AZIMUTHAL AND SINGLE TRANSVERSE SPIN ASYMMETRIES IN HADRONIC COLLISIONS

Francesco Murgia – INFN Sezione di Cagliari

QCD@Work – International Workshop on QCD – Theory and Experiment

20-23 June 2010 – Martina Franca, Valle d'Itria - Italy

Outline

- **Motivations** (theory vs. challenging exp. results – circa 1980/90)
- **Azimuthal and transverse single spin asymmetries** *(*short introduction*)*
- **Theoretical approaches**
  - TMD generalized parton model [inclusion of spin and intrinsic parton motion (k_T) effects]
  - TMD color gauge invariant approach (+ pQCD color-gauge links)
  - Twist-three collinear factorization formalism (qqg correlators)
- **Applications**
- **Open points, future developments**

Transverse spin physics

It was an early common belief that transverse spin effects should play a negligible role in high-energy hadronic reactions

In a frame where a particle with mass m is moving very fast (with energy E $\gg$ m) the transverse spin components are suppressed with respect to the longitudinal one by a factor m/E

$$s^\mu = s^\mu_\parallel + s^\mu_\perp = \frac{\lambda}{m} p^\mu + s^\mu_\perp \qquad s^2 = \lambda^2 + s^2_\perp = -1$$

However, this does not mean that ALL transverse polarization phenomena are subleading. Some of them are neither kinematically nor dynamically suppressed

In fact, there are several transv. spin effects contradicting this prejudice:

quark transversity distribution

transverse single spin asymmetries
transverse hyperon polarization in unpol. hadronic collisions

spin-spin correlations in pp elastic scattering

Transverse spin physics

A new class of leading twist (dominant terms in a 1/Q power expansion, with Q the large energy scale) spin and transverse momentum dependent (TMD) partonic distribution and fragmentation functions can play a fundamental role in this game

Polarized TMD distributions are intimately related to:

parton orbital motion inside hadrons

hadron structure in the impact parameter space

generalized parton distributions in Deeply Virtual Compton Scattering

light-cone hadronic wave functions

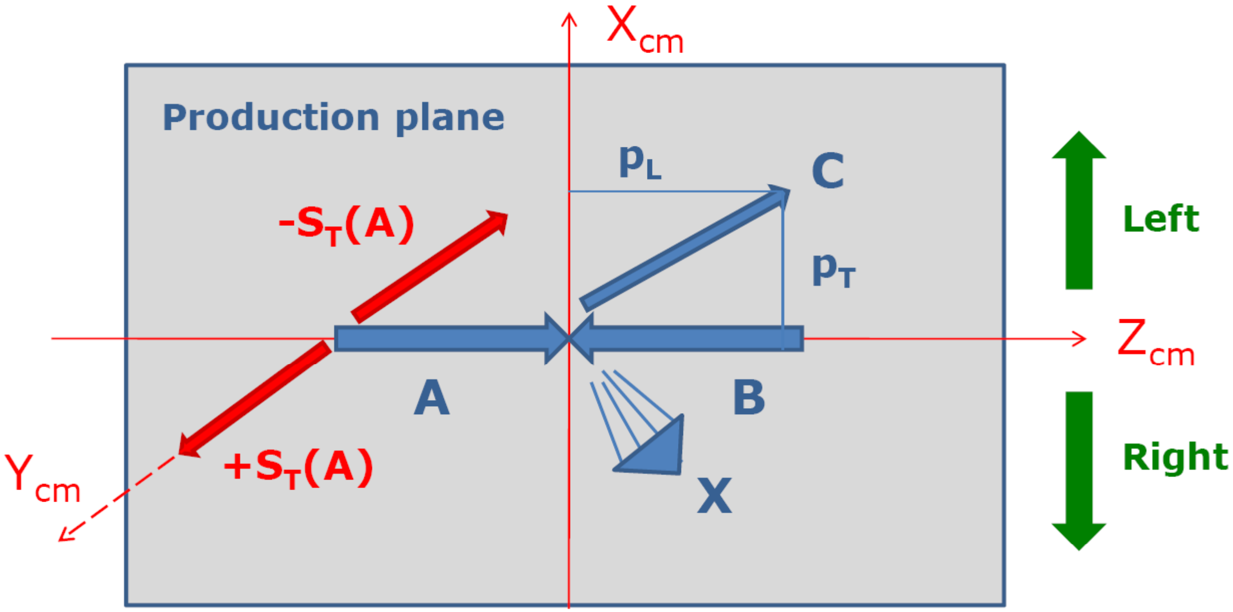
[violation of helicity conservation rules in QCD exclusive processes]

The study of transversely polarized observables in different kinematical situations and in different processes will hopefully clarify in much more detail the dynamical structure of hadrons

Single spin asymmetries in high-energy inclusive and semi-inclusive particle production at moderately large p_T

Transverse (left-right) single spin asymmetries (SSA), A_N (A_{LR})

Not forbidden by parity invariance of strong interactions



$$A_N(A^\uparrow B \to CX) = \frac{d\sigma^{A^\uparrow B\to CX} - d\sigma^{A^\downarrow B\to CX}}{d\sigma^{A^\uparrow B\to CX} + d\sigma^{A^\downarrow B\to CX}} = \frac{d\Delta_N\sigma(A^\uparrow B \to CX)}{2d\sigma^{\rm unp}(AB \to CX)}$$

$$= \frac{d\sigma^{A^\uparrow B\to CX}(p_T) - d\sigma^{A^\uparrow B\to CX}(-p_T)}{d\sigma^{A^\uparrow B\to CX}(p_T) + d\sigma^{A^\uparrow B\to CX}(-p_T)} \equiv A_{LR}$$

Single spin asymmetries in high-energy inclusive and semi-inclusive particle production

Theoretical expectactions (circa 1980)

Transverse single spin asymmetries (SSA), A_N

Expected to be negligible in high-energy hadronic processes
Transverse SSAs are related to the imaginary part of interference terms between two elementary scattering amplitudes, off-diagonal (helicity-flip) in the helicity indices of the involved (transversely polarized) parton

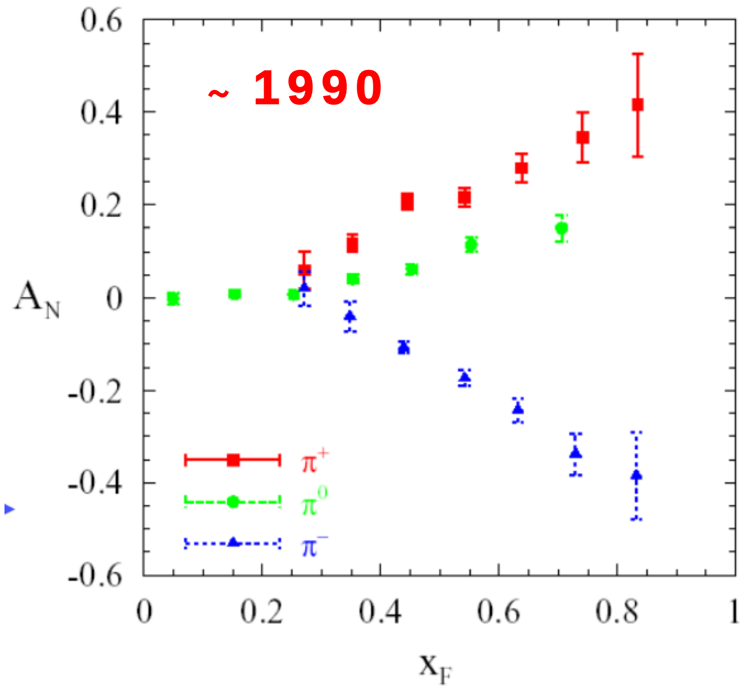
$$\boxed{|\uparrow,\downarrow\rangle_y = (1/\sqrt{2})(|+\rangle \pm i|-\rangle) \Longrightarrow |\langle\ |...|\uparrow\rangle|^2 - |\langle\ |...|\downarrow\rangle|^2 \propto \mathrm{Im}\langle\ |...|\pm\rangle\langle\ |...|\mp\rangle^*}$$

At tree level, all helicity amplitudes are real
Imaginary parts can only arise through higher-order (loop) contributions
The QCD massless q–g coupling preserves helicity at all perturbative orders
Helicity flip contributions in the amplitudes must be prop. to (powers of) m_q/E_q

$$\boxed{\hat{a}_N = \frac{d\hat{\sigma}^{\,a^\uparrow b\to cd} - d\hat{\sigma}^{\,a^\downarrow b\to cd}}{d\hat{\sigma}^{\,a^\uparrow b\to cd} + d\hat{\sigma}^{\,a^\downarrow b\to cd}} \propto \alpha_s(\hat{s})\,\frac{m_q}{\hat{s}} \sim \alpha_s(p_T)\,\frac{m_q}{p_T}}$$

Kane, Pumplin, Repko PRL 41 (1978)

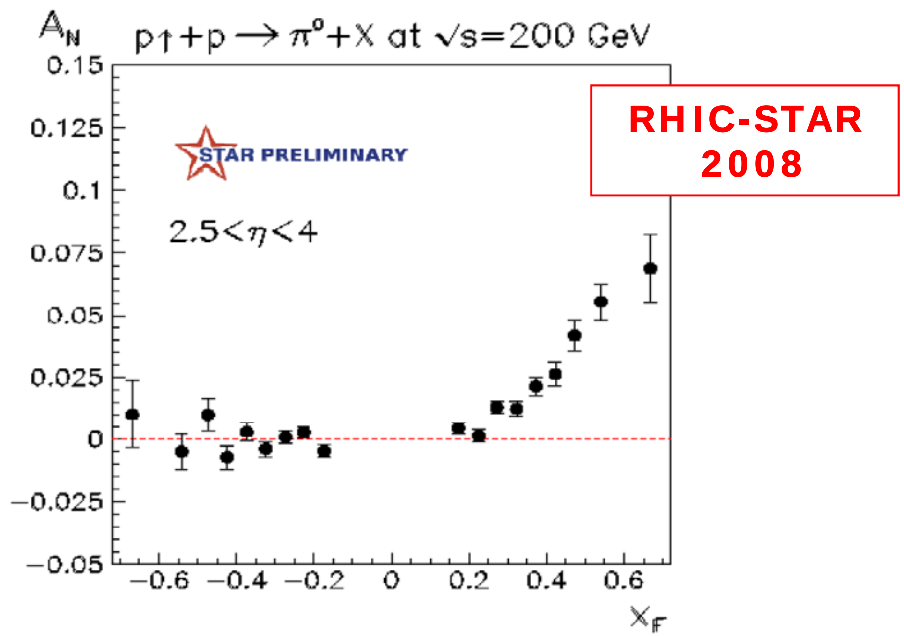
Unexpected experimental results for pion SSAs in pp collisions

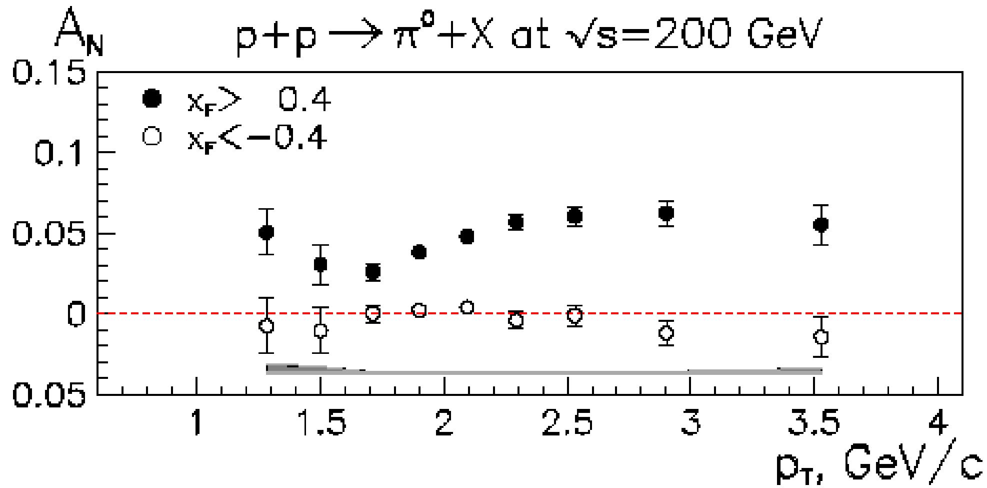


Fermilab E704: $A_N(p^\uparrow p \to \pi X)$

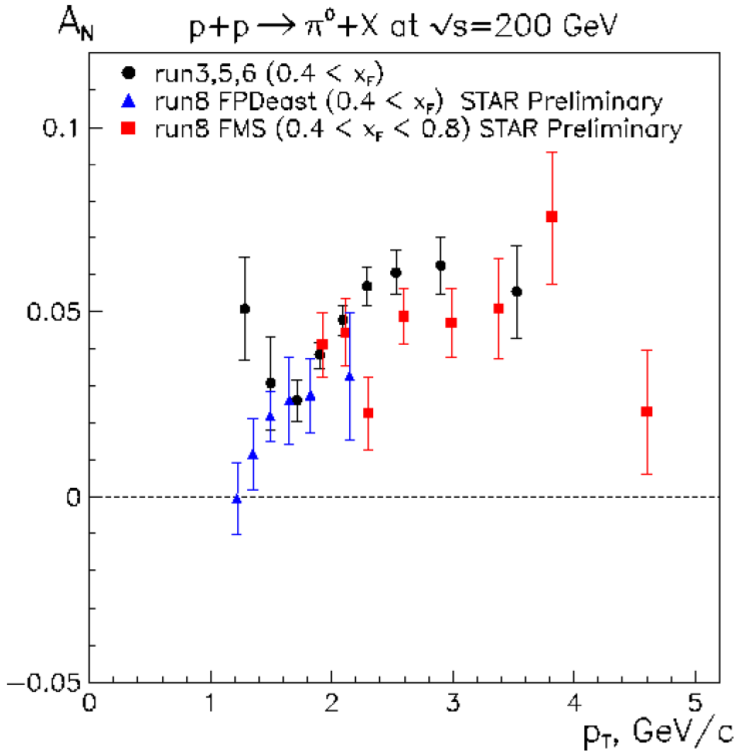
$\sqrt{s} = 20$ GeV, $0.7 < p_T < 2.0$ GeV

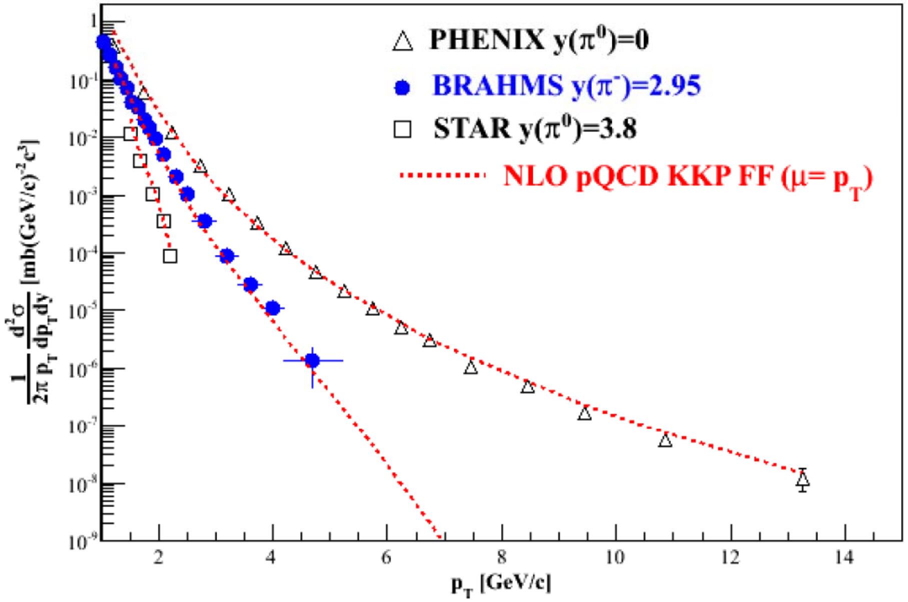
$$\boxed{x_F = 2p_L/\sqrt{s}}$$





More RHIC results for SSAs





Good description at 200 GeV over all rapidities down to p_T of 1-2 GeV/c

Warning:

Presently we are able to calculate SSAs at leading-twist or even twist-three accuracy **BUT only at the LO level**

Transverse hyperon polarization in unpolarized pN collisions

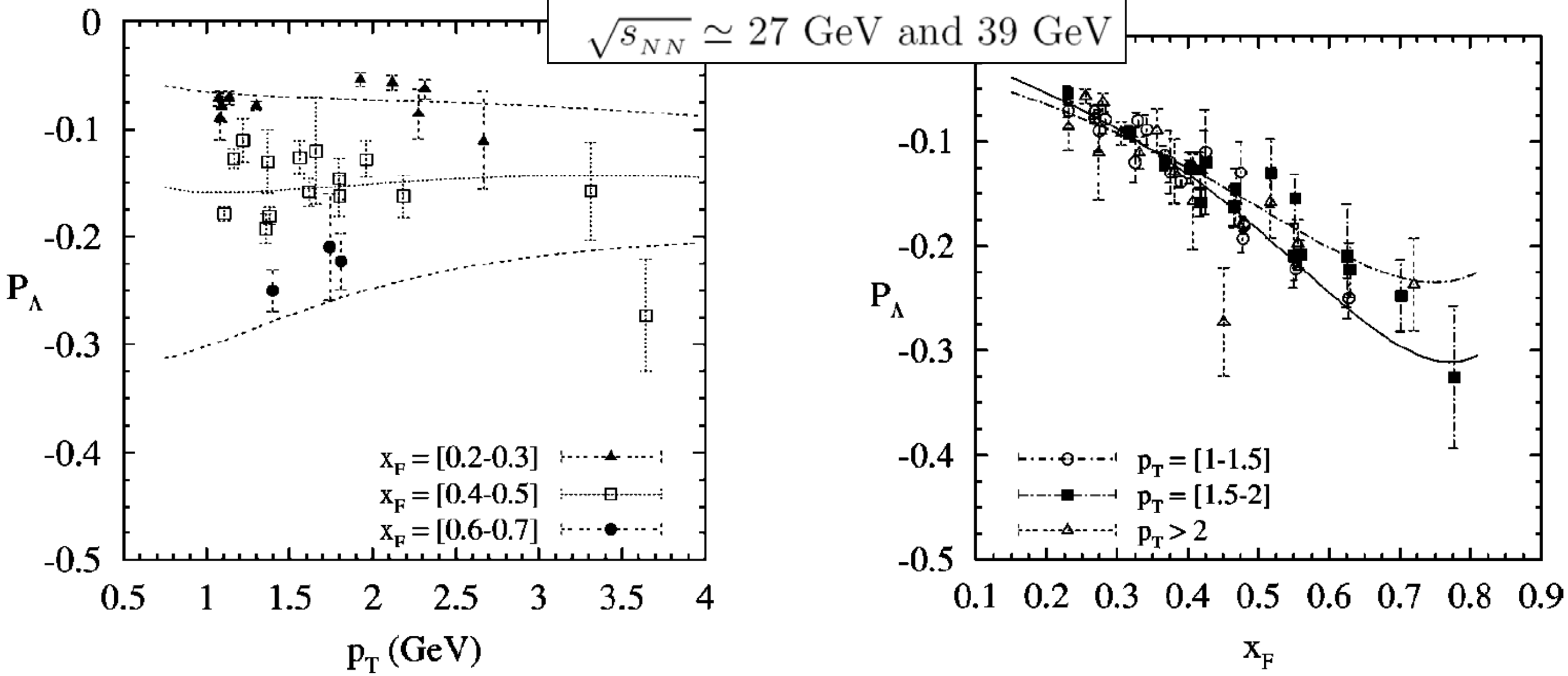
$$P_\Lambda = \frac{d\sigma^{AB\to\Lambda^\uparrow X} - d\sigma^{AB\to\Lambda^\downarrow X}}{d\sigma^{AB\to\Lambda^\uparrow X} + d\sigma^{AB\to\Lambda^\downarrow X}}$$

Feasible also at RHIC
LHC (Λ+jet)

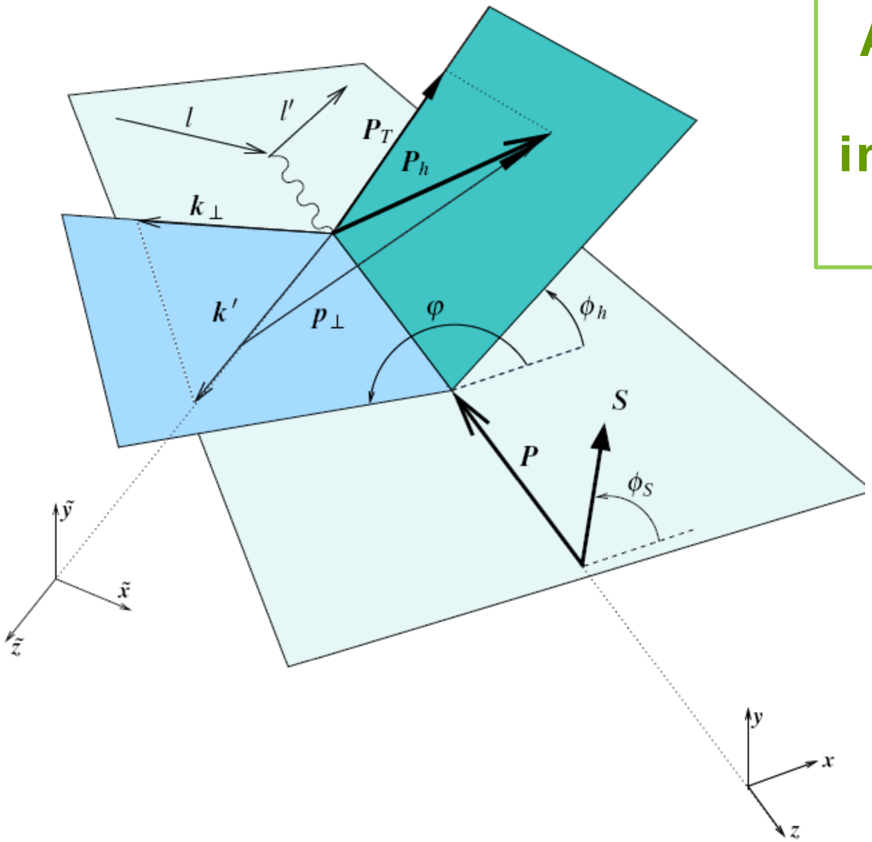
$\Lambda \to p\pi^-$ $\qquad W(\theta,\phi) \propto 1 + \alpha_\Lambda \boldsymbol{P}_\Lambda \cdot \hat{\boldsymbol{r}}$

$P_\Lambda(p\,Be \to \Lambda^\uparrow X)$

$\sqrt{s_{NN}} \simeq 27$ GeV and 39 GeV



Heller et al - Lundberg et al - Ramberg et al (1978-1994)



Azimuthal asymmetries in semi-inclusive deeply inelastic scattering (SIDIS) $lp \to l'h + X$

FIG. 1 (color online). Three-dimensional kinematics of the SIDIS process, according to Trento conventions [14]. The photon and the proton collide along the $\hat{z}$-axis, while the leptonic plane defines the $\hat{x}\hat{z}$ plane. The fragmenting quark and the final hadron h are emitted at azimuthal angles φ and ϕ_h, and the proton transverse spin direction is identified by ϕ_S.

HERMES-DESY
COMPASS-CERN
JLAB

$$A_{S_B\,S_T}^{W(\phi_h,\phi_S)} = 2\langle\, W(\phi_h,\phi_S)\,\rangle = 2\,\frac{\int \mathrm{d}\phi_h \mathrm{d}\phi_S\, W(\phi_h,\phi_S)\,\left[\,\mathrm{d}\sigma(\phi_h,\phi_S) - \mathrm{d}\sigma(\phi_h,\phi_S+\pi)\,\right]}{\int \mathrm{d}\phi_h \mathrm{d}\phi_S\,\left[\,\mathrm{d}\sigma(\phi_h,\phi_S) + \mathrm{d}\sigma(\phi_h,\phi_S+\pi)\,\right]}$$

$B =$ lepton beam, $S_B = U,\, L$ $\qquad$ $T =$ nucleon target, $S_T = U,\, L,\, T$

Azimuthal asymmetries in SIDIS - HERMES results

$$A_{UT}^{\sin(\phi_h+\phi_S)} \qquad\qquad A_{UT}^{\sin(\phi_h-\phi_S)}$$

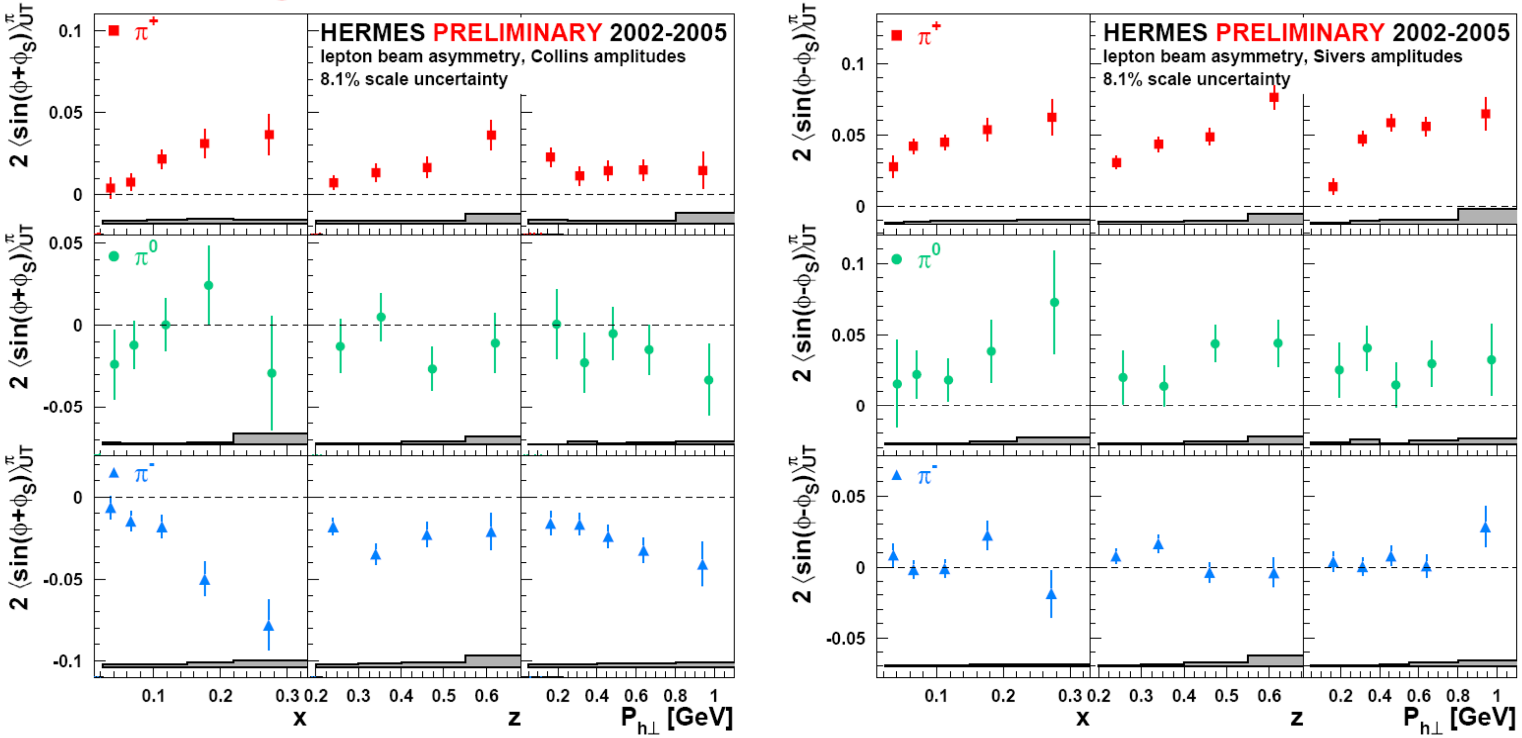
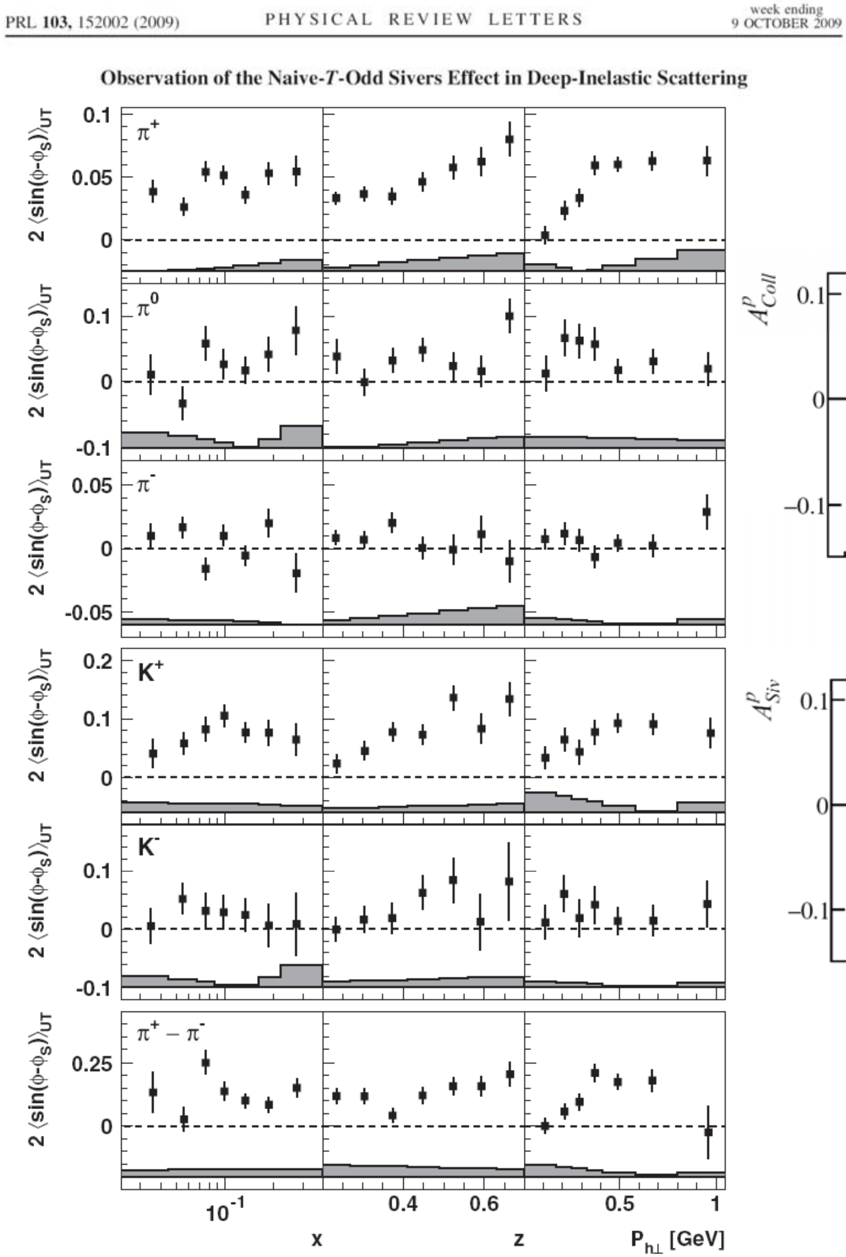
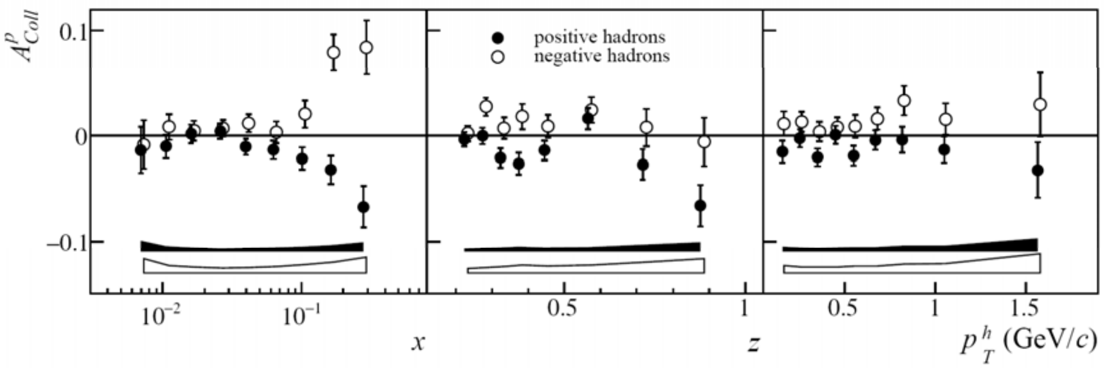
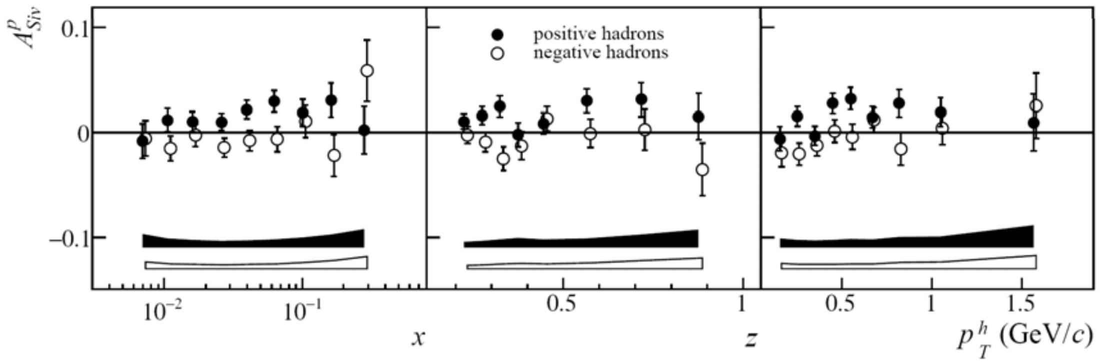


Figure 1: Collins amplitudes (left column) and Sivers amplitudes (right column) for π-mesons (as labelled) as function of x, z and $\boldsymbol{P}_{h\perp}$. The error bands represent the maximal systematic uncertainty; the common overall 8.1% scaling uncertainty is due to the target polarisation uncertainty.

Azimuthal asymmetries in SIDIS
HERMES and COMPASS results







COMPASS Collaboration
ArXiv:1005.5609 [hep-ex]

Azimuthal asymmetries for inclusive hadron pair production in e⁺e⁻ collisions (Belle)

$$\langle \cos(\phi_1 + \phi_2) \rangle$$

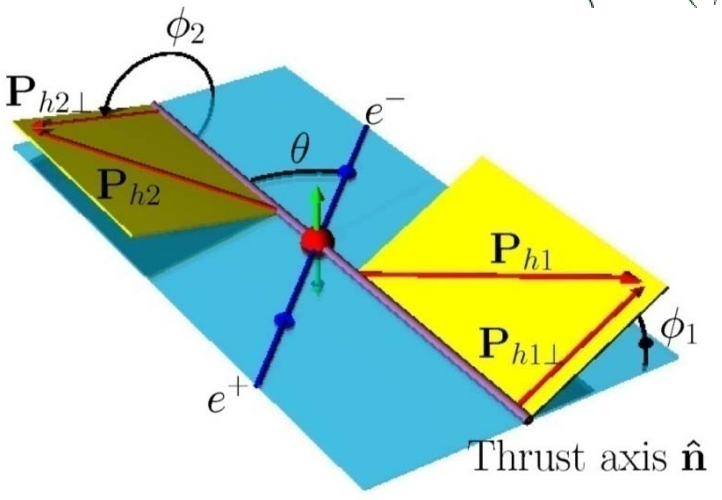


FIG. 2: Definition of the azimuthal angles ϕ_1 and ϕ_2 of the two hadrons, between the scattering plane and their transverse momenta $\mathbf{P}_{hi\perp}$ around the thrust axis $\hat{n}$. The angle θ is defined as the angle between the lepton axis and the thrust axis.

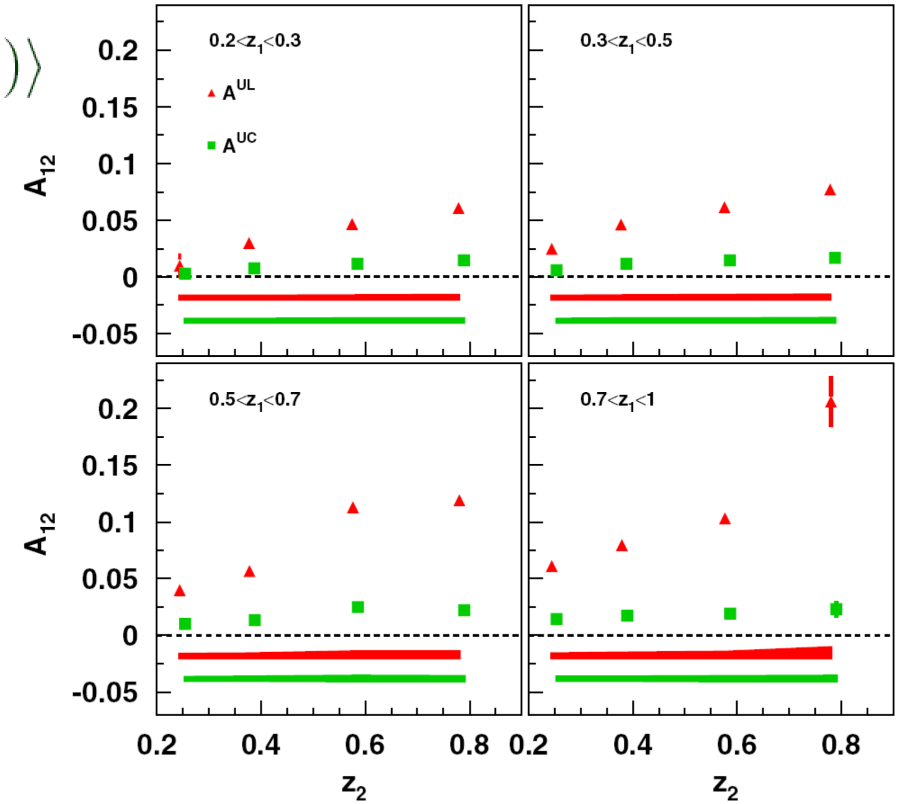


FIG. 18 (color online). Light quark (uds) A_{12} asymmetry parameters as a function of z_2 for 4 z_1 bins. The UL data are represented by triangles and the systematic error by the upper error band. The UC data are described by the squares and their systematic uncertainty by the lower error band.

Notice: large scale here is approx. M_γ^2 = 100 GeV²

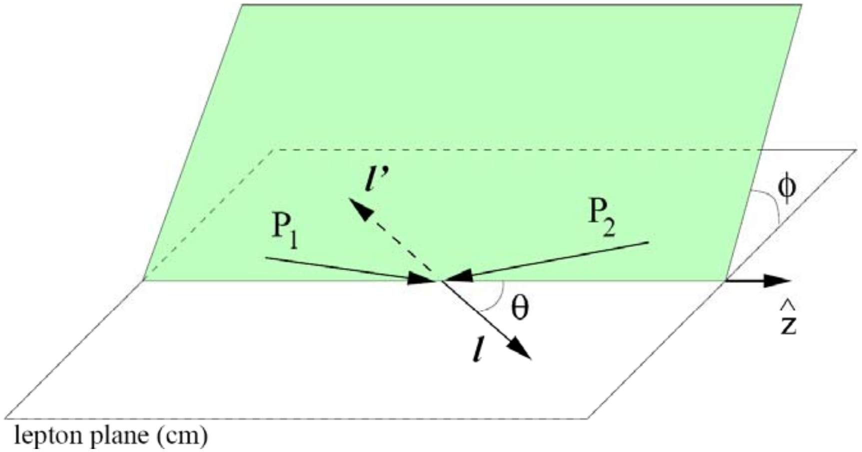
Azimuthal asymmetries in (un)polarized Drell-Yan processes

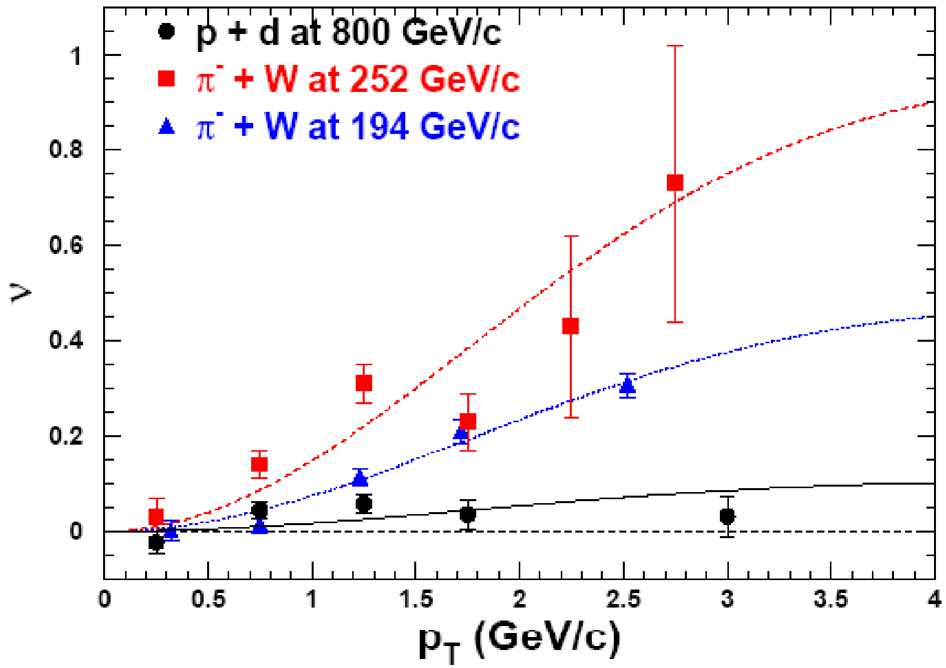
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

In the "naive" collinear parton model: $\lambda = 1$ and $\mu = \nu = 0$

QCD corrections and intrinsic parton motion may imply $\lambda \neq 1$ and $\mu, \nu \neq 0$

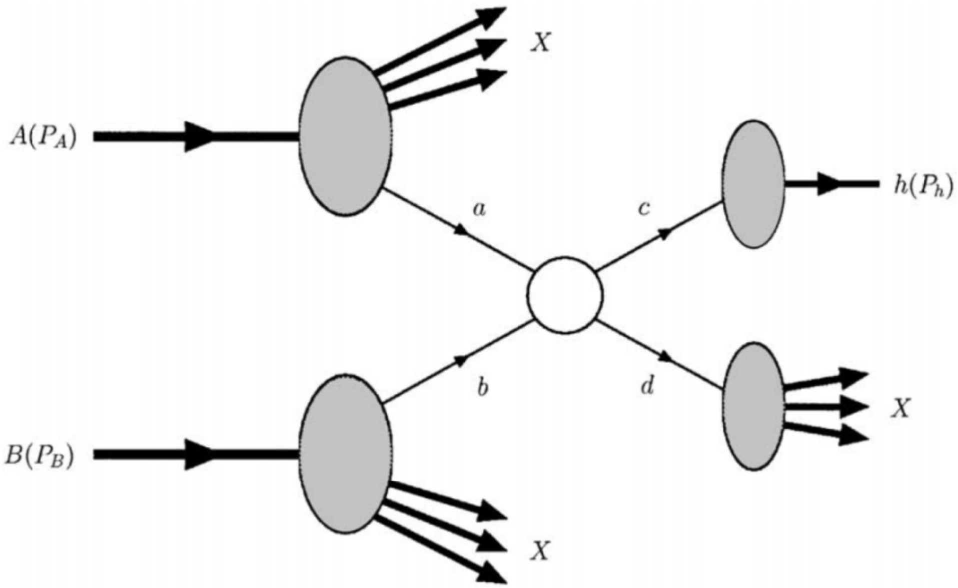
Lam-Tung relation(preserved by higher order QCD corrections): $\boxed{1 - \lambda = 2\nu}$





Fermilab
COMPASS-CERN (pol)
RHIC (pol)
PAX-GSI (antiprotons)

Inclusive single particle production in pp collisions in the "collinear" QCD-inspired parton model



$$\frac{E_C\, d\sigma^{AB\to C\,X}}{d^3\boldsymbol{p}_C} = \sum_{a,b,c,d} \int dx_a\, dx_b\, dz\, f_{a/A}(x_a, Q^2)\, f_{b/B}(x_b, Q^2)\, \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}\, \frac{\hat{s}}{\pi z^2}\, \delta(\hat{s}+\hat{t}+\hat{u})\, D_{C/c}(z, Q^2)$$

Unable to explain the large azimuthal and single spin asymmetries observed
In this scheme they originate entirely from the underlying partonic process

$$\sim \alpha_s(p_T)\,\frac{m_q}{p_T}$$

Generalized parton model in the helicity formalism: Polarized leading-twist TMD PDFs and FFs

Consider as an example the doubly polarized invariant differential cross section for inclusive single particle production, $A(S_A)\ B(S_B) \longrightarrow C + X$:

$$\boxed{\begin{aligned}\frac{E_C\, d\sigma^{(A,S_A)+(B,S_B)\to C+X}}{d^3\boldsymbol{p}_C} = \sum_{a,b,c,d,\{\lambda\}} & \int \frac{dx_a\, dx_b\, dz}{16\pi^2 x_a x_b z^2 s}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{k}_{\perp C}\, \delta(\boldsymbol{k}_{\perp C}\cdot\hat{\boldsymbol{p}}_c)\, J(\boldsymbol{k}_{\perp C}) \\ & \times\ \rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\, \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a})\, \rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\, \hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b}) \\ & \times\ \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\, \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b}\, \delta(\hat{s}+\hat{t}+\hat{u})\, \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})\,,\end{aligned}}$$

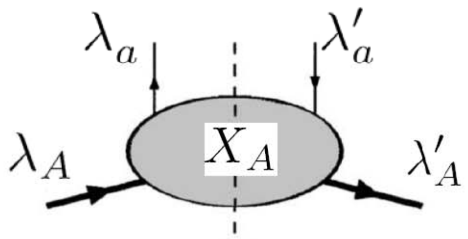
$$\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\, \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) = \sum_{\lambda_A,\lambda'_A} \rho^{A,S_A}_{\lambda_A,\lambda'_A} \sum\!\!\!\!\!\!\!\!\int_{X_A,\lambda_{X_A}} \hat{\mathcal{F}}_{\lambda_a,\lambda_{X_A};\lambda_A}\hat{\mathcal{F}}^*_{\lambda'_a,\lambda_{X_A};\lambda'_A} \equiv \sum_{\lambda_A,\lambda'_A} \rho^{A,S_A}_{\lambda_A,\lambda'_A}\, \hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}$$

$$\rho^{A,S_A}_{\lambda_A,\lambda'_A} = \frac{1}{2}\begin{pmatrix} 1+P_Z^A & P_X^A - \mathrm{i}P_Y^A \\ P_X^A + \mathrm{i}P_Y^A & 1-P_Z^A \end{pmatrix}_{A,S_A} = \frac{1}{2}\begin{pmatrix} 1+P_L^A & P_T^A e^{-\mathrm{i}\phi_{S_A}} \\ P_T^A e^{\mathrm{i}\phi_{S_A}} & 1-P_L^A \end{pmatrix}_{A,S_A}$$

Helicity Density Matrix of hadron A

$$\hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a,\boldsymbol{k}_{\perp a}) \equiv \sum\!\!\!\!\!\!\!\!\int_{X_A,\lambda_{X_A}} \hat{\mathcal{F}}_{\lambda_a,\lambda_{X_A};\lambda_A}(x_a,\boldsymbol{k}_{\perp a})\hat{\mathcal{F}}^*_{\lambda'_a,\lambda_{X_A};\lambda'_A}(x_a,\boldsymbol{k}_{\perp a})$$

Related to the leading twist hadronic correlator



Rotational invariance

$$\hat{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a,\boldsymbol{k}_{\perp a}) = F^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a,k_{\perp a})\exp[i(\lambda_A-\lambda'_A)\phi_a]$$

Parity invariance of strong interactions

$$F^{-\lambda_a,-\lambda'_a}_{-\lambda_A,-\lambda'_A} = (-1)^{2(S_A-s_a)}(-1)^{(\lambda_A-\lambda_a)+(\lambda'_A-\lambda'_a)}F^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}$$

Some parity relations are different for quarks (s_q=1/2) and gluons (s_g=1)

Angular momentum conservation in the forward direction ($k_T \to 0$)

$$F^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a,k_{\perp a}) \sim \left(\frac{k_{\perp a}}{M}\right)^{|\lambda_A-\lambda_a-(\lambda'_A-\lambda'_a)|}\tilde{F}^{\lambda_a,\lambda'_a}_{\lambda_A,\lambda'_A}(x_a,k_{\perp a})$$

We end up with 8 independent leading twist TMD functions (e.g. for quarks)

$F^{++}_{++} \pm F^{--}_{++}$ $\Rightarrow$ Obviously purely real quantities
Unpolarized and longitudinally polarized PDFs, f_1 and g_{1L}

$F^{+-}_{+-} \pm F^{-+}_{+-}$ $\Rightarrow$ Purely real(imaginary) quantities for quarks(gluons)
Contributions to the quark TMD transversity DF,: h_1, $h_{1T}^{\perp}$

$F^{++}_{+-} \pm F^{--}_{+-}$ $\Rightarrow$ Sivers function and $g_{1T}^{\perp}$ PDF

$F^{+-}_{++} \pm F^{+-}_{--}$ $\Rightarrow$ Boer-Mulders function and $h_{1L}^{\perp}$ PDF

These last 4 complex functions are not independent; can also be written in terms of the real and imaginary parts of two of them

TMD fragmentation functions into unpol. hadrons (leading twist)

Introducing the soft, nonperturbative helicity fragmentation amplitudes for the process c $\to$ C + X, the following properties hold for their products:

$$\hat{D}^{\lambda_C,\lambda'_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C}) = \sum\!\!\!\!\!\!\!\int_{X,\lambda_X} \hat{\mathcal{D}}_{\lambda_C,\lambda_X;\lambda_c}(z,\boldsymbol{k}_{\perp C})\,\hat{\mathcal{D}}^*_{\lambda'_C,\lambda_X;\lambda'_c}(z,\boldsymbol{k}_{\perp C})$$

$$\hat{D}^{\lambda_C,\lambda'_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C}) = D^{\lambda_C,\lambda'_C}_{\lambda_c,\lambda'_c}(z,k_{\perp C})\, e^{i(\lambda_c-\lambda'_c)\phi^H_C}$$

$$\hat{D}^C_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C}) = \sum_{\lambda_C,\lambda_C} \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C}) = D^C_{\lambda_c,\lambda'_c}(z,k_{\perp C}) e^{i(\lambda_c-\lambda'_c)\phi^H_C}$$

$$D^C_{-\lambda_c,-\lambda'_c}(z,k_{\perp C}) = (-1)^{2s_c}(-1)^{\lambda_c+\lambda'_c} D^C_{\lambda_c,\lambda'_c}(z,k_{\perp C})$$

Quark sector

$$\hat{D}^{C/q}_{++}(z,\boldsymbol{k}_{\perp C}) = D^{C/q}_{++}(z,k_{\perp C}) \equiv \hat{D}_{C/q}(z,k_{\perp C})$$

$$2\,\mathrm{Im}\, D^{C/q}_{+-}(z,k_{\perp C}) \equiv \Delta^N \hat{D}_{C/q^\uparrow}(z,k_{\perp C})$$

Gluon sector

$$\hat{D}^{C/g}_{++}(z,\boldsymbol{k}_{\perp C}) = D^{C/g}_{++}(z,k_{\perp C}) \equiv \hat{D}_{C/g}(z,k_{\perp C})$$

$$2\,\mathrm{Re}\, D^{C/g}_{+-}(z,k_{\perp C}) \equiv \Delta^N \hat{D}_{C/T^g_1}(z,k_{\perp C})$$

Notice: for spin 1/2 hadrons (Λ's,...) in analogy with the PDF case there are again 8 independent TMD FFs

The most phenomenologically relevant for SSAs are

Sivers distribution function (chiral-even, naively T-odd)

$$\boxed{\Delta\hat{f}_{a/A^\uparrow}(x,\boldsymbol{k}_\perp) \equiv \hat{f}_{a/A^\uparrow}(x,\boldsymbol{k}_\perp) - \hat{f}_{a/A^\downarrow}(x,\boldsymbol{k}_\perp) = \hat{f}_{a/A^\uparrow}(x,\boldsymbol{k}_\perp) - \hat{f}_{a/A^\uparrow}(x,-\boldsymbol{k}_\perp)}$$

Transverse SSAs in polarized AB → C+X, SIDIS, DY

Boer-Mulders function (chiral odd, naively T-odd)

$$\boxed{\Delta\hat{f}_{a^\uparrow/A}(x,\boldsymbol{k}_\perp) \equiv \hat{f}_{a^\uparrow/A}(x,\boldsymbol{k}_\perp) - \hat{f}_{a^\downarrow/A}(x,\boldsymbol{k}_\perp) = \hat{f}_{a^\uparrow/A}(x,\boldsymbol{k}_\perp) - \hat{f}_{a^\uparrow/A}(x,-\boldsymbol{k}_\perp)}$$

Azimuthal Asy.s in unpolarized AB → C+X, SIDIS, DY

Collins fragmentation function (chiral-odd, naively T-odd)

$$\boxed{\Delta\hat{D}_{C/q^\uparrow}(z,\boldsymbol{k}_\perp) \equiv \hat{D}_{C/q^\uparrow}(z,\boldsymbol{k}_\perp) - \hat{D}_{C/q^\downarrow}(z,\boldsymbol{k}_\perp) = \hat{D}_{C/q^\uparrow}(z,\boldsymbol{k}_\perp) - \hat{D}_{C/q^\uparrow}(z,-\boldsymbol{k}_\perp)}$$

Azimuthal and transv. Asy.s in (un)polarized AB → h+X, SIDIS, DY, e+e- → h h X

"Polarizing" fragmentation function (chiral even, naively T-odd)

$$\boxed{\Delta\hat{D}_{\Lambda^\uparrow/q}(z,\boldsymbol{k}_\perp) \equiv \hat{D}_{\Lambda^\uparrow/q}(z,\boldsymbol{k}_\perp) - \hat{D}_{\Lambda^\downarrow/q}(z,\boldsymbol{k}_\perp) = \hat{D}_{\Lambda^\uparrow/q}(z,\boldsymbol{k}_\perp) - \hat{D}_{\Lambda^\uparrow/q}(z,-\boldsymbol{k}_\perp)}$$

Transv. Hyperon polarization in unpolarized AB → C+X, SIDIS

Fits of data and parameterizations

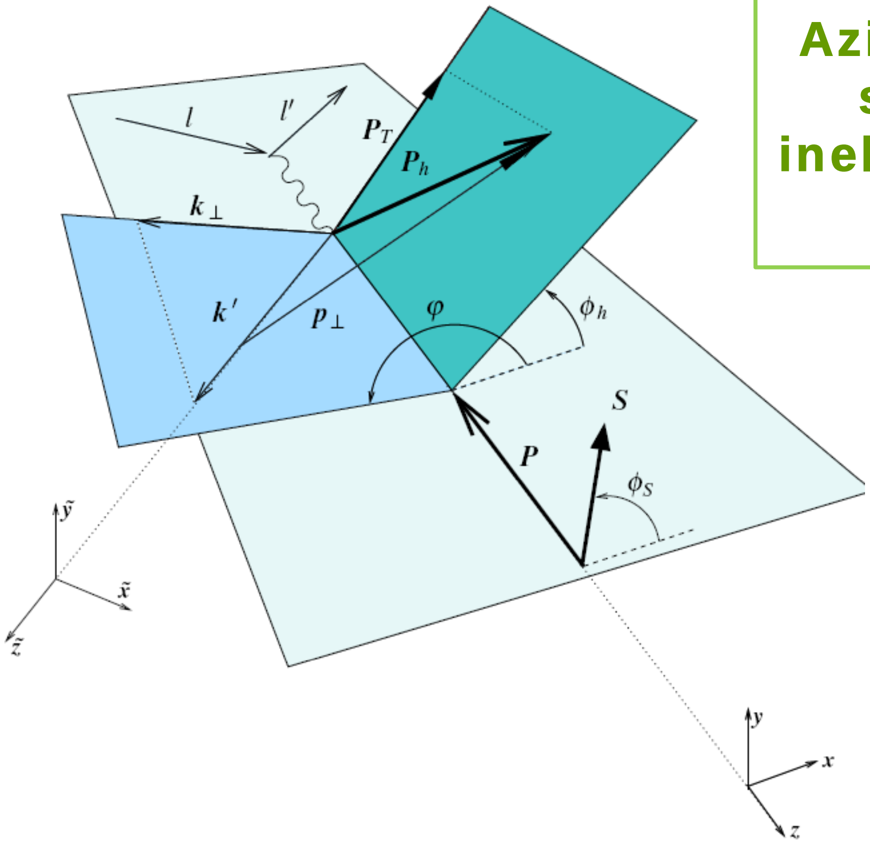
Transversity and Sivers distribution - Collins F.Function

Work in collaboration with

M. Anselmino, M. Boglione, A. Kotzinian (Torino)
U. D'Alesio (Cagliari)
E. Leader (London)
S. Melis (Alessandria,ECT*)
A. Prokudin (Jlab)

Sivers function: PRD 72, 094007 (2005) - EPJ A 39, 89 (2009)

Transversity & Collins FF: PRD75 054032 (2007) – NPB Proc. Suppl 191, 98 (2009)



Azimuthal asymmetries in semi-inclusive deeply inelastic scattering (SIDIS) $lp \to l'h+X$

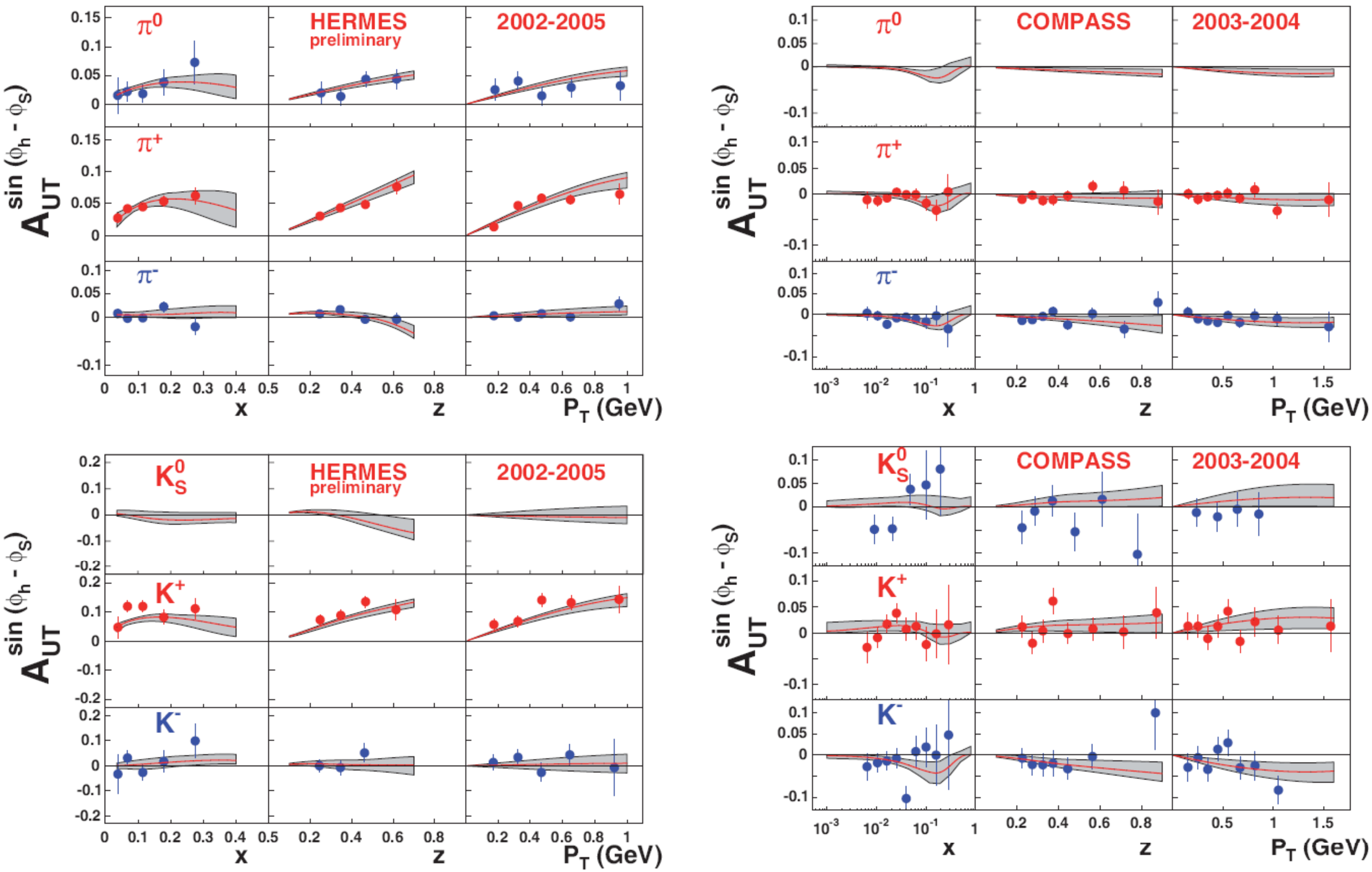
FIG. 1 (color online). Three-dimensional kinematics of the SIDIS process, according to Trento conventions [14]. The photon and the proton collide along the $\hat{z}$-axis, while the leptonic plane defines the $\hat{x}\hat{z}$ plane. The fragmenting quark and the final hadron h are emitted at azimuthal angles φ and ϕ_h, and the proton transverse spin direction is identified by ϕ_S.

HERMES
COMPASS
JLAB

$$A_{S_B\,S_T}^{W(\phi_h,\phi_S)} = 2\langle\, W(\phi_h,\phi_S)\,\rangle = 2\,\frac{\int \mathrm{d}\phi_h \mathrm{d}\phi_S\, W(\phi_h,\phi_S)\,\left[\,\mathrm{d}\sigma(\phi_h,\phi_S) - \mathrm{d}\sigma(\phi_h,\phi_S+\pi)\,\right]}{\int \mathrm{d}\phi_h \mathrm{d}\phi_S\,[\,\mathrm{d}\sigma(\phi_h,\phi_S) + \mathrm{d}\sigma(\phi_h,\phi_S+\pi)\,]}$$

$B =$ lepton beam, $S_B = U,\, L$ $\qquad$ $T =$ nucleon target, $S_T = U,\, L,\, T$

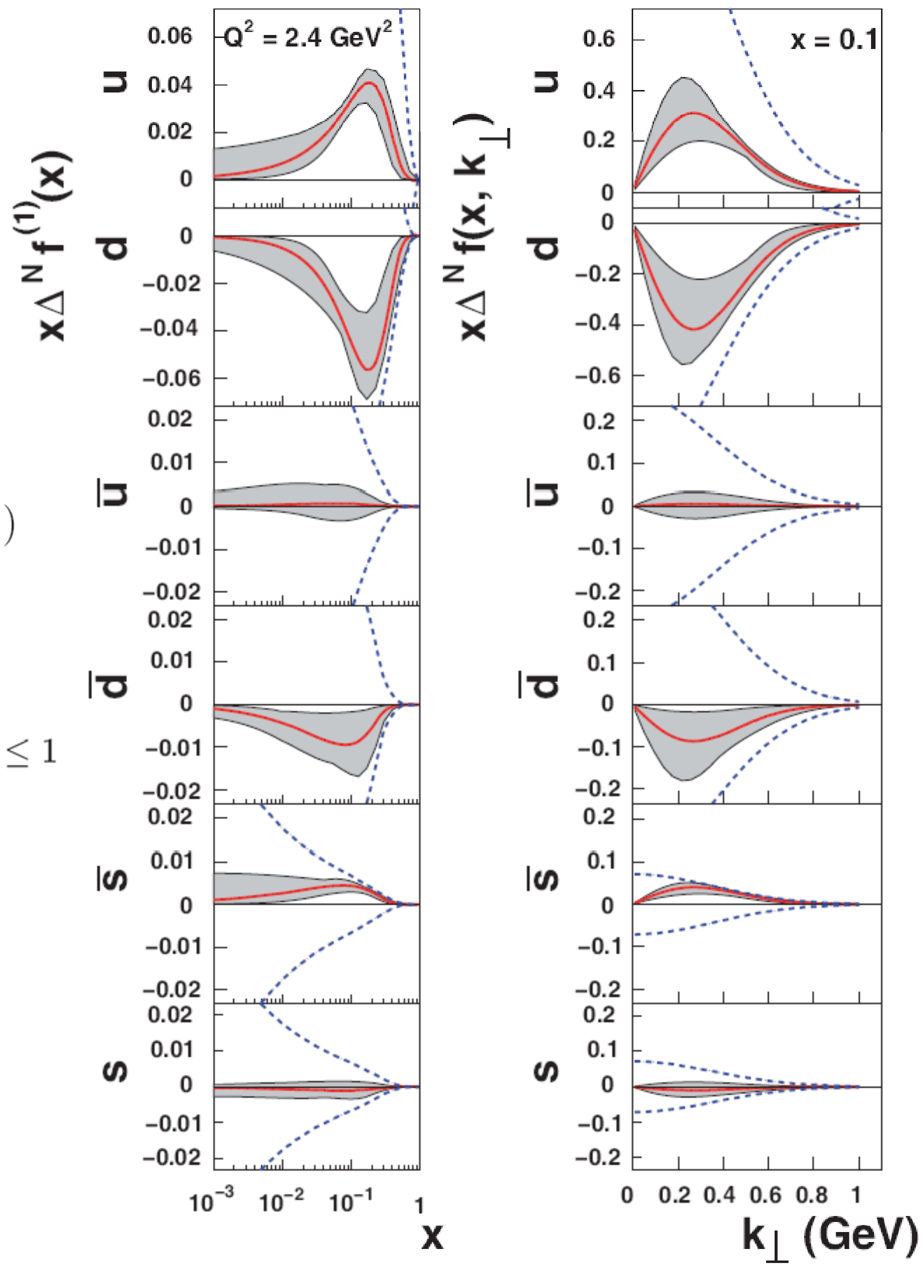
TMD generalized parton model
Fits to SIDIS [HERMES and COMPASS] Sivers Asymmetry



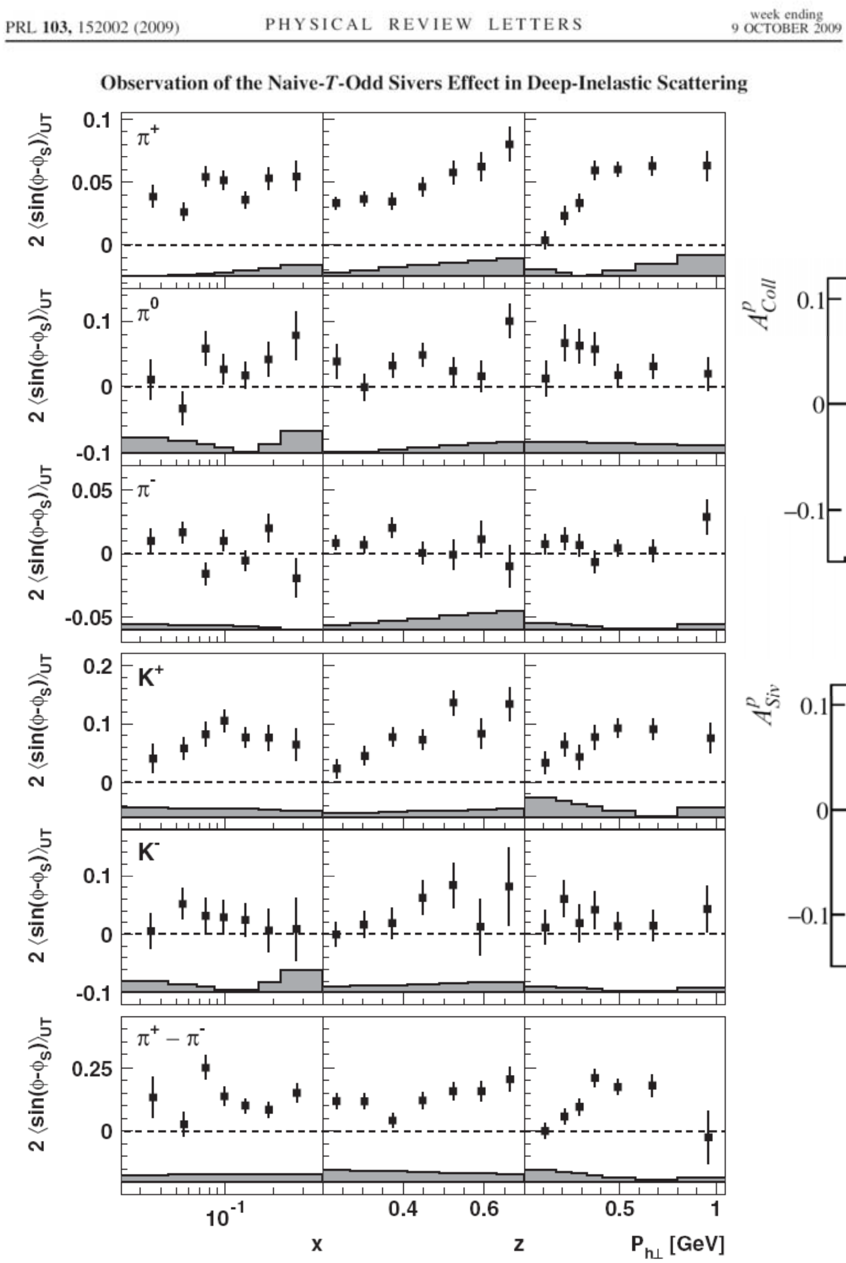
Parametrization of Sivers distribution

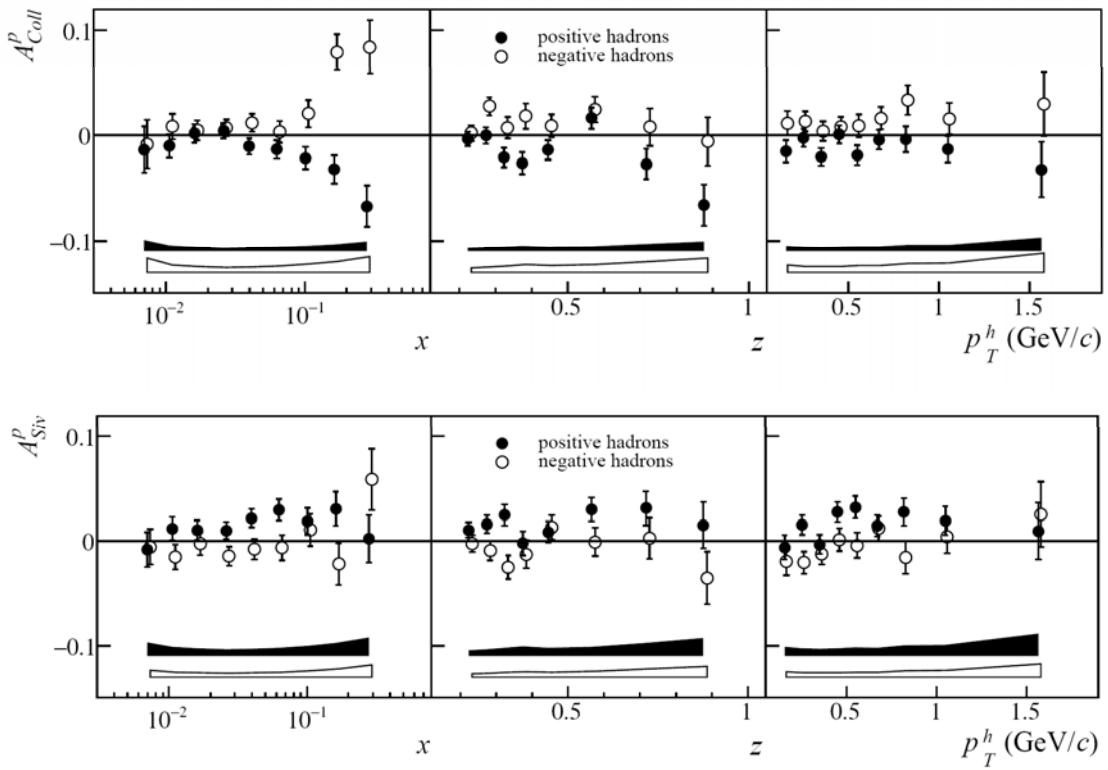
$$\Delta^N f^{(1)}_{q/p^\uparrow}(x) \equiv \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{4m_p}\, \Delta^N f_{q/p^\uparrow}(x, k_\perp)$$

$$\left|\frac{\Delta^N f_{q/p^\uparrow}(x,\boldsymbol{k}_\perp)}{2\, f_{q/p}(x,\boldsymbol{k}_\perp)}\right| = \left|\frac{f_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) - f_{q/p^\downarrow}(x,\boldsymbol{k}_\perp)}{f_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) + f_{q/p^\downarrow}(x,\boldsymbol{k}_\perp)}\right| \leq 1$$



Azimuthal asymmetries in SIDIS
HERMES and COMPASS results





COMPASS Collaboration
ArXiv:1005.5609 [hep-ex]

Azimuthal asymmetries for inclusive hadron pair production in e+e- collisions (Belle)

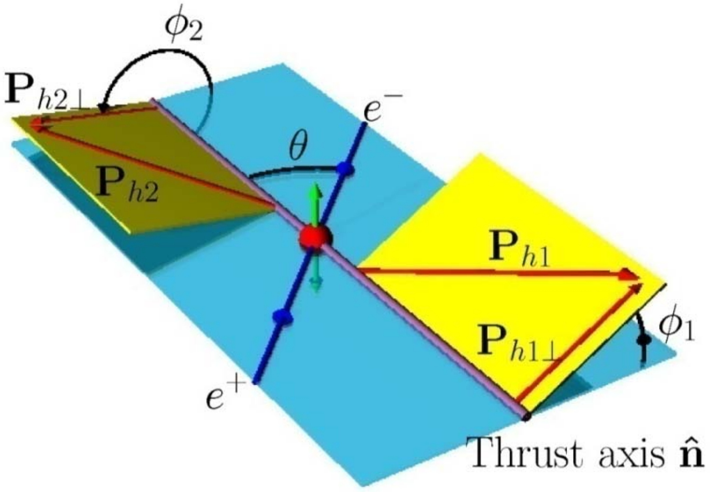
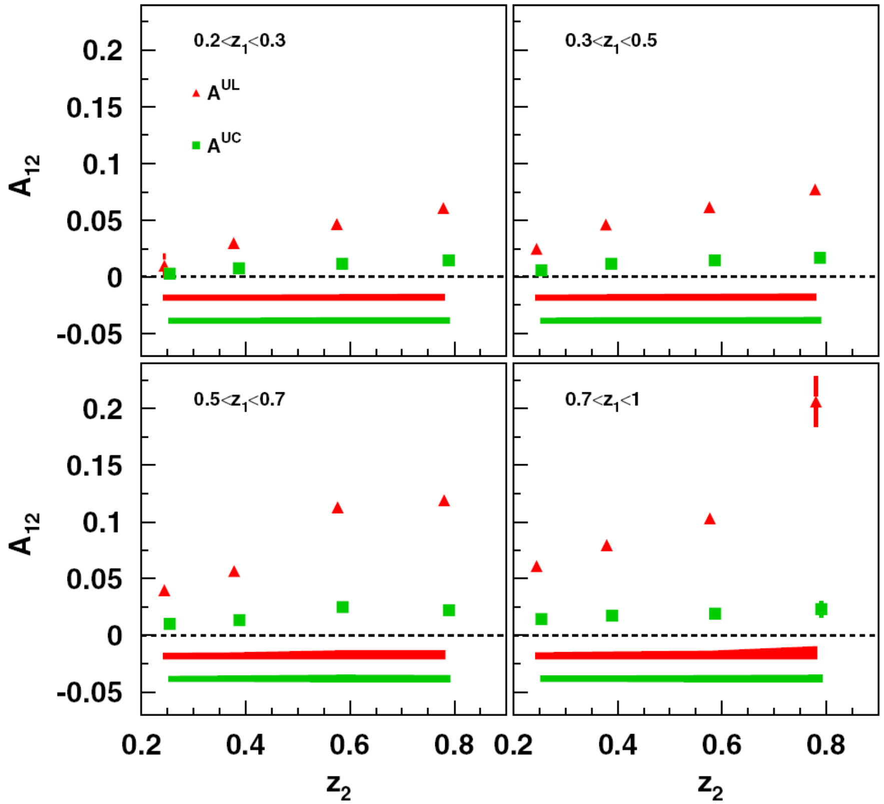


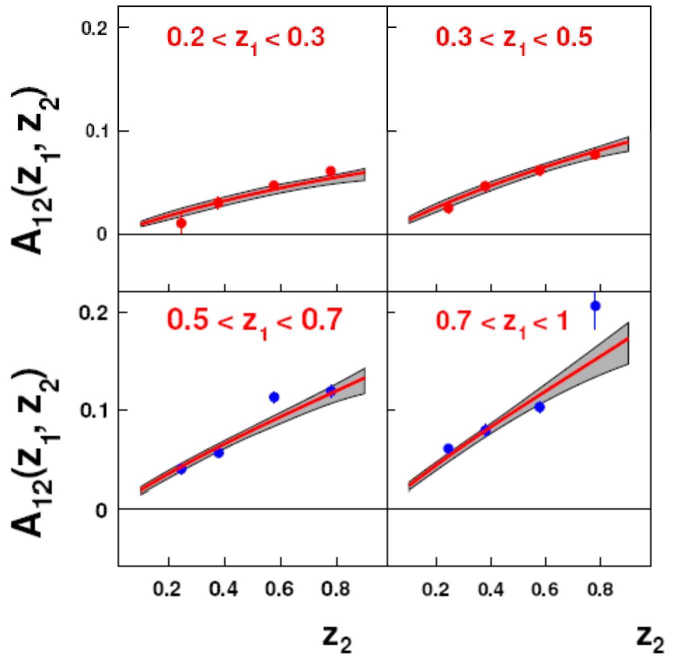
FIG. 2: Definition of the azimuthal angles ϕ_1 and ϕ_2 of the two hadrons, between the scattering plane and their transverse momenta $\mathbf{P}_{hi\perp}$ around the thrust axis $\hat{n}$. The angle θ is defined as the angle between the lepton axis and the thrust axis.

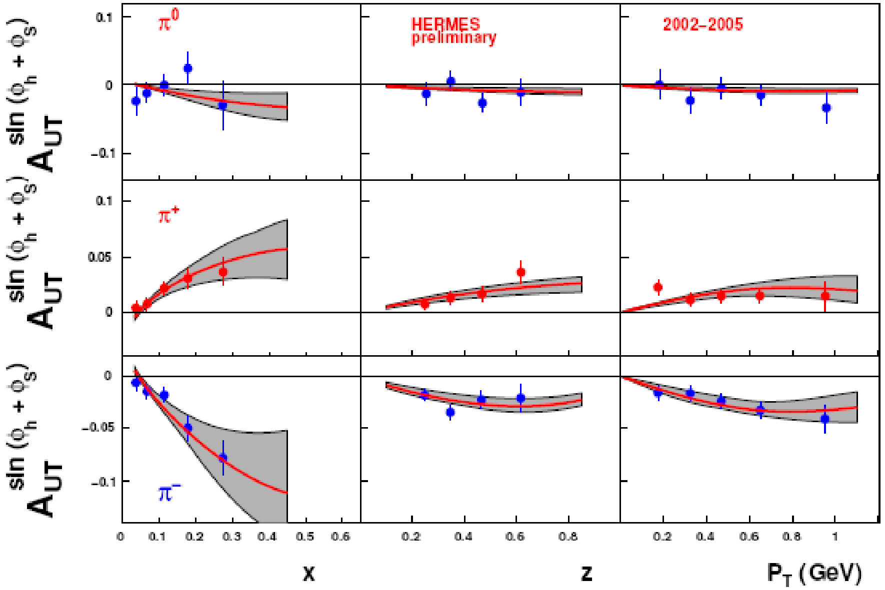


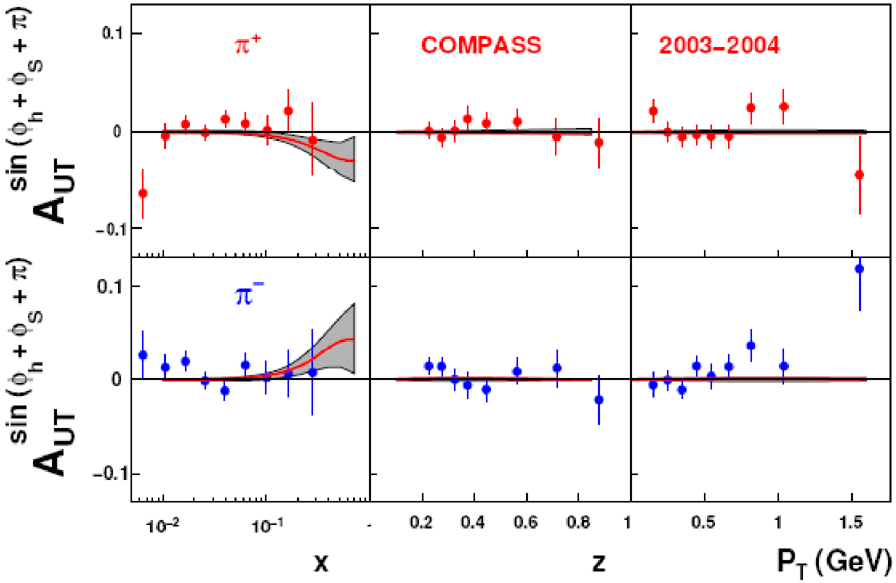
Notice: large scale here is approx. M_Υ^2 = 100 GeV²

FIG. 18 (color online). Light quark (uds) A_{12} asymmetry parameters as a function of z_2 for 4 z_1 bins. The UL data are represented by triangles and the systematic error by the upper error band. The UC data are described by the squares and their systematic uncertainty by the lower error band.

Fits to transversity distribution and Collins fragm. function from a combined analysis of Belle asymmetry in e+e- →ππ X and of Collins asymmetry in SIDIS [HERMES, COMPASS]







Parameterizations of transversity distribution and Collins fragmentation function

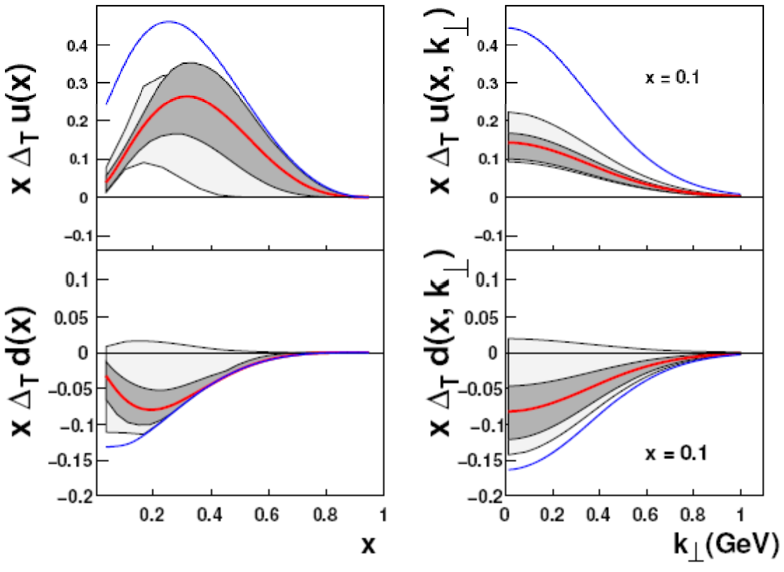


Figure 5. The transversity distribution functions for u and d flavours as determined by our global fit, at $Q^2 = 2.4$ GeV^2; we also show the Soffer bound [46] (highest or lowest lines) and the (wider) uncertainty bands of our previous extraction [20].

First ever available fit for transversity

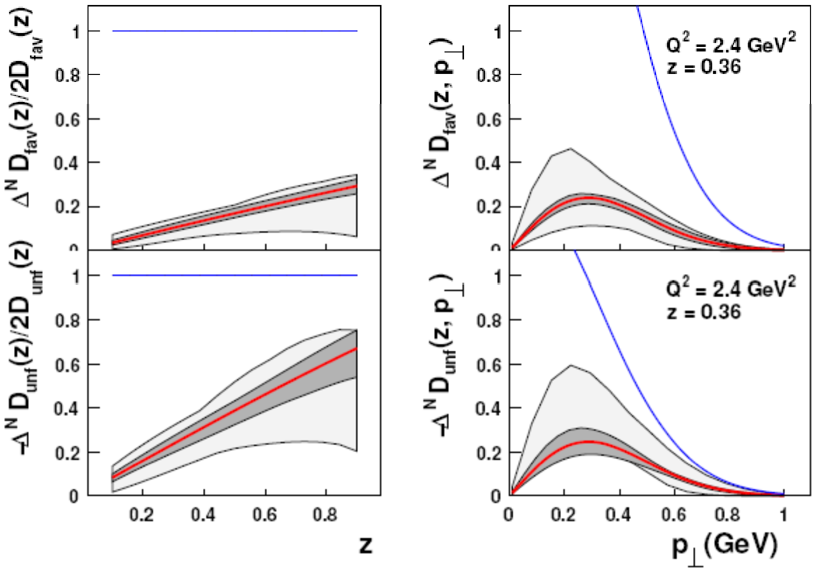
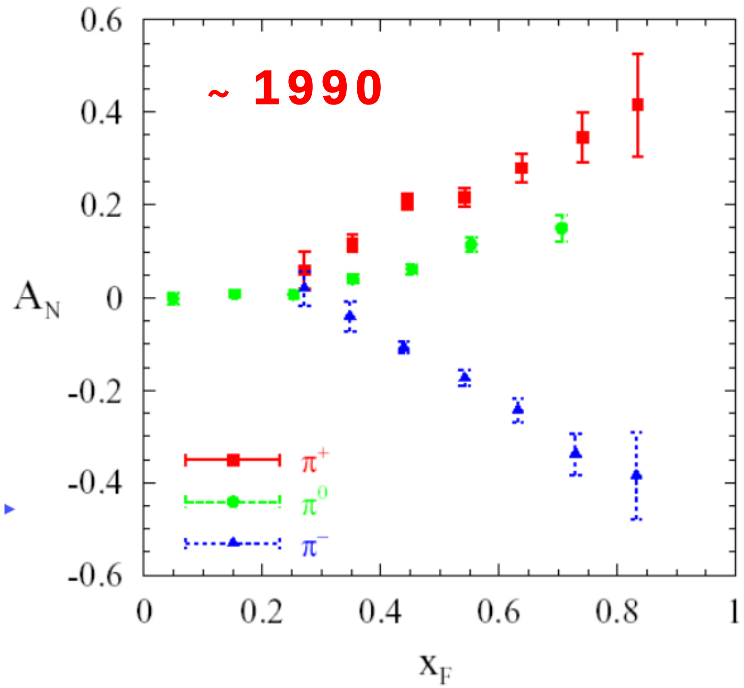


Figure 6. Favoured and unfavoured Collins fragmentation functions as determined by our global fit, at $Q^2 = 2.4$ GeV^2; we also show the positivity bound and the (wider) uncertainty bands as obtained in Ref. [20].

$$D_{\rm fav}(z) = D_u^{\pi^+}(z), D_{\bar d}^{\pi^+}(z), \ldots$$

$$D_{\rm unf}(z) = D_d^{\pi^+}(z), D_{\bar u}^{\pi^+}(z), \ldots$$

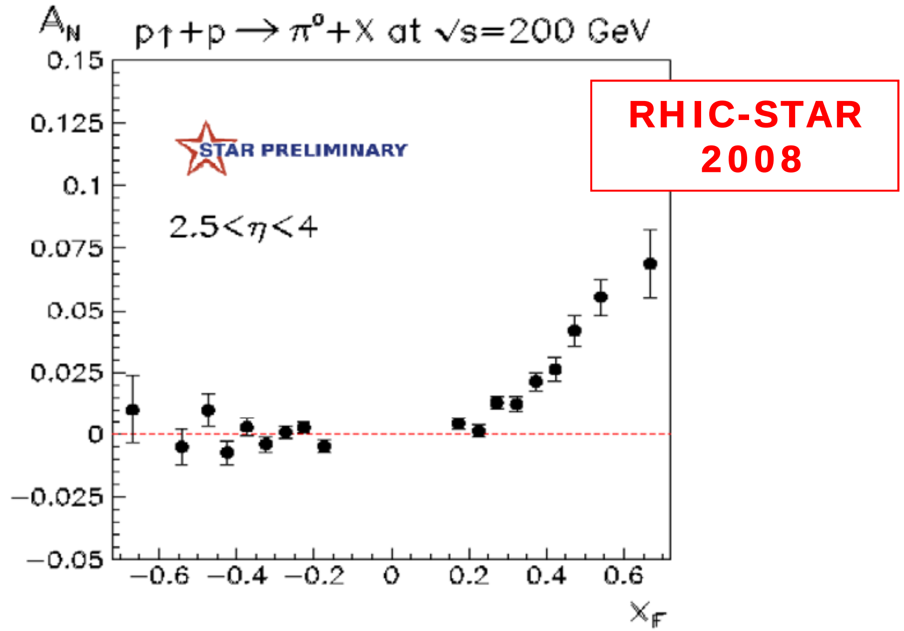
What about the results for pion SSAs in pp collisions?

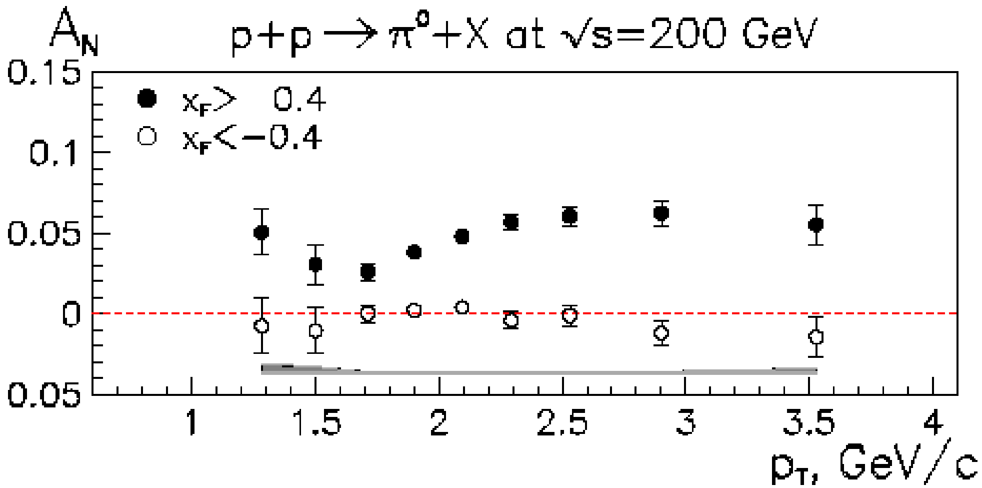


Fermilab E704: $A_N(p^\uparrow p \to \pi X)$

$\sqrt{s} = 20$ GeV, $0.7 < p_T < 2.0$ GeV

$$\boxed{x_F = 2p_L/\sqrt{s}}$$



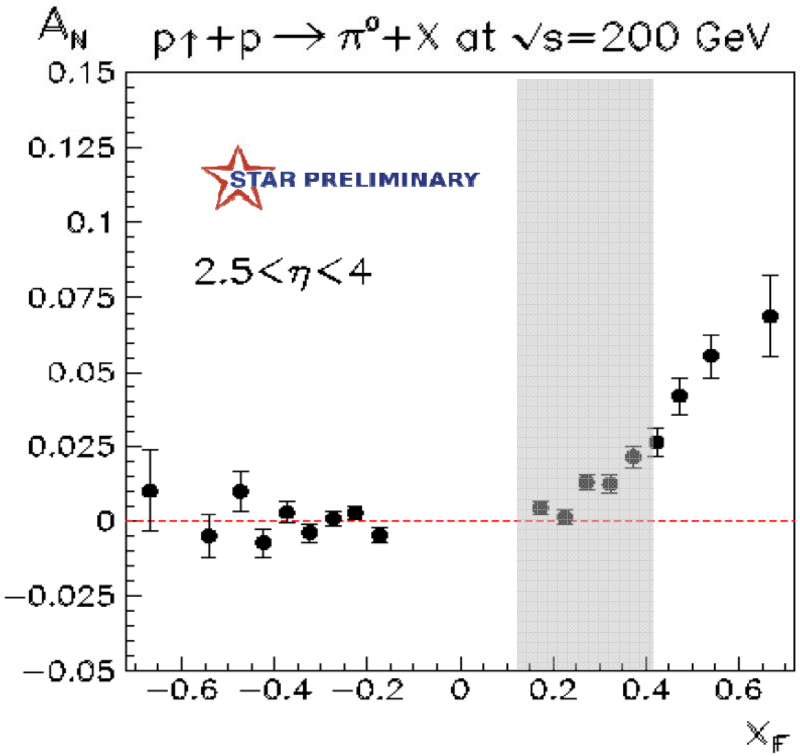


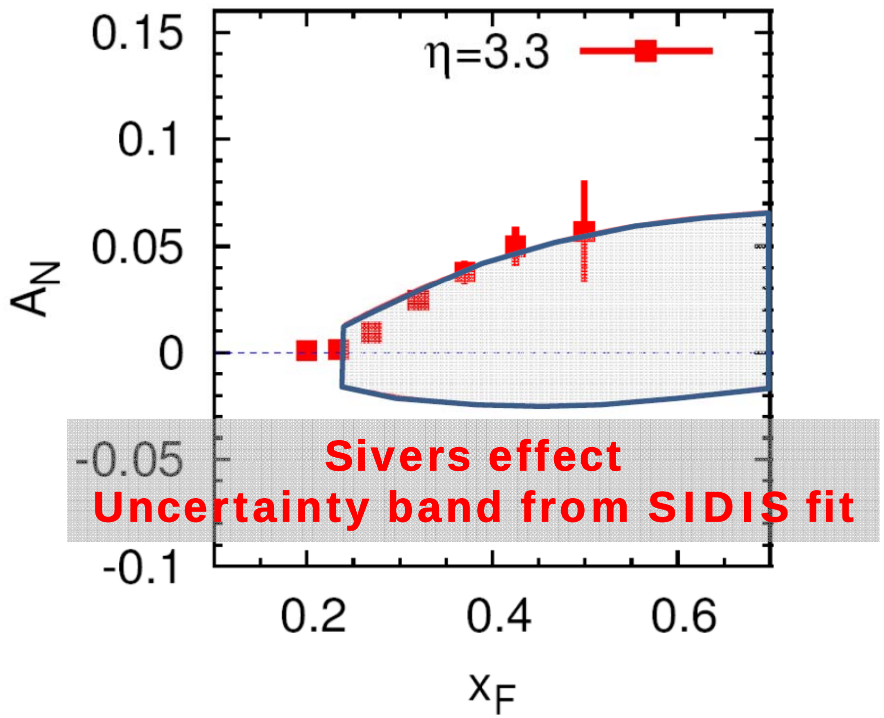
Pion SSAs in polarized pp collisions

Potentially can be described by both Siver and Collins effects separately
No direct way to discriminate between Sivers and Collins effect

SSAs are huge in the forward Feynman x region

SIDIS data used to parametrize the transversity and Sivers functions cover only the region $x_B < 0.3$
They almost do not constrain the parameterizations in the region of interest for pp collisions





Summary of interesting accessible processes and effects involved

Process	Twist	Siv	Coll	B-M	Pol FF	Th. status	Discr. power
SIDIS	2	●	●	●	●	* * * *	* * * *
Drell-Yan	2	●		●		* * * *	* * * *
$e^+e^- \to h_1 h_2 X$	2		●		●	* * * *	* * * *
$AB \to h\ X$	3	●	●	●	●	* *	* *
$AB \to \gamma\ X$	3	●				* * *	* * * *
$AB \to h_1 h_2 X$	2	●	●	●	●	* * *	* * *
$AB \to j\ X$	3	●		●		* *	* * * *
$AB \to j(h)X$	3	●	●	●	●	* * *	* * * *

Open points, outlook

- Factorization for particle inclusive production in the TMD approach
- Evolution with scale of TMD distribution and fragmentation functions
  [Henneman, Boer, Mulders; Ceccopieri, Trentadue; Cherednikov, Stefanis]
- Soft factors from soft-gluon radiation (spin independent?)
  [Ji, Ma, Yuan; Collins, Metz; formal aspects of factorization]
- Potential suppression of azimuthal asymmetries due to Sudakov factors
  [D. Boer]
- Parton off-shellness , fully unintegrated parton correlation functions
  [Watt, Martin, Riskin; Linnyk, Leupold, Mosel; Collins, Rogers, Stasto]
- Experimental tests of universality (breaking?) for TMD PDFs and FFs
- Improved parameterizations and phenomenological constraints

Useful references on spin physics

[reversed chronological order]

- U. D’Alesio, FM, Prog. Part. Nucl. Phys. 61, 394 (2008)
- V. Vogelsang, J. Phys. G 34, S149 (2007)
- S.D. Bass, Rev. Mod. Phys. 77 1257 (2005)
- V. Barone, P. Ratcliffe, Transverse Spin Physics, World Scientific (2003)
- V. Barone, A. Drago. P. Ratcliffe, Phys. Rep. 359, 1 (2002)
- E. Leader, Spin in Particle Physics, Cambridge UP (2001)
- B.W. Filippone, X.-D. Ji, Adv. Nucl. Phys. 26, 1 (2001)
- G. Bunce, N. Saito, J. Soffer, W. Vogelsang, Ann. Rev. Nucl. Part. Sci. 50, 525 (2000)
- B. Lampe, E. Reya, Phys. Rep. 332, 1 (2000)
- Z.-t. Liang, C. Boros, Int. J. Mod. Phys. A 15, 927 (2000)
- J. Felix, Mod. Phys. Lett. A 14, 827 (1999)
- S.B. Nurushev, Int. J. Mod. Phys. A 12, 3433 (1997)
- U. Stiegler, Phys. Rep. 277, 1 (1996)
- M. Anselmino, A. Efremov, E. Leader, Phys. Rep. 261, 1 (1995)
- S.M. Troshin, N.E. Tyurin, Spin Phenomena in Particle Interactions, WSP (1994)
- L.G. Pondrom, Phys. Rep. 122, 57 (1985)
- C. Bourrely, J. Soffer, E. Leader, Phys. Rep. 59, 95 (1980)