Pb-Pb collisions at the SPS: from hadronic to deconfined matter

- Event geometry
- Hadroproduction
- Strangeness enhancement
- Charmonia suppression
- Photon and lepton studies
- Outlook

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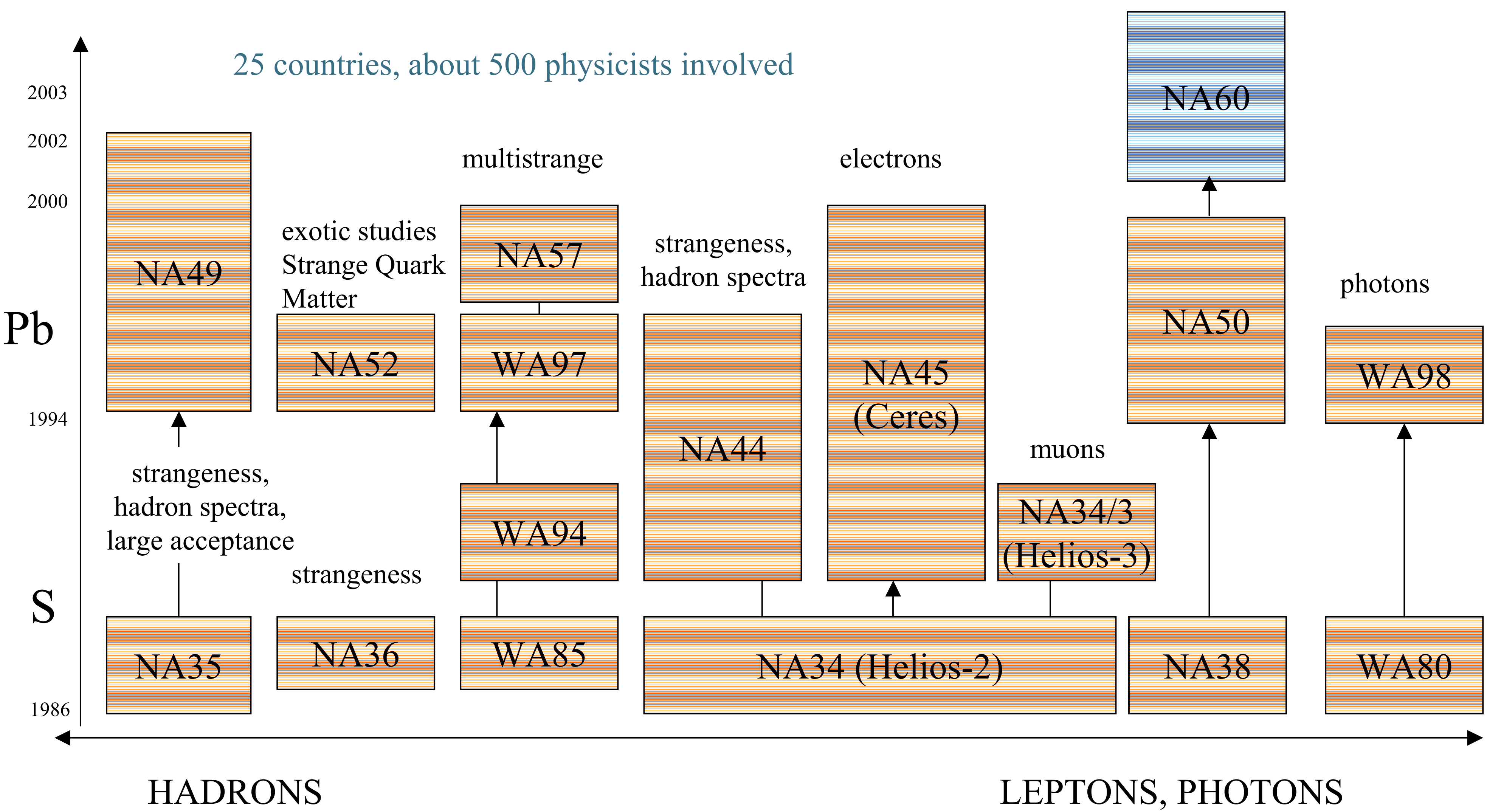
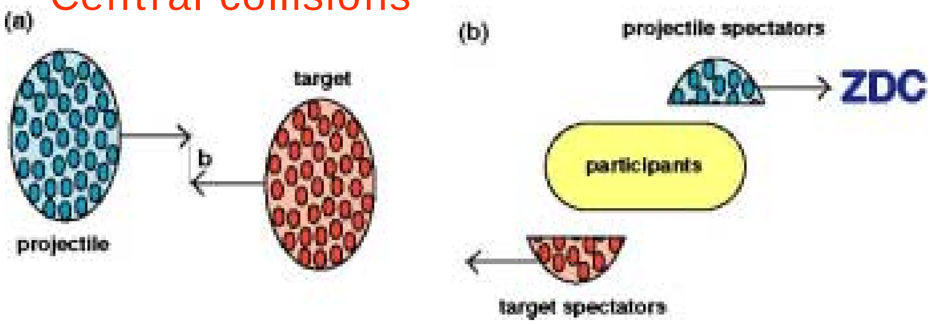
The SPS-Ion Experimental Program

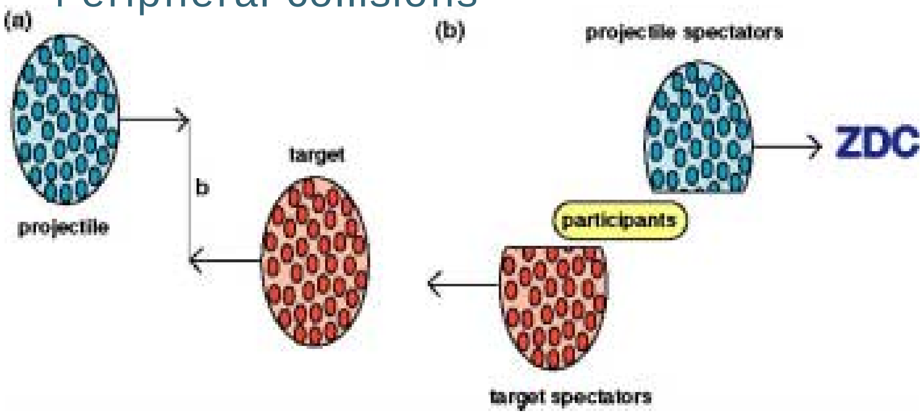


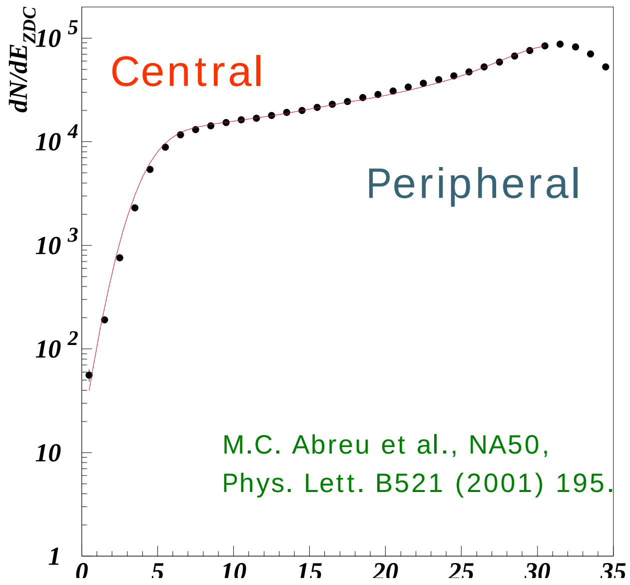
Event Characterization

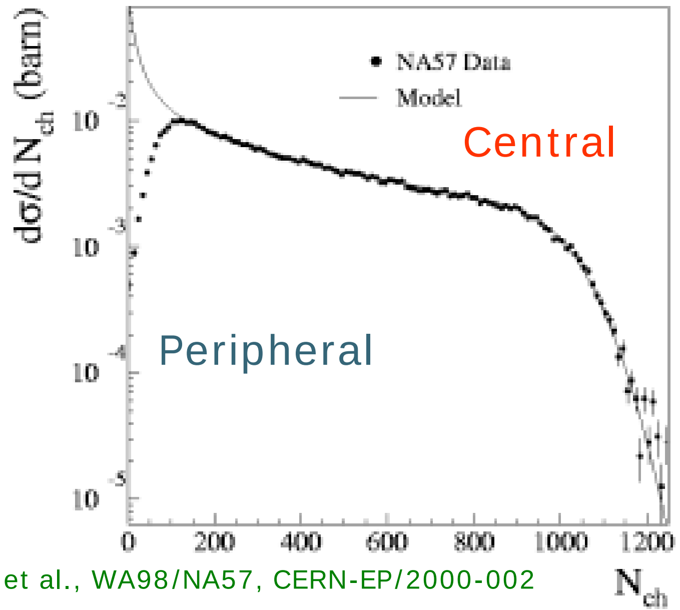
Central collisions



Peripheral collisions





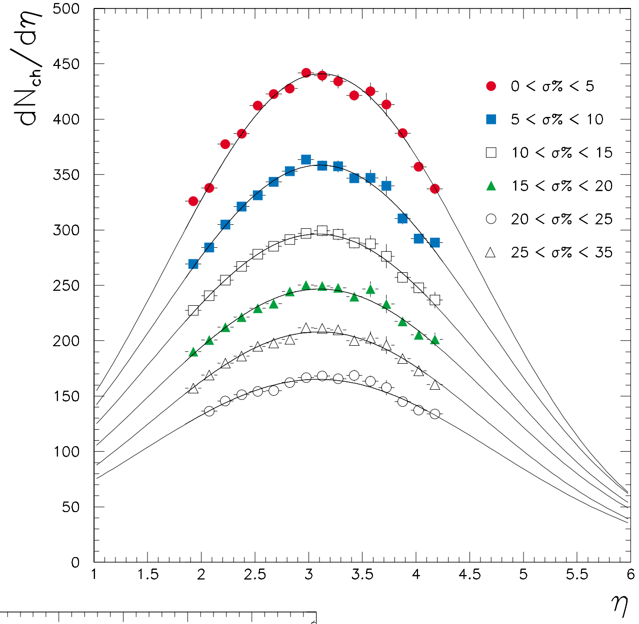


F. Antinori et al., WA98/NA57, CERN-EP/2000-002

Hadroproduction

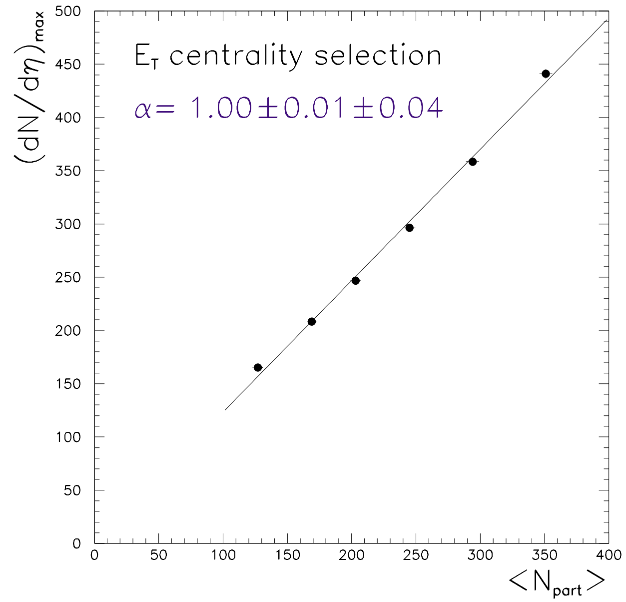
- The collision geometry is estimated through measured N_{ch},E_T,E_{ZDC} distributions
- Use Glauber model to analyze the spectra
- Physics assumption:

$<E_T>, <N_{ch}> \propto (N_{wound}) = (A+B-N_{spect})$ (wounded nucleon model, WNM)



- NA57: data agree with WNM (α=1)
- If α is left free $\rightarrow$ α=1.05±0.05

- NA50: α=1.00±0.01±0.04

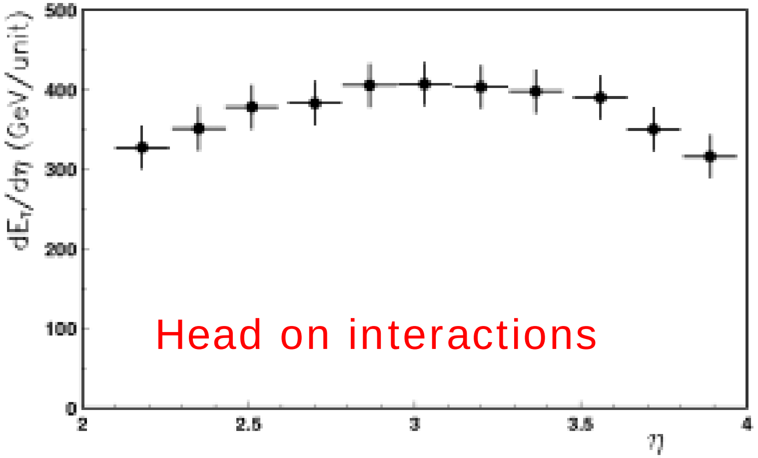


M.C. Abreu et al., NA50, CERN-EP/2002-018

Energy Density

- E_T measurements at mid-rapidity (NA49)
- Using Bjorken's estimate

$$\varepsilon = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

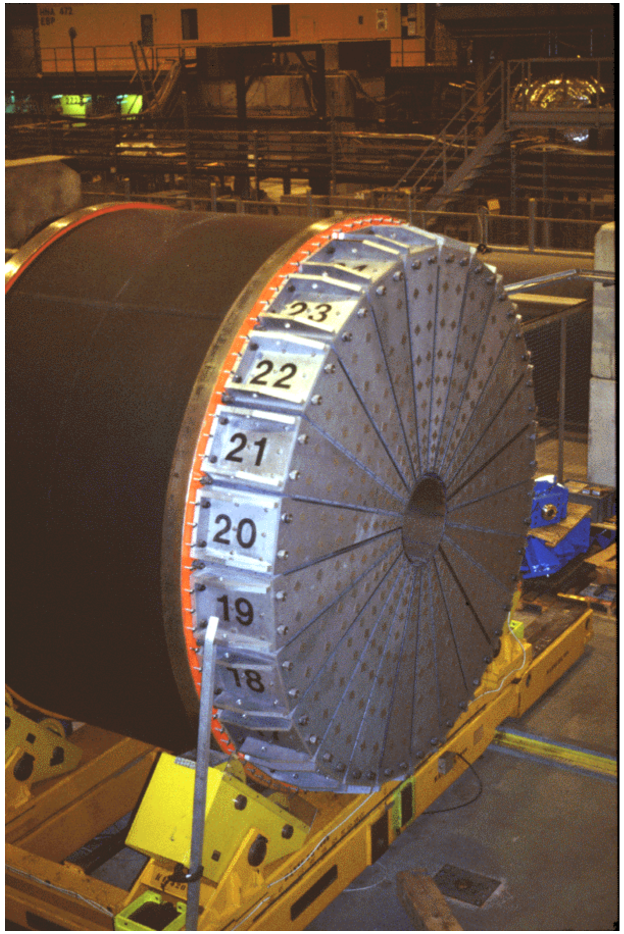


- ε =3.2 GeV/fm^3 for Pb-Pb collisions
- Well above the expected value of $\varepsilon_{crit} \approx$ 1 GeV/fm^3

K. Karsch,
Nucl. Phys. A698 (2002) 199c.

System	E_{LAB}/A (GeV)	$n_{part.}^{total}$	$E_T^{4\pi,Bb}$/part. (GeV)	E_T^{max}/part. (GeV)	S_R	ε (GeV/fm^3)
S+S	200	58	3.2	6.9	0.47	1.3
S+Au	200	113	3.2	6.1	0.52	2.6
Pb+Pb	158	390	3.5	6.0	0.57	3.2

T. Alber et al., NA49, Phys. Lett. 75 (1995) 3814.

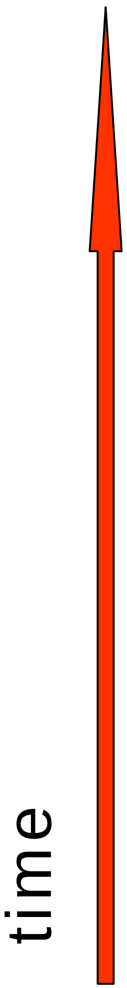


24 (φ) * 10 (r) sectors

16 χ_0 (=1λ_I) + 6 λ_I

R_{in}=28 cm, R_{out}=150 cm

QGP Signals



- Strangeness enhancement

  particle species are fixed at the last inelastic scattering but reflect the chemical composition of the deconfined phase

- Charmonia suppression

  $c\bar{c}$ pair is created <u>before</u> the formation of the plasma (hard scattering). Its evolution is sensitive to the surrounding medium

- Thermal photons and thermal dileptons

  are produced in the deconfined phase. They don’t interact strongly with the surrounding medium. They carry information about the early stage of the collision

Strangeness in a QGP

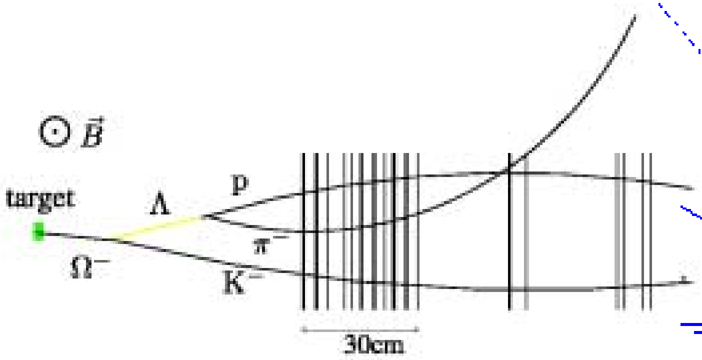
- High gluon density → production by gluon fusion

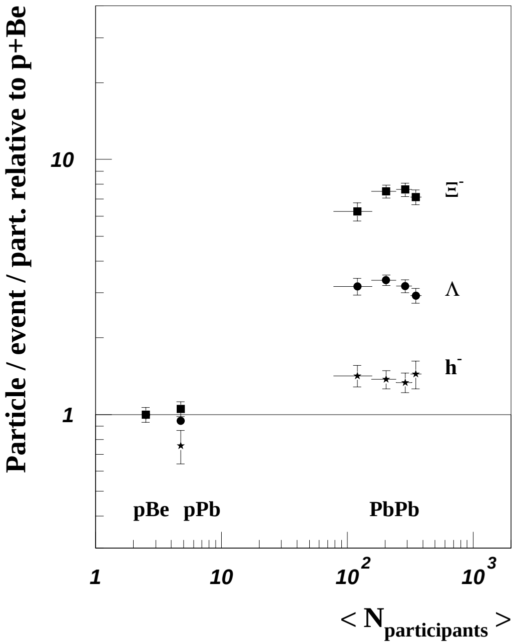
- Restoration of chiral symmetry: lower mass for the strange quarks → lower production threshold

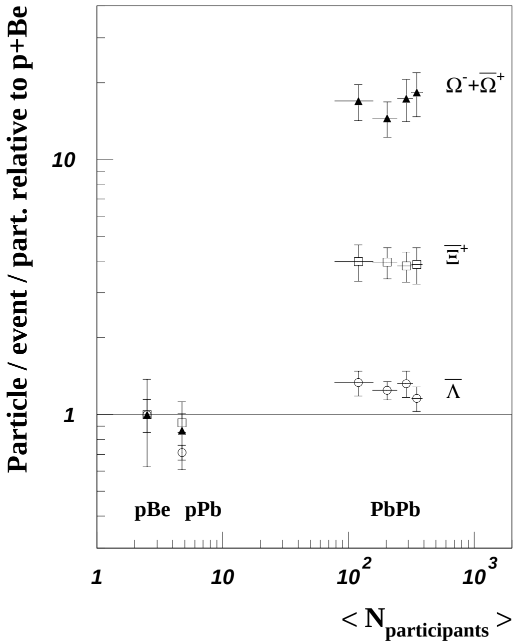
- In a baryon rich QGP it's energetically convenient to create strange quarks because Fermi levels of light quarks are occupied (AGS-SPS)

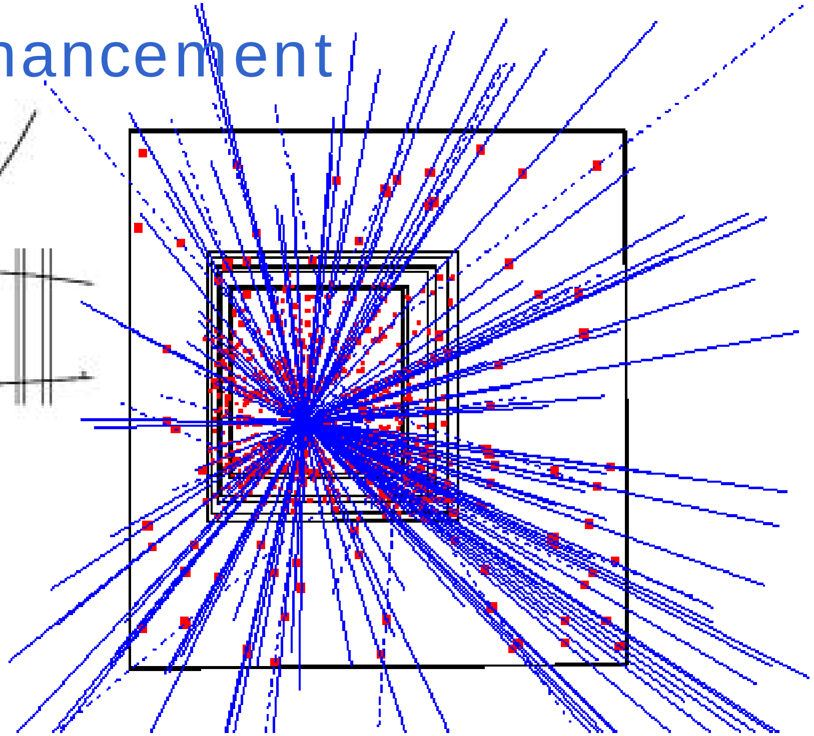
WA97/NA57: Strangeness enhancement

- PID through kinematic analysis of decay chain (no TOF)
- Small-acceptance, granular silicon detector









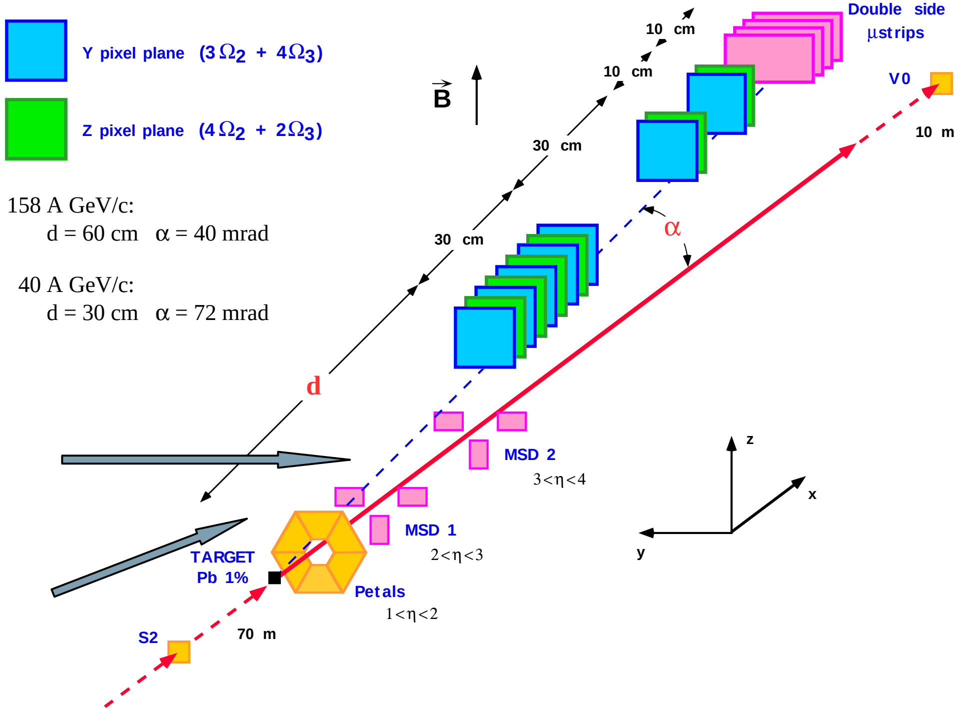
Precise tracking in a high multiplicity environment

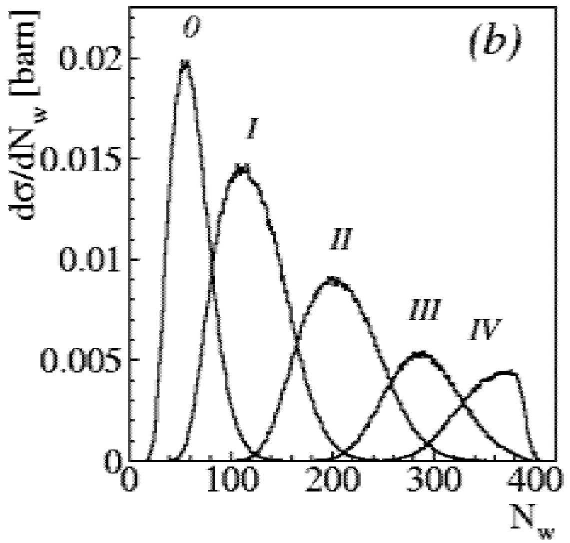
F. Antinori et al., Nucl. Phys. A661 (1999) 130c-139c. R.A. Fini et al., J. Phys. G: Nucl. Part. Phys. 27 (2001) 375.

NA57 experimental setup

F. Antinori et al., NA57, Nucl. Phys. A698 (2002) 127c.

- Silicon pixel telescope
- New magnet
- New DAQ to cope with higher trigger rates (60% of total Pb-Pb inelastic c.s.)



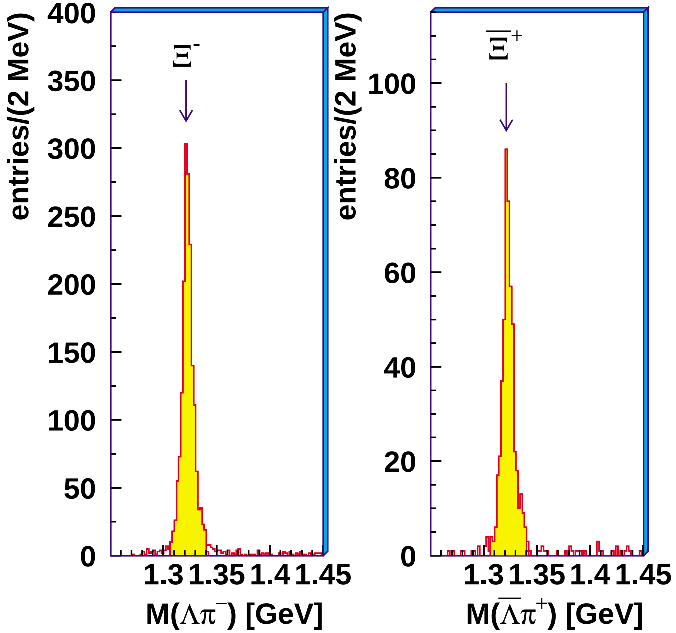


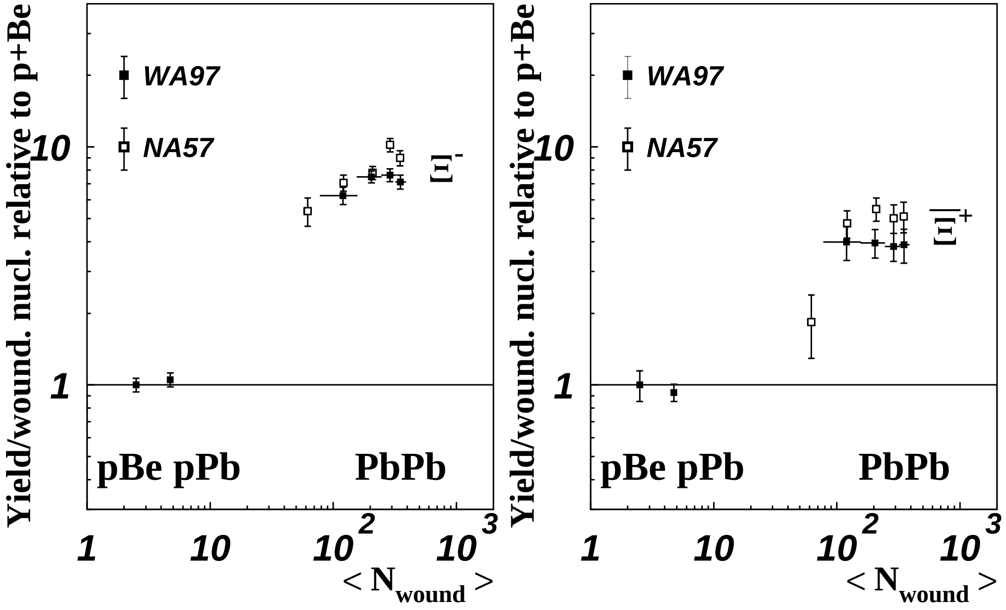
Centrality estimation

Centrality trigger

- 13 silicon pixel detector planes (75/50x500 μm^2) ≈ 1.6 10^6 channels
- Average vertex position measured every ½ hour during the run (beam spot: 350 x 650 μm^2)
- Pb-Pb @ 40A GeV and 158A GeV with reference pA data for both energies

NA57: first results





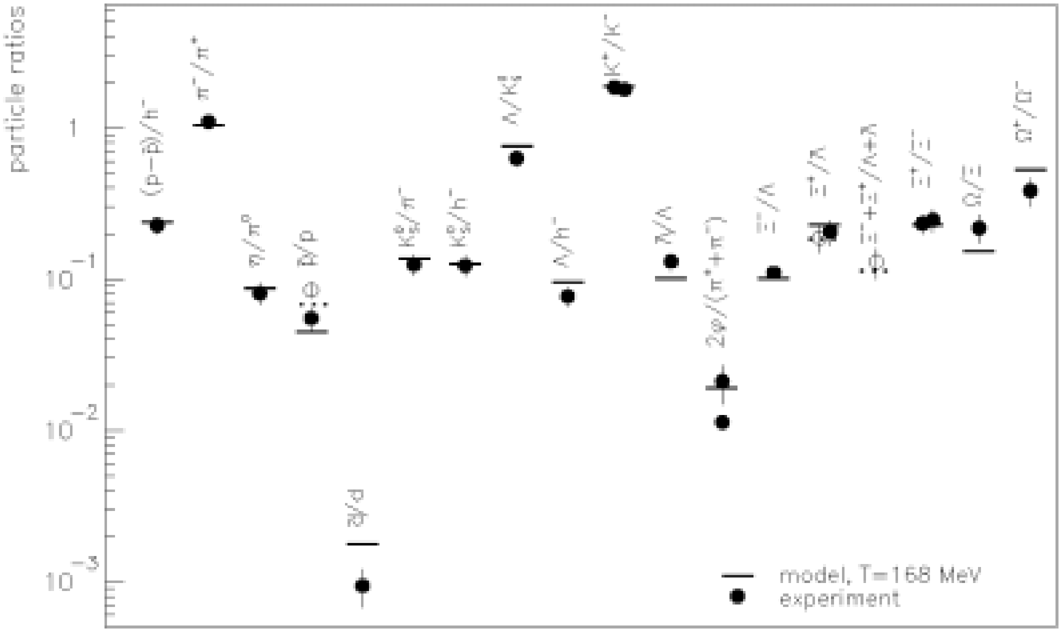
F. Antinori et al., NA57, Nucl. Phys. A698 (2002) 127c.

- Saturation of strangeness enhancement in Pb-Pb over 150 wounded nucleons
- Possible threshold for the enhancement in peripheral Pb-Pb collisions between 50 and 100 wounded nucleons
- Most peripheral point roughly corresponds in centrality to the discontinuity in J/Ψ suppression observed by NA50

Analysis of the full set of enhancements and new results from the 40A GeV Pb-Pb and p-Be data taking may help in clarifying the enhancement pattern

Thermal Models

- Test the data against statistical models which assume thermal and chemical equilibrium
- Reproduce particle ratio and abundances with a small set of parameters: T=168 MeV, μ_B=266 MeV, $\gamma_s \equiv 1$



P. Braun-Munzinger et al., Phys. Lett. B465 (1999) 15

- Similar T values for $e^+e^-, p\bar{p}, AA$ (slightly larger in AA)
- Higher γ_s in AA collisions; very close to strange quark equilibration

See: R. Stock, Nucl. Phys. A661 (1999) 282c.

- Need accurate hadron data integrated over phase space $\rightarrow$ NA49
- Hadrochemical equilibrium temperatures close to predicted T_{crit} values
- Fast equilibration of strangeness $\rightarrow$ points to a deconfined medium in the early stage

Charmonia Suppression As a Signature for Deconfinement:

"colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region... J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation" (Matsui,Satz Phys. Lett. B178 (1986) 416.)

$c\bar{c}$ pairs are produced very early in the collision by gluon fusion ⇨ probe the medium they cross

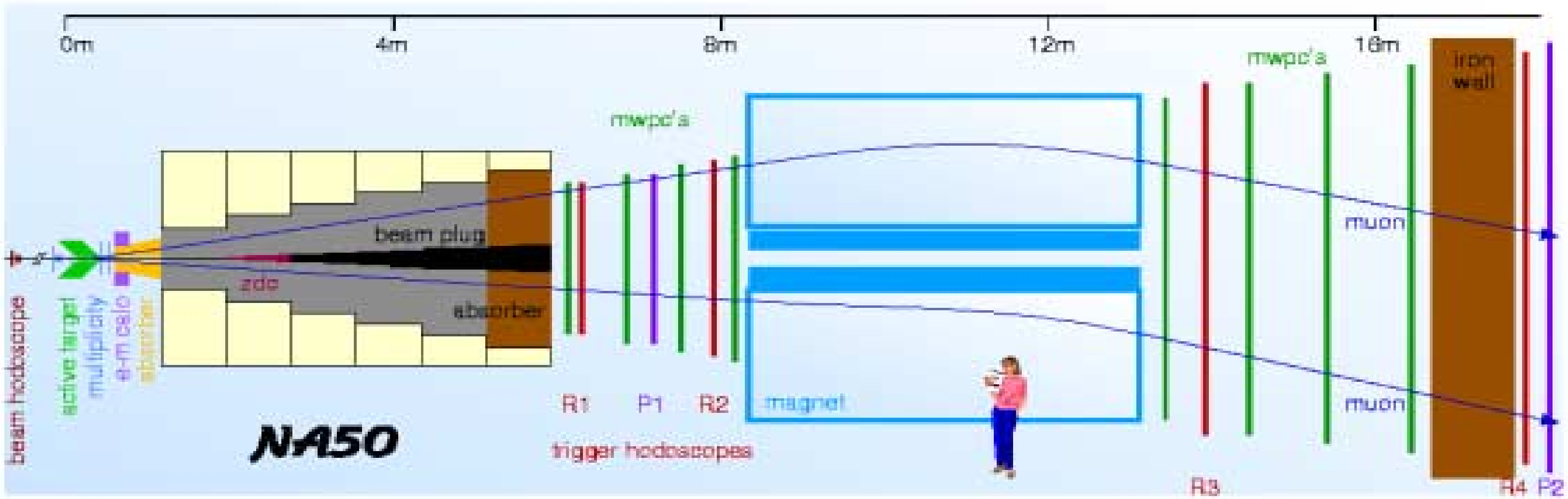
strongly bound states are not easy to break in the (relatively) soft interactions with comoving hadrons.
Anyway they can interact with nuclear matter from target/projectile → effect to be estimated experimentally

Binding energy:
J/ψ ≈ 650 MeV
χ_c ≈ 250 MeV
ψ' ≈ 50 MeV

↑ Hierarchy of suppression

NA38/NA50 experimental apparatus

Muon spectrometer: $2.8<y_{lab}<4$, $|\cos\theta_{Collins\text{-}Soper}| <0.5$, good p_T coverage up to 4 GeV/c



3 independent centrality detectors:
- ZDC: projectile spectator nucleons
- EMCAL: transverse energy $1.1< \eta < 2.3$ (NA50), $1.7< \eta <4.1$ (NA38)
- MD: charged multiplicity $1.11< \eta <3.51$ (MD1), $1.61< \eta <4.13$ (MD2)

- Low cross sections: $\sigma^{tot}_{J/\psi}\approx 3$ nb/nucleon @ SPS Pb energy
- High intensity beams ($>10^7$ s^{-1})

$\rightarrow$ radiation hard detectors

$\rightarrow$ extremely selective dimuon trigger!

Analysis techniques

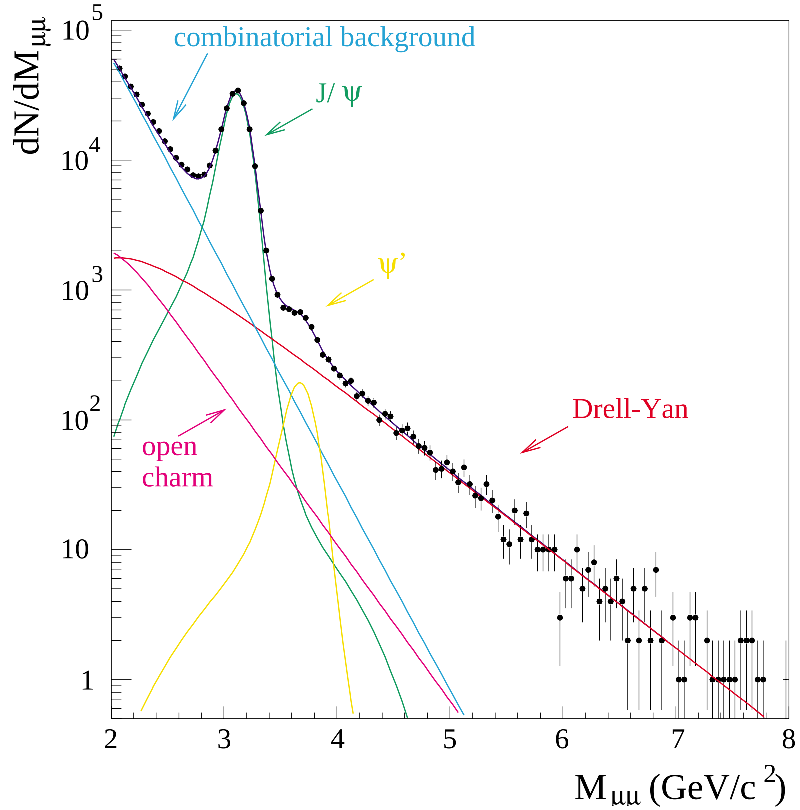
"Standard analysis": estimation of the different components to the invariant mass spectrum by means of a fit

$$\frac{B_{\mu\mu}\,\sigma(J/\psi)}{\sigma(DY)}$$

Comparison of J/ψ production with DY allows to:

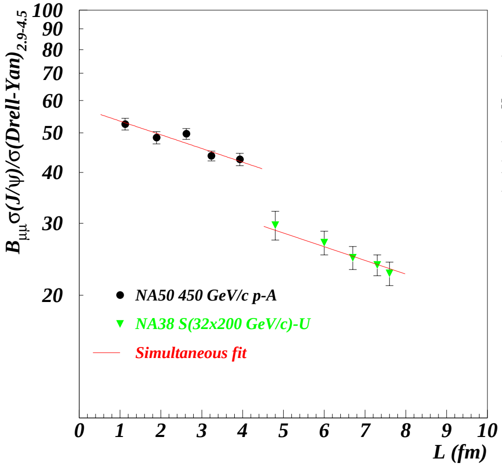
• cancel most systematic uncertainties on: acceptance and trigger/reconstruction efficiencies

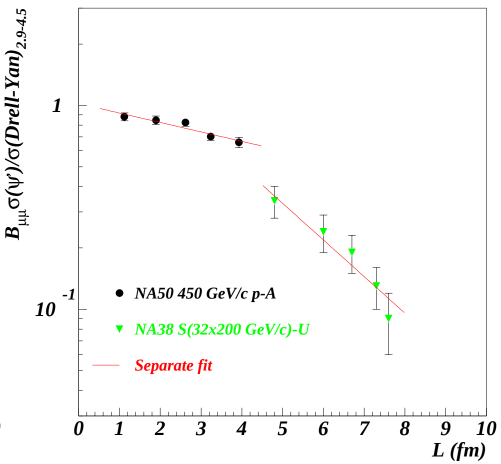
• study J/ψ cross section per nucleon-nucleon collisions since $\sigma(DY) \propto N_{coll}$

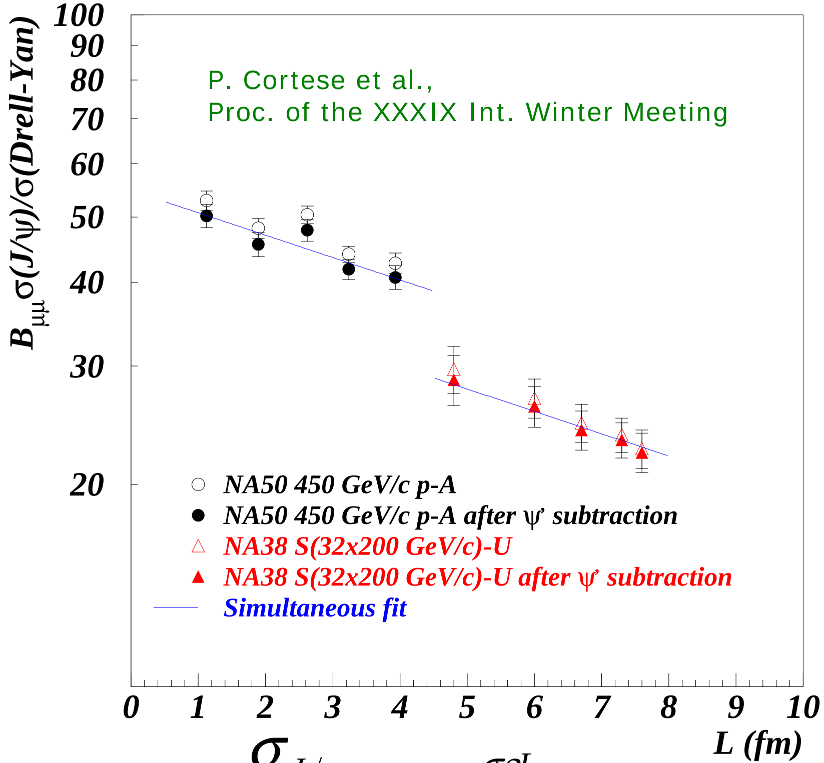


"Minimum bias analysis": DY is calculated with a Glauber model starting from minimum bias events

NA38/NA50 the “normal” absorption







$$\frac{\sigma_{J/\psi}}{\sigma_{DY}} \propto e^{-\sigma\rho L}$$

- $\sigma_{J/\psi}/\sigma_{DY}$ slopes are compatible in pA and S-U collisions: simultaneous fit gives χ^2/dof=0.7
- Separate exponential fit gives:

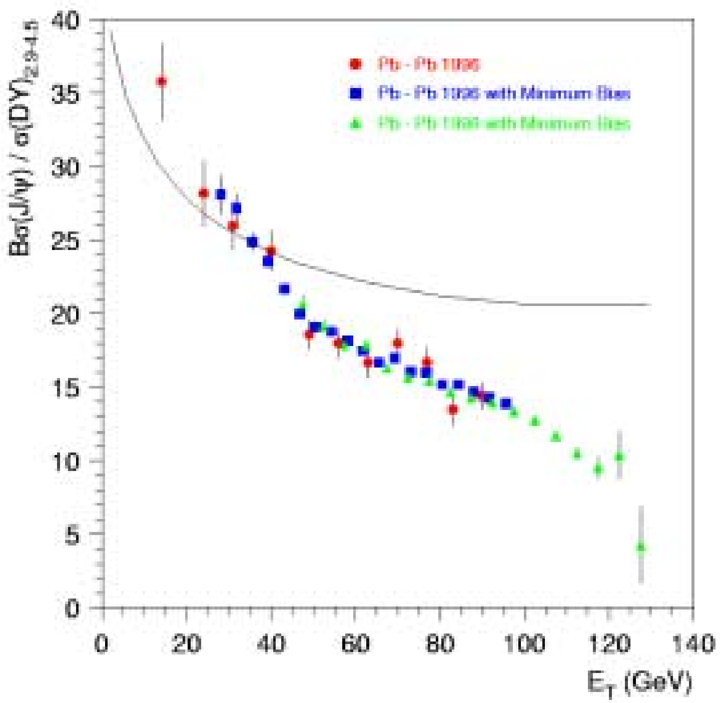
$\sigma_{J/\psi\text{-}N}^{SU} - \sigma_{J/\psi\text{-}N}^{pA} = 1.4 \pm 2.1$ mb

- Using measured ψ'/DY ratios and known branching ratios $\psi'\to\mu\mu$, $\psi'\to J/\psi$, remove ψ' contribution from J/ψ spectra
- Gives better fit quality: now χ^2/dof=0.55
- Separate exponential fit gives now $\sigma_{J/\psi\text{-}N}^{SU} - \sigma_{J/\psi\text{-}N}^{pA} = 0.9 \pm 2.2$ mb

Where $L=\langle\rho L\rangle/\rho_0$ is the average path of the resonance in nuclear matter

NA50 Results (1)

M.C. Abreu et al., Phys. Lett. B477(2000) 28

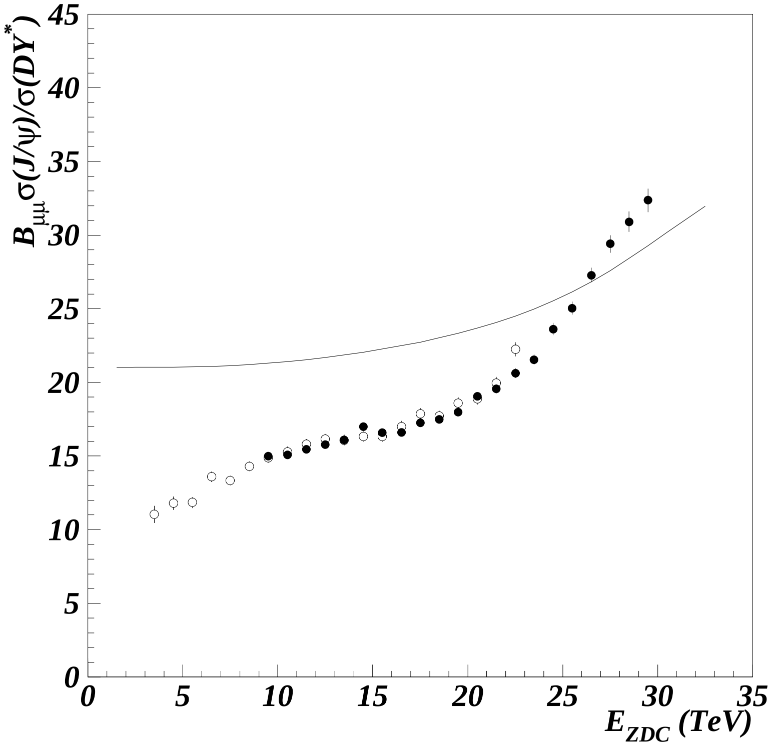


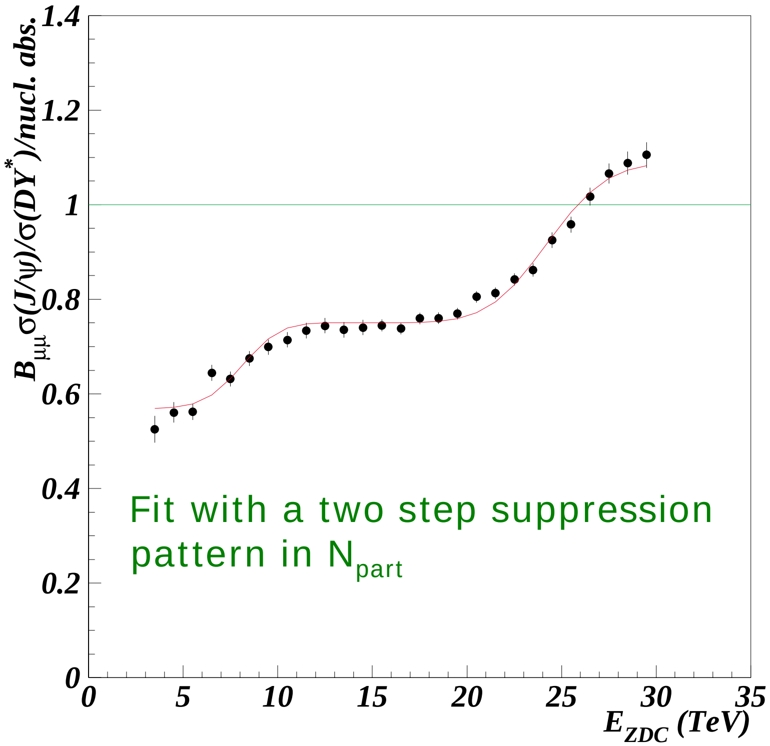
- Two-step pattern
- Qualitative interpretation in a deconfinement scenario:
  - The χ melt in Pb-Pb collisions producing E_T>40 GeV; J/ψ from $\chi \rightarrow J/\psi+\gamma$ are not seen any more
  - The directly produced J/ψ melt in Pb-Pb collisions producing E_T>90 GeV
- Hadronic models cannot produce neither thresholds nor successive steps in the suppression

- Crucial feature of NA50 analysis: narrow centrality bins as a way to detect thresholds in measurable quantities
- Peripheral points still need some refinement → 2000 data taking
- Departure from "normal absorption curve" only in PbPb and not in SU

NA50 Results (2)

M.C. Abreu et al., NA50, Phys. Lett. B521 (2001) 195.



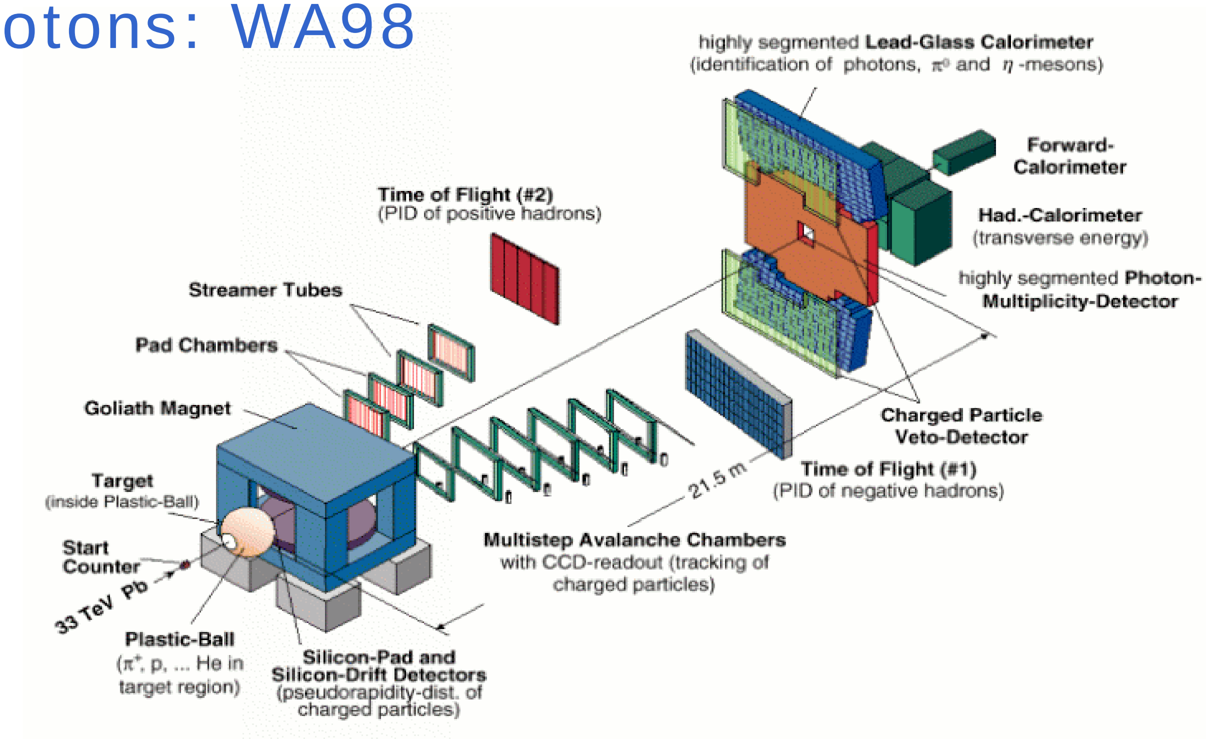


Two step absorption pattern clearly visible

E_{ZDC} measures N_{part}

Pattern compatible with a sharp onset in the N_{part} variable at $N_1=122$, $N_2=334$

Direct photons: WA98



- Large acceptance experiment, hadron and photon spectrometer
  - Magnetic spectrometer: dipole magnet, tracking+TOF
  - Plastic Ball: particles in the target rapidity region ($-1.7<\eta<0.5$, full azimuth)
  - Photon multiplicity detector (converter,lead+scintillator, 54000 pads, $2.8<\eta<4.4$)
  - Lead glass calorimeter (LEDA) (10080 modules, $2<\eta<3$)
  - E_T (MIRAC, $3.5<\eta<5.8$), ZDC, N_{ch}
- Direct photons measurement: large background (especially $\pi^0,\eta\rightarrow\gamma\gamma$)

$\rightarrow$ induces non-negligible systematic errors

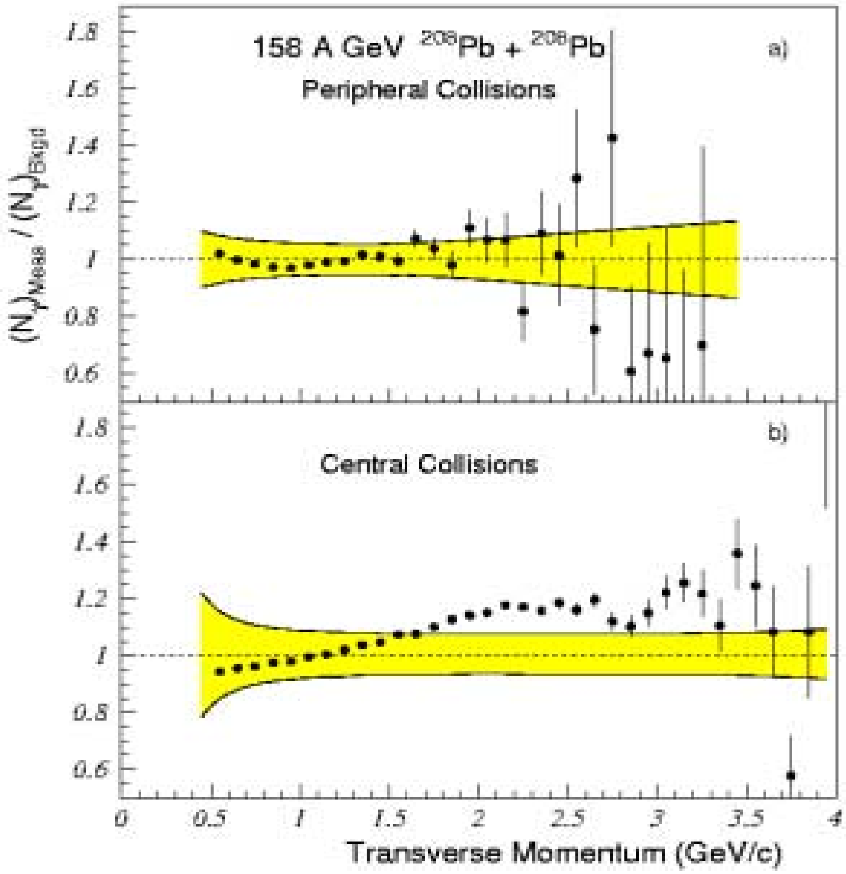
A direct photon signal in Pb-Pb collisions

- Preliminary result: ~10% photon excess over background

- Systematic errors: most important contribution comes from η decay background

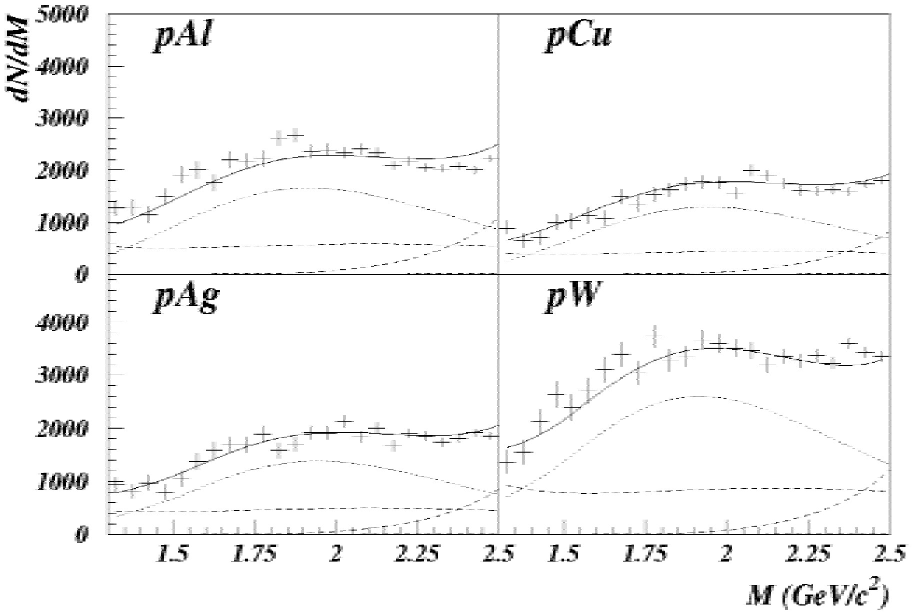
- Calculations not simple: between perturbative and non-perturbative regimes

  - Hydrodynamical models with T_i=335 MeV@τ_i=0.2 fm/c agree with data

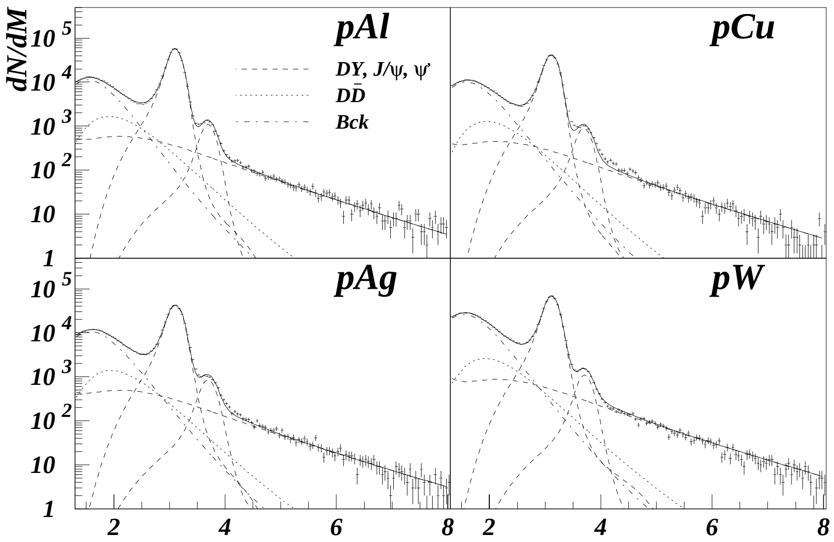


M.M. Aggarwal et al., WA98, Nucl. Phys. A698 (2002) 135c.

Search for thermal dimuons in the Intermediate Mass Region (NA38/NA50)



Open Charm Reference: pA interactions

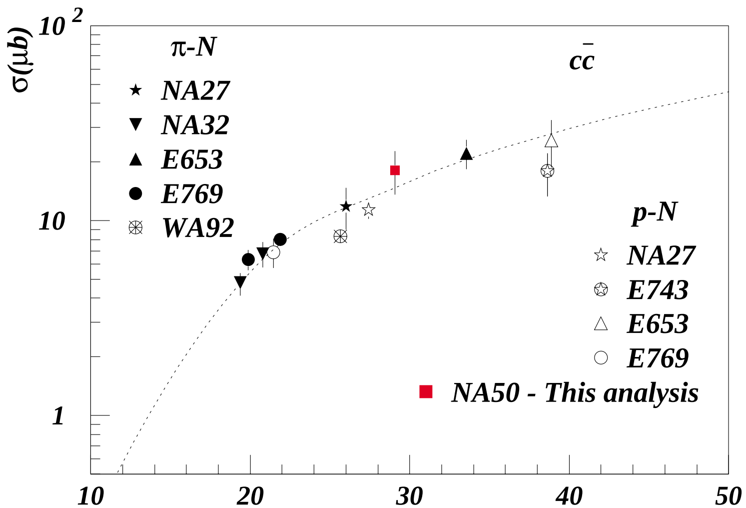


M.C. Abreu et al., Eur. Phys. J. C14 (2000) 443. M (GeV/c²)

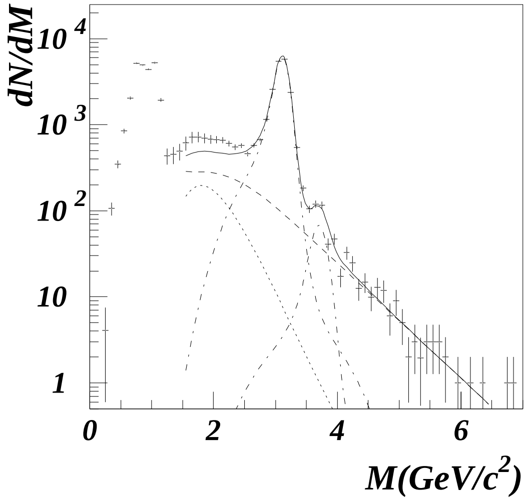
Open charm and DY both scale as the number of collisions → constant ratio in different systems

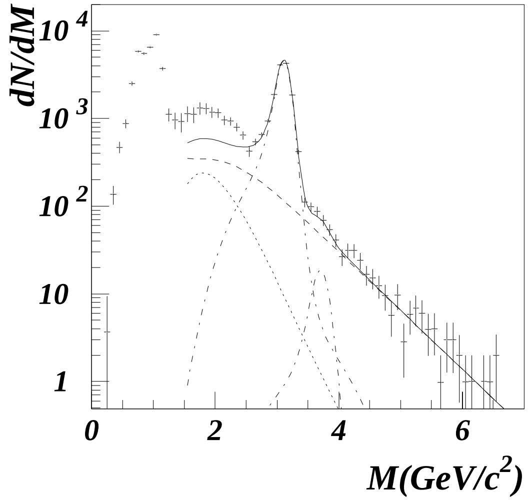
From a simultaneous fit to pA extract charm cross section ($x_F>0$)

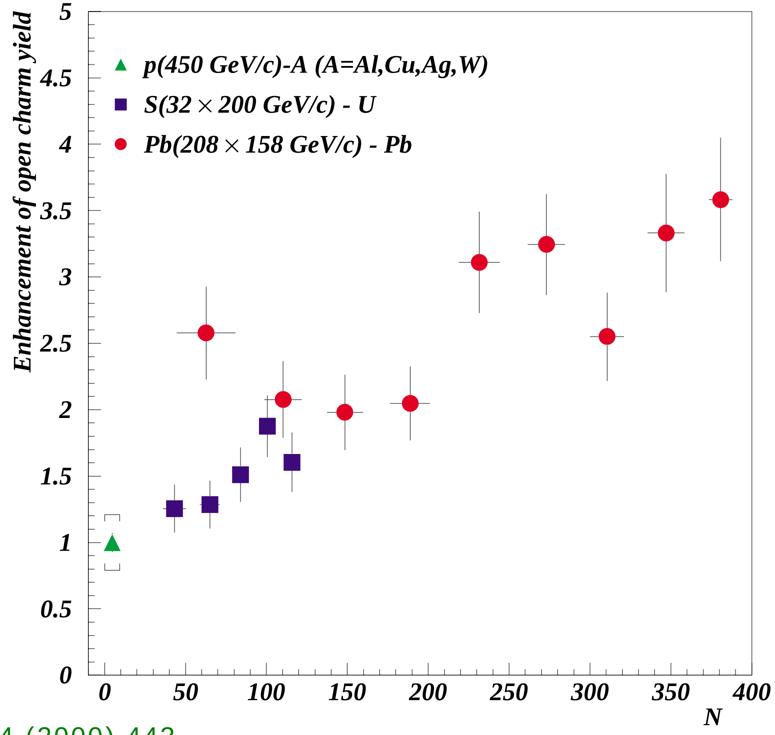
Good agreement with direct measurements

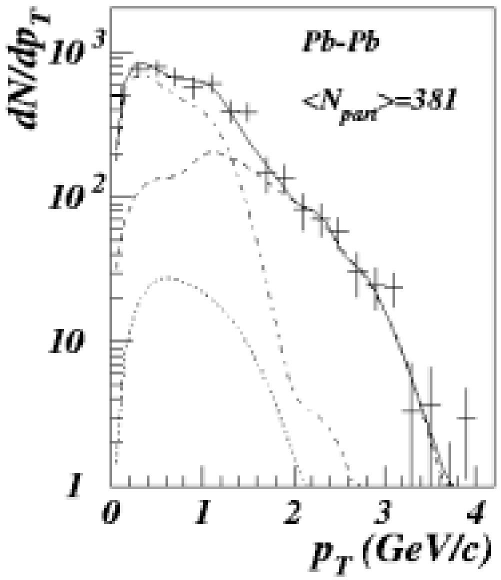


IMR in Pb-Pb collisions









M.C. Abreu et al., Eur. Phys. J. C14 (2000) 443.

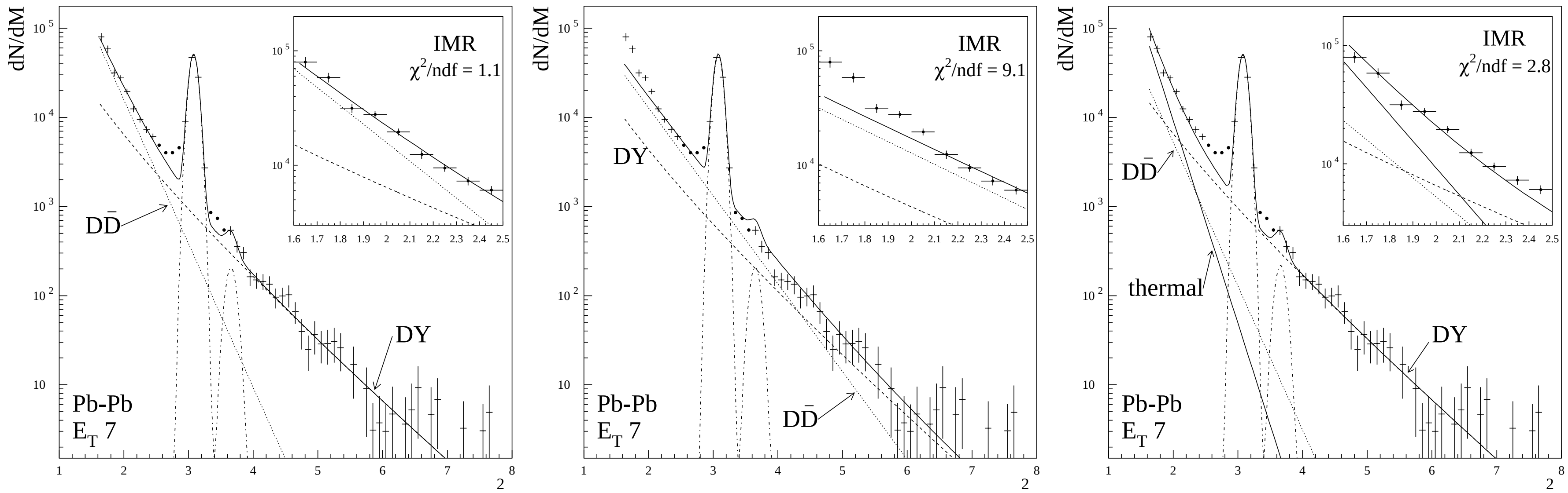
- Excess of dimuon production in A-A collisions compatible with an enhancement (~factor 3) of open charm production for the most central Pb-Pb collisions

Accounts for observed mass and p_t spectra

But thermal charm production is not expected at these energies!

IMR Excess vs. Models

L. Capelli et al., NA38/NA50, Nucl. Phys. A698 (2002) 539c.



Deconvolution technique to correct for acceptance and smearing. A direct comparison with model calculations is possible

Test with:

• Charm enhancement (left)

• D mesons rescattering (middle): Z. Lin and X.N. Wang, Phys. Lett. B444 (1998) 245.

• Thermal production(right) T ≈ 175-200 MeV in the deconfined phase: R. Rapp and E. Shuryak, Phys. Lett. B473 (2000) 13.

The excess is compatible with charm enhancement and thermal production

Open Questions

• What is the origin of the excess production of intermediate mass dimuons? Thermal dimuon production or open charm enhancement?

• What is the open charm production cross section in nucleus-nucleus collisions?

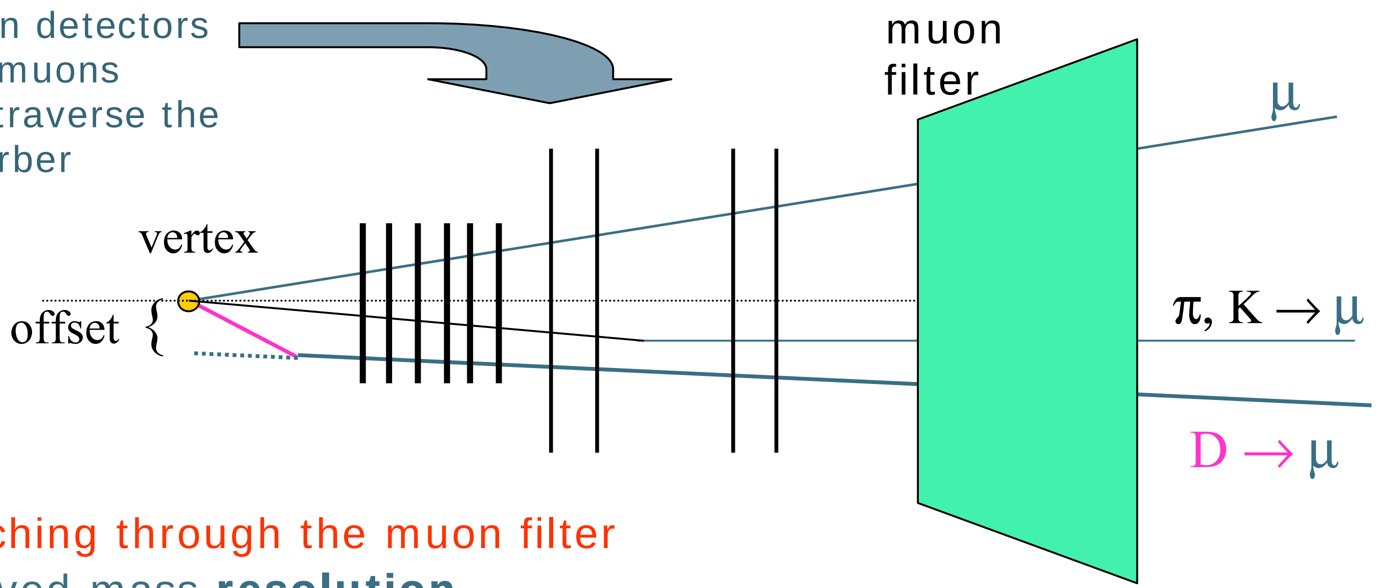
• What is the physics variable that rules the onset of J/ψ suppression?

• Which fraction of the J/ψ yield comes from χ_c decays?

• What is the nuclear dependence of χ_c production in p-A collisions?

NA60 detector concept: upgraded NA50 spectrometer

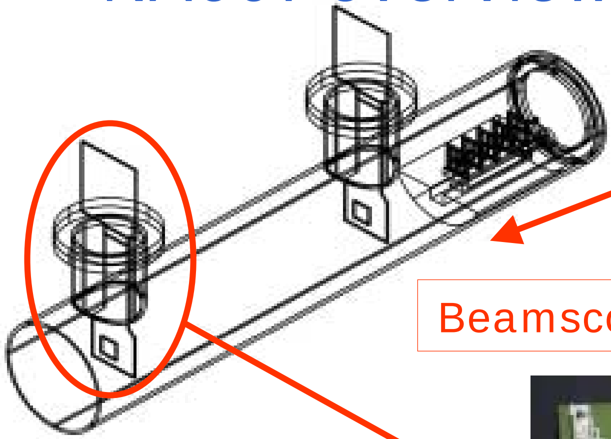
Adding silicon detectors to track the muons before they traverse the hadron absorber

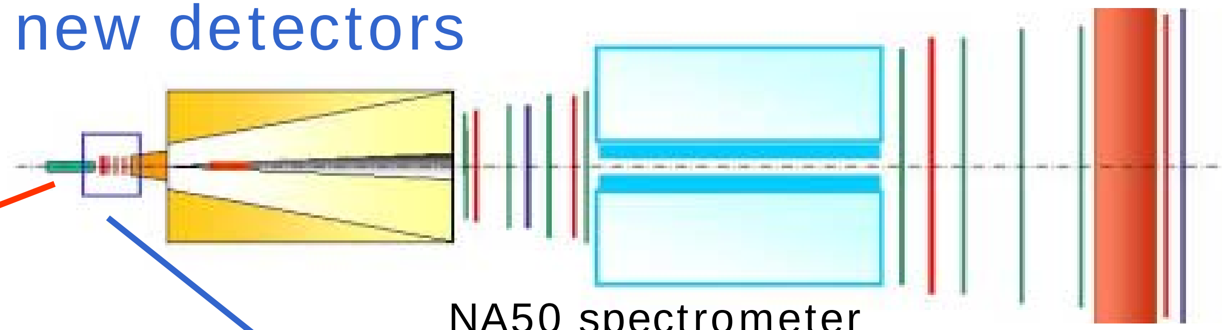


- Track matching through the muon filter
  - Improved mass **resolution**
  - Improved **signal / background** ratio (rejection of π and K decays)
  - Improved systematical uncertainties (vertex reconstruction)

- Muon track offset measurement
  - Separate **charm** from **prompt** (thermal) dimuons

NA60: overview of new detectors





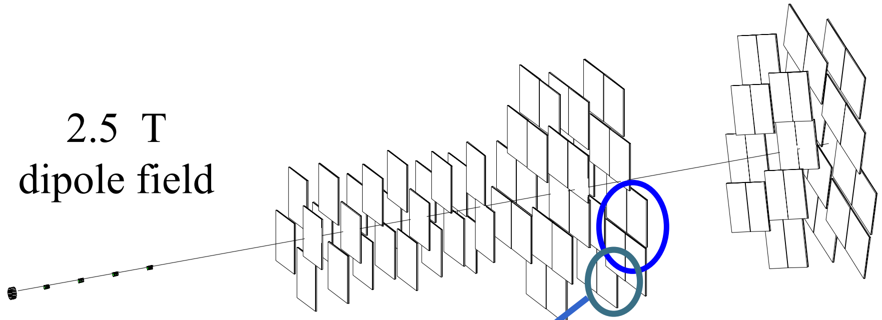
NA50 spectrometer

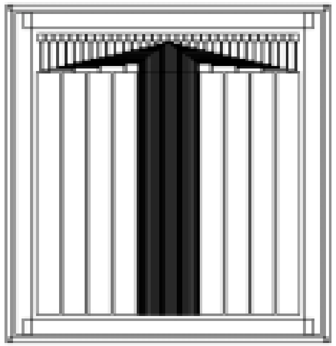
Beamscope

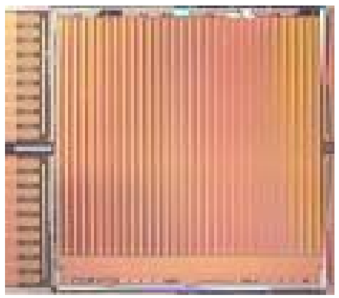
Silicon pixel telescope

- 2 x-y stations of m-strip Si detectors at T = 130 K
- ~ 20 µm resolution on the transverse coordinates of the beam ions

2.5 T dipole field

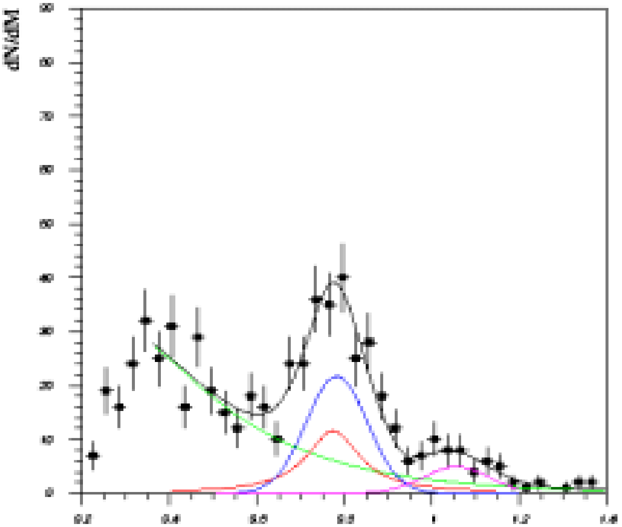


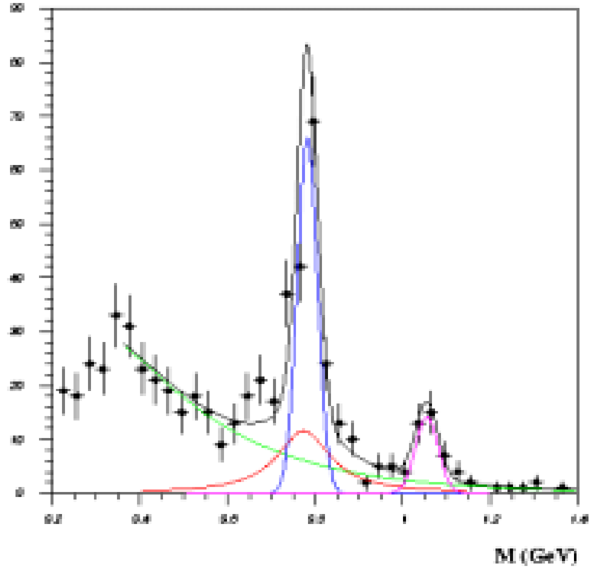


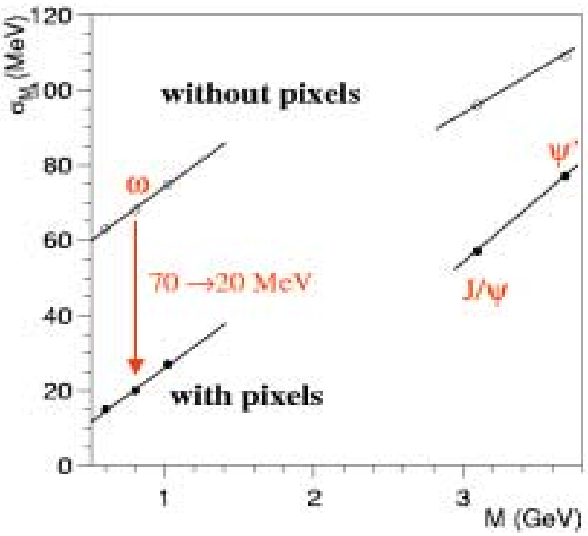


- 10 planes
- 88 pixel readout chips
- 720 000 channels
- pixel size : $50 \times 425\ \mu m^2$

NA60 dimuon mass resolution







Data:
450 GeV,
3 days, ~10^8 protons / burst,
10 mm Be target (5 % λ_{int})

Clear improvement in mass resolution, thanks to the vertex spectrometer

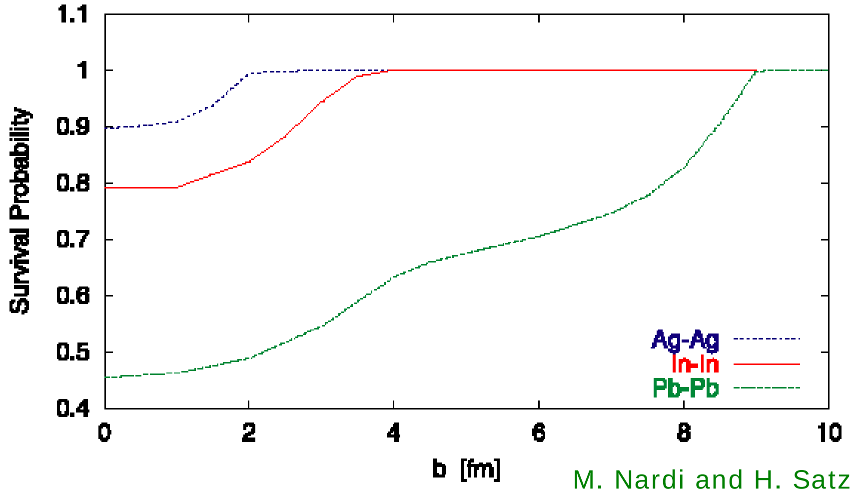
σ_M at M = 1 GeV :

70 MeV in NA50; 20 MeV in NA60

Good agreement data ↔ simulation

Approved NA60 program

- 2002: p-Be, p-Pb @ 450 GeV/c
- Fall 2002: Pb-Pb @ 158A GeV
- 2003: In-In @ 200A GeV



M. Nardi and H. Satz, private communication

- Study of χ_C nuclear dependence p-Be and p-Pb α_χ
- Open charm production/direct thermal dileptons
- Strangeness enhancement $\phi/(\rho+\omega)$
- Charmonia suppression
  - Pb-Pb → confirmation of NA50 result, better study of ψ'
  - In-In → Clarification of the suppression pattern and of what parameter governs suppression

Conclusion: fingerprints of a deconfined phase

- Energy density above critical value for deconfined phase: $\varepsilon \approx 3$ GeV/fm^3, $\varepsilon_{crit} \approx 1$ GeV/fm^3
- Strangeness enhancement ≈ 15 for Ω
- Particle yields reproduced by thermal models $T \approx 170$ MeV
- Hierarchy of suppression of charmonia resonances: χ melts at $b \approx 8$fm, J/ψ at $b < 3.6$ fm
- Indications of thermal radiation