On the role of Sivers effect in A_N for pp --> h+X

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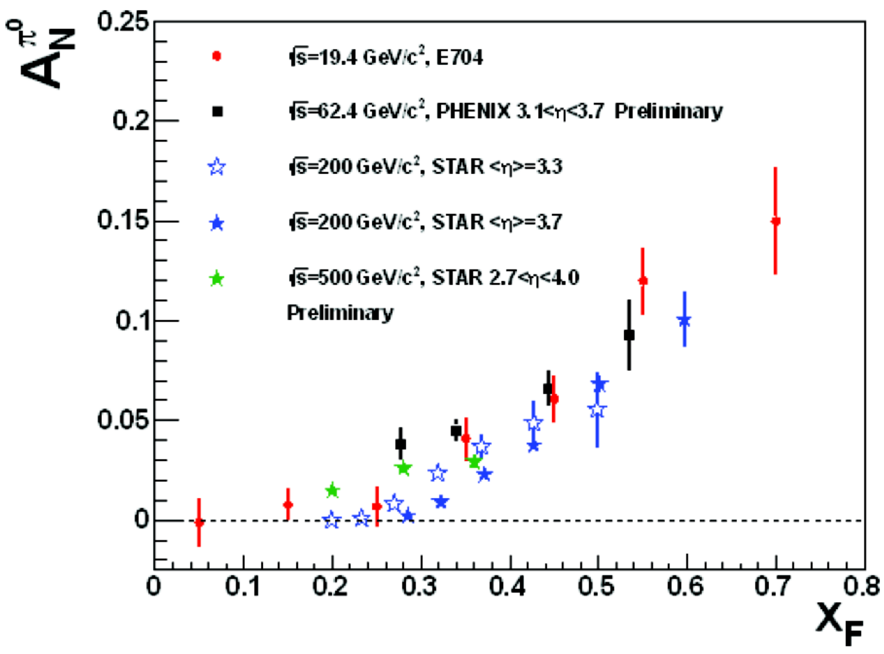
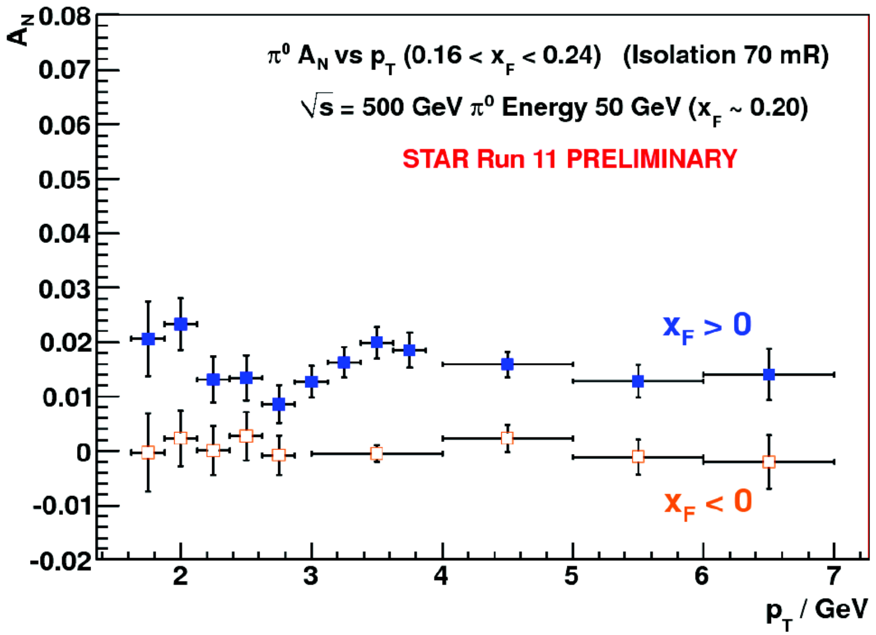
Outline

- Single Spin Asymmetries in inclusive hadron production
- Generalized Parton Model (GPM)
- Role of the Sivers effect in inclusive hadron production
- Conclusions

Single Spin Asymmetries in $pp^{\uparrow} \rightarrow h{+}X$

$$A_N = \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\downarrow}(\boldsymbol{P}_T)}{d\sigma^{\uparrow}(\boldsymbol{P}_T) + d\sigma^{\downarrow}(\boldsymbol{P}_T)} = \frac{d\sigma^{\uparrow}(\boldsymbol{P}_T) - d\sigma^{\uparrow}(-\boldsymbol{P}_T)}{2\, d\sigma^{\mathrm{unp}}(P_T)}$$





- SSA A_N are large, and persist even at high energies and high P_T.

Single Spin Asymmetries in $pp^{\uparrow} \to h+X$

- Puzzling in perturbative QCD at leading twist:

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{\Delta_T f_a}_{\text{transversity}} \otimes f_b \otimes \underbrace{[d\hat{\sigma}^{\uparrow} - d\hat{\sigma}^{\downarrow}]}_{\text{pQCD elementary SSA}} \otimes \underbrace{D_{\pi/c}}_{\text{FF}}$$

- The asymmetry can be generated only at partonic level:

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \hat{a}_N \propto \frac{m_q}{E_q}\alpha_s \sim 0$$

- Negligible at high energies, large transverse momenta

Single Spin Asymmetries in $pp^{\uparrow} \to h+X$

- Possible solutions:
  - Going beyond twist 2:

    collinear pQCD factorization at twist-3

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  - Going beyond collinear approximation

    Generalized Parton Model (TMD)

Single Spin Asymmetries in $pp^{\uparrow} \to h+X$

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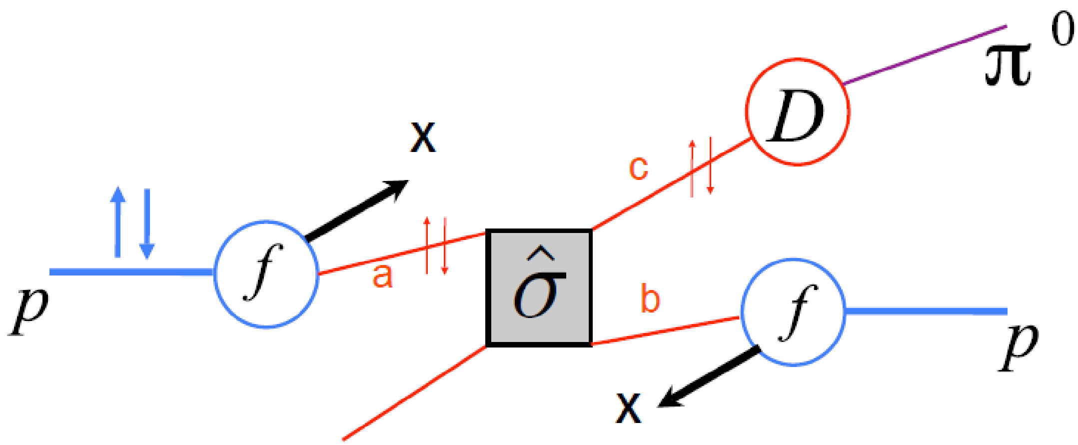
    Generalized Parton Model (TMD)

Single Spin Asymmetries in pp$^{\uparrow}$ → h+X

- Going beyond collinear approx.: Generalized Parton Model (TMD)



$$d\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} \underbrace{f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a})} \otimes \underbrace{f_{b/p}(x_b, \boldsymbol{k}_{\perp b})} \otimes d\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \underbrace{D_{\pi/c}(z, \boldsymbol{p}_{\perp \pi})}$$

single spin effects in TMDs

- Warning: Factorization is assumed.

Generalized Parton Model

$$d\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a}) \otimes f_{b/p}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\hat{\sigma} \otimes D_{h/c}(z, p_{\perp h})$$

- Example: Sivers effect

$$\hat{f}_{q/p^{\uparrow}}(x, \boldsymbol{k}_{\perp}) = f_{q/p}(x, k_{\perp}) + \frac{1}{2}\Delta^N f_{q/p^{\uparrow}}(x, k_{\perp})\, \boldsymbol{S} \cdot (\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}}_{\perp})$$

Unpolarized TMD PDF

Generalized Parton Model

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Sivers function

$$\Delta^N f_{q/p^{\uparrow}}(x, k_{\perp}) = -\frac{2\, k_{\perp}}{m_p}\, f_{1T}^{\perp q}(x, k_{\perp})$$

Generalized Parton Model

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Vanishes in collinear approx.

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- Example: Sivers effect

$$\begin{aligned} f_{q/p^{\uparrow}}(x, \boldsymbol{k}_{\perp}) - f_{q/p^{\downarrow}}(x, \boldsymbol{k}_{\perp}) &= \Delta^N f_{q/p^{\uparrow}}(x, k_{\perp})\, \boldsymbol{S}_T \cdot (\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}}_{\perp}) \\ &= \Delta^N f_{q/p^{\uparrow}}(x, k_{\perp}) \sin(\varphi - \phi_S) \end{aligned}$$

The asymmetry is at level of PDFs and can be large

Generalized Parton Model

- The asymmetry is given by the sum of different contributions:

$$d\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a}) \otimes f_{b/p}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\hat{\sigma} \otimes D_{h/c}(z, p_{\perp h})$$

$$A_N = \Delta^N f_{q/p^{\uparrow}} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{h/c}$$ Sivers effect

$$+$$

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$$+ \; \Delta_T q \otimes \Delta f_{q^\uparrow/p} \otimes d\hat{\sigma} \otimes D_{h/c}$$ Boer-Mulders effect

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$+$ Other quark TMD effects + Other gluon TMD effects

Anselmino et al., PRD73,014020

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$$A_N \simeq \Delta^N f_{q/p^{\uparrow}} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{h/c}$$ Sivers effect

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Generalized Parton Model

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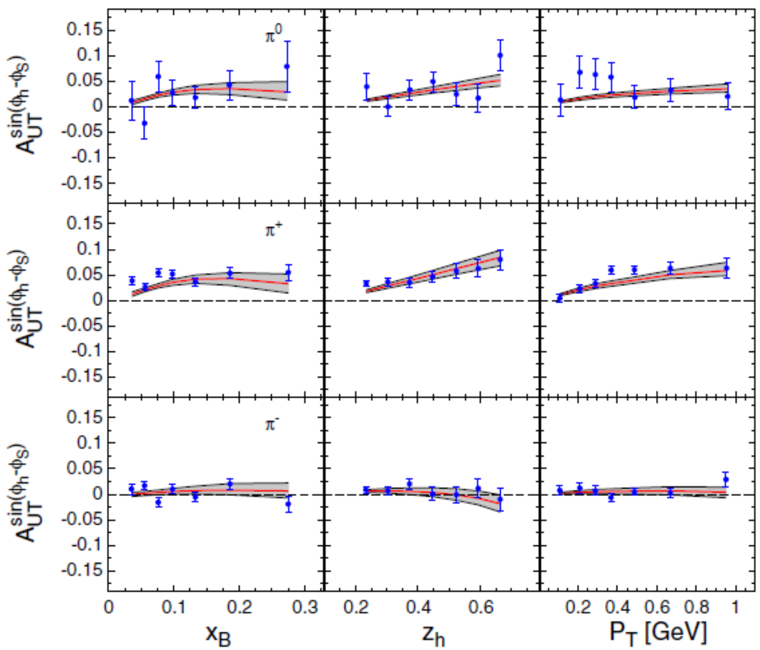
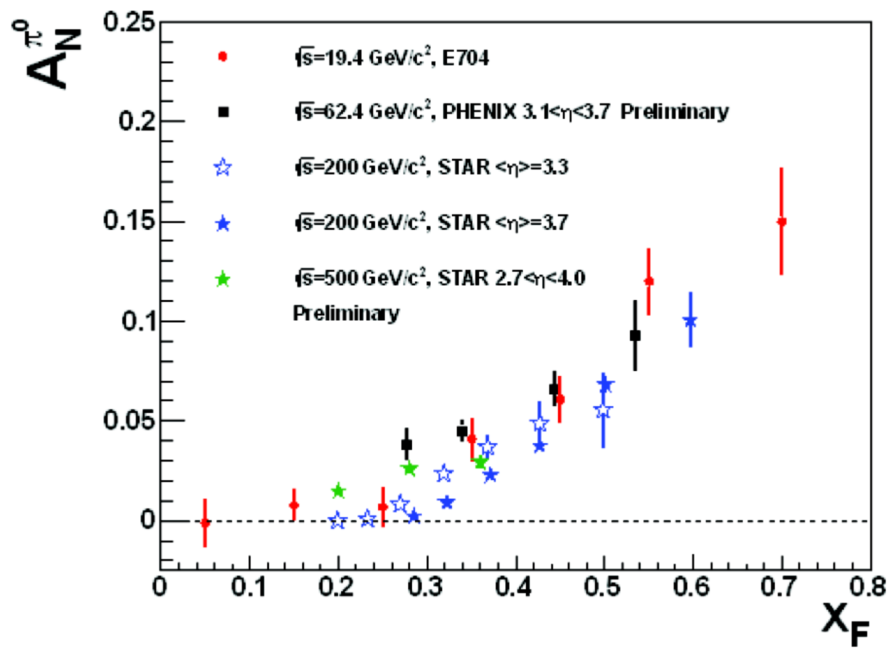
$$+ \; \Delta_T q \otimes f_{b/p} \otimes d\hat{\sigma} \otimes \Delta^N D_{h/q^{\uparrow}} \quad \text{Collins effect}$$

- Current information on TMDs comes from the SIDIS experiment
- We can use this information to study TMD effects in inclusive hadron production
- Already done for Collins: Anselmino et al, PRD86,074032 (2012)

Phenomenology





➢However SIDIS data cover only a limited kinematical region x<0.3, while in pp large x region are very important.

$$X_F < X < 1$$

Parametrization of the Sivers function

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = 2\,\mathcal{N}_q^S(x)\, f_{q/p}(x)\, h(k_\perp)\, \frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M}\, e^{-k_\perp^2/M^2}$$

$$\mathcal{N}_q^S(x) = N_q^S x^{\alpha_q}(1-x)^{\beta_q}\,\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\,\beta_q^{\beta_q}}$$

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Controls the small x behavior

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Controls the small x behavior

Controls the large x behavior

- The beta parameters are poorly known from SIDIS, but are crucial for pp asymmetries at high x_F strongly depends β_u / β_d

Scan procedure

I. We fit SIDIS data leaving β_u and β_d as free parameter.
You get you best χ^2_0

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$0 < \beta_u < 4$ $0 < \beta_d < 4$ At steps of 0.5

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$\chi^2 \leq \chi_0^2 + \Delta\chi^2$ Statistical criteria to accept the new function

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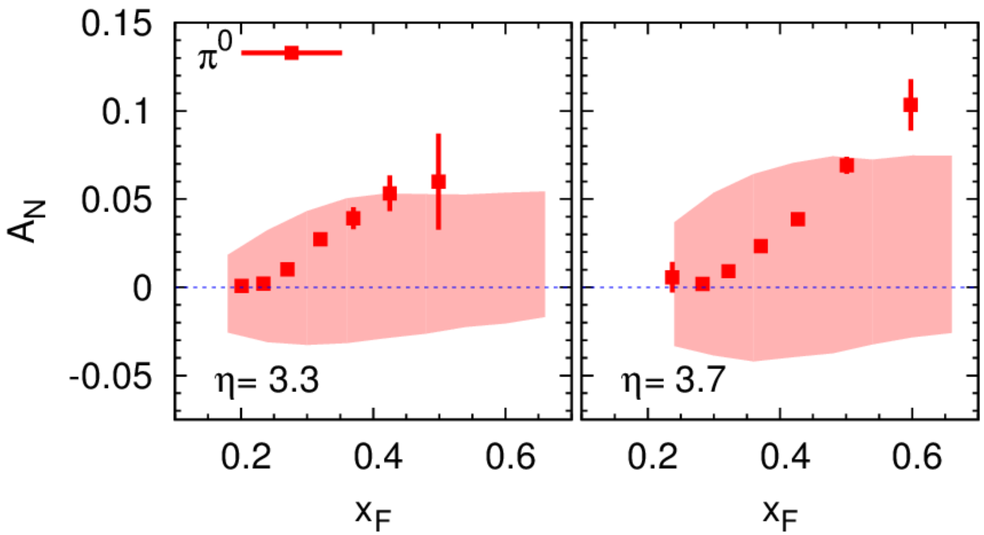
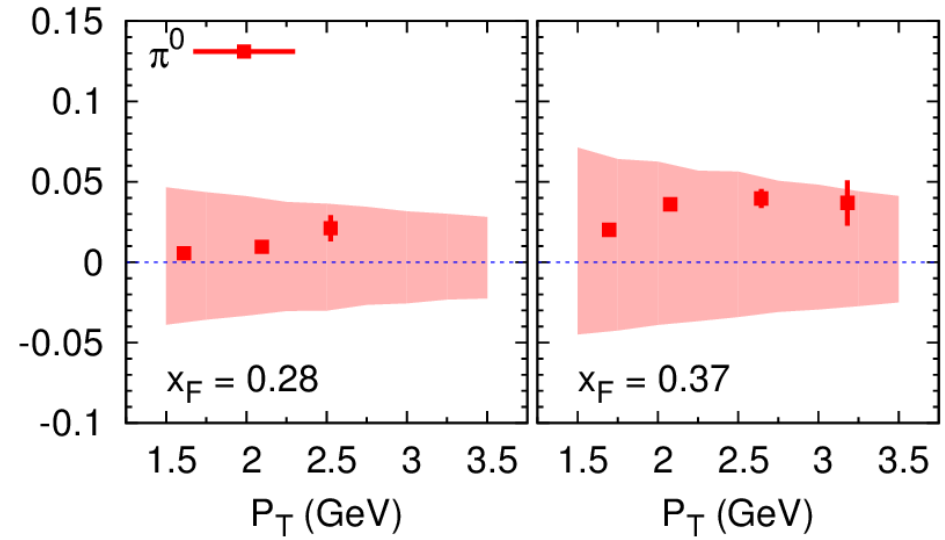
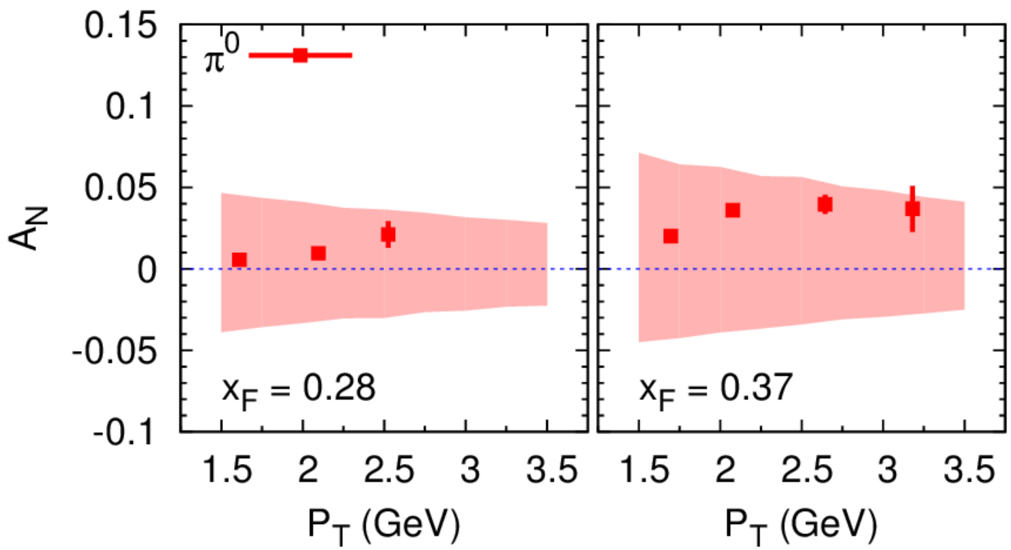
IV. Use the function able to describe the SIDIS data to calculate the Sivers effect in pp

Results



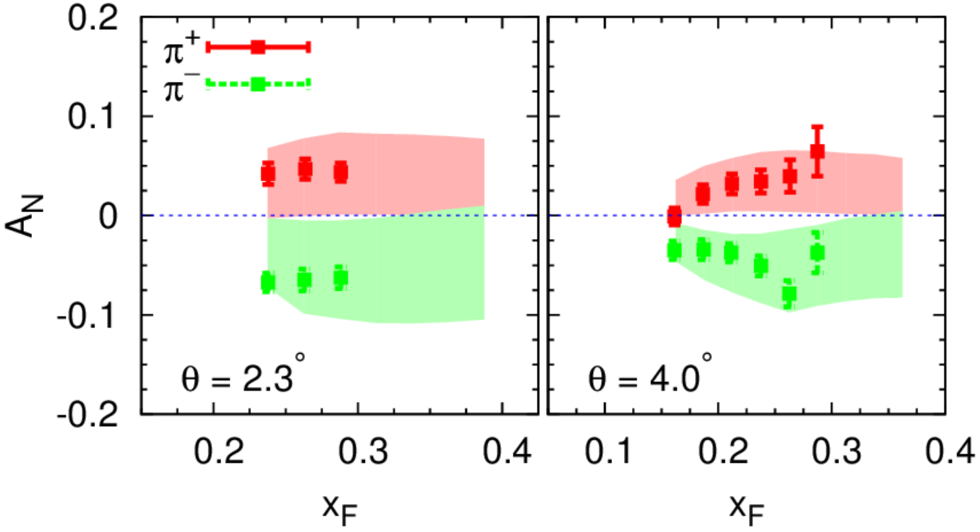




STAR@RHIC

$$\sqrt{s} = 200 \text{ GeV}$$

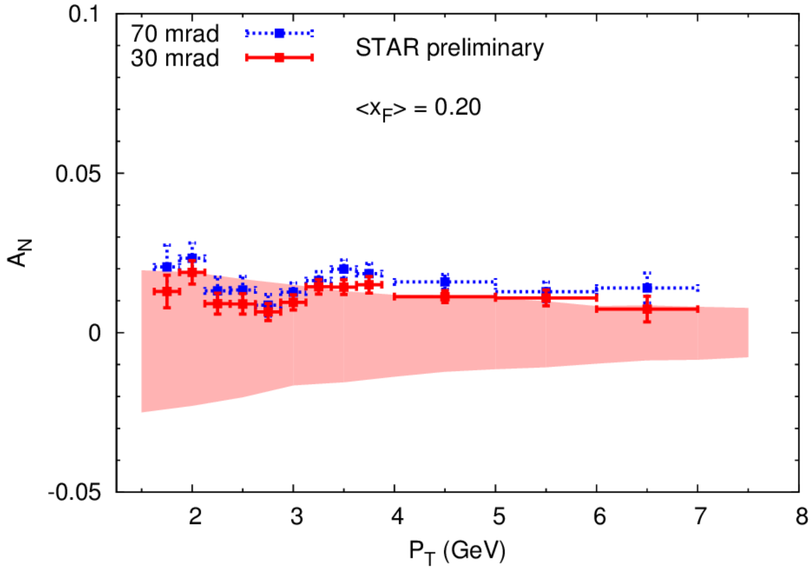
Results

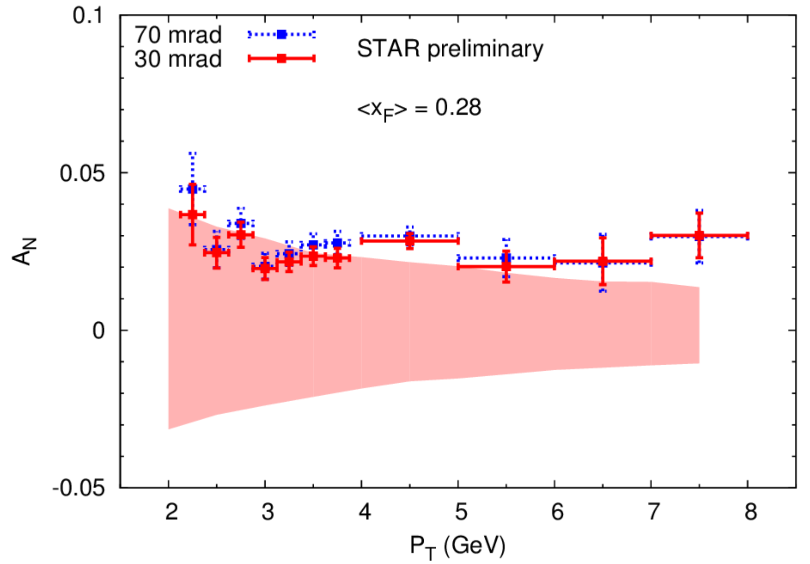


BRAHMS@RHIC

$\sqrt{s} = 200\ \mathrm{GeV}$

Results





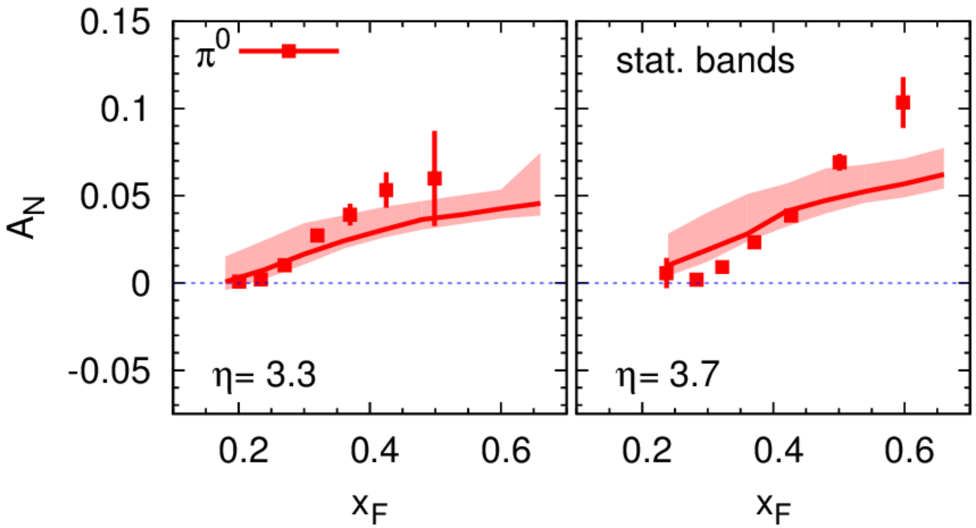
STAR@RHIC

$\sqrt{s} = 500$ GeV,

Results

- Can we find a Sivers function able to explain qualitatively the data alone?

Results



STAR@RHIC

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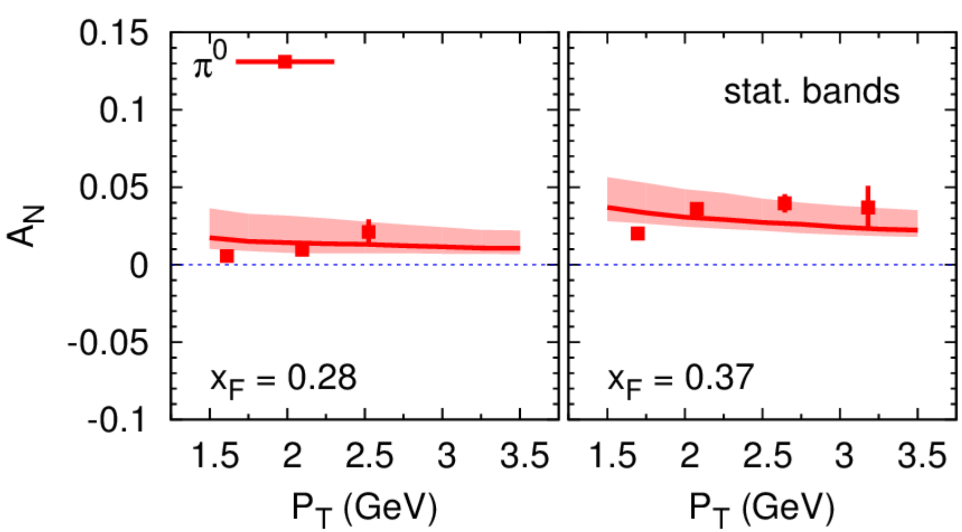
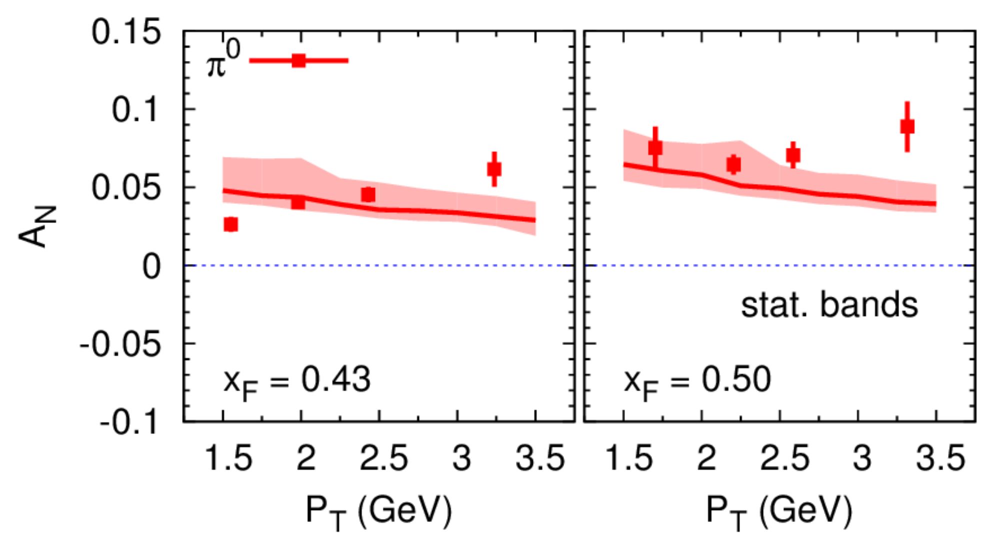
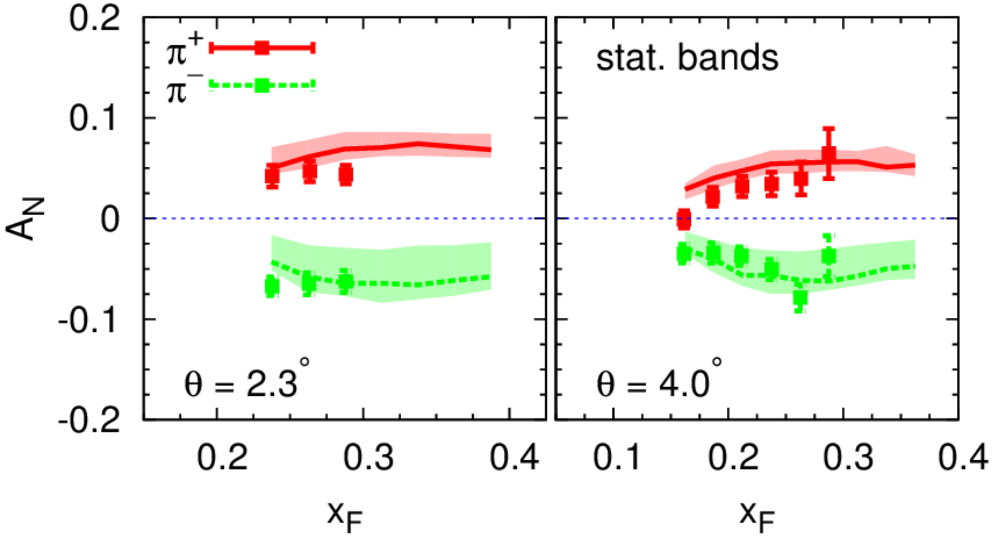




Results



BRAHMS@RHIC

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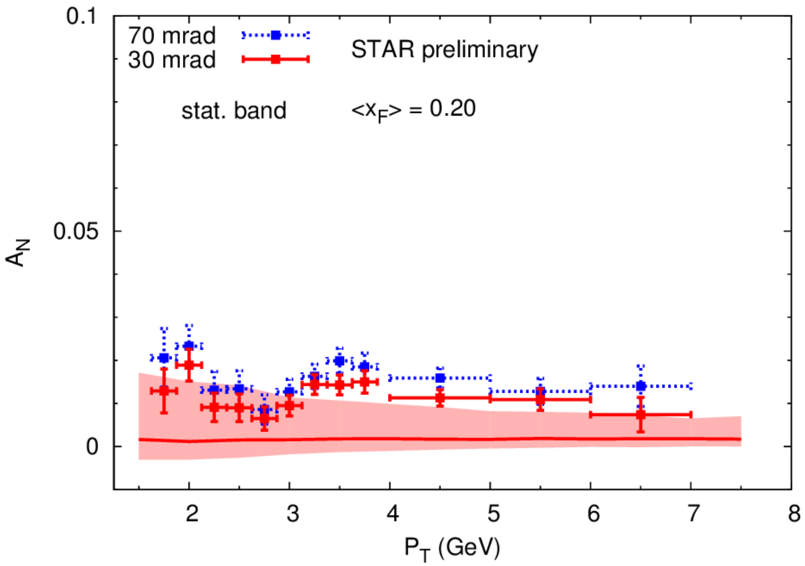

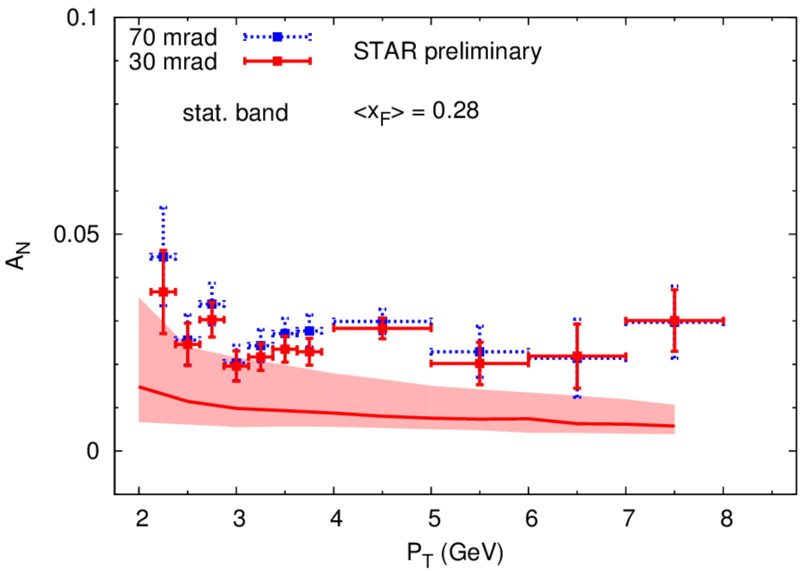

STAR@RHIC

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Conclusions

- We used SIDIS data to estimate the Sivers effect in pp-->pion+X
- The Sivers effect can be large enough to explain A_N asymmetry
- In principle we can found a Sivers function able,alone, to explain the asymmetry, but do not forget Collins effect!
- Further necessary development: Factorization & evolution, data at large x

Back up slides

Scan procedure: some choices

- Valence quark dominate pp. We neglect sea quarks in our procedure. This minimize the number of parameter:

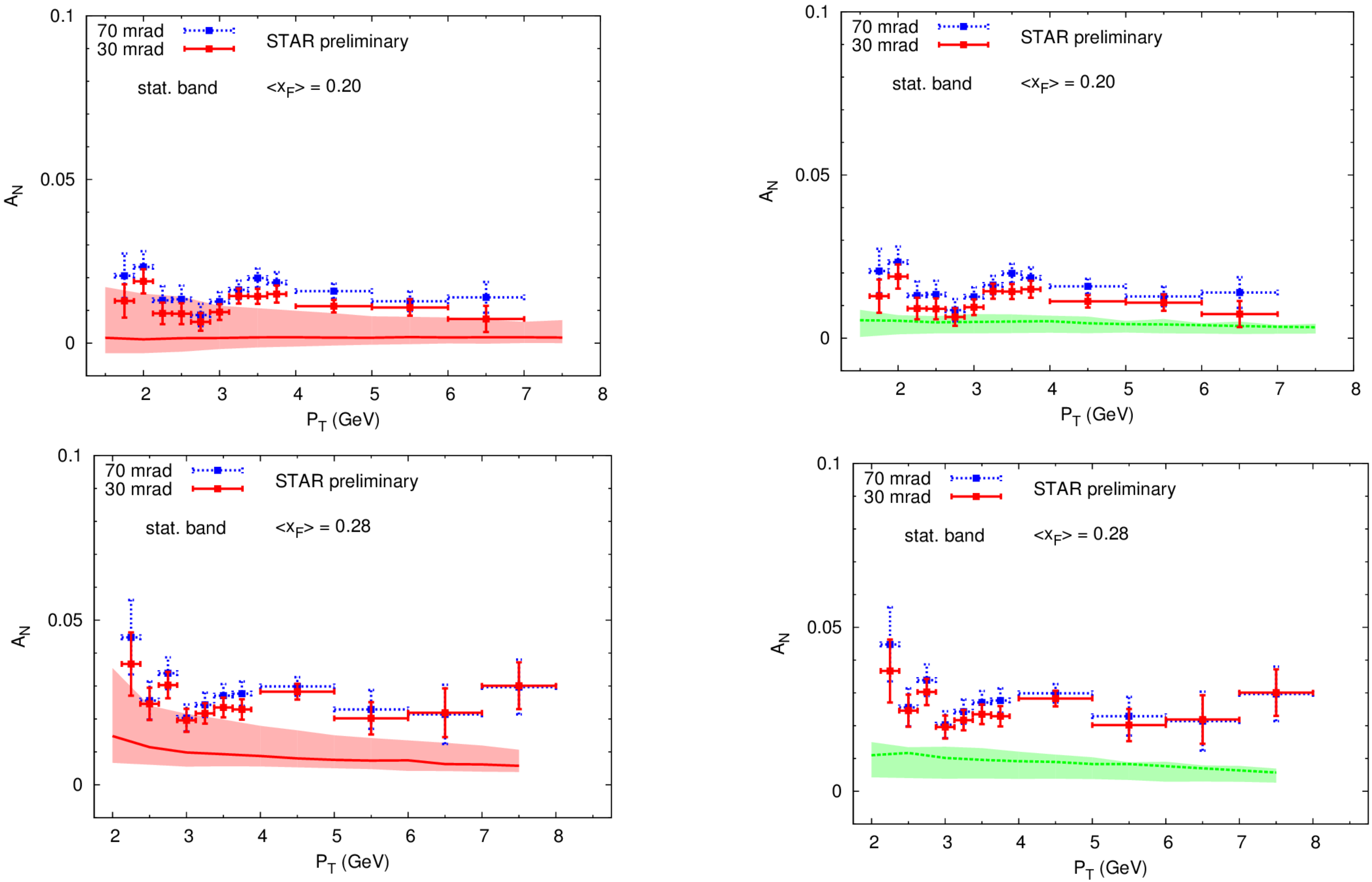
$$\mathcal{N}_q^S(x) = N_q^S x^{\alpha_q}(1-x)^{\beta_q} \frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}}$$

$$N_u,\ N_d,\ \alpha_u,\ \alpha_d,\ \beta_u,\ \beta_d,\ M$$

- We fit only HERMES data (in order to avoid problems related to evolution)

- GRV98 for PDFs and Kretzer FF

Results



70 mrad
30 mrad
STAR preliminary
stat. band
<x_F> = 0.20
A_N
P_T (GeV)
70 mrad
30 mrad
STAR preliminary
stat. band
<x_F> = 0.20
A_N
P_T (GeV)
70 mrad
30 mrad
STAR preliminary
stat. band
<x_F> = 0.28
A_N
P_T (GeV)
70 mrad
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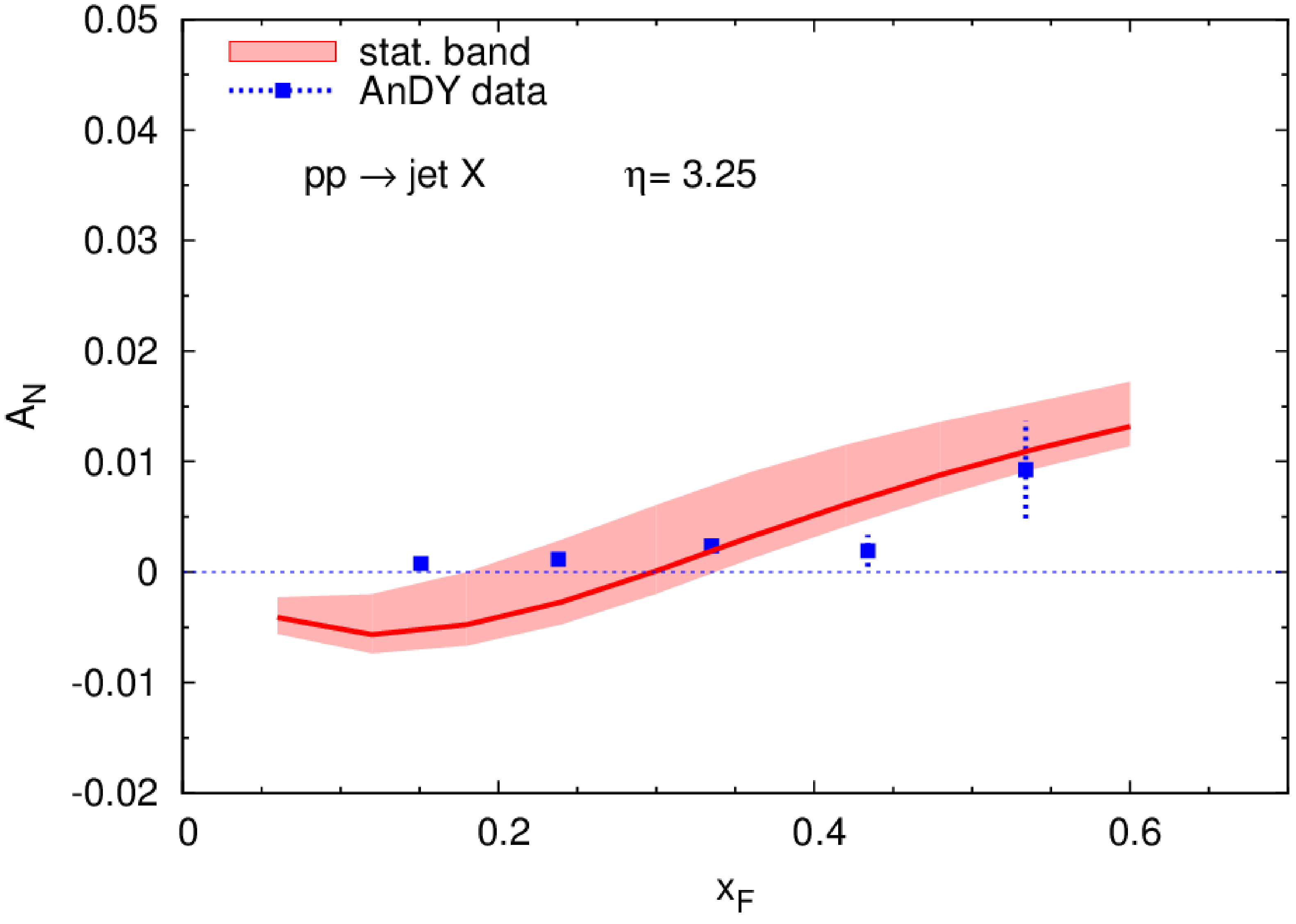
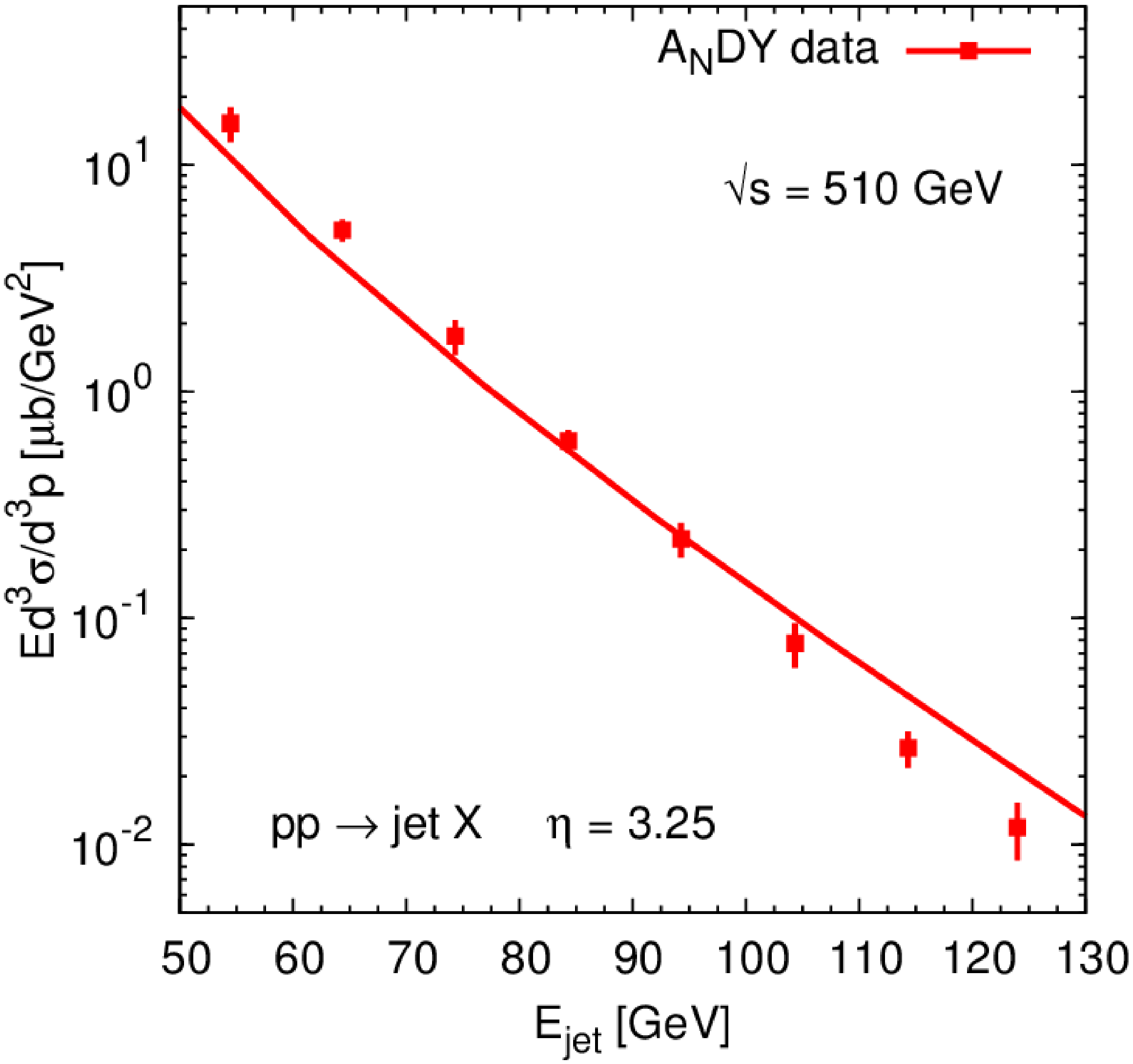
STAR preliminary
stat. band
<x_F> = 0.28
A_N
P_T (GeV)

Results

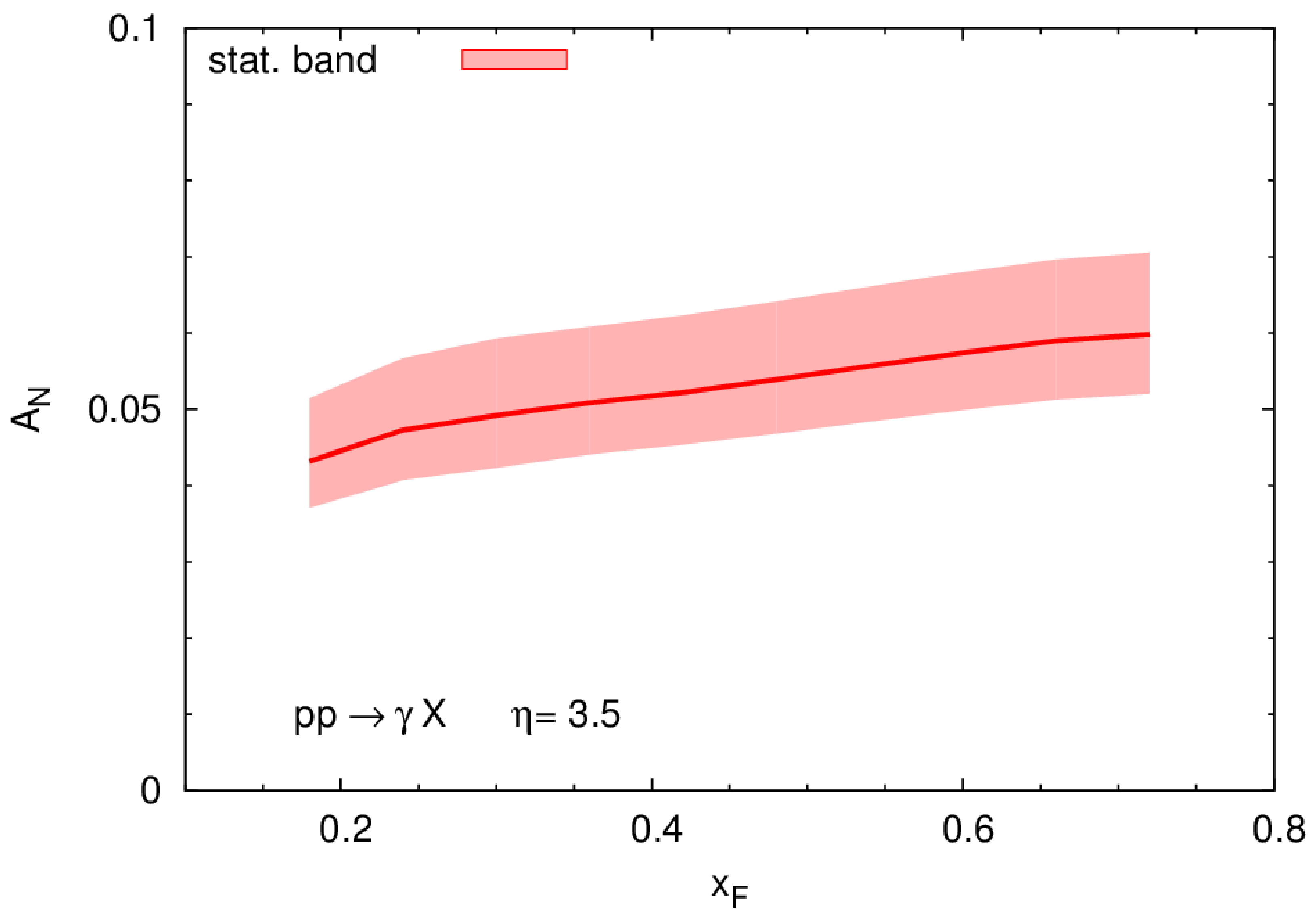

stat. band
AnDY data
pp → jet X
η= 3.25
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
A_N
0
0.2
0.4
0.6
x_F

Results

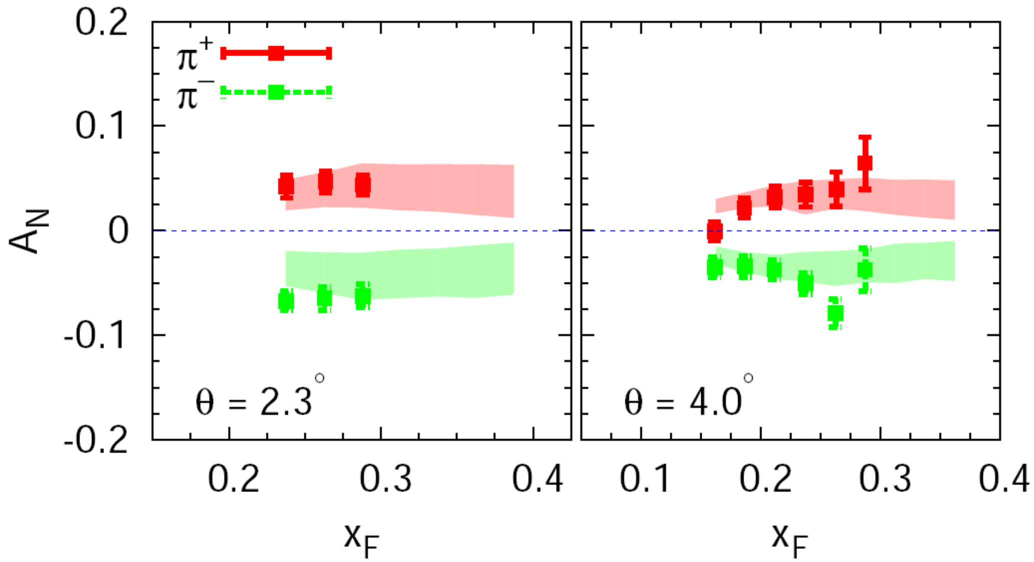


A_NDY data
$\sqrt{s}$ = 510 GeV
pp → jet X   η = 3.25
$Ed^3\sigma/d^3p$ [μb/GeV^2]
10^{1}
10^{0}
10^{-1}
10^{-2}
50 60 70 80 90 100 110 120 130
E_{jet} [GeV]

Results

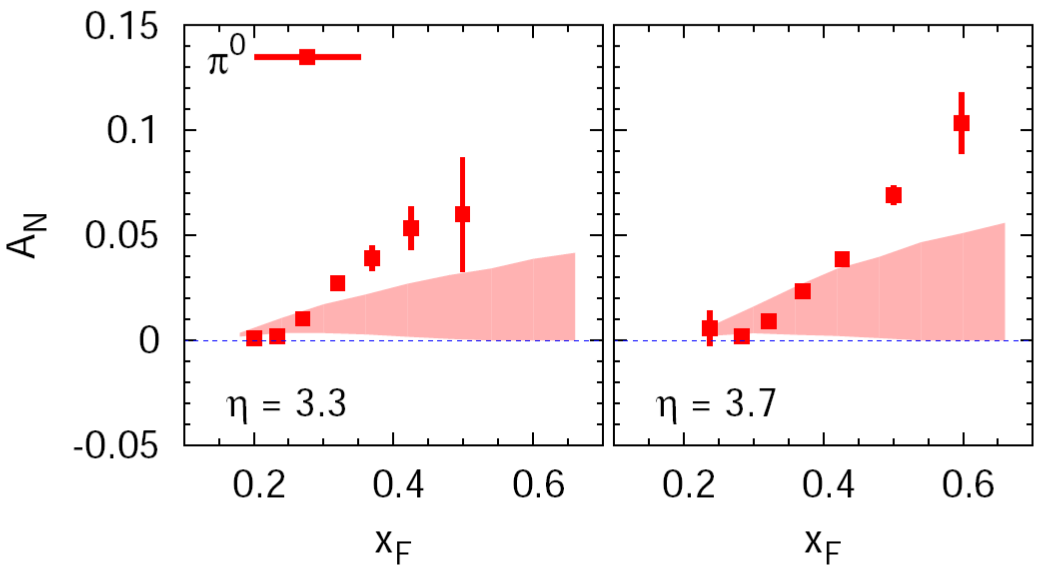


Results: Collins



BRAHMS@RHIC

$\sqrt{s} = 200$ GeV



STAR@RHIC

$\sqrt{s} = 200$ GeV

Single Spin Asymmetries in pp$^{\uparrow}$ → h+X

- Possible solution II:
  - Going beyond twist 2: collinear pQCD factorization at twist-3

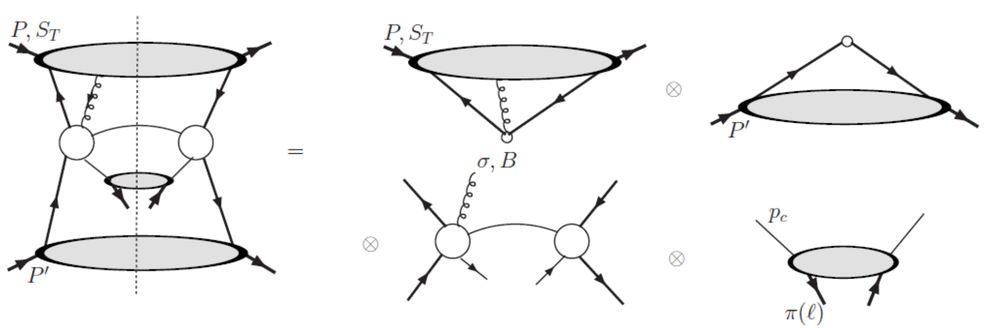
$$A_N = \phi^{(3)}_{q/p^{\uparrow}} \otimes f_{q/p} \otimes D_{h/q}$$

$$+ \quad \Delta_T q \otimes f_{q/p} \otimes D^{(3)}_{h/q}$$

$$+ \quad \Delta_T q \otimes \phi_{q^{\uparrow}/h} \otimes D_{h/q}$$

$$+ \quad \ldots$$

$$\phi^{(3)}_{q/p^{\uparrow}} \to g T_q(x,x)$$ ETQS Corr.func



Kouvaris, (2006), Kanazawa-Koike (2000), Kang-Yuan-Zhou (2010),Kang(2011)

Relation between theTwist 3 and the TMD approaches

- Notice that in process like SIDIS and DY, where two factorization scale appears, we have:

$$q_T \ll Q \qquad\qquad q_T \gg Q$$

Asymmetry described by TMDs — Asymmetry described by Twist3

- Twist3 functions and TMDs can be formally related to each other, for instance:

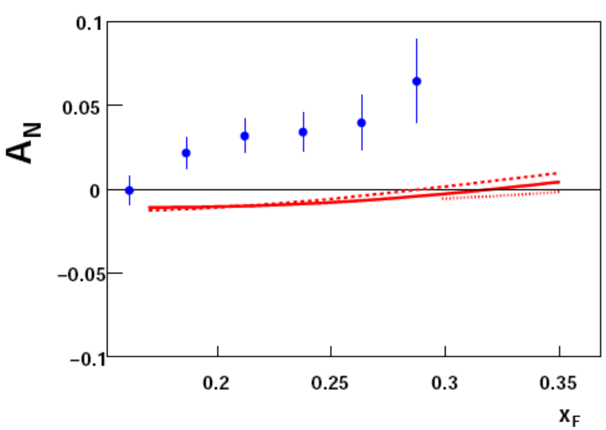
$$\int d^2\boldsymbol{k}_\perp \left(\frac{\boldsymbol{k}_\perp^2}{M}\right) f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)|_{\rm SIDIS} = -g\, T_q(x, x)$$

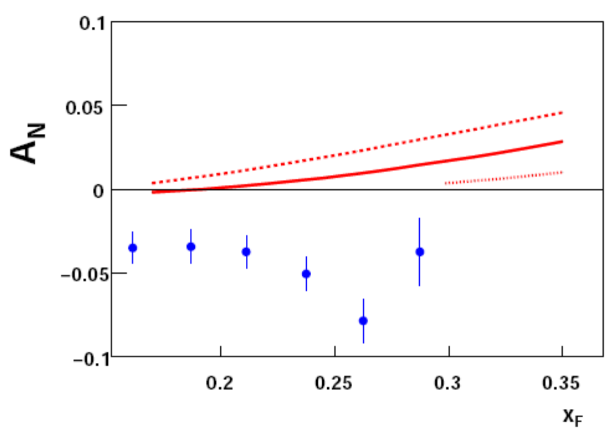
Sign mismatch?

➢Currently we do not have information on $T_q(x,x)$ from SIDIS, but we can use this relation in order to give an estimation of A_N in inclusive production

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

➢Brahms data: opposite sign.





Prokudin and Kang, PRD85,074 008 (2013)

Single Spin Asymmetries in $pp^{\uparrow} \rightarrow h+X$

- Possible solutions:
  - Going beyond twist 2: collinear pQCD factorization at twist-3
    - Factorization& universality proved
    - Not well known: requires P_T>>Q in SIDIS, no data
    - Sign mismatch problem… (very indirect…)
  - Going beyond collinear approx.: Generalized Parton Model (TMD)
    - Successfully applied in SIDIS lot of data
    - Factorization& universality are assumed for inclusive hadron production

The Sivers function from SIDIS data

- We can build an azimuthal weighted asymmetry

$$A_{UT}^{\sin(\phi_h-\phi_S)} = 2\,\frac{\int d\phi_S\, d\phi_h\, [d\sigma^{\uparrow} - d\sigma^{\downarrow}]\, \sin(\phi_h-\phi_S)}{\int d\phi_S\, d\phi_h\, [d\sigma^{\uparrow} + d\sigma^{\downarrow}]}$$

- In details:

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{\sum_q \int d\phi_S\, d\phi_h\, d^2\boldsymbol{k}_\perp\; \Delta^N f_{q/p^\uparrow}(x,k_\perp)\, \sin(\varphi-\phi_S)\, \frac{d\hat{\sigma}^{\ell q\to \ell q}}{dQ^2}\; D_q^h(z,p_\perp) \sin(\phi_h-\phi_S)}{\sum_q \int d\phi_S\, d\phi_h\, d^2\boldsymbol{k}_\perp\; f_{q/p}(x,k_\perp)\, \frac{d\hat{\sigma}^{\ell q\to \ell q}}{dQ^2}\; D_q^h(z,p_\perp)}$$