Single Spin Asymmetries in Hadronic Interactions within the GPM Approach

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3DSPIN MAPPING THE PROTON IN 3D

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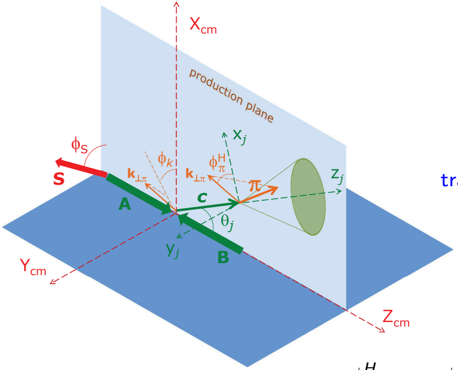
$$A(P_A; S) + B(P_B) \to \mathrm{jet}(P_\mathrm{j}) + h(P_h) + X$$

in the c.m.s. of the two spin $1/2$ hadrons A, B; the jet is in the XZ plane
A is polarized with transverse spin $S = (0, \cos\phi_S, \sin\phi_S, 0)$

D'Alesio, Murgia, CP, PRD 83 (2011) 034021; PEPAN 45 (2014) 676



ϕ_π^H: azimuthal distribution of the pion inside the jet, around the jet axis

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

ϕ_π^H: same angle, but measured in the H frame, where the jet (parton c) is along z_j

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

$c.m.$ and H frames: related by a rotation around Y_{cm} by θ_j, polar angle of the jet

- Spin and intrinsic parton motion effects in initials hadrons and fragm.
Assumption: factorization holds for large p_T jet/hadron production

- SSA and azimuthal asymmetries are generated by TMD PDFs & FFs
Most relevant: $f_{1T}^{\perp}$ (Sivers), $h_1^{\perp}$ (Boer-Mulders), $H_1^{\perp}$ (Collins)
Anselmino *et al.*, PRD 73 (2006) 014020;
Aschenauer, D'Alesio, Murgia, 1512.05379
Notation: Meissner, Metz, Goeke, PRD 76 (2007) 034002

- Factorization proven in a simpler framework: intrinsic parton motion only in fragmentation. 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

Why looking at pions inside a jet?

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

  Anselmino *et al.*, PRD 71 (2005) 014002;
  Anselmino *et al.*, PRD 73 (2006) 014020

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

- Jets coming from quark or gluon fragmentation could be identified, since the pion azimuthal distribution is different in the two cases:
  - symmetric pion distribution: fragmentation of an unpolarized parton (D_1)
  - $\cos\phi_\pi^H$ distribution for a transversely polarized quark jet ($H_1^{\perp q}$)
  - $\cos 2\phi_\pi^H$ distribution for a linearly polarized gluon jet ($H_1^{\perp g}$)

- Complex measurement, but feasible and under consideration at RHIC

  Fatemi [STAR], talk at QCD evolution (2015);
  Drachenberg [STAR], PoS (DIS2015) 193

Weighted cross sections

- General structure of the single transverse polarized cross section

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

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

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

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

- Unpolarized cross section:

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

- Numerator of the single spin asymmetry:

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

- Azimuthal moments, $W(\phi_S, \phi_\pi^H) = \sin\phi_S,\ \sin(\phi_S - \phi_\pi^H),\ \ldots$

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

will single out the different contributions (analogy with SIDIS)

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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 q and $\bar{q}$ in all allowed combinations

$qq \to qq$: max number of terms ($gg \to gg$ similar, but with $\phi_\pi^H \to 2\phi_\pi^H$)

Unpolarized cross section:

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

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

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

Neglecting $k_\perp$ effects, only $f_1 f_1 D_1$ and $h_1 f_1 H_1^\perp$ contribute

Collins asymmetries $A_N^{\sin(\phi_S - \phi_\pi^H)}$

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

- 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 (Kretzer, DSS) evolved at the scale $\mu = P_{\mathrm{j}T}$
- 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)

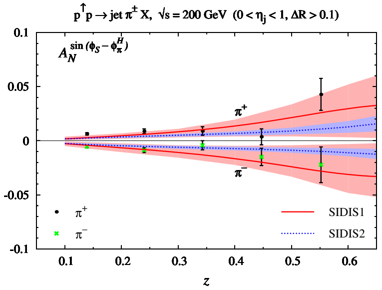
Anti-k_T jet reconstruction algorithm with parameter R

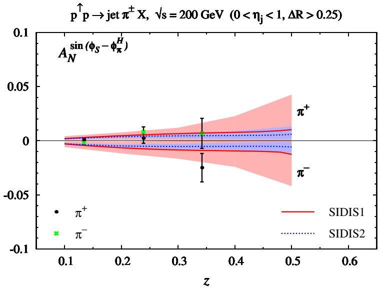
Center of mass energy $\sqrt{s} = 200$ GeV

- Kinematic cuts on the jet:
  $R = 0.6$
  $0 < \eta_{\mathrm{j}} < 1$
  $10 < P_{\mathrm{j}T} < 31.6$ GeV
- Kinematic cuts on the pion:
  $0.1 < z_{\mathrm{exp}} \equiv \frac{E_\pi}{E_{\mathrm{j}}} < 0.6$
  $0.2 < P_{\pi T} < 30$ GeV
  $0.125 < k_{\perp\pi} < 4.5$ GeV

$$\Delta R = \sqrt{(\eta_j - \eta_\pi)^2 + (\phi_j - \phi_k)^2} > 0.1\ (0.25)$$

We take $R \approx \Delta R$





All other (partonic) variables are integrated over, with

$$\langle x_a \rangle \sim \langle x_b \rangle \sim 0.2\,, \quad \langle k_{\perp\pi} \rangle \sim 0.5 - 0.4 \text{ GeV}\,, \quad \langle P_{jT} \rangle \sim 11.8 - 11.9 \text{ GeV}$$

Center of mass energy $\sqrt{s} = 500$ GeV

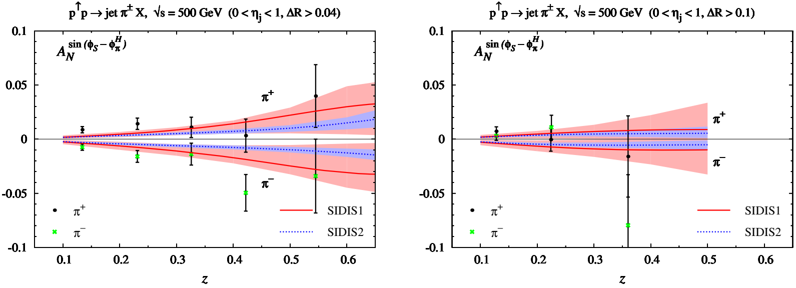
- Kinematic cuts on the jet:

$$R = 0.5$$
$$0 < \eta_{\mathrm{j}} < 1$$
$$22.7 < P_{\mathrm{j}T} < 55 \text{ GeV}$$

- Kinematic cuts on the pion:

$$0.1 < z_{\mathrm{exp}} \equiv \frac{E_\pi}{E_{\mathrm{j}}} < 0.8$$
$$0.2 < P_{\pi T} < 30 \text{ GeV}$$
$$0.1 < k_{\perp\pi} < 2 \text{ GeV}$$
$$\Delta R = \sqrt{(\eta_j - \eta_\pi)^2 + (\phi_j - \phi_k)^2} > 0.04 \ (0.1)$$

The QCD evolution of $A_N^{\sin(\phi_S - \phi_\pi^H)}$ can be tested



Similarly to $\sqrt{s} = 200$ GeV:

$$\langle x_a \rangle \sim \langle x_b \rangle \sim 0.2\,, \quad \langle k_{\perp\pi} \rangle \sim 0.3 - 0.8\ \mathrm{GeV}\,,$$

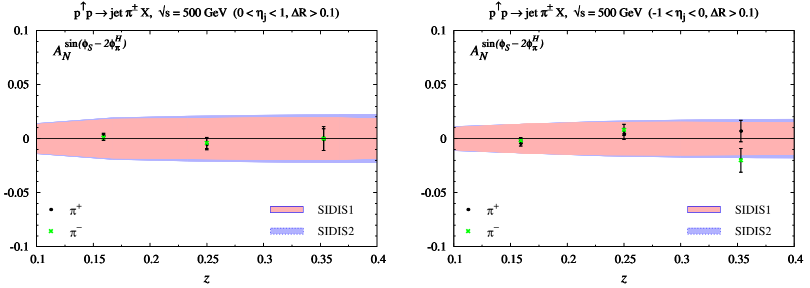
while the hard scale takes larger values, $\langle P_{jT} \rangle \sim\ 27 - 25$ GeV

Collins-like asymmetries $A_N^{\sin(\phi_S - 2\phi_\pi^H)}$

Comparison with STAR data

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

h_1^g, $H_1^{\perp g}$ are unknown, but their positivity bounds $\longrightarrow$ upper bounds on $A_N^{\sin(\phi_S - 2\phi_\pi^H)}$



[STAR Preliminary] R. Fatemi, QCD Evolution 2015

$$\langle x_a \rangle \sim \langle x_b \rangle \sim 0.05\,; \qquad \langle k_{\perp\pi} \rangle \sim 0.3 - 0.6 \text{ GeV}\,; \qquad \langle P_{jT} \rangle \sim 8 - 7 \text{ GeV}$$

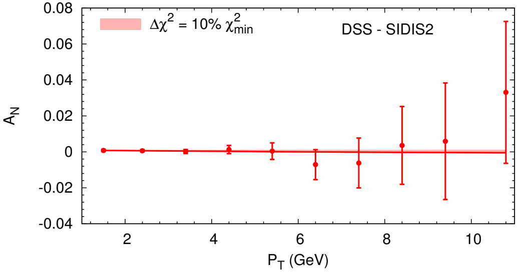
$H_1^{\perp g}$ can be determined separately from e^+e^- experiments

$h_1^g \neq h_1^{\perp g}$ (distribution of linearly polarized gluons inside an *unpolarized* proton)

Assumption: Factorization and universality of TMDs (Test of the GPM)

Motivation: New highly precise mid-rapidity RHIC data for A_N in $p^\uparrow p \to \pi^0 X$

$\sqrt{s} = 200$ GeV $\qquad |\eta_\pi| \leq 0.35$



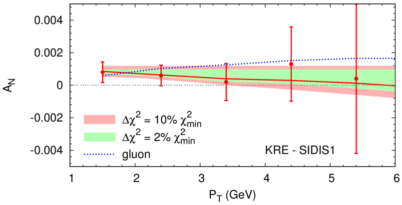
[PHENIX Coll.] PRD 90 (2014) 012006

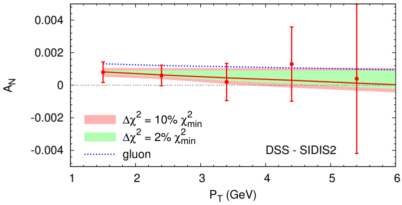
Data for $A_N(p^\uparrow p \to \mathrm{jet}\, X)$ not included in the fit, but consistent with new bound

[STAR Coll.] PRD 86 (2012) 032006

$$A_N = A_N^{\text{quark}} + A_N^{\text{gluon}} \qquad \chi^2 = \sum \frac{\left(A_N^{\text{gluon}} + A_N^{\text{quark}} - A_N^{\text{exp}}\right)^2}{\sigma_{\text{exp}}^2 + \sigma_{\text{quark}}^2} \qquad (4\ \textit{parameters})$$

σ_{quark}: Estimated theoretical uncertainty on the quark contribution





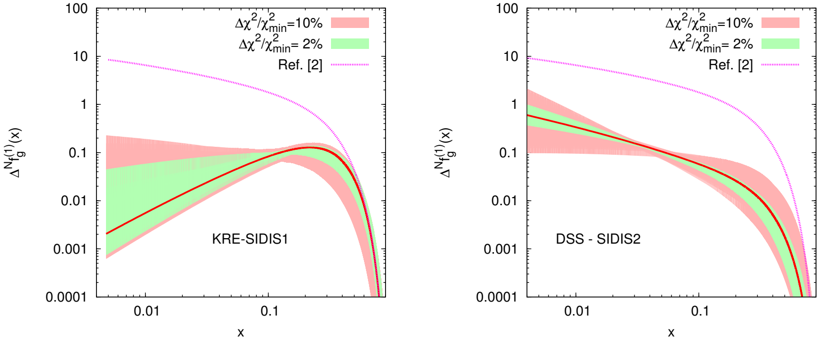
Uncertainty bands: envelope of A_N curves generated by all parameter sets in the explored phase space giving $\chi^2 \leq \chi^2_{\text{min}} + \Delta\chi^2$, $\Delta\chi^2 = (2\%, 10\%)\,\chi^2_{\text{min}}$

Open issues: factorization, process dependence, relation to twist-three approach

Boer, Lorcé, CP, Zhou, AdHEP (2015)

Small, positive GSF, mainly constrained in the range $0.05 < x < 0.3$ (SIDIS)

$$\Delta^N f^{(1)}_{g/p^\uparrow}(x) \equiv \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{4M_p}\Delta^N f_{g/p^\uparrow}(x,k_\perp) = -f_{1T}^{\perp(1)g}(x)$$



D'Alesio, Murgia, CP, JHEP 1509 (2015) 119

Ref. [2]: Old bound on the gluon Sivers function

Anselmino, D'Alesio, Melis, Murgia, PRD74 (2006) 094011

- Study of the process $p^{\uparrow} p \to \mathrm{jet}\, \pi\, X$, under active investigation at RHIC, within a TMD generalized factorization scheme
- In contrast to $p^{\uparrow} p \to \pi\, X$ and similarly to SIDIS, one can discriminate among different effects by taking moments of the asymmetries
- Measurements of Collins asymmetries: indication on the size and sign of transversity in a new kinematic region
- Comparison with similar studies in DY, SIDIS, e^+e^-: validation of universality of the Collins function
- Test of TMD factorization
- First extraction of the GSF from A_N data on $pp \to \pi^0\, X$