Transverse momentum distributions and jets in SCET

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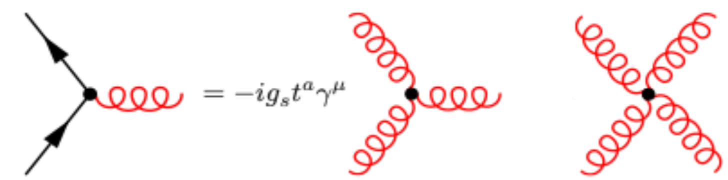
第五届重味物理与量子色动力学研讨会　华中科技大学　武汉　Apr 22 2023

QCD and jet physics

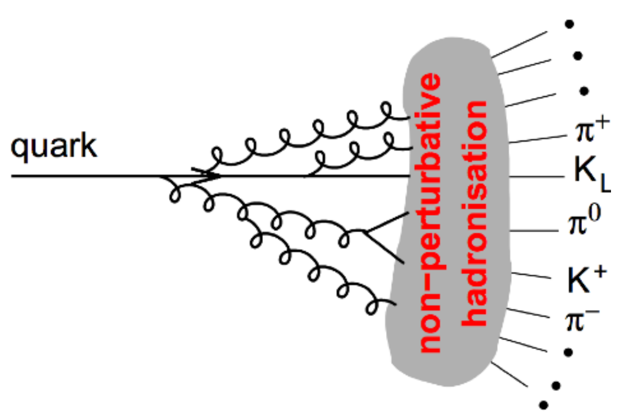
QCD: non-abelian Yang-Mills theory

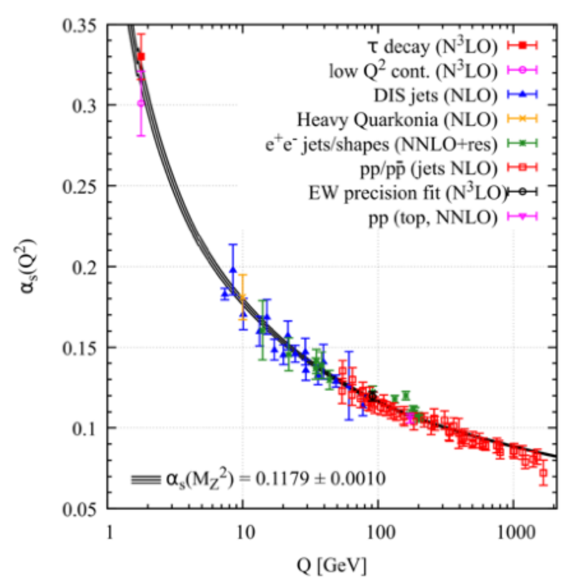
$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$



$\sim C_F = \frac{4}{3}$ $\sim C_A = 3$

Jets: Parton (quark or gluon) fragmentation and hadronization





Jets are emergent property of QCD

- **Soft-collinear singularity**
- **Asymptotic freedom**
- **Color string breaks**

Dynamics of jets formation: from short to long distance in quantum field theory

$$J\,(\text{ scale }\mu_2) \sim J\,(\text{scale}\,\mu_1)\exp\left[\int_{\mu_1}^{\mu_2} \frac{d\mu'}{\mu'} \int dx P\,(x, \alpha_s\,(\mu'))\right]$$

Jets at the LHC

Jets are produced copiously at the LHC

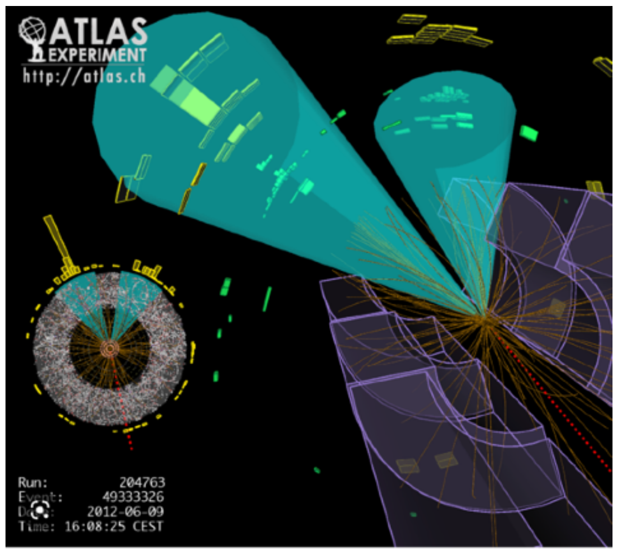
Not jets (QED jets?): $e \quad \mu \quad \gamma$

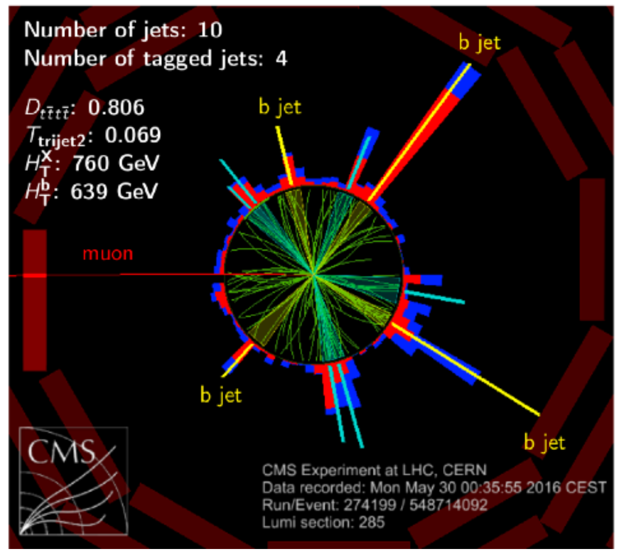
Tau jets: τ

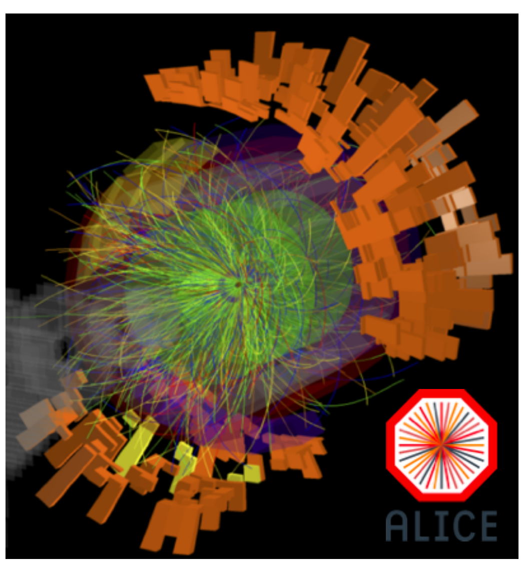
Light Jets: $u\ d\ s\ g$

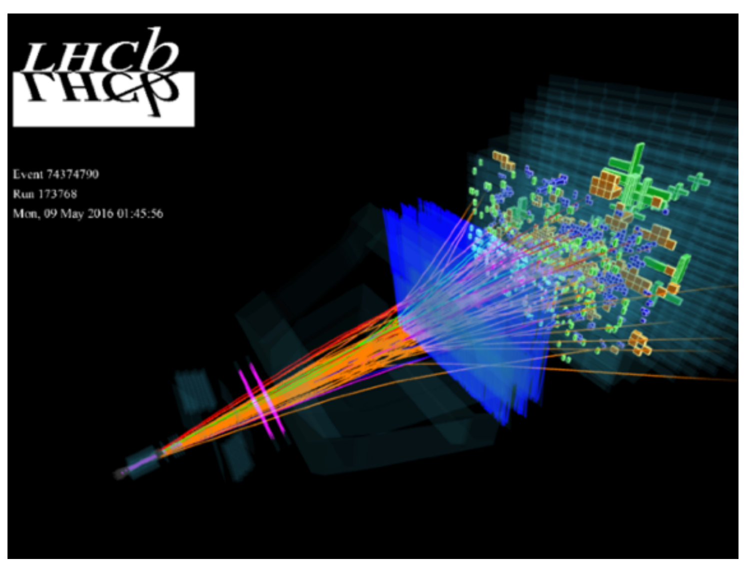
Heavy Jets: $c\ b$

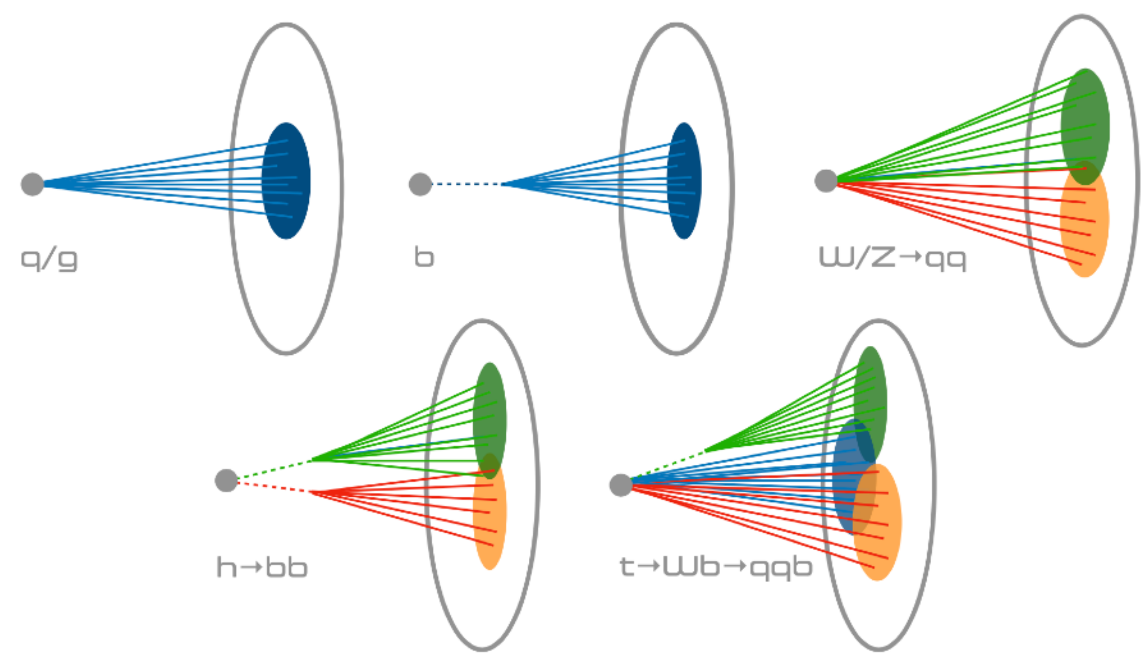
Fat Jets: $W\ Z\ H\ t$



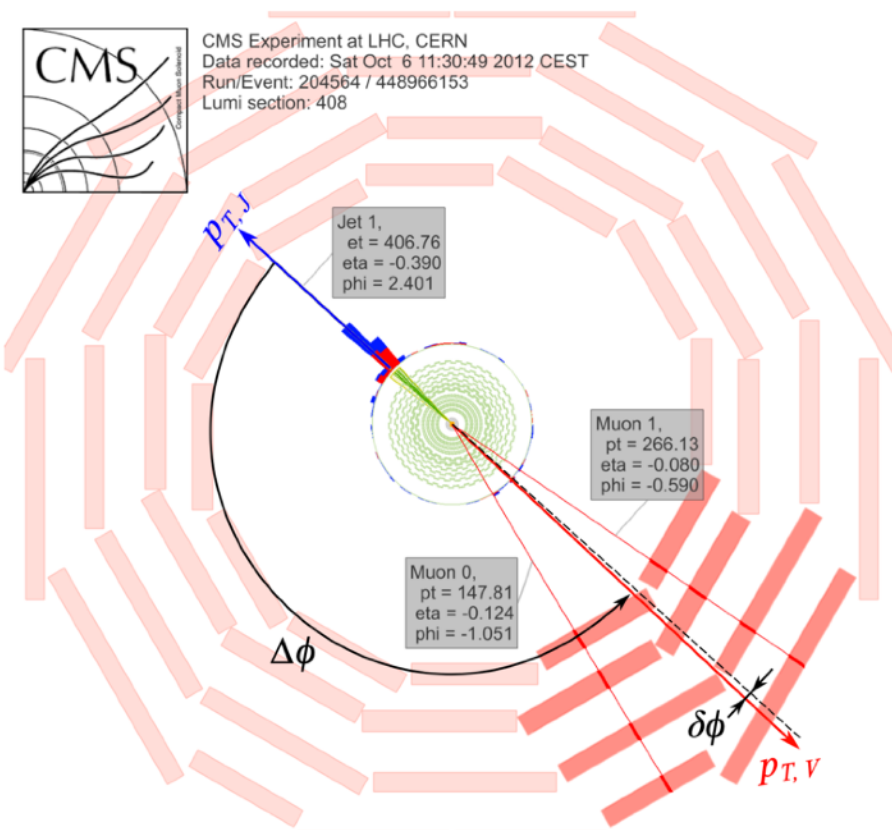


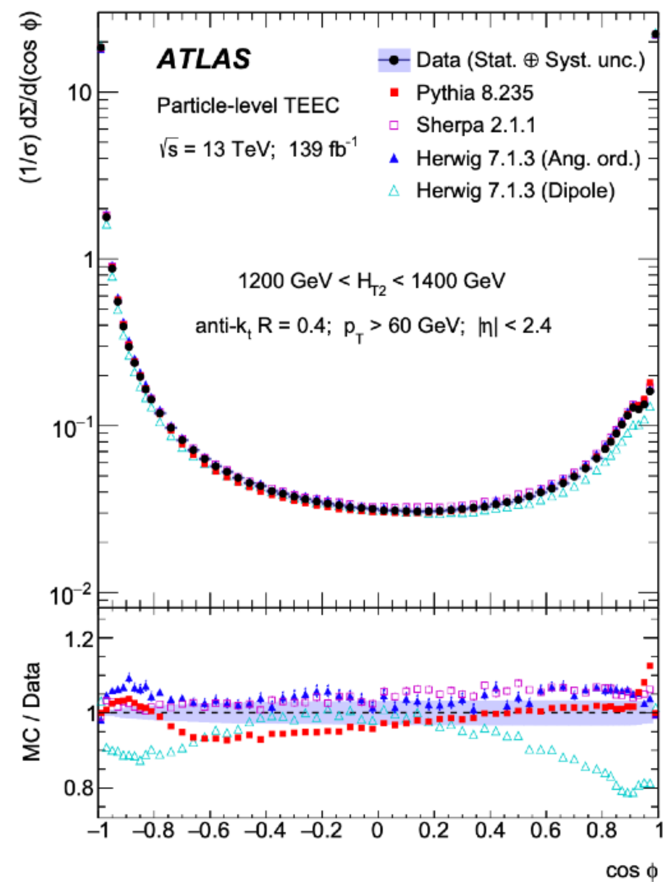


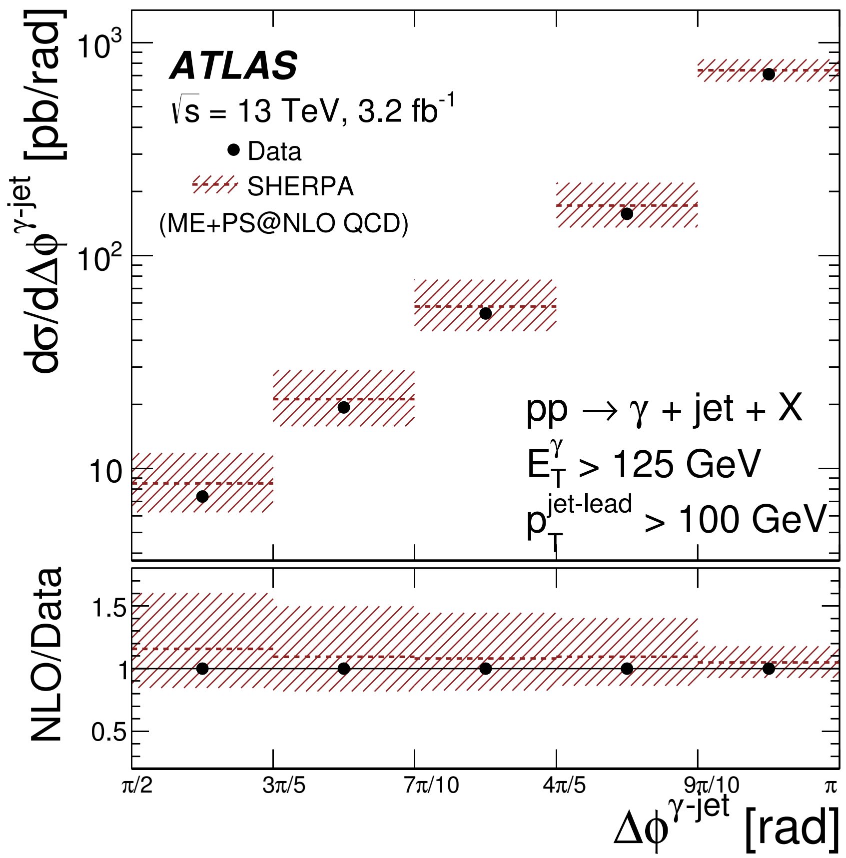




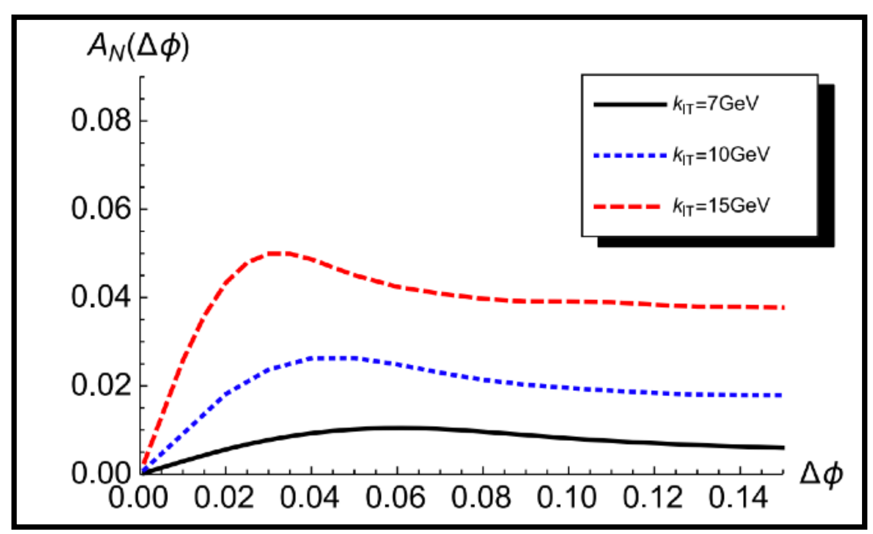
Jet TMDs and azimuthal decorrelation



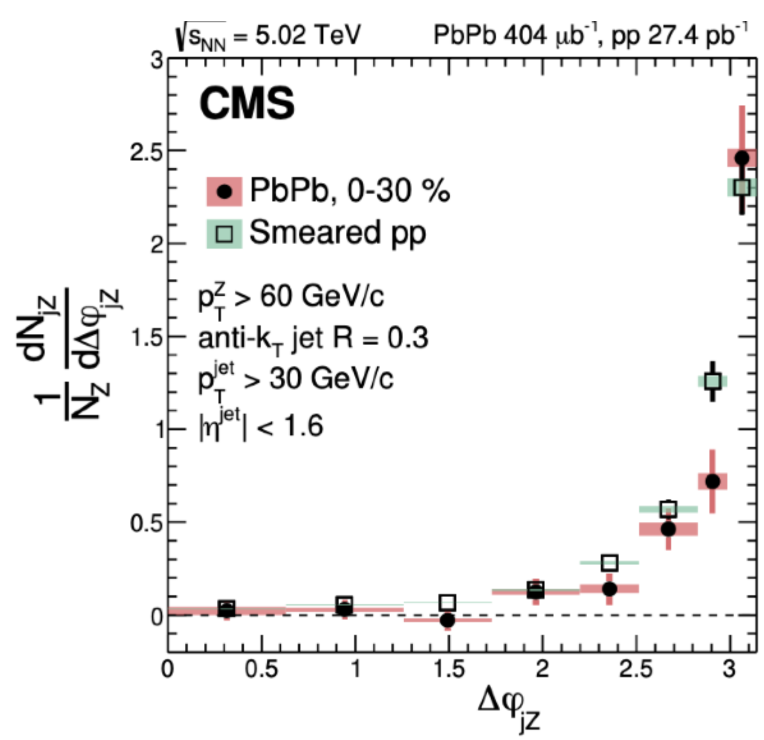




- strong coupling measurement
- jet calibration
- spin asymmetry
- TMDPDF, TMDFF, nTMDPDF
- energy loss
- naive factorization violation
- …



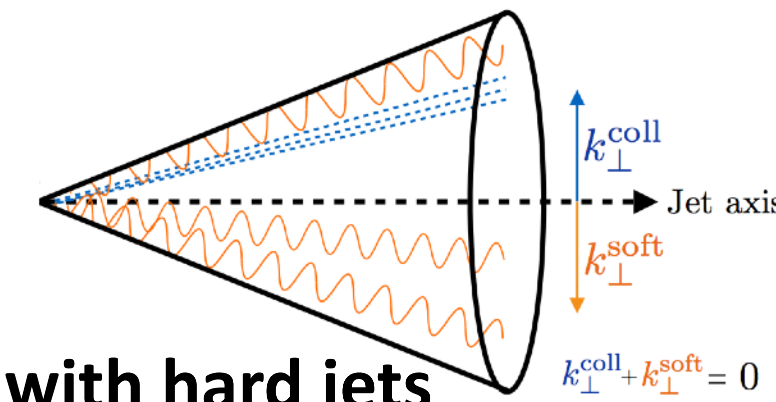
(Liu, Ringer, Vogelsang, Yuan '19 PRL)



Jet TMD and its all-order structure

- **Large logarithms in jet TMDs**

$$q_T = \Big| \sum_{i \notin \text{ jets}} \vec{k}_{T,i} \Big| + \mathcal{O}\left(k_T^2\right) \ll Q$$



  - **sum over all soft and collinear partons not combined with hard jets**
  - **deviation from q_T=0 are only caused by particle flow outside the jet regions**
  - **non-global observables** (Dasgupta & Salam '01)
- **Recoil absent for the p_T^n-weighted recombination scheme** (Banfi, Dasgupta & Delenda '08)

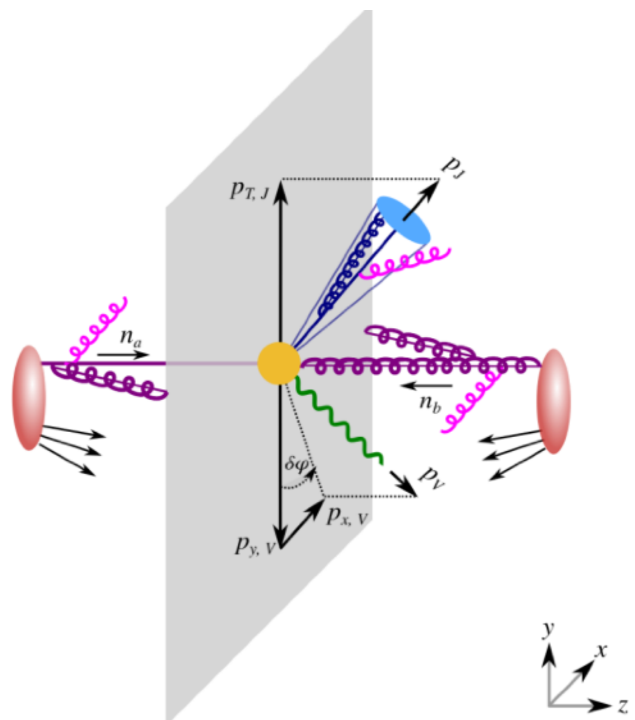
$$\begin{aligned} p_{t,r} &= p_{t,i} + p_{t,j}\,, \\ \phi_r &= (w_i\phi_i + w_j\phi_j)/(w_i + w_j) \\ y_r &= (w_i y_i + w_j y_j)/(w_i + w_j) \end{aligned} \qquad w_i = p_t^n$$

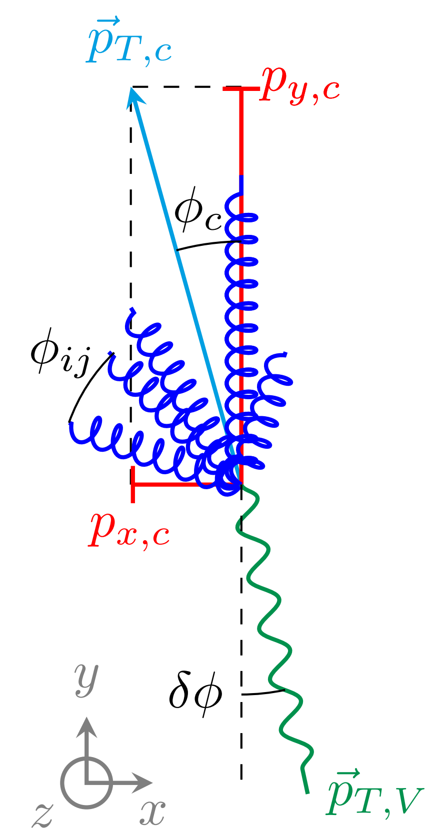
$n \to \infty$ **Winner-take-all scheme** (Salam; Bertolini, Chan, Thaler '13)

- **N^{3}LL resummation for jet q_T @ ee and ep** (Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '18 '19)
- **NNLL resummation for $\delta\phi$ @ LHC** (Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB)

Recoil-free azimuthal angle for boson-jet correlation

(Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB)





$$\pi - \Delta\phi \equiv \delta\phi \approx \sin(\delta\phi) = |p_{x,V}|/p_{T,V}$$

Transverse momentum conservation: $\vec{p}_{T,a} + \vec{p}_{T,b} + \vec{p}_{T,S} + \vec{p}_{T,c} + \vec{p}_{T,V} = 0$

Transverse momentum imbalance: $\vec{q}_T \equiv \vec{p}_{T,V} + \vec{p}_{T,J} = \vec{p}_{T,J} - \vec{p}_{T,c} - \vec{p}_{T,a} - \vec{p}_{T,b} - \vec{p}_{T,S}$

Azimuthal decorrelation

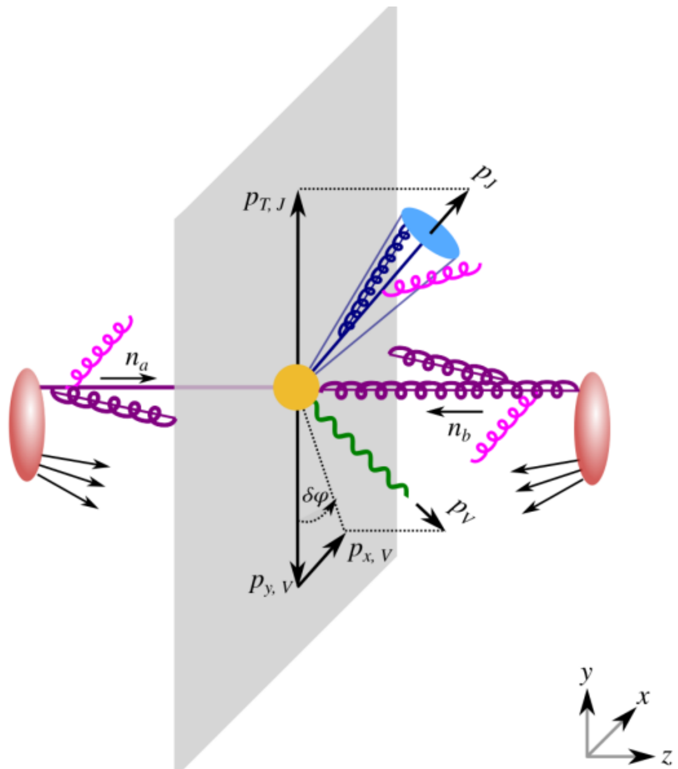
$$\begin{aligned} q_x &= p_{x,V} + p_{x,J} \\ &= p_{x,V} \\ &= -p_{x,a} - p_{x,b} - p_{x,S} - p_{x,c} \end{aligned}$$

Radial decorrelation

$$\begin{aligned} q_y &= p_{y,V} + p_{y,J} \\ &= p_{y,J} - p_{y,a} - p_{y,b} - p_{y,S} - p_{y,c} \end{aligned}$$

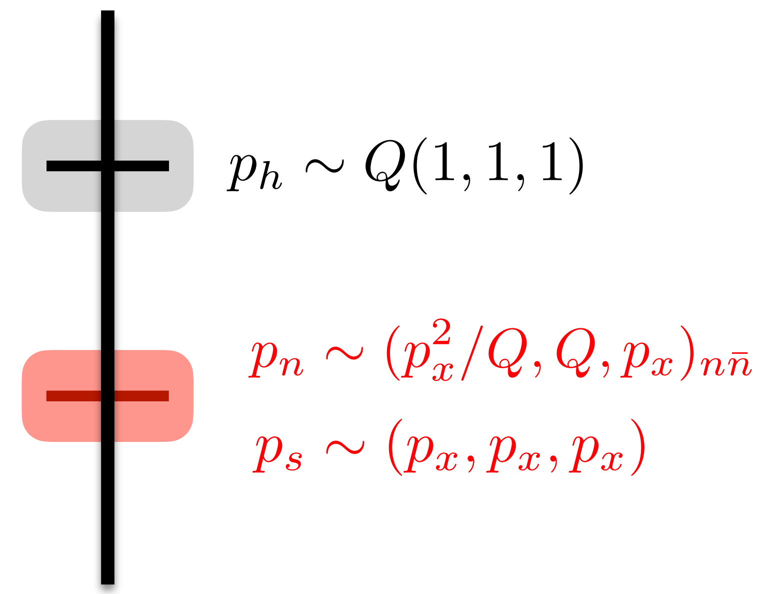
Recoil-free azimuthal angle for boson-jet correlation

(Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB)



$$\pi - \Delta\phi \equiv \delta\phi \approx \sin(\delta\phi) = |p_{x,V}|/p_{T,V}$$

Standard SCET2 (CSS ...) $\delta\phi \ll \mathcal{O}(1)$



Effect of soft radiation in jet algorithm is power suppressed

Following the standard steps in SCET2 we obtain the following factorization formula

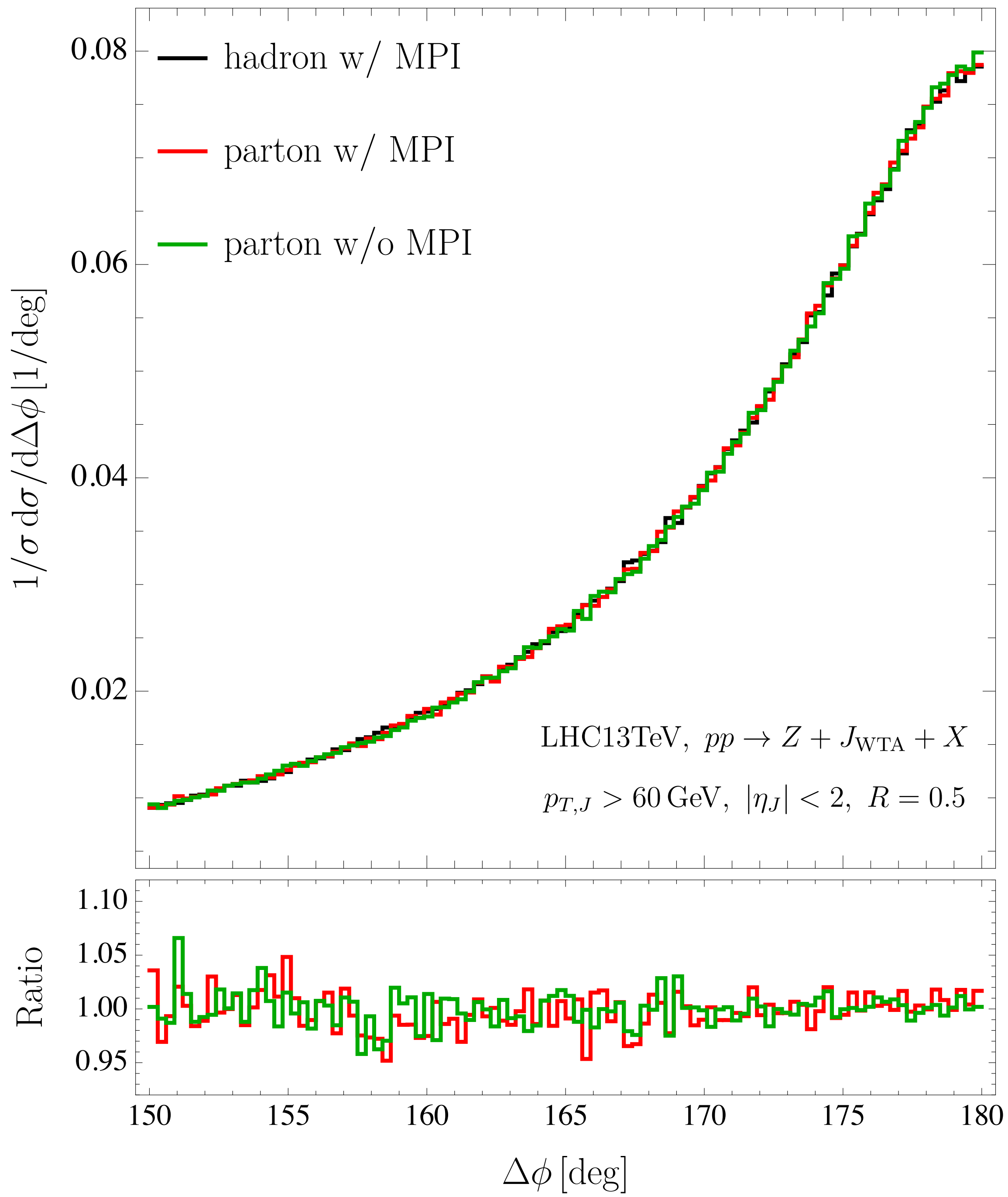
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{x,V}\,\mathrm{d}p_{T,J}\,\mathrm{d}y_V\,\mathrm{d}\eta_J} = \int \frac{\mathrm{d}b_x}{2\pi}\, e^{\mathrm{i}p_{x,V}b_x} \sum_{i,j,k} B_i(x_a, b_x) B_j(x_b, b_x) S_{ijk}(b_x, \eta_J) H_{ij\to Vk}(p_{T,V}, y_V - \eta_J) J_k(b_x)$$

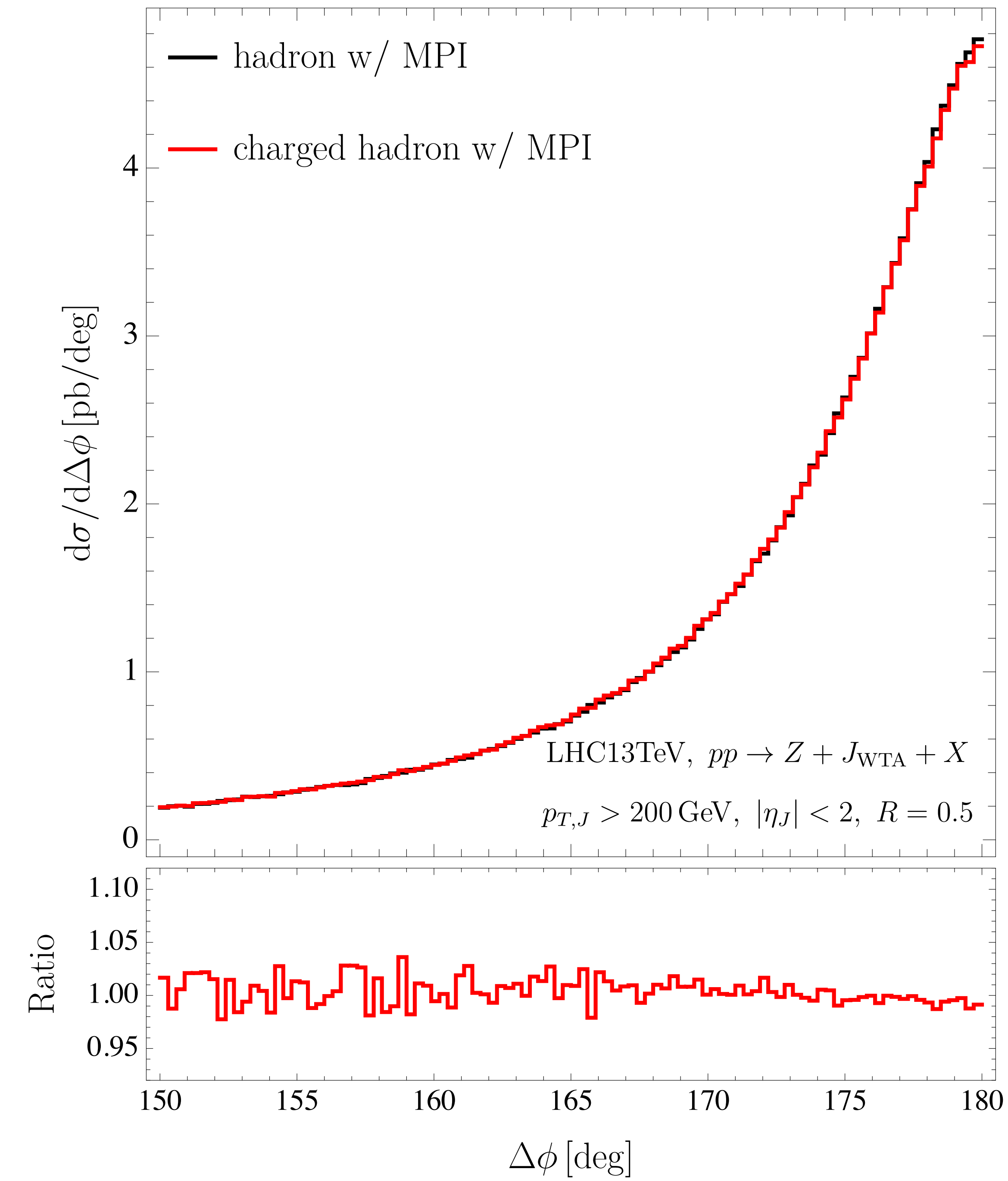
Fourier transformation in 1-dim

Soft function can be obtained by boosted invariance

(also see Gao,Li,Moult,Zhu '19 PRL,...)

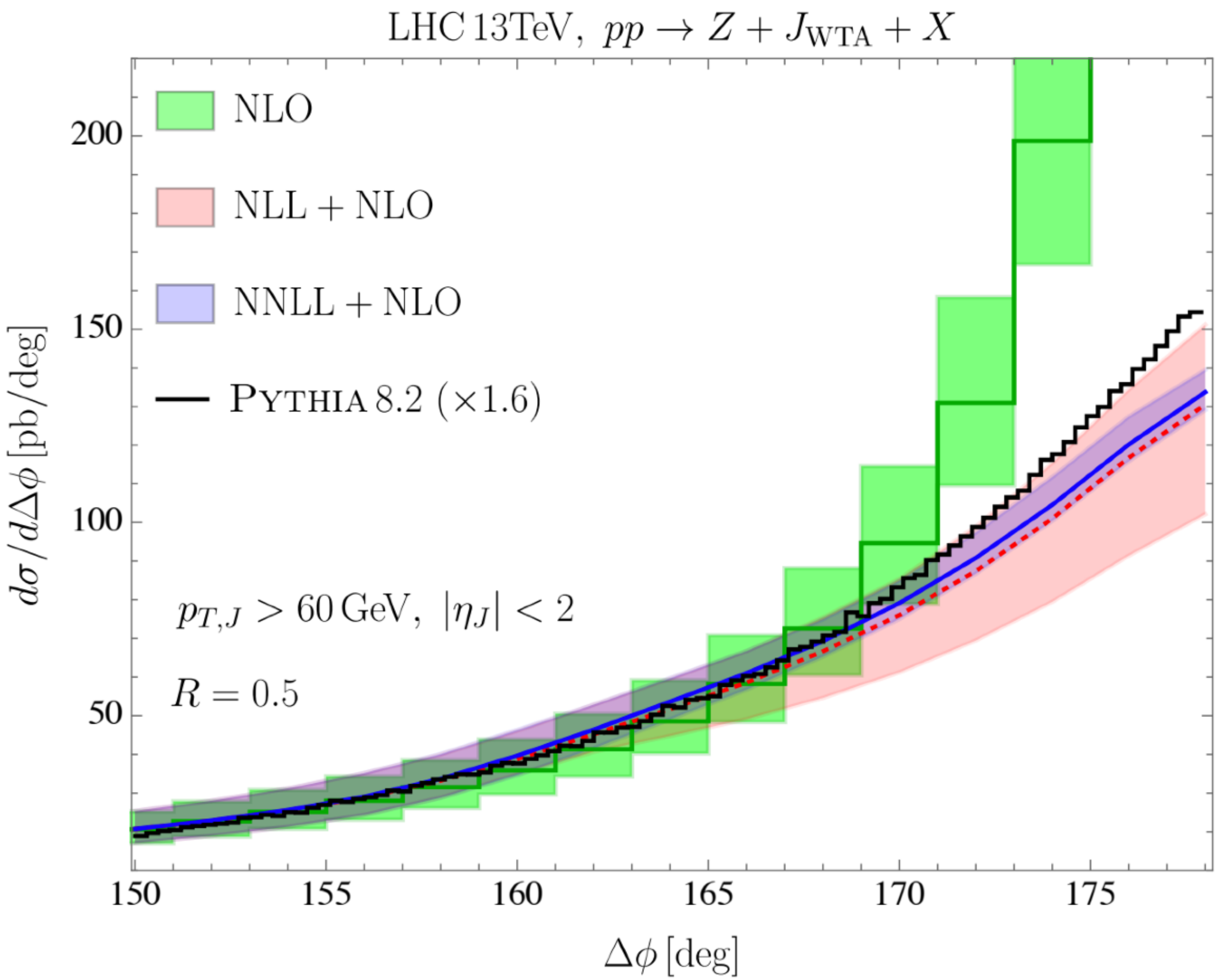
Pythia simulation results





- Non-perturbative effects (hadronization and MPI) are mild

Numerical results



- **first N²LL resummation including full jet dynamics**
- **good perturbative convergence**
- **N³LL resummation in on progress**
- **interesting to perform the same measurement at the LHC**

Azimuthal decorrelations of jets with the standard jet axis

- **All-order resummation of azimuthal decorrelation of QCD jets was first studied by** (Banfi, Dasgupta & Delenda '08)

$$q_T = \Big| \sum_{i \notin \text{jets}} \vec{k}_{T,i} \Big| + \mathcal{O}\left(k_T^2\right)$$

- **CSS framework**
  - **dijet** (Sun, Yuan & Yuan '14 & '15) **jet + V** (Sun, Yuan & Yuan '18; Chen, Qin, Wang, Wei, Xiao, Zhang '18) **lepton + jet** (Liu, Yuan & Felix '19) **jet + top** (Cao, Sun, Yan, Yuan & Yuan '18 & '19) … …

Resummation formula:

$$\frac{d\sigma}{d\Delta\phi} = x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b) \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} b\, J_0(|\vec{q}_\perp| b) e^{-S(Q,b)}$$

Perturbative Sudakov factor:

$$S_P(Q,b) = \sum_{q,g} \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[A \ln \frac{Q^2}{\mu^2} + B + D \ln \frac{1}{R^2} \right]$$

Jet radius and TMD joint resummation for boson-jet correlation

(Chien, DYS & Wu '19 JHEP)

$$N_1(P_1) + N_2(P_2) \to \underbrace{\text{boson}(p_V) + \text{jet}(p_J)}_{q_T} + X$$

$$q_T \ll Q, R \ll 1$$

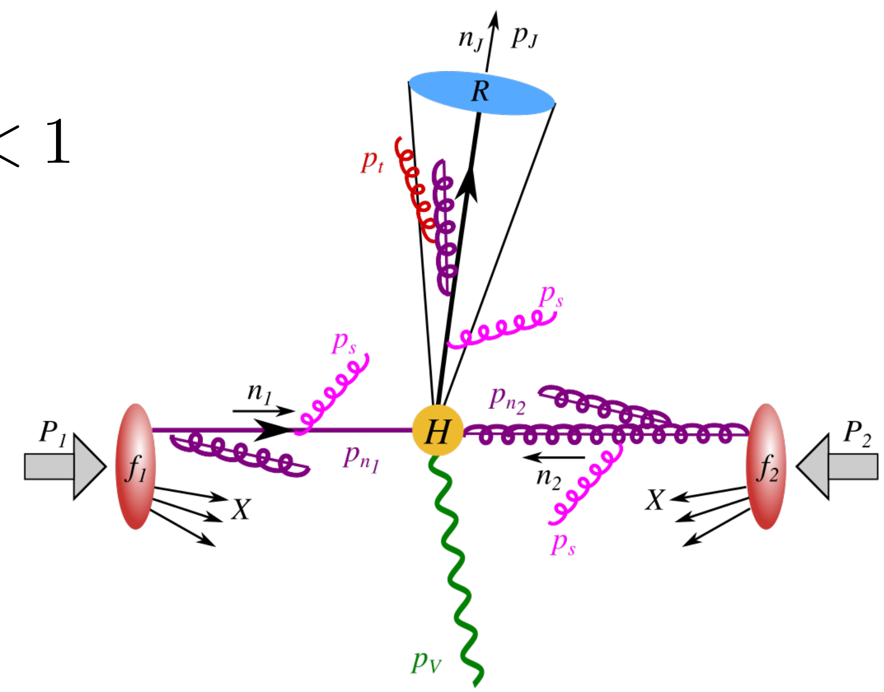
$p_h \sim Q(1,1,1)$

$p_{n_J} \sim p_T^J\,(R^2, 1, R)_{n_J \bar{n}_J}$

$p_{n_1} \sim (q_T^2/Q, Q, q_T)_{n_1 \bar{n}_1}$

$p_s \sim (q_T, q_T, q_T)$

$p_t \sim q_T\,(R^2, 1, R)_{n_J \bar{n}_J}$



Construction of the theory formalism

- **Multiple scales in the problem**
- **Rely on effective field theory: SCET + Jet Effective Theory** (Becher, Neubert, Rothen, DYS '16 PRL)

$$\frac{d\sigma}{d^2q_T d^2p_T d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2x_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{x}_T} \mathcal{S}_{ij\to Vk}(\vec{x}_T,\epsilon)\mathcal{B}_{i/N_1}(\xi_1, x_T, \epsilon)\mathcal{B}_{j/N_2}(\xi_2, x_T, \epsilon)$$

$$\times \mathcal{H}_{ij\to Vk}(\hat{s},\hat{t},m_V,\epsilon) \sum_{m=1}^{\infty} \langle \boldsymbol{\mathcal{J}}_m^k(\{\underline{n_J}\}, R\,p_J,\epsilon) \otimes \boldsymbol{\mathcal{U}}_m^k(\{\underline{n_J}\}, R\,\vec{x}_T,\epsilon)\rangle$$

New divergence in the ϕ-integral

The anomalous dimensions of the global soft function and collinear-soft function are given by

$$\gamma^{S_{\text{global}}} = \frac{\alpha_s C_F}{\pi}\left[2y_J + \ln\left(\frac{\mu^2}{\mu_b^2}\right) + \ln\left(4\cos^2\phi_x\right) - i\pi\,\text{sign}\left(\cos\phi_x\right)\right],$$
$$\gamma^{S_{\text{cs}}} = -\frac{\alpha_s C_F}{\pi}\left[\ln\left(\frac{\mu^2}{\mu_b^2 R^2}\right) + \ln\left(4\cos^2\phi_x\right) - i\pi\,\text{sign}\left(\cos\phi_x\right)\right],$$

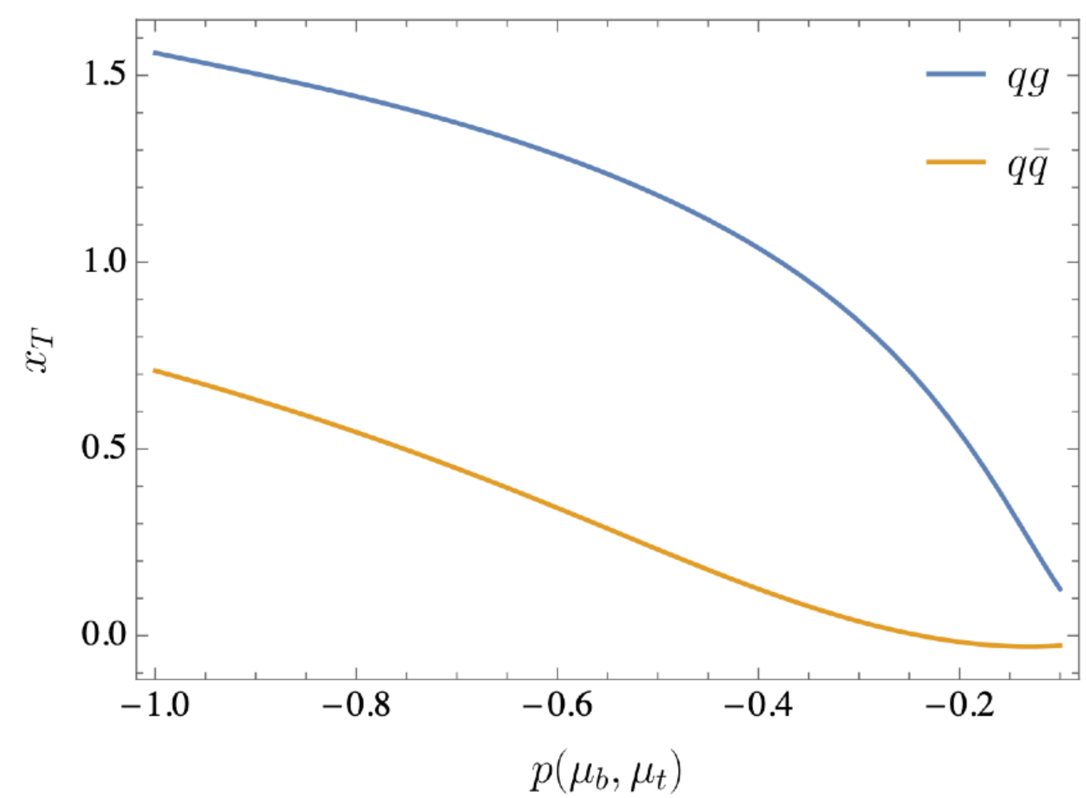
- **Scale separation introduced by the narrow cone approximation** $R \ll 1$
- **Both soft and collinear-soft functions are divergent as** $\phi_x = \pi/2$
- ϕ **dependent term in the RG solution between soft and collinear-soft scales reads**

$$|\cos\phi_x|^{p(\mu_b, R\mu_b)}$$

the ϕ-integral is convergent only if

$$-1 < p(\mu_b,\mu_t) \equiv \frac{4C_k}{\beta_0}\log\frac{\alpha_s(\mu_b)}{\alpha_s(\mu_t)} \approx -\frac{2\alpha_s(\mu_t)}{\pi}\log\frac{1}{R}$$

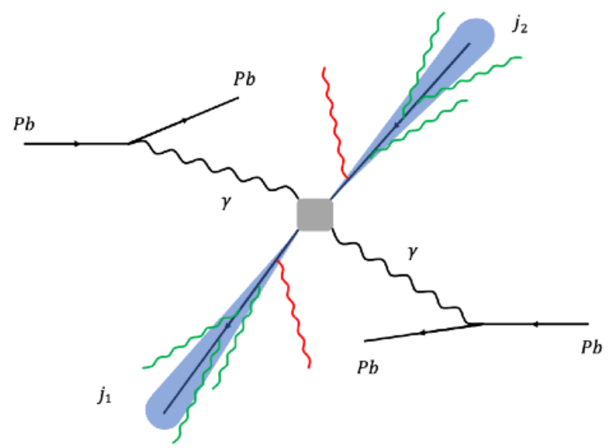
One encounters such a divergence when the collinear-soft scale approaches to the non-perturbative region



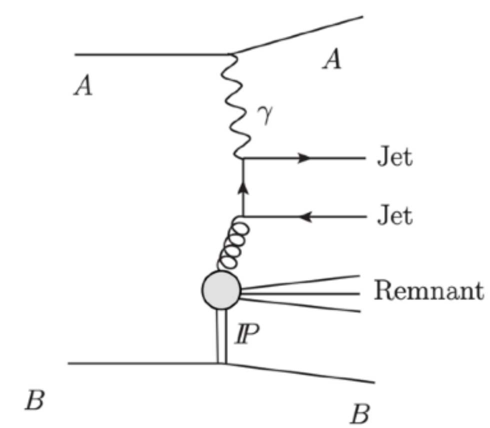
Azimuthal decorrelation of QCD jets in ultra-peripheral collisions

(Zhang, Dai, DYS, '23 JHEP)

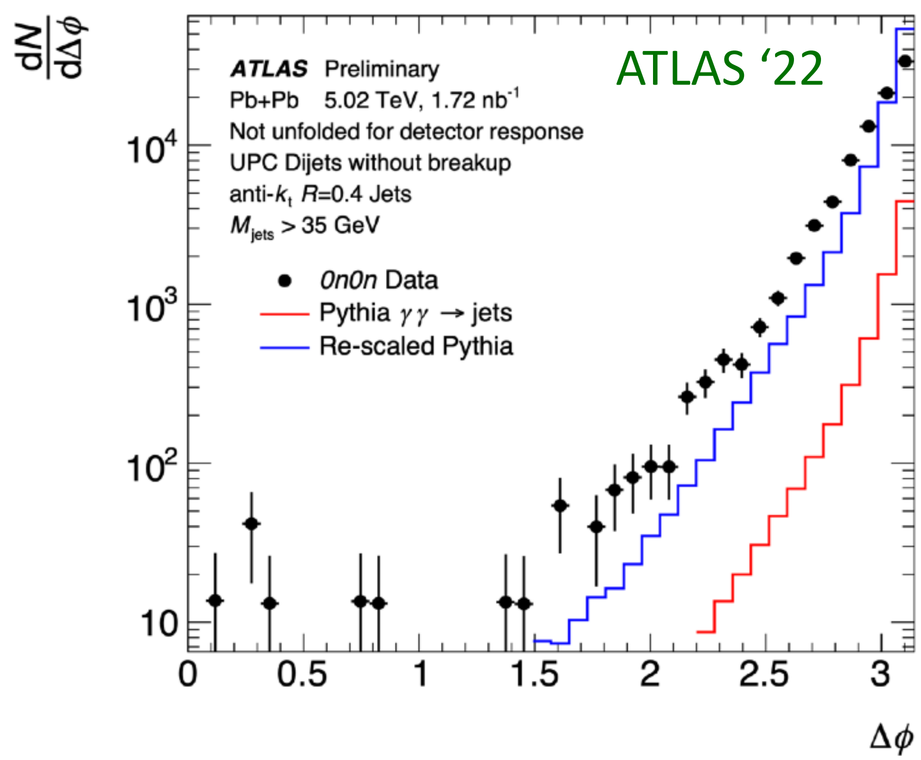
Dijet production with no nuclear breakup



Photon-photon fusion



diffractive photo-production

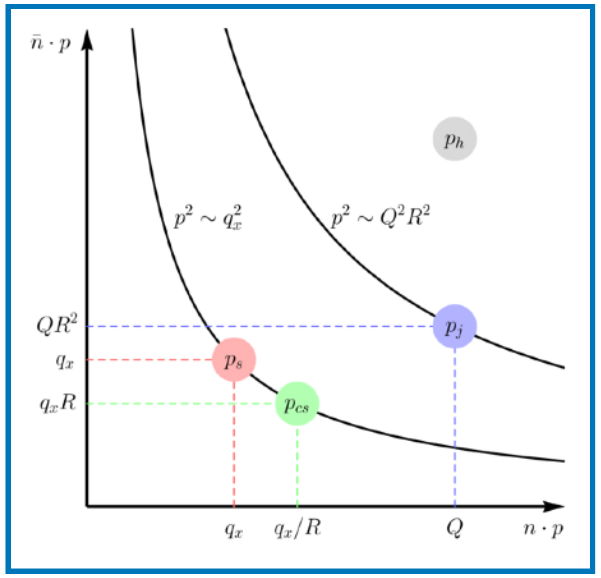


We apply equivalent photon approximation + SCET

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}q_x\mathrm{d}p_T\mathrm{d}y_1\mathrm{d}y_2} = \int_{-\infty}^{+\infty}\frac{\mathrm{d}b_x}{2\pi}e^{iq_xb_x}\tilde{B}(b_x,p_T,y_1,y_2)H(p_T,\Delta y,\mu)\tilde{S}(b_x,y_1,y_2,\mu,\nu)\,\tilde{U}_1(b_x,R,y_1,\mu,\nu)J_1(p_T,R,\mu)\tilde{U}_2(b_x,R,y_2,\mu,\nu)J_2(p_T,R,\mu)$$

Impact parameter dependent Born cross section from EPA (Fermi 1924; Weizsacker 1934; Williams 1935)

Also see 《物理学报》"高能重离子超边缘碰撞中极化光致反应" 浦实、肖博文、周剑、周雅瑾



Collinear anomaly and resummation formula

Refactorization and collinear anomaly in TMD resummation of Drell-Yan process

(Becher, Neubert `10)

$$\left[\mathcal{B}_{q/N_1}(z_1, x_T^2, \mu)\, \bar{\mathcal{B}}_{\bar{q}/N_2}(z_2, x_T^2, \mu)\right]_{q^2} = \left(\frac{x_T^2 q^2}{b_0^2}\right)^{-F_{q\bar{q}}(x_T^2, \mu)} B_{q/N_1}(z_1, x_T^2, \mu)\, B_{\bar{q}/N_2}(z_2, x_T^2, \mu)$$

which is also known as Collins-Soper treatment or rapidity renormalization group

Refactorization and jet radius resummation (Zhang, Dai, DYS, '22)

$$\tilde{U}_1(b, R, y_1, \mu, \nu)\tilde{U}_2(b, R, y_2, \mu, \nu)\tilde{S}(b, y_1, y_2, \mu, \nu) = R^{2F_{q\bar{q}}(b,\mu)} W(b, \Delta y, \mu)$$

Verified at one loop

$$\tilde{S}(b_x, y_1, y_2, \mu, \nu)\tilde{U}_1(b_x, y_1, \mu, \nu)\tilde{U}_2(b_x, y_2, \mu, \nu) = 1 + C_F \frac{\alpha_s}{\pi}\left[\ln R^2 - \ln(2 + 2\cosh \Delta y)\right]\left(\frac{1}{\epsilon} + \ln \frac{b_x^2 \mu^2}{b_0^2}\right)$$

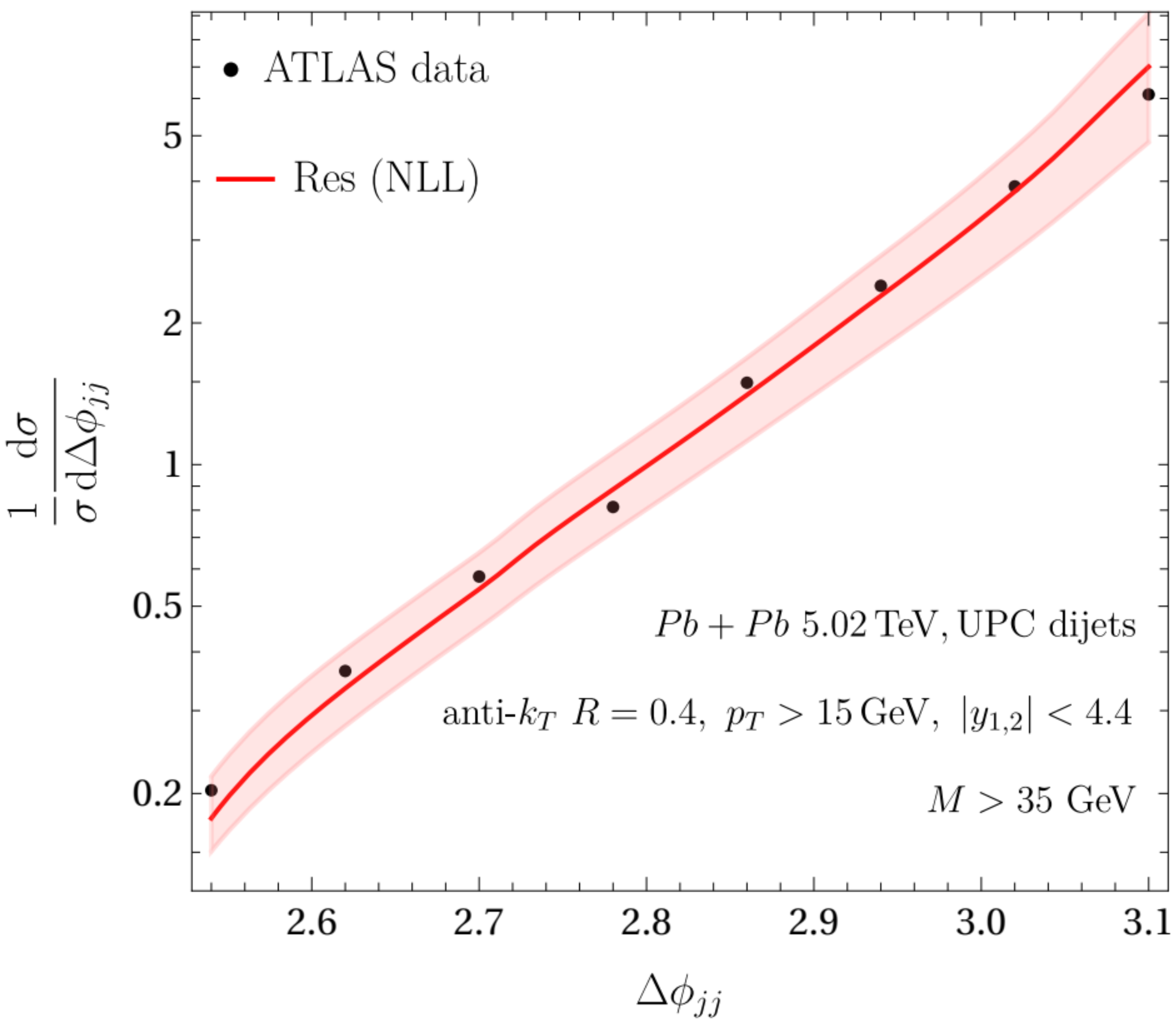
Resummation formula

$$\frac{\mathrm{d}^4\sigma^{\mathrm{NLL}}}{\mathrm{d}q_x \mathrm{d}p_T \mathrm{d}y_1 \mathrm{d}y_2} = \int_0^\infty \frac{\mathrm{d}b_x}{\pi} \cos(q_x b_x) \tilde{B}(b_x, p_T, y_1, y_2) \exp\left[\int_{\mu_h}^{\mu_b} \frac{\mathrm{d}\mu}{\mu} \Gamma_H(\alpha_s) + 2\int_{\mu_j}^{\mu_b} \frac{\mathrm{d}\mu}{\mu} \Gamma_J(\alpha_s)\right] U_{\mathrm{NG}}^2(\mu_b, \mu_j)$$

We choose the intrinsic scales as $\mu_h = M, \quad \mu_j = p_T R, \quad \mu_b = \dfrac{b_0}{b_*(b_x)}$

Numerical results

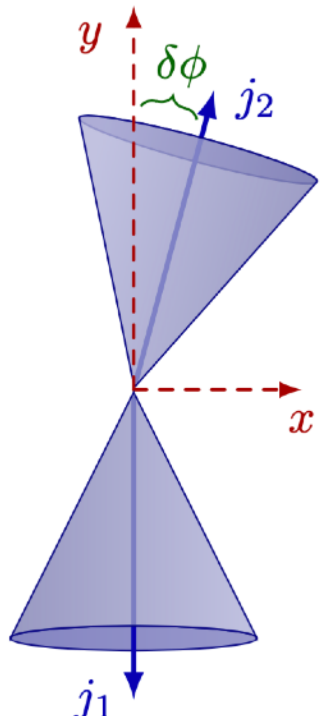
(Zhang, Dai, DYS, '23 JHEP)



- **A good agreement with the ATLAS data in the nearly back-to-back region**
- **Photo-productions may enhance the dijet production rate, but should barely change the shape**

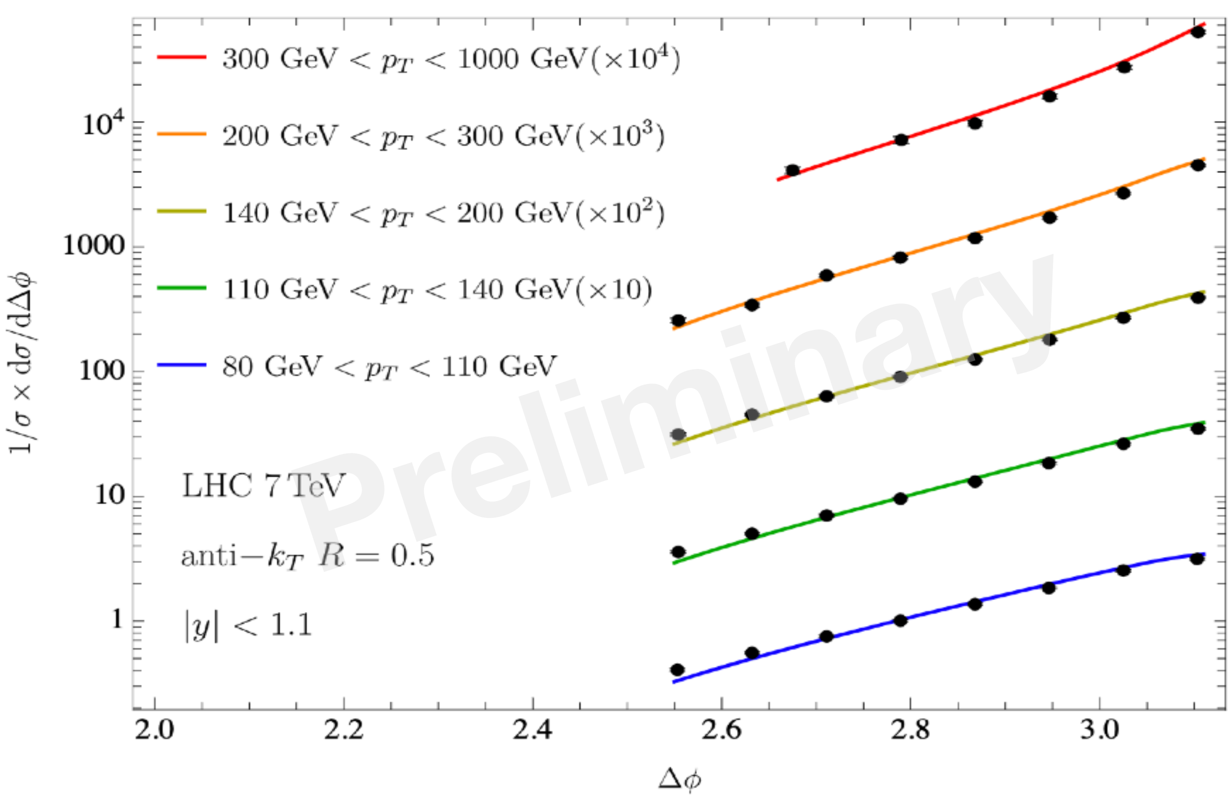
QCD resummation of the azimuthal decorrelation of dijets in pp and pA

Gao, Kang, DYS, Terry, Zhang in progress

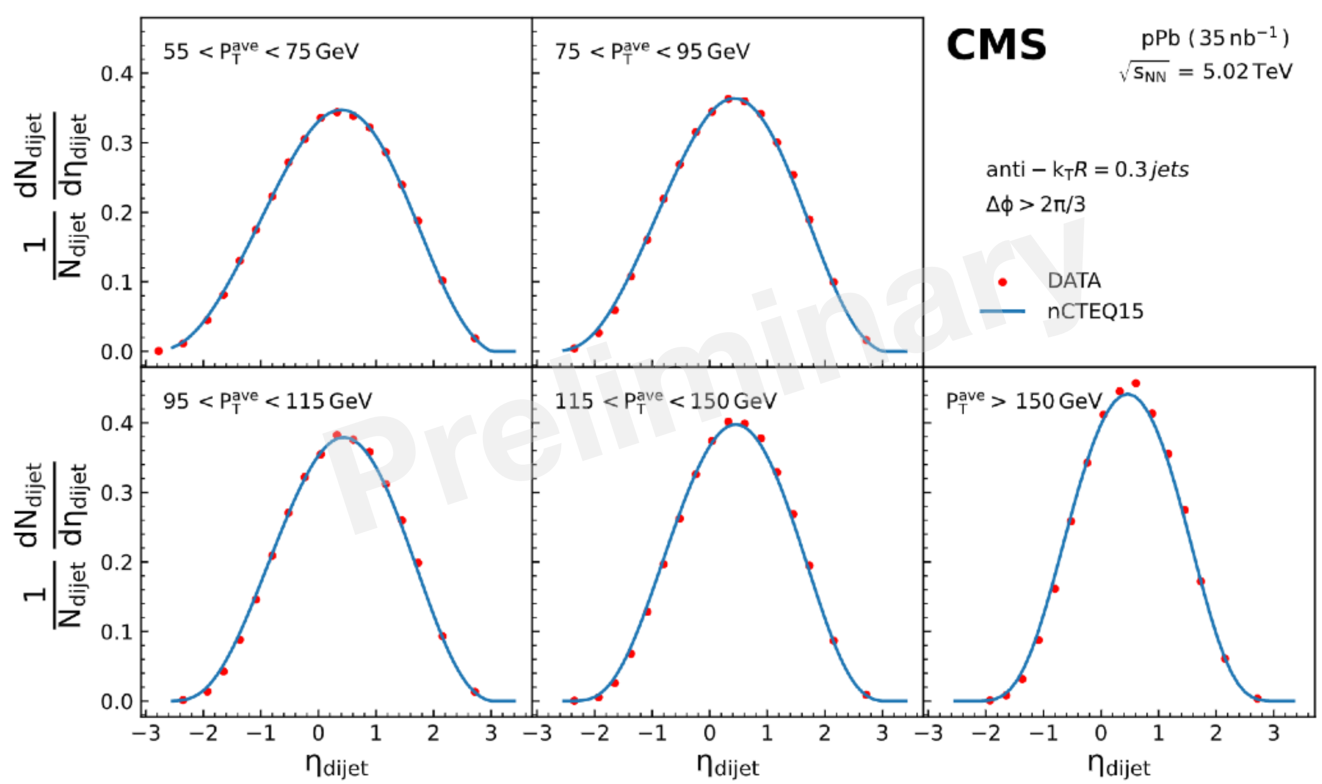


Factorization and resummation formula in SCET

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}y_c\mathrm{d}y_d\mathrm{d}p_T^2\mathrm{d}\delta\phi} = \sum_{abcd}\frac{p_T}{16\pi\hat{s}^2}\frac{1}{1+\delta_{cd}}\int\frac{\mathrm{d}b}{2\pi}e^{ibp_T\delta\phi}x_a\tilde{f}^{\mathrm{unsub}}_{a/p}(x_a,b,\mu,\zeta_a/\nu^2)x_b\tilde{f}^{\mathrm{unsub}}_{b/p}(x_b,b,\mu,\zeta_b/\nu^2)$$
$$\times\,\mathrm{Tr}\left[\boldsymbol{H}_{ab\to cd}(\hat{s},\hat{t},\mu)\tilde{\boldsymbol{S}}^{\mathrm{unsub}}_{ab\to cd}(b,\mu,\nu)\right]J_c(p_TR,\mu)\tilde{S}^{\mathrm{cs}}_c(b,R,\mu,\nu)$$
$$\times\,J_d(p_TR,\mu)\tilde{S}^{\mathrm{cs}}_d(b,R,\mu,\nu),$$



(also see Sun, Yuan, Yuan '14 PRL)



Nuclear modified TMD PDFs (Alrashed, Anderle, Kang, Terry & Xing, '22)

Summary

- TMD jets play essential roles in understanding QCD dynamics in many aspects.
- Recoiling-free azimuthal decorrelation achieves first NNLL accuracy with full jet dynamics, and we find the non-perturbative corrections are mild.
- Our result can serve as a baseline for studying naive factorization violation, spin asymmetry and energy loss in QGP.
- We understand why azimuthal decorrealtion is simpler than standard transverse momentum imbalance, and the new divergence in q_T corresponds to the rapidity divergence of azimuthal decorrelation.
- We study the dijet azimuthal decorrelation in pp, pA, AA(UPC) processes and find good agreement.

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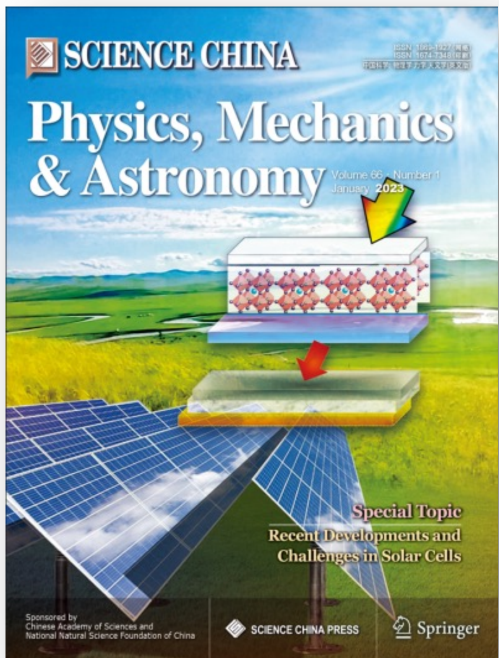

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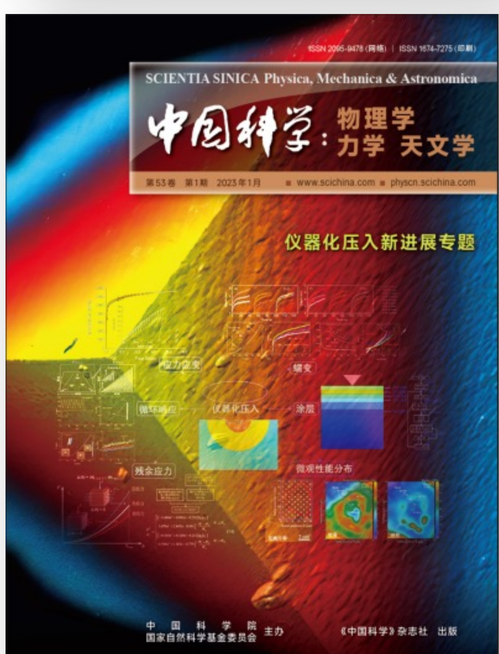

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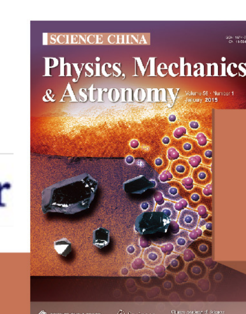

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