Process dependent transverse spin asymmetry
- understand inclusive hadron production

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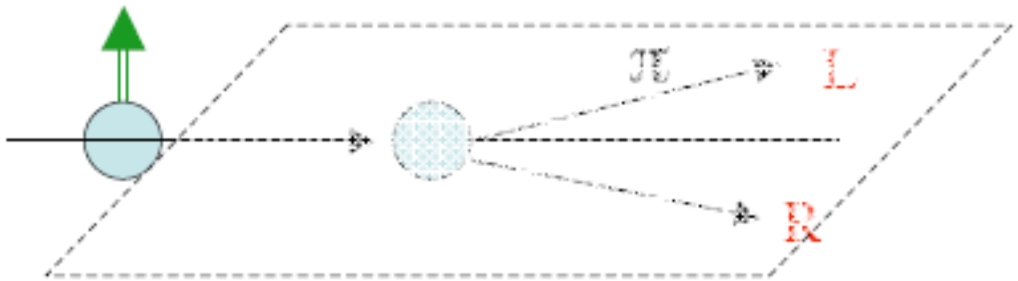
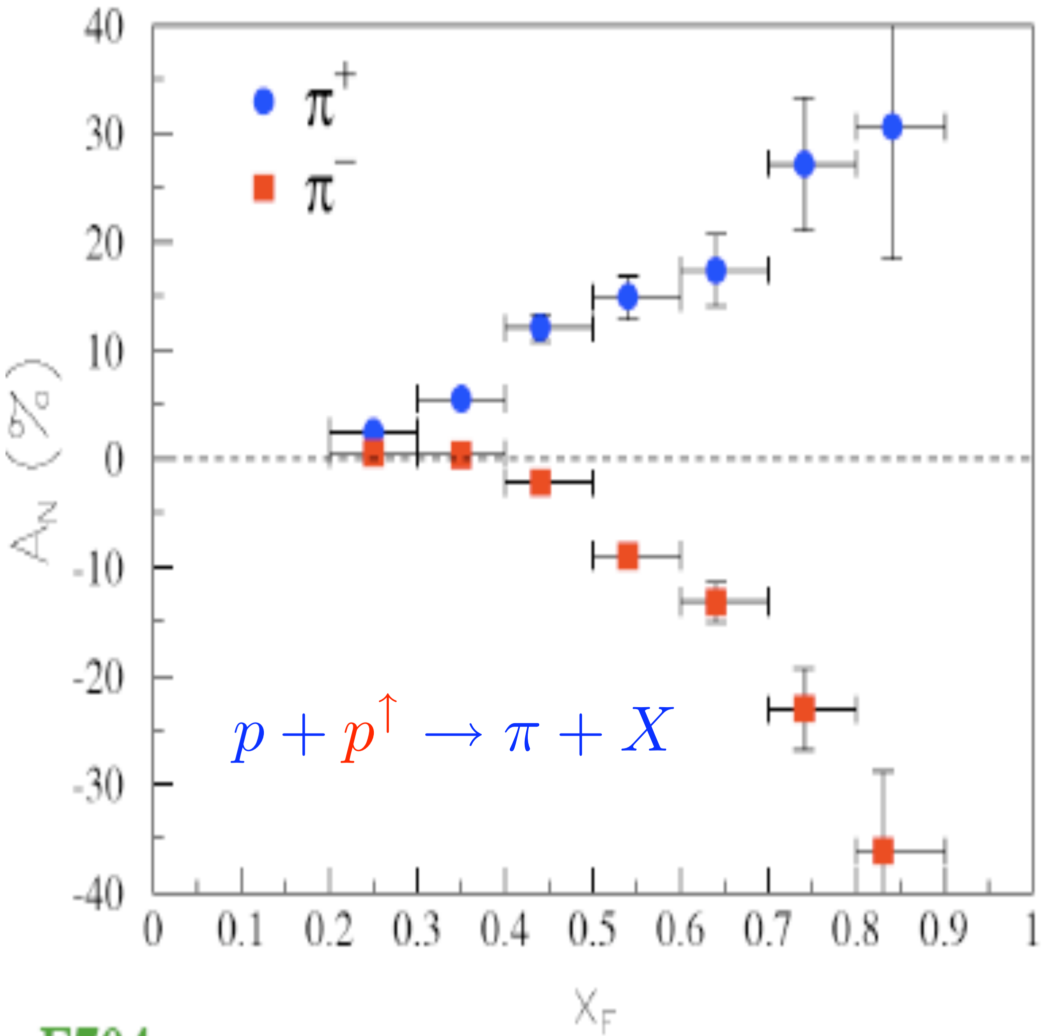
Gamberg, Kang, arXiv:1009.1936
ask for latest version if interested

Experiment: Single transverse spin asymmetries (SSAs)

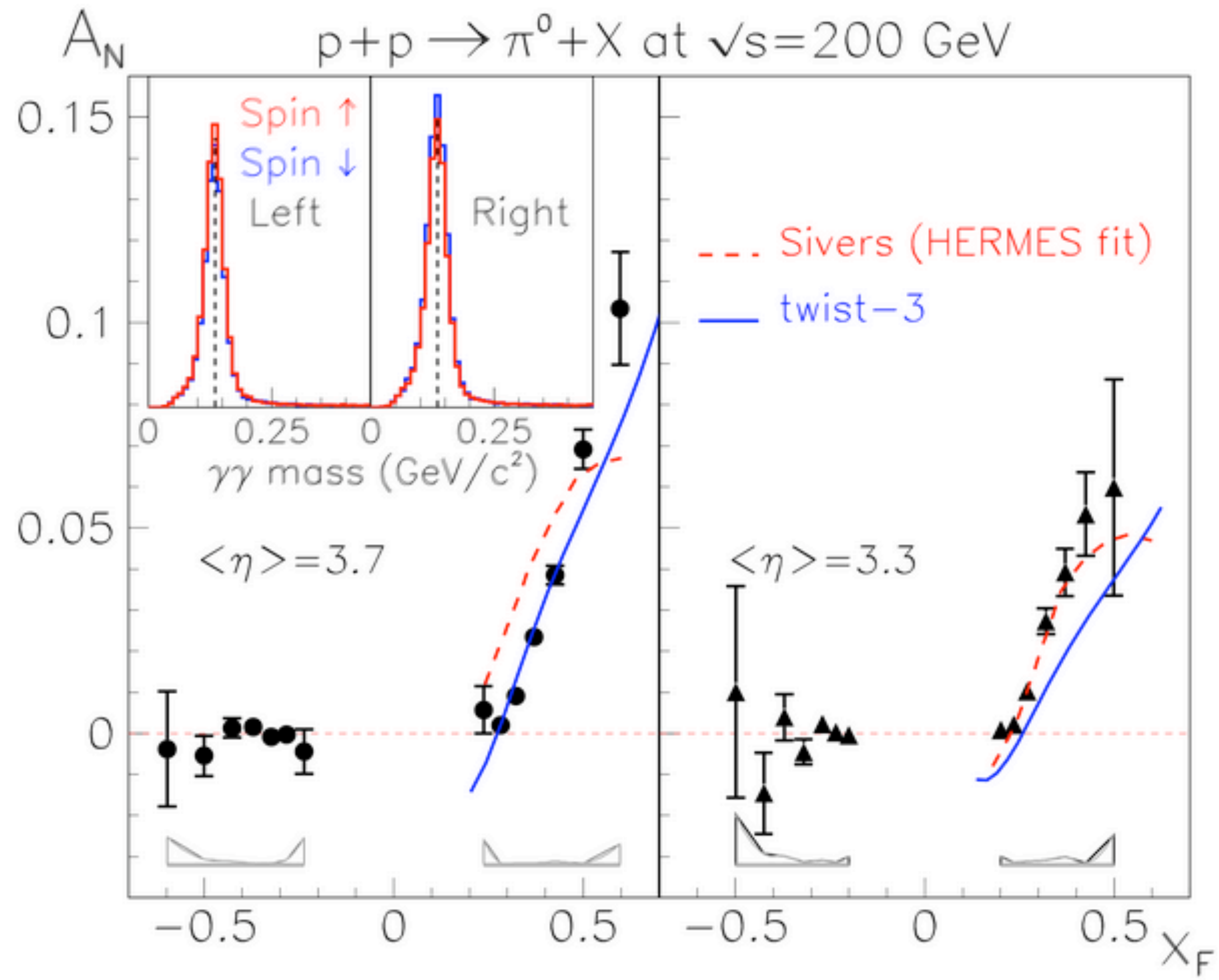
- Fermilab E704, STAR, PHENIX, BRAHMS, COMPASS, HERMES, JLAB:



$$A_N \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$



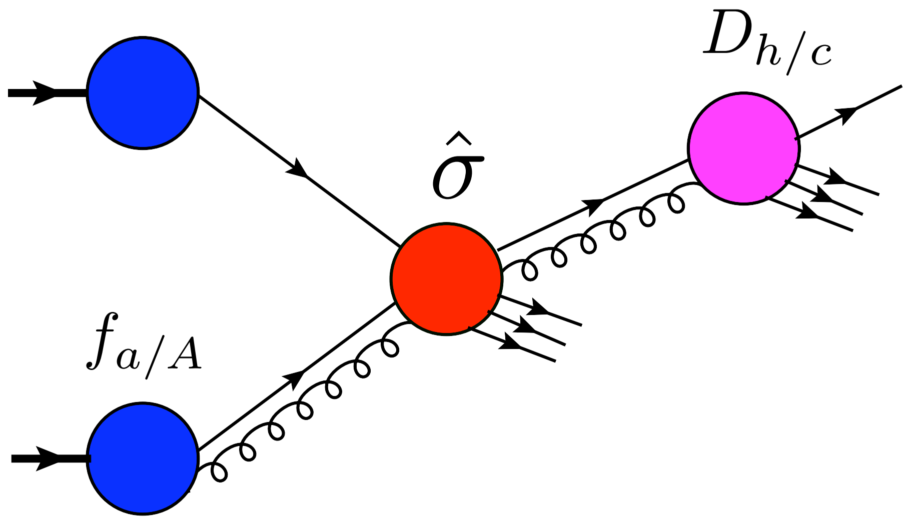
E704



STAR

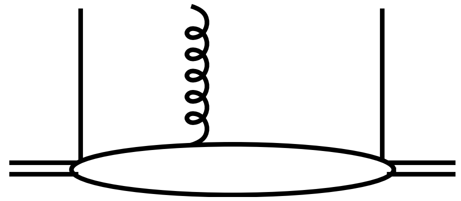
Two approaches for inclusive hadron production - I

- Collinear twist-3 factorization approach:

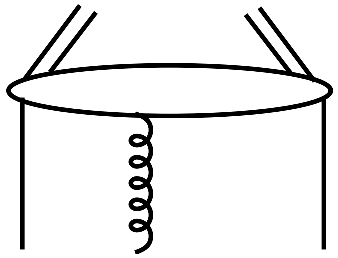


$$\sigma(p_h, s_\perp) \propto f_{a/A}^{s_\perp}(x) \otimes D_{h/c}(z) \otimes \hat{\sigma}_{\text{parton}}$$

  - Twist-3 three-parton corrlation functions (PDFs)
  - Twist-3 three-parton fragmentation functions



Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98, …



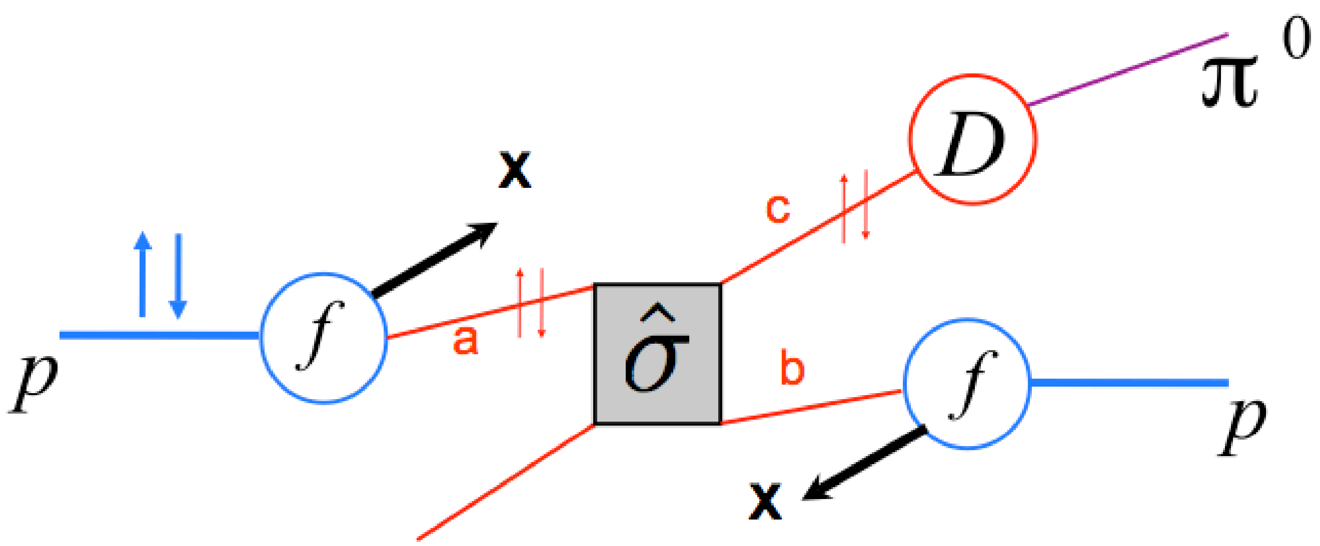
Koike, 02, Kang, Yuan, Zhou 2010

- Factorization is expected to hold

Two approaches for inclusive hadron production - II

- Generalized Parton Model (GPM) approach:

(assuming factorization)



$$d\sigma^{\uparrow} = \sum_{a,b,c=q,\bar{q},g} \underbrace{f_{a/p^{\uparrow}}(x_a, \boldsymbol{k}_{\perp a})} \otimes \underbrace{f_{b/p}(x_b, \boldsymbol{k}_{\perp b})} \otimes d\hat{\sigma}^{ab\to cd}(\boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \underbrace{D_{\pi/c}(z, \boldsymbol{p}_{\perp\pi})}$$

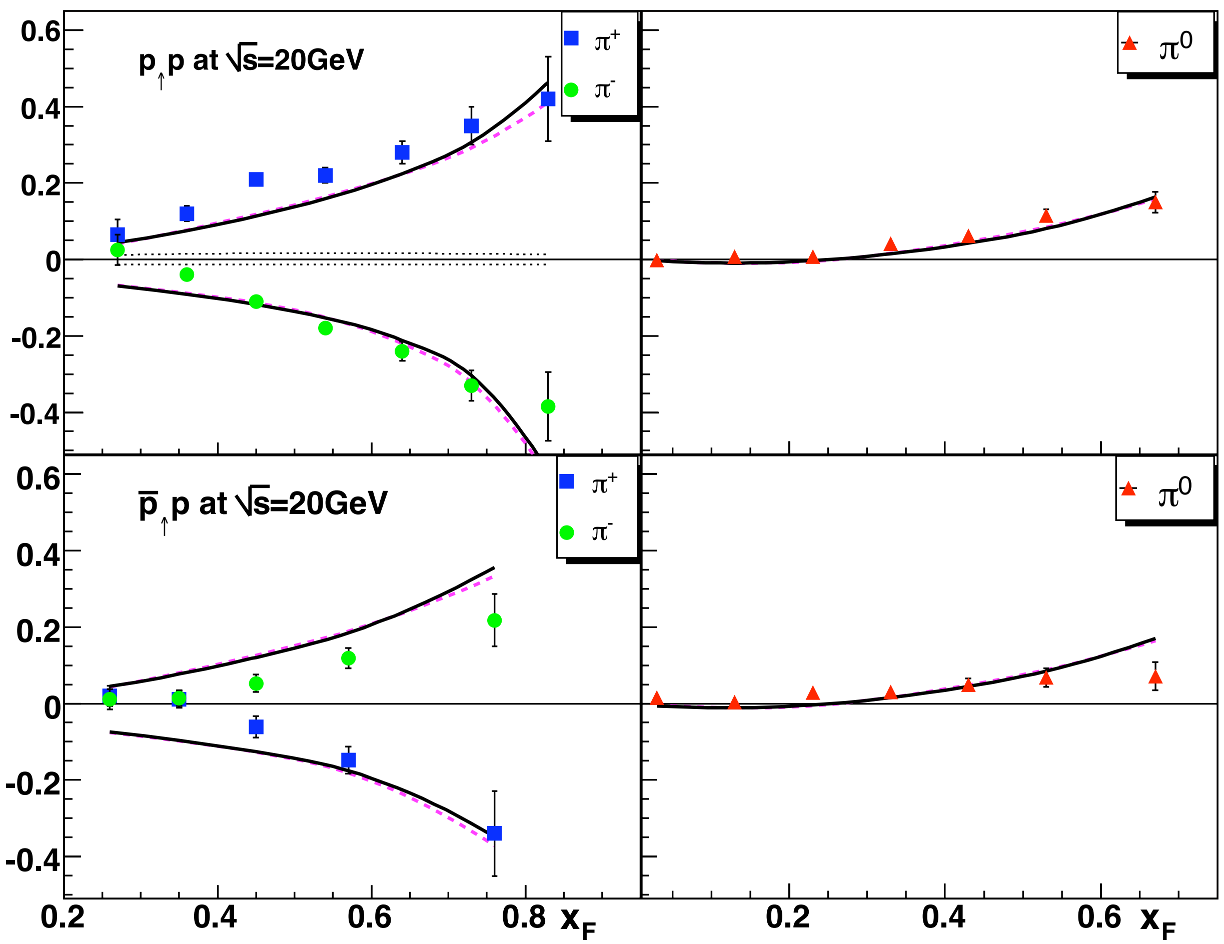
single spin effects in TMDs

M.A., M. Boglione, U. D'Alesio, E. Leader, S. Melis, F. Murgia, A. Prokudin, ...
(first proposed by Field-Feynman in unpolarized case)

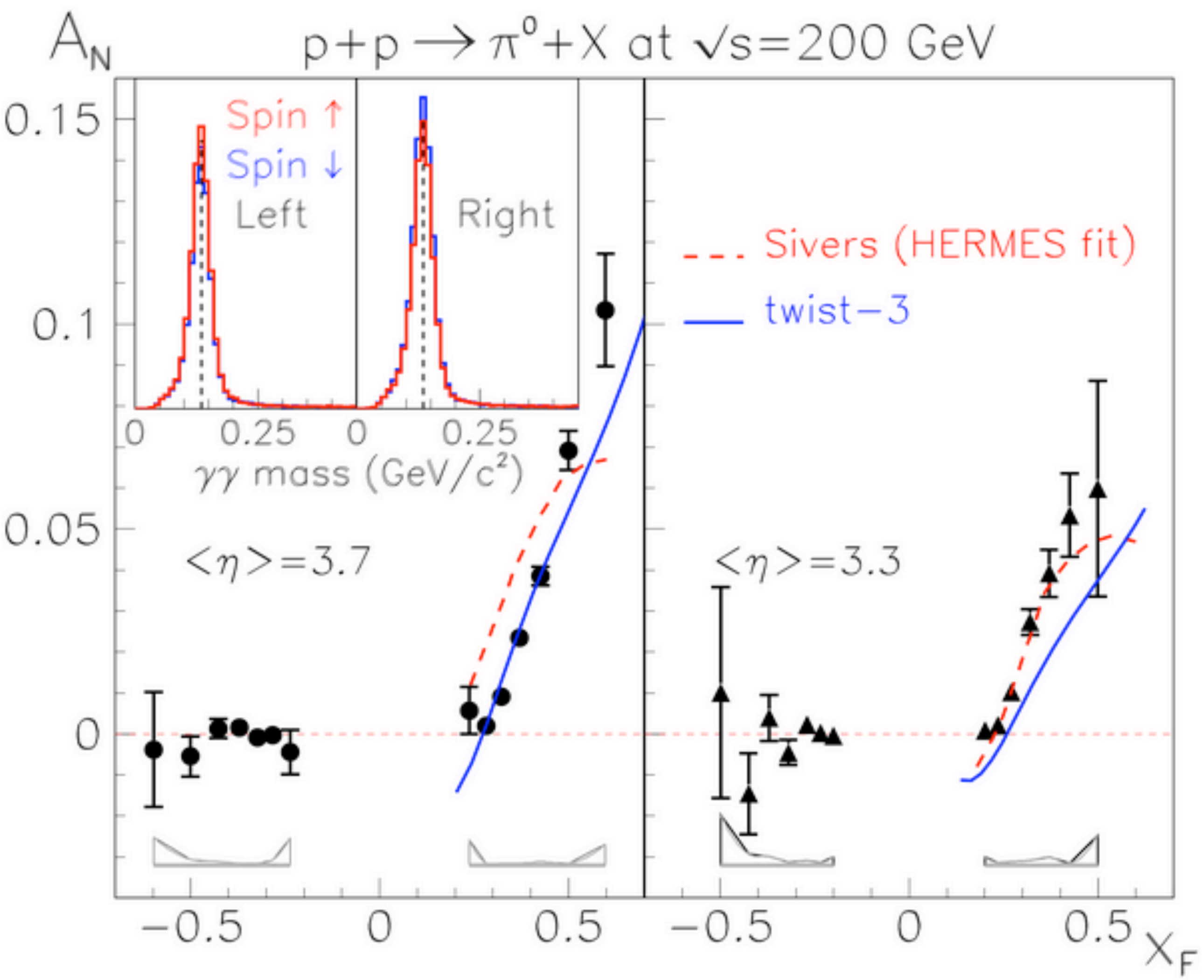
  - Sivers and Collins effect
- TMD factorization is assumed, and no rigorous proof, unlikely to hold
  - TMD factorization is only proved for SIDIS, DY, e+e- (to two hadrons)

Both approaches seem to be successful - I

- Collinear twist-3 factorization approach describe data well



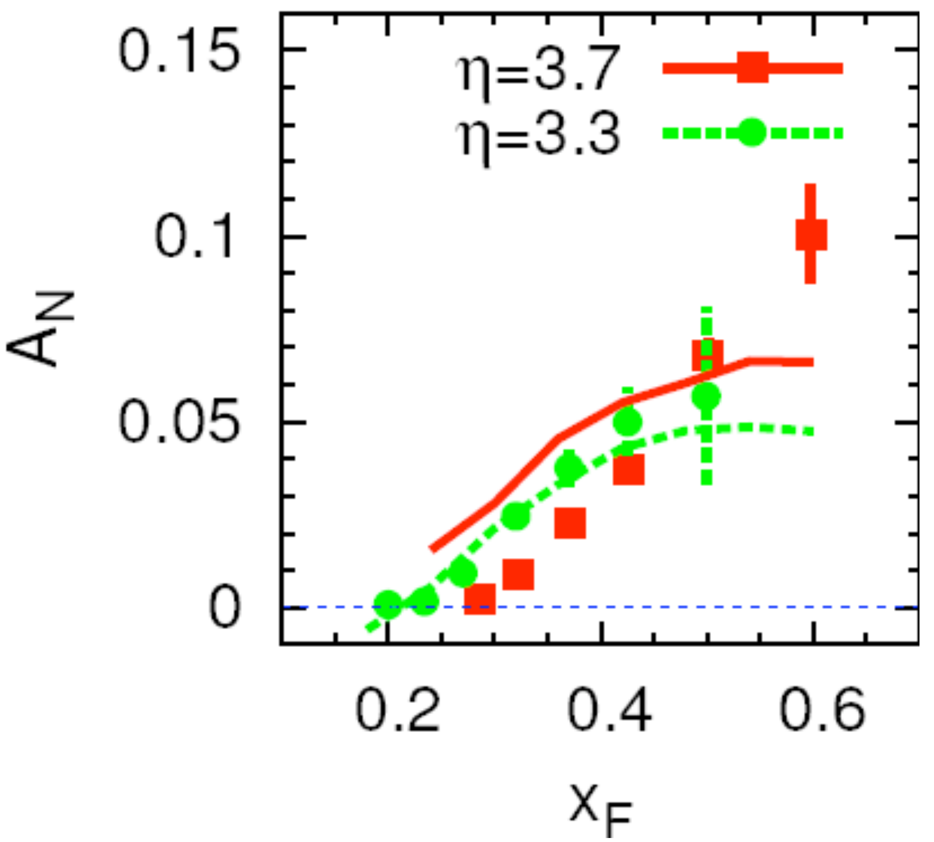
Kouvaris, Qiu, Vogelsang, Yuan, 2006



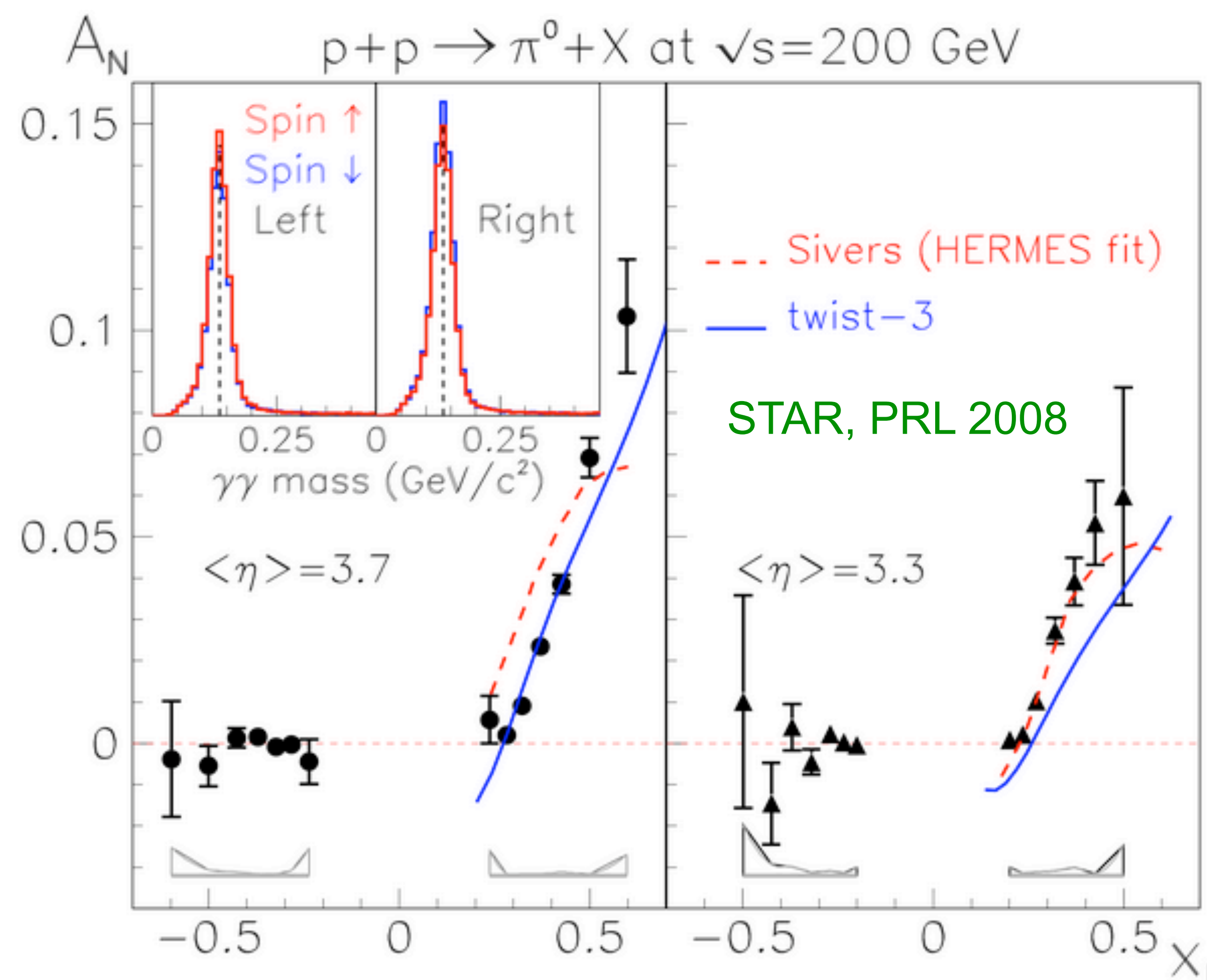
STAR, PRL 2008

Both approaches seem to be successful - II

- GPM also describe data well:



Boglione, D'Alesio, Murgia, 2008



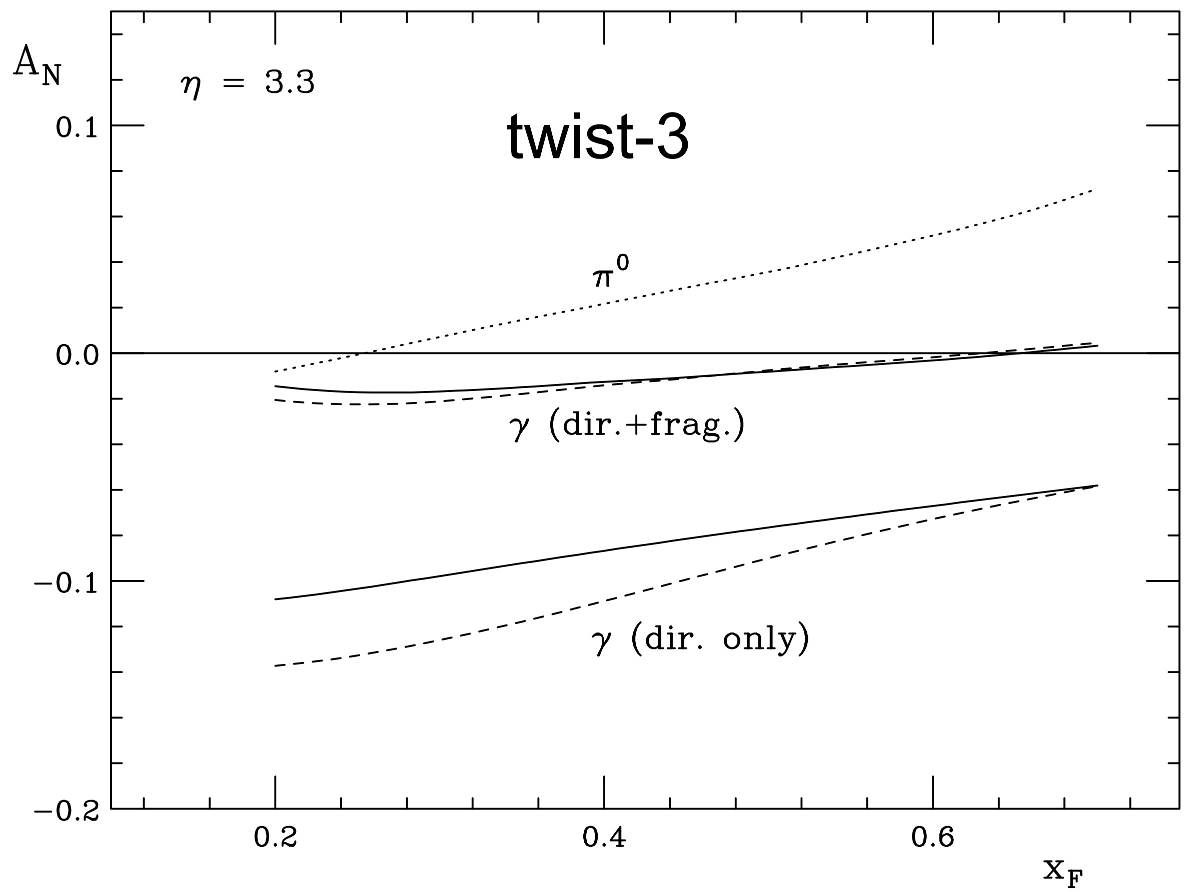
STAR, PRL 2008

  - Using Sivers functions extracted from HERMES, make predictions for inclusive hadron at RHIC

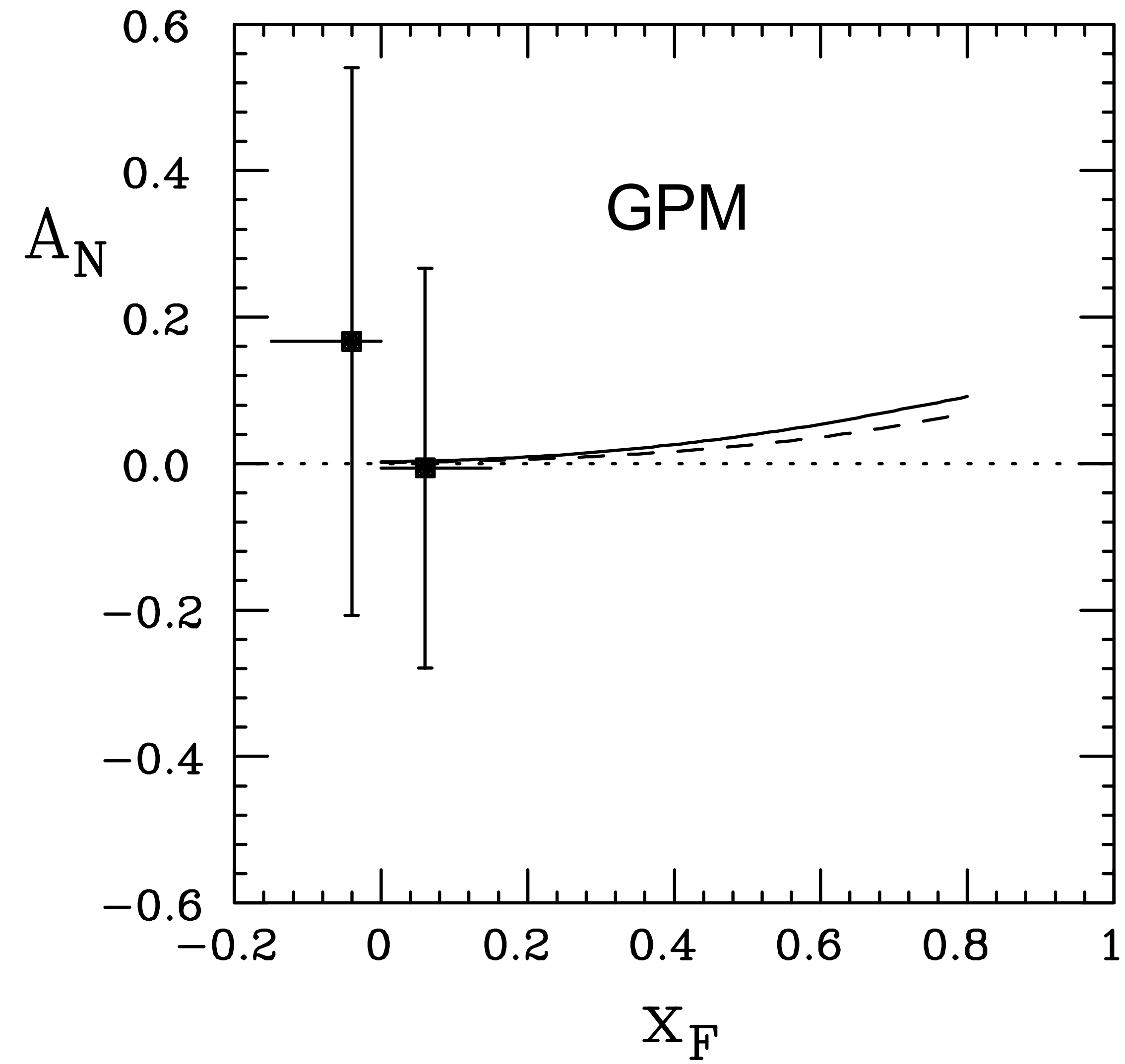
- Question: Sivers function is process dependent, how can we be sure the Sivers function in $pp^{\uparrow} \to \pi + X$ is the same as in SIDIS, especially when we know that in DY $pp^{\uparrow} \to [\gamma^* \to \ell^+\ell^-] + X$ is opposite?

Differences between two approaches

- Collinear twist-3 approach takes care of the process-dependence (color flow) of the Sivers function



Kouvaris, Qiu, Vogelsang, Yuan, 2006

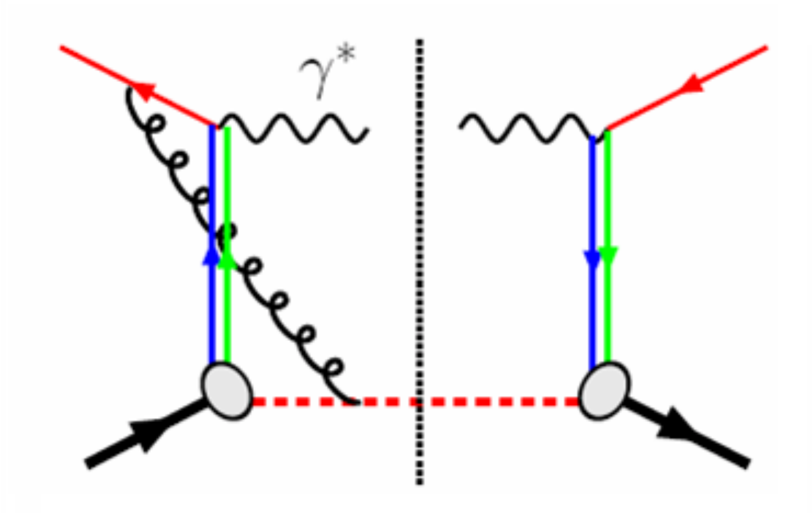


Anselmino, Murgia, 98

- GPM approach does NOT consider the process-dependence

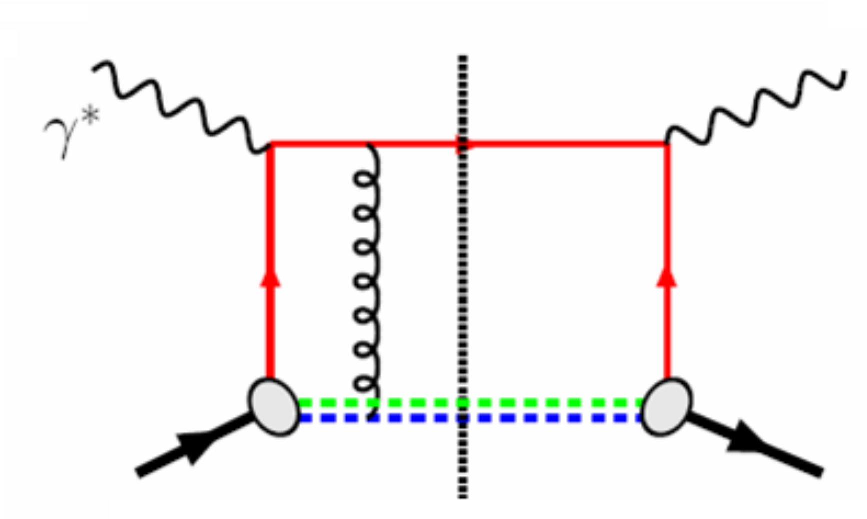
Process dependence of the Sivers functions

- Gauge links (initial- and final-state interactions) are important for the existence of the Sivers functions
  - Without gauge links, the Sivers function vanishes   Collins 93
  - With gauge links (generated from initial- and final-state interactions), the Sivers function exists, but non-universal (process-dependent) due to the difference from initial- and final-state interactions



$p^\uparrow + p \to [\gamma^* \to \ell^+\ell^-] + X$

DY: repulsive



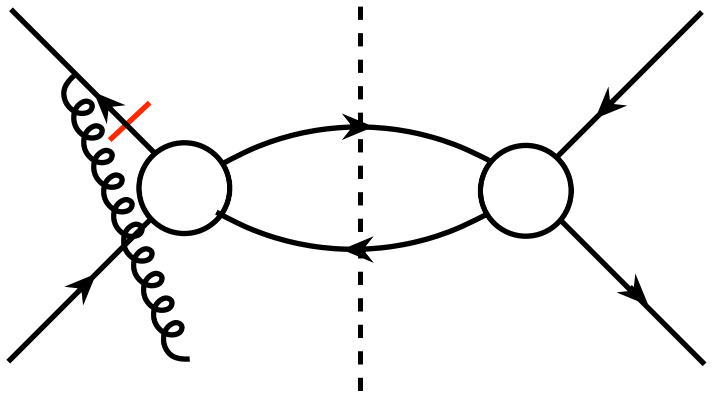
$\ell + p^\uparrow \to \ell + \pi + X$

SIDIS: attractive

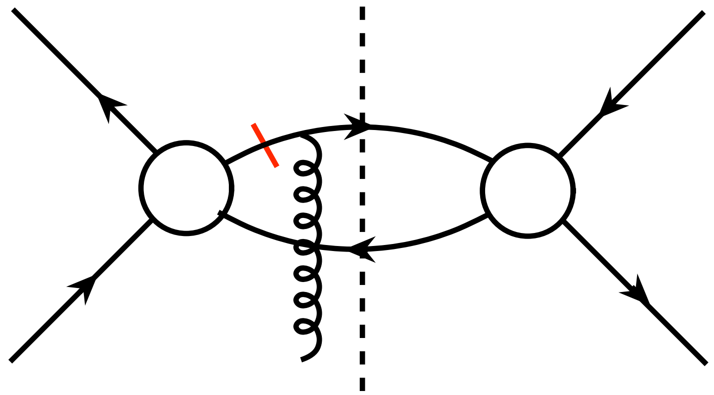
$$\Delta^N f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\mathrm{DY}}(x, k_\perp)$$

What about inclusive hadron production in pp collisions?

- Both initial- and final-state interactions exist for inclusive hadron productions
  - Sivers function in general can NOT be the same as those in SIDIS, as assumed in current GPM approach



(a)



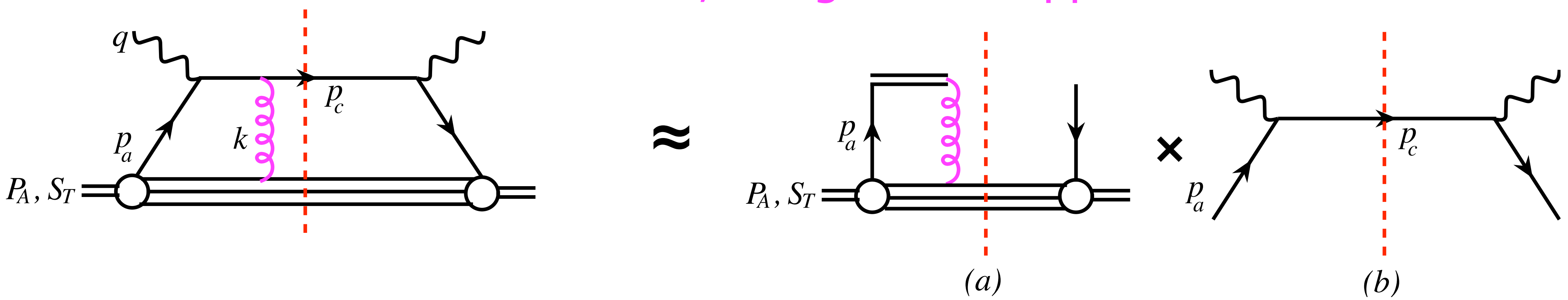
(c)

$$q\bar{q} \longrightarrow q\bar{q}$$

- One needs to consider these interactions to determine the proper Sivers function to be used in inclusive hadron production, to have a more consistent picture

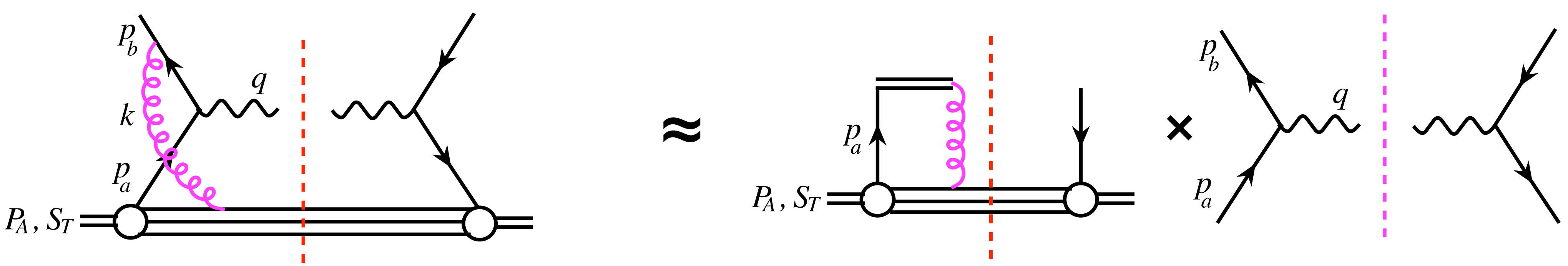
How to determine the appropriate Sivers functions

- Lesson from SIDIS and DY processes: one-gluon exchange
  - SIDIS: final-state interaction, using eikonal approximation



$$\bar{u}(p_c)(-ig)\gamma^- T^a \frac{i(\not{p}_c - \not{k})}{(p_c - k)^2 + i\epsilon} \approx \bar{u}(p_c)\left[\frac{g}{-k^+ + i\epsilon} T^a\right]$$

  - DY: initial-state interaction

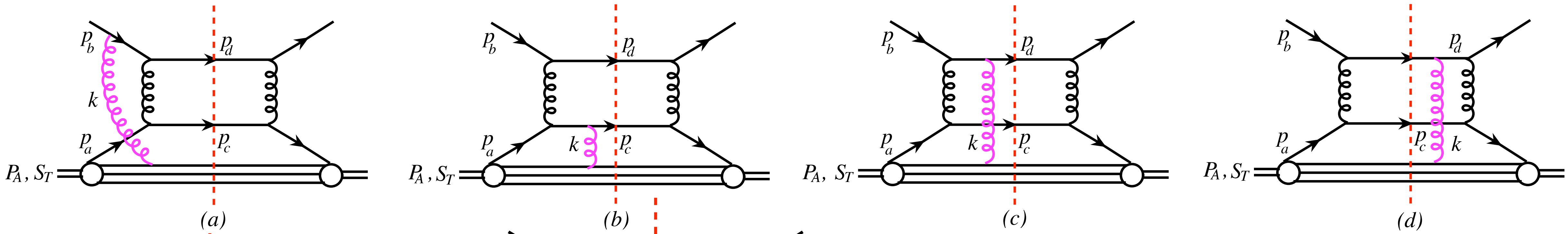


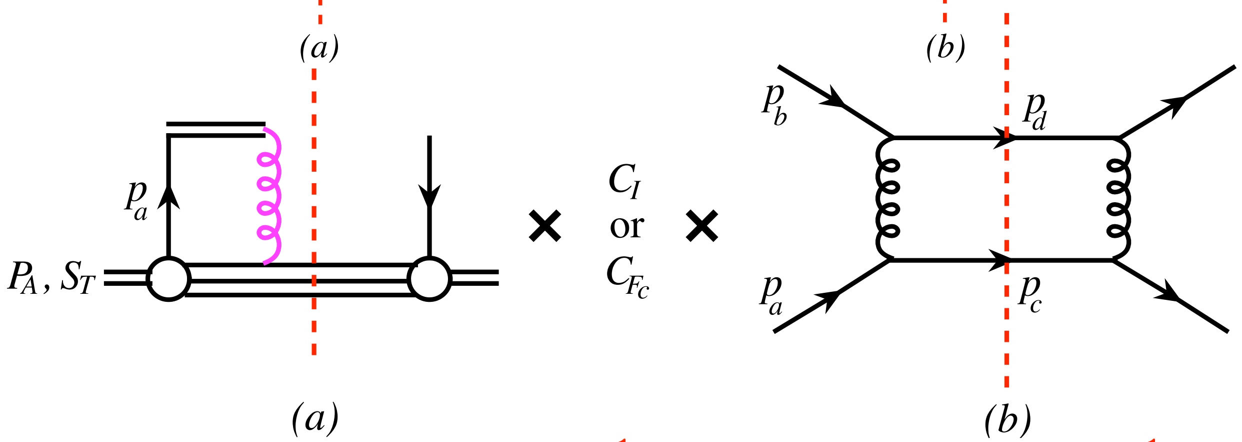
$$\bar{v}(p_b)(-ig)\gamma^- T^a \frac{-i(\not{p}_b + \not{k})}{(p_b + k)^2 + i\epsilon} \approx \bar{v}(p_b)\left[\frac{g}{-k^+ - i\epsilon} T^a\right]$$

  - Imaginary part (1st term of gauge link expansion) leads to the sign change

Do the same for inclusive hadron production

- Take qq′→qq′ as an example:





$$f_{1T}^{\perp a, qq'\to qq'} = \frac{C_I + C_{F_c}}{C_u} f_{1T}^{\perp a,\mathrm{SIDIS}}$$

$$C_I = -\frac{1}{2N_c^2}, \qquad C_{F_c} = -\frac{1}{4N_c^2}, \qquad C_u = \frac{N_c^2-1}{4N_c^2}.$$

- One might shift this factor to the hard part function (under this order only)

$$f_{1T}^{\perp a,\mathrm{SIDIS}} H^U_{qq'\to qq'} \equiv f_{1T}^{\perp a,\mathrm{SIDIS}} [C_u h_{qq'\to qq'}]$$ GPM

Modified GPM

$$f_{1T}^{\perp a, qq'\to qq'} H^U_{qq'\to qq'} = \frac{C_I + C_{F_c}}{C_u} f_{1T}^{\perp a,\mathrm{SIDIS}} H^U_{qq'\to qq'} = f_{1T}^{\perp a,\mathrm{SIDIS}} [C_I h_{qq'\to qq'} + C_{F_c} h_{qq'\to qq'}]$$

Many other channels also contribute

- Do the same for all other channels: $q\bar{q} \to q\bar{q}, qg \to qg, qg \to gq, q\bar{q} \to gg, \cdots$
- Eventually, we obtain a new (modified) GPM formalism:
  - Contains process-dependence of the Sivers functions

$$E_h \frac{d\Delta\sigma}{d^3P_h} = \frac{\alpha_s^2}{S} \sum_{a,b,c} \int \frac{dx_a}{x_a} d^2k_{aT} f_{1T}^{\perp a,\mathrm{SIDIS}}(x_a, k_{aT}^2) \frac{\epsilon^{k_{aT} S_A n \bar{n}}}{M} \int \frac{dx_b}{x_b} d^2k_{bT} f_{b/B}(x_b, k_{bT}^2)$$
$$\times \int \frac{dz_c}{z_c^2} D_{h/c}(z_c) H_{ab\to c}^{\mathrm{Inc}}(\hat{s}, \hat{t}, \hat{u}) \delta(\hat{s}+\hat{t}+\hat{u})$$

$$\updownarrow$$

$$H_{ab\to c}^{U}(\hat{s}, \hat{t}, \hat{u}) \quad \text{GPM}$$

$$H_{ab\to c}^{\mathrm{Inc}}(\hat{s}, \hat{t}, \hat{u}) = \underbrace{H_{ab\to c}^{\mathrm{Inc-I}}(\hat{s}, \hat{t}, \hat{u})}_{\text{initial-state}} + \underbrace{H_{ab\to c}^{\mathrm{Inc-F}}(\hat{s}, \hat{t}, \hat{u})}_{\text{final-state}}$$

  - Hard-part functions (both initial- and final-) are exactly the same as those in collinear twist-3 approach in terms of Mandelstam variables $\hat{s}, \hat{t}, \hat{u}$
  - Collinear twist-3: parton momenta are collinear, so are $\hat{s}, \hat{t}, \hat{u}$
  - GPM: parton momenta depend on kt, so are $\hat{s}, \hat{t}, \hat{u}$

Twist-3 nature of the SSAs

- Even though it is claimed sometimes that GPM is a leading twist formalism, it is NOT

$$E_h \frac{d\Delta\sigma}{d^3P_h} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int \frac{dx_a}{x_a} d^2k_{aT} f_{1T}^{\perp a,\mathrm{SIDIS}}(x_a, k_{aT}^2) \frac{\epsilon^{k_{aT}S_A n\bar{n}}}{M} \int \frac{dx_b}{x_b} d^2k_{bT} f_{b/B}(x_b, k_{bT}^2)$$
$$\times \int \frac{dz_c}{z_c^2} D_{h/c}(z_c) H_{ab\to c}^{\mathrm{Inc}}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u})$$

  - Because of the linear kt from Sivers function definition, one needs to pick up another linear kt from the expansion of the hard-part function, thus it is the kt-expansion term contributes
  - One has to keep the kt-dependence in the hard-part functions, otherwise the integral vanishes (no SSAs can be generated from this approach)
- This is not TMD factorization formalism (no TMD factorization established for inclusive hadron production)
  - Typically TMD factorization applies for processes with two scales: SIDIS, DY
  - Typically hard-part functions do NOT contain any soft scale, like kt in our case

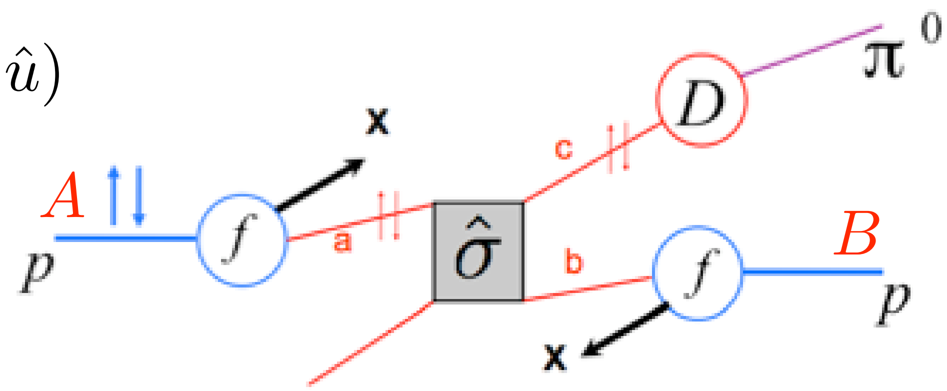
Hope modified GPM is a reasonable approximation?! - I

- What is the first kt-expansion

$$E_h \frac{d\Delta\sigma}{d^3P_h} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dx_a}{x_a}d^2k_{aT}f_{1T}^{\perp a,\mathrm{SIDIS}}(x_a,k_{aT}^2)\frac{\epsilon^{k_{aT}S_A n\bar{n}}}{M}\int\frac{dx_b}{x_b}d^2k_{bT}f_{b/B}(x_b,k_{bT}^2)$$

$$\times\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H^{\mathrm{Inc}}_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u})$$

$$p_a^\mu \approx x_a P_A^\mu + k_{aT} \qquad p_b^\mu \approx x_b P_B^\mu$$



$$\delta(\hat{s}+\hat{t}+\hat{u}) = \frac{1}{x_bS+T/z_c}\delta\left(x_a - x - \frac{2P_{hT}\cdot k_{aT}}{z_cx_bS+T}\right) \quad \text{where,} \quad x_a = x + \frac{2P_{hT}\cdot k_{aT}}{z_cx_bS+T}$$

no kt-dependence

- $\tilde{s},\tilde{t},\tilde{u}$ no kt-dependence

$$\hat{s} = \tilde{s} - \frac{\tilde{s}}{\tilde{u}}2P_{hT}\cdot k_{aT}/z_c, \qquad \hat{t} = \tilde{t} + \frac{\tilde{s}}{\tilde{u}}2P_{hT}\cdot k_{aT}/z_c, \qquad \hat{u} = \tilde{u}$$

Hope modified GPM is a reasonable approximation?! - II

- The relation between twist-3 correlation function $T_F(x, x)$ and Sivers function

$$T_{a,F}(x,x) = -\frac{1}{M}\int d^2k_{aT}|\vec{k}_{aT}|^2 f_{1T}^{\perp a,\mathrm{SIDIS}}(x,k_{aT}^2)$$

- Finally, the first term in kt-expansion

$E_h\frac{d\Delta\sigma^{(a)}}{d^3P_h}$: exactly the same as the collinear twist-3 formalism

$$\frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)\frac{\epsilon^{P_{hT}S_A n\bar{n}}}{z_c\tilde{u}}\frac{1}{x}\left[T_{a,F}(x,x)-x\frac{d}{dx}T_{a,F}(x,x)\right]\int\frac{dx_b}{x_b}f_{b/B}(x_b)H^{\mathrm{Inc}}_{ab\to c}(\tilde{s},\tilde{t},\tilde{u})\frac{1}{x_bS+T/z_c}$$

$E_h\frac{d\Delta\sigma^{(b)}}{d^3P_h}$: an extra term, which is proportional to the non-derivative term

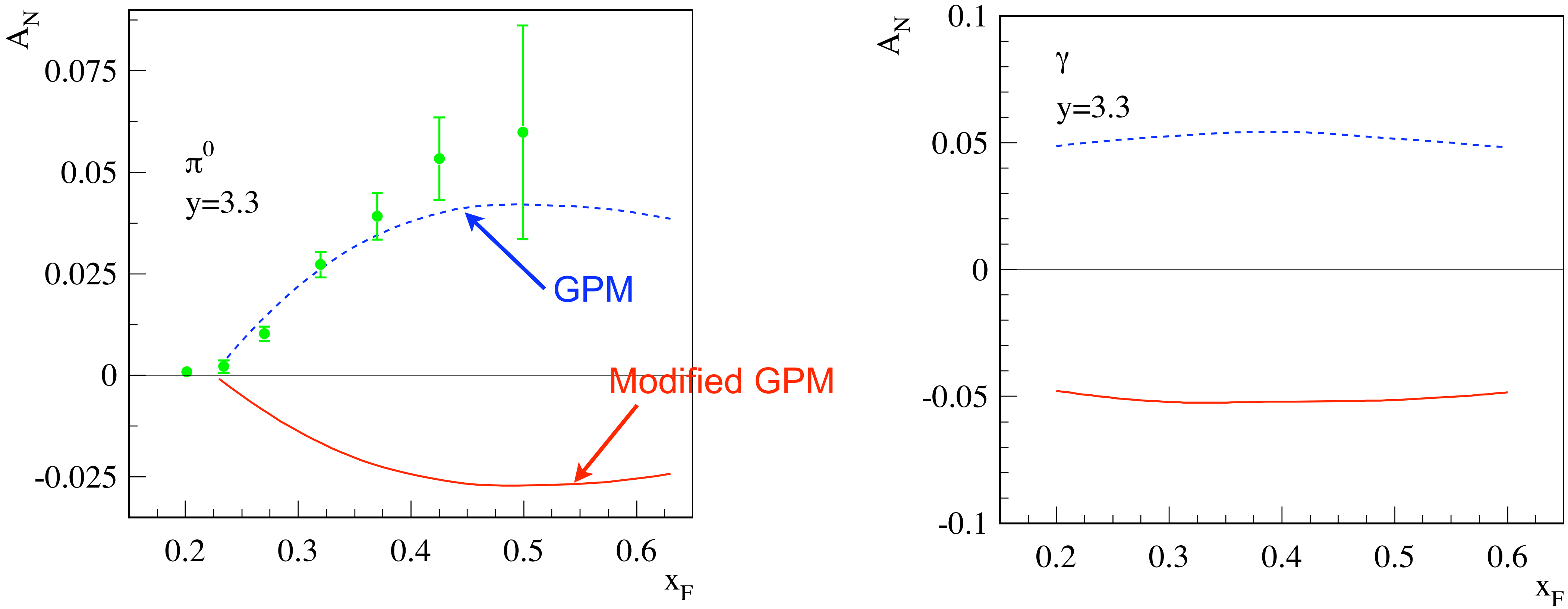
$$\frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)\frac{\epsilon^{P_{hT}S_A n\bar{n}}}{z_c\tilde{u}}\frac{1}{x}T_{a,F}(x,x)\int\frac{dx_b}{x_b}f_{b/B}(x_b)\left[-\tilde{s}\frac{\partial}{\partial\tilde{s}}H^{\mathrm{Inc}}_{ab\to c}(\tilde{s},-\tilde{s}-\tilde{u},\tilde{u})\right]\frac{1}{x_bS+T/z_c}$$

  - Since the derivative term is dominant contribution in forward region, the extra term should be small numerically, thus a reasonable approximation?!

Numerical estimates - I: GPM .vs. Modified GPM

- Using the slightly earlier Sivers function parameterizations

Anselmino, et.al., PRD, 2005

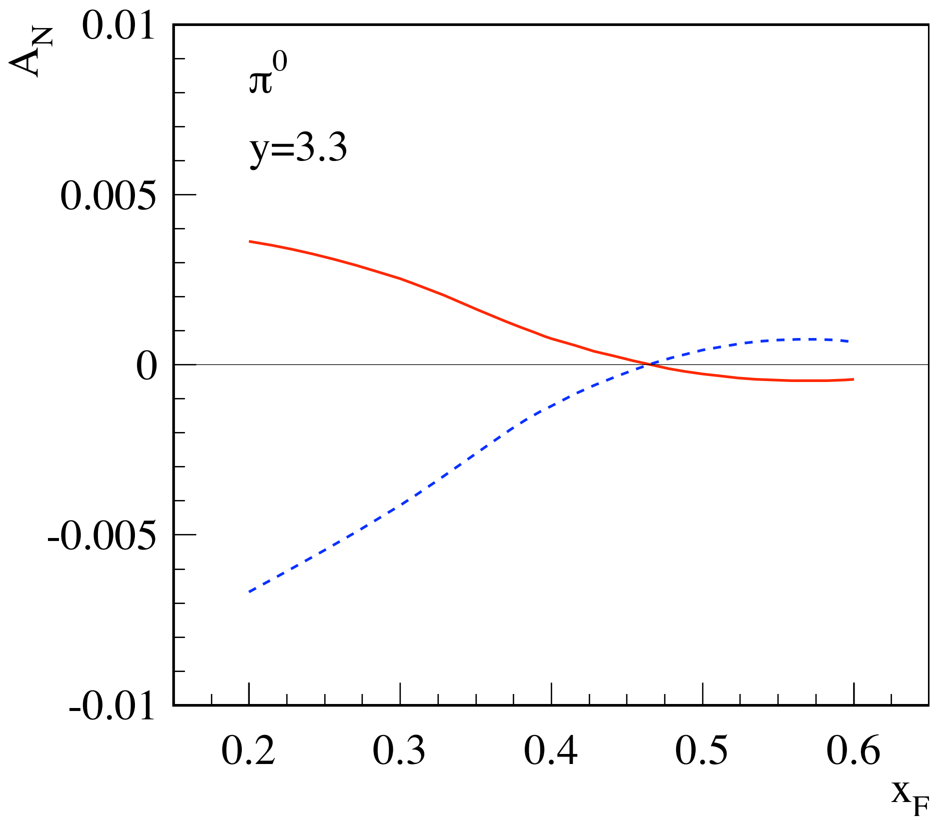


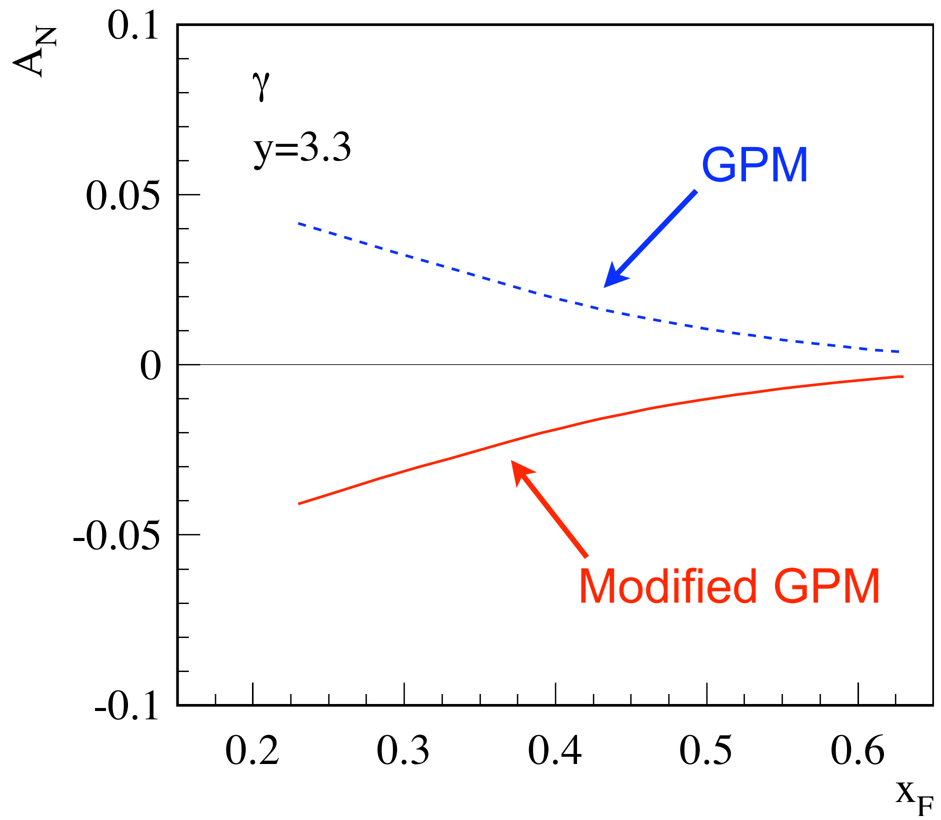
- The predictions of modified GPM are almost opposite to those from GPM
- With Sivers effect alone, one cannot describe the data any more
- To compare with inclusive pion data, one also needs to add Collins effect
- Predictions for direct photon is the same between modified GPM and twist-3

Numerical estimates - II: GPM .vs. Modified GPM

- Using the latest Sivers functions

Anselmino, et.al., EPJA, 2009



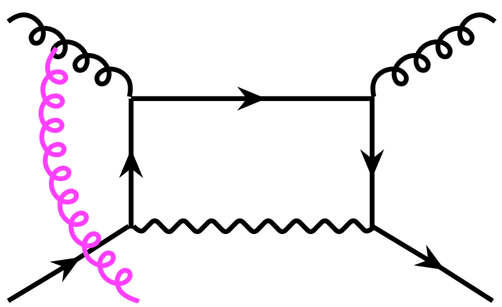


- The latest Sivers functions extracted from SIDIS generate very small asymmetry
- New global fitting is on the way
- To compare with inclusive pion data, one also needs to add Collins effect

Why does sign change?

- For direct photon production, the dominant channel at forward direction is qg→γq
  - Without initial-state interaction

$$H^U_{qg\to\gamma q} = \frac{1}{N_c}e_q^2\left[-\frac{\hat{t}}{\hat{s}}-\frac{\hat{s}}{\hat{t}}\right]$$

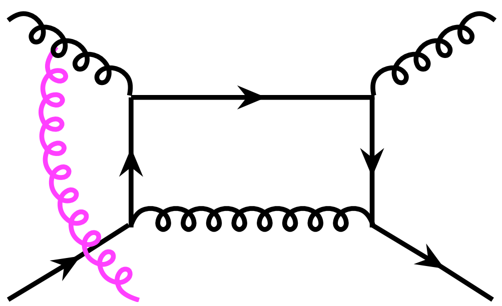


  - With initial-state interaction

$$H^{\rm Inc}_{qg\to\gamma q} = -\frac{N_c}{N_c^2-1}e_q^2\left[-\frac{\hat{t}}{\hat{s}}-\frac{\hat{s}}{\hat{t}}\right]$$

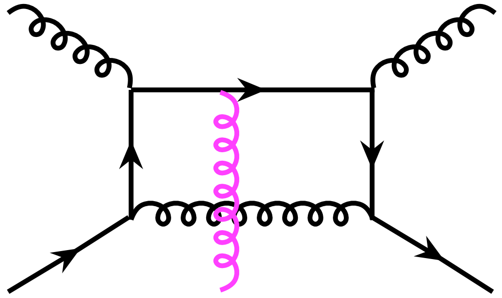
- For inclusive pion production, the dominant channel at forward direction is qg→qg
  - Without initial- and final-state interactions

$$H^U_{qg\to qg} \to \frac{2\hat{s}^2}{\hat{t}^2}$$



  - With both initial- and final-state interactions

$$H^{\rm Inc}_{qg\to qg} = H^{\rm Inc-I}_{qg\to qg} + H^{\rm Inc-F}_{qg\to qg} \to -\frac{N_c^2+2}{N_c^2-1}\frac{\hat{s}^2}{\hat{t}^2}$$



Some comments

- There is no TMD factorization for GPM or our modified GPM approaches, use it with caution
- GPM does not take into account the process-dependence of the Sivers function, it is only a nice intuitive picture, which might be used for illustration only
- Modified GPM contains the process-dependence of the Sivers function to some degree (only under one-gluon exchange), numerically seems close to the well-established collinear twist-3 formalism, should be used if one wants to study the SSAs within GPM framework
- Modified GPM predicts same sign as the collinear twist-3 formalism, but the conventional GPM has opposite predictions, thus direct photon might be a very good channel to test the associated initial color interactions
- Since these process dependence has the same origin as the sign change between SIDIS and DY, we hope to have DY measurements as soon as possible (a much cleaner channel, TMD factorization is proved, no final-state interactions, ...)

Thank you