Parton intrinsic motion in inclusive particle production: unpolarized cross sections, single spin asymmetries and the Sivers effect

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Part of a larger collaboration including:

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[See also talks by U. D'Alesio, M. Boglione (tomorrow) and A. Prokudin (Thursday)]

Based on the paper by U.D. and F.M., hep-ph/0408092; PRD, in press (2004)
[see this paper for detailed references]

Summary

- **Motivations**
- **Goal**
- **Basics of approach**
- **Details of numerical calculations**
- **(Selected) Results for unpolarized cross sections**
- **(selected) Results for $A_N(p^\uparrow p \to \pi, \gamma + X)$ [Sivers effect only]**
- **Conclusions and outlook**

Motivations (1)

- Role of $\boldsymbol{k}_\perp$ effects studied starting from early applications of pQCD to $AB \to C + X$ processes; generalizations of the usual collinear pQCD approach attempted.

- NLO collinear pQCD underestimates experimental results for incl. π, γ production in hadronic collisions [$y \sim 0$, moderately large p_T]; $\boldsymbol{k}_\perp$ effects reconcile (in most cases) theoretical calculations with experimental results.

- Almost independently, the role of $\boldsymbol{k}_\perp$ effects has received attention in the context of polarized inclusive particle production [SSA (A_N), $P_T(\Lambda)$] at high energy and moderately large p_T, in particular at medium-large x_F.

- As originally suggested by Sivers and Collins, pQCD with proper inclusion of spin and $\boldsymbol{k}_\perp$ effects in PDF/FF and in parton dynamics could be able to explain exp. results on $A_N(\pi)$. This suggestion has been further extended in a number of subsequent papers by different collaborations.

Motivations (2)

- There are several alternative (nonperturbative) possible explanations for SSA.

- Recently, Bourrely and Soffer have claimed that most of the experimental data on SSA cannot be explained by pQCD, on the basis that collinear pQCD fails to reproduce the corresponding unpolarized cross sections by 1-2 orders of magnitude.

- In early approaches to SSA within pQCD-based approaches, a detailed analysis of unpolarized cross sections was not performed, mainly because a number of effects (scale dependences, NLO corrections) might cancel out in the SSA, which are ratios of (polarized) cross sections. Only leading $\boldsymbol{k}_\perp$ effects (required to get $A_N \neq 0$) where taken into account.

Goal

- Detailed study of unp. cross sections and SSA, within the same pQCD approach.

- Analysis of a large amount of data on unpolarized cross sections for inclusive particle production in several processes and in different kinematical situations.

- Approach and aim different from (and complementary to) those of other NLO pQCD studies of unp. cross sections in the central rapidity region: the main interest remains the study of SSA. Most of the interesting results on SSA are in the kinematical region 1 GeV$/c \lesssim p_T \lesssim 3$ GeV/c and medium-large $|x_F| = 2|p_L|/\sqrt{s}$.

- No attempt of reproducing with very high precision experimental results on unpolarized cross sections.

- The same approach used for SSA, at the same level of accuracy (LO), reproduces unp. cross sections for several processes and different kinematical situations, up to a reasonable factor (of the order of 2-3) which may be attributed to NLO corrections (K-factors), scale dependences, etc., which we expect to cancel out, at least partly, in the SSA.

Basics of approach (1)

- Inclusive production of moderately large p_T particles in high-energy hadron collisions. Generalization, including spin and $\boldsymbol{k}_\perp$ effects, of the well-known collinear pQCD factorized expression for the corresponding differential cross section:

$$\frac{E_C\, d\sigma^{AB\to C\,X}}{d^3\boldsymbol{p}_C} = \sum_{a,b,c,d} \int dx_a\, dx_b\, dz \prod_i d^2\boldsymbol{k}_{\perp i}\, \hat{f}_{a/A}(x_a, \boldsymbol{k}_{\perp a})\, \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b})$$
$$\times \frac{\hat{s}}{x_a x_b s} \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(x_a, x_b, \hat{s}, \hat{t}, \hat{u})\, \frac{\hat{s}}{\pi}\, \delta(\hat{s}+\hat{t}+\hat{u})\, \frac{1}{z^2}\, J(z, |\boldsymbol{k}_{\perp C}|)\, \hat{D}_{C/c}(z, \boldsymbol{k}_{\perp C})$$

- Formal proof of factorization still missing [Collins, Ji and collab.]

- Formal definition of spin and $\boldsymbol{k}_\perp$ dependent PDF/FF and of their evolution properties still missing [universality].

- Fully consistent higher-twist treatment of the process missing: new, unknown non-perturbative (higher-twist) PDF/FF and quark-gluon correlations; usual partonic interpretation of PDF/FF lost.

- Only enhanced higher-twist effects are included [see next slide].

- Additional contributions to the unpolarized cross section are in principle possible; however, they give negligible contributions [see talk by U. D'Alesio].

Basics of approach (2): enhanced $k_\perp$ effects

- $\boldsymbol{k}_\perp$'s shift the position of the $x_{a,b}$, z regions contributing most to the integrals. Even a small shift can have a substantial effect in the region of x/z where PDF/FF vary rapidly [$f(x_i) \propto (1-x_i)^{n_i}$].

- Due to intrinsic motion, the partonic scattering angle in the pp c.m. frame might be much smaller than the hadronic production angle, thus enhancing the moderately large p_T production of particles.

- Enhancement factor $\mathcal{K} = \sigma(\boldsymbol{k}_\perp)/\sigma(\boldsymbol{k}_\perp = 0)$ for $pp \to \gamma\, X$ [Wong, Wang]:

$$\mathcal{K} \sim \exp\left[\frac{2n_a n_b \langle k_\perp^2 \rangle}{(\sqrt{(1-|x_F|)s} - p_T)^2}\right] \times \frac{p_T^2}{p_T^2 - \langle k_\perp^2 \rangle}$$

- Concerning SSA, e.g. for Sivers contribution [$\Delta^N f_{a/p^\uparrow} = (-2k_\perp/M_p) f_{1T}^\perp$]:

$$\text{Num}(A_N) \propto \Delta^N f_{a/p^\uparrow}(+\boldsymbol{k}_\perp)[\hat{\sigma}(+\boldsymbol{k}_\perp) - \hat{\sigma}(-\boldsymbol{k}_\perp)]$$

If $\hat{\sigma}(+\boldsymbol{k}_\perp) \gg \hat{\sigma}(-\boldsymbol{k}_\perp)$ then A_N can be large [provided that the Sivers function is also large (comparable to the unp. PDF), that is there is a strong azimuthal asymmetry in the trans. momentum distribution of unpolarized partons inside a transversely polarized proton].

Details of numerical calculations

- Factorized, Gaussian-like and flavour-independent behaviour for the $\boldsymbol{k}_\perp$-dependent part of PDF/FF $[1/\beta(\beta') = \langle\, k^2_{\perp a(C)}\,\rangle^{1/2}]$:

$$\hat{f}_{a/A}(x, \boldsymbol{k}_{\perp a}) = f_{a/A}(x)\,\frac{\beta^2}{\pi}\,e^{-\beta^2\,k^{\,2}_{\perp a}} \qquad \hat{D}_{C/c}(z, \boldsymbol{k}_{\perp C}) = D_{C/c}(z)\,\frac{\beta'^2}{\pi}\,e^{-\beta'^2\,k^{\,2}_{\perp C}}$$

- $d\hat{\sigma}^{ab\to cd}/d\hat{t}$ calculated at LO in α_s, with $\boldsymbol{k}_\perp$-modified partonic invariants $\hat{s}$, $\hat{t}$, $\hat{u}$. To avoid soft propagators and break-down of PT we introduce a regulator mass, $\mu = 0.8$ GeV, shifting all partonic invariants: $\hat{t} \to \hat{t} - \mu^2, \quad \hat{u} \to \hat{u} - \mu^2, \quad \hat{s} \to \hat{s} + 2\mu^2$

- $\alpha_s(Q^2) = \frac{1}{\beta_0}\left[\frac{1}{\log(Q^2/\Lambda^2)} + \frac{\Lambda^2}{\Lambda^2 - Q^2}\right], \qquad \beta_0 = (33 - 2n_f)/12\pi;$ $n_f = 4$, and $\Lambda = 0.2$ GeV/c [Shirkov and Solovtsov].

- Renormalization and factorization scales set to $Q = \hat{p}^*_T/2$ [transv. momentum of the fragmenting parton in the partonic c.m frame.]

- K-factors: Numerical curves in plots always rescaled by a fixed (for that curve) K-factor, obeying some general trends as a function of the main kinematical variables ($\sqrt{s}$, p_T, x_F) and estimated by using the numerical code INCNLL [Aurenche et al., Aversa et al.]

Details of numerical calculations (2): PDF/FF sets

- PDF set: **MRST01 (LO)**; $[1/\beta = 0.8 \text{ GeV}/c]$ [see also next slide]
- FF set:
  - neutral pions: **Kretzer [K], Kniehl, Kramer, Potter [KKP] (LO).**
  - charged pions: **Kretzer, KKP-1, KKP-2** [model sets based on **KKP** set]

KKP-1: $D_{\pi^+/d}(z) = D_{\pi^0/s}(z) \Longrightarrow D_{\pi^+/u}(z) = 2D_{\pi^0/u}(z) - D_{\pi^0/s}(z)$

KKP-2: $D_{\pi^+/d}(z) = (1-z)^{1.3} D_{\pi^+/u}(z)$

$$\Longrightarrow D_{\pi^+/u}(z) = 2D_{\pi^0/u}(z)/[1+(1-z)^{1.3}]$$

$$\begin{aligned} 1/\beta'(z) &= \langle\, k^2_{\perp\pi}(z)\,\rangle^{1/2} = 0.7\, z^{0.8}\,(1-z)^{0.15} \quad [\text{GeV}/c] \quad [\textbf{KKP}] \\ 1/\beta'(z) &= \langle\, k^2_{\perp\pi}(z)\,\rangle^{1/2} = 1.4\, z^{1.2}\,(1-z)^{0.35} \quad [\text{GeV}/c] \quad [\textbf{Kretzer}] \end{aligned}$$

- No complete best-fit procedure (computing time; not very significant at this stage): optimized choice of parameters within a limited subset of the full parameter phase-space; In principle it may be improved.

Processes and kinematics

- $pp \Rightarrow \mu^+\mu^- X$

  $20 \leq \sqrt{s} \leq 60$ GeV $\quad 5 \leq M \leq 10$ GeV $\quad q_T < 3$ GeV/c

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$$\frac{d^4\sigma}{dy\,dM^2 d^2\boldsymbol{q}_T} = \frac{\hat\sigma_0}{\pi s}\,\frac{\beta^2\bar\beta^2}{\beta^2+\bar\beta^2}\,\exp\left[-\frac{\beta^2\bar\beta^2}{\beta^2+\bar\beta^2}\,q_T^2\right]\sum_q e_q^2\, f_{q/p}(x_a)\, f_{\bar q/p}(x_b)$$

$$q_T^2 \ll M^2 \qquad k_{\perp a,b}^2 \simeq q_T^2\,, \qquad \langle q_T^2\rangle = \langle q_T^2\rangle_{\rm intr} + \langle q_T^2\rangle_{\rm pert}$$

$$\left(\langle q_T^2\rangle_{\rm intr}/2\right)^{1/2}\Big|_{\sqrt{s}=20\,\text{GeV}} = 1/\beta_0 = 0.8\ \ \text{GeV}/c$$

- $pp \Rightarrow \gamma X \qquad \bar p p \Rightarrow \gamma X$

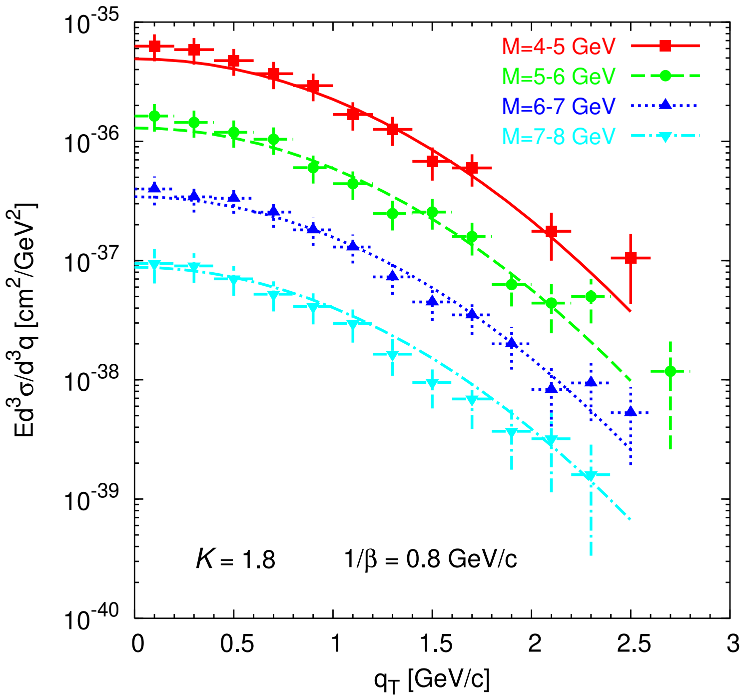
  $20 \leq \sqrt{s} \leq 60$ GeV $\quad 1.5 \leq p_T \leq 10$ GeV/c $\quad |x_F| < 0.4$

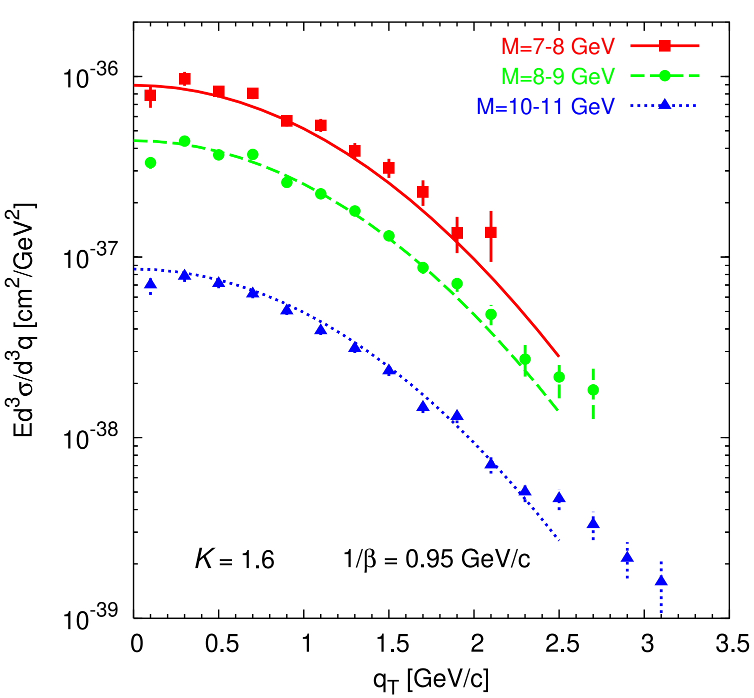
  $\sqrt{s} \simeq 600$ GeV $\quad 10 \leq p_T \leq 80$ GeV/c

- $pp \Rightarrow \pi X$

  $20 \leq \sqrt{s} \leq 200$ GeV $\quad 1.5 \leq p_T \leq 14$ GeV/c $\quad |x_F| < 0.8$

Drell-Yan process

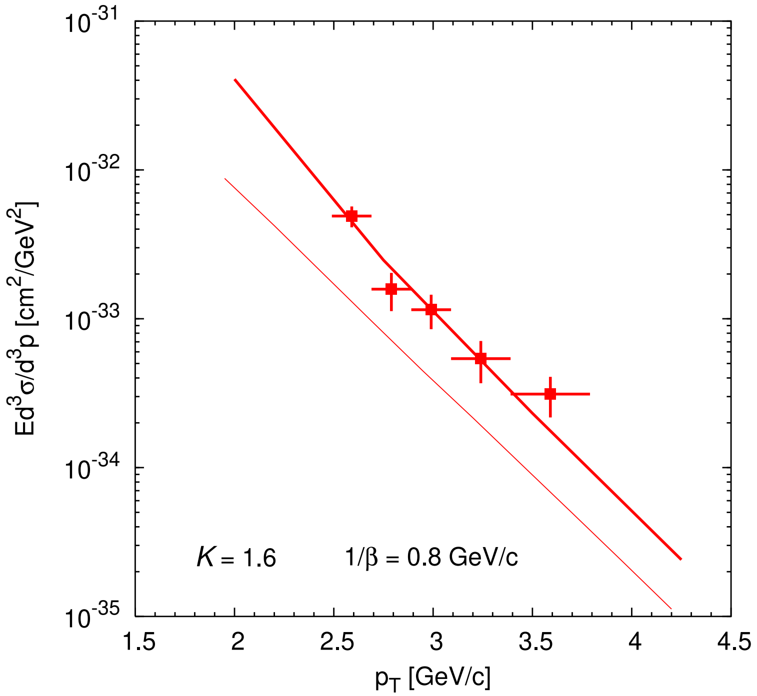


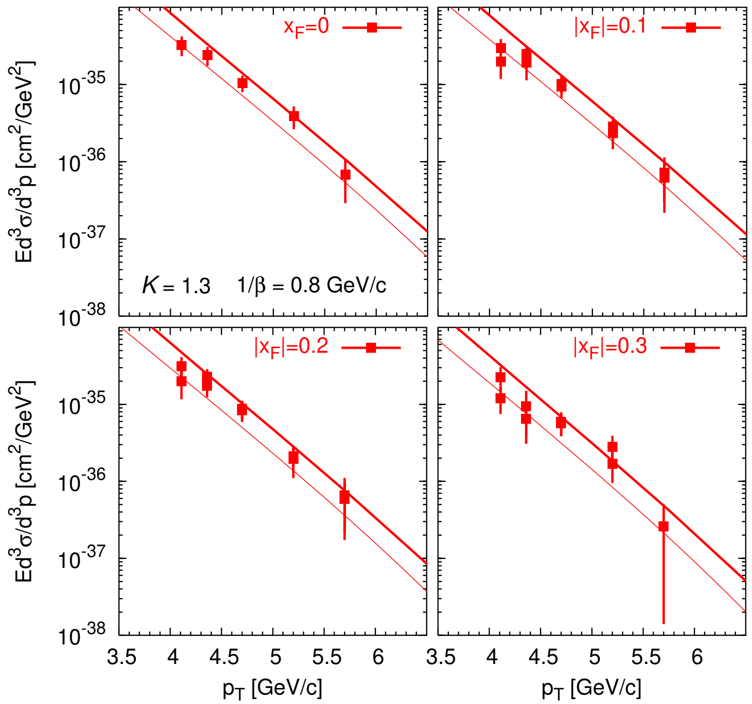


Invariant cross section for DY process; $\sqrt{s} \simeq 20$ GeV, $y = 0.4$, vs. q_T for several invariant mass bins (in GeV).
MRST01 PDF.
Data from Ito et al. PRD 23 (1981).

Invariant cross section for DY process; $\sqrt{s} \simeq 39$ GeV, $x_F = 0.1$, vs. q_T for several invariant mass bins (in GeV).
MRST01 PDF.
Data from Moreno et al. PRD 43 (1991).

Prompt photon production

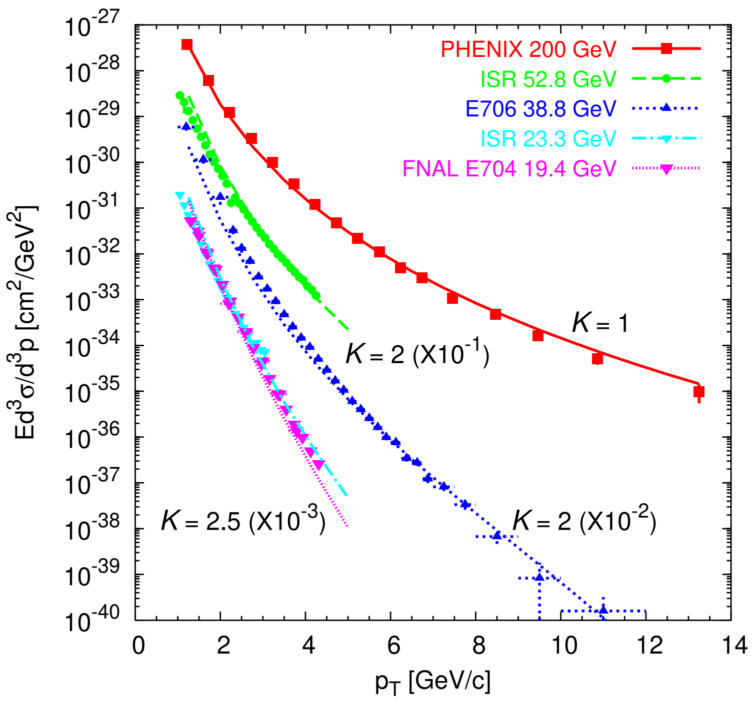


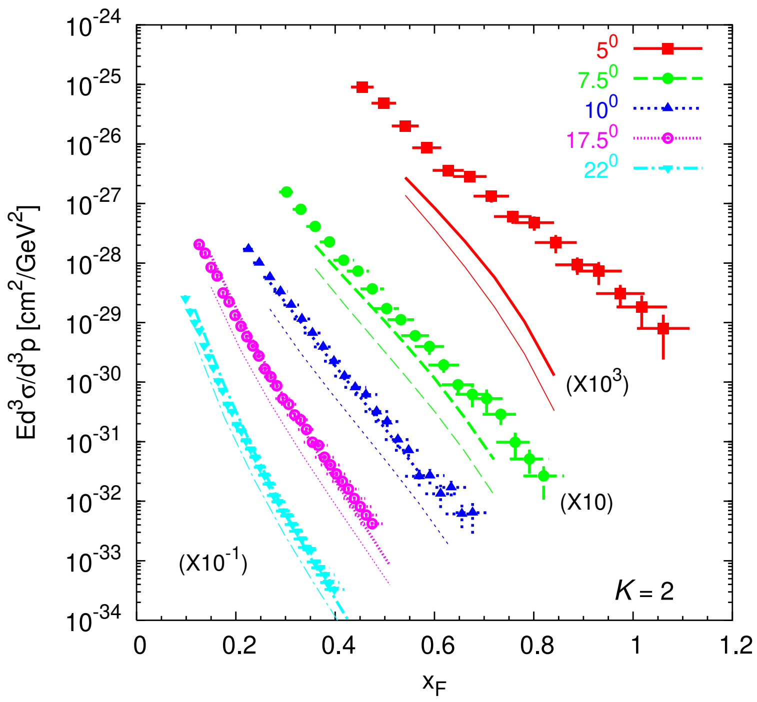


Invariant cross section for $pp \to \gamma\, X$; $\sqrt{s} \simeq 20$ GeV, $x_F = 0$, vs. p_T; Thin line: collinear pQCD; MRST01 PDF. Data from E704 Collab., PLB 345 (1995).

Invariant cross section for $pp \to \gamma\, X$; $\sqrt{s} \simeq 23$ GeV, vs. p_T at different x_F values; Thin line: collinear pQCD; MRST01 PDF. Data from WA70 Collab., ZPC 38 (1988).

Neutral pion production (1)

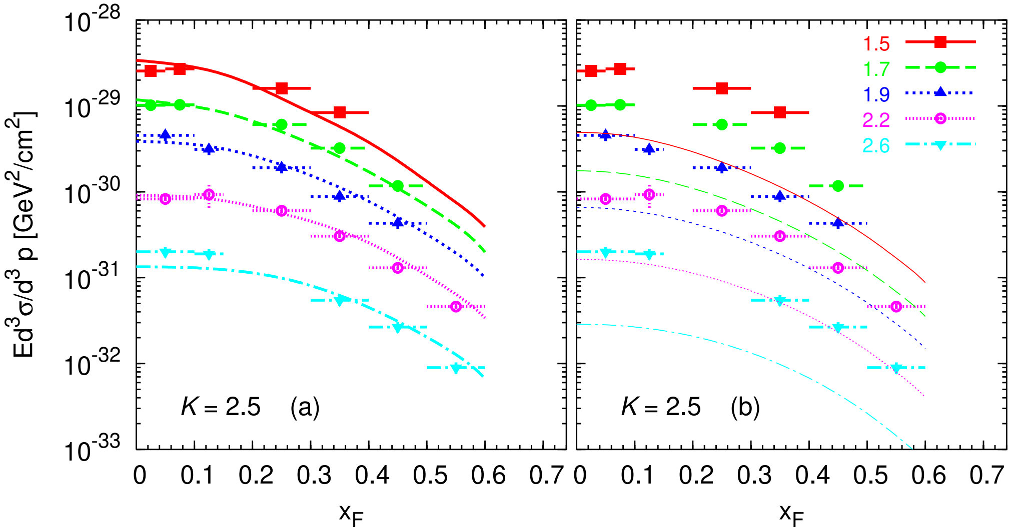


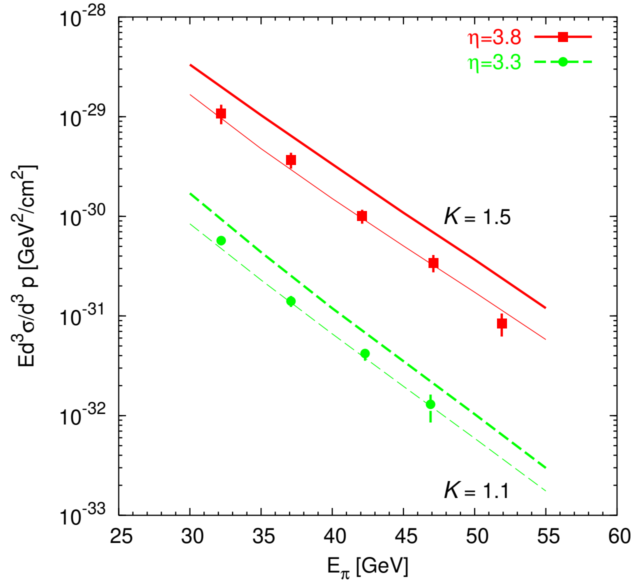


Inv. cross section for $pp \to \pi^0 X$; $y = 0$, vs. p_T at different c.m. energies; MRST01 PDF; KKP FF. Data from E704, E706, ISR, PHENIX.

Inv. cross section for $pp \to \pi^0 X$; $\sqrt{s} \simeq 53$ GeV, vs. x_F at different scattering angles; Thin lines: collinear pQCD; MRST01 PDF; KKP FF. Data from Owen et al. PRL 45 (1980).

Neutral pion production (2)

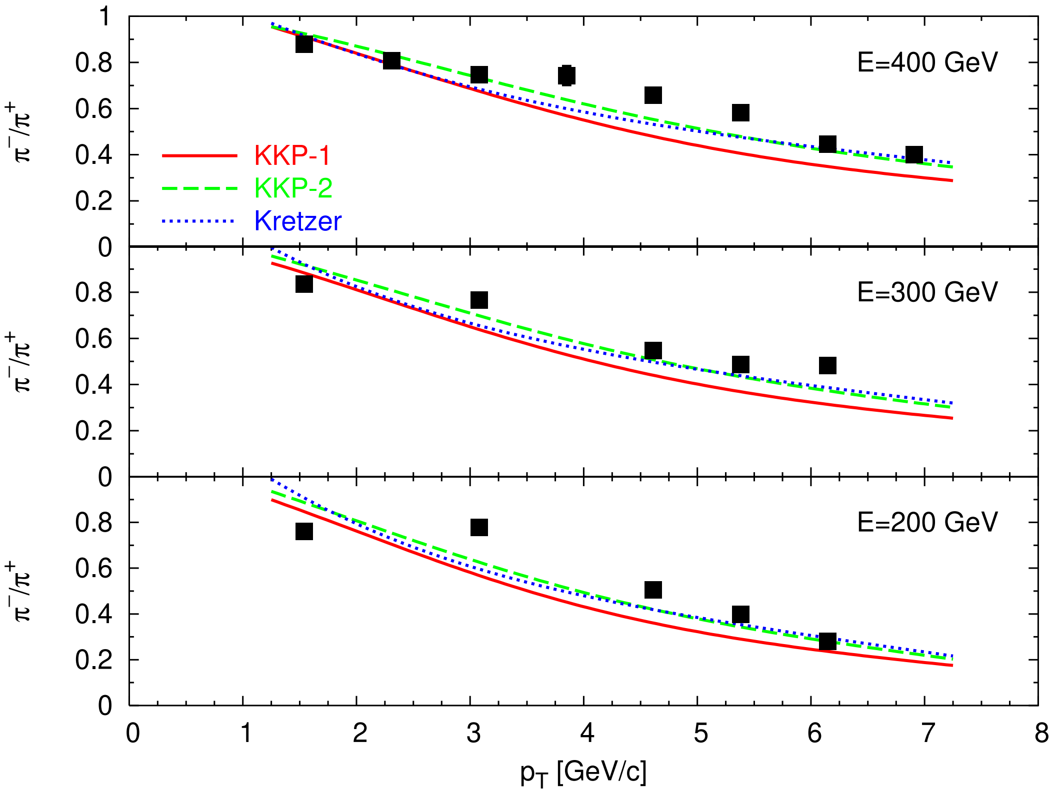




Invariant cross section for $pp \to \pi^0 X$; $\sqrt{s} \simeq 20$ GeV, vs. x_F at different p_T values; Right panel: collinear pQCD; MRST01 PDF; KKP FF. Data from FNAL-E268 Collab., PLB 73 (1978).

Inv. cross section for $pp \to \pi^0 X$; $\sqrt{s} = 200$ GeV, vs. E_π for two values of the pseudo-rapidity η; Thin lines: collinear pQCD; MRST01 PDF; KKP FF. Data from STAR Collab., PRL 92 (2004).

Charged pion production



Ratios of Invariant cross section for $pp \to \pi^{\mp} X$; $\theta = 77$ mrad ($x_F \simeq 0$), vs. p_T at different LAB energies; MRST01 PDF; K, KKP-1, KKP-2 FF. Data from FNAL-E100/E300 Collab., PRD 19 (1979).

SSA [Sivers effect only] (1)

Num$[\, A_N(p^\uparrow p \to \pi\, X)\,] =$

$$\sum_{a,b,c,d} \int dx_a\, dx_b\, dz \prod_i d^2\boldsymbol{k}_{\perp i}\, \Delta^N f_{a/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a})\, \hat{f}_{b/p}(x_b, \boldsymbol{k}_{\perp b})$$

$$\times \frac{\hat{s}}{x_a x_b s} \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(x_a, x_b, \hat{s}, \hat{t}, \hat{u})\, \frac{\hat{s}}{\pi}\, \delta(\hat{s}+\hat{t}+\hat{u})\, \frac{1}{z^2}\, J(z, |\boldsymbol{k}_{\perp\pi}|)\, \hat{D}_{\pi/c}(z, \boldsymbol{k}_{\perp\pi})$$

$$\Delta^N f_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) - \hat{f}_{q/p^\downarrow}(x, \boldsymbol{k}_\perp) = \Delta^N f_{q/p^\uparrow}(x, k_\perp)\, \sin(\phi_P - \phi_{k_\perp})$$

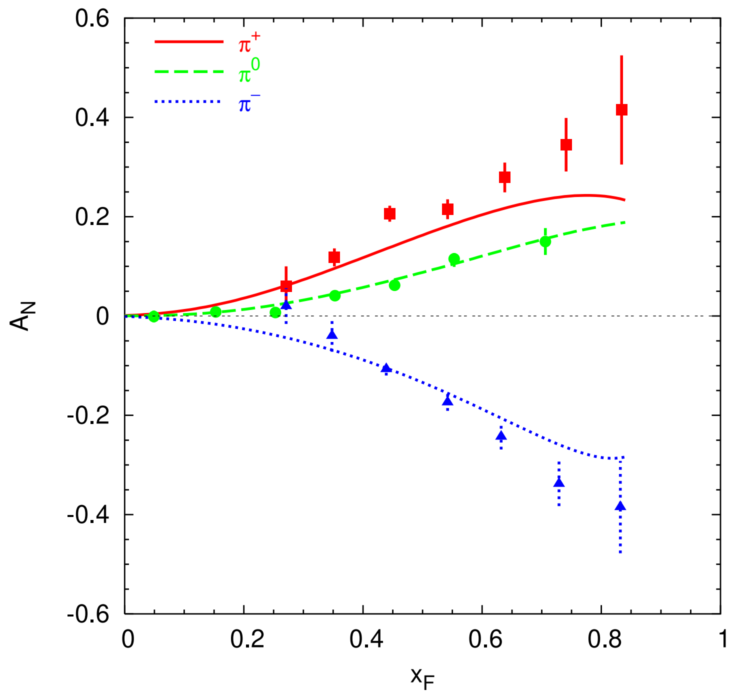
$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = 2\, \mathcal{N}_q(x)\, f_{q/p}(x)\, \frac{\beta^2}{\pi} \sqrt{2\, e\, (\alpha^2-\beta^2)}\, k_\perp\, e^{-\alpha^2 k_\perp^2} \left[\frac{2 k_\perp M_0}{k_\perp^2 + M_0^2} \right]$$

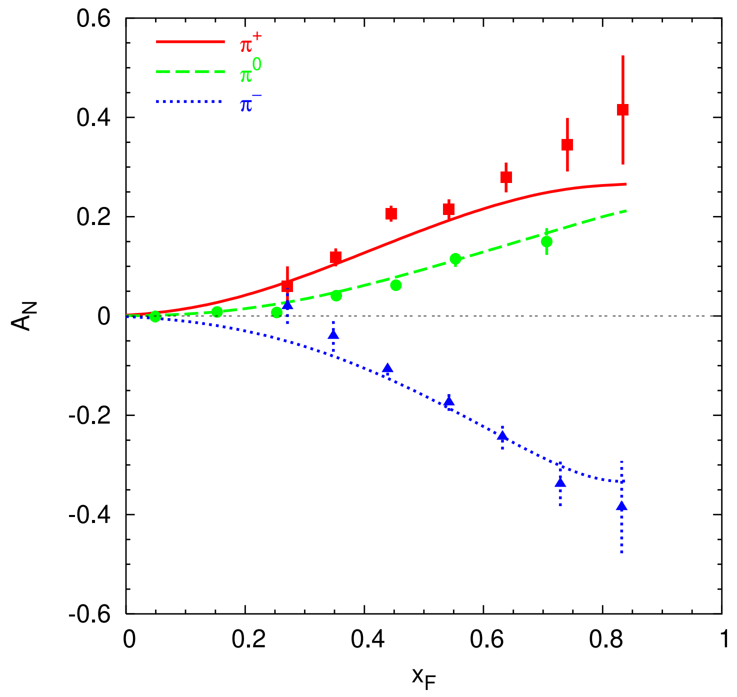
$$\mathcal{N}_q(x) = N_q\, x^{a_q} (1-x)^{b_q} \frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q}\, b_q^{b_q}}\,, \quad |N_q| \le 1$$

$$\begin{aligned} 1/\beta &= 0.8\,\text{GeV}/c & \alpha^2 &= \beta^2/0.7 & & \\ N_u &= +0.40 & a_u &= 3.0 & b_u &= 0.6 \\ N_d &= -1.00 & a_d &= 3.0 & b_d &= 0.5 \end{aligned}$$

[Kretzer]

SSA [Sivers effect only] (2)

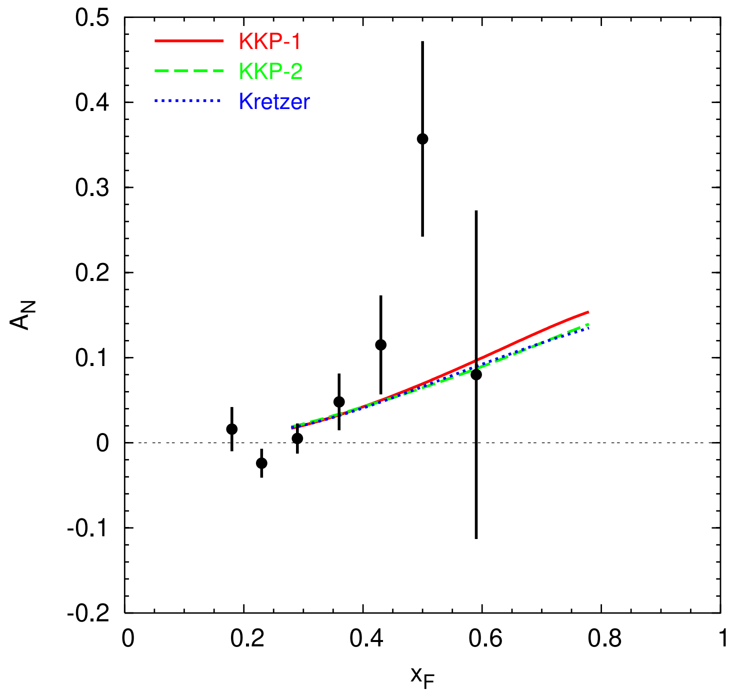


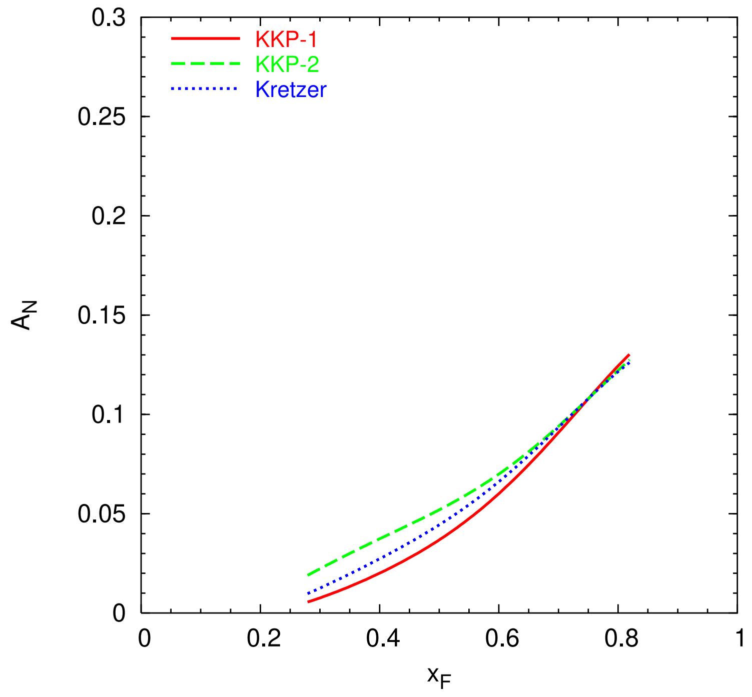


A_N for $pp \to \pi X$; $\sqrt{s} \simeq 20$ GeV, $p_T = 1.5$ GeV$/c$, vs. x_F; MRST01 PDF; Kretzer FF. Data from E704 Collab., PLB 261 (1991), PLB 264 (1991), ZPC 56 (1992).

A_N for $pp \to \pi X$; $\sqrt{s} \simeq 20$ GeV, $p_T = 1.5$ GeV$/c$, vs. x_F; MRST01 PDF; KKP-2 FF. Data from E704 Collab., PLB 261 (1991), PLB 264 (1991), ZPC 56 (1992).

SSA [Sivers effect only] (2)





A_N for $pp \to \pi^0 X$; $\sqrt{s} = 200$ GeV, $\eta = 3.8$, vs. x_F; MRST01 PDF; K, KKP-1/2 FF. Data from STAR Collab., PRL 92 (2004).

(Predicted) A_N for $pp \to \gamma X$; $\sqrt{s} = 200$ GeV, $\eta = 3.8$, vs. x_F; MRST01 PDF; K, KKP-1/2 FF.

Conclusions and outlook

- With few noticeable exceptions, our LO approach (complemented with proper NLO K-factors) is in reasonable agreement with a large set of experimental data for unpolarized cross sections, giving support to the validity of the same approach in the study of SSA.

- SSA in inclusive π and prompt γ production [Sivers contribution only]: good agreement with E704 data on $A_N(\pi)$ by using physically reasonable parameterizations of the Sivers function for valence quark contributions. Predictions in agreement with STAR data at $\sqrt{s} = 200$ GeV and comparable x_F and p_T ranges.

- Detailed treatment of $\boldsymbol{k}_\perp$ effects confirms all main results and conclusions of our former studies performed keeping only leading contributions in $\boldsymbol{k}_\perp$ and using a simplified partonic configuration **[see talk by U. D'Alesio for Collins effect]**.

- A lot of work remains to be done, in particular on the more formal aspects of the approach.

- $P_T^\Lambda(pp \to \Lambda\, X)$: our approach is in principle able to reproduce most of the striking features of the experimental data available [polarizing fragmentation function]. A combined analysis of SSA and unpolarized cross sections, like that performed here for the Drell-Yan process and inclusive pion and photon production, is under way.