Azimuthal asymmetries in $p^{\uparrow}p \to \mathrm{jet}\,\pi\,X$

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- Study of $p^{(\uparrow)}p \to \mathrm{jet}\,\pi\,X$ within the Generalized Parton Model
- Azimuthal asymmetries attributed to polarized TMD PDFs and FFs
- Phenomenology of Collins and Sivers asymmetries at RHIC
- Test of the process dependence of the Sivers function

In collaboration with U. D'Alesio (Univ. & INFN Cagliari) and F. Murgia (INFN Cagliari)

Kinematics

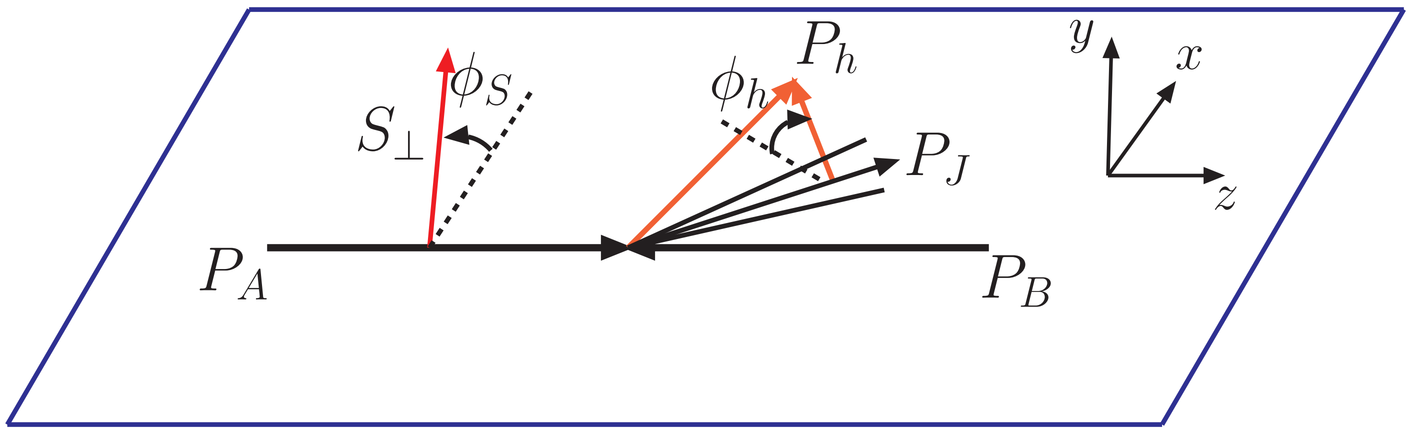
We consider the process

$$A(P_A; S_\perp) + B(P_B) \to \text{jet}(P_\text{j}) + h(P_h) \; + \; X$$

in the c.m. frame of the two spin $1/2$ hadrons A, B; with the jet in the xz plane

A is polarized with transverse spin $S_\perp = (0, \cos\phi_S, \sin\phi_S, 0)$

D'Alesio, Trento 2007



F. Yuan, PRL 100 (2008) 032003

ϕ_h^H: azimuthal distribution of hadron h inside the jet, around the jet axis

ϕ_h: azim. angle of h' s intrinsic transv. momentum w.r.t. the jet direction

ϕ_h^H: same angle, but measured in the H frame, where the jet is along z

$$\tan\phi_h^H = \tan\phi_h \cos\theta_\text{j}$$

The two frames are related by a rotation around y by θ_j, polar angle of the jet

D'Alesio, Murgia, CP, PRD 83 (2011) 034021

The TMD generalized parton model (GPM)

- Spin and intrinsic parton motion effects in initials hadrons and in the fragmentation
Phenomenological assumption: factorization holds for large p_T jet production

- SSA and azimuthal asymmetries are generated by TMD polarized pdfs and FFs
Most relevant ones: $f_{1T}^{\perp}$ (Sivers), $h_1^{\perp}$ (Boer-Mulders), $H_1^{\perp}$ (Collins)
Anselmino, Boglione, D'Alesio, Leader, Melis, Murgia, PRD 73 (2006) 014020;
Notation: Meissner, Metz, Goeke, PRD 76 (2007) 034002

- Factorization proven in a more simplified theoretical scheme: intrinsic parton motion only in the fragmentation process. Only Collins effect for quarks is at work
F. Yuan, PRL 100 (2008) 032003;
PRD 77 (2008) 074019

- The present, more general, scheme requires a severe scrutiny by comparison with experimental results to clarify the validity of factorization and the relevance of possible universality-breaking terms for the TMD distributions

Why studying the distribution of pions inside a jet?

- SSA in $p\,p^{\uparrow} \to \pi\,X$, due to Collins and Sivers effects, cannot be disentangled

  Anselmino, Boglione, D'Alesio, Leader, Murgia, PRD 71 (2005) 014002;
  Anselmino, Boglione, D'Alesio, Leader, Melis, Murgia, PRD 73 (2006) 014020

  while in $p\,p^{\uparrow} \to \mathrm{jet}\,\pi\,X$, Collins, Sivers and other TMDs can be singled out

- Jets coming from quark or gluon fragmentation could be identified without ambiguity, since the pion azimuthal distribution is different in the two cases:
  - symm. pion distribution for the fragmentation of an unpolarized parton jet (D_1)
  - $\cos\phi_{\pi}^{H}$ distribution for a transversely polarized quark parton jet $(H_1^{\perp q})$
  - $\cos 2\phi_{\pi}^{H}$ distribution for a linearly polarized gluon parton jet $(H_1^{\perp g})$

- Complex measurement, but feasible and under active consideration at RHIC

  Fatemi [STAR], AIP Conf. Proc. 1441 (2012) 233;
  Poljak [STAR], J. Phys. Conf. Ser. 295 (2011) 012102

Weighted cross sections

- General structure of the single transverse polarized cross section

$$
\begin{aligned}
2\mathrm{d}\sigma(\phi_S,\phi_\pi^H) \quad \sim \quad & \mathrm{d}\sigma_0 + \mathrm{d}\Delta\sigma_0 \sin\phi_S + \mathrm{d}\sigma_1 \cos\phi_\pi^H + \mathrm{d}\sigma_2 \cos 2\phi_\pi^H \\
& + \mathrm{d}\Delta\sigma_1^- \sin(\phi_S - \phi_\pi^H) + \mathrm{d}\Delta\sigma_1^+ \sin(\phi_S + \phi_\pi^H) \\
& + \mathrm{d}\Delta\sigma_2^- \sin(\phi_S - 2\phi_\pi^H) + \mathrm{d}\Delta\sigma_2^+ \sin(\phi_S + 2\phi_\pi^H)
\end{aligned}
$$

- Average values of appropriate functions $W(\phi_S,\phi_\pi^H) = 1$, $\sin\phi_S$, $\cos\phi_\pi^H$, ...

$$
\langle\, W(\phi_S,\phi_\pi^H)\,\rangle = \frac{\int \mathrm{d}\phi_S \mathrm{d}\phi_\pi^H W(\phi_S,\phi_\pi^H)\mathrm{d}\sigma(\phi_S,\phi_\pi^H)}{\int \mathrm{d}\phi_S \mathrm{d}\phi_\pi^H \mathrm{d}\sigma(\phi_S,\phi_\pi^H)}
$$

single out $\mathrm{d}\sigma_0$, $\mathrm{d}\Delta\sigma_0$, $\mathrm{d}\sigma_1$, ...

Single spin asymmetries

- Unpolarized cross section:

$$\mathrm{d}\sigma(\phi_S,\phi_\pi^H)+\mathrm{d}\sigma(\phi_S+\pi,\phi_\pi^H)\equiv 2\mathrm{d}\sigma^{\mathrm{unp}}(\phi_\pi^H)\sim \mathrm{d}\sigma_0+\mathrm{d}\sigma_1\cos\phi_\pi^H+\mathrm{d}\sigma_2\cos 2\phi_\pi^H$$

- Numerator of the single spin asymmetry:

$$\begin{aligned}&\mathrm{d}\sigma(\phi_S,\phi_\pi^H)-\mathrm{d}\sigma(\phi_S+\pi,\phi_\pi^H)\\ &\quad\sim \mathrm{d}\Delta\sigma_0\sin\phi_S+\mathrm{d}\Delta\sigma_1^-\sin(\phi_S-\phi_\pi^H)+\mathrm{d}\Delta\sigma_1^+\sin(\phi_S+\phi_\pi^H)\\ &\qquad +\mathrm{d}\Delta\sigma_2^-\sin(\phi_S-2\phi_\pi^H)+\mathrm{d}\Delta\sigma_2^+\sin(\phi_S+2\phi_\pi^H)\end{aligned}$$

- Appropriate azimuthal moments, with $W(\phi_S,\phi_\pi^H)=\sin\phi_S,\ \sin(\phi_S-\phi_\pi^H)$, ...

$$A_N^W\equiv 2\langle\, W(\phi_S,\phi_\pi^H)\,\rangle = 2\,\frac{\int \mathrm{d}\phi_S\mathrm{d}\phi_\pi^H W(\phi_S,\phi_\pi^H)[\mathrm{d}\sigma(\phi_S)-\mathrm{d}\sigma(\phi_S+\pi)]}{\int \mathrm{d}\phi_S\mathrm{d}\phi_\pi^H[\mathrm{d}\sigma(\phi_S)+\mathrm{d}\sigma(\phi_S+\pi)]}$$

will single out the different contributions (analogy with SIDIS)

Example: the $qq \to qq$ channel

- Eight distinct partonic channels contribute to the cross section

$$qq \to qq \quad qg \to qg \quad qg \to gq \quad gq \to qg \quad gq \to gq$$
$$gg \to q\bar{q} \quad q\bar{q} \to gg \quad gg \to gg$$

in the first line q stays for both quarks and antiquarks in all allowed combinations

- $qq \to qq$: max number of terms (similar structures for $gg \to gg$ with $\phi_\pi^H \to 2\phi_\pi^H$)
  - Unpolarized cross section:

$$2\mathrm{d}\sigma^{\mathrm{unp}}(\phi_\pi^H) \sim \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1 \cos\phi_\pi^H$$
$$\mathrm{d}\sigma_0 \sim f_1 f_1 D_1 \qquad h_1^\perp h_1^\perp D_1$$
$$\mathrm{d}\sigma_1 \sim h_1^\perp f_1 H_1^\perp \quad f_1 h_1^\perp H_1^\perp$$

  - Numerator of the SSA: $\mathcal{N} \equiv \mathrm{d}\sigma(\phi_S, \phi_\pi^H) - \mathrm{d}\sigma(\phi_S + \pi, \phi_\pi^H)$

$$\mathcal{N} \sim \mathrm{d}\Delta\sigma_0 \sin\phi_S + \mathrm{d}\Delta\sigma_1^- \sin(\phi_S - \phi_\pi^H) + \mathrm{d}\Delta\sigma_1^+ \sin(\phi_S + \phi_\pi^H)$$
$$\mathrm{d}\Delta\sigma_0 \sim f_{1T}^\perp f_1 D_1 \quad h_1 h_1^\perp D_1 \quad h_{1T}^\perp h_1^\perp D_1$$
$$\mathrm{d}\Delta\sigma_1^- \sim h_1 f_1 H_1^\perp \quad f_{1T}^\perp h_1^\perp H_1^\perp$$
$$\mathrm{d}\Delta\sigma_1^+ \sim h_{1T}^\perp f_1 H_1^\perp \quad f_{1T}^\perp h_1^\perp H_1^\perp$$

- Neglecting intrinsic motion of initial partons, only $f_1 f_1 D_1$ and $h_1 f_1 H_1^\perp$ contribute

Upper bounds of the asymmetries

- $\langle W \rangle$ (A_N^W) calculated for $p^{(\uparrow)}\, p \to \mathrm{jet}\, \pi\, X$ mainly at $\sqrt{s} = 200$ GeV
  Other energies ($\sqrt{s} = 62.4$, 500 GeV) considered
  D'Alesio, Murgia, CP, PRD 83 (2011) 034021

- $\langle W \rangle$ and A_N^W given as function of $P_{\mathrm{j}T}$ and η_{j}; all other variables are integrated over, with $0.3 \le z \le 1$

- Assumption for TMDs: $\mathcal{F}^{q,g}(x, \boldsymbol{k}_\perp^2) = f^{q,g}(x) g(\boldsymbol{k}_\perp^2)$, with $g(\boldsymbol{k}_\perp^2)$ being a flavor independent Gaussian-like function

- Parameterizations of the usual collinear LO pdfs (GRV98, GRSV2000) and FFs (Kre) evolved at the scale $\mu = P_{\mathrm{j}T}$

- Over-maximized scenario: all TMDs are maximized in size by imposing natural positivity bounds (Soffer bound for h_1^q) and *the relative signs* of all active partonic contributions are chosen so that they sum up additively

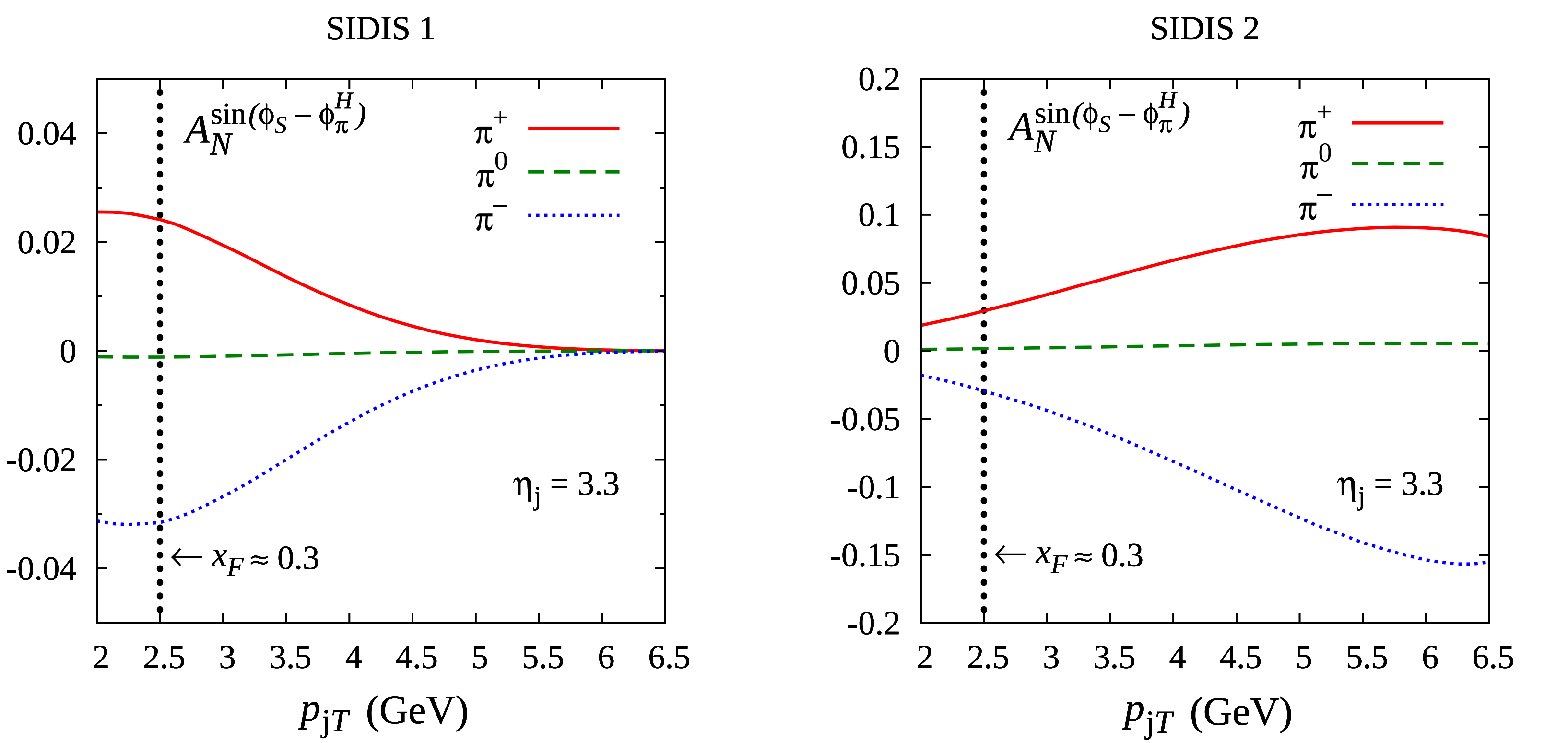
  Advantage: upper bound on the absolute value of any effect playing a role in the asymmetries. All marginal effects in this scenario may be discarded

  Example:

$$A_N^{\sin(\phi_S+\phi_\pi^H)} \sim \left[f_{1T}^{\perp q} h_1^{\perp q} + h_{1T}^{\perp q} f_1 \right] H_1^{\perp q} \quad (\text{and } A_N^{\sin(\phi_S+2\phi_\pi^H)} \text{ for gluons}) \approx 0$$

Collins asymmetries in $p^{\uparrow}p \to \text{jet}\,\pi\,X$ at $\sqrt{s} = 200$ GeV

$A_N^{\sin(\phi_S - \phi_\pi^H)} \sim h_1^q f_1 H_1^{\perp q}$, h_1^q, $H_1^{\perp q}$ from SIDIS , e^+e^- data by Anselmino *et al:* PRD 75 (2007) 054032 (SIDIS 1); NP (Proc. Suppl.) 191 (2009) 98 (SIDIS 2)



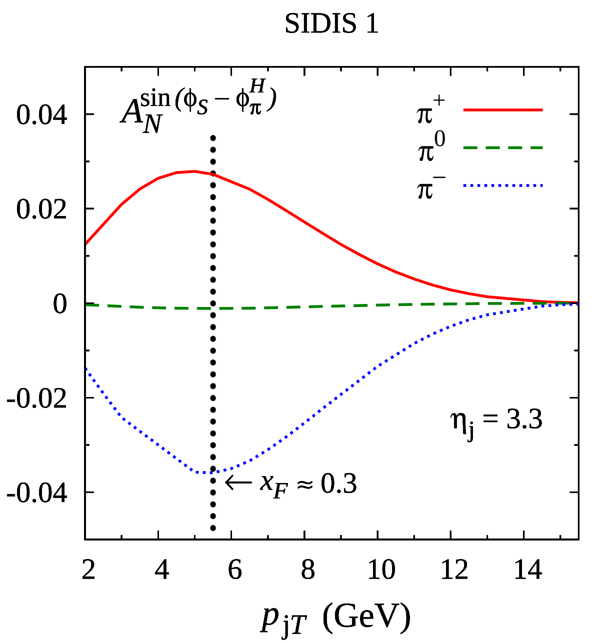
$A_N^{\sin(\phi_S - \phi_\pi^H)} \approx 0$ at $\eta_j = 0$. Preliminary data: $A_N^{\sin(\phi_S - \phi_\pi^H)} \approx 0$ for π^0 at $\eta = 3.3$

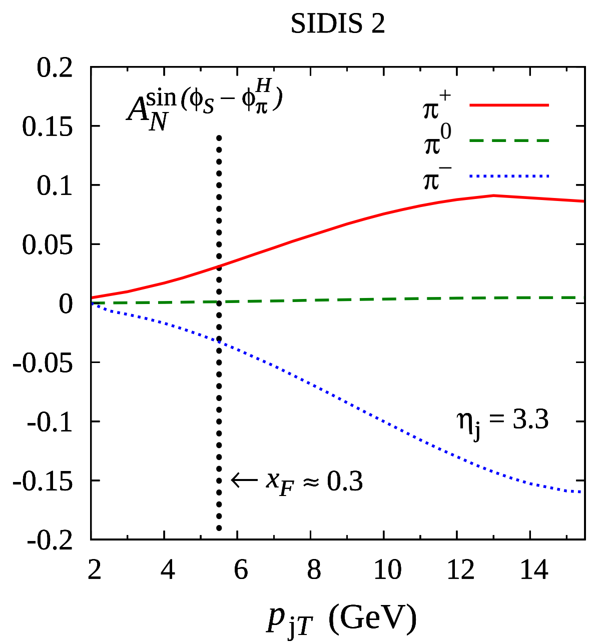
Poljak [STAR], J. Phys. Conf. Ser. 295 (2011) 012102

Predictions reliable only for $x_F \leq 0.3$ (region covered by present SIDIS data)

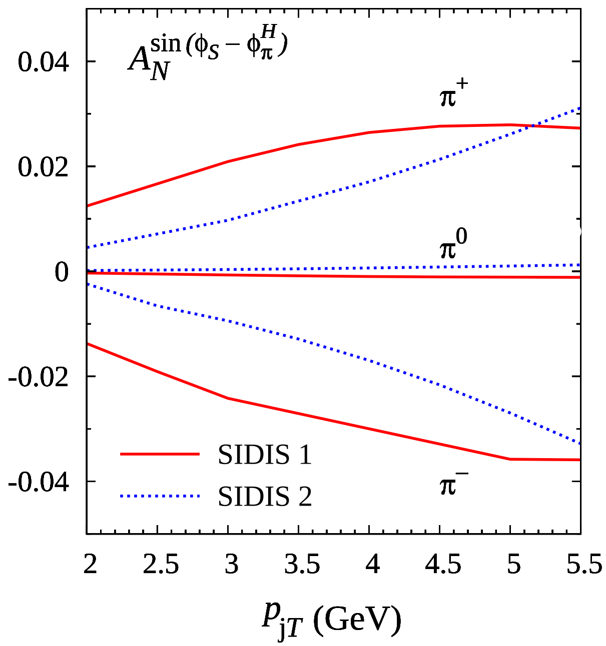
Measurements useful to constrain h_1^q in a new kinematic region!

Collins asymmetries in $p^{\uparrow}p \to \mathrm{jet}\,\pi\,X$ *at* $\sqrt{s} = 500$ *GeV*





D'Alesio, Murgia, CP, arXiv:1307.4880



Asymmetries still sizeable at $\sqrt{s} = 500$ GeV

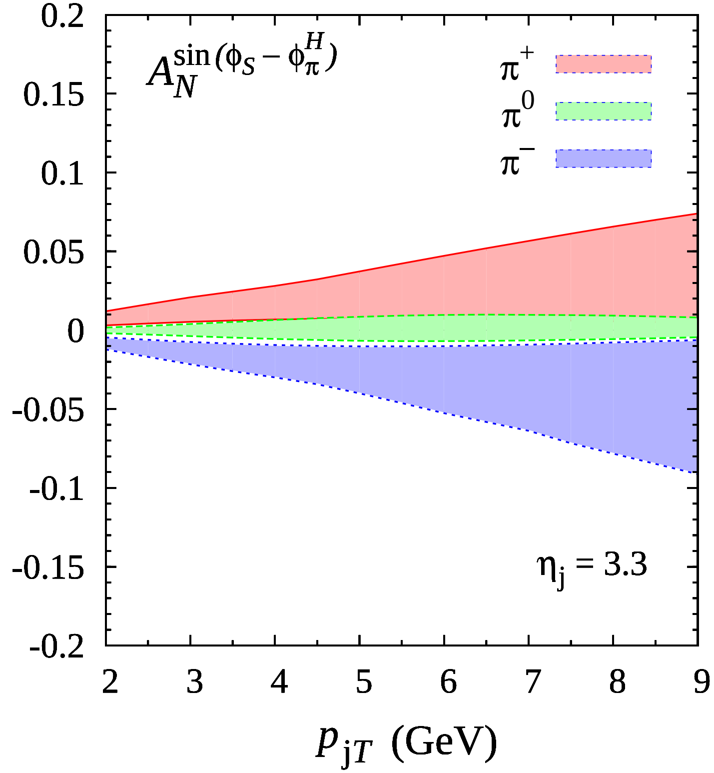
Region $x_F \leq 0.3$ wider:

SIDIS 1-2 give comparable predictions

Collins asymmetries at $\sqrt{s} = 500$ GeV: estimates of the uncertainties

- Uncertainties grow with $P_{\mathrm{j}T}$: agreement with alternative and complementary study

Anselmino *et al*, PRD 86 (2012) 074032



D'Alesio, Murgia, CP, arXiv:1307.4880

- Large x behaviour of $h_1^{\perp q} \propto (1-x)^{\beta_q}$, but β_q unconstrained by SIDIS data
- Parameterizations from fits (with acceptable χ^2): total of 81 different $\{\beta_u, \beta_d\}$ pairs
- Bands given by the full envelope of the asymmetry values obtained from these sets

Comparison with premiliminary STAR results

- Center of mass energy:

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

- Kinematic cuts on the jet:

$$0 < \eta_{\mathrm{j}} < 0.9$$

$$p_{\mathrm{j}T} > 10 \text{ GeV}$$

- Kinematic cuts on the pion:

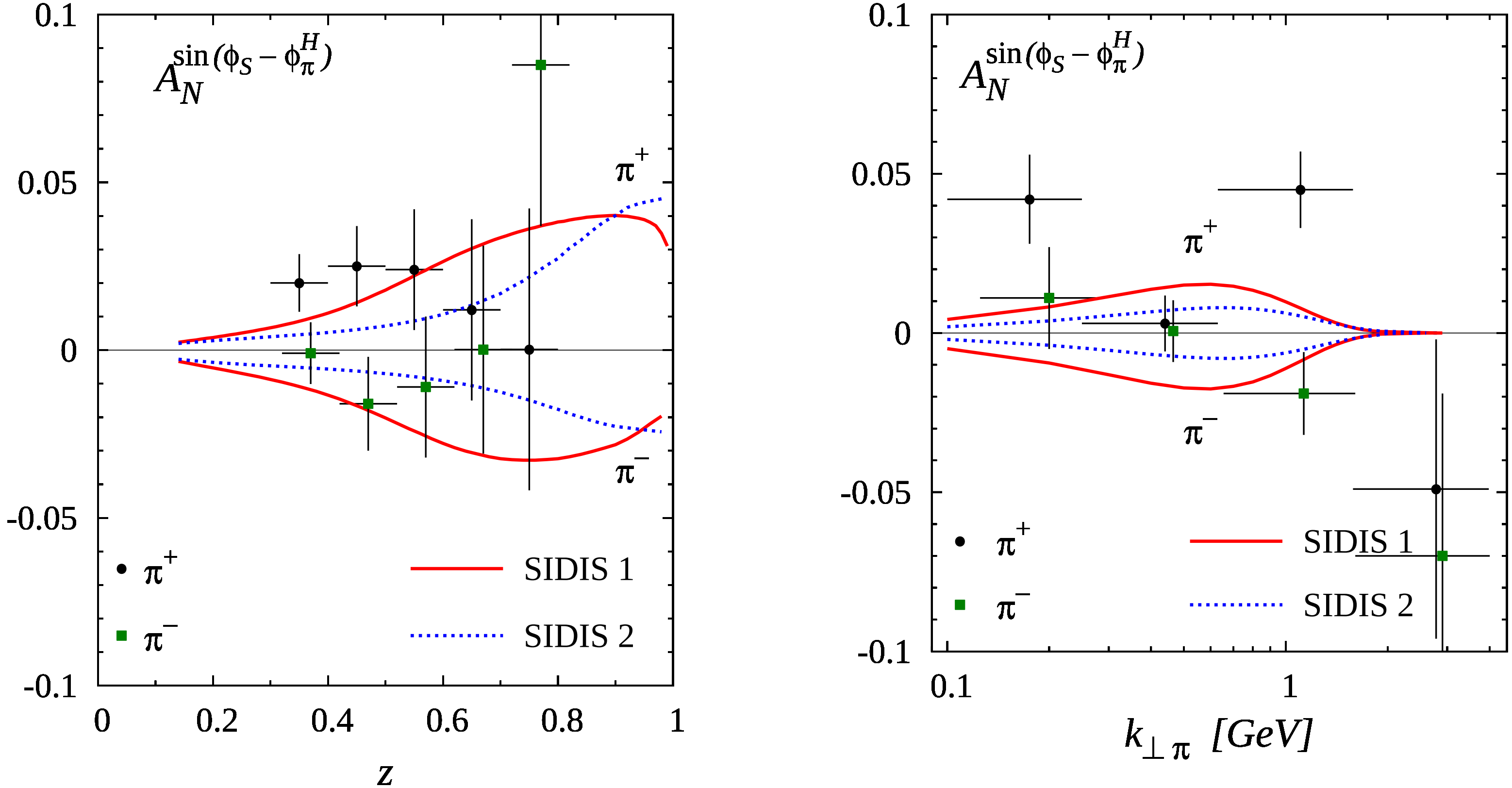
$$0.1 < z_{\mathrm{exp}} \equiv \frac{E_\pi}{E_{\mathrm{j}}} < 0.8$$

$$-1 < \eta_\pi < 1$$

$$k_{\perp\pi} > 0.1 \text{ GeV}$$

Comparison with STAR results

Preliminary 2006 RHIC data at $\sqrt{s} = 200$ GeV



Fatemi [STAR], AIP Conf. Proc. 1441 (2012) 233;

- Systematic errors ± 0.023 not shown; data horizontally offset for clarity

Predictions for STAR kinematics at $\sqrt{s} = 500$ GeV

- Center of mass energy:

$$\sqrt{s} = 500 \text{ GeV}$$

- Kinematic cuts on the jet:

$$-1 < \eta_{\rm j} < 1$$

$$6 \text{ GeV} < p_{{\rm j}T} < 16.3 \text{ GeV}$$

$$0.1 < R < 0.6, \qquad R \equiv \sqrt{(\eta_{\rm j} - \eta_\pi)^2 + (\phi_{\rm j} - \phi_\pi)^2}$$

- Kinematic cuts on the pion:

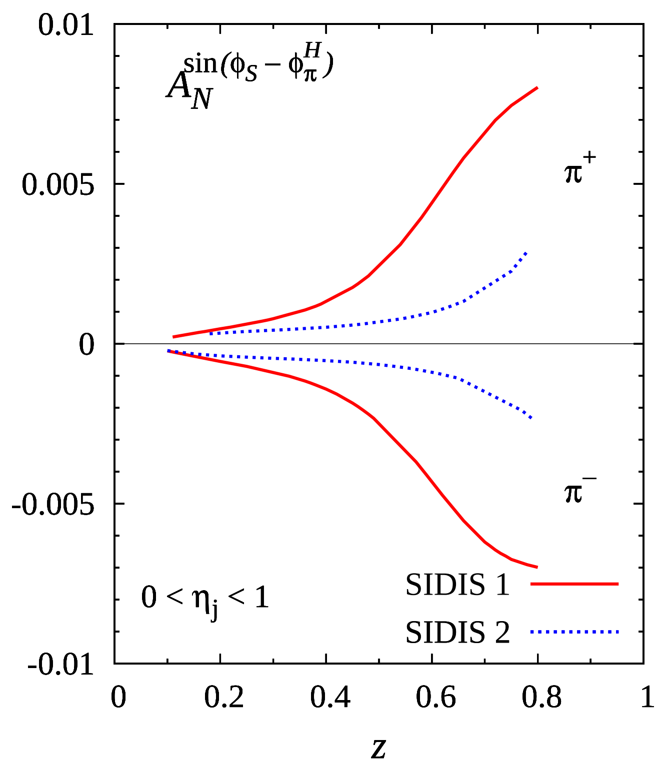
$$0.1 < z_{\rm exp} < 0.8$$

Preliminary data from STAR now available

J. Drachenberg, talk at MENU 2013

Collins asymmetries: $\sqrt{s} = 500$ *GeV*

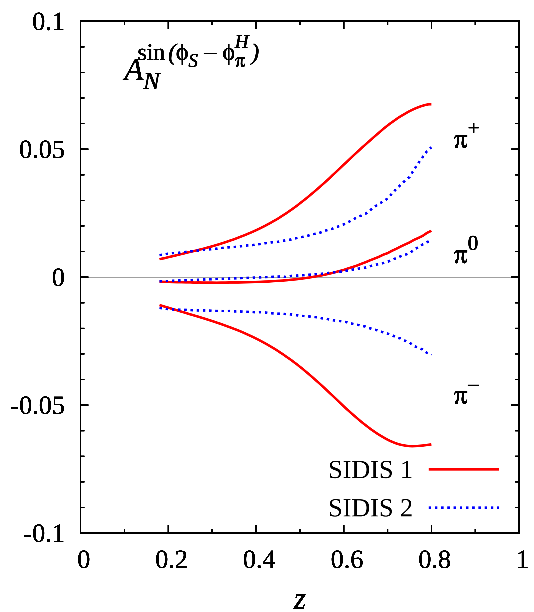
- In the backward region $-1 < \eta_{\rm j} < 0$ the Collins asymmetry is lower than 0.001

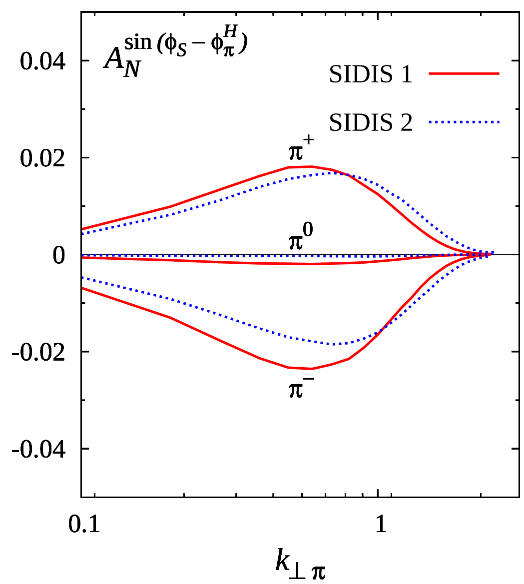


- $A_N^{\sin(\phi_S - \phi_\pi^H)}$ vs $k_{\perp\pi}$ negligible: less than permille $(0.1 < z < 0.8)$

- Asymmetries would be slightly larger for larger $z_{\rm min}$, but still tiny

Collins asymmetries for PHENIX kinematics at $\sqrt{s} = 200$ GeV





- Kinematic cuts on the jet:

$$2.5 < \eta_{\rm j} < 3.5$$
$$2 \text{ GeV} < p_{{\rm j}T} < 6 \text{ GeV}$$
$$E_{\rm j} > 10 \text{ GeV}$$
$$R < 0.5, \qquad R \equiv \sqrt{(\eta_{\rm j} - \eta_\pi)^2 + (\phi_{\rm j} - \phi_\pi)^2}$$

- Kinematic cuts on the pion:

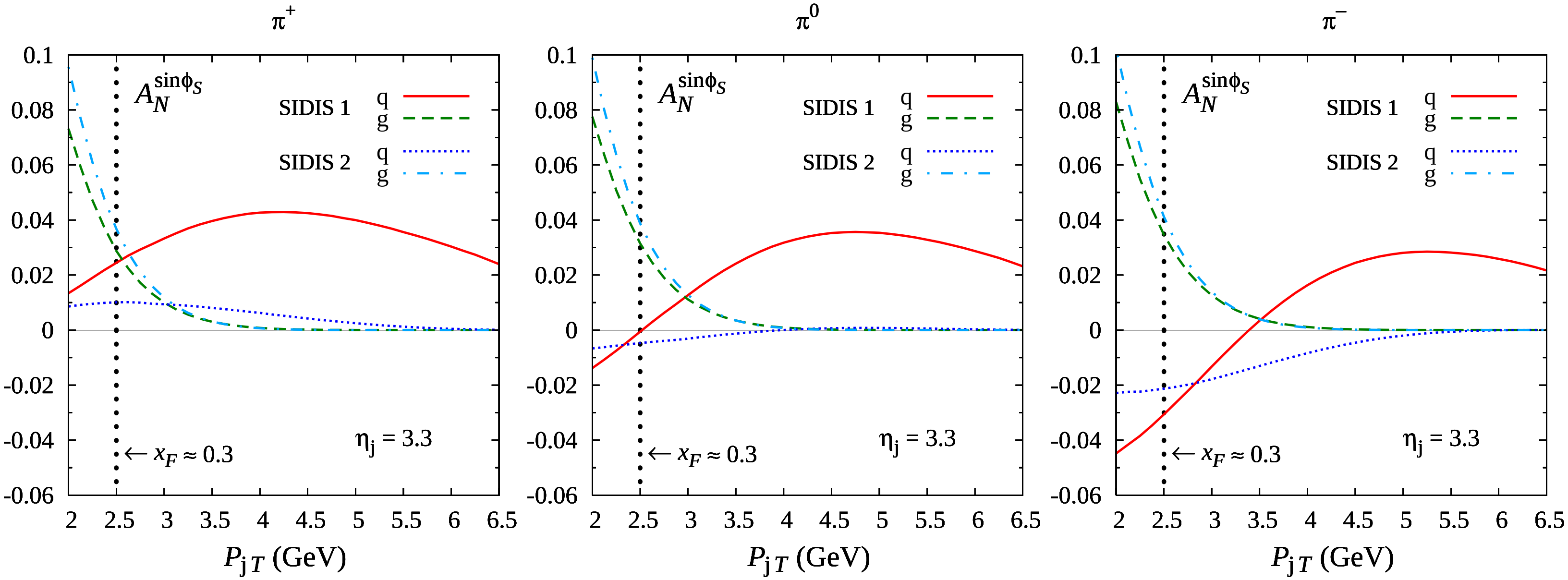
$$2 < \eta_\pi < 4$$
$$0.2 < z_{\rm exp} < 0.8$$
$$k_{\perp\pi} > 0.1 \text{ GeV}$$

Sivers asymmetry in $p^\uparrow p \to \text{jet}\,\pi\,X$ *at* $\sqrt{s} = 500$ *GeV*

$A_N^{\sin\phi_S} \sim f_{1T}^\perp f_1 D_1$ estimated using param. of $f_{1T}^{\perp q}$ from SIDIS by Anselmino *et al*

SIDIS 1 PRD 72 (2005) 094007

SIDIS 2 EPJA 39 (2009) 39



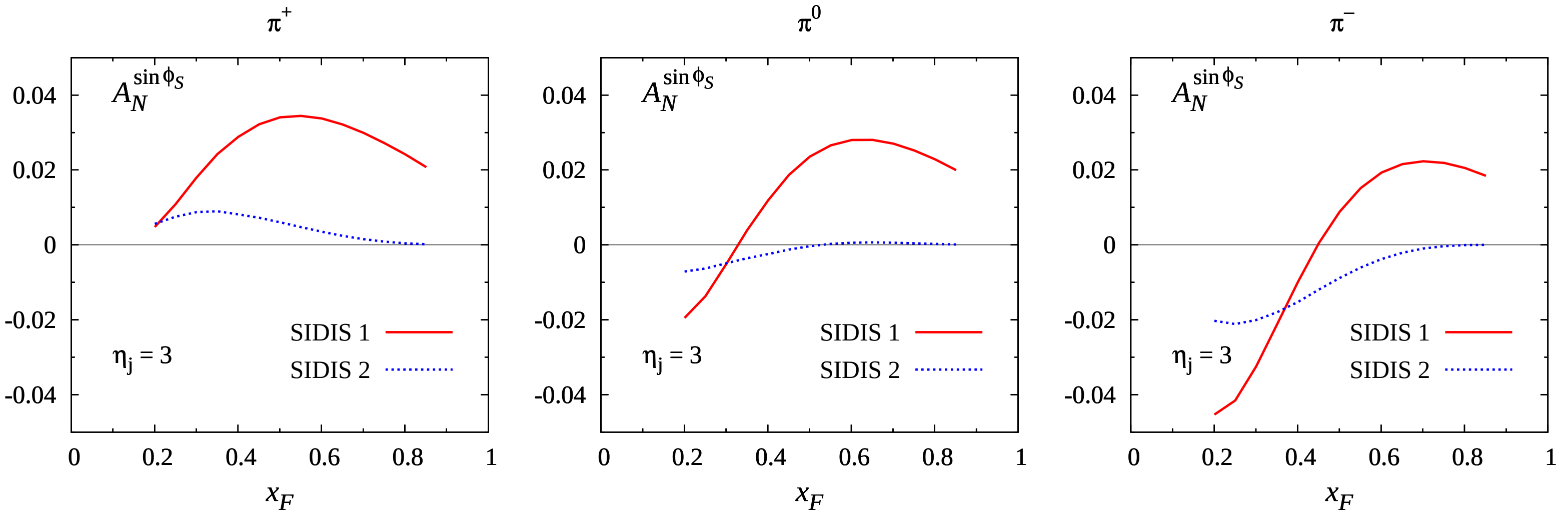
Upper bound on $f_{1T}^{\perp g}$ from analyses of SSA in $p^\uparrow p \to \pi X$ at midrapidity (updated)

Anselmino, D'Alesio, Melis, Murgia, PRD 74 (2006) 094011

$A_N^{\sin(\phi_S - \phi_\pi^H)}$ in $p^\uparrow p \to \text{jet}\,X$ similar to the one in $p^\uparrow p \to \text{jet}\,\pi^0\,X$

Measurements will provide indications on the size of $f_{1T}^{\perp q}$ for $x_F \geq 0.3$

Sivers asymmetries for PHENIX kinematics at $\sqrt{s} = 200$ GeV



- Kinematic cuts on the jet:

$$2 \text{ GeV} < p_{jT} < 6 \text{ GeV}$$
$$E_j > 10 \text{ GeV}$$
$$R < 0.5, \qquad R \equiv \sqrt{(\eta_j - \eta_\pi)^2 + (\phi_j - \phi_\pi)^2}$$

- Kinematic cuts on the pion:

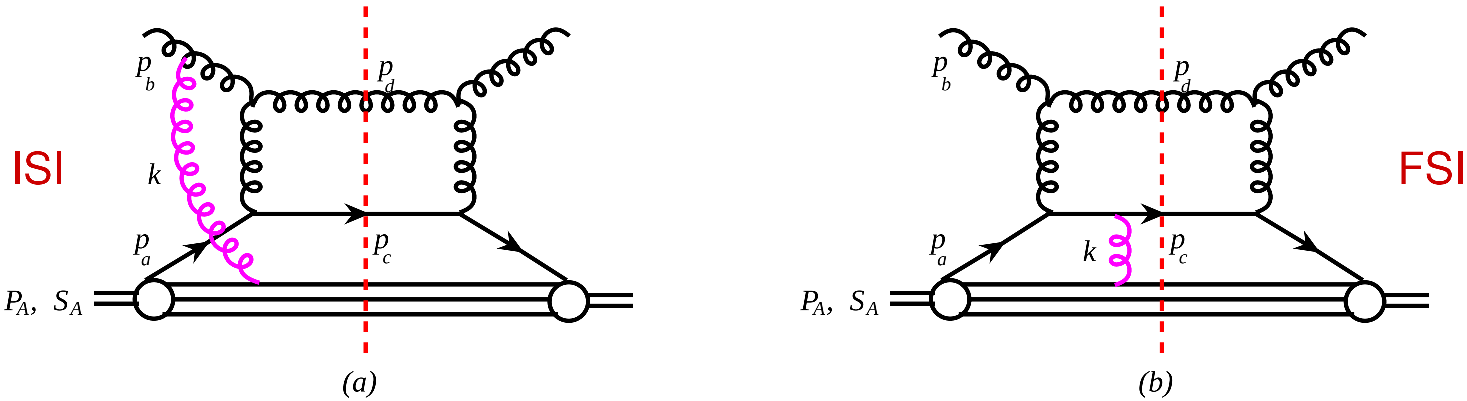
$$2 < \eta_\pi < 4$$
$$0.2 < z_{\text{exp}} < 0.8$$
$$k_{\perp\pi} > 0.1 \text{ GeV}$$

Color gauge invariant (CGI) generalized parton model

- In the GPM: the Sivers function is assumed to be *universal*, $f_{1T}^{\perp q} \equiv f_{1T}^{\perp q,\,\mathrm{SIDIS}}$
- In the CGI (GPM): the Sivers function is *non-universal*
  - Initial and final state interactions (ISIs/FSIs) considered between the struck parton and the spectators from the polarized hadron through gluon exchange
  - ISIs/FSIs depend on the scattering process $\Longrightarrow$ A different $f_{1T}^{\perp q}$ has to be used for each partonic subprocess $a\,b \to c\,d$ contributing to $p^{\uparrow}\,p \to \mathrm{jet}\,\pi\,X$
- The process dependent Sivers function $f_{1T}^{\perp q,\,ab\to cd}$ is known for $p^{\uparrow}\,p \to \pi\,X$

Gamberg, Kang, PLB 696 (2011) 1009

Example: $q\,g \to q\,g$

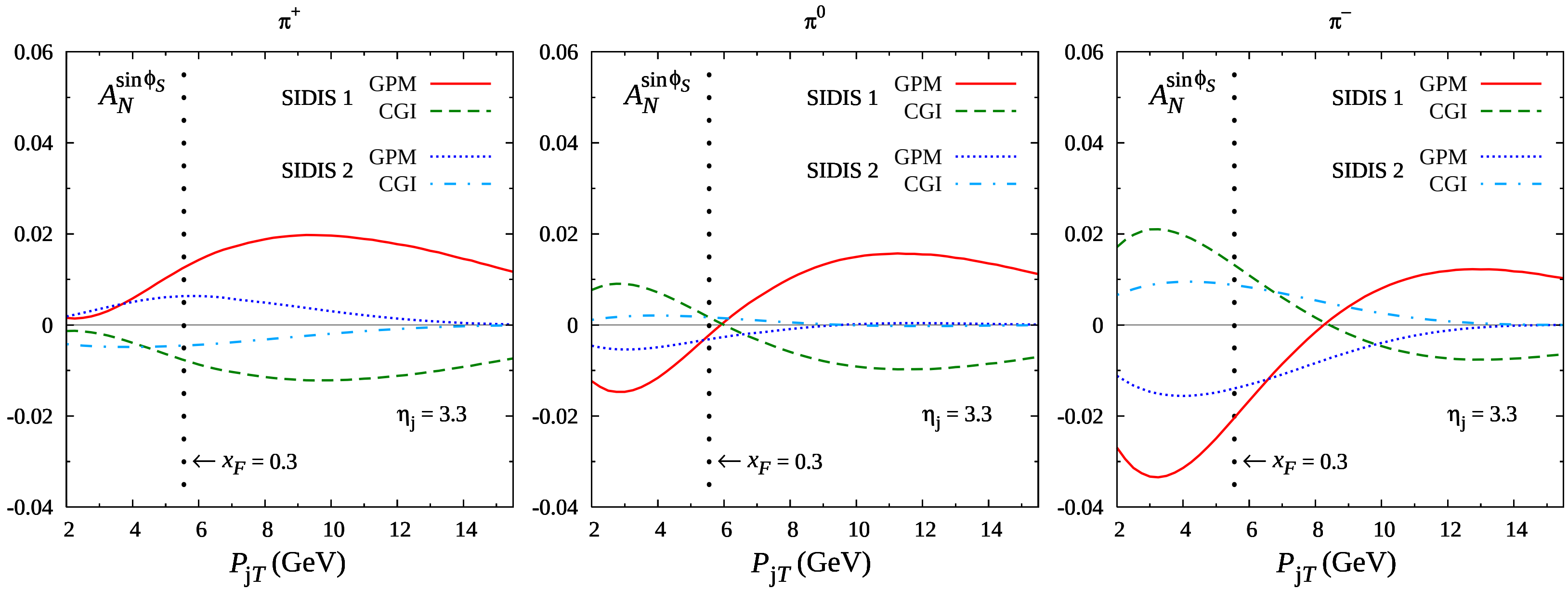


$$f_{1T}^{\perp q,\,qg\to qg} \approx -\frac{N_c^2+2}{2(N_c^2-1)}\,f_{1T}^{\perp q,\,\mathrm{SIDIS}} = -\frac{11}{16}\,f_{1T}^{\perp q,\,\mathrm{SIDIS}}$$

Test of the process dependence of the Sivers function

GPM *vs* CGI at $\sqrt{s} = 500$ GeV

D'Alesio, Gamberg, Kang, Murgia, CP, PLB 704 (2011) 637



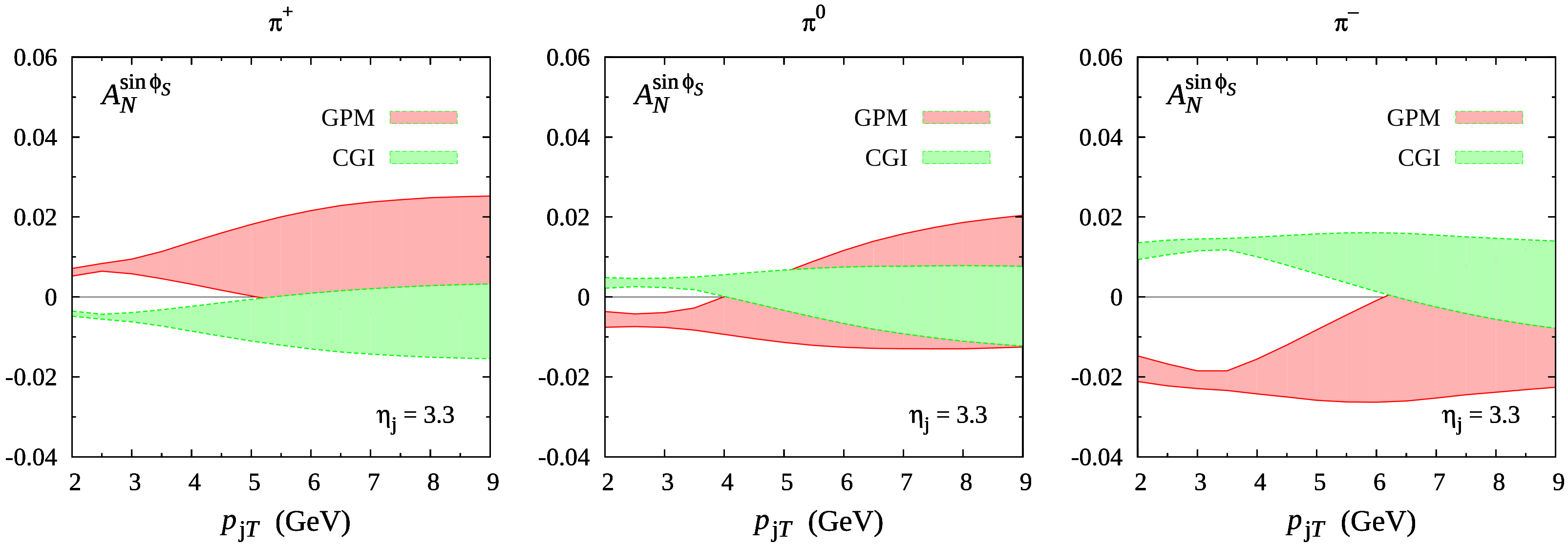
SIDIS1: $A_N^{\sin(\phi_S-\phi_\pi^H)}[\mathrm{GPM}] \approx -A_N^{\sin(\phi_S-\phi_\pi^H)}[\mathrm{CGI}]$; the same holds true for SIDIS2

- change of sign due to the dominant channel at forward rapidity, $qg \to qg$
- $x_F \leq 0.3$: optimal region to discriminate between the two approaches

At $\sqrt{s} = 200$ GeV, similar results with larger asymmetries, but narrower range of P_{jT}

Sivers asymmetry in $p^{\uparrow}p \to \mathrm{jet}\,\pi\,X$ *at* $\sqrt{s} = 500$ *GeV: uncertainties*

Scan bands for the quark Sivers effect in the GPM and CGI GPM models
Anselmino *et al*, PRD 86 (2012) 074032; 88 (2013) 054023



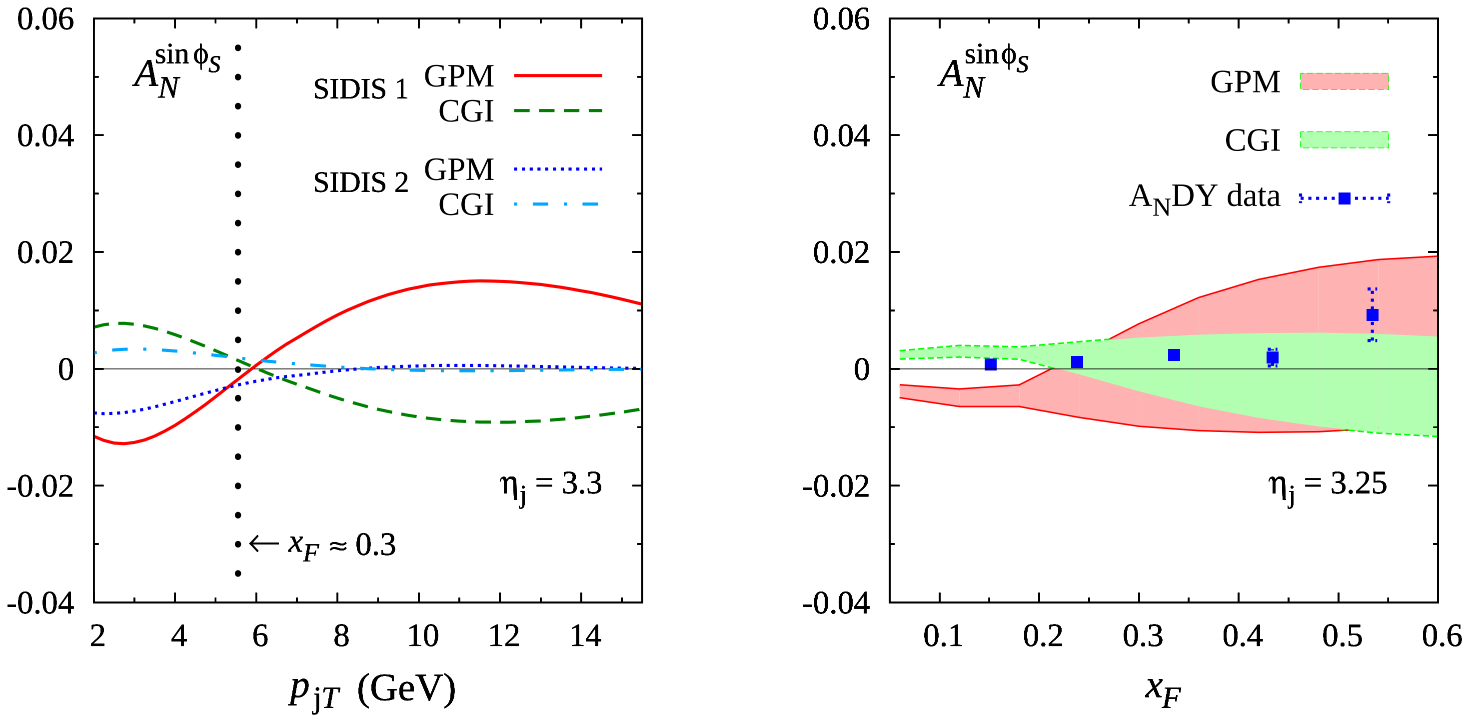
D'Alesio, Murgia, CP, arXiv:1307.4880

Predictive power lost for p_{jT} beyond $4-6$ GeV

Best situation for π^-: larger asymm. and well separated bands up to $p_{jT} = 5$ GeV

Sivers asymmetry in $p^\uparrow p \to \text{jet}\, X$ *at* $\sqrt{s} = 500$ *GeV*

Quark contribution to $A_N^{\sin\phi_S}$: results similar to the ones for $p^\uparrow p \to \text{jet}\, \pi^0\, X$



D'Alesio, Murgia, CP, arXiv:1307.4880

GPM vs CGI GPM: comparison with A_NDY data not conclusive

Bland *et al*, arXiv:1304.1454

Similar study within the twist-three approach

Gamberg, Kang, Prokudin, PRL 110 (2013) 232301

Summary and conclusions

- Study of the process $p^{(\uparrow)}p \to \mathrm{jet}\,\pi\,X$, which is under present active investigation at RHIC, within a TMD generalized factorization scheme
- The observable leading-twist azimuthal asymmetries are related to both quark and gluon-originated jets (in principle distinguishable)
- In contrast to single inclusive pion production and in analogy with SIDIS, one can discriminate among different effects by taking moments of the asymmetries
- Measurements of sizeable Collins and Sivers asymmetries: indication on the size and sign of transversity and quark Sivers function in a new kinematic region
- Comparison with similar studies in DY, SIDIS, e^+e^-: validation of universality of the Collins function, test of the process dependence of the Sivers function
- From the phenomenological point of view, the measurement of such types of asymmetries would be a crucial test for the TMD factorization approach