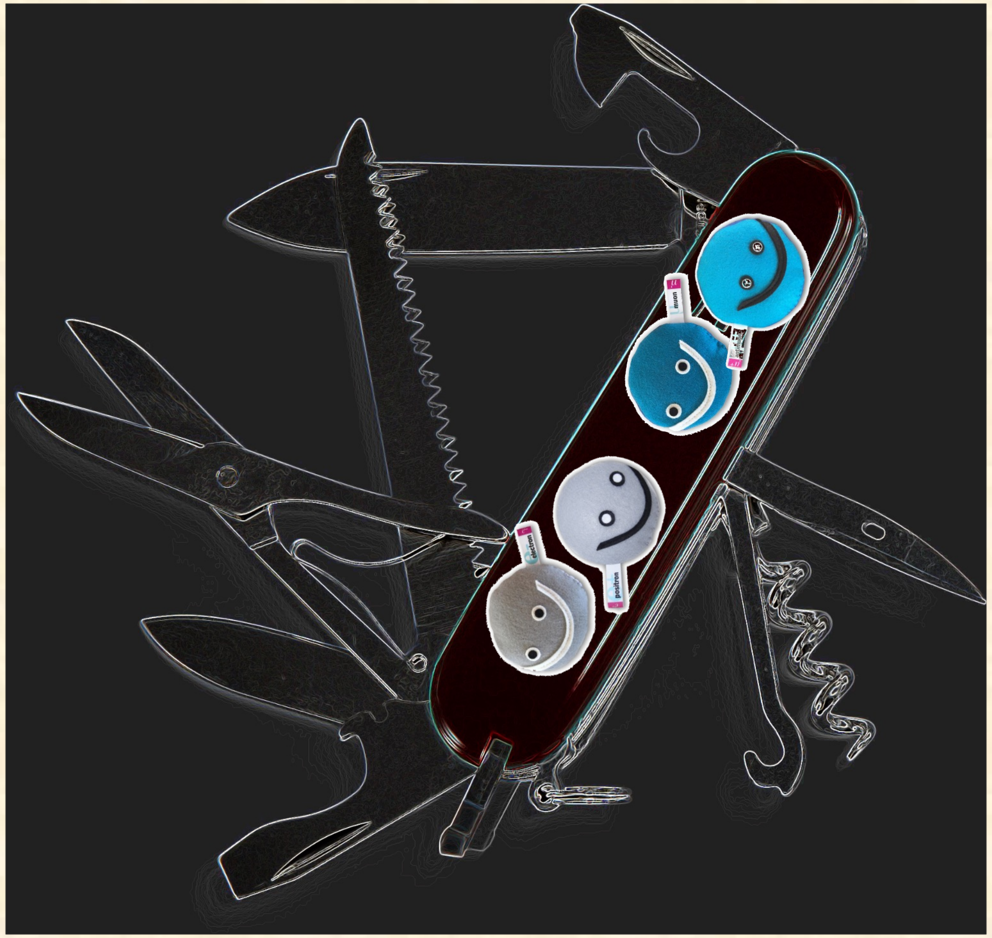


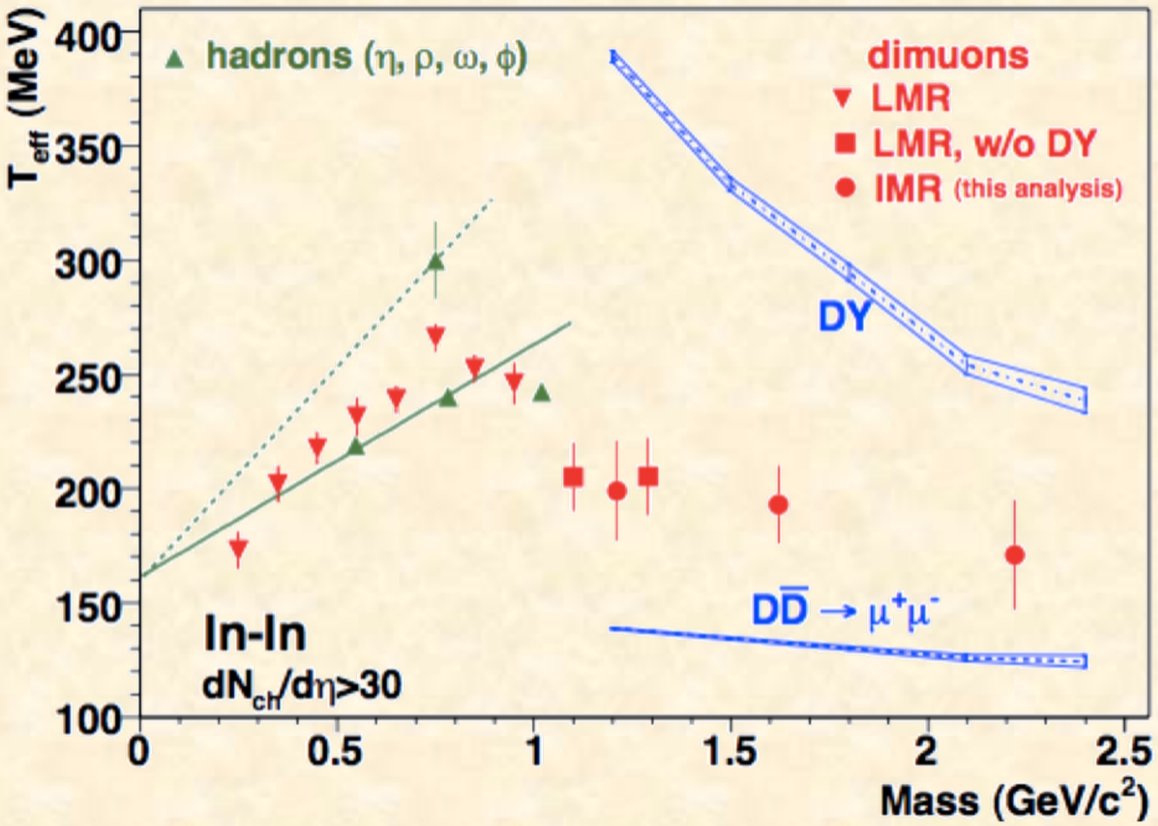
Dileptons as barometer

m_T distributions:

take medium flow into account

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \exp(-\frac{m_T}{T_{eff}})$$

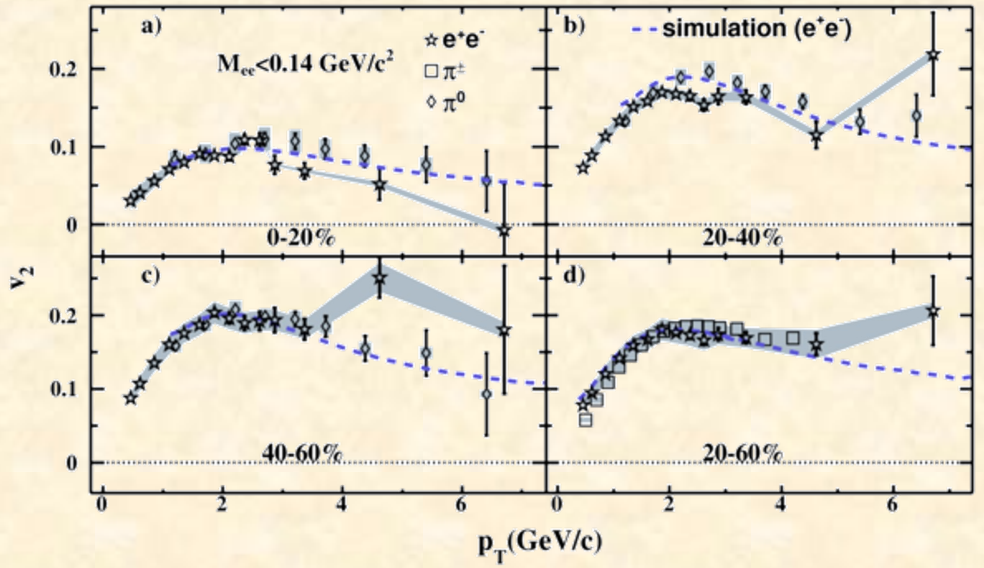
- LMR: inverse slopes show mass dependence
  - T_{eff} linearly rises, and peaks at m_ρ
  - radiation pushed by radial flow
- IMR: no indication of mass dependence
  - sudden drop of T_{eff} by ~50 MeV
  - dominant source from hadronic to partonic matter
  - T_{eff} ~ 200 MeV



NA60, EPJ C 59 (2009) 607

Dileptons as barometer

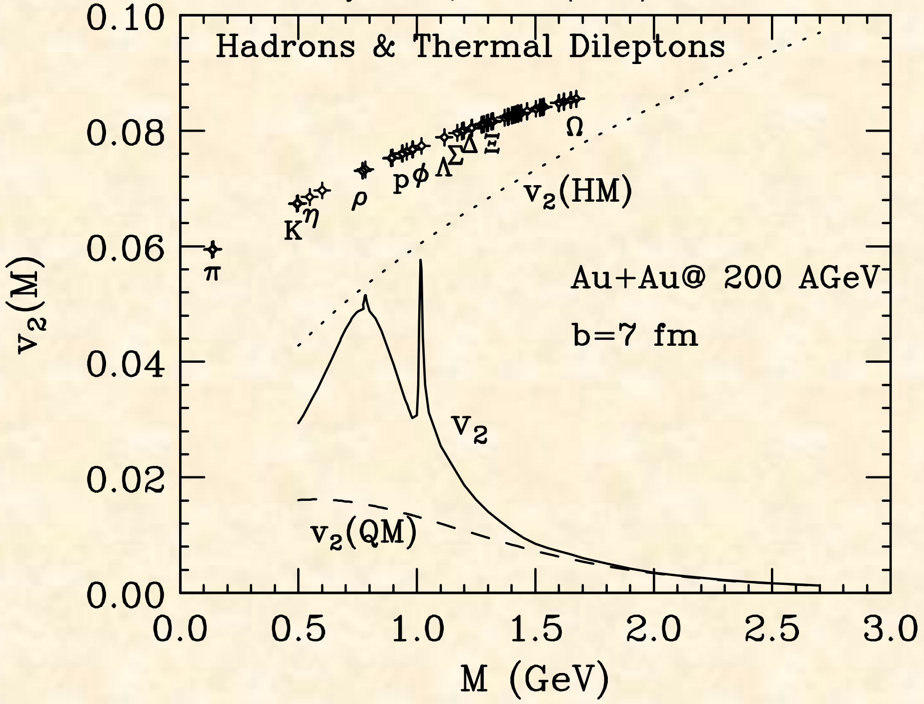
v$_2$ from π^0 Dalitz decay consistent with simulations based on published π^0 v$_2$



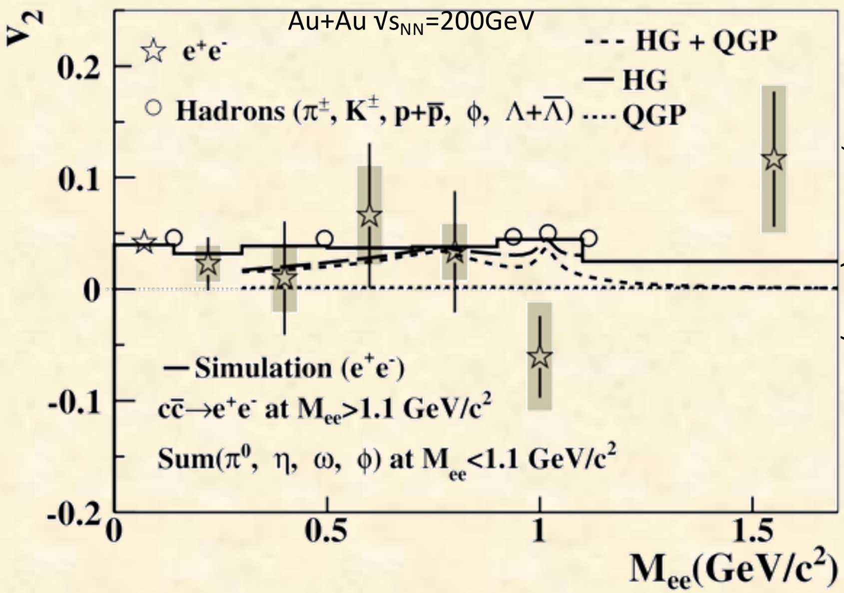
Azimuthal anisotropy

challenge: isolate v$_2$ of excess dielectrons

- to distinguish between HG and QGP need uncertainties <4% …



STAR inclusive e$^+$e$^-$



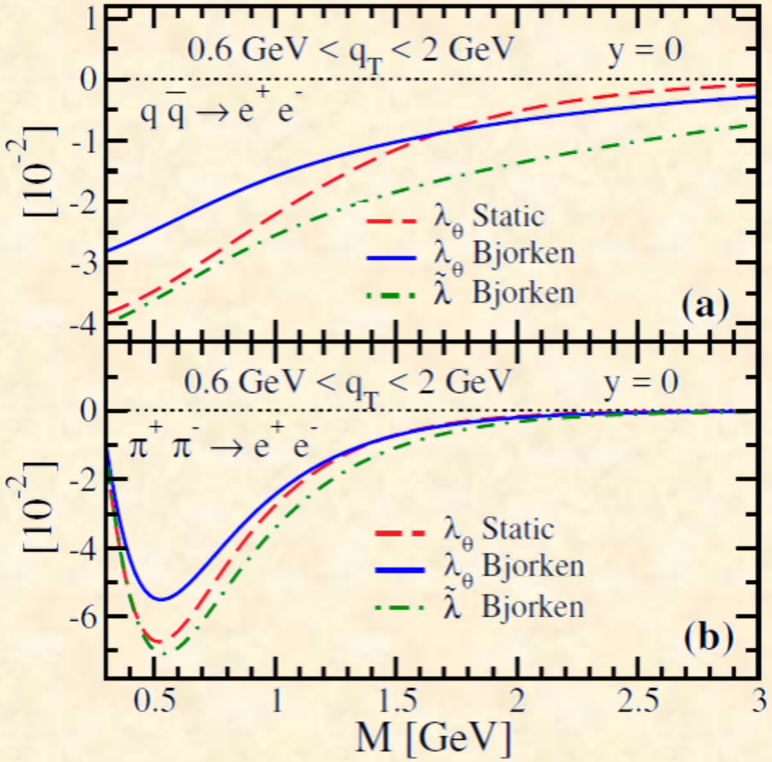
STAR, PRC 90 (2014) 64904

Dileptons as a polarimeter

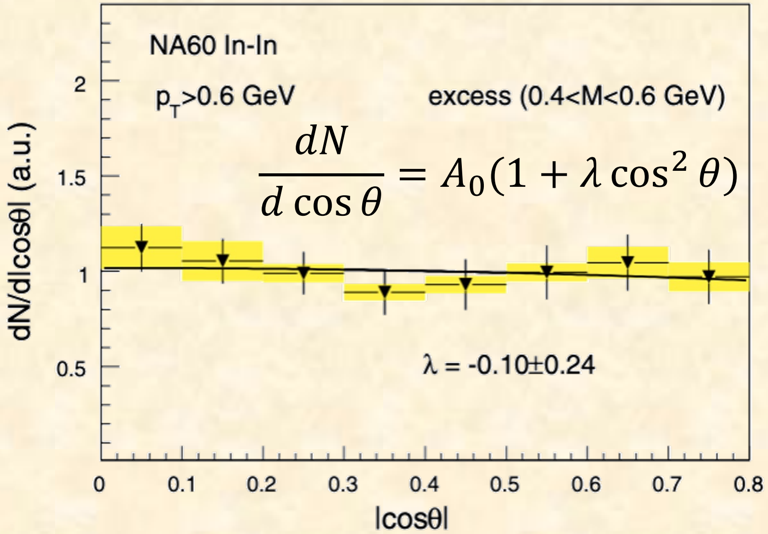
Use the angular distribution of dilepton rates

$$\frac{dR}{d^4q\,d\Omega_l} = N\left(1 + \lambda_\theta \cos^2\theta_l + \lambda_\varphi \sin^2\theta_l \cos 2\varphi_l + \cdots\right)$$

- anistropy coefficients λ:
  - give info on γ^* polarization
  - relate to production mechanisms
    - e.g., $\lambda_\theta = +1$ (T) for DY, and -1 (L) in ππ annihilation
- integrated over M, q_T, y coefficients $\lambda_\theta \lesssim 1\%$
  - expect small, but finite polarization in a thermal system
  - consistent NA60's null finding within uncertainties
- need high-statistics future experiments
  - systematic study of all relevant process required



E. Speranza, et al., PLB764 (2017) 282



NA60, PRL102 (2009) 222301

Dileptons as multimeter: electrical conductivity

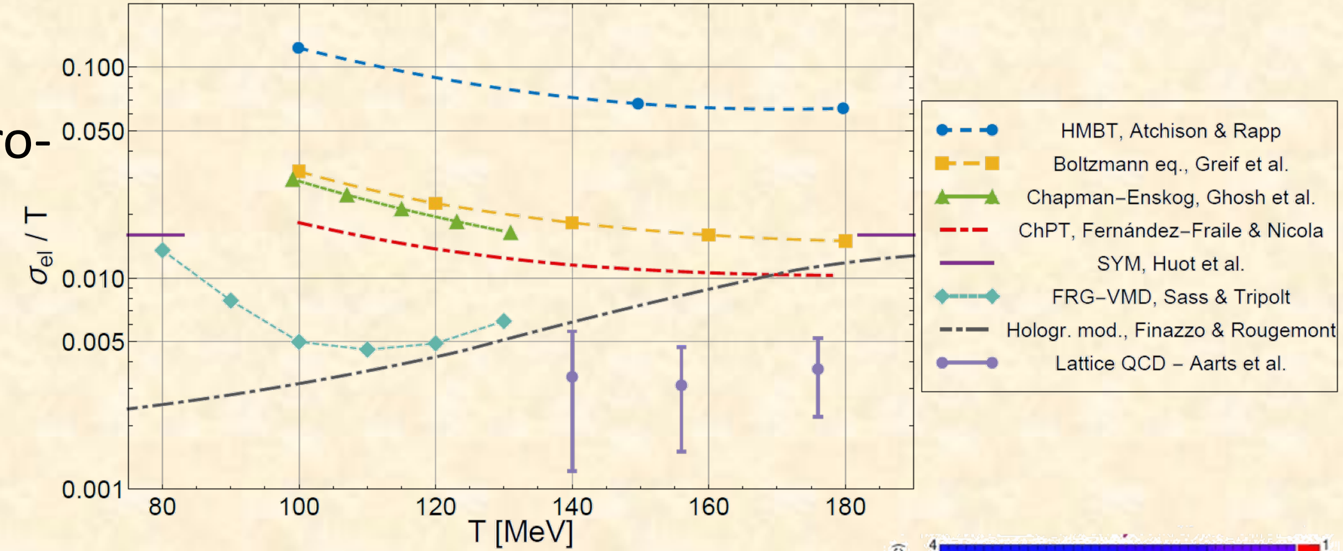
- Electrical conductivity defined as

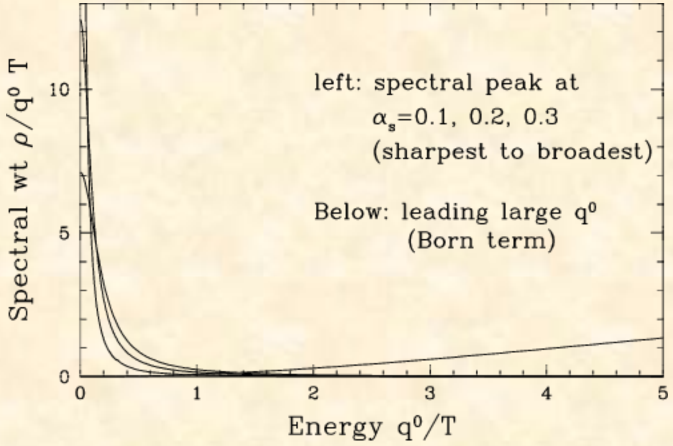
$$J^{\mu} = \sigma_{el} E^{\mu}$$

- Can be extracted from EM correlator in the zero-momentum, low-energy limit:

$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\mathrm{Im}\Pi_{\mathrm{em}}(q_0, \vec{q} = 0, T)}{q_0}$$

➢ wide range of theory predictions



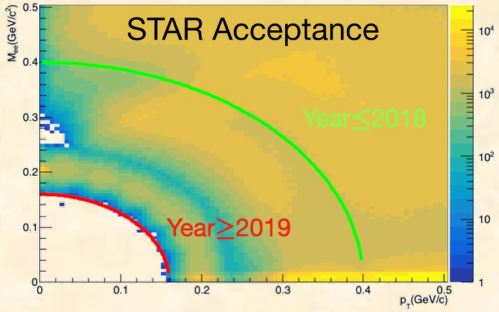


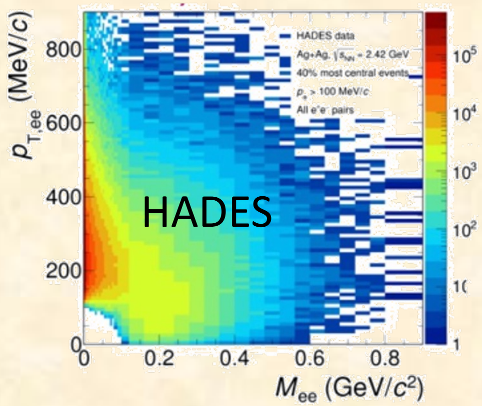
Moore, Robert, hep-ph/0607172

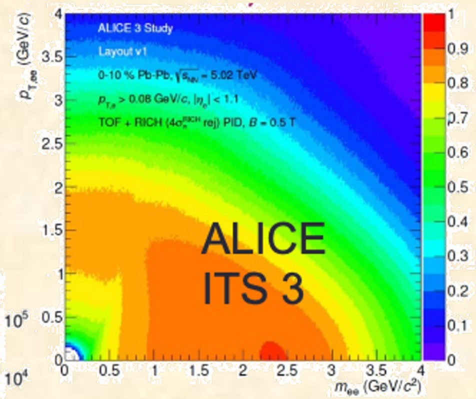
e.g. Greif, Greiner, Denicol, PRD93 (2016) 096012
Atchinson, Rapp, J.Phys.Conf.Ser.832 (2017) 012057

Experimental challenge:

- low invariant mass and low p_T
- precise knowledge of (elastic) cross sections among hadrons







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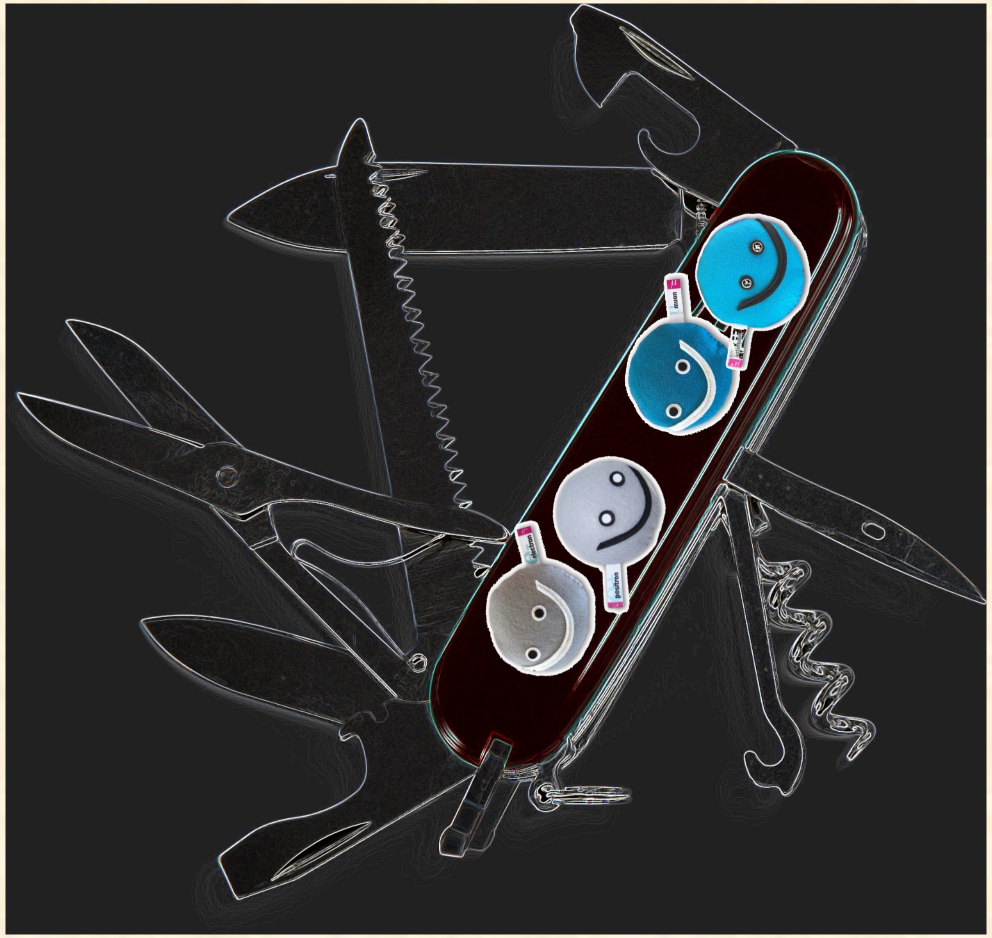
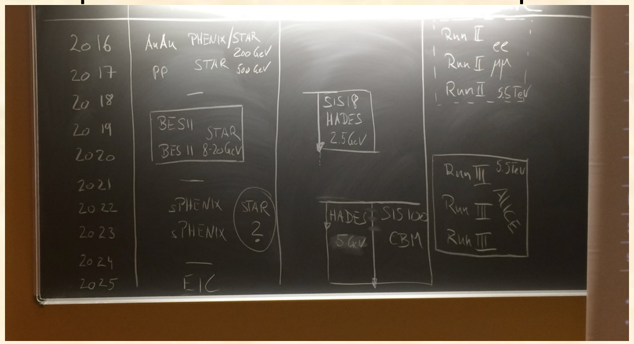
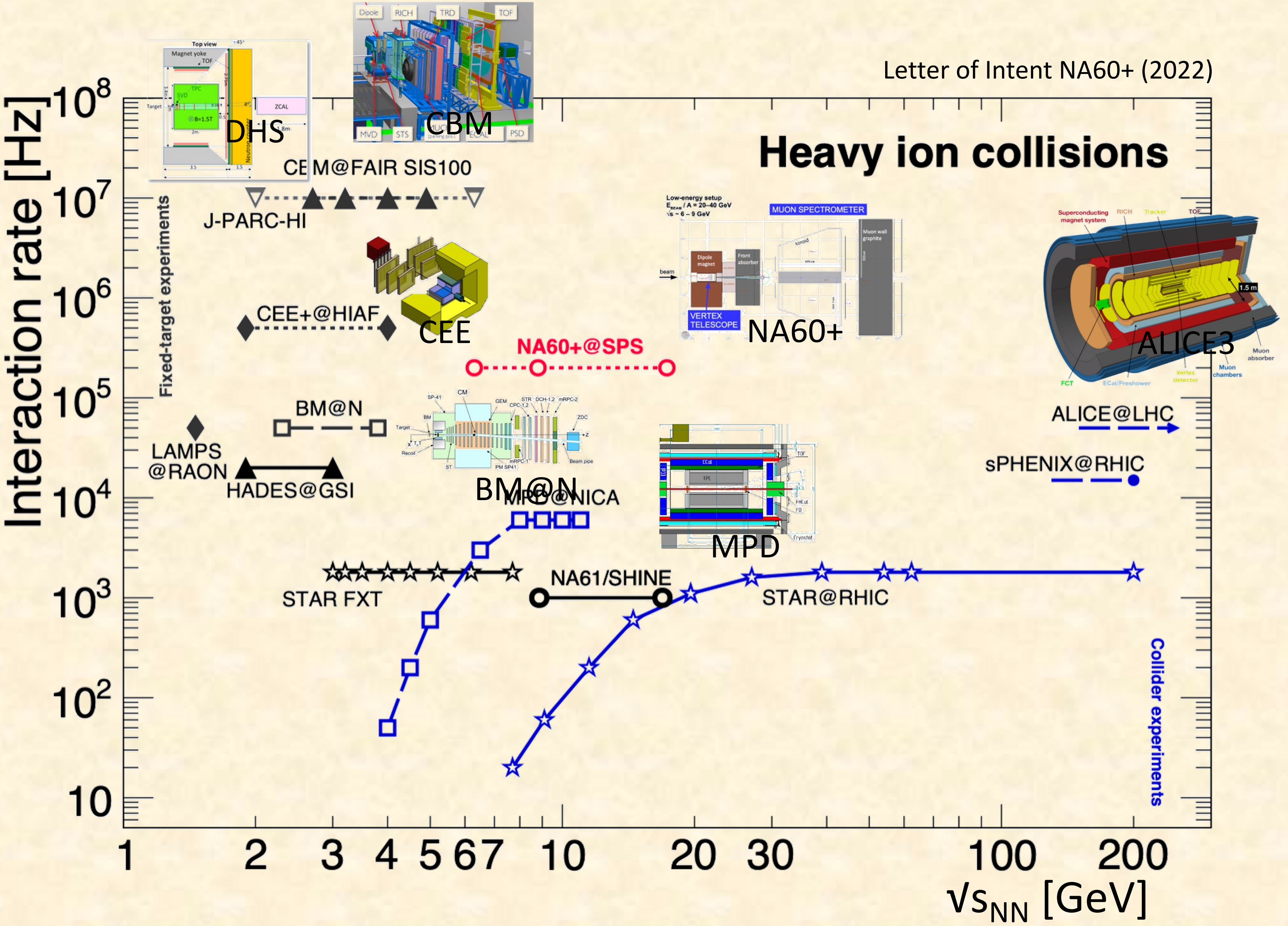


Future Prospects

ECT* 2015 Workshop
"New Perspectives on Photons and Dileptons …"



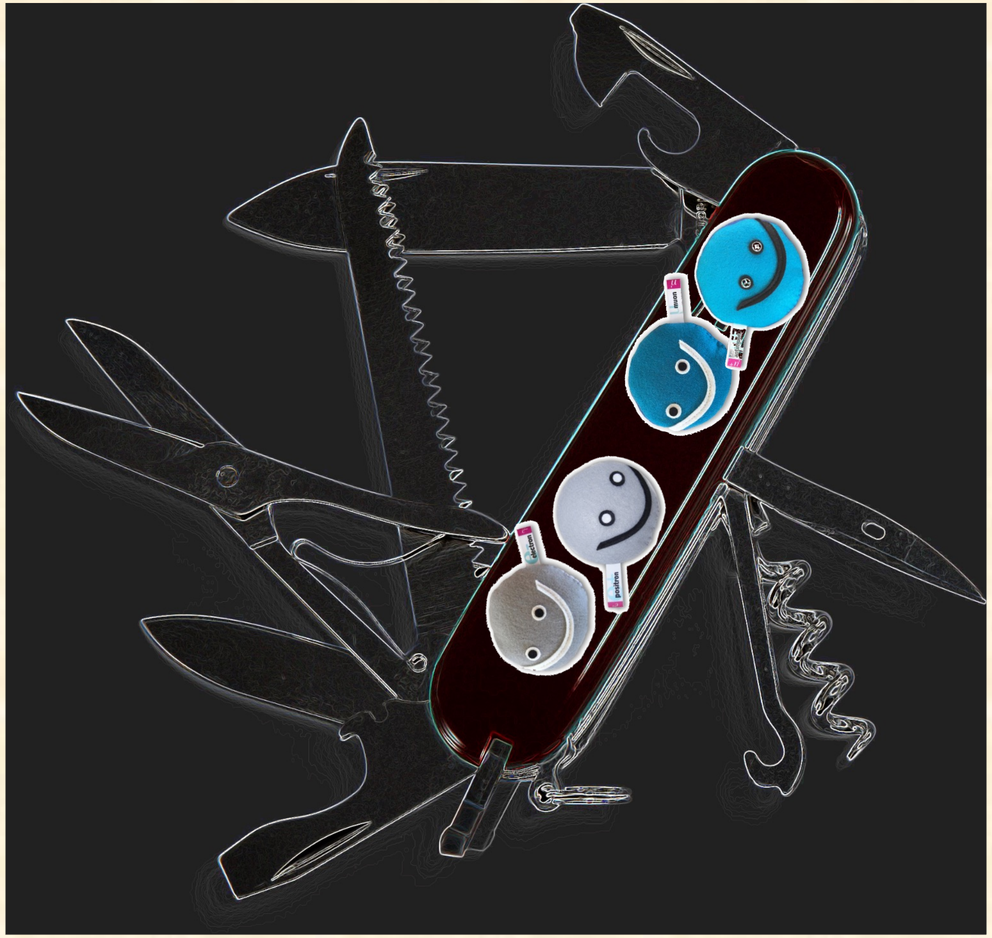
Letter of Intent NA60+ (2022)



Future Measurements

- high statistics
  - high interaction rates
  - large acceptance
- precise references
  - cocktail (mesons, HF, DY)
  - multipurpose detectors
- good control on backgrounds
  - materials: conversion rejection
  - $e^{+/-}$ $\mu^{+/-}$ purity

Summary



- Dilepton measurements provide access to wide range of unique physical observables
  - lifetime, temperature, transport properties, chiral symmetry restoration, …
- Potential of accurate dilepton measurements is well demonstrated at SPS, SIS18, RHIC, and LHC energies
  - combined with new theoretical developments and insights
- For future experimental progress high-statistics data is key
  - an increasing world-wide effort to map out the QCD phase map and deliver its landmarks