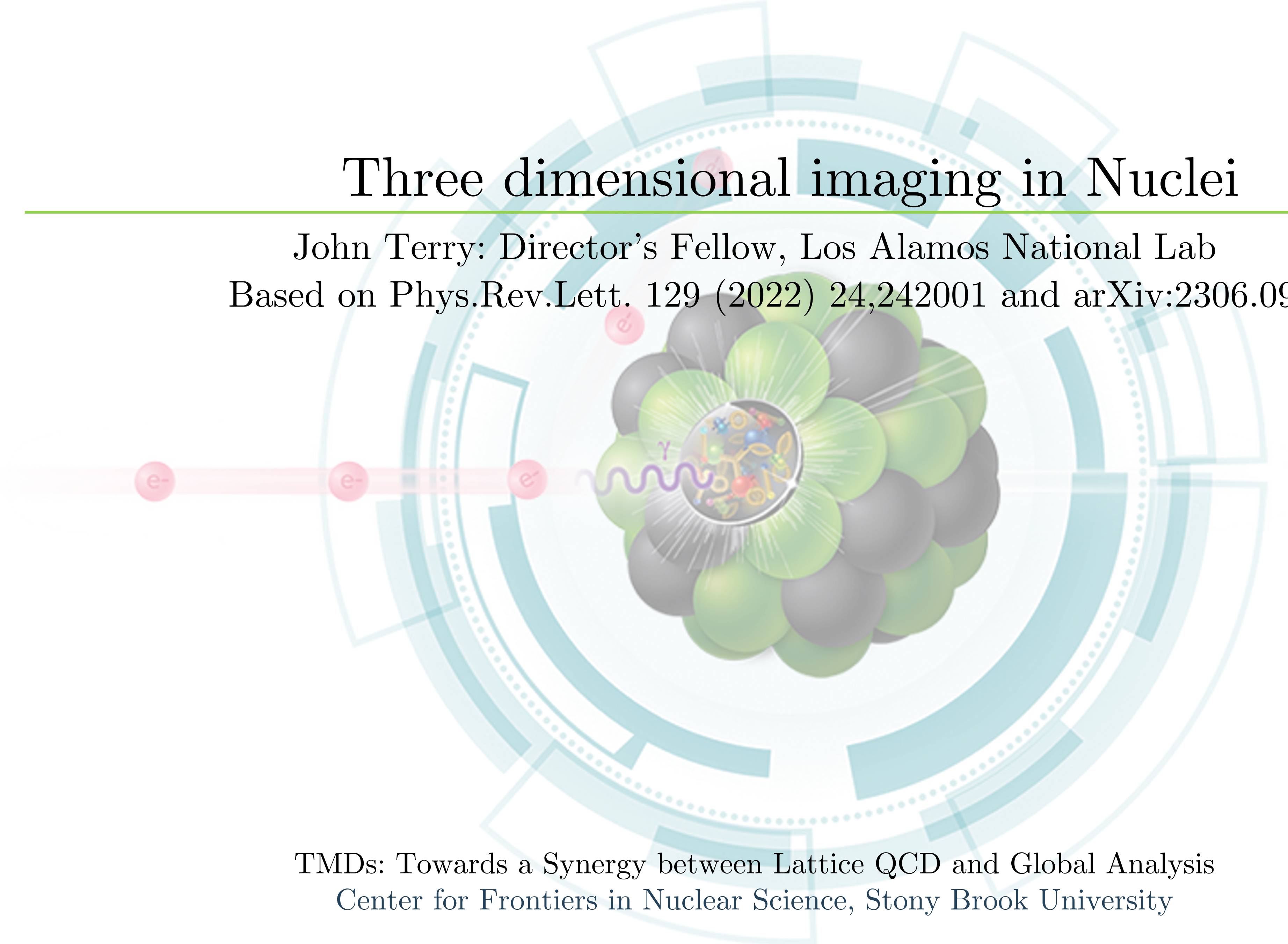
Three dimensional imaging in Nuclei

John Terry: Director's Fellow, Los Alamos National Lab

Based on Phys.Rev.Lett. 129 (2022) 24,242001 and arXiv:2306.09317

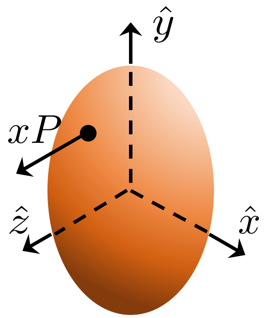


TMDs: Towards a Synergy between Lattice QCD and Global Analysis

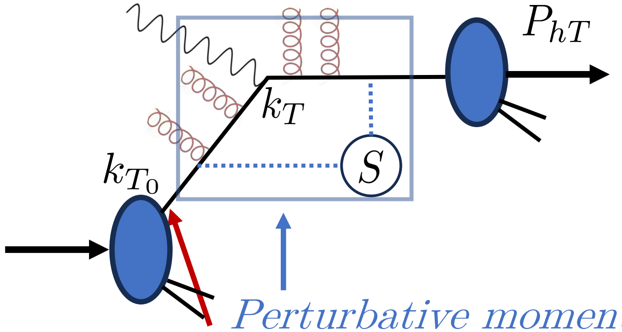
Center for Frontiers in Nuclear Science, Stony Brook University

Factorization Theorems

TMDs are non-perturbative



Inject large current

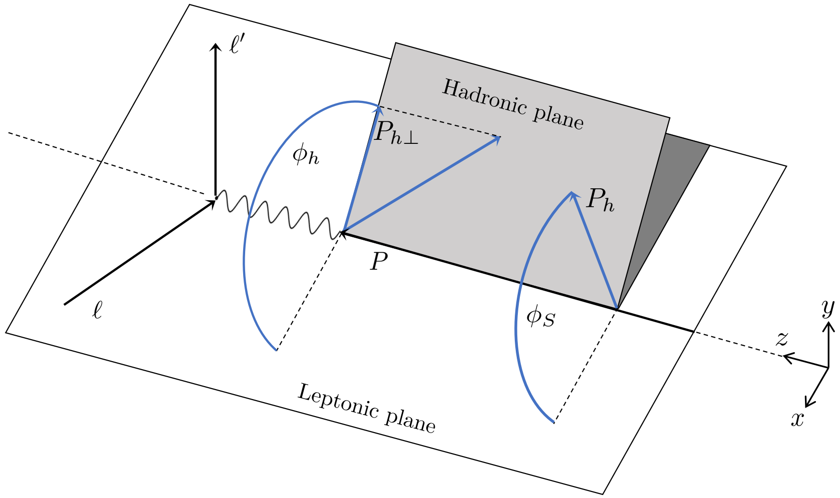


Perturbative momentum

Intrinsic/non-perturbative momentum

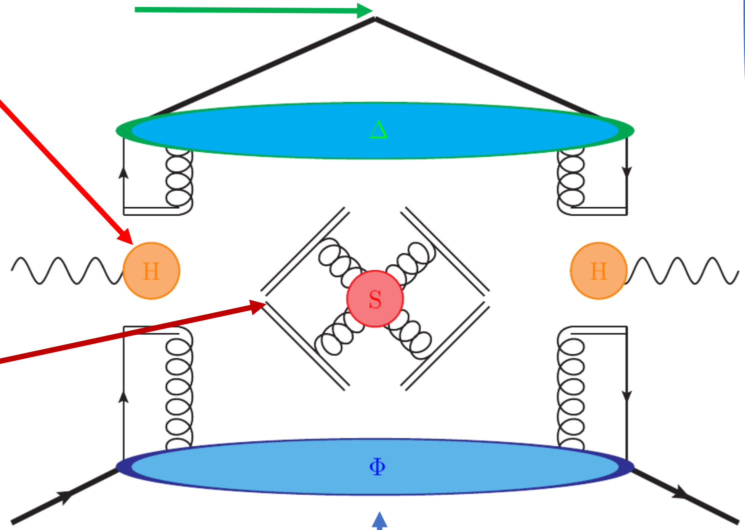
Cross section involves convolution of non-perturbative and perturbative transverse momenta

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



TMD FF

Hard



Soft

TMD PDF

Fit

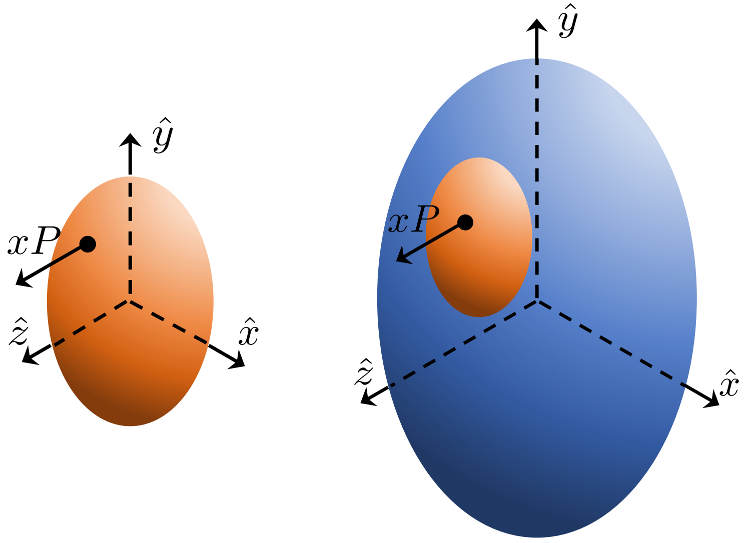
$$S^{D}_{\text{NP}}\left(z, b, Q_0, Q\right)$$

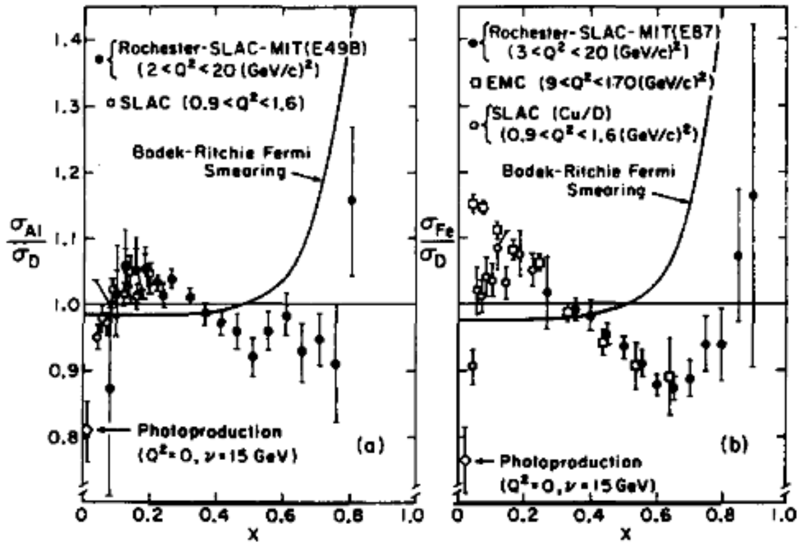
$$S_{\text{pert}}\left(\mu_i, \mu_f, \zeta_i, \zeta_f\right) = \int_{\mu_i}^{\mu_f} \frac{d\mu'}{\mu'}\left[\gamma^V + \Gamma_{\text{cusp}} \ln\left(\frac{\zeta_f}{\mu'^2}\right)\right] + D(b; \mu_i) \ln\left(\frac{\zeta_f}{\zeta_i}\right)$$

$$S^{f}_{\text{NP}}\left(x, b, Q_0, Q\right)$$

Calculate

EMC effect was discovered 40 years ago





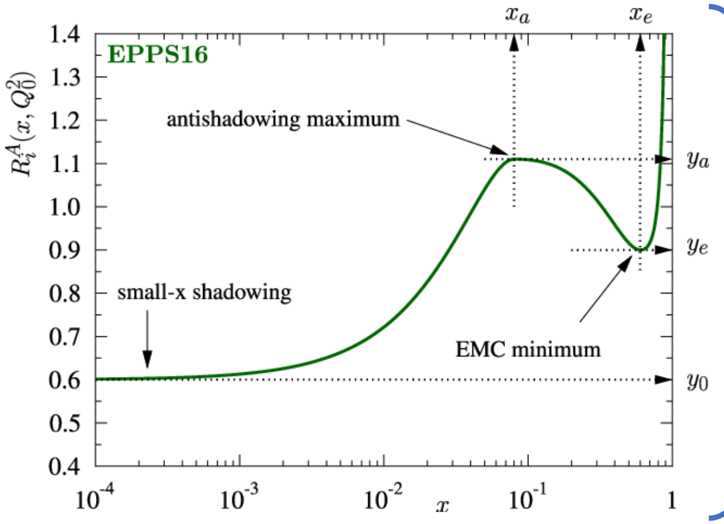
Aubert; et al. (1983) Phys. Lett. B. 123B (3–4)

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

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

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



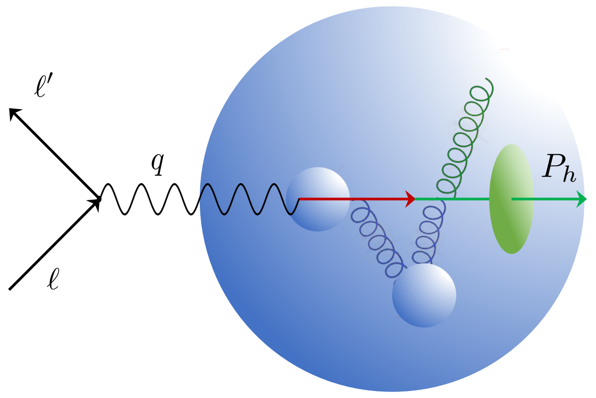
Eskola, Kolhinen, Ruuskanen, Nucl. Phys. B 535 (1998) 351

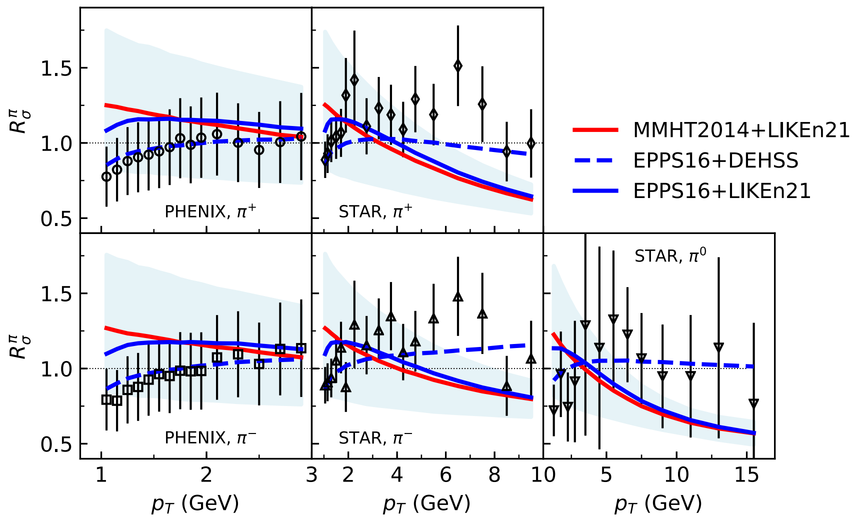
Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C 77, 163 (2017)

Nuclear modifications are absorbed into the non-perturbative parameterization.

Nuclear modifications to collinear FFs

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





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

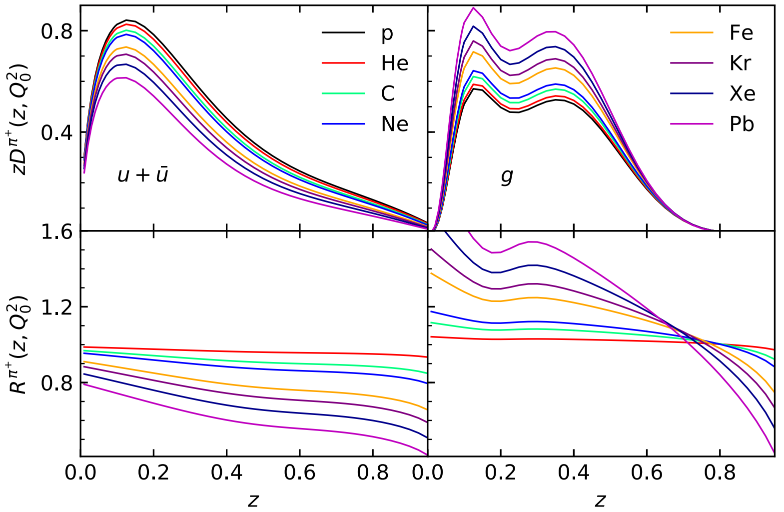
Zurita (2021)

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)

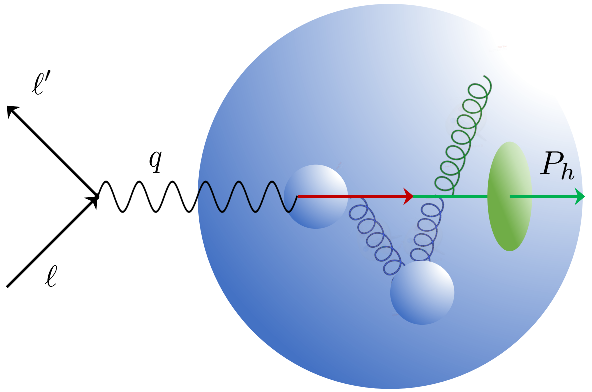
Adams et al. (STAR), Phys. Lett. B 637, 161 (2006)

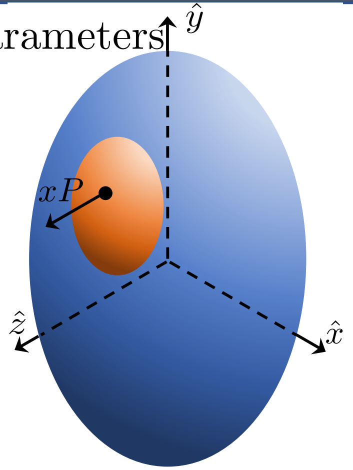
Adare et al. (PHENIX), Phys. Rev. C 88, 024906 (2013)

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

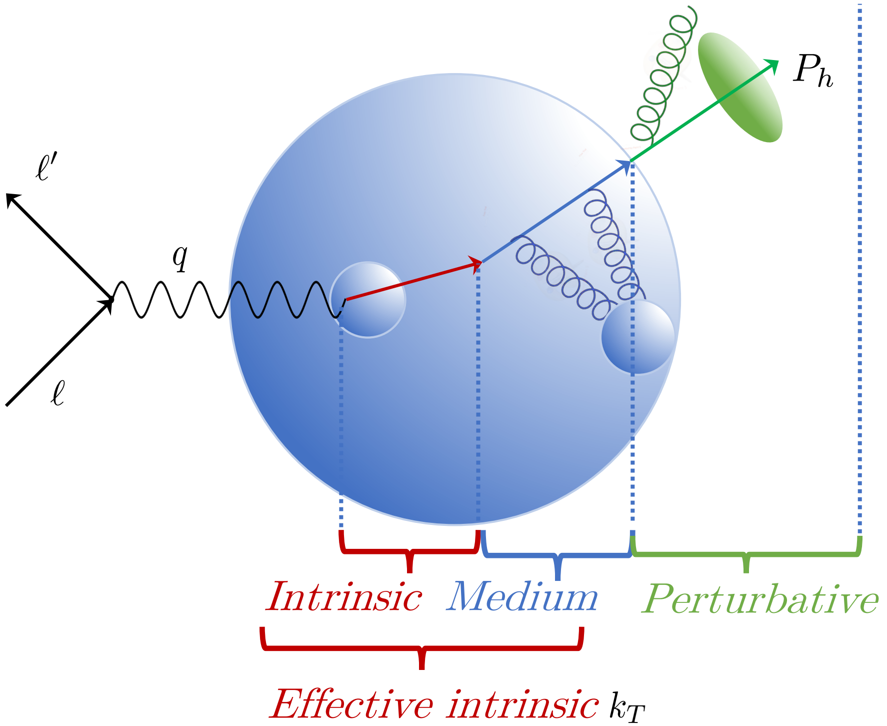
Collinear distributions to TMDs

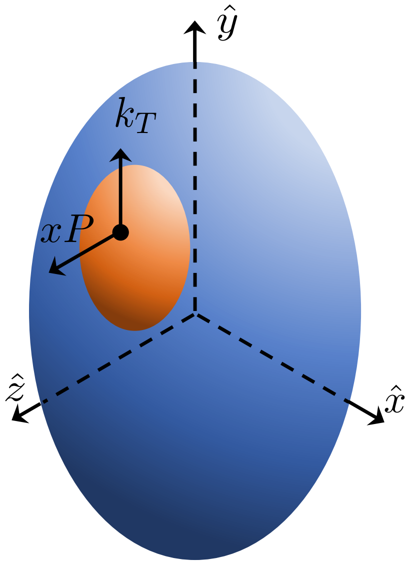
Previous work with collinear distributions absorbed medium effects into parameters





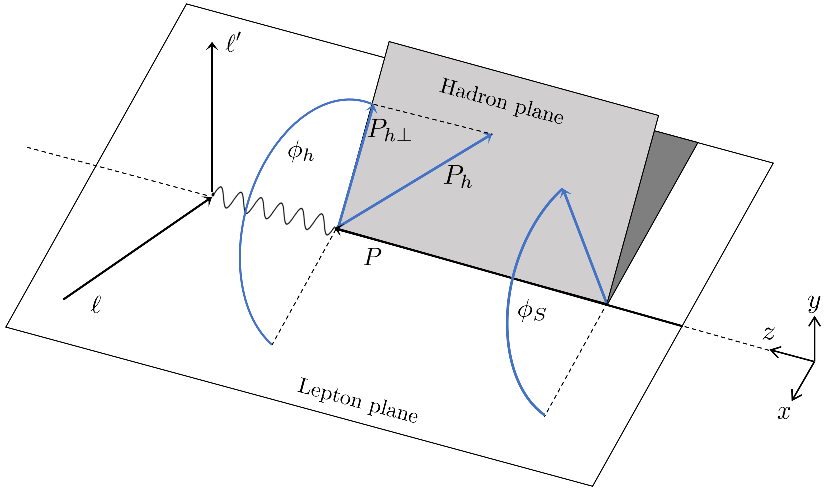
We absorb all medium effects in the intrinsic (NP) parameterization





Available data

Semi-Inclusive DIS for e-A collisions



Multiplicity ratio

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

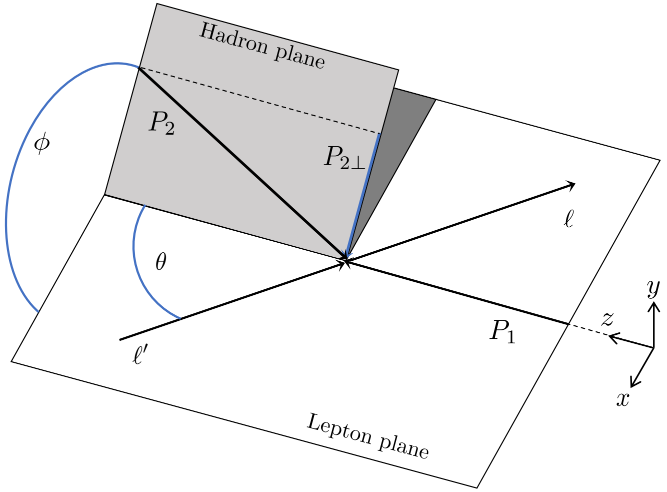
SIDIS cross section $\dfrac{d\sigma_A^h}{\mathcal{PS}\, d^2P_{h\perp}}$

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

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 = π^+, π^-

Drell-Yan production in p-A collusions



Cross section and cross section ratio for p-A collisions

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

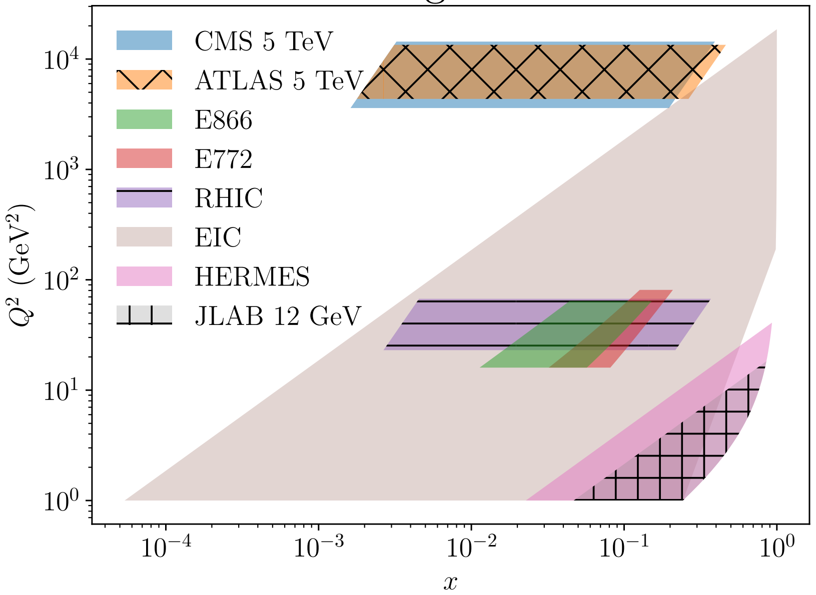
E772: A = C; B = D

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)

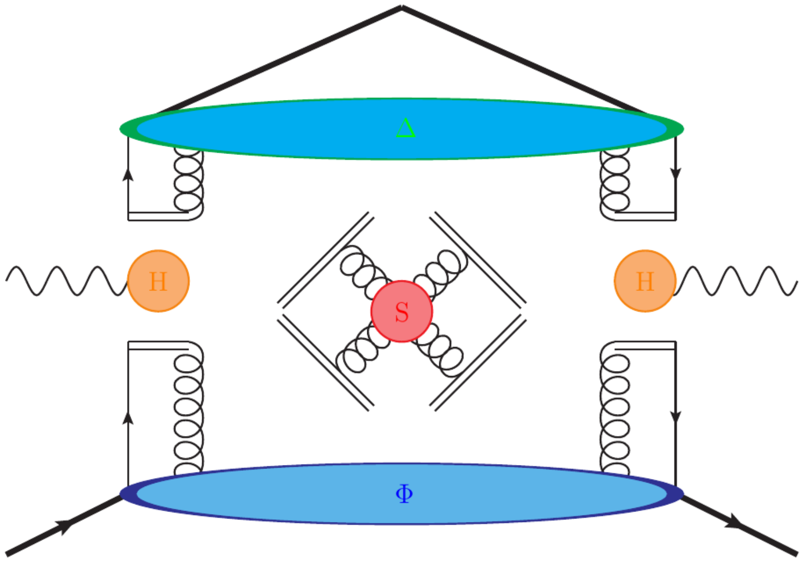
Khachatryan et al. (CMS), Phys. Lett. B 759, 36 (2016)

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

Factorization and resummation

Differential cross section for Semi-Inclusive DIS is given by

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



TMDs can be matched onto the collinear distributions

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

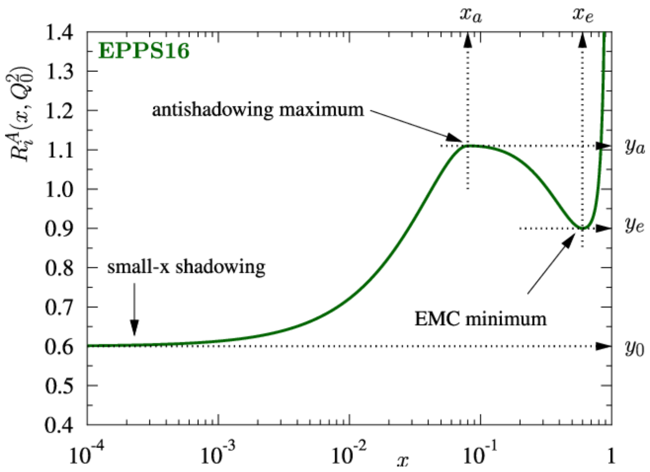
$$D_{h/q}^A(b,z;\mu,\zeta_1) = [\hat{C} \otimes D](z;\mu_i) \exp\left[-S_{\rm pert}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\rm NP}^{D\,A}(z,b;Q_0,\mu,\zeta_i,\zeta)\right]$$

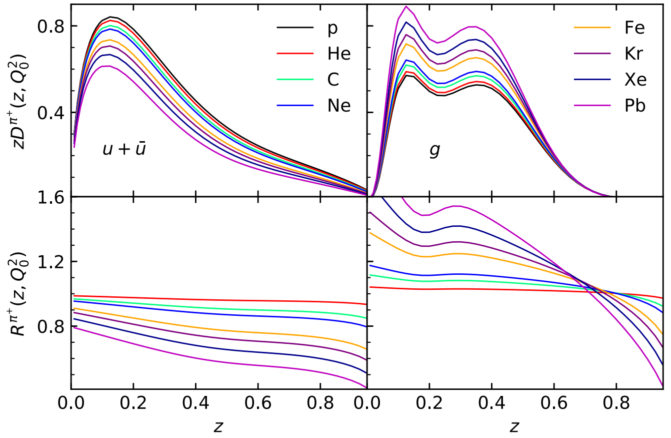
Perturbative *Non-perturbative*

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

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

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 treatment

Non-perturbative contributions given by

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

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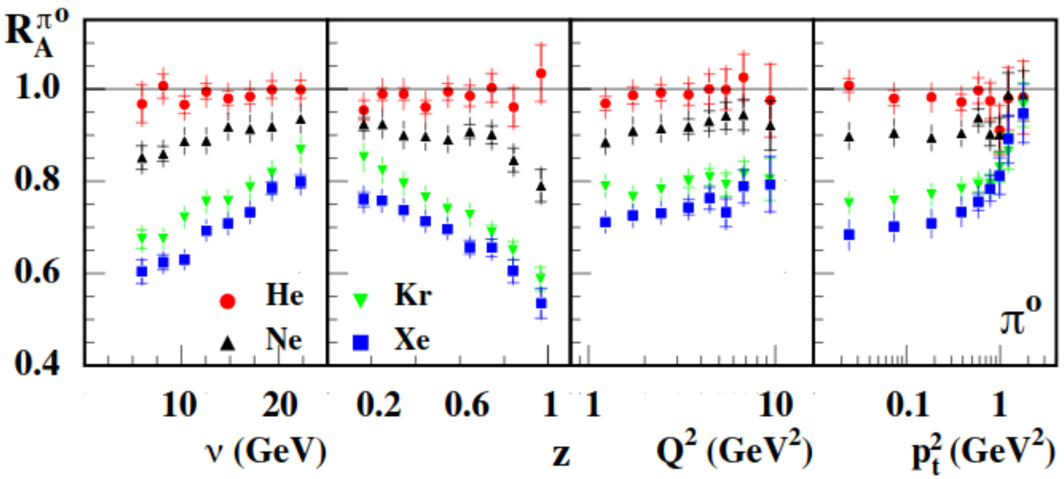
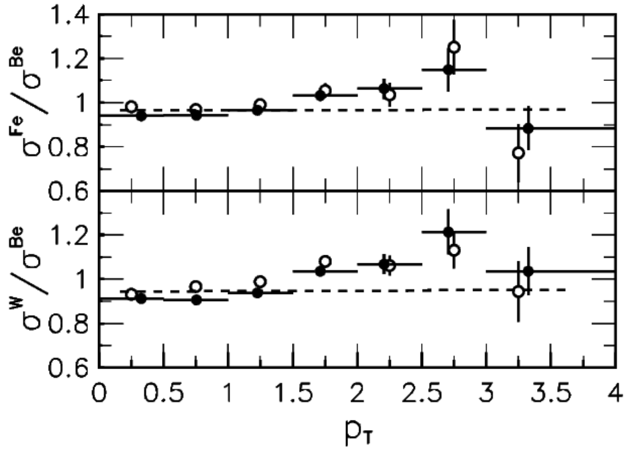
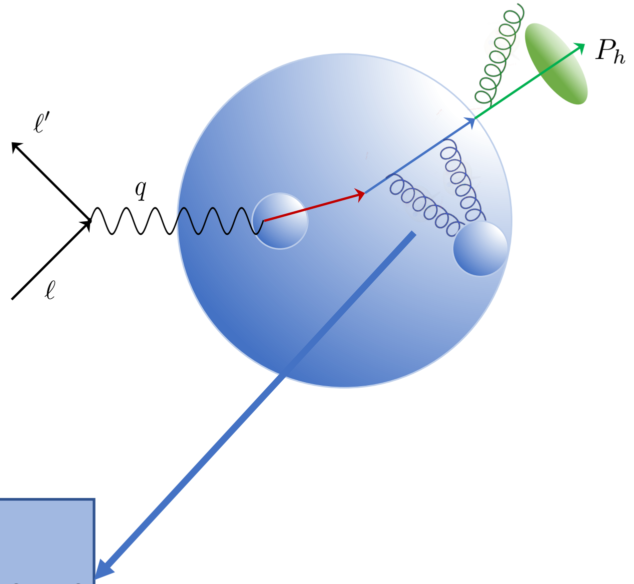
Non-perturbative Sudakov given by



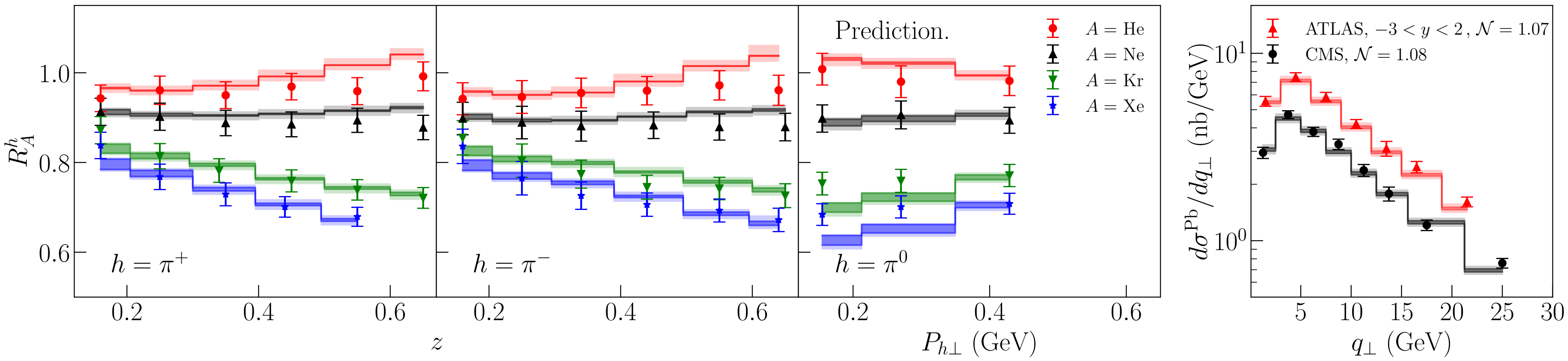




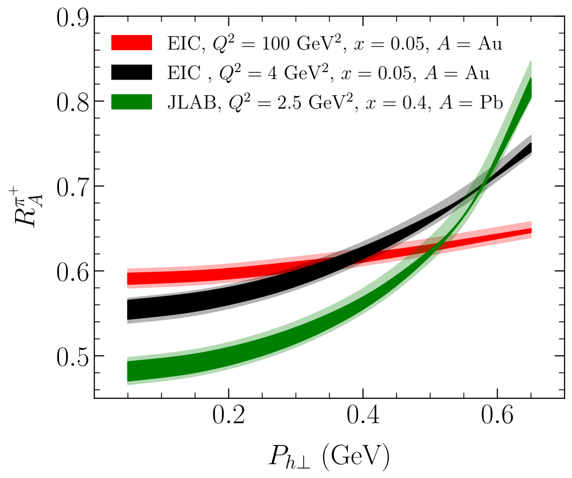
$$S^{f\,A}_{\rm NP}(b;Q_0,\mu,\zeta_i,\zeta) = S^{f}_{\rm NP}(b;Q_0,\mu,\zeta_i,\zeta) + a_N\left(1-A^{1/3}\right)b^2$$
$$S^{D\,A}_{\rm NP}(z,b;Q_0,\mu,\zeta_i,\zeta) = S^{D}_{\rm NP}(z,b;Q_0,\mu,\zeta_i,\zeta) + b_N\left(1-A^{1/3}\right)b^2/z^2$$

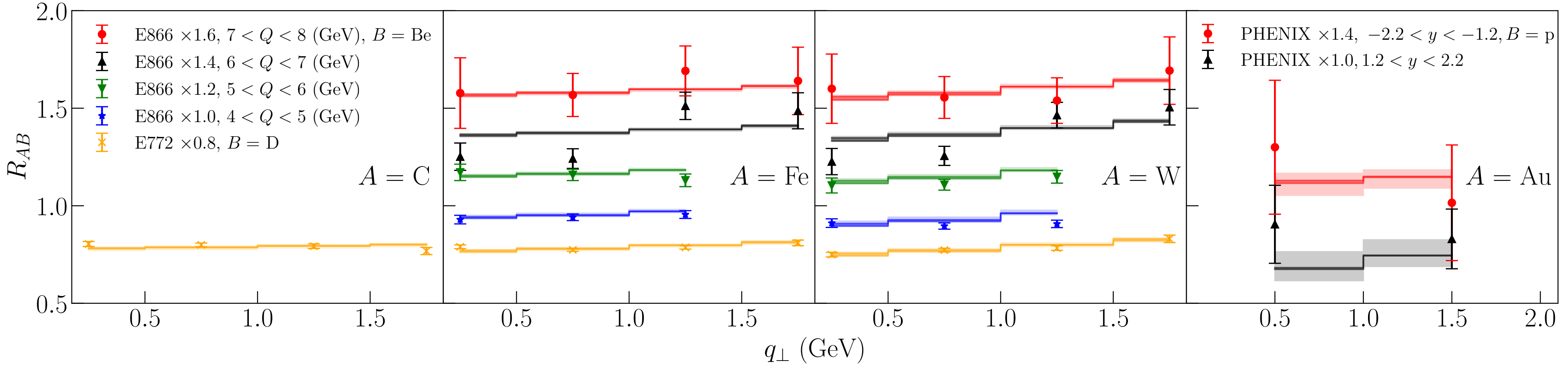
Description of the data and predictions

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



Prediction

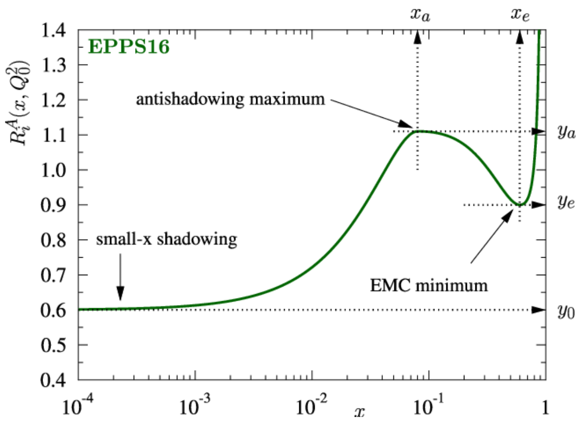




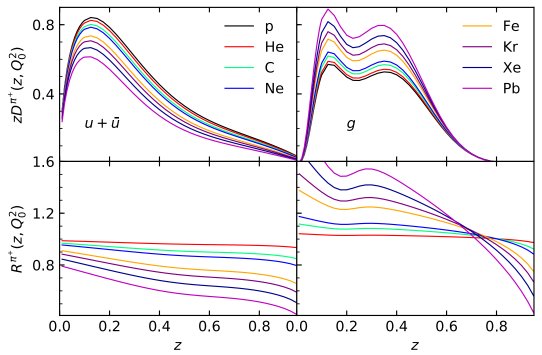
See also the talk by Leonard

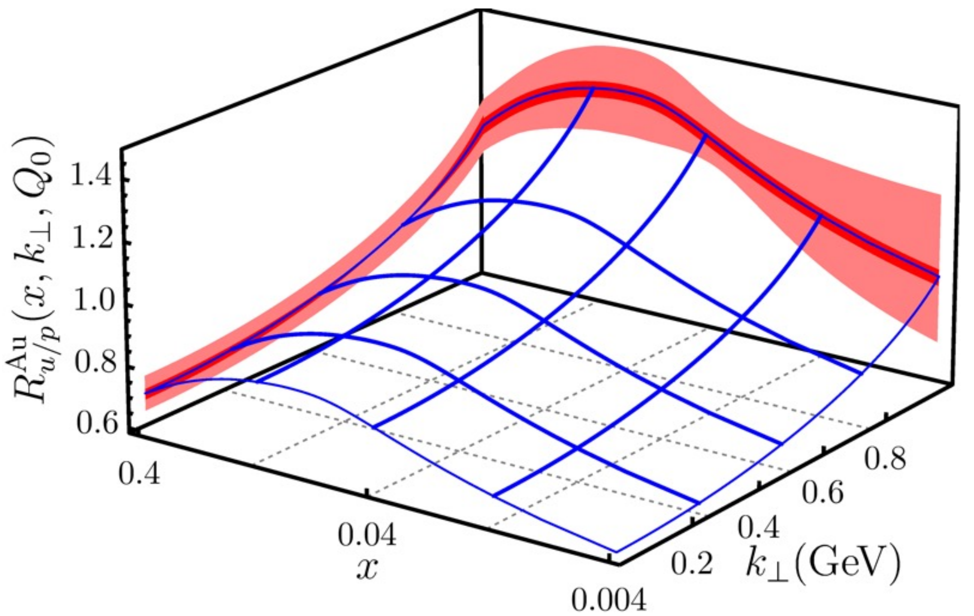
Ratios defined for nPDF and nFF

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

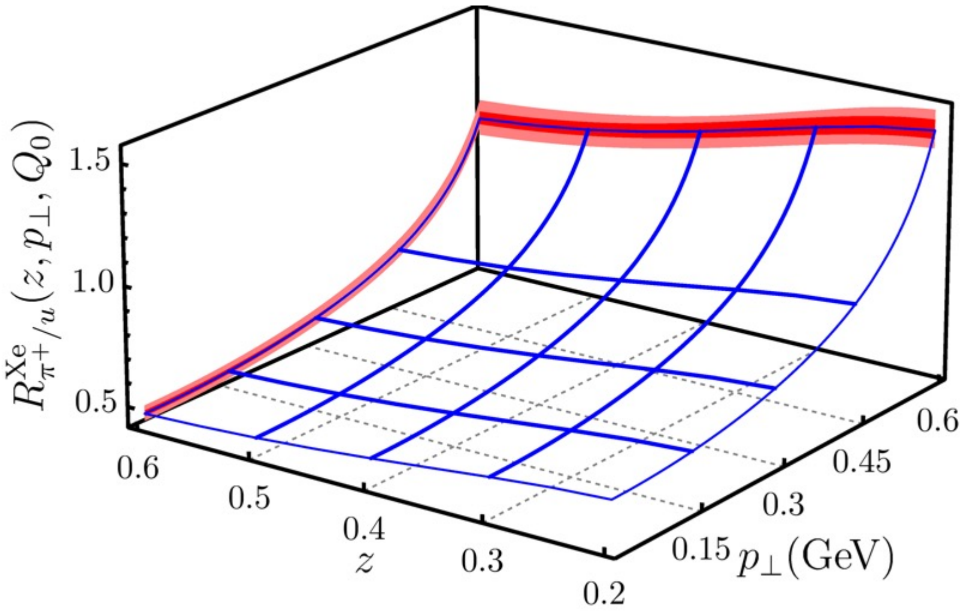


$$R_i^A\left(z,Q_0^2\right)=\frac{D_{h/i}^A\left(z,Q_0^2\right)}{D_{h/i}\left(z,Q_0^2\right)}$$





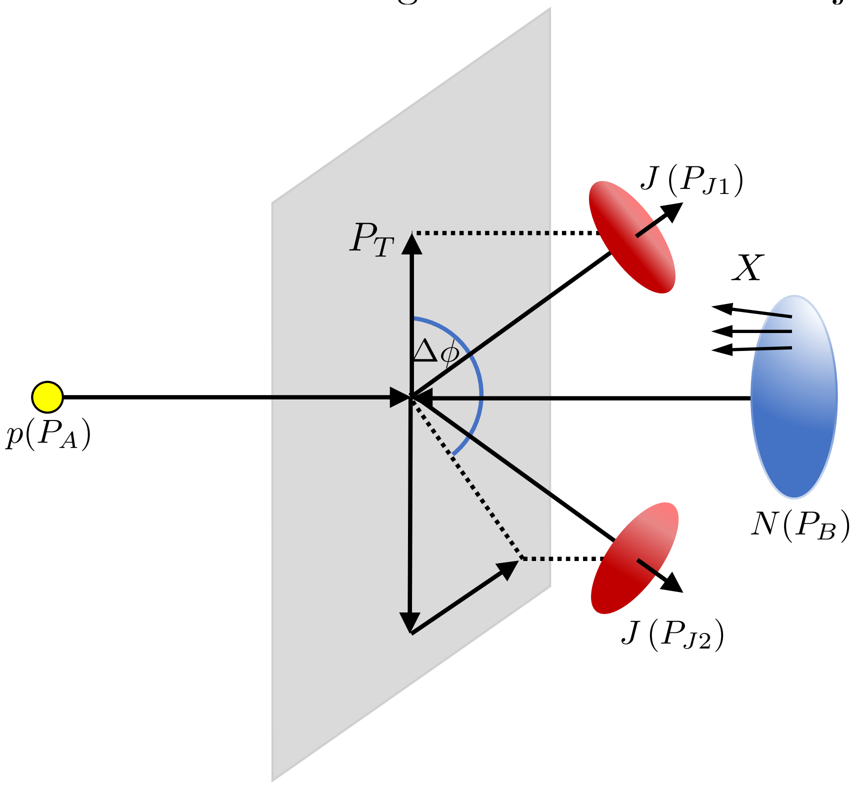
$$R_{u/p}^{\mathrm{Au}}(x,k_\perp,Q)=\frac{f_{u/p}^{\mathrm{Au}}(x,k_\perp,Q)}{f_{u/p}(x,k_\perp,Q)}$$



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

Can jets serve as a probe of nTMDs?

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs

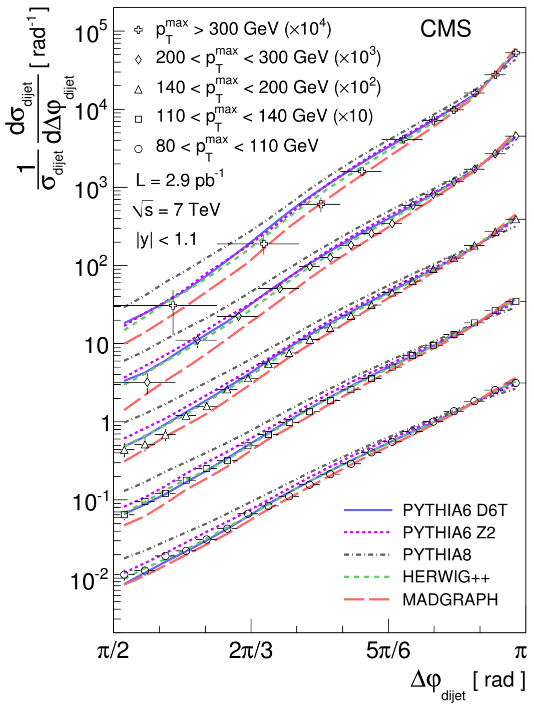


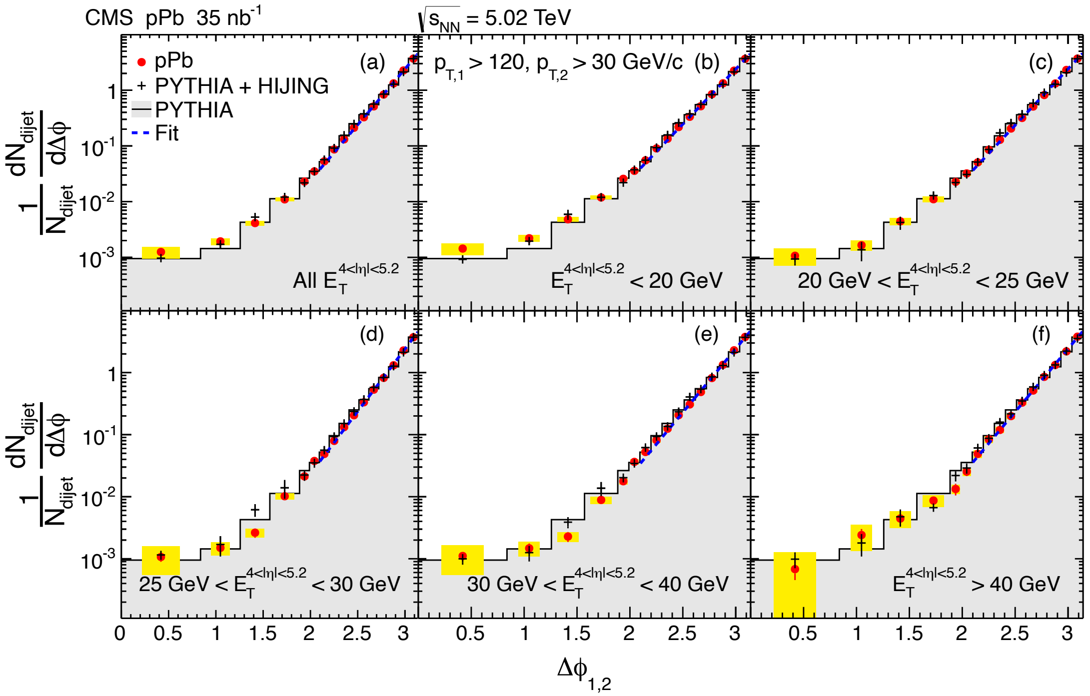
Back-to-back region is sensitive to the 1+1 dimensional TMDs

See first talk by Johannes

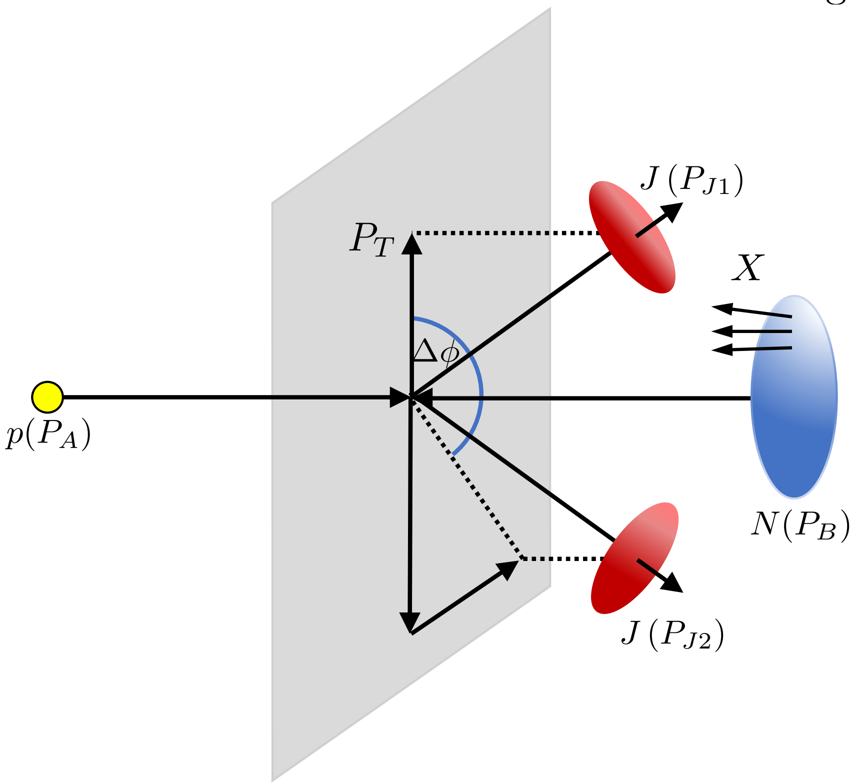
CMS Measurements in pp and pA collisions

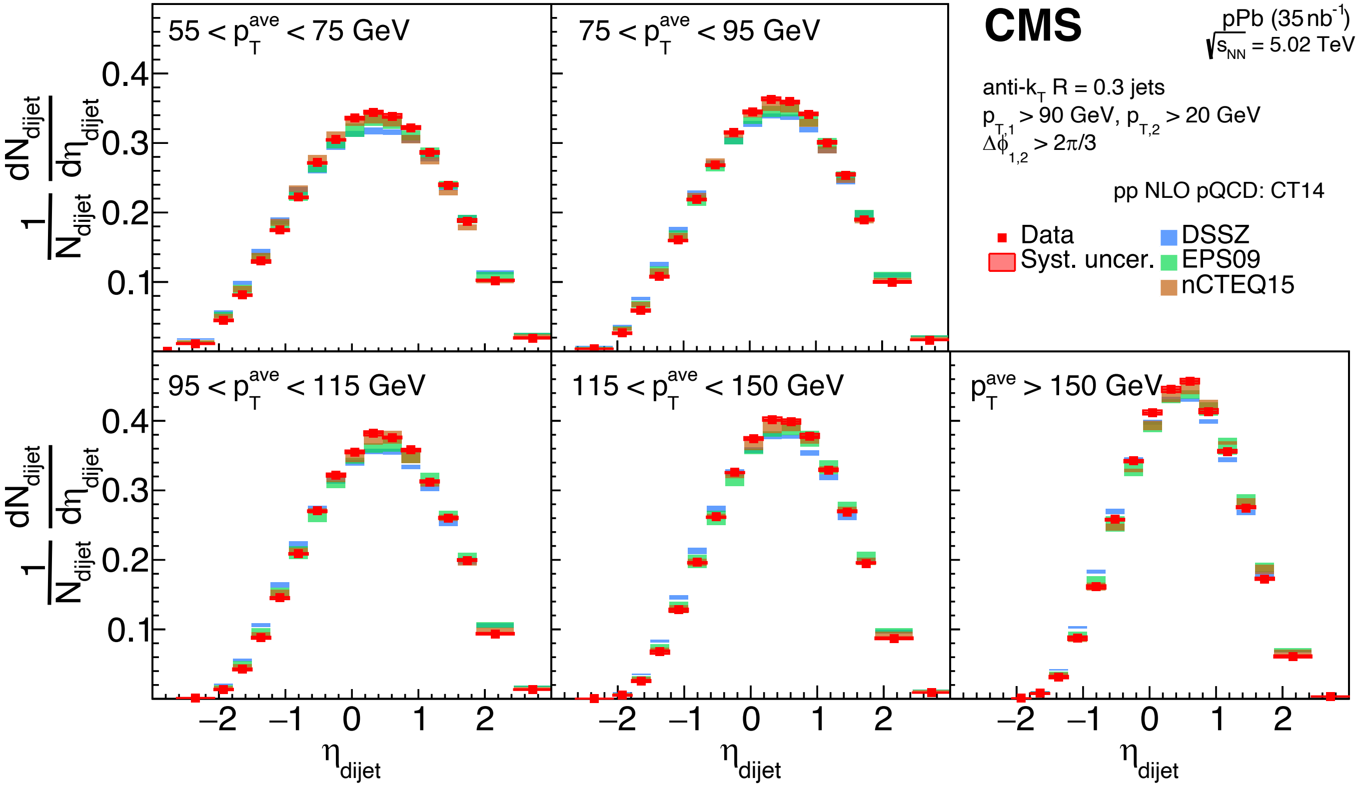
Phys.Rev.Lett.106:122003,2011
Eur. Phys. J. C 74 (2014) 2951
Phys. Rev. Lett. 121, 062002 (2018)





Additional measurements of the integrated azimuthal angle decorrelation

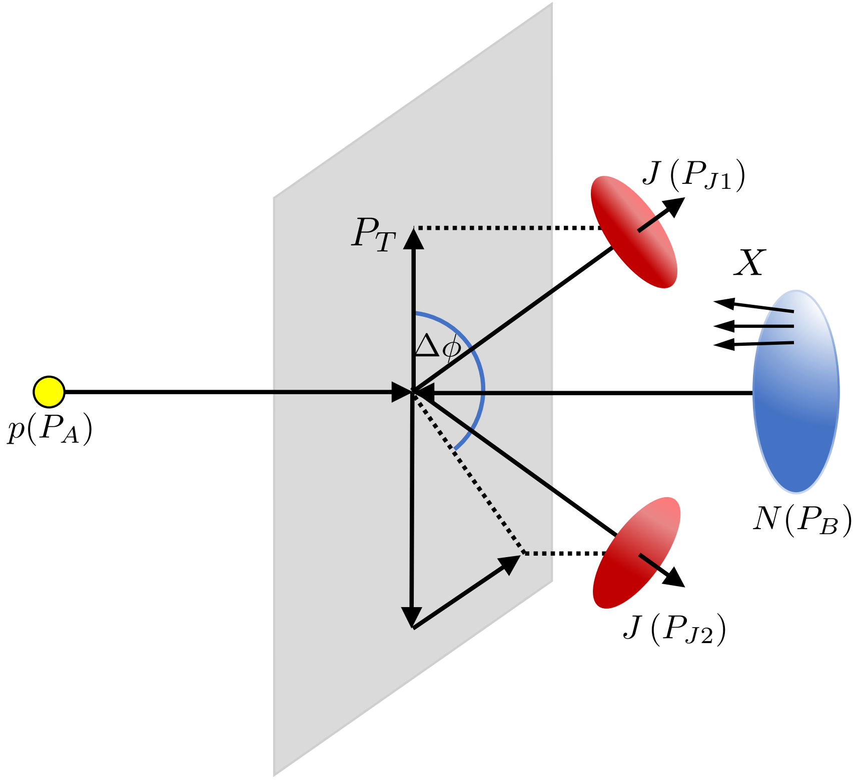




Integration in region $\Delta\phi > 2\pi/3$ performed using a collinear approximation. However, there are issues with this approach as $\Delta\phi \to \pi$ due to large logarithms.

Generating the factorization in SCET

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs

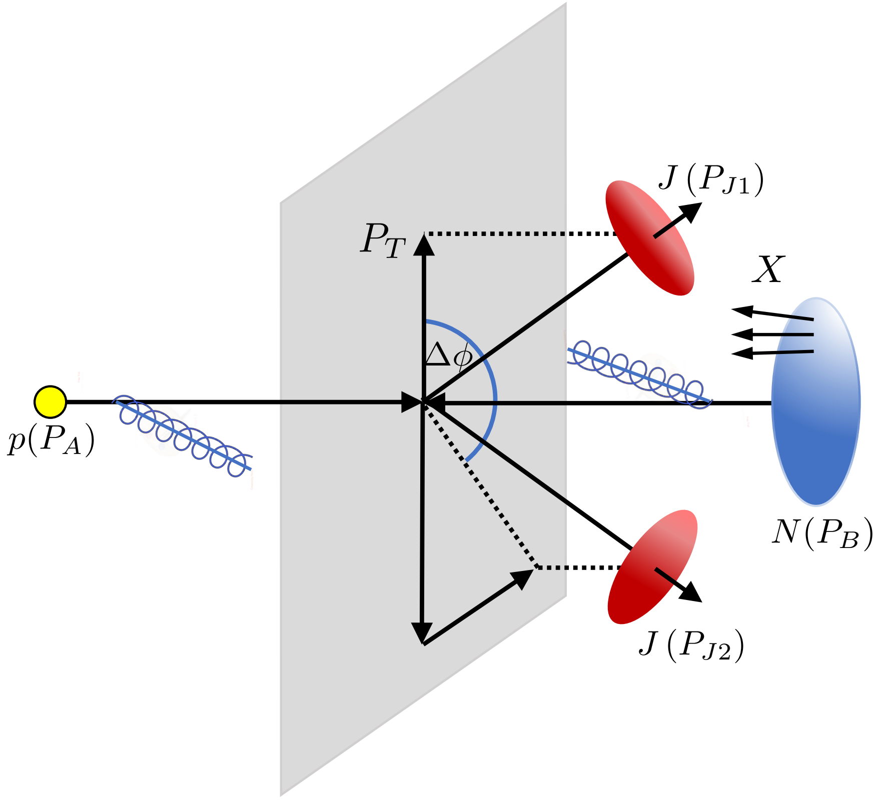


Factorization and resummation derived in a SCET framework

$$\textbf{hard}: \; p_h^\mu \sim p_T(1,1,1)$$

Generating the factorization in SCET

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs

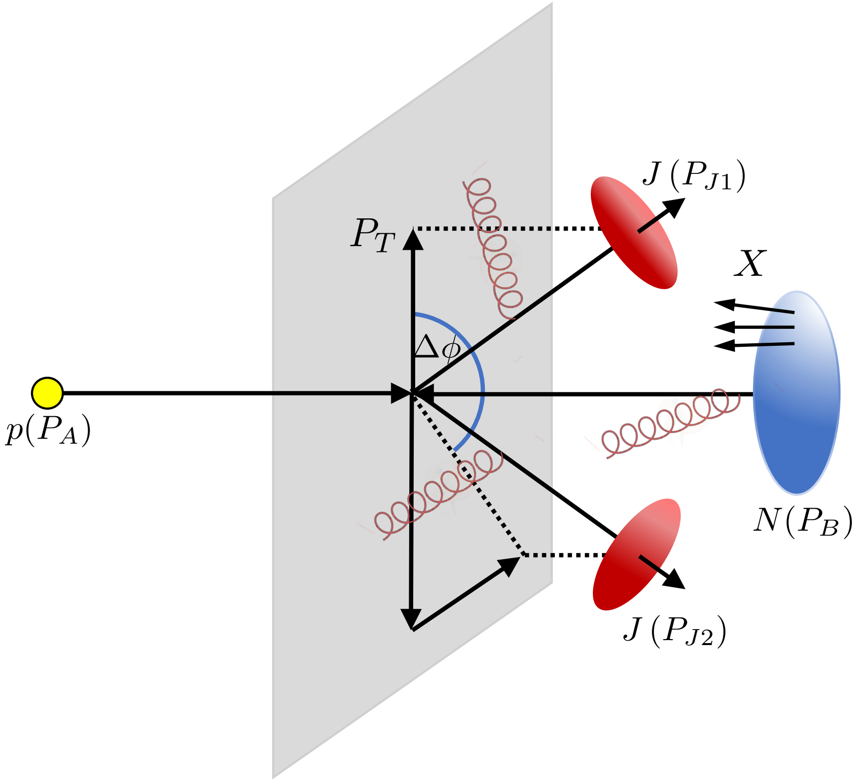


Factorization and resummation derived in a SCET framework

$$\textbf{hard}: \; p_h^\mu \sim p_T(1,1,1)$$
$$n_{a,b}\textbf{-collinear}: \; p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i \bar{n}_i},$$

Generating the factorization in SCET

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs

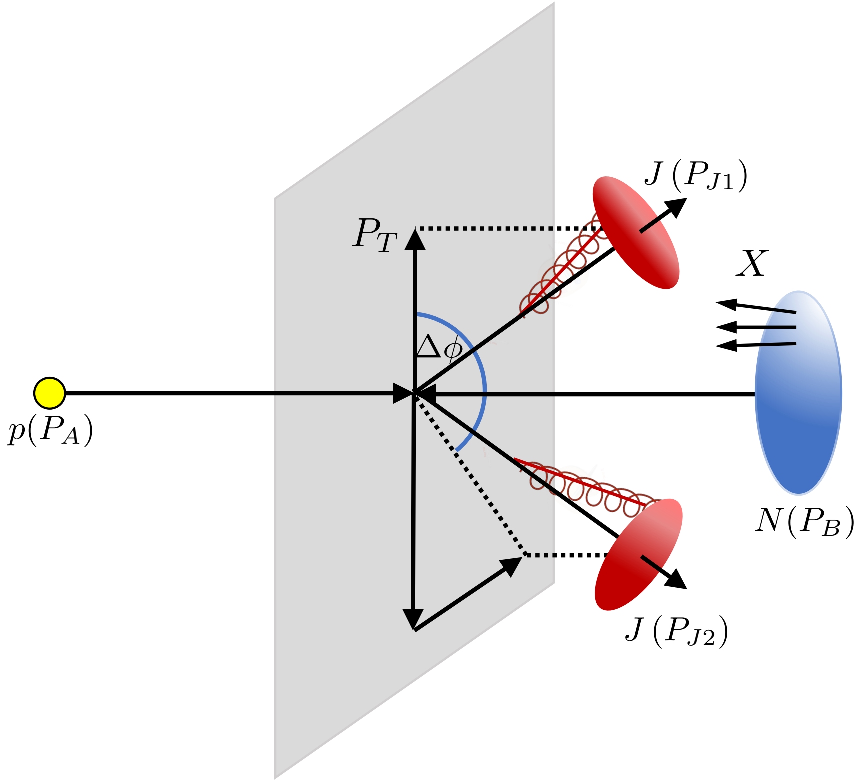


Factorization and resummation derived in a SCET framework

$$\begin{aligned} \textbf{hard}: &\quad p_h^\mu \sim p_T(1,1,1) \\ n_{a,b}\textbf{-collinear}: &\quad p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i\bar{n}_i}, \\ \textbf{soft}: &\quad p_s^\mu \sim p_T\,(\delta\phi, \delta\phi, \delta\phi), \end{aligned}$$

Generating the factorization in SCET

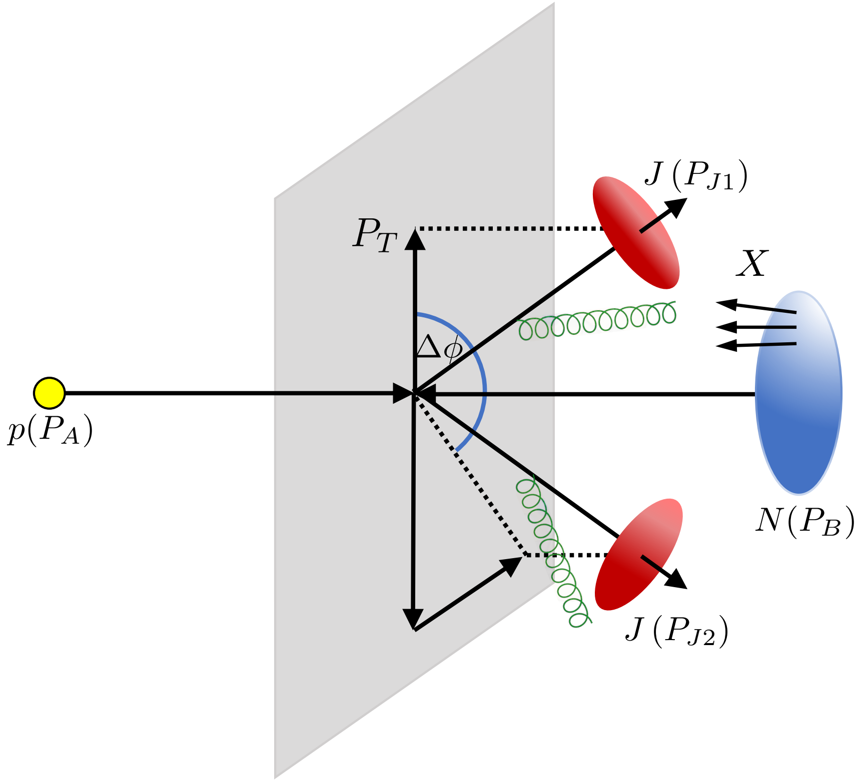
Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs



Factorization and resummation derived in a SCET framework

$$\begin{aligned} \textbf{hard}: &\quad p_h^\mu \sim p_T(1,1,1) \\ n_{a,b}\textbf{-collinear}: &\quad p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i\bar{n}_i}, \\ \textbf{soft}: &\quad p_s^\mu \sim p_T\,(\delta\phi, \delta\phi, \delta\phi), \\ n_{c,d}\textbf{-jet}: &\quad p_{c_i}^\mu \sim p_T\,(R^2, 1, R)_{n_i\bar{n}_i}, \end{aligned}$$

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs

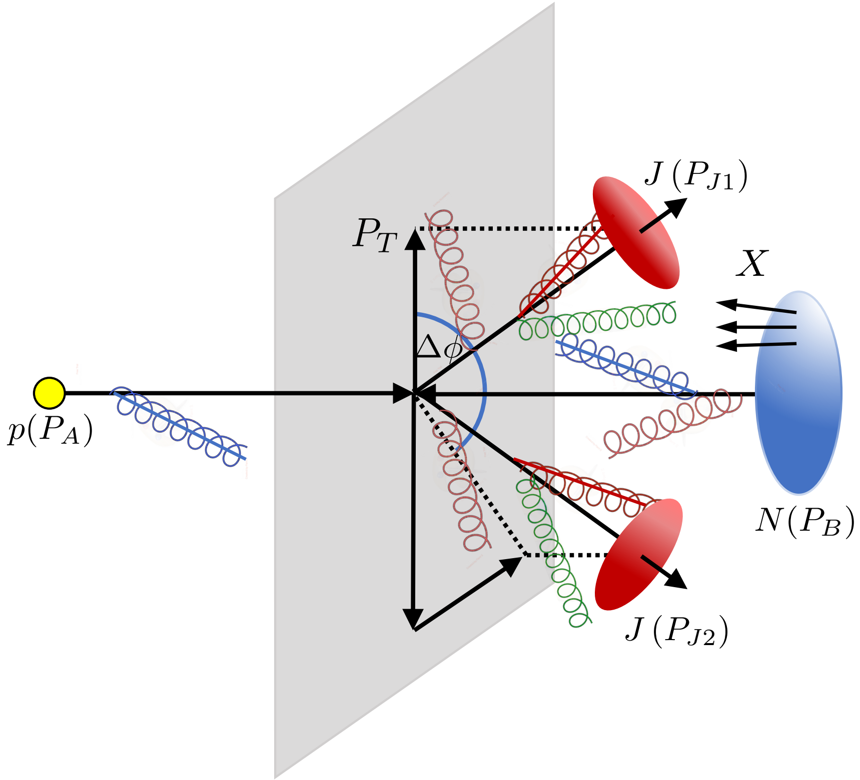


Factorization and resummation derived in a SCET framework

$$\begin{aligned}
\textbf{hard}: &\quad p_h^\mu \sim p_T(1,1,1) \\
n_{a,b}\textbf{-collinear}: &\quad p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i\bar{n}_i}, \\
\textbf{soft}: &\quad p_s^\mu \sim p_T\,(\delta\phi, \delta\phi, \delta\phi), \\
n_{c,d}\textbf{-jet}: &\quad p_{c_i}^\mu \sim p_T\,(R^2, 1, R)_{n_i\bar{n}_i}, \\
n_{c,d}\textbf{-collinear-soft}: &\quad p_{cs_i}^\mu \sim \frac{p_T\,\delta\phi}{R}(R^2, 1, R)_{n_i\bar{n}_i},
\end{aligned}$$

Generating the factorization in SCET

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs



Factorization and resummation derived in a SCET framework

$$\begin{aligned}
\textbf{hard}:&\quad p_h^\mu \sim p_T(1,1,1)\\
n_{a,b}\textbf{-collinear}:&\quad p_{c_i}^\mu \sim p_T\,(\delta\phi^2,1,\delta\phi)_{n_i\bar{n}_i},\\
\textbf{soft}:&\quad p_s^\mu \sim p_T\,(\delta\phi,\delta\phi,\delta\phi),\\
n_{c,d}\textbf{-jet}:&\quad p_{c_i}^\mu \sim p_T\,(R^2,1,R)_{n_i\bar{n}_i},\\
n_{c,d}\textbf{-collinear-soft}:&\quad p_{cs_i}^\mu \sim \frac{p_T\,\delta\phi}{R}(R^2,1,R)_{n_i\bar{n}_i},
\end{aligned}$$

Factorization and resummation at NLL:

$$\begin{aligned}
\frac{\mathrm{d}^4\sigma_{pp}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}\delta\phi} &= \sum_{abcd}\frac{p_T}{16\pi\hat{s}^2}\frac{1}{1+\delta_{cd}}\int_0^\infty \frac{2\mathrm{d}b}{\pi}\cos(bp_T\delta\phi)x_a\tilde{f}_{a/p}(x_a,\mu_{b_*})x_b\tilde{f}_{b/p}(x_b,\mu_{b_*})\\
&\times \exp\left\{-\int_{\mu_{b_*}}^{\mu_h}\frac{\mathrm{d}\mu}{\mu}\left[\gamma_{\rm cusp}\left(\alpha_s\right)C_H\ln\frac{\hat{s}}{\mu^2}+2\gamma_H\left(\alpha_s\right)\right]\right\}\\
&\times \sum_{KK'}\exp\left[-\int_{\mu_{b_*}}^{\mu_h}\frac{\mathrm{d}\mu}{\mu}\gamma_{\rm cusp}\left(\alpha_s\right)\left(\lambda_K+\lambda_{K'}^*\right)\right]H_{KK'}\left(\hat{s},\hat{t},\mu_h\right)W_{K'K}\left(b_*,\mu_{b_*}\right)\\
&\times \exp\left[-\int_{\mu_{b_*}}^{\mu_j}\frac{\mathrm{d}\mu}{\mu}\Gamma^{J_c}\left(\alpha_s\right)-\int_{\mu_{b_*}}^{\mu_j}\frac{\mathrm{d}\mu}{\mu}\Gamma^{J_d}\left(\alpha_s\right)\right]U_{\rm NG}^c\left(\mu_{b_*},\mu_j\right)U_{\rm NG}^d\left(\mu_{b_*},\mu_j\right)\\
&\times \exp\left[-S_{\rm NP}^a(b,Q_0,\sqrt{\hat{s}})-S_{\rm NP}^b(b,Q_0,\sqrt{\hat{s}})\right].
\end{aligned}$$

Nuclear modifications in dijet production

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs

nTMDs can be matched onto the collinear distributions

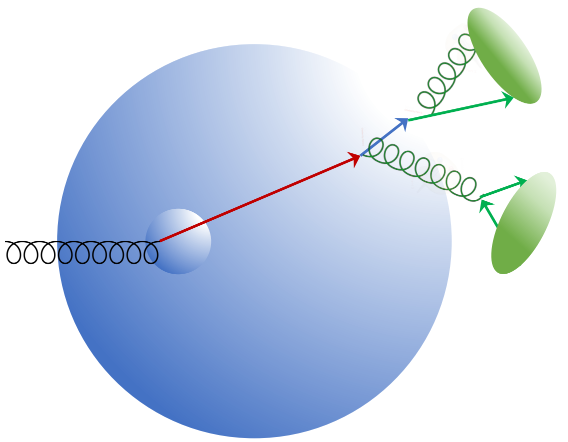
$$f_{q/N}^{A}(b,x;\mu,\zeta_1) = [C \otimes f](x;\mu_i)\,\exp\left[-S_{\rm pert}(b;\mu_i,\mu,\zeta_i,\zeta_1) - S_{\rm NP}^{f\,A}(b;Q_0,\mu,\zeta_i,\zeta)\right]$$

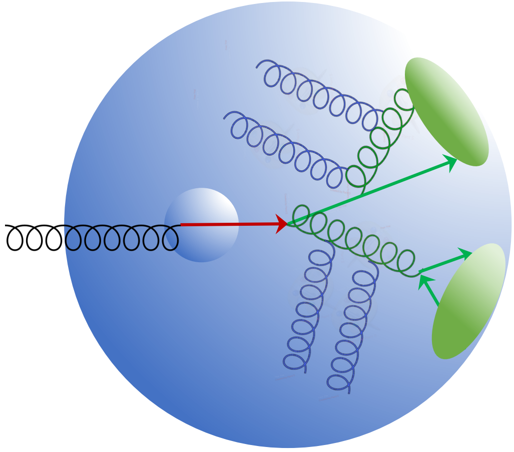
Perturbative

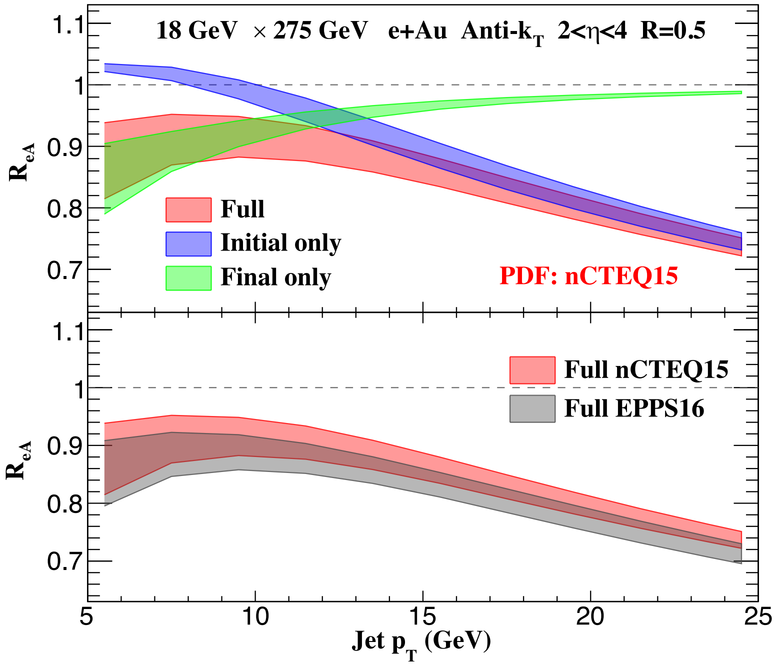
Non-perturbative: Contains all medium contributions

We ignore all final-state interactions between the jets and the medium.
High energy jets are not expected to be affected by the medium

Li, Vitev, Phys. Rev. Lett. 126, 252001 (2021)

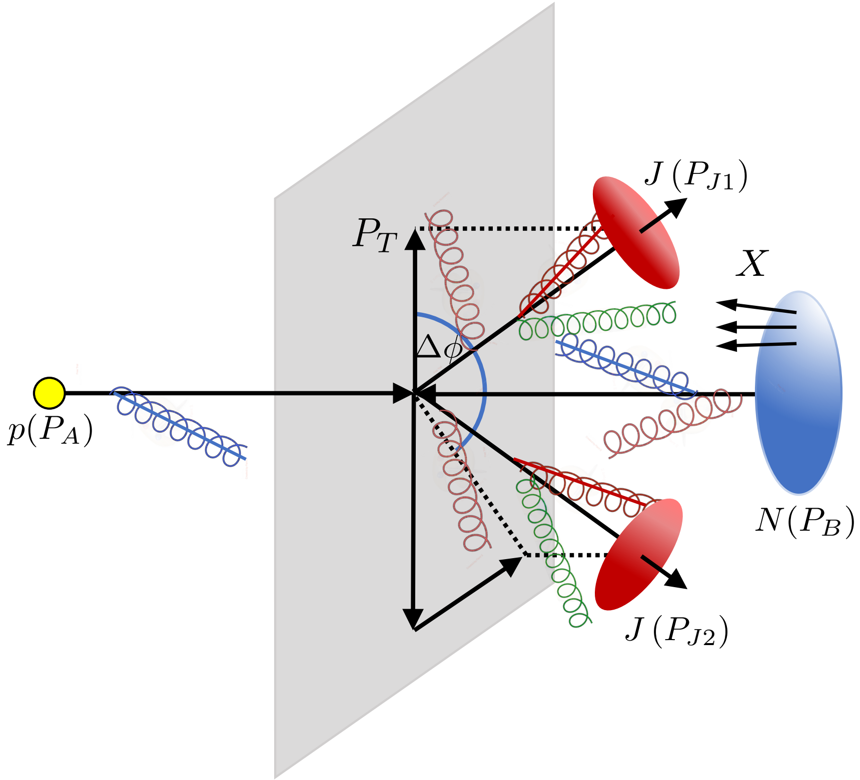






Factorization in p-A collisions

Azimuthal angle decorrelations of di-jets measured at the CMS, are sensitive to nTMDs



Factorization and resummation derived in a SCET framework

$$\begin{aligned}
\textbf{hard}: &\quad p_h^\mu \sim p_T(1,1,1)\\
n_{a,b}\textbf{-collinear}: &\quad p_{c_i}^\mu \sim p_T\left(\delta\phi^2,1,\delta\phi\right)_{n_i\bar{n}_i},\\
\textbf{soft}: &\quad p_s^\mu \sim p_T\left(\delta\phi,\delta\phi,\delta\phi\right),\\
n_{c,d}\textbf{-jet}: &\quad p_{c_i}^\mu \sim p_T\left(R^2,1,R\right)_{n_i\bar{n}_i},\\
n_{c,d}\textbf{-collinear-soft}: &\quad p_{cs_i}^\mu \sim \frac{p_T\,\delta\phi}{R}\left(R^2,1,R\right)_{n_i\bar{n}_i},
\end{aligned}$$

Factorization and resummation:

$$\begin{aligned}
\frac{\mathrm{d}^4\sigma_{pA}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}\delta\phi} &= \sum_{abcd}\frac{p_T}{16\pi\hat{s}^2}\frac{1}{1+\delta_{cd}}\int_0^\infty\frac{2\mathrm{d}b}{\pi}\cos(bp_T\delta\phi)x_a\tilde{f}_{a/p}(x_a,\mu_{b_*})x_b\tilde{f}_{b/A}(x_b,\mu_{b_*})\\
&\times\exp\left\{-\int_{\mu_{b_*}}^{\mu_h}\frac{\mathrm{d}\mu}{\mu}\left[\gamma_{\rm cusp}\left(\alpha_s\right)C_H\ln\frac{\hat{s}}{\mu^2}+2\gamma_H\left(\alpha_s\right)\right]\right\}\\
&\times\sum_{KK'}\exp\left[-\int_{\mu_{b_*}}^{\mu_h}\frac{\mathrm{d}\mu}{\mu}\gamma_{\rm cusp}\left(\alpha_s\right)\left(\lambda_K+\lambda_{K'}^*\right)\right]H_{KK'}\left(\hat{s},\hat{t},\mu_h\right)W_{K'K}\left(b_*,\mu_{b_*}\right)\\
&\times\exp\left[-\int_{\mu_{b_*}}^{\mu_j}\frac{\mathrm{d}\mu}{\mu}\Gamma^{J_c}\left(\alpha_s\right)-\int_{\mu_{b_*}}^{\mu_j}\frac{\mathrm{d}\mu}{\mu}\Gamma^{J_d}\left(\alpha_s\right)\right]U_{\rm NG}^c\left(\mu_{b_*},\mu_j\right)U_{\rm NG}^d\left(\mu_{b_*},\mu_j\right)\\
&\times\exp\left[-S_{\rm NP}^a(b,Q_0,\sqrt{\hat{s}})-S_{\rm NP}^{b,A}(b,Q_0,\sqrt{\hat{s}})\right]
\end{aligned}$$

Factorization breaking effects?

Glauber mode note treated in our paper

$$\begin{aligned}
\textbf{hard}: &\quad p_h^\mu \sim p_T(1,1,1) \\
n_{a,b}\textbf{-collinear}: &\quad p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i\bar{n}_i}, \\
\textbf{soft}: &\quad p_s^\mu \sim p_T\,(\delta\phi, \delta\phi, \delta\phi), \\
n_{c,d}\textbf{-jet}: &\quad p_{c_i}^\mu \sim p_T\,(R^2, 1, R)_{n_i\bar{n}_i}, \\
n_{c,d}\textbf{-collinear-soft}: &\quad p_{cs_i}^\mu \sim \frac{p_T\,\delta\phi}{R}(R^2, 1, R)_{n_i\bar{n}_i}, \\
n_G\textbf{-Glauber}: &\quad p_G^\mu \sim p_T(\delta\phi^2, \delta\phi^2, \delta\phi)_{n_i\bar{n}_i}
\end{aligned}$$

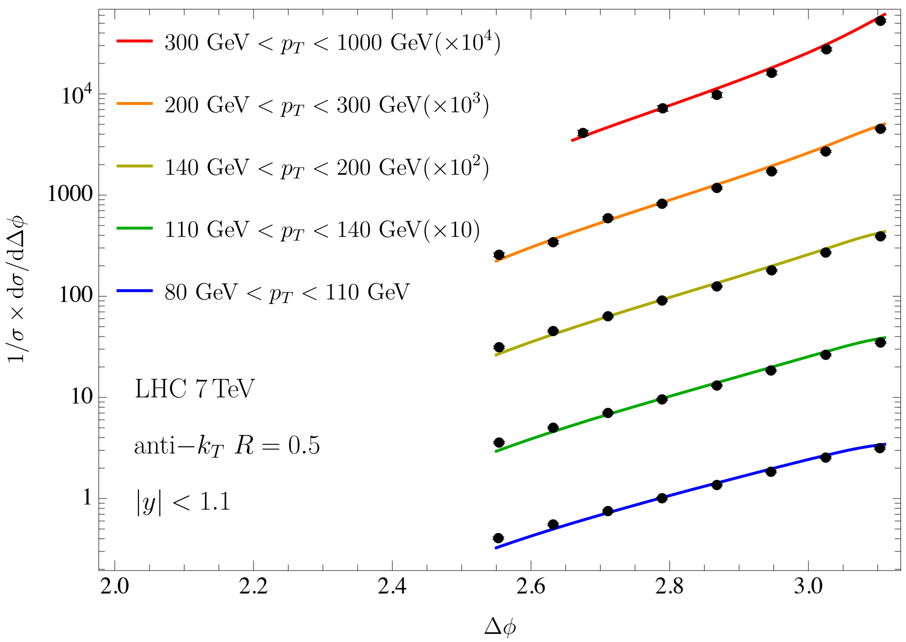
Factorization breaking effects in dijet production studied in

Collins, Qiu Phys.Rev.D75:114014,2007
Collins (2007)

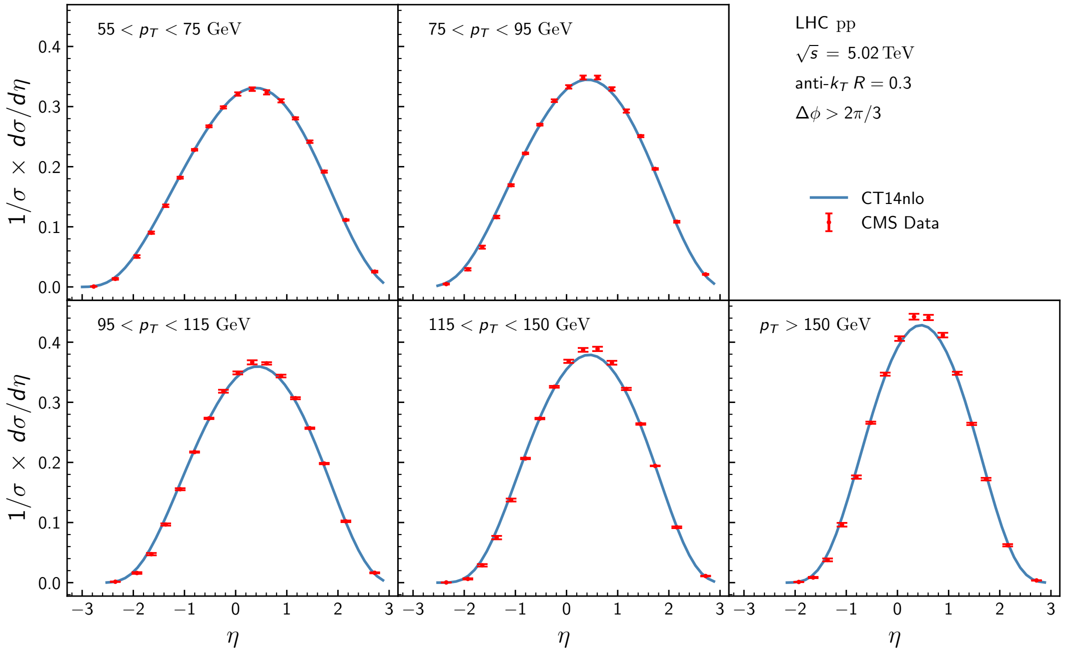
The experimental data is well-described by the experimental data in the back-to-back region, within the error bars

$$\frac{\mathrm{d}^4\sigma_{pp}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}\delta\phi}$$

Phys.Rev.Lett.106:122003,2011



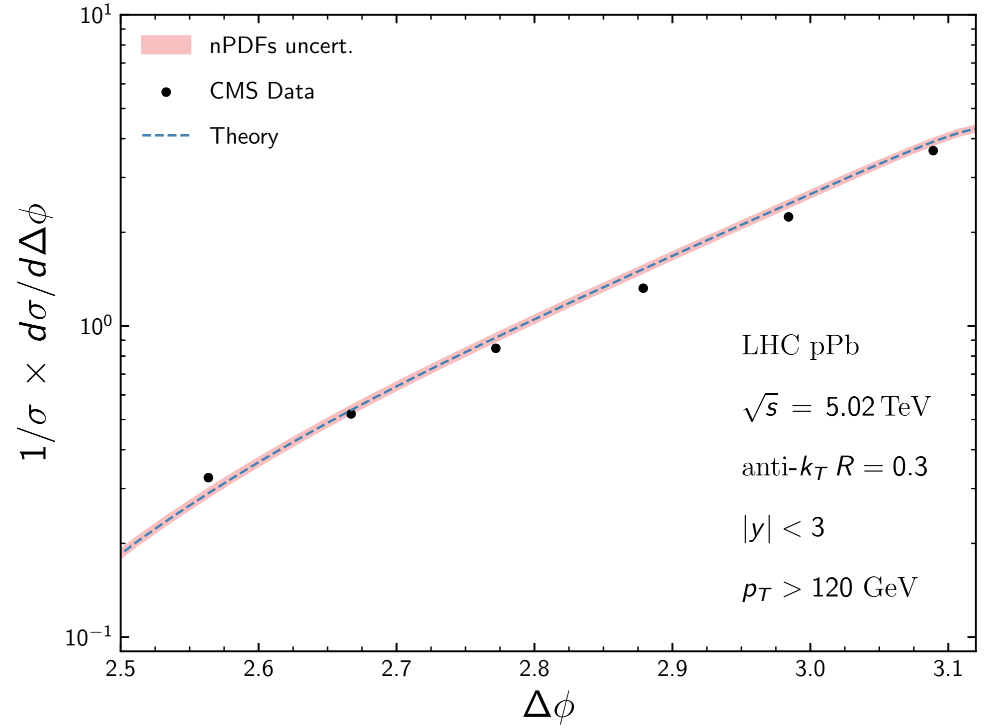
Phys. Rev. Lett. 121, 062002 (2018)



Description of pA data

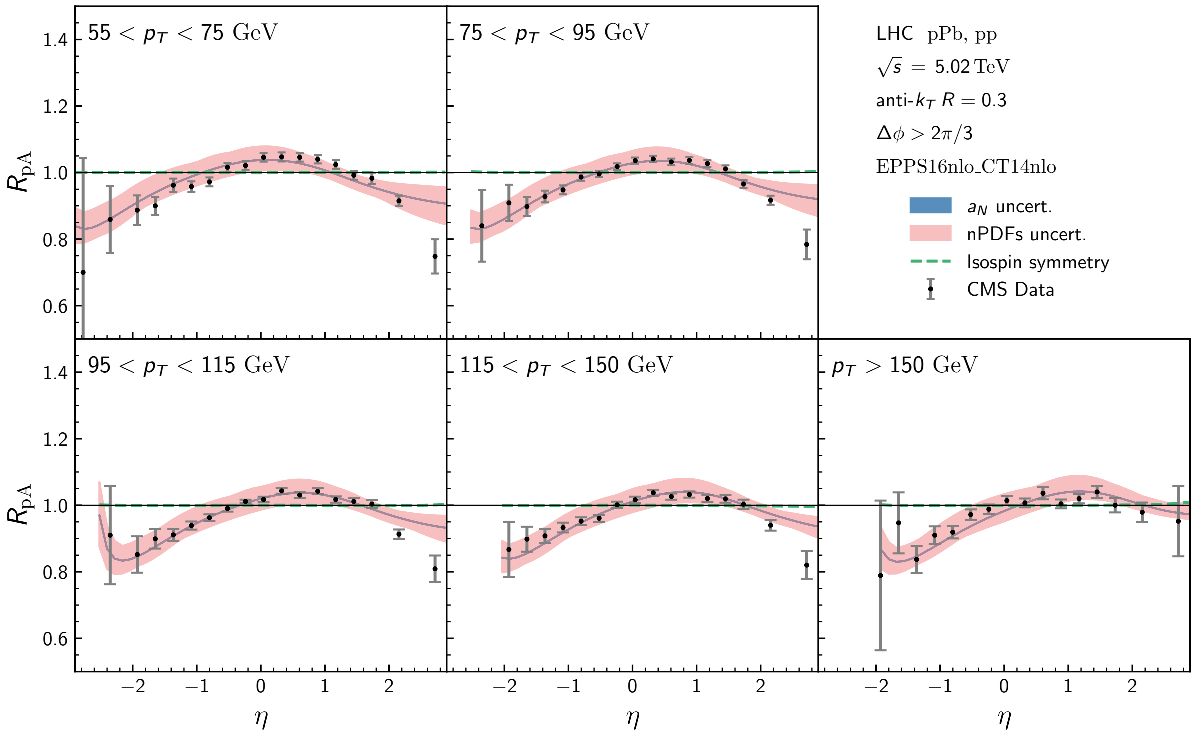
Strong consistency with the CMS measurements of the azimuthal angle decorrelation in pA and the ratio of the integrated azimuthal angle decorrelation.

$$\frac{\mathrm{d}^4\sigma_{pA}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}\delta\phi}$$



Eur. Phys. J. C 74 (2014) 2951

$$R_{\mathrm{pA}} = \frac{1}{A}\frac{\mathrm{d}^4\sigma_{pA}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}\Delta\phi} \Big/ \frac{\mathrm{d}^4\sigma_{pp}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}\Delta\phi}$$

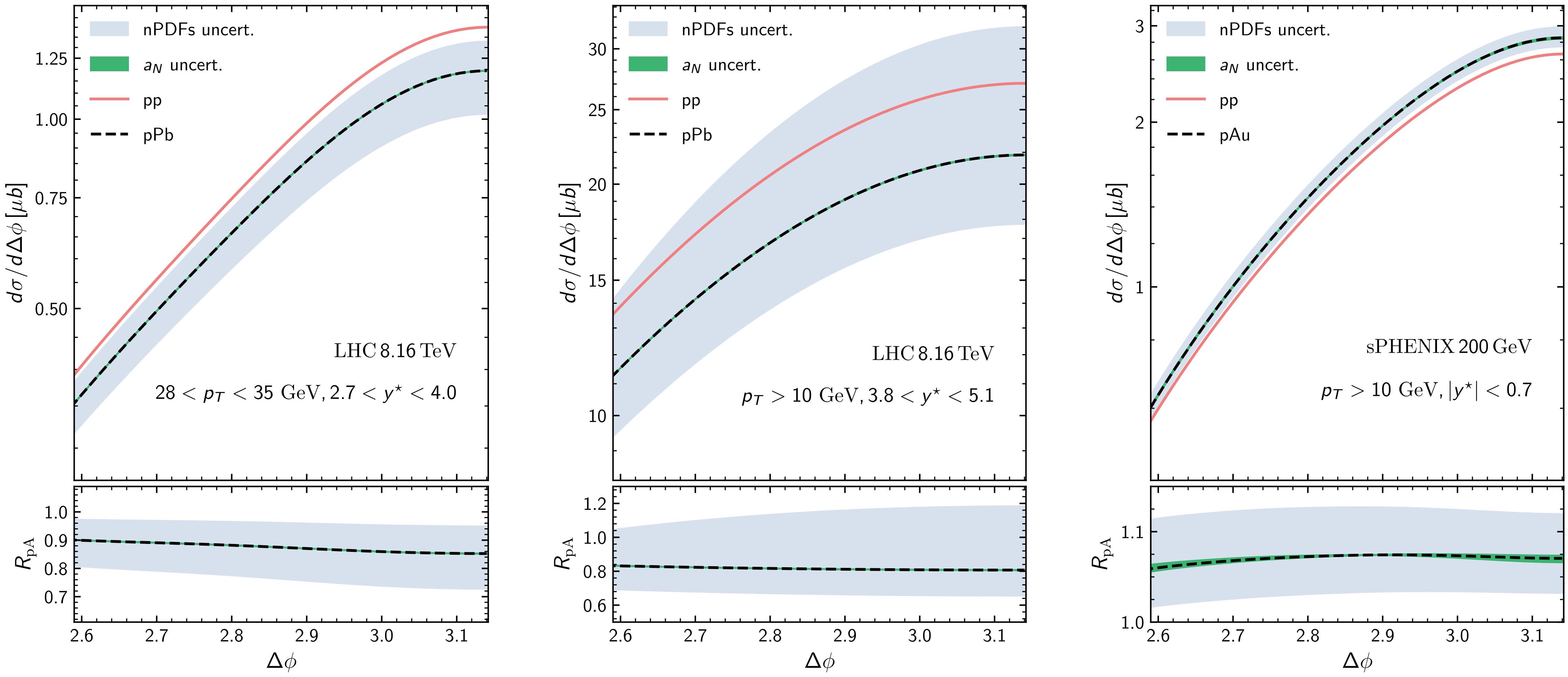


Phys. Rev. Lett. 121, 062002 (2018)

Red band is the uncertainty from the EPPS sets, small blue band from the uncertainty of the nTMDs and is very small for high pT jet production.

Predictions at ATLAS, ALICE, and sPHENIX

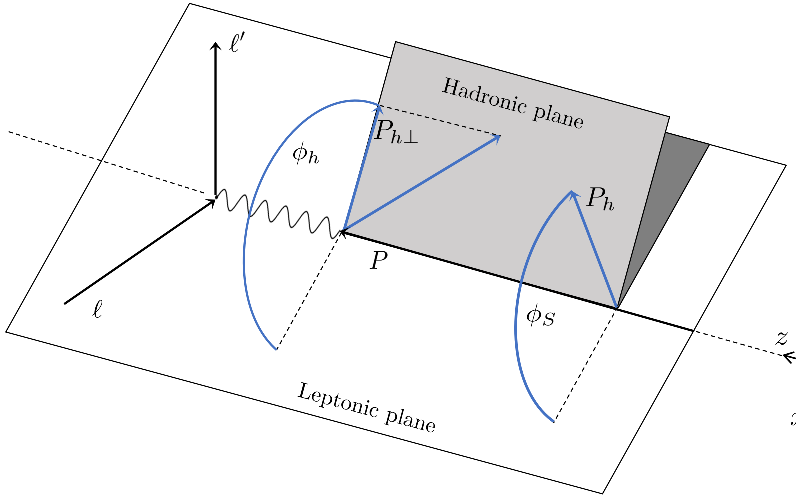
At the LHC, the collinear uncertainties are more dominant due to the large perturbative transverse momenta that are generated. Uncertainty band of the broadening becomes larger at lower center of mass energies



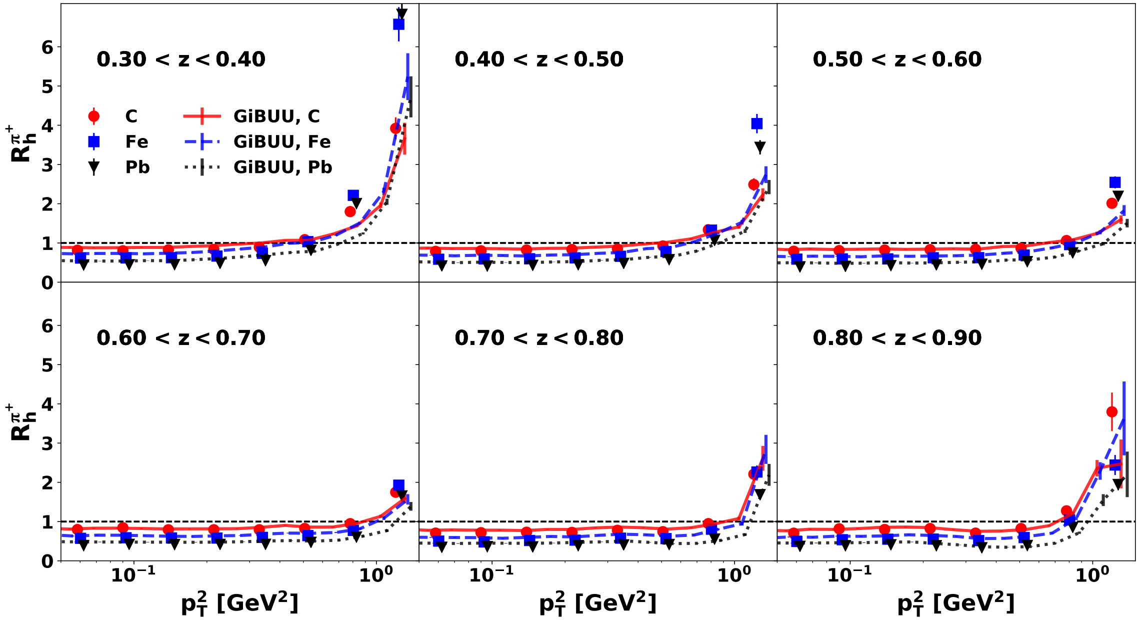
CLAS measurements

Semi-Inclusive DIS

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

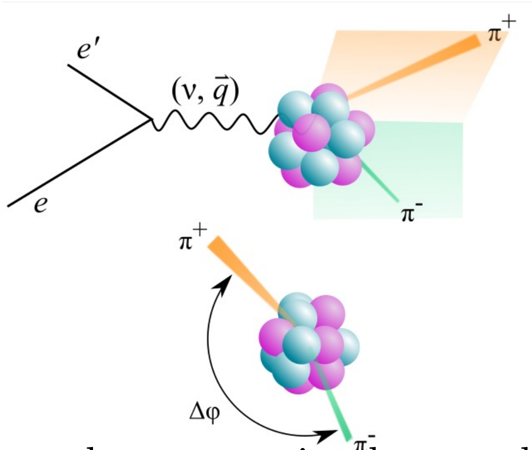


Hadron-multiplicity data can be incorporated into the fit

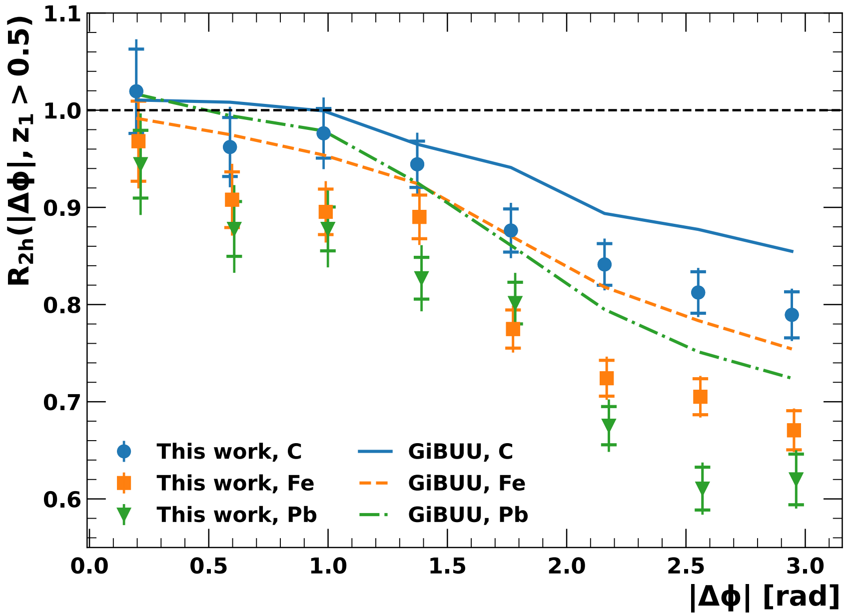


Measurements have been performed for angular decorrelation

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

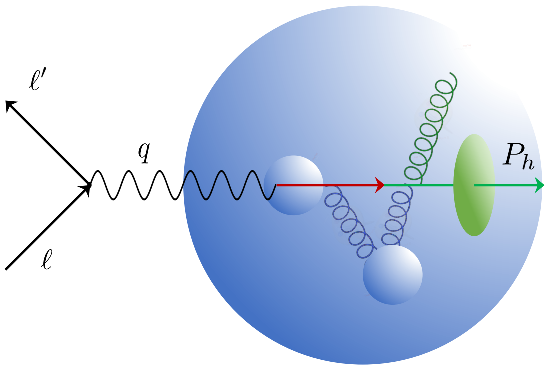


Factorization and resummation has not been established



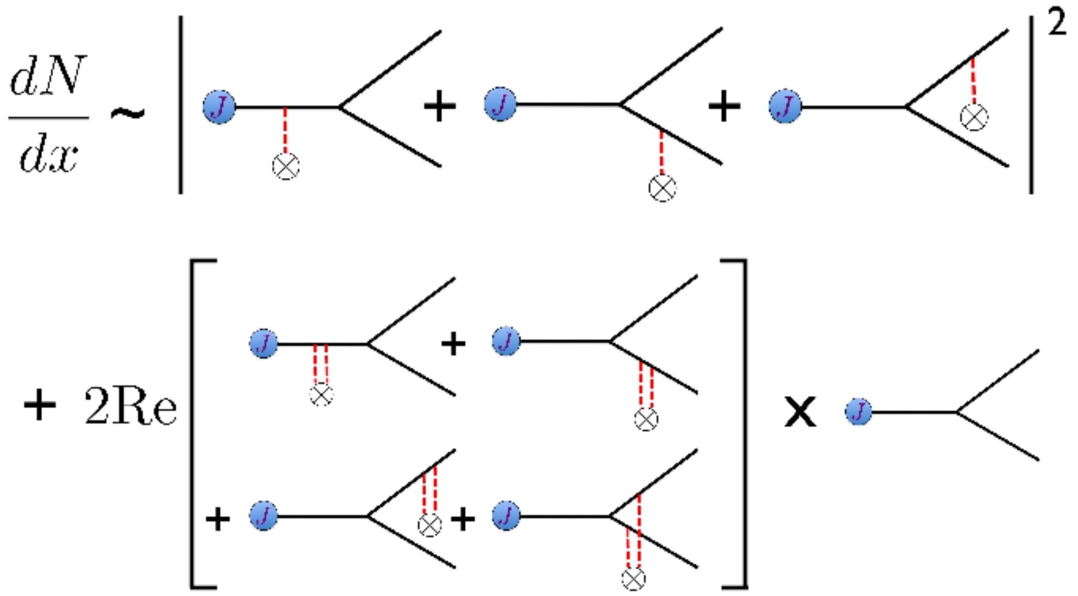
Medium modified evolution

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



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

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



See for instance Ovanesyan, Vitev Physics Letters B Volume 706, Issues 4–5, Jan 2012

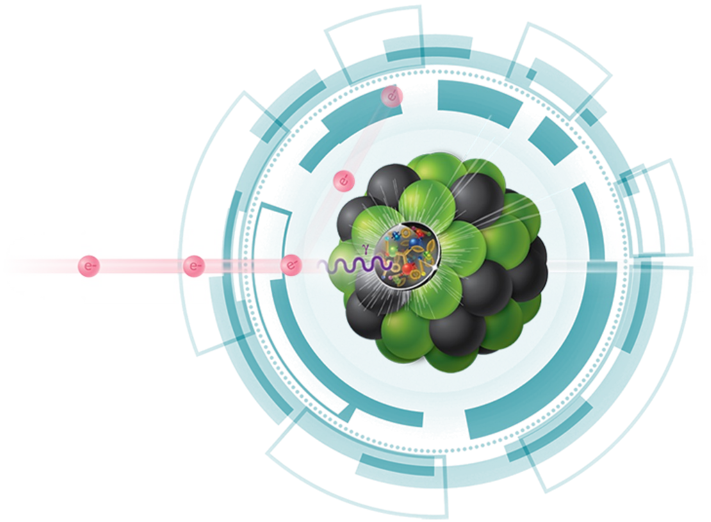
Medium modification can be implemented into the fit, but introduces additional scales. Future work in this community will involve including the medium modified DGLAP into the fit, as well as calculating the medium modifications to the RG and Collins-evolution of the TMDs.

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

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

Conclusion

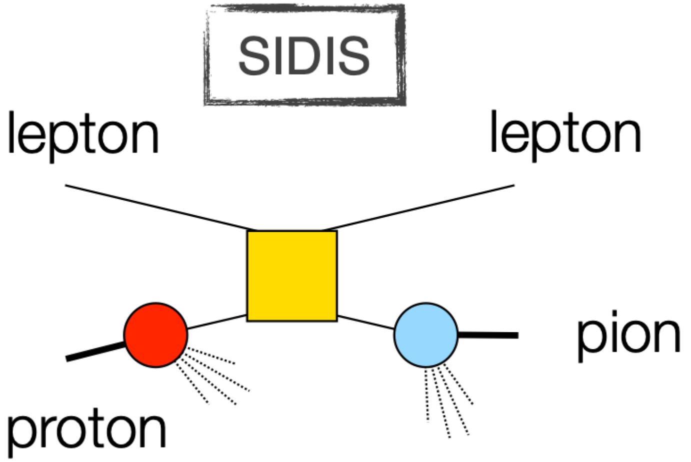
- We develop a formalism for approximating broadening effects in Drell-Yan and Semi-Inclusive DIS.
- We find that we can absorb medium modifications into the intrinsic widths of the TMDs to define nTMDs.
- We perform the first extraction of both the nTMD PDF and nTMD FF from the world data of Semi-Inclusive DIS and Drell-Yan.
- We studied jet production in pA collisions at the LHC and sPHENIX and find good agreement with the data.
- Many future applications such as a more rigorous treatment of the power counting associated with jet formation. Can explore using recoil free jets to remove the NGLS and the collinear-soft function and improve perturbative accuracy. Can also explore the use of EECs (TEECs) to study the medium and the nTMDs. Can also involve spin-dependent fragmentation in the medium and hadron in jet fragmentation. Lastly, we can study the collinear matching of the nTMDs in relation to jet transport.



Thank you!

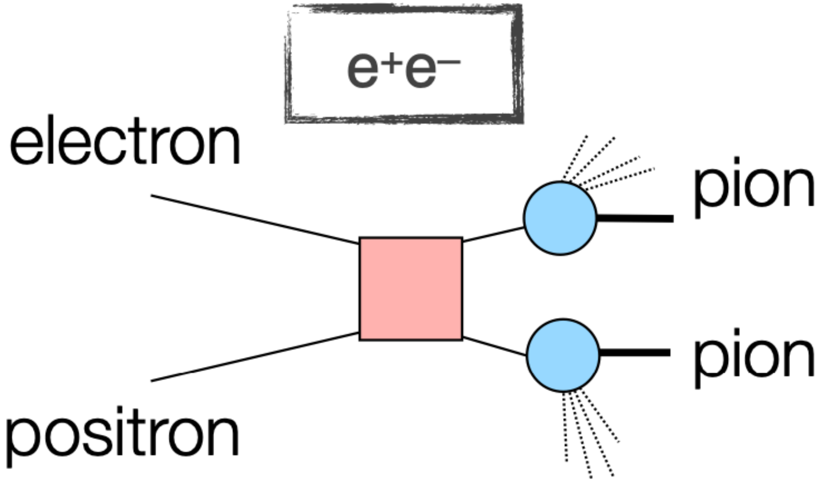
Standard processes

TMD PDFs and *TMD FFs*



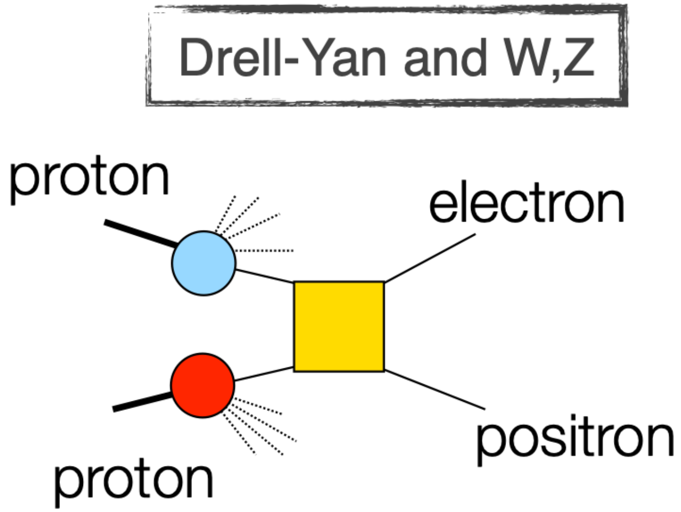
Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

TMD FFs



Collins asymmetries
BELLE, BaBar, BESIII data

TMD PDFs



Sivers asymmetries
COMPASS, STAR data