Status of Transverse Spin Physics

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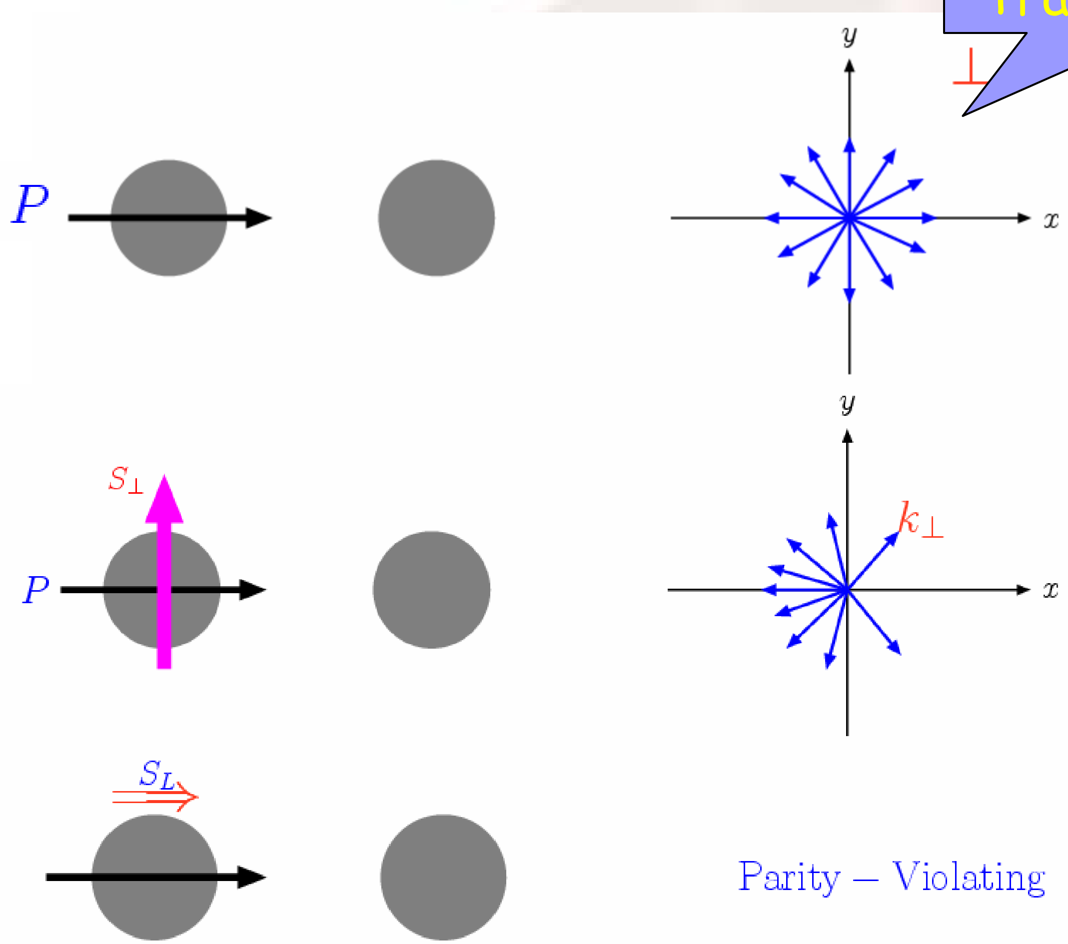
Transverse spin physics at RHICII and eRHIC

- Double transverse spin asymmetry
  - A_TT for Drell-Yan, jet, hadron, etc. to measure the quark transversity
- Single transverse spin asymmetry
  - Various TMD physics (additional information on nucleon structure) see more in Gamberg's talk
  - Sivers function (PDF)
  - Collins function (FF)
  - …

What's Single spin asymmetry?

Transverse plane



Final state particle is Azimuthal symmetric

$$d\sigma \propto \vec{S}_\perp \cdot (\vec{P} \times \vec{K}_\perp)$$

Single Transverse Spin Asymmetry (SSA)

$$A_N = \frac{L-R}{L+R}$$

No hadronic single spin asymme
Associated with S_L

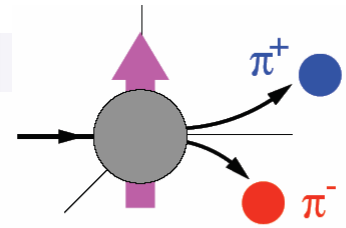
Single Spin Asymmetry

- Motivations:
  - Its strong tied with the quark orbital angular momentum
  - We have beautiful data
  - Nontrivial QCD dynamics, and fundamental test of the factorization, and the universality of PDFs, FFs,…

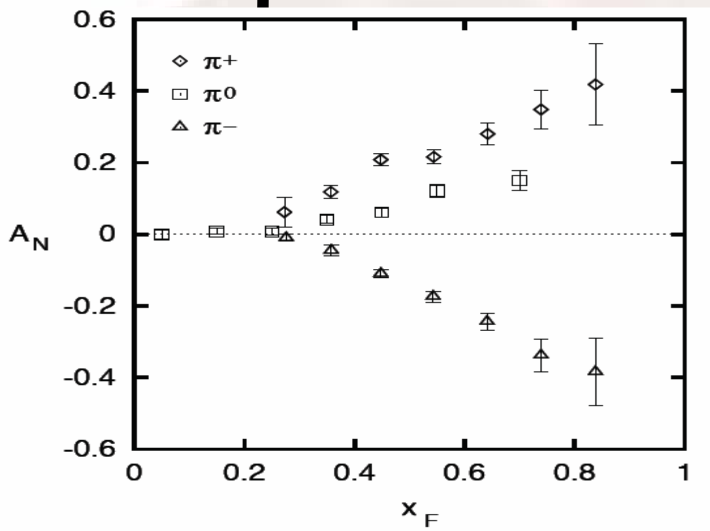
Transverse spin physics: a Renaissance

- Single transverse spin asymmetry has long been observed in high energy hadronic reactions (late 70's and 80's)
- Naïve Parton model fails to explain large Single transverse spin asymmetry (G. Kane et al, PRL41, 1978), we have to go beyond to understand the large SSAs
- Many activities in recent years

SSAs in "Ancient" age: fixed target exp.



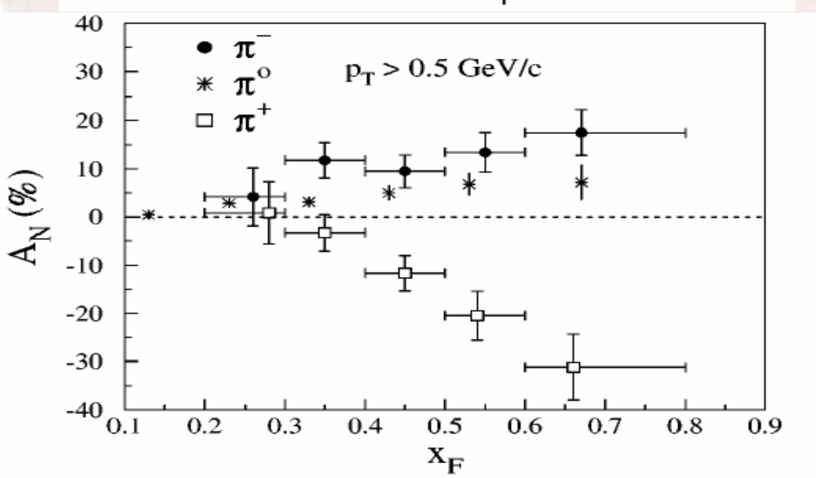
$$A_N = \frac{L-R}{L+R}$$



$\sqrt{s} = 20GeV$

Hadron production in p↑p

Adams, et al., PLB264 (1991)

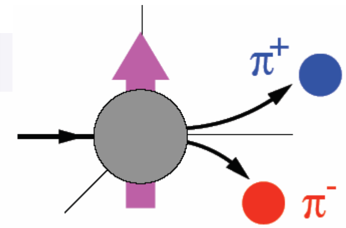


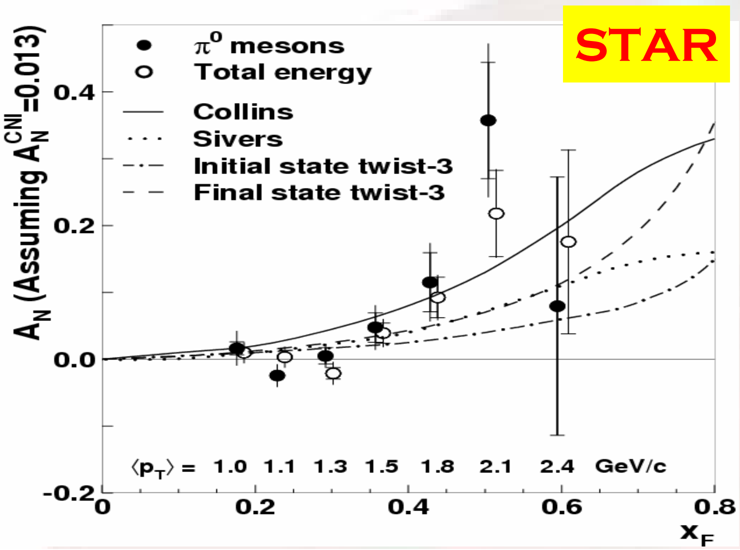
$\sqrt{s} = 20GeV$

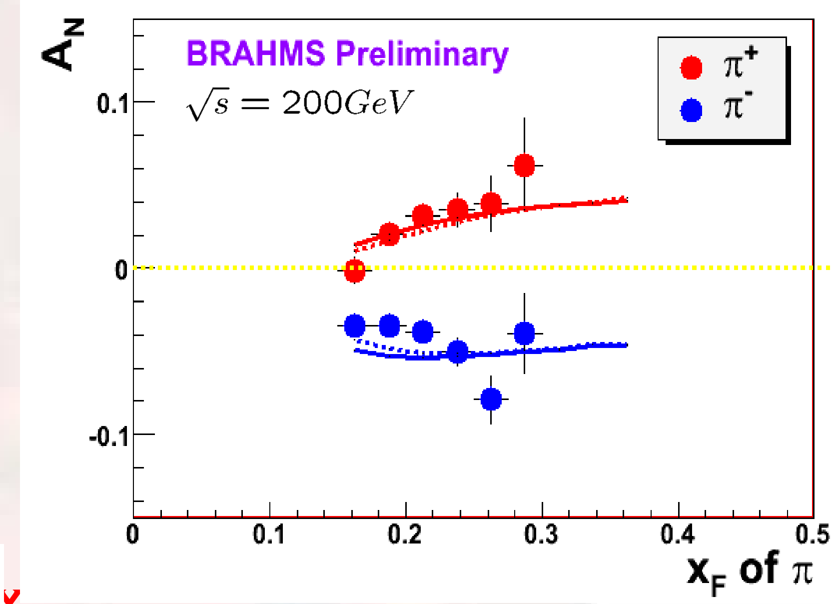
hadron production in p̄↑p

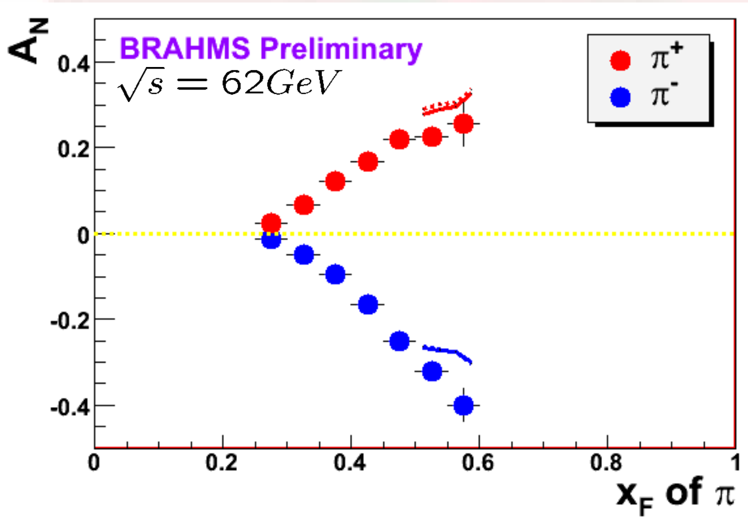
A. Bravar et al.,E704, PRL77(1996)

SSAs in Modern era: RHIC



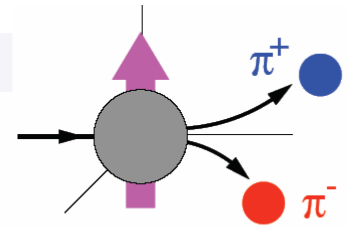




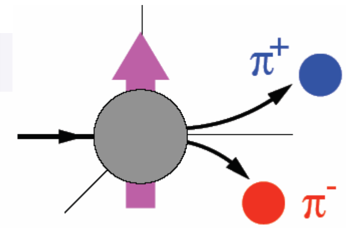


Large SSA continues at Collider experiments!!
(Also in *ep* DIS exp.)

Why Does SSA Exist?

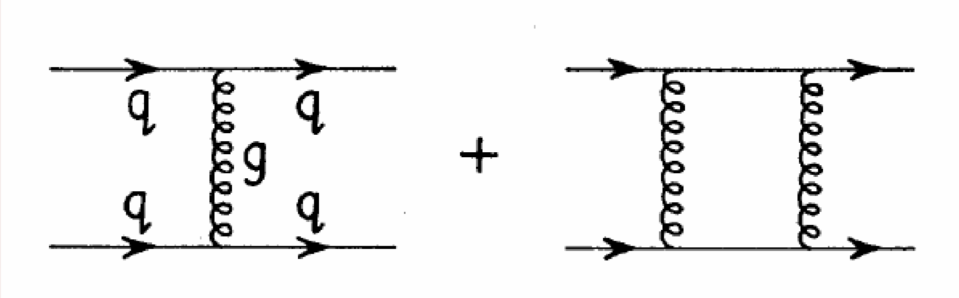


- **Single Spin Asymmetry requires**
  - **Helicity flip**: one must have a reaction mechanism for the hadron to change its helicity (in a cut diagram)
  - **A phase difference**: the phase difference is needed because the structure $S \cdot (p \times k)$ violate the naïve time-reversal invariance

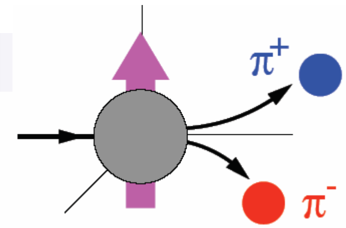


Naïve parton model fails?

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: (G. Kane et al, 1978),

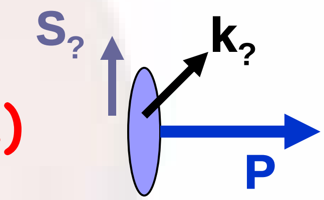


  - It is in general suppressed by $\alpha_S m_q/Q$
- We have to go beyond this naïve picture

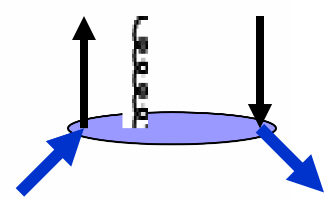


Two mechanisms in QCD

- Spin-dependent transverse momentum dependent (TMD) function
  - Sivers 90 **Sivers function » S?¢ (P£k?)**
  - Brodsky,Hwang,Schmidt, 02 (FSI)
  - Gauge Property: Collins 02;Belitsky-Ji-Yuan,NPB03
  - Factorization: Ji-Ma-Yuan,PRD04;Collins,Metz,04



- Twist-3 quark-gluon correlations (coll.)
  - Efremov-Teryaev, 82, 84
  - Qiu-Sterman, 91,98



Regions

- Twist-three: the single inclusive hadron production in pp, require large P_T, SSA is suppressed by $1/P_t$
- TMD: low P_T, require additional hard scale like Q^2 in DIS and Drell-Yan, $P_T \ll Q$, SSA survives in Bjorken limit
- Overlap: $\Lambda_{QCD} \ll P_t \ll Q$, unifying these two

Recent theoretical developments (twist-three)

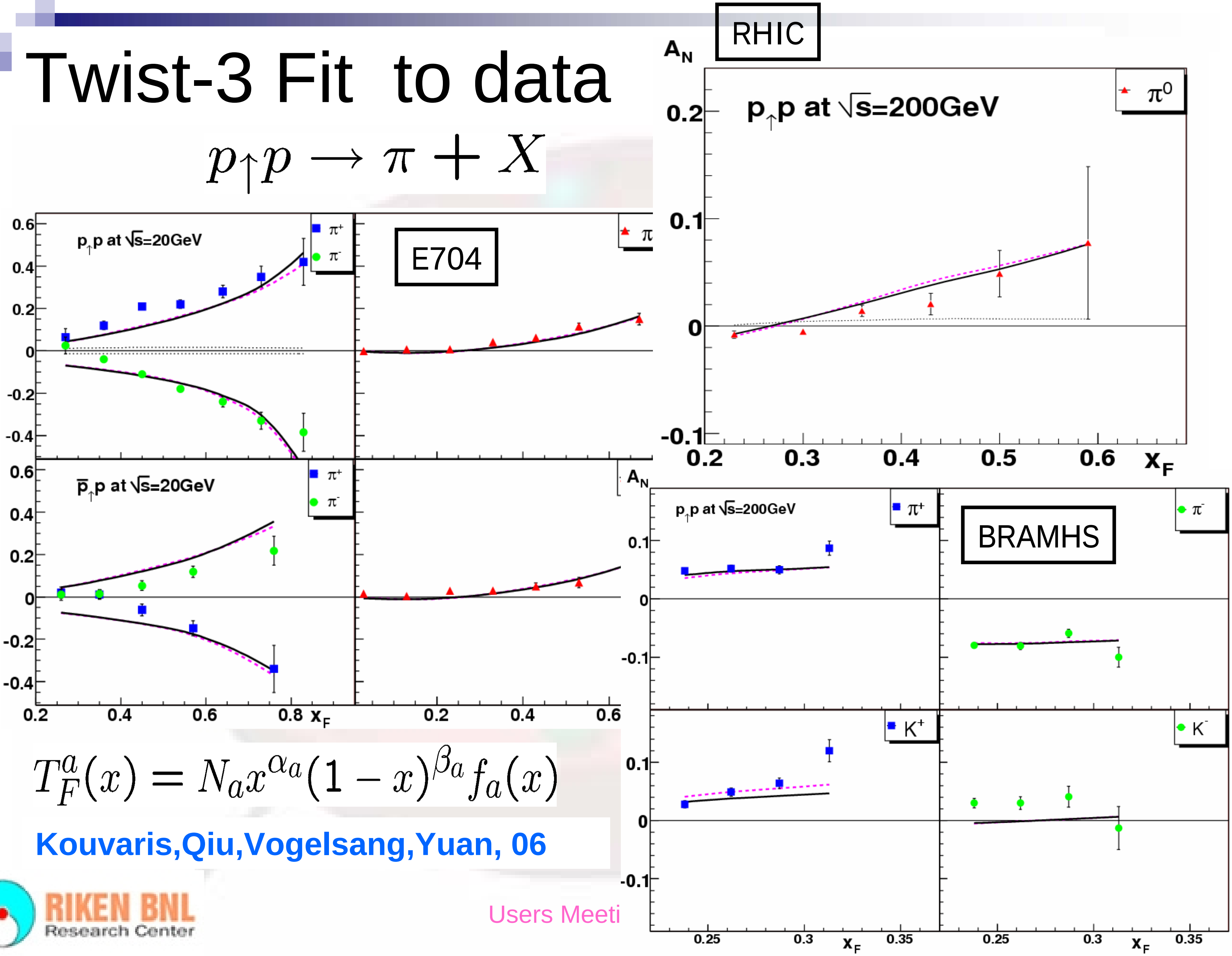
- Complete formalism for single inclusive hadron production in pp collision has been derived, including the derivative and non-derivative terms

$$E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int_{z_{\rm min}}^1 \frac{dz}{z^2} D_{c\to h}(z) \int_{x'_{\rm min}}^1 \frac{dx'}{x'} \frac{1}{x'S+T/z}\phi_{b/B}(x')$$
$$\times \sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{\ell s_T n\bar{n}}}{z\hat{u}}\right)\frac{1}{x}\left[T_{a,F}(x,x) - x\left(\frac{d}{dx}T_{a,F}(x,x)\right)\right]H_{ab\to c}(\hat{s},\hat{t},\hat{u})$$

Qiu, Sterman, 91, 98
Kouvaris,Qiu,Vogelsang,Yuan, 06
See also Koike, et al., 06,07

Twist-3 Fit to data

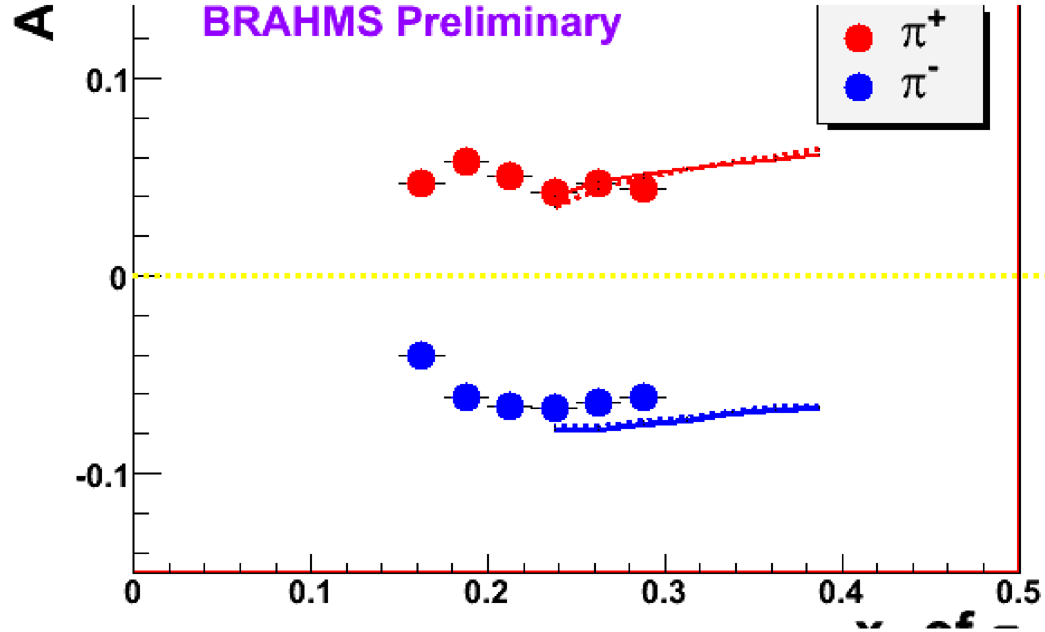
$$p_{\uparrow}p \to \pi + X$$

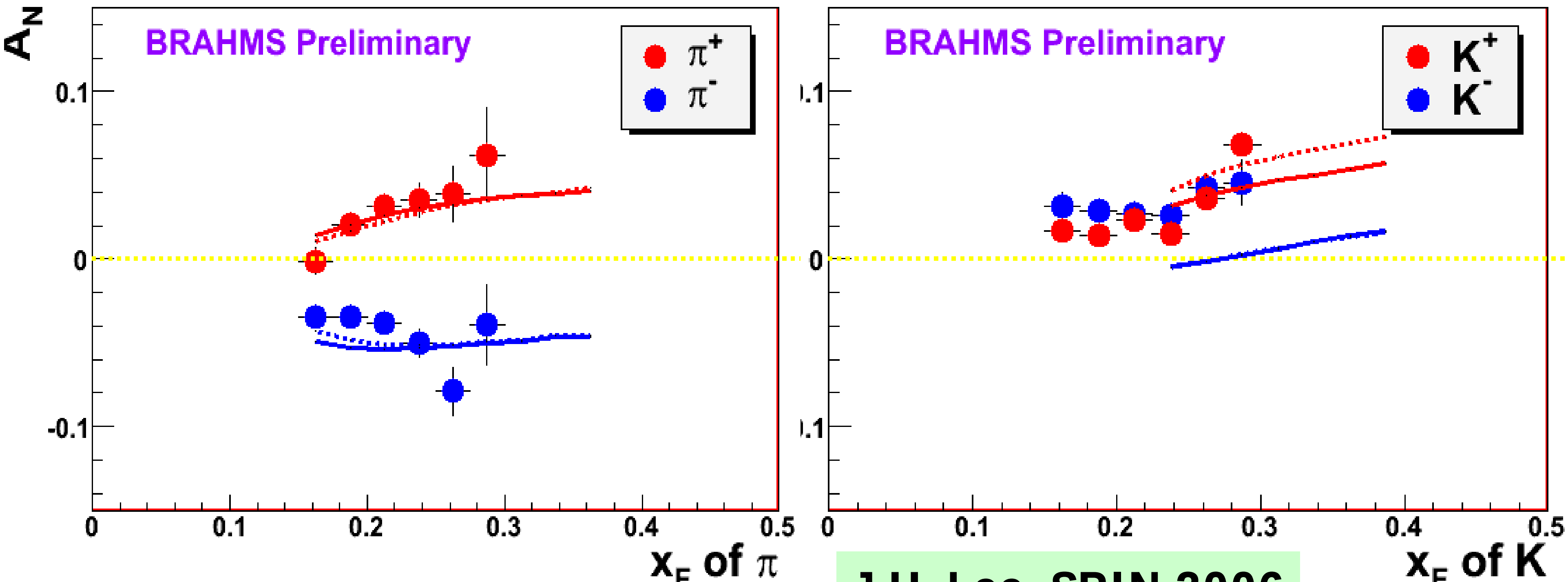


$$T_F^a(x) = N_a x^{\alpha_a}(1-x)^{\beta_a} f_a(x)$$

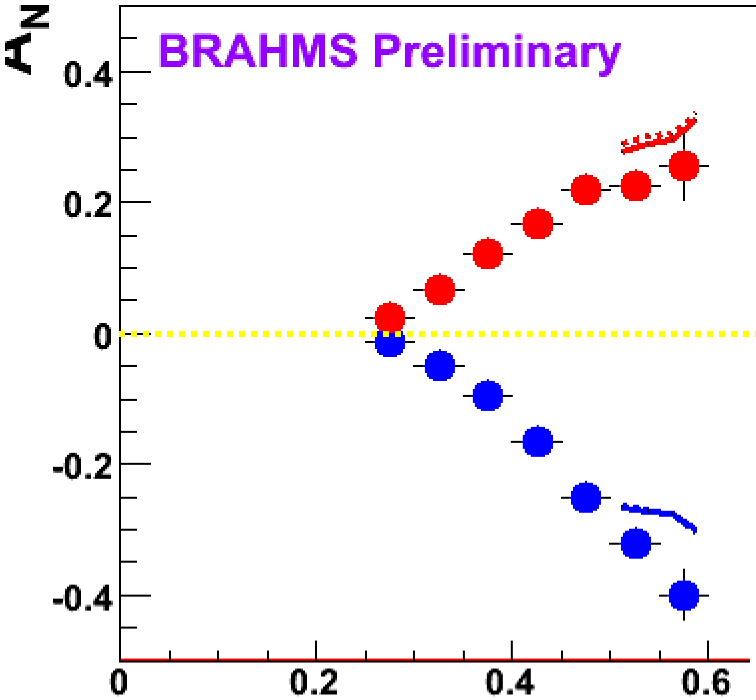
Kouvaris,Qiu,Vogelsang,Yuan, 06

Compare to 2006 data from RHIC

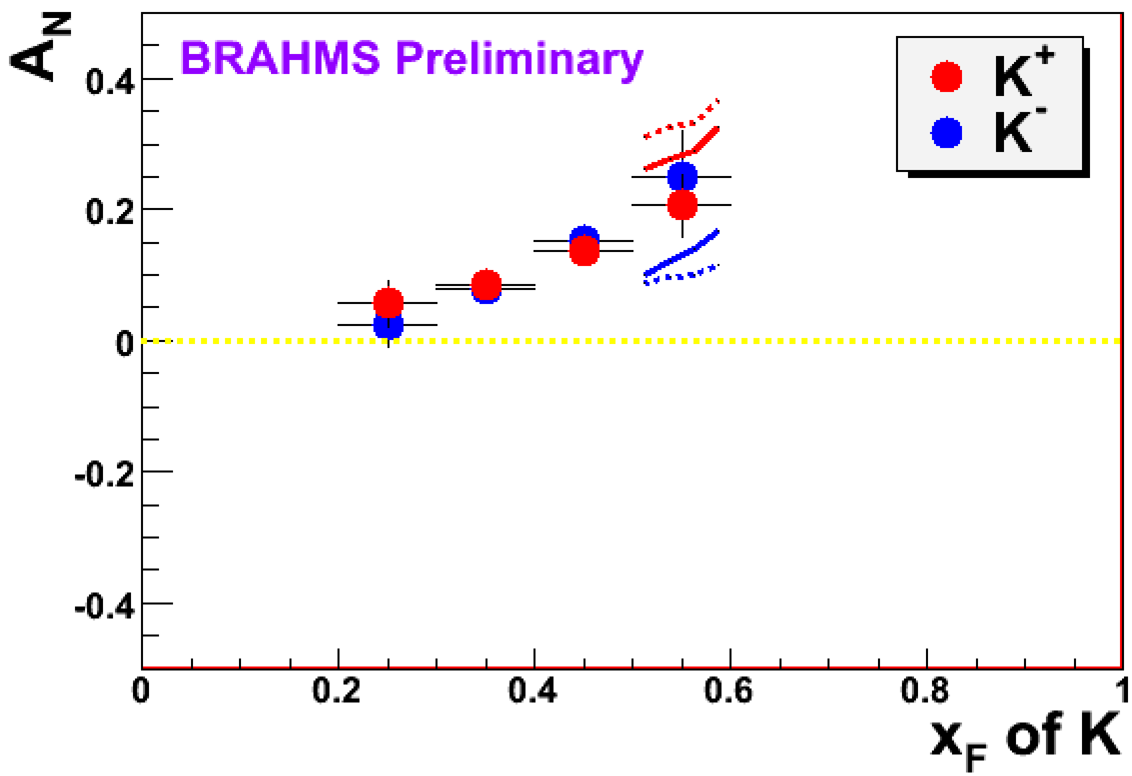




J.H. Lee, SPIN 2006



$$\sqrt{s} = 62GeV$$



RIKEN BNL Research Center

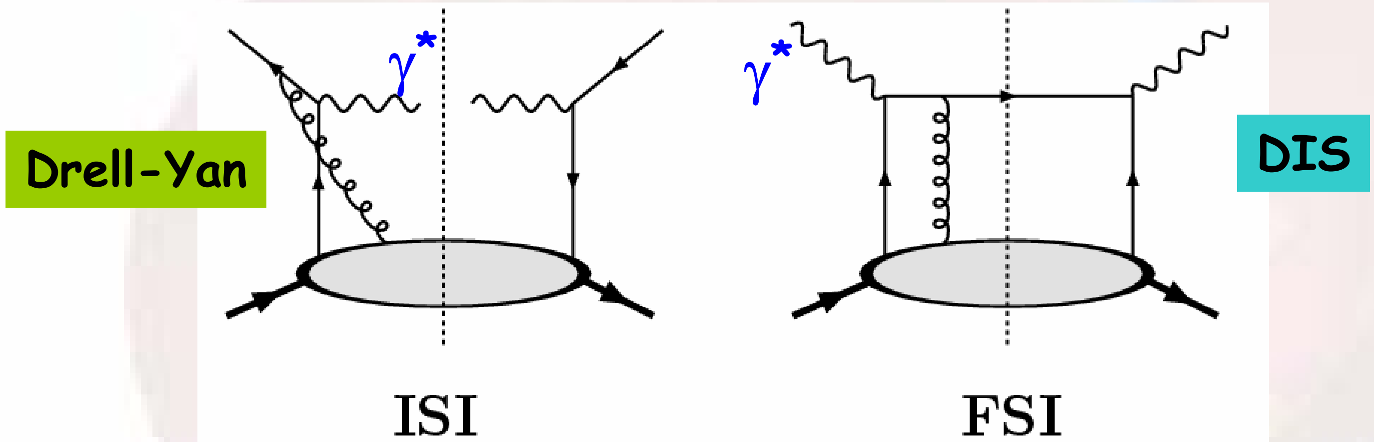
A unified picture for SSA

- In DIS and Drell-Yan processes, SSA depends on Q and transverse-momentum P_γ
  - At large P_γ, SSA is dominated by twist-3 correlation effects
  - At moderate P_γ, SSA is dominated by the transverse-momentum-dependent parton distribution/fragmentation functions
- The two mechanisms at intermediate P_γ generate the same physics!

Ji-Qiu-Vogelsang-Yuan, Phys.Rev.Lett.97:082002,2006

Testable prediction at RHIC

- Initial state vs. final state interactions



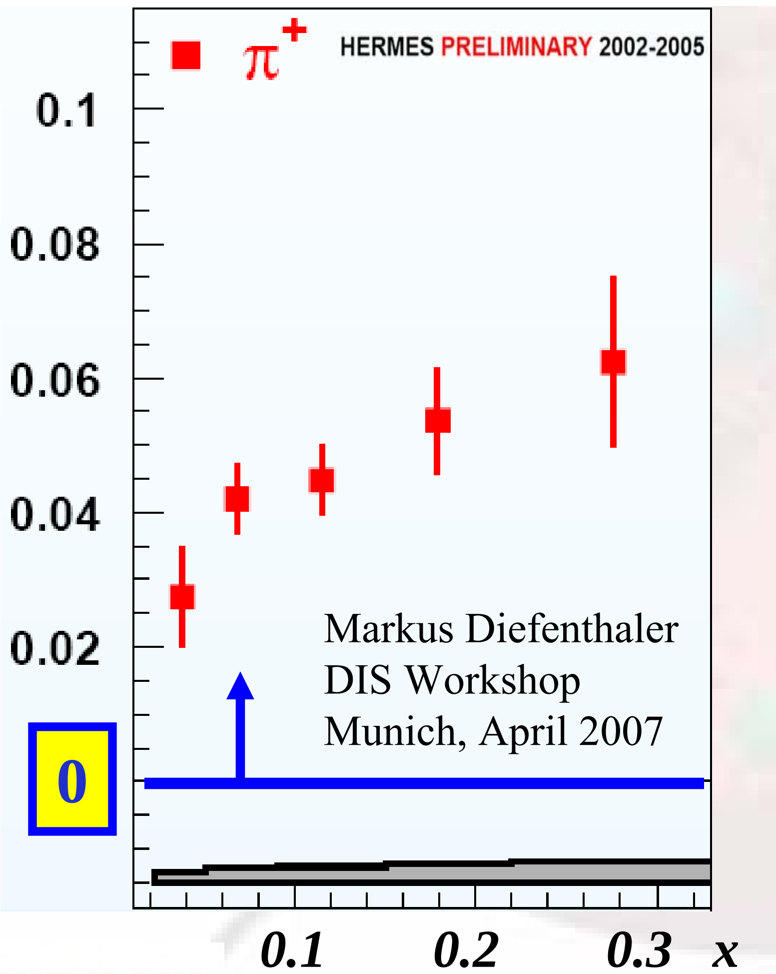
$$\text{Sivers}|_{DY} = -\text{Sivers}|_{DIS}$$

HERMES

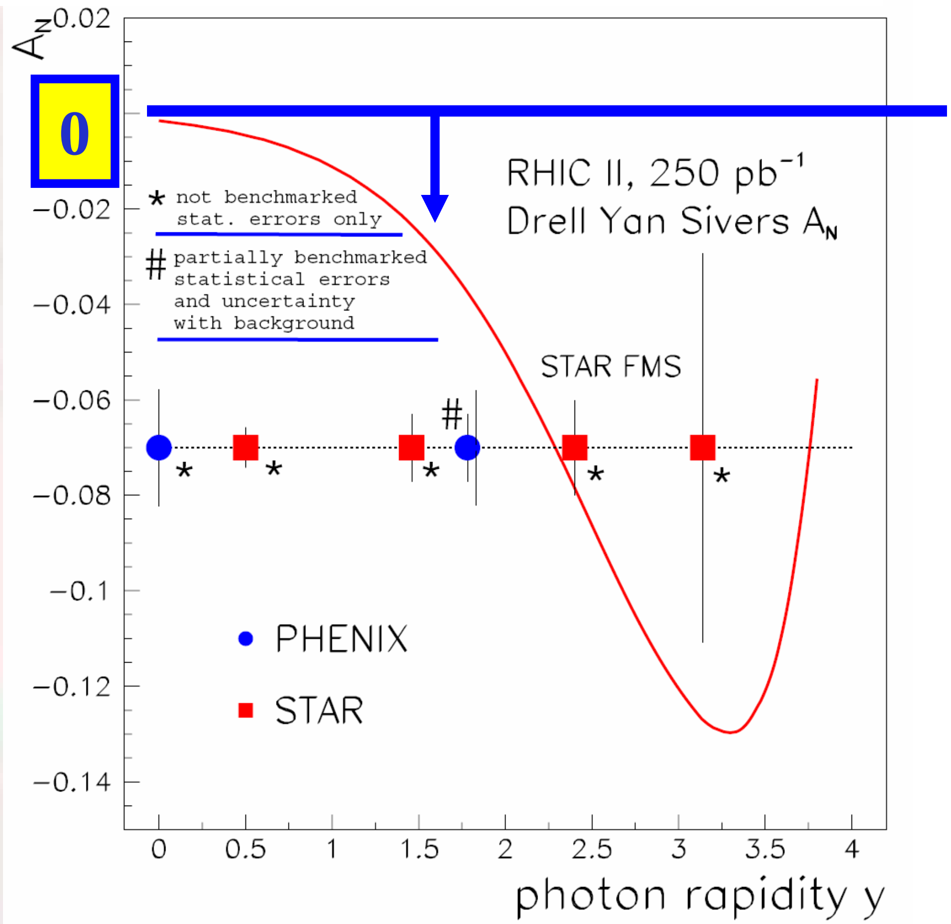
- "Universality": fundamental QCD prediction

Experiment SIDIS vs Drell Yan

HERMES Sivers Results

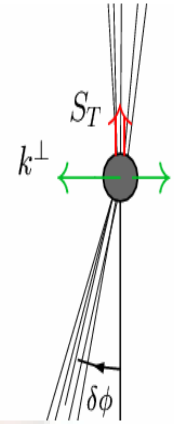


RHIC II Drell Yan Projections



http://spin.riken.bnl.gov/rsc/

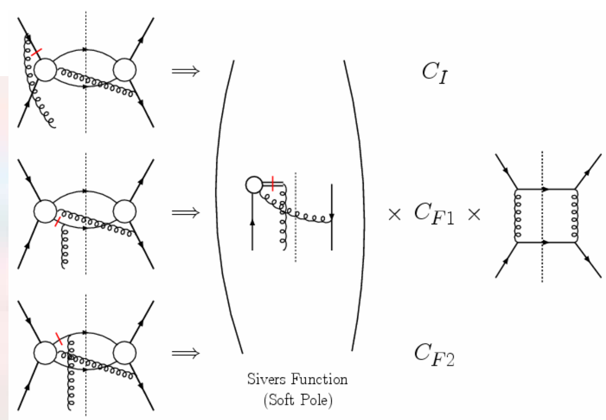
Alternative: Dijet-correlation at RHIC?



- Proposed by Boer-Vogelsang
  - Pheno. studies: Vogelsang-Yuan 05; Bomhof-Mulders-Vogelsang-Yuan 07
- Initial state and/or final state interactions?
  - Bacchetta-Bomhof-Mulders-Pijlman: hep-ph/0406099, hep-ph/0505268, hep-ph/0601171, hep-ph/0609206
  - Qiu-Vogelsang-Yuan, arXiv:0704.1153; 0706.1196
  - Collins-Qiu, arXiv:0705.2141
  - Mulders, et al., 07?
- Factorization? Universality?

The asymmetry can be related to that in DIS, in leading power of $q_?/P_t$, universality of the parton distributions?

$$\frac{d\sigma_{TU}}{d^2\vec{q}_\perp} = \sum_{ab}\int d^2k_{1\perp}d^2k_{2\perp}d^2\lambda_\perp \frac{\vec{k}_{1\perp}\cdot\hat{\vec{q}}_\perp}{M} x_a q_{Ta}^{(\text{DIS})}(x_a,k_{1\perp})x_b f_b(x_b,k_{2\perp})$$
$$H_{ab\to cd}^{\text{sivers}}(P_\perp^2)\delta^{(2)}(\vec{k}_{1\perp}+\vec{k}_{2\perp}-\vec{q}_\perp)$$



- q_T^{DIS}--- Sivers function from DIS
  $q_?$--- imbalance of the dijet
  H^{sivers} depends on subprocess

$$H_{ab\to cd}^{(\text{sivers})} = \frac{\alpha_s^2\pi}{\hat{s}^2}\sum_i\left(C_I^i + C_{F1}^i + C_{F2}^i\right)h_{ab\to cd}^i(\hat{s},\hat{t},\hat{u})$$

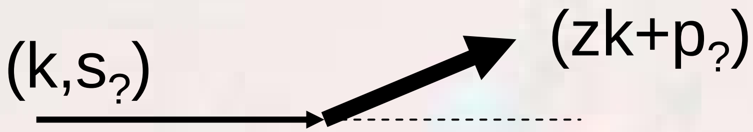
Qiu,Vogelsang,Yuan, 07

Questions…

- To what extend the factorization breaks down?
- Does a modified (weak) factorization hold if a general factorization breaks?
  - Universality will be an issue
- …
- More rigorous works need to be done to draw any conclusion
- Experiments at RHIC and future eRHIC can help us to answer these questions

Collins effects

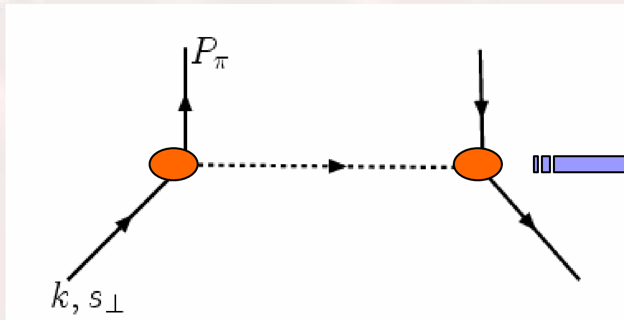
- An important ingredient to extract the quark transversity distribution



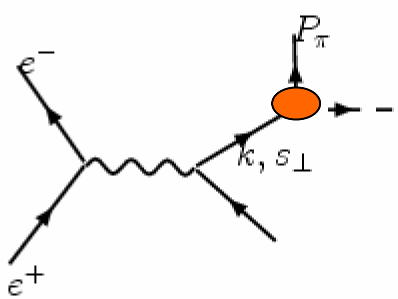
$\propto p_\perp \times s_\perp$

- Its universality property has attracted many theoretical and experimental investigations
  - Metz 02, Collins-Metz 02, 04
  - Boer-Mulders-Pijlman, 03
  - Gamberg-Goldstein, …
  - HERMES and Belle experiments, PRL 05-06

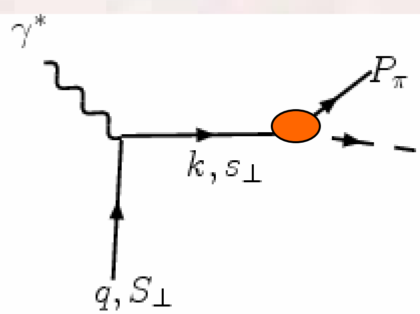
Simple model a la Collins 93



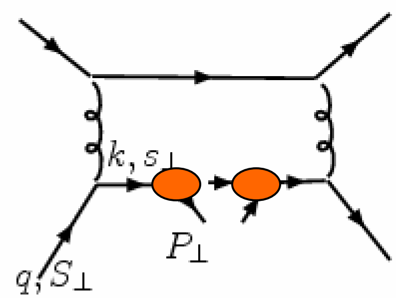
Phase information in the vertex
Collins-93



e^+e^- annihilation



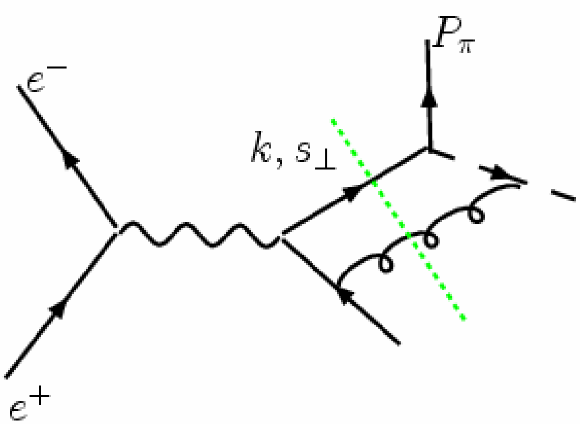
Semi-inclusive DIS

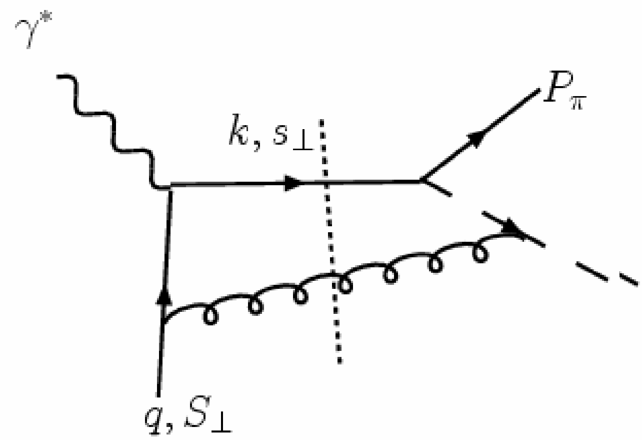


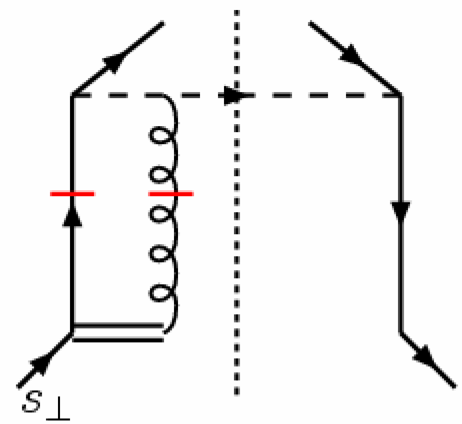
Hadron in a jet in pp

Universality of the Collins Function!!

One-gluon exchange (gauge link)?

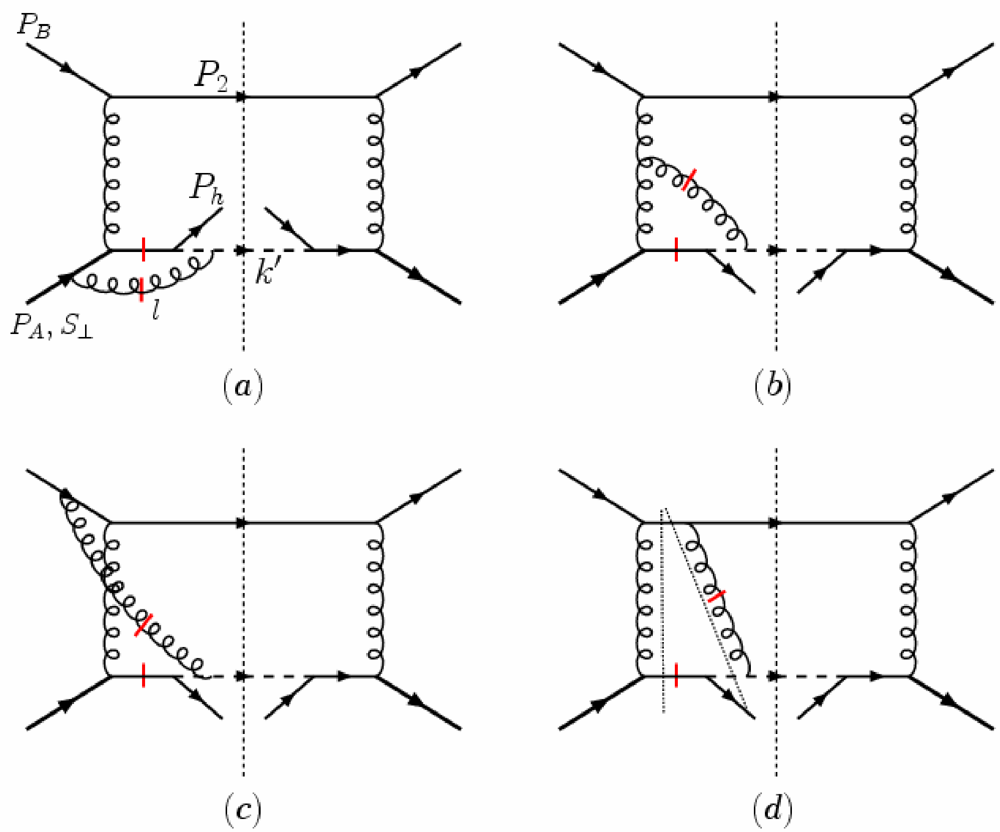




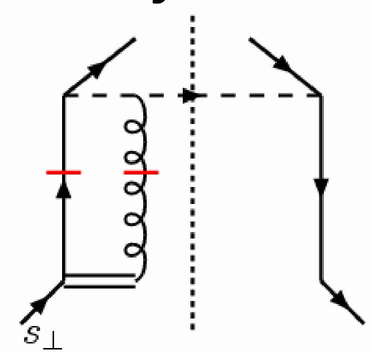


Metz 02, Collins-Metz 04:
Universality of the Collins function!!

Similar arguments for pp collisions



By using the Ward Identity:



same Collins fun.

Vogelsang, Yuan, to appear

Conjecture: the Collins function will be the same as e^+e^- and SIDIS

Open questions

- Universality for the SSA in the time-like region (fragmentation)
  - Experiments at Belle, RHIC, eRHIC are crucial
- Link with the quark-gluon correlation in the fragmentation process
  - Koike et al., 00-06
- Scale(Q^2)-dependence of all these SSAs

Summary

- We are in the early stages of a very exciting era of transverse spin physics studies, where the future RHICII and eRHIC will certainly play very important roles
- We will learn more about nucleon structure from these studies, especially for the quark orbital motion

What can we learn from SSA

- **Quark Orbital Angular Momentum**

  e.g, Sivers function ~ the wave function amplitude with nonzero orbital angular momentum!

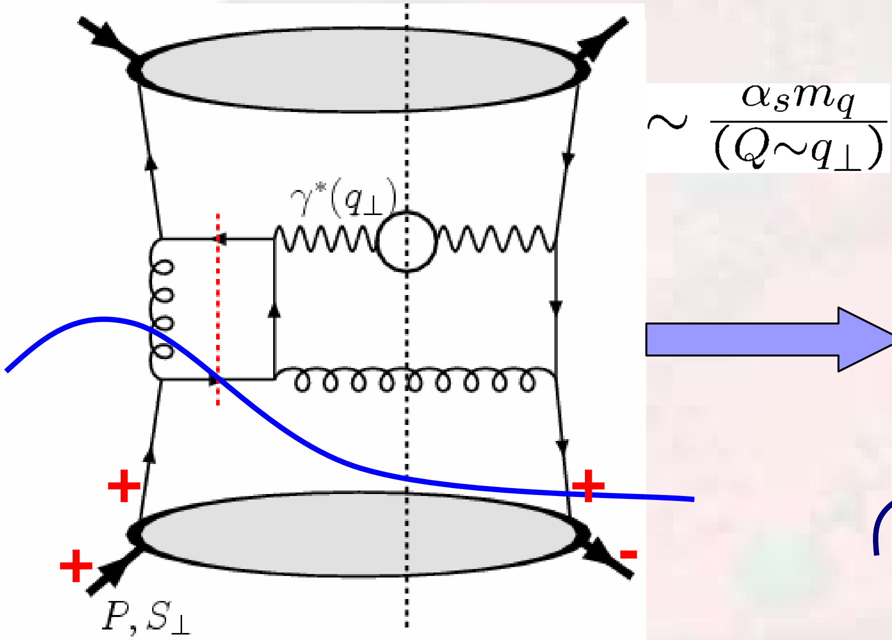
  Vanishes if quarks only in s-state!

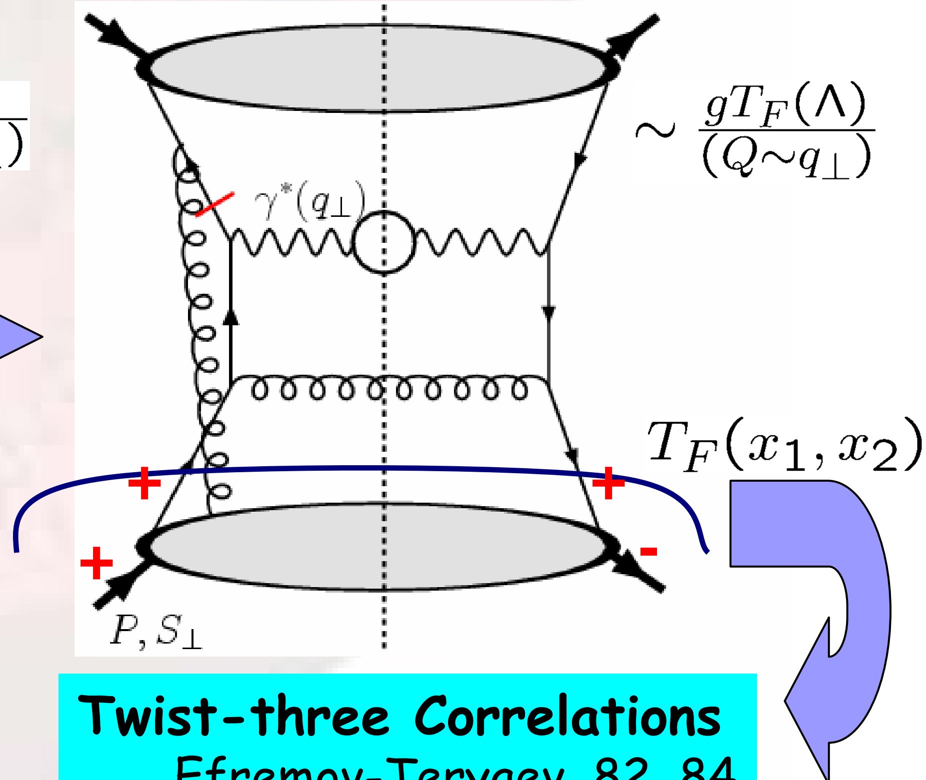
Ji-Ma-Yuan, NPB03
Brodsky-Yuan, PRD06

Take Drell-Yan as an example

(with non-zero transverse momentum q?)

- We need a loop to generate a phase



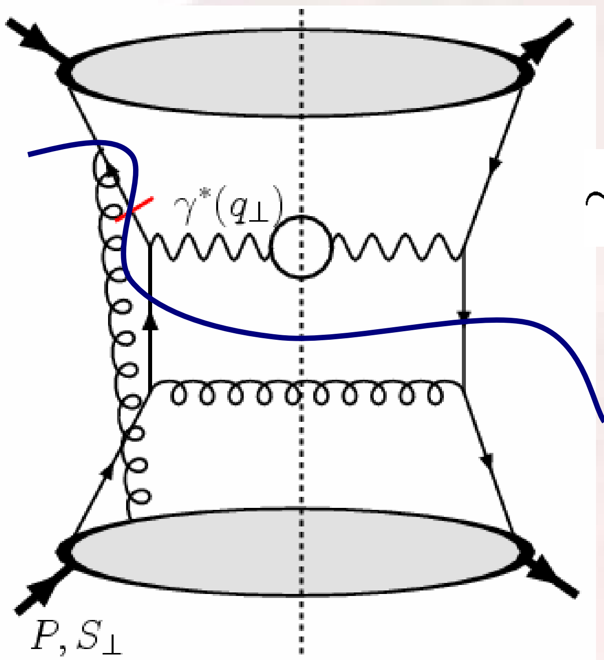


Kane et al., hard parton model

Twist-three Correlations
Efremov-Teryaev, 82, 84
Qiu-Sterman, 91,98

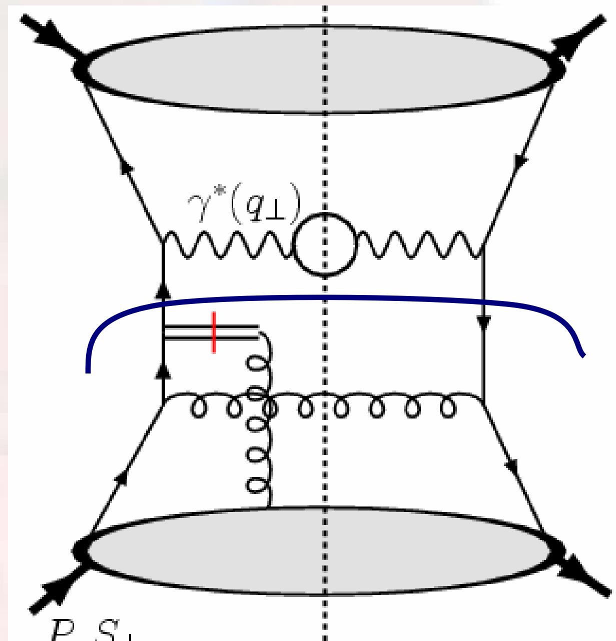
Further factorization ($q_? \ll Q$)

- The collinear gluons dominate



$q_? \ll Q$

$$\sim \frac{gT_F(\Lambda)}{q_\perp}$$

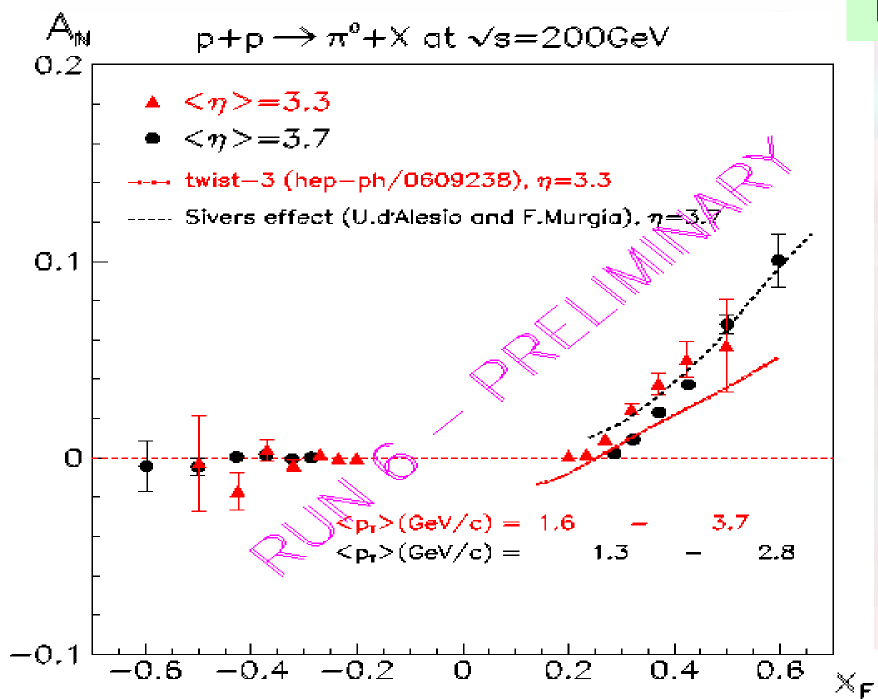


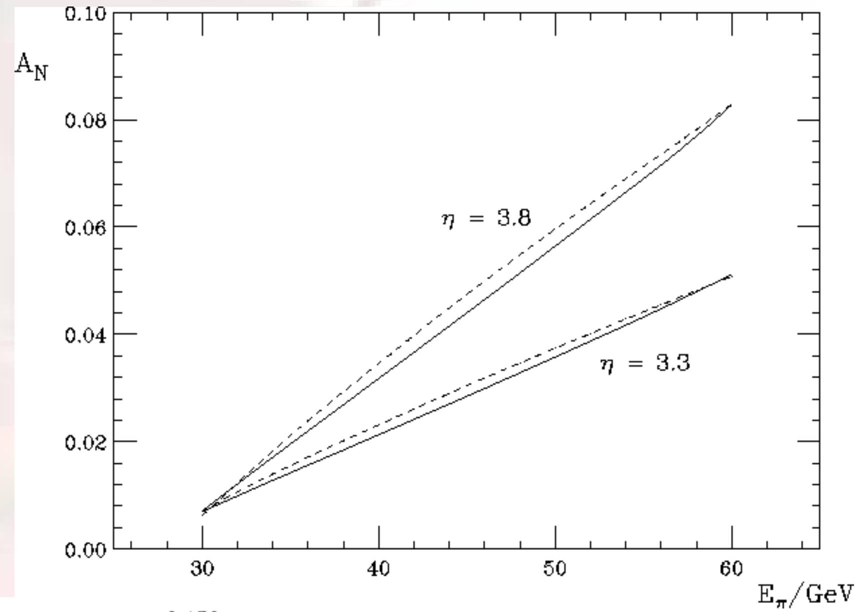
Twist-three Correlations
- Efremov-Teryaev, 82, 84
- Qiu-Sterman, 91,98

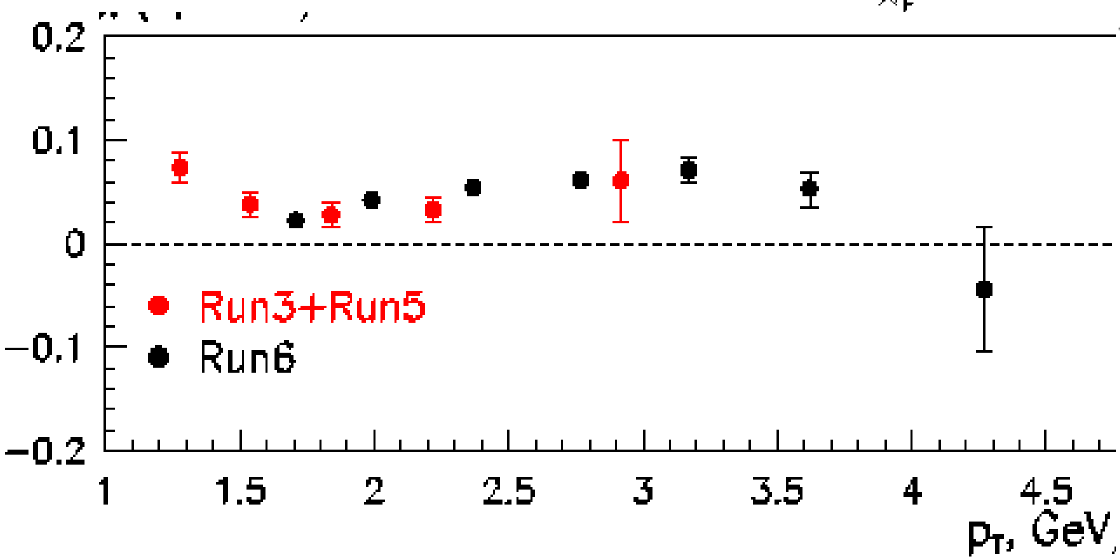
Transverse Momentum Dependent distributions
- Sivers, 90, Collins, 93,02
- Brodsky-Hwang-Schmidt,02
- Ji-Qiu-Vogelsang-Yuan,06

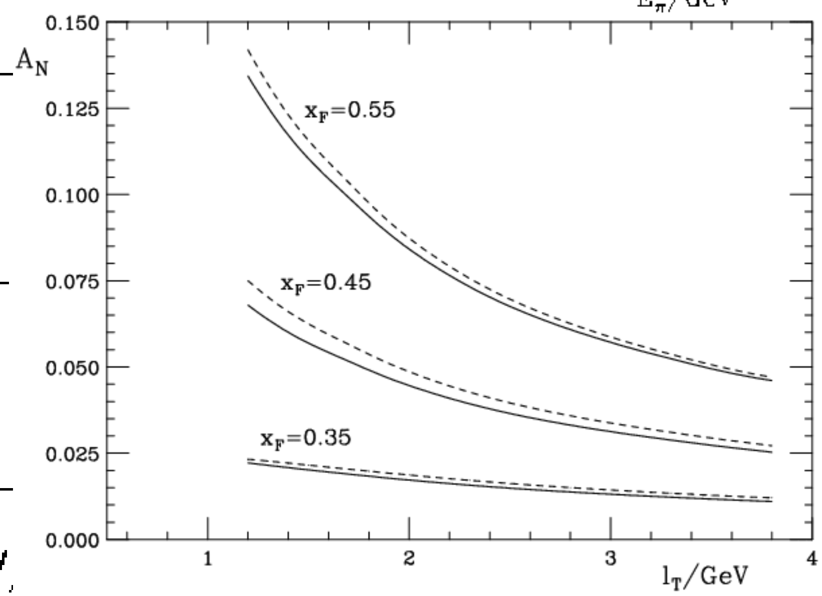
New challenge from STAR data (2006)

Talks by Ogawa and Nogach in SPIN2006









Some comments

- It's difficult to explain this pattern in the current theoretical approaches
- One possible reason could be the partial cancellation between the favored and disfavored contribution to Pi^0 production
  - Check with the charged pions?

Final Results

- $P_?$ dependence

$$\frac{d\triangle\sigma}{d^2q_\perp dy} = \int q_T(z_1,k_\perp)\bar{q}(z_2,k_\perp) + \left(\frac{d\triangle\sigma^{QS}}{d^2q_\perp dy} - \frac{d\triangle\sigma^{QS}}{d^2q_\perp dy}|_{aspt.}\right)$$

Sivers function at low $P_?$

Qiu-Sterman Twist-three

- Which is valid for all $P_?$ range
- SSA is suppressed by $1/P_t$ at large P_t

Extend to all other TMDs: large P_t power counting

- k_t-even distributions have the same dependence on k_t
- k_t-odd distributions are suppressed at large k_t
- Power Counting Rule

k_t-even: $1/k_t^2$

k_t-odd: $1/k_t^4$

SIDIS cross sections at large P_t

$$
\begin{aligned}
d\sigma \quad \propto \quad & (1-y+y^2/2)x_B F_{UU}^{(1)} \\
& -(1-y)x_B\cos(2\phi_h)F_{UU}^{(2)} \\
& +\lambda_\ell \lambda y(1-y/2)x_B F_{LL} \\
& +\lambda_\ell |S_\perp| y(1-y/2)x_B\cos(\phi_h-\phi_S)F_{LT} \\
& +\lambda(1-y)x_B\sin(2\phi_h)F_{UL} \\
& +|S_\perp|(1-y+y^2/2)x_B\sin(\phi_h-\phi_S)F_{UT}^{(1)} \\
& +|\vec{S}_\perp|(1-y)x_B\sin(\phi_h+\phi_S)F_{UT}^{(2)} \\
& +|\vec{S}_\perp|(1-y)x_B\sin(3\phi_h-\phi_S)F_{UT}^{(3)}/2
\end{aligned}
$$

$1/P_t^2$

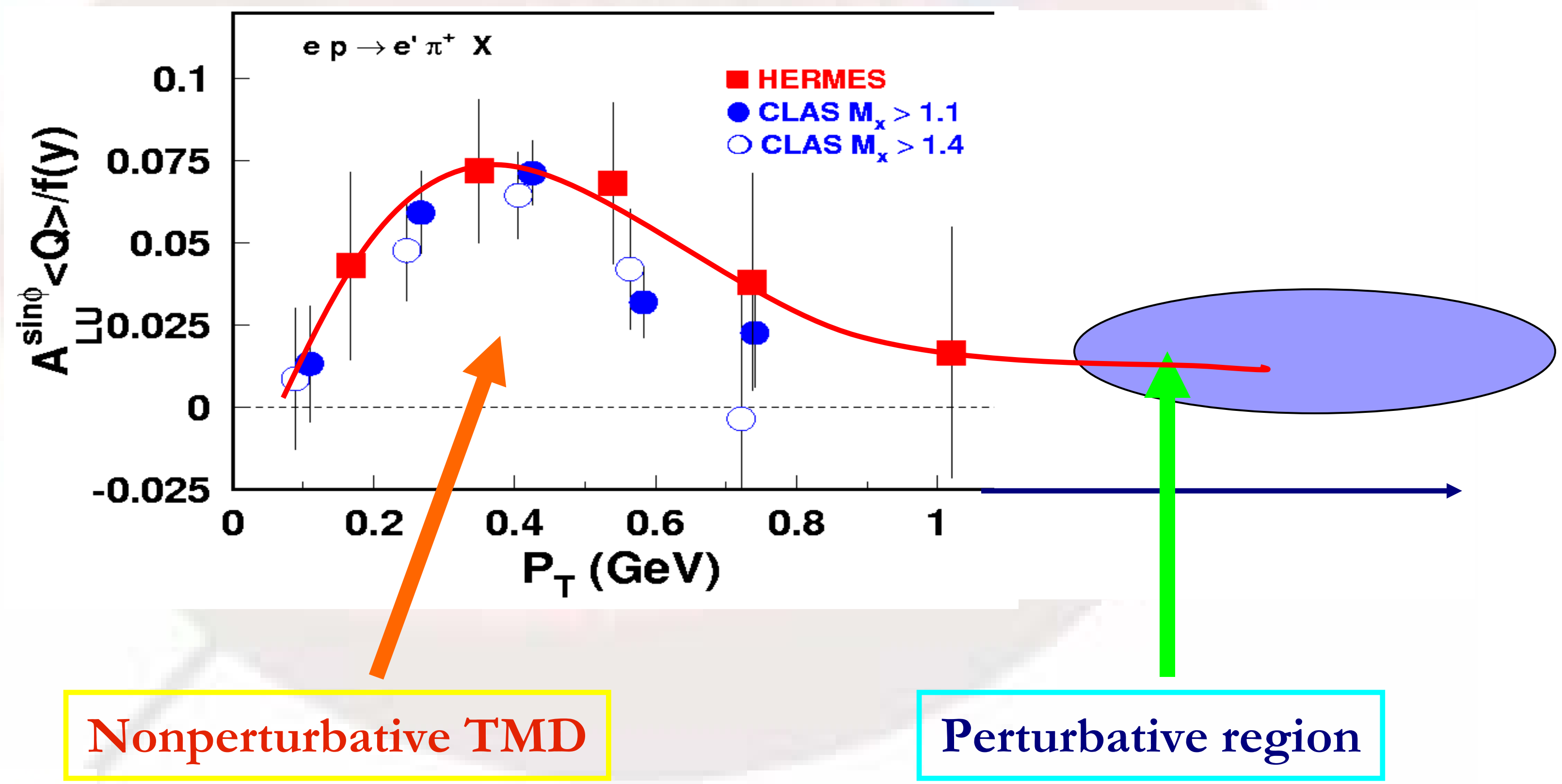
$1/P_t^4$

$1/P_t^3$

$1/P_t^5$

Transition from Perturbative region to Nonperturbative region?

- Compare different region of $P_?$



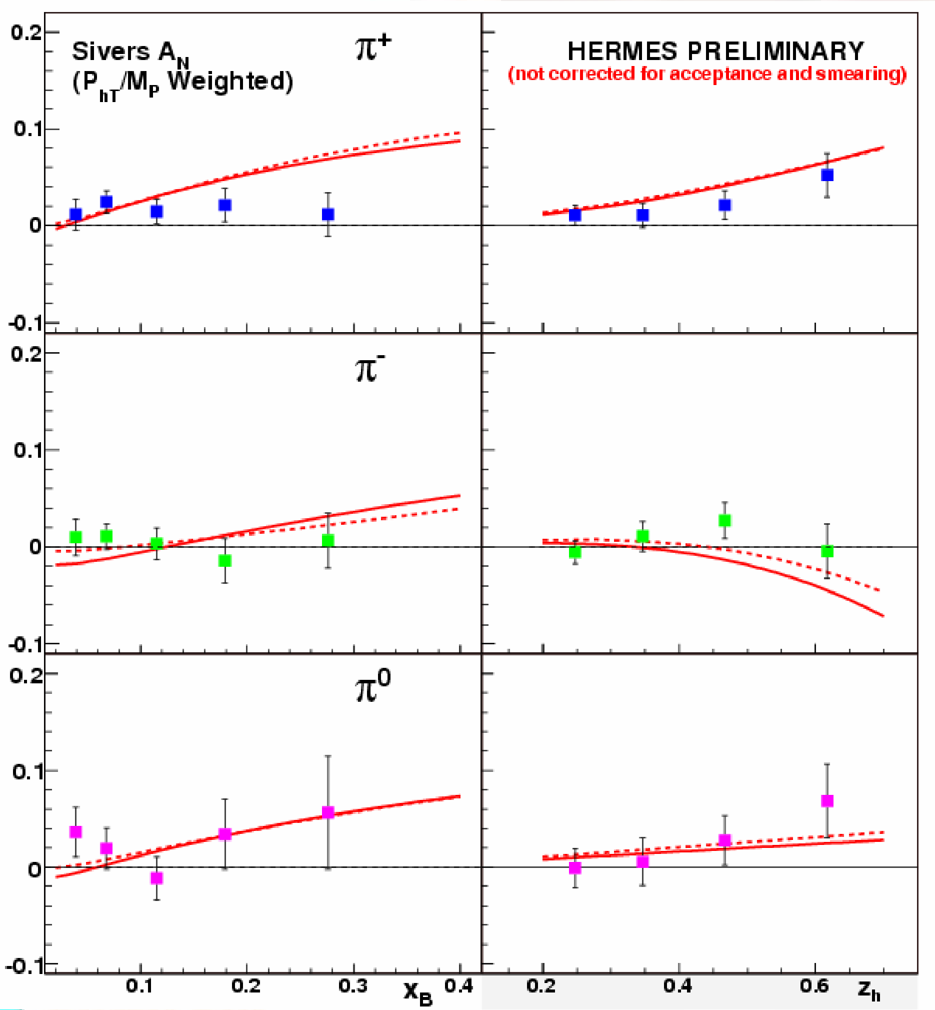
More over

- At low $P_{?}$¿ Q, the second term vanishes, use the Sivers function only
- $P_{?}$-moment of the asymmetry can be calculated from twist-three matrix element
  - In SIDIS, for the Sivers asymmetry

$$2\langle \frac{P_{h\perp}}{M_P} \sin(\phi_h - \phi_S) \rangle = \frac{\int \frac{1}{Q^4}(1-y+\frac{y^2}{2})\frac{z_h}{M_P} x_B \boxed{g_s T_F(x_B)} D(z_h)}{\int \frac{1}{Q^4}(1-y+\frac{y^2}{2}) x_B f_q(x_B) D(z_h)}$$

Boer-Mulders-Tangelmann, 96,98

Compare to the HERMES data



- T_F from the fit to single inclusive hadron data
  - Kouvaris-Qiu-Vogelsang-Yuan, hep-ph/0609238
- This comparison is very nontrivial, because the SSA in DIS depends on final state interactions, whereas in hadronic collision both initial and final state interactions contribute
- Indicate the consistency of SSAs in DIS and hadron collisions

See also, Efremov, et al., PLB612,233 (20005)

A new way to study higher-twist quark-gluon correlation functions?

- Large p_t SIDIS certainly will provide information on higher-twist distributions
- P_t-weighted azimuthal asymmetries will also give constraints on these distributions
  - Systematic analysis has to be done
  - Evolution, NLO corrections, …
  - It indeed opens a new window for studying higher-twsit quark-gluon correlations in SIDIS