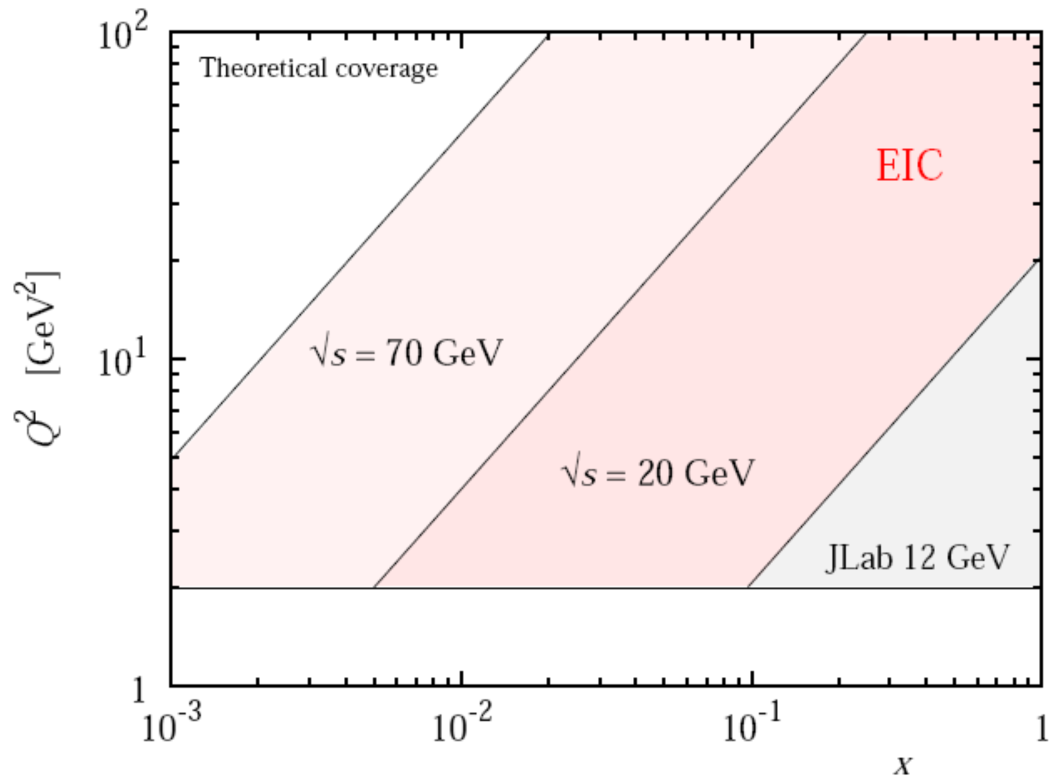
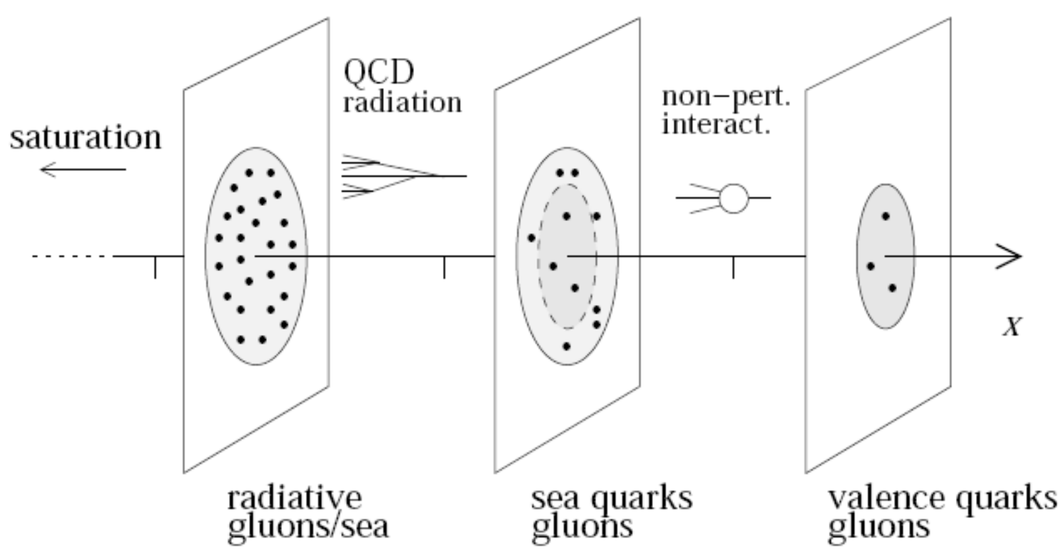
# Pion-in-jet asymmetries at RHIC: test of QCD factorization?

Alexei Prokudin

PennState Berks

# Nucleon landscape




**Nucleon is a many body dynamical system of quarks and gluons**

Changing x we probe different aspects of nucleon wave function

How **partons move** and how they are distributed in **space** is one of the directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions and Transverse Momentum Dependent distributions

These distributions are also referred to as **3D (three-dimensional) distributions**

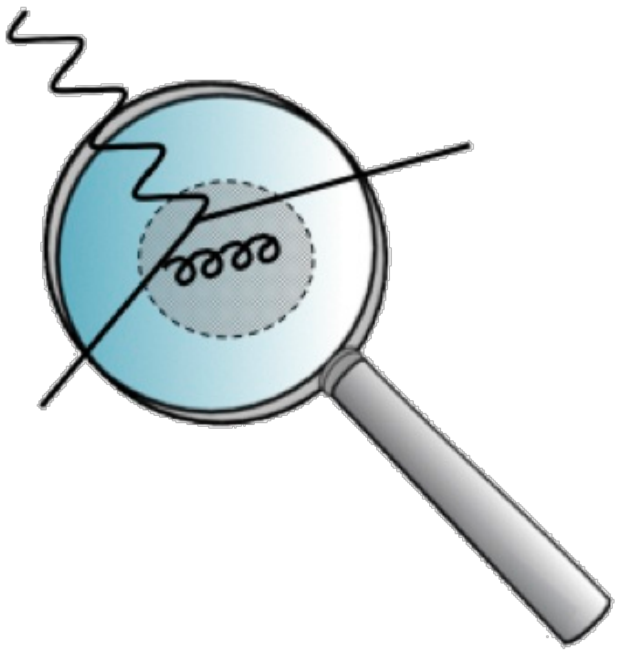
# TMDs evolve

Just like collinear PDFs, TMDs also depend on the scale of the probe = evolution

**Collinear PDFs**

$F(x, Q)$

- ✓ DGLAP evolution
- ✓ Resum $\left[\alpha_s \ln(Q^2/\mu^2)\right]^n$
- ✓ Kernel: purely perturbative



**TMDs**

$F(x, k_\perp; Q)$

- ✓ Collins-Soper/rapidity evolution equation
- ✓ Resum $\left[\alpha_s \ln^2(Q^2/k_\perp^2)\right]^n$
- ✓ Kernel: can be non-perturbative when $k_\perp \sim \Lambda_{\rm QCD}$

$$F(x, Q_i)$$
$$\downarrow$$
$$R^{\rm coll}(x, Q_i, Q_f)$$
$$\downarrow$$
$$F(x, Q_f)$$

$$F(x, k_\perp, Q_i)$$
$$\downarrow$$
$$R^{\rm TMD}(x, k_\perp, Q_i, Q_f)$$
$$\downarrow$$
$$F(x, k_\perp, Q_f)$$

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*slide courtesy of Z. Kang*

# TMD evolution in b-space

$$F(x, k_\perp; Q)$$

- We have a TMD above measured at a scale Q. So far the evolution is written down in the Fourier transformed space (convolution → product)

$$F(x, b; Q) = \int d^2k_\perp e^{-ik_\perp \cdot b} F(x, k_\perp; Q)$$

- In the small b region ($1/b >> \Lambda_{QCD}$), one can then compute the evolution to this TMD, which goes like

$$F(x, b; Q_f) = F(x, b; Q_i) \exp\left\{-\int_{Q_i}^{Q_f} \frac{d\mu}{\mu}\left(A \ln\frac{Q_f^2}{\mu^2} + B\right)\right\}\left(\frac{Q_f^2}{Q_i^2}\right)^{-\int_{c/b}^{Q_i} \frac{d\mu}{\mu} A}$$

$$A = \sum_{n=1} A^{(n)} \left(\frac{\alpha_s}{\pi}\right)^n, \qquad B = \sum_{n=1} B^{(n)} \left(\frac{\alpha_s}{\pi}\right)^n$$

Only valid for small b

Collins-Sopoer-Sterman papers
Kang, Xiao, Yuan, PRL 11,
Aybat, Rogers, Collins, Qiu, 12,
Aybat, Prokudin, Rogers, 12,
Sun, Yuan, 13,
Echevarria, Idilbi, Schafer, Scimemi, 13,
Echevarria, Idilbi, Kang, Vitev, 14,
Kang, Prokudin, Sun, Yuan, 15, 16, …



*slide courtesy of Z. Kang*

# TMD evolution and non-perturbative compone

- Fourier transform back to the momentum space, one needs the whole b region (large b): need some non-perturbative extrapolation
  - Many different methods/proposals to model this non-perturbative part

$$F(x, k_\perp; Q) = \frac{1}{(2\pi)^2}\int d^2b e^{ik_\perp\cdot b}F(x,b;Q) = \frac{1}{2\pi}\int_0^\infty db\, bJ_0(k_\perp b)F(x,b;Q)$$

Collins, Soper, Sterman 85, ResBos, Qiu, Zhang 99, Echevarria, Idilbi, Kang, Vitev, 14, Aidala, Field, Gamberg, Rogers, 14, Sun, Yuan 14, D'Alesio, Echevarria, Melis, Scimemi, 14, Rogers, Collins, 15, …

- Eventually evolved TMDs in b-space

$$F(x,b;Q) \approx C\otimes F(x,c/b^*) \times \exp\left\{-\int_{c/b^*}^{Q}\frac{d\mu}{\mu}\left(A\ln\frac{Q^2}{\mu^2}+B\right)\right\} \times \exp\left(-S_{\text{non-pert}}(b,Q)\right)$$

longitudinal/collinear part

transverse part

✓ Non-perturbative: fitted from data

✓ The key ingredient – ln(Q) piece is spin-independent

**Since the polarized scattering data is still limited kinematics, we can use unpolarized data to constrain/extract key ingredients for the non-perturbative part**

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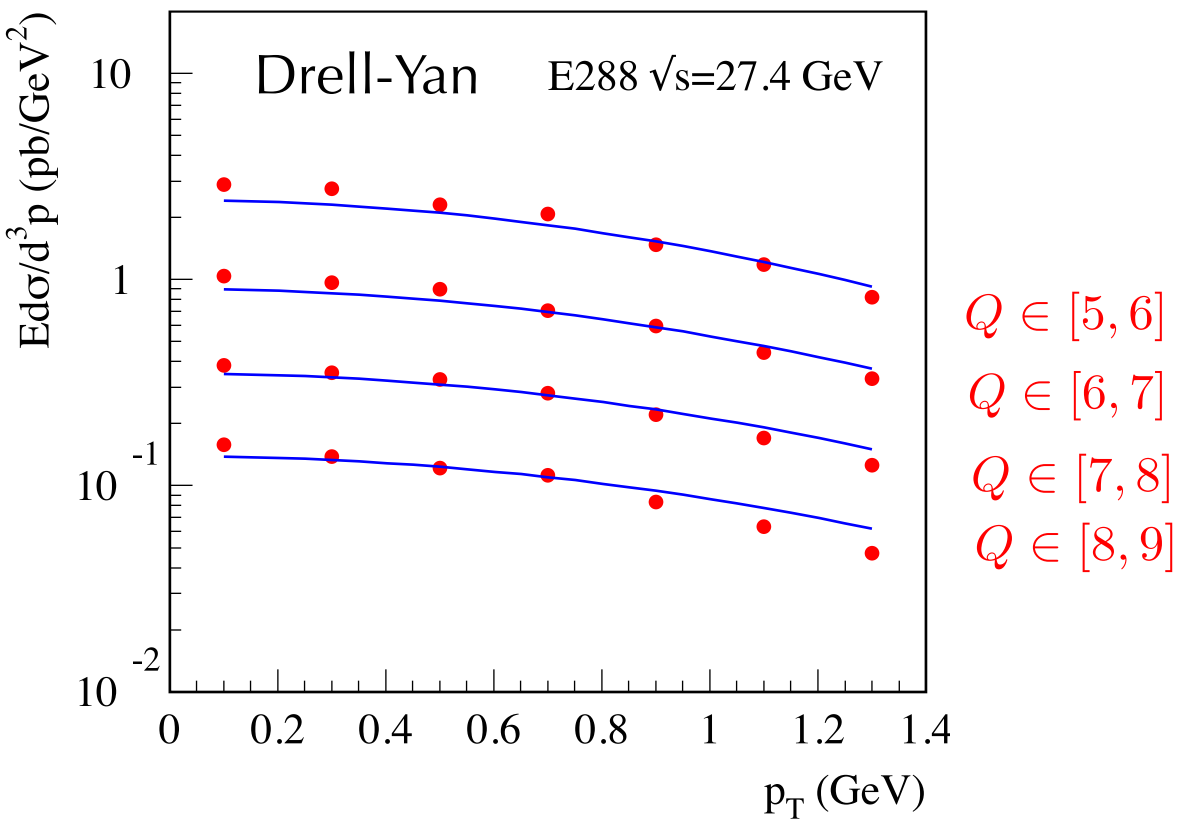
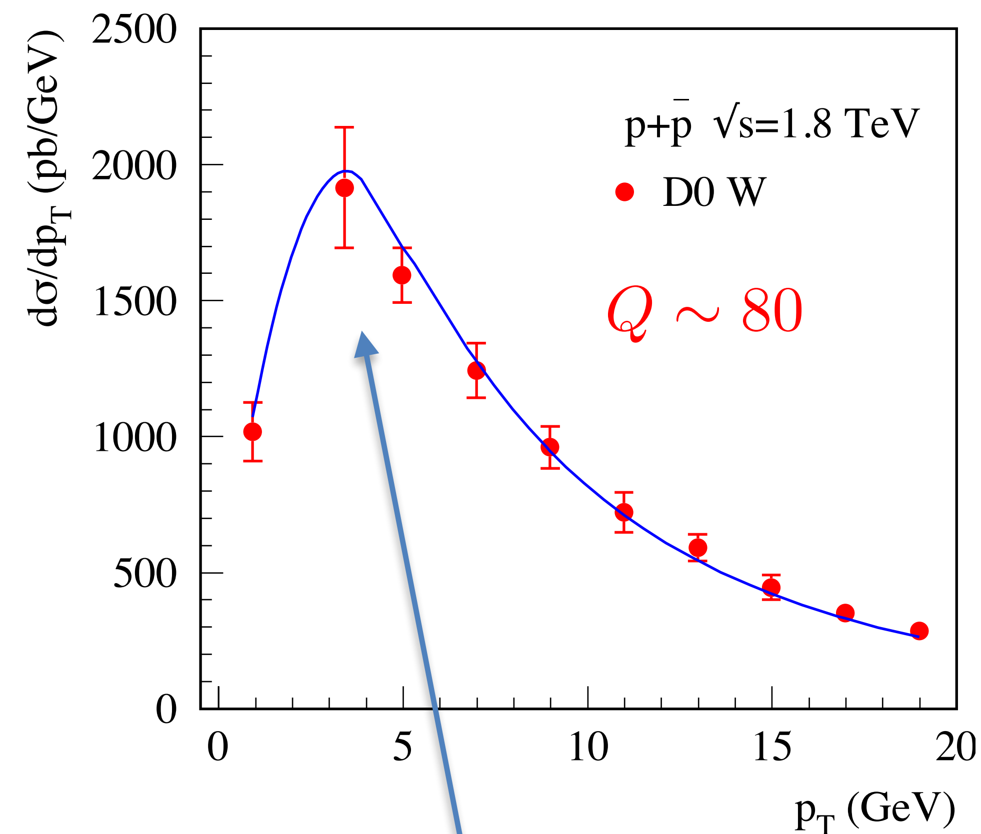
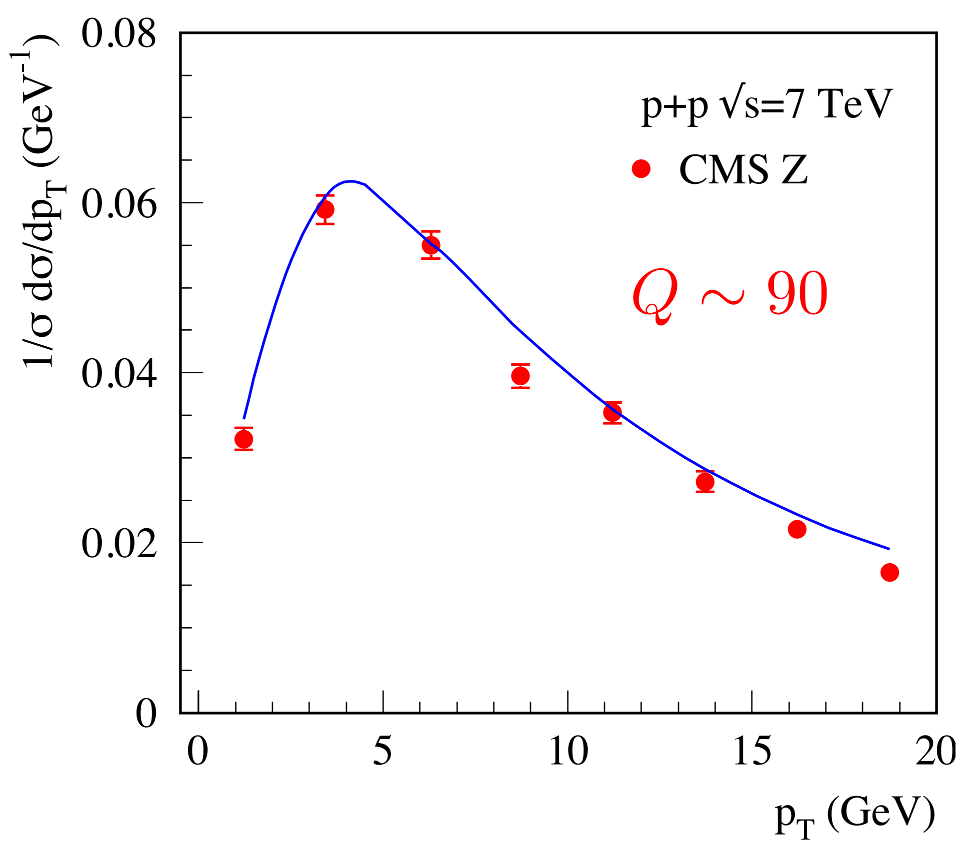
*slide courtesy of Z. Kang*

# Evolution in the data

- There's plenty of evidence that TMD evolution works for unpolarized data




Distributions become wider and shift towards higher $P_T$ as Q grow

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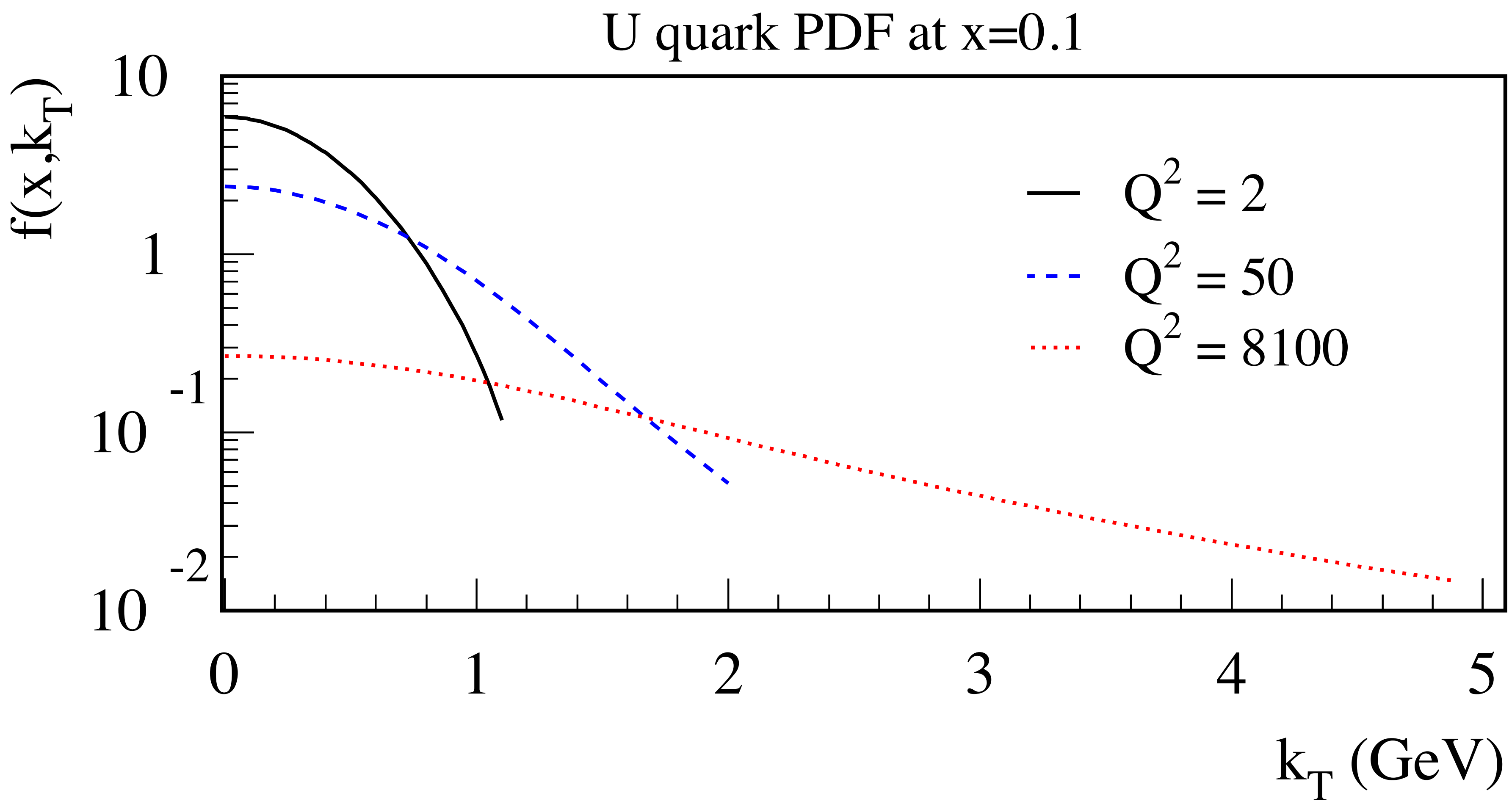
# What TMD evolution does?

- Distributions spread out to larger $k_T$ due to gluon radiation
- Distributions decrease at low $k_T$ as $Q^2$ grow

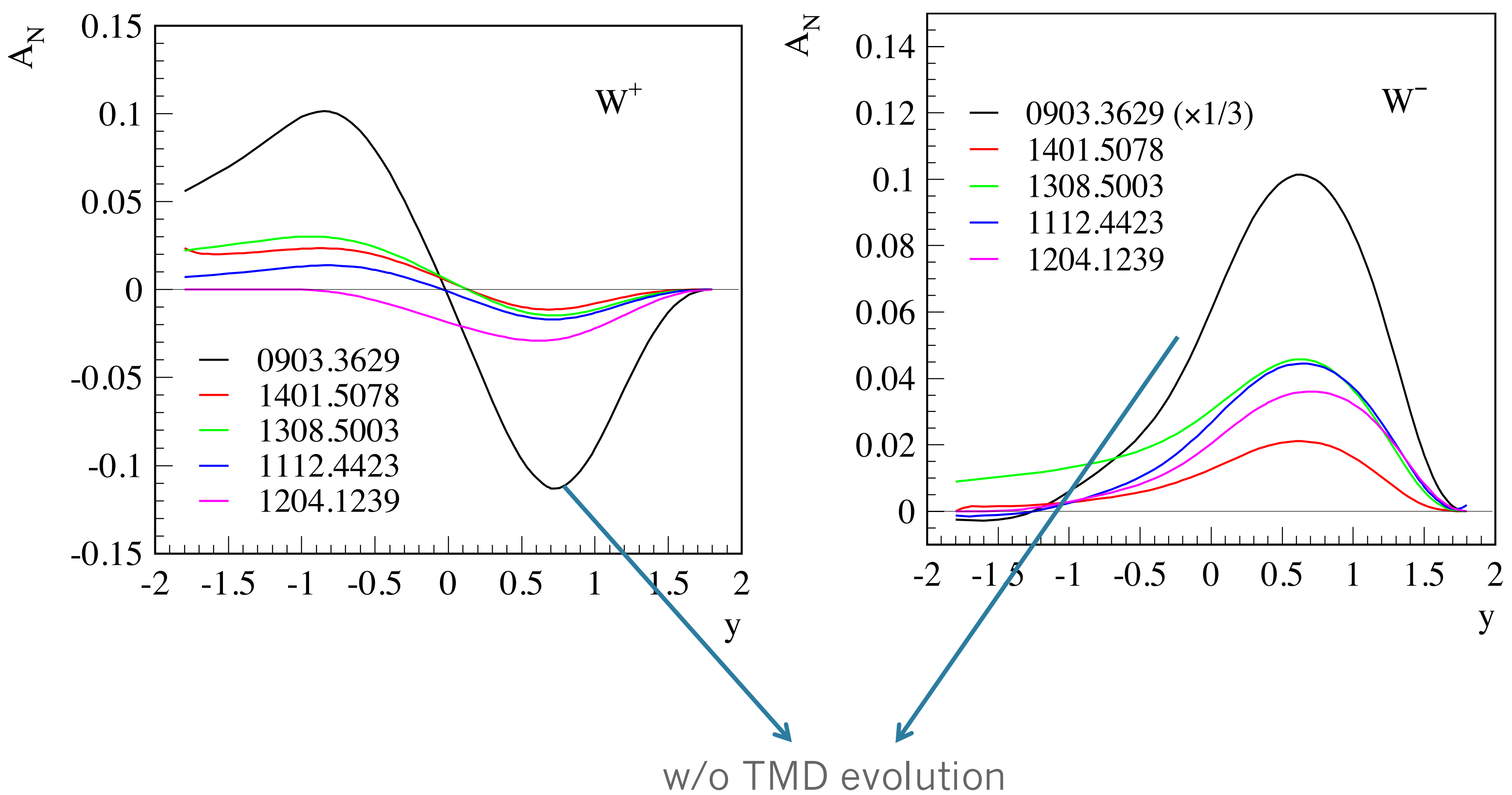
Based on Echevarria, Idilbi, Kang, Vitev, 14



# Evolution in the data

- Arguably TMD evolution was never observed in spin asymmetries
- The naive expectation: asymmetry should decrease rapidly with $Q^2$

Kang, 2015



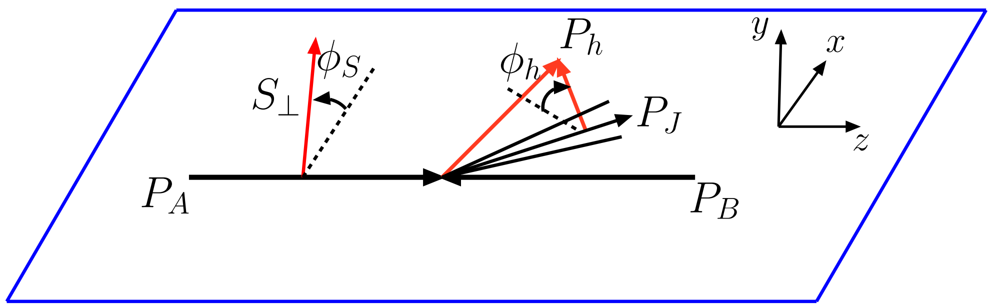

Predictions vary drastically
based on non-perturbative evolution kernel

# Hadron within a jet

- Consider a process P P scattering where jet is produced and a hadron is measured inside the jet

$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right] + p \to [\text{jet}\, h(\phi_H)] + X$$

*Feng Yuan (2008), D'Alesio, Murgia, Pisano (2014)*



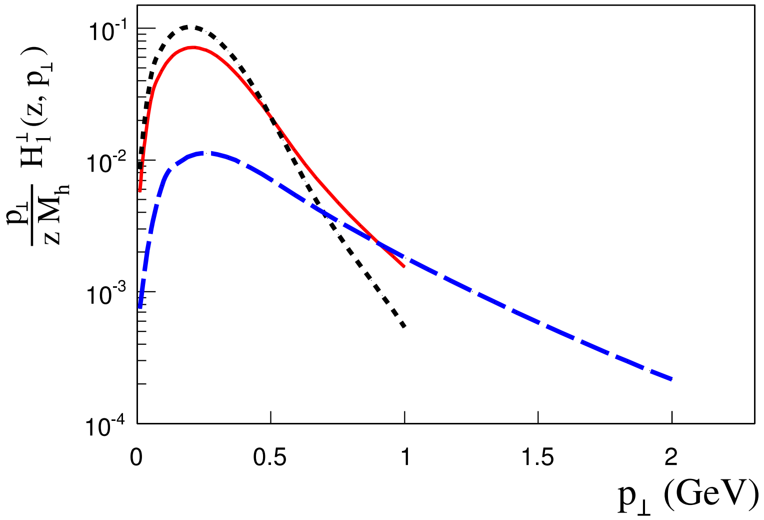

- Azimuthal modulation is related to convolution of Collins FF and transversity

*Kang, Prokudin, Sun, Yuan (2015)*

$$\frac{d\sigma}{dy d^2p_{\perp}^{\text{jet}} dz d^2 j_T} = F_{UU} + \sin(\phi_S - \phi_H) F_{UT}^{\sin(\phi_S-\phi_H)}$$

$$F_{UT}^{\sin(\phi_S-\phi_H)} \propto h_1^a(x_1) \otimes f_{b/B}(x_2) \otimes \frac{j_T}{zM_h} H_1^{\perp c}(z, j_T^2) \otimes H_{ab\to c}^{\text{Collins}}(\hat{s}, \hat{t}, \hat{u})$$

$j_T$ : hadron transverse momentum with respect to the jet direction

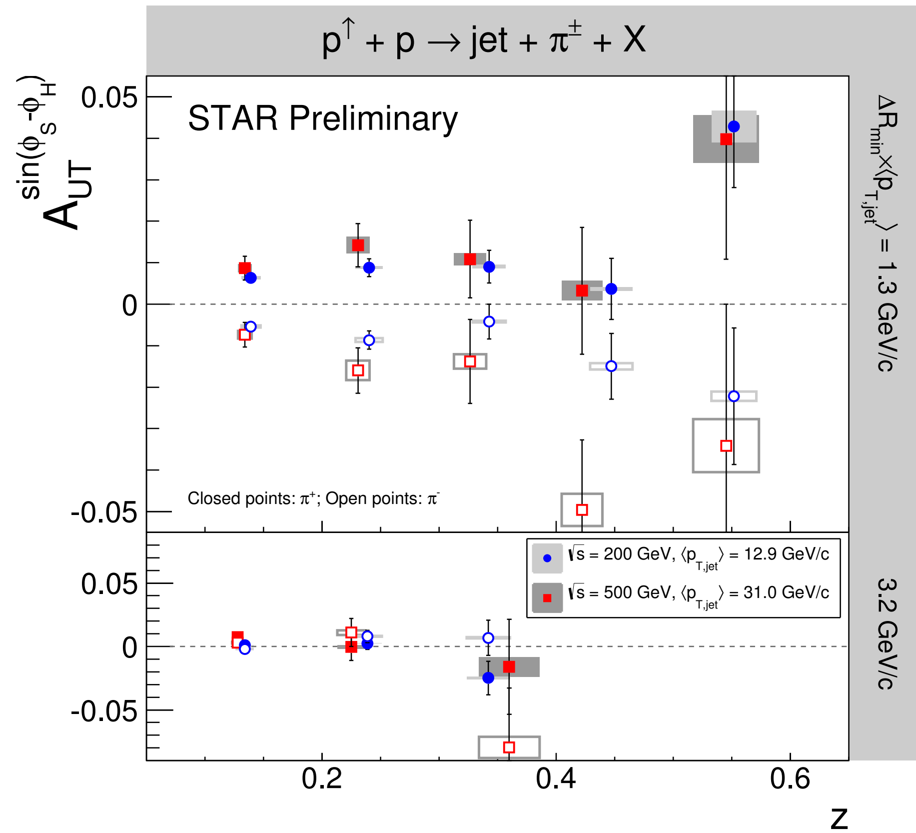



*Kang, Prokudin, Ringer, Yuan (2017) in preparation*

**Asymmetry should depend on $Q^2$**

# 200 vs. 500 GeV Comparison

J. Kevin Adkins, University of Kentucky
For the STAR Collaboration
APS Division of Nuclear Physics – Fall Meeting 2015
Santa Fe, NM
October 29, 2015




$$\langle P_{T,jet}\rangle \simeq \ 31\ GeV$$

Red data points

$$\langle P_{T,jet}\rangle \simeq \ 12\ GeV$$

Blue data points

- Matching kinematics to sample lower $<j_T>$ (top) shows that the two energies have asymmetries which are extremely similar in shape and magnitude

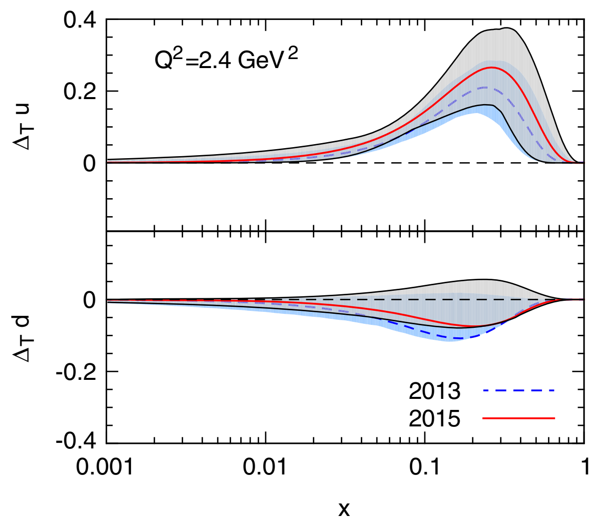
No sign of TMD evolution?

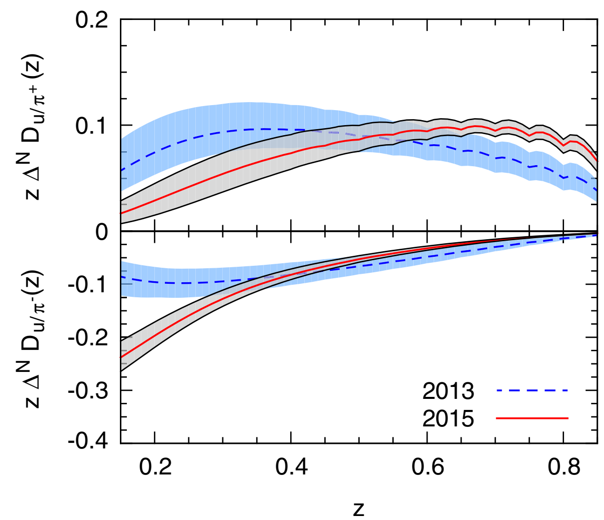
# Test of QCD evolution

*Kang, Prokudin, Ringer, Yuan (2017) in preparation*

- Compute the asymmetry without TMD evolution

*functions: Anselmino et al (2015)*

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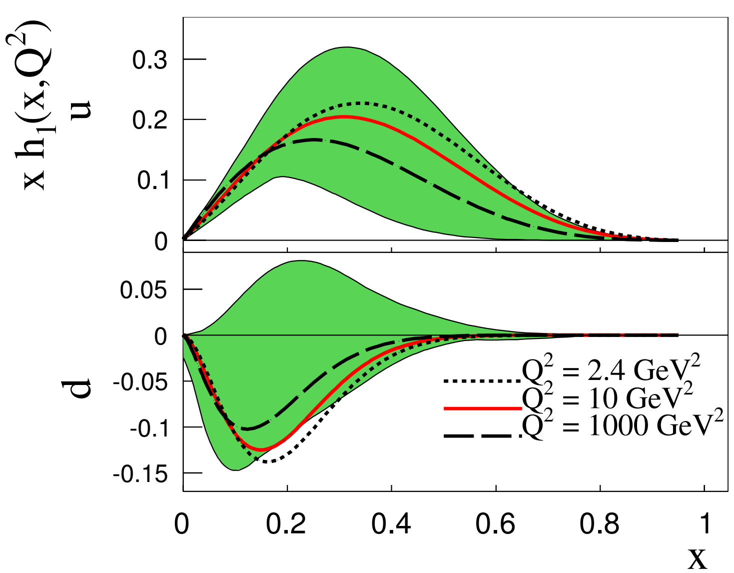


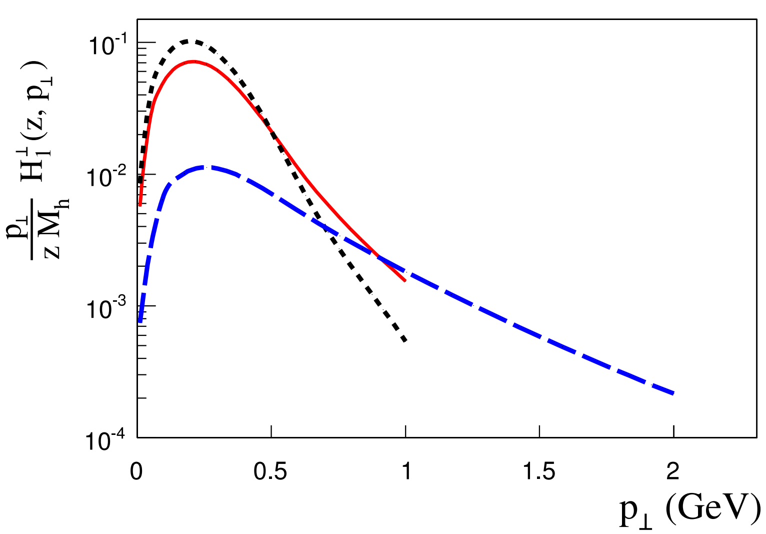

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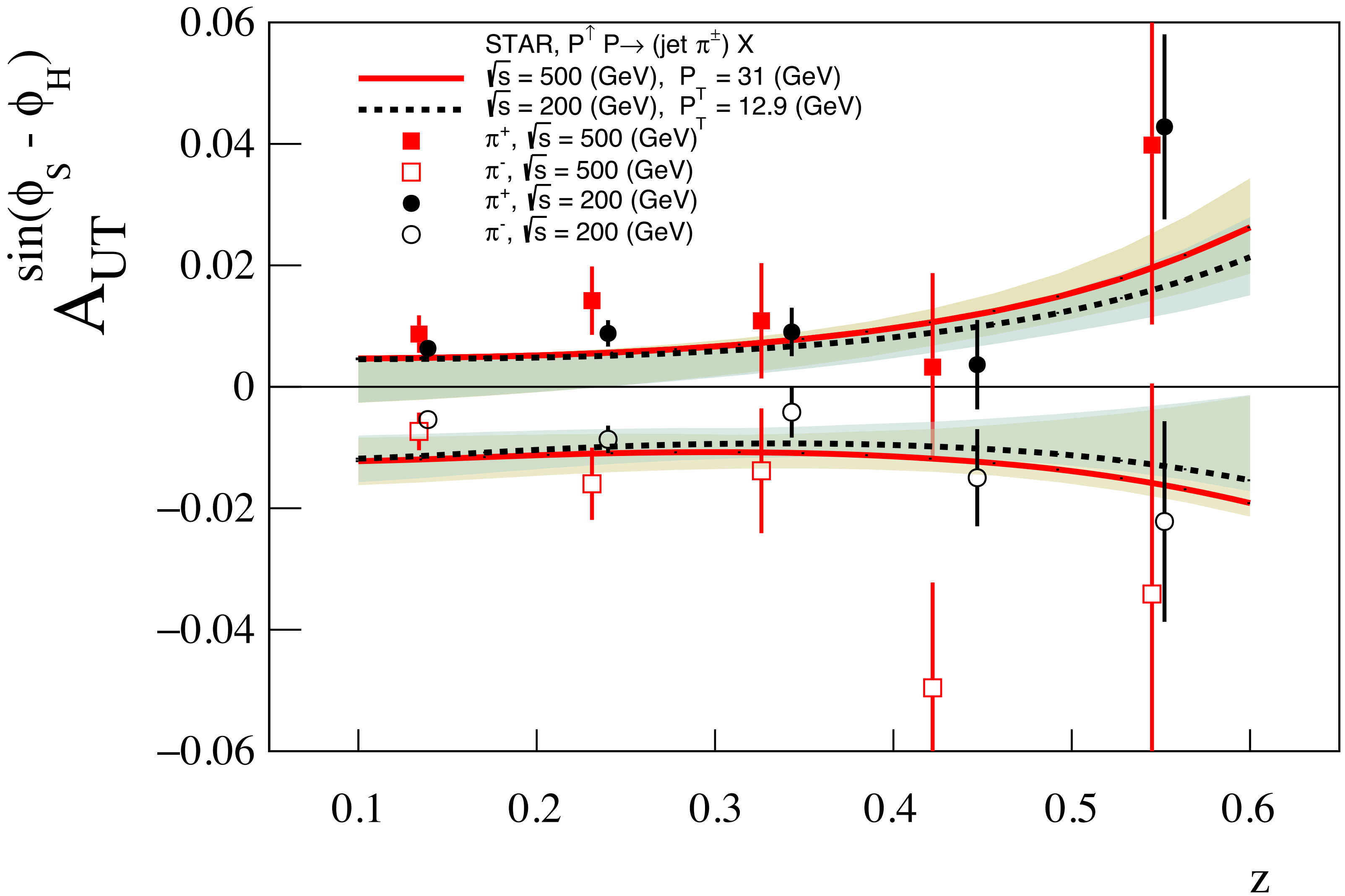


- Similar results for 200 GeV and 500 GeV
- Results are compatible with data within uncertainties

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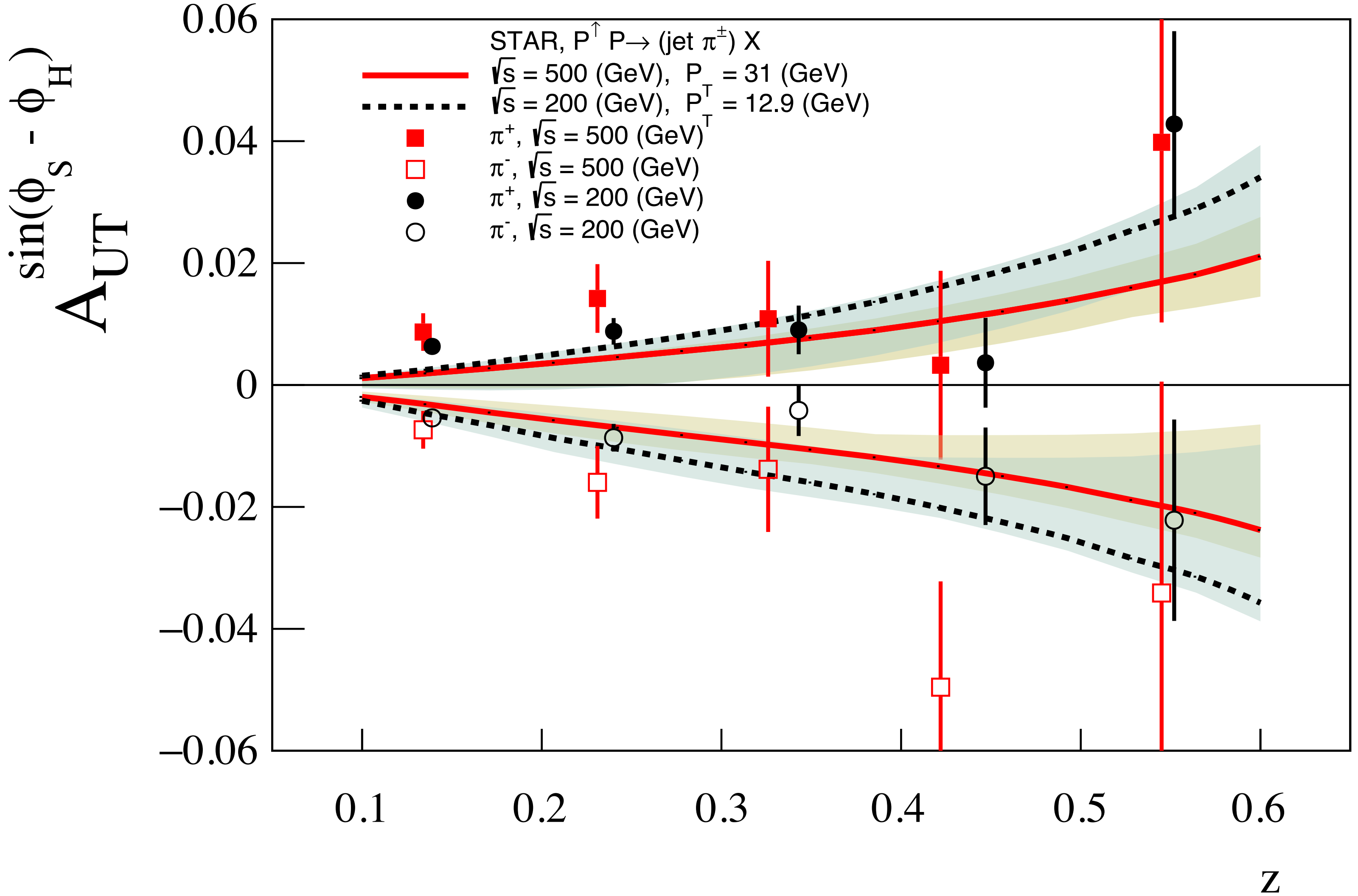


- Slight reduction for 500 compared to 200 GeV due to TMD evolution
- Results are compatible with data within uncertainties

# Why it happens?

*Kang, Prokudin, Ringer, Yuan (2017) in preparation*

- Results of evolution in Q depend on non-perturbative evolution kernel, this kernel vanishes as b goes to 0

No evolution ⟵ Evolution at moderate Q ⟶ High Q evolution

$$S_{NP}(b) \equiv 0$$

$$S_{NP}(b) \simeq -g_2 \ln\left(1 + \frac{b^2}{b_{max}^2}\right) \ln\frac{Q}{Q_0}$$

$$S_{NP}(b) \simeq -g_2 b^2 \ln\frac{Q}{Q_0}$$

"Valid" perhaps only in large b region where non-perturbative functions dominate

Tames high-b behavior, compatible with low-b behavior known from data

Valid perhaps only in small b region where perturbative functions dominate

# Conclusions

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- More precise data are clearly needed to test dependence of the data on the scale and thus TMD evolution

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**Thank you!**