Workshop on opportunities for DY at RHIC
BNL May 10 - 13

Sivers function from SIDIS,PP

Alexei Prokudin
Jefferson Laboratory

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Sivers function from SIDIS,PP

and DY

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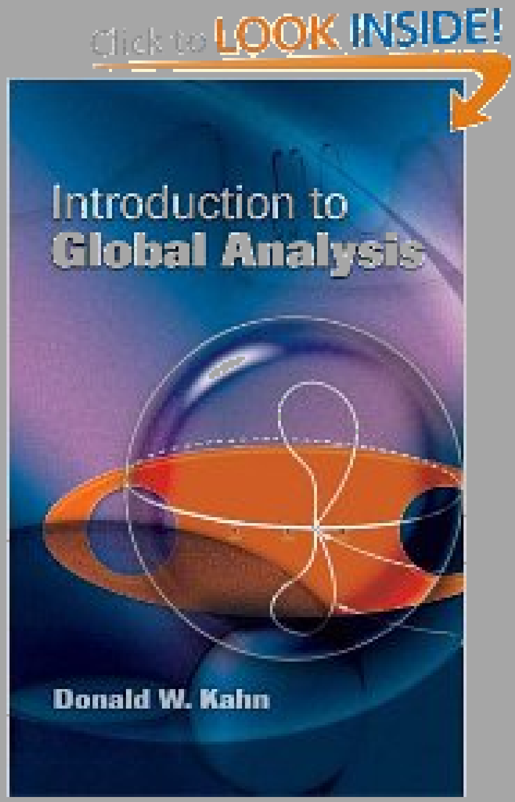
Global analysis



Ingredients: Factorization theorems

- Related: Factorization Theorems:
  - Semi-Inclusive deep inelastic scattering. ✓
  - Drell-Yan. ✓
  - e^+/e^- annihilation. ✓
  - ~~$p + p \rightarrow h_1 + h_2 + X$~~ !!

- TMD factorization

$$\Lambda^2_{QCD} < P^2_{h\perp} \ll Q^2$$

Sensitive to parton transverse motion.

Talks of John Collins, Piet Mulders, Ted Rogers, Jian-Wei Qui, George Sterman

- Related: Factorization Theorems:
  - Semi-Inclusive deep inelastic scattering. ✓
  - Drell-Yan. ✓
  - e^+/e^- annihilation. ✓
  - $p + p \rightarrow h_1 + h_2 + X$ ✓

- Collinear factorization

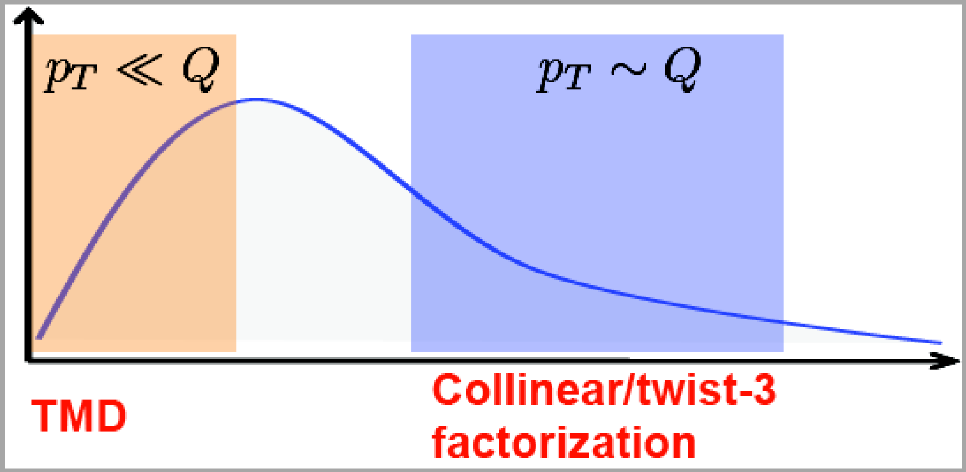
$$\Lambda^2_{QCD} \ll P^2_{h\perp}, Q^2$$

Sensitive to multy parton correlations.

Talks of John Collins, Piet Mulders, Ted Rogers, Jian-Wei Qui, George Sterman

TMD and Collinear factorizations

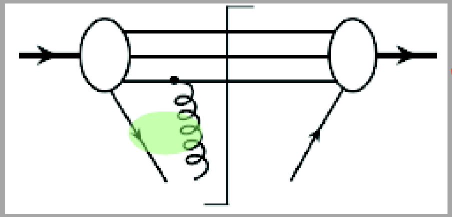
Both factorizations are consistent in the overlap region



Talks of John Collins, Piet Mulders, Ted Rogers, Jian-Wei Qui, Alessandro Bacchetta

Relation of multyparton correlations and moments of TMDs

$$\int d^2 p_T \frac{p_T^2}{M} f_{1T}^{\perp}(x, p_T^2) + \mathrm{UVCT}(\mu^2) = T_F(x, x, \mu^2) \qquad f_{1T}^{\perp(1)} \equiv \int d^2 p_T \frac{p_T^2}{2M^2} f_{1T}^{\perp}(x, p_T^2)$$



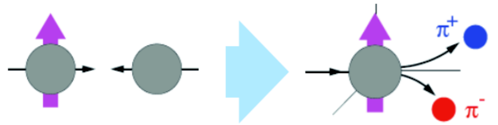
Sivers function is related to TF, but counterterm matters!

Talks of John Collins, Piet Mulders, Ted Rogers, Jian-Wei Qui

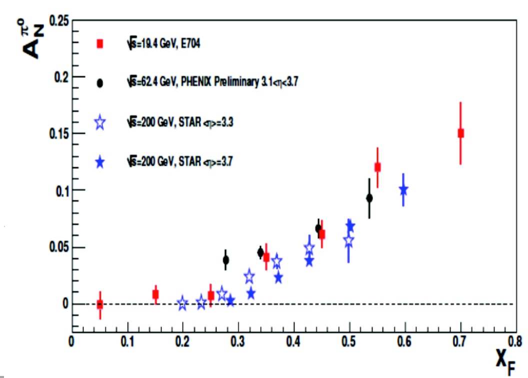
Data analysis

Proton Proton

$$A(p_A, s_\uparrow) + B(p_B) \to \pi(p) + X$$



$$A(\ell, \vec{s}) \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$



Only one scale P_T

Collinear analysis:

Kouvaris, Qiu, Vogelsang, Yuan (2006)

Kanazava, Koike (2010)

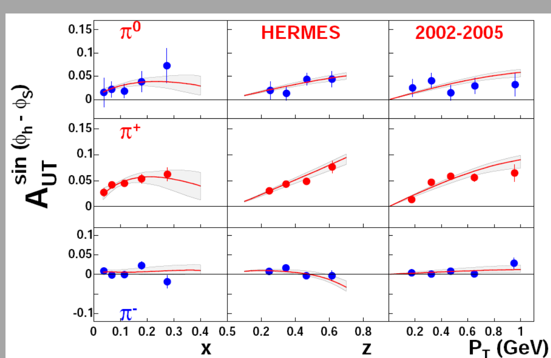
TMD analysis:

Anselmino et al (2006)

SIDIS

$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$$d\sigma^\uparrow - d\sigma^\downarrow \propto \underbrace{f_{1T}^\perp \otimes D_1 \sin(\phi_h - \phi_S)}_{\text{Sivers effect}}$$



Two scales P_T, Q

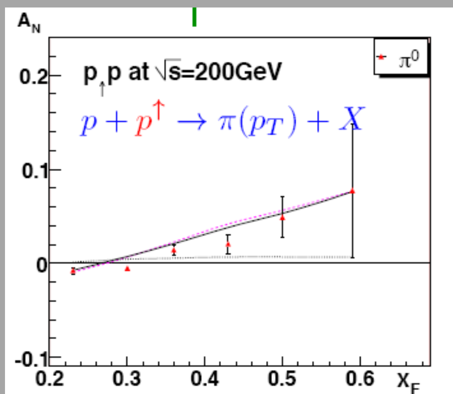
$$\Lambda^2_{QCD} < P^2_{h\perp} \ll Q^2$$

TMD analysis: Anselmino et al (2008); Collins et al (2007) ; Vogelsang, Yuan (2006)

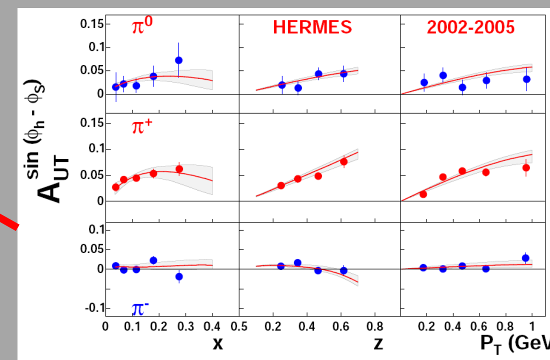
Comparison of results

Talk of Zhongbo Kang

$$g_s T_F(x,x) = -2M f_{1T}^{\perp(1)}(x)$$



Collinear analysis: Kouvaris, Qiu, Vogelsang, Yuan (2006)



TMD analysis:

Anselmino et al (2008)

Comparison of results

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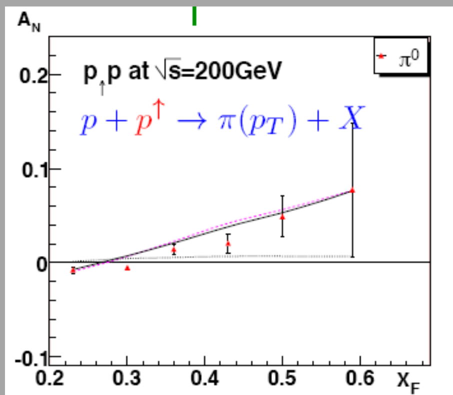
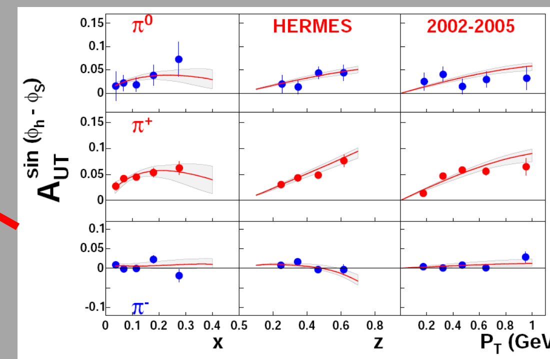
Compare



Collinear analysis: Kouvaris, Qiu, Vogelsang, Yuan (2006)



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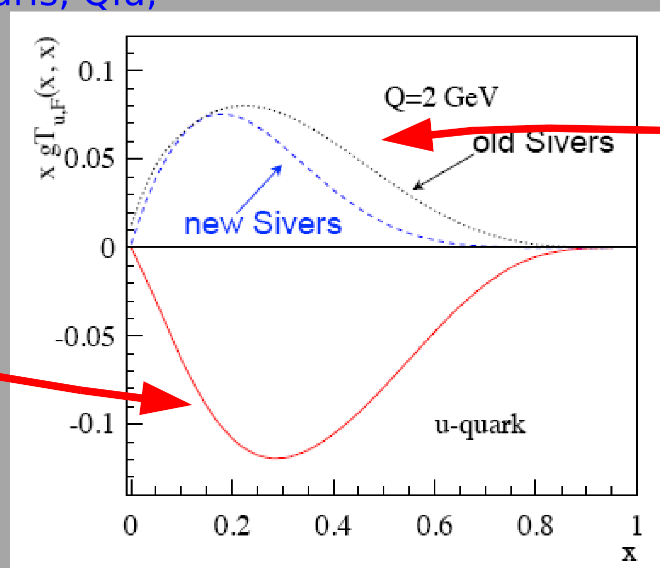
Anselmino et al (2008)



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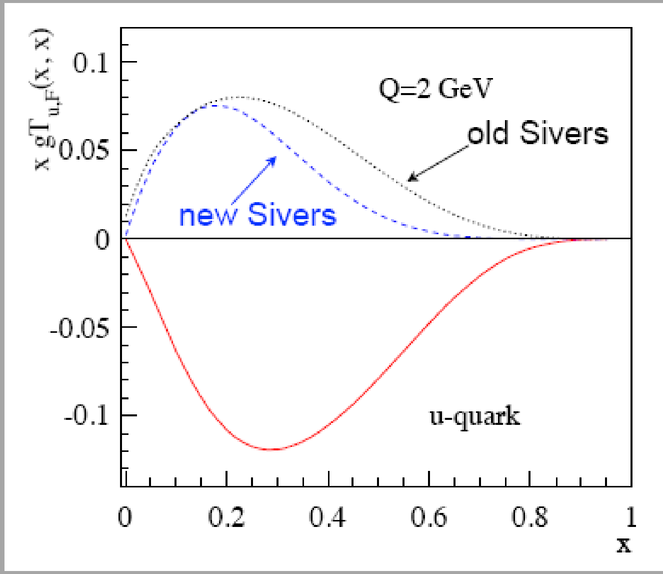


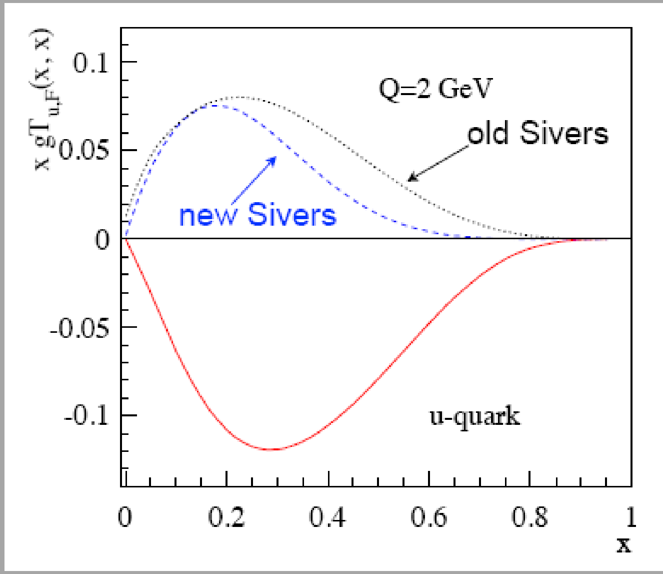
Kang, Qiu, Vogelsang, Yuan arXiv:1103.1591

- Magnitudes are similar
- Sign is opposite

Comparison of results

Talk of Zhongbo Kang

$$g_s T_F(x,x) = -2M f_{1T}^{\perp(1)}(x)$$



Kang, Qiu, Vogelsang, Yuan arXiv:1103.1591

- Magnitudes are similar
- Sign is opposite

It is a puzzle!

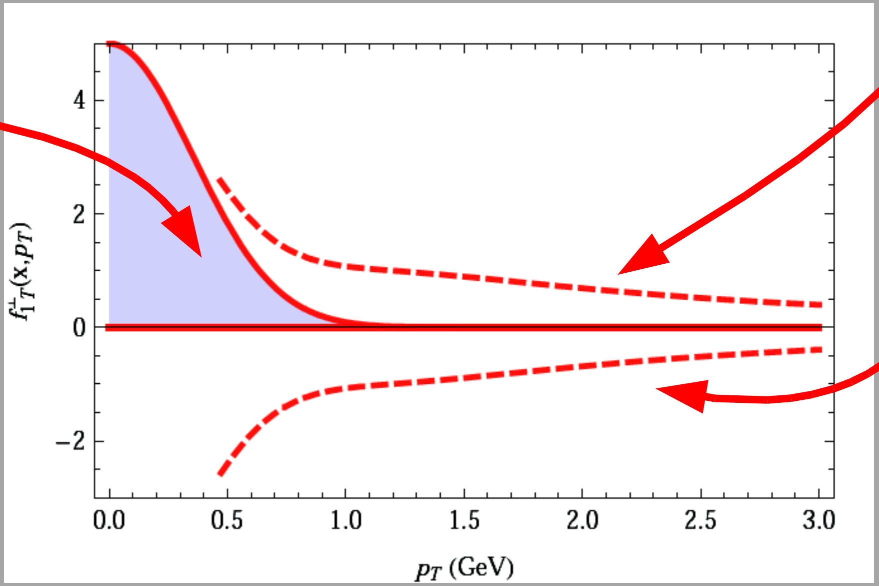
Possible explanations

Sivers function can have nodes in $\mathbf{p_T}$.

Talk of Zhongbo Kang

SIDIS $\mathbf{T_F > 0}$

Perturbarive tail $\propto \frac{\mathbf{M^2}}{\mathbf{p_T^4}} \alpha_\mathbf{s}$



Bacchetta, Boer, Deihl, Mulders 2008

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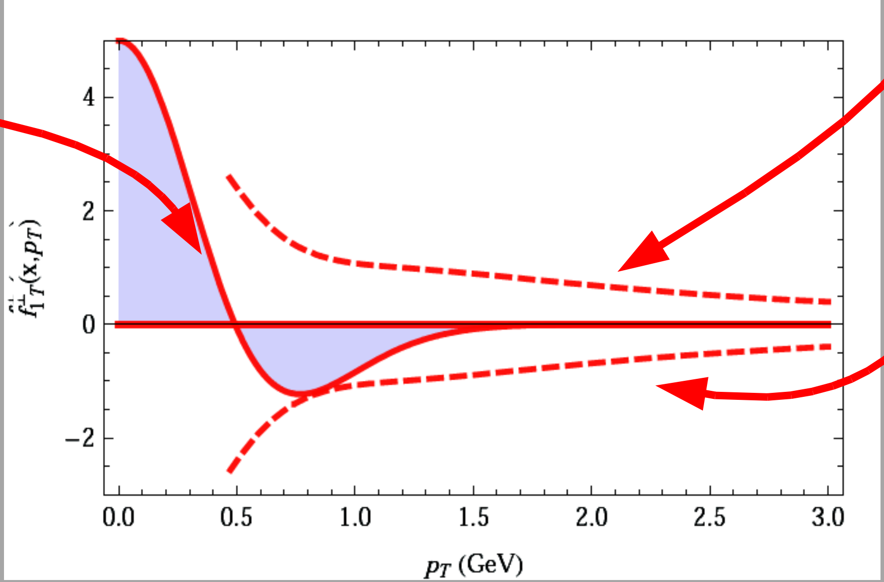

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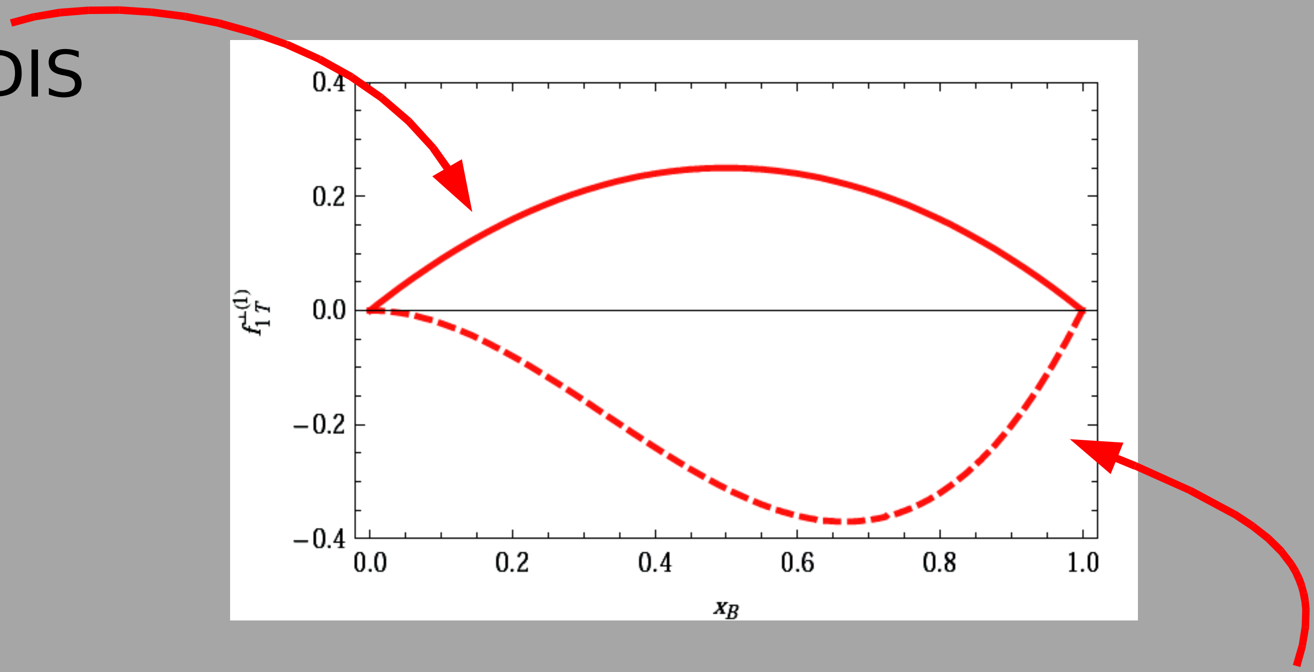
Possible explanations

Sivers function can have nodes in x.

Boer (2011)

Bacchetta et al, model calculation (2010)



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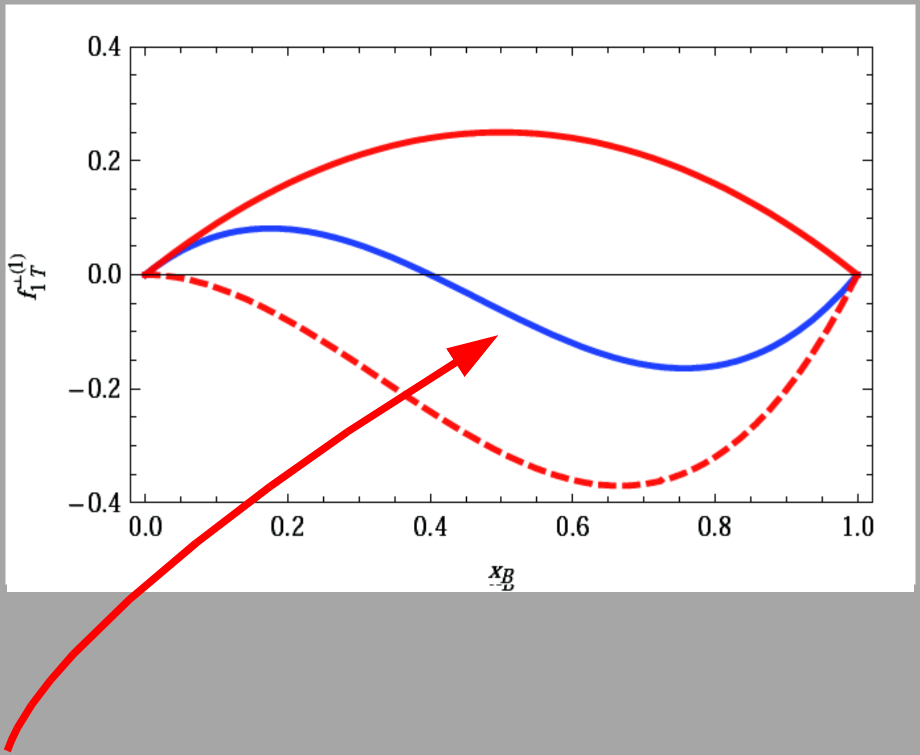
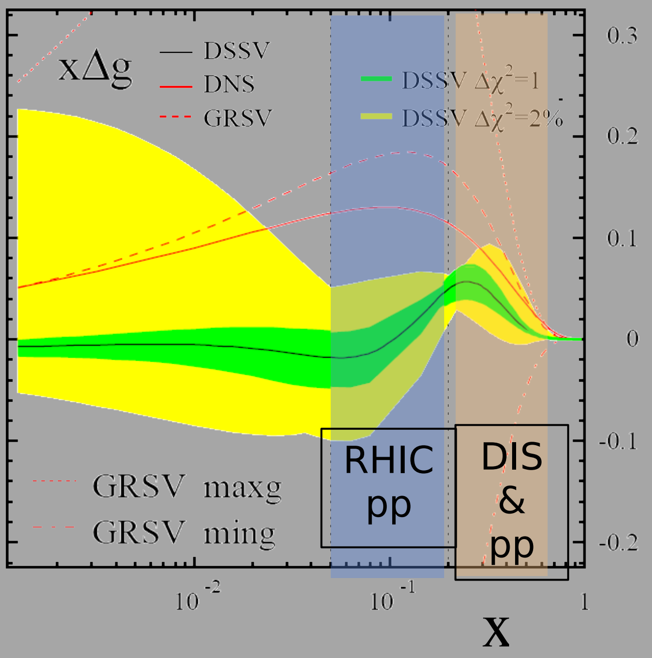


If PP and SIDIS probe different regions of x

Are nodes so strange?

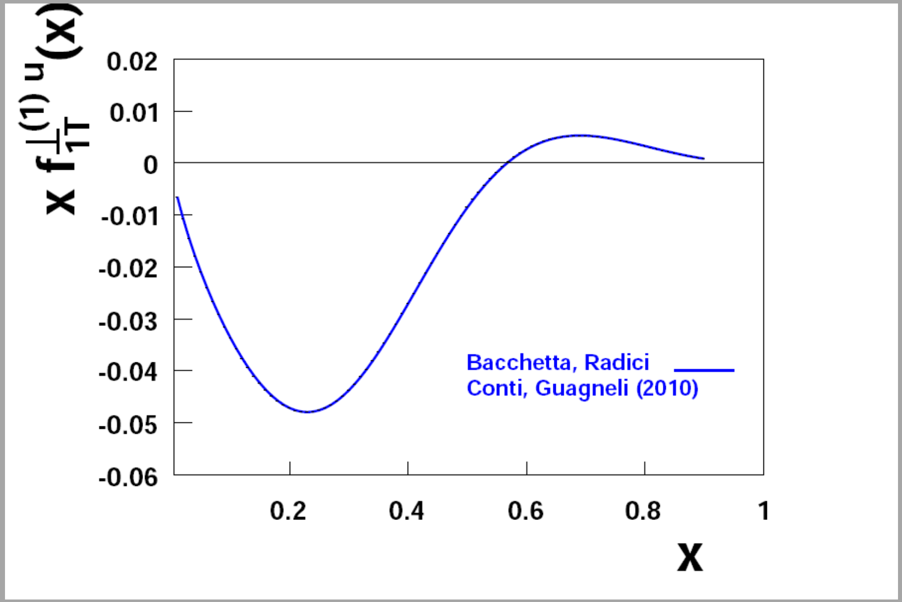


Node in $\Delta g(x)$ from DSSV global fit De Florian, Sassot, Stratmann, Vogelsang

$$\Delta f \propto f(S) - f(-S)$$

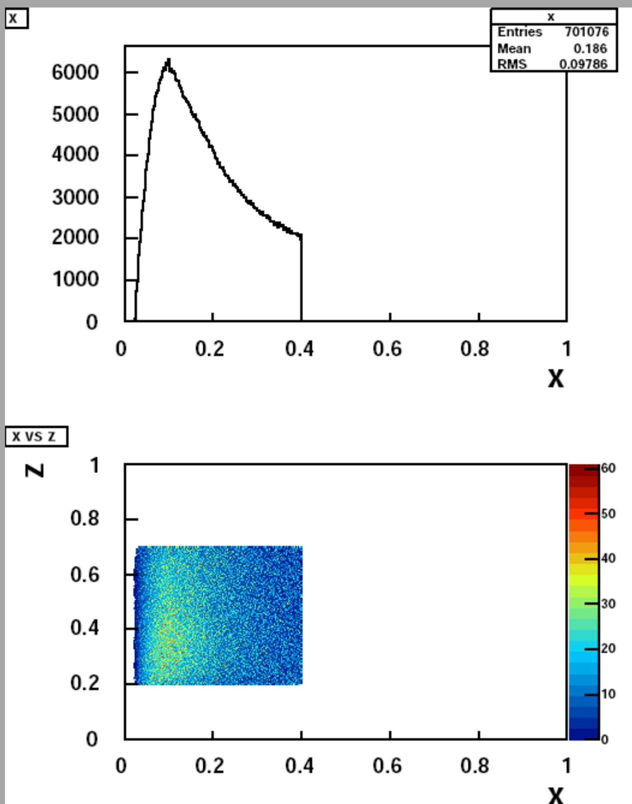
Talk of Jian-wei Qiu

Node in Sivers function
Bacchetta, Radici,
Conti, Guagneli (2010)



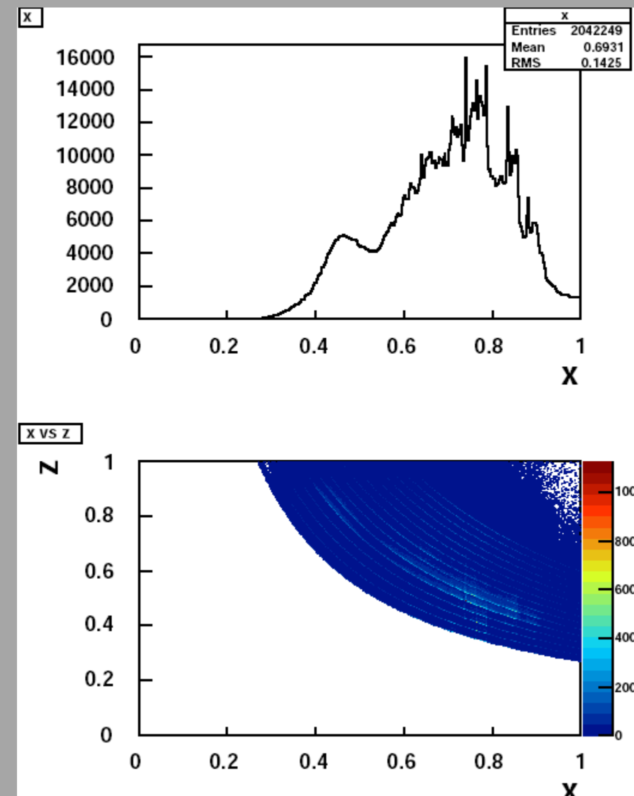
SIDIS vs PP kinematics

SIDIS HERMES



$$\mathbf{x} < \mathbf{0.4}$$

PP STAR



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SIDIS vs PP kinematics

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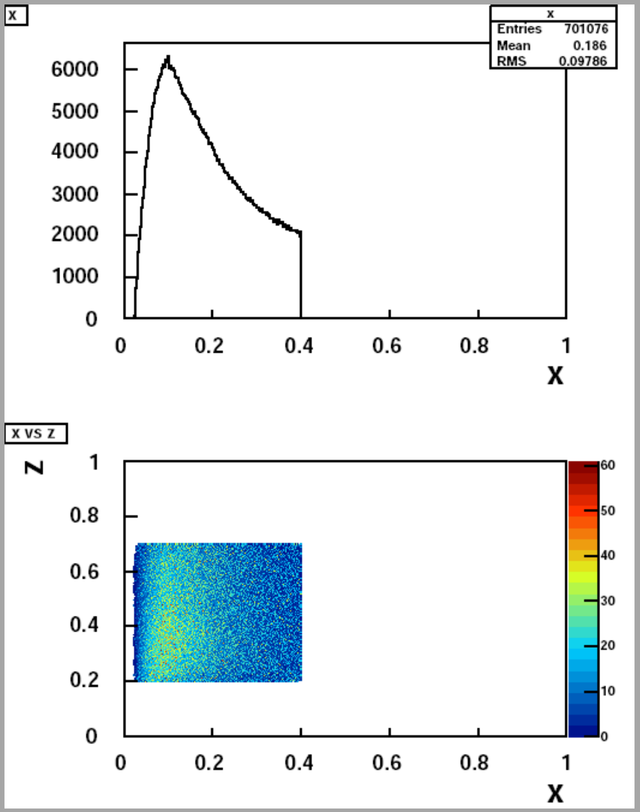
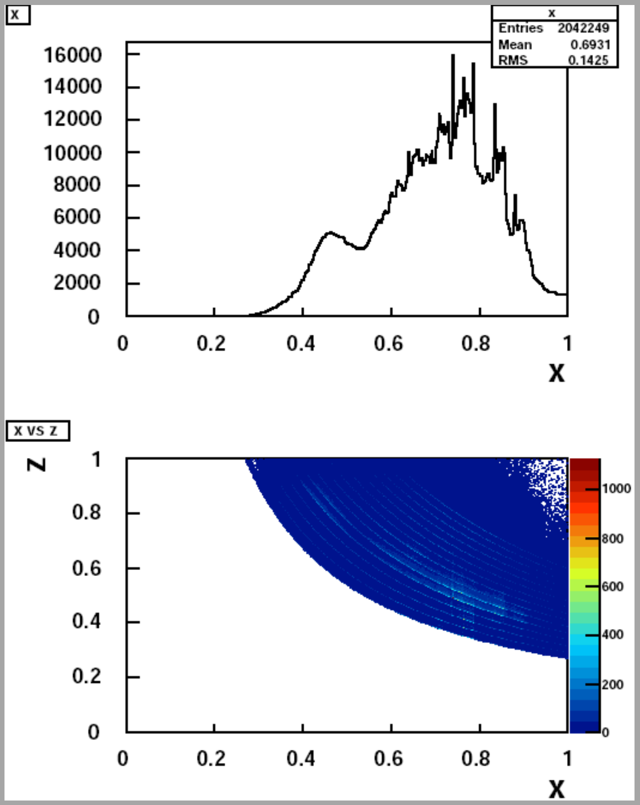


$\mathbf{x < 0.4}$

PP STAR



$\mathbf{x > 0.4}$

SIDIS and PP probe different regions in x !

We are looking at the same function

... from diferent prospective!

Parametrization

$$\mathbf{f}_{\mathbf{1T}}^{\perp\mathbf{q}} \propto \mathbf{x}^{\alpha_\mathbf{q}}(\mathbf{1}-\mathbf{x})^{\beta_\mathbf{q}}(\mathbf{1}-\eta_\mathbf{q}\mathbf{x})$$

as in De Florian, Sassot, Stratmann, Vogelsang (2009)

$\mathbf{1}-\eta_\mathbf{q}\mathbf{x}$ has a node if $\eta_\mathbf{q} > \mathbf{0}$

SIDIS: HERMES, COMPASS data $\pi^{\pm}, \mathbf{K}^{\pm}$

$$\mathbf{A}_{\mathbf{UT}}^{\sin(\mathbf{\Phi_h}-\mathbf{\Phi_S})} \sim \mathbf{f}_{\mathbf{1T}}^{\perp} \otimes \sigma \otimes \mathbf{D_1}$$

PP: STAR data $\pi^{\mathbf{0}}$

$$\mathbf{A_N} \sim \mathbf{T_F} \otimes \sigma \otimes \mathbf{D_1}$$

using PDF GRV98 and FF DSSV

Parametrization

$$\mathbf{f_{1T}^{\perp q} \propto x^{\alpha_q}(1-x)^{\beta_q}(1-\eta_q x)}$$

as in De Florian, Sassot, Stratmann, Vogelsang (2009)

$\mathbf{1-\eta_q x}$ has a node if $\mathbf{\eta_q > 0}$

SIDIS: HERMES, COMPASS data $\pi^{\pm}, \mathbf{K}^{\pm}$

TMD

$$\mathbf{A_{UT}^{\sin(\Phi_h-\Phi_S)} \sim f_{1T}^{\perp} \otimes \sigma \otimes D_1}$$

PP: STAR data $\pi^{\mathbf{0}}$

$$\mathbf{A_N \sim T_F \otimes \sigma \otimes D_1}$$

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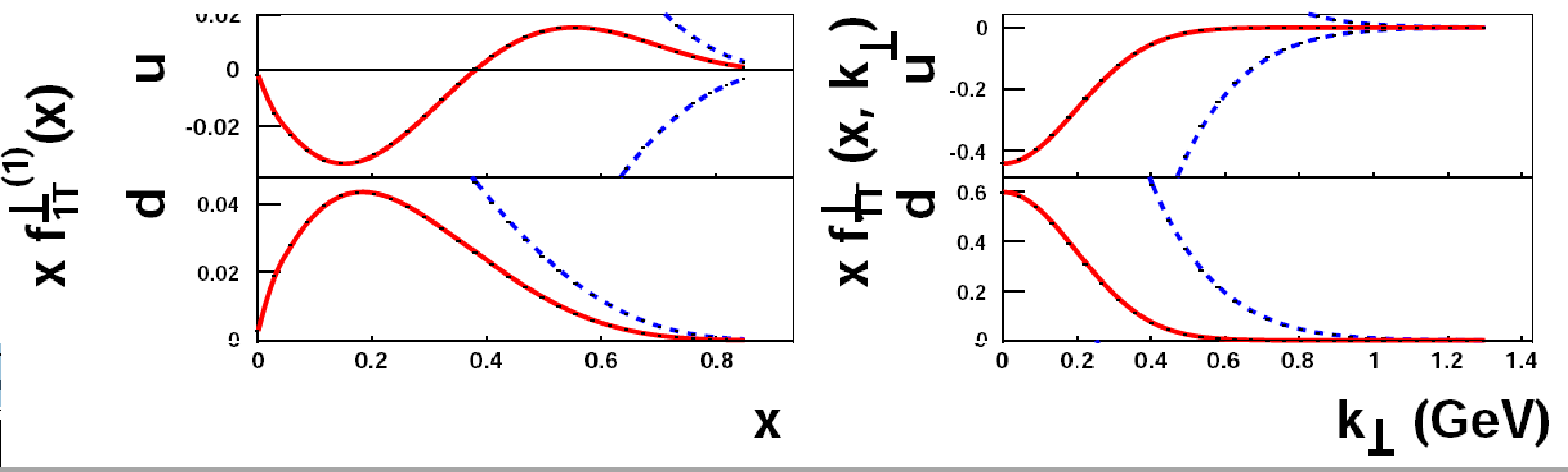
Twist-3

using PDF GRV98 and FF DSSV

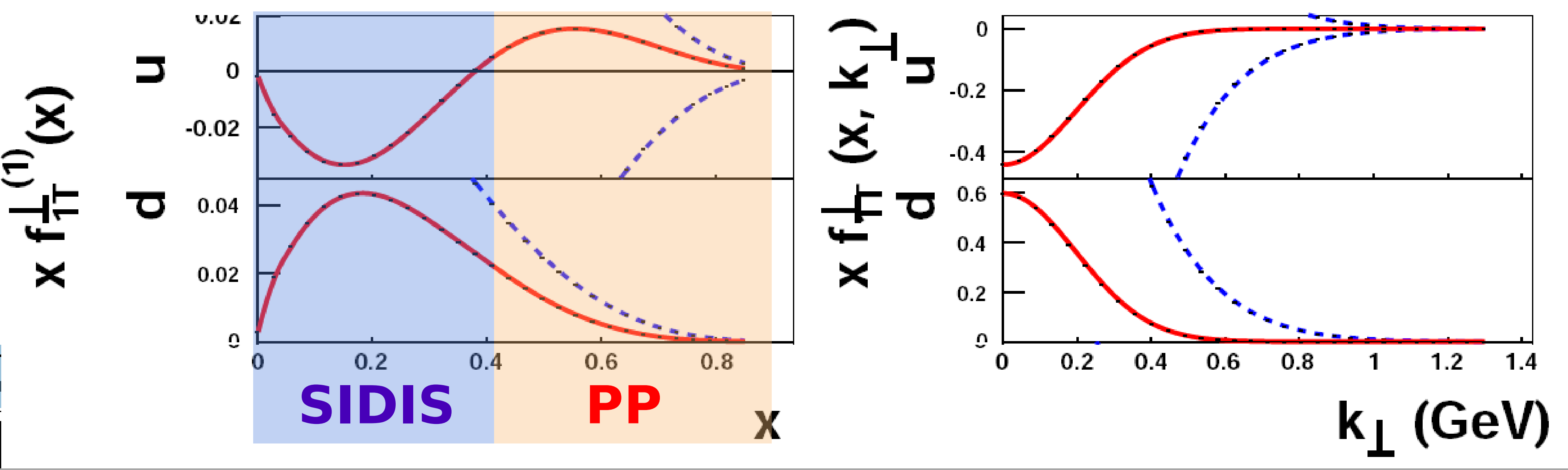
Results: Sivers function



Sivers function has a node!

$$x_{node} \sim 0.4$$

Results: Sivers function



Sivers function has a node!

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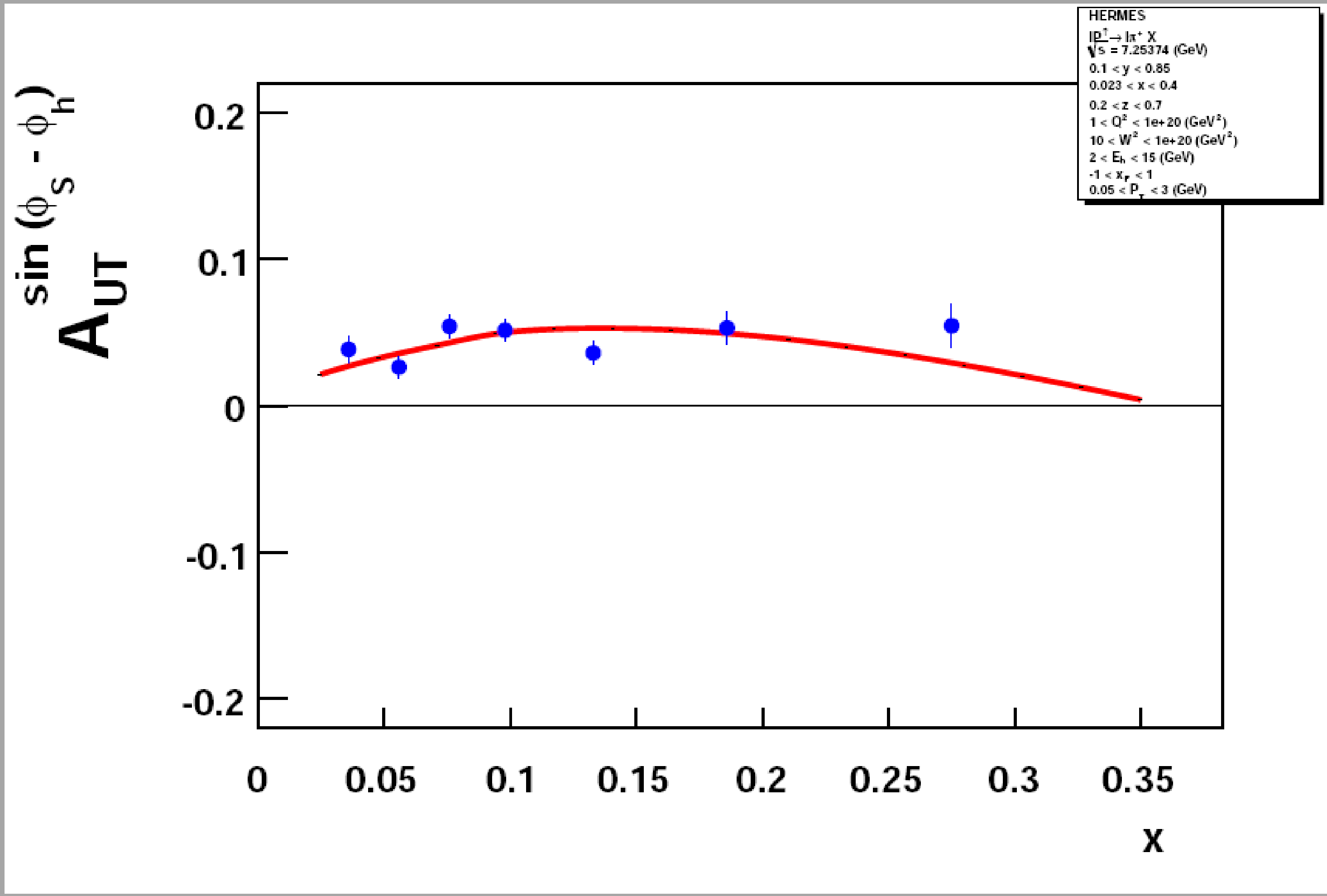
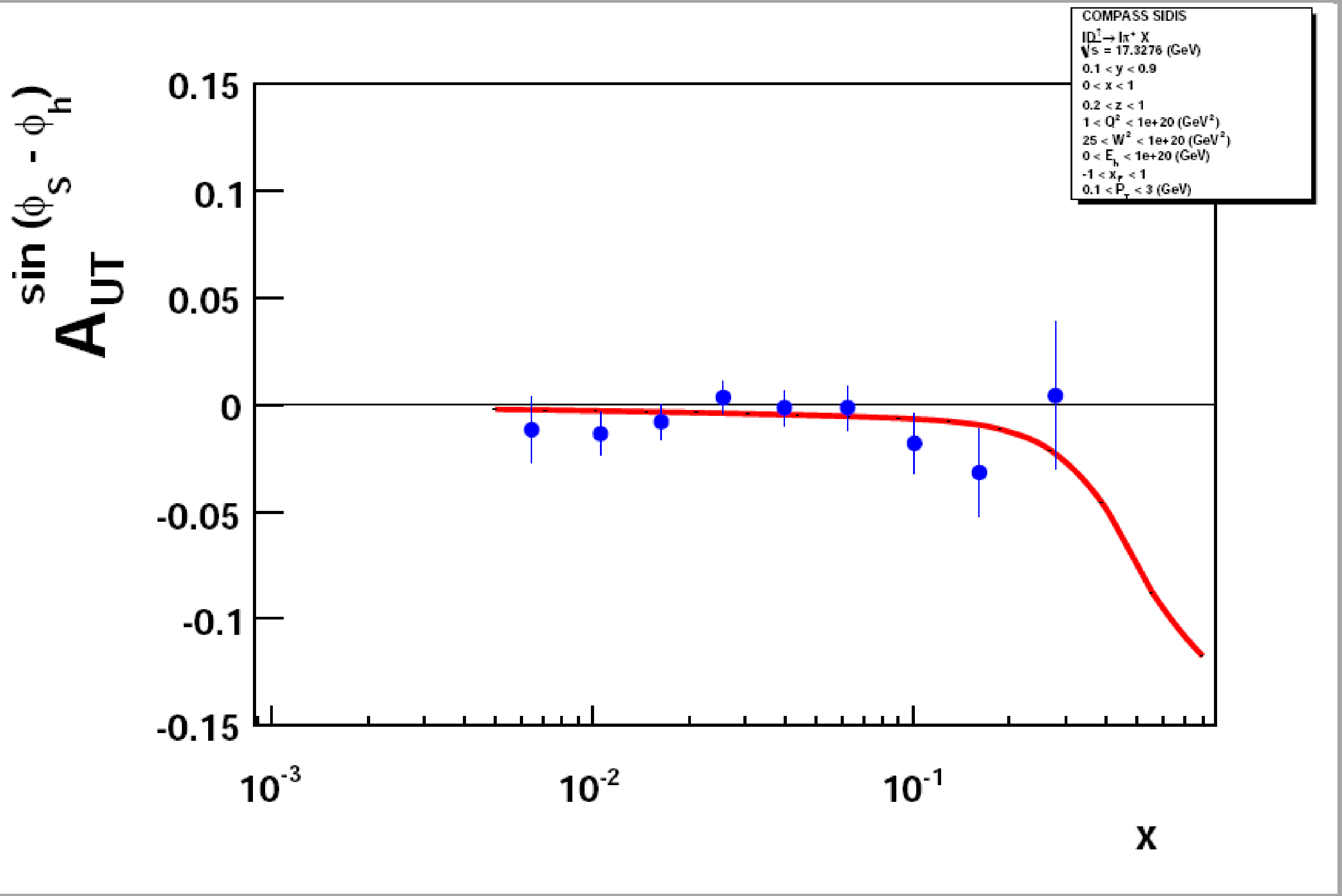
Results: SIDIS



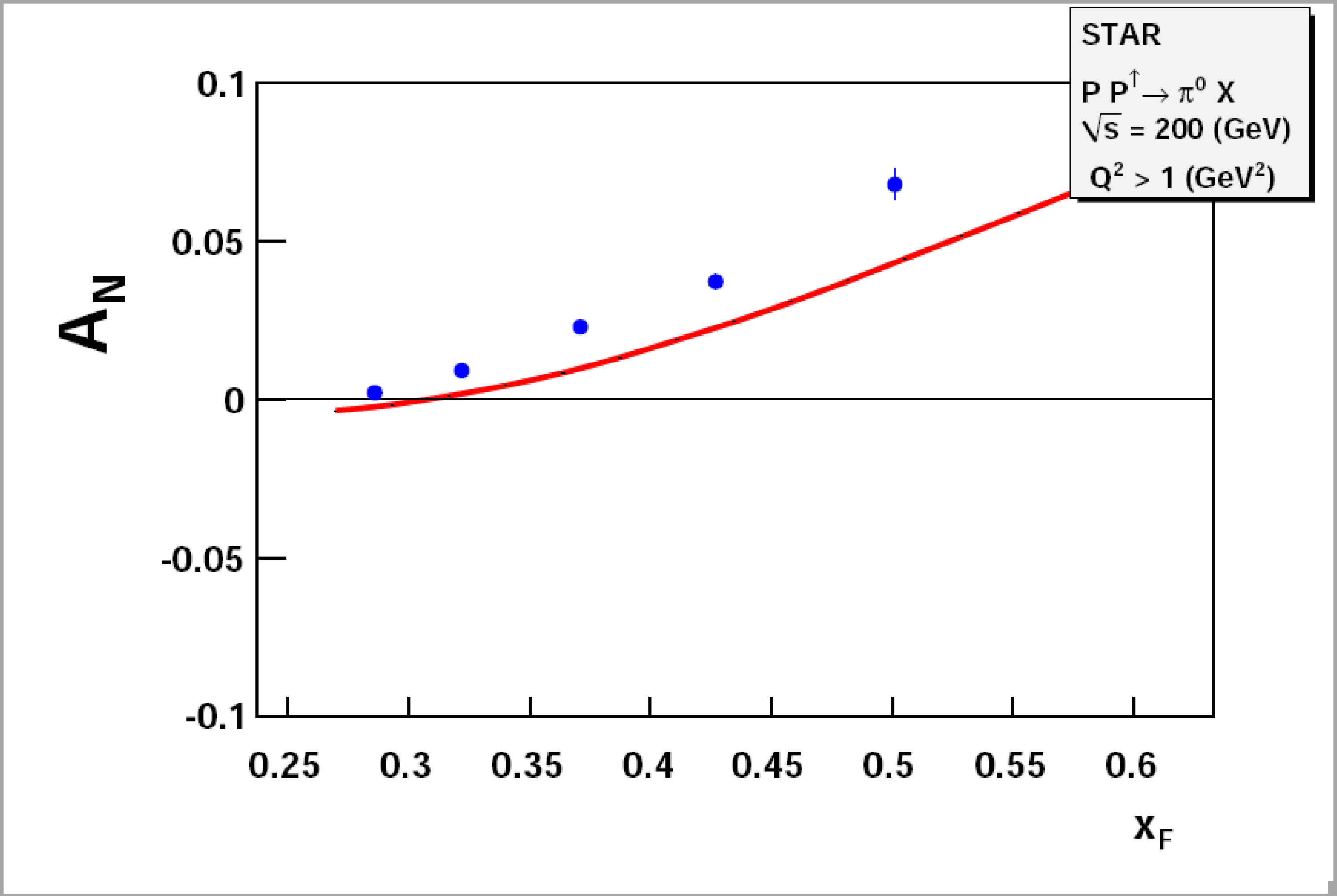
HERMES data, good description

Results: SIDIS



COMPASS data, good description

Results: PP



STAR data $\pi^0, \; y = 3.7$, reasonable description

… but something is missing!

What is missing?

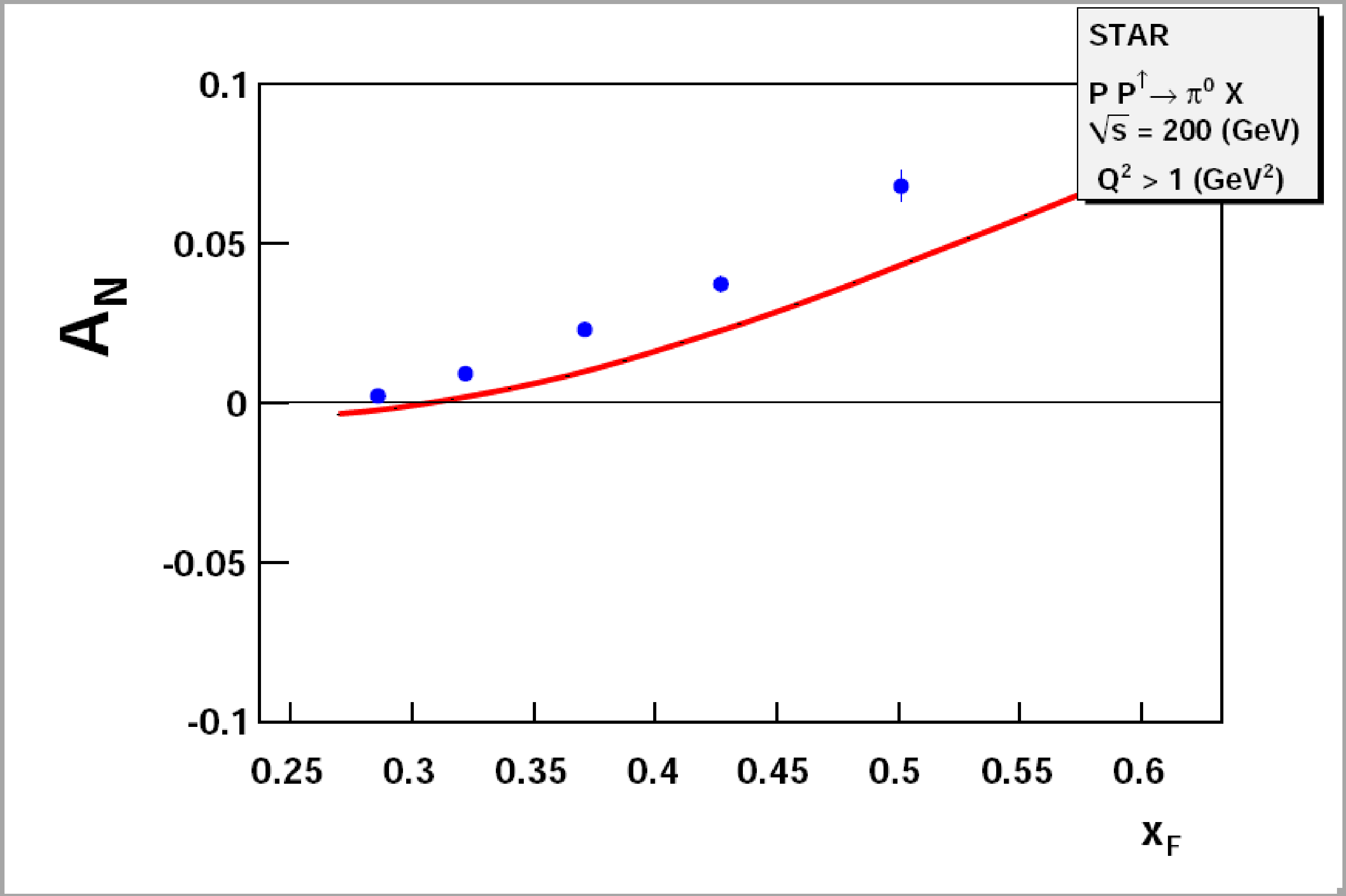
Twist-3 formalism:

$$\mathbf{A_N} \sim \mathbf{T_F} \otimes \sigma \otimes \mathbf{D_1} + \mathbf{h_1} \otimes \sigma \otimes \mathbf{H_F} + \ldots$$

We considered only Sivers effect, SGP. Other parts should be added: sea-quarks, SFP contribution, Collins effect etc.

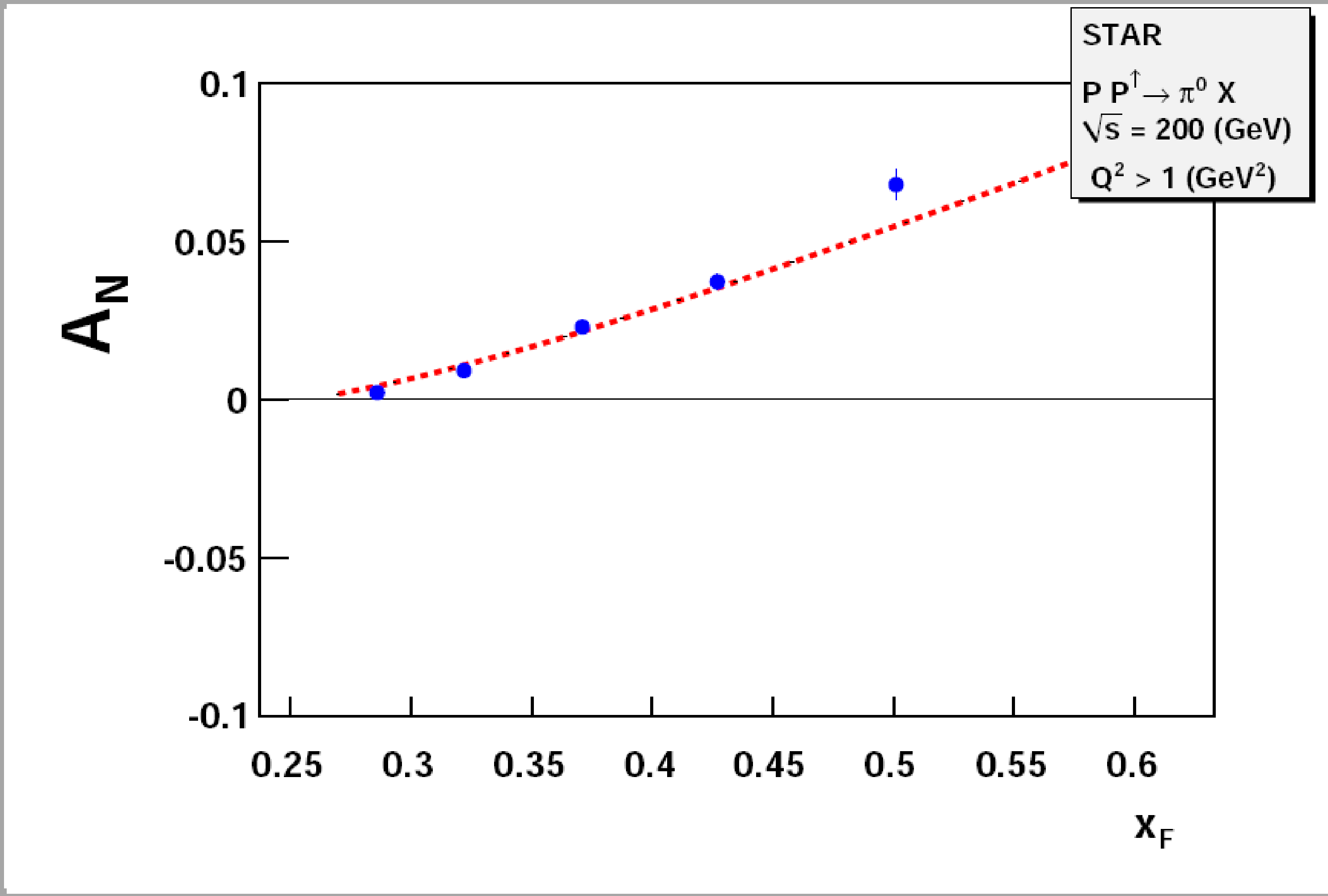
For **Global analysis** one should combine
SIDIS, PP and e^+e^- data

PP scale dependence



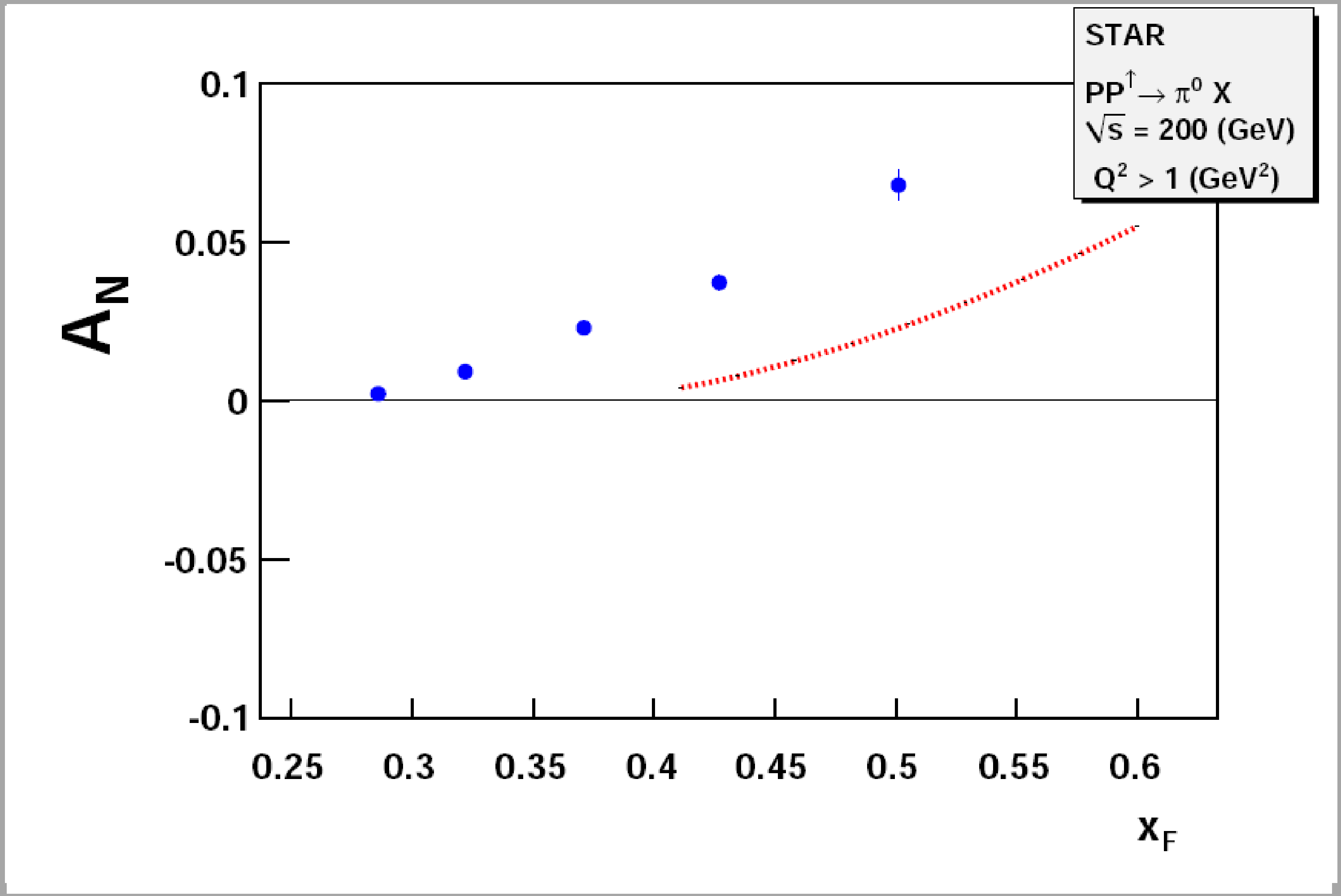
STAR data $$\mathbf{Q = P_T}$$

PP scale dependence



STAR data $$Q = 2P_T$$

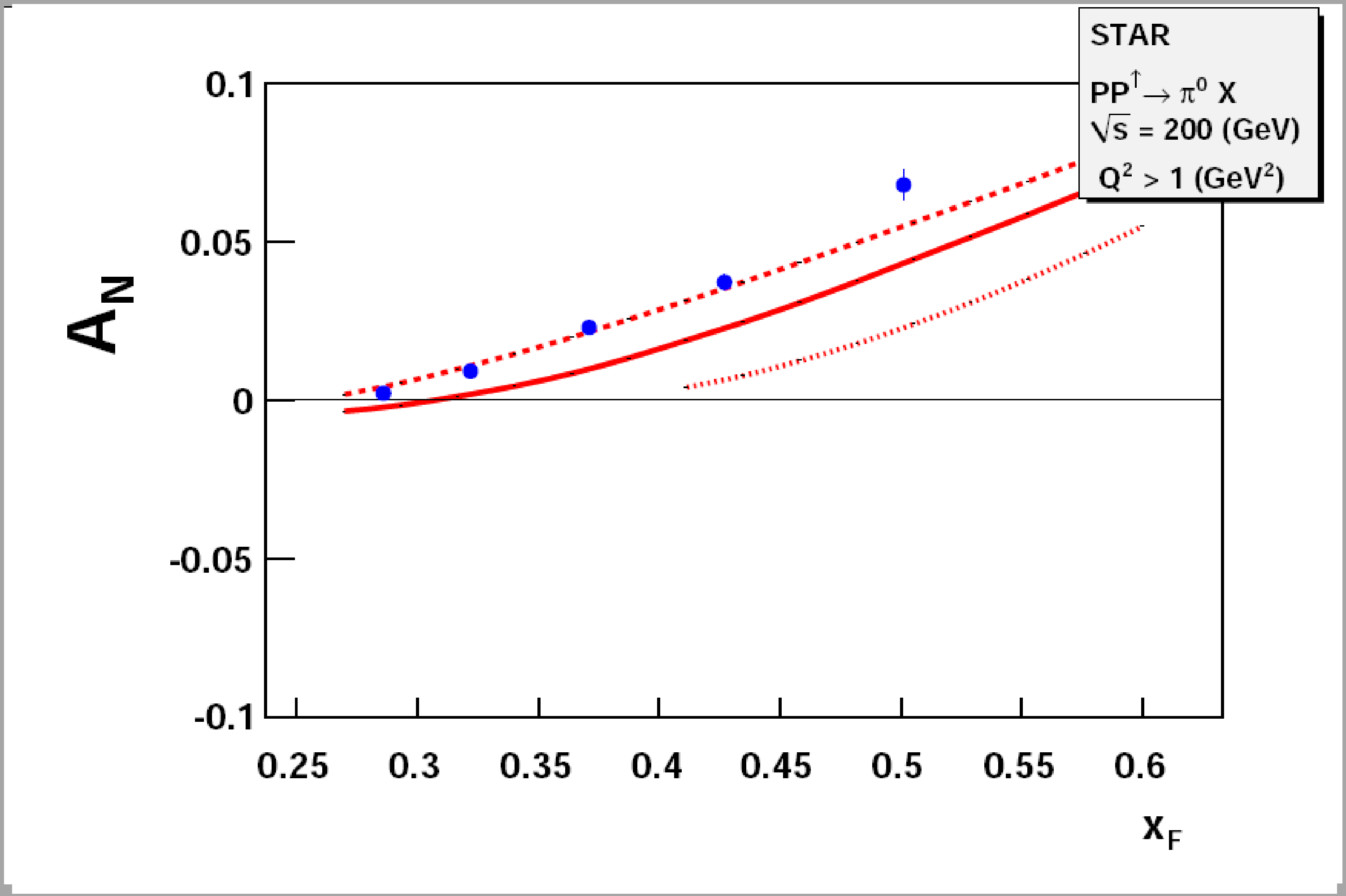
PP scale dependence



STAR data

$$Q = P_T/2$$

PP scale dependence



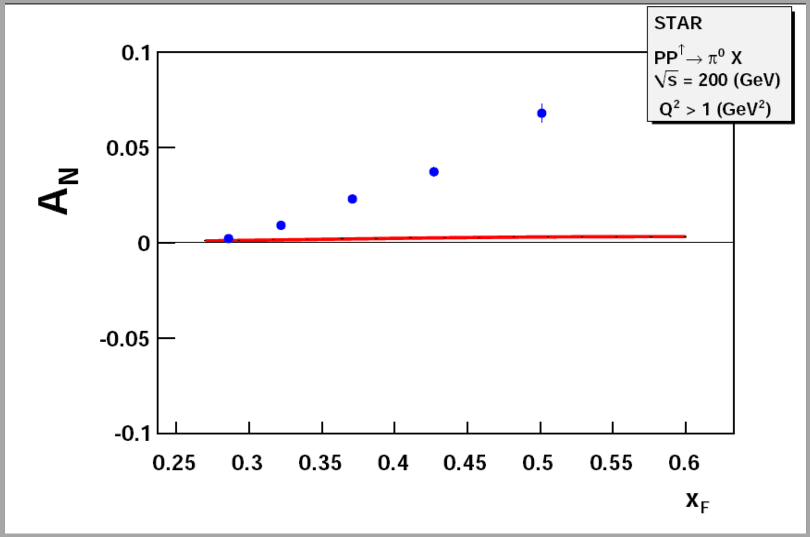
STAR data $\mathbf{Q = P_T/2 ... 2PT}$

Twist-3 Collins effect

$$A_N \sim h_1 \otimes \sigma \otimes H_F$$

Where twist-3 function is related to Collins FF

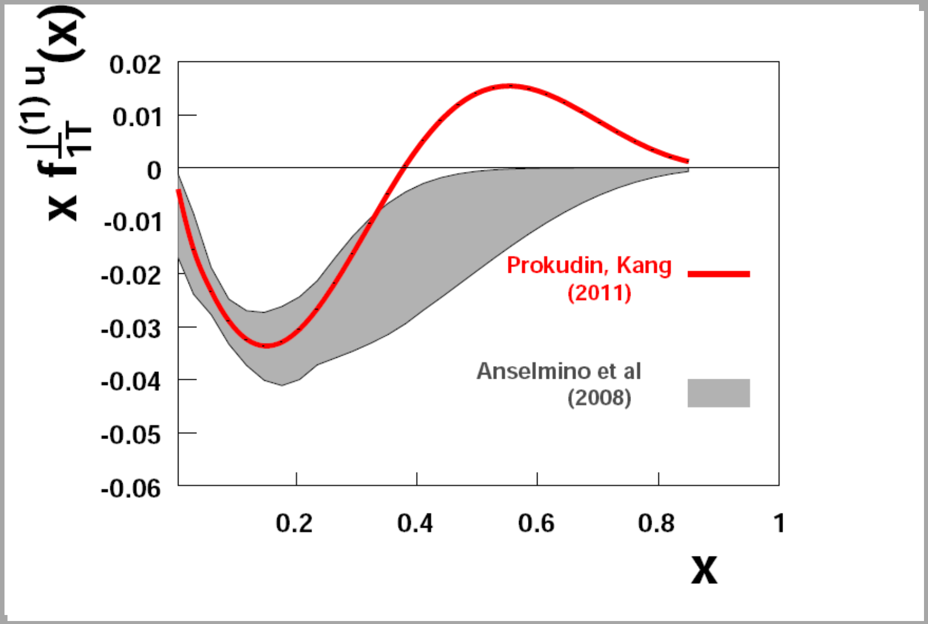
Kang, Yuan, Zhou (2009) $H_F = -\frac{zM_h}{2} H_1^{\perp(1)}$

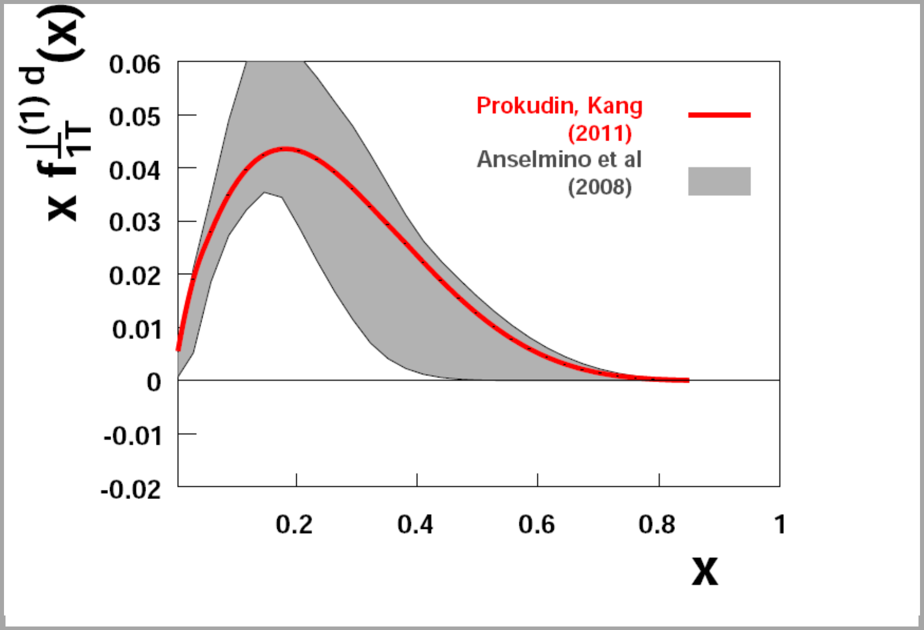


STAR data,
Collins function from
Anselmino et al (2008)

Collins effect is suppressed, but
z > 0.5 region is not yet explored

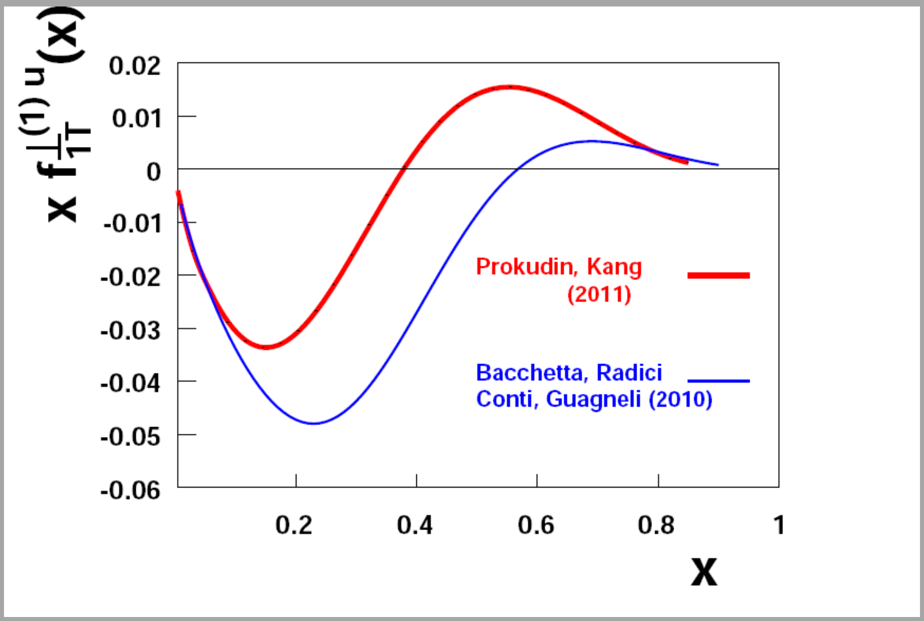
Comparison with Anselmino et al

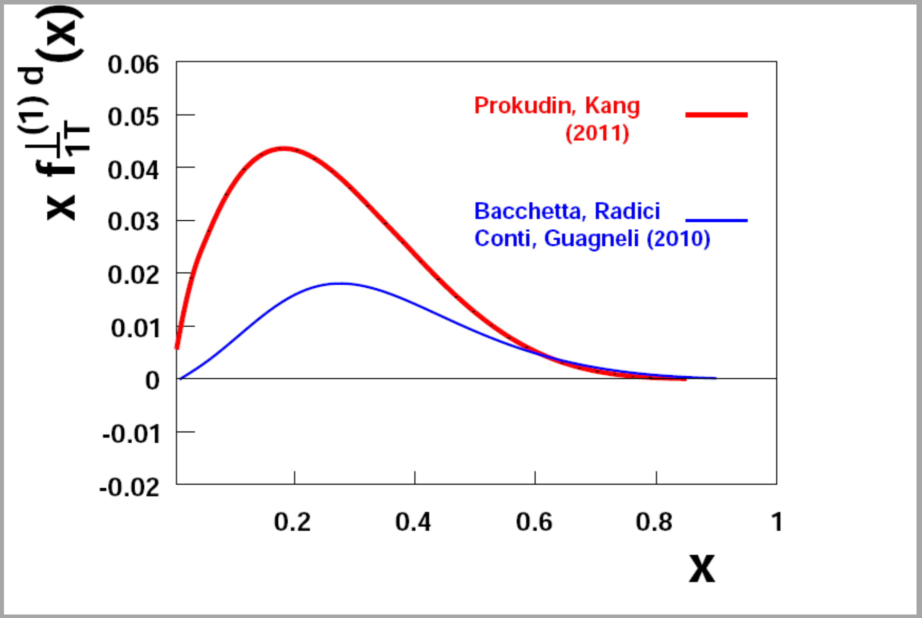




Comparison with Sivers function extracted from SIDIS only

Comparison with models





This result compared with quark -diquark model calculation

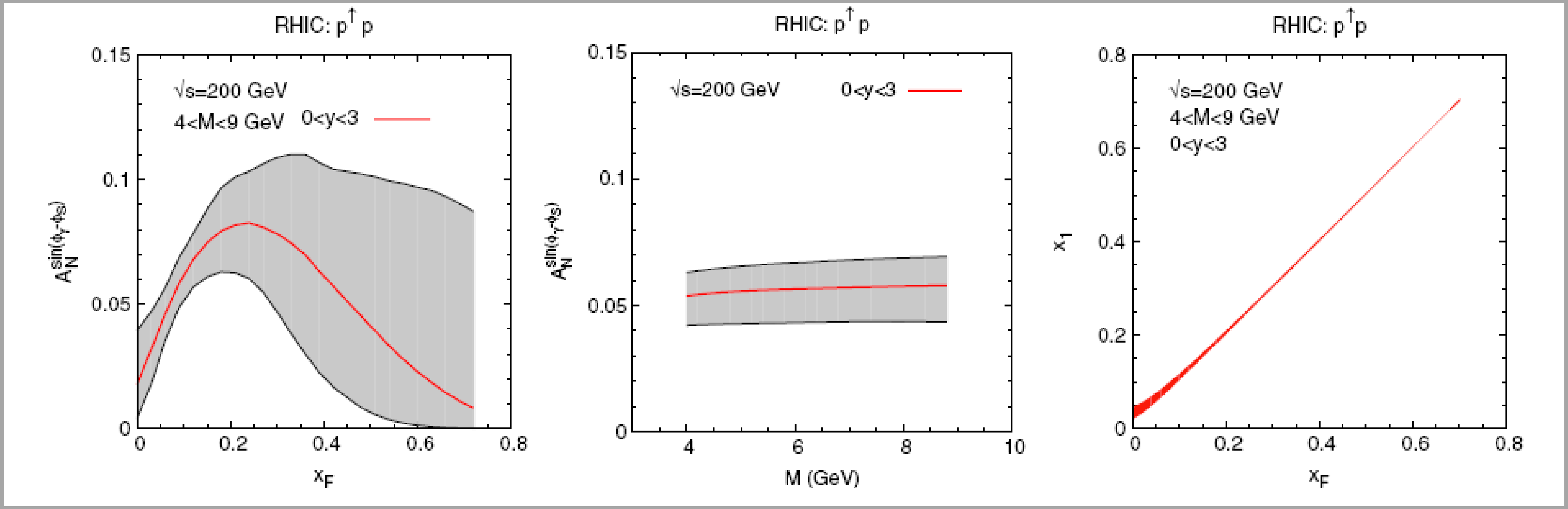
Drell Yan

$$A_N = \frac{\sum_q f_{1T}^{\perp q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}{\sum_q f_1^{q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}$$

Analysis at LO in hadronic cm frame
Anselmino et al (2009)

$$x_1 = \frac{x_F + \sqrt{x_F^2 + 4M^2/s}}{2} \approx x_F$$

In DY we probe Sivers function at x_F
Anselmino et al (2009)



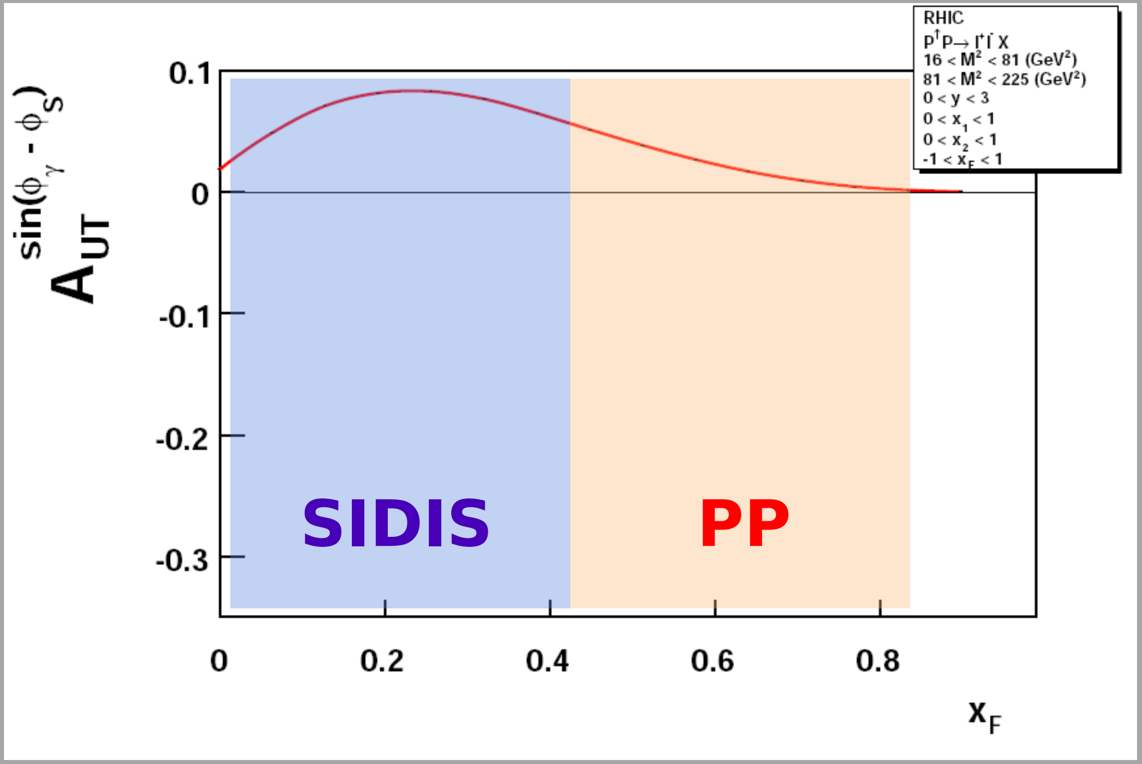
Drell Yan

$$A_N = \frac{\sum_q f_{1T}^{\perp q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}{\sum_q f_1^{q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}$$

Analysis at LO in hadronic cm frame

Kang, AP (2011)

Anselmino et al 2009



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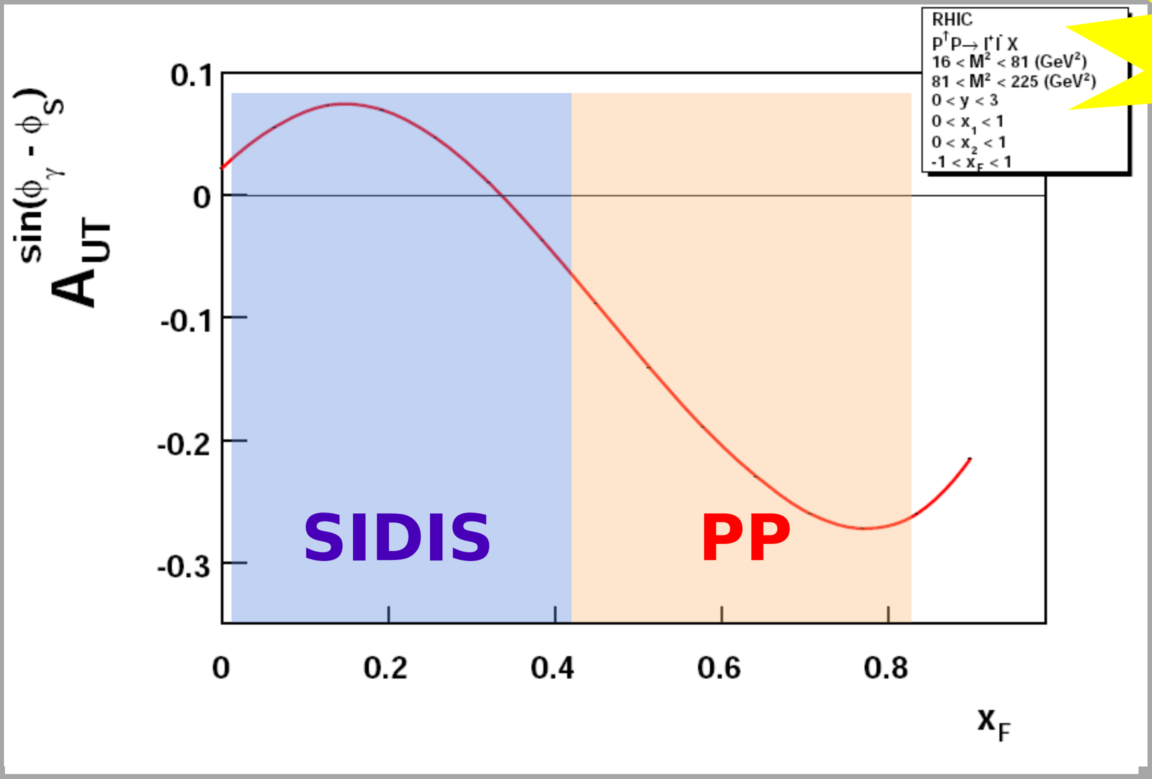
AP, Kang 2011

Analysis at LO in hadronic cm frame

Kang, AP (2011)

New!



Drell Yan

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AP, Kang 2011

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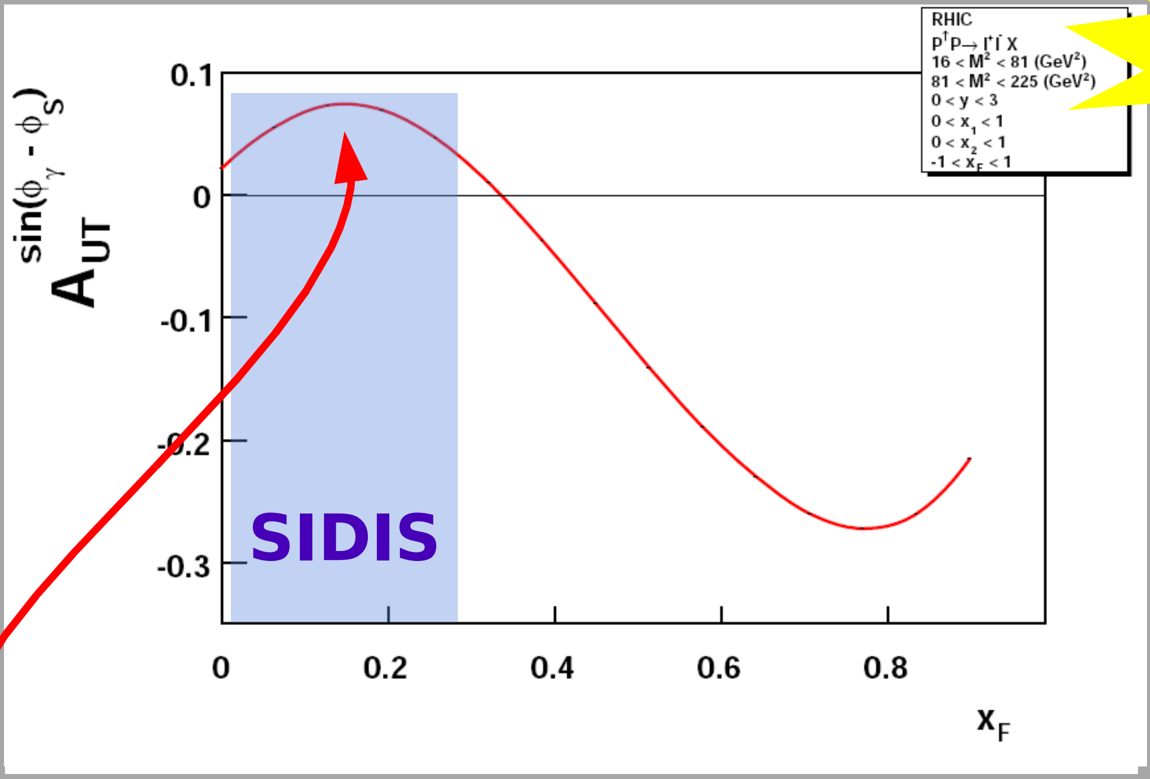


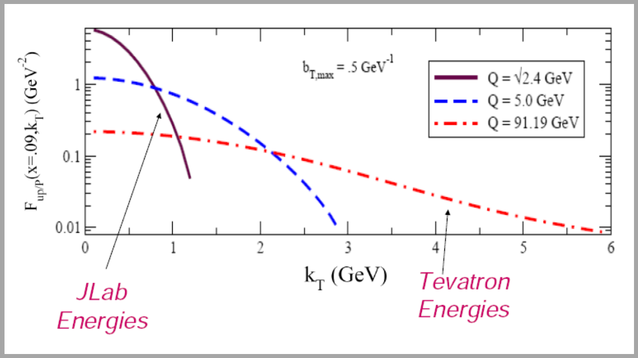
To measure in order to check

$$-f_{1T}^{\perp}|_{DY} = f_{1T}^{\perp}|_{SIDIS}$$

Future of TMD&Twist-3 phenomenology

Global analysis of SIDIS, PP and e^+e^- data using TMD and twist-3 formalisms.
Kang, AP (2011), others ...

TMD phenomenology:
NLO accuracy
Collins (2011), Aybat, Rogers (2011), ...



Twist-3 phenomenology:
NLO accuracy of hard functions
Vogelsang, Yuan (2009), ...

$$A_N \propto \Delta\sigma(Q, S_\perp) \propto T_f^{(3)}(x,x) \otimes \hat{H}_f \otimes \ldots$$

Beyond LO!

CONCLUSIONS

- Sivers function may have a node
- SIDIS, $e^{+}e^{-}$ and PP data can be used in global analysis
- $\mathbf{x_F} \sim \mathbf{0...0.2}$ is "safe" for DY measurement

CONCLUSIONS

- Sivers function may have a node
- SIDIS, e^+e^- and PP data can be used in global analysis
- Working together

... we can resolve puzzles!