Nucleon and Nuclear TMDs

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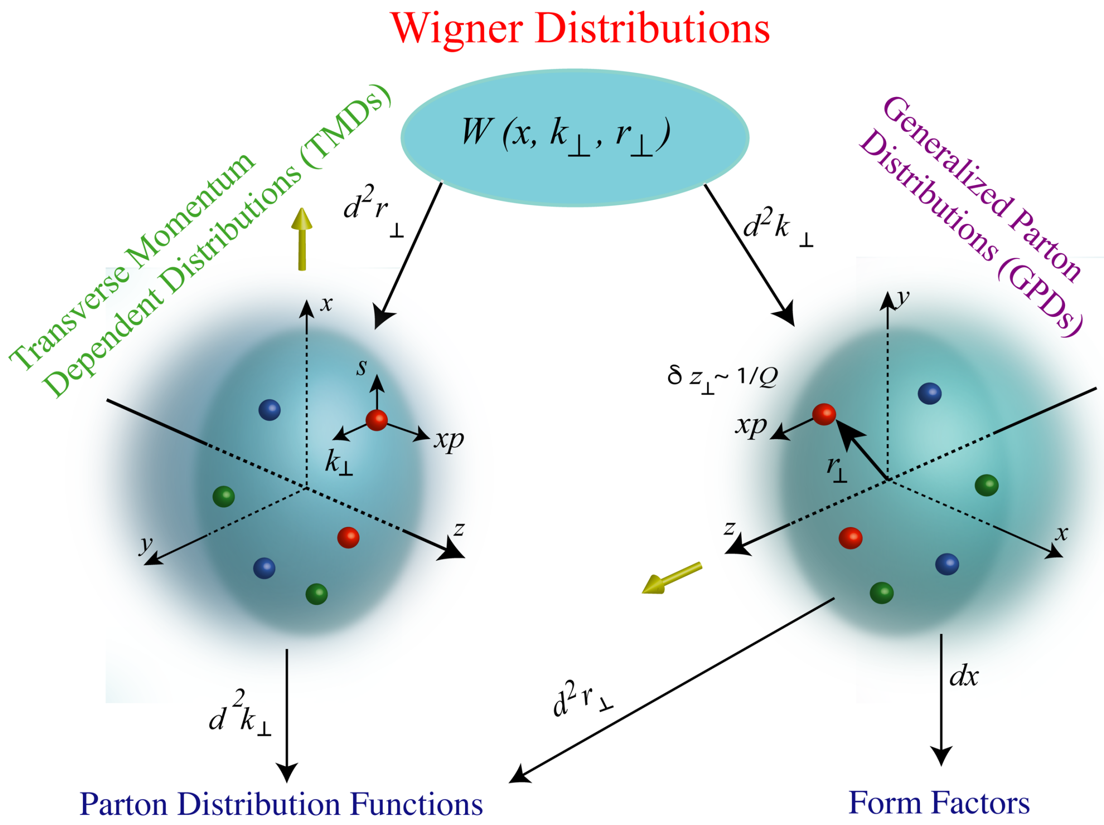
Based on Phys.Rev.Lett. 129 (2022) 24,242001

1st International Workshop on a 2nd Detector for the Electron-Ion Collider

Temple University

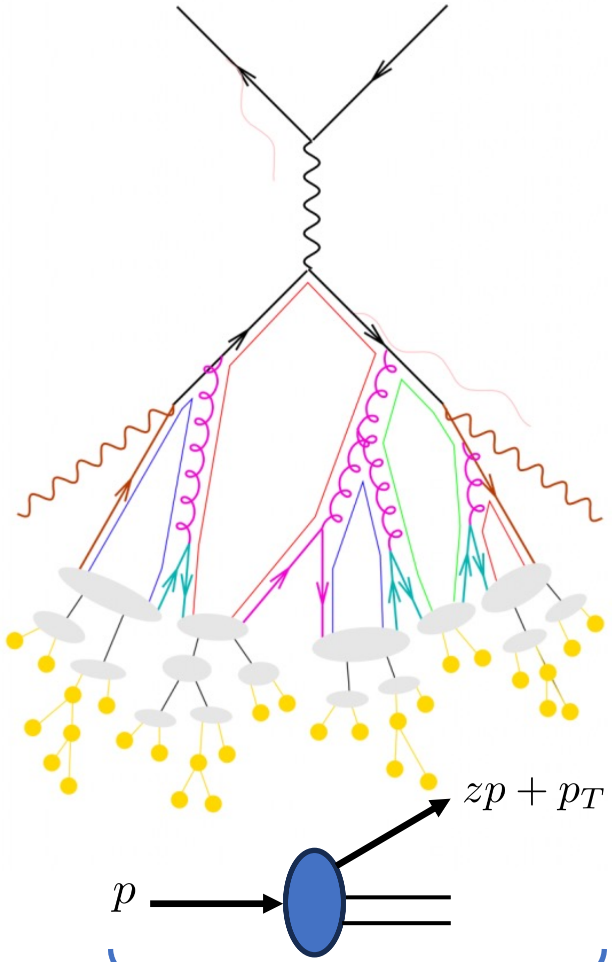
Transverse momentum distributions (TMDs)

Provide information for distributions of partons in hadrons



TMD PDF

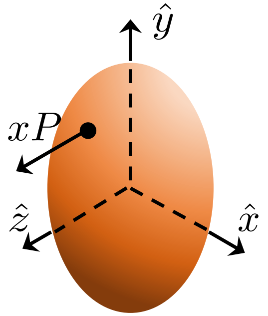
Provide information for transverse momentum of hadron relative to parent quark



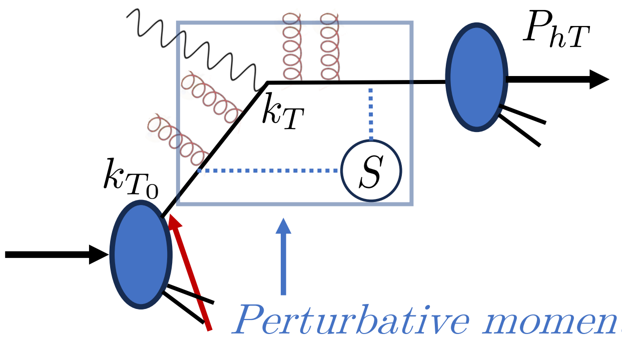
TMD FF

Factorization Theorems

TMDs are non-perturbative



Inject large current

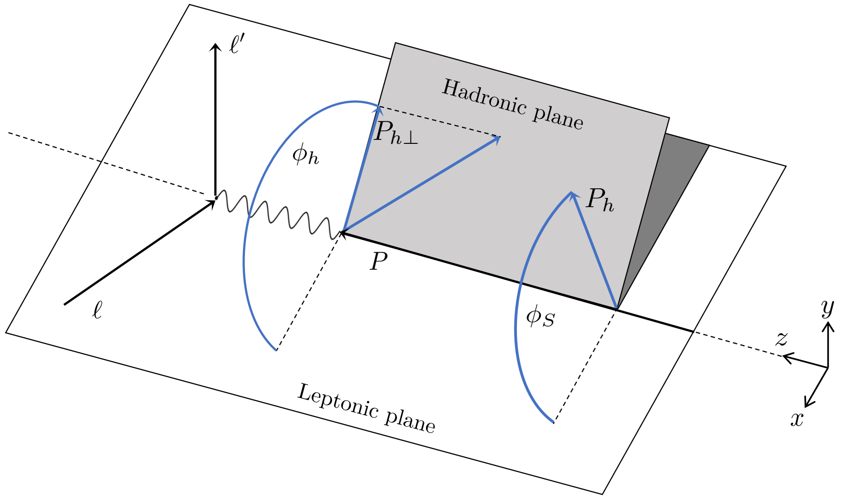


Perturbative momentum

Intrinsic/non-perturbative momentum

Cross section involves convolution of non-perturbative and perturbative transverse momenta

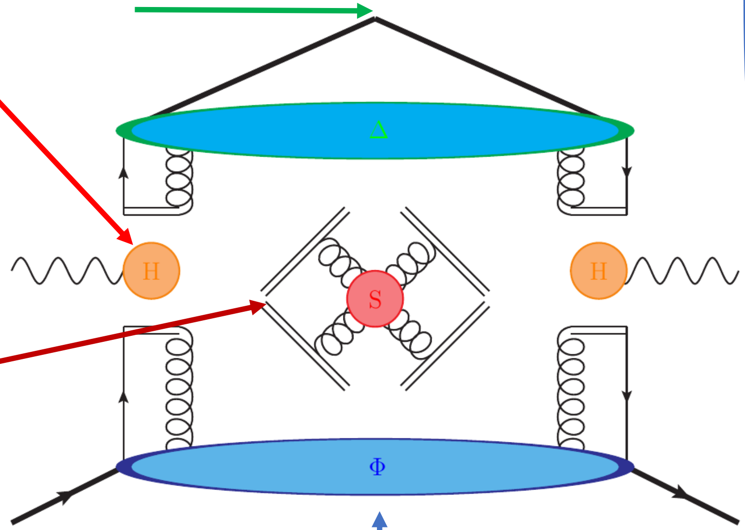
Perturbative and non-perturbative contributions decouple using ***factorization theorems***



TMD FF

Hard

Soft



TMD PDF

Fit

$S^D_{\mathrm{NP}}(z, b, Q_0, Q)$

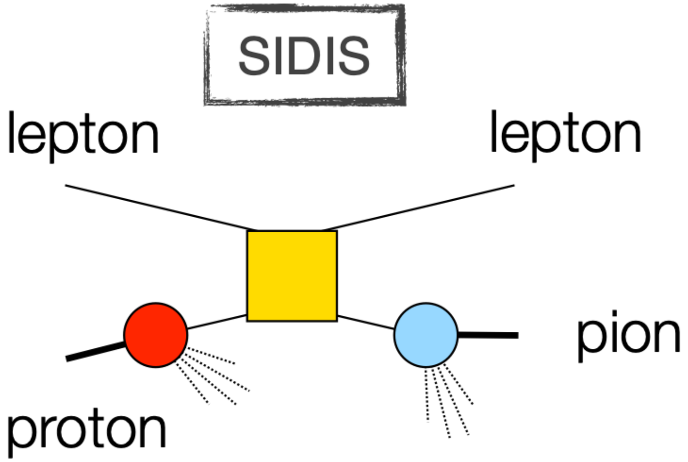
$$S_{\mathrm{pert}}(\mu_i, \mu_f, \zeta_i, \zeta_f) = \int_{\mu_i}^{\mu_f} \frac{d\mu'}{\mu'}\left[\gamma^V + \Gamma_{\mathrm{cusp}} \ln\left(\frac{\zeta_f}{\mu'^2}\right)\right] + D(b;\mu_i)\ln\left(\frac{\zeta_f}{\zeta_i}\right)$$

$S^f_{\mathrm{NP}}(x, b, Q_0, Q)$

Calculate

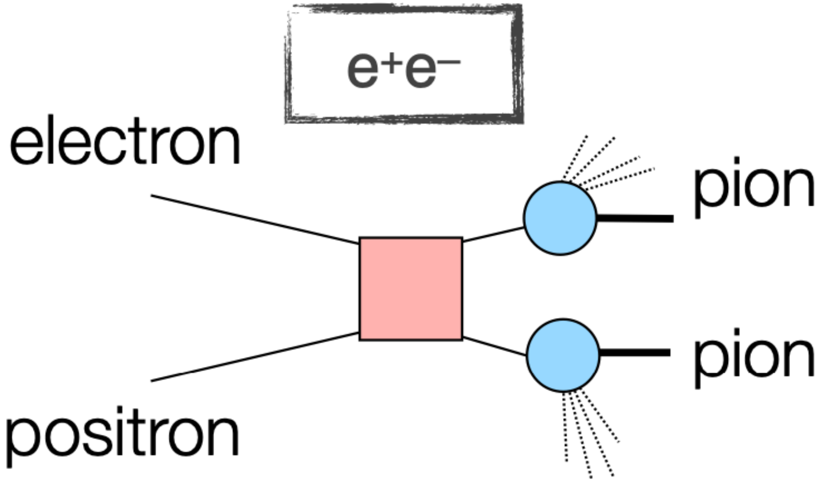
Standard processes

TMD PDFs and *TMD FFs*



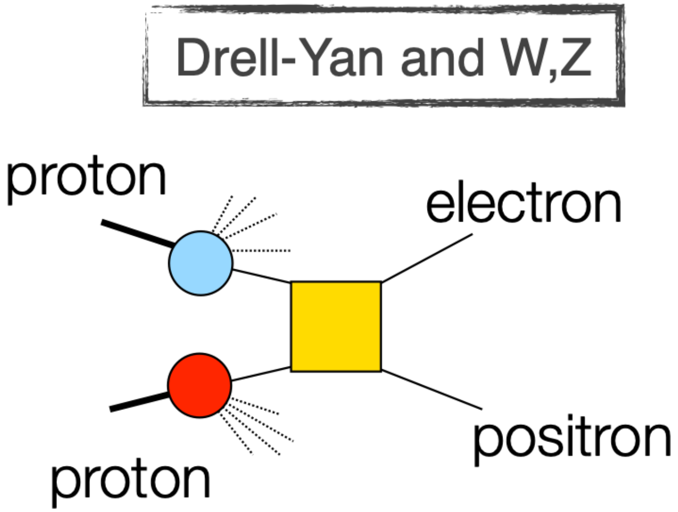
Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

TMD FFs



Collins asymmetries
BELLE, BaBar, BESIII data

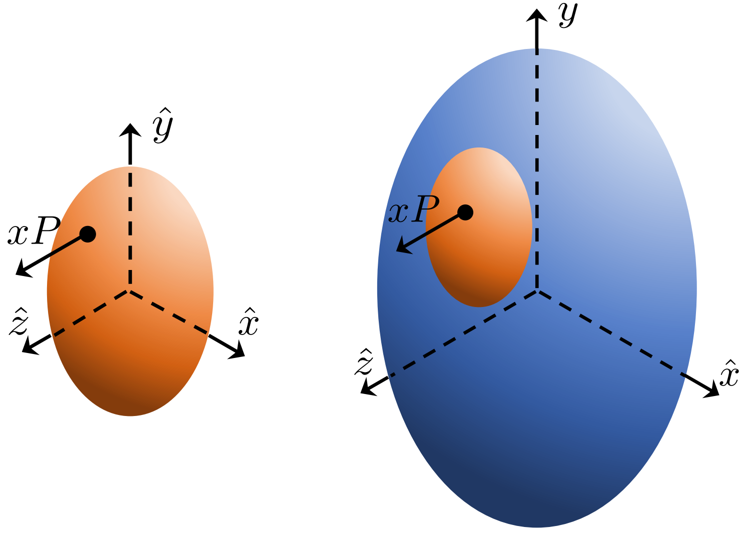
TMD PDFs

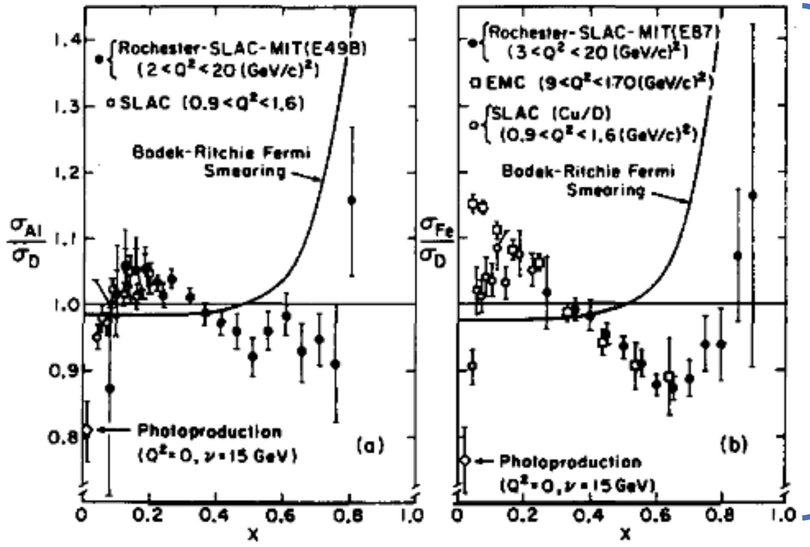


Sivers asymmetries
COMPASS, STAR data

Nuclear modifications to collinear PDFs

EMC effect was discovered 40 years ago





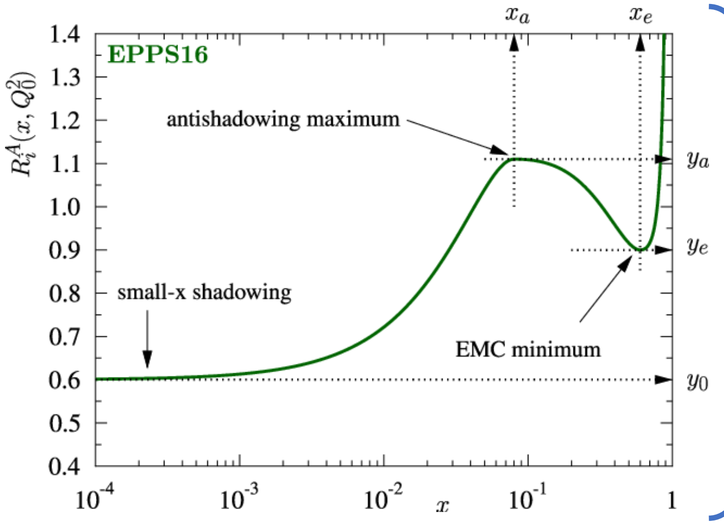
Aubert; et al. (1983) Phys. Lett. B. 123B (3–4)

Data diverged from Fermi-motion picture. Reason for EMC effect still not well understood.

LP TMD factorization cannot address how multiple partons are correlated with one another

$$R_i^A(x,Q) = \frac{f_{i/p}^A(x;Q)}{f_{i/p}(x;Q)}$$

$$R_i^A(x,Q_0^2) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1, \end{cases}$$

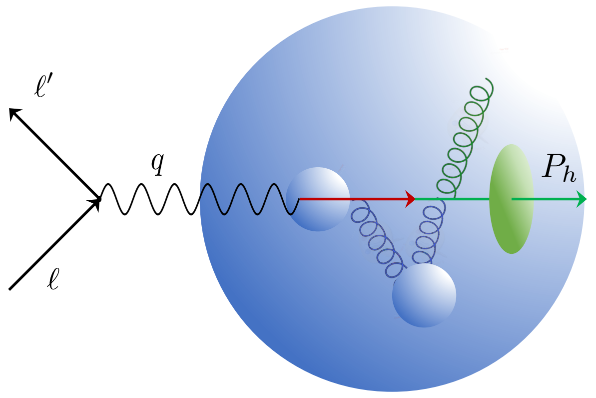


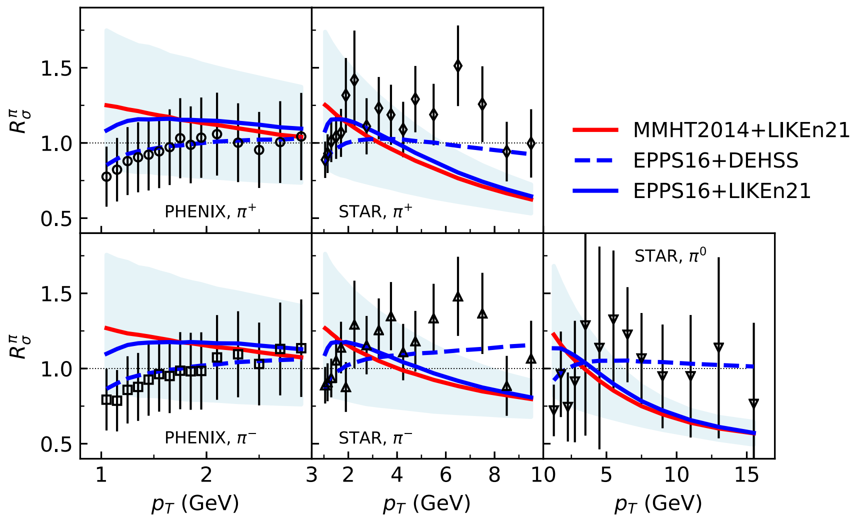
Eskola, Kolhinen, Ruuskanen, Nucl. Phys. B 535 (1998) 351

Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C 77, 163 (2017)

Nuclear modifications are absorbed into the non-perturbative parameterization.

Ejected quark undergoes multiple scattering in the nuclear medium, modifies the fragmentation functions





D. de Florian, R.S. . Phys.Rev.D69 074028 (2004)

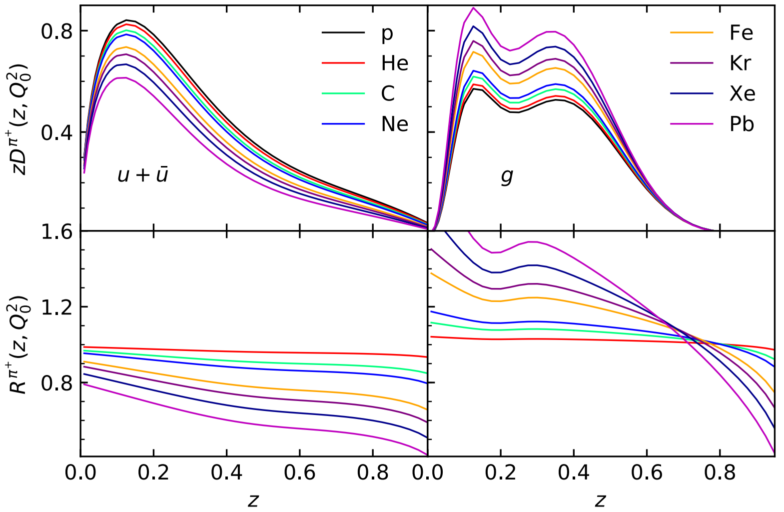
Zurita (2021)

Simultaneous extraction from hadroproduction in p-A collisions from PHENIX and STAR, and Semi-Inclusive DIS (collinear) from HERMES

$$D_i^h(z, Q_0) = \tilde{N}_i z^{\alpha_i}(1-z)^{\beta_i}\left[1+\gamma_i(1-z)^{\delta_i}\right]$$

$$\tilde{N}_i \rightarrow \tilde{N}_i\left[1+N_{i,1}(1-A^{N_{i,2}})\right]$$

$$c_i \rightarrow c_i + c_{i,1}(1-A^{c_{i,2}})$$



Abelev et al. (STAR), Phys. Rev. C 81, 064904 (2010)

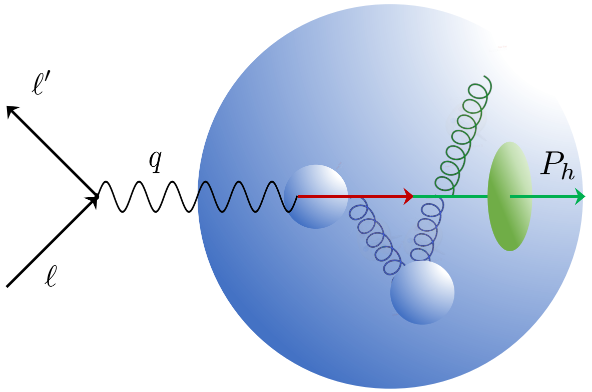
Adams et al. (STAR), Phys. Lett. B 637, 161 (2006)

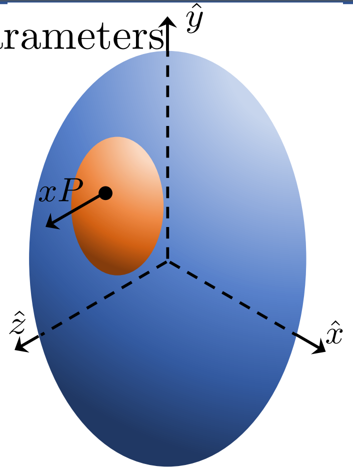
Adare et al. (PHENIX), Phys. Rev. C 88, 024906 (2013)

Airapetian et al. (HERMES), Nucl. Phys. B 780, 1 (2007)

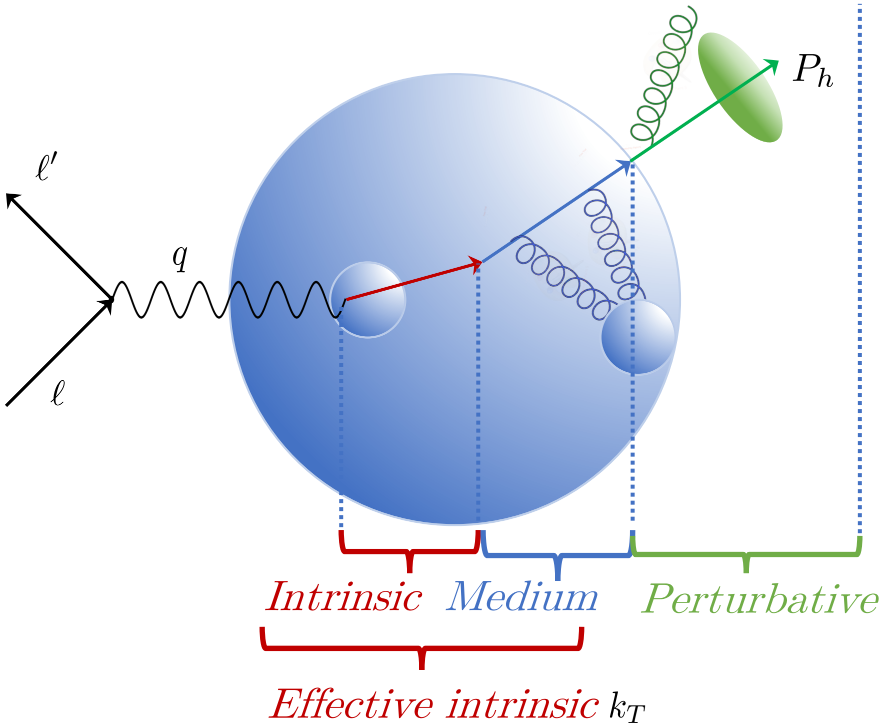
Collinear distributions to TMDs

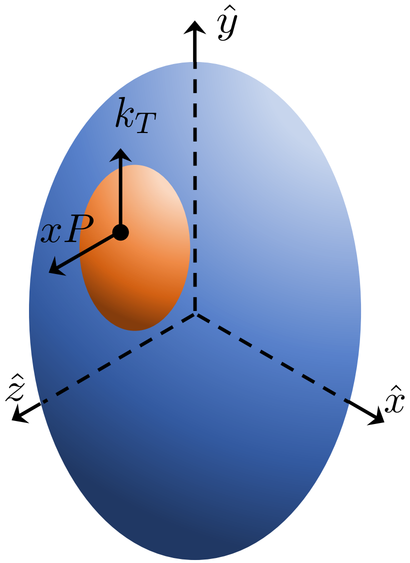
Previous work with collinear distributions absorbed medium effects into parameters





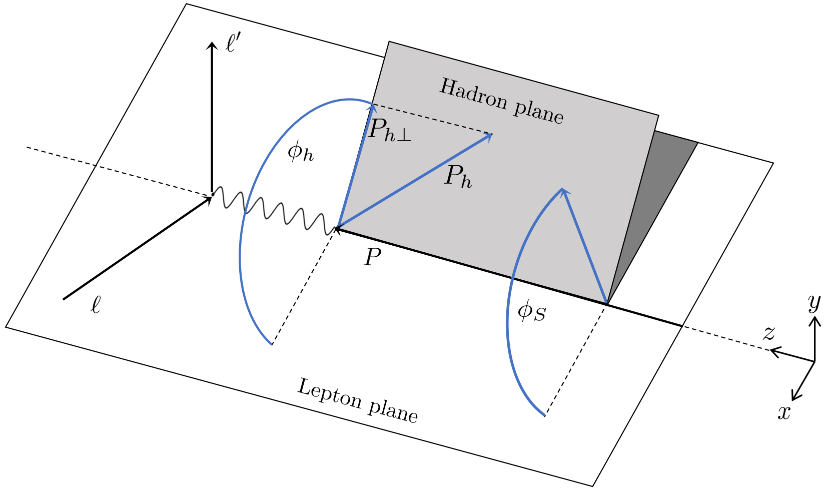
We absorb all medium effects in the intrinsic (NP) parameterization





Available data

Semi-Inclusive DIS for e-A collisions



Multiplicity ratio

$$R_A^h = \frac{d\sigma_A^h/\mathcal{PS}\, d^2P_{h\perp}}{d\sigma_A/\mathcal{PS}} \frac{d\sigma_D/\mathcal{PS}}{d\sigma_D^h/\mathcal{PS}\, d^2P_{h\perp}}$$

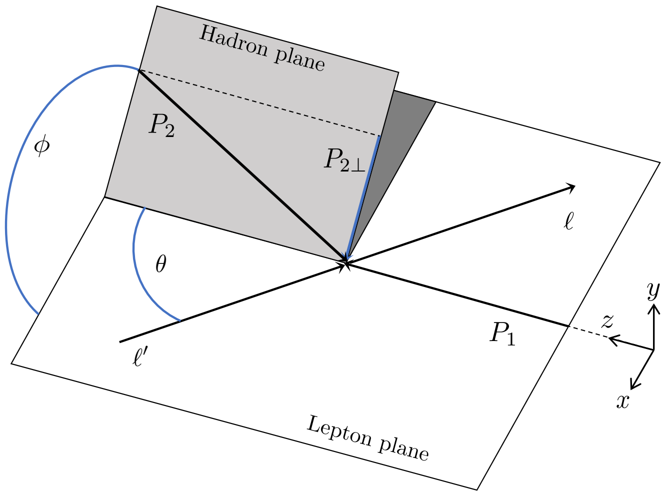
SIDIS cross section $\frac{d\sigma_A^h}{\mathcal{PS}\, d^2P_{h\perp}}$

DIS cross section $\frac{d\sigma_A}{\mathcal{PS}}$

HERMES ratio for A = He, Ne, Kr, Xe
h $= \pi^+, \pi^-, \pi^0, K^+, K^-, K^0$

Jefferson Lab ratio for A = C, Fe, Pb
h $= \pi^+, \pi^-$

Drell-Yan production in p-A collusions



Cross section and cross section ratio for p-A collisions

$$R_{\text{AB}} = \frac{d\sigma_A}{d\mathcal{PS}\, d^2q_\perp} \frac{d\mathcal{PS}\, d^2q_\perp}{d\sigma_B}$$

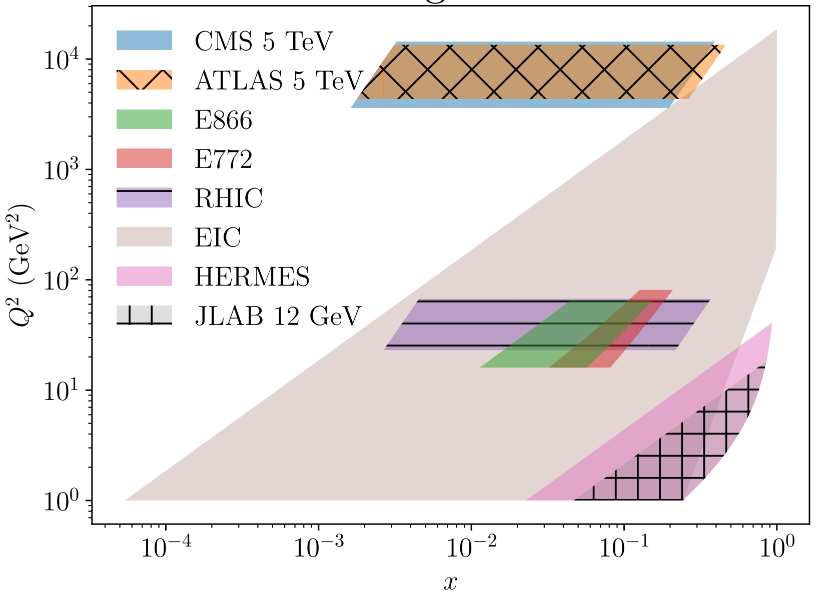
E772: A = C; B = D

E866: A = Fe, W; B = Be

RHIC: A = Au; B = p

ATLAS, CMS: $q_\perp$ distribution p-Pb

Kinematic coverage of the data



Airapetian et al. (HERMES), Nucl. Phys. B 780, 1 (2007)

Dudek et al., Eur. Phys. J. A 48, 187 (2012)

Burkert, in CLAS 12 RICH Detector Workshop (2008)

Alde et al., Phys. Rev. Lett. 64, 2479 (1990)

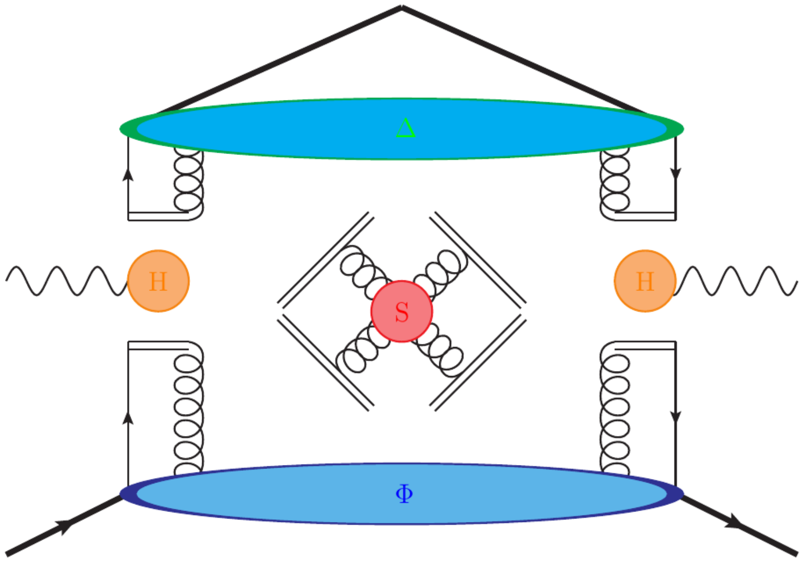
Vasilev et al. (NuSea), Phys. Rev. Lett. 83, 2304 (1999)

Leung (PHENIX), PoS HardProbes2018, 160 (2018)

Khachatryan et al. (CMS), Phys. Lett. B 759, 36 (2016)

Aad et al. (ATLAS), Phys. Rev. C 92, 044915 (2015)

Differential cross section for Semi-Inclusive DIS is given by



$$\frac{d\sigma}{d\mathcal{PS}\, d^2P_{h\perp}} = \sigma_0 H(Q;\mu) \sum_q e_q^2 \int \frac{bdb}{2\pi} J_0\left(\frac{bP_{h\perp}}{z}\right) f_{q/N}^A(x,b;\mu,\zeta_1)\, D_{h/q}^A(z,b;\mu,\zeta_2)$$

Hard *TMD PDF* *TMD FF*

TMDs can be matched onto the collinear distributions

$$f_{q/N}^A(b,x;\mu,\zeta_1) = [C \otimes f](x;\mu_i) \exp\left[-S_{\text{pert}}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\text{NP}}^{f\,A}(b;Q_0,\mu,\zeta_i,\zeta)\right]$$

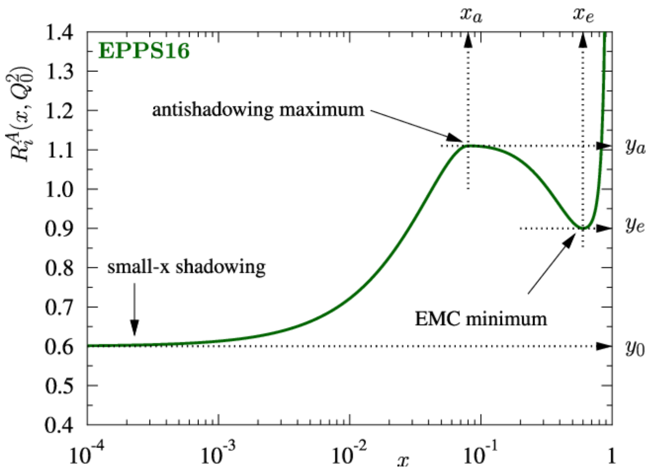
$$D_{h/q}^A(b,z;\mu,\zeta_1) = [\hat{C} \otimes D](z;\mu_i) \exp\left[-S_{\text{pert}}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\text{NP}}^{D\,A}(z,b;Q_0,\mu,\zeta_i,\zeta)\right]$$

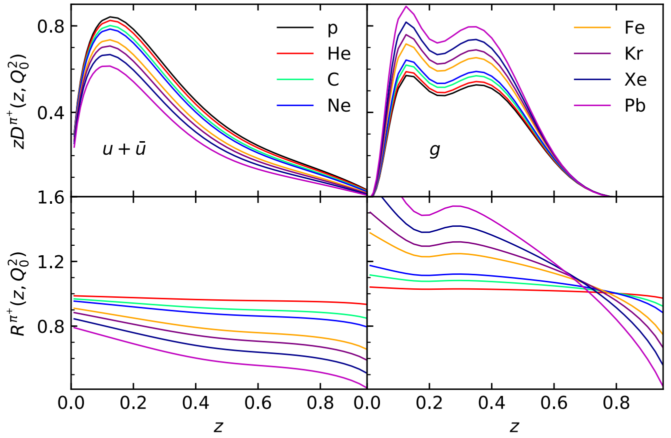
Perturbative *Non-perturbative*

Large logarithms are are resumed to all orders in the perturbative Sudakov

$$S_{\text{pert}}(b;\mu_i,\zeta_i,\mu_f,\zeta_f) = \int_{\mu_i}^{\mu_f} \frac{d\mu'}{\mu'}\left[\gamma^V + \Gamma_{\text{cusp}} \ln\left(\frac{\zeta_f}{\mu'^2}\right)\right] + D(b;\mu_i)\ln\left(\frac{\zeta_f}{\zeta_i}\right)$$

nPDFs and nFFs are known only to NLO





TMDs can be matched onto the collinear distributions

$$\frac{d\sigma}{d\mathcal{PS}\, d^2P_{h\perp}} = \sigma_0 H(Q;\mu) \sum_q e_q^2 \int \frac{bdb}{2\pi} J_0\left(\frac{bP_{h\perp}}{z}\right) f_{q/N}^A(x,b;\mu,\zeta_1)\, D_{h/q}^A(z,b;\mu,\zeta_2)$$

$$f_{q/N}^A(b,x;\mu,\zeta_1) = [C \otimes f](x;\mu_i)\, \exp\left[-S_{\text{pert}}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\text{NP}}^{f\,A}(b;Q_0,\mu,\zeta_i,\zeta)\right]$$

$$D_{h/q}^A(b,z;\mu,\zeta_1) = \left[\hat{C} \otimes D\right](z;\mu_i)\, \exp\left[-S_{\text{pert}}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\text{NP}}^{D\,A}(z,b;Q_0,\mu,\zeta_i,\zeta)\right]$$

One loop expression

$$S_{\text{pert}}(b;\mu_i,\zeta_i,\mu_f,\zeta_f) = \int_{\mu_i}^{\mu_f} \frac{d\mu'}{\mu'}\left[\gamma^V + \Gamma_{\text{cusp}} \ln\left(\frac{\zeta_f}{\mu'^2}\right)\right] + D(b;\mu_i)\ln\left(\frac{\zeta_f}{\zeta_i}\right)$$

Two loop *Three loop*

Non-perturbative contributions given by

$$f_{q/N}^{A}(b,x;\mu,\zeta_1) = [C \otimes f](x;\mu_i)\,\exp\left[-S_{\text{pert}}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\text{NP}}^{f\,A}(b;Q_0,\mu,\zeta_i,\zeta)\right]$$
$$D_{h/q}^{A}(b,z;\mu,\zeta_1) = \left[\hat{C} \otimes D\right](z;\mu_i)\,\exp\left[-S_{\text{pert}}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\text{NP}}^{D\,A}(z,b;Q_0,\mu,\zeta_i,\zeta)\right]$$

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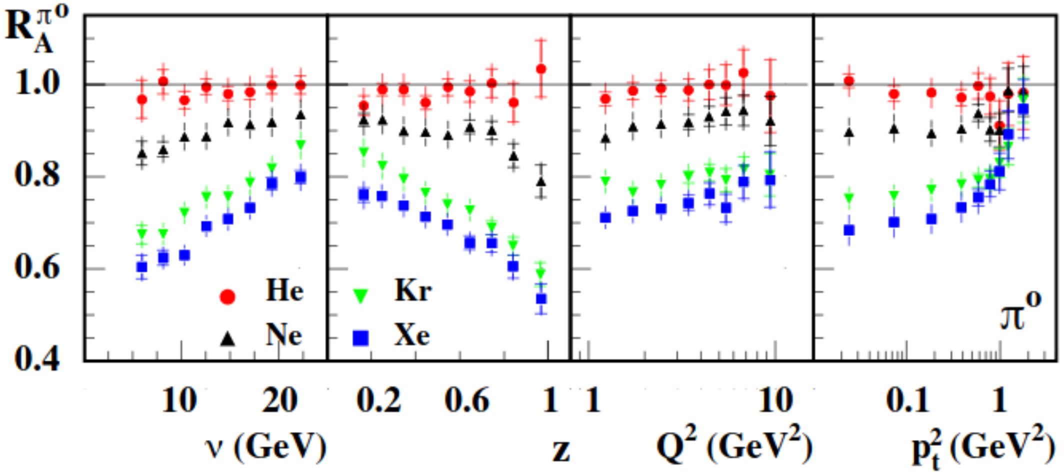
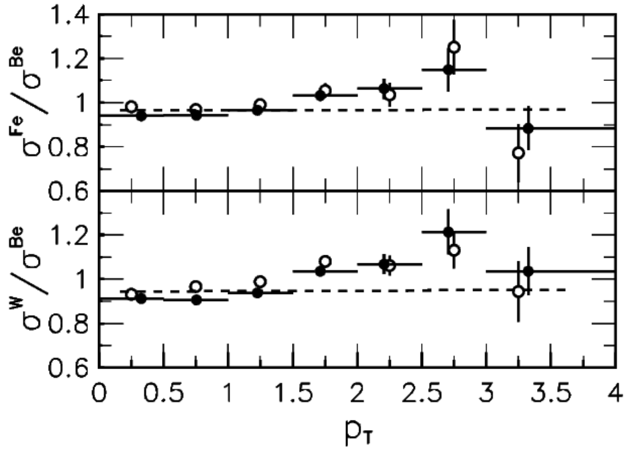
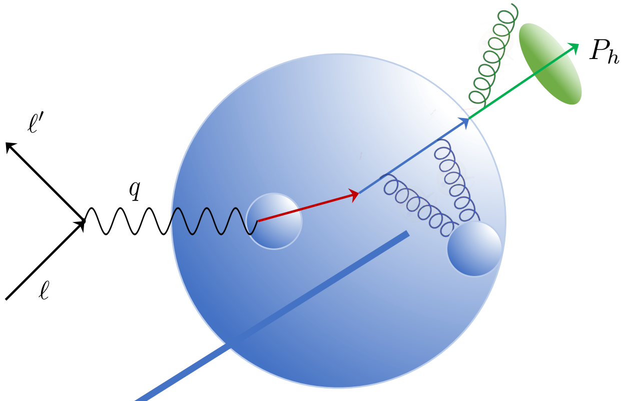
Non-perturbative Sudakov given by



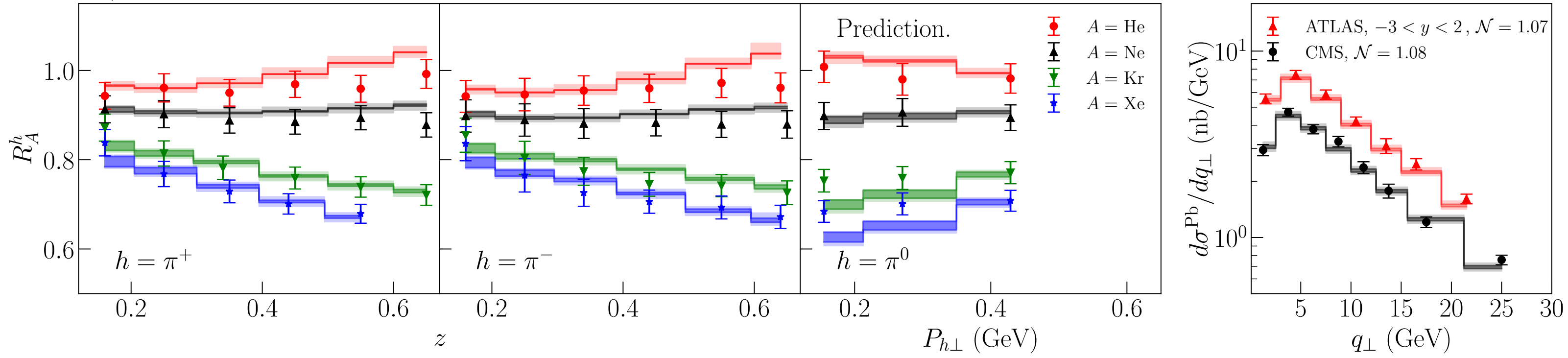


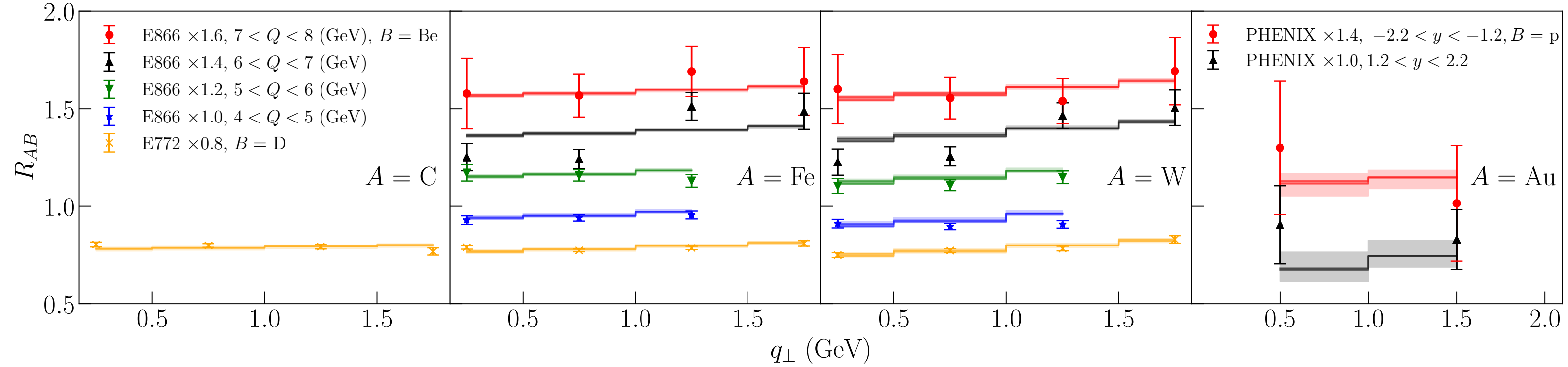


$$S_{\text{NP}}^{f\,A}(b;Q_0,\mu,\zeta_i,\zeta) = S_{\text{NP}}^{f}(b;Q_0,\mu,\zeta_i,\zeta) + a_N\,b^2$$
$$S_{\text{NP}}^{D\,A}(z,b;Q_0,\mu,\zeta_i,\zeta) = S_{\text{NP}}^{D}(z,b;Q_0,\mu,\zeta_i,\zeta) + b_N\,b^2/z^2$$

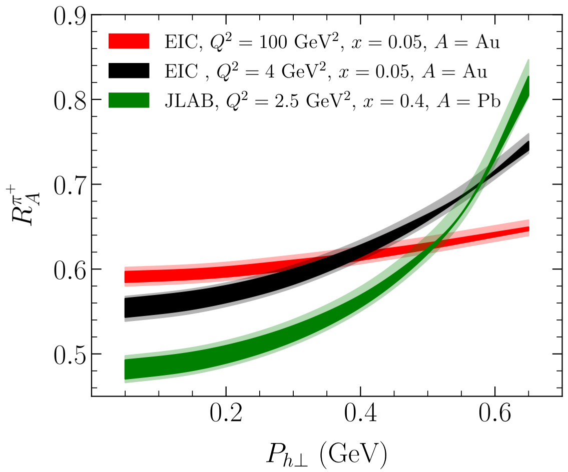
Description of the data and predictions

We achieve a χ^2/dof of 1.196 with parameter values $a_N = 0.016 \pm 0.003$ $b_N = 0.0097 \pm 0.0007$

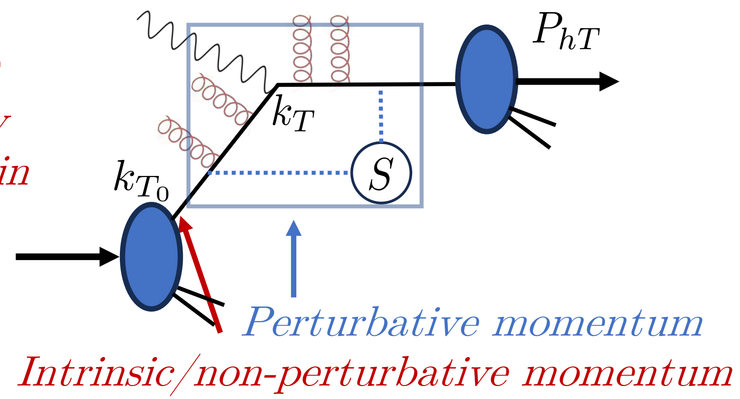




Prediction



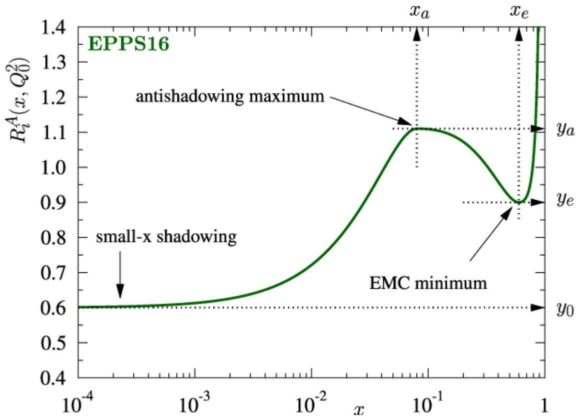
Broadening washed out by perturbative momentum in ratio.



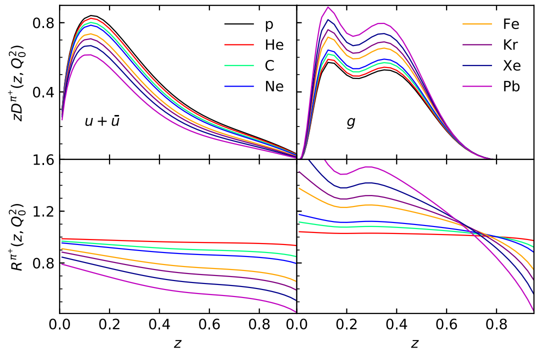
Three-dimensional images

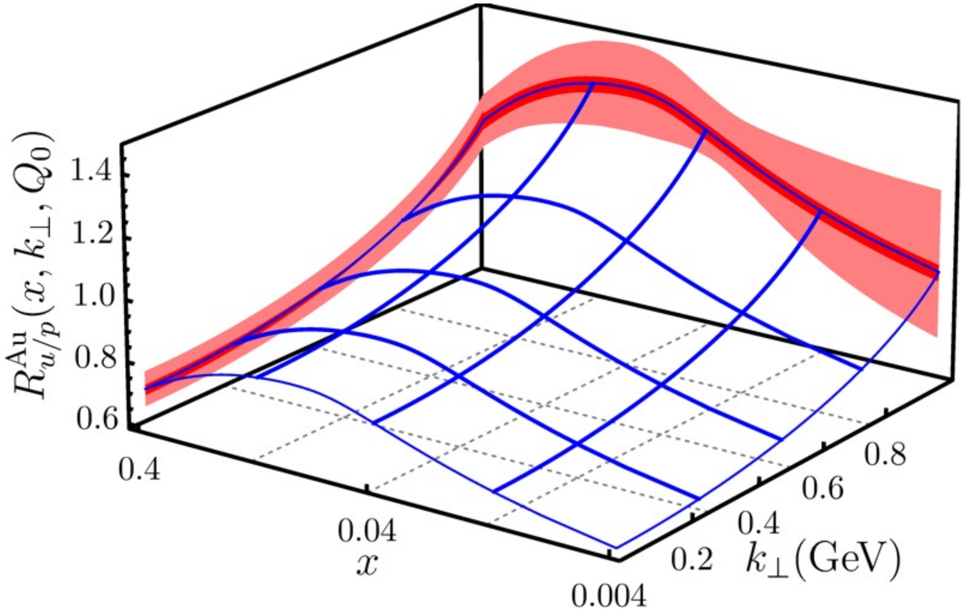
Ratios defined for nPDF and nFF

$$R_i^A\left(x, Q_0^2\right) = \frac{f_{i/p}^A\left(x, Q_0^2\right)}{f_{i/p}\left(x, Q_0^2\right)}$$

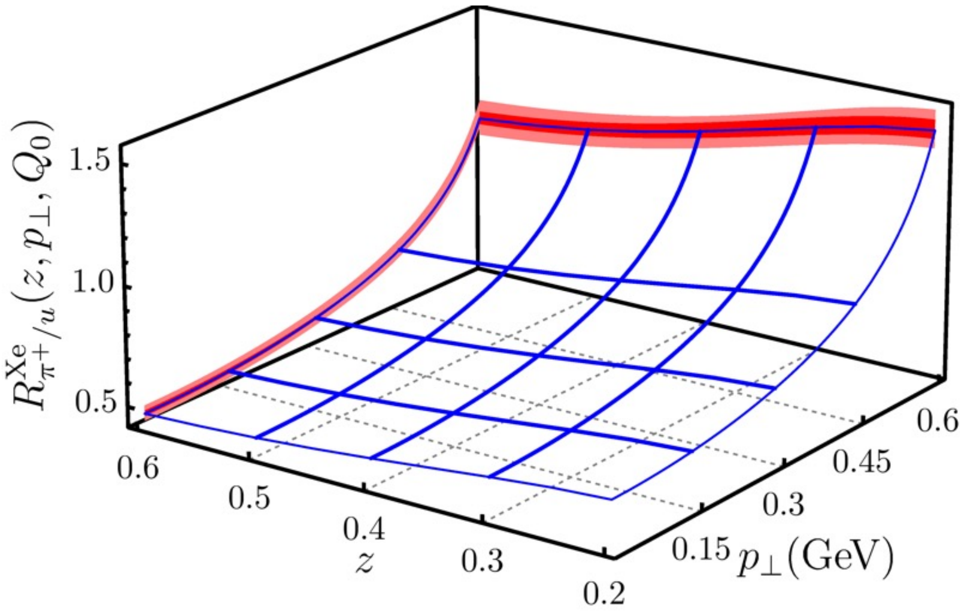


$$R_i^A\left(z, Q_0^2\right) = \frac{D_{h/i}^A\left(z, Q_0^2\right)}{D_{h/i}\left(z, Q_0^2\right)}$$





$$R_{u/p}^{\mathrm{Au}}(x, k_\perp, Q) = \frac{f_{u/p}^{\mathrm{Au}}(x, k_\perp, Q)}{f_{u/p}(x, k_\perp, Q)}$$

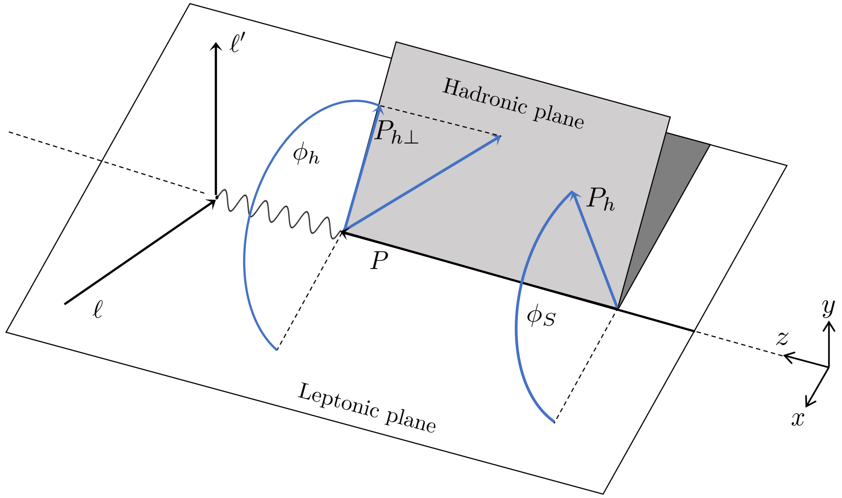


$$R_{\pi^+/u}^{\mathrm{Xe}}(x, k_\perp, Q) = \frac{f_{\pi^+/u}^{\mathrm{Xe}}(x, k_\perp, Q)}{f_{\pi^+/u}(x, k_\perp, Q)}$$

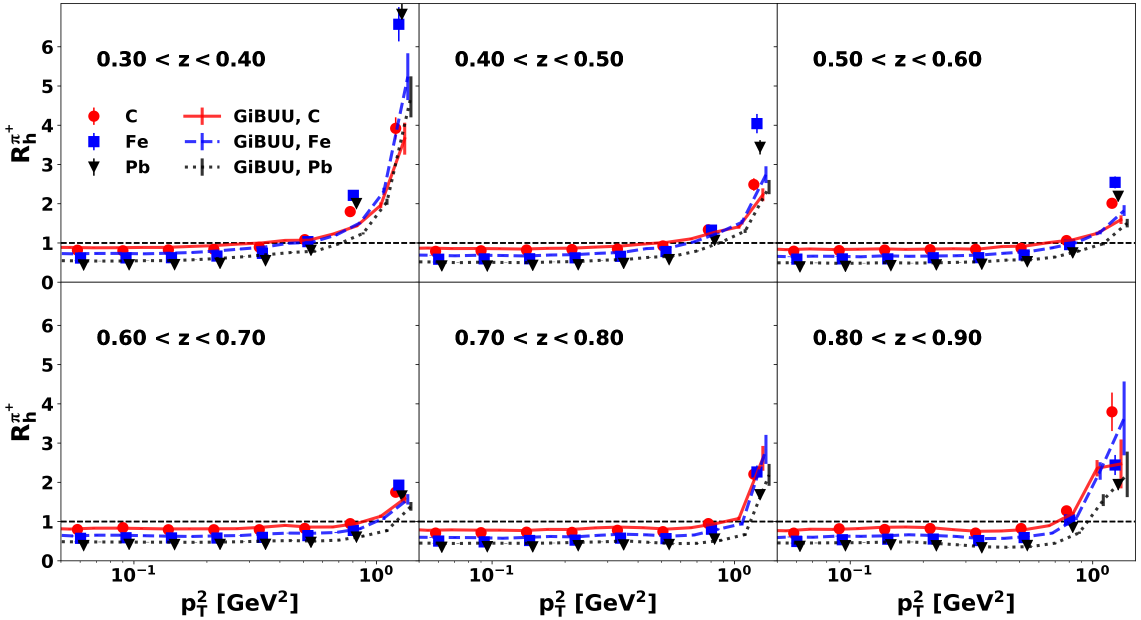
CLAS measurements

Semi-Inclusive DIS

Morán *et al.* (CLAS Collaboration) Phys. Rev. C **105**, 015201

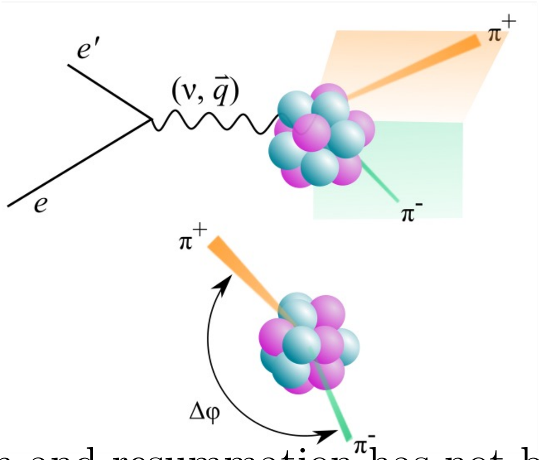


Hadron-multiplicity data can be incorporated into the fit

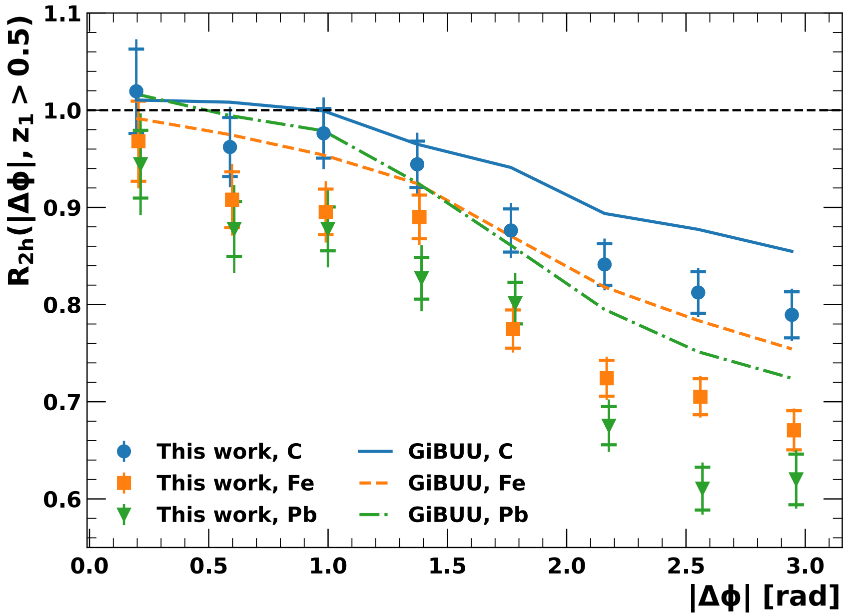


Measurements have been performed for angular decorrelation

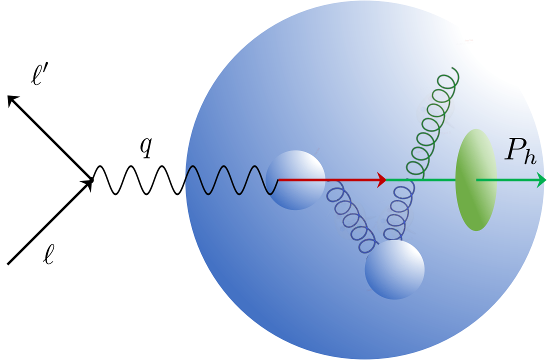
Paul *et al.* (CLAS Collaboration) Phys. Rev. Lett. **129**, 182501



Factorization and resummation has not been established

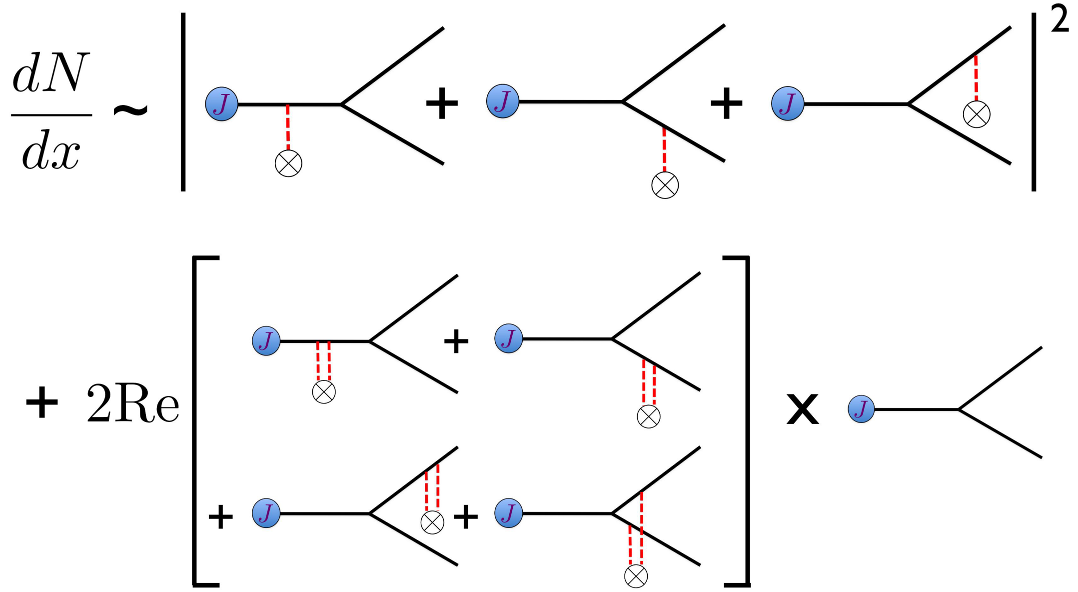


Previous work has been done in QCD and SCET to derive medium modified evolution equations



$$\frac{\partial \tilde{D}_{h/j}(z;\mu)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu)}{2\pi} \sum_i \left[\tilde{P}_{ij} \otimes \tilde{D}_{h/i}\right](z;\mu)$$

$$\tilde{P}_{ij}(z;\mu) = \tilde{P}_{ij}(z) + \Delta\tilde{P}_{ij}(z;\mu)$$



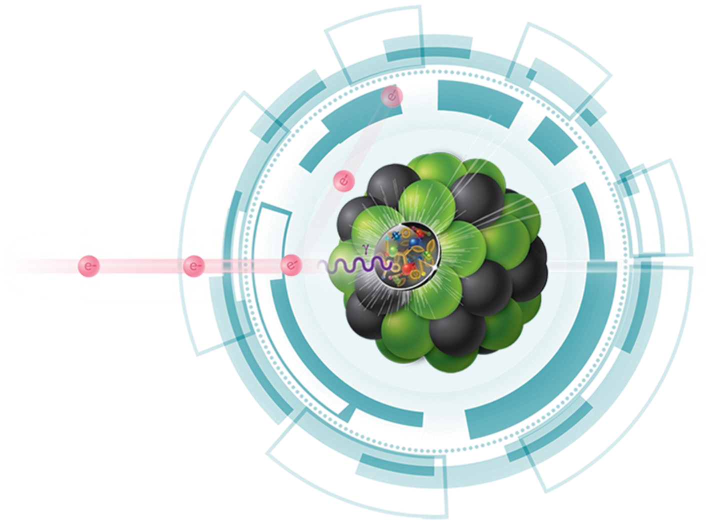
Medium modification can be implemented into the fit, but introduces additional scales. Future work in this community will involve including the medium modified DGLAP into the fit, as well as calculating the medium modifications to the RG and Collins-evolution of the TMDs.

$$f^A_{q/N}(b,x;\mu,\zeta_1) = [C \otimes f](x;\mu_i)\, \exp\left[-S_{\rm pert}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S^{f\,A}_{\rm NP}(b;Q_0,\mu,\zeta_i,\zeta)\right]$$

Matching and evolution are all up for grabs in the future!

Conclusion

- We develop a formalism for approximating broadening effects in Drell-Yan and Semi-Inclusive DIS.
- We find that we can absorb medium modifications into the intrinsic widths of the TMDs to define nTMDs.
- We perform the first extraction of both the nTMD PDF and nTMD FF from the world data of Semi-Inclusive DIS and Drell-Yan.
- Future work will involve investigating the medium modified evolution effects and extracting purely non-perturbative quantities, will also investigate the Jefferson Lab data.



Thank you!