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

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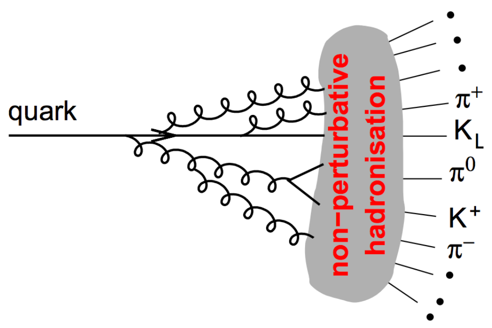
Jets in Particle Collisions

- 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:

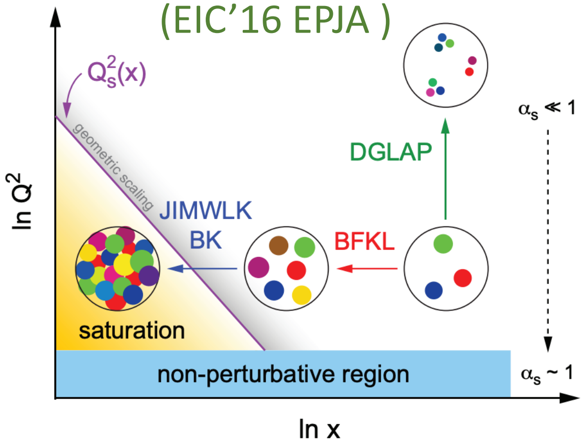
- DGLAP-based approach
  - PDFs -> nuclear modified PDFs (nPDFs) (Eskola, Paukkunen & Salgado '13 JHEP)
  - nuclear modification: parameterization of the initial conditions for the DGLAP evolution
- Color glass condensate (CGC) approach
  - gluon mergers and interactions dynamically lead to the nonlinear 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 $\delta\phi \rightarrow 0$

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

- All-order resummation: TMD-like factorization

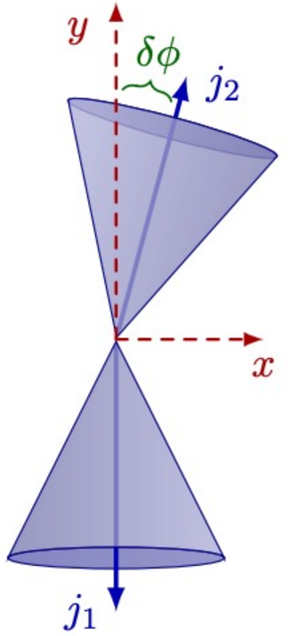
(Sun, Yuan , Yuan '14 PRL)

  - 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

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

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

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

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

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

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

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

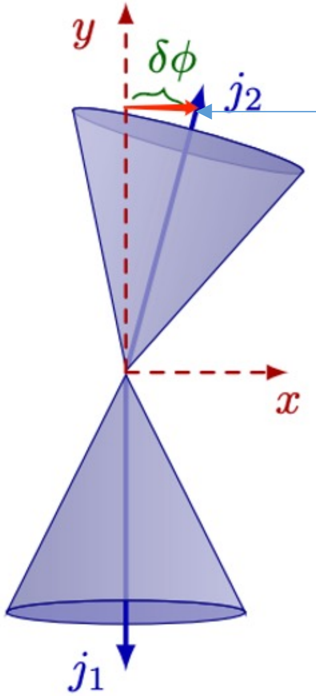
rapidity divergences

Factorization in SCET

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

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

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

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

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

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

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

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

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

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

RG evolution and resummation formula

- The jet functions satisfies the RG equation

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

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

- the properly-defined TMDPDFs are obtained

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

(Boussarie et al. '23)

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

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

RG evolution and resummation formula

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

(Becher & Neubert '11 EPJC)

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

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

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

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

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

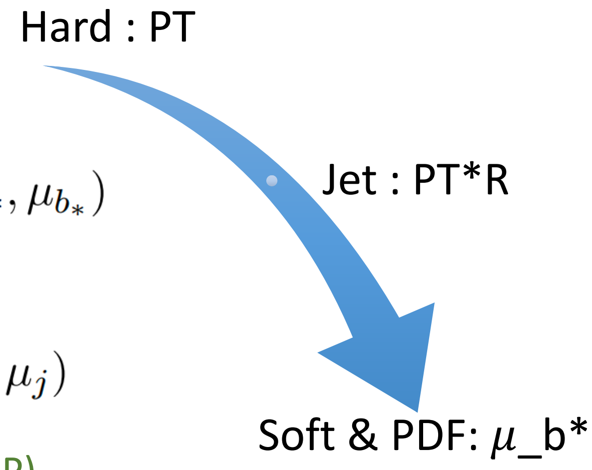
- Obtain the RG invariance of the cross section as

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

RG evolution and resummation formula

- NLL expression for azimuthal angular distribution

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



(Chien, Shao & Wu '19 JHEP)

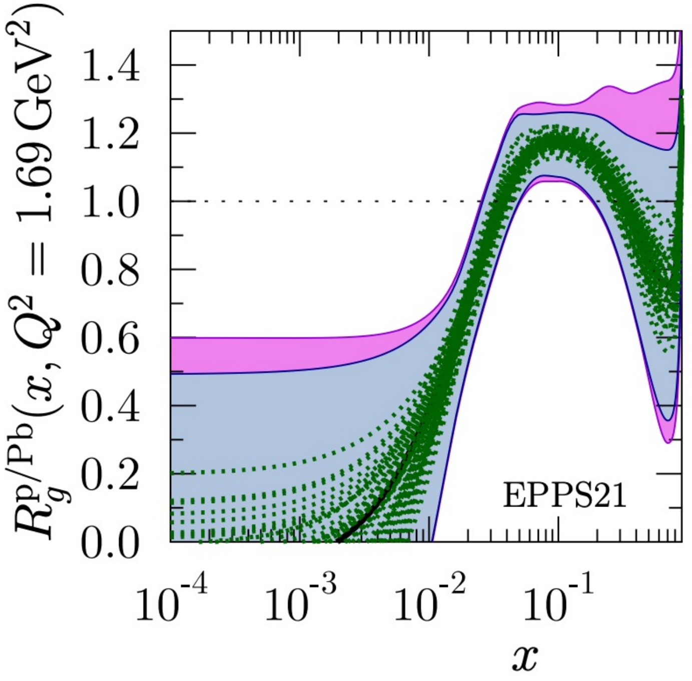
p-p and p-A

- 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)

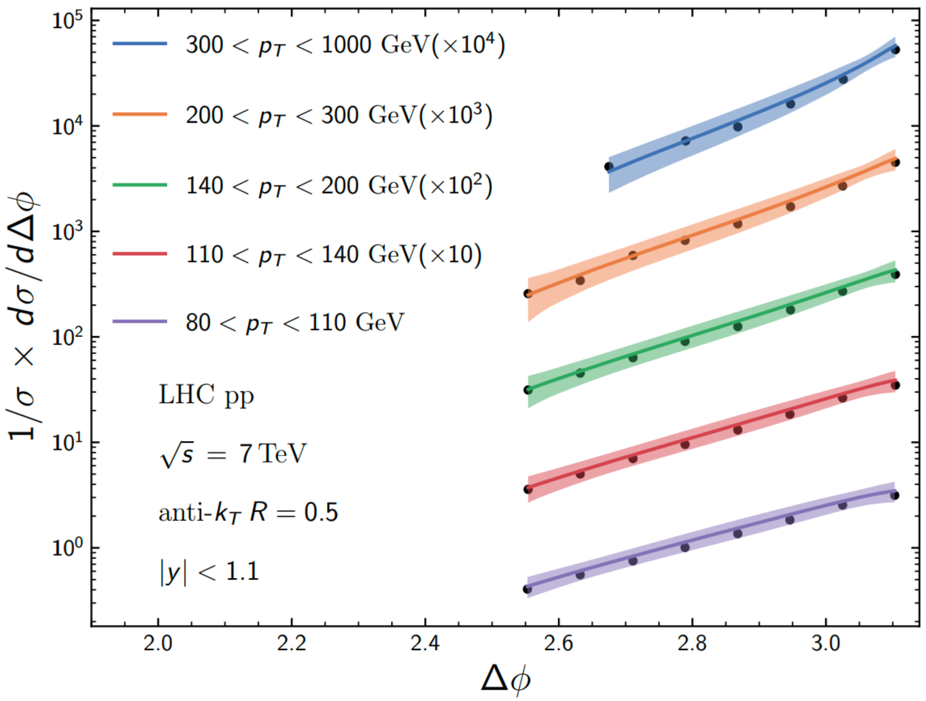
$$S_{\mathrm{NP}}^{a,b}(b,Q_0,Q) = g_1^f b^2 + \frac{g_2}{2}\frac{C_{a,b}}{C_F}\ln\frac{Q}{Q_0}\ln\frac{b}{b_*}$$

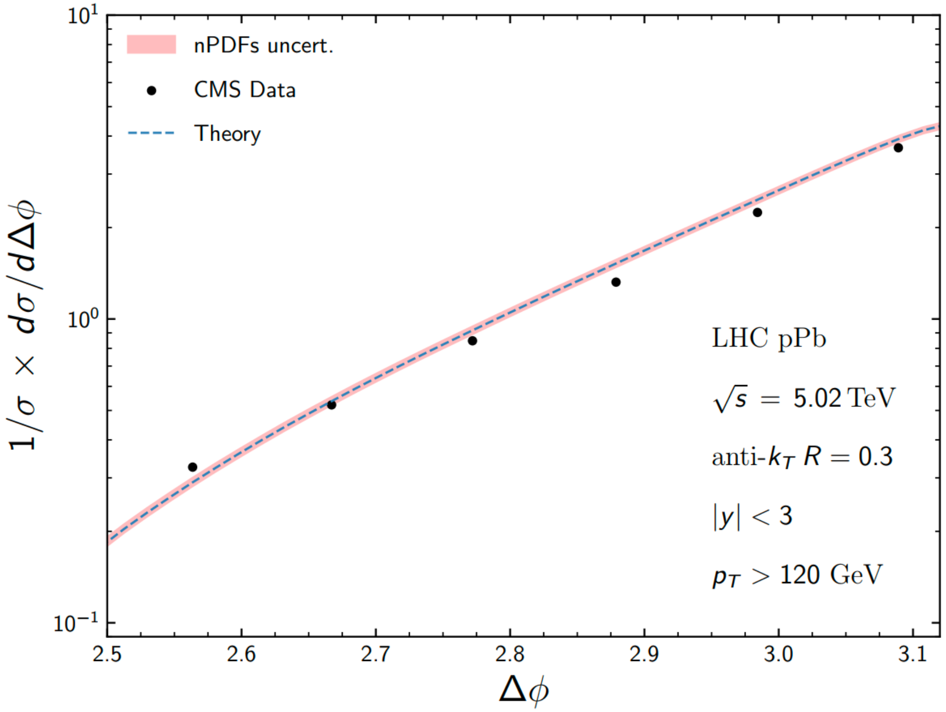
⇓

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

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

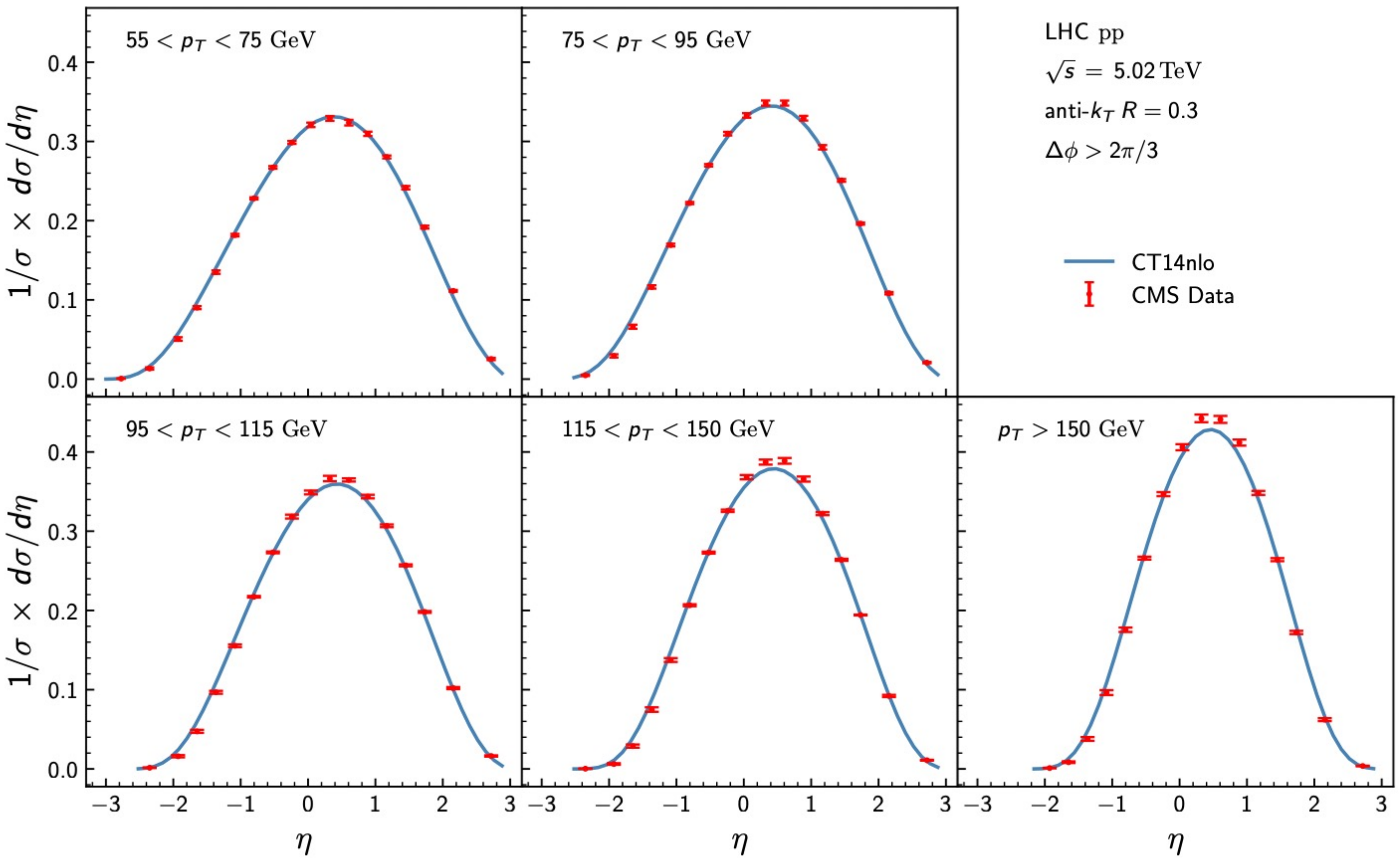
The azimuthal decorrelation



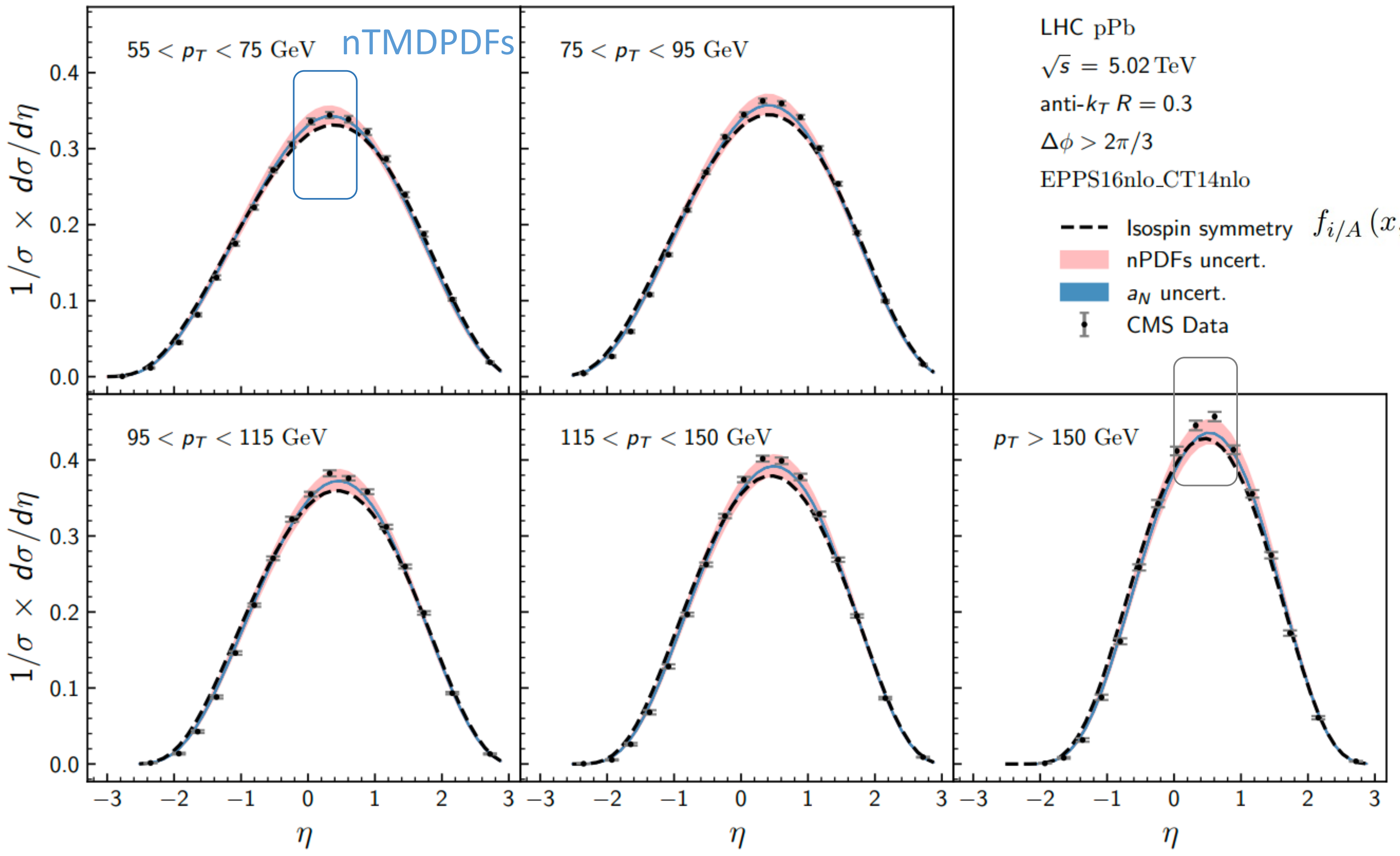


Left: Comparison between theoretical calculations of the azimuthal decorrelation with the CMS data
Right: A comparison of the dijet azimuthal angle decorrelation in pPb collisions from the CMS collaboration at the LHC

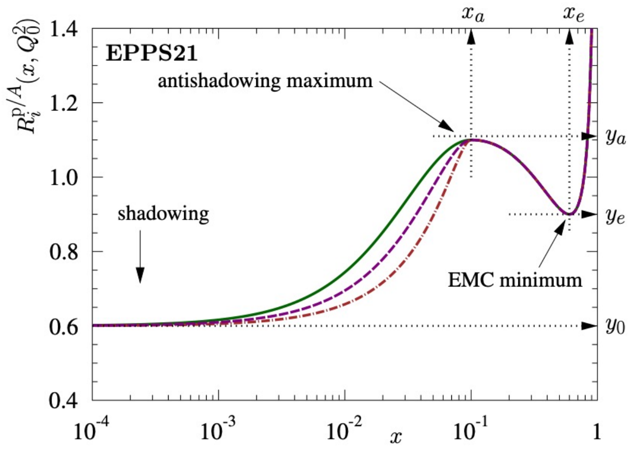
Theoretical calculations



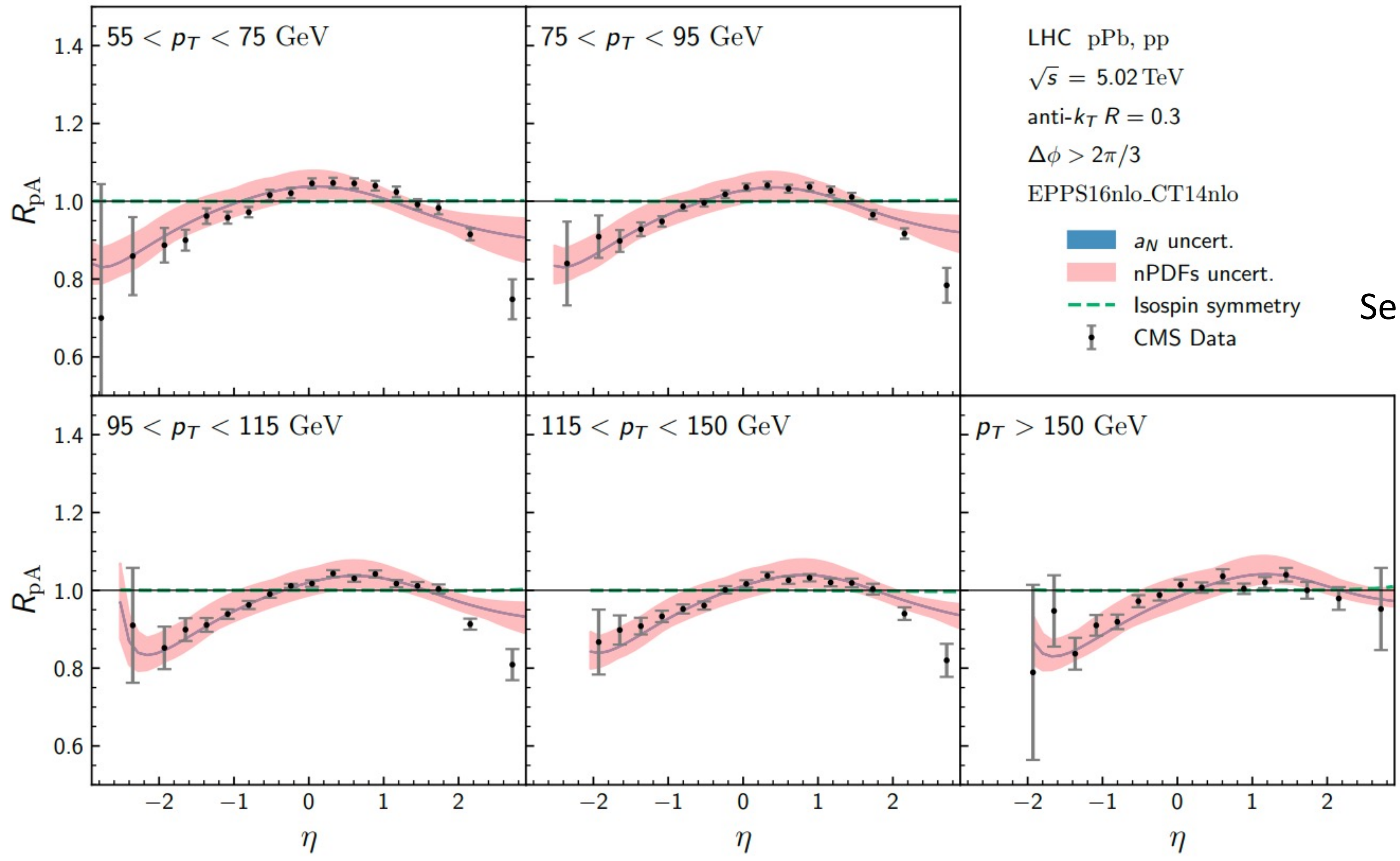
Dijet integrated angular decorrelation plotted as a function of the pseudorapidity ETA are compared with the CMS data in proton-proton collisions for different kinematic cuts



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

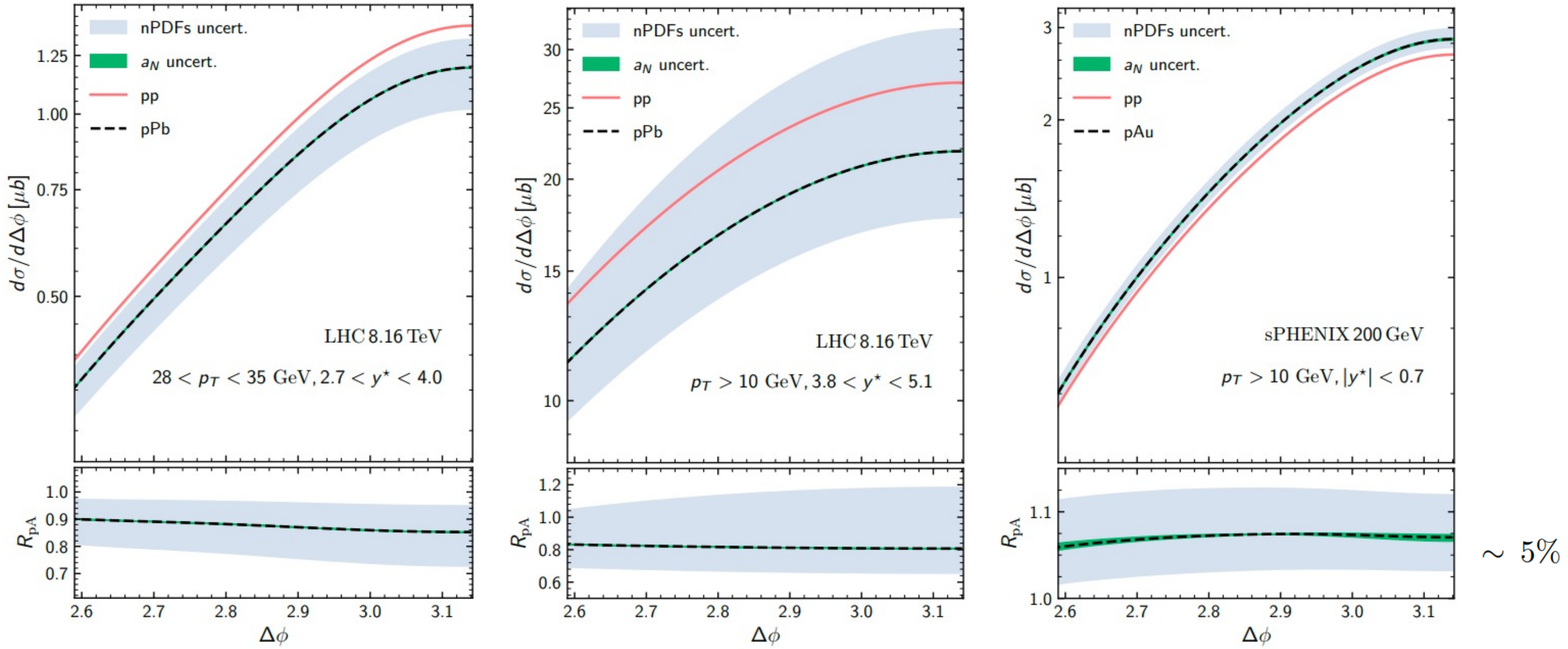


Theoretical calculations for dijet integrated angular decorrelation plotted as a function of the pseudorapidity ETA are compared with the CMS data in proton-lead collisions for different kinematic cuts.



Sensitive to gluon

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



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.

Conclusion & outlook

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

- In the future, we anticipate following applications
  - perform a simultaneous fit to both collinear and transverse momentum dependent contributions to the nTMDPDFs
  - extend our results to other kinematic regions
  - Incorporate the contributions from higher-order corrections (WTA at NNLL)
  - generalize our formalism to describe dijet production in the polarized scattering

THANK YOU

Parameterization

- the resummation of the NGLs

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

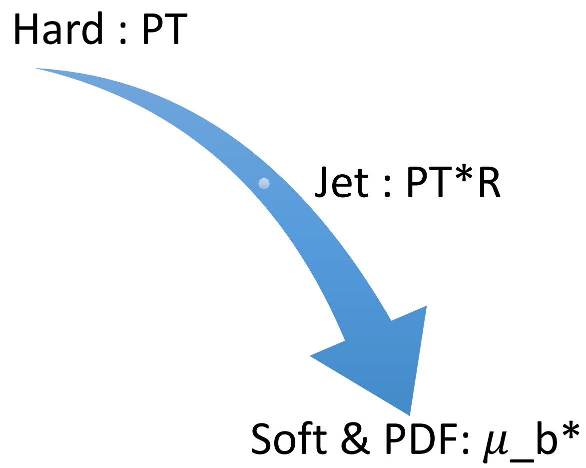
square

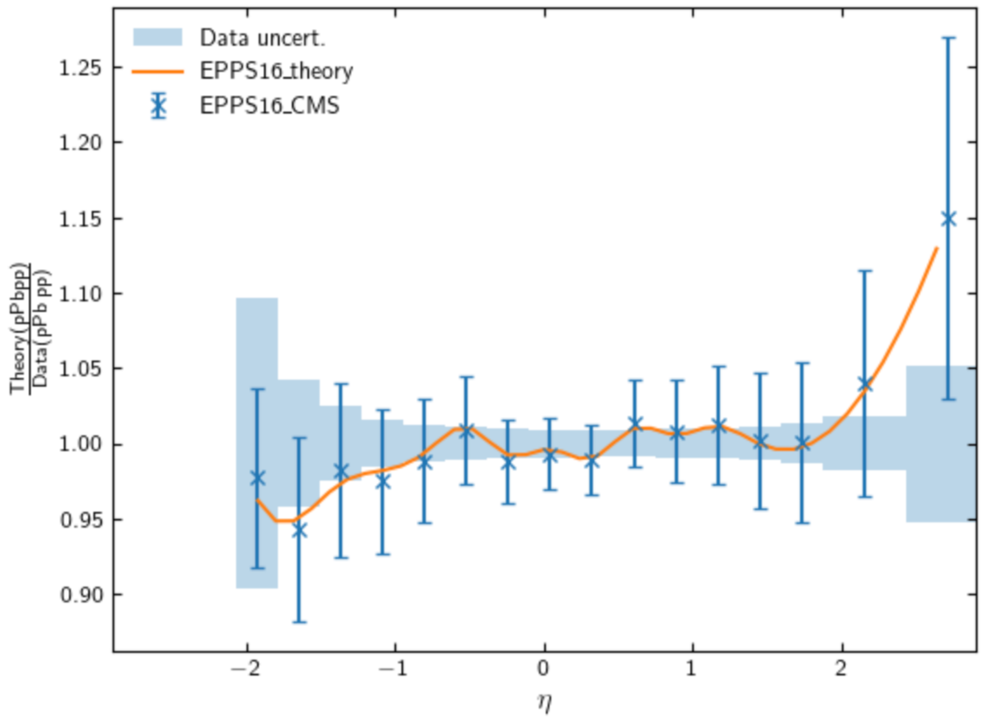
$$u = \ln[\alpha_s(\mu_{b_*})/\alpha_s(\mu_j)]/\beta_0,\ a = 0.85\,C_A,\ b = 0.86\,C_A \text{ and } c = 1.33$$

- the intrinsic scales in the resummation formula

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

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





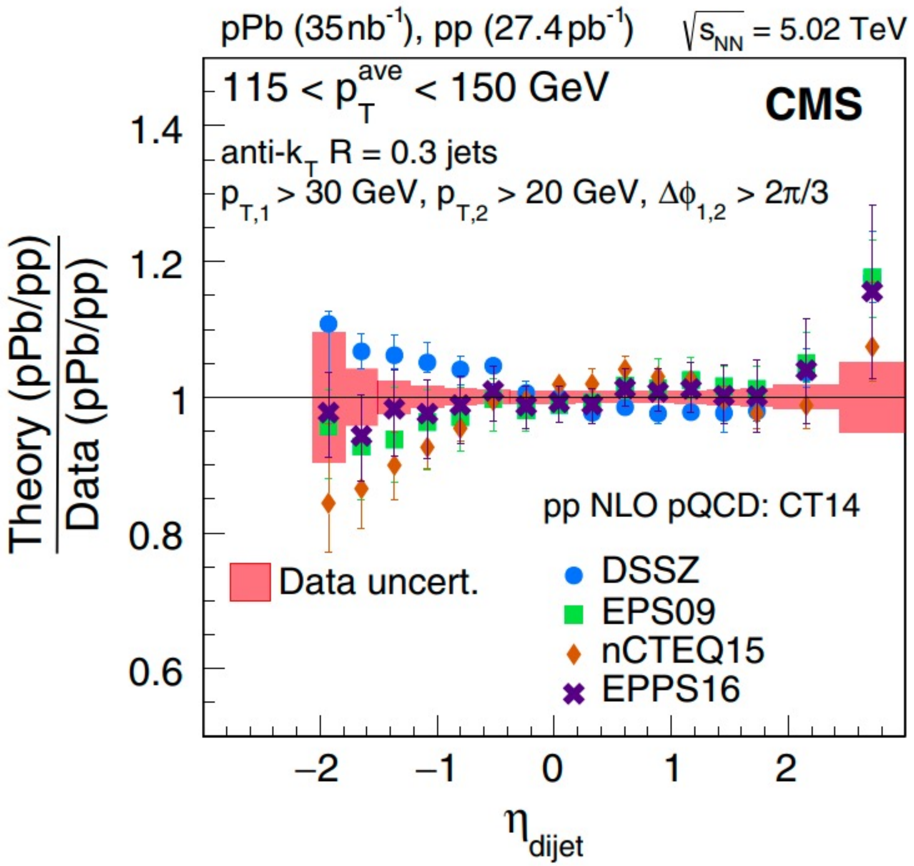


FIG. 3. Ratio of theory to data, for the ratio of the pPb to pp η_{dijet} spectra for $115 < p_{\mathrm{T}}^{\mathrm{ave}} < 150$ GeV. Theory points are from the NLO pQCD calculations of DSSZ [18], EPS09 [14], nCTEQ15 [15], and EPPS16 [16] nPDFs, using CT14 [58] as the baseline PDF. Red boxes indicate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

Factorization in SCET

- $\mathcal{C}_x$ can be simplified by working in b-space, the conjugate space to qx

$$\mathcal{C}_x\left[f_{a/p}^{\text{unsub}} f_{b/p}^{\text{unsub}} \boldsymbol{S}_{ab\to cd,IJ}^{\text{unsub}} S_c^{\text{cs}} S_d^{\text{cs}}\right] = \int \frac{db}{2\pi} e^{ibp_T\delta\phi} \boldsymbol{S}_{ab\to cd,IJ}^{\text{unsub}}(b,\mu,\nu)$$
$$\times f_{a/p}^{\text{unsub}}(x_a,b,\mu,\zeta_a/\nu^2)\, f_{b/p}^{\text{unsub}}(x_b,b,\mu,\zeta_b/\nu^2)\, S_c^{\text{cs}}(b,R,\mu,\nu)\, S_d^{\text{cs}}(b,R,\mu,\nu)\,,$$

- The factorization cross section

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}q_x} = \sum_{abcd} \frac{x_a x_b}{16\pi\hat{s}^2} \frac{1}{1+\delta_{cd}} \boldsymbol{H}_{ab\to cd,JI}(\hat{s},\hat{t},\mu)\, J_c(p_T R,\mu)\, J_d(p_T R,\mu)$$
$$\times \int \frac{db}{2\pi} e^{ibp_T\delta\phi} \boldsymbol{S}_{ab\to cd,IJ}^{\text{unsub}}(b,\mu,\nu)\, S_c^{\text{cs}}(b,R,\mu,\nu)\, S_d^{\text{cs}}(b,R,\mu,\nu)$$
$$\times f_{a/p}^{\text{unsub}}(x_a,b,\mu,\zeta_a/\nu^2)\, f_{b/p}^{\text{unsub}}(x_b,b,\mu,\zeta_b/\nu^2)\,.$$

pp > j j

$$\frac{d^3\sigma}{dy_3 dy_4 dp_T^2} = \frac{1}{16\pi s^2} \sum_{i,j,k,l=q,\bar{q},g} \frac{f_i(x_1,\mu^2)}{x_1} \frac{f_j(x_2,\mu^2)}{x_2} \times \overline{\sum} |\mathcal{M}(ij \to kl)|^2 \frac{1}{1+\delta_{kl}}$$

$$\hat{s} = x_a x_b s, \text{ and } \hat{t} = -x_a p_T \sqrt{s} e^{-y_c}$$

$$x_a = \frac{p_T}{2E_p}\left(e^{y_c} + e^{y_d}\right), \quad x_b = \frac{p_T}{2E_p}\left(e^{-y_c} + e^{-y_d}\right),$$

```
ptemp = qqbQQb;
Tr[HF[ptemp, 0, r, Sqrt[s], mu, 3, 5].Soft[ptemp] / Nfactor[ptemp]] - (4/9 (t^2 + u^2)/s^2) /.
  {r → -t / s, Nc → 3, CF → 4 / 3, u → -t - s} // Simplify
ptemp = qqbqqb;
Tr[HF[ptemp, 0, r, Sqrt[s], mu, 3, 5].Soft[ptemp] / Nfactor[ptemp]] - (4/9 ((s^2 + u^2)/t^2 + (u^2 + t^2)/s^2) - 8/27 u^2/(s t)) /.
  {r → -t / s, Nc → 3, CF → 4 / 3, u → -t - s} // Simplify

ptemp = qqbgg;
Tr[HF[ggqqb, 0, r, Sqrt[s], mu, 3, 5].Soft[ptemp] / Nfactor[ptemp]] - (32/27 (t^2 + u^2)/(t u) - 8/3 (t^2 + u^2)/s^2) /.
  {r → -t / s, Nc → 3, CF → 4 / 3, u → -t - s} // Simplify

ptemp = ggqqb;
Tr[HF[ptemp, 0, r, Sqrt[s], mu, 3, 5].Soft[ptemp] / Nfactor[ptemp]] - (1/6 (t^2 + u^2)/(t u) - 3/8 (t^2 + u^2)/s^2) /.
  {r → -t / s, Nc → 3, CF → 4 / 3, u → -t - s} // Simplify

ptemp = qgqg;
Tr[HF[ptemp, 0, r, Sqrt[s], mu, 3, 5].Soft[ptemp] / Nfactor[ptemp]] - (-4/9 (s^2 + u^2)/(s u) + (s^2 + u^2)/t^2) /.
  {r → -t / s, Nc → 3, CF → 4 / 3, u → -t - s} // Simplify

Tr[HF[qgqg, 0, r, Sqrt[s], mu, 3, 5].Soft[gqgq] / Nfactor[gqgq]] - (-4/9 (s^2 + u^2)/(s u) + (s^2 + u^2)/t^2) /.
  {r → -t / s, Nc → 3, CF → 4 / 3, u → -t - s} // Simplify

ptemp = gggg;
Tr[HF[ptemp, 0, r, Sqrt[s], mu, 3, 5].Soft[ptemp] / Nfactor[ptemp]] - 9/2 (3 - (t u)/s^2 - (s u)/t^2 - (s t)/u^2) /.
  {r → -t / s, Nc → 3, CF → 4 / 3, u → -t - s} // Simplify
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