Collins effect in $p^{\uparrow}p \to \mathrm{jet}\,\pi\,X$ at RHIC

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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
- Collins and Collins-like asymmetries
- Phenomenology for STAR and PHENIX kinematics

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

Kinematics

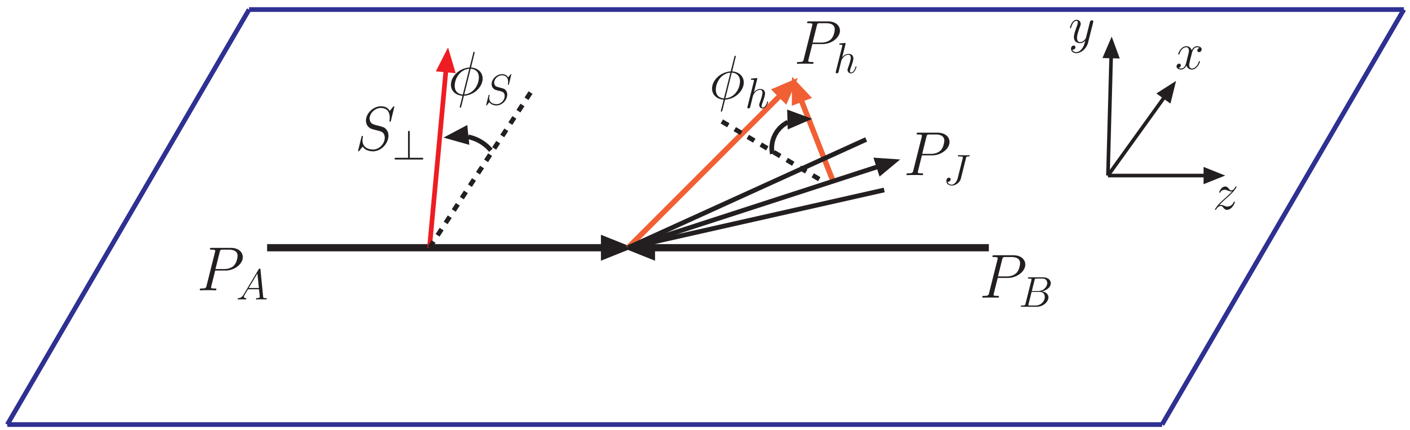
We consider the process

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

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

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

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
  J. Drachenberg's talk

Weighted cross sections

- General structure of the single transverse polarized cross section

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

- Unpolarized cross section:

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

- Average values of appropriate functions $W(\phi_S,\phi_\pi^H) = 1$, $\cos\phi_\pi^H$, $\cos 2\phi_\pi^H$

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

single out $\mathrm{d}\sigma_0$, $\mathrm{d}\sigma_1$, $\mathrm{d}\sigma_2$ respectively

Single spin asymmetries

- 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:

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

  - 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

Phenomenology at RHIC

- $\langle W \rangle \, (A_N^W)$ 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 $0.3 \leq z \leq 1$

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

- 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

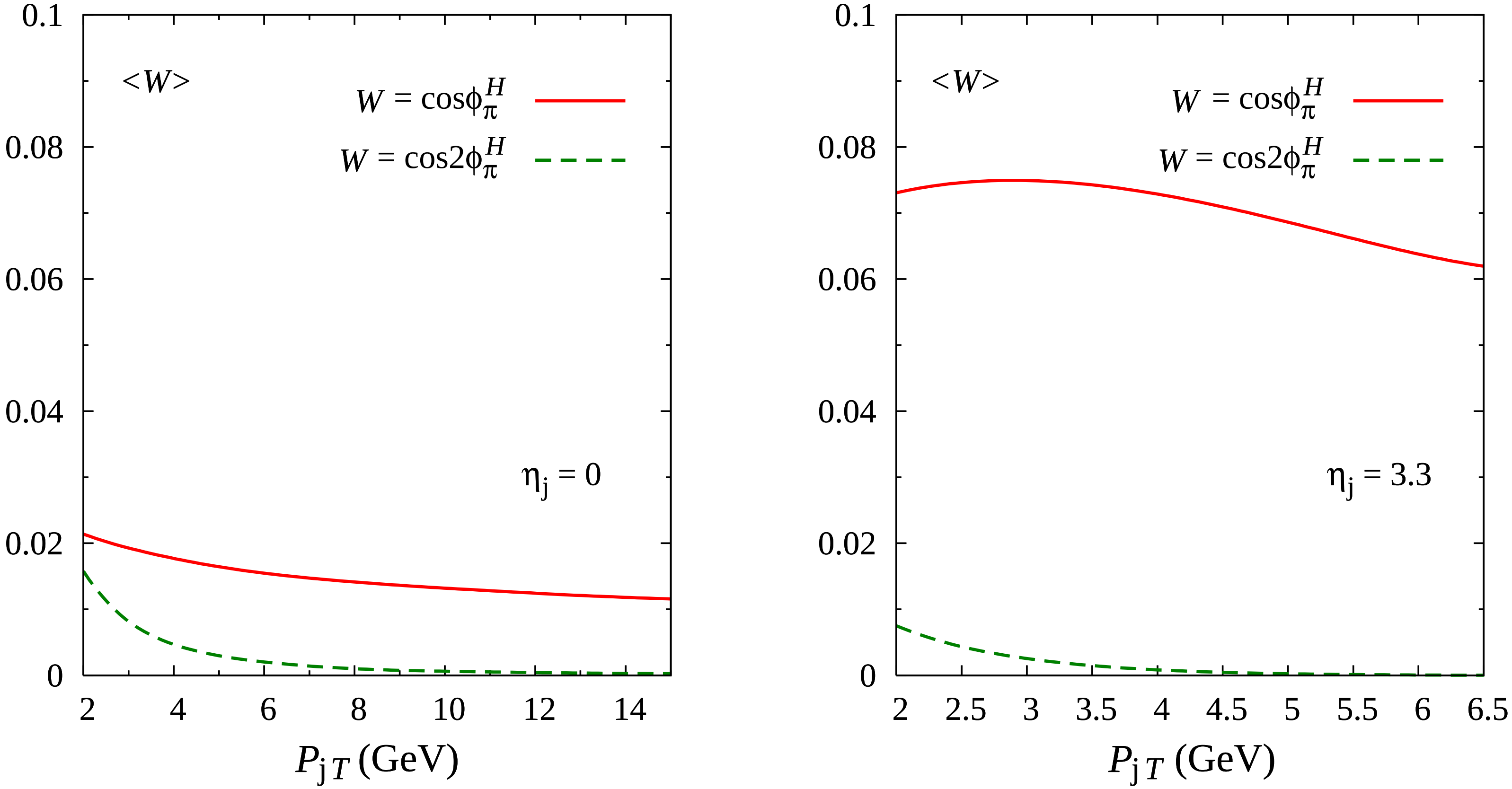
  Advantage: upper bound on the absolute value of any effect playing a role in the asymmetries. All marginal effects in this scenario may be discarded

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

Weighted cross sections for $pp \to \text{jet}\,\pi^+ X$ *: upper bounds*

$\langle \cos\phi_\pi^H \rangle \sim h_1^{\perp q} f_1 H_1^{\perp q} \oplus f_1 h_1^{\perp q} H_1^{\perp q}$ $\langle \cos 2\phi_\pi^H \rangle \sim h_1^{\perp g} f_1 H_1^{\perp g} \oplus f_1 h_1^{\perp g} H_1^{\perp g}$

$x_F = \frac{2P_{jL}}{\sqrt{s}} = 0$ $0.27 \leq x_F \leq 0.88$



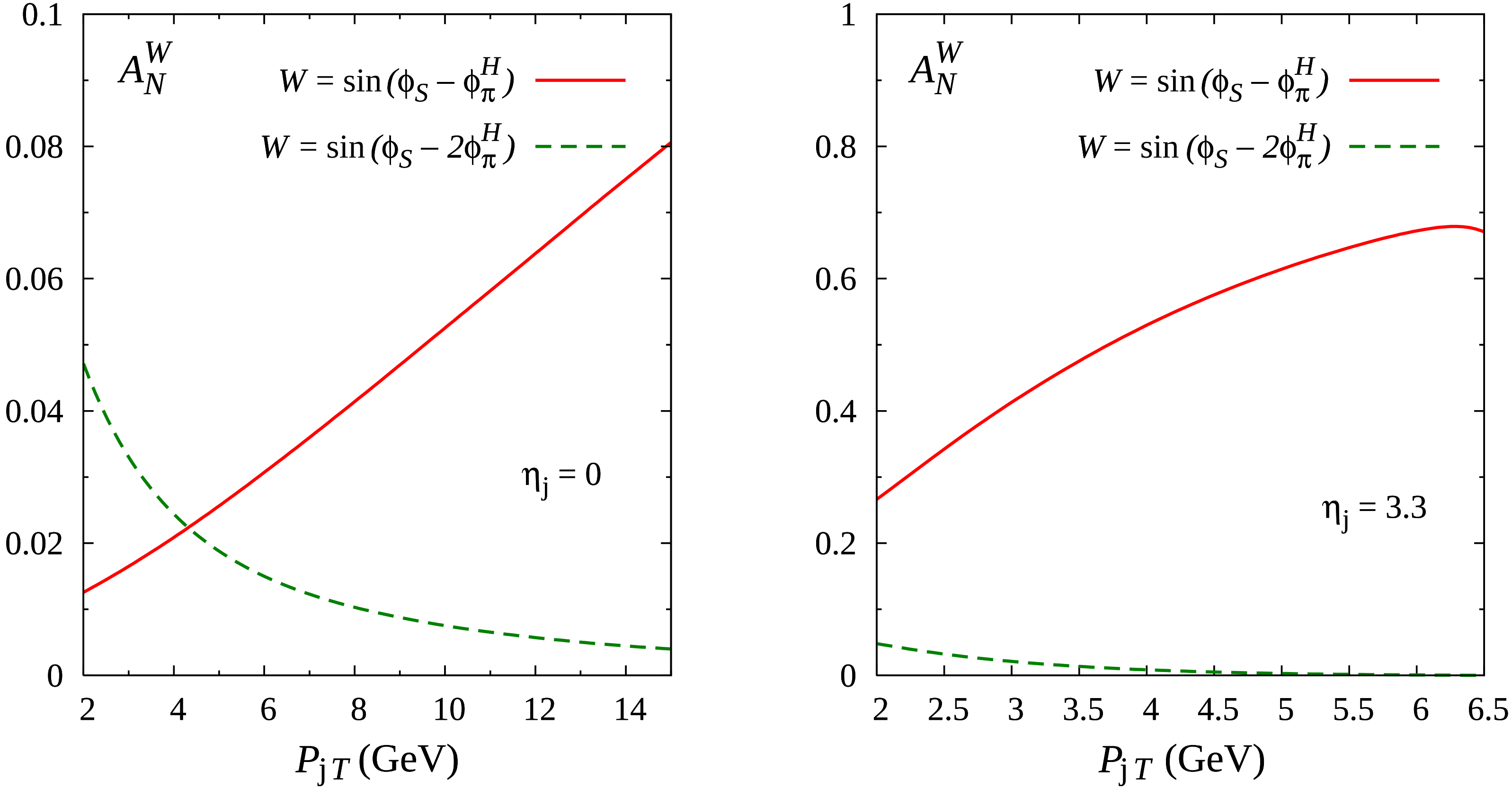
- $h_1^{\perp g}$: impact on physics at the LHC, especially on Higgs and quarkonium studies

Boer, CP, PRD 86 (2012) 094007
Boer, den Dunnen, CP, Schlegel, Vogelsang, PRL 108 (2012) 032002
Boer, den Dunnen, CP, Schlegel, PRL 111 (2013) 032002

Collins(like) asymmetries in $p^{\uparrow}p \to \text{jet}\,\pi^{+}\,X$*: upper bounds*

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

$A_N^{\sin(\phi_S-\phi_\pi^H)} \sim h_1^q f_1 H_1^{\perp q}$ $\qquad$ $A_N^{\sin(\phi_S-2\phi_\pi^H)} \sim h_1^g f_1 H_1^{\perp g}$

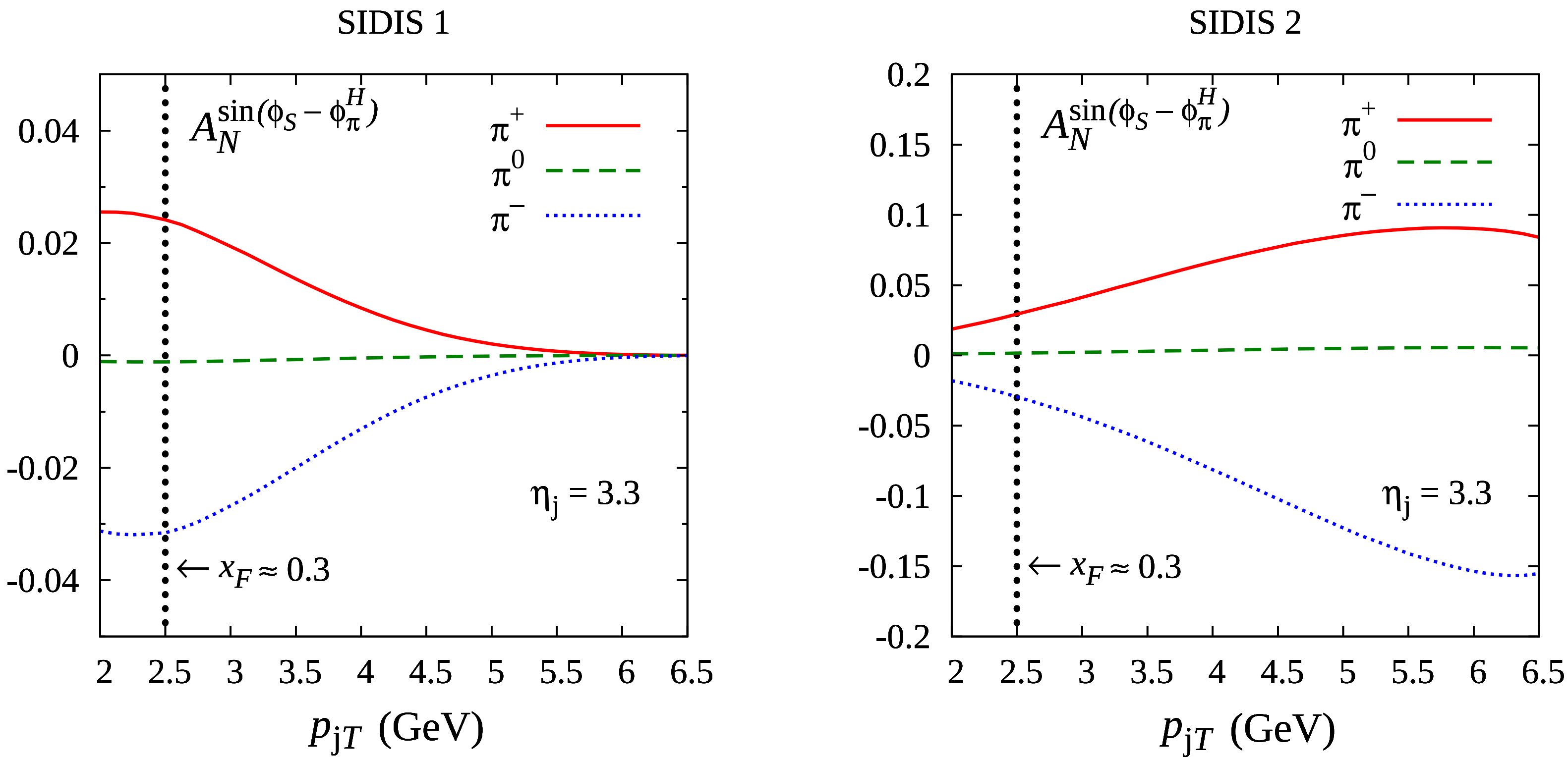


$A_N^{\sin(\phi_S-\phi_\pi^H)}$ large at $\eta_j = 3.3$, grows with P_{jT}; $A_N^{\sin(\phi_S-2\phi_\pi^H)}$ at most 5%

DSS set of FF: similar results, but quark (gluon) contributions to A_N^W are slightly smaller (larger). The same holds true for the Sivers asymmetry

Collins asymmetries in $p^\uparrow p \to \text{jet}\,\pi\,X$: parameterizations

Parameterizations of h_1^q, $H_1^{\perp q}$ from SIDIS and e^+e^- data by Anselmino *et al:*
PRD 75 (2007) 054032 (SIDIS 1); NP (Proc. Suppl.) 191 (2009) 98 (SIDIS 2)



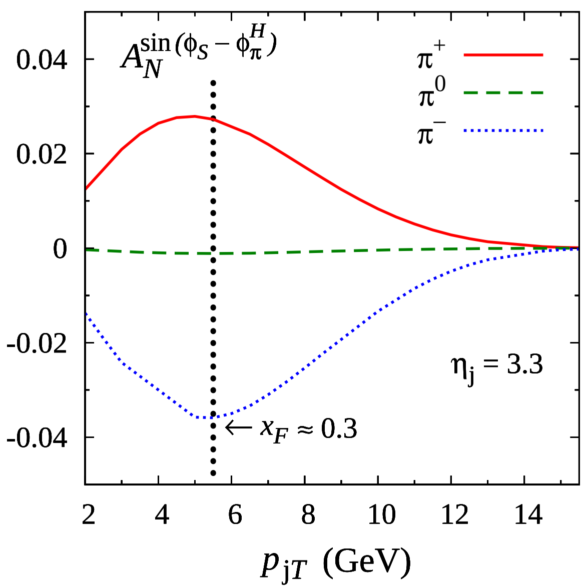
$A_N^{\sin(\phi_S-\phi_\pi^H)} \approx 0$ at $\eta_{\text{j}} = 0$. Preliminary data: $A_N^{\sin(\phi_S-\phi_\pi^H)} \approx 0$ for π^0 at $\eta = 3.3$
Poljak [STAR], J. Phys. Conf. Ser. 295 (2011) 012102

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

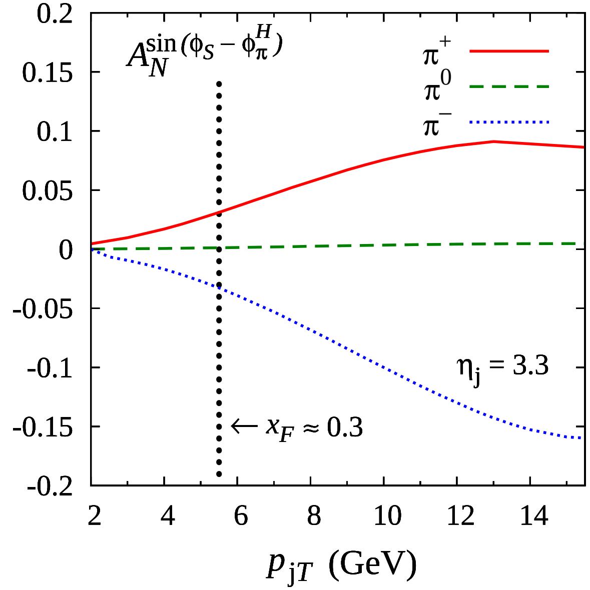
Measurements useful to constrain h_1^q in a new kinematic region!

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

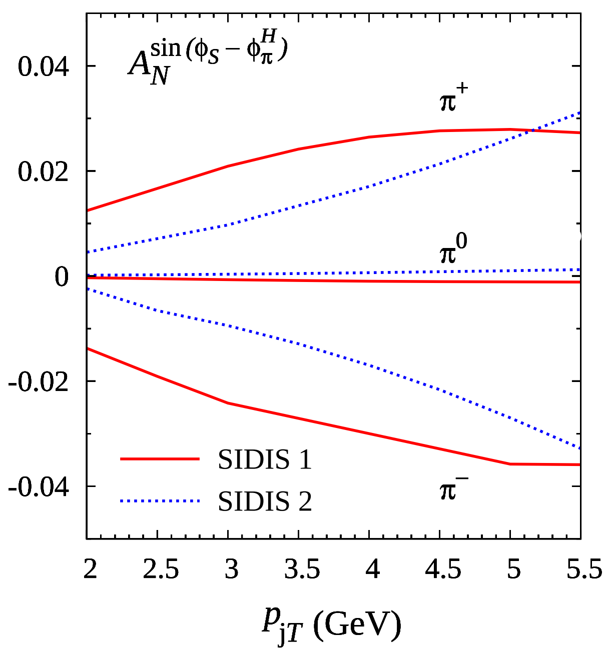
SIDIS 1



SIDIS 2



D'Alesio, Murgia, CP, arXiv:1307.4880



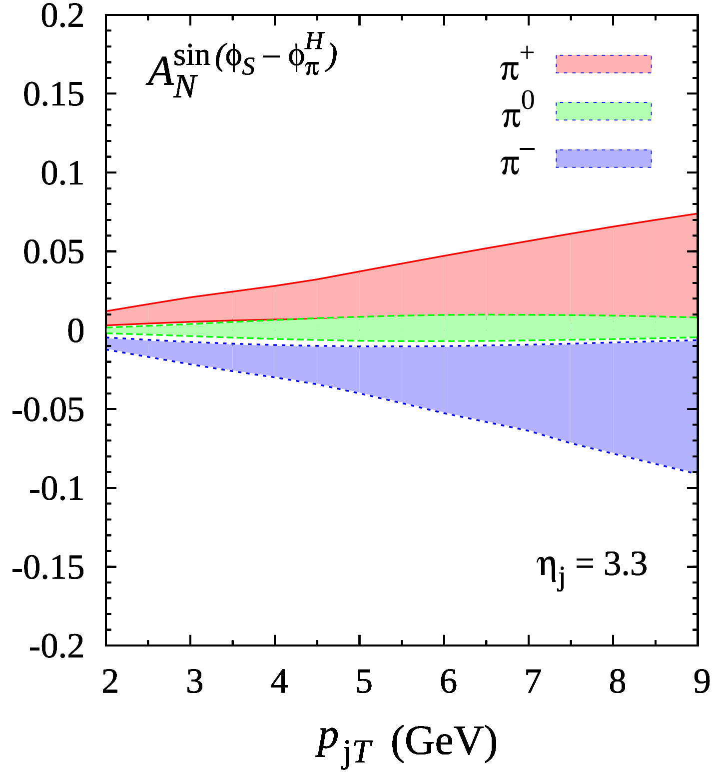
Asymmetries still sizeable at $\sqrt{s} = 500$ GeV

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_{jT}: 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:

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

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

- Kinematic cuts on the pion:

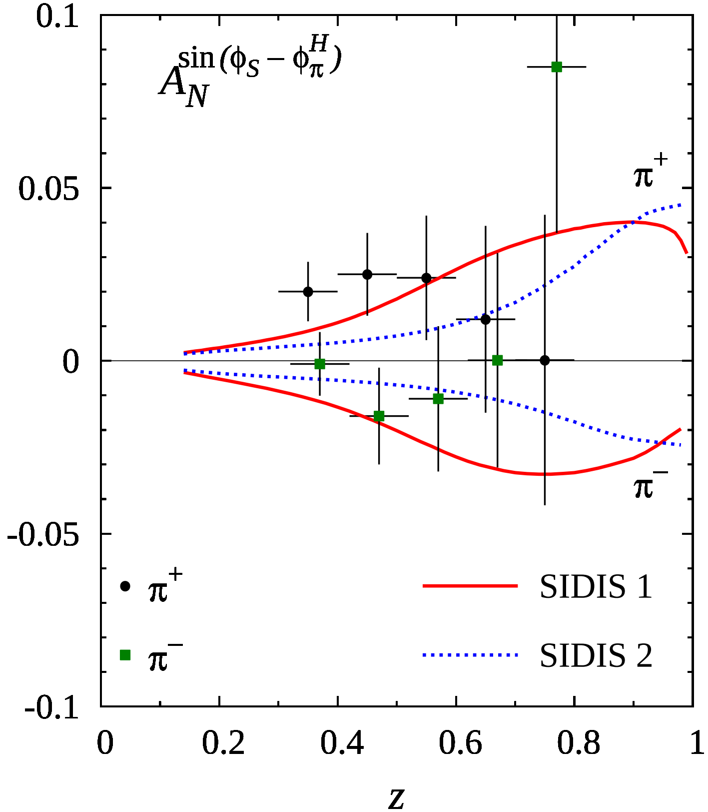
$$0.1 < z_{\rm exp} \equiv \frac{E_\pi}{E_{\rm j}} < 0.8$$

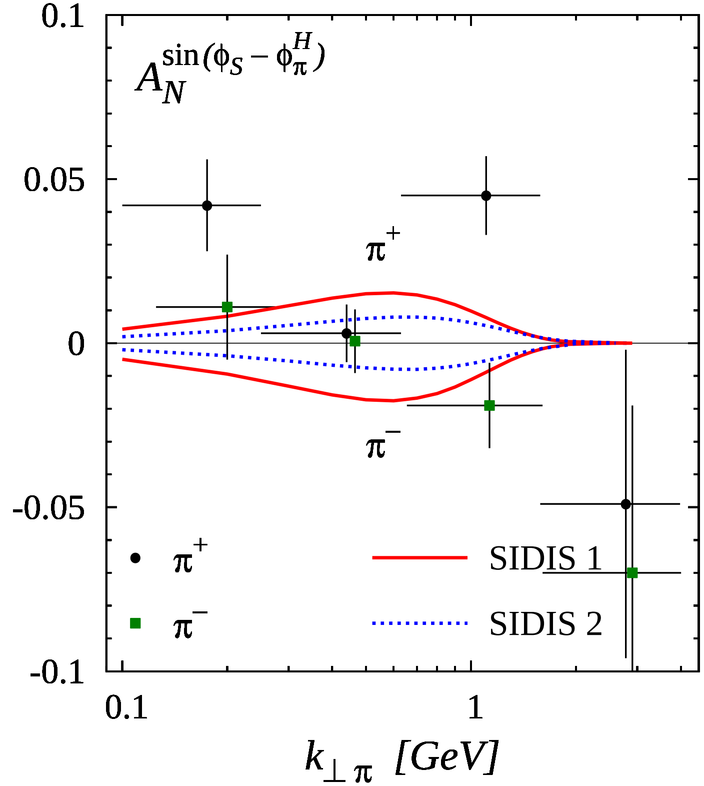
$$-1 < \eta_\pi < 1$$

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

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:

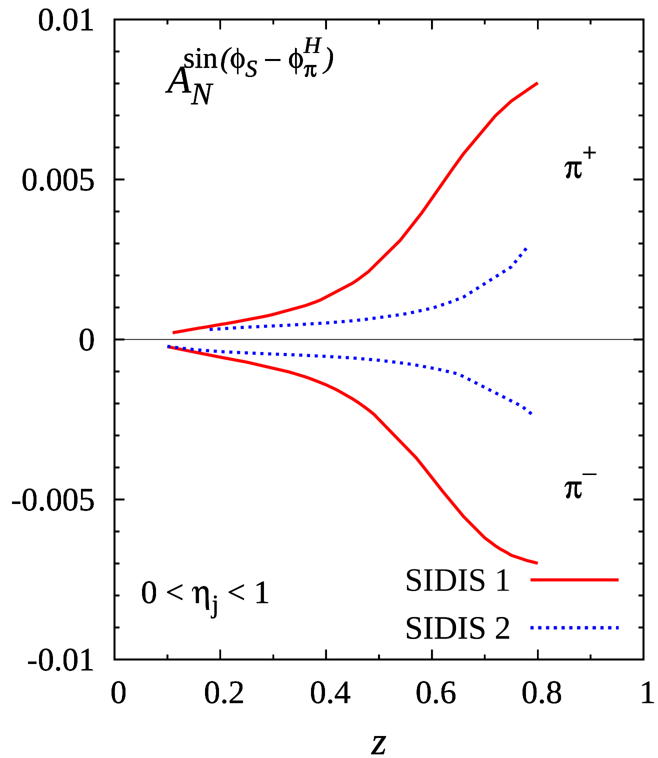
$$0.1 < z_{\rm exp} < 0.8$$

Preliminary data from STAR now available

J. Drachenberg's talk

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

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

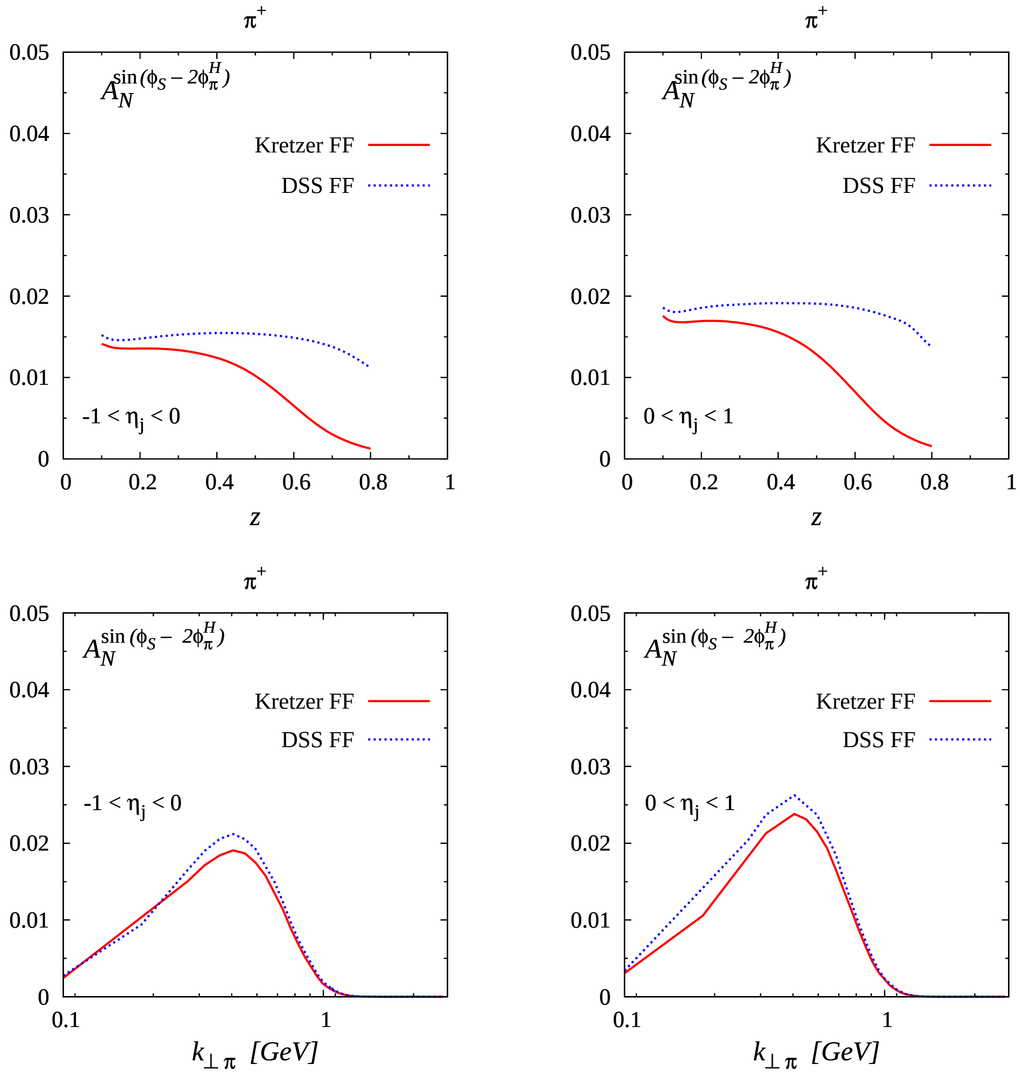


- $A_N^{\sin(\phi_S - \phi_\pi^H)}$ vs $k_{\perp\pi}$ negligible: less than permille $(0.1 < z < 0.8)$

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

Upper bounds for Collins-like asymmetries: $\sqrt{s} = 500$ GeV

$$A_N^{\sin(\phi_S - 2\phi_\pi^H)} \sim h_1^g \, f_1 \, H_1^{\perp g}$$



For π^- asymmetries are very similar. Any data for this effect would be helpful in constraining the completely unknown gluon TMDs h_1^g and $H_1^{\perp\, g}$

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

- Center of mass energy:

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

- Kinematic cuts on the jet:

$$2.5 < \eta_{\rm j} < 3.5$$

$$2 \text{ GeV} < p_{{\rm j}T} < 6 \text{ GeV}$$

$$E_{\rm j} > 10 \text{ GeV}$$

$$R < 0.5, \qquad R \equiv \sqrt{(\eta_{\rm j} - \eta_\pi)^2 + (\phi_{\rm j} - \phi_\pi)^2}$$

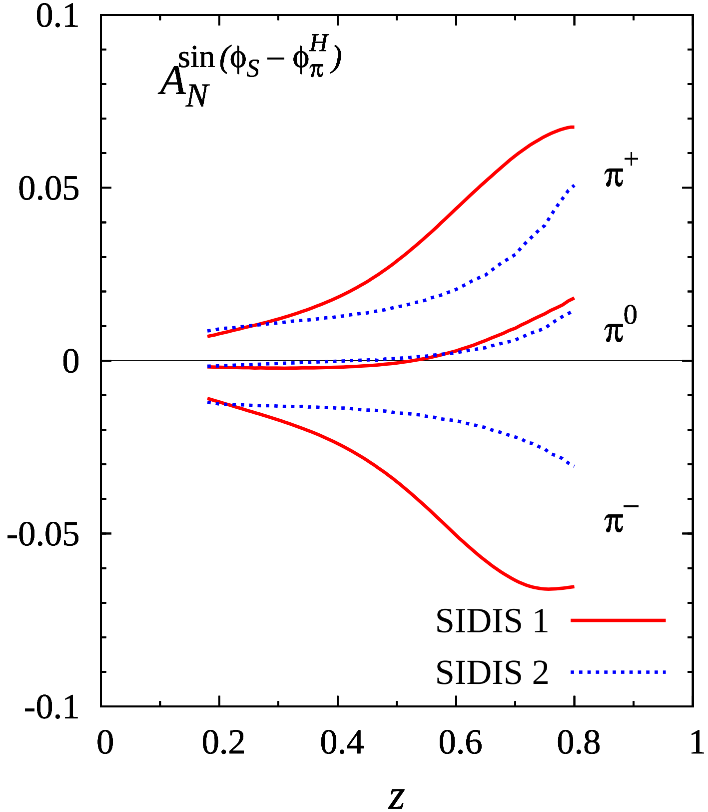
- Kinematic cuts on the pion:

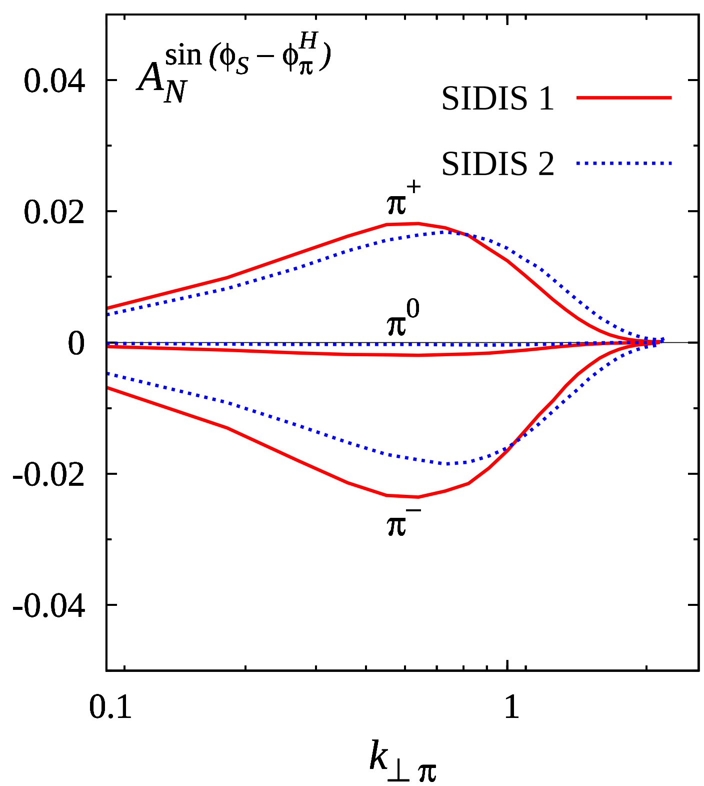
$$2 < \eta_\pi < 4$$

$$0.2 < z_{\rm exp} < 0.8$$

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

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





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
- From the phenomenological point of view, the measurement of such types of asymmetries would be a crucial test for the TMD factorization approach
- Measurements of a sizeable Collins asymmetry could give an indication on the size and sign of the quark transversity distribution in a new kinematic region
- Comparison with analogous studies in DY and SIDIS:
  validation of expected universality of the Collins fragmentation function