Pion Hadron Production in NA61

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for the NA61 Collaboration

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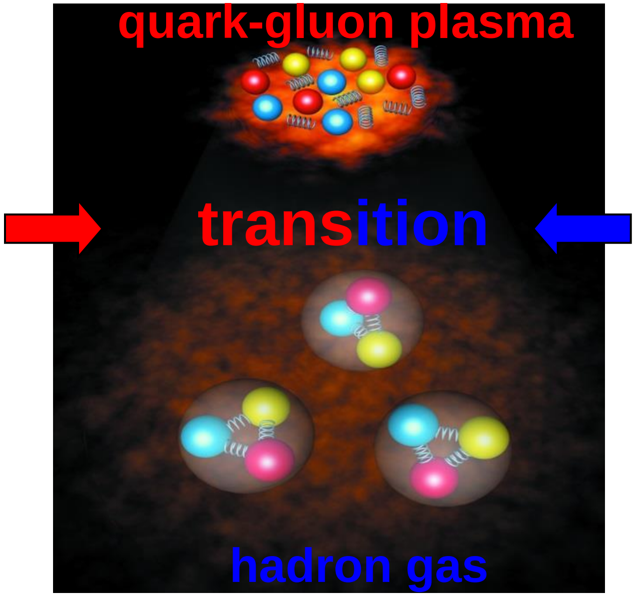
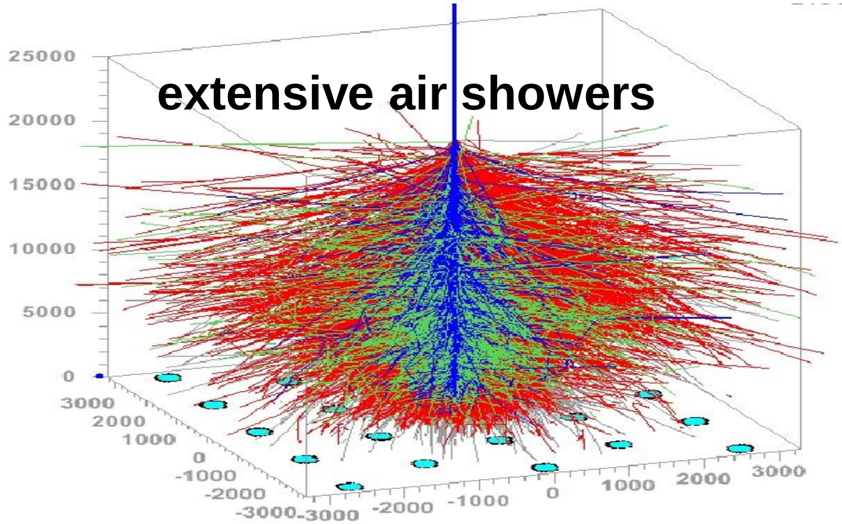
NA61 Physics Program



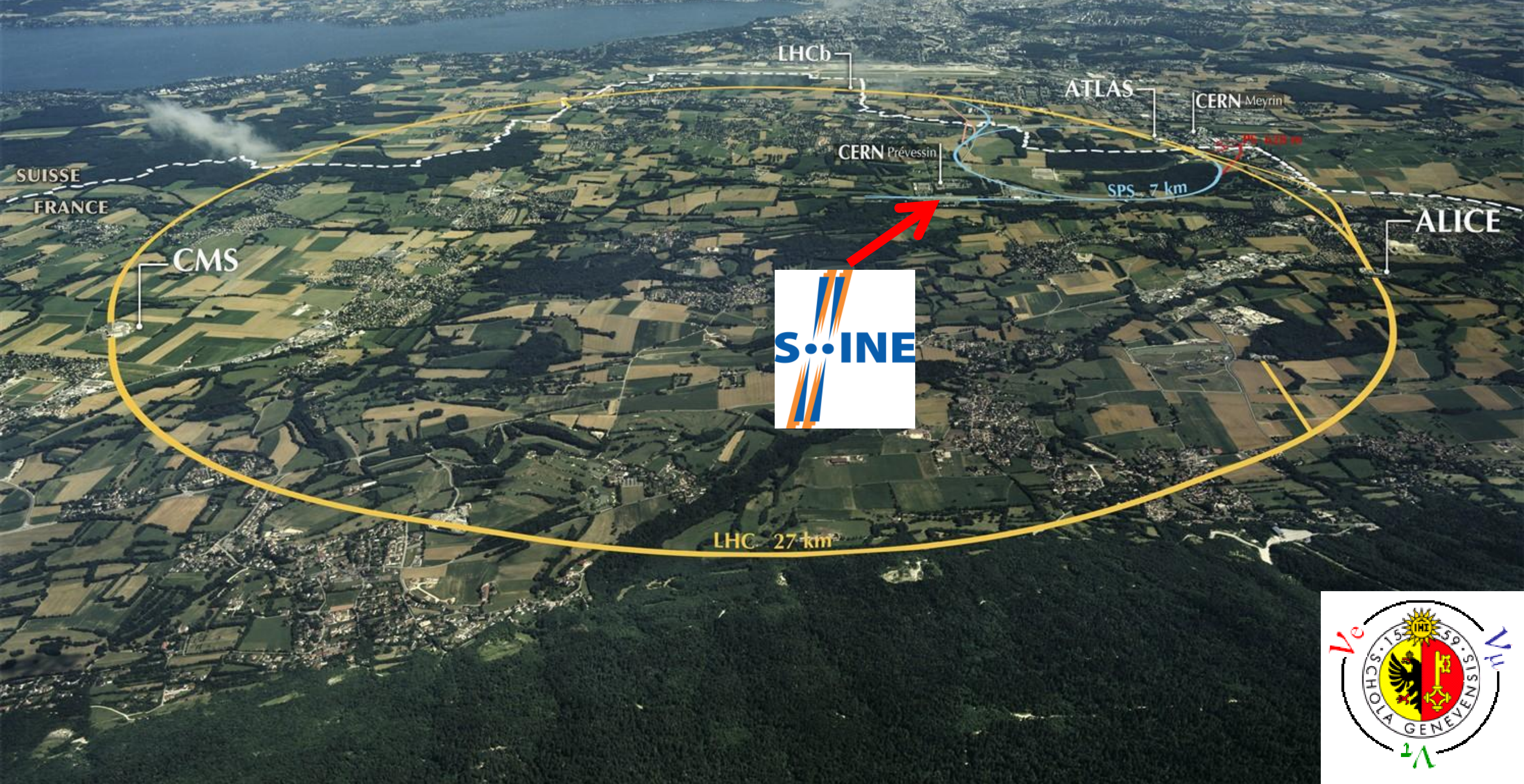
Physics of strongly interacting matter
in heavy ion collisions
Search of the QCD critical point
(AA and pA collisions)

Hadron production measurements
on the T2K target (p+C) to
characterize the T2K neutrino beam
soon also measurements for NuMI

Measurement of hadron production
in p+C interactions needed for the
description of cosmic-ray air showers
(Pierre Auger Observatory
and KASCADE experiments)

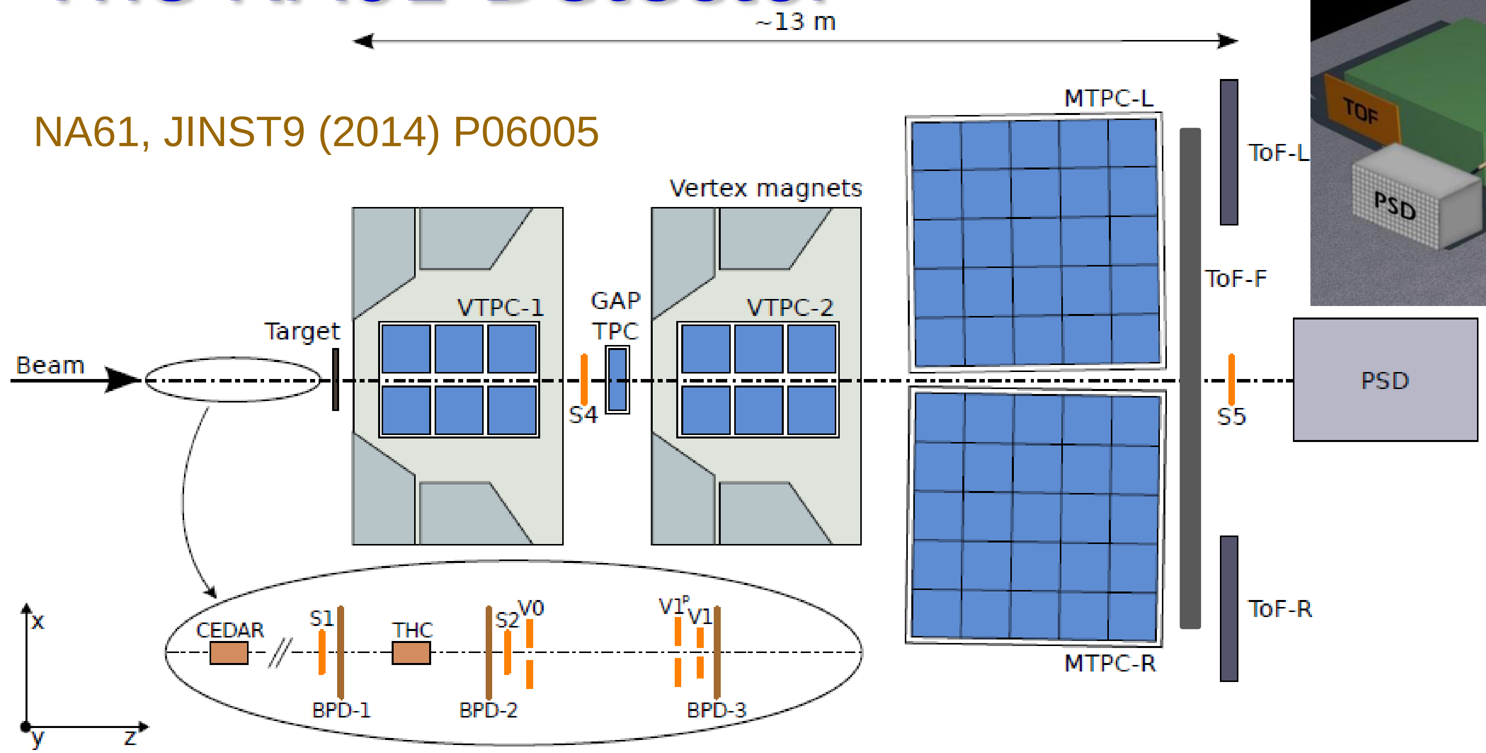


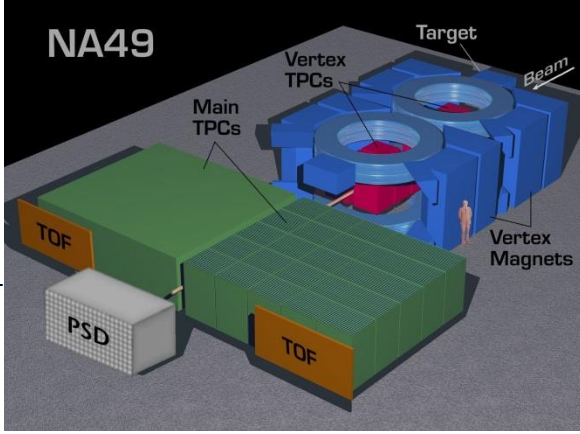
NA61/SHINE – unique multipurpose facility:
hadron production in h + p (20 – 350 GeV/c),
h + A (20 – 350 GeV/c),
A + A (13*A* - 150*A* GeV/c)



The NA61 Detector

NA61, JINST9 (2014) P06005





large acceptance spectrometer for charged particles

4 large volume TPCs as main tracking devices

2 dipole magnets with bending power of max 9 Tm over 7 m length (T2K runs: ∫Bdl ~ 1.14 Tm)

high momentum resolution

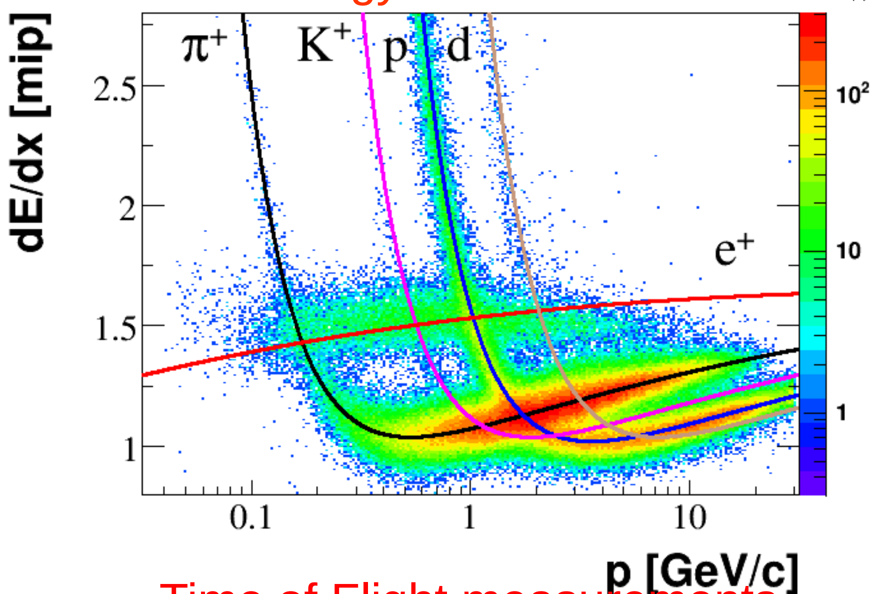
good particle identification: σ(ToF-L/R) ≈ 100 ps, σ(dE/dx)/<dE/dx> ≈ 0.04, $\sigma(m_{inv}) \approx 5$ MeV

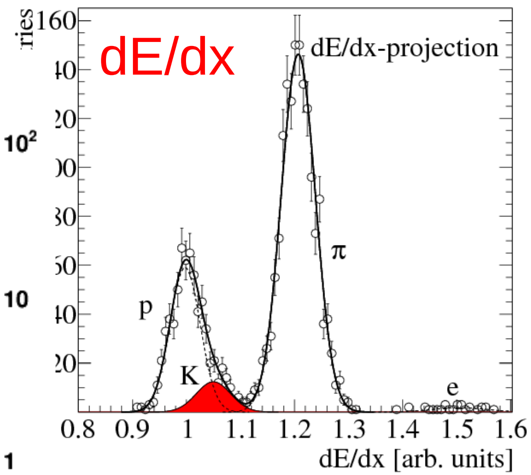
new ToF-F to entirely cover T2K acceptance (σ(ToF-F) ≈ 100 ps, $1 < p < 5$ GeV/c, $\theta < 250$ mrad)

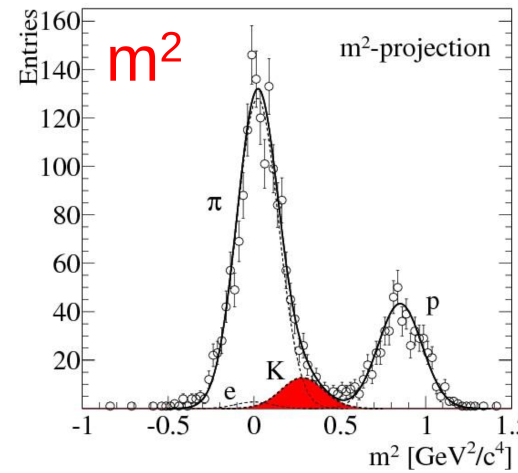
several additional upgrades are under way

Particle Identification in NA61

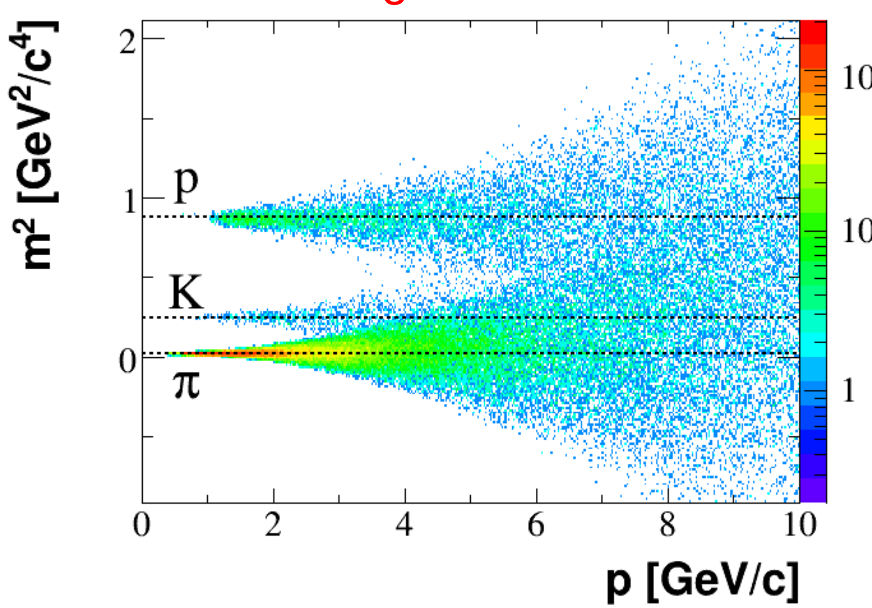
Energy loss in TPCs



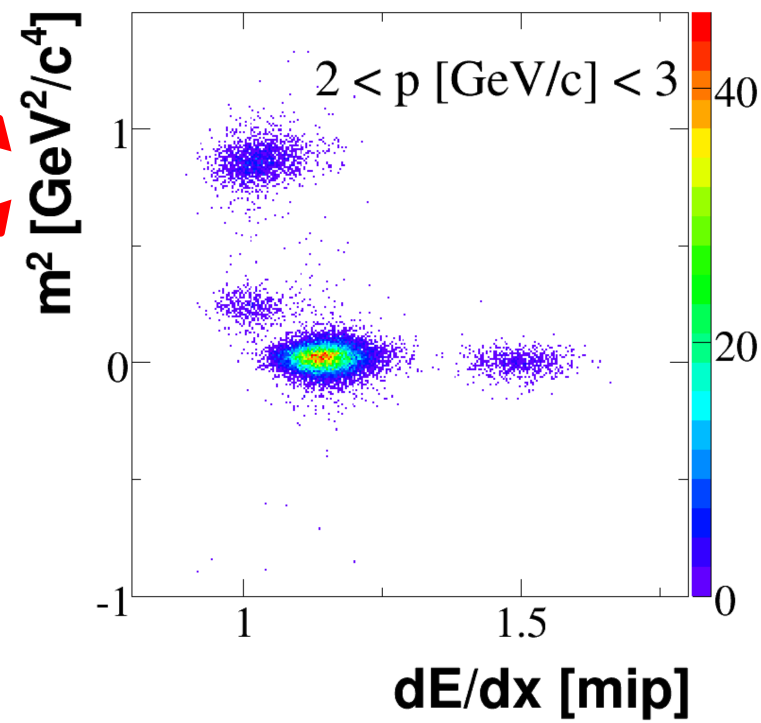




Time of Flight measurements

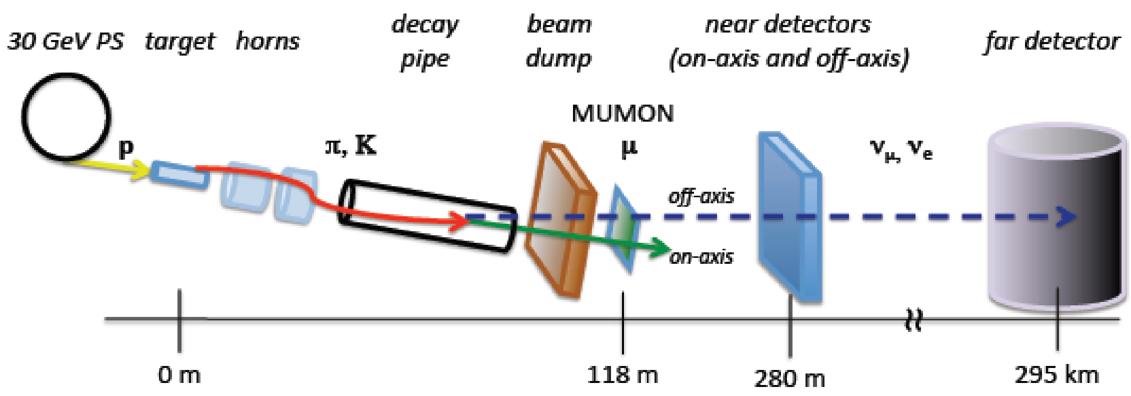


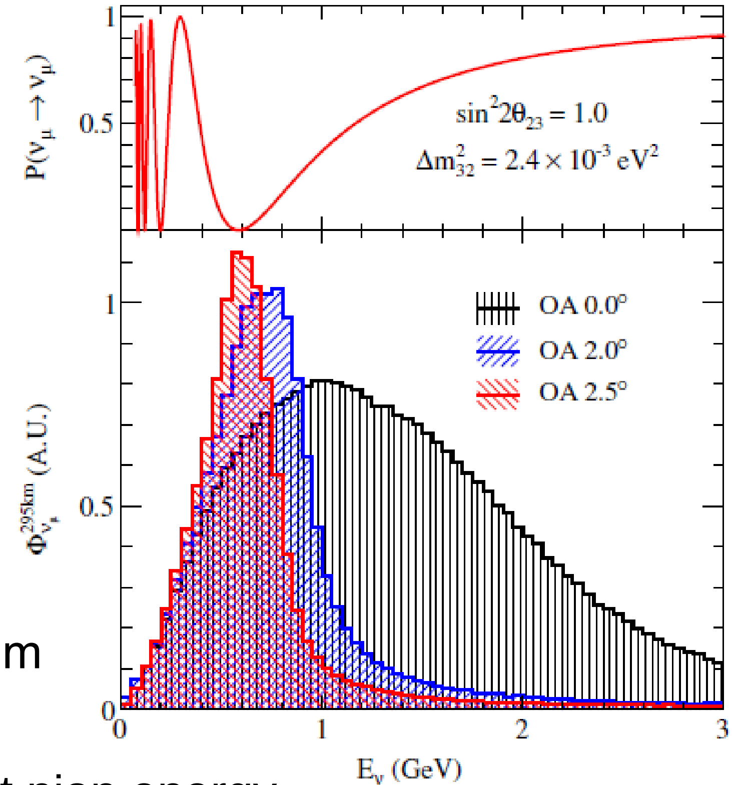
combined ToF + dE/dx



The Off-Axis T2K ν Beam

T2K, PRD87 (2013) 012001





2.5[0] off-axis neutrino beam

- Neutrino beam energy "tuned" to oscillation maximum
- Very narrow energy spectrum (narrow band)
- Neutrino beam energy almost independent of parent pion energy

Neutrino source created by interactions of 30 GeV protons on a 90 cm long graphite rod

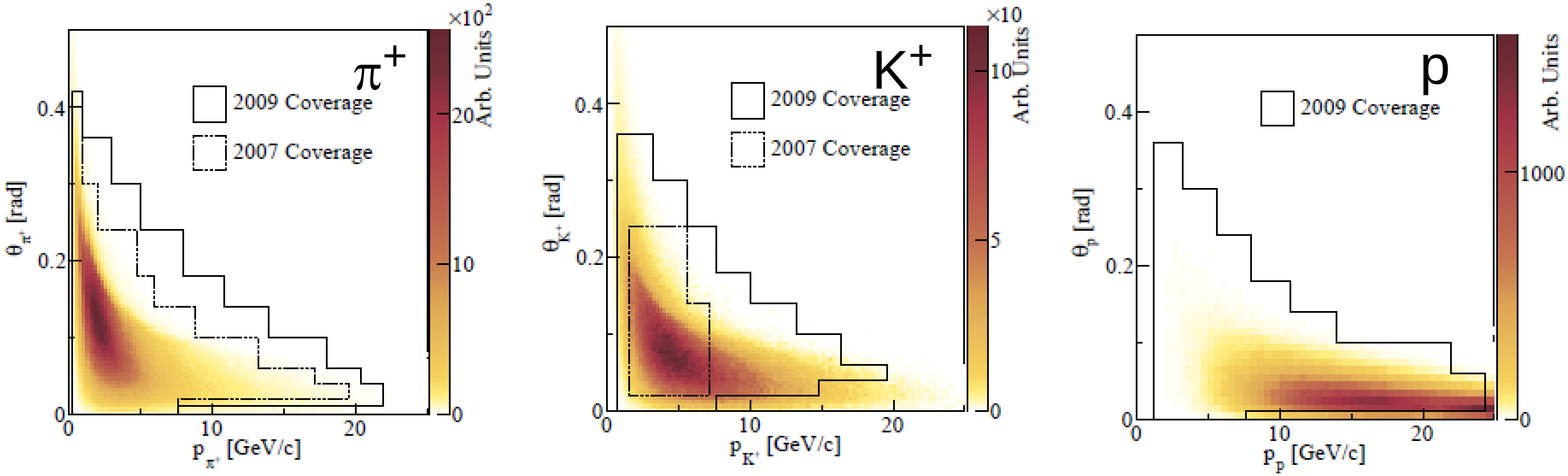
Neutrino beam predictions rely on modeling the proton interactions and hadron production in the target

Horn focusing cancels partially the p_T dependence of the parent pion

Precise hadron production measurements allow to reduce uncertainties on neutrino flux prediction

Required Acceptance for ν Flux Calculations

T2K ν parent hadron phase space
30 GeV proton beam on the 90 cm long T2K graphite target



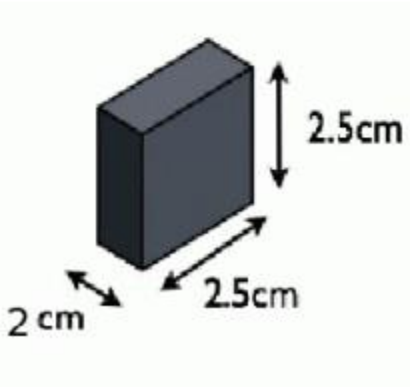
note: this is not a cross section
it shows the distributions of π, K, and contributing to the ν flux at SK

need to cover this kinematical region and identify the outgoing hadrons
K component important for ν_e appearance signal

requires detector with large acceptance
with excellent particle ID capabilities
with high rate capabilities to accumulate sufficient statistics

The NA61 Targets

2 different graphite (carbon) targets



Thin Carbon Target
- length=2 cm, cross section 2.5 x 2.5 cm^2
- ρ = 1.84 g/cm^3
- ~0.04 λ_{int}

T2K replica Target
- length = 90 cm, Ø=2.6 cm
- ρ = 1.83 g/cm^3
- ~1.9 λ_{int}

	2007 pilot run	2009 run	2010 run
Thin target:	~660k triggers	~6 M triggers	
		(⇒ 200 k π^+ tracks in T2K acc.)	
Replica target:	~230k triggers	~2 M triggers	~10 M triggers

Analysis Methods

Different analysis procedures adopted depending on the kinematical region covered:

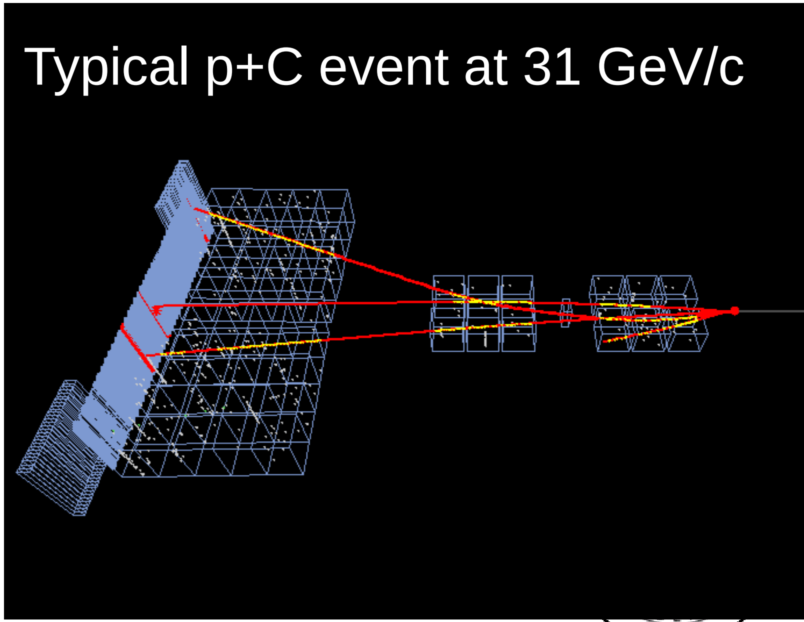
1) negative hadrons: at this beam energy (31 GeV/c) most (> 90%) negative hadrons are π^- with small K^- contamination (< 5%)
pure tracking with no PID, large acceptance, global MC correction

2) p < 1 GeV/c PID based on dE/dx only (below cross-over region in dE/dx)

3) p > 0.8 GeV/c PID combined ToF – dE/dx analysis
(π / K / p separation)
particles must reach the ToF, reduced acc.;
factorize all corrections (i.e. acc., recon. eff., decays, etc.), some corrections estimated directly from data, rely less on MC

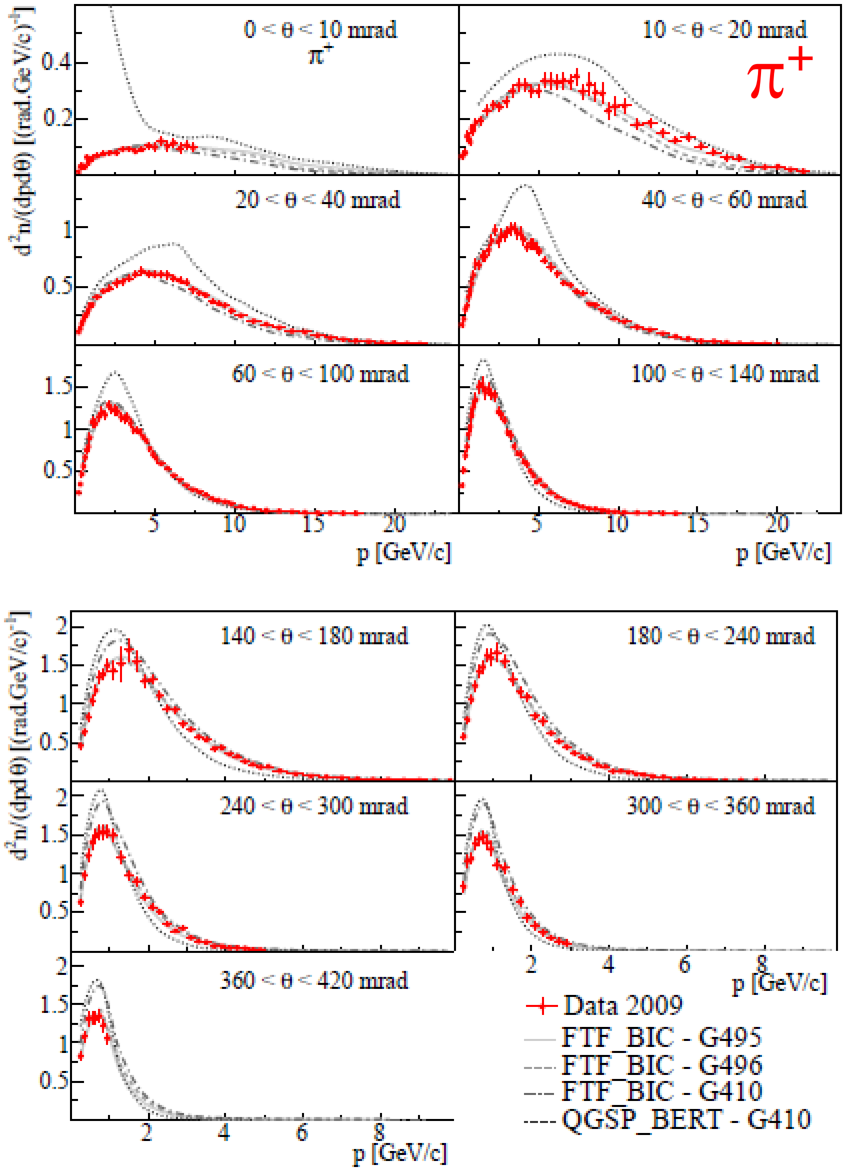
raw measured particle spectra corrected for:

- geometrical acceptance
- reconstruction efficiency
- non-pion contributions
- weak decays (feed-down)
- trigger bias

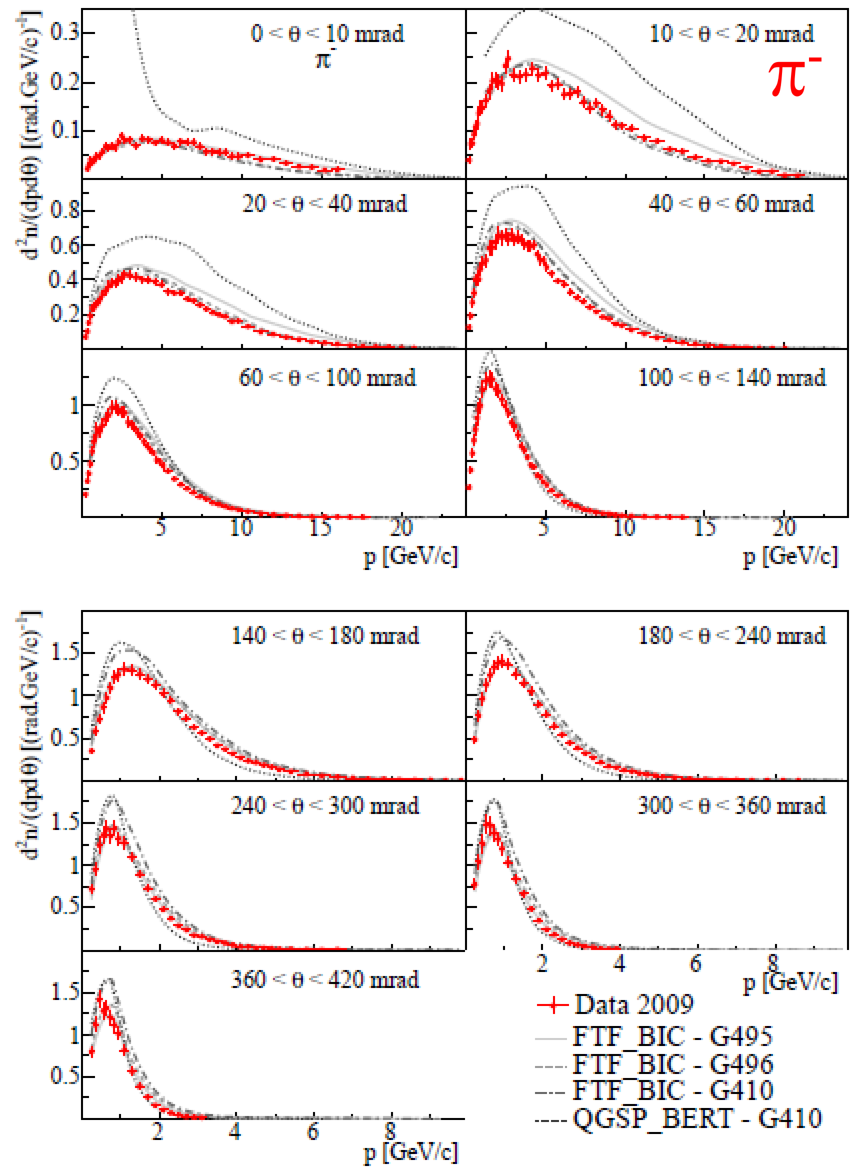


Typical p+C event at 31 GeV/c

NA61 p + C → $\pi^{+/-}$ + X @ 31 GeV/c

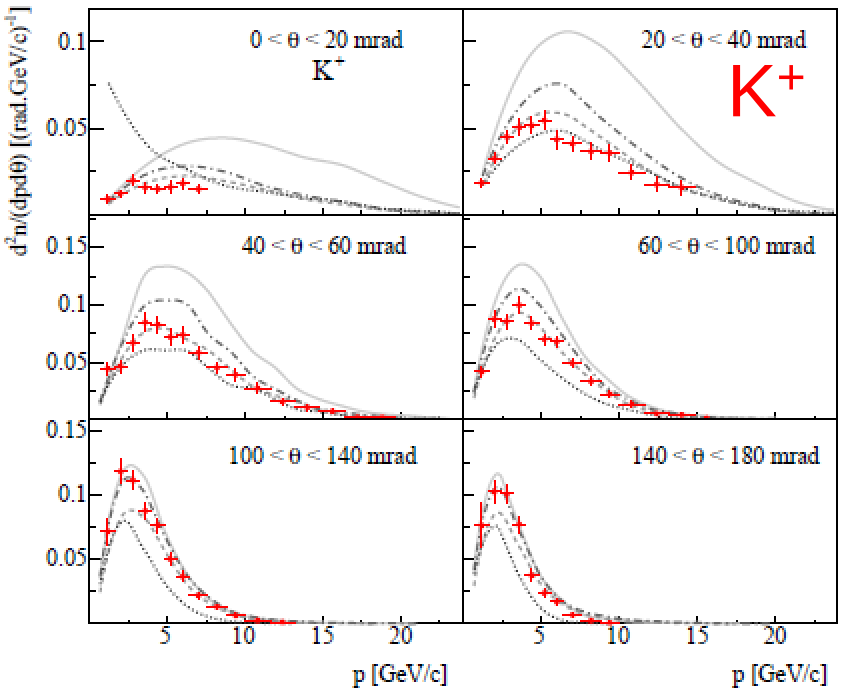


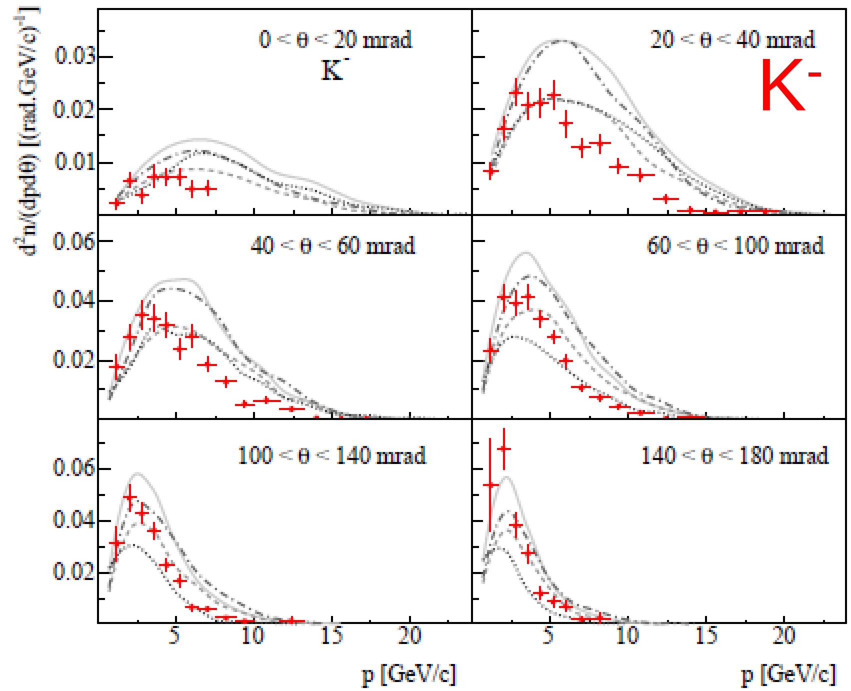
NA61 preliminary



Relative uncertainty in the T2K region ~ 4%

NA61 p + C → $K^{+/-}$ + X @ 31 GeV/c





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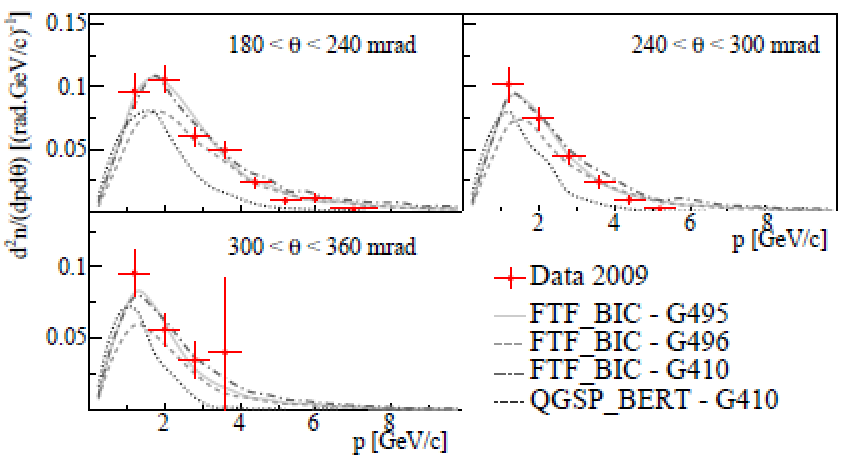
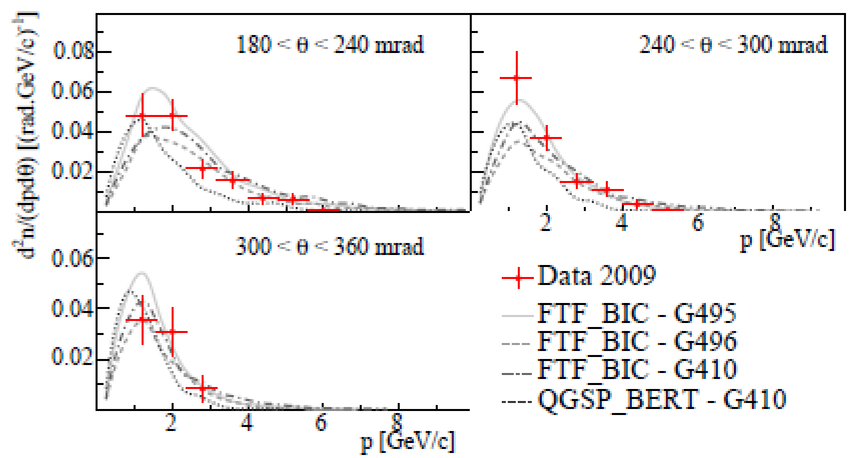
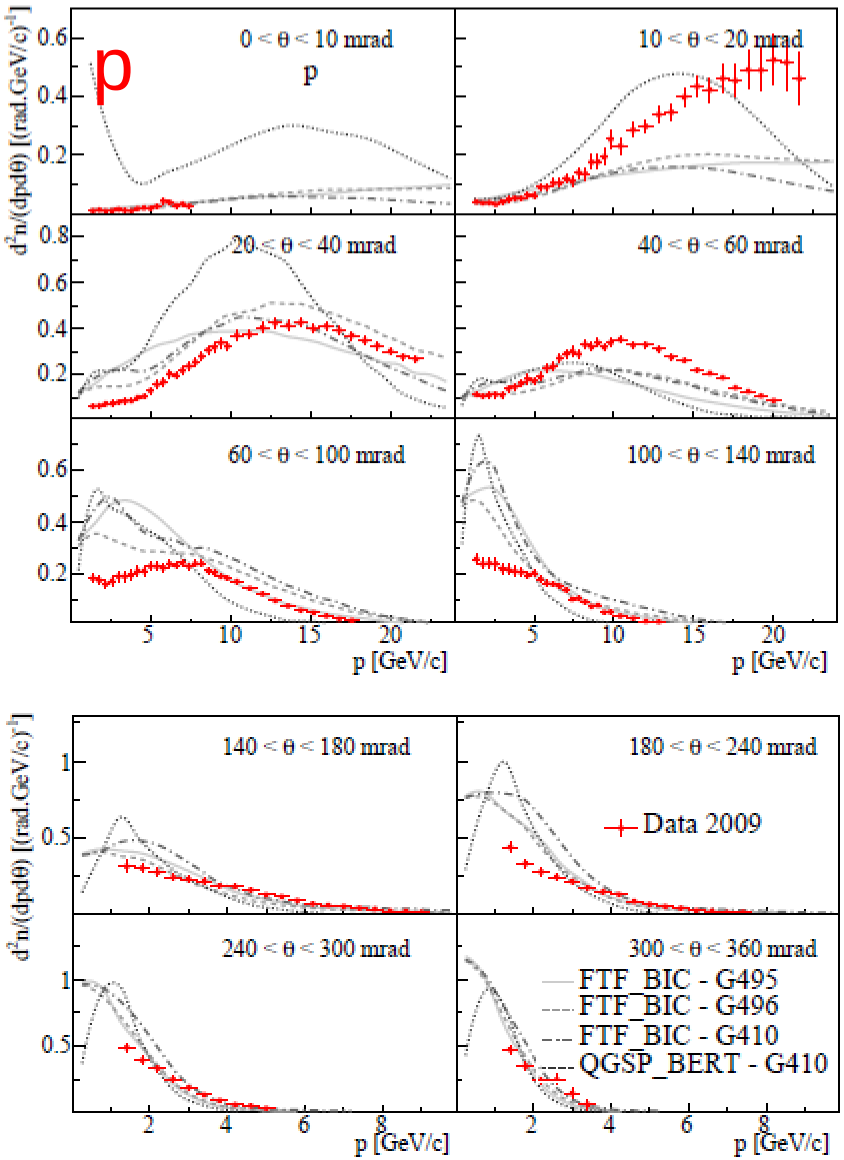


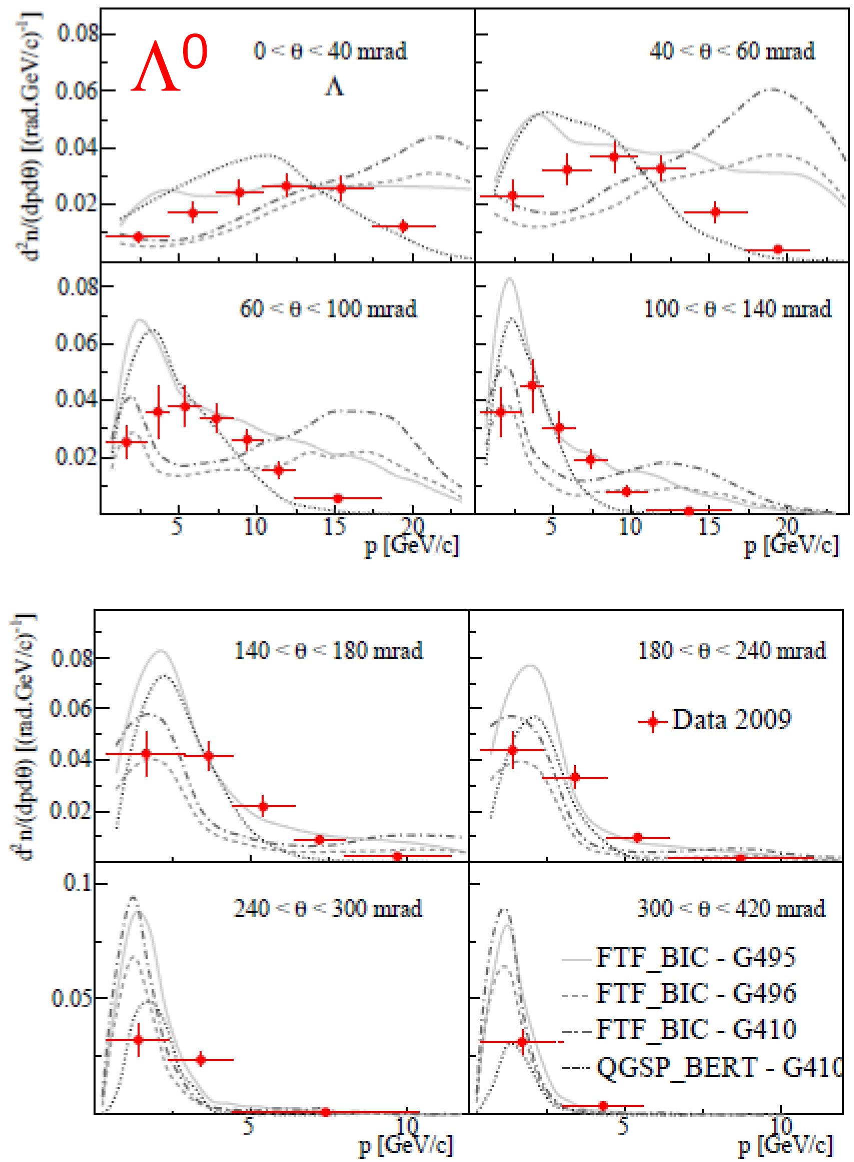


Relative uncertainty in the T2K region ~ 15%

NA61 p + C → p / Λ + X @ 31 GeV/c

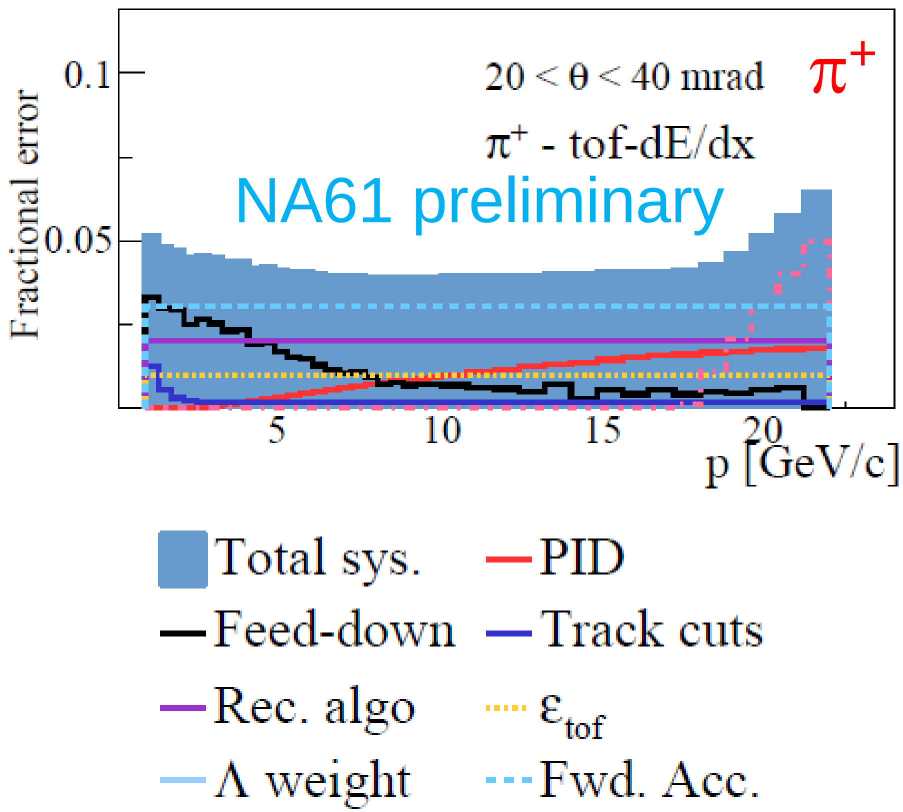


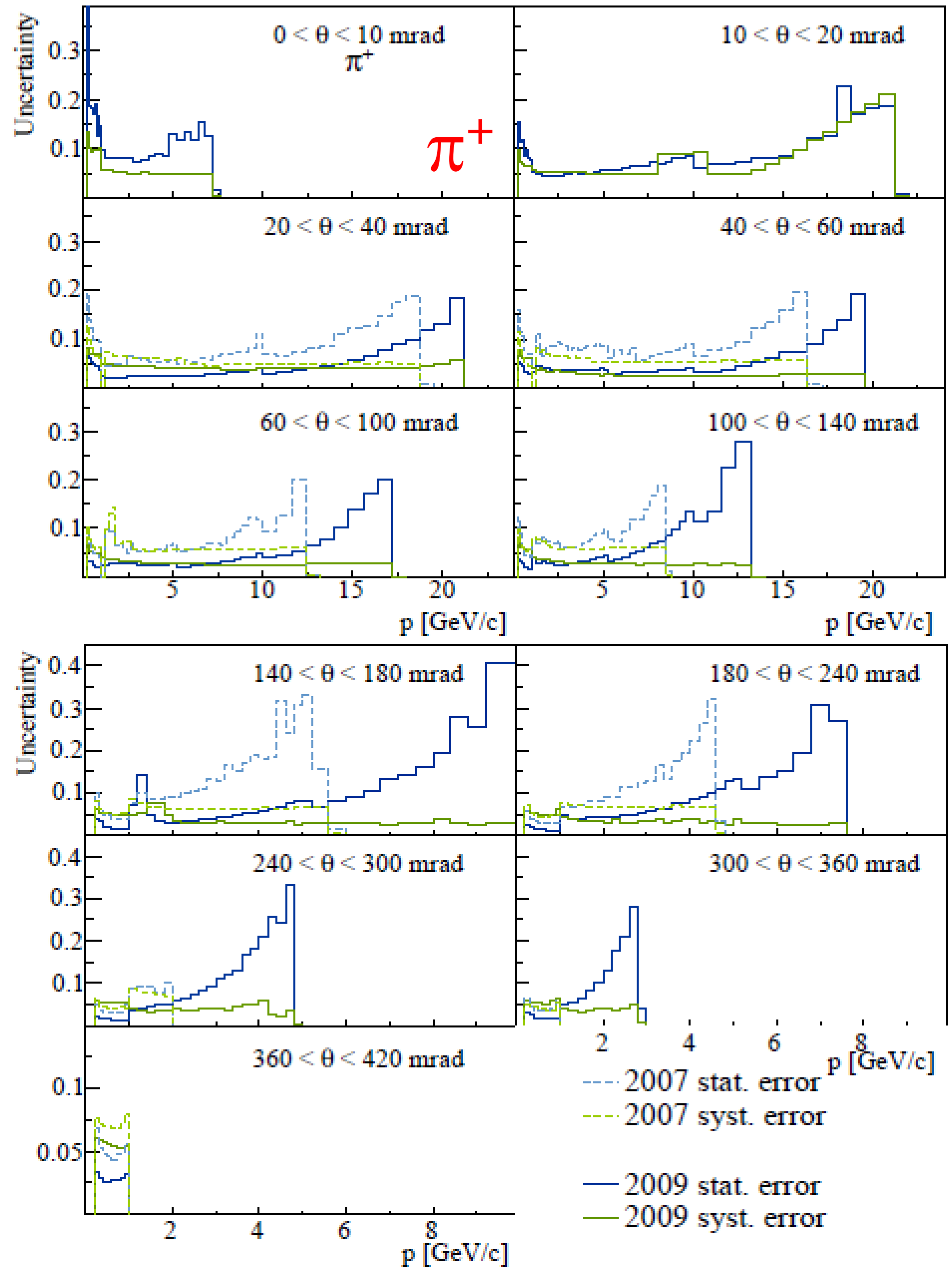
NA61 preliminary



NA61 p + C → π^+ + X Uncertainties (dN/dp)

Compared to 2007 data:
statistical uncertainty
improved by ~3
systematical uncertainty
reduced by ~ 2

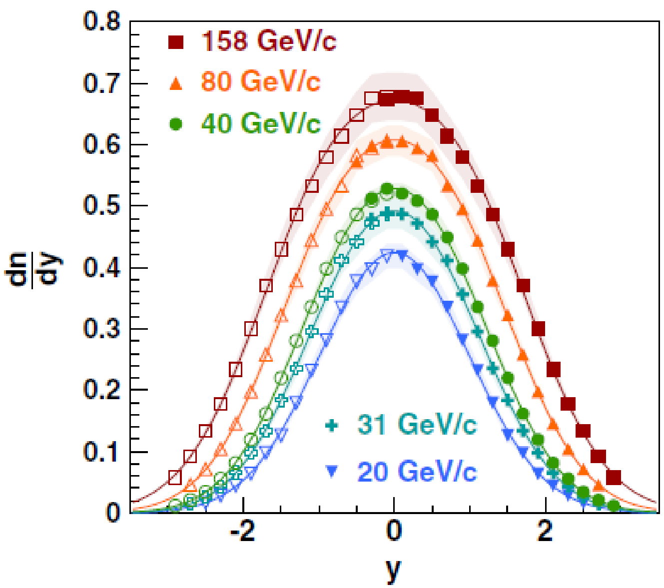


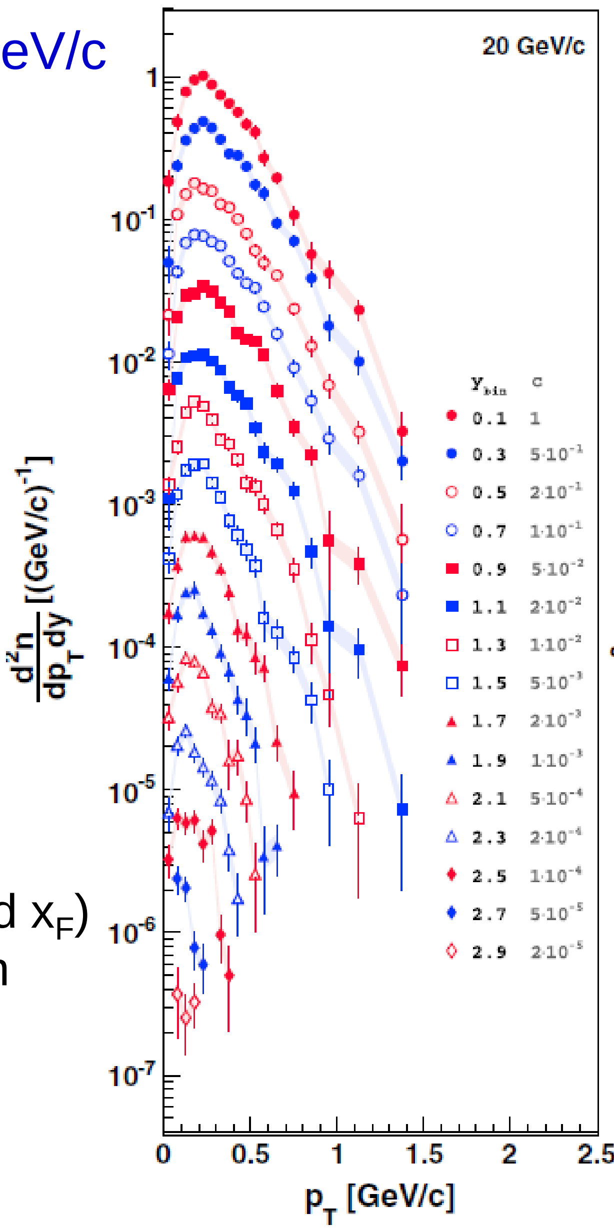


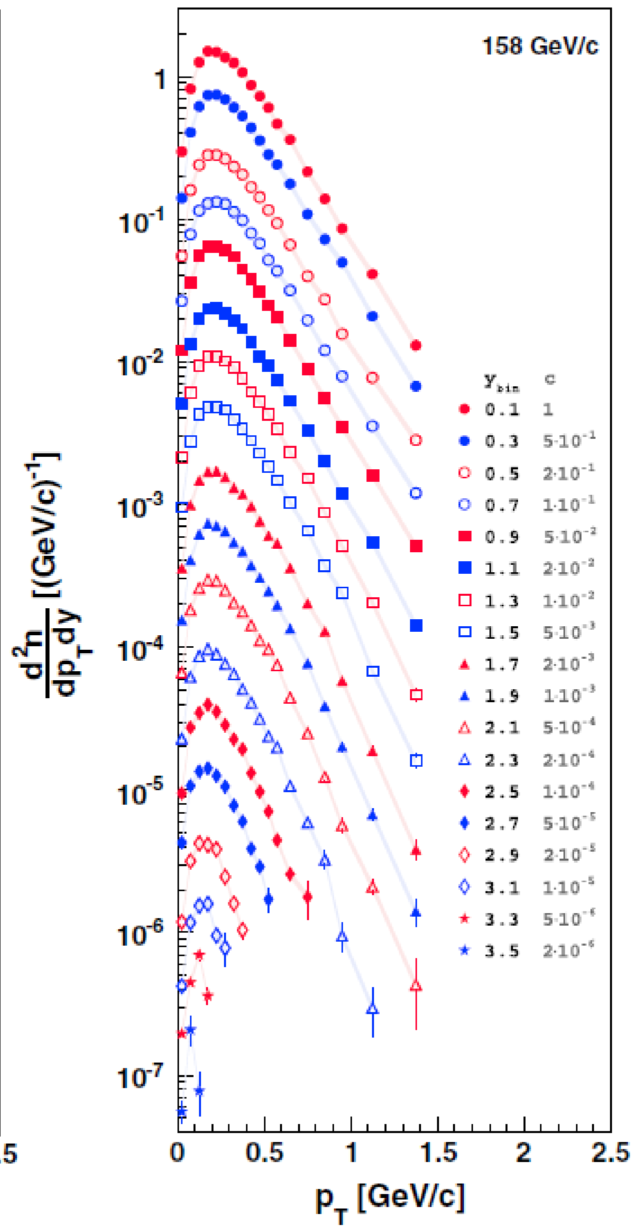
π^- Spectra in p + p → π^- + X Energy Scan

p_{lab} = 20, 30, 40, 80, 158 GeV/c

NA61, EPJC 74 (2014) 2794







p + p symmetric in rapidity (and x_F)
negative *y* (x_F) by reflection

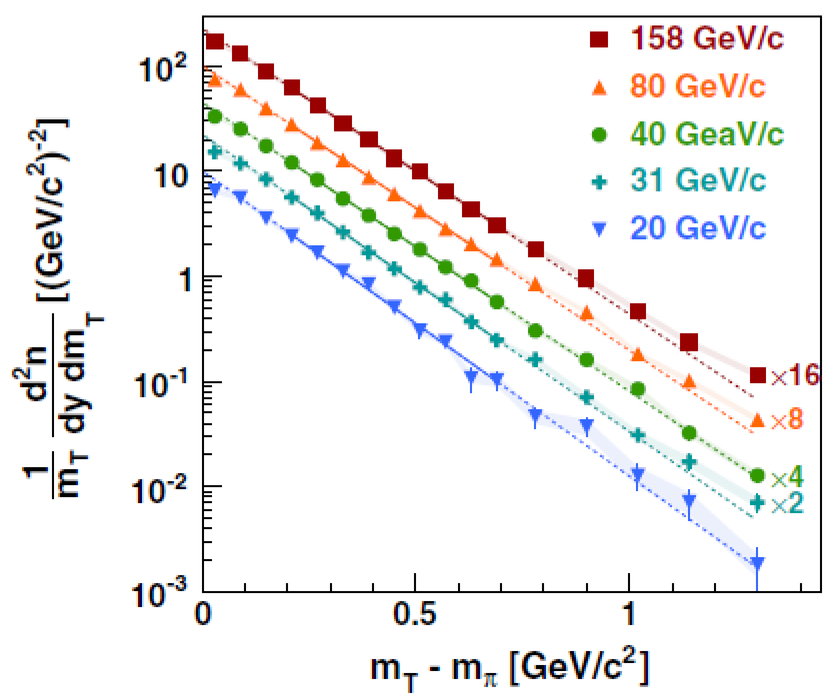
($y = 0 \rightarrow x_F = 0$)

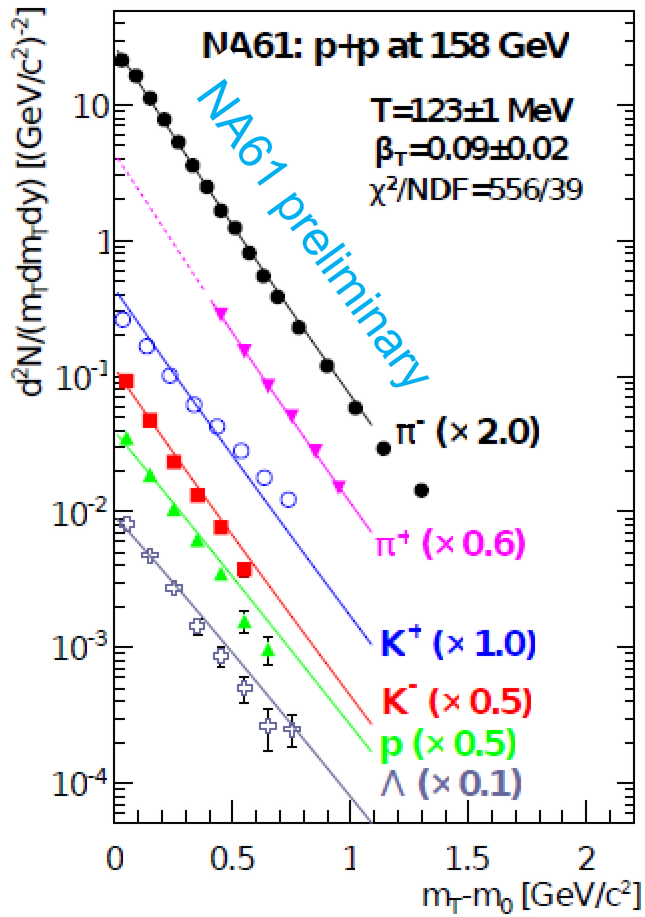
Transverse Mass Spectra at Mid-Rapidity

$p + p \rightarrow h + X$ @ 158 GeV/c

transverse mass: $m_T^2 = m_0^2 + p_T^2$ mid-rapidity: $y = 0$ ($x_F = 0$)

NA61, EPJC 74 (2014) 2794

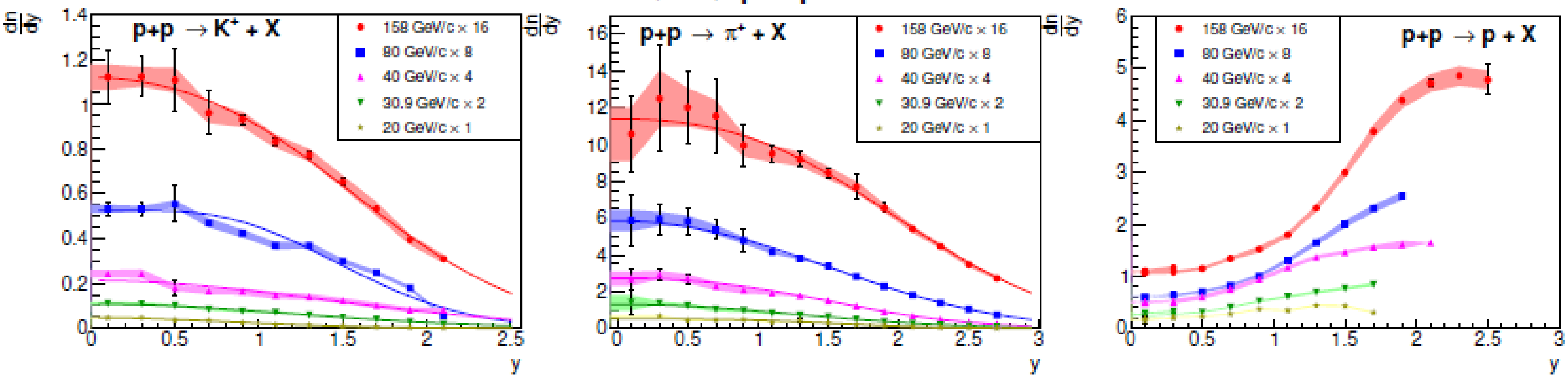




Transverse mass spectra are approximately exponential in p + p interactions

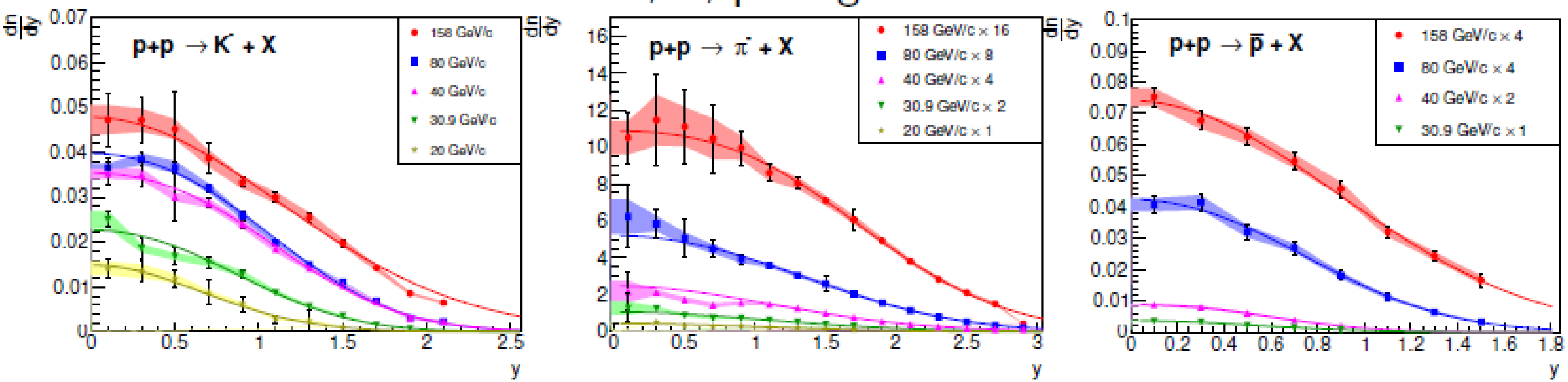
p + p → h + X : dn/dy (Energy Scan)

K, π, p: positive



NA61 preliminary

K, π, p: negative



π Multiplicities and K/π Ratios

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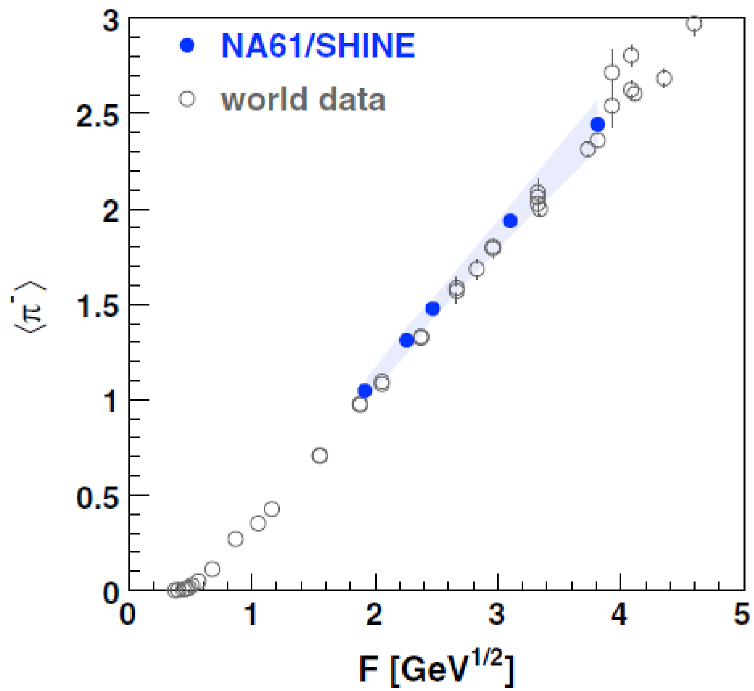
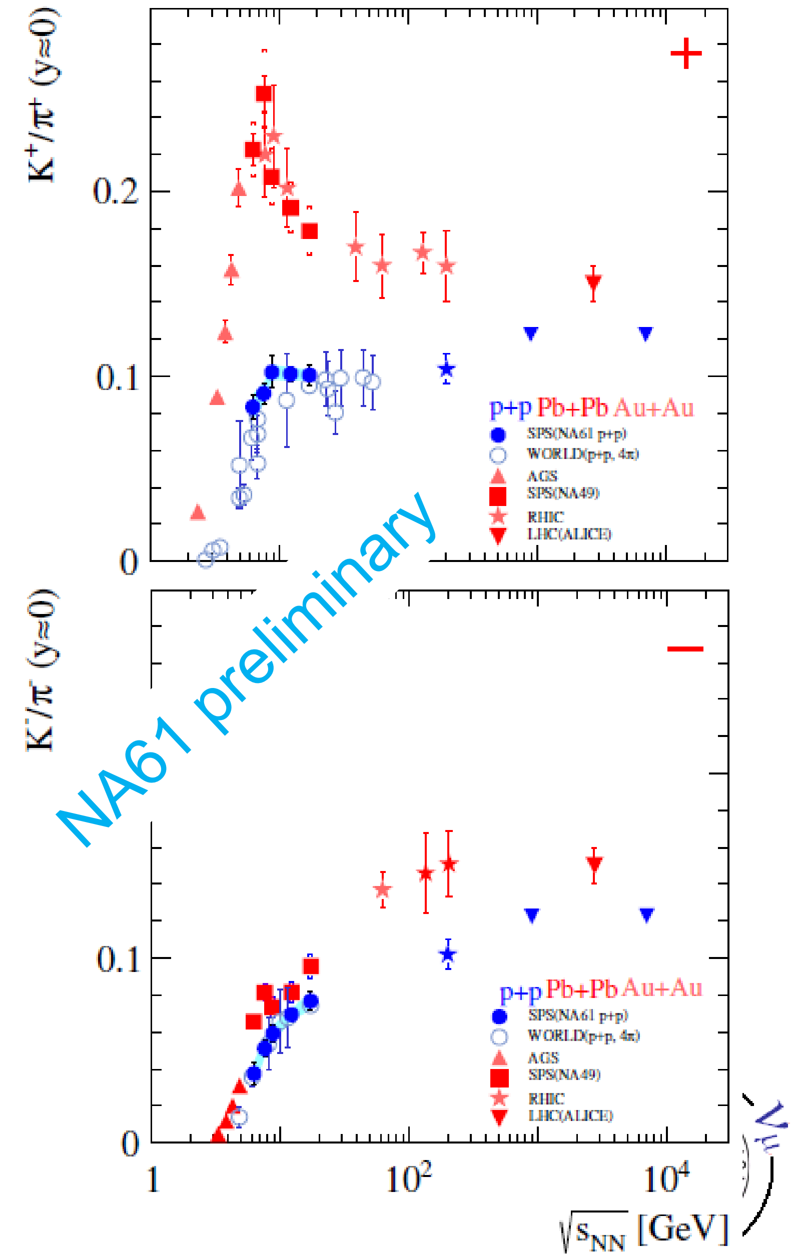
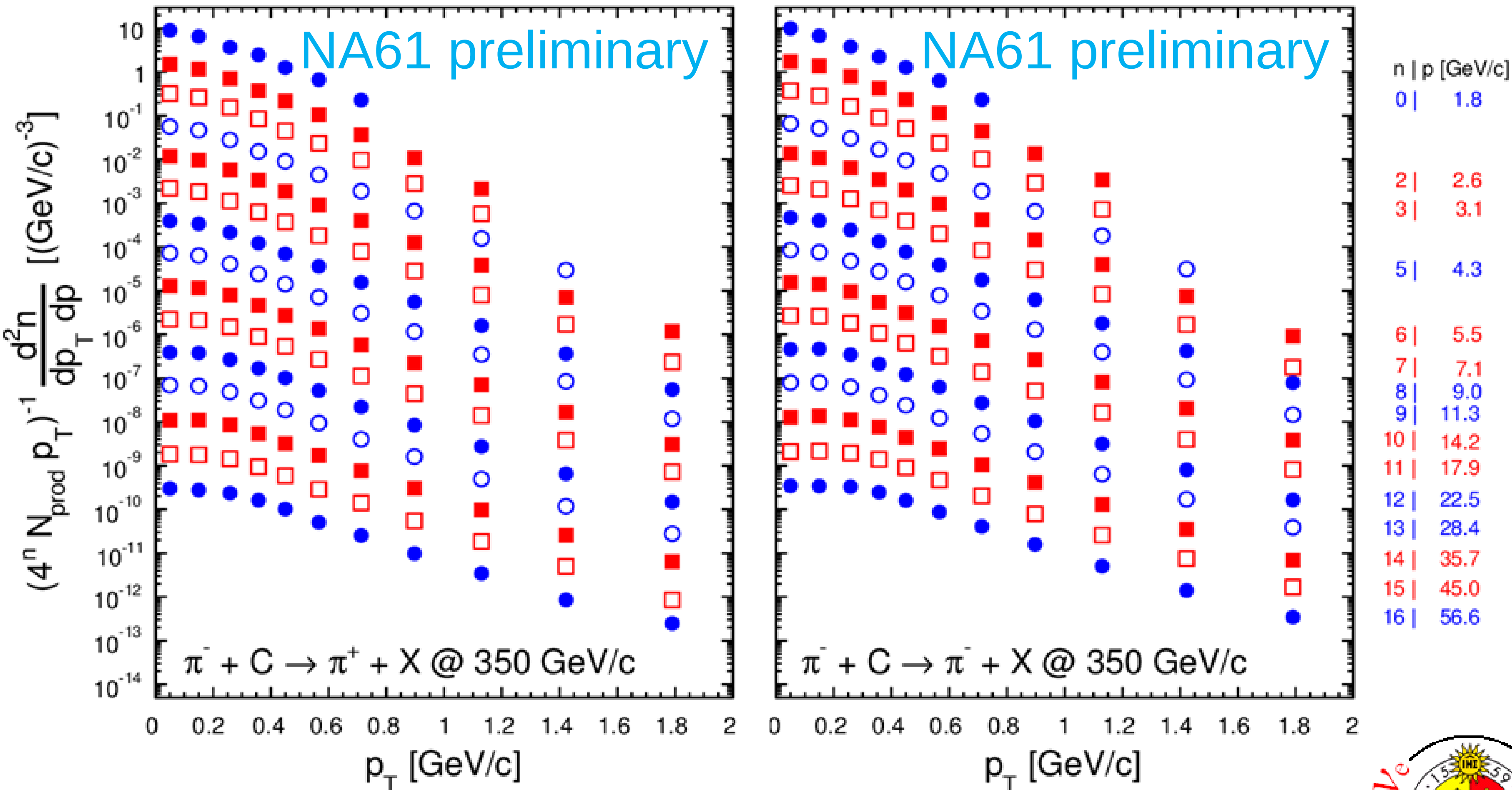


Fermi energy

$$F \equiv \left[\frac{(\sqrt{s_{NN}} - 2m_N)^3}{\sqrt{s_{NN}}} \right]^{1/4}$$



Charged π spectra in π^- + C Interactions



Some Observations

p + p and p + C data is unexpectedly interesting

None of the models describes satisfactorily ensemble of the p + C $\rightarrow$ h + X hadroproduction data

Models do not describe well the NA61/SHINE data on p + p interactions

High precision NA61/SHINE data presents a challenge for models and allow for significant improvement of models

Even in p + p the energy dependence of the K^+/π^+ ratio exhibits rapid changes in the SPS energy range

Soon p + C data at different energies (60 GeV/c, 120 GeV/c)
Also Be, Al, Pb

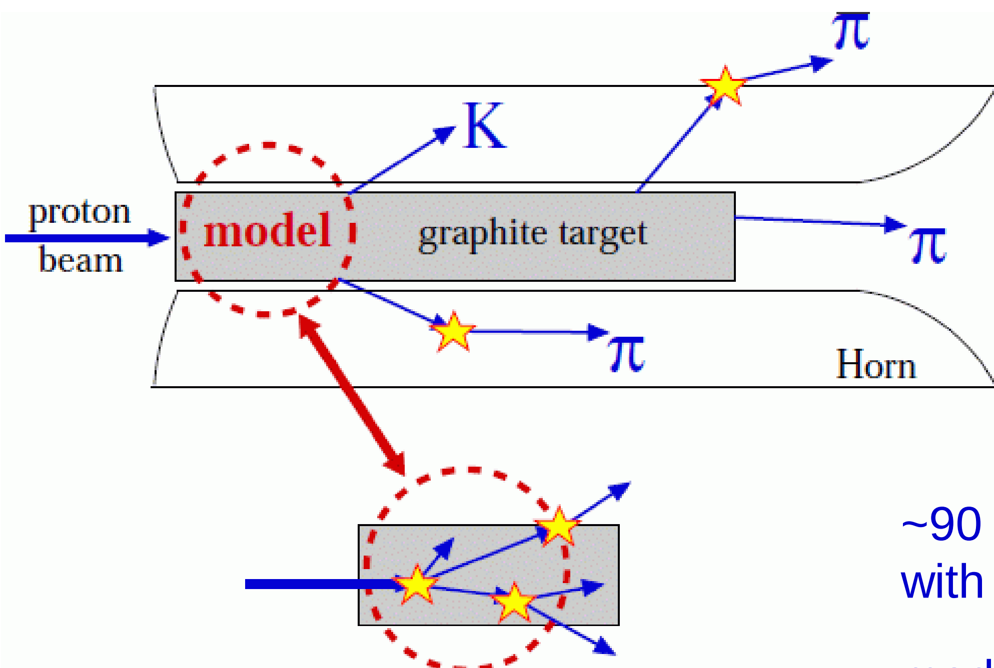
Soon comparison of p + p and p + A hadroproduction data
- $\rightarrow$ A dependence
- $\rightarrow$ energy dependence

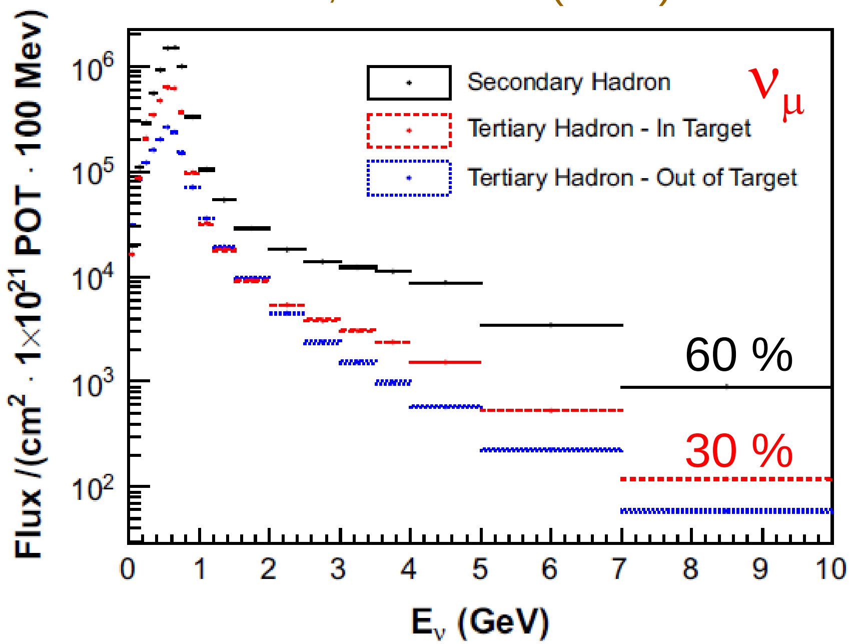
ν Flux Prediction with T2K Replica Target

Neutrinos originate from hadrons produced in **primary interactions** (~60%) and from hadrons produced in (re)interactions **in the production target** (~30%) and in the **surrounding materials in the beamline** (~10%).

NA61, NIM A701 (2013) 99

We see only particles coming out of the target
We do not see what happens inside the target





~90 % of the neutrino flux can be constrained with the T2K replica target measurements

model dependencies are reduced down to 10 % as compared to 40 %

Neutrino Source Production

direct contribution:

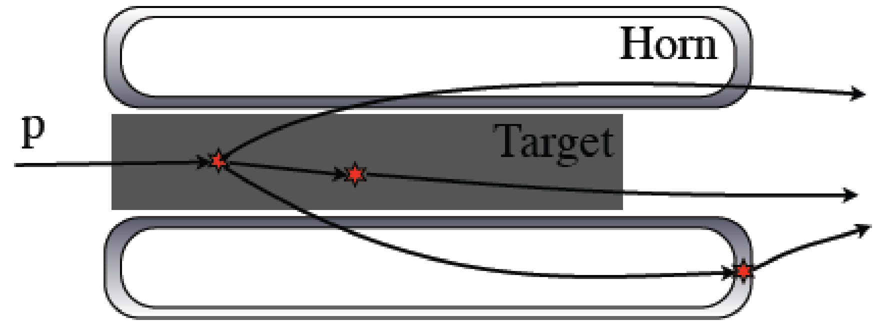
secondary hadrons exit the target and decay into ν

target contribution:

secondary and tertiary hadrons exiting the target and decaying into ν

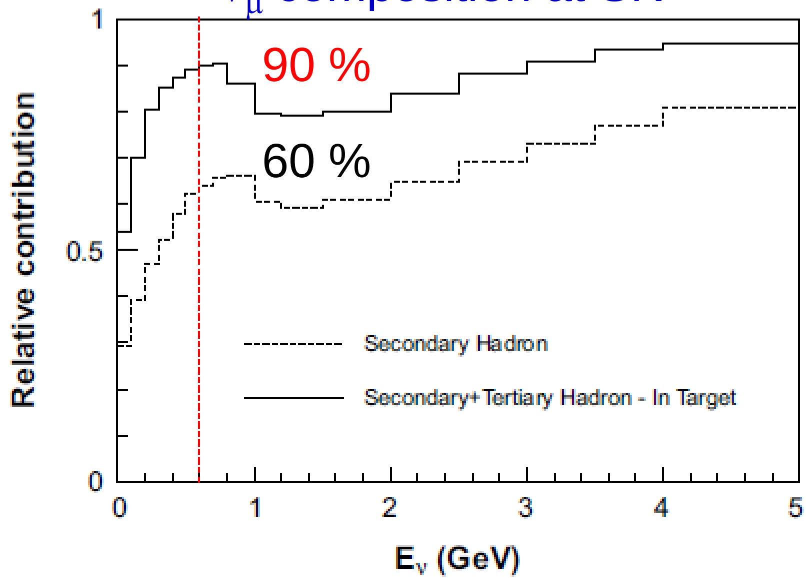
non-target contribution:

re-interaction in the target surrounding material

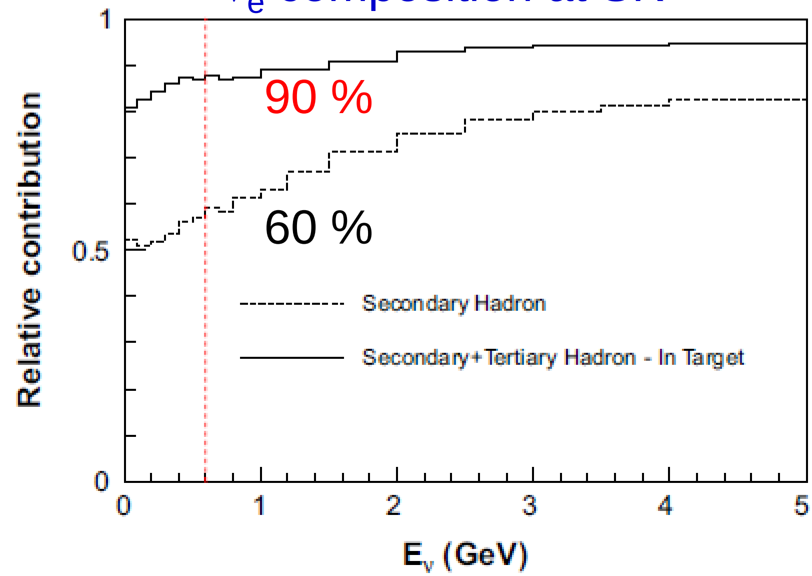


NA61, NIM A701 (2013) 99

ν_μ composition at SK

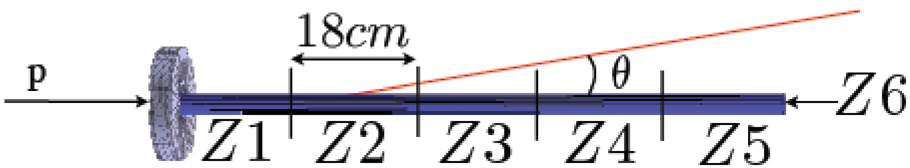


ν_e composition at SK



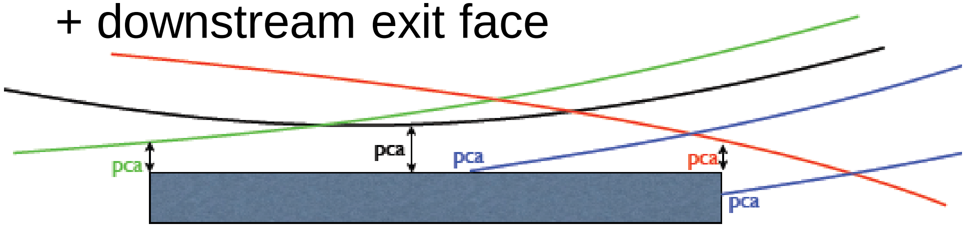
π^+ Hadroproduction on T2K Replica Target

Hadron multiplicities are measured at the target surface in bins of {p, θ, z}



Tracks are extrapolated backwards to the target surface (point of closest approach)

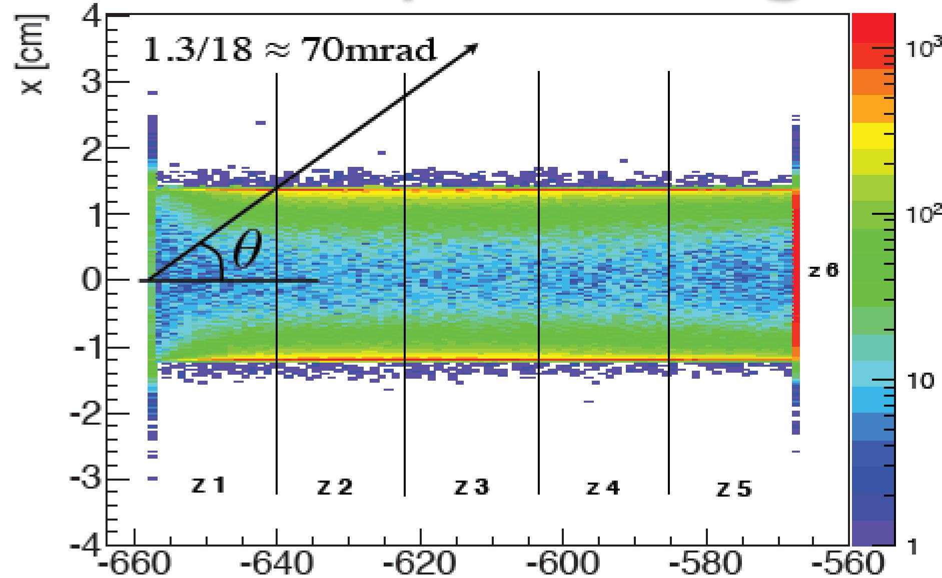
the target is sliced in 5 bins in z
+ downstream exit face



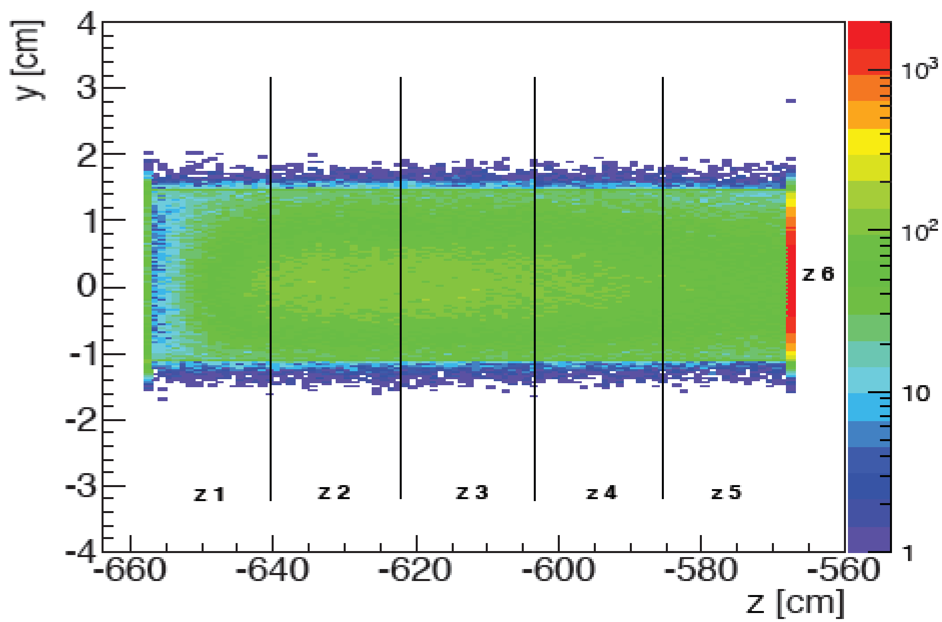
No interaction vertex reconstruction can study also as a function of r

Statistical precision ~5%

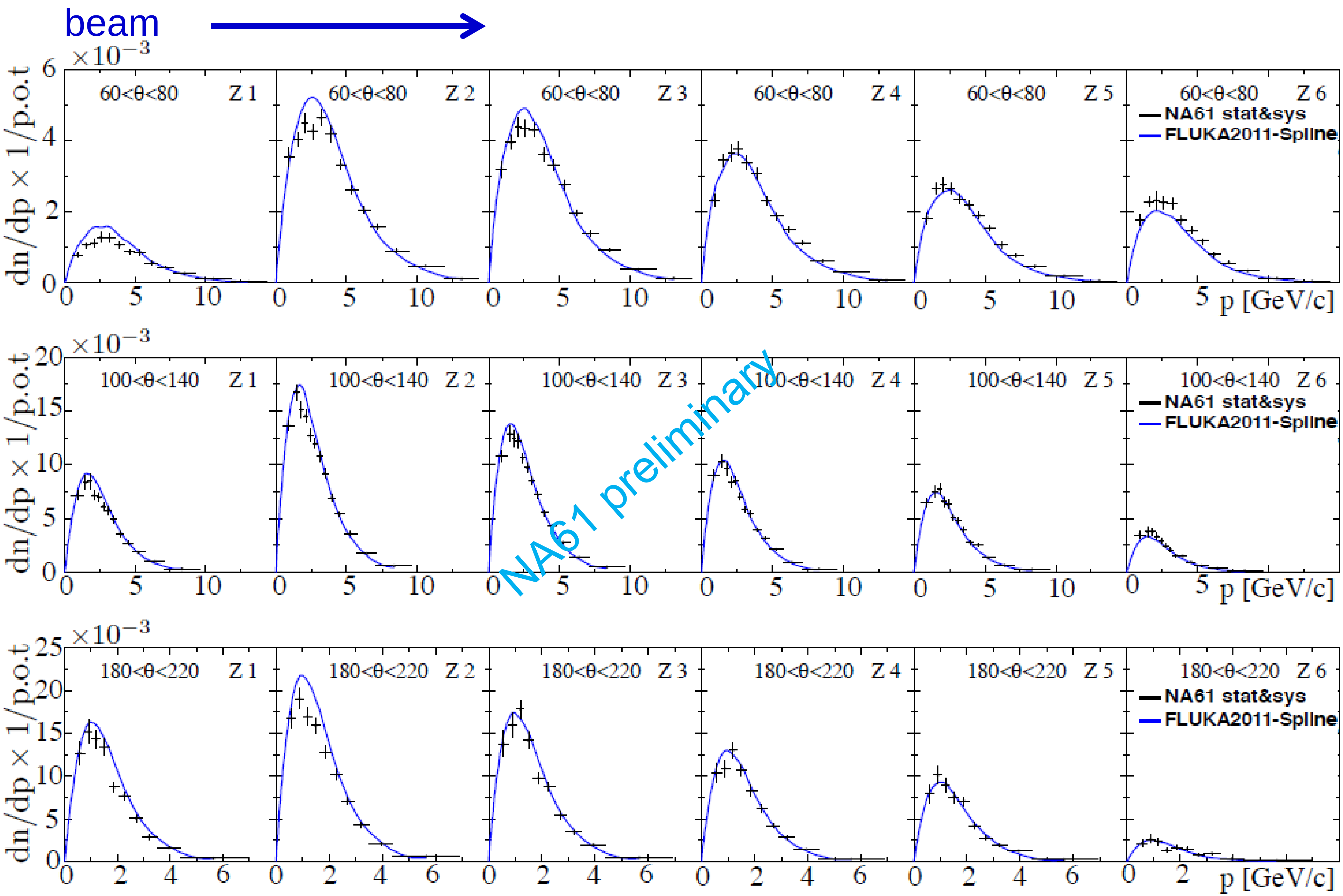
Systematic error ~5%



reconstructed target profile



π^+ Spectra on Target Surface

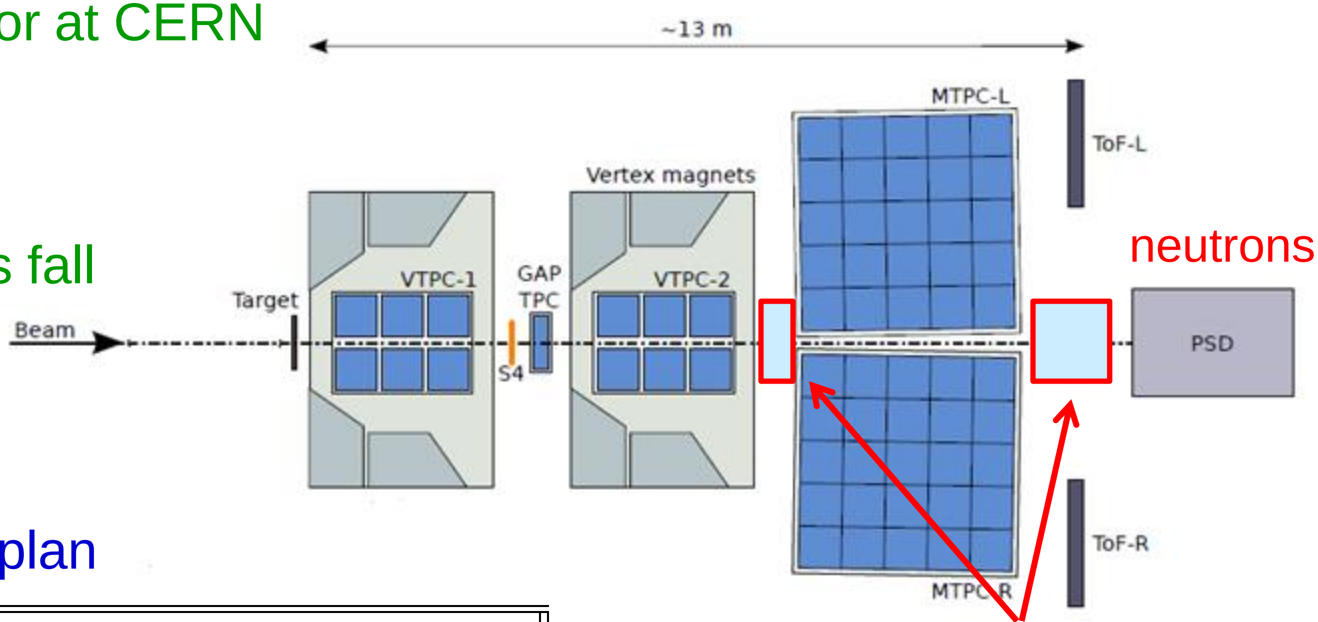


NA61 4 NuMI (USNA61)

Perform hadron production measurements to characterize the NuMI ν beam using the NA61 detector at CERN

mainly US groups

Data taking to start this fall



2 new Forward TPCs

tentative run plan

proton+pion event totals	Incident proton/pion beam momentum		
Target	120 GeV/c	60 GeV/c	30 GeV/c
NuMI (spare) replica	(*future*)		
LBNE replica	(*future*)		
thin graphite ($< 0.05\lambda_I$)	3M	3M	(T2K data)
thin aluminum ($< 0.05\lambda_I$)		3M	(*future*)
thin steel ($< 0.05\lambda_I$)	(*future*)	(*future*)	(*future*)
thin beryllium ($< 0.05\lambda_I$)	3M	3M	(*future*)

Upgrades:

- add forward tracking
- forward calorimetry (neutrons)
- new DAQ based on the DRS

Conclusions

NA61 is providing valuable data to constrain the T2K neutrino flux

NA61 initial goals for T2K: 5% error on absolute neutrino fluxes
3% error on the far-to-near ratio

Hadro production measurements require
- large acceptance detectors with PID over whole kinematical range
- large statistics
- different targets to study various particle production effects

Hadroproduction of $\pi^{+/-}$, $K^{+/-}$, p, K^0_s, Λ in p + p and p + C interactions at different energies
Soon also on Be, Al, and Pb targets
- $\rightarrow$ comparison of p + p and p + A data
- $\rightarrow$ A dependence

Hadroproduction measurements also with π beams

High precision NA61/SHINE data presents a challenge for hadroproduction models

NA61 to continue with hadron production measurements for NuMI, starting this fall