Planck-like Radiation and the Parton-Hadron Phase Transition in QCD

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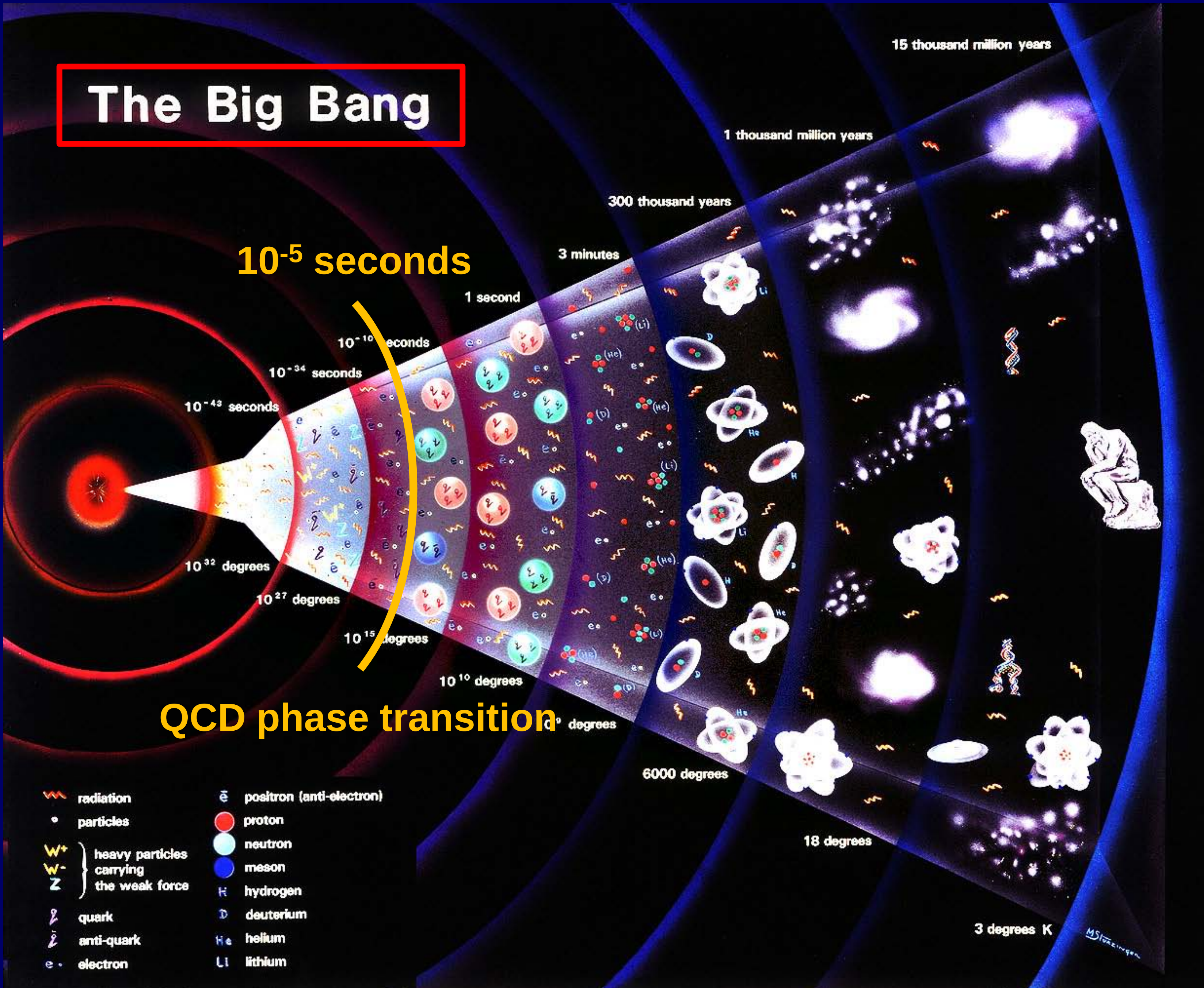
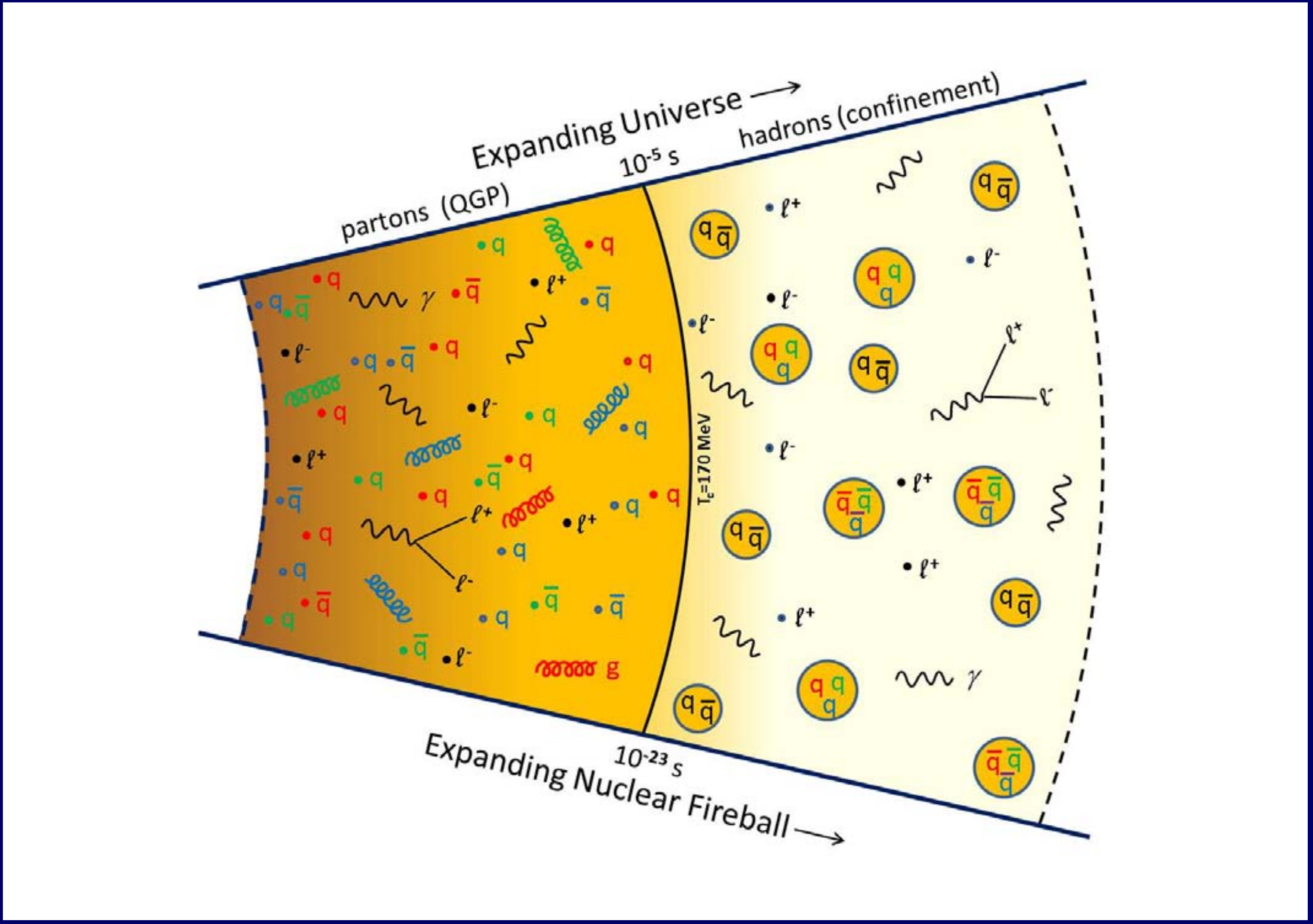
Outline

- Motivation and history
- NA60 at the CERN SPS
- Thermal radiation and deconfinement
- The ρ spectral function and chiral restoration
- ‘Hubble’ expansion and the EoS close to T_c
- Concluding remarks

Motivation


The Big Bang
10^{-5} seconds
QCD phase transition
10^{-43} seconds
10^{-34} seconds
10^{-10} econds
1 second
3 minutes
300 thousand years
1 thousand million years
15 thousand million years
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W^+ W^- Z heavy particles carrying the weak force
quark
anti-quark
e electron
ē positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

The QCD Phase Transition



Up to 10^{-5} seconds, quarks and gluons were free

then a phase transition occurred, confining quarks and gluons into hadrons, and empty space, the "vacuum", was born

The Big Bang in the Laboratory

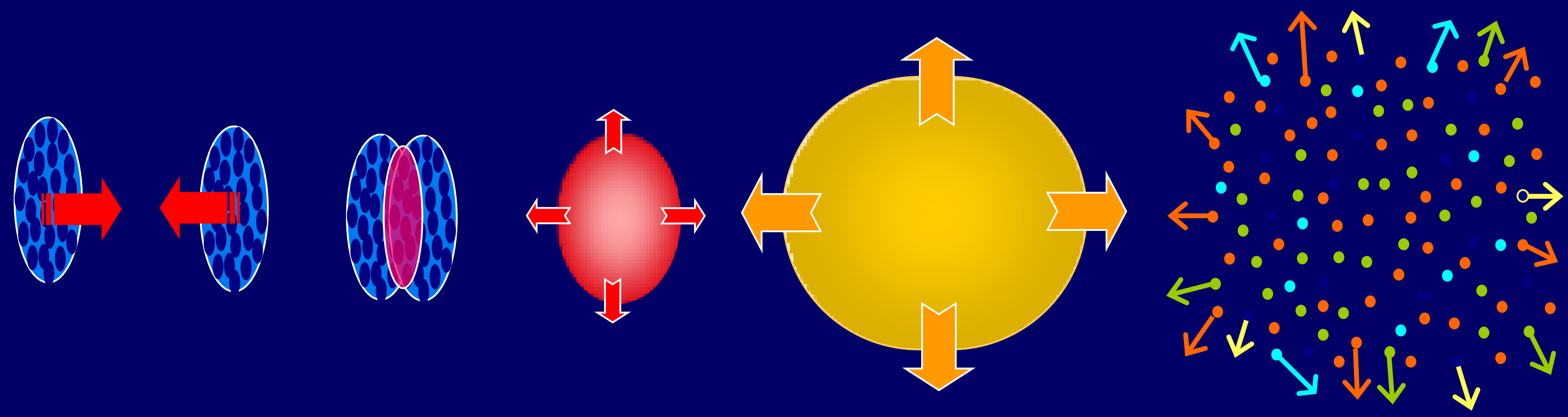
Recreate the first few μs after the Big Bang

Probe the quark-hadron phase transition

Probe the chiral transition (origin of light hadron masses)

Needs Nuclear Collisions to answer these questions

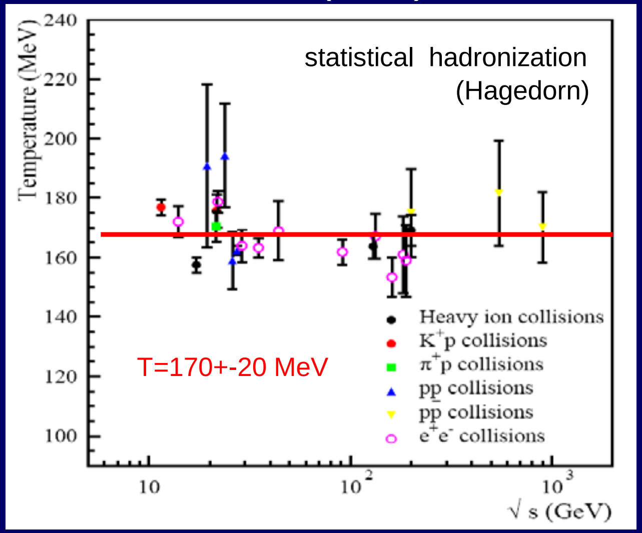
Time evolution of a nuclear collision: hadron production



A+A   ***NN*-coll.**   **QGP**   **Hadron Gas**   **Freeze-Out**

"Hubble" expansion: T= 250→170   170→110   ~110 (MeV)

H.Satz (2008)



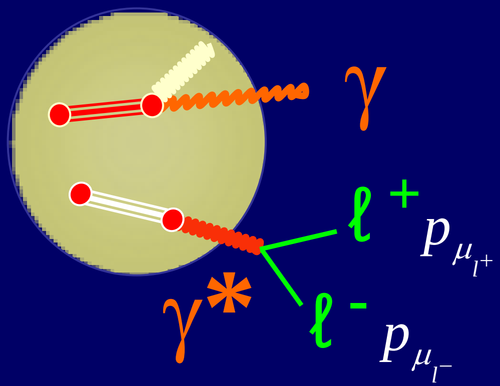
99.99% of the produced particles are hadrons

hadron yields: temperature at creation
(statistical hadronization)

hadron p_T: temperature at freeze-out
expansion velocity at freeze-out

other: elliptic flow, HBT, quarkonia, jets

Electromagnetic Probes: Photons *versus* Lepton Pairs



1 variable: p_T

2 variables: M, p_T $\left(M = \sqrt{p^2_{\mu_{l^+}} + p^2_{\mu_{l^-}}}\right)$

($\ell \leftrightarrow e, \mu, \tau$)

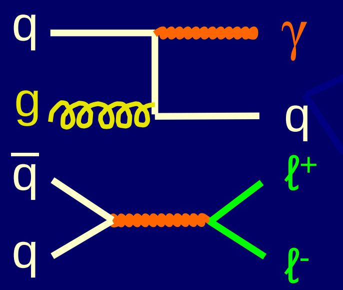
Relevant for thermal radiation:

(1) p_T sensitive to temperature and expansion velocity

M only sensitive to temperature (Lorentz invariant)

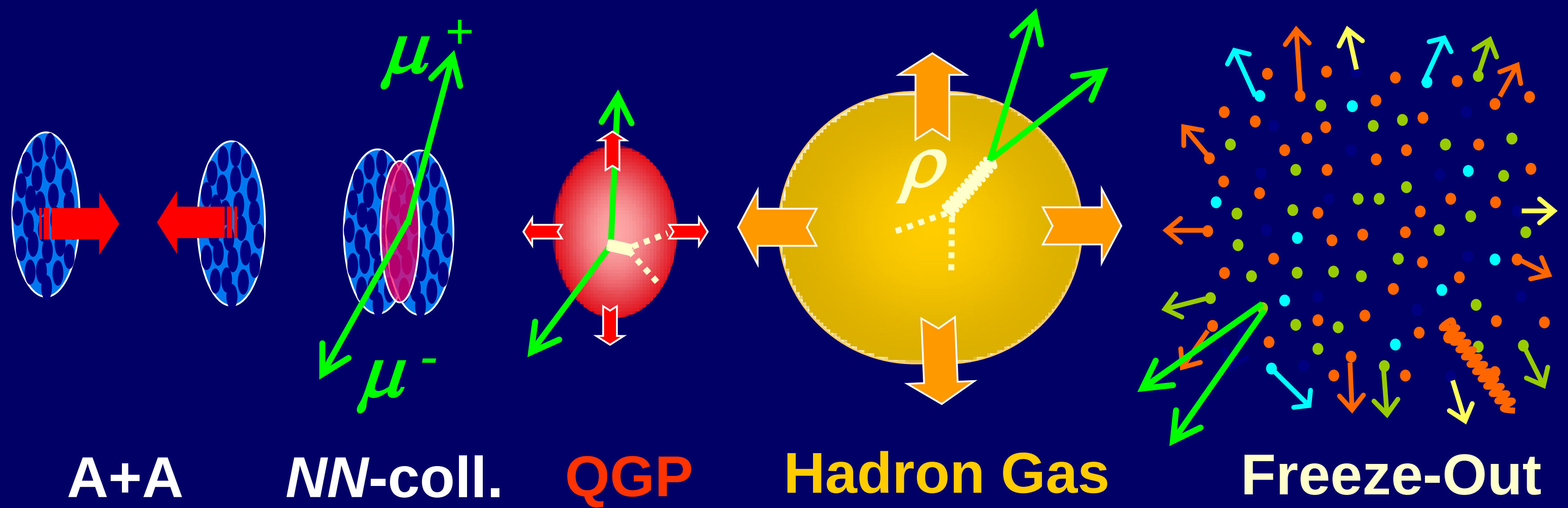
(2) lowest order rate ~ $\alpha_{em}\alpha_s$

lowest order rate ~ α_{em}^2



dileptons more rich and more rigorous than photons

Time evolution of a nuclear collision: dilepton production

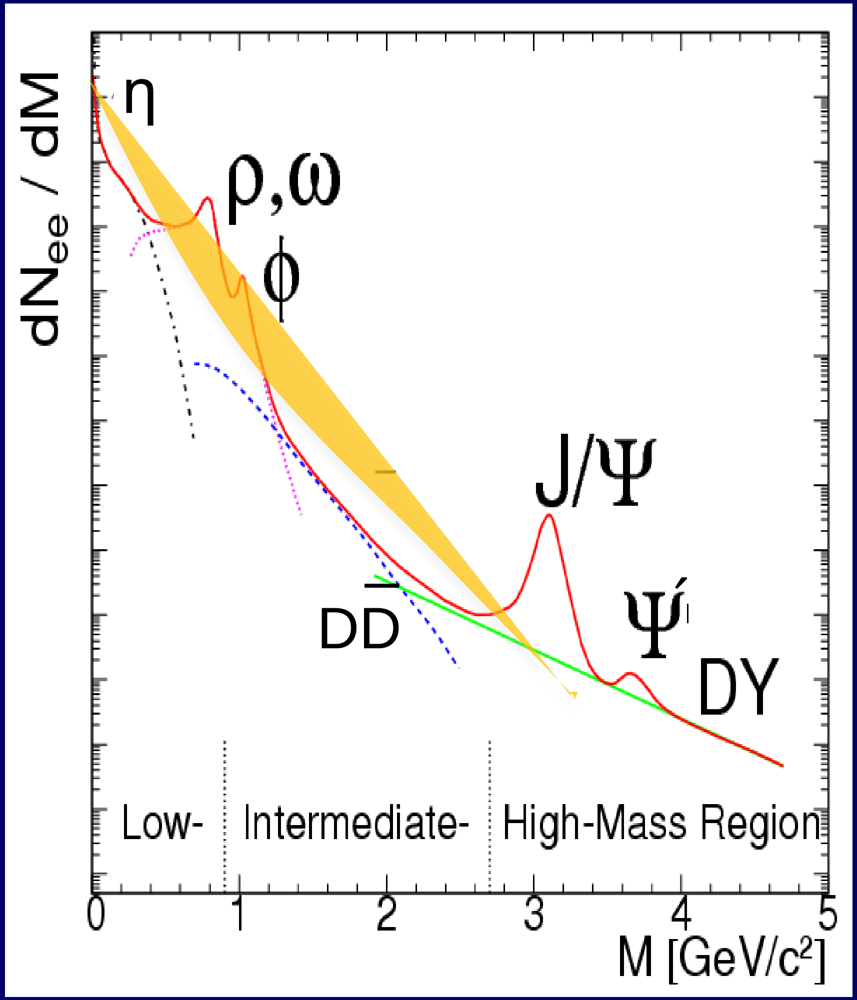


Lepton pairs emitted at all stages; no final state interactions

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

NN-collisions:	Drell-Yan, $D\bar{D}$ pairs
QGP:	thermal $q\bar{q}$ annihilation
Hot+Dense Hadron Gas:	thermal $\pi^+\pi^-$ annihilation
Freeze-out:	free hadron decays

Sources of lepton pairs – standard *versus* thermal



LMR: M<1 GeV

hadronic: $\pi^+\pi^- \rightarrow \rho^*$ (1^{--}) $\rightarrow \ell^+\ell^-$

prime probe for restoration of chiral symmetry

(*R. Pisarski, PLB 1982*)

IMR: M>1 GeV

hadronic: ???

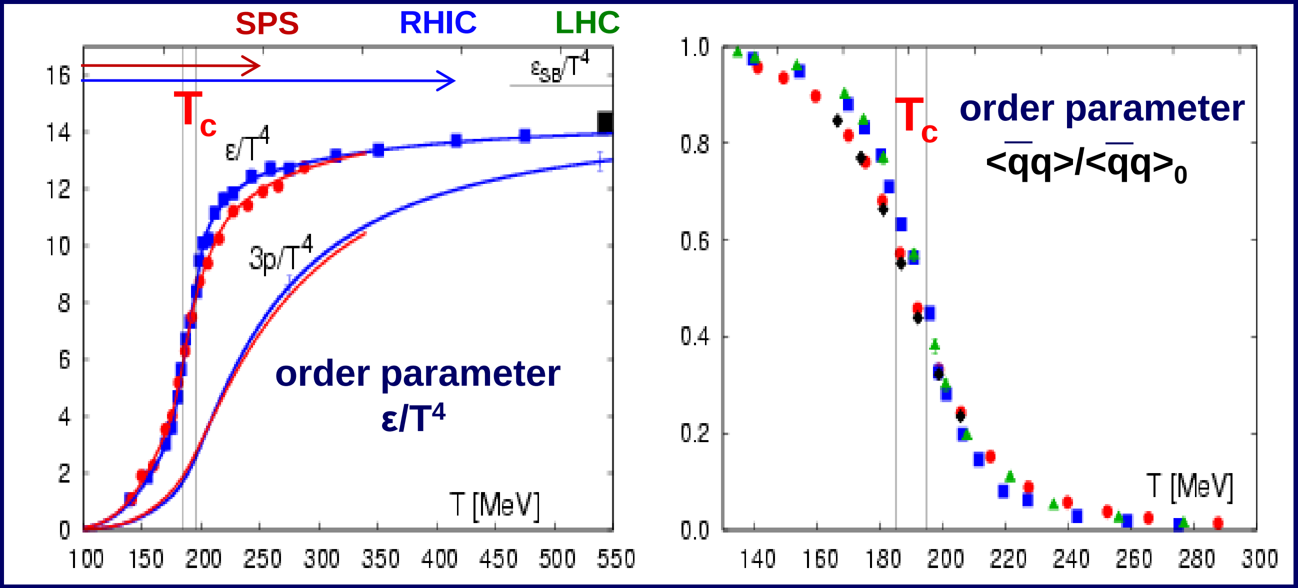
partonic: $q\bar{q} \rightarrow \ell^+\ell^-$

prime probe of deconfinement

(Kajantie, McLerran, al., 1982 ff)

Theoretical guidance by finite-temperature lattice QCD

Hot QCD coll.: A. Bazavov et al., Phys.Rev.D 80 (2009) 014504



μ_B=0
2+1 flavors (u,d,s)

two phase transitions at the same critical temperature T_c

(1) deconfinement transition

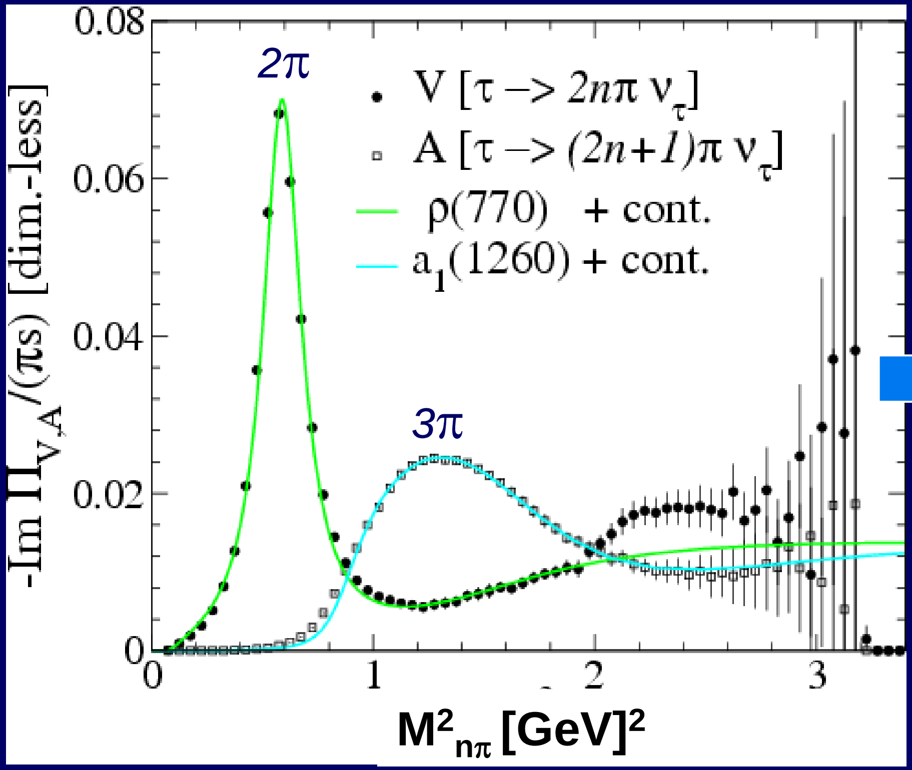
(2) chiral symmetry restoration

rapid rise of energy density ε, slow rise of pressure p (not ideal gas)
→ EoS above T_c very soft initially (c_s minimal)

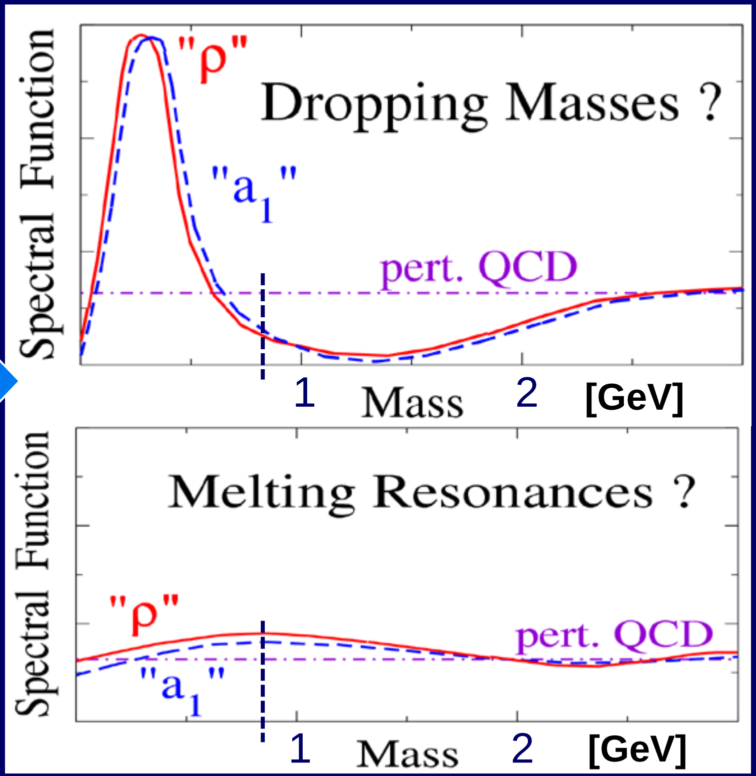
spontaneous chiral symmetry breaking
→ quark condensate $<\bar{q}q>_0 \neq 0$ (-0.8 fm^{-3}), mass generation, chiral doublets...
restoration affects spectral properties of hadrons (masses,widths)

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

ALEPH data (also OPAL): Vacuum



at T_c: Chiral Restoration



In nuclear collisions: thermal dileptons with M<1 GeV mediated by the vector ρ :

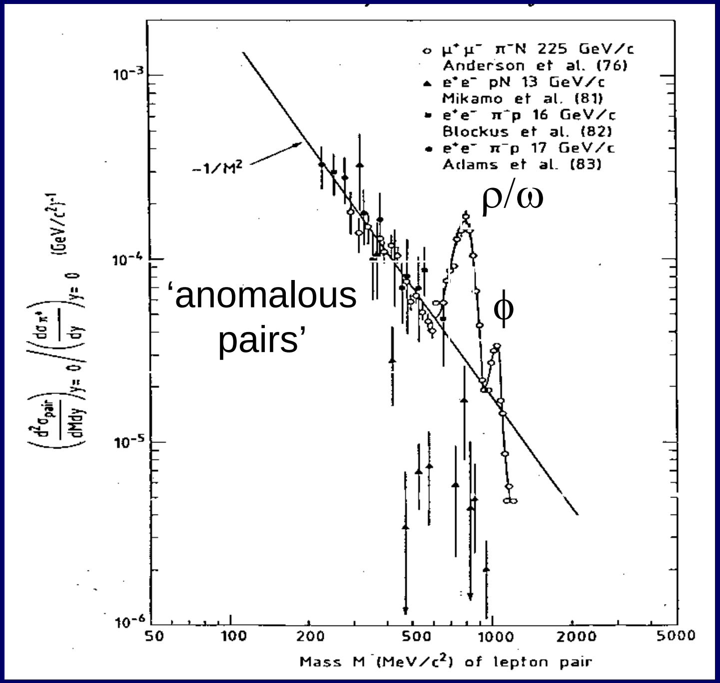
1. life time τ_ρ =1.3 fm << $\tau_{collision}$ > 10 fm
2. continuous "regeneration" by $\pi^+\pi^-$ → sample in-medium evolution

axial vector a_1 very difficult to observe ($\pi\, a_1 \rightarrow 4\pi$…)

History

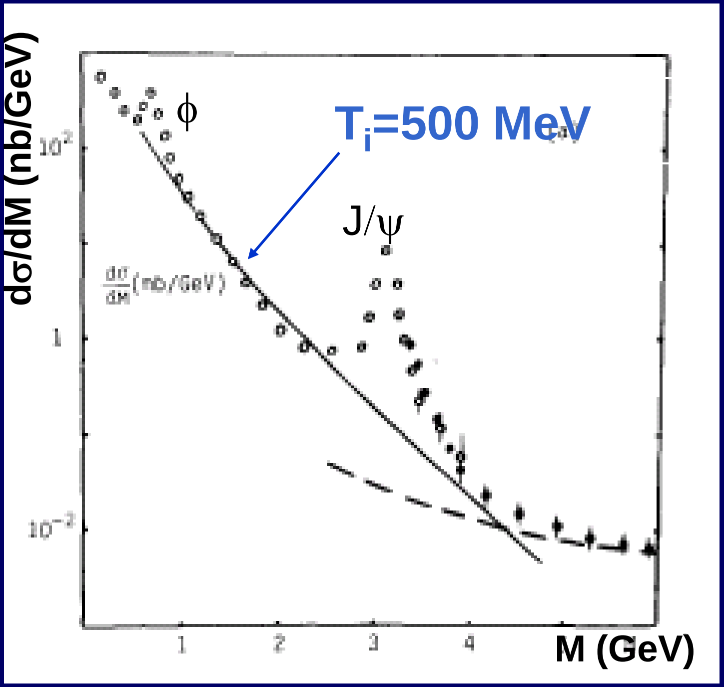
Proton-proton collisions in the 1970s

Summary of lepton pair data in the low-mass region (LMR) (*H.J.S., QM Helsinki 1984*)



Bjorken/Weisberg, Phys.Rev.D ‘76
dileptons from partons produced in collision > than Drell-Yan (10-100)

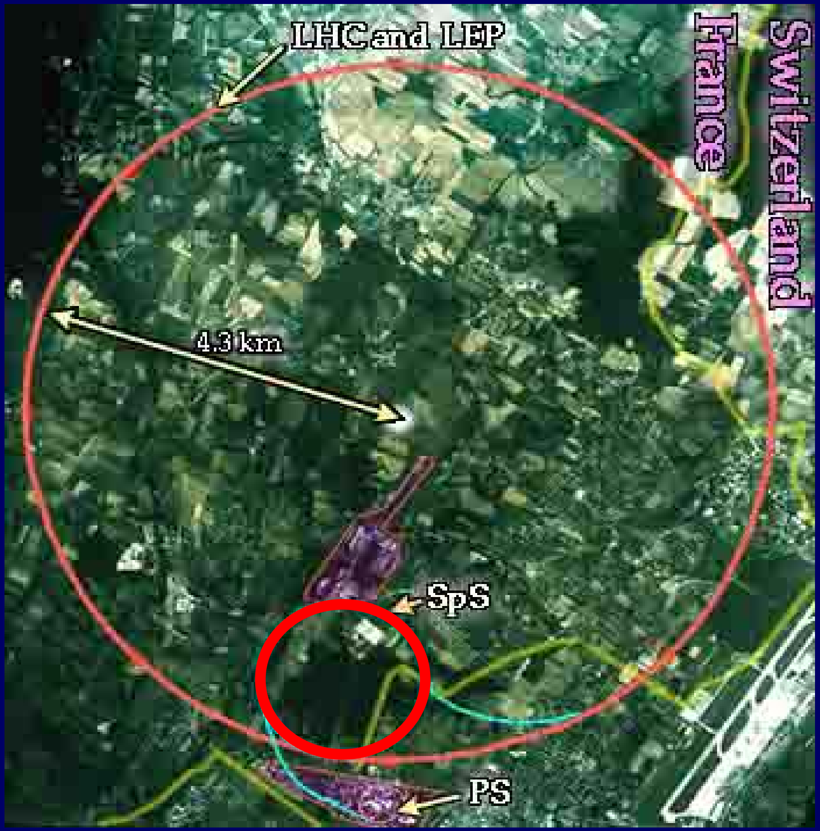
Lepton pair data from FNAL in intermediate-mass region (IMR) (*Branson et al., PRL 1977*)



E.Shuryak, Phys.Lett.B ‘79
thermal radiation from ‘Quark-gluon plasma’

Unsuitable data, but milestones in theoretical interpretation

Nuclear-collision experiments at the CERN SPS



first generation
1984 – 1987
HELIOS / NA34-2
NA38

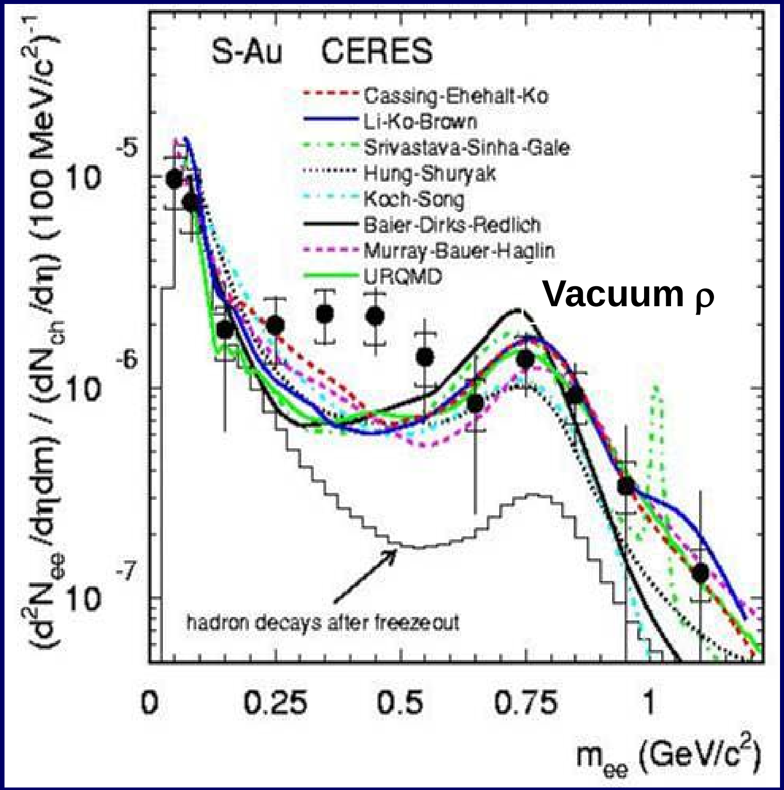
second generation
1988 – 2000
CERES/NA45
HELIOS / NA34-3
NA38/NA50

third generation
2002 – 2004
NA60

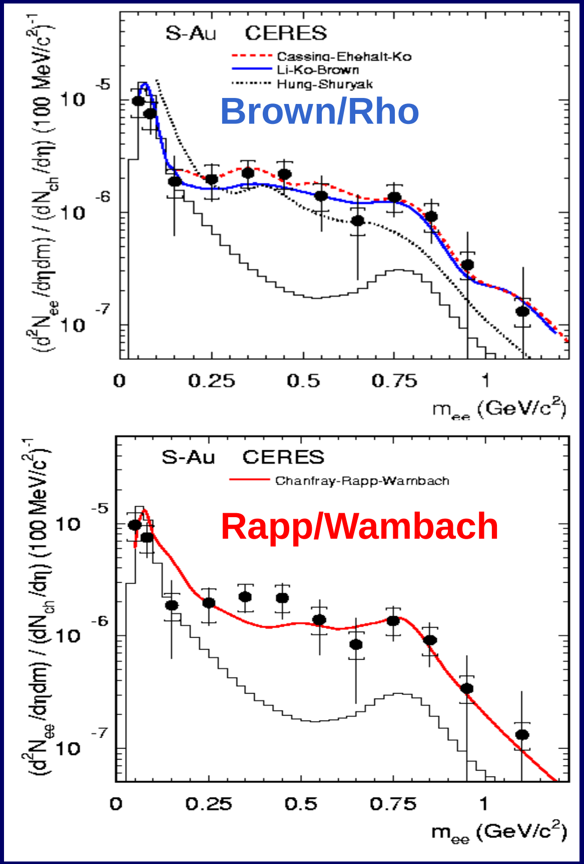
RHIC experiments (PHENIX,STAR) still evolving, after 10 years
LHC experiments (ALICE,ATLAS,CMS) just started

LMR: CERES/NA45 results for S-Au

Phys.Rev.Lett.75 (1995)



First clear sign of new physics in LMR



strong excess of dileptons above meson decays

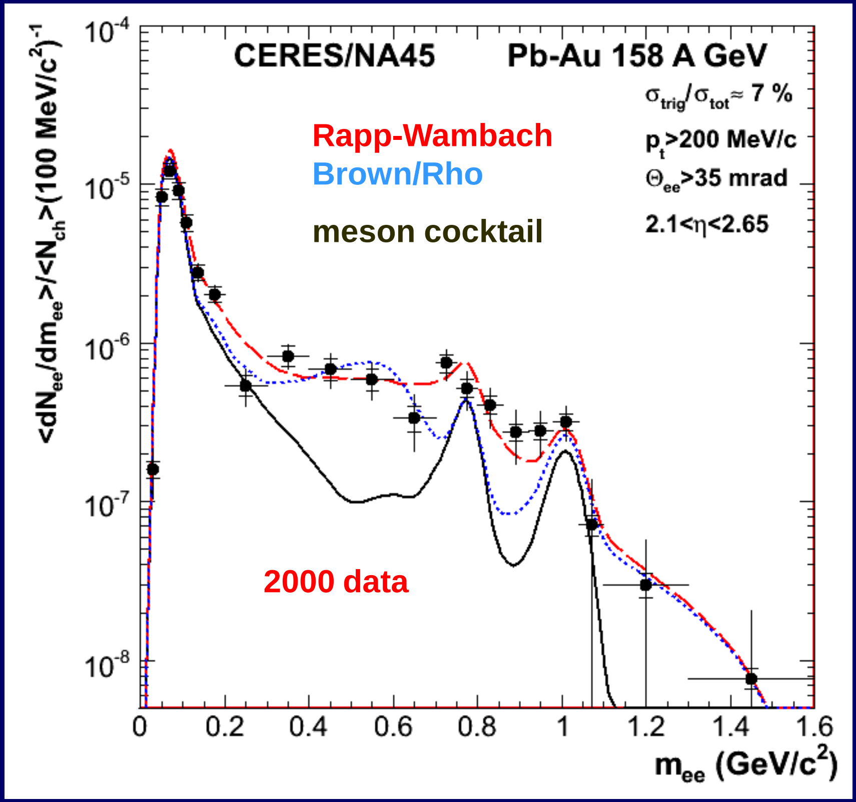
enormous boost to theory (~ 500 citations)

surviving interpretation: $\pi^+\pi^- \rightarrow \rho^* \rightarrow e^+e^-$, but in-medium effects required

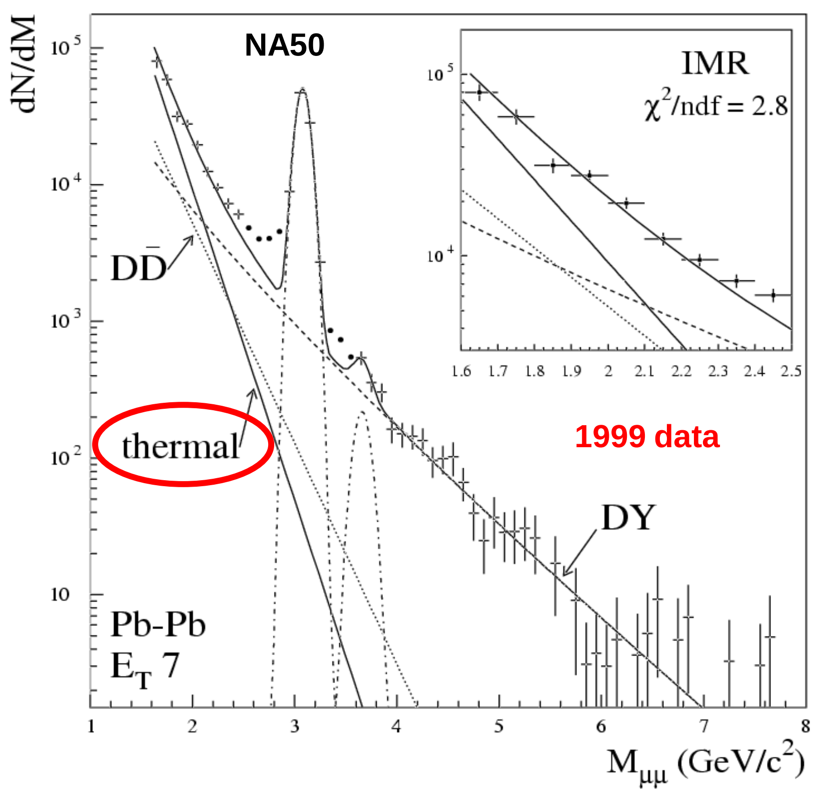
ambiguity : mass shift and broadening indistinguishable

Further SPS results on excess dileptons

LMR: NA45/CERES; PLB (2008)



IMR: NA50, EPJC 2000

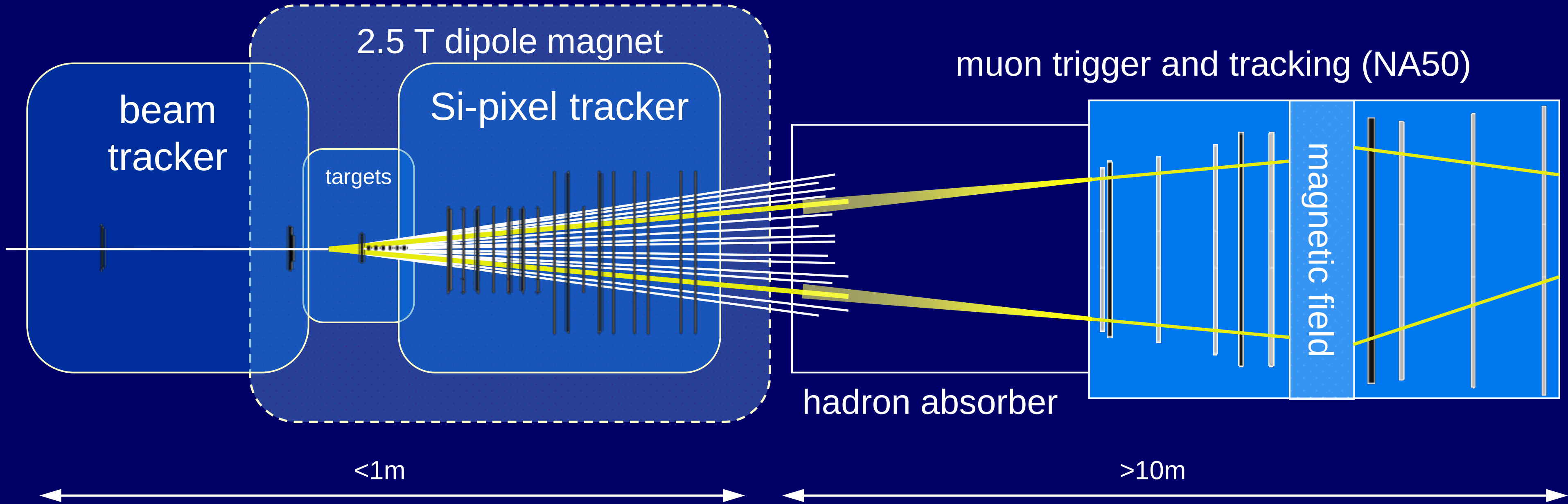


statistical accuracy and resolution remained insufficient to determine in-medium spectral properties of the ρ

excess dileptons also in the IMR but experimental ambiguity: prompt source or open charm?

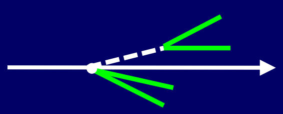
NA60

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

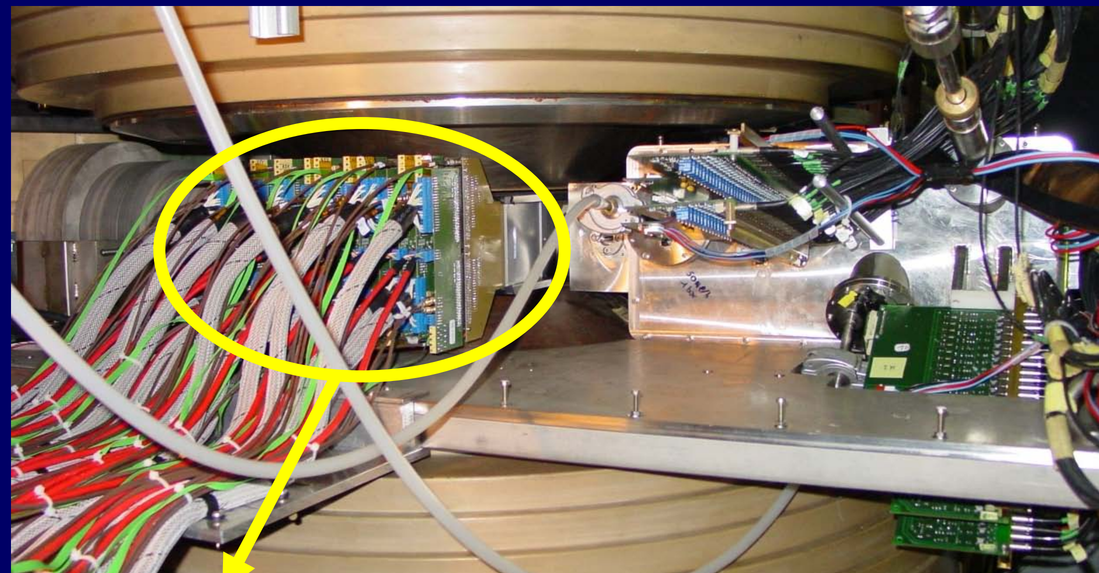
- Dimuon coverage extended to low p_T

Radiation-hard silicon pixel detectors (LHC development)

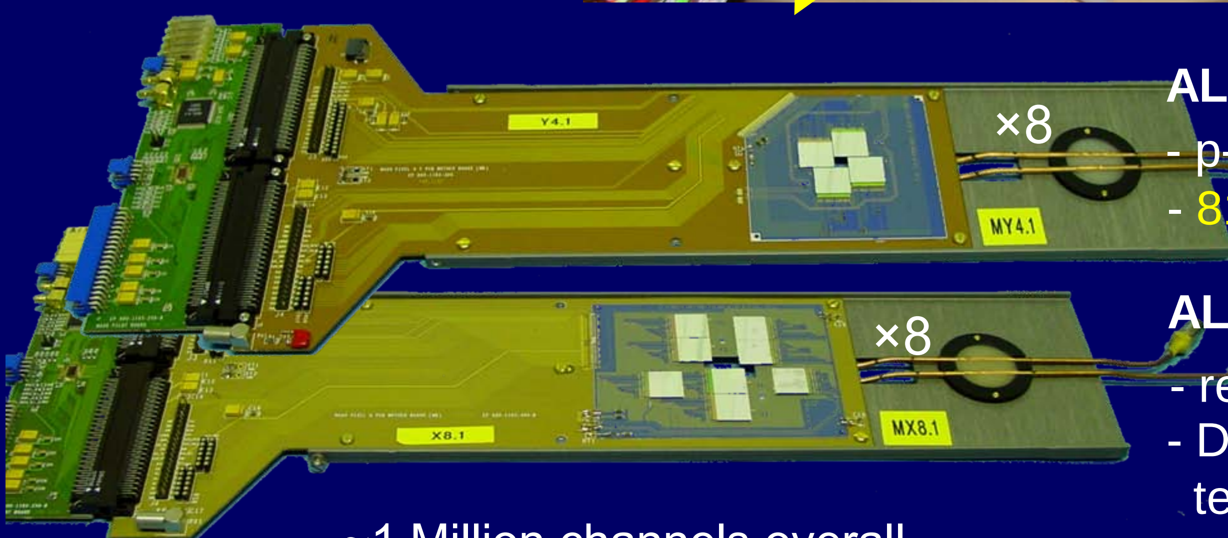
- High luminosity of dimuon experiments maintained

The Silicon Pixel Telescope

Beam tracker, target and silicon pixel telescope in the dipole magnet gap in front of the hadron absorber



pixel-detector planes



ALICE pixel sensors

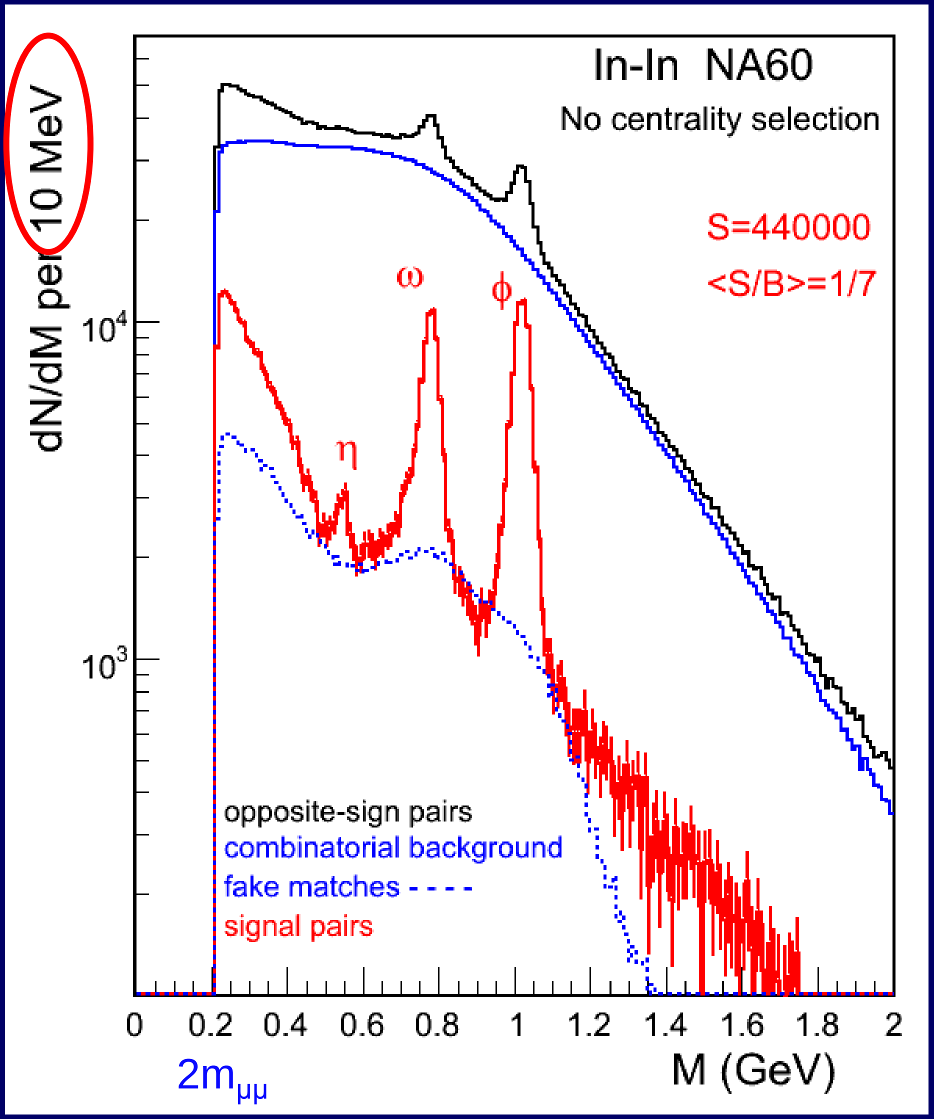
- p-on-n silicon, 15 kΩcm
- 8192 pixel cells of 50×425 μm²

ALICE1LHCb readout chips

- readout system with 10 MHz
- DeepSubMicron radiation-hard, tested up to 12 Mrad

~1 Million channels overall

Data sample for 158A GeV In-In



subtraction of

- combinatorial background
- fake matches between the two spectrometers

net sample:
440 000 events

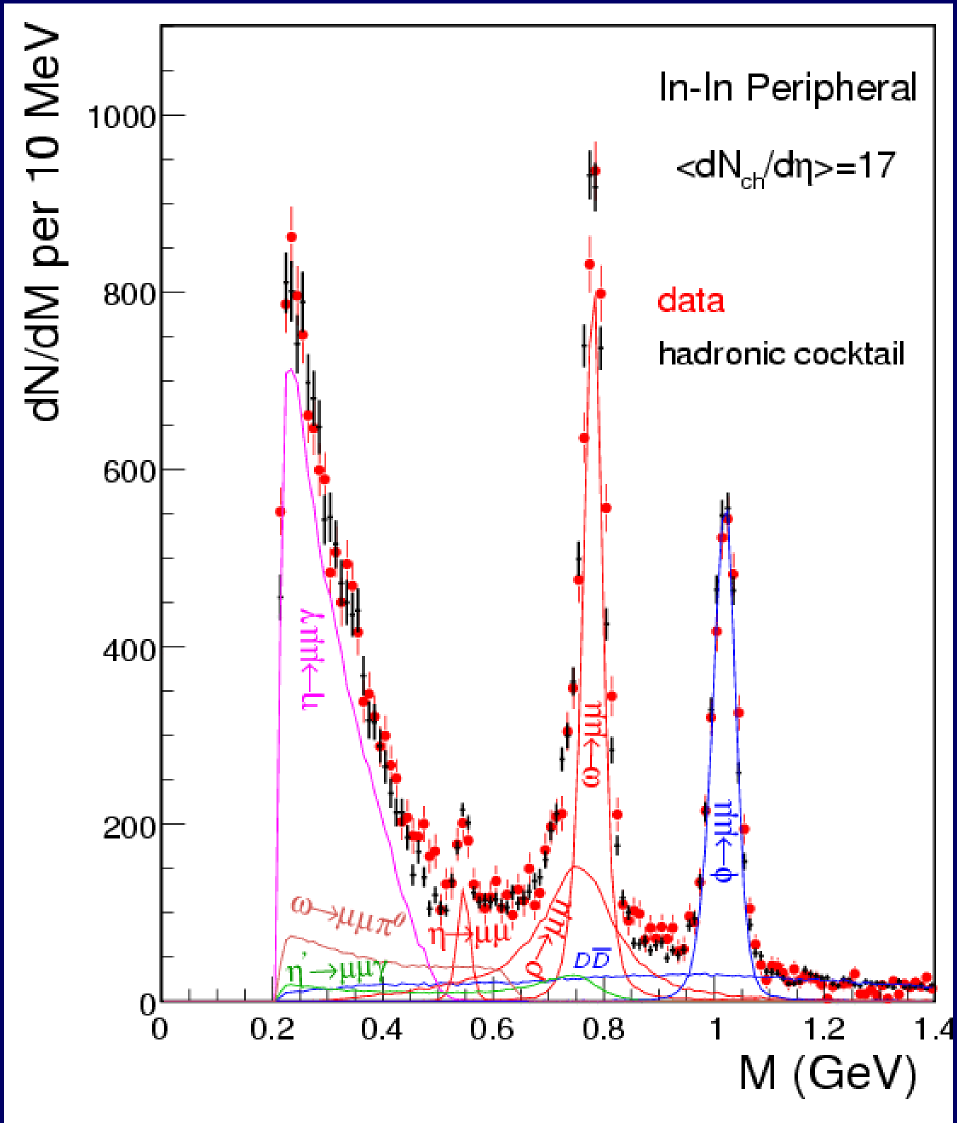
for the first time, η, ω, ϕ clearly visible in dilepton channel in AA

mass resolution:
20 MeV at the ω position

Progress over the past:

statistics: factor>1000
resolution: factor 2-5

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, PDG (2011)

semileptonic decays:

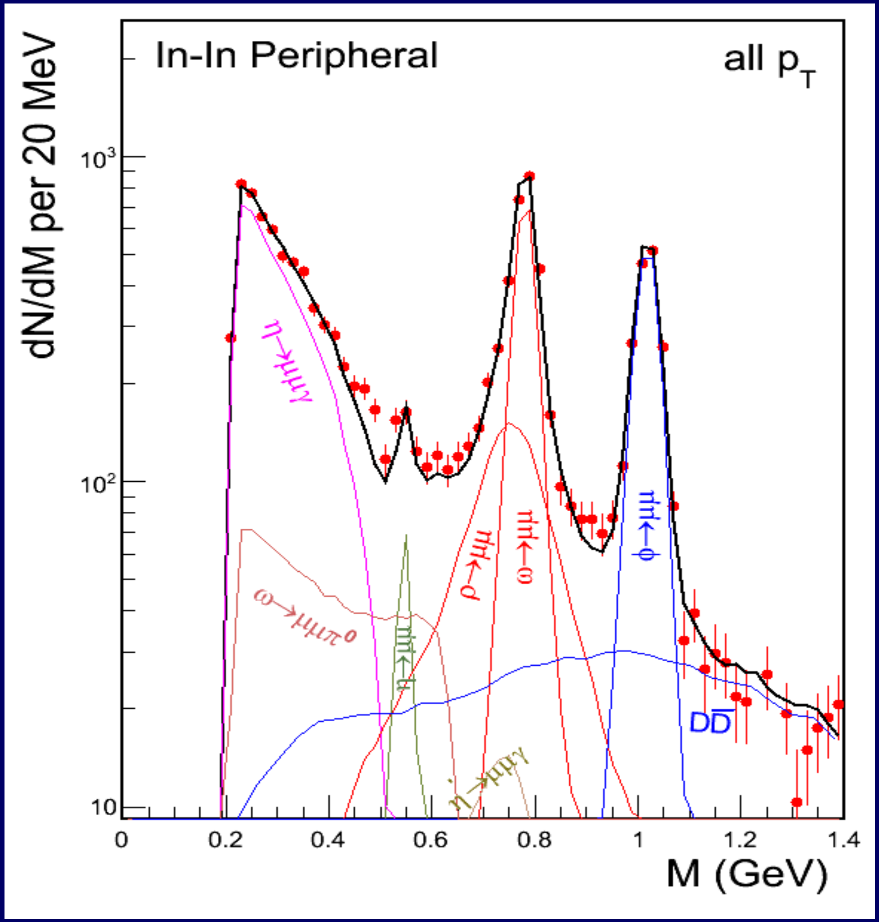
uncorr. $\mu^+\mu^-$ from $D\bar{D}$

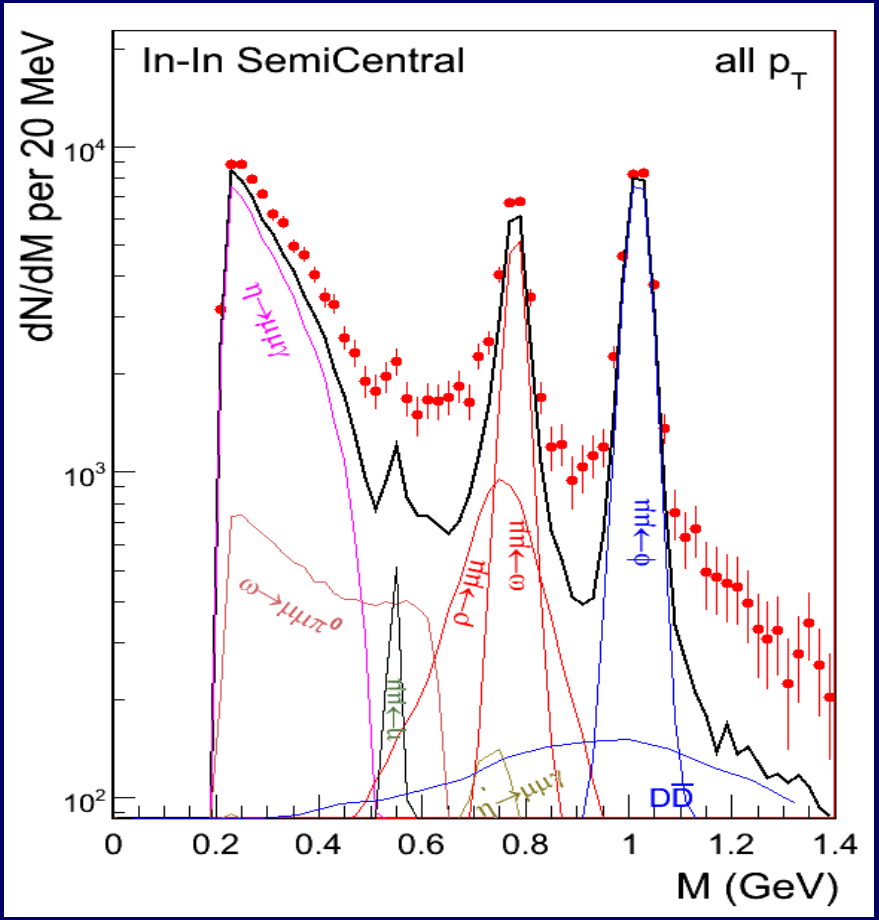
fit with free parameters:

η/ω, ρ/ω, ϕ/ω, $D\bar{D}$

perfect description of the data

Moving to higher centralities



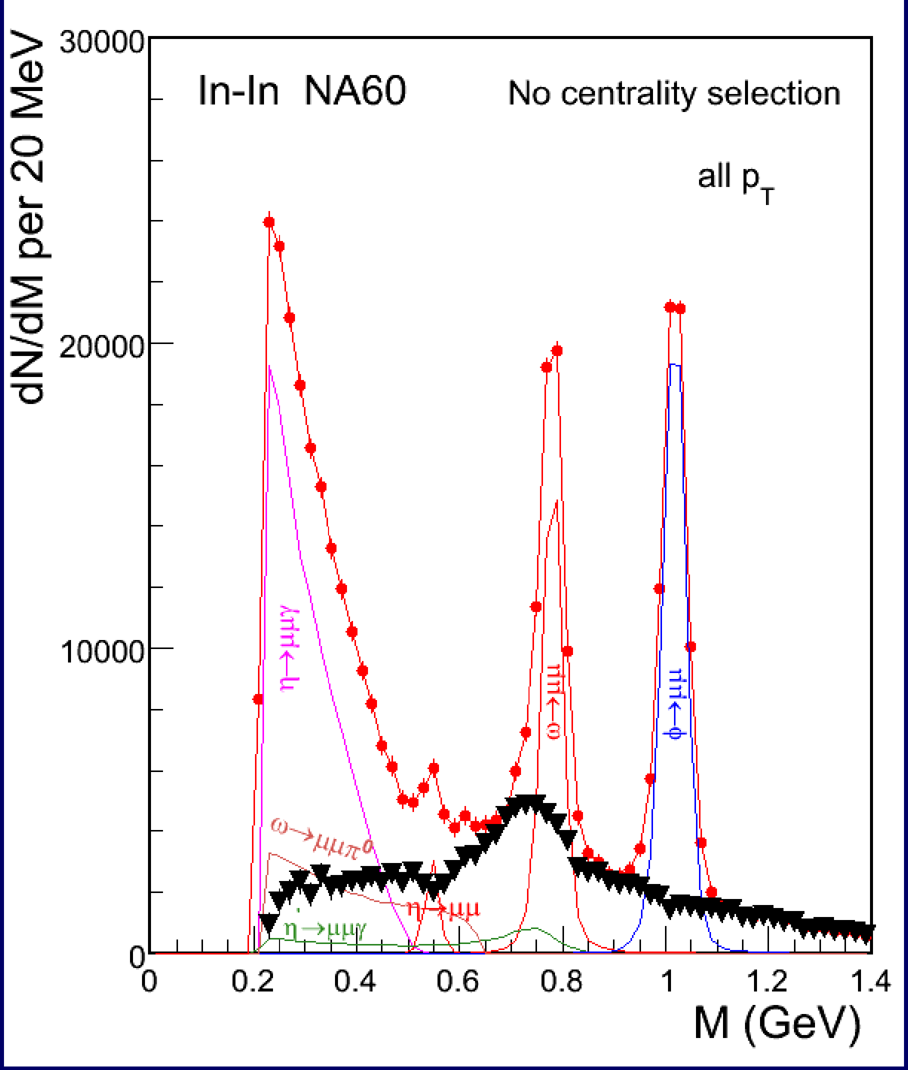


<u>Peripheral data</u>
well described by meson decay 'cocktail' (η, η', ρ, ω, ϕ) and $D\bar{D}$

<u>More central data</u>
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

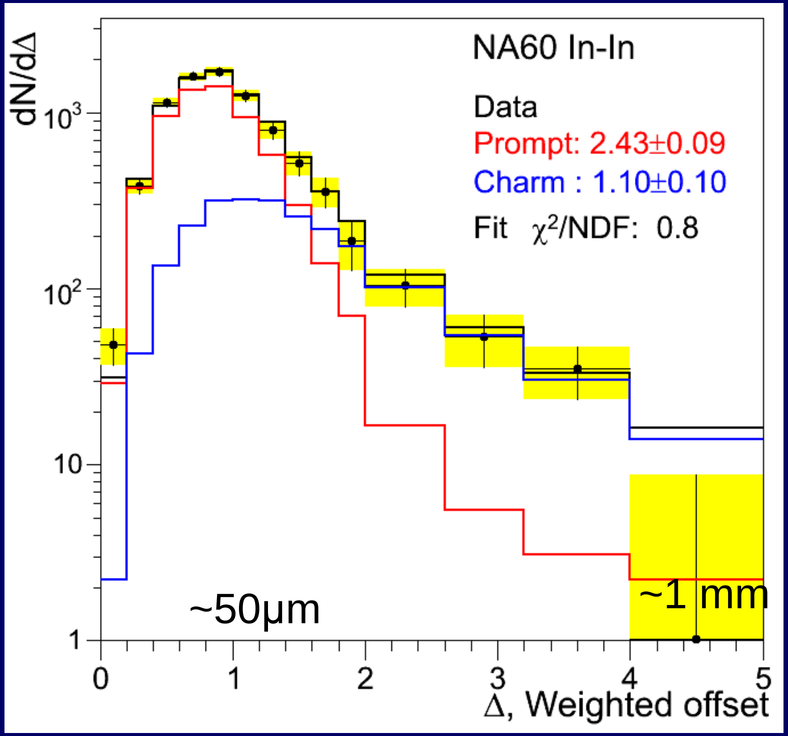
accuracy 2-3%, but results robust to mistakes even at the 10% level

keep information on subtracted hadrons and process separately

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

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

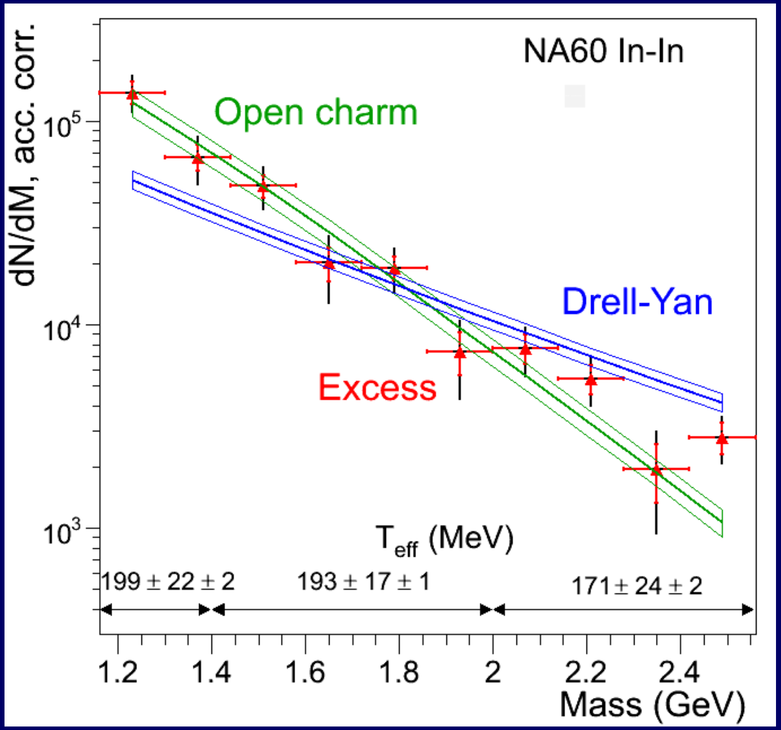
measurement of muon offsets $\Delta\mu$: distance between interaction vertex and track impact point



charm not enhanced

excess prompt; 2.4 x DY

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



excess similar to open charm

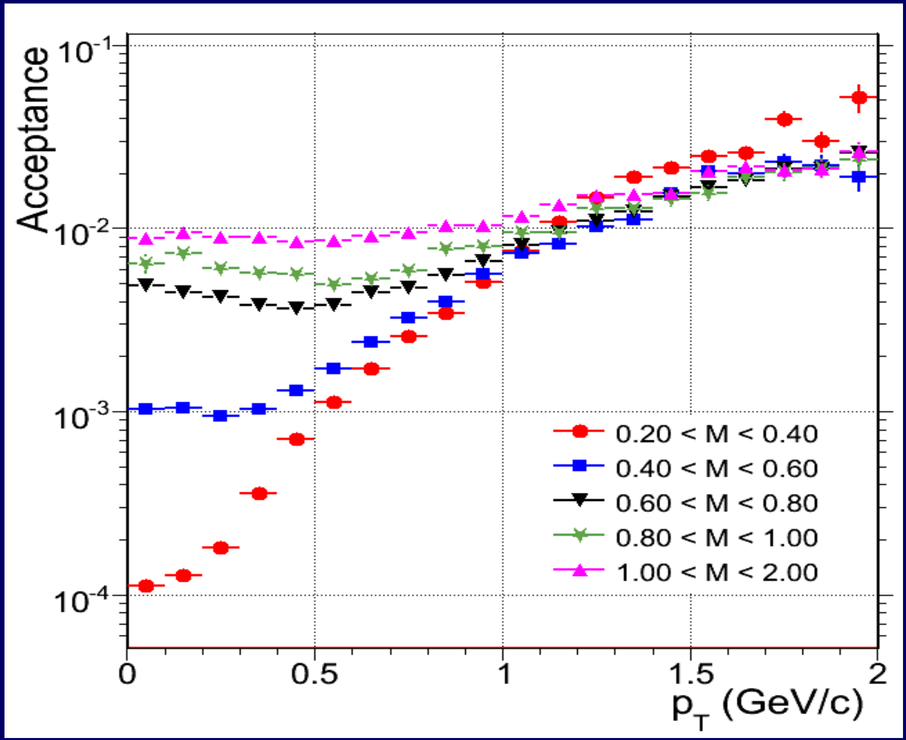
steeper than Drell-Yan

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

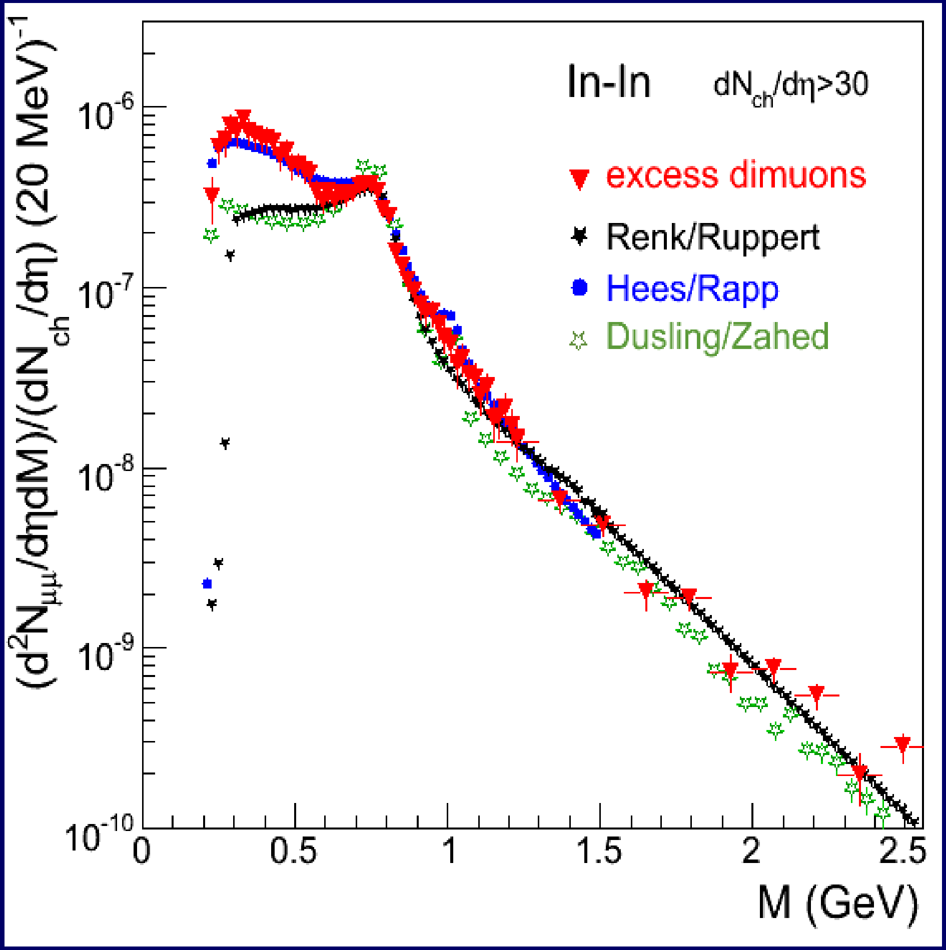
acceptance vs. M, p_T, y, and cosΘ understood to within <10%, based on a detailed study of the peripheral data



Thermal Radiation

Inclusive excess mass spectrum up to 2.6 GeV

Eur. Phys. J. C 59 (2009) 607;
CERN Courier 11/2009



all known sources subtracted

integrated over p_T

fully corrected for acceptance

absolutely normalized to $dN_{ch}/d\eta$

Thermal radiation?

M<1 GeV

Modulation around the ρ

Mass shift, broadening, both?

M>1 GeV

Exponential fall-off over 3 orders

Hadronic, partonic, mixed source?

Or duality?

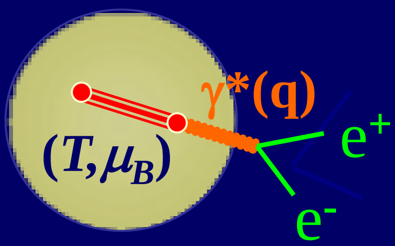
Let the data themselves give the answer…

Are the observed excess dimuons thermal?

Required features:

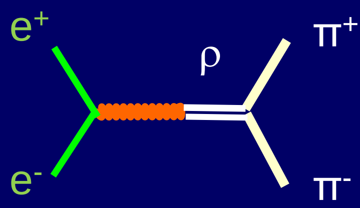
- Planck-like exponential shape of mass spectra (for flat spectral function)
- exponential transverse m_T spectra, $m_T = (p_T^2 + M^2)^{1/2}$
- absence of any polarization in the dilepton production
- agreement between data and thermal models in yields and spectral shapes

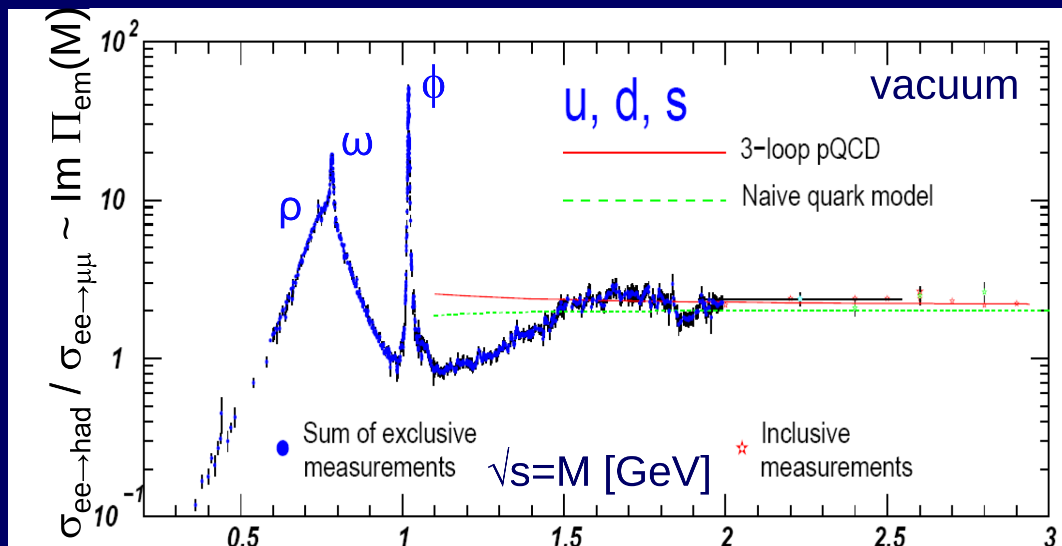
Dilepton Rate in a strongly interacting medium

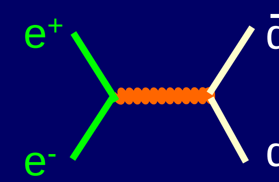


$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T)\ \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

photon selfenergy







in-medium spectral functions

invoking VMD

$\mathrm{Im}\Pi_{em} \sim [\mathrm{Im}\,D_\rho + \mathrm{Im}\,D_\omega /10 + \mathrm{Im}\,D_\phi /5]$

flat spectral function

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

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

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

quark basis $dN_{\mu\mu}/dM \propto M^{3/2} \times \langle \exp(-M/T) \rangle$ ‘Planck-like’

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. al1993	→	↗
Pisarski 1995	↗	↗
Chanfray, Rapp, Wambach 1996 ff	→	↗
Weise et al. 1996 ff	→	↗

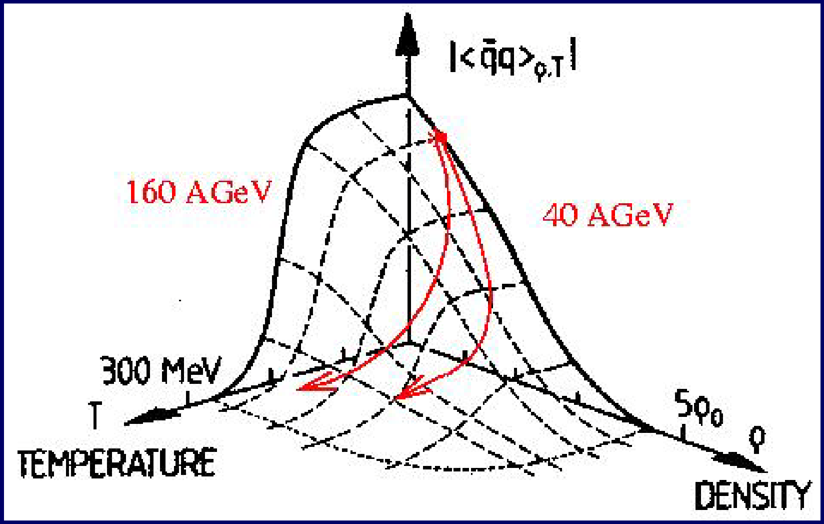
very confusing, experimental data crucial

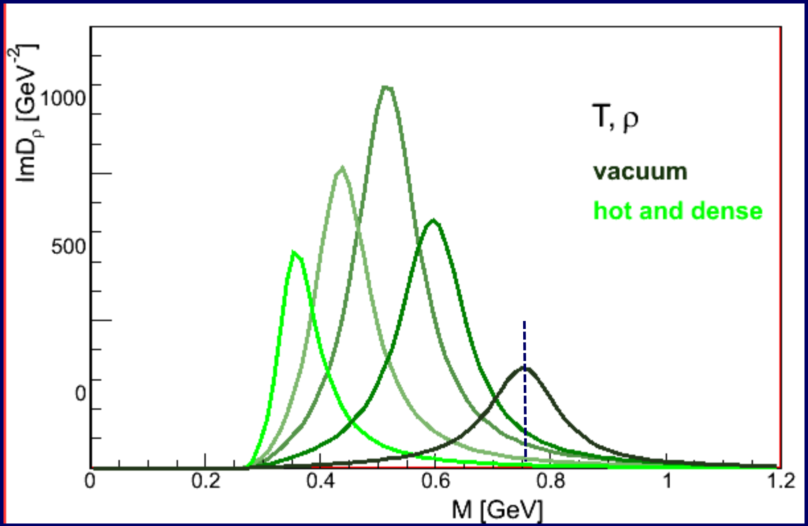
ρ spectral function in hot and dense hadronic matter (I)

Dropping mass scenario Brown/Rho et al., Hatsuda/Lee

explicit connection between hadron masses and chiral condensate

universal scaling law $m_\rho^* / m_\rho^0 = \langle \bar{q}q \rangle_{\rho,T}^{1/2} \Big/ \langle \bar{q}q \rangle_0^{1/2}$





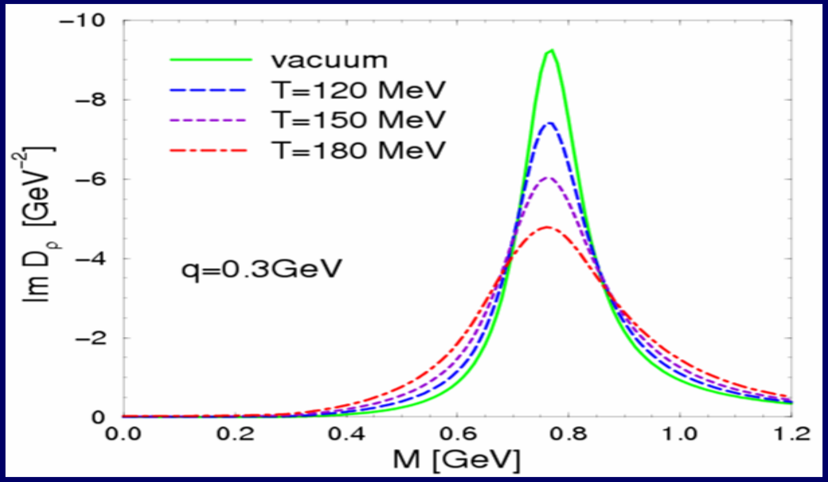
$$\langle \bar{q}q \rangle_{\rho,T}^{1/2} \Big/ \langle \bar{q}q \rangle_0^{1/2} = (1 - C\frac{\rho}{\rho_0})(1 - (T/T_c^{\chi})^2)^{\alpha}$$

continuous evolution of pole mass with T and ρ ; broadening at fixed (T, ρ) ignored

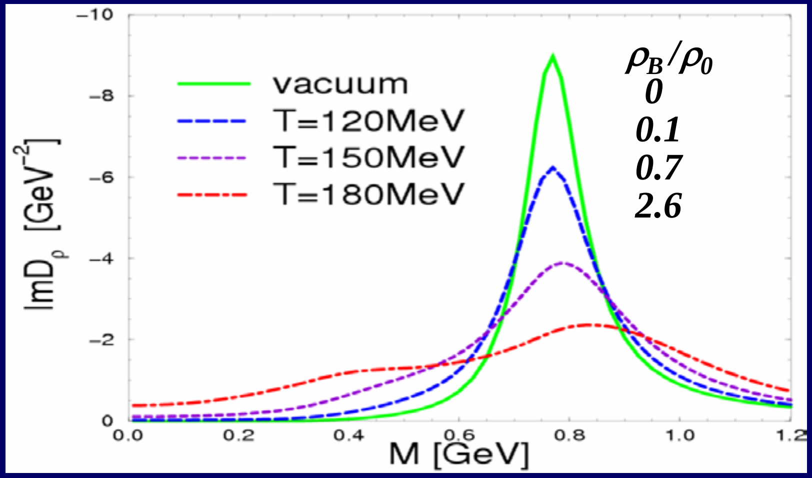
ρ spectral function in hot and dense hadronic matter (II)

Hadronic many-body approach   Rapp/Wambach et al., Weise et al.

hot matter



hot and baryon-rich matter



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

ρ is dressed with:

hot pions $\Sigma_{\rho\pi\pi}$,

baryons $\Sigma_{\rho B}$ (N,Δ ..)

mesons $\Sigma_{\rho M}$ (K,a_1..)

ρ 'melts' in hot and dense matter

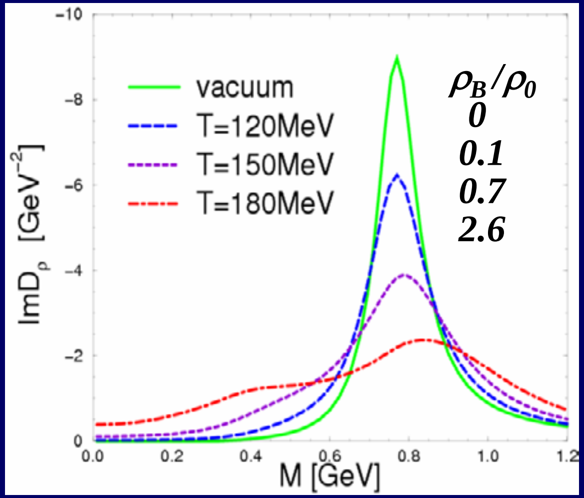
- pole position roughly unchanged
- broadening mostly through baryon interactions

Final mass spectrum

continuous emission of thermal radiation during life time of the expanding fireball → integration of rate equation over space-time and momenta required

example: broadening scenario

ρ spectral functions from hadronic many-body approach (Rapp et al.)



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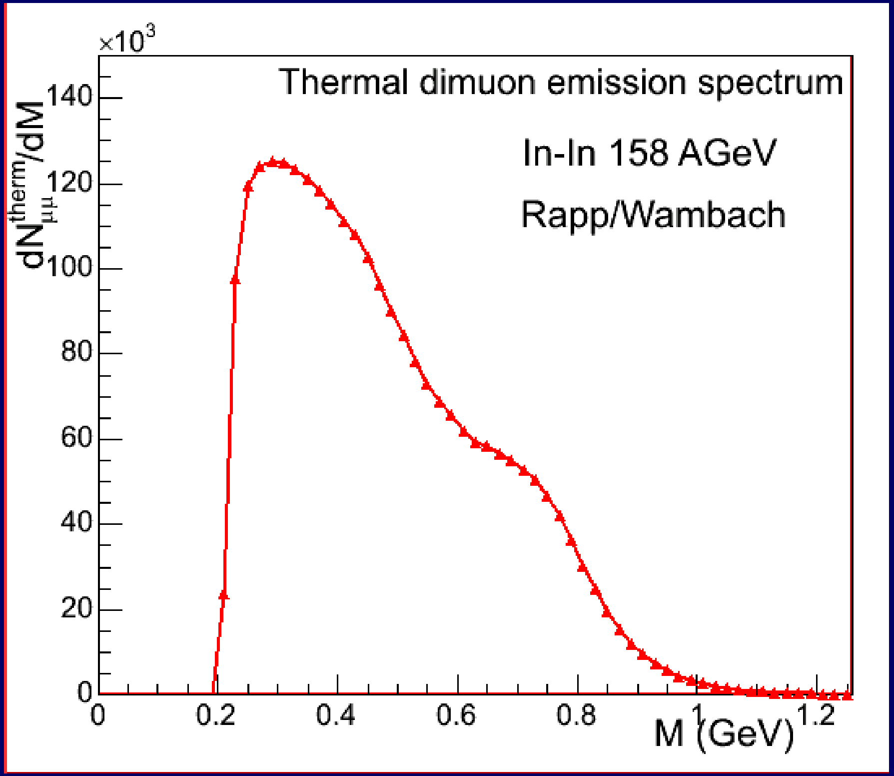


‘Unfolding’ the Rho Spectral Function

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

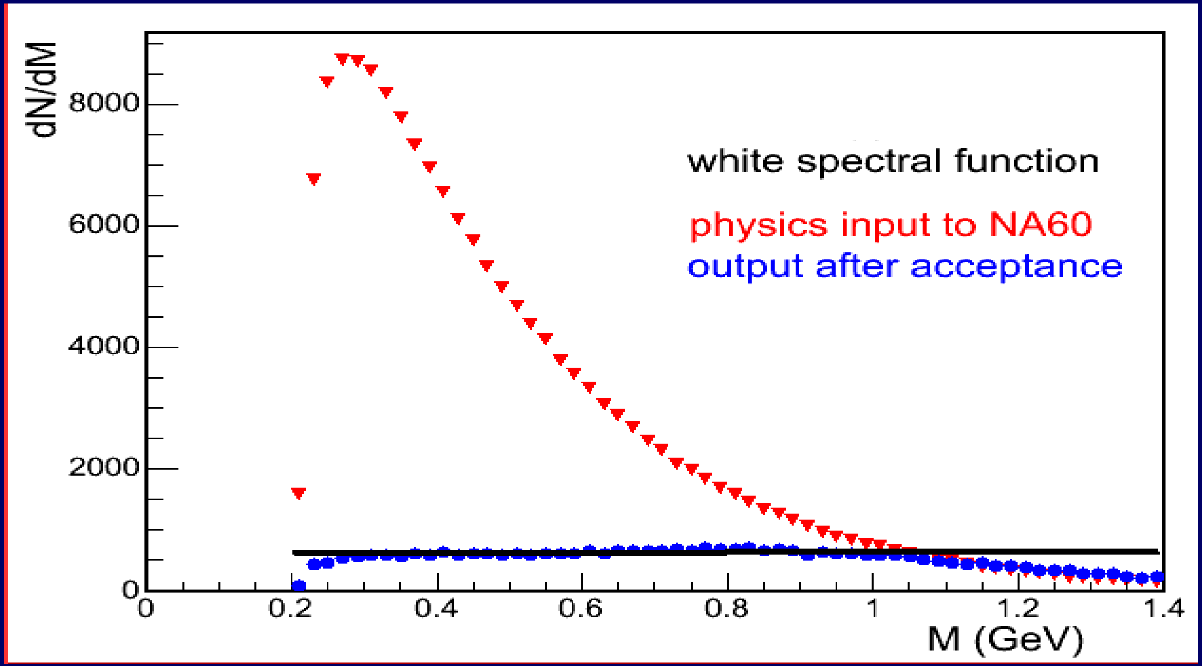
By pure chance

↓

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

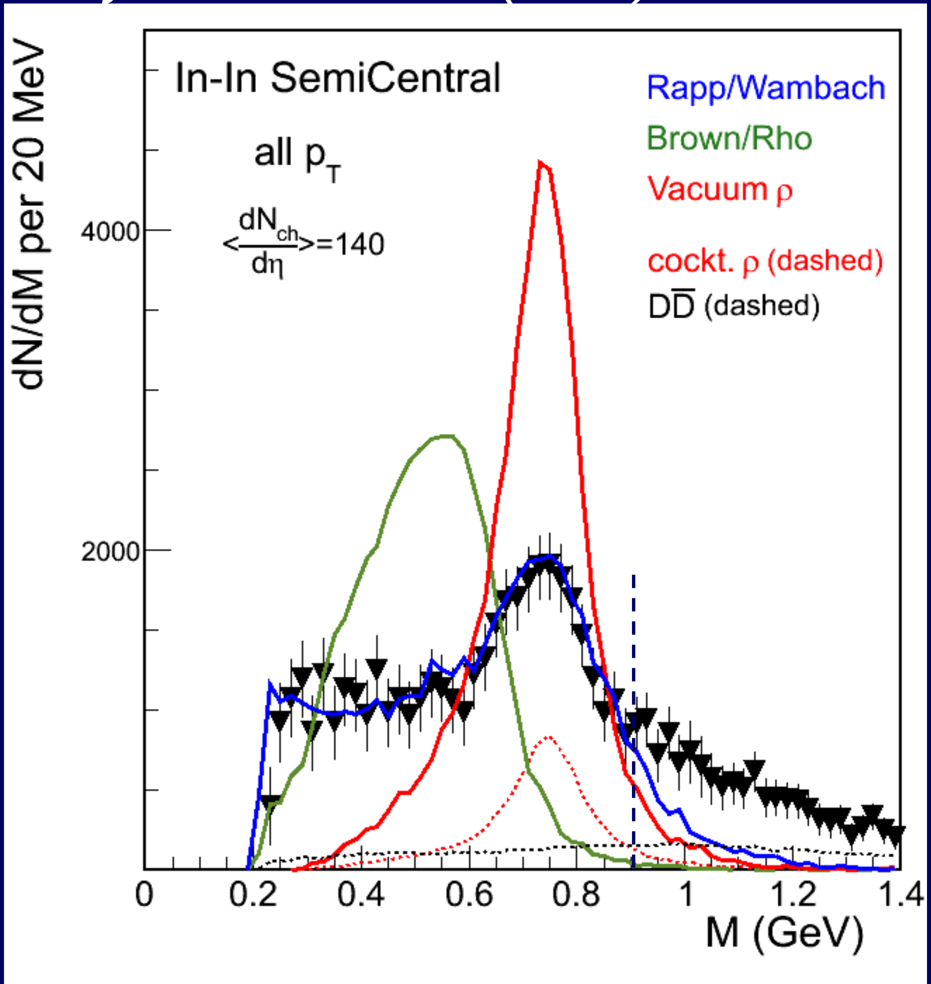
output:

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



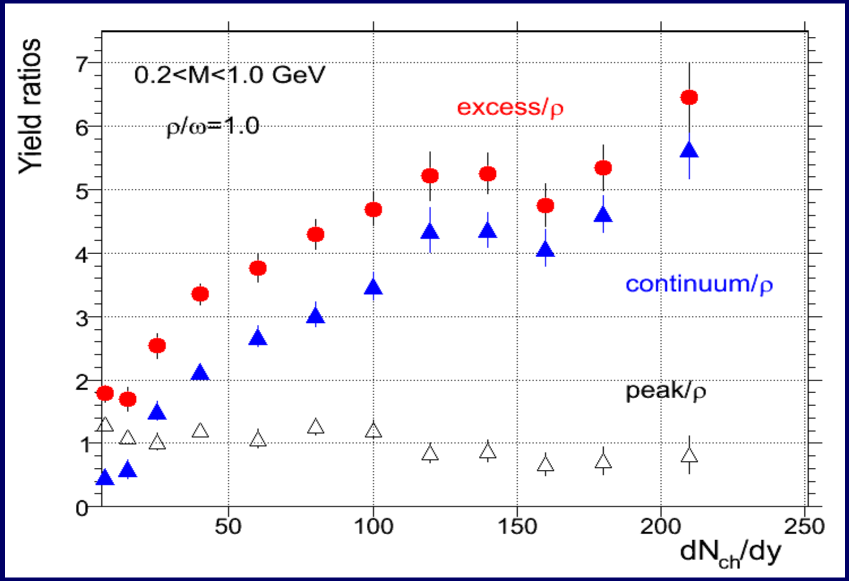
Predictions by Rapp (2003) for all scenarios

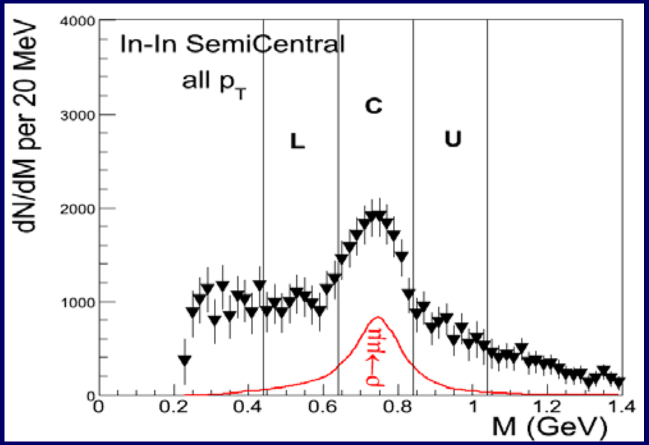
Theoretical yields normalized to data for M<0.9 GeV

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

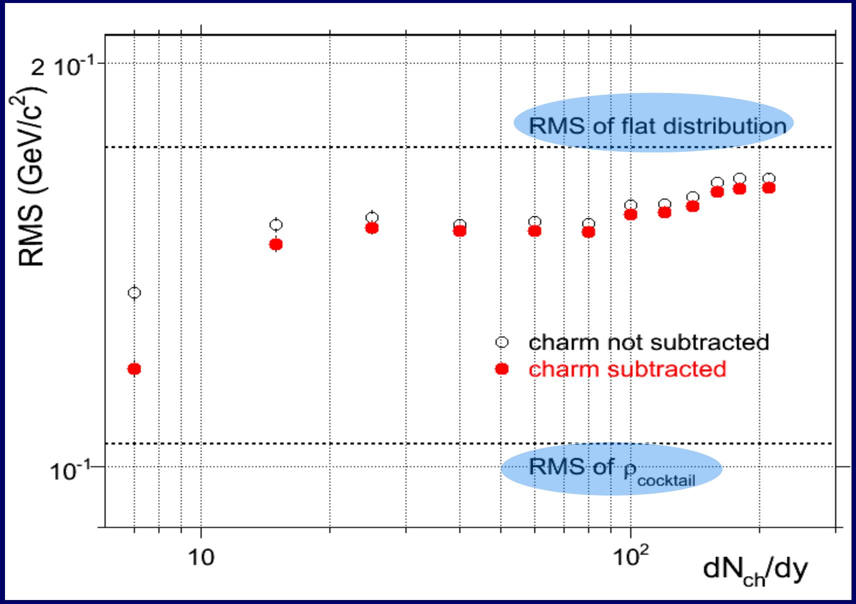
Only broadening of ρ (RW) observed, no mass shift (BR)

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 $\pi^+\pi^- \rightarrow \rho^* \rightarrow \mu^+\mu^-$

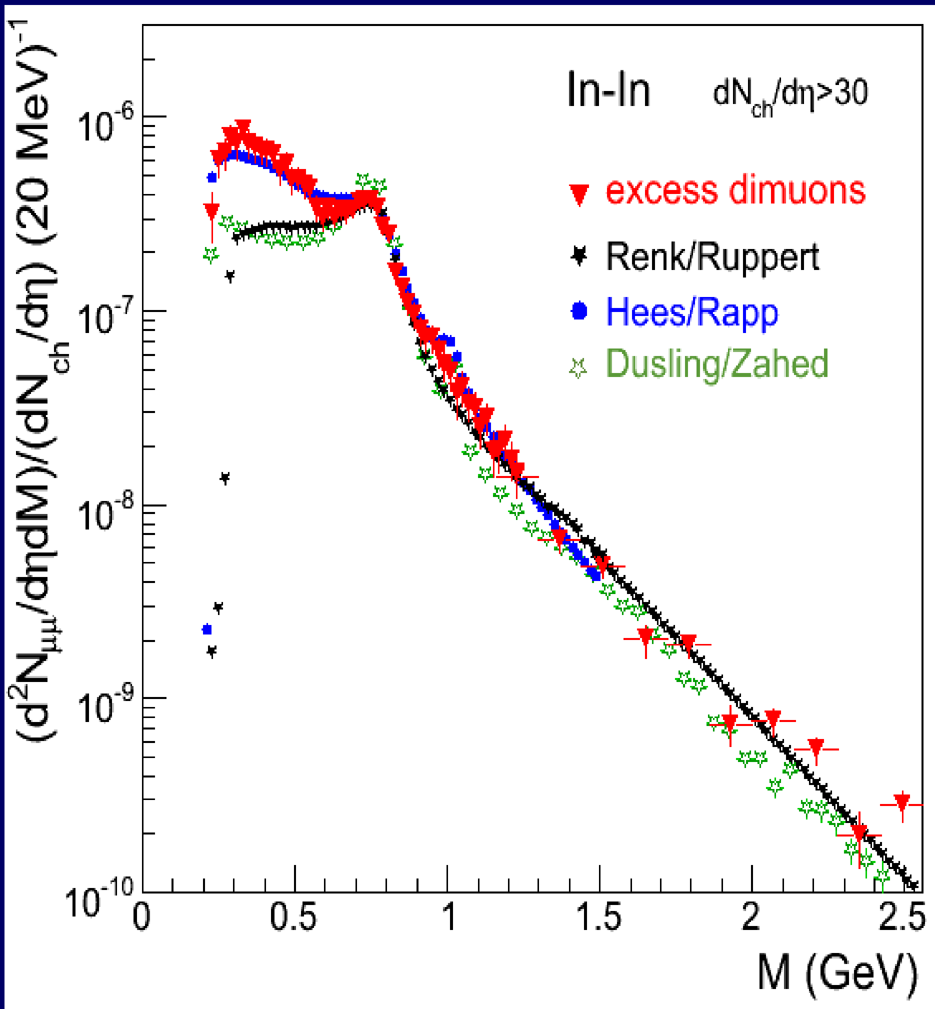
→ ‘ρ clock’

- near divergence of the width

→ ‘melting’ of the ρ

Conclusions from inclusive mass spectrum

Eur. Phys. J. C 59 (2009) 607
CERN Courier 11/ 2009



M<1 GeV

ρ dominates, 'melts' close to T_c

best described by H/R model

(baryon interactions strongest
→ FAIR, neutron stars)

explicit connection to chiral symmetry restoration???

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

‘Hubble’ expansion

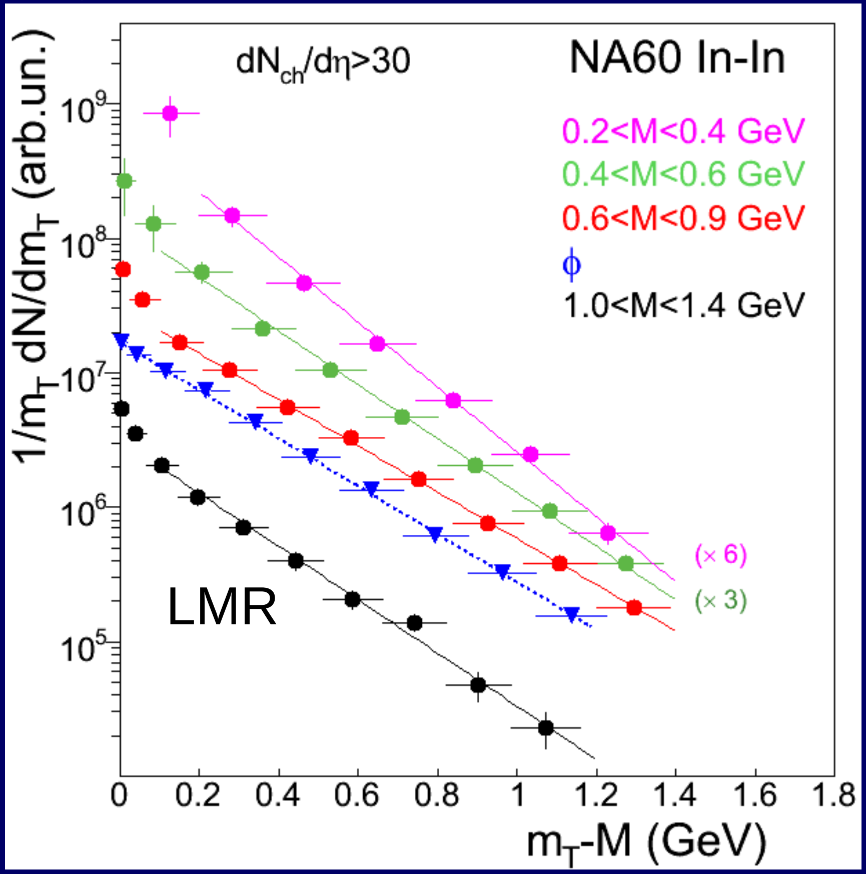
Radial Flow

Origin of dileptons

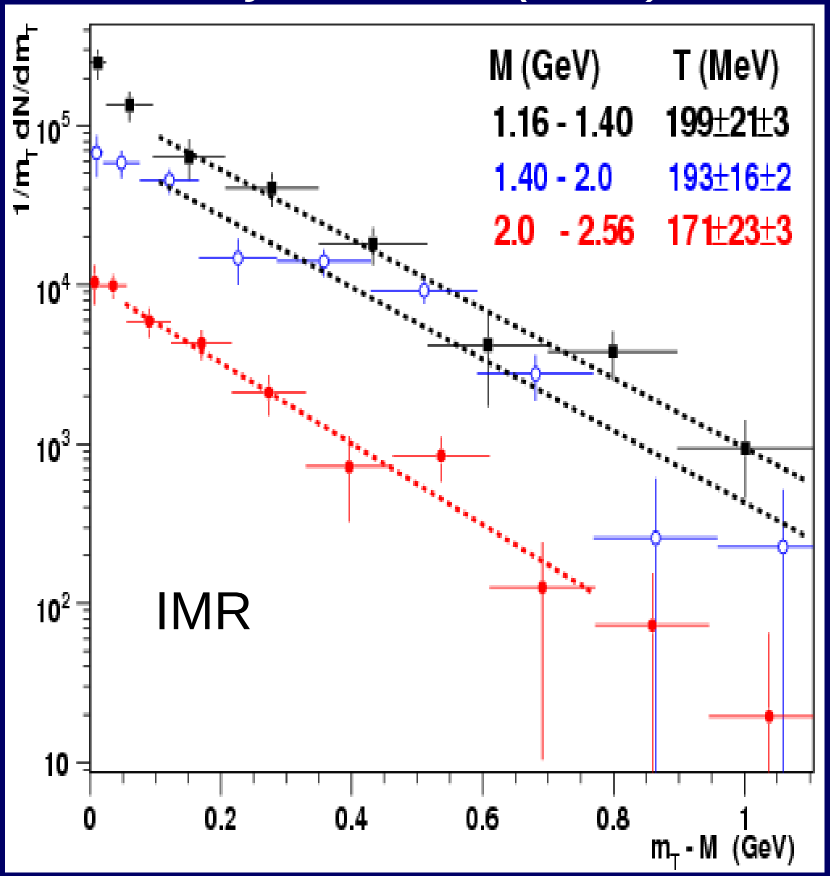
Transverse mass distributions of excess dimuons

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

Phys. Rev. Lett. 100 (2008) 022302



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

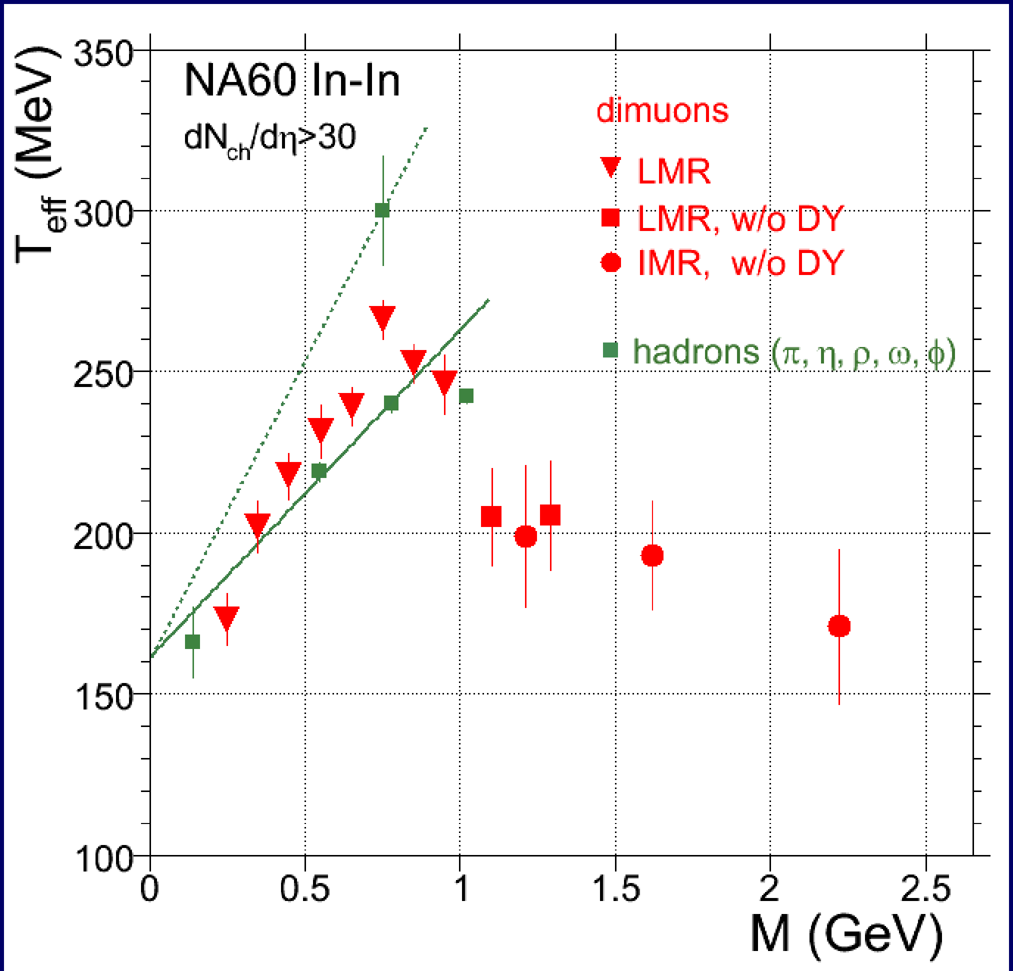


all m_T spectra exponential for m_T-M > 0.1 GeV; <0.1 GeV ??

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

'Effective Temperature' (T_{eff}) of excess dimuons

Phys. Rev. Lett. 100 (2008) 022302



M < 1GeV

strong, almost linear rise of T_{eff} with dimuon mass (not observed before)

linear rise also seen for hadrons (observed before by NA44, NA49, at RHIC)

M > 1GeV

sudden drop of T_{eff} by 50 MeV, followed by an almost flat plateau (not observed before)

A highly non-trivial result...

Understanding hadron transverse momentum spectra

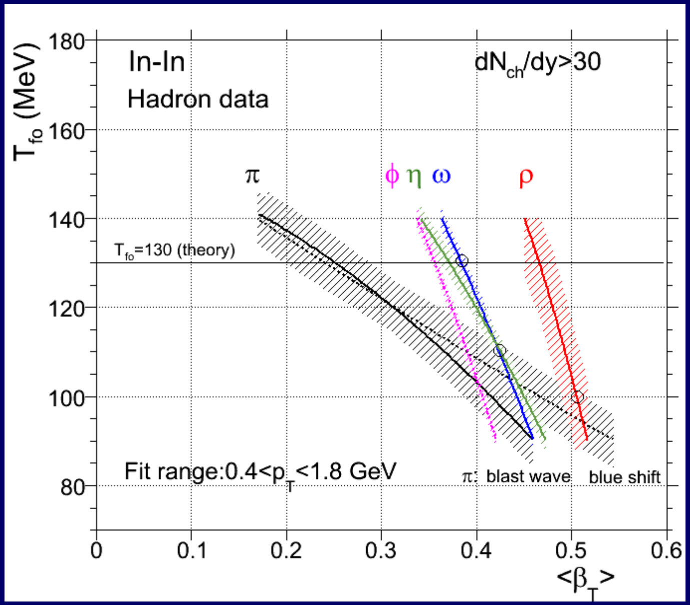
two components in p_T spectra: thermal and flow

$p_T = p_T^{th} + M\, v_T$ → $T_{eff} \sim T_f + M <v_T>^2$ → 'blue shift'

thermalization due to interactions

collective (flow) velocity v_T, ~ same for all particles → mass ordering

hadron p_T spectra: → determined at freeze-out



use of Blast wave code (simplified analysis)

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

crossing of the lines with π defines the (T_f, v_T) reached at freeze-out for the respective hadron

→ different hadrons have different coupling to pions (ρ maximal): hierarchy of freeze-out

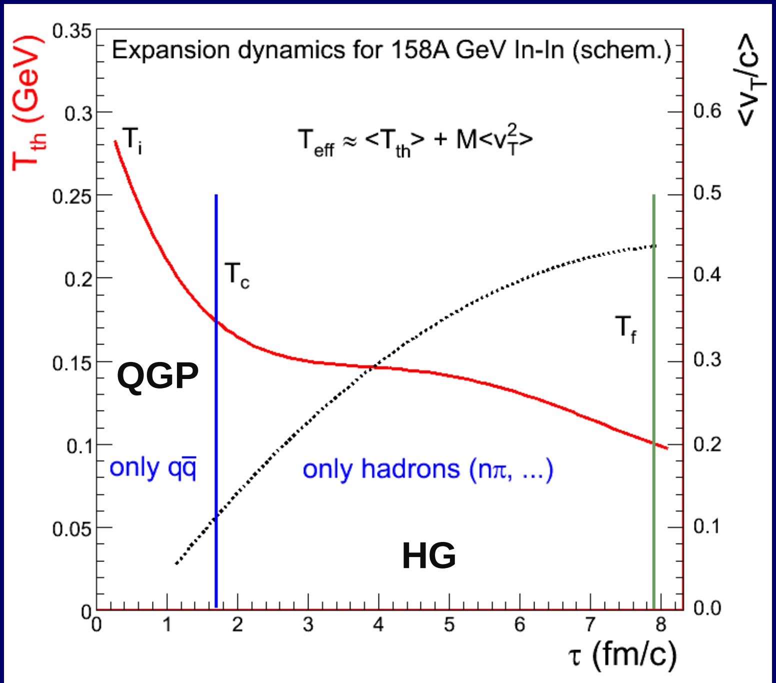
Disentanglement of temperature and flow; max v_T ~50% of speed of light

Understanding dilepton transverse momentum spectra

three contributions to p_T spectra

T - dependence of thermal distribution of "mother" hadrons/partons
M - dependent collective radial flow (v_T) of "mother" hadrons/partons
(p_T - dependence of spectral function; dispersion relation)

$$p_T = p_T^{th} + M\, v_T \quad \rightarrow \quad T_{eff} \sim T_f + M <v_T>^2$$



hadron p_T spectra:
determined at T_f (restricted information)

dilepton p_T spectra:
superposition from all fireball stages

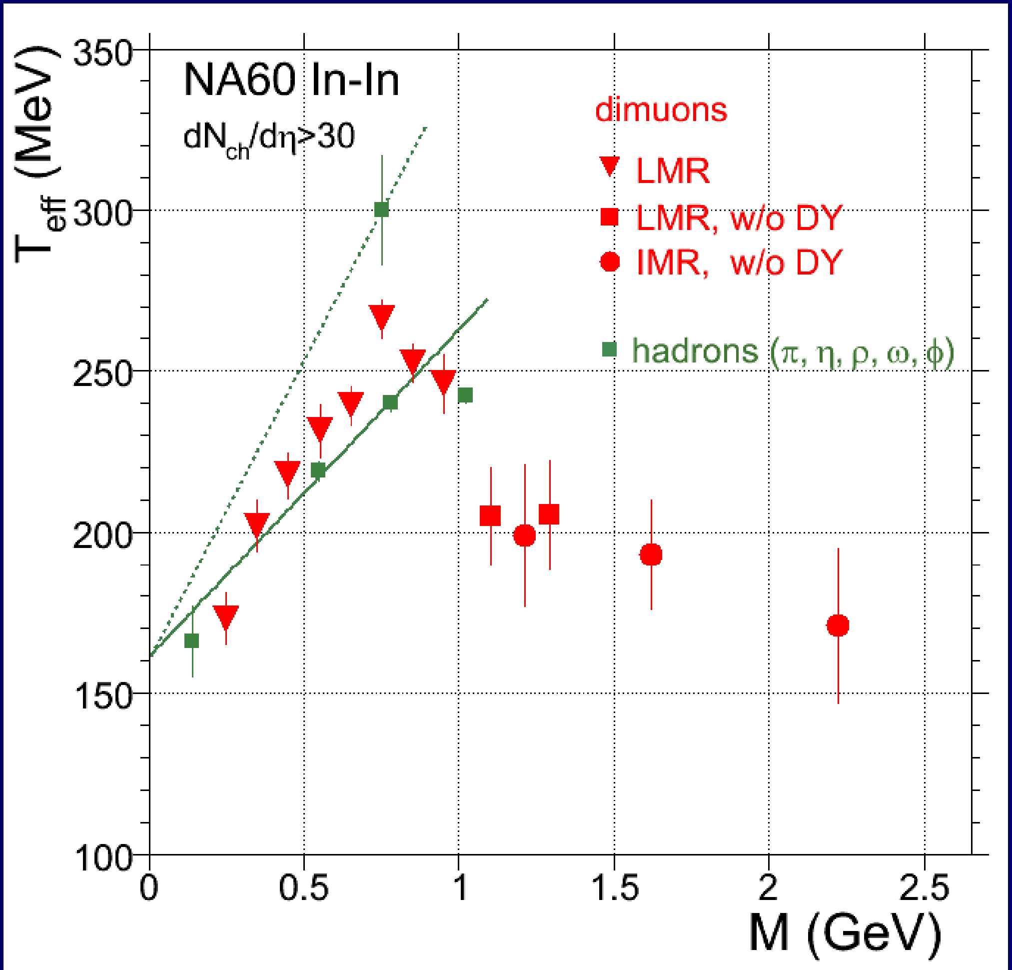
early emission: high T, low v_T
late emission: low T, high v_T

final spectra from space-time folding
over T-v_T history from $T_i \rightarrow T_f$
note: small flow in the QGP phase

→ handle on emission region, i.e. nature of emitting source

The rise and fall of radial flow of thermal dimuons

Phys. Rev. Lett. 100 (2008) 022302



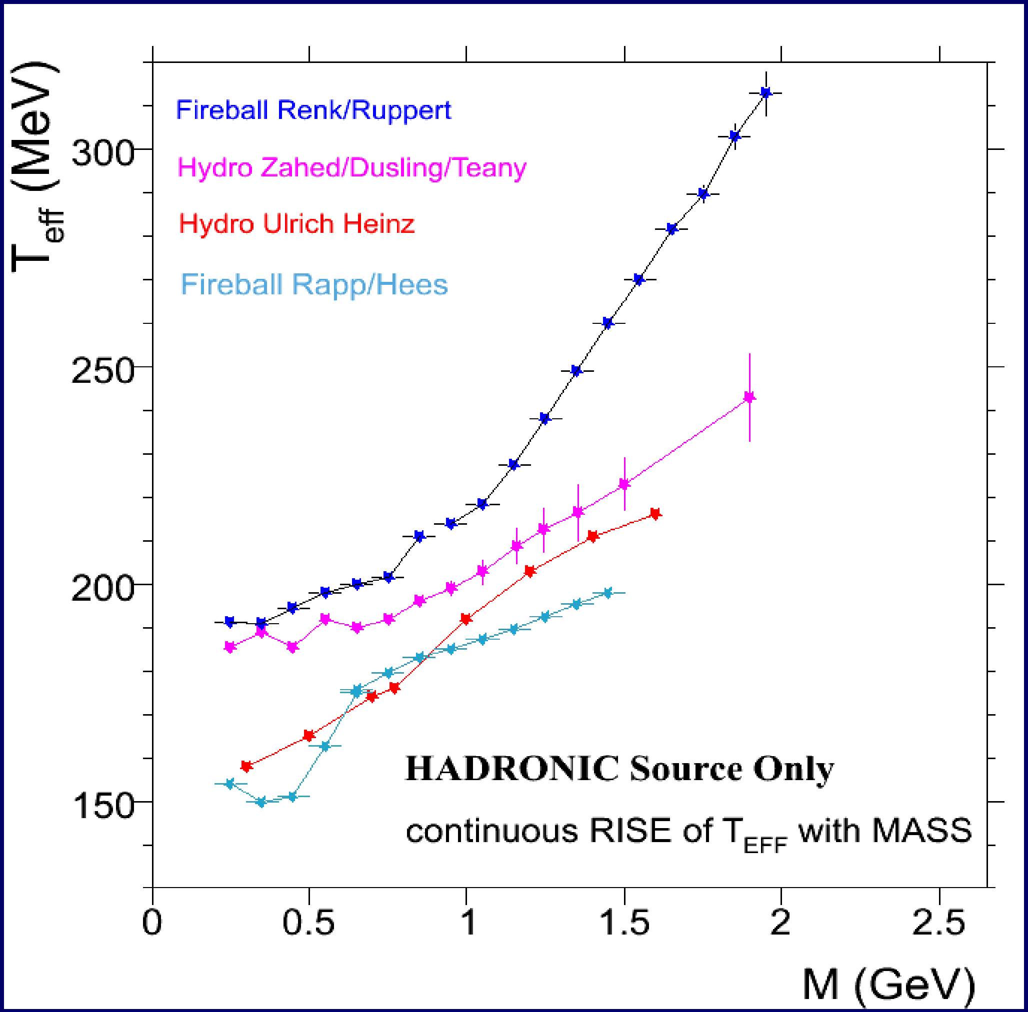
Strong rise of T_{eff} with dimuon mass, followed by a sudden drop for M>1 GeV

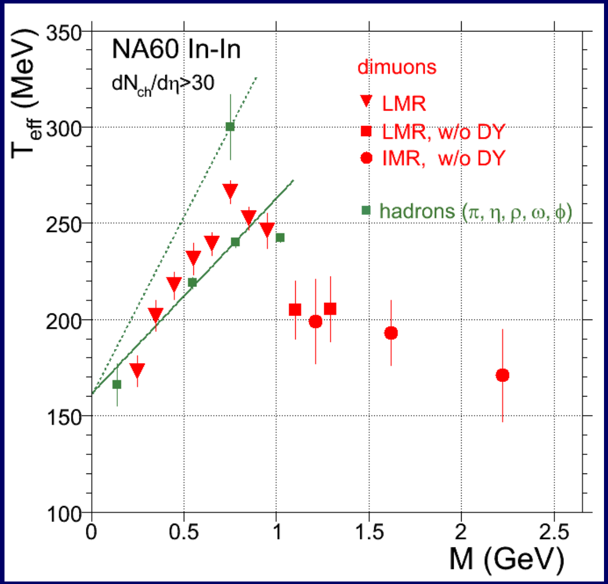
Rise consistent with radial flow of a hadronic source (here $\pi^+\pi^-\to\rho\to\mu^+\mu^-$), taking the freeze-out ρ as the reference (from a separate analysis of the ρ peak and the continuum)

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

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

Dominance of partons for M>1GeV: theoretical support



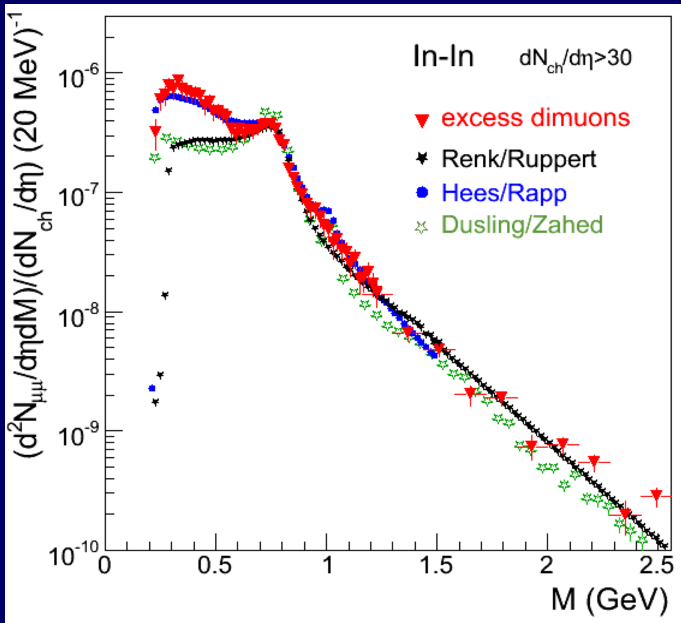


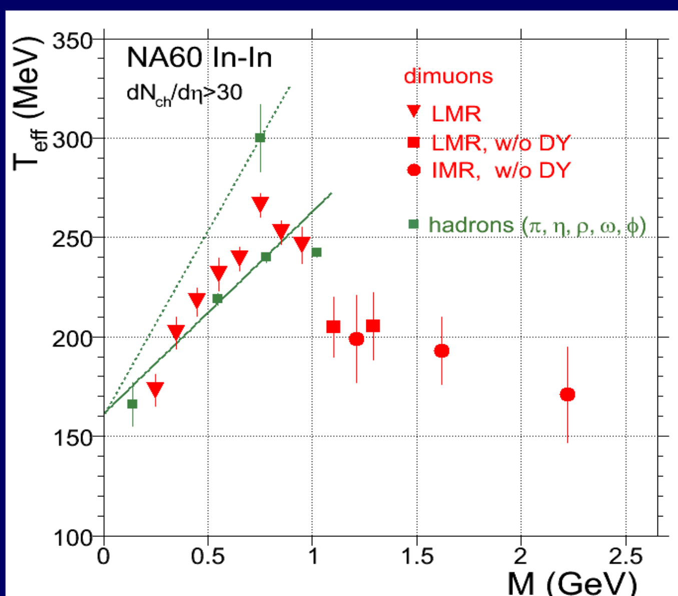
HADRONIC sources alone (2π +4π +$a_1\pi$ processes)

→ continuous rise of T_{eff} ; no discontinuity at M=1 GeV or at any other mass value

A dominantly hadronic source cannot produce a discontinuity

Combined conclusions from mass and p_T spectra





M <1 GeV

extrapolate T_{eff} to M=0 (zero flow)
apply relativistic correction for M<p_T

$\langle T_{th}\rangle$=130 – 140 < T_c=170 (MeV)

all consistent with hadronic phase

M >1 GeV

- T_{eff} independent of mass within errors

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

- same values within errors

$\langle T_{th}\rangle$ ~200 MeV > T_c=170 (MeV)

negligible flow → soft EoS above T_c

all consistent with partonic phase

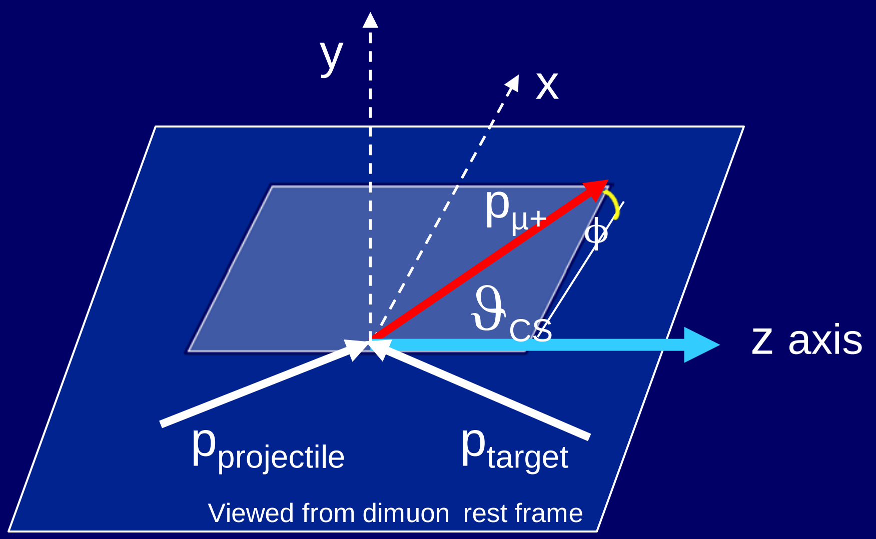
Angular distributions

Angular distributions

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

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)



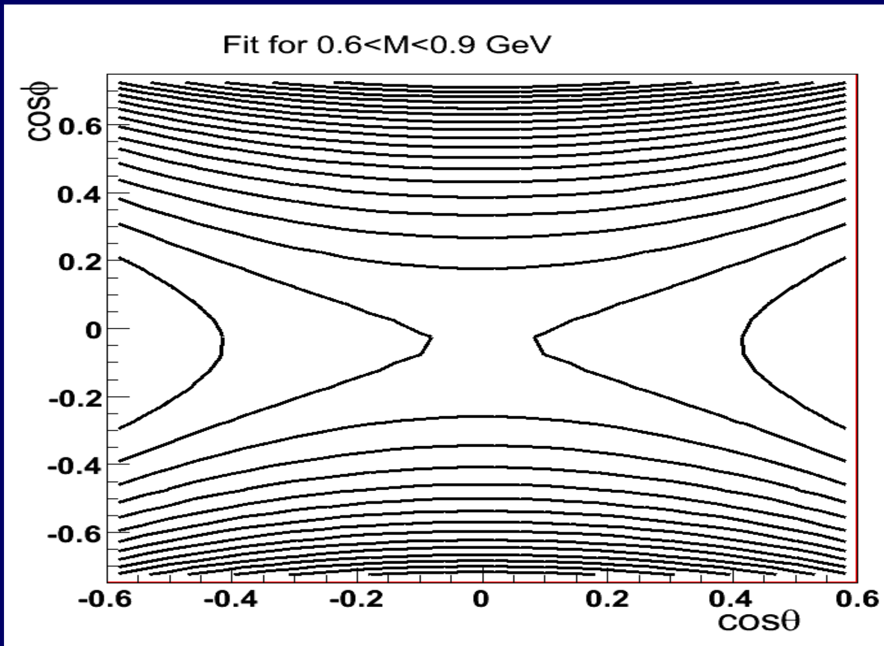
In rest frame of virtual photon:

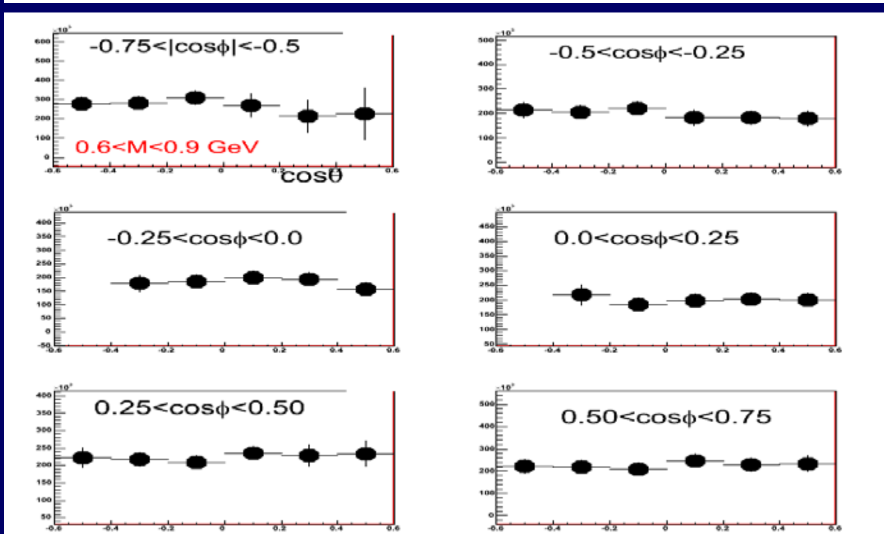
θ : angle between the positive muon $\mathbf{p}_{\mu+}$ and the z-axis.

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





example:
excess 0.6<M<0.9 GeV

method 1:
2-dim fit to data with

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

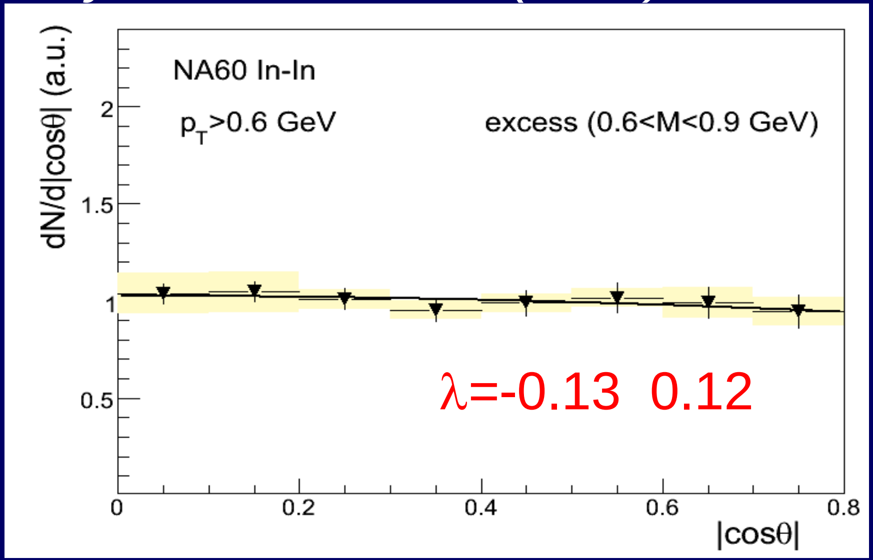
results:

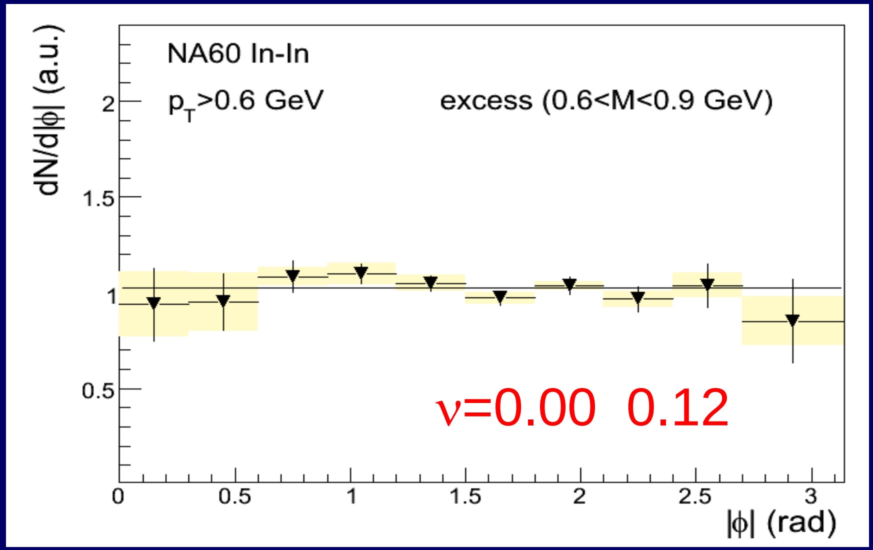
λ = -0.19 0.12
ν = 0.03 0.15
μ = 0.05 0.03

all parameters zero within errors

Results on structure coefficients λ, ν

Phys. Rev. Lett. 102 (2009) 222301





example:
excess 0.6<M<0.9 GeV

method 2:
set $\mu = 0$ 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

Conclusions

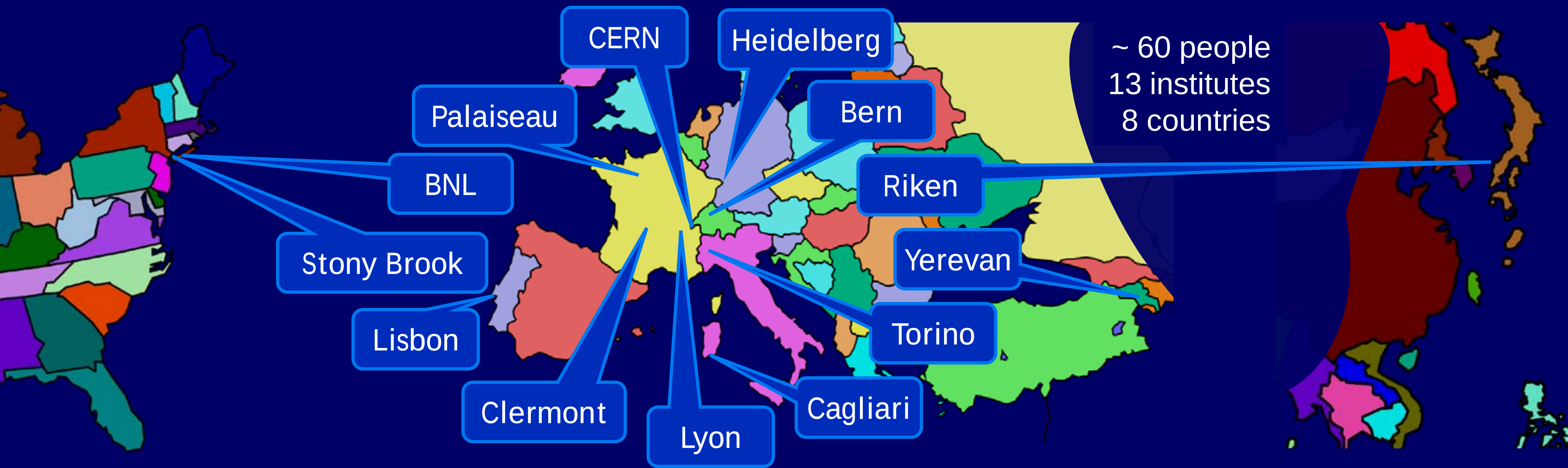
Planck-like exponential mass spectra, exponential m_T spectra, zero polarization and general agreement with thermal models consistent with interpretation of excess dimuons as thermal radiation

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



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

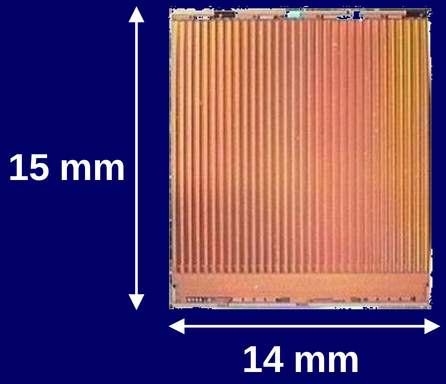
BKP

The NA60 Silicon Pixel Detector

Single chip assemblies:

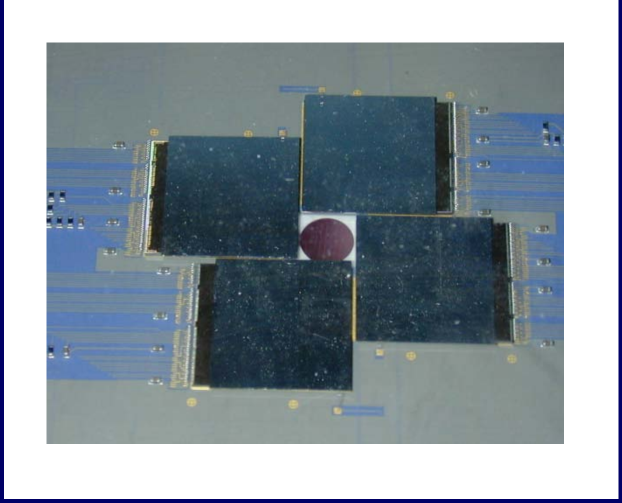
ALICE1LHCb readout chips

- 8192 pixel cells of $50 \times 425\ \mu m^2$
- PCI based readout system operated at 10 MHz
- DeepSubMicron radiation-hard, tested up to 12 Mrad



ALICE Pixel sensors

- p-on-n silicon
- 15kΩcm

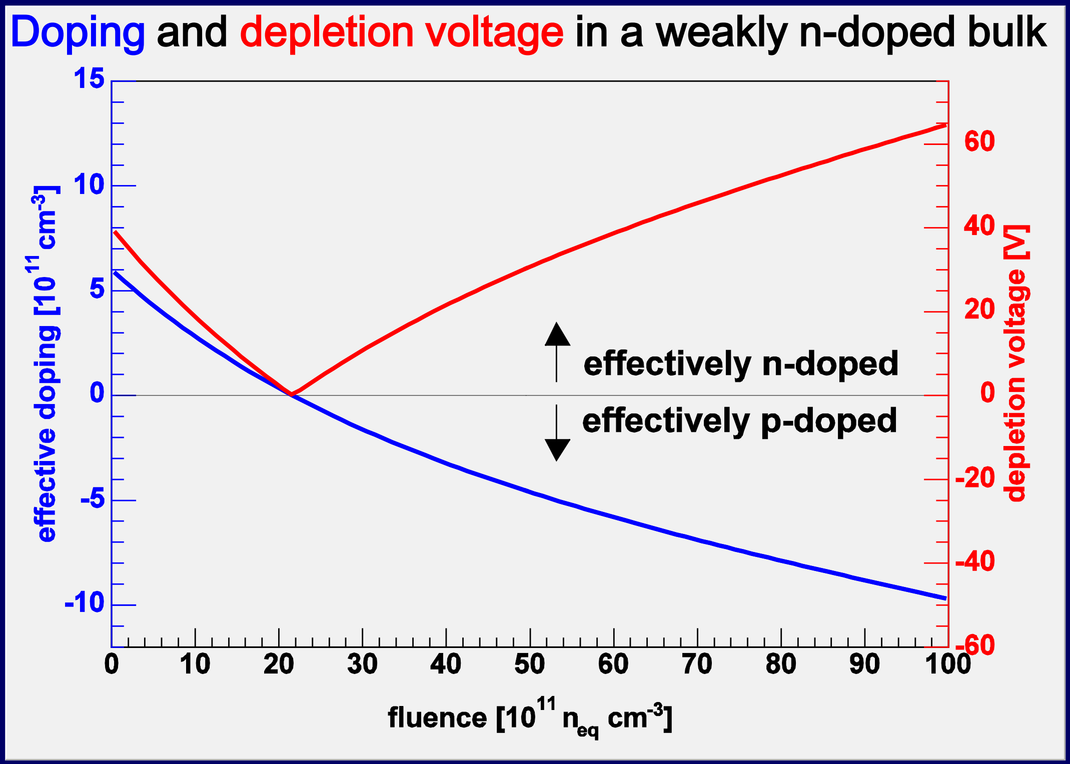


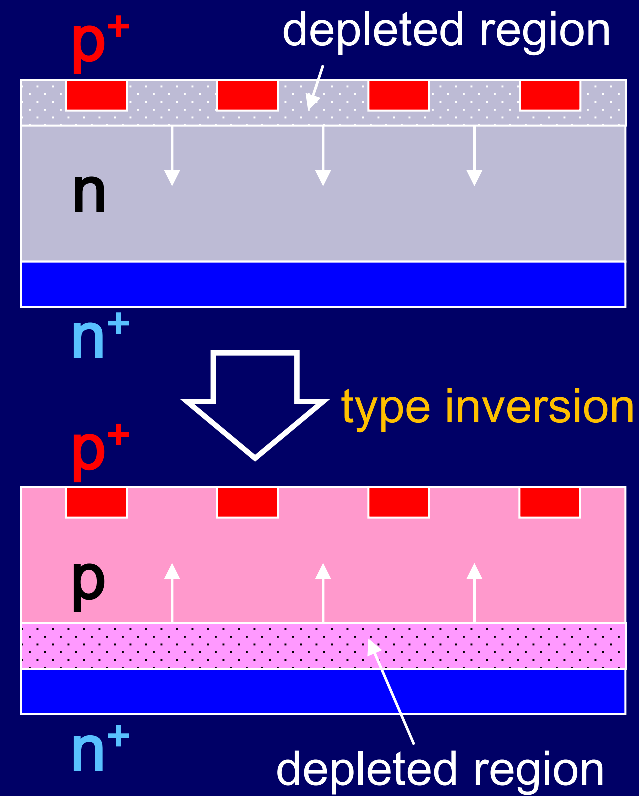
Hybrid:

Assemblies glued and wire-bonded on ceramic support

Beam hole: ∅ 6 mm

Type Inversion following Radiation Damage





radiation decreases effective doping concentration in n-type bulk:

- bulk eventually becomes effectively p-type (type inversion)
- p-n junction moves from p^+ implants to n^+ back plane
- full depletion necessary to prevent pixels from being short-circuited
- depletion voltage decreases until type inversion, then increases

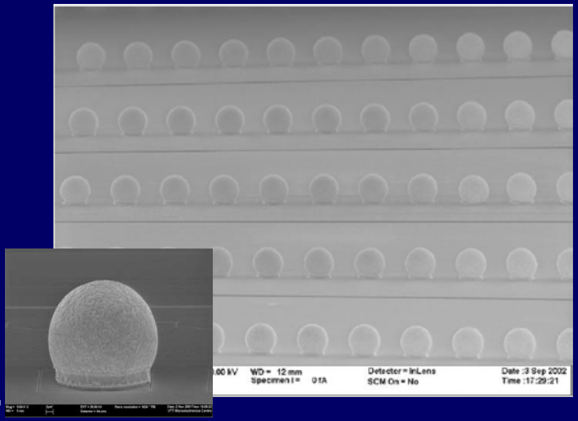
The Readout Chip

The Sensor Chip

+

- ALICE1/LHCb
- 750 µm thick
- 32   256 pixels of 425 µm   50 µm
- operated at 10 MHz
- 32 columns read out in parallel
- radiation tolerant architecture
- designed for ALICE and LHCb
  by CERN Microelectronics Group

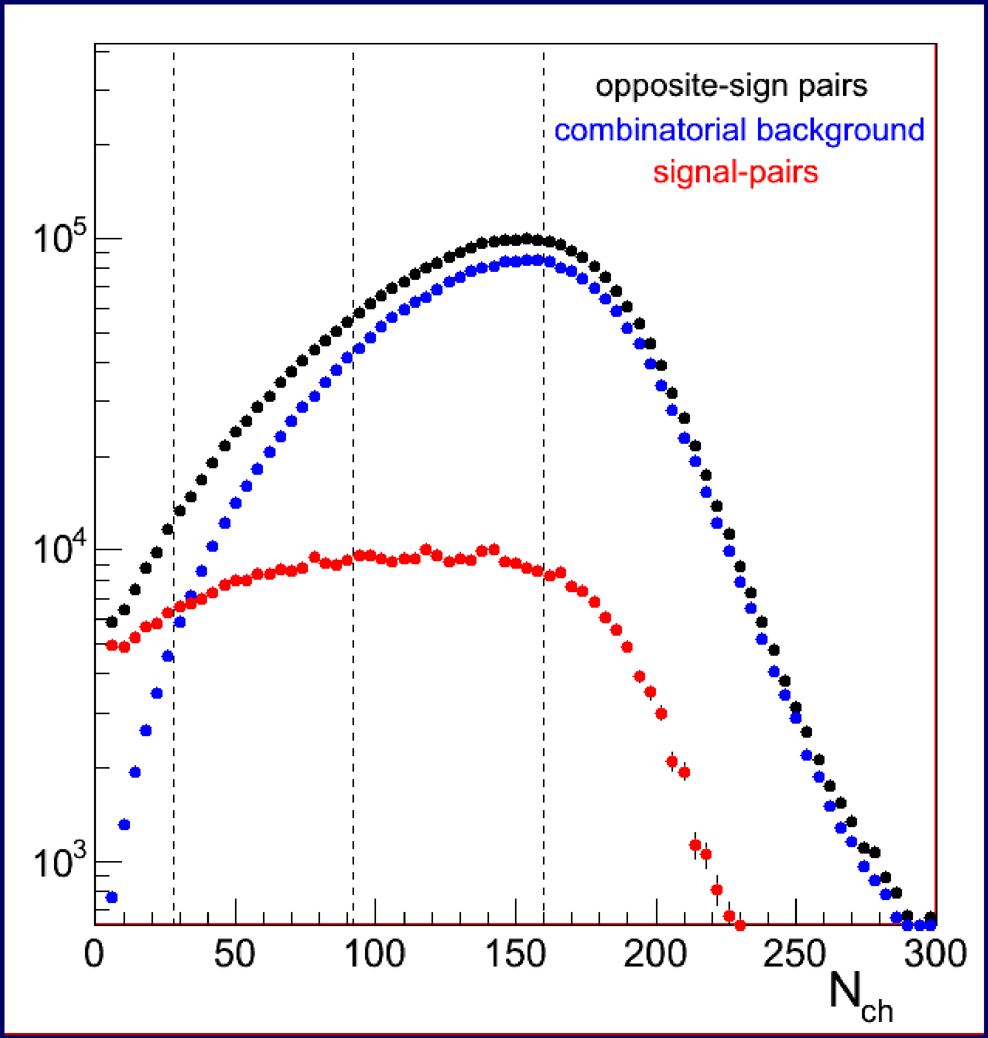
- 300 µm thick
- 32   256 pixels of 425 µm   50 µm
- p implants on n bulk



Bump-bonded together
with 25 µm solder bumps.

Fabrication and pixel detector module construction during 2002 and 2003.

Associated track multiplicity distribution



Track multiplicity from VT tracks for triggered dimuons

Complete coverage from “pp-like” to central

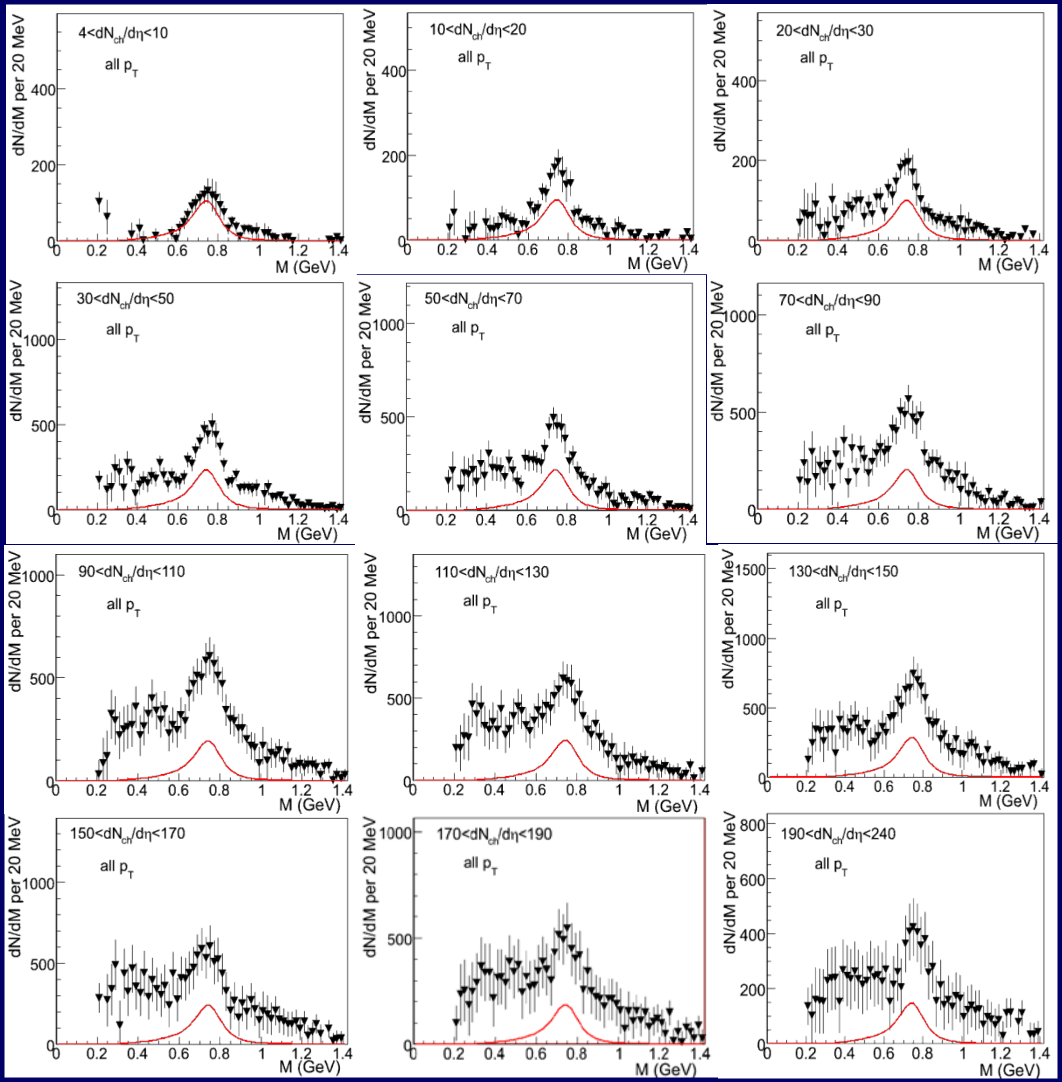
4 multiplicity windows:

Centrality bin	multiplicity	$\langle dN_{ch}/d\eta \rangle_{3.8}$
Peripheral	4-30	17
Semi-Peripheral	30-110	70
Semi-Central	110-170	140
Central	170-240	190

some part of the analysis also in 12 multiplicity windows

Excess mass spectra in 12 centrality windows

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



all p_T

no cocktail ρ subtracted
DD subtracted

clear excess above the cocktail ρ (bound to the ω with ρ/ω=1.0)

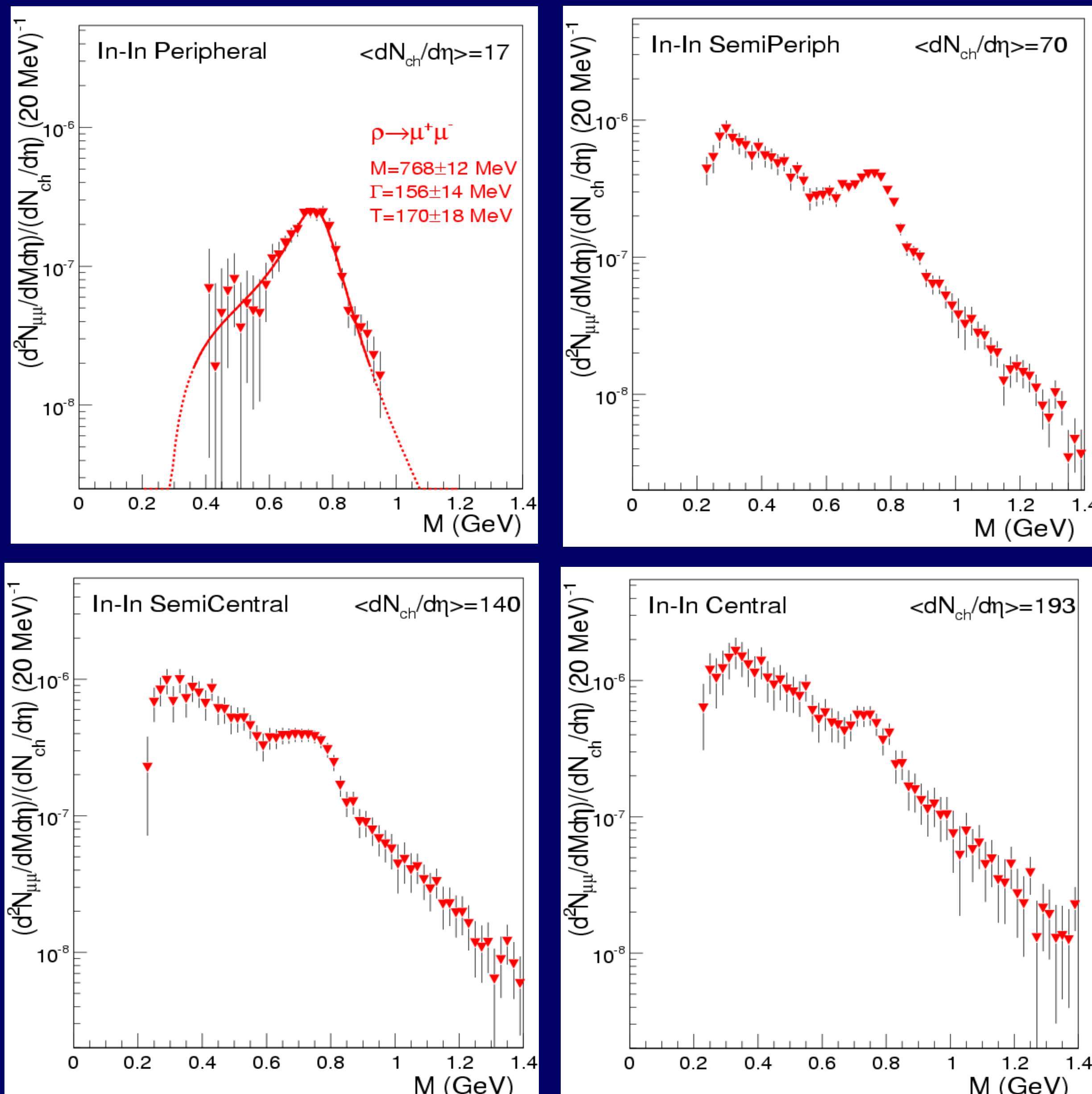
excess centered at the nominal ρ pole rising with centrality

monotonic broadening with centrality

↓

"melting" of the ρ

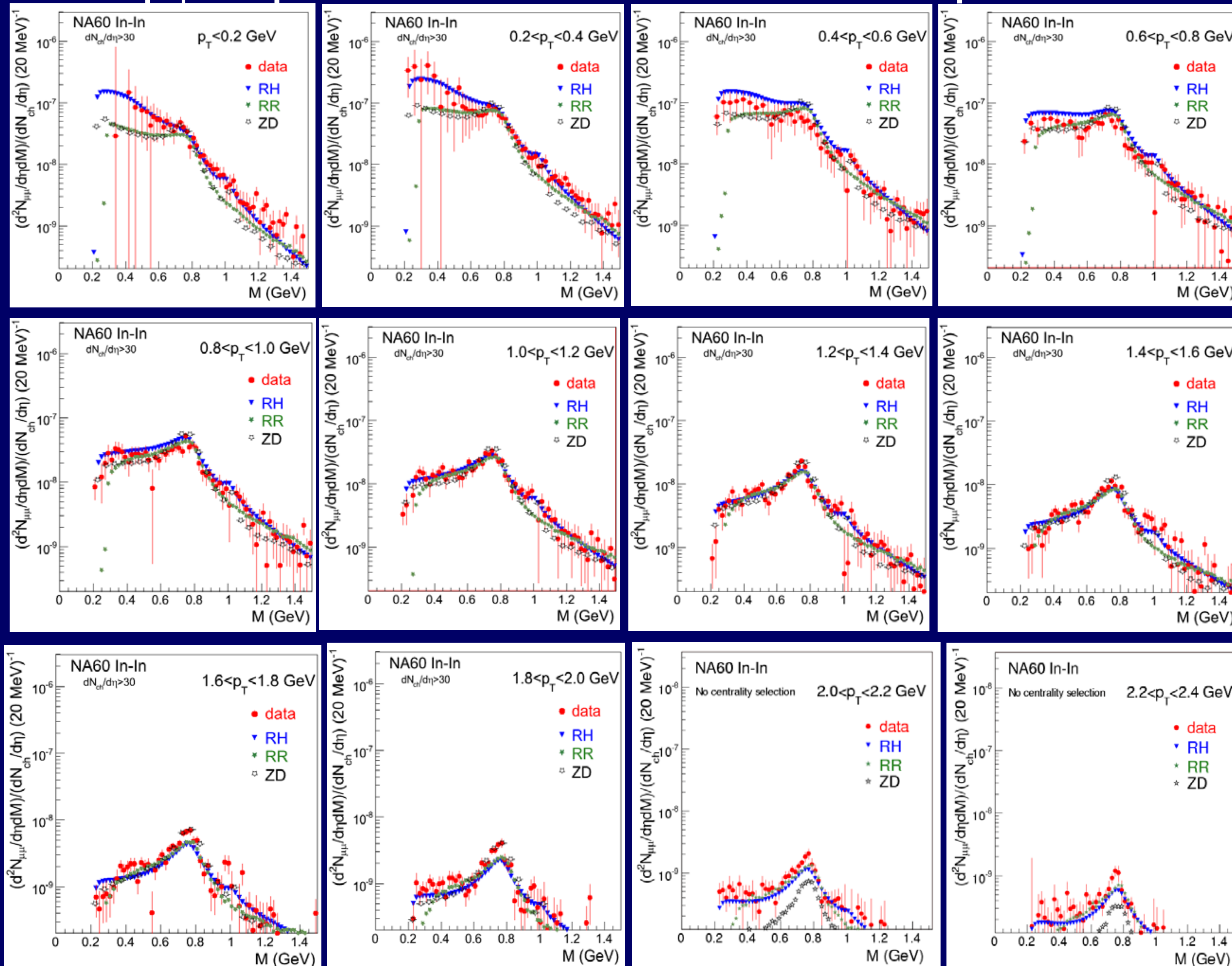
Centrality dependence of excess mass spectra



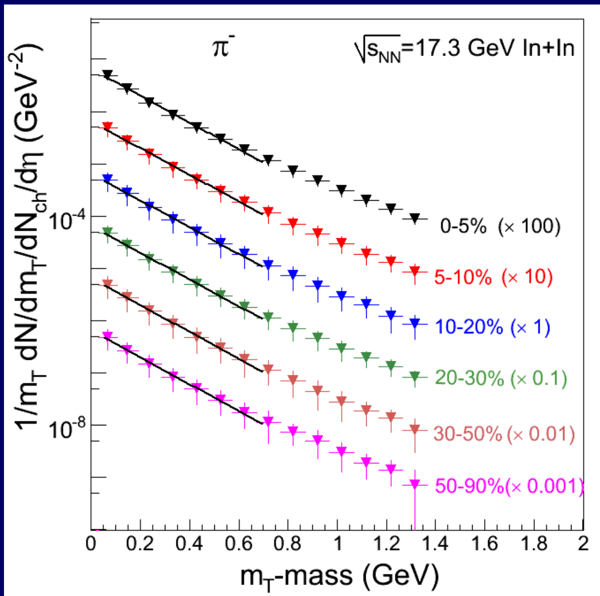
very fast evolution from vacuum ρ to Planck-like spectra

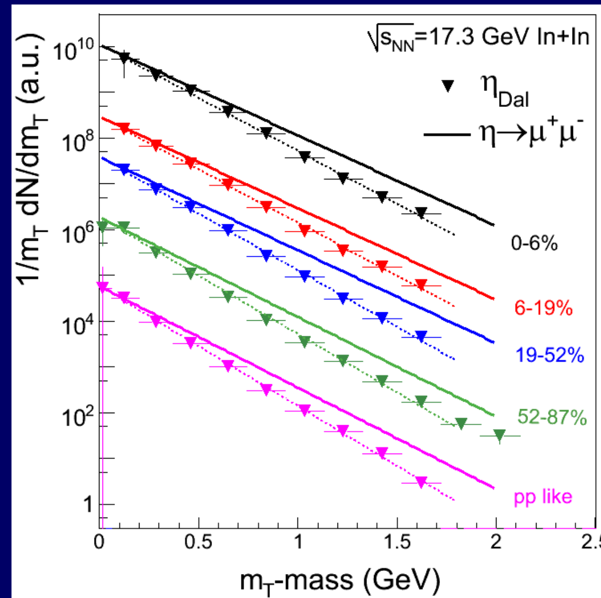
increasing masking of residual freeze-out ρ

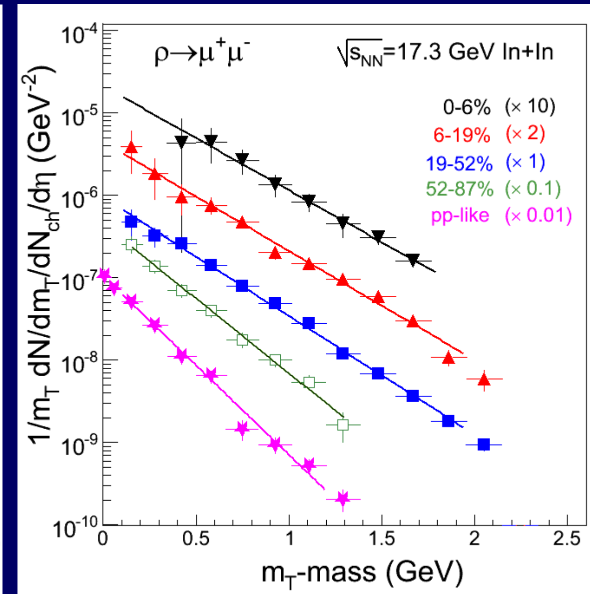
p_T dependence of excess mass spectra

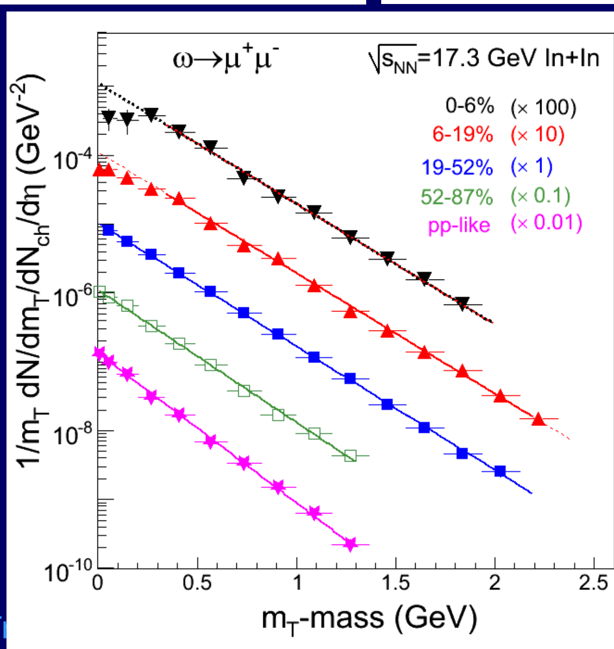


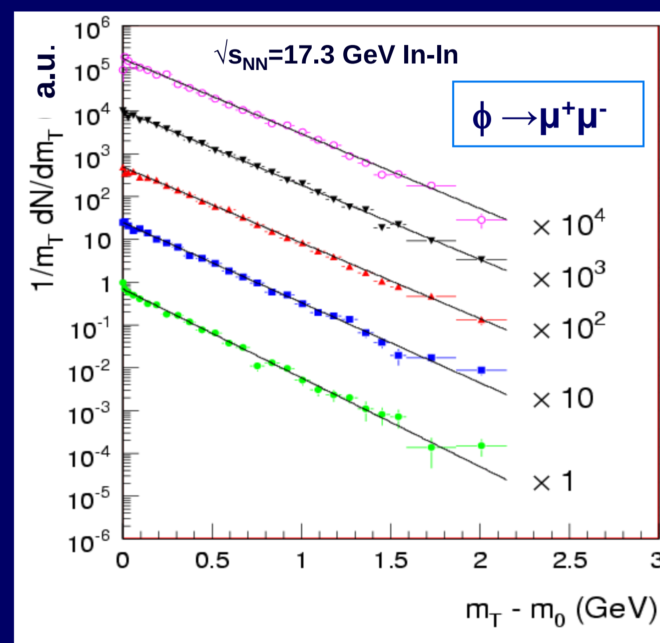
Light -flavoured hadrons in NA60





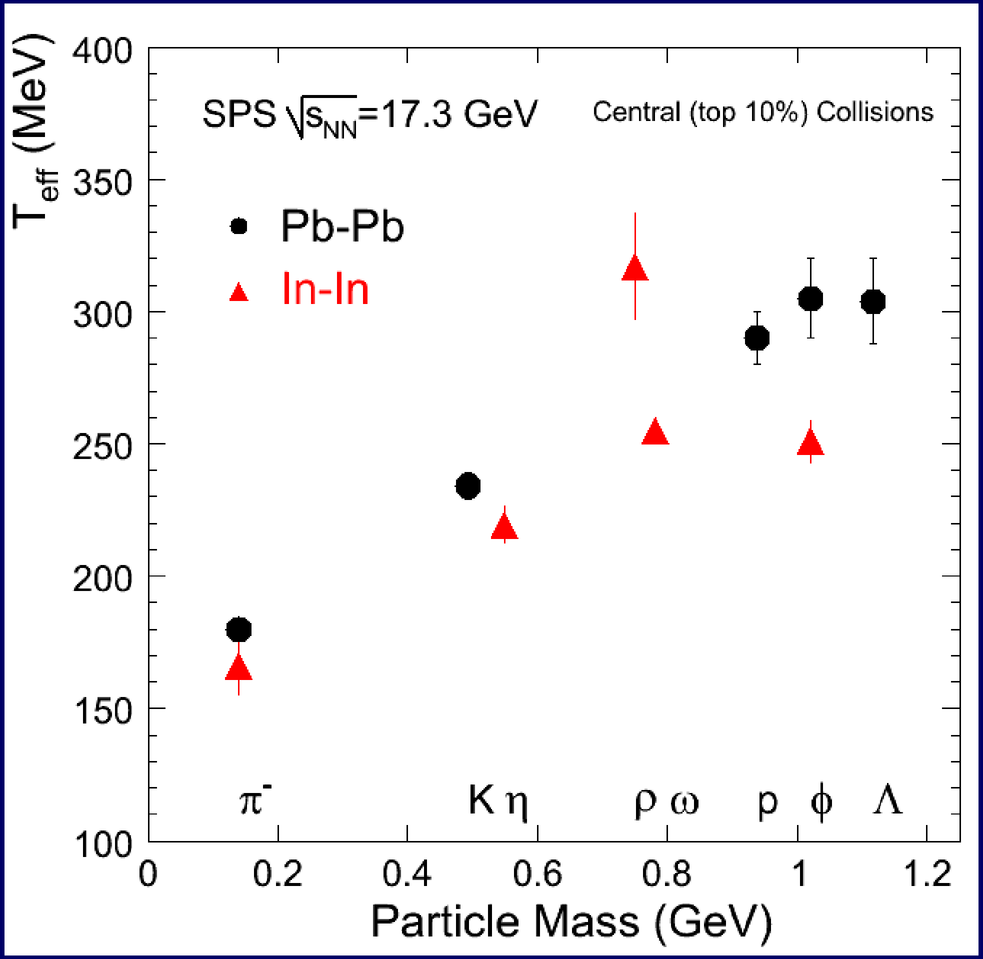






Systematics of T_{eff} vs. mass at SPS Energies

In-In data from Phys. Rev. Lett. 100 (2008) 022302

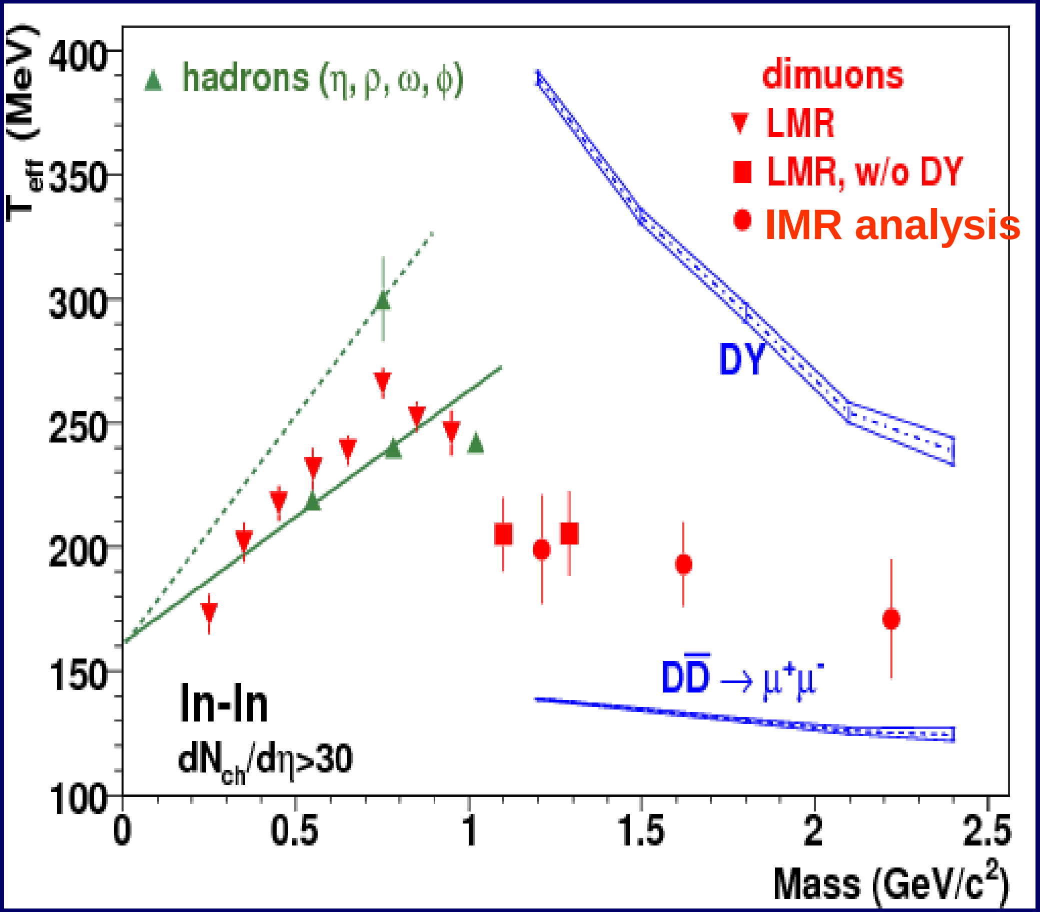


Inverse slope parameter T_{eff} of the transverse mass distributions of hadrons vs. hadron mass for central (top 10%) 158A GeV Pb+Pb and In-In collisions

ρ In-In above protons Pb-Pb (both max. coupled to pions)

ϕ Pb-Pb misleading (should be lower: phi-puzzle)

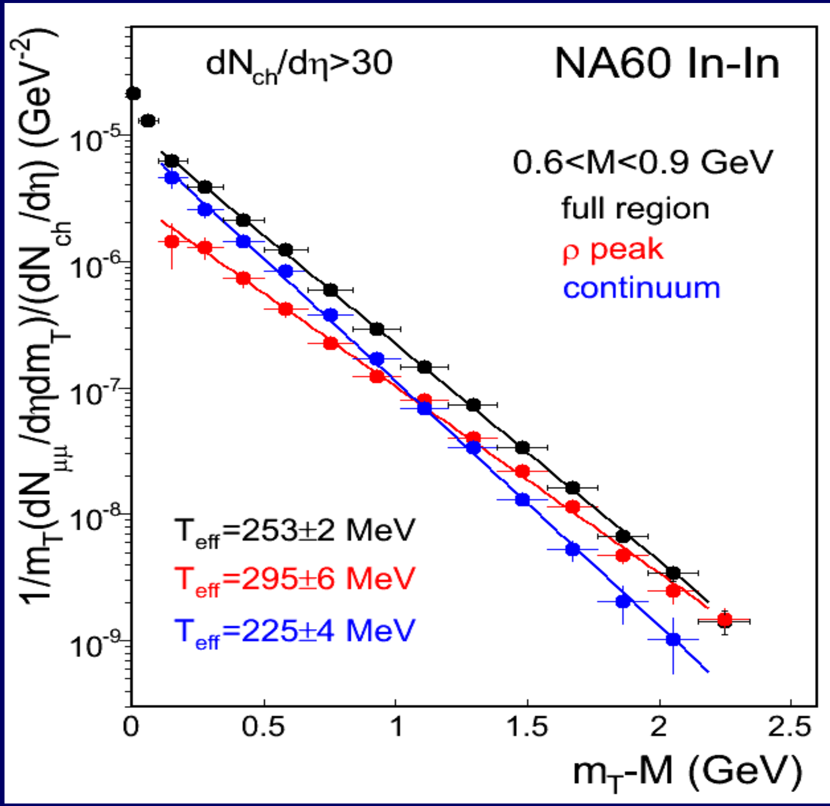
Comparison of IMR to DY and DD



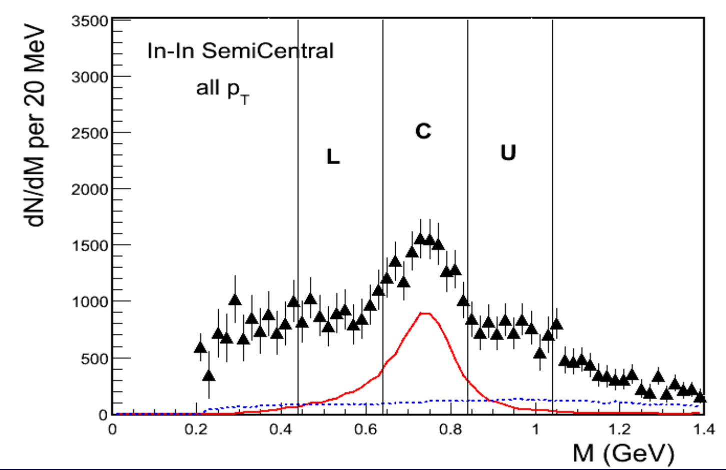
Disentangling the m_T spectra of the ρ peak and the continuum

Shape analysis and p_T spectra

identify the ρ peak with the freeze-out ρ in the dilute final stage, when it does not experience further in-medium influences.



use side-window subtraction method



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

m_T spectra very different for the ρ peak and continuum:

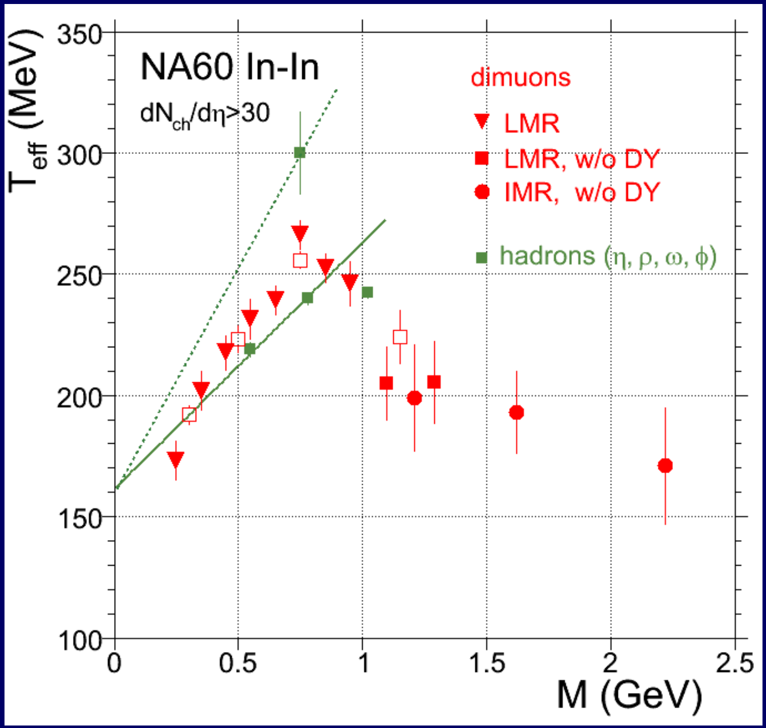
T_{eff} of peak higher by 70+-7 MeV than that of the continuum !

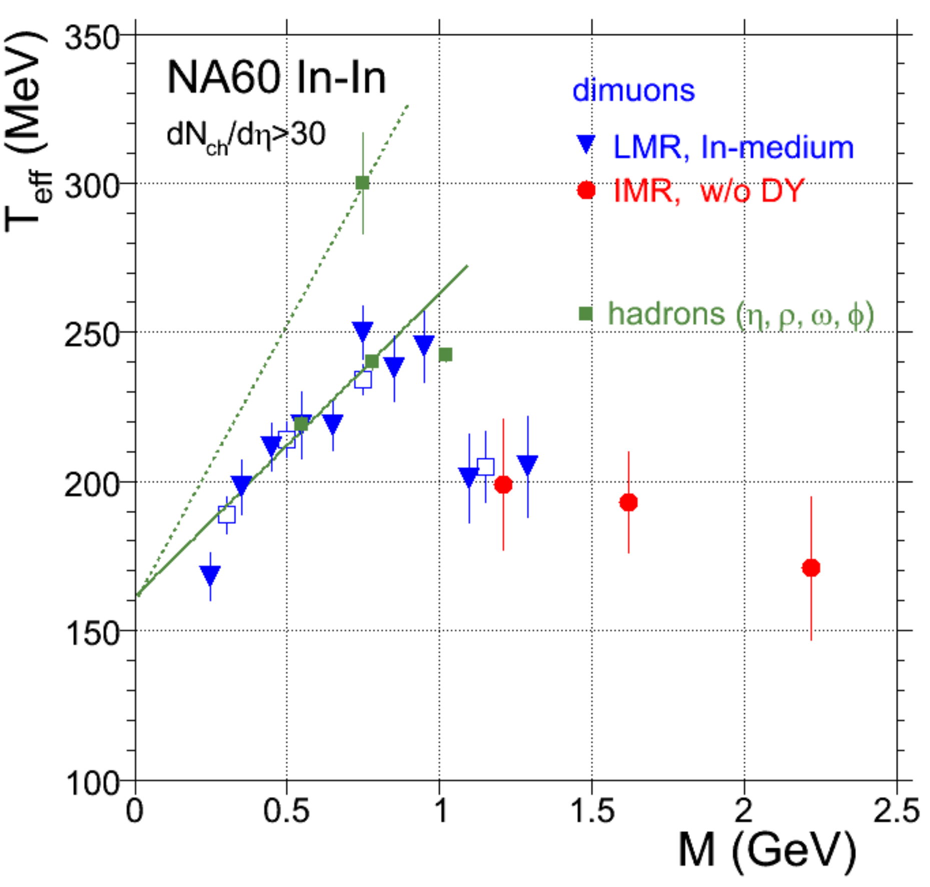
all spectra pure exponential, no evidence for hard contributions

The rise and fall of radial flow of thermal dimuons

Correction of T_{eff} for the contribution from the freeze-out ρ

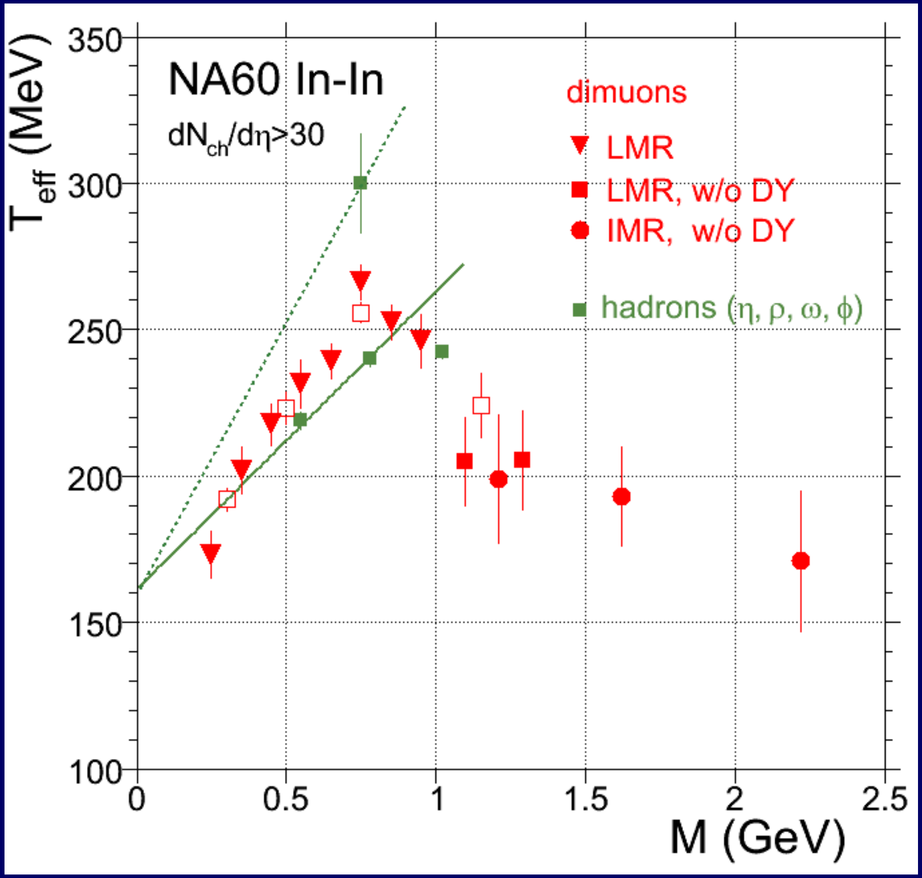
Phys. Rev. Lett. 100 (2008) 022302

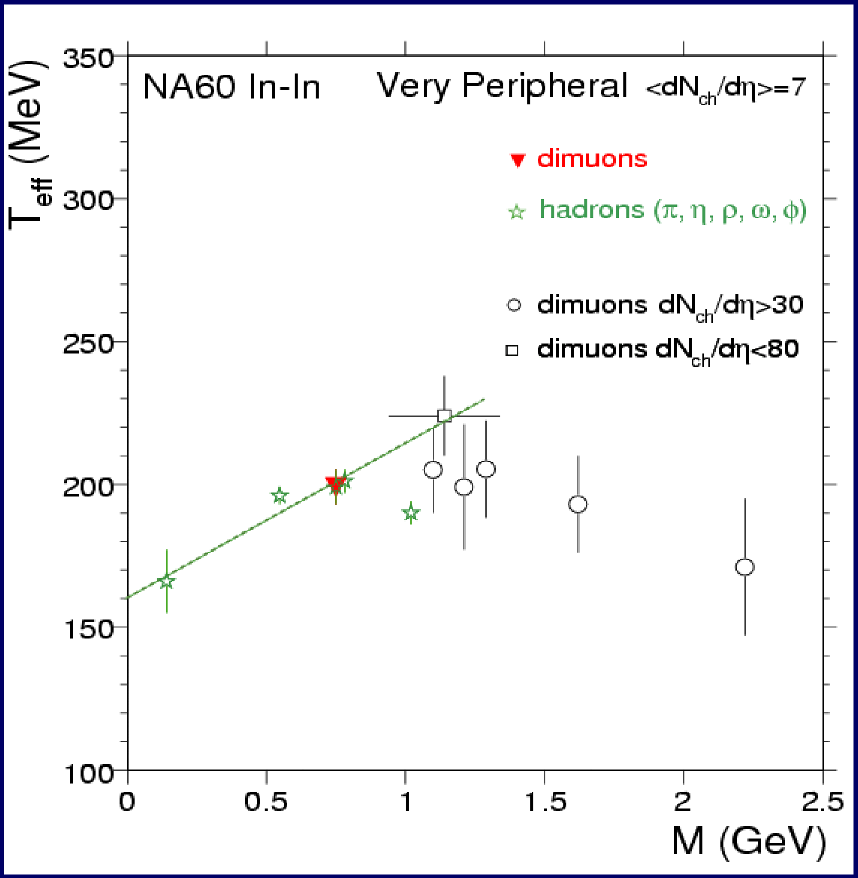




Sudden decline in T_{eff} solely due to the in-medium radiation

Teff systematics for peripheral data



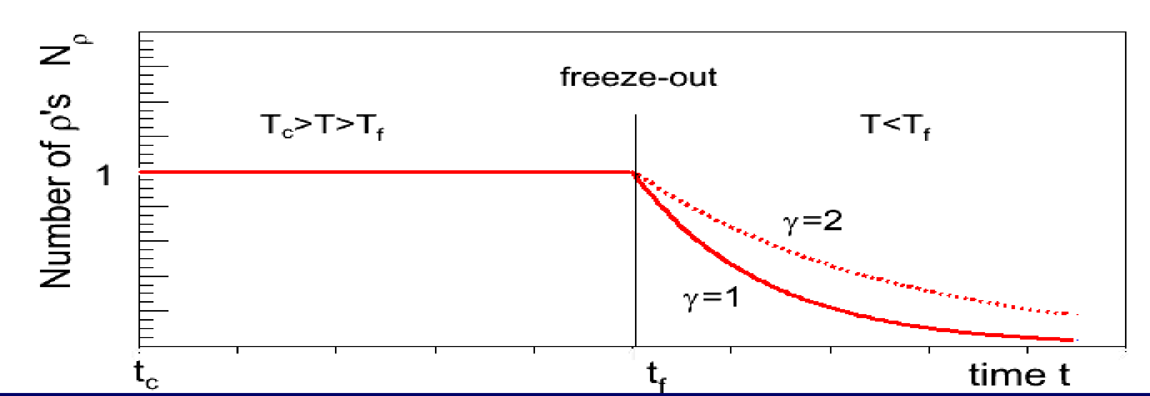


No sudden decline in T_{eff}

ω and ρ identical

Understanding the difference in T_{eff} between peak and continuum

continuum emission (very schematic)



post freeze-out emission

detailed balance between formation and decay → N_ρ fixed

free exponential decay of N_ρ

decay rate:

$$\frac{dN_{\mu\mu}}{dt} = N_\rho B_{\mu\mu} \frac{1}{\gamma\tau_\rho}$$

$$\frac{dN_{\mu\mu}}{dt} = N_\rho B_{\mu\mu} \frac{1}{\gamma\tau_\rho} e^{-(t-t_f)/\gamma\tau_\rho}$$

time integral:

$$N_{\mu\mu} = N_\rho B_{\mu\mu} \frac{t_f - t_c}{\gamma\tau_\rho}$$

$$N_{\mu\mu} = N_\rho B_{\mu\mu}$$

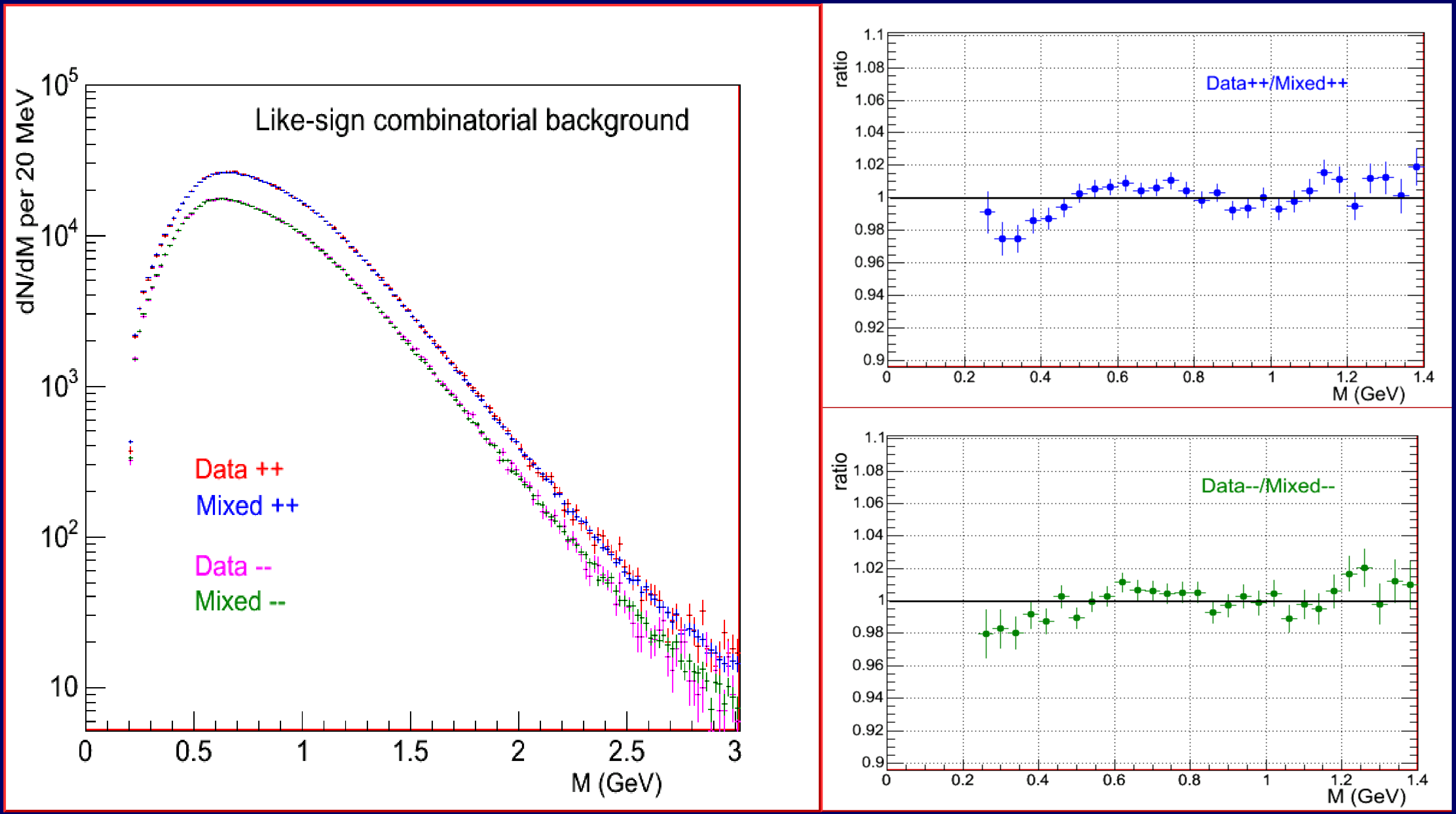
p_T spectra:

softened by 1/γ
average over T_{th},v_T,

unsoftened
fixed at $T=T_f$ with max v_T

softening and averaging contribute about equally to the 70 MeV

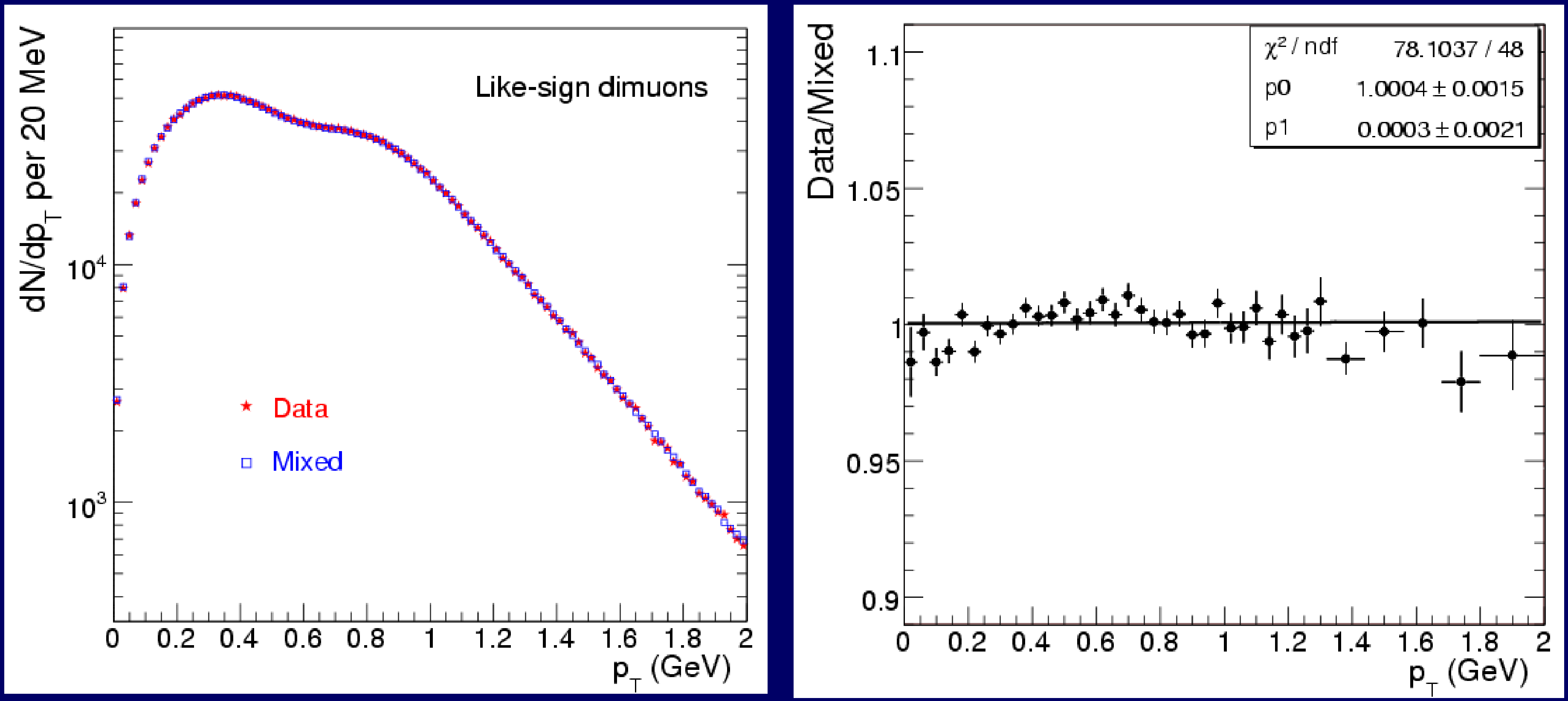
Combinatorial Background from $\pi,K\rightarrow\mu$ decays



Agreement of data and mixed CB over several orders of magnitude

Accuracy of agreement ~1%

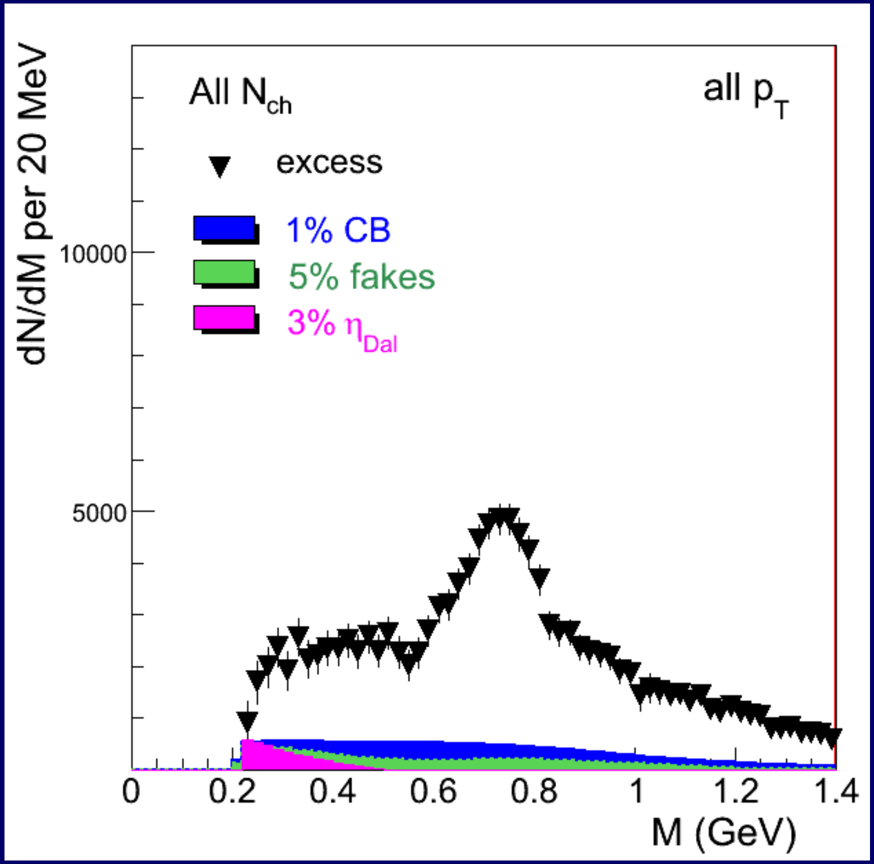
Combinatorial Background from $\pi, K \rightarrow \mu$ decays

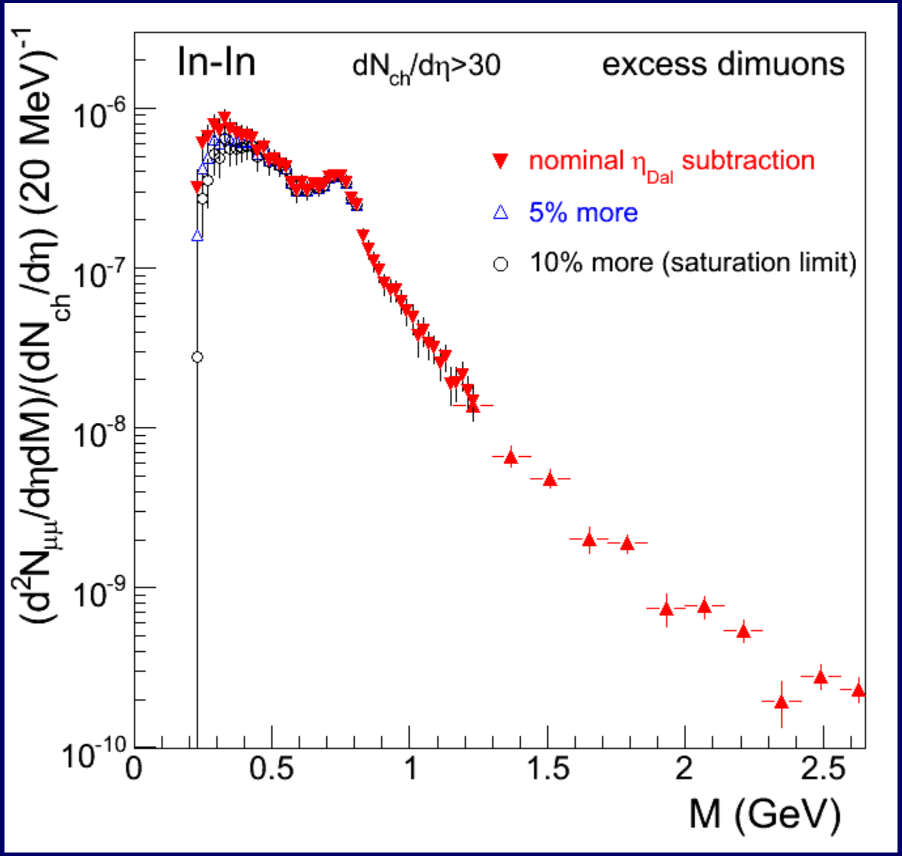


Agreement of data and mixed CB over several orders of magnitude

Accuracy of agreement ~1%

Systematics due to subtraction of total Background and eta Dalitz contribution





Electromagnetic Transition Form Factors of the η and ω Dalitz decays

Electromagnetic Transition Form Factors

The high quality of the peripheral In-In data offers the possibility to measure, with a much higher accuracy than before, the transition form factors of $\eta \rightarrow \mu^+\mu^-\gamma$ and $\omega \rightarrow \mu^+\mu^-\pi^0$

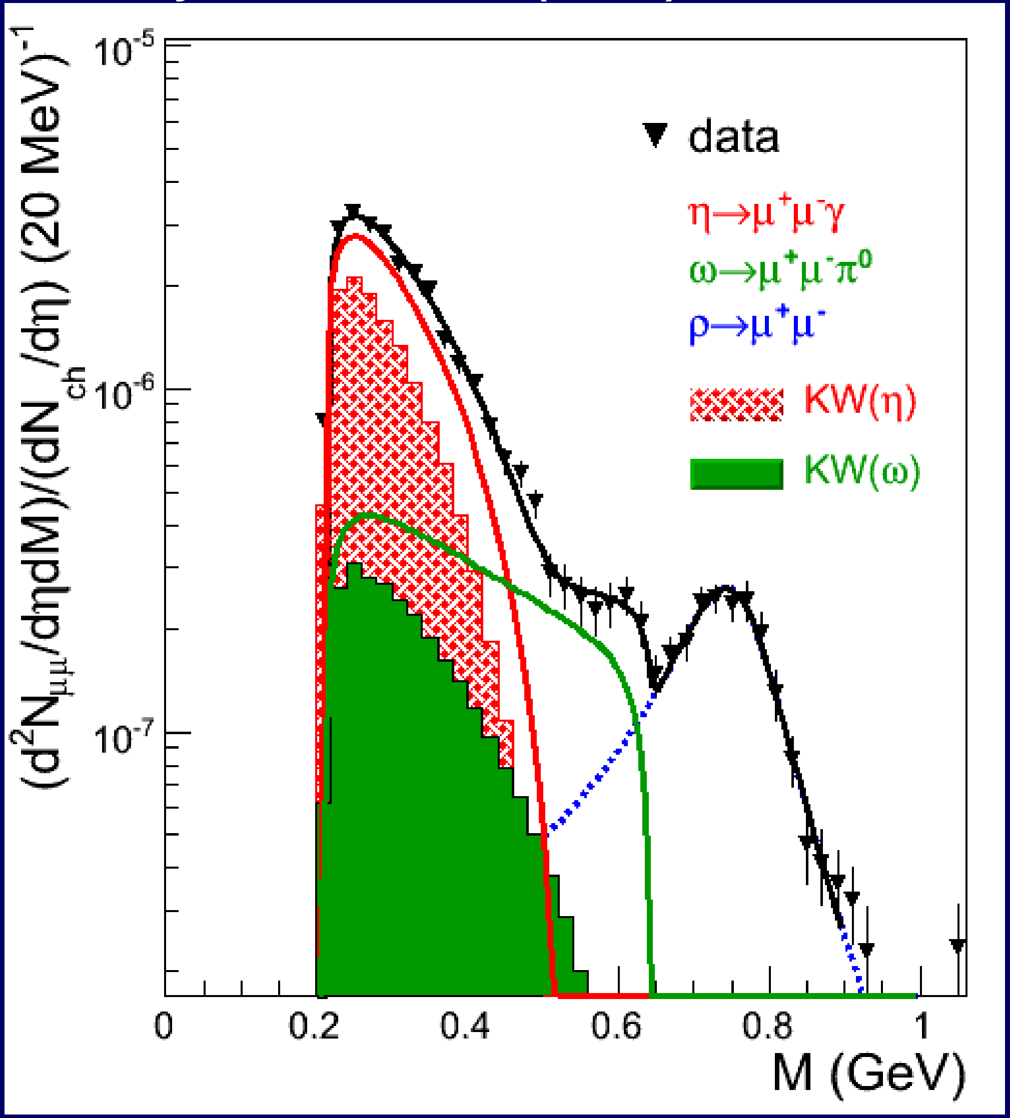
Probability of formation of a lepton pair with mass $m_{\mu+\mu-}$ in a Dalitz decay strongly modified by the dynamic electromagnetic structure arising at the vertex of the transition A→B . Formal description by $|F_{AB}(m_{\mu\mu}^2)|^2$

$$dN(A \rightarrow B\mu^+\mu^-)/dm_{\mu\mu}^2 = [QED(m_{\mu\mu}^2)] \times |F_{AB}(m_{\mu\mu}^2)|^2$$

By comparing the measured spectrum of lepton pairs in decay A→ B μ+μ- with a QED calculation for point-like particles it is possible to determine experimentally the transition form factors $|F_{AB}|^2$

Isolating the Dalitz region in the peripheral data

Phys. Lett. B 677 (2009) 260



subtraction of

- η, ω, ϕ resonance decays

also

- η' Dalitz decay (η'/η=0.12)
- uncorr. $\mu^+\mu^-$ from DDbar

(both nearly negligible ;
→ systematic errors)

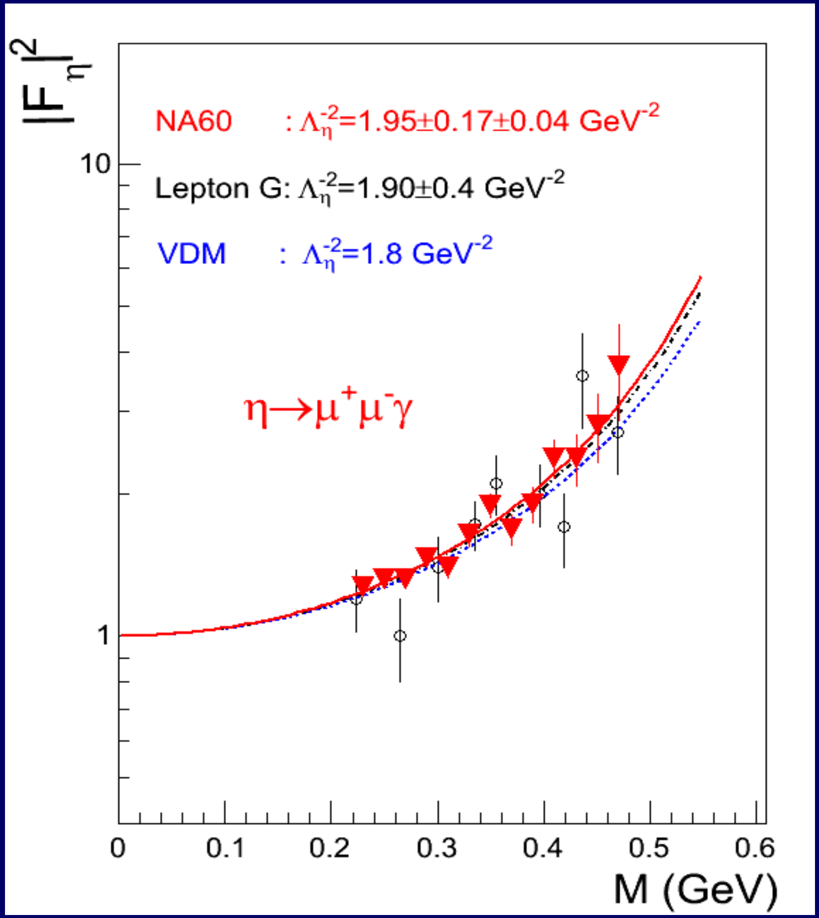
correct for acceptance

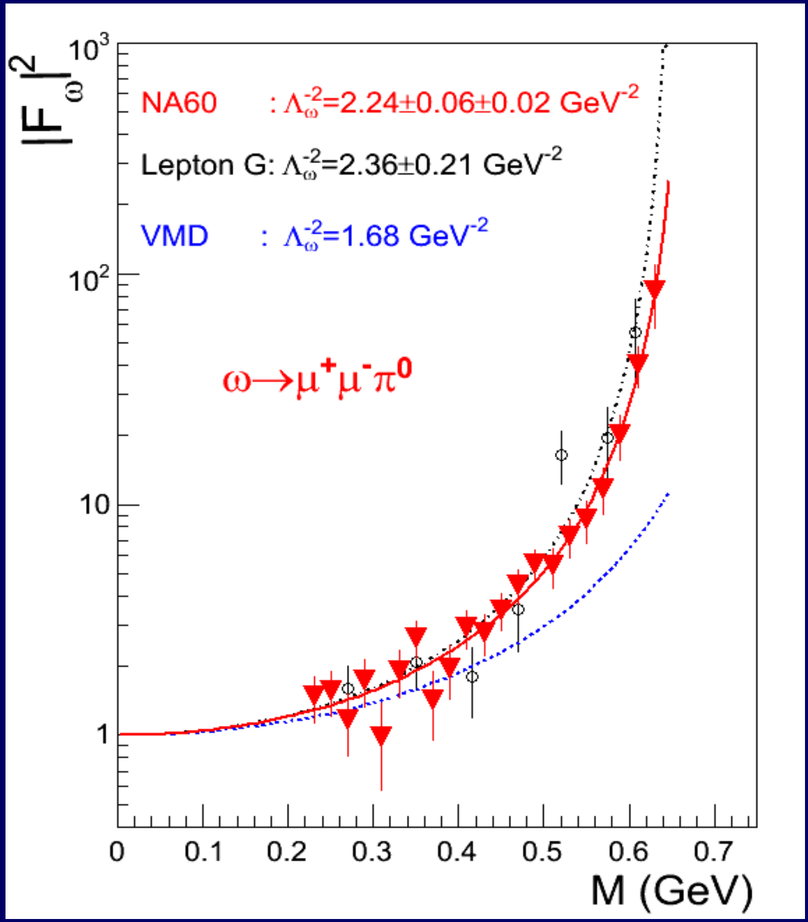
fit remaining sources η, ω and ρ;
χ^2/ndf~1, globally and locally

anomaly of ω form factor
directly visible in the spectrum

Final results on form factors

Phys. Lett. B 677 (2009) 260





Perfect agreement of NA60 and Lepton G, confirming ω anomaly

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

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 $I = 0$ $(\eta, \eta', h, h', \omega, \phi, f, f')$: $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

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

$\omega(782)$ BRANCHING RATIOS

PDG 2008

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

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

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

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	158A 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.

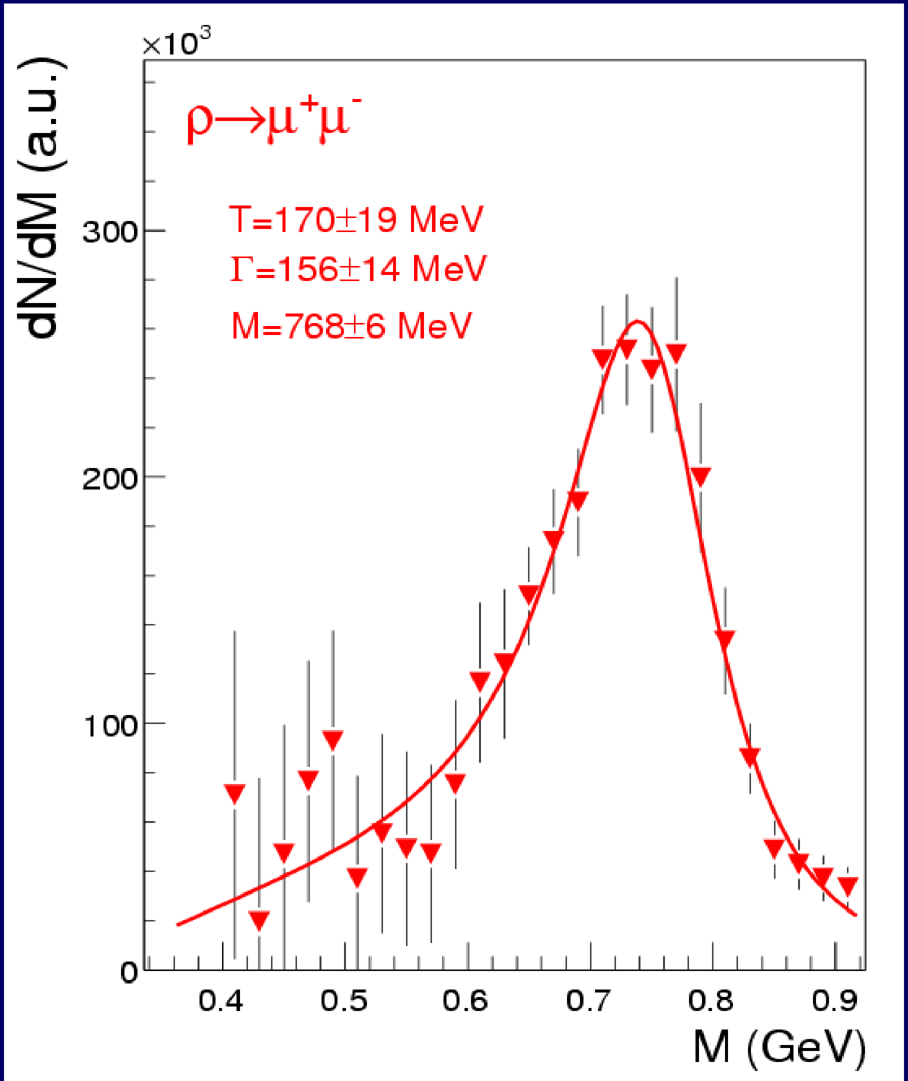
VALUE (GeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.668±0.009±0.003	3k	ARNALDI 09	NA60	158A In–In collisions
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.65 ±0.03		DZHELYADIN 81B	CNTR	25–33 $\pi^- p \to \omega n$

$\omega(782)$ 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

Byproduct of the analysis: $\rho \rightarrow \mu^+\mu^-$ line shape



strong asymmetry of the ρ line shape due to the Boltzmann factor (see Eq. in the slide 14)

associated temperature parameter

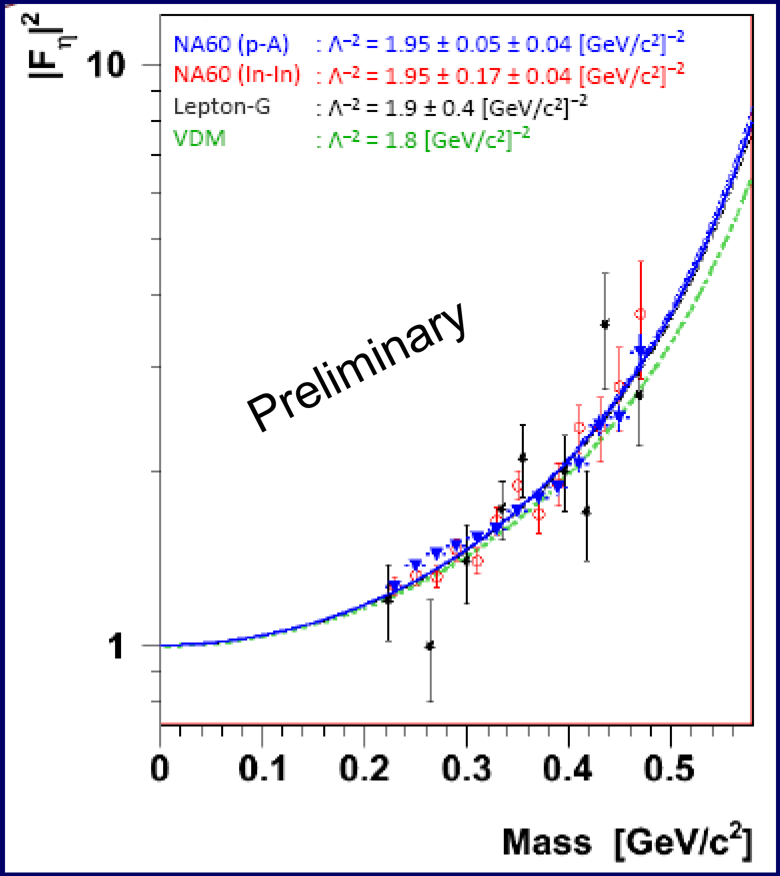
T = 170 +- 19(stat) +- 3(syst)

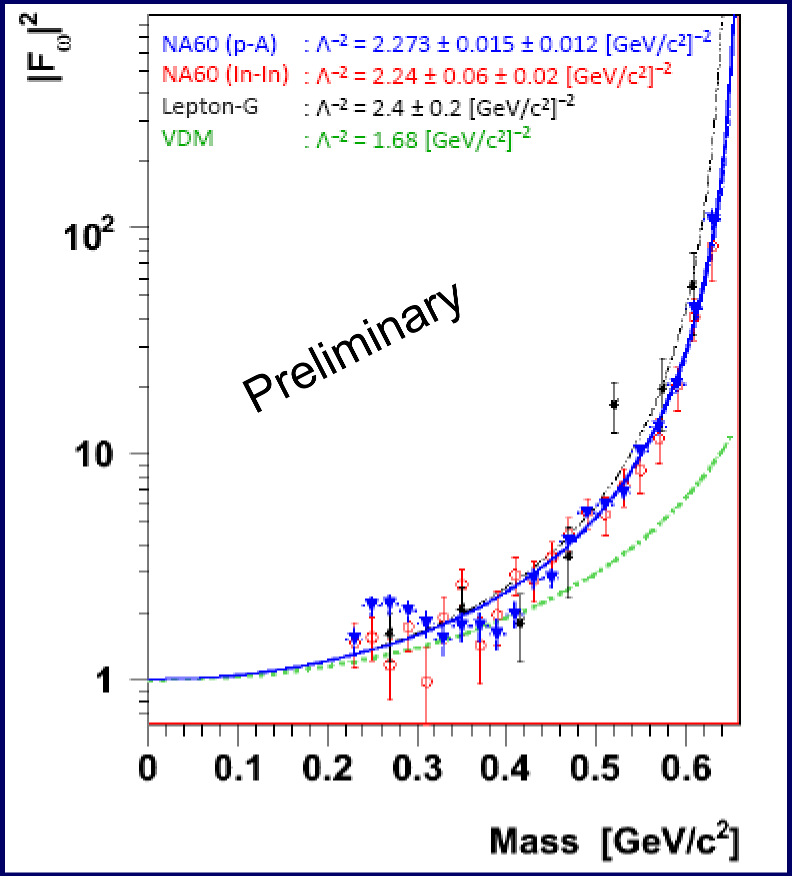
measured for the first time in hadro-production

consistent with Hagerdorn temperature

New results on form factors from the NA60 p-A data

Hot Quarks 2010 (A. Uras)

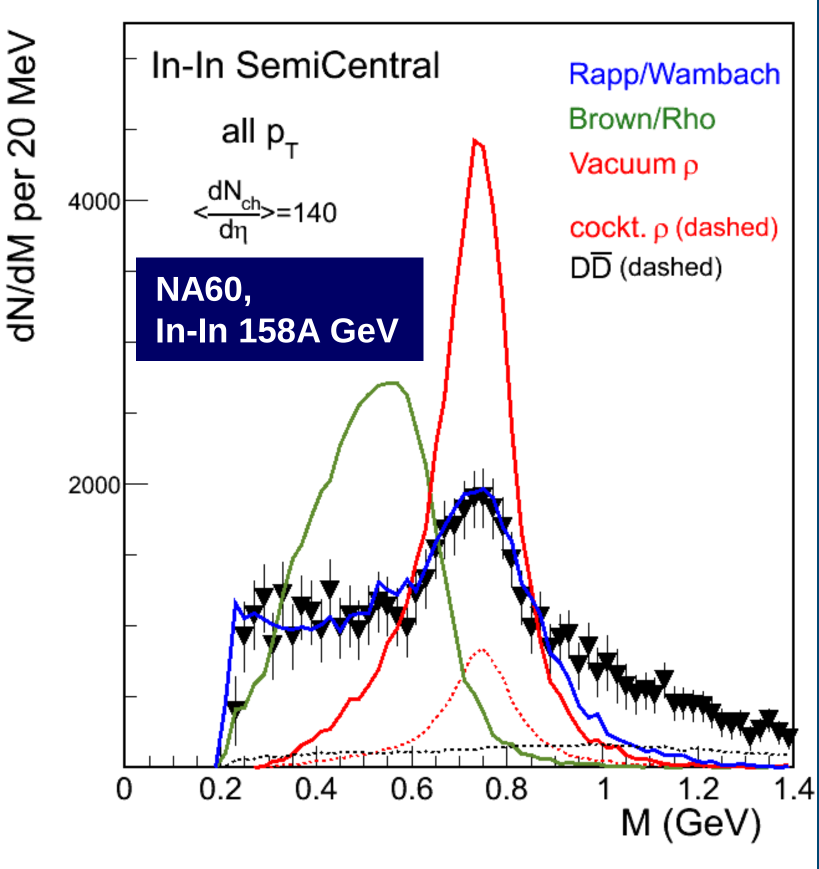




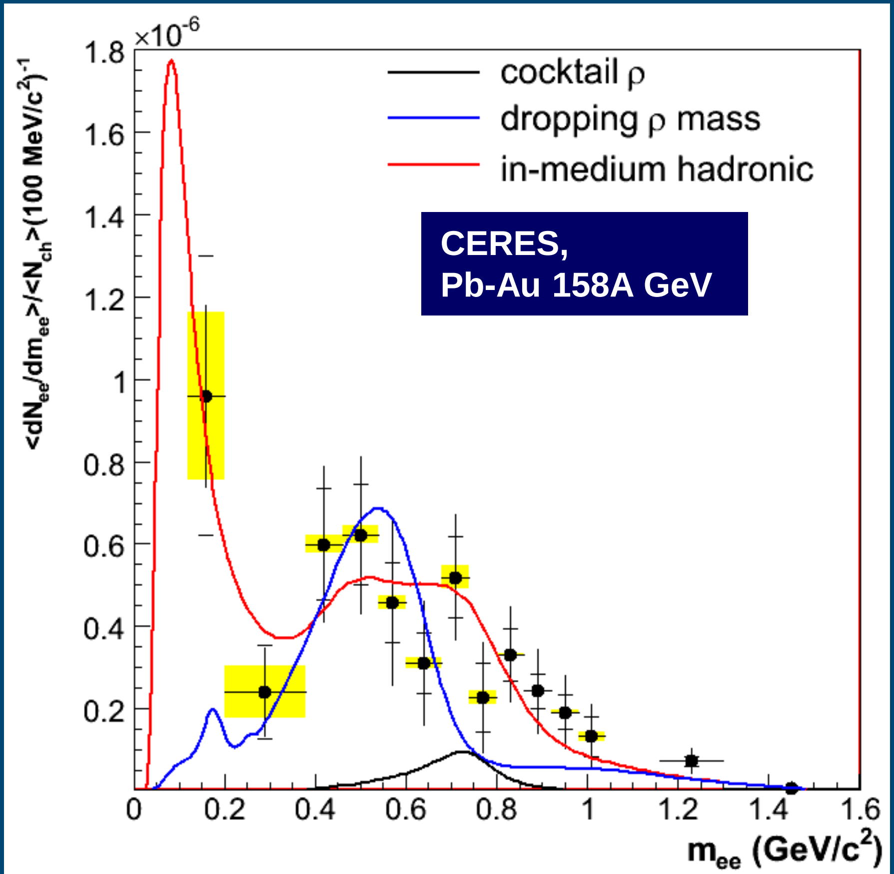
further improvement in statistics by about a factor of 10
systematics under investigation

LMR Excess: ρ dropping mass vs broadening

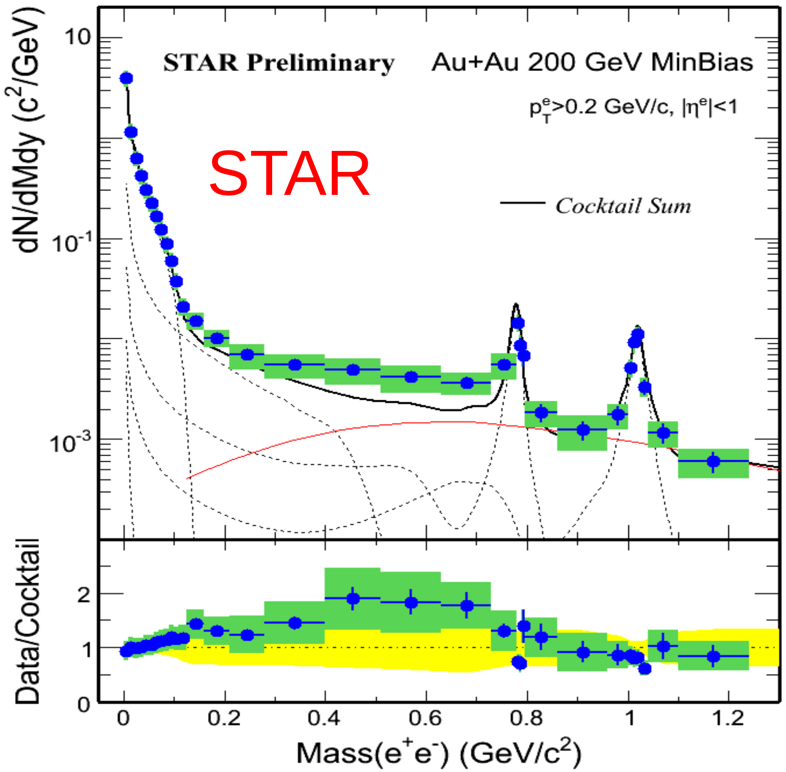
Phys. Rev. Lett. 96 (2006) 162302

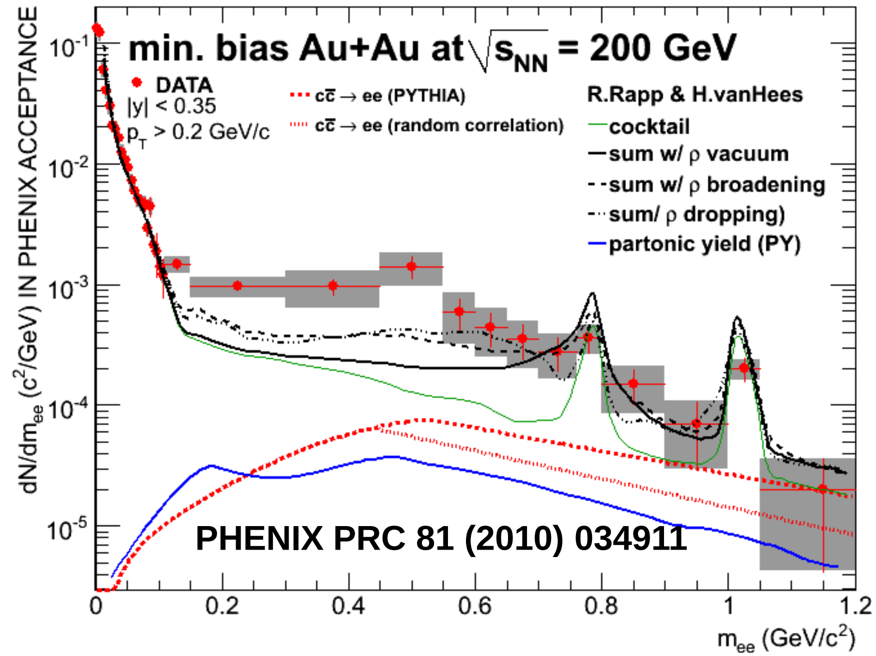


Phys. Lett. B666 (2008) 425



Dilepton Mass Spectra - STAR vs. PHENIX (QM2011)



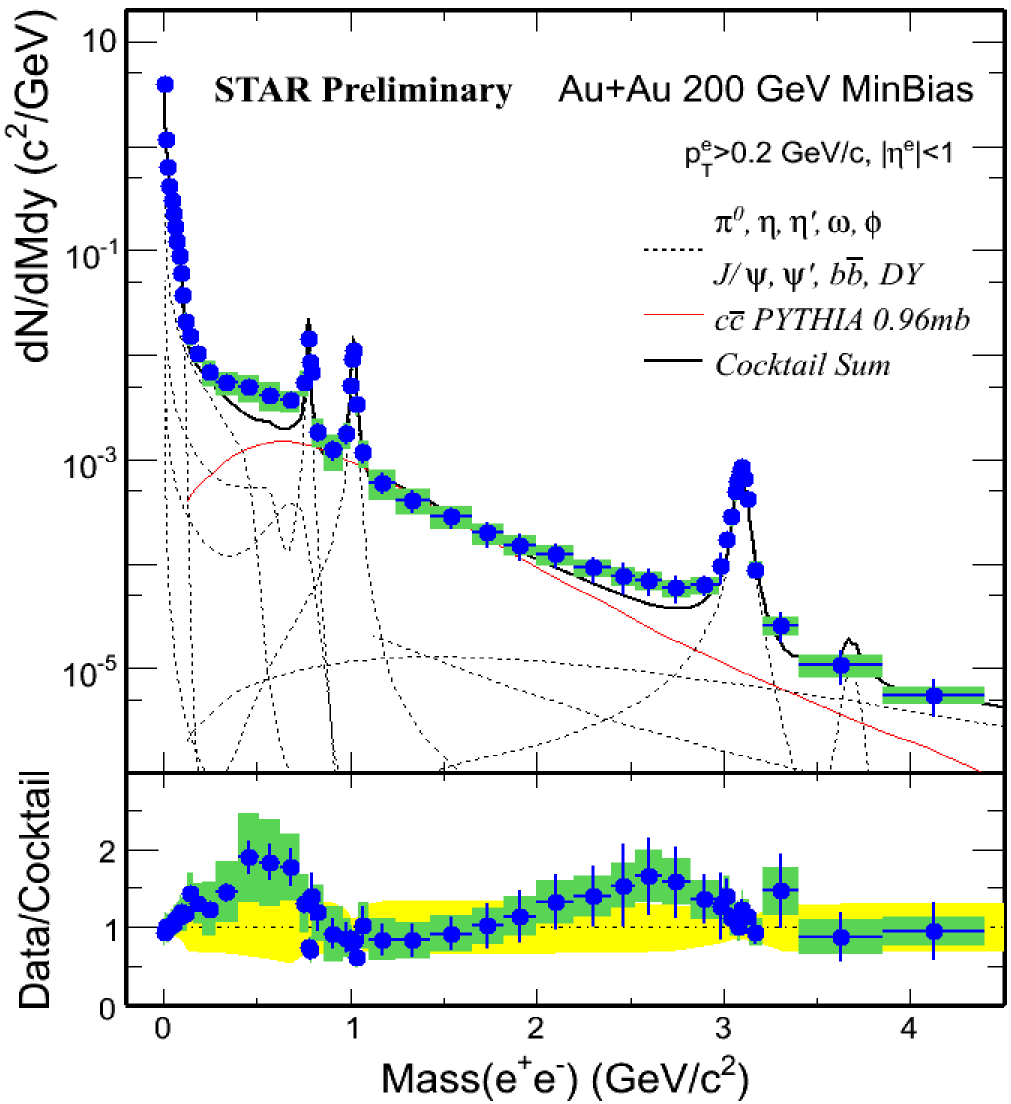


Enhancement factor in $0.15<M_{ee}<0.75$ Gev/c²

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	1.53 ± 0.07 ± 0.41 (w/o ρ) 1.40 ± 0.06 ± 0.38 (w/ ρ)	1.72 ± 0.10 ± 0.50 (w/o ρ) 1.54 ± 0.09 ± 0.45 (w/ ρ)
PHENIX	4.7 ± 0.4 ± 1.5	± 0.5 ± 1.3
Difference	2.0 σ	4.2 σ

Di-electron production in Au + Au collisions

QM 2011



~ 270M Au+Au MinBias events

➢**Data show a hint of enhancement at LMR compared to the hadron cocktails w/o ρ.**

- ρ contribution not included in the cocktail

- *charm = PYTHIA*N_{bin} *(0.96 mb) real contribution in Au+Au is an open question*

- *π^0(π), ϕ from STAR*
- *η, ω J/ψ from PHENIX*

- *Green box: syst. errors on data*
- *Yellow band: syst. errors on cocktail*