Single spin asymmetry in forward pA collisions: phenomenology at RHIC

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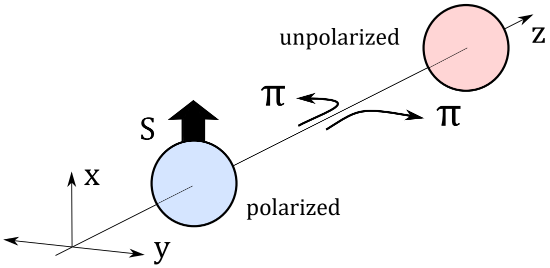
S. B. Hatta, Phys. Rev. D **99**, no. 9, 094012 (2019)

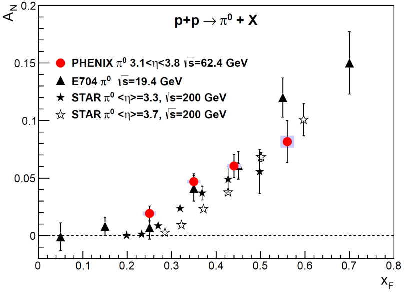
Pacific Spin 2019, Miyazaki, Japan, August 30, 2019

Single spin asymmetry



$$A_N = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$
$$\sim (\boldsymbol{S} \times \boldsymbol{P}_h) \cdot \boldsymbol{k}$$

SSA in pp

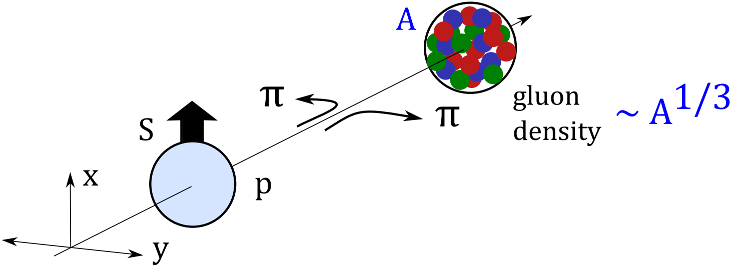


- A_N persists to high energies
- A_N largest in the forward direction $x_F \to 1$

$$x_F = 2P_h^z/\sqrt{s}$$

PHENIX, Phys. Rev. D **90**, no. 1, 012006 (2014)

SSA in pA

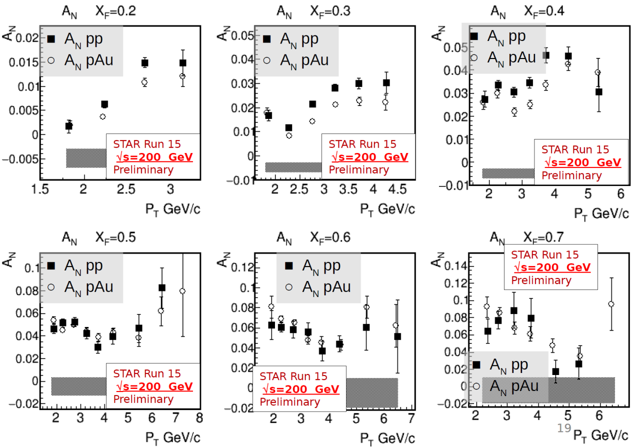


- SSA largest in the forward direction

  $\rightarrow$ small-x in the nuclei

  $\rightarrow$ interplay between transverse spin physics and small-x physics

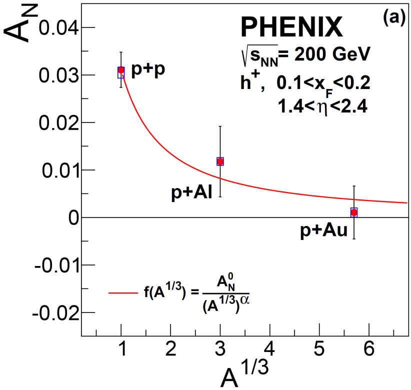
SSA in pA: STAR



- no A-dependence? $A_N \sim A^0$

STAR, PoS DIS2016, 212 (2016)
talk : A. Ogawa, Tue, 09:00

SSA in pA: PHENIX

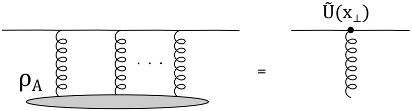


- A-dependence? $A_N \sim A^{-1/3}$

PHENIX, 1903.07422
talk : K. A. Barish, Tue, 09:35

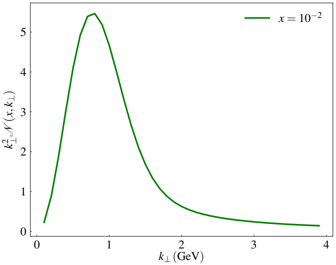
Color Glass Condensate

- quark scattering on a nuclei



- gluon dipole

$$F(x,k_\perp) \equiv (\pi R_A^2) \int \frac{d^2\mathbf{x}_\perp}{(2\pi)^2} e^{-i\mathbf{k}_\perp\cdot\mathbf{x}_\perp} \frac{1}{N_c} \left\langle \mathrm{Tr}\left[\tilde{U}(\mathbf{x}_\perp)\tilde{U}^\dagger(0)\right]\right\rangle_Y$$

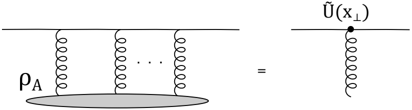


$$F \sim \exp(-k_\perp^2/Q_S^2)$$

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

Color Glass Condensate

- quark scattering on a nuclei



- unpolarized cross section

$\left(x_q = \frac{P_{h\perp}}{z\sqrt{s}} e^{y_h} \; x_g = \frac{P_{h\perp}}{z\sqrt{s}} e^{-y_h}\right)$

$$\frac{d\sigma}{d^2 P_{h\perp} dy_h} = \int_{z_{\min}}^{1} \frac{dz}{z^2} x_q f(x_q) F(x_g, P_{h\perp}/z) D(z)$$

Dumitru, Hayashigaki, Jalilian-Marian, Nucl. Phys. A **765** (2006) 464

SSA in pA: $k_\perp$-factorization

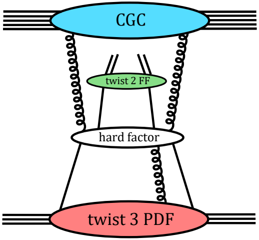
- Sivers: $A_N \sim A^{-1/3}$
  Boer, Dumitru, Hayashigaki, Phys. Rev. D **74** (2006) 074018
- Collins: $A_N \sim A^{-1/3}$
  Kang, Yuan, Phys. Rev. D **84** (2011) 034019
- consistent with PHENIX but inconsistent with STAR?!

SSA in pA: hybrid framework

- ETQS

$$\Delta\sigma \sim G_F(x,x) \otimes \frac{d\left(P_{h\perp}^2 F\left(x_g, \frac{P_{h\perp}}{z}\right)\right)}{dP_{h\perp}} \otimes D(z)$$
$$+ \frac{dG_F(x,x)}{dx} \otimes F\left(x_g, \frac{P_{h\perp}}{z}\right) \otimes D(z)$$

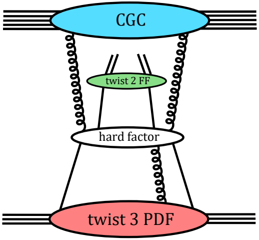
- probing the shape of the dipole!



Hatta, Xiao, Yoshida, Yuan, Phys. Rev. D **94** (2016) no.5, 054013

SSA in pA: hybrid framework

- ETQS
- $G_F(x, x)$ term: $A_N \sim A^{-1/3}$ (Sivers-like)
- $dG_F(x, x)/dx$ term: $A_N \sim A^0$



Hatta, Xiao, Yoshida, Yuan, Phys. Rev. D **94** (2016) no.5, 054013

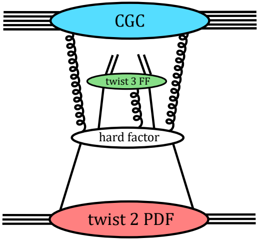
SSA in pA: hybrid framework

- Twist-3 FF

$$\Delta\sigma \sim h_1(x) \otimes \frac{dF\left(x_g, \frac{P_{h\perp}}{z}\right)}{dP_{h\perp}} \otimes \mathrm{Im}\tilde{e}(z)$$

$$+ h_1(x) \otimes F\left(x_g, \frac{P_{h\perp}}{z}\right)\left(1 + \int_{l_\perp}^{P_{h\perp}/z'} F(x_g, l_\perp)\right) \otimes \mathrm{Im}\hat{E}_F(z', z)$$

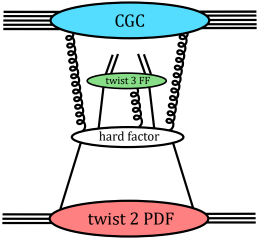
- probing the shape of the dipole!



Hatta, Xiao, Yoshida, Yuan, Phys. Rev. D **95** (2017) no.1, 014008

SSA in pA: hybrid framework

- Twist-3 FF
- $\mathrm{Im}\tilde{e}(z)$ term: $A_N \sim A^{-1/3}$ (Collins-like)
- $\mathrm{Im}\hat{E}_F(z', z)$ term: $A_N \sim A^0 + A^{-1/3}$



Hatta, Xiao, Yoshida, Yuan, Phys. Rev. D **95** (2017) no.1, 014008

ETQS vs twist-3 FF in pp

- -'11 ETQS dominates? ($dG(x,x)/dx$ term)

- '11 sign mismatch: ETQS function extracted from SIDIS and from $p^{\uparrow}p$ have a different sign
  Kang, Qiu, Vogelsang, Yuan, Phys. Rev. D **83** (2011) 094001

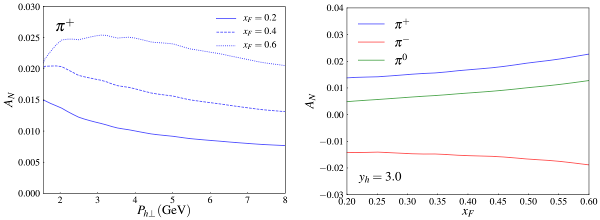
- '10-'13 twist-3 fragmentation contribution
  Kang, Yuan, Zhou, Phys. Lett. B **691** (2010) 243
  Metz, Pitonyak, Phys. Lett. B **723** (2013) 365
  Kanazawa, Koike, Phys. Rev. D **88** (2013) 074022

- '14- fragmentation contribution dominates
  Kanazawa, Koike, Metz, Pitonyak, Phys. Rev. D **89** (2014) no.11, 111501
  Gamberg, Kang, Pitonyak, Prokudin, Phys. Lett. B **770** (2017) 242

Independent check: SSA in pA UPC

- nuclei as a source of photons

  $p^{\uparrow} + A \to h + A + X$
- cross sections enhanced as Z^2
- can be measured at RHIC!



SB, Hatta, Phys. Rev. D **98** (2018) no.9, 094025

Twist-3 FF contrib. in pA

- polarized

$$\frac{d\Delta\sigma(S_\perp)}{d^2P_{h\perp}dy_h} = \frac{M}{2}S_{\perp i}\epsilon^{ij}\sum_a\int_{z_{\min}}^1 \frac{dz}{z^2}x_q h_1^a(x_q,Q^2)$$
$$\times\Bigg\{-\mathrm{Im}\tilde{e}^{h/a}(z,P_{h\perp}^2)\frac{dF(x_g,P_{h\perp}/z)}{d(P_h^j/z)}$$
$$+4\frac{P_{hj}}{P_{h\perp}^2}\int_z^\infty\frac{dz_1}{z_1^2}\frac{z}{\frac{1}{z}-\frac{1}{z_1}}\frac{\mathrm{Im}\hat{E}_F^{h/a}(z_1,z,P_{h\perp}^2)}{N_c^2-1}$$
$$\times\left[\frac{2\pi N_c^2}{\pi R_A^2}\int_0^{P_{h\perp}/z_1}l_\perp dl_\perp F(x_g,l_\perp)+\frac{1}{z_1}\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\right]F(x_g,P_{h\perp}/z)\Bigg\}$$

Hatta, Xiao, Yoshida, Yuan, Phys. Rev. D **95** (2017) no.1, 014008

Twist-3 FF contrib. in pA

- equation of motion relation (EOMR)

$$\hat{e}_1^a(z) = z\mathrm{Im}\tilde{e}^a(z) + z\int_z^\infty \frac{dz'}{z'^2}\frac{\mathrm{Im}\hat{E}_F^a(z',z)}{\frac{1}{z'}-\frac{1}{z}}$$

- Lorentz invariance relation (LIR)

$$\hat{e}_1^a(z) = \frac{1}{2}\frac{d}{d(1/z)}\left(\frac{\mathrm{Im}\tilde{e}^a(z)}{z}\right) + \frac{1}{z}\int_z^\infty \frac{dz'}{z'^2}\frac{\mathrm{Im}\hat{E}_F^a(z',z)}{\left(\frac{1}{z}-\frac{1}{z'}\right)^2}$$

- $\hat{e}_1^a(z)$ - intrinsic twist-3 FF
  $\mathrm{Im}\tilde{e}^a(z)$ - kinematical (Collins-like)
  $\mathrm{Im}\hat{E}_F^a(z',z)$ - dynamical FF

Kanazawa, Koike, Metz, Pitonyak, Schlegel, Phys. Rev. D **93**, no. 5, 054024 (2016)

Twist-3 FF contrib. in pA

- polarized

$$\frac{d\Delta\sigma(S_\perp)}{d^2P_{h\perp}dy_h} = \frac{M}{2}S_{\perp i}\frac{P_{hj}}{P_{h\perp}}\epsilon^{ij}\sum_a\int_{z_{\min}}^1 \frac{dz}{z^2}x_q h_1^a(x_q, P_{h\perp}^2)$$
$$\times\left\{\mathrm{Im}\tilde{e}^{h/a}(z, P_{h\perp}^2)\frac{dF(x_g, P_{h\perp}/z)}{d(P_{h\perp}/z)} + \frac{4}{P_{h\perp}}\frac{1}{N_c^2-1}\right.$$
$$\times\left[\frac{2\pi N_c^2}{\pi R_A^2}\int_0^{P_{h\perp}/z} l_\perp dl_\perp F(x_g, l_\perp)\left(z\mathrm{Im}\tilde{e}^{h/a}(z, P_{h\perp}^2) - \hat{e}_{\bar{1}}^a(z, P_{h\perp}^2)\right)\right.$$
$$+ 2\hat{e}_{\bar{1}}^{h/a}(z, P_{h\perp}^2) - z\mathrm{Im}\tilde{e}^{h/a}(z, P_{h\perp}^2)$$
$$\left.\left. - \frac{z}{2}\frac{d}{d(1/z)}\left(\frac{\mathrm{Im}\tilde{e}^{h/a}(z, P_{h\perp}^2)}{z}\right)\right]F(x_g, P_{h\perp}/z)\right\}$$

Nuclear dependence

$$d\Delta\sigma(S_\perp) \sim \frac{dF}{d(P_{h\perp}/z)} + F$$

Nuclear dependence

$$A_N \sim \frac{1}{F}\frac{dF}{d(P_{h\perp}/z)} + 1$$

Nuclear dependence

- assume

$$F \sim e^{-k_\perp^2/Q_S^2} \qquad Q_S^2 \sim A^{1/3}$$

$$A_N \sim A^{-1/3} + A^0$$

Nuclear dependence

- assume

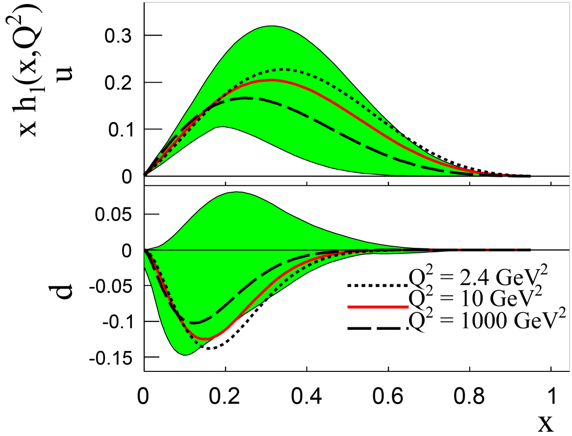
$$F \sim e^{-k_\perp^2/Q_S^2} \qquad Q_S^2 \sim A^{1/3}$$

$$A_N \sim A^{-1/3} + A^0$$

- valid only for $P_{h\perp}/z \lesssim Q_S$!

Calculation setup

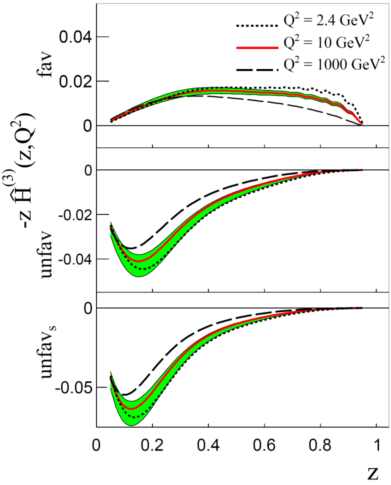
- transversity



Gamberg, Kang, Pitonyak, Prokudin, Phys. Lett. B **770**, 242 (2017)

Calculation setup

- twist-3 FF



Gamberg, Kang, Pitonyak, Prokudin, Phys. Lett. B **770**, 242 (2017)

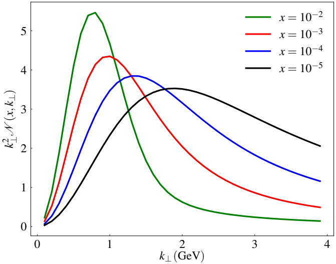
Calculation setup

- initial condition: McLerran-Venugopalan model

$$F(k_\perp \lesssim Q_S) \sim e^{-k_\perp^2/Q_S^2} \qquad F(k_\perp \gg Q_S) \sim 1/k_\perp^4$$

$$(Q_{S,0}^A)^2 = cA^{1/3}(Q_{S,0}^p)^2 \qquad c = 0.5$$

- evolution: rcBK equation



Dusling, Gelis, Lappi, Venugopalan, Nucl. Phys. A **836** (2010) 159

Calculation setup

- model parameters fitted to *ep* HERA data

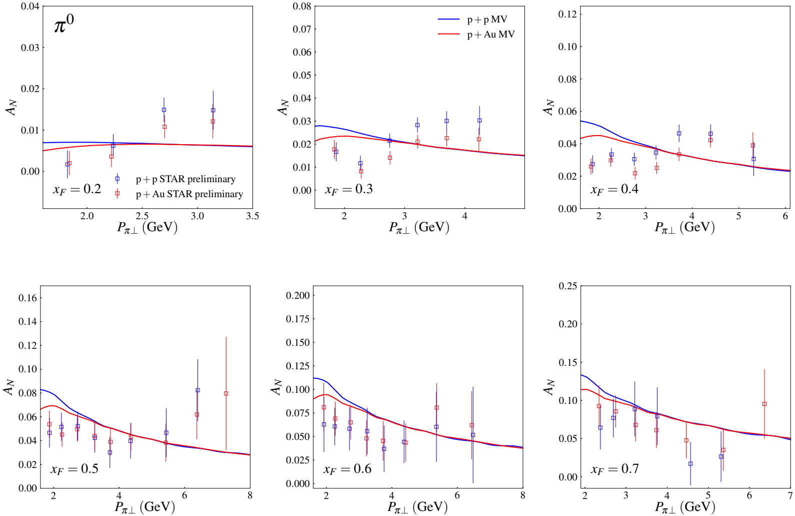
- decent description of:

  - hadron spectra in *pp* at RHIC

  - nuclear modification factor R_{pA} (BRAHMS data)

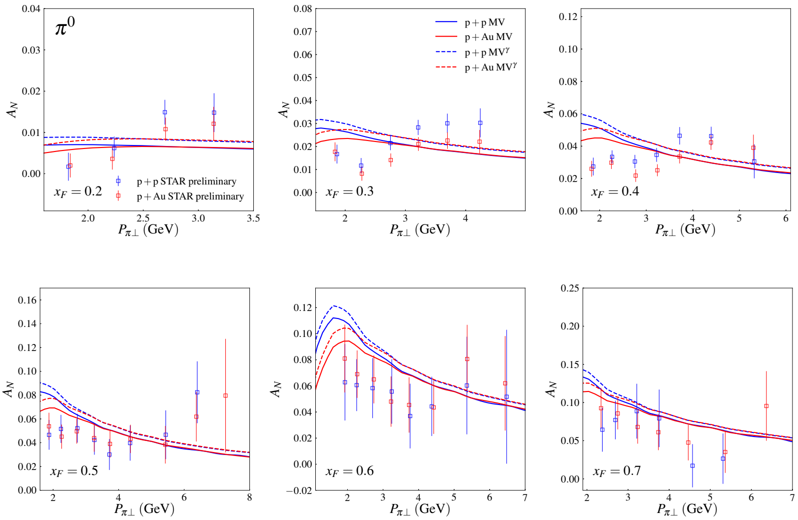
  - di-hadron angular correlations: *pA* vs *pp*

Results: vs STAR



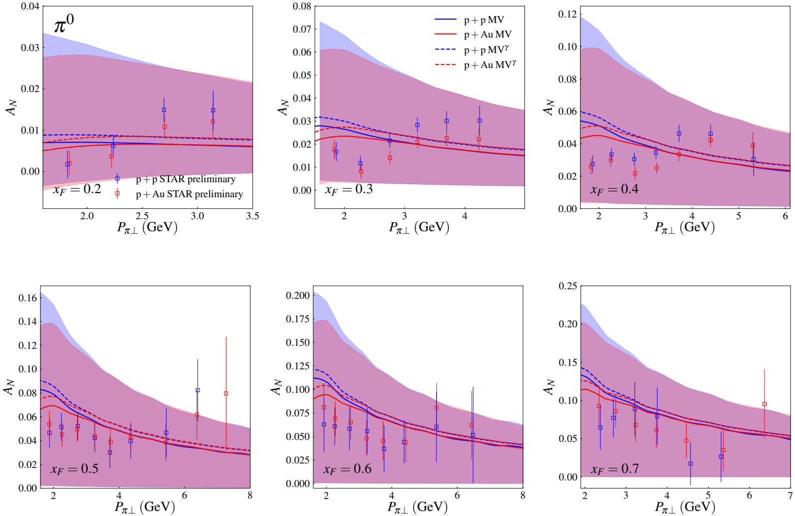
STAR, PoS DIS2016, 212 (2016)
SB, Hatta, Phys. Rev. D **99**, no. 9, 094012 (2019)

Results: vs STAR



STAR, PoS DIS2016, 212 (2016)
SB, Hatta, Phys. Rev. D **99**, no. 9, 094012 (2019)

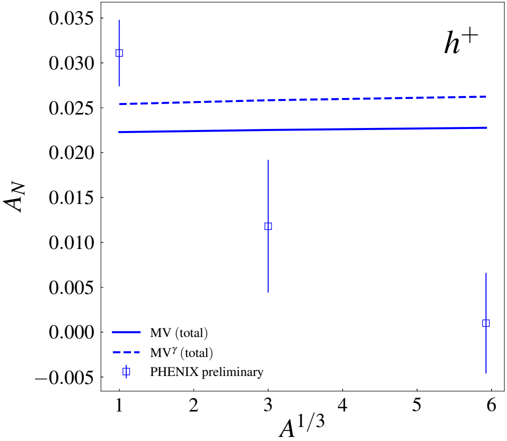
Results: vs STAR



STAR, PoS DIS2016, 212 (2016)
SB, Hatta, Phys. Rev. D **99**, no. 9, 094012 (2019)

Results: vs PHENIX

- $\langle P_{h\perp} \rangle = 2.9$ GeV, $\langle x_F \rangle = 0.12$



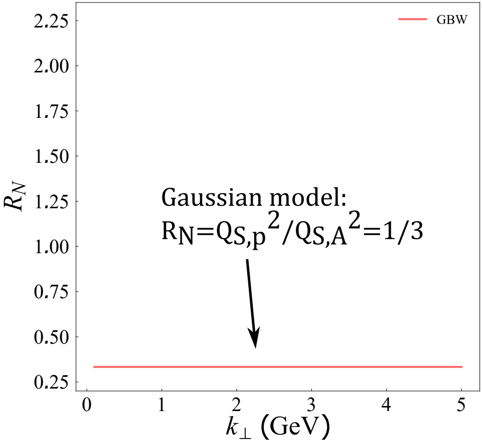
PHENIX, 1903.07422
SB, Hatta, Phys. Rev. D **99**, no. 9, 094012 (2019)

Toy model

- assume A_N is dominated by dF-term
- define

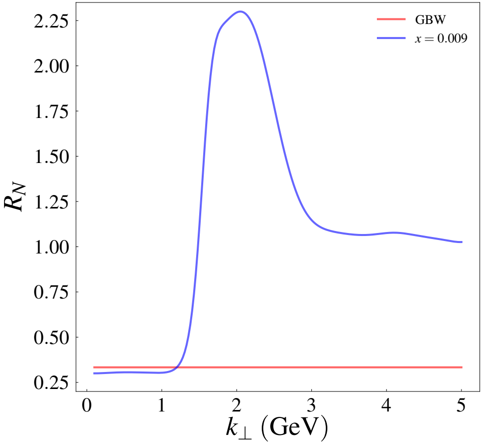
$$R_N \equiv \frac{(dF/dk_\perp/F)_A}{(dF/dk_\perp/F)_p}$$

Toy model



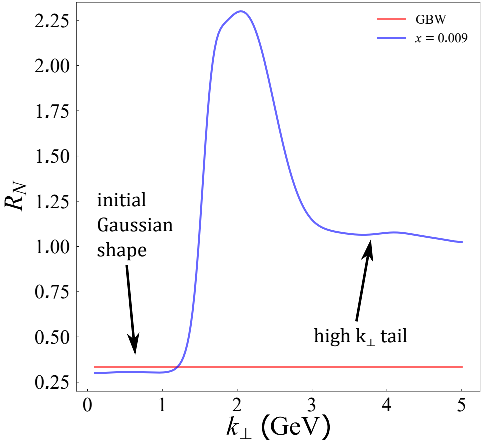
GBW
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
R_N
Gaussian model:
$R_N = Q_{S,p}^2 / Q_{S,A}^2 = 1/3$
0
1
2
3
4
5
$k_\perp$ (GeV)

Toy model

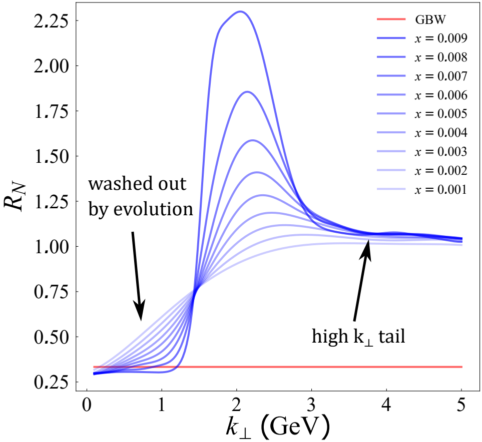


GBW
$x = 0.009$
R_N
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0
1
2
3
4
5
$k_\perp$ (GeV)

Toy model


GBW
x = 0.009
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
R_N
initial
Gaussian
shape
high $k_\perp$ tail
0
1
2
3
4
5
$k_\perp$ (GeV)

Toy model



GBW
x = 0.009
x = 0.008
x = 0.007
x = 0.006
x = 0.005
x = 0.004
x = 0.003
x = 0.002
x = 0.001
washed out
by evolution
high k⊥ tail
R_N
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0
1
2
3
4
5
$k_\perp$ (GeV)

Conclusion

- Gaussian model for F too naive
  $\rightarrow A^{-1/3}$ scaling too naive

- realistic model for F contains perturbative tail
  $\rightarrow$ Gaussian only up to $k_\perp \sim Q_S \sim 1$ GeV
  $\rightarrow$ washed out by evolution

Conclusion

- data:

$$P_{h\perp}^{\text{STAR}} \gtrsim 2\,\text{GeV} \qquad \langle P_{h\perp}^{\text{PHENIX}} \rangle \sim 3\,\text{GeV}$$

$\rightarrow$ already in the perturbative tail of F

high x_F data (STAR): can apply CGC $\rightarrow$ no nuclear effect $\rightarrow$ agrees with the data

Conclusion

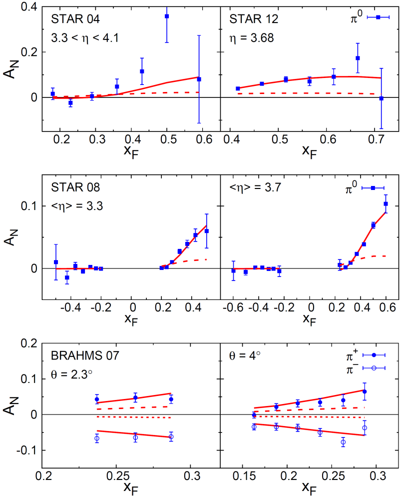
low x_F data (PHENIX and STAR):

1. CGC still ok to use, but we need a new contribution at $x_F \sim 0.1 - 0.2$

2. some nuclear effect but should not use CGC $\rightarrow A^{-1/3}$ scaling in PHENIX data could be just a coincidence

- data at smaller $P_{h\perp}$

Twist-3 FF dominates

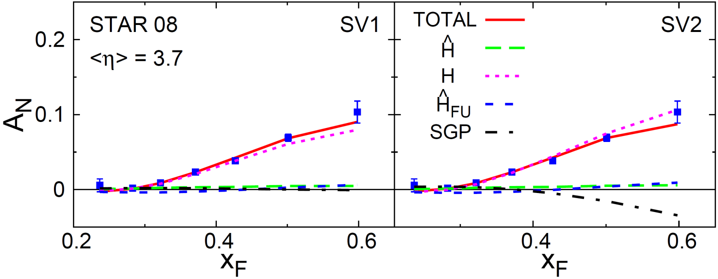


- full: ETQS + twist-3 FF
- dashed: ETQS
- difficult to explain the data without twist-3 FF
- independent check?

Kanazawa, Koike, Metz, Pitonyak, Phys. Rev. D **89** (2014) no.11, 111501

$A^{-1/3}$ vs A^0 contribution from $p^\uparrow p$

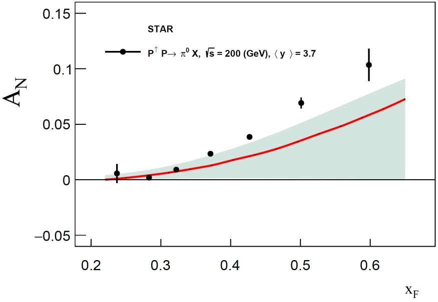
- $A^{-1/3}$ is more important



Kanazawa, Koike, Metz, Pitonyak, Phys. Rev. D **89** (2014) no.11, 111501

$A^{-1/3}$ vs A^0 contribution from $p^\uparrow p$

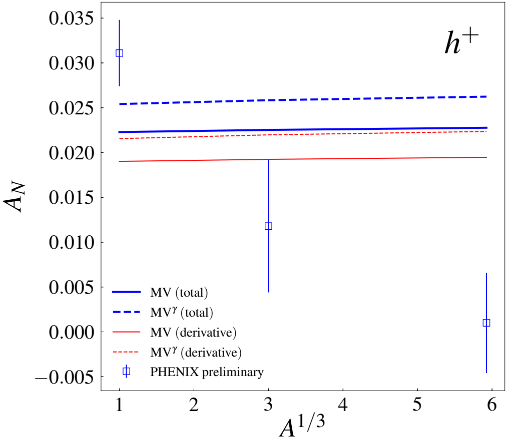
- re-analysis with Lorentz invariance relation
- A^0 is more important



Gamberg, Kang, Pitonyak, Prokudin, Phys. Lett. B **770** (2017) 242

Results: vs PHENIX

- contribution from $A^{-1/3}$ term dominates



PHENIX, 1903.07422
SB, Hatta, Phys. Rev. D **99**, no. 9, 094012 (2019)

Results: vs PHENIX

- $(Q^A_{S,0})^2 = N \times (Q^p_{S,0})^2$