Concluding remarks on NA60 (and beyond)

Hans J. Specht

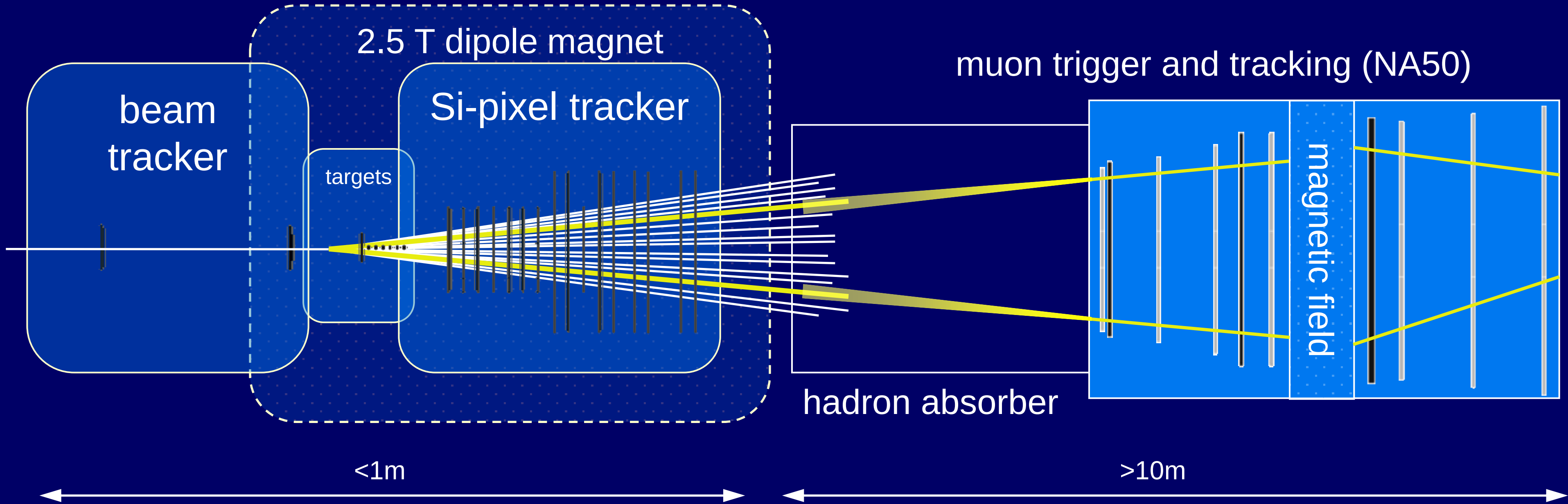
Physikalisches Institut
Universität Heidelberg

Erice, 20 September 2012

Outline

- Planck-like radiation and deconfinement
- The ρ spectral function and chiral restoration
- Radial expansion and the EoS close to T_c
- Hadron results
- Remarks on other dilepton experiments

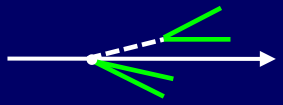
Measuring dimuons in NA60: concept



Track matching in coordinate and momentum space

Improved dimuon mass resolution

Distinguish prompt from decay dimuons



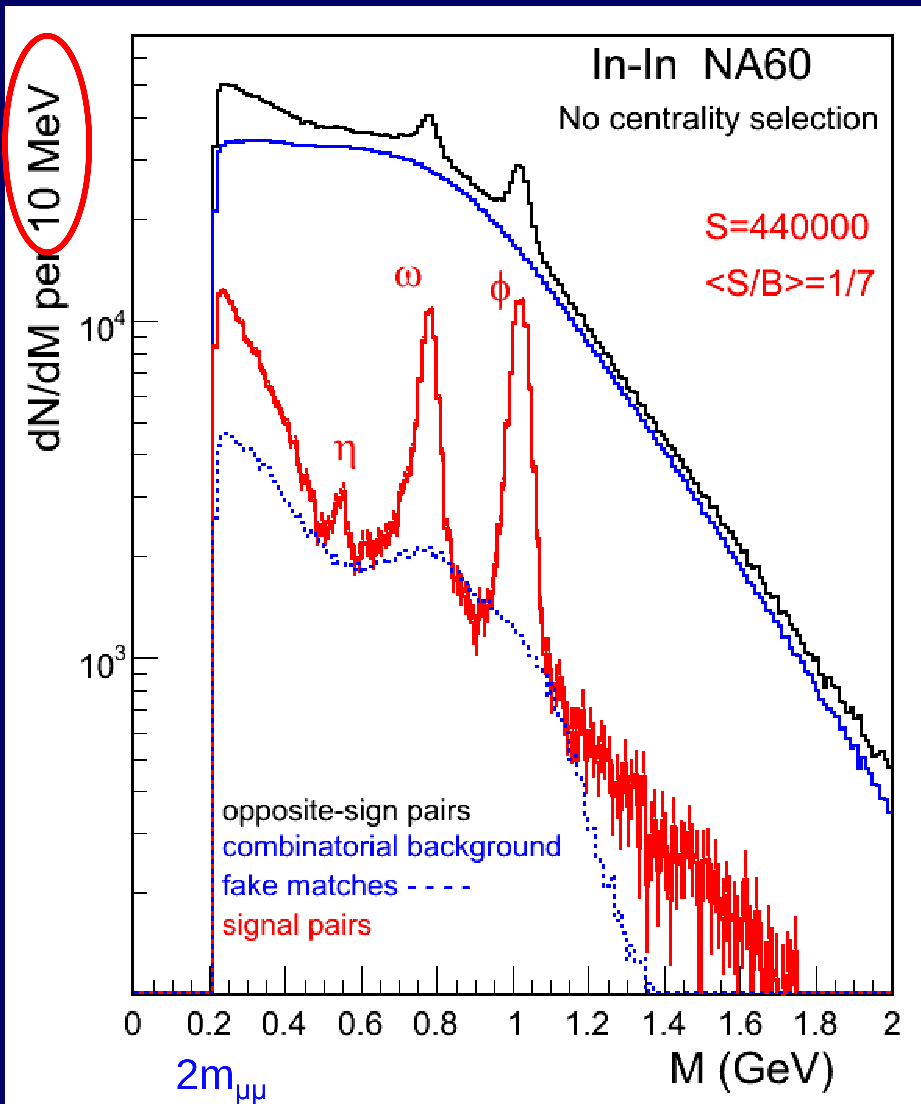
Additional bend by the dipole field

Dimuon coverage extended to low p_T

Radiation-hard silicon pixel detectors (LHC development)

High luminosity of dimuon experiments maintained

Data sample for 158A GeV In-In



subtraction of

- combinatorial background
- fake matches between the two spectrometers

S/B highest of all experiments, past and present (see below)

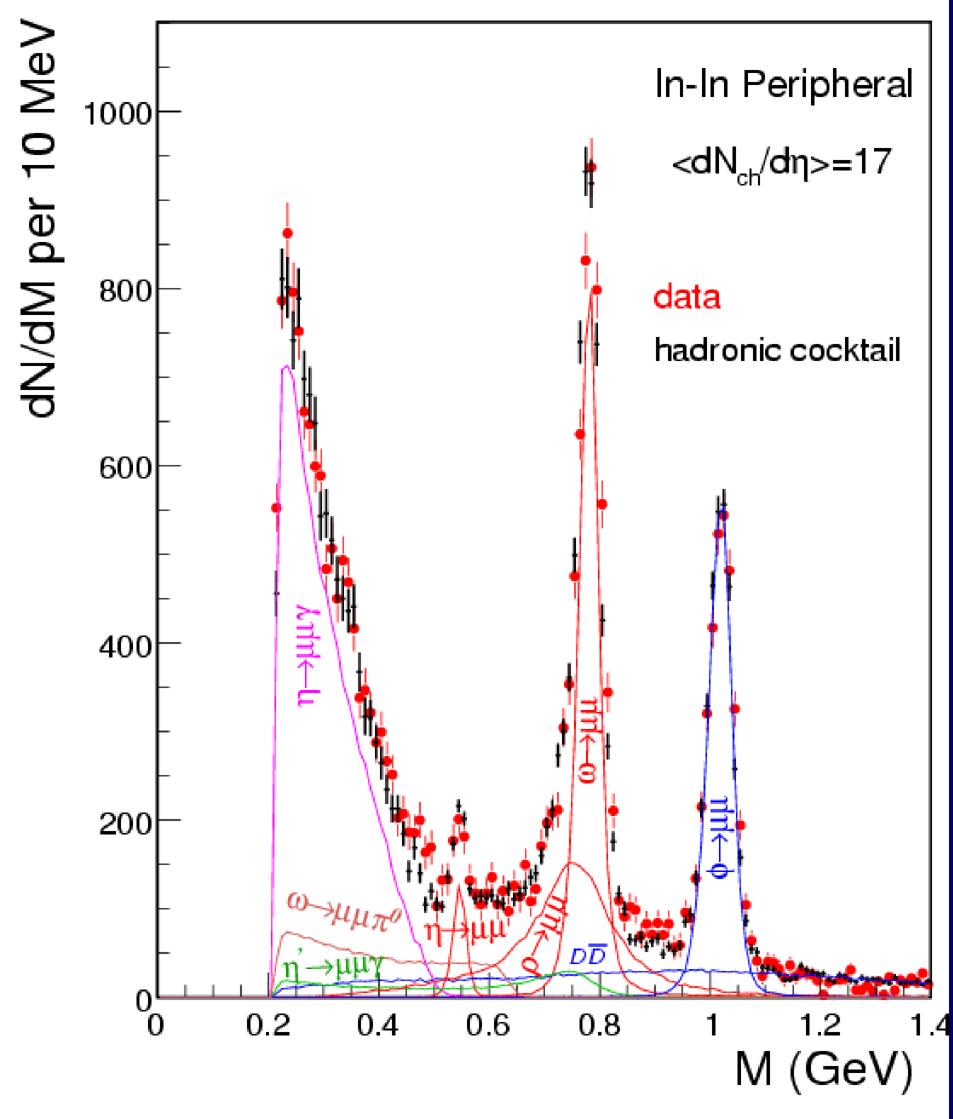
net sample:
440 000 events

effective statistics also highest of all experiments

mass resolution:
20 MeV at the ω position

η, ω, φ completely resolved

Understanding the peripheral data



Monte Carlo simulation of the expected dilepton sources:

electromagnetic decays:

2-body: $\eta, \rho, \omega, \phi \rightarrow \mu^+\mu^-$

Dalitz : $\eta, \eta' \rightarrow \mu^+\mu^- \gamma$

$\omega \rightarrow \mu^+\mu^-\pi^0$

EM transition form factors of the η and ω Dalitz decays remeasured here

semileptonic decays:

uncorr. $\mu^+\mu^-$ from $D\bar{D}$

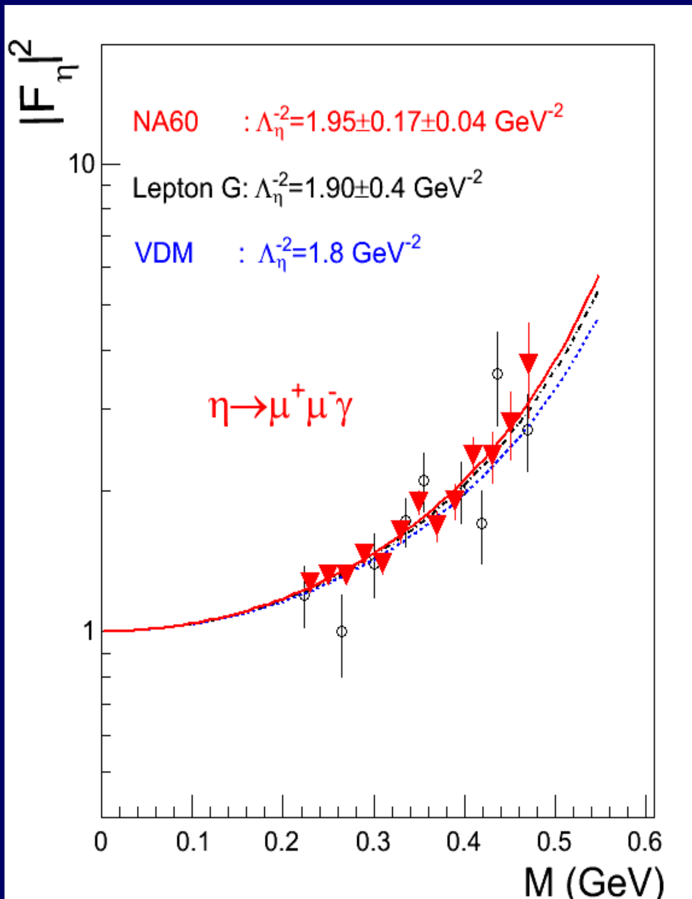
fit with free parameters:

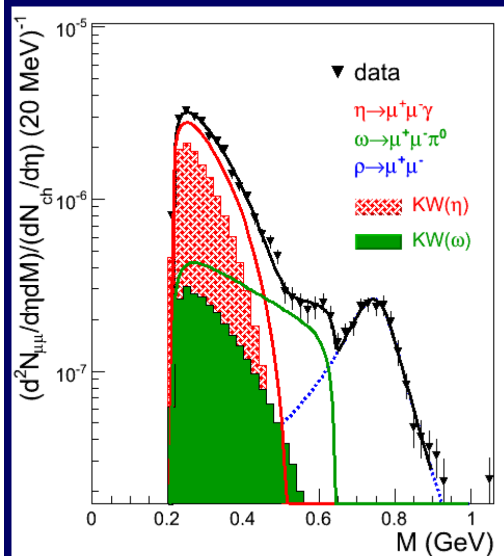
η/ω, ρ/ω, ϕ/ω, $D\bar{D}$

'perfect' description of the data

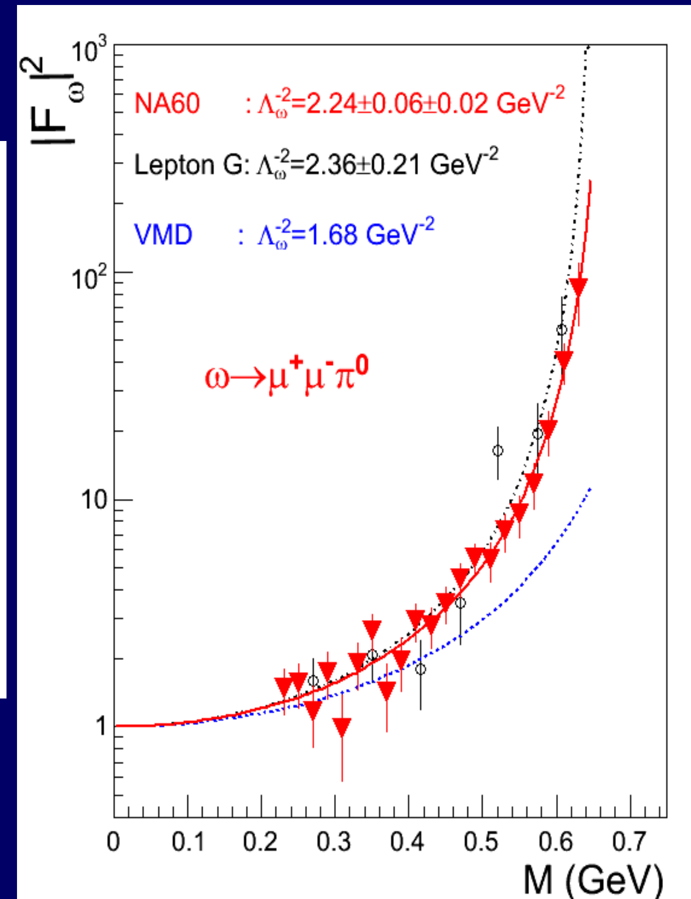
Results on Electromagnetic Transition Form Factors

Phys. Lett. B 677 (2009) 260





data corrected for acceptance



Perfect agreement of NA60 and Lepton G, confirming ω anomaly

Large improvement in accuracy; for ω, deviation from VMD 3 → 10 σ

NA60 p-A data: complete agreement, still higher accuracy (to be published)

NA60 results in the new edition of the PDG

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u} - d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\omega(782)$ $\qquad I^G(J^{PC}) = 0^-(1^{--})$

ω(782) BRANCHING RATIOS

PDG 2008

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ $\qquad \Gamma_7/\Gamma$

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
0.96±0.23 OUR FIT				
0.96±0.23	DZHELYADIN	81B	CNTR	25–33 $\pi^- p \to \omega n$

PDG 2010

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{\text{total}}$ $\qquad \Gamma_7/\Gamma$

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.3 ±0.4 OUR NEW AVERAGE		Error includes scale factor of 2.1. [(0.96 ± 0.23) × 10^{-4} OUR 2009 AVERAGE]			
1.72±0.25±0.14	3k	ARNALDI	09	NA60	158*A* In–In collisions
0.96±0.23		DZHELYADIN	81B	CNTR	25–33 $\pi^- p \to \omega n$

PARAMETER Λ IN $\omega \to \pi^0\mu^+\mu^-$ DECAY

In the pole approximation the electromagnetic transition form factor for a resonance of mass M is given by the expression:

$$|F|^2 = (1 - M^2/\Lambda^2)^{-2},$$

where for the parameter Λ vector dominance predicts $\Lambda = M_\rho \approx 0.770$ GeV. The ARNALDI 09 measurement is in obvious conflict with this expectation. Note that for $\eta \to \mu^+\mu^-\gamma$ decay ARNALDI 09 and DZHELYADIN 80 obtain the value of Λ consistent with vector dominance.

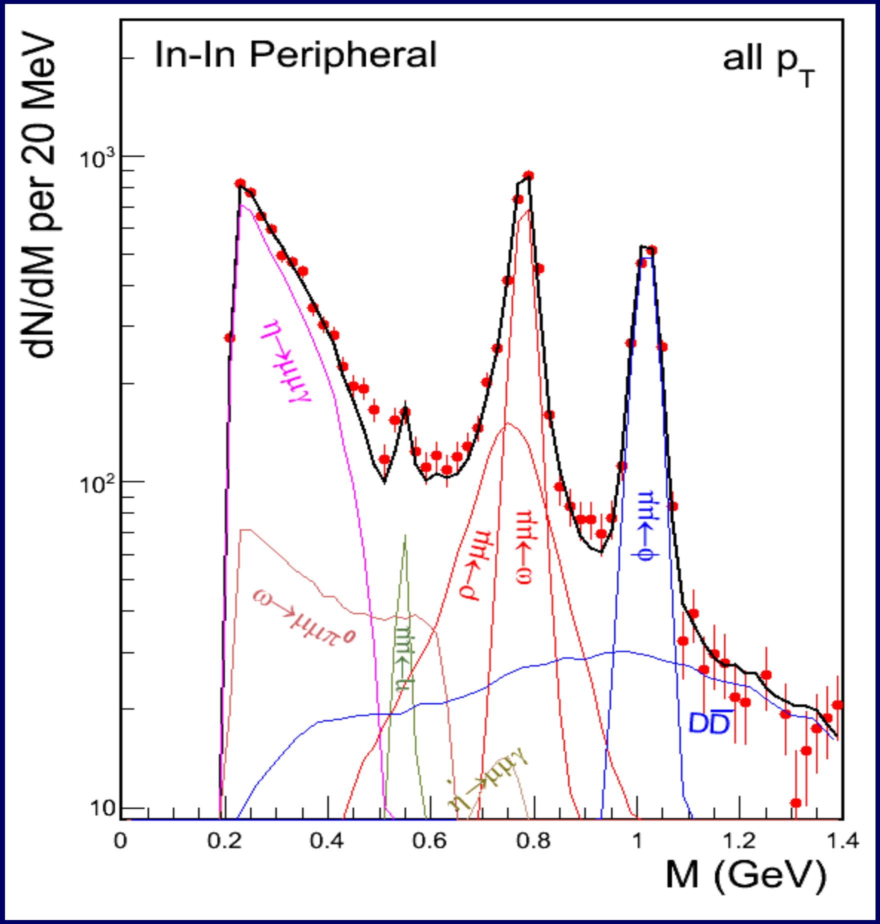
VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.668±0.009±0.003	3k	ARNALDI	09	NA60	158*A* In–In collisions
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.65 ±0.03		DZHELYADIN	81B	CNTR	25–33 $\pi^- p \to \omega n$

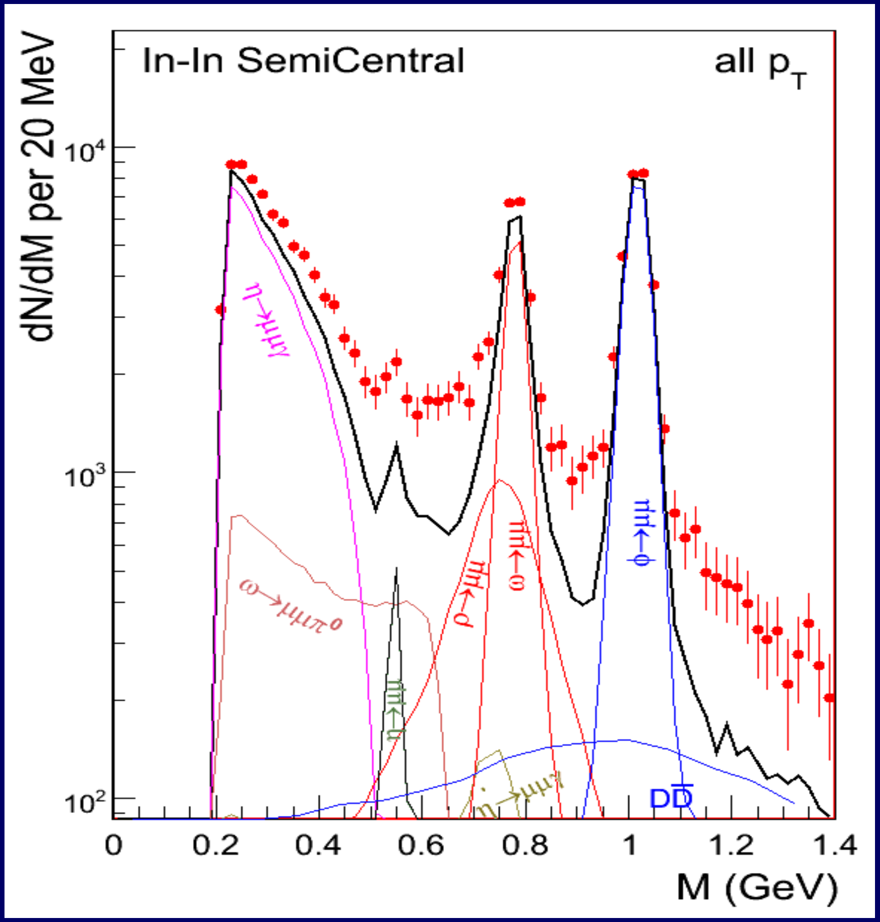
ω(782) REFERENCES

ARNALDI 09 PL B677 260 R. Arnaldi *et al.* (NA60 Collab.)
DZHELYADIN 81B PL 102B 296 R.I. Dzhelyadin *et al.* (SERP)
DZHELYADIN 80 PL 94B 548 R.I. Dzhelyadin *et al.* (SERP)

First result from a heavy-ion experiment in the PDG ever

Moving to higher centralities



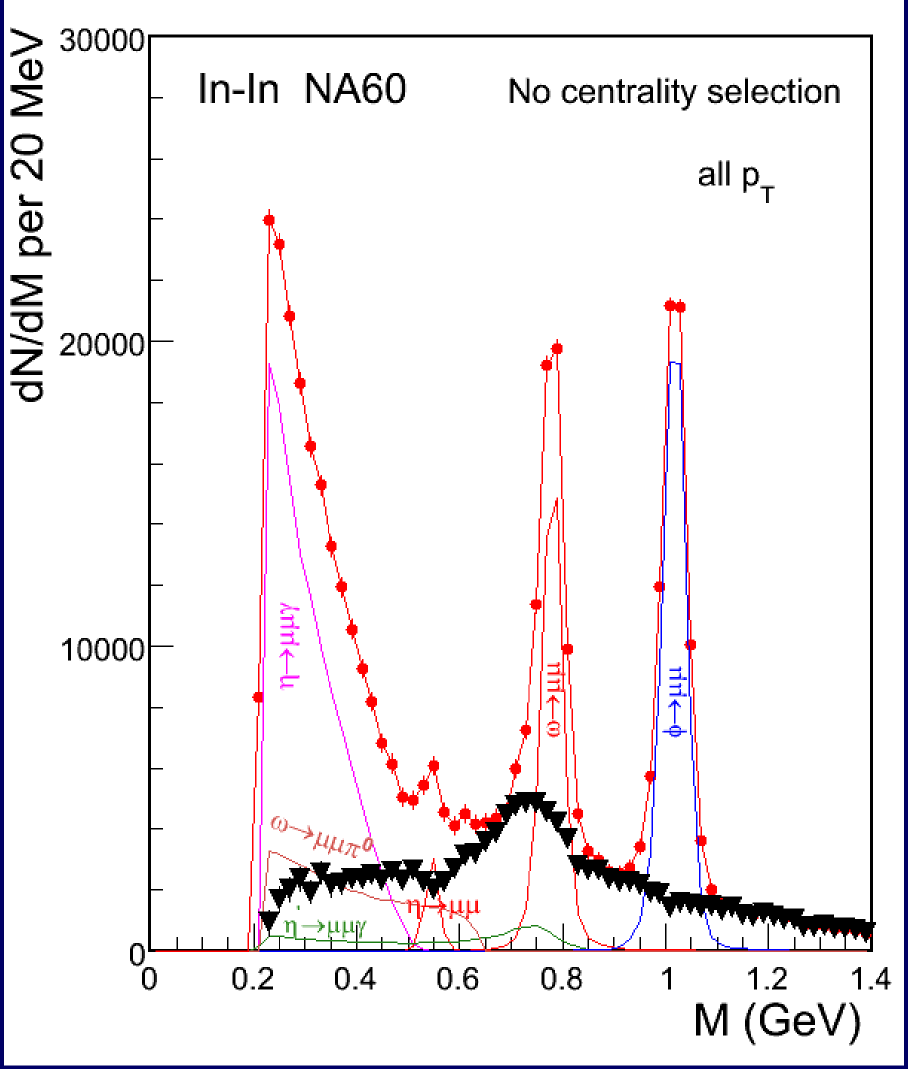


Peripheral data
well described by meson decay cocktail (η, η', ρ, ω, ϕ) and $D\bar{D}$

More central data
clear excess of data above decay cocktail; spectral shape ???

LMR (M<1 GeV) - isolation of excess dimuons

Phys. Rev. Lett. 96 (2006) 162302



isolation of excess by subtraction of measured decay cocktail (without ρ), based solely on local criteria for the major sources η, ω and ϕ

ω and ϕ : fix yields such as to get, after subtraction, a smooth underlying continuum

η : fix yield at p_T >1 GeV, based on the very high sensitivity to the spectral shape of the Dalitz decay

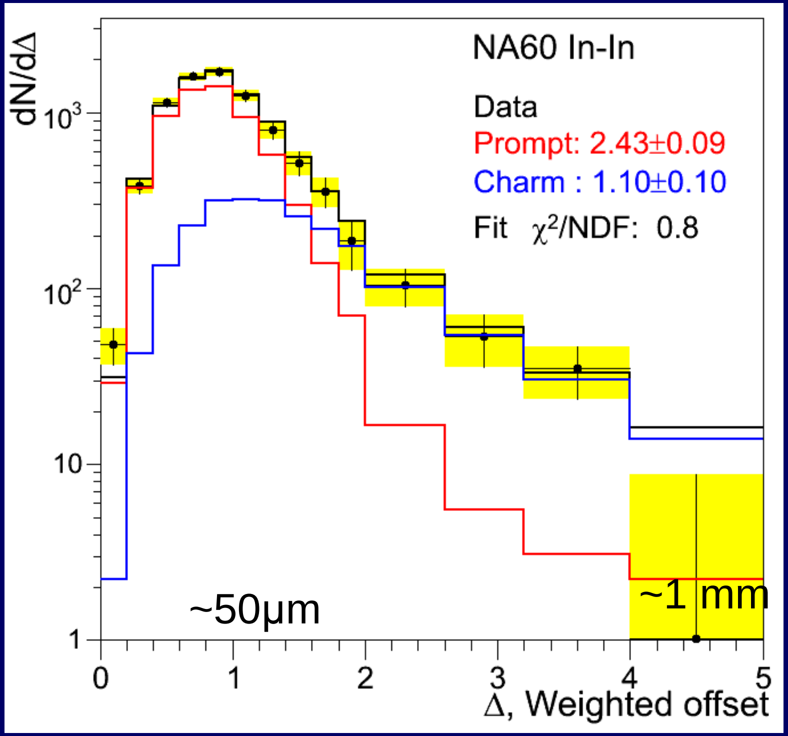
accuracy 2-3%, but results robust to mistakes even at the 10% level

keep information on subtracted hadrons and process separately

IMR (M>1GeV) – isolation of excess dimuons

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

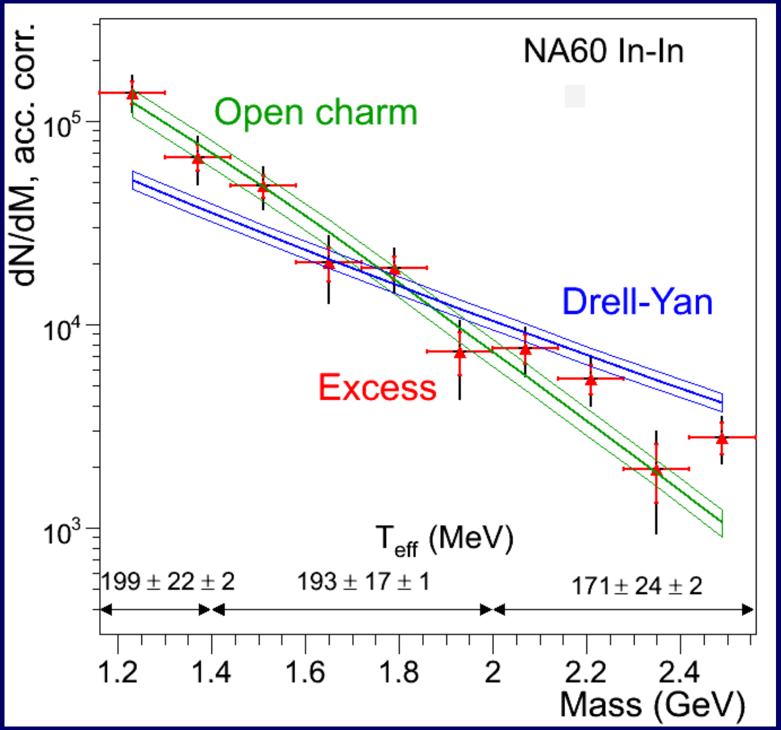
measurement of muon offsets $\Delta\mu$: distance between interaction vertex and track impact point



charm not enhanced

excess prompt; 2.4 × DY

isolation of excess by subtraction of measured open charm and Drell-Yan



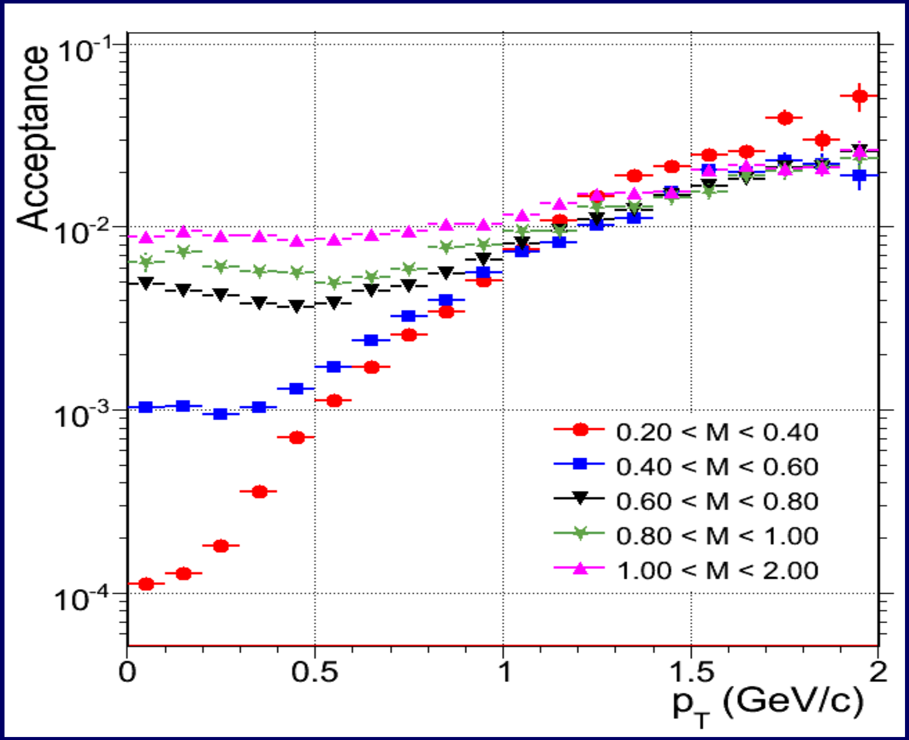
excess similar to open charm
steeper than Drell-Yan

Acceptance correction

reduce 4-dimensional acceptance correction in M-p_T -y-cosΘ_{CS} to (mostly) 2-dimensional corrections in pairs of variables. Example M-p_T, using measured y distributions and measured cosΘ_{CS} distributions as an input; same for other pairs (iteration)

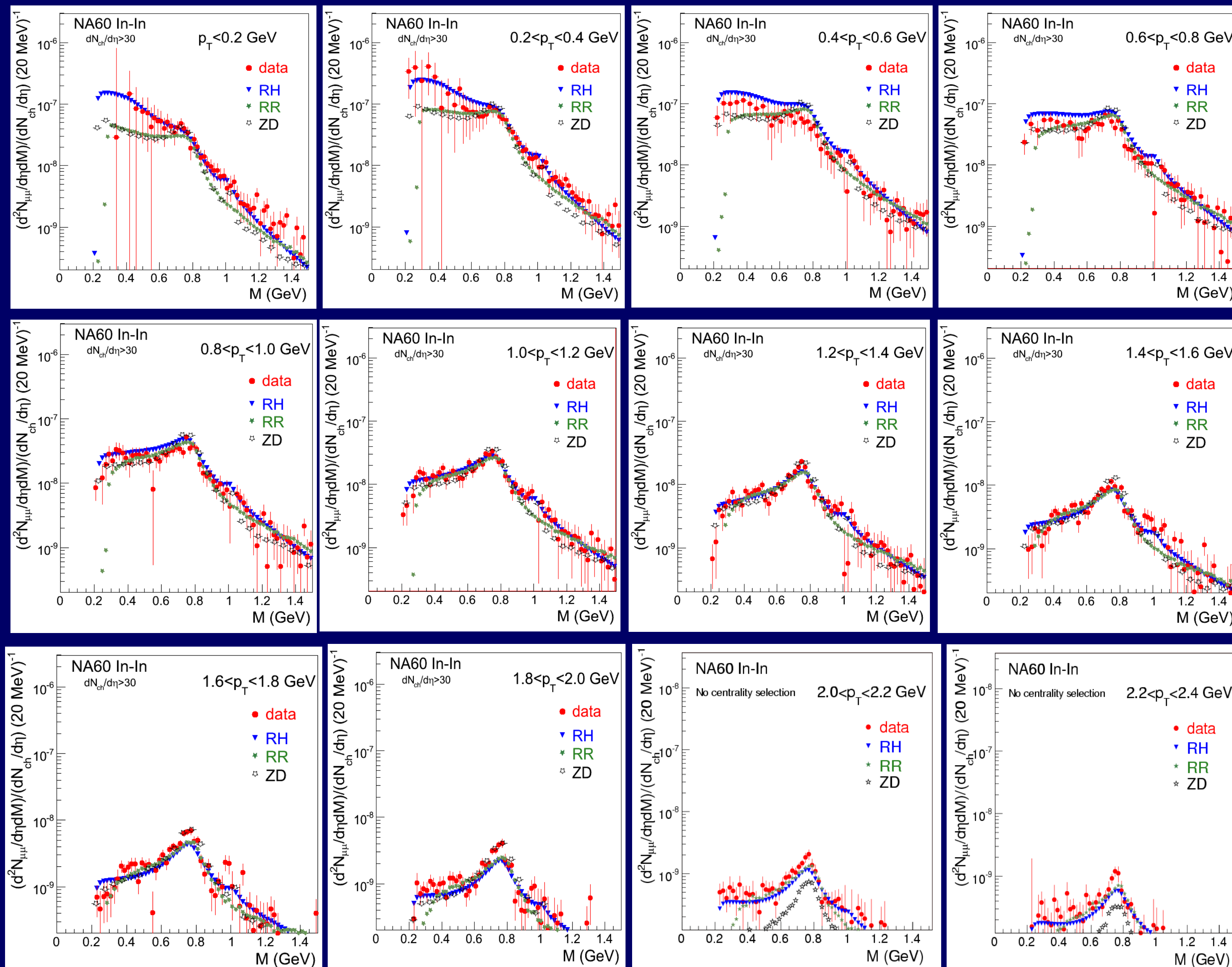
requires separate treatment of the excess and the other sources, due to differences in the y and the cosΘ_{CS} distributions

acceptance vs. M, p_T, y, and cosΘ understood to within <10%, based on a detailed study of the peripheral data



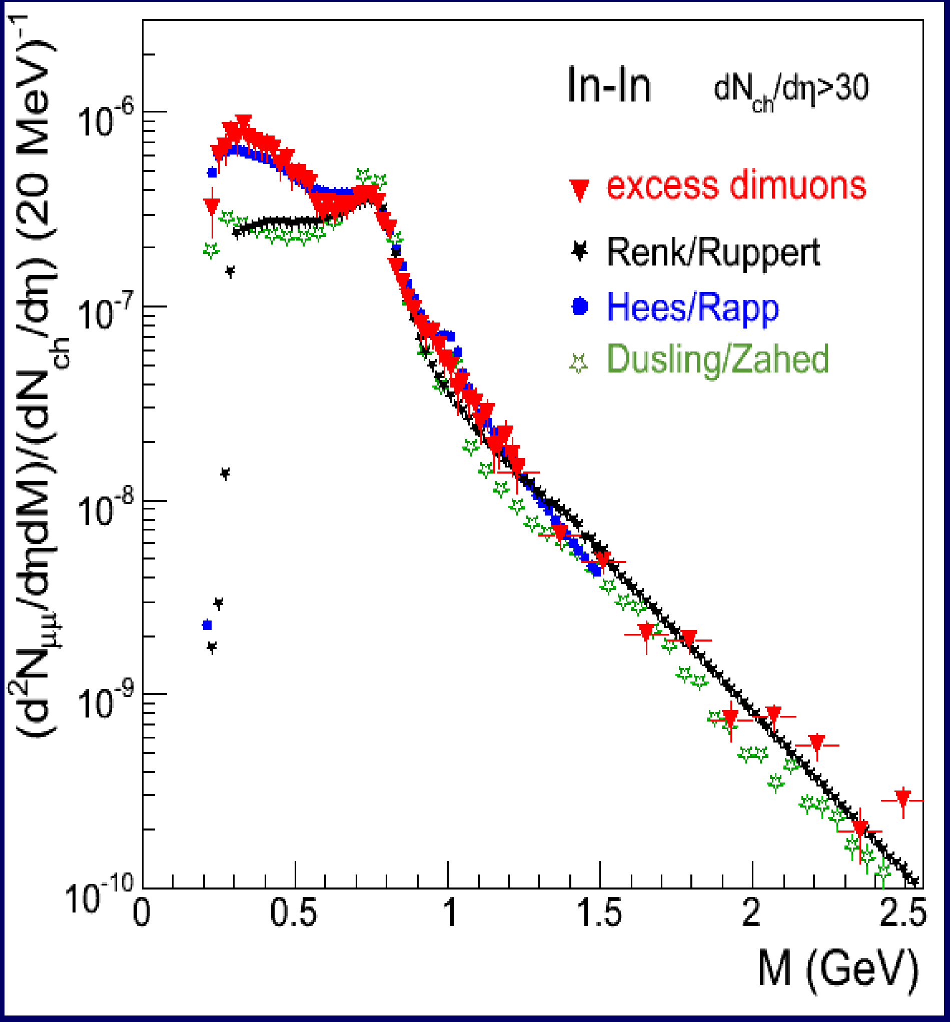
Thermal Radiation

Acceptance-corrected M-p_T matrix of excess



Inclusive excess mass spectrum

[Eur. Phys. J. C 59 (2009) 607-623]
CERN Courier 11/ 2009, 31-35
Chiral 2010 , AIP Conf.Proc. 1322 (2010) 1-10



all known sources subtracted
integrated over p_T
fully corrected for acceptance
absolutely normalized to $dN_{ch}/d\eta$

M<1 GeV

ρ dominates, 'melts' close to T_c

best described by H/R model

M>1 GeV

~ exponential fall-off → 'Planck-like'

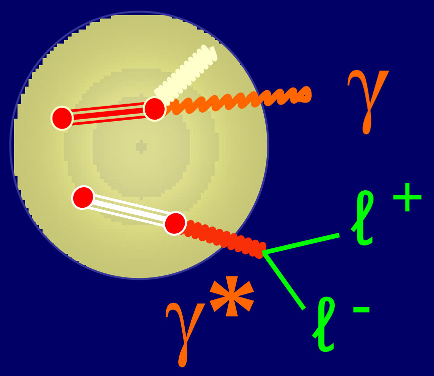
fit to $dN/dM \propto M^{3/2} \times \exp(-M/T)$

range 1.1-2.0 GeV: T=205±12 MeV
1.1-2.4 GeV: T=230±10 MeV

$T>T_c$: partons dominate

only described by R/R and D/Z models

Electromagnetic Probes: the case for lepton pairs



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)

approximate mass spectrum (for flat spectral function, and interpreting T as the average temperature over the space-time evolution)

$$dN/dM \propto M^{3/2} \times \exp(-M/T)$$ → 'Planck-like'

the only true (Lorentz invariant) thermometer of the field

systematic uncertainties:

theory, from fits to RR and DZ: T =215 MeV; $T_{1.2\ \mathrm{GeV}}$=205, $T_{2.5\ \mathrm{GeV}}$ = 225

data: oversubtraction of DY by 20/30% → ΔT= -10/-20 MeV

Rho Spectral Function

Unfolding the convoluted mass spectrum?

- Pure spectral function completely masked by the required convolution steps towards observable thermal radiation

- Strict unfolding impossible

- Realistic way: project out space-time averaged ρ-spectral function by use of a suitable correction function

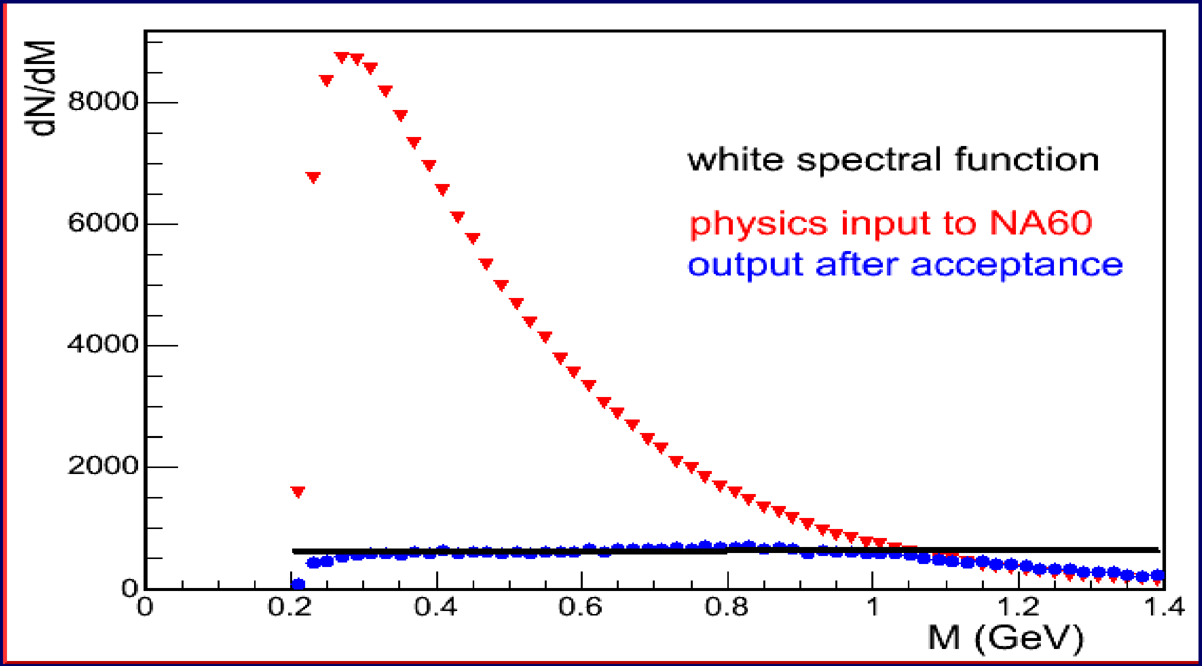
By pure chance

↓

Acceptance filtering by the NA60 set-up

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

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



all p_T

input:

thermal radiation based on a white spectral function

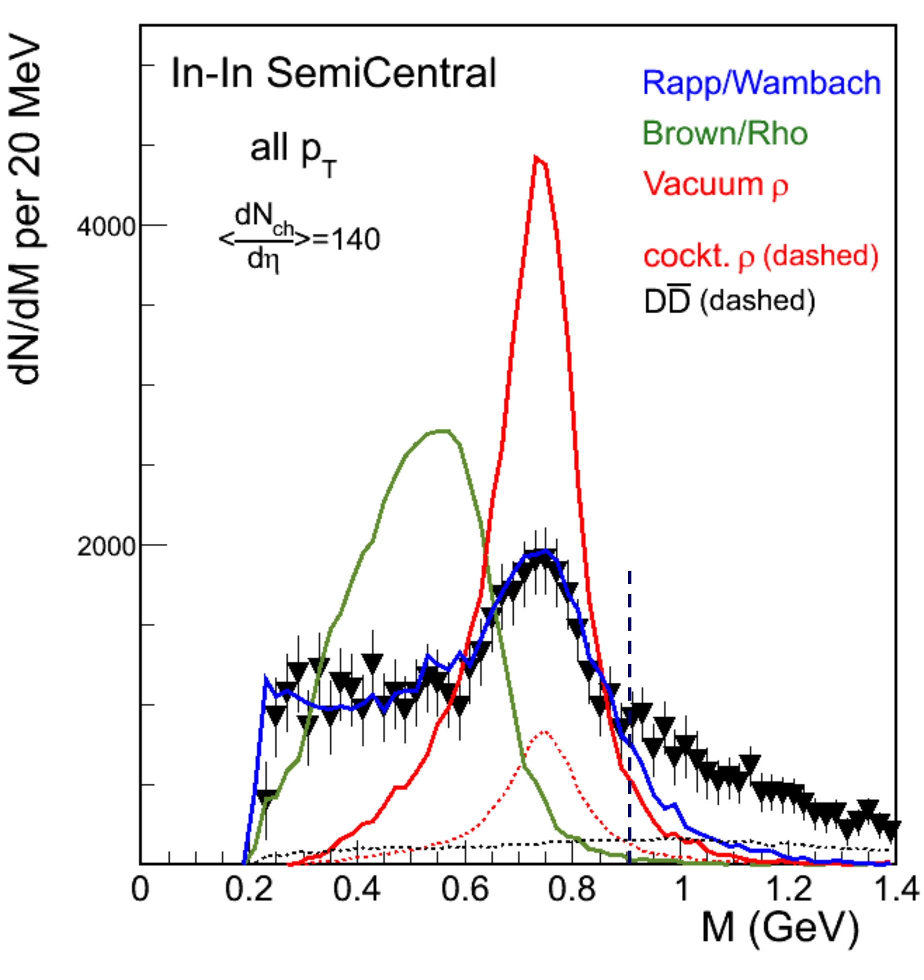
output:

white spectrum !

By pure chance,
for the M-p_T characteristics of thermal radiation, without p_T selection, the NA60 acceptance roughly compensates for the phase-space factors and directly 'measures' the <spectral function>

Comparison of data to RW, BR and Vacuum ρ

Phys. Rev. Lett. 96 (2006) 162302



Predictions by Rapp (2003) for all scenarios

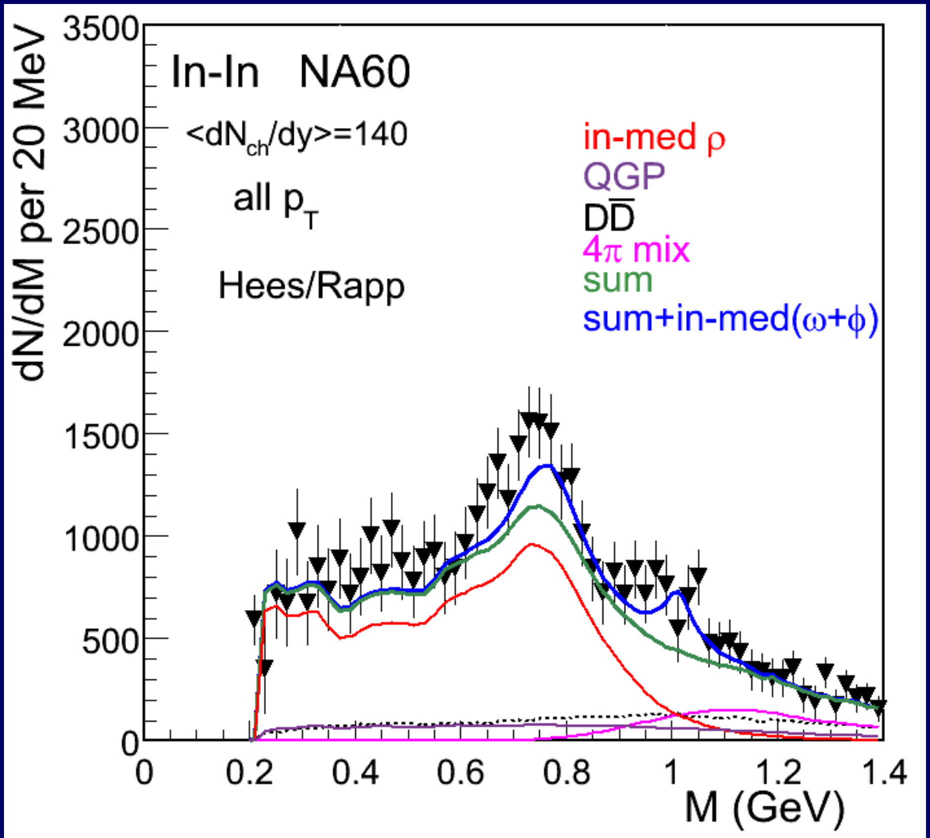
Theoretical yields normalized to data for M<0.9 GeV

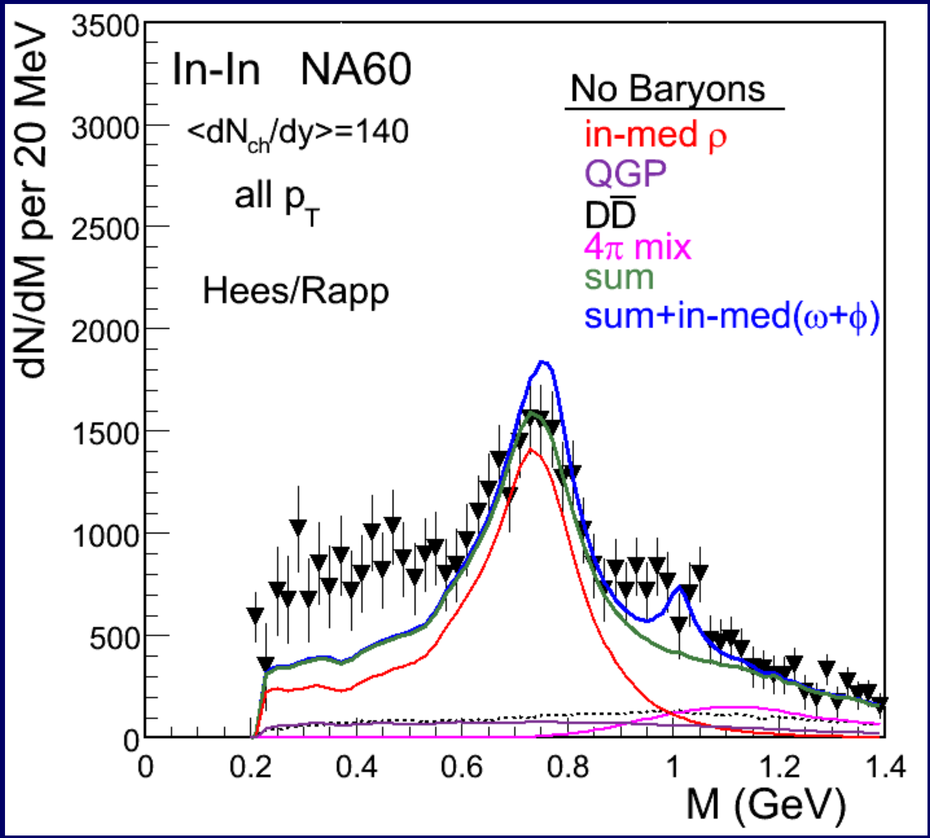
Data and predictions as shown, after acceptance filtering, roughly mirror the ρ spectral function, averaged over space-time and momenta.

Only broadening of ρ (RW) observed, no mass shift (BR)

Role of baryons in broadening the ρ

van Hees and Rapp, Phys.Rev.Lett. 97 (2006) 102301

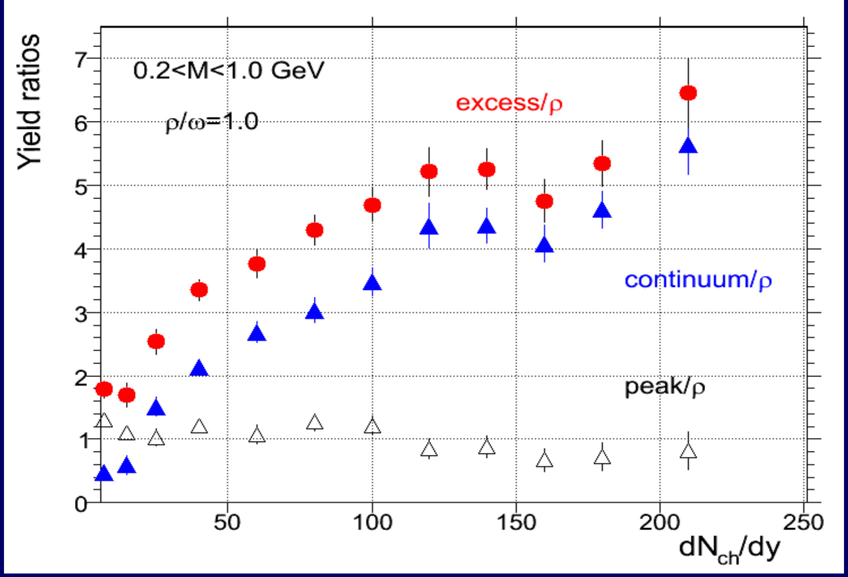


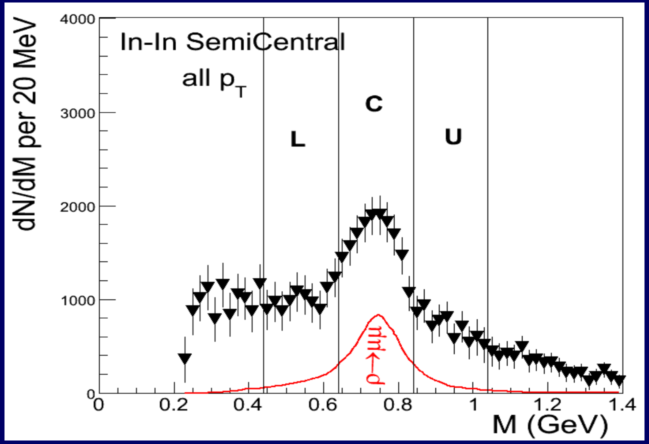


Whole spectrum reasonably well described, even in absolute terms

In this model, low-mass tail requires baryon interactions

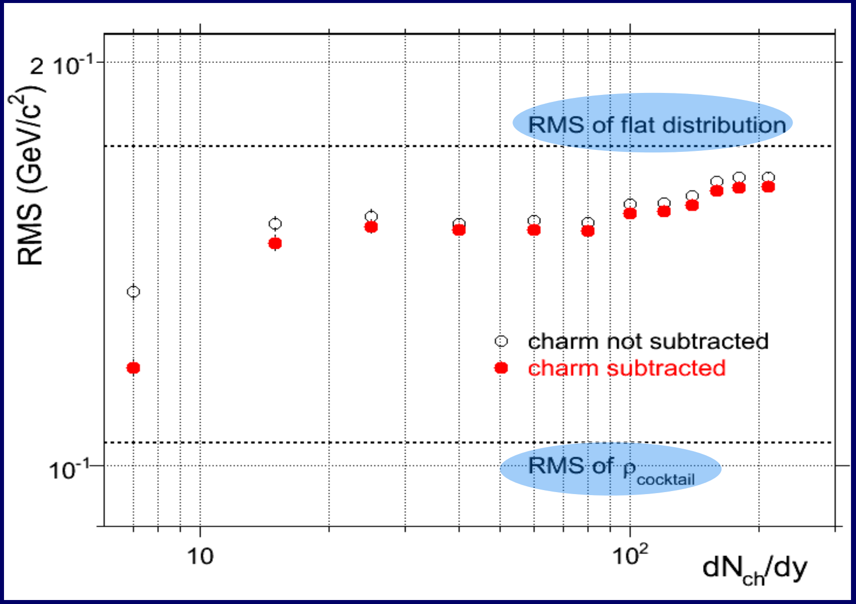
Centrality dependence of spectral shape





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

continuum: $3/2(L+U)$



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

→ 'ρ clock'

- near divergence of the width

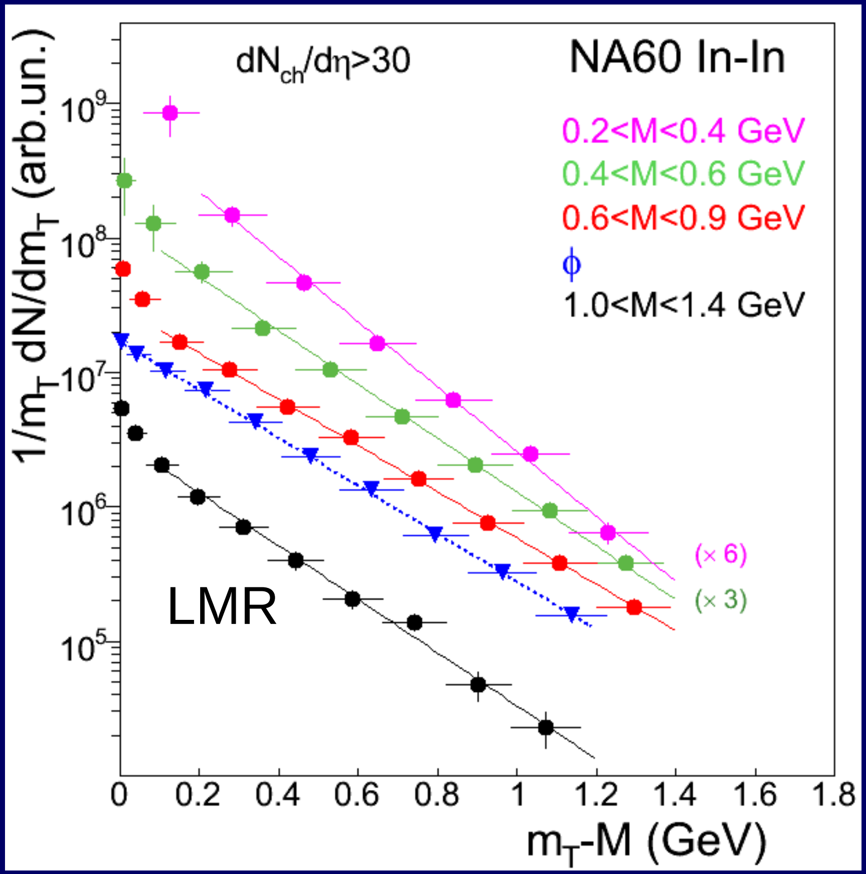
→ 'melting' of the ρ

Radial expansion and the EoS close to T_c

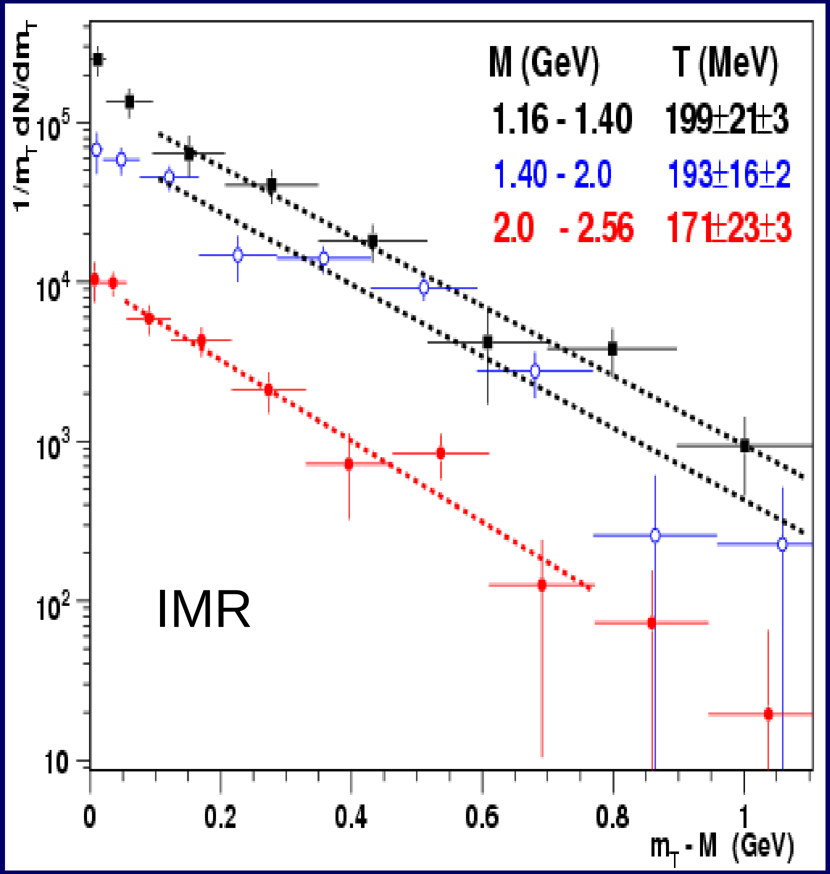
Transverse mass distributions of excess dimuons

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

Phys. Rev. Lett. 100 (2008) 022302



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

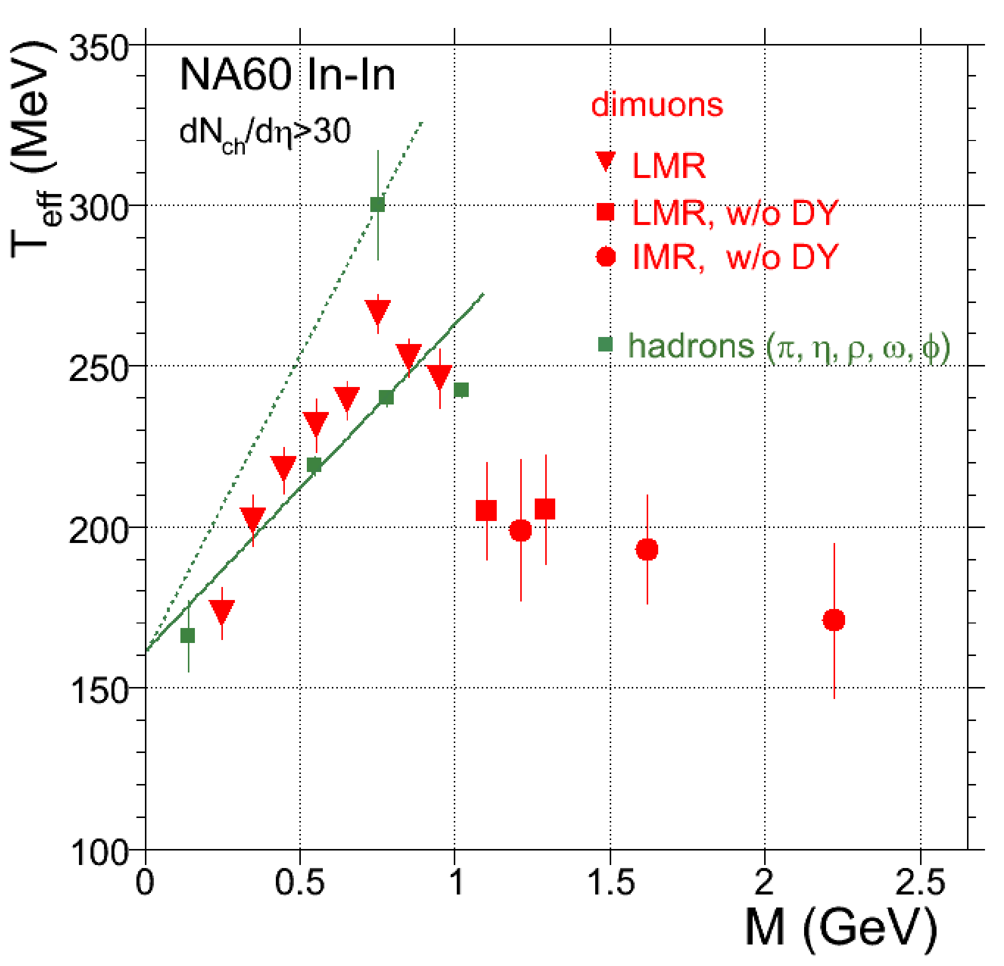


all m_T spectra exponential for m_T-M > 0.1 GeV; <0.1 GeV ??

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

The rise and fall of radial flow of thermal dimuons

Phys. Rev. Lett. 100 (2008) 022302



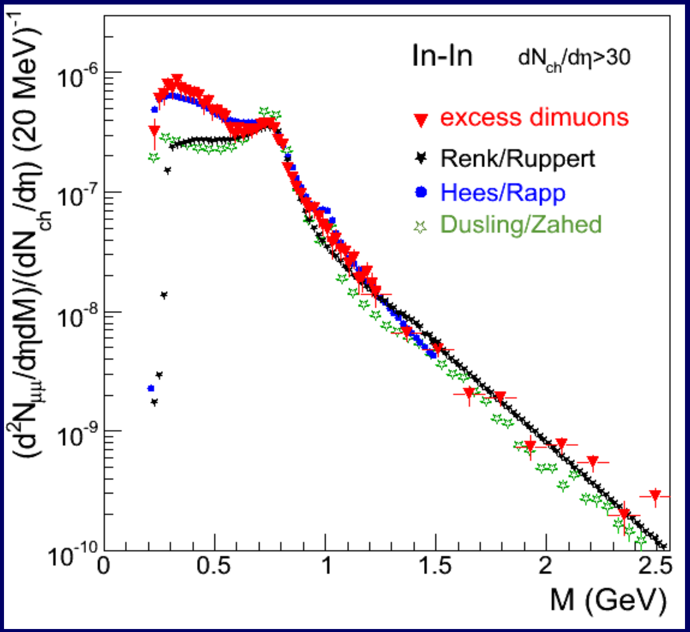
Strong rise of T_{eff} with dimuon mass, followed by a sudden drop for M>1 GeV

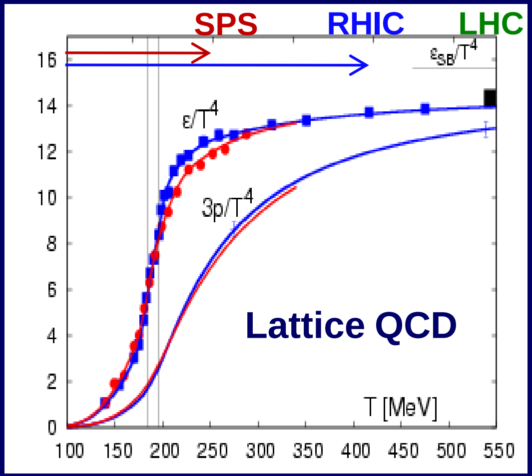
Rise consistent with radial flow of a hadronic source (here $\pi^+\pi^-\rightarrow\rho\rightarrow\mu^+\mu^-$), taking the freeze-out ρ as the reference (from a separate analysis of the ρ peak and the continuum)

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

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

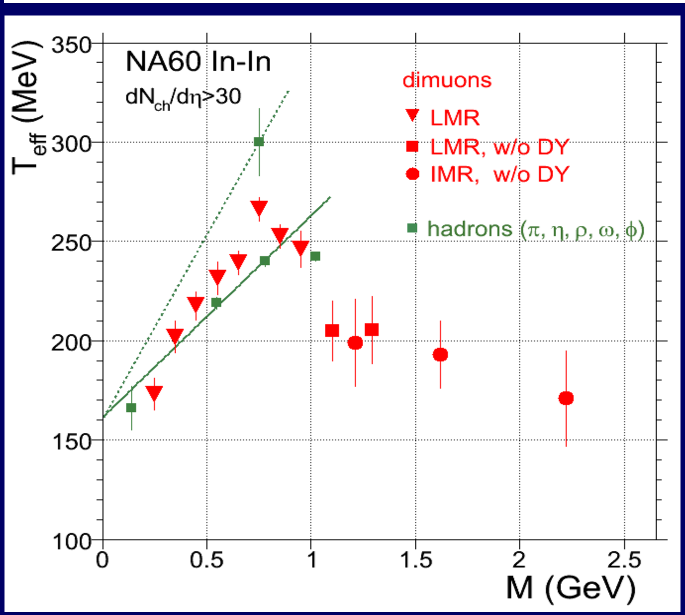
Combined conclusions from mass and p_T spectra





rapid rise of energy density ε, slow rise of pressure p (not ideal gas)

→ EoS above T_c very soft initially (c_s minimal)



M >1 GeV

- T_{eff} independent of mass within errors

mass spectrum: T = 205±12 MeV
p_T spectra: $\langle T_{eff}\rangle$ = 190±12 MeV

- same values within errors

T = 205 MeV > T_c = 170 (MeV)

negligible flow → soft EoS above T_c

all consistent with partonic phase

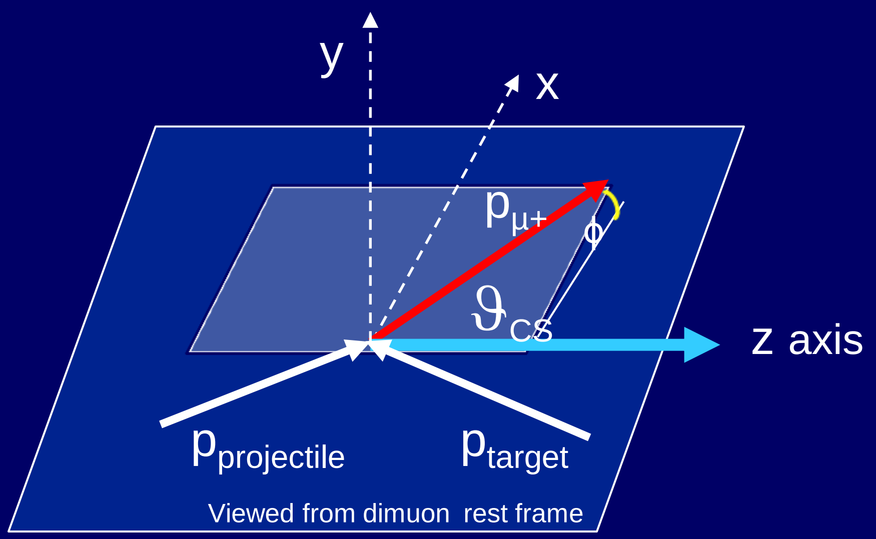
Angular distributions

Angular distributions

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

$\lambda, \ \mu, \ \nu$: 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:

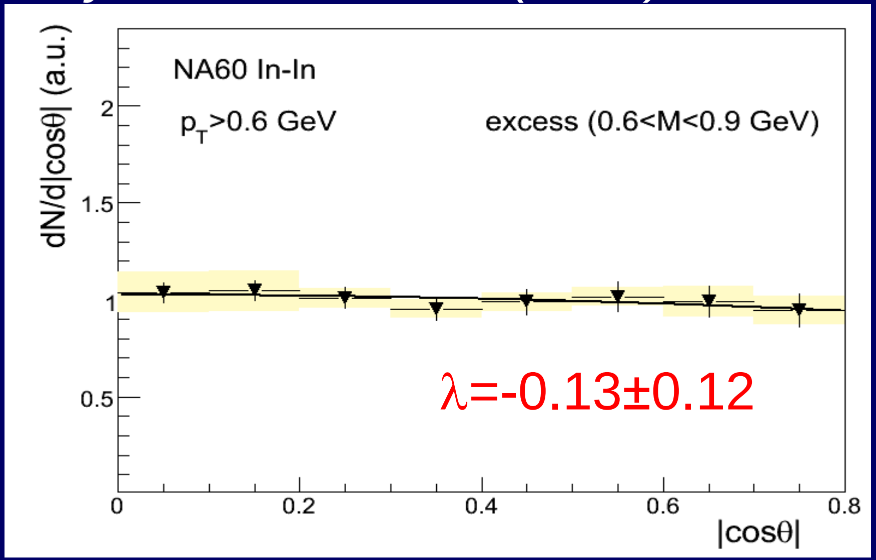
θ : angle between the positive muon $\mathbf{p}_{\mu+}$ and the z-axis.

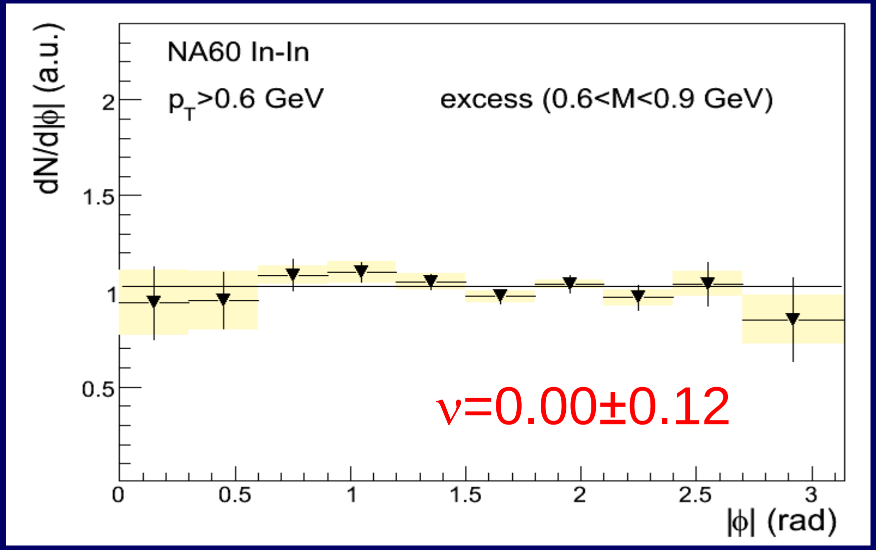
z axis : bisector between $\mathbf{p}_{proj}$ and $-\mathbf{p}_{target}$

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

μ = 0.05 ± 0.03 (~0 as expected)
set μ = 0 and fit projections

fit function for polar angle

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

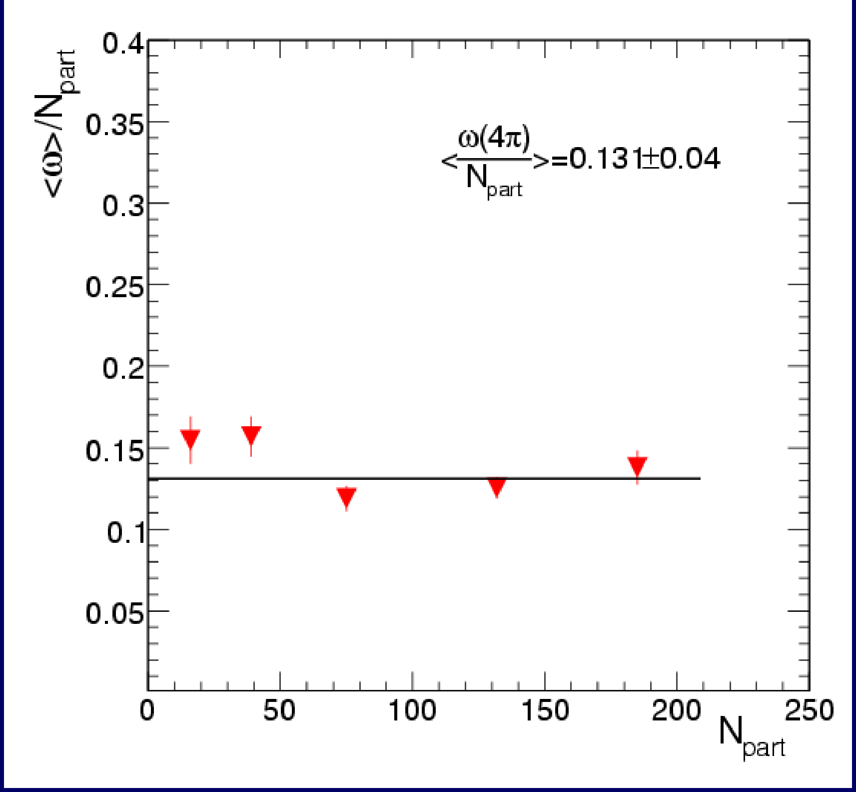
fit function for azimuth angle

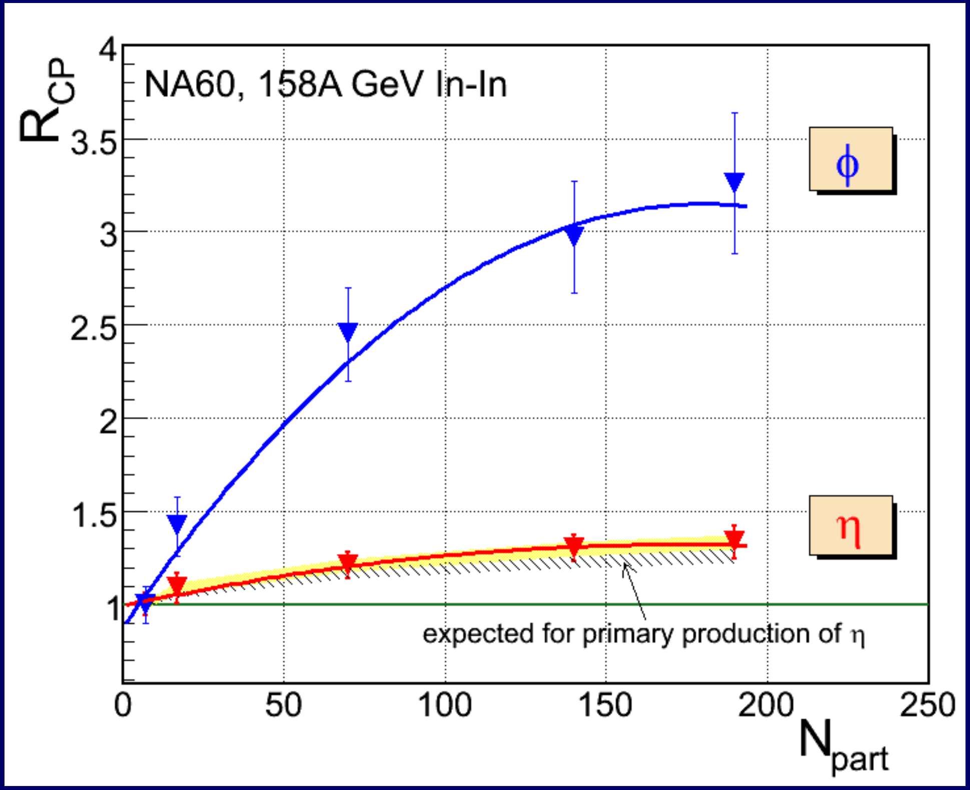
$$\frac{dN}{d|\phi|} \propto \left(1+\frac{1}{3}\lambda+\frac{\nu}{3}\cos 2\phi\right)$$

Zero polarization within errors

Hadron results

Centrality dependence of hadron yields





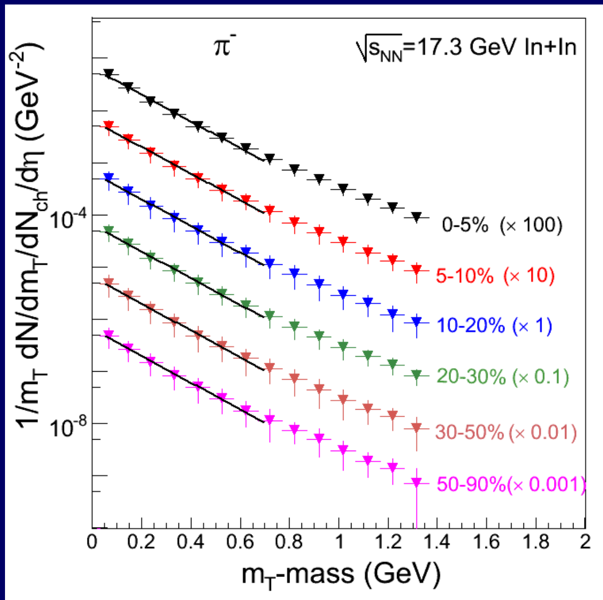
ω yield scales with N_{part}

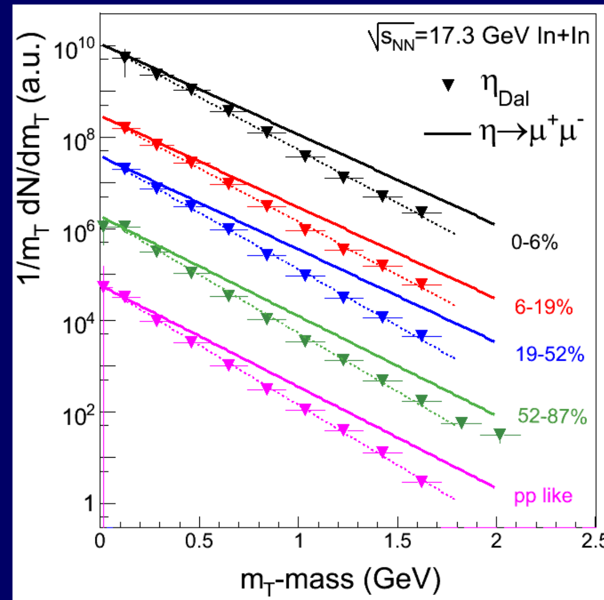
no nuclear enhancement

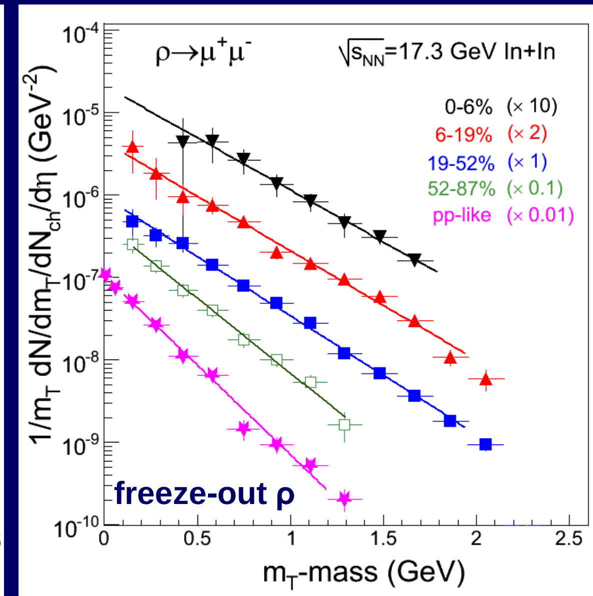
yields of hadrons with strangeness (η, ϕ) increase with N_{part}

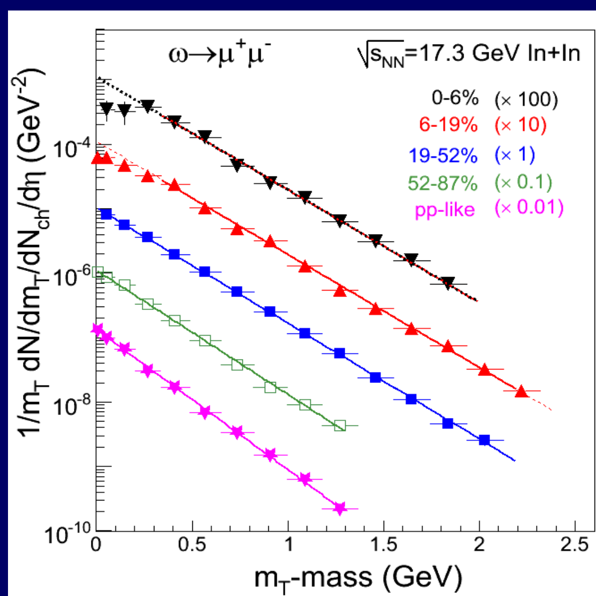
difference between η and ϕ consistent with wave function content of ssbar

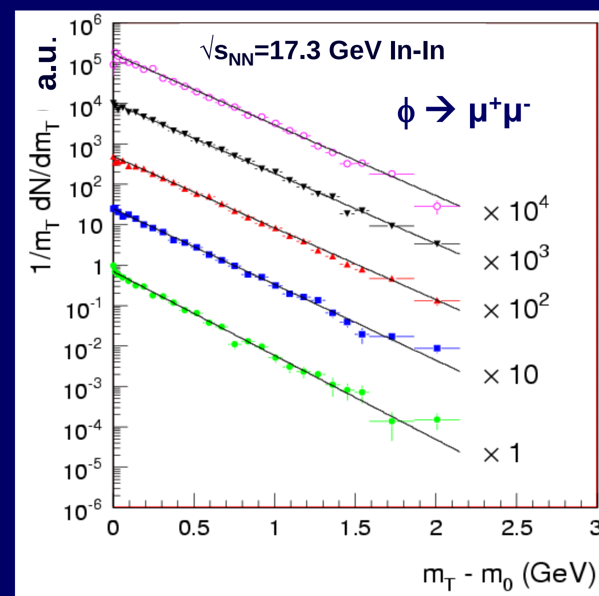
Light-flavoured hadrons in NA60



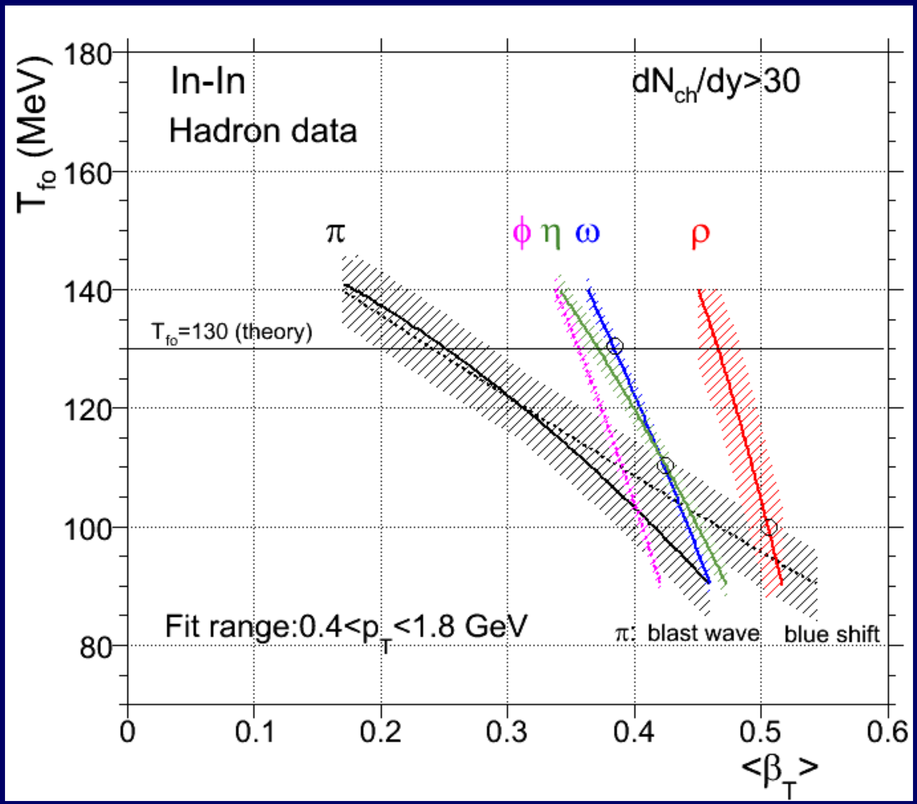


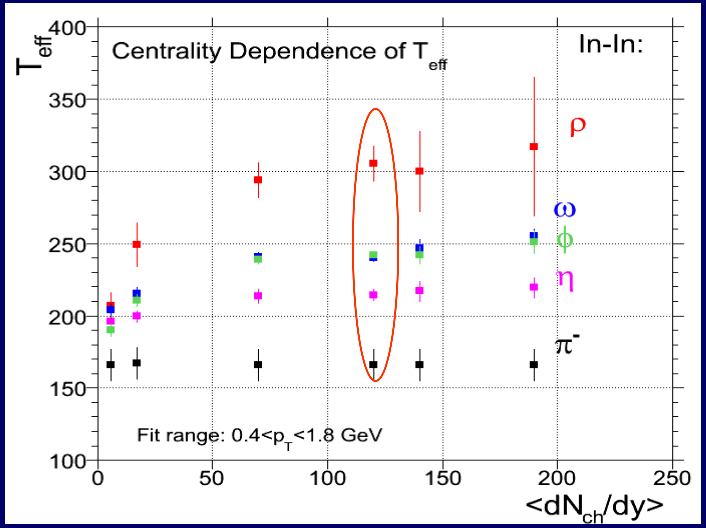






Hierarchy in hadron freeze-out





large difference between ρ and ω (same mass)

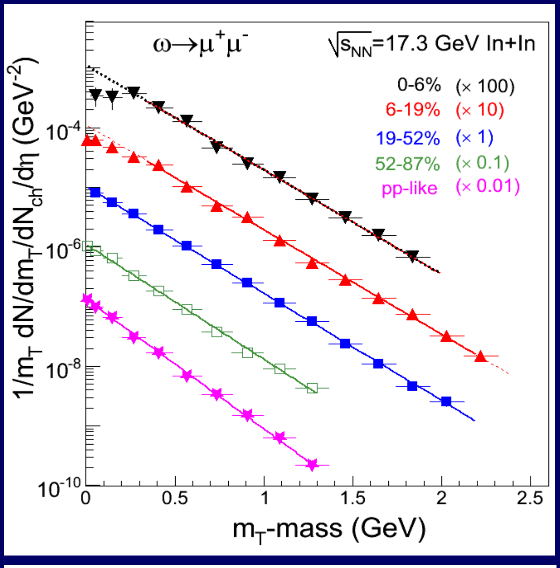
← use of Blast wave code

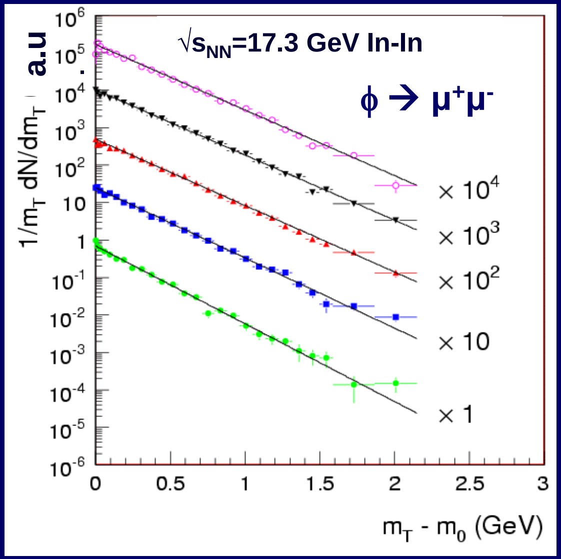
for a given hadron M, the measured T_{eff} defines a line in the T_{fo}-v_T plane

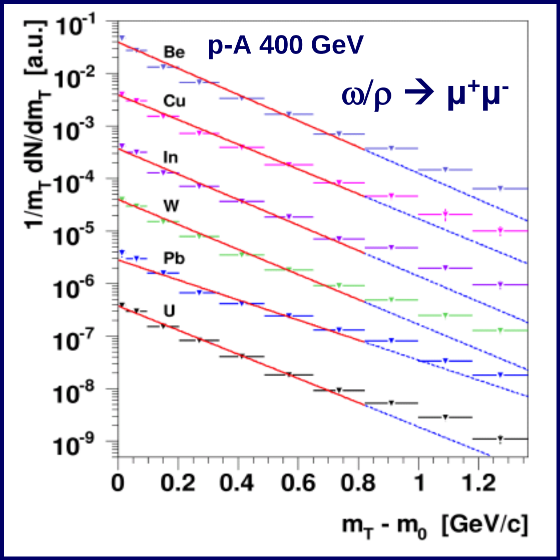
crossing of hadrons with π defines T_f, v_T max reached at respective hadron freeze-out

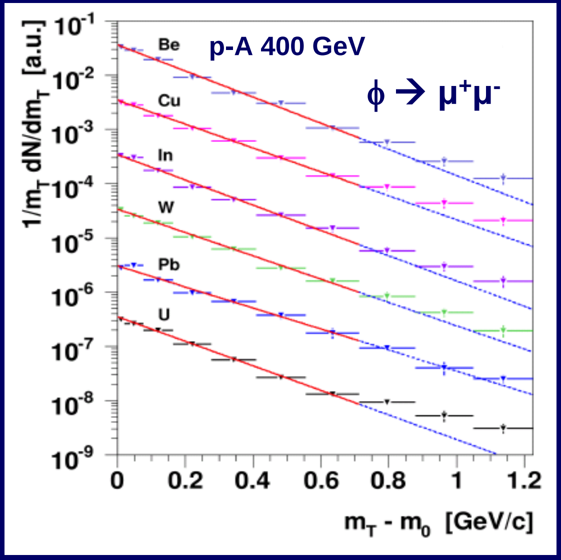
different hadrons have different coupling to pions (ρ maximal)
→ clear hierarchy of freeze-out (also for light-flavored hadrons)

Light-flavoured hadrons in NA60









In-In at 158A GeV

low mass sample size 440 000
(peripheral alone < 10%)

pure exponential m_T spectra

p-A at 400 GeV

low mass sample size 180 000
(NA27: insufficient statistics
for ρ/ω and ϕ → no p_T spectra)

upward bend of m_T spectra
→ hard scattering components

no hard scattering components at 158A GeV

Conclusions

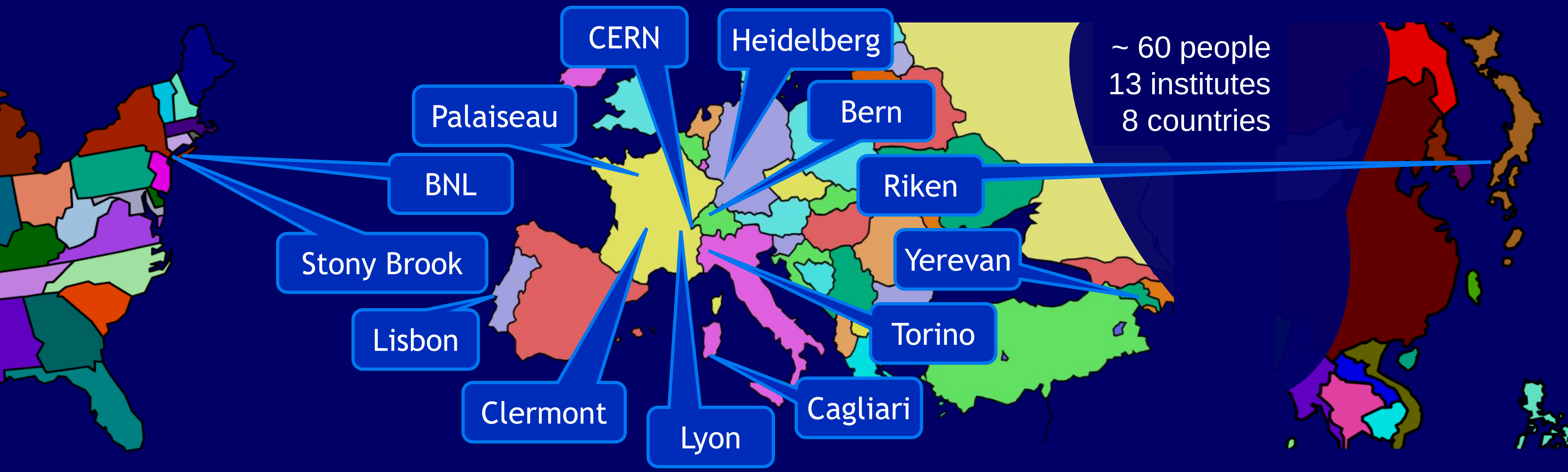
Planck-like exponential mass spectra, exponential m_T spectra, zero polarization and general agreement with thermal models consistent with interpretation of excess dimuons as thermal radiation

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; direct connection to deconfinement at the SPS

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

The NA60 experiment

http://cern.ch/na60



~ 60 people
13 institutes
8 countries

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. Ramalhete, P. Rosinsky, E. Scomparin, J. Seixas, S. Serci, R. Shahoyan, P. Sonderegger, H.J. Specht, R. Tieulent, E. Tveiten, G. Usai, H. Vardanyan, R. Veenhof and H. Wöhri

Remarks on other dilepton experiments

Dilepton experiments beyond NA60

The high energy frontier

- RHIC PHENIX, STAR
- LHC ALICE

The low energy frontier

- RHIC LE PHENIX, STAR
- SPS NA60-like
- SIS300 CBM
- SIS100 HADES, CBM

Relevance

M <1 GeV → chiral restoration
M >1 GeV → hadrons vs. partons (precise meas. of T)

Dream: energy dependence from

$\sqrt{s}$ = 4 − 5500 AGeV

with data quality equivalent to NA60

Principal obstacle to reach this:
colliders not competitive to fixed-target experiments in terms of interaction rate

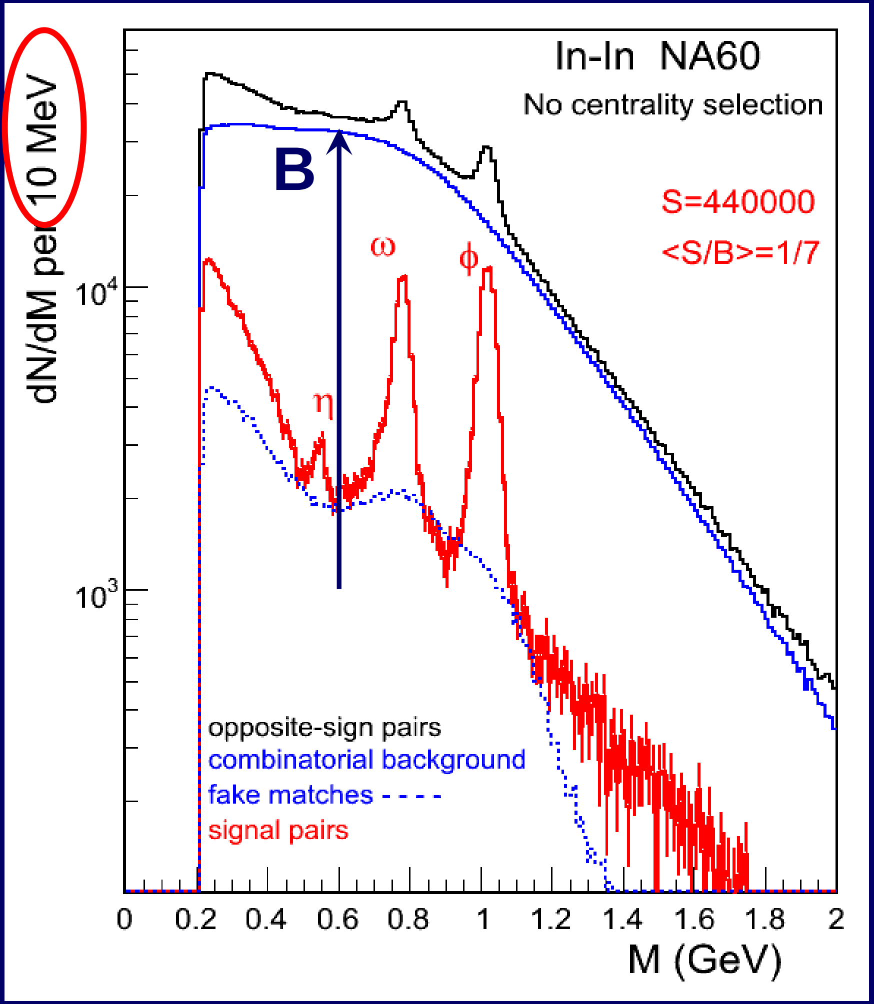
Data quality

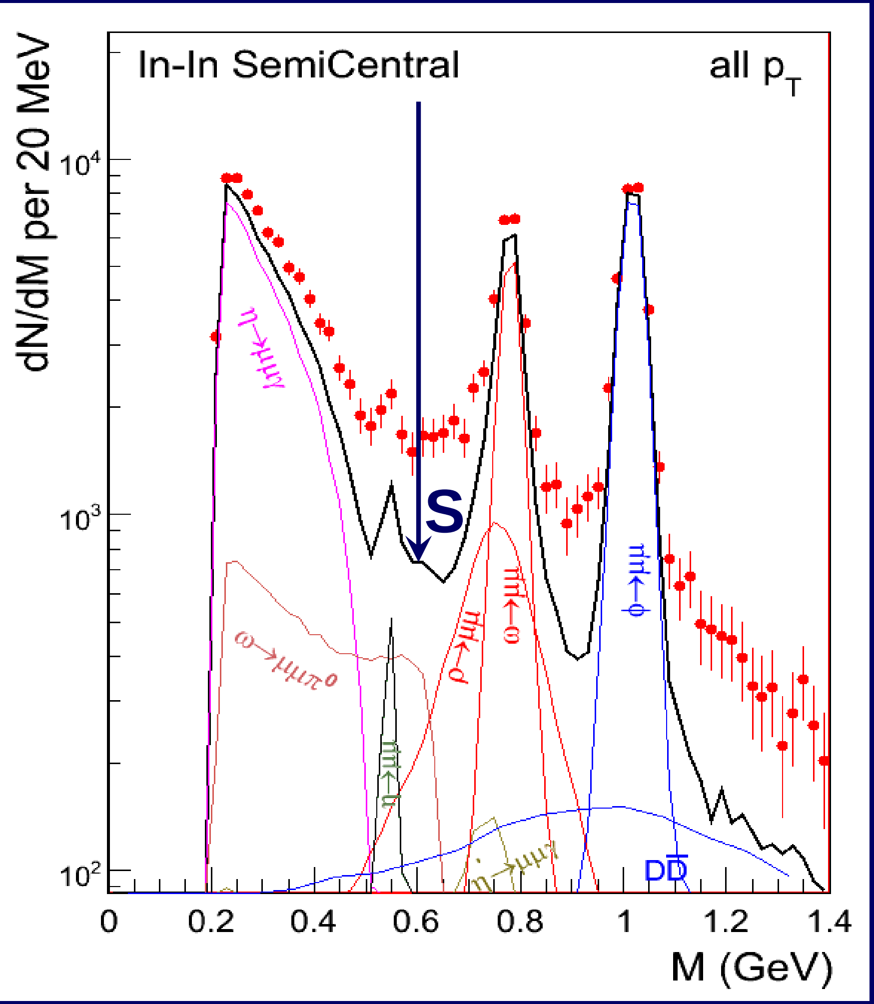
decisive parameters: Number of Interactions and Signal/Background

range of B/S: 20 - 1000 → B/S >>1; dynamic range 50 between exp.(!)

- effective sample size: $S_{eff} \sim I \times S/B$ reduction by factors of 20-1000
- systematics: $\delta S_{eff}/S_{eff} = \delta B/B \times B/S$ $\delta B/B = 2 \ldots 5 \times 10^{-3}$

Assessment of B/S: choice of S





choose hadron cocktail in mass window 0.5-0.6 GeV for S

- free from prejudices on any excess; no 'bootstrap'; most sensitive region
- unambiguous scaling between experiments; B/S $\propto$ dN_{ch}/dy

Combinatorial Background/Signal in Dilepton Experiments

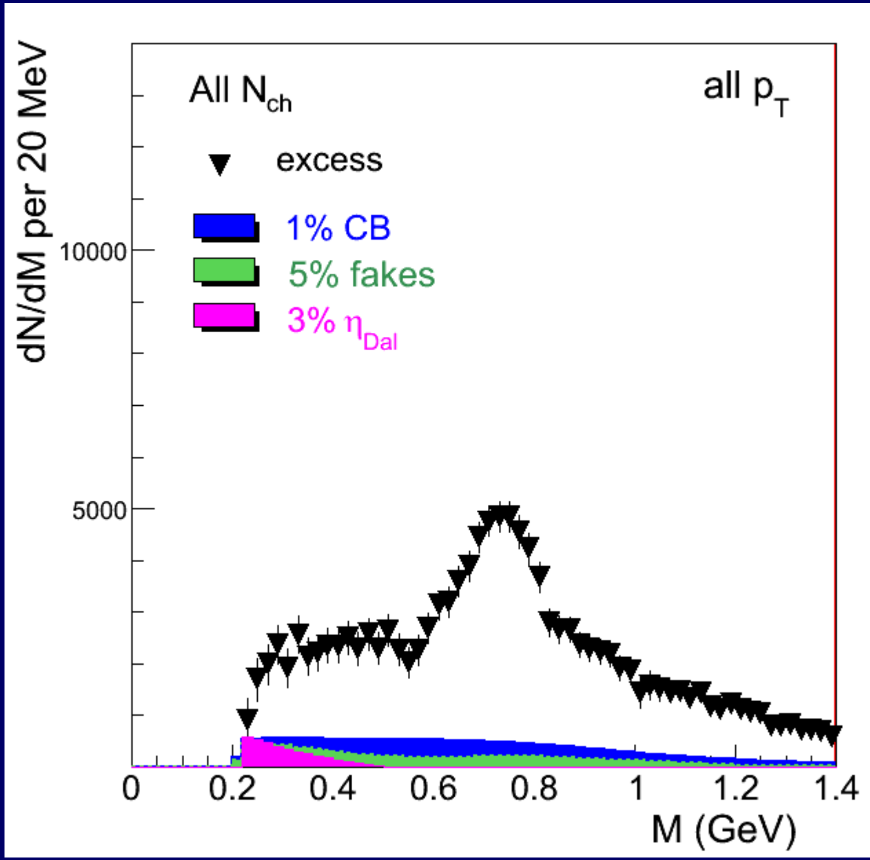
Reference: hadron cocktail at masses of 0.5-0.6 GeV

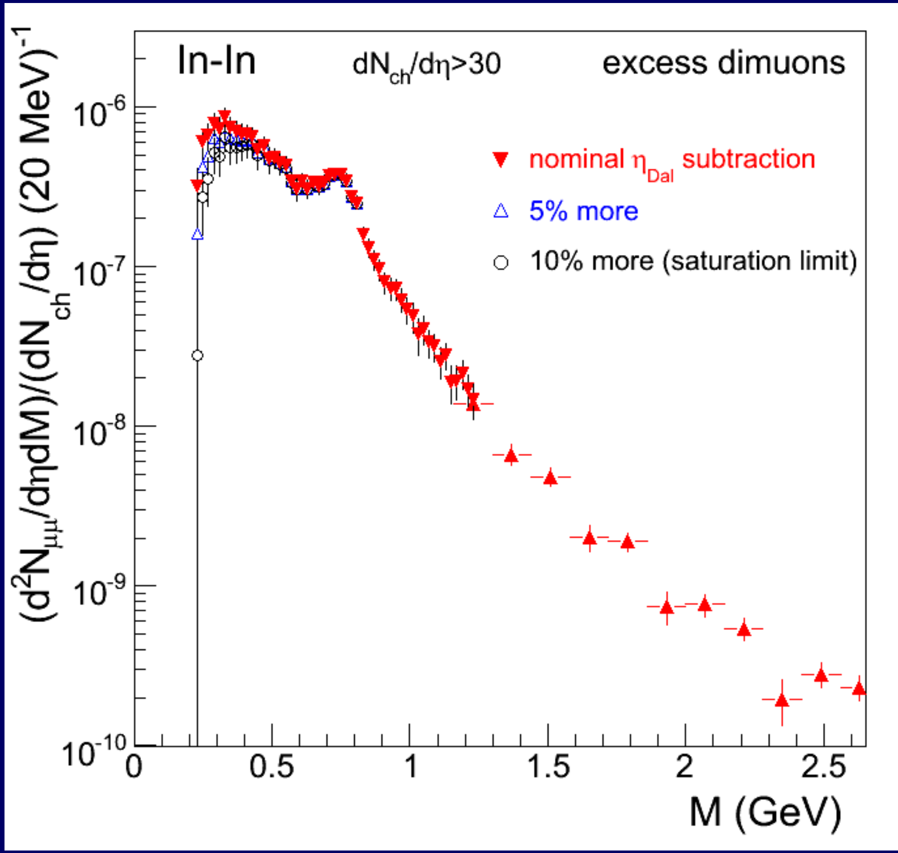
Experiment	Centrality	Lepton flavor	B/S as meas. or simul.	B/S rescaled to dN_{ch}/dy=300	B/S field data ×1/3	B-field at vertex
HADES-SIS100	semicentr	e^+e^-	20	60	60	−
CERES DR	semicentr	e^+e^-	80	100	100	−
CERES SR/TPC	central	e^+e^-	110	100	100	−
PHENIX with HBD	central	e^+e^-	250	100	100	−
PHENIX w/o HBD	central	e^+e^-	1300	600	200	+
STAR	central	e^+e^-	400	200	70	+
ALICE Upg ITS	central	e^+e^-	1200	200	70	+
CBM-SIS100	central	e^+e^-	200	300	100	+
CBM-SIS300	central	e^+e^-	200	200	70	+
NA60	semicentr	$\mu^+\mu^-$	55	80	80	
CBM-SIS300	central	$\mu^+\mu^-$	600	600	600	

→ ‘penalty’ factor 3 (4) for B-field, hindering optimal rejection of low-mass pairs

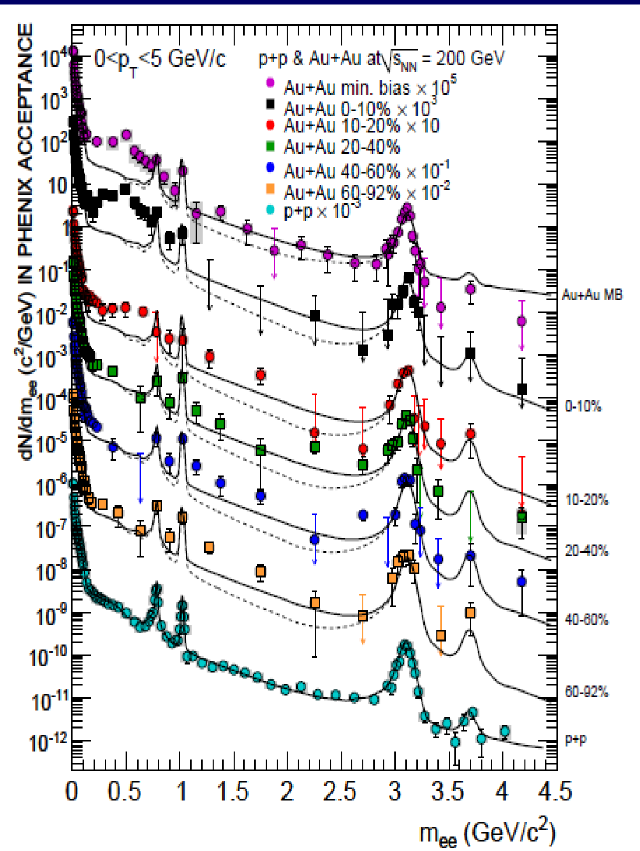
→ ‘reduced’ values 80±20 (w/o red) → only small influences of experimental details

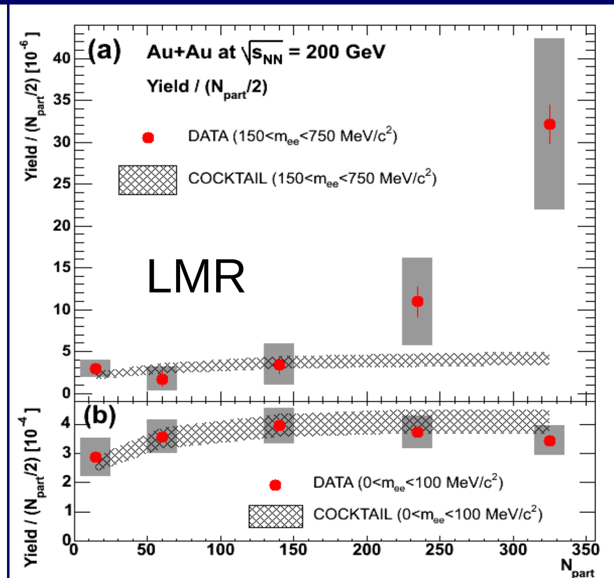
Systematic errors for dimuons in NA60

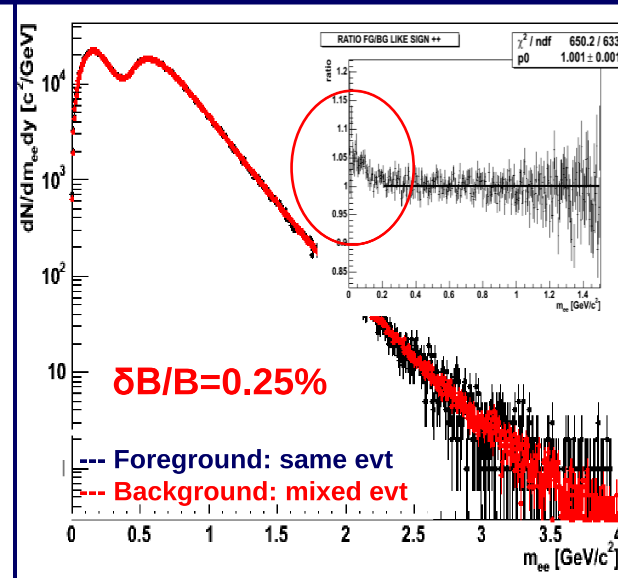


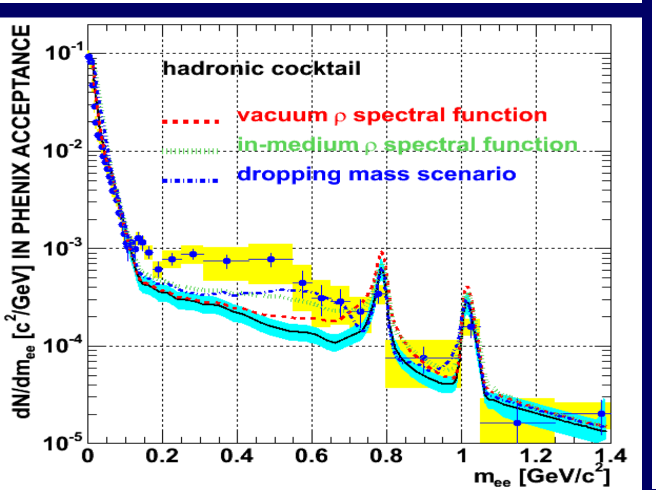


Di-electron results from PHENIX



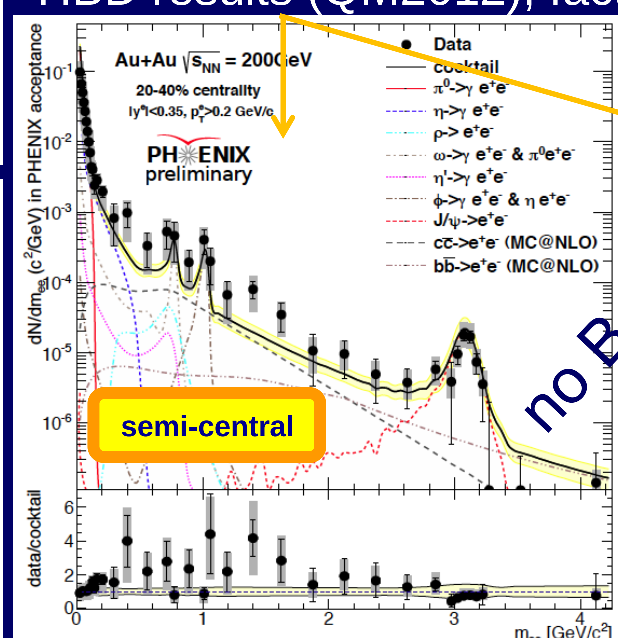


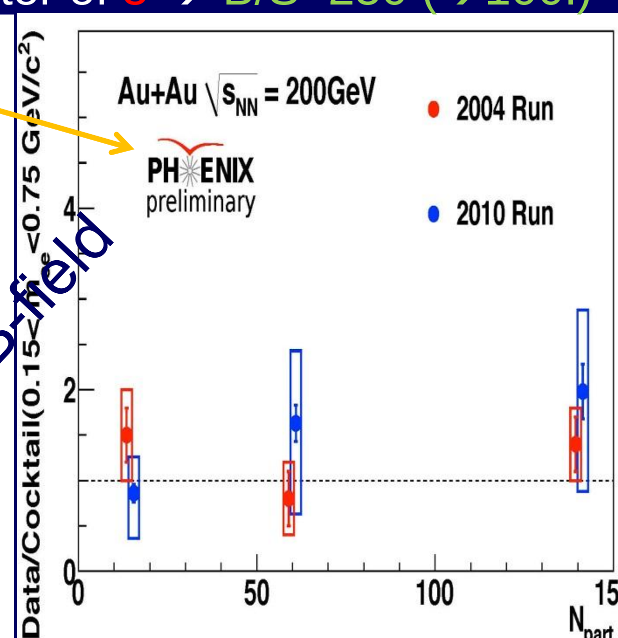




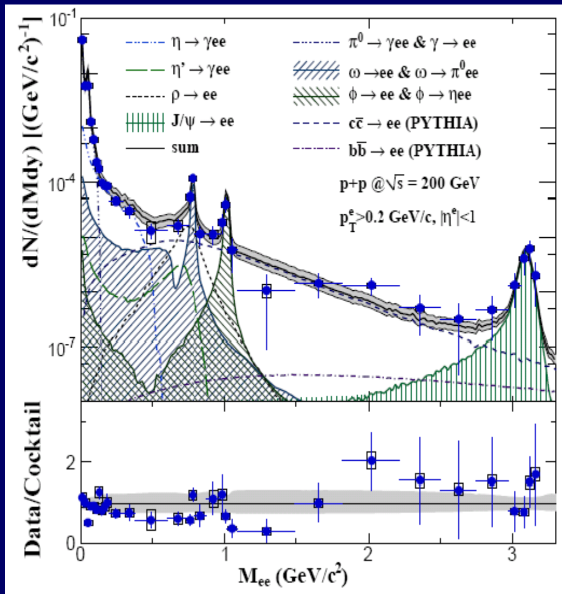
Previous results (PRC 2010); B/S=1300 (central)

HBD results (QM2012); factor of 5 → B/S=250 (→100!)





Di-electron results from STAR (QM2012)



B/S=400 (central)

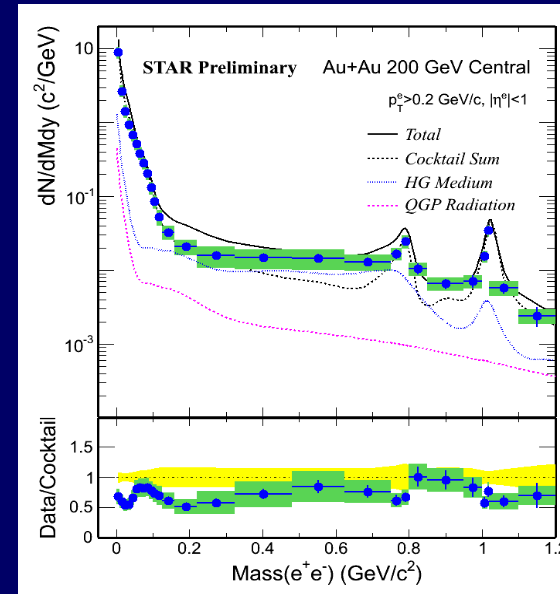
← data/cocktail <1 →

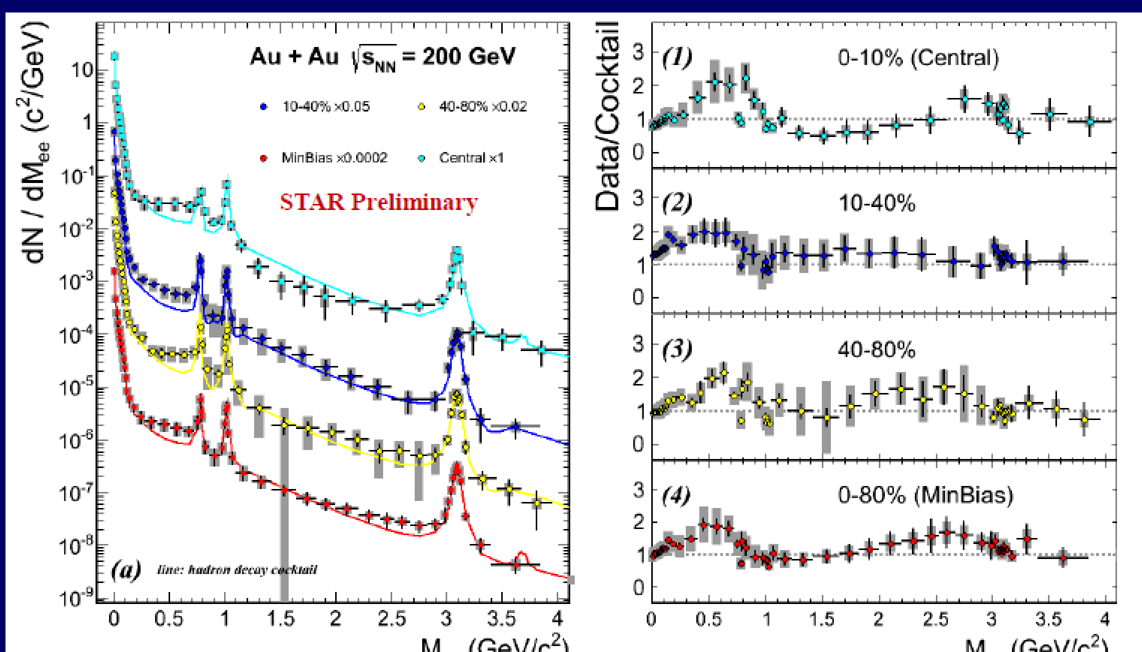
cocktail normalization?

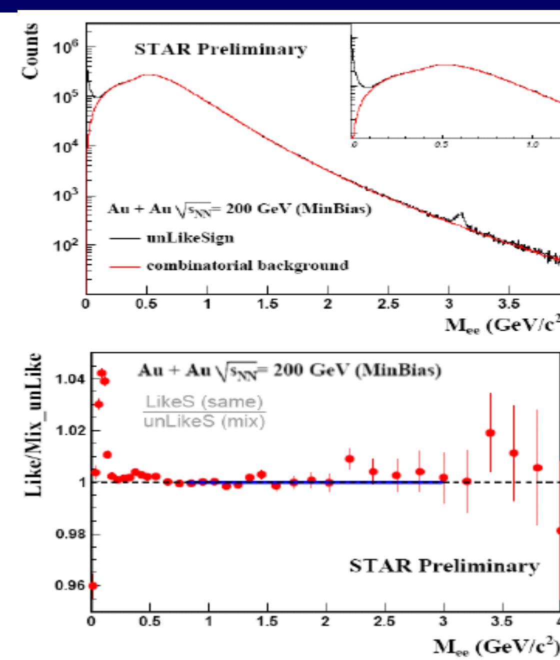
no centrality dependence of enhancement

background problem?

oversubtraction by 0.2%?







Di-muons simulations for CBM-SIS300 (2009ff)

B/S=600

Difference mostly due to the larger acceptance angles at lower energies ?

B/S=55 → 80