New results from the NA49 experiment on hadron production in p+p and p+C interactions and survey of backward hadrons in p+C collisions

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Introduction

1. Hadron-proton interactions
   - ➜ p + p
   - n + p
   - $\pi^{\pm}$ + p
2. Hadron-nucleus interactions
   - d + p
   - ➜ p + C
   - p + Pb (with controlled centrality)
   - $\pi^{\pm}$ + Pb
3. Nucleus-nucleus interactions
   - Pb+Pb

- Precision data in variety of reactions, syst. $<5\%$
- Maximum phase space coverage
- Detailed comparison with existing measurements
- Model independent analysis and interpretation of the data

Participating institutions:

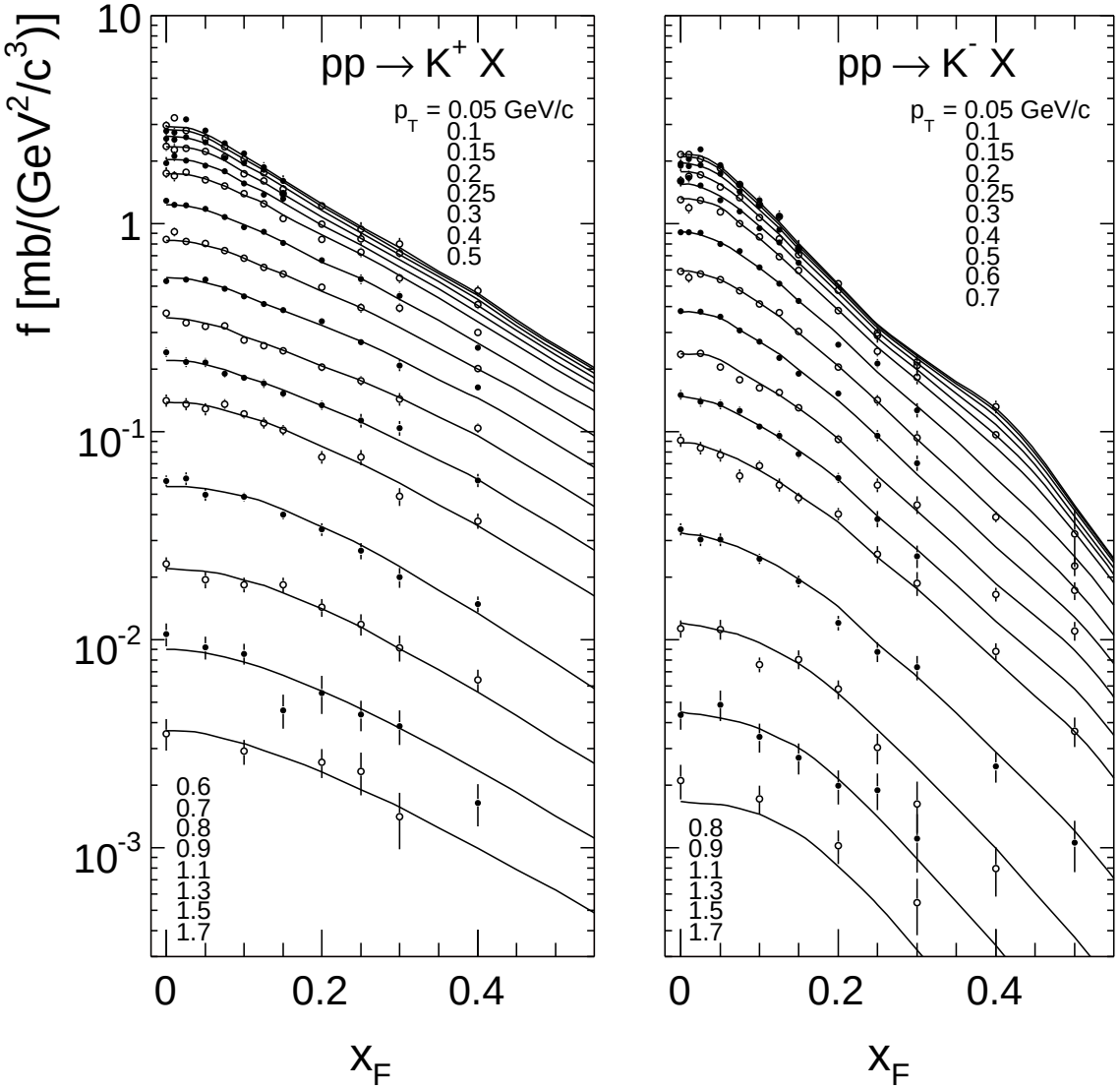
- Eötvös Loránd University, Budapest, Hungary
- H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
- CERN, Geneva, Switzerland
- Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
- Institute for Nuclear Research and Nuclear Energy, BAS, Sofia, Bulgaria

Outline

1. Inclusive production in proton-proton interactions at 158 GeV/c beam momentum
   - charged pions – *C. Alt et al., Eur. Phys. J.* **C45** *(2006) 343*
   - ➜ kaons – *T. Anticic et al., Eur. Phys. J.* **C68** *(2010) 1*
   - ➜ baryons (p,$\overline{\text{p}}$,n) – *T. Anticic et al., Eur. Phys. J.* **C65** *(2010) 9*
2. Inclusive production in proton-carbon interaction at 158 GeV/c beam momentum
   - charged pions – *C. Alt et al., Eur. Phys. J.* **C49** *(2007) 897*
   - ➜ baryons and light ions (p,$\overline{\text{p}}$,n,d,t) – *arXiv:1207.6520v1 [hep-ex]*
   - charged kaons – *in preparation*
3. Survey of backward production of protons and pions in p+C interactions from 1 to 400 GeV/c beam momentum
   - ➜ 19 experiments
   - ➜ $f(1/\sqrt{s}, cos(\Theta_{lab}), p_{lab})$ – *in preparation*

Proton-proton interactions

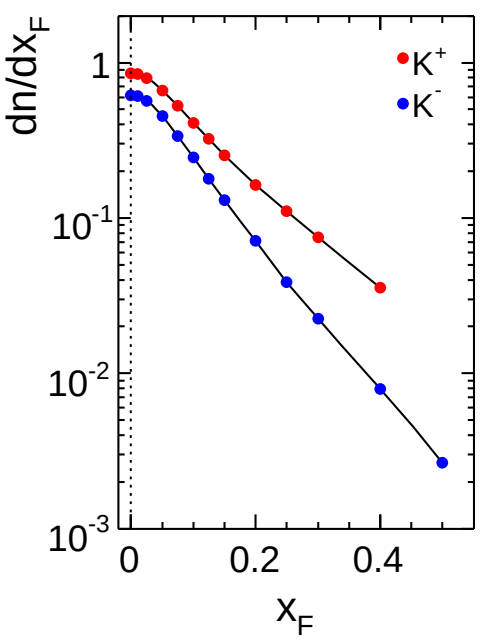
Kaons in p+p: double differential

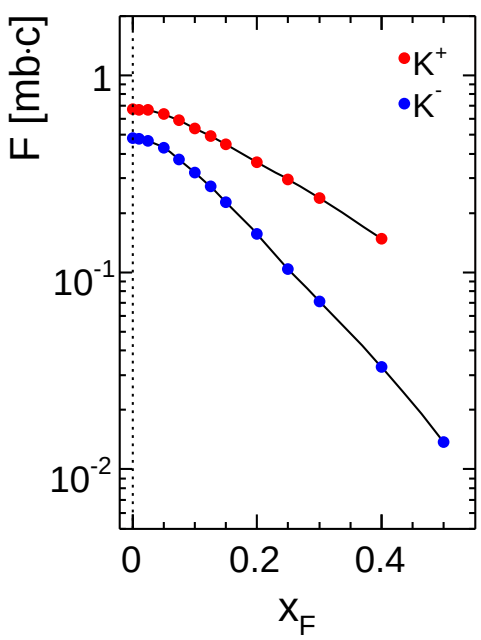


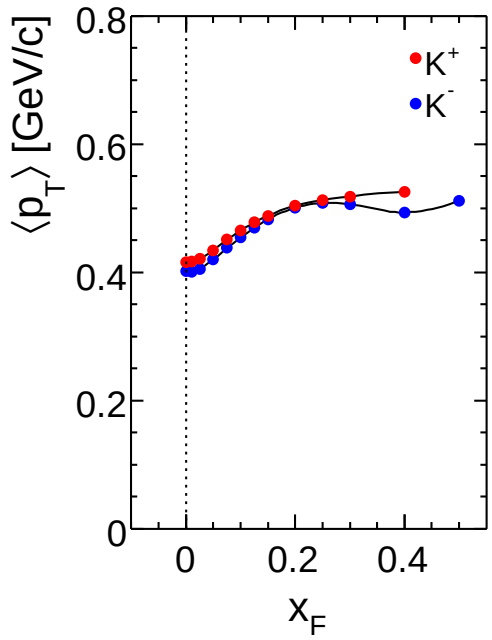
$$x_F = \frac{p_L^{cms}}{\sqrt{s}/2}$$

- $x_F = 0 \div 0.4$ and $p_T = 0 \div 1.7$ GeV/c for K^+
- $x_F = 0 \div 0.5$ and $p_T = 0 \div 1.7$ GeV/c for K^-

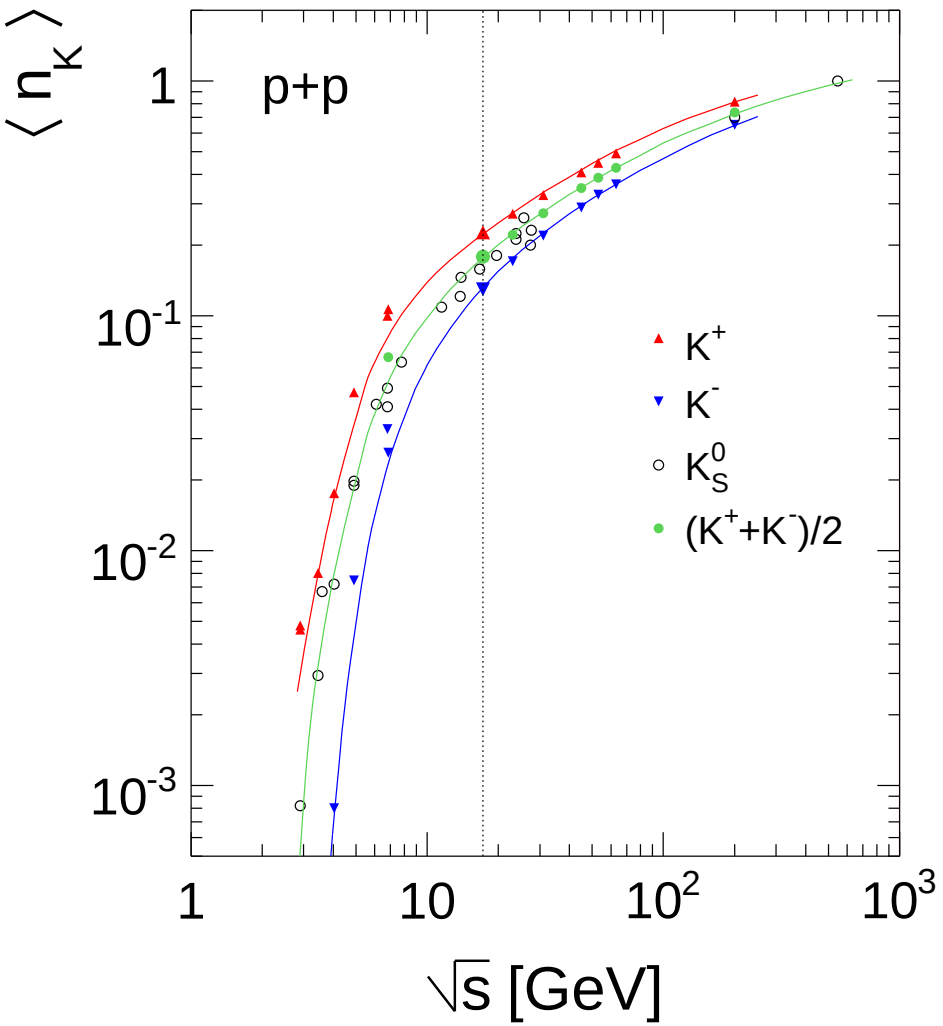
Kaons in p+p: p_T integrated





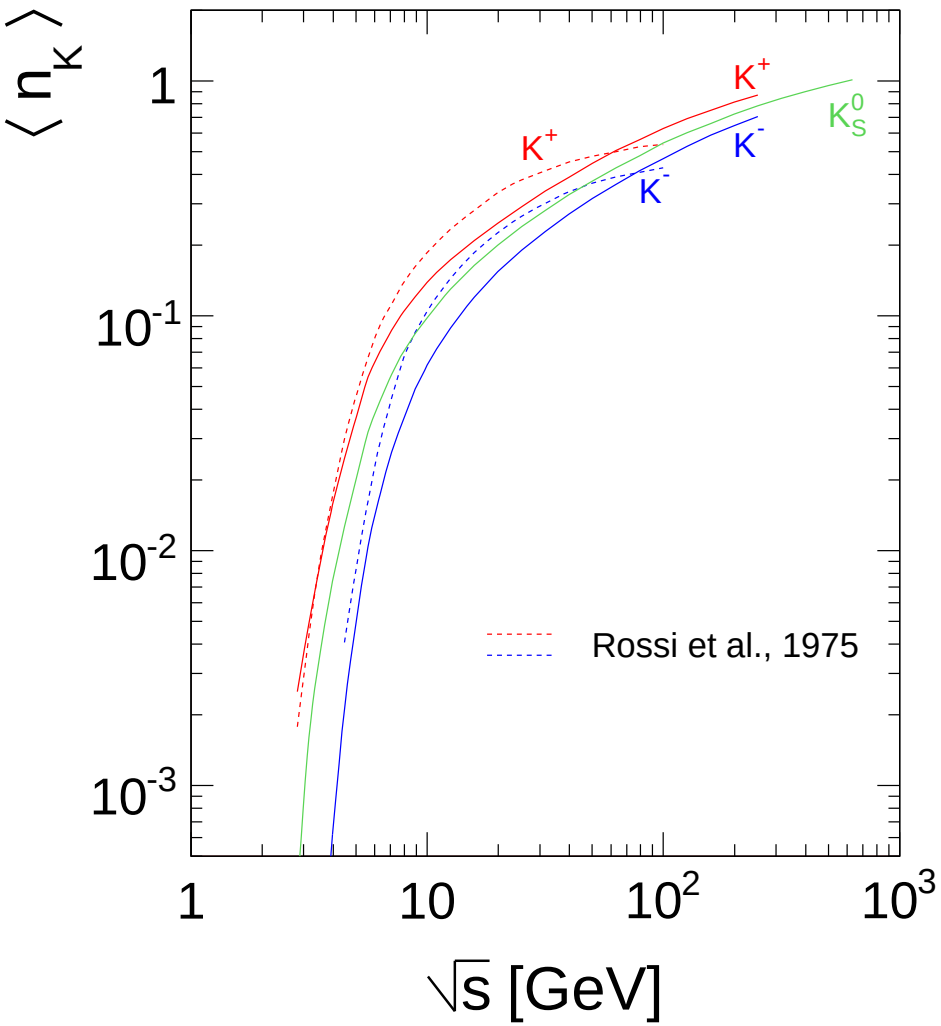


Kaons in p+p: total yields as a function of $\sqrt{s}$



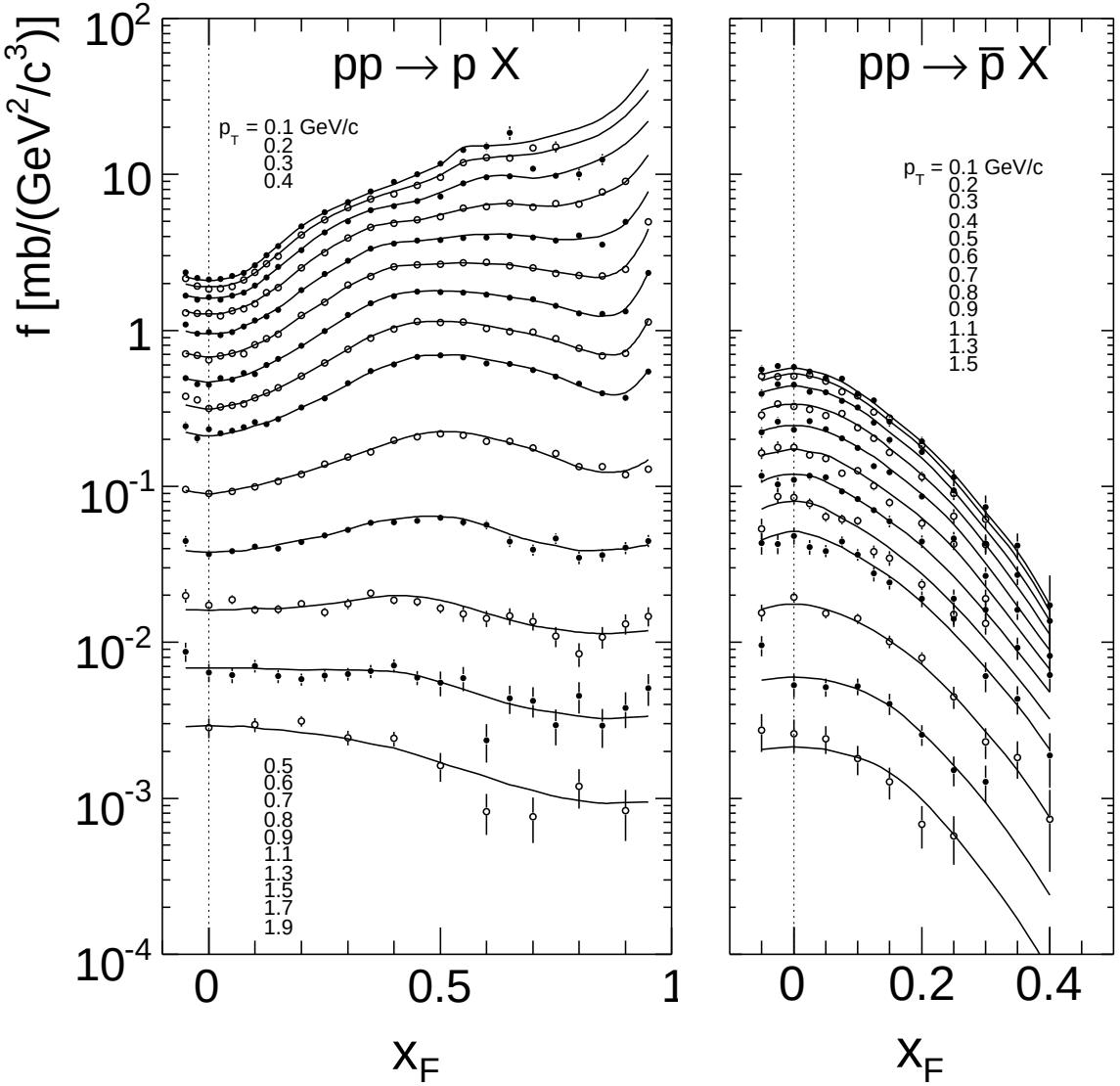
- Precise determination of total yields $\langle n_{\mathrm{K}} \rangle$
- NA49 result used as a reference
- Re-analysed all existing data
- Total yields re-established from threshold up to collider energies
- K^0_S and ($K^+ + K^-$)/2 equals

Kaons in p+p: total yields as a function of $\sqrt{s}$



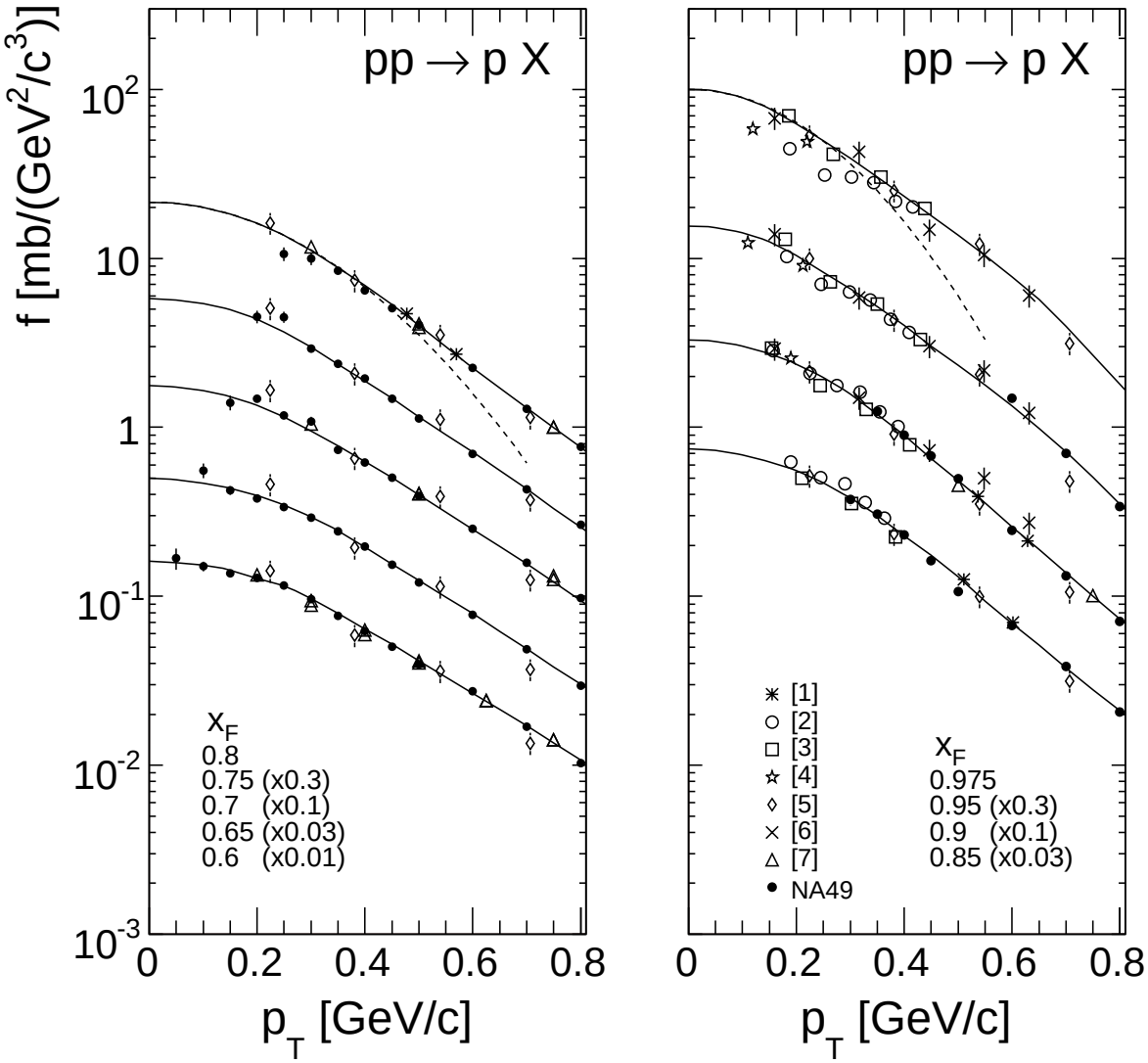
- This should replace the old evaluation of $\langle n_{\mathrm{K}} \rangle$ by Rossi (1975)

Protons and anti-protons in p+p: double differential



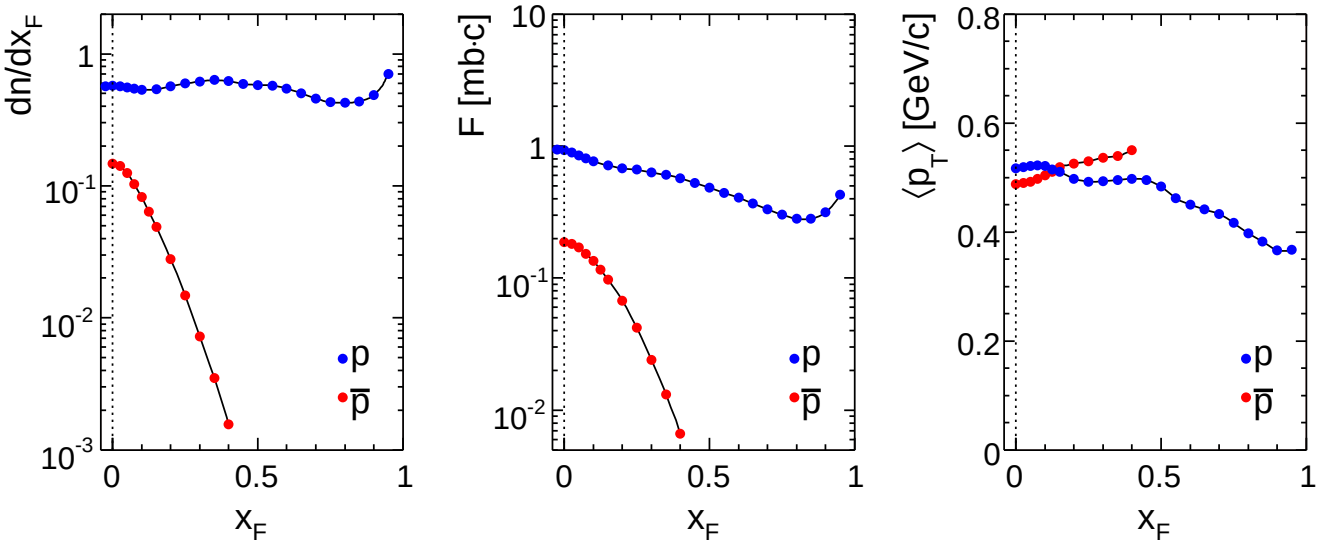
- $x_F = 0 \div 0.95$ and $p_T = 0 \div 1.9$ GeV/c for p
- $x_F = 0 \div 0.4$ and $p_T = 0 \div 1.5$ GeV/c for $\overline{\mathrm{p}}$

Protons in p+p: large x_F

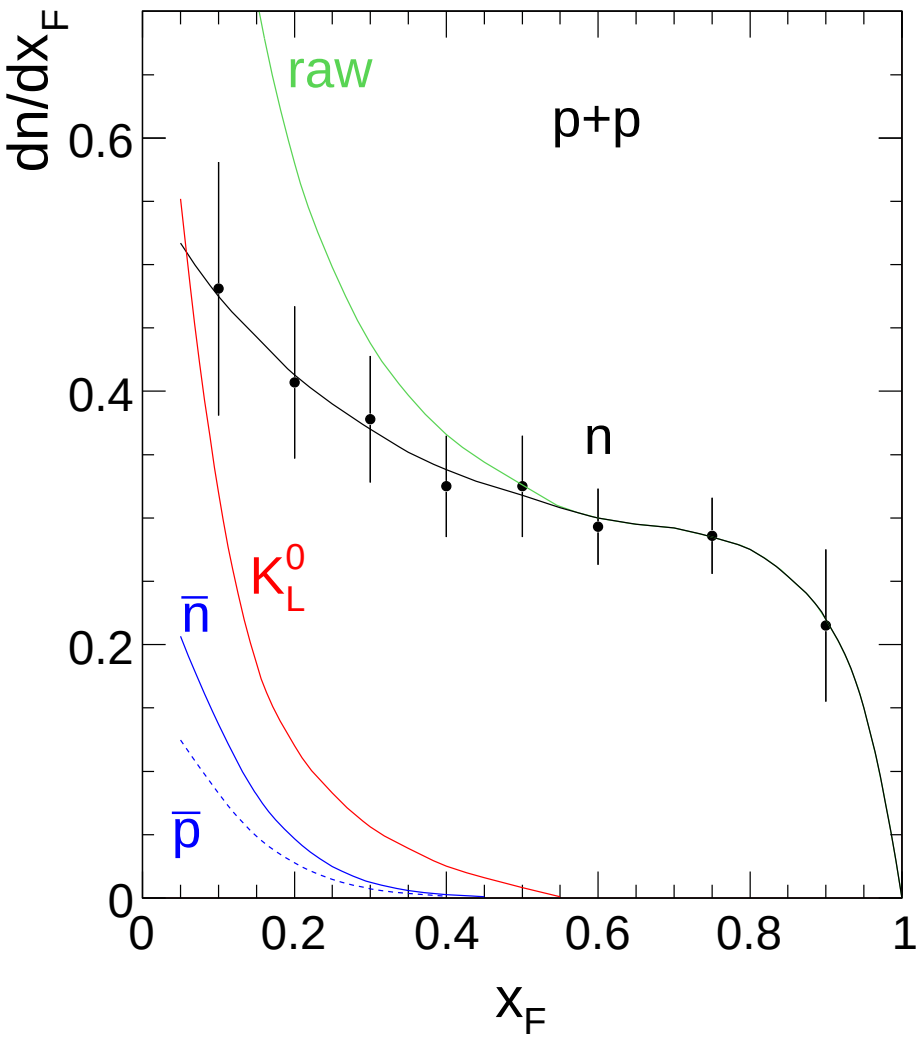


- Extending coverage at low p_T and large x_F
- Using all available measurements at SPS and ISR energy range
- Compatible with NA49 in p_T overlap ranges

Protons and anti-protons in p+p: p_T integrated



Neutrons in p+p:p_T-integrated



- feeddown (weak decays)
- K^0_L:

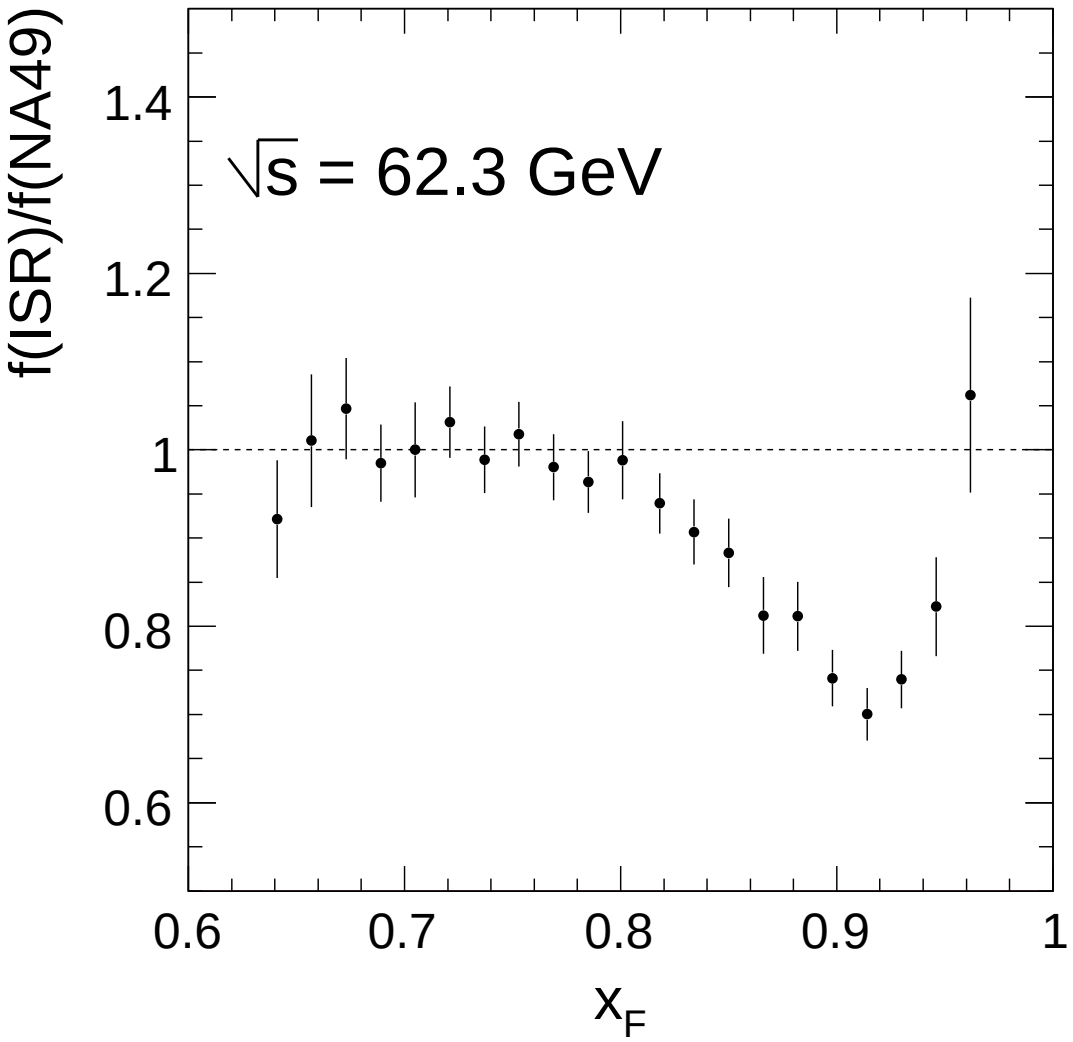
$$K^0_L = \frac{K^+ + K^-}{2}$$

- $\overline{\mathrm{n}}$:

I_3	-1	0	1
baryon pairs	$\overline{\mathrm{p}}\mathrm{n}$	$\overline{\mathrm{p}}\mathrm{p}$ $\overline{\mathrm{n}}\mathrm{n}$	$\overline{\mathrm{n}}\mathrm{p}$
relative yield	0.5	1 1	1.5

$$\overline{\mathrm{n}}/\overline{\mathrm{p}} = 1.66$$

Comparison to ISR p+p data at 62.3 GeV/c



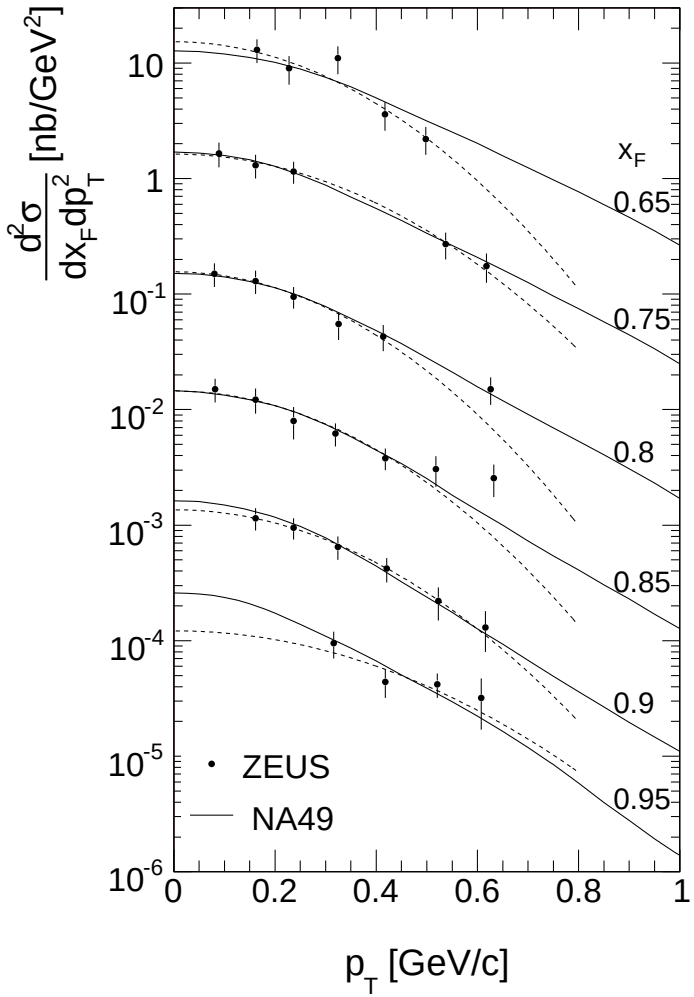
- Scaling up to $x_F = 0.8$
- Depletion at $x_F > 0.8$
- Diffractive peak

Comparison to HERA

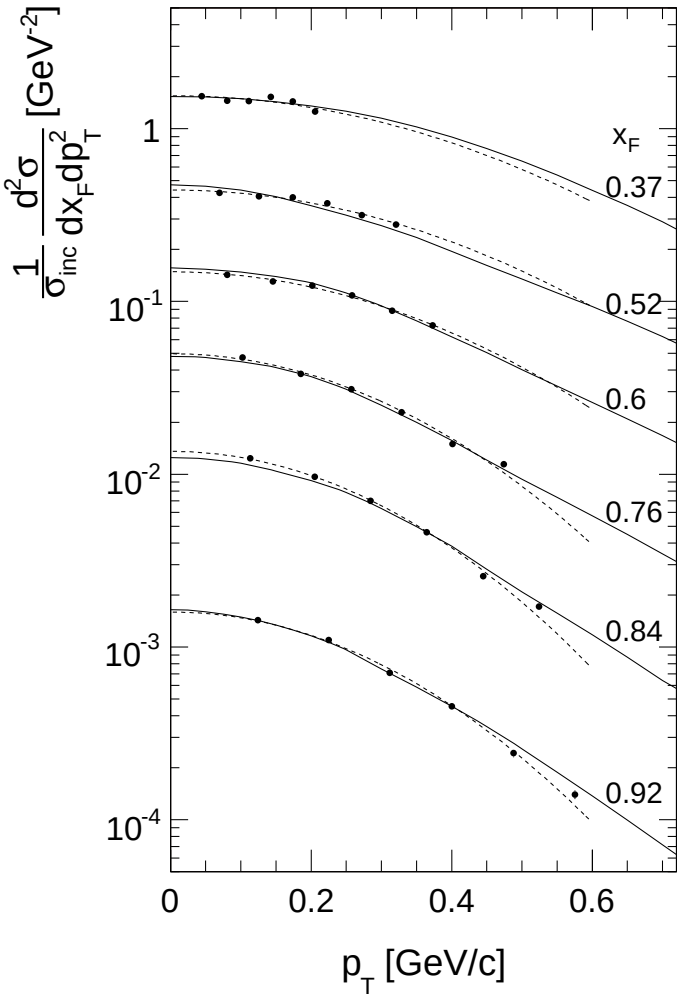
- Comparison between p+p and e+p data
- Check for hadronic factorization

ZEUS proton and neutron p_T distributions at $\sqrt{s} = 130$ GeV

protons

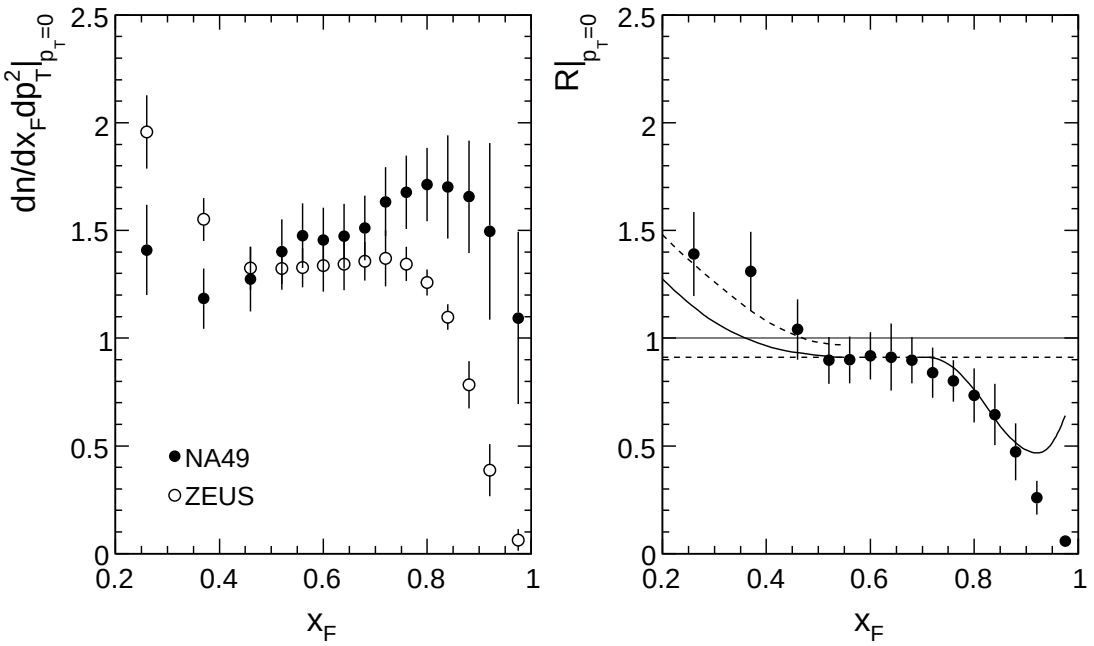


neutrons



- NA49 proton distributions normalized to ZEUS data
- $\sqrt{s} = 130$ GeV
- The same shape of the p_T distributions between
  - protons and neutrons
  - SPS and HERA energies
  - p+p and e+p interactions

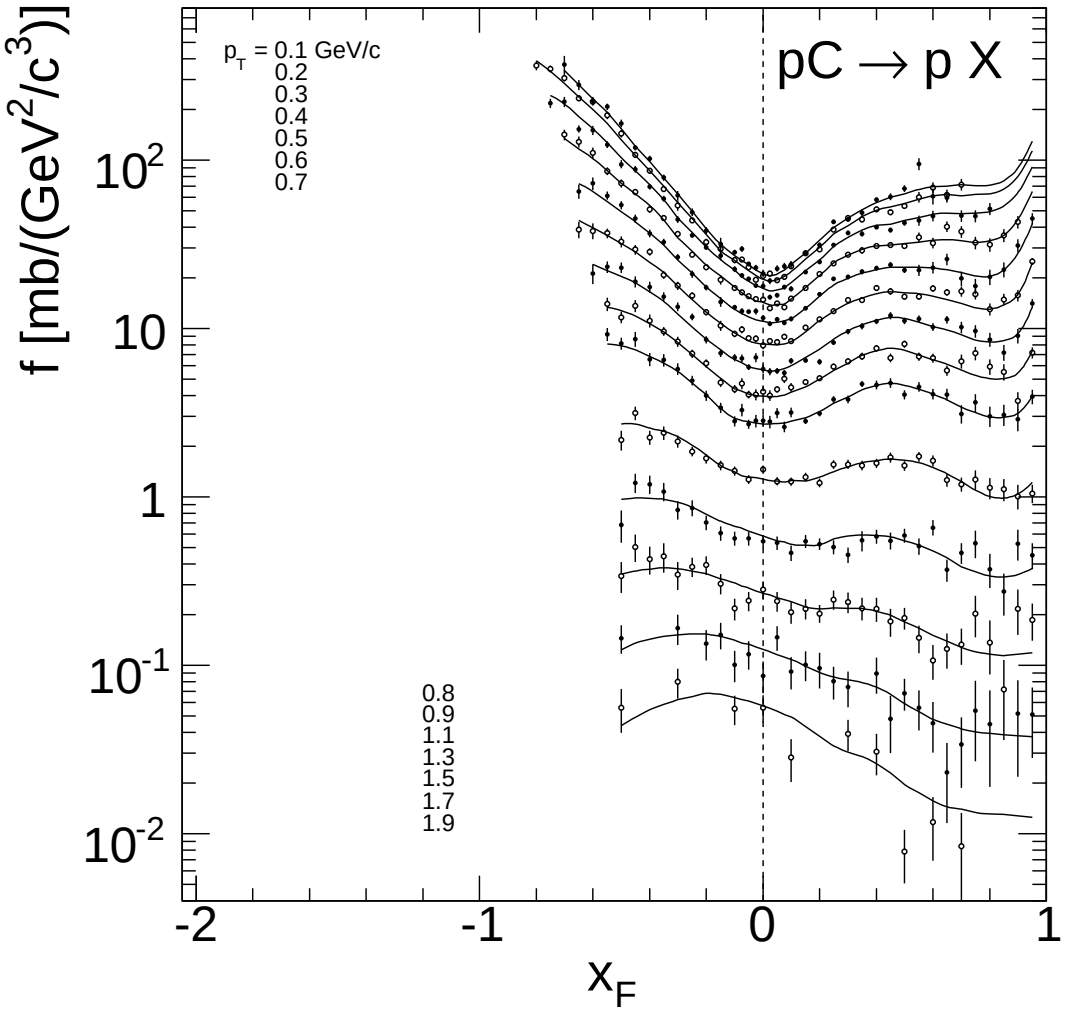
ZEUS neutron $p_T = 0$ GeV/c

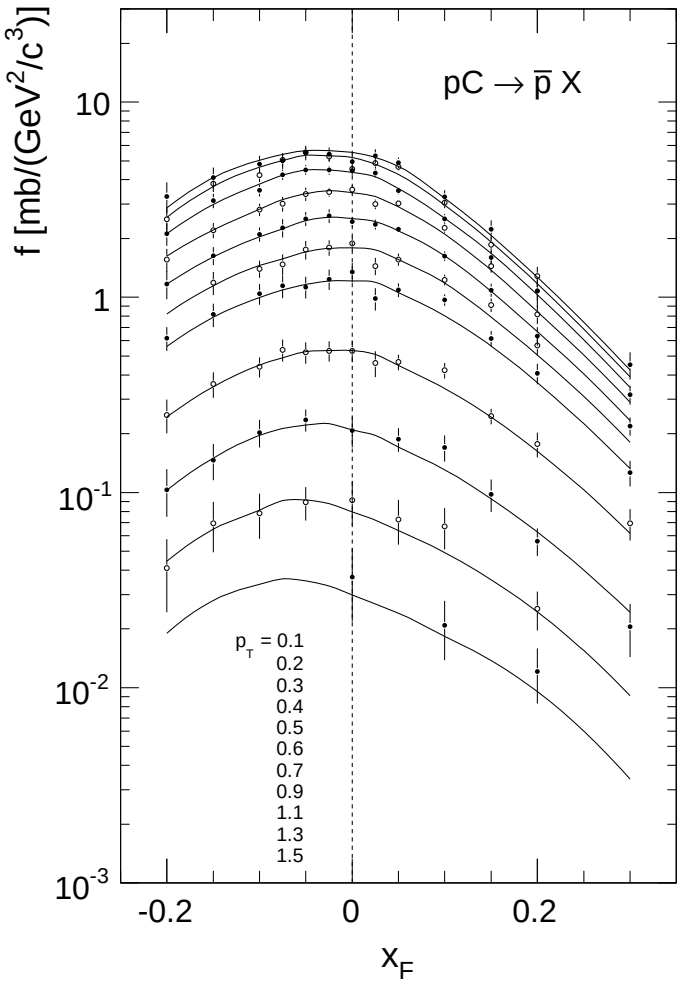


- Extracting neutrons at $p_T = 0$ GeV using proton p_T distributions
- K^0_L and $\overline{n}$ contribution below $x_F = 0.5$
- At $x_F = 0.45 \div 0.7$ yields are equal within 7–8%
- Depletion similar to protons from ISR p+p data
- No diffractive peak for neutrons
- Hadronic factorization

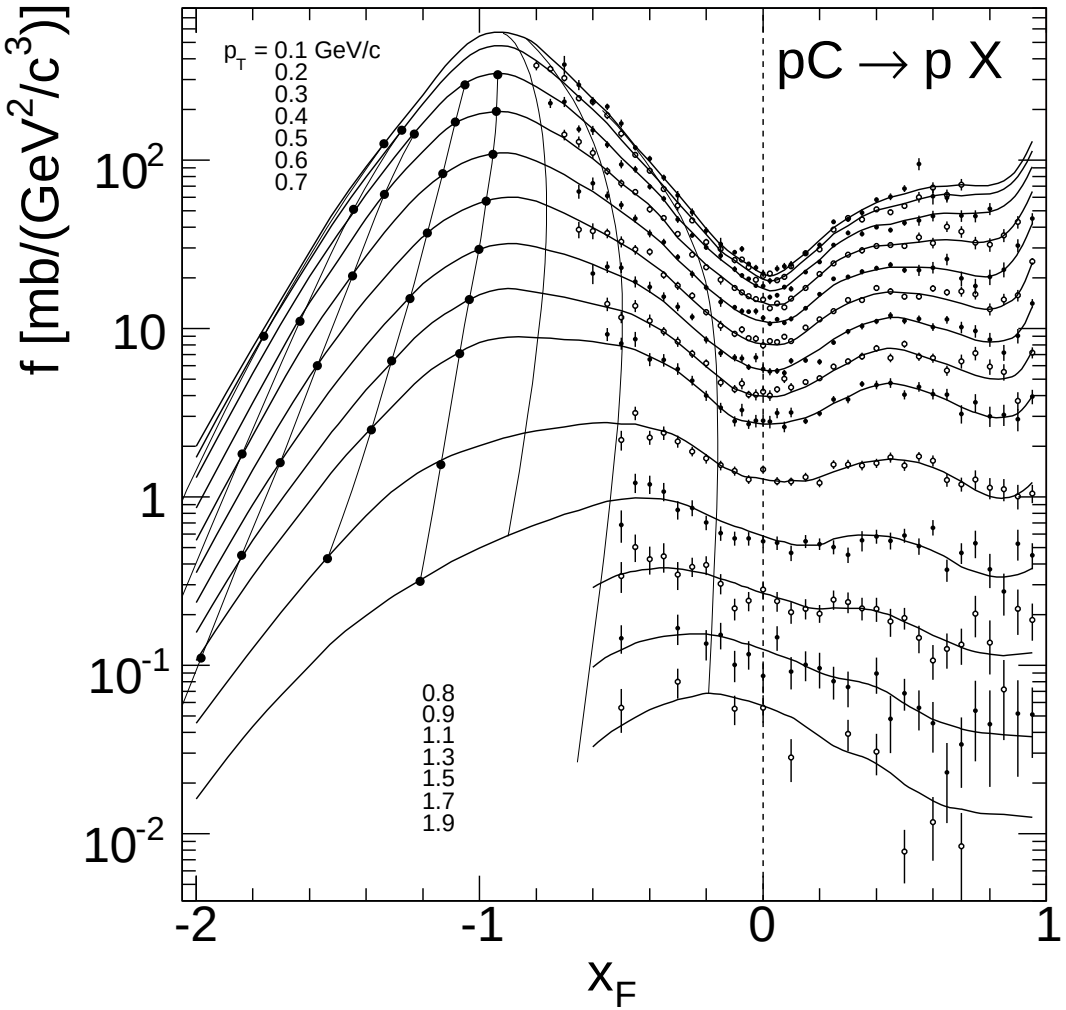
Proton-carbon interactions

Protons and anti-protons in p+C: double differential



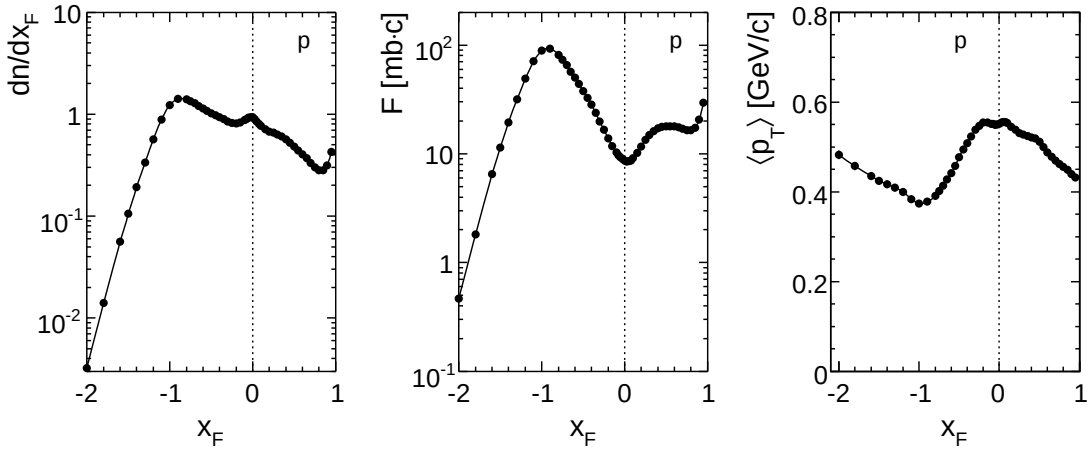


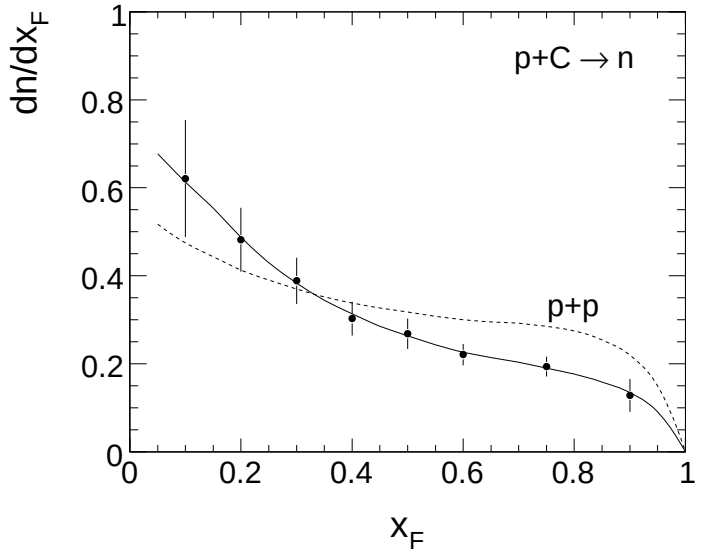
Protons and anti-protons in p+C: double differential

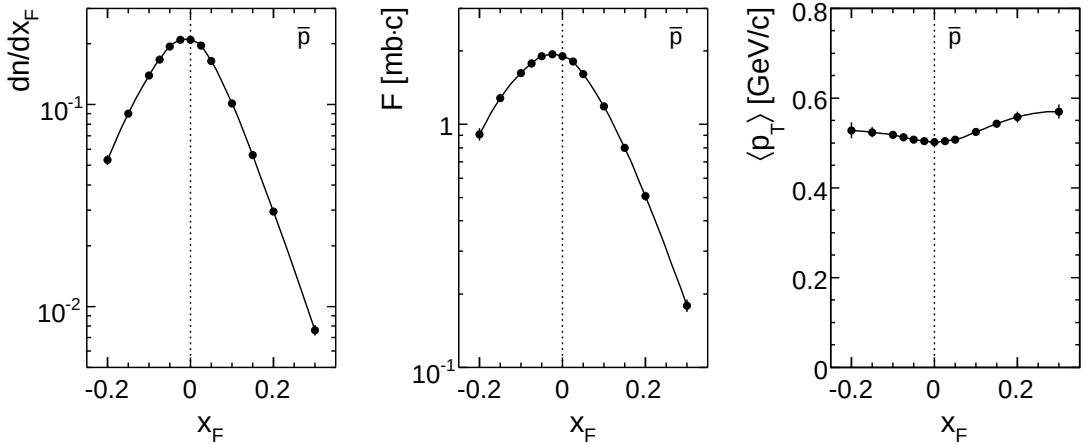


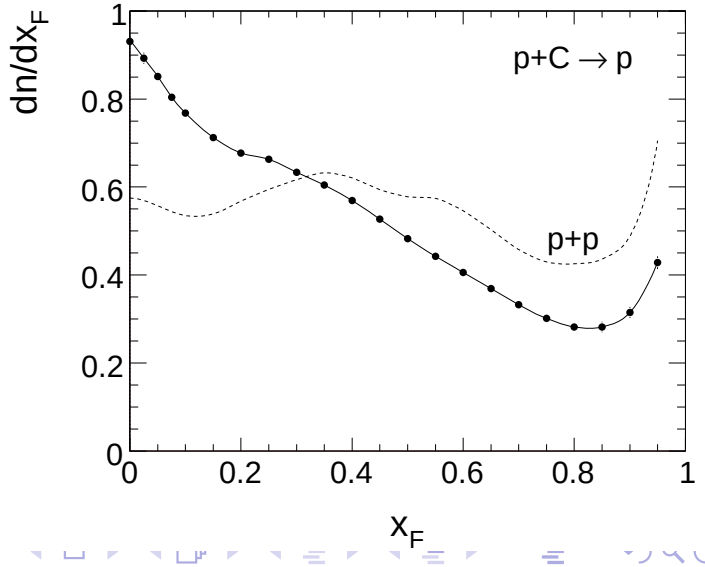
- Data from *Y. D. Bayukov et al., Phys. Rev.* **C20**, *(1979) 764* at 400 GeV/c beam momentum
- *s*-dependence is negligible
- Measurement from x_F =-2 to $x_F = 1$
- No indication of diffractive structure close to x_F = -1
- Maximum of the distributions is at x_F = -0.92

Protons, anti-protons and neutrons in p+C: p_T integrated

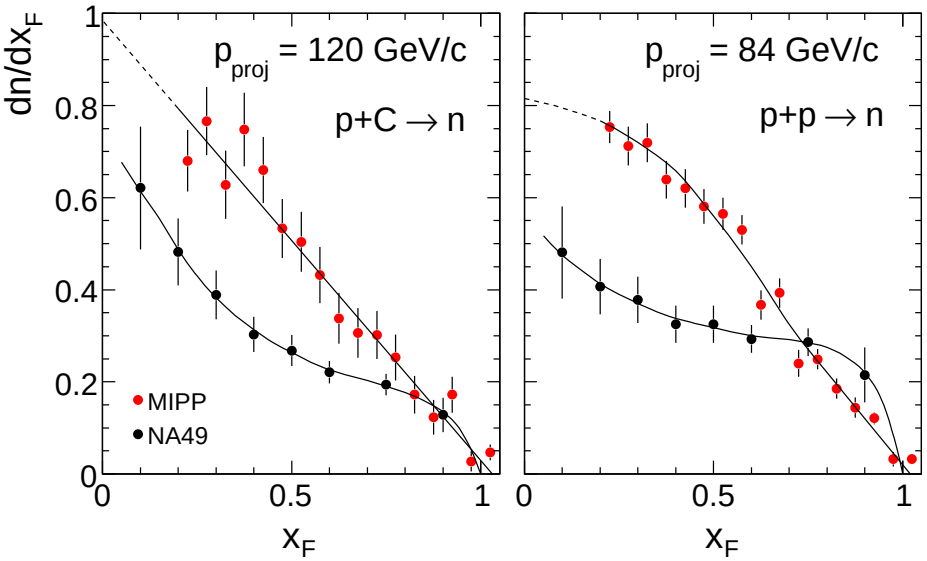


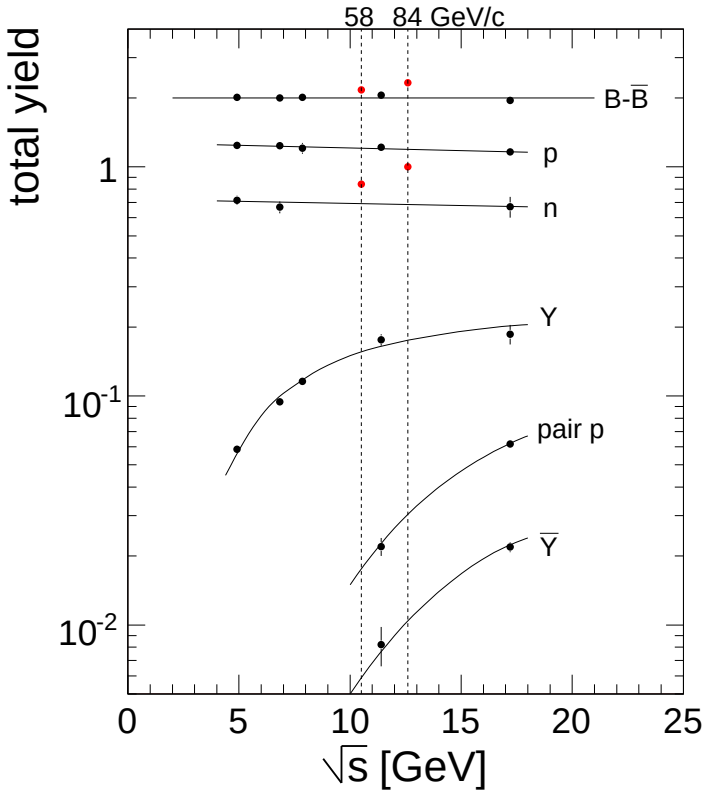






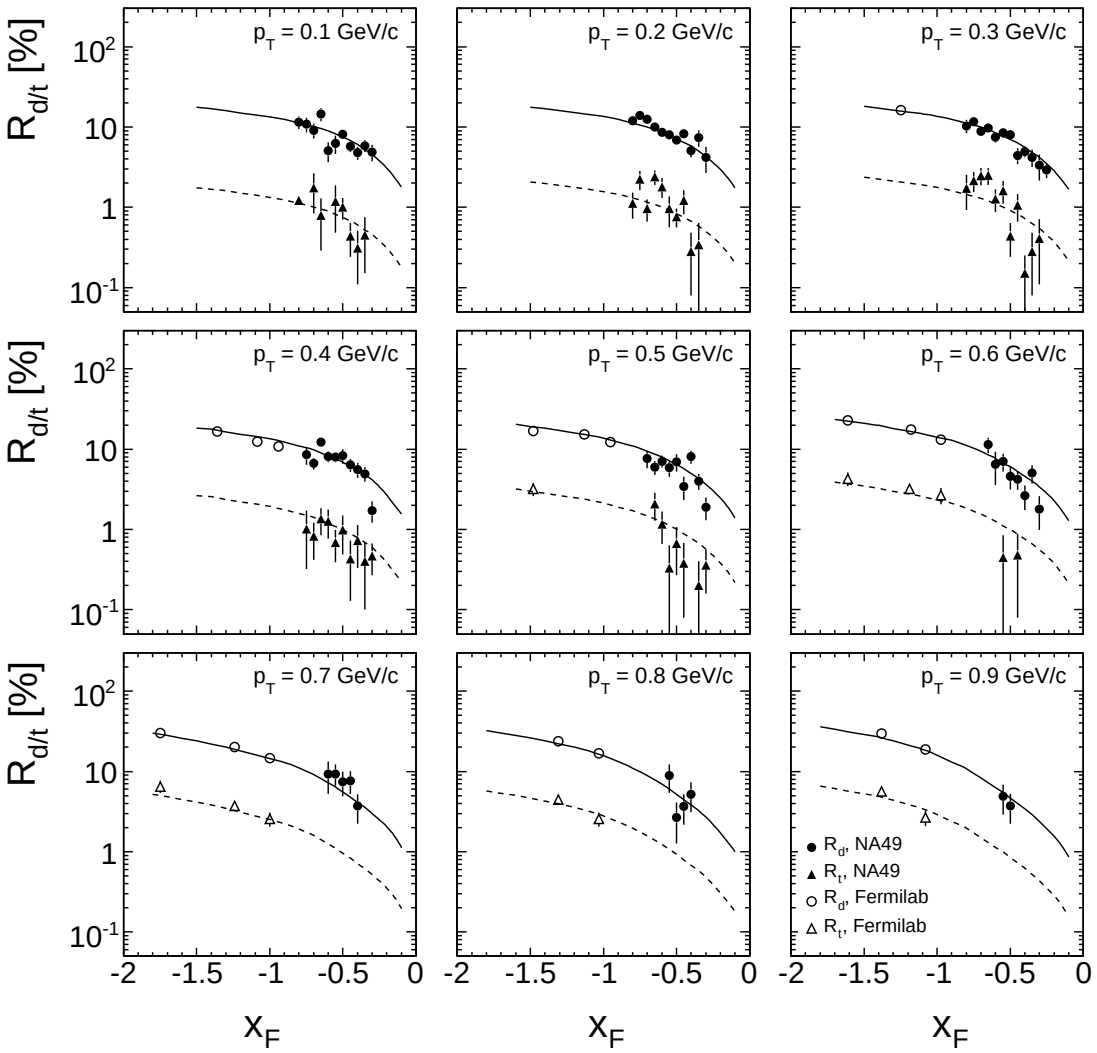
Neutrons from MIPP





- MIPP data are above the NA49 data below $x_F = 0.8$
- Total neutron yields obtained by extrapolation towards $x_F = 0$
- Problem with baryon number conservation

Deuteron to proton and triton to proton ratios in p+C



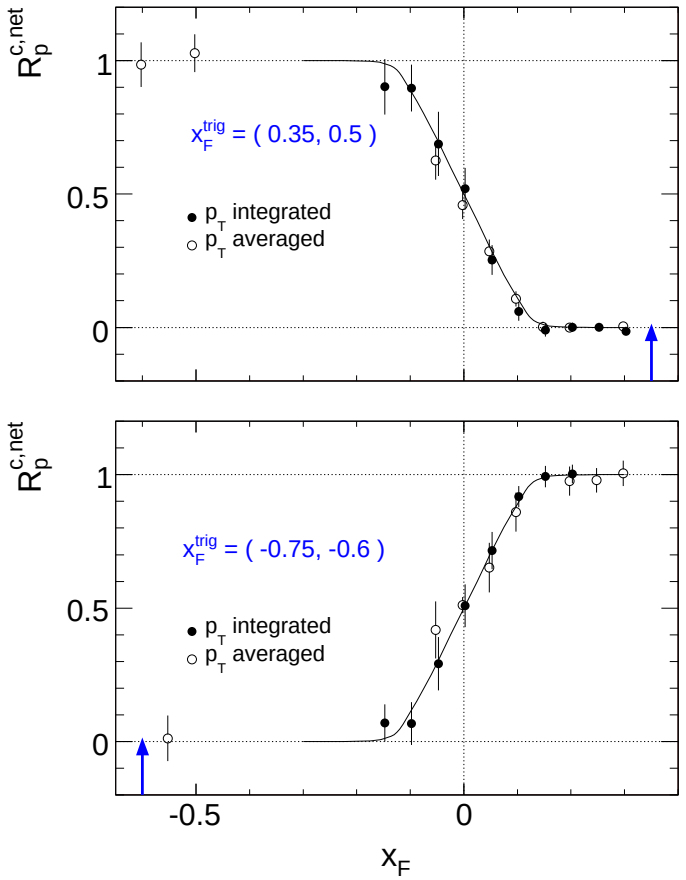
- First data at low p_T
- Agreement with Fermilab data
- First data approaching $x_F = 0$
- The ratio d/p $\approx 1\%$ at $x_F = 0$ which is also measured in Pb+Pb

Three component mechanism in p+C interactions

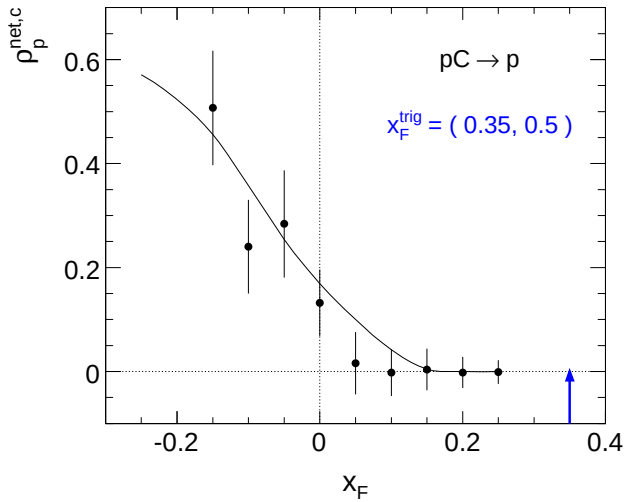
- Three components
  - Target fragmentation
  - Projectile fragmentation
  - Nuclear cascading
- Separate components
- What is the overlap between target and projectile?

Proton overlap function

p+p



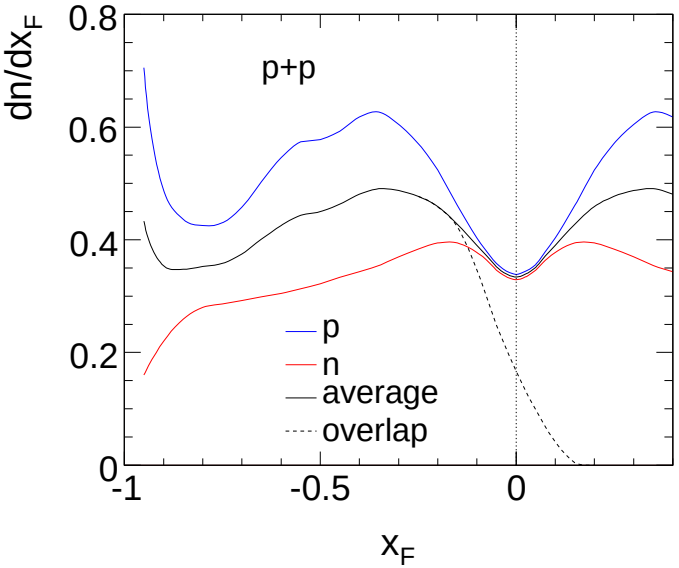
p+C

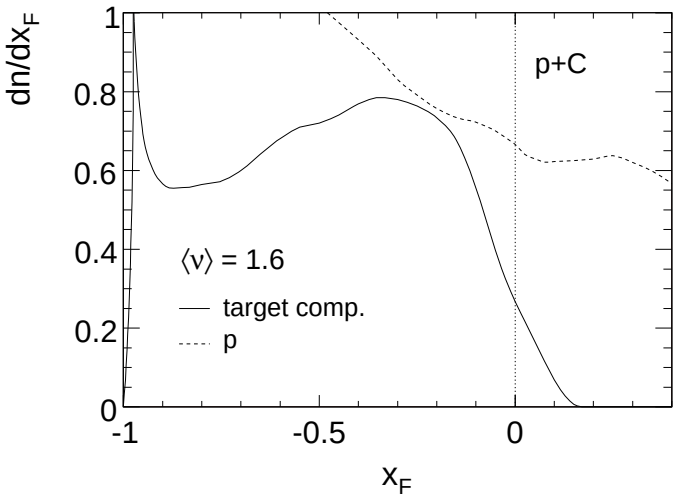


- Study of proton overlap function between target and projectile fragmentation in p+p and p+C by fixing the baryon number
- Overlap range is $|x_F| < 0.2$

Target and projectile component of protons in p+C

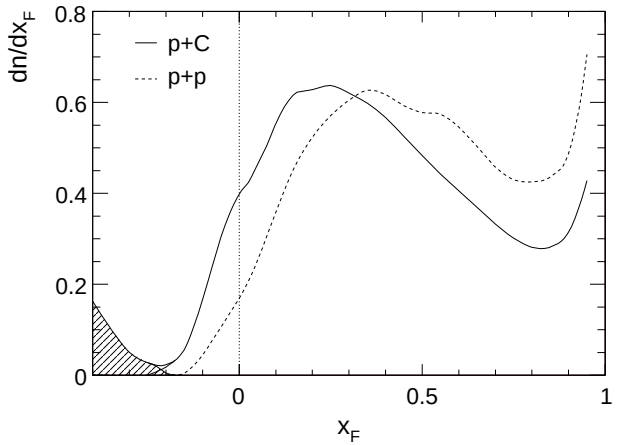
Target fragmentation





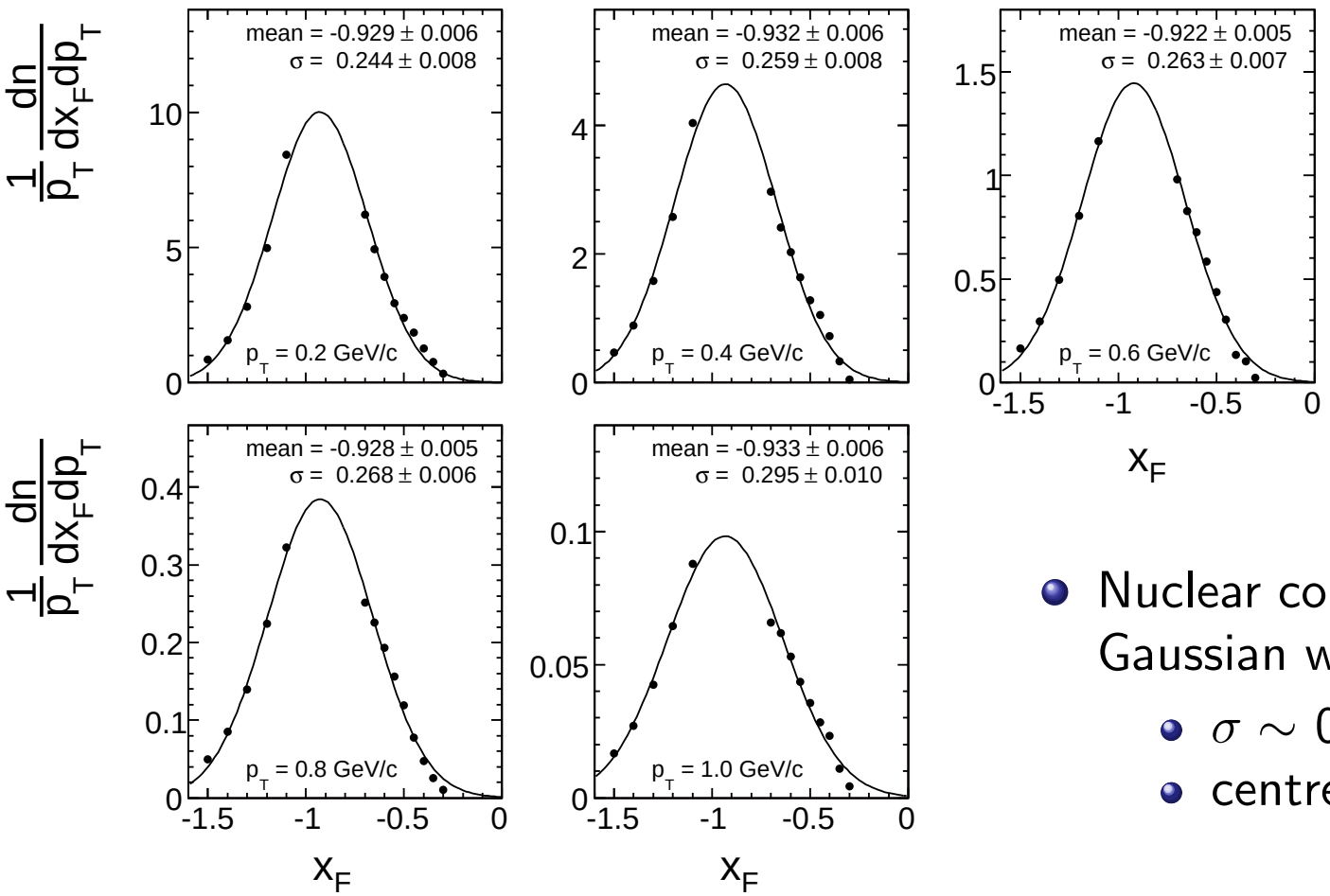
- Target component predicted from p+p collisions
- Isoscalar nucleus – average between protons and neutrons

Projectile fragmentation



- Shift in $x_F \sim 0.15$
- Verifies baryon number conservation
- Below x_F = -0.2 onset of nuclear component

Nuclear cascading of protons in p+C



- Nuclear component described by Gaussian with:
  - $\sigma \sim 0.26$ units of x_F
  - centred at $x_F \sim$ -0.93

Survey in backward region in p+C collisions

Survey of proton and pion production in backward region ($x_F <= 0$) in p+C collisions from 1 to 400 GeV/c beam momentum

Survey in backward region in p+C collisions

- Variables: p_{lab}, Θ_{lab}, p_{proj}
- 19 experiments and ∼3500 data points

p

interaction	Experiment	p_{proj} (GeV/c)	lab angle coverage (degrees)	p_{lab} coverage (GeV/c)	number of data points	errors [%] $\langle\sigma_{stat}\rangle$	$\langle\sigma_{syst}\rangle$
p+C	Bayukov	400	70–160	0.4–1.3	35	6	20
	NA49	158	10–40	0.3–1.6	40	7	5
	Belyaev	17–56	159	0.3–1.2	125	5	15
	HARP-CDP	3–15	25–112	0.45–1.5	202	4	6
	Burgov	2.2–8.5	162	0.35–0.85	36	15	5
	Bayukov	1.87–6.57	137	0.3–1.1	55	10	20
	Geaga	1.8–5.8	180	0.3–1.0	50	17	15
	Frankel	1.22	180	0.45–0.8	6	7	
	Komarov	1.27	105–160	0.34–0.54	∼200	8	15
n+C	Franz	0.84–1.15	51–160	0.3–0.8	553	5	10

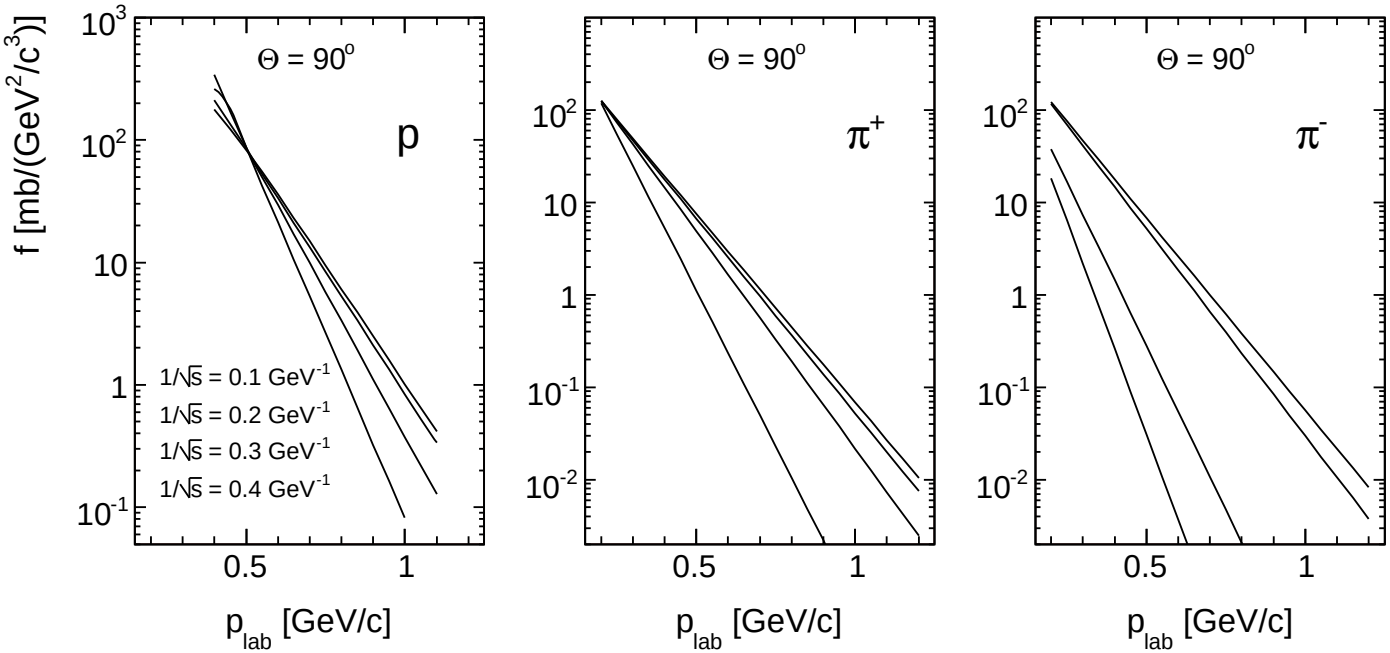
π

Experiment	p_{proj} (GeV/c)	lab angle coverage (degrees)	p_{lab} coverage (GeV/c)	number of data points	errors [%] $\langle\sigma_{stat}\rangle$	$\langle\sigma_{syst}\rangle$
Nikiforov	400	70–160	0.2–1.3	59	12	
NA49	158	5–45	0.1–1.2	174	5	4
Belyaev	17–57	159	0.25–1.0	218	4	15
Abgrall	31	0.6–22.3	0.25–16	624	6	7
HARP-CDP	3–15	25–112	0.2–1.6	829	6	8
HARP	3–12	25–117	0.125–0.75	605	12	
Burgov	2.2–8.5	162	0.25–0.6	29	20	
Baldi	6.0, 8.4	180	0.2–1.25	45	10	
Cochran	1.38	15–150	0.1–0.7	199	3	12
Crawford	1.20	22.5–135	0.1–0.4	50	8	7

- Used variables: p_{lab}, $cos(\Theta_{lab})$, $1/\sqrt{s}$

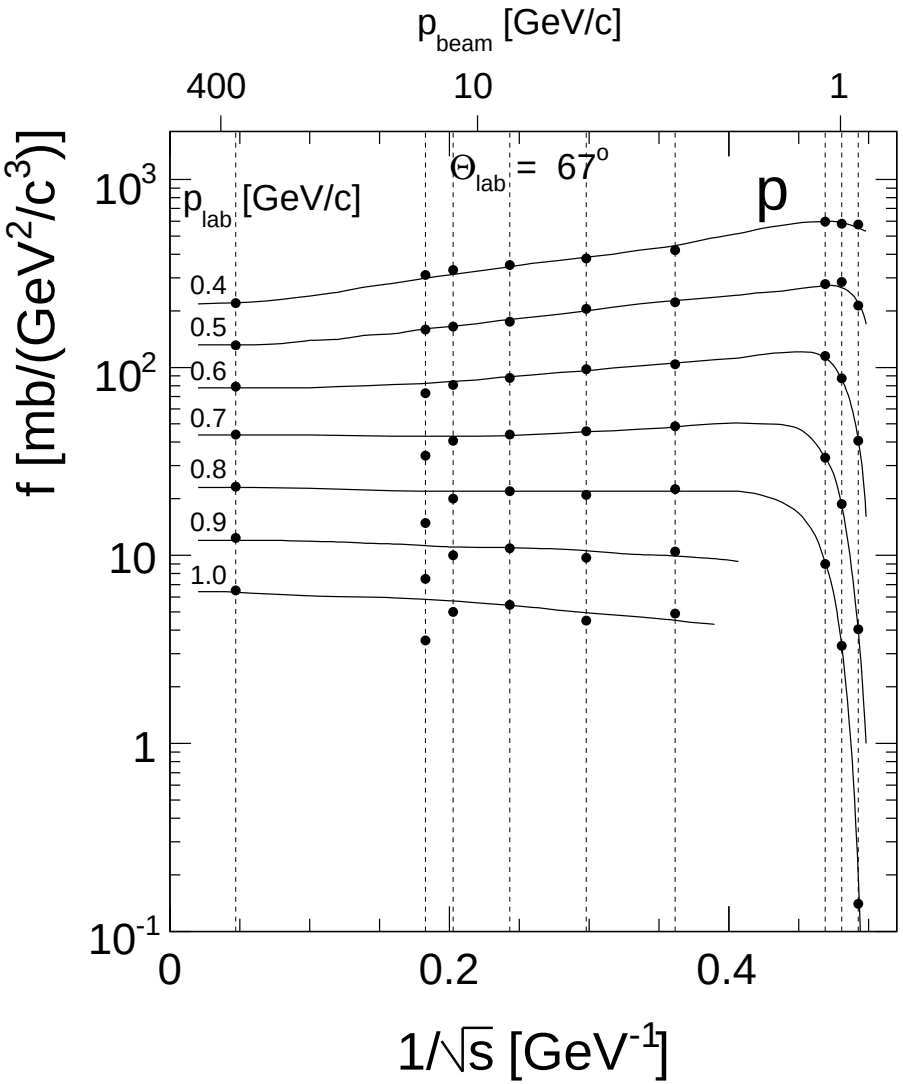
Lab momentum dependence

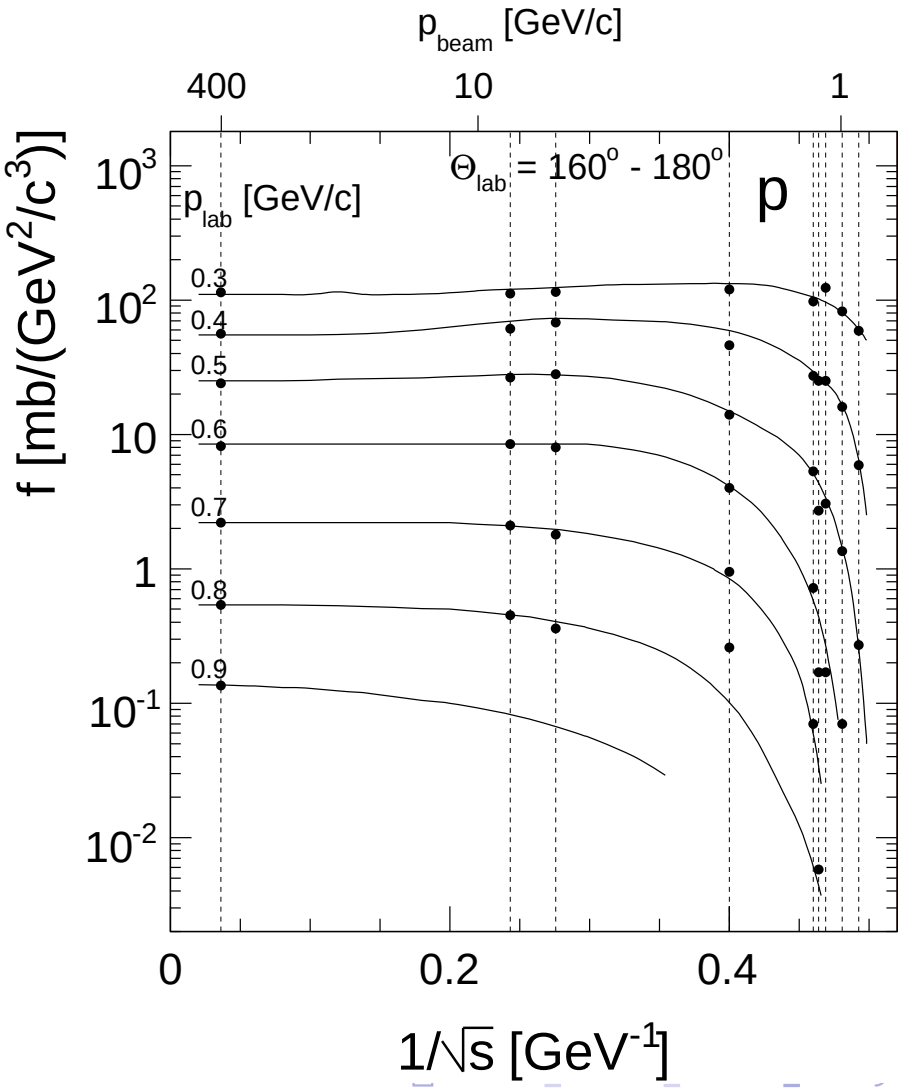
- Transform all data to invariant cross section
- Need of interpolation because data are not defined in appropriate points of phase space
- p_{lab} dependence is basically exponential



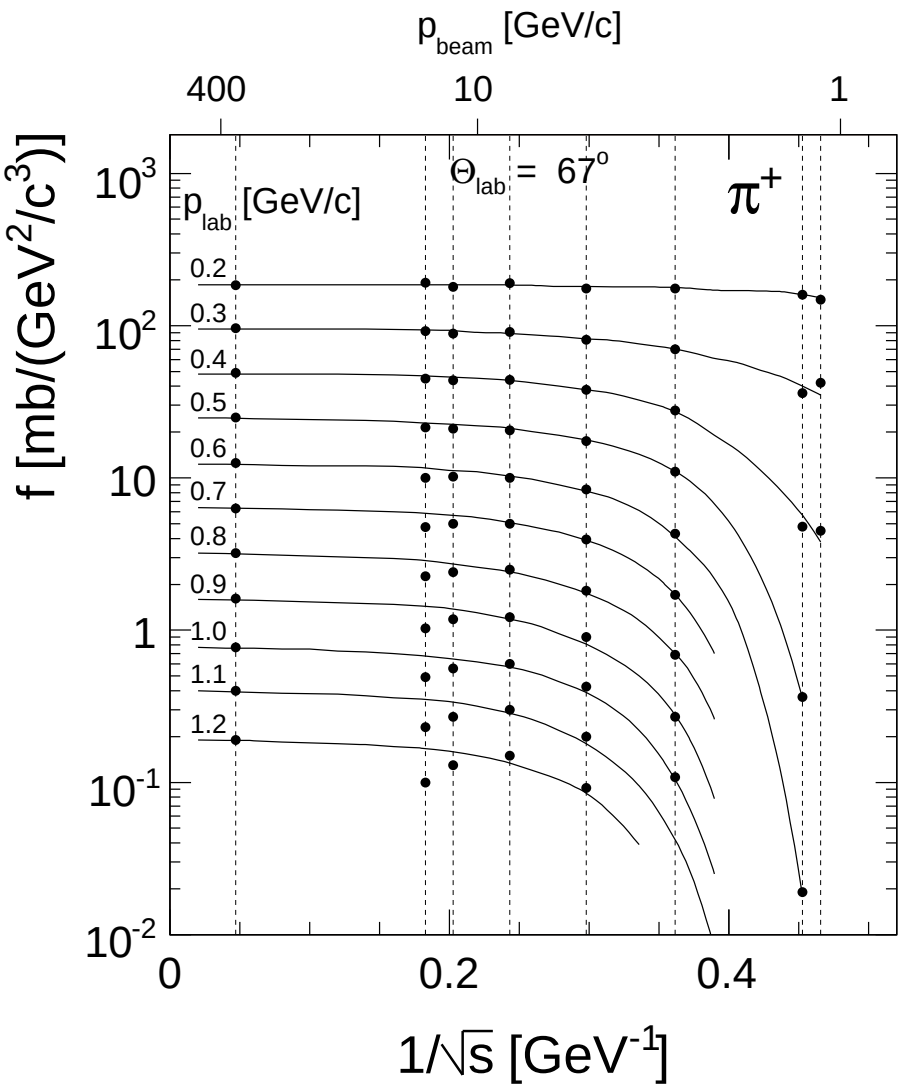
$1/\sqrt{s}$ dependence: protons

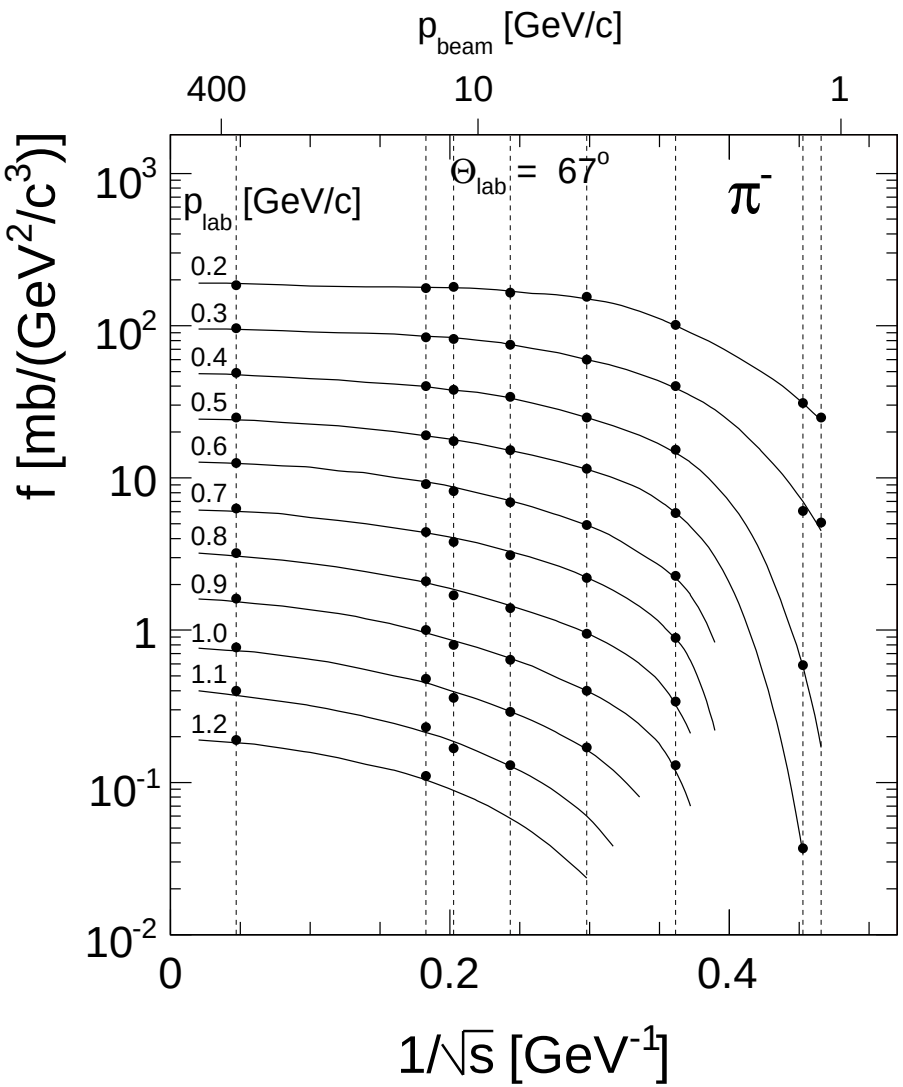
- Plot interpolated cross section as a function of $1/\sqrt{s}$
- Check for continuity and smoothness





$1/\sqrt{s}$ dependence: pions

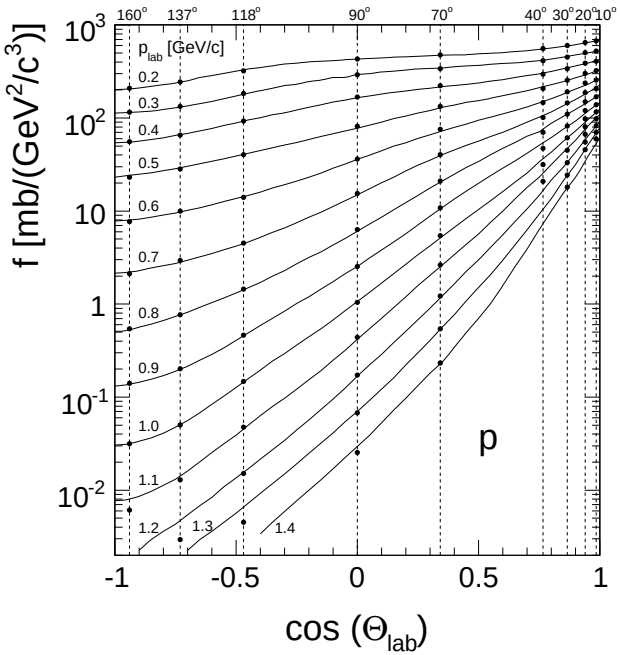


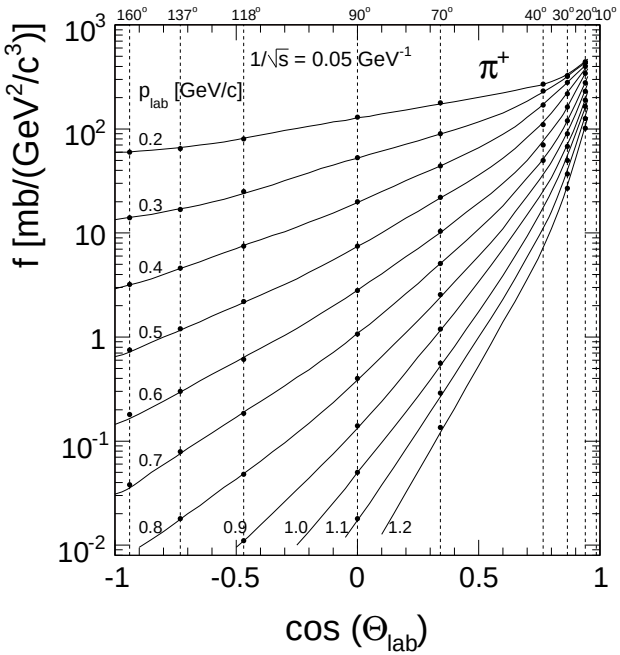


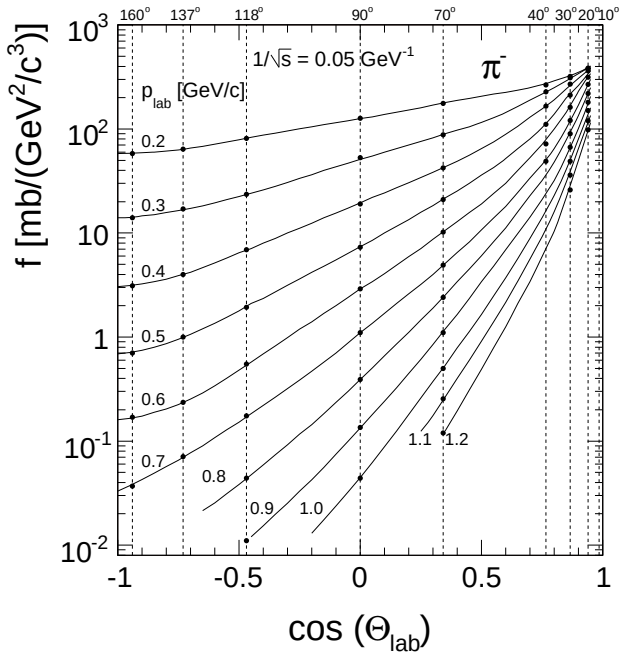
Angular dependence

- Check for continuity and smoothness of $\cos(\Theta_{lab})$ distributions

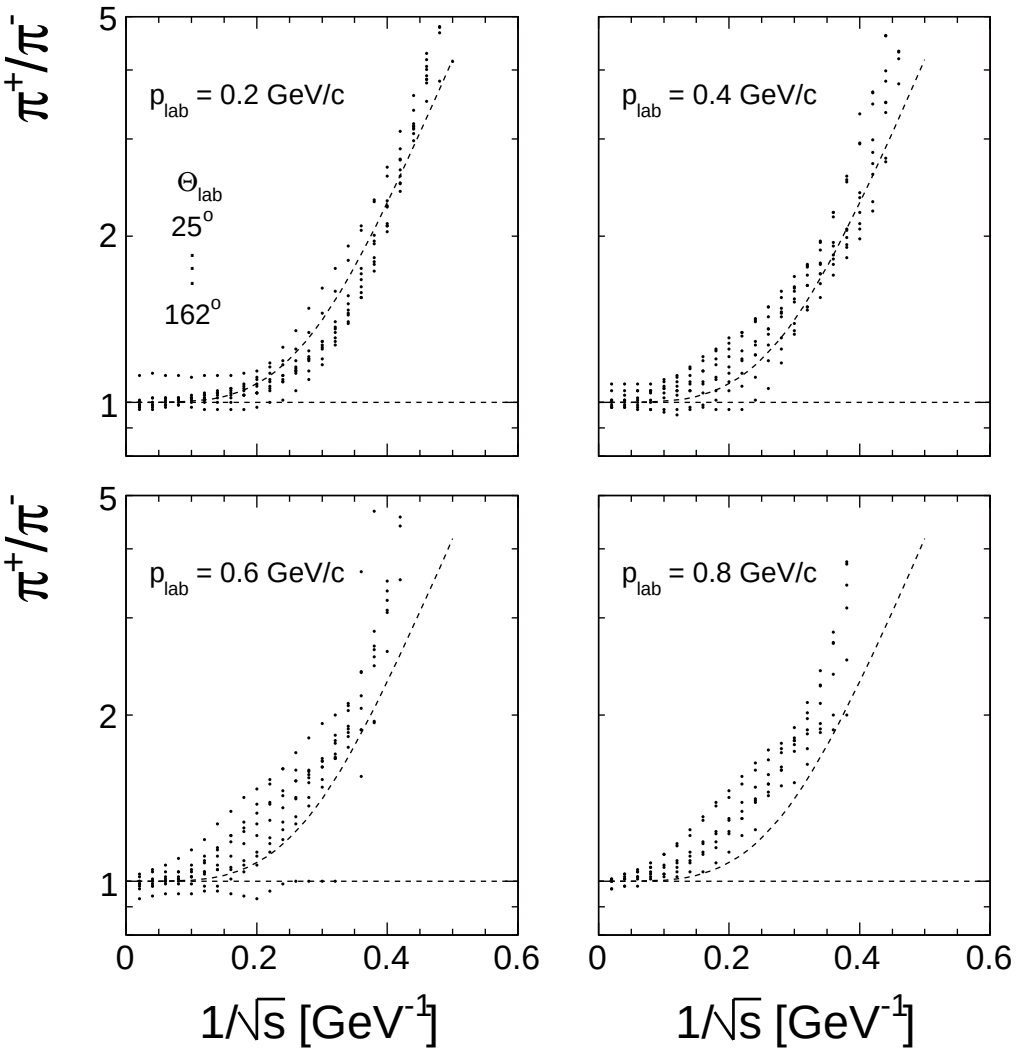
$$\frac{1}{\sqrt{s}} = 0.05 \text{ GeV}^{-1}$$







π^+/π^- ratio as a function $1/\sqrt{s}$



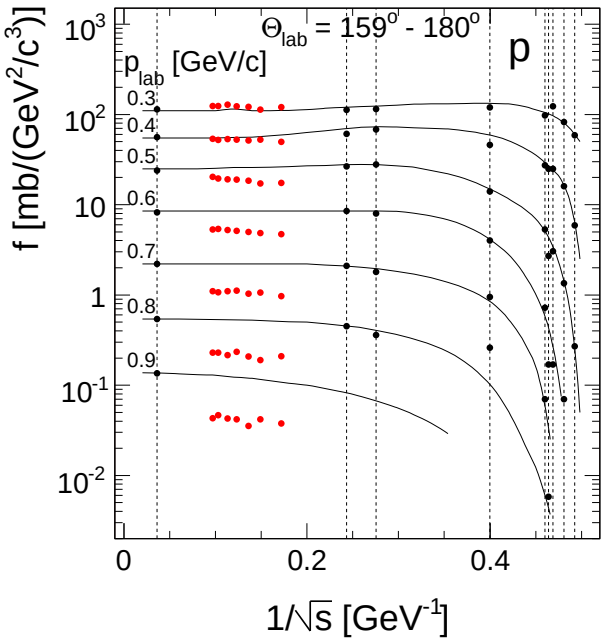
- Important constrain in comparing different experiments
- Independent on angle
- Slight increase with p_{lab}
- At low energies particle production is governed by pion exchange described by Regge theory: $f_{exch} \sim s^{2\alpha_\pi - 2}$, with $\alpha_\pi = 0$–0.1
- Lines $1 + \frac{const}{s^2}$
- Describe ratio approach to 1 at high energies

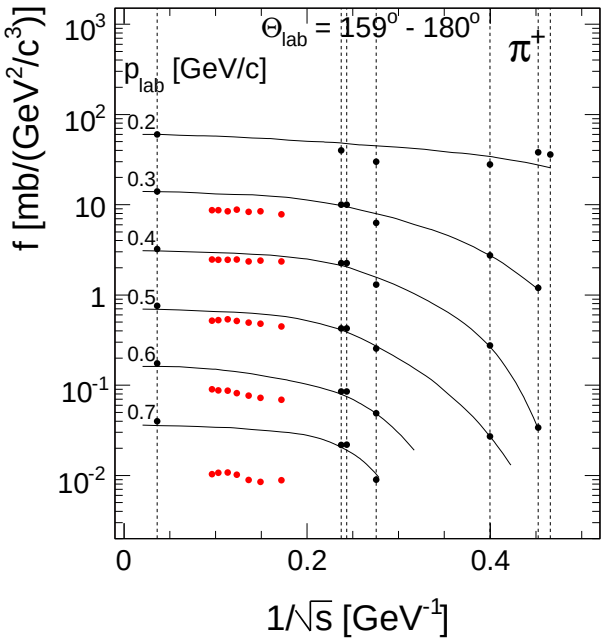
Survey in backward region in p+C collisions

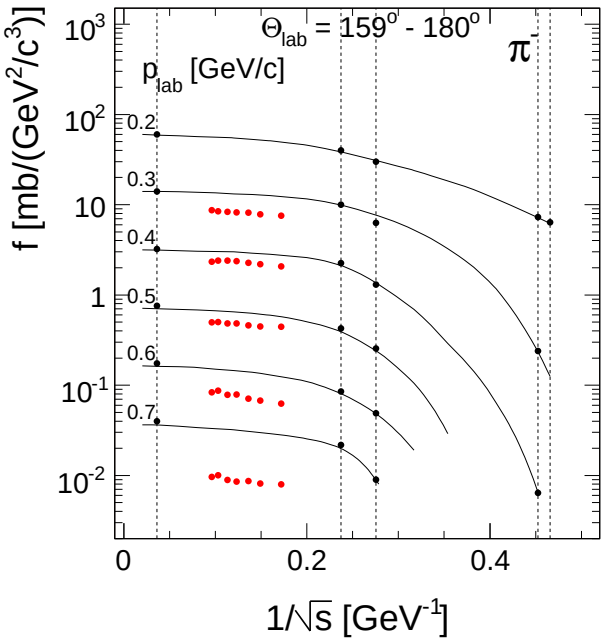
- 15 experiments are used for interpolation
- 4 of the 19 experiments show systematic deviations from the global interpolation
- 3 will be discussed

Serpukhov data between 17 and 57 GeV/c at 159° lab angle

- Experiment cover important region between PS and SPS energies
- The *s*-dependence follows precisely the shape of interpolation
- There is a strong suppression of the cross section with increasing the p_{lab} for all particles

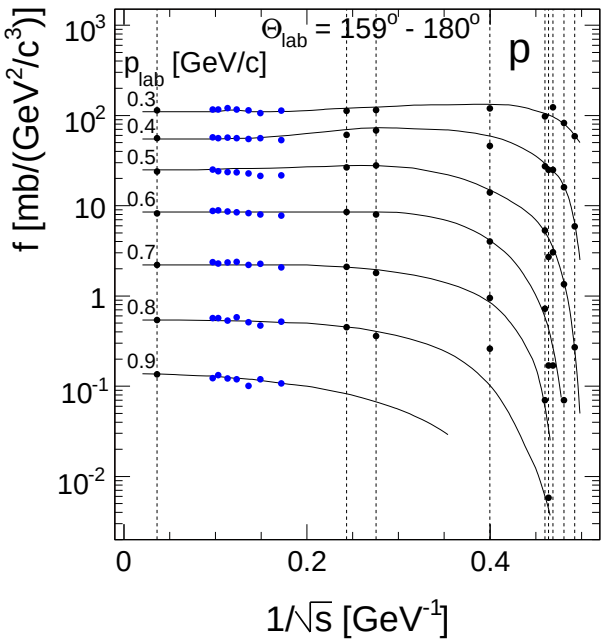


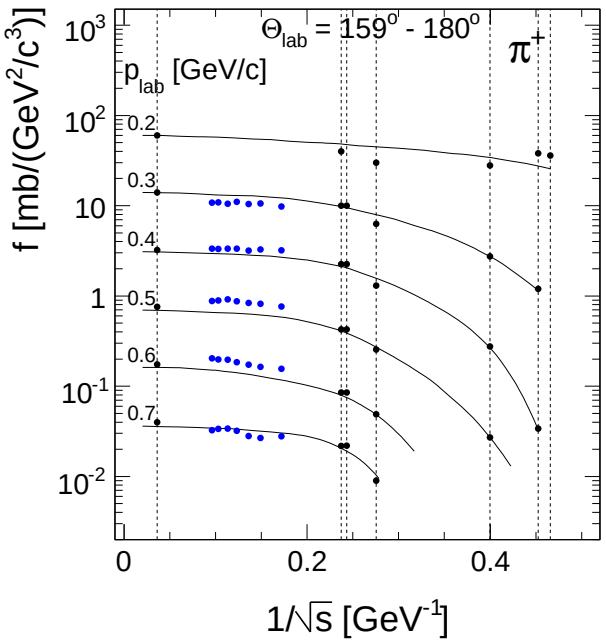


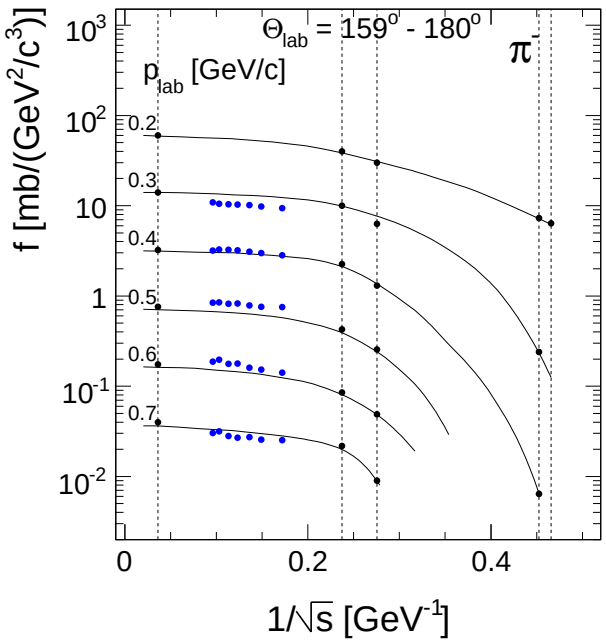


Serpukhov data between 17 and 57 GeV/c at 159° lab angle

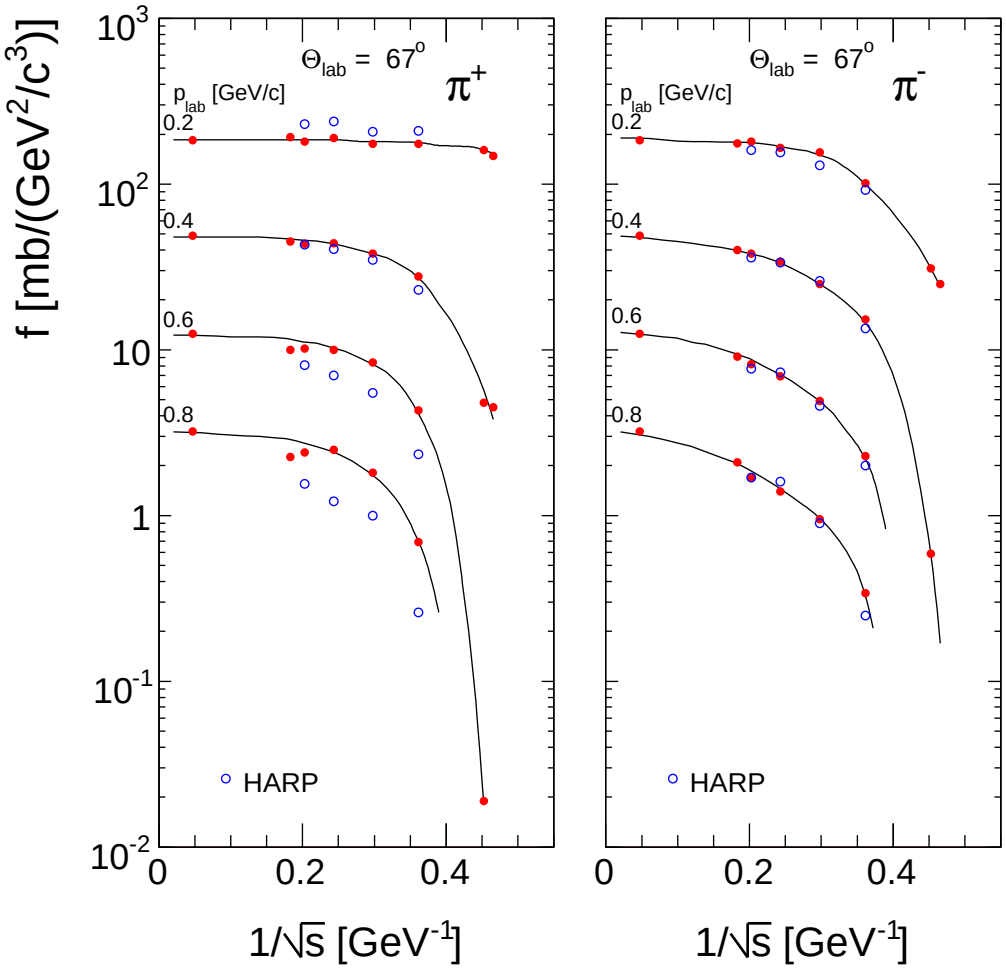
- Corrected for momentum shift of 9%



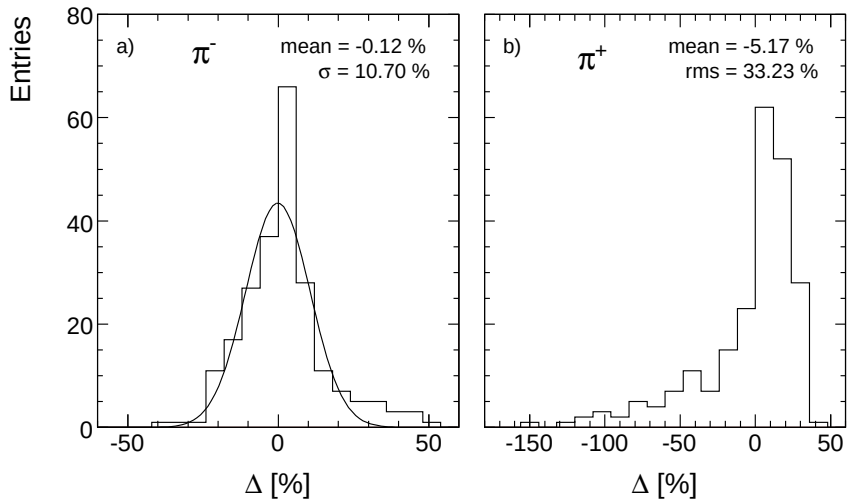




HARP data for π^+

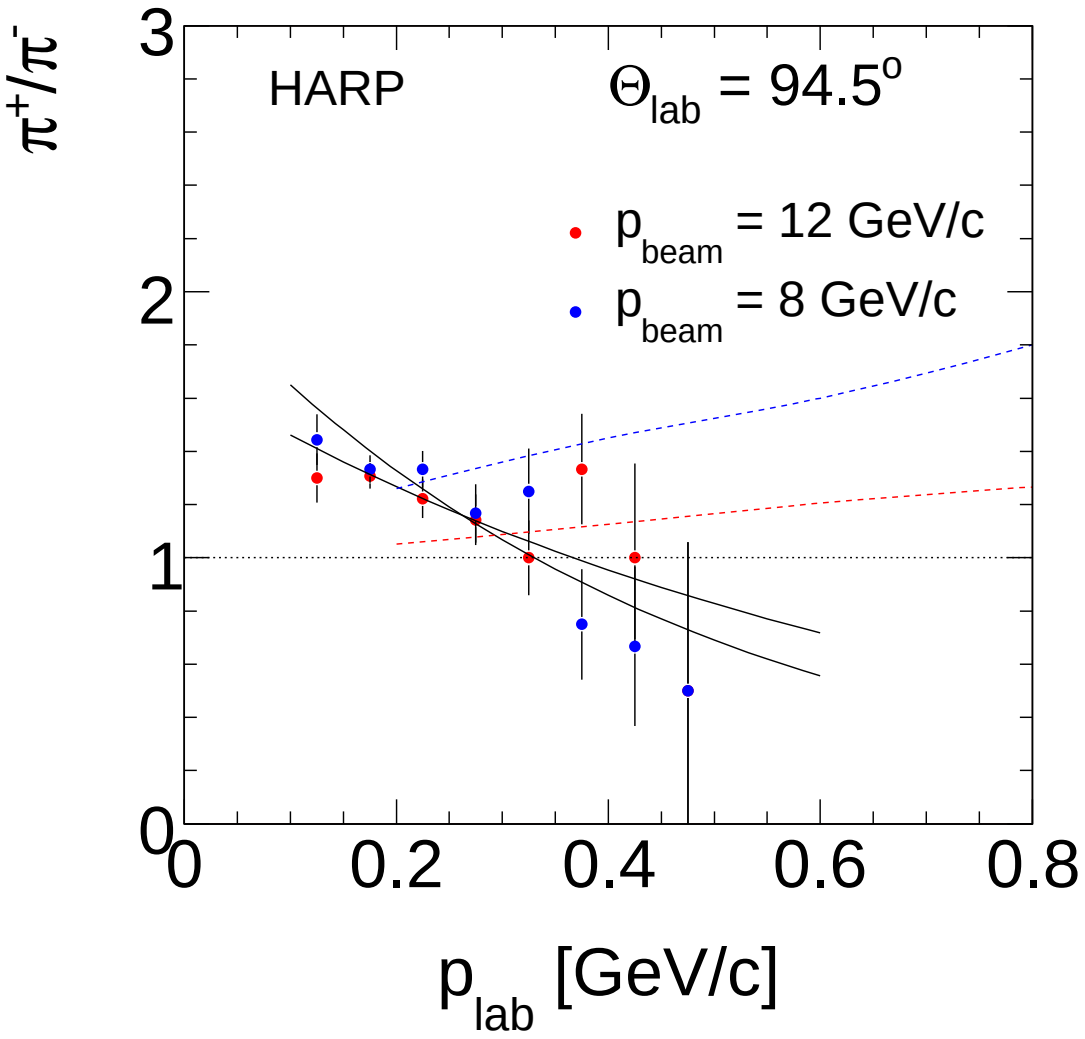


Difference between HARP and HARP-CDP



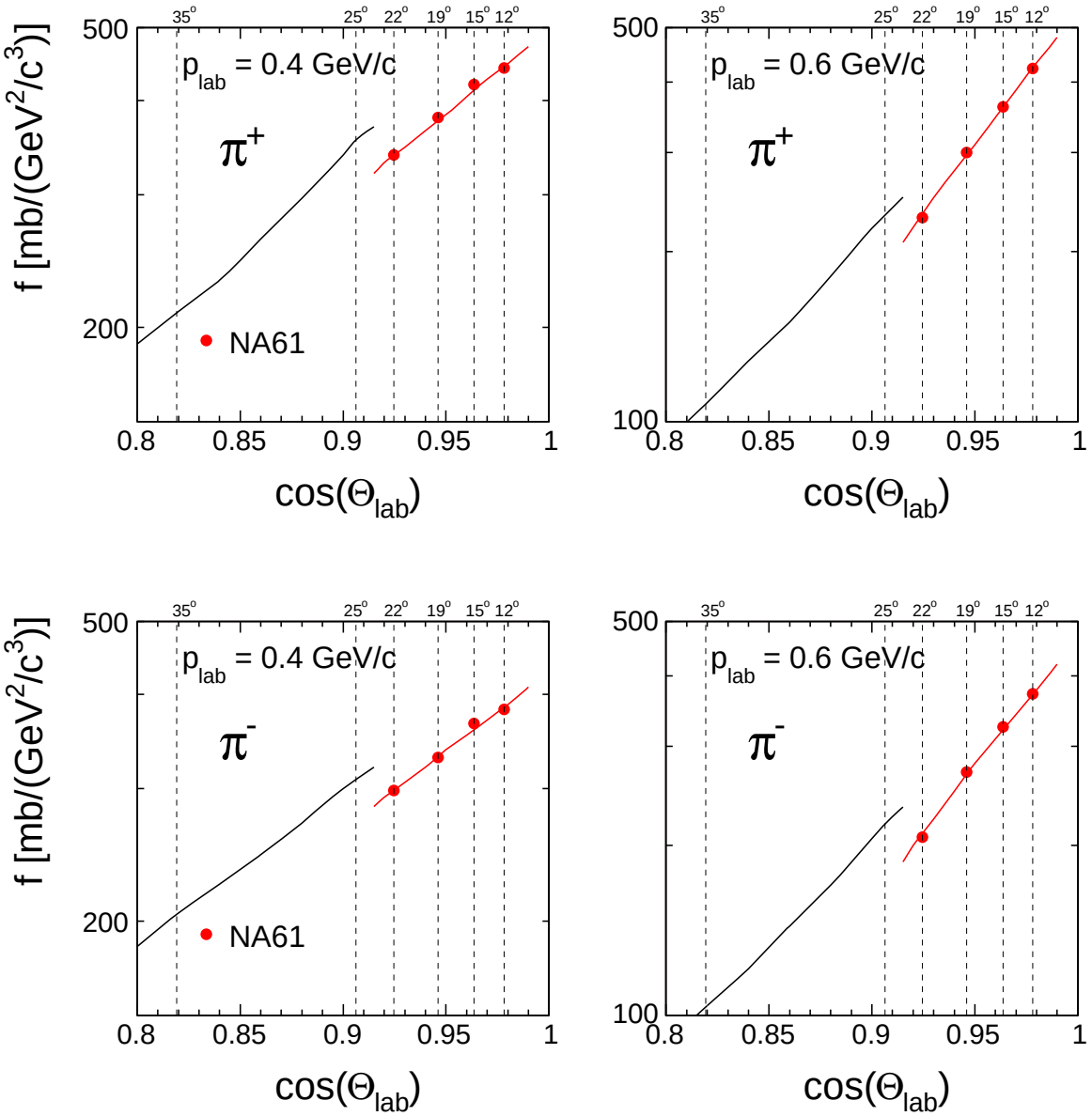
- π^- rms of $\pm 10\%$
- π^+ deviation from $+40\%$ to -100%

HARP π^+/π^- ratio



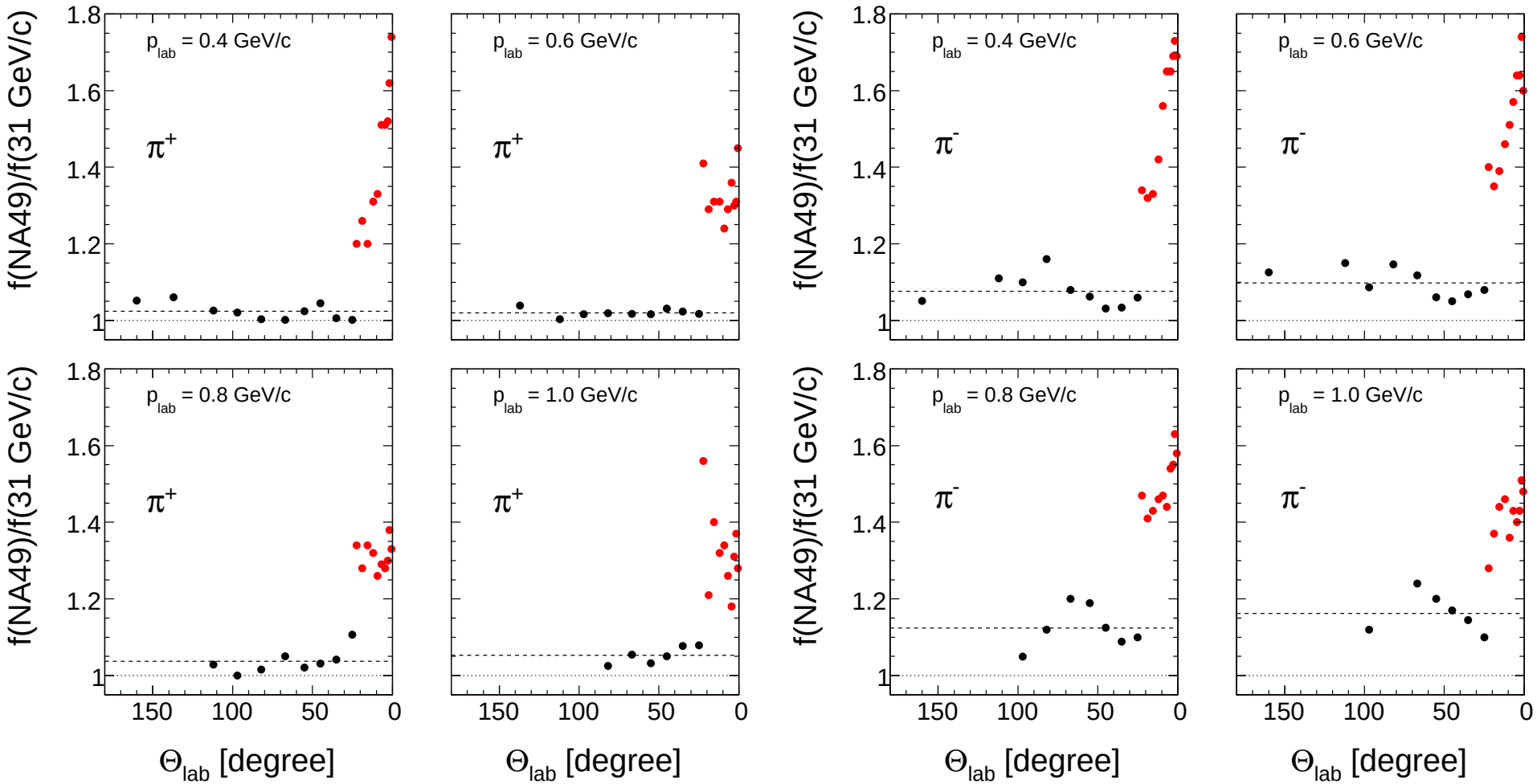
- Tendency of the HARP ratios to decrease with energy
- Ratios reach unphysical values below 1
- Dashed lines expected π^+/π^- ratio

NA61 results at 31 GeV/c beam momentum



- Angular dependence
- NA61 deviates at approach around $\Theta_{lab} = 22$–25^o for both π^+ and π^-

f(NA49)/f(p_{beam} = 31 GeV/c) ratio



Conclusions

- Inclusive cross sections of pions, kaon and baryons in p+p and p+C
- Three proton components in p+C are extracted
- Survey of hadron production in backward region ($x_F < 0$) in p+C collisions from 1 to 400 GeV/c beam momentum