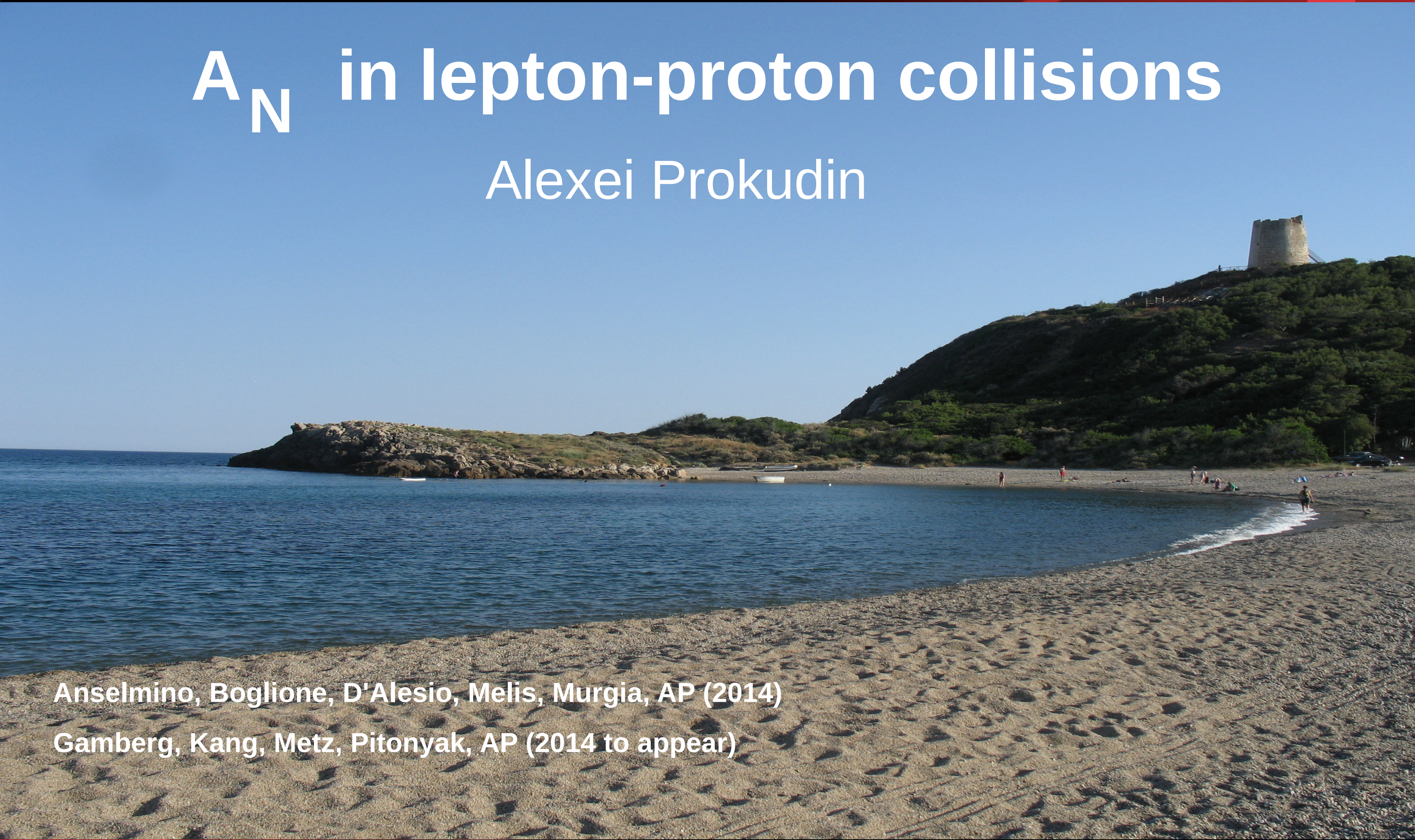
A_N in lepton-proton collisions

Alexei Prokudin

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

Gamberg, Kang, Metz, Pitonyak, AP (2014 to appear)



June 12, 2014

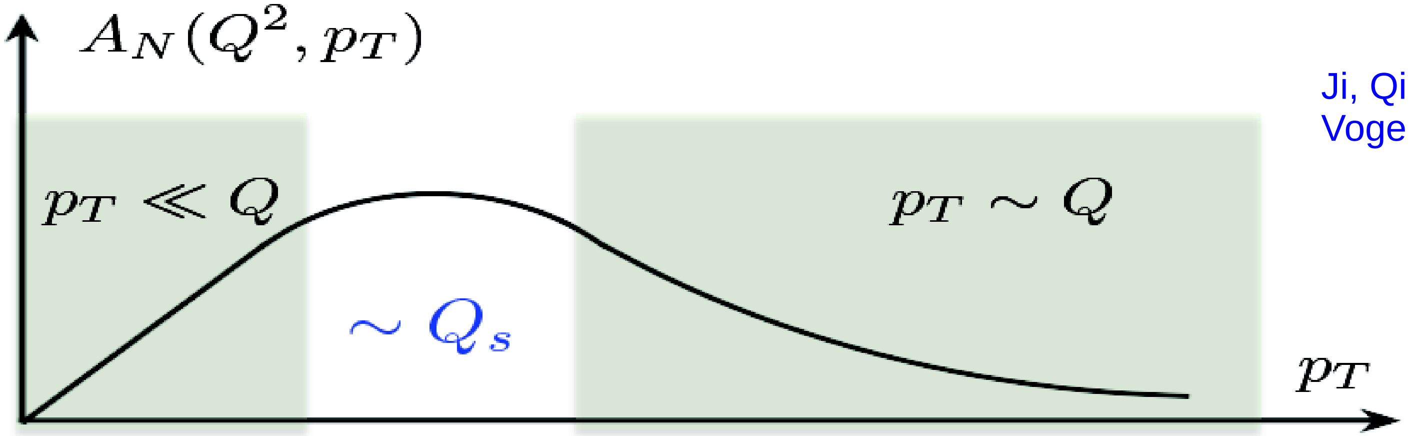
Collinear vs TMD factorization

Two types of factorization

$$Q_1, Q_2, \ldots \gg \Lambda_{QCD}$$ Collinear

$$Q_1 \gg Q_2 > \Lambda_{QCD}$$ TMD

- Twist-3 – integration over parton momenta
- TMD – direct information on partonic transverse motion



Ji, Qiu, Yuan, Vogelsang, Koike

Intermediate region, both formalisms are applicable and related in SIDIS

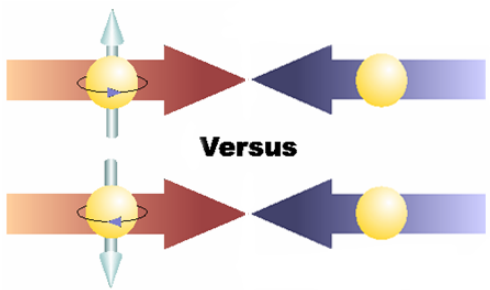
Ji, Qiu, Vogelsang, Yuan (2006) etc

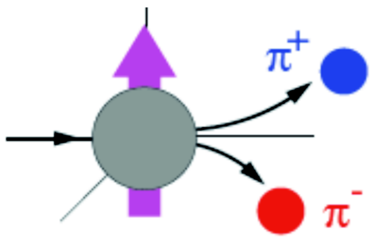
Consistent in the overlap region!

Asymmetry

See talks by Mauro Anselmino, Yuji Koike, Daniel Pitonyak

Consider A_N in hadron hadron collision:





$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

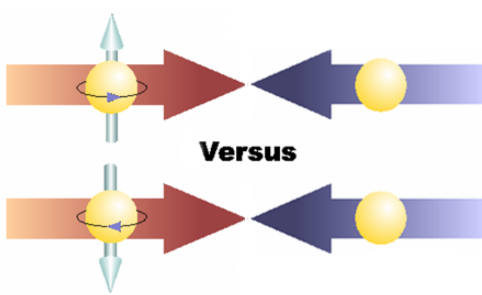
One scale P_T

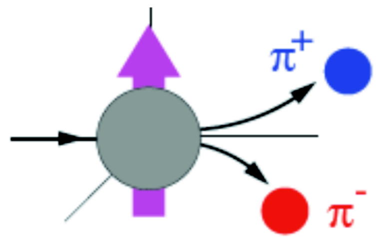
Sub process $qq,\ gq,\ gg$

Asymmetry

See talk by Les Bland

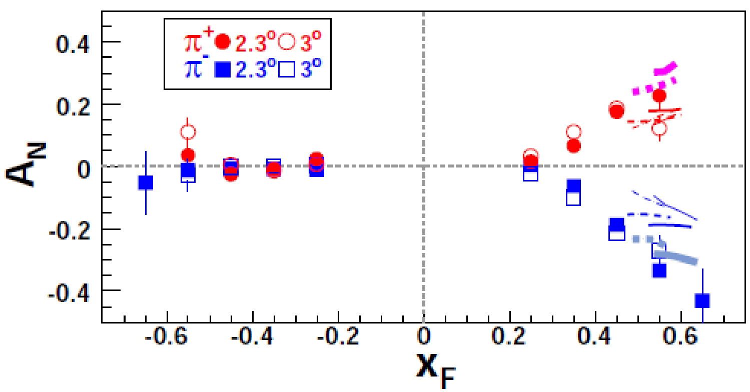
Consider A_N in hadron hadron collision:

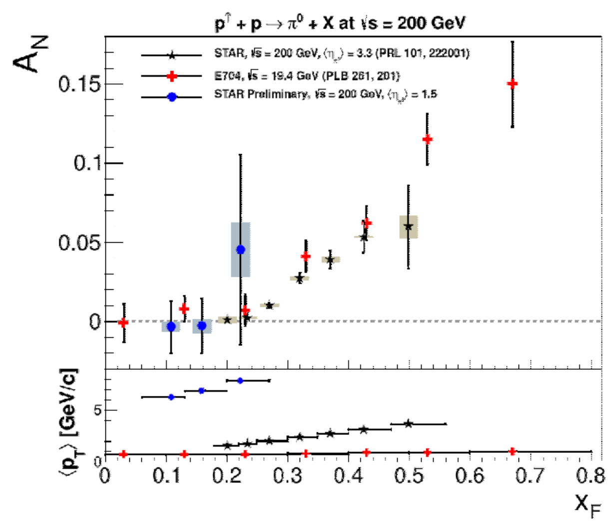




$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$\sqrt{s} = 62$ GeV

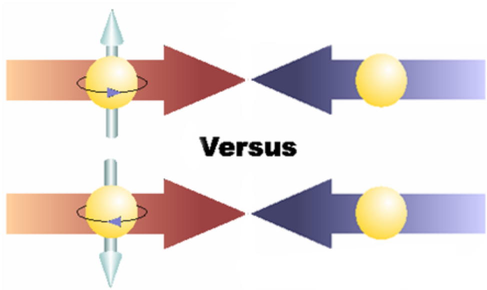


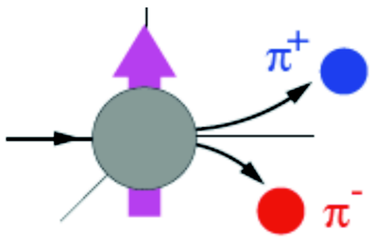


RHIC: PHENIX, BRAHMS and STAR

Asymmetry

Consider A_N in hadron hadron collision:





$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

TMD phenomenology — See talk by Mauro Anselmino

Sivers, Collins effects etc

Anselmino, D'Alesio, Murgia, Boglione etc

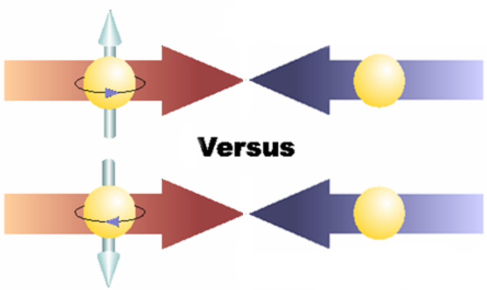
Twist-3 phenomenology — See talks by Yuji Koike, Daniel Pitonyak

Effects in distribution and fragmentation

Vogelsang, Yuan, Koike, Metz, Pitonyak, Kang etc

Lepton – Proton

Consider A_N in lepton hadron collision:



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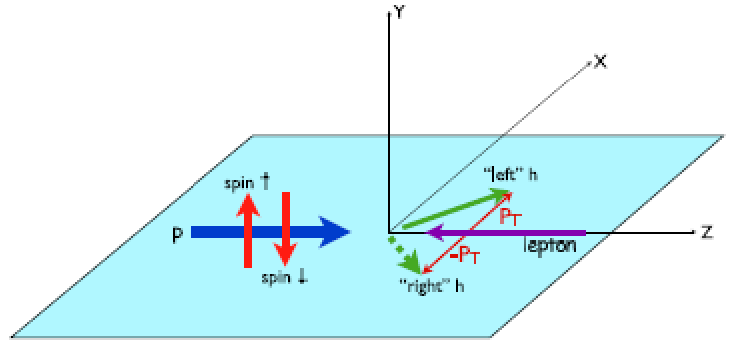
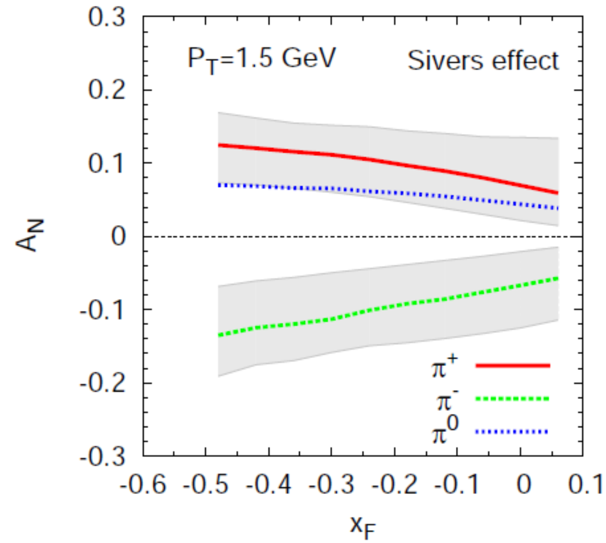


Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2010)

One scale P_T

Sub process ℓq



Backward region

Assuming TMD factorization

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2010, 2014)

$$d\sigma^{p\ell\to hX} = \sum_q f_{q/p}(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{q\ell\to q\ell} \otimes D_{h/q}(z, \boldsymbol{p}_\perp; Q^2)$$

Asymmetry

$$d\sigma^\uparrow - d\sigma^\downarrow = \sum_q \Big\{ \Delta^N f_{q/p^\uparrow} \cos\phi_q \otimes d\hat{\sigma} \otimes D_{h/q}$$

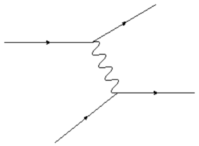
$$+ h_1^{q/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{h/q^\uparrow} \cos\phi_C$$

$$+ h_{1T}^{\perp q/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{h/q^\uparrow} \cos(\phi_C - 2\phi_q) \Big\}$$

Sivers x Unpolarised FF

Transversity x Collins FF

Pretselosity x Collins FF



$$d\hat{\sigma} \simeq e_q^2 \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \qquad d\Delta\hat{\sigma} \simeq -e_q^2 \frac{\hat{s}\hat{u}}{\hat{t}^2}$$

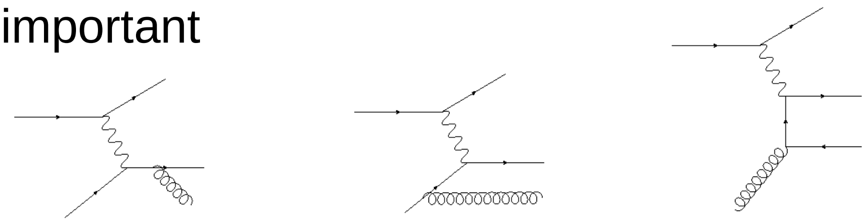
Elementary cross-sections

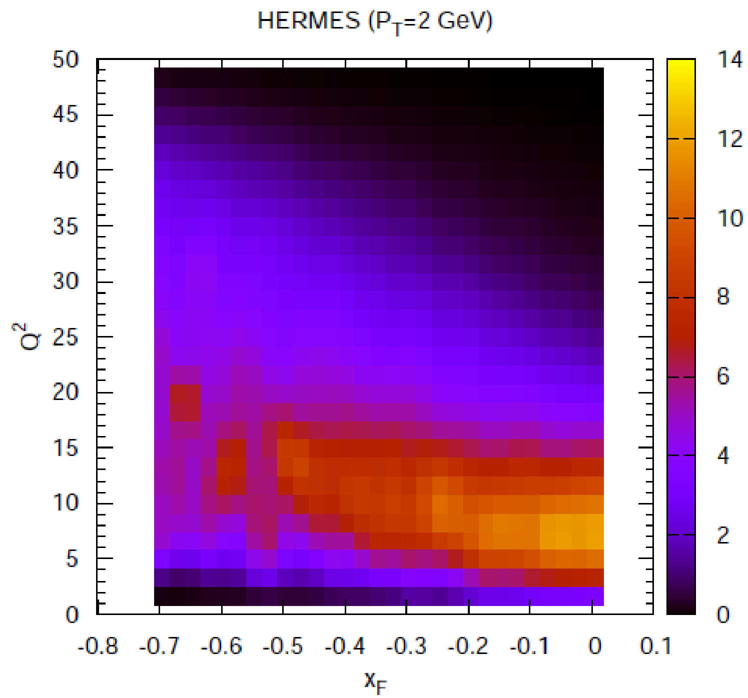
$$\phi_C \equiv \phi_h^H + \phi_{q'}$$

Hard scattering – large $Q^2 \equiv -\hat{t} = -(p_{q'} - p_q)^2 > 1\ (\mathrm{GeV}^2)$

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2010, 2014)

Photo-production might dominate cross section and higher orders will be important





Monte-carlo TMD integration indicates that in backward region Q^2 can be large

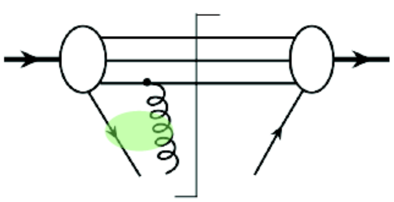
Twist-3

Kang, Metz, Qiu, Zhou 2011
Eguchi, Koike, Tanaka 2007
Kang, Yuan, Zhou 2010
Metz, Pitonyak 2013

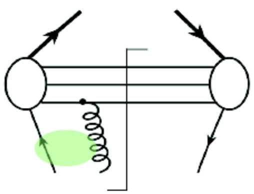
$$d\sigma = H \otimes f_{a/A(3)} \otimes D_{c/C(2)}$$

$$+ H'' \otimes f_{a/A(2)} \otimes D_{c/C(3)}$$

$T^{(3)}(x, x, S_\perp) \propto$



$D^{(3)}(z, z) \propto$



Twist-3

Kang, Metz, Qiu, Zhou 2011
Eguchi, Koike, Tanaka 2007
Kang, Yuan, Zhou 2010
Metz, Pitonyak 2013

$$
\begin{aligned}
P_h^0 \frac{d\sigma_{UT}}{d^3\vec{P}_h} = -\frac{8\alpha_{\rm em}^2}{S}\, \varepsilon_{\perp\mu\nu}\, S_\perp^\mu\, P_{h\perp}^\nu \sum_q e_q^2 \int_{z_{\rm min}}^1 \frac{dz}{z^3}\, \frac{1}{S+T/z}\, \frac{1}{x} \\
\times \Bigg\{ -\frac{\pi M}{\hat{u}}\, D_1^{h/q}(z) \left(F_{FT}^q(x,x) - x\frac{dF_{FT}^q(x,x)}{dx} \right) \left[\frac{\hat{s}(\hat{s}^2+\hat{u}^2)}{2\hat{t}^3} \right] \\
+ \frac{M_h}{-x\hat{u}-\hat{t}}\, h_1^q(x) \Bigg\{ \left(\hat{H}^{h/q}(z) - z\frac{d\hat{H}^{h/q}(z)}{dz} \right) \left[\frac{(1-x)\hat{s}\hat{u}}{\hat{t}^2} \right] \\
+ \frac{1}{z} H^{h/q}(z) \left[\frac{\hat{s}(\hat{s}^2+(x-1)\hat{u}^2)}{\hat{t}^3} \right] + 2z^2 \int_z^\infty \frac{dz_1}{z_1^2}\, PV \frac{1}{\frac{1}{z}-\frac{1}{z_1}}\, \hat{H}_{FU}^{h/q,\Im}(z,z_1) \left[\frac{x\hat{s}^2\hat{u}}{\xi_z\, \hat{t}^3} \right] \Bigg\} \Bigg\}
\end{aligned}
$$

Twist-3

Kang, Metz, Qiu, Zhou 2011
Eguchi, Koike, Tanaka 2007
Kang, Yuan, Zhou 2010
Metz, Pitonyak 2013

$$P_h^0 \frac{d\sigma_{UT}}{d^3\vec{P}_h} = -\frac{8\alpha_{\rm em}^2}{S}\,\varepsilon_{\perp\mu\nu}\,S_\perp^\mu\,P_{h\perp}^\nu \sum_q e_q^2 \int_{z_{\rm min}}^1 \frac{dz}{z^3}\,\frac{1}{S+T/z}\,\frac{1}{x}$$

$$\times\Bigg\{-\frac{\pi M}{\hat{u}}\,D_1^{h/q}(z)\left(F_{FT}^q(x,x) - x\frac{dF_{FT}^q(x,x)}{dx}\right)\left[\frac{\hat{s}(\hat{s}^2+\hat{u}^2)}{2\hat{t}^3}\right]$$

$$+\frac{M_h}{-x\hat{u}-\hat{t}}\,h_1^q(x)\,\Bigg\{\left(\hat{H}^{h/q}(z) - z\frac{d\hat{H}^{h/q}(z)}{dz}\right)\left[\frac{(1-x)\hat{s}\hat{u}}{\hat{t}^2}\right]$$

$$+\frac{1}{z}H^{h/q}(z)\left[\frac{\hat{s}(\hat{s}^2+(x-1)\hat{u}^2)}{\hat{t}^3}\right] + 2z^2\int_z^\infty \frac{dz_1}{z_1^2}\,PV\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\,\hat{H}_{FU}^{h/q,\Im}(z,z_1)\left[\frac{x\hat{s}^2\hat{u}}{\xi_z\,\hat{t}^3}\right]\Bigg\}\Bigg\}$$

"Sivers"

$$\pi\,F_{FT}^q(x,x) = \int d^2\vec{k}_\perp\,\frac{\vec{k}_\perp^2}{2M^2}\,f_{1T}^{\perp q}(x,\vec{k}_\perp^2)\Big|_{\rm SIDIS}$$

Boer, Mulders, Piljman 2003

Twist-3

Kang, Metz, Qiu, Zhou 2011
Eguchi, Koike, Tanaka 2007
Kang, Yuan, Zhou 2010
Metz, Pitonyak 2013

$$P_h^0 \frac{d\sigma_{UT}}{d^3\vec{P}_h} = -\frac{8\alpha_{\rm em}^2}{S}\,\varepsilon_{\perp\mu\nu}\,S_\perp^\mu\,P_{h\perp}^\nu \sum_q e_q^2 \int_{z_{\min}}^1 \frac{dz}{z^3}\,\frac{1}{S+T/z}\,\frac{1}{x}$$

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“Sivers”

$$+\frac{M_h}{-x\hat{u}-\hat{t}}\,h_1^q(x)\left\{\left(\hat{H}^{h/q}(z) - z\frac{d\hat{H}^{h/q}(z)}{dz}\right)\left[\frac{(1-x)\hat{s}\hat{u}}{\hat{t}^2}\right]\right.$$

“Collins”

$$\left.+\frac{1}{z}H^{h/q}(z)\left[\frac{\hat{s}(\hat{s}^2+(x-1)\hat{u}^2)}{\hat{t}^3}\right] + 2z^2\int_z^\infty \frac{dz_1}{z_1^2}\,PV\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\,\hat{H}_{FU}^{h/q,\Im}(z,z_1)\left[\frac{x\hat{s}^2\hat{u}}{\xi_z\,\hat{t}^3}\right]\right\}\Bigg\}$$

$$\pi F_{FT}^q(x,x) = \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^{\,2}}{2M^2}\,f_{1T}^{\perp q}(x,\vec{k}_\perp^{\,2})\Big|_{\rm SIDIS}$$

Boer, Mulders, Piljman 2003

$$\hat{H}^{h/q}(z) = z^2\int d^2\vec{p}_\perp \frac{\vec{p}_\perp^{\,2}}{2M_h^2}\,H_1^{\perp h/q}(z, z^2\vec{p}_\perp^{\,2})$$

Yuan, Zhou 2009
Kang, Yuan, Zhou 2010
Metz, Pitonyak 2013

Twist-3

Kang, Metz, Qiu, Zhou 2011
Eguchi, Koike, Tanaka 2007
Kang, Yuan, Zhou 2010
Metz, Pitonyak 2013

$$P_h^0 \frac{d\sigma_{UT}}{d^3\vec{P}_h} = -\frac{8\alpha_{\rm em}^2}{S}\,\varepsilon_{\perp\mu\nu}\,S_\perp^\mu\,P_{h\perp}^\nu \sum_q e_q^2 \int_{z_{\rm min}}^1 \frac{dz}{z^3}\,\frac{1}{S+T/z}\,\frac{1}{x}$$

$$\times\Bigg\{-\frac{\pi M}{\hat{u}}\,D_1^{h/q}(z)\left(F_{FT}^q(x,x) - x\frac{dF_{FT}^q(x,x)}{dx}\right)\left[\frac{\hat{s}(\hat{s}^2+\hat{u}^2)}{2\hat{t}^3}\right]$$

“Sivers”

$$+\frac{M_h}{-x\hat{u}-\hat{t}}\,h_1^q(x)\,\Bigg\{\left(\hat{H}^{h/q}(z) - z\frac{d\hat{H}^{h/q}(z)}{dz}\right)\left[\frac{(1-x)\hat{s}\hat{u}}{\hat{t}^2}\right]$$

“Collins”

$$+\frac{1}{z}\,H^{h/q}(z)\left[\frac{\hat{s}(\hat{s}^2+(x-1)\hat{u}^2)}{\hat{t}^3}\right] + 2z^2\int_z^\infty \frac{dz_1}{z_1^2}\,PV\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\,\hat{H}_{FU}^{h/q,\Im}(z,z_1)\left[\frac{x\hat{s}^2\hat{u}}{\xi_z\,\hat{t}^3}\right]\Bigg\}\Bigg\}$$

“Collins-type”

$$\pi\,F_{FT}^q(x,x) = \int d^2\vec{k}_\perp\,\frac{\vec{k}_\perp^{\,2}}{2M^2}\,f_{1T}^{\perp q}(x,\vec{k}_\perp^{\,2})\Big|_{\rm SIDIS}$$

Boer, Mulders, Piljman 2003

$$\hat{H}^{h/q}(z) = z^2\int d^2\vec{p}_\perp\,\frac{\vec{p}_\perp^{\,2}}{2M_h^2}\,H_1^{\perp h/q}(z, z^2\vec{p}_\perp^{\,2})$$

Yuan, Zhou 2009
Kang, Yuan, Zhou 2010
Metz, Pitonyak 2013

$$H^{h/q}(z) = -2z\hat{H}^{h/q}(z) + 2z^3\int_z^\infty \frac{dz_1}{z_1^2}\,PV\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\,\hat{H}_{FU}^{h/q,\Im}(z,z_1)$$

Metz, Pitonyak 2013

See talk by Daniel Pitonyak

HERMES data

HERMES Physics Letters B 728 (2014) 183–190

$$d\sigma = d\sigma_{UU}[1+S_T \sin\psi\, A_{UT}^{\sin\psi}]$$

$\sin\psi = \hat{\boldsymbol{S}}_T \cdot (\hat{\boldsymbol{P}}_T \times \hat{\boldsymbol{k}})$ and $\hat{\boldsymbol{k}} = -\hat{\boldsymbol{p}}$

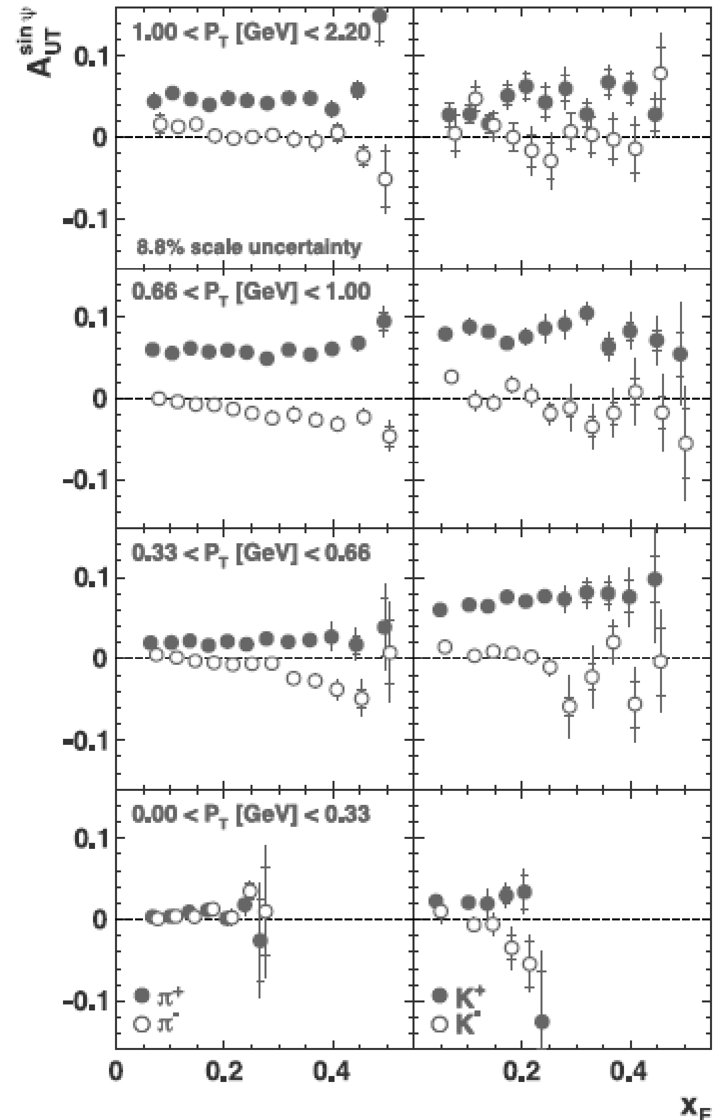
Left ↔ right interchanged, so that $x_F^H = -x_F$
positive mean backward hemisphere

$$A_{UT}^{\sin\psi}(x_F, P_T)|_{\mathrm{HERMES}} = A_N^{p^\uparrow \ell \to h X}(-x_F, P_T)$$

We can use only $P_T > 1\ (\mathrm{GeV})$

Only one bin $\langle P_T \rangle \simeq 1\ (\mathrm{GeV})$

Additional tagged sample with $Q^2 > 1\ (\mathrm{GeV}^2)$



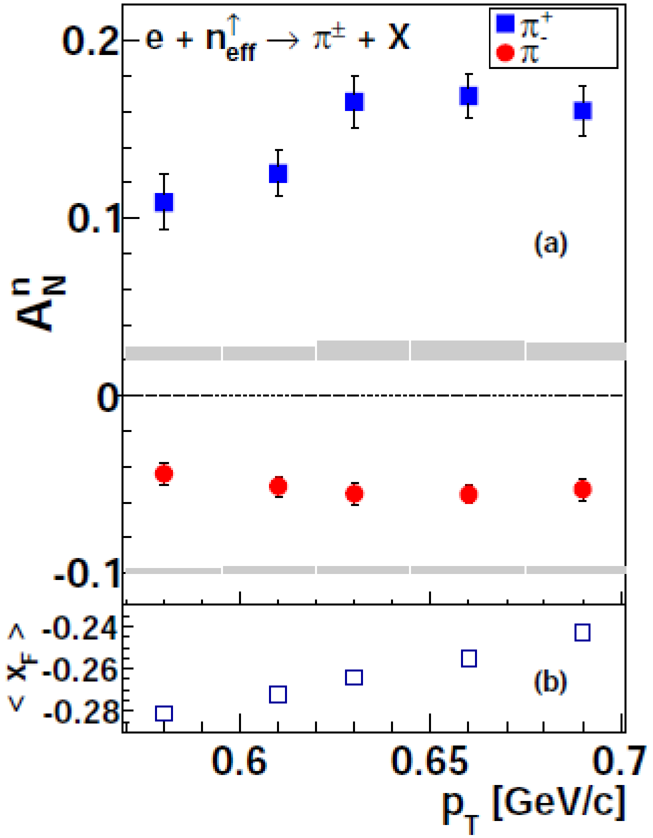
JLab data

JLab Phys. Rev. C 89, 042201 (2014)

Definition is such that

$$A_N(x_F)|_{\text{JLab}} = -A_N(x_F)$$

We can use only $P_T > 1\ (\text{GeV})$



Phenomenology TMD

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

Ingredients

Sivers and Collins mechanisms

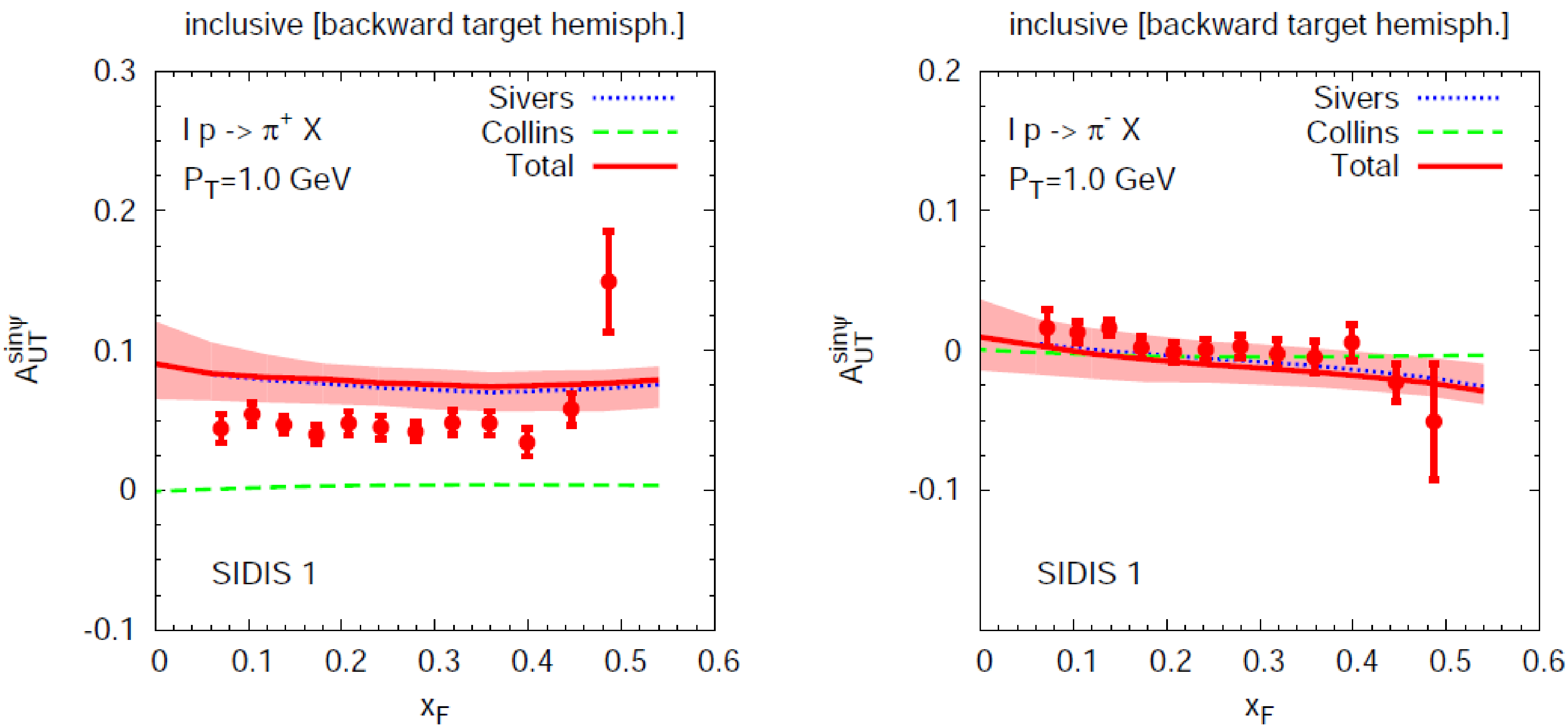
SIDIS I: Sivers extraction 2005 (Anselmino et al, 05) with Kretzer FF (Kretzer 2000),
Transversity and Collins FF extraction 2007 (Anselmino et al. 07)

SIDIS II: Sivers extraction 2009 with sea quarks (Anselmino et al. 09)
with DSS FF (De Florian-Sassot-Stratmann 07),
Transversity and Collins FF extraction 2009 (Anselmino et al. 09)

All uncertainties are estimated in extractions as envelope of parameters that generate the error band (200 copies)

Phenomenology TMD: SIDIS I

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)



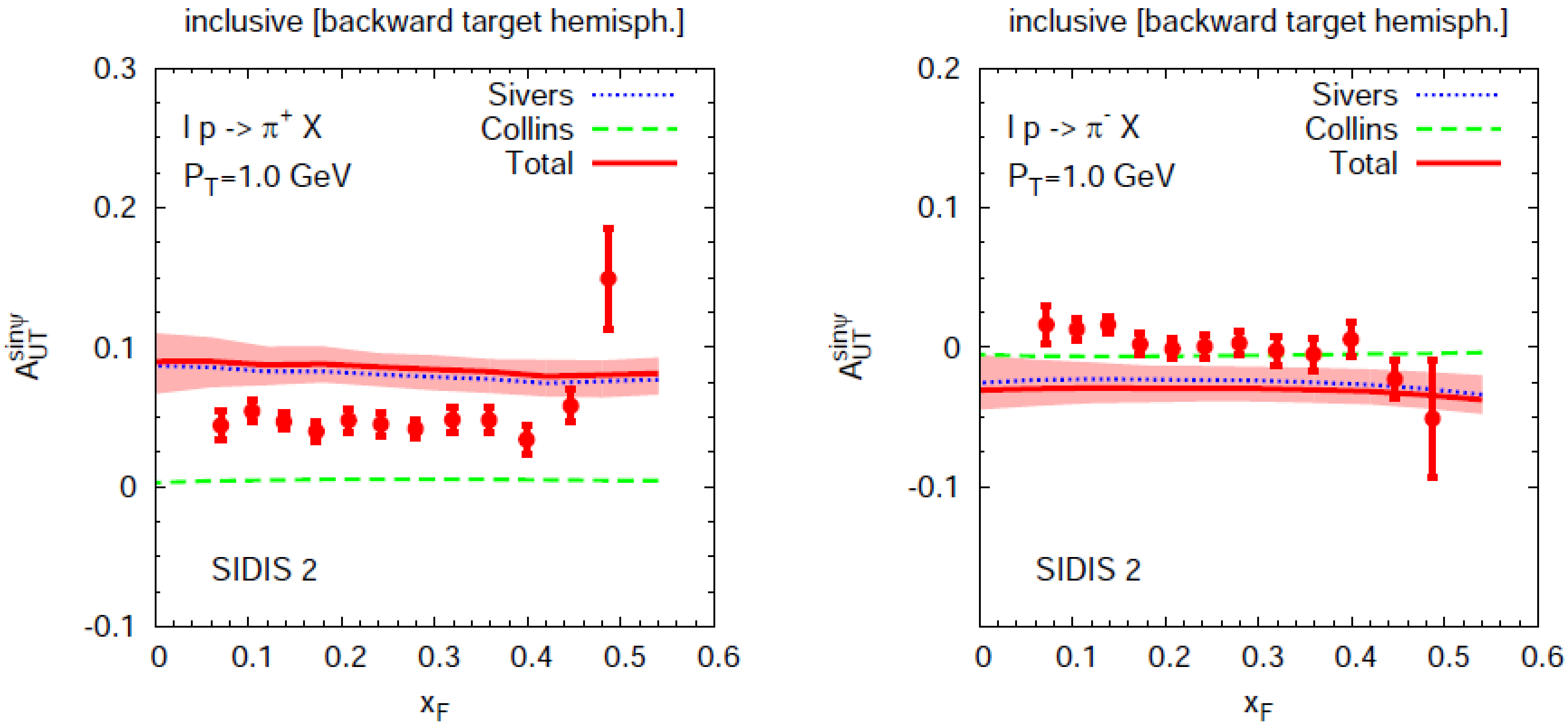
Collins contribution is suppressed, Sivers dominates.

Flat behavior in x_F

Sivers extraction 2005 with Kretzer FF, π^- dominated by u quark and unfavored FF

Phenomenology TMD: SIDIS II

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)



Collins contribution is suppressed, Sivers dominates. π^+ similar to SIDIS I.

Flat behavior in x_F

Sivers extraction 2009 with DSS FF, π^- dominated by d quark and favored FF

Phenomenology twist-3

Gamberg, Kang, Metz, Pitonyak, AP (to appear)

Ingredients

$F_{FT}^{q}(x,x)$ related to Sivers, Sivers extraction 2009 with sea quarks (Anselmino et al. 09)

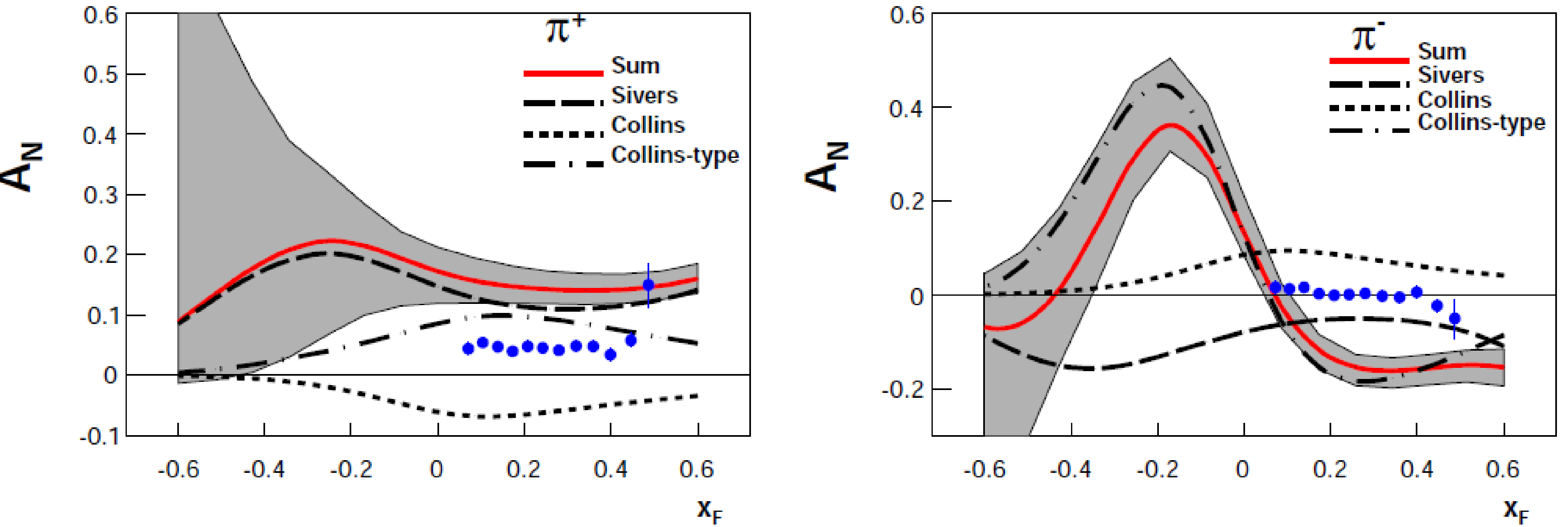
$\hat{H}^{h/q}(z)$ related to Collins FF, Transversity and Collins FF extraction 2013 (Anselmino et al. 13)

$H^{h/q}(z)$, $\hat{H}_{FU}^{h/q,\Im}(z,z_1)$ functions from PP, (Kanazawa, Koike, Metz, Pitonyak 14)

All uncertainties are estimated in extractions as envelope of parameters that generate the error band only for Sivers and Collins

Phenomenology: twist-3

Gamberg, Kang, Metz, Pitonyak, AP (to appear)



Collins contribution is suppressed, Sivers dominates for π^+

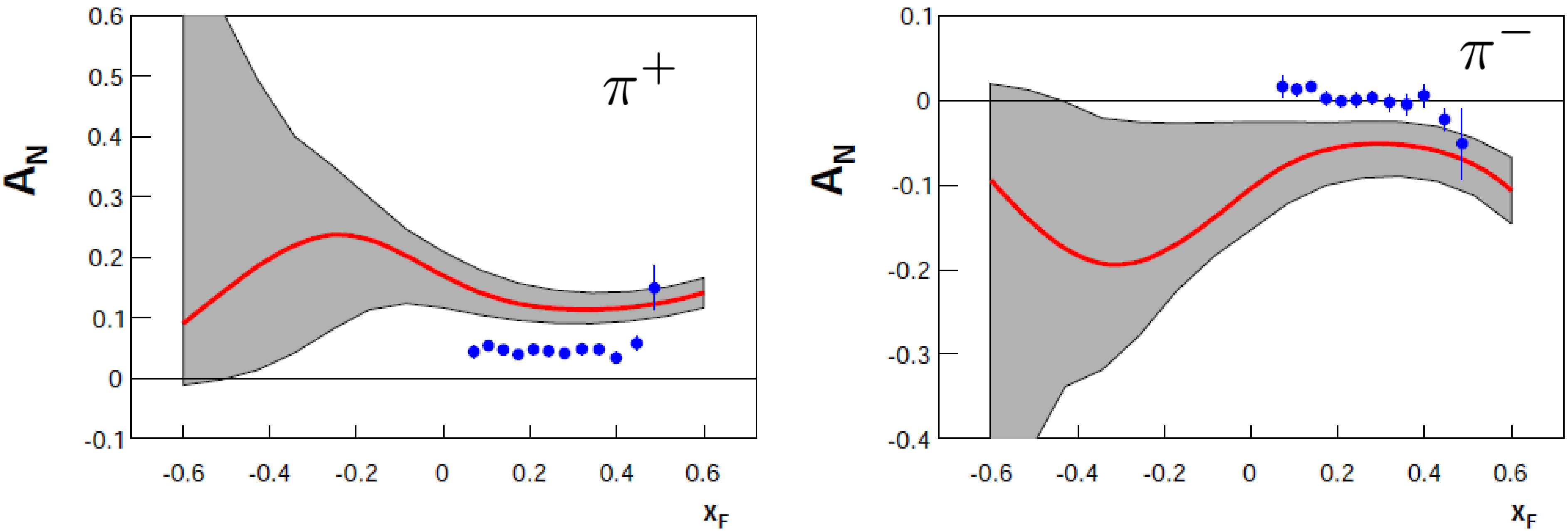
Sivers extraction 2009 with DSS FF. π^- dominated by “Collins-type” contribution.

Error bands are underestimated as error on $\hat{H}_{FU}^{h/q}$ is not included

Phenomenology: twist-3

Gamberg, Kang, Metz, Pitonyak, AP (to appear)

$\hat{H}_{FU}^{h/q} = 0$ allows for a comparison with TMD results directly

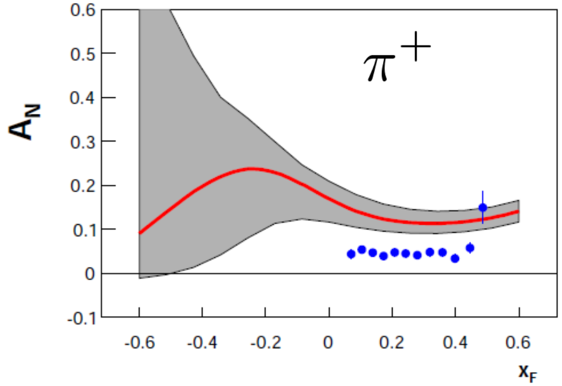


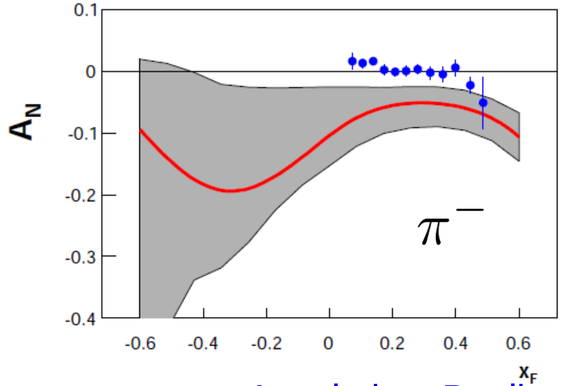
Collins contribution is not suppressed, Sivers dominates. $\pi^+\pi^-$ similar to TMD

Phenomenology: comparison

Gamberg, Kang, Metz, Pitonyak, AP (to appear)

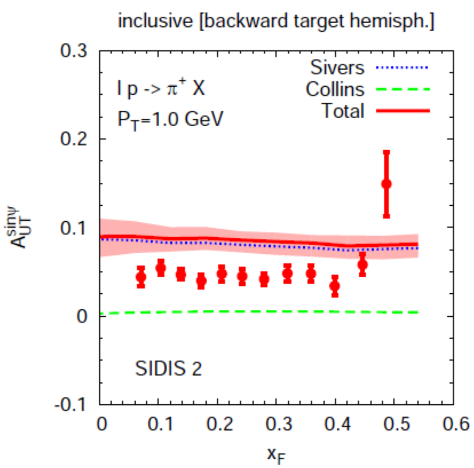
$\hat{H}_{FU}^{h/q} = 0$ allows for a comparison with TMD results

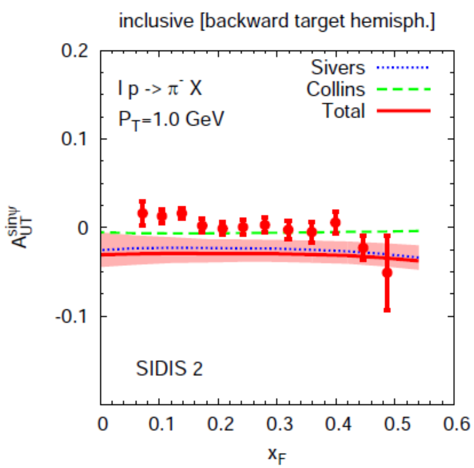




twist-3

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)





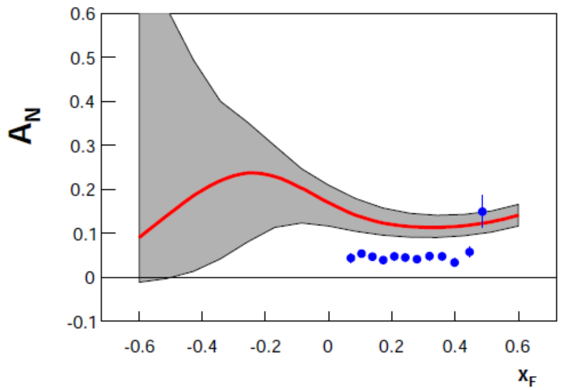
TMD

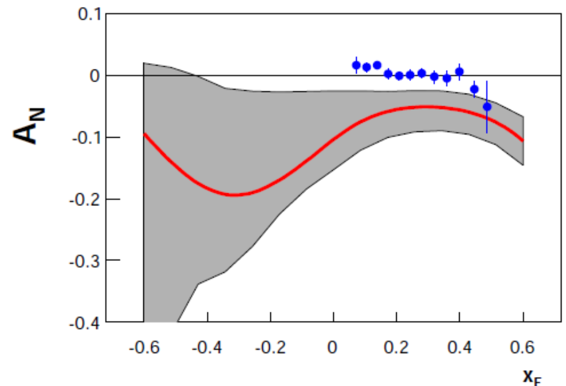
Same signs of asymmetry. Twist-3 is bigger in absolute value. Same behavior in x_F

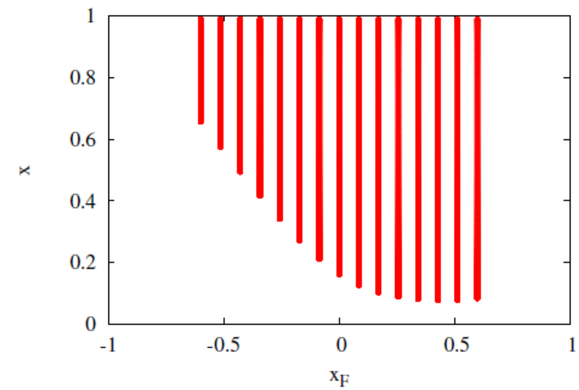
Phenomenology: twist-3

Gamberg, Kang, Metz, Pitonyak, AP (to appear)

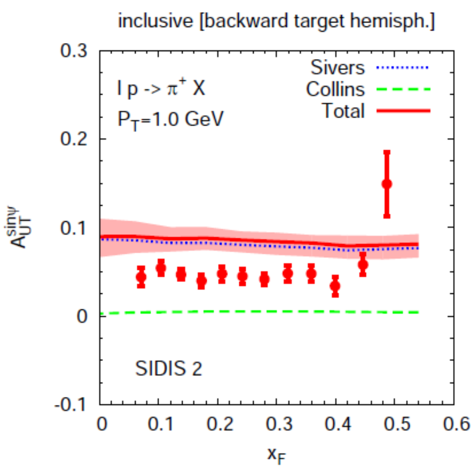
$\hat{H}_{FU}^{h/q} = 0$ allows for a comparison with TMD results

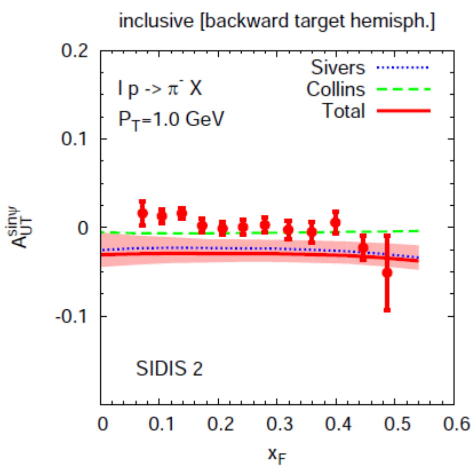






Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

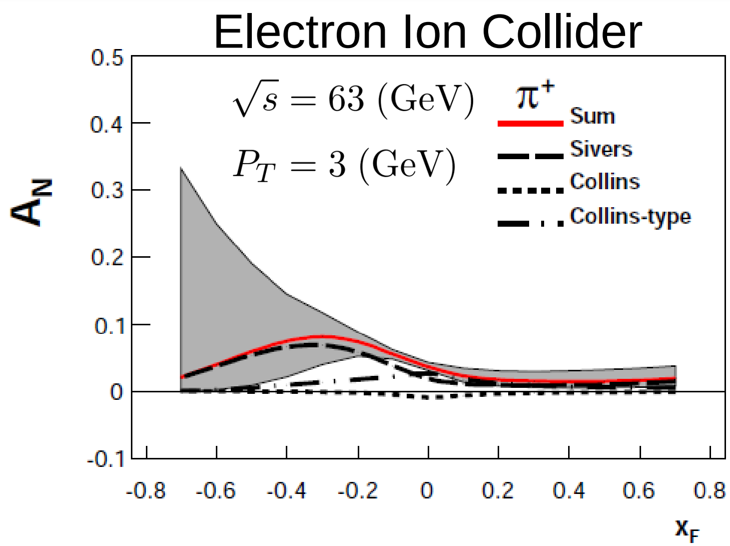




TMD

Same signs of asymmetry. Twist-3 is bigger in absolute value. Same behavior in x_F

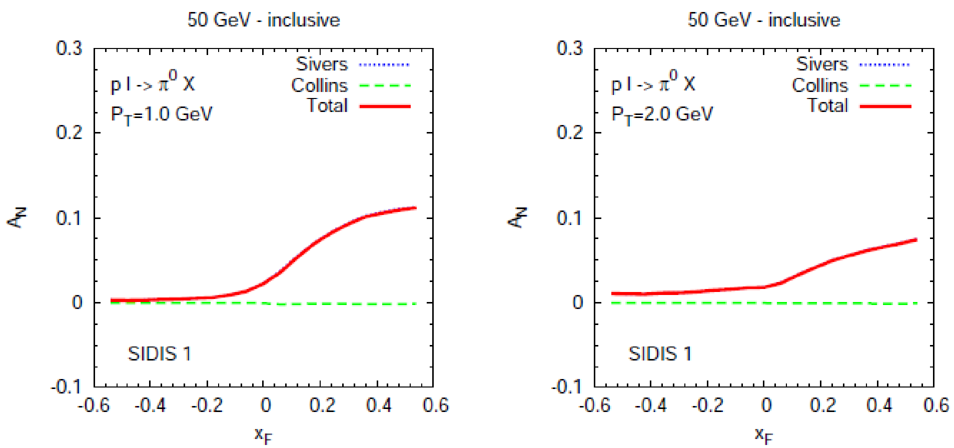
Predictions



Gamberg, Kang, Metz, Pitonyak, AP (to appear)

Forward region $x_F < 0$

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)



$P_T = 1$ GeV $P_T = 2$ GeV

$p^\uparrow$ along $+Z_{cm}$, i.e. forward region $\equiv x_F > 0$

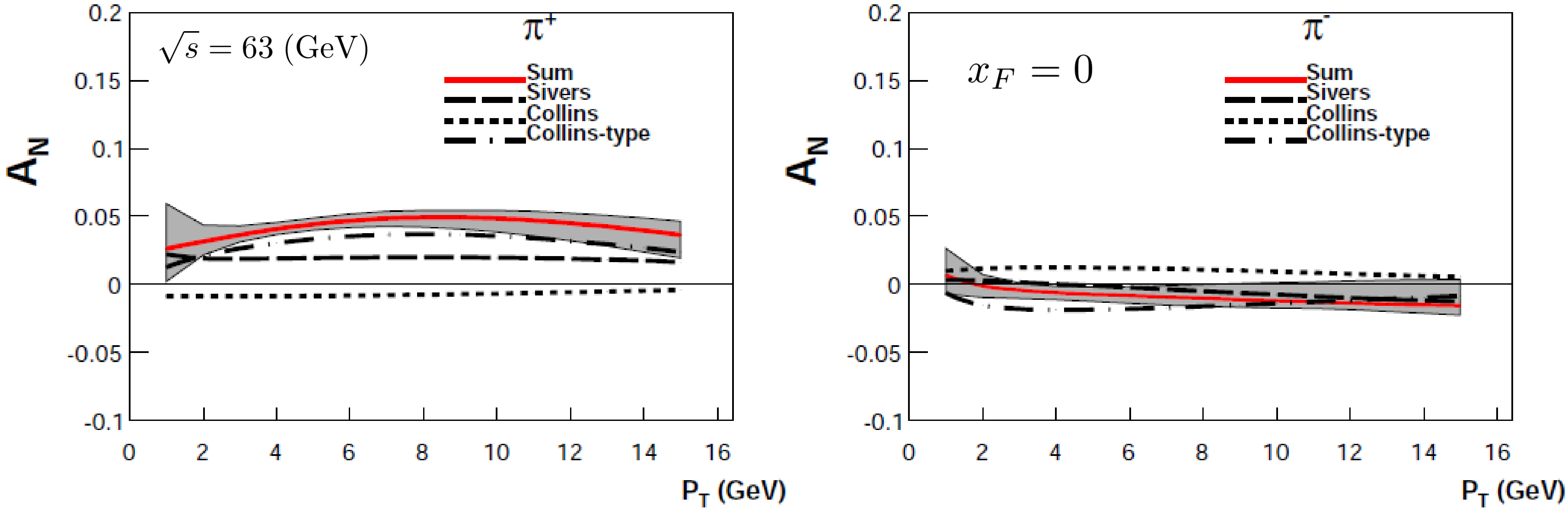
behaviour similar to A_N in $p^\uparrow p \to \pi X$

Same signs of asymmetry in both formalisms

Predictions

Gamberg, Kang, Metz, Pitonyak, AP (to appear)

Electron Ion Collider



Similar behavior to PP, see talk by Daniel Pitonyak

Conclusions

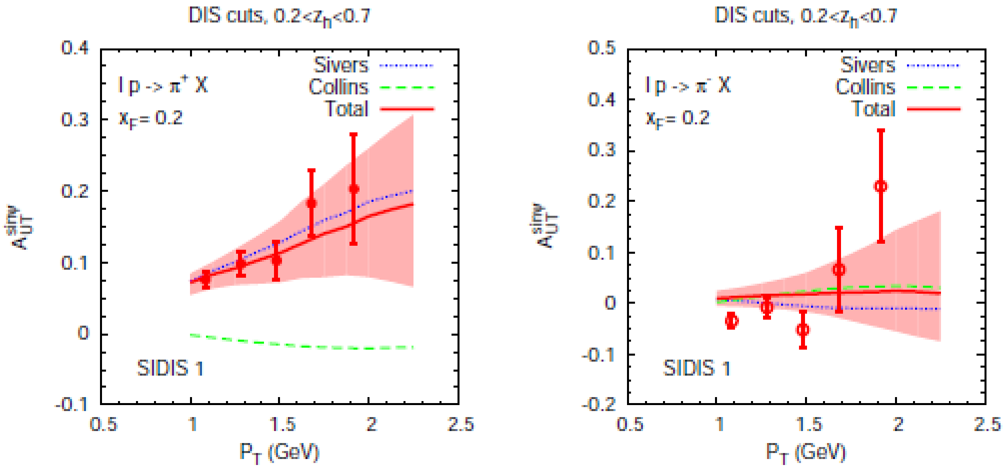
- AN in lp → h X is considered in TMD and twist-3 approaches
- Similar size and sign of asymmetry in both approaches
- Role of new "Collins-like" contributions to be investigated further
- NLO corrections are to be investigated and cross-section experimental measurements are very welcome

Back up slides

HERMES: DIS sample

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

lepton-tagged - SIDIS 1

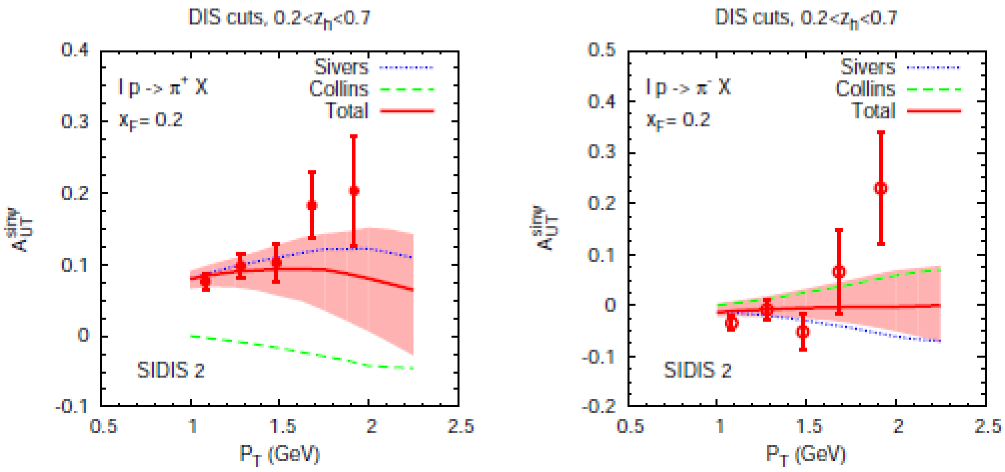


- Collins effect only partially suppressed (Collins phase picks to -1)
- Sivers effect sizeable (cancelation in π^- due to the large role of up quark)

HERMES: DIS sample

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

lepton-tagged - SIDIS 2

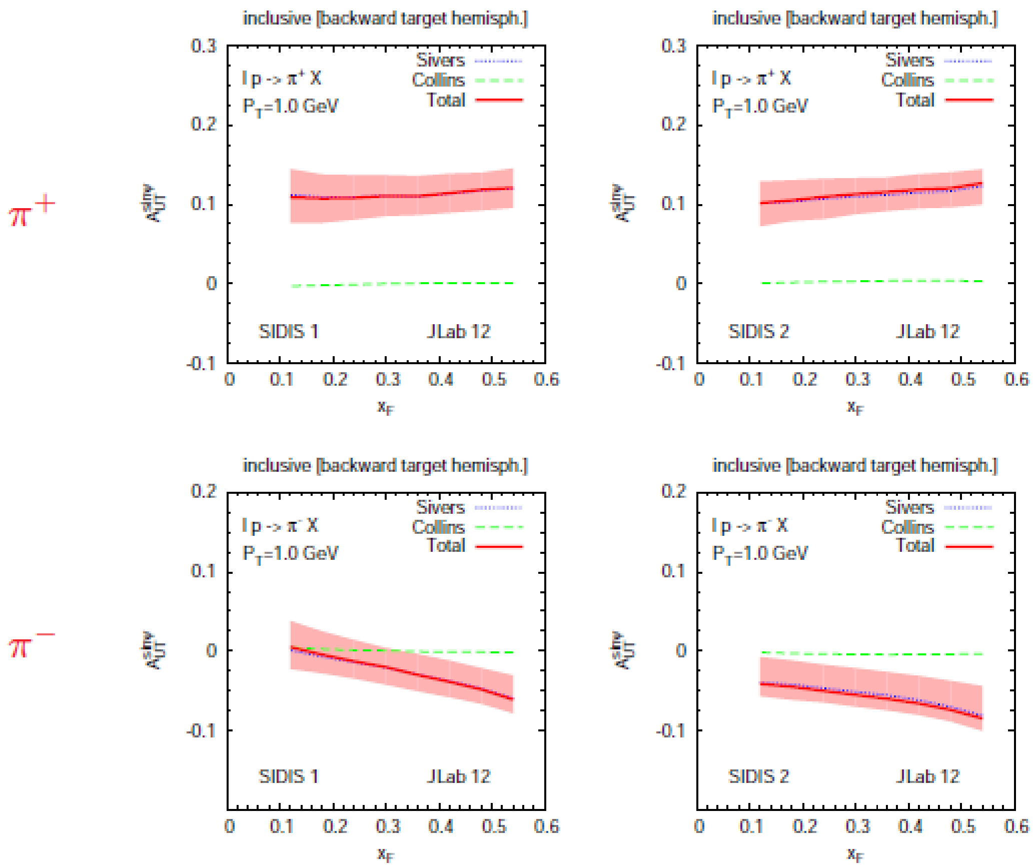


- Collins effect: larger w.r.t. SIDIS 1 (transversity unsuppressed at large x)
- Sivers effect: no cancelation in π^- (same large x behaviour of up and down quarks)

Predictions: JLab

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

Predictions: JLab 12



Predictions: COMPASS

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

Error band

Anselmino, Boglione, D'Alesio, Melis, Murgia, AP (2014)

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: $\chi^2_{\min} \to \boldsymbol{a}_0$

Error band: all sets of parameters such that $\chi^2(\boldsymbol{a}_j) \leq \chi^2_{\min} + \Delta\chi^2$
- $\Delta\chi^2 = 1 \leftrightarrow 1\text{-}\sigma$: 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

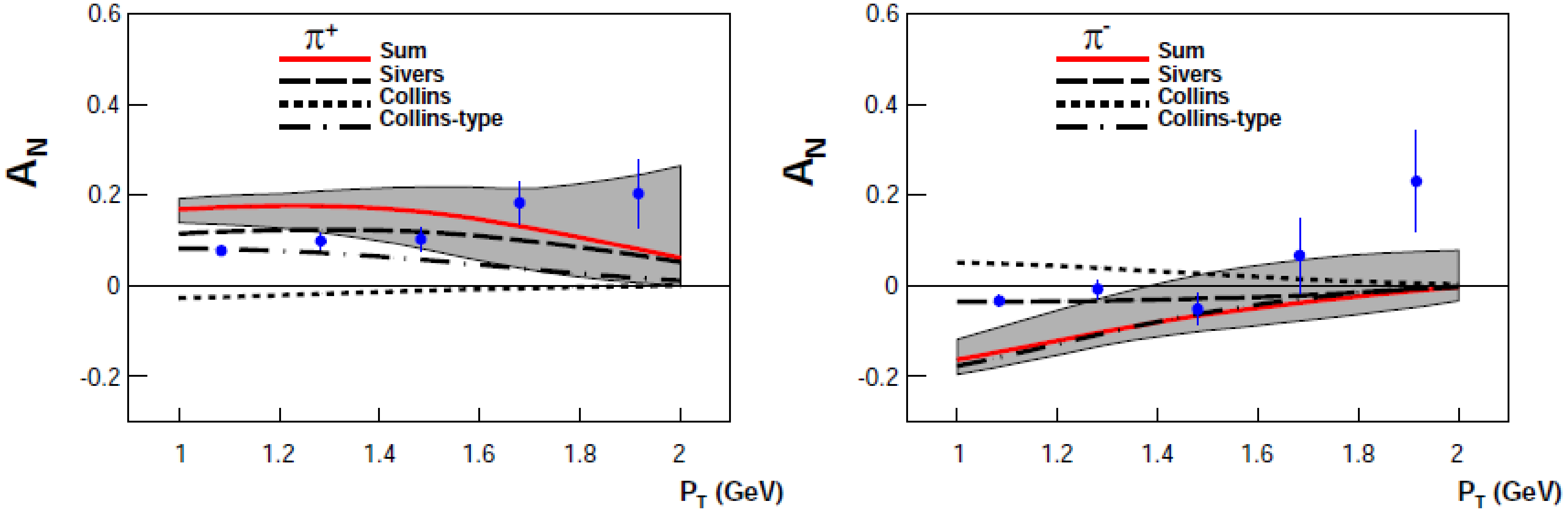
$[P = 0.68 \leftrightarrow 1\text{-}\sigma,\ P = 0.95 \leftrightarrow 2\text{-}\sigma]$

HERMES: DIS sample

Gamberg, Kang, Metz, Pitonyak, AP (to appear)

$$P_h^0 \frac{d\sigma_{UU}}{d^3\vec{P}_h} = \frac{2\alpha_{\rm em}^2}{S} \sum_q e_q^2 \int_{z_{\rm min}}^1 \frac{dz}{z^2} \frac{1}{S+T/z} \frac{1}{x} f_1^q(x)\, D_1^{h/q}(z) \left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right]$$

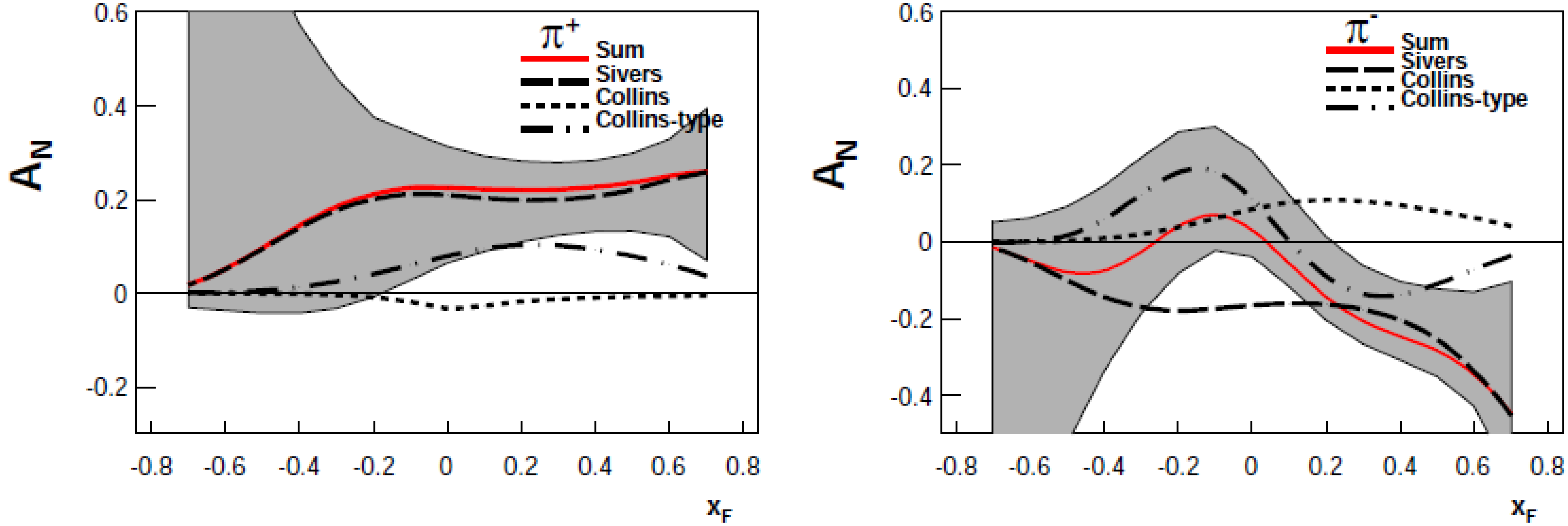
$$0.2 < z < 0.7$$



Jefferson Lab

Predictions: JLab

Gamberg, Kang, Metz, Pitonyak, AP (to appear)



Predictions: COMPASS

Gamberg, Kang, Metz, Pitonyak, AP (to appear)