Single Spin Asymmetries, unpolarized cross sections and the role of partonic intrinsic transverse momentum

Outline: [In collaboration with: F. Murgia (Cagliari)]

- Sizable SSA: $P_T^{pp}(\Lambda^\uparrow)$, $A_N^{p^\uparrow p}(\pi)$, $A_N^{\ell p^\uparrow}(\pi)$.
  Description in terms of $\boldsymbol{k}_\perp$ - dependent distribution and fragmentation functions;
- Consistent treatment (LO) of unpol. cross sections: role of $\boldsymbol{k}_\perp$ in
  - $pp \Rightarrow \ell^+\ell^- X$
  - $pp \Rightarrow \gamma X$
  - $pp \Rightarrow \pi X$
- E704 $A_N(p^\uparrow p \Rightarrow \pi X)$ data re-analysed (full $\boldsymbol{k}_\perp$ kinematics) in terms of Sivers effect. Preliminary estimates for RHIC;
- Conclusions and outlook;

A generalized pQCD approach to Single Spin Asymmetries

1) Extension of usual pQCD formalism (based on factorization theorems) for (semi)inclusive hadronic processes, $A\,B \;\Rightarrow\; C\,X$, at large energies and (moderately) large p_T

2) Inclusion of spin and intrinsic (partonic) transverse momentum, $\boldsymbol{k}_\perp$, effects

3) New, nonperturbative, twist-two, spin and $\boldsymbol{k}_\perp$-dependent partonic distribution/fragmentation functions are introduced

4) Soft, nonperturbative dynamics generates correlations between the hadron(parton) transverse spin and the parton(hadron) transverse momentum, which imply an azimuthal asymmetry in the $\boldsymbol{k}_\perp$ probability distribution. This in turn originates the asymmetries observed at the hadronic level

- $\Delta^N f_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) - \hat{f}_{q/p^\downarrow}(x, \boldsymbol{k}_\perp)$ [$f_{1T}^\perp$] [Sivers (90)]
- $\Delta^N f_{q^\uparrow/p}(x, \boldsymbol{k}_\perp) = \hat{f}_{q^\uparrow/p}(x, \boldsymbol{k}_\perp) - \hat{f}_{q^\downarrow/p}(x, \boldsymbol{k}_\perp)$ [$h_1^\perp$]
- $\Delta^N D_{h^\uparrow/q}(z, \boldsymbol{k}_\perp) = \hat{D}_{h^\uparrow/q}(z, \boldsymbol{k}_\perp) - \hat{D}_{h^\downarrow/q}(z, \boldsymbol{k}_\perp)$ [$D_{1T}^\perp$]
- $\Delta^N D_{h/q^\uparrow}(z, \boldsymbol{k}_\perp) = \hat{D}_{h/q^\uparrow}(z, \boldsymbol{k}_\perp) - \hat{D}_{h/q^\downarrow}(z, \boldsymbol{k}_\perp)$ [$H_1^\perp$] [Collins (93)]

Note: $\hat{f}_{q/p^\downarrow}(x, \boldsymbol{k}_\perp) = \hat{f}_{q/p^\uparrow}(x, -\boldsymbol{k}_\perp)$ and so on

General formalism and applications

P.J. Mulders, R.D. Tangerman, NPB**461** (96); D. Boer, P.J. Mulders, PRD**57** (98); D. Boer, PRD**60** (99), D. Boer *et al.*, NPB**564** (00); M. Anselmino *et al.*, PLB**362** (95); M. Anselmino, F.Murgia, PLB**442** (98); M. Anselmino *et al.*, PRD**60** (99); M. Anselmino *et al.*, EPJC**13** (00); M. Anselmino, F.Murgia, PLB**483** (00);

Role of intrinsic $k_\perp$ in unpolarized cross sections

SSA are calculated as $\frac{d\Delta\sigma}{(2)d\sigma}$ where the unpolarized cross section for a generic process $A\,B \Rightarrow C\,X$ reads:

$$d\sigma = \sum_{a,b,c} \hat{f}_{a/A}(x_a, \boldsymbol{k}_{\perp a}) \otimes \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\hat{\sigma}^{ab\to c\ldots}(x_a, x_b, \boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \hat{D}_{C/c}(z, \boldsymbol{k}_{\perp C})$$

Not proven in general but widely used from the pioneering work of Feynman et al. [77] to recent papers of Zhang et al. [02].

NLO calculations within collinear factorization not completely in agreement with data;

Our approach and goal:

- LO treatment (consistent with SSA)
- partonic $\boldsymbol{k}_\perp$ effects in $d\hat{\sigma}$ and in pdf's (ff's) through Gaussian distributions:
  $\hat{f}_{q/p}(x, \boldsymbol{k}_\perp) = f_{q/p}(x)\,\frac{\beta^2}{\pi}\,e^{-\beta^2\,k_\perp^2}$
- up to an overall factor ≈ 2 (compatible with NLO K-factors and scale dependences)

Processes and kinematics

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

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

- $pp \Rightarrow \gamma X$ $\bar{p}p \Rightarrow \gamma X$

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

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

- $pp \Rightarrow \pi X$

  $20 \leq \sqrt{s} \leq 60$ GeV $1.5 \leq p_T \leq 10$ GeV/c $|x_F| < 0.5$

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

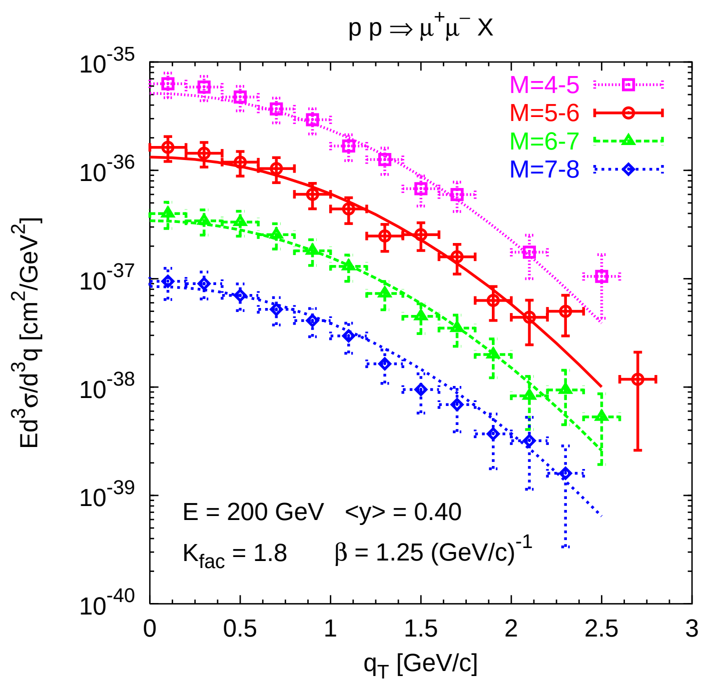
- LO $\Longrightarrow$ elementary process: $q\bar{q} \Rightarrow \ell^+\ell^-$
- collinear fact. $\Longrightarrow$ $q_{_T} \equiv 0$
- $q_{_T} \neq 0 \Longrightarrow$ direct access to intrinsic $\boldsymbol{k}_\perp$ $\Longrightarrow$ fixing $\langle \boldsymbol{k}_\perp^2 \rangle^{1/2} \equiv 1/\beta(x)$

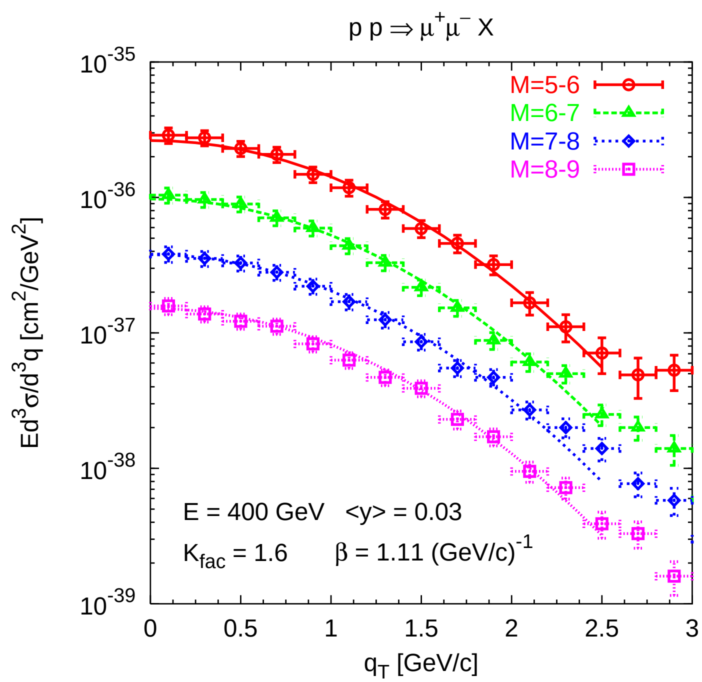
$$q_{_T}^2 \ll M^2 \qquad \delta^4(p_q + p_{\bar{q}} - q) \Rightarrow \delta(x_a - M/\sqrt{s}\, \mathrm{e}^{y})\, \delta(x_b - M/\sqrt{s}\, \mathrm{e}^{-y})$$
$$\boldsymbol{k}_\perp^2 \approx q_{_T}^2 \qquad \times\ \delta^2(\boldsymbol{k}_{\perp a} + \boldsymbol{k}_{\perp b} - \boldsymbol{q}_{_T})$$

$$\frac{d^4\sigma}{dy\,dM^2 d^2\boldsymbol{q}_{_T}} = \frac{\hat{\sigma}_0}{\pi s}\,\frac{\beta^2\bar{\beta}^2}{\beta^2 + \bar{\beta}^2}\,\exp\left[-\frac{\beta^2\bar{\beta}^2}{\beta^2+\bar{\beta}^2}\,q_{_T}^2\right]\sum_q e_q^2\, f_{q/p}(x_a)\, f_{\bar{q}/p}(x_b)$$

$\hat{\sigma}_0 = 4\pi\alpha_{em}^2/(9M^2)$, $\beta = \beta(x_a)$ and $\bar{\beta} = \beta(x_b)$.

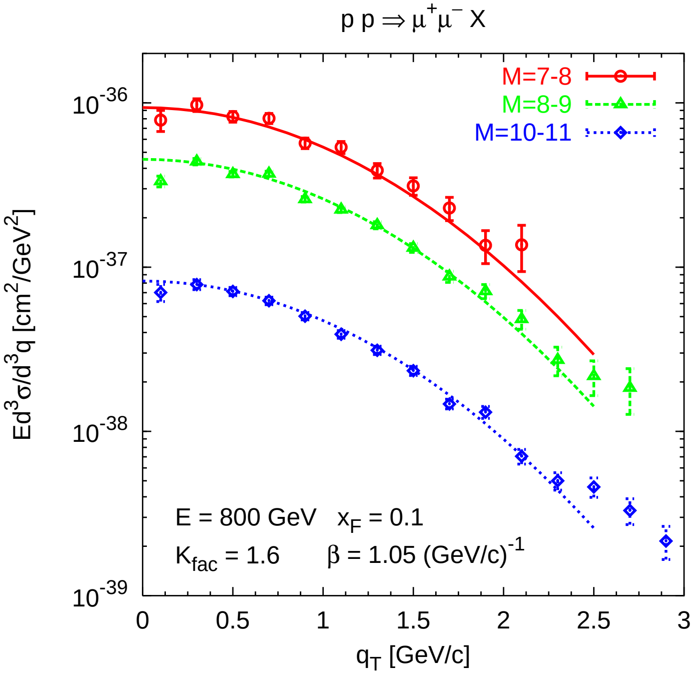
pdf set GRV94 – Best value $\beta = 1.25[\sqrt{s} = 20] - 1[\sqrt{s} = 60]$ (GeV/c)$^{-1}$
i.e. $\langle \boldsymbol{k}_\perp^2 \rangle^{1/2} = 0.8 - 1$ (GeV/c)

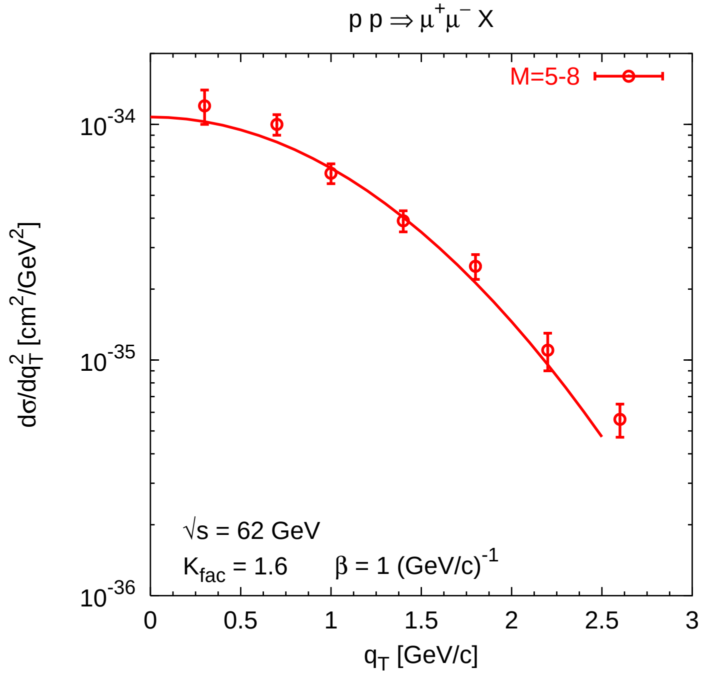




Estimates of the invariant cross section at E = 200 GeV vs. q_T for several different invariant mass bins (in GeV) at fixed rapidity y = 0.4. Distribution function set: GRV94. Data are from Ito et al. PRD 23 (1981).

Estimates of the invariant cross section at E = 400 GeV vs. q_T for several different invariant mass bin (in GeV) at fixed rapidity y = 0.03. Distribution function set: GRV94. Data are from Ito et al. PRD 23 (1981).





Estimates of the invariant cross section at E = 800 GeV vs. q_T for several different invariant mass bin (in GeV) at fixed x_F = 0.1. Distribution function set: GRV94. Data are from Moreno et al. PRD 43 (1991).

Estimates of the p_T distribution at $\sqrt{s}$ = 62 GeV vs. q_T integrated over the invariant mass and x_F. Distribution function set: GRV94. Data are from Antreaysan et al. PRL D 48 (1982).

Prompt photons: $pp \Rightarrow \gamma X$

[For a compilation of data and discussion at NLO see Vogelsang, Whalley (97)]

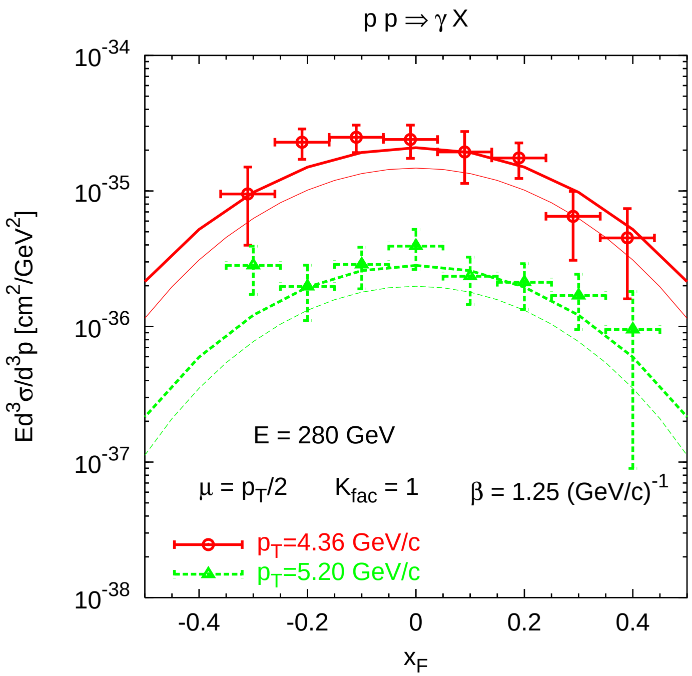
Strong dependence of pQCD calculations on factorization scale.

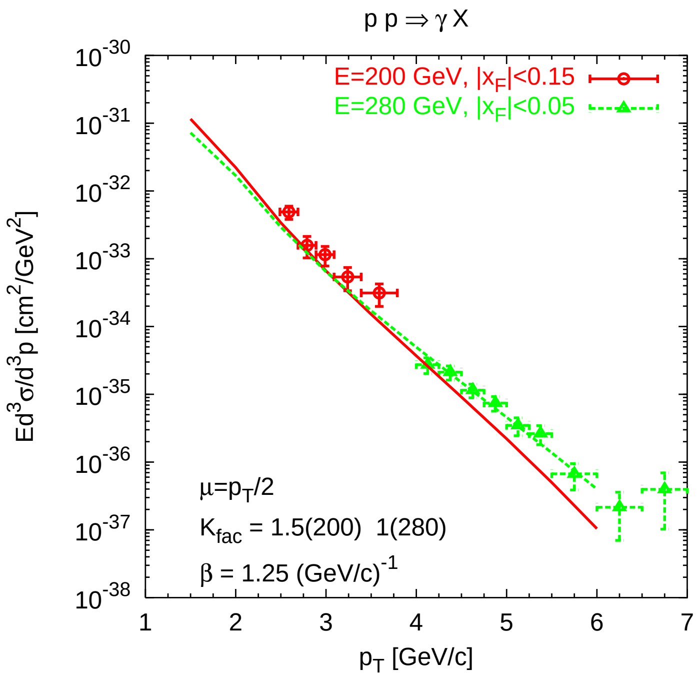
Moderate $p_T \Longrightarrow k_\perp/p_T$ significant effects [Owens (87)]:

- shift in $\langle x_{\rm Bj}\rangle$ to lower values $\Longrightarrow$ larger pdf's $\simeq (1-\langle x_{\rm Bj}\rangle)^n$
- shift in $\hat{t}$, $\hat{u}$ to lower values $\Longrightarrow$ larger $d\hat{\sigma}/d\hat{t} \simeq C(1/\hat{t}+1/\hat{u})$

We use $\mu = p_T/2$ and control IR singularities [$\hat{t} \to 0$] by shifting $\hat{t} \to \hat{t} - \mu_0^2$ $[\mu_0 = 0.8$ GeV$]$. Similar to work by Wang, Wong (98).

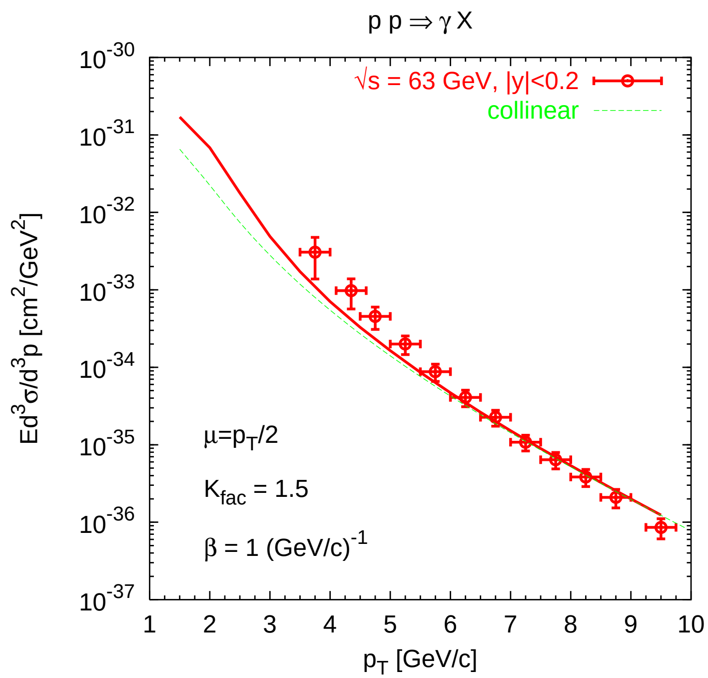
Notice: the enhancing factor from intrinsic $\boldsymbol{k}_\perp$ is a function of $\sqrt{s}$ and p_T. In particular it goes as exp$[(1-x_T)^{-2}]$ and grows as $\sqrt{s}$ decreases ($x_T \equiv 2p_T/\sqrt{s}$).

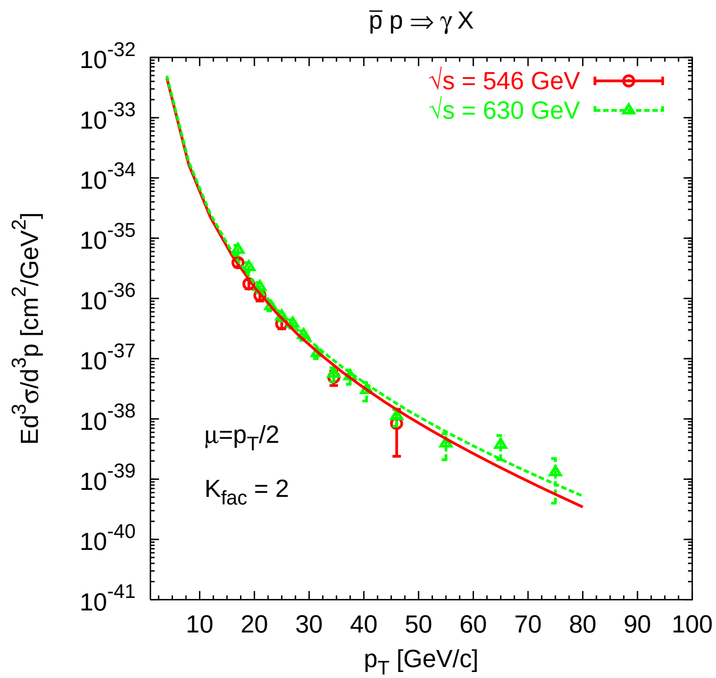




Estimates of the invariant cross section at E = 280 GeV for two different p_T vs. x_F, with $\boldsymbol{k}_\perp$ effects (thick lines) and without them (thin lines). Distribution function set: GRV94. Data are from Bonesini et al. ZP C 38 (1988).

Estimates of the invariant cross section at E = 200 GeV and 280 GeV at x_F = 0 vs. p_T. Distribution function set: GRV94. Data are from Bonesini et al. ZP C 38 (1988) [WA70-E = 280 GeV] and Adams et al. PL 345B (1995) [E704-E = 200 GeV].





Estimates of the invariant cross section at $\sqrt{s}$ = 62 GeV vs. p_T at y = 0, with $\boldsymbol{k}_\perp$ effects (thick line) and without them (thin line). Distribution function set: GRV94. Data are from Anassontzis [R806] et al. ZP C 13 (1982).

Estimates of the invariant cross section at $\sqrt{s}$ = 546 GeV and 630 GeV vs. p_T at y = 0. Distribution function set: GRV94. Data are from Albajar et al. [UA1] PLB 209 (1988). Notice: $\boldsymbol{k}_\perp$ effects here are negligible.

$pp \Rightarrow \pi^0 X \qquad pp \Rightarrow \pi^\pm X$

Fragmentation $\Longrightarrow$ extra $\boldsymbol{k}_\perp$ - dependence: $D_c^\pi(z, \boldsymbol{k}_\perp) = D_c^\pi(z)\, \frac{\beta'^2}{\pi}\, e^{-\beta'^2\, k_\perp^2}$

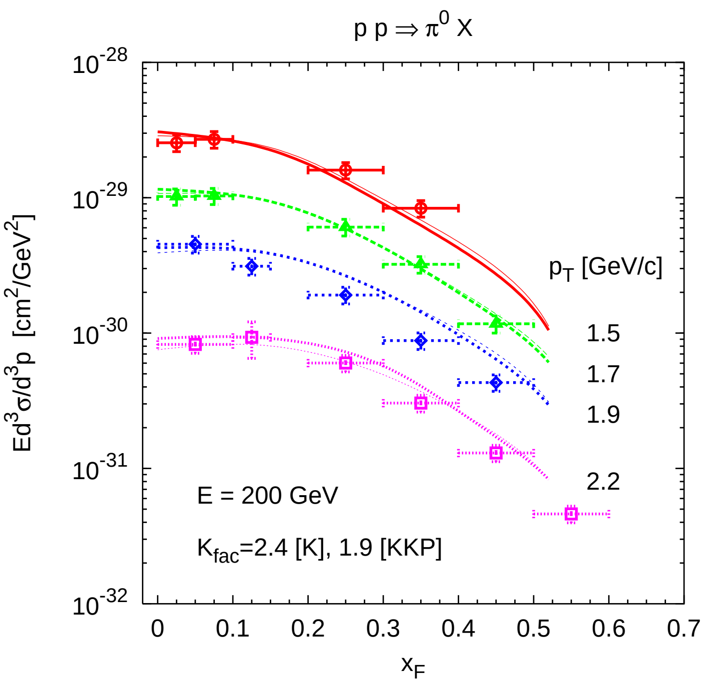
Uncertainties on $D_c^\pi(z)$:

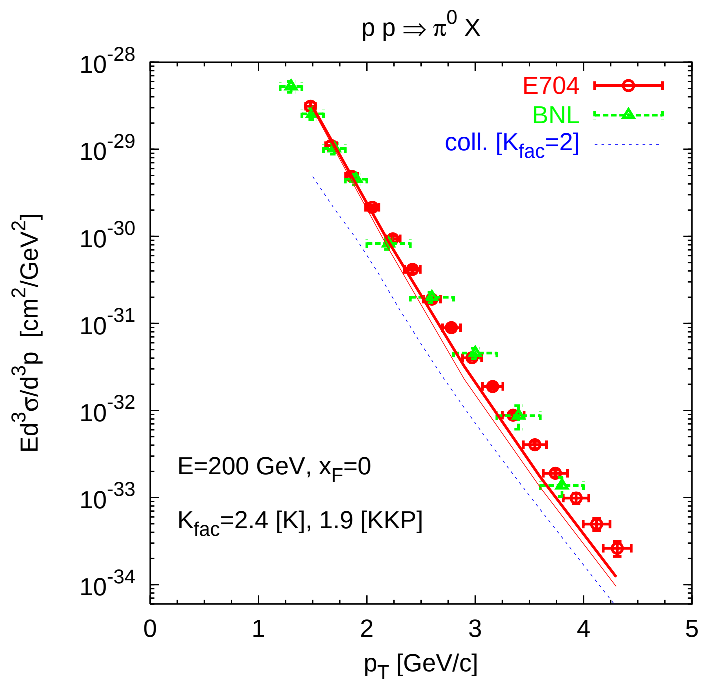
- Kretzer (00) [K]: $\pi^0, \pi^\pm$ with $D_{d,s}^{\pi^+} = (1-z)^1 D_u^{\pi^+}$ (assumption) ;
- Kramer et al. (00) [KKP]: π^0 $D_s^{\pi^0} \ll D_{u,d}^{\pi^0}$ $z \geq 0.1$ (from fit);
  $D_d^{\pi^+} = D_s^{\pi^0} \ll D_u^{\pi^+} = 2D_u^{\pi^0} - D_s^{\pi^0}$ (assumption)
- We also consider a set with $D_{u,d}^{\pi^0}$ from [K] but $D_{d,s}^{\pi^+} = (1-z)^{1.5} D_u^{\pi^+}$ [K-mod].

Previous studies at $x_F = 0$ and with collinear fragm. functions: Apanasevich et al. [98,02], Zhang et al. [02]

Extension to $x_F \neq 0 \Leftrightarrow$ role of $D_c^\pi(z, \boldsymbol{k}_\perp)$

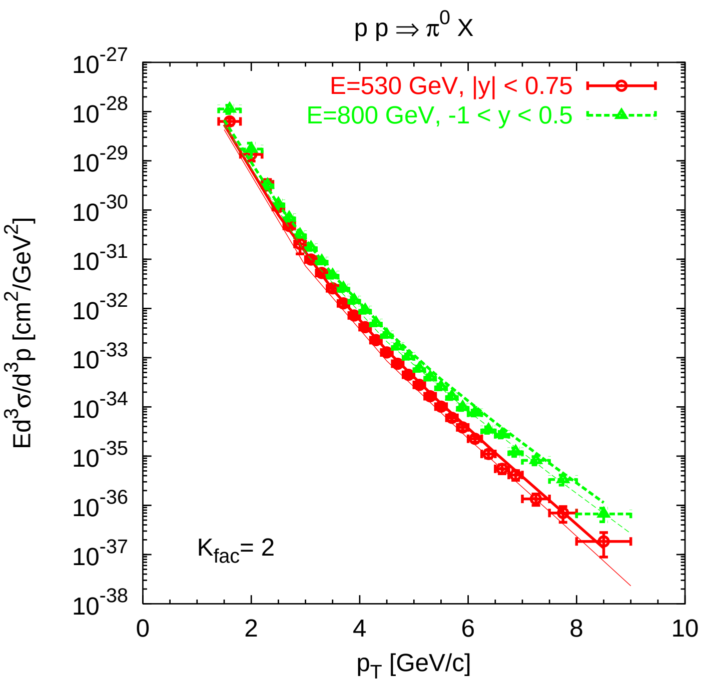
Comparison with BNL π^0 data: best value $[\beta'(z)]^{-1} = 1.4 z^{1.3}(1-z)^{0.2}$ (GeV/c).

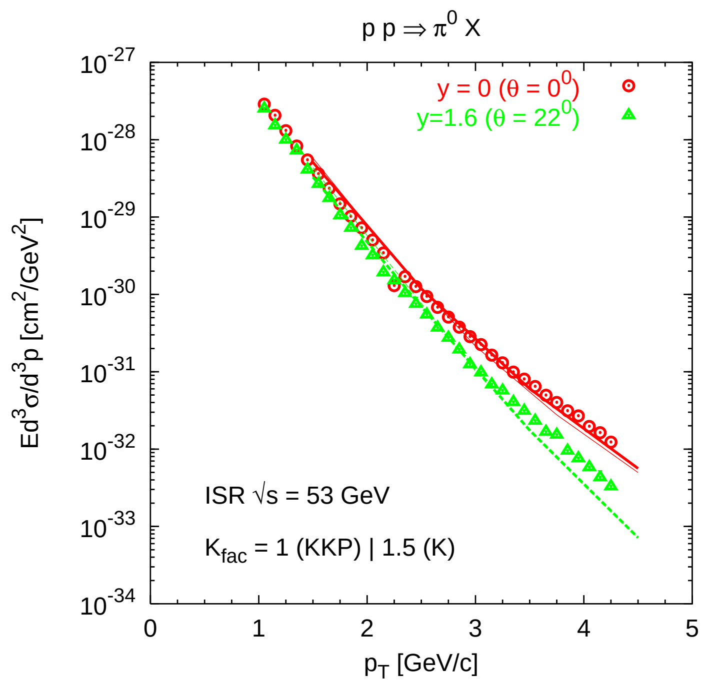




Estimates of the invariant cross section at E= 200 GeV vs. x_F for different p_T values. Distribution function set: GRV94; fragmentation function sets: K(thin lines) and KKP(thick lines). Data are from Donaldson et al. [BNL] PLB 73 (1978).

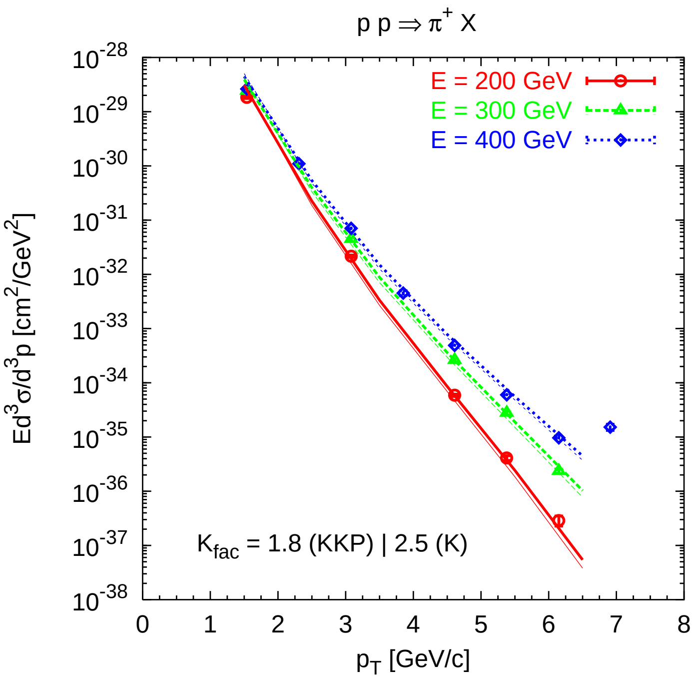
Estimates of the invariant cross section at E= 200 GeV vs. p_T at x_F = 0. Distribution function set: GRV94; fragmentation function sets: K(thin lines) and KKP(thick lines). Data are from Donaldson et al. [BNL] PLB 73 (1978) and Adams et al. [E704] PRD 53 (1996).

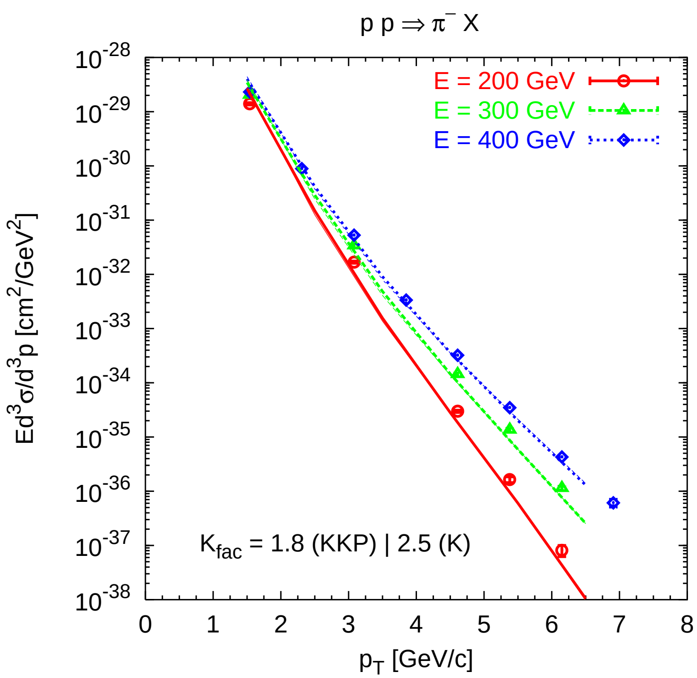




Estimates of the invariant cross section at E= 530 GeV and 800 GeV vs. p_T averaged over y. Distribution function set: GRV94; fragmentation function sets: K(thin lines) and KKP(thick lines). Data are from Apanasevich et al. [E706] hep-ex/0204031 (2002).

Estimates of the invariant cross section at $\sqrt{s}$= 53 GeV vs. p_T for 2 rapidity values (y = 0, 1.6). Distribution function set: GRV94; fragmentation function sets: K(thin lines) and KKP(thick lines). Data are from Lloydowen et al. [ISR] PRL 45 (1980).





Estimates of the invariant cross section for π^+ production at E = 200 GeV, 300 GeV and 400 GeV vs. p_T at fixed rapidity y = 0. Distribution function set: GRV94; fragmentation function sets: K(thin lines) and KKP(thick lines). Data are from Antreasyan et al. PRD 19 (1979)

Estimates of the invariant cross section for π^- production at E = 200 GeV, 300 GeV and 400 GeV vs. p_T at fixed rapidity y = 0. Distribution function set: GRV94; fragmentation function sets: K(thin lines) and KKP(thick lines). Data are from Antreasyan et al. PRD 19 (1979)

SSA in $p^{\uparrow}p \Rightarrow \pi X$: Sivers effect

$A_N\ [x_F > 0]$:
- Sivers effect (asymmetry in pdf)
- Collins effect (asymmetry in ff) $\Longrightarrow$ access to transversity
- or both competing?

Previous studies [Anselmino et al. (95-98)]:

effective averaging on $\boldsymbol{k}_{\perp}$ and simplified kinematical configuration

Now:

complete $\boldsymbol{k}_{\perp}$ kinematics and reasonable reproduction of unpolarized cross sections.

Sivers effect: upgraded (similar results); Collins effect: in progress.

$$d\sigma^{p^{\uparrow}p\to\pi X} - d\sigma^{p^{\downarrow}p\to\pi X} \sim \sum_{abcd} \int dx_a\, dx_b\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^2\boldsymbol{k}_{\perp\pi}$$
$$\times \left\{ \Delta^N f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a})\, \hat{f}_{b/p}(x_b, \boldsymbol{k}_{\perp b})\, \frac{d\hat{\sigma}}{dt}(x_a, x_b; \boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b})\, \hat{D}_{\pi/c}(z, \boldsymbol{k}_{\perp\pi}) + \cdots \right\}$$

Sivers effect

Brief history:

90: proposed by Sivers [T-odd function]

93: proof of its vanishing by Collins [Time reversal invariance]

95: way out (Anselmino et al.) [Initial state interactions]

01: way out (Anselmino et al.) [Non standard Time reversal: up $\Rightarrow -$ down]

02: quark-diquark model (Brodsky et al.) [SSA in SIDIS different from Collins effect]

proof against its vanishing by Collins himself [compatible with factorization;

original proof invalidated by path-ordered exponential of gluon field: $q^{DY} = -q^{DIS}$]

Ji, Metz ...

Open issues: factorization, universality, evolution.

Sivers function: parameterization and fixing

$$\Delta^N f_{q/p^\uparrow}(x, \boldsymbol{k}_\perp) = \Delta^N f_{q/p^\uparrow}(x, k_\perp)\,(\hat{\boldsymbol{P}} \cdot \hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp) \approx k_\perp\, e^{-\alpha^2\, k_\perp^2} \sin\phi_{\hat{\mathbf{P}},\hat{\mathbf{k}}}$$

Positivity bound:

$$\frac{|\Delta^N f_{q/p^\uparrow}(x, k_\perp)|}{2\, f_{q/p}(x, k_\perp)} = \frac{|f_{q/p^\uparrow}(x, k_\perp) - f_{q/p^\downarrow}(x, k_\perp)|}{f_{q/p^\uparrow}(x, k_\perp) + f_{q/p^\downarrow}(x, k_\perp)} \leq 1 \quad \forall\, x,\, k_\perp$$

Fulfilled by writing $[\text{cfr.}\;\; f_{q/p}(x, k_\perp) = f_{q/p}(x)\, g(k_\perp)]$

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = \Delta^N f_{q/p^\uparrow}(x)\, h(k_\perp)$$

where $\quad \Delta^N f_{q/p^\uparrow}(x) = \mathcal{N}_q(x)\, 2 f_{q/p}(x) \qquad\qquad h(k_\perp) = \mathcal{H}(k_\perp)\, g(k_\perp)$

with $\quad |\mathcal{N}_q(x)| \leq 1 \quad \forall x, \qquad |\mathcal{H}(k_\perp)| \leq 1 \quad \forall k_\perp :$

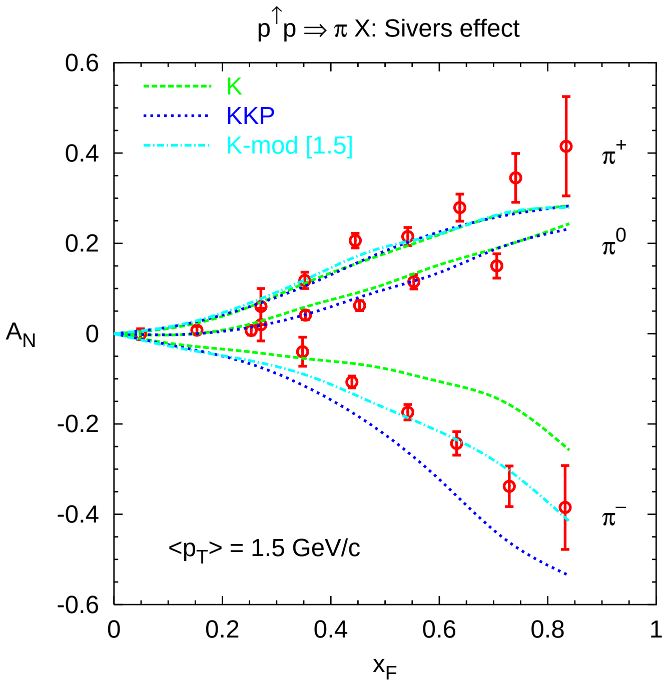
$$\mathcal{N}_q(x) = N_q\, x^{a_q} (1-x)^{b_q}\, \frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q}\, b_q^{b_q}}\,,\ |N_q| \leq 1$$

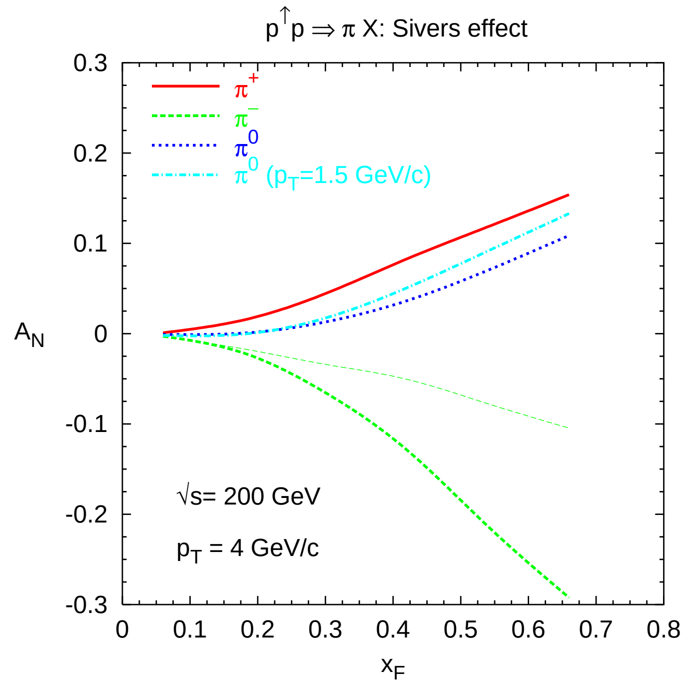
$$\mathcal{H}(k_\perp) = \left(2\, e\, \frac{1-r}{r}\right)^{1/2} \beta\, k_\perp \ \exp\left[\,-(1-r)/r\, \beta^2 k_\perp^2\,\right]\,, r = \beta^2/\alpha^2 < 1$$

Best parameters choice [$\beta = 1.25$ (GeV/c)$^{-1}$] from E704 $A_N(\pi)$ data:

$$r = 0.7$$
$$N_u = 0.5 \quad a_u = 2 \quad b_u = 0.3$$
$$N_d = -1 \quad a_d = 1.5 \quad b_d = 0.2$$

[PRELIMINARY]





Estimates of A_N with Sivers effect at E = 200 GeV vs. x_F at p_T = 1.5 GeV/c. Distribution function set: GRV94; fragmentation function sets: K, KKP and K-mod (a modified version of K). Data are from Adams et al. [E704] PL B261 (1991)

Estimates of A_N with Sivers effect at $\sqrt{s}$ = 200 GeV [RHIC] vs. x_F at p_T = 4 GeV/c (also 1.5 GeV/c for π^0). Distribution function set: GRV94; fragmentation function sets: K(thin line) and KKP(thick lines).

Conclusions and outlook

- Preliminary results of a combined analysis of unpolarized cross sections for several processes and SSA for $pp \Rightarrow \pi X$ assuming Sivers effect, within pQCD + spin and $\boldsymbol{k}_\perp$ - dependent pdf's and ff's:
  - good account of unpol. cross section up to a factor $\approx$ 2 (NLO, scale depend.)
  - $\langle \boldsymbol{k}_\perp^2 \rangle_{\rm pdf}^{1/2} \simeq 0.8 - 1$ GeV$/c$ $\langle \boldsymbol{k}_\perp^2 \rangle_{\rm ff}^{1/2} \simeq 1.4\, z^{1.3}(1-z)^{0.2}$ GeV$/c$
  - good account of A_N [E704] data with reasonable parameters for Sivers function (x- shape similar to previous calculations);
- Preliminary results for SSA at RHIC: $A_N(\pi)$;
- Collins effect: in progress. Access to transversity;
- RHIC data at larger energies and at large p_T essential to test and improve our knowledge on SSA and spin and $\boldsymbol{k}_\perp$ - dependent pdf's and ff's.