Hadronization and related topics in SIDIS

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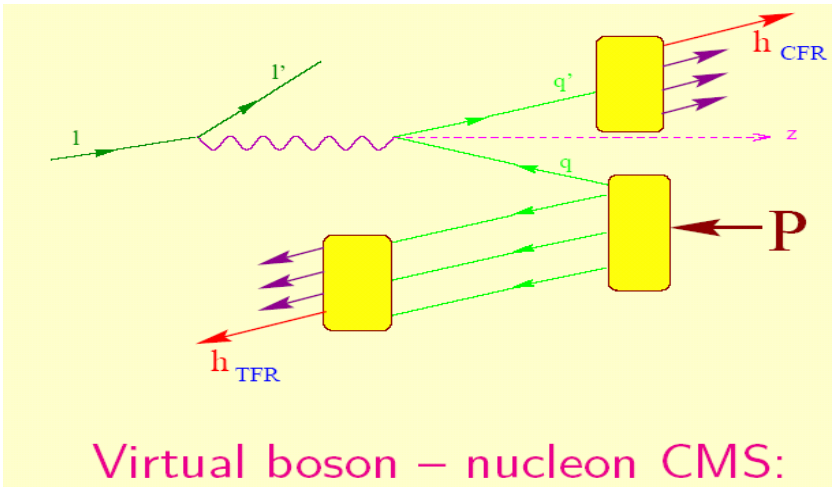
On leave in absence from YerPhI, Armenia and JINR, Russia

- SIDIS
  - Distribution Functions
  - Quark Fragmentation Functions
  - Fracture Functions
- Single target spin asymmetries
  - Sivers effect
- Spin physics with unpolarized target
  - Λ transverse and longitudinal polarization
  - ρ polarization study (H. Fischer)

SIDIS



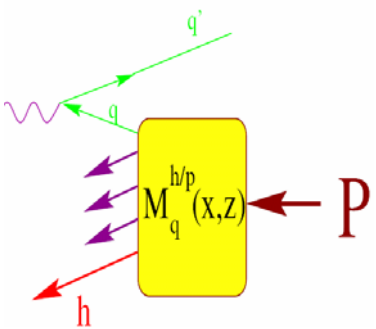
Virtual boson – nucleon CMS:

$$\frac{d\sigma_p^h}{dx\,dy\,dz_h} = \frac{1+(1-y)^2}{2y^2} \sum_{i=q,\bar{q}} c_i f_{i/p}(x) D_{h/i}(z_h)$$

$$c_i = 4\pi e_{q_i}^2 \alpha^2 / x(P+l)^2$$

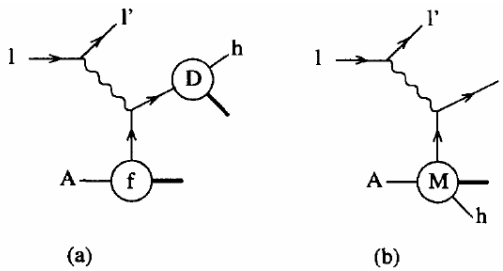
$x_F > 0$ – current fragmentation (CFR)

$x_F < 0$ – target fragmentation (TFR)



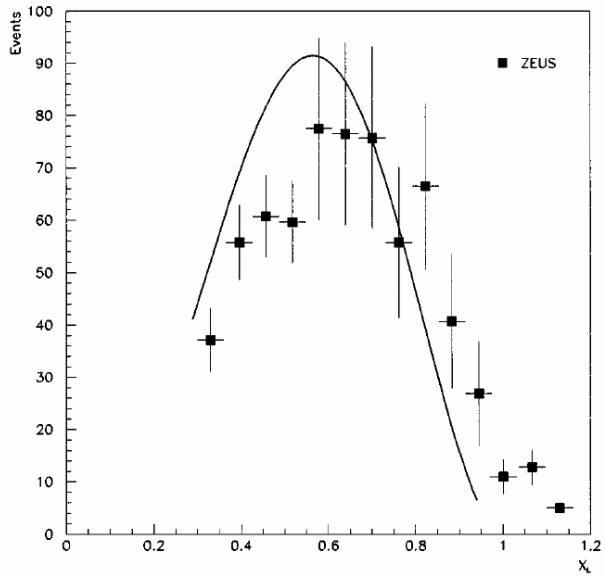
- Trentadue & Veneziano: fracture function $M_q^{h/p}(x,z)$ – probability of finding a parton q with momentum fraction x and a hadron h with the CMS energy fraction $z = E_h/E_P$ in the proton.

Fracture Functions



The parton-model process for the current contribution (a) and target contribution (b).

Leading neutron production: pion exchange



$$x_L \equiv \widetilde{E_n}/\widetilde{E_p}$$

Proton in TFR

Pomeron + reggeon:

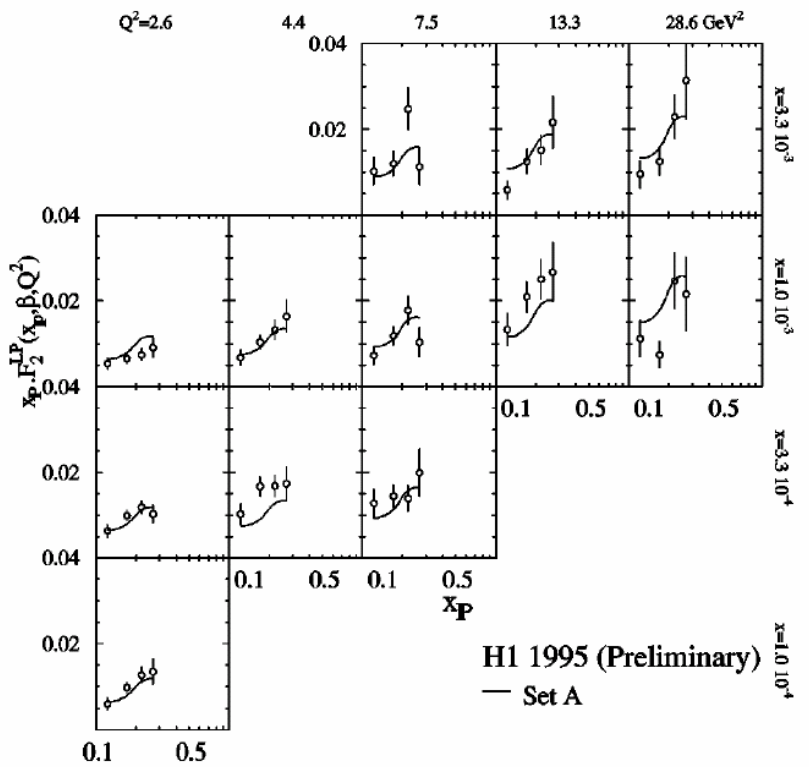
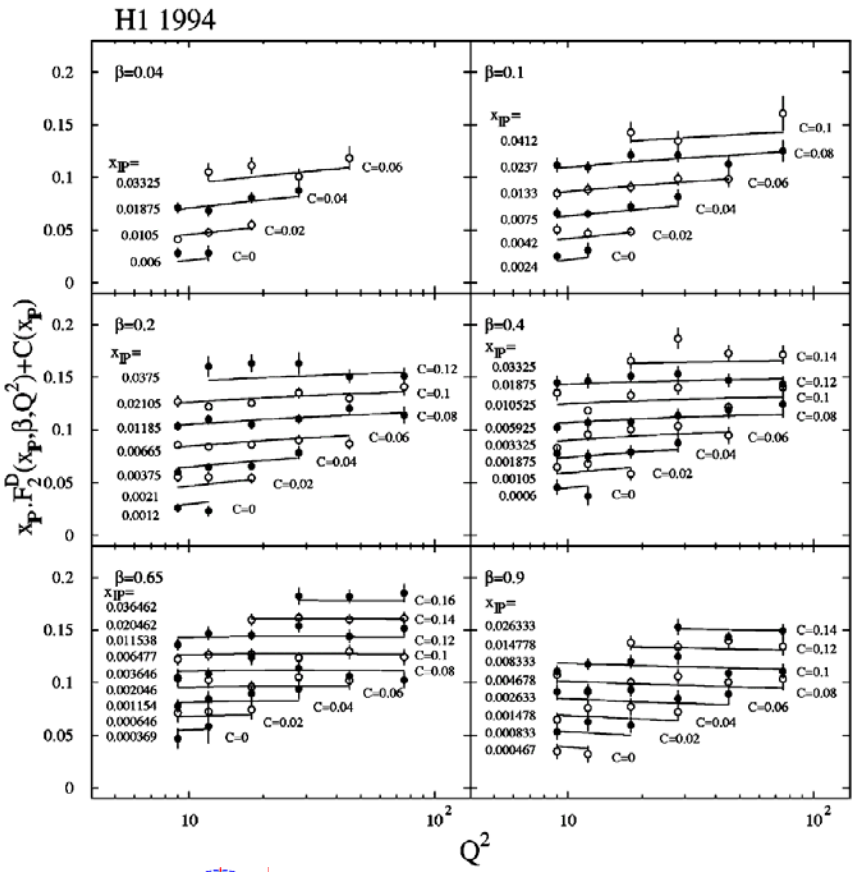
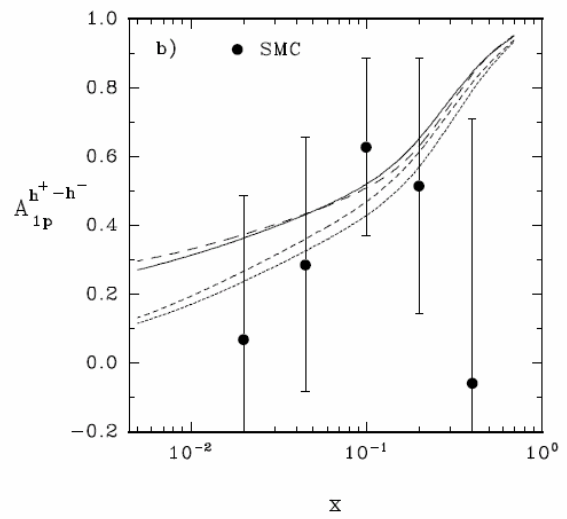


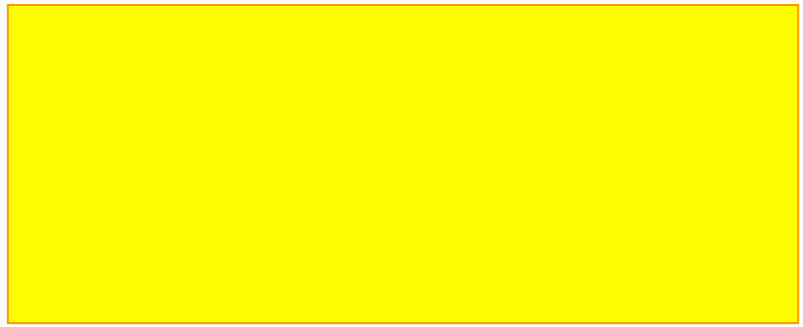
FIG. 2. H1 leading-proton data against the outcome of the fracture function parametrization (solid lines).



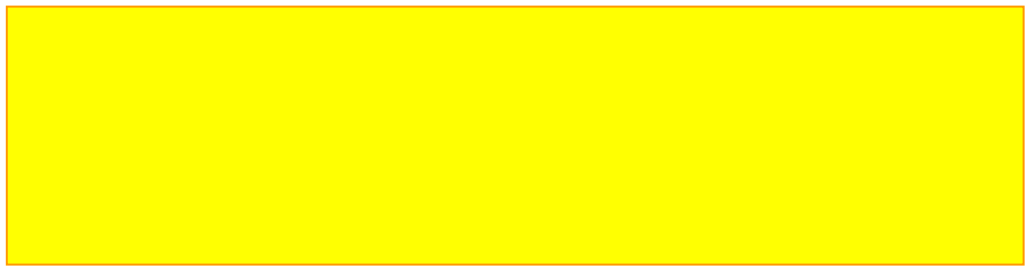
Pions in TFR

Passive quark fragmentation:





“Meson cloud” like model:



TMD distribution Functions

$$\mathcal{M}(x,k_\perp,\mu,x\zeta,\rho) = p^+ \int \frac{d\xi^-}{2\pi} e^{-ix\xi^- P^+} \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{k}_\perp} \times \frac{\left\langle PS \left| \overline{\psi}_q(\xi^-,0,\vec{b}_\perp)\mathcal{L}_v^\dagger(\infty;\xi^-,0,\vec{b}_\perp)\mathcal{L}_v(\infty;0)\psi_q(0) \right| PS \right\rangle}{S(\vec{b}_\perp,\mu^2,\rho)}$$

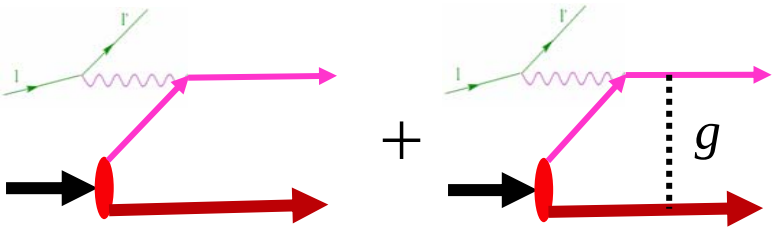
$$\mathcal{L}_v(\infty;\xi) = \exp\left(-ig\int_0^\infty d\lambda v\cdot A(\lambda v+\xi)\right)$$

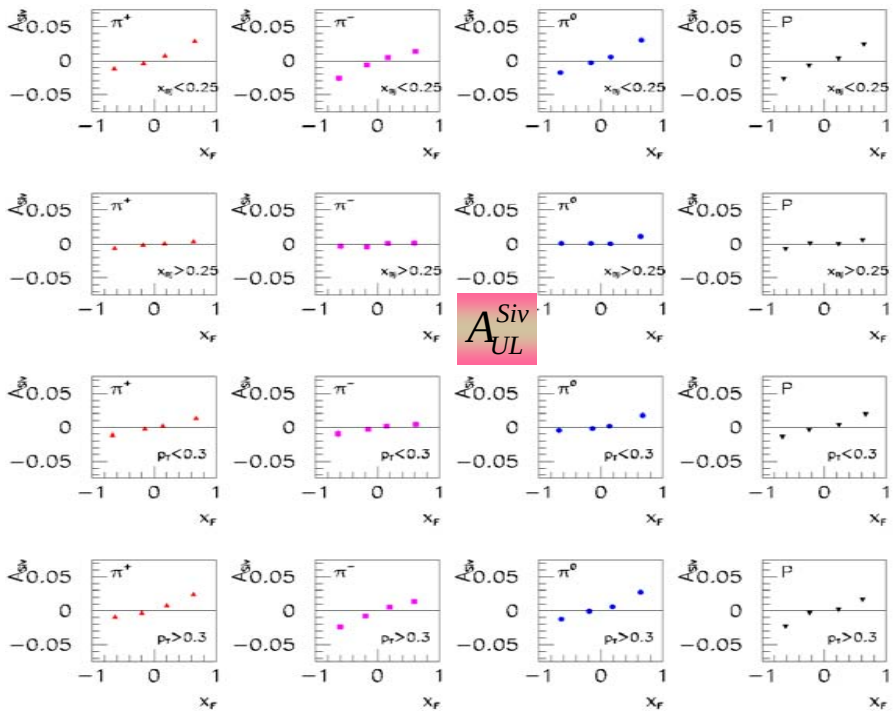
SIDIS DY

$$\mathcal{M} = \frac{1}{2}\left[q(x,k_\perp)\ \not{p} + \frac{1}{M}\delta q(x,k_\perp)\sigma^{\mu\nu}k_\mu p_\nu + \Delta q_L(x,k_\perp)\lambda\gamma_5\ \not{p} \right. \quad (4)$$
$$+\frac{1}{M}\Delta q_T(x,k_\perp)\gamma_5\ \not{p}(\vec{k_\perp}\cdot\vec{S}_\perp) + \frac{1}{M}\delta q_L(x,k_\perp)\lambda i\sigma_{\mu\nu}\gamma_5 p^\mu k_\perp^\nu + \delta q_T(x,k_\perp) i\sigma_{\mu\nu}\gamma_5 p^\mu S_\perp^\nu$$
$$\left. +\frac{1}{M^2}\delta q_{T'}(x,k_\perp) i\sigma_{\mu\nu}\gamma_5 p^\mu \left(\vec{k}_\perp\cdot\vec{S}_\perp k_\perp^\nu - \frac{1}{2}\vec{k}_\perp^2 S_\perp^\nu\right) + \frac{1}{M} q_T(x,k_\perp)\epsilon^{\mu\nu\alpha\beta}\gamma_\mu p_\nu k_\alpha S_\beta \right] ,$$

Sivers effect

$$f_{\uparrow}(x,\mathbf{k}_T) = f_1(x,k_T)\cdot\left(1+S_T A^q_{Siv}(x,k_T)\sin(\phi_{Siv})\right)$$





Nonzero Sivers modulation

FSI = gauge link!

Due to transverse momentum conservation the target remnant transverse momentum is also modulated with opposite sign.

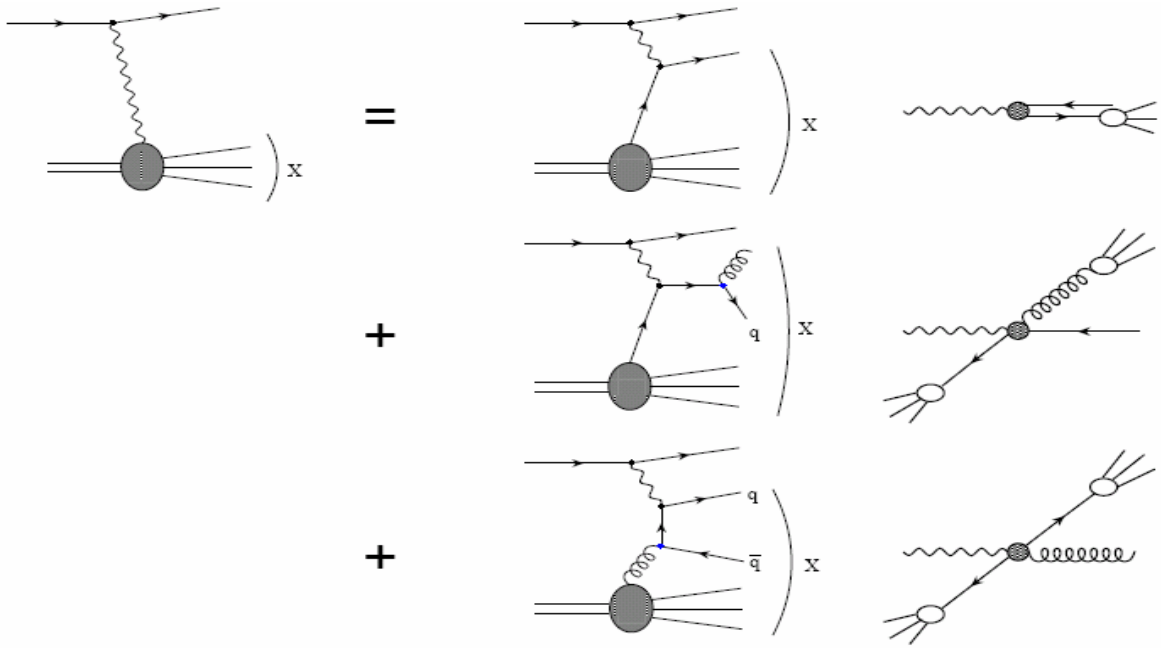
Is FSI gluon totally absorbed in DF?

Zoology of FracFun:

$$^{P;L,T}M^{h;\stackrel{\perp}{\longrightarrow},\ldots}_{q;\perp\Rightarrow\ldots}(x,\mathbf{k}_T;z,\mathbf{p}_T)$$

Intrinsic transverse momentum role

- Gluon polarization measurement

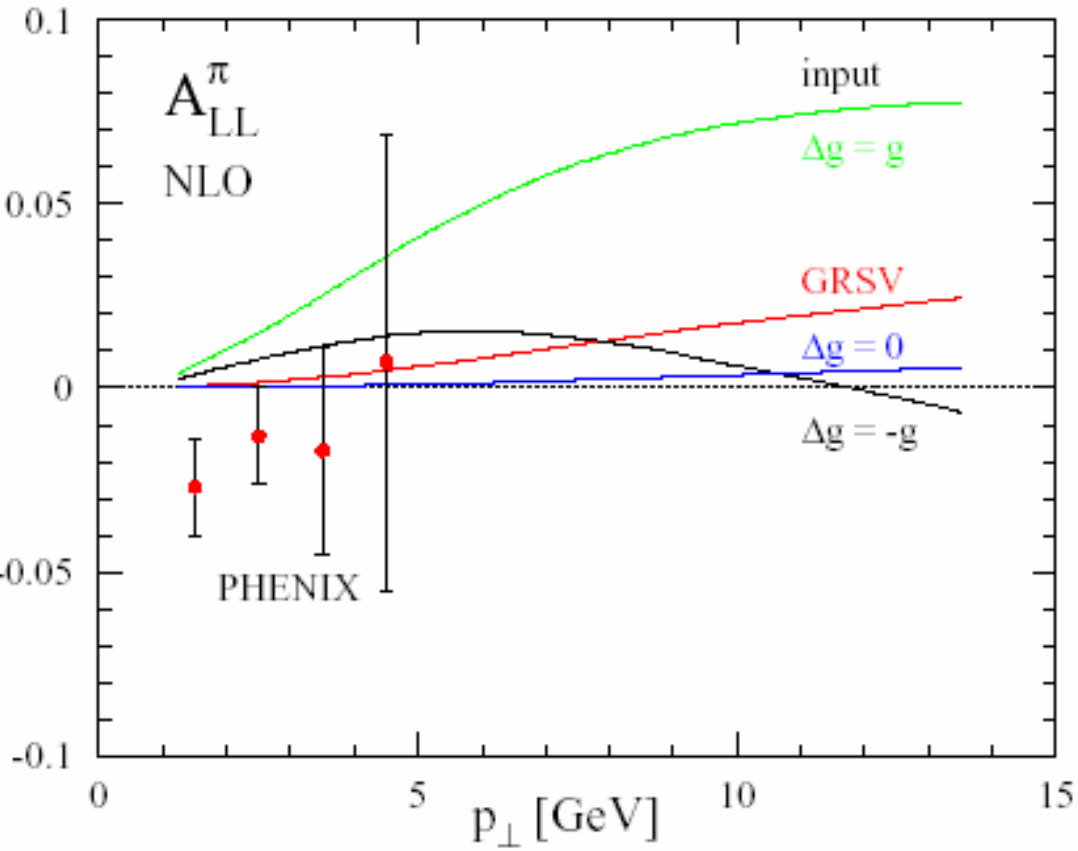


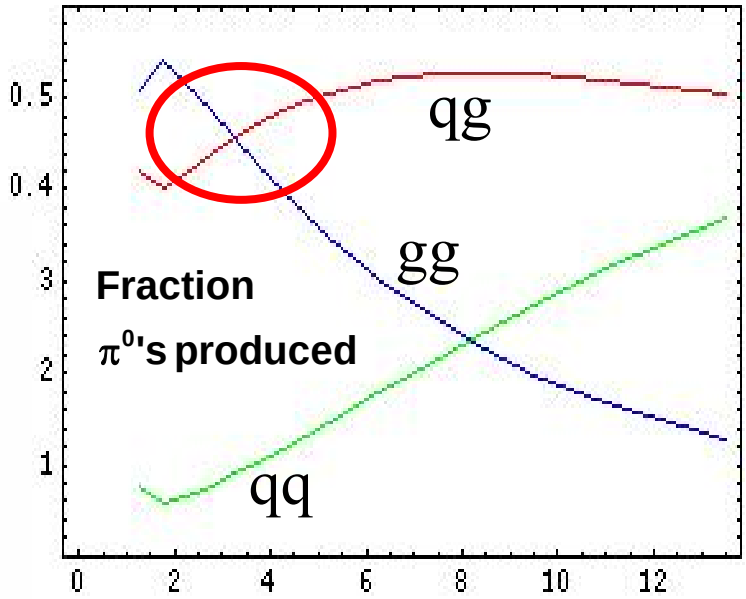
$$A^{lN\to lhhX} = \frac{\Delta G}{G}\langle \hat{a}_{LL}\rangle^{PGF} R^{PGF} + \frac{\Delta q}{q}\left[\langle \hat{a}_{LL}\rangle^{LP} R^{LP} + \langle \hat{a}_{LL}\rangle^{QCDC} R^{QCDC}\right]$$

R strongly depend on the intrinsic $\langle k_T \rangle$ and fragmentation $\langle p_T \rangle$

ΔG from PP⇨π^0+X (C. Aidala)

PHENIX $A_{LL}(\pi^0)$ at $|\eta|<0.35$, hep-ex/0404027
plot from Vogelsang hep-ph/0405069



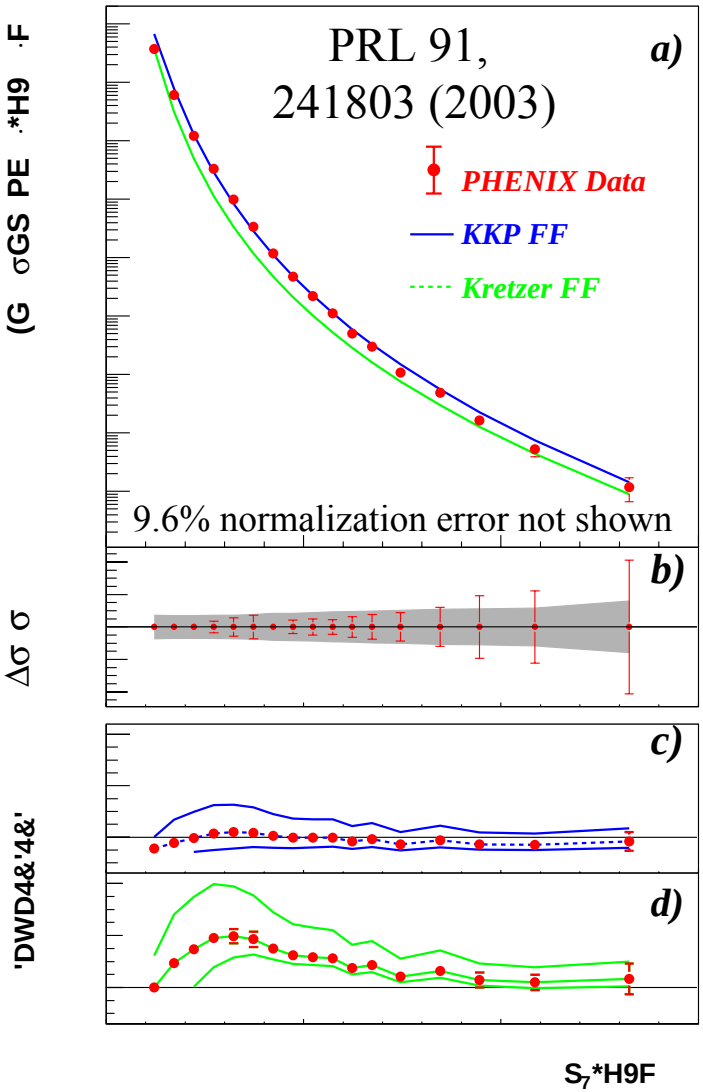


First results on longitudinal double spin asymmetries from RHIC

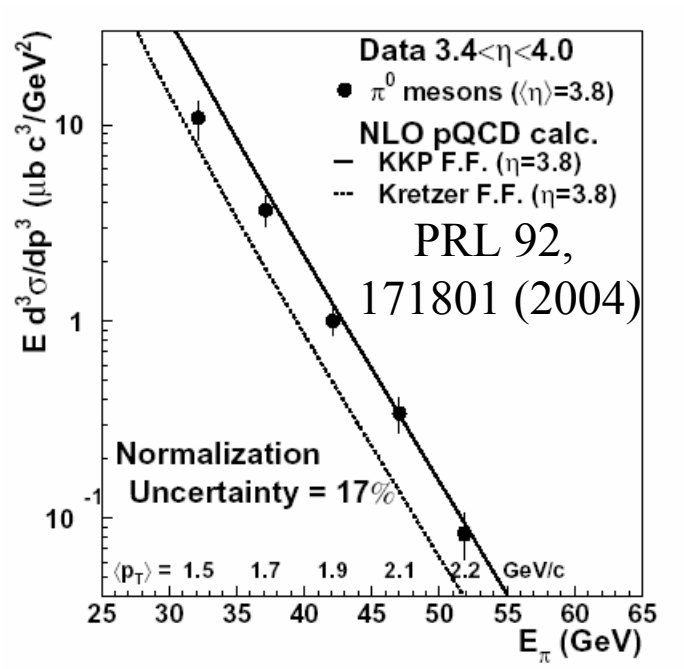
→consistent with DIS sample
→result disfavors large ΔG
→eg $\int Ldt = 3pb^{-1}$ and P-0.4 (2005) errors will reduce by factor 8

π^0 Cross Section from 2001-2 Run (C. Aidala)

PHENIX, $|\eta| < 0.35$



STAR, $3.4 < \eta < 4.0$

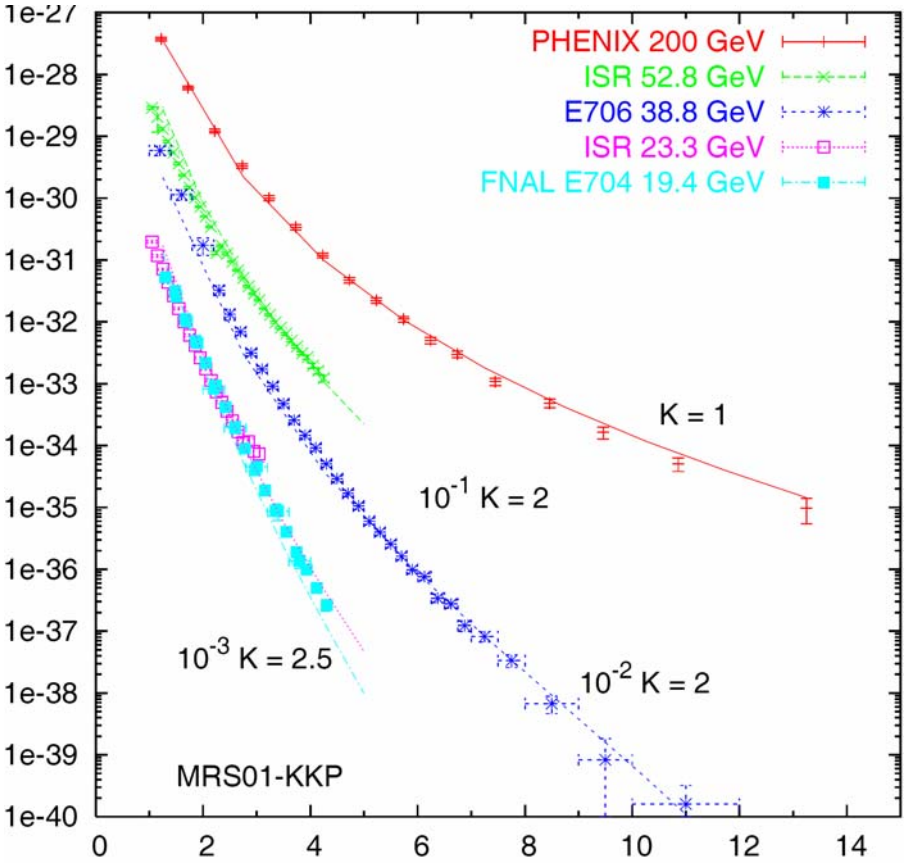


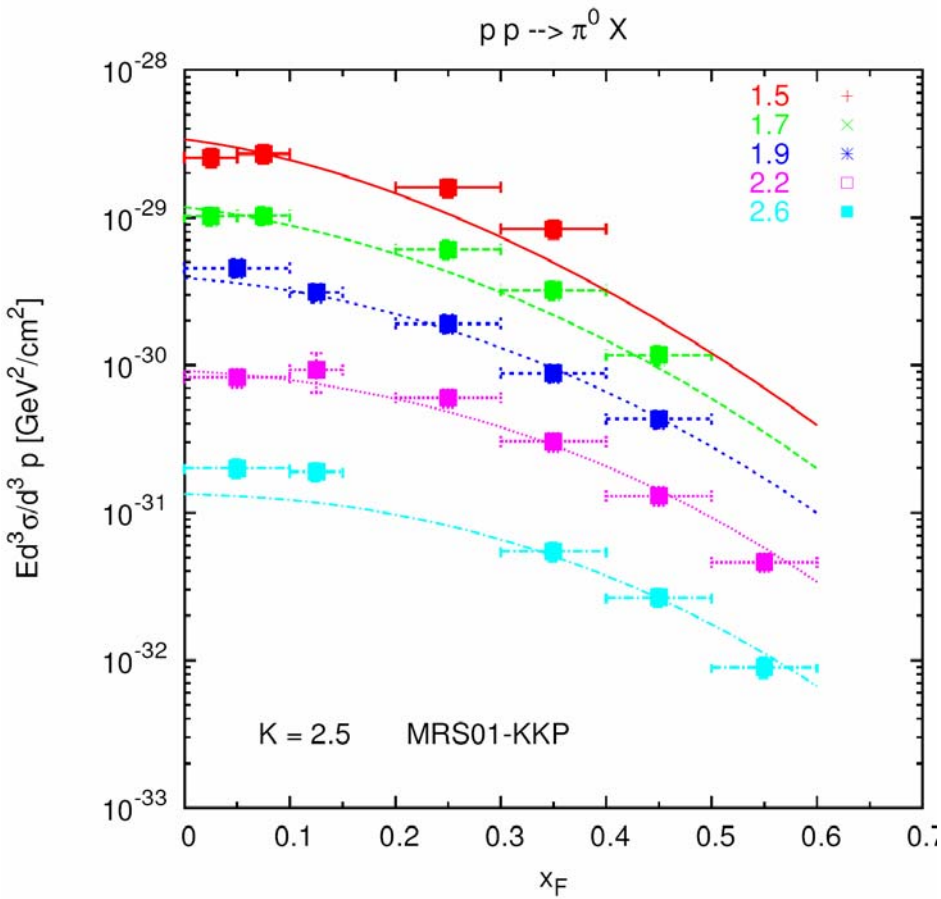
- Good agreement between NLO pQCD calculations and experiment
  - Can use NLO pQCD analysis to extract spin-dependent pdf's

$$\langle k_T \rangle = 0 \qquad \langle p_T \rangle = 0$$

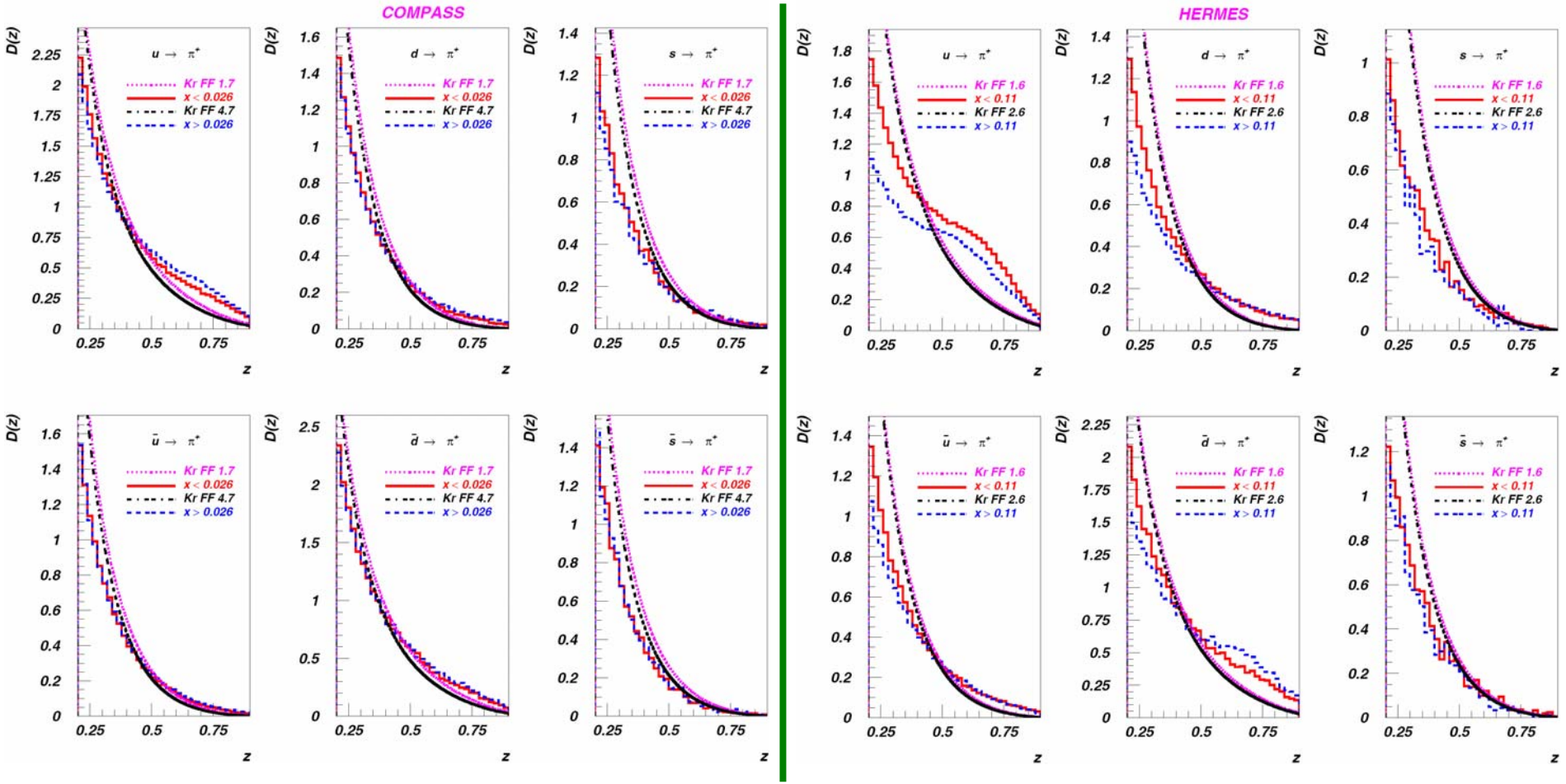
π^0 Cross Section (U. d'Alesio)

$\langle k_T \rangle \neq 0$ $\langle p_T \rangle \neq 0$

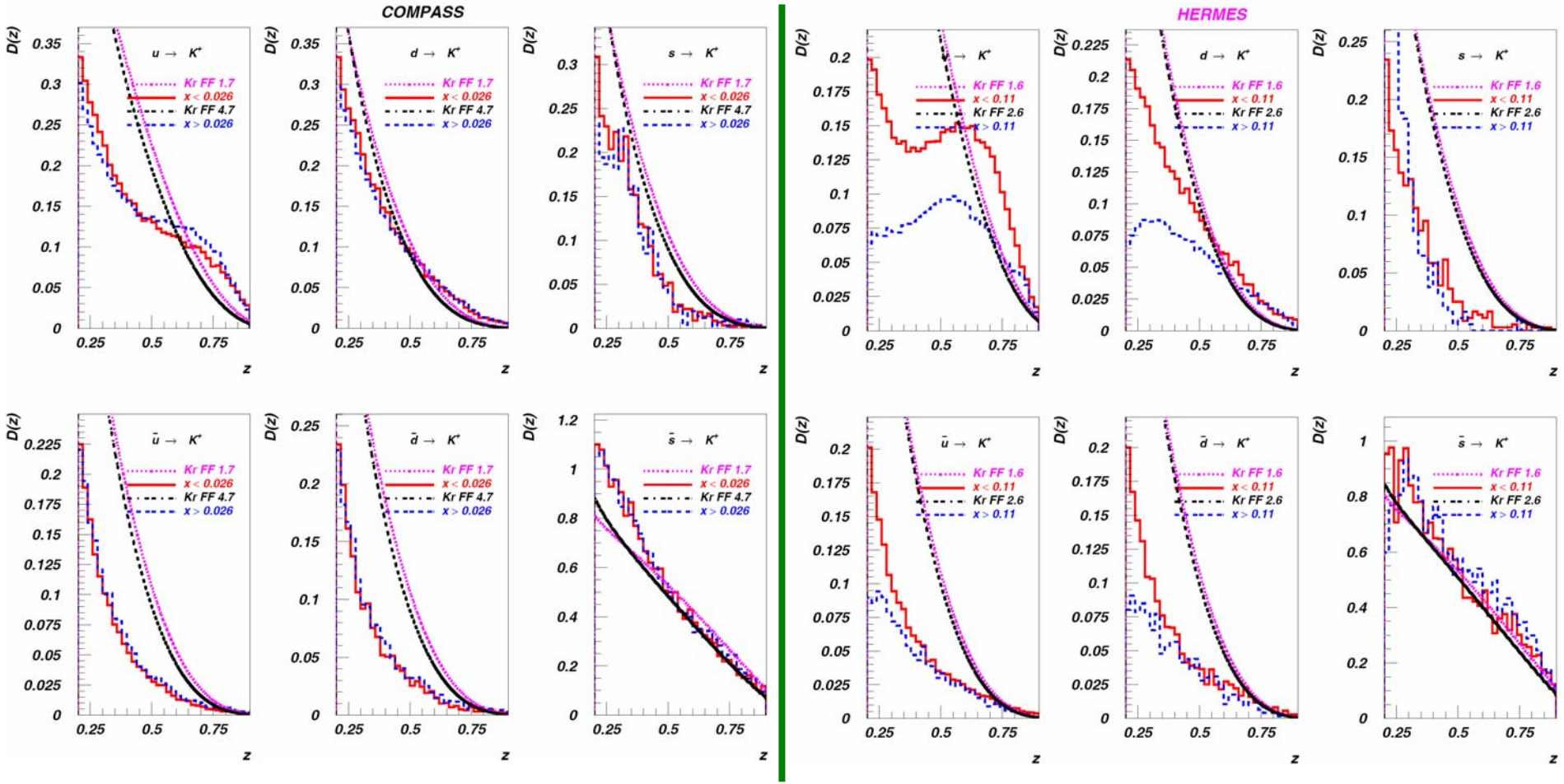




LO Fragmentation Functions in LEPTO



LO Fragmentation Functions in LEPTO



LUND string fragmentation

The primary hadrons produced in string fragmentation come from the string as a whole, rather than from an individual parton.

PYTHIA 6.2

Physics and Manual

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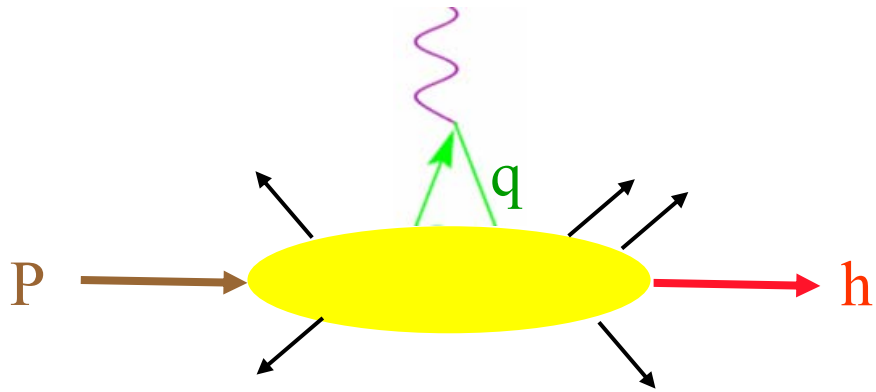
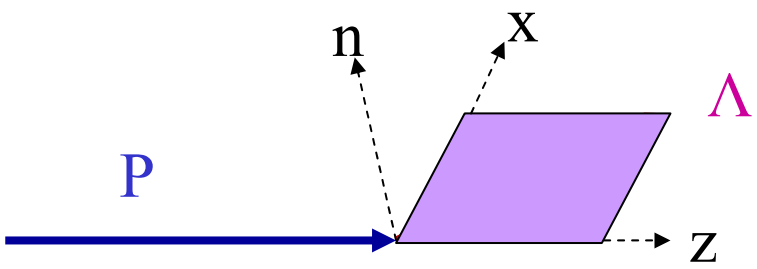
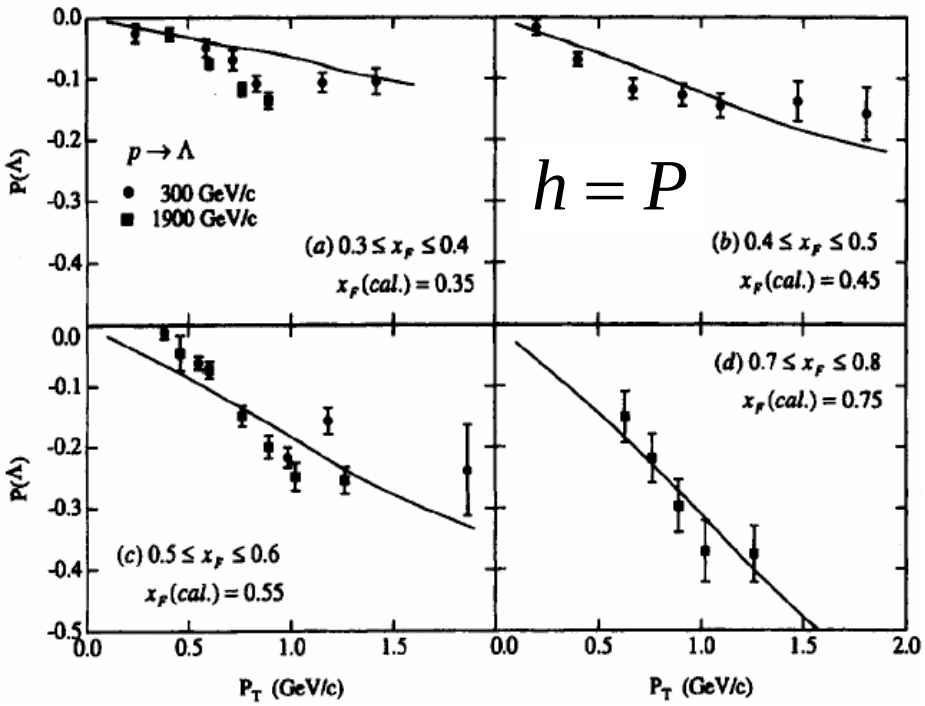


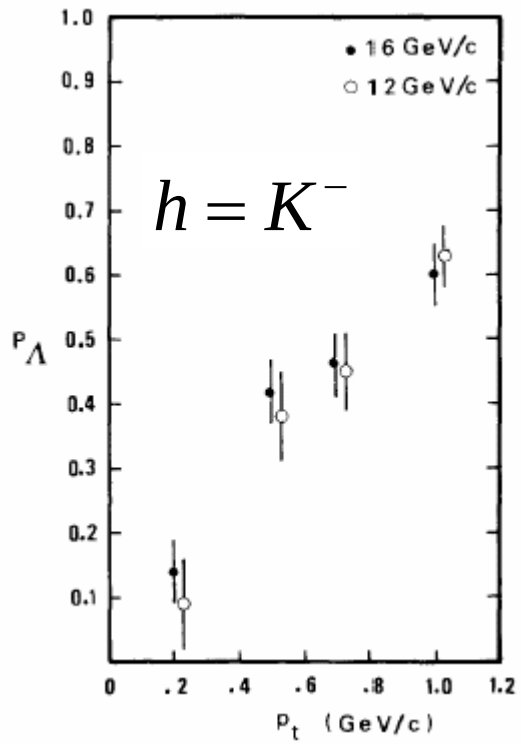
Transverse Polarization of Λ in h+p/A reactions



Normal to production plane

$$\mathbf{n} = \frac{\mathbf{P}_{Beam} \times \mathbf{P}_{\Lambda}}{\left|\mathbf{P}_{Beam} \times \mathbf{P}_{\Lambda}\right|}$$



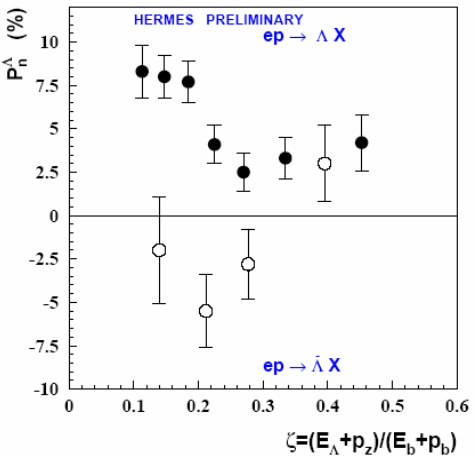


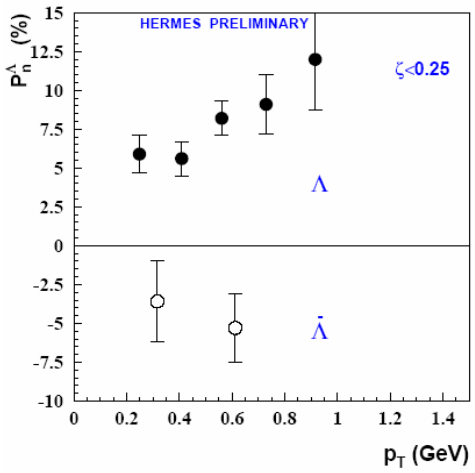
Empiric relation: $S_T^{\Lambda} \propto a_{T\,\mathrm{arg}\,et} x_F P_T^{\Lambda}$

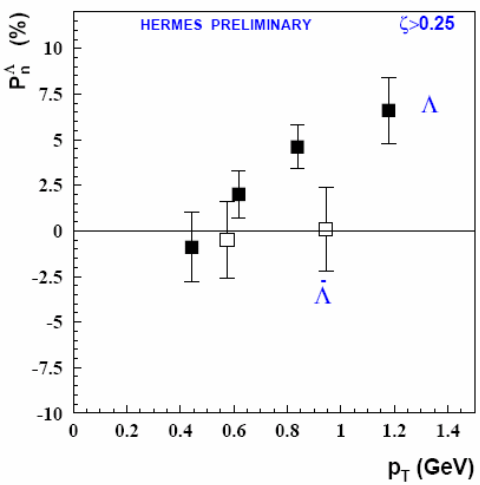
$x_F \ge 0.6$

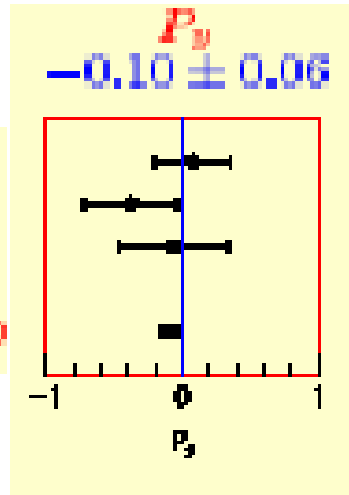
Some Open Questions

- No transverse polarization observed at LEP
- Positive transverse polarization at HERMES ($Q^2 \approx 0\,\mathrm{GeV}^2/c^2$)
  - Qualitatively can be explained in DM model with VMD approach
  - Parton model: u-quark dominance? Compare with neutrino data.





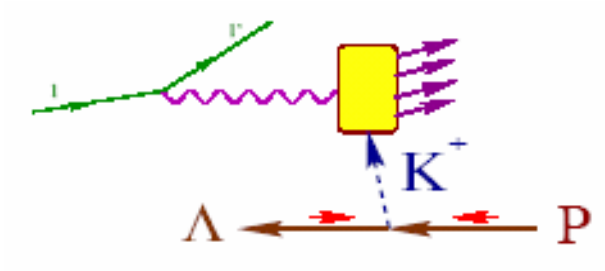




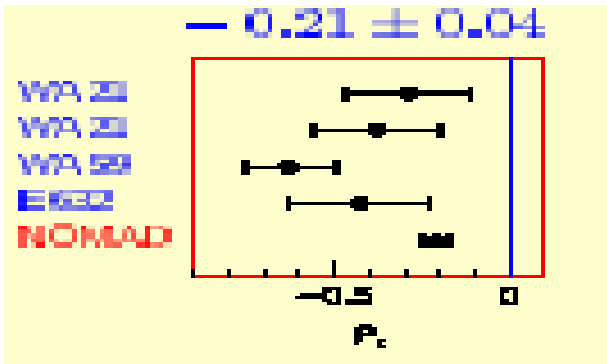
$x_F > 0$

Longitudinal polarization of Λ

- Melnitchouk & Thomas: Meson Cloud Model $x_F < 0$



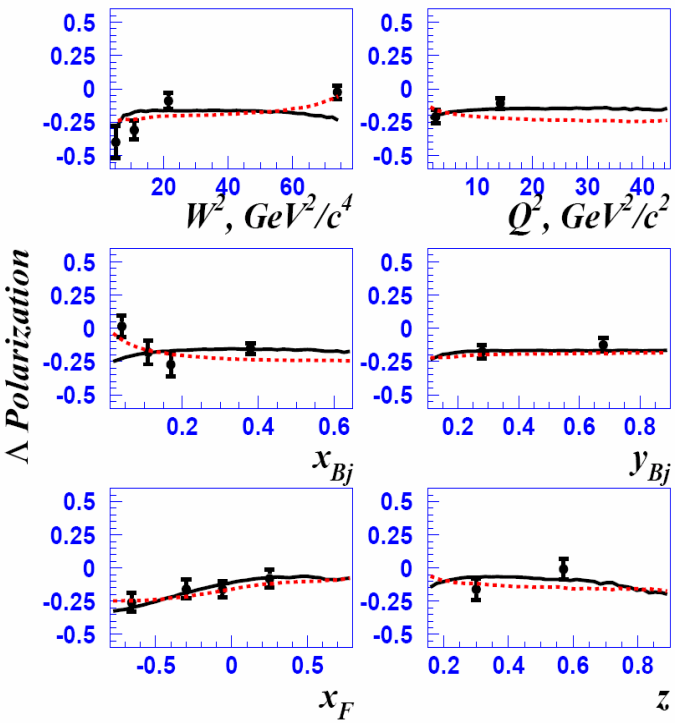
- 100 % anticorrelated with target polarization
  - contradiction with neutrino data for unpolarized target
    - Longitudinal polarization of Λ in the TFR in neutrino SIDIS



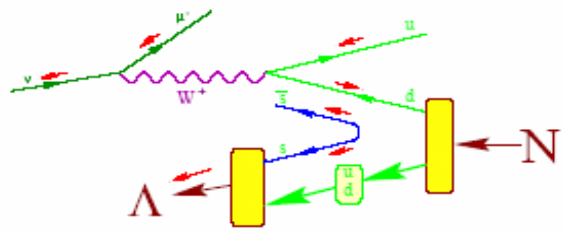
Intrinsic Strangeness Model

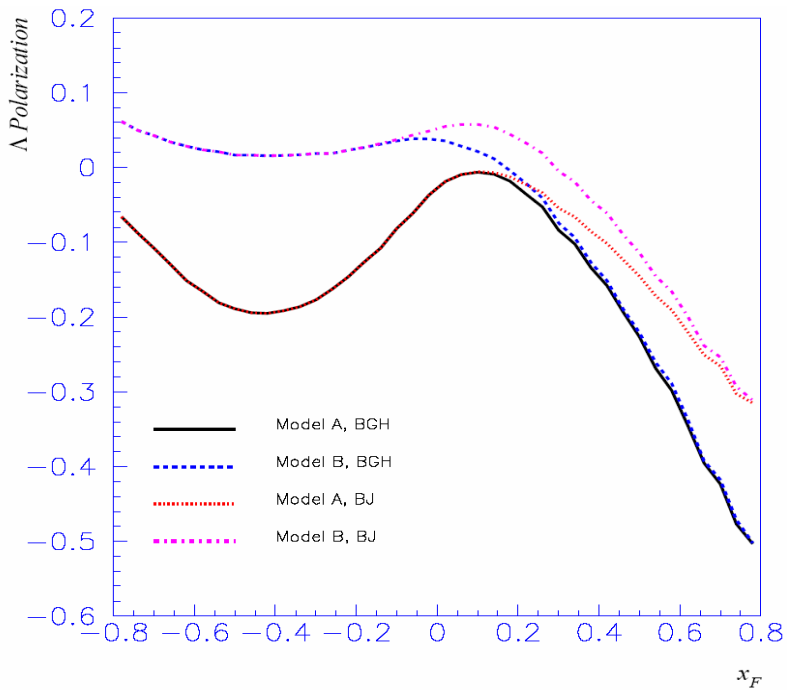
- Alberg, Ellis, Karliner, Kharzeev, A.K. & Sapozhnikov

$$|p\rangle = a\sum_{X=0}^{\infty}|uudX\rangle + b\sum_{X=0}^{\infty}|uud\bar{s}sX\rangle + \ldots$$



NOMAD





EIC(5+50 = 500GeV)

Some conclusions

- SIDIS on unpolarized target will allow
  - To investigate the transverse momentum distribution for different hadrons in the TFR and CFR
  - Cahn effect in the TFR
    - Flavor, x, z – dependence of intrinsic transverse momentum
- It is important to investigate the SSA in the TFR
  - Sivers effect or Collins effect in the polarized target remnant hadronization?
- With polarized muon beam we can investigate spin phenomena in hadronization.
  - We need more developments in the theory of hadronization