Experiments on Lepton Pairs
The CERN SPS Era

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High-Energy Nucleus-Nucleus Collisions: Prime Goal of Dilepton Experiments

Precision study of the QCD phase diagram

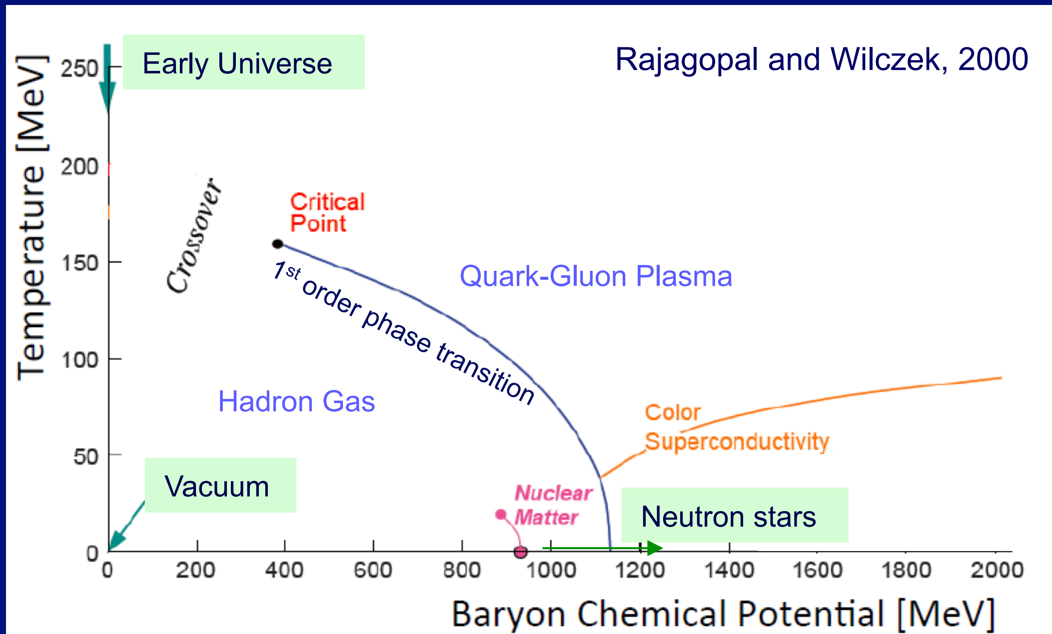
Phase transitions

- ✓ Probe the quark-hadron transition
- ✓ Probe the chiral transition (origin of light hadron masses)
- Beam-energy scans down to low energies mandatory

Bulk properties

- Probe high-temperature partonic matter: early Universe
- Probe high-density baryonic matter: neutron stars

Theoretical guidance for the QCD phase diagram



Small μ_B (Lattice QCD)

crossover transition
ε_c~1 GeV/fm^3, T_c~160 MeV

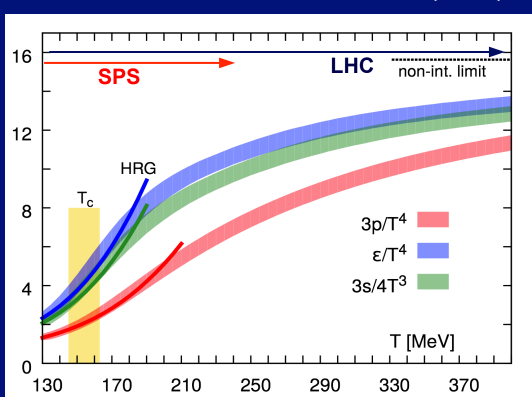
Large μ_B, moderate T (field th.)

QCD critical point,
1st order transition

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

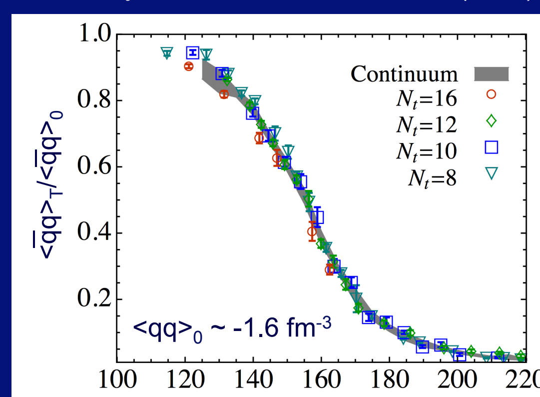
QCD mass (u,d) dominant in the visible part of the Universe

Hot QCD coll., arXiv:1407.6387 (2014)



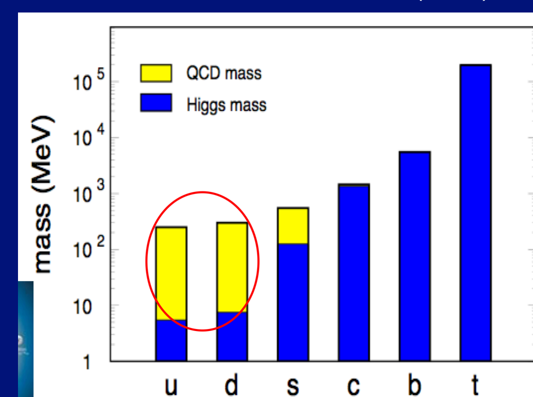
deconfinement transition

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



chiral symmetry restoration

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



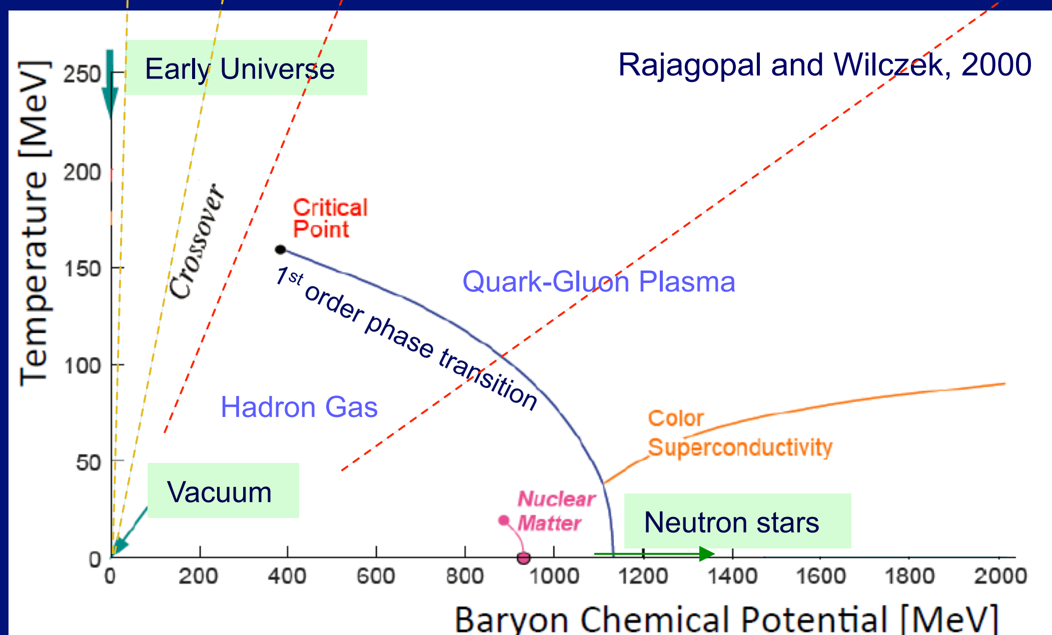
chiral symmetry breaking:
masses of the 6 quark flavours

Lattice QCD, μ_B=0

QCD phase diagram and accelerator energies

Very high energies, central production
(LHC; RHIC)

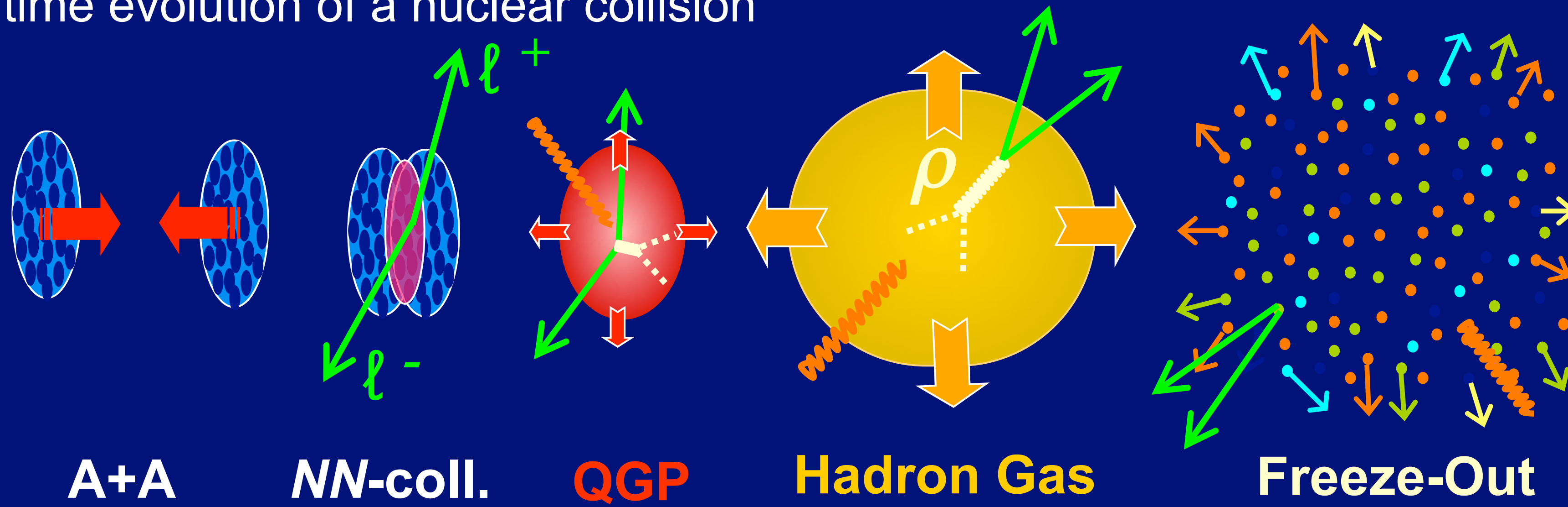
Moderate and low energies:
SPS
(BES-RHIC; FAIR; NICA)



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

Observables and physics goals: dilepton production

time evolution of a nuclear collision



“Hubble” expansion: T= 240→170 170→110 ~110 (MeV)

Lepton pairs emitted at all stages; no final state interactions

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

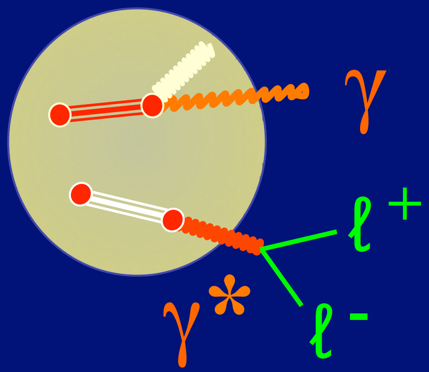
NN-collisions: Drell-Yan, $D\bar{D}$ pairs (physical background)

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)

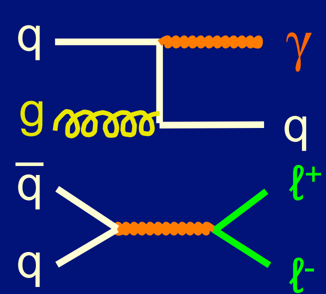
for flat spectral functions, i.e. for hadron-parton duality (M>1.5 GeV)

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

the only Lorentz-invariant thermometer of the field

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

lowest order rate ~ α_{em}^2

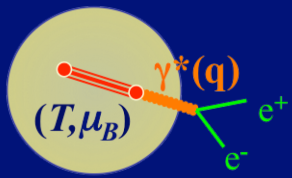


QCD Compton

$q\bar{q}$ annihilation

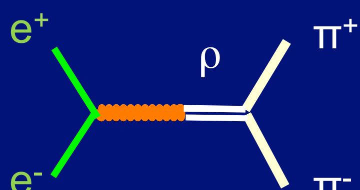
dileptons more rich and more rigorous than photons

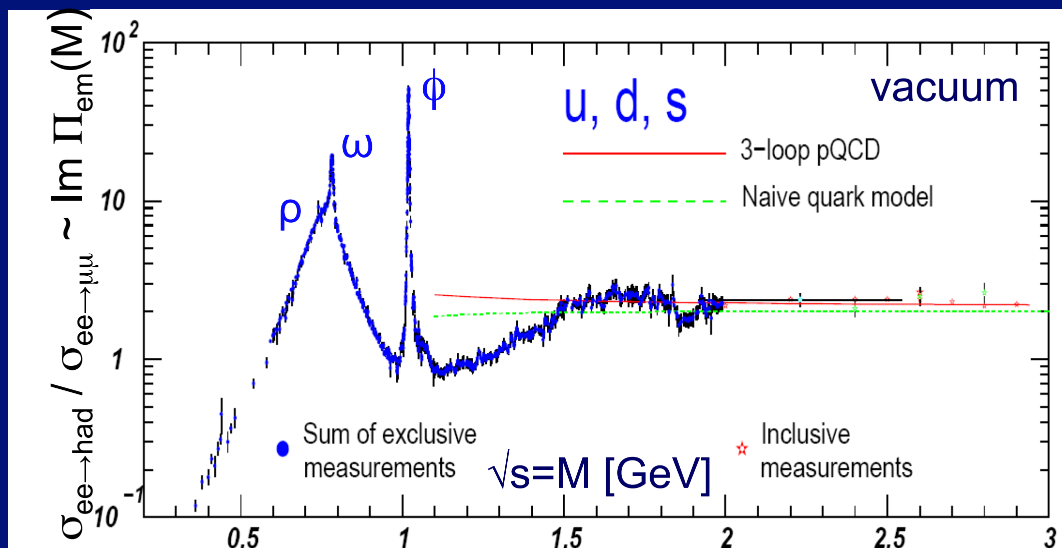
Dilepton Rate in a strongly interacting medium

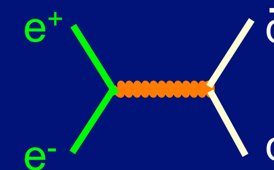


$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T) \times \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

photon self-energy







non-perturbative
in-medium
spectral function(s)

$\mathrm{Im}\Pi_{em} \sim \mathrm{Im}\, D_\rho + \ldots$

perturbative
hadron-parton
duality (flat SF)

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

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

hadron basis
M<1.5 GeV

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

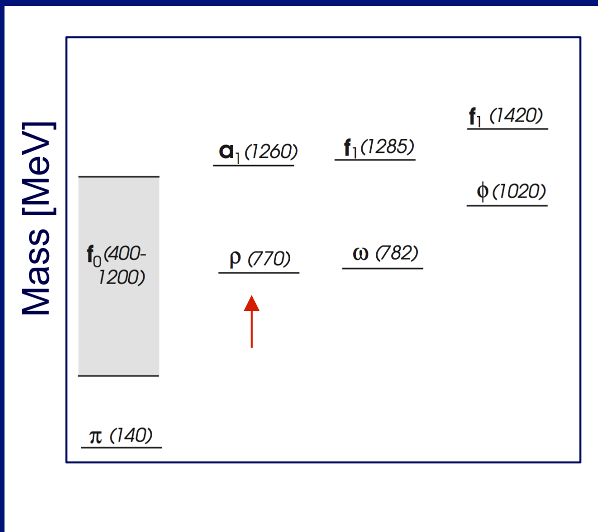
M>1.5 GeV

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

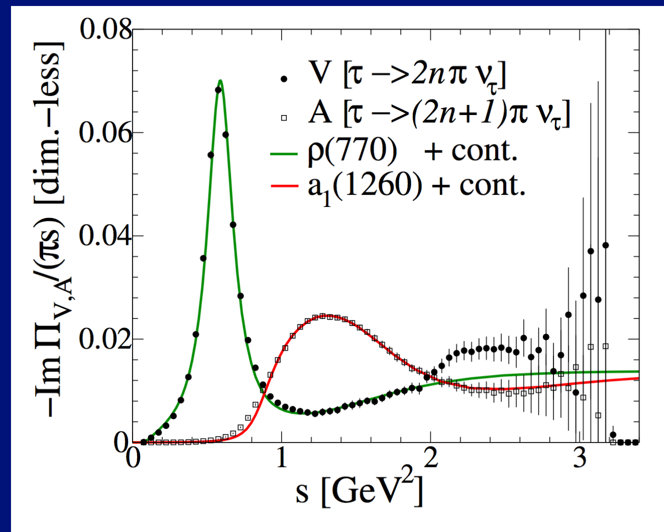
'Planck-like'→ thermometer
distinguishes partons and hadrons

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

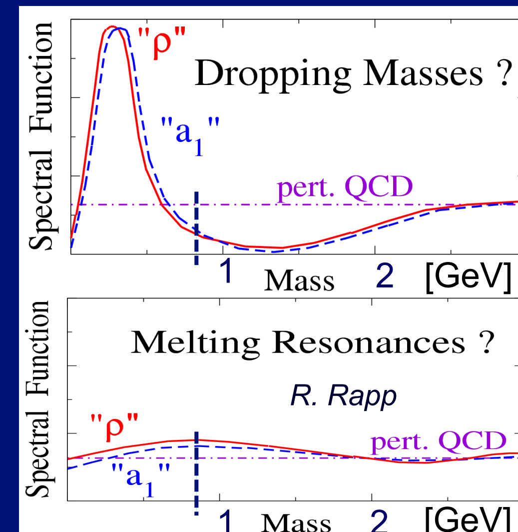
P-S, V-A splitting in the physical vacuum due to spontaneous breaking of chiral symmetry



Splitting of chiral partners

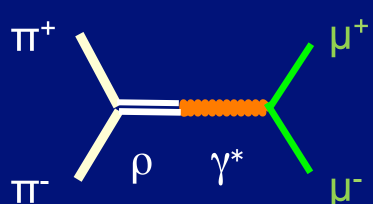


ALEPH data: Vacuum



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 τ_ρ =1.3 fm << $\tau_{collision}$ > 10 fm (unique in the PDG)
- continuous "regeneration" by $\pi^+\pi^-$ → sample in-medium evolution

axial vector a_1 (1^{++}) accessible through chiral mixing ($\pi\, a_1 \rightarrow \mu^+\mu^-$, '4π')

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

Selected theoretical references (status 2005)

	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

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)

chiral mixing a_1 'visible' in $\ell^+\ell^-$ channel (direct probe)

Common to both transitions

beam energy scan (below √s of 20 GeV/u)

onset of transitions
order of transitions
critical point
(structure in scan; extended τ_{FB})

Experiments and Results

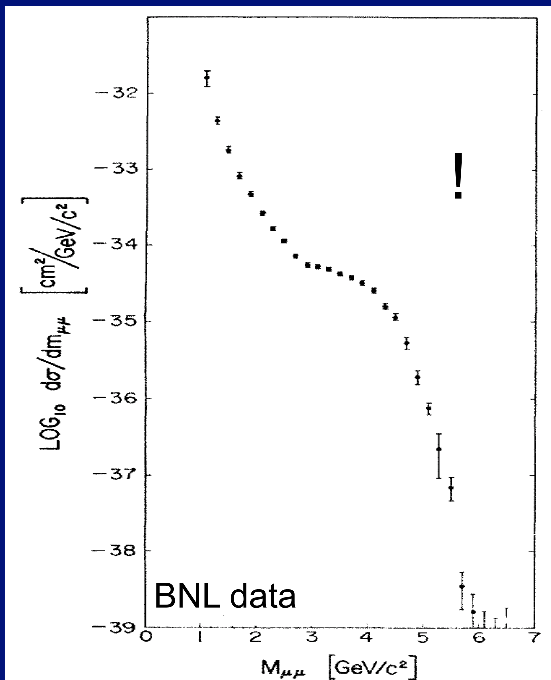
Roots of Heavy Ion Physics at the CERN SPS

Colloquium CERN 60th, H. Specht, 2014

	Worksh./Conf.	Accelerators	Physics	Persons/Actions
1974	Columbia (BeV/u Coll. of HI)	BEVALAC LBL (1st beam)	EoS Compress. Nucl. Matt.; π Condensates	Contract LBL-GSI (Grunder-Bock,Stock)
1975 -1978	LBL and GSI (alternating)	Start ISR Discuss. (Pugh/Santa Fe')	First ideas on QGP Cabibbo/Parisi 1975 Dileptons in pp	CERN DG L. van Hove (1977)
1979	Pre QM LBL	VENUS Prop. LBL SIS100 Prop. GSI	↓	M.Jacob,B.Willis et al.
1980	'I QM' GSI		αα collisions ISR	PS LoI GSI/LBL SPS Disc. LvH/BW/HS
1981	BNL (ISABELLE)	SIS12/100 Prop. GSI Start SPS Discussion		CERN DG H. Schopper
1982	II QM Bielefeld (M.Jacob/H.Satz)	ISR to be stopped (CERN Council)		PS Prop. Stock et al. (^{16}O ECR ion source)
1983	III QM BNL	ISR last run	Dileptons in pp (R807/808)	SPS LoI Willis et al. Contract CERN/GSI/LBL
1984	IV QM Helsinki	SPS-CERN firm AGS-BNL firm SIS18-GSI firm		Approval of 1st Gen. Experiments at SPS

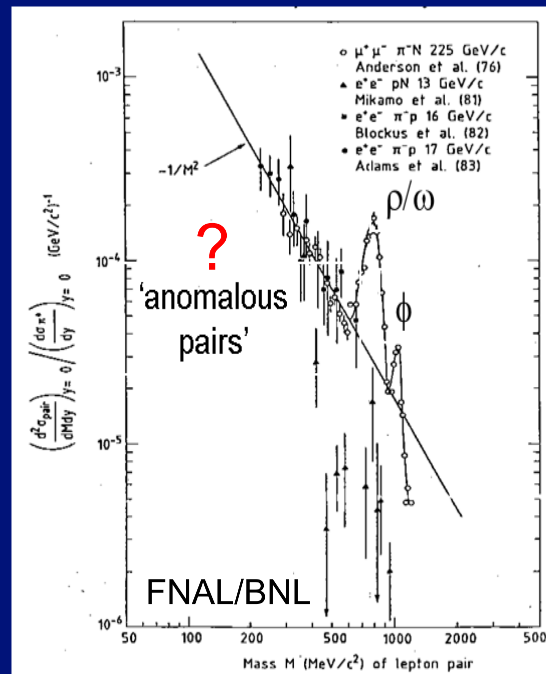
The 1970's: dilepton experiments in pp and theoretical ideas

Lepton pair data in the IMR
Christenson et al., PRL 1970



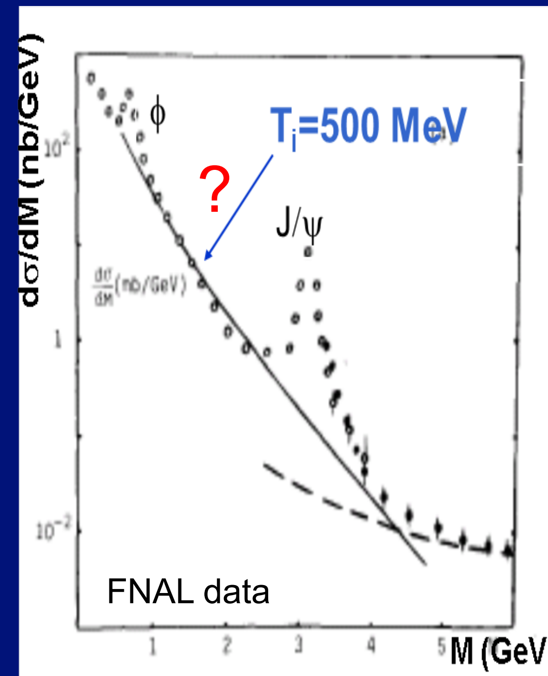
Drell/Yan, PRL 1970
hard production from valence and sea quarks

Lepton pair data in the LMR
Anderson et al., PRL 1976
(Summary HJS, QM1984)



Bjorken/Weisberg, PRD 1976
dileptons from produced ('wee') partons
> Drell-Yan by factors of 10-100

Lepton pair data in the IMR
Branson et al., PRL 1977

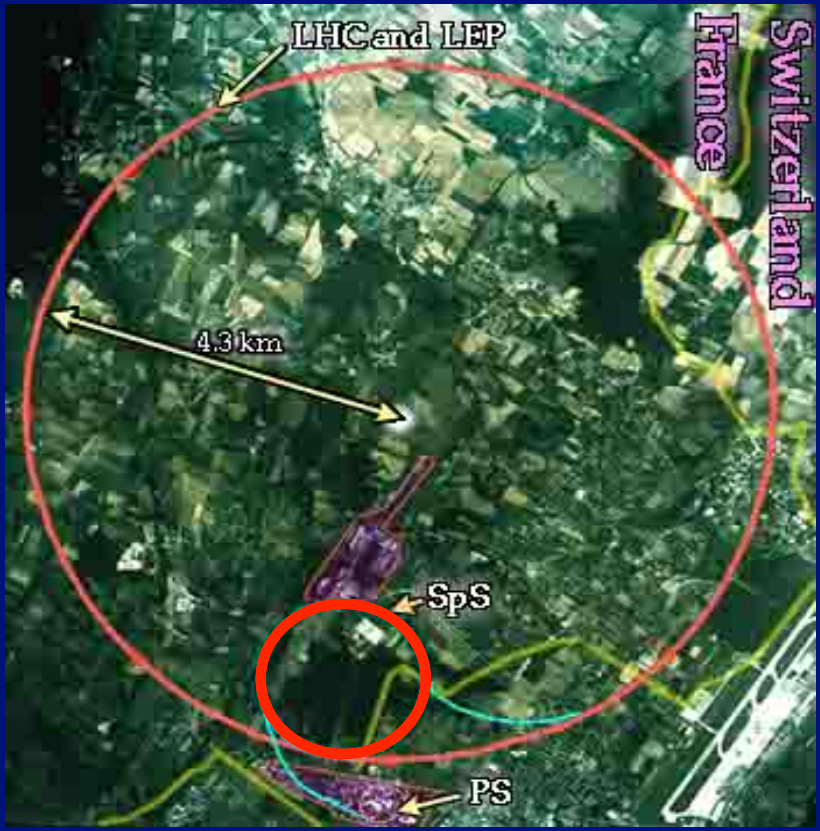


E.Shuryak, PLB 1978
thermal dileptons from 'Quark Gluon Plasma'

Problematic data, but milestones in theoretical interpretation

First theory paper on 'Quark Matter' (T-μ_B plane): *M.Cabibbo/G.Parisi PLB 1975*

Dilepton 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

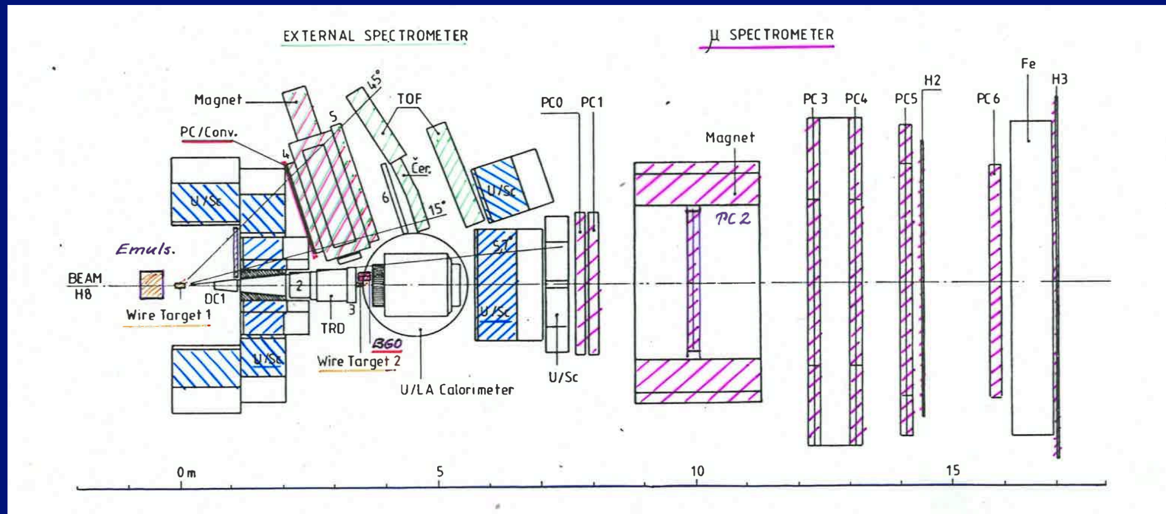
First-generation Experiments ('Recuperation Era')

Experiment	Detectors	approved
NA34-2	4π calorim.,Si, hadron spectrom., dimuons, γ's (U-scint.cal. + NaI R807/808, NA3 spectrom.,…)	11/1984
NA35	streamer chamber, mid-rapidity calorim.,… (NA5 str.ch.+cal., magn. WA78, NA24 γ PPD,…)	11/1984
NA36	TPC, calorim., → strange mesons, hyperons (EHS+new TPC,…)	11/1984
NA38	dimuon spectrom., → thermal radiation, charmonia (NA10+active target + EM cal.,…)	09/1985
WA80	plastic ball, EM calorimeters, multiplicity detect. (plastic ball GSI/LBL, Pb-glass,…)	09/1985
WA85/ WA94	Ω' spectrometer, → strange mesons, hyperons (Ω' spectrometer + RICH)	04/1987

1st and 2nd generation Experiments 1984-2000 (LMR)

NA34-1
(1984)
N.McCubbin

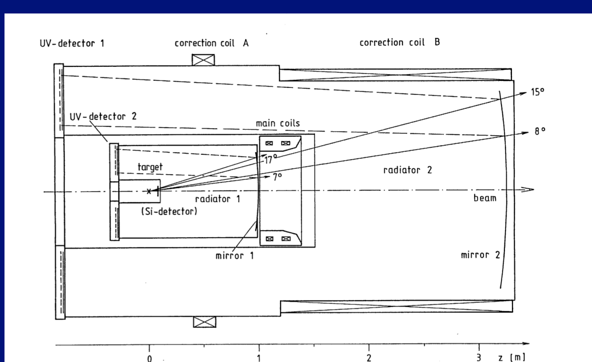
pBe collisions
e^+e^-, $\mu^+\mu^-$,
$e\mu$, γ



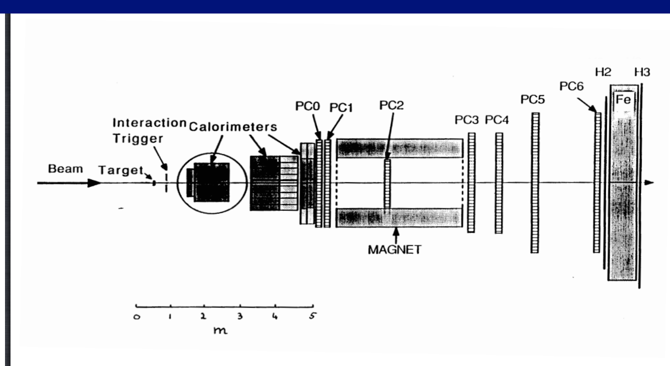
NA34-2
(1984)
H.Specht

AA collisions
($\mu^+\mu^-$), γ
hadrons

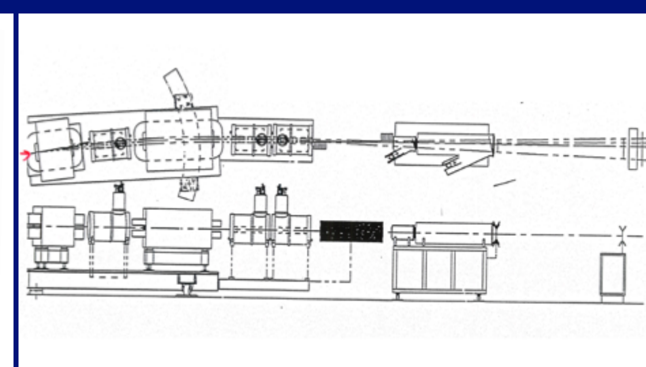
2 years after the first O beam 1986



NA45 (1989), e^+e^-
H.Specht

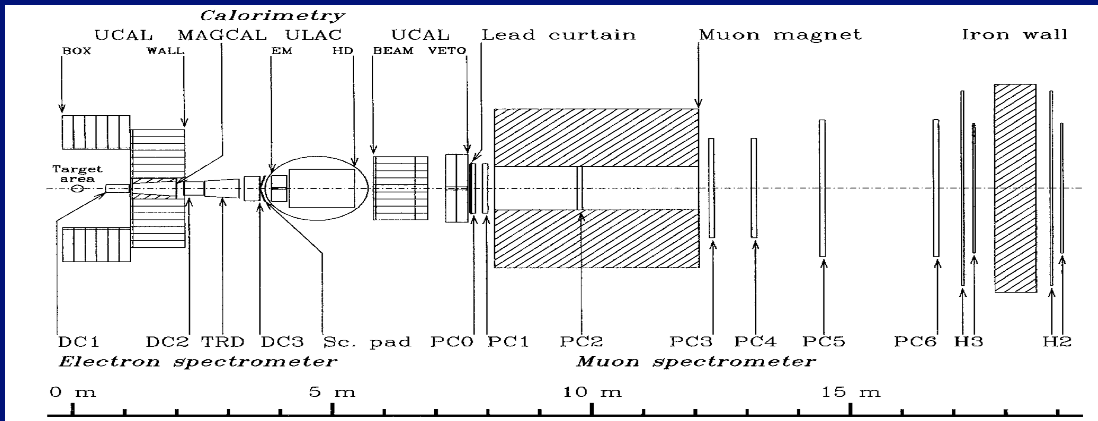


NA34-3 (1989), $\mu^+\mu^-$
G.London



NA44 (1989), hadrons
H.Bøggild

Example of results from NA34-1: 'anomalous' dileptons



much reduced set-up compared to NA34-2

restricted to e^+e^-, $\mu^+\mu^-$, $e\mu$, γ

η-Dalitz determined by $\eta \rightarrow \mu^+\mu^-\gamma$

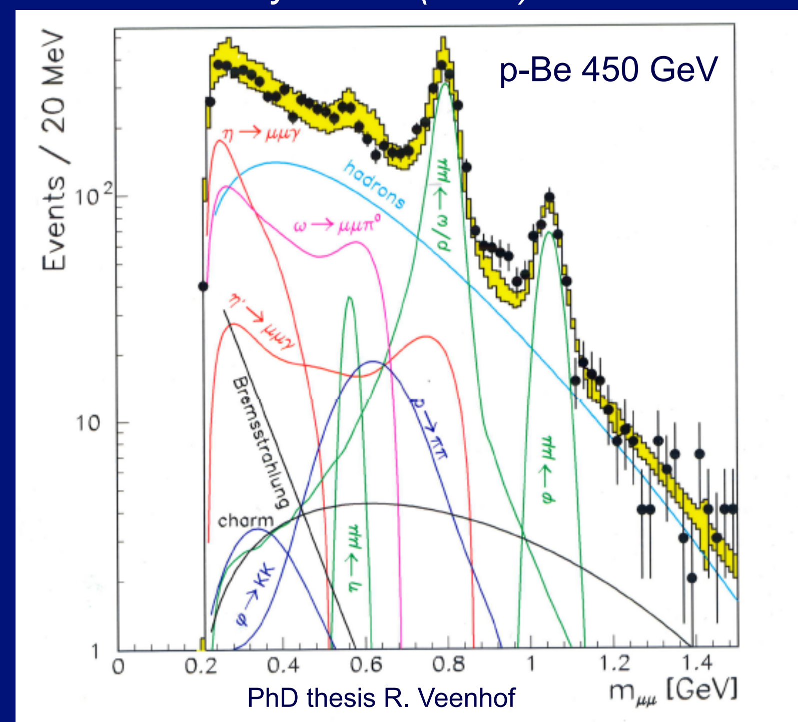
→ underestimate of η-Dalitz in all previous experiments (but not in pp at the ISR)

no LMR excess in p-Be within errors

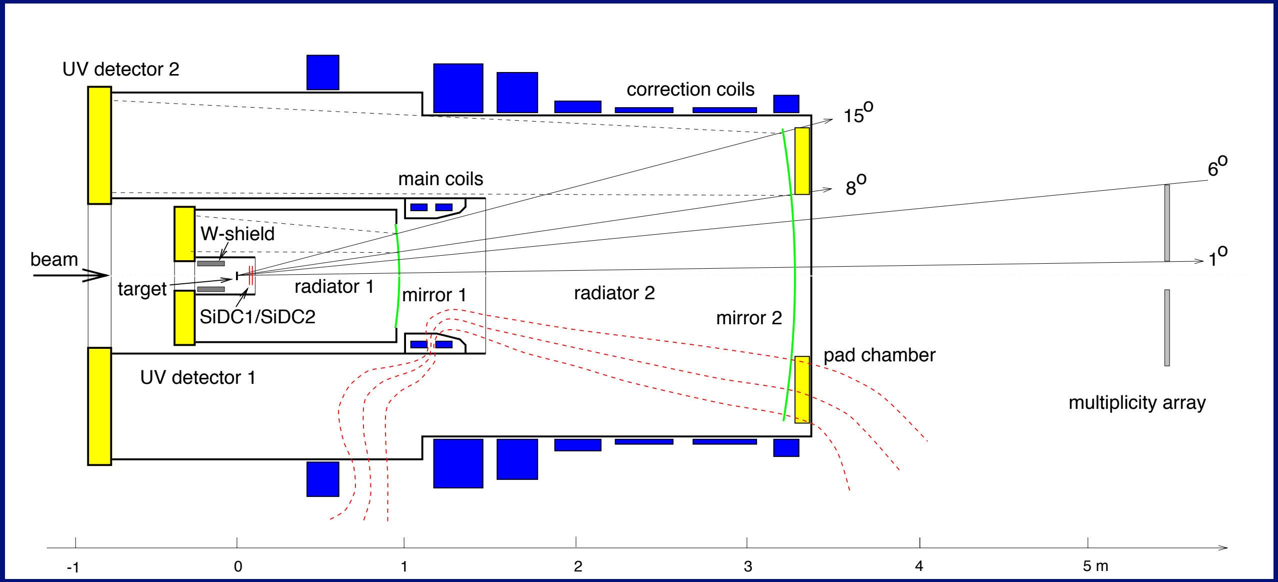
→ no 'anomalous' dileptons in low-energy p-Be (pp-like)

later confirmed by CERES/NA45 in p-Be and p-Au (Eur.Phys.J C 4,1998,249)

Z.Phys.C 68 (1995) 47



Dedicated di-electron spectrometer: CERES/NA45

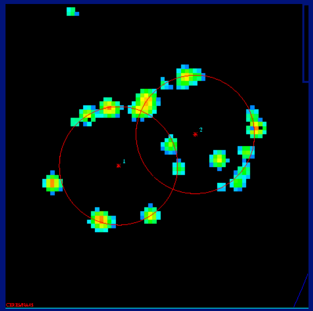


Pioneering experiment built 1989-1991

focused on Low Mass Region (LMR)

Running periods:

- 1992-1993
  ^{32}S and proton beams
- 1995-1996
  ^{208}Pb beams

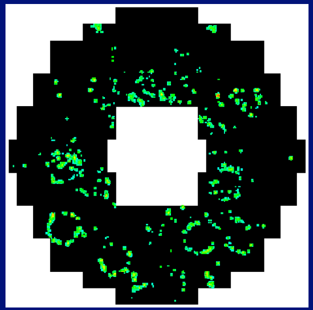


Cherenkov rings

Original set-up (p and ^{32}S):
puristic hadron-blind tracking with 2 RICH detectors

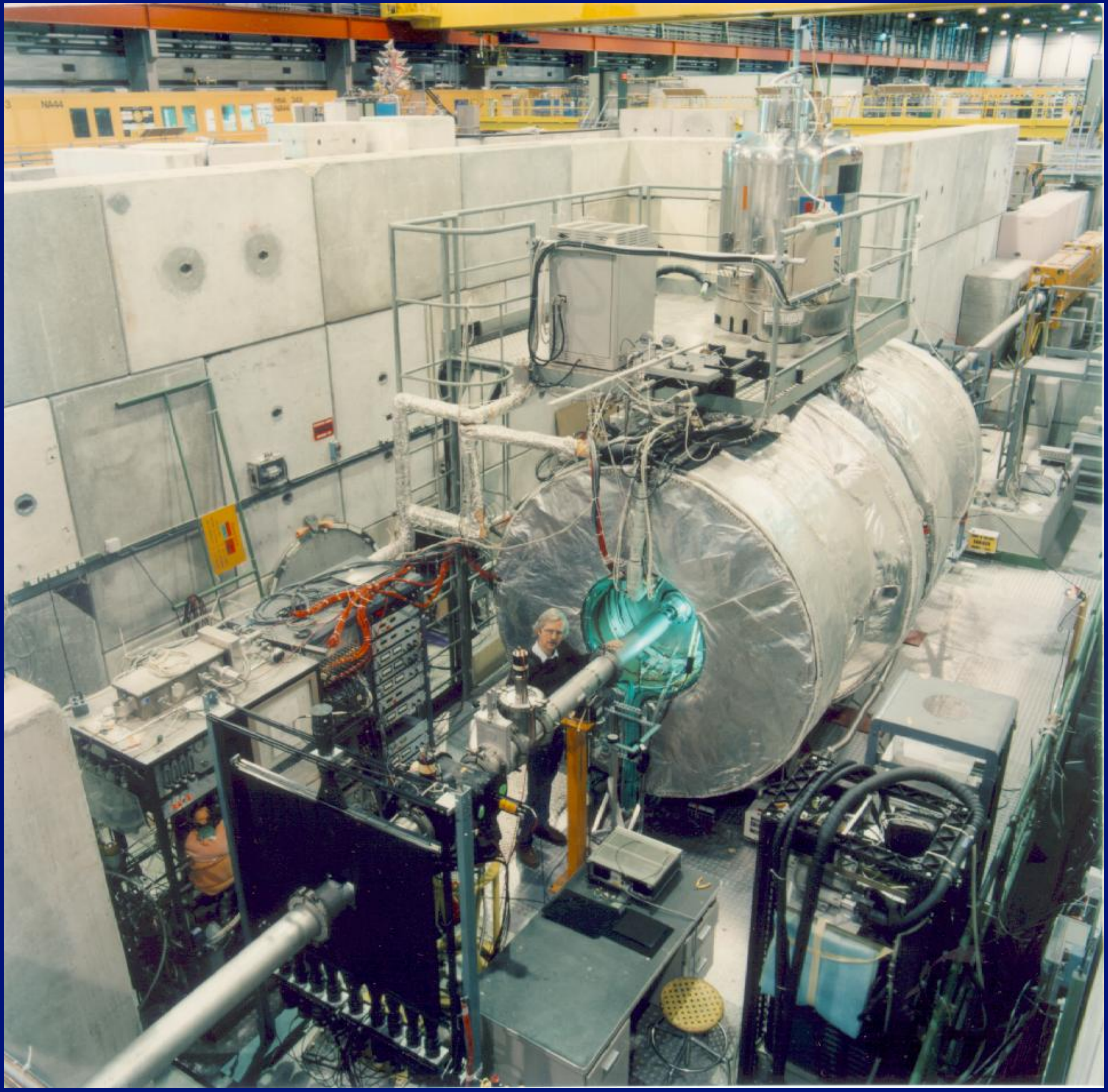
Later addition (^{208}Pb):
2 SiDC detectors + pad (multi-wire) chamber

Low field (air coils), limited tracking → limited resolution
slow detectors, no trigger → very limited statistics



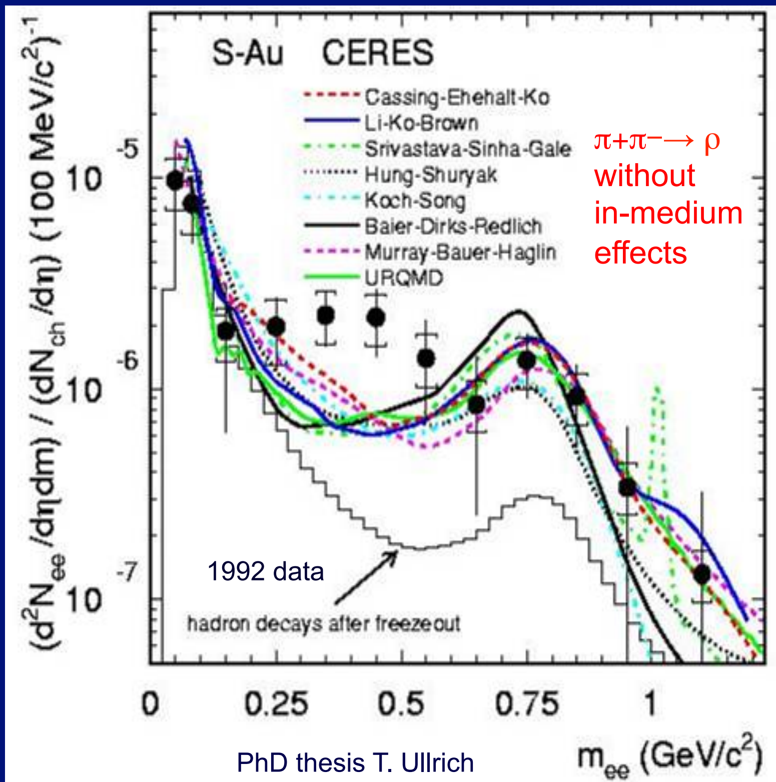
Cherenkov rings in RICH1

CERES setup 1994



CERES/NA45 results for S-Au

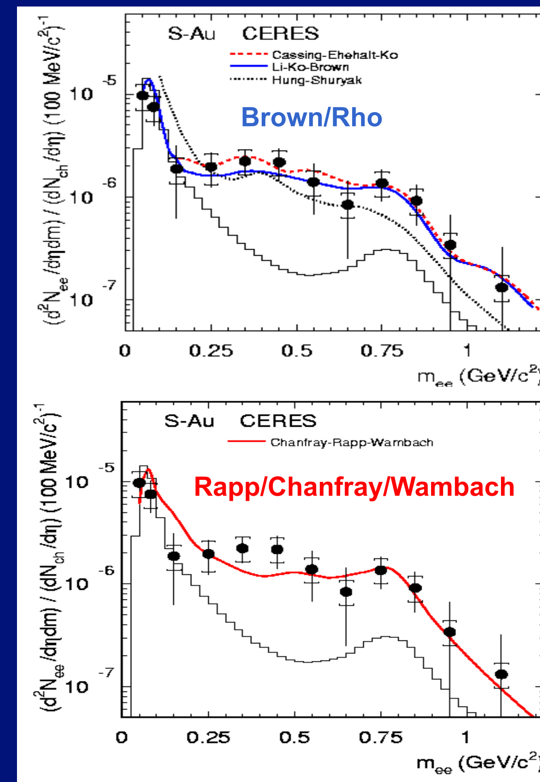
Data: QM'95; Phys.Rev.Lett.75 (1995)1272



A. Drees, QM'96, NPA 610 (1996) 436c

'First' clear sign of new physics in LMR

Li,Ko,Brown, NPA 606 (1996) 568



R/C/W, NPA 617 (1997) 472

strong excess of dileptons above meson decays

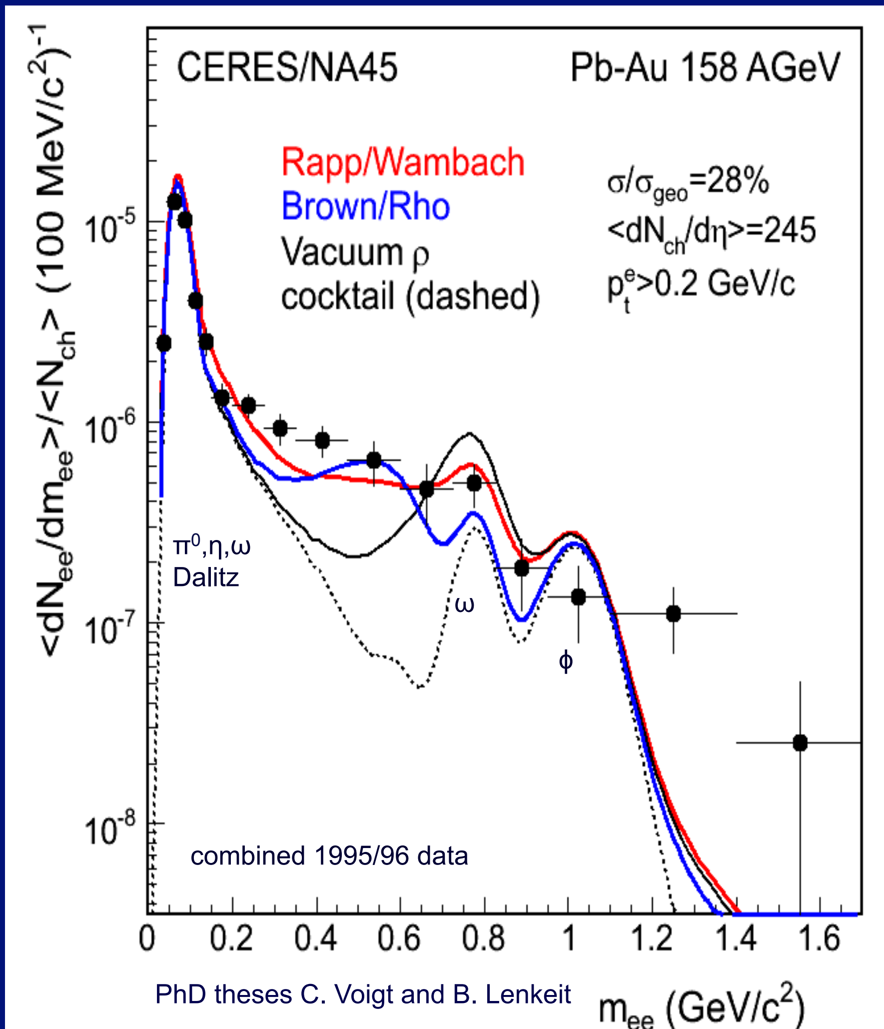
enormous boost to theory: 534 citations, most cited SPS paper (orig.data)

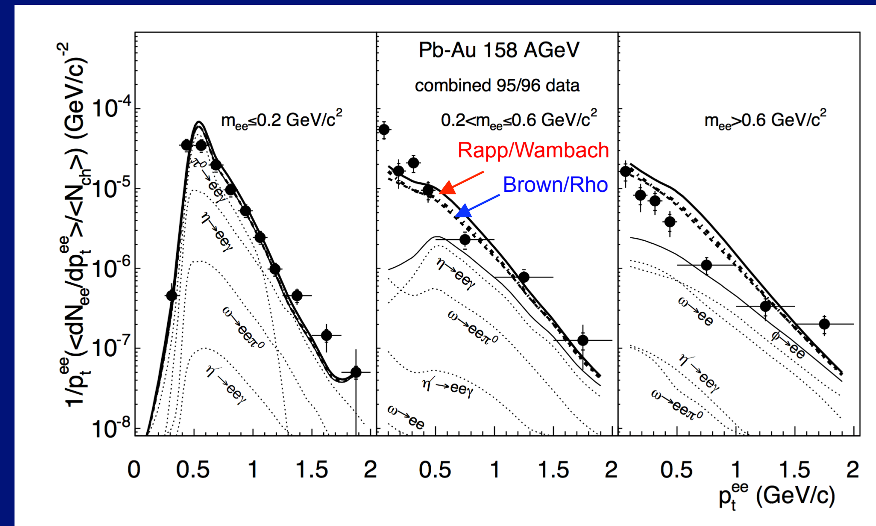
surviving interpretation: $\pi^+\pi^- \rightarrow \rho^* \rightarrow e^+e^-$, but in-medium effects required

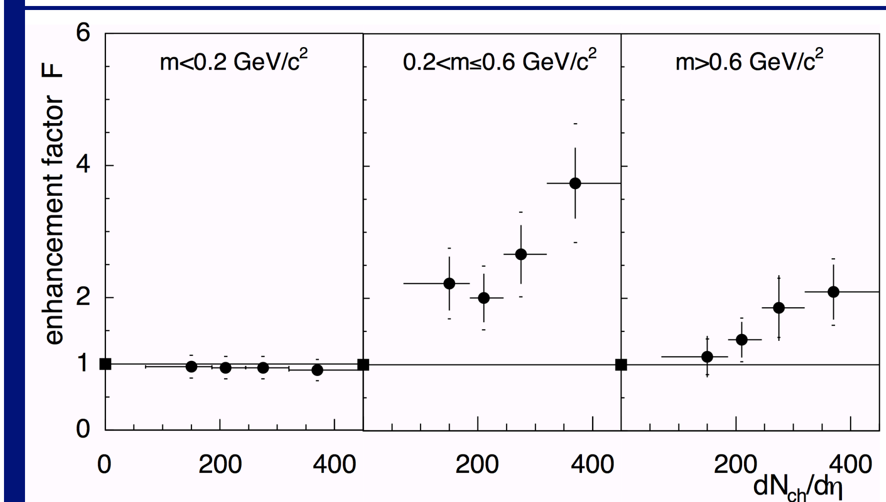
lasting ambiguity (10 a): mass shift and broadening indistinguishable

CERES/NA45: Summary of the Pb-beam results

[PLB 422 (1998) 405; NPA 661 (1999) 23c]; Eur. Phys. J C 41 (2005) 475-513





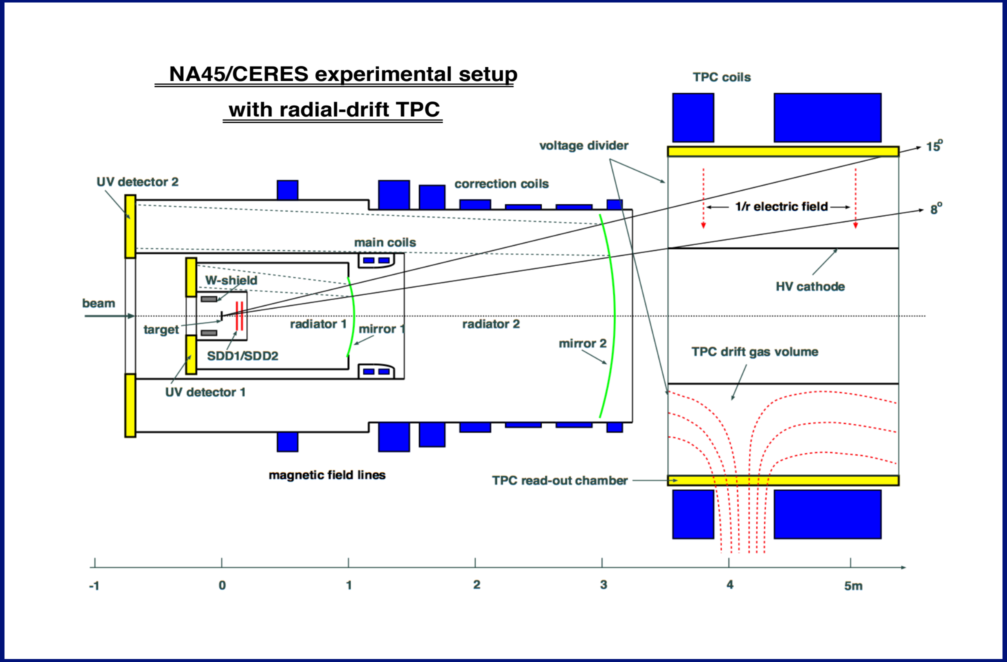


Resolution and statistical accuracy improved, but
mass shift and broadening still indistinguishable

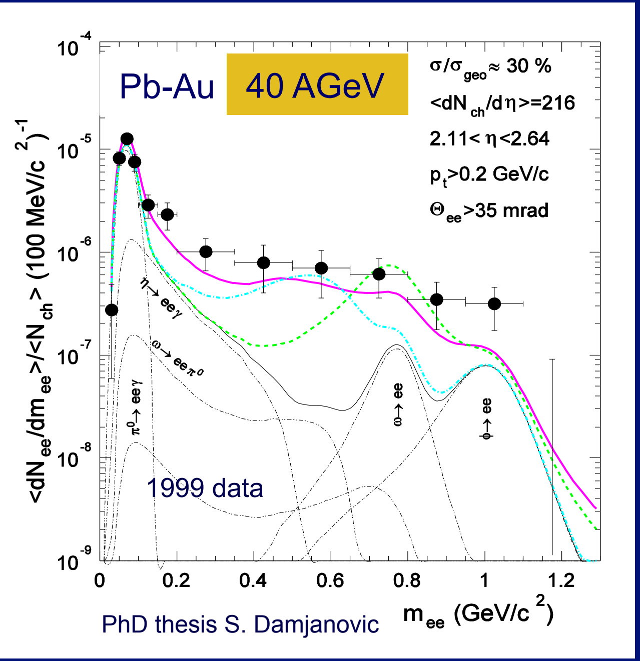
Upgraded CERES setup including a TPC (1999)

First run at 40AGeV → only dilepton data at low beam energies so far

Set-up 1999 (spokesperson J. Stachel)



Phys. Rev. Lett. 91 (2003) 042301



- - - - vacuum ρ
-·-·- Brown-Rho scaling
—— broadening of ρ

Addition of TPC with radial drift

- slightly improved mass resolution
- dE/dx → hadron identification
  improved electron ID

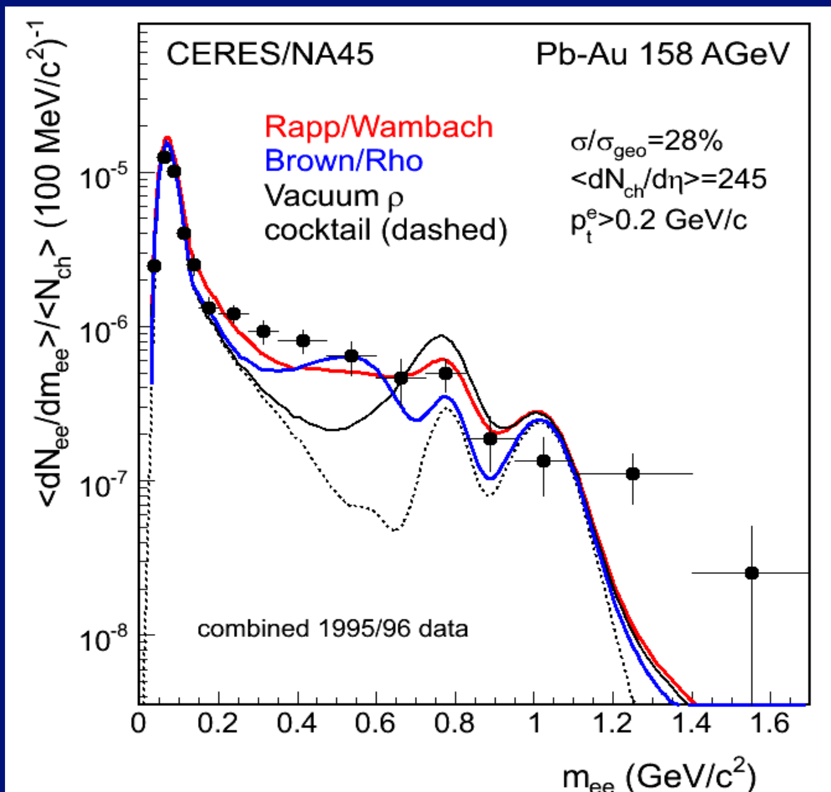
Runs in 1999/2000 at 40/158 AGeV

Enhancement relative to hadron decays:
5.9±1.5(stat.)±1.2(syst.)

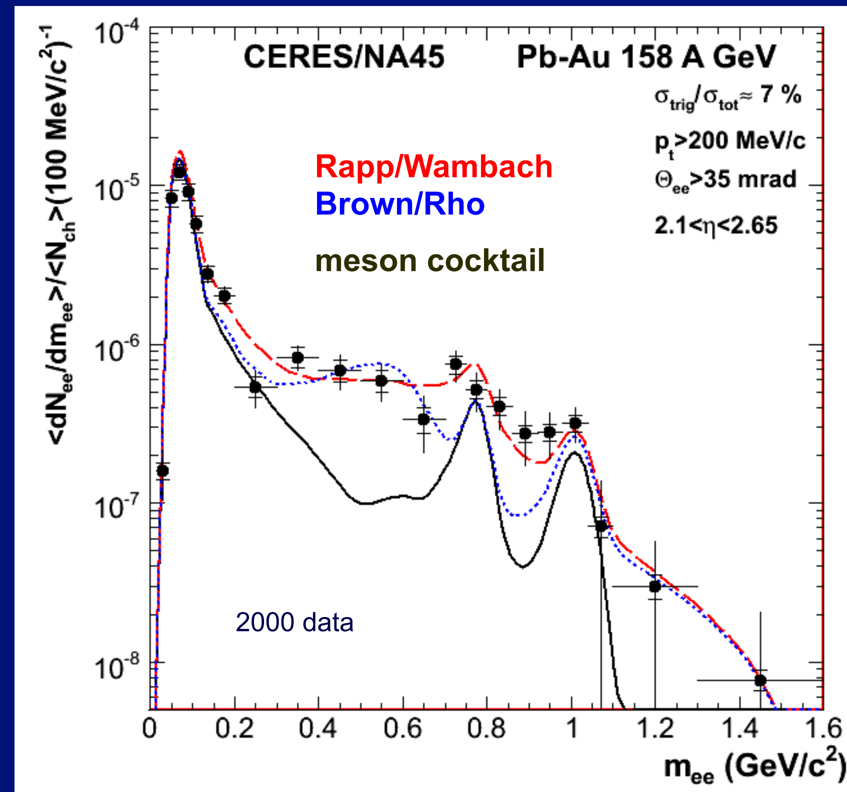
Higher baryon density at lower energy (40 AGeV) → increased enhancement

Result at 158AGeV for the upgraded (TPC) setup

Eur. Phys. J C 41 (2005) 475



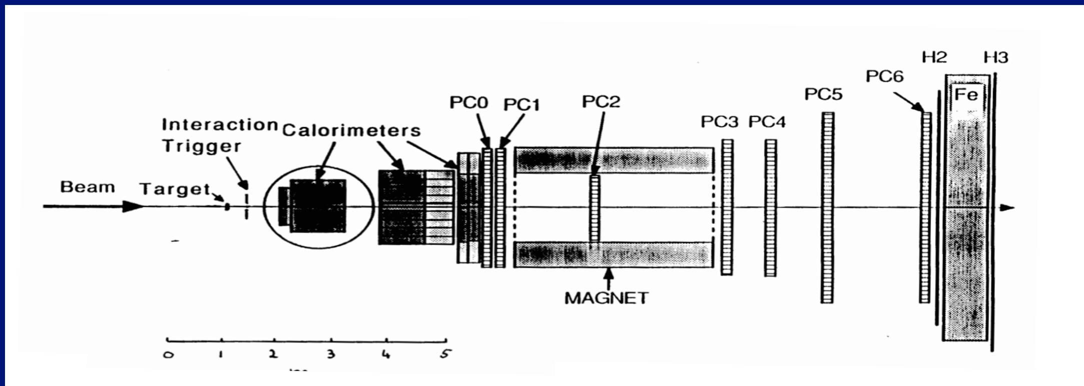
QM2005; Phys.Lett.B 666 (2008) 425



Improved mass resolution (4% vs. 6.5%) → ω and ϕ well separated

"… between the ω and ϕ, the data clearly favor the broadening scenario…"

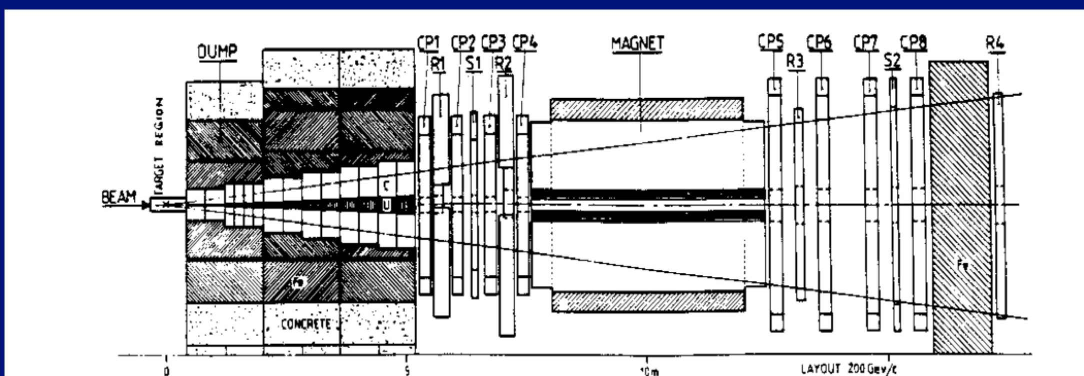
1st and 2nd generation Experiments 1985-2000 (IMR)



NA34-3 (1989)
G.London

Full mass range

Only S-beam

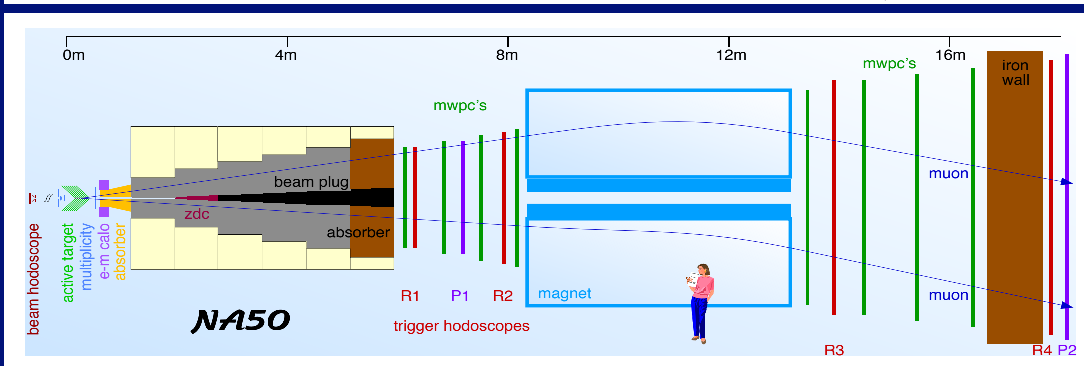


NA38 (1985)
L.Kluberg

Dual goal:

Charmonia

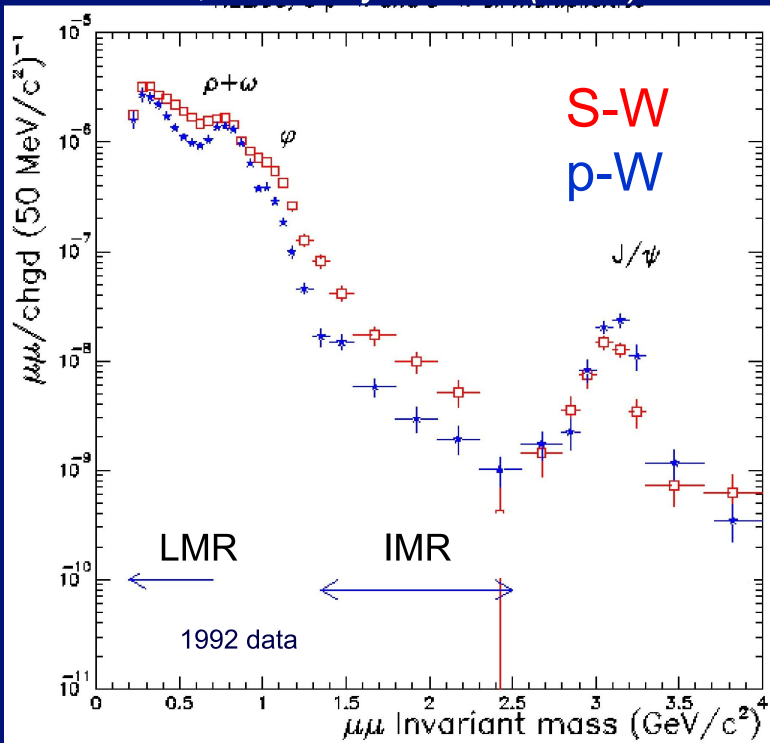
Hard dimuon continua



NA50 (1992)
L.Kluberg

HELIOS/NA34-3 diumuon results for S-W

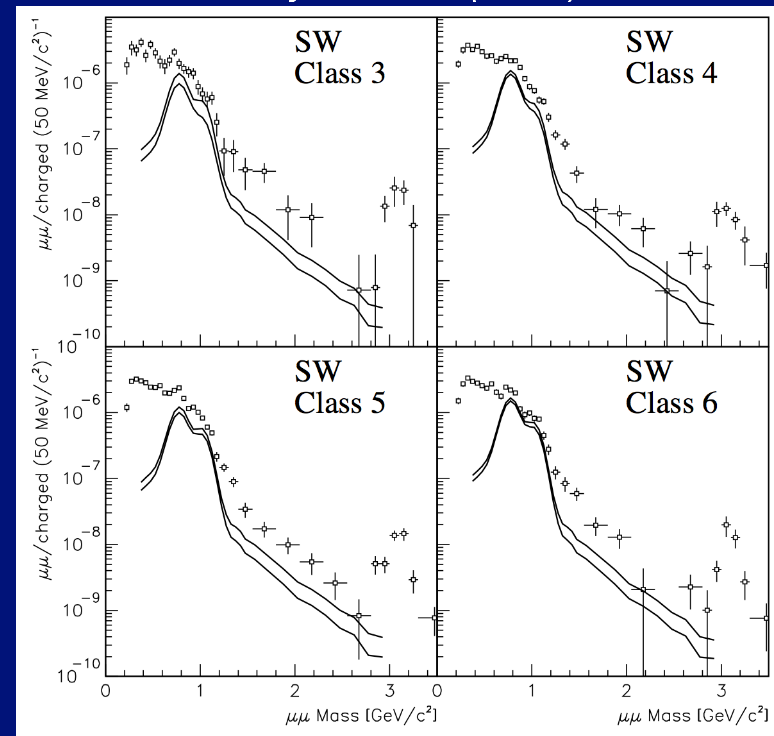
QM95, Nucl.Phys. A590 (1995) 93c



Excess dileptons in LMR and IMR relative to p-W, but LMR not really explored (resolution, forward y,...)

'First' clear sign of new physics in IMR

Eur. Phys. J C13 (2000) 433

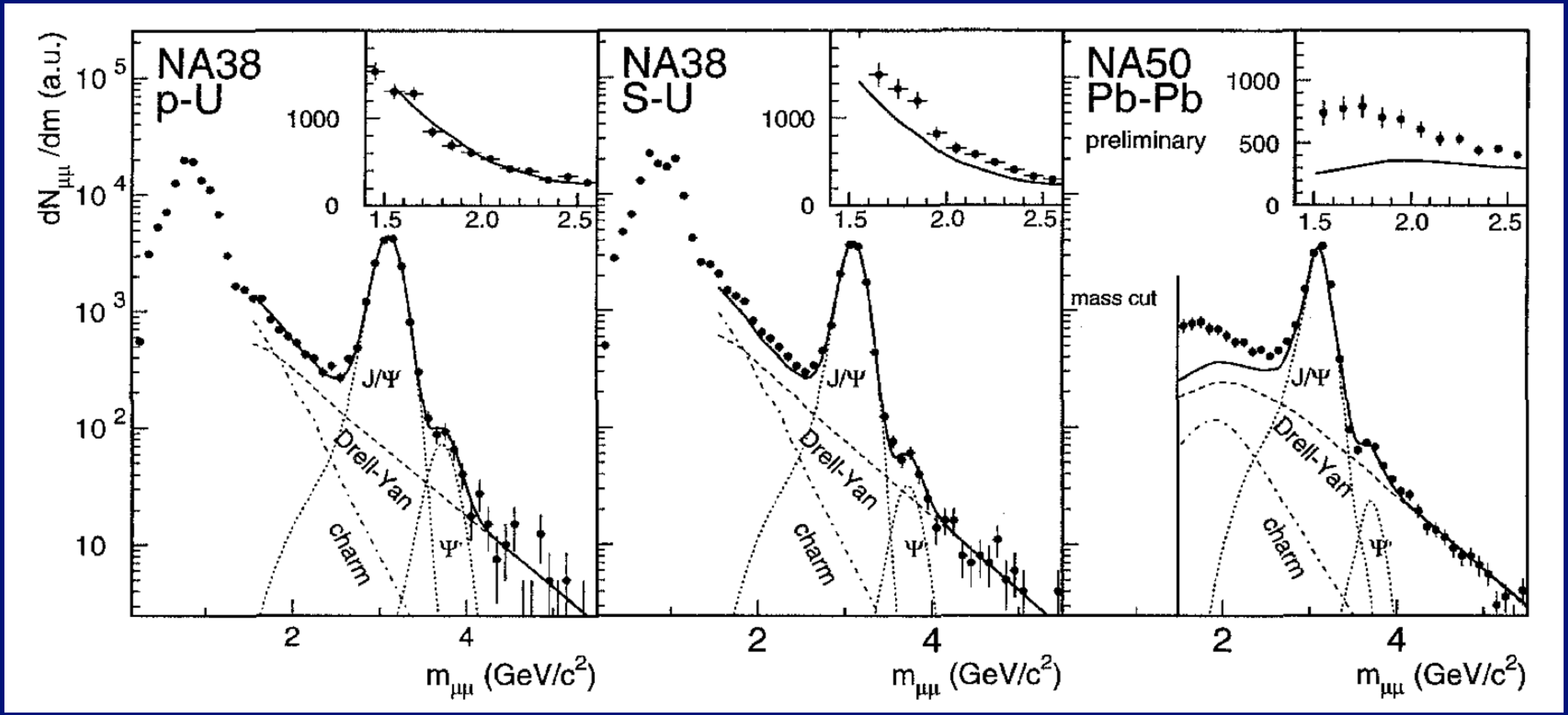


Excess in IMR relative to known sources vectors mesons, open charm and Drell-Yan quantified

Quantitative theoretical description of IMR excess by Lee and Gale, PRL 81 (1998) 1572. Leading source found to be $\pi a_1(4\pi) \rightarrow \mu^+\mu^-$ via chiral (V-A) mixing QGP formation not considered

Early NA38 and NA50 results compared

NA38: C.Lourenco PhD thesis (1995); NA50: QM'96, Nucl. Phys. A 610 (1996) 331c

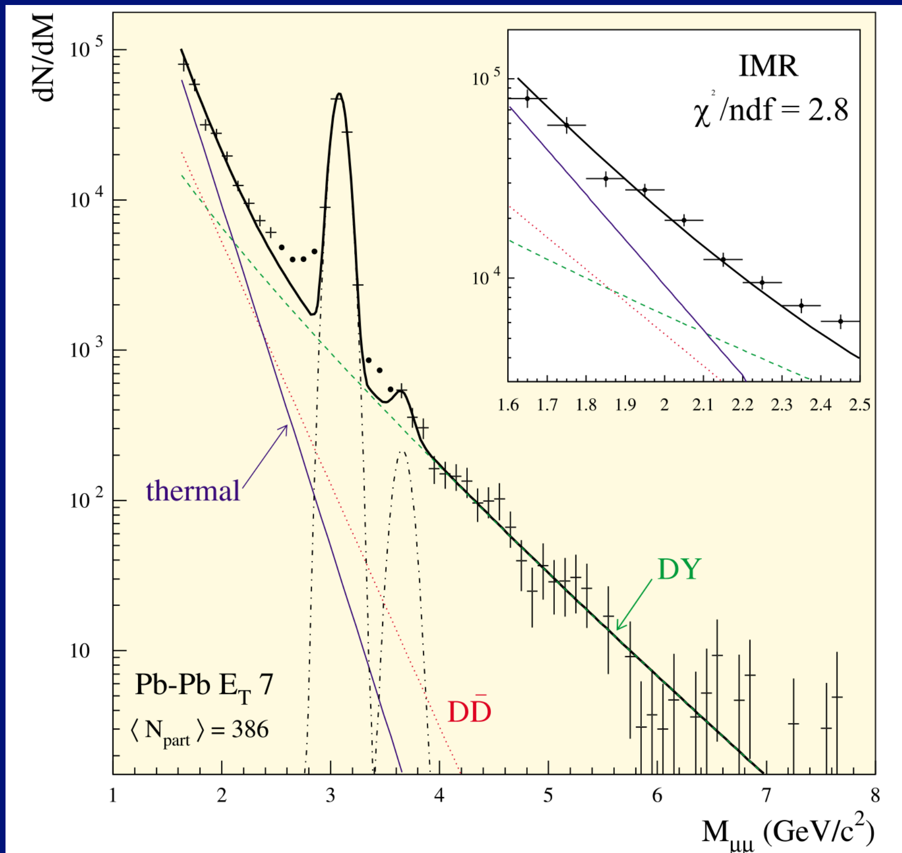


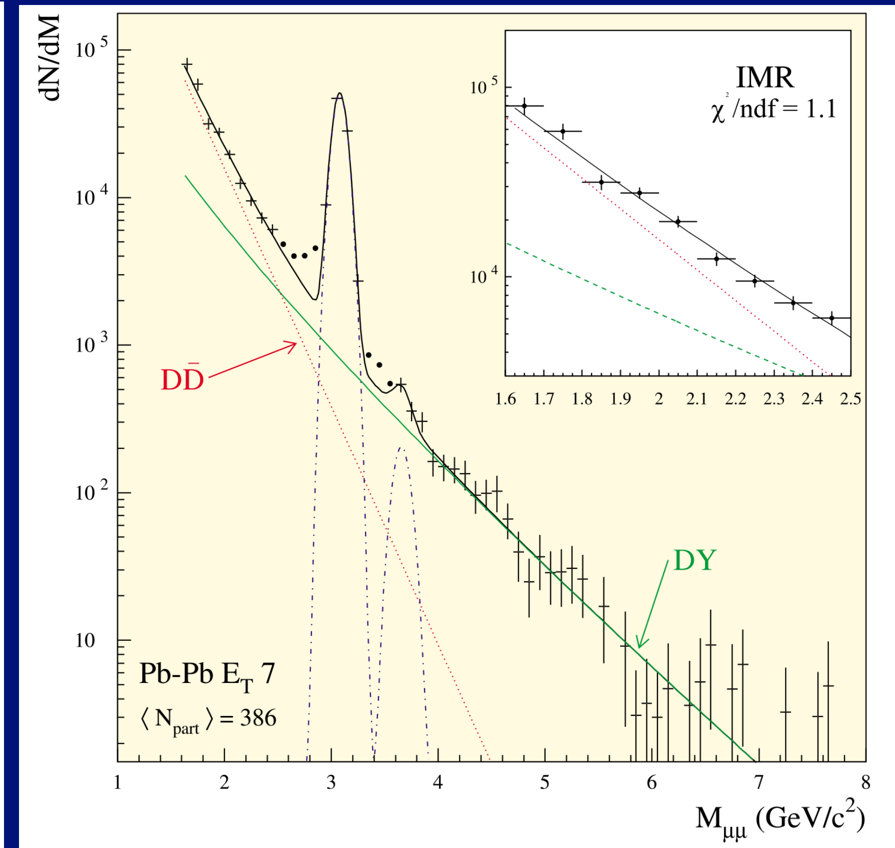
Compilation: A. Drees, QM'96, Nucl. Phys. A 610 (1996) 436c

Clear enhancement above the known sources (Drell-Yan and open charm), rising from 1.3 in S-U to 2 in Pb-Pb

Final NA50 dimuon results for Pb-Pb

L.Capelli et al., QM2001, Nucl.Phys.A 698 (2002); final publ. draft on NA50 web page





Thermal radiation (T_i=190 MeV)

Rapp and Shuryak, PLB 473 (2000) 13

Enhanced open charm production

Ambiguity between thermal radiation and enhanced open charm ($D\overline{D}$)

Press Conference – ‘New State of Matter created at CERN’

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

PR01.00
10.02.00

New State of Matter created at CERN

At a special seminar on 10 February, spokespersons from the experiments on CERN's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Professor Luciano Maiani, CERN[1] Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*

The aim of CERN's Heavy Ion programme was to collide lead ions so as to create immensely high energy densities which would break down the forces which confined quarks inside more complex particles. A very high energy beam of lead ions (33 TeV) was accelerated in CERN's Super Proton Synchrotron (SPS) and crashed into targets inside the seven different experimental detectors. The collisions created temperatures over 100 000 times as hot as the centre of the sun, and energy densities twenty times that of ordinary nuclear matter, densities which have never before been reached in laboratory experiments. The collected data from the experiments gives compelling evidence that a new state of matter has been created. This state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma, the primordial soup in which quarks and gluons existed before they clumped together as the universe cooled down.

The lead beam programme started in 1994, after the CERN accelerators has been upgraded by a collaboration between CERN and institutes in the Czech Republic, France, India, Italy, Germany, Sweden and Switzerland. A new lead ion source was linked to pre-existing, interconnected accelerators, at CERN, the Proton Synchrotron (PS) and the SPS. The seven large experiments involved measured different aspects of lead-lead and lead-gold collisions. They were named NA44, NA45, NA49, NA50, NA52, WA97/NA57 and WA98. Some of these experiments use multipurpose detectors to measure and

[1] CERN, the European Laboratory for Particle Physics, has its headquarters in Geneva. At present, its Member States are Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom. Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO have observer status.

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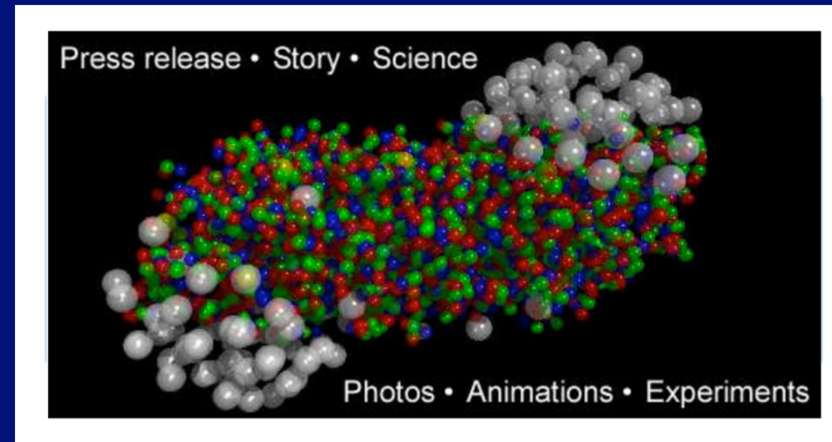
Press Release



Preparatory Workshop Chamonix 1998

Press Conference CERN, 10 Feb. 2000

CERN DG L. Maiani
Talks by all experiments
Paper PR01 U. Heinz and M. Jacob

‘White Paper’- U. Heinz and M. Jacob
(arXiv:nucl-th/0002042v1 16 Feb. 2000)

CERN Courier, April 2000

Press Conference – ‘New State of Matter created at CERN’

‘White Paper’- U. Heinz and M. Jacob, 2000

“It walks like a duck, it quacks like a duck, . . . ”:

which more than 99.9% are hadrons. Evidence for or against formation of an initial state of deconfined quarks and gluons at the SPS thus must be extracted from a careful and quantitative analysis of the observed final state.

A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.

. . .

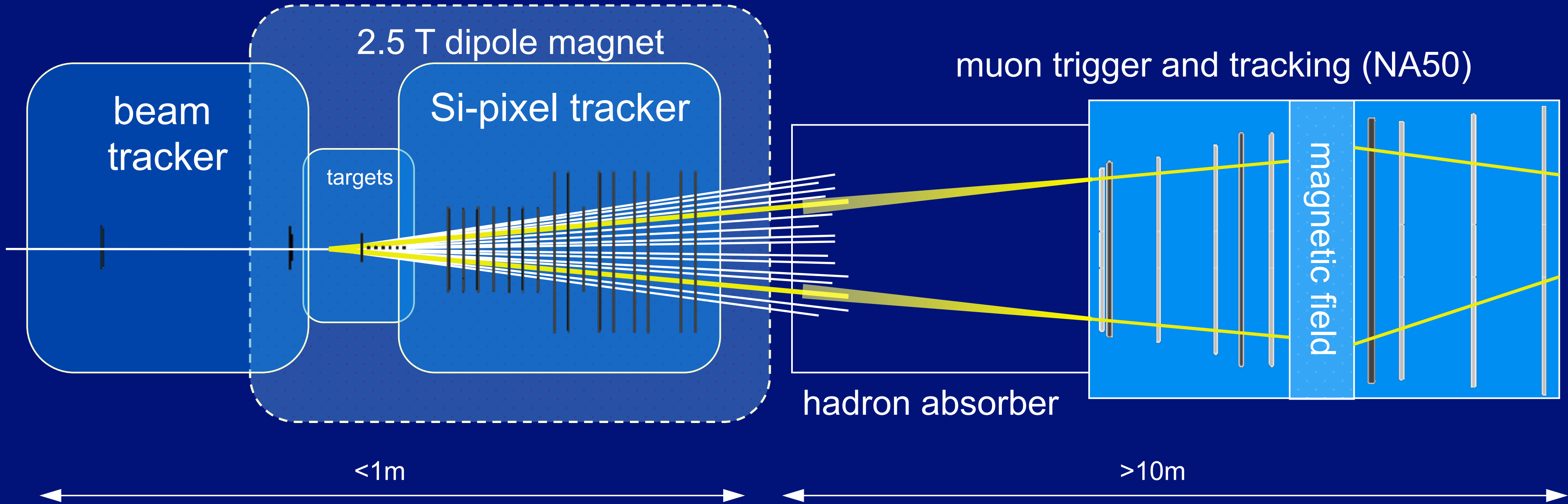
has disappeared. It is expected that the present “proof by circumstantial evidence” for the existence of a quark-gluon plasma in high energy heavy ion collisions will be further substantiated by more direct measurements (e.g. electromagnetic signals which are emitted directly from the quarks in the QGP) which will become possible at the much higher collision energies and fireball temperatures provided by RHIC at Brookhaven and later the LHC at CERN.

↓

SPS !

3rd generation Experiment: Dimuons in NA60

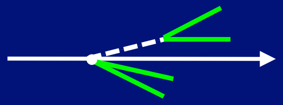
(basic idea P. Sonderegger, exp. approved 2000, spokespersons C. Lourenço, later G. Usai)



Track matching in coordinate and momentum space

Improved dimuon mass resolution

Distinguish prompt from decay dimuons



Additional bend by the dipole field

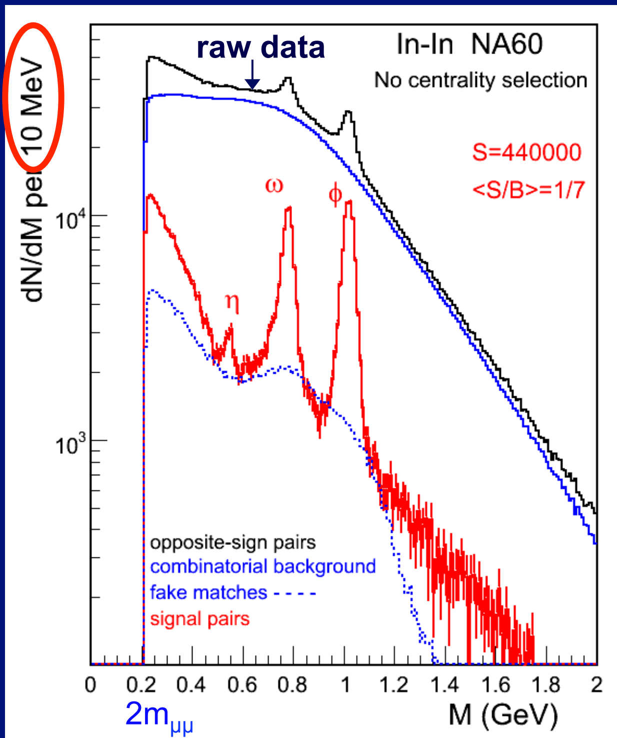
Dimuon coverage extended to low p_T

Radiation-hard silicon pixel detectors (LHC development)

High luminosity of dimuon experiments maintained

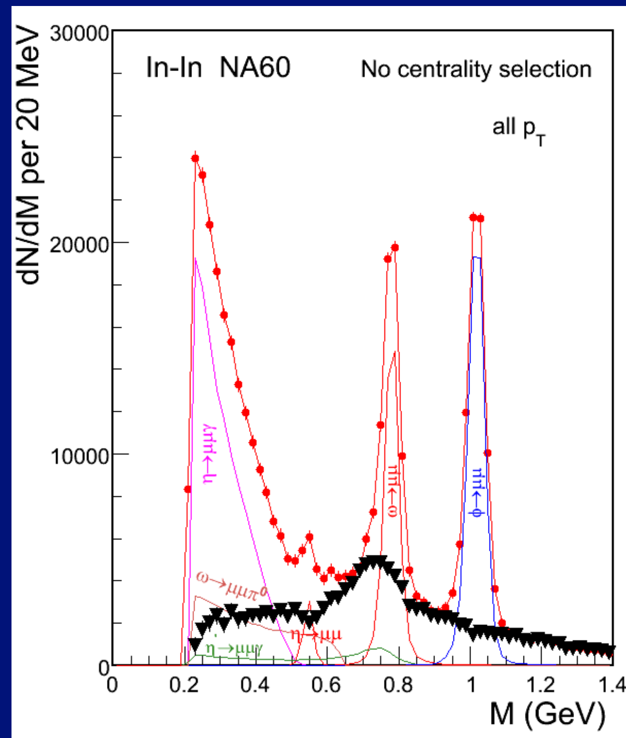
In-In 158 GeV/u: NA60 2003 data and major analysis steps

Phys. Rev. Lett. 96 (2006) 162302



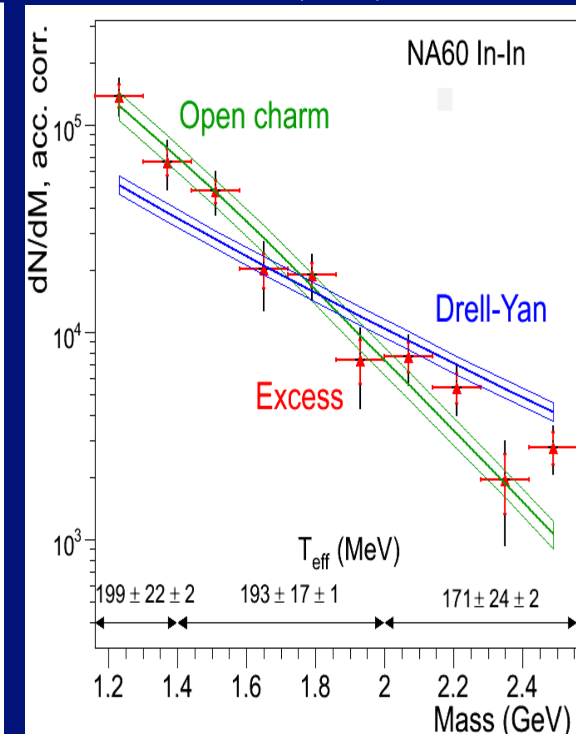
subtraction of combinatorial background and fake matches
~10^6 net, 10^8 triggers, 10^{12} int.

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



subtraction of measured decay cocktail with accuracy of 2-3%
→ isolation of the LMR excess

EPJ C 59 (2009) 607



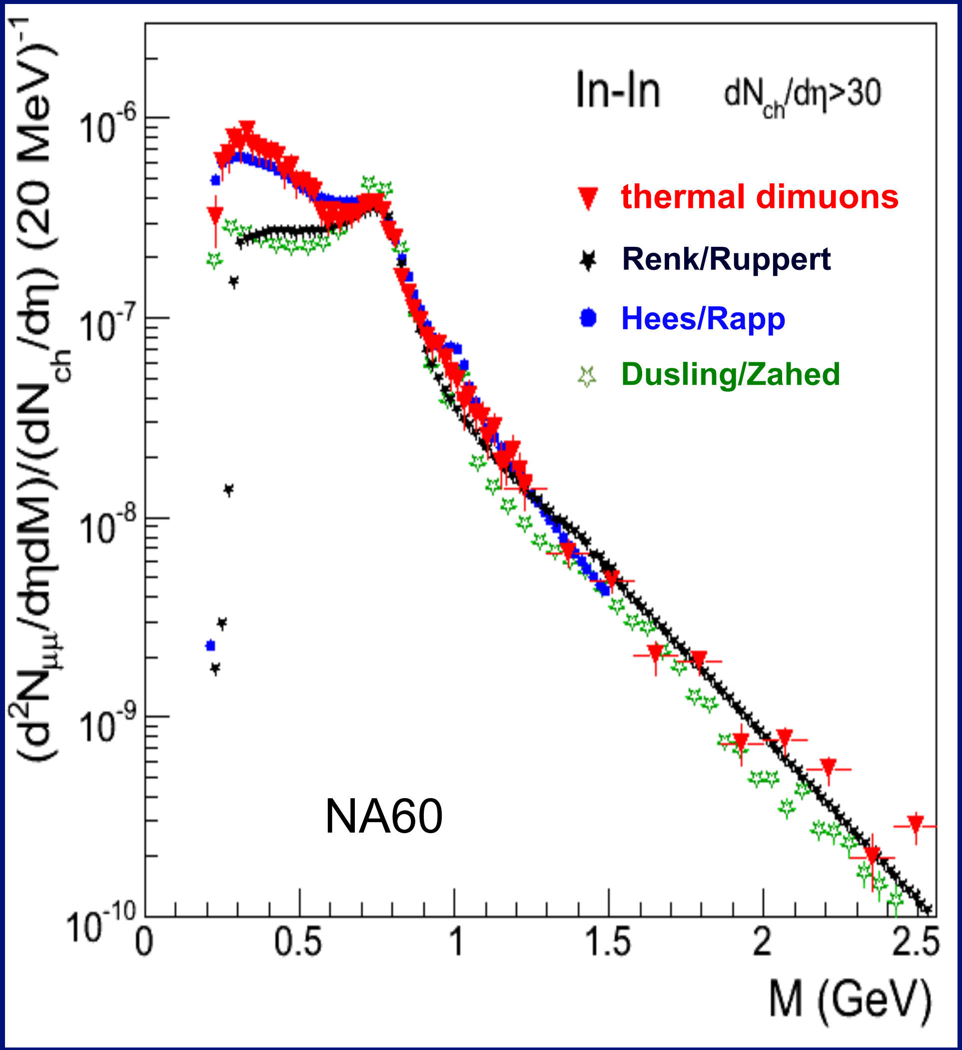
IMR: subtraction of Drell-Yan and measured open charm (by displaced decay vertices)

Final step: acceptance correction

reduce 4-dimensional acceptance correction in M-p_T-y-cosΘ_{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 GeV

ρ dominates, 'melts' close to T_c (sl.35)

M>1 GeV

~ exponential fall-off → 'Planck-like'

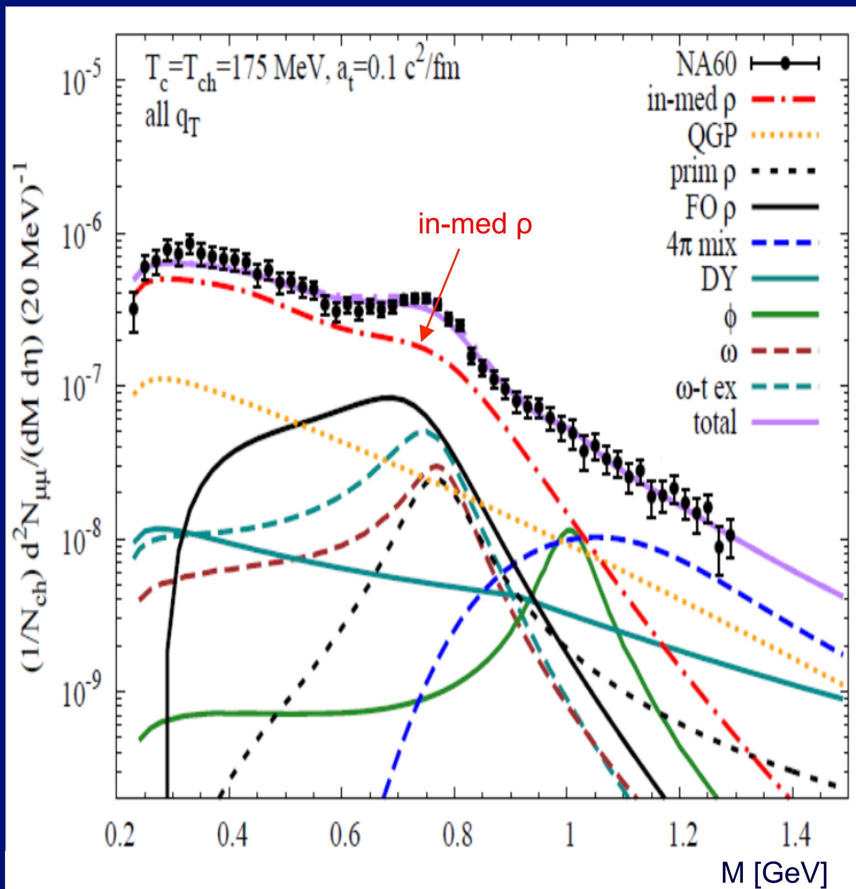
fit to $dN/dM \propto M^{3/2} \times \exp(-M/T)$

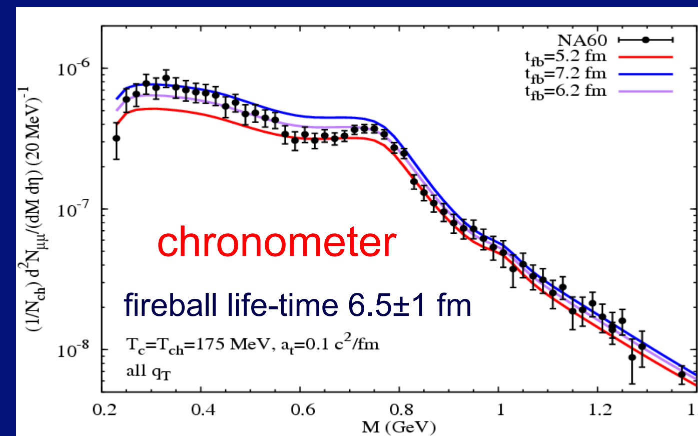
range 1.1-2.0 GeV: T=205±12 MeV
1.1-2.4 GeV: T=230±10 MeV

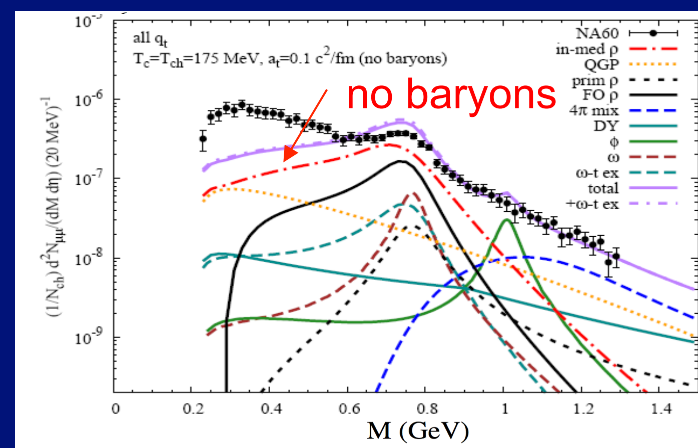
T>T_c=160-170 MeV: partons dominate

Theoretical description of LMR by v.Hees/Rapp

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







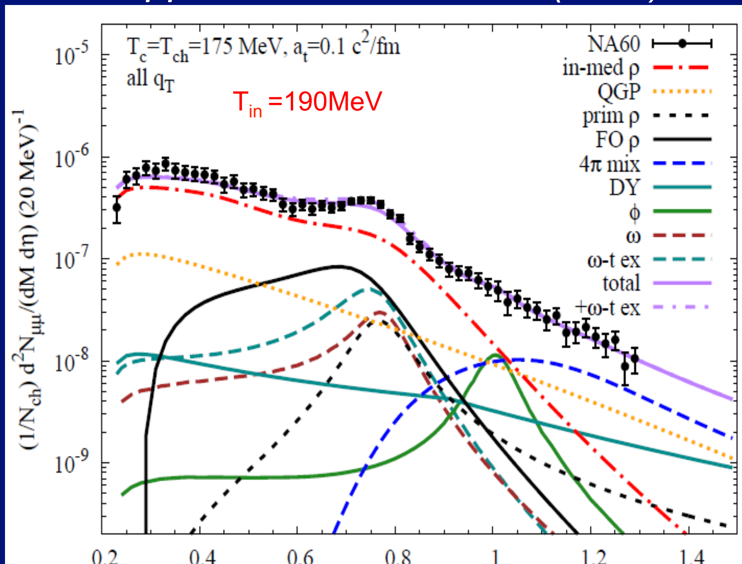
Perfect agreement in absolute terms

Rapp: ‘spectrum directly reflects thermal emission rate’

broadening of the ρ dominated by baryon interactions

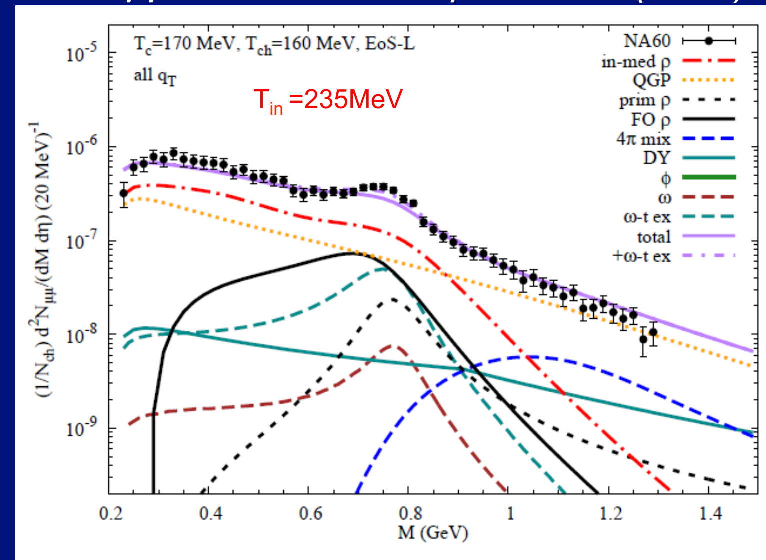
Update of the v.Hees/Rapp description of the NA60 data

R.Rapp, arXiv:1110.434511 (2011)



First-Order EoS + HTL Rate

R.Rapp, FAIR Workshop, Worms (2014)



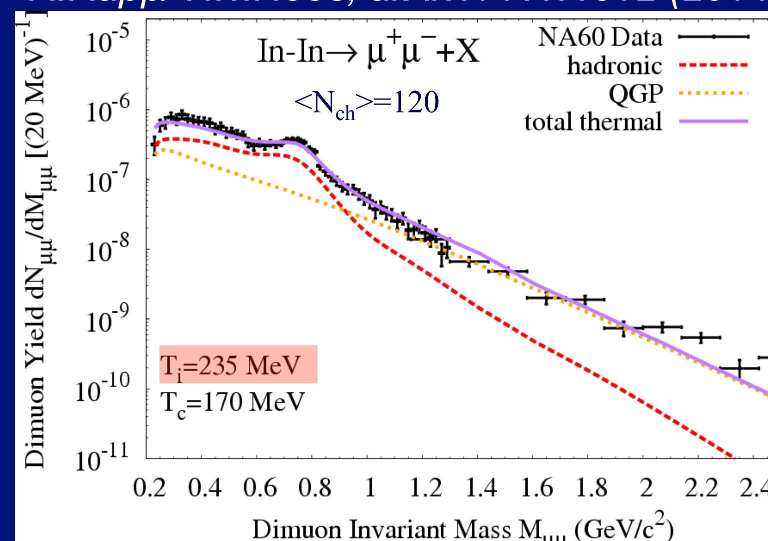
Lattice EoS + Lat-QGP Rate

Various changes, including an increase of T_i from 190 to 235 MeV, strongly affect the partition QGP/HG

→ IMR now properly described

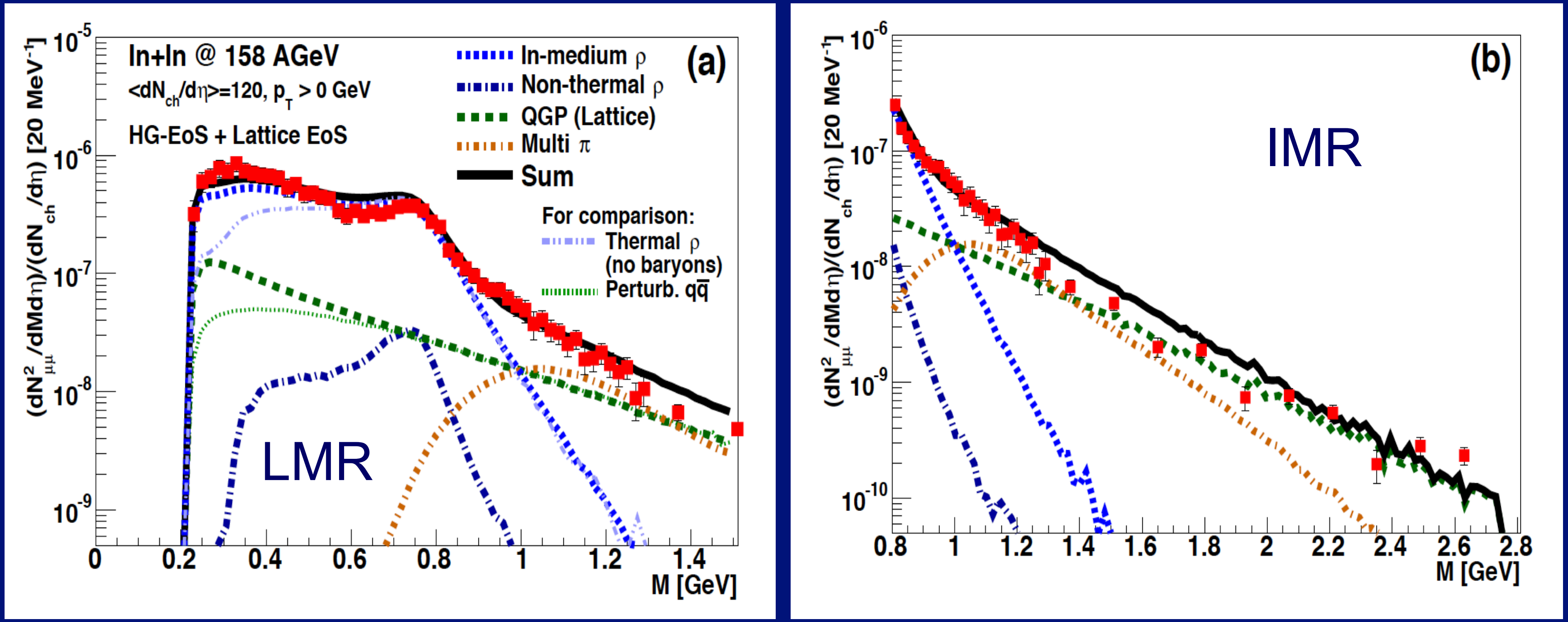
→ LMR spectral shape robust

R.Rapp/ H.v.Hees, arXiv:1411.4612 (2014)



Theoretical description of LMR by Endres et al.

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

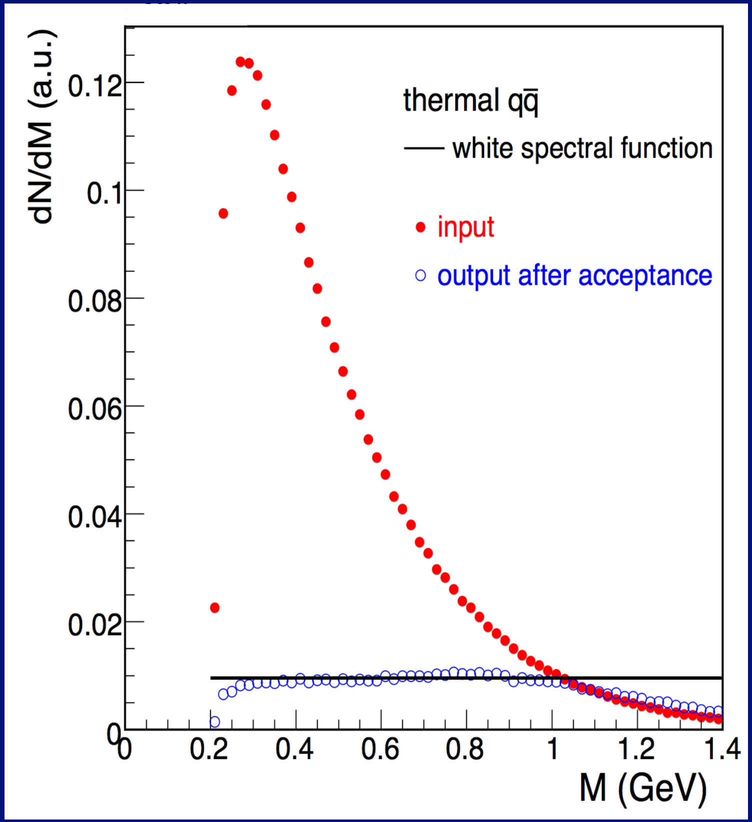
perfect agreement in absolute terms

partonic emission dominant for M>1.5 GeV

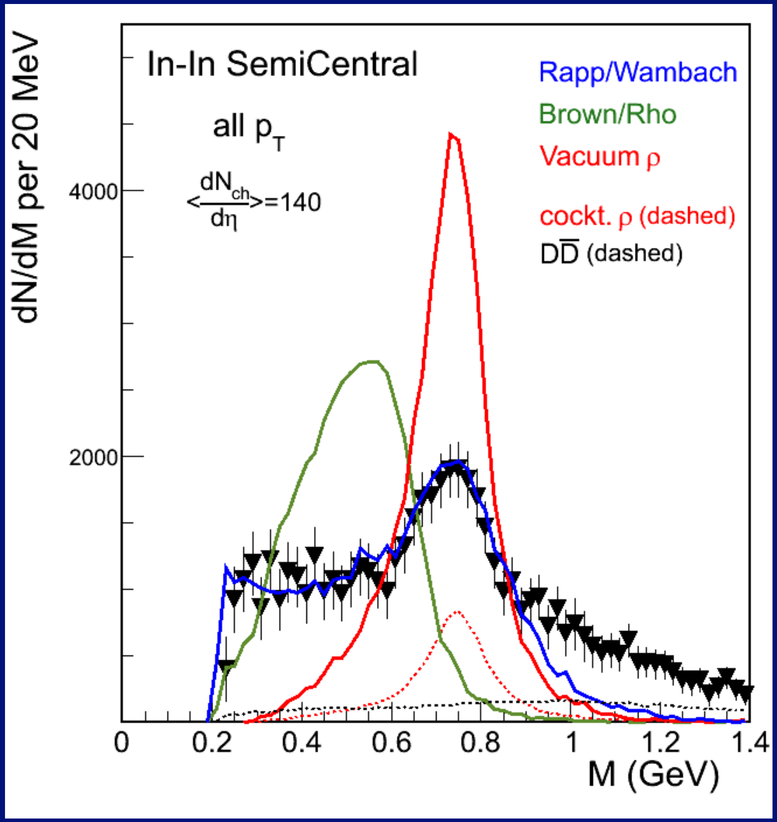
deconfinement at SPS energies now well described by four independent groups

Towards chiral restoration: mass shift vs. broadening

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



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



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

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

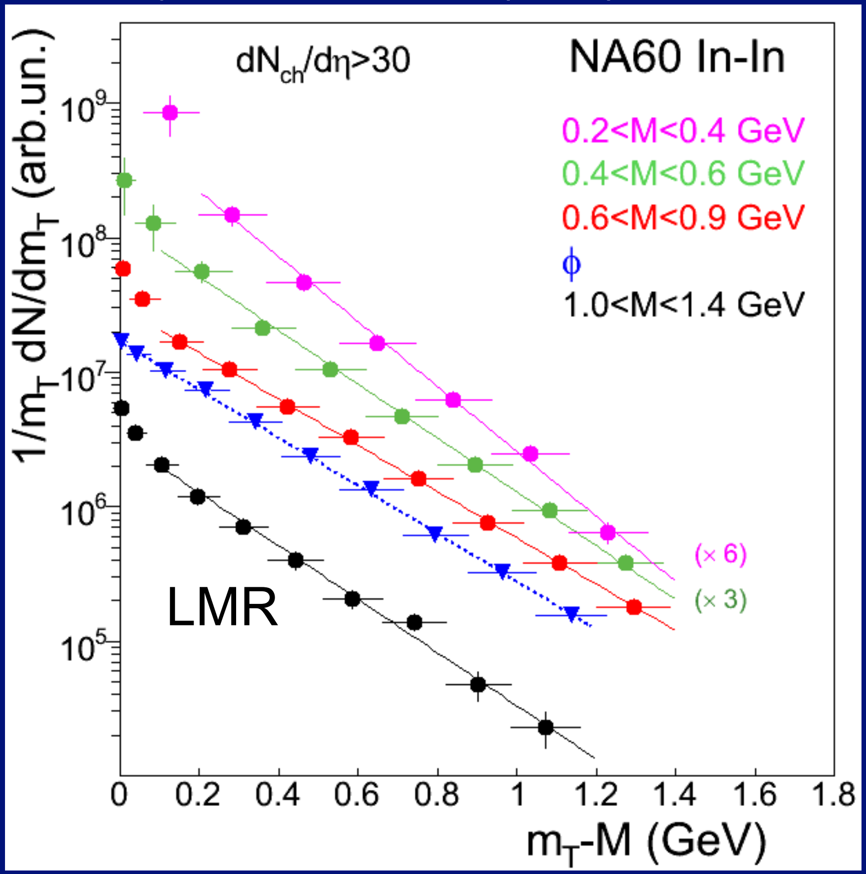
only broadening of ρ observed, no mass shift → 'hadrons melt'

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

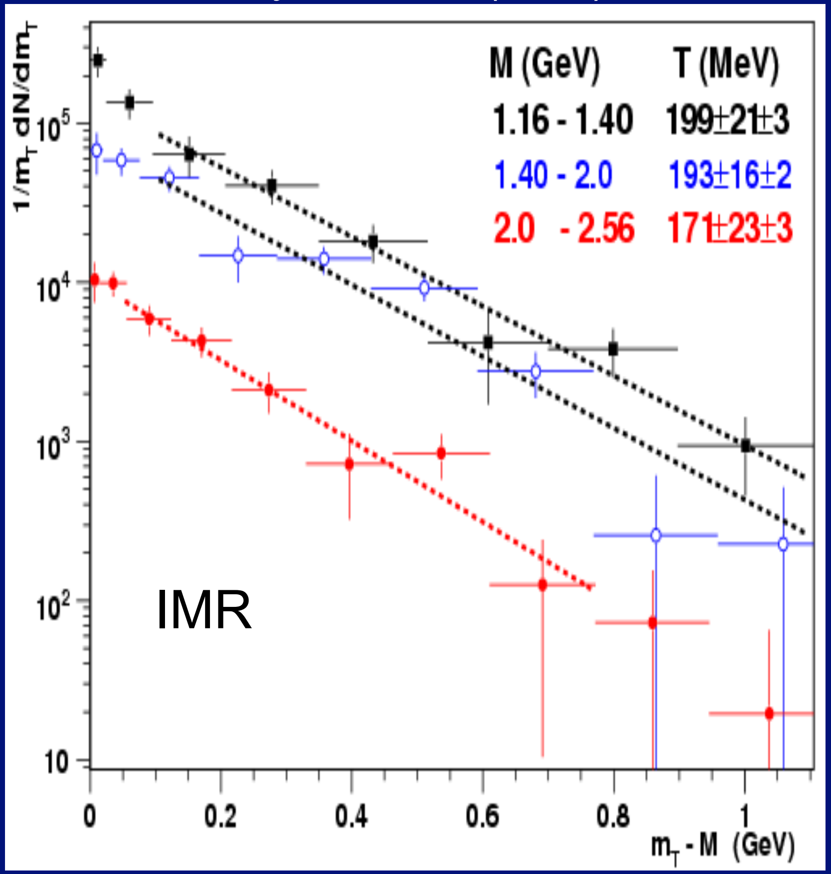
The other variable of dileptons: p_T spectra – 'Barometer'

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

Phys. Rev. Lett. 100 (2008) 022302



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

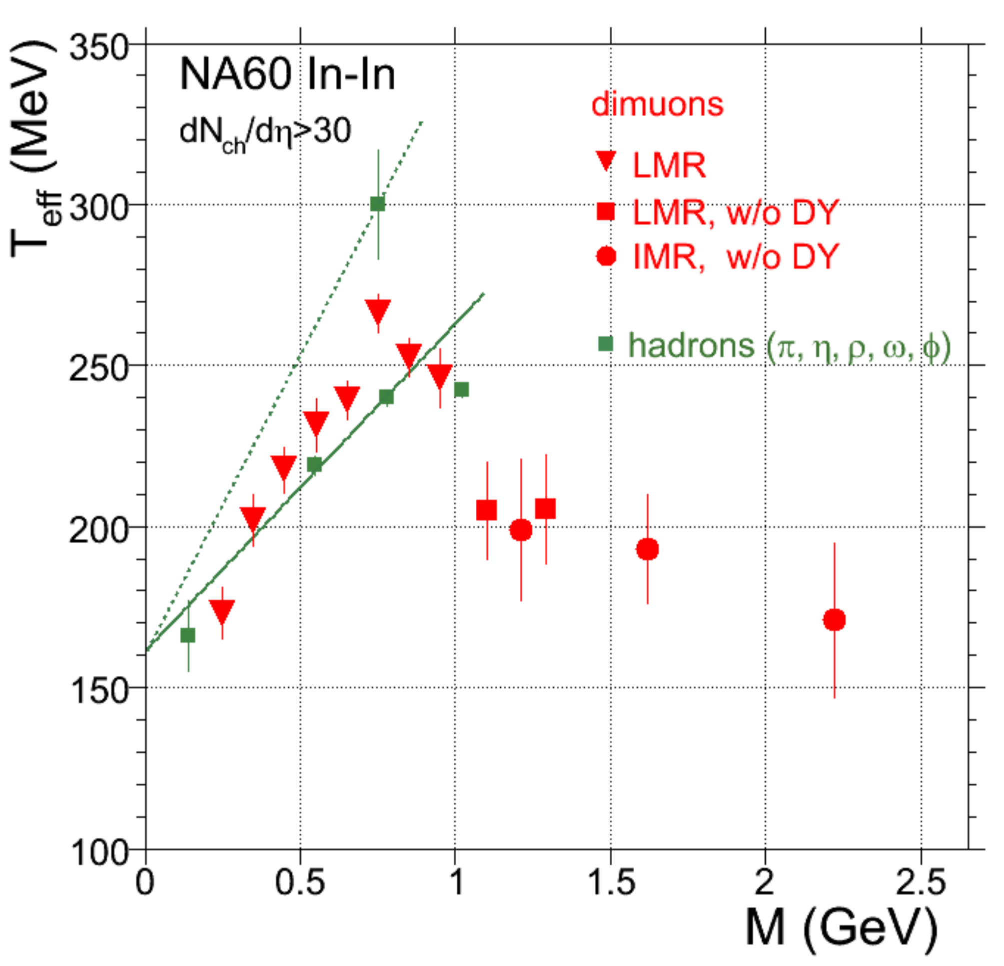


all m_T spectra exponential for m_T-M > 0.1 GeV; <0.1 GeV ??

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

The rise and fall of radial flow of thermal dimuons

Phys. Rev. Lett. 100 (2008) 022302



Initial linear rise of T_{eff} with M

↓

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

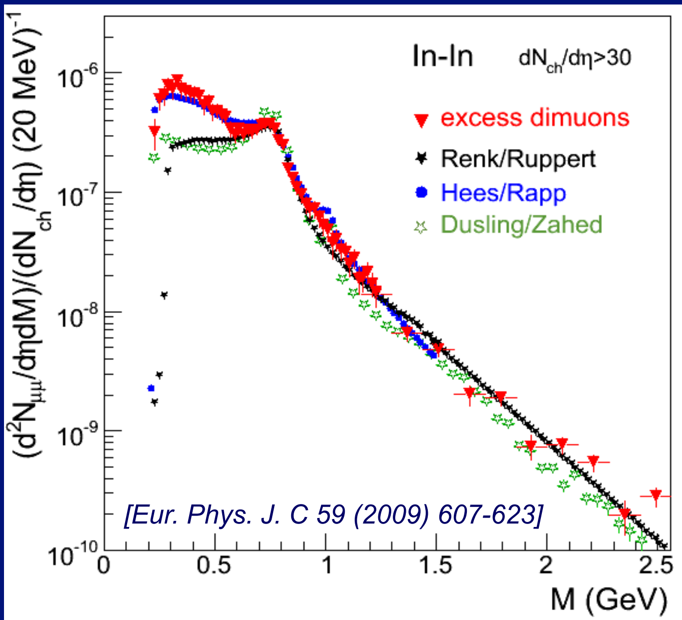
$T_{eff} \sim T_f + M <v_T>^2$ v_T~0.5c

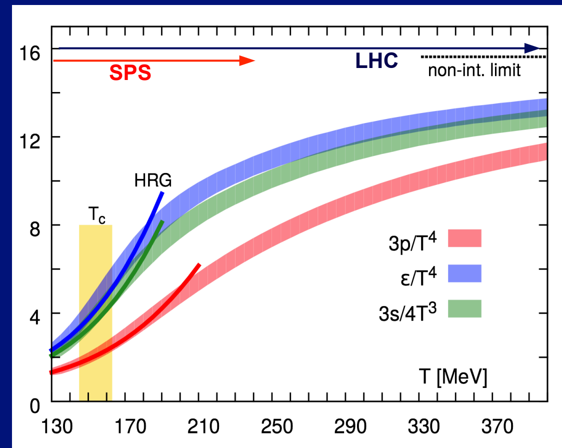
Rise up to 1 GeV consistent with radial flow of a hadronic source (here $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$)

Drop at 1 GeV signals sudden transition to a low-flow, i.e. an early source → 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

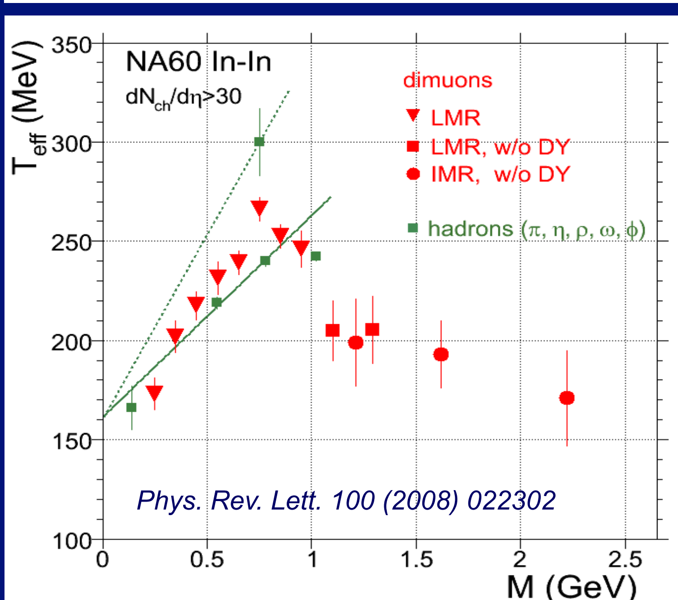




Lattice QCD:

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

- same values within errors

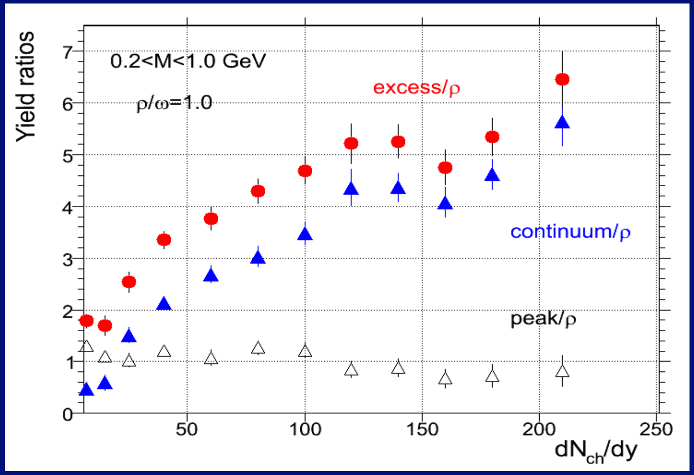
negligible flow → soft EoS above T_c

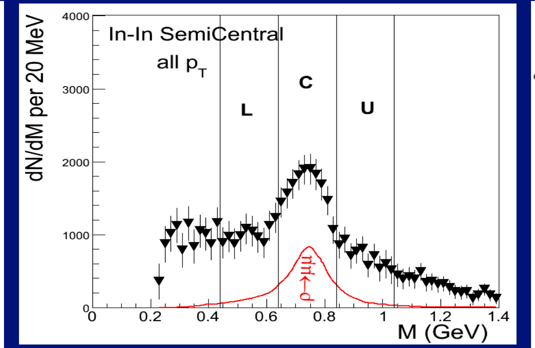
Centrality dependences: the ‘ρ clock’

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.)

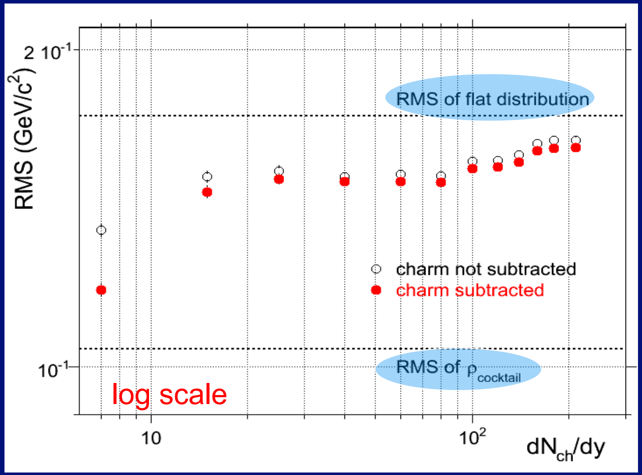
Eur. Phys. J. C61 (2009) 711





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

→ ‘ρ clock’

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

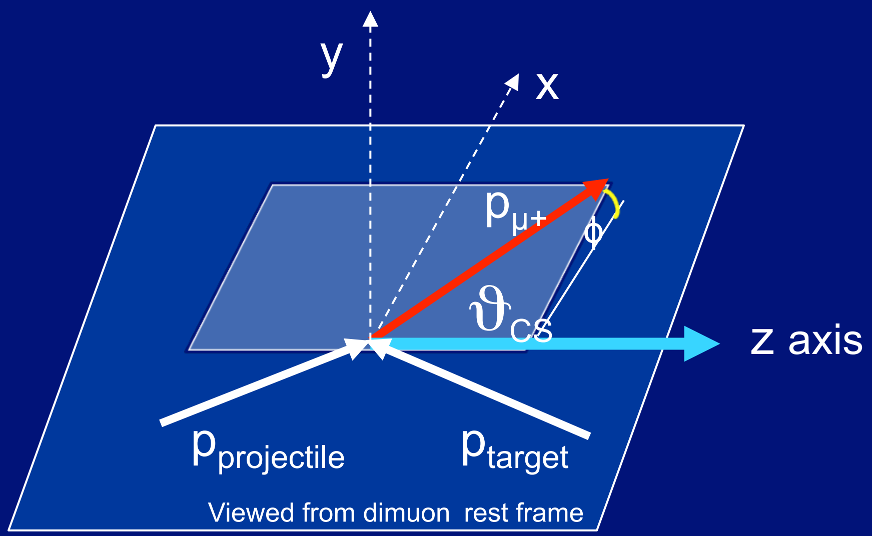
→ ‘melting’ of the ρ

Angular distributions

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

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

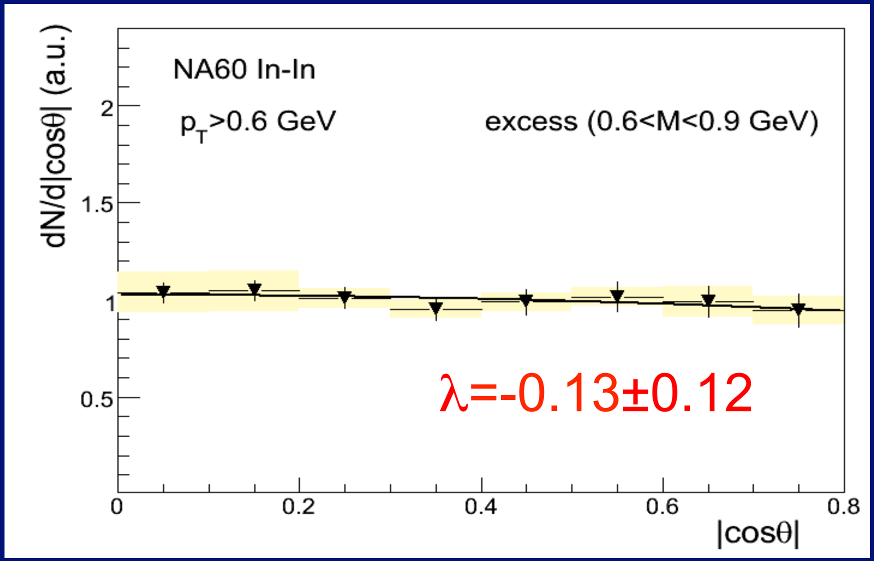
θ : angle between the positive muon $\mathbf{p}_{\mu+}$ and the z-axis.

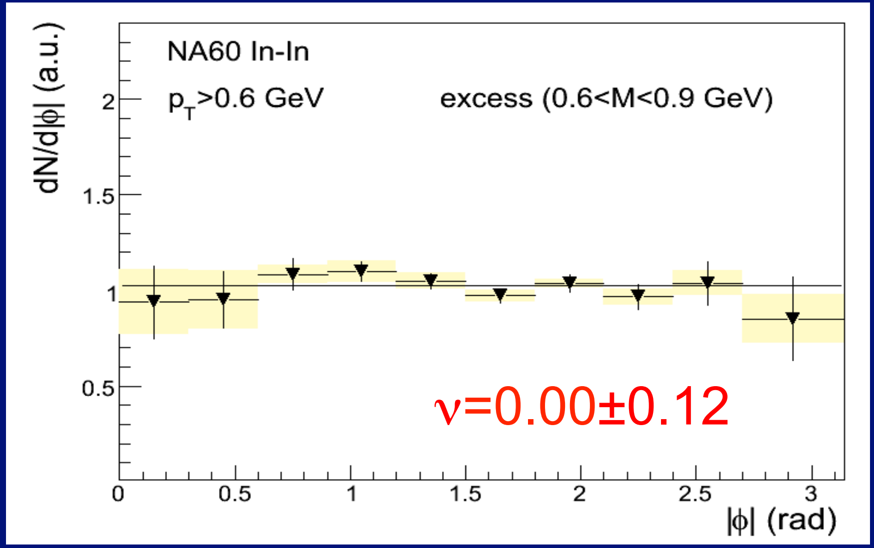
z axis : bisector between $\mathbf{p}_{proj}$ and $-\mathbf{p}_{target}$

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

Outlook: the present world scene and beyond

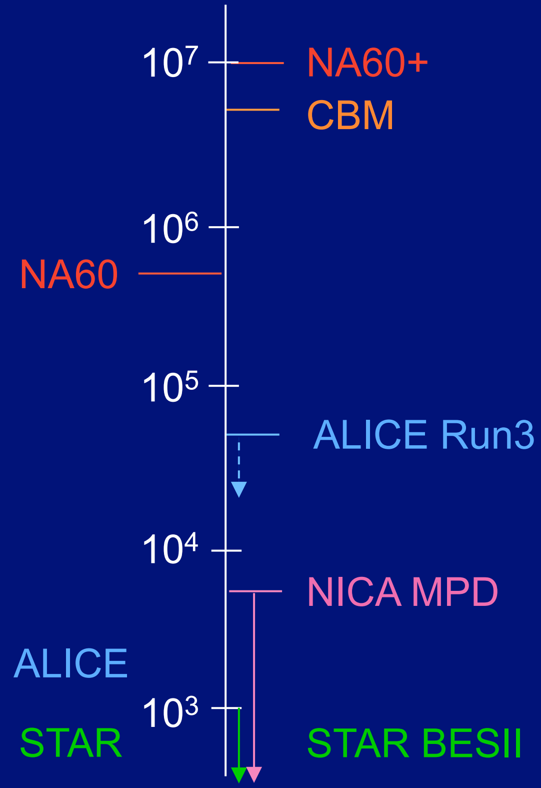
The high energy frontier

- 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 ~ 1/(20-1000)

→ effective signal size: S_{eff} ~ IR × S/B reduction by 20-1000 !

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

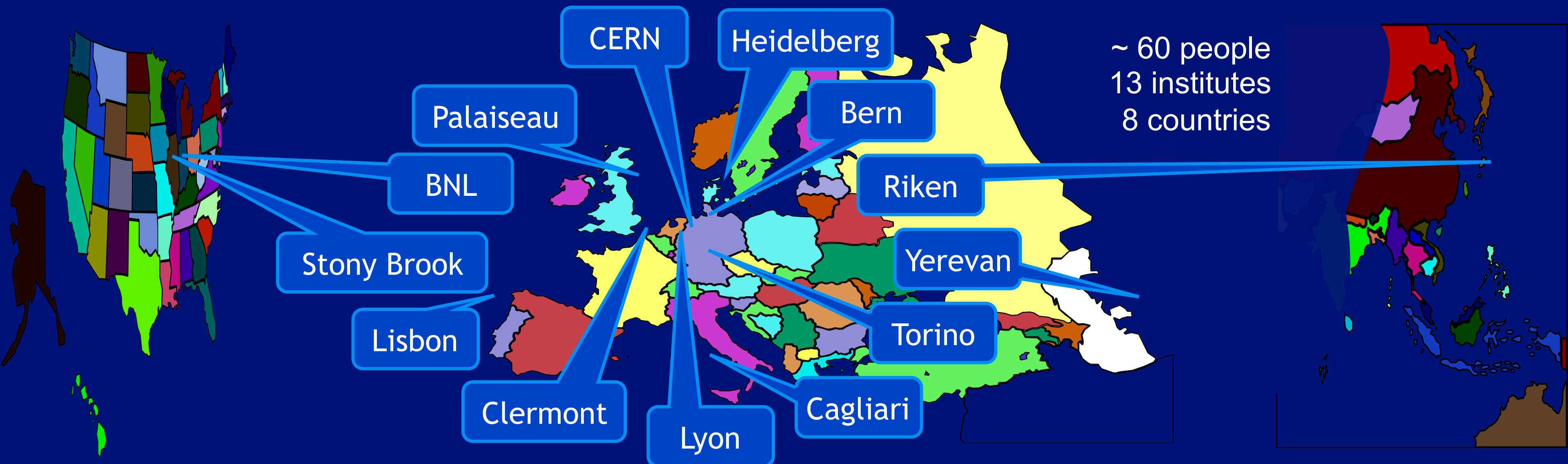
Emission sources of thermal dileptons mostly hadronic ($\pi^+\pi^-$ annihilation) for M<1 GeV, and mostly partonic ($q\bar{q}$ annihilation) for M>1 GeV; associated temperatures quantified; hints at soft EoS close to T_c: proof for deconfinement already at SPS energies

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 machine SPS, complemented by SIS100

The NA60 experiment

http://cern.ch/na60



~ 60 people
13 institutes
8 countries

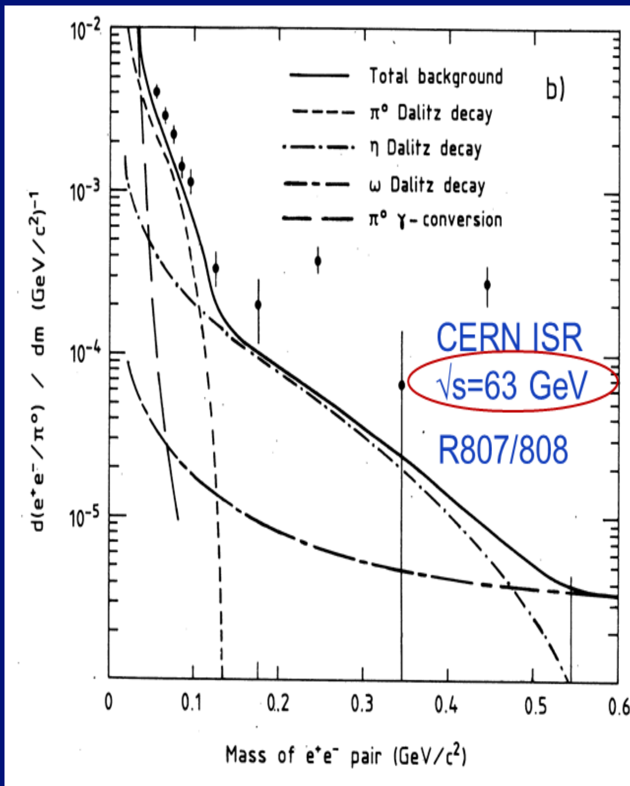
R. Arnaldi, K. Banicz, K. Borer, J. Buytaert, J. Castor, B. Chaurand, W. Chen,B. Cheynis, C. Cicalò, A. Colla, P. Cortese, S. Damjanovic, A. David, A. de Falco, N. de Marco, A. Devaux, A. Drees, L. Ducroux, H. En'yo, A. Ferretti, M. Floris, A. Förster, P. Force, A. Grigorian, J.Y. Grossiord, N. Guettet, 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

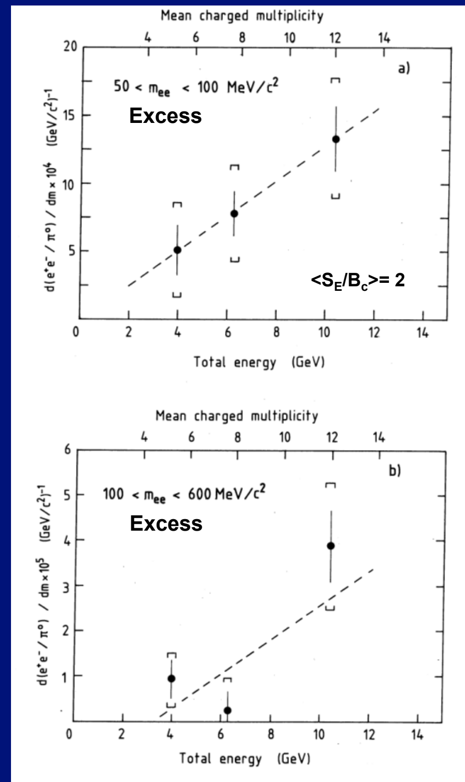
BKP

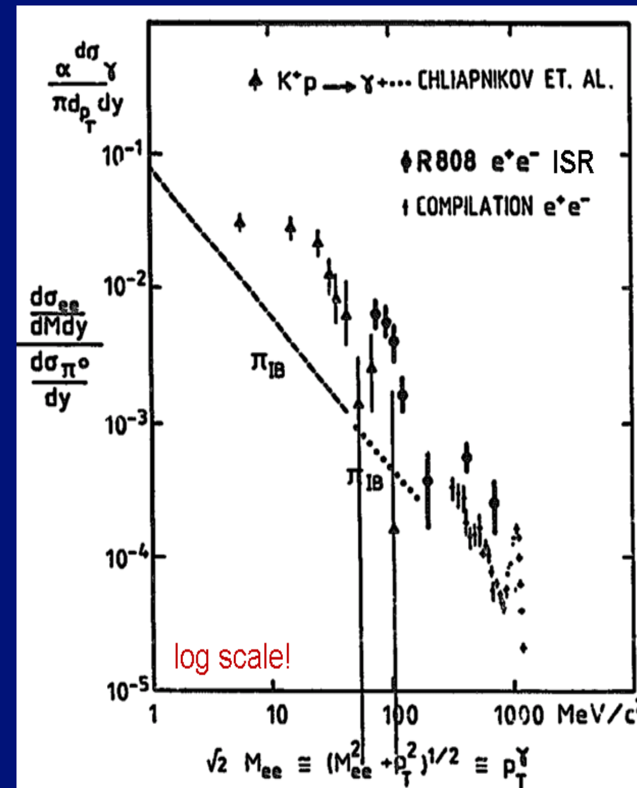
LMR results in pp at ISR energies

T. Akesson et al., PLB152 (1985) 411 and PLB192 (1987) 463;
W. Hedberg, PhD thesis,Lund (1987)

W.J. Willis, PANIC, Kyoto 1987
Nucl.Phys. A478 (1988) 151c







the only LMR excess ever established in pp;
multiplicity dependence almost quadratic

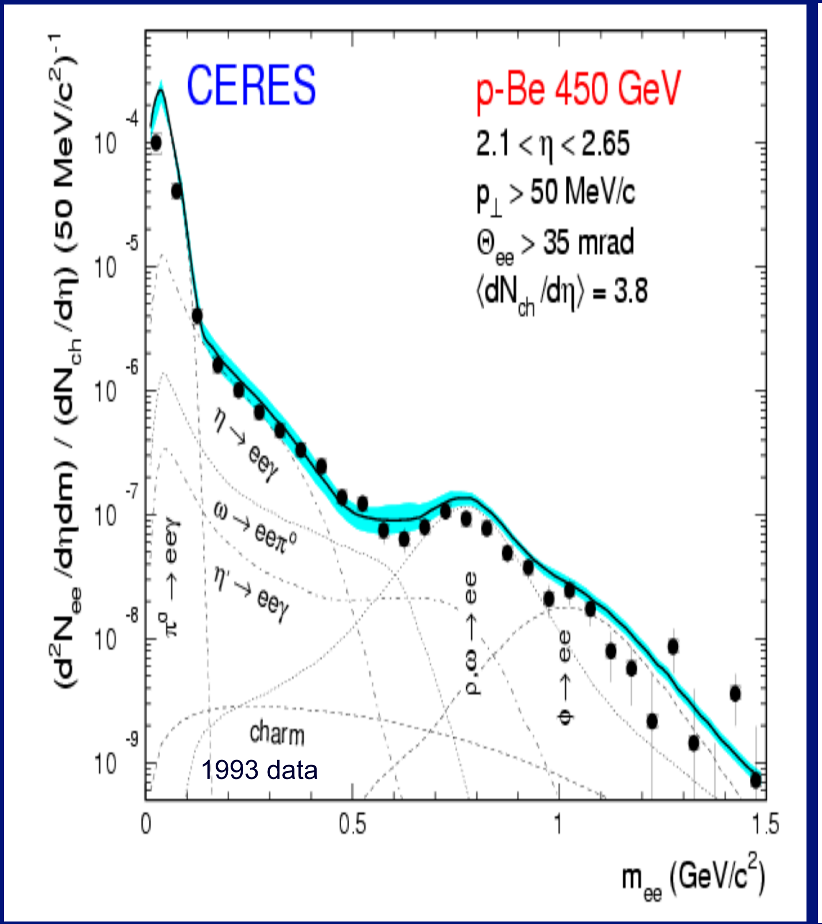
Challenge for the future

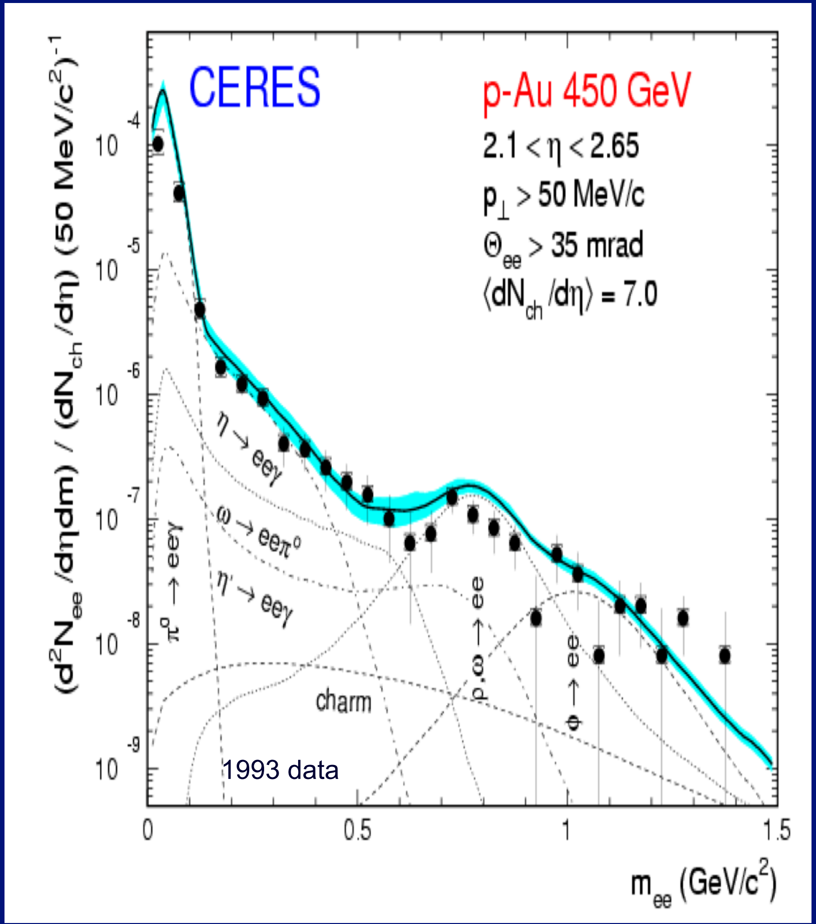
unification of dilepton excess with ‘soft photons’:

P. Chliapnikov et al. (1984), J. Antos et al. (1993), V. Perepelitsa et al., DELPHI (2004,2006, 2010)

CERES/NA45: low-mass dielectrons in pA

Eur. Phys. J. C 4 (1998) 231-247





p-Be and p-Au data well described in terms of known hadronic sources

SPS Proposals NA34-1, NA34-2 and NA34-3 (HELIOS)

NA34-1

CERN-SPSC/83-51
SPSC/P189
22 Aug. 1983

PROPOSAL TO THE SPSC

LEPTON PRODUCTION

H. Gordon, T. Ludlam, V.A. Polychronakos, D.C. Rahm, I. Stumer
Brookhaven National Laboratory

T. Åkesson, H. Atherton, H. Breuker, C.W. Fabjan, U. Goerlach, G. London*, L. Olsen, W.J. Willis
CERN

P. Glaessel, J. Schukraft, H.J. Specht
Heidelberg University

S. Mayburov, A. Shmeleva
Lebedev Institute, Moscow

V. Sidorov
Novosibirsk Institute of Nuclear Physics

S. Almehed, G. Jarlskog, B. Lörstad
Lund University

V. Cherniatin, B. Dolgoshein, Yu. Golubkov, A. Kalinovsky, V. Kantserov, P. Nevsky, A. Sumarakov
Moscow Physical Engineering Institute

N.A. McCubbin
Rutherford Appleton Laboratory

D. Bettoni, M. Goldberg, N. Horwitz, G.C. Moneti
Syracuse University

O. Benary, S. Dagan, D. Lissauer, Y. Oren
Tel Aviv University

ABSTRACT

This experiment aims to settle open questions in the production of electrons, muons, and neutrinos. Prominent among these are e/μ universality, anomalies in the production of single leptons, the contribution of charm decay to lepton pair (Drell-Yan) production, and the "anomalous" low mass pairs. The experimental design optimizes the combination of electron identification, muon identification, missing energy measurement (for neutrinos), and vertex determination, thus allowing a general survey of single and multi-lepton production.

* Permanent address: Saclay, France

NA34-2

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

SPSC/84-43
SPSC/P-203
21st May 1984

STUDY OF HIGH ENERGY DENSITIES OVER EXTENDED NUCLEAR VOLUMES VIA NUCLEUS-NUCLEUS COLLISIONS AT THE SPS

NA34 Collaboration

(Brookhaven-CERN-Heidelberg-Los Alamos-Lund-McGill/Montreal-Moscow Novosibirsk-Pittsburgh-Saclay-Syracuse and Tel-Aviv)

Spokesman: H.J. Specht, Heidelberg

ABSTRACT

We propose to examine in detail the characteristics of ultra-relativistic nucleus-nucleus interactions using ^{16}O beams of 200 GeV/A from the SPS. The experiment combines 4π calorimeter coverage with measurements of inclusive particle spectra, two-particle correlations, low- and high-mass lepton pairs and photons. A multi-wire active target allows maximum interaction rates with a minimum of secondary interactions.

100P/mm

NA34-3

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSC 88-21
SPSC/ P-203 Add1
13 June 1988

ADDENDUM TO PROPOSAL P-203

^{32}S-NUCLEUS COLLISIONS WITH AN UPGRADED HELIOS SPECTROMETER

The HELIOS Collaboration

1

SPS Proposal NA45 (CERES)

CERN/SPSC 88-25
SPSC/P237
15 June 1988

PROPOSAL

STUDY OF ELECTRON PAIR PRODUCTION IN HADRON AND NUCLEAR COLLISIONS AT THE CERN SPS

U. Faschingbauer, M.G. Trauth, J.P. Wurm

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

A. Drees, P. Fischer, P. Glässel, M. Guckes, D. Irmscher, L.H. Olsen, A. Pfeiffer, H. Ries, A. Schön, H. Sickmüller, H.J. Specht (Spokesman), T.S. Ullrich

Physikalisches Institut, Universität Heidelberg, Germany

E. F. Barasch, A. Breskin, R. Chechik, Z. Fraenkel, D. Sauvage, V. Steiner, I. Tserruya

Weizmann Institute of Science, Rehovot, Israel

(Other groups are expected to join later)

Abstract

We propose to measure e^+e^- pairs produced in hadron and nuclear collisions at SPS energies. The goal is to systematically study the pair continuum in the mass region from 100 MeV/c^2 to beyond 3 GeV/c^2 and the vector mesons ρ/ω and Φ. The experimental set-up is centered around a novel magnetic spectrometer, based solely on ring-image Cherenkov techniques. The apparatus also allows a high-statistics study of real photons and high-$p_\perp$ pions.

SPS Proposals NA38 and NA50

NA38

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSC/85-20
SPSC/P 211
11 March 1985

P R O P O S A L

STUDY OF HIGH-ENERGY NUCLEUS-NUCLEUS INTERACTIONS
WITH THE ENLARGED NA10 DIMUON SPECTROMETER

Bergen[1]-Bordeaux[2]-CERN[3]-Clermont-Ferrand[4]-
Ecole Polytechnique[5]-Lisbon[6]-Lyon[7]-Neuchâtel[8]-Orsay[9]-
Strasbourg[10]-Valencia[11] Collaboration

A. Baldit[4], G.P. Barreira[6], M. Bedjidian[7], P. Bordalo[6],
S. Borenstein[5], J. Britz[10], P. Busson[5], A. Casaca[6],
J. Castor[4], B. Chaurand[5], E. Descroix[7], J. Fargeix[4],
P. Force[4], J.M. Gago[6], C. Gerschel[9], P. Gorodetzky[10],
A. Guichard[7], R. Haroutunian[7], P.S. Iversen[1*], L. Kluberg[5],
G. Landaud[4], A. Maio[6], D. Perrin[8], G. Peyrard[4],
M. Pimenta[6], J.R. Pizzi[7], J. Quebert[2], S. Ramos[6],
A. Romana[5], R. Salmeron[5], P. Sonderegger[3],
J. Varela[6], and J. Velasco[11**]

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2 Centre d'Etudes Nucléaires, Univ. de Bordeaux I, Gradignan, France.
3 CERN, Geneva, Switzerland.
4 Lab. de Physique Corpusculaire, Université de Clermont-Ferrand, France.
5 LPNHE, Ecole Polytechnique, Palaiseau, France.
6 INIC, Instituto Nacional de Investigaçao Cientifica, Lisbon, Portugal.
7 Inst. de Physique Nucléaire, Université de Lyon, Villeurbanne, France.
8 Inst. de Physique, Université de Neuchâtel, Neuchâtel, Switzerland.
9 Inst. de Physique Nucléaire, Université de Paris-Sud, Orsay, France.
10 Centre de Recherches Nucléaires and Université Louis Pasteur, Strasbourg, France.
11 Facultad de Ciencias (IFIC), Burjasot, Valencia, Spain.
* At present Fellow at CERN, Geneva, Switzerland.
** Subject to approval by the Spanish High-Energy Physics Commission.

0001C/S8/sm

NA50

ATION FOR NUCLEAR RESEARCH

CERN/SPSLC 91-55
SPSLC/P 265-Rev
November 6, 1991

PROPOSAL

STUDY OF MUON PAIRS AND VECTOR MESONS
PRODUCED IN HIGH ENERGY Pb-Pb INTERACTIONS

M.C. Abreu[4], C. Baglin[1], A. Baldit[2], C. Barrière[2], M. Bedjidian[9],
V. Bisi[8], P. Bordalo[4], A. Bussière[1], J. Castor[2], P. Cerello[8],
T. Chambon[2], B. Chaurand[6], E. Chiavassa[8], D. Contardo[9], G. Dellacasa[8],
N. De Marco[8], E. Descroix[9], A. Devaux[2], O. Drapier[9], B. Espagnon[2],
J. Fargeix[2], R. Ferreira[4], F. Ferrero[8], P. Force[2], L. Fredj[2],
J. Gago[4], M. Gallio[8], C. Gerschel[5], P. Giubellino[8], Ph. Gorodetzky[7],
P. Guaita[8], B. Grosdidier[7], J.Y. Grossiord[9], A. Guichard[9], J.P. Guillaud[1],
R. Haroutunian[9], D. Jouan[5], L. Kluberg[6], R. Kossakowski[1], G. Landaud[2],
D. Lazic[7], P. Liaud[1], C. Lourenço[4], F. Malek[9], F. Martelli[8],
A. Marzari[8], M. Masera[8], R. Mazini[7], A. Musso[8], L. Peralta[4],
A. Piccotti[8], J.R. Pizzi[9], C. Racca[7], L. Ramello[8], S. Ramos[4],
L. Riccati[8], A. Romana[6], S. Sartori[8], E. Scomparin[8], S. Silva[4],
P. Sonderegger[3], X. Tarrago[5], J. Varela[4], F. Vazeille[2] and E. Vercellin[8].

Spokesman : L. Kluberg
Contactman : P. Sonderegger

[1] LAPP, CNRS-IN2P3, Annecy-le Vieux, France.
[2] LPC, Univ. de Clermont-Ferrand and CNRS-IN2P3, France.
[3] CERN, Geneva, Switzerland.
[4] LIP, Lisbon, Portugal.
[5] IPN, Univ. de Paris-Sud and CNRS-IN2P3, Orsay, France.
[6] LPNHE, Ecole Polytechnique and CNRS-IN2P3, Palaiseau, France.
[7] CRN, CNRS-IN2P3 and Univ. Louis Pasteur, Strasbourg, France.
[8] Università di Torino/INFN, Torino, Italy
[9] IPN, Univ. de Lyon and CNRS-IN2P3, Villeurbanne, France.

Note: Discussions are under way with the Institute of Atomic Physics, Bucharest, Romania, in view of a collaboration on this Proposal.

1

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 $\eta \to \mu^+\mu^-\gamma$ and $\omega \to \mu^+\mu^-\pi^0$

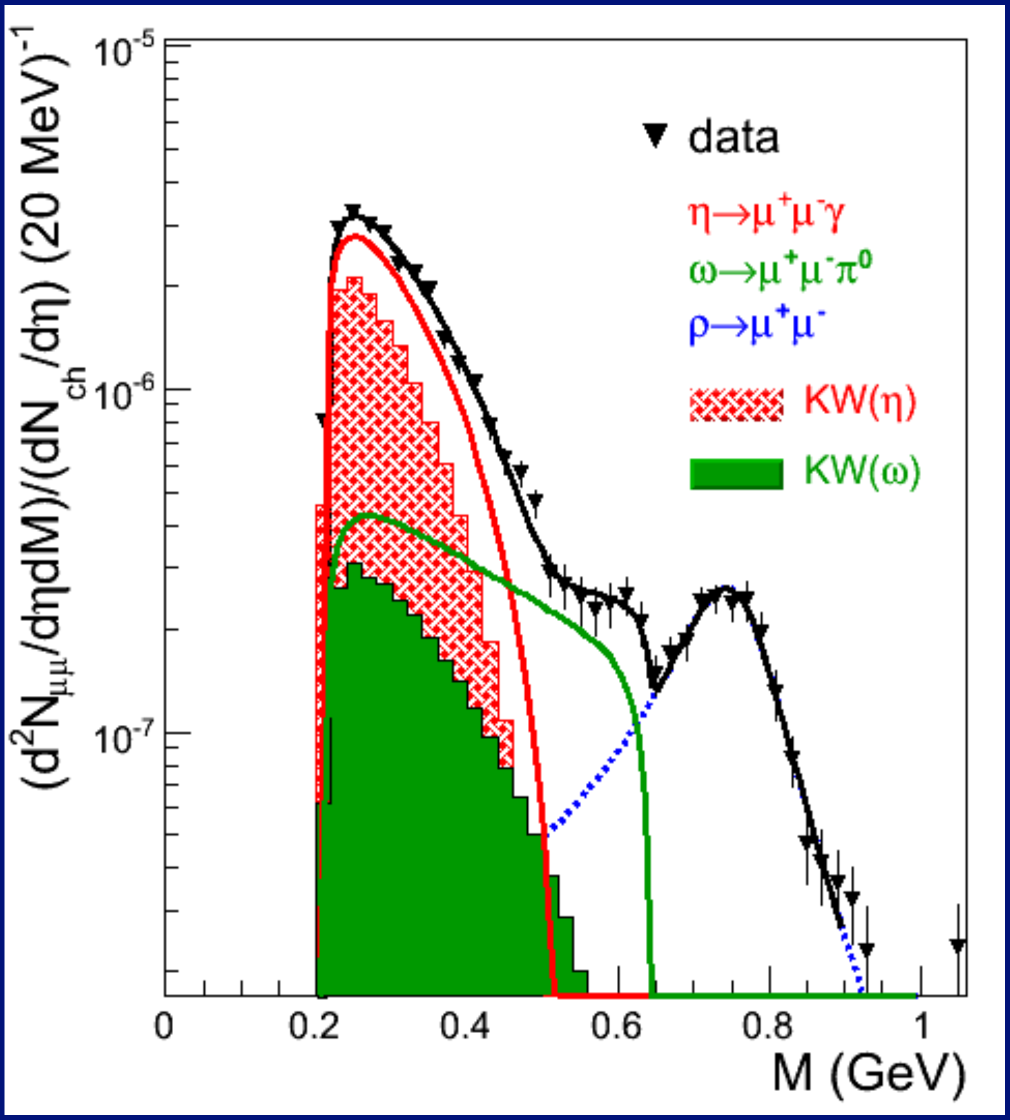
Probability of formation of a lepton pair with mass $m_{\mu+\mu-}$ in a Dalitz decay strongly modified by the dynamic electromagnetic structure arising at the vertex of the transition A→B . Formal description by $|F_{AB}(m_{\mu\mu}{}^2)|^2$

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

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)

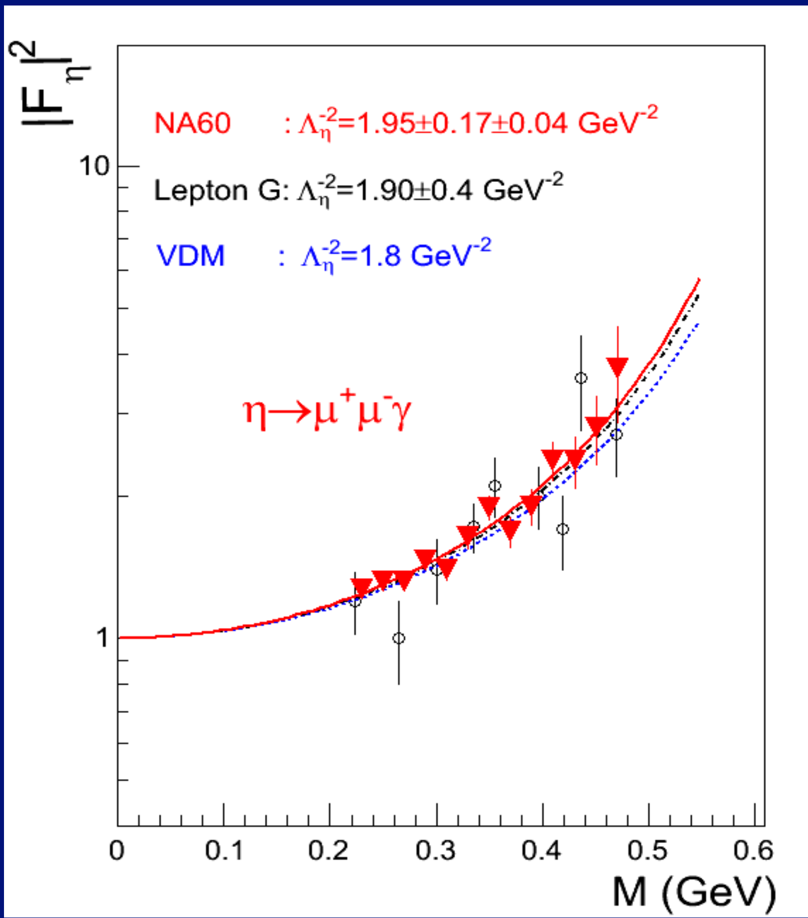
correct for acceptance

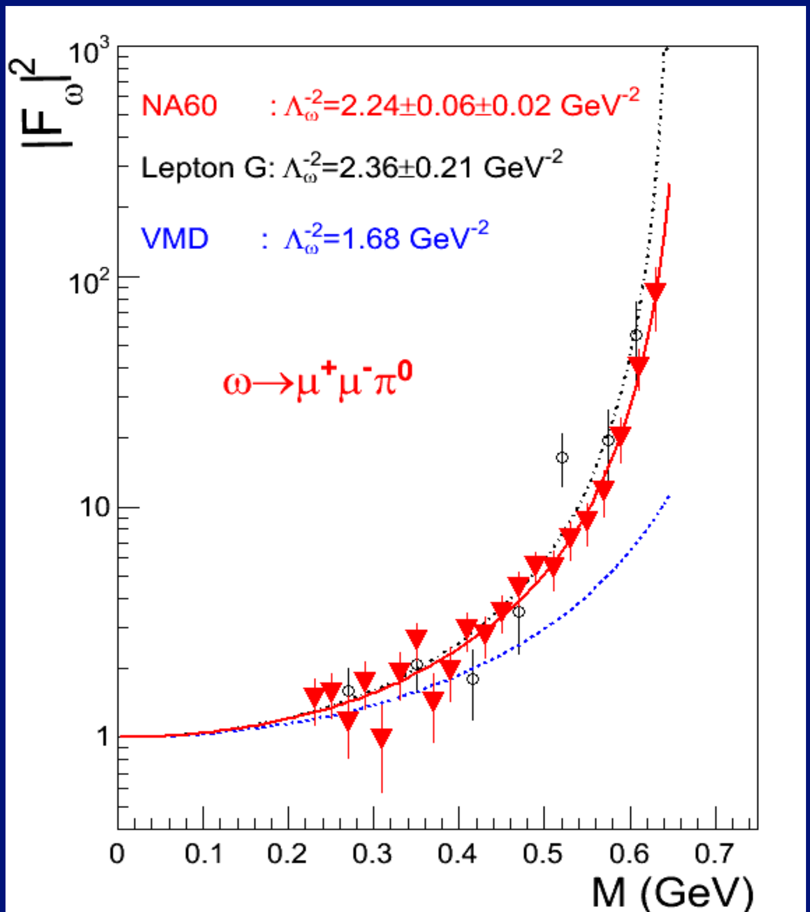
fit remaining sources η, ω and ρ;
χ^2/ndf~1, globally and locally

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

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

$\omega(782)$ BRANCHING RATIOS

PDG 2008

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ Γ_7/Γ

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

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ Γ_7/Γ

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