# Single-Spin Asymmetry in p+A Collisions

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# Outline

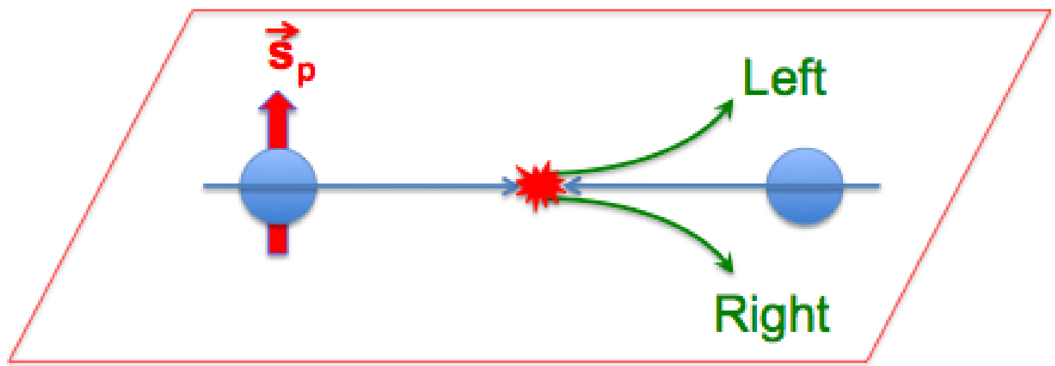
- Introduction (STSA, saturation/CGC)
- STSA in Drell-Yan vs SIDIS: will the sign flip be seen in DY in $p^{\uparrow}$+A ?
- Hadronic STSA in pA (CGC and other approaches):
  - Sivers effect in the nuclear background: does STSA get larger or smaller in $p^{\uparrow}$+A than in $p^{\uparrow}$+p?
  - Odderon exchange with the unpolarized nucleus: can this be measured?
- Conclusions and outlook

# Introduction

# Single Transverse Spin Asymmetry

- Consider transversely polarized proton scattering on an unpolarized proton or nucleus.

$$p(\vec{s}_\perp) + p \to h(\pi^\pm, \pi^0, ...) + X$$

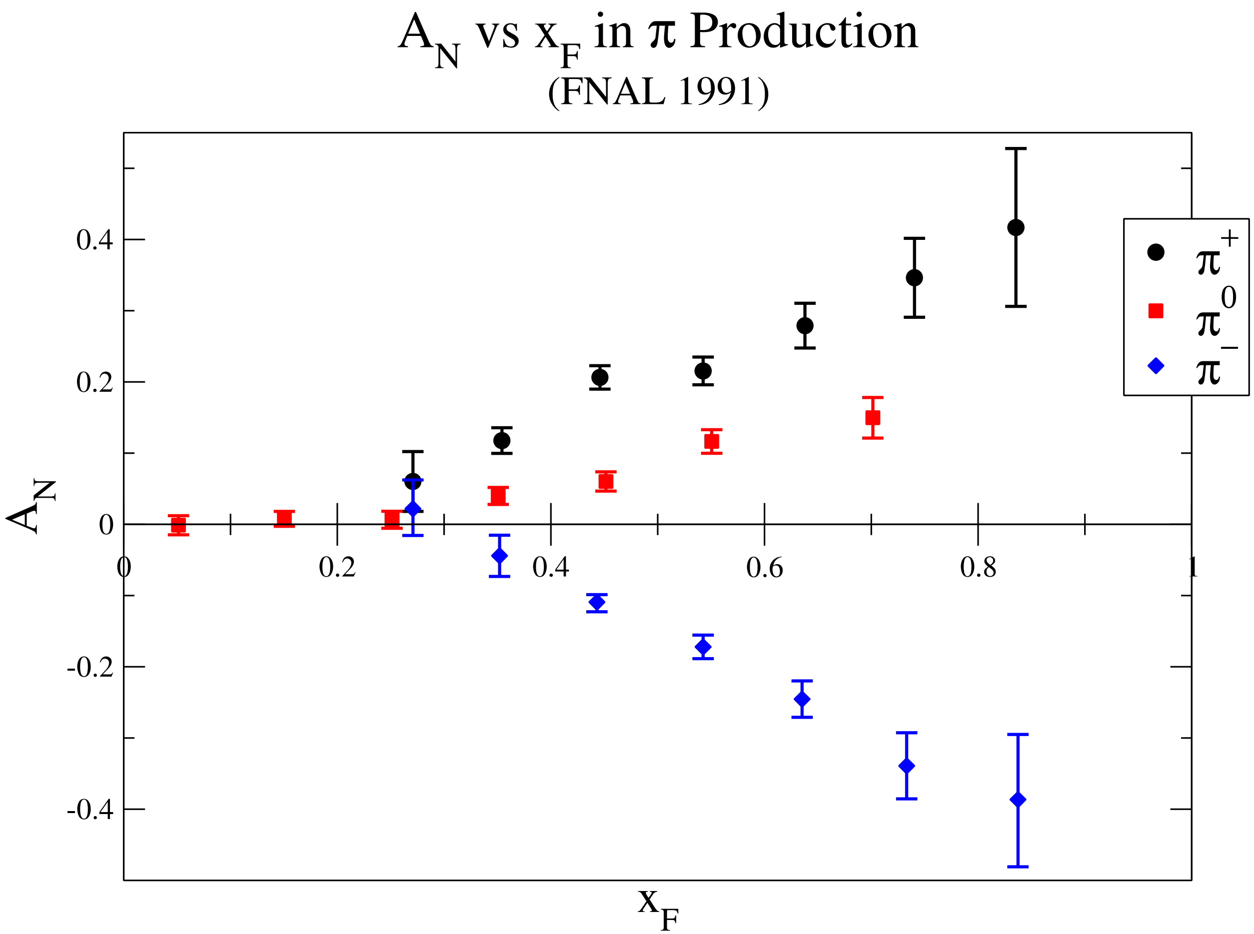



- Single Transverse Spin Asymmetry (STSA) is defined by

$$A_N(\mathbf{k}) \equiv \frac{\frac{d\sigma^\uparrow}{d^2k\,dy} - \frac{d\sigma^\downarrow}{d^2k\,dy}}{\frac{d\sigma^\uparrow}{d^2k\,dy} + \frac{d\sigma^\downarrow}{d^2k\,dy}} = \frac{\frac{d\sigma^\uparrow}{d^2k\,dy}(\mathbf{k}) - \frac{\mathbf{d}\sigma^\uparrow}{\mathbf{d^2k\,dy}}(-\mathbf{k})}{\frac{d\sigma^\uparrow}{d^2k\,dy}(\mathbf{k}) + \frac{\mathbf{d}\sigma^\uparrow}{\mathbf{d^2k\,dy}}(-\mathbf{k})} \equiv \frac{d(\Delta\sigma)}{2\,d\sigma_{unp}}$$

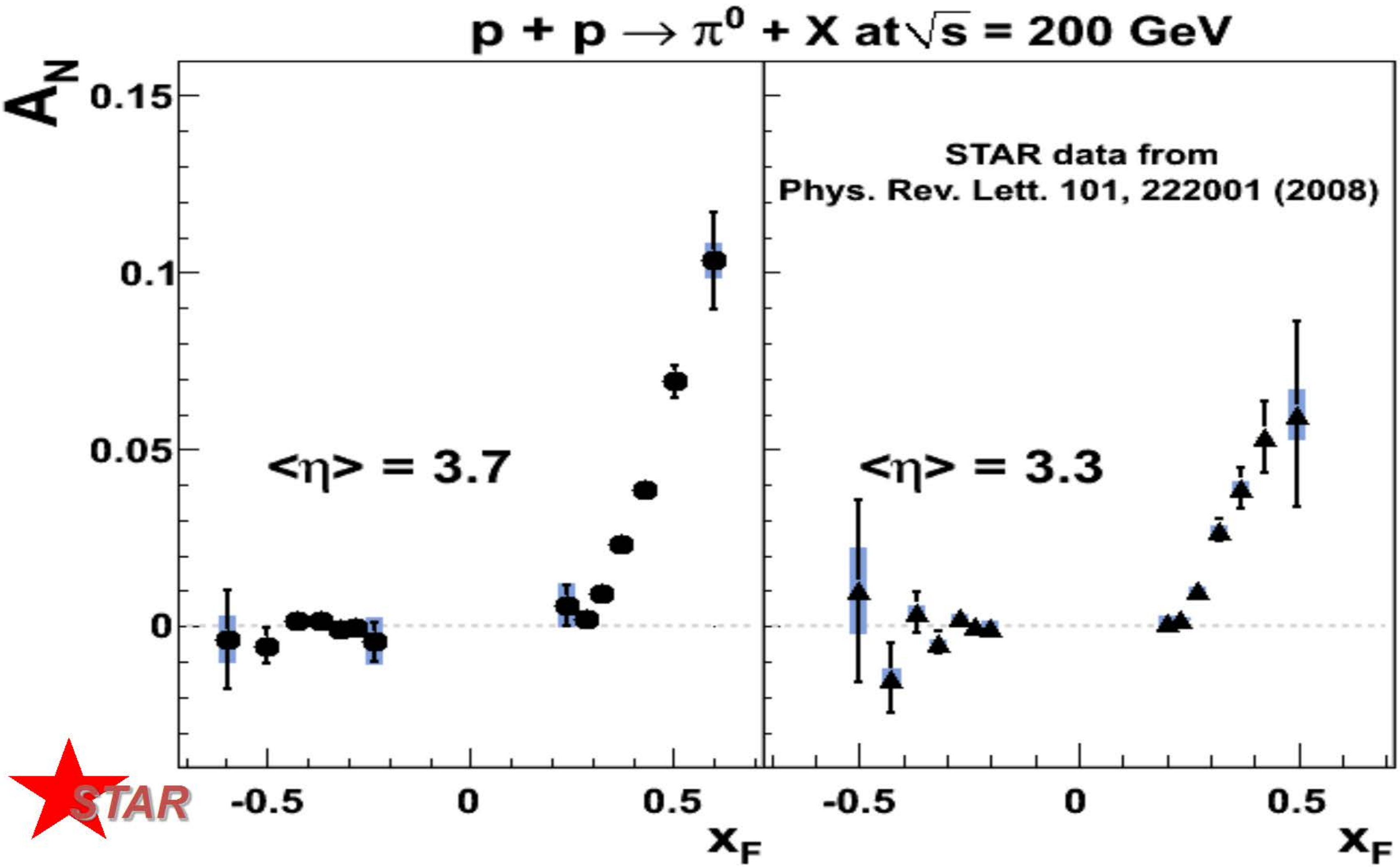
# STSA: the data

- The asymmetry is non-zero, and is an increasing function of Feynman-x of the polarized proton: a large-x effect in p↑



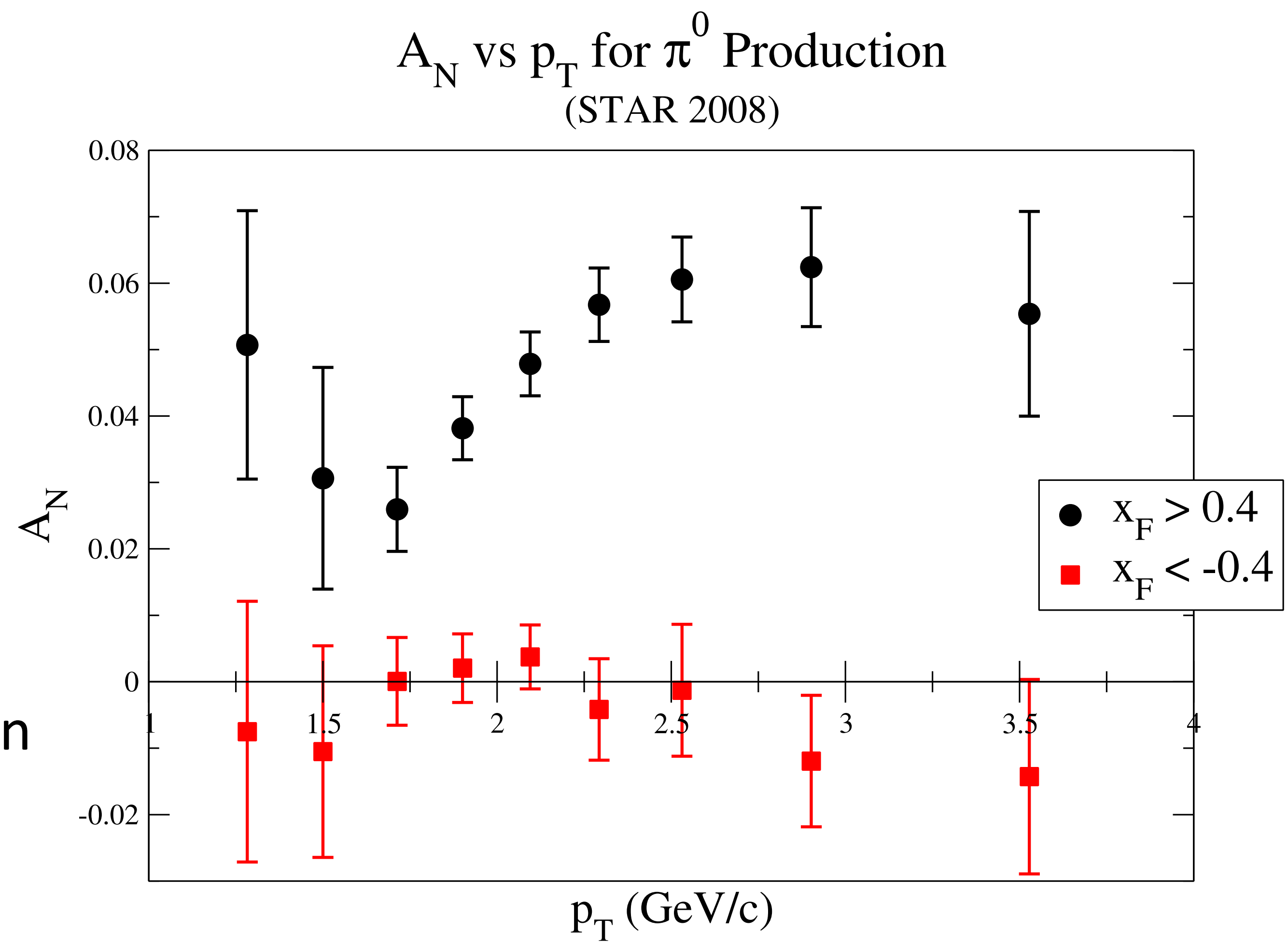

Fermilab E581 & E704 collaborations 1991

# STSA: a more recent data



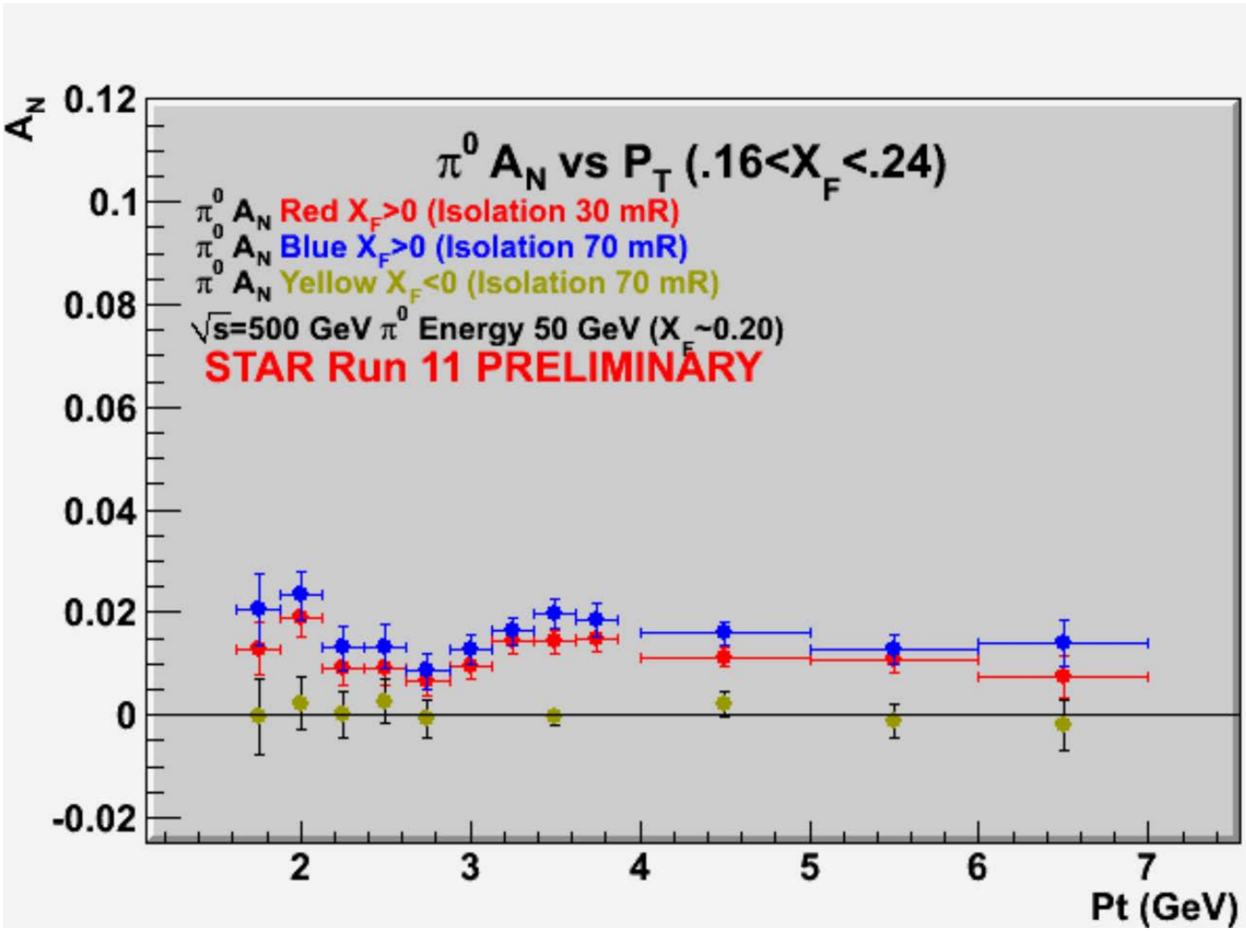
# STSA: the data

- STSA is also a non-monotonic function of transverse momentum $p_T$, which may have zeroes (nodes), where its sign changes:




RHIC,
STAR collaboration
2008

# STSA: a more recent data



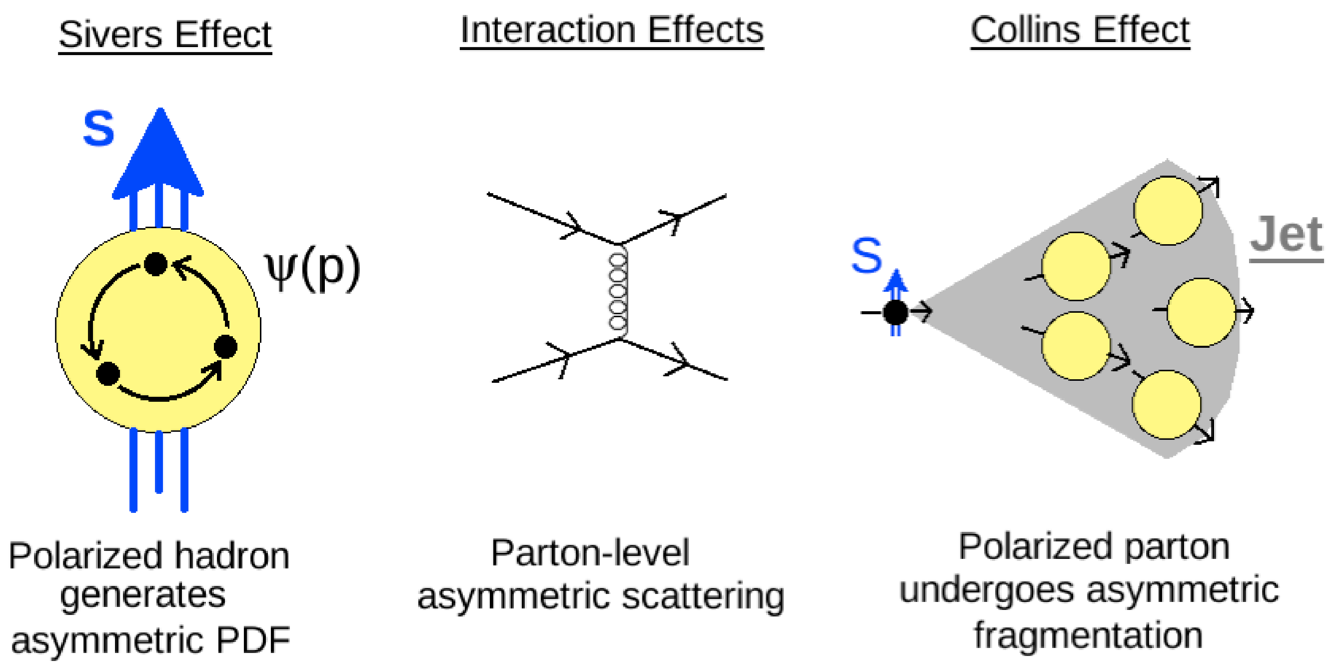

S. Heppelmann, ‘12

STSA is small but non-vanishing at high-$p_T$: an unsolved theory problem.

# Theoretical Explanations
# (TMD factorization framework)

The origin of STSA is in

- polarized PDF (Sivers effect)
- polarized fragmentation (Collins effect)
- hard scattering



# Need to understand STSAs in the saturation/CGC framework

- At RHIC, even p↑+p collisions reach small values of x in the unpolarized proton → saturation effects may be present
- For p↑+A scattering, nuclear target would further enhance saturtion/CGC effects, making understanding the role of saturation in STSA a priority
- Spin-dependent probes may provide new independent tests of saturation/CGC physics.

# High Energy QCD: saturation physics

- Saturation physics is based on the existence of a large internal momentum scale $Q_S$ which grows with both energy s and nuclear atomic number A

$$\boxed{Q_S^2 \sim A^{1/3}\ s^{\lambda}}$$

such that

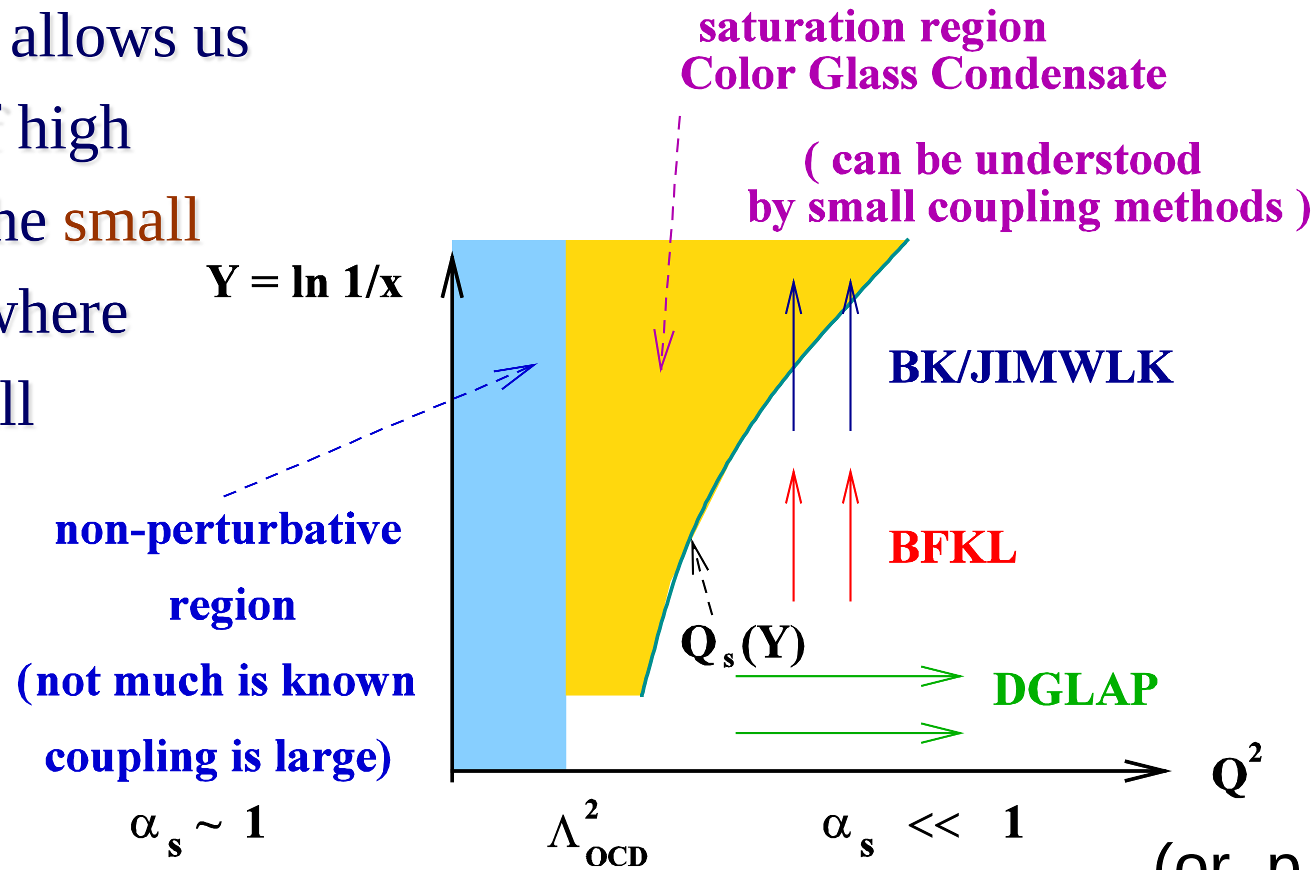
$$\boxed{\alpha_S = \alpha_S\left(Q_S\right) << 1}$$

and we can calculate total cross sections, particle spectra and multiplicities, etc, from <u>first principles</u>.

- Bottom line: everything is considered perturbative.

# Map of High Energy QCD

Saturation physics allows us to study regions of high parton density in the small coupling regime, where calculations are still under control!

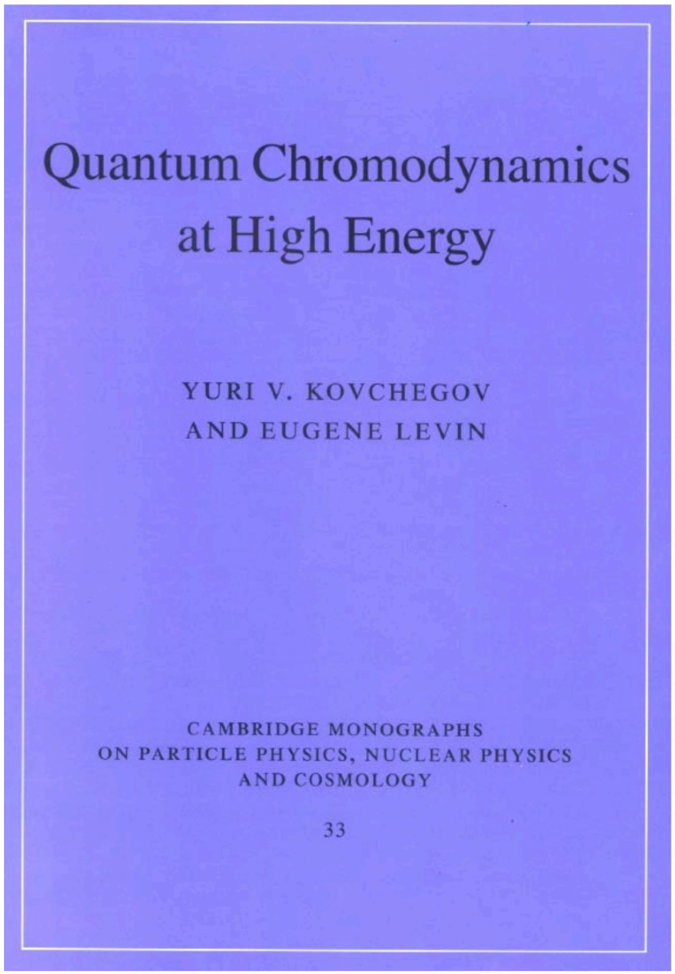



(or $p_T^2$)

Transition to saturation region is characterized by the saturation scale

$$Q_S^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

# A reference

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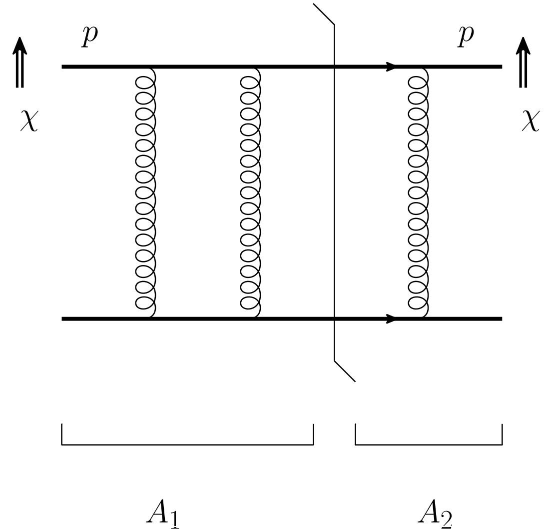
# STSA in SIDIS and Drell-Yan

# What generates STSA




Efremov, Teryaev '82

- To obtain STSA need
  - transverse polarization ($\chi$) dependence (comes with a factor of "i")

$$\bar{u}_\chi(p)\,\Gamma\,u_\chi(p) \sim a + i\,\chi\,b, \qquad a, b \text{ real}$$

However, cross section has to be real

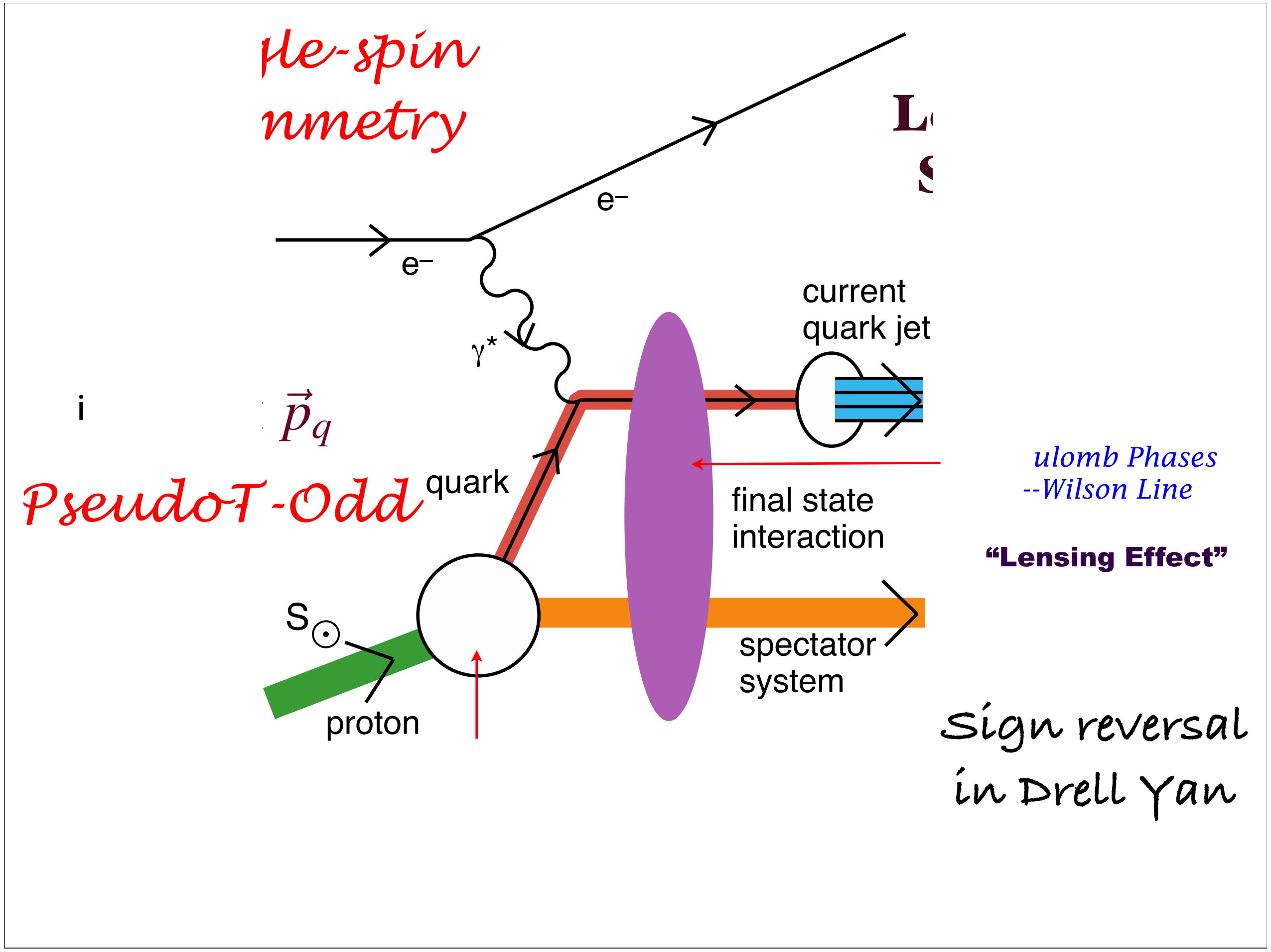
$$\sigma \sim \bar{u}_\chi(p)\,\Gamma\,u_\chi(p)\,A_1\,A_2^* + \text{c.c} = (a + i\,\chi\,b)\,A_1\,A_2^* + (a - i\,\chi\,b)\,A_1^*\,A_2$$
$$= (\chi - \text{independent}) + i\,\chi\,b\,(A_1\,A_2^* - A_1^*\,A_2)$$

such that we also need

  - a complex phase difference between the amplitude ($A_1$) and the cc amplitude ($A_2$) to cancel the "i" from $\chi$-dependence

(from Qiu and Sterman, early 90's)

# STSA IN SIDIS

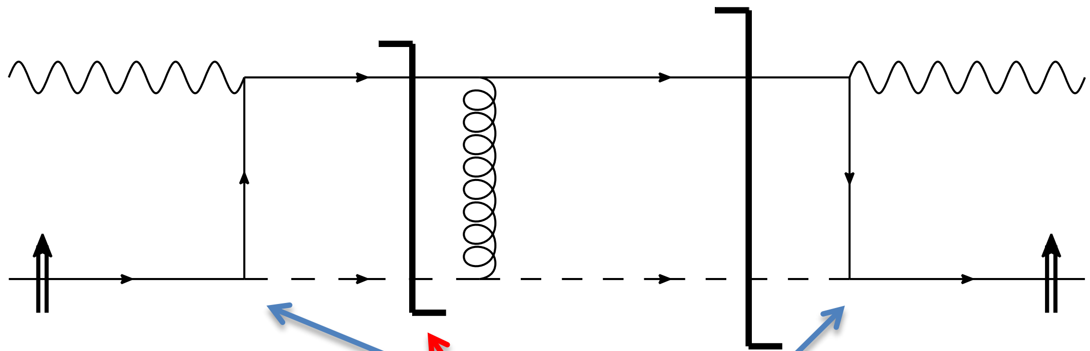



Brodsky, Hwang, Schmidt '02; Collins '02

- To generate STSA need a final state interaction (the blob above).
- In TMD factorization this is usually absorbed into the polarized proton TMD and is referred to as the initial-state effect, and hence identified with the Sivers effect.

# STSA in SIDIS

- STSA arises from the interference diagrams between Born-level and the one-rescattering graphs:



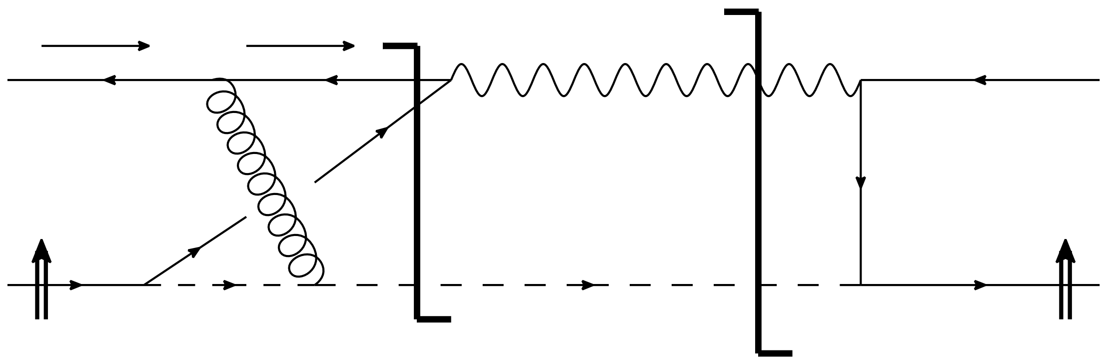
- Spin-dependence comes from the vertex.

- The phase is generated by an extra rescattering, which gives the amplitude an Im part represented by the second “cut”.

Brodsky, Hwang, YK, Schmidt, Sievert ‘13

# STSA in Drell-Yan

- Here we also need interference between the Born level amplitude and a one-rescattering correction to it.



- The DY STSA is also caused by two essential ingredients: (i) spin dependence from the quark-proton vertex and (ii) phase due to the extra cut (intermediate state) in the amplitude.
- Even though the cuts in SIDIS and DY are different, at large $Q^2$ the two STSAs are equal up to a sign reversal:

$$A_N^{DY} = -A_N^{SIDIS}$$

(Collins ’02; Brodsky, Hwang, Schmidt ’02; same+ YK, Sievert ‘13).

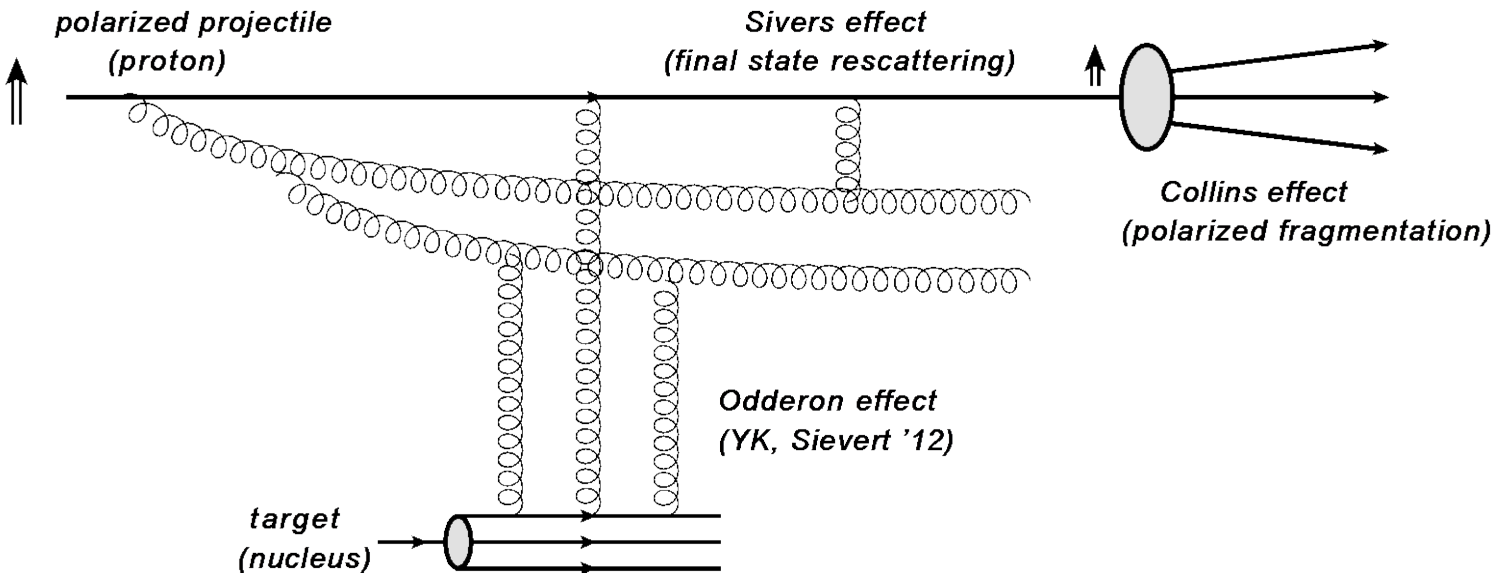
# STSA Sign Reversal in SIDIS vs DY

- RHIC p🠉+A program could complement the p🠉+p program by studying the sign reversal of STSA in DY vs SIDIS.

- If a sign reversal is observes in p🠉+p, it is interesting to see if it persists in p🠉+A.
  - TMD factorization violations? (Some higher twist corrections are enhanced by nuclear effects.)
  - Not clear whether the STSA in the DY process is described by the same diagrams as I showed above in high energy p🠉+A collisions: this is an open theoretical problem.

# Calculation of STSA in CGC

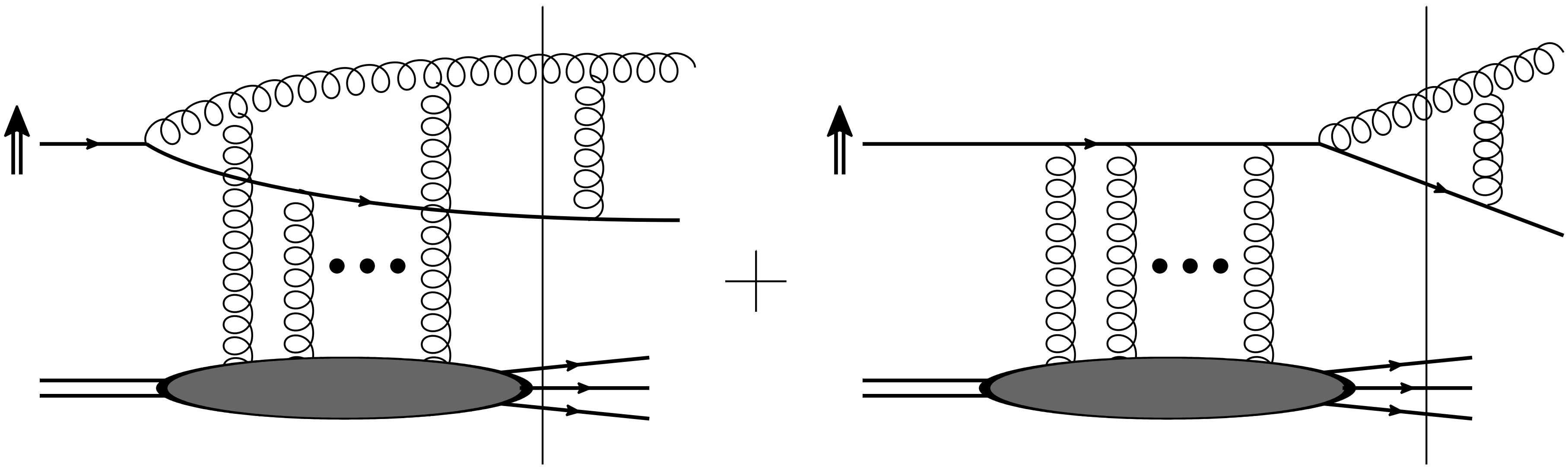
# Theoretical Explanations (CGC framework)




- In the CGC-based approaches STSA originates in
  - the light-cone wave function (spin-dependence) + late-time scattering on the polarized proton projectile (phase) = Sivers effect
  - the light-cone wave function (spin-dependence) + scattering on the unpolarized target (phase) = odderon mechanism
  - polarized fragmentation (Collins effect)

# STSA in CGC: Sivers Effect

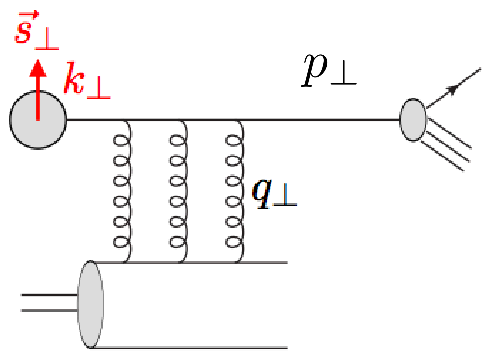
# Sivers effect in CGC



- This is the analogue of the works by Brodsky, Hwang, Schmidt '02 and Collins '02 in the saturation language.
- Both the phase and spin-dependence come from the top of the diagram. The phase is denoted by a cut (Im part = Cutkosky rules).
- This is still work in progress (YK, M. Sievert). In the saturation framework spin-dependence could also come in through the extra rescattering.
- In absence of theoretical calculations there are models: usually one assumes that Sivers effect is generated in the initial state, and includes interactions with the target using the CGC formalism.

# Naively incorporate Sivers effect

- Thinking about the incoming quark has a small kt-component, which generates a Sivers type correlation in the proton wave function (Sivers function)




$$p_\perp = z\,(k_\perp + q_\perp)$$

$$f_{q/p^\uparrow}(x, k_\perp) = f_{q/p}(x, k_\perp^2) + \frac{\epsilon_{\alpha\beta} s_\perp^\alpha k_\perp^\beta}{M_p} f_{1T}^{\perp,q}(x, k_\perp^2)$$

- Now spin-dependent cross section becomes

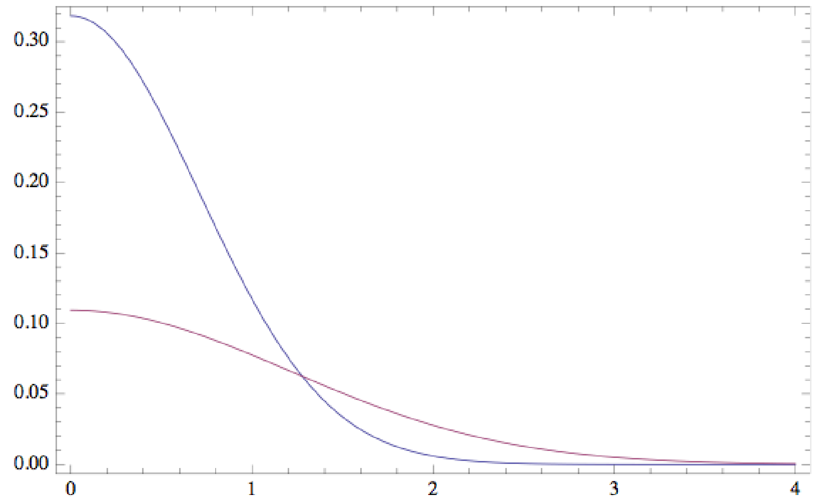
$$\frac{d\sigma}{dy d^2p_\perp} = \frac{K}{(2\pi)^2}\int d^2b \int_{x_F}^1 \frac{dz}{z^2}\int d^2k_\perp x\epsilon^{\alpha\beta} s_\perp^\alpha k_\perp^\beta f_{1T}^{\perp,q}(x, k_\perp^2) F(x_A, q_\perp = p_\perp/z - k_\perp) D_{h/q}(z)$$

  - Linear kt associated with Sivers function, need another kt to have kt-integral non-vanishing, which can only come from the gluon distribution
  - Spin asymmetry is sensitive to the slope of the dipole gluon distribution in kt-space

# Take GBW (MV) model as an example

- Take GBW model as an example: Qs = 1GeV in proton

$$F(x, q_\perp) = \frac{1}{\pi Q_s^2(x)} e^{-q_\perp^2/Q_s^2(x)}$$

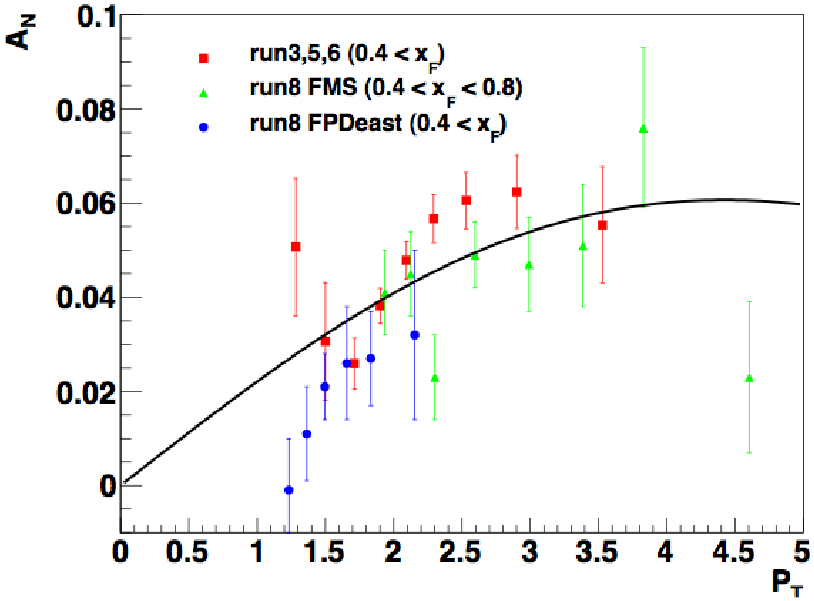


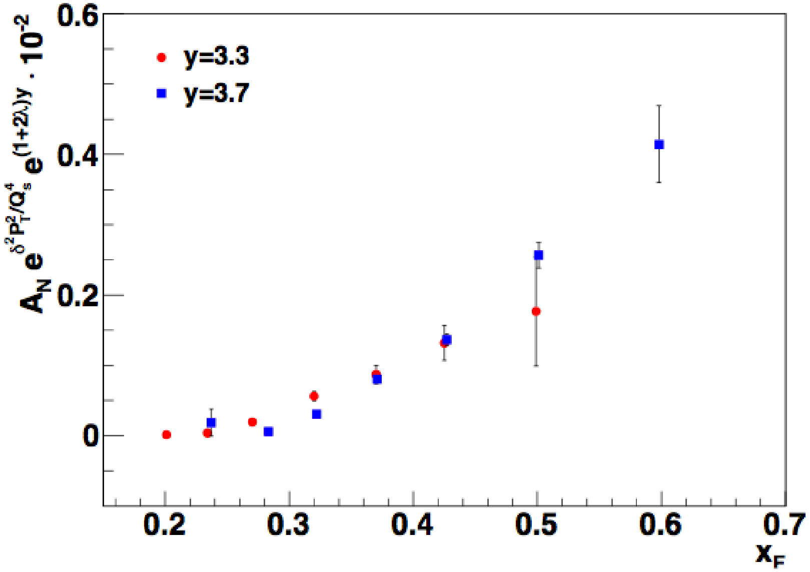

$$Q_{sA}^2 = cA^{1/3}Q_{sp}^2$$ DUsling-Gelis-Lappi-Venugolalan, arXiv:0911.2720

- Broadening might be difficult to see (as M. Chiu mentioned in his talk), but the slope could be easy to see
  - Comparing the $A_N$ of pp and pA at small pt, which should give these information

# Data seems to support scaling analysis

- Scaling analysis for pt and xf dependence




$$A_N \sim \frac{P_{h\perp}\Delta}{Q_s^2} e^{-\frac{\delta^2 P_{h\perp}^2}{(Q_s^2)^2}}$$

$$A_N e^{\delta^2 P_{h\perp}^2/Q_s^4} e^{(1+2\lambda)y_h} \sim x_F^{(1+\lambda)} \mathcal{F}(x_F)$$

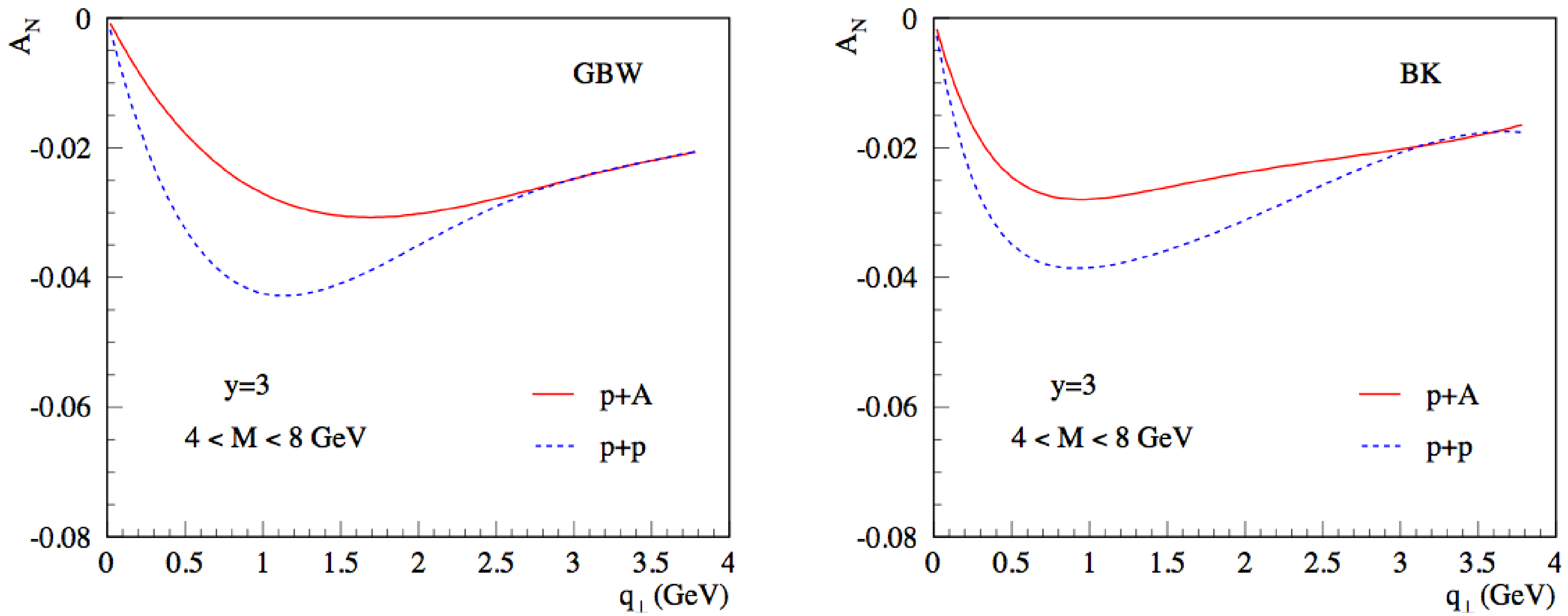
- Compare pp and pA collisions

$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}} \qquad \frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\gg Q_s^2} \approx 1$$

# Spin asymmetry at RHIC 510 GeV - I

- Transverse momentum dependence

Drell-Yan process, Kang & Xiao '12

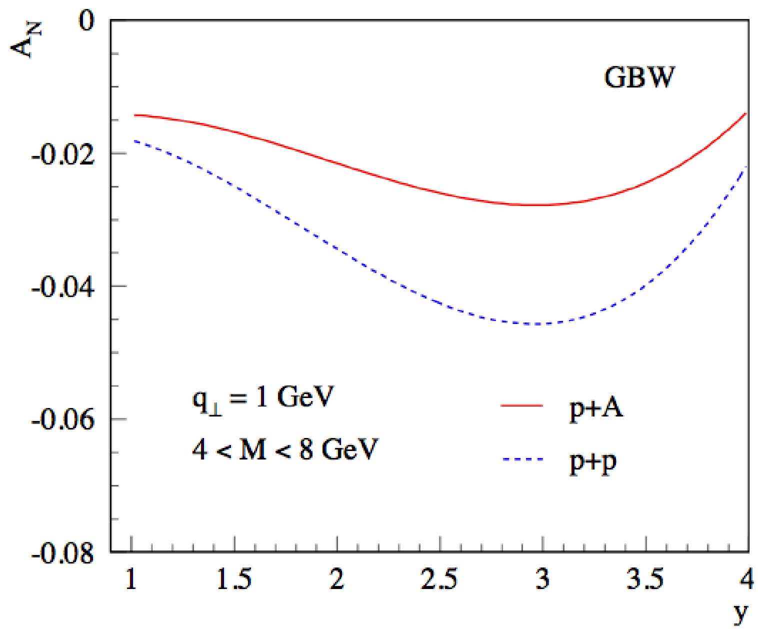


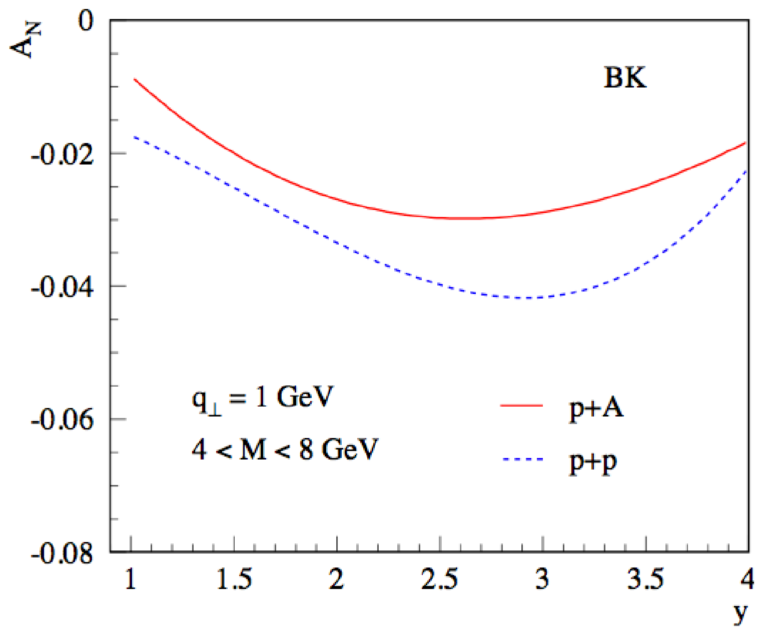

- Spin asymmetry is smaller in pA compared to pp, due to larger saturation scale

# Spin asymmetry at RHIC 510 GeV - II

- Rapidity dependence

Drell-Yan process, Kang & Xiao '12



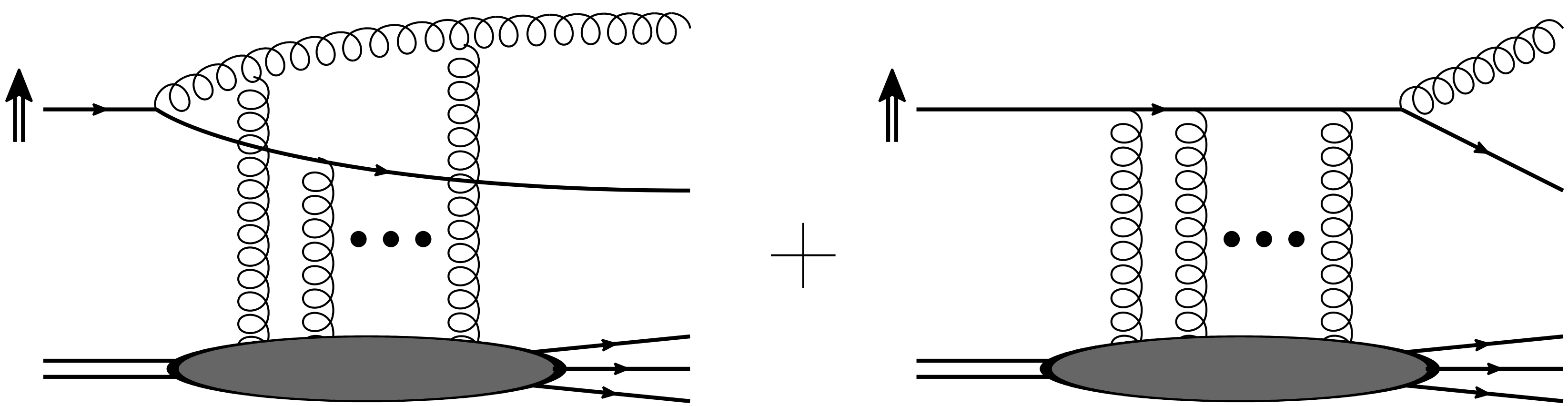

- The maximum happens at y~3, which corresponds to xp ~ 0.2 in the polarized proton (the Sivers function is largest at around this point)

# STSA in CGC: Odderon mechanism

YK, Sievert '12

# Spin-dependent quark production

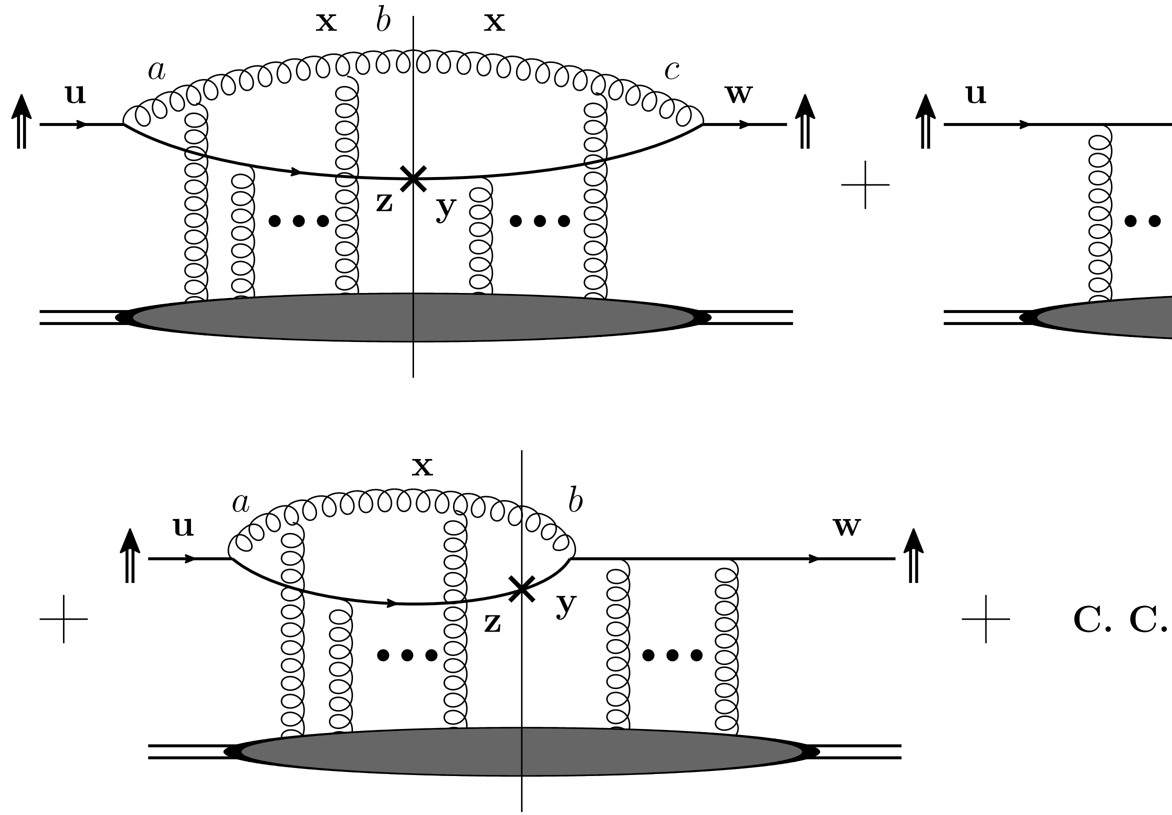
The only way to include spin dependence without 1/s suppression is through the splitting in the projectile before or after the collision with the target:



Let's calculate the corresponding quark production cross section, find its spin-dependent part, and see if it gives an STSA.

# Production Cross Section

Squaring the amplitude we get the following diagrams contributing to the production cross section:



# Extracting STSA

- STSA can be thought of as the term proportional to

$$(\vec{S} \times \vec{p}) \cdot \vec{k}$$

- To get a $k_T$-odd part of the cross section

$$\frac{d\sigma^{(q)}}{d^2k\, dy_q} = \frac{C_F}{2\,(2\pi)^3}\, \frac{\alpha}{1-\alpha} \int d^2x\, d^2y\, d^2z\, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})}\, \Phi_\chi(\mathbf{z}-\mathbf{x}\,,\, \mathbf{y}-\mathbf{x})\, \mathcal{I}^{(\mathbf{q})}(\mathbf{x}\,,\, \mathbf{y}\,,\, \mathbf{z})$$

  we need the $\mathbf{y} \leftrightarrow \mathbf{z}$ anti-symmetric part of the integrand.
- This may either come from the wave function squared or from the interaction with the target.
- Our LO wave function is symmetric: need to find the anti-symmetric interaction!

# C-even and C-odd dipoles

- To find the anti-symmetric interaction we decompose the dipole amplitude into real symmetric (C-even) and imaginary anti-symmetric (C-odd) parts:

$$\frac{1}{N_c}\left\langle \mathrm{tr}\left[V_{\mathbf{x}}\, V_{\mathbf{y}}^{\dagger}\right]\right\rangle = S_{\mathbf{x}\,\mathbf{y}} + i\, O_{\mathbf{x}\,\mathbf{y}}$$

- The symmetric part is

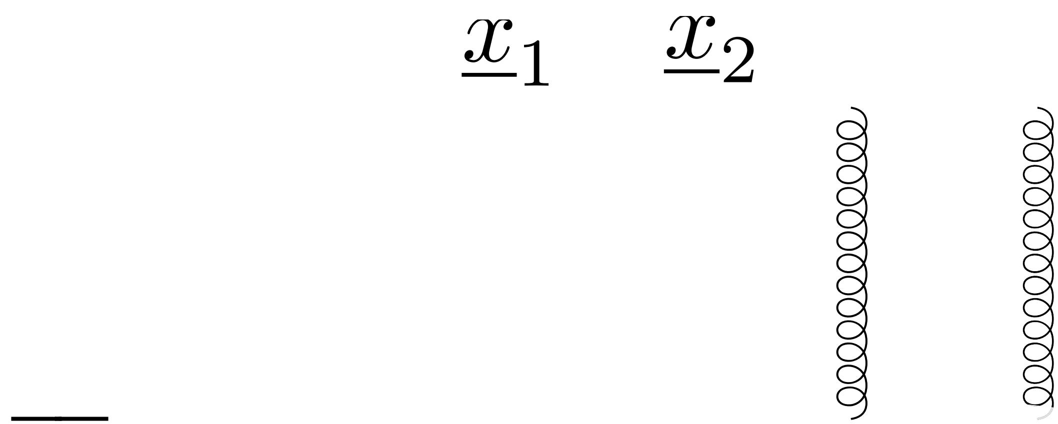
$$S_{\mathbf{x}\,\mathbf{y}} = \frac{1}{2}\left\{\frac{1}{N_c}\left\langle \mathrm{tr}\left[V_{\mathbf{x}}\, V_{\mathbf{y}}^{\dagger}\right]\right\rangle + \frac{1}{N_c}\left\langle \mathrm{tr}\left[V_{\mathbf{y}}\, V_{\mathbf{x}}^{\dagger}\right]\right\rangle\right\}$$

- The anti-symmetric part is

$$O_{\mathbf{x}\,\mathbf{y}} = \frac{1}{2\,i}\left\{\frac{1}{N_c}\left\langle \mathrm{tr}\left[V_{\mathbf{x}}\, V_{\mathbf{y}}^{\dagger}\right]\right\rangle - \frac{1}{N_c}\left\langle \mathrm{tr}\left[V_{\mathbf{y}}\, V_{\mathbf{x}}^{\dagger}\right]\right\rangle\right\}$$

- As $\mathbf{x} \leftrightarrow \mathbf{y}$ interchanges quark and antiquark, it is C-parity!

# Wilson lines



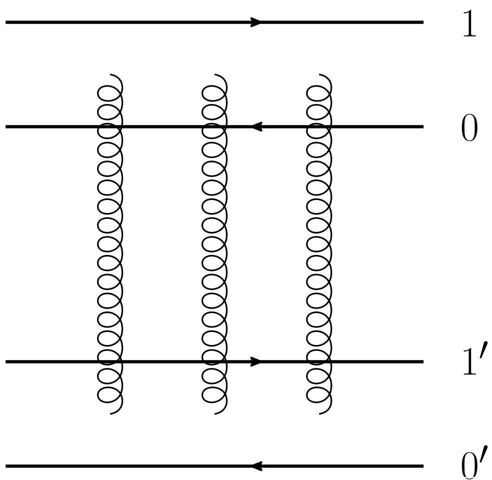

- The eikonal quark propagator is given by the Wilson line

$$V(\underline{x}) = \mathrm{P}\exp\left[ i\,g \int\limits_{-\infty}^{\infty} dx^+ \, A^-(x^+, x^- = 0, \underline{x}) \right]$$

with the light cone coordinates $\quad x^{\pm} = \frac{t \pm z}{\sqrt{2}}$

# C-even and C-odd dipoles

- $S_{xy}$ is the usual C-even dipole amplitude, to be found from the BK/JIMWLK equations: describes DIS, unpolarized quark and gluon production
- $O_{xy}$ is the C-odd odderon exchange amplitude, obeying a different evolution equation (Yu.K., Szymanowski, Wallon ’03; Hatta et al ‘05)
- At LO the odderon is a 3-gluon exchange:




- The intercept of the odderon is zero (Bartels, Lipatov, Vacca ’99):

$$\sigma_{odd} \sim s^0 \sim const$$

- In our setup, odderon naturally generates STSA.

# Odderon STSA

- When the dust settles, the spin-dependent part of the production cross section is

spin-dependence

$$d(\Delta\sigma^{(q)}) = \frac{C_F}{(2\pi)^3}\,\frac{\alpha}{1-\alpha}\int d^2x\, d^2y\, d^2z\, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})}\,\Phi_{pol}(\mathbf{z}-\mathbf{x}\,,\,\mathbf{y}-\mathbf{x})\,\mathcal{I}^{(\mathbf{q})}_{\mathbf{anti}}(\mathbf{x}\,,\,\mathbf{y}\,,\,\mathbf{z})$$

with the C-odd interaction with the target

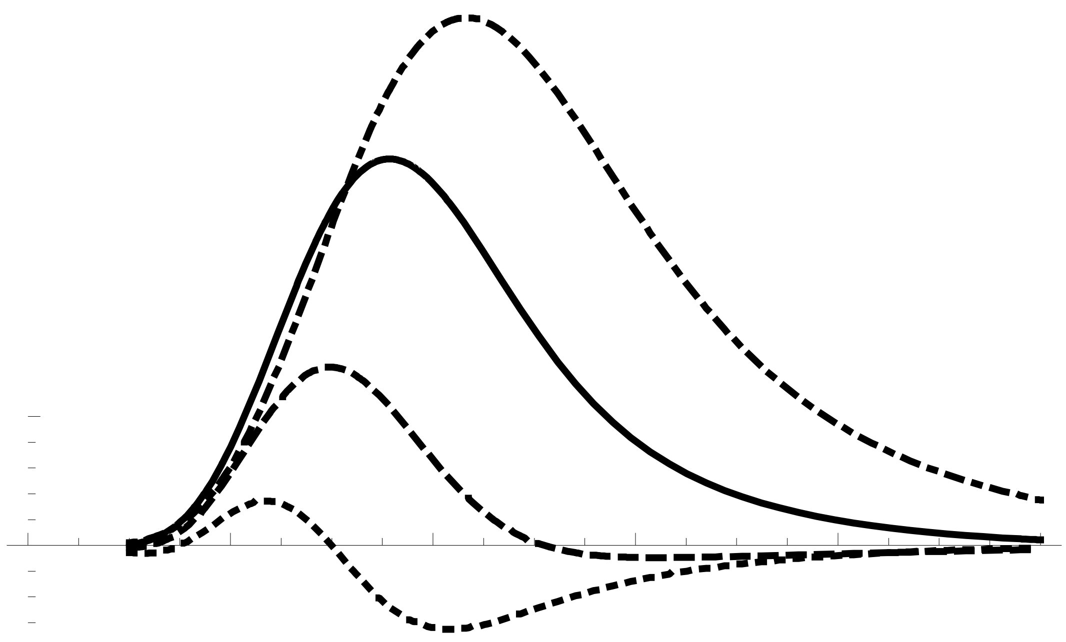
phase

$$\mathcal{I}^{(q)}_{anti}\Big|_{\text{large}-N_c} = i\,[O_{\mathbf{z}\,\mathbf{y}} + O_{\mathbf{u}\,\mathbf{w}} - O_{\mathbf{z}\,\mathbf{x}}\,S_{\mathbf{x}\,\mathbf{w}} - O_{\mathbf{u}\,\mathbf{x}}\,S_{\mathbf{x}\,\mathbf{y}} - S_{\mathbf{z}\,\mathbf{x}}\,O_{\mathbf{x}\,\mathbf{w}} - S_{\mathbf{u}\,\mathbf{x}}\,O_{\mathbf{x}\,\mathbf{y}}]$$

- Note that the interaction contains nonlinear terms: only those survive in the end.
- The expression for the interaction at any $N_c$ is known.

# Odderon STSA properties

Our odderon STSA is a non-monotonic function of transverse momentum and an increasing function of Feynman-x:



Warning: very crude approximation of the formula. ($Q_s$=1 GeV)
Curves are for (Feynman-x) $\alpha$ =0.9 (dash-dotted), 0.7 (solid), 0.6 (dashed), 0.5 (dotted).

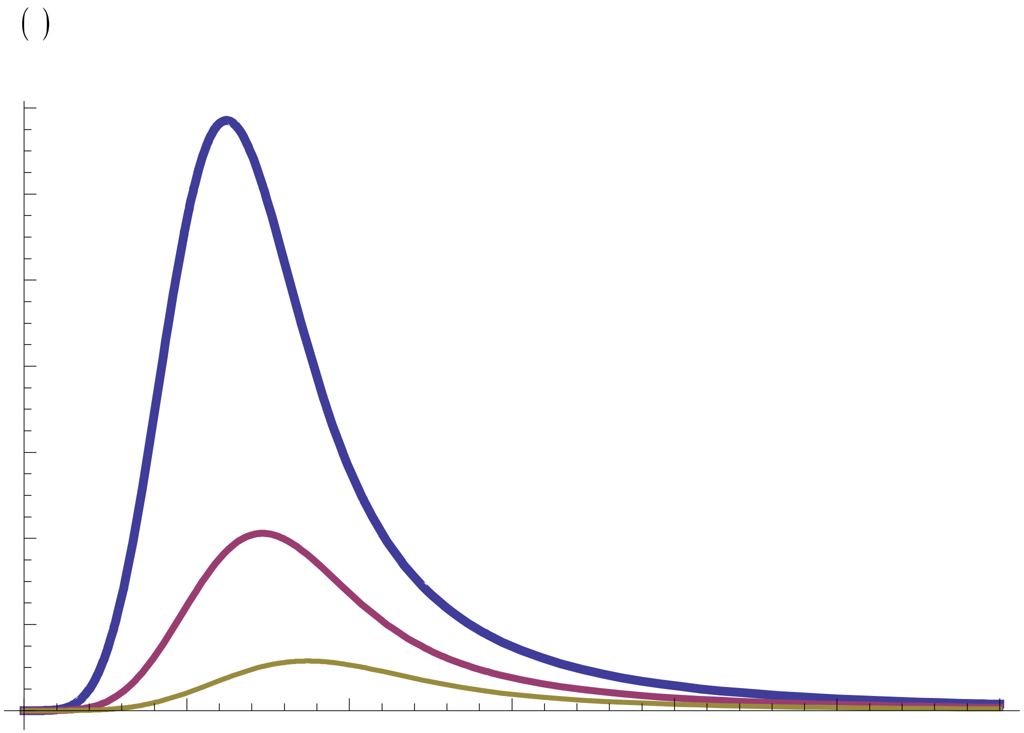
# Odderon STSA at high-$p_T$

- The odderon STSA is a steeply-falling function of $p_T$:

$$A_N^{(q)}\Big|_{p_T \gg Q_s} \propto \frac{1}{p_T^5}$$

- However, the suppression at high transverse momentum is gone for $p_T \sim Q_s$ (from one to a few GeV).

# Nuclear (unpolarized) target




Target radius is R=1 fm (top curve), R=1.4 fm (middle curve), R=2 fm (bottom curve): strong suppression of odderon STSA in nuclei. Warning: crude approximation of the exact formula!

# Prompt photon STSA

- is zero (in this mechanism).
- The photon asymmetry originated in the following spin-dependent production cross-section

$$d(\Delta\sigma^{(\gamma)}) = \frac{1}{(2\pi)^3} \int d^2x\, d^2y\, d^2z\, e^{-i\mathbf{k}\cdot(\mathbf{z}-\mathbf{y})}\, \Phi_{pol}(\mathbf{x}-\mathbf{z}\,,\, \mathbf{x}-\mathbf{y}, \alpha)\, \mathcal{I}^{(\gamma)}_{\mathbf{anti}}(\mathbf{x}\,,\, \mathbf{y}\,,\, \mathbf{z})$$

with the interaction with the target linear in the odderon exchange $\mathcal{I}^{(\gamma)}_{anti} = i\,[O_{\mathbf{u}\,\mathbf{w}} - O_{\mathbf{x}\,\mathbf{w}} - O_{\mathbf{u}\,\mathbf{x}}]$

- This cross section is zero since $\int d^2x\, O_{\mathbf{x},\,\mathbf{x}+\mathbf{y}} = 0$

for any odd function $O_{\mathbf{x},\,\mathbf{y}} = -O_{\mathbf{y},\,\mathbf{x}}$

# Sivers vs Odderon effects in CGC

- Sivers effect is likely lower-twist than the odderon STSA,

$$A_N\Big|_{p_T \gg Q_s} \propto \frac{1}{p_T^3} \ (?\,\mathrm{tbc})$$

Sivers

$$A_N^{(q)}\Big|_{p_T \gg Q_s} \propto \frac{1}{p_T^5}$$

Odderon

  but the two may be comparable for $k_T \sim Q_s$.
- Sivers effect would lead to non-zero STSA for prompt photons; the odderon mechanism gives zero.
- Perhaps the odderon STSA contribution can be found by subtracting photon STSA from the hadron STSA, though there is also the Collins mechanism for hadron STSA.

# Non-CGC (?) STSA in p$\uparrow$+A

# STSA in p↑+A vs p↑+p

- It appears from the works of Kang et al on Sivers effect in CGC that due to multiple recsatterings in the nucleus the hadronic and leptonic STSA would be washed out, leading to smaller STSA in p↑+A vs p↑+p.

- The same qualitative conclusion results from the odderon mechanism.

- However, not every theorist agrees here: J. Qiu has argued that multiple rescatterings push the parton to higher-x, which, since STSA is larger at high-x, in turn, pushes STSA to larger values, compensating for the depletion due to multiple rescatterings.

- STSA experiments in p↑+A can help discriminate between the models.

# Resummation of power corrections

Qiu and Vitev, PRL (2004)

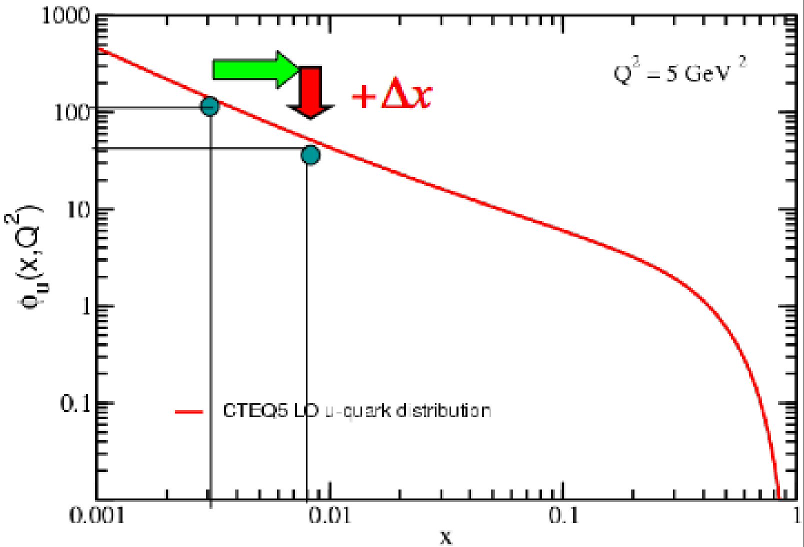
- Transverse structure function:

$$F_T(x_B,Q^2) = \sum_{n=0}^{N} \frac{1}{n!}\left[\frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)\right]^n x_B^n \frac{d^n}{dx_B^n} F_T^{(0)}(x_B,Q^2)$$

$$\approx F_T^{(0)}(x_B(1+\Delta),Q^2)$$

$$\Delta \equiv \frac{\xi^2}{Q^2}\left(A^{1/3}-1\right)$$

$$\xi^2 = \frac{3\pi\alpha_s}{8R^2}\langle F^{+\alpha}F_\alpha{}^{+}\rangle$$




Single parameter for the power correction, and is proportional to the same characteristic scale

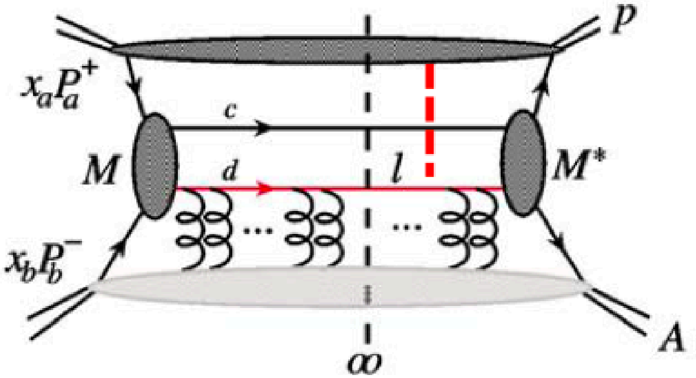
- Similar result for longitudinal structure function:

# SSA in pA collisions

- **To numerator:**

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

- **Leading power approximation:**




**The momenta of all additional scatterings are fixed by the unpinched poles!**

- **Same shift from the coherent multiple scattering:**

$$A_N(pp) \sim A_N(pA) \qquad \textbf{When} \quad \ell_T^2 \gg Q_s^2$$

**Only small difference due to the convolution over $T_F(x,x)$ vs. $q(x)$**

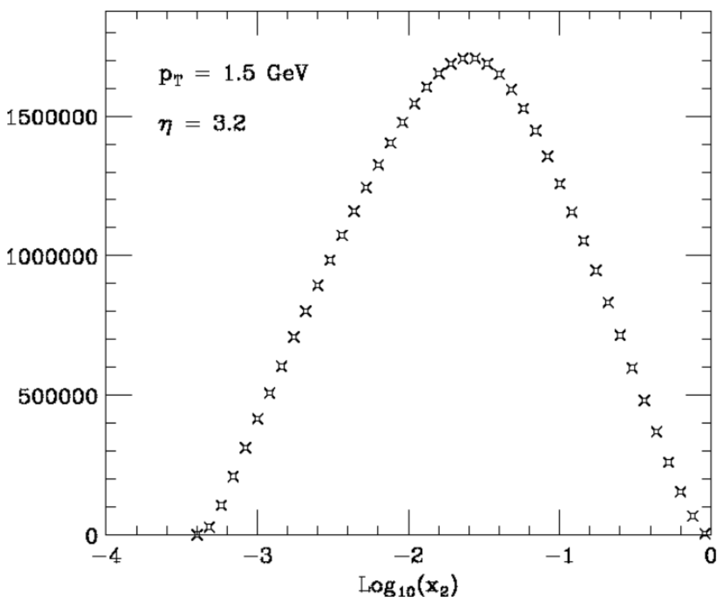
**Note: $A_N$(photon) =\= 0!**

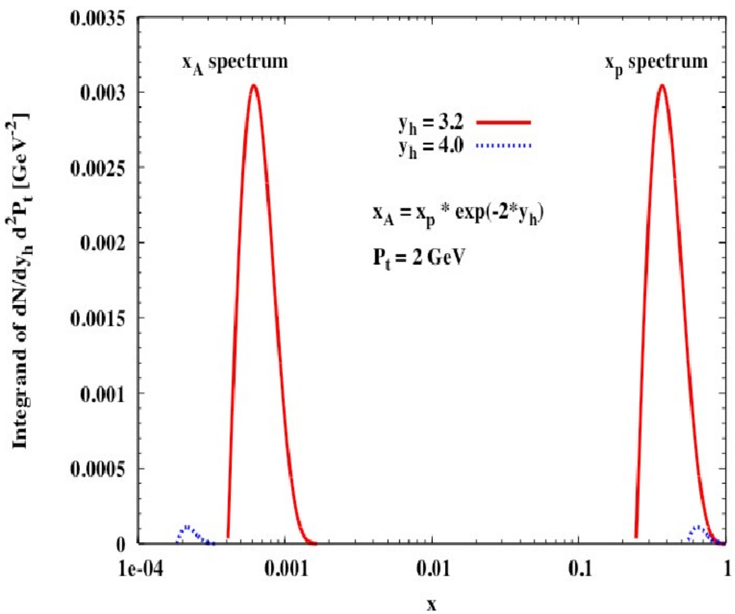
# Conclusions

- It seems STSA in $p^{\uparrow}$+A collisions can be generated by three possible mechanisms: Sivers, Collins, and odderon-mediated.
- Odderon mechanism has right qualitative features of STSA, but falls off fast at high $p_T$ . It is much smaller in $p^{\uparrow}$+A than in $p^{\uparrow}$+p. Predicts zero photon/DY STSA.
- Sivers effects is leading at high-$p_T$ (compared to the odderon), and probably is also suppressed in $p^{\uparrow}$+A vs $p^{\uparrow}$+p, but this needs to be confirmed. Photon/DY STSA is non-zero.
- By studying STSA in $p^{\uparrow}$+A collisions one can learn a lot about both the small-x physics in nuclear wave functions (CGC/saturation, multiple rescatterings) and about spin structure of the proton.

# Backup Slides

# $2 \rightarrow 2$ vs. $2 \rightarrow 1$




**GSV**

**DHJ**