What did we learn from 200 and 62 GeV pp collisions at RHIC ?

A BRAHMS perspective

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SIXTY YEARS
OF DISCOVERY
1947-2007

BROOKHAVEN
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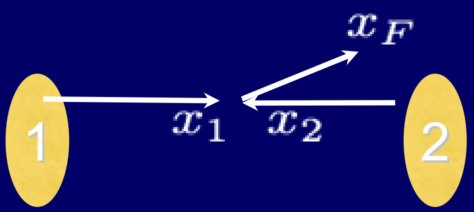
Outline of the presentation

- Background.
- pp at 200 GeV
  - Bulk properties
  - results and comparisons to NLO pQCD.
- pp at 62 GeV
  - Preliminary results and comparison to pQCD
- A BRAHMS unexpected benefit:
  - Single Spin Asymmetries at 200 and 62 GeV

Introduction

- Forward rapidity at RHIC collider $\sqrt{s}$ = 200 GeV offers insight into pp, p(d)A and AA in
  - Low-x region (for target like p, A)
  - Probing larger x_F region where kinematic constraints may be important. $\sqrt{s}$

Today's focus on pp collisions, which also serves as reference for HI data.



$$x_F = x_1 - x_2$$

$$x_1 x_2 = \frac{m_T^2}{s}$$

$$x_1 \sim \frac{m_T}{\sqrt{s}} e^{y} \quad x_2 \sim \frac{m_T}{\sqrt{s}} e^{-y}$$

pp data and pQCD

- At mid-rapidity NLO pQCD works well for p0. This even down to lower energies.
- Question to ask is how well it works at more forward rapidities in view of previous failures?

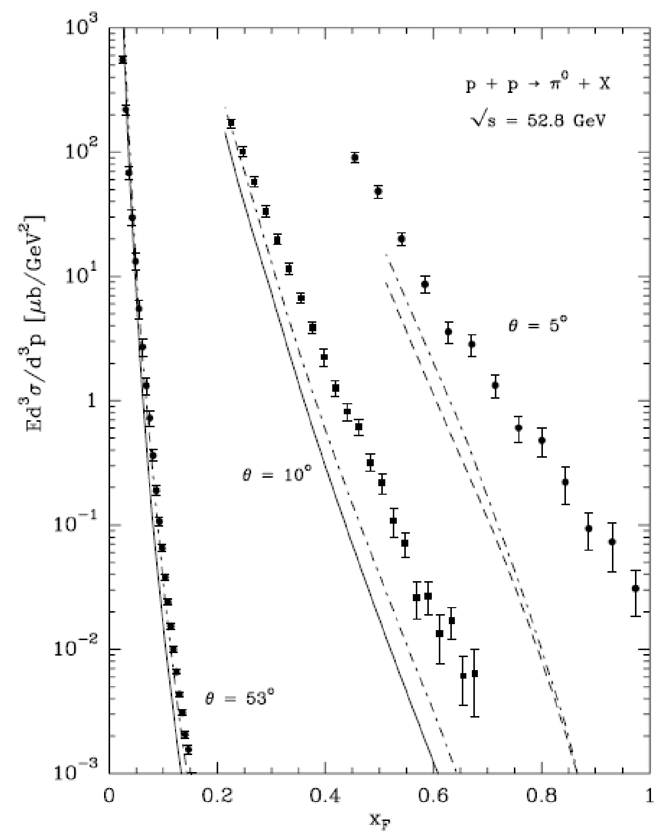


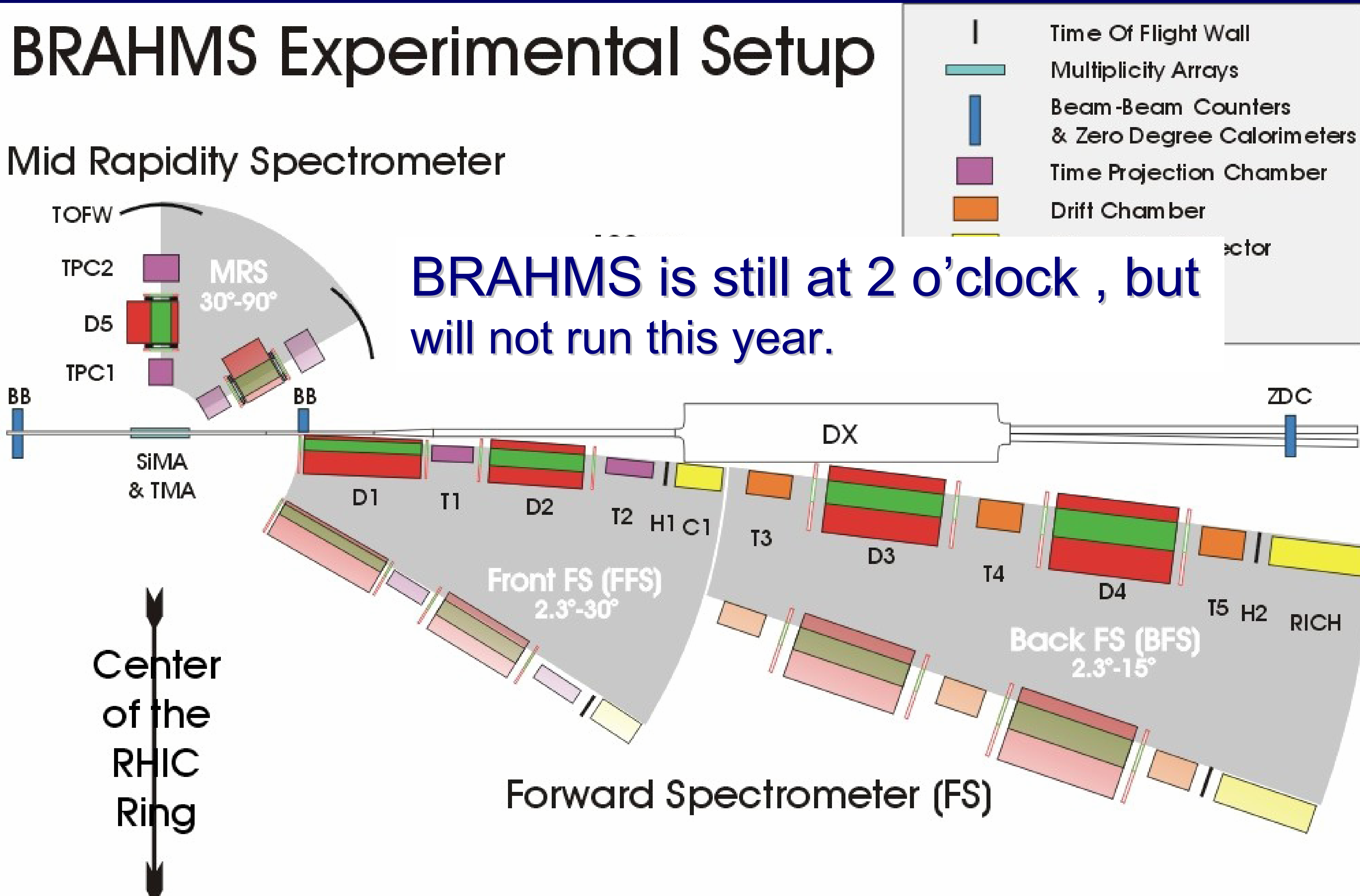
Fig. 4. $Ed^3\sigma/d^3p$ at $\sqrt{s} = 52.8\,\mathrm{GeV}$, as a function of x_F for three different scattering angles. The data are from [20] and the curves are the corresponding NLO pQCD calculations with $\mu = p_T$. The dotted-dashed curves are for $\mu = p_T/2$

p_T [GeV/c]

C.Bourrely and J.Soffer Eur.Phys. J.C36,371 (2004)

BRAHMS Experimental Setup

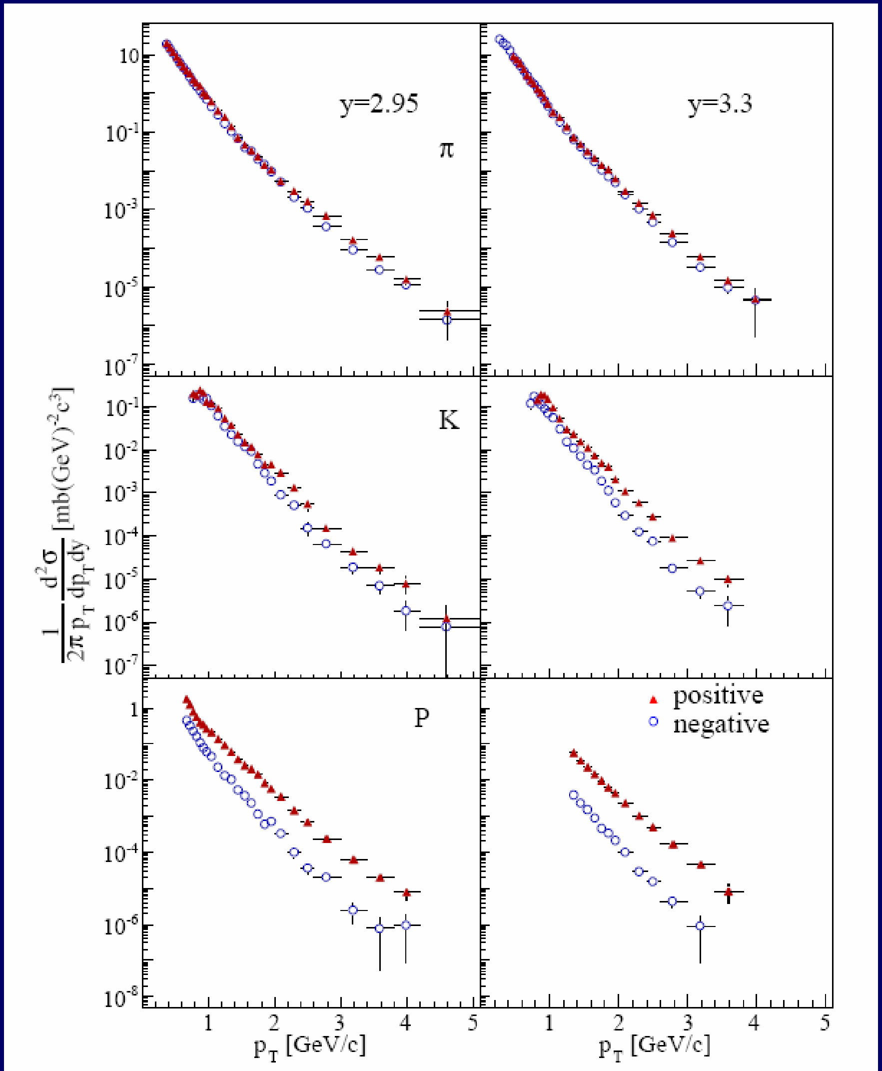
BRAHMS is still at 2 o'clock , but will not run this year.



Spectra at forward rapidity (pp collisions) – comparison to NLO pQCD

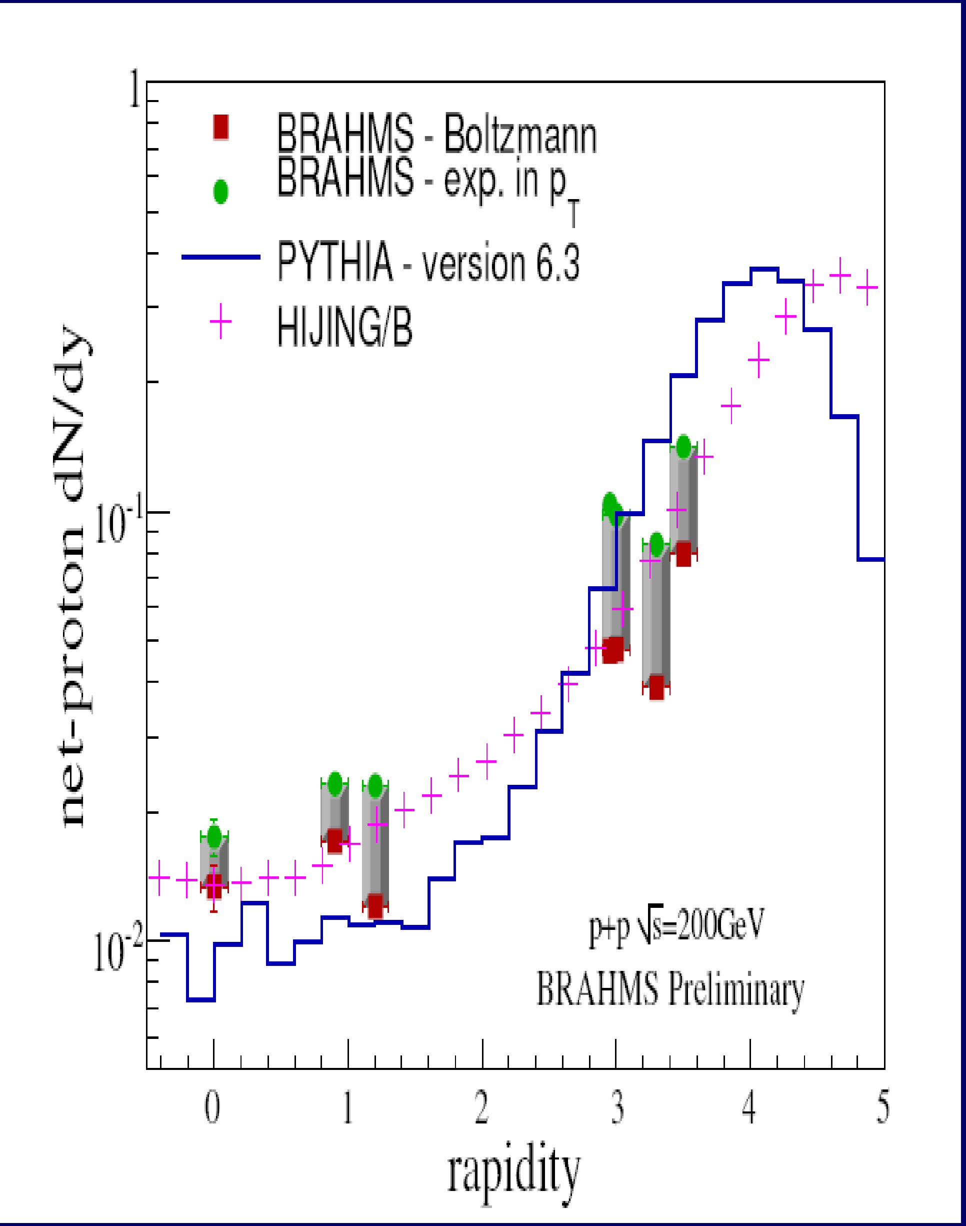
The long 200 GeV pp run5 have resulted in high quality pp reference spectra at high rapidity.

Together with mid rapididity data look at net-p

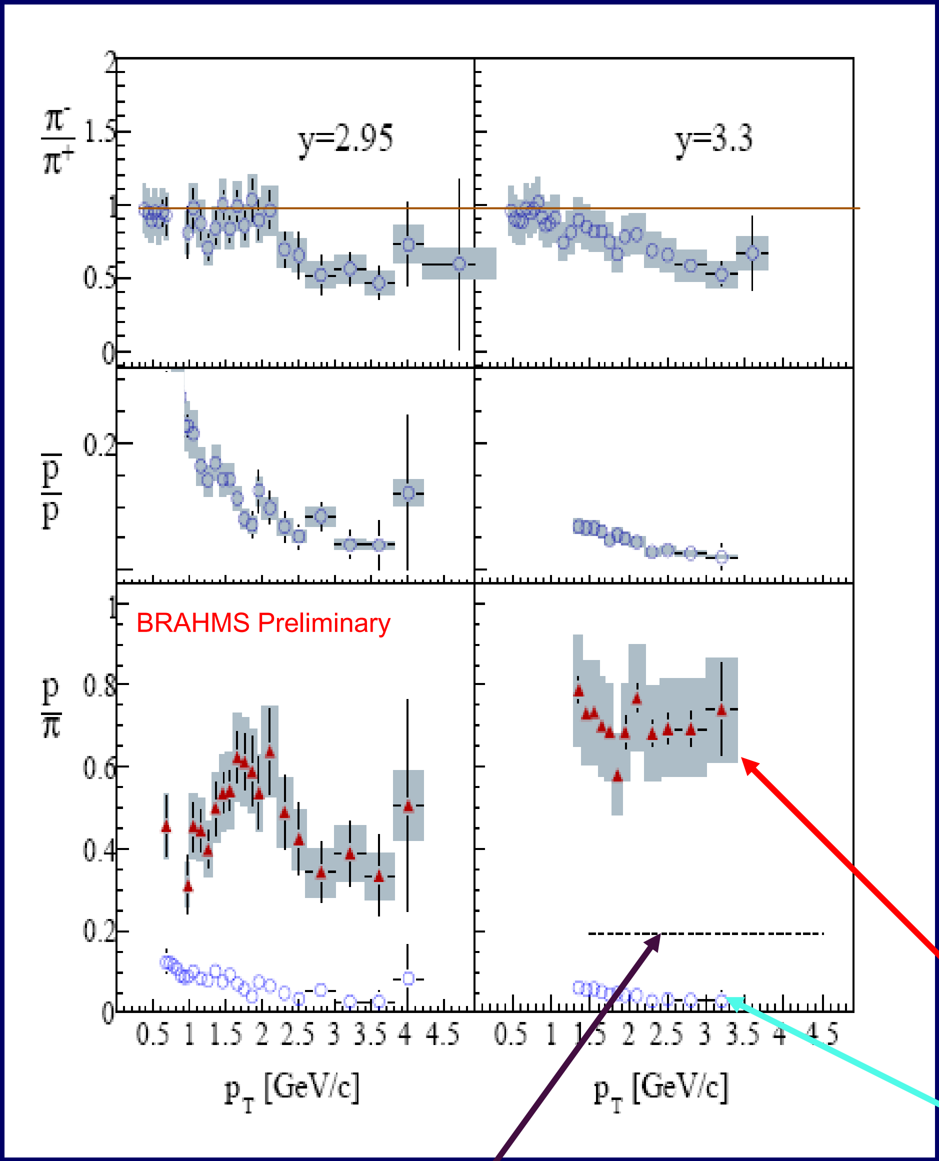


Together with mid-rapididity data look at net-protons.

Despite larger systematic uncertainties better agreement with the baryon transport in Hijing/B



Ratios p/π^+ at y=3.0 and 3.3



The π^-/π^+ ratio is consistent with dominance of valence quarks at these rapidities at the higher p_T.

Small $\bar{p}$/p ratio eliminates possible strong gluon -> p or $\bar{p}$ fragmentation (p/$\bar{p}$~1)

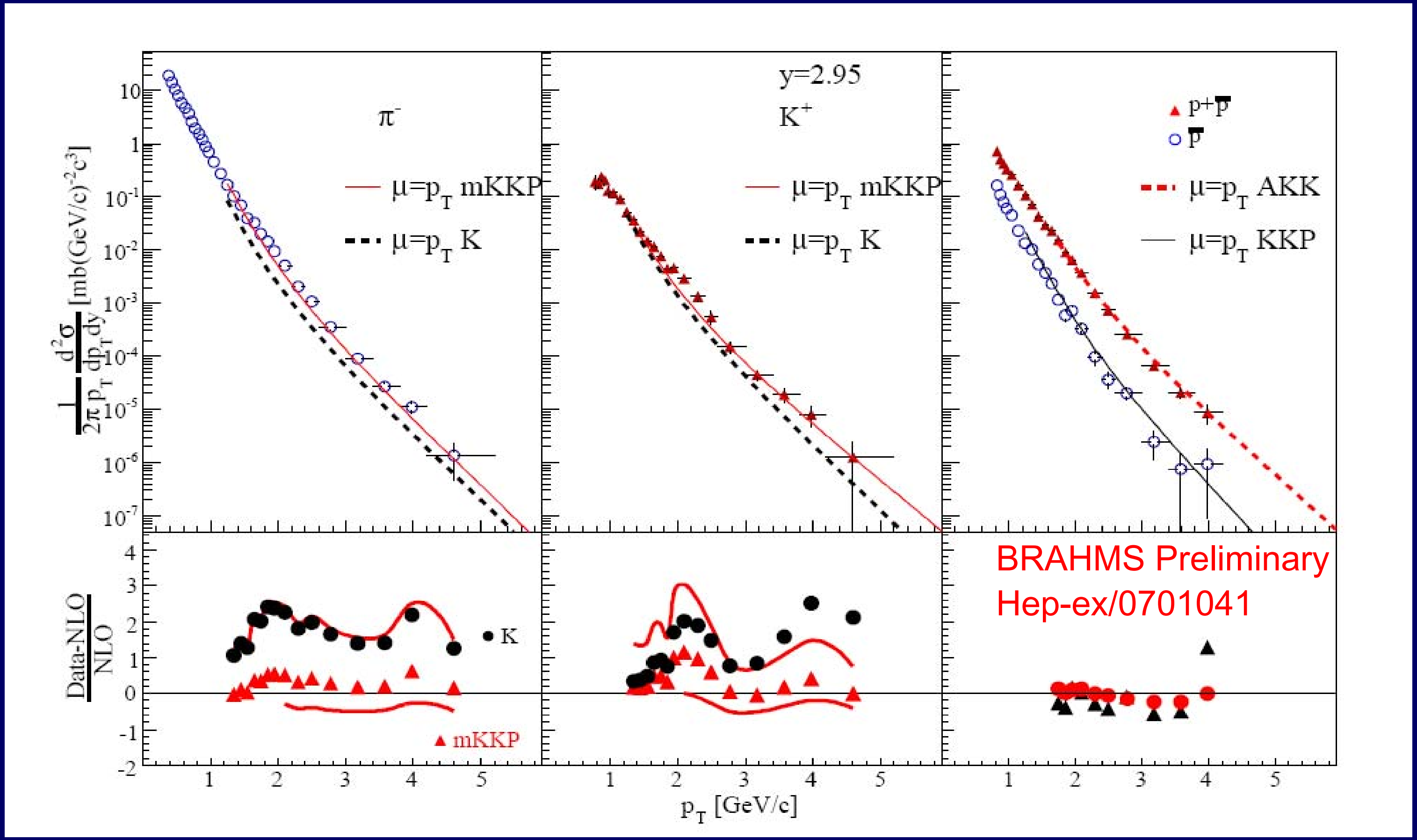
The difference between protons and anti-protons indicates another mechanism besides fragmentation that puts so many protons at high pT.

Red: p/π^+

Blue: $\bar{p}$/ π^-

e$^+$e$^-$ p+pbar/π^++ π^- ALEPH

NLO pQCD comparisons to BRAHMS data

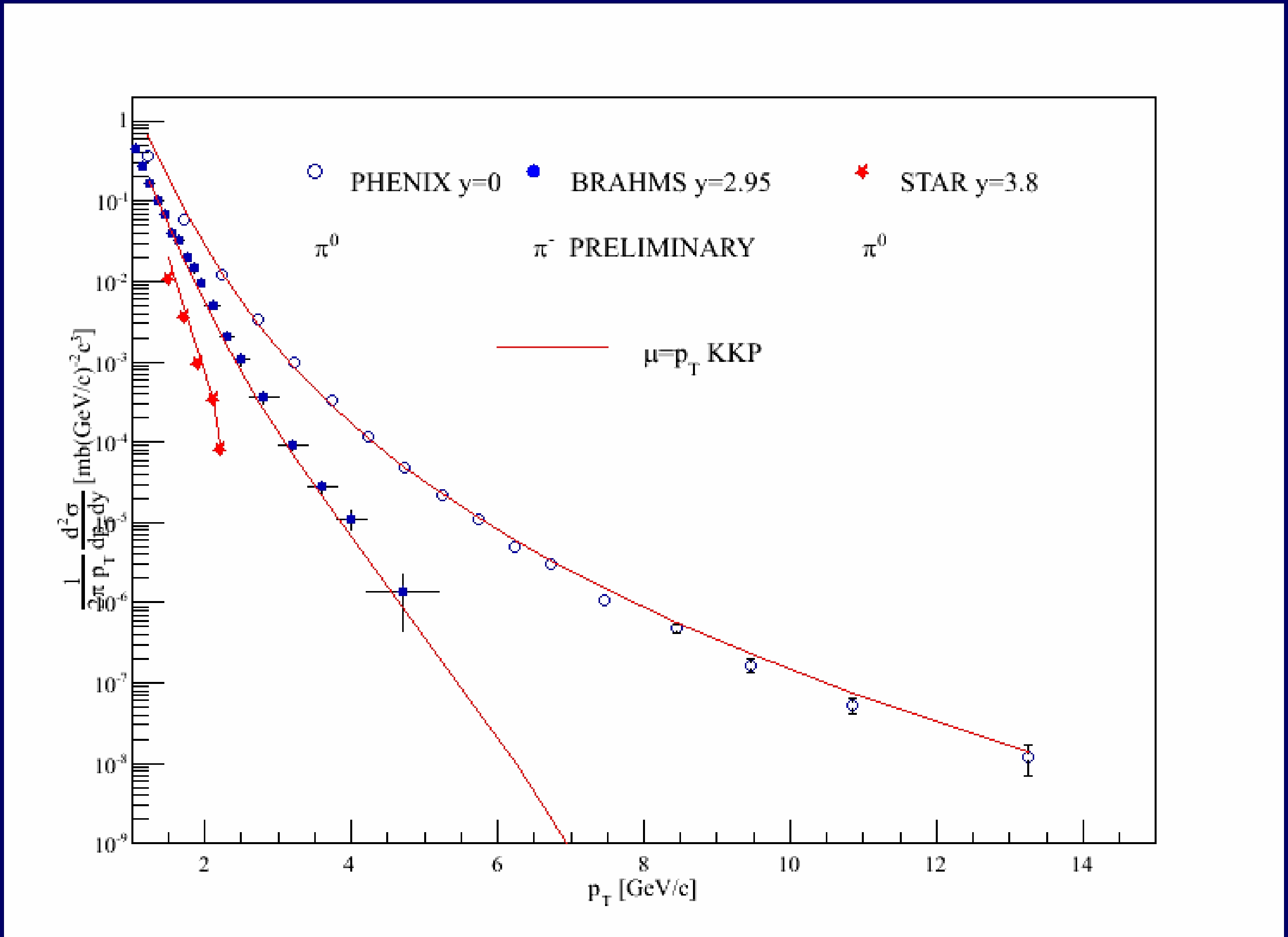


Calculations done by W. Vogelsang. Only one scale $\mu = p_T$ and the same fragmentation functions as used for the PHENIX/STAR comparisons.

KKP has only π^0 frag. Modifications were needed to produce charged pions

KKP FF does a better job compared to Kretzer, Pi and Kaon production still dominated by gg and gq at these rapidities apart from the highest p_T

Another view of rapidity dependence .

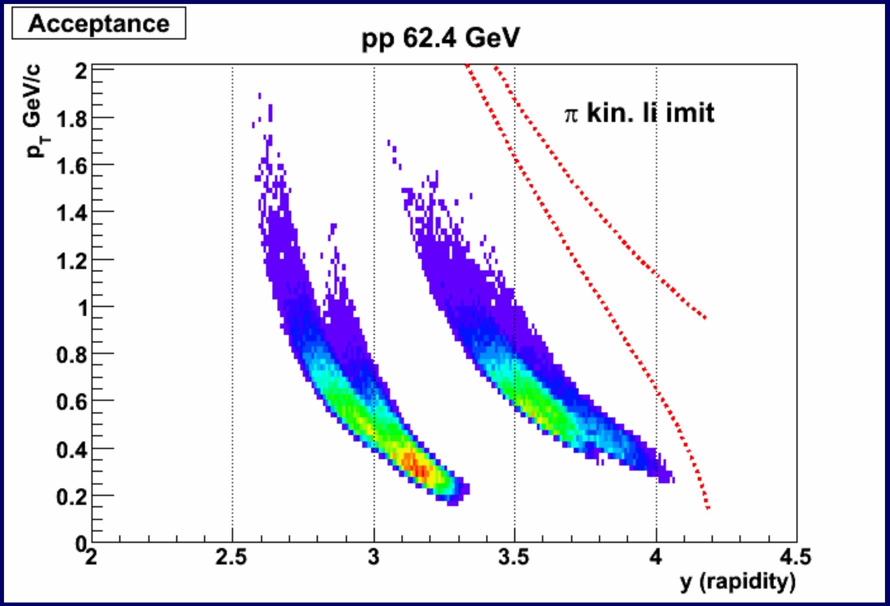


Notice the significant change in shape due to available phase space

pp at 62 GeV

Brahms had the last data taking during the two-week 62.4 GeV in June 2006.
The focus was on
- Reference spectra for AuAu
- Single Spin asymmetries.

Coverage for π^- at forward rapidities. Note the kinematic limits.



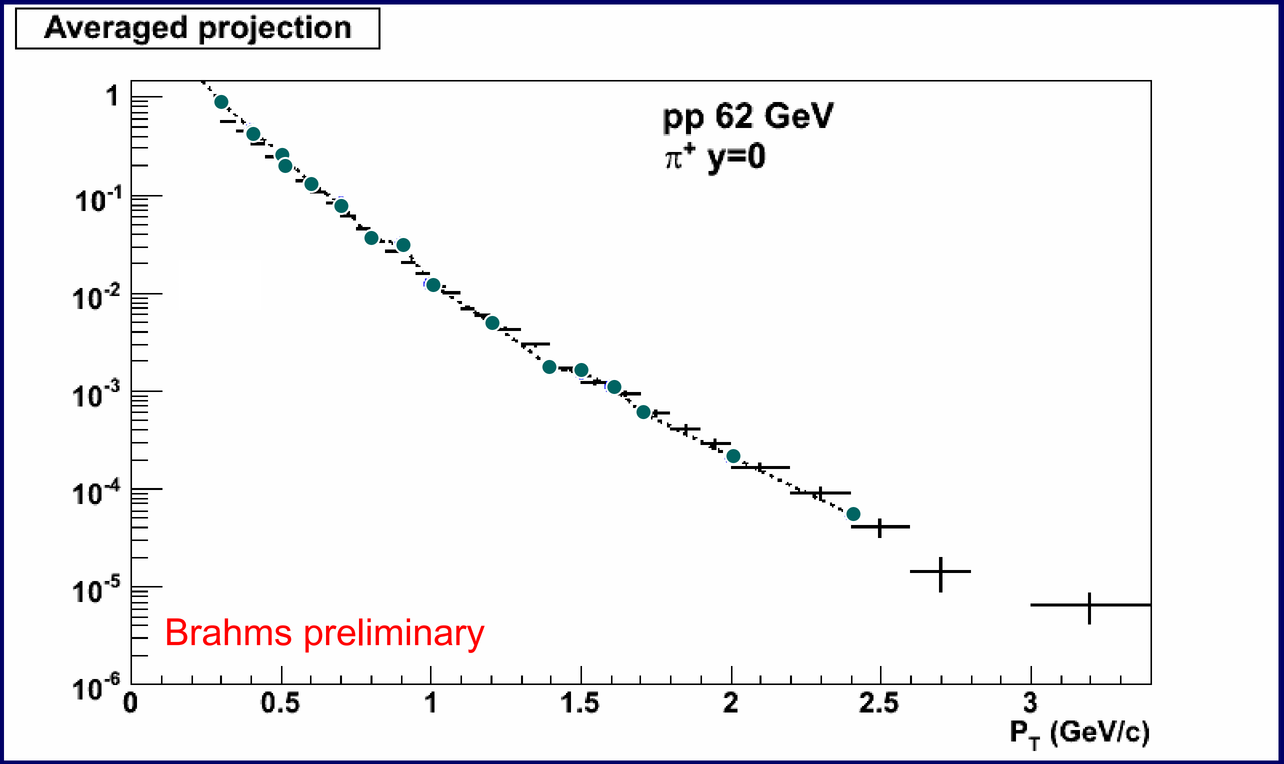
Spectra

Near mid-rapidity

Y~0 and y~1

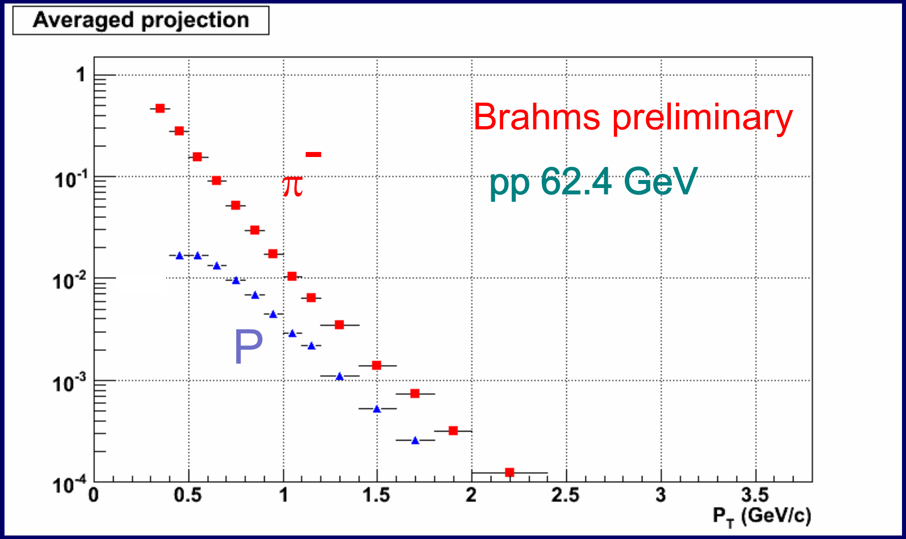
Spectra for pi,K and p using Time-of-flight.

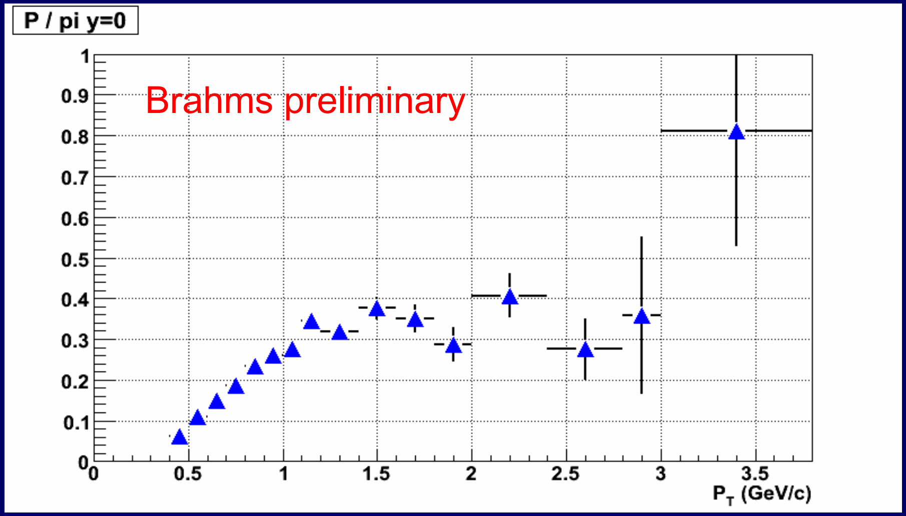
dn/dy for pi+ at y=0 compared to Alper et.al. ISR



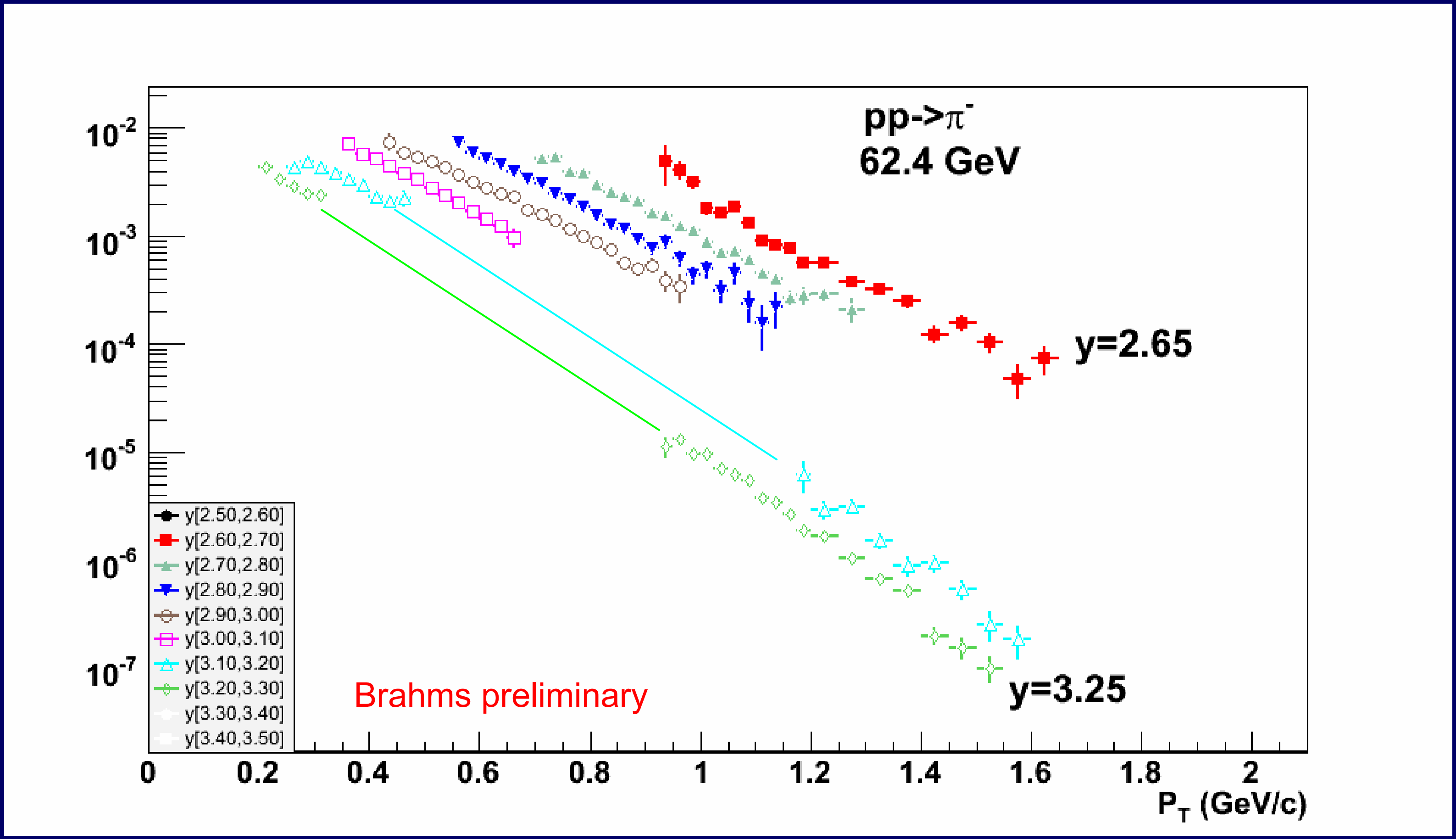
Particle Ratios

Proton, pion spectra and particle ratio p/π at y~0. As know in pp the p/π saturates at ~0.4

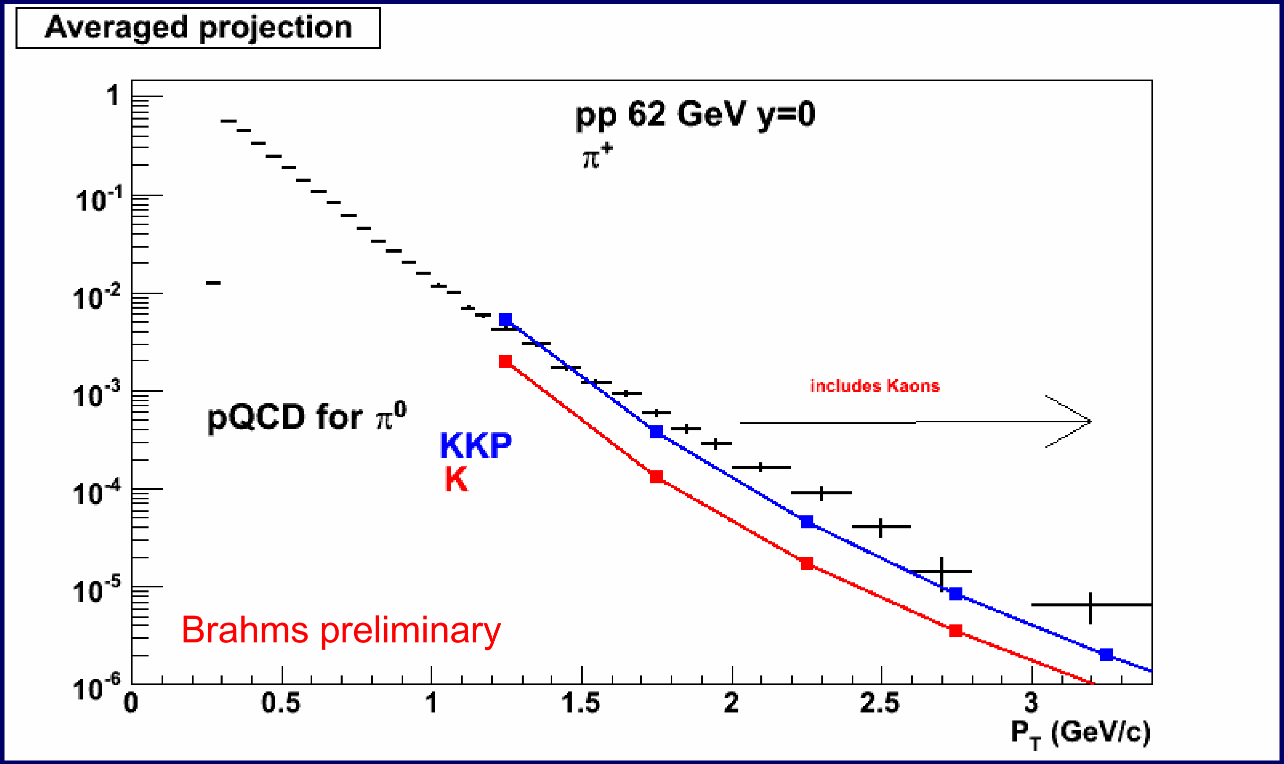




Pions at high rapidity

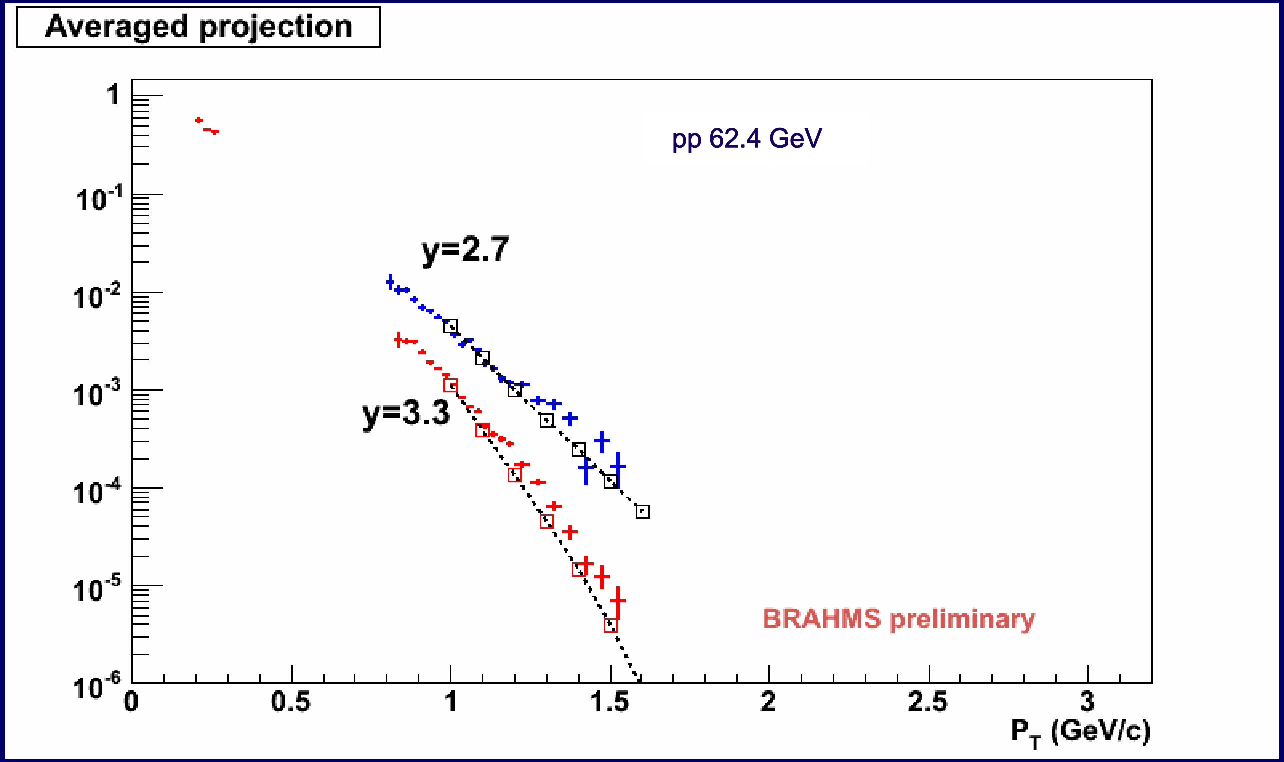


Pion spectra compared to NLO pQCD



Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS pi- data.
Calculation is for pi0, but $\pi^+/\ \pi^0$ ~1 with 5% in range of pt - measured.

High rapidity pp->π^-



Comparison of NLO pQCD calculations (Vogelsang) with BRAHMS π^- data at high rapidity. The calculations are for KKP and a scale factor of μ=pt.

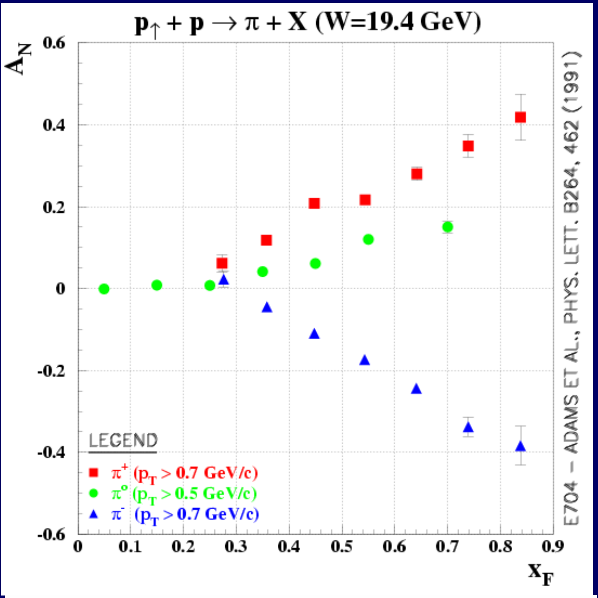
The agreement is surprisingly good. The kinematic cutoffs as moving to higher y is reproduced.

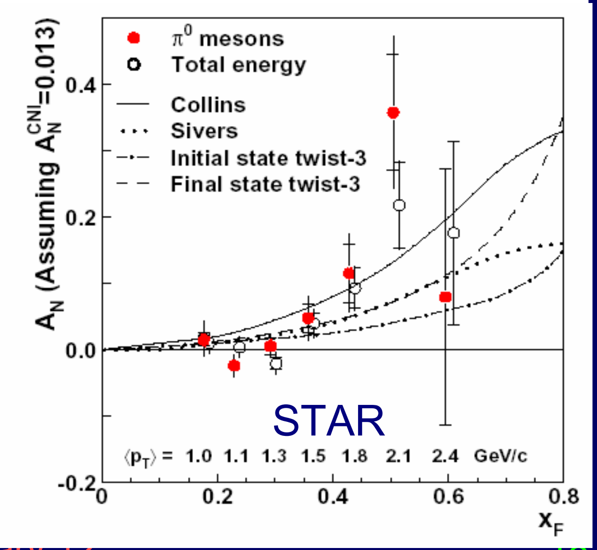
Summary pp spectra

- At RHIC we now have identified charged particle production at high rapidity to large p_T
- NLO pQCD calculations describe the pion and kaon production with fragmentation functions known as mKKP. This agreement imply a dominance of gq and gg processes at these high rapidities as was the case for the measurements of neutral pions at mid-rapidity.
- The behavior of protons around y=3 cannot be explained with NLO calculation and the abundance of protons (with respect to positive pions) at high p_T is an open question clear related to baryon transport; Protons have larger mass-scale and larger number of constituents
- Even at 62.4 GeV the NLO pQCD describes the data at high rapidity. This is surprising in view of the previous studies (Soffer). It may be related to the kinematic range studied in our data.

Single transverse Spin Asymmetry (SSA): Introduction

- Large SSAs have been observed at forward rapidities in hadronic reactions: E704/FNAL and STAR/RHIC
- SSA is suppressed in naïve parton models ($\sim\alpha_s m_q/Q$)
- Non-zero SSA at partonic level requires
  - Spin Flip Amplitude, and
  - Relative phase
- SSA: Unravelling the spin-orbital motion of partons?





Beyond Naïve Parton Models to accommodate large SSA

- Spin and Transverse-Momentum-Dependent parton distributions
  -"Final state" in Fragmentation (Collins effect),
  -"Initial state" in PDF (Sivers effect)
- Twist-3 matrix effects
  -Hadron spin-flip through gluons and hence the quark mass is replaced by Λ_{QCD}
  -Efremov, Teryaev (final state)
  -Qiu, Sterman (initial state)
- Or combination of above
  -Ji, Qiu, Vogelsang, Yuan…

Challenge to have a consistent partonic description:

-Energy dependent SSA vs. x_F, p_T,

-Flavor dependent SSA

-Cross-section

SSA measurements in $p^{\uparrow}+p = \pi/K/p + X$ at 200/62 GeV

BRAHMS measures identified hadrons (π,K,p,pbar)
in the kinematic ranges of
- $0 < x_F < 0.35$ and $0.2 < p_T < 3.5$ GeV/c at $\sqrt{s}$=200 GeV
- $0 < x_F < 0.6$ and $0.2 < p_T < 1.5$ GeV/c at $\sqrt{s}$=62 GeV for

- x_F, p_T, flavor, $\sqrt{s}$ dependent SSA
- cross-section of un-polarized hadron production
  (constraint for theoretically consistent description)

Data:

- Run-5: $\sqrt{s}$ = 200 GeV 2.5 pb^{-1} recorded (45-50% of polarization)
- Run-6: $\sqrt{s}$ = 62 GeV 0.21 pb^{-1} recorded (45-65%)

  Data from Forward Spectrometer at 2.3-4 deg. covering "high"-x_F ($0.15 < x_F < 0.6$) are presented.

Determination of Single Spin Asymmetry: A_N

- Asymmetries are defined as

$$A_N = (\sigma^+ - \sigma^-)/(\sigma^+ + \sigma^-) = \varepsilon / \mathcal{P}$$

- For non-uniform bunch intensities

$$\varepsilon = (N^+/\mathcal{L}^+ - N^-/\mathcal{L}^-) / (N^+/\mathcal{L}^+ + N^-/\mathcal{L}^-)$$
$$= (N^+ - \mathcal{L}^* N^-) / (N^+ + \mathcal{L}^* N^-)$$

where $\mathcal{L}$ = relative luminosity = $\mathcal{L}^+ / \mathcal{L}^-$

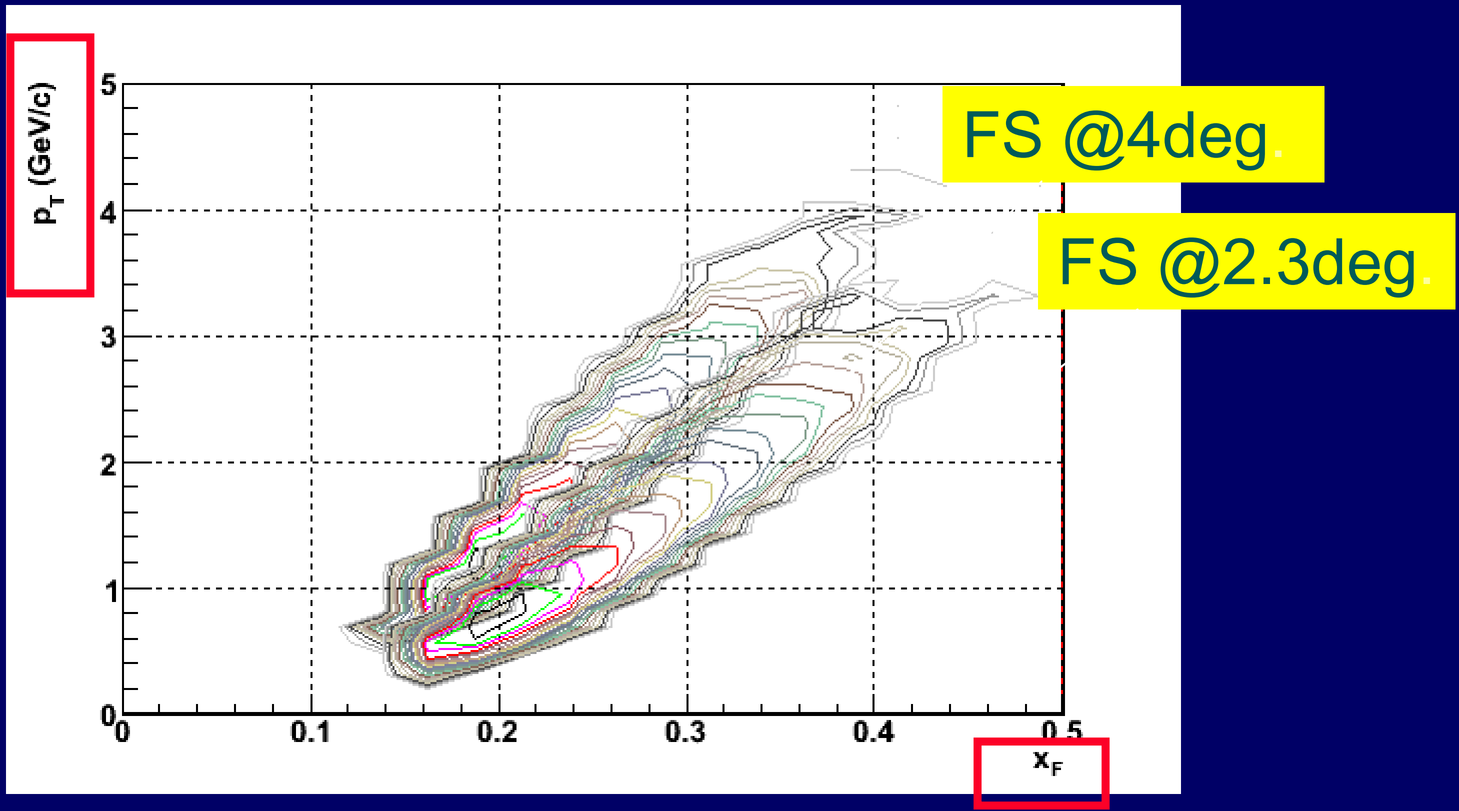
and the yield of in a given kinematic bin with the beam spin direction is N^+ (up) and N^- (down).

- Most of the systematics in N^+/N^- cancel out
- Uncertainties on relative luminosity $\mathcal{L}$ estimated to be < 0.3%
- Beam polarization $\mathcal{P}$ from on-line measurements:

systematic uncertainty of ~18%

- Overall systematic error on A_N: ~ 25%-30%

BRAHMS FS Acceptance at 2.3 deg. and 4 deg. /Full Field (7.2 Tm) at $\sqrt{s}$ = 200 GeV



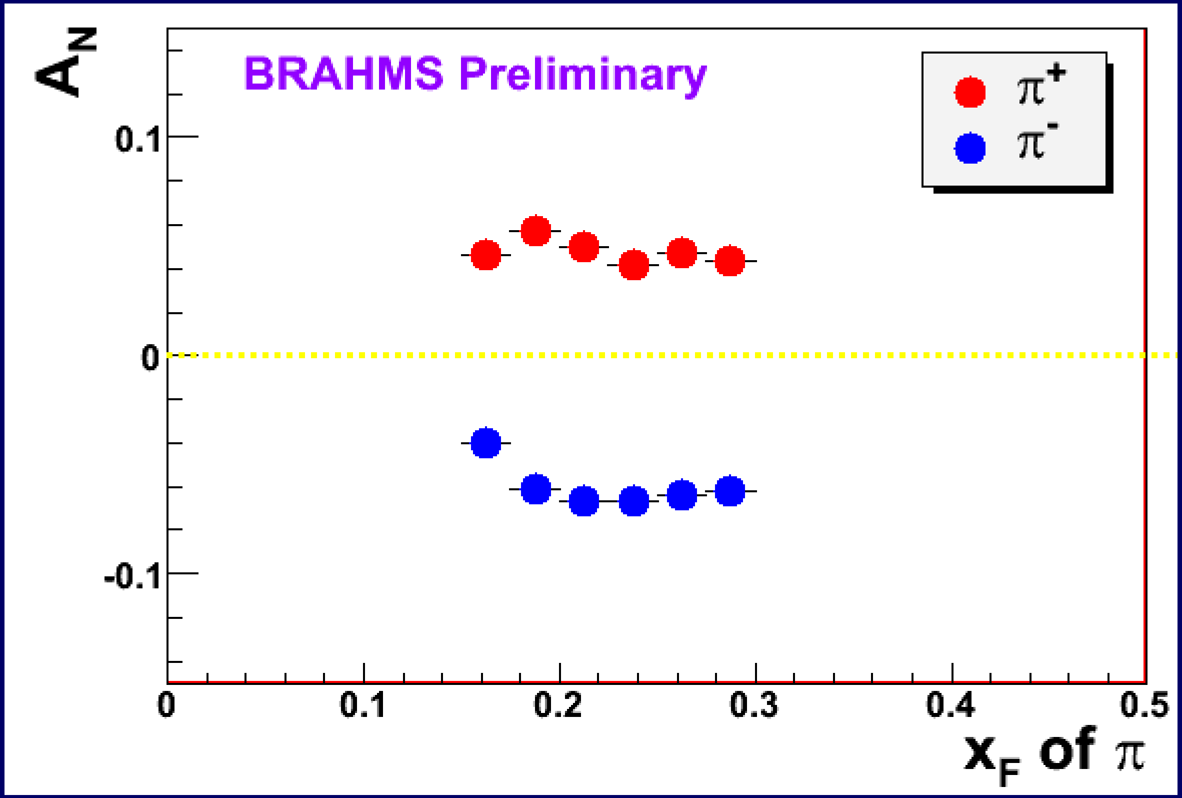
- Strong x_F-p_T correlation due to limited spectrometer solid angle acceptance

Calculations compared at the BRAHMS kinematic region

- **Twist-3 parton correlation** calculation provide by F. Yuan
  - Kouvarius, Qiu, Vogelsang, Yuan
  - "Extended" with non-derivative terms
    ("moderate" effects at BRAHMS kinematics)
  - Two flavor (*u,d*) and valence+sea+antiquarks Fits
- **Sivers effect** calculation provided by U. D'Alesio
  - Anselmino, Boglione, Leader, Melis, Murgia
  "Sivers effect with complete and consistent k_T kinematics plus description of unpolarized cross-section"

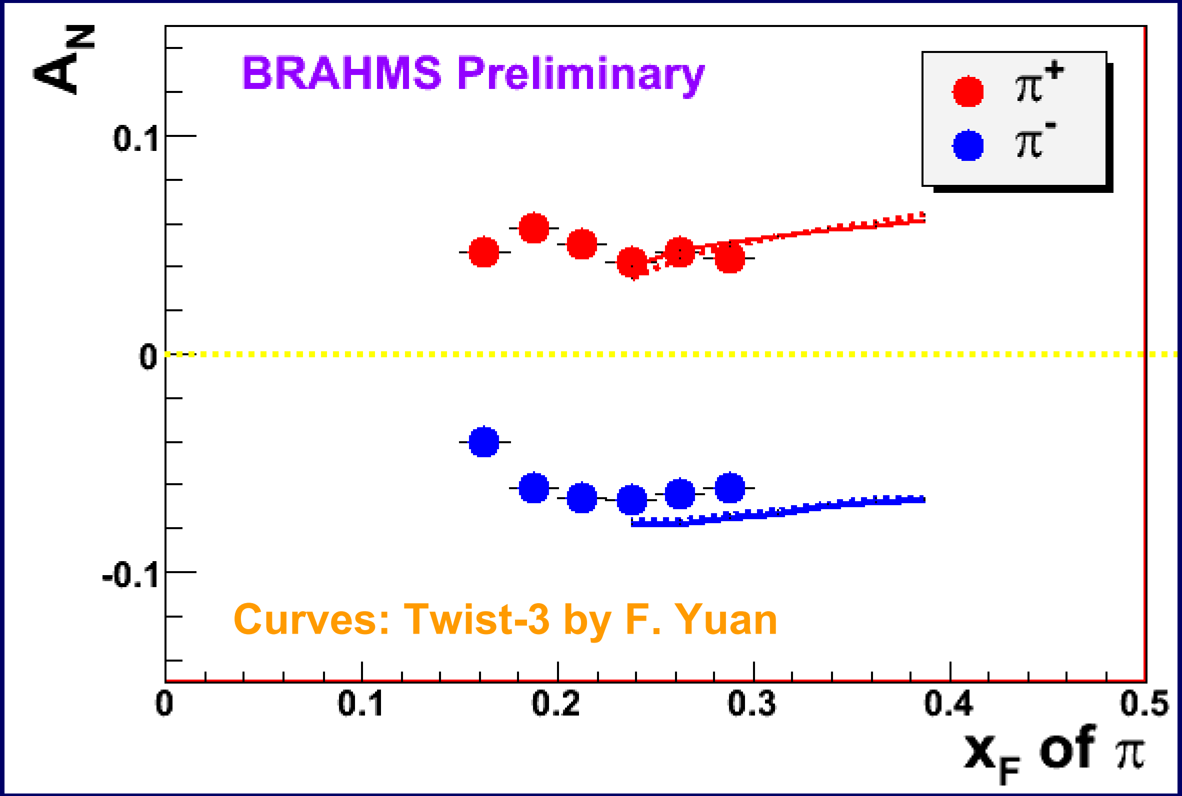
These models describe the low energy data reasonably well.

$A_N(\pi)$ at 2.3 deg. at $\sqrt{s}$ = 200 GeV



- $A_N(\pi^+)$: positive ~(<) $A_N(\pi^-)$: negative: 4-6% in 0.15 <x_F< 0.3

$A_N(\pi)$ at 2.3 deg. at $\sqrt{s}$ = 200 GeV compared with Twist-3

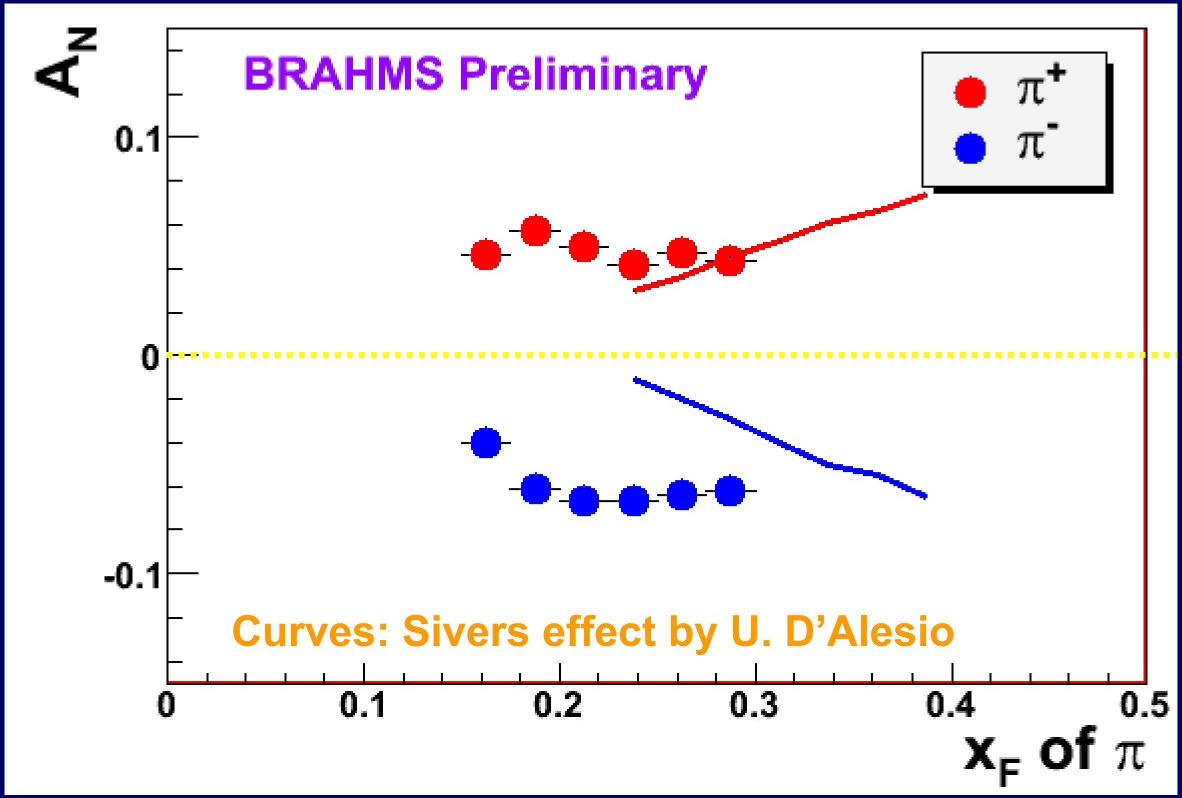


Solid lines: two-flavor (*u*, *d*) fit

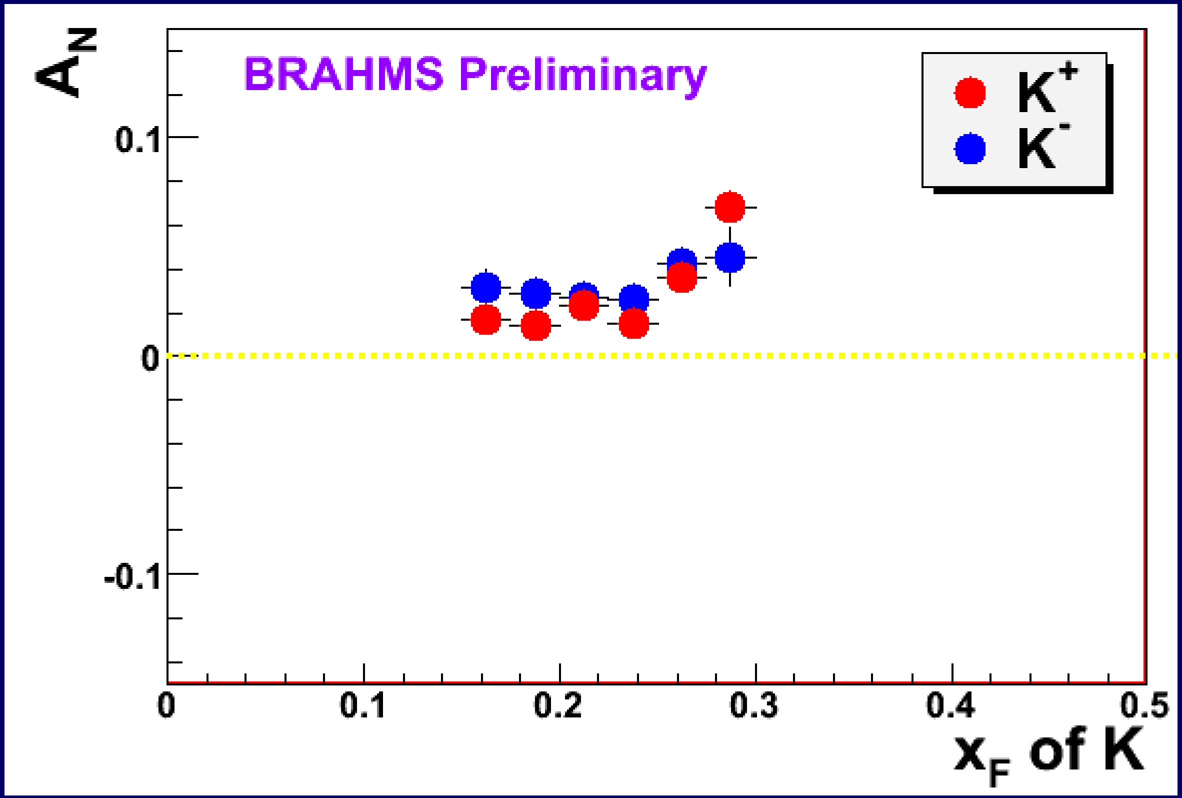
Dashed lines: valence + sea, anti-quark

Calculations done only for $\langle p_T(\pi) \rangle$ > 1 GeV/c

$A_N(\pi)$ at 2.3 deg. at $\sqrt{s}$ = 200 GeV compared with Sivers effect

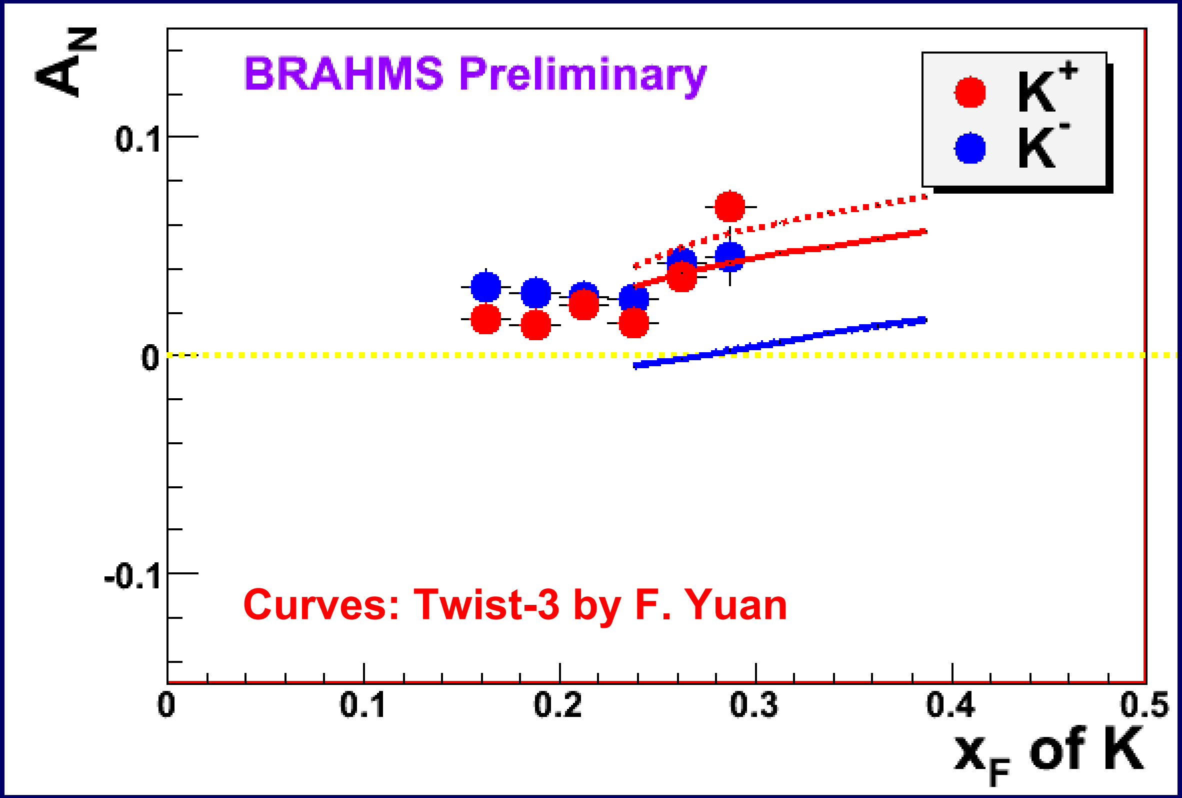


$A_N(K)$ at 2.3 deg at $\sqrt{s}$ = 200 GeV



- $A_N(K^+) \sim A_N(K^-)$: positive 2-5% for $0.15 < x_F < 0.3$
- If main contribution to A_N at large x_F is from valence quarks: $A_N(K^+) \sim A_N(\pi^+)$, $A_N(K^-) \sim 0$: disagreement with naïve expectations

A_N(K) at 2.3 deg at √s = 200 GeV compared with Twist-3

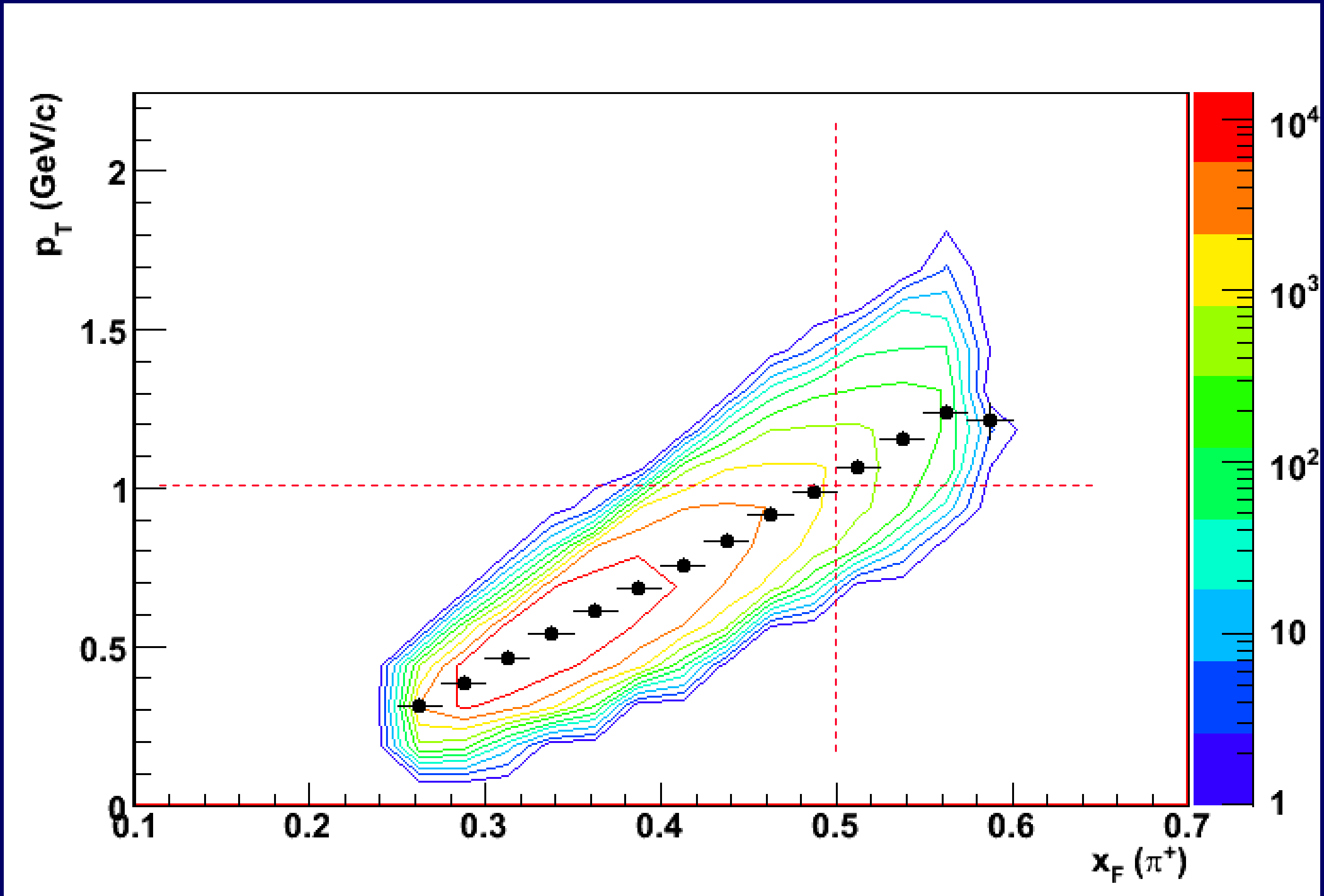


Solid lines: two-flavor (*u*, *d*) fit

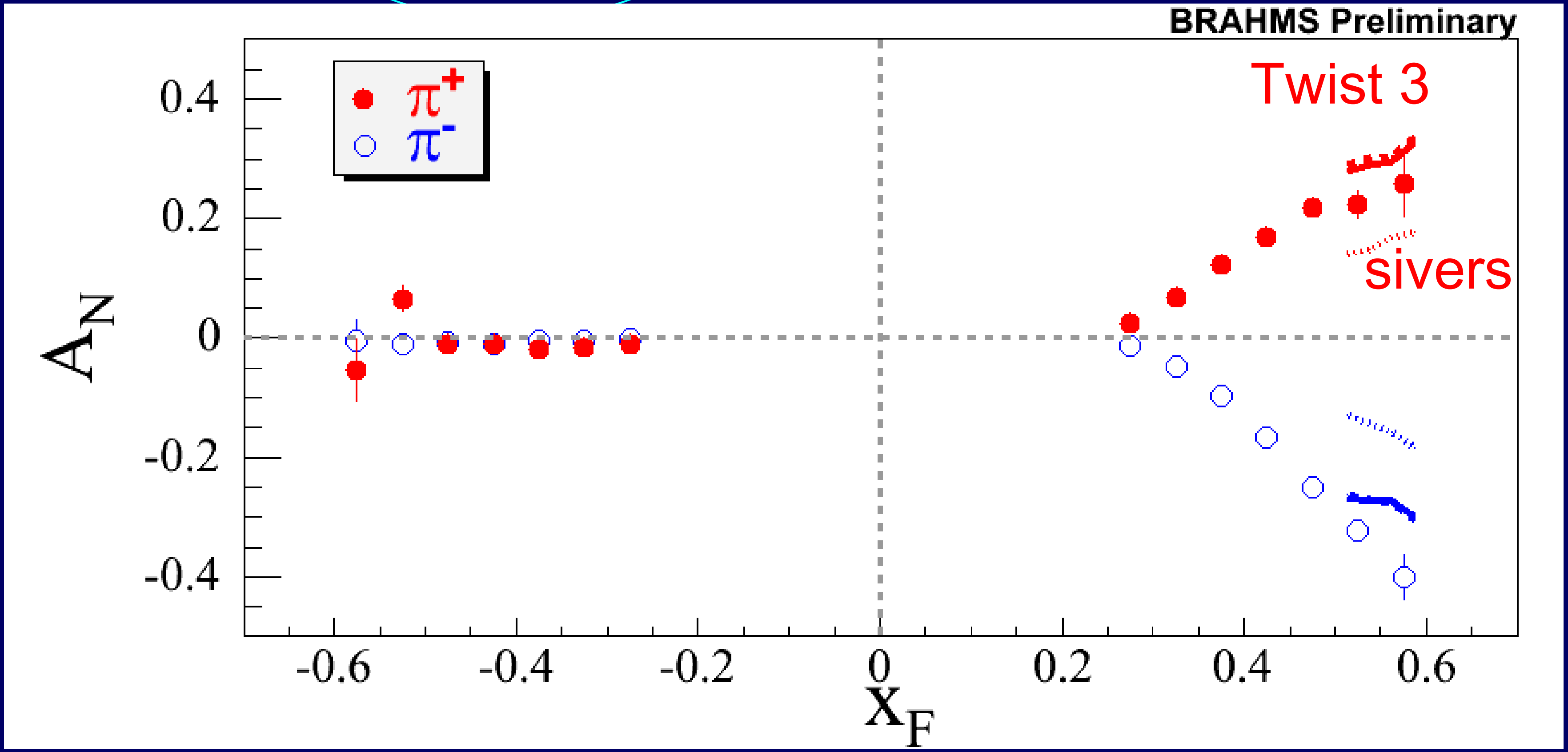
Dashed lines: valence + sea, anti-quark

Calculations done only for <$p_T(\pi)$> > 1 GeV/c

Kinematic coverage at $\sqrt{s}$ = 62 GeV (FS at 2.3 and 3 deg)

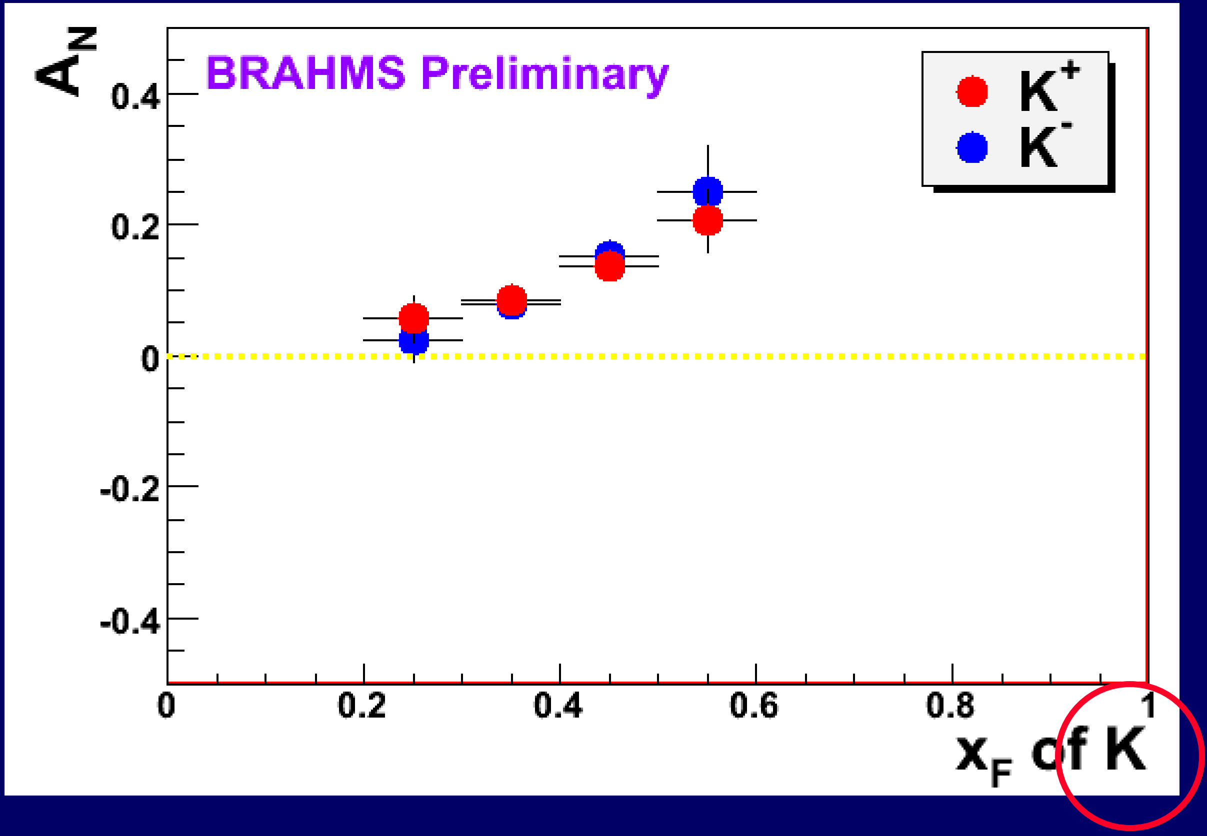


$A_N(\pi)$ at $\sqrt{s}$ = 62 GeV

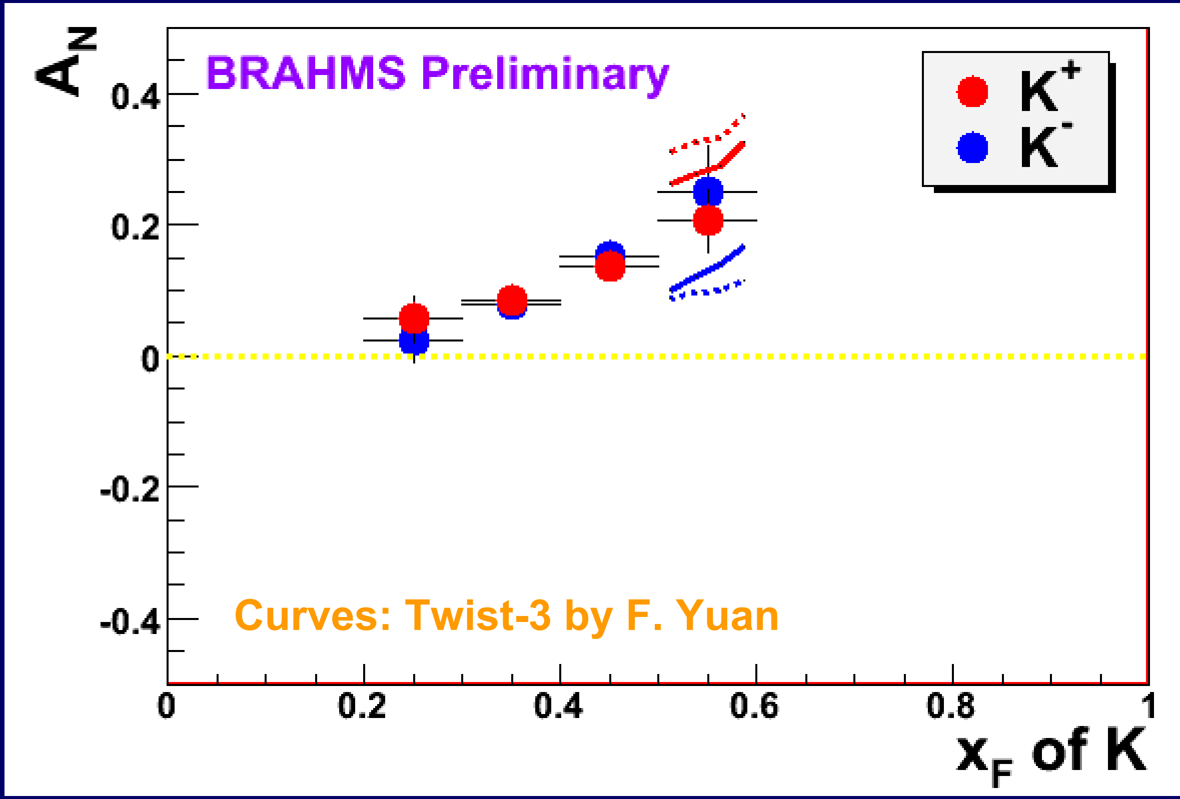


- Large $A_N(\pi)$: 40% at x_F~0.6 p_T~1.3 GeV
- Strong x_F -p_T dependence ("Alligator")
- $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F-p_T

$A_N(K)$ at $\sqrt{s}$ = 62 GeV



$A_N(K)$ at $\sqrt{s}$ = 62 GeV compared with Twist-3



Summary

BRAHMS measures A_N of identified hadrons at 62 GeV and 200 GeV

- P, K cross-section at 200 GeV described by NLO pQCD . AT 62 GeV intriguing results showing that pQCD may actaully still be valid at large y.
- **Large SSAs seen for pions and kaons**

Suggesting:

- Sivers mechanism plays an important role.
- described (qualitatively) by Twist-3
- main contributions are from leading (favored) quarks
- power-suppression $1/p_T$ set the scale

Questioning:

- where the large positive $A_N(K^-)$ come from then?
- Sea quark contributions not well understood: A_N(K-) and A_N(pbar)
- how well pQCD applicable at 62 GeV
  (cross-sections at 62 GeV will be delivered)
- what can (not) be learned from A_N at p_T < 1 GeV/c
- $A_N(-x_F) \sim 0$ set limits on Sivers-gluon contribution?
- can A_N (p, pbar) be described in the consistent framework?
- What are the theoretical uncertainties, pT ~ 1 GeV valid for QCD description?

BRAHMS Collaboration

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