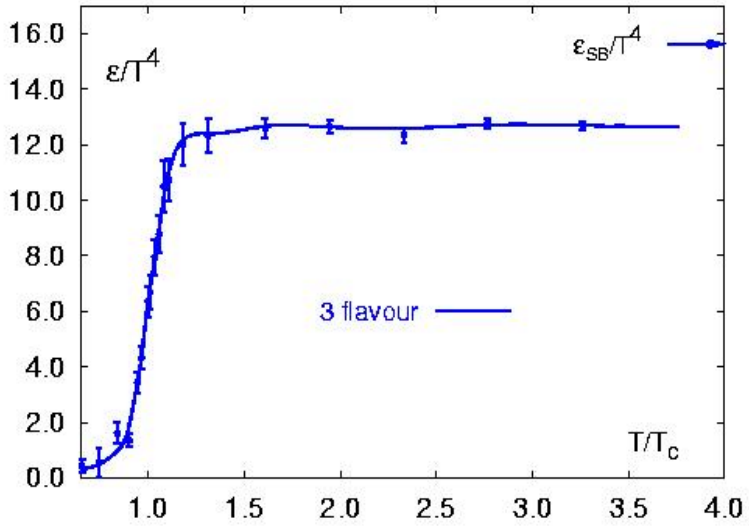
Searching for Quark Matter at the SPS

Goal : Study the QCD phase transition
hadrons ⇔ deconfined partonic matter

- 15 years of experimental data
- A few exciting results
- Some open questions
- Future prospects

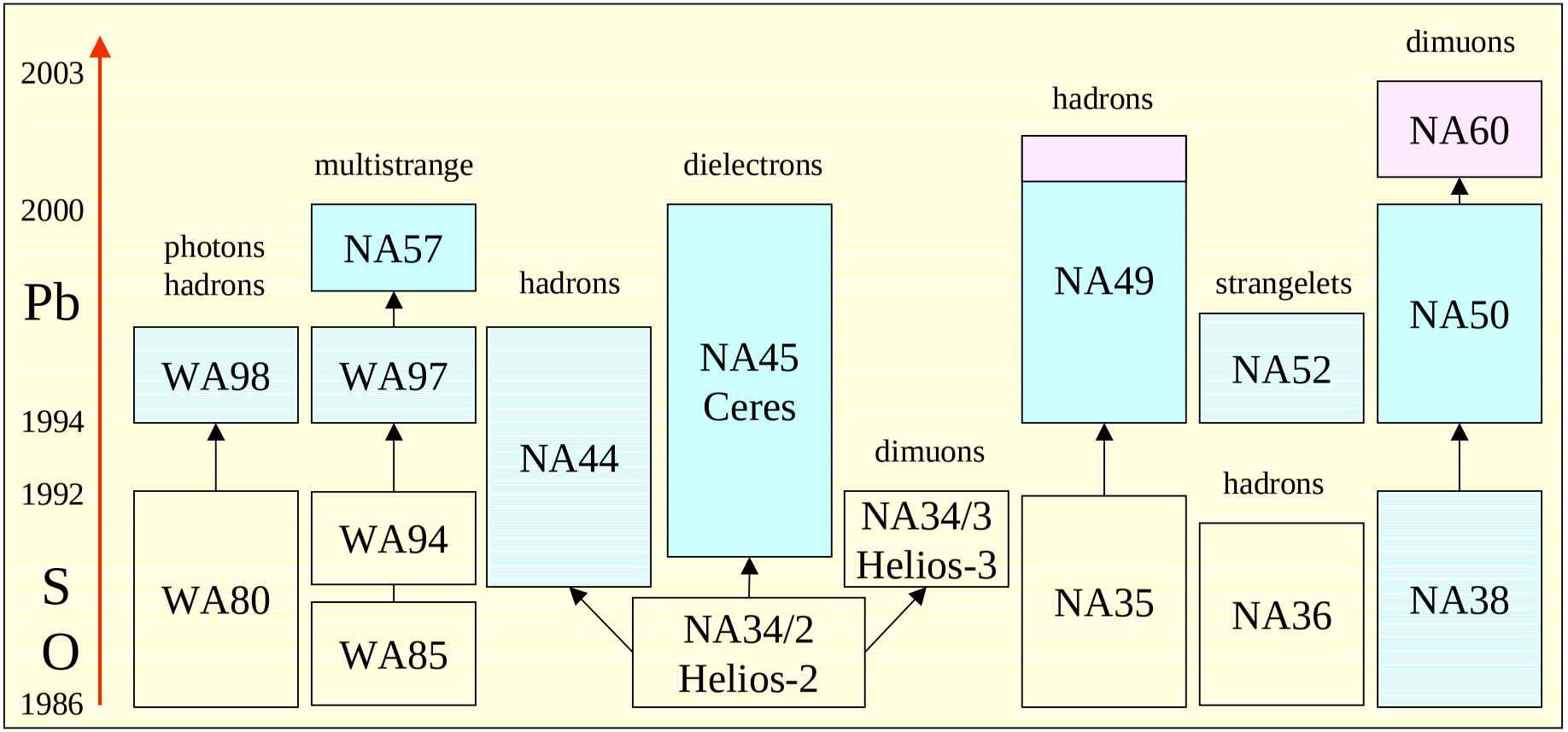


Carlos Lourenço, CERN
QM 2001, January 2001

The SPS heavy ion physics program

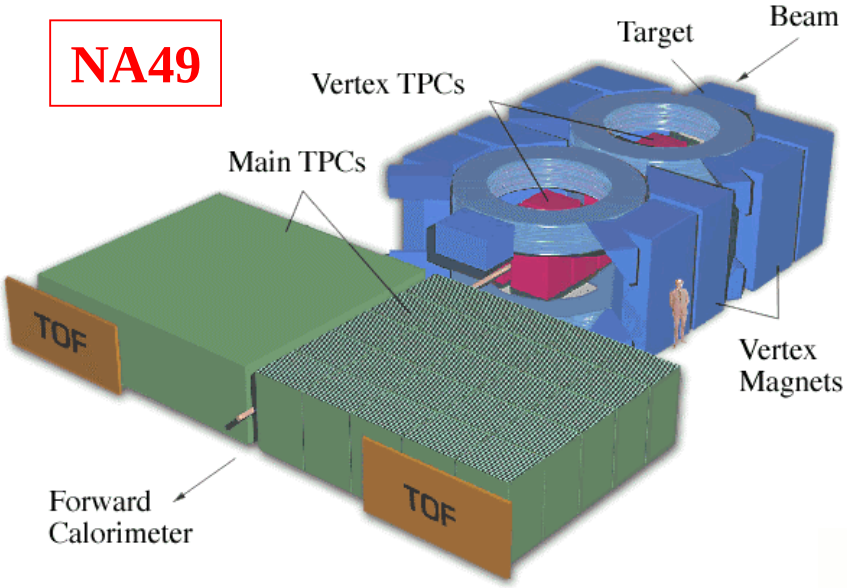
- 1986 - 1987 : Oxygen @ 60 & 200 GeV/nucleon
- 1987 - 1992 : Sulphur @ 200 GeV/nucleon
- 1994 - 2000 : Lead @ 40, 80 & 158 GeV/nucleon
- 2002 - 2003 : Indium and Lead @ 158 GeV/nucleon

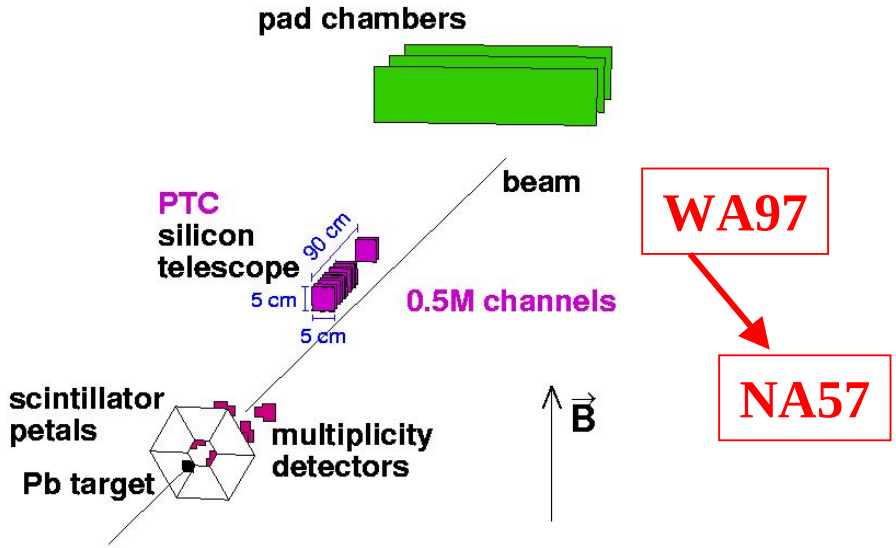
And proton beams
for reference studies
of p-A collisions



SPS heavy ion experiments (1)

NA49

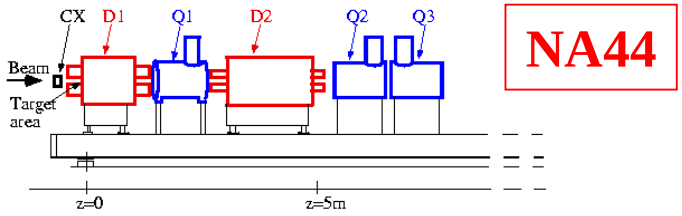


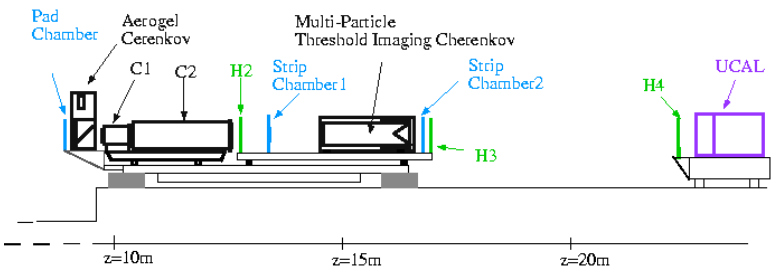


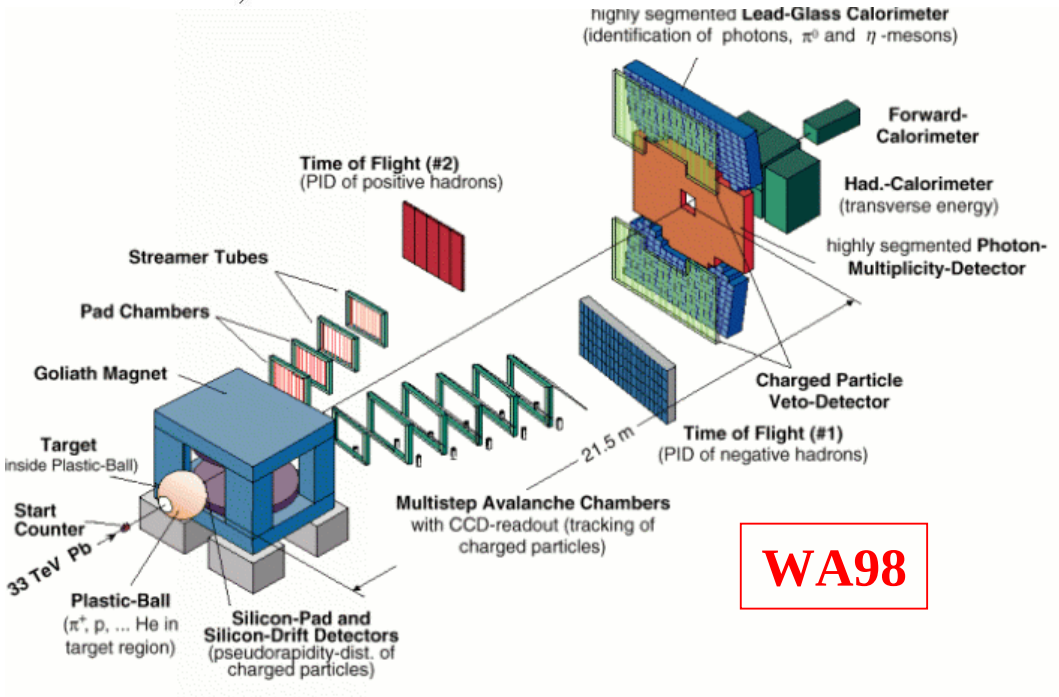
WA97

NA57

NA44

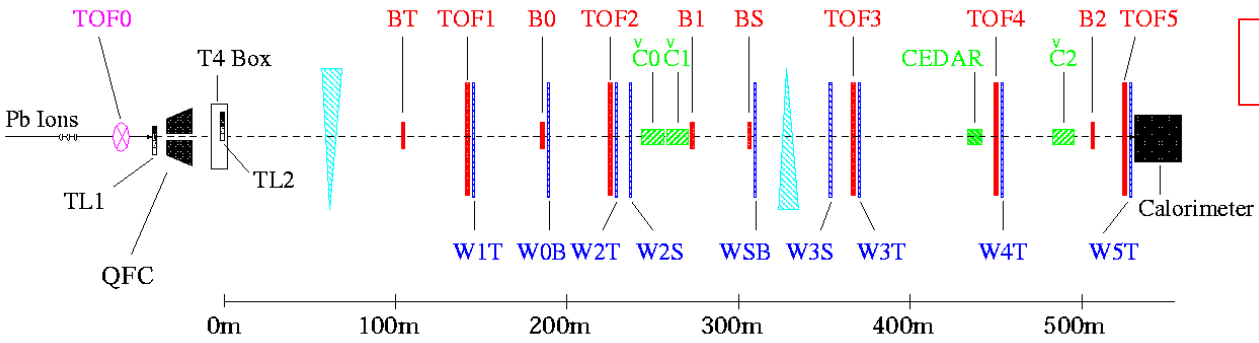




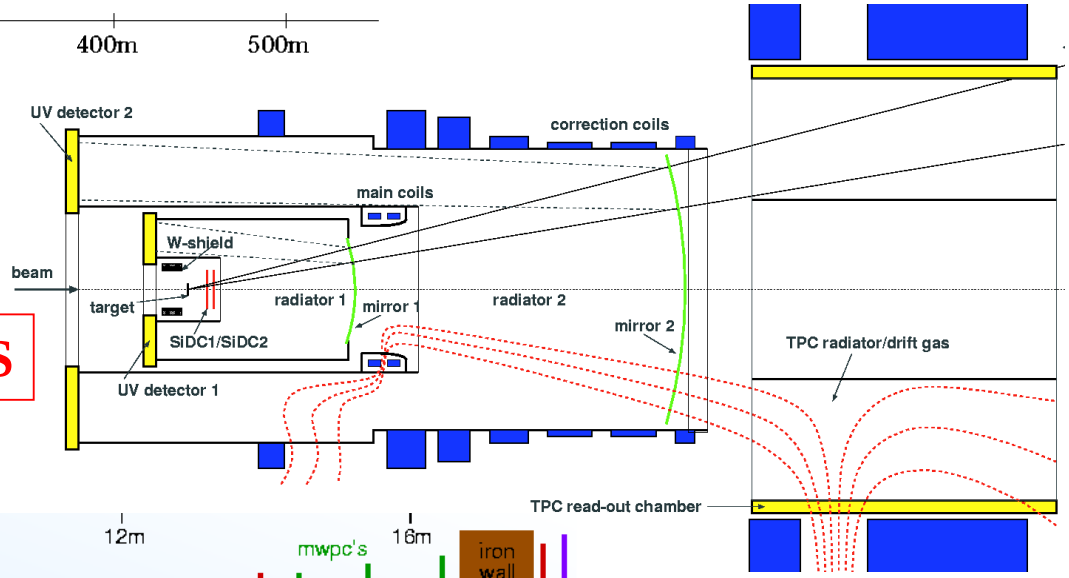


WA98

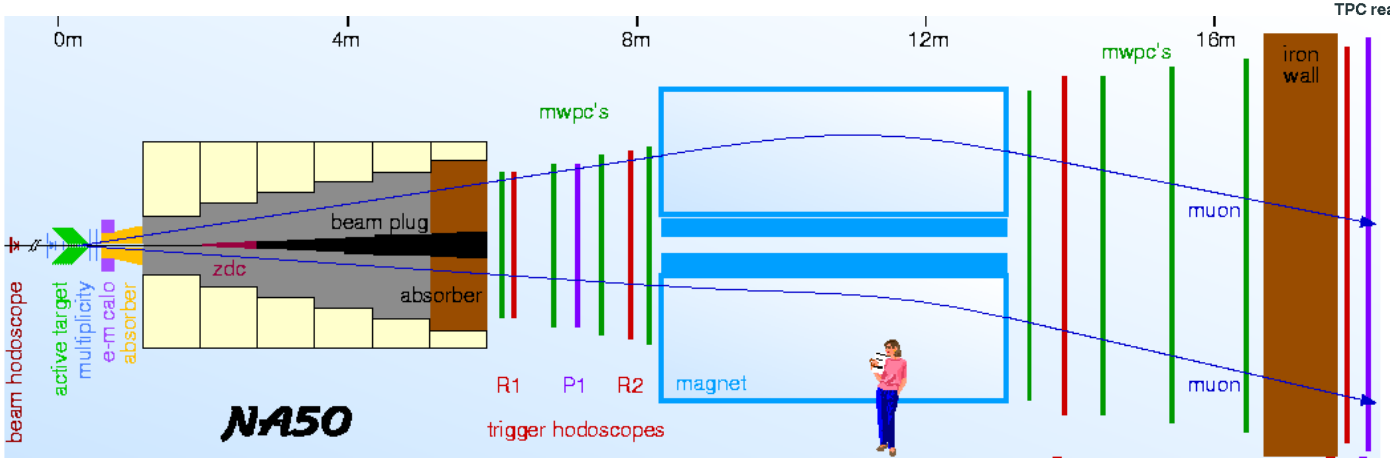
SPS heavy ion experiments (2)



NA52



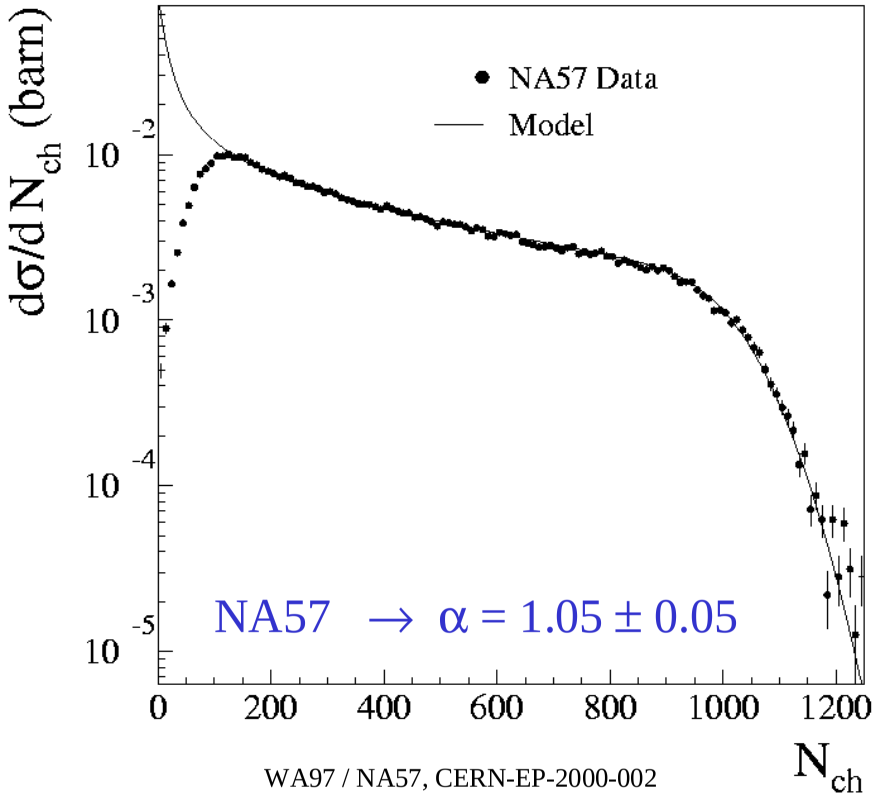
NA45 / CERES



NA38 / NA50

Collision geometry

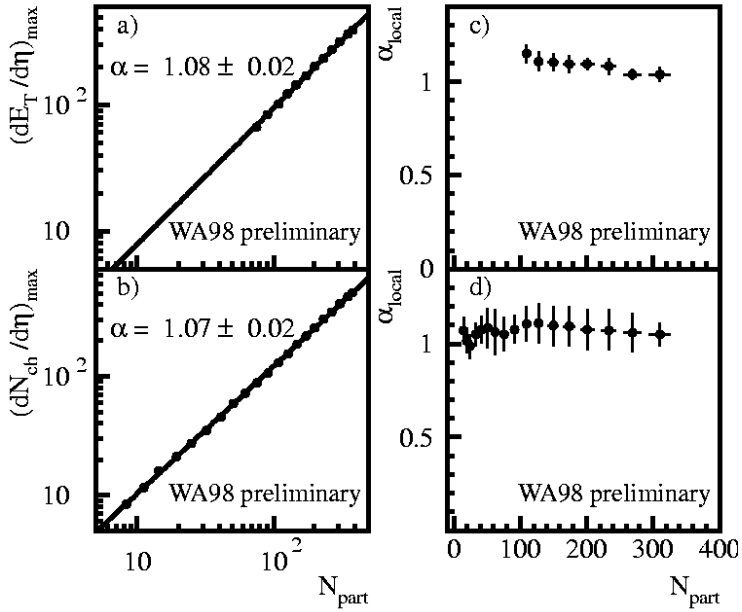
- The measured N_{ch}, E_T, and E_{ZDC} distributions can be used to estimate N_{part} , the number of nucleons participating in the collision, using the Glauber model
  $\Rightarrow$ The physics signals can be studied as a function of the collision centrality
- N_{ch} and E_T are proportional to N_{part}^{α}



WA97 / NA57, CERN-EP-2000-002

WA98 → α = 1.07 ± 0.02

"local" α decreases with N_{part}

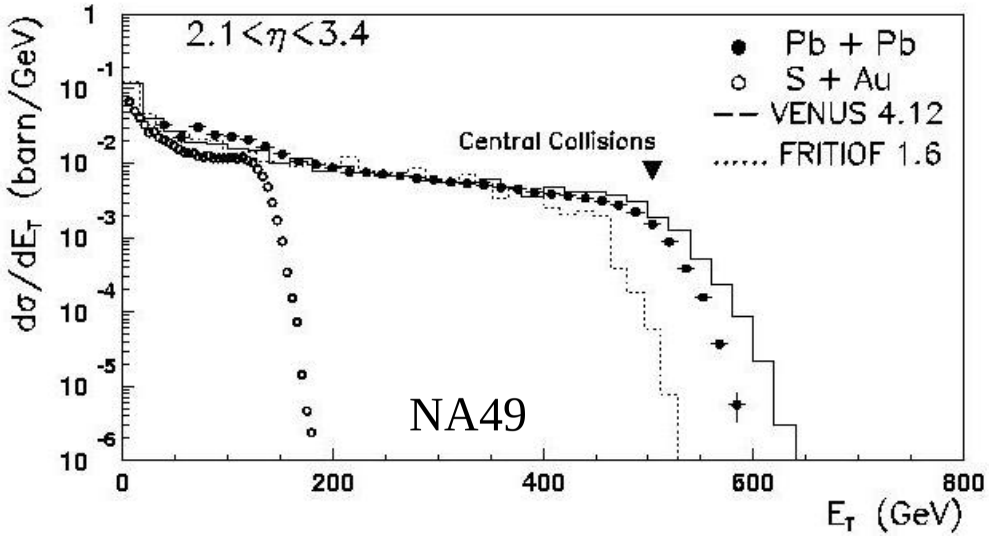


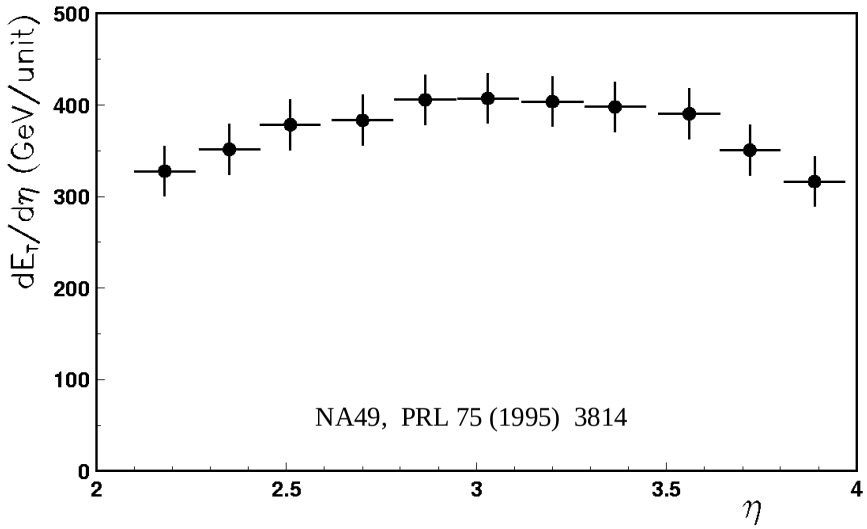
WA98, NPA 661 (1999) 191c

Energy density estimate

From transverse energy to energy density using Bjorken's estimate

$$\varepsilon_{Bj}(\tau_0) = \frac{1}{\pi R^2 \tau_0} \frac{dE_T}{d\eta}$$





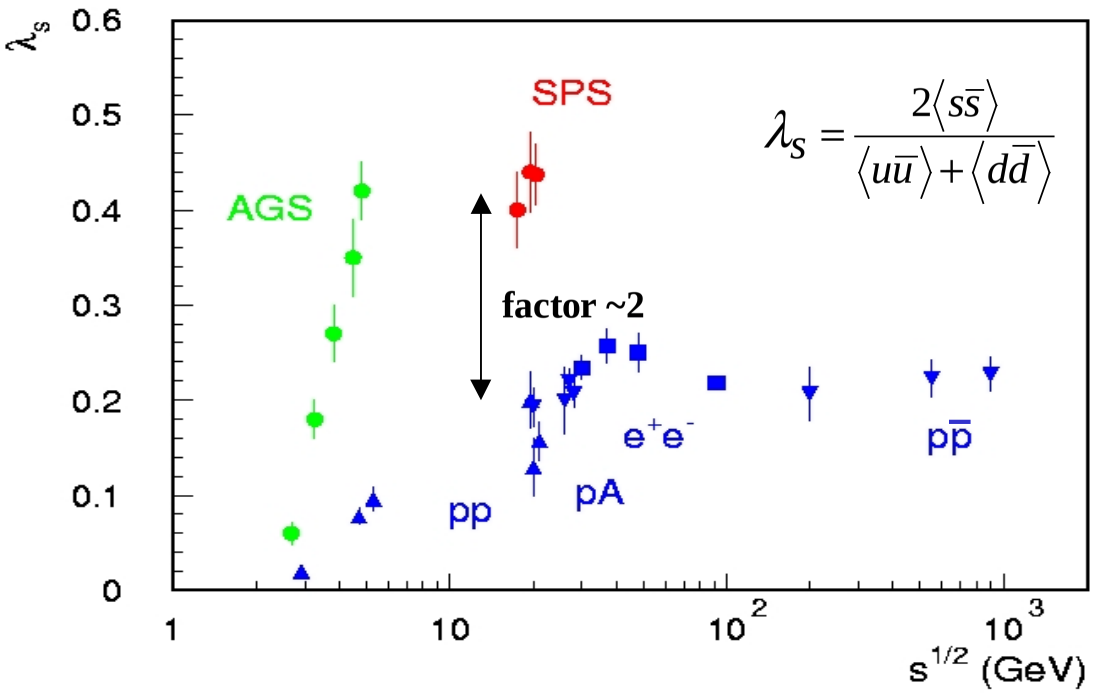
System	E_{LAB}/A (GeV)	$n_{part.}^{total}$	ε (GeV/fm^3)
S+S	200	58	1.3
S+Au	200	113	2.6
Pb+Pb	158	390	3.2

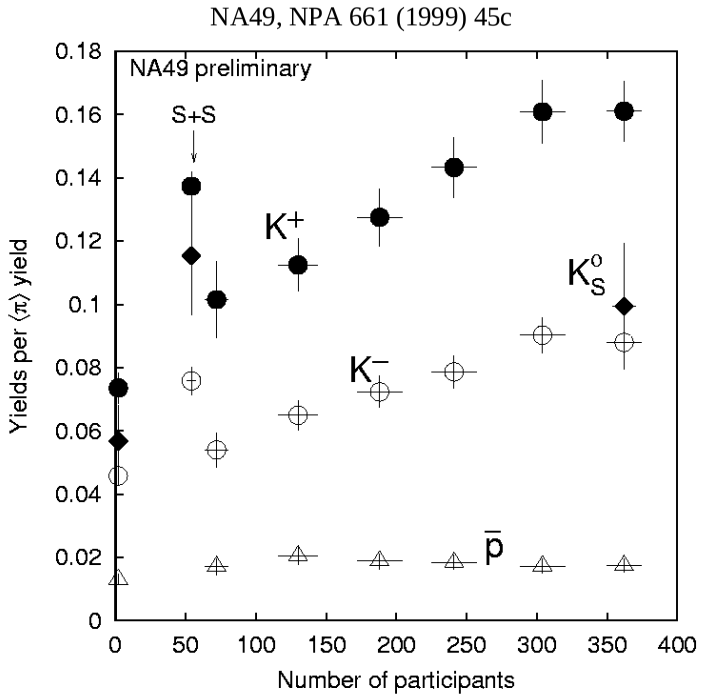
ε = 3.2 GeV/fm^3 for Pb-Pb collisions

well above the value expected for the critical energy density

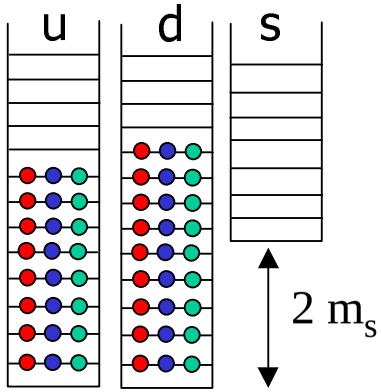
$\varepsilon_{crit} \approx 1$ GeV/fm^3

Strangeness production





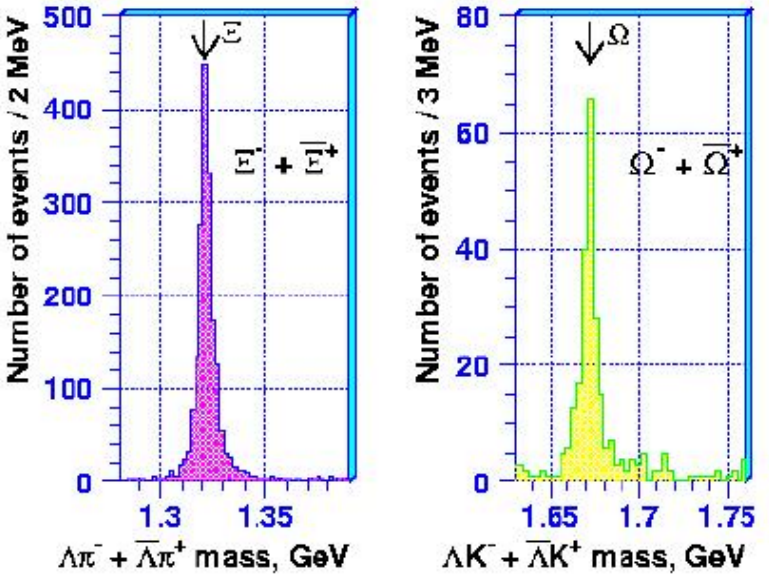
- Kaons carry about 75 % of the global strangeness content of the final state
- Factor two strangeness enhancement, already in central S-S collisions
- Study of K production versus centrality
  → smooth pattern ? (see also NA52 data)

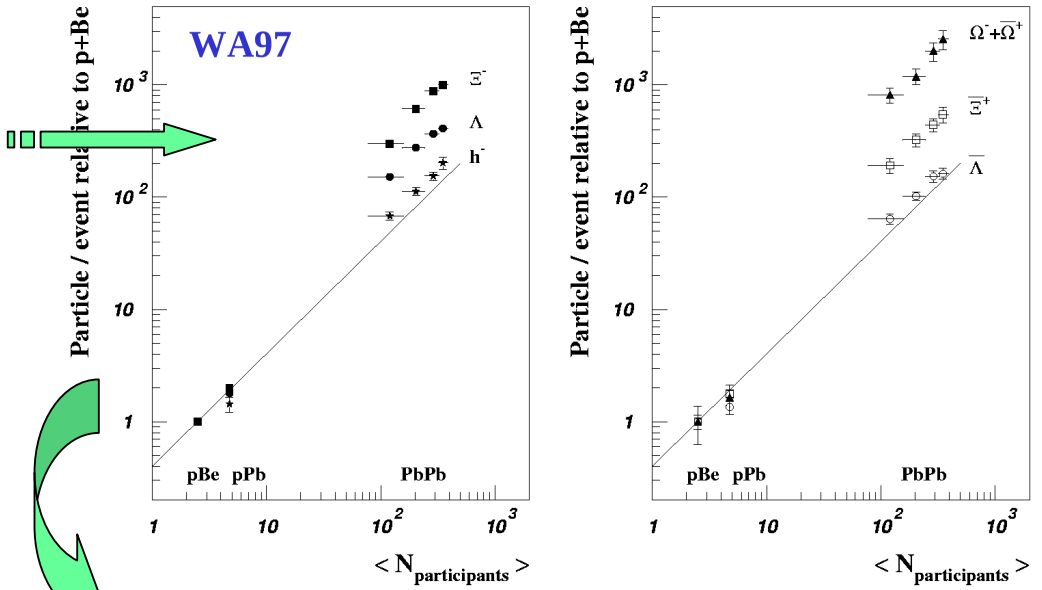


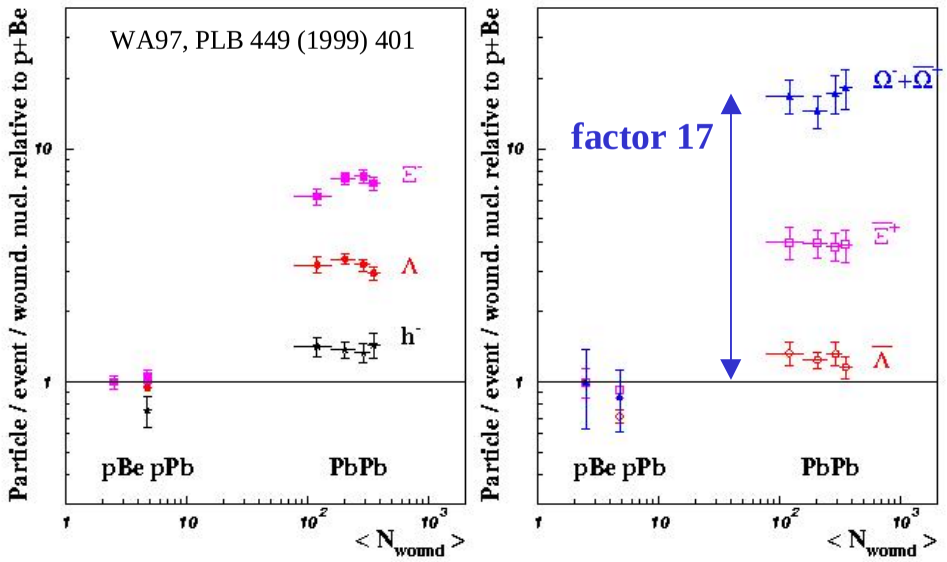
- **u, d quark levels occupied**
- **reduction in m_s**

⇒ strangeness production enhanced in HI collisions

Multi-strange hyperon enhancement







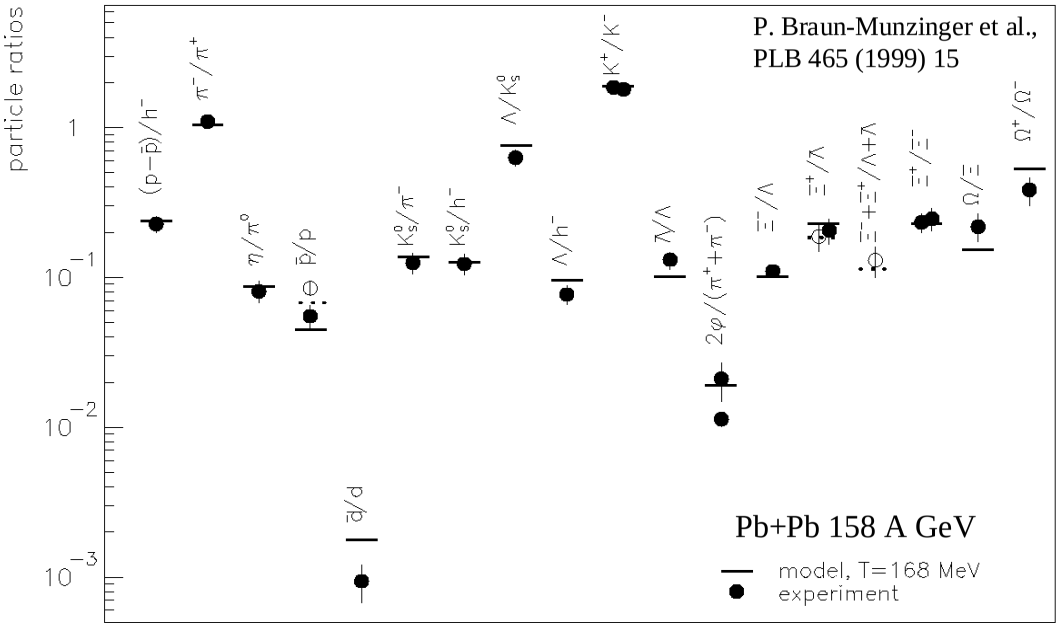
- Hierarchy of enhancement : $E_\Lambda < E_\Xi < E_\Omega$

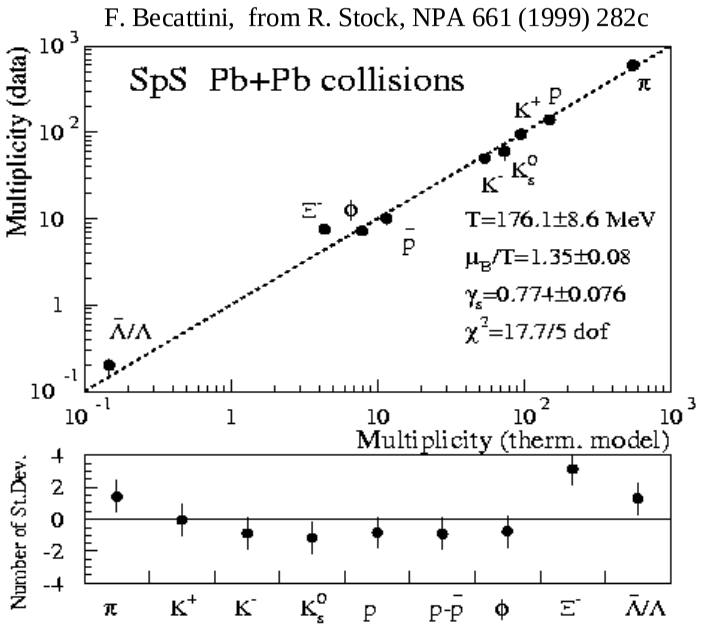
- Enhancement of Ω production in Pb-Pb by factor 17 with respect to p-Be and p-Pb

- Cannot be explained by multiple interactions within the lifetime of the hadronic system

- Is there a threshold behaviour ?
What happens in the range $N_{part} = 10 — 100$?

Thermal model for hadron production





parameters : **temperature T**

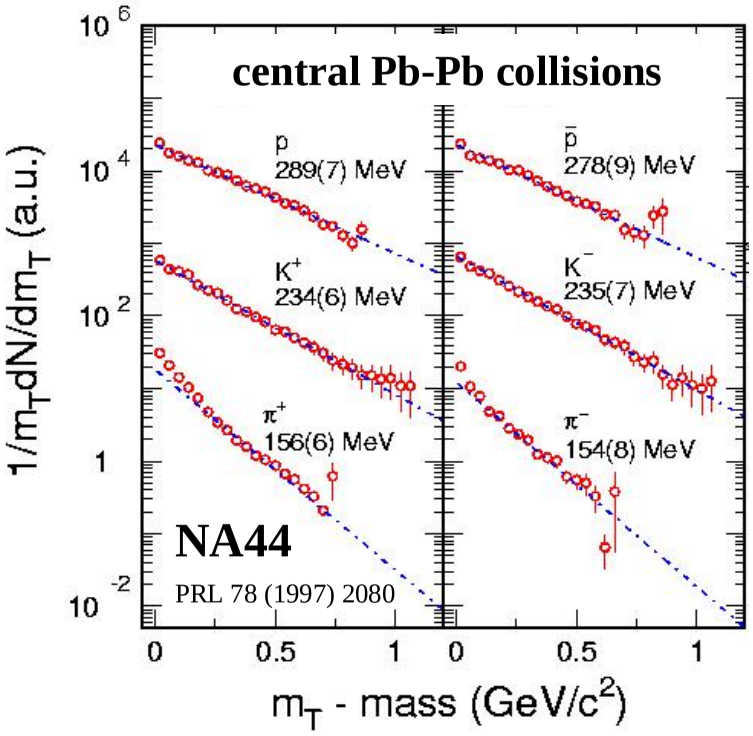
baryon chemical potential μ_b

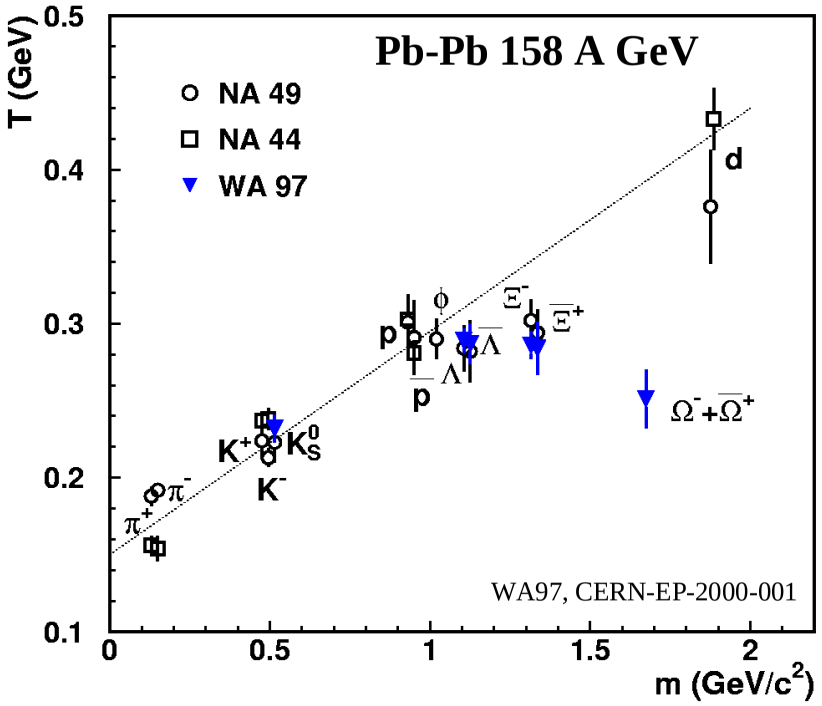
strangeness equilibration γ_s

good description of hadron ratios assuming statistical production out of a partonic system in chemical equilibrium

$\Rightarrow$ chemical freeze-out at **T ~ 170 — 180 MeV**

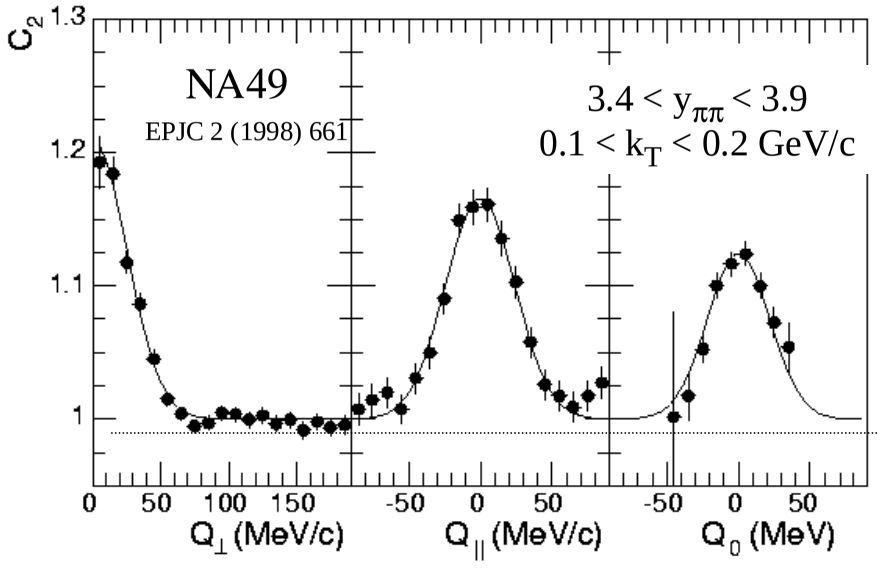
Transverse mass spectra

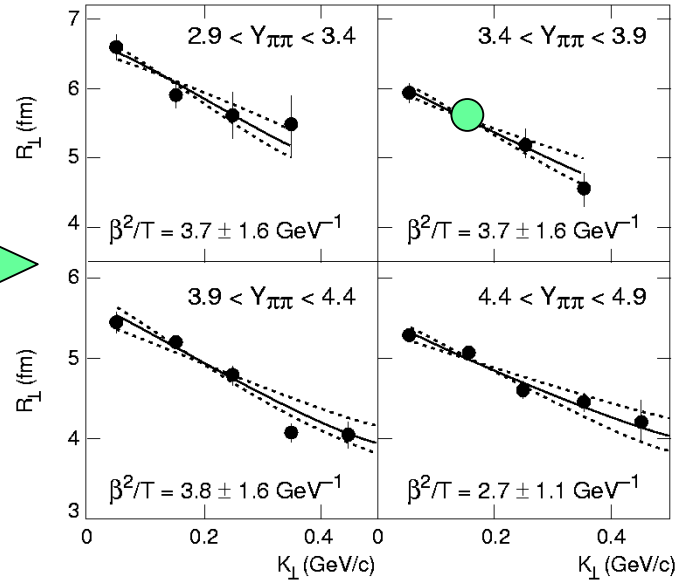


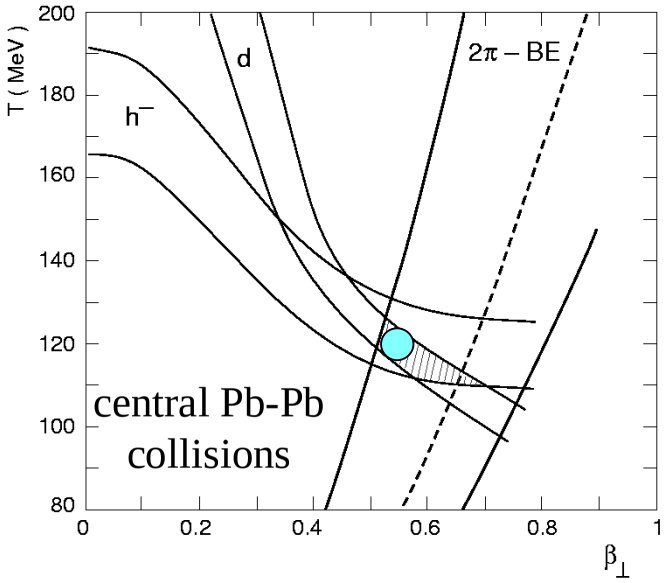


- $\mathbf{m_T}$ spectra consistent with Boltzmann distribution : $\mathbf{m_T}\ \mathbf{exp(-m_T/T)}$
- Inverse slope parameter increases with particle mass : $\mathbf{T_{eff} = T_{fo} + 0.5\, m \langle v_\perp \rangle^2}$
  (non-relativistic regime)
- Thermal motion plus collective transverse flow (expansion of the reaction volume)
  all hadrons move with average velocity $\langle \mathbf{v}_\perp \rangle = \beta_\perp \mathbf{c}$
- Why is the Ω an exception ? Early decoupling from the expanding hadronic medium ?

Freeze-out of reaction volume





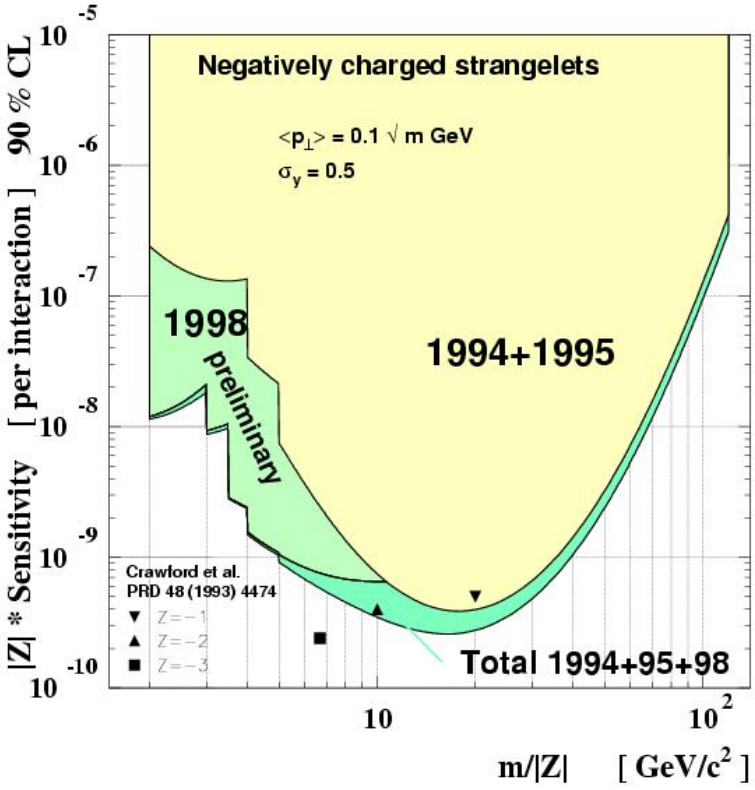


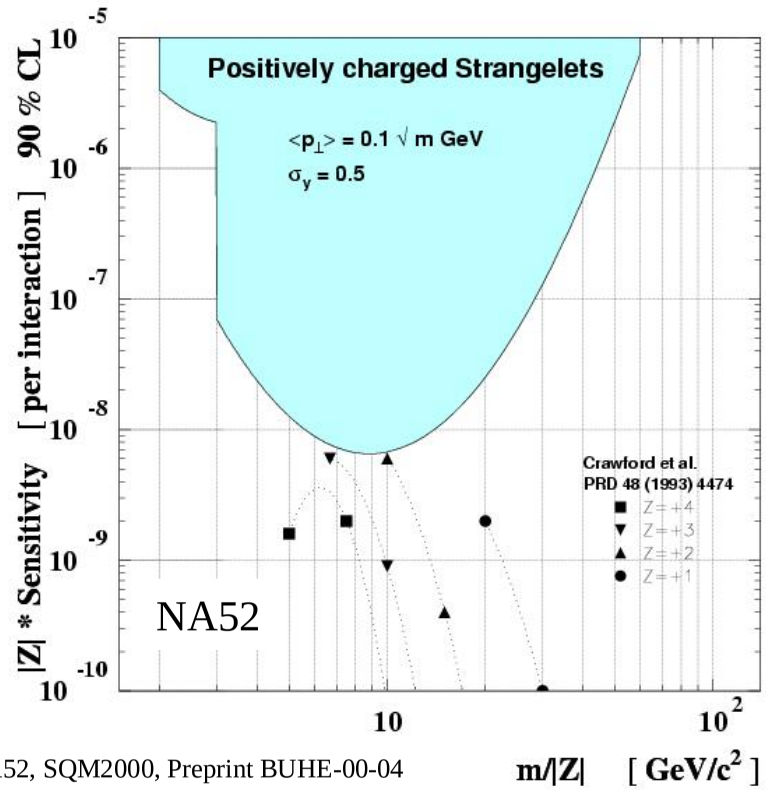
- From the dependence of the HBT correlation parameters on the **y** and $\mathbf{p_T}$ of the pion pair we get a correlation between **T** and $\beta_\perp$

- Together with the $\mathbf{m_T}$ spectra analysis :

T ~ 120 MeV
$\beta_\perp$ ~ 0.55 **"Little Bang expansion"**

Looking for strangelets

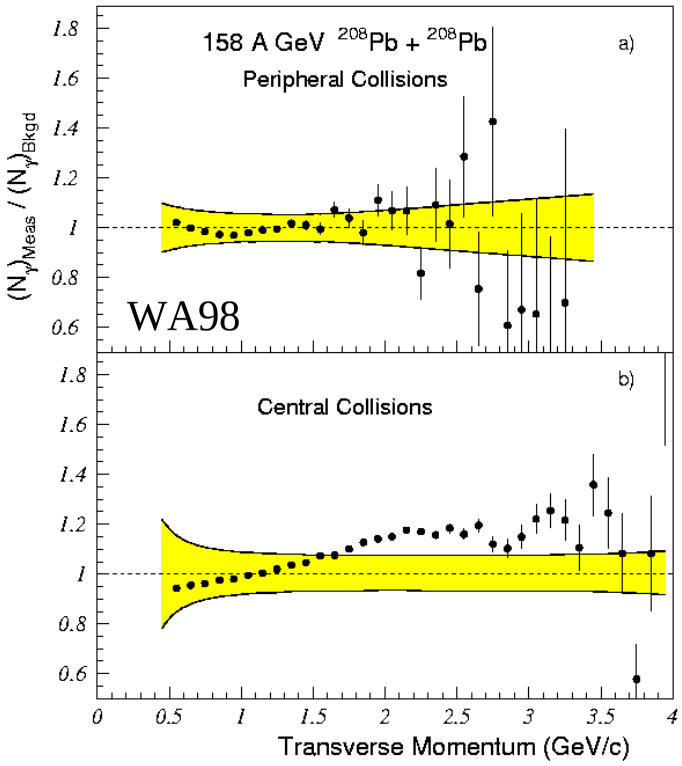


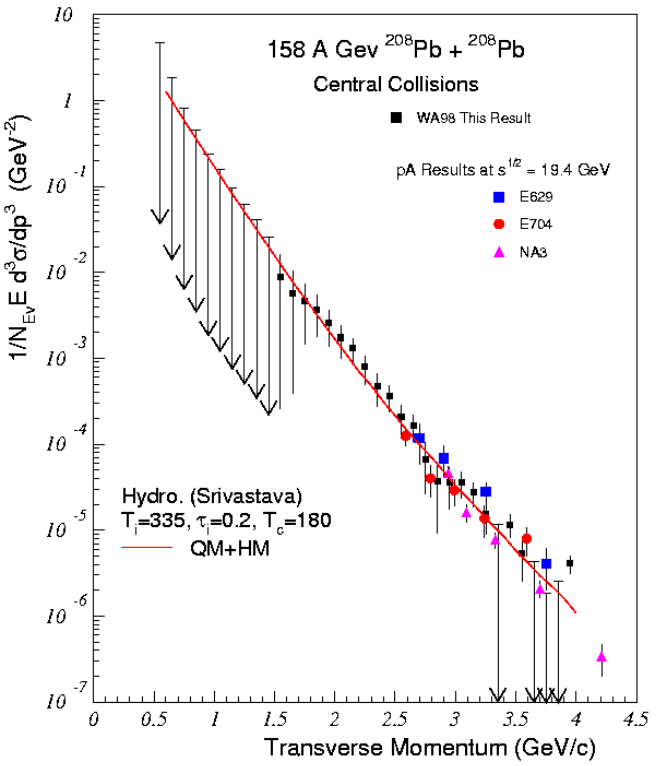


NA52, SQM2000, Preprint BUHE-00-04

- No candidate found !
- Upper limits calculated for the absolute production probability
  (depend on the assumed strangelet production model)
- Interesting NA52 by-product : studies of nuclei and anti-nuclei production
  (up to anti-Helium)

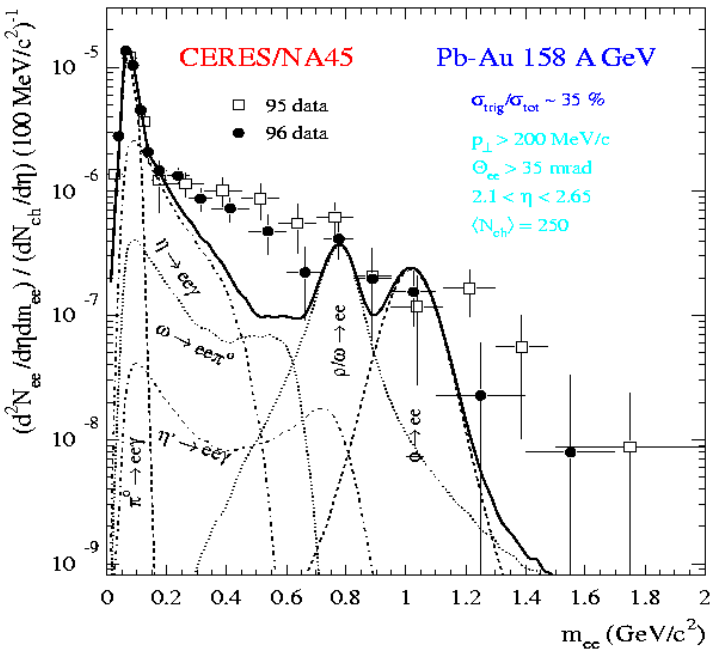
Looking for direct photons





- Preliminary result : ~ 10 % photon excess over background in central Pb-Pb collisions
- Systematic errors : most important contribution comes from the η decay background
- Hydrodynamical models with T_I = 335 MeV and τ_I = 0.2 fm/c compatible with data

Low mass dilepton production



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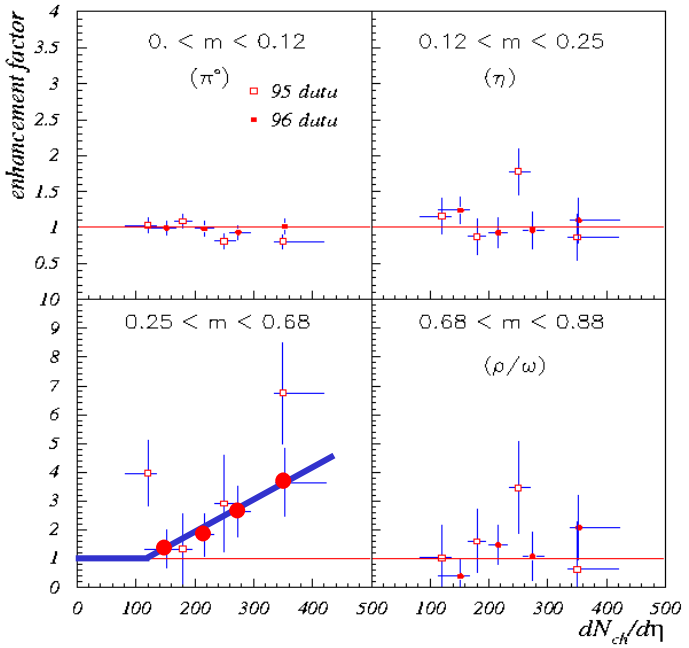
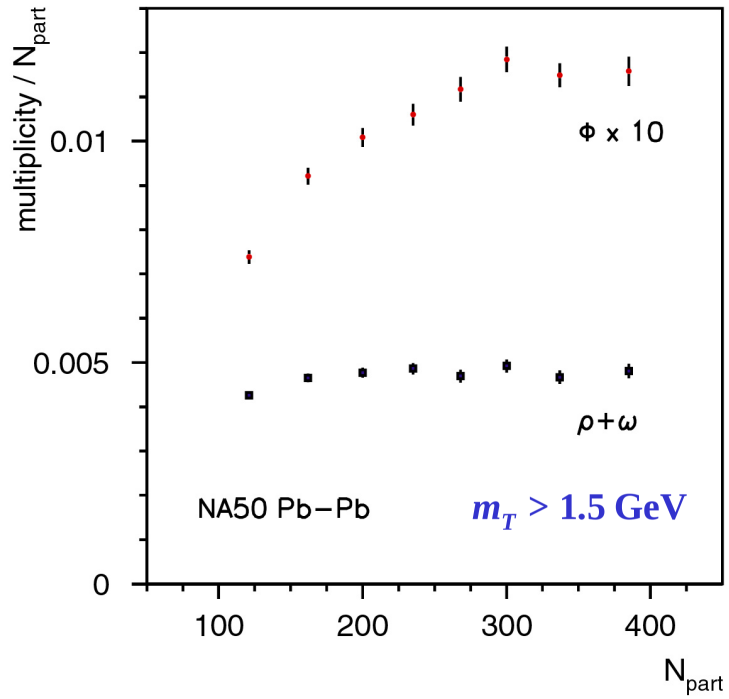
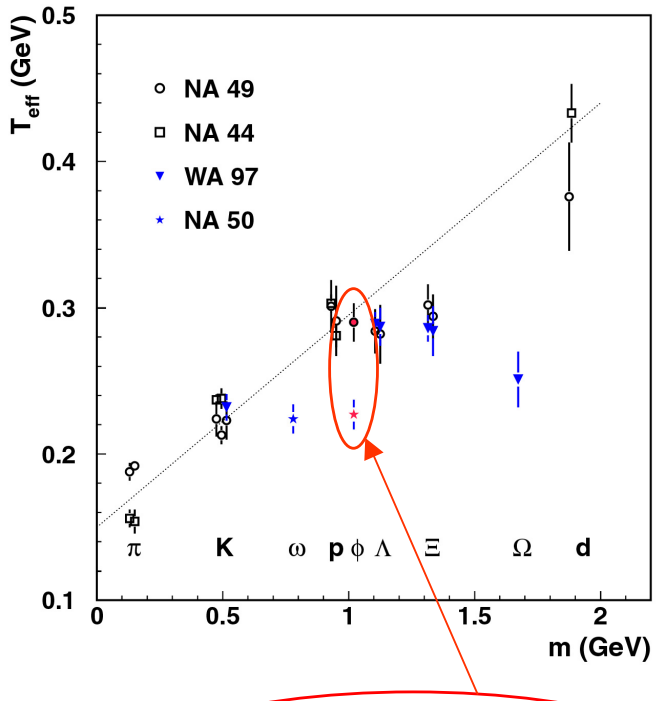
NPA 661 (1999) 23c



- The p-A data are properly described by the standard cocktail of hadronic decays
- The Pb-Au signal is enhanced by a factor 2.6 in the mass window 250 - 700 MeV/c^2
- Quadratic dependence of the excess on the charged particle multiplicity
- Is there a threshold at around $dN_{ch}/d\eta = 100$?
- Enhancement more pronounced at low p_T
  - No resonances visible in the Pb-Au data $\Rightarrow$ In medium effects in dense matter !
  - Mass shift and / or broadening of the ρ line shape ?
  - Degeneracy of ρ and $\mathbf{a_1}$ spectral functions ? Chiral symmetry (partially) restored ?

ϕ enhancement in Pb-Pb collisions



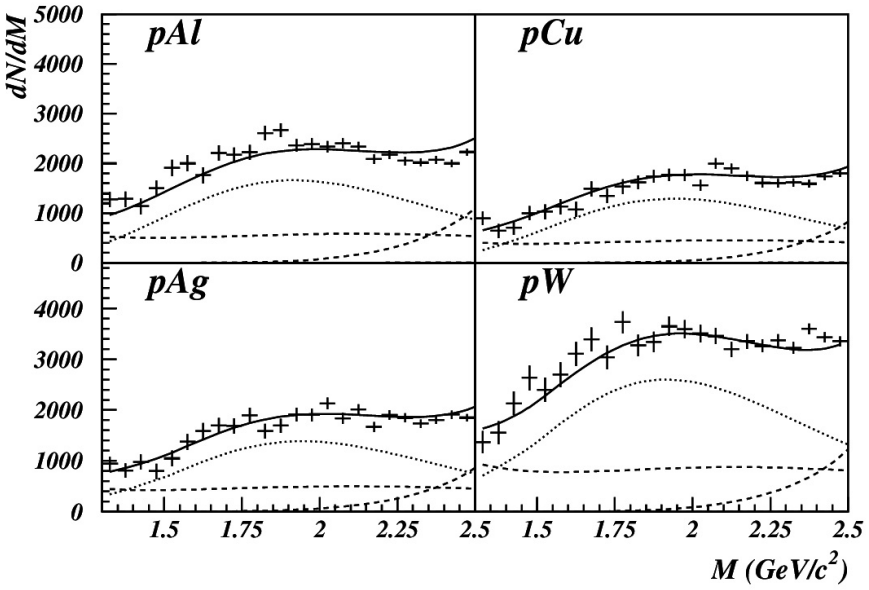


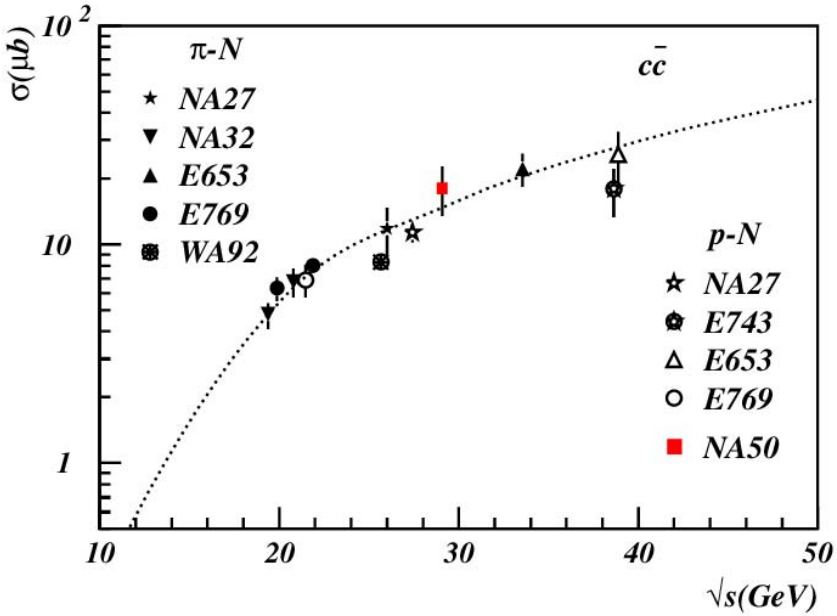
3 σ discrepancy between NA49 and NA50 measurements

- Anomalous ϕ enhancement relative to N_{part}
- What is the value of T for the ϕ meson ?
- New dimuon data needed to cover the low p_T region
- Is the observed ϕ enhancement a specific feature of heavy ion collisions ?
- The ϕ yield measured by HELIOS-1 in p-Be collisions at 450 GeV shows a quadratic dependence with charged particle multiplicity

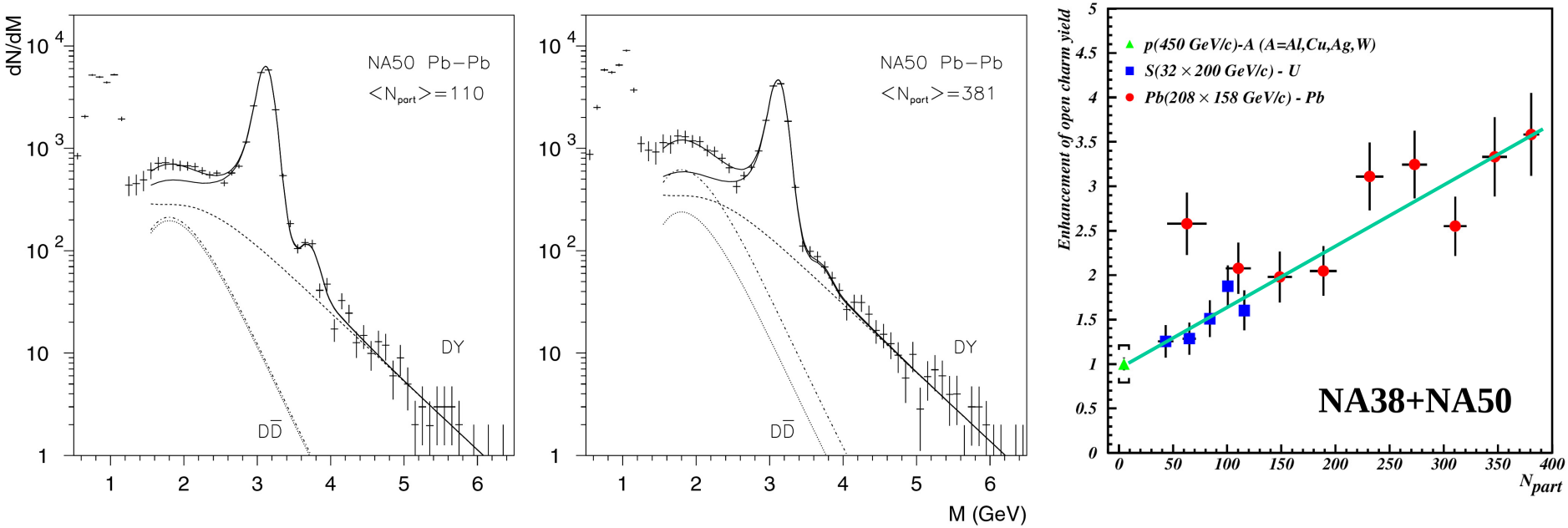
Intermediate mass dimuons in p-A collisions

- The p-A data is properly described by a superposition of Drell-Yan and $D\bar{D}$ decays, in the dimuon mass, p_T, rapidity and $\cos(\theta_{CS})$ variables
- The required charm cross-section is consistent with previous direct measurements





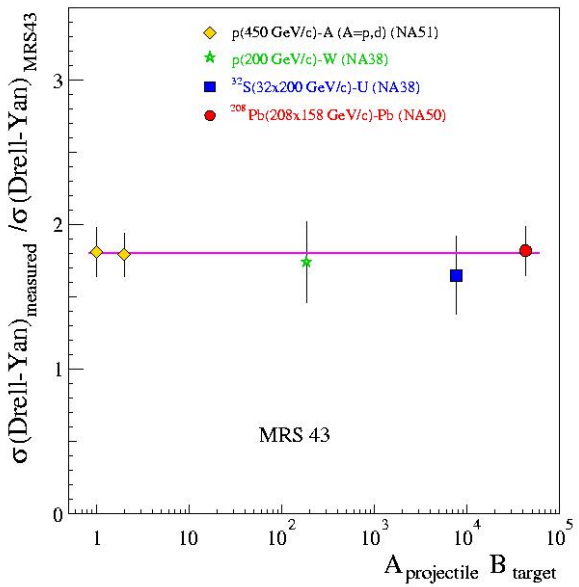
Excess production of intermediate mass dimuons

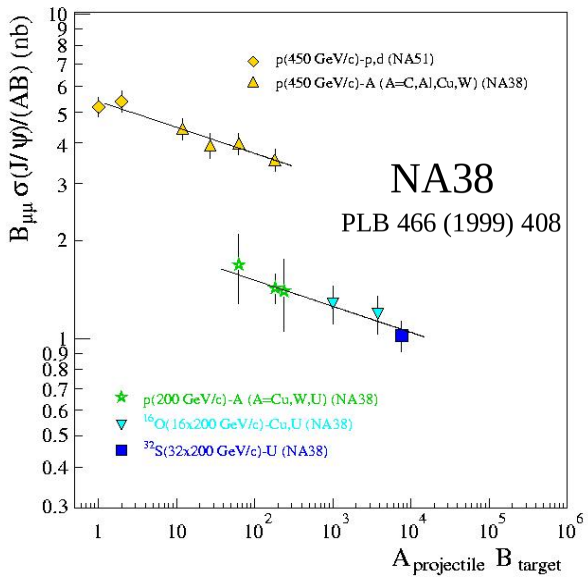


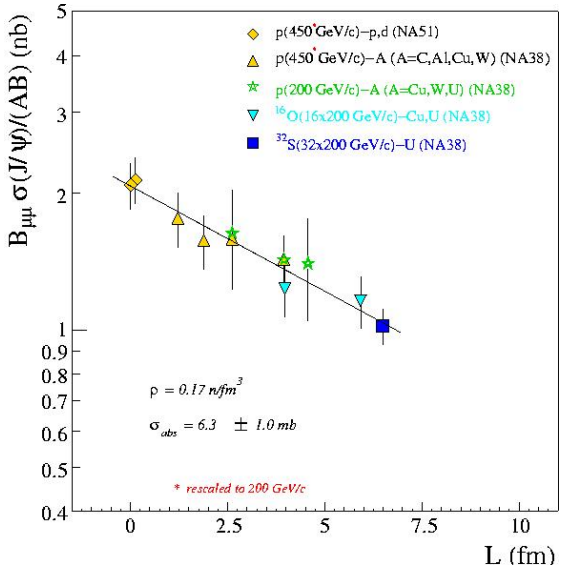
- Big excess, compatible with an enhancement of charm production
- Thermal dimuon production ? ⇒ Maybe; also compatible with the present data
- Redistribution of charm in phase space ? ⇒ Existing models were ruled out
- Can charm yield be enhanced by a factor 3.5 ? ⇒ A much better measurement is needed

See parallel talk by Laurent Capelli

Reference data for J/ψ production studies







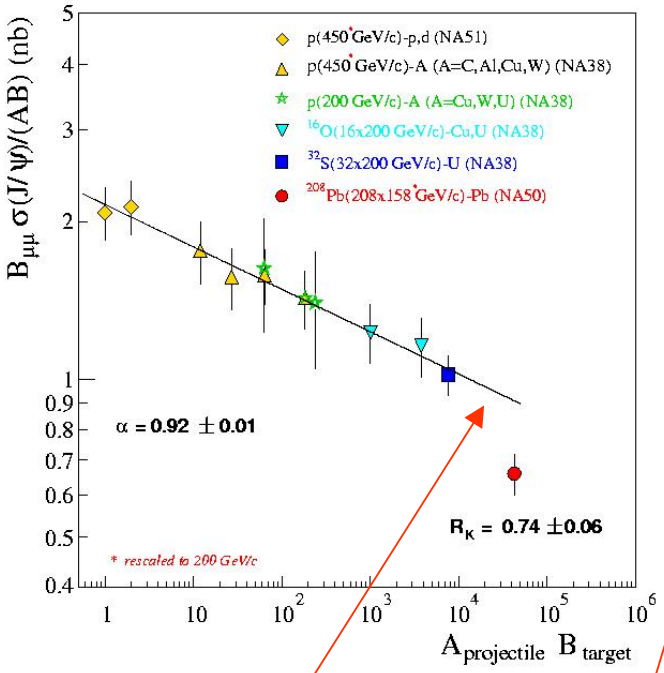
- Drell-Yan : same K factor from pp to Pb-Pb relative to the LO calculation
  (MRS A parton distribution functions; no nuclear effects)

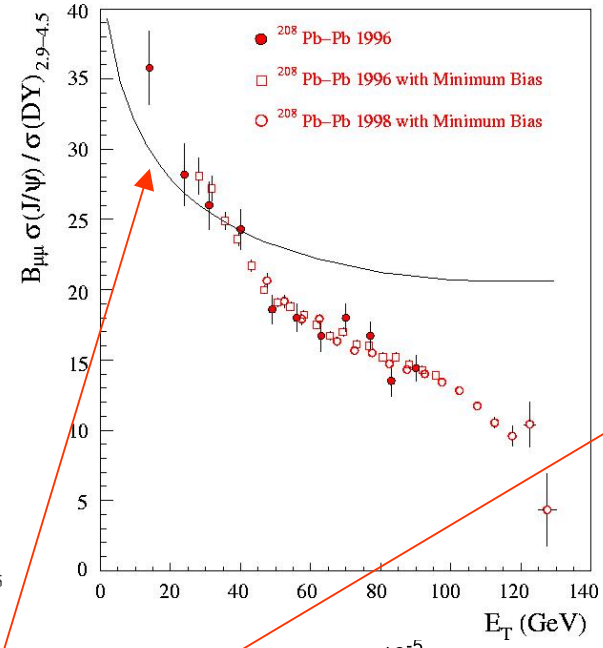
➔ Drell-Yan is a good reference process in the study of charmonia suppression
  (at SPS energies)

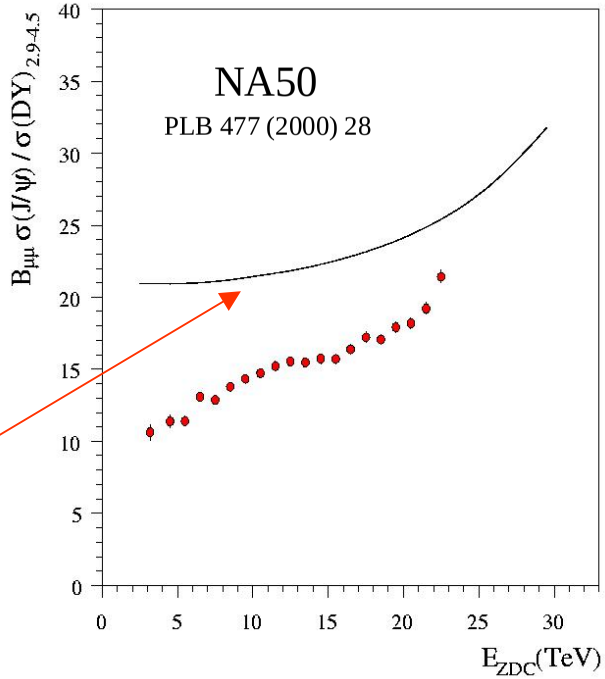
- J/ψ : same A-dependence at 200 and 450 GeV ; $\alpha \sim 0.92$

- J/ψ suppression in p-A and S-U collisions is well described by pre-resonance absorption
  ⇒ good reference for the study of Pb-Pb data

Anomalous J/ψ suppression in Pb-Pb collisions

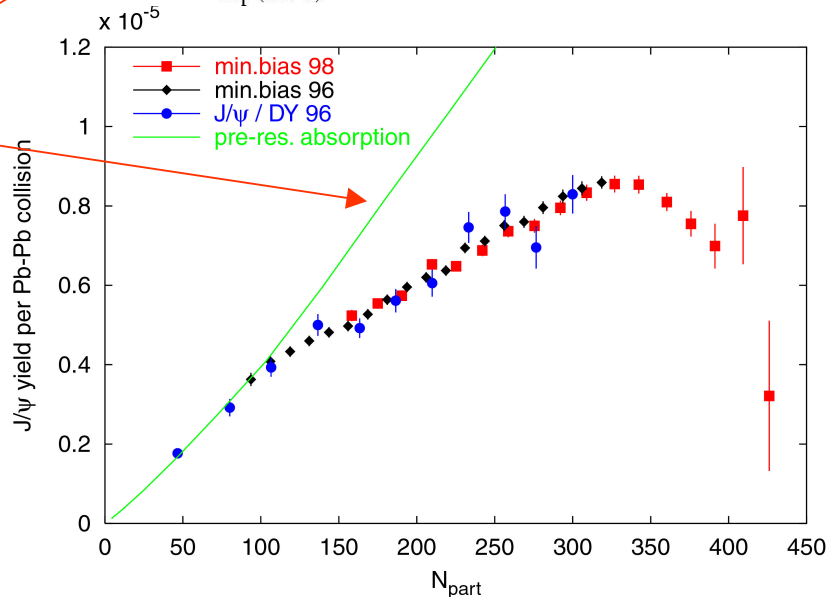






Normal nuclear absorption

$\sigma_{abs} = 6.4 \pm 0.8$ mb

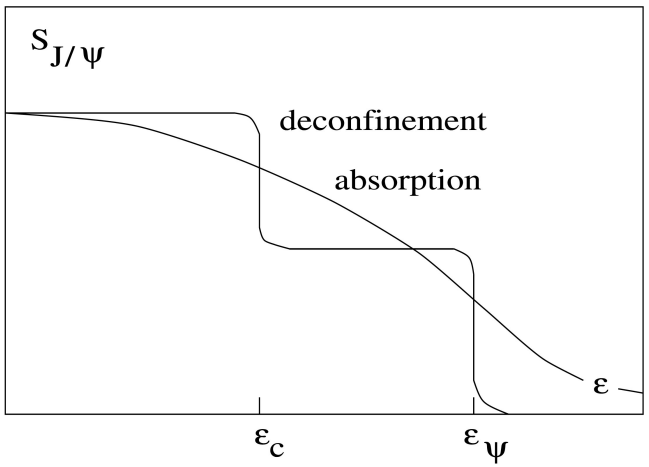


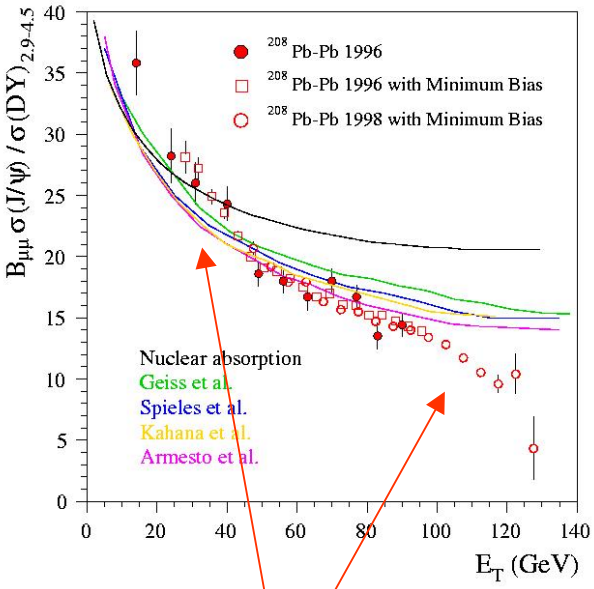
J/ψ "anomalous" suppression when :

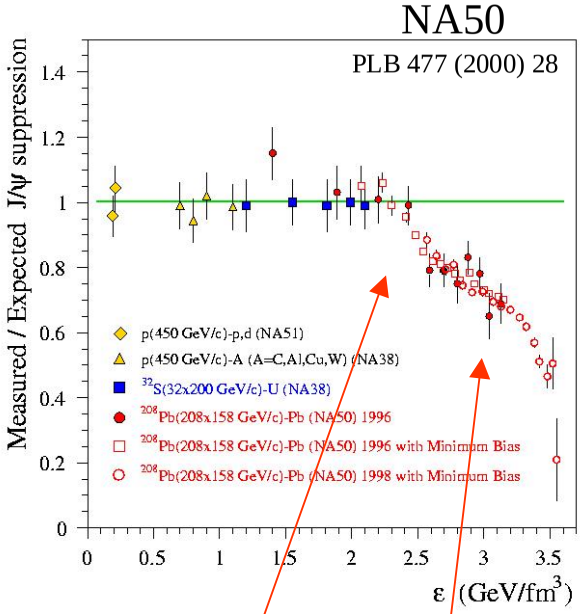
- $E_T > 40$ GeV ; $E_{ZDC} < 24$ TeV (?)
- $N_{part} > 100$; $L > 8$ fm ; $b < 8$ fm

J/ψ suppression as a probe of deconfinement

Status after 4 years of S-U runs and 4 years of Pb-Pb runs :







- Hadronic absorption :
  → smooth pattern
- Deconfinement :
  → step-wise pattern

conventional hadronic models are ruled out

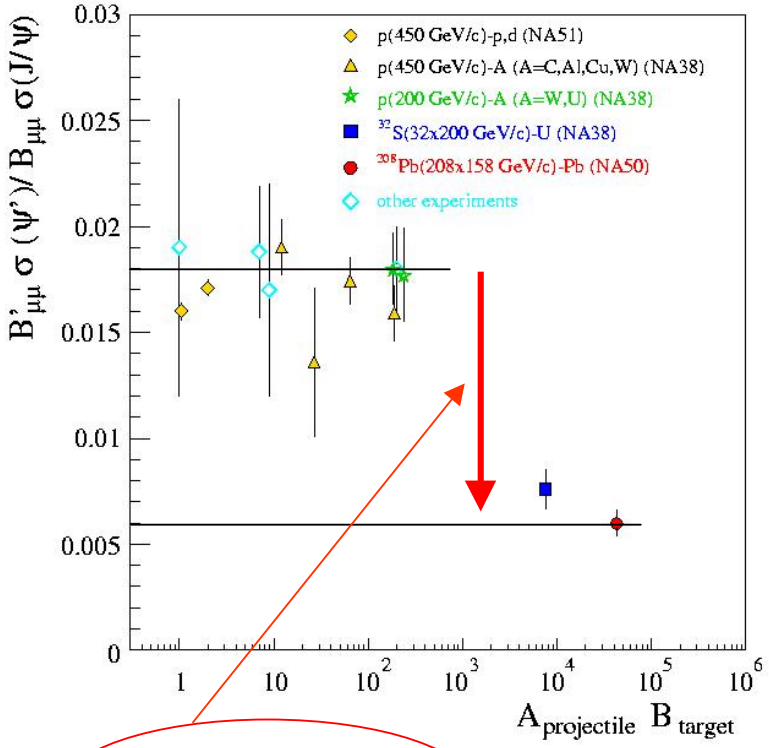
melting of χ_c ?

melting of directly produced J/ψ ?

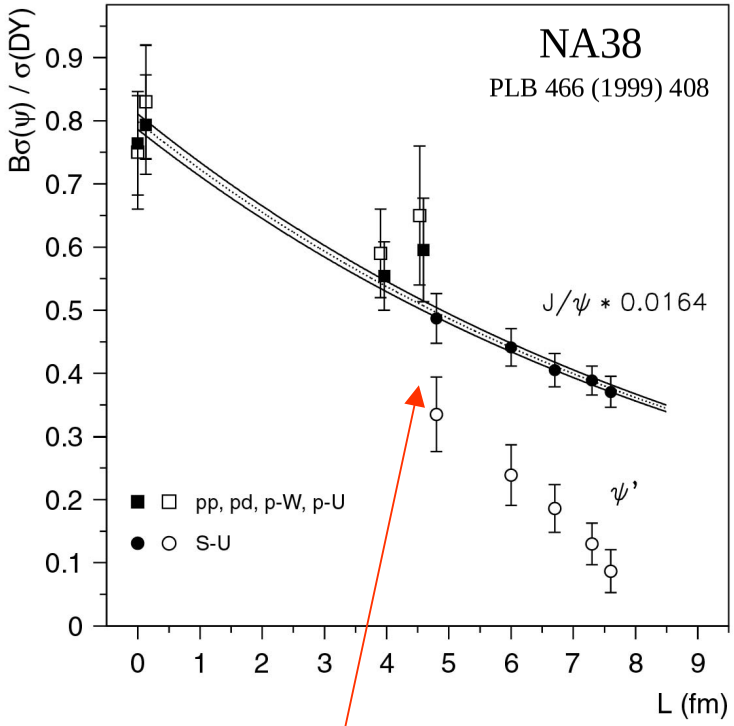
- Centrality scan allows to detect thresholds in measurable quantities
  peripheral points need better measurement
- Color screening prevents charmonium formation in a deconfined medium
  binding energies : ψ' ≈ 50 MeV, χ ≈ 250 MeV, J/ψ ≈ 650 MeV

ψ' production and suppression

- The ψ' is strongly suppressed in S-U collisions
  - ➔ hadronic absorption or melting ?



Drop by factor ~ 3

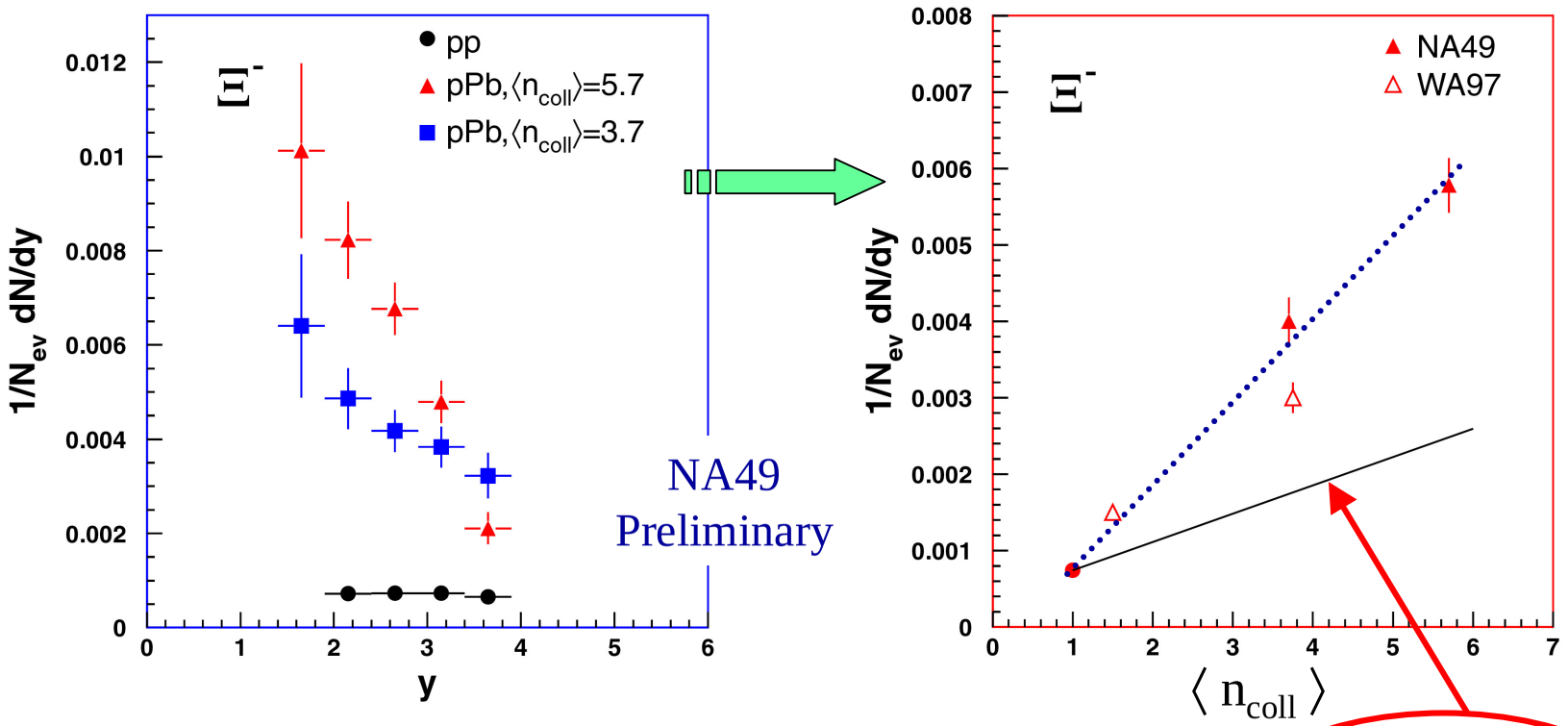


melting of ψ' **?**

Some open questions

- The present SPS results are very interesting but **important issues remain unclear** :
  - Where is the onset of the multi-strange hyperon enhancement ?
    Do we properly understand the p-A reference line ?
  - Is the ρ meson modified by the medium ? → measure the ω !
    Is there a threshold in the dilepton enhancement ?
  - Is the observed ϕ enhancement a specific feature of heavy ion collisions ?
    Is the ϕ sensitive to flow ? What is the "inverse slope", T, of the ϕ meson ?
  - What is the origin of the intermediate mass dimuon excess ? Thermal dimuons ?
  - Is the open charm yield enhanced in nucleus-nucleus collisions ?
    How does it compare to the suppression pattern of bound charm states ?
  - What is the variable that rules the onset of ψ', χ_c and J/ψ suppression ?
  - What is the physical origin of the ψ' suppression ?
    If it is Debye screening, what is its melting temperature ($\Leftrightarrow$ value of T_c) ?
  - What fraction of J/ψ come from χ_c decays ? Does it change from p-Be to p-Pb ?

Strangeness production in p-A collisions



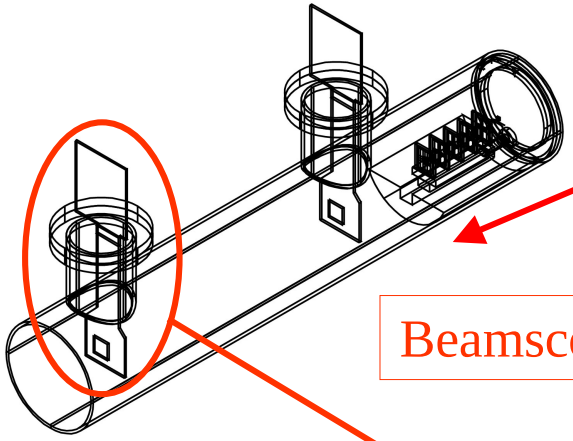
- NA49 sees a **stronger** increase than WA97 in the Ξ production yields, at mid-rapidity, as a function of the number of collisions the incident proton makes in pp and p-Pb collisions
  - → smaller relative enhancement in Pb-Pb ?

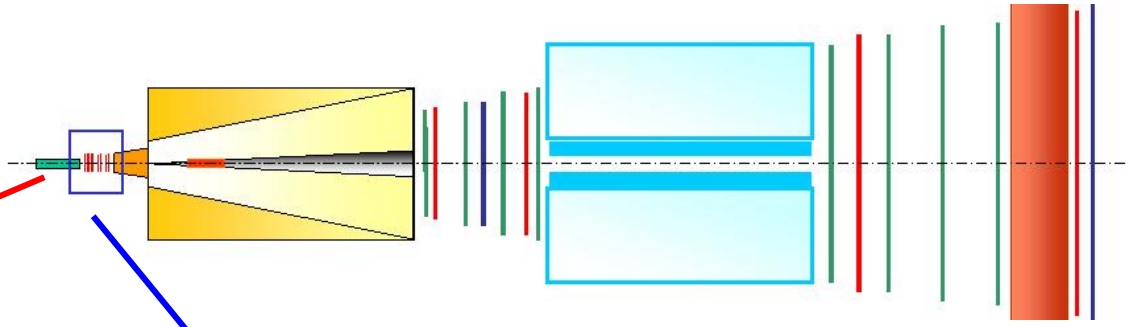
Scaling with the mean number of wounded nucleons

- NA49-hadrons will continue taking data for a few more years !

See parallel talk by Tanja Susa

NA60 : a new SPS heavy ion experiment

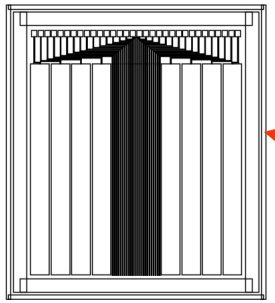




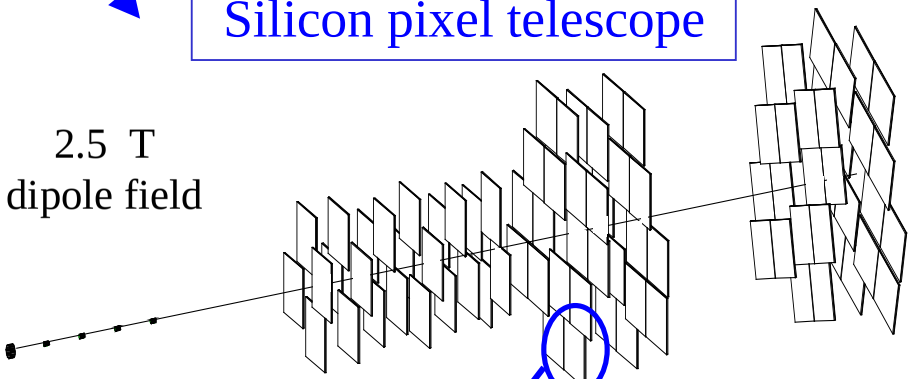
Beamscope

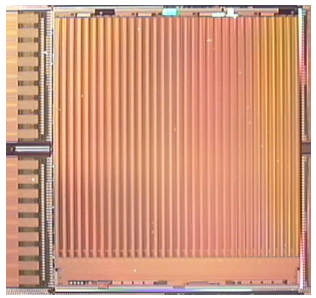
Silicon pixel telescope

- 2 x-y stations of μ-strip Si detectors at T = 130 K
- ~ 20 μm resolution on the transverse coordinates of the beam ions
- still working after 10^{13} Pb ions passed in 1 mm^2 !!!



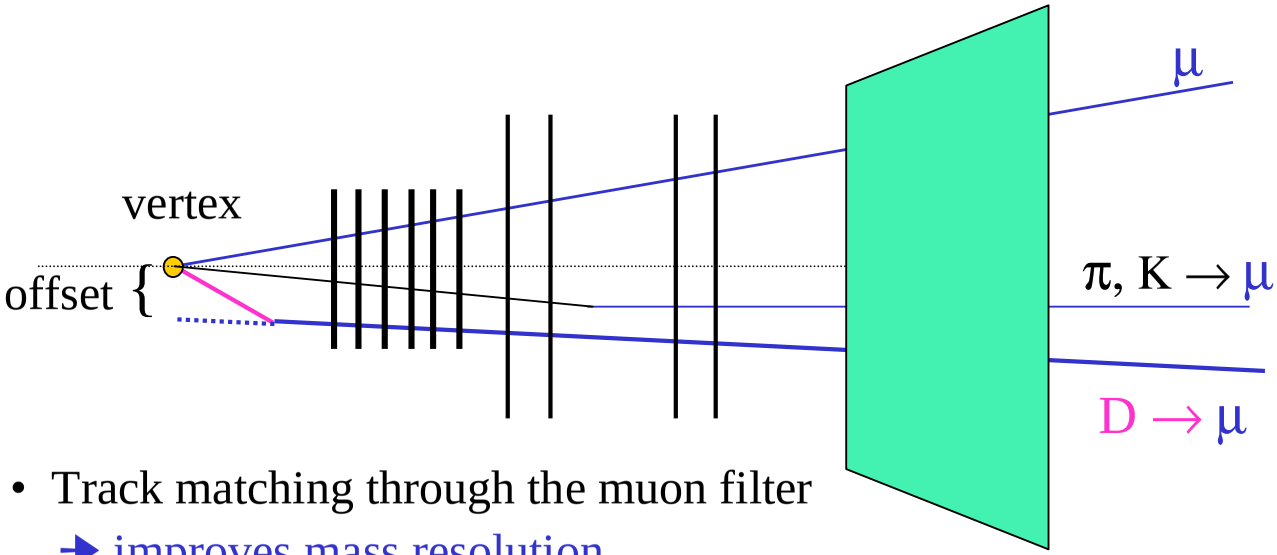
2.5 T
dipole field



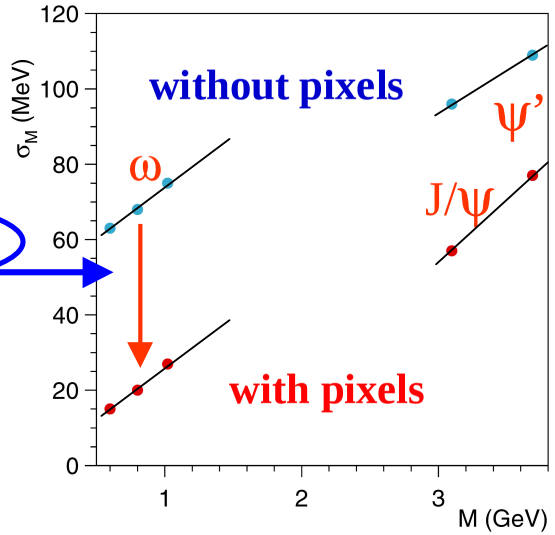


- 10 planes
- 88 pixel readout chips
- 720 000 channels
- pixel size : 50×425 $μm^2$

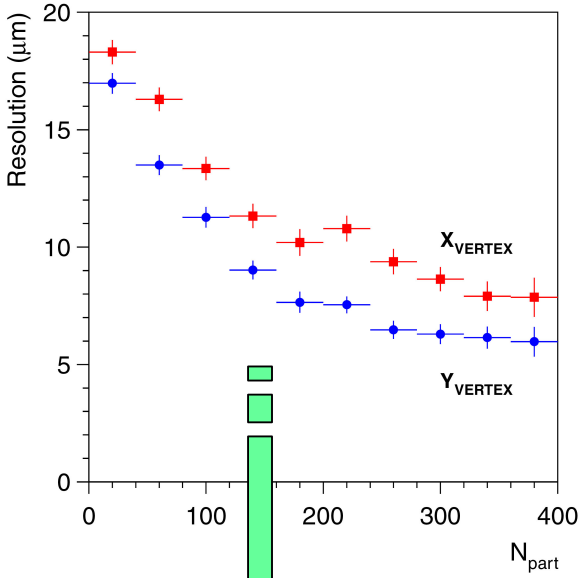
NA60 concept and performance

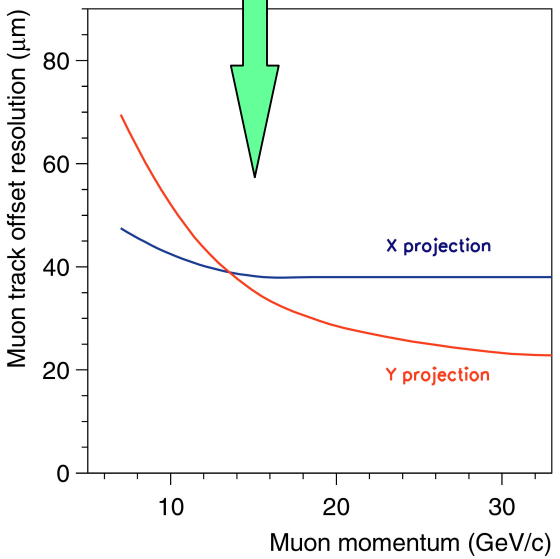


- Track matching through the muon filter
  - ➔ improves mass resolution, signal / backround and systematics in ψ' studies



70 → 20 MeV





- Muon track offset measurement
  - ➔ provides charm tagging to separate **charm** from **prompt** (thermal) dimuons

Conjectures and refutations in heavy ion physics

Scientific hypotheses cannot be proven; they can only be falsified

"Nature never tells you when you are right, only when you are wrong"

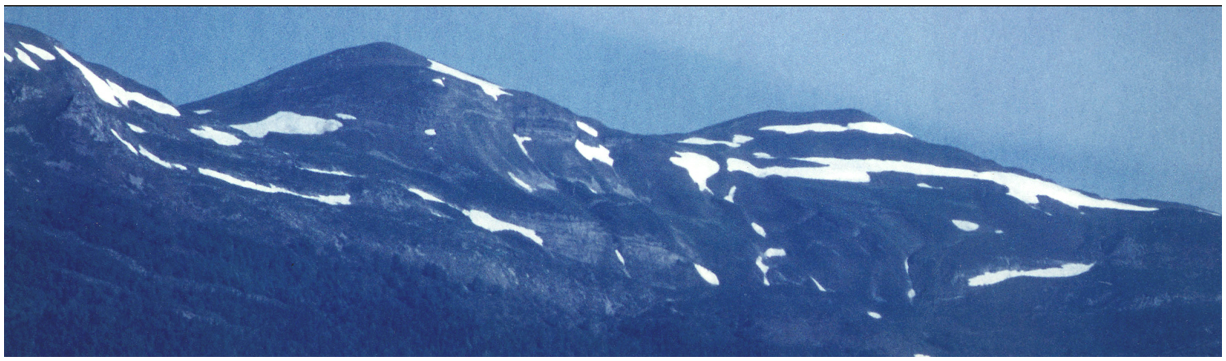
K. Popper, Bacon, Bo Andersson

- The 'measured' energy density (≈ 3 GeV / fm^3) **exceeds the critical value** estimated for the QCD phase transition
- The yields of strange (anti-)baryons **are strongly enhanced**
- The low mass dilepton spectrum **is modified**
- The J/ψ and ψ' **are suppressed** beyond the normal nuclear absorption, showing a threshold behavior

$\Rightarrow$ We have **failed to falsify** the hypothesis :

A state of deconfined matter has been formed in Pb-Pb collisions at the SPS

A phase transition seen from CERN



- A skier (quark) is confined inside snow patches (hadrons)

- the skier can move further …
a new phase develops

- the skier (quark ?) can move freely over long distances …

T

Luciano Maiani, February 2000

What are we missing ?

NA49

- A detailed centrality dependence of the Pb-Pb data
- A careful comparison of the existing 40, 80 and 158 GeV data
- A solid baseline reference from hadron production in h-A collisions

NA57

- A robust p-A (and light ion) reference line
- A scan of the energy density region between p-Pb and Pb-Pb

CERES

- Improved resolution, statistics and signal to background
- A study of the excess as a function of the energy density

NA50

- Accurate low E_T Pb-Pb data to compare with the normal absorption curve
- High precision p-A data for the J/ψ and ψ' suppression patterns

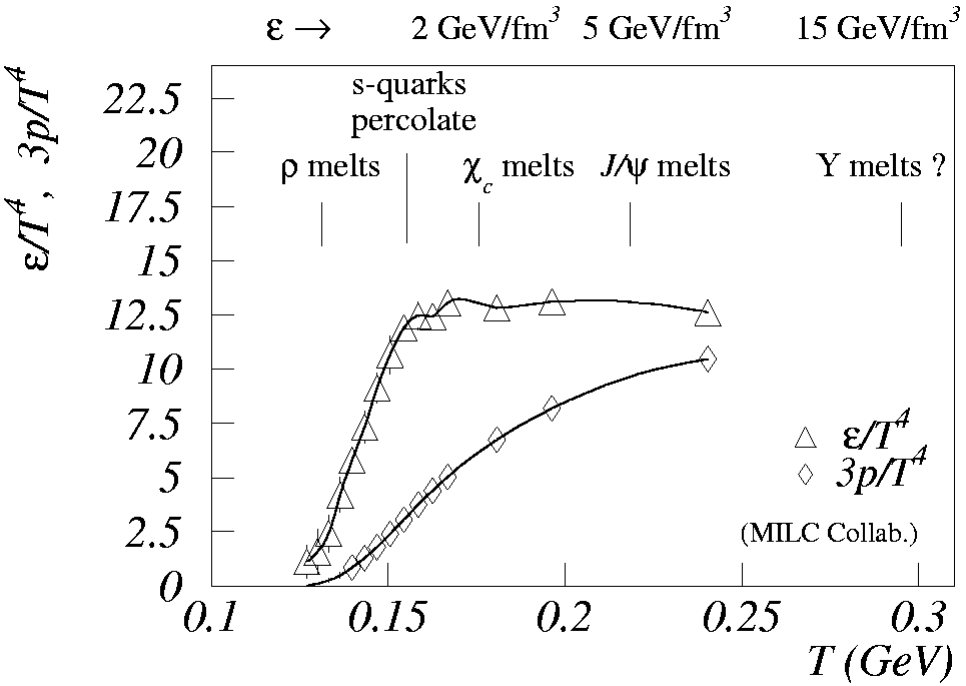
Towards the future

- Higher energies improve the signals … but also increase the backgrounds !
  - ➔ no replacement for systematic and careful studies
- Do not underestimate the importance of the baseline reference
  - ➔ take accurate p-A and light ion data
- To improve our understanding, we need falsifiable models !
  - ➔ when a model is disproved by data, we have learned something
- Heavy ion physics is a complicated field
  - ➔ to study the critical nature of QCD … we must keep a critical mind

The end of the beginning

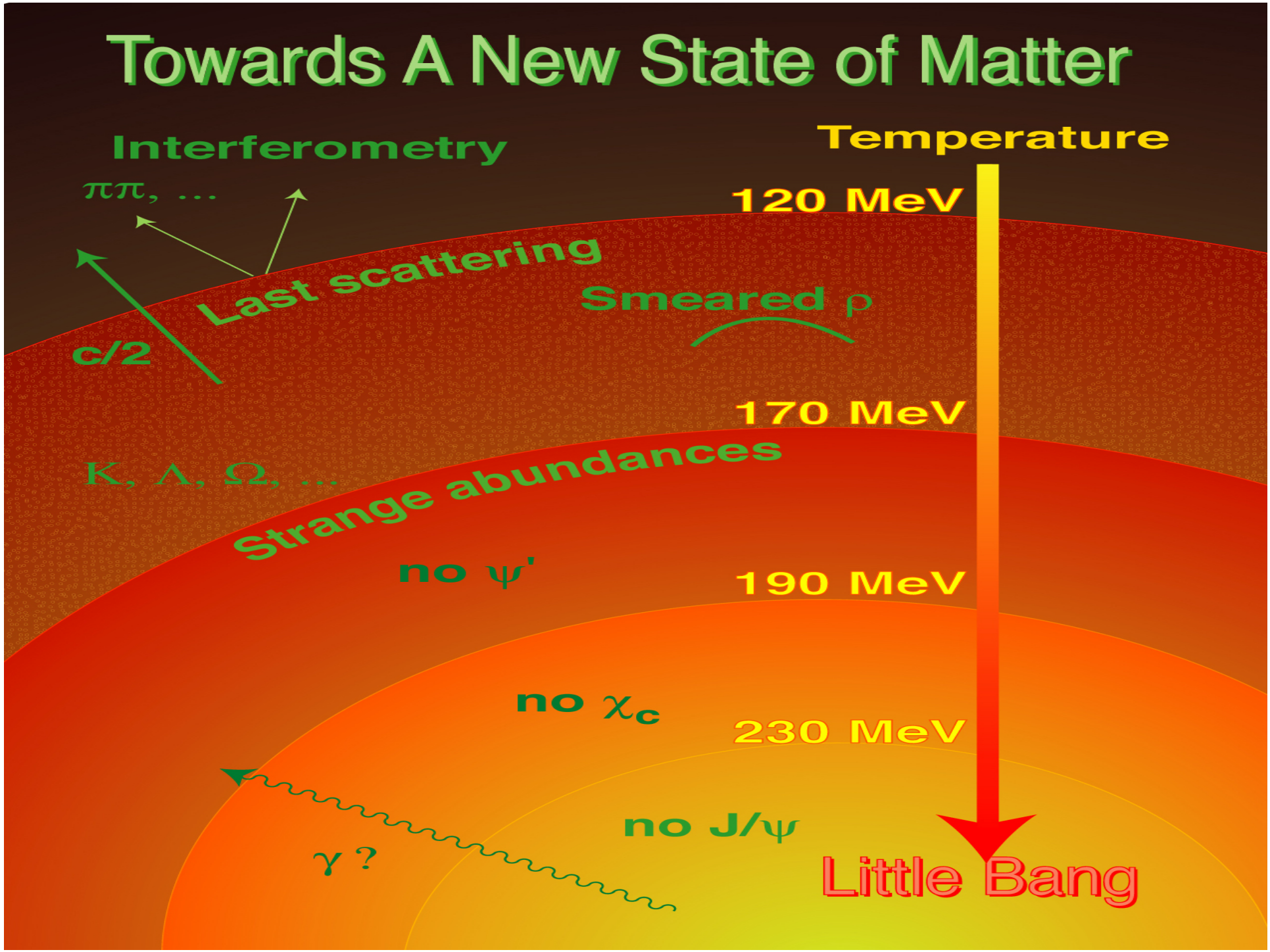
Berndt Müller, concluding talk at Quark Matter 1999 :

"… all the observations are consistent with a *succession of several stages* of dissolution of hadronic states as the energy density increases from light to heavy nuclear collision systems at the SPS."



In Quark Matter 2001 we will certainly see more quantitative information to clarify this idea

…and to make the bridge from the SPS to the RHIC results !


Towards A New State of Matter
Interferometry
ππ, …
c/2
Last scattering
Temperature
120 MeV
Smeared ρ
170 MeV
K, Λ, Ω, …
Strange abundances
no ψ'
190 MeV
no χc
230 MeV
no J/ψ
γ ?
Little Bang