

Thermal Dileptons and the QCD Phase Transitions

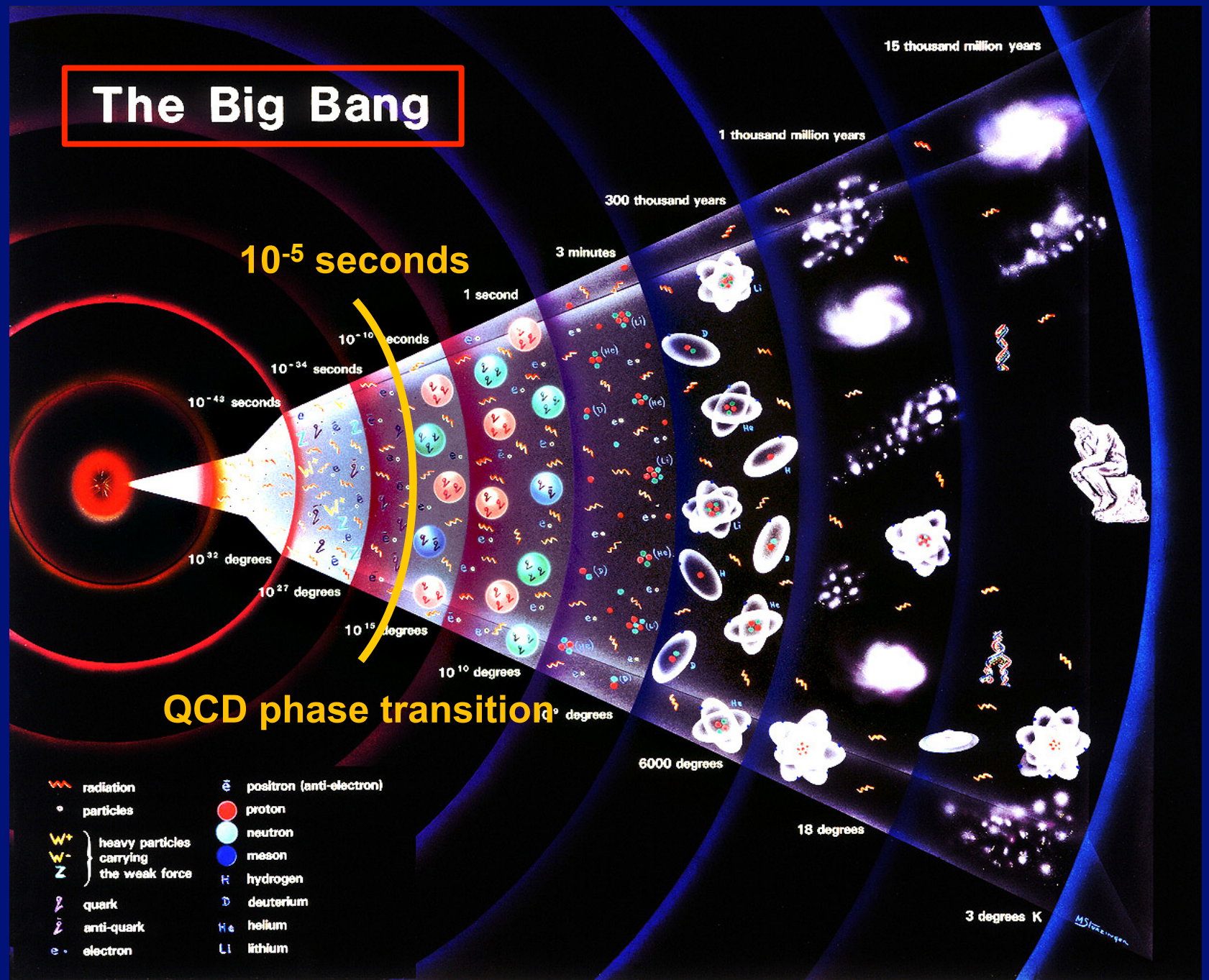
Hans J. Specht
Universität Heidelberg



Kolymbari, Greece, August 24, 2015

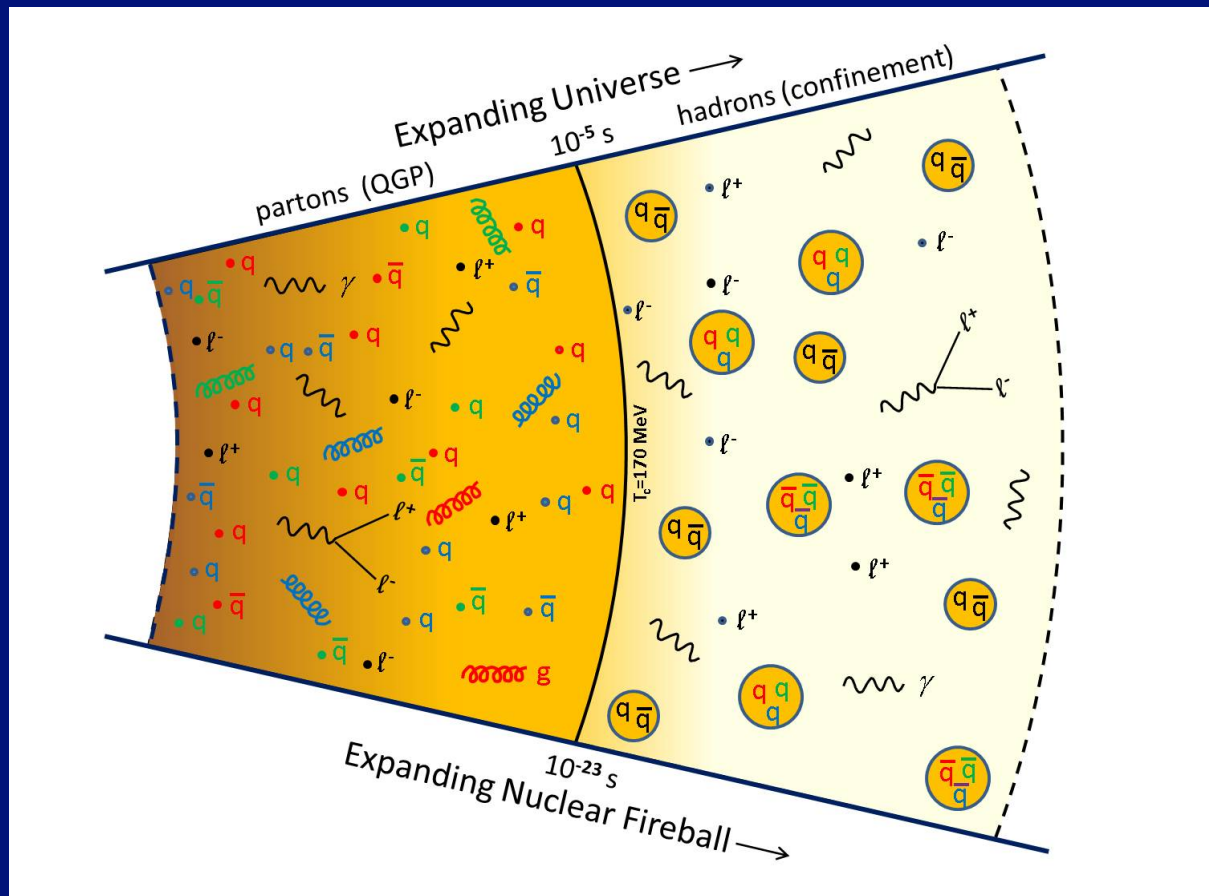


The Big Bang



The QCD Phase Transitions

up to 10^{-5} s, plasma of quarks and gluons (QGP) plus leptons and photons



at the phase border:

- 'confinement' of quarks and gluons into hadrons and anti-hadrons (symmetry)
- 'chiral symmetry breaking' (Higgs-like): creation of 98% of their mass
- birth of empty space: the 'vacuum'

High-Energy Nucleus-Nucleus Collisions: The Big Bang in the Laboratory

Study of QCD in the complete **temperature/baryon-density** plane

Phase transitions

- Probe the quark-hadron transition

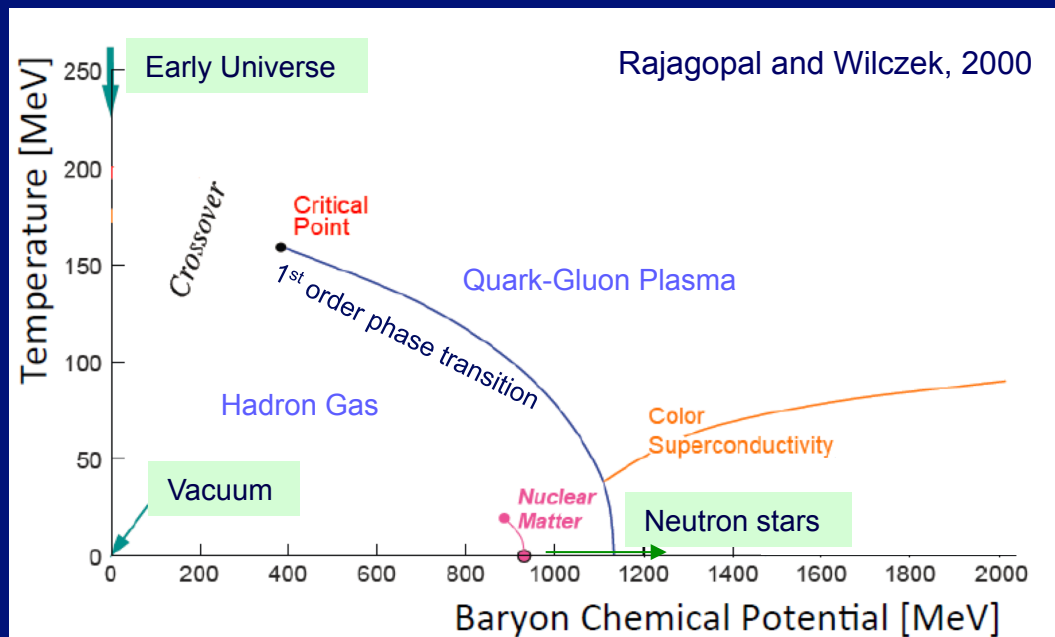
- Probe the chiral transition (origin of light hadron masses)

Bulk properties

- Probe high-temperature partonic matter: early Universe

- Probe high-density baryonic matter: neutron stars

Theoretical guidance for the QCD phase diagram



μ_B related to density of (baryons - anti-baryons)

Small μ_B (Lattice QCD)

crossover transition

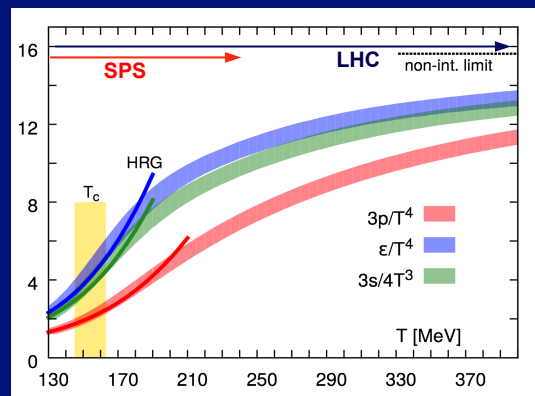
$\epsilon_c \sim 1 \text{ GeV/fm}^3$, $T_c \sim 160 \text{ MeV}$

Large μ_B , moderate T (field th.)

QCD critical point,
1st order transition

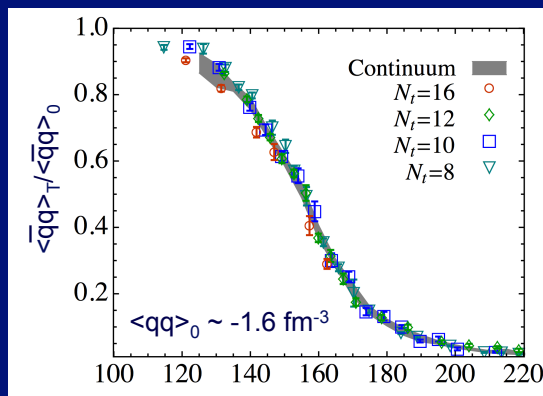
QCD mass (u,d) dominant in
the visible part of the Universe

Hot QCD coll., arXiv:1407.6387 (2014)



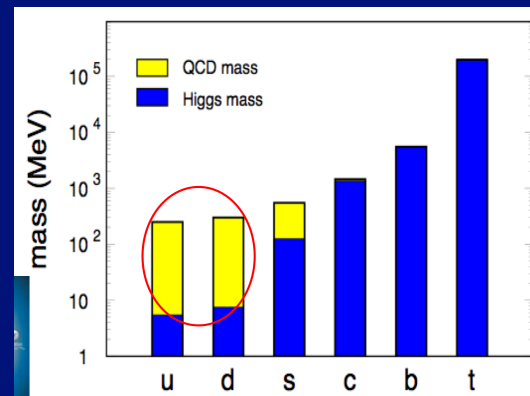
deconfinement transition

Borsanyi et al., arXiv:1011.4030.v1 (2010)



chiral symmetry restoration

B. Mueller, arXiv:0404015.v2 (2004)



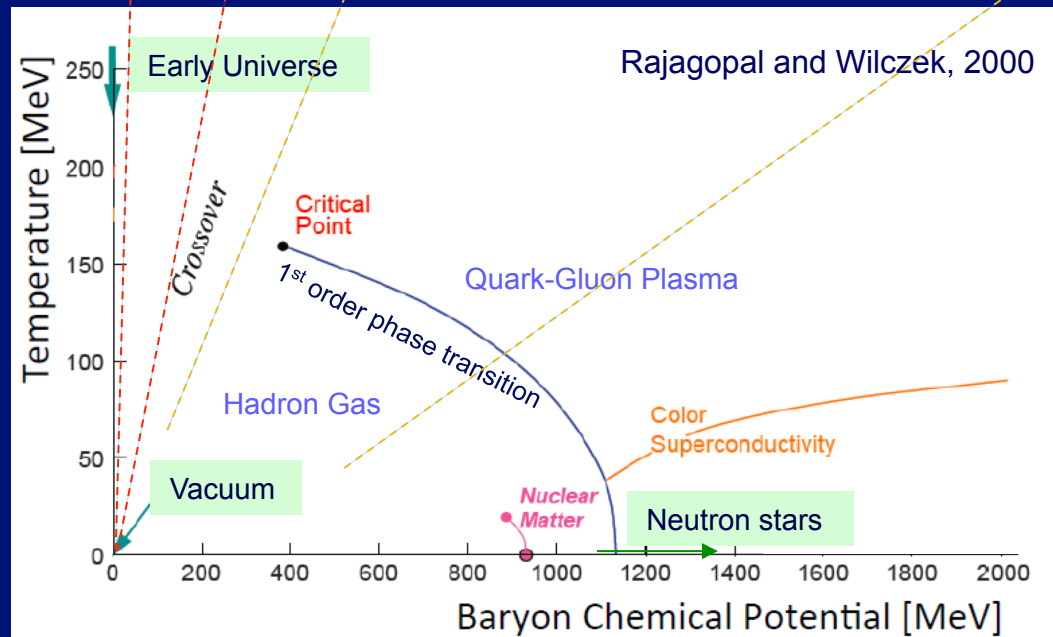
chiral symmetry breaking:
masses of the 6 quark flavours

Lattice QCD, $\mu_B=0$

QCD phase diagram and accelerator energies

Very high energies, central production
(LHC; RHIC)

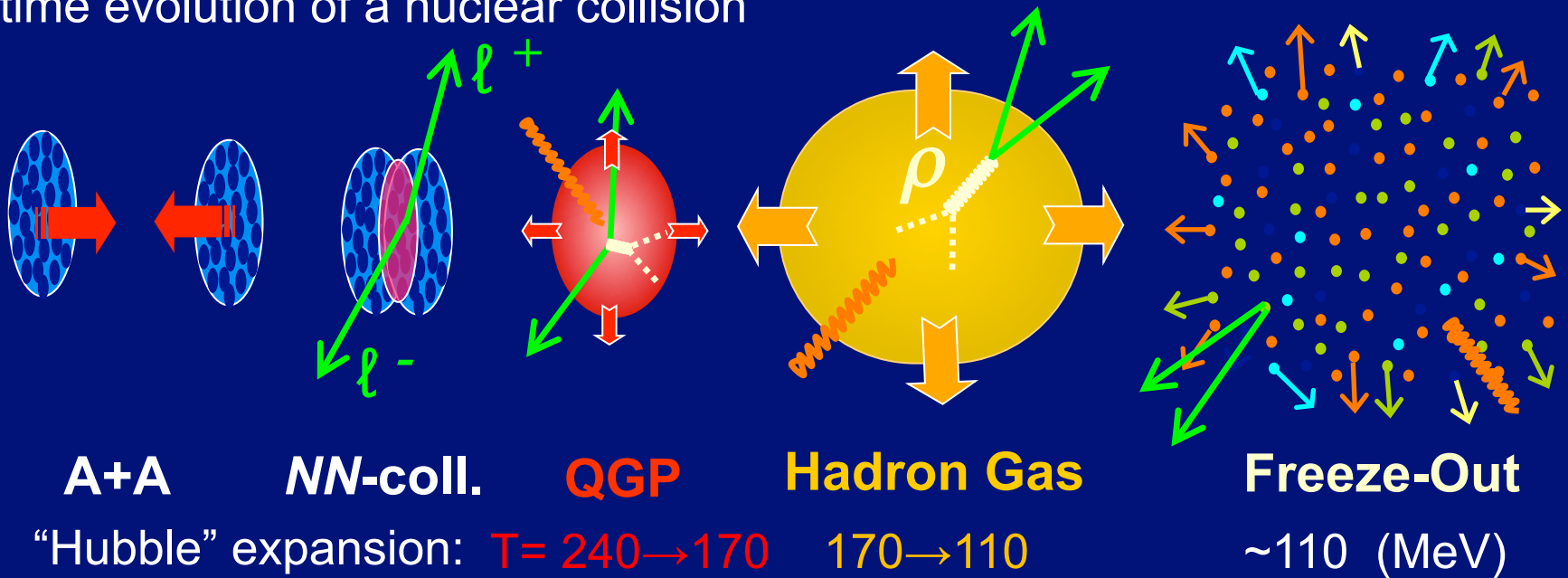
Moderate and low energies
(low-energy RHIC; SPS; FAIR; NICA)



μ_B related to density of (baryons - anti-baryons)

Observables and physics goals: dilepton production

time evolution of a nuclear collision

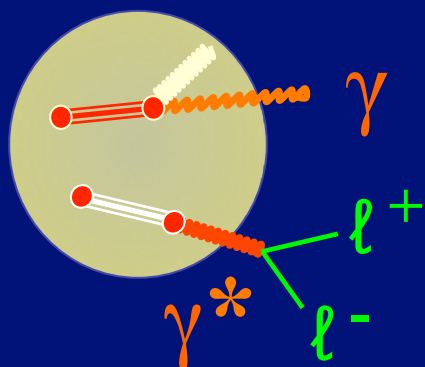


Lepton pairs emitted at all stages; no final state interactions

difficulties: 10^{-4} (α_{em}^2) of hadrons; overlay of different sources

NN-collisions:	Drell-Yan, $D\bar{D}$ pairs (physical background)
QGP:	thermal $q\bar{q}$ annihilation (deconfinement)
Hot+Dense Hadron Gas:	ρ (ρ -a ₁) modification (chiral restoration)
Freeze-out:	free hadron decays (physical background)

Electromagnetic probes: dileptons vs. real photons



photons: 1 variable: p_T

lepton pairs: 2 variables: M, p_T

relevant for thermal radiation:

p_T sensitive to temperature and **expansion velocity**

M only sensitive to temperature (Lorentz invariant)

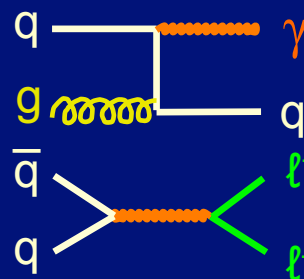
for flat spectral functions, i.e. for hadron-parton duality ($M > 1.5$ GeV)

(1) $dN/dM \sim M^{3/2} \times \exp(-M/T) \rightarrow$ 'Planck-like' (see next slide)

the only Lorentz-invariant thermometer of the field

(2) lowest order rate $\sim \alpha_{em} \alpha_s$

lowest order rate $\sim \alpha_{em}^2$

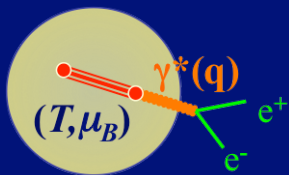


QCD Compton

$q\bar{q}$ annihilation

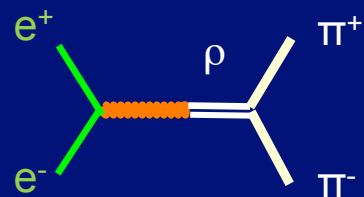
dileptons more rich and more rigorous than photons

Dilepton Rate in a strongly interacting medium

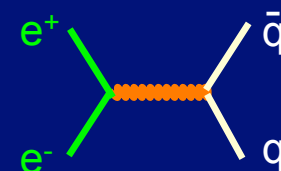
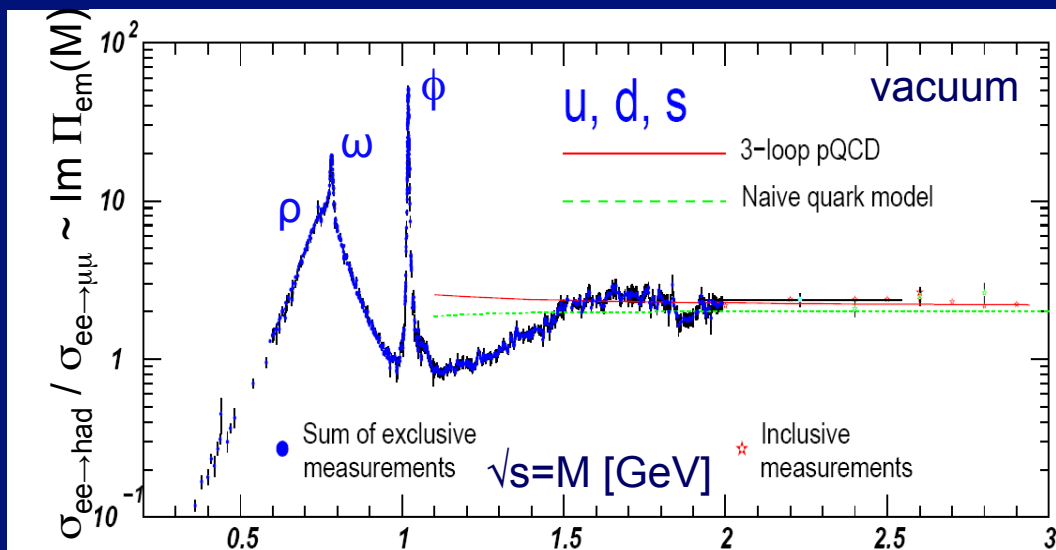


$$\frac{dN_{ee}}{d^4x d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0, T) \times \text{Im } \Pi_{em}(M, q; \mu_B, T)$$

photon
self-energy



non-perturbative
in-medium
spectral function(s)



perturbative
hadron-parton
duality (flat SF)

$$\text{Im } \Pi_{em} \sim \text{Im } D_\rho + \dots$$

$$\text{Im } \Pi_{em} \sim N_c \sum (e_q)^2$$

after integration of rate equation over momenta and emission 4-volume:

hadron basis
 $M < 1.5 \text{ GeV}$

$$dN_{\mu\mu} / dM \propto M^{3/2} \times \langle \exp(-M / T) \rangle \times \langle \text{spectral function}(M) \rangle$$

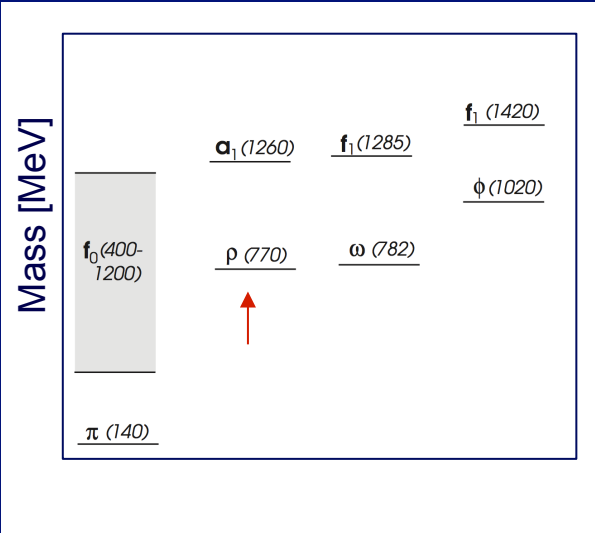
$M > 1.5 \text{ GeV}$

$$dN_{\mu\mu} / dM \propto M^{3/2} \times \langle \exp(-M / T) \rangle$$

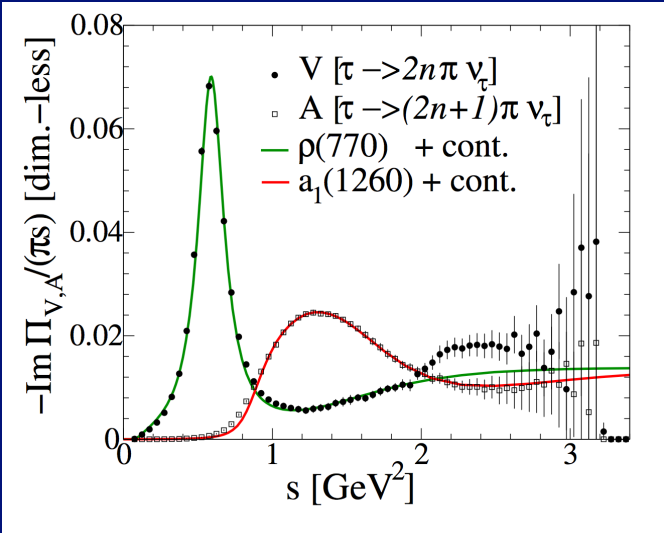
'Planck-like' $\rightarrow$ thermometer
distinguishes partons and hadrons

Dileptons and the spectral functions of the chiral doublet ρ/a_1

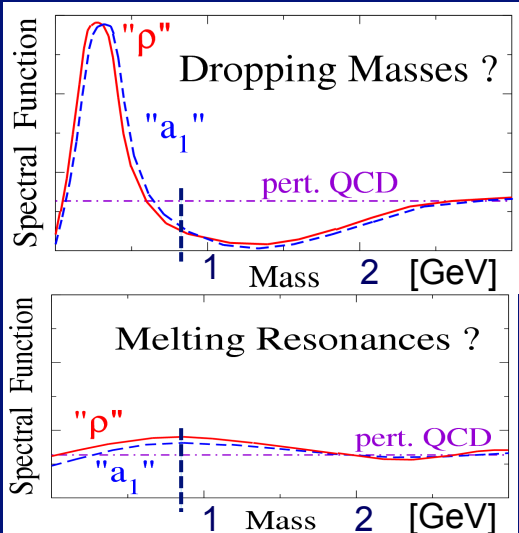
P-S, V-A splitting in the physical vacuum due to spontaneous breaking of chiral symmetry



Splitting of chiral partners

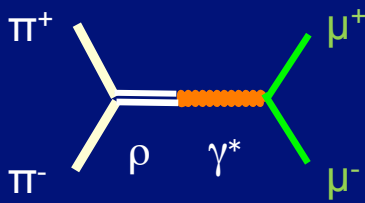


ALEPH data: Vacuum



at T_c : Chiral Restoration

thermal dileptons with $M < 1$ GeV mostly mediated by the **vector meson ρ** (1^{--})



strong coupling of γ^* to ρ (VMD)

- life time $\tau_\rho = 1.3 \text{ fm} \ll \tau_{\text{collision}} > 10 \text{ fm}$ (unique in the PDG)
- continuous “regeneration” by $\pi^+\pi^- \rightarrow$ **sample in-medium evolution**

axial vector a_1 accessible through ρ - a_1 chiral mixing ($\pi a_1 \rightarrow 4\pi \dots$)

In-medium changes of the ρ properties (relative to vacuum)

Selected theoretical references

	mass of ρ	width of ρ
Pisarski 1982		
Leutwyler et al 1990 (π ,N)		
Brown/Rho 1991 ff		
Hatsuda/Lee 1992		
Dominguez et. al 1993		
Pisarski 1995		
Chanfray, Rapp, Wambach 1996 ff		
Weise et al. 1996 ff		

very confusing, experimental data crucial

Dilepton observables directly related to the QCD phase diagram

Signals of deconfinement transition

- | | |
|--|--|
| T of thermal $\ell^+\ell^-$ (high M) | ✓ $T > T_c$ partonic, $T < T_c$ hadronic sources |
| T_{eff} of thermal $\ell^+\ell^-$ | ✓ drop of inverse slope of m_T spectra
(based on soft EoS above T_c) |

Signals of chiral symmetry restoration

- | | |
|-----------------------------|--|
| ρ spectral function | ✓ in-medium properties (indirect probe) |
| ρ - a_1 (V-A) mixing | a_1 visible in $\ell^+\ell^-$ channel (direct probe) |

Common to both transitions

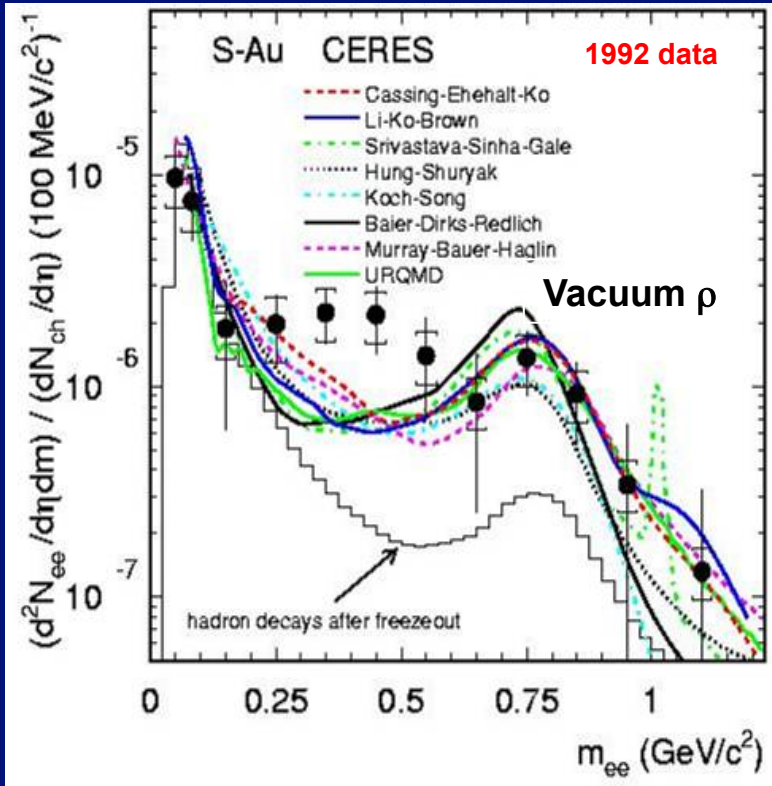
- | | |
|--|---|
| beam energy scan
(below $\sqrt{s}$ of 20 GeV/u) | onset of transitions
order of transitions
critical point
(structure in scan; extended τ_{FB}) |
|--|---|

Experimental Results

SPS Energies

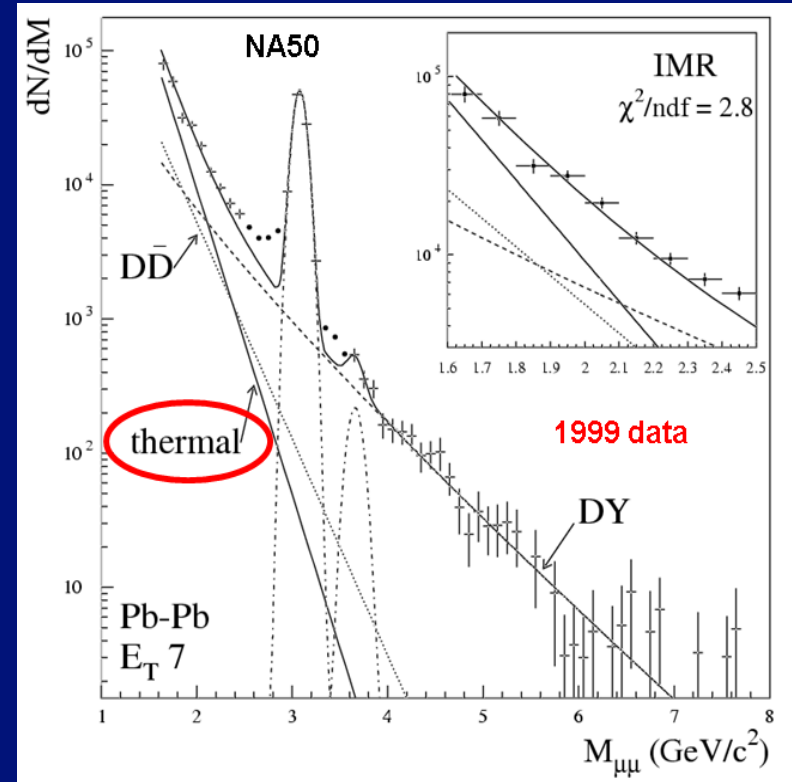
The Pioneering Experiments

LMR: CERES/NA45, PRL 75 (1995) 1272



First
clear
signs
of
new
physics
in
LMR
and
IMR

IMR: NA50, Nucl.Phys.A698 (2002) 539c



strong excess of dileptons above the known sources

enormous boost to theory (~ 500 citations)
surviving interpretation: $\pi^+\pi^- \rightarrow \rho^* \rightarrow e^+e^-$;
ambiguity of the ρ in-medium effects:
mass shift vs. broadening of the ρ

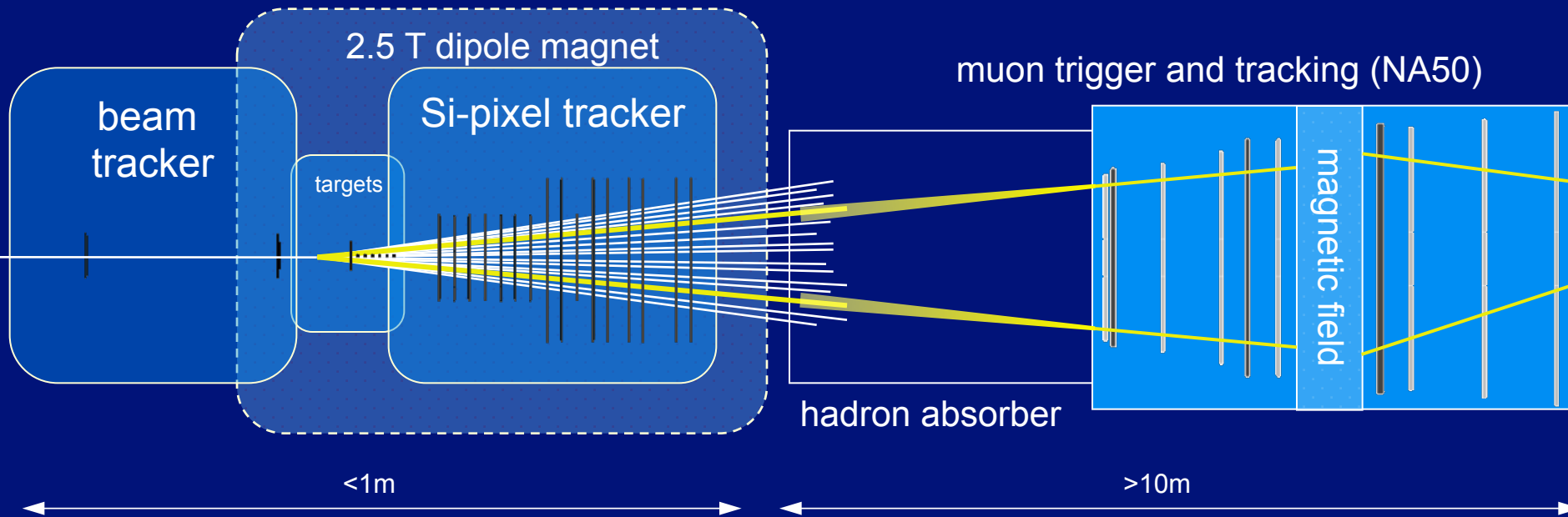
Chiral restoration?

continuum excess in the IMR
possible interpretation: $q\bar{q} \rightarrow \mu^+\mu^-$
ambiguity of the excess:
prompt radiation vs. enhanced open charm

Deconfinement?

Measuring dimuons in NA60

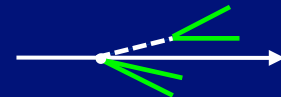
(basic idea P. Sonderegger, exp. approved 2000, spokespersons C. Lourenço, later G. Usai)



Track matching in coordinate and momentum space

Improved dimuon mass resolution

Distinguish prompt from decay dimuons



Additional bend by the dipole field

Dimuon coverage extended to low p_T

Radiation-hard silicon pixel detectors (LHC development)

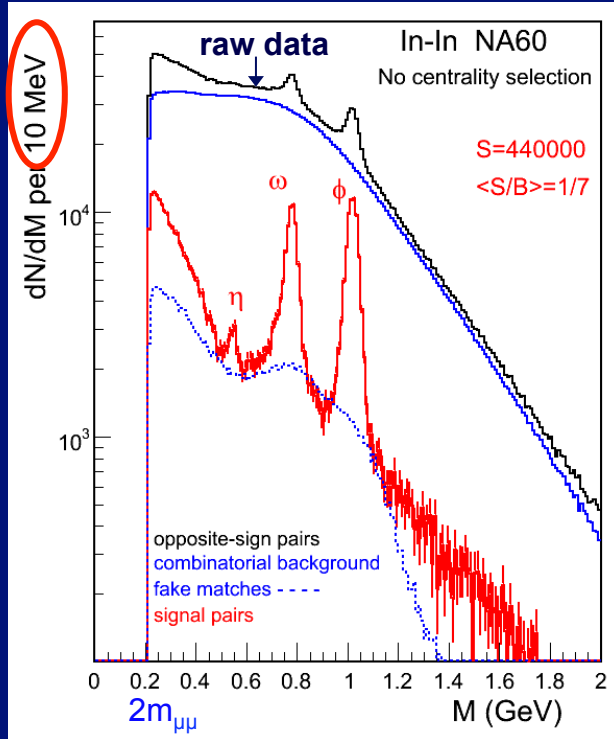
High luminosity of dimuon experiments maintained

In-In 158 GeV/u: NA60 2003 data and major analysis steps

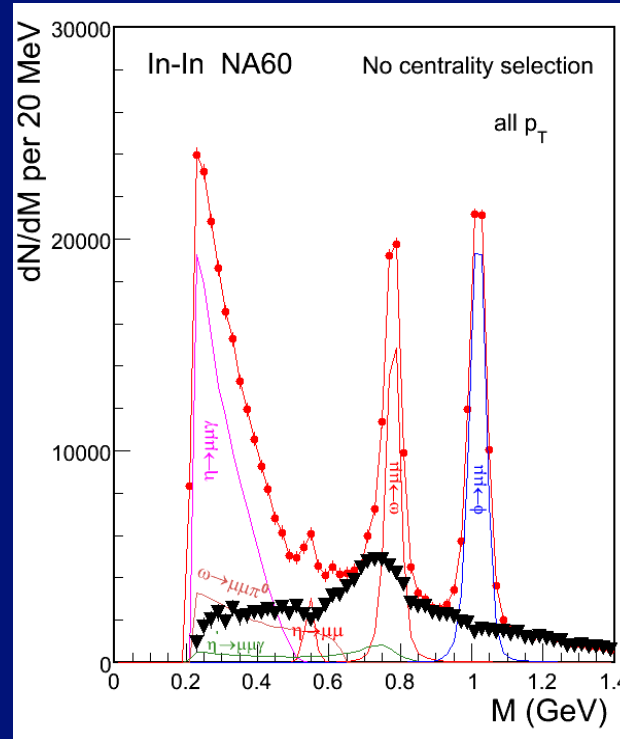
Phys. Rev. Lett. 96 (2006) 162302

PRL 96 (2006) 162302; EPJ C 61 (2009) 711

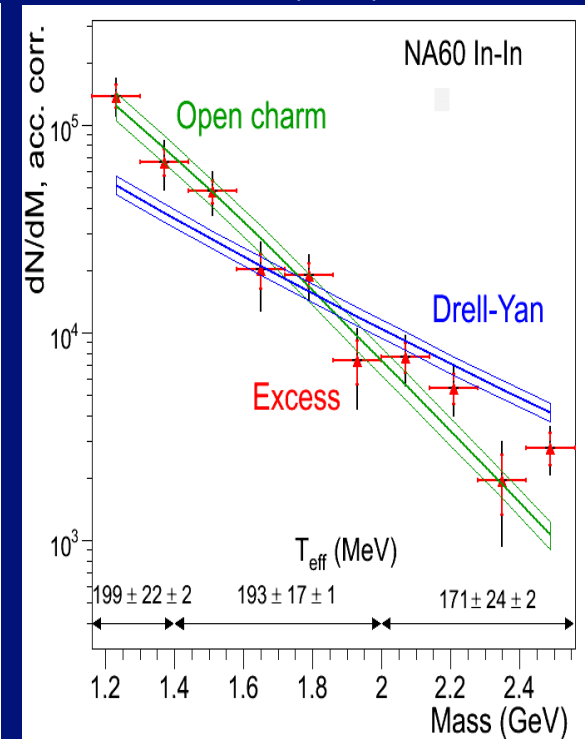
EPJ C 59 (2009) 607



subtraction of combinatorial background and fake matches
 $\sim 10^6$ net, 10^8 triggers, 10^{12} int.



subtraction of **measured** decay cocktail with accuracy of 2-3%
 $\rightarrow$ isolation of the LMR excess



IMR: subtraction of Drell-Yan and **measured** open charm (by displaced decay vertices)

Final step: acceptance correction

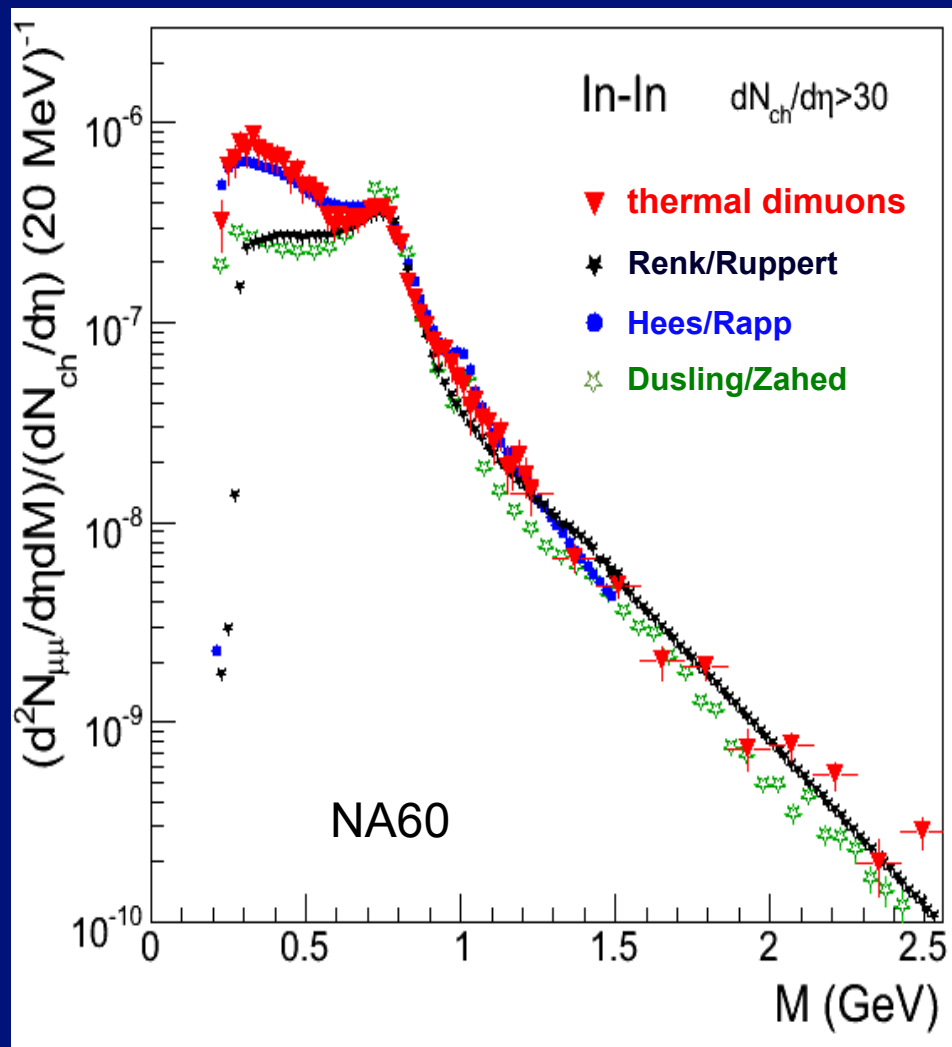
reduce **4-dimensional acceptance correction** in M - p_T - y - $\cos\Theta_{CS}$ to (mostly) 2-dim corrections in pairs of variables, separate for the excess and all other sources

Thermal dimuon mass spectrum: proof of deconfinement

[Eur. Phys. J. C 59 (2009) 607]

→ CERN Courier 11/ 2009, 31-34

Chiral 2010 , AIP Conf.Proc. 1322 (2010) 1



all physics background sources subtr.
integrated over p_T
fully corrected for acceptance
absolutely normalized to dN_{ch}/η

effective statistics highest of all
experiments, past and present
(by a factor of nearly 1000)

$M < 1 \text{ GeV}$

ρ dominates, 'melts' close to T_c (sl.19)

$M > 1 \text{ GeV}$

~ exponential fall-off → 'Planck-like'
fit to $dN/dM \propto M^{3/2} \times \exp(-M/T)$

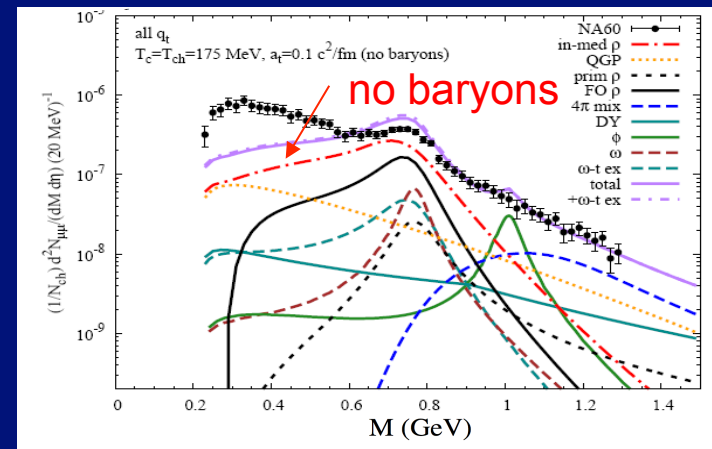
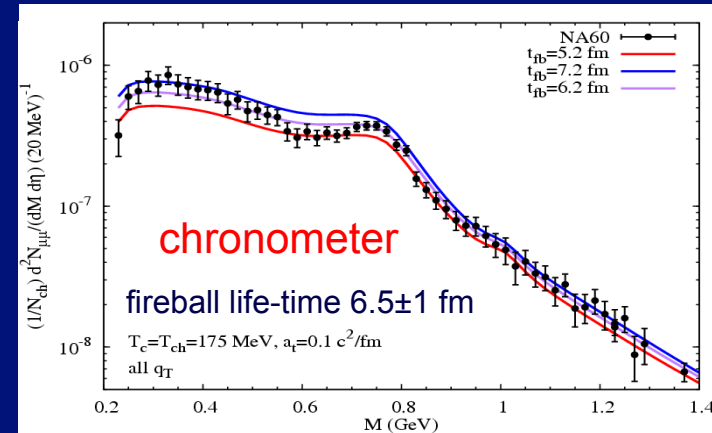
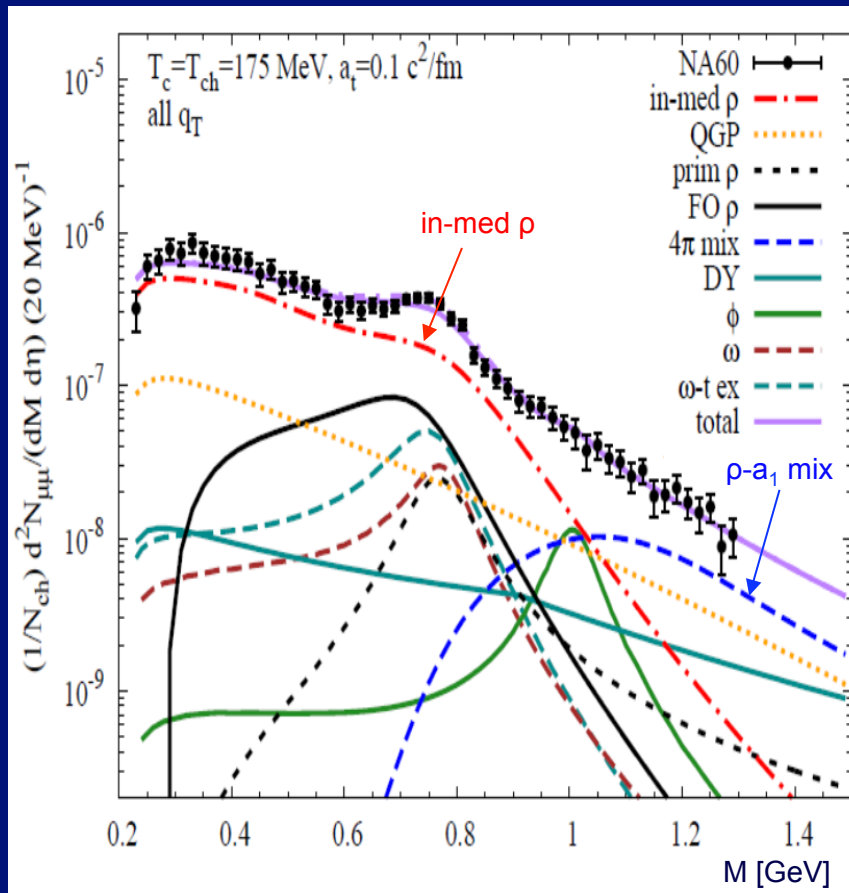
range 1.1-2.0 GeV: $T = 205 \pm 12 \text{ MeV}$

1.1-2.4 GeV: $T = 230 \pm 10 \text{ MeV}$

$T > T_c = 160\text{-}170 \text{ MeV}$: partons dominate

Theoretical description of low-mass region (I)

H. v. Hees, R. Rapp, NPA A 806 (2008) 339 (basis); R. Rapp, figs. arXiv:1110.434511 (2011)



Perfect agreement in absolute terms

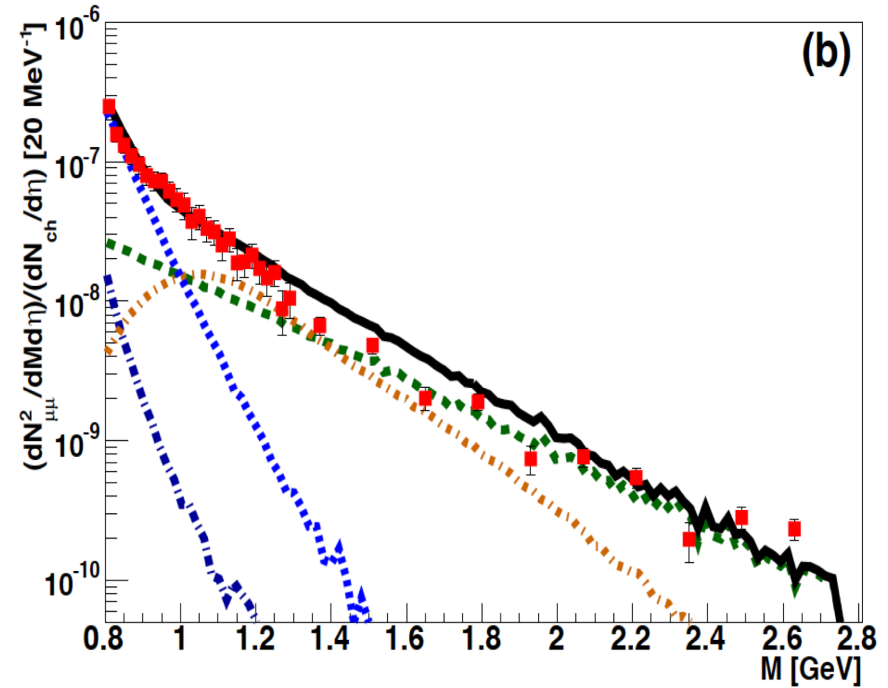
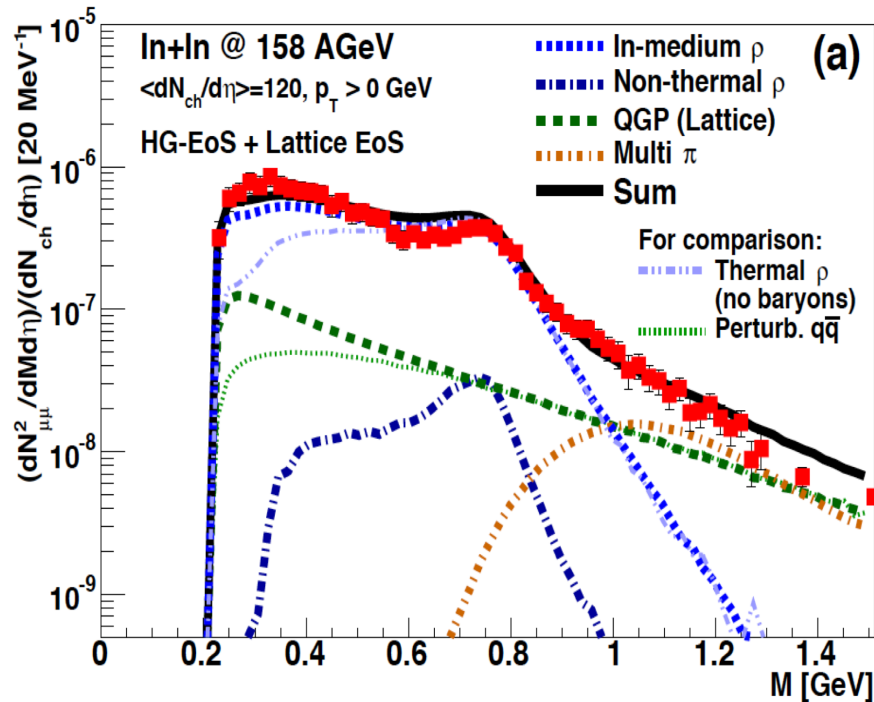
Rapp: 'spectrum directly reflects thermal emission rate'

First calculation: Chanfray, Rapp, Wambach, Nucl.Phys. A 617 (1997) 472

broadening of the ρ dominated by baryon interactions

Theoretical description of low-mass region (II)

S.Endres, H. van Hess, J. Weil and M. Bleicher, Phys. Rev. C 91 (2015) 054911



Basis: Coarse-graining approach plus UrQMD transport model

ρ spectral function a la Rapp/Wambach

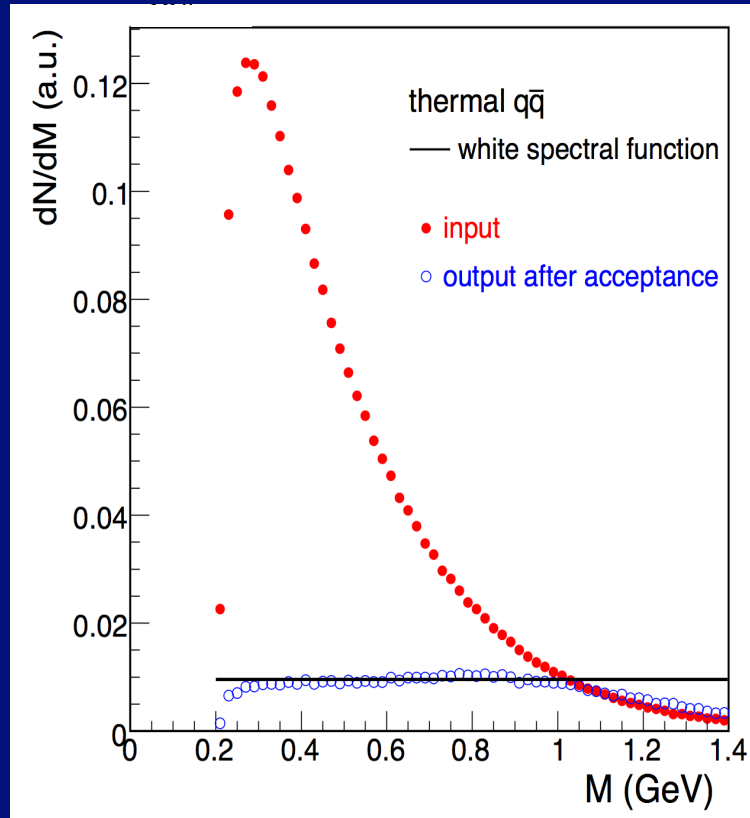
perfect agreement in absolute terms

partonic emission dominant for $M > 1.5$ GeV

deconfinement at SPS energies now well described by four independent groups

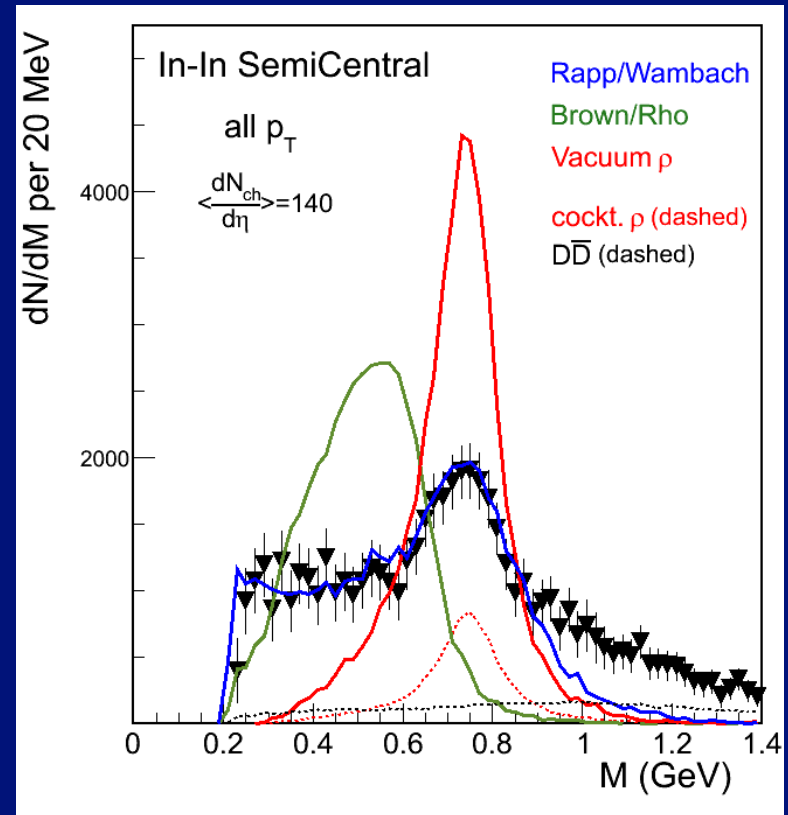
Towards chiral restoration: mass shift vs. broadening

Eur. Phys. J. C 49 (2007) 235



NA60 acceptance compensates for the phase space factors of thermal radiation: flat spectral function in $\rightarrow$ flat spectrum out (by pure chance)

PRL 96 (2006) 162302; AIP Conf.Proc. 1322 (2010) 1



before acceptance correction:
 ρ spectral function, averaged over space-time and momenta
 (BR+Vac normalized to data <0.9 GeV)

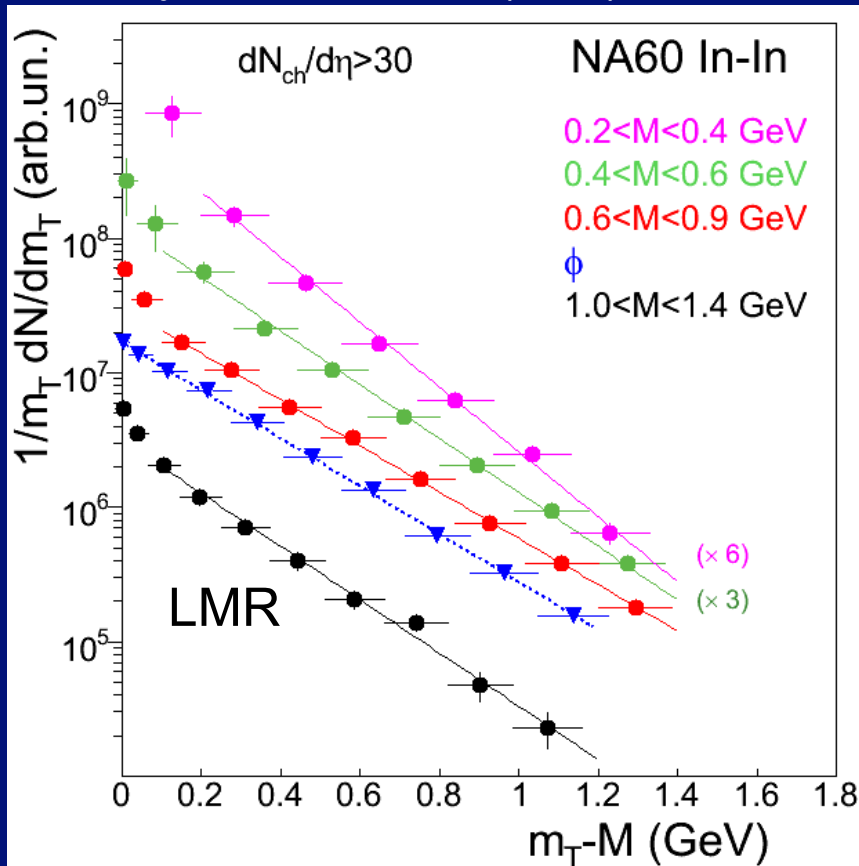
only broadening of ρ observed, no mass shift $\rightarrow$ 'hadrons melt'

On chiral restoration and ρ melting: *P.M.Hohler and R. Rapp, PLB 731 (2014) 103*

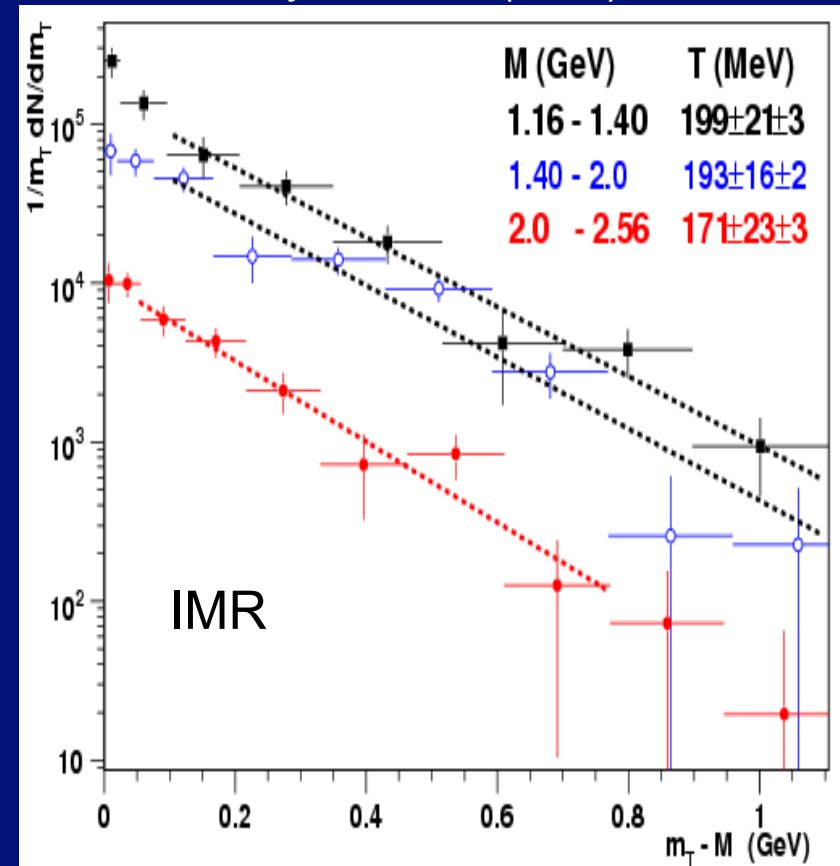
The **other** variable of dileptons: p_T spectra – 'Barometer'

transverse mass: $m_T = (p_T^2 + M^2)^{1/2}$

Phys. Rev. Lett. 100 (2008) 022302



Eur. Phys. J. C 59 (2009) 607

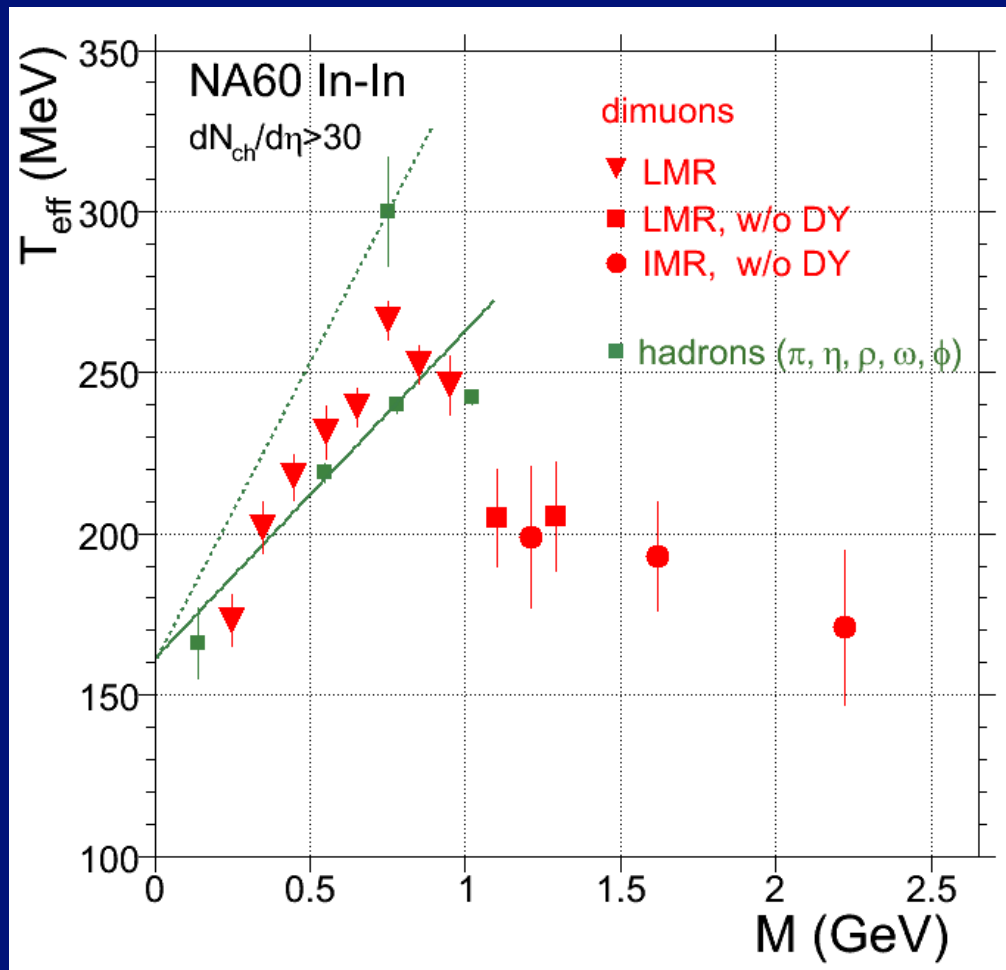


all m_T spectra exponential for $m_T - M > 0.1$ GeV; < 0.1 GeV ??

fit with $1/m_T dN/dm_T \sim \exp(-m_T/T_{eff})$; T_{eff} – 'effective temperature'

The rise and fall of radial flow of thermal dimuons

Phys. Rev. Lett. 100 (2008) 022302



Initial linear rise of T_{eff} with M

two components in m_T spectra:
thermal and radial collective
(‘Hubble’) expansion

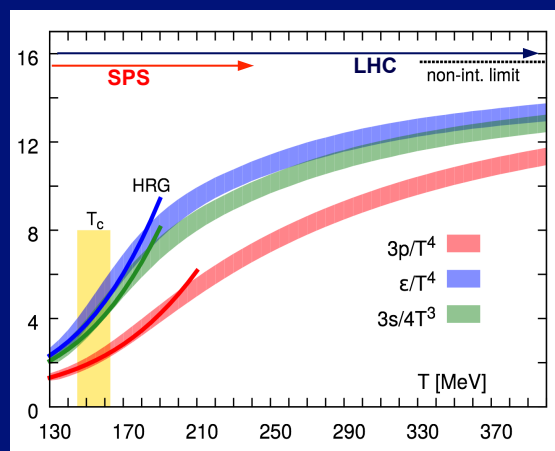
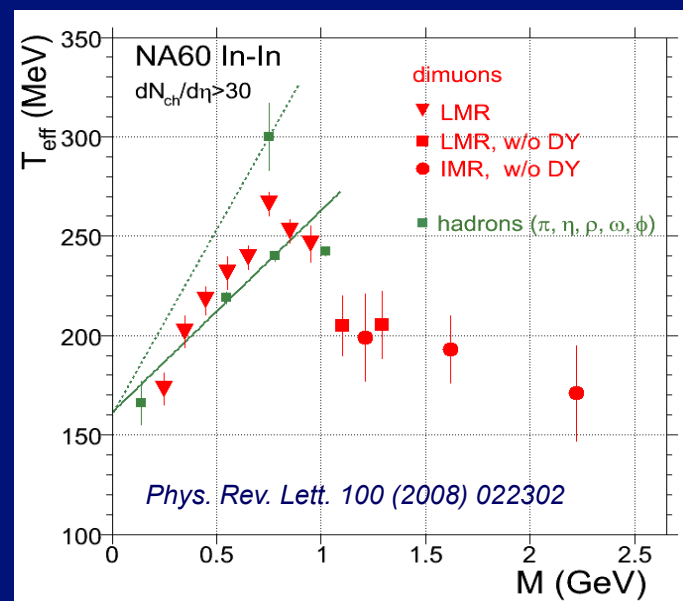
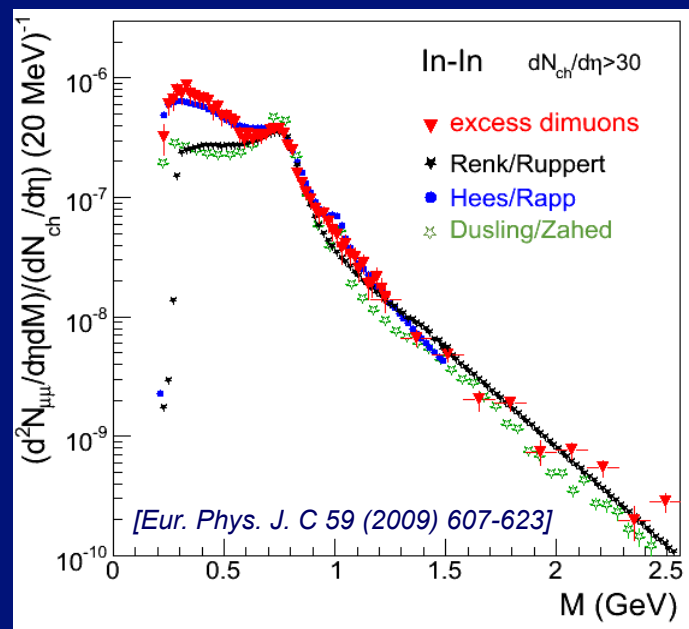
$$T_{eff} \sim T_f + M \langle v_T \rangle^2 \quad v_T \sim 0.5c$$

Rise up to 1 GeV consistent with
radial flow of a hadronic source
(here $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$)

Drop at 1 GeV signals sudden
transition to a low-flow, i.e. an
early source $\rightarrow$ partonic origin
(here $q\bar{q} \rightarrow \mu^+\mu^-$)

Dominance of partons for $M > 1$ GeV also from p_T spectra

Combined conclusions from mass and p_T/m_T spectra



Lattice QCD:

rapid rise of energy density ϵ , slow rise of pressure p
(far from ideal gas)

EoS above T_c very **soft** initially (c_s minimal)

$M > 1$ GeV: parton-dominated

- T_{eff} independent of mass within errors

mass spectrum: $T = 205 \pm 12$ MeV

m_T spectra: $\langle T_{\text{eff}} \rangle = 190 \pm 12$ MeV

- same values within errors

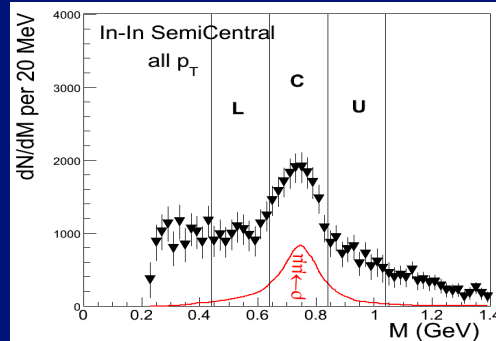
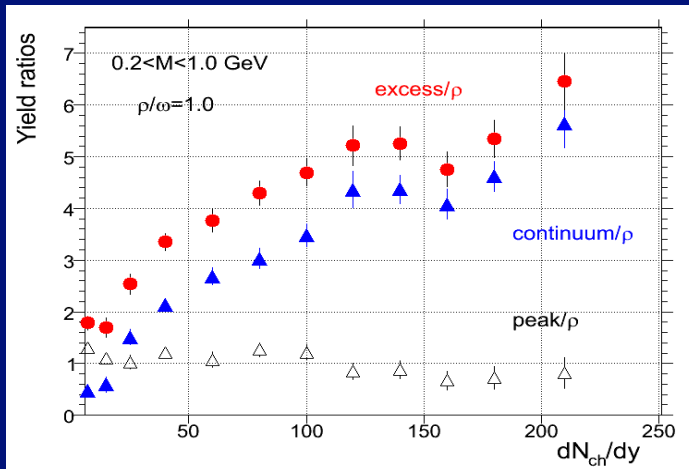
negligible flow $\rightarrow$ soft EoS above T_c

Centrality dependences: the 'p clock'

Comprehensive results on the centrality dependence of all acceptance-corrected mass and p_T/m_T spectra and their correlations

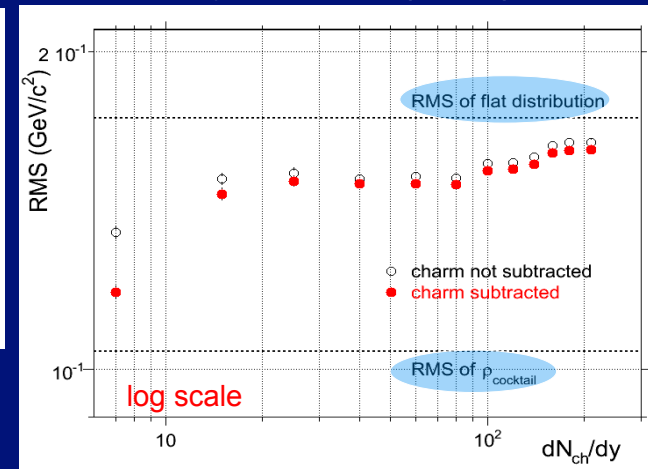
Specific example: shape of the ρ spectral function (data before acc. corr.)

Eur. Phys. J. C61 (2009) 711



peak: $R = C - 1/2(L + U)$
continuum: $3/2(L + U)$

Eur. Phys. J. C61 (2009) 711



rapid initial increase of relative yield; reflects the number of ρ regenerated in $\pi^+\pi^- \rightarrow \rho^* \rightarrow \mu^+\mu^-$

→ 'p clock'

monotonic increase of the width, approaching that of a flat distribution

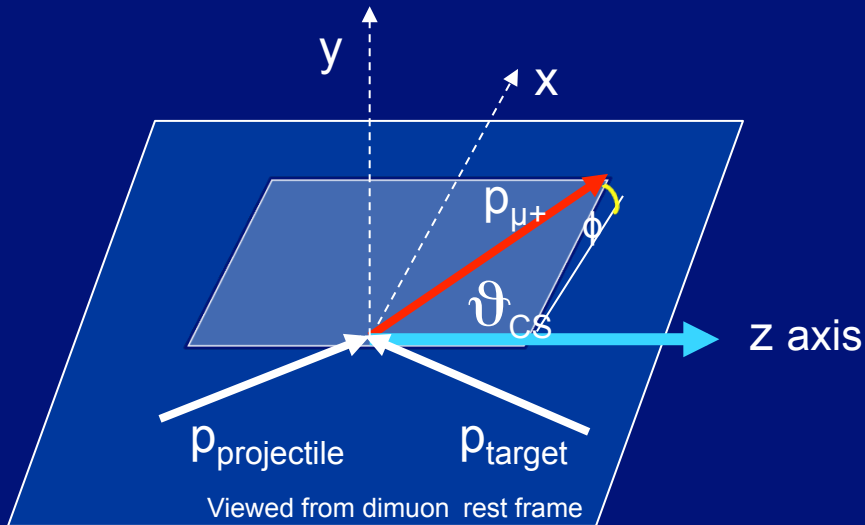
→ 'melting' of the ρ

Angular distributions

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta d\phi} = \left(1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right)$$

λ, μ, ν : structure functions related to helicity structure functions and the spin density matrix elements of the virtual photon

Choice of reference frame: Collins-Soper (CS)



In rest frame of virtual photon:

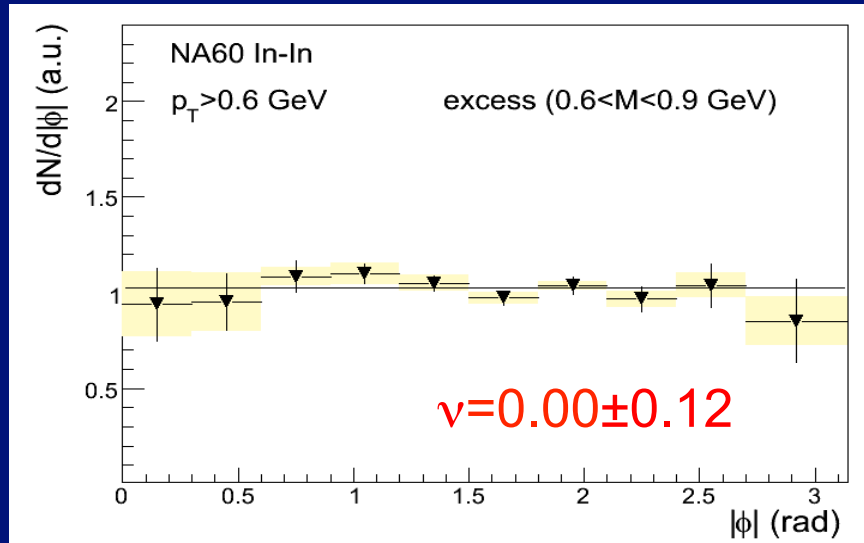
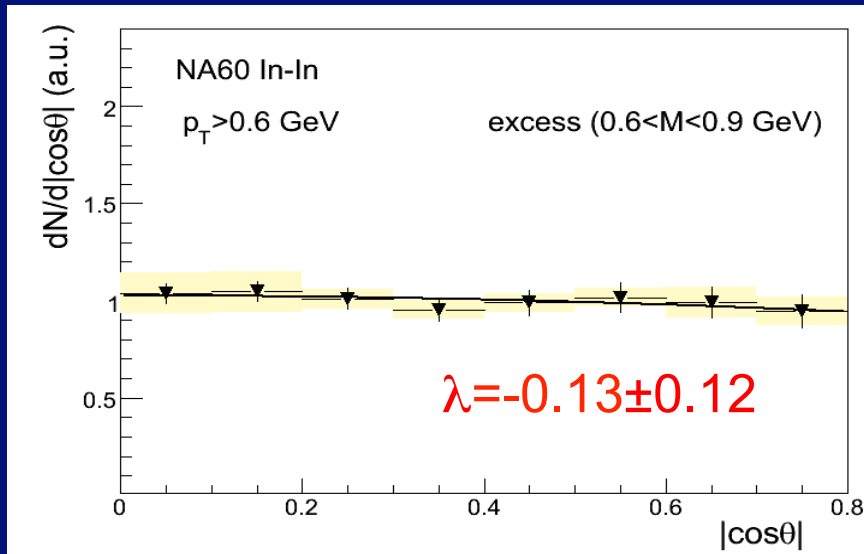
θ : angle between the positive muon $\mathbf{p}_{\mu+}$ and the z-axis.

z axis : bisector between $\mathbf{p}_{\text{proj}}$ and $-\mathbf{p}_{\text{target}}$

Expectation: completely random orientation of annihilating particles (pions or quarks) in 3 dimensions would lead to $\lambda, \mu, \nu = 0$

Results on structure coefficients λ , μ , ν

Phys. Rev. Lett. 102 (2009) 222301



example:

excess $0.6 < M < 0.9$ GeV

$\mu = 0.05 \pm 0.03$ (~ 0 as expected)

set $\mu = 0$ and fit projections

fit function for polar angle

$$\frac{dN}{d|\cos\theta|} \propto (1 + \lambda \cos^2 \theta)$$

fit function for azimuth angle

$$\frac{dN}{d|\phi|} \propto \left(1 + \frac{1}{3} \lambda + \frac{\nu}{3} \cos 2\phi \right)$$

Zero polarization within errors

Other dilepton experiments

The World Scene: Present and Future

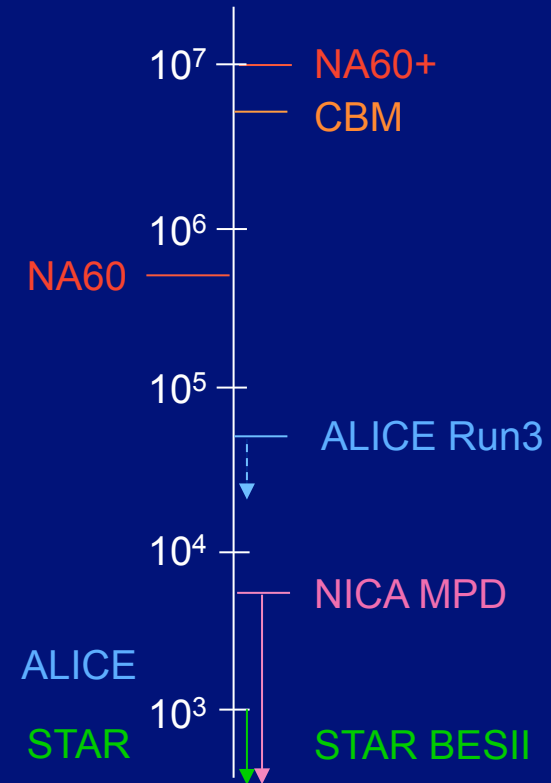
The high energy frontier

- RHIC ~~PHENIX~~, STAR
- LHC ALICE

The low energy frontier

- RHIC BES STAR
- SPS NA60+
- (SIS300 CBM)
- SIS100 CBM, HADES
- NICA MPD

'Interaction' Rate [Hz]



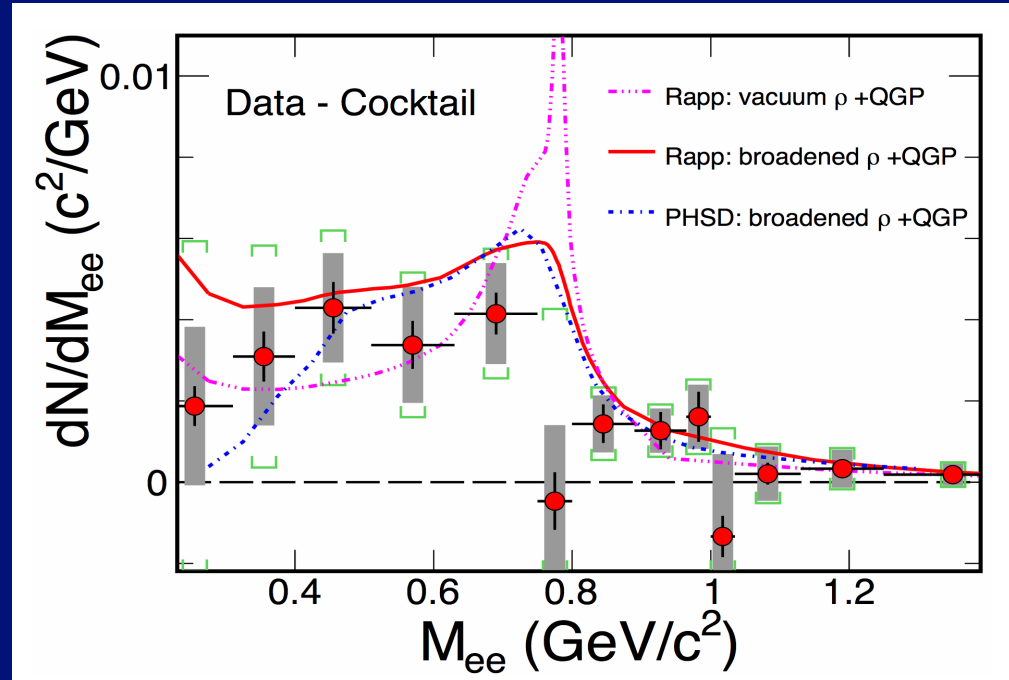
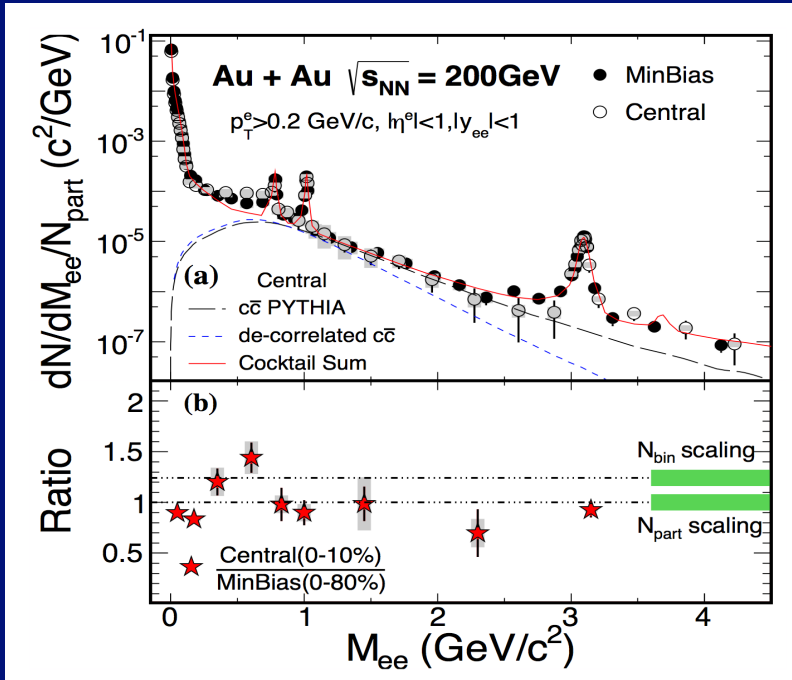
As important: ratio Signal/(Combinatorial Background) S/B

- range of B/S for different experiments: 20 - 1000 → **B/S >> 1**
- effective signal size: $S_{\text{eff}} \sim IR \times S/B$ reduction by 20-1000 !

The high-energy frontier

STAR: di-electron results at 200 GeV/u (2015)

arXiv:1504.01317v1 (2015)



Integrated data from runs 2010/2011, 10^9 minbias int., improved to PRL 113 (2014) 022301

Comparison MinBias and Central collisions (rescaled with N_{part})

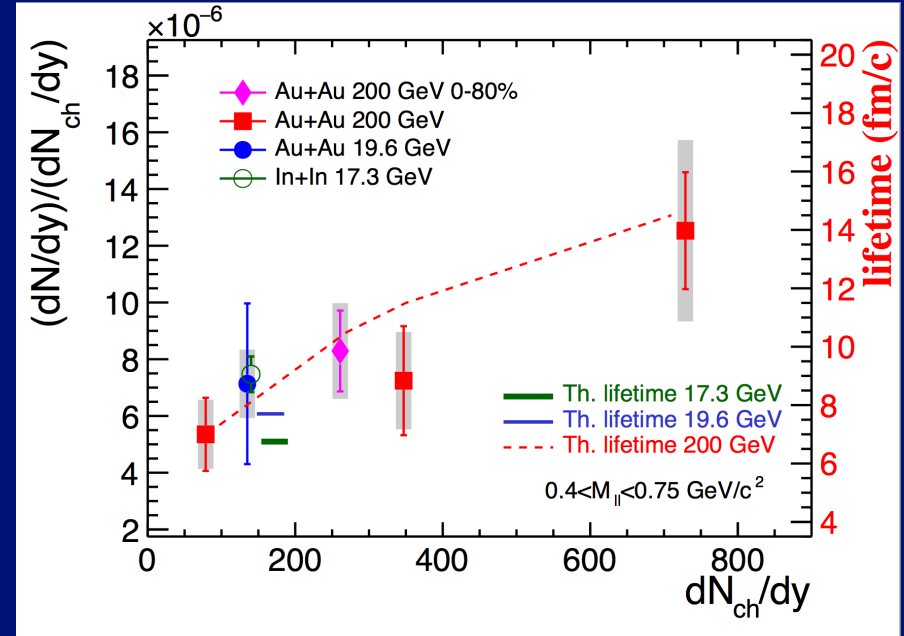
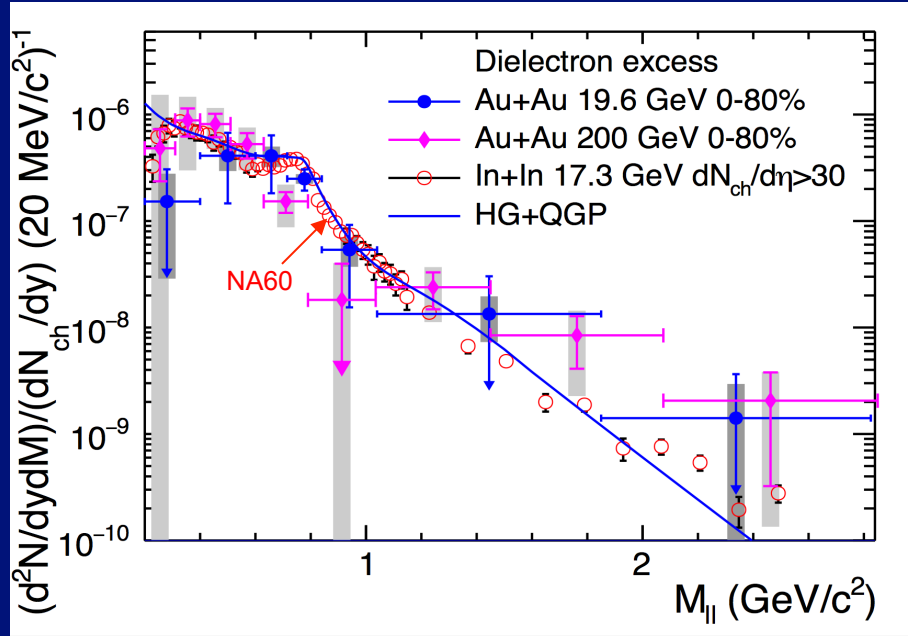
Excess mass spectrum (data-cocktail)
no acceptance correction

p_T spectra measured, but not evaluated as to radial flow

Results consistent with theoretical models

STAR: di-electron results at 19.6 and 200 GeV/u

arXiv:1501.05341v2 (2015), PLB



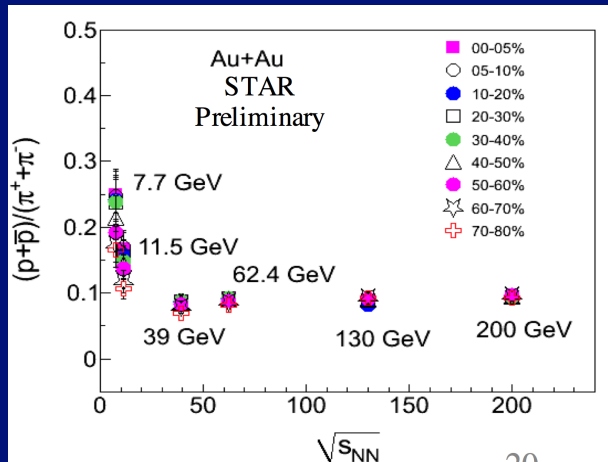
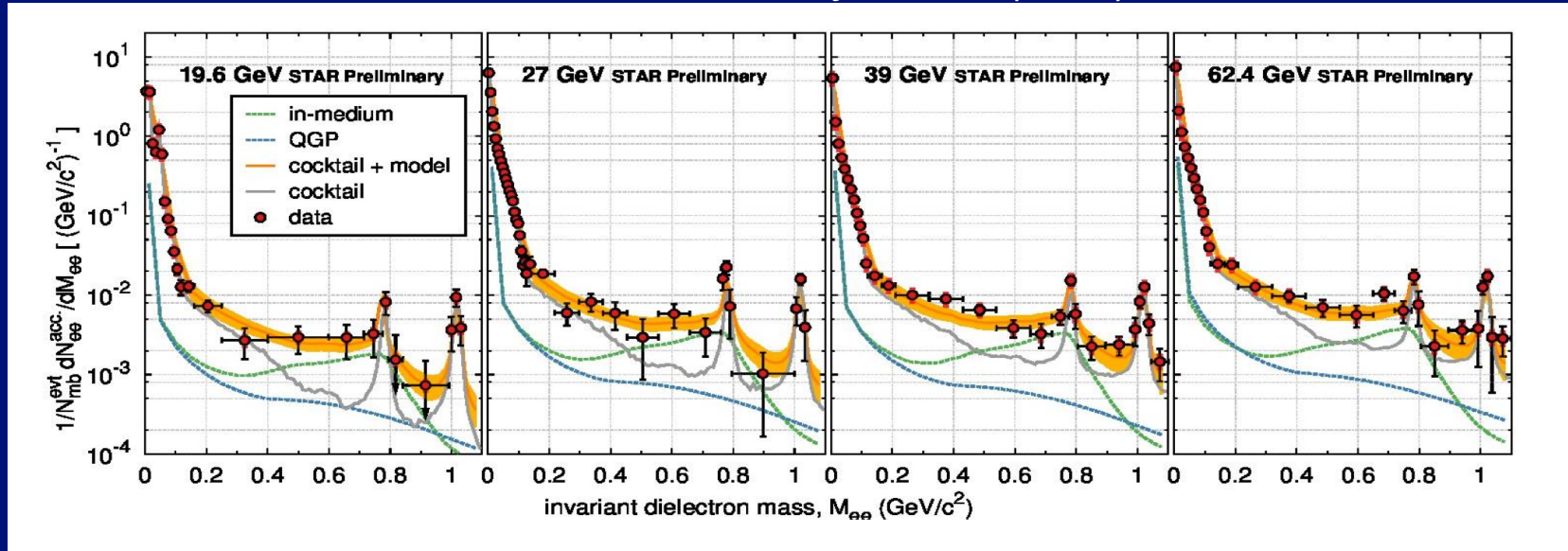
200 GeV/u data from run 2010, 19.6 GeV/u data from run 2011

Acceptance-corrected spectra for the full mass region up to 2.8 GeV for Au+Au compared to the NA60 In-In data at 17.3 GeV/u; independent absolute scales

Normalized excess yields for the mass region $0.4 < M < 0.75$ GeV vs. dN_{ch}/dy
Correlation with the fireball life-times à la R. Rapp et al.

STAR: di-electron results from beam energy scan

F. Geurts, STAR, Nucl.Phys. A 904(2013) 217c



general agreement of the data for all beam energies from 19.6 GeV/u (SPS- like) up to 200 GeV/u with theoretical model of Rapp/Wambach

$dN(p+\bar{p})/dy = 110$ and 102 at SPS and highest RHIC energy, respectively

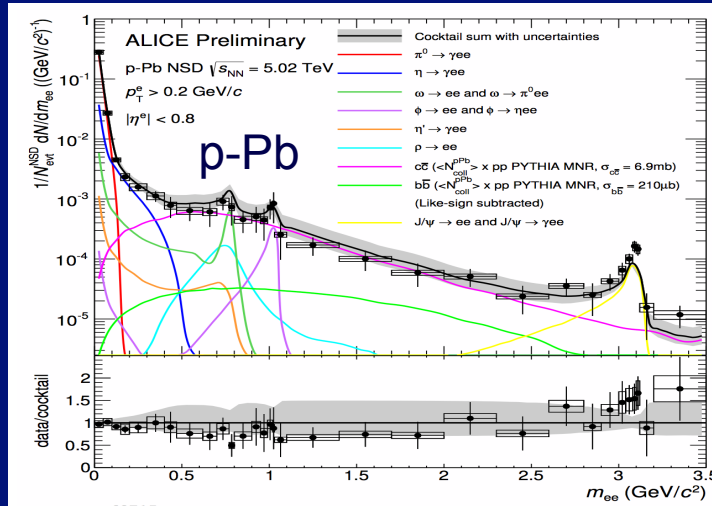
↓
strong change of net baryon density, but total baryon density same at the SPS and at RHIC

The sum of baryon- and anti-baryon interactions dominates p broadening

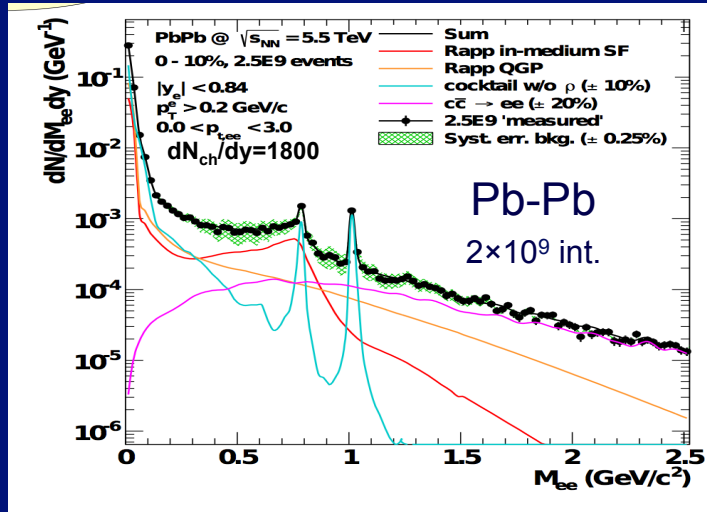
Dileptons in ALICE

Dielectrons

M.K.Koehler, ALICE, Nucl.Phys.A 931(2014) 665

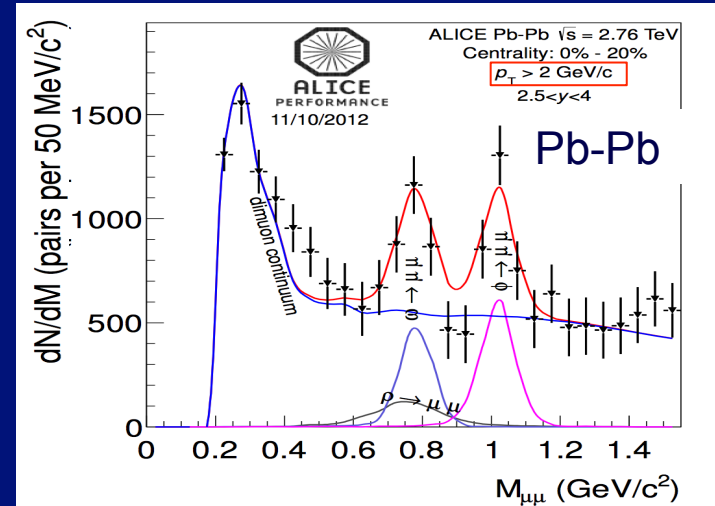


ALICE TDR (2012); J.Stachel ICNFP (2014)

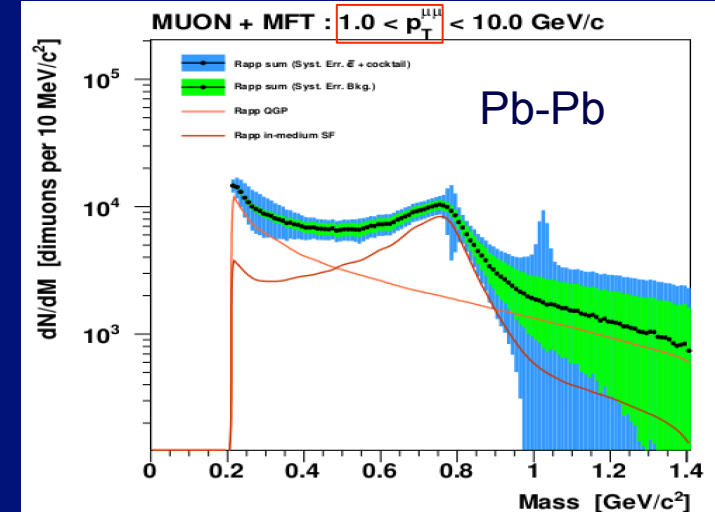


Dimuons

A. De Falco, ALICE, Reson. Worksh. Catania, 2014



ALICE TDR Dimuon Arm, CERN-LHCC (2015)



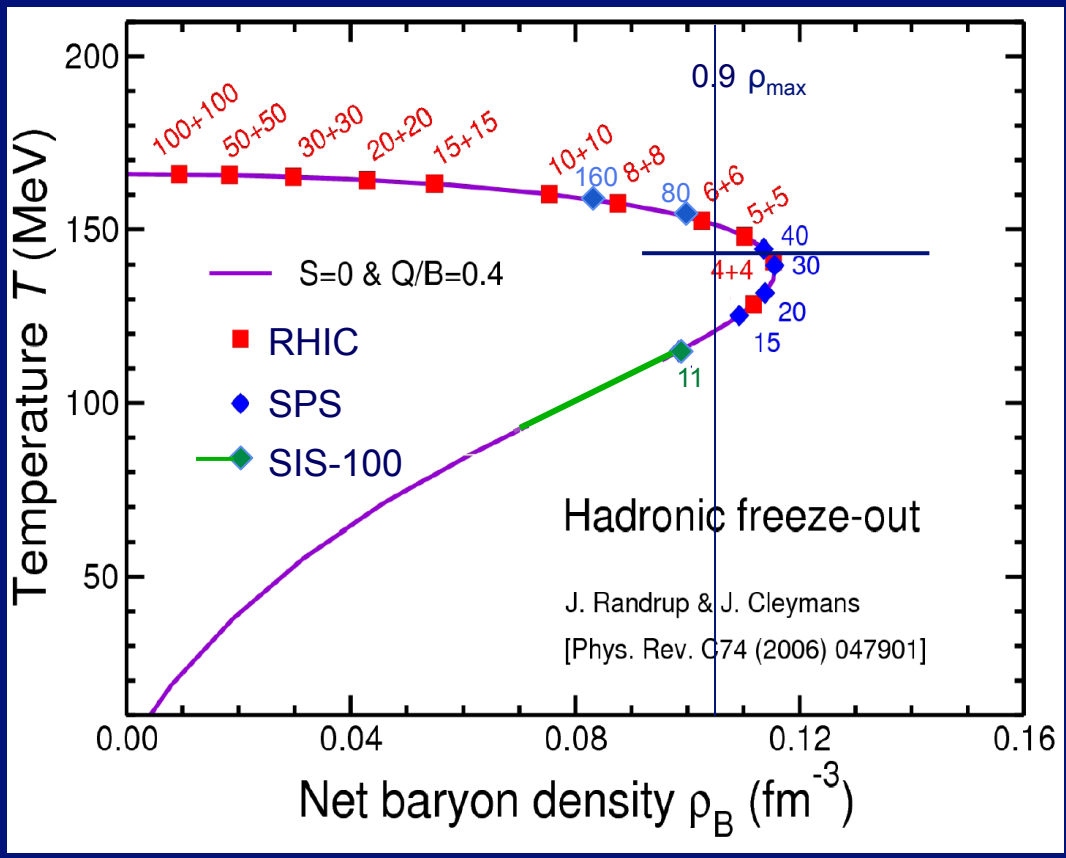
Upgrade for Run 3 essential for any dilepton measurements in ALICE

The low-energy frontier

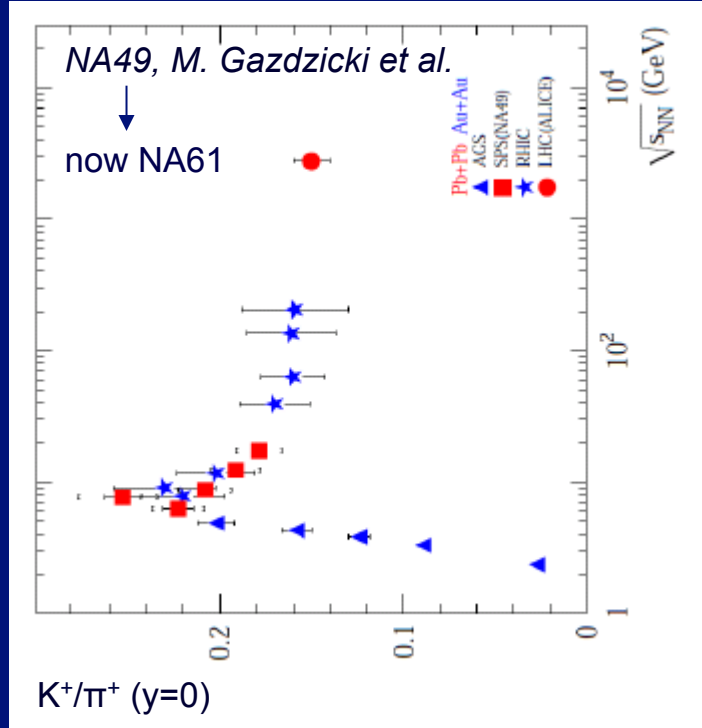
SPS best machine in the world to cover the low energy range

Systematic measurements of EM radiation over the full energy range from SIS100 (11 GeV/u) to top SPS (160 GeV/u)

Interaction rates SIS100 and SPS $10^7/s$



only structure known in BES



onset of deconfinement?

the SPS is a running machine

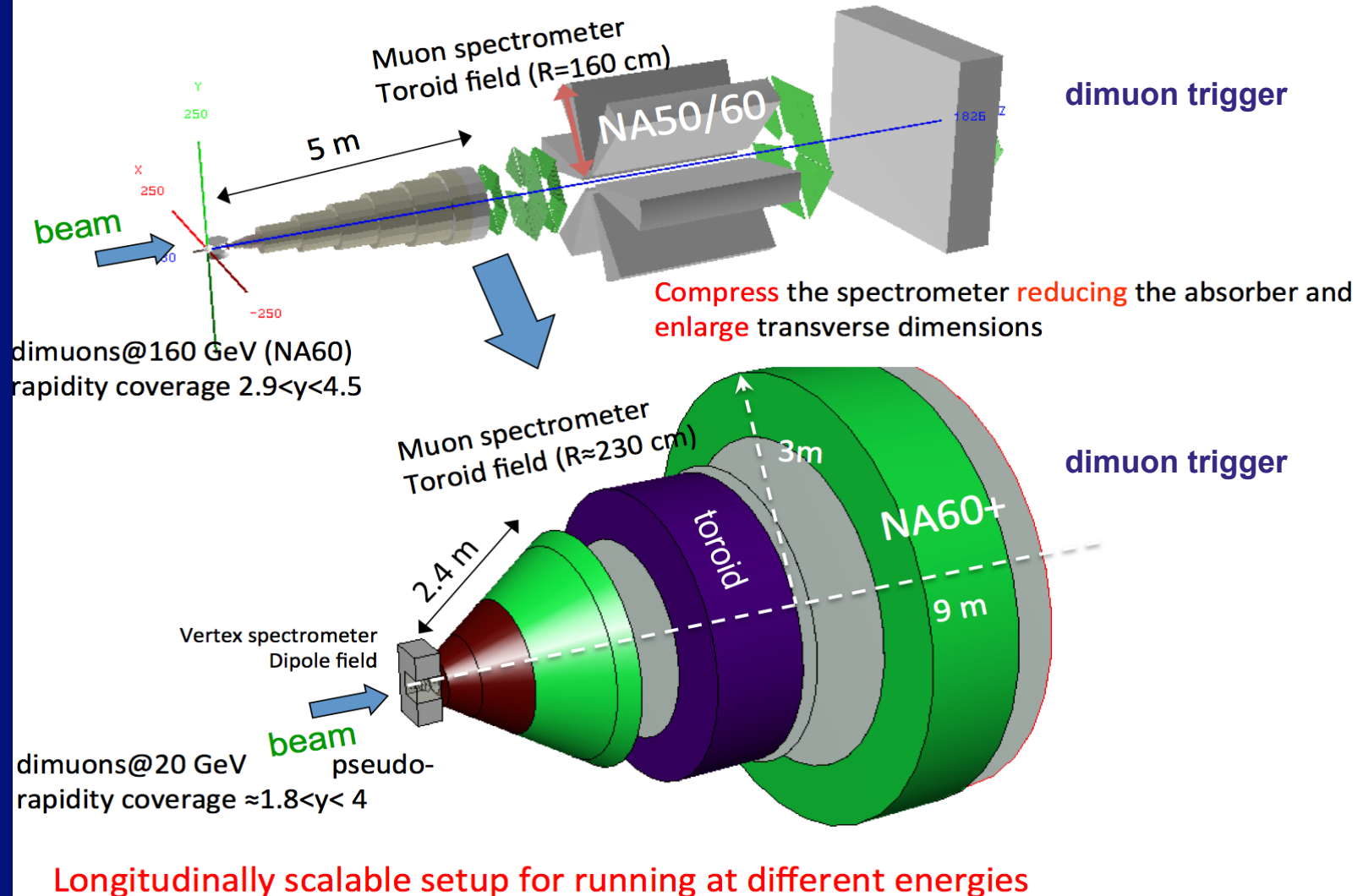
NA60+ to complement NA61

CBM at SIS100 to complement
HADES (talk by T.Galatyuk)

Principal set-up of a successor experiment to NA60

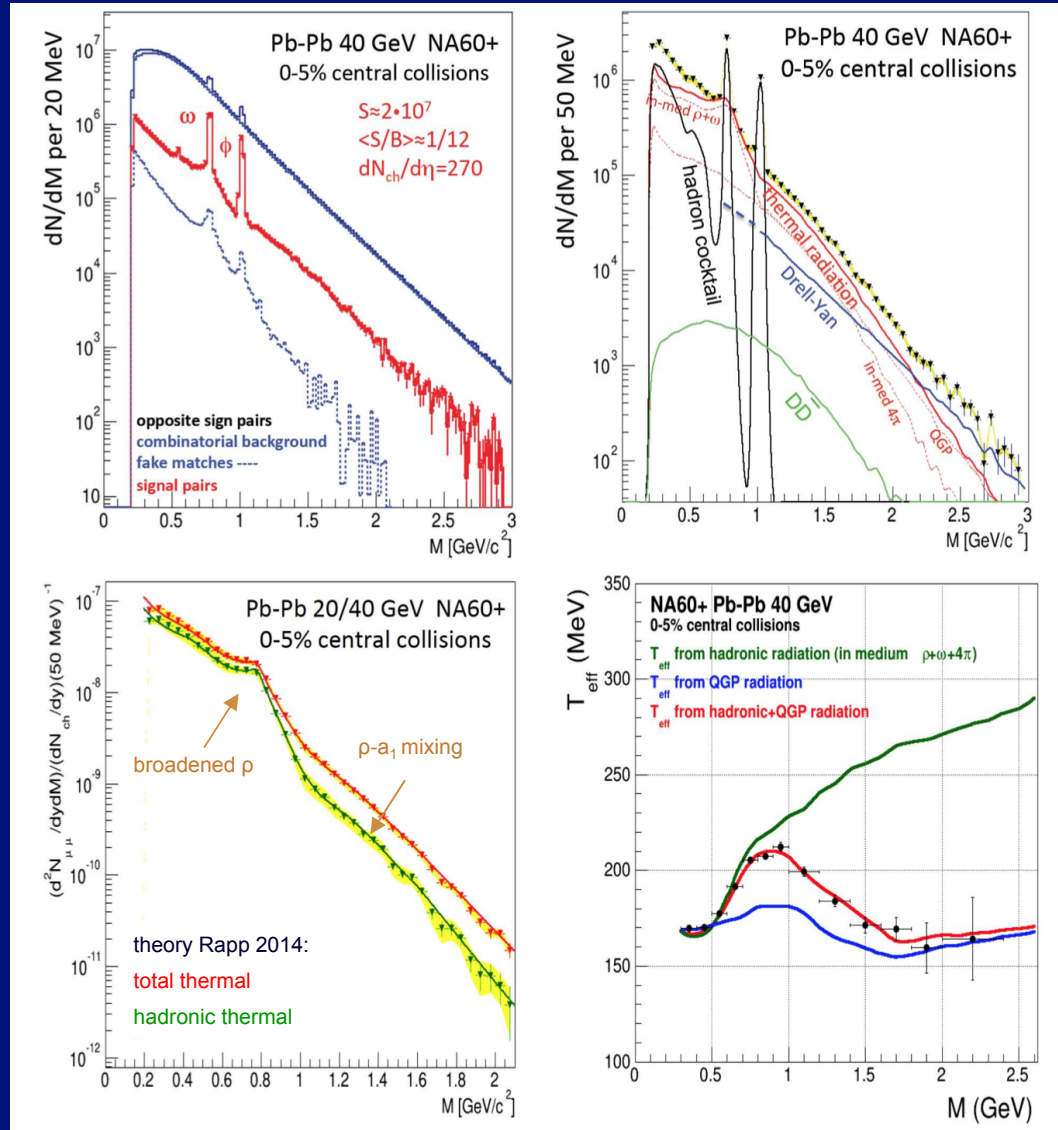
G. Usai, Nucl.Phys. A931 (2014) 729

Measuring dimuons for $20 < E_{\text{lab}} < 160$ GeV at the CERN SPS



Performance studies: Pb-Pb 0-5% central at 40 GeV/u

G. Usai, Nucl.Phys. A931 (2014) 729



Simulations: all analysis steps as done in NA60

Statistics: progress by a factor of **~ 100** over NA60 (interaction rate $10^8/\text{s}$ beam $\times$ 10% target, better acceptance+reconstr. eff.)

Sample size: 2×10^7 reconstr. pairs per energy in ~ 15 days; **accuracy $\sim \text{MeV}$** for T and T_{eff}

Thermal dilepton spectrum: measurable up to **$2.5\text{-}3 \text{ GeV}$**

Spectrum from hadronic phase: best sensitivity to **ρ - a_1 mixing**

T_{eff} : strong sensitivity to small parton contributions (**onset**)

Scan: 20-30-40-60-80-160 GeV

Present Physics Conclusions from Dileptons

Planck-like exponential mass spectra, exponential m_T spectra, zero polarization and general agreement with thermal models consistent with interpretation of excess dimuons as **thermal radiation**

Emission sources of thermal dileptons mostly hadronic ($\pi^+\pi^-$ annihilation) for $M < 1$ GeV, and mostly partonic ($q\bar{q}$ annihilation) for $M > 1$ GeV; associated temperatures quantified; hints at soft EoS close to T_c : proof for **deconfinement already at SPS energies**

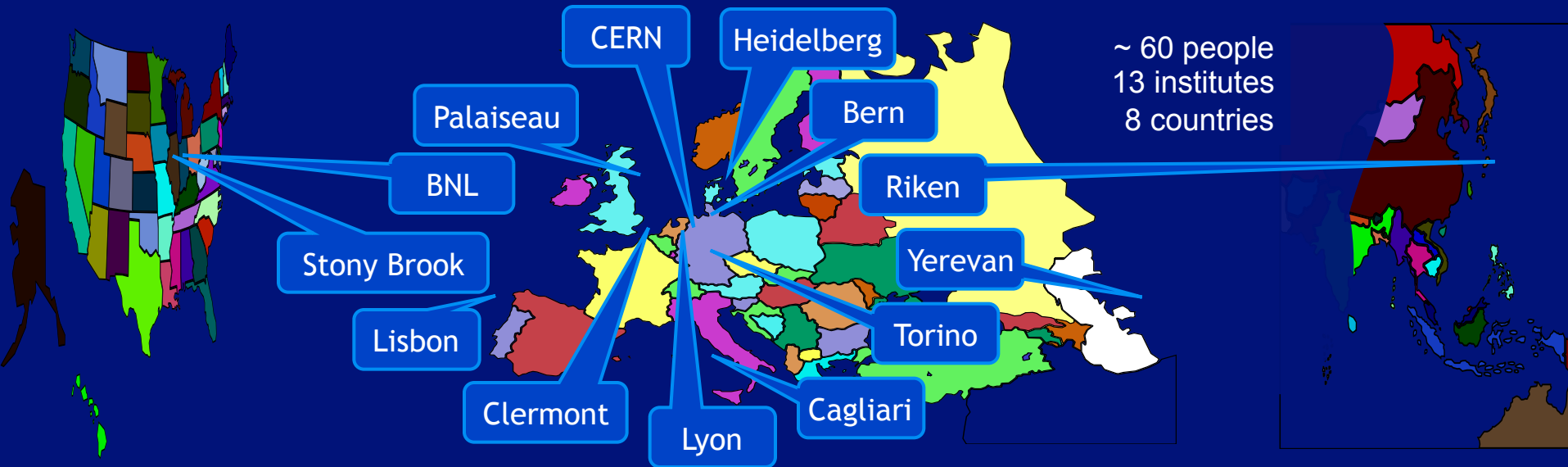
In-medium ρ spectral function identified; no significant mass shift of the intermediate ρ , only broadening; (indirect) proof for **chiral symmetry restoration**

Future: much more emphasis to be placed on running at energies optimal for the study of the QCD phase transitions and high baryon densities; most suitable machines SPS, complemented by SIS100



The NA60 experiment

<http://cern.ch/na60>

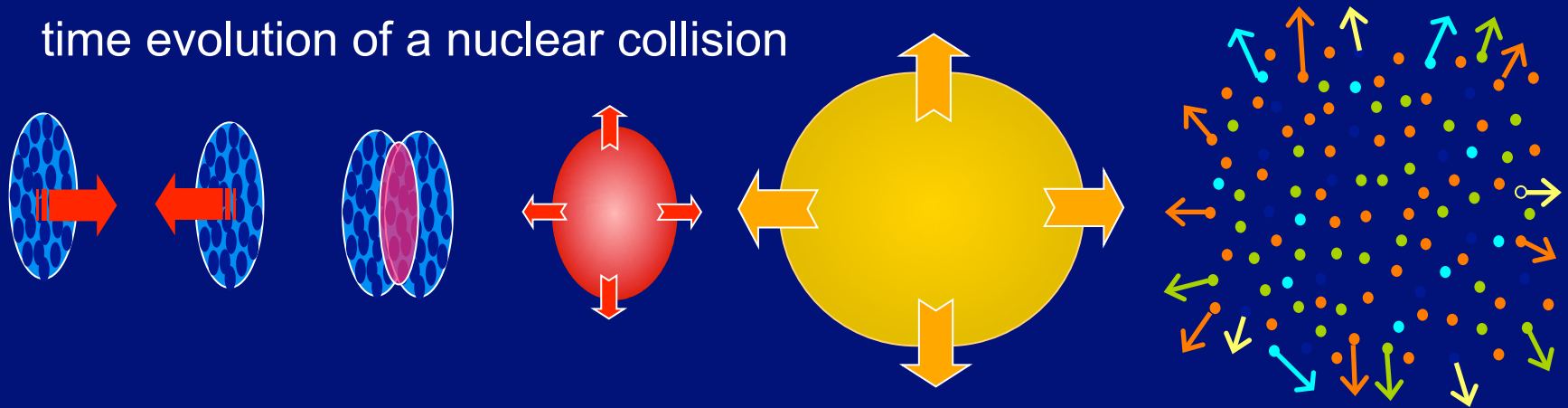


R. Arnaldi, K. Banicz, K. Borer, J. Buytaert, J. Castor, B. Chaurand, W. Chen, B. Cheynis, C. Cicalò, A. Colla, P. Cortese, **S. Damjanovic**, A. David, A. de Falco, N. de Marco, A. Devaux, A. Drees, L. Ducroux, H. En'yo, A. Ferretti, M. Floris, A. Förster, P. Force, A. Grigorian, J.Y. Grossiord, N. Guettet, A. Guichard, H. Gulkanian, J. Heuser, M. Keil, L. Kluberg, Z. Li, C. Lourenço, J. Lozano, F. Manso, P. Martins, A. Masoni, A. Neves, H. Ohnishi, C. Oppedisano, P. Parracho, P. Pillot, G. Puddu, E. Radermacher, P. Ramalhte, P. Rosinsky, E. Scomparin, J. Seixas, S. Serici, **R. Shahoyan**, P. Sonderegger, H.J. Specht, R. Tieulent, E. Tveiten, G. Usai, H. Vardanyan, R. Veenhof and H. Wöhri

BKP

Observables and physics goals: hadron production

time evolution of a nuclear collision



A+A

NN-coll.

QGP

Hadron Gas

Freeze-Out

“Hubble” expansion: $T = 240 \rightarrow 170$ $170 \rightarrow 110$

~ 110 (MeV)

99.99% of the produced particles are hadrons

hadron yields: temperature at creation (statistical hadronization)

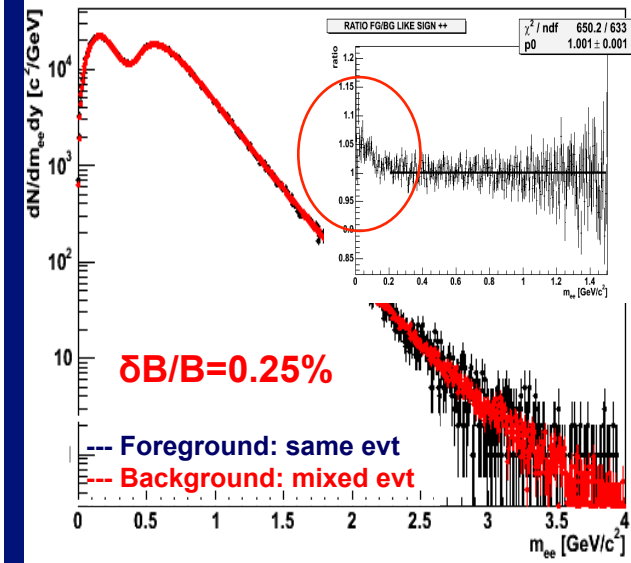
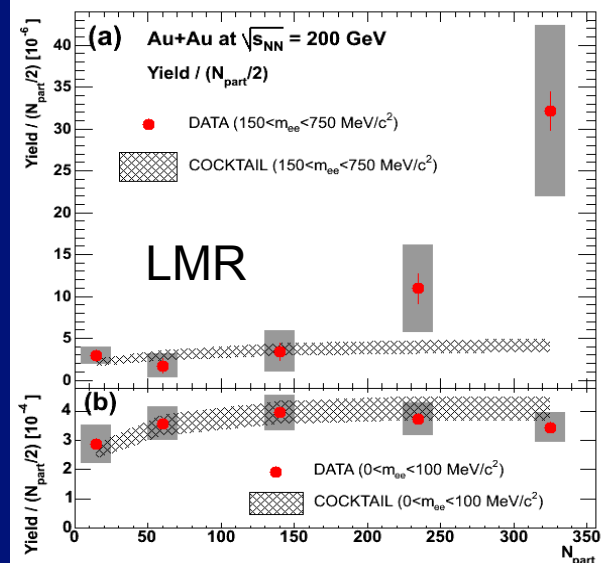
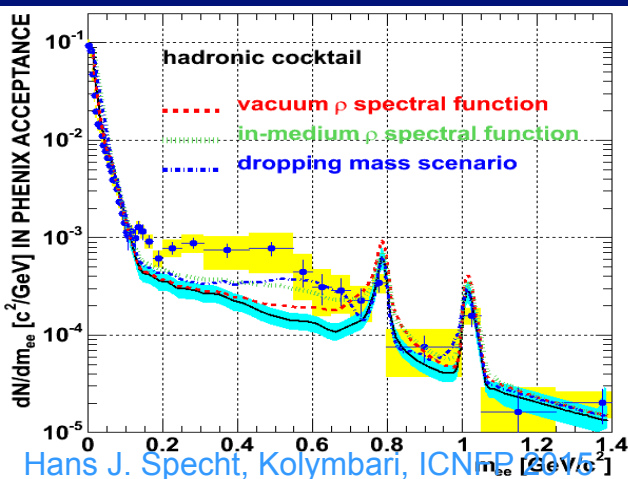
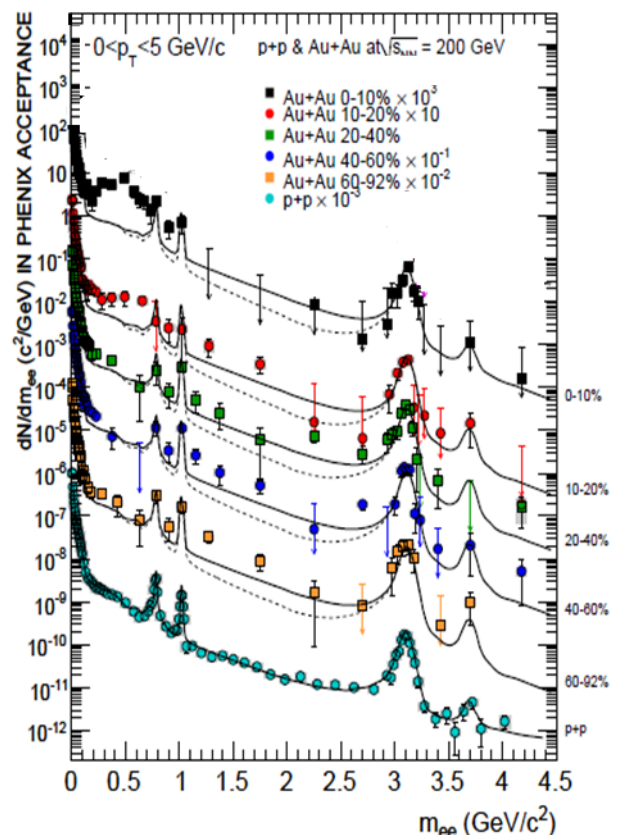
hadron flavors: strangeness enhancement (flavor equilibration)

J/ψ suppression (color screening)

hadron p_T : space-time evolution (temperature and radial-expansion velocity at freeze-out, ‘blue shift’)

hadron correl.: (HBT, elliptic flow)

Di-electron results from PHENIX



Previous results (PRC 2010); $B/S=1300$ (central)
HBD results (QM2012); factor of 5 $\rightarrow B/S=250$ ($\rightarrow 100!$)

