Recoil-free azimuthal angle for precision boson-jet correlation at the LHC

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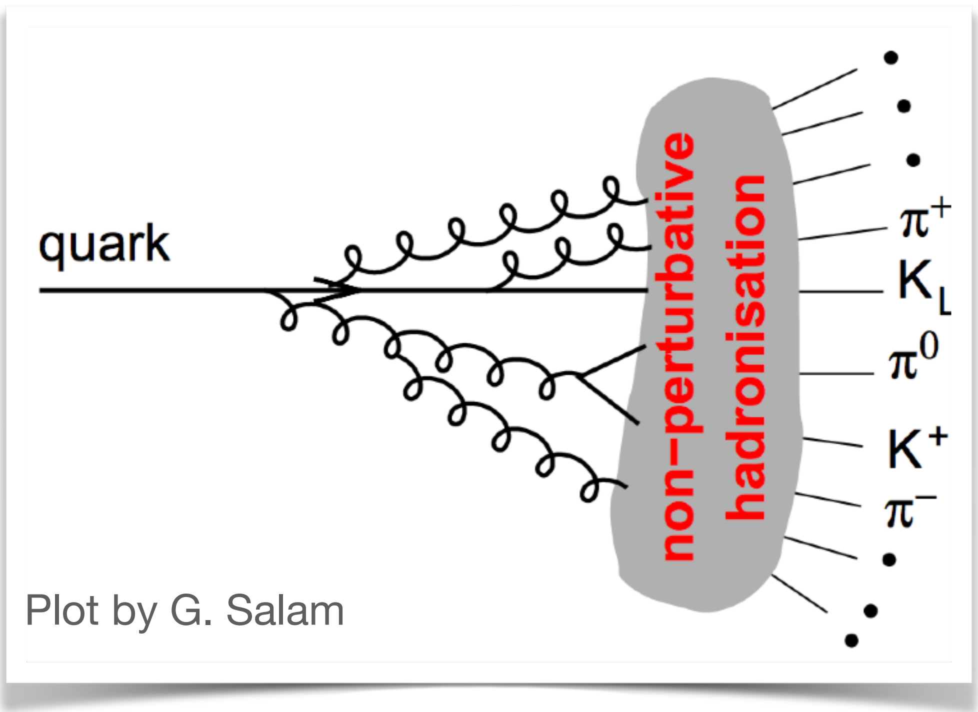
Jets and their substructure from LHC data   June 1, 2021

Jets: our windows on quark and gluon

Parton (quark or gluon) fragmentation and hadronization



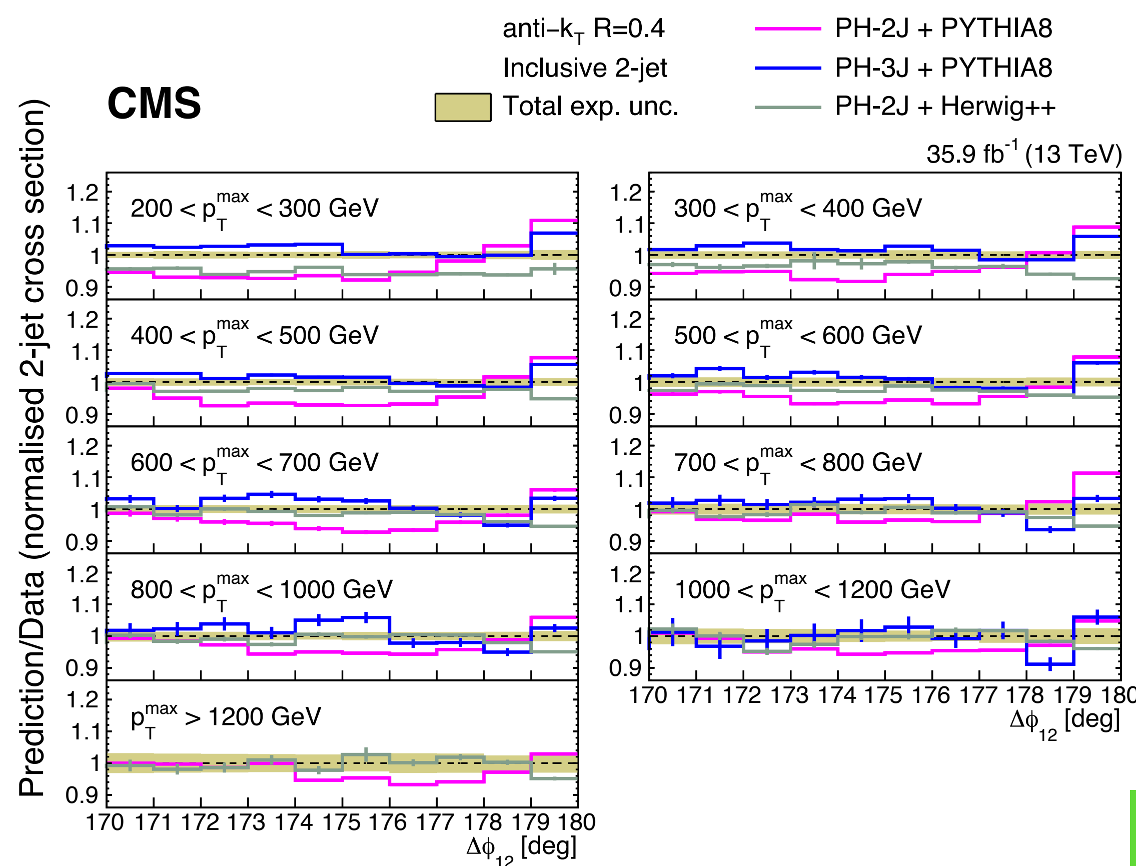
From short to long distances in quantum field theory

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

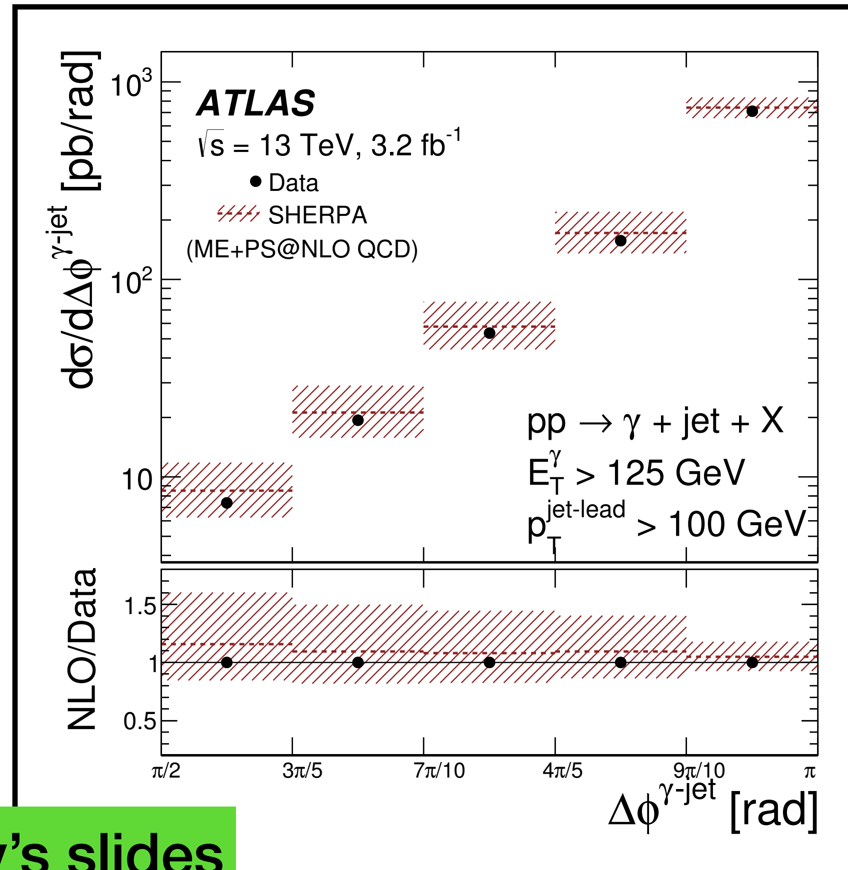
Jets are not the same as partons

Jets inherit quantum property of partons

Azimuthal correlation in the back-to-back limit



- PH-3j+Pythia 8 agrees better with the data
- PH-2j+Herwig++ prediction is similar to PH-3j+Pythia 8, except for the lowest p_T^{max} region.



Bilin & Starovoitov's slides

- **jet calibration at pp**
- **energy loss study at HIC**
- **gluon TMD PDF (linearly-polarization)**
- **TMD factorization violation**
- **…**

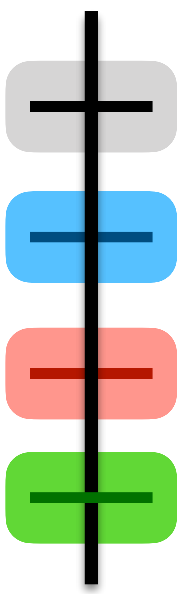
In the back-to-back limit, one needs all-order results ($\log(\pi-\Delta\phi)$ resummation)

Jet radius and q_T joint resummation for boson-jet correlation

(Chien, **DYS** & Wu '19 JHEP)

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

$$q_T \ll p_T^J, \quad R \ll 1$$



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

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

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

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

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

Factorization formula:

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

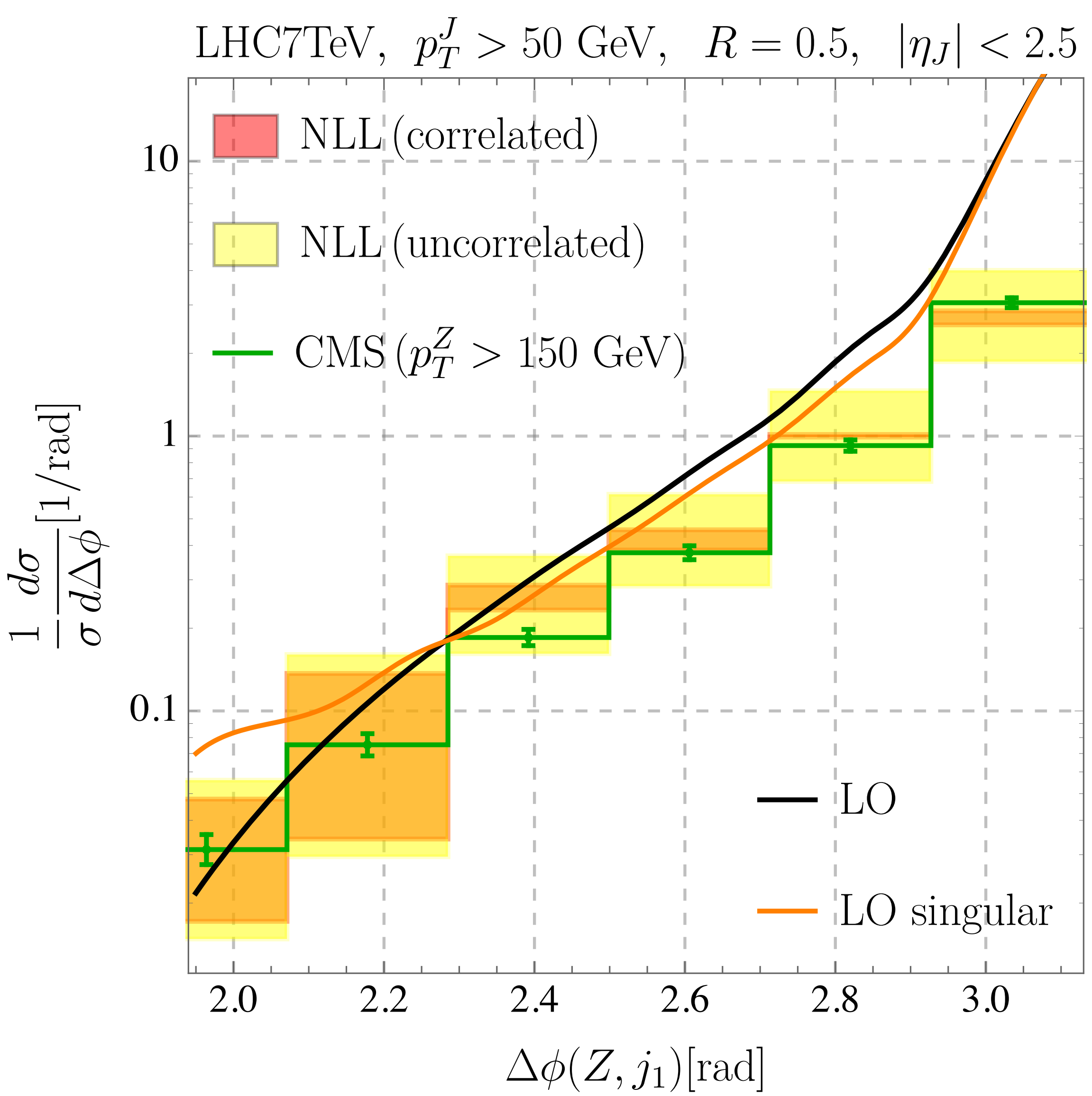
$$\times \mathcal{H}_{ij\to Vk}(\hat{s}, \hat{t}, m_V, \epsilon) \sum_{m=1}^{\infty} \langle \boldsymbol{\mathcal{J}}_m^k(\{\underline{n_J}\}, R\,p_J, \epsilon) \otimes \boldsymbol{\mathcal{U}}_m^k(\{\underline{n_J}\}, R\,\vec{x}_T, \epsilon) \rangle$$

(also see Sun,Yuan,Yuan '14; Buffing,Kang,Lee,Liu '18,…)

- **Multiple scales in the problem; Rely on effective field theory: SCET**
- **Coft modes:** $p_t^\mu \sim q_T (R^2, 1, R)_{n_J \bar{n}_J}$ **for the jet radius resummation** (Becher, Neubert, Rothen & **DYS** '15; Chien, Hornig & Lee '15; Kolodrubetz, Pietrulewicz, Stewart, Tackmann & Waalewijn '16; ……)
- **Multi-Wilson-Line operators describe radiations along the jet direction for NGLs resummation** (Caron-Hout '15; Becher, Neubert, Rothen & **DYS** '15; ……)

Numerical results

(Chien, **DYS** & Wu '19 JHEP)

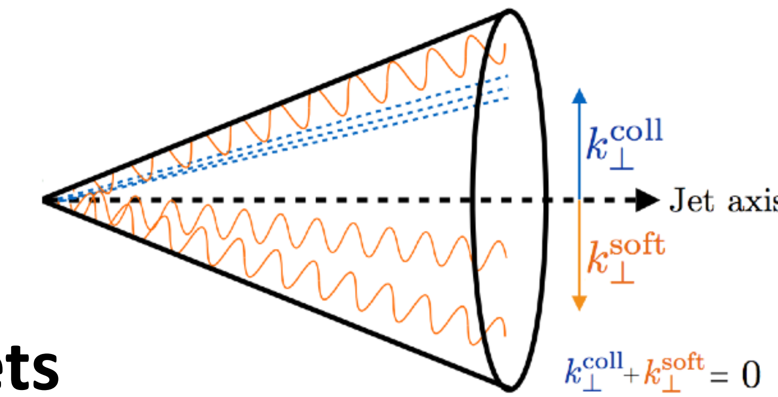


- **NLL resummation result is consistent with CMS data**
- **NLL result has 20-30% scale uncertainties.**
- **Azimuthal correlation can be a clean probe of *factorization violation*** (Collins & Qiu '07, Rogers & Mulders '10, ……)

- **Higher accuracy?**
  - **NNLL? (NLL NGL resummation** Banfi, Dreyer, Monni '21**)**
  - **NNNLL?**
- **Better angular resolution?**
- **Reduce contamination?**

Jet TMDs and non-global logs

- **Non-global logs in jet TMD resummation**



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

  - **sum over all soft 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)

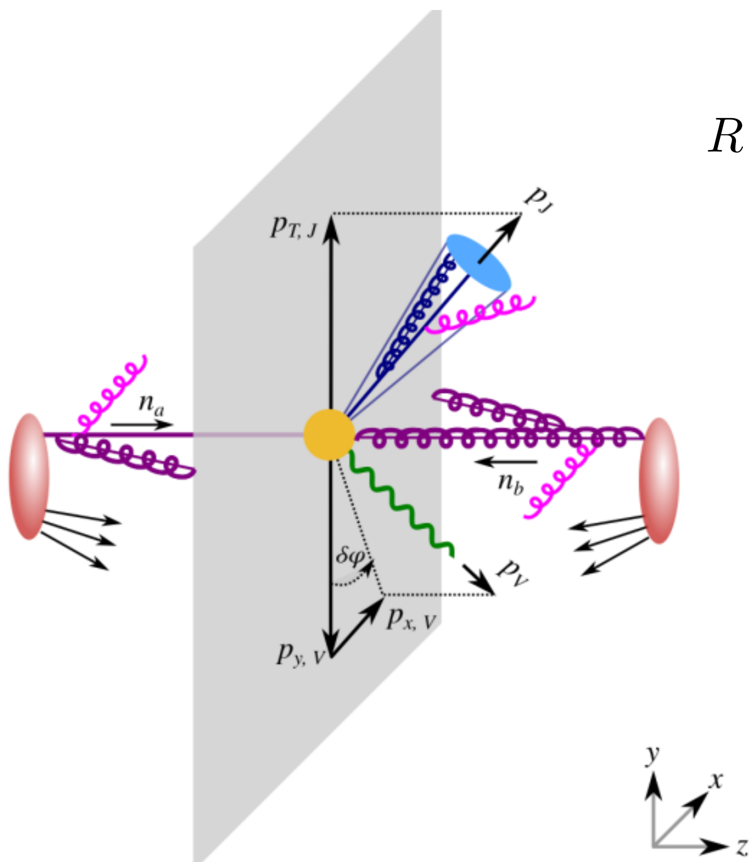
$$\begin{aligned} p_{t,r} &= p_{t,i} + p_{t,j}\,, \\ \phi_r &= (w_i\phi_i + w_j\phi_j)/(w_i + w_j) \\ y_r &= (w_i y_i + w_j y_j)/(w_i + w_j) \end{aligned} \qquad w_i = p_t^n$$

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

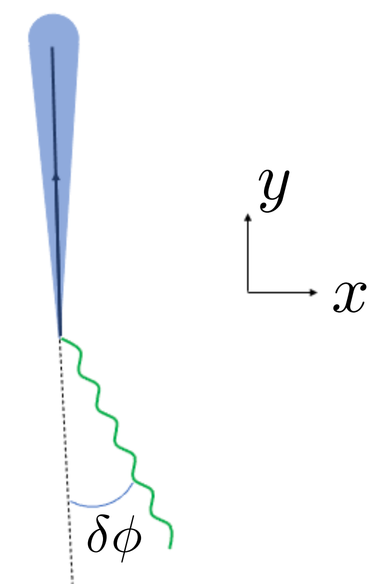
- **N³LL resummation for jet TMDs @ e+e- and ep** (Gutierrez-Reyes, Scimemi, Wouter, Zoppi '18 '19)
- **NNLL resummation for V+j @ LHC** (Chien, Rahn, Schrignder van Velzen, **DYS**, Waalewijn & Wu '21 PLB)

Recoil-free azimuthal angle for boson-jet correlation

(Chien, Rahn, Schrignder van Velzen, **DYS**, Waalewijn & Wu ’21 PLB)

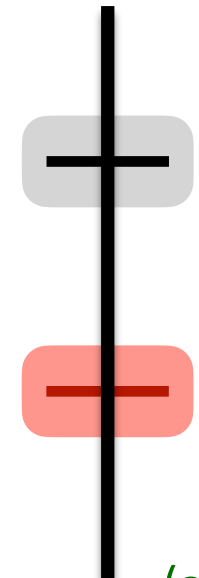


$R \sim \mathcal{O}(1)$



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

Standard SCET$_2$ (CSS …) $\delta\phi \ll \mathcal{O}(1)$



(also see Gao,Li,Moult,Zhu ’19,…)

Effect of soft radiation in jet algorithm is power suppressed

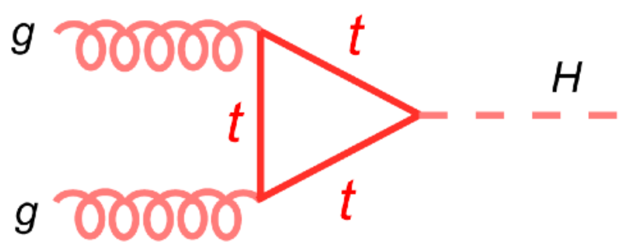
Following the standard steps in SCET$_2$ we obtain the following factorization formula

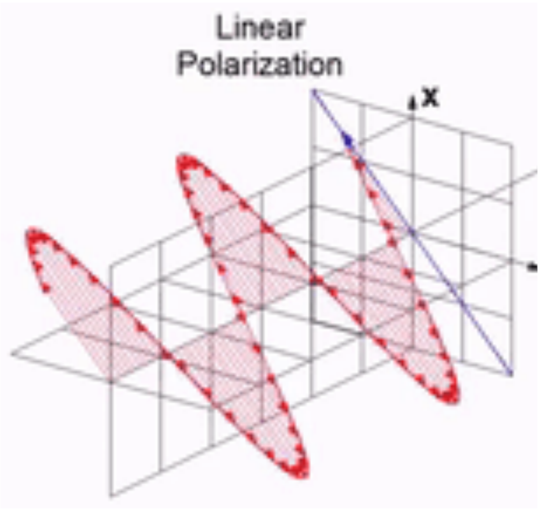
$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{x,V}\,\mathrm{d}p_{T,J}\,\mathrm{d}y_V\,\mathrm{d}\eta_J} = \int \frac{\mathrm{d}b_x}{2\pi}\, e^{\mathrm{i}p_{x,V}b_x} \sum_{i,j,k} B_i(x_a, b_x) B_j(x_b, b_x) S_{ijk}(b_x, \eta_J) H_{ij\to Vk}(p_{T,V}, y_V - \eta_J) J_k(b_x)$$

standard jet axis $\quad S_c(bR) \otimes J(QR)$

Linearly-polarized gluon TMDs

For Higgs production linearly-polarized gluon TMDs arises from spin interference between multiple initial-state gluons (Catani, Grazzini '10)

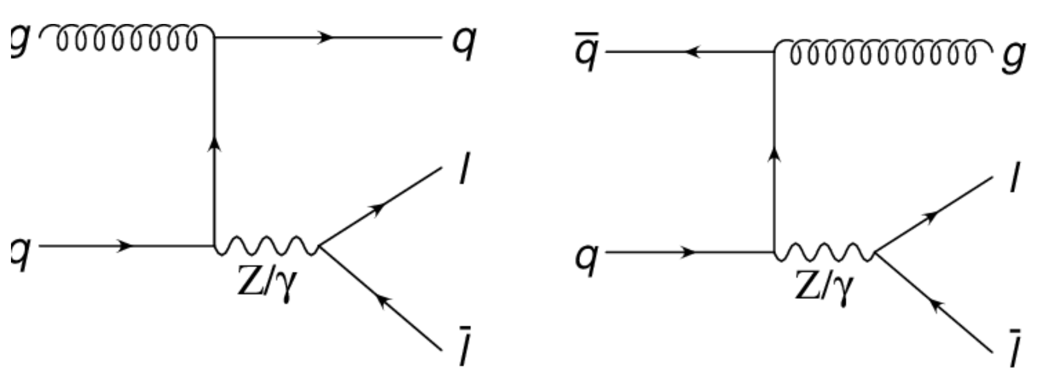


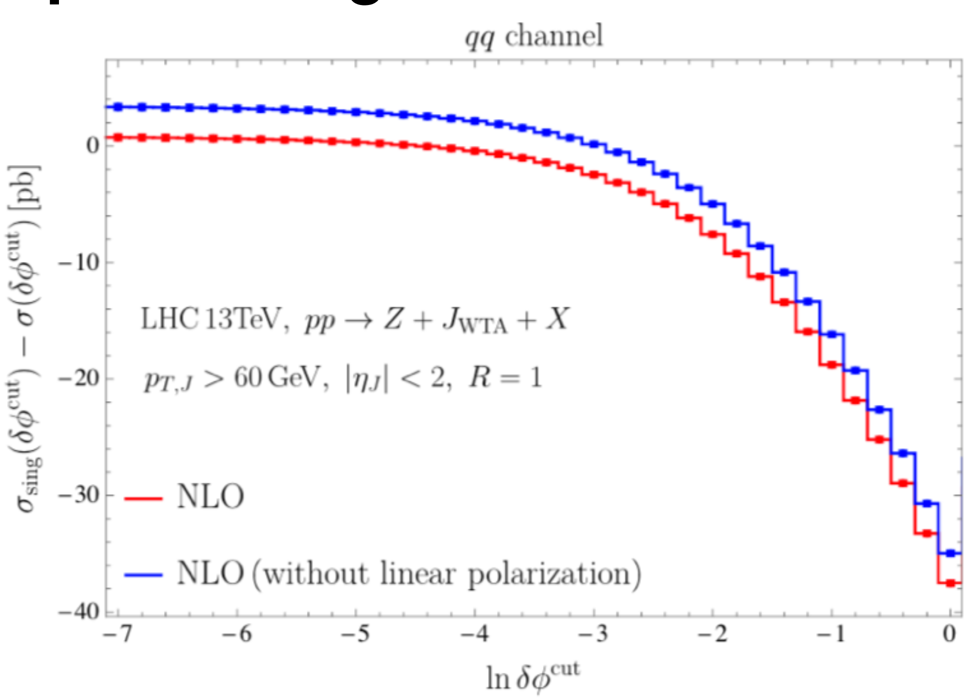


$$\Phi_g^{\mu\nu}(x, \boldsymbol{p}_T) = \frac{n_\rho n_\sigma}{(p \cdot n)^2} \int \frac{d(\xi \cdot P) d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi} \langle P | \mathrm{Tr}\left[F^{\mu\rho}(0) F^{\nu\sigma}(\xi)\right] | P\rangle \Big|_{\mathrm{LF}}$$

$$= \frac{1}{2x}\left\{-g_T^{\mu\nu} f_1^g(x, \boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M^2} + g_T^{\mu\nu}\frac{\boldsymbol{p}_T^2}{2M^2}\right) h_1^{\perp g}(x, \boldsymbol{p}_T^2)\right\}$$

Boson-jet correlation can be used to probe linear-polarized gluon TMDs inside the proton (Boer, Mulders, Pisano, Zhou '16)





Linearly-polarized gluon jets

(Chien, Rahn, Schrigndner van Velzen, **DYS**, Waalewijn & Wu '21 PLB)

The linearly-polarized jet function describes the effect of a spin-superposition of the gluon initiating the jet

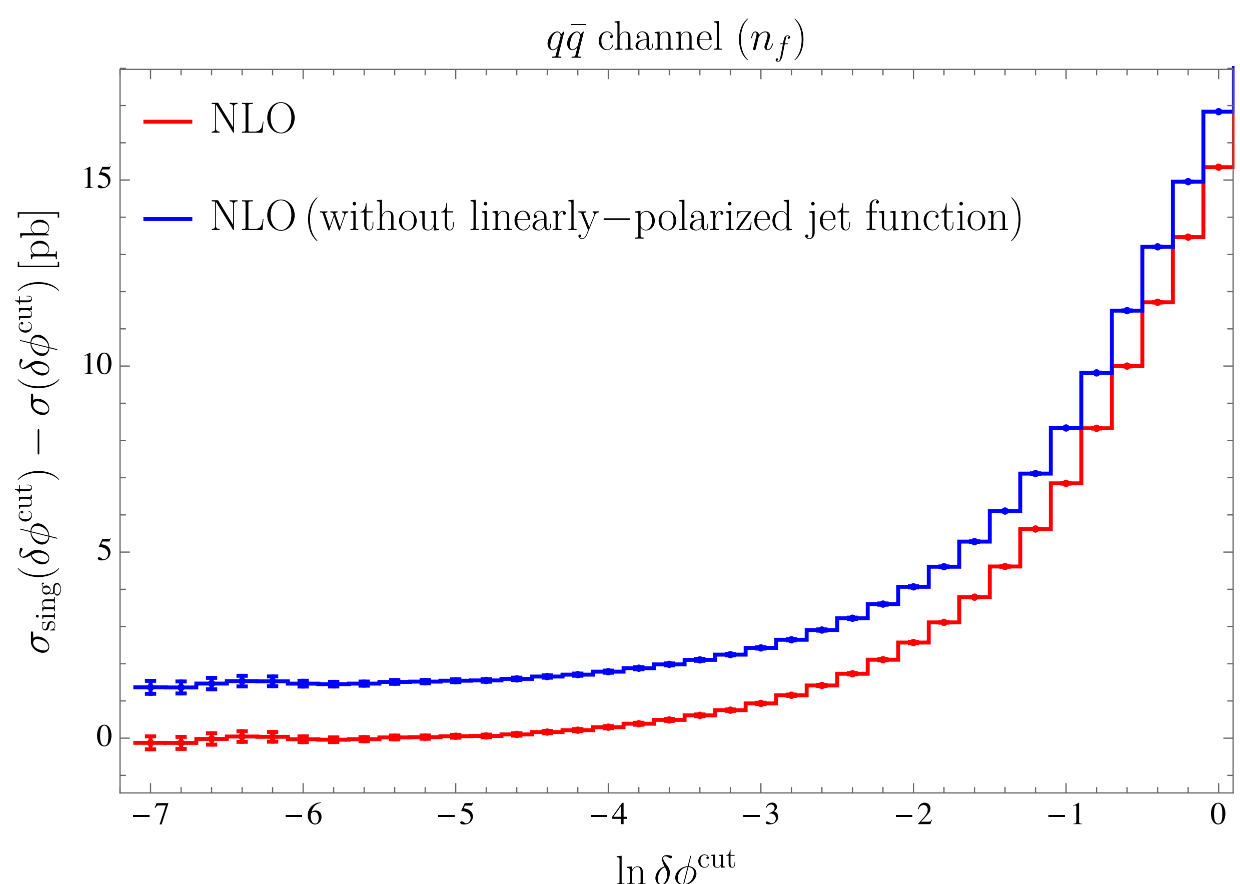
$$J_g^L(\vec{b}_\perp,\mu,\nu) = \left[\frac{1}{d-3}\left(\frac{g_\perp^{\mu\nu}}{d-2} + \frac{b_\perp^\mu b_\perp^\nu}{\vec{b}_\perp^2}\right)\right]\frac{2(2\pi)^{d-1}\omega}{N_c^2-1}\langle 0|\delta(\omega - \bar{n}\cdot\mathcal{P})\delta^{d-2}(\mathcal{P}_\perp)\mathcal{B}^a_{n\perp\mu}(0)e^{i\vec{b}_\perp\cdot\hat{\vec{k}}_\perp}\mathcal{B}^a_{n\perp\nu}(0)|0\rangle$$

The first non-vanishing order is one loop

$$J_g^{L(1)}(\vec{b}_\perp,\mu,\nu) = -\frac{1}{3}C_A + \frac{2}{3}T_F n_f$$

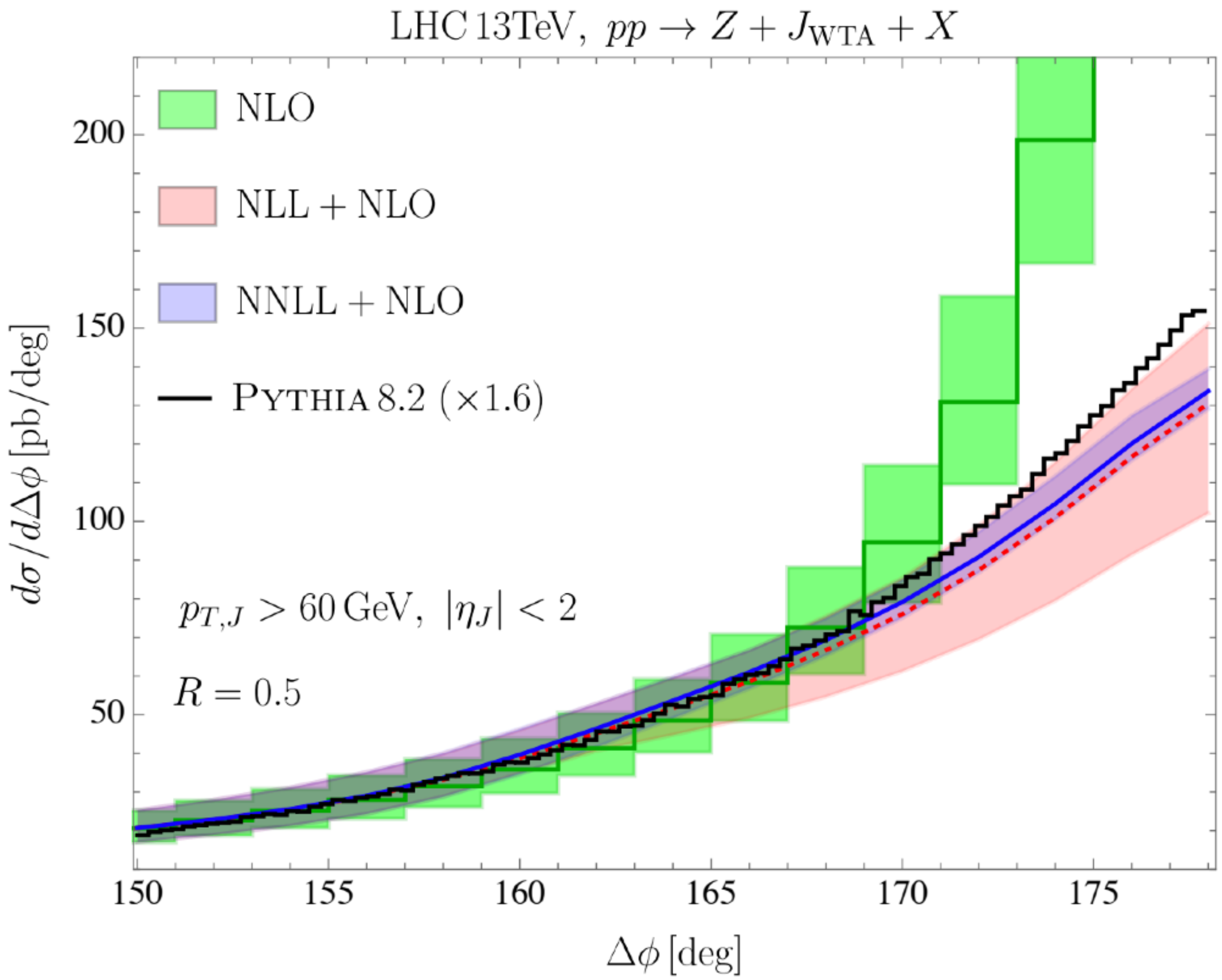
same as EEC gluon jet function up to $\mathcal{O}(\epsilon)$ Luo, Yang, Zhu, Zhu ` 20

We provide evidence for contributions from linearly-polarized gluon jet functions using MCFM



Numerical Results

(Chien, Rahn, Schrignder van Velzen, **DYS**, Waalewijn & Wu '21 PLB)



Small b ($\delta\phi \sim \mathcal{O}(1)$): match onto NLO

Large b ($\delta\phi \sim \mathcal{O}(\Lambda_{\mathrm{QCD}}/p_{T,J})$): avoid Landau pole with b* prescription $b_* = b/\sqrt{1 + b^2/b_{\mathrm{max}}^2}$

good perturbative convergence

Pythia agrees well

It will be interesting to perform the same measurement at the LHC

Track-based jet definition

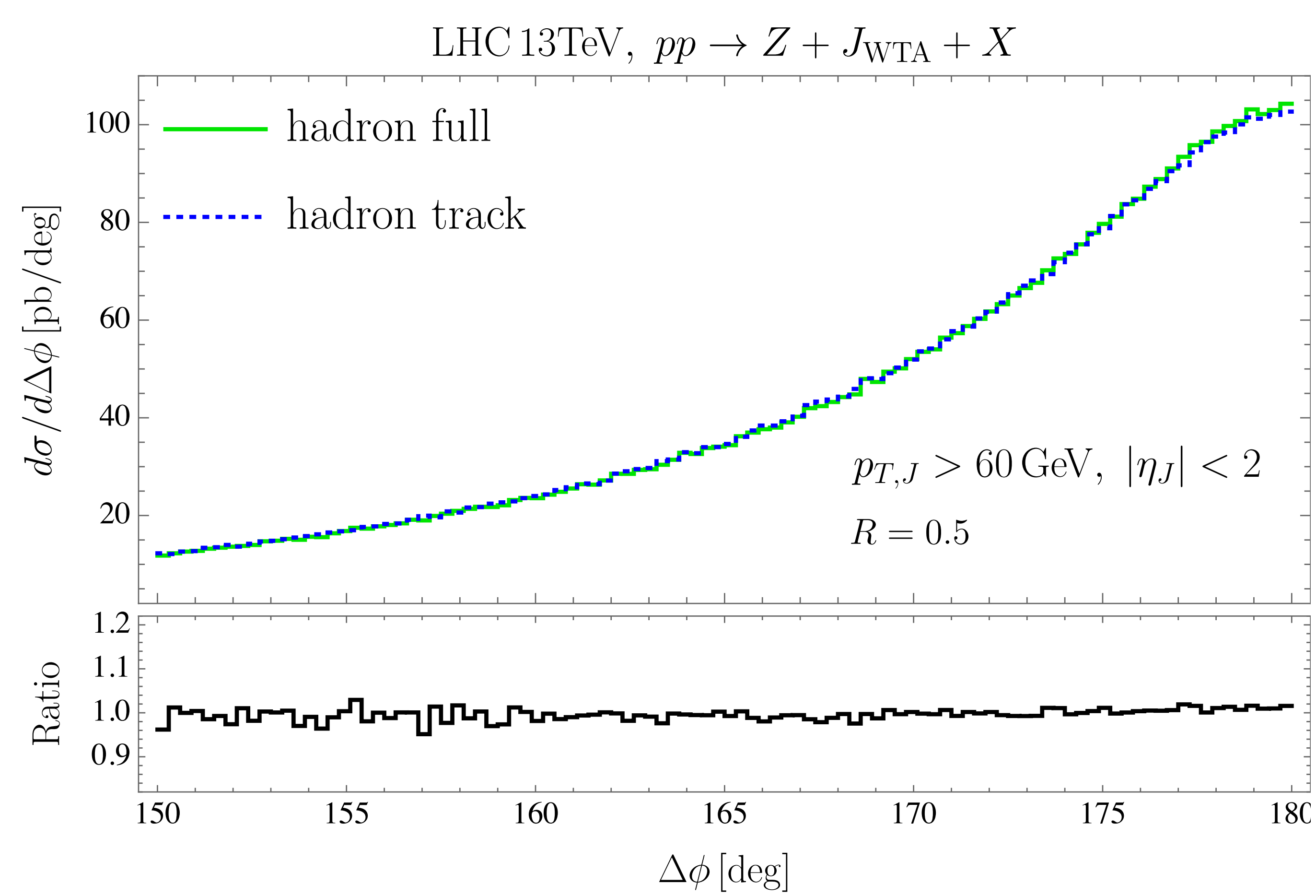
- **The angular resolution of jet measurements is about 0.1 radians, limiting access to the back-to-back region**
- **This can be overcome by measuring the jet using only charged particles, exploiting the superior angular resolution of the tracking systems at the LHC.**

Tracking jet function:

Chang, Procura, Thaler, & Waalewijn '13
See Schrignder van Velzen's talk

$$\bar{\mathscr{J}}_q^{(1)} = \mathscr{J}_q^{(1)} + 4C_F \int_0^1 \mathrm{d}x \, \frac{1+x^2}{1-x} \ln \frac{x}{1-x} \int_0^1 \mathrm{d}z_1 \, T_q(z_1, \mu) \times \int_0^1 \mathrm{d}z_2 \, T_g(z_2, \mu) [\theta(z_1 x - z_2(1-x)) - \theta(x - \tfrac{1}{2})]$$

We have verified that using tracks only has a minimal effect on this measurement



Summary and Outlook

- QCD Jets are our windows on partons
- The quantum properties of the initiating partons are encoded in the distribution of energy inside and around jets
- Recoil-free azimuthal correlation achieves first NNLL (NNNLL in progress) accuracy with small non-perturbative corrections.
- Our theoretical framework includes full jet dynamic, and it can be used to probe the linearly-polarization states of gluon
- Track-based jets provide superior angular resolution
- Our result serves as a baseline for pinning down the inner workings of nuclear matter using hard probes
- It will be interesting to perform the same measurement at the LHC

Thank you