Transverse momentum distributions of hadrons within jets

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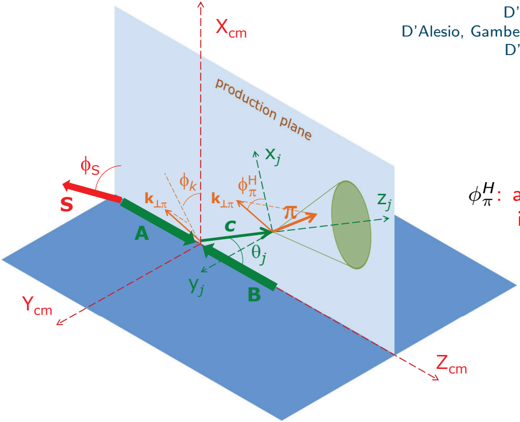
3DSPIN MAPPING THE PROTON IN 3D

Theoretical framework and motivation

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

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

D'Alesio, Murgia, CP, PRD 83 (2011) 034021
D'Alesio, Gamberg, Kang, Murgia, CP, PLB 704 (2011) 637
D'Alesio, Murgia, CP, PEPAN 45 (2014) 676;
PLB 773 (2017) 300



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

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

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

The TMD generalized parton model (GPM)

- 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;
  Kang, Prokudin, Ringer, Yuan, PLB 774 (2017) 635

- 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;
  STAR Collaboration, arXiv:1708.07080

- 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 $W(\phi_S,\phi_\pi^H) = 1,\ \sin\phi_S,\ \cos\phi_\pi^H,\ \ldots$

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

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

Azimuthal moments

- 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:

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

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

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

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

$$\mathcal{N} \sim \mathrm{d}\Delta\sigma_0 \sin\phi_S + \mathrm{d}\Delta\sigma_1^- \sin(\phi_S - \phi_\pi^H) + \mathrm{d}\Delta\sigma_1^+ \sin(\phi_S + \phi_\pi^H)$$

$$\mathrm{d}\Delta\sigma_0 \sim f_{1T}^\perp f_1 D_1 \quad h_1 h_1^\perp D_1 \quad h_{1T}^\perp h_1^\perp D_1$$
$$\mathrm{d}\Delta\sigma_1^- \sim h_1 f_1 H_1^\perp \quad f_{1T}^\perp h_1^\perp H_1^\perp$$
$$\mathrm{d}\Delta\sigma_1^+ \sim h_{1T}^\perp f_1 H_1^\perp \quad f_{1T}^\perp h_1^\perp H_1^\perp$$

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

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Collins asymmetries

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

D'Alesio, Murgia, CP, PLB 773 (2017) 300

- 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);
PRD 87 (2013) 094019 (Fit 2013)

Anti-k_T jet reconstruction algorithm with parameter R

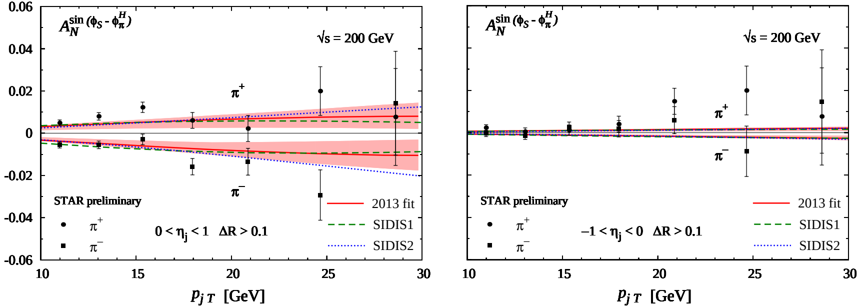
Center of mass energy $\sqrt{s} = 200$ GeV

- Kinematic cuts on the jet:
$$R = 0.6$$
$$0 < \eta_{\mathrm{j}} < 1$$
$$10 < P_{\mathrm{j}T} < 31.6 \text{ GeV}$$

- Kinematic cuts on the pion:
$$0.1 < z_{\mathrm{exp}} \equiv \frac{E_\pi}{E_{\mathrm{j}}} < 0.6$$
$$0.2 < P_{\pi T} < 30 \text{ GeV}$$
$$0.125 < k_{\perp\pi} < 4.5 \text{ GeV}$$
$$\Delta R = \sqrt{(\eta_j - \eta_\pi)^2 + (\phi_j - \phi_k)^2} > 0.1$$

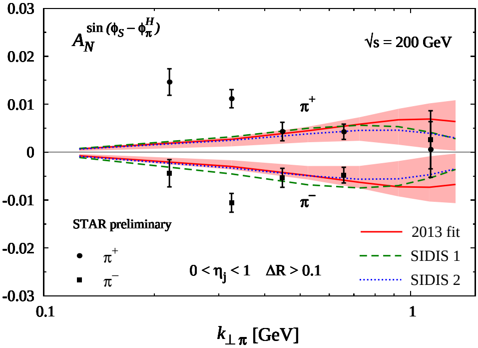
We take $R \approx \Delta R$

Comparison with STAR results
$\sqrt{s} = 200$ GeV



Predictions differ as $p_{jT} > 20$ GeV ($\langle x_a \rangle \geq 0.3$): h_1^q not constrained by data

Comparison with STAR results
$\sqrt{s} = 200$ GeV



Some discrepancies between theory and data appear at small values of $k_{\perp\pi}$

- If data are confirmed, hint for a different $k_{\perp\pi}$ behaviour of FFs
- Agreement improves at $\sqrt{500}$ GeV for $\langle z \rangle = 0.13,\ 0.37$

Kang, Prokudin, Ringer, Yuan, PLB 774 (2017) 635
STAR Collaboration, arXiv:1708.07080

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

- Kinematic cuts on the jet:

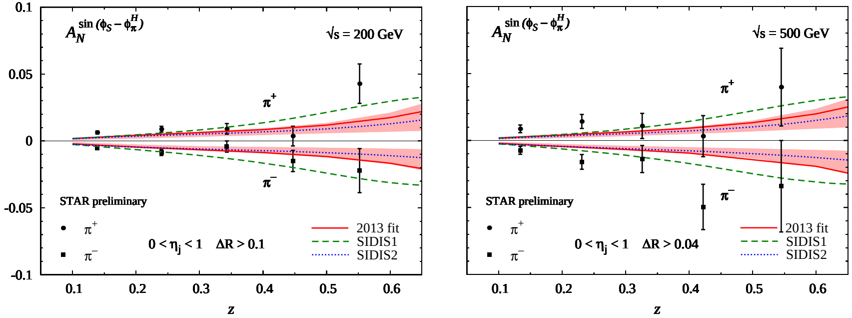
$$R = 0.5$$
$$0 < \eta_{\mathrm{j}} < 1$$
$$22.7 < P_{\mathrm{j}T} < 55 \text{ GeV}$$

- Kinematic cuts on the pion:

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

Comparison with STAR results
$\sqrt{s} = 500$ GeV

The QCD evolution of $A_N^{\sin(\phi_S - \phi_\pi^H)}$ can be tested: almost no energy dependence



$$\sqrt{s} = 200 \text{ GeV}: \quad \langle x_a \rangle \sim \langle x_b \rangle \sim 0.2\,, \quad \langle k_{\perp\pi} \rangle \sim 0.4 - 0.5 \text{ GeV}\,, \quad \langle P_{jT} \rangle \sim 12 \text{ GeV}$$

$$\sqrt{s} = 500 \text{ GeV}: \quad \langle x_a \rangle \sim \langle x_b \rangle \sim 0.2\,, \quad \langle k_{\perp\pi} \rangle \sim 0.3 - 0.8 \text{ GeV}\,, \quad \langle P_{jT} \rangle \sim 25 - 27 \text{ GeV}$$

h_1^q probed in the valence region, where it is known

SIDIS 1 predictions larger because of the different unpolarized FF set

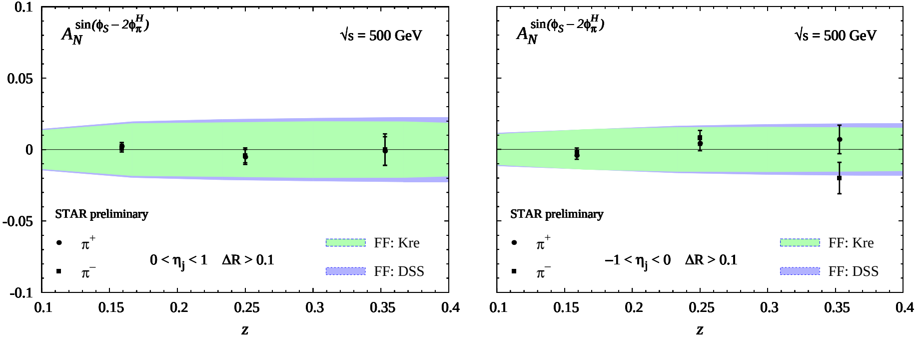
Collins-like asymmetries

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; their positivity bounds $\longrightarrow$ upper bounds on $A_N^{\sin(\phi_S - 2\phi_\pi^H)} \approx 2\%$



[STAR Preliminary] R. Fatemi, QCD Evolution 2015

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

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

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

- The process $p^\uparrow p \to \mathrm{jet}\,\pi\,X$, under active investigation at RHIC, is studied 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
- STAR data on Collins asymmetries are described by a universal Collins function, with discrepancies only in the description of their $k_{\perp\pi}$-behavior
- Neither factorization-breaking nor TMD evolution effects emerge
- The size of the Collins-like asymmetries, involving linearly polarized gluons, is constrained for the first time by STAR data