



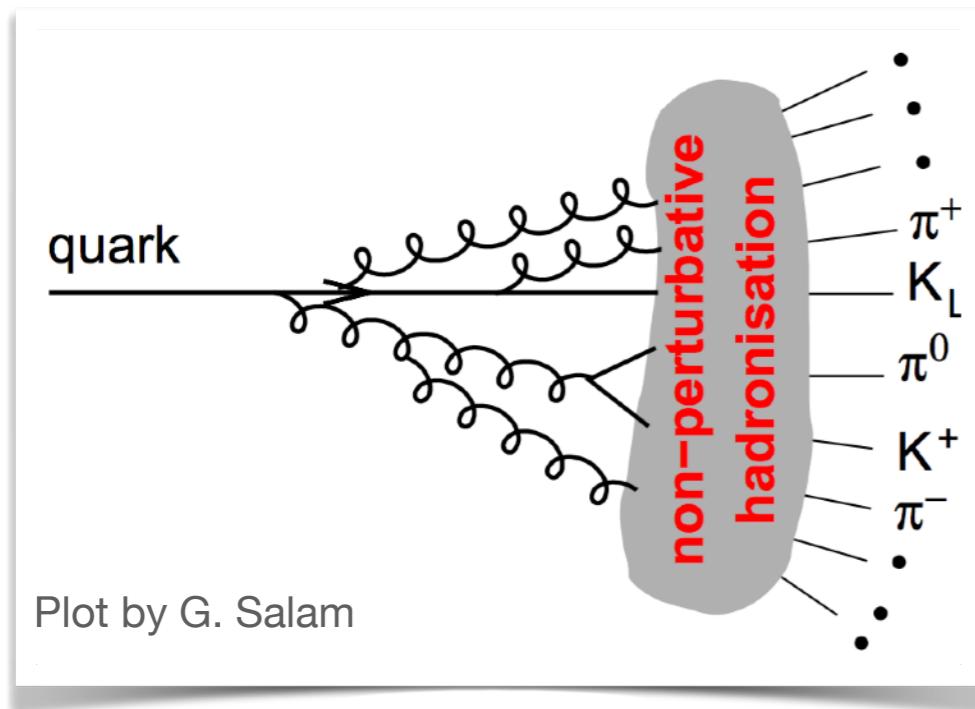
High precision boson-jet correlation at the LHC

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Jets: our windows on quark and gluon

Parton (quark or gluon) fragmentation and hadronization



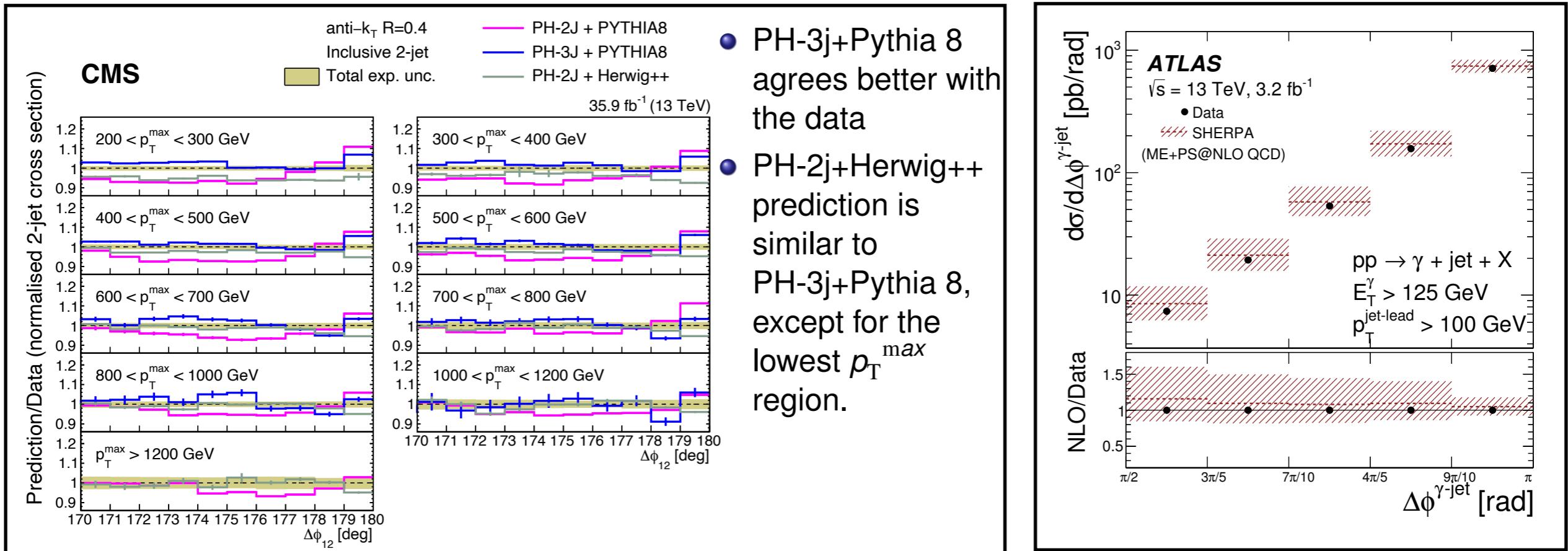
From short to long distances in quantum field theory

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

Jets are not the same as partons

Jets inherit quantum property of partons

Azimuthal correlation in the back-to-back limit



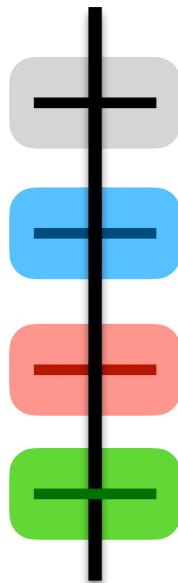
- jet calibration at pp
- energy loss study at Heavy Ion Collision
- gluon TMD PDF (linearly-polarization)
- TMD factorization violation
- ...

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)

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



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

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

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

Factorization formula: (neglecting Glauber modes)

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

$$\frac{d\sigma}{d^2q_T d^2p_T d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2x_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{x}_T} \mathcal{S}_{ij \rightarrow V k}(\vec{x}_T, \epsilon) \mathcal{B}_{i/N_1}(\xi_1, x_T, \epsilon) \mathcal{B}_{j/N_2}(\xi_2, x_T, \epsilon) \\ \times \mathcal{H}_{ij \rightarrow V k}(\hat{s}, \hat{t}, m_V, \epsilon) \sum_{m=1}^{\infty} \langle \mathcal{J}_m^k(\{\underline{n}_J\}, R p_J, \epsilon) \otimes \mathcal{U}_m^k(\{\underline{n}_J\}, R \vec{x}_T, \epsilon) \rangle$$

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

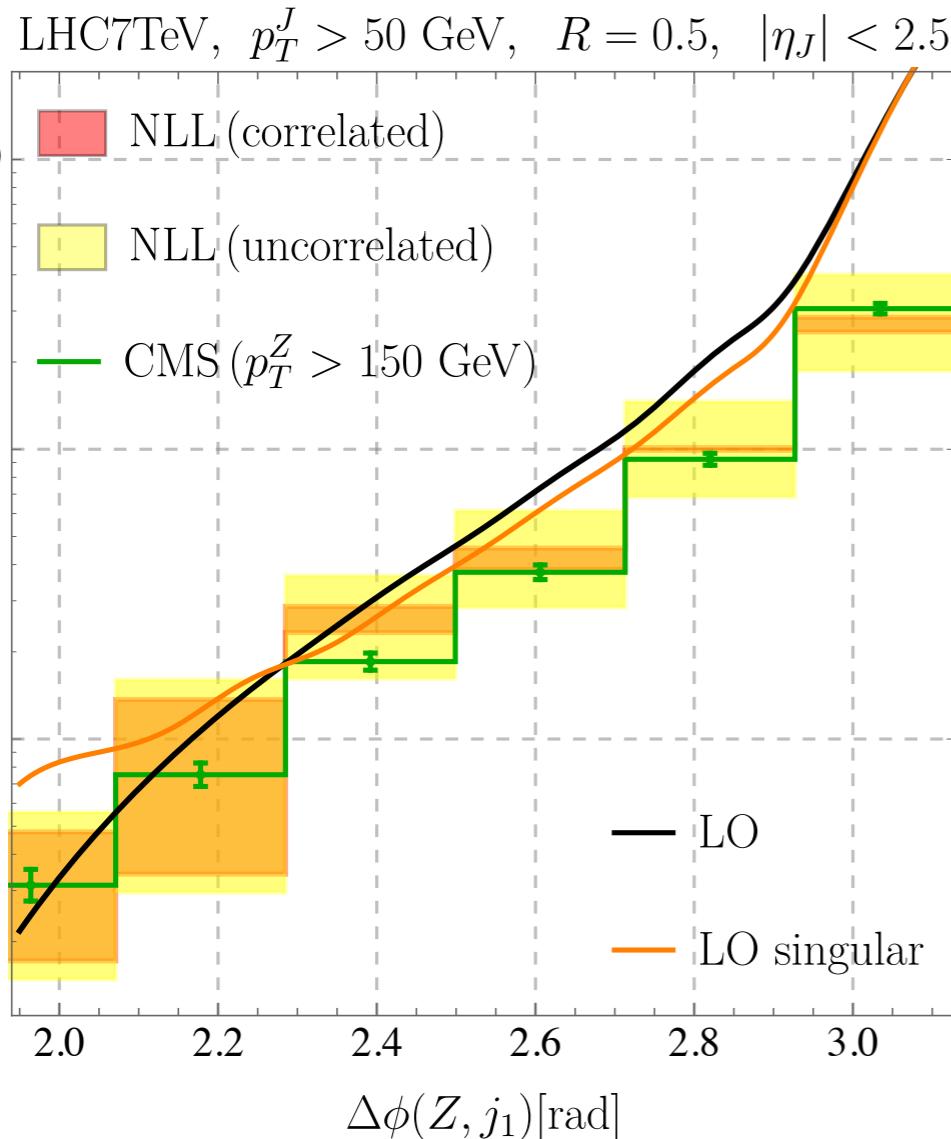
$$p_t \sim q_T (R^2, 1, R)_{n_J \bar{n}_J}$$

(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 PRL;)

Numerical results

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

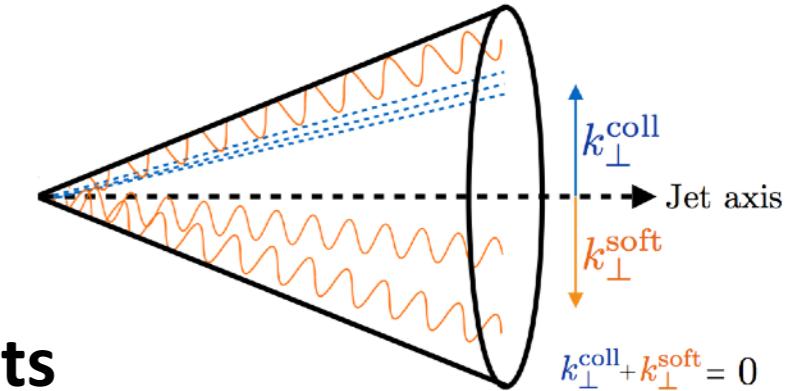


- **NLL resummation result is consistent with CMS data**
- **NLL result has 20-30% scale uncertainties.**
- **Azimuthal correlation can be a clean probe of factorization violation** (Collins & Qiu '07, Rogers & Mulders '10,)
- **Higher accuracy?**
 - NNLL?
 - NNNLL?
- **Better angular resolution?**
- **Reduce contamination?**

Jet TMDs and non-global logs

- Non-global logs in jet TMD resummation

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



- 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)

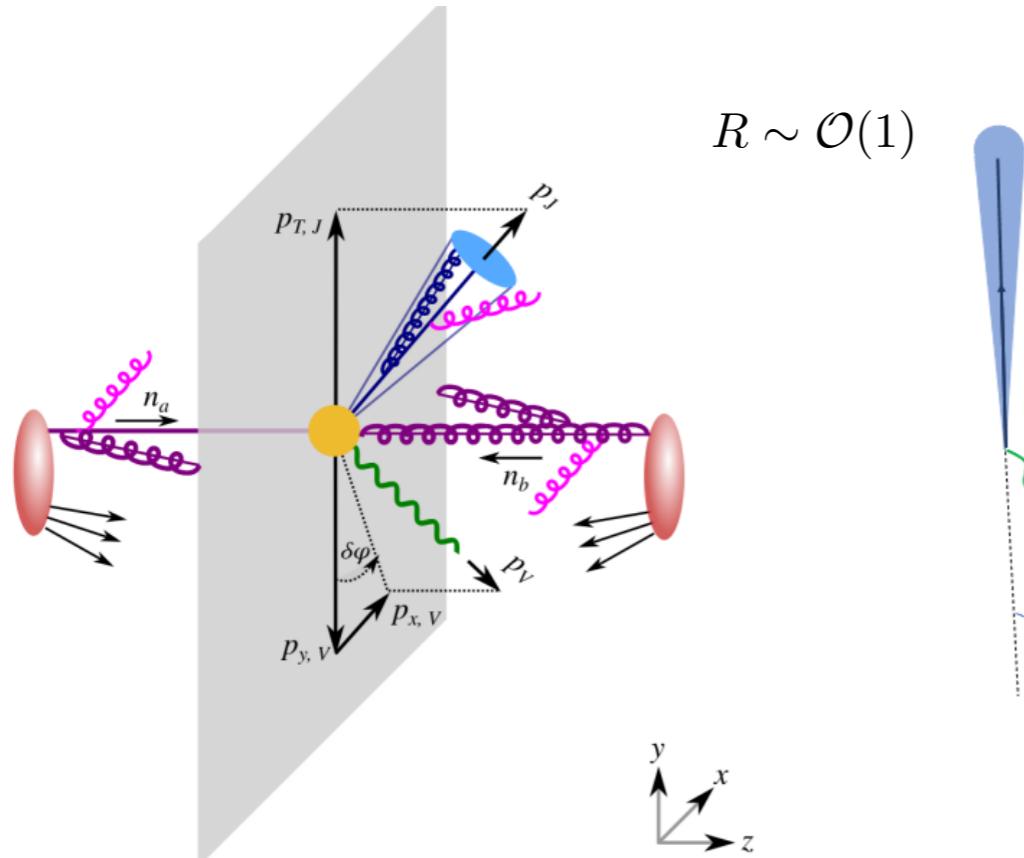
$$\begin{aligned} p_{t,r} &= p_{t,i} + p_{t,j}, \\ \phi_r &= (w_i \phi_i + w_j \phi_j) / (w_i + w_j) & w_i &= p_t^n \\ y_r &= (w_i y_i + w_j y_j) / (w_i + w_j) \end{aligned}$$

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

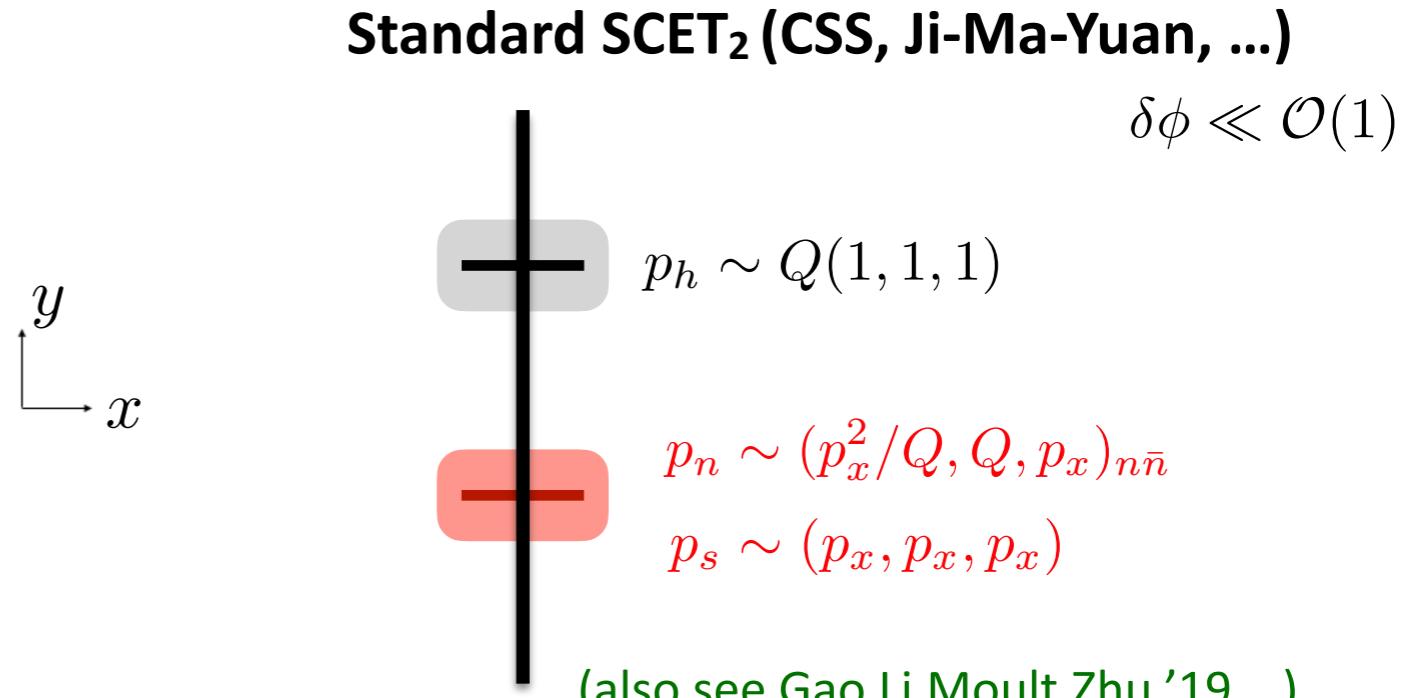
- N³LL resummation for jet TMDs @ ee and ep (Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '18 '19)
- NNLL resummation for V+j @ LHC (Chien, Rahn, Schrignder van Velzen, DYS, Waalewijn & Wu '21 PLB)

Recoil-free azimuthal angle for boson-jet correlation

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



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



Effect of soft radiation in jet algorithm is power suppressed

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

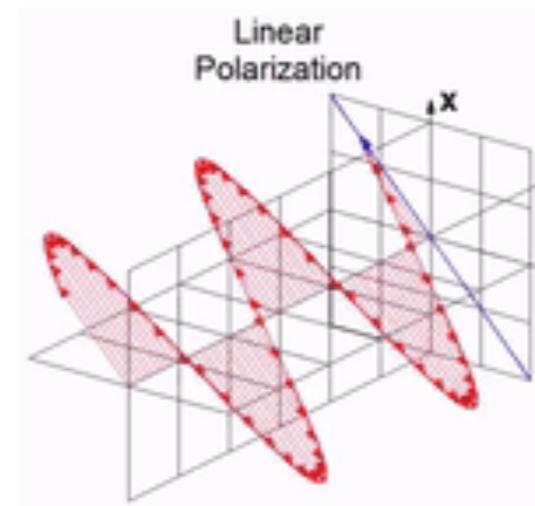
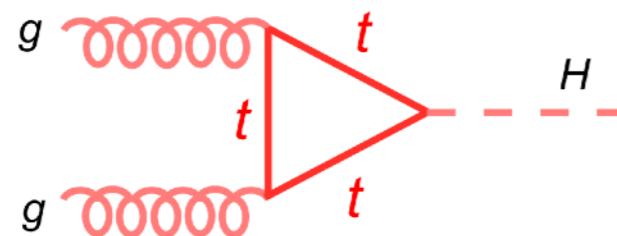
Following the standard steps in SCET₂ we obtain the following factorization formula

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

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

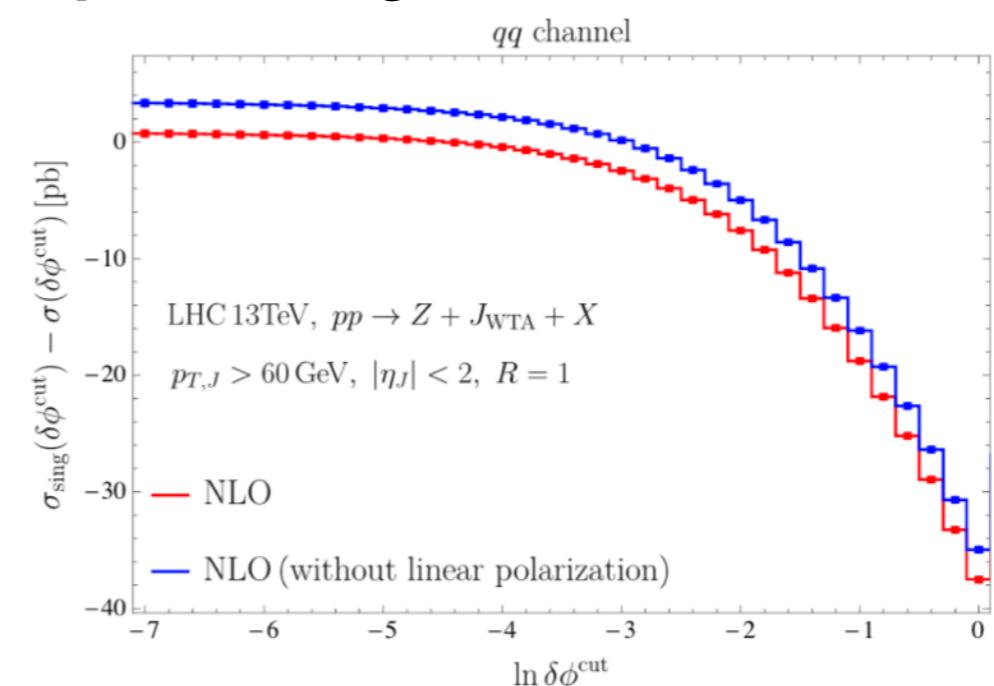
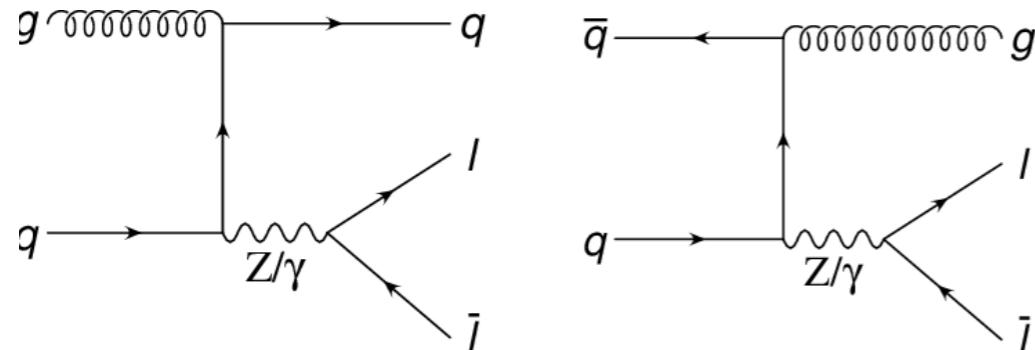
Linearly-polarized gluon TMDs

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



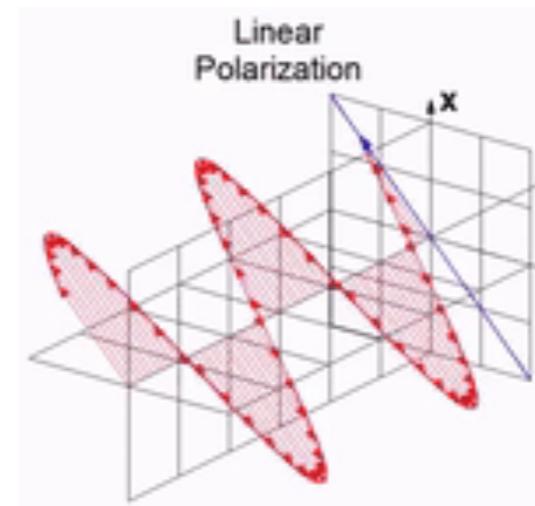
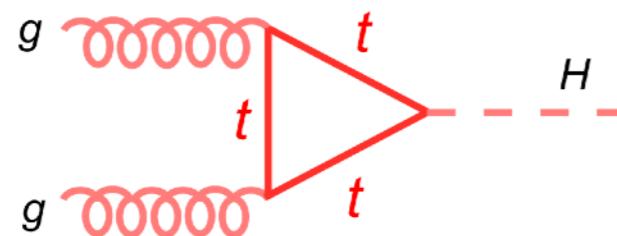
$$\begin{aligned}\Phi_g^{\mu\nu}(x, \mathbf{p}_T) &= \frac{n_\rho n_\sigma}{(p \cdot n)^2} \int \frac{d(\xi \cdot P) d^2 \xi_T}{(2\pi)^3} e^{ip \cdot \xi} \langle P | \text{Tr} [F^{\mu\rho}(0) F^{\nu\sigma}(\xi)] | P \rangle \Big|_{\text{LF}} \\ &= \frac{1}{2x} \left\{ -g_T^{\mu\nu} f_1^g(x, \mathbf{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M^2} + g_T^{\mu\nu} \frac{\mathbf{p}_T^2}{2M^2} \right) h_1^{\perp g}(x, \mathbf{p}_T^2) \right\}\end{aligned}$$

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



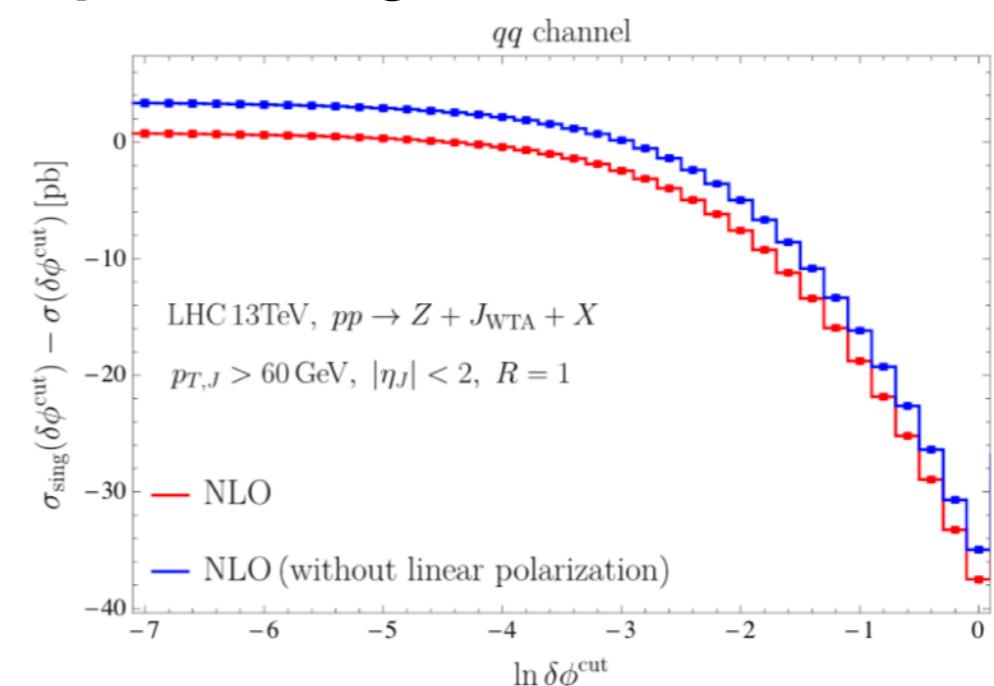
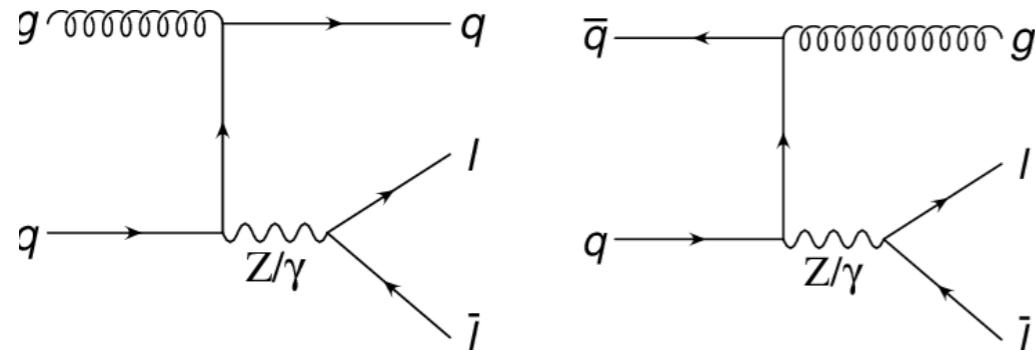
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Linearly-polarized gluon jets

(Chien, Rahn, Schrignder 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

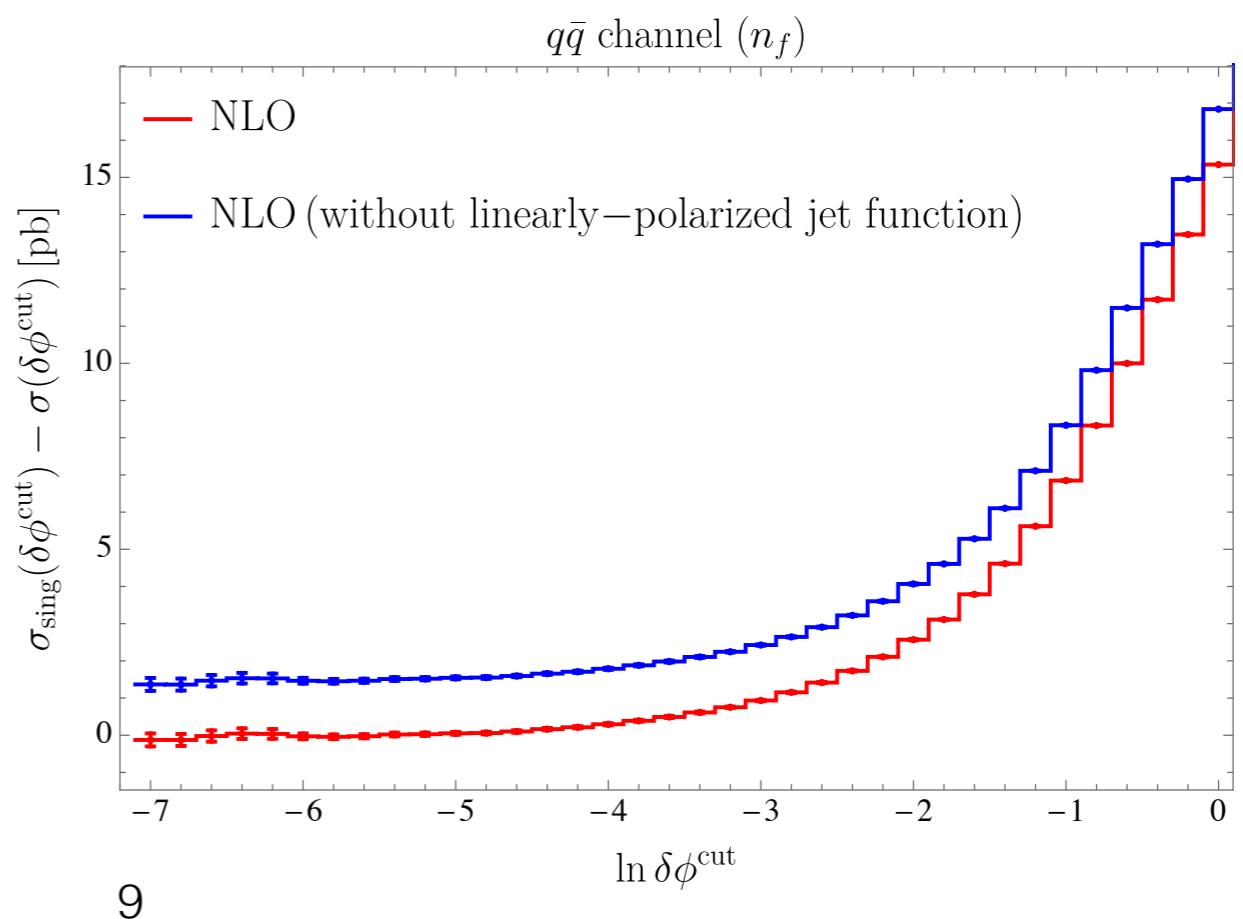
$$J_g^L(\vec{b}_\perp, \mu, \nu) = \left[\frac{1}{d-3} \left(\frac{g_\perp^{\mu\nu}}{d-2} + \frac{b_\perp^\mu b_\perp^\nu}{\vec{b}_\perp^2} \right) \right] \frac{2(2\pi)^{d-1}\omega}{N_c^2 - 1} \langle 0 | \delta(\omega - \bar{n} \cdot \mathcal{P}) \delta^{d-2}(\mathcal{P}_\perp) \mathcal{B}_{n\perp\mu}^a(0)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

The first non-vanishing order is one loop

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

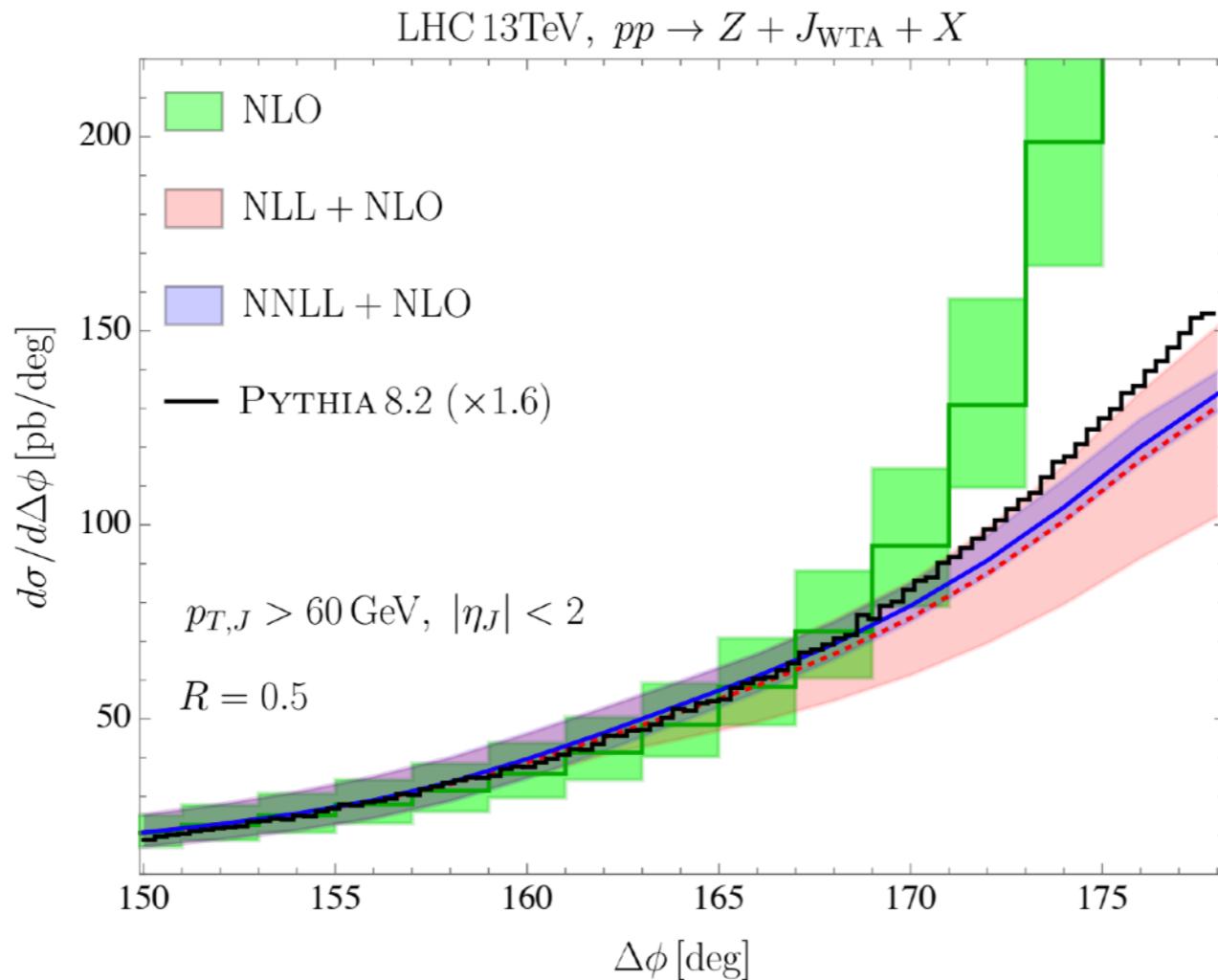
same as EEC gluon jet function up to $\mathcal{O}(\epsilon)$ Luo, Yang, Zhu, Zhu ` 20

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

good perturbative convergence

Pythia agrees well

Track-based jet definition

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

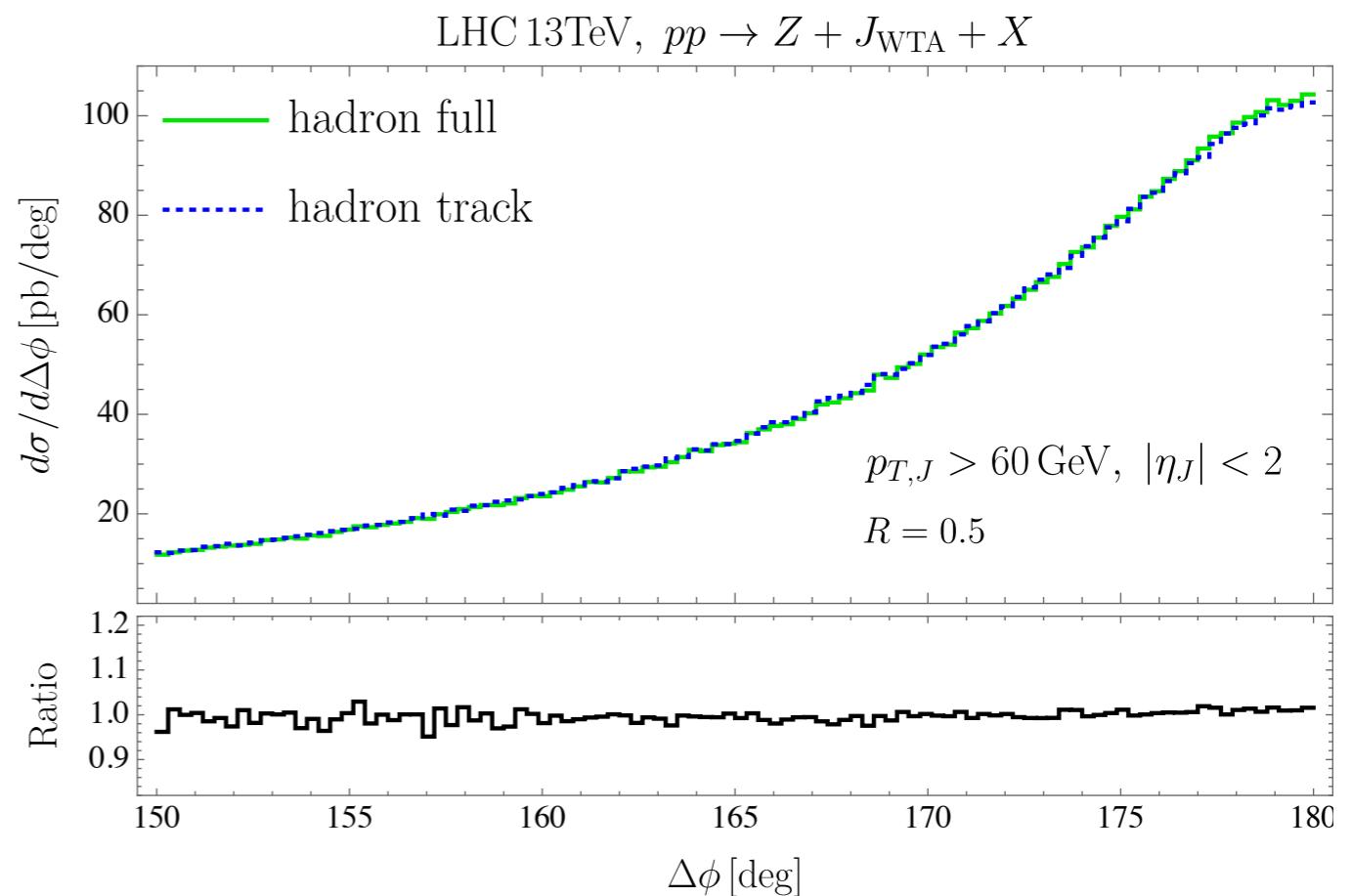
- The angular resolution of jet measurements is about **0.1** radians, limiting access to the back-to-back region
- This can be overcome by measuring the jet using only charged particles, exploiting the superior angular resolution of the tracking systems at the LHC.

Tracking jet function:

Chang, Procura, Thaler, & Waalewijn '13

$$\bar{\mathcal{J}}_q^{(1)} = \mathcal{J}_q^{(1)} + 4C_F \int_0^1 dx \frac{1+x^2}{1-x} \ln \frac{x}{1-x} \int_0^1 dz_1 T_q(z_1, \mu) \\ \times \int_0^1 dz_2 T_g(z_2, \mu) [\theta(z_1 x - z_2(1-x)) - \theta(x - \frac{1}{2})]$$

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



Glauber gluon and super-leading logs resummation

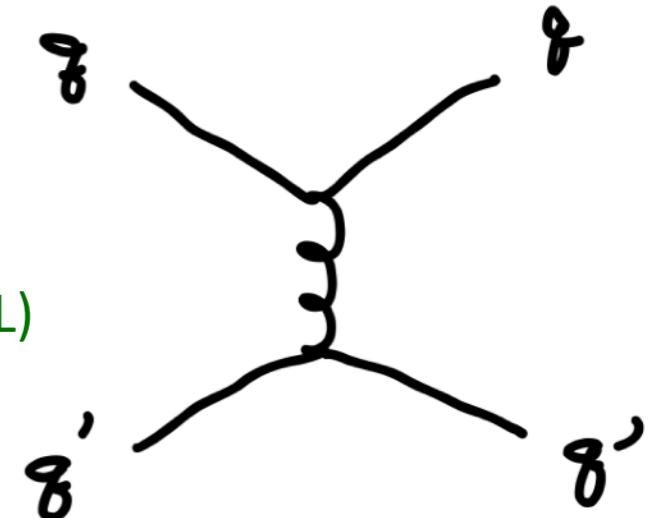
(Becher, Neubert, **DYS** '21)

Consider the processes $q_1 q'_2 \rightarrow q_3 q'_4$

LO hard function: $\mathcal{H}_4 = t_{\alpha_3 \alpha_1}^a t_{\alpha_4 \alpha_2}^a t_{\beta_1 \beta_3}^b t_{\beta_2 \beta_4}^b \sigma_0$

Expand the expansion kernel (Becher, Neubert, Rothen, **DYS** '15 PRL)

$$\begin{aligned} \mathcal{H}_4 U(\mu_s, \mu_h) &= \mathcal{H}_4 P \exp \left[\int_{\mu_s}^{\mu_h} \frac{d\mu}{\mu} \Gamma^H(Q, \mu) \right] \\ &= \mathcal{H}_4 + \int_{\mu_s}^{\mu_h} \frac{d\mu}{\mu} \mathcal{H}_4 \Gamma^H(Q, \mu) + \int_{\mu_s}^{\mu_h} \frac{d\mu}{\mu} \int_{\mu}^{\mu_h} \frac{d\mu'}{\mu'} \mathcal{H}_4 \Gamma^H(Q, \mu') \Gamma^H(Q, \mu) \end{aligned}$$



The first non-zero contribution of has factor arises at 3-loop order

$$S^{(3)} = \langle \mathcal{H}_4 V^I V^I (\bar{V}_4 + \bar{R}_4) \rangle \left(\frac{\alpha_s}{4\pi} \right)^3 \frac{1}{3!} \ln^3 \left(\frac{Q}{\mu} \right) = - \left(\frac{\alpha_s}{4\pi} \right)^3 \frac{16 C_F}{3} \pi^2 L_Q^3 J_1 \sigma_0$$

Super-leading logs at 4-loop order:

$$J_1 = 2\Delta Y \operatorname{sign}(\eta_J)$$

$$S_0^{(4)} = \left\langle \mathcal{H}_4 V^I \left[\sum_{i=1}^4 V_i^L V^I (\bar{V}_4 + \bar{R}_4) + \sum_{i=1}^4 R_i^L V^I (\bar{V}_5 + \bar{R}_5) \right] \right\rangle \left(\frac{\alpha_s}{4\pi} \right)^4 \frac{(-2)}{5!} \ln^5 \left(\frac{Q}{\mu} \right)$$

Forshaw, Kyrieleis, Seymour '06

All-order results of super-leading logs

(Becher, Neubert, **DYS** '21)

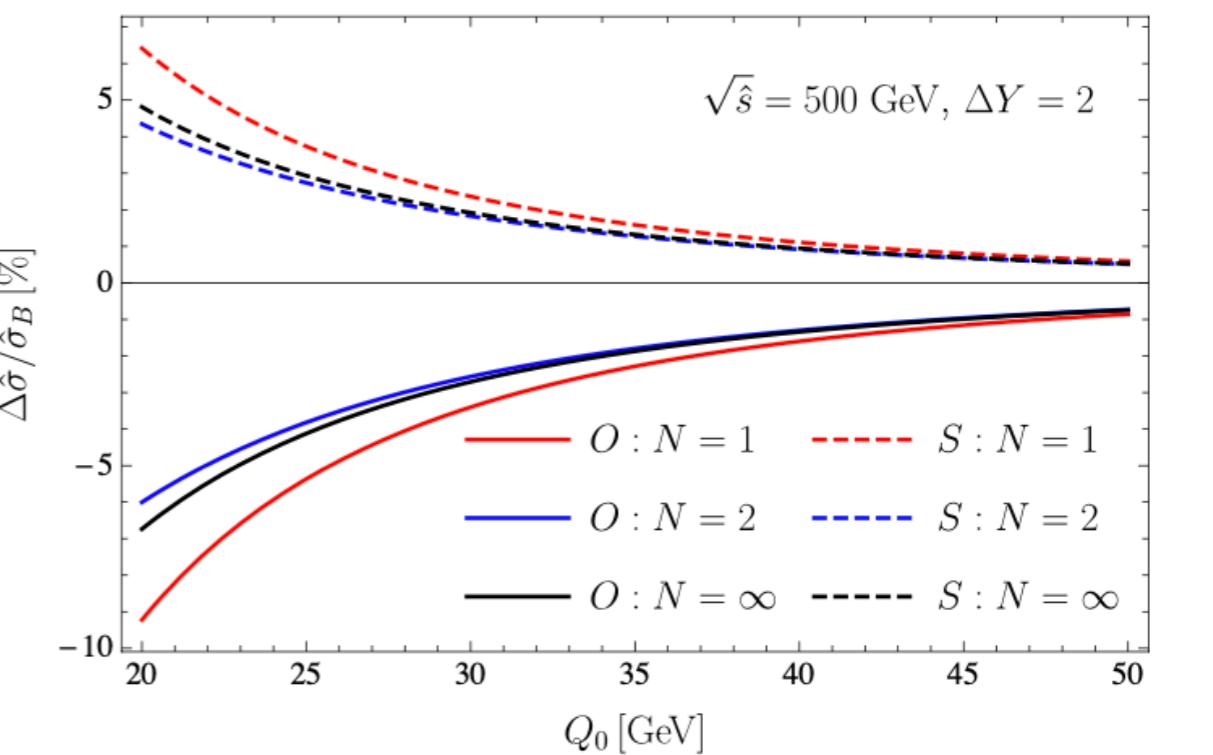
$$\omega \sim \alpha_s L^2$$

$$S_O = \left(\frac{\alpha_s}{\pi}\right)^3 \pi^2 \ln^3 \frac{Q}{\mu_s} \frac{1}{N_c} \left[N_c^2 (4f_1(w) - 2f_\delta(w)) - 4f_2(\omega) + 2f_\delta(w) \right] \Delta Y \sigma_0$$

Sudakov suppression of the superleading logarithms is weaker than the one present for global observables

$$\begin{aligned} \text{Global logs} &\longrightarrow e^{-\omega} \\ \text{Superleading logs} &\xrightarrow{\omega \rightarrow \infty} \frac{1}{\omega} \end{aligned}$$

Numerical results



Red: Four loop

Blue: Five loop

Black: all order

All-order results of super-leading logs

(Becher, Neubert, **DYS '21**)

hypergeometric function

$$f_\delta(w) = \frac{1}{3} {}_2F_2\left(1, 1; 2, \frac{5}{2}; -w\right)$$

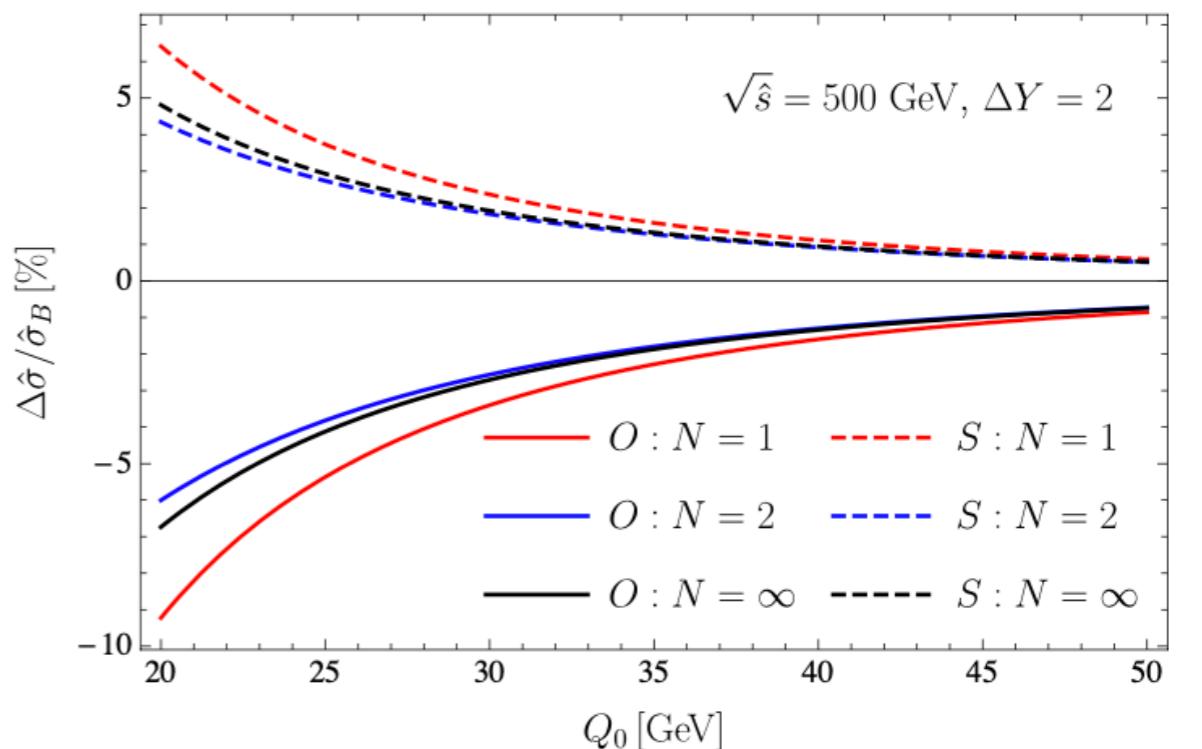
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error function

$$f_2(w) = \frac{1}{w} - \frac{\sqrt{\pi}}{2w^{3/2}} \operatorname{erf}(\sqrt{w})$$

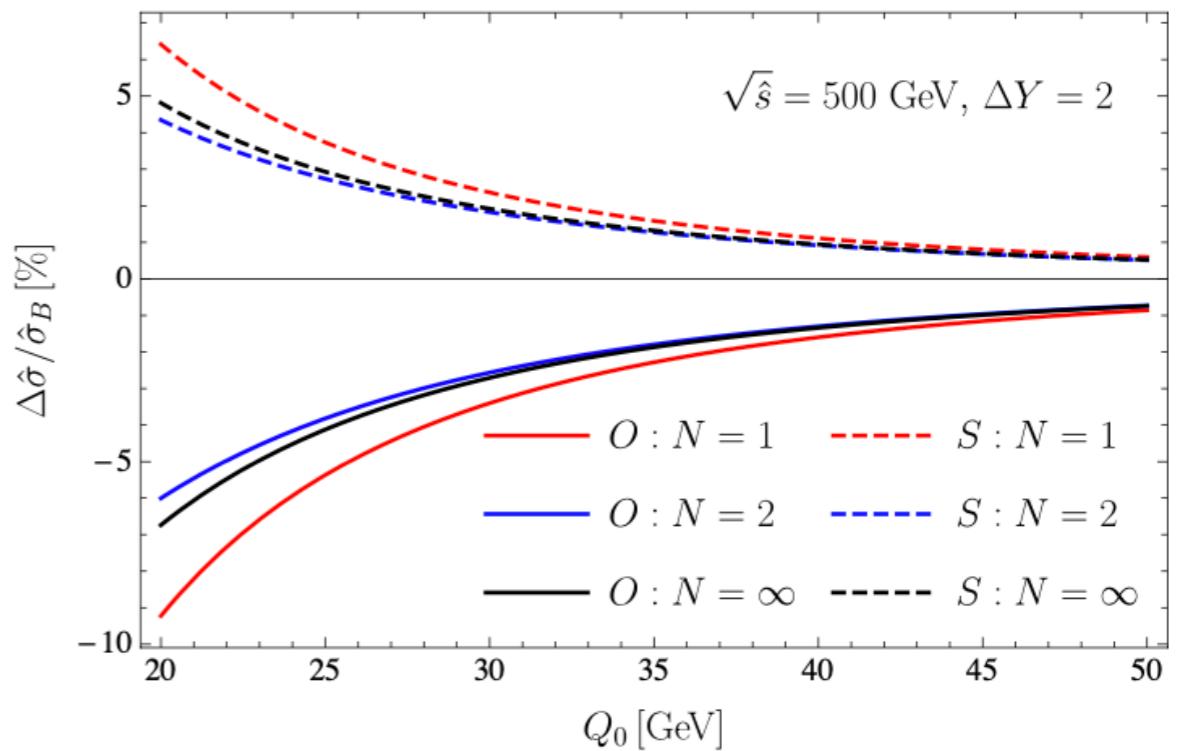
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All-order results of super-leading logs

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Owen's T function

$$f_1(w) = \frac{\sqrt{\pi}}{2w} \int_0^{\sqrt{\frac{w}{2}}} \frac{dz}{z^2} \left[\operatorname{erf}(z) - \frac{e^{-2z^2}}{i} \operatorname{erf}(iz) \right]$$

hypergeometric function

$$f_\delta(w) = \frac{1}{3} {}_2F_2 \left(1, 1; 2, \frac{5}{2}; -w \right)$$

error function

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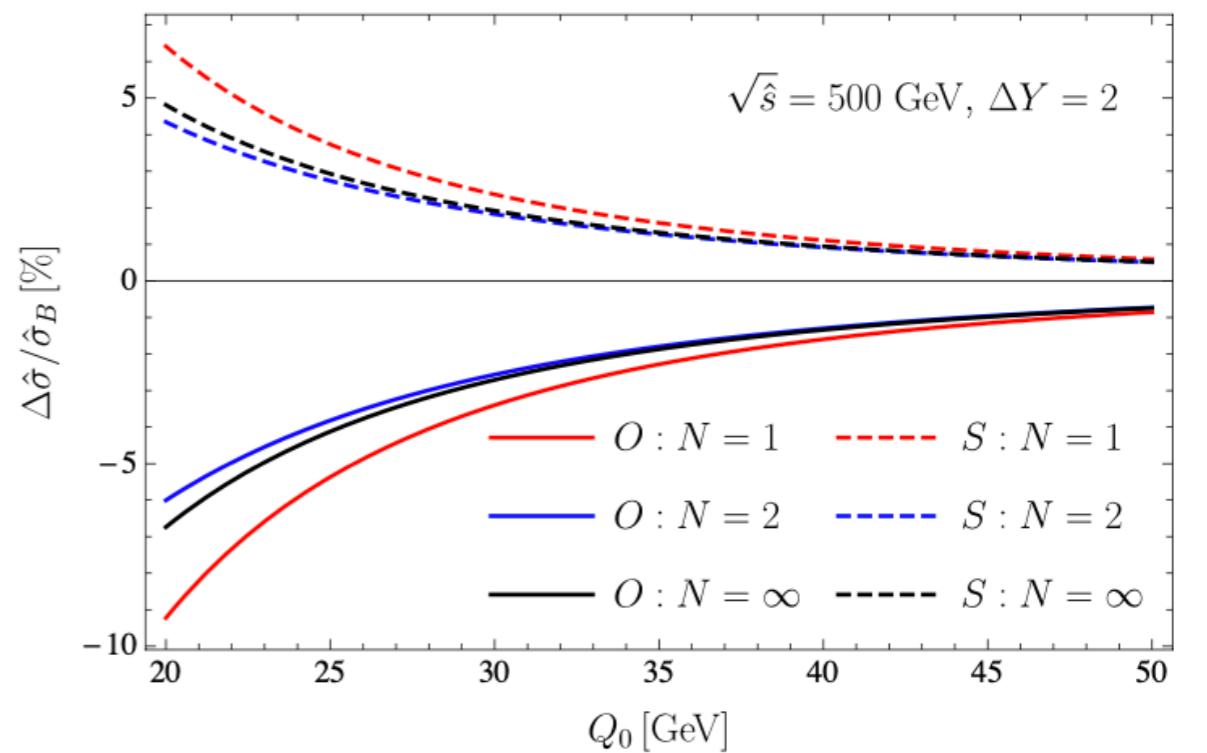
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Summary

- QCD Jets are our windows on partons
- 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
- We derive, for the first time, the all-order structure of these “super-leading logarithms” for generic scattering processes at hadron colliders and resum them in closed form

Thank you