Measurement of Total, Inelastic, Coherent, and (Quasi-)Elastic Cross-sections in $p(\pi) - A$ Scattering Using the NA61 Facility

Expression of Interest

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draft

Abstract

Currently, the leading uncertainties in neutrino flux predictions come from normalization and interaction lengths uncertainties [1], i.e. the total cross-sections and not so much from the hadro-production cross-section uncertainties. In this proposal we try to address these issues.

NA61 has performed precise pion-production differential cross-section measurements in $p + C$ interactions at 31 GeV/c [2]. The measurement of cross-sections, however, are not as precise, because of the inability of the NA61 detector to precisely measure total cross sections without large model dependent corrections and the inability to separate coherent and (quasi-)elastic contributions to the total cross-section, which reflects also in the less precise pion multiplicity determination.

Here we propose to complete the existing NA61 measurements with precise total, inelastic, coherent, and (quasi-)elastic cross-section measurements in $p + C$ collisions at 31 GeV/c, such to reduce the related uncertainties to below the % level. The same approach can be used to perform elastic cross-section measurements with different targets and beam particles, and at different beam energies. At the same time we will attempt to measure directly the interaction lengths.

NA61++
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Normalization of Cross-sections

hadro-production cross-sections $\frac{d\sigma}{dp\,d\vartheta}\left(p + C \rightarrow \pi^{+} + X\right)$

$$\frac{\Delta\sigma_{trig}}{\sigma_{trig}} = \frac{2.7\text{ mb (stat)} + 1.0\text{ mb (sys)}}{305.7\text{ mb}} = 0.88\%\text{ (stat)} + 0.33\%\text{ (sys)} \simeq \boxed{1.0\%}$$

dominated by statistics (we did not take enough beam triggers ☹)

can reach < 0.5% using same normalization procedure !

total, inelastic, … cross-sections

$$\frac{\Delta\sigma_{inel}}{\sigma_{inel}} = 1.2\%\text{ (stat)} + 0.5\%\text{ (det)} + 2.7\%\text{ (sys)} \simeq \boxed{3.0\%}$$

“beam killer” not best approach

need to estimate trigger acceptance and extrapolate to full solid angle

need to subtract elastic component

model dependent based on very old data and models

could be super-correct or wrong … can’t say (also for errors!)

proposal: measure this quantities to better than 1% !

Why so Important?

Experiment measure
hadro-production cross sections and total cross-sections

To be used in a simulation, need to transform into "probabilities":

interaction probability, interaction length
controls primary interaction vertex distribution in target

$$\lambda \sim \frac{1}{\sigma_{int}}$$

average particle multiplicities
generate particles following a Poissonian distribution
once the beam particle has interacted

$$\frac{\sigma(pC \to \pi^{+} X)}{\sigma_{inel}}$$

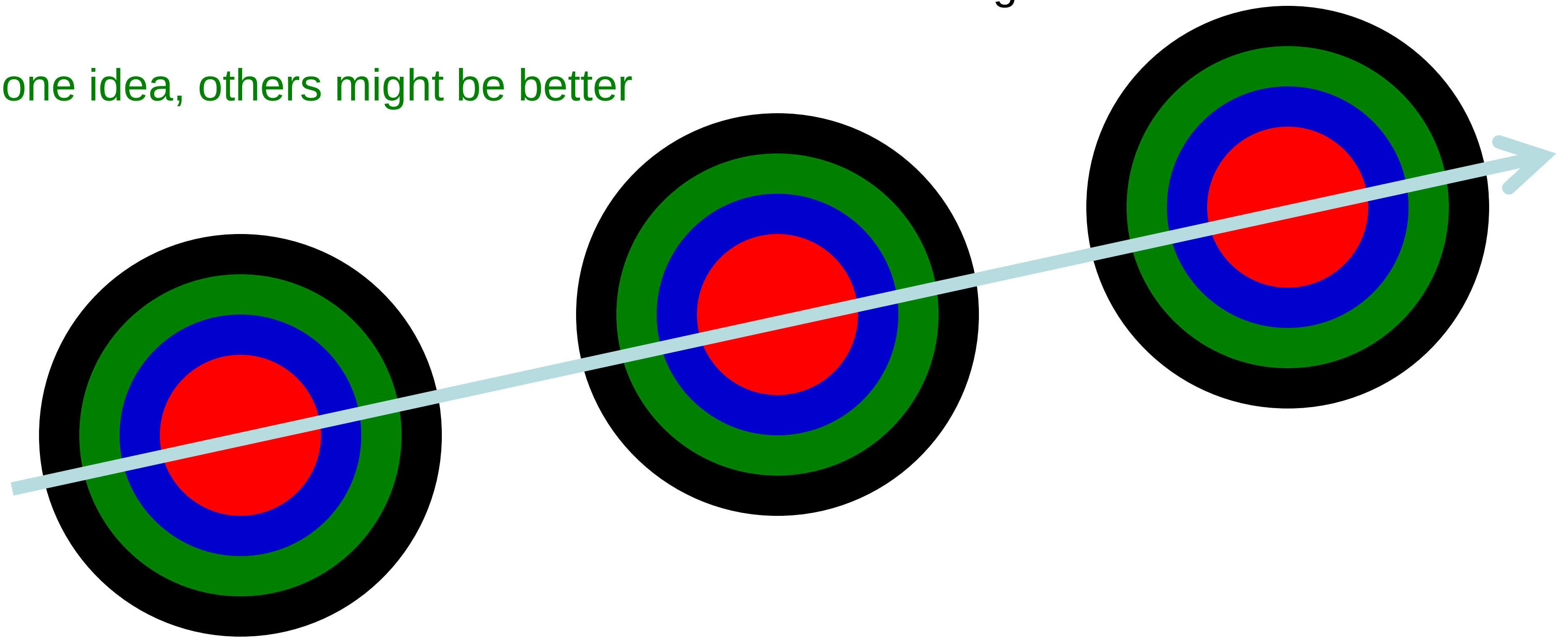
note that "same" cross-sections enters in both

Total Corss-sections

“beam killer” simplest approach, gives excellent normalization,
but not best for total cross-section measurements, since not 100% acceptance

use several differential transmission counters along the beam line

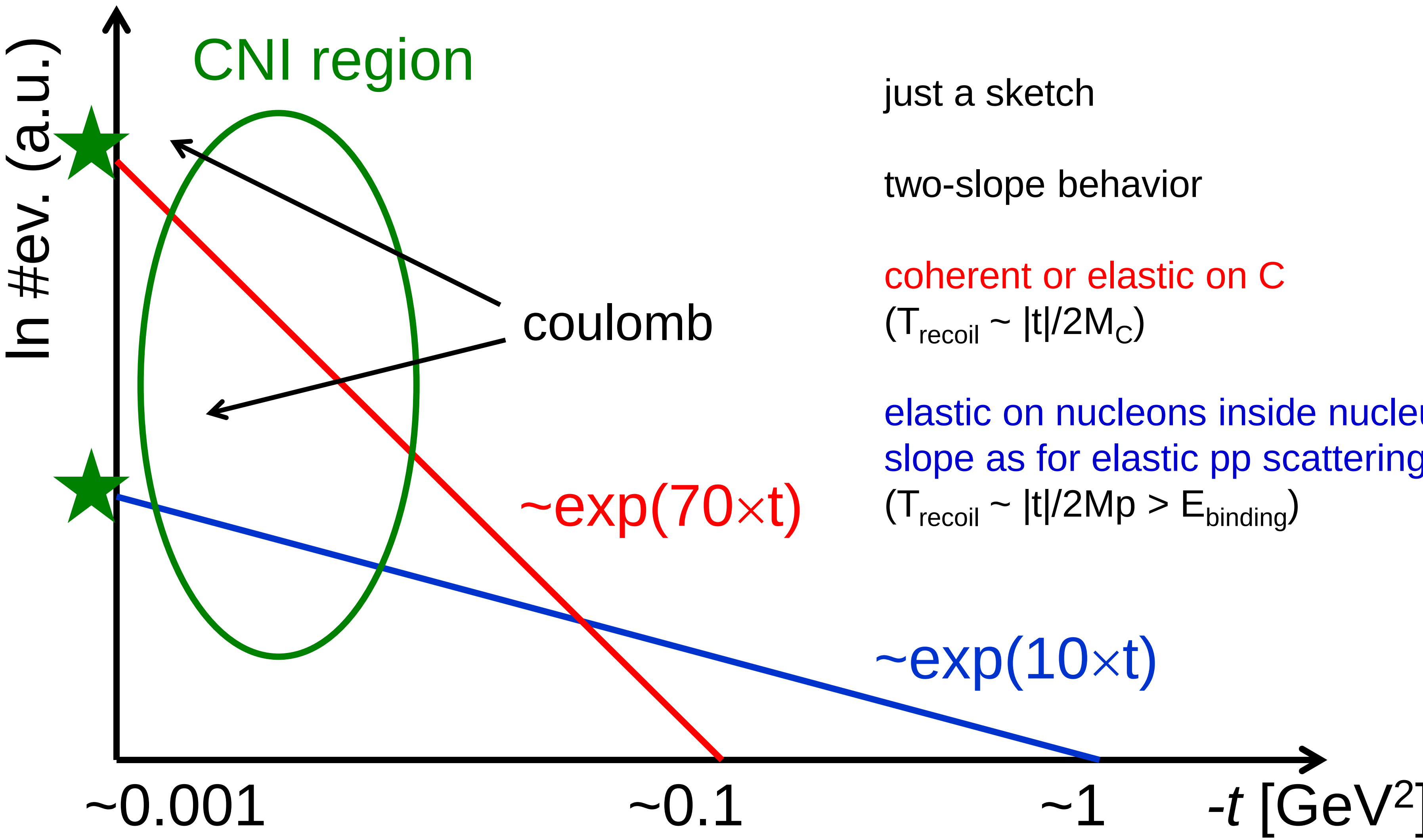
one idea, others might be better



place several counter segmented in polar angle along the beam line

- sufficiently large to cover most of the solid angle (small acc. correction)
- pointing geometry
- coincidence measurement, not fooled by secondary particles

Elastic Cross-section



just a sketch

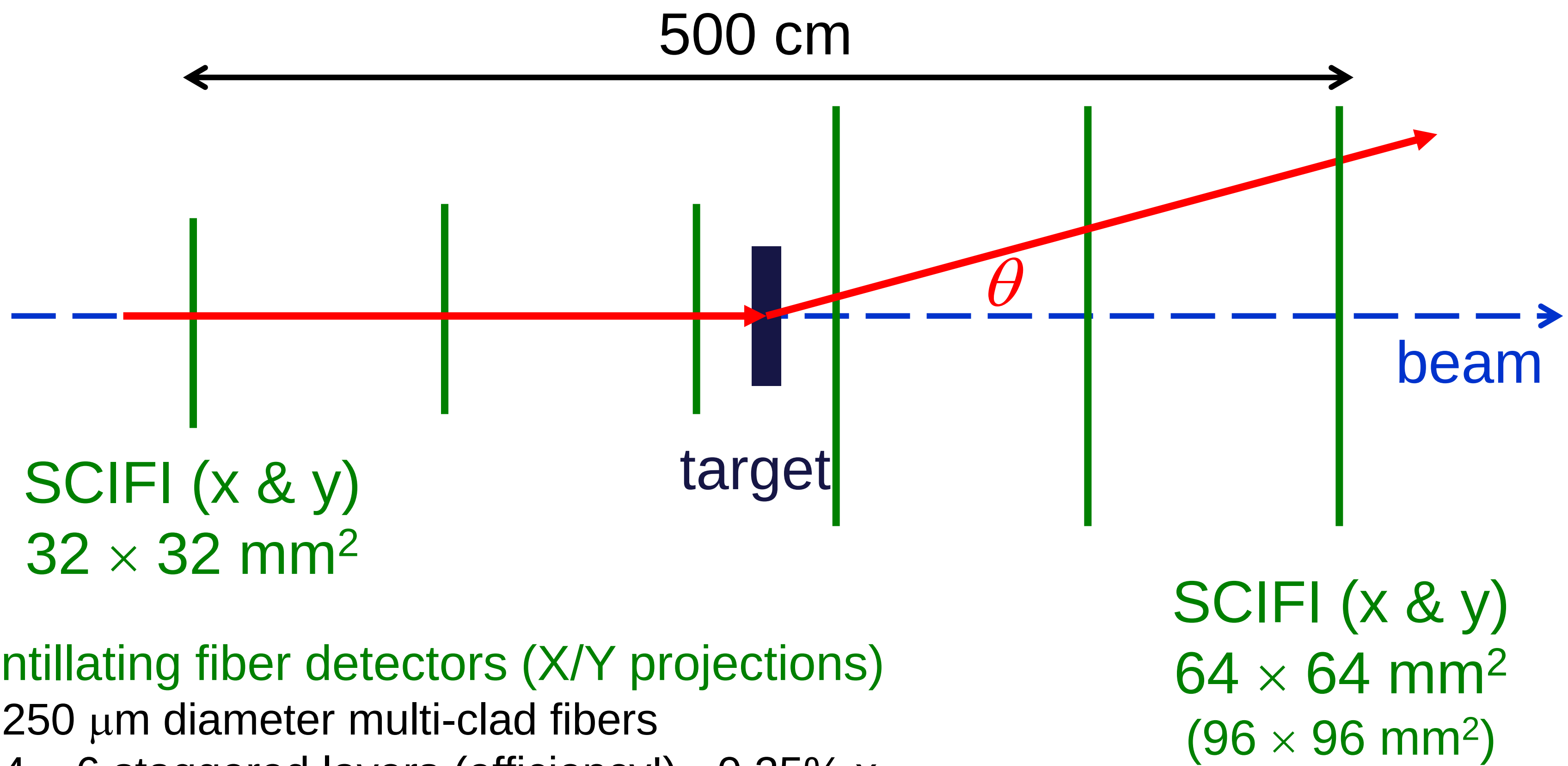
two-slope behavior

coherent or elastic on C
(T_{recoil} ~ |t|/$2M_C$)

elastic on nucleons inside nucleus
slope as for elastic pp scattering
(T_{recoil} ~ |t|/2Mp > $E_{binding}$)

$-t$:	~0.001	~0.1	~1 GeV^2
p_T:	~0.030	~0.300	~1 GeV
θ_{30GeV}:	~1	~10	~33 mrad

Vertex Detector



scintillating fiber detectors (X/Y projections)

- 250 μm diameter multi-clad fibers
- 4 – 6 staggered layers (efficiency!) ~0.25% x_0
- Si-PM arrays readout with 250 μm pitch
- ~3000 channels (not identified yet optimal readout ASIC)

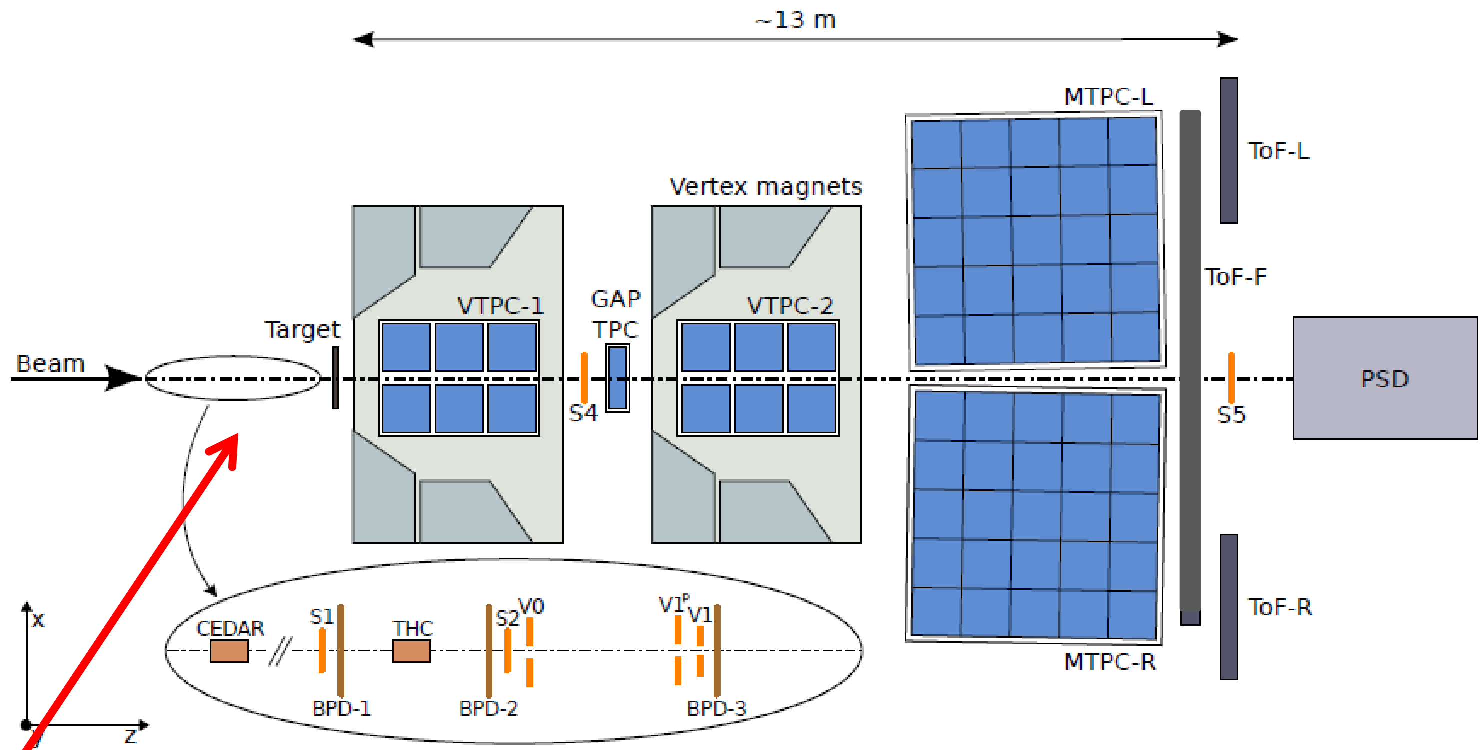
spatial resolution ~70 μm

time resolution < 0.5 ns

angular resolution < 100 μrad

resolution dominated by multiple scattering in target ~100 μrad (1 cm graphite)

NA61 Detector



vertex detector for elastic scattering measurements

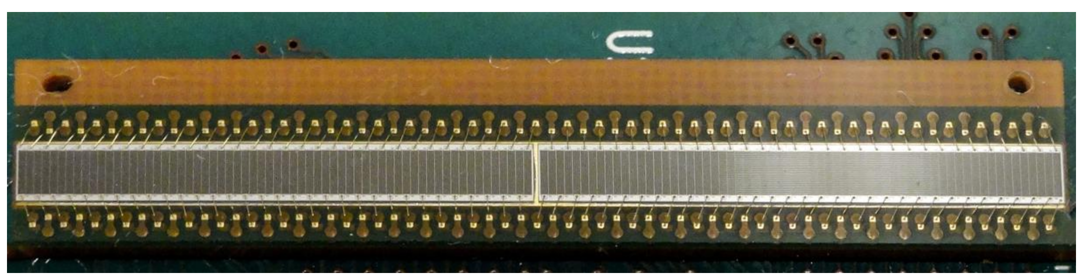
The SciFi Detector

prototypes already tested

possible replacement for BPDs

HI: only two staggered layers
effective thickness < 350 μm, < 0.1% x_0
100% efficient

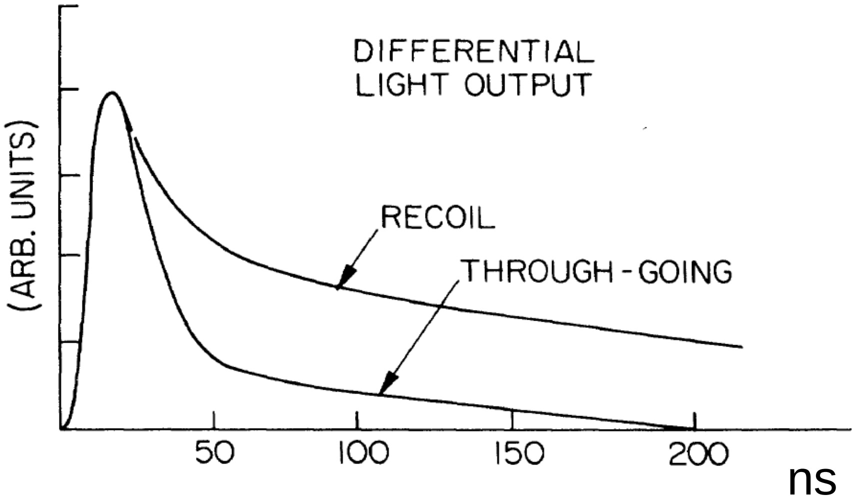
Si-PM array
32 mm wide
250 μm readout pitch
128 channels

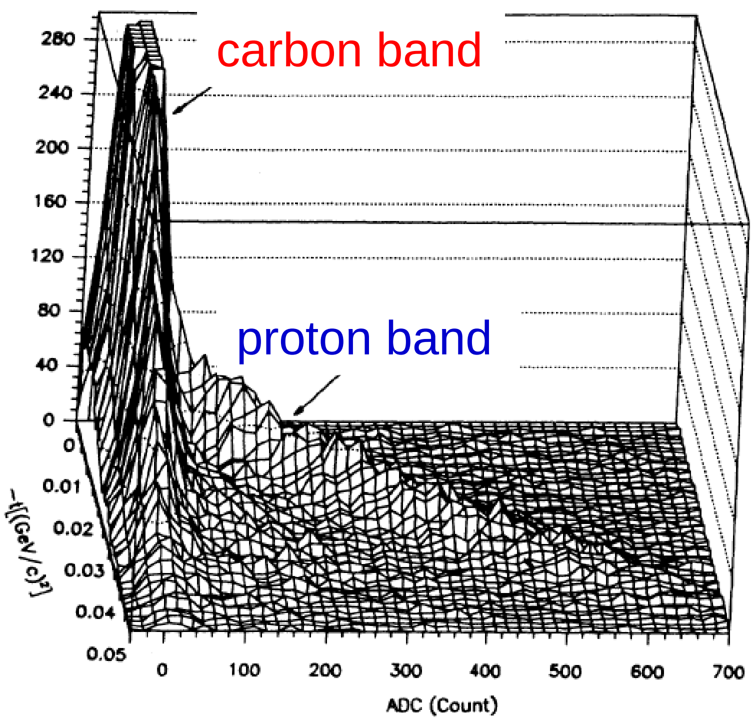


Active Targets

Unfortunately we can detect only the scattered particle, not the recoil one.
(the carbon nucleus is absorbed after few μm, single arm experiment !)
Should not be a big problem, since at low |t| inelastic channels are below threshold.

Alternatively, could also use active targets with pulse shape discrimination capabilities. One such material is trans-stilbene, however it is an CH compound.





measure (or trigger on) deposited energy with a delayed gate
and correlate to |t| measured in the vertex detector and NA61 spectrometer

$$T_{recoil} \approx \frac{|t|}{2M}$$

measure *pp* elastic scattering for free

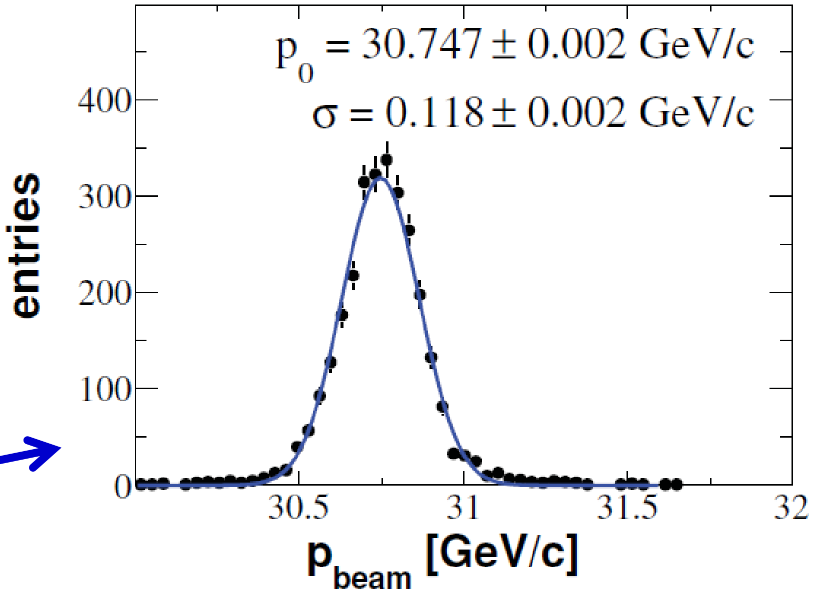
Triggering

Reconstruct incoming and scattered beam particle in the SciFi vertex detector in real time with FPGAs or GPUs, 5 μs or less.

If kink sufficiently large, trigger the readout of the main detector.

Momentum reconstruction (why NA61 detector is needed)

Inelastic interactions can add background to elastic processes.
In diffractive events, at least one π^0 is created.
Consider for instance $p + C \to p + \rho^0 + C$,
and two neutrinos would be created
in the decay chain of the ρ^0.
At 100 GeV (not at 30 GeV) this could happen,
the proton would loose only few % of its energy,
If momentum resolution is better than m_π,
one can identify such events, and reject them.
Need to operate the NA61 spectrometer
at maximum field.



Beam momentum measurement at 30 GeV with the NA61 spectrometer at full field.
Almost there !

Interaction Length Measurements

Finally, try to measure the interaction length directly
and verify that the primary vertex distribution is indeed exponential
and controlled by λ_I.

Using targets of different lengths, for instance 0.1, 0.25, 0.5, 1 λ_I,
measure the attenuation of the proton beam
$\rightarrow$ attenuation length and cross-section.

With not too long targets, study elastic scattering and
reconstruct the interaction vertex position to few cm (at not too small |t|).

Same setup as for elastic scattering with longer targets.

Comments on M&C

There is a general tendency in comparing multiplicities rather than cross-sections.
I'd rather see comparisons of (hadro-production) cross-sections.
For consistency, one should use the same cross-section in M&C and in multiplicity extraction from measured hadro-production cross-sections in order to disentangle normalization effects and make progress.

With a "thin" target this is not a big deal.

With a long target it is a big deal !
Note that the cross section governs also the primary vertex distribution.
Example: to reduce the pion flux off a long target naively one would expect that he/she should use a smaller cross-section.

A smaller cross-section yields a smaller number of interactions in the target, however the average particle multiplicities per interaction increase.
Who wins? The multiplicities ($\int \exp(-1/\sigma)$ vs. $1/\sigma$) !
Therefore, contrary to expectations, the pion flux will increase.
In order to reduce the pion flux off a long target, instead, one should increase the Interaction cross-section: the number of interactions will increase but the pion multiplicities per interaction will decrease !

Since the cross-section is an observable (i.e. measurable) there can be only one !

Conclusions

These measurements would complete the NA61 hadro-production results.

Can be performed also with different beam particles and/or energies.

Interesting measurements on its own, although today not actual (“old physics”).
To my knowledge, nobody measured in detail the elastic forward hadronic amplitudes off nuclear targets, in particular of the real part (in very old publications systematically assumed that it is fully imaginary).
On the other hand, there is a very active elastic scattering program at the LHC.

Not too difficult nor expensive setup. We master the technology.
Some applications of SciFi’s already being considered in NA61.

If there is interest in NA61, complete the proposal, design of detectors, rate estimates, etc.

Existing data are quite old, and questionable !

Ideally, first pilot and copilot runs should happen already in 2018,
in particular test the feasibility of the measurements.