Orlando
and the discovery of hyperon enhancements

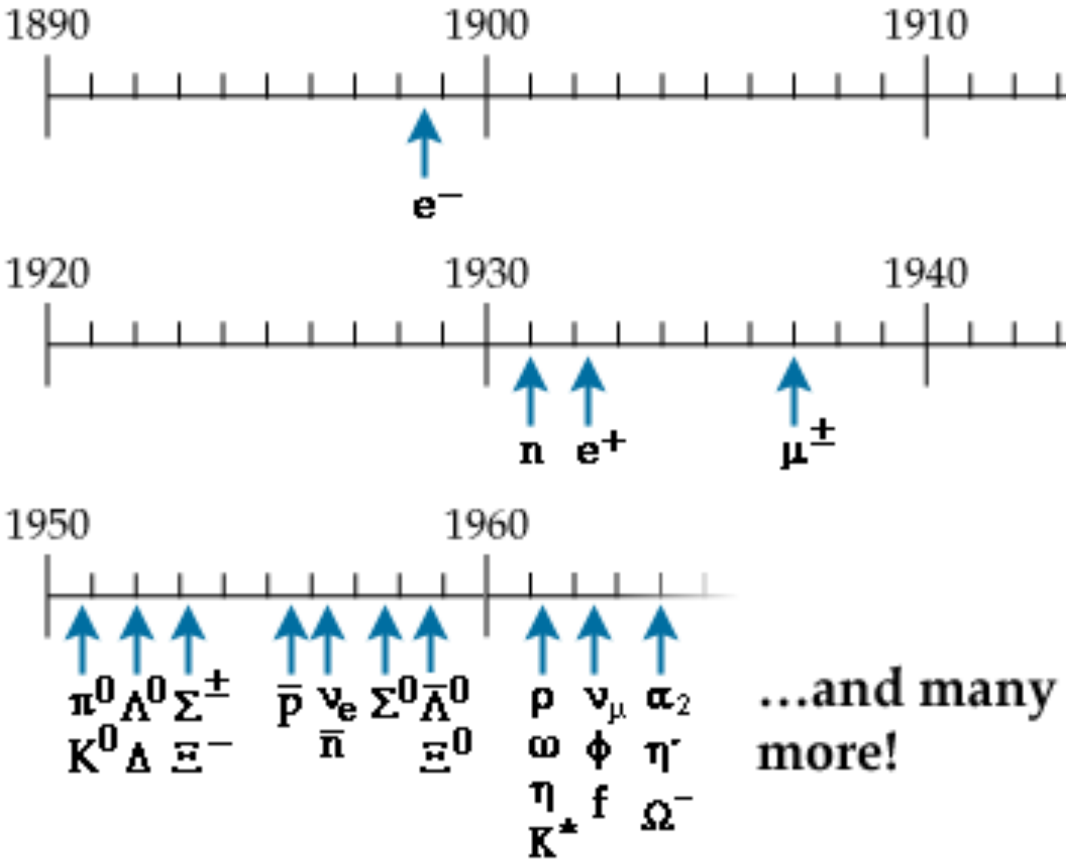
Federico Antinori

and friends:

Domenico Elia, Vito Lenti, Roman Lietava,

Emanuele Quercigh, Karel Šafařík, Tiziano Virgili, ...

Discovery of subnuclear particles...



Statistical Bootstrap and Hagedorn Temperature

- very elegant idea:
  - hadrons are made of hadrons which in turn are made of hadrons which in turn...
  - no fundamental hadron (“nuclear democracy”)
  - very popular in the sixties (pre-quarks)

    (very much “sixties”, in fact: F Capra takes the idea and runs away with it in “The Tao of Physics”)

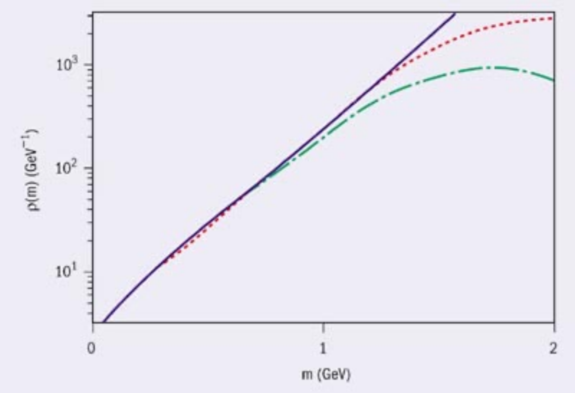
- pioneered by Geoffrey Chew (UC Berkeley)
  - e.g.: G. Chew (1962). *S-Matrix theory of strong interactions*. New York: W A Benjamin

- developed by Rolf Hagedorn (CERN) to a full-fledged theory of strong interactions
  - e.g.: R Hagedorn: Statistical thermodynamics of strong interactions at high energies 1965 Nuovo Cim. Suppl. 3 147

- very successful in calculating hadronic collision cross sections
  - e.g.: H Grote, R Hagedorn and J Ranft, Atlas of particle spectra, CERN-report (1970)
  - calculated based on hadron exchange → <u>needs mass spectrum of all existing hadrons</u>

Spectrum of hadron masses

- spectrum of hadrons from "bootstrap equation": $\rho(m) \propto m^{-3} \exp(\frac{m}{T_H})$
  - exponential growth of number of hadrons at higher and higher masses!
  - controlled by "Hagedorn temperature", T_H ~ 150-160 MeV



green: states known in 1967
red: states known by mid-1990's
blue: expected spectrum for T_H = 158 MeV

- btw, still holds: very similar results from lattice QCD
  - e.g.: A Majumder, B Müller, PRL 105:252002,2010
  - that's why bootstrap theory worked well for hadron interactions!
    (the idea was very deep, even if the picture was not the correct fundamental one!)

Hagedorn temperature: a limiting value?

e.g. following K Redlich, H Satz in "Melting Hadrons, Boiling Quarks", J Rafelski ed (Springer, 2016)

- partition function for a system of non-interacting pions:

$$\ln \mathcal{Z}(T,V) = \frac{VTm_0^2}{2\pi^2} K_2(\frac{m_0}{T})$$

- interactions as resonance formation:
  - interacting system of pions ←→ non-interacting gas of all possible resonances

$$\ln \mathcal{Z}(T,V) = \sum_i \frac{VTm_i^2}{2\pi^2} \rho(m_i) K_2(\frac{m_i}{T}) \approx \frac{VT}{2\pi^2} \int dm\, m^2 \rho(m) K_2(\frac{m}{T})$$

- inserting Hagedorn's spectrum:

$$\ln \mathcal{Z}(T,V) \approx V \left[\frac{T}{2\pi}\right]^{3/2} \int \frac{dm}{m^{3/2}} e^{-\left[\frac{m}{T} - \frac{m}{T_H}\right]}$$ ← diverges for $T \to T_H$

  - energy pumped into such a system, goes to creating heavier and heavier resonances
  - asymptotically reaching T_H

→ T_H would then be the maximum possible temperature!

... Quarks enter the scene...

- the other main idea proposed in the 60’s to explain the multitude of hadrons
- 1961: “eightfold way” (SU(3) flavour symmetry, Murray Gell-Mann)
- 1965: quark hypothesis (Murray Gell-Mann, George Zweig)
- 1968: observation of “partons” in Deep Inelastic Scattering at SLAC
- 1970: GIM mechanism (Sheldon Glashow, John Iliopoulis, Luciano Maiani)
  - to explain absence of flavour-changing neutral currents
  - proposal of fourth quark (charm) → cancellation of flavour-changing terms
- 1974: discovery of charm (J/ψ) at Brookhaven and SLAC (+ Frascati 5 days later)

→ quark hypothesis widely accepted, and in 1975...

1975, Cabibbo and Parisi: “quark liberation” at high T

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

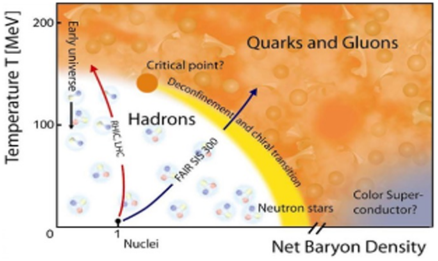
EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

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 confine



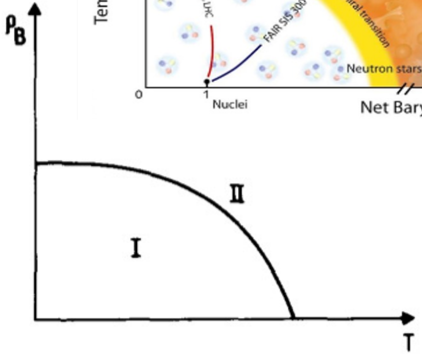


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

- T_H not maximum attainable, simply: for $T > T_H$ quarks not confined any more

1975, Collins and Perry: “quark soup” 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)

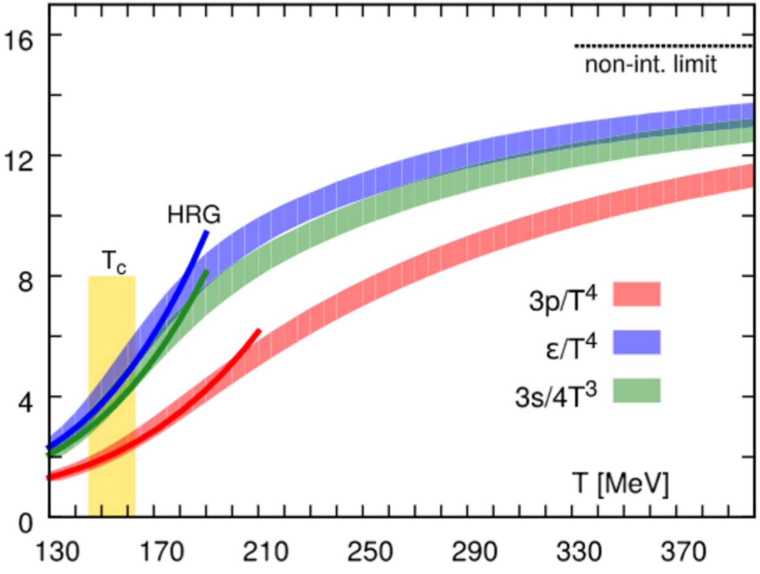
We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic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

the basic argument is contained in only a few lines...

A neutron has a radius[10] of about 0.5–1 fm, and so has a density of about 8×10^{14} g cm^{-3}, whereas the central density of a neutron star[1,2] can be as much as 10^{16}–10^{17} g cm^{-3}. In this case, one must expect the hadrons to overlap, and their individuality to be confused. Therefore, we suggest that matter at such high densities is a quark soup.

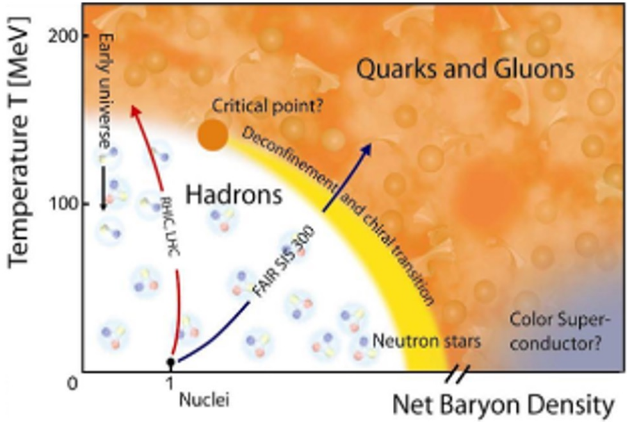
Lattice QCD

- the rigorous way of performing calculations in the non-perturbative regime of QCD
- discretisation on a space-time lattice
  - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided



A Bazavov et al. PRD 90 094503 (2014)

- around critical temperature (T_C): rapid change of
  - energy density ε
  - entropy density s
  - pressure p
- due to activation of partonic degrees of freedom
- at zero baryon density → smooth crossover
- T_C = (156.5 ± 1.5) MeV [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
- $\varepsilon \sim O(\mathrm{GeV/fm^3})$



1980's: the hunt is on ...

- how to access this physics experimentally? high-energy nuclear collisions!
  - since the 70's nuclear physicists were already colliding heavy ions
    - Coulomb barrier, shock waves...
    - UNILAC (GSI), Super-Hilac and Bevalac (Berkeley), Synchrophasotron (Dubna)
  - it was realised that nuclear collisions could provide the conditions for QGP formation
  - but to reach T_c higher-energy accelerators were needed → ultrarelativistic AA collisions
- starting from the mid-80's: high-energy beams of nuclei on fixed target
  - at the Alternating Gradient Synchrotron (AGS)
    - at Brookhaven National Laboratory (New York)
    - $\sqrt{s_{NN}}$ ~ 5 GeV
    - O (1986), Si (1987), Au (1993)
  - at the Super-Proton Synchrotron (SPS)
    - at CERN (Geneva)
    - $\sqrt{s_{NN}}$ ~ 17 GeV
    - O (1987), S (1987), Pb (1994)

Two historic predictions...

- QGP phase, if existed, would obviously be very short-lived, how to observe it?
  - is there a memory of the passage through the QGP phase?
  - are there “signatures” of the QGP that we can look for in the final state?

two major proposals made in the 80’s:

- strangeness enhancement (Johann Rafelski and Berndt Müller)
  - enhanced production of strange quarks in the QGP

  → enhancement of strange particles in the final state

- J/ψ suppression (Tetsuo Matsui and Helmut Satz)
  - colour field screened at short distances in QGP

  → suppression of production of tightly-bound quarkonium states

Strangeness enhancement

Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller
Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany
(Received 11 January 1982)

Rates are calculated for the processes $gg \to s\bar{s}$ and $u\bar{u}, d\bar{d} \to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \geqslant 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-24} sec.

PACS numbers: 12.35.Ht, 21.65.+f

Given the present knowledge about the interactions between constituents (quarks and gluons), it appears almost unavoidable that, at sufficiently high energy density caused by compression and/or excitation, the individual hadrons dissolve in a new phase consisting of almost-free quarks and gluons.[1] This quark-gluon plasma is a highly excited state of hadronic matter that occupies a volume large as compared with all characteristic length scales. Within this volume individual color charges exist and propagate in the same manner as they do inside elementary particles as described, e.g., within the Massachusetts Institute of Technology (MIT) bag model.[2]

It is generally agreed that the best way to create a quark-gluon plasma in the laboratory is with collisions of heavy nuclei at sufficiently high energy. We investigate the abundance of strangeness as function of the lifetime and excitation of the plasma state. This investigation was motivated by the observation that significant changes in relative and absolute abundance of strange particles, such as $\bar{\Lambda}$,[3] could serve as a probe for quark-gluon plasma formation. Another interesting signature may be the possible creation of exotic multistrange hadrons.[4] After identifying the strangeness-producing mechanisms we compute the relevant rates as functions of the energy density ("temperature") of the plasma state and compare them with those for light u and d quarks.

In lowest order in perturbative QCD $s\bar{s}$-quark pairs can be created by annihilation of light quark-antiquark pairs [Fig. 1(a)] and in collisions of two gluons [Fig. 1(b)]. The averaged total cross sections for these processes were calculated by

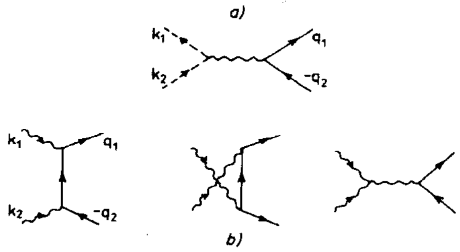
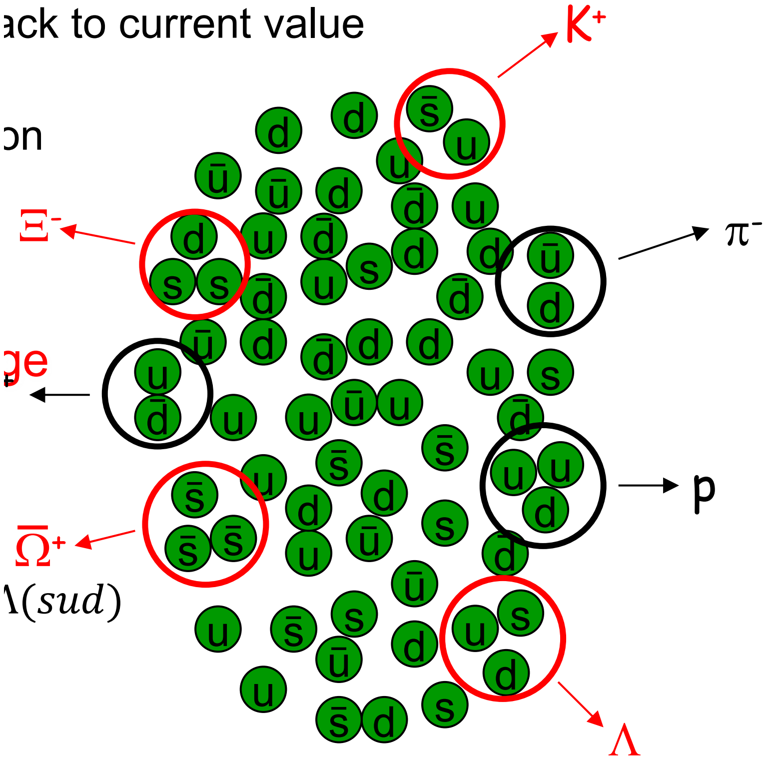


FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q} \to s\bar{s}$, (b) $gg \to s\bar{s}$.

on of s
ack to current value
on
ge
Λ(sud)



Strangeness enhancement

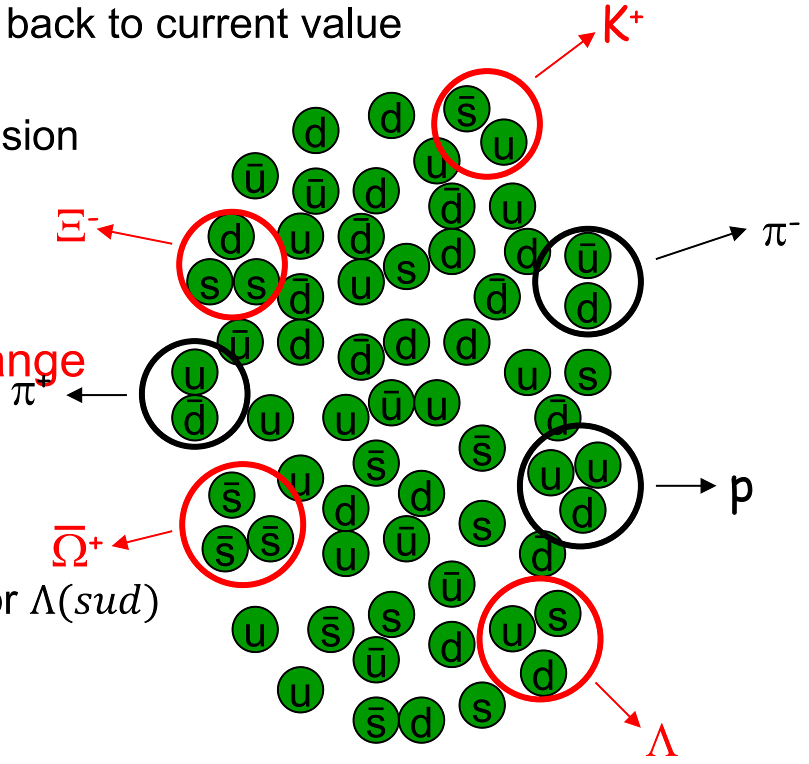
- restoration of χ symmetry -> increased production of s
  - mass of strange quark in QGP expected to go back to current value
    - m_S ~ 150 MeV ~ Tc
  - → copious production of $s\bar{s}$ pairs, mostly by gg fusion

    [J Rafelski: Phys. Rep. 88 (1982) 331]

    [J Rafelski and B Müller: Phys. Rev. Lett. 48 (1982) 1066]

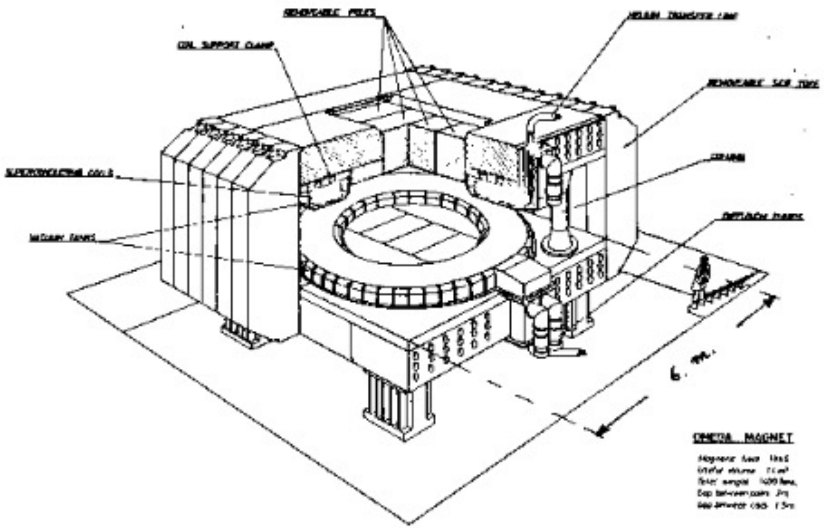
- deconfinement → stronger effect for multi-strange
  - can be built recombining s quarks
  - → strangeness enhancement increasing with strangeness content
  - → expect larger for $\Omega(sss)$ than for $\Xi(ssd)$ than for $\Lambda(sud)$

    [P Koch, B Müller and J Rafelski: Phys. Rep. 142 (1986) 167]

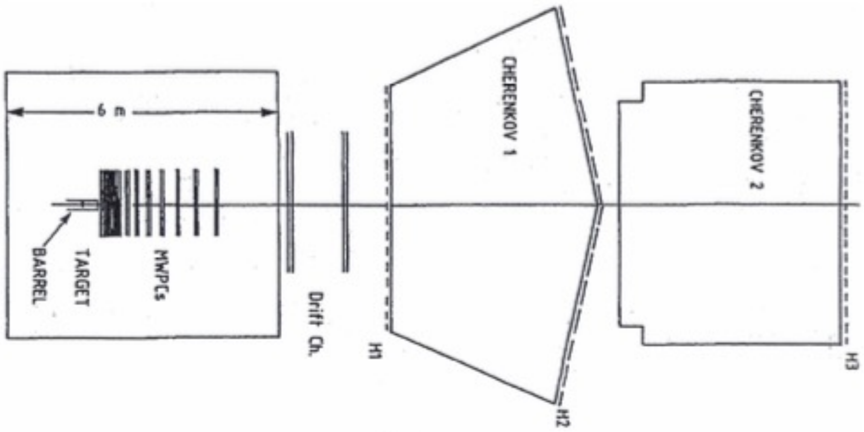


A good place to do this!

- OMEGA: a state-of-the art spectrometer...
  - superconducting magnet (1.8T)
    - built in the early 70’s, for a hadron spectroscopy programme
  - fixed-target, first at the PS, then at the SPS
  - tracking based on spark chambers at first, then MWPCs



(a)



(b)

- ... with state-of-the-art experts!

Volume 78B, number 2,3 PHYSICS LETTERS 25 September 1978

A STUDY OF THE LIFETIME AND SPIN OF Ω^- PRODUCED IN K^-p INTERACTIONS AT 8.25 GeV/*c*

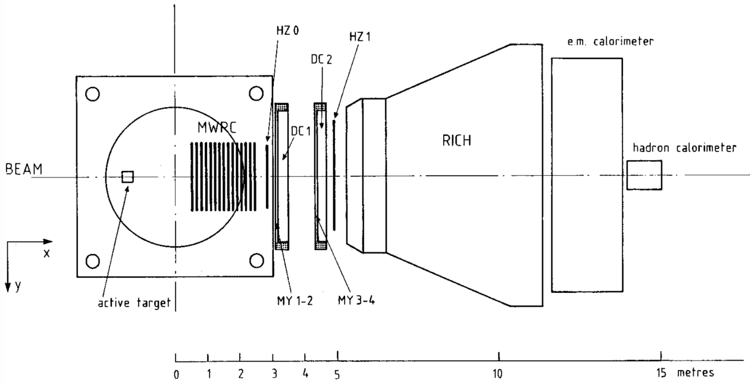
Birmingham[a]–CERN[b]–Glasgow[c]–Michigan State[d,1]–Paris LPNHE[e,2] Collaboration

M. BAUBILLIER[e], I.J. BLOODWORTH[a], G.J. BOSSEN[b], A. BURNS[c], J.N. CARNEY[a], M.J. CORDEN[a], C.A. COWAN[a], G.F. COX[a], C.J. De LIMA[a], D. DIXON[c], Ph. GAVILLET[b], J.B. KINSON[a], K. KNUDSON[b], F. LEVY[e], H. McCANN[c], M. MacDERMOTT[a], P.J. NEGUS[c], B.H. OH[d], M. PRATAP[d], E. QUERCIGH[b], M. RIVOAL[e], J.M. SCARR[c], J.C. SHIERS[a], G.A. SMITH[d], D. TEODORO[b], O. VILLALOBOS BAILLIE[a], M.F. VOTRUBA[a], J. WHITMORE[d] and R. ZITOUN[e]

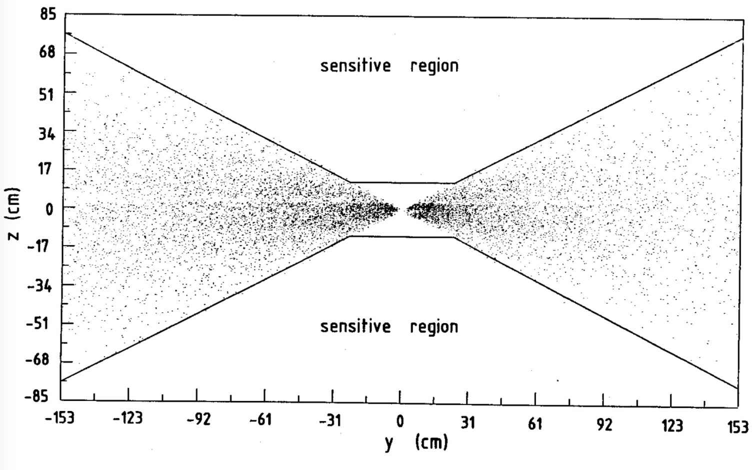
Received 20 June 1978

Using the decay mode $\Omega^- \to \Lambda K^-$, we have obtained a measurement of the Ω^- lifetime $\tau_\Omega = (0.80 \pm {}^{0.16}_{0.12}) \times 10^{-10}$ s. The Ω^- decay angular distribution is consistent with $W(\cos\theta^*) \propto 1 + 3\cos^2\theta^*$. The probability of consistency with a flat distribution is ~1/300 indicating $J \neq \frac{1}{2}$.

Butterflies!

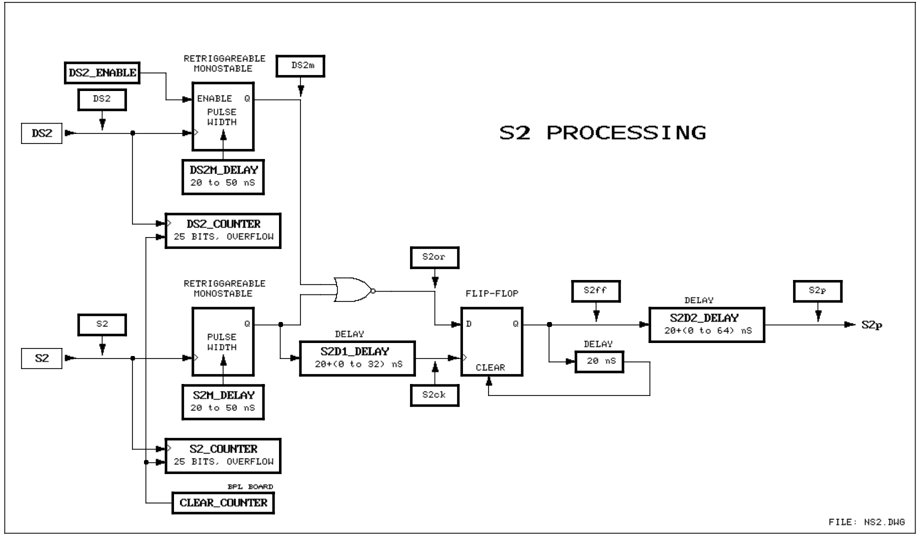


- the OMEGA MWPCs were being used for pp, hA
  - → typically a dozen or so particles/event
- but 100's particles expected in S+W collisions!
- solution: high-p_T selection
  - transverse dipole B field: bulk of tracks (low-p_T) in a butterfly-shaped region
  - only high-pT tracks in complementary region

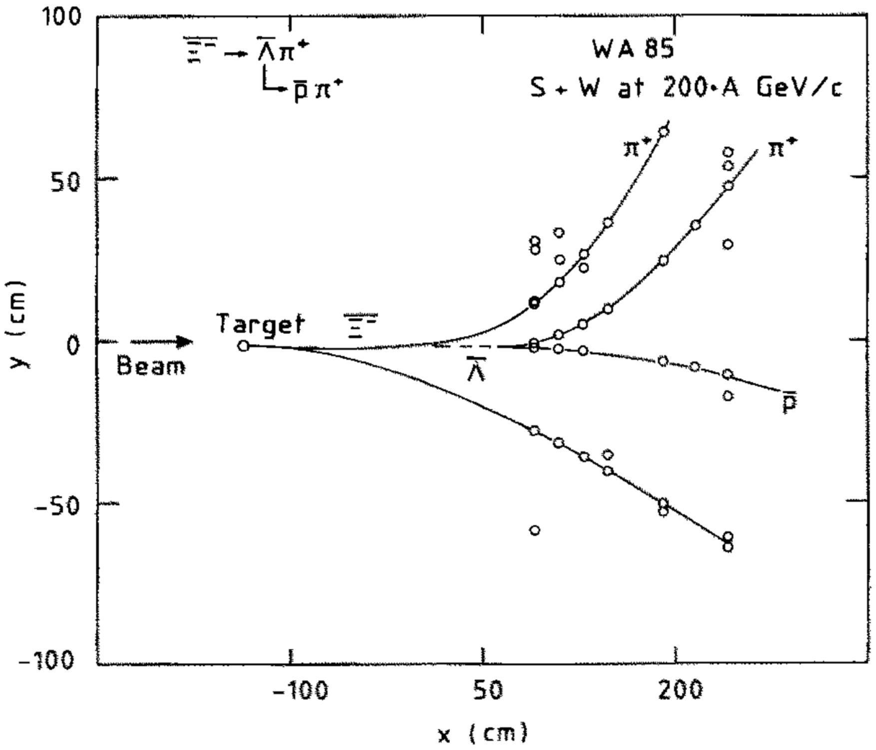


- technique first developed for WA77 trigger (on 2 MWPC)
- here extended to all MWPCs!
- cathode planes were divided into 3 insulated sections
- 20% voltage reduction to make intermediate part insensitive
- → MWPC made sensitive only to p_T > 600 MeV/c
- a brilliant (and daring!) idea, that payed off handsomely!

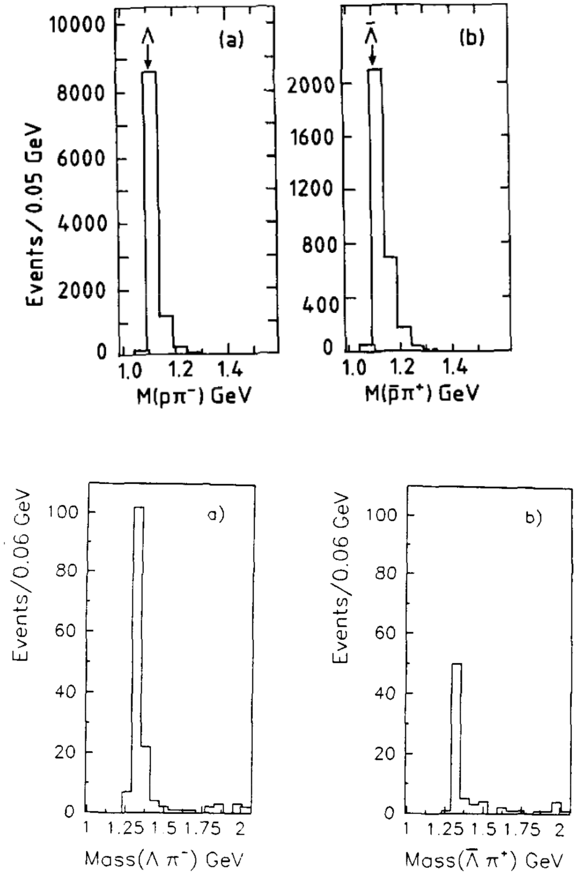
... and of course: the trigger!



Success!



$\bar{\Xi}^- \rightarrow \bar{\Lambda}\pi^+$
$\llcorner \bar{p}\pi^+$
WA 85
S + W at 200·A GeV/c
π^+
π^+
Target
$\bar{\Xi}^-$
Beam
$\bar{\Lambda}$
$\bar{p}$
100
50
0
-50
-100
y (cm)
-100
50
200
x (cm)



Events / 0.05 GeV
10000
8000
6000
4000
2000
0
Λ
(a)
1.0
1.2
1.4
$M(p\pi^-)$ GeV
$\bar{\Lambda}$
(b)
2000
1600
1200
800
400
0
1.0
1.2
1.4
$M(\bar{p}\pi^+)$ GeV
Events/0.06 GeV
100
80
60
40
20
0
a)
1
1.25
1.5
1.75
2
Mass($\Lambda\,\pi^-$) GeV
b)
Mass($\bar{\Lambda}\,\pi^+$) GeV

Birmingham show at Quark Matter 1990 (Menton)!

Multi-Strange Baryon and Antibaryon Production in Sulphur-Tungsten and Proton-Tungsten Interactions at 200 GeV/c per Nucleon

The WA85 Collaboration.

S. Abatzis[1], R.P. Barnes[3], M. Benayoun[5], W. Beusch[4], I.J. Bloodworth[3], A. Bravar[6], J.N. Carney[3], J.P. Dufey[4], D. Evans[3], R. Falcone[2], R. Fini[2], B.R. French[4], B. Ghidini[2], A. Jacholkowski[4], J. Kahane[5], J.B. Kinson[3], A. Kirk[4], K. Knudson[4], J.C. Lassalle[4], V. Lenti[2], Ph. Leruste[5], L. Lima Frances[5], R.A. Loconsole[2], A. Malamant[5], V. Manzari[2], F. Navach[2], J.L. Narjoux[5], A. Palano[2], A. Penzo[6], E. Quercigh[4], L. Rossi[4*], M. Sené[5], R. Sené[5], M. Stassinaki[1], M. Tamazouzt[5], M.T. Trainor[4†], G. Vassiliadis[1], O. Villalobos Baillie[3], A. Volte[5] and M.F. Votruba[3].

Presented by: D. Evans

geometrical acceptance and reconstruction efficiency corrections have not been performed. These should have a similar effect on Ξ and $\bar{\Xi}$ within a given beam sample. The preliminary (uncorrected) ratios are

$$\bar{\Xi}/\Xi = 0.43 \pm 0.07(^{32}\mathrm{SW}),$$

$$\bar{\Xi}/\Xi = 0.27 \pm 0.06(pW),$$

where the errors are statistical only. Fully corrected yields should be determined soon (allowing the $\bar{\Xi}/\bar{\Lambda}$ and Ξ/Λ ratios to be calculated) and a significant increase in statistics is expected in 1990.

STRANGENESS IN RELATIVISTIC HEAVY ION COLLISIONS AN EXPERIMENTAL SURVEY

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School of Physics and Space Research, The University of Birmingham, Edgbaston, Birmingham, United Kingdom. B15 2TT

In the short time since experiments on relativistic heavy ion collisions have begun, a large quantity of data on production of strange particles has accumulated, covering a number of different particle species. In this paper the principal results from Brookhaven and CERN are summarized.

Ξ^- enhancements!

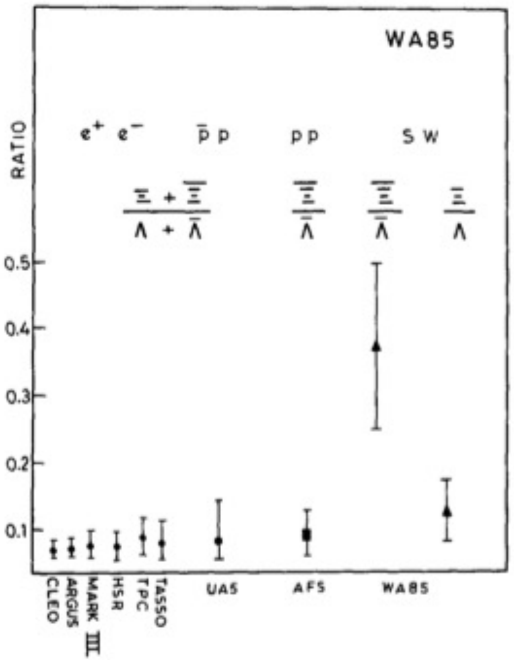


Fig. 3. Ξ^-/Λ and $\overline{\Xi}^-/\bar{\Lambda}$ ratios for different experiments.

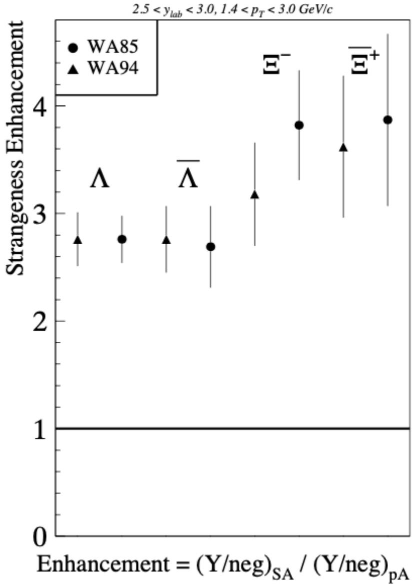


Figure 6. Strange and multi-strange hyperon enhancements in SS and SW interactions.

S Abatzis et al: PLB 270 (1991) 123

D Evans et al: JPhysG 25 (1999) 209 (SQM `98, Padova)

... then the Ω^-!

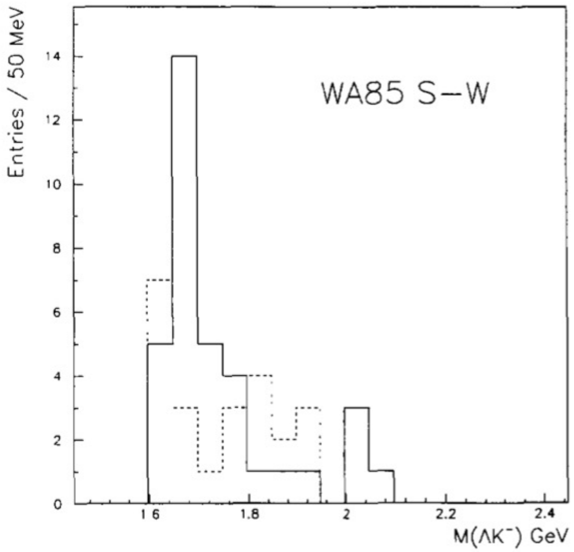


Fig. 3. $\Lambda K^- + \bar{\Lambda} K^+$ final spectrum. Solid line : data, dashed line : combinatorial background.

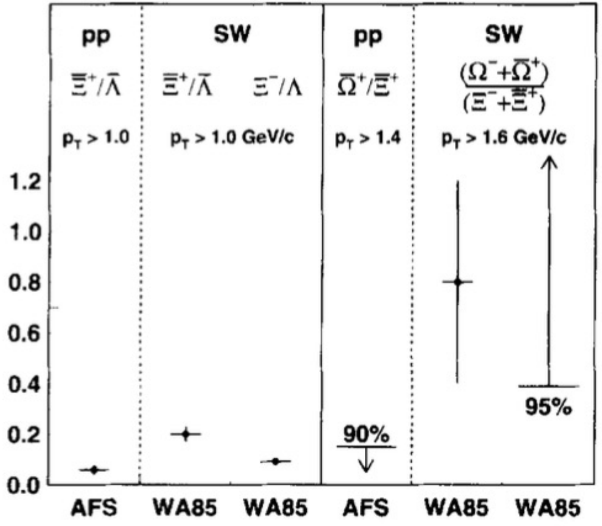


Fig. 3. Comparison of Ξ/Λ and Ω/Λ ratios in proton–proton and central S–W collisions.

S Abatzis et al: PLB 316 (1993) 615

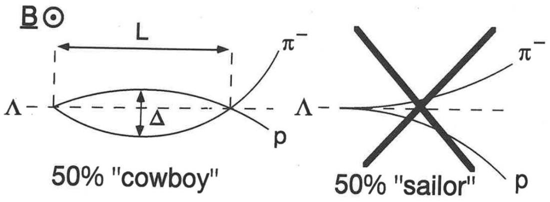
S Abatzis et al: PLB 347 (1995) 615

Si Pixels!

- next step: Pb beams in SPS! (1994)
- ~ 1 order of magnitude in multiplicity!
  - can't rely on MWPCs anymore...
- idea:
  - hyperon decays can be measured with small telescope
  - if high-precision can be reached over short length!
  - → don't need large Si area!

• Decays can be contained in a small x-section detector

e.g.: $\Lambda \rightarrow p\,\pi^-$ in a magnetic field



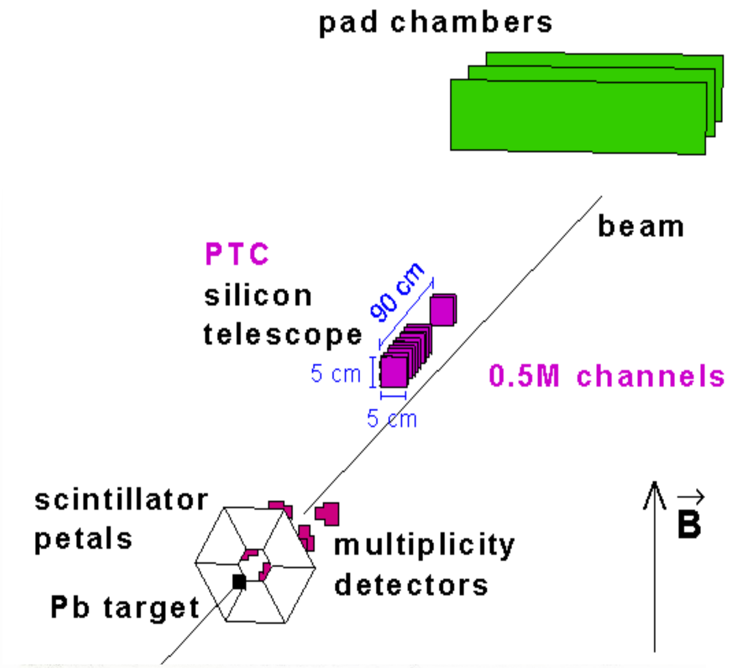
L Lorentz invariant, $\leq L_{MAX} \propto \frac{p^*}{|B|}$

B = 1.8 Tesla $\rightarrow$ $L_{MAX} \sim 40$ cm

$\Delta \sim 5/\gamma$ cm

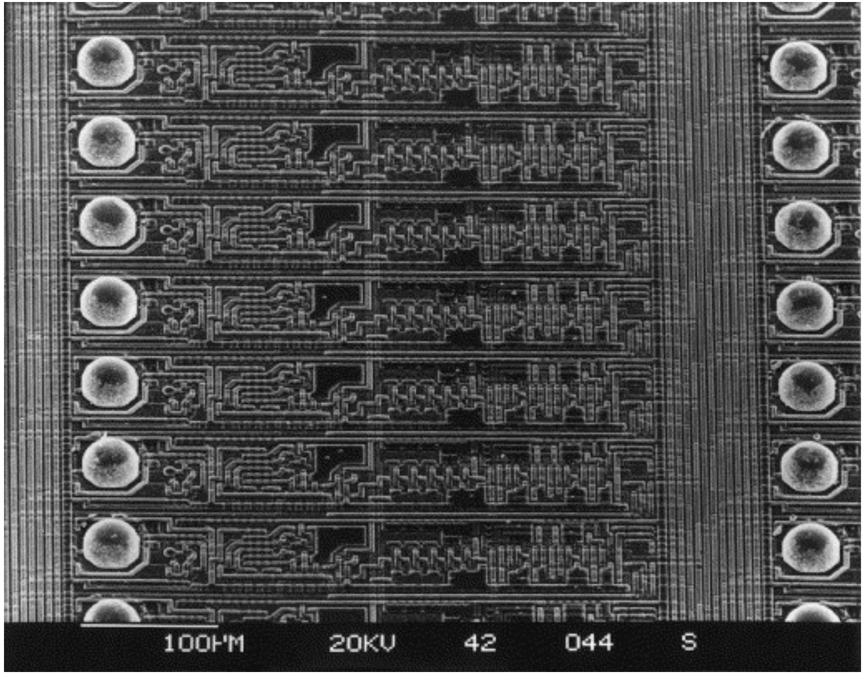
1994 Pb RUN

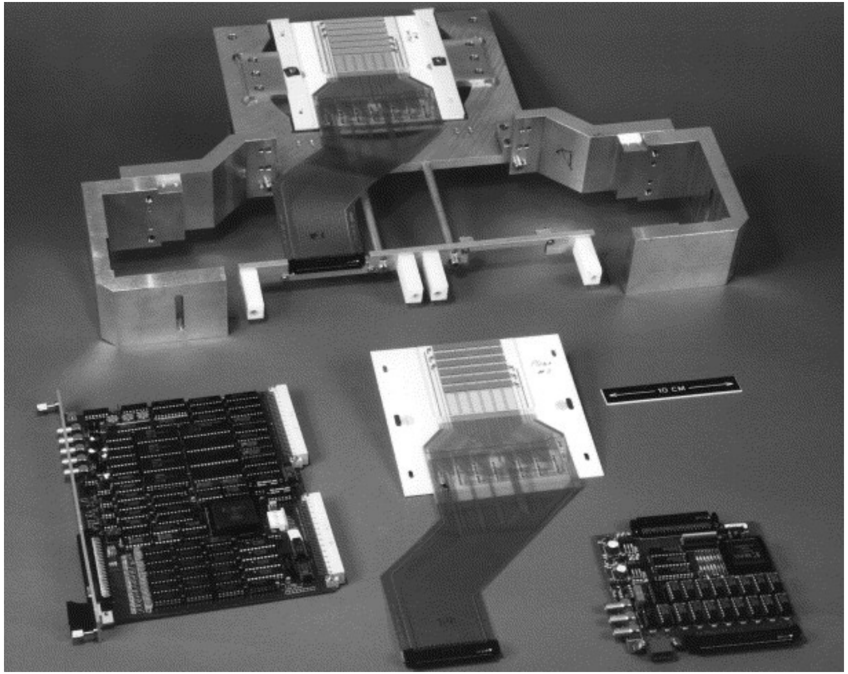
WA97 set-up in the Omega magnet



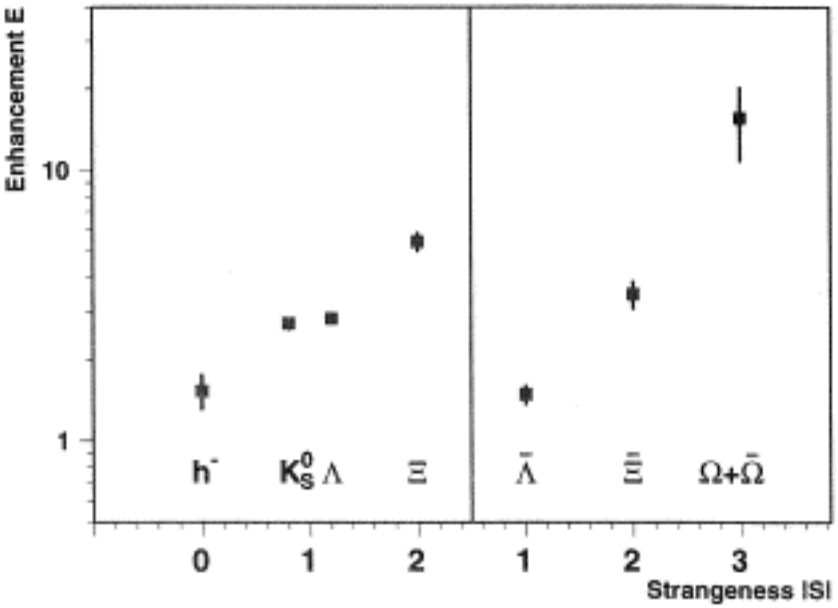
WA97: the first Si pixel detectors!

- Omega2 (WA97-RD19 collaboration)
  - hybrid (bump-bonded) pixel sensors



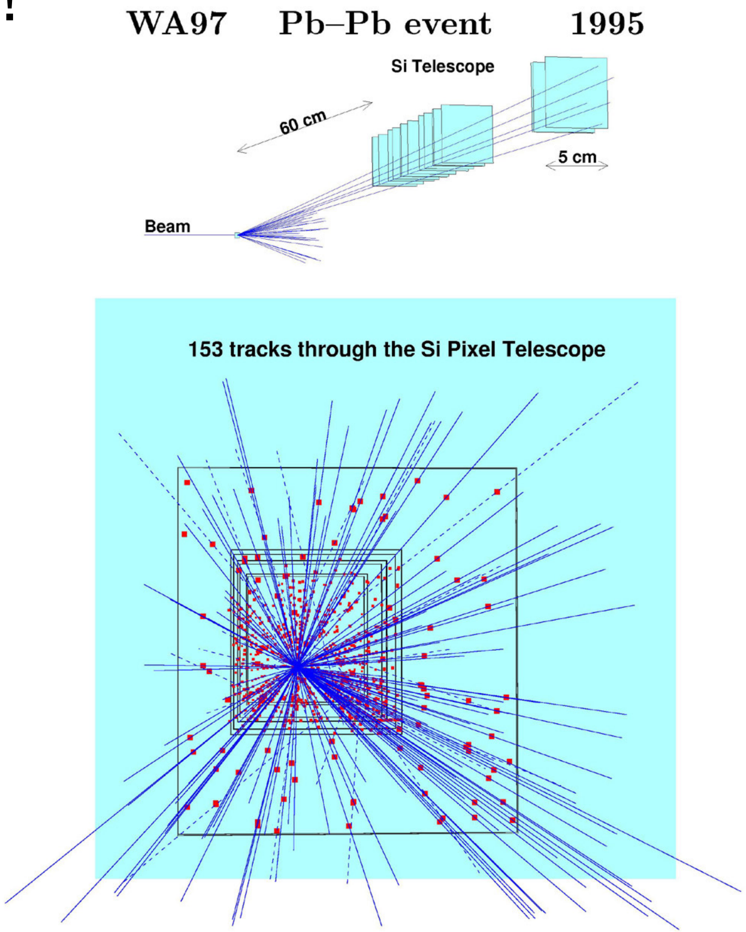


Hyerarchical enhancement pattern!



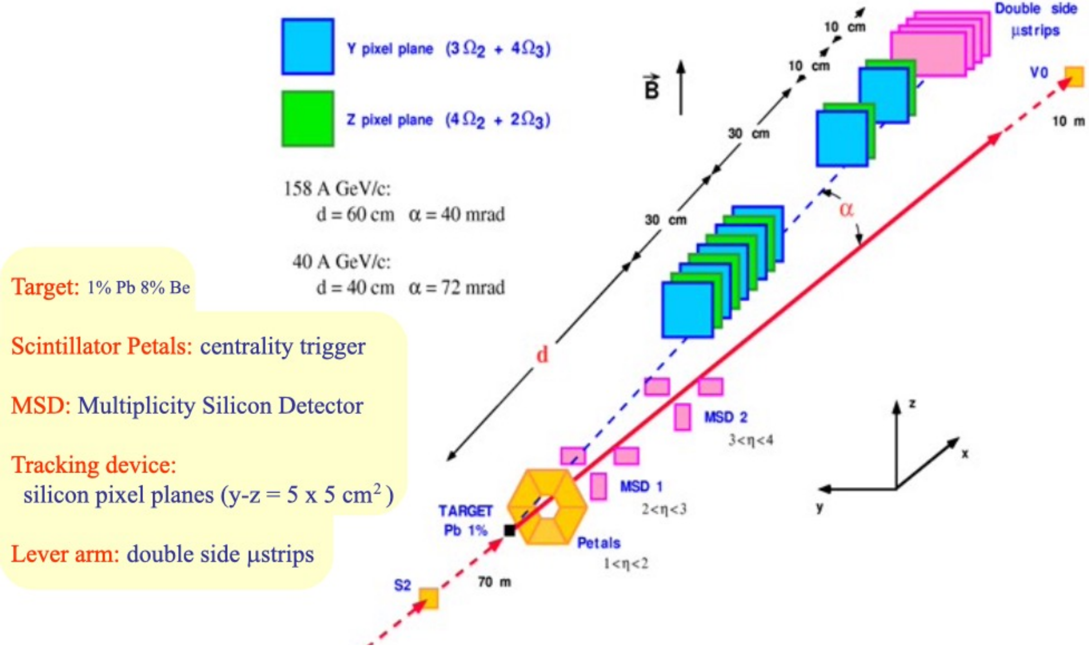
E Andersen et al: PLB 449 (1999) 615

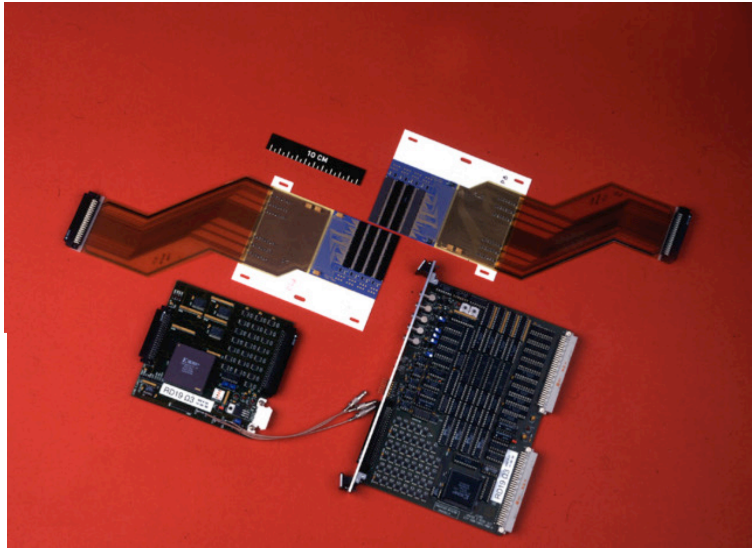
→ WA97 clinched the issue!



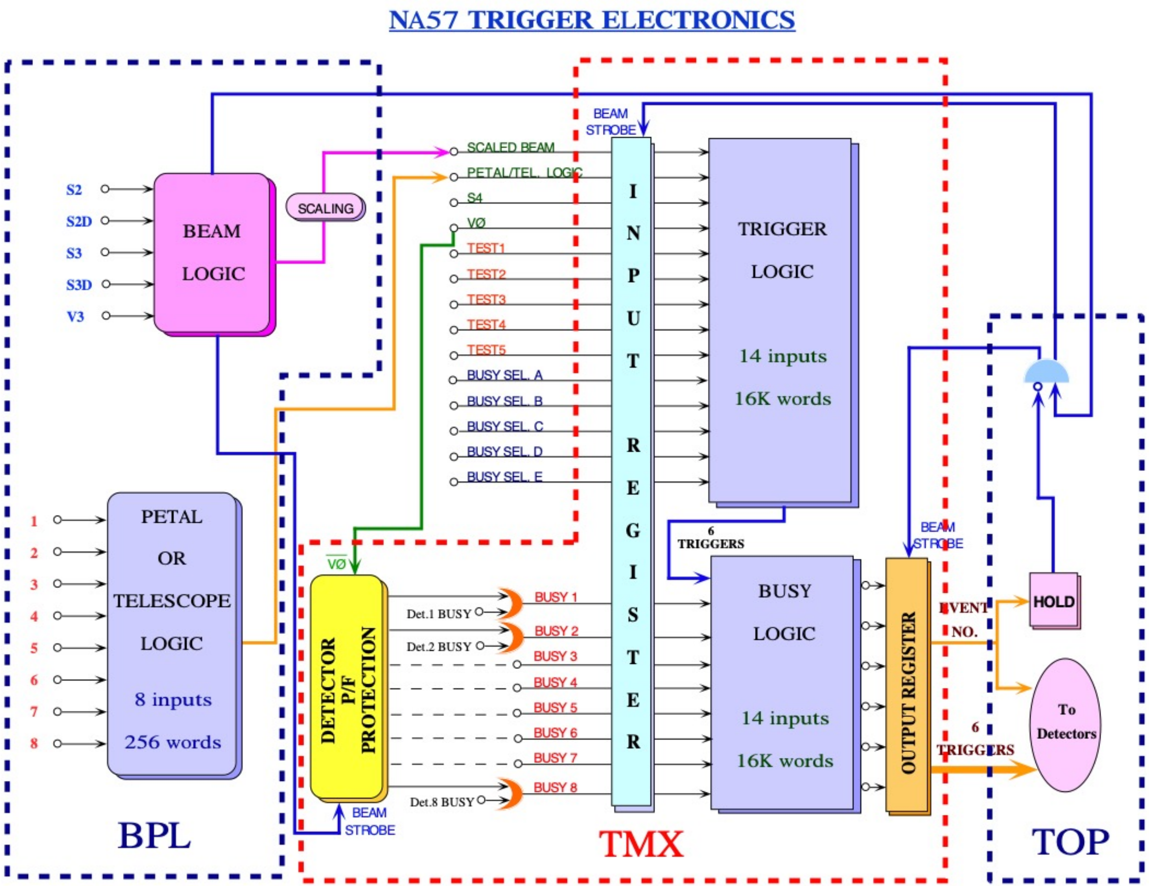
NA57

- focus: centrality and energy dependences
- pixel-only telescope
  - new generation (Omega3)
  - move to North Area, Goliath magnet



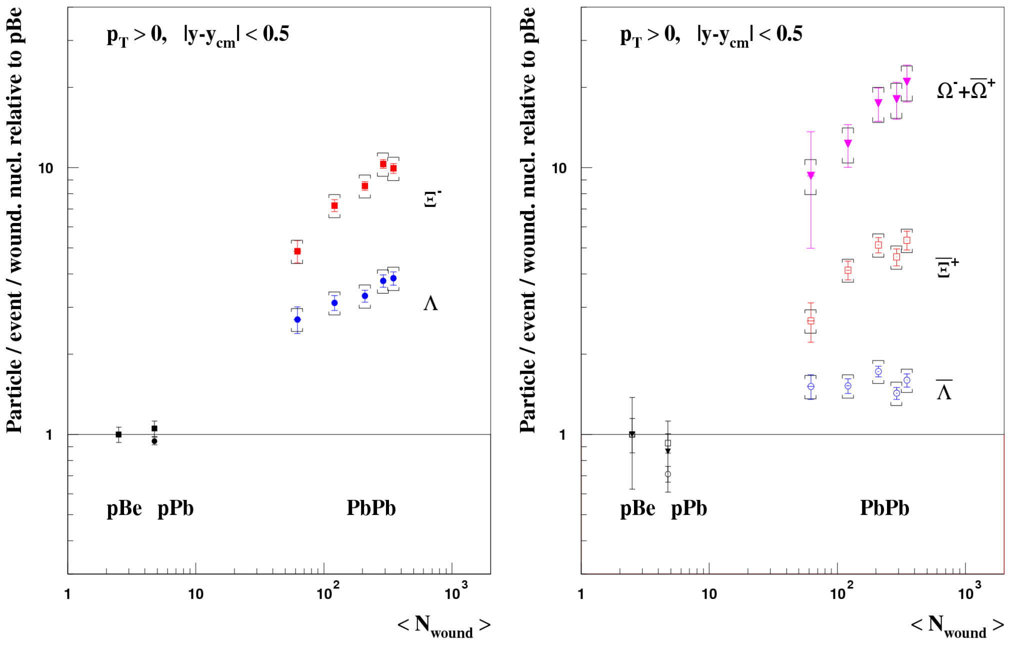


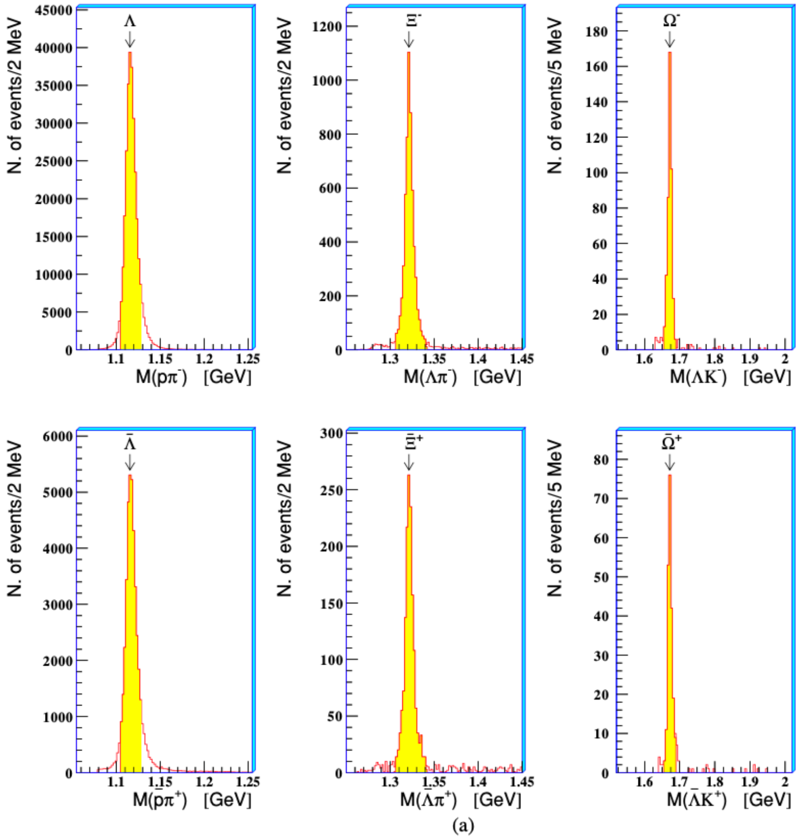
New VME-based trigger (prototype of ALICE CTP!)



NA57

- hyperon enhancements in full glory!





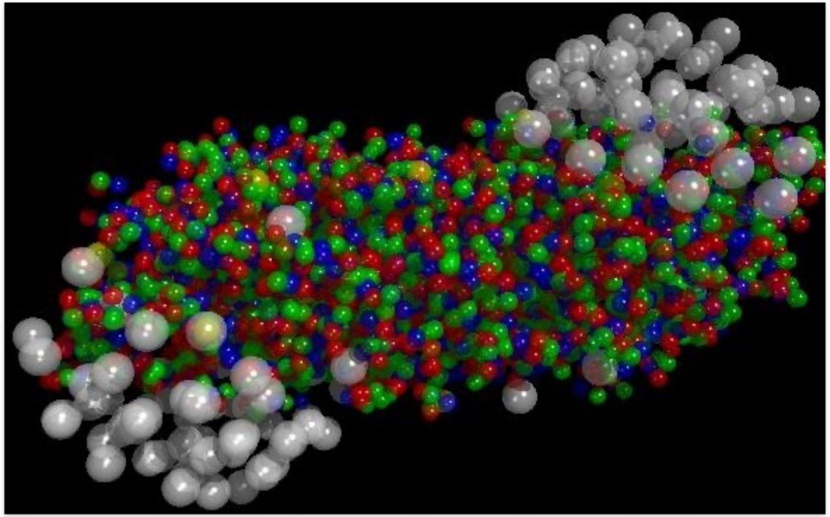
F Antinori et al: JPhysG 32 (2006) 427

One of two pillars of year 2000 announcement!

- strangeness enhancement, J/ψ suppression

New State of Matter created at CERN

10 FEBRUARY, 2000



Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'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.

C

SPECIAL SEMINAR

TITLE	:	A New State of Matter: Results from the CERN Lead-Beam Programme
TIME	:	Thursday 10 February at 09.30 hrs
PLACE	:	Council Chamber, bldg 503

ABSTRACT

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/ψ 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, CERN)
Summary.

Maître à penser...

Annu. Rev. Nucl. Part. Sci. 2000. 50:299–342

STRANGENESS PRODUCTION IN HEAVY-ION COLLISIONS

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Key Words quark-gluon plasma, hyperons, Pb-Pb, Au-Au, AGS, SPS, RHIC, LHC

■ **Abstract** Strangeness production is a very useful diagnostic tool in finding the quark-gluon plasma. We review its uses in understanding relativistic heavy-ion collisions. A brief introduction to the main theoretical tools used in interpreting strangeness production is given, and the experimental methods used to extract the signals are discussed in detail. The experimental results from the Brookhaven AGS and CERN SPS programs are presented. We discuss the interpretation of these results, emphasizing their role in the discovery of deconfined quark matter at CERN. Future experiments at RHIC and at the CERN LHC are described.

No paper could be submitted...

- ... unless properly “Orlandizzato”...

The ALICE CTP, of course...

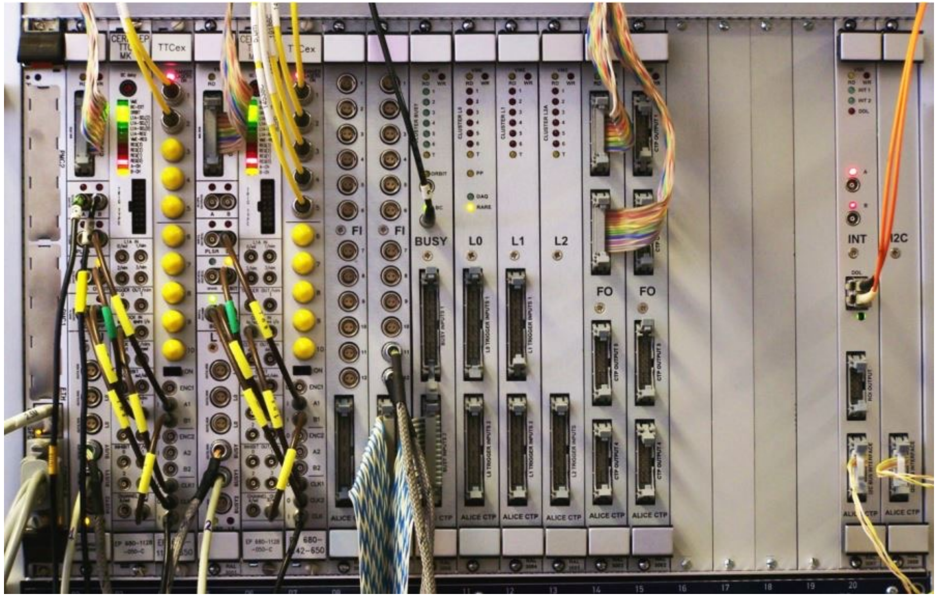
ALICE trigger system: Present and Future

Orlando Villalobos Baillie (University of Birmingham) for the ALICE Collaboration 19th Mar 2019

ALICE Trigger Run 2 data

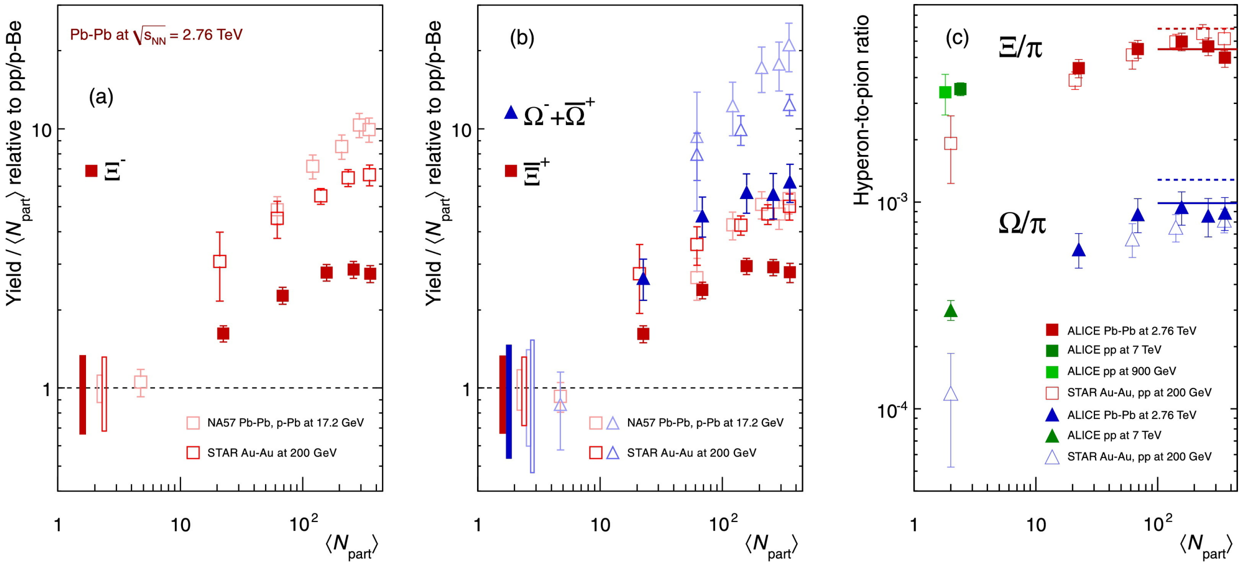
The purpose of any trigger system is to select an event sample strongly enriched in physics processes of interest, while rejecting those not of interest, and to do so in such a way as to make efficient use of the available detectors.

The prime objective of the ALICE experiment is a comprehensive study of ultrarelativistic heavy ion interactions at LHC energies. The strong-interaction cross-section for such interactions is very large (σ = 8 barns), but, compared with what is achieved in pp



→ see talk by Roman!

Hyperon enhancements at the LHC!



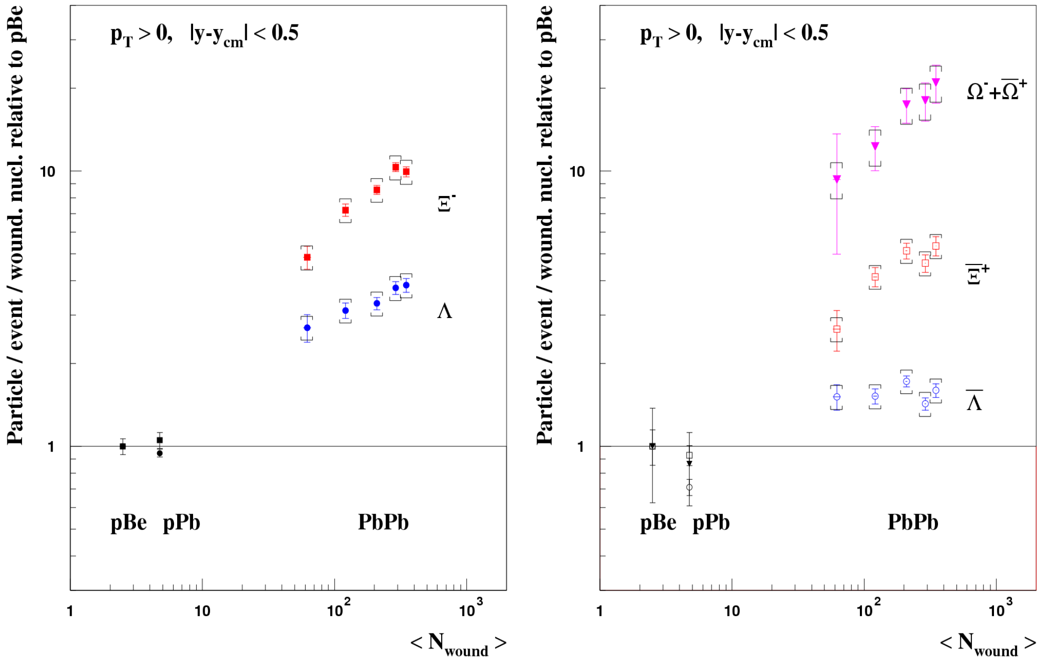
ALICE Collaboration: PLB 728 (2014) 216

SQM 2013


Delegate Handbook
Strangeness in Quark Matter
Conference 2013
BIRMINGHAM
SQM
2013
22nd – 27th July
University of Birmingham
Birmingham
United Kingdom
http://www.ep.ph.bham.ac.uk/SQM2013

SQM 2013

Thank you Orlando!



- for your sharp mind...
- for your physics depth and vision...
- for your technical competence...
- for your wide culture...
- for your sense of humour...

Cheers!

... and all the best for your next adventures!