Search for the rare charm decay $D^0 \rightarrow \mu^+\mu^-$
in the NA60 experiment

Outline:

- Summary of the detector capabilities
- Physics motivation
- Expectations from Monte Carlo simulation
- Related detector issues

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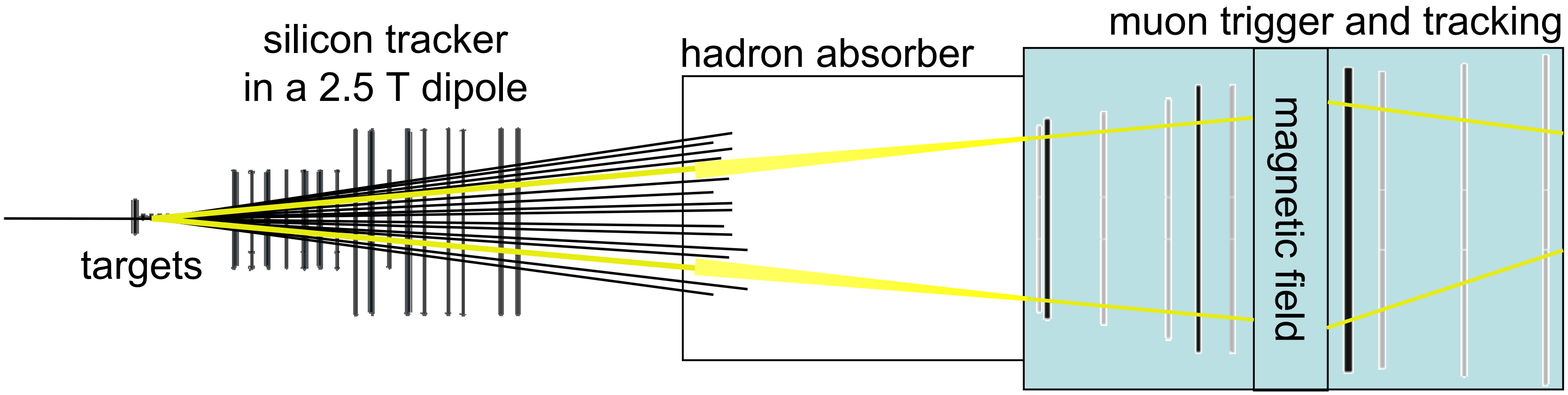
Summary of the detector capabilities

- The NA60 experiment has been designed to withstand the harsh conditions of high-energy heavy-ion collisions. It has a very clean and selective dimuon trigger, which allows for running at very high luminosities, associated to a high granularity and radiation tolerant silicon tracker in the target region.
- By matching the muons to the tracks in the vertex region, in coordinate and momentum space, the dimuon mass resolution is considerably improved and we can distinguish between prompt and displaced muon pairs.
- Can we profit from this existing experiment to probe rare charm decays?

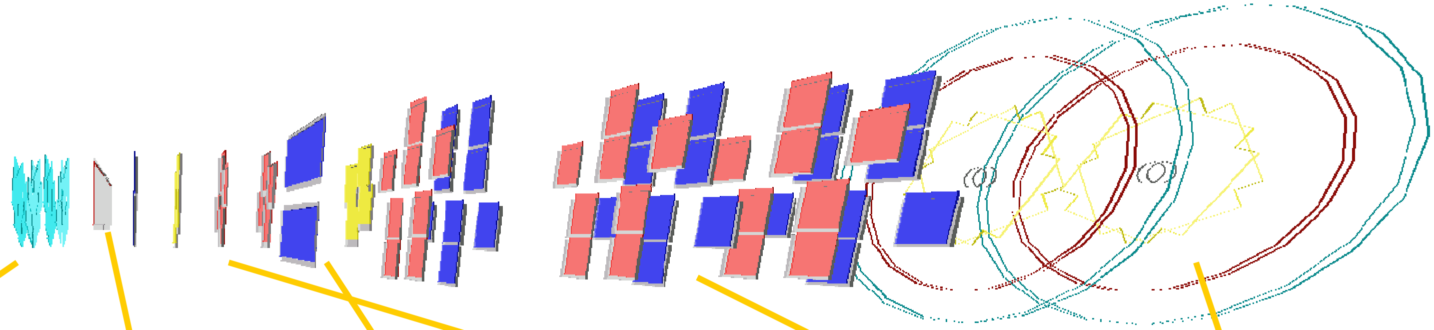


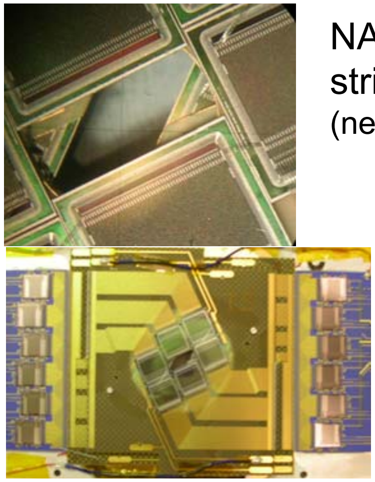
The NA60 setup in the 2004 proton run

- Four different kinds of silicon tracking detectors: pixels (good granularity) and strips (good timing)
- 400 GeV protons at 2 × 10^9 p/burst; ~ 10 % interaction length target; ⇒ ~ 40 MHz collision rate

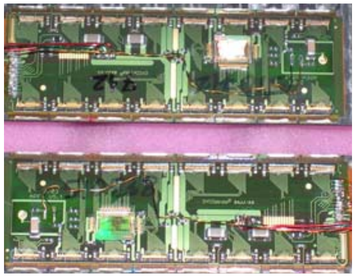
7 different nuclear targets

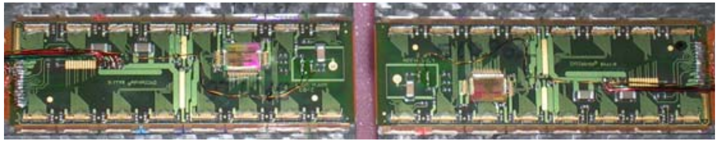
(Be, Al, Cu, In, W, Pb, U)

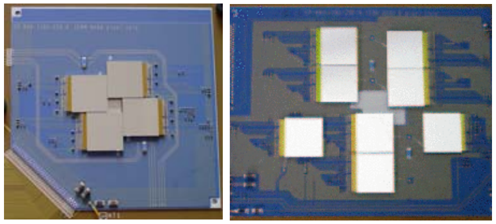




NA60-ATLAS
strip & pixel planes
(new, 40 MHz, rad-hard)

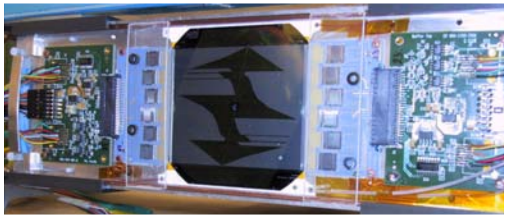




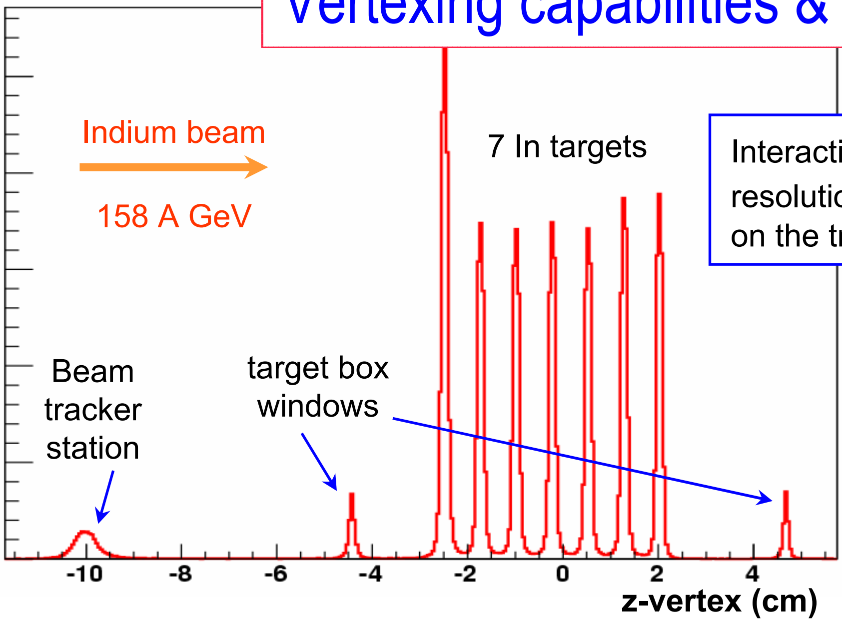


NA60-BNL
strip planes
(used in 2002, 40 MHz)

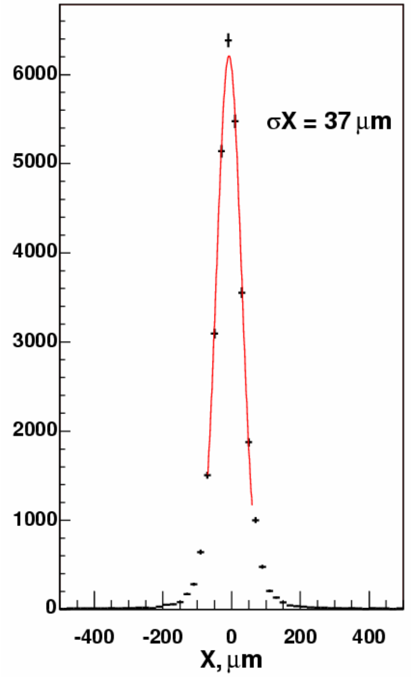
NA60-ALICE
pixel planes
(used in 2003, 10 MHz)



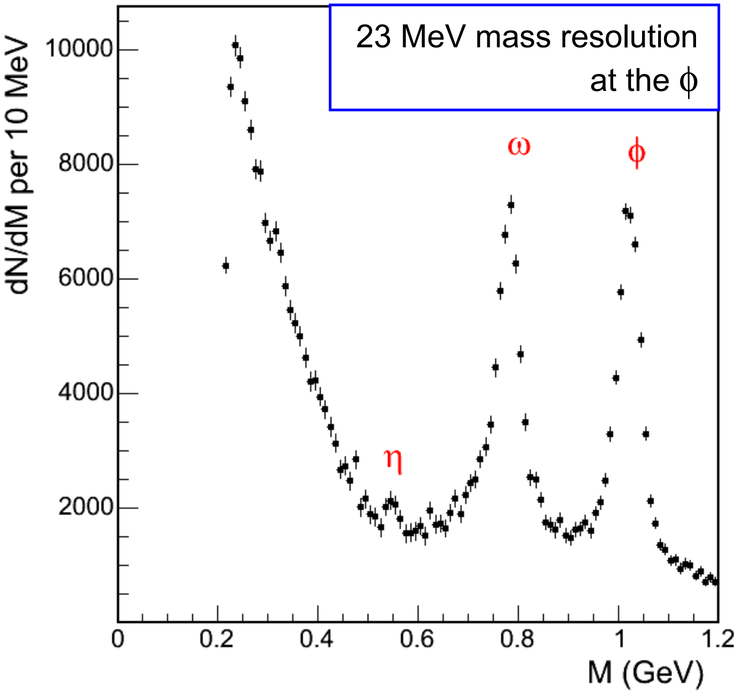
Vertexing capabilities & dimuon mass resolution



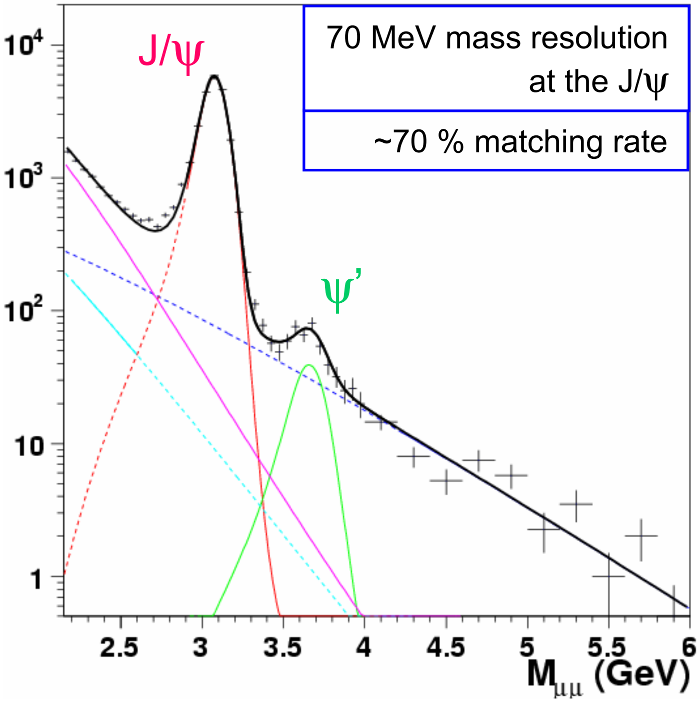
Interaction vertices determined with ~200 µm resolution along the beam axis and ~20 µm on the transverse coordinates



Muon track offset resolution: around 40 µm (to be improved)

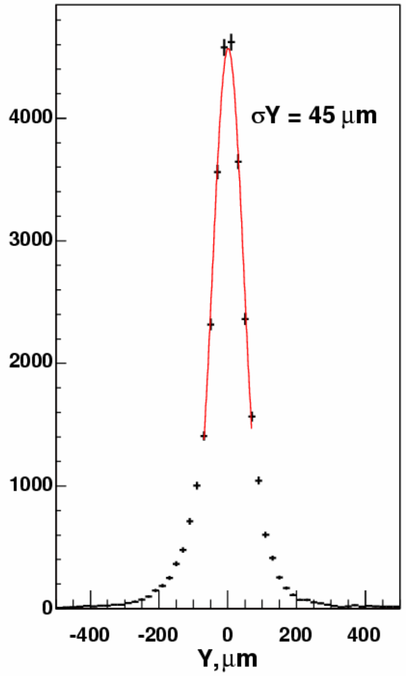


23 MeV mass resolution at the ϕ



70 MeV mass resolution at the J/ψ

~70 % matching rate



Searching for $D^0 \to \mu^+\mu^-$ decays: why?

“**Flavor-changing neutral currents.** In the Standard Model the neutral-current interactions do not change flavor. One cannot isolate flavor-changing neutral current (FCNC) effects in non leptonic decays. Tests for FCNC are therefore limited to hadron decays into lepton pairs. Such decays are expected only in second-order in the electroweak coupling in the Standard Model.”

PDG

Standard Model expectation for the $D^0 \to \mu^+\mu^-$ Branching Ratio:

- at tree level $\sim 10^{-18}$
- long distance effects may enhance it to $\sim 3 \times 10^{-13}$ ⇒ too small to be measured

But it can be significantly enhanced with New Physics !

An MSSM variant with R-parity violation, for instance, predicts up to 3.5×10^{-6}

Other models, with multiple Higgs doublets, horizontal gauge bosons, extra fermions, or extra dimensions, give values in the range 10^{-10} to 10^{-8}

⇒ Observing $D^0 \to \mu^+\mu^-$ events would be a sign of physics beyond the Standard Model

⇒ Failure to find them restricts the parameter space of SM extensions

PDG 2004 upper limit: 4.1×10^{-6} at 90% CL, from WA92 and E771

CDF and HERA-B recently reached 2.5×10^{-6}

→ NA60 can improve these values by more than a factor 10

Monte Carlo simulation

The events were simulated with Pythia and GEANT, and reconstructed with the standard NA60 offline software, using the present NA60 setup (not optimized for this study)

Enough events were generated to have 100 000 surviving the trigger criteria for each relevant physics process: Drell-Yan dimuons, simultaneous semi-muonic decays of D mesons (DDbar) and $D^0 \rightarrow \mu^+\mu^-$ decays

The dimuon mass resolution at the D^0 mass is 40 MeV

The dimuon acceptances times reconstruction and matching efficiencies, with respect to full phase space, for Drell-Yan, DDbar and $D^0 \rightarrow \mu^+\mu^-$ are 1.2, 0.4 and 1.9 %, respectively

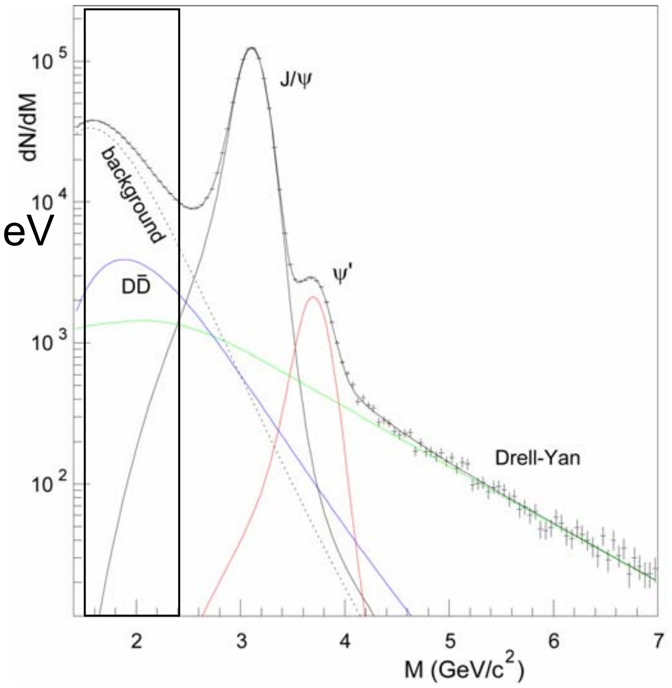
Inputs for the normalization of the D^0 yield:

→ 20 μb ccbar cross-section in pp collisions at 400 GeV

→ per ccbar, we get 1.17 D^0 mesons (including D^0bar)

→ charm scales as a hard process: $\sigma_{pA} = \sigma_{pp}\, A$

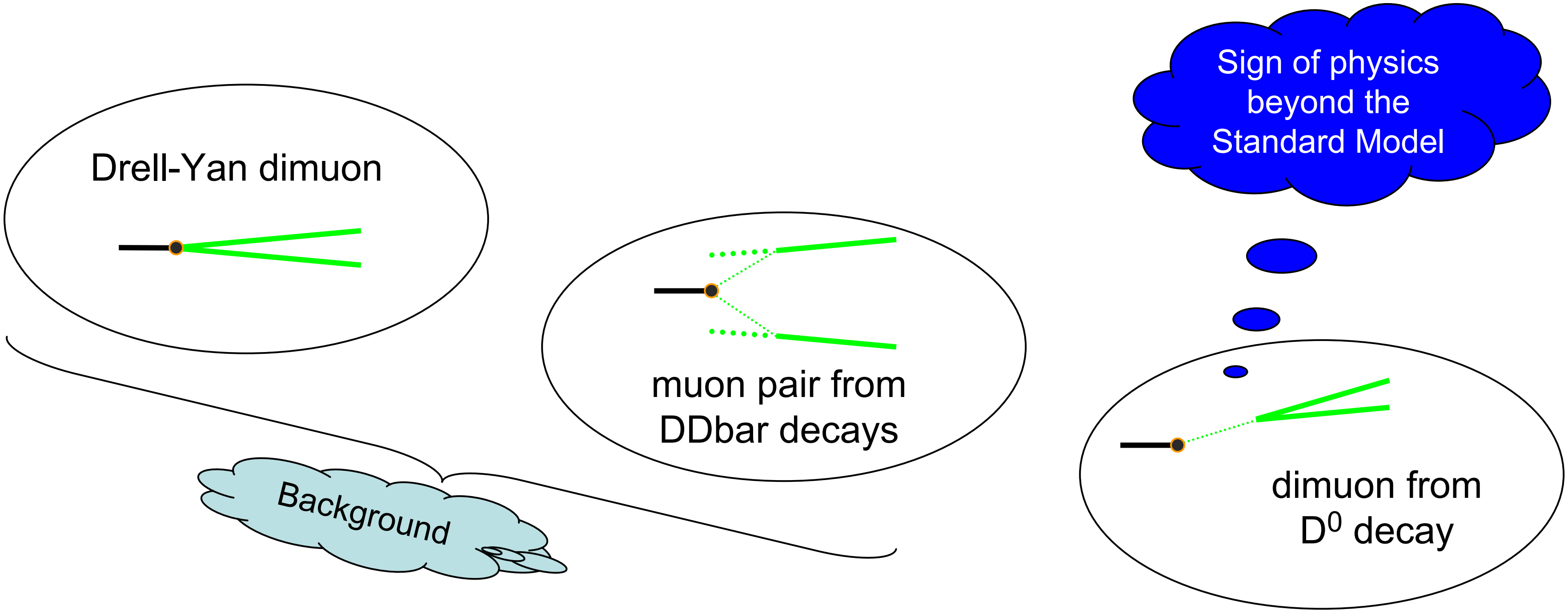
No hadronic event has been added (yet)



Event selection

Selecting a window of ±60 MeV around the D^0 mass retains 80% of the D^0 "peak", while strongly reducing the yield of DDbar and Drell-Yan (continuum) events.

Applying certain topological selection cuts, using the distances at the points of closest approach between the two muons and the interaction point, we retain ~40% of the previously selected $D^0 \rightarrow \mu^+\mu^-$ events, while the yields of DDbar and Drell-Yan events are further reduced by factors 10 and 100, respectively.



Drell-Yan dimuon

muon pair from DDbar decays

Background

Sign of physics beyond the Standard Model

dimuon from D^0 decay

Foreseeable results

With 10 Uranium targets, 1 mm thick each, and a beam intensity of 10^{10} protons per burst, we have a collision rate of 200 MHz, or one p-U collision every 5 ns, on average.

After 3 months of run, we will probe 3×10^{14} p-U collisions, equivalent to 7×10^{16} pp collisions, which will produce 8×10^{11} D^0 mesons. They will lead to around 1.5×10^{10} D^0 *decay candidates* accepted, reconstructed and matched.

If the branching ratio is 2.5×10^{-7}, i.e. 10 times smaller than the current upper limits, we are left with a signal of 1000 counts on a background of 30000 events: a 5 σ observation.

The background level (mostly DDbar) can be further reduced if we restrict the data analysis to the D^0 mesons resulting from the decay $D^{*+} \rightarrow D^0 \pi^+$, as done in CDF.

More home work is needed to clarify some questions. For instance:

- Which other decay channel should we use for normalization?
- Are there other sources of background events?

We will soon learn more, after looking at the (Indium-Indium) data we have on tape

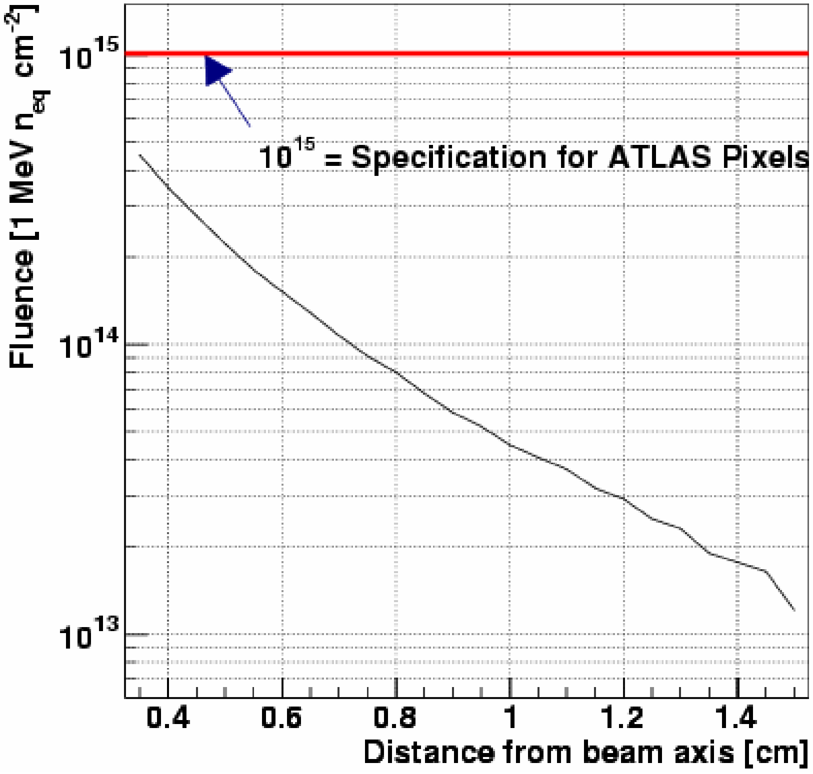
Radiation issues

Would the ATLAS pixel planes, placed next to the targets, survive the radiation dose?

Yes. Tests have shown that such modules remain fully operational up to (at least) the specification of ATLAS: 10^{15} 1MeV n_{eq}/cm^2. The expected fluence integrated over three months at 10^9 interactions per burst, for the most affected pixel cells, is a factor 2 below.

⇒ In terms of radiation hardness,
the proposed measurement is feasible
with existing pixel sensors and electronics.

However, the ALICE pixel planes would
not resist such radiation doses (besides
being too slow, 10 MHz)

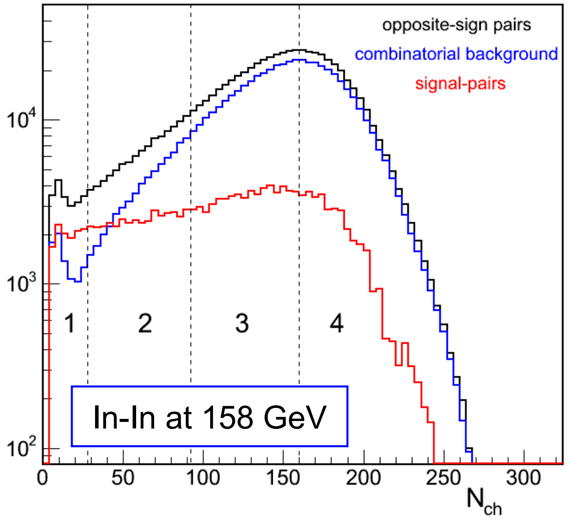


Tracking and timing issues

Can we track all the particles produced with the triggered dimuon?

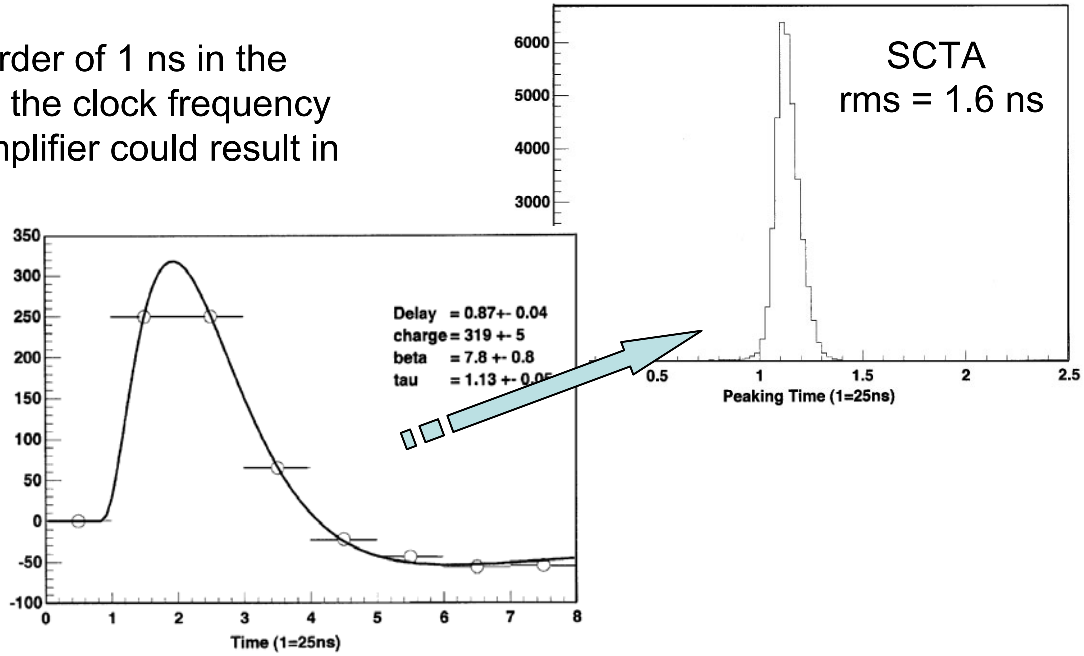
The present ATLAS pixel detectors operate at 40 MHz.
Within the 50 ns readout gate (imposed by the asynchronous trigger) we will have 10 pile-up p-U collisions, giving around 100 tracks in the detectors. Similar to the 2003 Indium run.

The time accuracy (~2 ns) of the strip/pad planes at 30–40 cm from the targets will allow us to reject most of the pile-up tracks (not in time coincidence with the dimuon trigger).



> “As can be observed, a precision of the order of 1 ns in the peaking time can be obtained. Increasing the clock frequency and optimizing the shaping time of the amplifier could result in sub-nanosecond resolution.”

C. Lacasta *et al.*, NIM A 500 (2003) 362.



Time scale for a first dedicated run

Such a measurement could be done with detector technologies already used by NA60 this year.

The new vertex tracker would have two kinds of silicon planes: ATLAS pixel planes close to the targets, where good granularity is needed for good tracking; and strip or pad detectors downstream, at 30–40 cm from the targets, for good timing accuracy.

The new strip/pad silicon sensors must be designed and produced, but their read-out electronics chain is essentially the one we have been using.

Main time constraint: we need a green light (or at least a strong encouragement) before producing new silicon detectors and refurbishing the old muon spectrometer (trigger and read-out electronics; tracking chambers).

If we can start working in early 2005, we can take data in 2006–2007

Summary

- A very selective dimuon trigger associated to existing fast and radiation hard silicon tracking detectors allows NA60 to cope with p-U collision rates at around 200 MHz

- After 300 000 effective bursts (3 months), at 10^{10} protons/burst, we will probe the equivalent of 7×10^{16} pp collisions, at 400 GeV, or 1.5×10^{10} D^0 decay candidates

- A signal at the 5 σ level should be visible if the Branching Ratio is 2.5×10^{-7}, a value 10 times smaller than the present upper limits

- If no signal is found, we should be able to set an upper limit around 10^{-7}

- Further developments in the timing accuracy of silicon pixel and pad detectors, feasible with currently available technology, should allow us to improve the statistics by another factor 10 by the year 2008

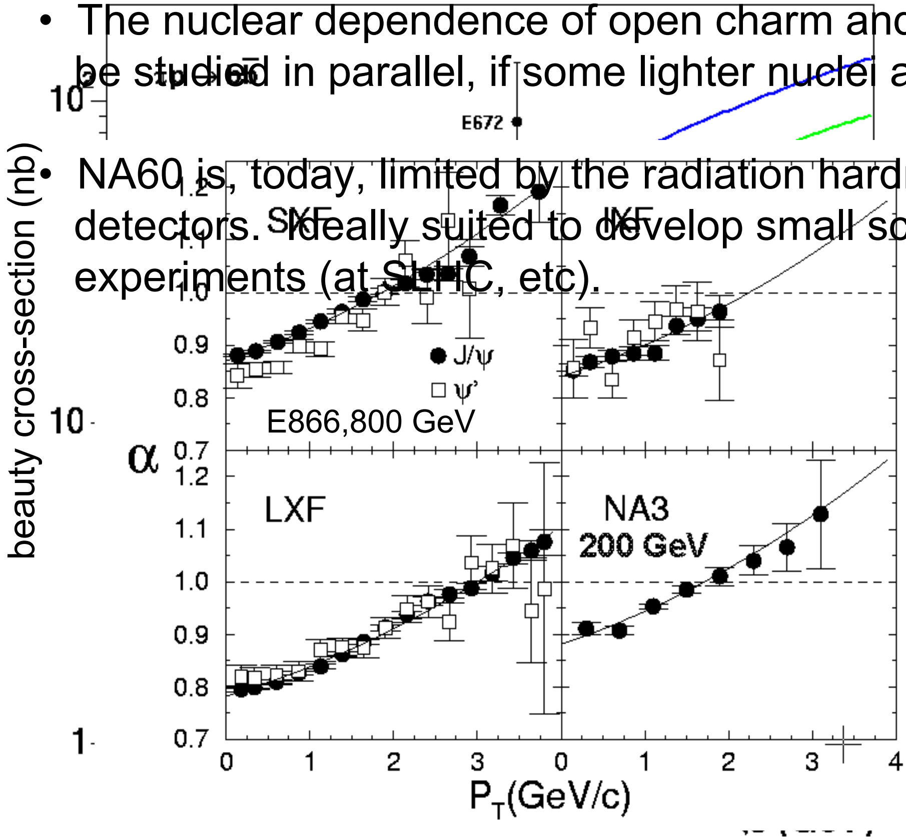
What else do we get “for free”?

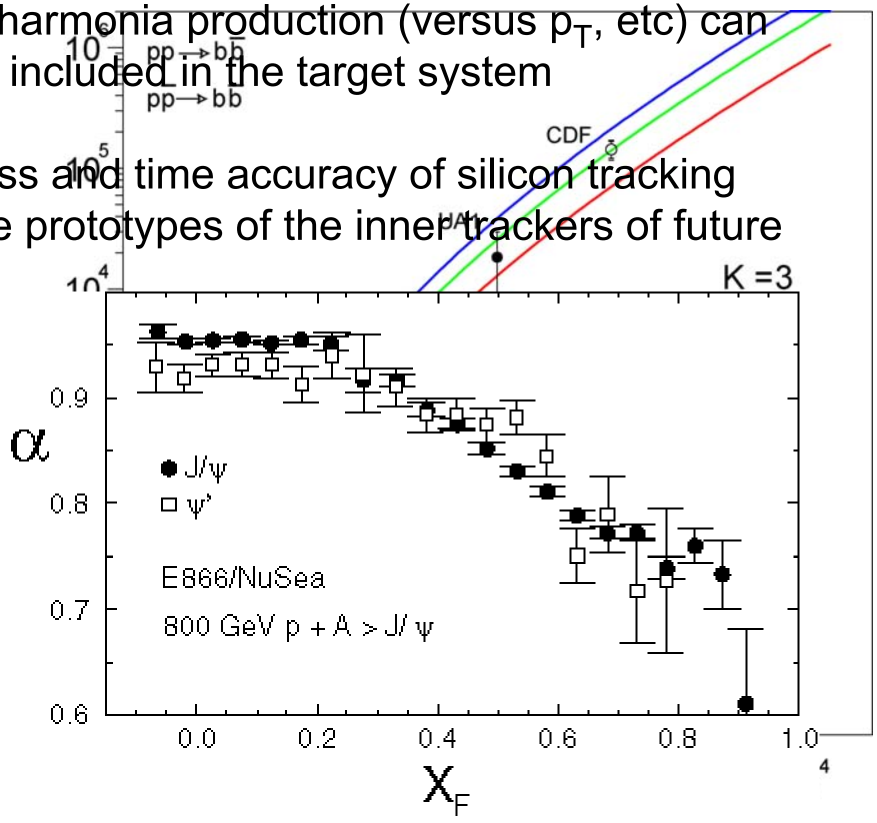
- We should be able to search for other “forbidden” decays, provided they have dimuons in the final state, such as
  $D^0 \rightarrow \omega\, \mu^+\mu^-$ (< 8.3 × 10^{-4}), $D^0 \rightarrow \rho\, \mu^+\mu^-$ (< 2.2 × 10^{-5}), $D^0 \rightarrow \phi\, \mu^+\mu^-$ (< 3.1 × 10^{-5});
  $D^+ \rightarrow \pi^+\, \mu^+\mu^-$ (< 8.8 × 10^{-6}), etc.

- The beauty production cross-section at sqrt(s) = 27 GeV comes as a by-product

- The nuclear dependence of open charm and charmonia production (versus p_T, etc) can be studied in parallel, if some lighter nuclei are included in the target system

- NA60 is, today, limited by the radiation hardness and time accuracy of silicon tracking detectors. Ideally suited to develop small scale prototypes of the inner trackers of future experiments (at SLHC, etc).





Medium term future perspectives

Improved pixel and strip detectors, in terms of timing accuracy, could be available for small-scale use in 2008, without requiring major R&D efforts.

Silicon strip/pad detectors with sub-nanosecond timing accuracy can be developed already today.

In what concerns the pixel detectors, the main work would be to add a time tagging capability to each pixel cell, with ~10 ns accuracy, keeping the read out frequency at 40 MHz. This would be enough to reduce the number of pile-up tracks by a factor 5. The selective trigger keeps the data volume written to permanent data storage within reasonable values.

Using 0.13 μm CMOS technology (today's standard) opens the door to smaller pixel cells, if the design layout is redone (a bigger but feasible effort in terms of microelectronics engineering).

⇒ Improving statistics by a factor 10 should be feasible by 2008 …
⇒ An upper limit down to around 3×10^{-8} comes into reach