QCD multiple scattering in cold nuclear matter

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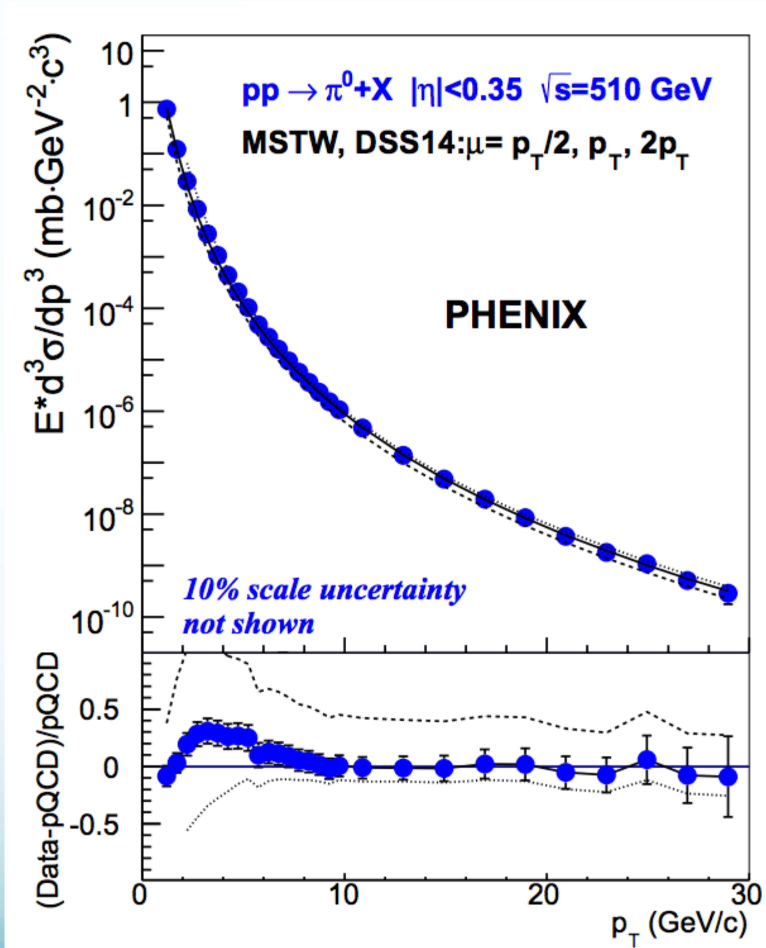
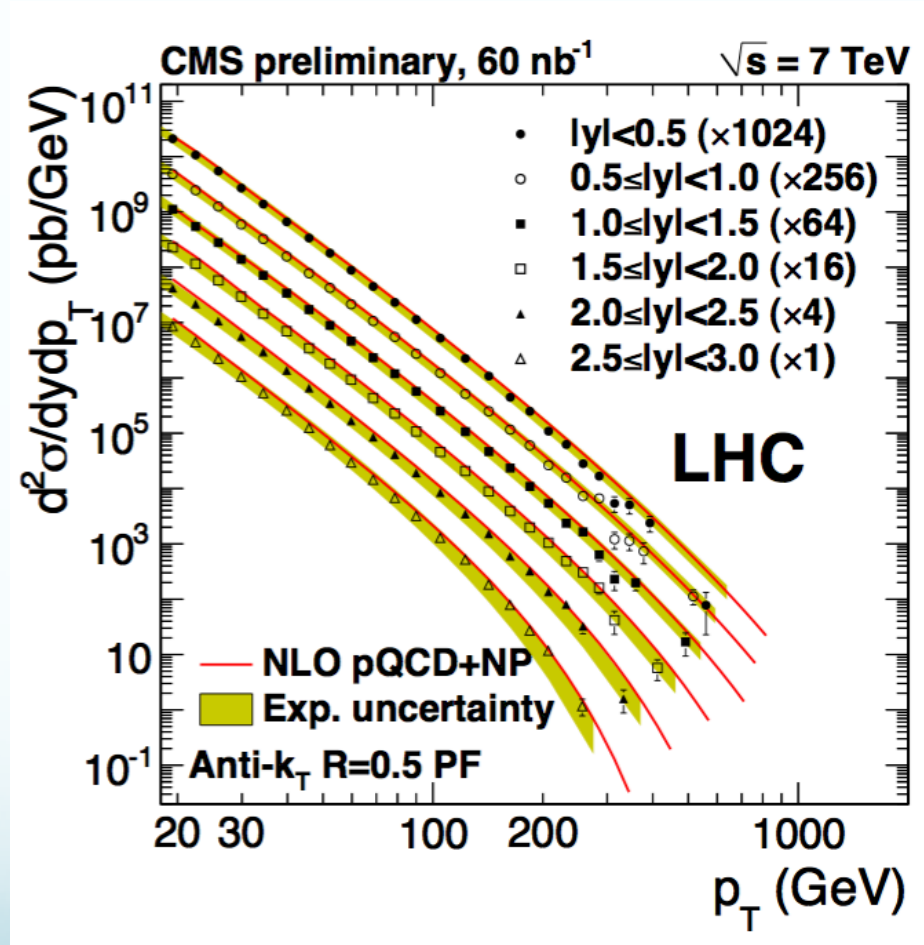
Perturbative QCD

- Perturbative QCD is very successful in describing and interpreting experimental data at e+e-, e-p, and p-p collisions



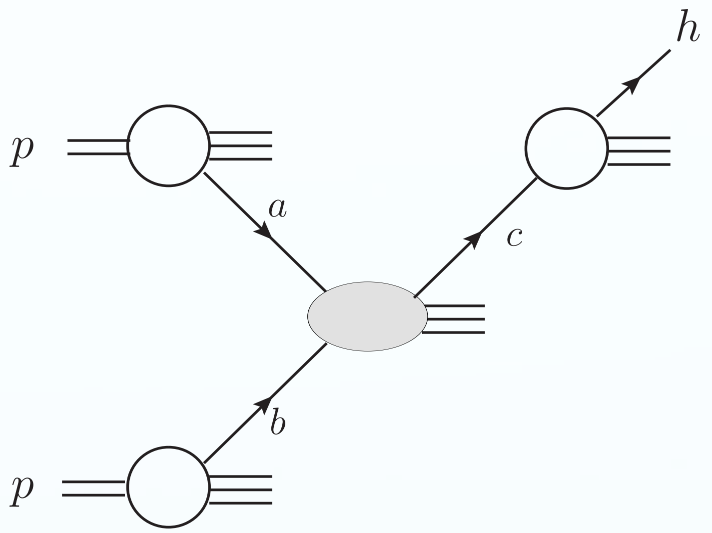
p+p→h+X



p+p→jet+X

QCD factorization at leading-twist

- Such a success relies on QCD factorization theorems at leading-twist, which is based on "single scattering picture"



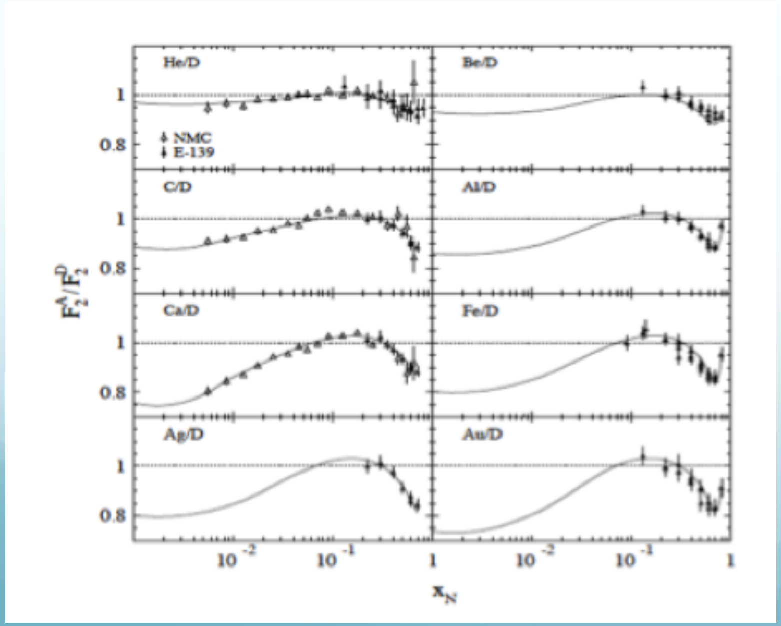
$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h$$

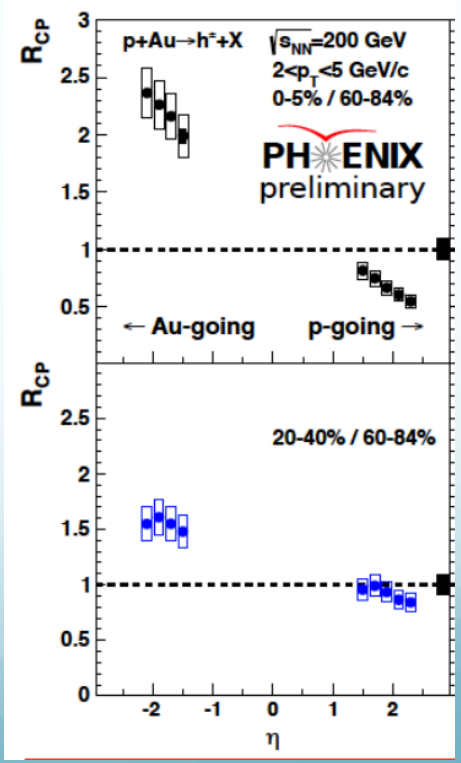
Proton to nucleus

- What do we expect when a proton is replaced by a heavy nucleus in high energy collisions?
  - Nuclear binding energy is about 8 MeV/nucleon << typical energy exchange in hard collisions
  - Should one expect a simple sum/superposition of individual nucleons?

- However, large and non-trivial nuclear dependence have been observed in almost all processes involving nuclear targets

$$R_{F_2} = \frac{\frac{1}{A}F_2^A(x,Q^2)}{\frac{1}{2}F_2^D(x,Q^2)} \neq 1$$

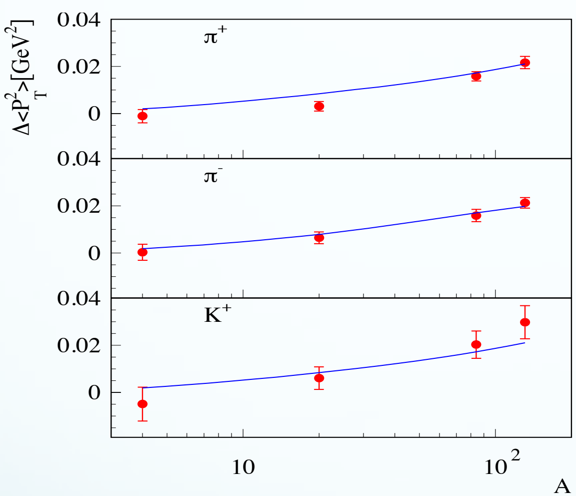




Nuclear broadening: nuclear size dependence

- Nuclear broadening of average transverse momentum of produced particles in p+A vs p+p

$$\langle p_T^2\rangle_{pA} = \langle p_T^2\rangle_{pp} + b\,A^{1/3}$$



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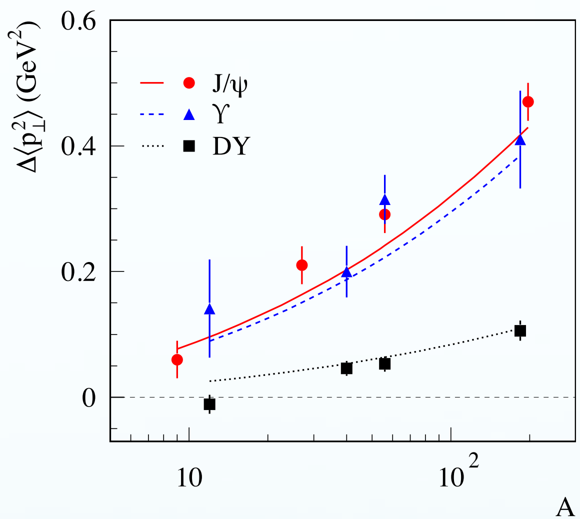
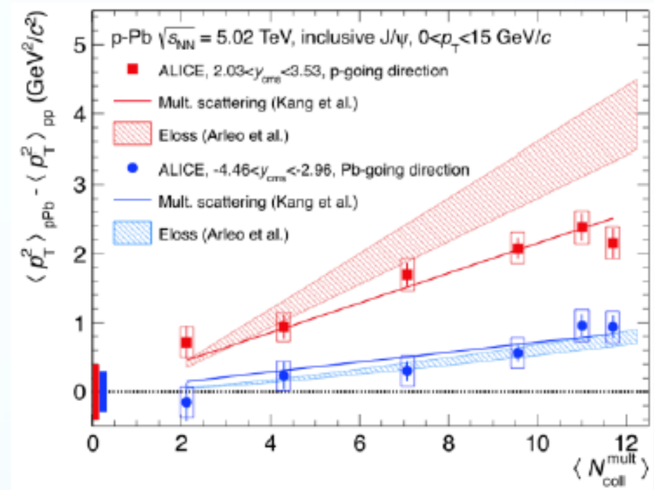


Fermilab, SPS



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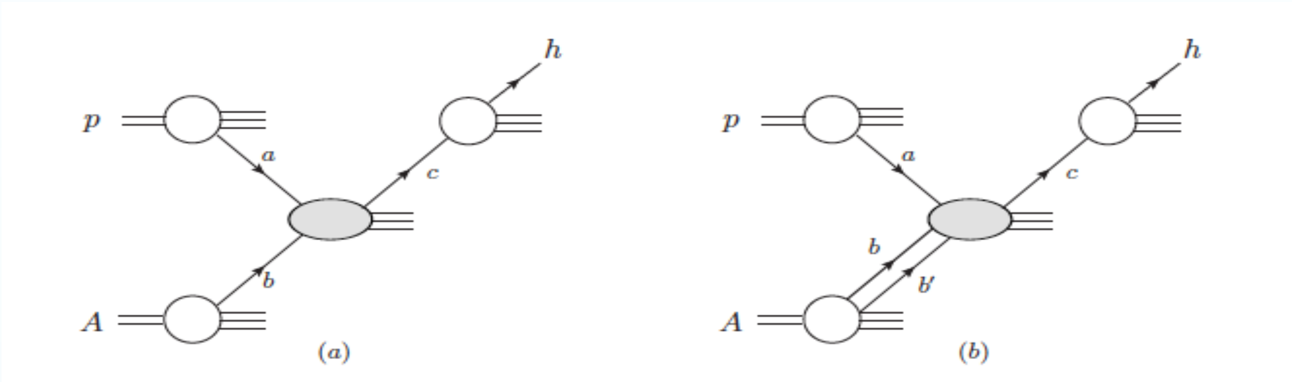
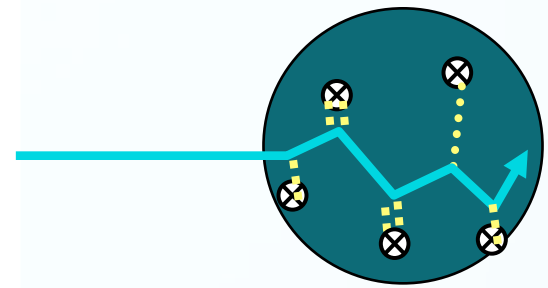
Single vs multiple scattering

- Single scattering is localized in space and cannot have size dependence, it is "multiple scattering" that plays an important role





- Generic structure of cross section for particle production

perturbative expansion

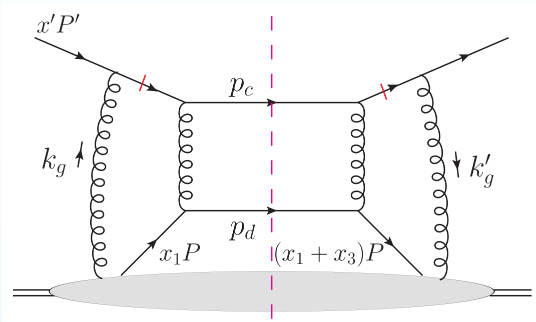
$$
\begin{aligned}
\sigma^h_{phys} = \quad & \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x) \Longrightarrow \text{leading twist} \\
+ \frac{1}{Q} & \left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x) \Longrightarrow \text{twist-3} \\
+ \frac{1}{Q^2} & \left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x) \Longrightarrow \text{twist-4} \\
+ \ldots &
\end{aligned}
$$

power expansion

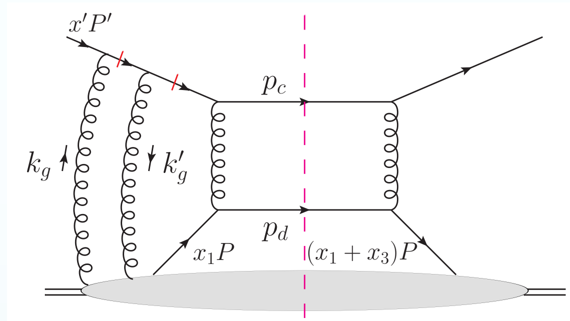
Generalized QCD factorization

- Framework to compute the contributions of multiple scattering
  - A generalized QCD factorization framework was developed by Qiu and Sterman in 1990s
  - Over the years, we have improved for fast/efficient implementation and for generic kinematic regions

- Example diagrams



(M)



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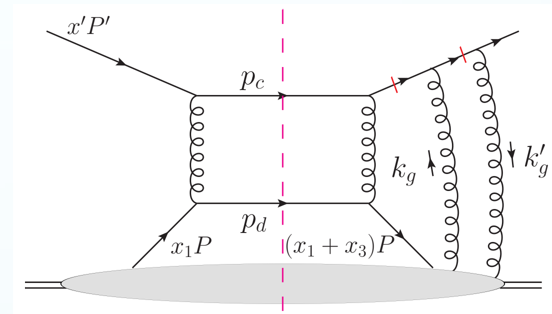
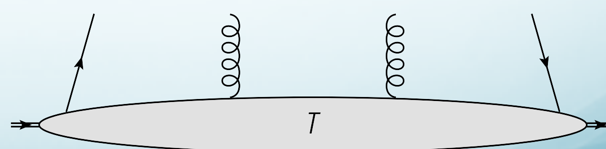


(R)

$$k_g = x_2 P + k_\perp \qquad k'_g = (x_2 - x_3)P + k_\perp$$

$$E_h \frac{d\sigma^{(D)}}{d^3P_h} \propto \int \frac{dz}{z^2} D_{c\to h}(z) \int \frac{dx'}{x'} f_{a/p}(x')$$

$$\times \int dx_1 dx_2 dx_3 T(x_1,x_2,x_3) \left(-\frac{1}{2} g^{\rho\sigma}\right) \left[\frac{1}{2} \frac{\partial^2}{\partial k_\perp^\rho \partial k_\perp^\sigma} H(x_1,x_2,x_3,k_\perp)\right]_{k_\perp \to 0}$$



Incoherent vs coherent multiple scattering

- The nature of the multiple scattering (incoherent vs coherent) depends on the probing length of the probe
  - At small-x region (forward region):

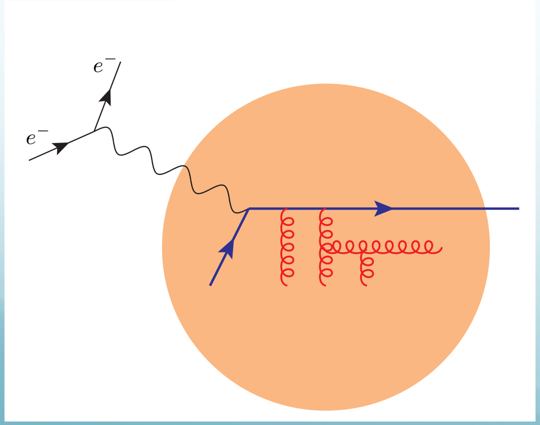
    coherent → suppression

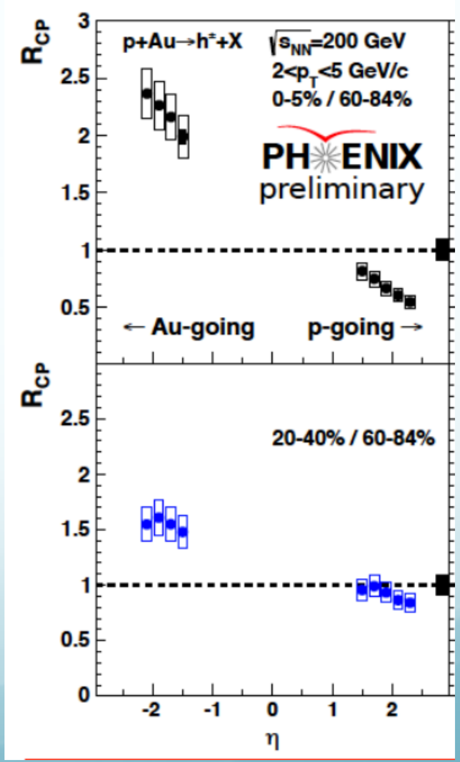
$$\frac{1}{Q} \sim \frac{1}{xP} \gg 2R\left(\frac{m}{p}\right)$$

  - At large-x region (backward region):

    incoherent → enhancement

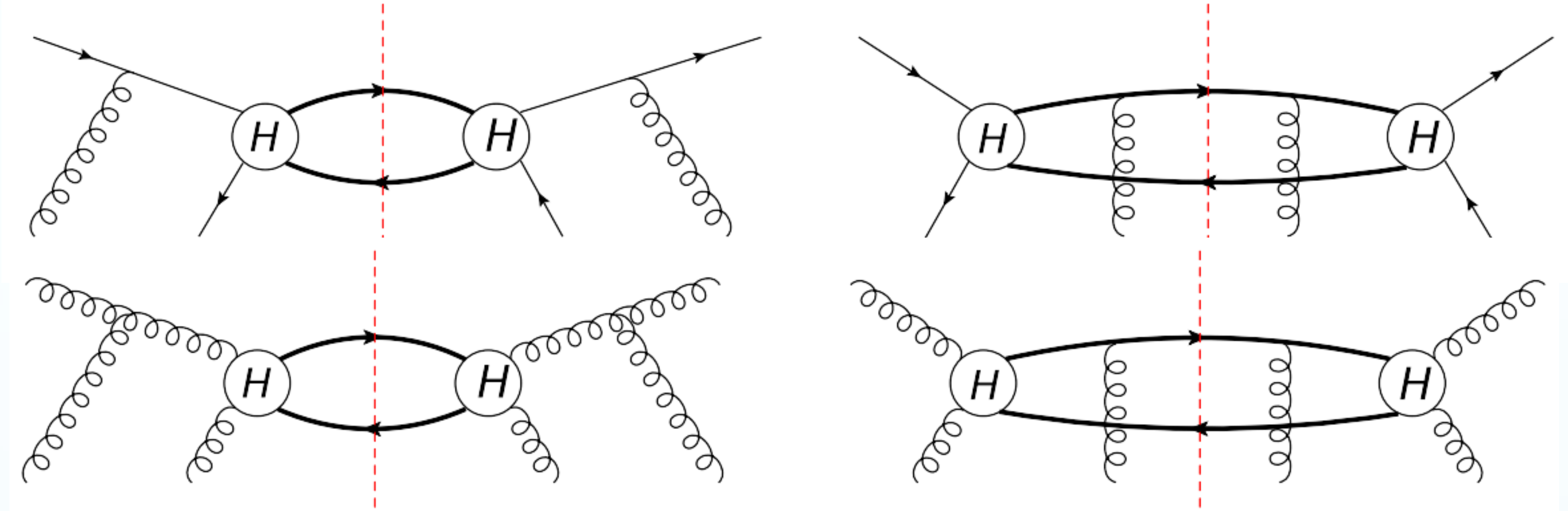
$$\frac{1}{Q} \sim \frac{1}{xP} < 2R\left(\frac{m}{p}\right)$$

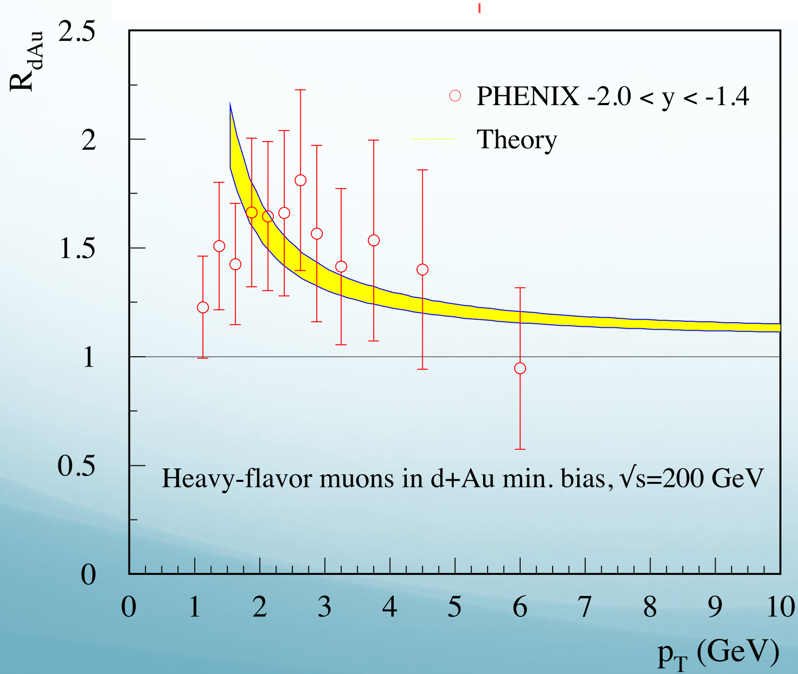


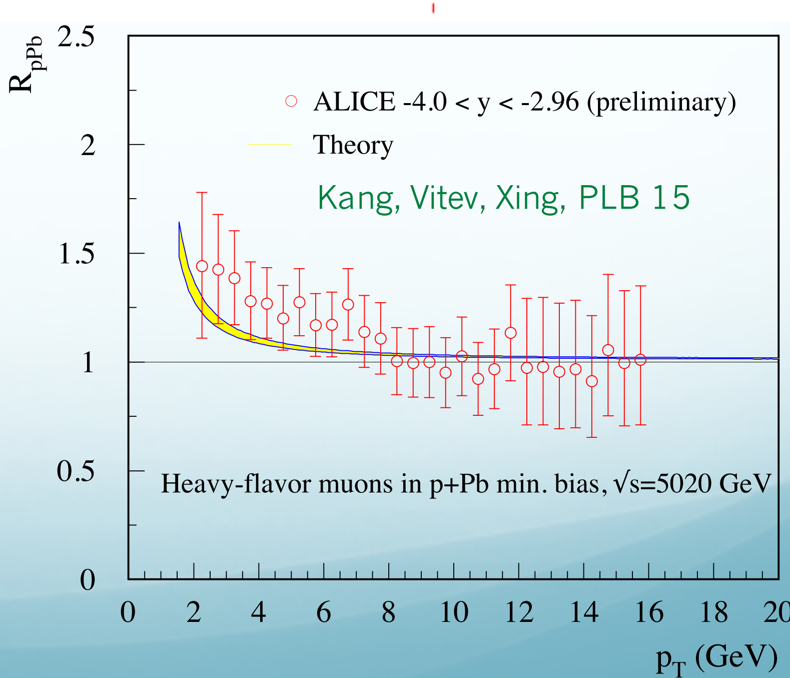


Heavy meson production in backward region

- Both initial-state and final-state double scattering contributions





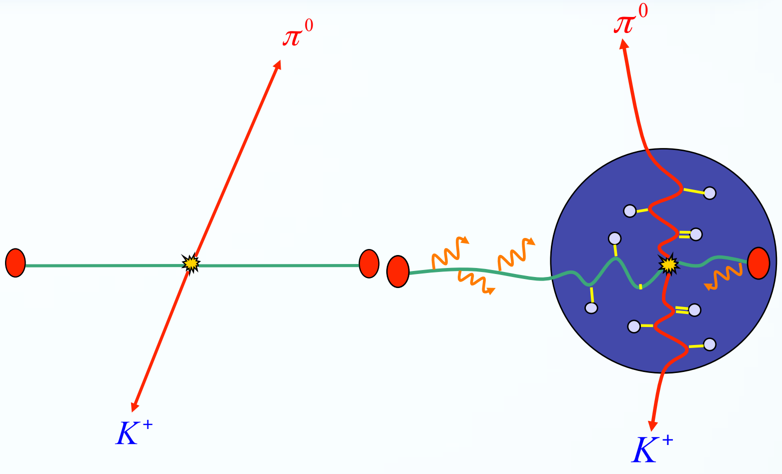


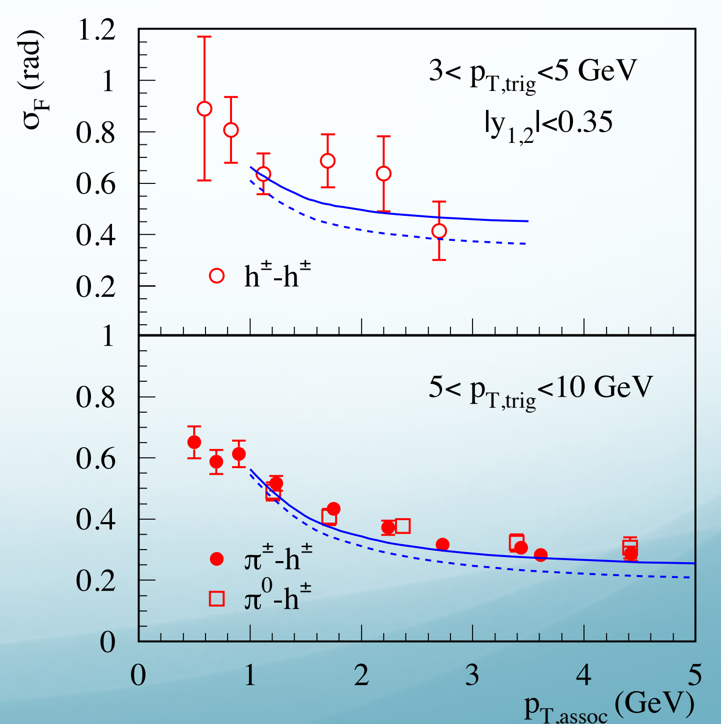
Dihadron correlation in forward region

- In p+p collisions, at LO, two hadrons are produced back-to-back in transverse plane
- However, in p+A/d+Au collisions, initial-state and final-state multiple scattering will lead to imbalance
- Nuclear broadening of dihadron imbalance

$$\Delta\langle q_\perp^2\rangle = \langle q_\perp^2\rangle_{\mathrm{pA}} - \langle q_\perp^2\rangle_{\mathrm{pp}}$$

$$\vec{q}_\perp = \vec{P}_\perp^{h1} + \vec{P}_\perp^{h2}$$



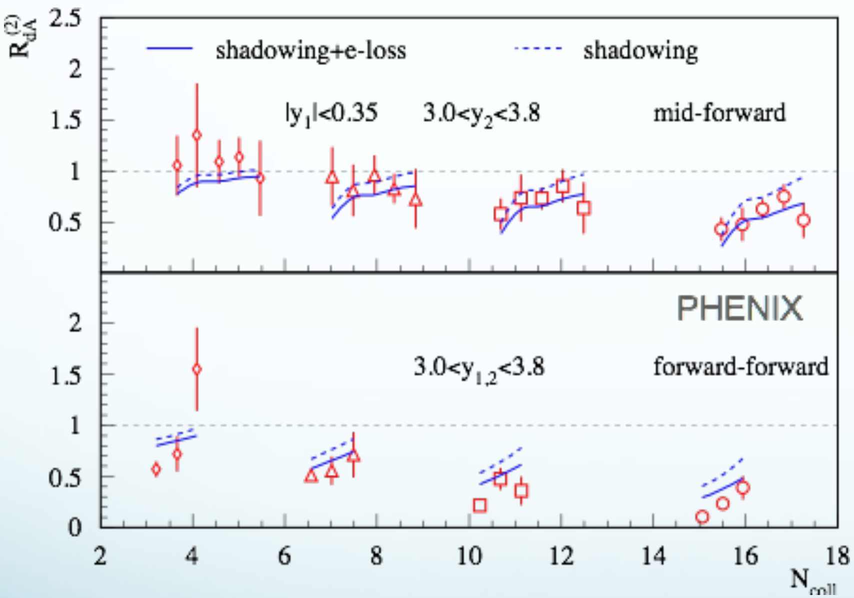


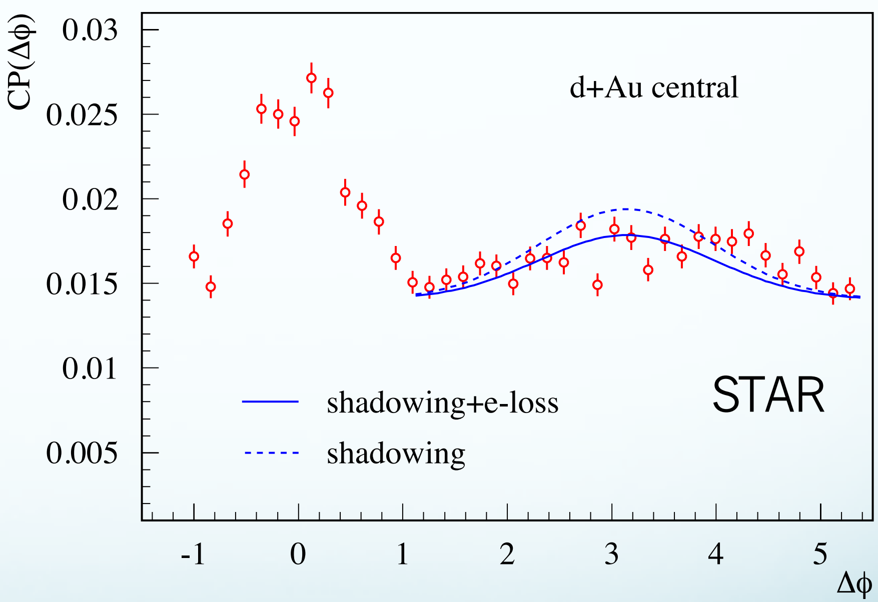
Kang, Vitev, Xing, PRD 2012

Dihadron suppression in forward region

- Combine suppression and nuclear broadening, one can predict the azimuthal decorrelation

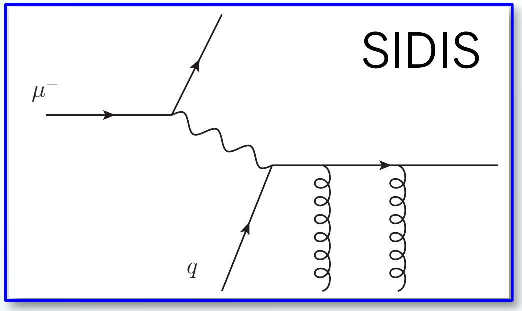
Kang, Vitev, Xing, PRD, 12





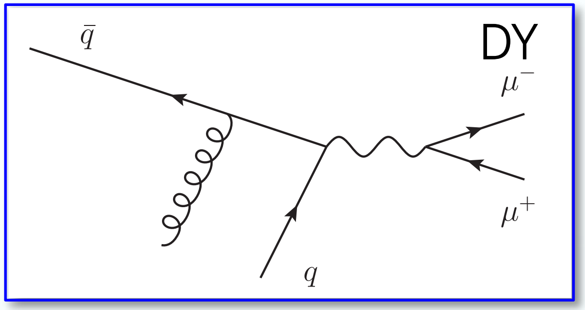
Explore multiple scattering in more channels

- Transverse momentum broadening also happens in other processes such as SIDIS, DY, J/ψ production
  - Comparing the theoretical computations and experimental data can validate our theoretical framework



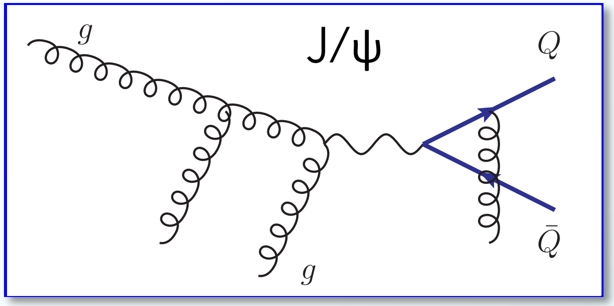
$e + A \to e + h + X$

Final-state



$p + A \to \mu^+\mu^- + X$

Initial-state

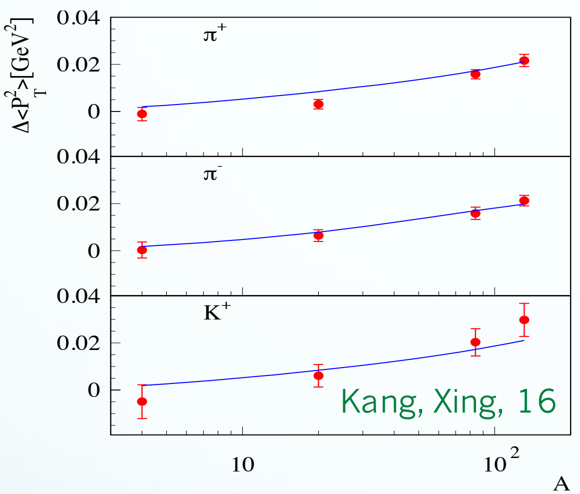


$p + A \to J/\psi + X$

Both

Works pretty well

- Description of the data using single set of correlation functions



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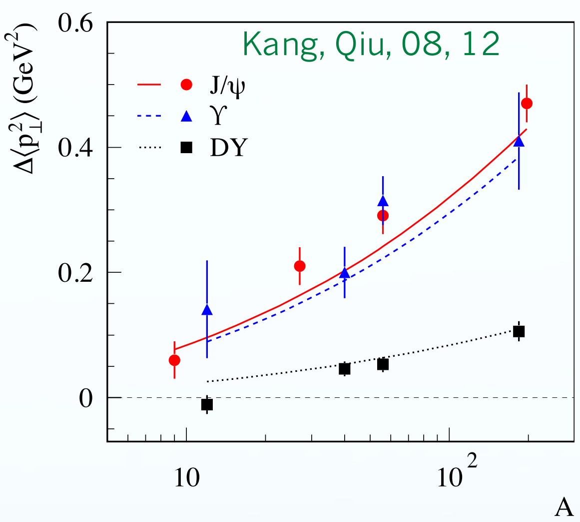
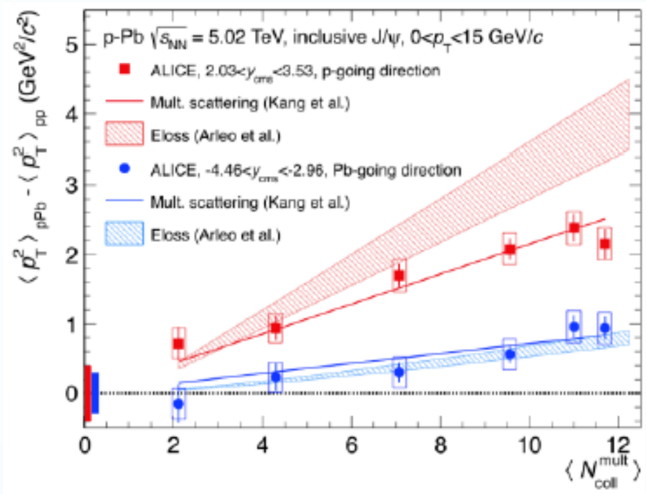


Fermilab, SPS



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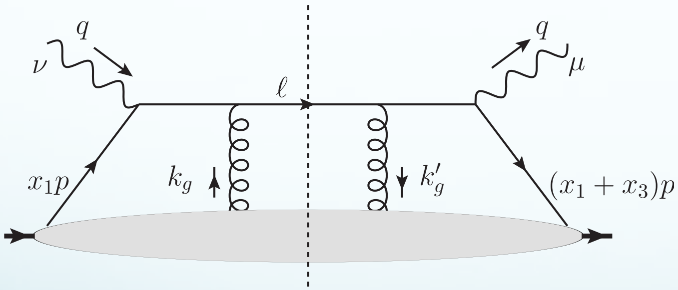
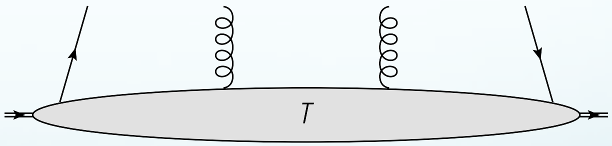
Going beyond: radiative corrections

- It would be highly desirable to carry out the multiple scattering computations to next-to-leading order (NLO)
  - Verify the factorization theorem at NLO and at next-to-leading power (twist-4)
  - Derive the evolution equations for the relevant correlation functions
  - Reduce the theoretical uncertainties
- We recently took this step, performed the NLO computations for SIDIS and DY processes



(a)

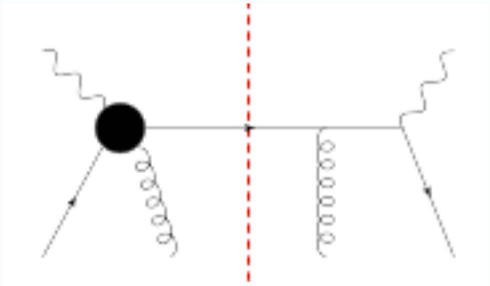
T-4 q-g correlation

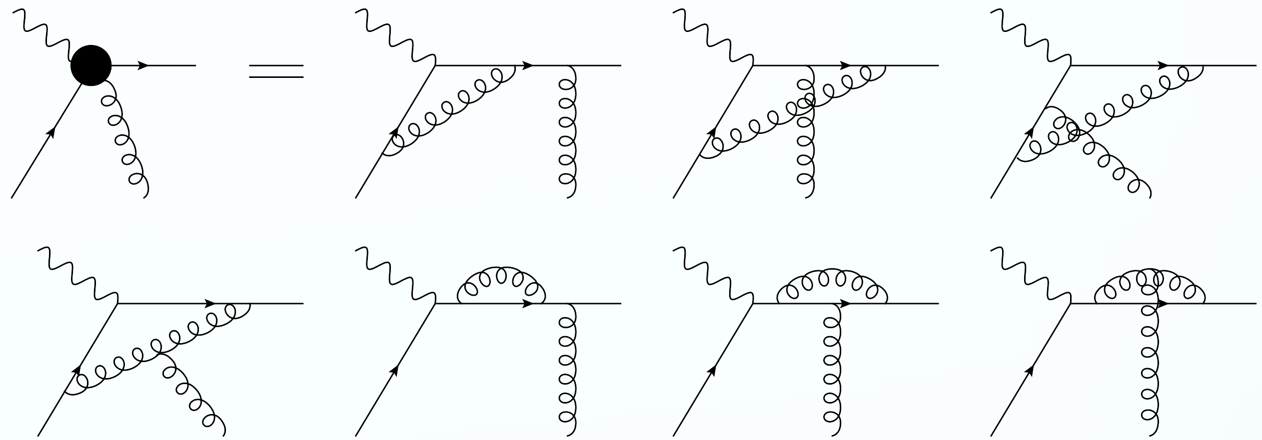


Double scattering in SIDIS at NLO

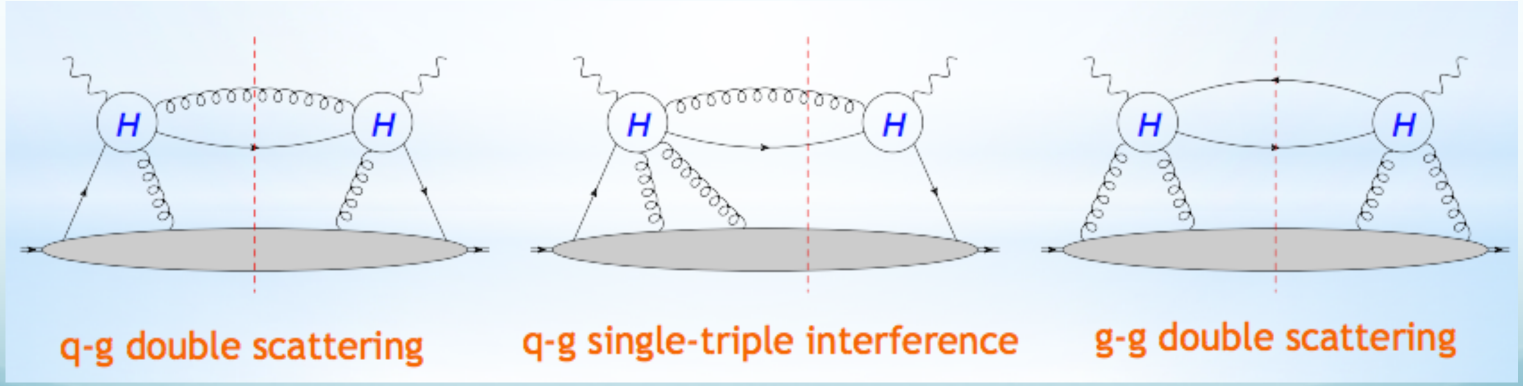
- Virtual diagrams (7)

Kang, Wang, Wang, Xing, PRL 13, PRD 17





- Real diagrams (69)



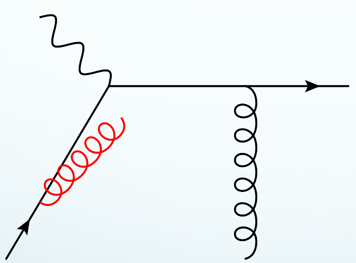
SIDIS: TMB at NLO

- Logic: make sense of all sorts of divergence
  - UV divergence: $k \to \infty$ taken care by renormalization
  - Soft divergence: $k \to 0$ cancel between real+virtual
  - Collinear divergence: $k // P$ long-distance physics, part of PDFs/FFs, leads to DGLAP evolution of these functions

collinear to IS

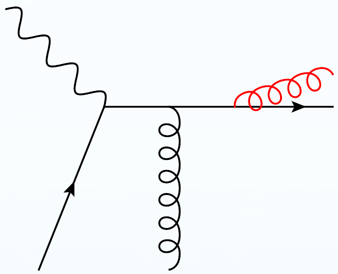
$$-\frac{1}{\epsilon}\delta(1-\hat{z})\mathcal{P}_{qg\to qg}(\hat{x}) \otimes T_{qg} D_{h/q}(z)$$

New splitting kernel



collinear to FS

$$-\frac{1}{\epsilon}\delta(1-\hat{x})T_{qg}(x,0,0)P_{qq}(\hat{z})$$



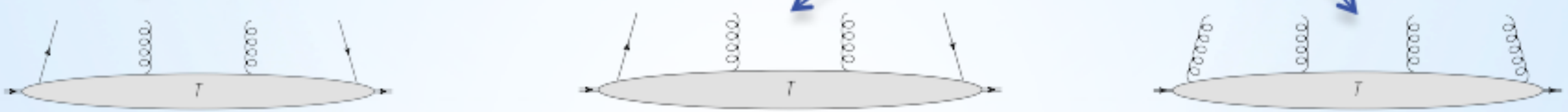
$$\mu^2 \frac{\partial D_{h/q}(z_h,\mu^2)}{\partial \mu^2} = \frac{\alpha_s}{2\pi}\int \frac{dz}{z} P_{qq}(\hat{z}) D_{h/q}(z,\mu^2)$$

$$T_{qg}(x_B,0,0,\mu_f^2) = T_{qg}(x_B,0,0) - \frac{\alpha_s}{2\pi}\left(\frac{1}{\hat{\epsilon}} + \ln\frac{\mu^2}{\mu_f^2}\right)\int_{x_B}^1 \frac{dx}{x}\left[\mathcal{P}_{qg\to qg}\otimes T_{qg} + P_{qg}(\hat{x})T_{gg}(x,0,0)\right]$$

New evolution equation

- Evolution equation for quark-gluon correlation function

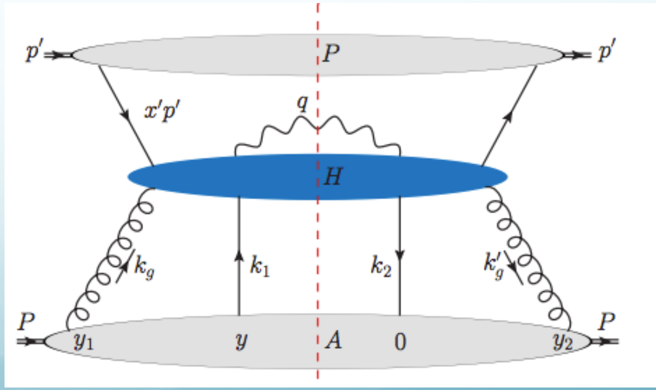
$$\mu_f^2 \frac{\partial}{\partial \mu_f^2} T_{qg}(x_B, 0, 0, \mu_f^2) = \frac{\alpha_s}{2\pi} \int_{x_B}^{1} \frac{dx}{x} \left[\mathcal{P}_{qg\to qg} \otimes T_{qg} + P_{qg}(\hat{x}) T_{gg}(x, 0, 0, \mu_f^2) \right]$$



- Perform the same calculation for DY production in p+A collisions
  - Same renormalized result at NLO for quark-gluon correlation function, indicating the universality of the function, independent of the hard process

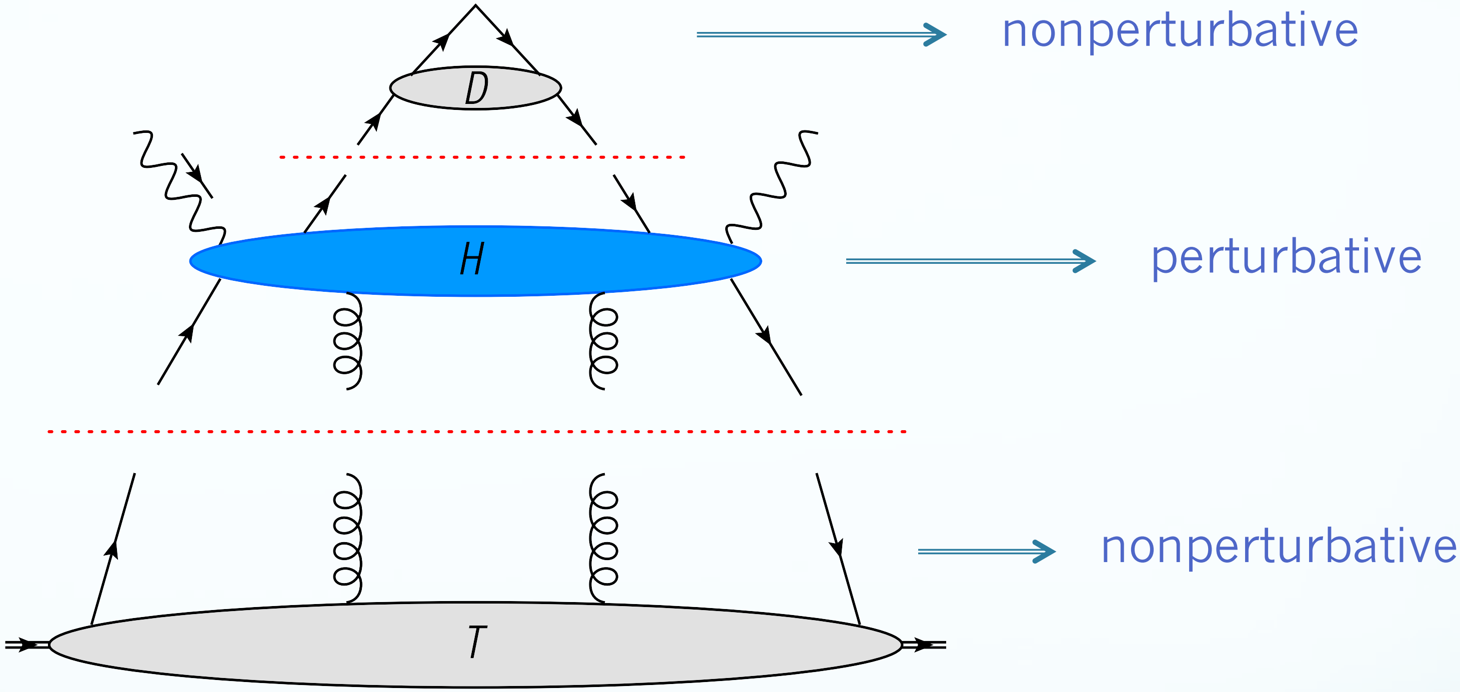
SIDIS vs DY
Final-state vs initial-state

Kang, Qiu, Wang, Xing, PRD 16



A full NLO calculation

- Factorization



$$\frac{d\langle \ell_{hT}^2 \sigma\rangle}{dz_h} \propto D_{q/h}(z,\mu^2)\otimes H^{LO}(x,z)\otimes T_{qg}(x,0,0,\mu^2)$$
$$+\frac{\alpha_s}{2\pi}D_{q/h}(z,\mu^2)\otimes H^{NLO}(x,z,\mu^2)\otimes T_{qg(gg)}(x,0,0,\mu^2)$$

Though quite involved, (1) the evolution equation can be derived; at the same time, (2) multiple scattering hard part (short-distance physics) can be rigorously computed

Summary

- Multiple scattering in high energy nuclear collisions are very important sources of nuclear dependence
- The effects of multiple scattering can be systematically calculated in a high-twist formalism
- QCD NLO computations for double scattering have been performed for the first time for SIDIS and DY processes
  - Looking forward to the precision analysis of p+A data in the future

Thank you!