Theory Overview: Present to Future

Jianwei Qiu
Iowa State University

Outline of my talk

Twenty years since the "spin crisis"

The goals of RHIC Spin program

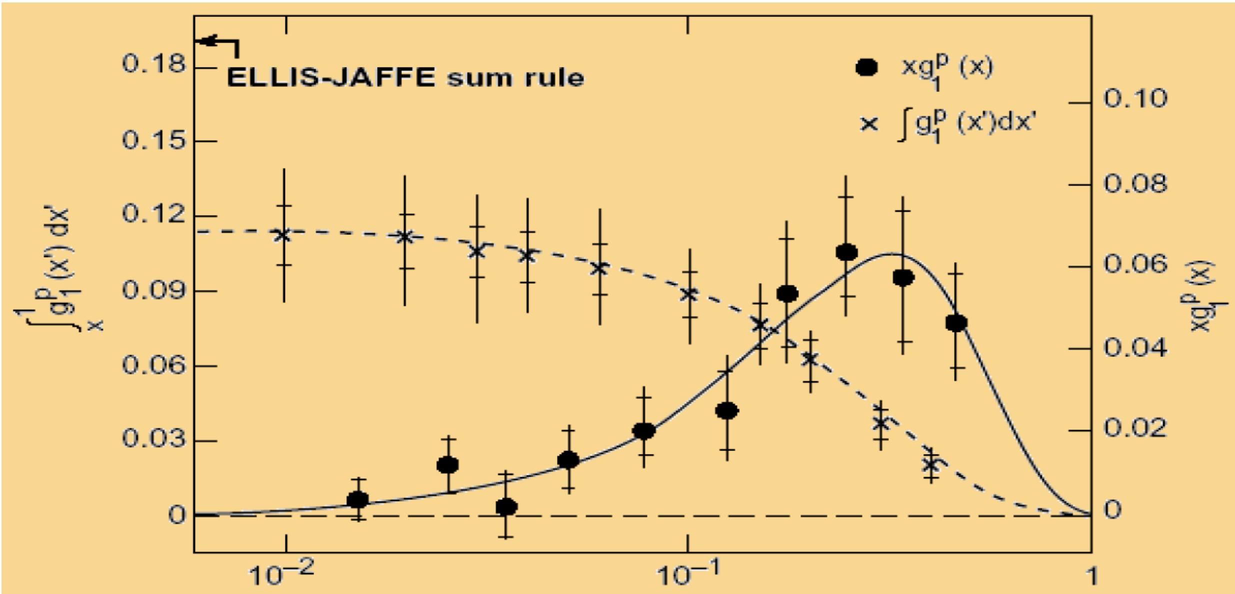
What we have achieved?

What we could achieve in next few years?

New opportunities

Twenty years since the "spin crisis"

- EMC experiment in 1988/1989 – "the plot":



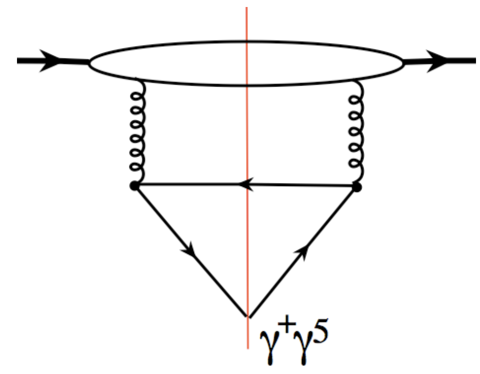
$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x) + \Delta\bar{q}(x)\right] + \mathcal{O}(\alpha_s) + \mathcal{O}(1/Q)$$

$$\Delta q = \int_0^1 dx \Delta q(x) = \langle P, s_{\parallel}|\overline{\psi}_q(0)\gamma^+\gamma_5\psi_q(0)|P, s_{\parallel}\rangle$$

- "Spin crisis": $\Delta\Sigma = \sum_q\left[\Delta q + \Delta\bar{q}\right] = 0.12 \pm 0.17$

Early "solution" to the "crisis"

❑ **Large ΔG to cancel the "true" Δq:**



$$\Delta q = \int_0^1 dx\, \Delta q(x) = \langle P, s_\parallel | \overline{\psi}_q(0)\gamma^+\gamma_5\psi_q(0)|P, s_\parallel\rangle$$

$$\Longrightarrow \quad \Delta\Sigma \to \Delta\Sigma - \frac{n_f\alpha_s(Q^2)}{2\pi}\Delta G(Q^2)$$

❑ **What value of ΔG is needed?**

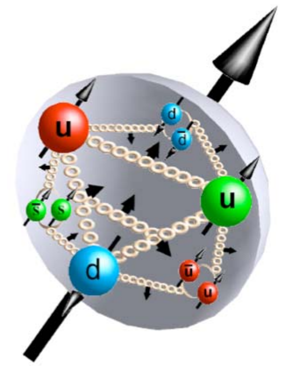
$$\Delta G(Q^2) \sim 2 \quad \text{at Q ~ 1 GeV}$$

❑ **Question: How to measure ΔG independently?**

- ✧ Precision inclusive DIS
- ✧ Jets in SIDIS
- ✧ Hadronic collisions – RHIC spin
- ✧ …

"Bigger" Questions?

- **Beyond ΔG:**
  - ✧ Antiquark helicity contribution?
  - ✧ Quark flavor separation?
  - ✧ Proton's spin structure?
  - ✧ QCD dynamics behind the spin structure?
  - ✧ ...



- **Proton spin = Angular momentum of the proton at rest:**

$$S = \sum_f \langle P, S_z = 1/2 |\, \hat{J}_f^z \,| P, S_z = 1/2 \rangle = \frac{1}{2}$$

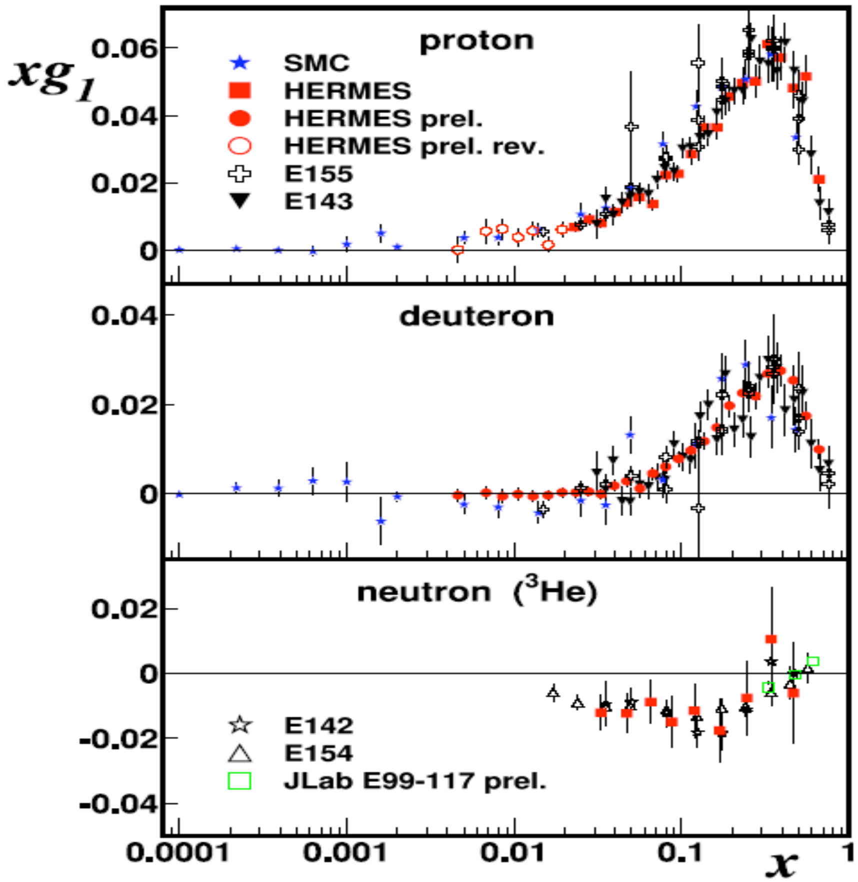
- **Spin sum rules:**

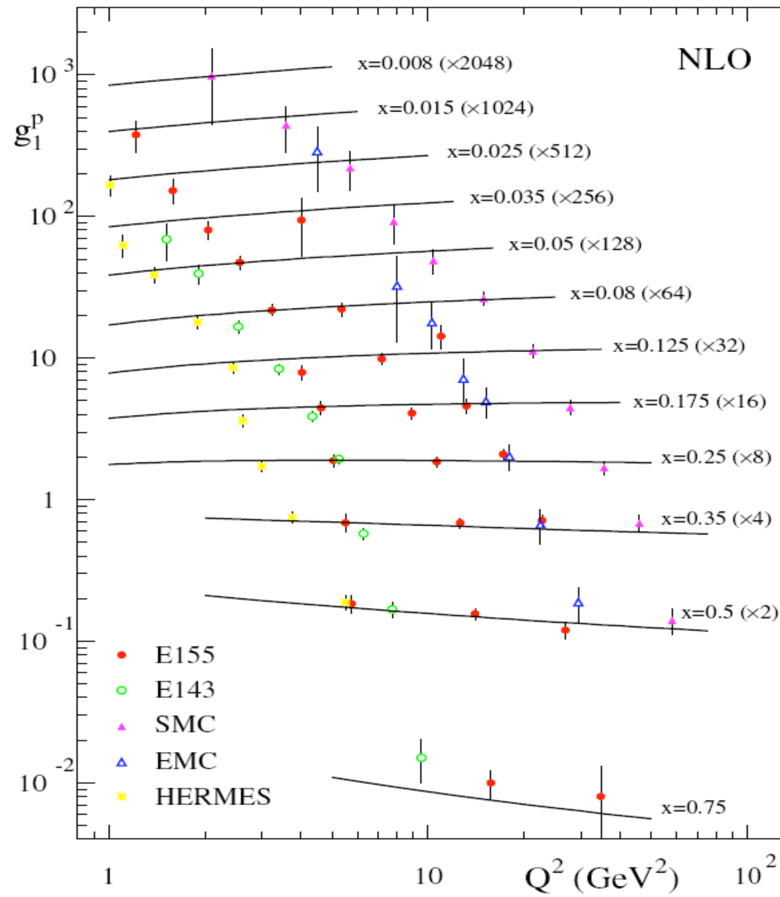
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma(\mu^2) + L_q(\mu^2)\right] + J_g(\mu^2)$$

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma(\mu^2) + L_q(\mu^2)\right] + \left[\Delta G(\mu^2) + L_g(\mu^2)\right]$$

Inclusive DIS

- The "Plot" is now much improved:



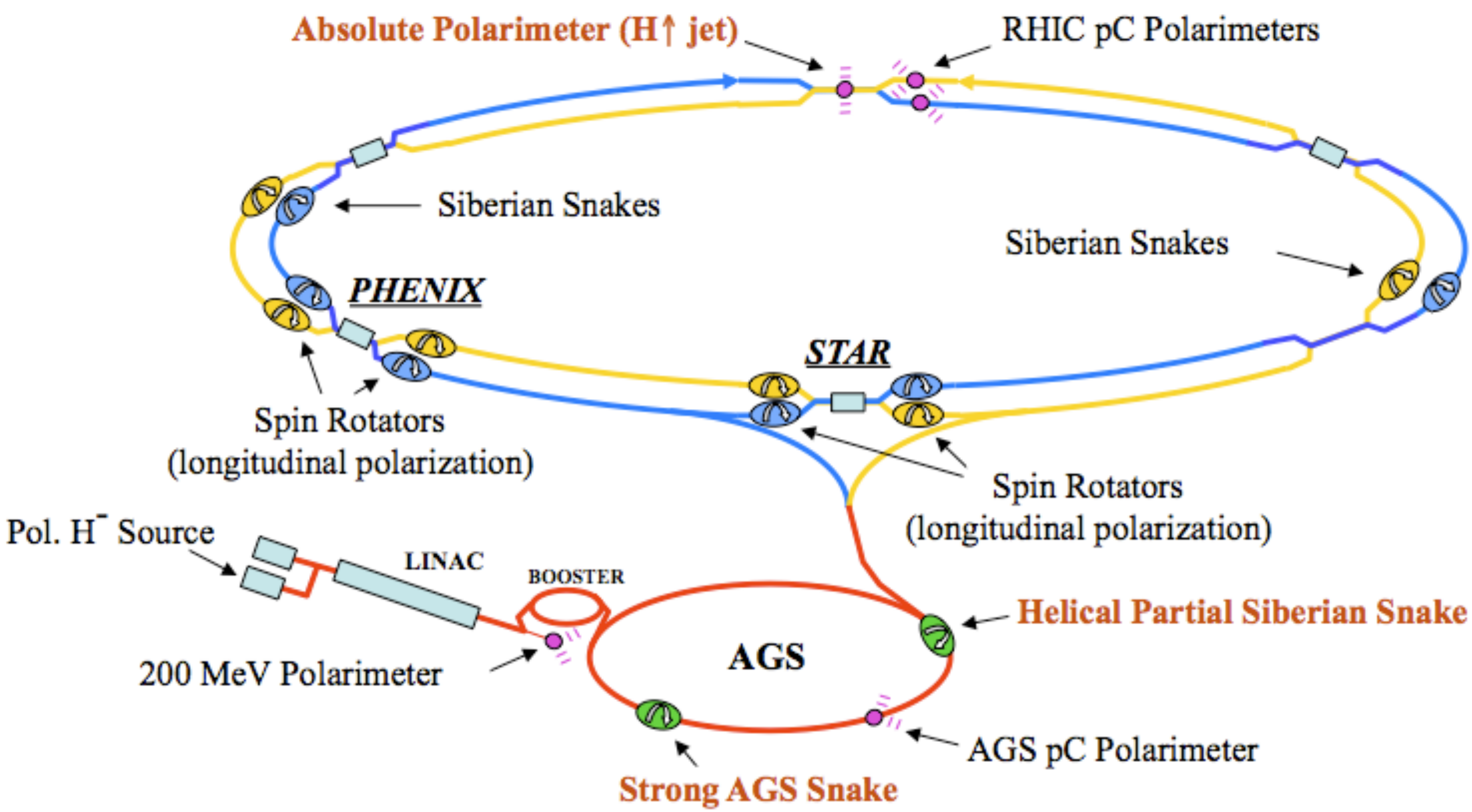


- Flavor separation - SIDIS:

See Elke's talk

RHIC Spin Program

❑ **The machine:**



Collider of two 100 GeV (250 GeV) polarized proton beams

The Goals of RHIC Spin Program

- ❑ Determination of polarized gluon distribution (ΔG) over a large range of momentum fraction x, using multiple probes

- ❑ Determination of flavor identified quark and anti-quark polarization using parity violating production of $W^{\pm}$

- ❑ Transverse spin phenomena in QCD: connections to parton orbital angular momentum (L_q) and transversity (δq)

Question

Experiments measure cross sections,

Not ΔG, Δq and $\Delta \bar{q}$!

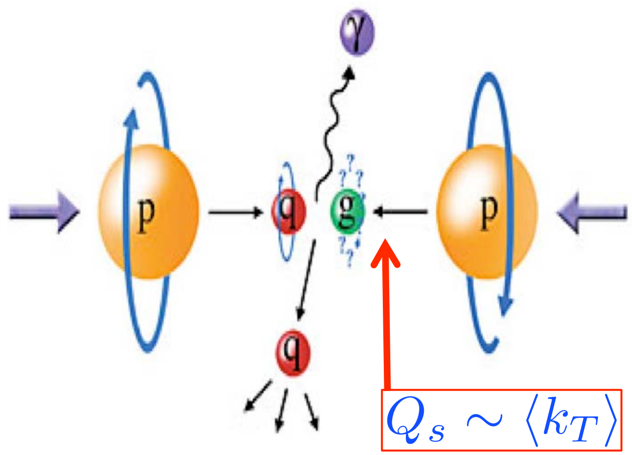
How reliable we can extract these quantities

from

the measured cross sections/asymmetries?

PQCD Collinear Factorization

❑ **Factorization is an approximation:**



$$\frac{d\sigma}{dy\,dp_T^2} = \int \frac{dx}{x} q(x) \int \frac{dx'}{x'} g(x') \frac{d\hat{\sigma}_{qg\to\gamma q}}{dy\,dp_T^2} + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{Q_s}{P_T}\right)^n$$

Convoluted with a fragmentation function for inclusive single particle production

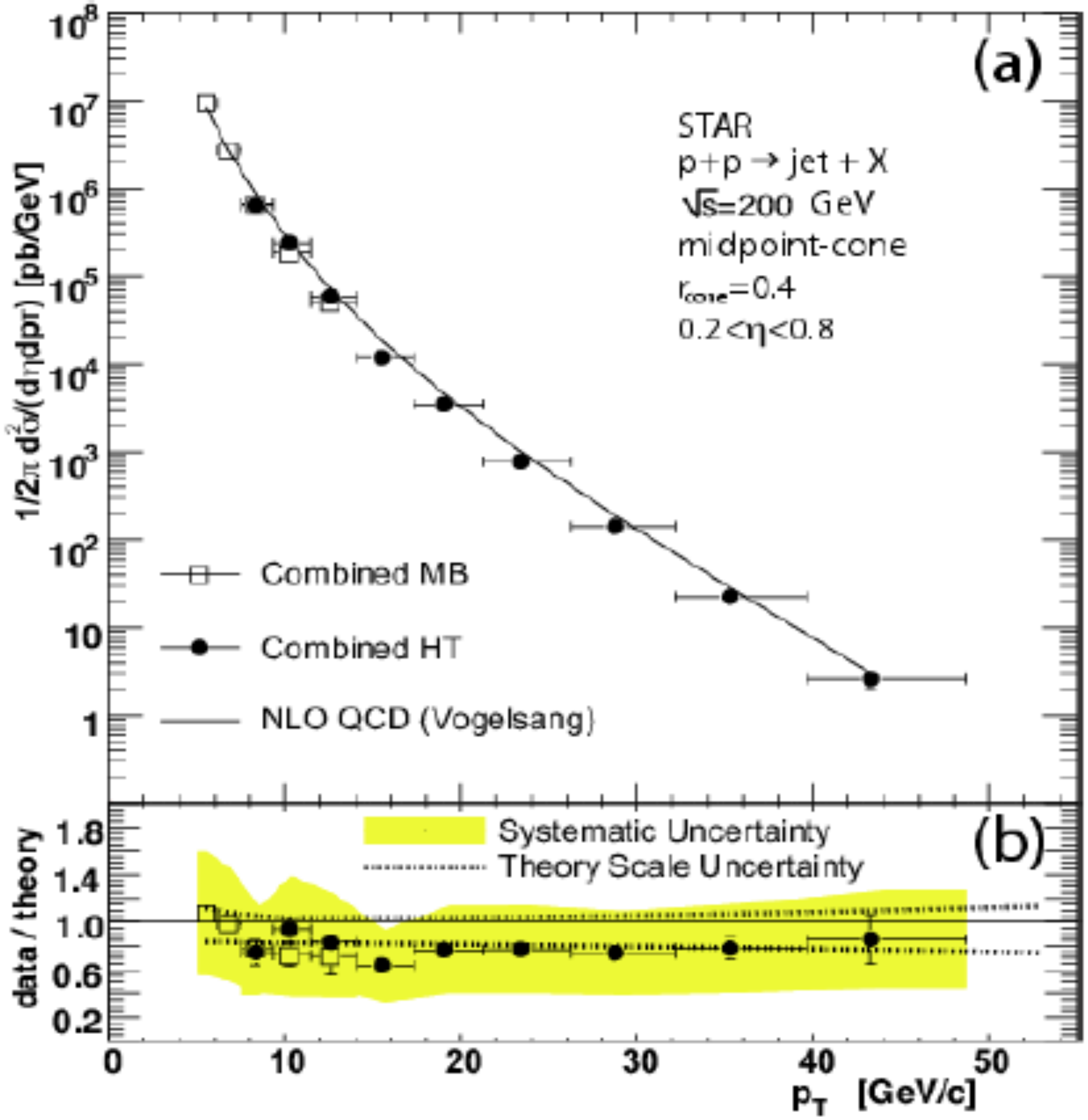
❑ **The proof was originally given for spin-averaged case**

✧ The same proof could be carried through for the leading power contribution to spin-dependent cross section

✧ But, the proof does not say anything about the spin dependence of the power corrections

Inclusive Jet at 200 GeV

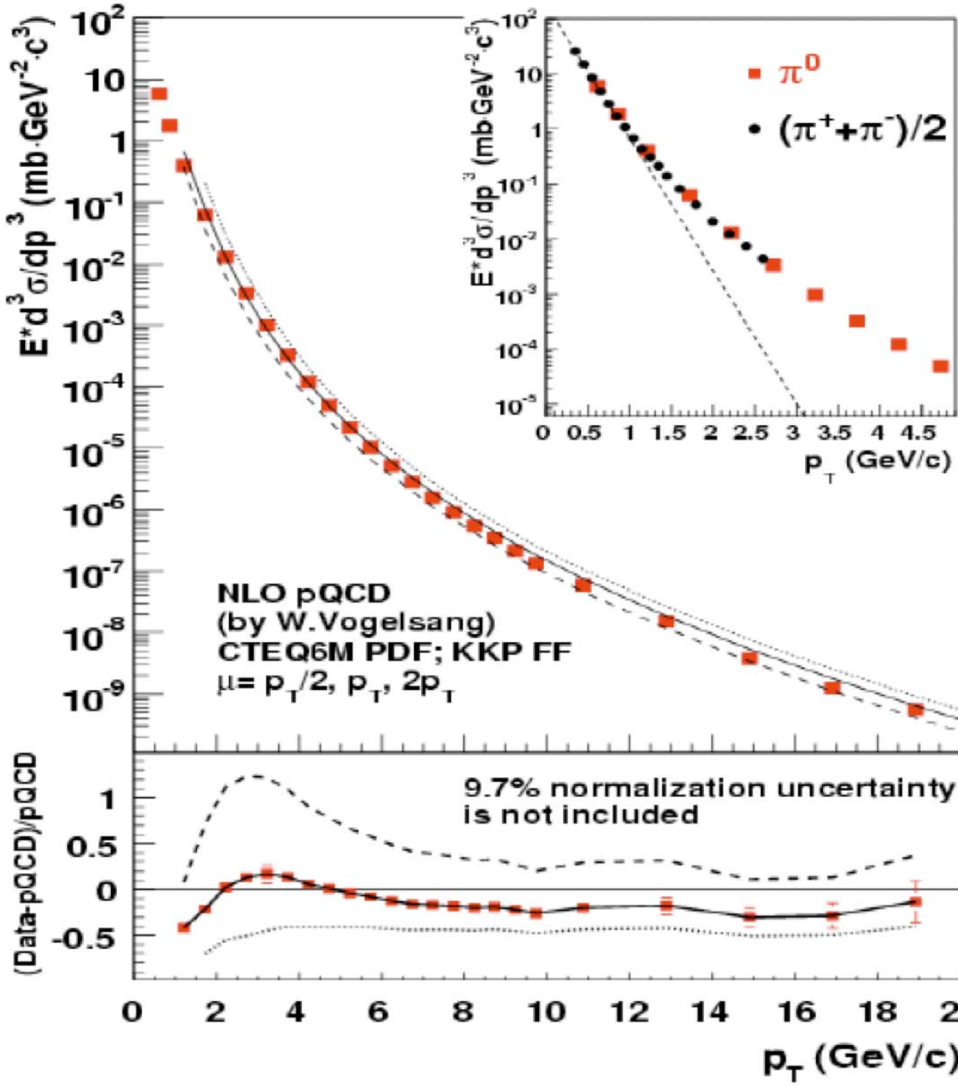
❑ **STAR:**



PRL97, 252001 (2006)

Inclusive single hadron at 200 GeV

- PHENIX:

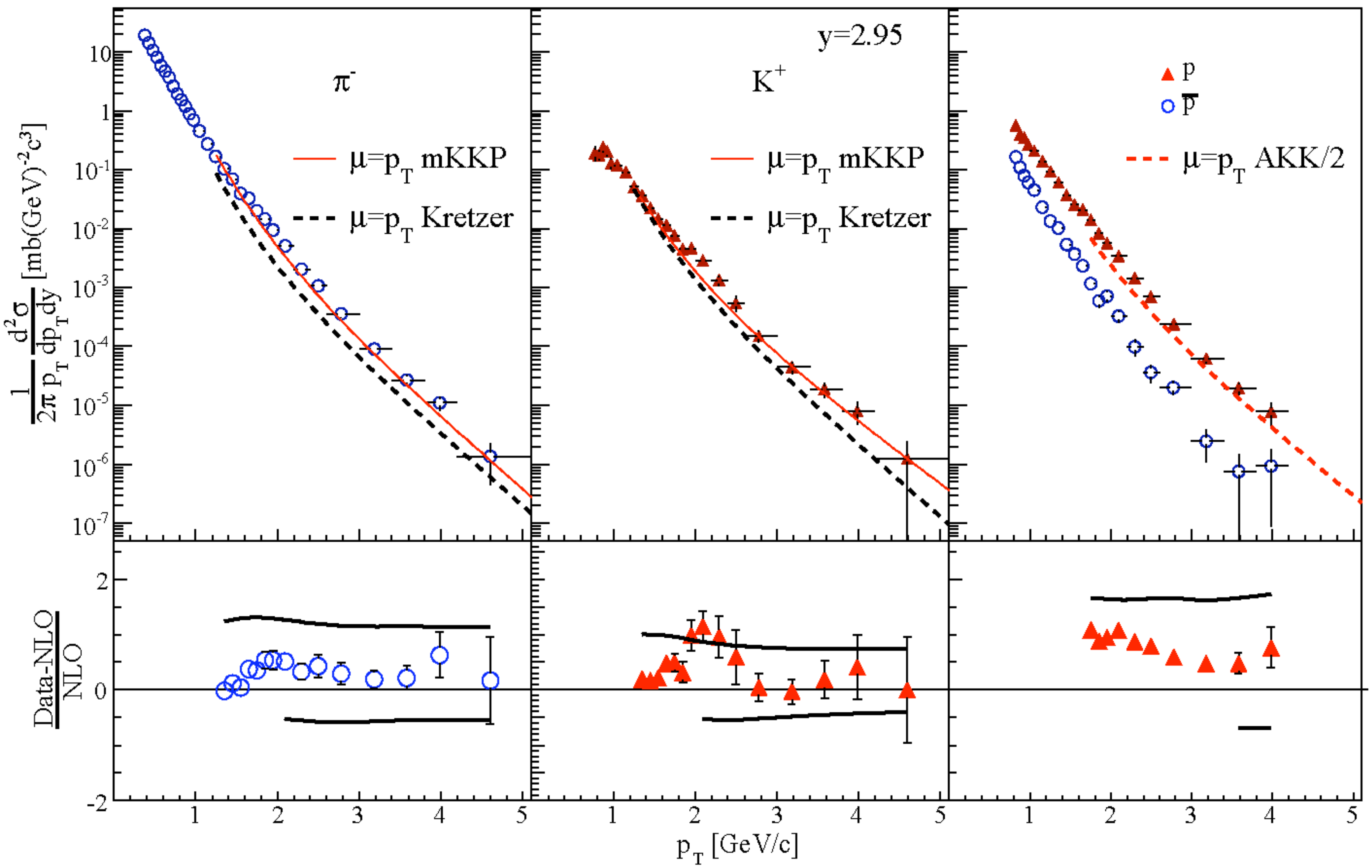


PRD76, 051106 (2007)

Extending x coverage and particle type

❑ **BRAHMS:** Large rapidity π,K,p cross sections for p+p, $\sqrt{s}$=200 GeV

PRL98, 252001 (2007)



Determination of ΔG

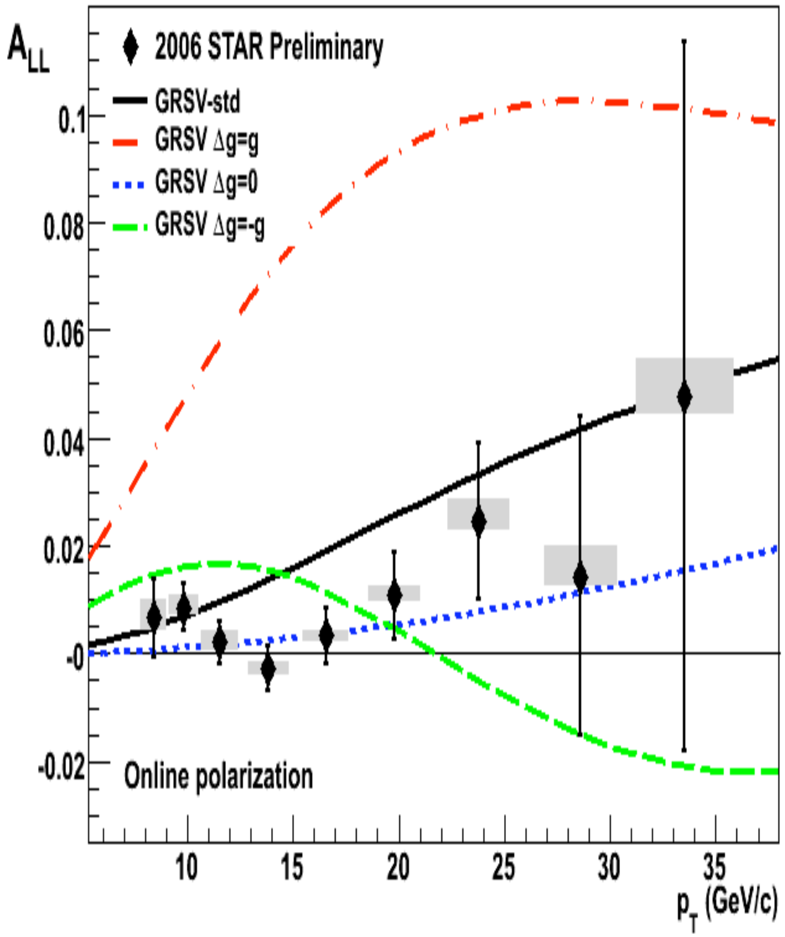
Leading power pQCD factorization theorem is valid for spin-dependent cross section at the same level of confidence as for spin-averaged observables

Many NLO pQCD calculations including jet-jet, particle-particle correlations are available

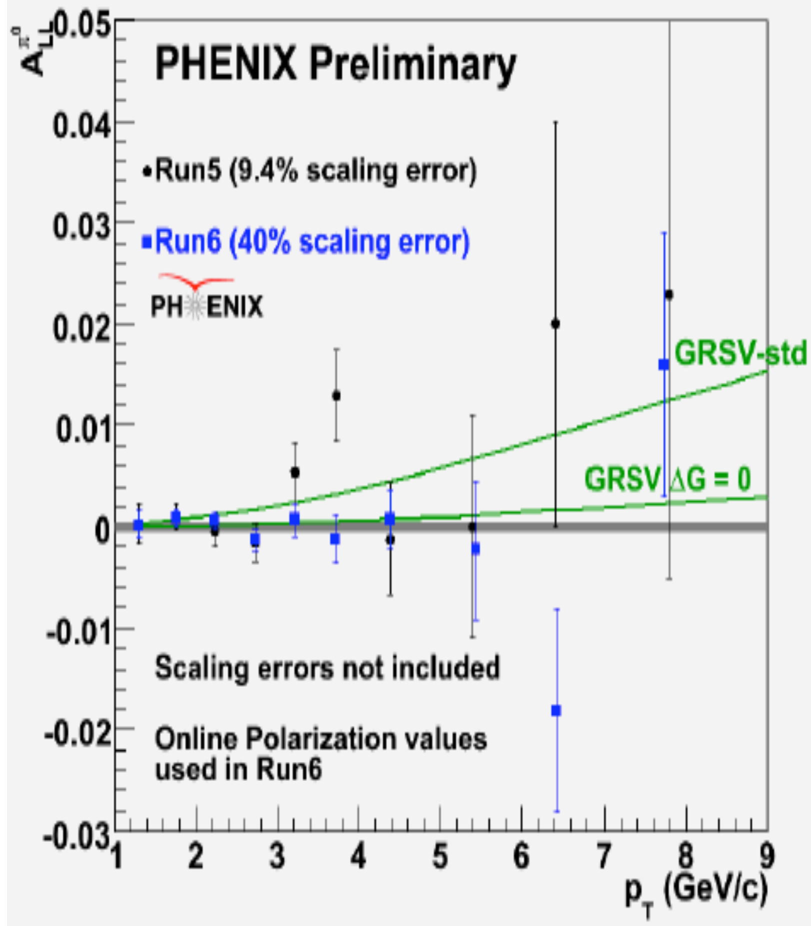
See Werner's talk

RHIC Measurements on ΔG

Star jet



Phenix π^0



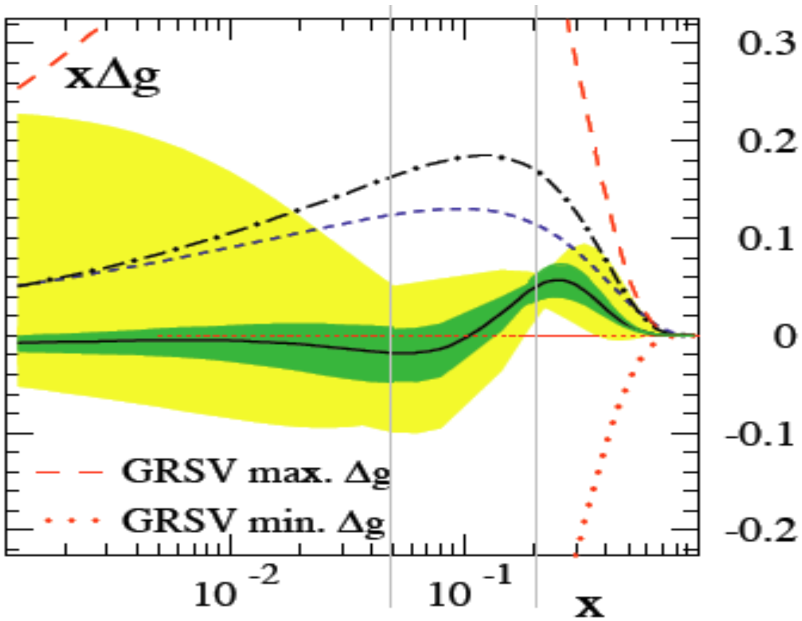
Small asymmetry leads to small gluon "helicity" distribution

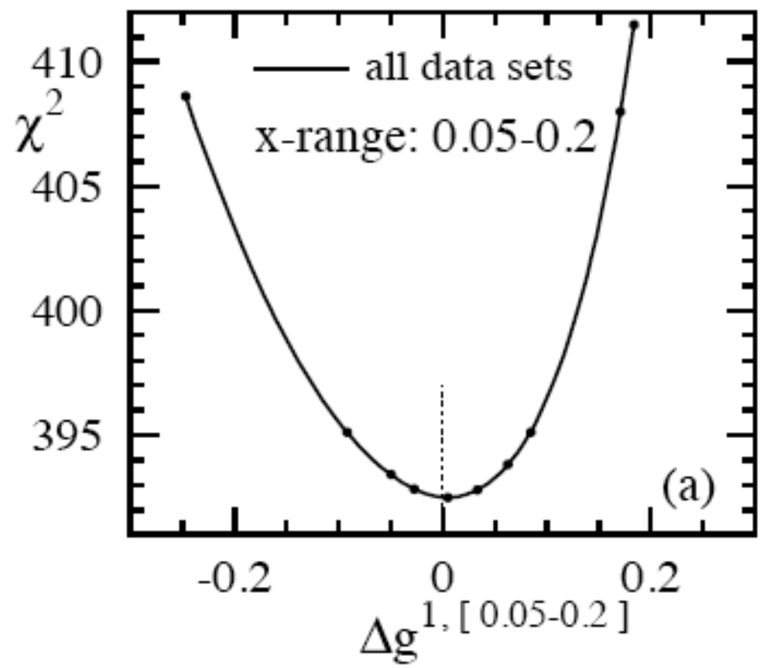
Current status on ΔG

- **Definition:** $$\Delta G = \int_0^1 dx\, \Delta G(x) = \langle P, s_{\parallel} | F^{+\mu}(0) F^{+\nu}(0) | P, s_{\parallel} \rangle (-i\epsilon_{\mu\nu})$$

- **NLO QCD global fit - DSSV:**

PRL101,072001(2008)





$$\Delta G \approx \int_{0.001}^{1} dx\, \Delta G(x) = -0.084$$

Strong constraint on ΔG from $0.05 \lesssim x \lesssim 0.2$

See Werner's talk

Improvement to ΔG

- ❑ **NNLO?** Probably not yet
- ❑ **Key: Extrapolation to low x and high x**
  - ✧ Large x: total contribution might be small due to the steep falling phase space
  - ✧ Small x: larger phase space for shower and smaller Q for a fixed collision energy $\Rightarrow$ Larger $\langle k_T \rangle$
- ❑ **Collinear factorization does not work when** $Q_s(x) \sim \langle k_T \rangle$

$$G(x) = G^+(x) + G^-(x) \propto \frac{1}{x^{1+\alpha}}$$ at small x

$$\Delta G(x) = G^+(x) - G^-(x)$$ Could be proportional to $\frac{1}{x^{\alpha}}$

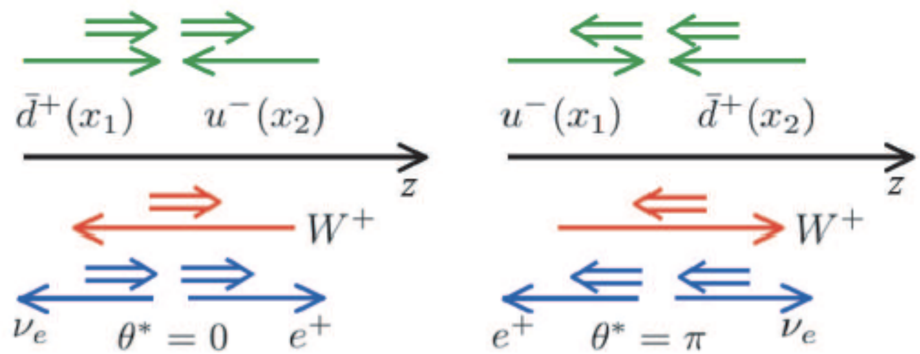
Not positive definite!

Uncertainty in extrapolation!

Sign change = sign of interesting dynamics

Determination of Δq and $\Delta\bar{q}$

- **W's are left-handed:**



- **Flavor separation:**

Lowest order:

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}}e^{y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}}e^{-y_W}$$

Forward W^+ (backward e^+):

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)} < 0$$

Backward W^+ (forward e^+):

$$A_L^{W^+} \approx -\frac{\Delta\bar{d}(x_2)}{\bar{d}(x_2)} < 0$$

- **Complications:**

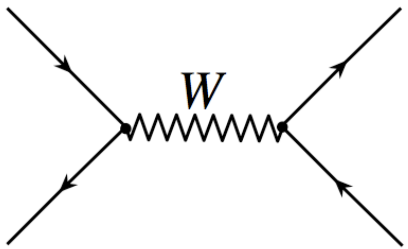
High order, W's p_T-distribution at low p_T

High order effect

- Fixed order pQCD calculation:

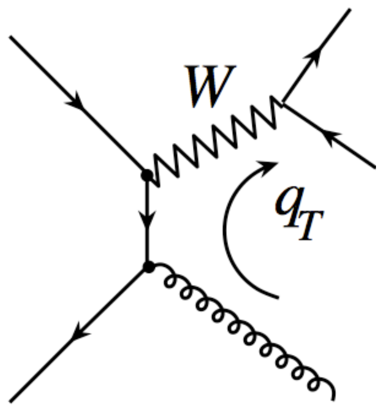
See Daniel's talk

LO:



$$\propto \delta^2(q_T)$$

NLO:

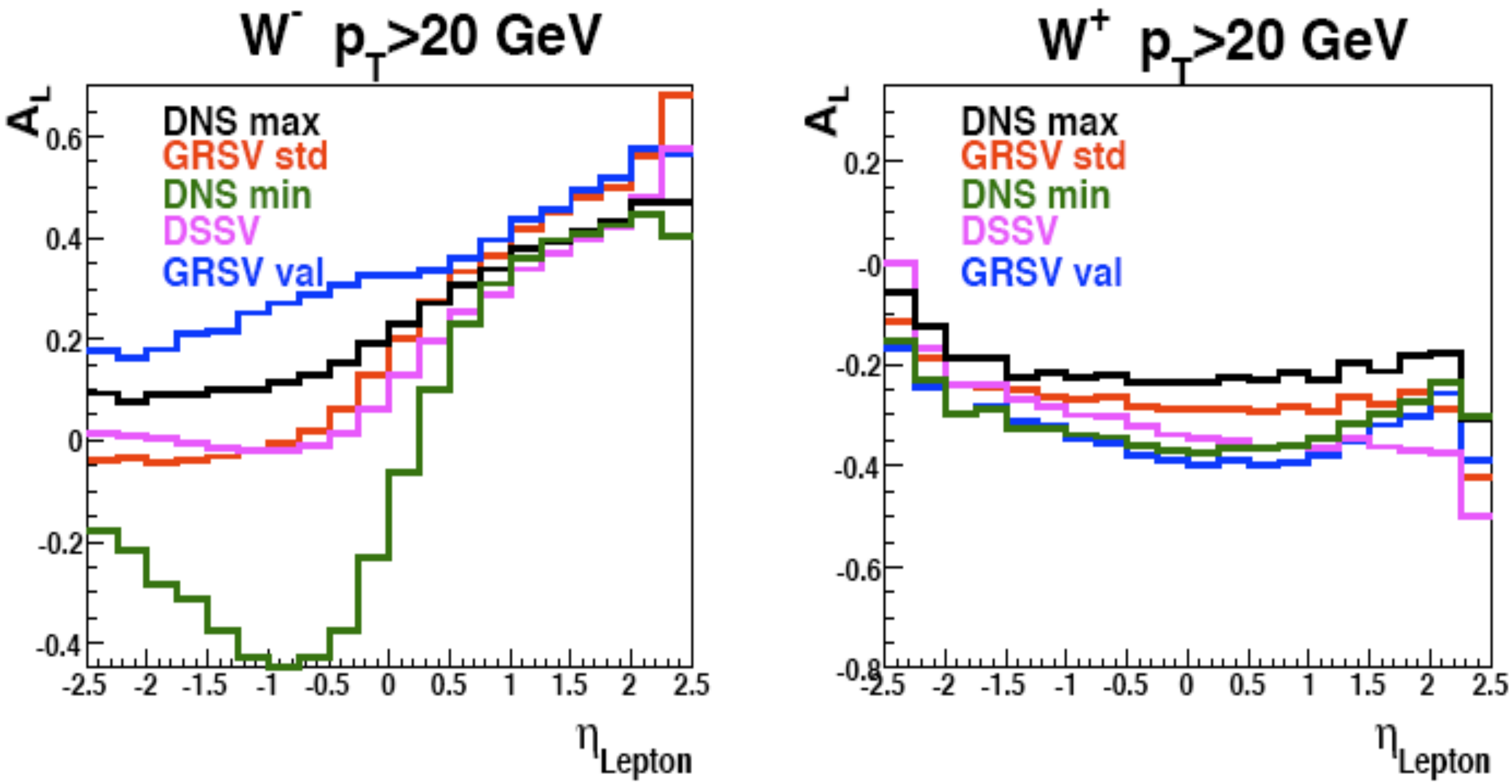


$$\propto \frac{1}{q_T^2} \quad \Rightarrow \infty \quad \text{as} \quad q_T^2 \to 0$$

- All order resummation is needed:

CSS formalism – implemented in RHICBOS

Predicted lepton asymmetry



RHICBOS – RS=500 GeV

Plan for the RHIC Spin Physics Program, 2008

Uncertainty in CSS formalism

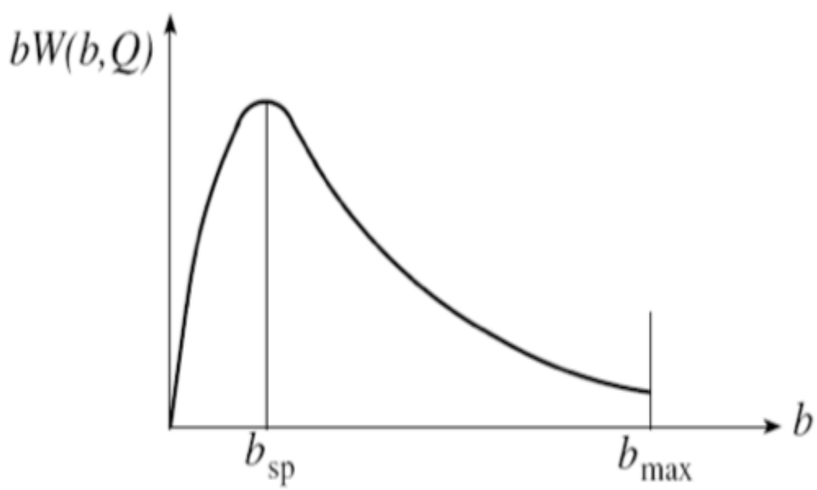
❑ CSS formalism:

$$\frac{d\sigma_{AB\to W}}{dy\,dq_T^2} = \frac{\sigma_0}{2\pi}\int_0^\infty db\, b\, J_0(q_T\, b)\, \widetilde{W}_{AB}(y,b,M_W) + Y_{AB}(y,q_T,M_W)$$

✧ Resummation is achieved by solving evolution equations of the b-space distribution: $\widetilde{W}_{AB}(y,b,M_W)$ at small b

$$\widetilde{W}^{\rm Pert}_{AB}(y,b,M_W) = \sum_{a,b,i,j} \sigma^{\rm LO}_{ij\to W}\left[\phi_{a/A}\otimes \mathcal{C}_{a\to i}\right]\otimes\left[\phi_{b/B}\otimes\mathcal{C}_{b\to j}\right]\times e^{-S(b,M_W)}$$

✧ Predictive power is sensitive to the distribution at large b



○ Large b tail is NOT universal – phase space sensitivity

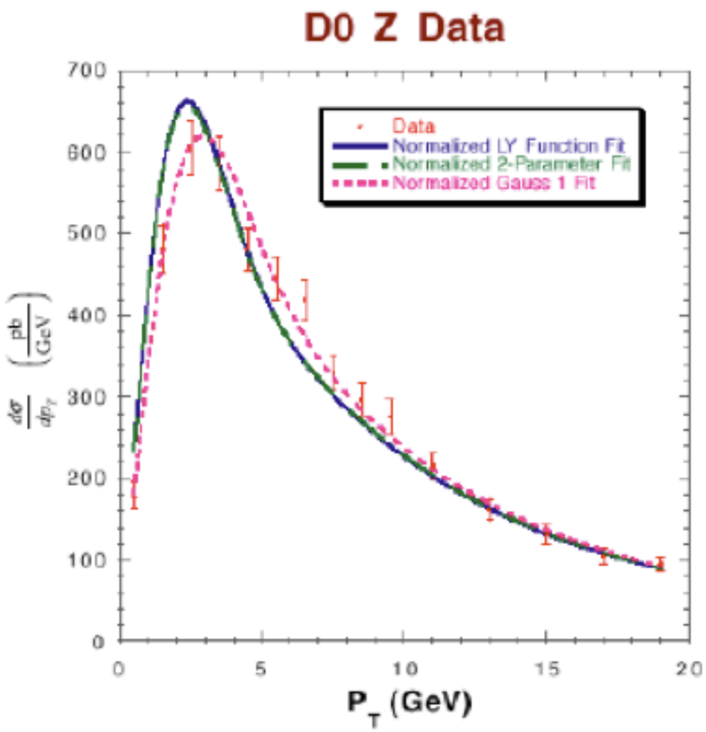
○ Reliable prediction if b-integration is dominated by low b

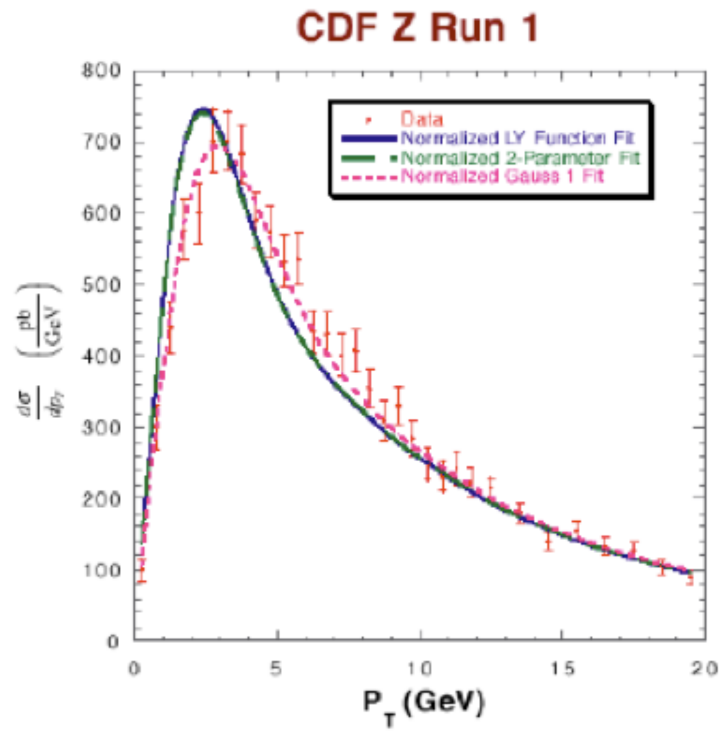
Extrapolation to large b

- **CSS prescription – used in RHICBOS:**

$$\widetilde{W}_{AB}(y,b,M_W) = \widetilde{W}_{AB}^{\text{Pert}}(y,b_*,M_W) \times e^{-S_{\text{NP}}(b,M_W)} \qquad b_* = \frac{b}{\sqrt{1+b^2/b_{\max}^2}}$$

Prescription changes both large b and small b region

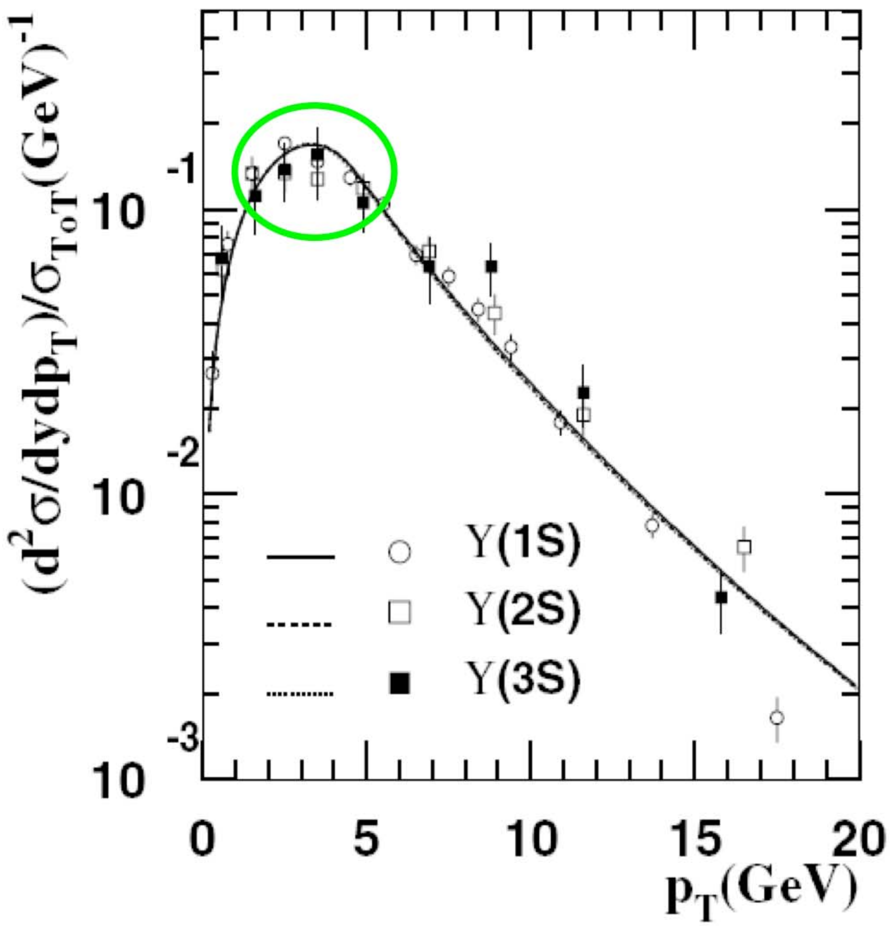




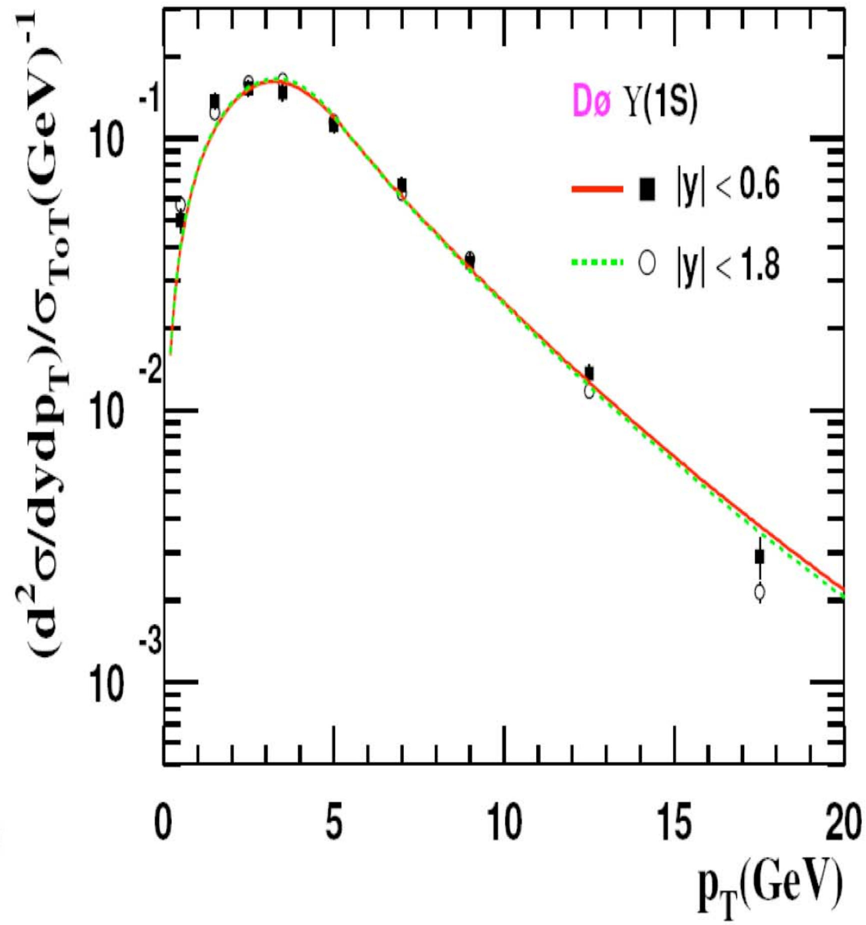
Different $S_{\text{NP}}(b,M_Z)$ **yields different cross section/shape at low q_T**

Upsilon production at Tevatron

CDF Run-I



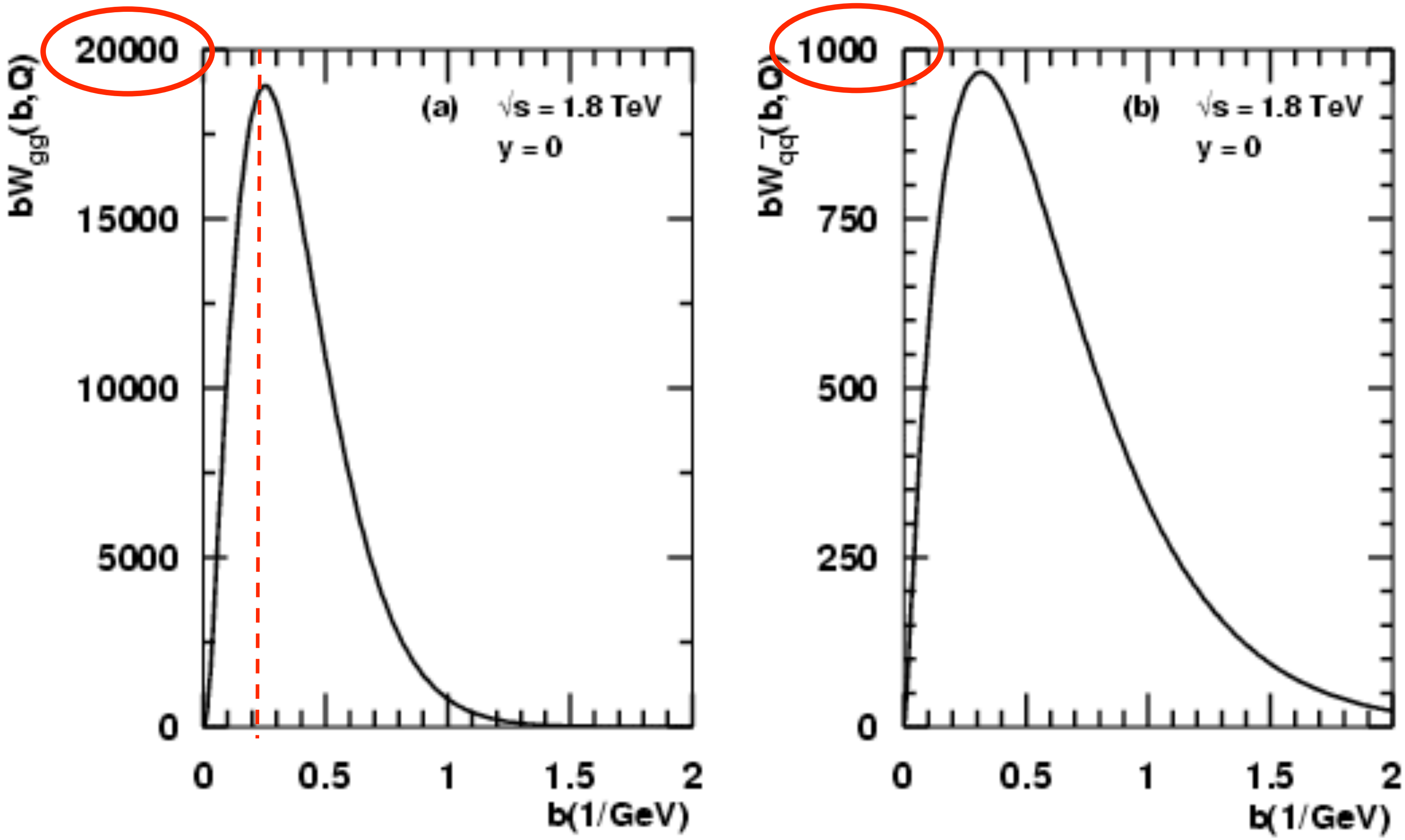
D0 Run-II



Why the shape works so well, while $M_\Upsilon \sim 10$ GeV?

Berger, Qiu, Wang, 2005

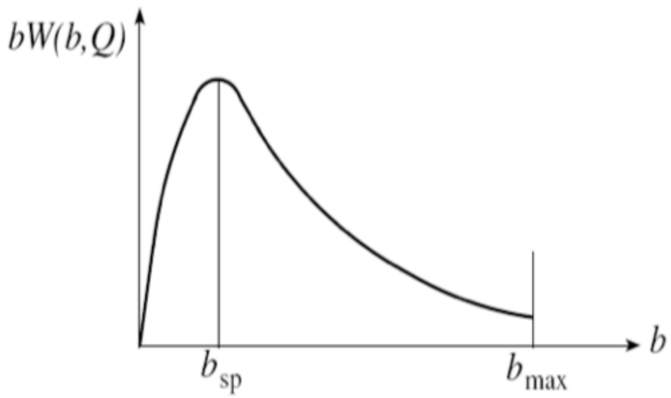
The b-space distribution



- ✧ Gluon-gluon dominate the production
- ✧ Dominated by perturbative contribution even M_Υ~10 GeV

Improvement to W production at RHIC

- Exam the b-space distribution at various y_W values:



✧ Contribution from the long b-tail?

✧ It is important to measure spin-averaged W cross section

- Possible "dilution" to the asymmetry of decay lepton

Existing calculation of lepton asymmetry is based on
lepton from boosted W + production of W-boson

✧ Production of W-boson (diagonal tensor): $\propto W^{\mu\nu} \times (-g_{\mu\nu})$

✧ Off-diagonal hadronic tensor: $\propto W^{\mu\nu} \times L_{\mu\nu}$

also contribute to lepton production (with resummation?)

Transverse spin phenomena in QCD

Double Transverse-Spin Asymmetry (A_{TT})

Probe the transversity distribution: $\delta q(x)$

Single Transverse-Spin Asymmetry (SSA)

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

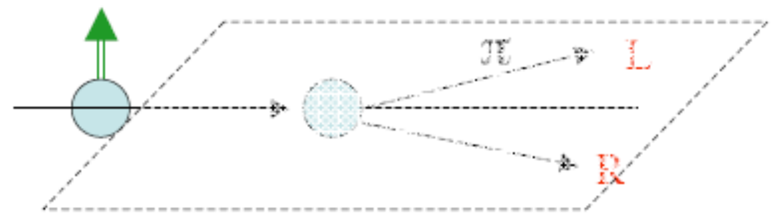
Chance to go beyond the collinear approximation

Probe parton's transverse motion?

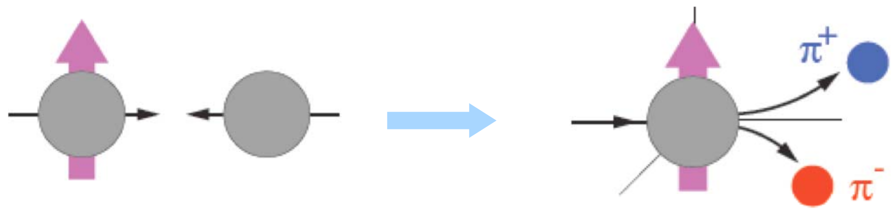
See Feng's talk

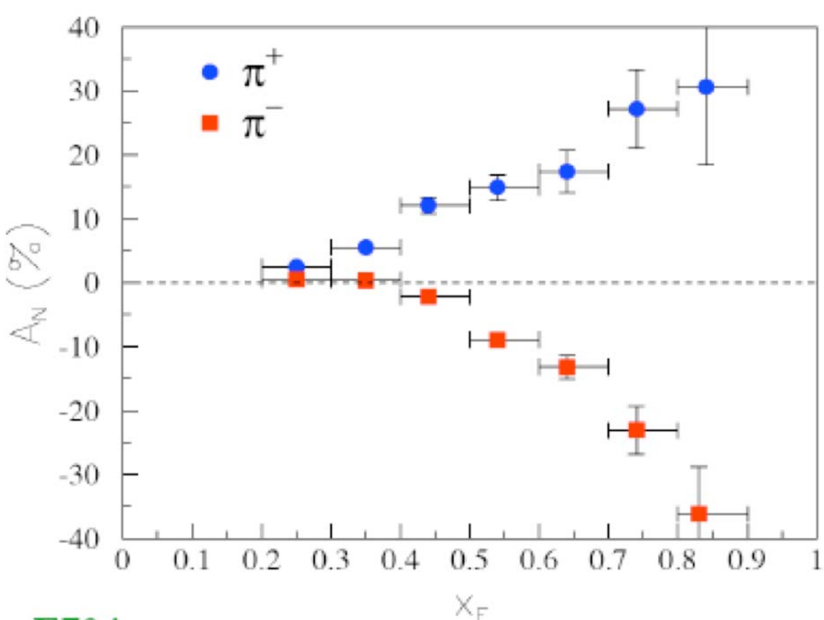
SSA in hadronic collisions

- **Hadronic** $p\uparrow + p \rightarrow \pi(l) X$:

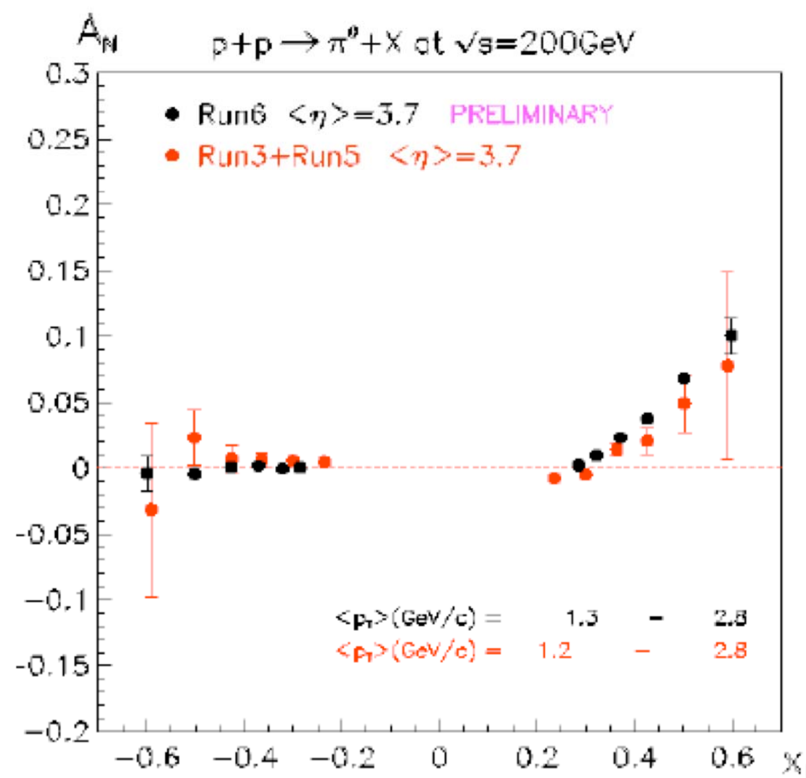


$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^{\pi}_{\text{left}} - N^{\pi}_{\text{right}}}{N^{\pi}_{\text{left}} + N^{\pi}_{\text{right}}}$$





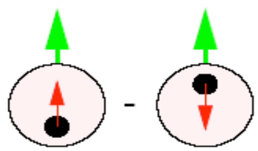
E704



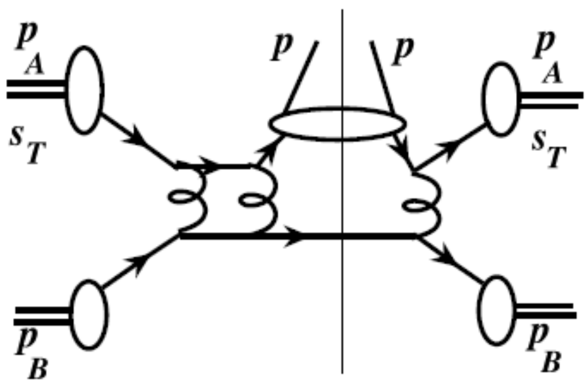
STAR (BRAHMS, too)

SSA in the parton model

- transverse spin information at leading twist – transversity:

$\delta q(x) =$  = Chiral-odd helicity-flip density

- the operator for δq has even γ's ⟹ quark mass term
- the phase requires an imaginary part ⟹ loop diagram



$\sim m_q \rightarrow 0$

⟹ SSA vanishes in the parton model

connects to parton's transverse motion

Cross section with ONE large scale

- Collinear factorization approach is more relevant

$$\left(\frac{\langle k_\perp \rangle}{Q}\right)^n$$ – Expansion

$$\sigma(Q, s_T) = H_0 \otimes f_2 \otimes f_2 + (1/Q)\, H_1 \otimes f_2 \otimes f_3 + \mathcal{O}(1/Q^2)$$

Too large to compete!

Three-parton correlation

- SSA – difference of two cross sections with spin flip is power suppressed compared to the cross section

$$\Delta\sigma(Q, s_T) \equiv [\sigma(Q, s_T) - \sigma(Q, -s_T)]/2$$
$$= (1/Q) H_1(Q/\mu_F, \alpha_s) \otimes f_2(\mu_F) \otimes f_3(\mu_F) + \mathcal{O}(1/Q^2)$$

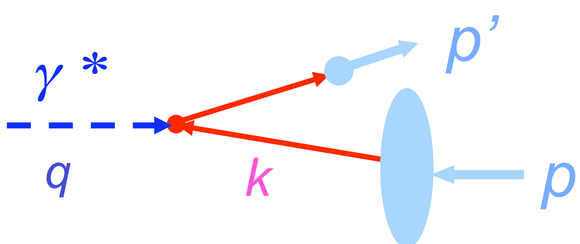
  - Sensitive to twist-3 multi-parton correlation functions
  - Integrated information on parton's transverse motion

Direct information on parton k_T

- Need processes with two observed momentum scales:

$$Q_1 \gg Q_2 \quad \begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse motion} \end{cases}$$

- Example – semi-inclusive DIS:



- Both p and p' are observed
- p'_T probes the parton's k_T
- Effect of k_T is not suppressed by Q

- Very limited processes with valid TMD factorization
  - Drell-Yan transverse momentum distribution: Q, q_T
    - quark Sivers function
    - low rate
  - Semi-inclusive DIS for light hadrons: Q, p_T
    - mixture of quark Sivers and Collins function

Bomhof and Mudlers, …
Collins, Qiu, …
Vogelsang, Yuan, …

TMD factorization

- **Factorization in terms of k_T-dependent PDFs:**

$$\sigma(Q_1, Q_2, s_{1T}, s_{2T}) = H_0 \otimes \mathcal{F}_2(k_T, s_{1T}) \otimes \mathcal{F}_2(k_T, s_{2T}) + \mathcal{O}(Q_2/Q_1, Q_2/M, M/Q_1)$$

Unlike the collinear factorization, we should include the scale of hadron mass when $Q_2 \sim \Lambda_{QCD}$

- **Sivers function:**

$$\mathcal{F}_{q/h}(x, k_T, s_T) \equiv \mathcal{F}_{q/h}(x, k_T) + f_{q/h}^{\mathrm{Sivers}}(x, k_T)\, \vec{s}_T \cdot (\hat{p} \times \hat{k}_T)$$

- **Parity and Time-reversal invariance of matrix element:**

$$\langle P, s_T | \hat{\mathcal{O}}(\psi, A_\mu) | P, s_T \rangle = \langle P, -s_T | \mathcal{P}\mathcal{T} \hat{\mathcal{O}}(\psi, A_\mu)^\dagger \mathcal{T}^{-1} \mathcal{T}^{-1} | P, -s_T \rangle$$

$$\Longrightarrow \quad \mathcal{F}_{q/h}^{\mathrm{SIDIS}}(x, k_T, s_T) = \mathcal{F}_{q/h}^{DY}(x, k_T, -s_T)$$

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

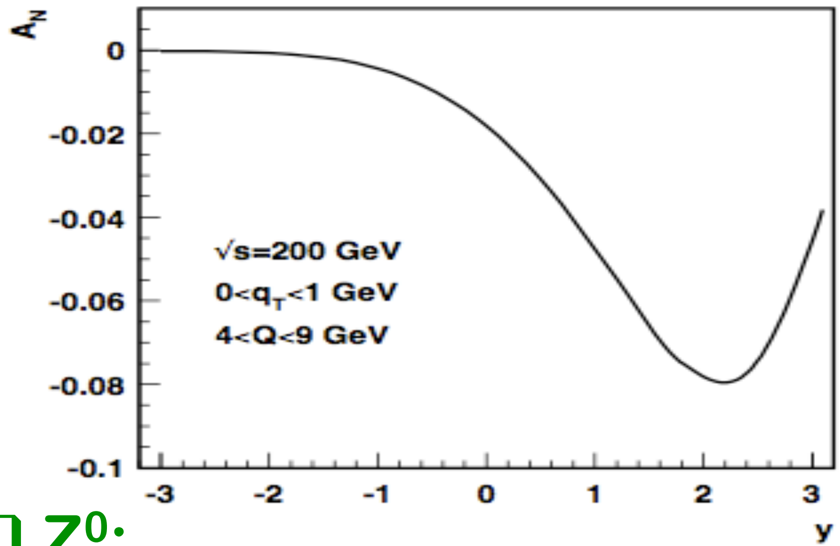
Time-reversal modified universality

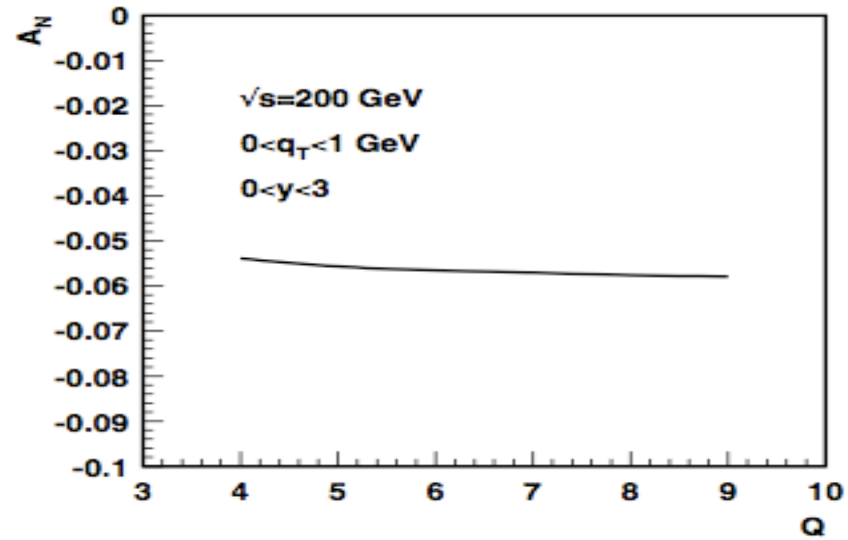
- **Collins function:** $\sigma(Q_1, Q_2, s_T) = H_0 \otimes \delta q(x, s_T) \otimes \mathcal{D}_2(k_T, Q_1) + \ldots$

The modified universality – Drell-Yan/Z^0

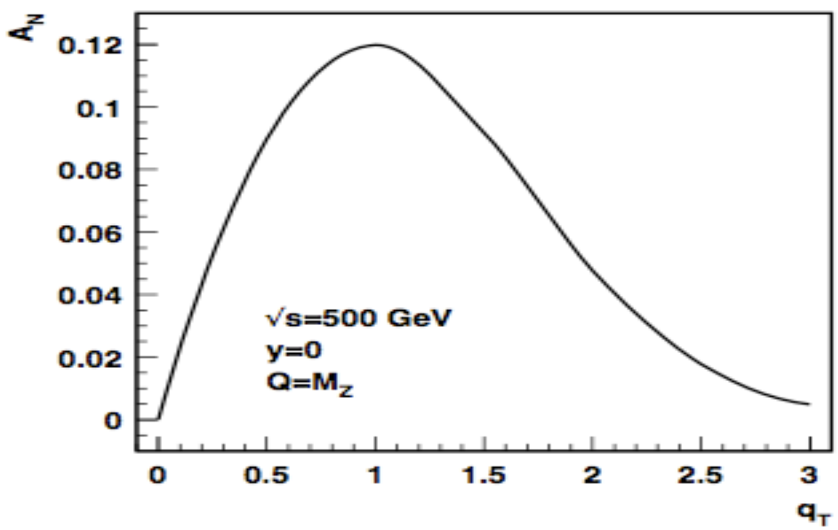
- Drell-Yan: $A_N^{\sin(\phi-\phi_s)} = -A_N$

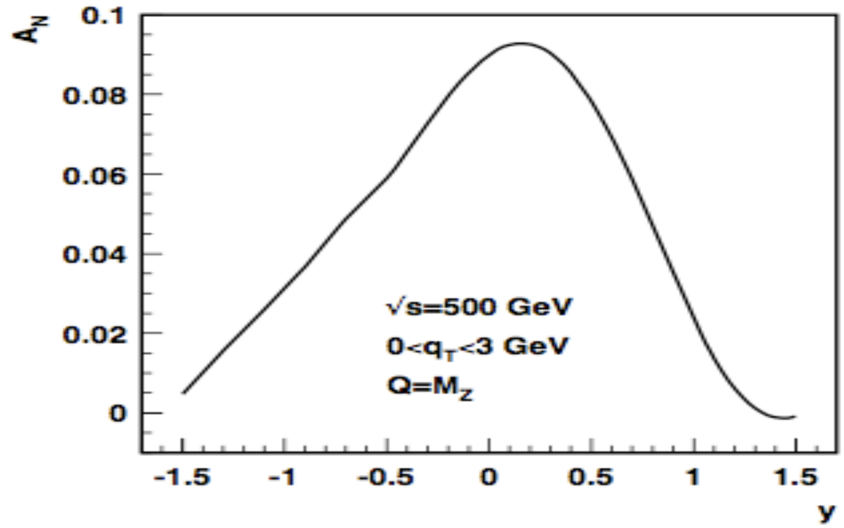
Collins et al. 2006
Kang, Qiu, 2009





- Z^0:



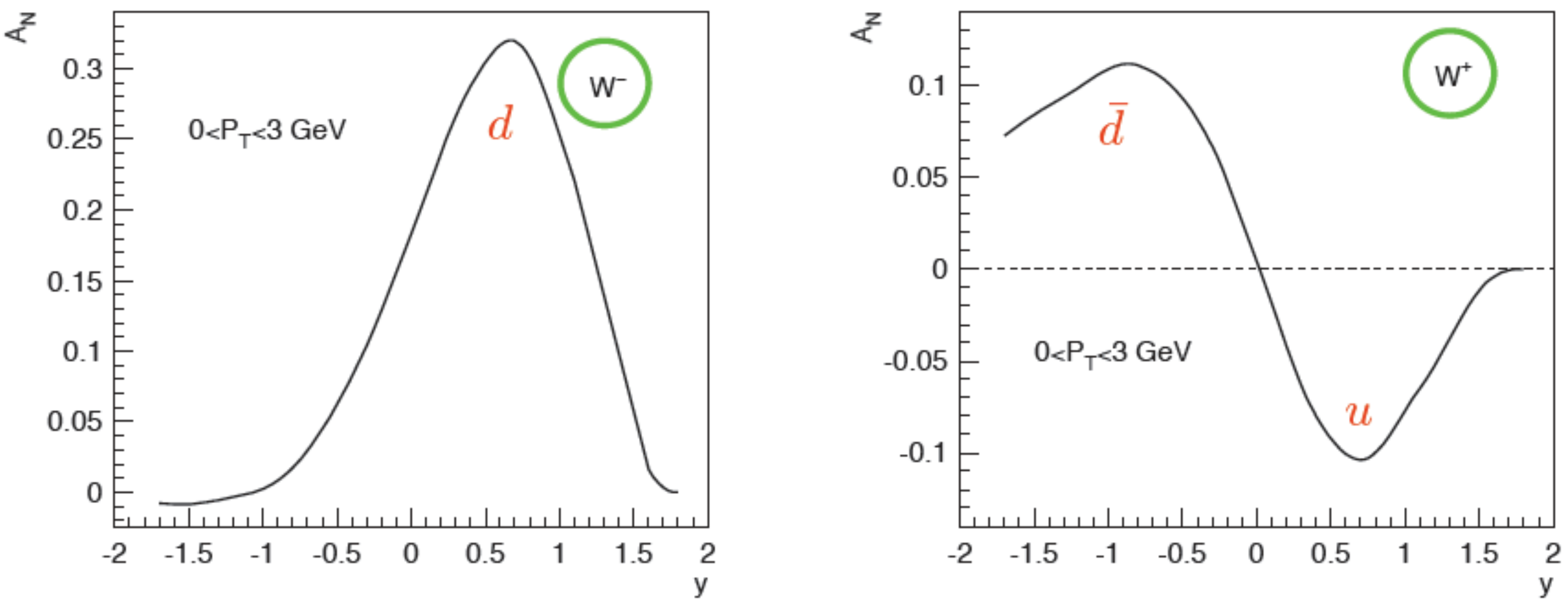


The modified universality – W production

Kang, Qiu, PRL 2009

❑ **SSA of W-production at RHIC :**

Sivers function same as DY, different from SIDIS by a sign



- flavor separation
- large asymmetry: should be able to see sign change

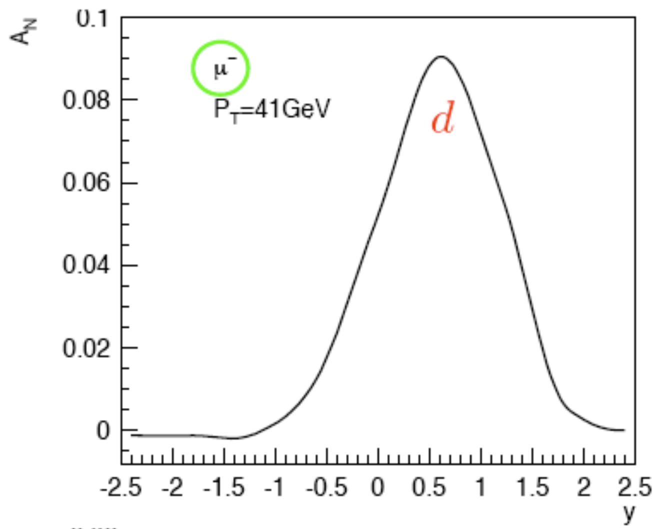
But, the detectors at RHIC cannot reconstruct the W's

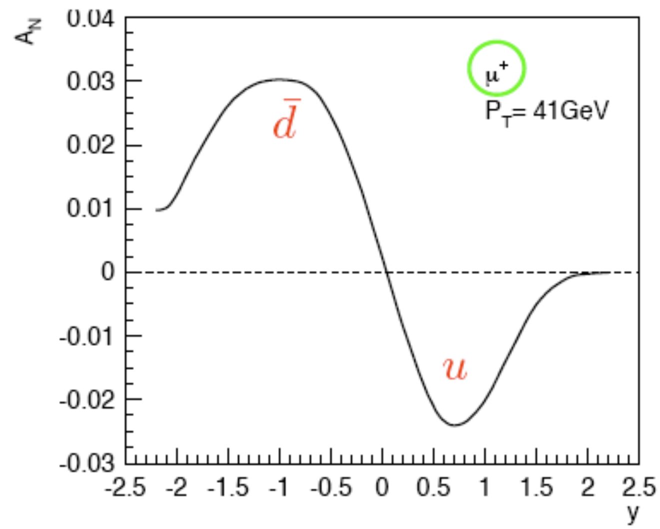
The Sivers functions from Anselmino et al 2009

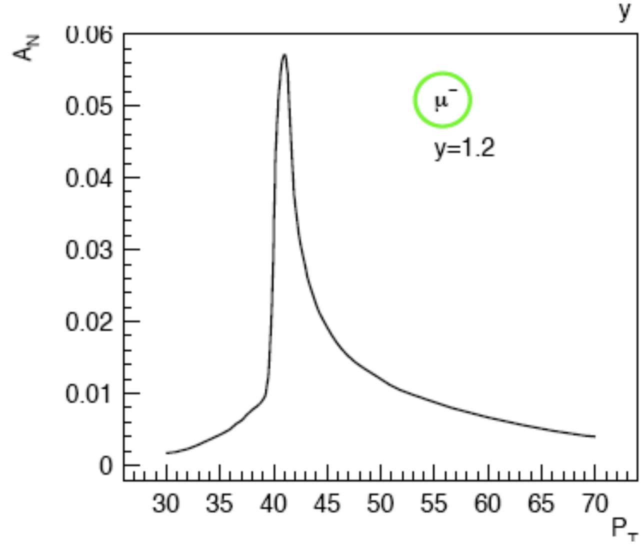
SSA of lepton from W-decay

Kang, Qiu, PRL 2009

❑ Lepton SSA is diluted from the decay:







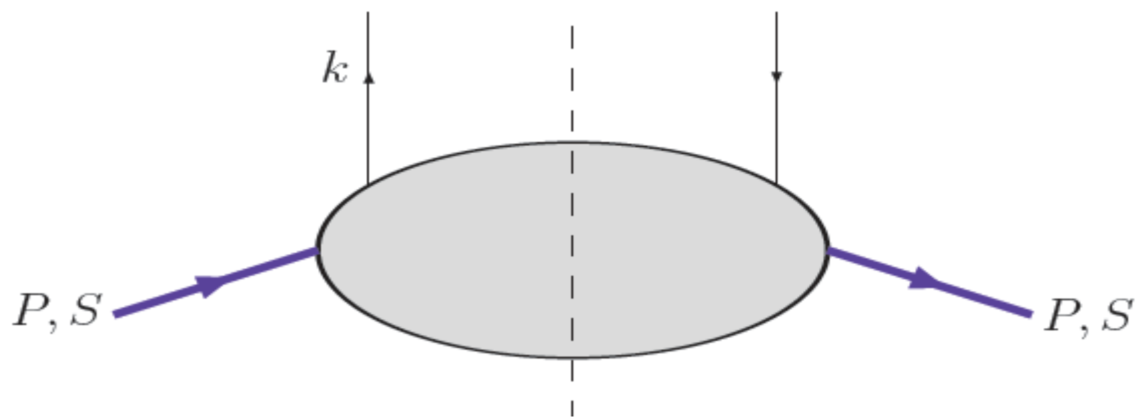
- flavor separation
- asymmetry gets smaller due to dilution
  should still be measurable by current
  RHIC sensitivity

Complimentary to Drell-Yan/Z^0 production

Other TMD distributions

- Quark TMD distributions:

$$\Phi(x, \boldsymbol{k}_\perp) = \frac{1}{2}\Big[f_1 \not{n}_+ + f_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu k_\perp^\rho S_T^\sigma}{M} + \left(S_L g_{1L} + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} g_{1T}^\perp \right) \gamma^5 \not{n}_+$$
$$+ h_{1T} i\sigma_{\mu\nu}\gamma^5 n_+^\mu S_T^\nu + \left(S_L h_{1L}^\perp + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_T}{M} h_{1T}^\perp \right) \frac{i\sigma_{\mu\nu}\gamma^5 n_+^\mu k_\perp^\nu}{M}$$
$$+ h_1^\perp \frac{\sigma_{\mu\nu} k_\perp^\mu n_+^\nu}{M} \Big]$$



Total 8 TMD quark distributions

- Gluon TMD distributions, …

Collinear vs TMD factorization

- **Relation between TMD distributions and collinear factorized distributions**

spin-averaged: $$\int d^2k_T\, f_a^{\text{SIDIS}}(x,k_T) + \text{UVCT}(\mu^2) = q_a(x,\mu^2)$$

Transverse-spin: $$\frac{1}{M_P}\int d^2\vec{k}_\perp \vec{k}_\perp^2\, q_T(x,k_\perp) = T_F(x,x)$$

- **Relation between two factorization schemes**

They are valid for different kinematical regions:

Collinear: $Q_1 \ldots Q_n \gg \Lambda_{QCD}$
TMD: $Q_1 \gg Q_2 > \Lambda_{QCD}$

Common region – perturbative region:

$Q_1 \gg Q_2 \gg \Lambda_{QCD}$
where both schemes are expected to be valid

Ji, Qiu, Vogelsang, Yuan,
Koike, Vogelsang, Yuan

SSA in QCD Collinear Factorization

Qiu, Sterman, 1998

❑ Factorization formalism for SSA of single hadron:

$$\Delta\sigma_{A+B\to\pi}(\vec{s}_T)=\sum_{abc}\ \phi^{(3)}_{a/A}(x_1,x_2,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H_{a+b\to c}(\vec{s}_T)\otimes D_{c\to\pi}(z)$$

$$+\sum_{abc}\ \delta q^{(2)}_{a/A}(x,\vec{s}_T)\otimes\phi^{(3)}_{b/B}(x'_1,x'_2)\otimes H''_{a+b\to c}(\vec{s}_T)\otimes D_{c\to\pi}(z)$$

$$+\sum_{abc}\ \delta q^{(2)}_{a/A}(x,\vec{s}_T)\otimes\phi_{b/B}(x')\otimes H'_{a+b\to c}(\vec{s}_T)\otimes D^{(3)}_{c\to\pi}(z_1,z_2)$$

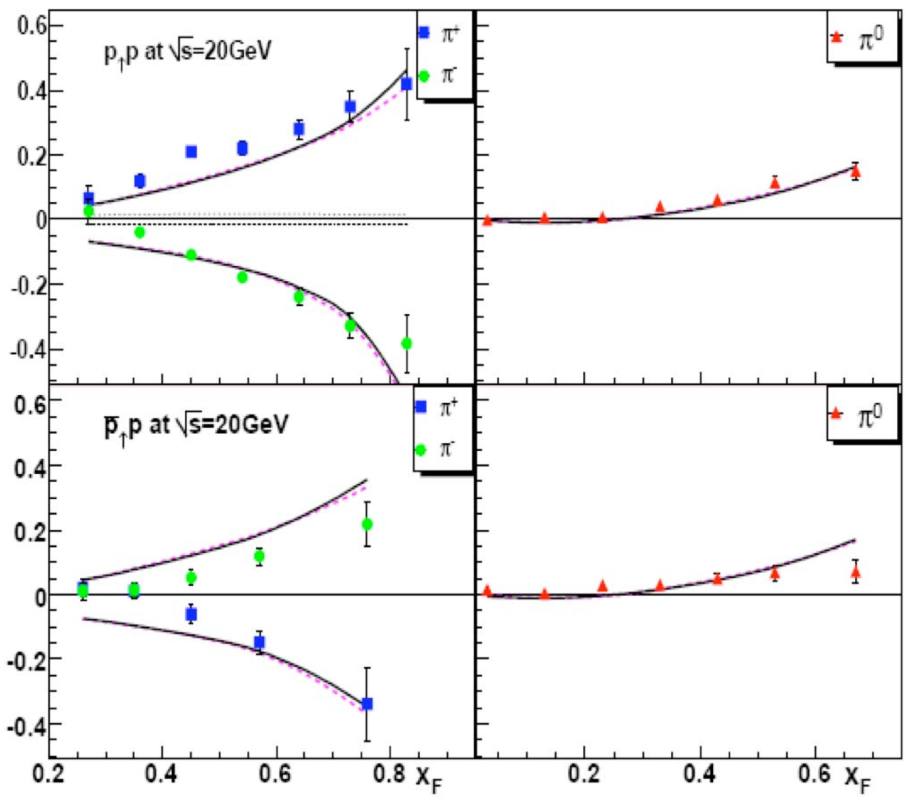
$$+\text{higher power corrections},$$

Only one twist-3 distribution in each term!

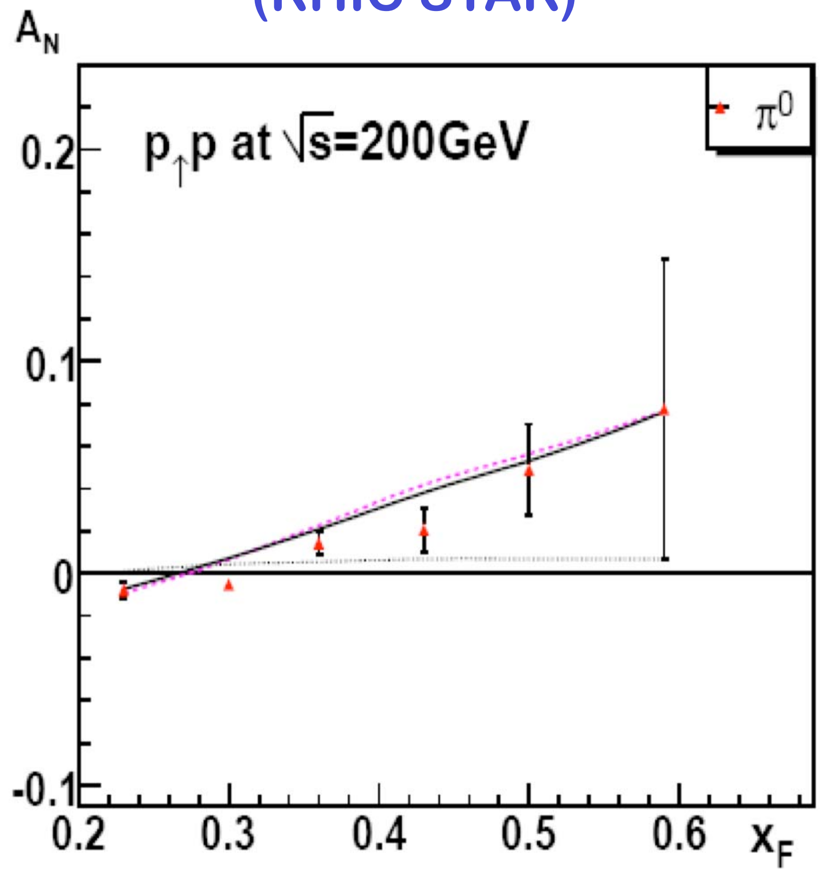
- ❖ 1[st] term: Collinear version of Sivers effect
- ❖ 2[nd] term: Collinear version of transversity + BM function
- ❖ 3[rd] term: Collinear version of Collins effect

Asymmetries from the $T_F(x,x)$

(FermiLab E704)



(RHIC STAR)



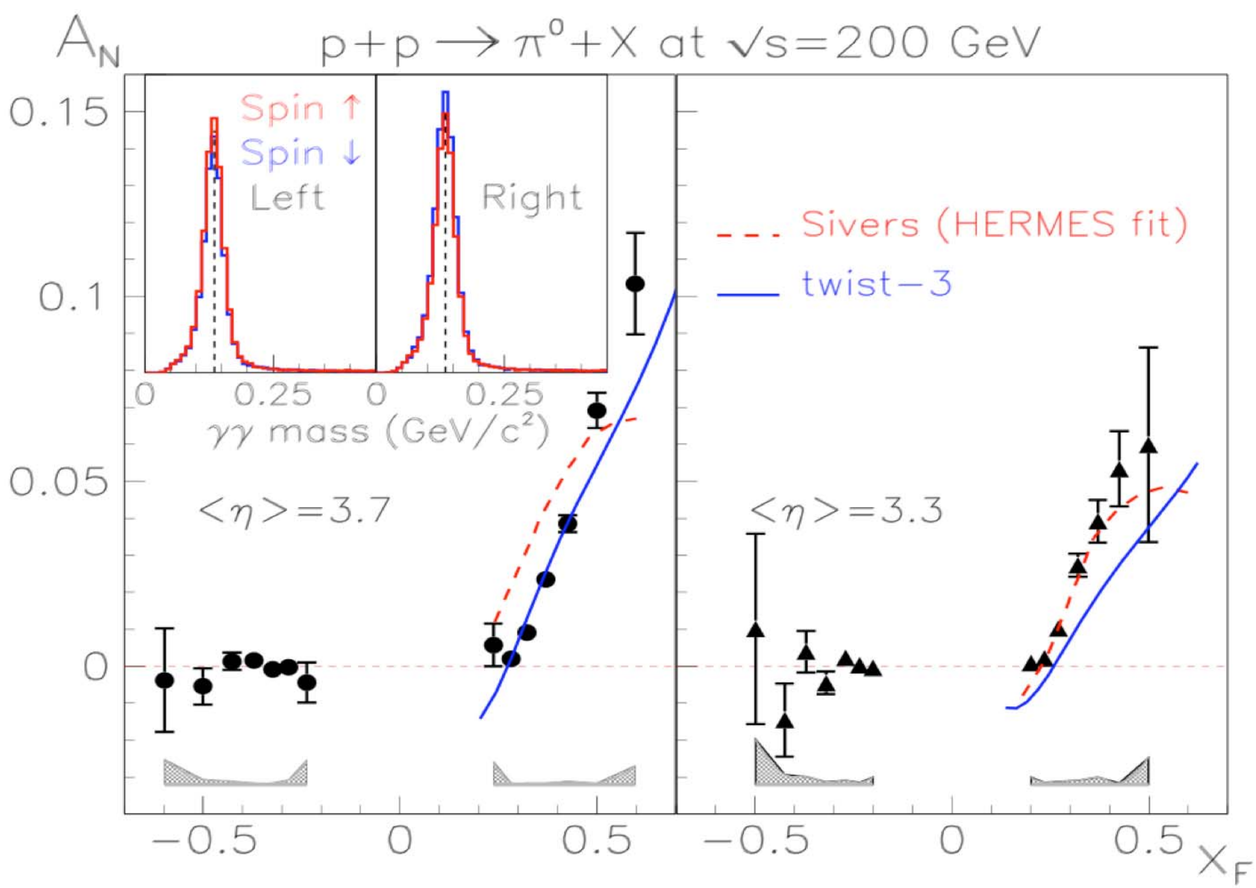
Kouvaris,Qiu,Vogelsang,Yuan, 2006

Nonvanish twist-3 function ⟶ Nonvanish transverse motion

Asymmetries generated by TMD distributions

❑ **STAR Run 6 inclusive π^0:**

PRL 101, 222001 (2008)
arXiv:0801.2990v1 [hep-ex]



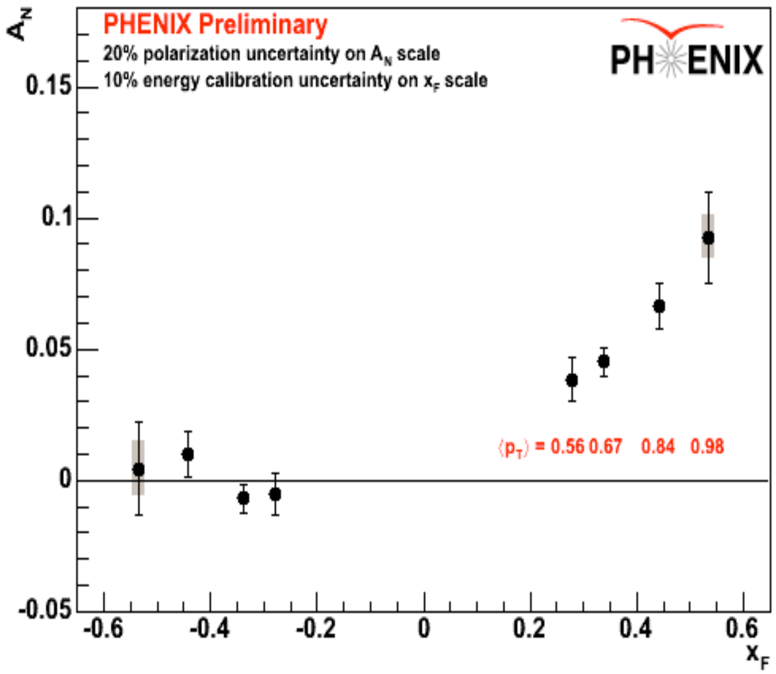
U. D'Alesio, F. Murgia
Phys. Rev. D 70, 074009 (2004)
arXiv:hep-ph/0712.4240

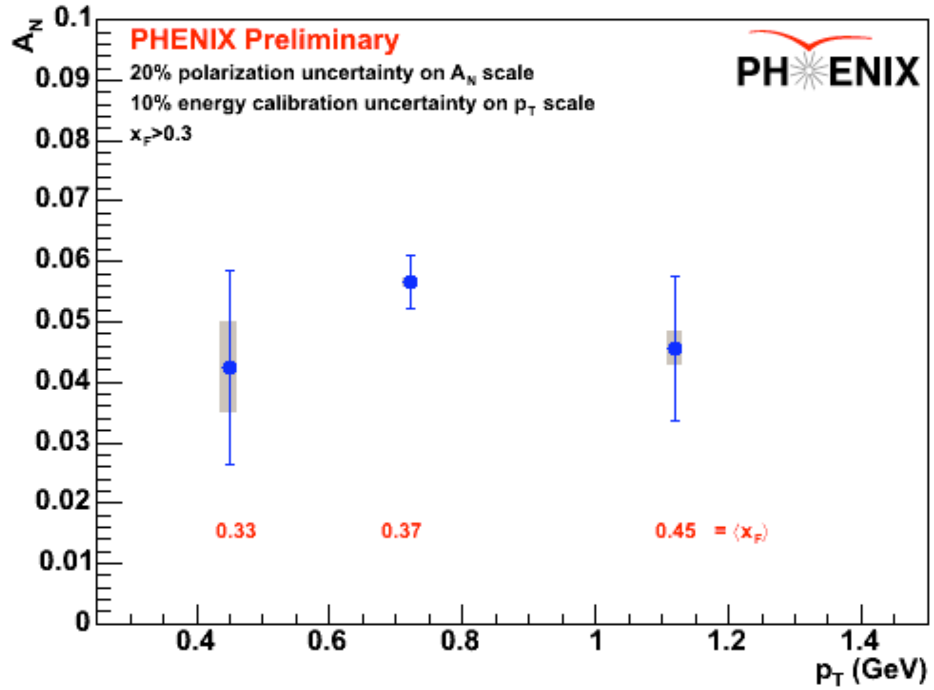
C. Kouvaris, J. Qiu, W. Vogelsang, F. Yuan,
Phys. Rev. D 74, 114013 (2006).

All RHIC experiments measured A_N

- PHENIX Run 6 forward π^0:

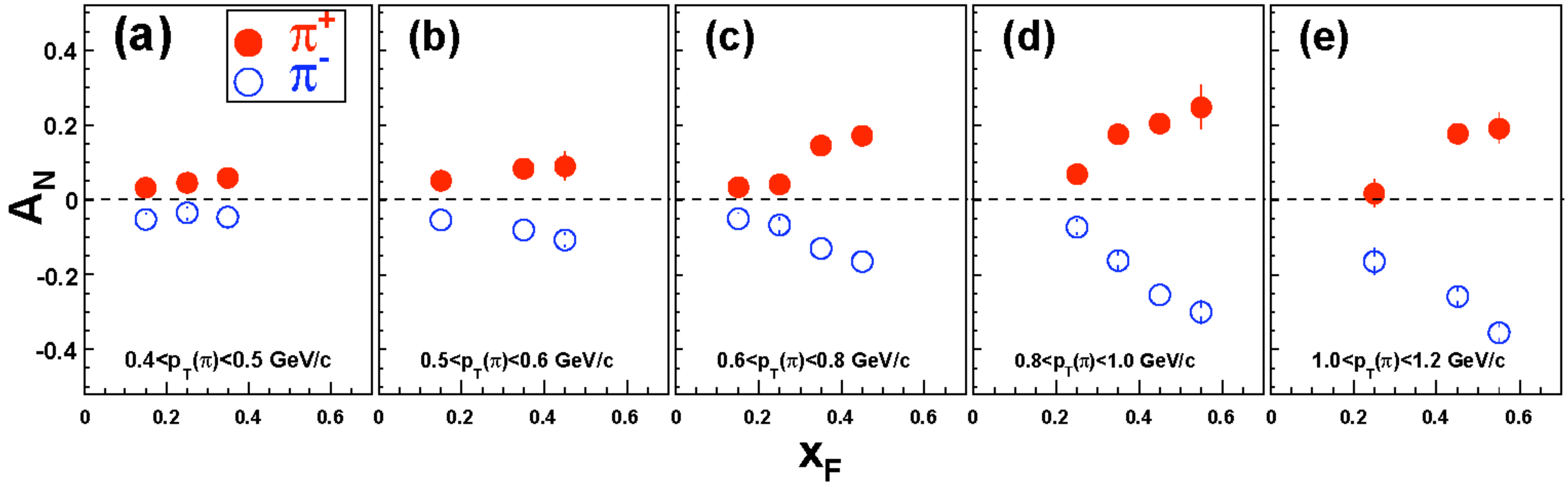
$p_\uparrow + p \rightarrow \pi^0 + X$, $\sqrt{s}$ = 62 GeV

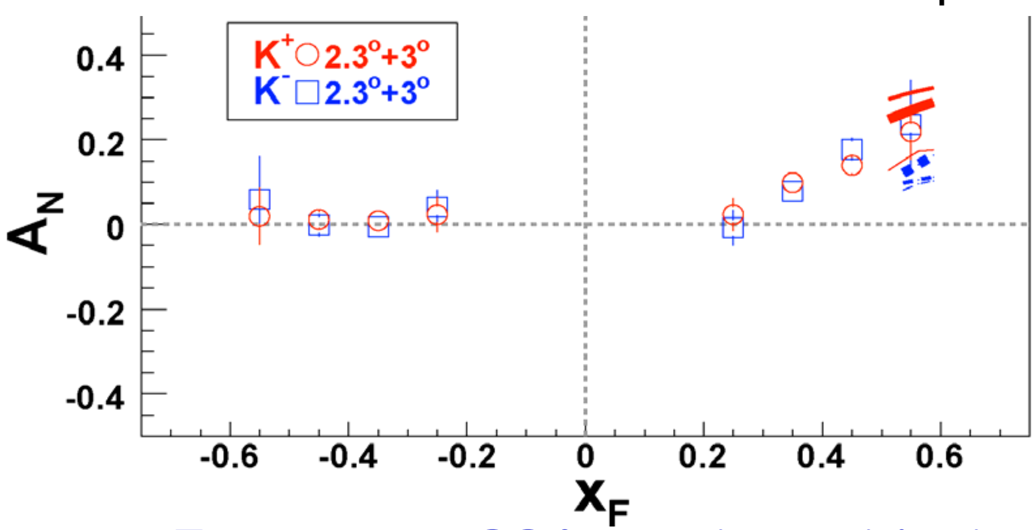




Transverse SSA persists with similar characteristics over a broad range of collision energy (20 < $\sqrt{s}$ < 200 GeV)

BRAHMS: $\pi^{\pm}$, Kaons





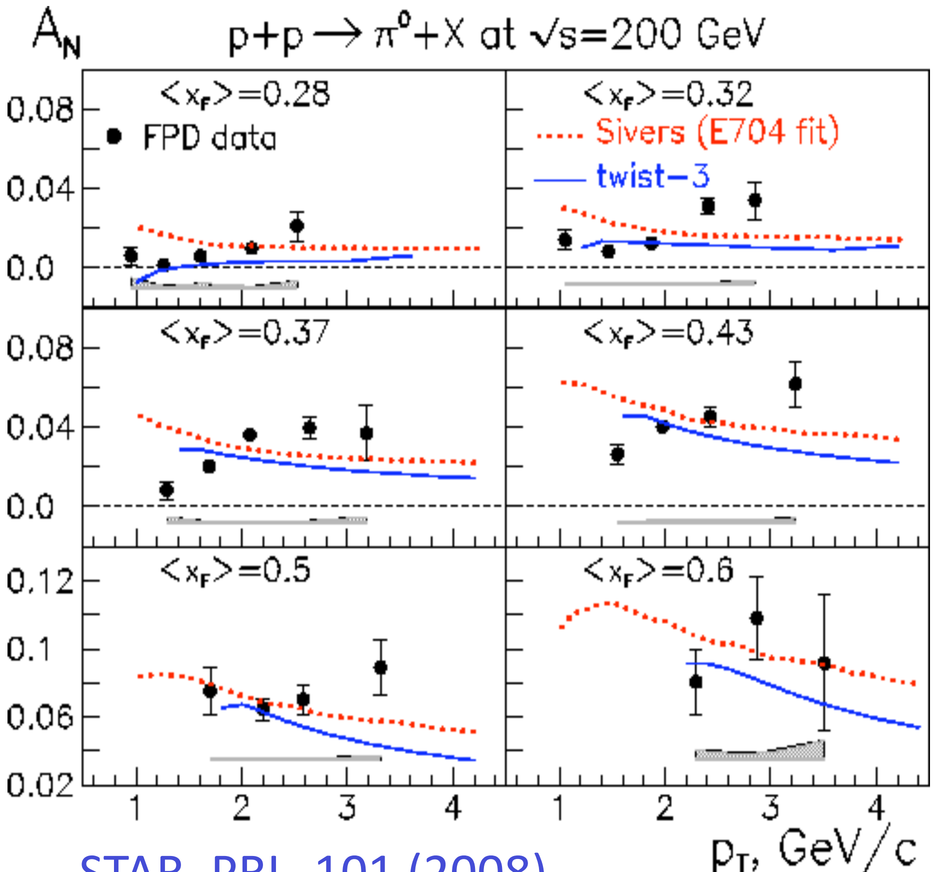
$\sqrt{s}$=62 GeV

PRL101 (2008) 042001

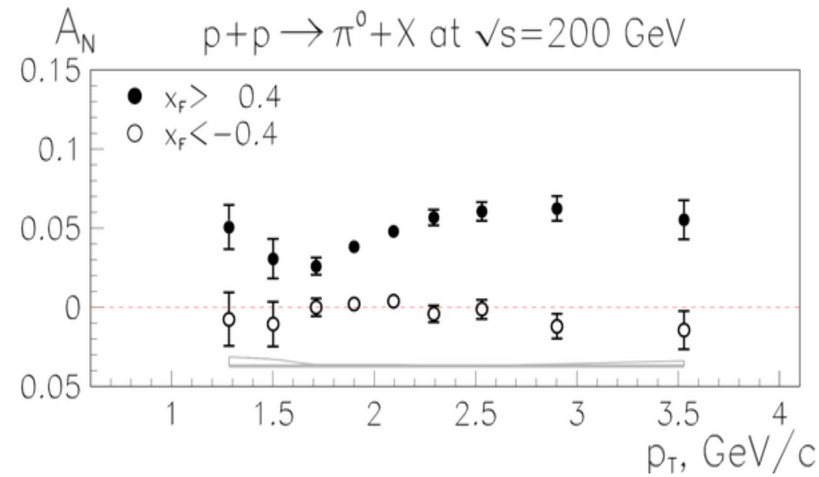
Transverse SSA persists with similar characteristics for producing different particles

p_T – dependence of A_N

❑ **STAR inclusive π^0 (Run 3,5,6):**



STAR, PRL 101 (2008) 222001



B.I. Abelev et al. (STAR) PRL **101** (2008) 222001

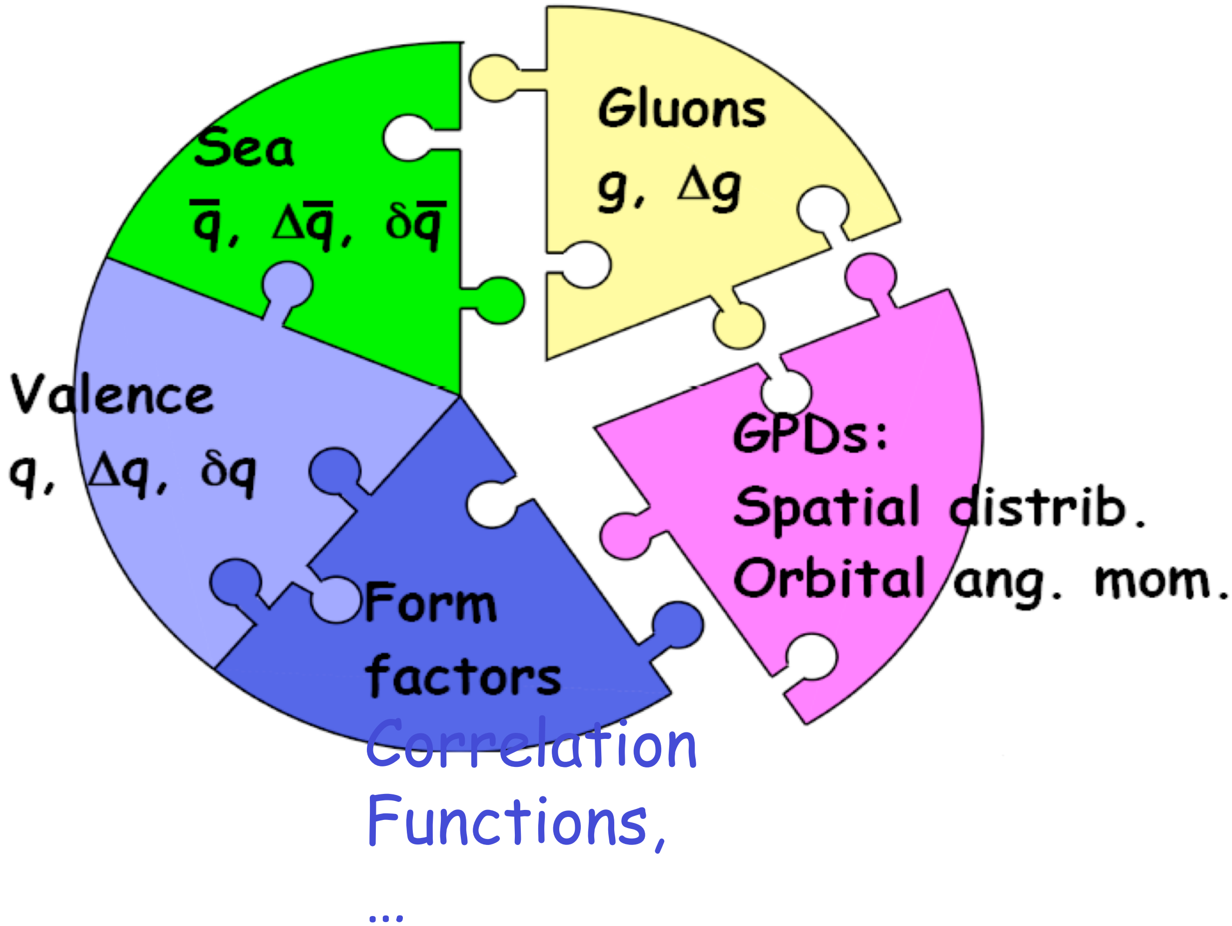
Rising P_T-dependence
Not explained

$$A_N^{\mathrm{Tw3}} \propto \frac{\epsilon_{\mu\nu} s_T^\mu p_T^\nu}{p_T^2} \Rightarrow \frac{\epsilon_{\mu\nu} s_T^\mu p_T^\nu}{p_T^2 + \mu^2}$$

See Feng's talk

Future: new opportunities

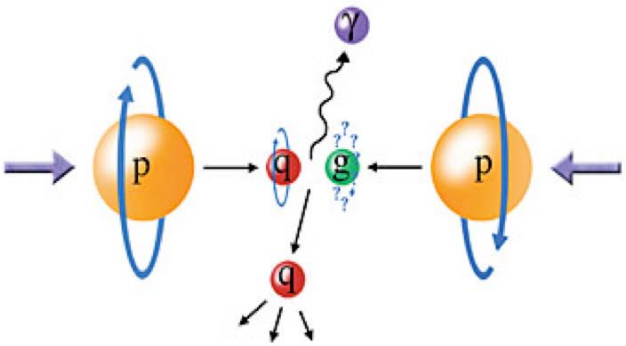
- RHIC will provide the much needed information on parton helicity distributions:



- RHIC can do much more than that!

Example: QCD quantum interference

- Cross section is a classical quantity – probability:
- Collinear factorized cross section:



Probability

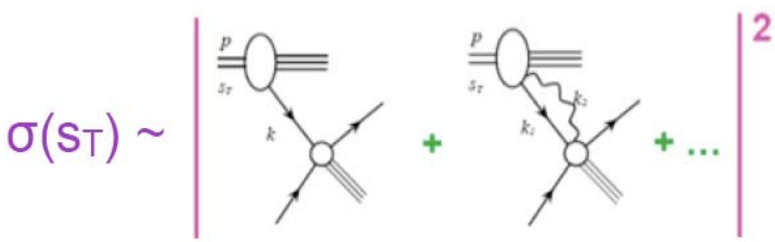
$$\frac{d\sigma}{dy\,dp_T^2} = \int \frac{dx}{x} q(x) \int \frac{dx'}{x'} g(x') \frac{d\hat{\sigma}_{qg\to\gamma q}}{dy\,dp_T^2} + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{Q_s}{P_T}\right)^n$$

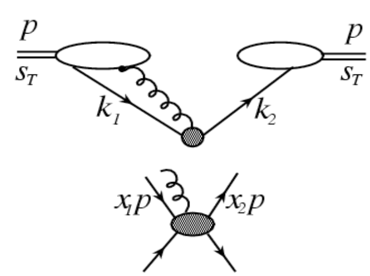
- SSA – Collinear factorization approach:

$$\sigma(Q, s_T) = H_0 \otimes f_2 \otimes f_2 + (1/Q)\, H_1 \otimes f_2 \otimes f_3 + \mathcal{O}(1/Q^2)$$

Short-distance interference

Long-distance interference





Important recent developments

- ❑ Identify all quark-gluon and tri-gluon correlation functions responsible to SSA

- ❑ One-loop evolution equations for these correlation functions – from several groups

- ❑ First NLO hard part was calculated

Kang, Qiu, …
Yuan, Zhou, …
Braun et al. …
Vogelsang, Yuan, …

Have the knowledge to make reliable predictions!

- ❑ RHIC Spin Program provide many new opportunities to learn/test QCD dynamics – no other collider can do

Thank you!