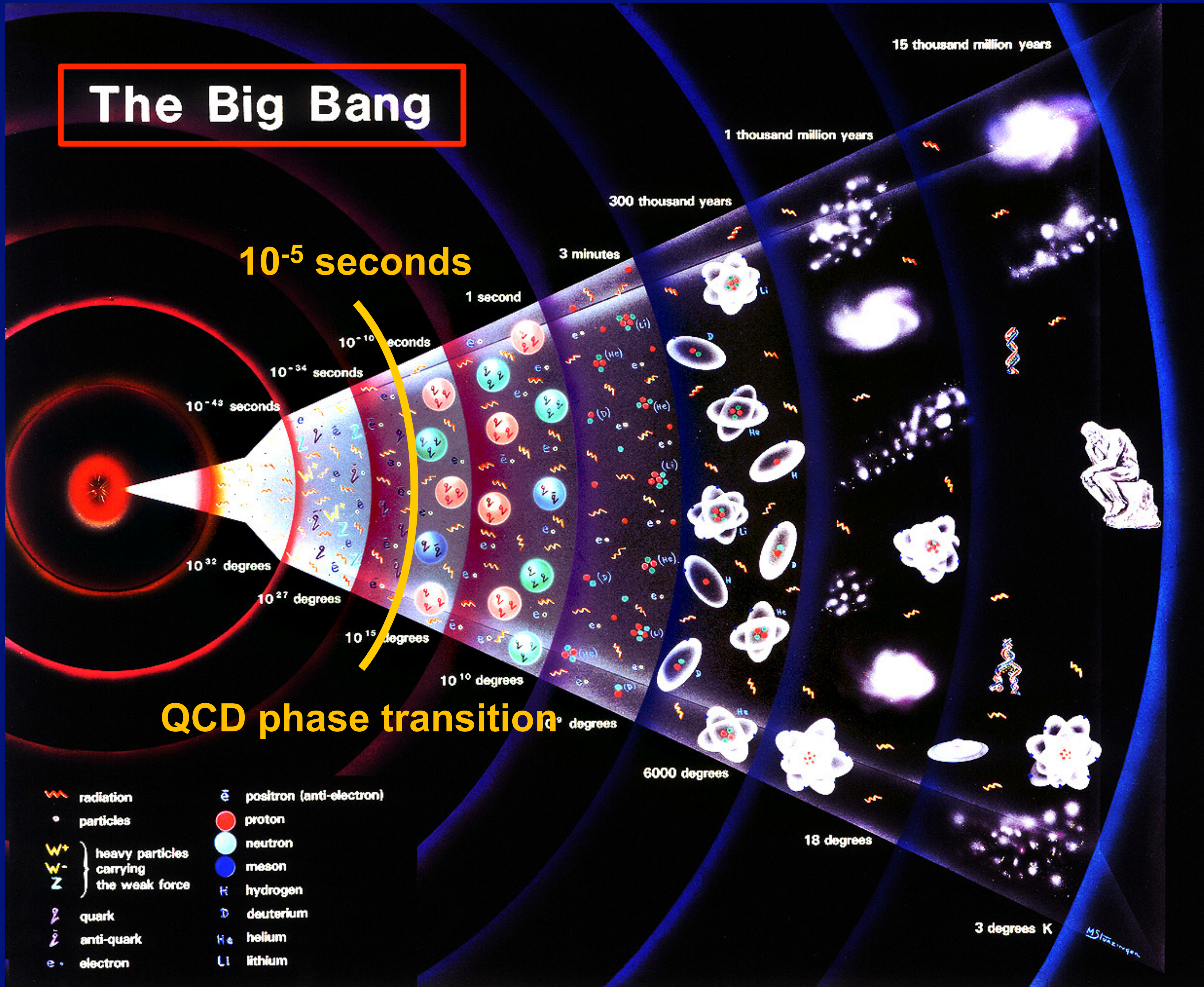
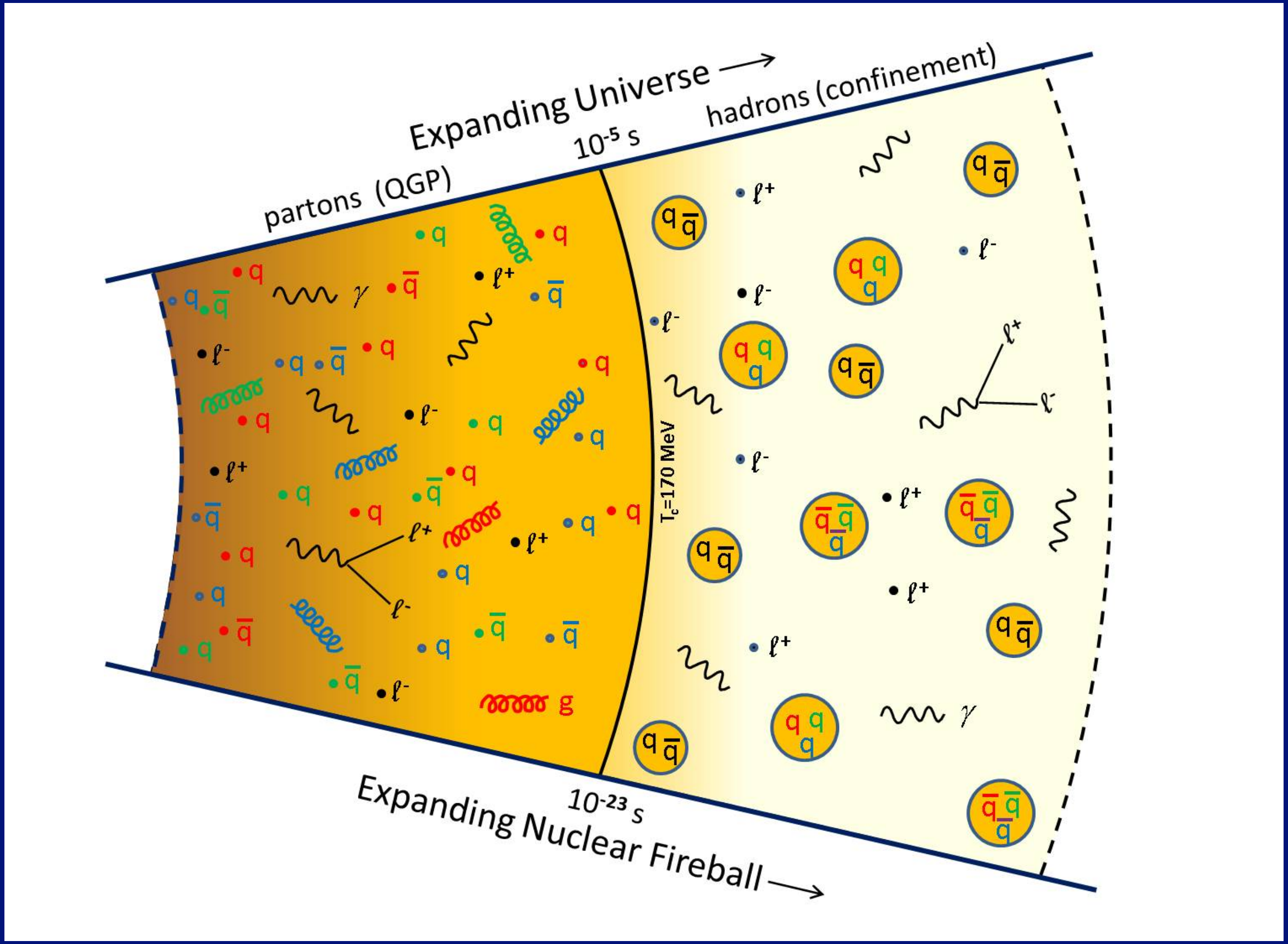
Heavy Ion Physics at the CERN SPS: Roots 1974-1984 and Key Results

Hans J. Specht
Universität Heidelberg

CERN, September 8, 2014


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

Probe the properties of the quark-gluon plasma, RHIC/LHC

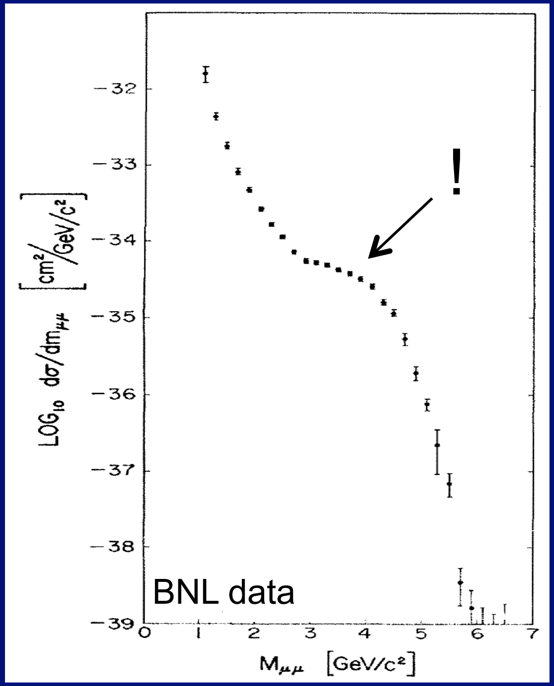
Needs Nuclear Collisions to answer these questions

The Roots 1974-1984: Nuclear and Particle Physics

	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

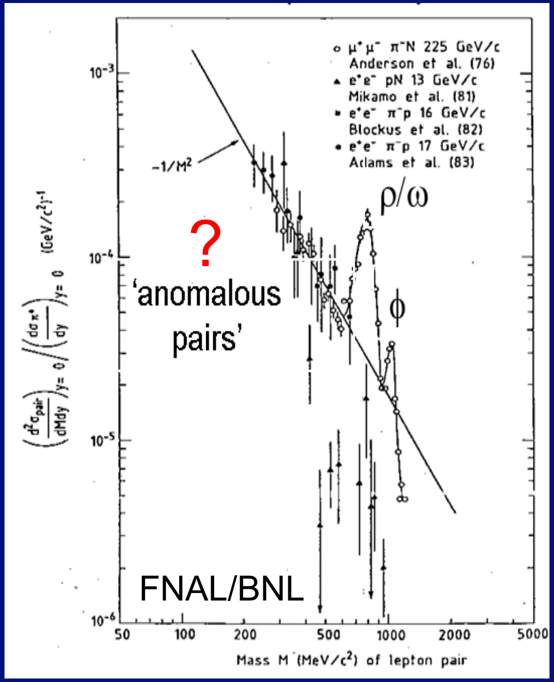
The 1970's: theory and pp experiments

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



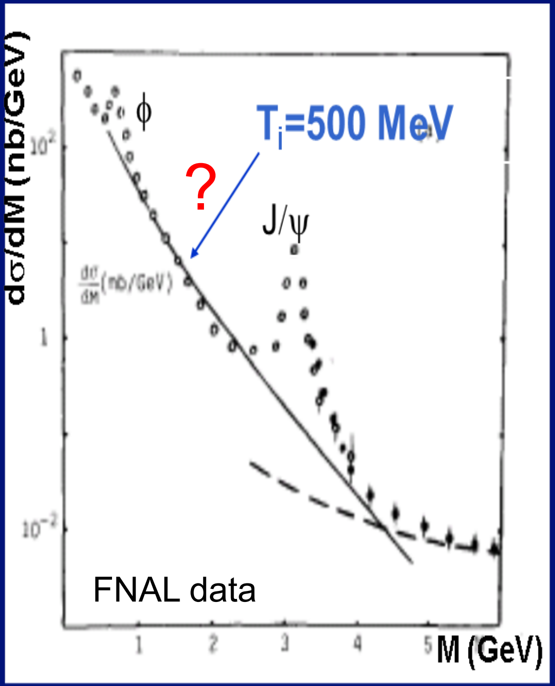
Drell/Yan, PRL1970
hard production from valence and sea quarks

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



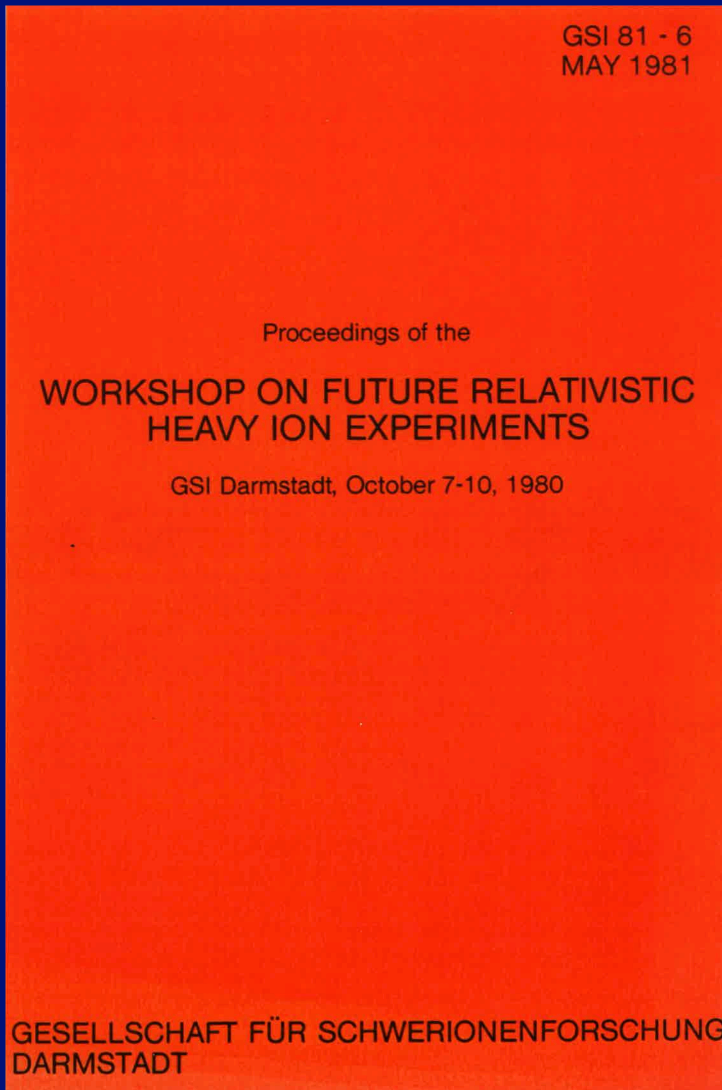
E.Shuryak, PLB 1978
thermal dileptons from 'Quark Gluon Plasma'

Problematic data, but milestones in theoretical interpretation

First theory papers on 'Quark Matter' ever (large ρ_B): *J.C.Collins/M.J.Perry PRL 1975*
(large ρ_B,T): *M.Cabibbo/G.Parisi PLB 1975*

‘First’ Quark Matter Conference (1980)

Organizers and Editors: R. Bock and R. Stock


GSI 81 - 6
MAY 1981

Proceedings of the

WORKSHOP ON FUTURE RELATIVISTIC
HEAVY ION EXPERIMENTS

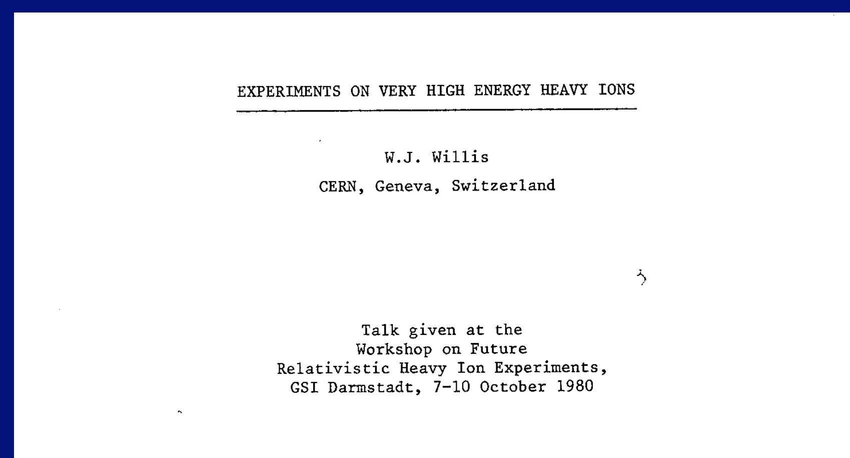
GSI Darmstadt, October 7-10, 1980

GESELLSCHAFT FÜR SCHWERIONENFORSCHUNG
DARMSTADT

Milestone

First organized discussions between particle and nuclear physicists on studying QGP formation in ultra-relativistic nucleus-nucleus collisions. Particle physicists ~30%. Discussions dominated by the dream of ‘keeping the ISR’ (*Summary H.S.*)

First talk of W.J.Willis on nuclear collisions (also published as CERN EP 81-21)


EXPERIMENTS ON VERY HIGH ENERGY HEAVY IONS

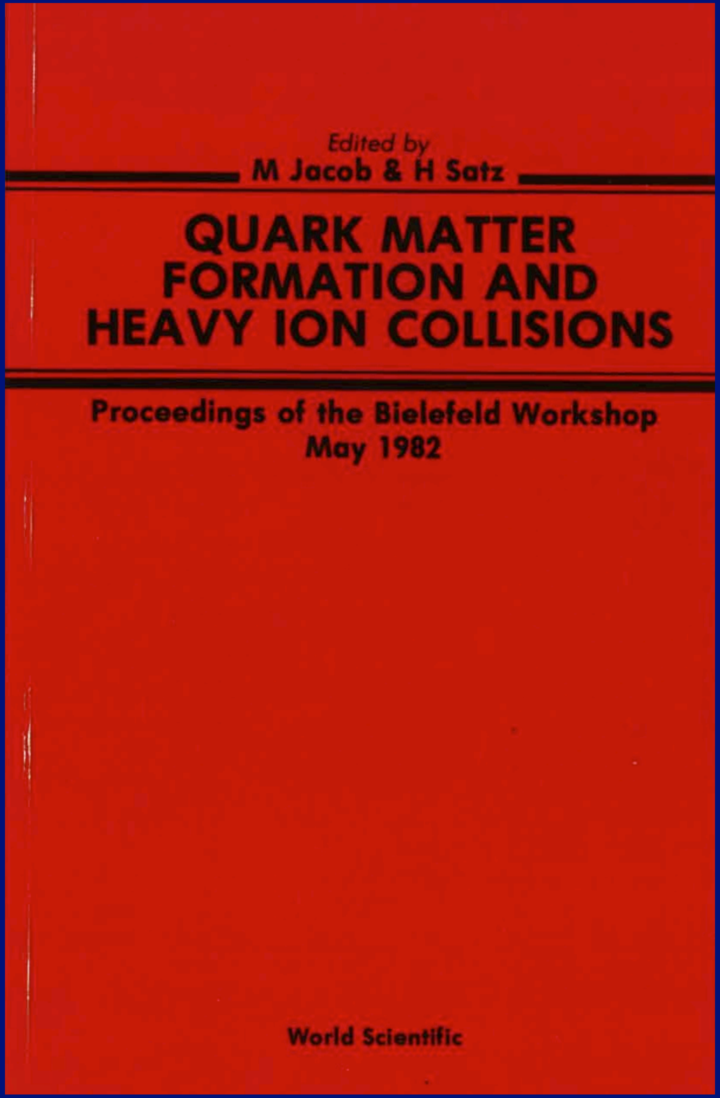
W.J. Willis

CERN, Geneva, Switzerland

Talk given at the
Workshop on Future
Relativistic Heavy Ion Experiments,
GSI Darmstadt, 7-10 October 1980

II Quark Matter Conference (1982)

Organizers and Editors: M. Jacob and H. Satz



Milestones

First systematic discussion between particle and nuclear physicists, on the theoretical and experimental aspects of QGP formation in ultra-relativistic nucleus-nucleus collisions. Particle physicists ~80%.

Basic physics ideas on all observables, including lepton pairs in all mass regions (J/ψ later, Satz/Matsui 1986)

Basic instrumental ideas on the 1st generation experiments at the CERN SPS

Also presented at QM82 Bielefeld: PS Proposal R. Stock et al.

CERN/PSCC/82-1
PSCC/P53
26 January, 1982

STUDY OF RELATIVISTIC NUCLEUS-NUCLEUS REACTIONS INDUCED

BY ^{16}O BEAMS OF 9-13 GEV PER NUCLEON AT THE CERN PS

Proposal submitted to the CERN PSCC by the

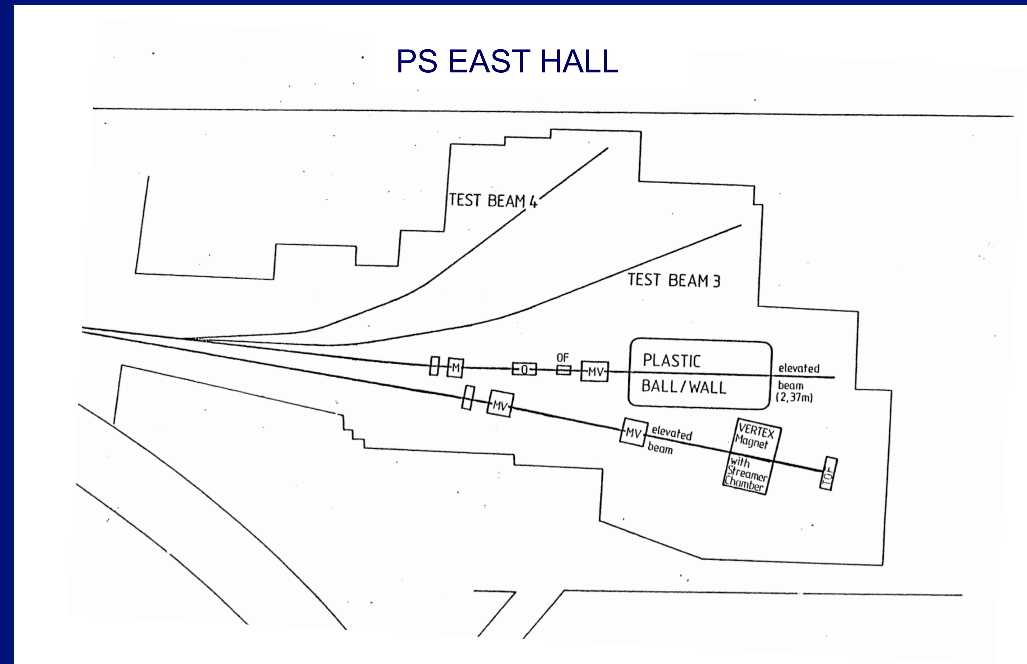
GSI[1]-LBL[2]-Heidelberg[3]-Marburg[4]-Warsaw[5]-Collaboration

February 1982

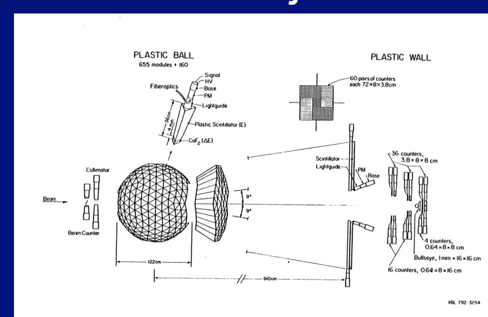
N. Angert[1], H. Bialkowska[5], R. Bock[1], H.H. Gutbrod[1], H. Harris[1], M.R. Maier[4], A.M. Poskanzer[2], F. Pühlhofer[4], H.G. Pugh[2], R.E. Renfordt[3], H.G. Ritter[1], A. Sandoval[1], L.S. Schroeder[2], E. Skrzypczak[5], R. Stock[1], H. Ströbele[1], R.Szwed[5], A. Warwick[1], F. Weik[1], H. Wiemann[1], K.L. Wolf[2]

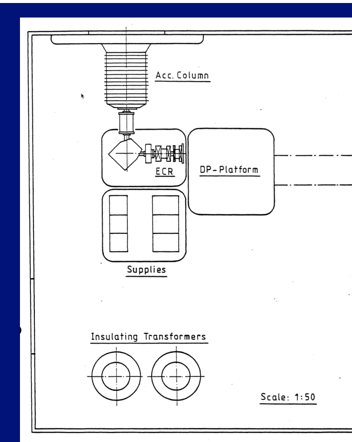
ABSTRACT

We propose to study the target fragmentation modes and $\pi^{\pm}$, K^0, Λ, $\bar{p}$ and $\bar{\Lambda}$ production in collisions of ^{16}O with target nuclei ranging from ^{40}Ca to ^{206}Pb. The acceleration of ^{16}O in the PS will be facilitated by a high charge state ion source installed by us at the Linac I. Experimental equipment will be the Plastic Ball spectrometer, currently employed by us at the Bevalac, LBL Berkeley, and the streamer chamber of the MPI-München group, presently used at the SPS inside a CERN Vertex magnet. The experiments require the acceleration of 10^7 oxygen ions per PS cycle and two splits in the East Hall external beam system delivering about 10^5 ions/s to the streamer chamber and the main part of the intensity to the Plastic Ball. A beam of hadrons (preferably protons) of similarly low intensity, in the 10 to 26 GeV energy range, is needed for setup purposes and in order to study the scaling with projectile mass. The anticipated date of data taking is spring 1984, with an initial request of 250 hours of devoted PS running time.



Milestone: offer of an Oxygen injector for LINAC1



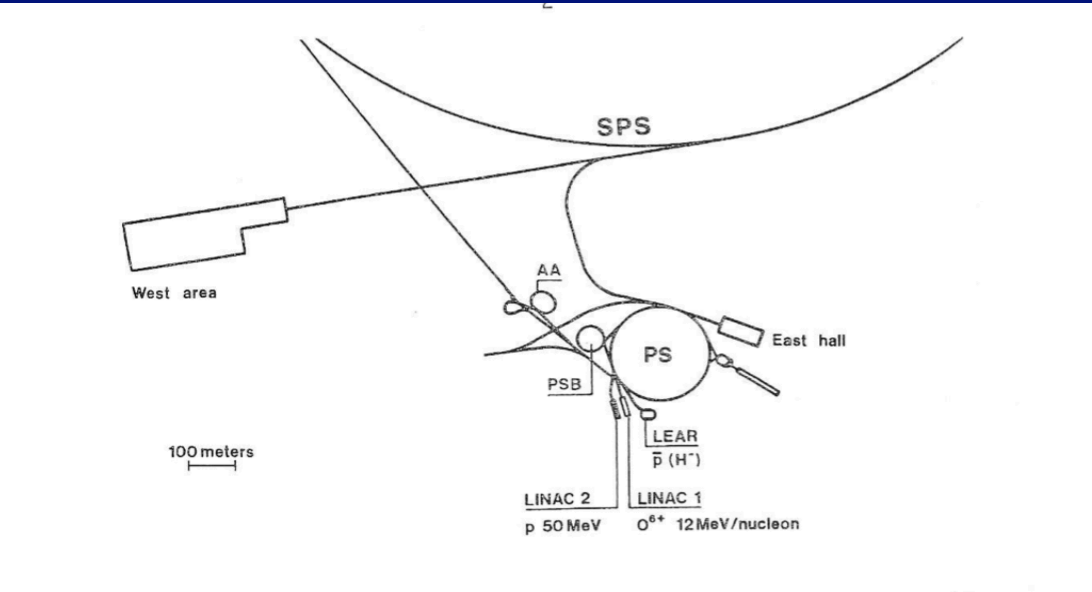


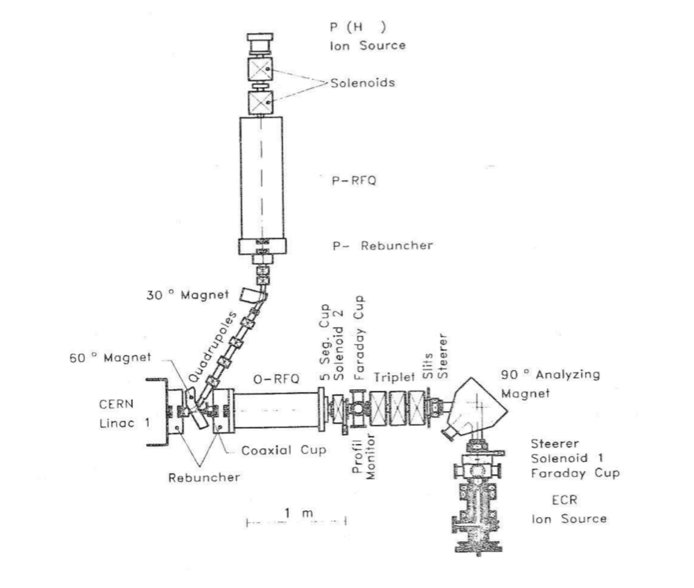
Birth of NA35 and WA80

Convergence at CERN 1983: Contract CERN-GSI-LBL

Construction of an $^{16}O/^{32}S$ injector for LINAC1

New element: Electron-Cyclotron-Resonance (ECR) Ion Source (Richard Geller, Grenoble)





Steps for full acceleration incl. SPS

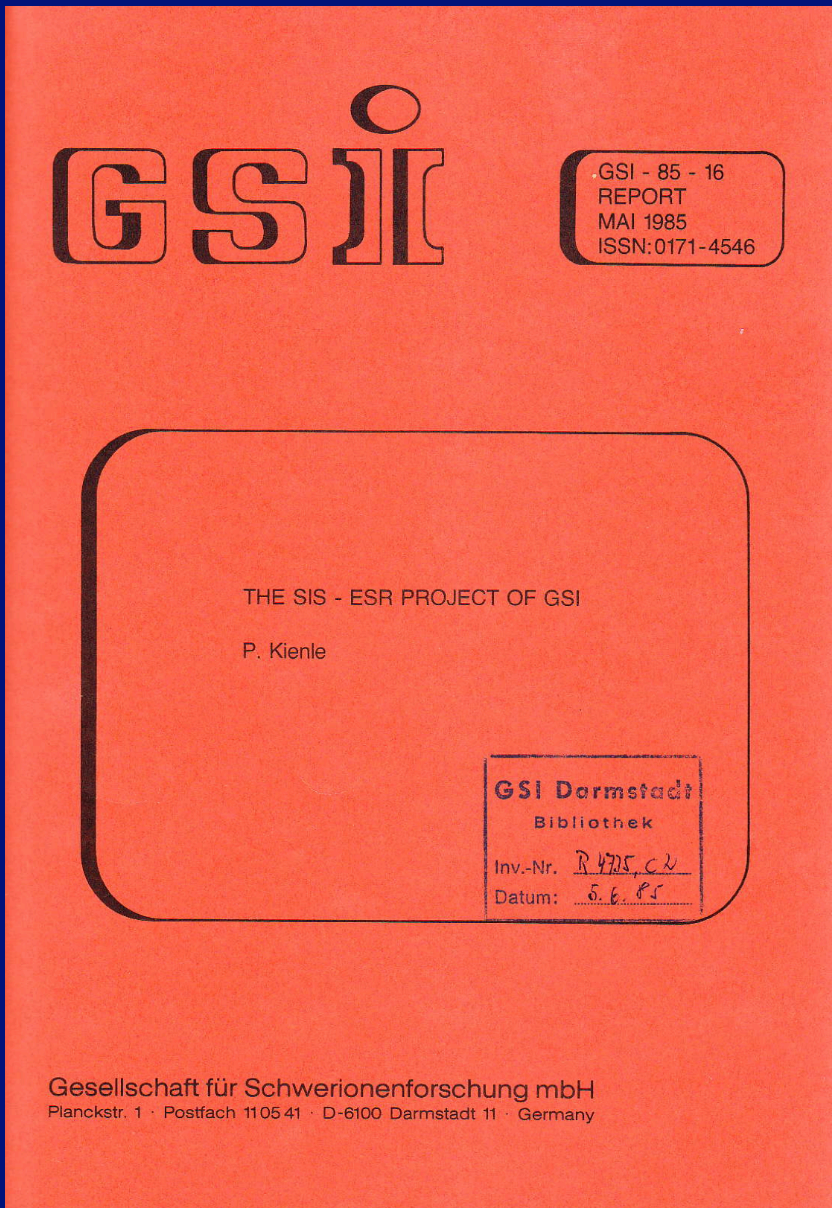
ECR source $^{16}O^{6+}$	5.6 keV/u
RFQ	140 keV/u
LINAC1, Stripper	12.5 MeV/u
Booster+PS	7.0 GeV/u
SPS	60-225 GeV/u

Intensity ~10^8 ions/SPS pulse

first ^{16}O beams 11/1986

first ^{32}S beams 09/1987

Convergence at GSI: SIS18 + ESR

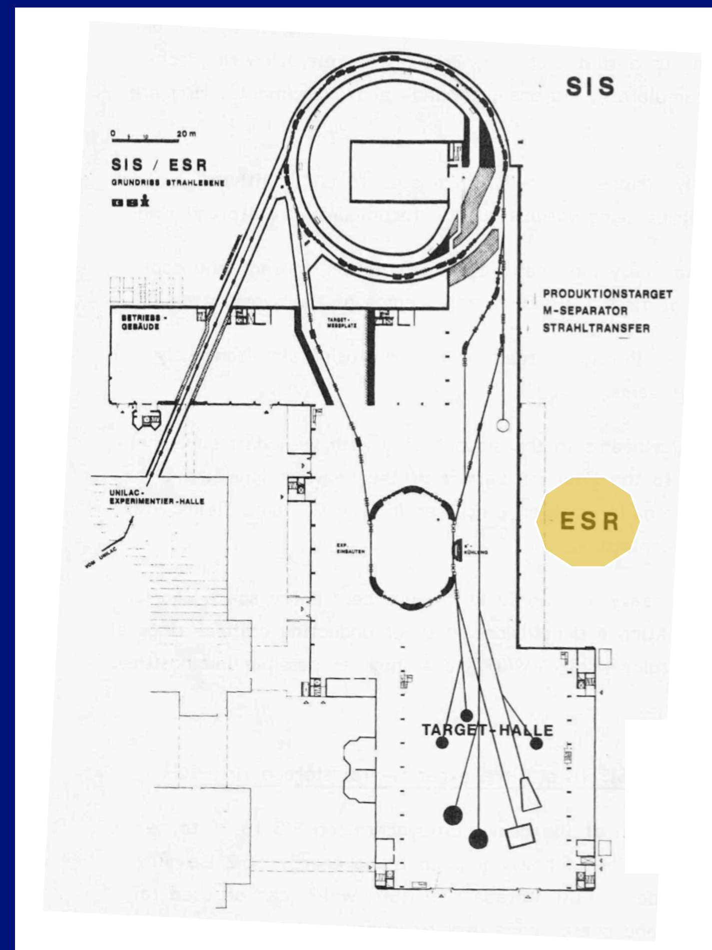

GSI - 85 - 16
REPORT
MAI 1985
ISSN:0171-4546

THE SIS - ESR PROJECT OF GSI

P. Kienle

Gesellschaft für Schwerionenforschung mbH
Planckstr. 1 · Postfach 11 05 41 · D-6100 Darmstadt 11 · Germany

Leon van Hove's verdict concerning the SIS/ESR project at GSI:
'Sunshine at GSI if cooling works, if not total darkness' (1984)

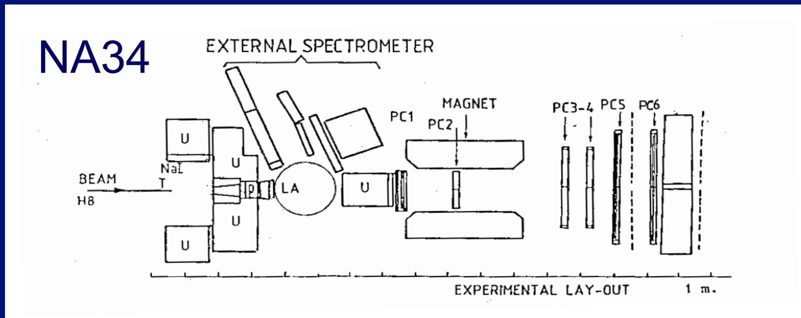


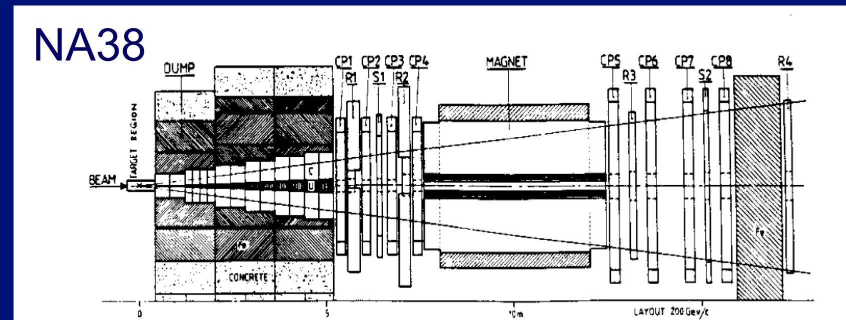
The first Experiments

First-generation Experiments ('Recuperation Era')

		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

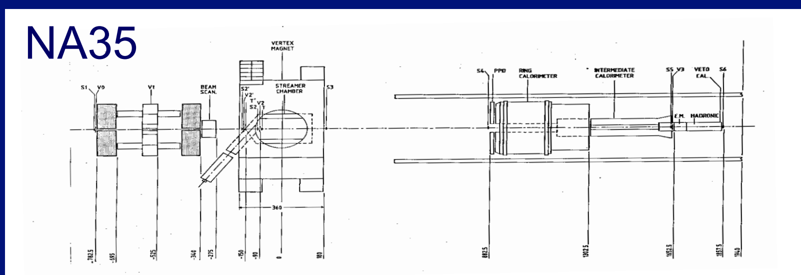
Setups of first generation experiments 1984-1987

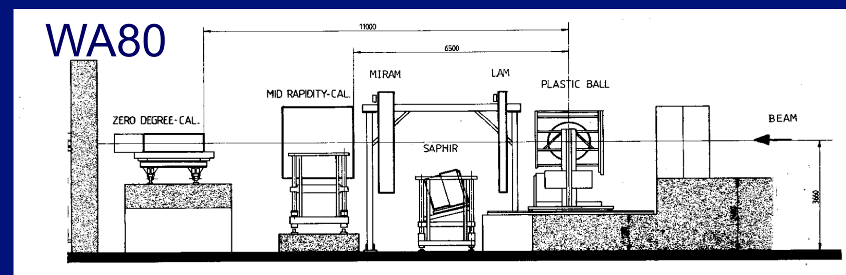




Spokespersons: H.J.Specht

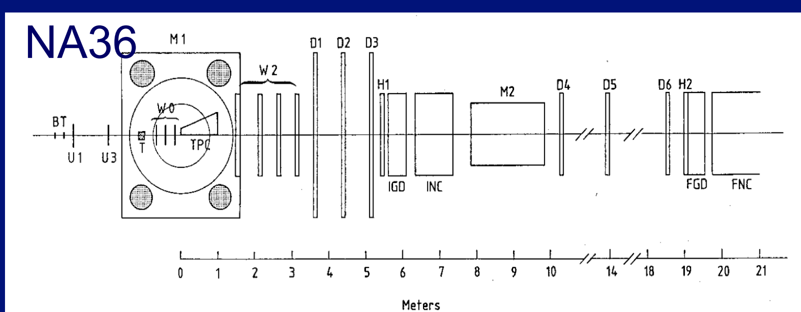
L.Kluberg

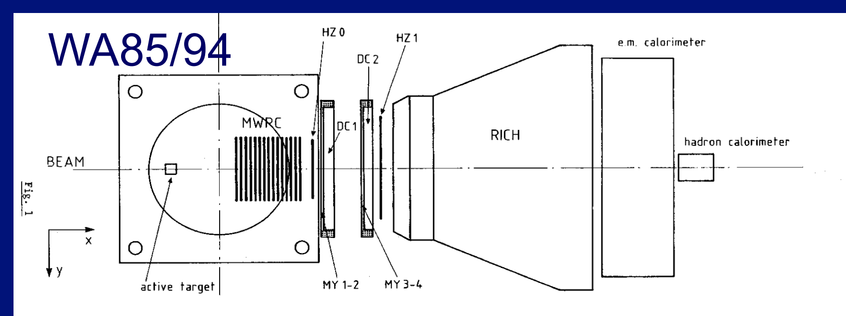




R.Stock

H.H.Gutbrod

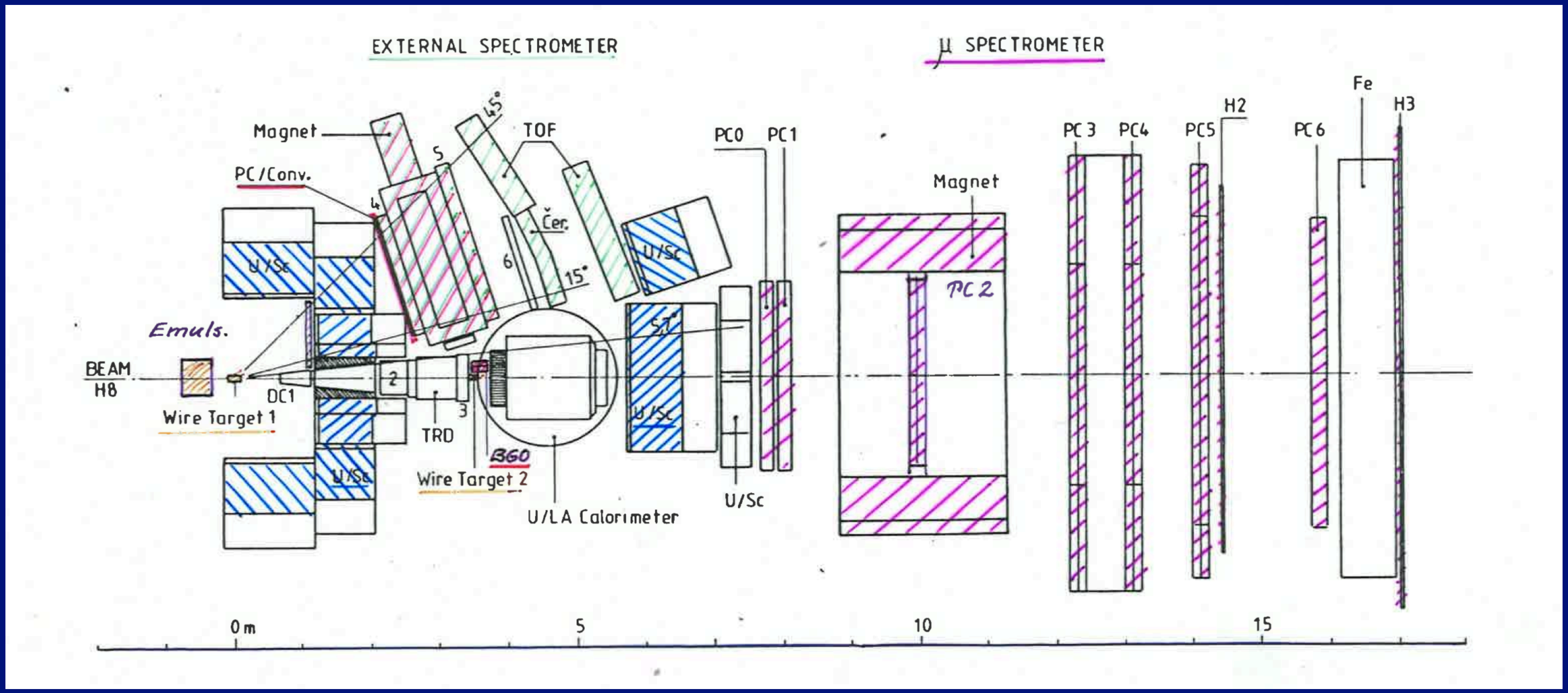


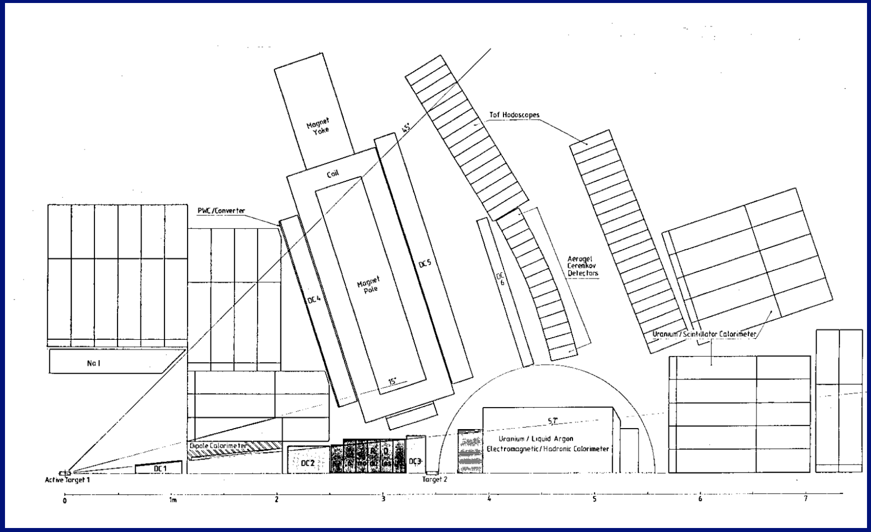


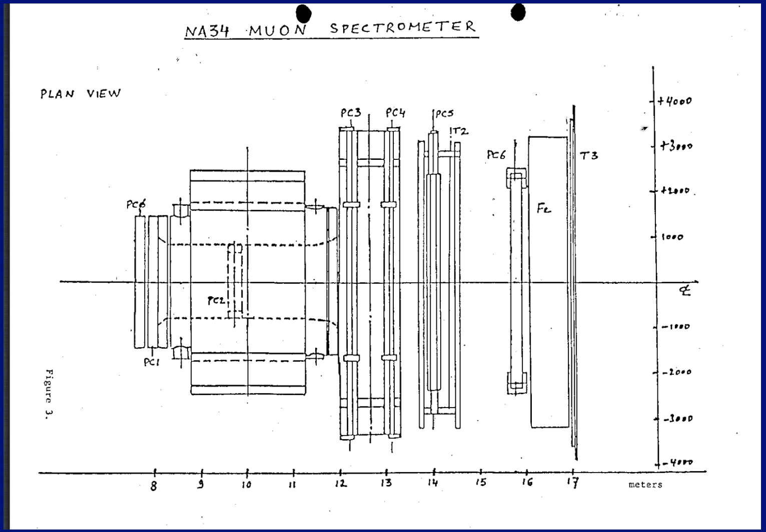
C.R.Gruhn

E.Quercigh

NA34-2


EXTERNAL SPECTROMETER
μ SPECTROMETER
Magnet
PC/Conv.
45°
S
TOF
Čer.
6
15°
4
U/Sc
Emuls.
BEAM
H8
DC1
Wire Target 1
2
TRD
3
BGO
Wire Target 2
U/LA Calorimeter
ST
PC0
PC1
U/Sc
Magnet
PC 2
PC 3
PC4
PC5
H2
PC 6
Fe
H3
0 m
5
10
15


Magnet Yoke
Coil
45°
Tof Hodoscopes
PWC/Converter
Magnet Pole
DC4
DC5
DC6
Aerogel Cerenkov Detectors
Uranium/Scintillator Calorimeter
15°
NaI
Dipole Calorimeter
DC1
DC2
DC3
S.T.
Uranium / Liquid Argon Electromagnetic/Hadronic Calorimeter
Active Target 1
Target 2
0
1m
2
3
4
5
6
7


NA34 MUON SPECTROMETER
PLAN VIEW
PC3
PC4
PC5
T2
PC6
T3
Fe
PC1
PC2
Figure 3.
+4000
+3000
+2000
1000
-1000
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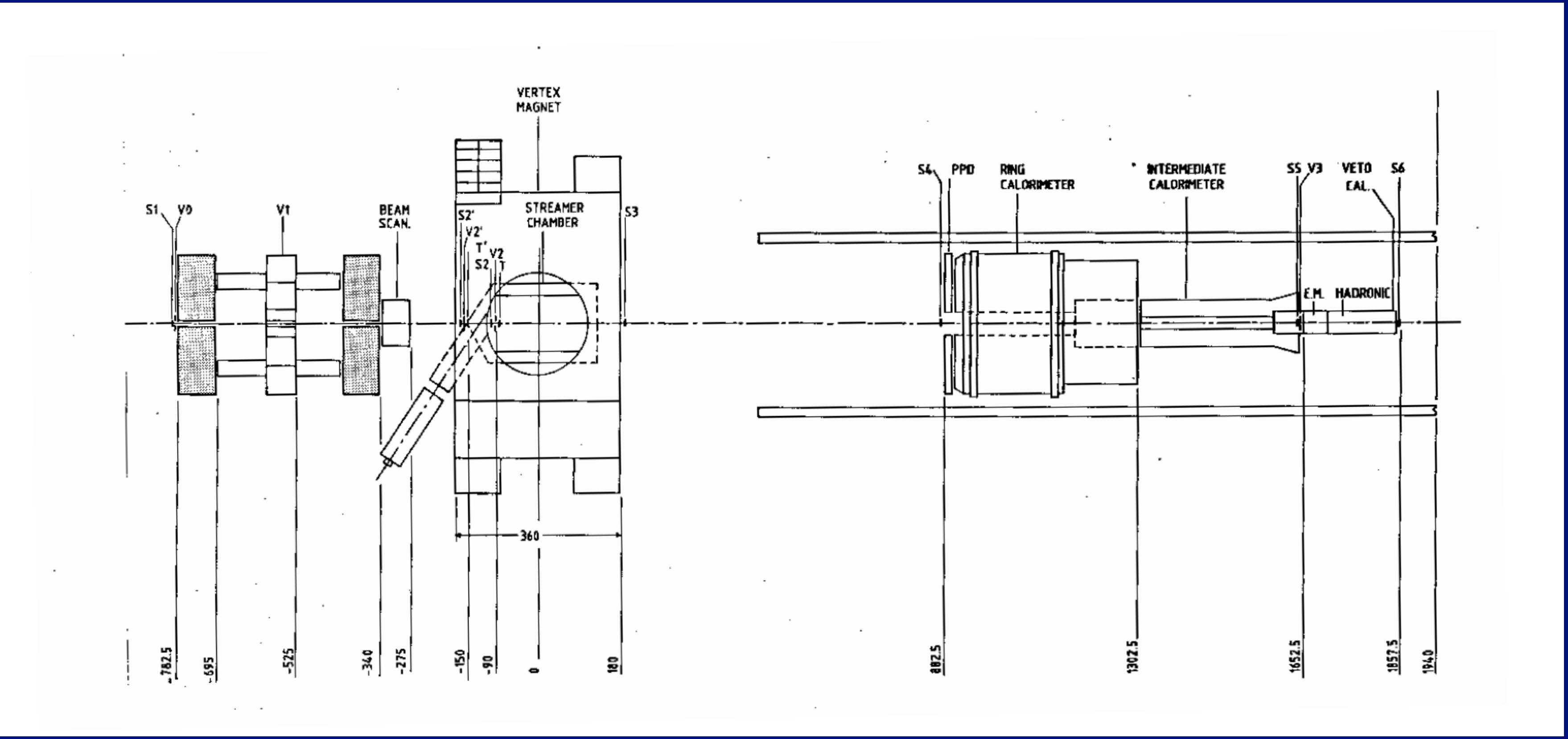
-3000
-4000
8
9
10
11
12
13
14
15
16
17
meters

NA35



Streamer chamber

Vertex magnet

Ring calorimeter

PRESSE

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics
Europäisches Laboratorium für Teilchenphysik

PR 23.87
30.10.87

CERN SUBATOMIC ACCELERATORS

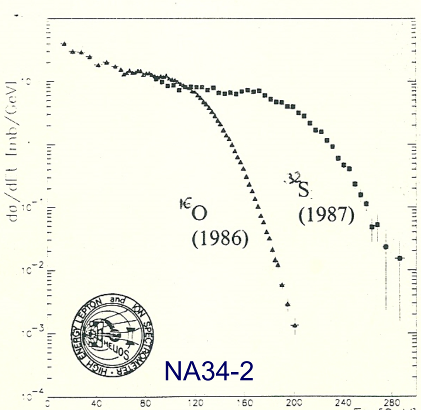
SET UP WORLD RECORD IN ACCELERATOR ENERGY

IN SEARCH FOR "QUARK-MATTER"

Already acknowledged as the world's most versatile system of subatomic particle accelerators, the CERN complex of big machines put on a spectacular performance in late September and early October, accelerating ions (=atomic nuclei) and taking them to the highest energy ever reached in a laboratory.

CERN machines usually work with protons (nuclei of hydrogen carrying one unit of electric charge), but to extend their studies of matter physicists worked with oxygen ions in 1986 and with sulphur ions this year. Ions are atoms stripped of electrons and are 16 times (oxygen) or 32 times (sulphur) heavier than protons carrying multiple (respectively 8 and 16) charges. To provide these ions, one of the CERN injector accelerators was adapted in collaboration with the German Gesellschaft für Schwerionenforschung (GSI - Darmstadt), and the Lawrence Berkeley Laboratory (California) using an ion source developed by the Centre d'Etudes Nucléaires (Grenoble). These research centres have strong traditions of research using ion beams, but only the unique CERN system of interlinked machines could provide the high energies needed to open up new horizons.

From 25 September to 14 October the CERN Super-Proton-Synchrotron (SPS) accelerated a beam of sulphur (^{32}S) atomic nuclei with a total energy of 6.4 TeV (i.e. 200 GeV per nucleon) surpassing its own world record mark of 3.2 TeV set last year in the oxygen nuclei (^{16}O) running period.



30.10.1987

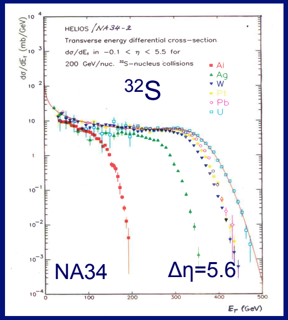
First results from a ^{32}S beam (one year after the start with the ^{16}O beam)

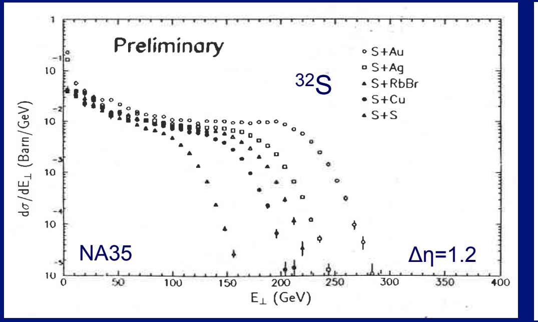
Results with beams of ^{16}O-/^{32}S and evolution until ^{208}Pb

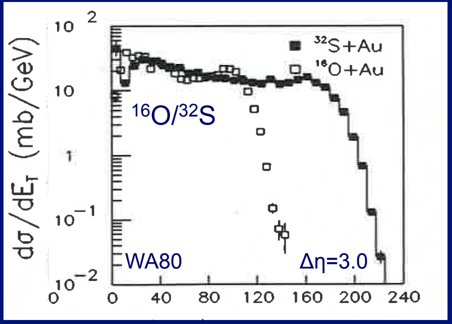
Beam times: first ^{16}O 1986
first ^{32}S 1987
last ^{32}S 1992

Energies 60 and 200 AGeV

The earliest result shown most frequently (QM1988)







large energy deposition

max. energy density (à la Bjorken)

ε=2-3 GeV/fm^3 → T_i>Tc

Initial results also on:

- hadron freeze-out
- hadron p_T spectra
- strangeness enhancement
- 2-particle corr. (HBT)
- photon spectra
- J/ψ production

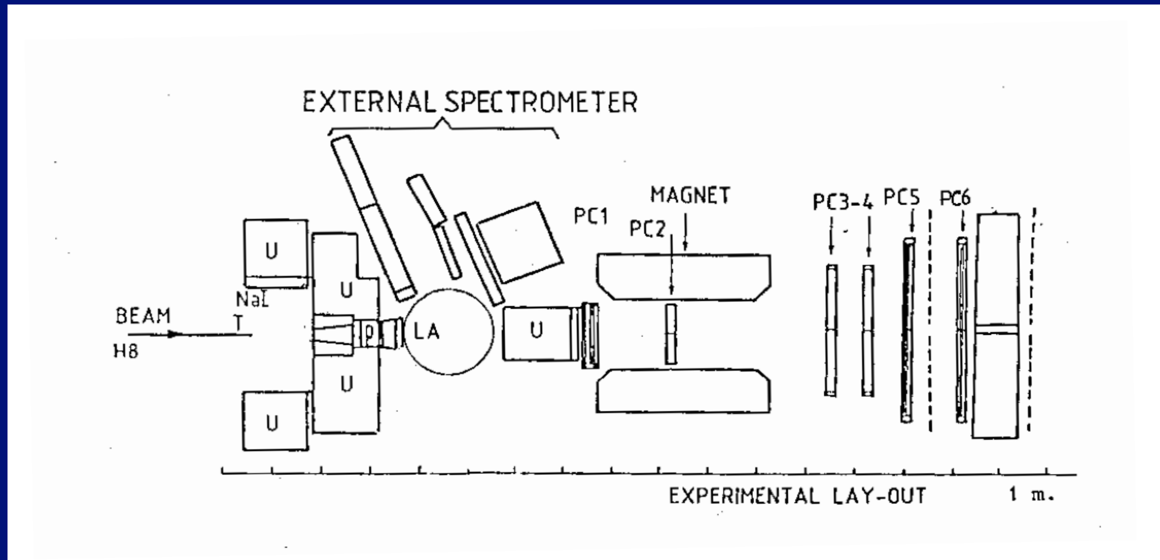
Final achievements:

- strangeness up to Ω^-, $\overline{\Omega}^-$ (WA85)
- dilepton excess above known sources (NA34-3/NA45)
- J/ψ production (NA38)

The most extreme learning process: the decay of NA34

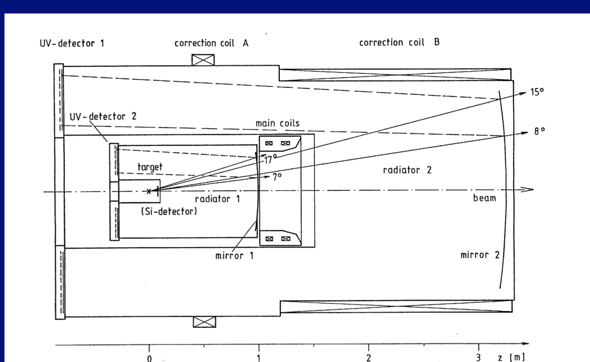
Names:
Spoksperson/
Contact person

Years:
proposed/
approved

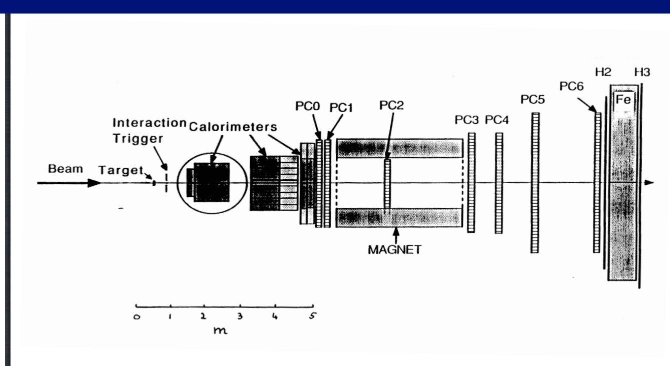


NA34-2
(1984/84)
H.Specht/C.Fabian

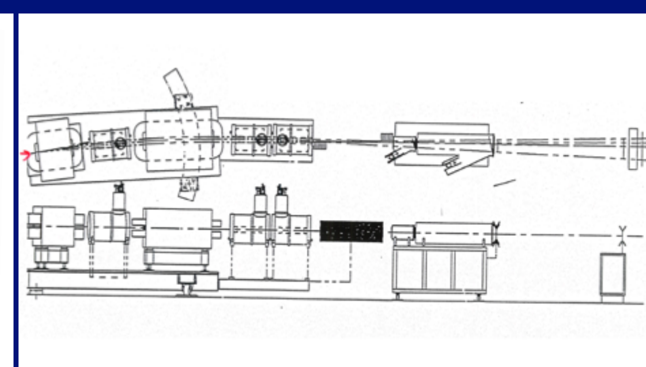
2 years after the first O beam 1986



NA45 (1988/89)
H.Specht/J.Schukraft



NA34-3 (1988/89)
G.London/U.Goerlach



NA44 (1988/89)
H.Bøggild/W.Willis

CERN Heavy-Ion Facility ‘LINAC 3’ for Pb Beams

CERN 93-01
28 April 1993

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN HEAVY-ION FACILITY DESIGN REPORT

N. Angert (GSI), M.P. Bourgarel (GANIL), E. Brouzet, R. Cappi, D. Dekkers, J. Evans, G. Gelato, H. Haseroth, C.E. Hill, G. Hutter (GSI), J. Knott, H. Kugler, A. Lombardi (INFN, Legnaro), H. Lustig, E. Malwitz (GSI), F. Nitsch, G. Parisi (INFN, Legnaro), A. Pisent (INFN, Legnaro), U. Raich, U. Ratzinger (GSI), L. Riccati (INFN, Torino), A. Schempp (IAP, Frankfurt), K. Schindl, H. Schönauer, P. Têtu, H.H. Umstätter, M. van Rooij, D. Warner, M. Weiss.

Editor: D. Warner

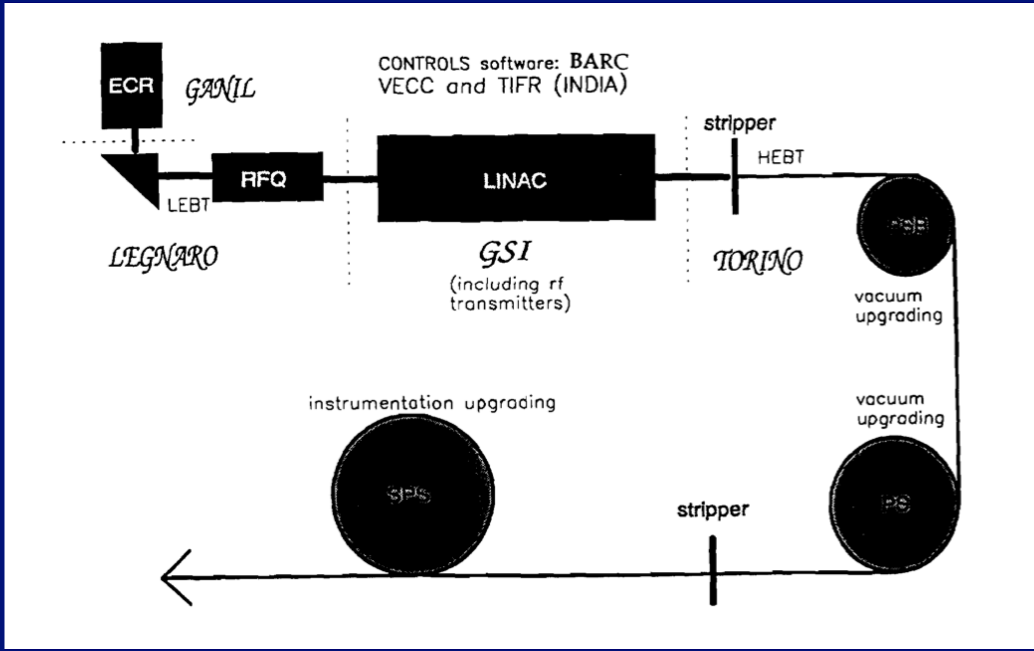
GENEVA
1993

H.Haseroth et al. ,Concept, CERN 90-01

Realization by international collaboration

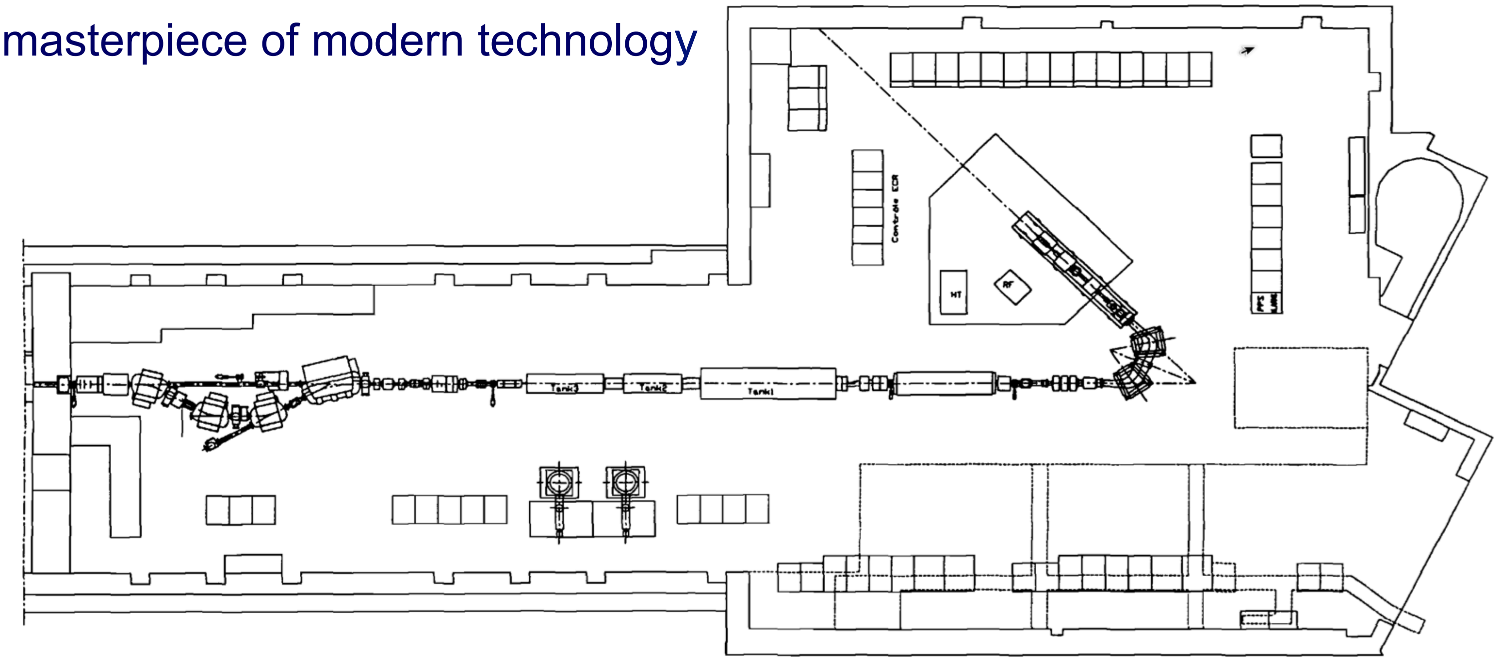
CERN, GANIL, GSI, INFN LEGNARO, INFN TORINO, IAP Frankfurt (assistance by Czech Republic, India, Sweden and Switzerland)

First Pb beams in 1994



CERN Heavy-Ion Facility ‘LINAC 3’ for Pb Beams

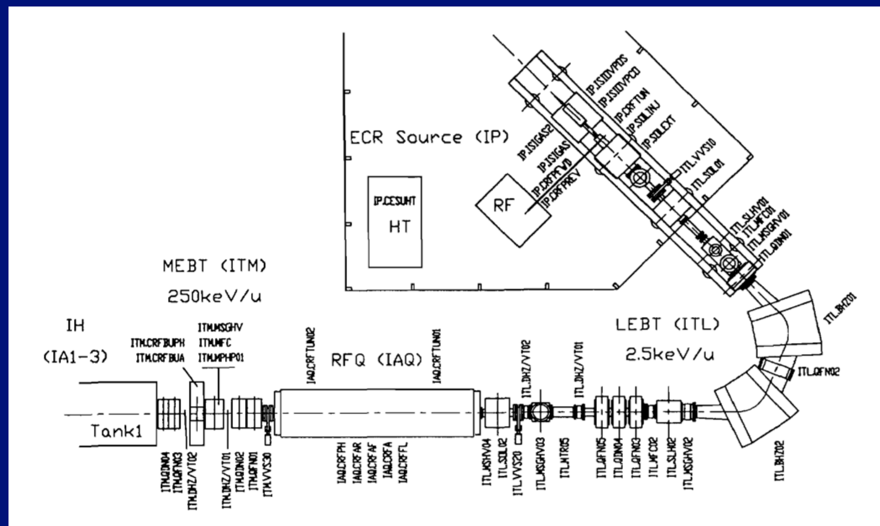
masterpiece of modern technology



Steps for full acceleration incl. SPS

ECR source Pb^{27+}		2.5 keV/u
RFQ		250 keV/u
LINAC 3		4.2 MeV/u
Stripper	$Pb^{27+} \rightarrow Pb^{53+}$	
Booster+PS		4.25 GeV/u
Stripper	$Pb^{54+} \rightarrow Pb^{82+}$	
SPS		20-158 GeV/u

Intensity ~10^8 Pb-ions/SPS pulse

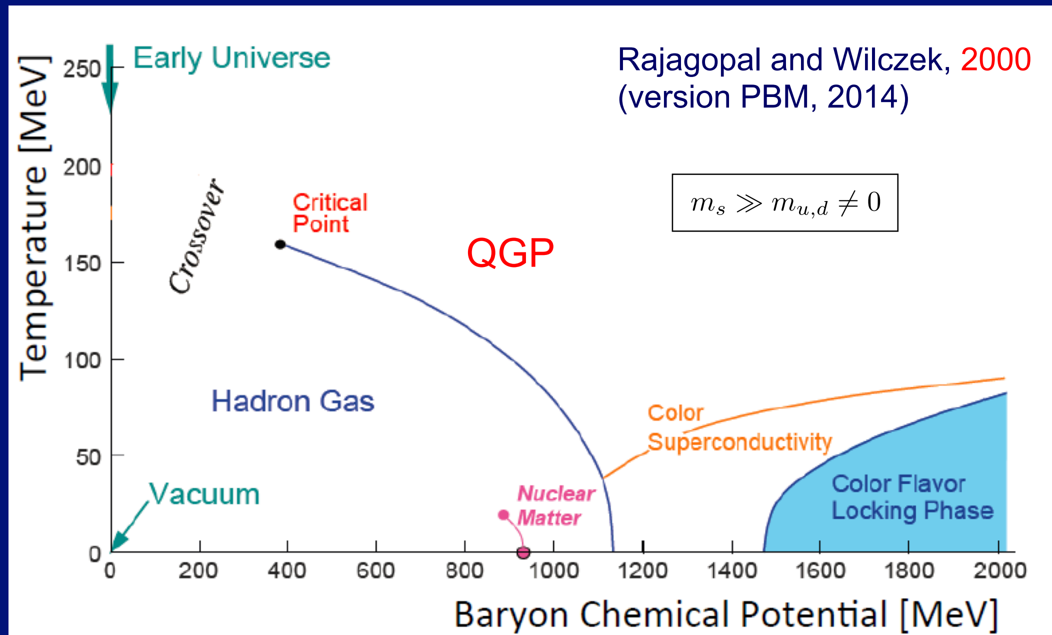


The 7 Experiments of the Pb Era

		approved
NA44	Small-angle focusing Spectrometer → 1 and 2 particles (new, pre Pb, spokesperson H.Bøggild)	1989
NA45	Double-Cherenkov Spectrometer → low-mass dielectrons (new, pre-Pb, spokesperson H.Specht)	1989
NA49	Large-acceptance hadron detector (TPCs, TOF, Calorim.) (new, spokesperson R. Stock)	1991
NA50	Muon Spectrometer → high-mass dimuons, charmonia (followed NA38, spokesperson L. Kluberg)	1992
NA52	NEWMASS Beam Spectrometer (550m) → strangelets (new, spokesperson K. Pretzl)	1991
WA97/ NA57	Ω' spectrometer, Si, RICH → hyperons/anti-hyperons (followed WA85, spokespersons E.Quercigh/F.Antinori)	1991
WA98	Large acceptance hadron and photon detector (followed WA80, spokesperson H.Gutbrod)	1991

Physics Results until 2000

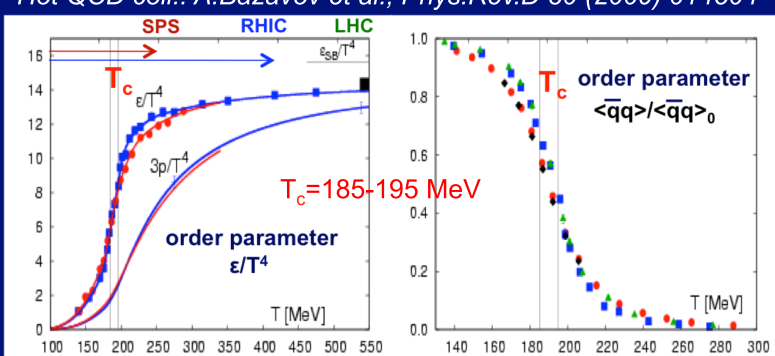
Theoretical guidance for the QCD phase diagram



Lattice 2009

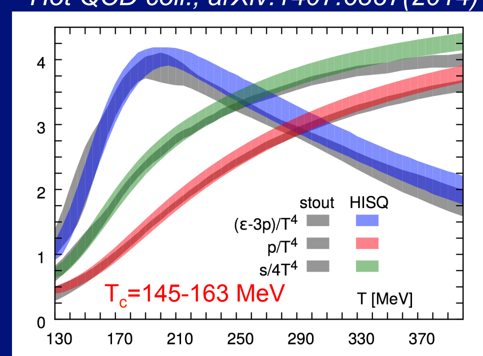
Lattice 2014

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



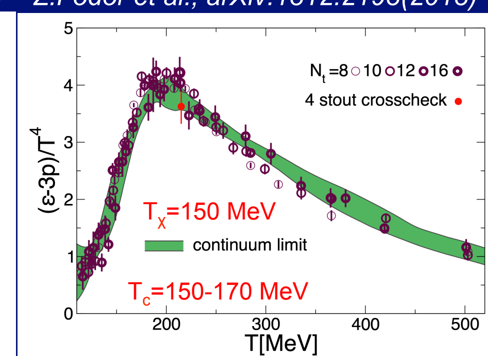
deconfinement transition chiral symmetry restoration

Hot QCD coll., arXiv:1407.6387(2014)



deconf. trans. and trace anomaly

Z.Fodor et al., arXiv:1312.2193(2013)

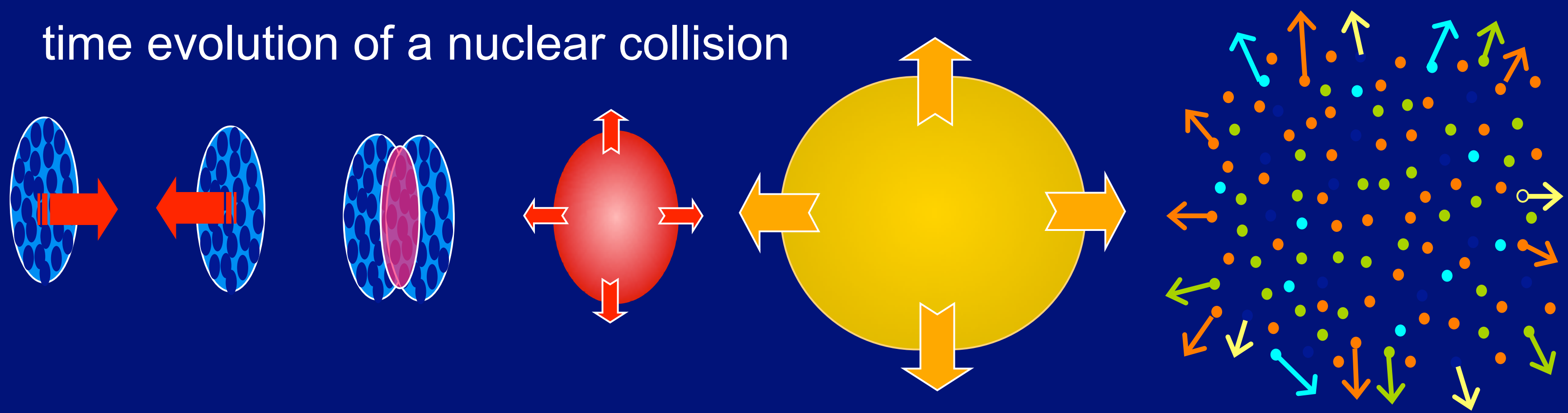


trace anomaly

Conclusions 2014: now crossover transition, soft EoS (stable), $T_c \sim T_X$

Observables and physics goals: hadron production

time evolution of a nuclear collision



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

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

99.99% of the produced particles are hadrons

hadron yields: temperature at creation (statistical hadronization)

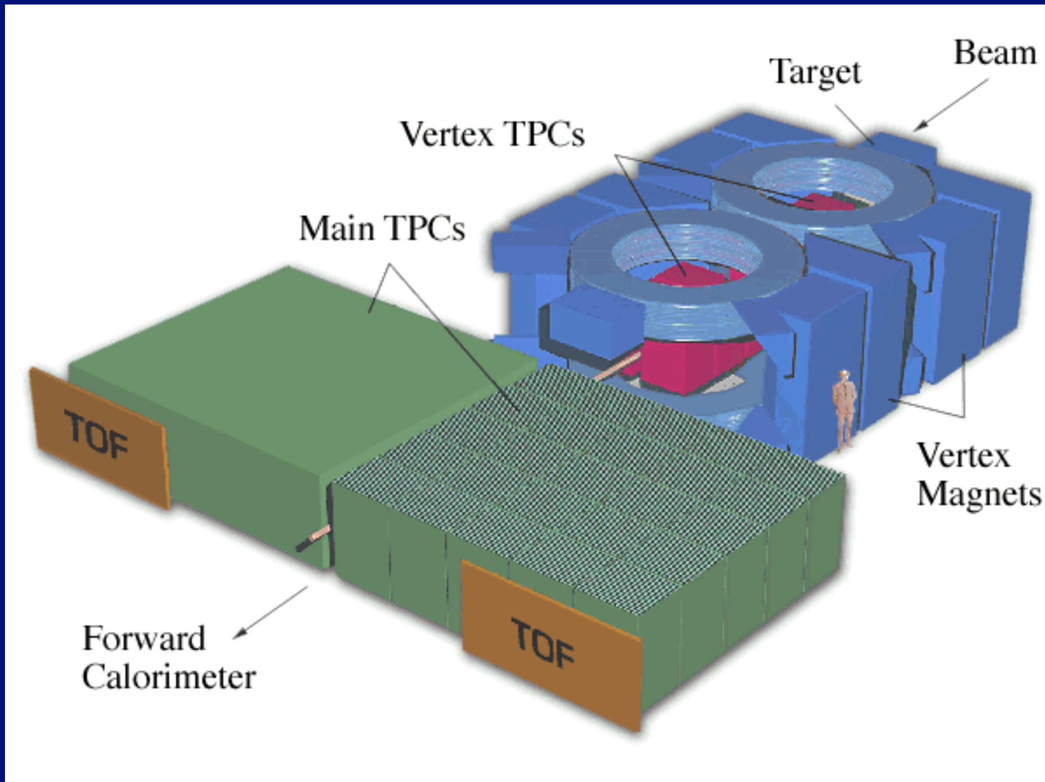
hadron flavors: strangeness enhancement (flavor equilibration)
J/ψ suppression (color screening)

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

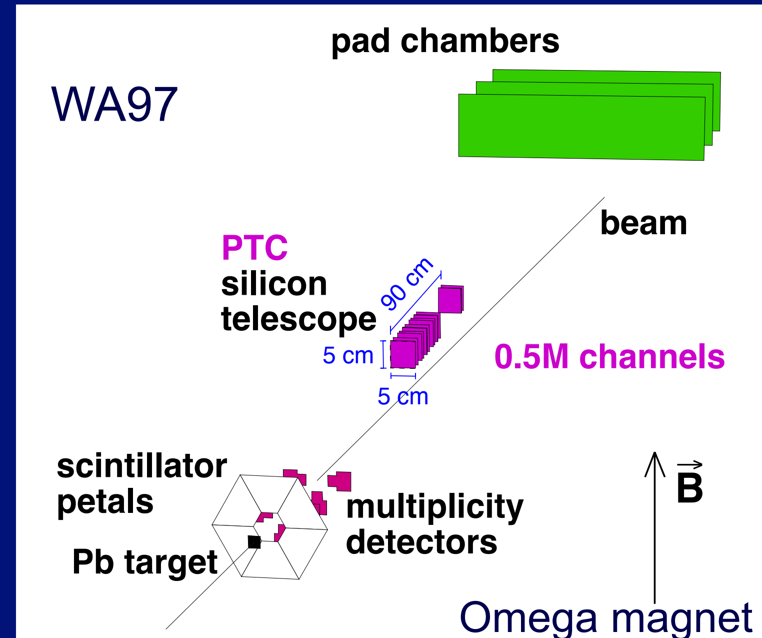
hadron correl.: (HBT, elliptic flow)

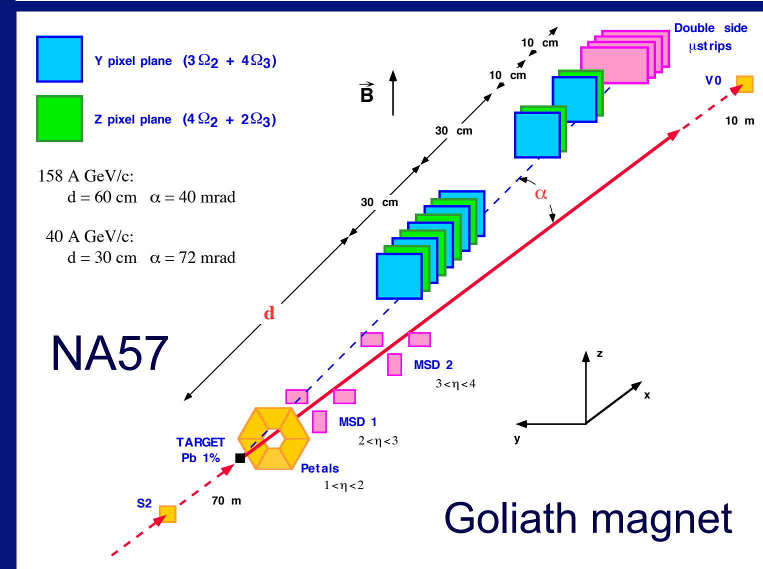
Experimental Setups

NA49



WA97/NA57

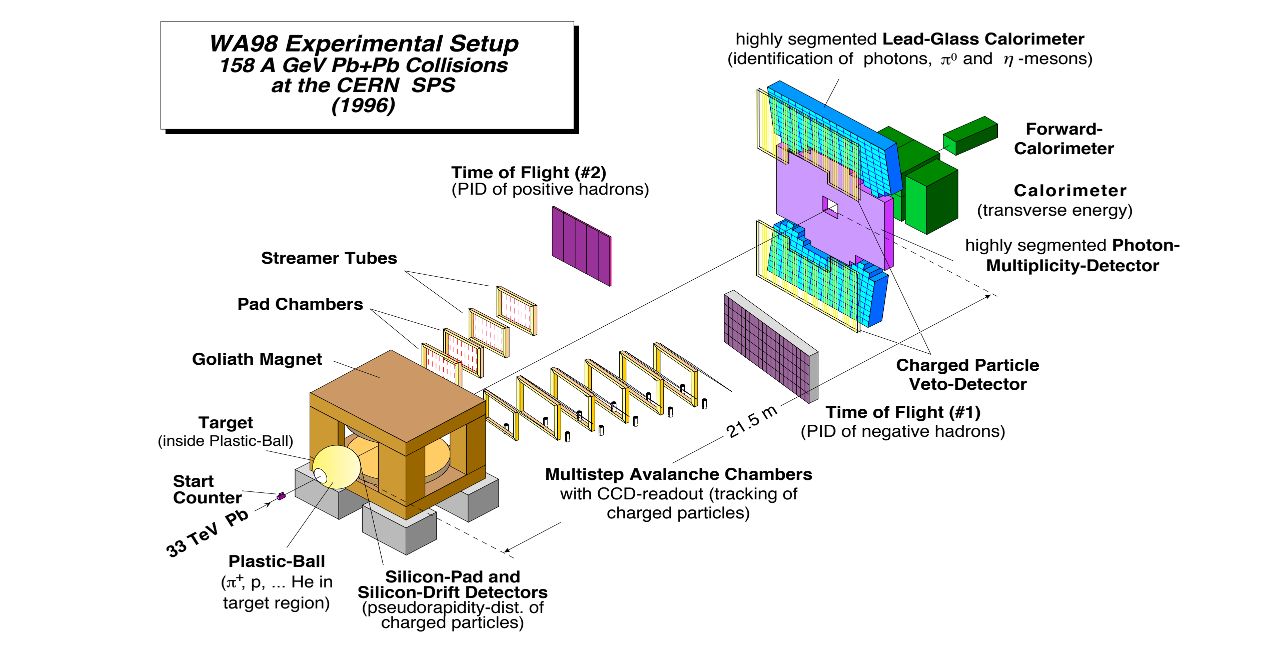




'universal' hadron coverage
with large acceptance

optimized for strangeness,
in particular hyperons; larger
centrality range in NA57

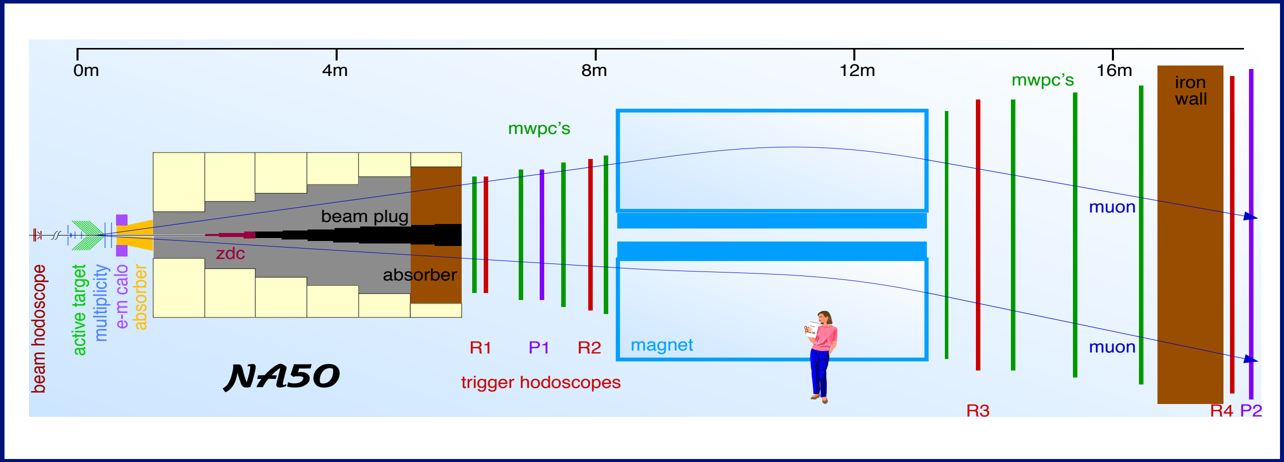
Experimental Setups



WA98

hadrons with large acceptance

photons (hadron decays and direct)



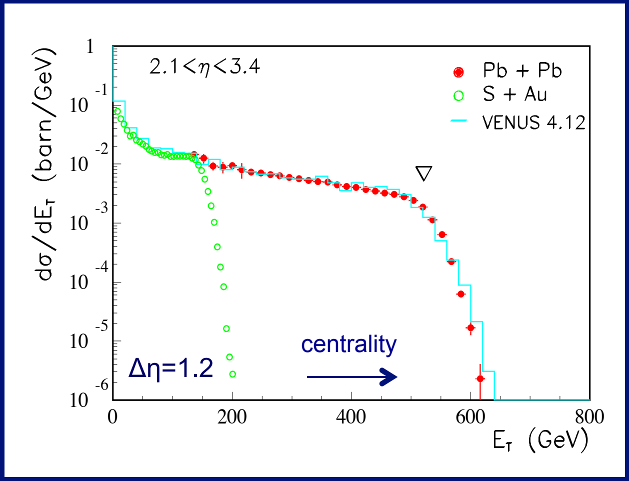
NA50

vector mesons including charmonia

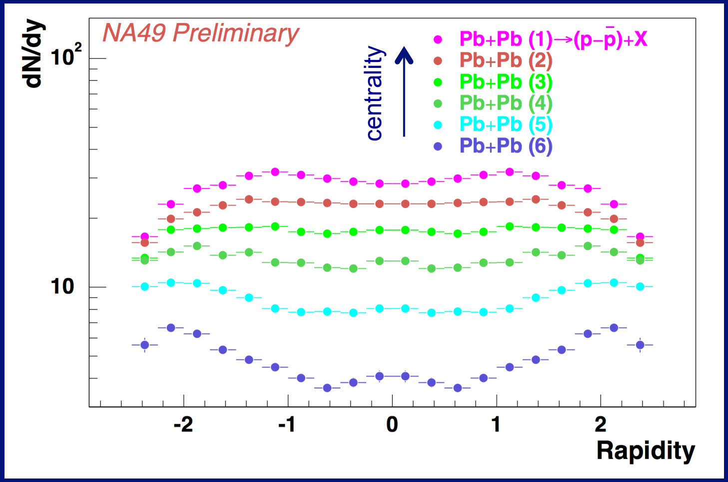
hard and soft dimuon continua

Initial Energy Density

Transverse Energy Flow, NA49

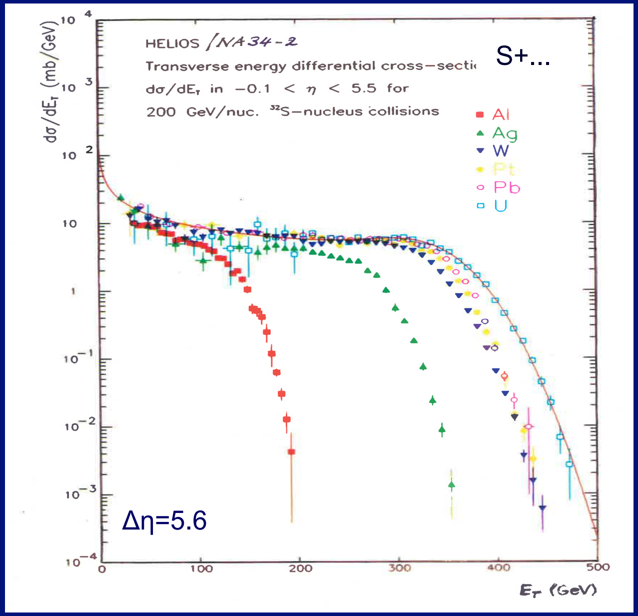


Baryon stopping, NA49 1999



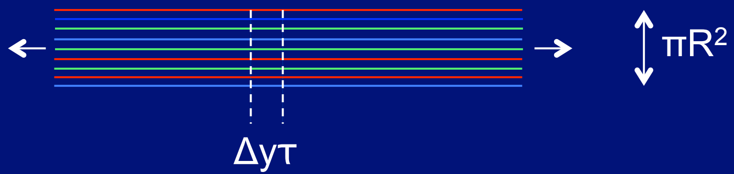
1:1 match between energy deposition and baryon stopping

Transverse Energy Flow, NA34-2



Shuryak-Bjorken:

comoving energy density at hadronization time τ



$\varepsilon = \Delta E_T / \Delta y \times 1/(\tau\, \pi R^2)$ $\tau = 1$ fm/c, $R = 1.12\, A^{1/3}$ fm

Central collisions: S-Au $\varepsilon = 2.6$

Pb-Pb $\varepsilon = 3.2$

$> \varepsilon_{crit} = 1$ GeV/fm^3

Hadron Yields – Statistical Hadronization

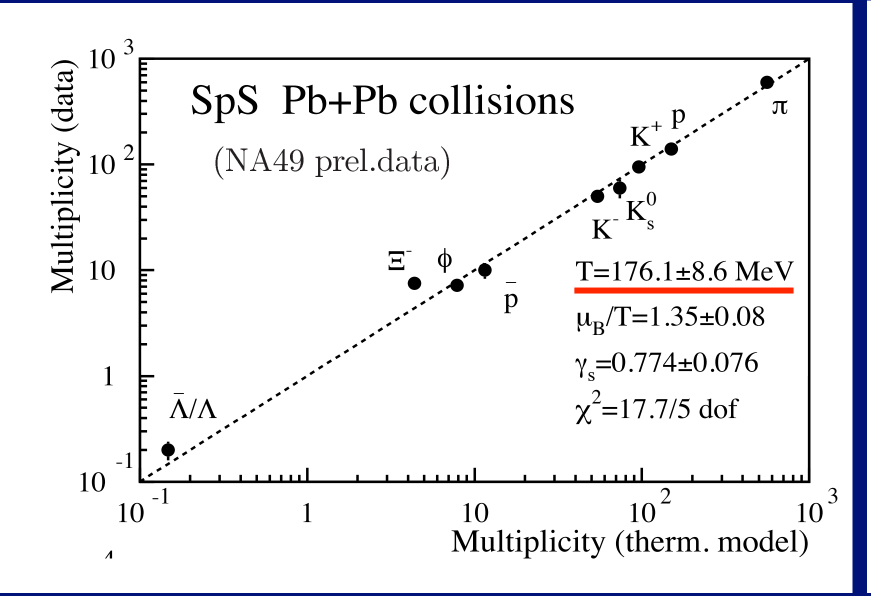
Since pp: Statistical Bootstrap Model (SBM), R.Hagedorn, Nuovo Cim.S. 1965
- populate hadron species according to phase space probabilities -

for AA:
grand canonical ensemble

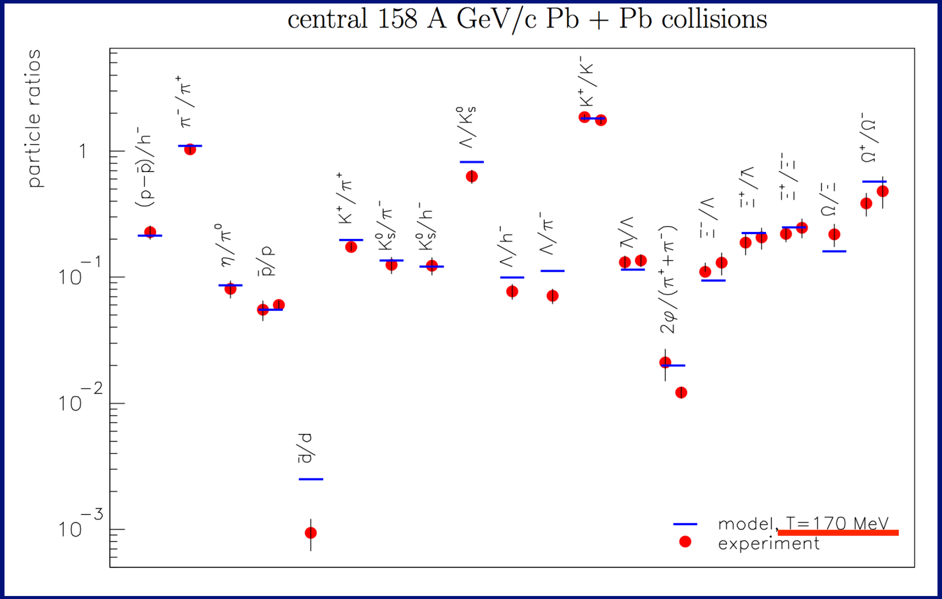
$$n_i = N/V = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp((E_i-\mu_i)/T)\pm 1} \qquad \mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

free parameters from fits to the data: T, μ_B (V, μ_S, μ_{I3} from conservation laws)

F.Becattini, J.Cleymans, K.Redlich et al.



P.Braun-Munzinger, J.Stachel et al.

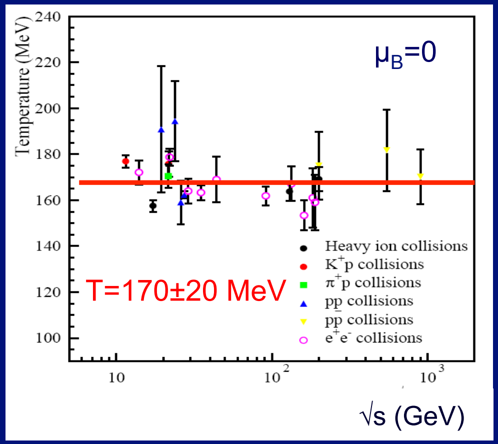


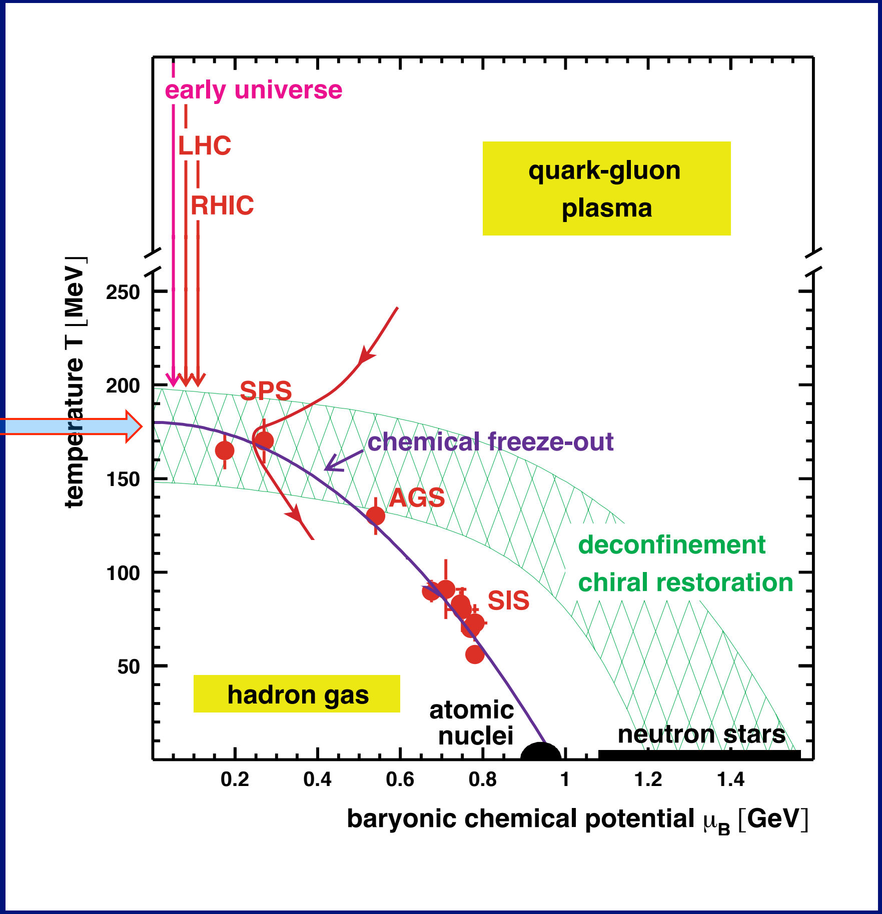
perfect agreement between yield data and model description

Beam-energy dependence of freeze-out parameters

J.Stachel, Nucl.Phys.A 654 (1999) 119c

H.Satz's déjà vu (2008)





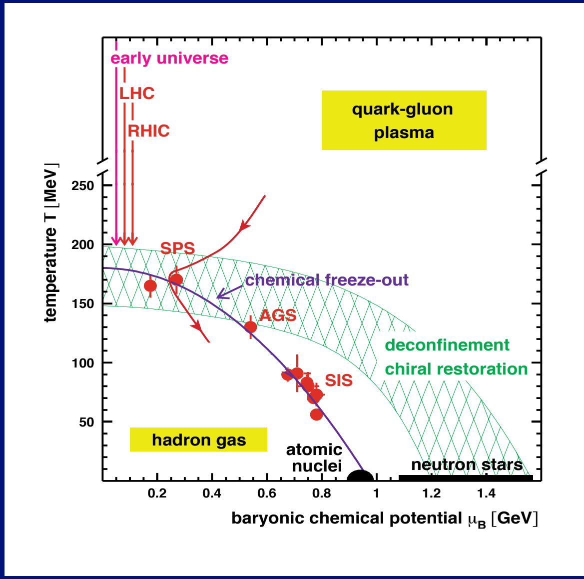
Hagedorn Temperature

T ~ 170 MeV

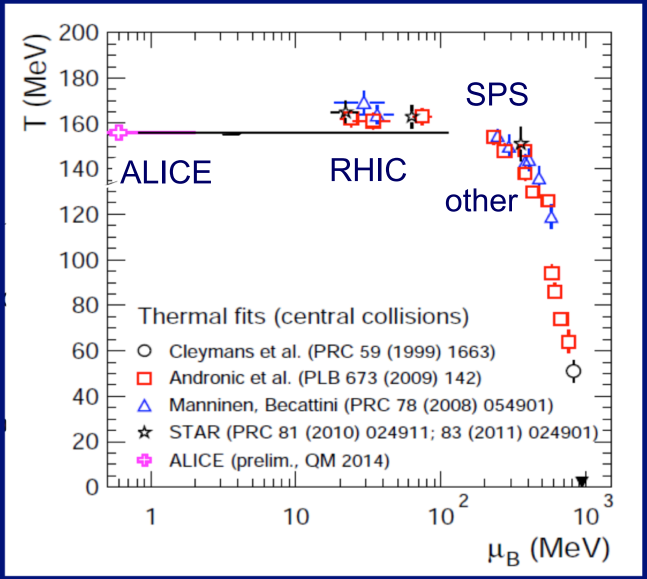
In the limit of small μ_B, most 'direct' connection between hadron results and the QCD phase boundary

Chemical freeze-out – Evolution up to today

J.Stachel, Nucl.Phys.A 654 (1999) 119c



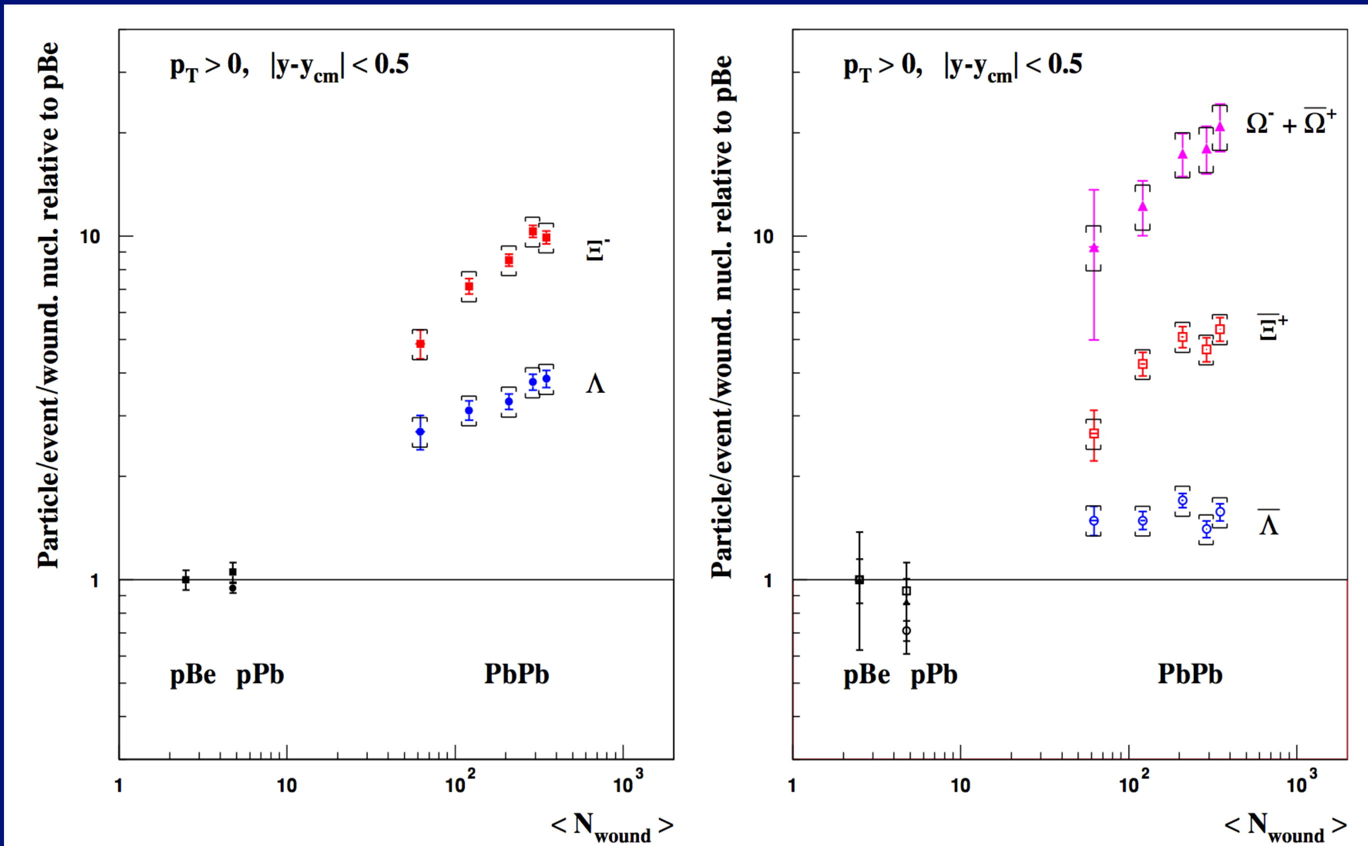
P.Braun-Munzinger, ICNFP Crete, 2014



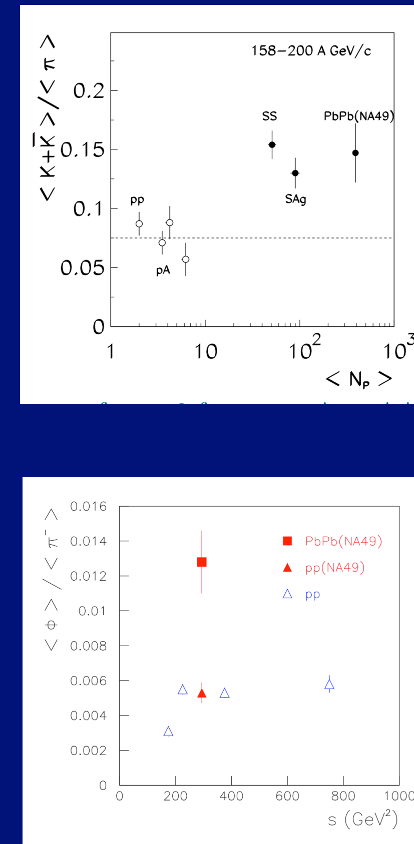
Increasing sophistication of various feeding corrections to the primary yield data → T (μ_B~ 0) now closer to 160 MeV

Most important: confirmation of an universal value towards μ_B = 0 over an extremely wide beam-energy range

Hadron Flavors – Strangeness Enhancement



NA57 (final: *J.Phys.G 32 (2006) 427*)



NA49 (1999)

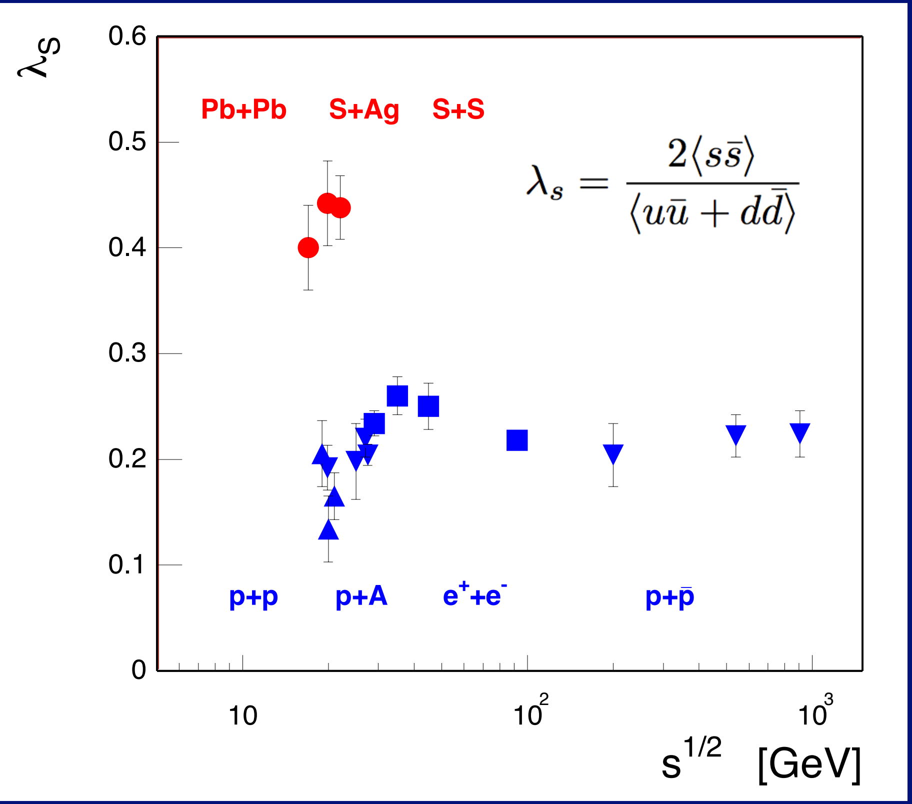
large enhancement of hyperon production relative to pPb
strong increase with number of strange valence quarks
(up to 20); consequence of non-zero μ_B

enhancement also for mesons, even for hidden strangeness ($\phi = s\bar{s}$)

Strangeness enhancement as QGP signal first proposed by
J.Rafelski 1980, GSI Rep. 81/6; J.Rafelski/B.Müller PRL 1982

'Origin' of Strangeness Enhancement

F.Becattini, M.Gazdzicki, J.Sollfrank, EPJC 5 (1998) 143



Strangeness suppression factor λ_S (Wroblewski)

ratio of newly created *primary* valence $s\bar{s}$ pairs to newly created non-strange primary quark pairs

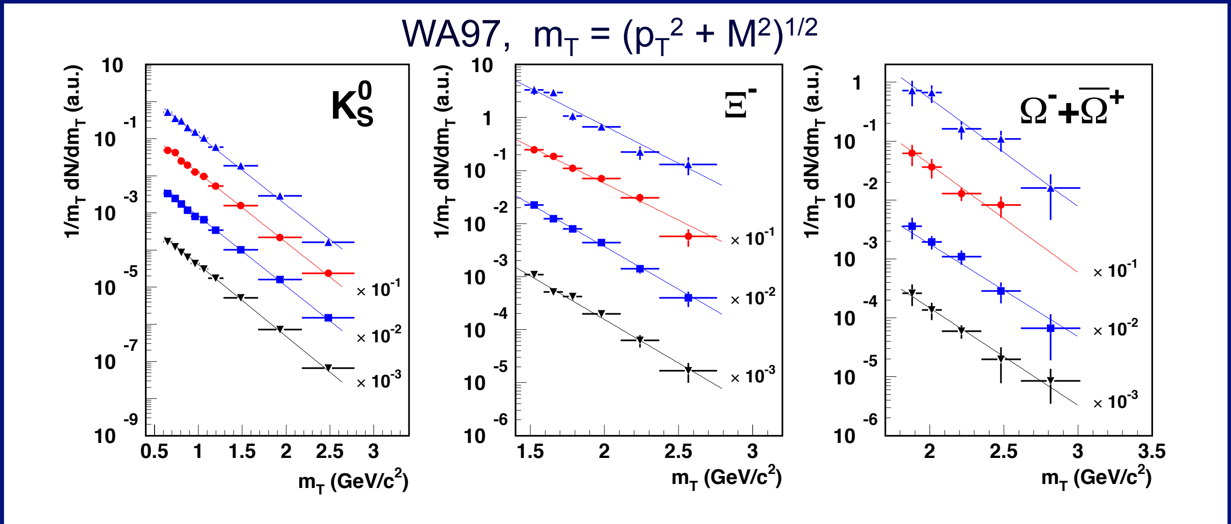
values obtained from fits of the statistical hadronization model to strange hadron production in AA (NA49) and elementary reactions

'Strangeness enhancement' in AA or 'Strangeness suppression' in pp, pA…?

Small systems described by canonical ensemble with *exact conservation of quantum numbers locally,* in contrast to grand canonical ensemble in AA

Canonical suppression as the 'origin' for strangeness enhancement, but dynamics?

Radial flow – 'Hubble' expansion of the fireball

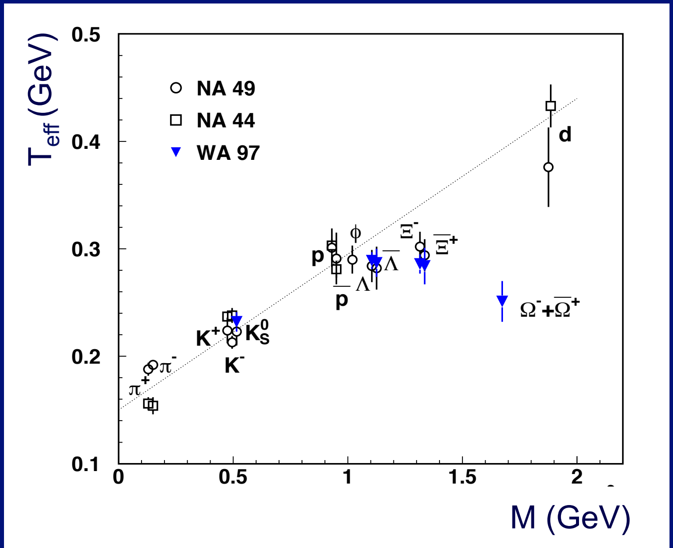


all m_T spectra exponential

fit with
$1/m_T\ dN/m_T \sim \exp(-m_T/T_{eff})$

T_{eff} – 'effective temperature'

Eur.Phys.J C 14 (2000) 633



linear rise of T_{eff} with M

→ two components in p_T/m_T spectra:
thermal and radial collective expansion

roughly $T_{eff} \sim T_f + M <\beta_T>^2$

precise procedure: 'Blast wave' analysis

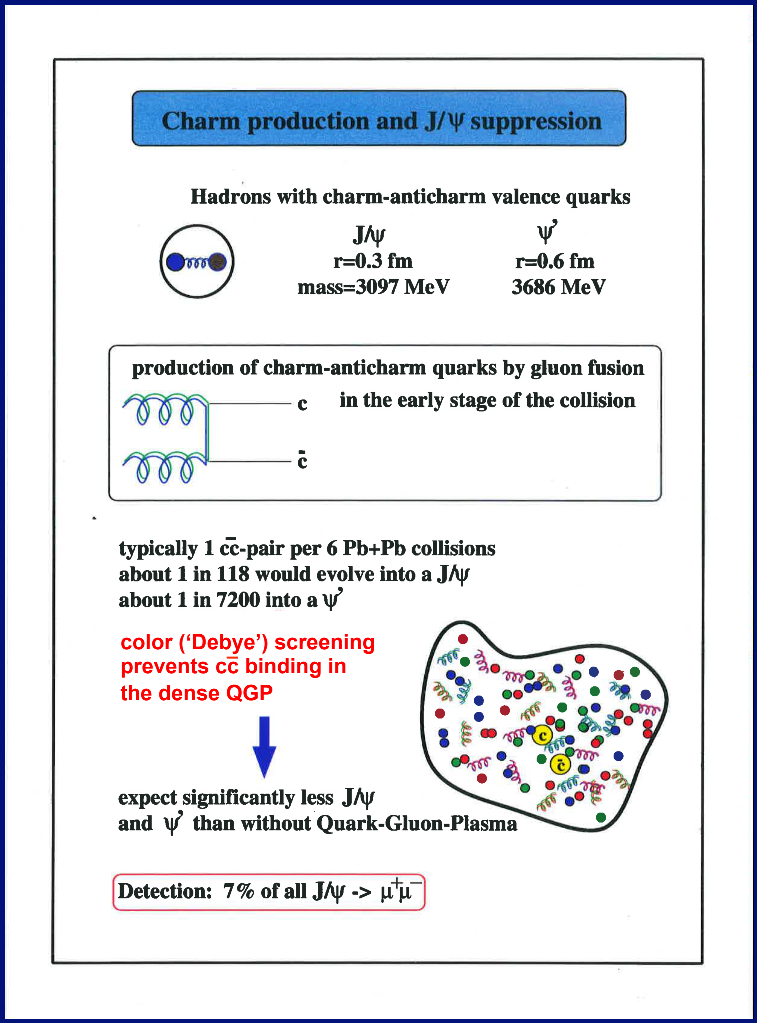
T_f temperature at thermal freeze-out: 100-120 MeV
v_T flow velocity at thermal freeze-out: ~ 0.5c

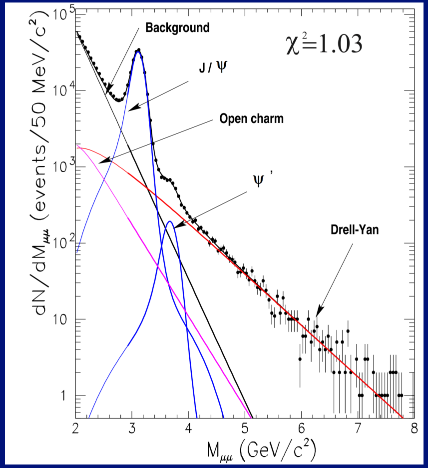
Almost explosive expansion → strong pressure at the earlier collision stages

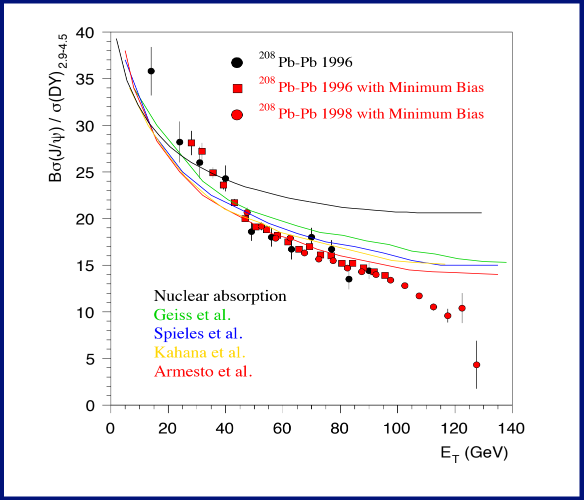
Hadron Flavors – NA50: J/ψ Suppression

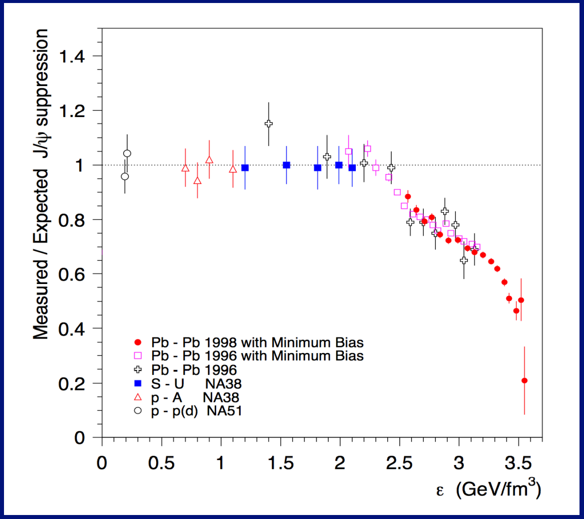
Proposal: T. Matsui and H. Satz, PLB 178 (1986) 416 (> 3000 citations)

Phys.Lett. B 477 (2000) 28





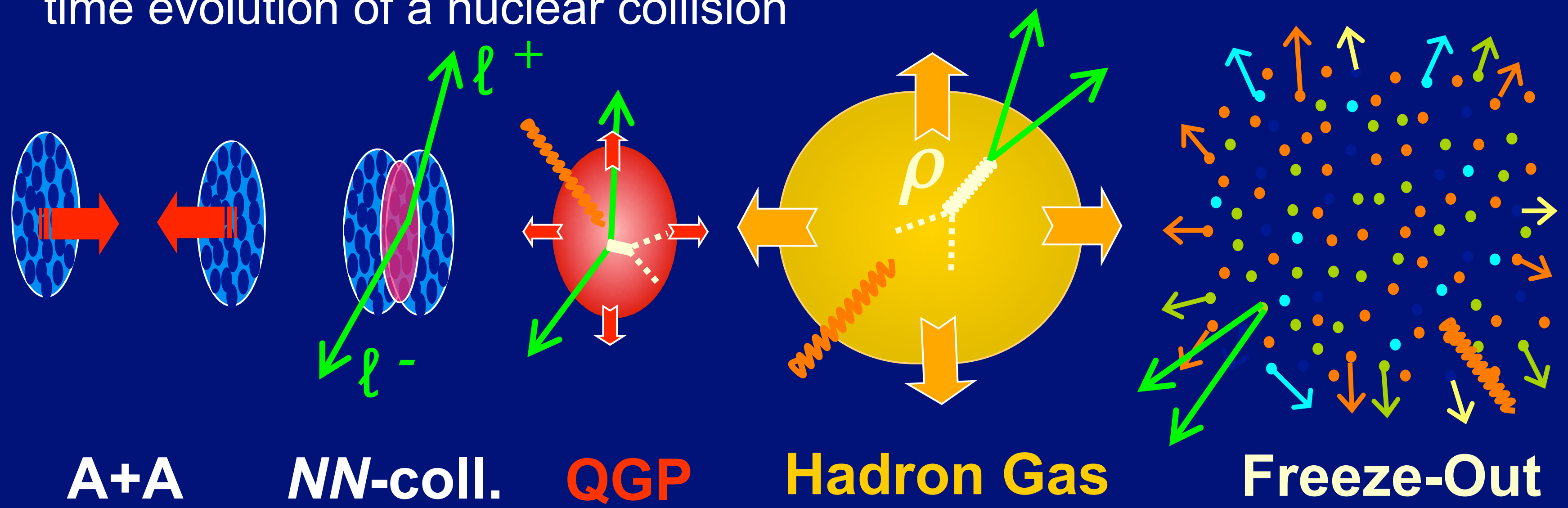




THE Smoking Gun for the QGP in the 1990's, largely accepted by 2000

Observables and physics goals: dilepton production

time evolution of a nuclear collision

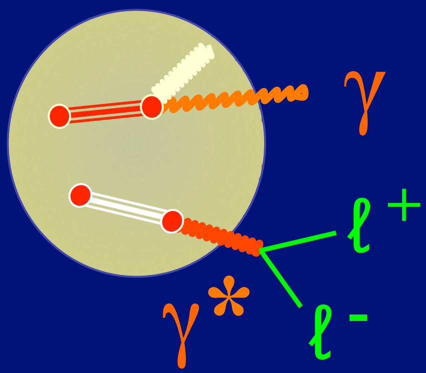


Lepton pairs emitted at all stages; no final state interactions

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

NN-collisions:	Drell-Yan, $D\bar{D}$ pairs (phys. bkg)
QGP:	thermal $q\bar{q}$ annihilation (deconfinement)
Hot+Dense Hadron Gas:	ρ (ρ-a_1) modification (chiral restoration)
Freeze-out:	free hadron decays (phys. bkg)

Observables and physics goals: photons *vs.* dileptons



photons: 1 variable: p_T

lepton pairs: 2 variables: M, p_T

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

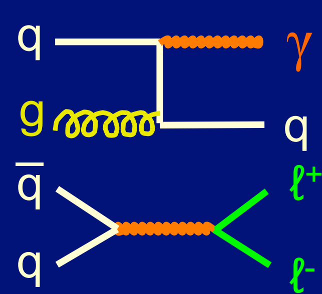
Relevant for thermal radiation:

(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



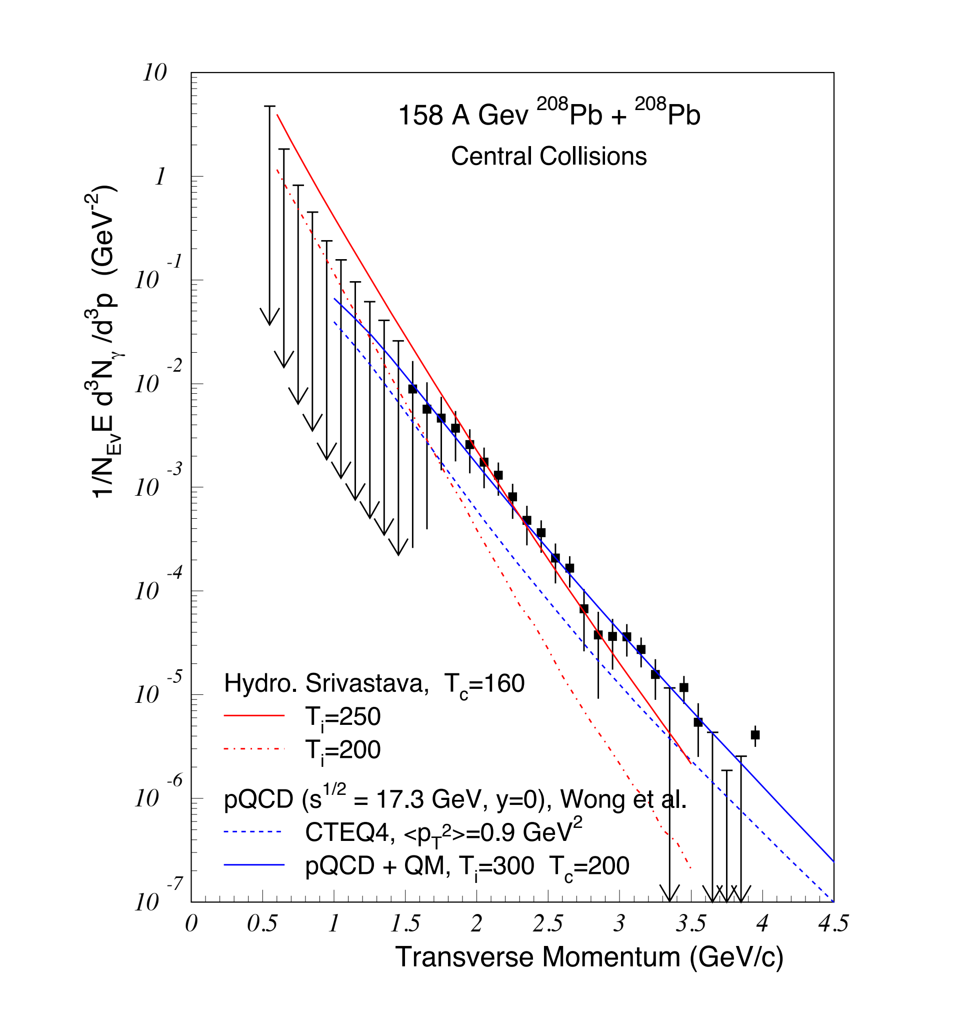
QCD Compton

$q\bar{q}$ annihilation

dileptons more rich and more rigorous than photons

WA98: Excess of real photons

PRL 85 (2000) 3595; nucl-ex/0006007 (PRC)



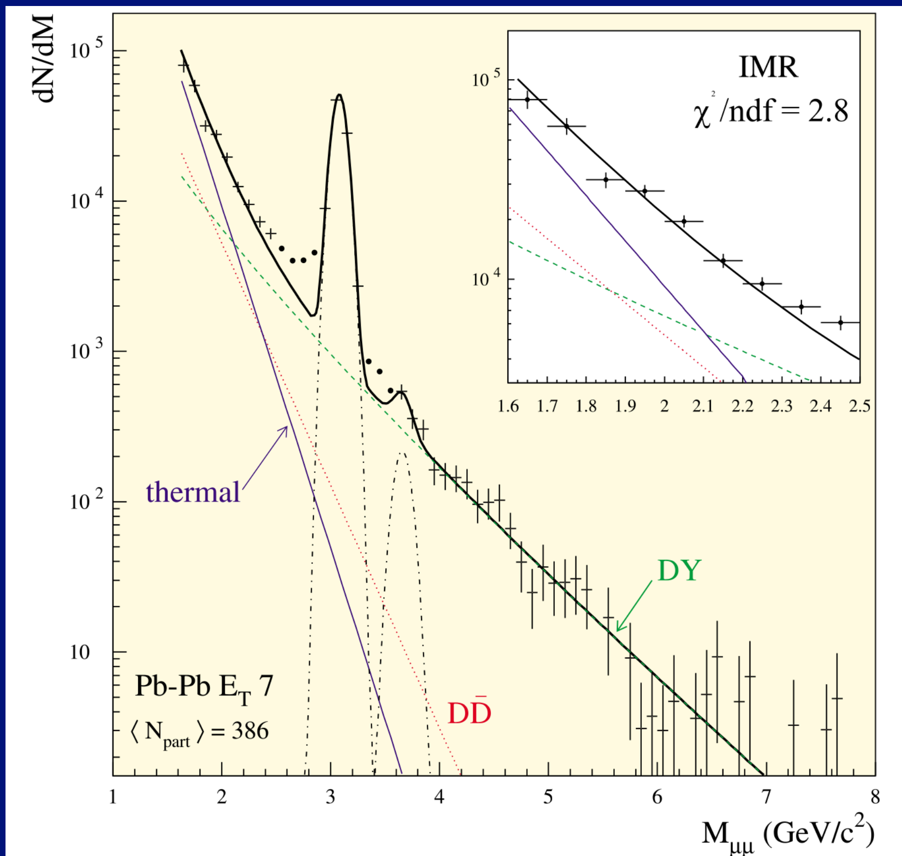
First and only excess of real photons seen at SPS (only upper limits by NA34-2 and CERES/NA45)

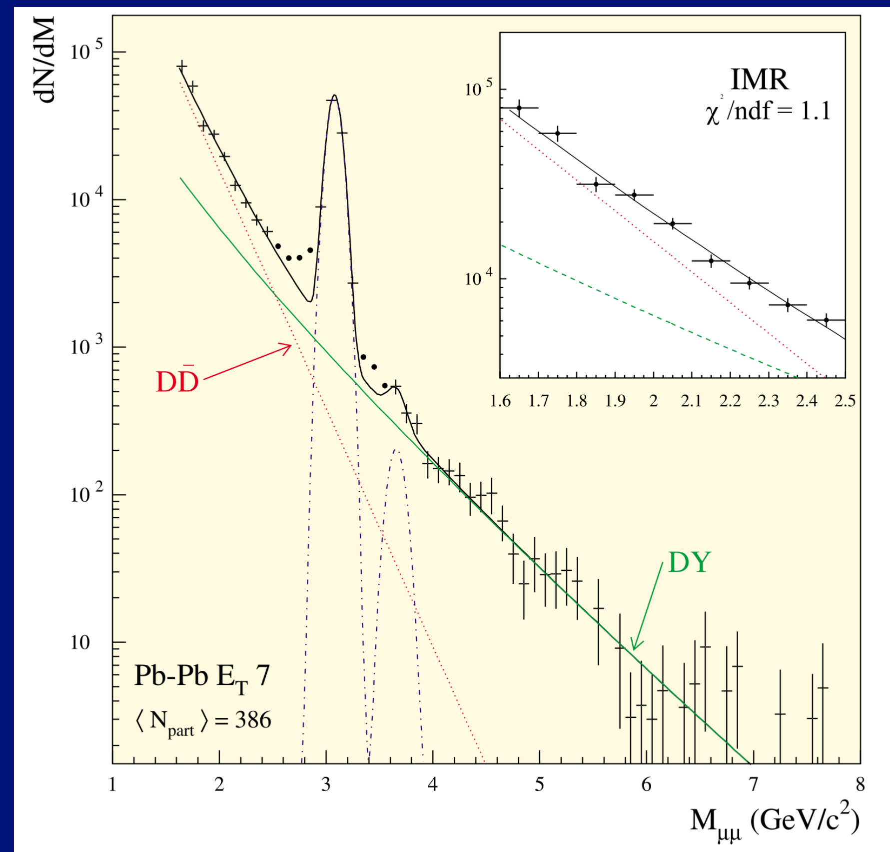
interpretation of excess as direct (thermal) photons on top of hard processes

quantitative description by theory ambiguous

NA50: Excess of intermediate-mass dimuons (IMR)

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





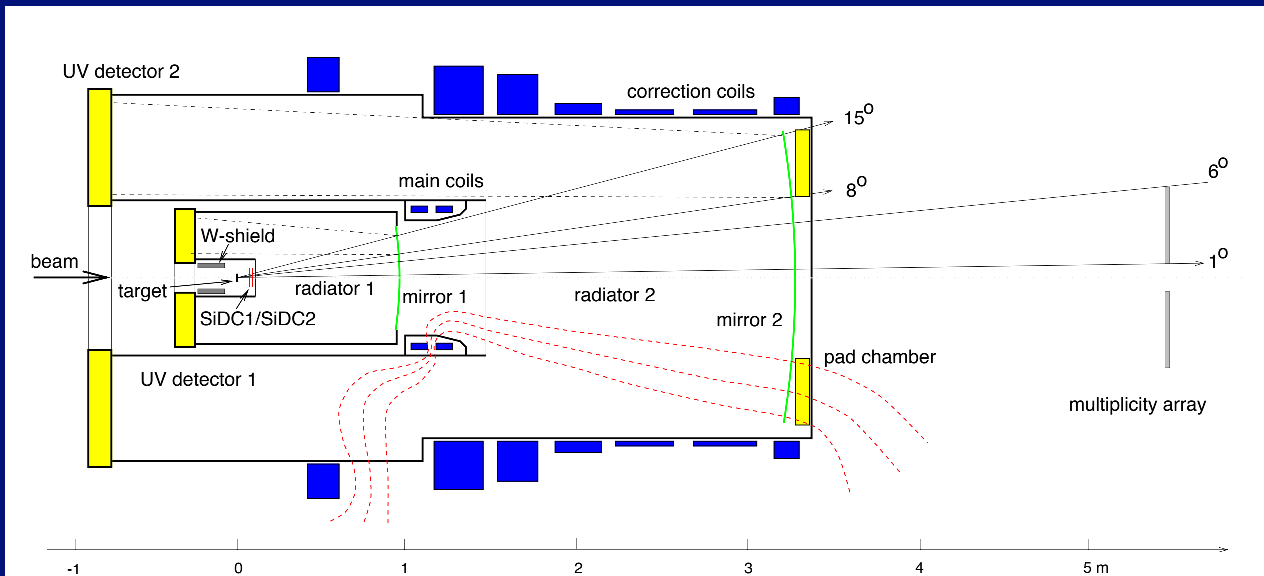
Thermal radiation (!)
(*Rapp and Shuryak, PLB2000*)

Enhanced open charm production

Excess also seen by NA34-3 (for S-W; *QM95, EPJC 1998 and 2000*)

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

Dedicated di-electron spectrometer: CERES/NA45

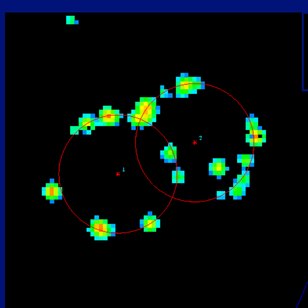


Pioneering experiment built 1989-1991

focused on Low Mass Region (LMR)

Running periods:

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

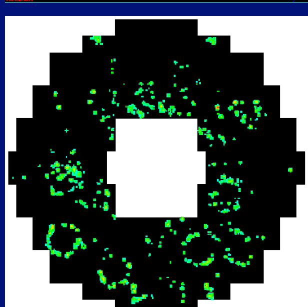


Cherenkov rings

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

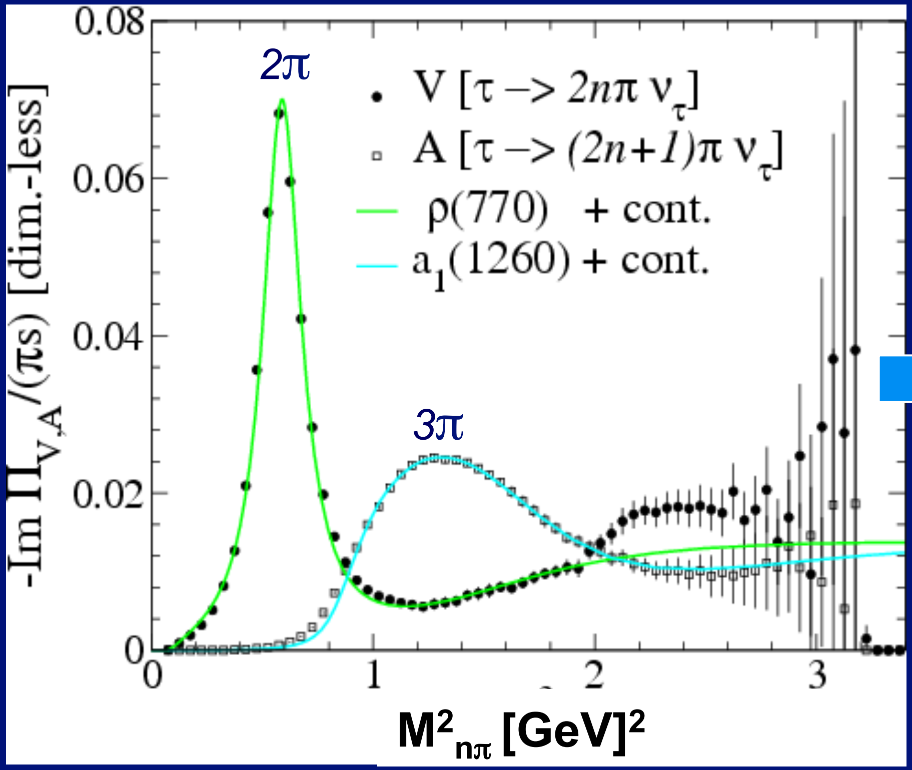
Low field (air coils), limited tracking → limited resolution
slow detectors, no trigger → very limited statistics



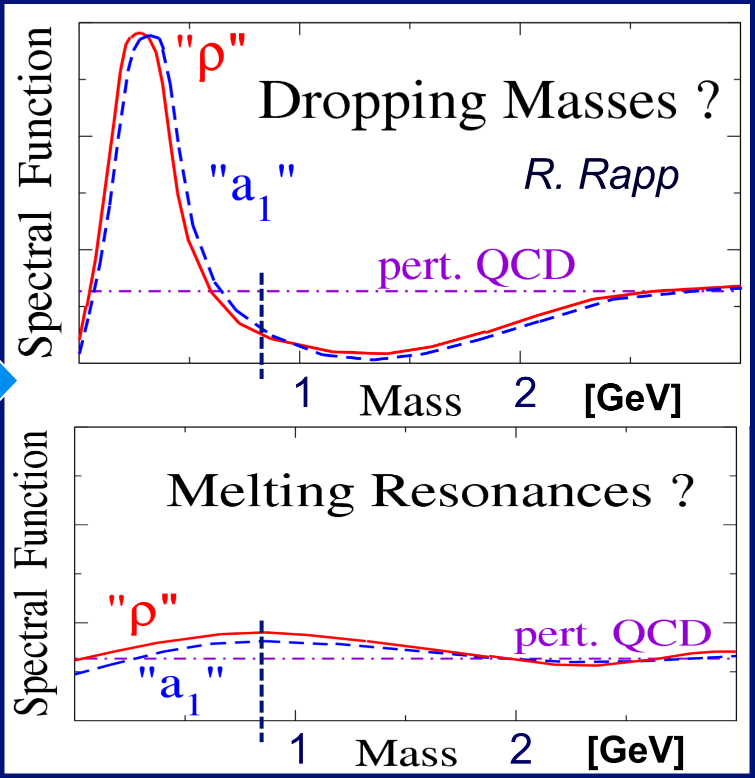
Cherenkov rings in RICH1

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 accessible through ρ-a_1 chiral mixing ($\pi\, a_1 \rightarrow 4\pi$…)

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

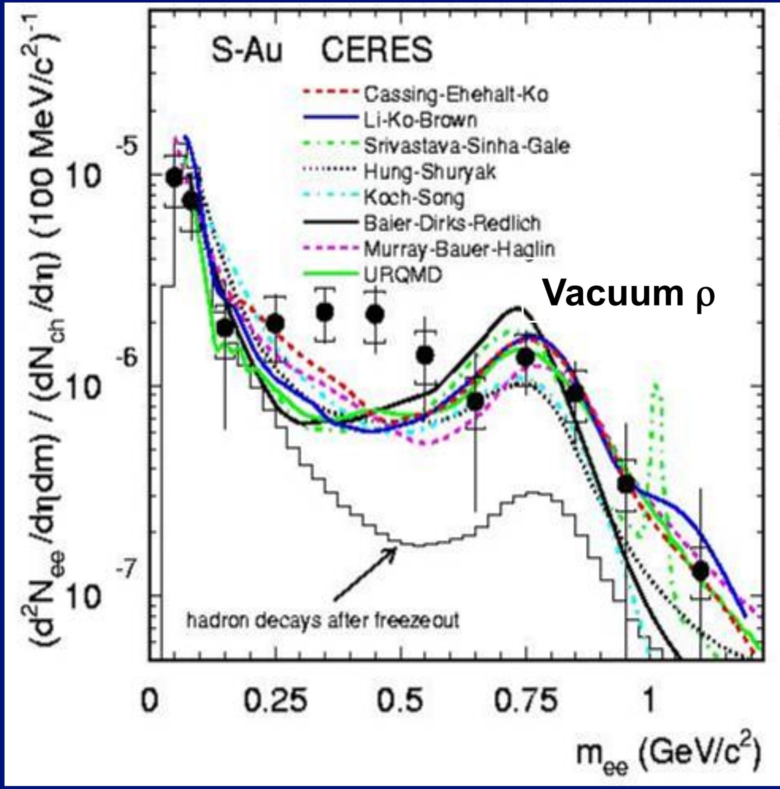
Selected theoretical references

	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

CERES/NA45: Excess of low-mass dielectrons (LMR)

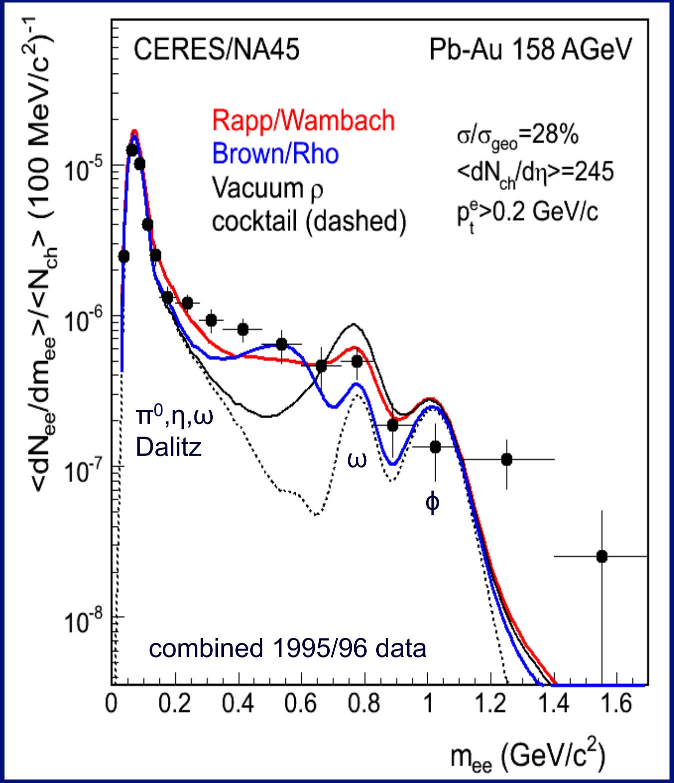
Phys.Rev.Lett.75 (1995)



First clear sign of new physics in LMR

also seen by NA34-3

PLB '98; NPA '99, EPJC '05



strong excess of dileptons above meson decays

enormous boost to theory (> 500 citations for S-Au)

surviving interpretation: $\pi^+\pi^- \rightarrow \rho^* \rightarrow e^+e^-$ with regeneration of the ρ ('clock')

but: resolution and statistical accuracy insufficient to determine the in-medium spectral properties of the ρ (mass shift vs. broadening)

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

PR01.00
10.02.00

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

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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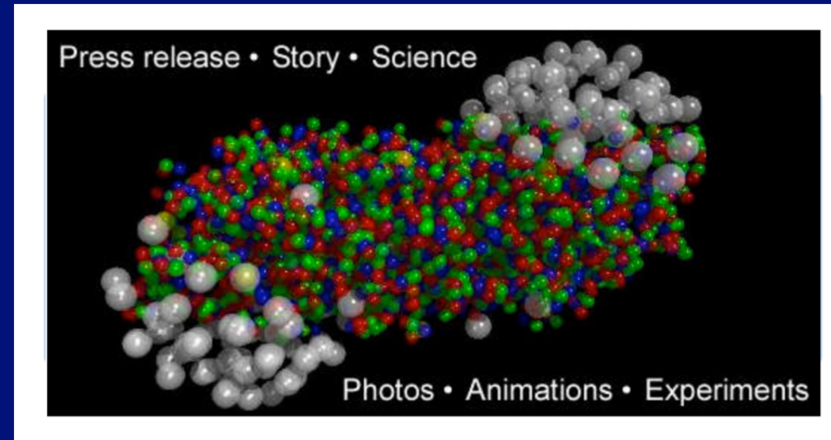
PRESS RELEASE



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.

↓

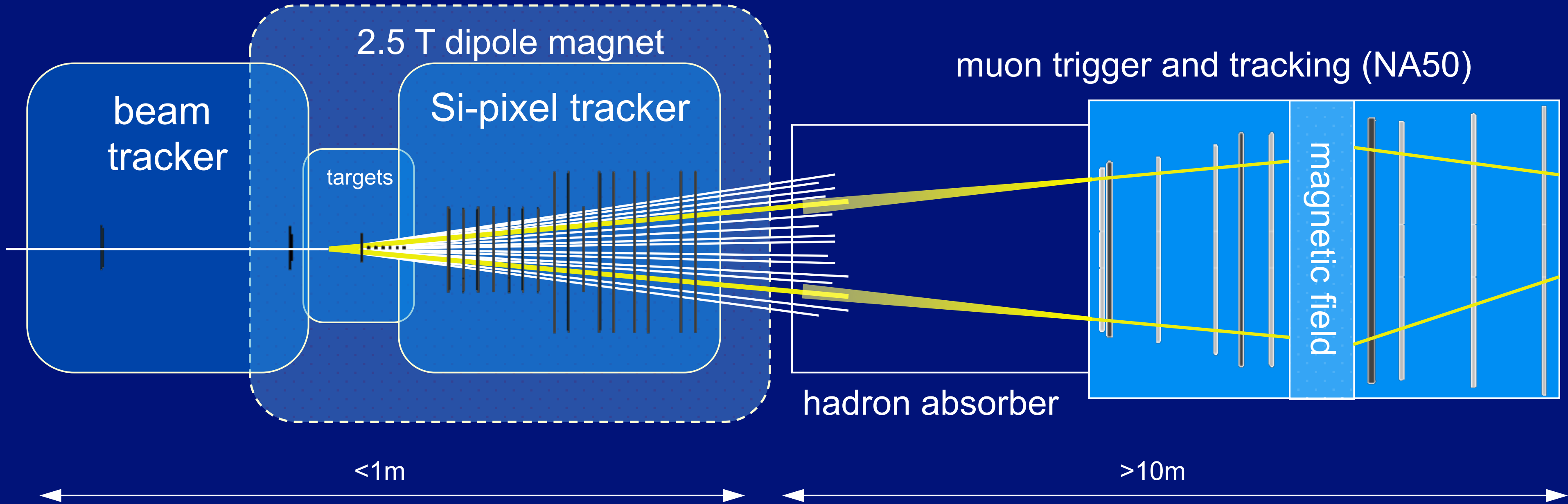
SPS !

Beyond 2000

NA60: 3rd generation results on dileptons

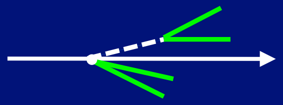
Measuring dimuons in NA60

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



Track matching in coordinate <u>and</u> momentum space

- Improved dimuon mass resolution
- Distinguish prompt from decay dimuons



Additional bend by the dipole field

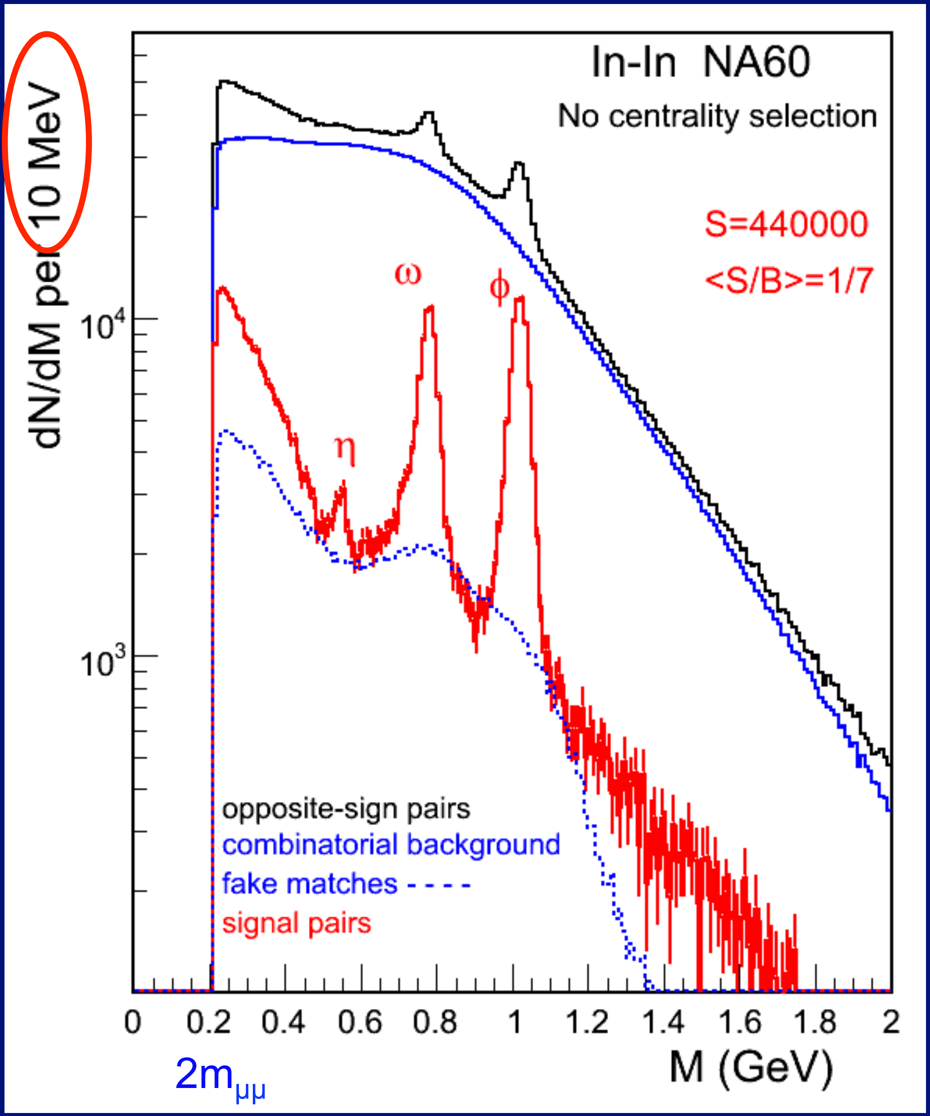
- Dimuon coverage extended to low p_T

Radiation-hard silicon pixel detectors (LHC development)

- High luminosity of dimuon experiments maintained

Data sample for 158A GeV In-In

Phys. Rev. Lett. 96 (2006) 162302



subtraction of

- combinatorial background
- fake matches between the two spectrometers

effective statistics highest of all experiments, past and present (by a factor > 500)

net sample: 440 000 events

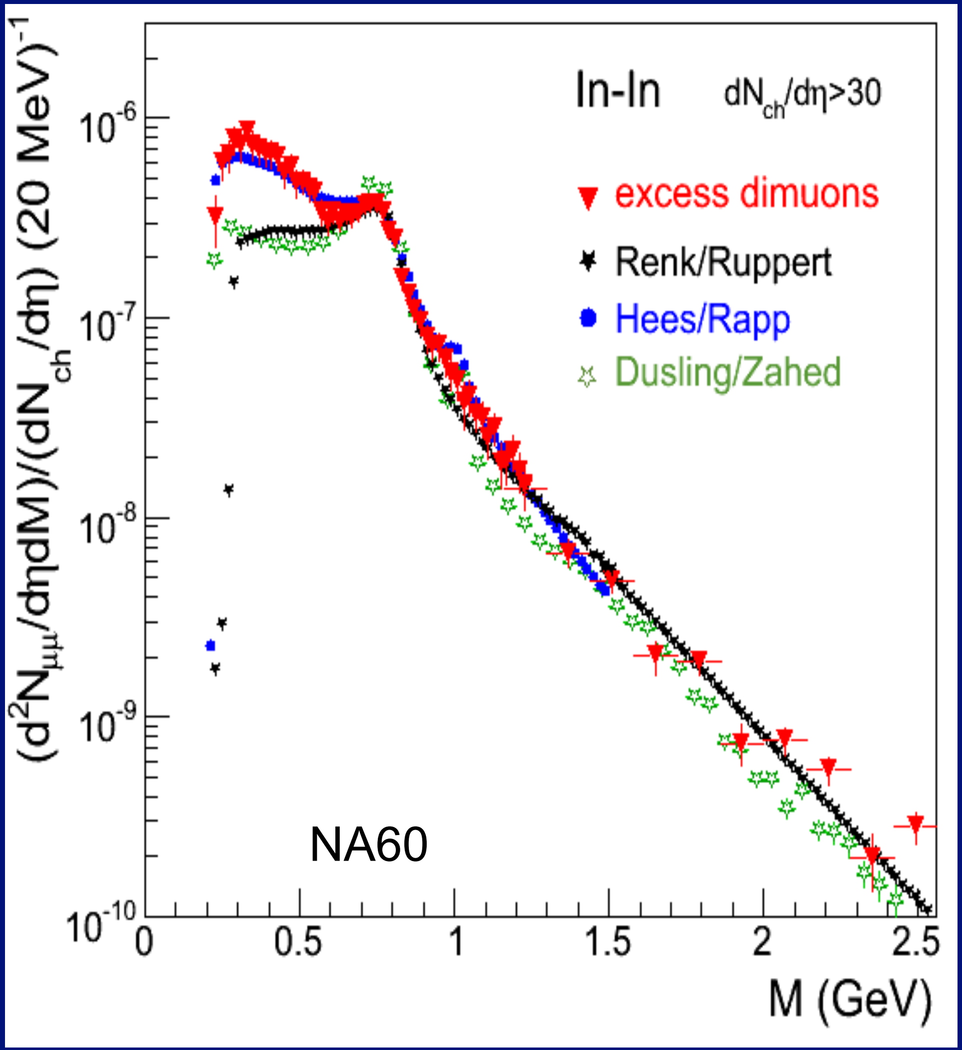
↓

for the first time, isolation of the dilepton excess possible:

subtraction of all known sources, i.e. hadron decays, open charm, Drell-Yan

Inclusive excess mass spectrum

[Eur. Phys. J. C 59 (2009) 607]
→ *CERN Courier 11/ 2009, 31-34*
Chiral 2010 , AIP Conf.Proc. 1322 (2010) 1



all known sources subtracted

integrated over p_T

fully corrected for acceptance

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

M<1 GeV

ρ dominates, 'melts' close to T_c

best described by H/R model

M>1 GeV

~ exponential fall-off → 'Planck-like'

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

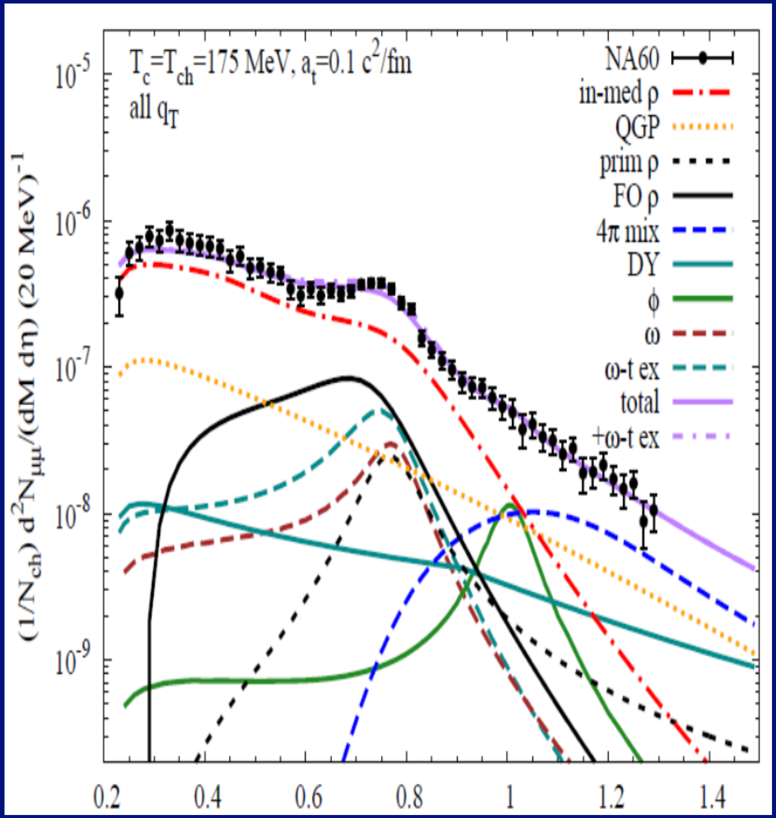
range 1.1-2.0 GeV: T=205±12 MeV
1.1-2.4 GeV: T=230±10 MeV

$T>T_c$: partons dominate

only described by R/R and D/Z models

The approach to chiral restoration

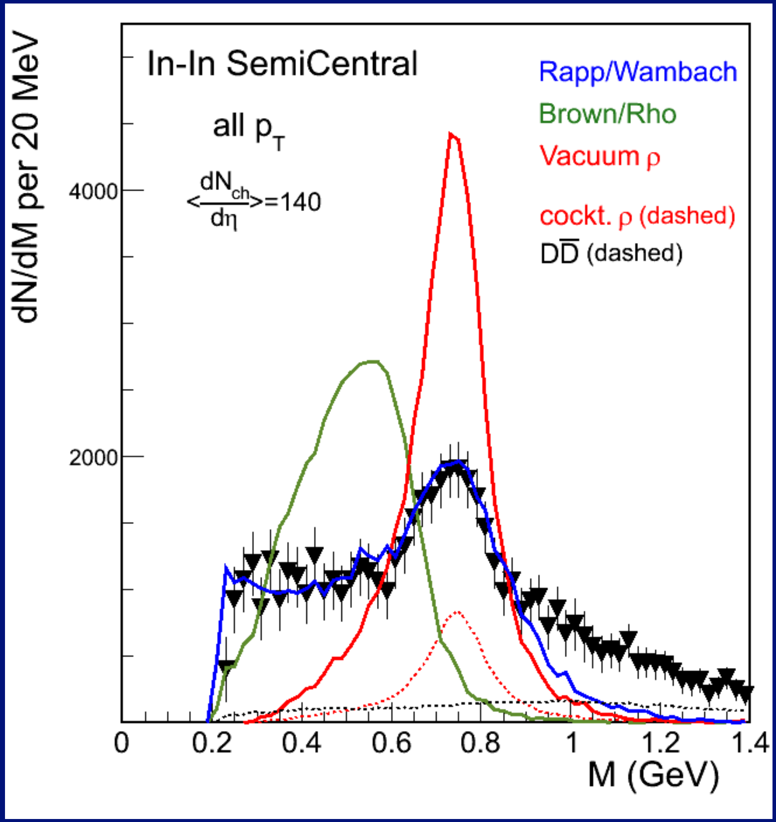
van Hees+Rapp (2008)



data acceptance-corrected

'spectrum directly reflects thermal emission rate' (Rapp)

Phys. Rev. Lett. 96 (2006) 162302

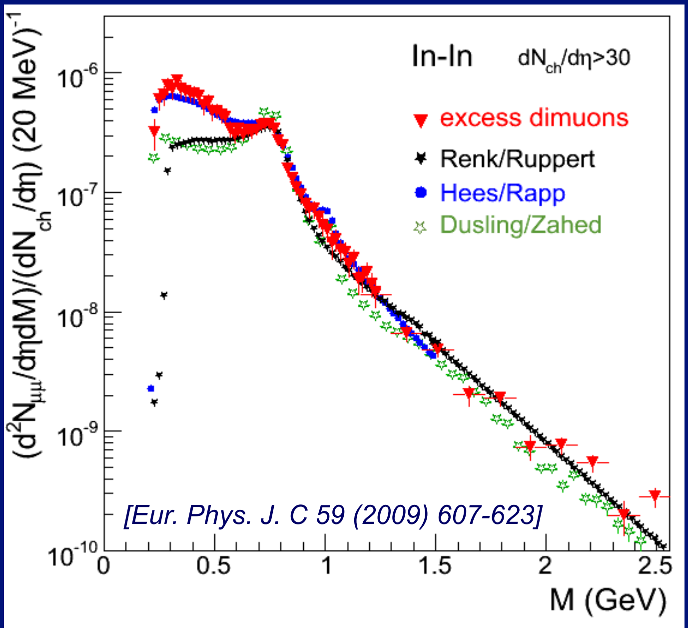


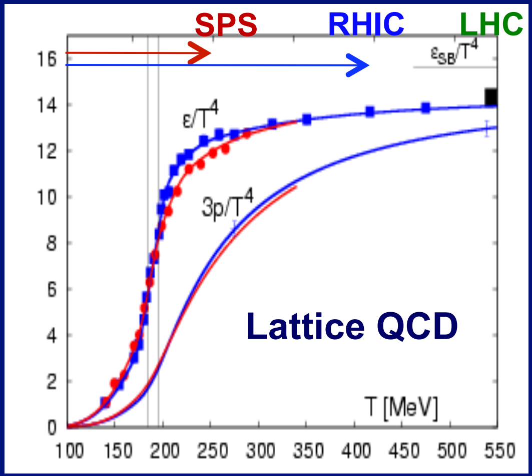
before acceptance correction:

underlying space-time averaged ρ spectral function (purely accidental)

Only broadening of ρ observed, no mass shift

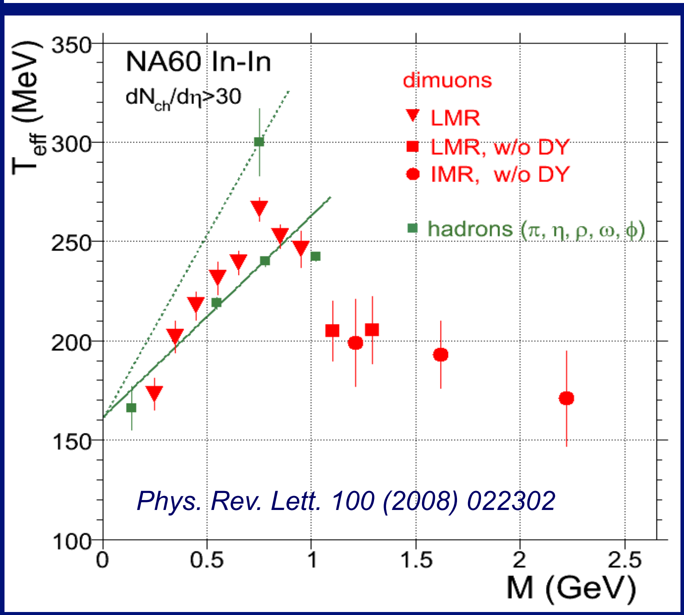
Combined conclusions from mass and p_T/m_T spectra





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

→ EoS above T_c very soft initially (c_s minimal)



M >1 GeV

- T_{eff} independent of mass within errors

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

- same values within errors

T = 205 MeV > T_c = 170 (MeV)

negligible flow → soft EoS above T_c

all consistent with partonic phase

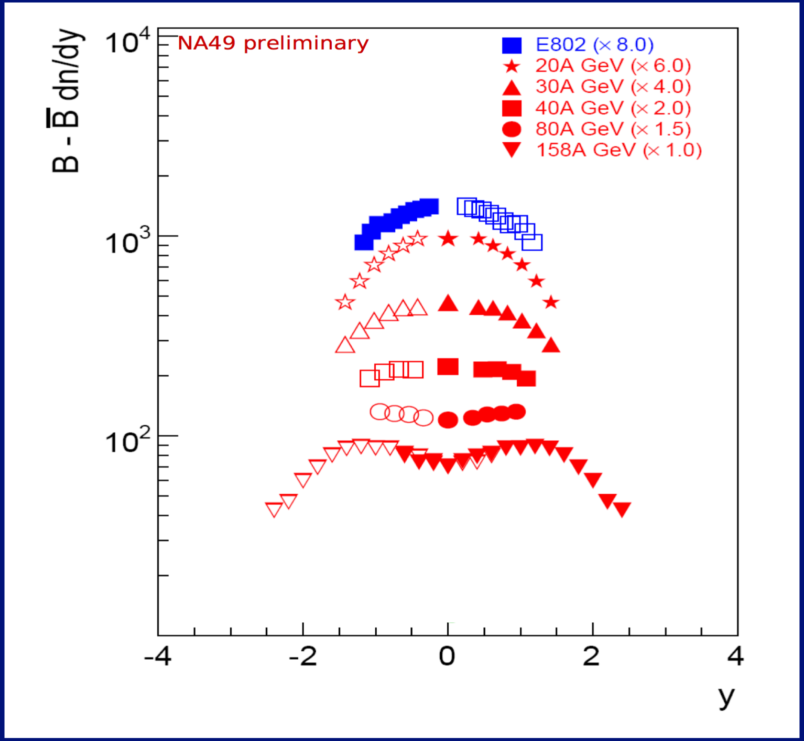
Beyond 2000

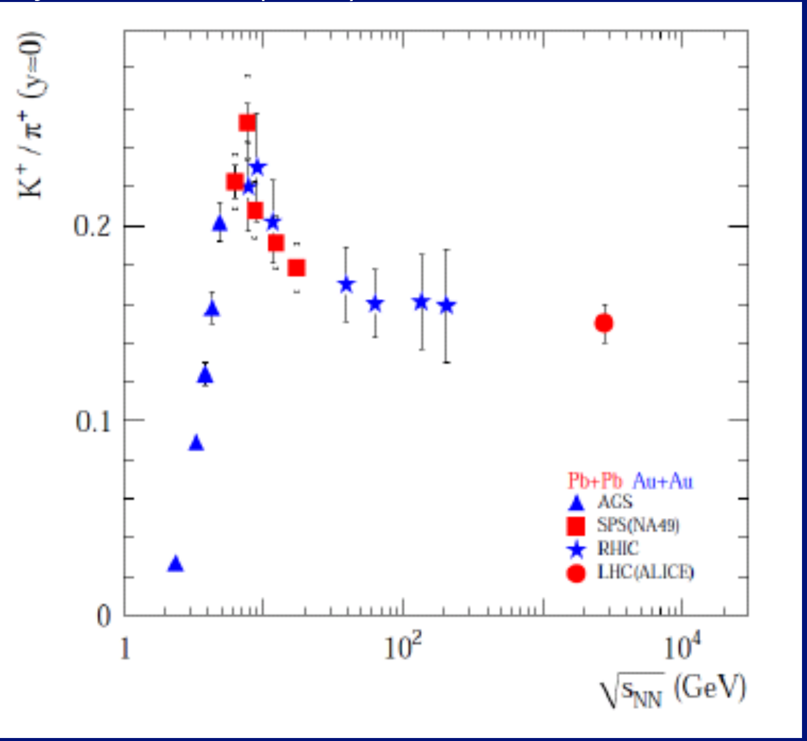
Results at lower SPS energies

NA49 Results at lower SPS Beam Energies

systematic energy scan for 158, 80, 40, 30, 20 AGeV

Phys. Rev. C77 (2008) 024903 for AGS and NA49





increased stopping at lower energies

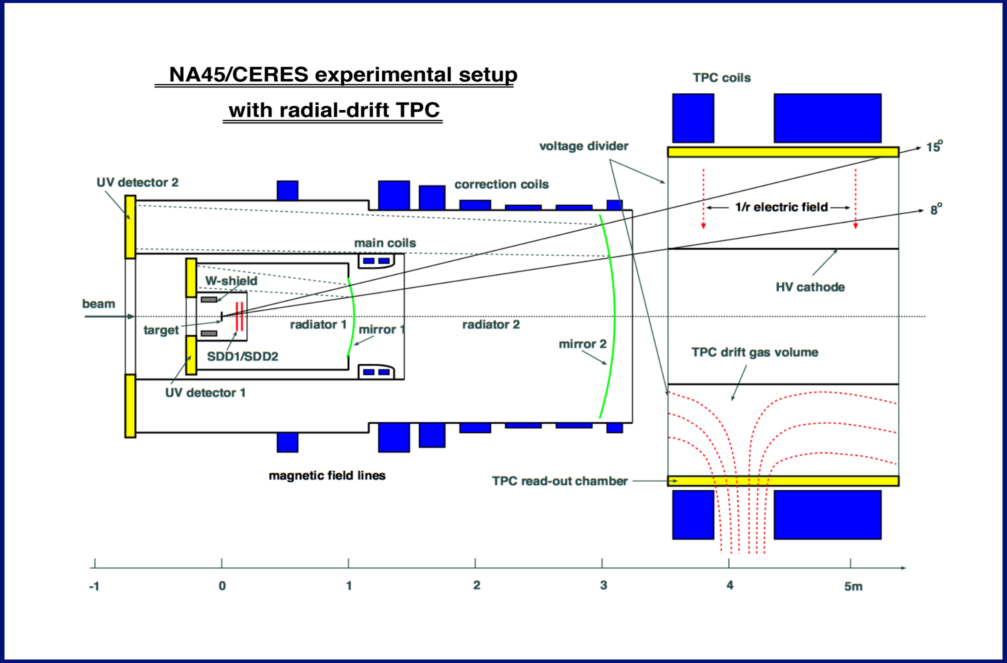
the only structure in the beam energy dependence of any heavy ion results

Onset of deconfinement? M. Gazdzicki

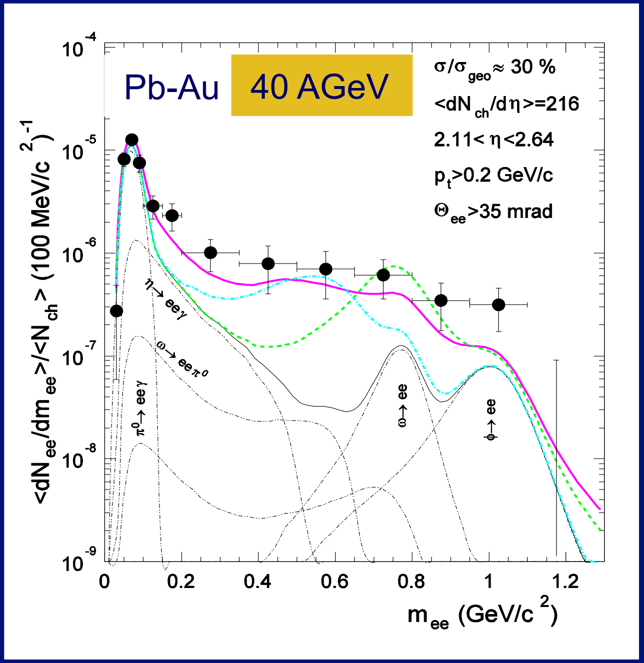
(ongoing program of NA61)

The only dilepton data at low beam energies so far

Modified 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
(158 AGeV data *Phys.Lett.B 666 (2008) 425)*

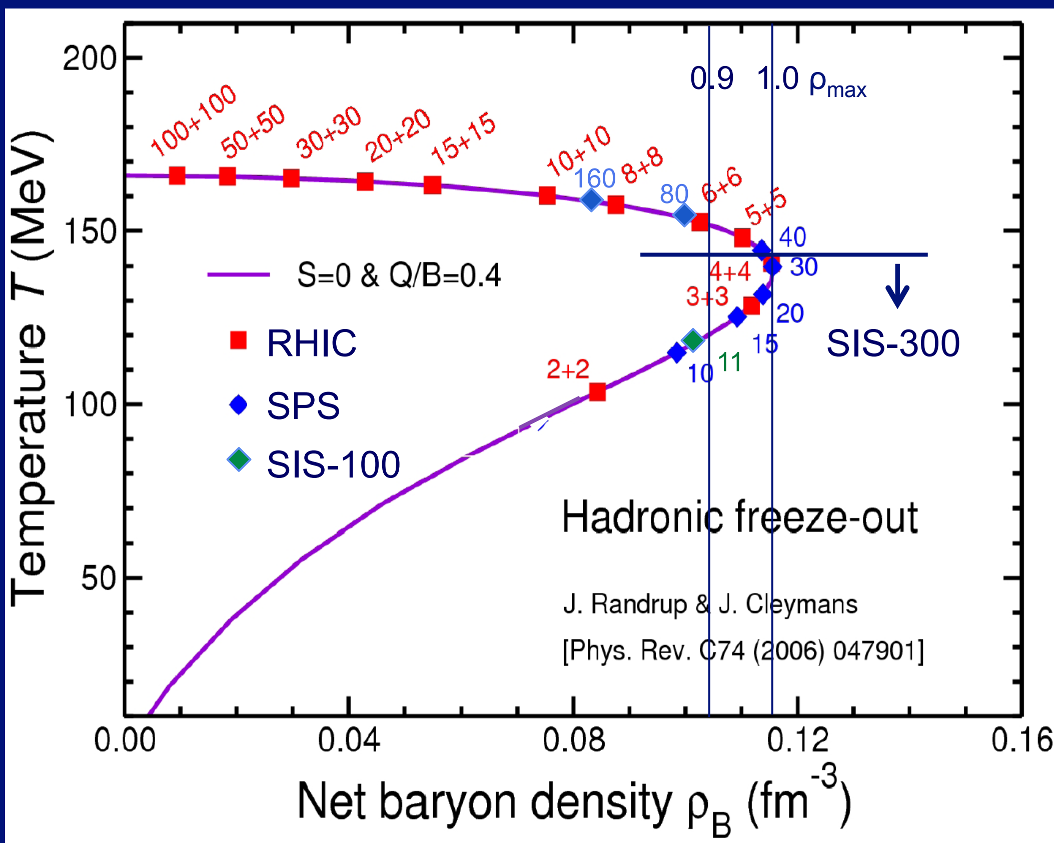
Enhancement relative to hadron decays:
5.9±1.5(stat.)±1.2(syst.)

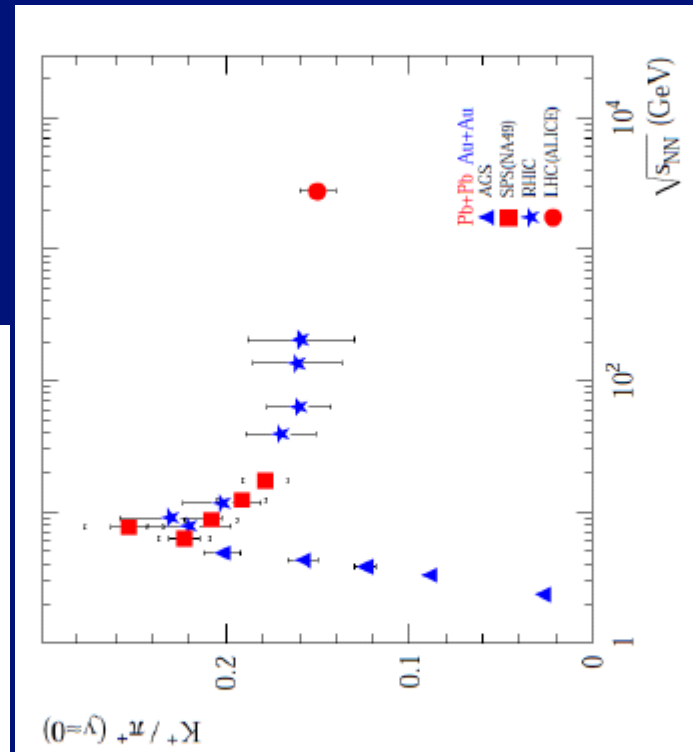
Higher baryon density at lower energy
(40 AGeV) → increased enhancement

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

Prime physics goal:

systematic measurement of EM radiation and charm over the full energy range from SIS-100 (11 AGeV) to top SPS (160 AGeV); SPS beam intensities 10^8/s





Alternative machine SIS300 at FAIR-GSI with maximum beam energy of 35 AGeV

only low side of peak covered, would not see onset of deconfinement (+ critical point?)

European Strategy for Particle Physics: Town meeting for Heavy Ion Physics at CERN June 2012

Conclusions of the Town Meeting: Relativistic Heavy Ion Collision

http://indico.cern.ch/event/HItownmeeting

On Friday 29 June 2012, a town meeting was held at CERN to collect input on the section of relativistic heavy ion collisions in the update of the European Strategy for Particle Physics. The meeting featured short presentations of existing and planned future heavy ion experiments at the CERN LHC, the Brookhaven RHIC, the CERN SPS, the FAIR facility in Darmstadt and the JINR in Dubna. In addition, the meeting provided a forum in which individual scientists and groups could contribute with short comments and statements. The meeting counted 237 registered participants that covered all experimental and theoretical activities in the field. The meeting concluded with an open 2-hour discussion of the priorities in the field.

The following text is not endorsed officially by any of the experimental collaborations and facilities mentioned, but summarizes the ***consensus view*** of the scientific community on the priorities of the field, as expressed by the participants of the town meeting. It is submitted to the Open Symposium of the European Strategy Group in Cracow by the convenors of the town meeting,

J.-P. Blaizot, K. Redlich, J. Wambach and U.A. Wiedemann.

The town meeting also observed that the CERN SPS would be well-positioned to contribute decisively and at a competitive time scale to central open physics issues at large baryon density. In particular, the CERN SPS will remain also in the future the only machine capable of delivering, heavy ion beams with energies exceeding 30 GeV/nucleon, and the potential of investigating rare penetrating probes at this machine is attractive.

Conclusions

- The SPS has been the pioneering machine for the field of Ultra-Relativistic Heavy Ion Collisions worldwide

- Key results obtained within its extensive experimental program:
  - hydrodynamic-like time evolution of the collisions, with initial QGP formation, hadron formation in a state of 'chemical' equilibrium at T ~ 170 MeV (Hagedorn) and final 'kinetic' freeze-out at T~120 MeV after 'explosive' expansion to ~0.5c
  - QGP formation consistent with strangeness enhancement, J/ψ suppression and indications of chiral restoration; finally proven by thermal dileptons with $\langle T \rangle \sim 220$ MeV $> T_c$

- Decisive learning processes on all physics observables and their match to the appropriate experimental techniques, with enormous influence on the next-generation experiments at RHIC and LHC

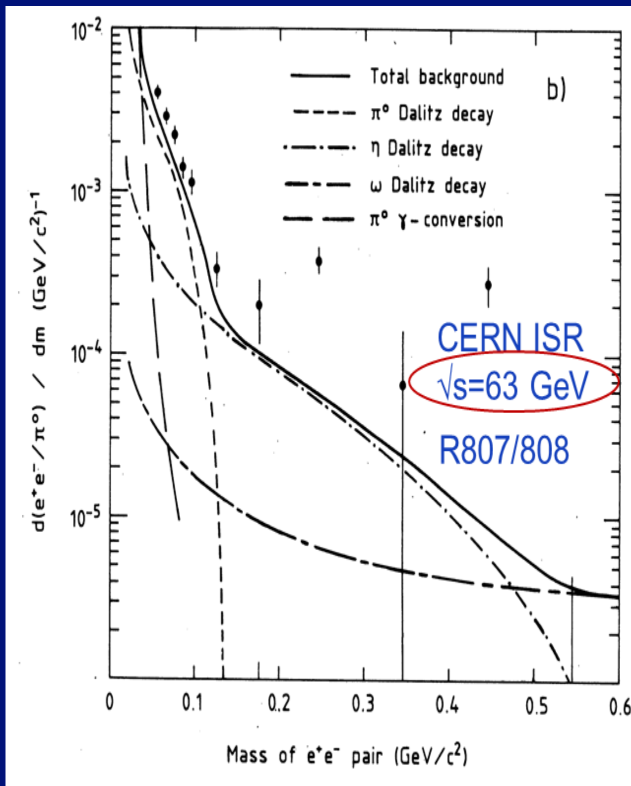
- Future role of the SPS: unique machine worldwide for precision studies of the different transitions within the QCD phase diagram

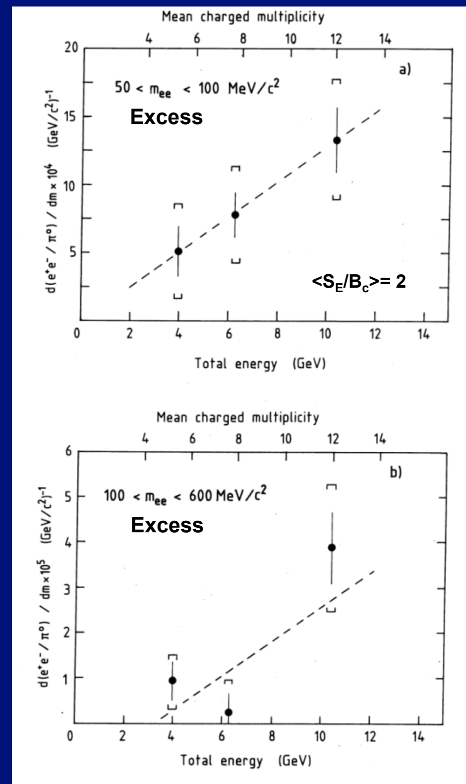
BKP

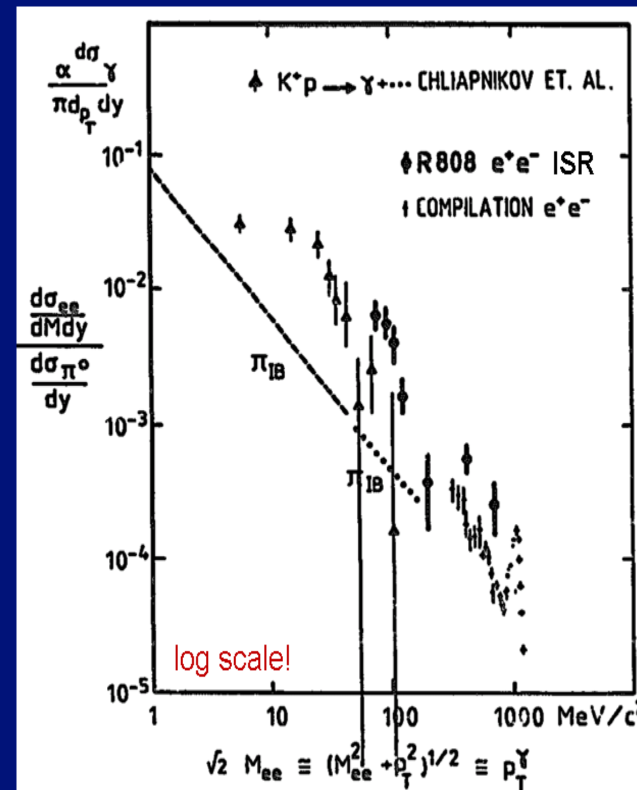
Final confirmation of ‘anomalous’ dileptons in pp

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







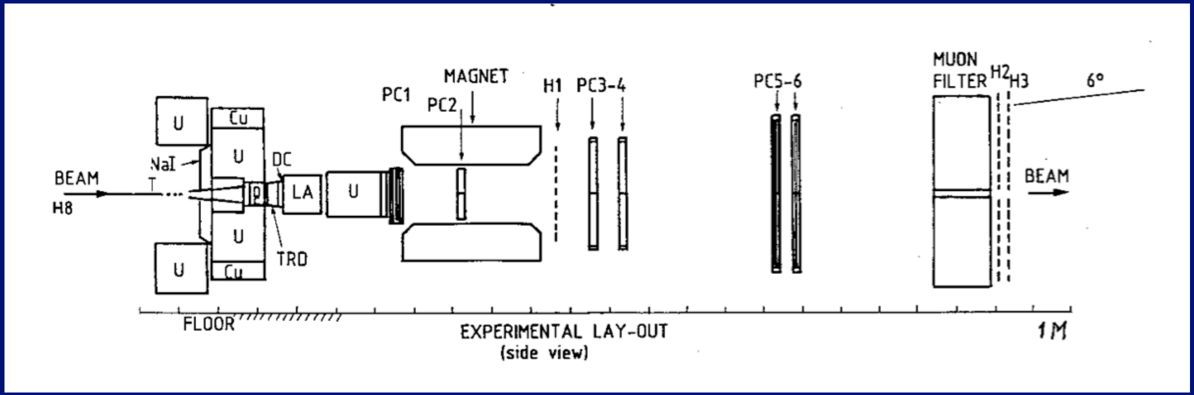
the only LMR excess ever established in pp;
multiplicity dependence almost quadratic

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)

Disproof of ‘anomalous’ dileptons in low-energy pp



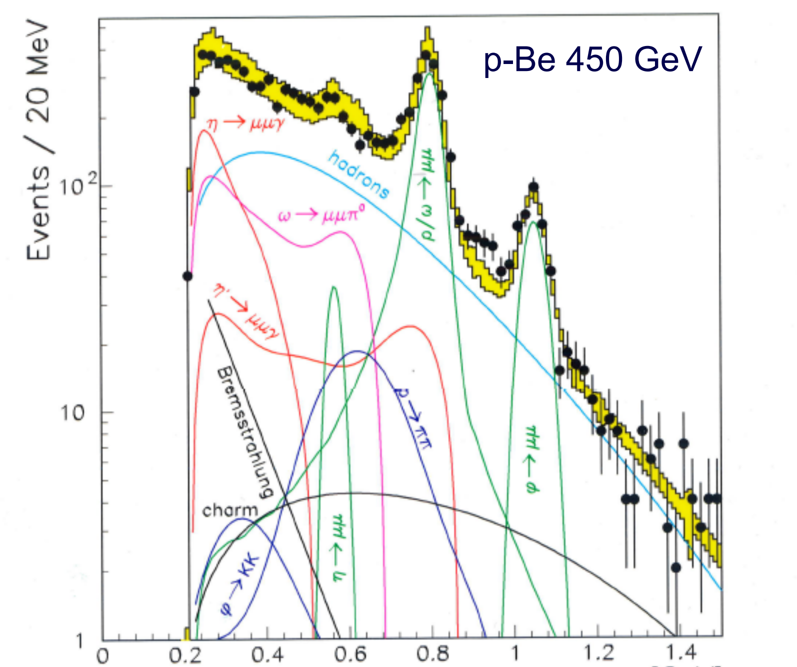
NA34-1, 1984
spokesperson
N. McCubbin

→ no LMR excess in p-Be within errors

later confirmed by CERES/NA45 in p-Be and p-Au (1998)

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

Z.Phys.C 68 (1995) 47



(PhD thesis R. Veenhof)