Azimuthal angular decorrelations of Jet production in high energy pp and pA collisions

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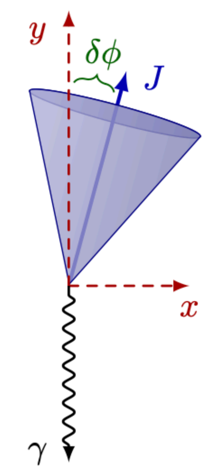
Introduction

In pursuing an enhanced understanding of high-energy collisions, the examination of jet production within proton-proton (pp) and proton-nucleus (pA) contexts emerges as a crucial endeavor. These collisions serve as probes into the Standard Model's predictions and seek out new physics through the intricate dynamics orchestrated by quantum chromodynamics (QCD). Our study uniquely explores these decorrelations through two jet recombination methods: the Standard Jet Axis (SJA) and the Winner-Take-All (WTA) scheme. Employing soft-collinear effective theory, we establish a factorization and resummation formalism, achieving next-to-leading logarithmic (NLL) accuracy for SJA and next-to-next-to-leading logarithmic (NNLL) accuracy for WTA, specifically in the back-to-back limit.

Photon-jet decorrelations in high energy pp and pA collisions

$$p(P_1) + N(P_2) \to \gamma(p_\gamma) + J(p_J) + X$$



- At leading order (LO), two partonic channels:
  - quark-antiquark annihilation ($q\bar{q} \to \gamma g$);
  - Compton process ($qg \to \gamma q$).
- QCD emissions from initial and final states leads to the azimuthal decorrelations $\delta\phi$.
- To avoid logarithmic singularities occurring in the back to back region ($\delta\phi \to 0$), perturbative convergence necessitates all-order resummation over large logarithmic terms in the azimuthal angle (and jet radius).

Factorization and resummation for the standard jet axis

- Kinematic modes:

n_i collinear : $p^\mu_{c_i} \sim p_T(\delta\phi^2, 1, \delta\phi)_i$,

n_j collinear : $p^\mu_{c_j} \sim p_T(\delta\phi^2, 1, \delta\phi)_j$,

n_k collinear : $p^\mu_{c_k} \sim p_T(R^2, 1, R)_k$,

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

soft : $p^\mu_s \sim p_T(\delta\phi, \delta\phi, \delta\phi)$.

- Factorization formula:

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

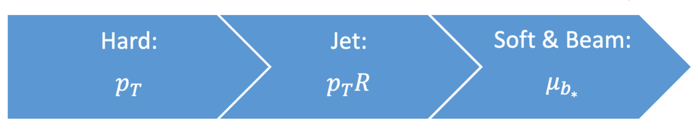
renormalization and rapidity scale

- RG and RRG consistence relation:

$$\gamma^{H_{ij\to\gamma k}}_\mu + \gamma^{S^{(u)}_{ijk}}_\mu + \gamma^{f^{(u)}_i}_\mu + \gamma^{f^{(u)}_j}_\mu + \gamma^{J_k}_\mu + \gamma^{C^{(u)}_k}_\mu = 0,$$

$$\gamma^{S^{(u)}_{ijk}}_\nu + \gamma^{f^{(u)}_i}_\nu + \gamma^{f^{(u)}_j}_\nu + \gamma^{C^{(u)}_k}_\nu = 0.$$

- Resummation formalism at NLL:



$$\frac{d\sigma^{\rm SJA}_{pA}}{d\delta\phi\, dp_T\, dy_\gamma\, dy_J} = \sum_{i,j,k} \int_0^\infty \frac{db}{\pi} 2\cos(bp_T\delta\phi) \times \exp\left[-\int_{\mu_{b_*}}^{\mu_h} \frac{d\mu}{\mu} \gamma^{\mathcal{H}_{ij\to\gamma k}}_\mu(\alpha_s)\right] \mathcal{H}_{ij\to\gamma k}(p_T, y_\gamma, y_J, \mu_h) \times \exp\left[-\int_{\mu_{b_*}}^{\mu_j} \frac{d\mu}{\mu} \gamma^{J_k}_\mu(\alpha_s)\right] f_{i/p}(x_1, \mu_{b_*}) f_{j/A}(x_2, \mu_{b_*}) \times \exp\left[-S^i_{\rm NP}(b, Q_0, \omega_i) - S^{j,A}_{\rm NP}(b, Q_0, \omega_j)\right] \times U^k_{\rm NG}(\mu_{b_*}, \mu_j)$$

Factorization and resummation for the winner-take-all axis

- Kinematic modes:

n_i collinear : $p^\mu_{c_i} \sim p_T(\delta\phi^2, 1, \delta\phi)_i$,

n_j collinear : $p^\mu_{c_j} \sim p_T(\delta\phi^2, 1, \delta\phi)_j$,

n_k collinear : $p^\mu_{c_k} \sim p_T(\delta\phi^2, 1, \delta\phi)_k$,

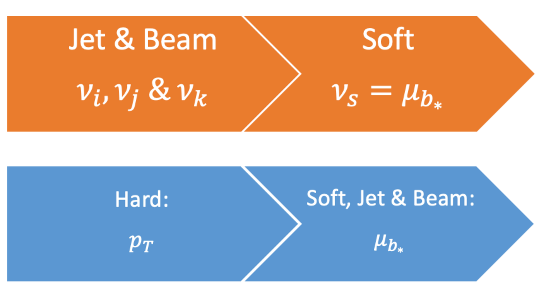
soft : $p^\mu_s \sim p_T(\delta\phi, \delta\phi, \delta\phi)$.

- Factorization formula:

$$\frac{d\sigma^{\rm WTA}_{pp}}{dq_x\, dp_T\, dy_\gamma\, dy_J} = \sum_{i,j,k} H_{ij\to\gamma k}(p_T, y_\gamma, y_J, \mu) \int \frac{db}{2\pi} e^{ibq_x} f^{(u)}_{i/p}(x_1, b, \mu, \zeta_i/\nu^2) f^{(u)}_{j/p}(x_2, b, \mu, \zeta_j/\nu^2) \times J^{(u)}_k(b, \mu, \zeta_k/\nu^2) S^{(u)}_{ijk}(b, y_\gamma, y_J, \mu, \nu)\,,$$

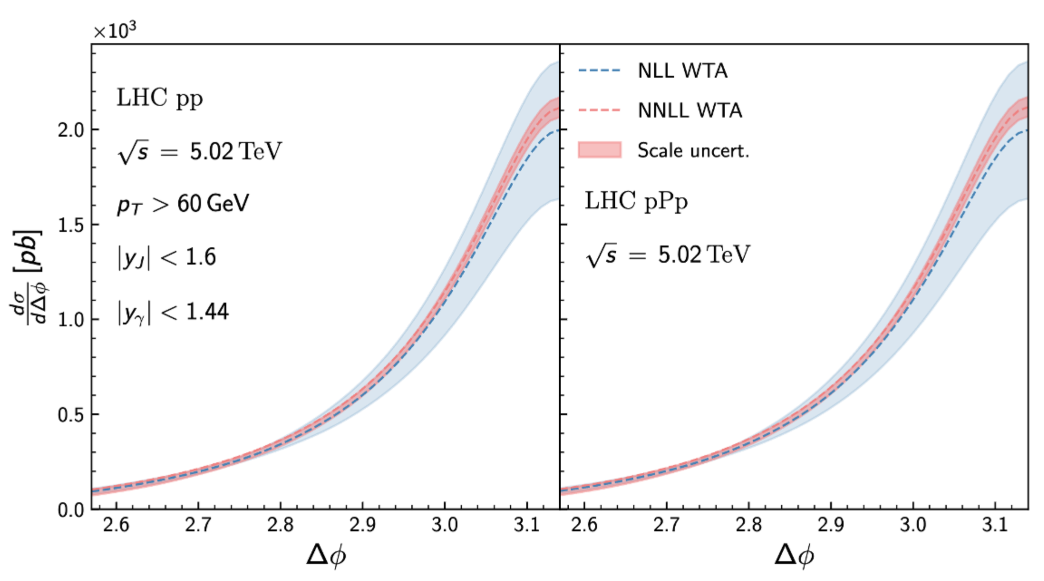
renormalization and rapidity scale

- Resummation formalism at NNLL:



$$\frac{d\sigma^{\rm WTA}_{pp}}{d\delta\phi\, dp_T\, dy_\gamma\, dy_J} = \sum_{i,j,k} \int_0^\infty \frac{db}{\pi} 2\cos(bp_T\delta\phi) \prod_{a=ijk} \left(\frac{\zeta_a}{\zeta_s}\right)^{\frac{1}{2}\gamma^a_\zeta(\mu_{b_*}, b)} \times \exp\left[-\int_{\mu_{b_*}}^{\mu_h} \frac{d\mu}{\mu} \gamma^{H_{ij\to\gamma k}}_\mu(\alpha_s)\right] H_{ij\to\gamma k}(p_T, y_\gamma, y_J, \mu_h) \times f^{\rm TMD}_{i/p}(x_1, b, \mu_{b_*}, \zeta_s) f^{\rm TMD}_{j/p}(x_2, b, \mu_{b_*}, \zeta_s) J^{\rm TMD}_k(b, \mu_{b_*}, \zeta_s) \times \mathcal{S}_{ijk}(b, \mu_{b_*}) \exp\left[-S^i_{\rm NP}(b, Q_0, \omega_i) - S^j_{\rm NP}(b, Q_0, \omega_j)\right].$$

Scale uncertainties in the WTA scheme



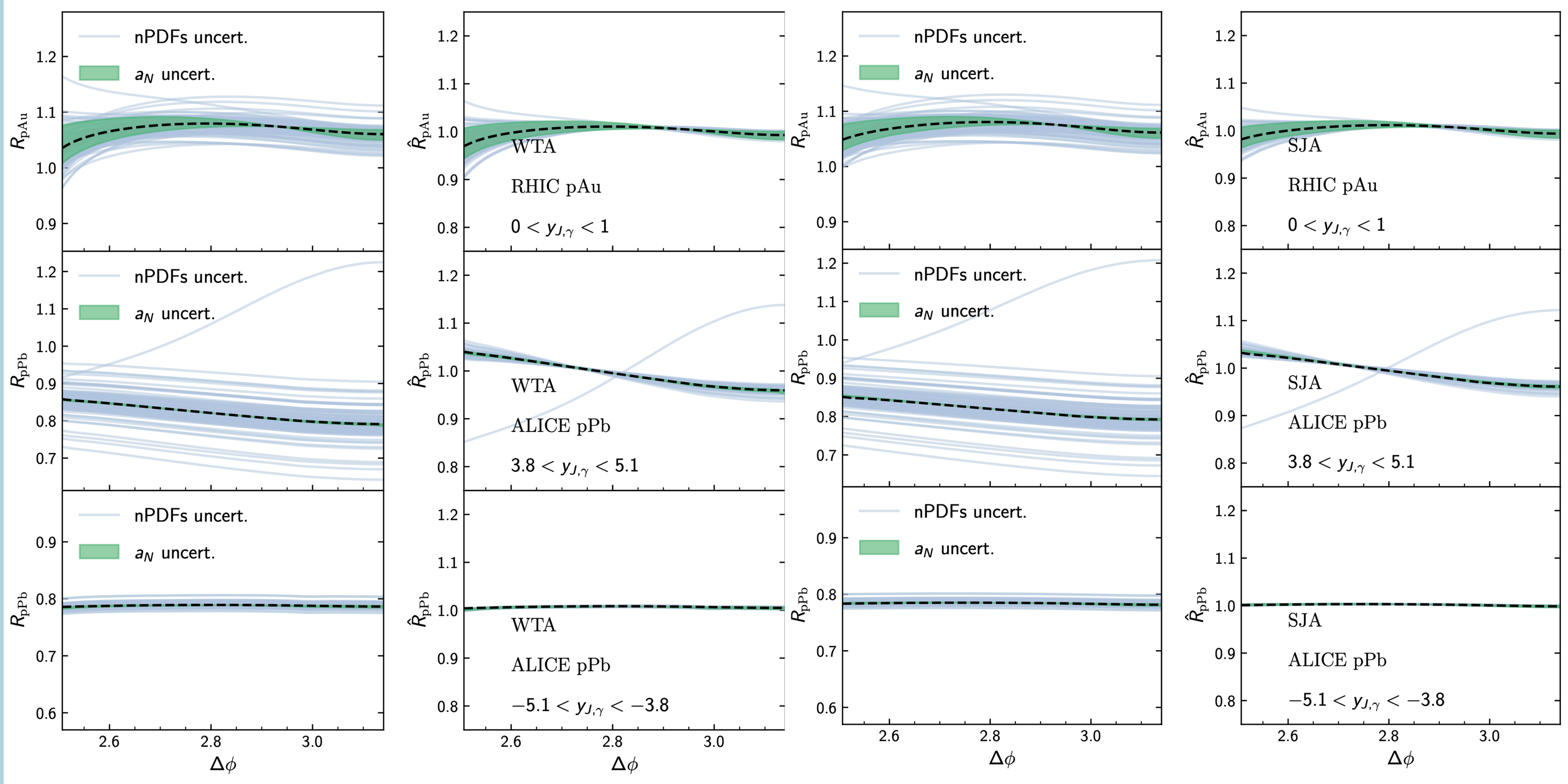
The theory uncertainties are reduced from NLL to NNLL

Nuclear modification and the extraction of a_N uncertainties

- To quantify the nuclear modification, we employ the standard definition for the nuclear modification factor R_{pA} and its normalized form $\hat{R}_{pA}$:

$$R_{pA} = \frac{d^4\sigma_{pA}}{dy_J dy_\gamma dp_T d\Delta\phi} \Big/ \frac{d^4\sigma_{pp}}{dy_J dy_\gamma dp_T d\Delta\phi}$$

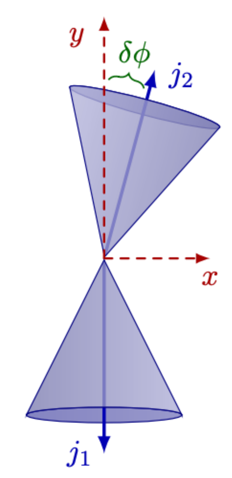
$$\hat{R}_{pA} = \frac{\sigma_{pp}}{\sigma_{pA}} \frac{d^4\sigma_{pA}}{dy_J dy_\gamma dp_T d\Delta\phi} \Big/ \frac{d^4\sigma_{pp}}{dy_J dy_\gamma dp_T d\Delta\phi}$$



- Compared with R_{pA}, the normalized ratio $\hat{R}_{pA}$ can effectively eliminate dependence on the nPDFs, leaving only the uncertainty of aN unchanged.

Dijet azimuthal decorrelations in high energy pp and pA collisions

$$p(P_1) + N(P_2) \to J(p_3) + J(p_4) + X$$



- Divergence due to logarithmic singularities at $\delta\phi \to 0$.
- Factorization and resummation: necessary in the nearly back-to-back region.
- Challenges:
  - Multiple partonic channels;
  - Complex color structure;
  - Standard factorization formula invalidation in high-logarithmic order calculation resulting from Glauber effect and spectator interaction.

RG evolution

- Renormalization group (RG) equation of hard function:

$$\frac{d}{d\ln\mu}\boldsymbol{H} = \boldsymbol{\Gamma}_H \boldsymbol{H} + \boldsymbol{H}\boldsymbol{\Gamma}^\dagger_H$$

- The anomalous dimension of hard function:

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

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

- Diagonalization of the anomalous dimension in color space:

$$\boldsymbol{M}_{ab\to cd} = \sum_{(i,j)} \frac{\mathbf{T}_i\cdot\mathbf{T}_j}{2}\left(\ln\frac{\mu^2}{-s_{ij}} - \ln\frac{\mu^2}{-s}\right) = (\ln r + i\pi)\boldsymbol{M}_{1,ab\to cd} + \ln\left(\frac{r}{1-r}\right)\boldsymbol{M}_{2,ab\to cd}$$

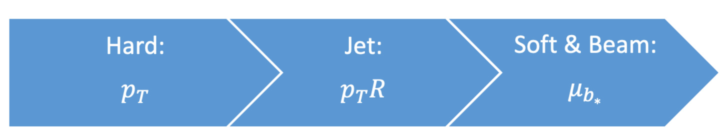
$$(F\cdot\boldsymbol{M}_{ab\to cd}\cdot F^{-1})_{KK'} = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{bmatrix}$$

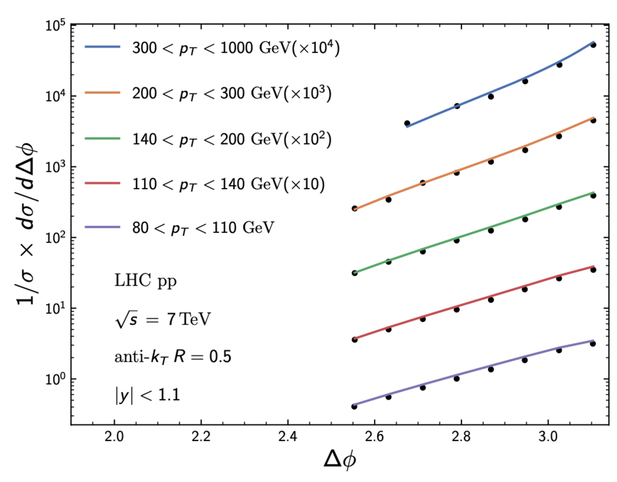
$$\frac{d}{d\ln\mu}\boldsymbol{H}_{KK'}(\mu) = \left[\gamma_{\rm cusp}\left(c_H \ln\frac{-s}{\mu^2} + \lambda_K + \lambda^*_{K'}\right) + 2\gamma_H\right]\boldsymbol{H}_{KK'}(\mu)$$

Resummation formula

- NLL expression for azimuthal angular distribution in the SJA scheme:

$$\frac{d^4\sigma_{pp}}{dy_c\, dy_d\, dp_T^2\, d\delta\phi} = \sum_{abcd} \frac{p_T}{16\pi\hat{s}^2}\frac{1}{1+\delta_{cd}} \int_0^\infty \frac{2db}{\pi} \cos(bp_T\delta\phi) x_a \tilde{f}_{a/p}(x_a, \mu_{b_*}) x_b \tilde{f}_{b/p}(x_b, \mu_{b_*}) \times \exp\left\{-\int_{\mu_{b_*}}^{\mu_h} \frac{d\mu}{\mu}\left[\gamma_{\rm cusp}(\alpha_s) C_H \ln\frac{\hat{s}}{\mu^2} + 2\gamma_H(\alpha_s)\right]\right\} \times \sum_{KK'} \exp\left[-\int_{\mu_{b_*}}^{\mu_h} \frac{d\mu}{\mu}\gamma_{\rm cusp}(\alpha_s)(\lambda_K + \lambda^*_{K'})\right] H_{KK'}(\hat{s}, \hat{t}, \mu_h) W_{K'K}(b_*, \mu_{b_*}) \times \exp\left[-\int_{\mu_{b_*}}^{\mu_j} \frac{d\mu}{\mu}\Gamma^{J_c}(\alpha_s) - \int_{\mu_{b_*}}^{\mu_j} \frac{d\mu}{\mu}\Gamma^{J_d}(\alpha_s)\right] U^c_{\rm NG}(\mu_{b_*}, \mu_j) U^d_{\rm NG}(\mu_{b_*}, \mu_j) \times \exp\left[-S^a_{\rm NP}(b, Q_0, \sqrt{\hat{s}}) - S^b_{\rm NP}(b, Q_0, \sqrt{\hat{s}})\right].$$





Comparison between theoretical calculations of the azimuthal decorrelations with the CMS data