Cold nuclear matter effects on jets production

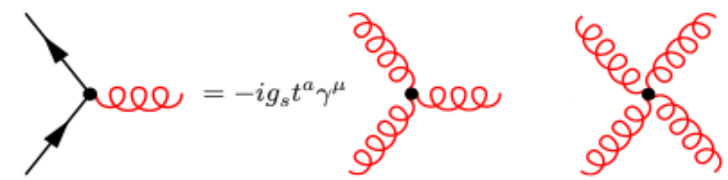
Ding-Yu Shao
Fudan University

第二十届全国中高能核物理大会暨第十四届全国中高能核物理专题研讨会
上海　2025年4月26日

QCD and jet physics

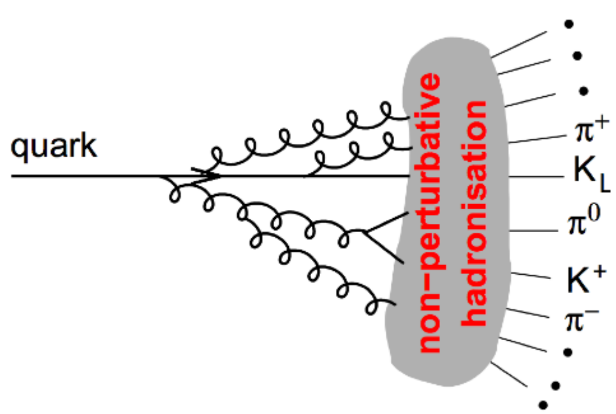
QCD: non-abelian Yang-Mills theory

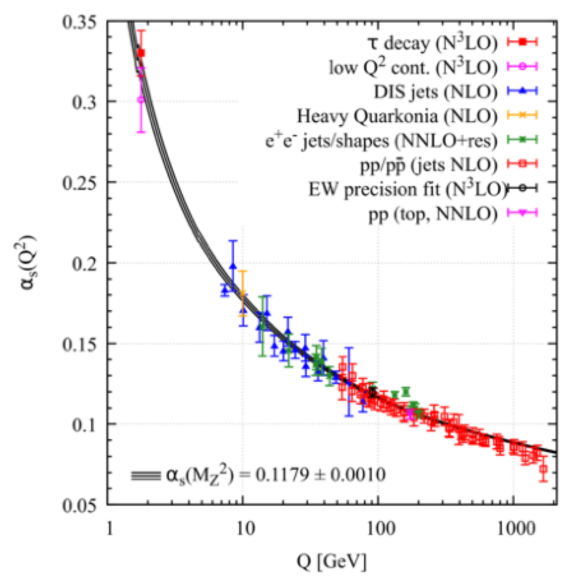
$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$



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

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

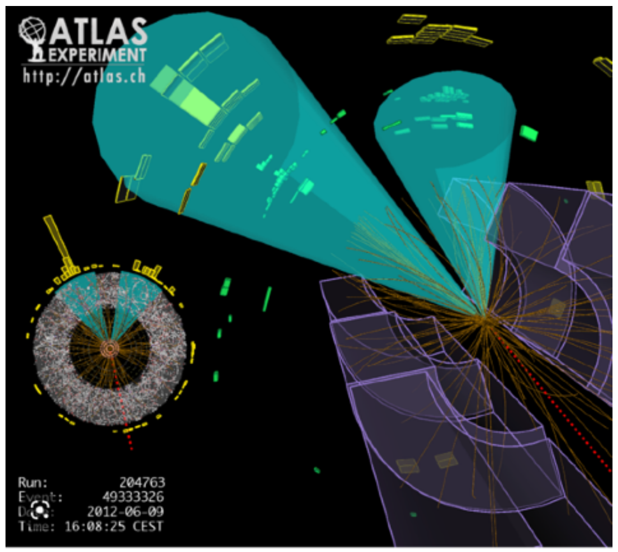
Not jets (QED jets?): $e \;\; \mu \;\; \gamma$

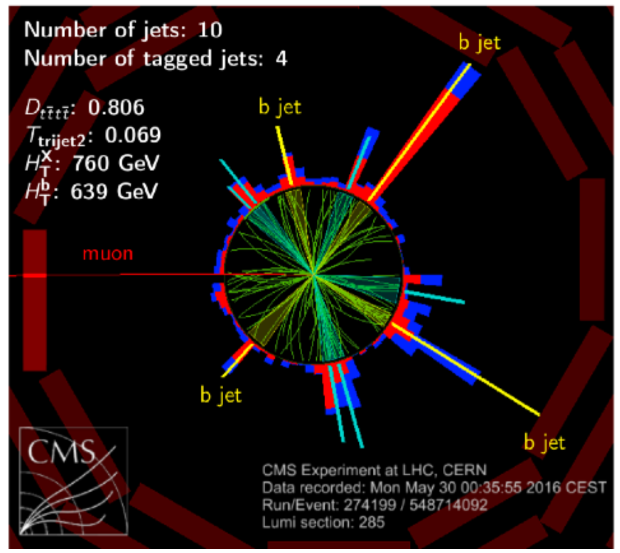
Tau jets: τ

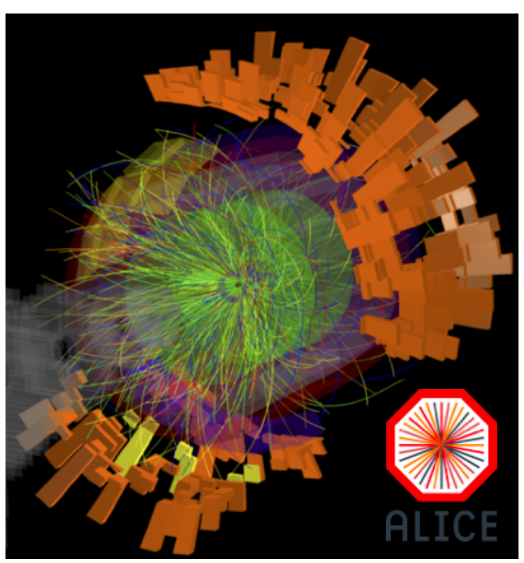
Light Jets: $u\ d\ s\ g$

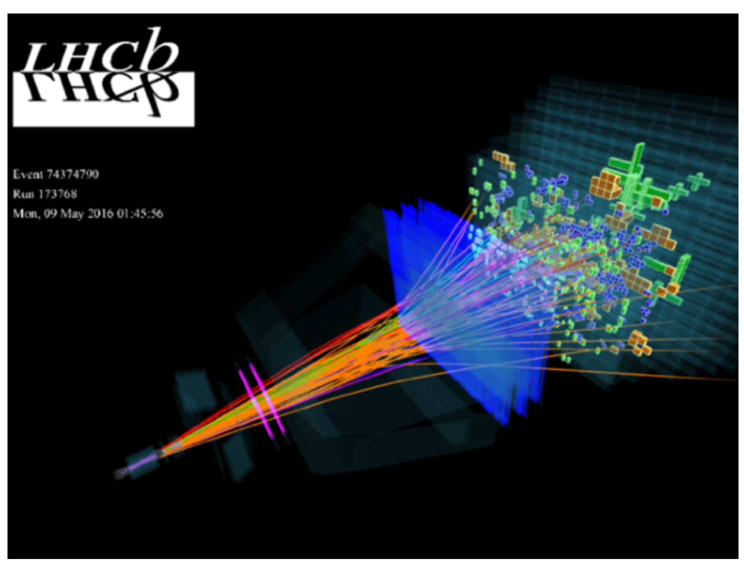
Heavy Jets: $c\ b$

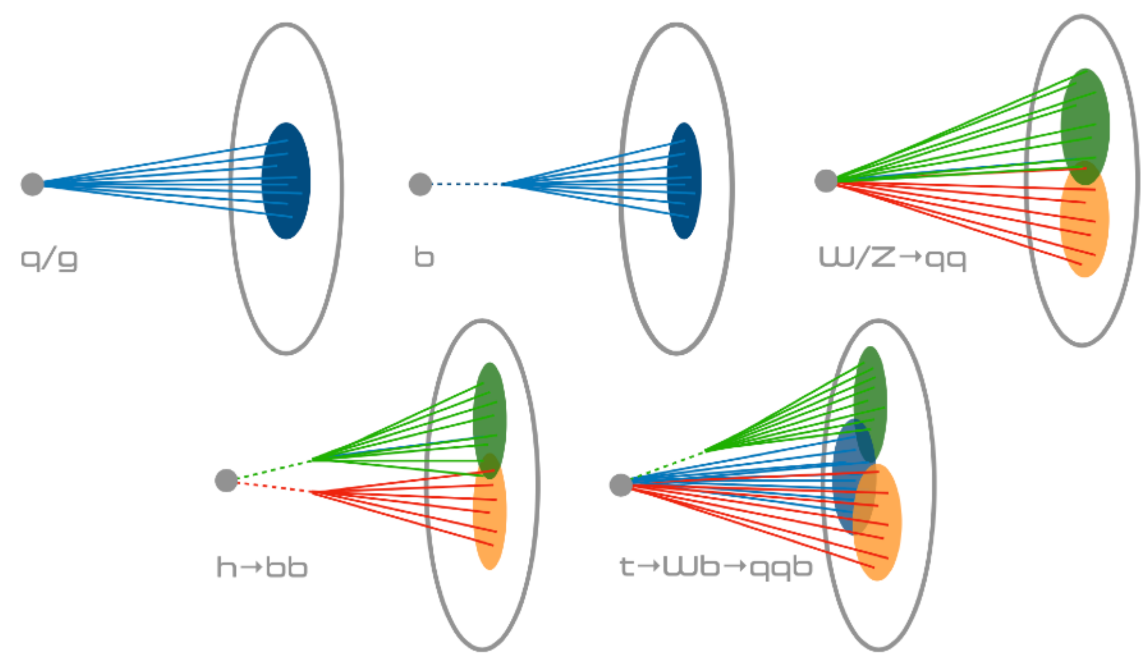
Fat Jets: $W\ Z\ H\ t$



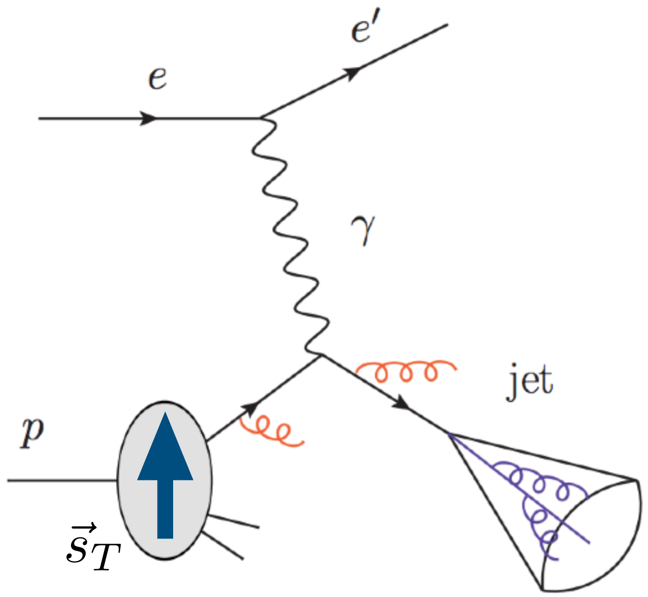


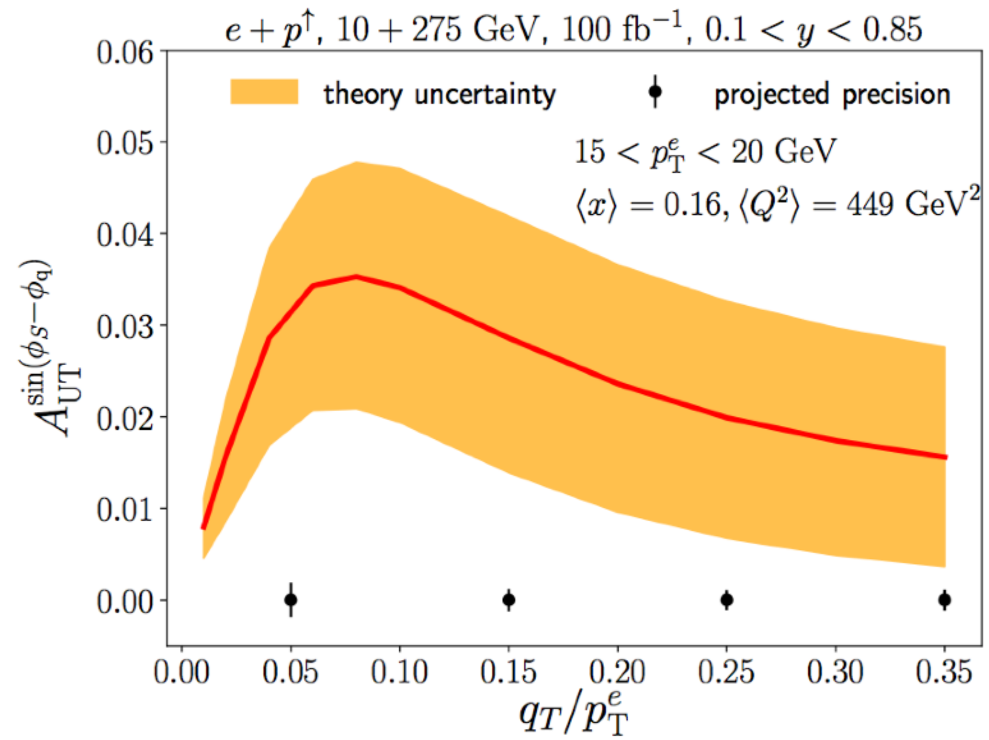




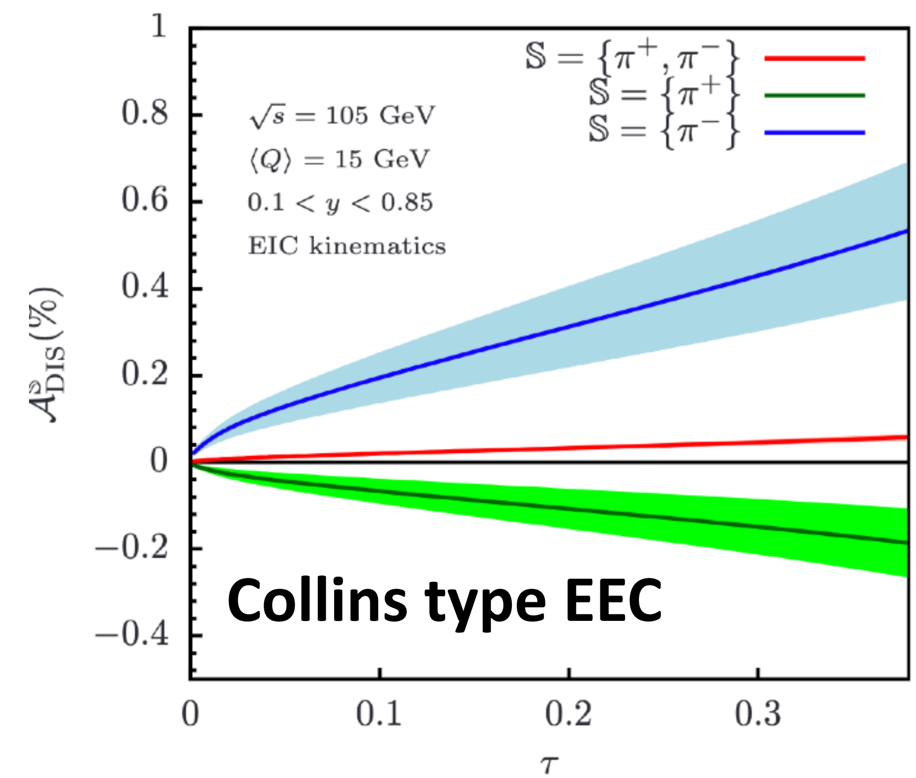


Jets and 3D imaging

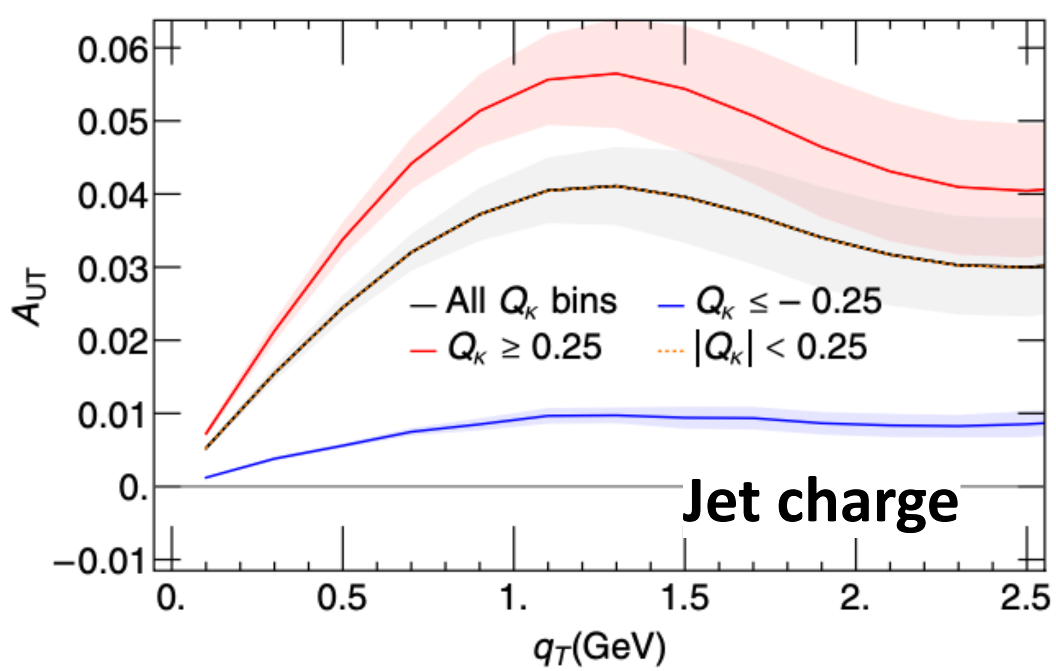




Arratia, Kang, Prokudin, Ringer ’19
Liu, Ringer, Vogelsang, Yuan ’19



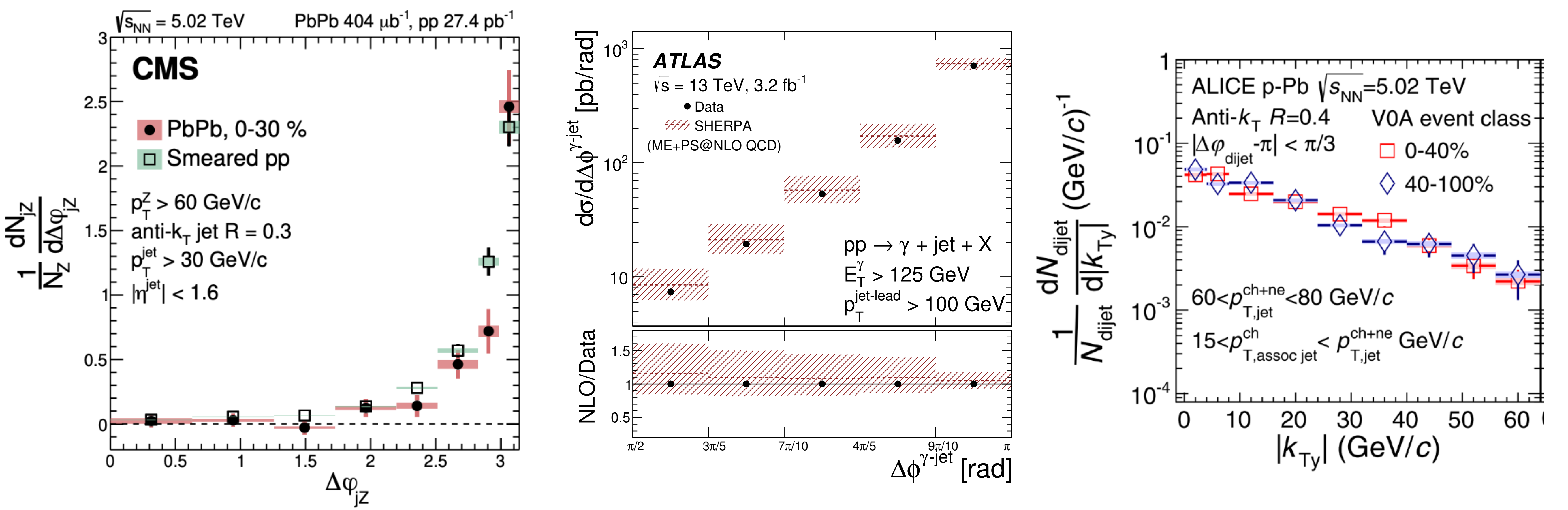
Kang, Lee, DYS, Zhao ’23 JHEP



Kang, Liu, Mantry, DYS ’20 PRL

- Jets are complementary to standard SIDIS extractions of TMDs
- Jet measurements allow independent constraints on TMD PDFs and FFs from a single measurement
- Azimuthal correlation between jet and lepton sensitive to TMD PDFs

Azimuthal correlation in the back-to-back limit

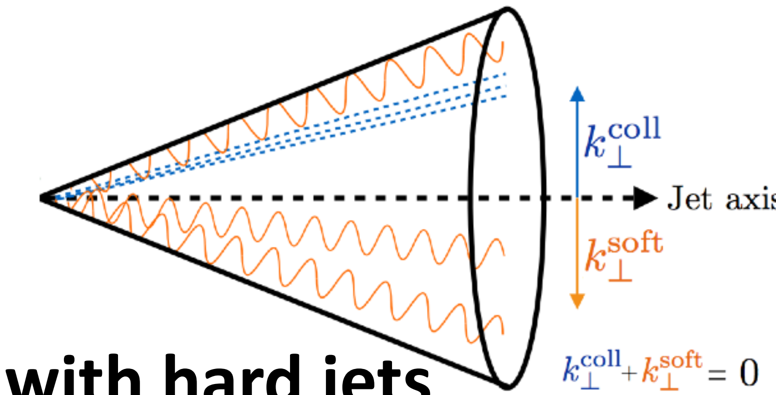


- **jet calibration at pp**
- **strong coupling measurement**
- **spin asymmetry**
- **TMDs, Nuclear TMDs**
- **QGP at HIC**
- **naive factorization violation**
- **…**

In the back-to-back limit, one needs all-order results (log(π-Δϕ) resummation)

Jet TMDs and all-order structure

- **Large logarithms in jet TMDs**



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

  - **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)

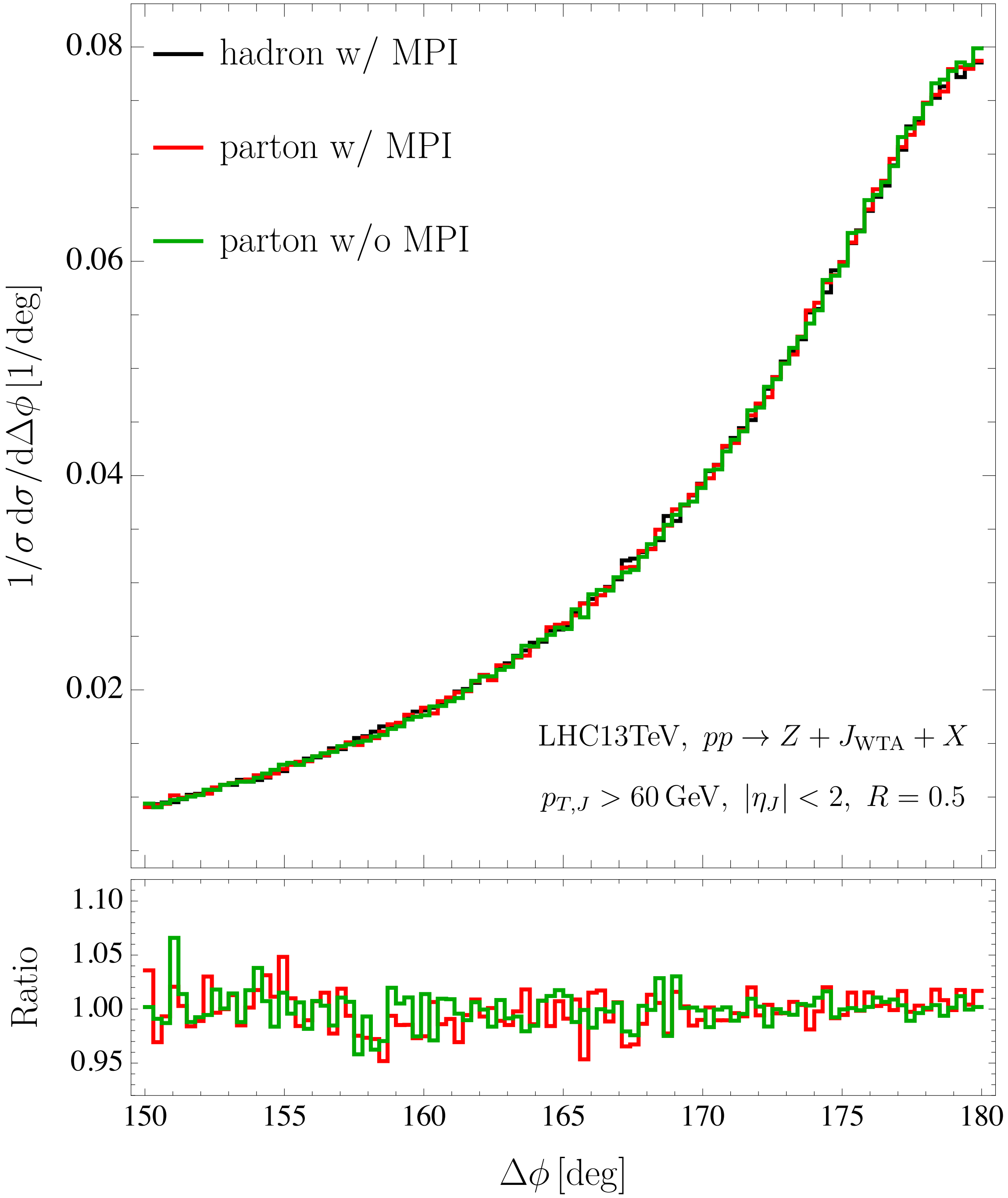
$$\begin{aligned} p_{t,r} &= p_{t,i} + p_{t,j} \,, \\ \phi_r &= (w_i\phi_i + w_j\phi_j)/(w_i + w_j) \\ y_r &= (w_i y_i + w_j y_j)/(w_i + w_j) \end{aligned} \qquad w_i = p_t^n$$

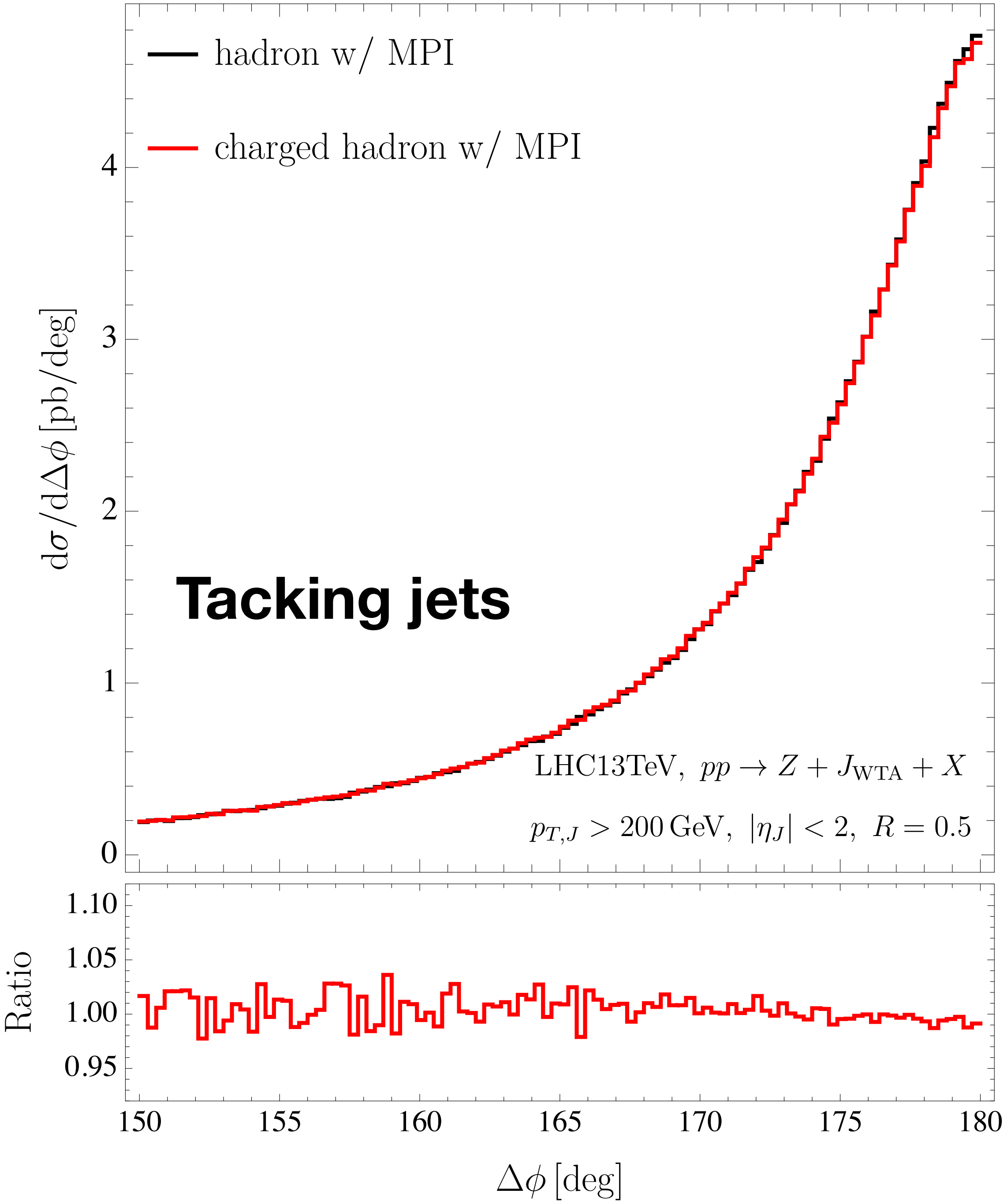
$n \to \infty$ **Winner-take-all scheme** (Salam; Bertolini, Chan, Thaler '13)

- **N^3LL 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)
- **NNLL resummation for $\delta\phi$ @ ep & eA** (Fang, Ke, DYS, Terry '23 JHEP)
- **N^3LL resummation for $\delta\phi$ @ ep** (Fang, Gao, Li, DYS, Terry '24 JHEP)

Pythia simulation results

(Chien, Rahn, DYS, Waalewijn & Wu '23 JHEP + Schrignder '21 PLB)





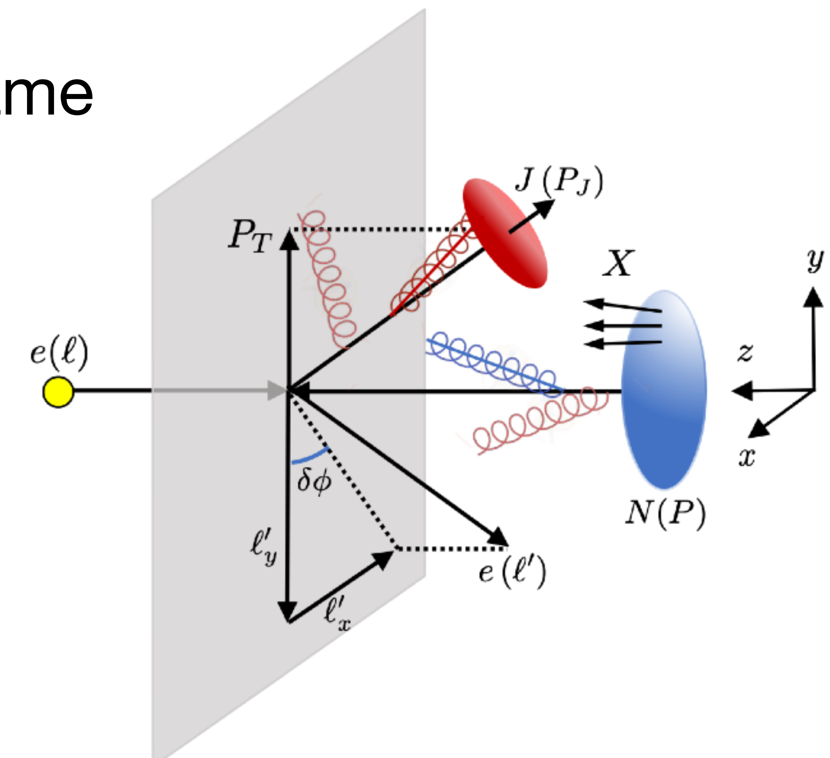
- Non-perturbative effects (hadronization and MPI) are mild

Recoil-free azimuthal angle for electron-jet correlation

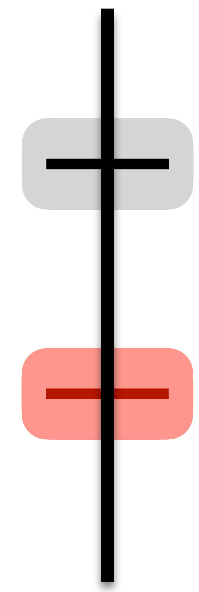
Fang, Ke, DYS, Terry '23 JHEP

$$e(\ell) + N(P) \to e(\ell') + J(P_J) + X$$

Lab frame



Standard TMD in back to back limit: $Q \gg q_T \sim l_T\,\delta\phi$



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

$p^{\mu}_{c_i} \sim l_T\left(\delta\phi^2, 1, \delta\phi\right)_{n_i\bar{n}_i}$

$p^{\mu}_{s} \sim l_T(\delta\phi, \delta\phi, \delta\phi)$

Effects of jet algorithm are suppressed, first appear at two loop

Following the standard steps in SCET and CSS, we obtain the following resummation formula

$$\frac{d\sigma}{d^2\ell'_T\, dy\, d\delta\phi} = \frac{\sigma_0\, \ell'_T}{1-y} H\left(Q, \mu\right) \int_0^\infty \frac{db}{\pi} \cos\left(b \ell'_T \delta\phi\right) \sum_q e_q^2\, f_{q/N}\left(x_B, b, \mu, \zeta_f\right) J_q\left(b, \mu, \zeta_J\right)$$

Hard factor

Fourier transformation in 1-dim

TMD PDF

Jet function

Predictions in e-p

Fang, Ke, DYS, Terry '23

TMD PDF (CSS treatment)

$$f_{q/N}(x_B,b,\mu,\zeta_f) = [C\otimes f]_{q/N}(x_B,b,\mu_f,\zeta_{fi})\, U_{\rm NP}^f(x_B,b,A,Q_0,\zeta_f) \times \exp\left[\int_{\mu_f}^{\mu}\frac{d\mu'}{\mu'}\gamma_\mu^f(\mu',\zeta_f)\right]\left(\frac{\zeta_f}{\zeta_{fi}}\right)^{\frac{1}{2}\gamma_\zeta^f(b,\mu_f)},$$

Jet function

$$J_q(b,\mu,\zeta_J) = J_q(b,\mu_J,\zeta_{Ji})\, U_{\rm NP}^J(b,A,Q_0,\zeta_J) \times \exp\left[\int_{\mu_J}^{\mu}\frac{d\mu'}{\mu'}\gamma_\mu^J(\mu',\zeta_J)\right]\left(\frac{\zeta_J}{\zeta_{Ji}}\right)^{\frac{1}{2}\gamma_\zeta^J(b,\mu_J)}$$

scale choice

$$\mu_H = Q\,, \qquad \mu_f = \mu_J = \sqrt{\zeta_{fi}} = \sqrt{\zeta_{Ji}} = \mu_b = 2e^{-\gamma_E}/b$$

b*-prescription to avoid Landau pole

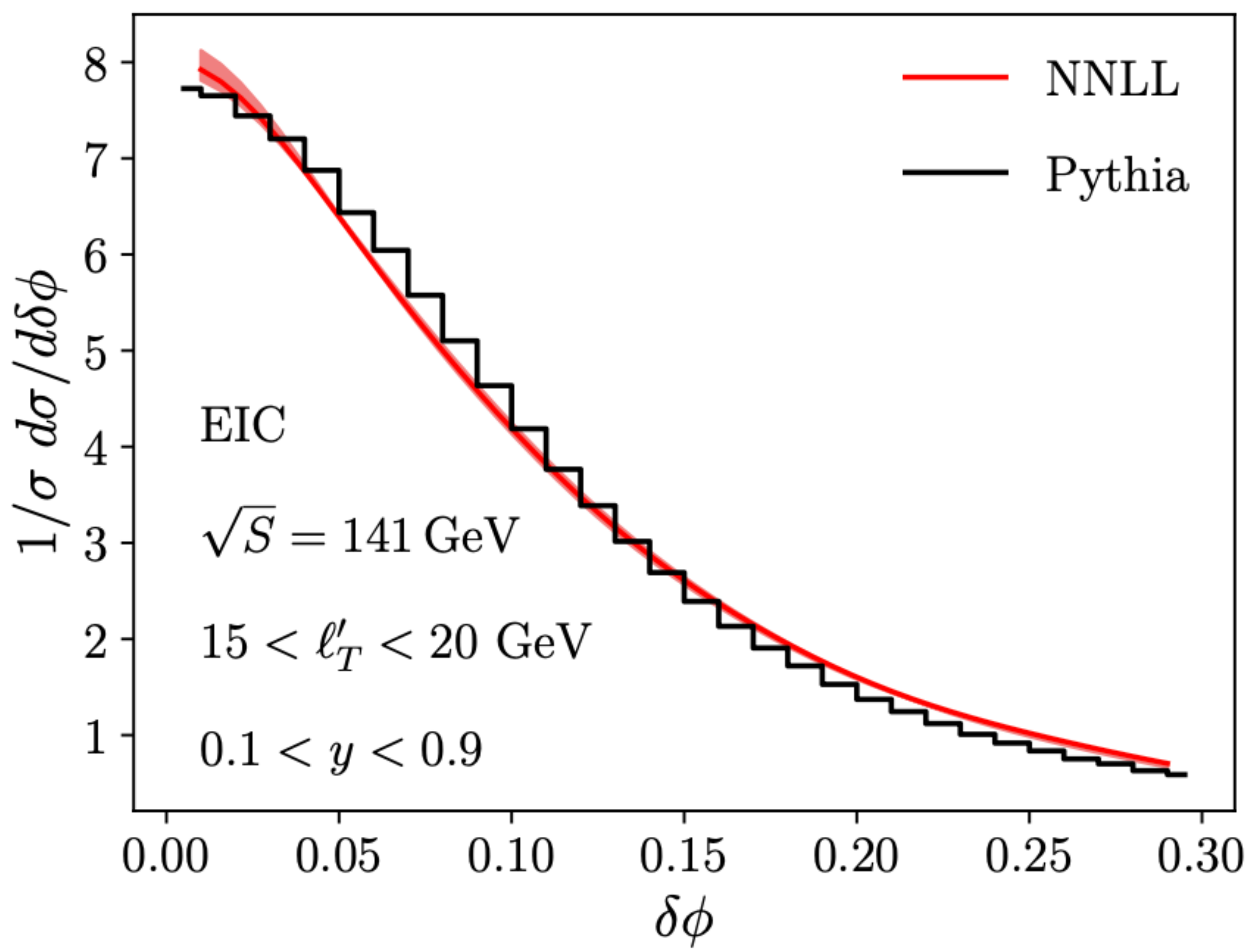
$$b_* = b/\sqrt{1+b^2/b_{\rm max}^2} \qquad \mu_{b_*} = 2e^{-\gamma_E}/b_*$$

non-perturbative model

$$U_{\rm NP}^f = \exp\left[-g_1^f b^2 - \frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b}{b_*}\right]$$

$$U_{\rm NP}^J = \exp\left[-\frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b}{b_*}\right]$$

Sun, Isaacson,Yuan,Yuan '14



μ_H varies between Q/2 and 2Q. μ_b is fixed

Predictions in e-A

Fang, Ke, DYS, Terry '23

We apply nuclear modified TMD PDFs

$$g_1^A = g_1^f + a_N(A^{1/3} - 1) \quad a_N = 0.016 \pm 0.003 \text{ GeV}^2$$

Collinear dynamics using EPPS16

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

We include LO momentum broadening of the jet within SCET$_G$

$$J_q^A(b,\mu,\zeta_J) = J_q(b,\mu,\zeta_J)e^{\chi[\xi b K_1(\xi b)-1]}$$

Opacity parameter $\chi = \frac{\rho_G L}{\xi^2}\alpha_s(\mu_{b_*})C_F$

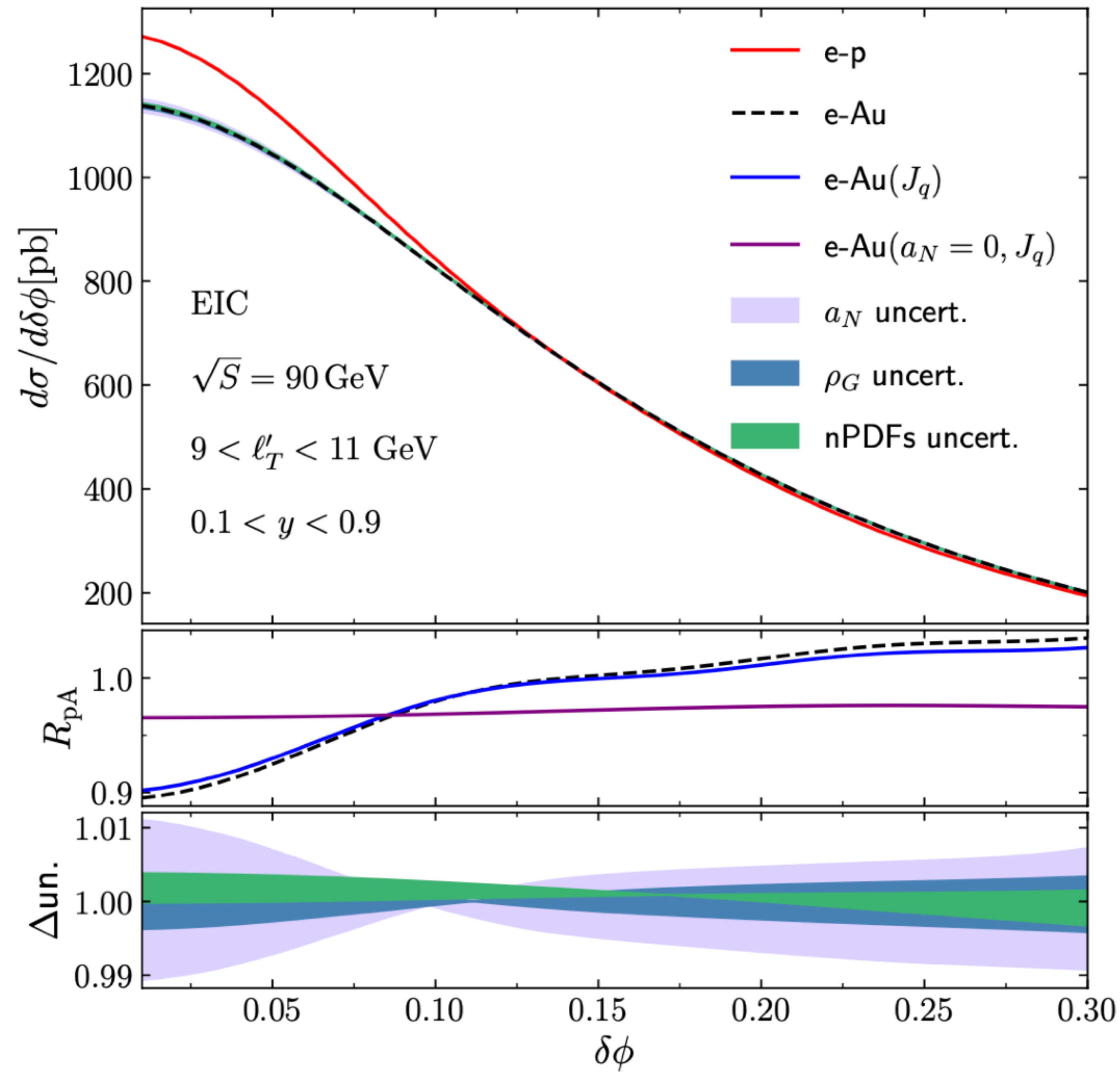
(Gyulassy, Levai, & Vitev '02)

ρ_G : density of the medium

ξ : the screening mass

L: the length of the medium

Parameter values are taken from a recent comparison between SCET$_G$ in e-A from the HERMES Ke and Vitev '23



The process is primarily sensitive to the initial state's broadening effects, thereby serving as a clean probe of nTMD PDF

方申 海报 ID74

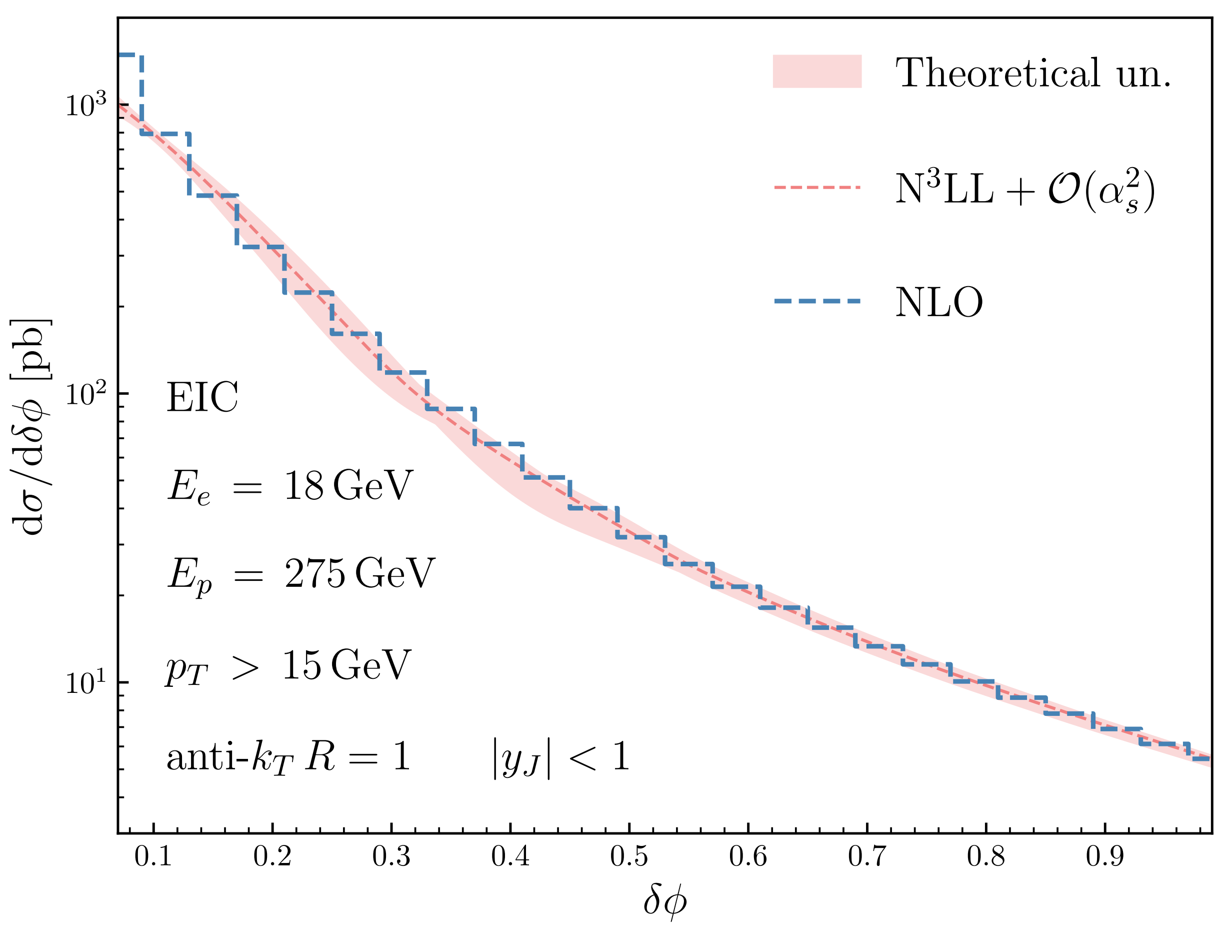
N³LL + $\mathcal{O}(\alpha_s^2)$ predictions on lepton jet azimuthal correlation in DIS

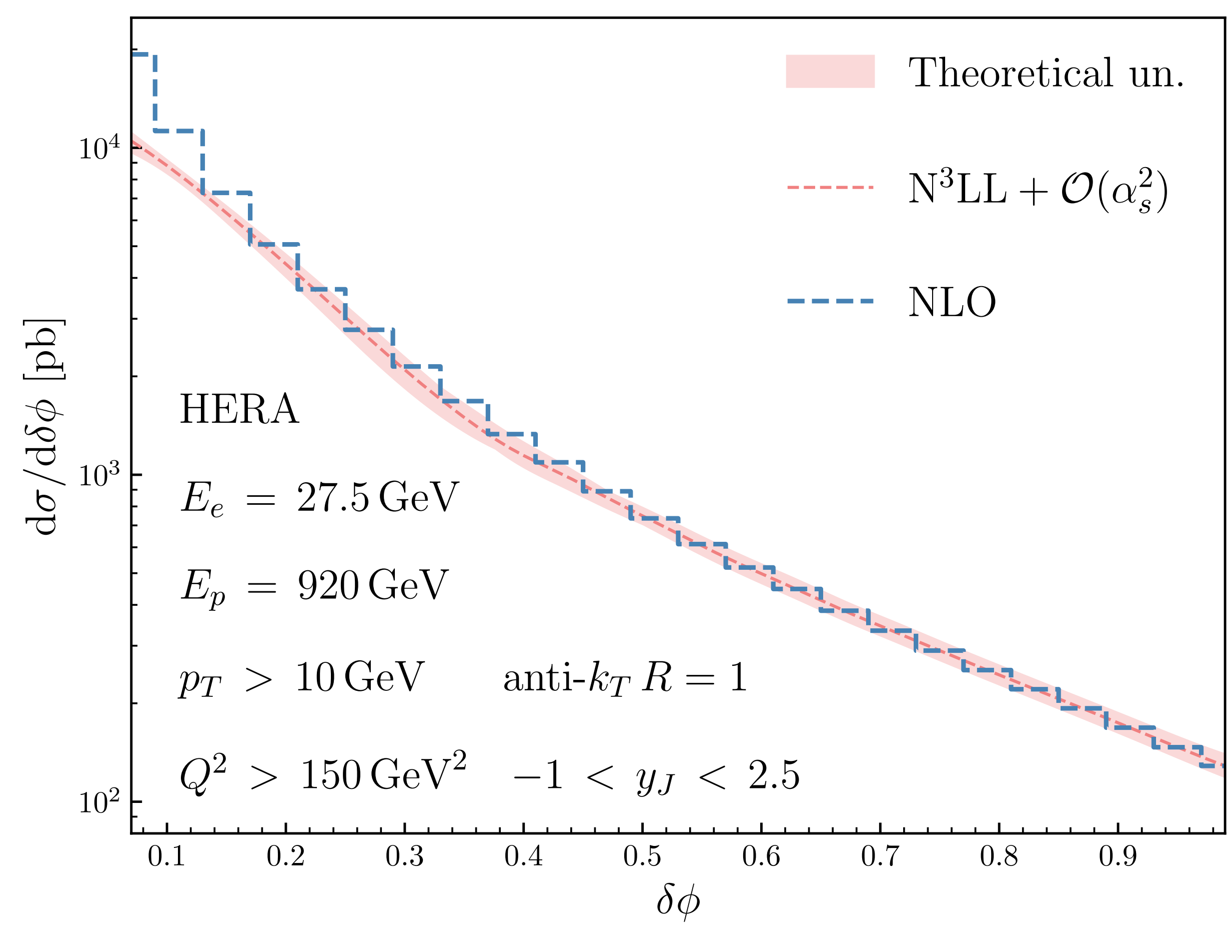
Fang, Gao, Li, DYS 25 JHEP

- **In the large $\delta\phi$ region the resummation formula receives significant matching corrections**
- **It is necessary to switch off the resummation and instead employ fixed-order calculations**

$$\mathrm{d}\sigma_{\mathrm{add}}\,(\mathrm{NNNLL}+\mathcal{O}(\alpha_s^2)) \equiv \mathrm{d}\sigma(\mathrm{NNNLL}) + \underbrace{\mathrm{d}\sigma(\mathrm{NLO}) - \mathrm{d}\sigma(\mathrm{NLO\ singular})}_{\mathrm{d}\sigma(\mathrm{NLO\ non\text{-}singular})}$$

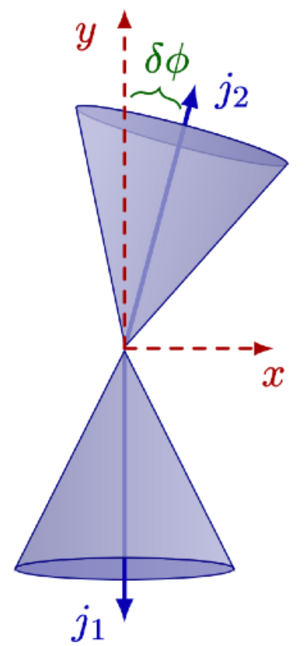
Y-term





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

Gao, Kang, DYS, Terry, Zhang '23 JHEP

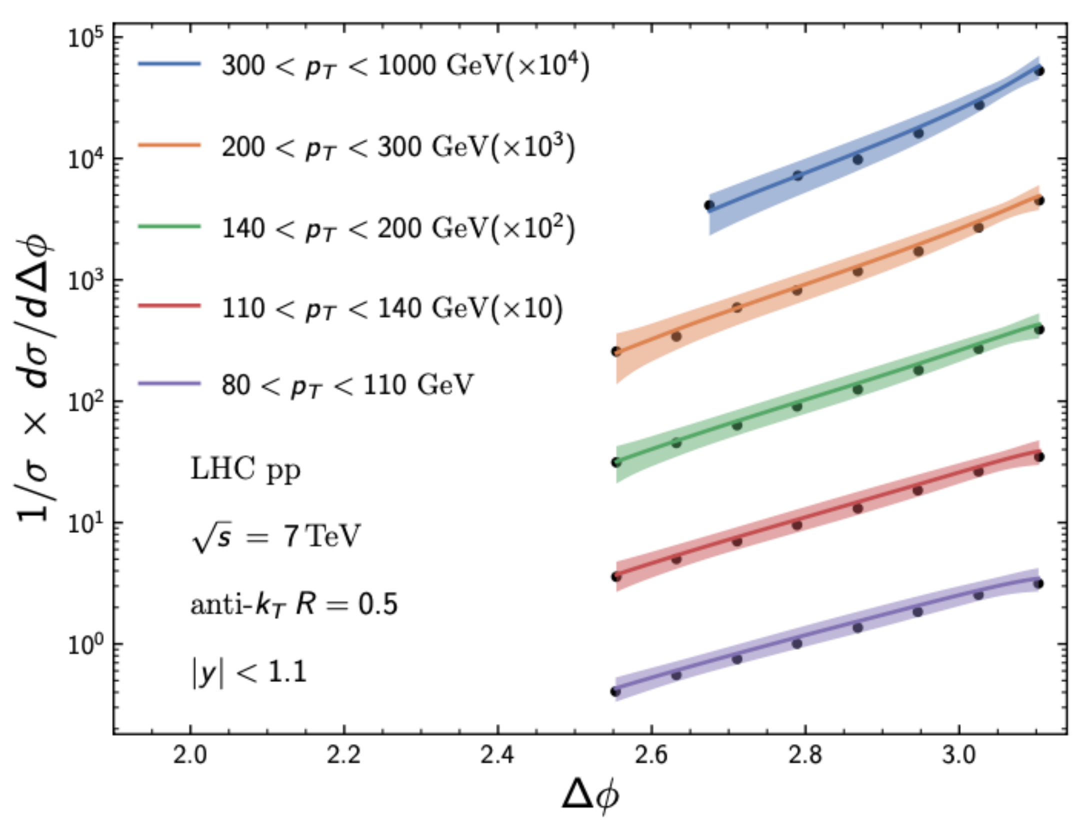


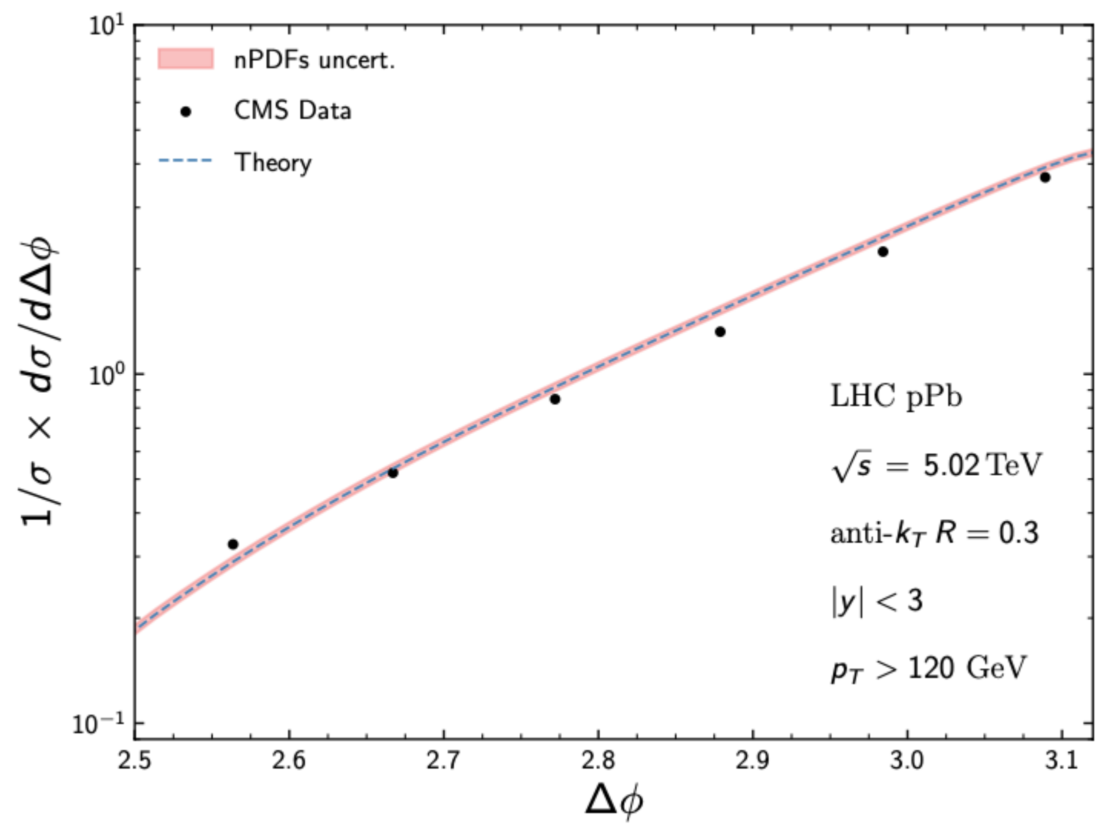
Factorization formula in SCET

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}y_c\mathrm{d}y_d\mathrm{d}p_T^2\mathrm{d}\delta\phi} = \sum_{abcd} \frac{p_T}{16\pi\hat{s}^2}\frac{1}{1+\delta_{cd}} \int \frac{\mathrm{d}b}{2\pi} e^{ibp_T\delta\phi} x_a \tilde{f}_{a/p}^{\text{unsub}}(x_a, b, \mu, \zeta_a/\nu^2) x_b \tilde{f}_{b/p}^{\text{unsub}}(x_b, b, \mu, \zeta_b/\nu^2)$$

$$\times \operatorname{Tr}\left[\boldsymbol{H}_{ab\to cd}(\hat{s},\hat{t},\mu)\tilde{\boldsymbol{S}}_{ab\to cd}^{\text{unsub}}(b,\mu,\nu)\right] J_c(p_T R,\mu)\tilde{S}_c^{\text{cs}}(b,R,\mu,\nu)$$

$$\times J_d(p_T R,\mu)\tilde{S}_d^{\text{cs}}(b,R,\mu,\nu),$$



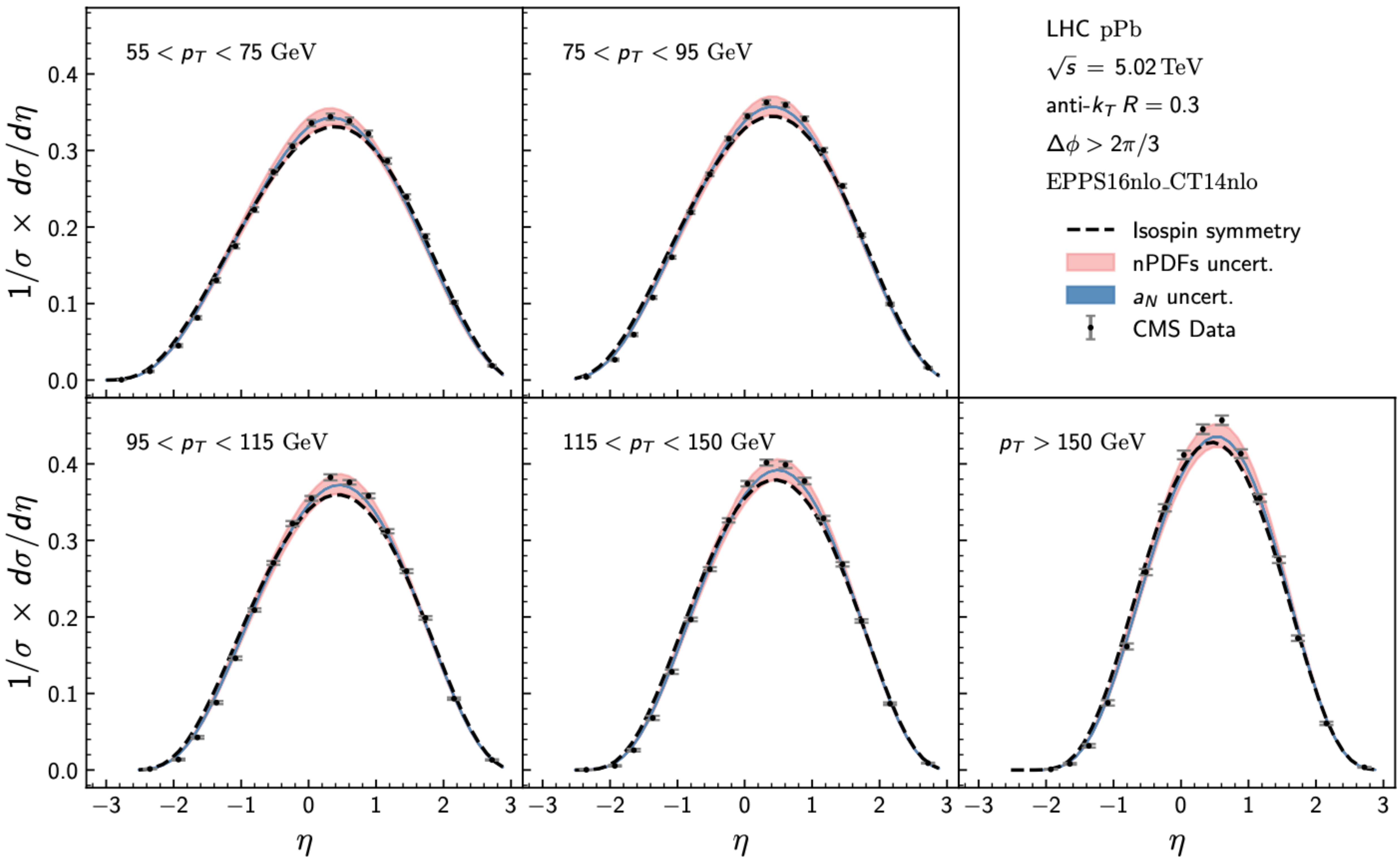


Also see (Sun, Yuan & Yuan '14 & '15)

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

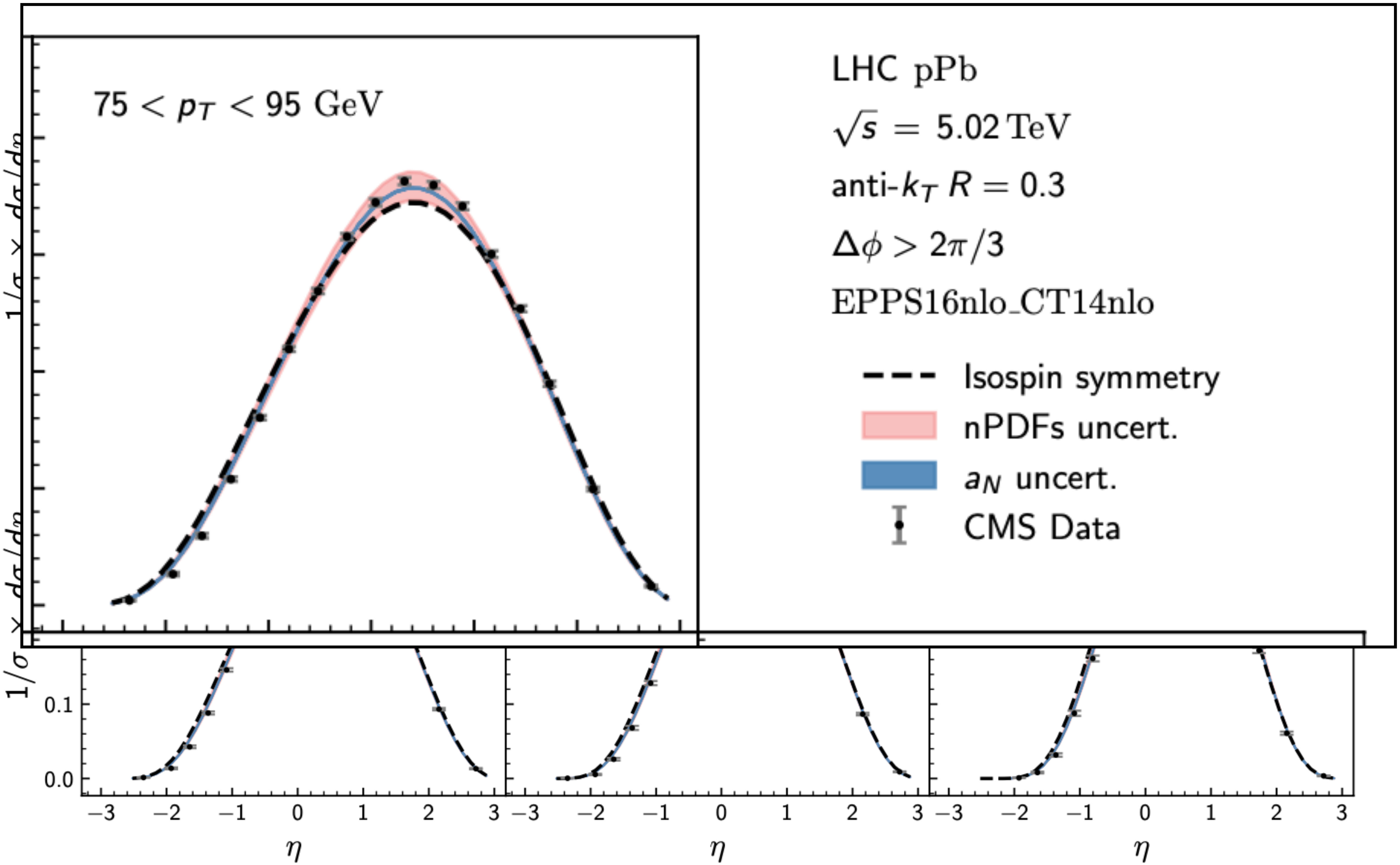
Numerical results in pA

Gao, Kang, DYS, Terry, Zhang ’23 JHEP



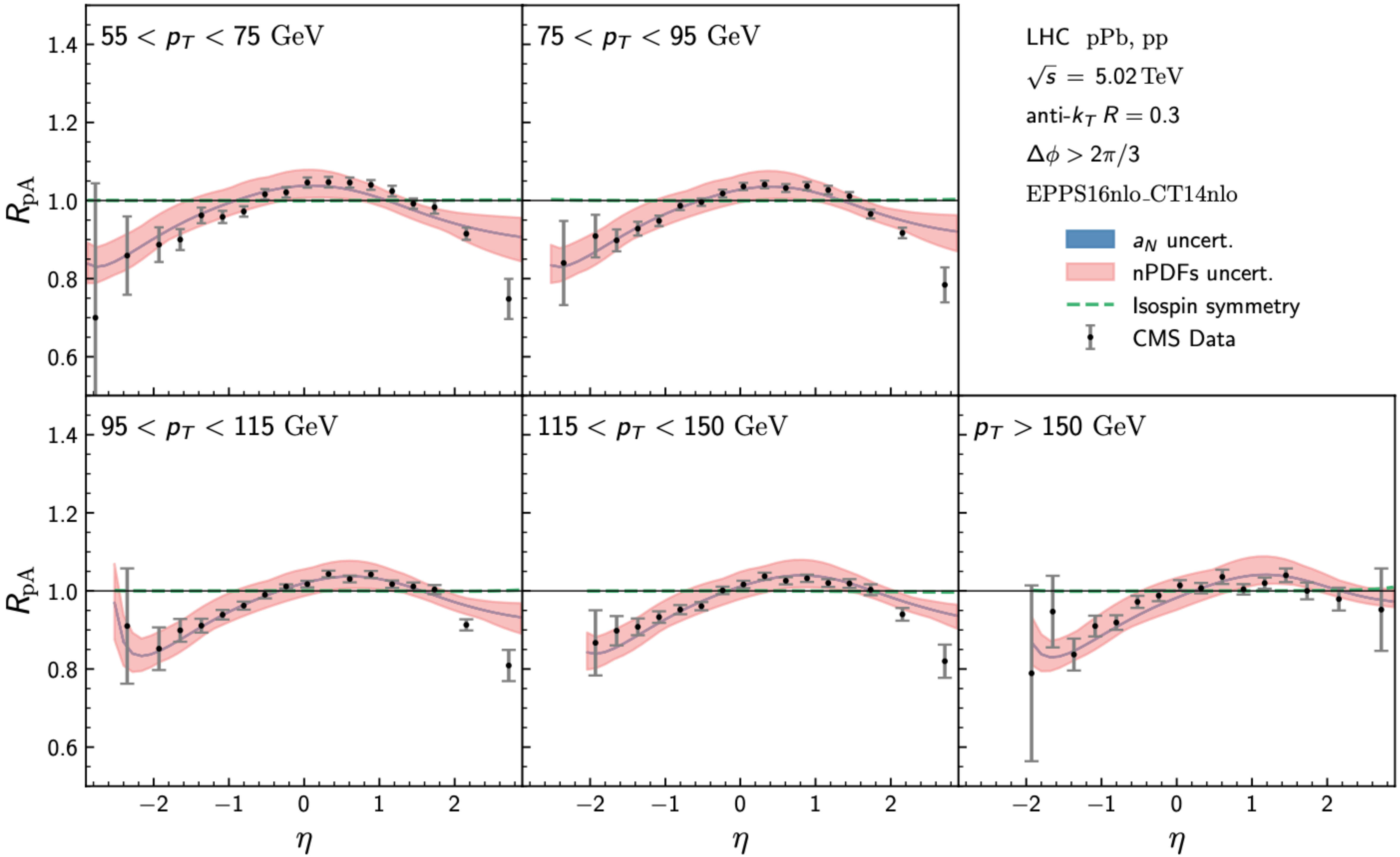
Numerical results in pA

Gao, Kang, DYS, Terry, Zhang '23 JHEP

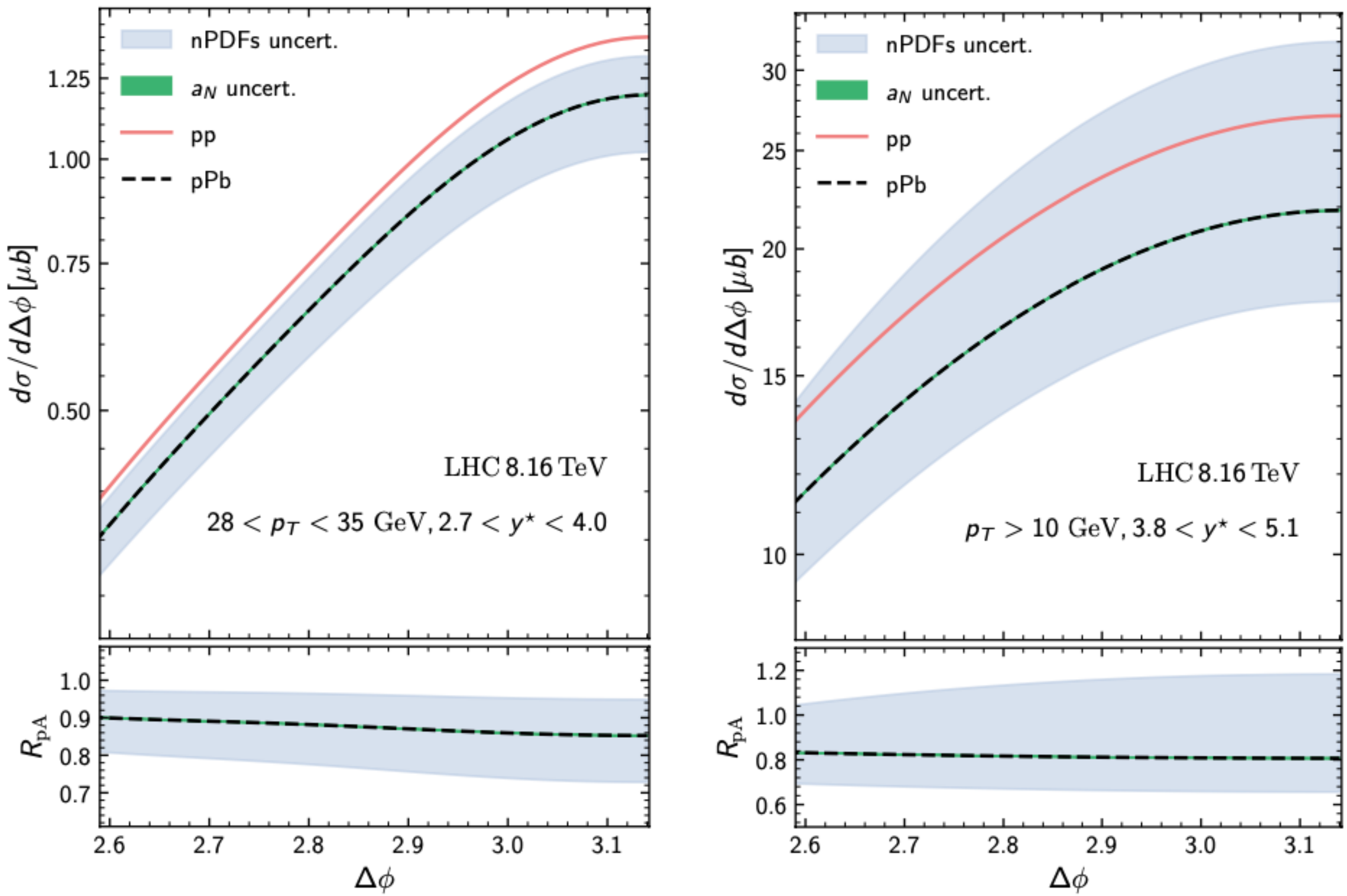


Numerical results in pA

Gao, Kang, DYS, Terry, Zhang '23 JHEP



Numerical results in pA

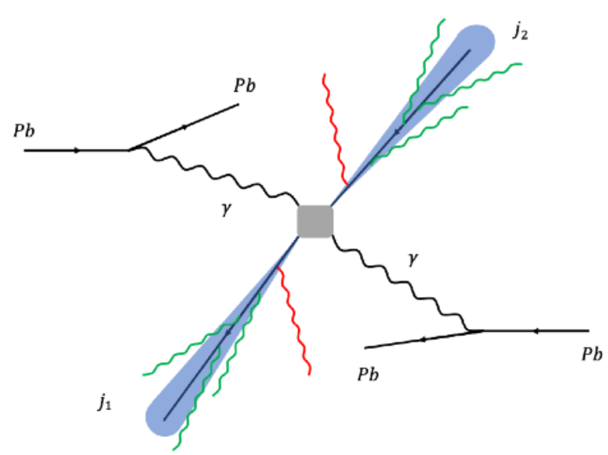


shadowing effect in the small-x region

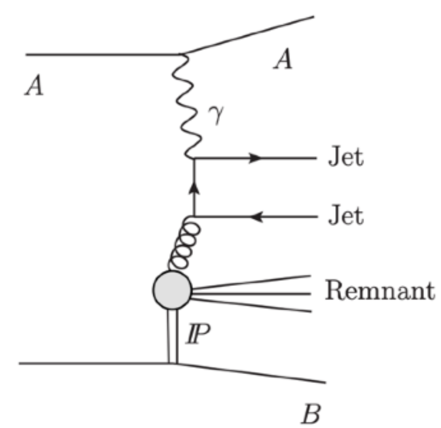
Azimuthal decorrelation of QCD jets in ultra-peripheral collisions

(Zhang, Dai, DYS, ’23 JHEP)

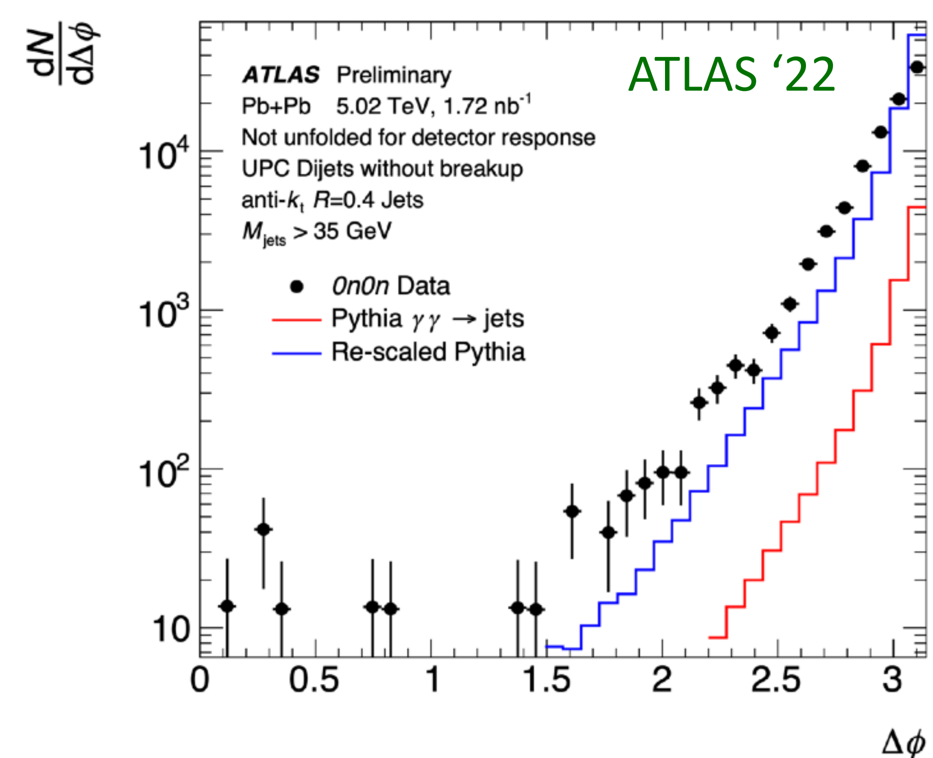
Dijet production with no nuclear breakup



Photon-photon fusion



diffractive photo-production

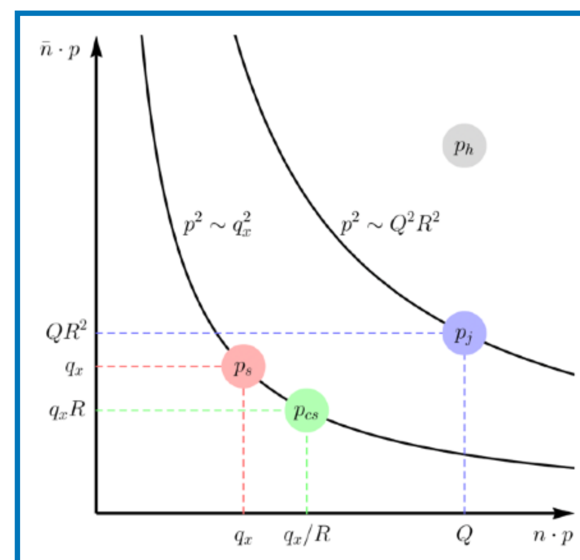


We apply equivalent photon approximation (Fermi 1924; Weizsacker 1934; Williams 1935) **+ SCET**

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

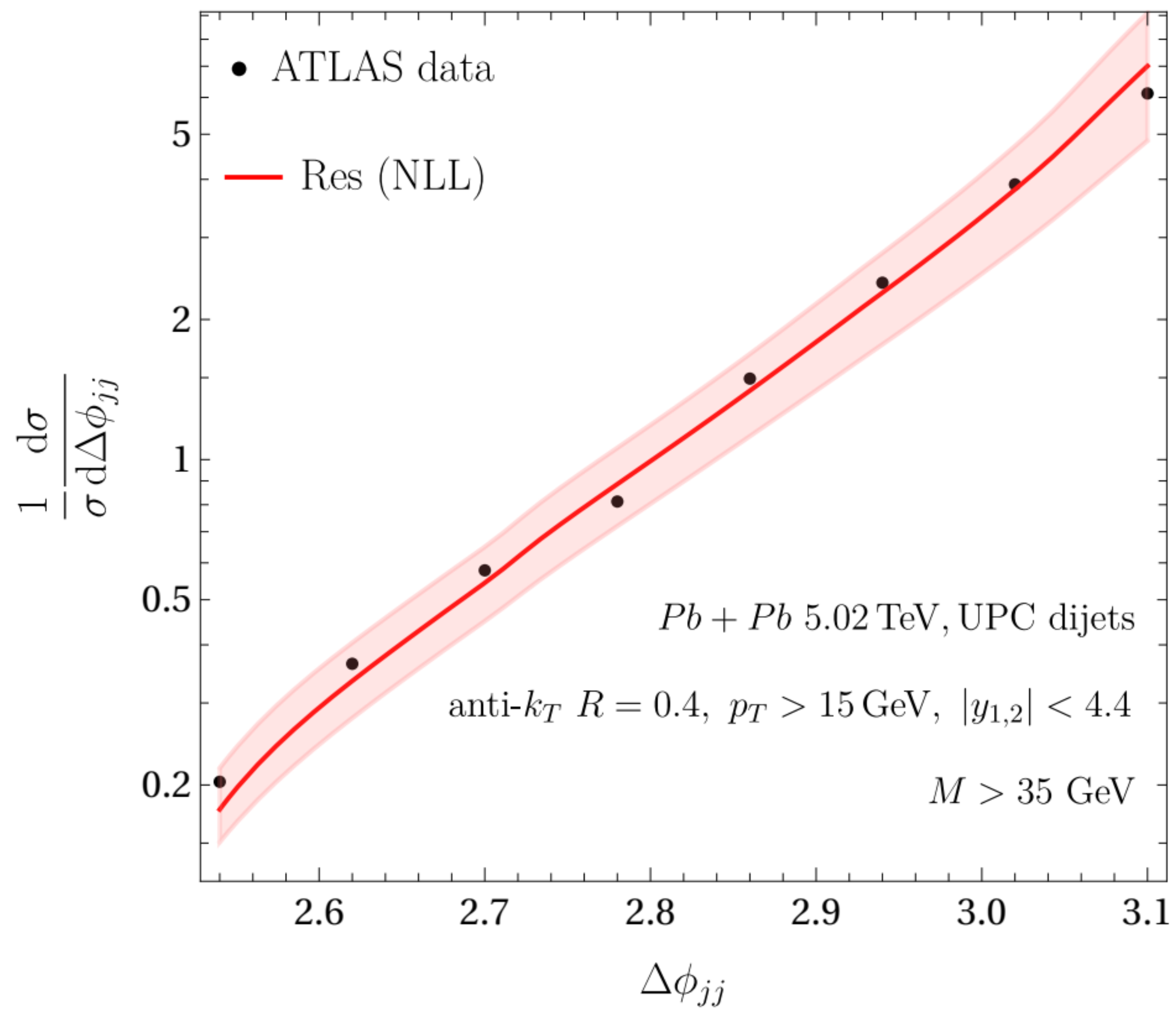
Photon Wigner distribution: (Klein, Mueller, Xiao, Yuan, ’20, also see Ji, ’03; Belitsky, Ji, Yuan, ’04, …)

$$xf_\gamma\left(x,k_T;b_\perp\right) = \int\frac{d^2\Delta_\perp}{(2\pi)^2}e^{i\Delta_\perp\cdot b_\perp}\int\frac{d\xi^- d^2r_\perp}{(2\pi)^3}e^{ixP^+\xi^- - ik_T\cdot r_\perp} \times\left\langle A,-\frac{\Delta_\perp}{2}\right|F^{+\perp}\left(0,\frac{r_\perp}{2}\right)F^{+\perp}\left(\xi^-,-\frac{r_\perp}{2}\right)\left|A,\frac{\Delta_\perp}{2}\right\rangle$$



Numerical results

(Zhang, Dai, DYS, '23 JHEP)

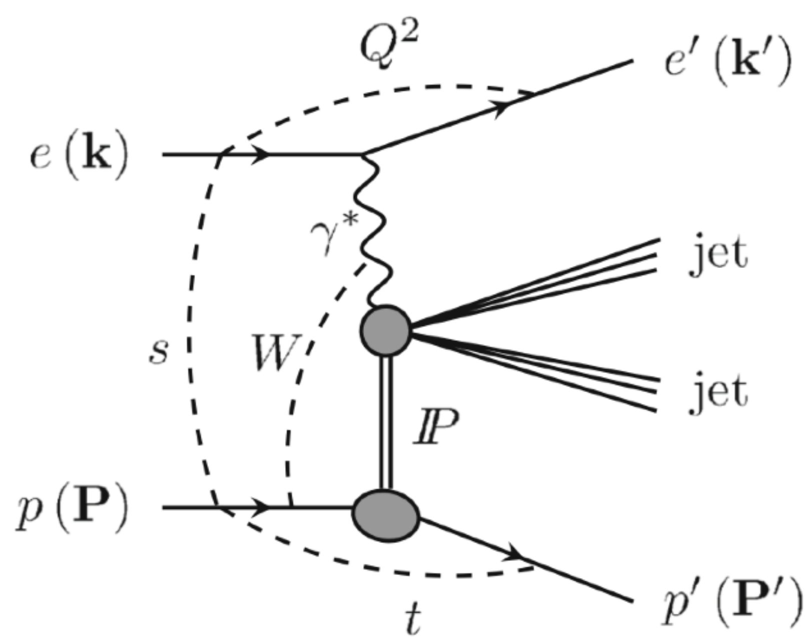


- **A good agreement with the ATLAS data in the nearly back-to-back region**
- **Photo-productions may enhance the dijet production rate, but should barely change the shape**

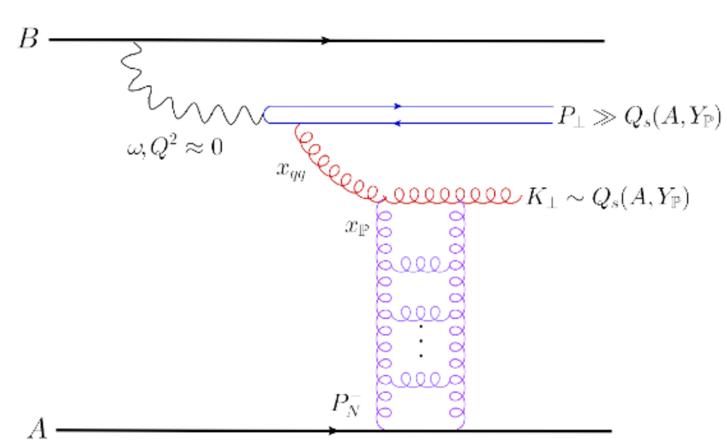
Diffractive dijets photo-production

DYS, Y. Shi, C. Zhang, J, Zhou, Y. Zhou '24 JHEP

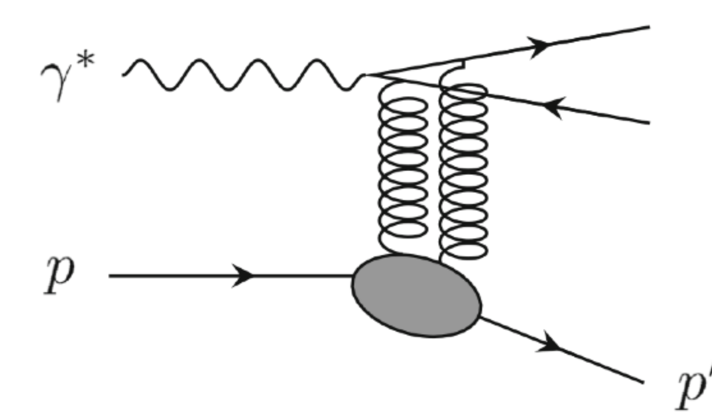
- **Diffractive di-jet production provide rich information on nucleon internal structure.**



diffractive production of (2+1) jets



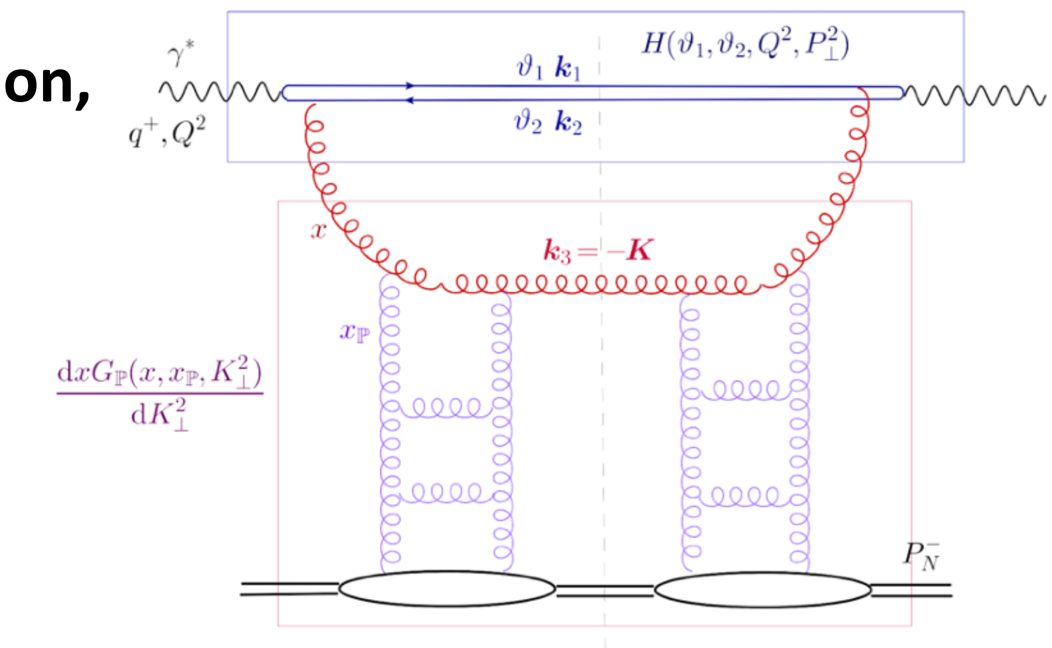
diffractive production of exclusive dijets



- **In cases of diffractive tri-jet production, where a semi-hard gluon is emitted towards the target direction and remains undetected, the experimental signature of this process becomes indistinguishable from that of exclusive di-jet production.**
- **Recent studies have shown that the cross section for coherent tri-jet photo-production significantly surpasses that of exclusive di-jet production** Iancu, Mueller & Triantafyllopoulos '21
- **The production of color octet hard quark-anti-quark dijets enables the emission of soft gluons from the initial state. This mechanism significantly influences the total transverse momentum $q_\perp$ distribution.**

Diffractive dijets photo-production

- **The CGC calculation of diffractive di-jet photo-production, accompanied by a semi-hard gluon emission, has been studied in** Iancu, Mueller & Triantafyllopoulos ’21; Iancu, Mueller, Triantafyllopoulos, & S. Y. Wei ’23



$$\gamma(x_\gamma p) + A \to q(k_1) + \bar{q}(k_2) + g(l) + A$$

- **The Born cross section for semi-inclusive diffractive back-to-back dijet production is expressed as**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}^2\boldsymbol{P}_\perp\mathrm{d}^2\boldsymbol{q}_\perp} = \sigma_0 x_\gamma f_\gamma(x_\gamma)\int \frac{\mathrm{d}x_{\mathbb{P}}}{x_{\mathbb{P}}} x_g G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, q_\perp)$$

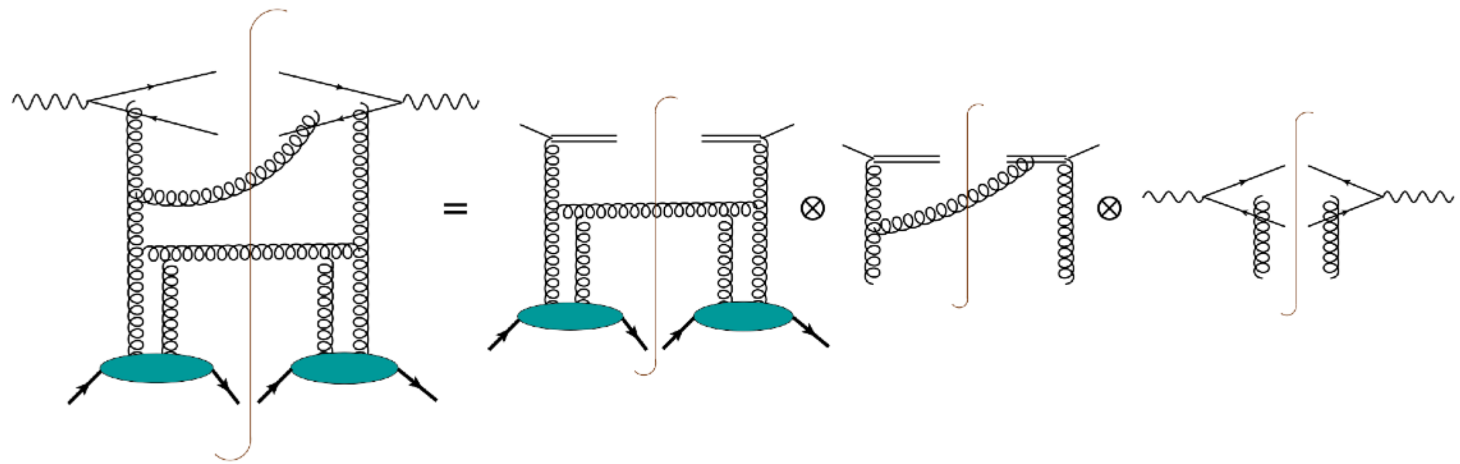
- **Within the CGC formalism, the gluon distribution of the pomeron is related to the gluon-gluon dipole scattering amplitude**

$$x_g G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, q_\perp) = \frac{S_\perp(N_c^2-1)}{8\pi^4(1-x)}\left[\frac{xq_\perp^2}{1-x}\int r_\perp \mathrm{d}r_\perp J_2(q_\perp r_\perp) K_2\left(\sqrt{\frac{xq_\perp^2 r_\perp^2}{1-x}}\right)\mathcal{T}_g(x_{\mathbb{P}}, r_\perp)\right]^2$$

dipole amplitude

Factorizaton and resummation

- **By treating the gluon DTMD as if it were an ordinary TMD, we assume that the standard TMD factorization framework can be used in the back-to-back region**
  Hatta, Xiao & Yuan '22



$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}^2\boldsymbol{P}_\perp\,\mathrm{d}^2\boldsymbol{q}_\perp} = \sigma_0 x_\gamma f_\gamma(x_\gamma) H_{\gamma^* g}(P_\perp, R, \mu) \int \mathrm{d}^2\boldsymbol{k}_\perp \mathrm{d}^2\boldsymbol{\lambda}_\perp \delta^{(2)}(\boldsymbol{q}_\perp - \boldsymbol{k}_\perp - \boldsymbol{\lambda}_\perp)$$
$$\times S(\boldsymbol{\lambda}_\perp, R, \mu) \int \frac{\mathrm{d}x_{\mathbb{P}}}{x_{\mathbb{P}}} x_g G_{\mathbb{P}}^{\mathrm{unsub}}(x_g, x_{\mathbb{P}}, k_\perp, \mu).$$

- **We refactorize the gluon DTMD as the matching coefficients and the integrated pomeron gluon function**

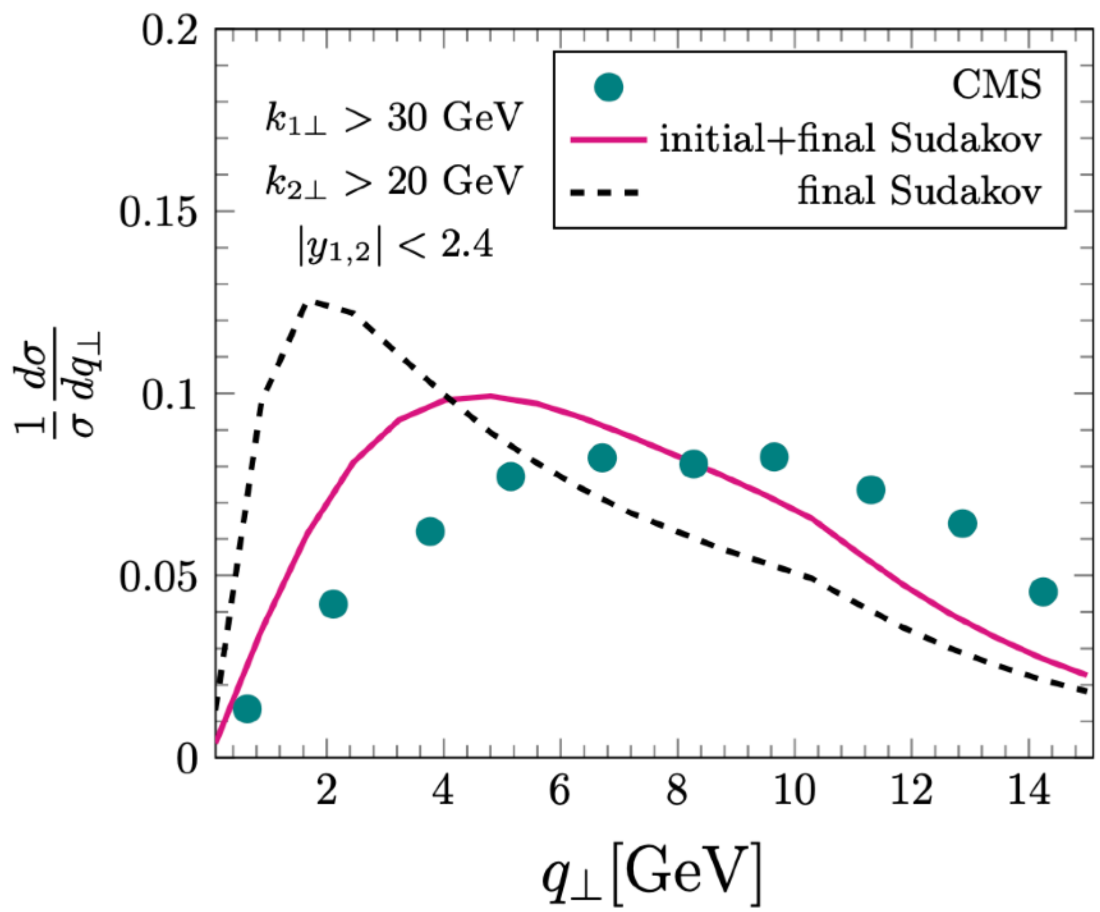
$$G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, k_\perp, \mu, \zeta) = \int_{x_g}^{1} \frac{\mathrm{d}z}{z} I_{g\leftarrow g}(z, k_\perp, \mu, \zeta) G_{\mathbb{P}}(x_g/z, x_{\mathbb{P}}, \mu) + G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, k_\perp)$$

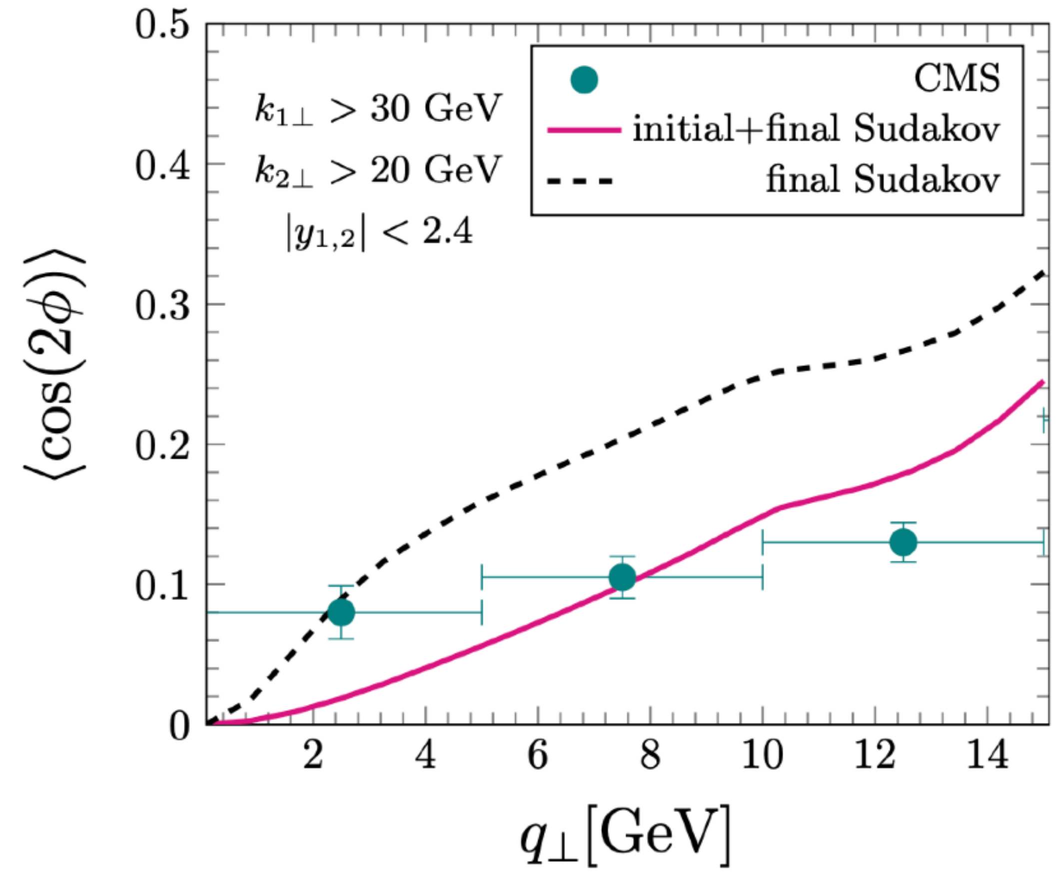
static source in the modified DGLAP Iancu, Mueller, Triantafyllopoulos, & Wei '23

- **Some recent theory progress:**
  - **Fracture Functions:** Chen, Ma, Tong '21 '24 + Chai '19 陈开宝's talk
  - **Glauber SCET:** Lee, Schindler, Stewart '25

Numerical results and measurements in UPCs

DYS, Y. Shi, C. Zhang, J, Zhou, Y. Zhou '24 JHEP





- **Incorporating the initial state gluon radiation offers a more accurate representation of the CMS data**
- **Difference remains.**

$$\langle\cos(2\phi)\rangle \equiv \frac{\int \mathrm{d}\mathcal{P}.\mathcal{S}.\cos(2\phi)\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}^2\boldsymbol{P}_\perp\mathrm{d}^2\boldsymbol{q}_\perp}}{\int \mathrm{d}\mathcal{P}.\mathcal{S}.\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\mathrm{d}y_2\mathrm{d}^2\boldsymbol{P}_\perp\mathrm{d}^2\boldsymbol{q}_\perp}}$$

The azimuthal asymmetry: Our result underestimates the asymmetry at low $q_\perp$ and overshoots it at high

Summary

- **Recoiling-free azimuthal decorrelation achieves first N3LL accuracy with full jet dynamics, and we find the non-perturbative corrections are mild.**
- **We study the dijet azimuthal decorrelation in pp, pA, AA(UPC) processes and find good agreement.**
- **In diffractive di-jet production process the production of color octet dijets expands the color space, enabling the emission of soft gluons in the initial state. This mechanism significantly influences the total transverse momentum distribution.**
- **Our new results quantitatively capture the overall trends in the $q_\perp$ distribution and the asymmetry observed by the CMS Collaboration, a sizable discrepancy between the experimental data and theoretical calculations remains.**

Thank you