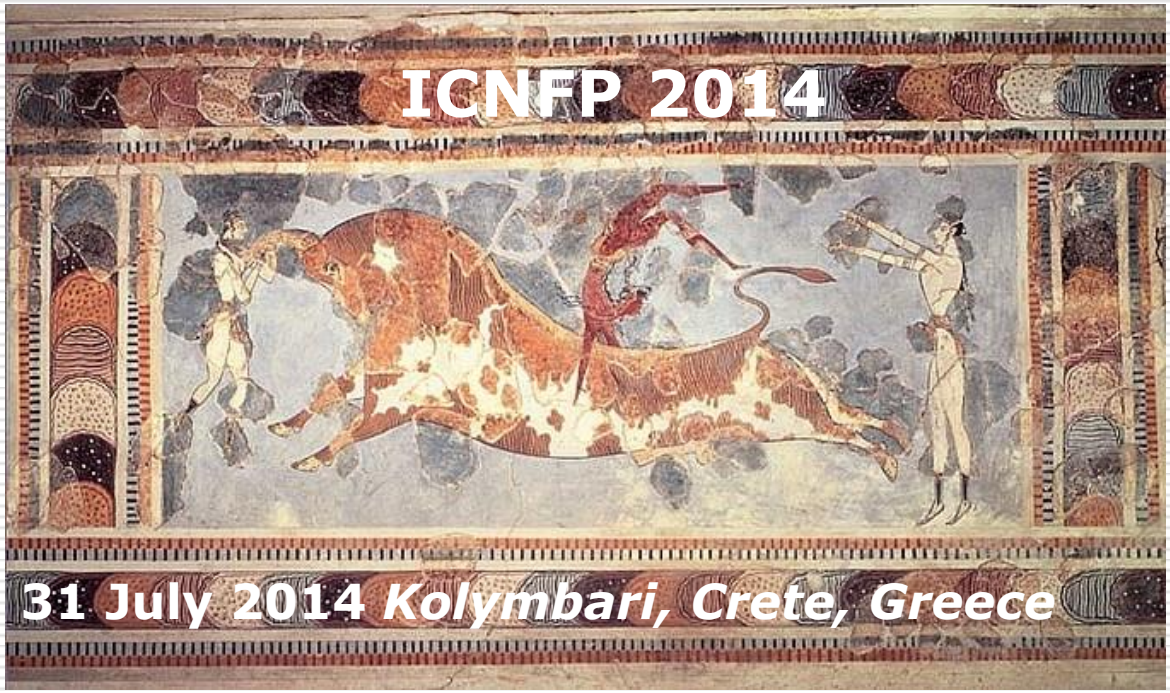
CERN achievements in Relativistic Heavy Ion Collisions

Giuseppe E Bruno
Università di Bari and INFN – Italy



CERN achievements in Relativistic Heavy Ion Collisions

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Outline:

- The *epic* past
- The *exciting* present
- The *bright* future

but actually I will speak most of the past

THE PAST

forewords

- What is my role in this section ?
- I was CERN summer student in 1998, and I should speak about, e.g., a Letter of Intent that dates back 1980
- my role is that of historian
  - definition, from a first dictionary: “an expert in or student of history, esp. that of a particular period, geographical region, or social phenomenon”
    - like that I should not worry that much: I’ve been studying some old papers in the last month !
  - from a second one: “a person who is an authority on history and who studies it and writes about it”
    - oh, oh ! I’m not an authority !

forewords

- moreover, I have to do this service in Greece
  … *where history was conceived by Herodotus*

- I will limit to stick to the following maxim from the medieval theology:

"*Factum infectum fieri non potest, neque Deus*"
a fact cannot become a "non-fact", even God cannot do that.

By the way, is *that* the reason why God has invented historians ?

- But actually, a similar argument was formulated implicitly much earlier by Διοδωροζ Χρονοζ (Diódôros Chrónos):
  ho kurieuôn logos (the Master argument, l'argument dominateur):
  1. every true statement about the past is necessary
  2. the impossible cannot derive from the possible
  3. it is possible what it is not true now and will not be true

  ho kurieuôn logos: if 1 and 2 are true, then 3 is false

forewords

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- coming back to my first sentence (*I was CERN summer student in 1998)*… We are physicists: facts and proofs !
  - I can proof it: have a closer look at my t-shirt !

Hagedorn: the limiting temperature

SUPPLEMENTO AL NUOVO CIMENTO
VOLUME III
N. 2, 1965

Statistical Thermodynamics of Strong Interactions at High Energies.

R. HAGEDORN
CERN - Geneva

(ricevuto il 12 Marzo 1965)

1. – Introduction.

Recently, the statistical model of Fermi [1] has been applied to large-angle elastic [2,3] and exchange [4] scattering with a rather unexpected success. Roughly, the result can be stated as follows: if one calculates with the (non-invariant) statistical model the probabilities P_j for all channels j of the reaction $p+p \to$ « channel j », then one finds for c.m. energies from 2 to 8 GeV the numerical formula

$$\left(\frac{P_0}{\sum_j P_j}\right)_{pp} = \exp[-3.30(E-2)] \qquad [E \text{ in GeV}] \tag{1}$$

[1] E. FERMI: *Progr. Theor. Phys.*, **5**, 570 (1950).
[2] G. FAST and R. HAGEDORN: *Nuovo Cimento*, **27**, 208 (1963).
[3] G. FAST, R. HAGEDORN and L. W. JONES: *Nuovo Cimento*, **27**, 856 (1963).
[4] R. HAGEDORN: *Nuovo Cimento*, **35**, 216 (1965).

SUPPLEMENTO
AL
NUOVO CIMENTO
A CURA DELLA SOCIETÀ ITALIANA DI FISICA

VOL. VI, N. 2 *Serie prima* 1968

Statistical Thermodynamics of Strong Interactions at High Energies.

II. - Momentum Spectra of Particles Produced in pp-Collisions.

R. HAGEDORN and J. RANFT (*)
CERN - Geneva

(ricevuto l'11 Dicembre 1967)

- the statistical bootstrap hypothesis leads to an exponentially increasing spectrum of hadronic states → there is a *limiting* temperature
  - hadronic matter cannot exist for $T > T_c$

Asymptotically free quarks in neutron stars ?

VOLUME 34, NUMBER 21 PHYSICAL REVIEW LETTERS 26 MAY 1975

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

There are several astrophysical and cosmological situations where one needs the equation of state for matter of densities greater than 10^{15} g cm^{-3}: in particular, the center of a neutron star,[1,2] the early phases of the big-bang universe,[3] and black-hole explosions.[4] However, such densities might at first sight appear to be outside the range of normal physics, so that nothing can

- J.C. Collins and J. Perry → quark deconfinement in superdense matter

The quark liberation

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

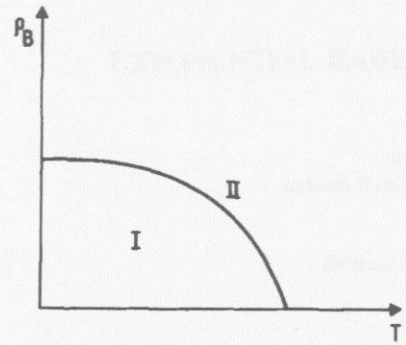


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

- N. Cabibbo and G. Parisi →
  - the Hagedorn limiting temperature is present in any system that undergoes a 2nd order phase transition
  - first phase diagram

The 1980 LoI by the GSI and LBL groups

CERN/PSCC/80-129
PSCC/I-56
27 October, 1980

Study of particle production and target fragmentation in central ^{20}Ne on Pb reactions, at 12 GeV per nucleon energy of the CERN PS external beam

Letter of Intent

GSI Darmstadt - LBL Berkeley - Collaboration

Abstract

We propose to study in two simultaneous experiments the target fragmentation modes, and π^-, K^0 and $\Lambda,\bar{\Lambda}$ production in central collisions of ^{20}Ne with a heavy target nucleus. The acceleration of ^{20}Ne at the PS will be facilitated by a high charge state ^{20}Ne source, provided by us. Experimental equipment will be the Plastic Ball and Wall spectrometer, currently employed by us at the Bevalac, LBL Berkeley, and a streamer chamber now used at CERN by the Munich group. The experiments require acceleration of about 10^7 Ne ions per PS cycle, and a split in the external beam delivering about 10^4 ions/s to the streamer chamber and the main part of the intensity to the Plastic Ball/Wall. The anticipated time of experiment is about the spring of 1983, with the long lead-time caused mostly by source construction and injector linac acceleration tests.

The group consists of the following scientific personal:

GSI Darmstadt: R. Bock, H.H. Gutbrod, J. Harris, H.G. Ritter, A. Sandoval, H. Stelzer, R. Stock, H. Ströbele, F. Weik, H. Wiemann.

University of Marburg/ GSI: M.R. Maier, F. Pühlhofer, R.E. Renfordt

LBL Berkeley/Argonne National Laboratory: A.M. Poskanzer, H. Pugh, L.S. Schroeder, A. Warwick, K.L. Wolf

Spokesman of the collaboration: R. Stock, GSI
Postfach 11 05 41
6100 Darmstadt, W. Germany
Tel. 06151-359653

A seminal document:

- 16 pages
- 3 figures
- → the two later NA35 and WA80 experiments, and their successors, derives from it !

to be compared with the present LoI for an upgrade of a sub-detector:

- e.g., the LoI for the ALICE ITS upgrade: 187 pages, 153 figures

The 1980 LoI by the GSI and LBL groups

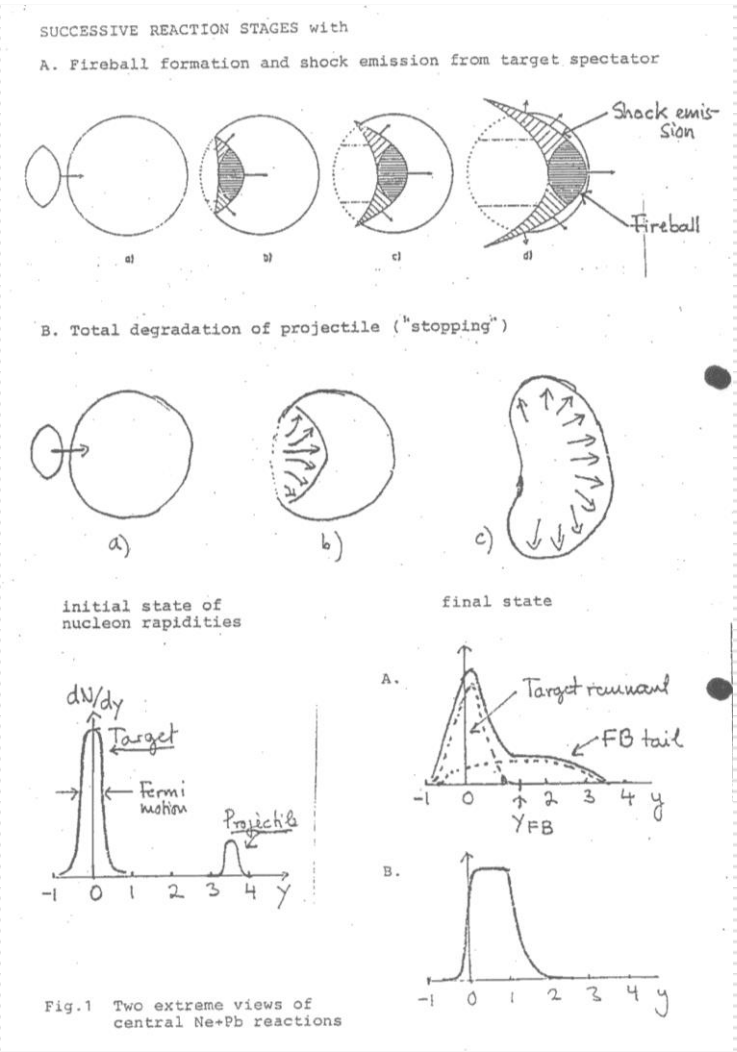


Fig.1 Two extreme views of central Ne+Pb reactions

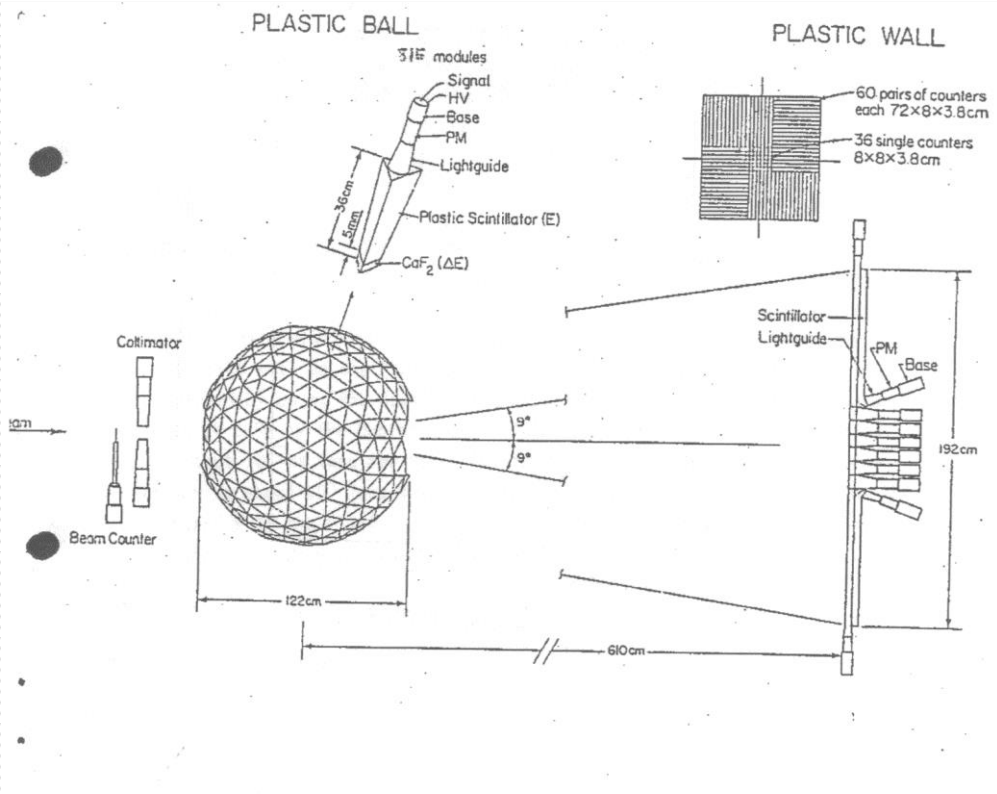


Fig.2 Sketch of the Plastic Ball / Wall detector system

1980 GSI Workshop

- in October 1980, at the initiative of Rudolf Bock and Reinhard Stock, a Workshop on Future Relativistic Heavy-Ion Experiments took place at GSI Darmstadt

Foreword

This report contains manuscripts of invited talks presented at the Workshop on Future Relativistic Heavy Ion Experiments that was held at GSI, Darmstadt, from 7 to 10 October 1980.

The purpose of this meeting was to discuss theoretical ideas, and instrumentation advances that might provide a basis for the next generation of experiments in the field of high energy nucleus-nucleus collisions. Energies much higher than the present Bevalac or Dubna domain are being discussed now, in connection with planned accelerator construction or modification for future relativistic heavy ion research. It may then be expected that the experimental techniques of present particle physics will become increasingly important. Although not always directly applicable to reactions with an extremely high product multiplicity, such instrumentation of today may serve as an orientation mark for future developments, devoted to heavy ion reactions.

The manuscripts are reproduced here in the order of their presentation at the workshop. We are very grateful to all colleagues who could provide us with a manuscript, thus making these proceedings rather comprehensive. We further wish to express our thanks to our co-organizers, to all the participants, and to the staff at GSI for their contribution to this conference.

R. Bock
R. Stock

TABLE OF CONTENTS

The early times

- In 1980 the atmosphere should have been of enthusiasm. The possibility to produce in laboratory, albeit for a very short period, a deconfined states of quark and gluons, the QGP, looked to be at hand.
- Few years passed before ion beams from SPS became available
  - at that time the CERN priority was the LEP
  - The Director of non-LEP activities, Robert Klapisch, had the mission to maintain a broad physics program, with reduced CERN investments
    - the CERN Heavy-ion facility was designed and constructed by several CERN member state laboratories with also contributions of non-member states: same approach later (1993) for the "from-light-to-heavy" upgrade
    - severe budgetary constraints, which did not permit any big investment in the building of new detectors
    - key moment was the "Workshop on the Future of Fixed Target Physics" (December 1982)
      - the group "Nuclear Beams and Targets" was convened by W.J. Willis and the summary given by M. Albrow
    - → the SPS community took interests in heavy-ion physics
    - → in Autumn 1984, seven new experiments were recommended by SPSC, two of them (NA35 and WA80) being the direct descendants of the 1980 Letter of Intent

The early times

Exp.	p_{lab}/A [GeV/c]	y_{nn}	y_f $^{16}O+Au$	Detector	Acceptance
Na34 Helios	200	3.03	2.37	U-Cal	$-0.1 < \eta < 5.5$
				LA-Cal	
				Si-Mult	$0.9 < \eta < 4.9$
				Ext. Spec.	$0.9 < \eta < 2.0$
					$\Delta\Phi < 5°$
Na35	60	2.42	1.80	Ring Cal	$2.08 < \eta < 3.72$
				PPD	$1.95 < \eta < 3.37$
				ZDC	$0 < \theta < 0.3°$
					$5.9 < \eta$
	200	3.03	2.37	Ring Cal	$2.28 < \eta < 3.94$
				PPD	$2.18 < \eta < 3.61$
				ZDC	$0 < \theta < 0.3°$
					$5.9 < \eta$
				Streamer Ch.	$0.6 < y < 4.6$
Na36	200	3.03	2.37	TPC	
Na38	200	3.03	2.37	EM Cal	$2 < \eta < 4.2$
				Di-Muon	$2 < M < 4$ GeV/c^2
					$2.8 < \eta < 4.0$
WA80	200	3.03	2.37	ZDC	$0 < \theta < 0.3°$
					$5.9 < \eta$
				MIRAC	$2.4 < \eta < 5.5$
				MIRAM	$2.17 < \eta < 4.74$
				LAM	$1.3 < \eta < 2.4$
				Plastic Ball	$30 < \theta < 160°$
					$1.31 > \eta$
				SAPHIR	$1.5 < \eta < 2.1$
					$\Delta\Phi < 20°$
WA85	200	3.03	2.37	Ω Spectr.	$2.2 < y < 3.2$
					$p_t > 0.6$ GeV/c

For experiments where the configuration did not change with beam energy, it is listed under 200 GeV/c

LA-Cal: Liquid Argon Calorimeter
PPD: Photon Position Detector
MIRAC: Mid Rapidity Calorimeter
Saphir: Pb Glass Photon Detector
MIRAM: Mid Rapidity Multiplicity
LAM : Large Angle Multiplicity

NA35: Study of Relativistic Nucleus-Nucleus Collisions at 60 and 200 GeV/nucleon

- collaboration: Athens, Bari, BNL, LBL, Cracow, GSI, Frankfurt, Friburg, Heidelberg, Marburg, München, Texas A&M, Warsaw, Zagreb
- spokesman: R. Stock
- successors: NA49, NA61

A simulated O^{16}-Xe collision

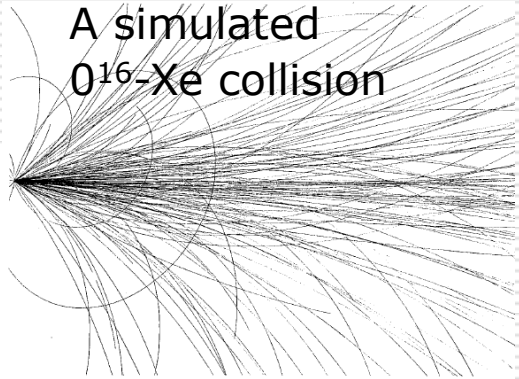


Fig. 2.1.1 A simulated central collision event of the reaction $^{16}O + Xe$, showing the charged particle tracks as seen in the Streamer Chamber.

Streamer-chamber picture of a central S-S collisions

The streamer chamber

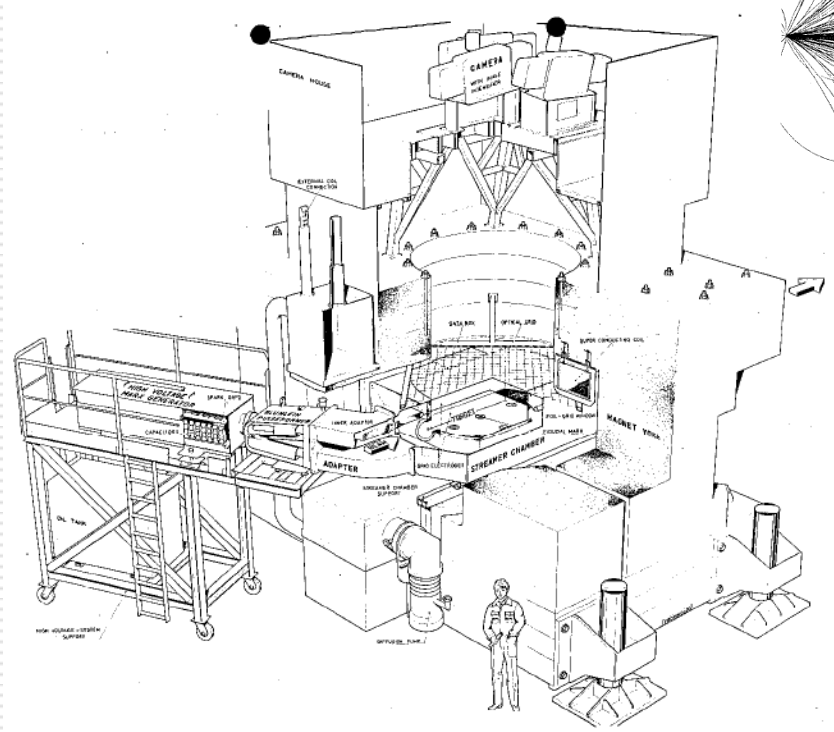
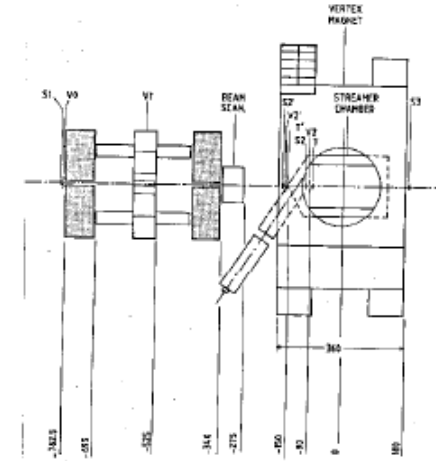
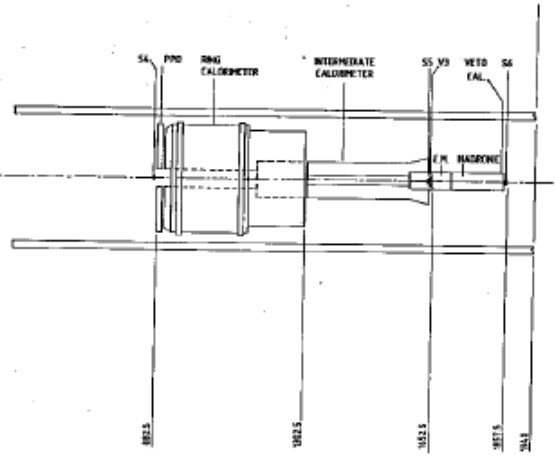


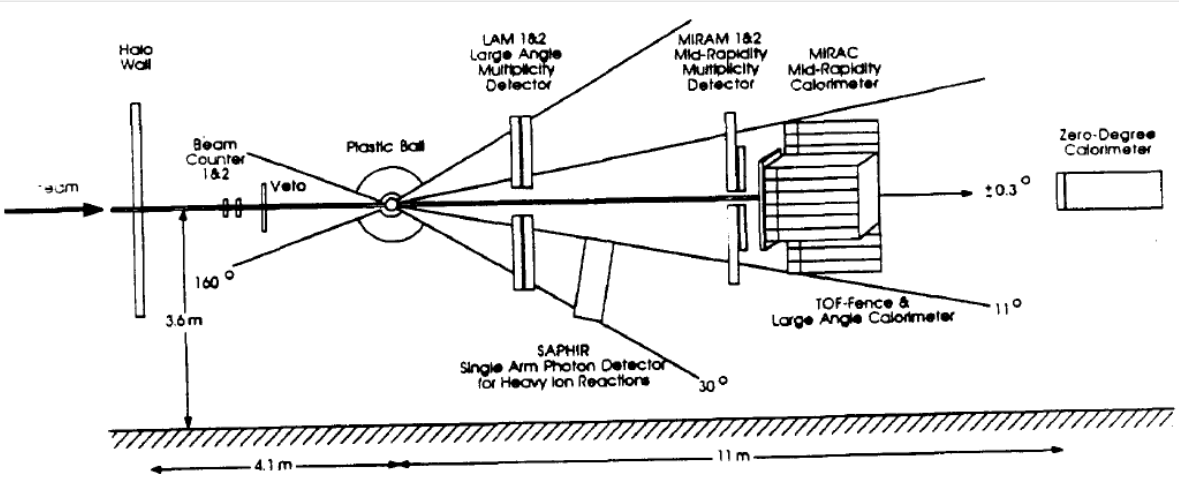
Fig. 1.2 The Streamer Chamber in the superconducting Vertex magnet.



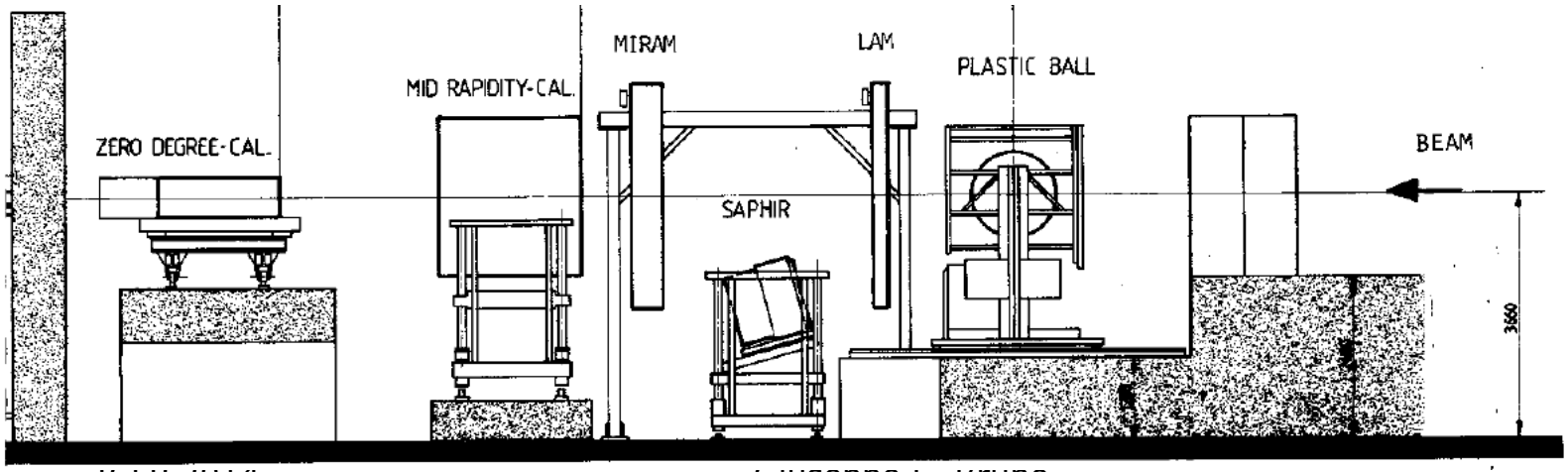


WA80: Study of Relativistic Nucleus-Nucleus Collisions at the CERN SPS

- Collaboration: BNL, GSI, Groningen, LBL, Lund, Moscow, Münster, Oak Ridge, Knoxville
- spokesman: H.H. Gutbrod
- successors: WA93

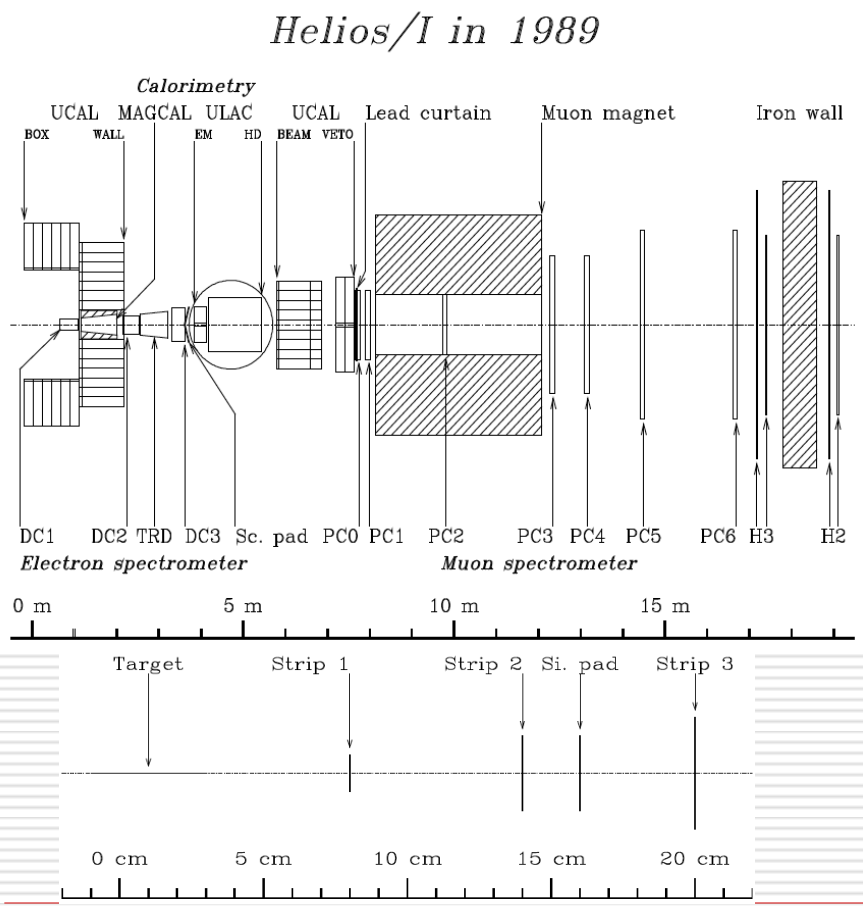


direct photons
+ π^0 and η



NA34/Helios2: Study of high energy densities over extended nuclear volumes via nucleus-nucleus collisions at the SPS

- collaboration: Bari, BNL, CERN, Heidelberg, Los Alamos, Lund, McGill/Montreal, Moscow, Novosibirisk, Pittsburgh, Rome, RAL, Gif—sur-Yvette, Salerno, Stockholm, Tel Aviv, Turin, London
- spokesman: H.J. Specht
- successors: HELIOS3

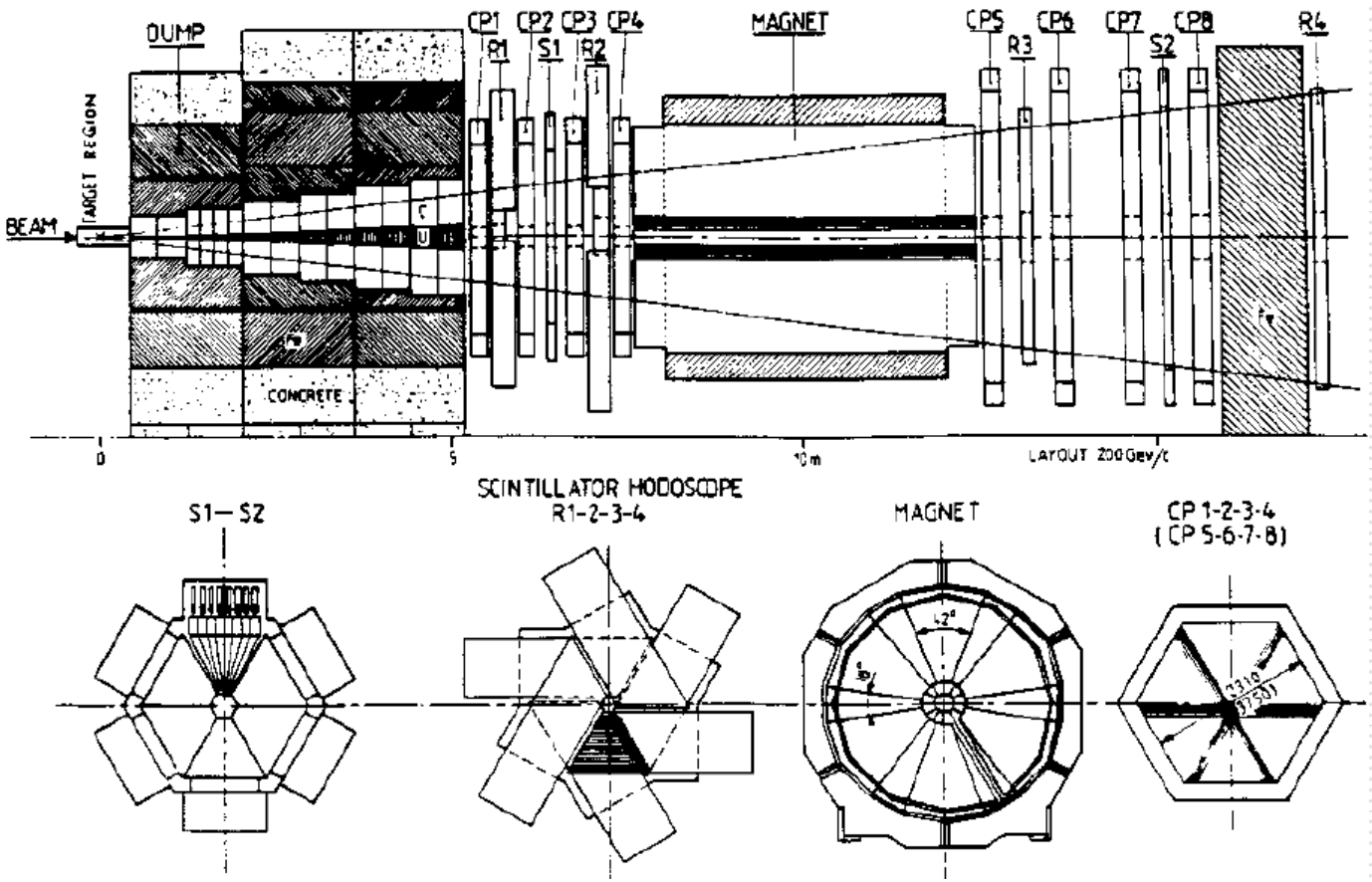


Sub-Detector	Main Characteristics	References
Electron Spectrometer:		
Si-Pad	400 Si "pads", situated 15cm down-stream of target. Pad size varies from $0.2 \times 2\,mm^2$ close to the beam direction to $2 \times 7\,mm^2$ at the outer perimeter of the detector. There is a central hole (diameter ~ 0.5mm) to allow the beam to pass through.	[4, 5]
Si-strips	3 planes of Si strip detectors, at 6, 12, and 18cm from the target. All strips are vertical and on a 25 μm pitch. The read-out uses capacitive charge-division.	[5]
Drift Chambers (DC)	DC1 : x,y,u,v,x,y planes. Total of 384 wires. DC2 : y,x,u,v,y,w planes. Total of 480 wires. DC3 : y,x,u,v,w planes. Total of 540 wires. The DC system has an angular resolution of 1.5 mrad. For reconstructed tracks in the multiplicities typical of high-energy pBe collisions, the two-track efficiency is $\sim 70\%$ for a track separation of 5mm, rising to full efficiency at around 1cm.	[6, 15]
MAGCAL	Dipole magnet with calorimetrised yoke. p_T kick $\sim 60\,MeV/c$ in horizontal (x-z) plane.	[7]
TRD	8 module Transition Radiation Detector. Each module is a 64mm thick radiator of 250 polypropylene foils, followed by a drift chamber filled with 95/5 Xenon/Isobutane and equipped with x and y read-out, using "cluster-counting". The TRD is fully efficient at $\gamma \sim 4000$. For isolated 5 GeV particles, the hadron rejection is $\sim 10^3$ for an electron efficiency of 90%. In the multiplicities typical of high energy pBe collisions, the hadron rejection is degraded by a factor of 10 to 20.	[8, 9, 16]
Scint-pad	Plane of 80 scintillator "pads" positioned between drift chamber (DC3) and calorimeter (ULAC). Pad size varies from $2 \times 4\,cm^2$ close to the beam direction to $10 \times 10\,cm^2$ at the outer perimeter of the detector. There is a central hole to allow the non-interacting beam to pass through.	
ULAC	Uranium Liquid Argon Calorimeter. Electro-magnetic section is 36 cells; total of $18X_0$. Each cell is (thicknesses in mm): U(1.7);Liq. Argon(2);Read-out plane(1.6); Liq. Argon(2) The granularity of the electro-magnetic section read out is $2 \times 2\,cm^2$ pads. Resolution: $11.6\%/\sqrt{E(GeV)}$ Hadronic section: 4.5λ	[10]
BEAM+VETO	Uranium-Scintillator calorimeter: 5.8λ	[7]
BOX+WALL	Uranium-Scintillator calorimeter covering wide angle region.	[7]
Muon Spectrometer:		
Proportional Chambers (PC)	PC0 : x,u,v planes. Total of 1536 wires. PC1 : x,u,v planes. Total of 1536 wires. PC2 : x,y,u,v,y,x planes. Total of 2688 wires. PC3 : x,y,u,v,y,x planes. Total of 5696 wires. PC4 : x,y,u,v,y,x planes. Total of 5824 wires. PC5 : x,x,y,u planes. Total of 5696 wires. PC6 : x,y,v,x planes. Total of 5952 wires.	[11, 12, 14]
Muon Magnet	Large aperture (1.6m diameter) super-conducting dipole magnet with p_T kick $\sim 1.2\,GeV/c$ in horizontal (x-z) plane.	[11, 14, 13]
Hodoscopes H2,H3	Each hodoscope consists of two layers of scintillators; each layer has 10(H3) or 11 (H2) rows. Each row contains two horizontal scintillator slabs, $3 \times 0.24\,m^2$.	see section 2.3.2

Table 1: Summary of main sub-detectors

NA38: Study of high energy nucleus-nucleus interactions with the enlarged NA10 di-muon spectrometer

- collaboration: Annecy, CERN, Clermont-Ferrand, Lisbon, Lyon, Orsay, Palaiseau, Strasbourg
- spokesman: L. Kluberg
- successors: NA50, NA60



NA36: The production of strange baryons and anti-baryons with relativistic light ion collisions at the CERN SPS

- collaboration: Bergen, LBL, Birmingham, CERN, Krakow, Madrid, Omaha, Santiago, Strasbourg, Wien
- spokesman: C.R. Gruhn

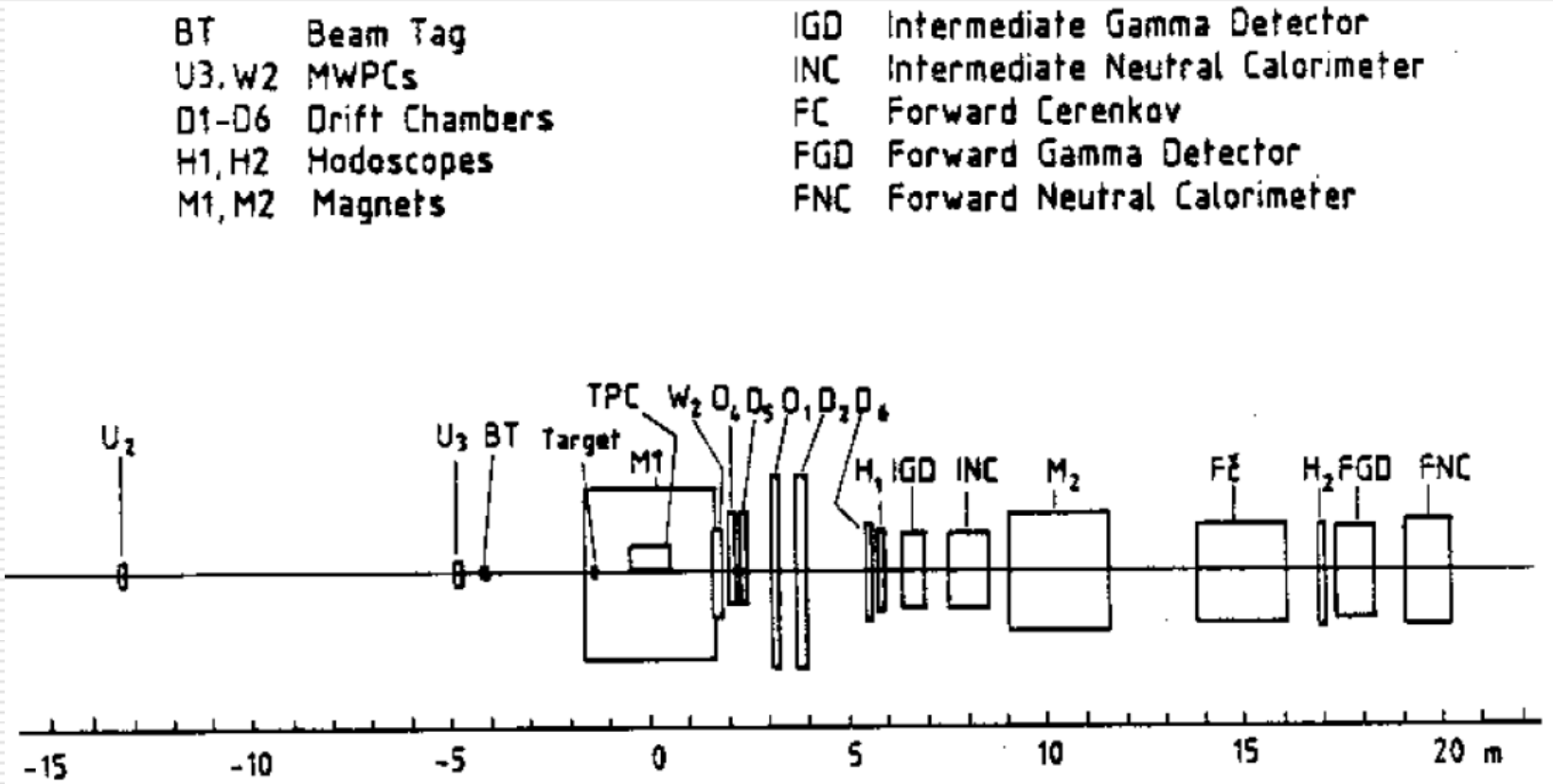
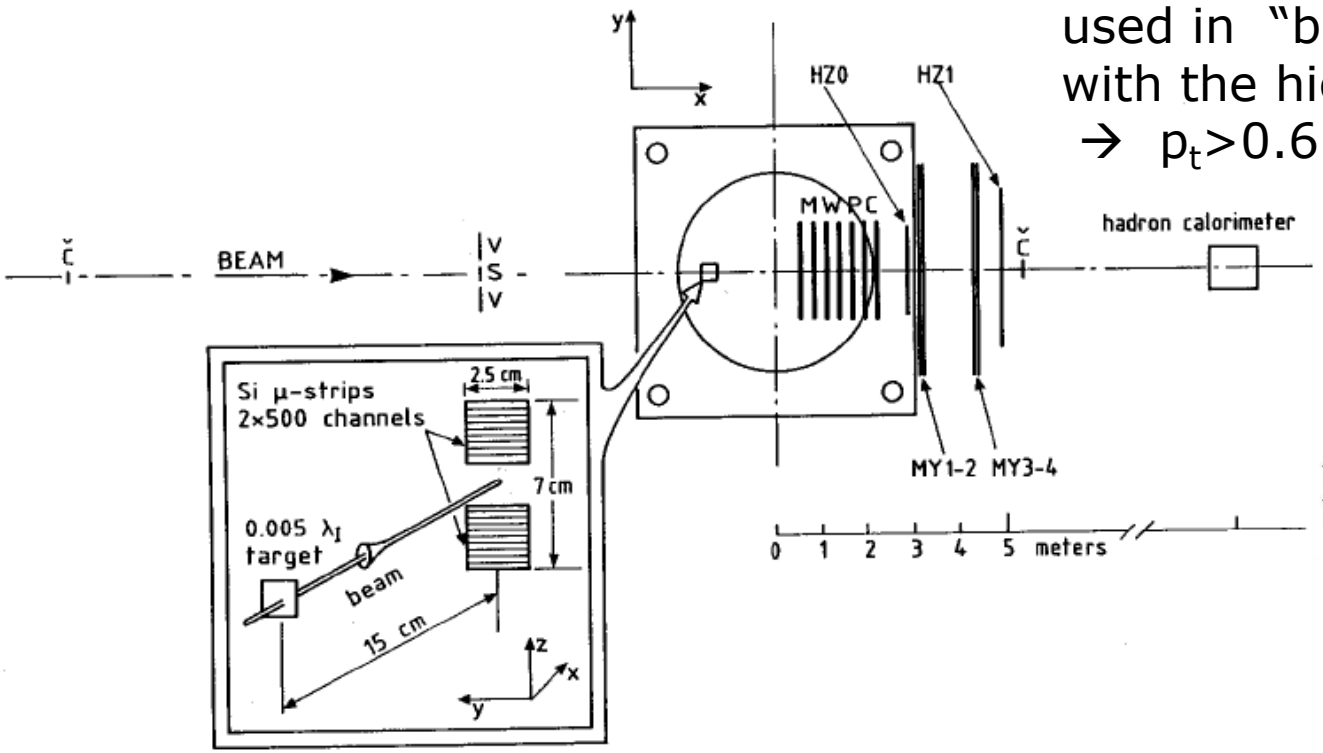


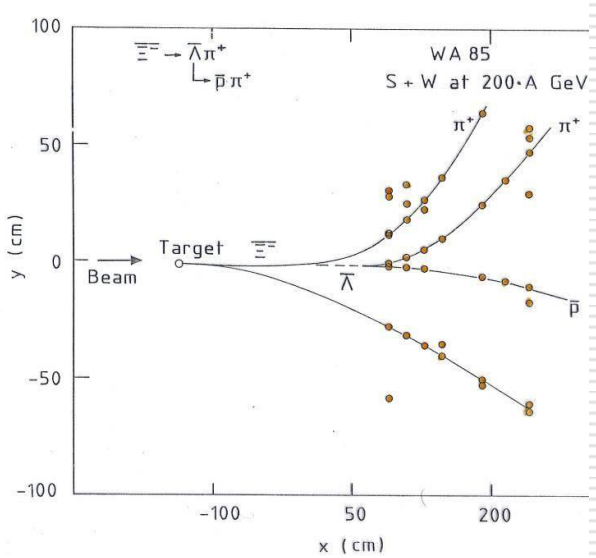
Figure 1: NA 36 experimental layout.

WA85: Study of high energy nucleus-nucleus interactions using the Ω′ spectrometer equipped with a multiparticle high p_t detector

- Athens, Bari, Bergen, Birmingham, CERN, Paris, Madrid, Oslo
- spokesman: R.Zitoun → E. Quercigh
- successors: WA94, WA97, NA57

MWPC of the OMEGA spectrometer used in "butterfly" mode, to cope with the high multiplicity:
→ p_t>0.6 GeV/c; $|y_{cms}|$<1





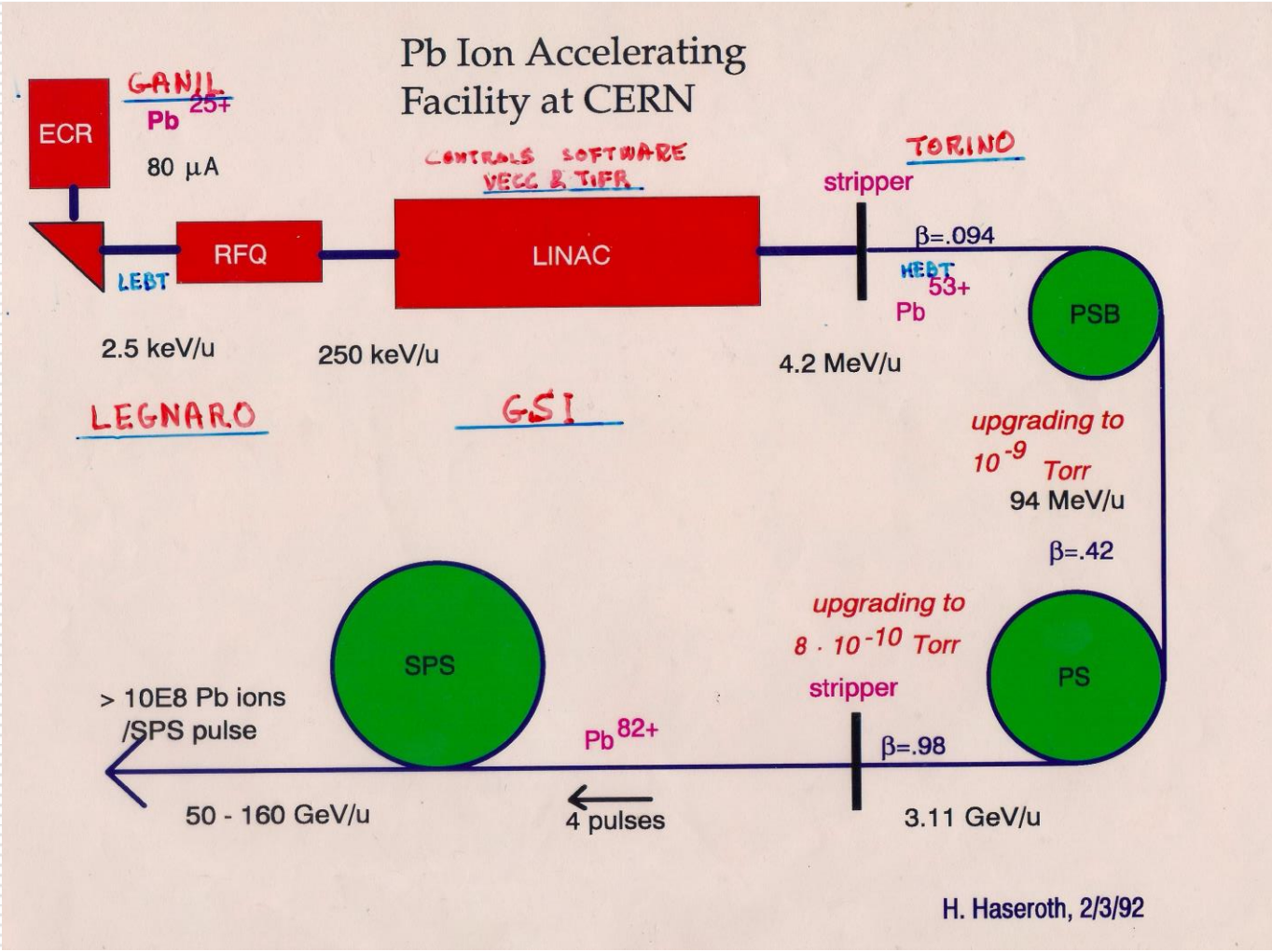
The early times

Table 1
Large ion experiments

Quark Matter Conference	87	88	90	91	93
BNL	E802	magn. spectr. part. ident. ——>			E859 → E866
	E814	~ 4π calorimeter forward spectr. ——>			E877 upgr. spectr.
	E810	TPC magn. field ——>			
				E858 spectr.	
CERN	NA34	Helios spectr. ——>		HELIOS 3	dimuon spectr.
	NA35	Streamer chamber ——>			+ TPC
	NA38	dimuon spectr. ——>			
		NA36	TPC magn. field ——>		
				NA44	focusing spectr. —>
				NA45	e^+e^- spectr. ——>
	WA80	Plastic Ball calorimetry ——>			WA93 magn. spectr.
		WA85	Omega ——>		WA94 RICH

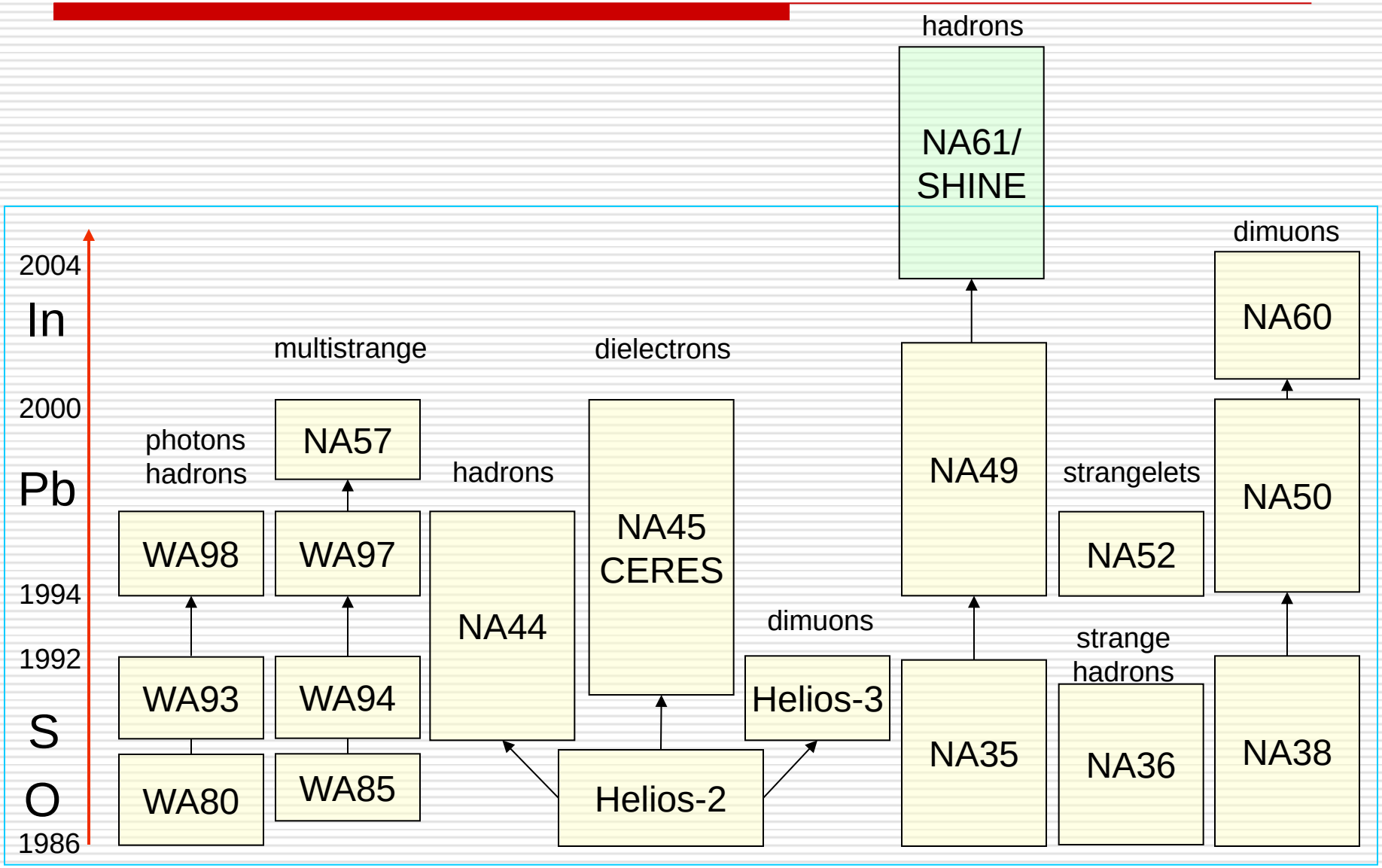
E. Quercigh "QM93: experimental highlights and outlook", Nucl. Phys. A566 (1993) 321c

From light to heavy ions



Ref: N. Angert et al. "Cern heavy-ion facility design Report" CERN-93-01

The CERN SPS heavy ion physics program



A new state of matter ?

Other Seminars

OTHER SEMINARS - A new state of matter: Results from the CERN Lead-Beam Programme

by L. Maiani, U. Heinz and representatives of the heavy-ion experiments (CERN)

Thursday, 10 February 2000 from **09:30** to **14:00** (Europe/Zurich)
at CERN (503-1-001 - Council Chamber)

Description This special seminar aims at an assessment of the results from the heavy ion programme with lead ion beams at CERN, which was started in 1994. A series of talks will cover the essential experimental findings and their interpretation in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the
characteristic features of the theoretically predicted Quark-Gluon Plasma.

Ulrich Heinz (CERN)
Making Quark-Gluon Matter in Relativistic Nuclear Collisions

Louis Kluberg (IN^2P^3)
The J/y suppression pattern observed in Pb-Pb collisions ions: a signature for the production of a new state of matter.

Johanna Stachel (University of Heidelberg)
Virtual and real photons radiated by the cooling and hadronizing fireball.

Reinhard Stock (University of Frankfurt)
Hadron Signals of the Little Bang.

Emanuele Quercigh (CERN)
Strange signals of a new state of matter from nuclear collisions at SPS.

Luciano Maiani (Director General)
Summary

Material: Video in CDS

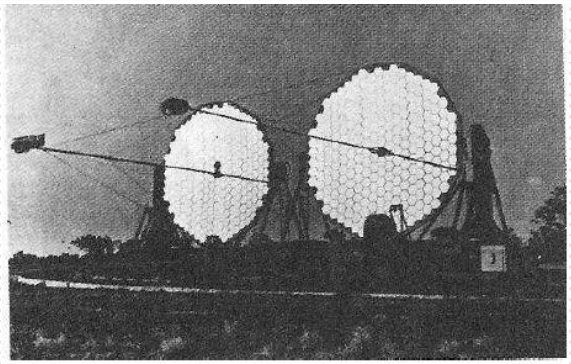
- in 2000 the baton was passed to RHIC (AGS→SPS→RHIC→**LHC**)
- at CERN a seminar was organized with the major experimental results

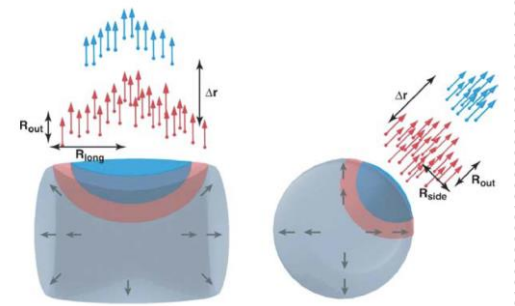
Main results from the SPS

- collective dynamics: HBT, radial flow, directed and and elliptic flow
- J/psi suppression
- strangeness enhancement
- low mass di-leptons productions
  - photons, vector bosons
- several others…
- search for the onset of deconfinement
  - back to the *present*: NA61/SHINE

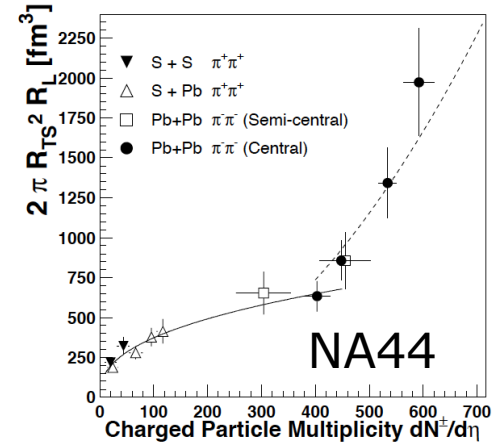
Collective motions

- HBT interferometry





Eur. Phys. J. C 18, 317–325 (2000)

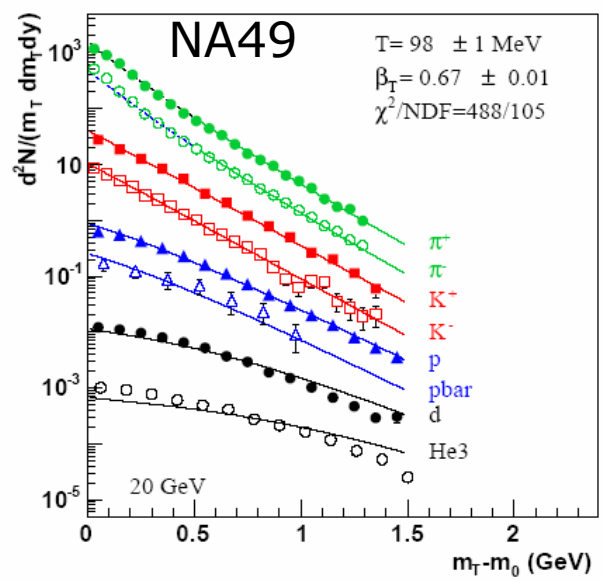


- radial flow

$$\frac{d^2N_j}{m_T dy dm_T} = \int_0^{R_G} A_j m_T \cdot K_1\left(\frac{m_T \cosh\rho}{T}\right) \cdot I_0\left(\frac{p_T \sinh\rho}{T}\right) r dr$$

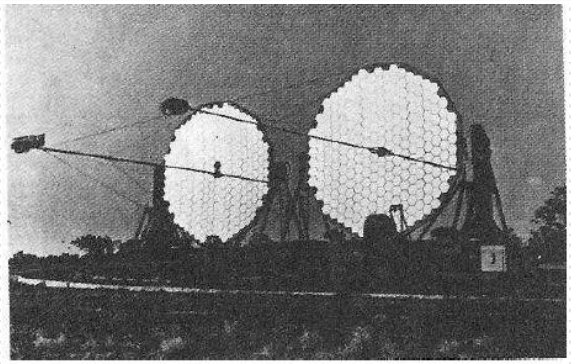
$$\rho(r) = \tanh^{-1}\beta_\perp(r) \qquad \beta_\perp(r) = \beta_S\left[\frac{r}{R_G}\right]^{n(=1)} \qquad r \le R_G$$

Schnedermann, Sollfrank, Heinz, PRC48 (1993) 2462

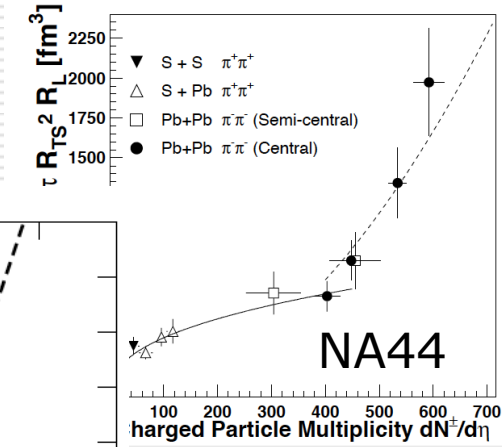


Collective motions

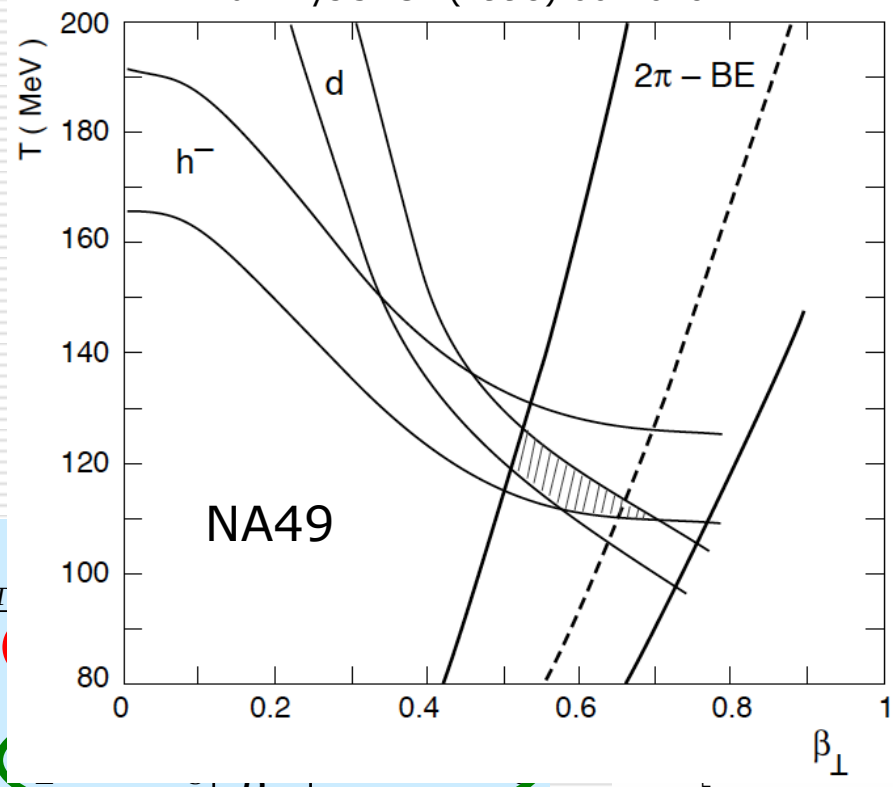
- HBT interferometry



Eur. Phys. J. C 18, 317–325 (2000)



Eur.Phys.J. C2 (1998) 661-670

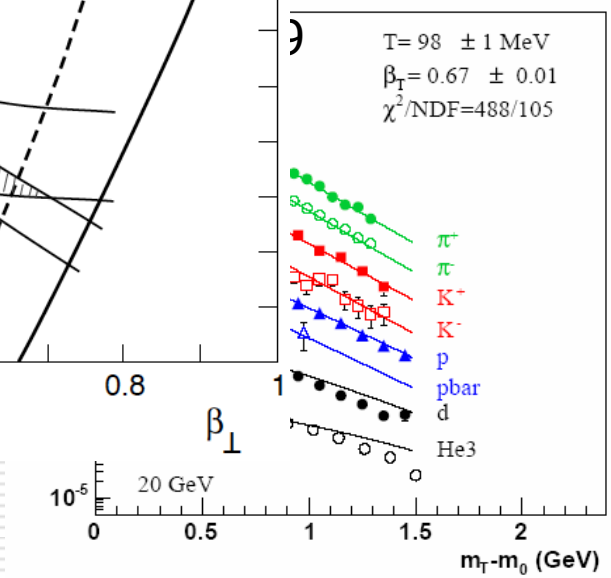


- radial flow

$$\frac{d^2 N_j}{m_T \, dy \, dm_T} = \int_0^{R_G} A_j m_T \cdot K_1\left(\frac{m_T}{\ldots} \right.$$

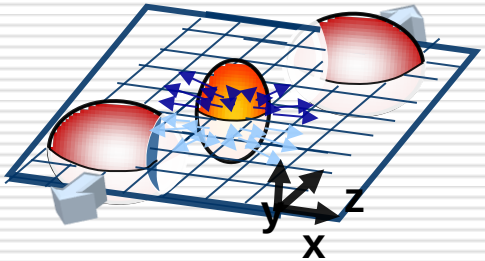
$$\rho(r) = \tanh^{-1} \beta_\perp(r)$$

$$\lfloor R_G \rfloor$$



Schnedermann, Sollfrank, Heinz, PRC48 (1993) 2462

Directed and elliptic flow



$$\frac{dN}{d(j - y_{RP})} \mu 1 + 2 \sum_{n=1} v_n \cos\left(n[j - y_{RP}]\right)$$

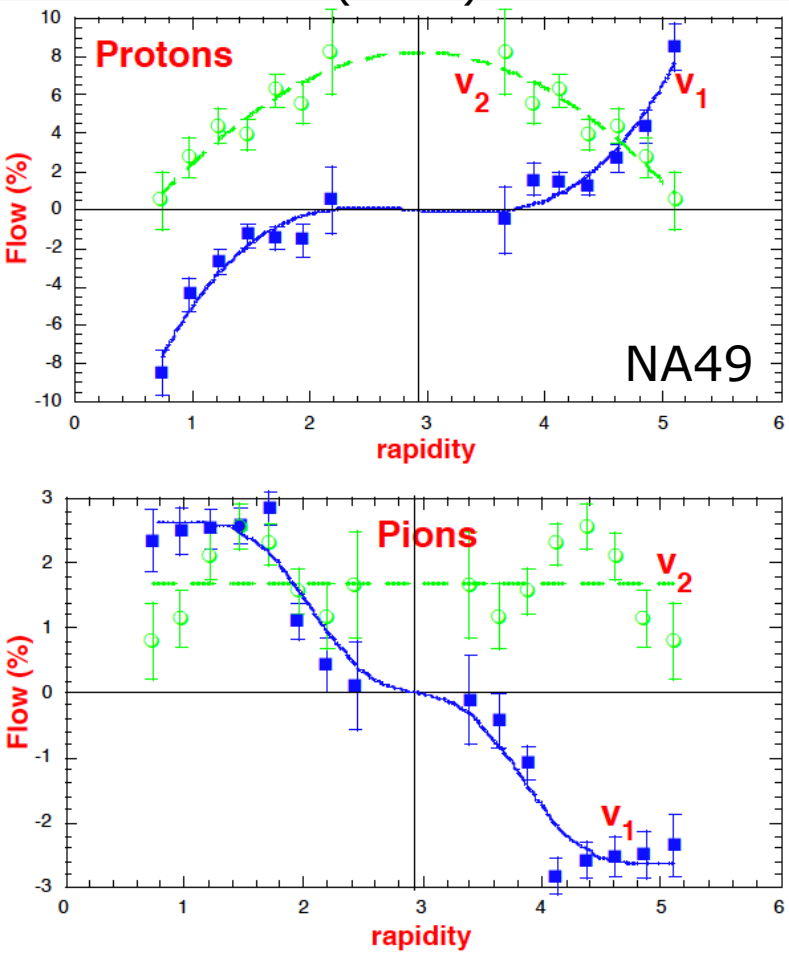
$$v_1 = \left\langle \cos(j - y_{RP}) \right\rangle \qquad v_2 = \left\langle \cos\left[2(j - y_{RP})\right] \right\rangle$$

- opposite directed flow at large rapidity for p and π
- $v_2(\pi)$ flat with y; $v_2(p)$ peaks at mid-y
- both π and p have the flow axis of the elliptic flow in the plane of the directed flow

→ shadowing by spectator matter cannot be at the origin of the elliptic flow

→ the elliptic flow is caused by the pressure in the high density region created during the initial collision

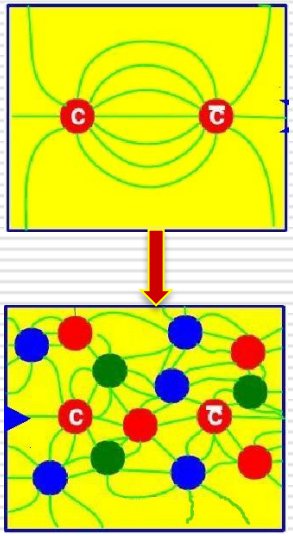
PRL 80 (1998) 4136



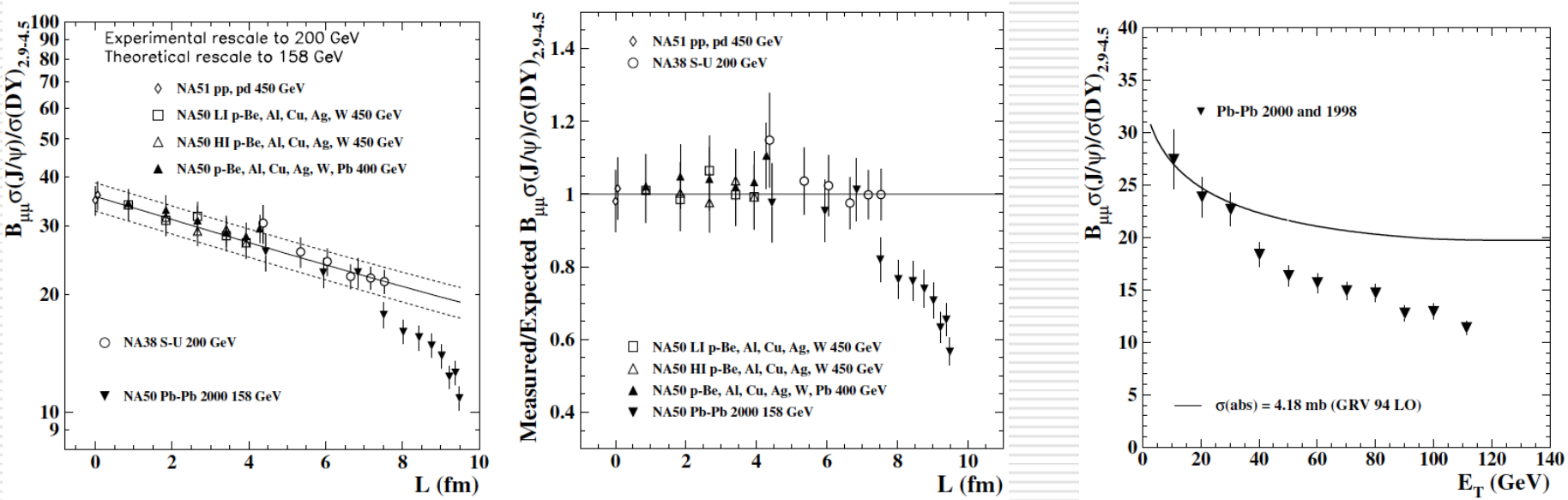
Pb-Pb 158 A GeV/c, semi-peripheral

The J/ψ suppression

- The idea behind (T. Matsui and H.Satz):
  - Debey screening of the color force between c and $\bar{c}$: the J/ψ melts in the QGP
- The main actors: NA38, NA51, NA50 and NA60



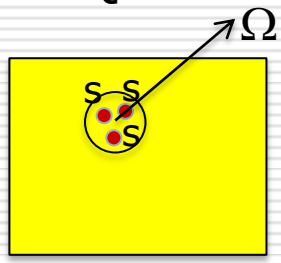
Eur. Phys. J. C 39, 335–345 (2005)



The strangeness enhancement

- The idea behind (J.Rafelski and B.Muller):
  - multi-strange (anti-)baryons much more abundantly produced in a QGP, then in hadronic system
- The main actors:
  - West area: WA85, WA94, WA97,
  - Nord area: NA35, NA36, NA44, NA49, NA52, NA57

In a QGP:



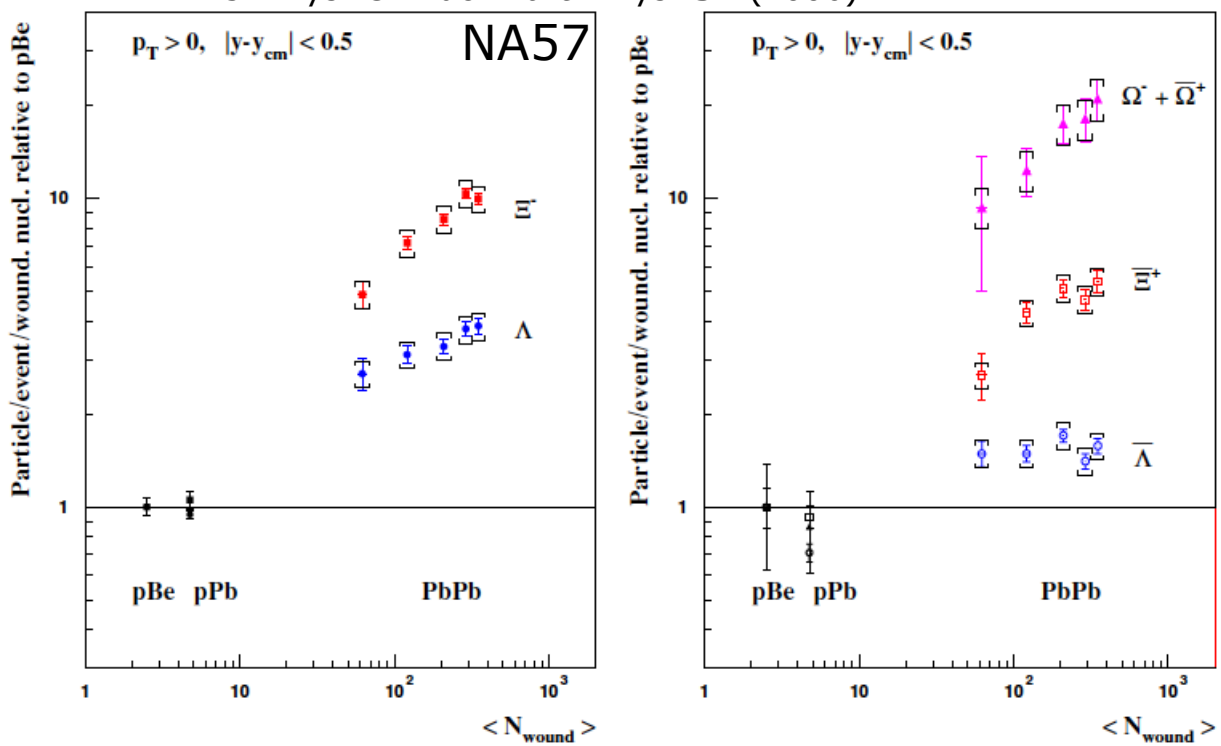
In a hadron gas:

$\pi + N \rightarrow K + \Lambda$

$\pi + \Lambda \rightarrow K + \Xi$

$\pi + \Xi \rightarrow K + \Omega$

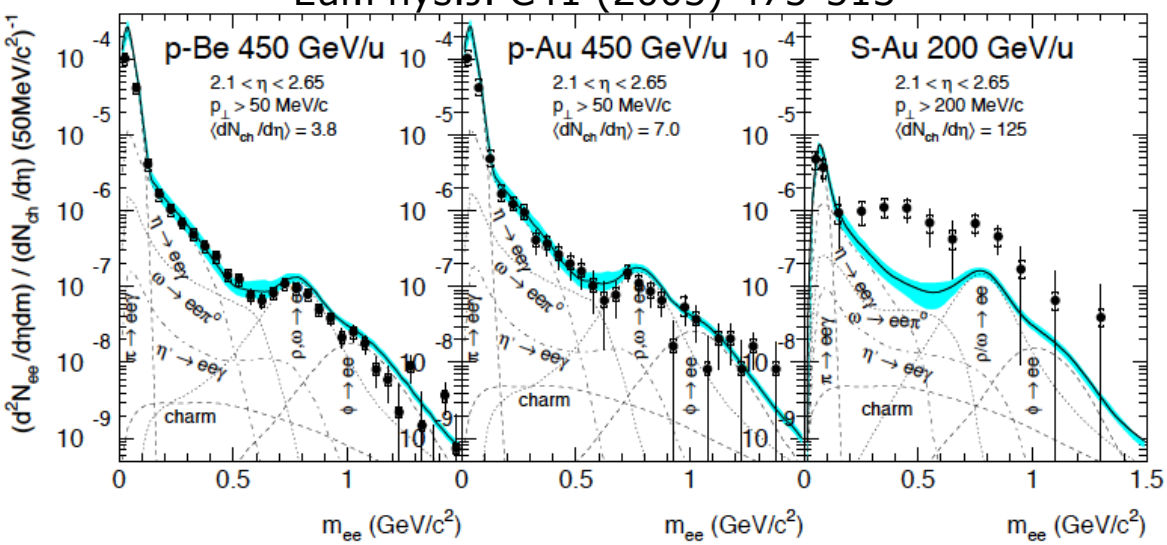
J. Phys. G: Nucl. Part. Phys. **32** (2006) 427–441



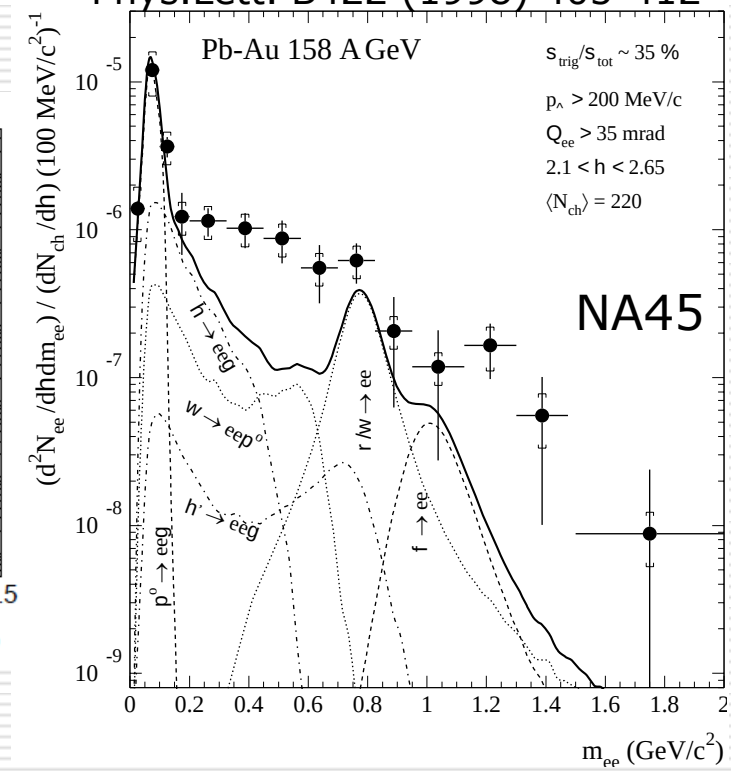
Low mass di-leptons

- The idea behind:
  - Photons and di-leptons are direct probes of the early collision stages; largest emission rates in hot and dense matter
  - vector meson (ρ, ω ,ϕ) modifications as a signature of the in-medium chiral symmetry restoration close to the QCD phase boundary
- The main actors: HELIOS3, NA38, NA45, NA60

Eur.Phys.J. C41 (2005) 475-513

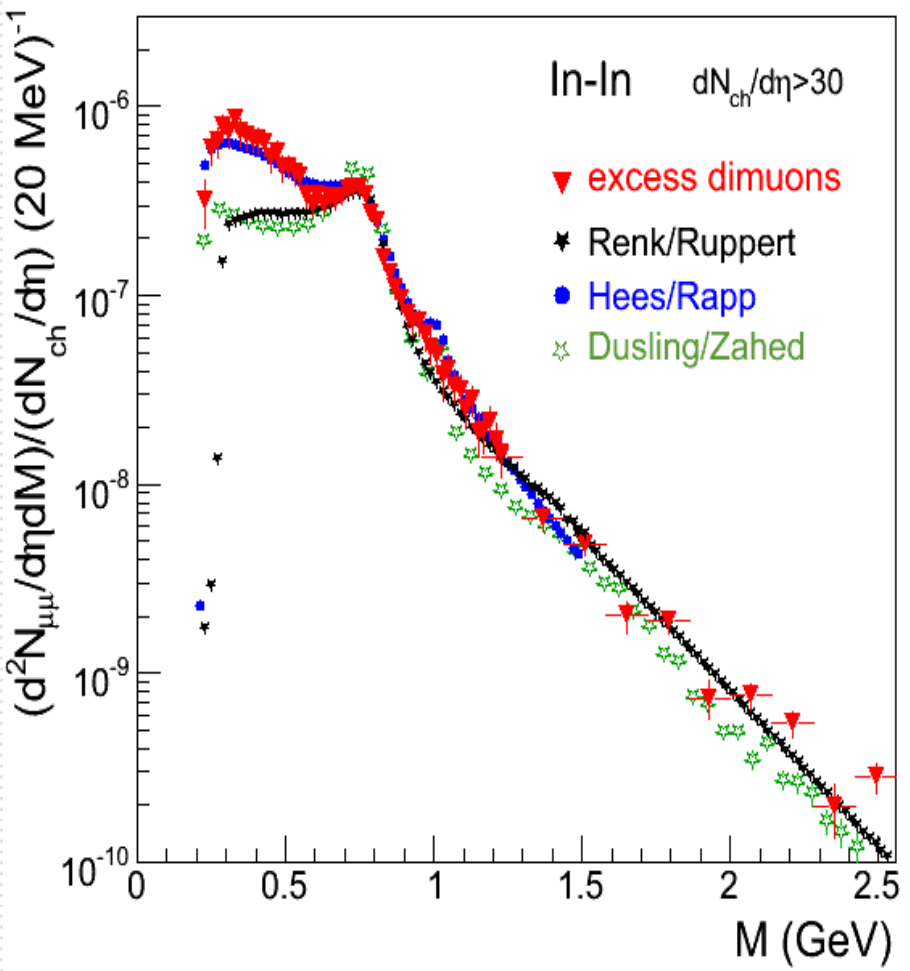


Phys.Lett. B422 (1998) 405-412



NA60: inclusive excess μμ mass spectrum

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



All known sources subtracted

integrated over p_T

Fully corrected for acceptance

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

M<1 GeV

ρ dominates, 'melts' close to T_c

best described by H/R model

M>1 GeV

~ exponential fall-off → 'Planck-like'

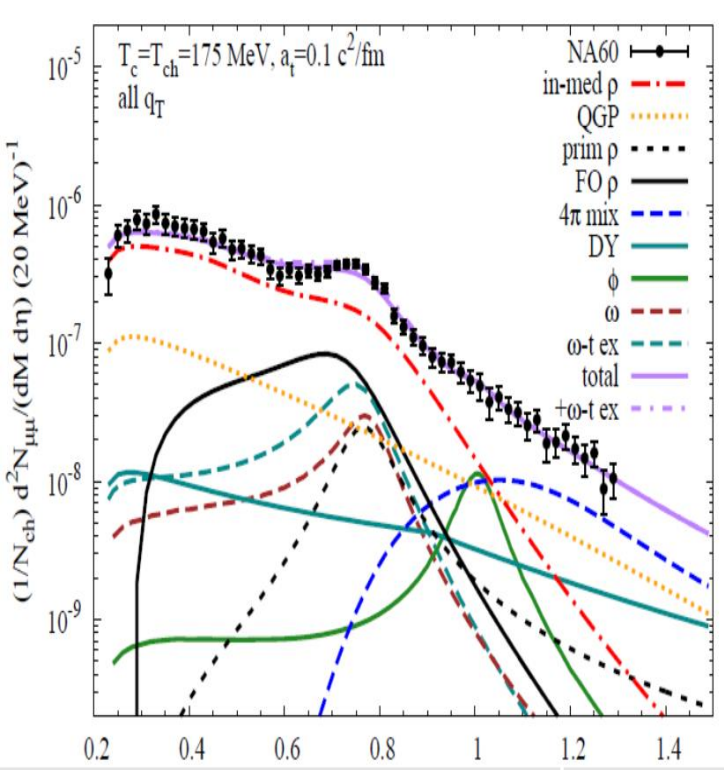
fit to $dN/dM \mu M^{3/2} \exp(-M/T)$

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

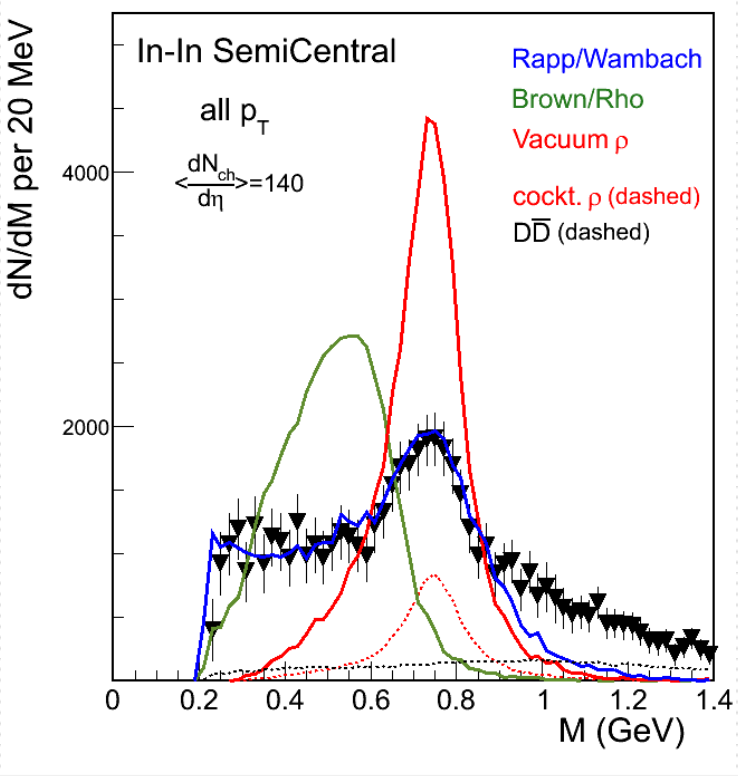
$T>T_c$: partons dominate

ρ meson: the approach to chiral restoration

van Hees+Rapp (2008)



Phys. Rev. Lett. 96 (2006) 162302



data acceptance-corrected

'spectrum directly reflects thermal emission rate' (Rapp)

before acceptance correction:

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

Only broadening of ρ observed, no mass shift

The CERN announcement in 2000
REVISITED

- "*... we now have compelling evidence that a new state of matter has indeed been created .... The new state of matter features many of the characteristics of the theoretically predicted quark gluon plasma ...*" *(L. Maiani)*

- If it is not a Quark Gluon Plasma, then what is this system ?

intermezzo

- while at the peak of this reach SPS program, the same community had to face the challenge of the LHC preparation
  - R&D for new detectors,
  - constructions
  - physics simulations, etc…

- but the real challenge was to coagulate into a single large collaboration several smaller groups

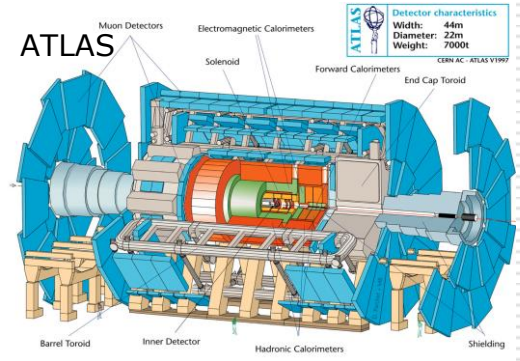
THE PRESENT

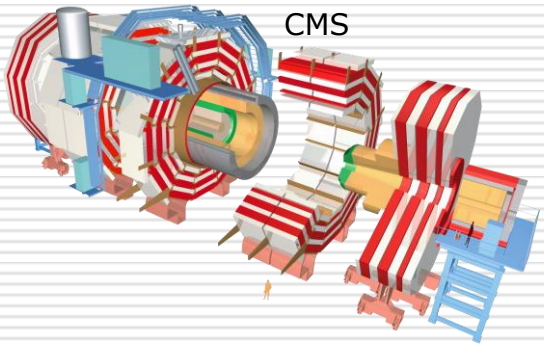
The present is LHC …

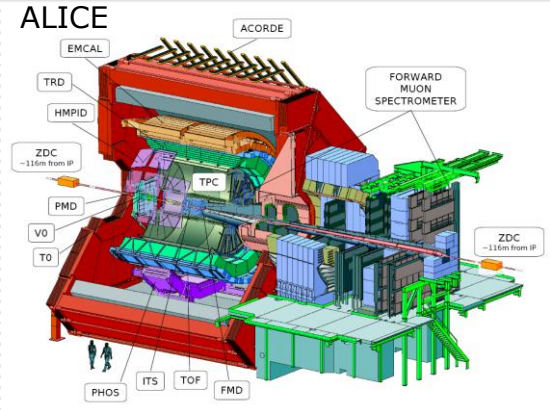
plenty of talks on LHC experimental results at this Conference: P. Jacobs, B. Cole, J. Kamin, A. De Caro, S. Sakai, F. Barile, D. Elia, J. Rak, G. Volpe, A. Badalà, C. Oppedisano

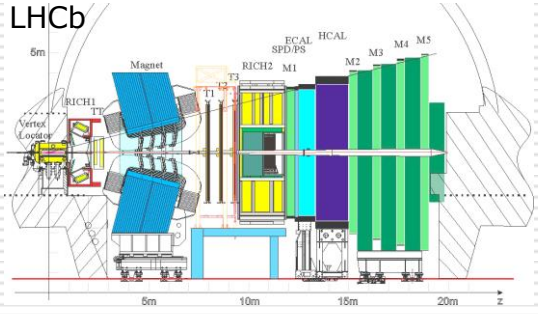
The LHC experiments

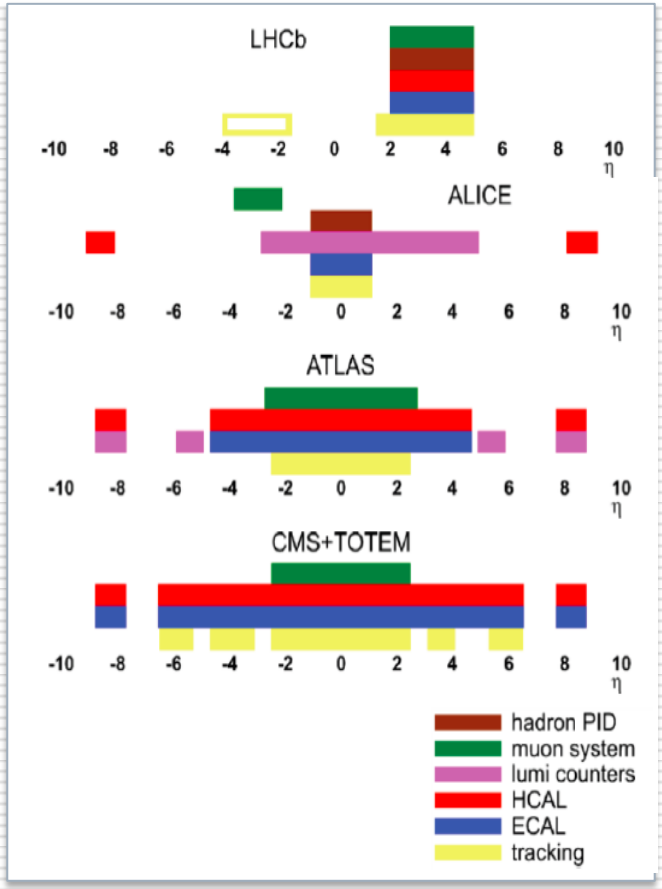
- complementary capabilities:
  - high pt, high rate, jets: the realm of CMS and ATLAS
  - low pt coverage, low material budget, excellent PID: ALICE
  - LHCb has not a heavy ion program, but is providing excellent results in pp and p-Pb interactions









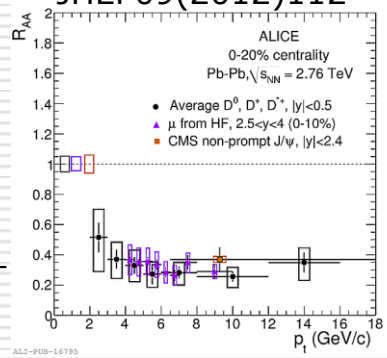


LHC is the realm of rare probes

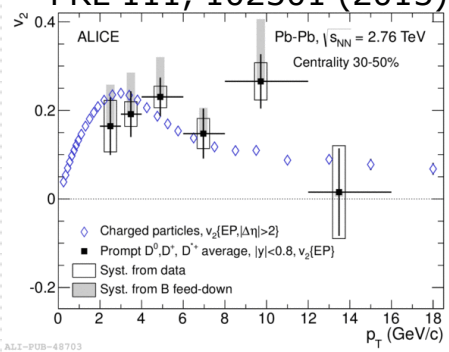
- Energy loss and elliptic flow in the HF sector

$$R_{AA} = \frac{d^2N^{AA}/dydp_T}{\langle N_{coll}\rangle d^2N^{pp}/dydp_T}$$

JHEP09(2012)112

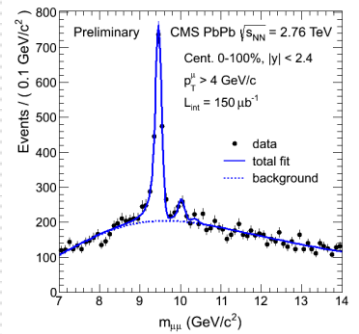


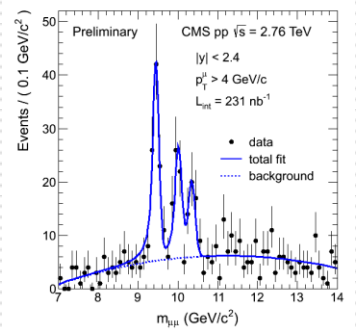
PRL 111, 102301 (2013)

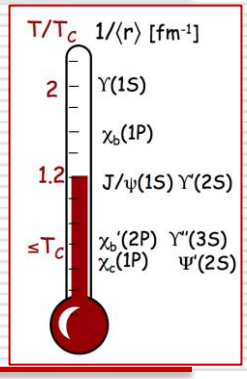


transport coefficients of the QGP

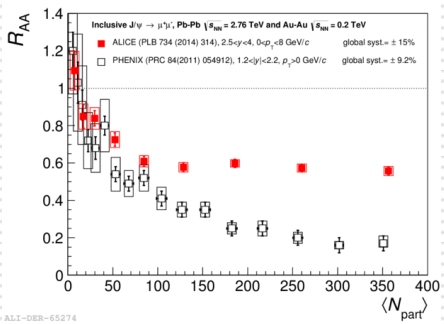
- The Upsilon sequential suppression

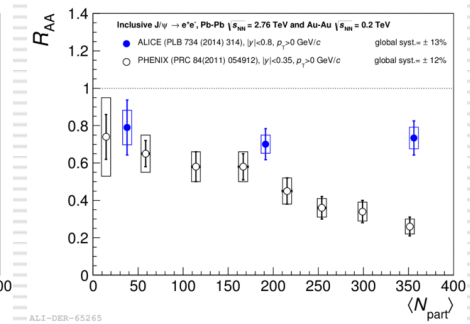


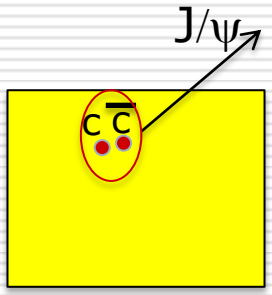




- From J/ψ suppression to the (re-)combination of $c\bar{c}$ pairs into J/ψ







Is the p-Pb just a control experiment at the LHC ?

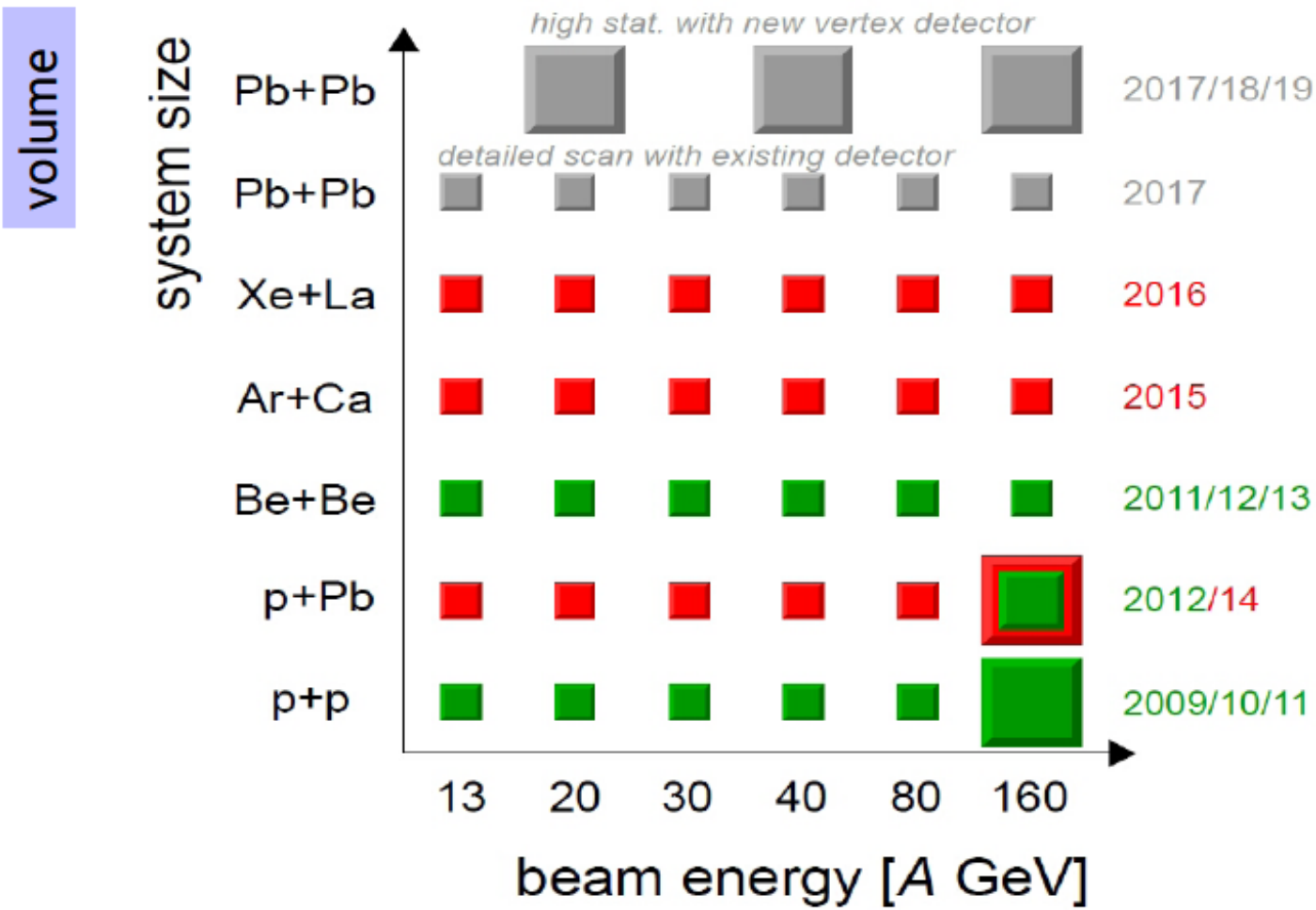
- unfortunately I have no time to discuss the p-Pb results

THE PRESENT

The present is LHC …

… and the SPS (NA61/SHINE experiment)

NA61/SHINE comprehensive scan in energy and size of colliding nuclei to study the properties of the transition between hadron gas and quark gluon plasma



*

Marek Gazdzicki, "Recent results and plans of NA61/SHINE"

THE FUTURE

THE FUTURE

The future is the LHC …

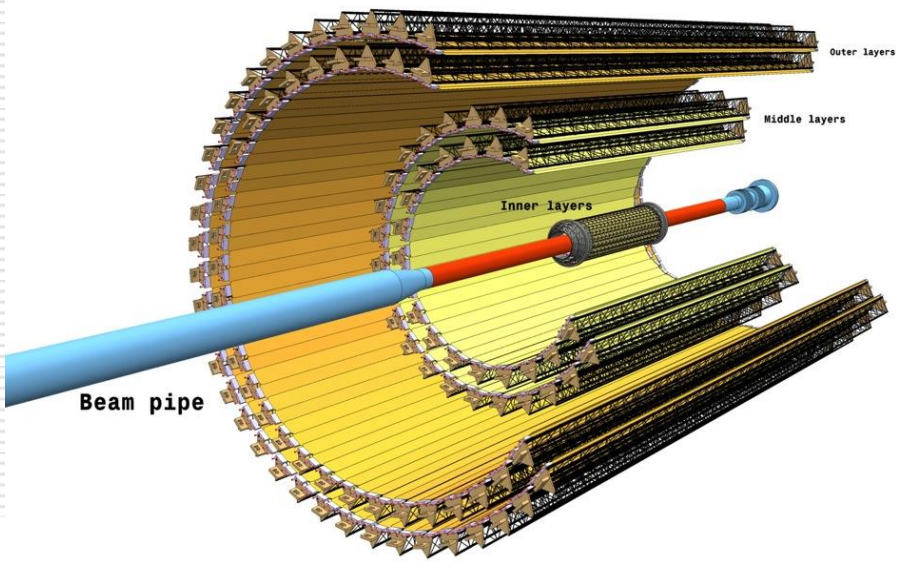
- high luminosity HI with the ALICE upgrade (and ATLAS, CMS)

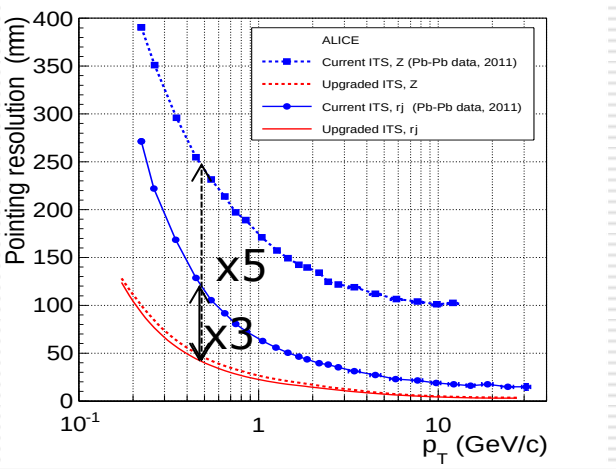
The ALICE ITS upgrade

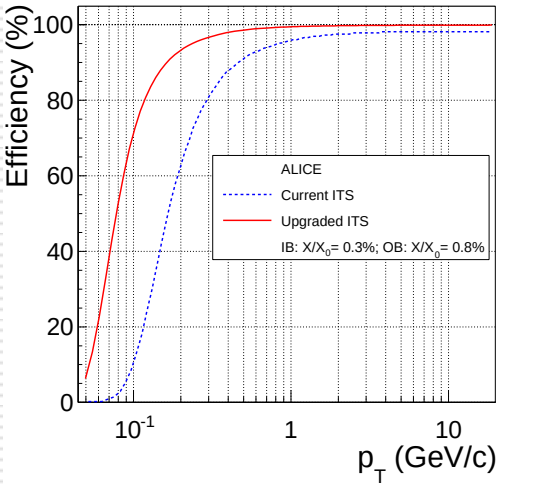
ALICE ITS TDR CERN-LHCC-2013-024

- First layer closer to IP: r_0 = *39mm* → *22mm*
- Reduced material budget: X/X_0 = *1.14%* → *0.3% for the IB layers*
- Improved tracking efficiency and p_T resolution at low p_T
- Faster readout: 50 kHz in Pb-Pb, 200 kHz in pp (currently limited at 1 kHz with full ITS)

7 layers of Monolithic Active Pixel Sensors







It will allow, e.g., to measure the charm production down to p_t=0 and the Λ_c in Pb-Pb

THE FUTURE

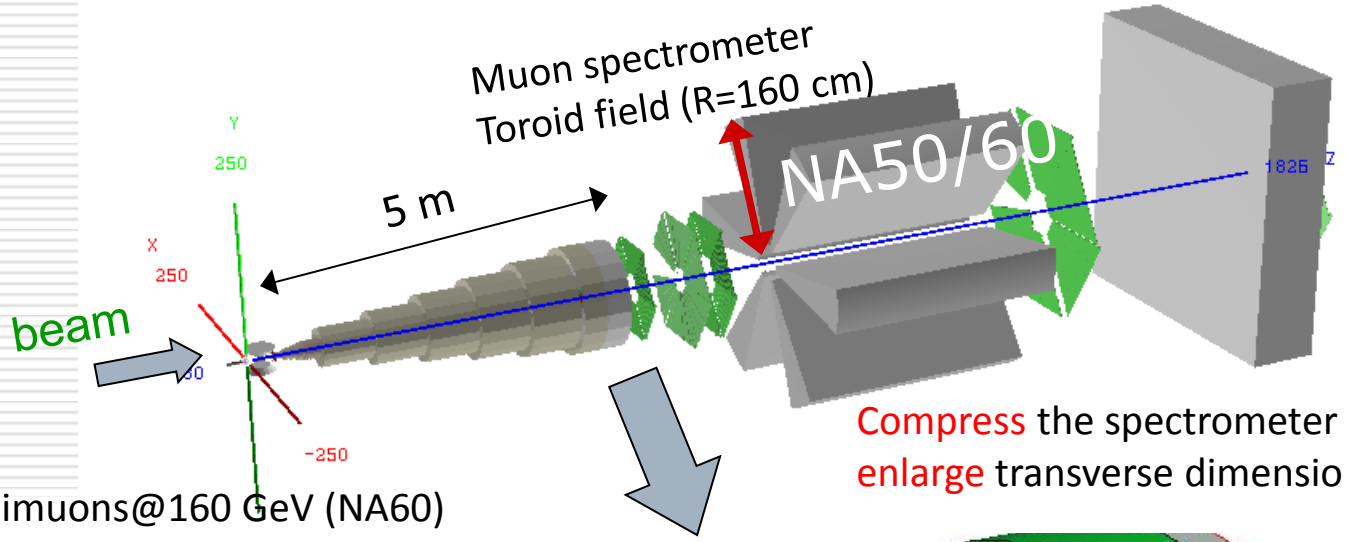
The future is the LHC …

- high luminosity HI with the ALICE upgrade (and ATLAS, CMS)
- A Fixed Target ExpeRiment at the LHC (AFTER)?

… and the SPS ?

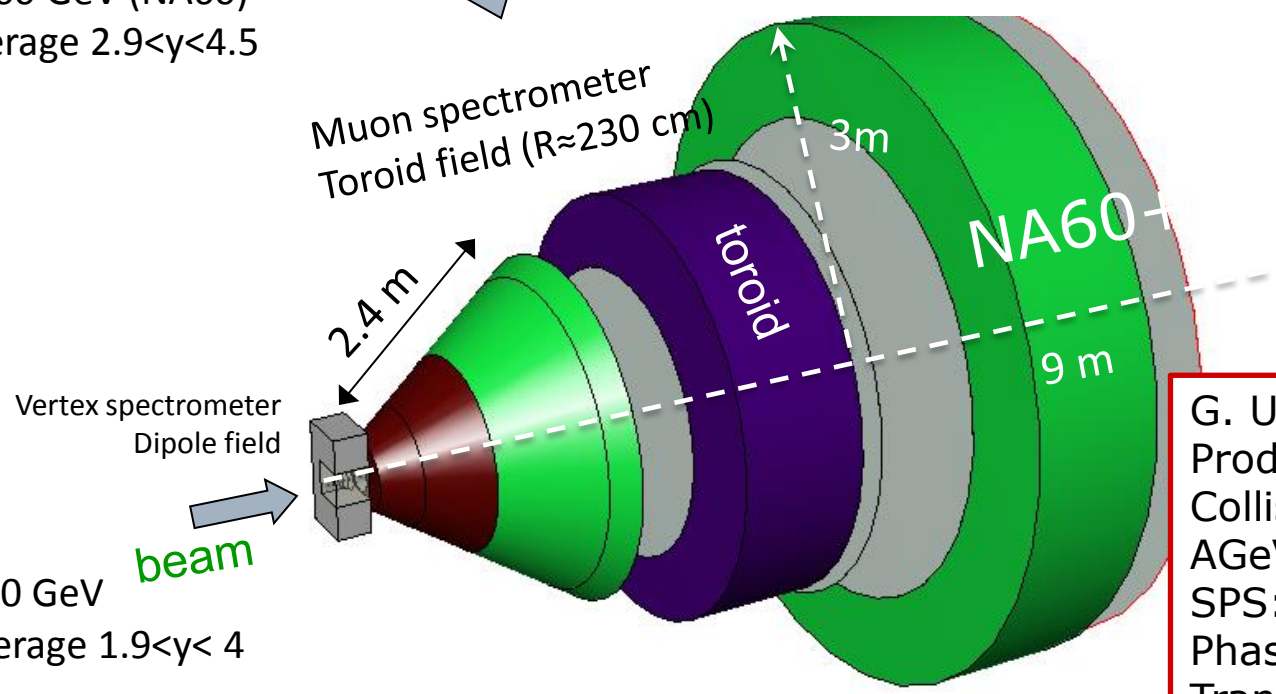
- NA60+
- CHIC experiment ?

NA60+: measuring dimuons at $20<E_{lab}<160$ GeV



dimuons@160 GeV (NA60)
rapidity coverage 2.9<y<4.5

Compress the spectrometer reducing the absorber and enlarge transverse dimensions



dimuons@20 GeV
rapidity coverage 1.9<y< 4

G. Usai "Dimuon Production In PbPb Collisions at 20-160 AGeV at the CERN SPS: Mapping the QCD Phase Diagram in the Transition Region"

Longitudinally scalable setup for running at different energies

THE FUTURE

The future is the LHC …

- high luminosity HI with the ALICE upgrade (and ATLAS, CMS)
- A Fixed Target ExpeRiment at the LHC (AFTER)?

… and the SPS ?

- NA60+
- CHIC experiment ?

The far future ?

- Heavy Ions with the FCC ??

"CERN: the next 60 years (the FCC study)" M. Koratzinos

Ions at FCC

- Centre-of-mass energy per nucleon-nucleon collision:

$$\sqrt{s_{NN}} = \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}\sqrt{s_{pp}} \quad \Rightarrow \quad \sqrt{s_{PbPb}} = 39\ TeV, \quad \sqrt{s_{pPb}} = 63\ TeV \quad \text{for } \sqrt{s_{pp}} = 100\ TeV$$

- First (conservative) estimates of luminosity: x5 larger L_{int} per month of running wrt LHC (after LS2)
- Physics opportunities with heavy ion beams at the FCC (AA, pA) are investigated by a dedicated WG within the FCC-hh group: next WS in September at CERN (https://indico.cern.ch/event/331669)
- Main directions:
  - Quark-Gluon Plasma studies: larger size, higher temperature, new hard probes available (e.g. top quarks)
  - Saturation of small-x gluon densities (with pA): reach down to $x \sim 10^{-6}$ (one order of magnitude smaller than at LHC)
  - Photon-induced collisions ($\gamma+\gamma$, γ+A): saturation and EW studies
- More details: https://indico.cern.ch/event/282344/session/16/contribution/109

Final words

- I would like to close, instead of with conclusions, with a citation which was quoted by Howell Pugh, at the beginning of the CERN heavy-ion adventure:

"*One does not discover new lands without consenting to lose sight of the shore for a very long time*"

from *« Les Faux-monneyeurs (The Counterfeiters) »*, *by* André Gide

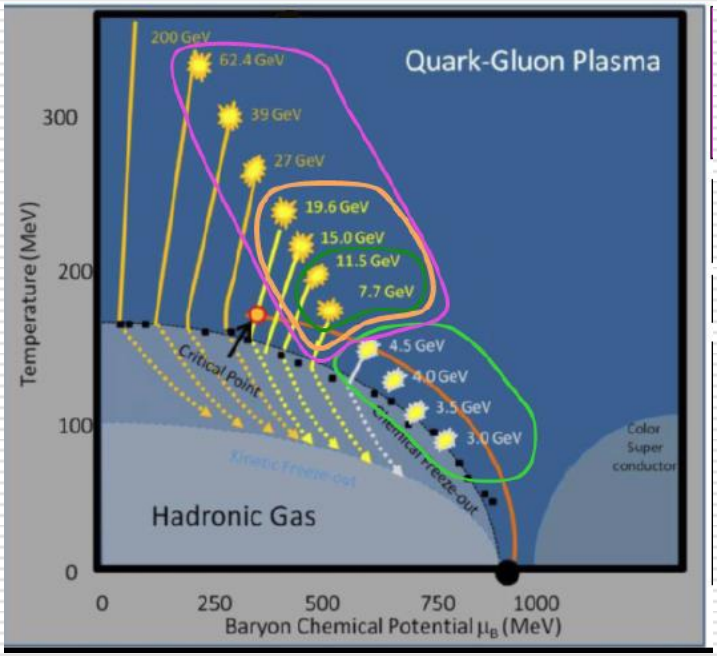
However, I have been advised that, given the title of the novel, a *historian* should better *not use* such a citation.

Acknowledgement

- I would like to thank my friends and colleagues, R. Arnaldi, C. Blume, A. Dainese, M. Gazdzicki, E. Quercigh, E. Scomparin, P. Seyboth, G. Usai, for their help in the preparation of this talk

Spares

Search for the onset of deconfinement



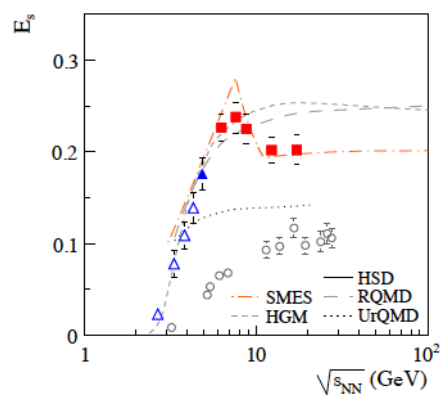
RHIC:
- good coverage, but much lower statistics than fixed target experiments

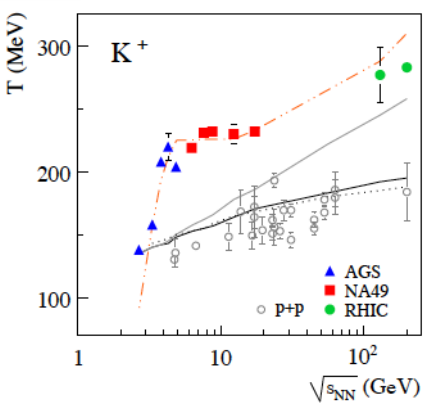
FAIR (CBM):
- SIS-100 (>2020) limited coverage
- SIS-300 better coverage but unclear timeline (>2025)

SPS:
- Wide coverage of phase diagram
- Existing facility
- Competitive high-intensity beams
- Other experimental program (NA61) already ongoing

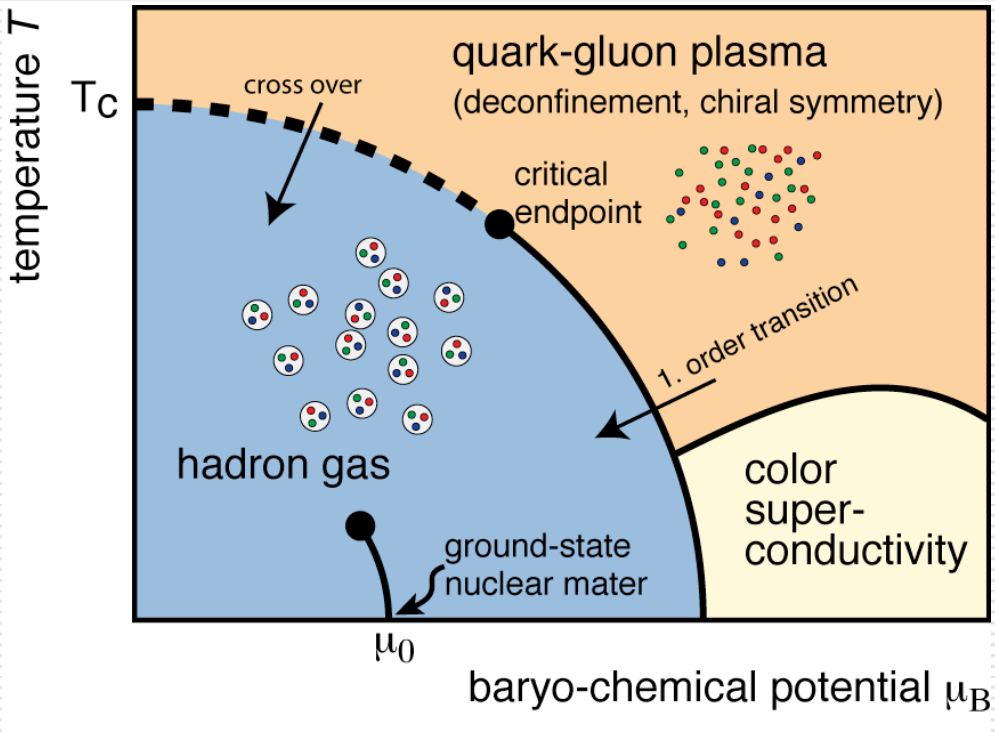
plot and text from G. Usai presentation on last Tuesday

NA49 started to pursue this search at the SPS (strangeness production, event by event fluctuations, etc…)
→ taken over by NA61/SHINE





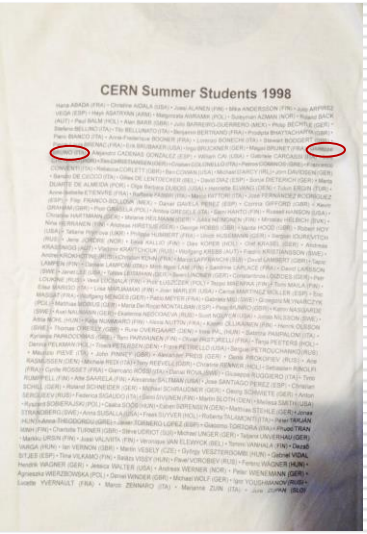
The Phase Diagram of QCD Matter

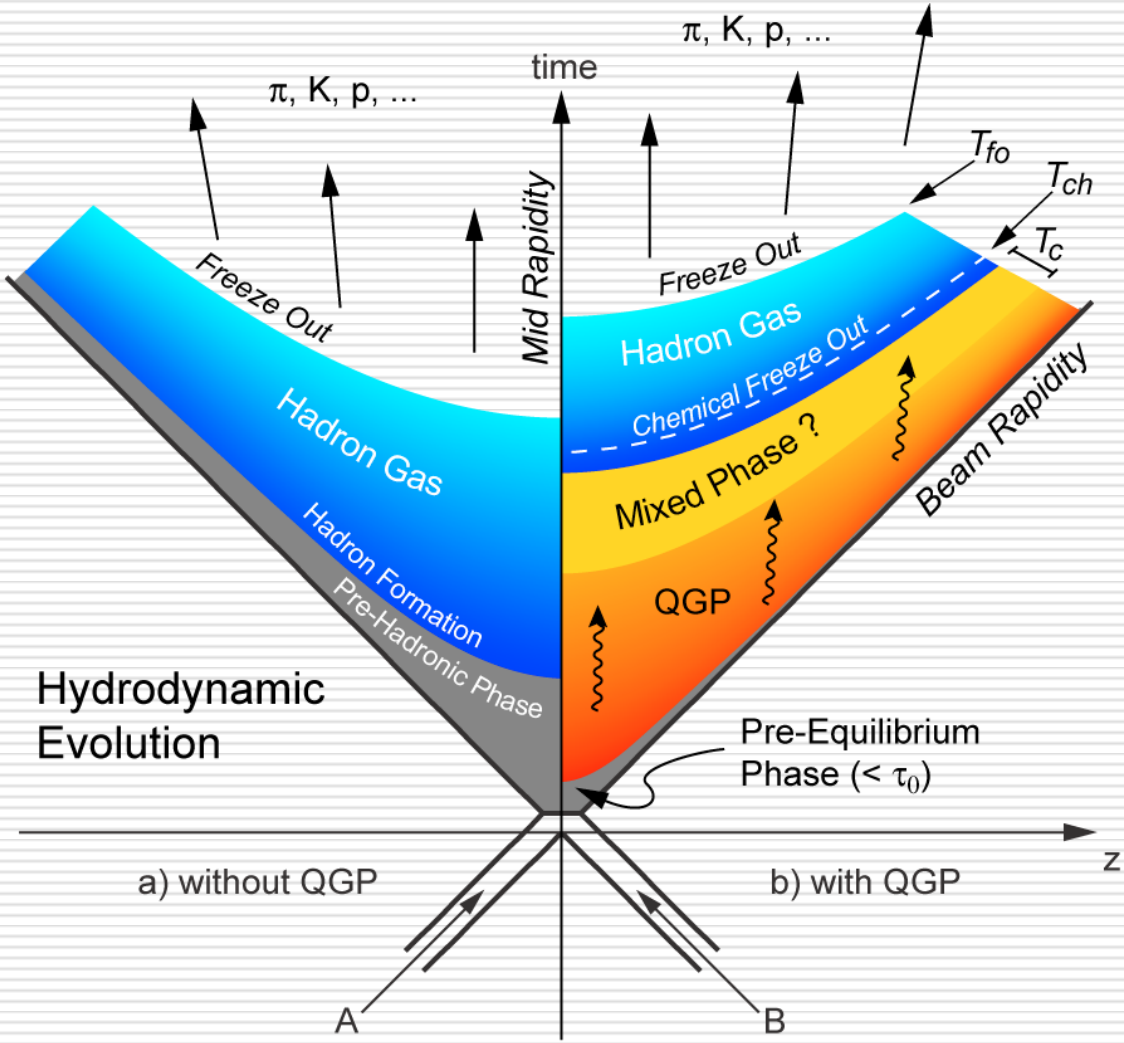


forewords

- I claimed that I was summer student in 1998. Some proofs

not enough ?




π, K, p, ...
time
π, K, p, ...
T_{fo}
T_{ch}
T_c
Freeze Out
Mid Rapidity
Freeze Out
Hadron Gas
Chemical Freeze Out
Hadron Gas
Mixed Phase ?
Beam Rapidity
Hadron Formation
Pre-Hadronic Phase
QGP
Hydrodynamic
Evolution
Pre-Equilibrium
Phase (< τ_0)
z
a) without QGP
b) with QGP
A
B

	Ioni	p_{fascio}/A (GeV/c)	$\sqrt{s_{NN}}$ (GeV)	Collaborazioni
AGS	Si	14.6	5.4	E802(E859), E810, E814, E858
AGS	Au	10.7	4.7	E866, E877, E878
SPS	O, S	200	19.4	NA34,35,36,38; WA80,85,94
SPS	Pb	160, 80, 40	17.3, 12.3, 8.8	NA44,45,49,50,52,57,60; WA97,98

ITS Timeline