Workshop "Summary"
in
30 minutes

- ✧ Good news
- ✧ Questions and opportunities?
- ✧ "Golden" measurements
- ✧ Challenges

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Brookhaven National Laboratory

Joint BNL-LANL-RBRC Workshop on "Physics of pA collisions at RHIC"
BNL Physics Building, January 7-9, 2013

Good news

From our colleagues at CAD:

M. Blaskiewicz, F. Karl
W. Fischer, V. Ranjbar,
S. Tepikian

- p+Au is possible
  max energy 100 GeV/nucleon for both beams

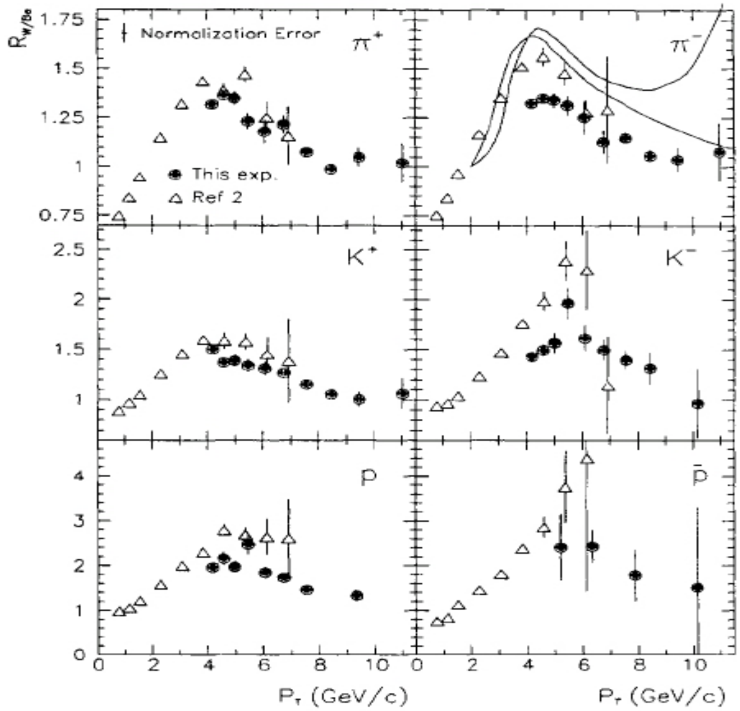
- A collision strategy is proposed for moving only the IP6 and IP8 DX magnets by at minimum of 1 *cm*, better at 1.5 *cm*

- This allows equal species to run as well

- Luminosity estimate based on p↑ beam available (anticipated), and Au beam available (anticipated)

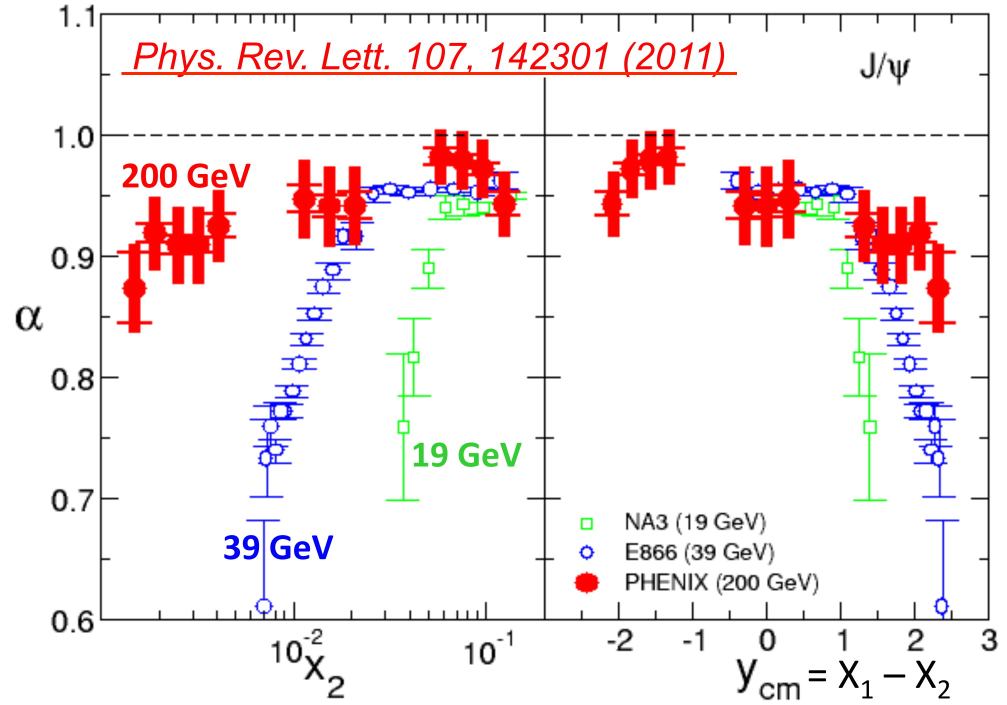
  L_{NN} = 15 pb/week min (now)
  L_{NN} = 37 pb/week max (few years)

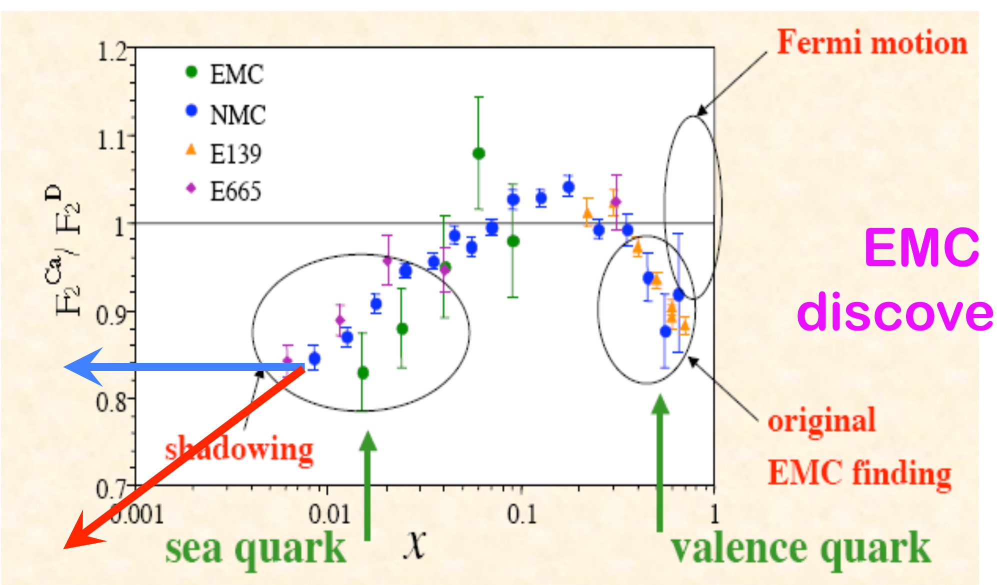
Non-trivial nuclear effects



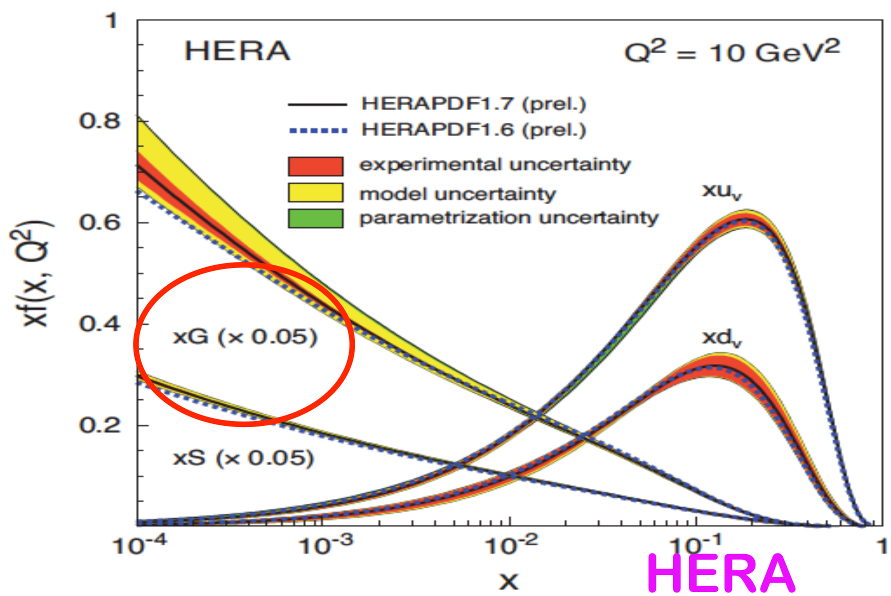
Leitch, ...

Cronin effect





EMC discovery



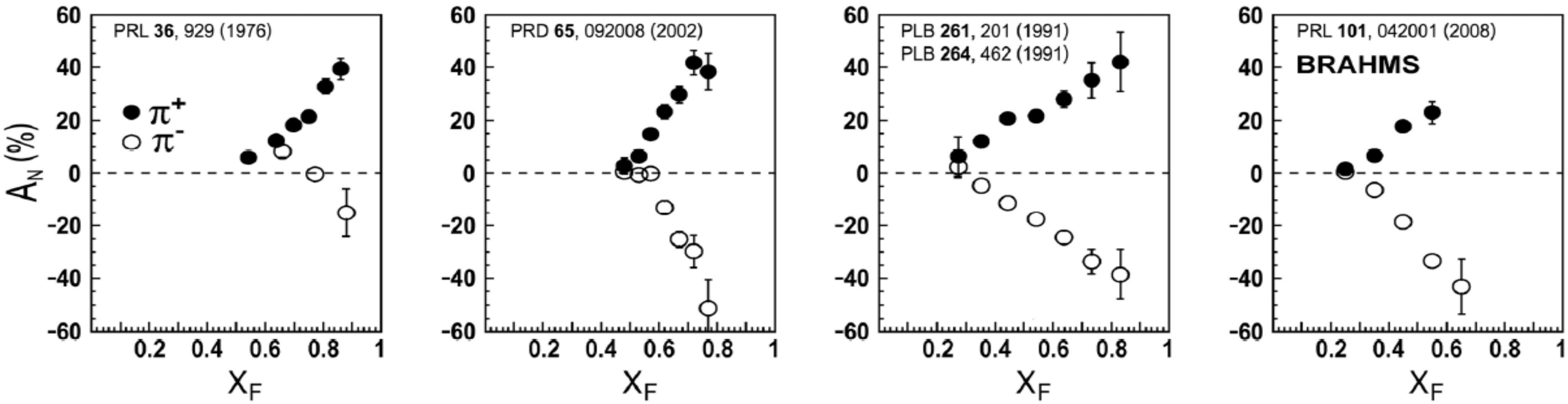
HERA discovery

Transverse single-spin asymmetry (SSA)

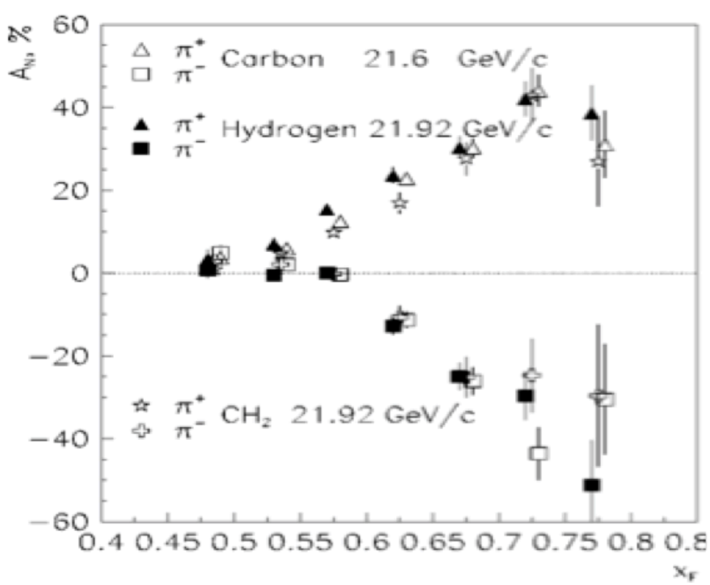
Kang, Makdisi, …

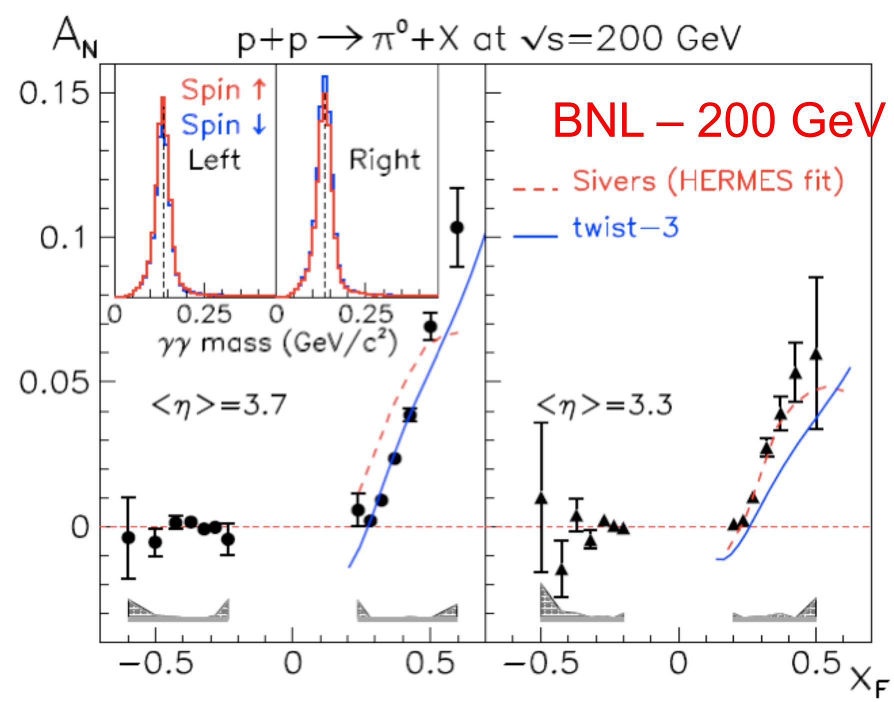
- Consistently observed for over 35 years!

ANL – 4.9 GeV | BNL – 6.6 GeV | FNAL – 20 GeV | BNL – 62.4 GeV



- Nuclear dependence:

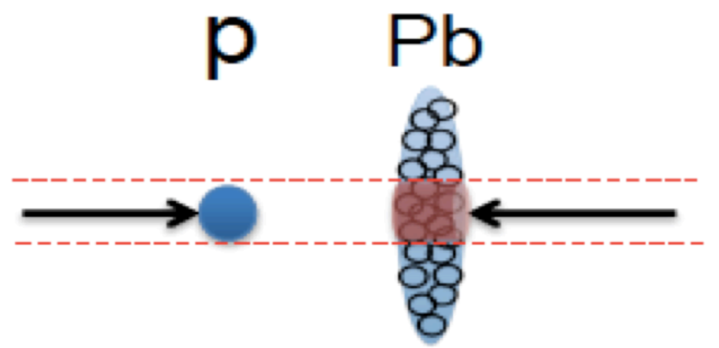




Proton-nucleus collisions

- New era:

Venugopalan, …



Collider p/d+A experiments: a new era in QCD at high parton densities

- Forward region:

$x_1 >> x_2$

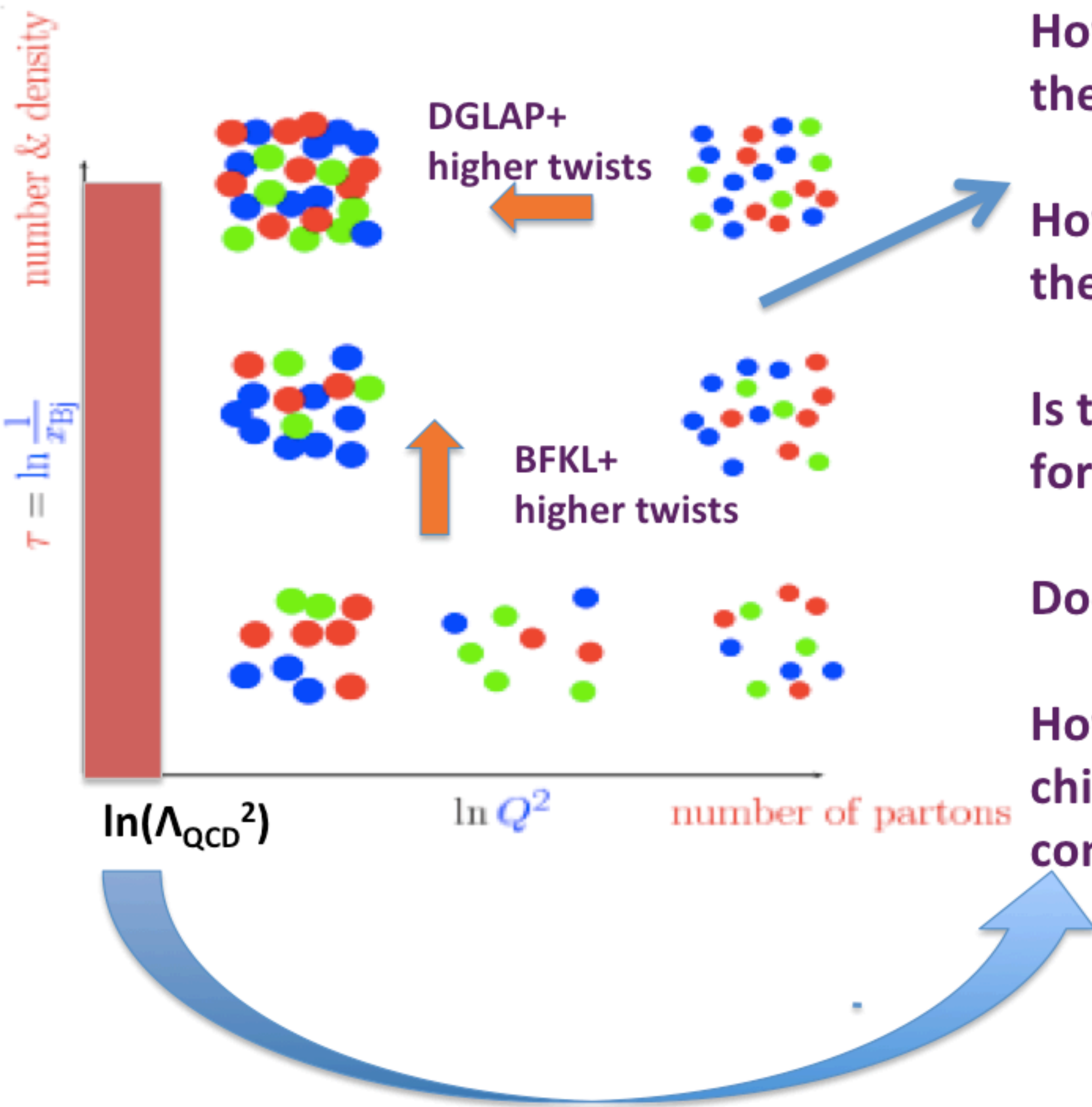
Well-known valence distribution from the proton
Less-known small-x distribution from the nucleus

where the spin physicists meet with the small-x physicists

- Polarization – "single" spin:

Probe the dynamics that cannot be "seen" by spin-averaged x-sections

Many-body dynamics of universal gluonic matter



How does this happen ? What are the right degrees of freedom ?

How do correlation functions of these evolve ?

Is there a universal fixed point for the RG evolution of d.o.f

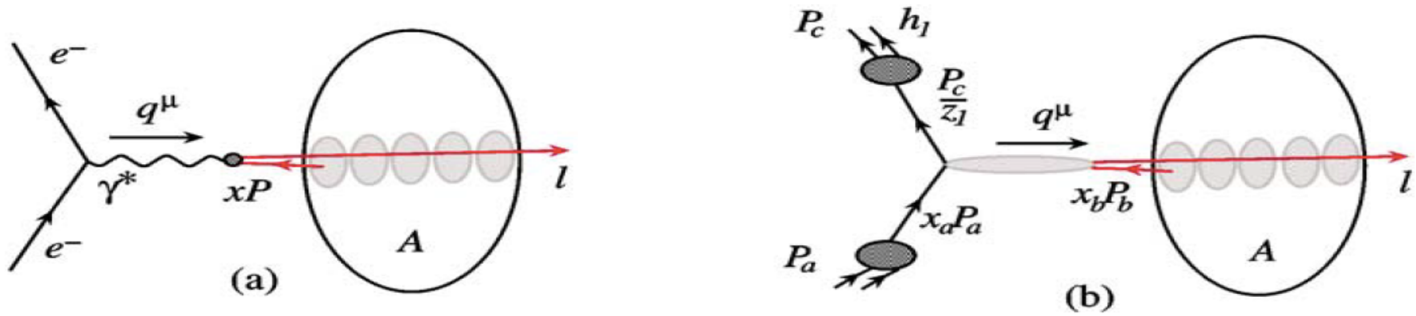
Does the coupling run with Q_s^2 ?

How does saturation transition to chiral symmetry breaking and confinement

Venugopalan, ...

Forward region and coherence

- Dominated production channel is similar to DIS:



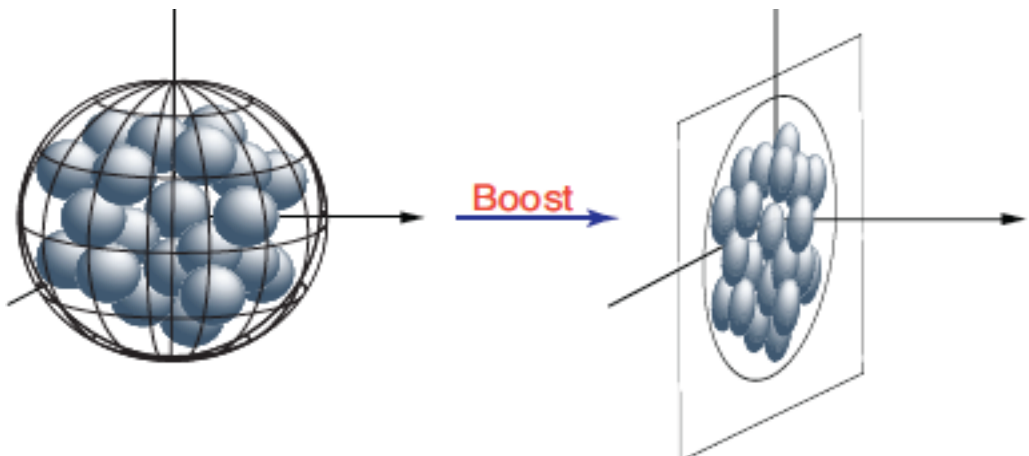
DIS

T-channel of pA

T → 0

U → -S

- "Snapshot" does not have a "sharp" depth at small x



Probe interacts with all soft partons at the same impact parameter coherently

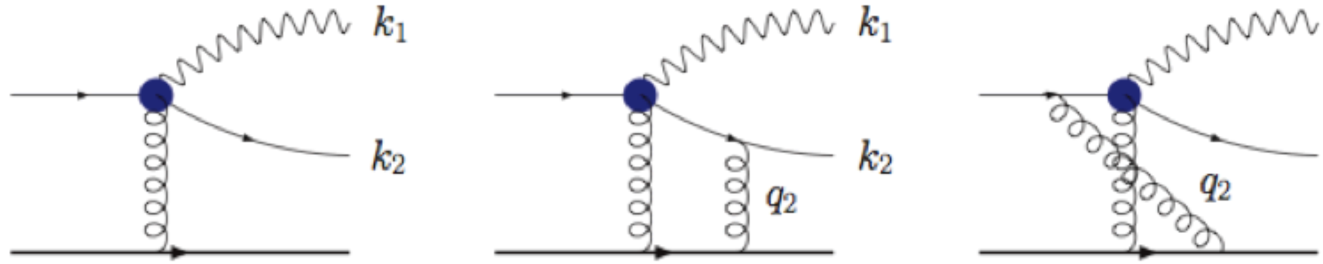
Probe size: transverse - $\frac{1}{Q} \ll 1\ \mathrm{fm}$, longitudinal size - $\frac{1}{xp} \sim \frac{1}{Q} \ll 1\ \mathrm{fm}$

Longitudinal size > Lorentz contracted nucleon: $\frac{1}{xp} > 2R\frac{m}{p}$

$$x < x_c = \frac{1}{2mR} \sim 0.1$$

Di-hadrons in p/d-A collisions

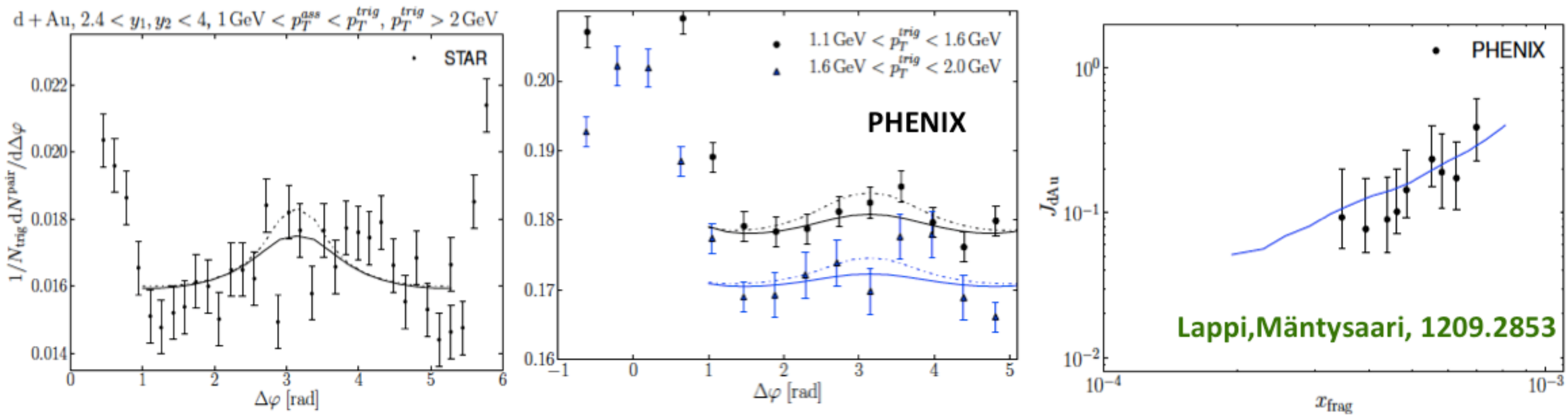
Jalilian-Marian, Kovchegov (2004)
Marquet (2007), Tuchin (2010)
Dominguez,Marquet,Xiao,Yuan (2011)
Strikman,Vogelsang (2010)



$$\frac{d\sigma^{qA\to qgX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[S_6(x,y,\bar{x},\bar{y}) - S_4(x,y,v) - \ldots\right]$$

$$\frac{N_c}{2C_F}\left\langle Q(x,y\,\bar{y},\bar{x})D(y,\bar{y}) - \frac{D(x,\bar{x})}{N_c}\right\rangle \quad \frac{N_c}{2C_F}\left\langle D(x,y)D(\bar{y},\bar{x}) - \frac{D(x,\bar{x})}{N_c}\right\rangle$$

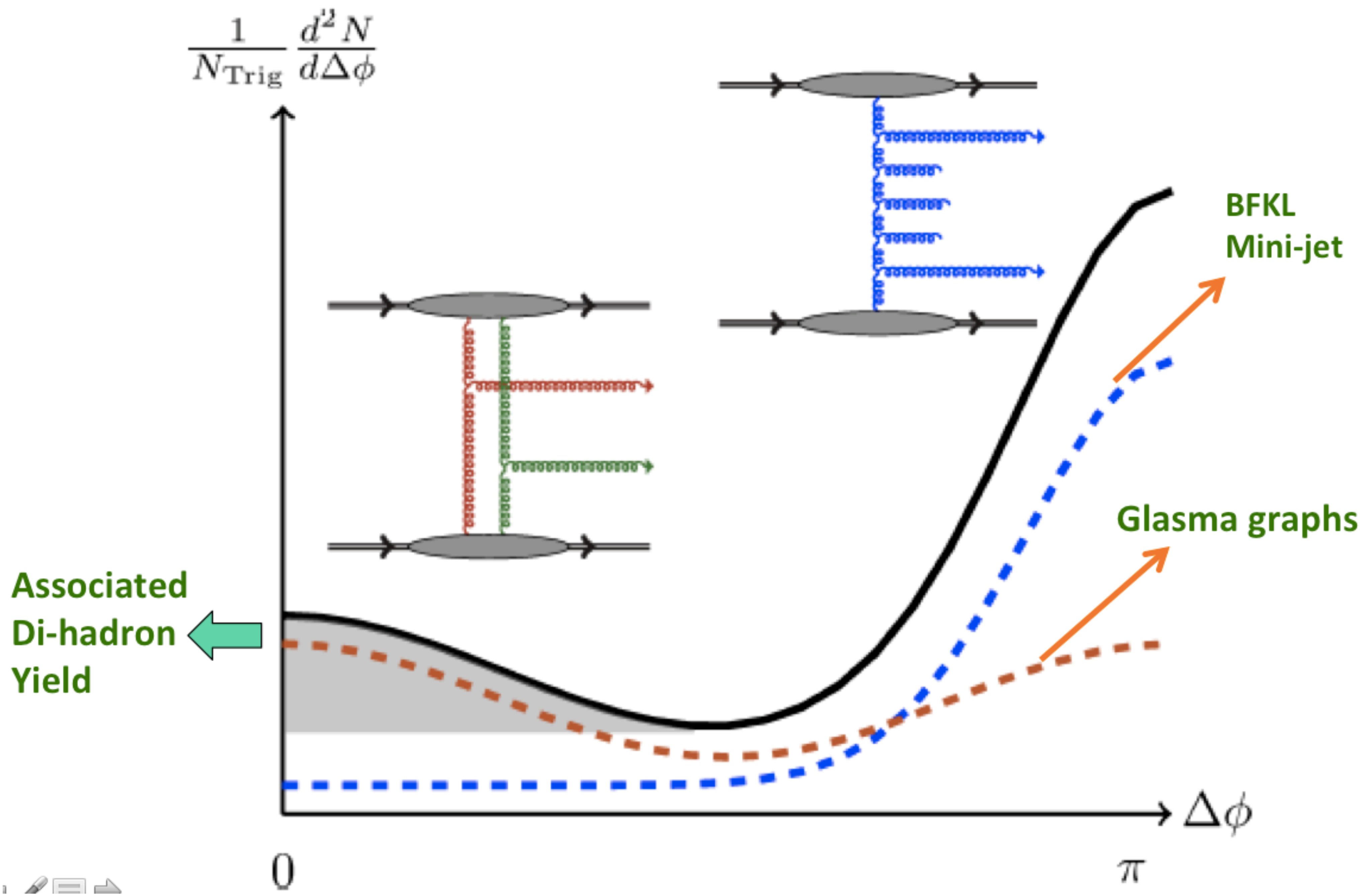
Forward-forward di-hadrons sensitive to both dipole and quadrupole correlators



Recent computations (Stasto,Xiao,Yuan + Lappi,Mäntysaari) include Pedestal, Shadowing (color screening) and Broadening (multiple scattering) effects in CGC

Venugopalan, …

Anatomy of long range di-hadron collimation



Venugopalan, …

Exciting results on proton lead collisions

Multiplicity

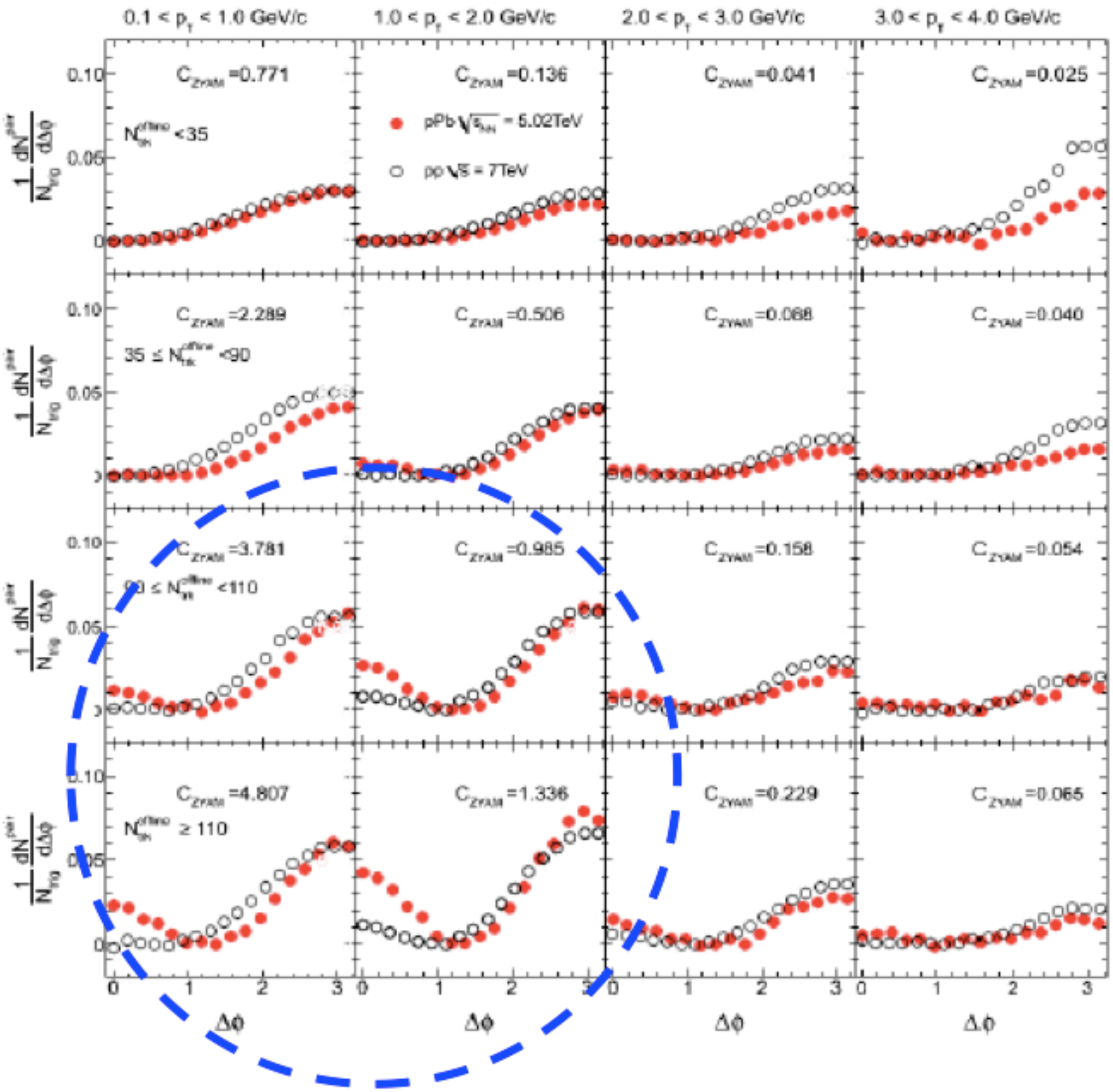
N<35

35<N<90

90<N<110

N>110

0 – 1　1 – 2　2 – 3　3 – 4　p_T (GeV/c)



CMS Preliminary

Predictions for pA at RHIC?

Conclusions on physics opportunities of pA:

- Will produce a novel information on strong interactions in the high gluon density kinematics for fixed nuclear thickness as a function of energy: *parton , groups of partons propagation through media in soft and hard regime including spin effects*

- Will complement pA run at LHC - critical for understanding how small x dynamics changes with energy

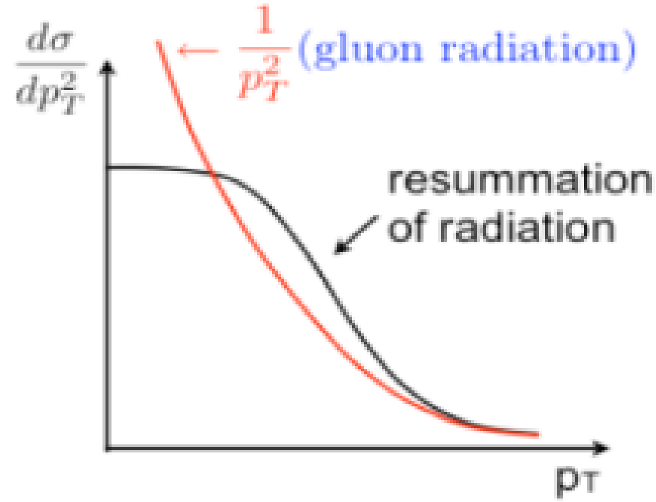
- Will allow to measure inelastic diffraction at the highest energy where it is still comparable/larger than e.m. contribution

- Check the color fluctuation dynamics for generic inelastic pA collisions

Strikman

Transverse momentum broadening

- **Transverse momentum distribution at low p_T is ill-defined in fixed order perturbative calculation**
  - All order resummation (CSS formalism)



- **Multiple scattering in medium:**
  - Each scattering is too soft to calculate perturbatively
  - Resummation + multiple scattering (not yet achieved)
- **Moment of p_T-distribution is less sensitive to low p_T region:**
  - based on observed particles only

$$\langle p_T^n \rangle = \int dp_T^2 \, p_T^n \frac{d\sigma(Q)}{dp_T^2} \Big/ \int dp_T^2 \frac{d\sigma(Q)}{dp_T^2}$$

- **Momentum broadening:**

$$\Delta \langle p_T^2 \rangle = \langle p_T^2 \rangle_{pA} - \langle p_T^2 \rangle_{pp}$$

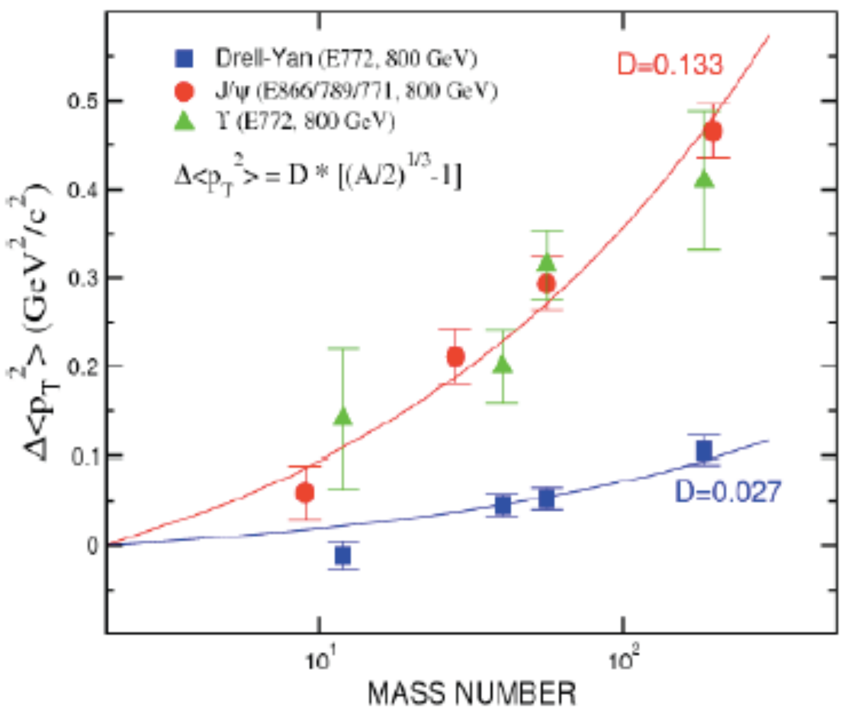
  - Sensitive to the medium properties
  - Perturbatively calculable

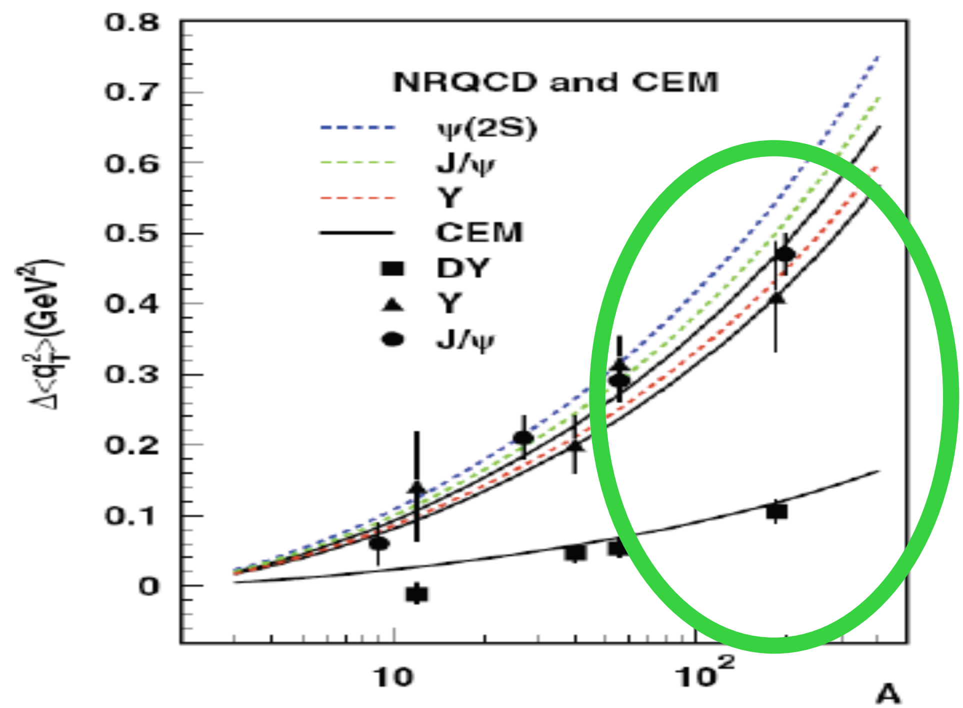
$$\Delta \langle p_T^n \rangle = \langle p_T^n \rangle_{AB} - \langle p_T^n \rangle_{NN}$$

Vector boson production

- ❑ **Data from fixed targets:**

Kang, Qiu, PRD77(2008)

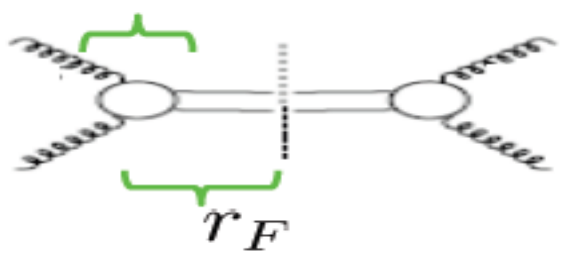




Energy dependence

- ❑ **Quarkonium cannot be formed 1/mc:**

$$r_H \leq \frac{1}{2m_c} \sim \frac{1}{15}\,\mathrm{fm}$$



Final-state interaction for Quarkonium formation

Calculated in both NRQCD and color evaporation model

A-dependence of PT spectrum

- Ratio of x-sections:

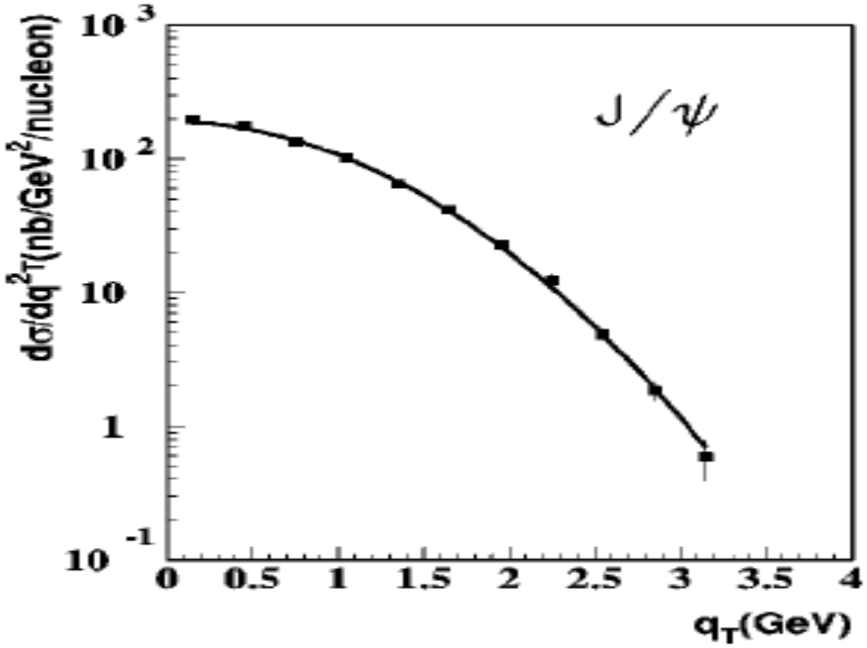
Guo, Qiu, Zhang, PRL, PRD 2000
Mike Leitch's talk

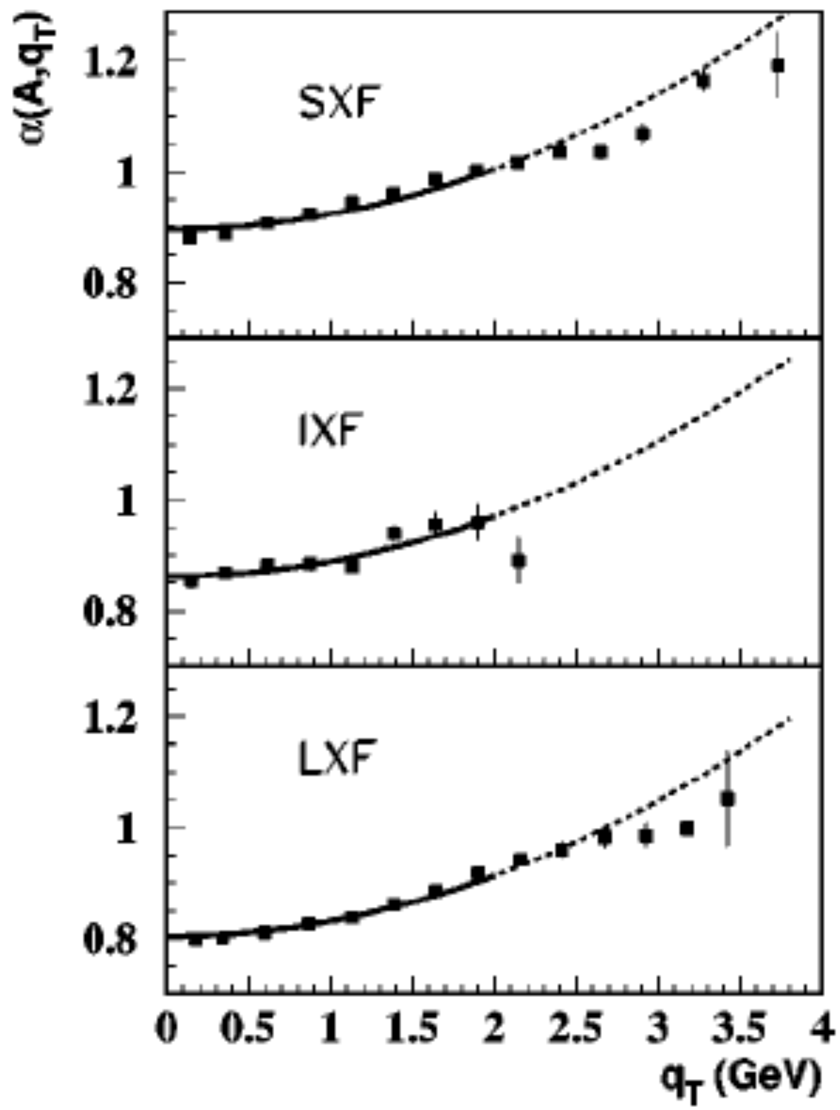
$$R(A,q_T) \equiv \frac{1}{A}\frac{d\sigma^{hA}}{dQ^2\,dq_T^2} \bigg/ \frac{d\sigma^{hN}}{dQ^2\,dq_T^2} \equiv A^{\alpha(A,q_T)-1}$$

$$\approx 1 + \frac{\Delta\langle q_T^2\rangle}{A^{1/3}\langle q_T^2\rangle_{\rm DY}^{hN}}\left[-1 + \frac{q_T^2}{\langle q_T^2\rangle_{\rm DY}^{hN}}\right]$$

Similar formula for J/ψ

- Spectrum and ratio:





SSA in the forward region of pA collisions

Excellent probe for distinguishing various contributions to SSA

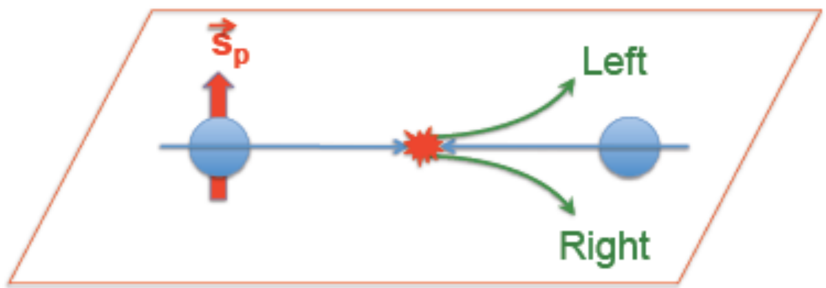
Excellent probe for studying small-x Physics

SSA increases as x_F (or y) increases

Polarized proton and A_N

❑ Definition:

Kang, Yuan, …



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

Difference of x-sections!

❑ A_N proportional to the k_T slop of TMD:

- Now spin-dependent cross section becomes

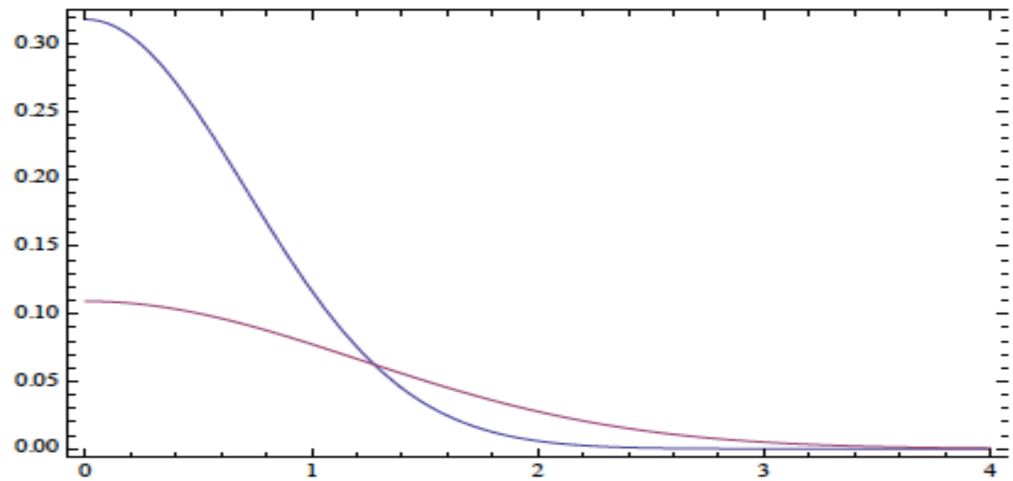
$$\frac{d\sigma}{dyd^2p_\perp} = \frac{K}{(2\pi)^2}\int d^2b \int_{x_F}^{1}\frac{dz}{z^2}\int d^2k_\perp x\epsilon^{\alpha\beta}s_\perp^\alpha k_\perp^\beta f_{1T}^{\perp,q}(x,k_\perp^2)F(x_A, q_\perp = p_\perp/z - k_\perp)D_{h/q}(z)$$

  - 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

Saturation scale depenence

- **Nuclear TMD is broadened:**

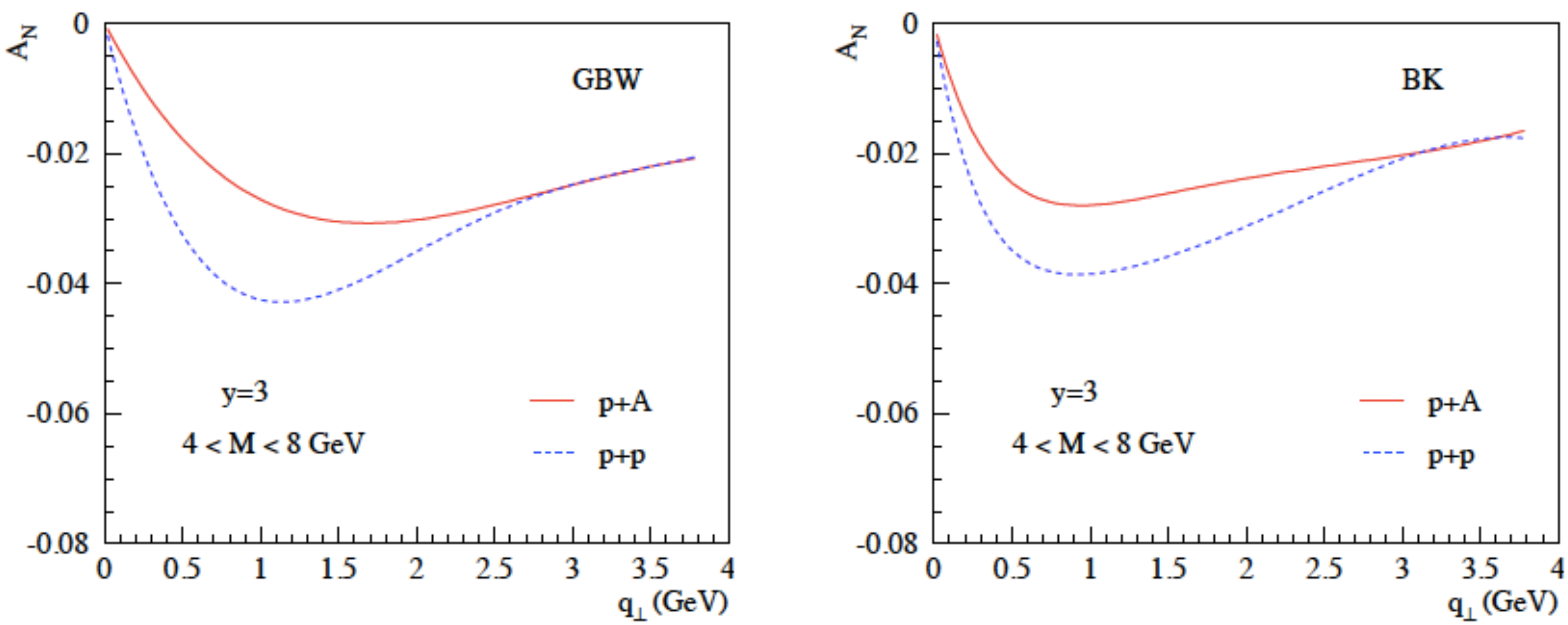
$$F(x, q_\perp) = \frac{1}{\pi Q_s^2(x)} e^{-q_\perp^2/Q_s^2(x)}$$



Smaller slop in kT

Smaller contribution to AN

- **Expectation:**



Sources of contribution to A_N

Kang

- The source of single spin correlation for $A^{\uparrow} + B \to h(p_\perp) + X$

$$\begin{aligned}
\Delta\sigma &= T_{a,F}(x,x)\otimes\phi_{b/B}(x')\otimes H_{ab\to c}(p_\perp,\vec{s}_T)\otimes D_{c\to h}(z) && \text{(I)}\\
&+ \delta q_{a/A}(x)\otimes T^{(\sigma)}_{b,F}(x',x')\otimes H'_{ab\to c}(p_\perp,\vec{s}_T)\otimes D_{c\to h}(z) && \text{(II)}\\
&+ \delta q_{a/A}(x)\otimes\phi_{b/B}(x')\otimes H''_{ab\to c}(p_\perp,\vec{s}_T)\otimes D^{(3)}_{c\to h}(z,z) && \text{(III)}\\
&+ m_q\delta q_{a/A}(x)\otimes\phi_{b/B}(x')\otimes H'''_{ab\to c}(p_\perp,\vec{s}_T)\otimes D_{c\to h}(z) && \text{(IV)}
\end{aligned}$$

Term	meaning	collinear	small-x	Remarks
(I)	Sivers $T_{q,F}(x,x)$	Qiu-Sterman 91, 98 hep-ph/9806356	Boer-Dumitru-Hayashigaki, 2006 Kang-Xiao, 1212.4809	process dependence of Sivers function
(II)	Boer-Mulders $T^{(\sigma)}_{q,F}(x',x')$	Kanazawa-Koike, 2000 hep-ph/000727		small in the collinear formalism
(III)	Collins $D^{(3)}_{c\to h}(z,z)$	Kang-Yuan-Zhou, 2010 1002.0399	Kang-Yuan, 2011 1106.1375	Collins function is universal
(IV)	Kane-Pumplin-Repko $m_q\delta q(x)$	Kane-Pumplin-Repko, 1978	(different from KPR) Kovchegov-Sievert 1201.5890	small?? (because of quark mass?)

Separation of various sources

Kang

- polarized p+p:

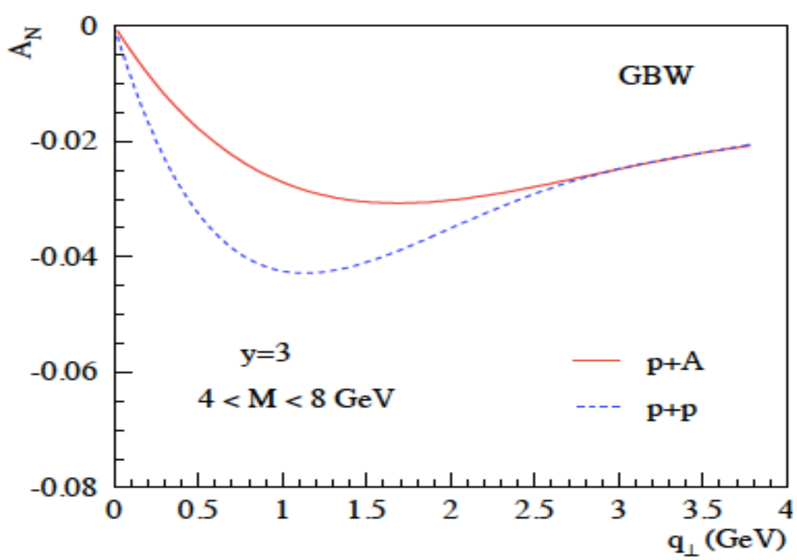
  Jet, photon, vs single hadron - Sivers vs Collins

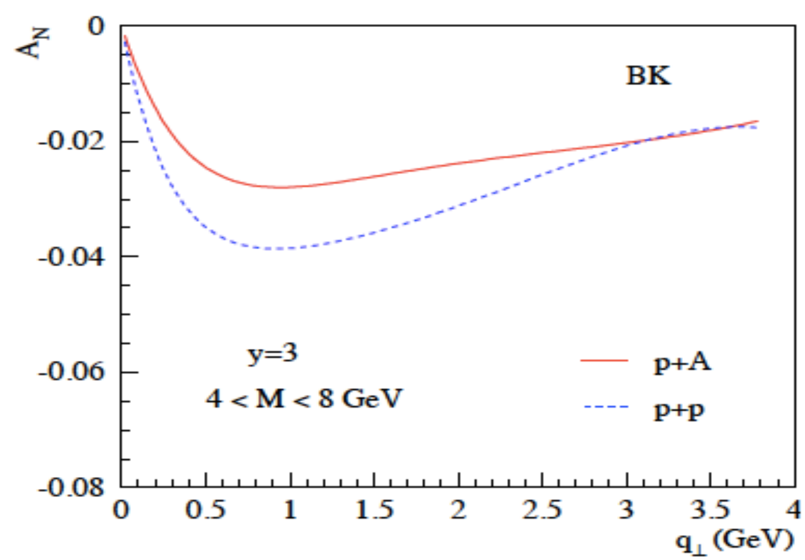
- polarized p+A:

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

  Interesting test: $\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\gg Q_s^2} \to 0$

Kovchegov





Another critical test of TMD factorization

❑ Predictive power of QCD factorization:

- ✧ Infrared safety of short-distance hard parts
- ✧ Universality of the long-distance matrix elements
- ✧ QCD evolution or scale dependence of the matrix elements

❑ QCD evolution:

If there is a factorization/invariance, there is an evolution equation

❑ Collinear factorization – DGLAP evolution:

$$\sigma_{\rm phy}(Q,\Lambda_{\rm QCD}) \approx \sum_f \hat{\sigma}_f(Q,\mu)\otimes\phi_f(\mu,\Lambda_{\rm QCD}) \quad \rightarrow \quad \frac{d}{d\mu}\sigma_{\rm phy}(Q,\Lambda_{\rm QCD}) = 0$$

Scaling violation of nonperturbative functions

Evolution kernels are perturbative – a test of QCD

Evolution equations for TMDs

Boer, 2001, 2009, Idilbi, et al, 2004
Aybat, Rogers, 2010
Kang, Xiao, Yuan, 2011
Aybat, Collins, Qiu, Rogers, 2011

❑ Collins-Soper equation:

– b-space quark TMD with γ^+

$$\frac{\partial \tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F)}{\partial \ln \sqrt{\zeta_F}} = \tilde{K}(b_T; \mu)\tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F) \qquad \tilde{K}(b_T; \mu) = \frac{1}{2}\frac{\partial}{\partial y_s} \ln\left(\frac{\tilde{S}(b_T; y_s, -\infty)}{\tilde{S}(b_T; +\infty, y_s)}\right)$$

❑ RG equations:

$$\frac{d\tilde{K}(b_T; \mu)}{d \ln \mu} = -\gamma_K(g(\mu)) \qquad \frac{d\tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F)}{d \ln \mu} = \gamma_F(g(\mu); \zeta_F/\mu^2)\tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F).$$

❑ Evolution equations for Sivers function:

$$F_{f/P^\uparrow}(x, k_T, S; \mu, \zeta_F) = F_{f/P}(x, k_T; \mu, \zeta_F) - F_{1T}^{\perp f}(x, k_T; \mu, \zeta_F)\frac{\epsilon_{ij} k_T^i S^j}{M_p}$$

CS: $$\frac{\partial \ln \tilde{F}_{1T}^{\prime\perp f}(x, b_T; \mu, \zeta_F)}{\partial \ln \sqrt{\zeta_F}} = \tilde{K}(b_T; \mu) \qquad \tilde{F}_{1T}^{\prime\perp f}(x, b_T; \mu, \zeta_F) \equiv \frac{\partial \tilde{F}_{1T}^{\perp f}(x, b_T; \mu, \zeta_F)}{\partial b_T}$$

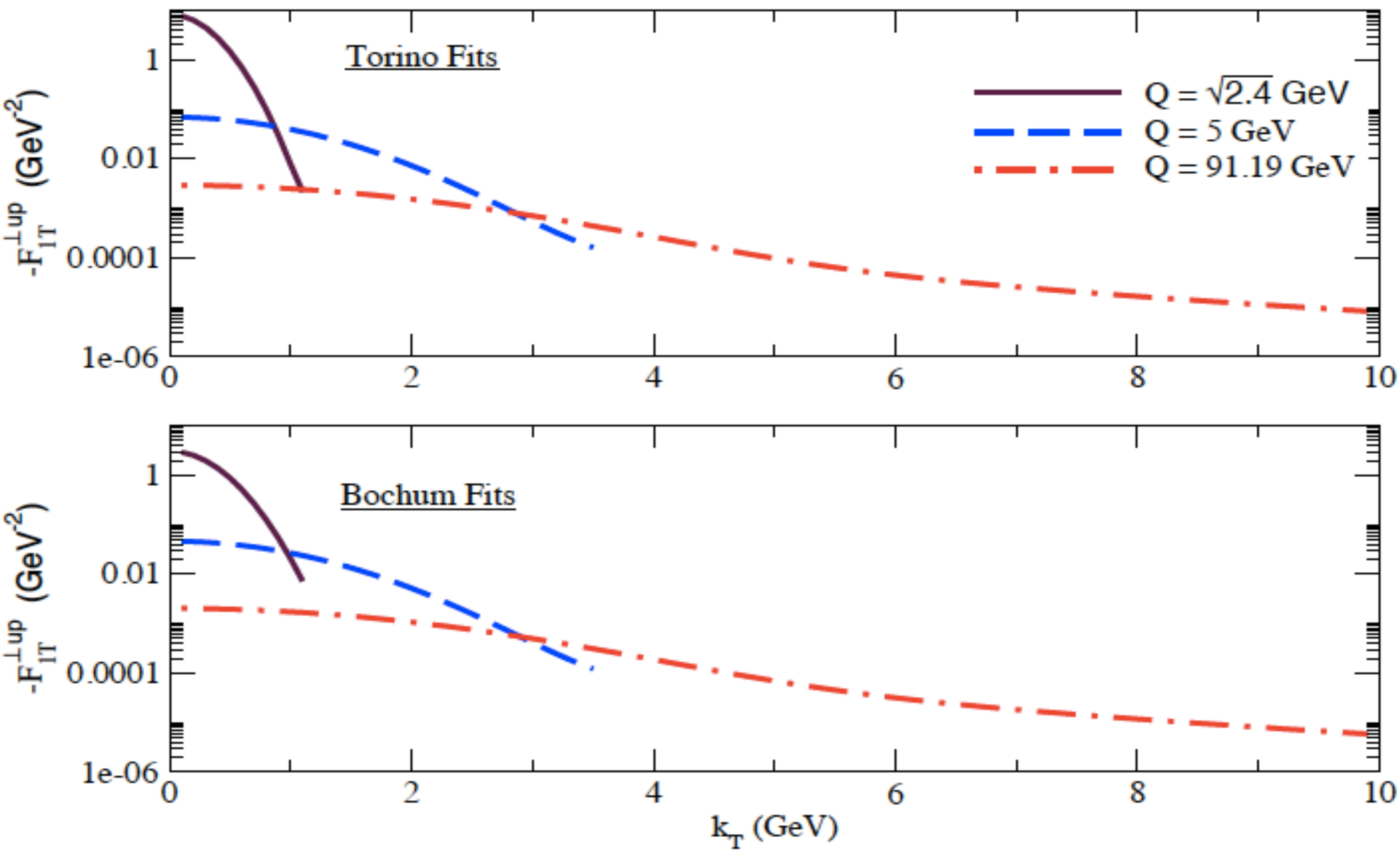
RGs: $$\frac{d\tilde{F}_{1T}^{\prime\perp f}(x, b_T; \mu, \zeta_F)}{d \ln \mu} = \gamma_F(g(\mu); \zeta_F/\mu^2)\tilde{F}_{1T}^{\prime\perp f}(x, b_T; \mu, \zeta_F)$$

$$\frac{d\tilde{K}(b_T; \mu)}{d \ln \mu} = -\gamma_K(g(\mu)) \quad \Longrightarrow \quad \frac{\partial \gamma_F(g(\mu); \zeta_F/\mu^2)}{\partial \ln \sqrt{\zeta_F}} = -\gamma_K(g(\mu)),$$

Scale dependence of Sivers function

Aybat, Collins, Qiu, Rogers, 2011

- Up quark Sivers function:

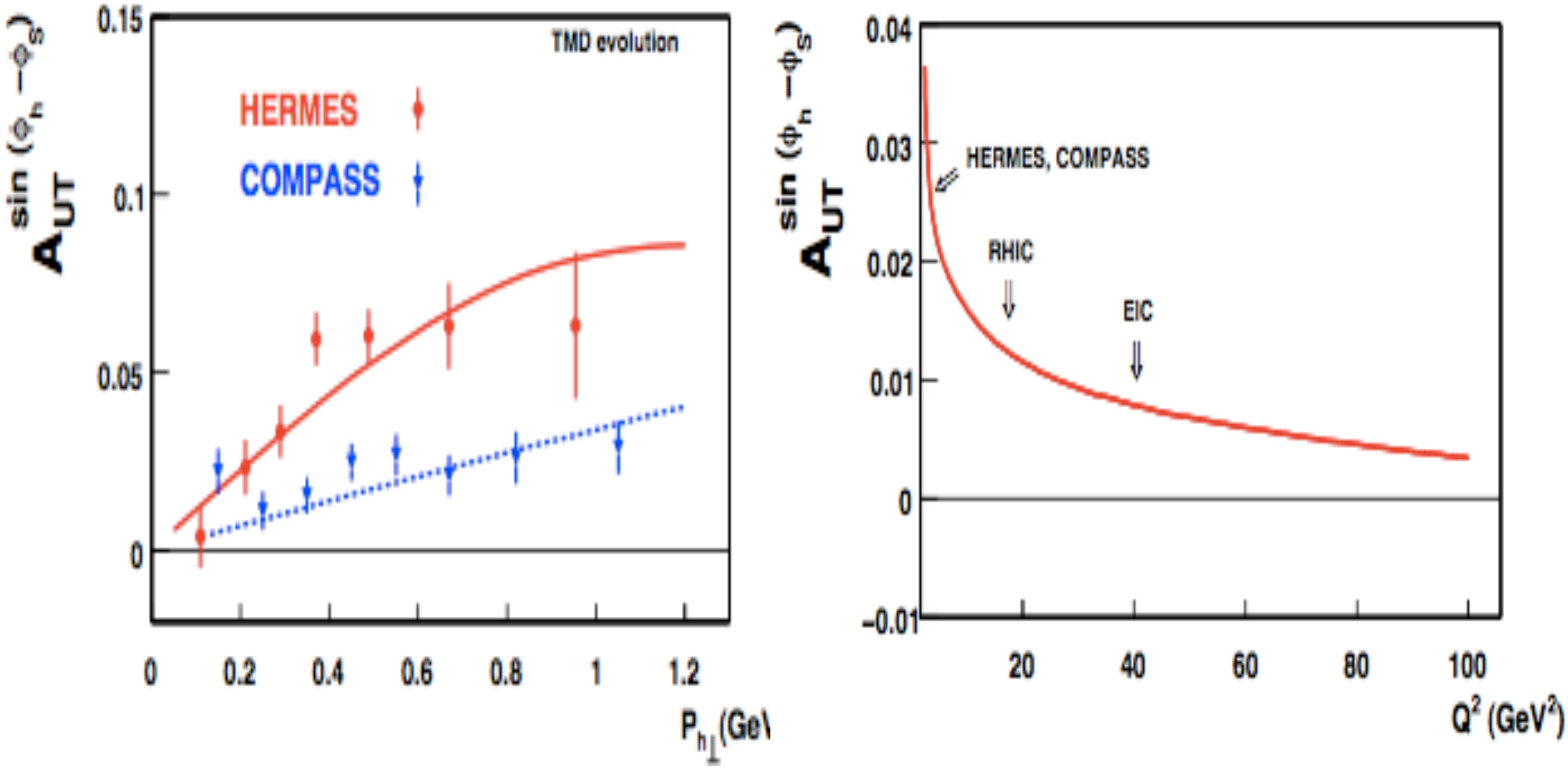


Very significant growth in the width of transverse momentum

Importance of the evolution

Aybat, Rogers, 2012

- SSAs – Sivers function:

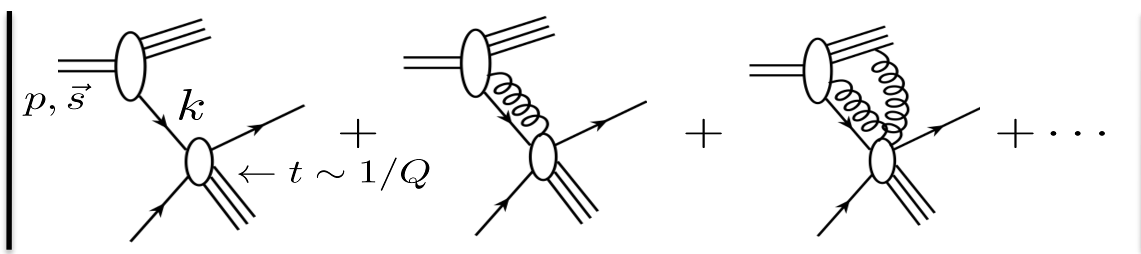


Q^2 dependence – effectiveness of the probe?

How collinear factorization generates SSA?

❑ Collinear factorization beyond leading power:

$\sigma(Q, \vec{s}) \propto$



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

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

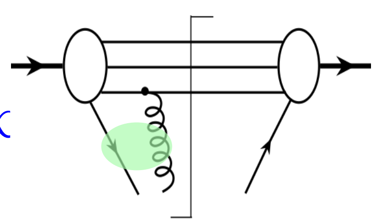
Too large to compete!

Three-parton correlation

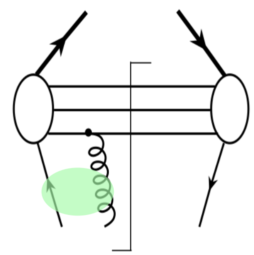
❑ Single transverse spin asymmetry:

Efremov, Teryaev, 82;
Qiu, Sterman, 91, etc.

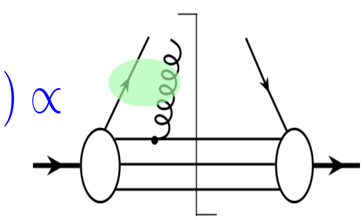
$$\Delta\sigma(s_T) \propto T^{(3)}(x, x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z, z) + \ldots$$

$T^{(3)}(x, x) \propto$ 

Qiu, Sterman, 1991, …

$D^{(3)}(z, z) \propto$ 

Kang, Yuan, Zhou, 2010

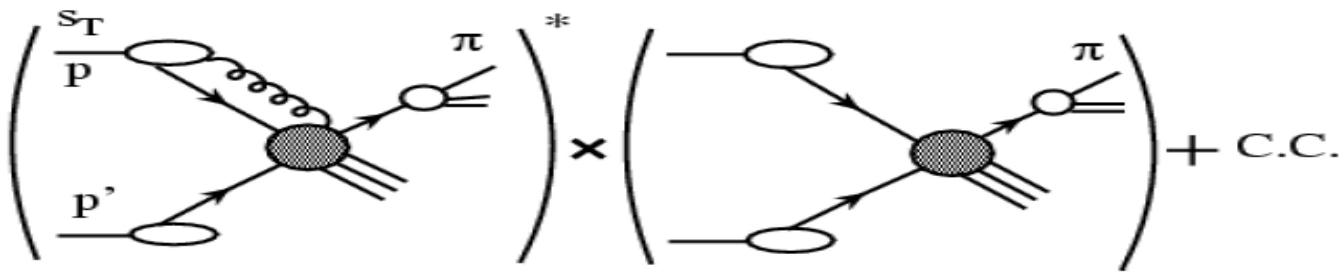
$T^{(3\sigma)}(x, x) \propto$ 

Kanazawa, Koike, 2000

Integrated information on parton's transverse motion!

SSAs generated by twist-3 PDFs

- First non-vanish contribution – interference:



- Dominated by the derivative term – forward region:

$$E\frac{d\Delta\sigma}{d^3\ell} \propto \epsilon^{\ell_T s_T n \bar{n}}\, D_{c\to\pi}(z) \otimes \left[-x\frac{\partial}{\partial x}T_F(x,x)\right]$$
$$\otimes \frac{1}{-\hat{u}}\left[G(x')\otimes\Delta\hat{\sigma}_{qg\to c} + \sum_{q'} q'(x')\otimes\Delta\hat{\sigma}_{qq'\to c}\right]$$

Qiu, Sterman, 1998, …

$$\boxed{A_N \propto \left(\frac{\ell_\perp}{-\hat{u}}\right)\frac{n}{1-x} \quad \text{if } T_F(x,x)\propto q(x)\propto(1-x)^n}$$

Kouvaris, Qiu, Vogelsang, Yuan, 2006

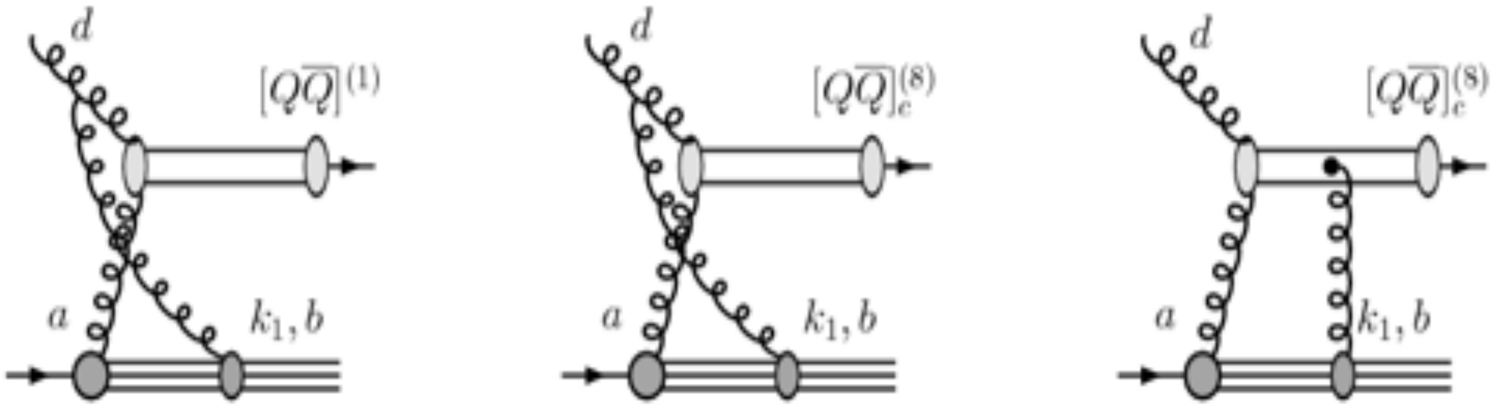
- Complete leading order contribution:

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

A_N of heavy quarkonium

Yuan

Naïve analysis from the leading order diagrams



(a) (b) (c)

- Color-singlet model: only initial state interaction, non-zero SSA
- Color-octet model: initial and final state interactions cancel out, no SSA

Low pT: $$A_N(P_{h\perp}) \propto \frac{P_{h\perp}\Delta}{Q_s^2} e^{-\frac{\delta^2 P_{h\perp}^2}{(Q_s^2)^2}}$$

High pT: $$A_N(P_{h\perp}) \approx \frac{2P_{h\perp}(\Delta^2+\delta^2)}{P_{h\perp}^2+6\Delta^2}$$

Summary

- Polarized pA at RHIC provides a completely new testing ground for QCD

  Dynamics cannot be accessed by unpolarized x-section

  QCD is much richer than the leading power!

- SSA in pA is an excellent observable to study small-x physics in a nucleus

- Let's make it real!

Thank you!

Backup slices