第六届重味物理与量子色动力学研讨会 @ Qingdao

QCD resummation of dijet and photon + jet azimuthal decorrelations in p-p and p-A collisions

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M.S. Gao, Z.B. Kang, D.Y. Shao, J. Terry, C. Zhang, JHEP 10 (2023) 013

R.J. Fu, M.S. Gao, D.Y. Shao, H.X. Xing, to appear

F. Shen, M.S. Gao, H.T. Li, D.Y. Shao, in progress

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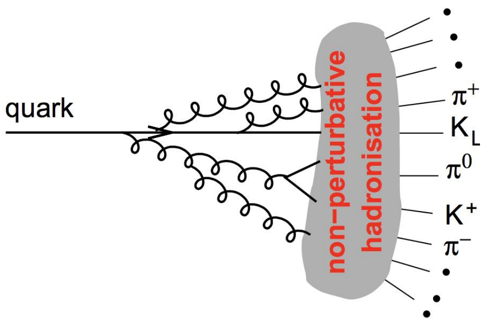
Jets in Particle Collisions

- Particle Collisions
  - proton–proton (pp) and proton–nucleus (pA) collisions
  - RHIC and LHC
  - the fundamental structure of matter and the strong interaction among its constituents

- Jets: tightly collimated sprays of particles, emerge from the fragmentation of quarks and gluons
  - Short–Distance Dynamics (Perturbative QCD)
  - Parton Shower and QCD Radiation
  - Hadronization
  - azimuthal angular distribution



Infrared and collinear

Dijet in pp and pA Collisions

Dijet pseudorapidity spectrum: collinear factorization (PDFs) (Martin, Stirling, Thorne & Watt ’09 EPJC)

From pp to pA collisions:

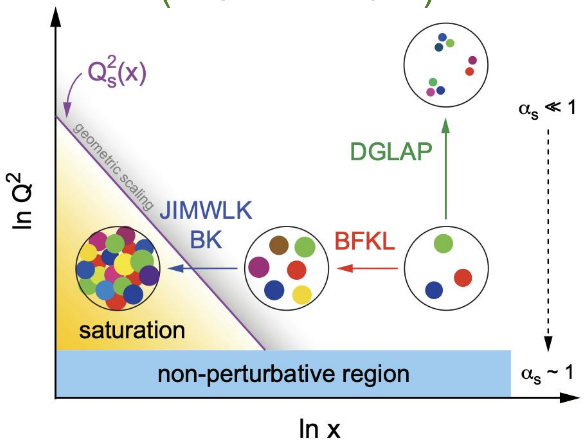
- DGLAP-based approach
  - PDFs –> nuclear modified PDFs (nPDFs) (Eskola, Paukkunen & Salgado ’13 JHEP)
  - nuclear modification: parameterization of the initial conditions for the DGLAP evolution
- Color glass condensate (CGC) approach
  - gluon mergers and interactions dynamically lead to the nonlinear BK–JIMWLK evolution equations (Marquet ’07 NPA + Kang, Qiu ’13 PLB)

- Encode nuclear modification of back-to-back dijet production inside nTMDPDFs

(Alrashed, Anderle, Kang, Terry & Xing '22 PRL)

(Barry, Gamberg, Melnitchouk et al. ‘23)

(EIC’16 EPJA)



Dijet azimuthal decorrelation

- Diverges due to logarithmic singularities at $\delta\phi \to 0$

(Banfi, Dasgupta & Delenda '08 PLB + Hautman & Jung '08 JHEP)

- All-order resummation: TMD-like factorization

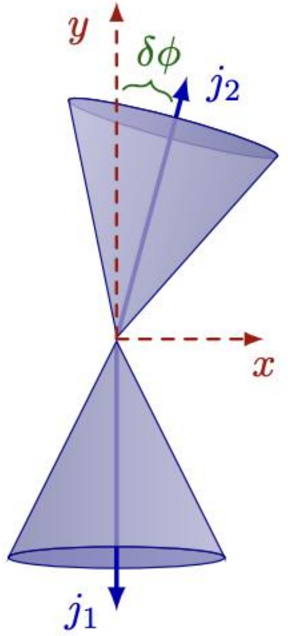
(Sun, Yuan , Yuan '14 PRL)

  - TMDPDFs (RHIC and LHC)

- Experimental measurements:
  - pp (CMS '14 PRL)
  - pPb (CMS '14 EPJC)
  - constrain nPDFS (nNNPDF3.0 EPPS16)

  (integrated azimuthal angular decorrelations and pseudorapidity spectrum)

- Simultaneous extraction of both collinear and transverse momentum effects in bound nucleons inside the heavy nucleus



Definition of the azimuthal angular δϕ of dijet pair production in the x-y plane

$\delta\phi = \pi - \Delta\phi \to 0 \qquad R \ll 1$

Factorization in SCET

(Becher, Neubert, Rothen & Shao '16 PRL)

- Indirect methods
  (Sun, Yuan & Yuan '13 PRL)
  - extraction of qT
  - induce divergences for R <<1
    (Chien, Shao & Wu '19 JHEP)

- Direct methods
  (Banfi, Dasgupta & Delenda '08 PLB)
  (Zhang, Dai & Shao '23 JHEP)
  - azimuthal angular distribution

In the back-to-back limit and with the narrow jet cone, the QCD modes which contribute to the cross section

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

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

$$\textbf{soft}: \; p_s^\mu \sim p_T\,(\delta\phi, \delta\phi, \delta\phi),$$

$$n_{c,d}\textbf{-collinear}: \; p_{c_i}^\mu \sim p_T\,(R^2, 1, R)_{n_i\bar{n}_i},$$

$$n_{c,d}\textbf{-collinear-soft}: \; p_{cs_i}^\mu \sim \frac{p_T\,\delta\phi}{R}(R^2, 1, R)_{n_i\bar{n}_i},$$

rapidity divergences

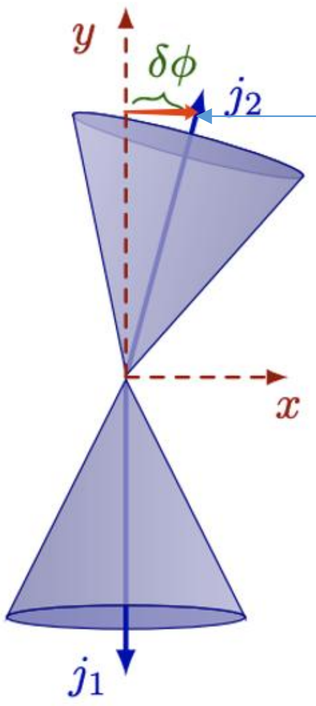
Factorization in SCET

- Factorization formula: (Becher, Broggio & Ferroglia '15 LNP)

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}q_x} = \sum_{abcd} \frac{x_a x_b}{16\pi \hat{s}^2} \frac{1}{1+\delta_{cd}} \mathcal{C}_x \left[f_{a/p}^{\mathrm{unsub}} f_{b/p}^{\mathrm{unsub}} \boldsymbol{S}_{ab\to cd,IJ}^{\mathrm{unsub}} S_c^{\mathrm{cs}} S_d^{\mathrm{cs}} \right]$$

$$\times\ \boldsymbol{H}_{ab\to cd,JI}(\hat{s},\hat{t},\mu)\, J_c(p_T R,\mu)\, J_d(p_T R,\mu)\,,$$

(Kelley & Schwartz '11 PRD)



$|q_x| = p_T \delta\phi$

$$\left|\mathcal{M}_{ab\to cd}(\hat{s},\hat{t};\mu)\right\rangle = \sum_I \frac{1}{\langle \mathcal{C}_I \mathcal{C}_I \rangle} \mathcal{M}_{ab\to cd}^I(\hat{s},\hat{t};\mu)\, |\mathcal{C}_I\rangle$$

$$\left|\mathcal{M}_{ab\to cd}^H(\hat{s},\hat{t};\mu)\right\rangle = \left|\mathcal{M}_{ab\to cd}(\hat{s},\hat{t};\mu)\right\rangle - \sum_i \left|\mathcal{M}_{ab\to cd}^i(\hat{s},\hat{t};\mu)\right\rangle$$

IR modes ⟷ $\boldsymbol{Z}_H(\hat{s},\hat{t};\mu)$ UV subtracted

$$\frac{\partial}{\partial \ln\mu} \left|\mathcal{M}_{ab\to cd}^{H\,\mathrm{sub}}(\hat{s},\hat{t};\mu)\right\rangle = \boldsymbol{\Gamma}_H(\hat{s},\hat{t};\mu) \left|\mathcal{M}_{ab\to cd}^{H\,\mathrm{sub}}(\hat{s},\hat{t};\mu)\right\rangle$$

$$\boldsymbol{\Gamma}_H(\hat{s},\hat{t};\mu) = \left[\frac{\partial}{\partial \ln\mu} \boldsymbol{Z}_H(\hat{s},\hat{t};\mu)\right] \boldsymbol{Z}_H^{-1}(\hat{s},\hat{t};\mu)$$

RG evolution and resummation formula

- Hard function satisfies RG equation

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\boldsymbol{H} = \boldsymbol{\Gamma}_H \boldsymbol{H} + \boldsymbol{H}\,\boldsymbol{\Gamma}_H^\dagger$$

- The anomalous dimension

$$\boldsymbol{\Gamma}_{H_{ab\to cd}} = \left[\frac{C_H}{2}\gamma_{\rm cusp}(\alpha_s)\left(\ln\frac{\hat{s}}{\mu^2} - i\pi\right) + \gamma_H(\alpha_s)\right]\mathbf{1} + \gamma_{\rm cusp}(\alpha_s)\boldsymbol{M}_{ab\to cd},$$

$$C_H = n_q C_F + n_g C_A \qquad\qquad \gamma_H = n_q\gamma_q + n_g\gamma_g$$

$$\boldsymbol{M}_{ab\to cd} = (\ln r + i\pi)\,\boldsymbol{M}_{1,ab\to cd} + \ln\frac{r}{1-r}\boldsymbol{M}_{2,ab\to cd},$$

(Broggio, Ferroglia, Pecjak & Zhang ’14 JHEP)

RG evolution and resummation formula

- The jet functions satisfies the RG equation

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu} J_i\left(p_T R, \mu\right) = \Gamma^{J_i}(\alpha_s) J_i\left(p_T R, \mu\right) \qquad \Gamma^{J_i}(\alpha_s) = -C_i \gamma_{\mathrm{cusp}}(\alpha_s) \ln\frac{p_T^2 R^2}{\mu^2} + \gamma^{J_i}(\alpha_s)$$

the leading logarithmic (LL) NGLs are resumed by a fitting function (Dasgupta & Salam ’01 PLB)

- the properly-defined TMDPDFs are obtained

$$\tilde{f}_{a/p}^{\mathrm{unsub}}\left(x_a, b, \mu, \zeta_a/\nu^2\right) \tilde{f}_{b/p}^{\mathrm{unsub}}\left(x_b, b, \mu, \zeta_b/\nu^2\right) \tilde{S}_{ab}(b, \mu, \nu) \equiv \tilde{f}_{a/p}\left(x_a, b, \mu, \zeta_a\right) \tilde{f}_{b/p}\left(x_b, b, \mu, \zeta_b\right)$$

(Boussarie et al. ’23)

$$\sqrt{\zeta_a}\frac{\mathrm{d}}{\mathrm{d}\sqrt{\zeta_a}} \tilde{f}_{a/p}(x_a, b, \mu, \zeta_a) = \tilde{\kappa}_a(b, \mu) \tilde{f}_{a/p}(x_a, b, \mu, \zeta_a)$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu} \tilde{f}_{a/p}(x_a, b, \mu, \zeta_{a,f}) = \left[C_a \gamma_{\mathrm{cusp}}(\alpha_s) \ln\frac{\mu^2}{\zeta_{a,f}} - 2\gamma_a(\alpha_s)\right] \tilde{f}_{a/p}(x_a, b, \mu, \zeta_{a,f})$$

RG evolution and resummation formula

- Using the collinear anomaly framework, we define soft function W

(Becher & Neubert ’11 EPJC)

$$\boldsymbol{W}_{ab\to cd}(b,\mu)R^{2F_{cd}(b,\mu)} \equiv \boldsymbol{S}^{\text{unsub}}_{ab\to cd}(b,\mu,\nu)\,\tilde{S}^{\text{cs}}_c(b,R,\mu,\nu)\,\tilde{S}^{\text{cs}}_d(b,R,\mu,\nu)/S_{ab}(b,\mu,\nu)$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}F_{cd}(b,\mu) = (C_c + C_d)\gamma_{\text{cusp}}(\alpha_s),$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\boldsymbol{W}(b,\mu) = \boldsymbol{\Gamma}^\dagger_W \boldsymbol{W}(b,\mu) + \boldsymbol{W}(b,\mu)\boldsymbol{\Gamma}_W$$

$$\tilde{\boldsymbol{s}}^{(0)} = \begin{pmatrix} N^2 & 0 \\ 0 & \frac{C_F N}{2} \end{pmatrix} \qquad \tilde{\boldsymbol{s}}^{(0)} = V\begin{pmatrix} N & 0 & 0 \\ 0 & \frac{N}{2} & 0 \\ 0 & 0 & \frac{N^2-4}{2N} \end{pmatrix}$$

$$\tilde{\boldsymbol{s}}^{(0)} = \frac{V}{N^2}\begin{pmatrix} C_1 & C_2 & C_2 & C_2 & C_2 & C_3 & NV & -N & NV \\ C_2 & C_1 & C_2 & C_2 & C_3 & C_2 & NV & NV & -N \\ C_2 & C_2 & C_1 & C_3 & C_2 & C_2 & -N & NV & NV \\ C_2 & C_2 & C_3 & C_1 & C_2 & C_2 & -N & NV & NV \\ C_2 & C_3 & C_2 & C_2 & C_1 & C_2 & NV & NV & -N \\ C_3 & C_2 & C_2 & C_2 & C_2 & C_1 & NV & -N & NV \\ NV & NV & -N & -N & NV & NV & N^2V & N^2 & N^2 \\ -N & NV & NV & NV & NV & -N & N^2 & N^2V & N^2 \\ NV & -N & NV & NV & -N & NV & N^2 & N^2 & N^2V \end{pmatrix},$$

- Obtain the RG invariance of the cross section as

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\mathrm{Tr}\left[\boldsymbol{H}_{ab\to cd}\boldsymbol{W}_{ab\to cd}\right] R^{2F_{cd}}\tilde{f}_{a/p}\tilde{f}_{b/p}J_cJ_d = 0$$

RG evolution and resummation formula

- NLL expression for azimuthal angular distribution

$$
\frac{\mathrm{d}^4\sigma_{pp}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}\delta\phi} = \sum_{abcd} \frac{p_T}{16\pi\hat{s}^2}\frac{1}{1+\delta_{cd}}\int_0^\infty \frac{2\mathrm{d}b}{\pi}\cos(bp_T\delta\phi)x_a\tilde{f}_{a/p}(x_a,\mu_{b_*})x_b\tilde{f}_{b/p}(x_b,\mu_{b_*})
$$

$$
\times \exp\left\{-\int_{\mu_{b*}}^{\mu_h}\frac{\mathrm{d}\mu}{\mu}\left[\gamma_{\mathrm{cusp}}(\alpha_s)C_H\ln\frac{\hat{s}}{\mu^2}+2\gamma_H(\alpha_s)\right]\right\}
$$

$$
\times \sum_{KK'}\exp\left[-\int_{\mu_{b*}}^{\mu_h}\frac{\mathrm{d}\mu}{\mu}\gamma_{\mathrm{cusp}}(\alpha_s)(\lambda_K+\lambda_{K'}^*)\right]H_{KK'}\left(\hat{s},\hat{t},\mu_h\right)W_{K'K}\left(b_*,\mu_{b_*}\right)
$$

$$
\times \exp\left[-\int_{\mu_{b*}}^{\mu_j}\frac{\mathrm{d}\mu}{\mu}\Gamma^{J_c}(\alpha_s)-\int_{\mu_{b*}}^{\mu_j}\frac{\mathrm{d}\mu}{\mu}\Gamma^{J_d}(\alpha_s)\right]U_{\mathrm{NG}}^c(\mu_{b*},\mu_j)\,U_{\mathrm{NG}}^d(\mu_{b*},\mu_j)
$$

$$
\times \exp\left[-S_{\mathrm{NP}}^a(b,Q_0,\sqrt{\hat{s}})-S_{\mathrm{NP}}^b(b,Q_0,\sqrt{\hat{s}})\right].
$$

(Chien, Shao & Wu ’19 JHEP)

Hard: PT → Jet: PT*R → Soft & Beam μb*

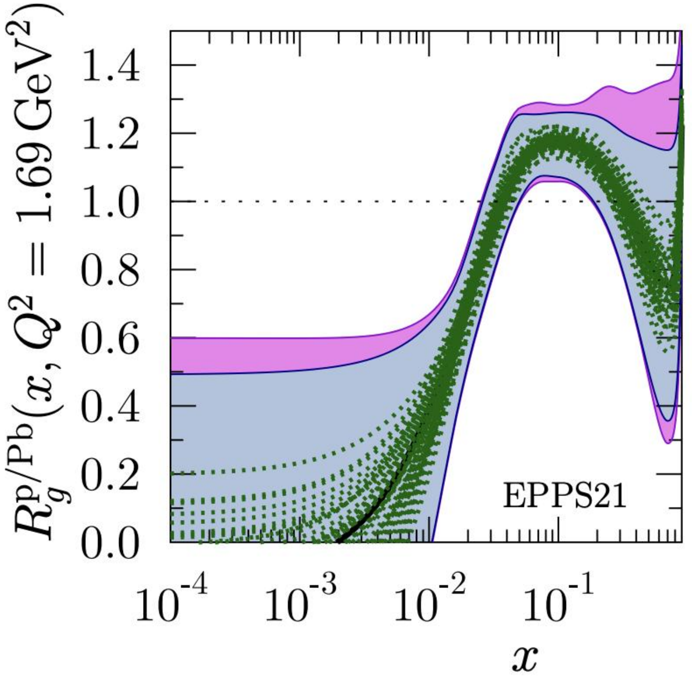
p-p and p-A

- PDF:

  CT14nlo -> EPPS16nlo_CT14nlo_Pb208

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q).$$

(Eskola, Paakkinen, Paukkunen & Salgado ‘22 EPJC)



- the non-perturbative Sudakov

(Alrashed, Anderle, Kang, Terry & Xing '22 PRL)

$$S_{\mathrm{NP}}^{a,b}(b, Q_0, Q) = g_1^f b^2 + \frac{g_2}{2}\frac{C_{a,b}}{C_F} \ln\frac{Q}{Q_0} \ln\frac{b}{b_*}$$

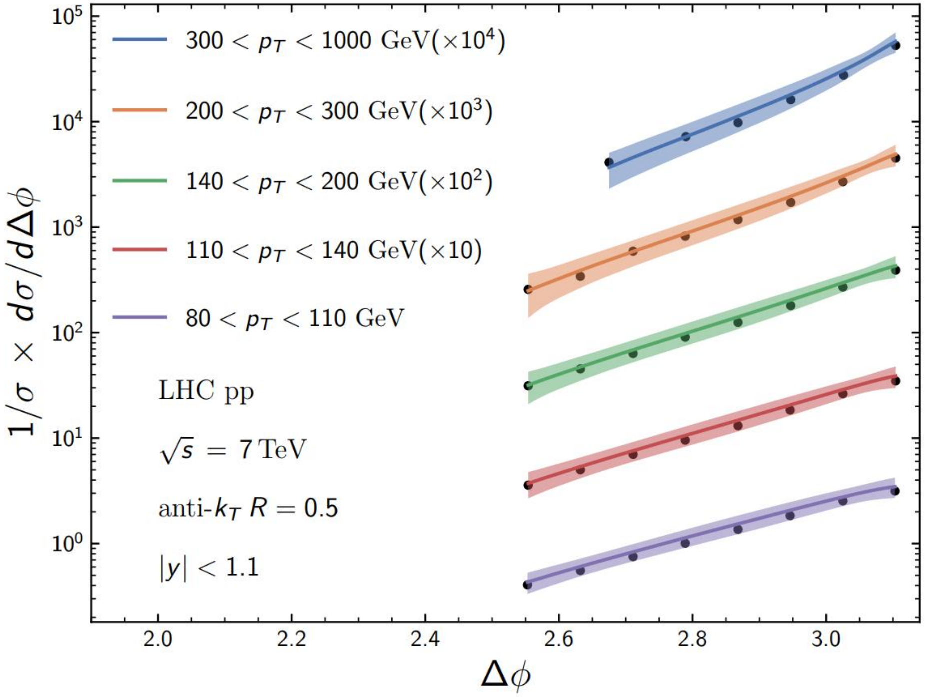
⬇

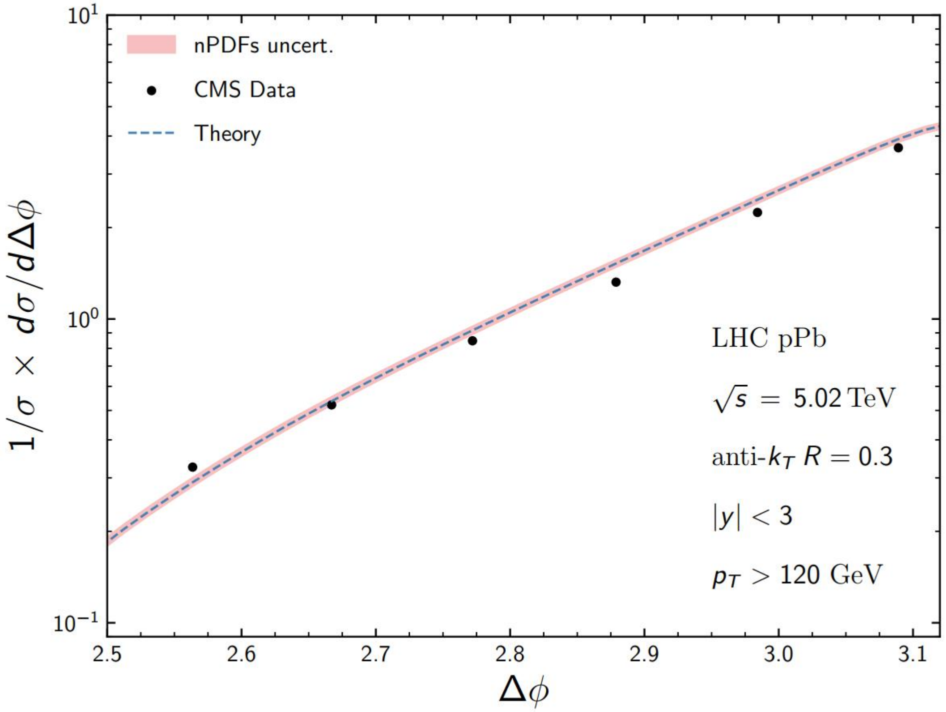
$$S_{\mathrm{NP}}^{b,A}(b, Q_0, Q) = g_1^A b^2 + \frac{g_2}{2}\frac{C_{a,b}}{C_F} \ln\frac{Q}{Q_0} \ln\frac{b}{b_*}.$$

$$g_1^A = g_1^f + a_N L \qquad L = A^{1/3} - 1$$

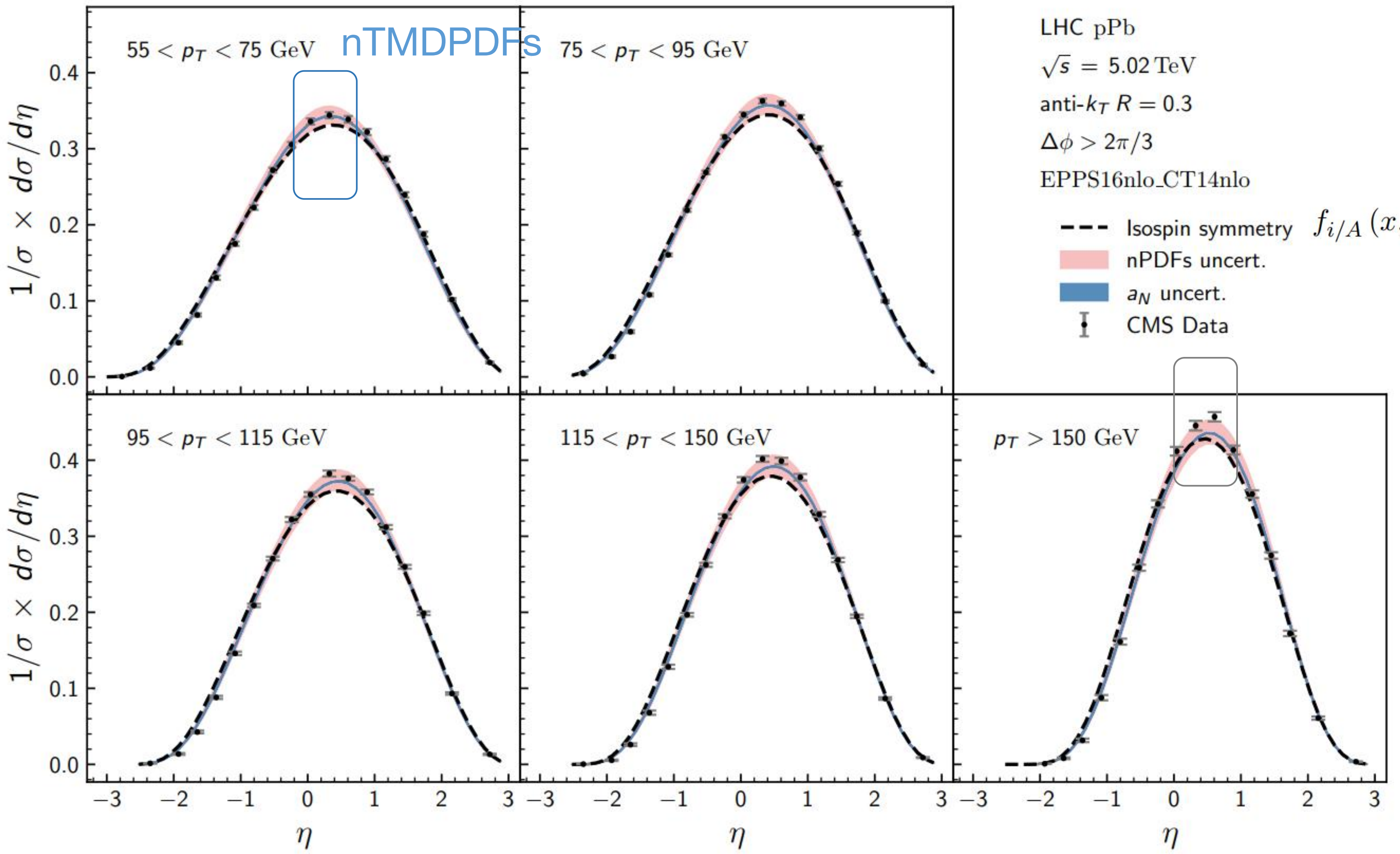
The azimuthal decorrelation

MSG, Kang, Shao, Terry, Zhang ‘23 JHEP

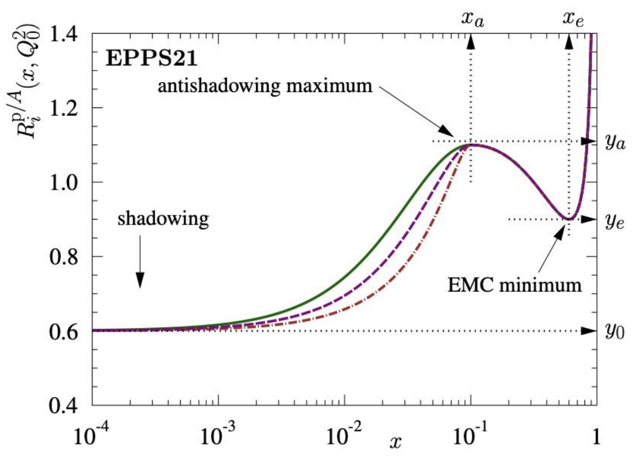




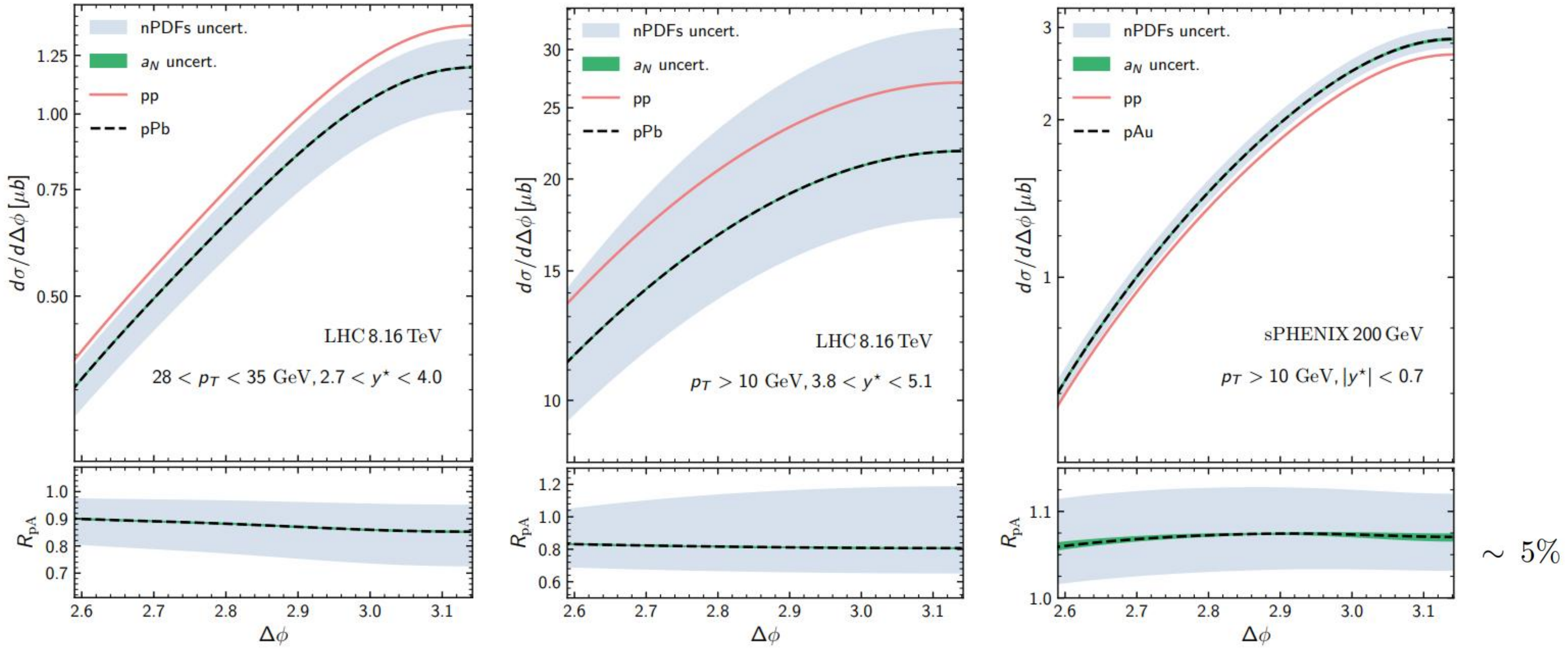
Left: Comparison between theoretical calculations of the azimuthal decorrelation with the CMS data
Right: A comparison of the dijet azimuthal angle decorrelation in pPb collisions from the CMS collaboration



$$f_{i/A}(x,\mu) = \frac{Z}{A} f_{i/p}(x,\mu) + \frac{A-Z}{A} f_{i/n}(x,\mu)$$



Theoretical calculations for dijet integrated angular decorrelation plotted as a function of the pseudorapidity ETA are compared with the CMS data in proton-lead collisions for different kinematic cuts.

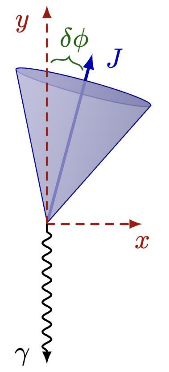


Top: The azimuthal angular distribution in pp (red curve) and pA (black curve) collisions for ATLAS (Left), ALICE (Middle), and sPHENIX (Right).

In the lower panel, we plot the nuclear modification factor RpA.

Isolated photon−jet correlations: Factorization and resummation for the standard jet axis

$$\frac{d\sigma_{pp}^{\rm SJA}}{dq_x\, dp_T\, dy_\gamma\, dy_J} = \sum_{i,j,k} H_{ij\to\gamma k}(p_T, y_\gamma, y_J, \mu) \int \frac{db}{2\pi} e^{ibq_x} f_{i/p}^{(u)}(x_1, b, \mu, \zeta_i/\nu^2) f_{j/p}^{(u)}(x_2, b, \mu, \zeta_j/\nu^2)$$
$$\times J_k(p_T R, \mu) C_k^{(u)}(b, \mu, \zeta_k/\nu^2) S_{ijk}^{(u)}(b, y_\gamma, y_J, \mu, \nu)\,,$$



renormalization and rapidity scales

RG and RRG consistence relation

$$\gamma_\mu^{H_{ij\to\gamma k}} + \gamma_\mu^{S_{ijk}^{(u)}} + \gamma_\mu^{f_i^{(u)}} + \gamma_\mu^{f_j^{(u)}} + \gamma_\mu^{J_k} + \gamma_\mu^{C_k^{(u)}} = 0,$$
$$\gamma_\nu^{S_{ijk}^{(u)}} + \gamma_\nu^{f_i^{(u)}} + \gamma_\nu^{f_j^{(u)}} + \gamma_\nu^{C_k^{(u)}} = 0.$$

n_i **collinear** : $p_{c_i}^\mu \sim p_T(\delta\phi^2, 1, \delta\phi)_i\,,$

n_j **collinear** : $p_{c_j}^\mu \sim p_T(\delta\phi^2, 1, \delta\phi)_j\,,$

n_k **collinear** : $p_{c_k}^\mu \sim p_T(R^2, 1, R)_k\,,$

n_k **collinear-soft** : $p_{cs_k}^\mu \sim p_T\delta\phi/R(R^2, 1, R)_k\,,$

soft : $p_s^\mu \sim p_T(\delta\phi, \delta\phi, \delta\phi)\,,$

Factorization and resummation for the standard jet axis

At NLL:

$$\frac{d\sigma_{pA}^{\mathrm{SJA}}}{d\delta\phi\, dp_T\, dy_\gamma\, dy_J} = \sum_{i,j,k} \int_0^\infty \frac{db}{\pi} 2\cos(bp_T\delta\phi)$$

$$\times \exp\left[-\int_{\mu_{b_*}}^{\mu_h} \frac{d\mu}{\mu} \gamma_\mu^{\mathcal{H}_{ij\to\gamma k}}(\alpha_s)\right] \mathcal{H}_{ij\to\gamma k}(p_T, y_\gamma, y_J, \mu_h)$$

$$\times \exp\left[-\int_{\mu_{b_*}}^{\mu_j} \frac{d\mu}{\mu} \gamma_\mu^{J_k}(\alpha_s)\right] f_{i/p}(x_1, \mu_{b_*})\, f_{j/A}(x_2, \mu_{b_*})$$

$$\times \exp\left[-S_{\mathrm{NP}}^{i}(b, Q_0, \omega_i) - S_{\mathrm{NP}}^{j,A}(b, Q_0, \omega_j)\right]$$

$$\times U_{\mathrm{NG}}^{k}(\mu_{b_*}, \mu_j)$$

Hard: PT → Jet: PT*R → Soft & Beam μb*

Factorization and resummation for the winner-take-all axis

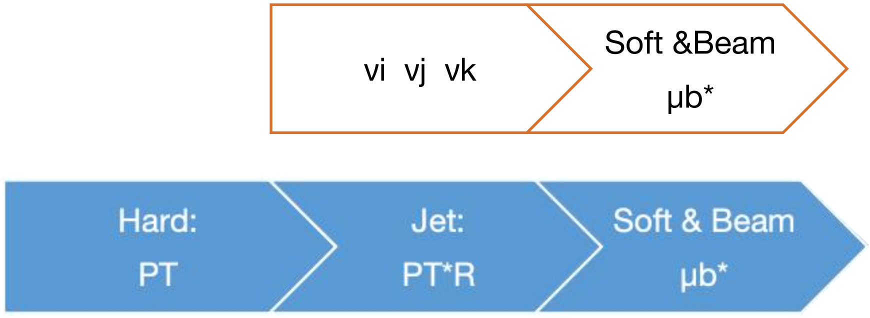
$$\frac{\mathrm{d}\sigma_{pp}^{\mathrm{WTA}}}{\mathrm{d}q_x\,\mathrm{d}p_T\,\mathrm{d}y_\gamma\,\mathrm{d}y_J} = \sum_{i,j,k} H_{ij\to\gamma k}(p_T,y_\gamma,y_J,\mu)\int\frac{\mathrm{d}b}{2\pi}e^{ibq_x} f_{i/p}^{(u)}(x_1,b,\mu,\zeta_i/\nu^2)\, f_{j/p}^{(u)}(x_2,b,\mu,\zeta_j/\nu^2)$$
$$\times\, J_k^{(u)}(b,\mu,\zeta_k/\nu^2)\, S_{ijk}^{(u)}(b,y_\gamma,y_J,\mu,\nu)\;,$$

the WTA jet function

$$n_i\ \textbf{collinear}:\ p_{c_i}^\mu \sim p_T(\delta\phi^2,1,\delta\phi)_i,$$
$$n_j\ \textbf{collinear}:\ p_{c_j}^\mu \sim p_T(\delta\phi^2,1,\delta\phi)_j,$$
$$n_k\ \textbf{collinear}:\ p_{c_k}^\mu \sim p_T(\delta\phi^2,1,\delta\phi)_k,$$
$$\textbf{soft}\ :\ p_s^\mu \sim p_T(\delta\phi,\delta\phi,\delta\phi),$$

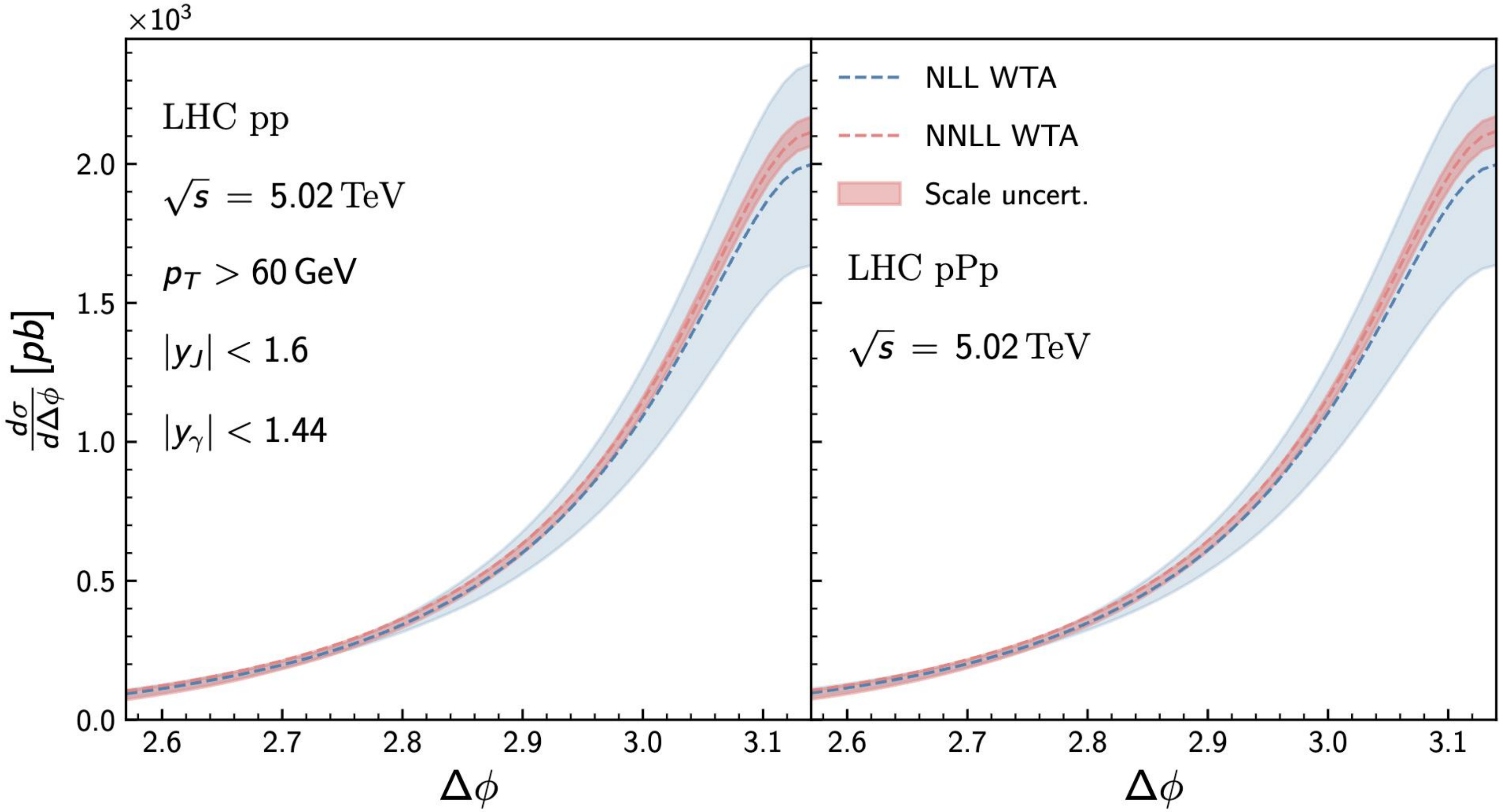
At NNLL :

$$\frac{\mathrm{d}\sigma_{pp}^{\mathrm{WTA}}}{\mathrm{d}\delta\phi\ \mathrm{d}p_T\ \mathrm{d}y_\gamma\ \mathrm{d}y_J} = \sum_{i,j,k}\int_0^\infty \frac{\mathrm{d}b}{\pi} 2\cos(bp_T\delta\phi)\prod_{a=ijk}\left(\frac{\zeta_a}{\zeta_s}\right)^{\frac{1}{2}\gamma_\zeta^a(\mu_{b_*},b)}$$
$$\times \exp\left[-\int_{\mu_{b_*}}^{\mu_h}\frac{\mathrm{d}\mu}{\mu}\gamma_\mu^{H_{ij\to\gamma k}}(\alpha_s)\right] H_{ij\to\gamma k}(p_T,y_\gamma,y_J,\mu_h)$$
$$\times\, f_{i/p}^{\mathrm{TMD}}(x_1,b,\mu_{b_*},\zeta_s)\, f_{j/p}^{\mathrm{TMD}}(x_2,b,\mu_{b_*},\zeta_s)\, J_k^{\mathrm{TMD}}(b,\mu_{b_*},\zeta_s)$$
$$\times\, \mathcal{S}_{ijk}(b,\mu_{b_*})\exp\left[-S_{\mathrm{NP}}^i(b,Q_0,\omega_i) - S_{\mathrm{NP}}^j(b,Q_0,\omega_j)\right].$$



Numerical Results

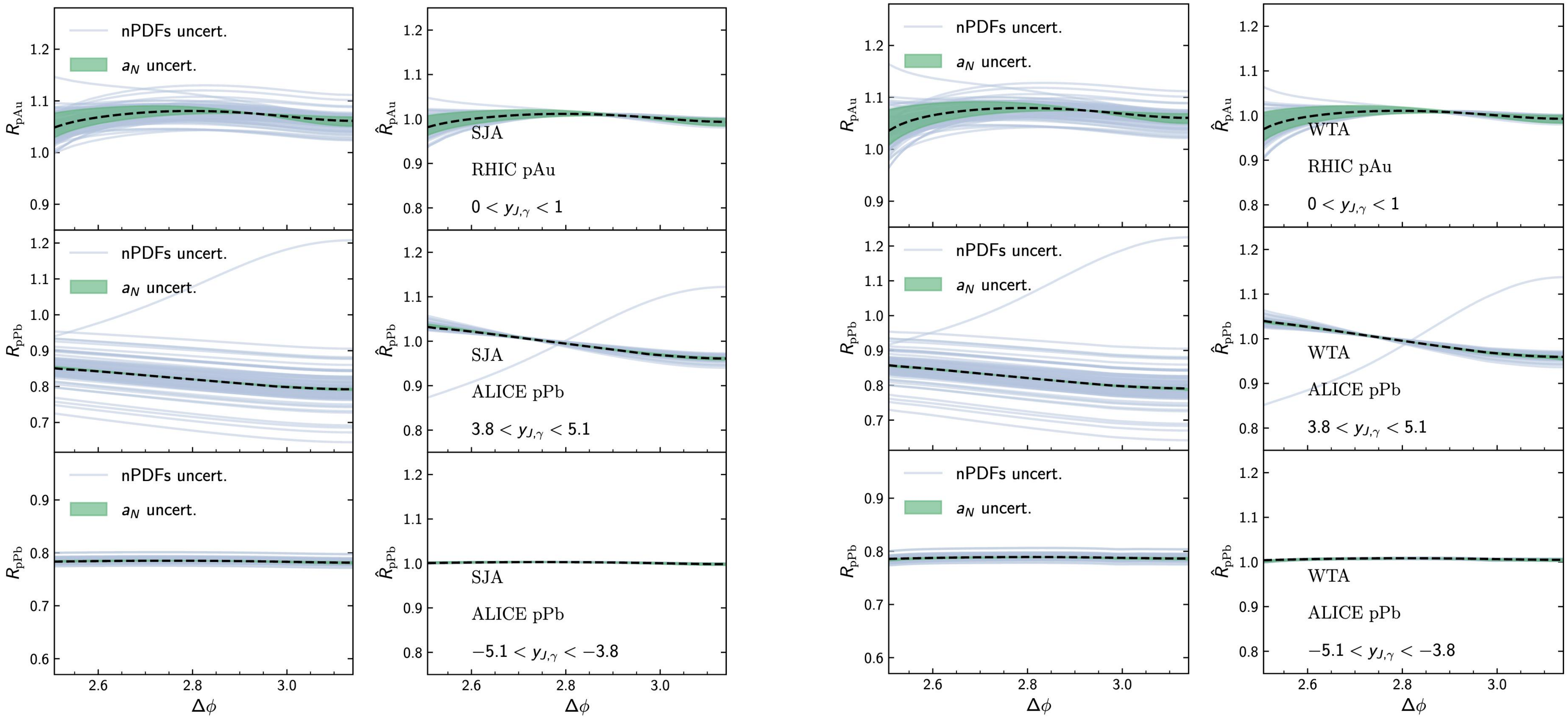
Fu, MSG, Shao, Xing   In progress



- The theory uncertainties are reduced from NLL to NNLL

Numerical Results

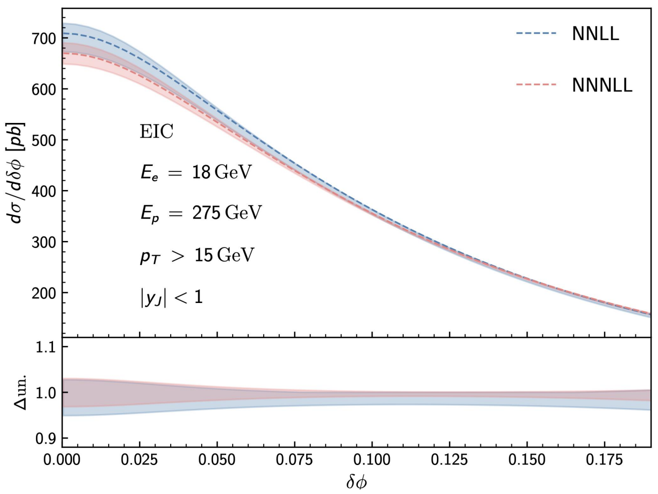
Fu, MSG, Shao, Xing   In progress

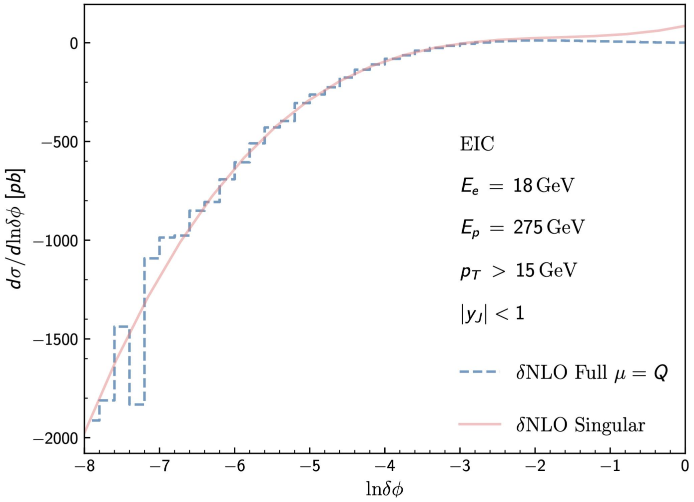


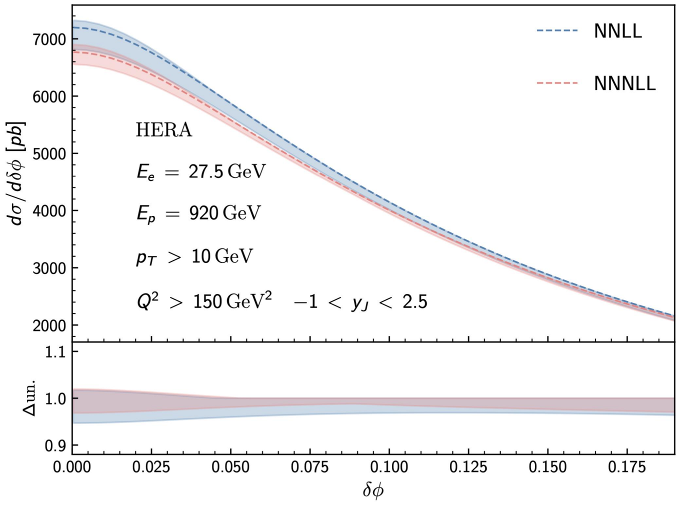
The normalized ratio R^pA effectively eliminates dependence on the nPDFs,

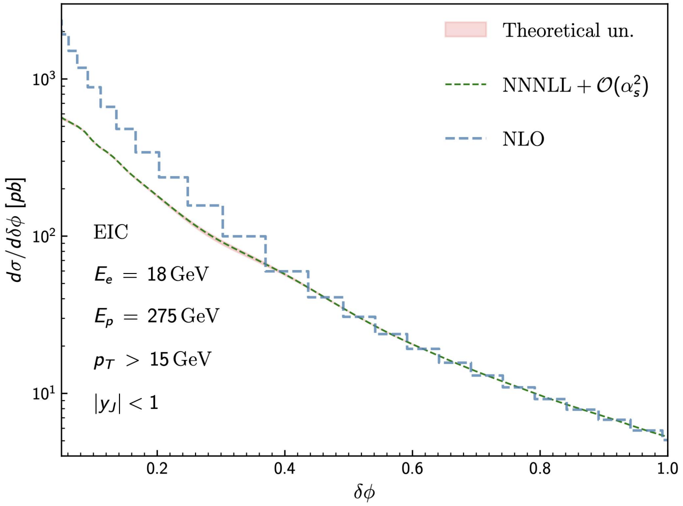
$N^3LL+O(\alpha_s^2)$ on lepton jet azimuthal correlation in DIS

Fang, MSG, Li, Shao In progress









Conclusion and outlook

- We derived a new resummation formula for the azimuthal decorrelation in dijet production in p-A collisions using SCET
  - found a strong agreement comparing to experiment
  - no significant TMD factorization breaking effects
  - predicts suppression of about 20% for the ATLAS and 30% for the ALICE and a small enhancement ~ 5% for the sPHENIX kinematics

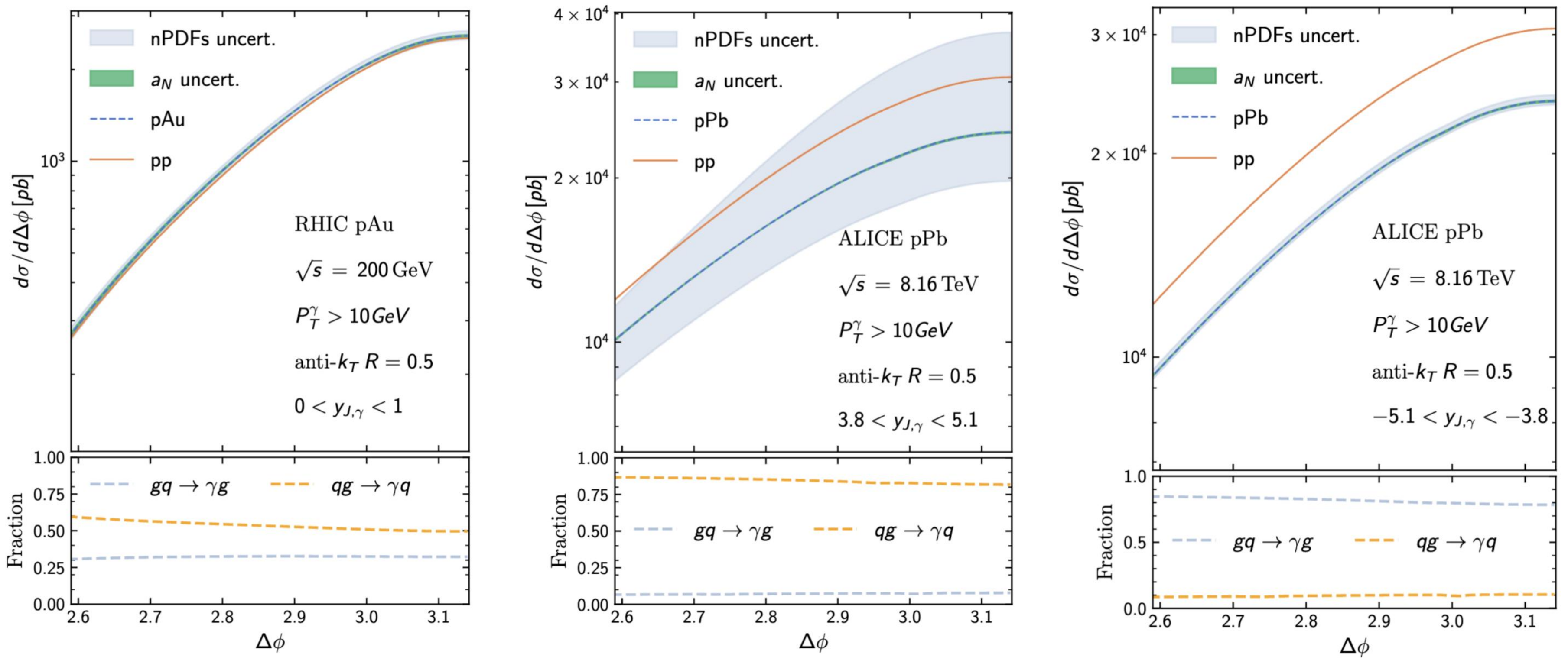
- We derived the resummation formula for the isolated photon-jet correlations at RHIC and LHC
  - SJA and the WTA scheme
  - validate our framework against CMS measurement
  - predictions to forward LHC and sPHENIX kinematics

- We have studied on the lepton-jet correlation in e-p collisions. Utilizing SCET, we derived a factorization theorem for back-to-back lepton-jet configurations. TMD resummation accuracy has been improved to N3LL + $O(\alpha_s^2)$ accuracy in e-p collisions.

- In the future, we anticipate following applications
  - extracting the 2-loop gluon jet function and utilizing trijet at NNLO to extract the 3-loop quark jet function.
  - perform a simultaneous fit to both collinear and transverse momentum dependent contributions to the nTMDPDFs
  - Incorporate the contributions from higher-order corrections (WTA N3LL at LHC and WTA N4LL at DIS)
  - generalize our formalism to describe dijet production in the polarized scattering

THANK YOU

Backup


nPDFs uncert.
a_N uncert.
pAu
pp
RHIC pAu
$\sqrt{s} = 200$ GeV
$P_T^\gamma > 10 GeV$
anti-k_T $R = 0.5$
$0 < y_{J,\gamma} < 1$
$d\sigma/d\Delta\phi\,[pb]$
10^3
1.00
0.75
0.50
0.25
0.00
Fraction
$gq \to \gamma g$
$qg \to \gamma q$
2.6
2.7
2.8
2.9
3.0
3.1
$\Delta\phi$
4×10^4
3×10^4
2×10^4
10^4
pPb
ALICE pPb
$\sqrt{s} = 8.16$ TeV
$3.8 < y_{J,\gamma} < 5.1$
$-5.1 < y_{J,\gamma} < -3.8$
1.0
0.5
0.0

Backup−Parameterization

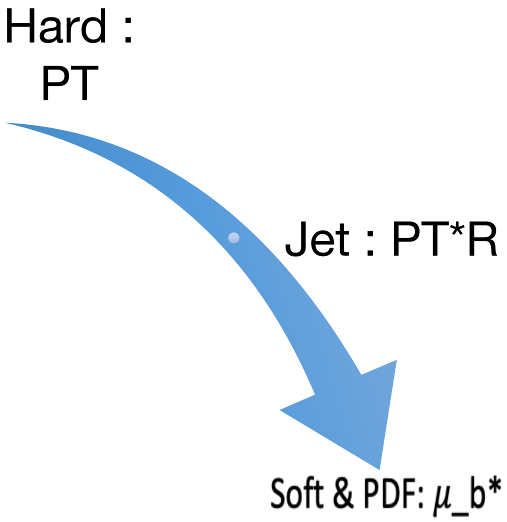
- the resummation of the NGLs

$$U^i_{\mathrm{NG}}\left(\mu_{b_*}, \mu_j\right) = \exp\left[-C_i C_A \frac{\pi^2}{3} u^2 \frac{1+(au)^2}{1+(bu)^c}\right]$$

square

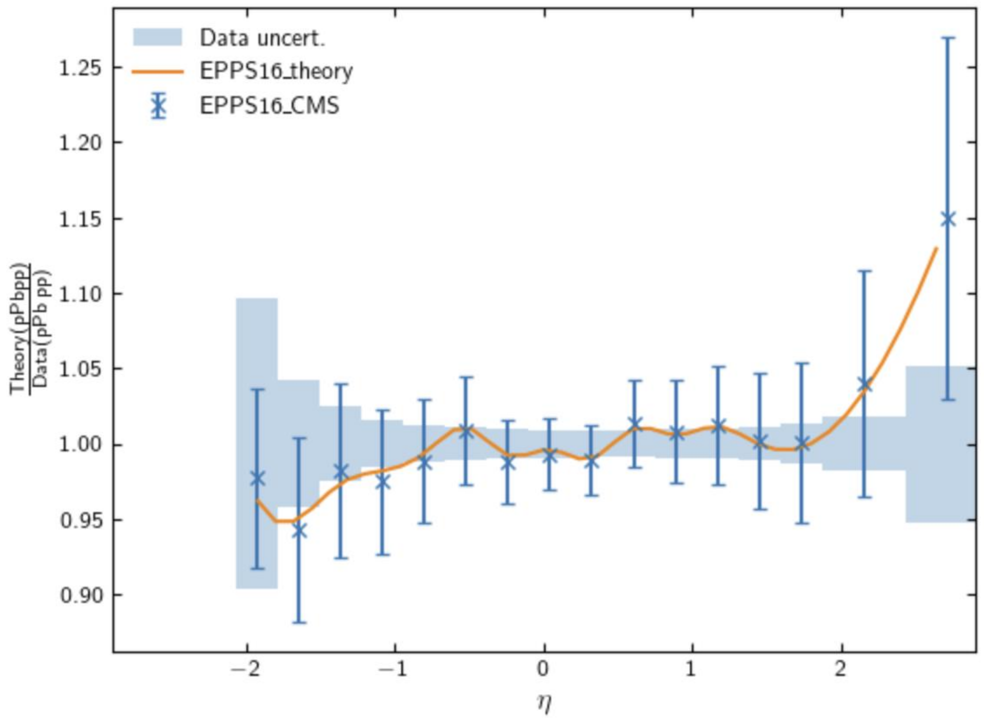
$$u = \ln[\alpha_s(\mu_{b_*})/\alpha_s(\mu_j)]/\beta_0, \; a = 0.85\, C_A, \; b = 0.86\, C_A \text{ and } c = 1.33$$

- the intrinsic scales in the resummation formula



$$\mu_h = p_T, \quad \mu_j = p_T R, \quad \mu_{b_*} = 2e^{-\gamma_E}/b_*.$$

$$b_* \equiv b/\sqrt{1+b^2/b^2_{\max}}.$$



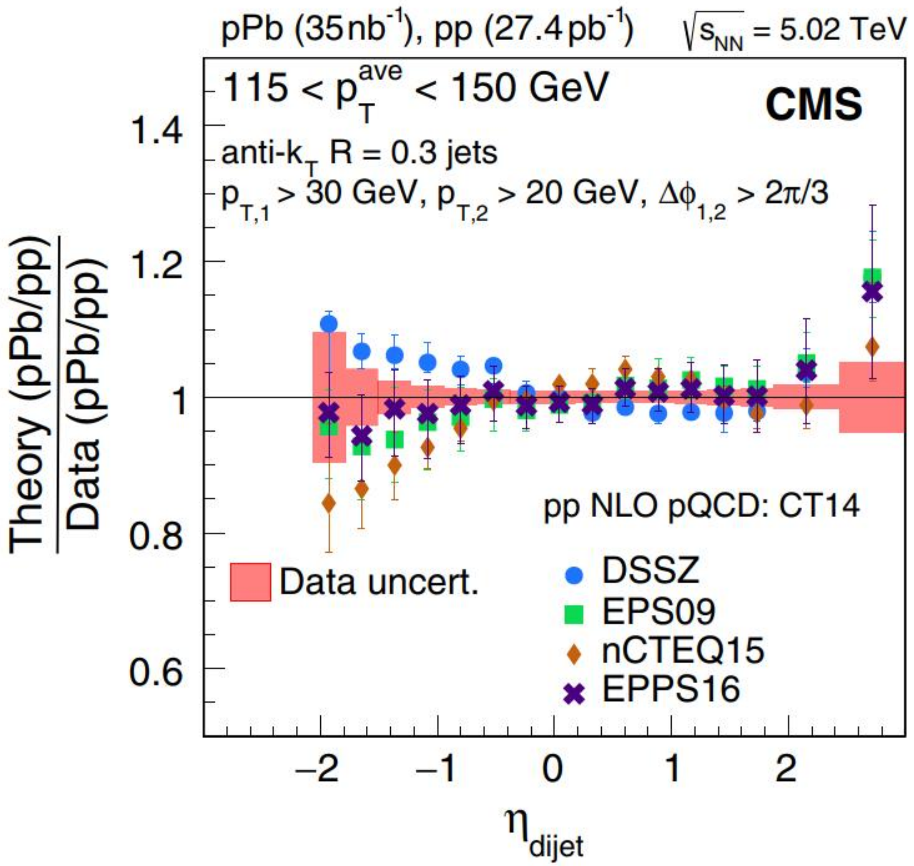


FIG. 3. Ratio of theory to data, for the ratio of the pPb to pp $\eta_{\rm dijet}$ spectra for $115 < p_T^{\rm ave} < 150$ GeV. Theory points are from the NLO pQCD calculations of DSSZ [18], EPS09 [14], nCTEQ15 [15], and EPPS16 [16] nPDFs, using CT14 [58] as the baseline PDF. Red boxes indicate the total (statistical and systematic) uncertainties in data, and the error bars on the points represent the nPDF uncertainties.