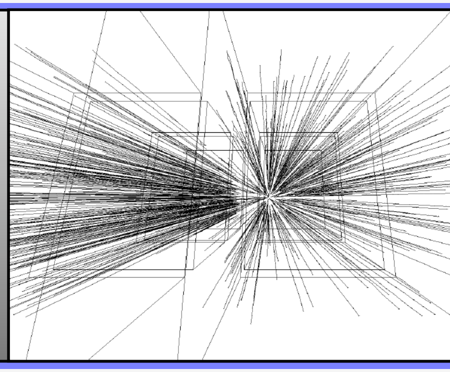
Cross Section Normalization in NA61



Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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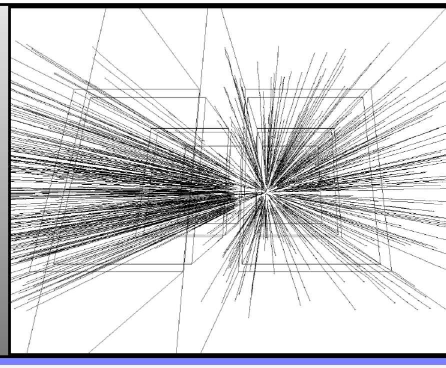
ν *Physics at Accelerators* – Workshop

27. – 28.01.2009, JINR



Outline

Introduction

- One of the main physics goals of NA61/SHINE:

> Precision measurements of hadron production
>
> for the prediction of ν-fluxes at T2K

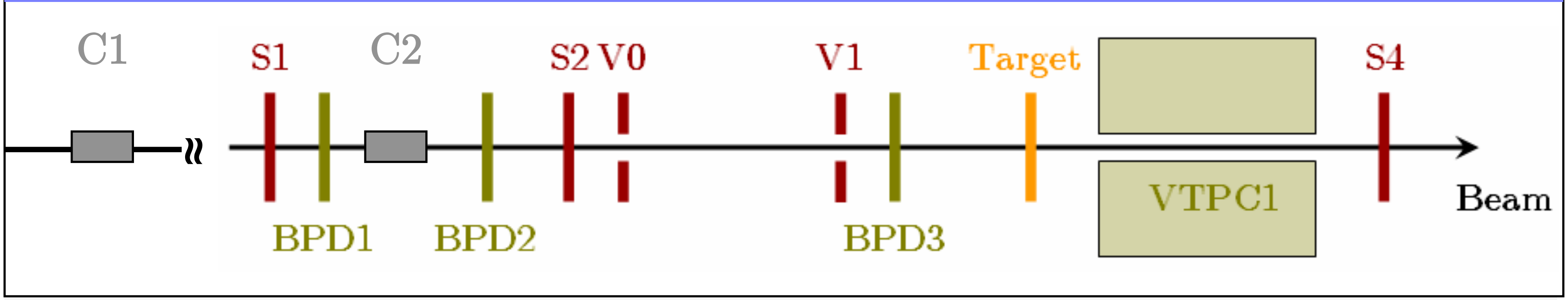
Strategy A:

- Measure the inclusive p+C cross section with a thin target over a broad kinematical range and different particles (π, K, p)

- Use the measured cross sections as input to the beam MC for generating the primary interaction. Secondary interactions will be described by hadronization models

- Compare the MC predicitions to the π/K yields measured off C-targets of different lengths (e.g. T2K replica target) and adjust the model accordingly

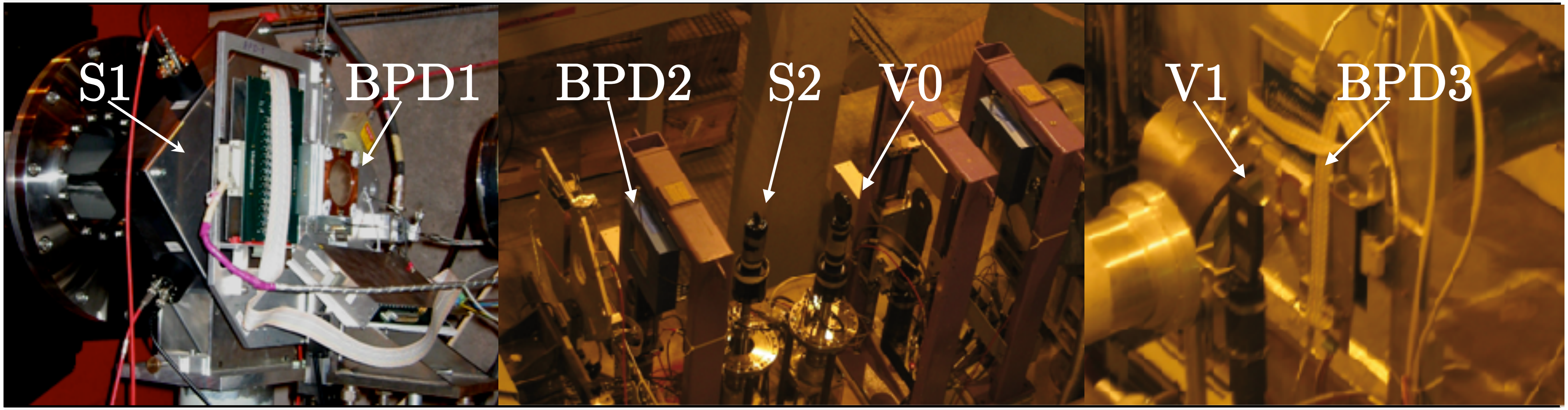
Setup of Beam-Line



- Secondary hadron beam composed of 83.7% π, 14.7% p and 1.6% K
- Proton beam particles identified by CEDAR (C1, 96% efficiency for 6th-fold coincidence) and threshold Cerenkov counters (C2)
- Incoming p then selected by several scintillator counters (S1, S2, $\overline{V0}$, $\overline{V1}$)
  → beam defined as Beam = S1•S2•$\overline{V}$•C1•$\overline{C2}$
- Trajectory of beam particles measured by the beam position detectors (BPD-1/-2/-3)
- Interactions in the target were selected by an anti-coincidence of the beam particle with a small scintillator S4 (Beam•$\overline{S4}$)

Setup of Beam-Line

BPDs and Trigger Counters



S1: 5 x 3 x 0.5 cm Scintillator, t=0 for ToF

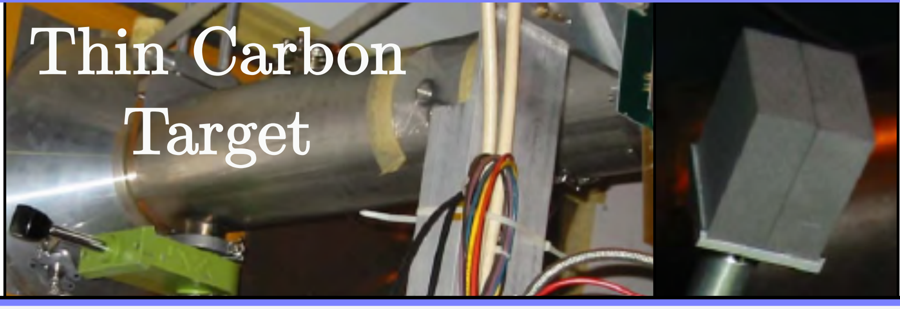
S2: 2 x 2 x 0.2 cm Scintillator

V0: Veto Scintillator, Ø=8cm and hole Ø=1cm

V1: Veto Scintillator, 10 x 10 cm and hole Ø=1cm

S4: 1cm thick Scintillator with Ø=2cm

Setup of Beam-Line – Target



- 2 different carbon targets (isotropic graphite, $\rho = 1.84$ g/cm^3):

Thin Carbon Target:	T2K Replica Target:
- 2.5 x 2.5 x 2cm^3,	- Ø=2.6cm x 90cm,
- int. length ~0.04	- int. length ~1.9

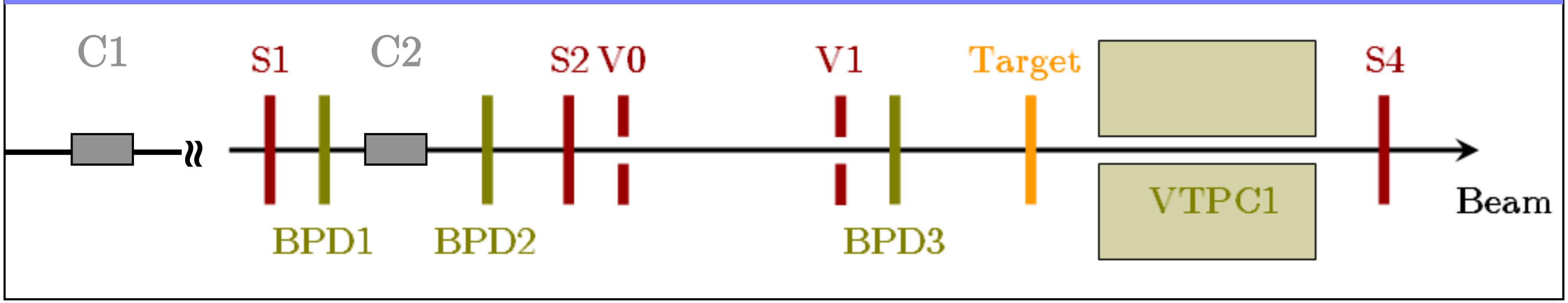
- Aims of the first NA61 run in October 2007:
  - to set up and test the NA61 apparatus and the detector prototypes
  - to take pilot physics data for T2K with 30.9 GeV/c protons:

Thin target: ~660k events

Replica target: ~230k events

Empty target: ~80k events

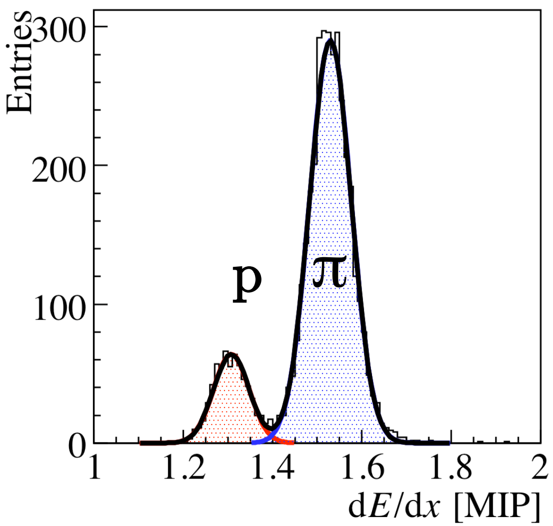
2007 Pilot Run – Proton Beam Properties

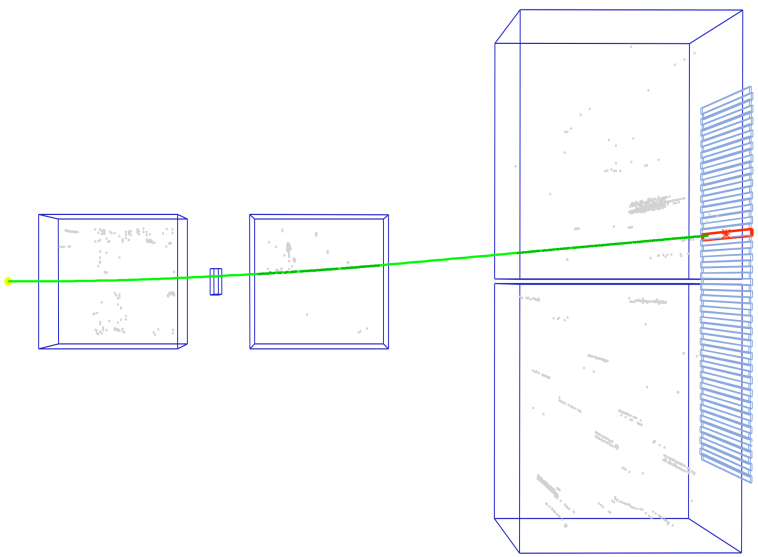


Beam Purity Check

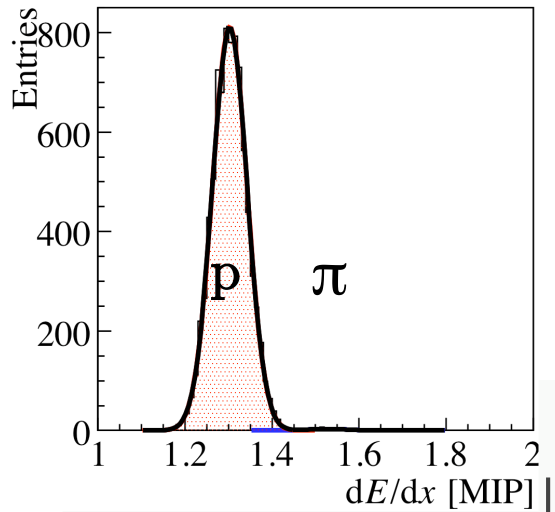
with special empty target run with full magnetic field and trigger on Beam (S1•S2•$\overline{\text{V}}$ and S1•S2•$\overline{\text{V}}$•C1•$\overline{\text{C2}}$)

All Beam Particles

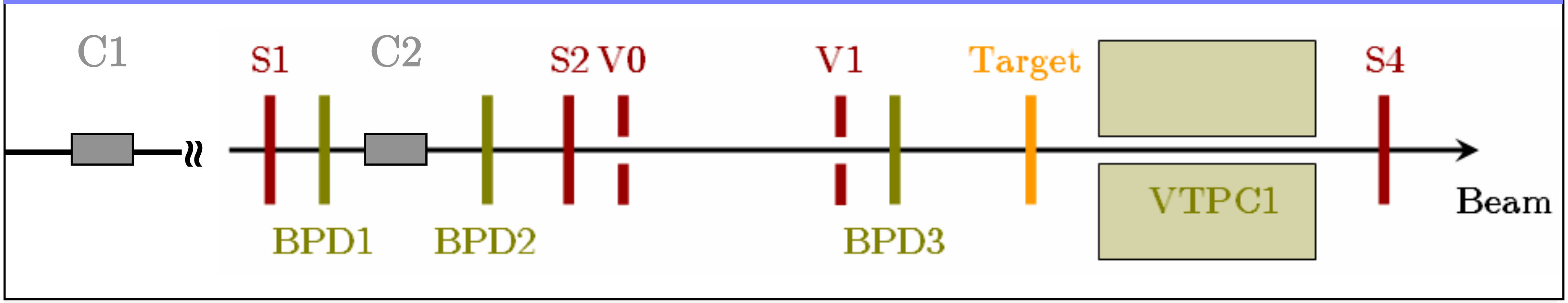




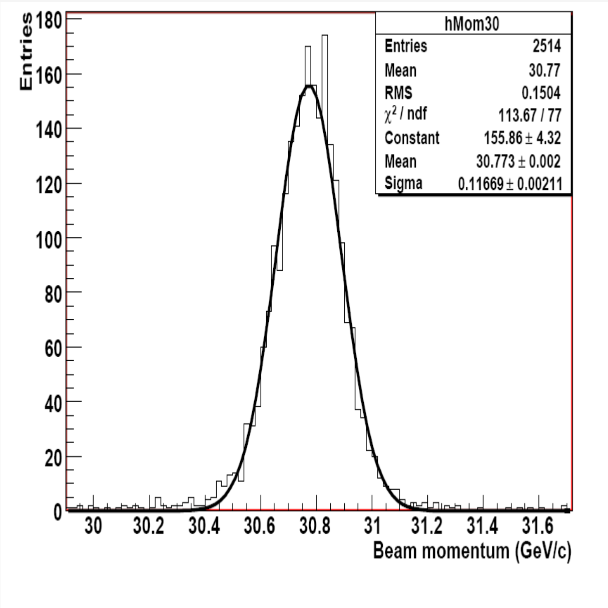
Triggered Protons (C1·$\overline{\text{C2}}$)



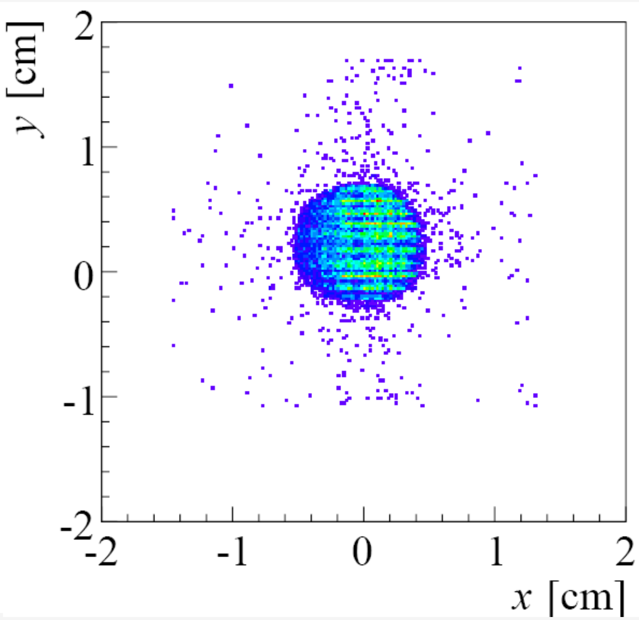
2007 Pilot Run – Proton Beam Properties



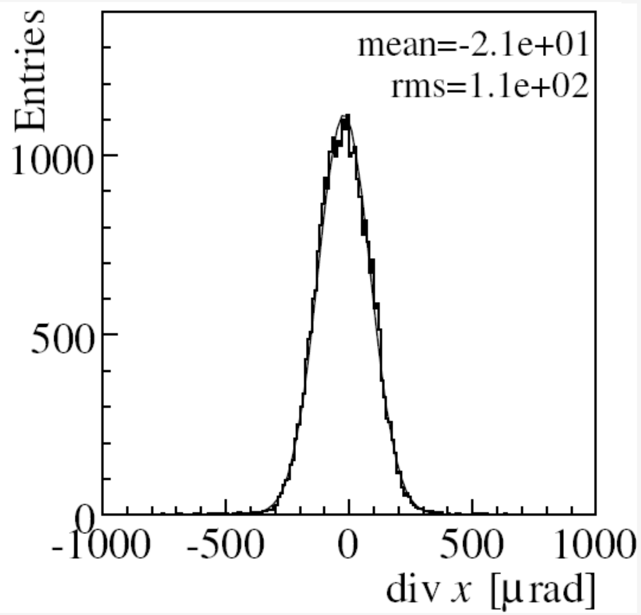
Beam Momentum from TPC



Beam Spot at BPD3



Beam Divergence



Cross Section Normalization

- For the thin target data the goal is to present data in terms of yields and invariant cross sections

→ NA49 approach is followed (Eur. Phys .J. C45 (2006) 343):

- Evaluate the trigger and the total inelastic cross section
- Trigger cross section can then be used to determine the invariant inclusive cross section:

$$f(x_F, p_T) = E(x_F, p_T)\cdot\frac{d^3\sigma}{dp^3}(x_F, p_T)$$

which is experimentally defined by the measured quantity:

$$f_{meas}(x_F, p_T, \Delta p^3) = E(x_F, p_T, \Delta p^3)\cdot\frac{\sigma_{trigger}}{N_{ev}}\cdot\frac{\Delta n(x_F, p_T, \Delta p^3)}{\Delta p^3},$$

with Δp^3: finite phase space defined by the bin width, N_{ev}:# of evts off the target, Δn: # of identified particles in a given bin Δp^3

→ Several steps of normalization and correction have to be applied in order to make $f_{meas}(x_F, p_T, \Delta p^3)$ approach $f(x_F, p_T)$

Cross Section Normalization – $\sigma_{trigger}$ Determination

- Trigger Cross Section $\sigma_{trigger}$:

  - Determined by the interaction probability:

$$\sigma_{trigger} = \frac{P_{int}}{\rho L_{eff} N_A / A}$$

$$L_{eff} = \lambda_{abs}(1 - e^{-L/\lambda_{abs}}),$$
$$\lambda_{abs} = \frac{A}{\rho N_A \sigma}$$

Target properties:

ρ: density

L: length

N_A: Avogadro const.

A: Atomic number

L_{eff}: effective length

λ_{abs}: abs. length

  - The real interaction probability (P_{int}) is calculated as the difference of probabilities obtained with and without target:

$$P_{\mathrm{int}} = \frac{Rate_{TargetIN} - Rate_{TargetOUT}}{Rate_{BeamTrigger}} = P_{TargetIN} - P_{TargetOUT}$$

- Calculation carried out in 3 steps:
  1) Estimate $\sigma_{trigger}$ with the real length of the target
  2) Use obtained value to compute the effective length (L_{eff})
  3) Determine the corrected value of $\sigma_{trigger}$

Cross Section Normalization – Interaction Rates

- Interaction rate (Data):

  - Empty target : $(1.72 \pm 0.01)\%$
  - Thin target: $(7.07 \pm 0.01)\%$

Statistical errors only!

Fake trigger $= 24.3\%$

$P_{int} = (5.35 \pm 0.01)\%$

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⇩

Fake trigger $= 24.3\%$

$P_{int} = (5.35 \pm 0.01)\%$

- Where does the high fake trigger rate come from?

  → important to clarify in order to be able to optimize the trigger for the following data taking

Cross Section Normalization – Fake Triggers

- Where does the high fake trigger rate come from?

  1) Broken beam tracks

Cross Section Normalization – Fake Triggers

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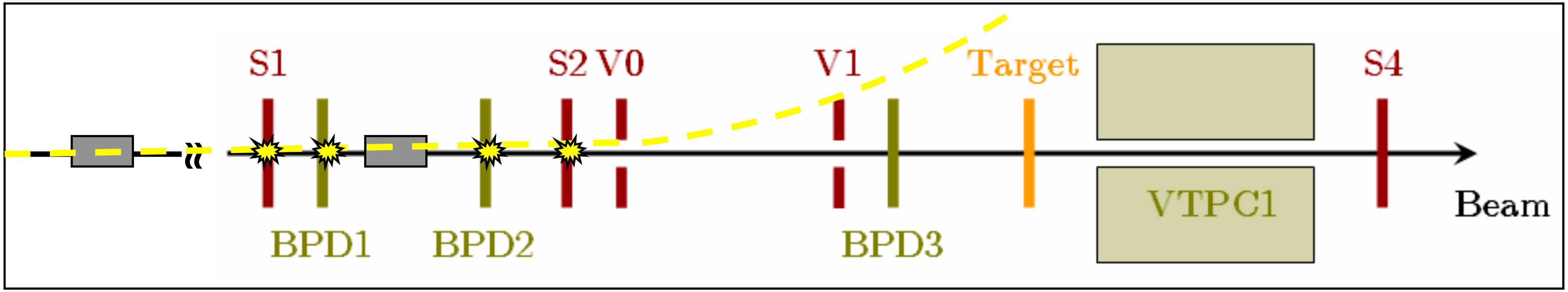

- Large amount of beam particles was not measured by all 3 BPDs (~22%)

- Here, the largest contribution comes from tracks, which did not have a hit in BPD3
  → not mainly due to BPD3 inefficiency, but rather due to broken tracks between
  BPD2+3 not reaching BPD3

- Studies have shown that ~38% of the fake trigger is due to these broken tracks
  and that ~13.5% of them are due to interactions in the light guide of S2

Cross Section Normalization – Fake Trigger

- Where does the high fake trigger rate come from?

  1) Broken beam tracks

  2) Inefficiencies of trigger counters (Veto-Counters, S4)

Cross Section Normalization – Fake Trigger

- Where does the high fake trigger rate come from?

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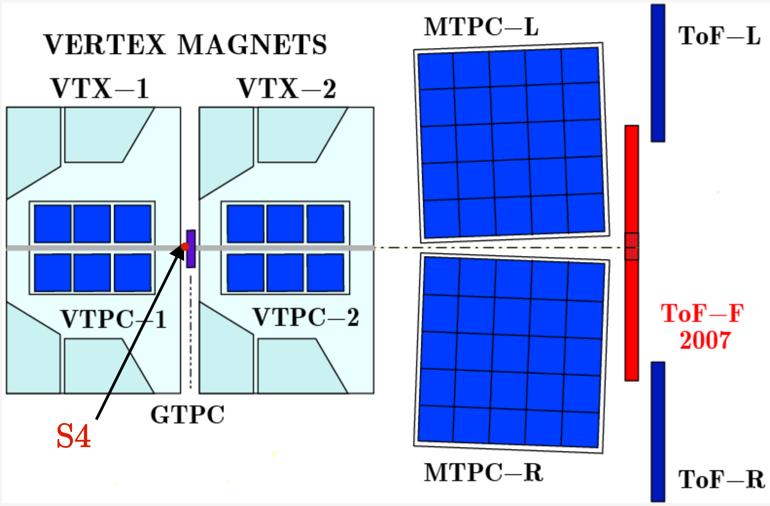
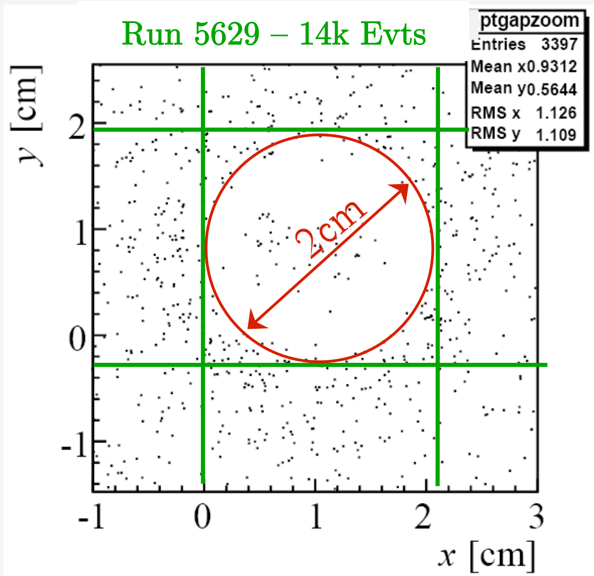
  2) Inefficiencies of trigger counters (Veto-Counters, S4)

  - S4 efficiency can be estimated with the help of the GTPC, where it‘s image can clearly be seen



Trigger
Beam·$\overline{S4}$



→ S4-inefficiency is very low (~ 0.07%)!

Cross Section Normalization – Fake Trigger

- Where does the high fake trigger rate come from?

  1) Broken beam tracks
  2) Inefficiencies of trigger counters (Veto-Counters, S4)
  3) Interactions in the material between BPD3 and S4

Cross Section Normalization – Fake Trigger

- Where does the high fake trigger rate come from?

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  3) Interactions in the material between BPD3 and S4

- Estimation of the material budget between BPD3 and S4

→ Total contribution to the fake trigger rate is between 36-54%

Material [cm]	Length [cm]	Position [cm]	λ_{coll} [%]	λ_{int} [%]	Comment
Scintillator	0.5	-211.6	0.922	0.649	Middle of S4
Air	41.2	-232.2	0.081	0.055	
Mylar	0.0125	-252.8	0.030	0.021	Beginning of VTPC1
N_2	2.0	-253.8	0.004	0.003	
Mylar	0.0125	-254.8	0.030	0.021	
Ar/CO_2 (90/10)	250.0	-379.8	0.570	0.364	Middle of VTPC1
Mylar	0.0125	-504.8	0.030	0.021	
N_2	2.0	-505.8	0.004	0.003	
Mylar	0.0125	-506.8	0.030	0.021	End of VTPC1
Air	13.2	-513.4	0.026	0.018	
Mylar	0.002	-520	0.005	0.003	
He	41.6	-540.8	0.013	0.010	He-bag
Mylar	0.002	-561.6	0.005	0.003	
Mylar	0.005	-561.6	0.012	0.008	
He	20.5	-571.6	0.007	0.005	He-tube
Carbon	2	-581.3	6.216	4.289	Target
He	67	-614.8	0.022	0.016	
Mylar	0.005	-648.3	0.012	0.008	
Air	13.2	-655.5	0.026	0.018	
Mylar	0.006	-661.5	0.015	0.010	
Ar/CH4	1.2	-662.66	0.003	0.002	Middle of BPD3
Material between BPD3 and S4 (w/o Target)			0.925	0.610	Sum

Cross Section Normalization – Fake Trigger

- Where does the high fake trigger rate come from?

  1) Broken beam tracks
  2) Inefficiencies of trigger counters (Veto-Counters, S4)
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→ Studies mostly explain why the interaction rate for target out events is so high

→ Important for optimizing the trigger for upcoming runs

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→ Studies mostly explain why the interaction rate for target out events is so high

→ Important for optimizing the trigger for upcoming runs

- Note that in any case, fake triggers are not a problem when determining $\sigma_{trigger}$ with the real interaction probability P_{int}, since one automatically corrects on them, when P_{int} is calculated as the difference of the probabilities obtained with and without target

$$P_{int} = \frac{Rate_{TargetIN} - Rate_{TargetOUT}}{Rate_{BeamTrigger}} = P_{TargetIN} - P_{TargetOUT}$$

Cross Section Normalization – $\sigma_{trigger}$ Determination

- Interaction rate (Data):

  - Empty target : $(1.72 \pm 0.01)\%$
  - Thin target: $(7.07 \pm 0.01)\%$

Statistical errors only!

Fake trigger = 24.3%

$P_{int} = (5.35 \pm 0.01)\%$

- Trigger Cross Section $\sigma_{trigger}$:

$\sigma_{trigger}$ can then be calculated from P_{int} with the described procedure (L_{eff} = 1.95 cm):

$$\sigma_{trigger} = 297.5 \pm 0.7 \text{ mb}$$

Cross Section Normalization – σ_{int} Determination

- Interaction Cross Section σ_{int}:

 - can be obtained from the $\sigma_{trigger}$ by applying 3 major corrections:

1) Subtract the $\sigma_{elastic}$ contribution

 i. e. remove those events where the primary particle undergoes a large angle coherent scattering on the target and does not reach S4. Therefore a trigger on the event is present even if no proton interaction occurred

2) Add the $\sigma_{loss\text{-}p}$ contribution

 i. e. take interactions into account where a secondary particle hits S4 and therefore prevents from triggering on the event. Here, the major contribution comes from quasi-elastic scattering of the incident protons

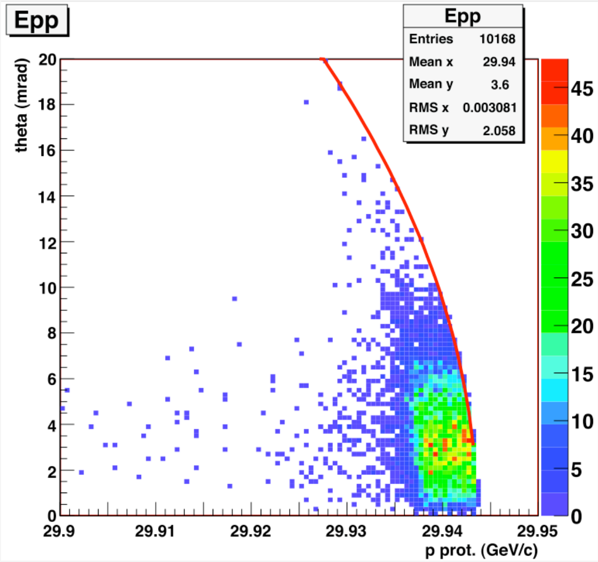
3) Add the $\sigma_{loss\text{-}\pi/K}$ contribution

 i. e. take interactions into account where a secondary pion or kaon at high x_F hits S4 and therefore prevents from triggering on the event

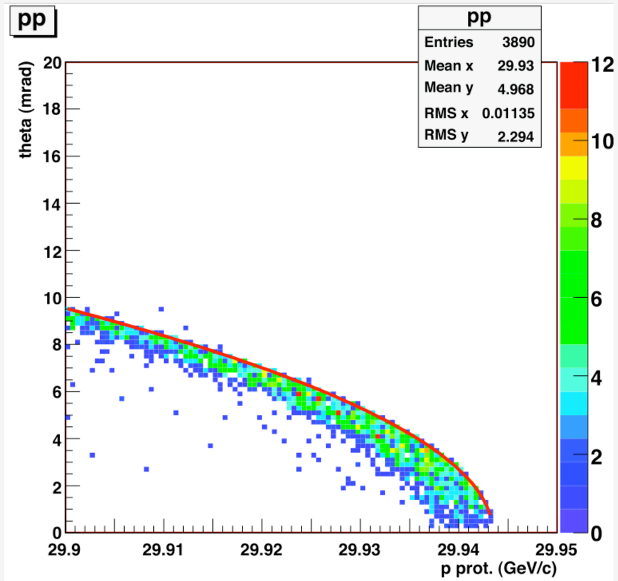
Cross Section Normalization – σ_{int} Determination

- These corrections have been estimated, up to now, with a Geant4 simulation of the trigger setup using the measured profile and divergence for the incoming p beam

Coherent elastic scattering on the nucleus



Quasi-elastic scattering on the nucleons



- Angular distributions for coherent elastic scattering and quasi-elastic scattering are in good agreement with experimental measurements*, however we note a 12% discrepancy on the total elastic cross section value

*G. Bellettini et al., Nucl. Phys. 79 609, S.P. Denisov et. al. Nucl. Phys. B61 62, A. Carroll et al., Phys. Lett. B80 319

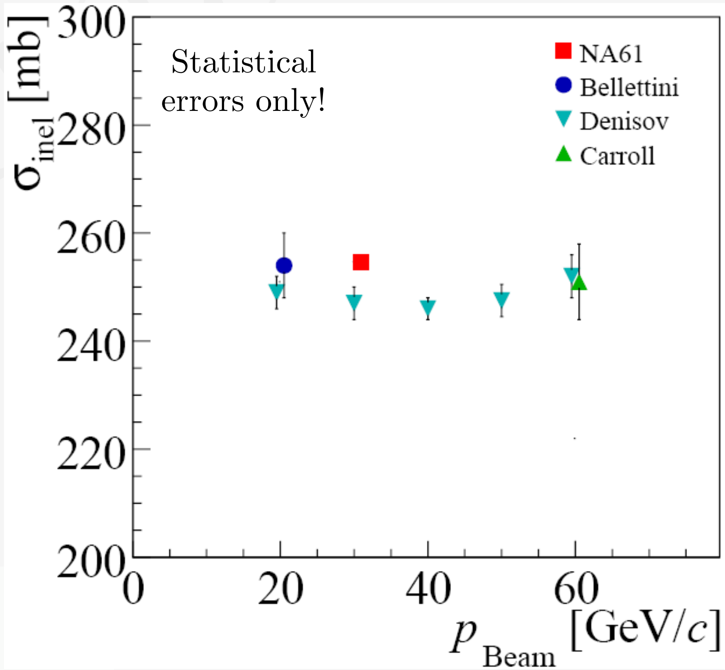
Cross Section Normalization – σ_{int} Determination

- Interaction cross section corrected using GEANT4 simulations

Statistical errors only!

σ contribution	Value	Comments
$\sigma_{trigger}$	297.5 ± 0.7 mb	Data
$\sigma_{loss\text{-}p}$	5.8 ± 0.2 mb	GEANT4
$\sigma_{loss\text{-}\pi/K}$	0.6 ± 0.1 mb	GEANT4
$\sigma_{elastic}$	-49.2 ± 0.6 mb	GEANT4
$\sigma_{interaction}$	254.7 ± 1.0 mb	GEANT4 corrected

The preliminary value for the σ_{int} is in good agreement with previous experiments



G. Bellettini et al., Nucl. Phys. 79 (1966) 609,

S.P. Denisov et. al. Nucl. Phys. B61 (1973) 62,

A. Carroll et al., Phys. Lett. B80 (1979) 319

Invariant Cross Section – Corrections

- The invariant inclusive cross section is generally defined as:

$$f(x_F, p_T) = E(x_F, p_T) \cdot \frac{d^3\sigma}{dp^3}(x_F, p_T)$$

$$\sigma_{trigger} = \frac{P_{int}}{\rho L_{eff} N_A / A}$$

$$P_{\text{int}} = P_{FT} - P_{ET}$$

which is experimentally defined by the measured quantity:

$$f_{meas}(x_F, p_T, \Delta p^3) = E(x_F, p_T, \Delta p^3) \cdot \frac{\sigma_{trigger}}{N_{ev}} \cdot \frac{\Delta n(x_F, p_T, \Delta p^3)}{\Delta p^3},$$

with Δp^3: finite phase space defined by the bin width, N_{ev}:# of evts off the target, Δn: # of identified particles in a given bin Δp^3

→ Several steps of normalization and correction have to be applied in order to make $f_{meas}(x_F, p_T, \Delta p^3)$ approach $f(x_F, p_T)$

Cross Section Normalization – Corrections

1) Corrections for acceptance and efficiency

   $\rightarrow$ will be evaluated with the NA61 MC simulation chain

2) Effect of the event selection (offline)

Cross Section Normalization – Corrections

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2) Effect of the event selection (offline)

Event Selection (Offline)

- In order to reduce the ET/FT rate (24%) and therefore also the statistical error of the final result suitable event cuts can be chosen

- To minimize sys. errors the NA49-aim was to create no bias due to event cuts

- Event cuts cause no bias if they fulfill one of the requirements below:

  a) Either the rejection from the real target interactions is random (rejection does not depend on topology, reconstruction efficiency, etc)

  b) or the cuts reject no target events at all

  The accepted fraction from target only events can be calculated from the accepted fraction of the FT and ET event sample:

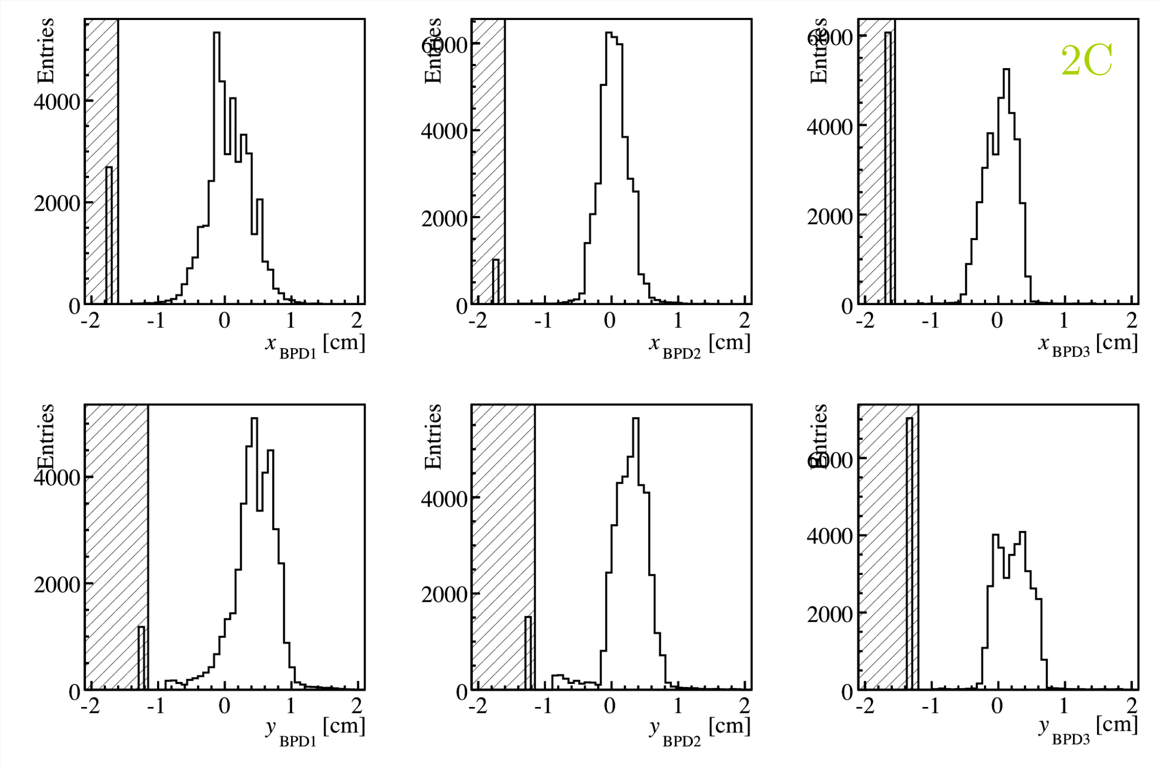
$$\frac{(N^{\text{Target}})'}{N^{\text{Target}}} = \frac{\frac{(N^{FT})'}{N^{FT}} - \varepsilon \frac{(N^{ET})'}{N^{ET}}}{1-\varepsilon}\quad \text{, where} \quad \varepsilon = R_{ET} / R_{FT}$$

Interaction rates

The cut is bias free if this accepted fraction is the same before and after the cut

Event Selection (Offline) – BPD Cuts

- A suitable cut to effectively reduce the ET/FT rate without producing any bias is for example a cut on the beam particle
- Ensure that x/y-positions of the beam particle were measured by all 3 BPDs



→ BPD-Cuts reduce ET/FT rate from 24.3% to 12.3%

→ further bias-free cuts are under investigation

Cross Section Normalization – Corrections

1) Corrections for acceptance and efficiency

→ will be evaluated with the NA61 MC simulation chain

2) Effect of the event selection (offline)

→ event selection (used to reduce the ET/FT rate (24%)) will be done in such a way that no bias will be created

→ due to this conservative approach no corrections will be needed

Cross Section Normalization – Corrections

1) Corrections for acceptance and efficiency

   → will be evaluated with the NA61 MC simulation chain

2) Effect of the event selection (offline)

   → event selection (used to reduce the ET/FT rate (24%)) will be done in such a way that no bias will be created

   → due to this conservative approach no corrections will be needed

3) Treatment of empty target contribution

   → will be evaluated from the data taken without a target

   → in NA49 pp and pC data at 158 GeV/c this was a rather small correction (3-4%)

Empty Target Contribution – NA49

- The particle yield $\Delta n/N_{\text{ev}}$ can in principle be determined from separate yield determinations in FT and ET conditions for each bin according to:

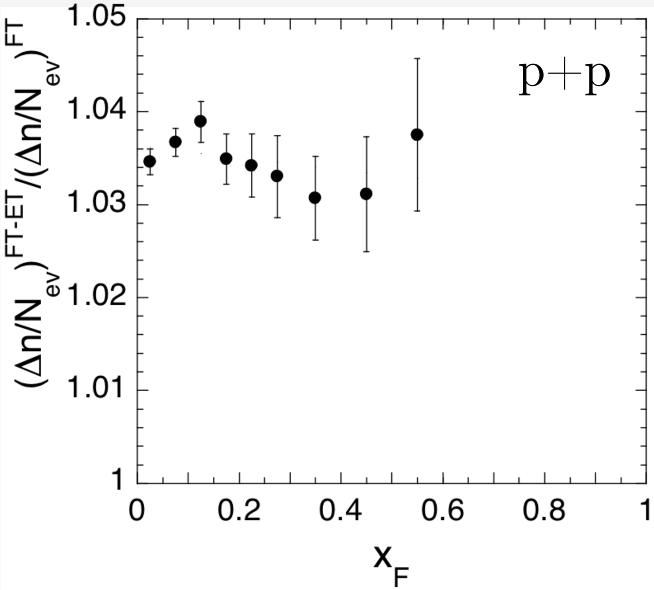
$$\left(\frac{\Delta n}{N_{ev}}\right)^{FT-ET} = \frac{1}{1-\varepsilon}\left(\left(\frac{\Delta n}{N_{ev}}\right)^{FT} - \varepsilon\left(\frac{\Delta n}{N_{ev}}\right)^{ET}\right)$$

, where $\varepsilon = R_{ET} / R_{FT}$ ← Interaction rates

- But in NA49 the ET event sample was too small to apply this bin-by-bin subtraction
- Therefore, the cross sections were extracted from FT runs alone and the ET contribution was only used as a small correction
- This was possible since the deviation of the complete normalized yield from the FT yield alone was small and defined by the different fraction of empty events in FT and ET conditions

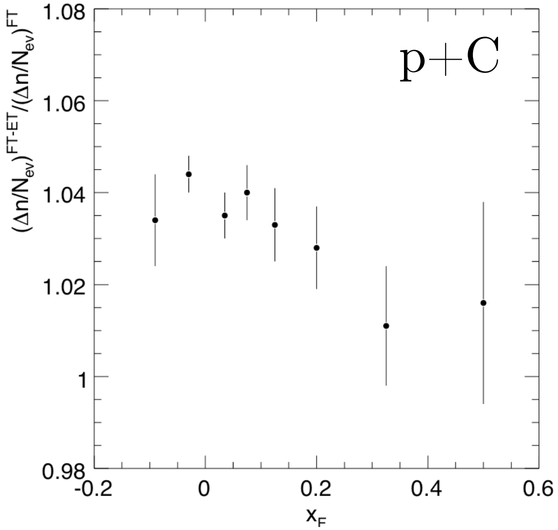
Empty Target Contribution – NA49

- The resulting NA49 correction, defined as the ratio between the bin contents for FT-ET and FT alone, is around 3-4% and only depends slightly on x_F (not on p_T or charge):

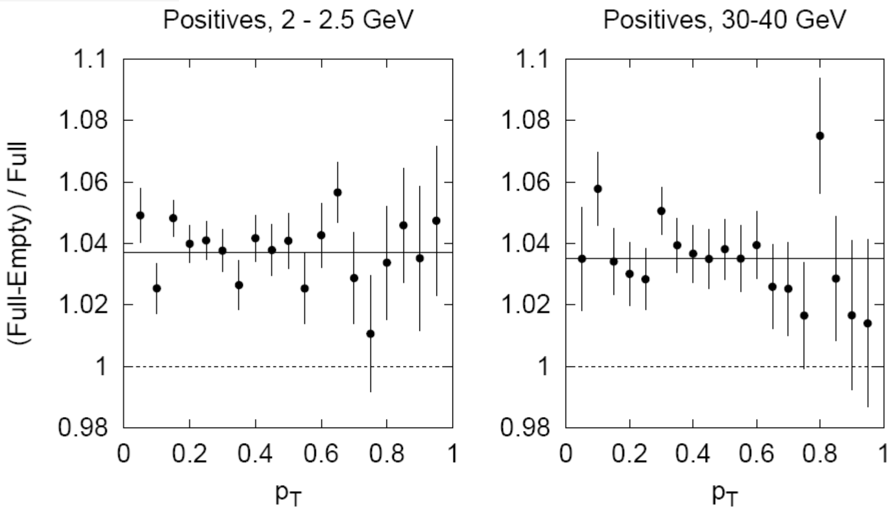


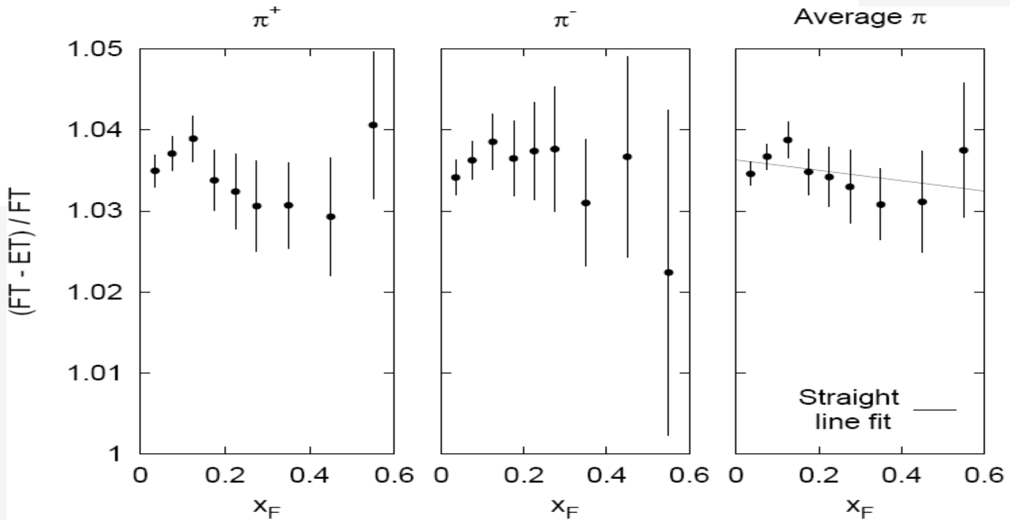
NA49

158 GeV/c



p+p





Cross Section Normalization – Corrections

4) Bias due to the interaction trigger

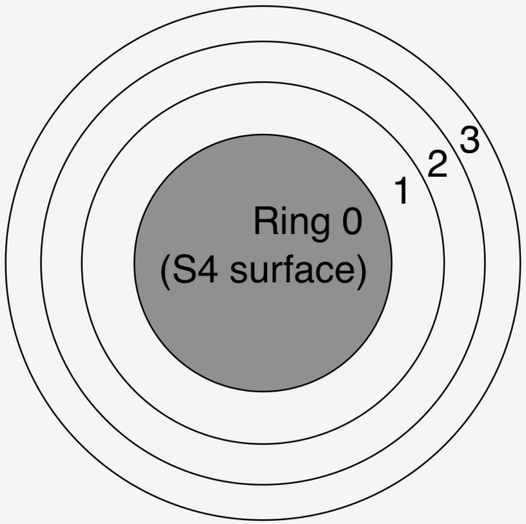
Trigger Bias Corrections

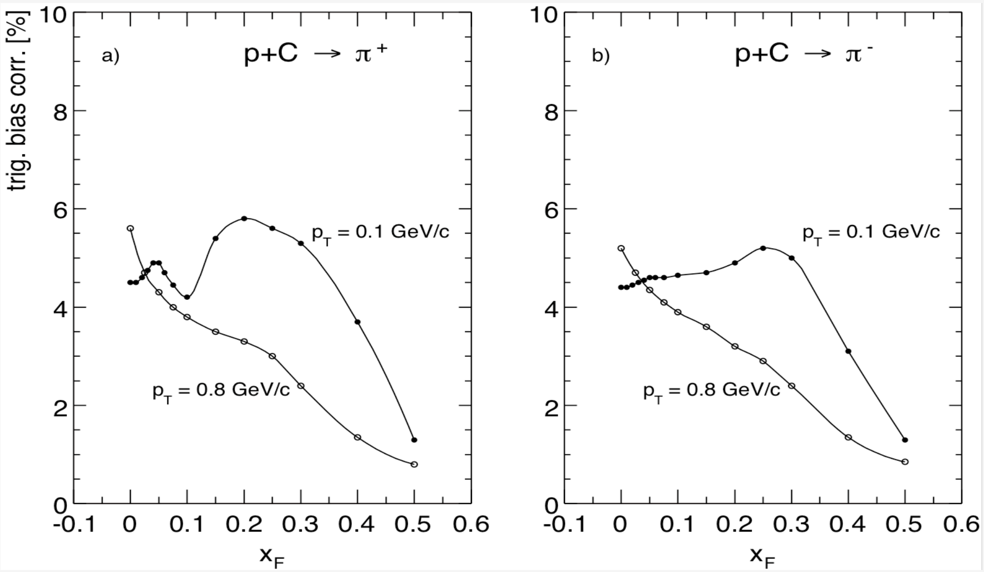
- The interaction trigger defined by S4 accepts not all inelastic events
- The bias will reflect into the measured cross section via the expression

$$f_{meas} \propto \sigma_{trig} \cdot \frac{\Delta n}{N_{ev}}$$

- The correction for it has been obtained experimentally by increasing the diameter of S4 and extrapolating the observed changed in the cross section to surface zero

NA49 p+C @ 158 GeV/c





Cross Section Normalization – Corrections

4) Bias due to the interaction trigger

$\rightarrow$ will be evaluated from the data by artificially increasing the diameter of S4 and extrapolating the observed changes in the cross section to surface zero

Cross Section Normalization – Corrections

4) Bias due to the interaction trigger

→ will be evaluated from the data by artificially increasing the diameter of S4 and extrapolating the observed changes in the cross section to surface zero

5) Re-interaction in the target volume

→ will be evaluated with some event generator (PYTHIA?)

Cross Section Normalization – Corrections

4) Bias due to the interaction trigger

→ will be evaluated from the data by artificially increasing the diameter of S4 and extrapolating the observed changes in the cross section to surface zero

5) Re-interaction in the target volume

→ will be evaluated with some event generator (PYTHIA?)

6) Corrections for π/K weak decay and absorption in the detector material and Feed-down from weak decays of strange particles

→ will be evaluated with the NA61 MC simulation chain

Cross Section Normalization – Corrections

4) Bias due to the interaction trigger

→ will be evaluated from the data by artificially increasing the diameter of S4 and extrapolating the observed changes in the cross section to surface zero

5) Re-interaction in the target volume

→ will be evaluated with some event generator (PYTHIA?)

6) Corrections for π/K weak decay and absorption in the detector material and Feed-down from weak decays of strange particles

→ will be evaluated with the NA61 MC simulation chain

7) Effect of finite bin width

→ will be evaluated from the data by determining the deviation of the real cross section at the bin center from the measured one (averaged over the bin)

Summary and Outlook

- The NA61 beam and trigger system has been studied and is well understood
- The strategy for the cross section normalization is defined
- σ_{trig} and σ_{int} were measured
  → σ_{int} is in good agreement with previous measurements
- So far the corrections for σ_{int} were based on GEANT4 results only, however a dedicated analysis of the data will allow for a better estimation of $\sigma_{loss\text{-}p/\pi/K}$ and $\sigma_{elastic}$ and also for a systematic error determination
- Introduce suitable event selection to clean up the event sample and to reduce the empty target background
- Determine differential corrections (x_F, p_T) in order to evaluate inclusive particle spectra
  → corrections should take into account all online and offline biases