TMD phenomenology and A_N in pp collisions

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Workshop on
Opportunities for Polarized Physics at FERMILAB

based on work in collaboration with
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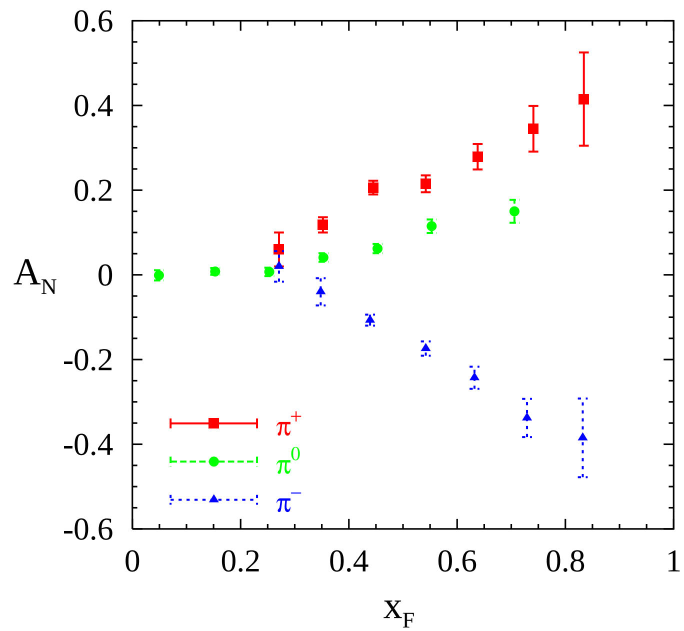
Outline

- A_N in $pp \to hX$
  - experimental status
  - theoretical approaches: Twist-3 vs. TMD approach
- TMD approach: Collins vs. Sivers effect in $pp \to h\,X$
- Access to the Sivers effect: $pp \to \mathrm{jet}\,X$ and $pp \to \gamma\,X$
- Access to the Collins effect: $pp \to \mathrm{jet}\,\pi X$
- A_N at midrapidity and the gluon Sivers function
- Conclusions

SSAs in $p^{\uparrow}p \to h\,X$

$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$ still challenging $x_F = 2p_L/\sqrt{s}$

started long time ago

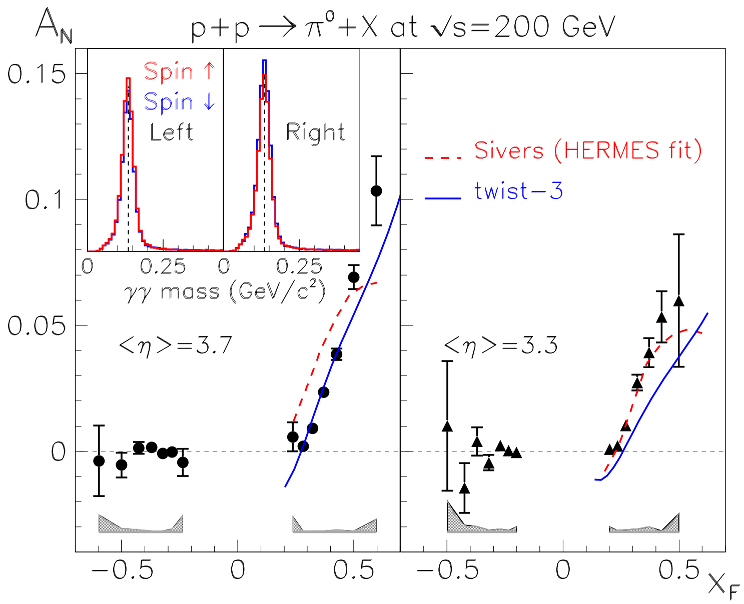


$\sqrt{s} = 20$ GeV *[E704 coll. 91]*

SSAs in $p^{\uparrow}p \to h\,X$

$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$ still challenging $\qquad x_F = 2p_L/\sqrt{s}$

confirmed at much larger energies

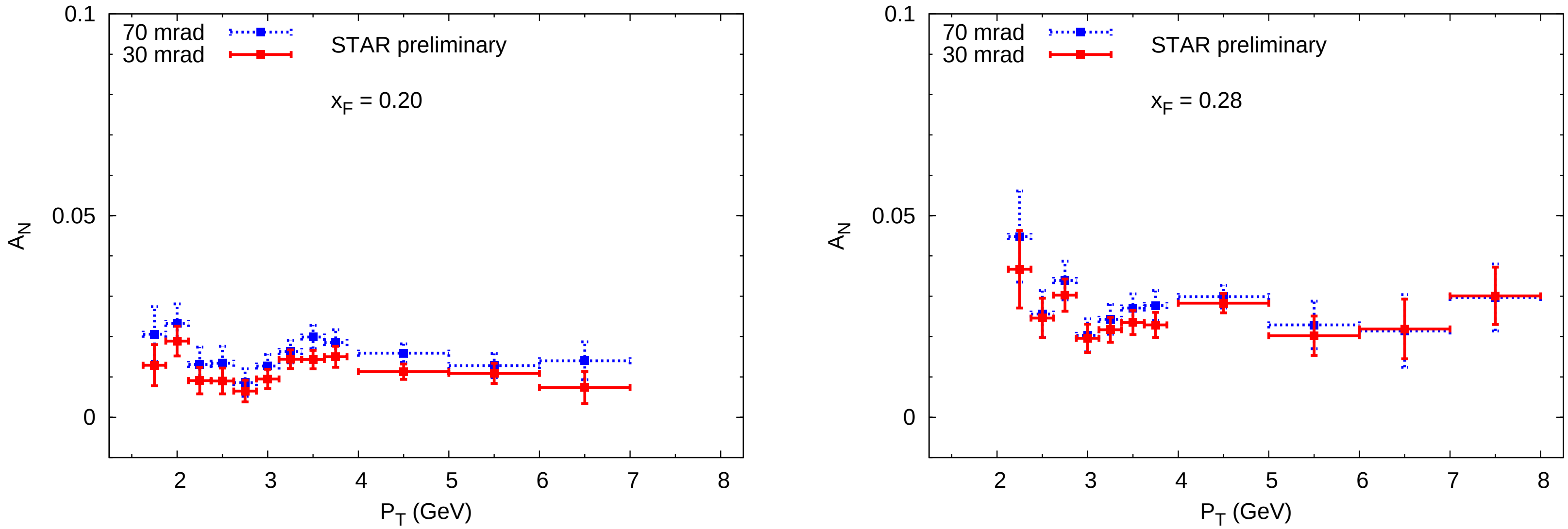


$\sqrt{s} = 200$ GeV *[STAR coll. 08]*

SSAs in $p^{\uparrow}p \to h\, X$

$A_N \equiv \frac{d\sigma^{\uparrow}-d\sigma^{\downarrow}}{d\sigma^{\uparrow}+d\sigma^{\downarrow}}$ still challenging $x_F = 2p_L/\sqrt{s}$

and at even larger energies and at large P_T



$\sqrt{s} = 500$ GeV *[STAR coll. 12]* [Preliminary]

- A_N: sizeable at large rapidity, increasing with x_F and P_T (RHIC)

- Theoretical approaches

  1. collinear pQCD factorization at twist-3:
     universal quark-gluon-quark correlators, (i.e. $T_F(x,x)$)
     [Efremov-Teryaev 82,85; Qiu-Sterman 91,92,98; Kouvaris et al. 06; Kanazawa- Koike 00,10; Kang et al. 11]

  2. Generalized Parton Model (GPM): TMD effects (*assuming* factorization)
     [Anselmino-Boglione-Murgia 95, Anselmino et al. 06; UD-Murgia 04,08; Anselmino et al. 12,13]

Motivations: phenom. point of view

- $pp \to h\, X$
  - suppression of the Collins effect REVISITED!
  - use of phenomenological information gathered from SIDIS and e^+e^- data
    potential role of Collins and Sivers effects in A_N in $pp \to \pi\, X$
  - sign mismatch issue
    Twist-3 qgq-correlation funct. from SIDIS Sivers funct.: wrong sign in A_N
- other final states (jet, γ, pion-jet)
  - disentangling Collins and Sivers effects and approaches
  - study of universality-breaking effects
- A_N at mid-rapidity: role, if any, of the gluon Sivers function

Twist-3 approach

Three contributions to A_N (schematic view) large x_F

$\Phi^{(3)}_{q/p^\uparrow} \otimes \; f_{q/p} \;\; \otimes \sigma \;\; \otimes D_{h/q}$ ✓ able [★] to describe A_N (FIT) *[Kouvaris et al. 06]*

$\Delta_T q \;\; \otimes \Phi^{(3)}_{q^\uparrow/p} \otimes \sigma' \otimes D_{h/q}$ ✓ negligible *[Kanazawa-Koike 00]*

$\Delta_T q \;\; \otimes f_{q/p} \;\; \otimes \sigma'' \otimes D^{(3)}_{h/q^\uparrow}$ **?** under study *[Kang-Yuan-Zhou 10, Metz-Pitonyak 12]*

Notice:

- $\Phi^{(3)}_{q/p^\uparrow} \to T_F(x,x)$ Efremov-Teryaev-Qiu-Sterman correlation function

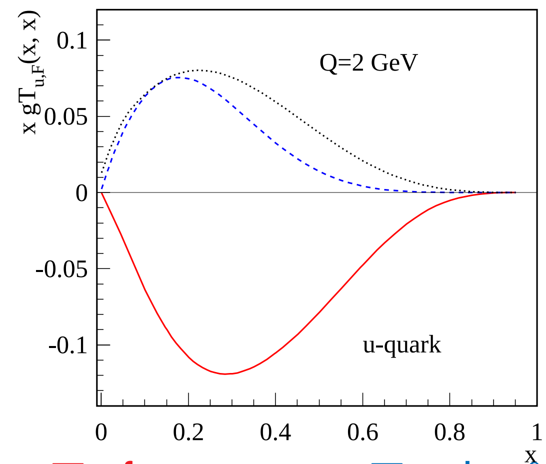
★ Correction of an overall sign in the definition of gT_F *[Kang et al. 11]*

The sign mismatch issue

Link between Sivers and ETQS functions *[Boer-Mulders-Piljman 03]*

$$\int d^2\boldsymbol{k}_\perp \Big(\frac{\boldsymbol{k}_\perp^2}{M}\Big) f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)|_{\rm SIDIS} = -g\, T_F(x,x)$$

★ sign mismatch in A_N (if only T_F!)
[Kang et al. 11]



T_F from pp vs. T_F via $f_{1T}^\perp$

Solutions:
- node in x *[Kang-Prokudin 12]* and/or in $k_\perp$ (likely ruled out)
- TMD evolution and $k_\perp$ spreading
- study of A_N in $lp \to l'X$ via $q\gamma q \Longleftrightarrow qgq$ correlators *[Metz et al. 12]*
- additional and LARGE twist-3 effects (fragmentation sector)? *[Metz-Pitonyak 12]*

still an open an intriguing issue!

TMD approach

Many contributions from nonplanar partonic kinematics (helicity formalism)

[Anselmino et al. 06]

$\Delta^N f_{q/p^\uparrow} \otimes \quad f_{q/p} \quad \otimes \sigma \quad \otimes D \cos\phi_q$ Sivers funct. $(f_{1T}^\perp)$

$\Delta_T q \quad \otimes \Delta^N f_{q^\uparrow/p} \otimes \sigma' \otimes D_{h/q} \cos\psi'$ Boer-Mulders funct. $(h_1^\perp)$

$\Delta_T q \quad \otimes \quad f_{q/p} \quad \otimes \sigma'' \otimes \Delta^N D_{h/q^\uparrow} \cos\psi''$ Collins funct. $(H_1^\perp)$

plus others and plus contributions from gluon TMDs

$\otimes$: convolutions on x, $\boldsymbol{k}_\perp$; ψ's *complicate* calculable azimuthal phases

Only Sivers and Collins effects survive under integration over angular depend.s

Let's consider separately the Collins and Sivers effects

Collins effect (revisited)

original claimed suppression due

- to wrong sign in the spin transfer for $qg \to qg$: one of the most important channels

- to relative cancelation with other channels: $qq \to qq$ and $q\bar{q} \to q\bar{q}$.

Role of intrinsic azimuthal phases: relevant but not totally suppressing

$\Rightarrow$ a new *realistic* reanalysis

[Anselmino-Boglione-UD-Leader-Melis-Murgia-Prokudin 12]

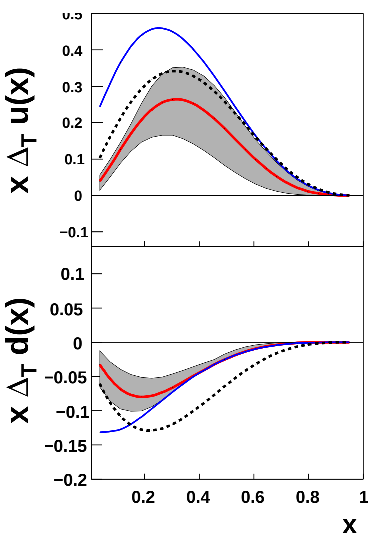
Phenomenology of the Collins effect

- use of available information on the Collins effect from SIDIS and e^+e^- data

- global fit not worth at this stage (non separable effects in pp)

- universality of the Collins function *[Collins-Metz 04, Yuan 08]*

- $\Delta_T q$ not constrained at large x (SIDIS data $x \leq 0.3$) impact on A_N at large x_F



Present status - large errors

large x behaviour $\simeq (1-x)^\beta$ with

1. $\beta = 4.74 \pm 5.45$ *[Anselmino et al. 07]*
2. $\beta = 0.84 \pm 2.30$ *[Anselmino et al. 09]* $\Leftarrow$
3. $\beta = 3.64^{+5.80}_{-3.37}$ *[Anselmino et al. 13]*

Large-x behaviour of the transversity

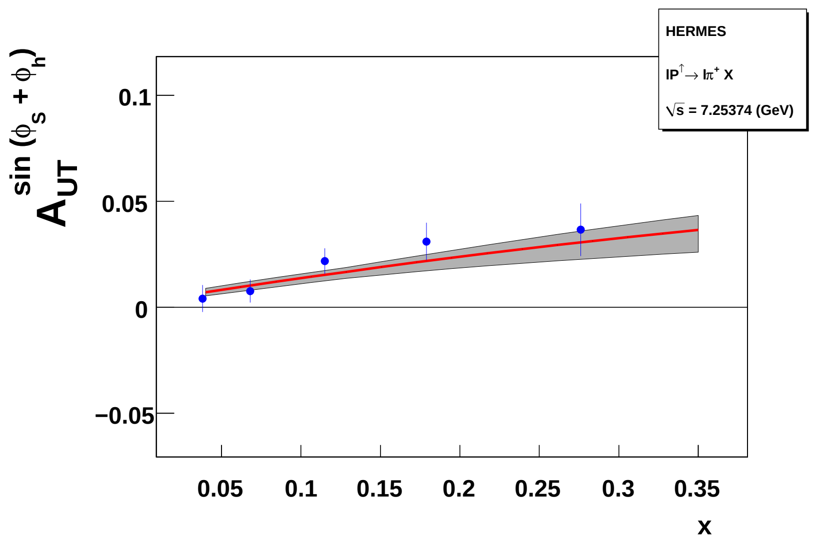
$$\Delta_T q(x, k_\perp) \simeq N_q^T \, x^{\alpha_q} \, (1-x)^{\beta_q} \, \frac{[q(x) + \Delta q(x)]}{2} \, g(k_\perp) \qquad q = u, d$$

- use of isospin symmetry + only favoured and disfavoured FFs
- flavour independent parameters except β_q
- proper evolution for $\Delta_T q$, DGLAP for $\Delta^N D$
- 9 parameters to be fitted: ... $\beta_u, \ \beta_d$ ...

Scan Procedure

I step

1. 9-parameter reference fit on SIDIS (HERMES, COMPASS) and e^+e^- (Belle) data
2. grid (scan) of the parameters, β_u, β_d within the range (0.0–4.0)
3. 7-parameter fit to SIDIS and e^+e^- data adopting the β_q-grid
4. selection via $\chi^2_{\rm scan} \leq \chi^2_{\rm min} + \Delta\chi^2|_{\rm ref.fit}$ (stat. uncert. band) [fulfilled by all fits]
5. computation of Collins pion SSA for pp collisions

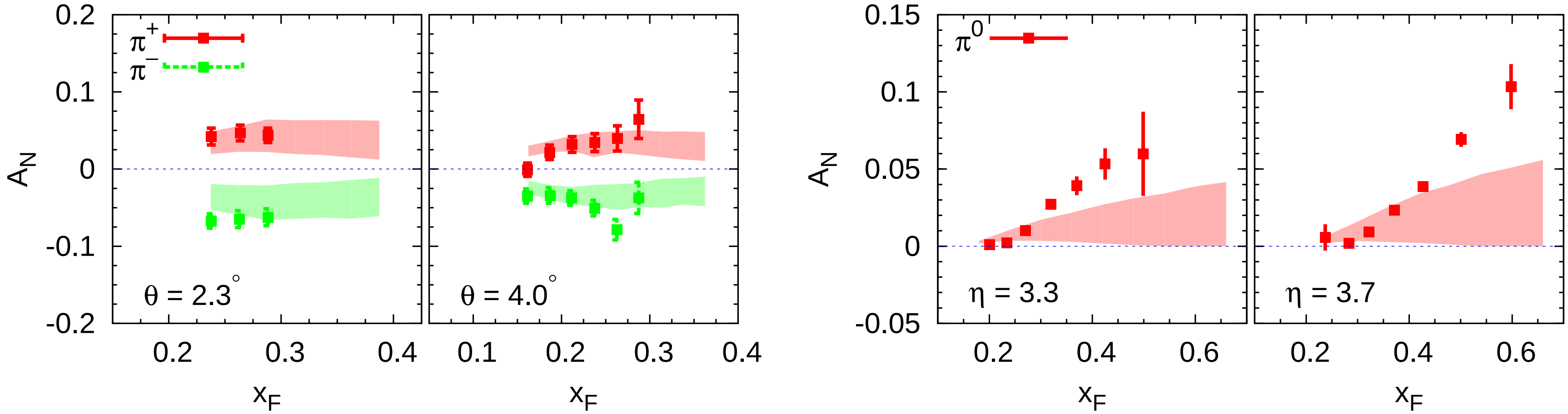


example of the fit with β fixed:
scan band on HERMES π^+ data

Results

Collins contribution

Envelope curves (scan band)



BRAHMS@RHIC 2007 $\sqrt{s} = 200$ GeV *STAR@RHIC 2008*

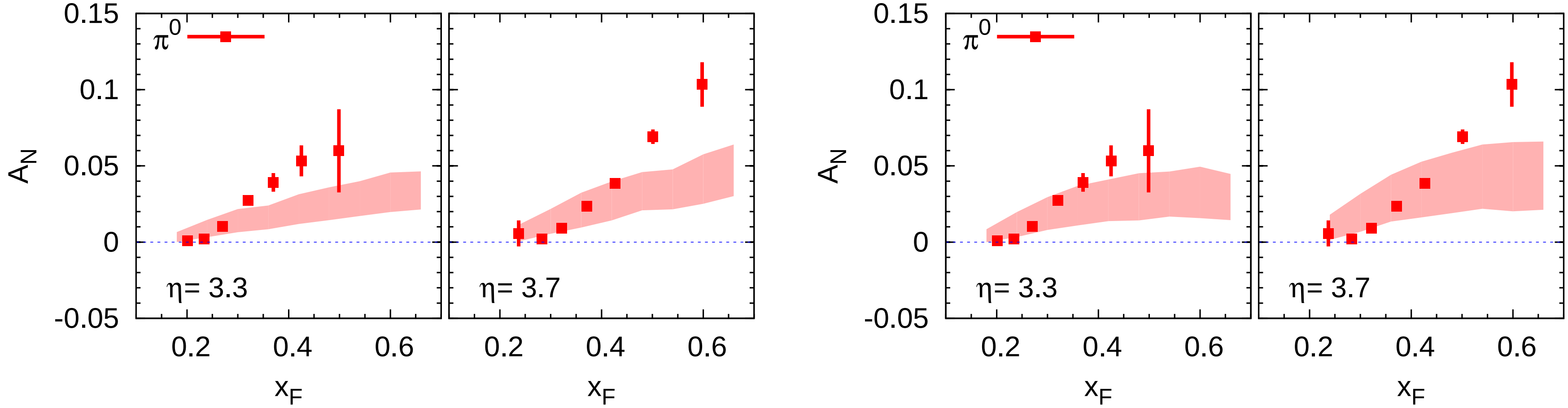
able to describe A_N for charged pions, but not the large-x_F neutral pion SSA data

II step: further tests

1. best curve within the scan and computation of its statistical error band (π^0-STAR)
2. allowance for full flavour dependence and back to step I (13-parameter fit)
3. also tried: a transversity-like evolution for the Collins function (not relevant)

Statistical uncertainty bands

Collins contribution



flavour-independent par. free parameters

$\nexists$ a single curve *good* at low and large x_F

Same conclusions for E704 data at $\sqrt{s} = 20$ GeV

Collins effect: conclusions

- The Collins effect, corrected, is sizeable
  1. able to reproduce the low x_F RHIC data.
  2. not sufficient at large x_F, where A_N increases
- Additional mechanisms are required: the Sivers effect?

Let's consider it along the same lines

Phenomenology of the Sivers effect

- universality and TMD evolution of the Sivers function...open issues
  - no proof of a TMD factorization for $pp \to hX$
  - its twist-3 counterpart gives sizeable A_N but wrong in sign
  - including Initial-final interactions results into a "wrong" sign [*Gamberg-Kang 11*]
  - ansatz...same Sivers functions as in SIDIS

- use of available information on the Sivers effect from SIDIS data
  - $\Delta^N f_{q/p^\uparrow}$ not constrained at $x \geq 0.3$ (SIDIS) $\to$ impact on A_N at large x_F
  - large-x behaviour $\simeq (1-x)^\beta$ with
    1. $\beta = 0.53 \pm 3.58$ *[Anselmino et al. 07]*
    2. $\beta = 3.46^{+4.87}_{-2.90}$ *[Anselmino et al. 09]*

A preliminary study based on fit (1) gave very encouraging results in $pp \to \pi X$ *[Boglione-UD-Murgia 08]*

Again, explore the large-x behaviour of the Sivers function

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) \simeq 2 N_q^S \, x^{\alpha_q} \, (1-x)^{\beta_q} \, f_{q/p}(x, k_\perp) \, h(k_\perp/M)$$

- DGLAP evolution for $\Delta^N f$ [TMD ansatz]

- focus on the valence region: sea Sivers functions set to zero

7 parameters to be fitted: ... $\beta_u, \; \beta_d$ ...

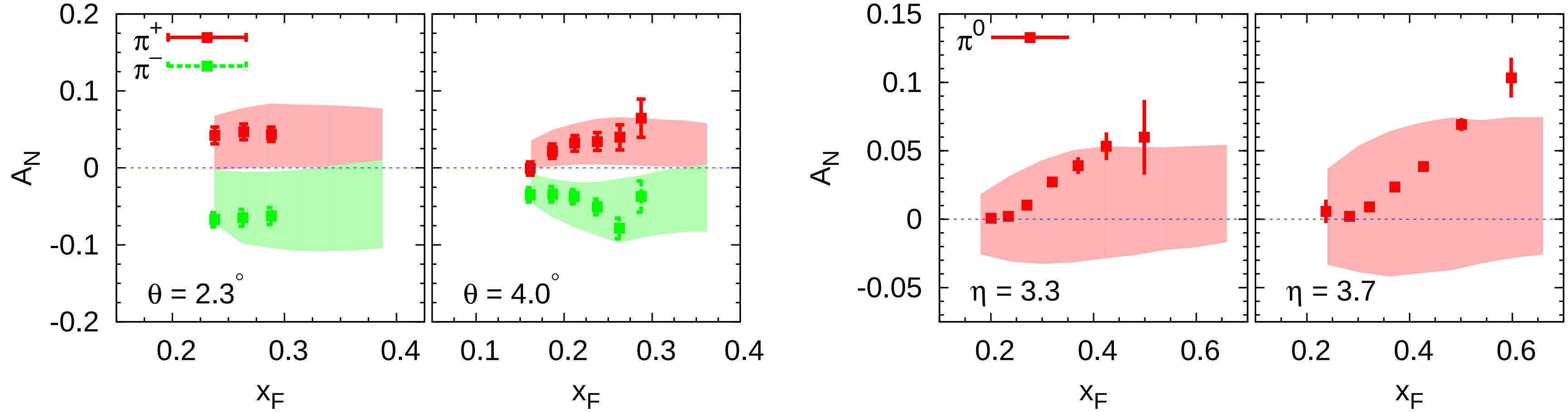
Scan Procedure

1. 7-parameter reference fit on SIDIS (HERMES, COMPASS) data
2. grid (scan) of the parameters, β_u, β_d within the range (0.0–4.0)
3. 5-parameter fit to SIDIS data adopting the β_q-grid
4. selection via $\chi^2_{\rm scan} \leq \chi^2_{\rm min} + \Delta\chi^2|_{\rm ref.fit}$ (stat. uncert. band) [fulfilled by all fits]
5. computation of Sivers SSA for pp collisions

[Anselmino-Boglione-UD-Melis-Murgia-Prokudin 13]

Results

Sivers contribution



BRAHMS@RHIC 2007 $\sqrt{s} = 200$ GeV *STAR@RHIC 2008*

Envelope curves (scan band)

able to describe A_N for charged pions, as well as the large-x_F neutral pion SSA data

I remark about Collins vs. Sivers effect in SSAs for neutral pion production

- the Collins effect suffers from 2 possible cancellations:
  1. opposite sign between u and d quark transversity distributions
  2. opposite sign between fav. and disfav. Collins FFs [$\pi^0 = (\pi^+ + \pi^-)/2$]

- the Sivers effect suffers only 1 possible cancellation:
  1. opposite sign between u and d flavours in the distribution sector

II remark

- full understanding:

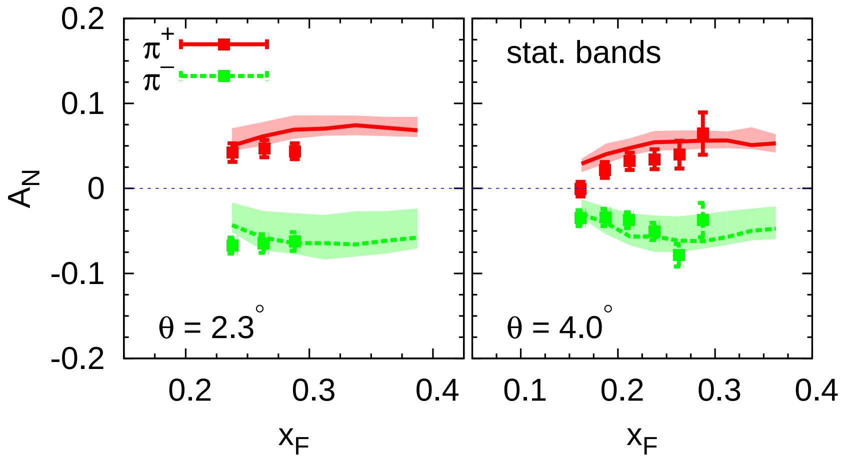
overall fit of SIDIS, e^+e^- and A_N data with Collins and Sivers effects [premature]

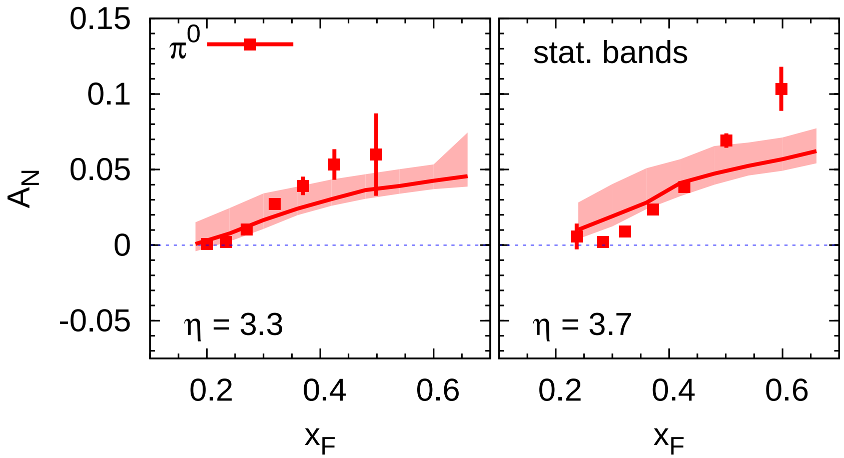
- a pragmatic view: look for a set among the Sivers scan able to describe the data

- we found more than one...and we computed its statistical error band

Results II

Sivers contribution

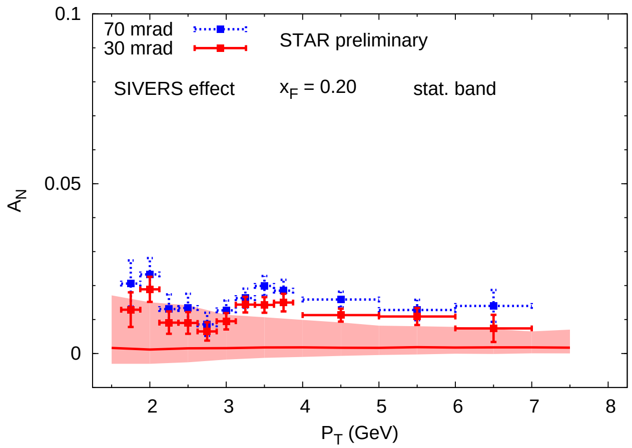


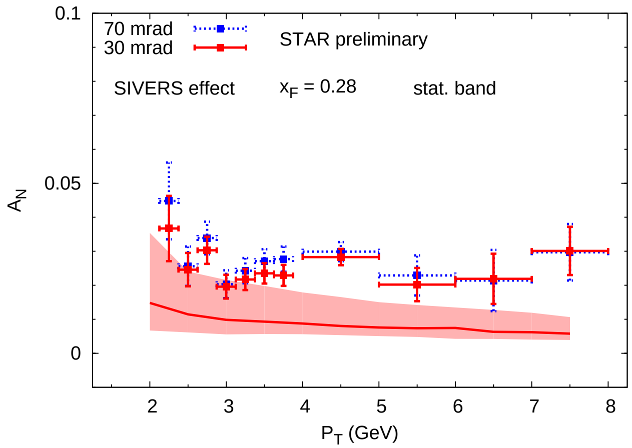


BRAHMS@RHIC 2007 $\sqrt{s} = 200$ GeV *STAR@RHIC 2008*

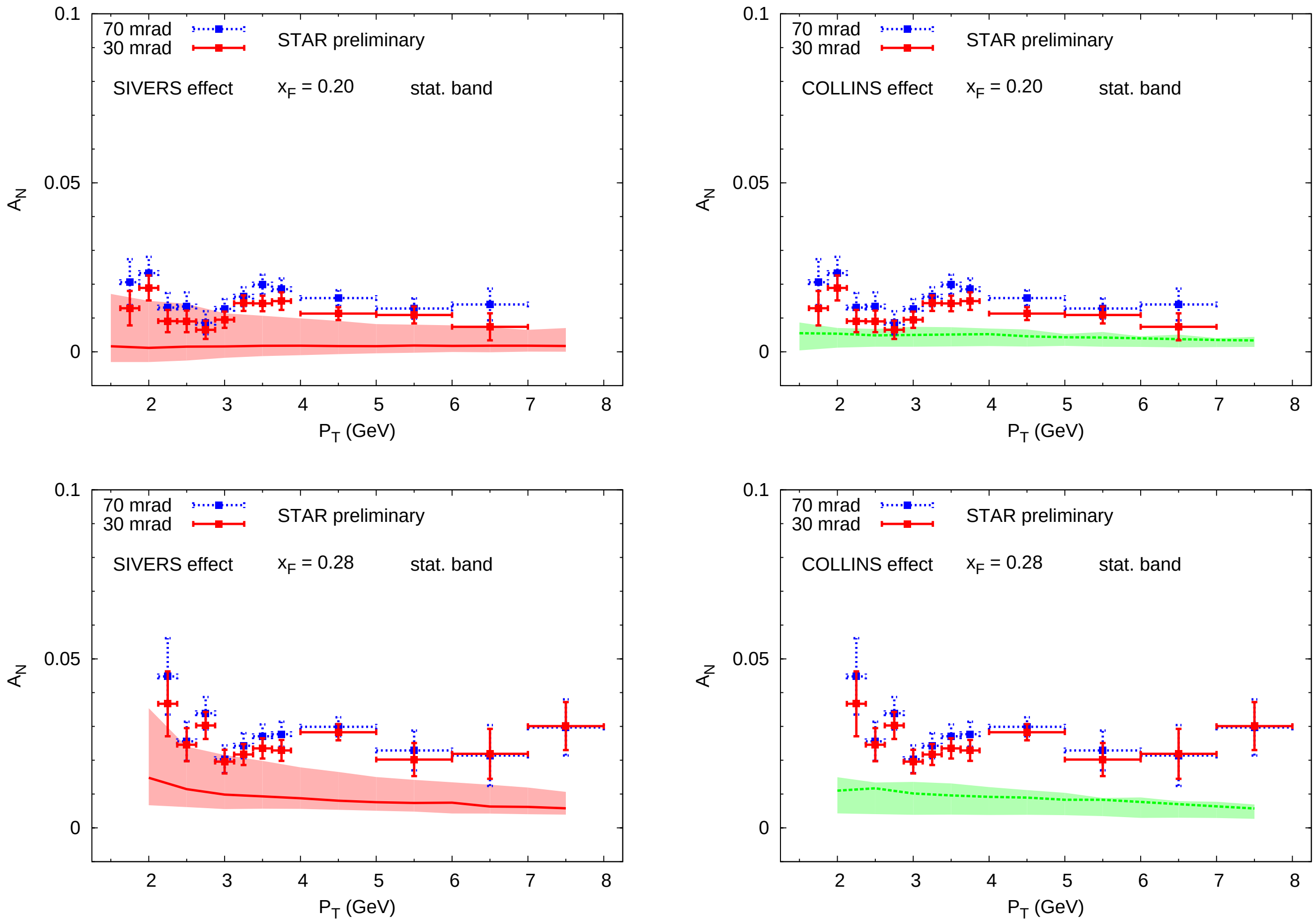
Best fit and statistical error band

An what about the latest *flat* STAR SSA data at 500 GeV and very large P_T?





Smaller but compatible trend



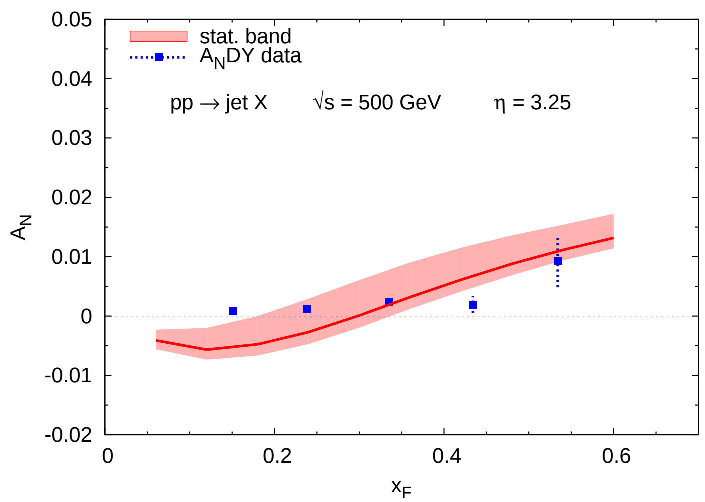
Smaller but compatible trend...same for the Collins effect

Caution! large P_T: evolution? larger $\langle k_\perp^2 \rangle$?...further study needed!

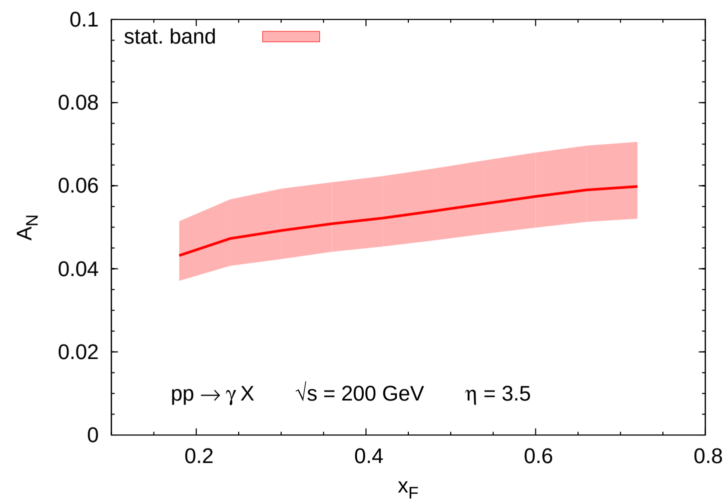
Access to the Sivers effect: $pp \to \text{jet}\, X$ and $pp \to \gamma\, X$

- in a TMD approach only the Sivers effect could play a role

- predictions (from the *optimal* Sivers function set) *[Anselmino et al. 13]*



$pp \to \text{jet}\, X$ - A_NDY data

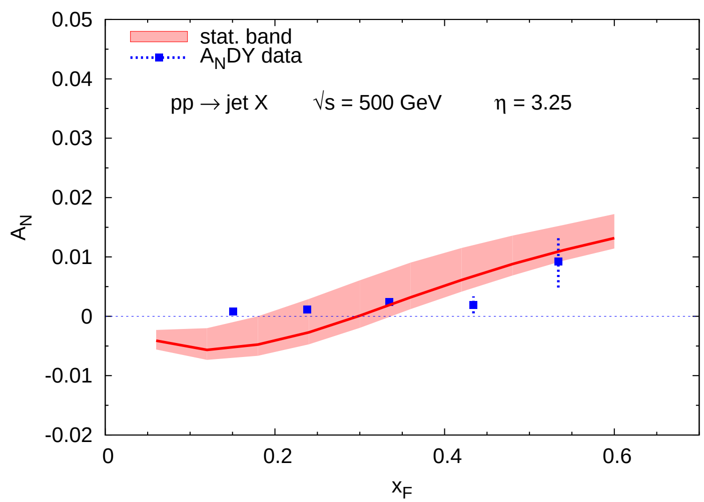


$pp \to \gamma\, X$

Access to the Sivers effect: $pp \to \text{jet}\, X$ and $pp \to \gamma\, X$

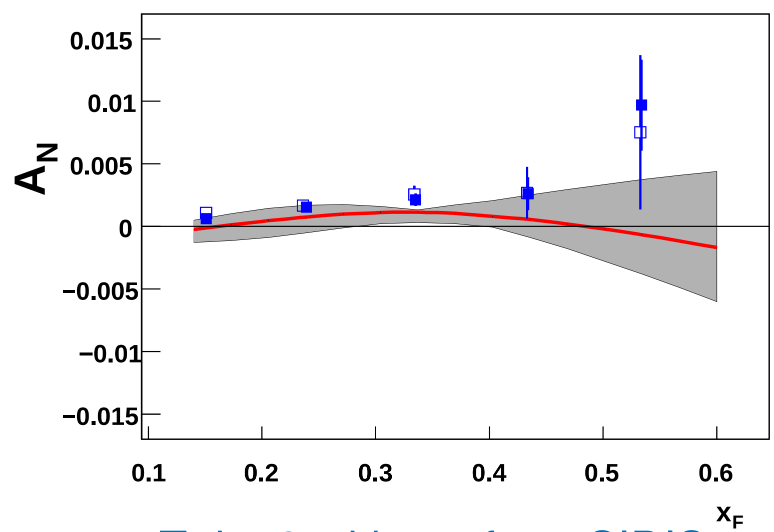
- comparison between TMD and (*indirect*) Twist-3 calculations

- indication of a process dependence ???



Sivers effect

[Anselmino et al. 13]



Twist-3 with T_F from SIDIS

[Gamberg-Kang-Prokudin 13]

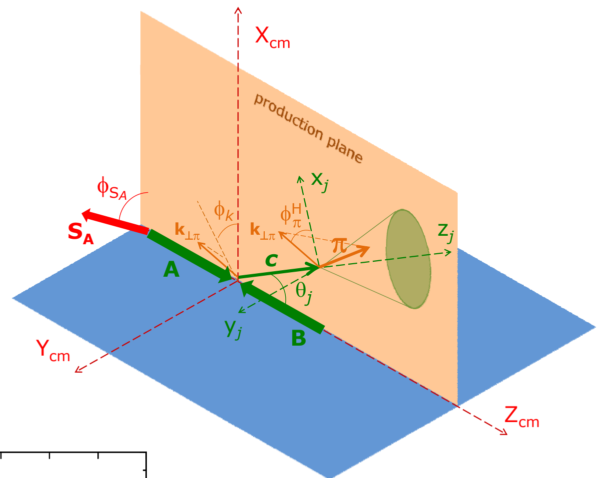
Notice: Sivers effect: stat. band; Twist-3 calculation: scan band

Access to the Collins effect: $pp \to \mathrm{jet}\,\pi\,X$

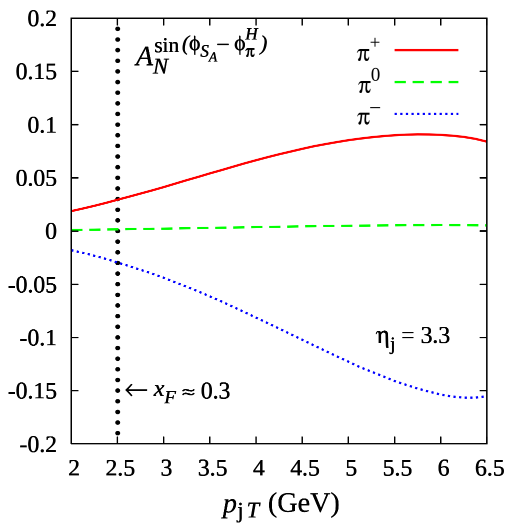
- $A_N \sim \cdots + \Delta_T q \otimes \Delta^N D_{\pi/q^\uparrow} \sin(\phi_S - \phi_\pi^H)$

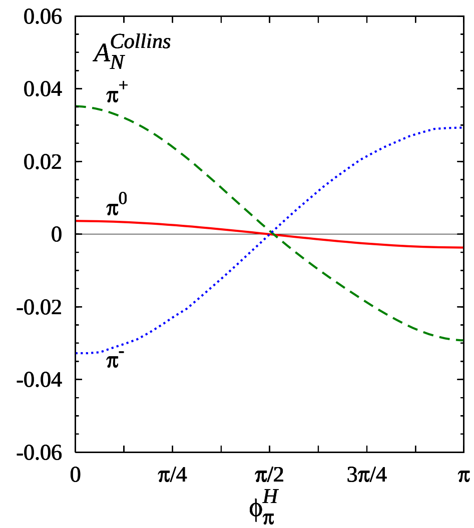
azimuthal distribution of pions inside a jet

[Yuan 08, UD-Murgia-Pisano 11]



At variance with the inclusive process $pp \to \pi X$, here TMD effects ARE separable (like SIDIS)





strong cancelation for π^0 SSA (consistent with preliminary STAR data)

A_N at midrapidity: the gluon Sivers function

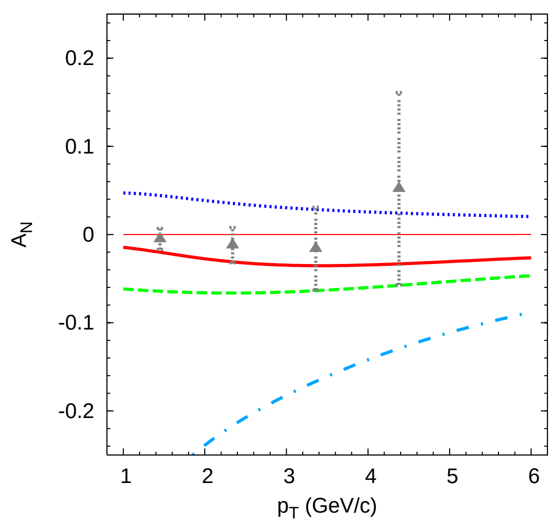
in a TMD approach for $pp \to \pi\, X$

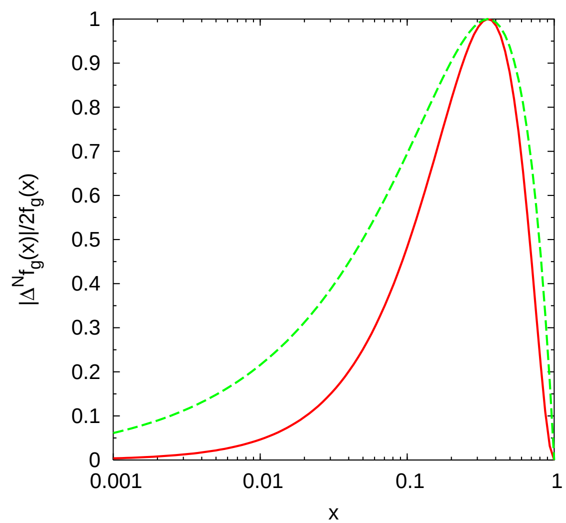
- only the Sivers effect and gluon (sea quark) contr.s could play a role

$\to$ constraint on the gluon Sivers function *[Anselmino-UD-Melis-Murgia 06]*

Strategy:

- use of PHENIX data *[Adler et al. 05]*
- no information on the sea quark contribution: saturated to their bounds

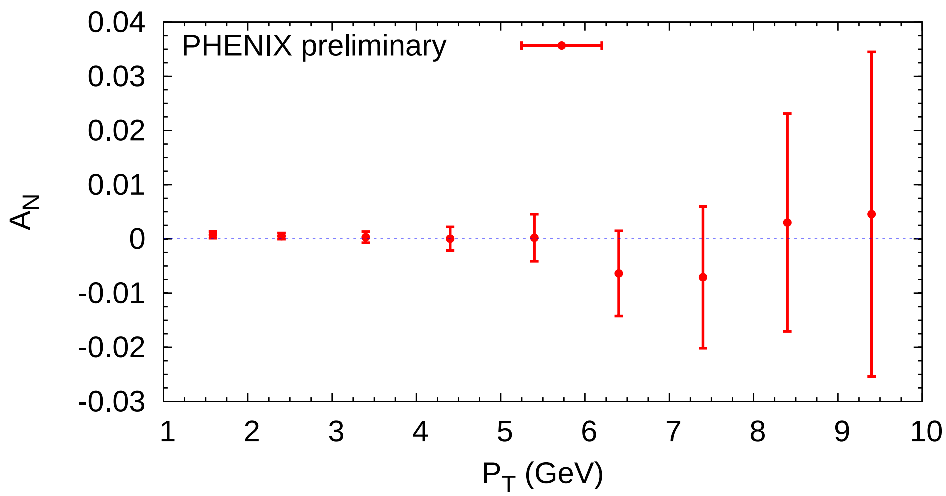




Updated analysis [preliminary]

[UD-Murgia-Pisano 13]

- use of new PHENIX data on π^0 *[Koster PhD thesis 10]*



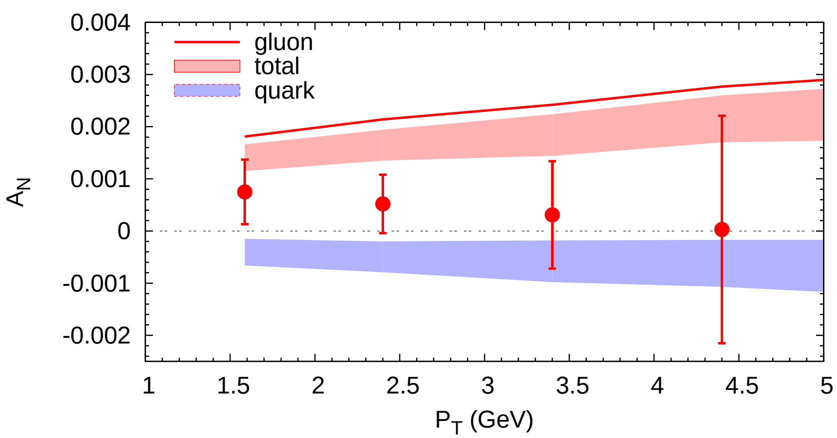
A_N compatible with zero:
- No valence quark contribution
- if no sea quark contr. $\rightarrow$
vanishing gluon Sivers funct. (node?)

A more conservative strategy: let's focus on the small p_T region (small errors)

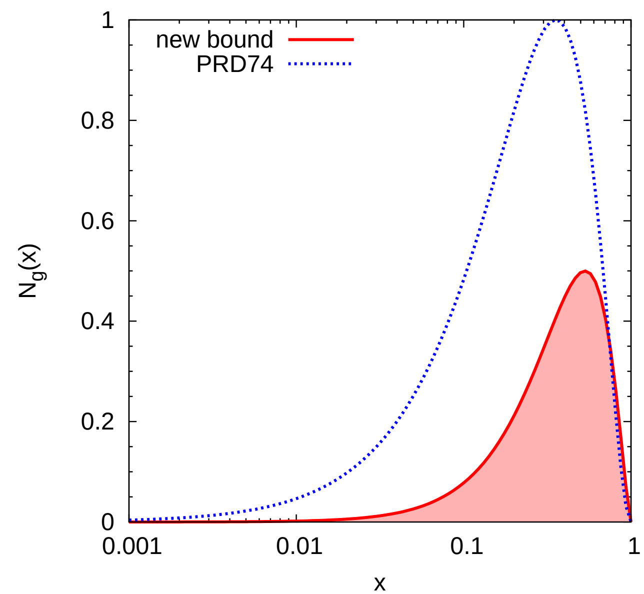
Updated analysis [preliminary]

[UD-Murgia-Pisano 13]

- use of information on the sea quark contr.n (stat. band from SIDIS)
- new upper bound for the gluon Sivers function ($\simeq$ one-σ)



$A_N(pp \to \pi^0\, X)$



$\Delta^N f_{g/p^\uparrow}/2f_{g/p}$

Updated analysis [preliminary]

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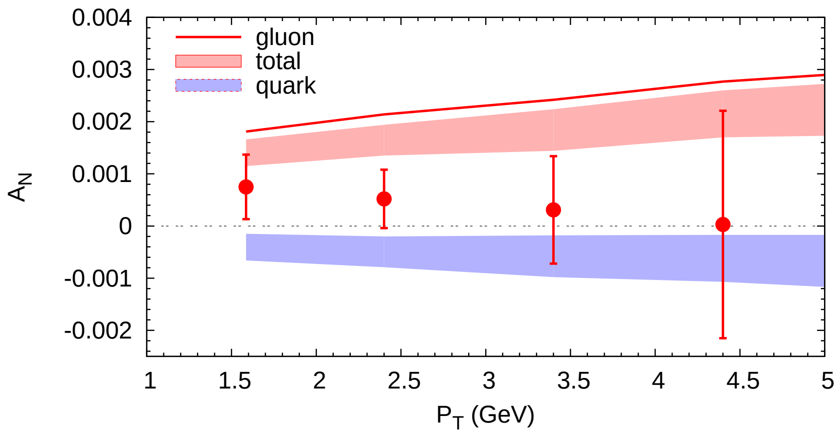
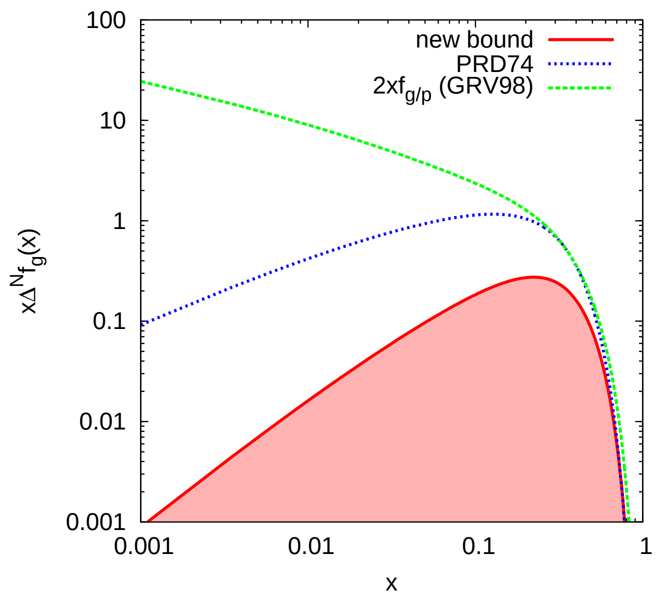




$A_N(pp \to \pi^0\, X)$

$\Delta^N f_{g/p^\uparrow}$ vs. $2 f_{g/p}$

Conclusions

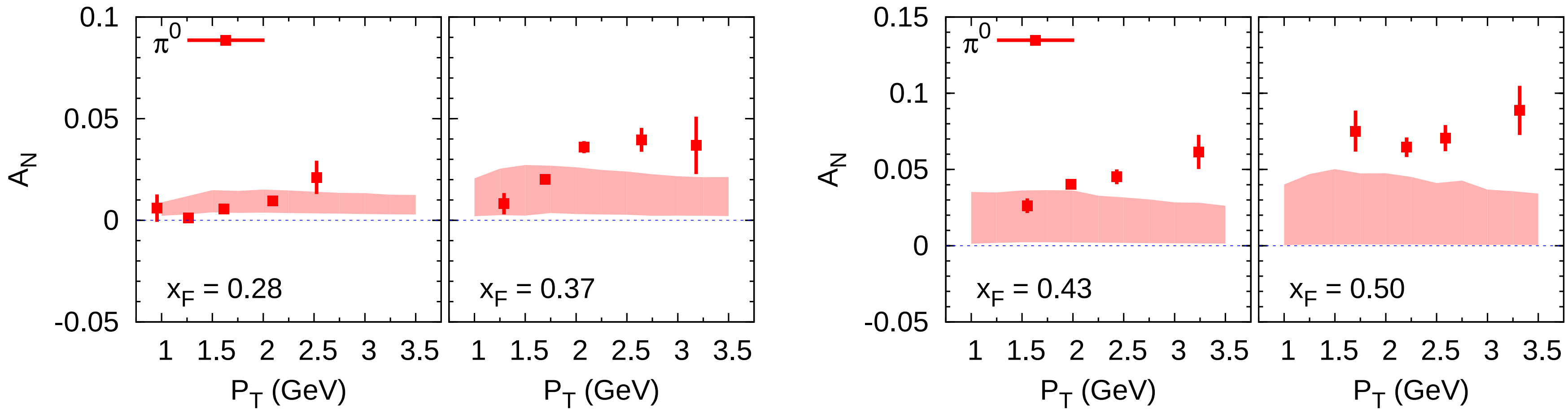
- SSAs in $pp \to hX$: still challenging from the phenom. point of view
- TMD and twist-3 approaches: both need further attention and work

- Study of A_N within a TMD scheme (assuming universality)
  - two effects could play a role in $pp \to hX$: the Collins and the Sivers effects
  - careful use of the information from SIDIS data unconstrained large x region
    1. the Collins effect: ok ONLY at low x_F
    2. the Sivers effect: ok over the most pion data in size and sign
    3. $pp \to \mathrm{jet}(\gamma)\, X$: access to the Sivers effect and disentangling approaches
    4. $pp \to \mathrm{jet}\, \pi\, X$: access the Collins effect in pp collisions

- A_N in $pp \to \pi\, X$ at midrapidity: access to the gluon Sivers function

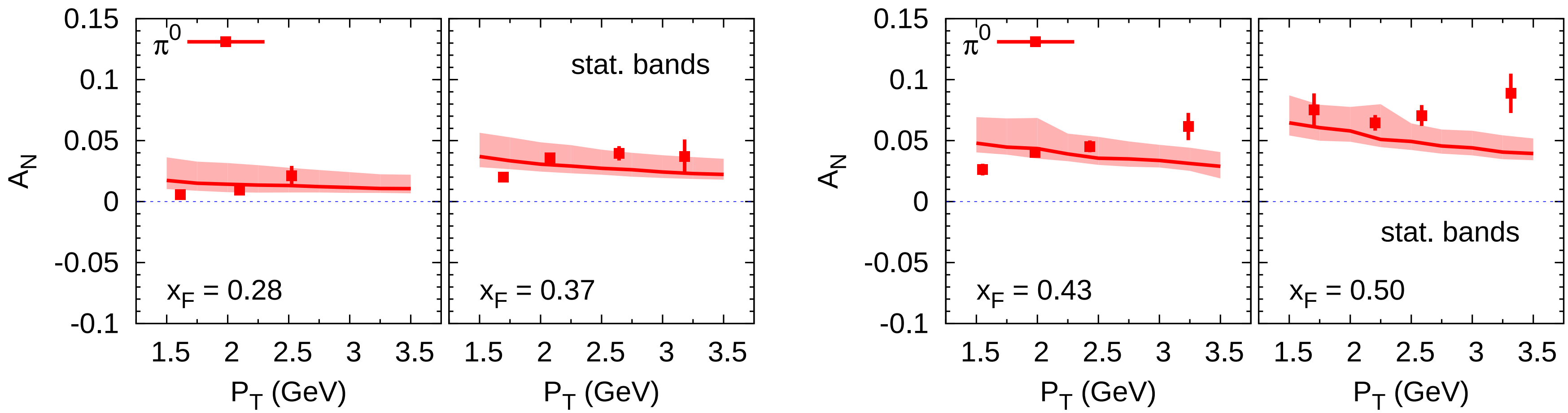
Back-up slides

Collins effect: scan band



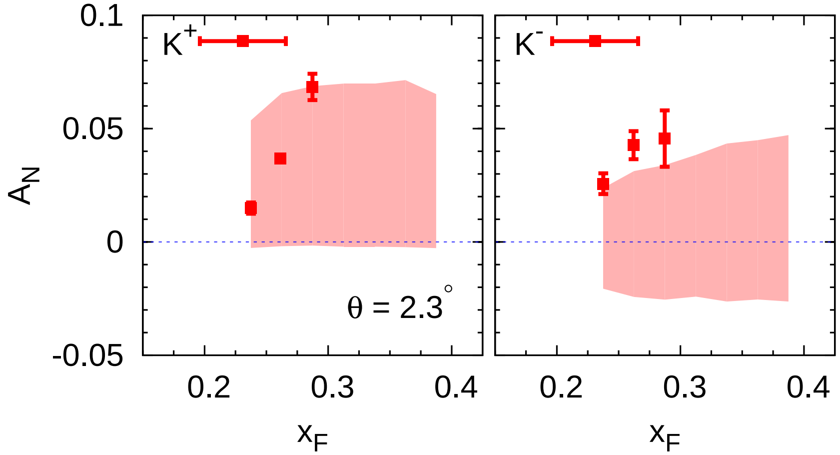
STAR@RHIC: A_N vs. p_T for different x_F bins at $\sqrt{s} = 200$ GeV

Sivers effect: statistical band

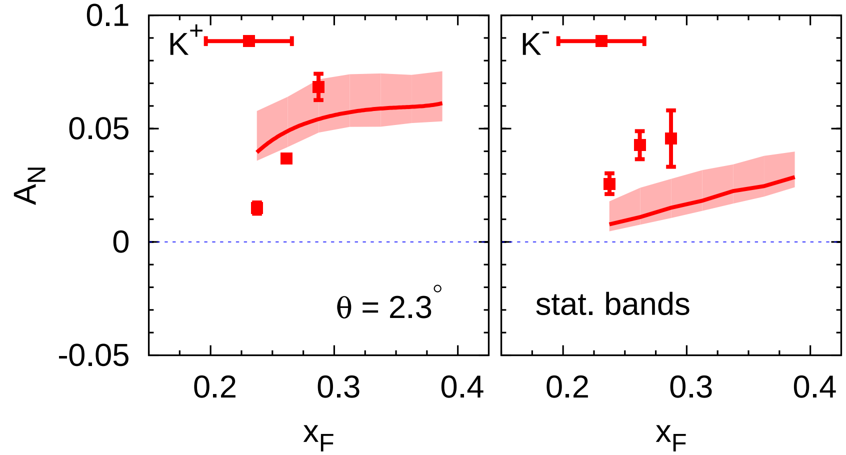


STAR@RHIC: A_N vs. p_T for different x_F bins at $\sqrt{s} = 200$ GeV

Sivers effect: $pp \to K^{\pm} X$



scan bands



statistical error bands

BRAHMS@RHIC: A_N vs. x_F

Flavour dependence

$h_1^d < 0$ and $\Delta^N D_{\rm unf} < 0$:

$$A_N(\pi^+) \sim h_1^u \Delta^N D_{\rm fav} + h_1^d \Delta^N D_{\rm unf} = h_1^u \Delta^N D_{\rm fav} + |h_1^d||\Delta^N D_{\rm unf}| > 0$$

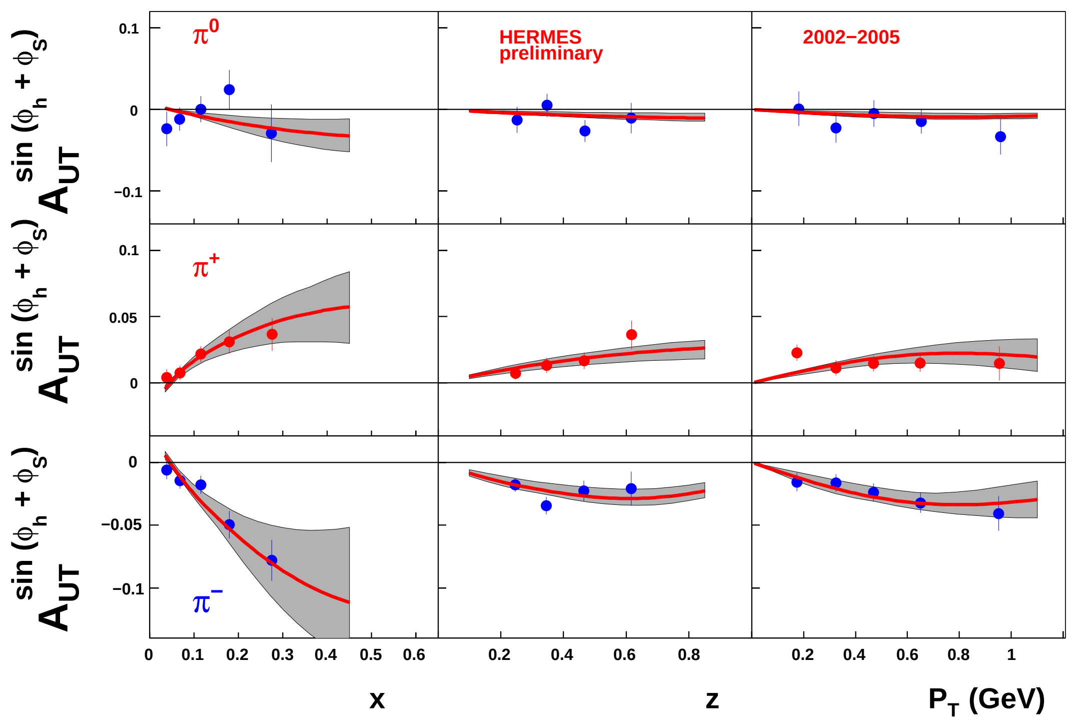
$$A_N(\pi^-) \sim h_1^u \Delta^N D_{\rm unf} + h_1^d \Delta^N D_{\rm fav} = -h_1^u |\Delta^N D_{\rm unf}| - |h_1^d| \Delta^N D_{\rm fav} < 0$$

$$A_N(\pi^0) \sim (h_1^u + h_1^d) \frac{1}{2} \left[\Delta^N D_{\rm fav} + \Delta^N D_{\rm unf}\right] = \left[h_1^u - |h_1^d|\right] \frac{1}{2} \left[\Delta^N D_{\rm fav} - |\Delta^N D_{\rm unf}|\right]$$

- up and down terms add in sign in $A_N(\pi^\pm)$ while

- cancel each other in $A_N(\pi^0)$

Notice: if $\Delta^N D_{\rm unf} \simeq -\Delta^N D_{\rm fav} \Rightarrow A_N^{\rm Collins}(\pi^0) \simeq 0$



fit to HERMES data and statistical uncertainty band [*Anselmino et al. 09*]

Statistical error band

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{y_i - F(x_i; \boldsymbol{a})}{\sigma_i} \right)^2$$

- N measurements y_i at known points x_i, with variance σ_i^2.
- $F(x_i; \boldsymbol{a})$ depends *non-linearly* on M unknown parameters a_i.
- Best fit: $\chi^2_{\rm min} \to \boldsymbol{a}_0$

Error band: all sets of parameters such that $\chi^2(\boldsymbol{a}_j) \leq \chi^2_{\rm min} + \Delta\chi^2$
- $\Delta\chi^2 = 1 \leftrightarrow 1\text{-}\sigma$: small errors, uncorrelated parameters, linearity, χ^2 parabolic
- $\Delta\chi^2$: fixed according to the coverage probability

$$P = \int_0^{\Delta\chi^2} \frac{1}{2\Gamma(M/2)} \left(\frac{\chi^2}{2} \right)^{(M/2)-1} \exp\left(-\frac{\chi^2}{2} \right) \mathrm{d}\chi^2$$

P= probability that true set of parameters falls inside the M-hypervolume

$[P = 0.68 \leftrightarrow 1\text{-}\sigma,\; P = 0.95 \leftrightarrow 2\text{-}\sigma]$