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Recoil-free azimuthal angle for precision boson-jet correlation

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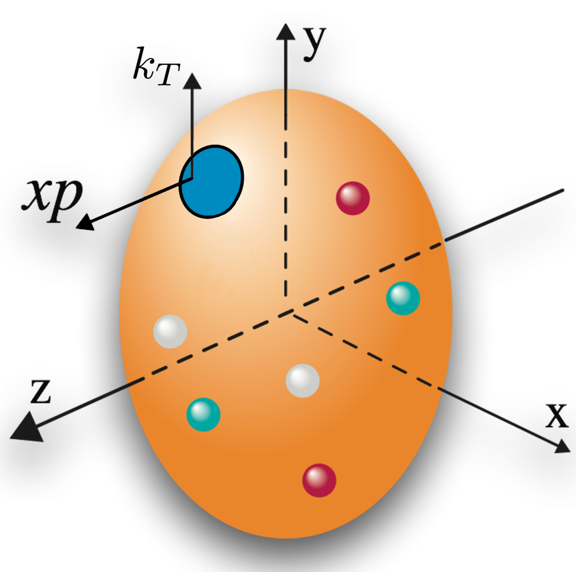
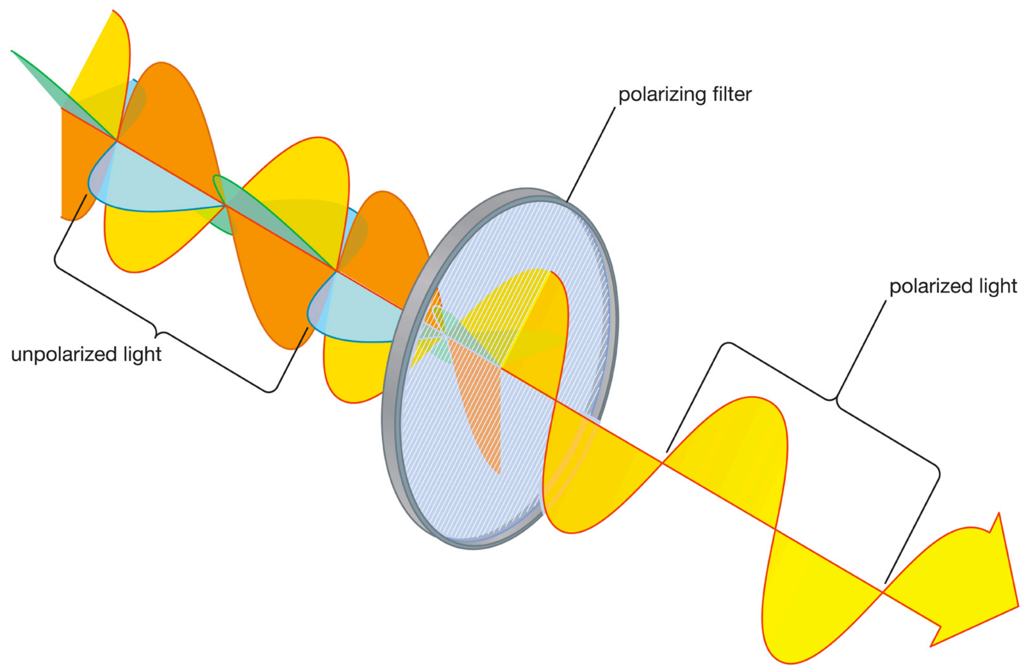
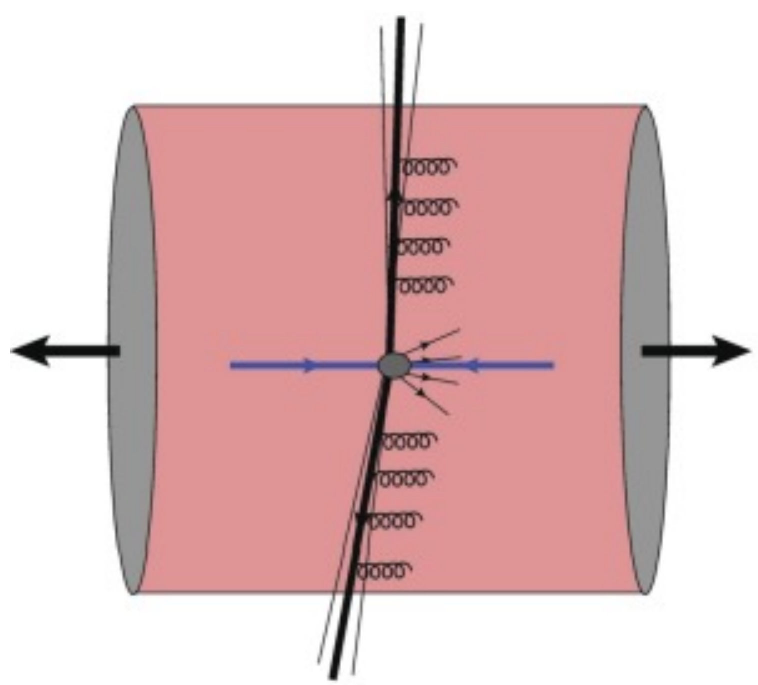
Introduction

- The back-to-back jets production is an essential hard probe in high energy collisions.
- Use azimuthal decorrelations to expose
  - Proton 3-D imaging in momentum space: gluon TMDs
  - Probe of fundamental physics: polarization of gluon
  - P_T broadening in heavy-ion collisions
  - … …

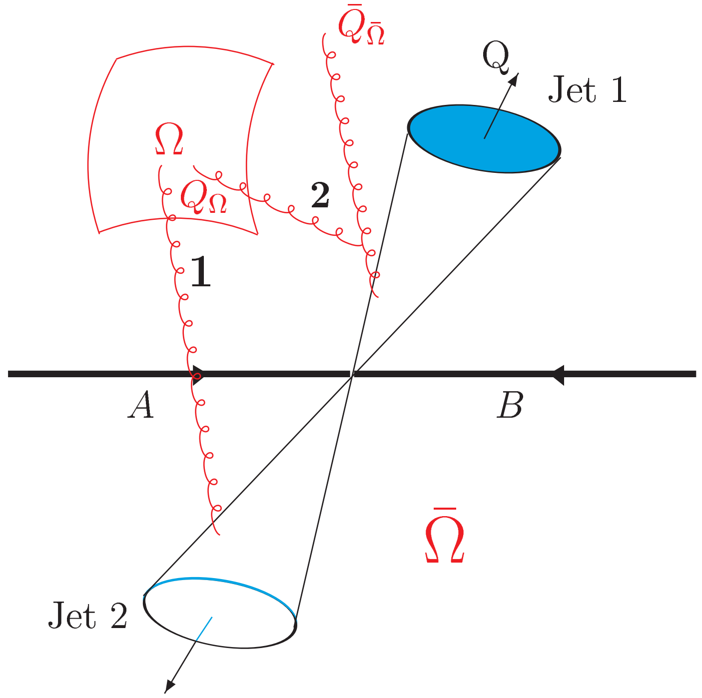




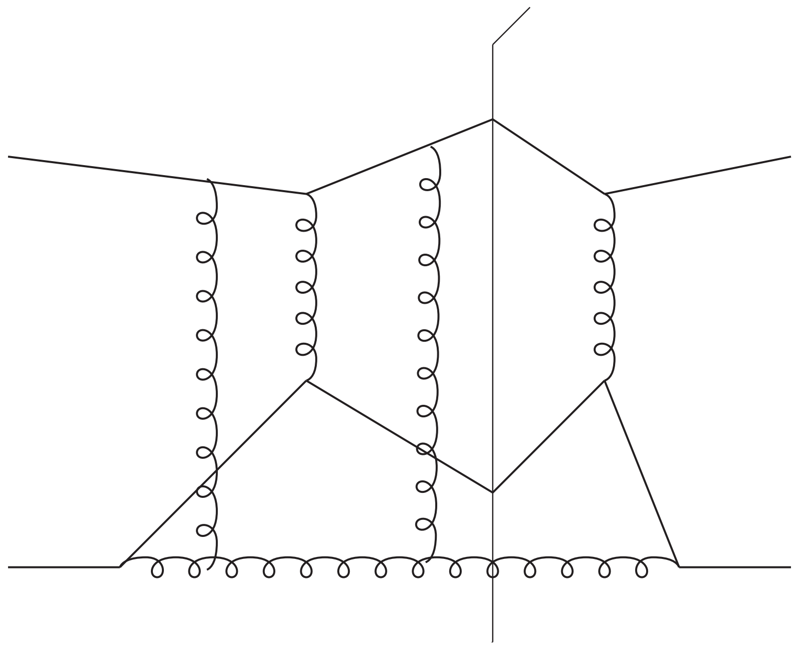


Theory challenges for TMD factorization of jets

- non-global structures (Dasgupta & Salam '02)
  - from jets of intermediate energy
  - reflect color flow at all scales
  - do not exponentiate in a simple manner
  - Non-linear evolution, BMS eq



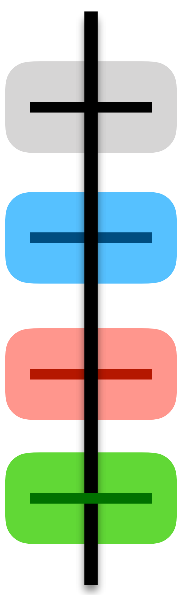
- factorization violation effects
  - No TMD factorization for dijet (Collins & Qiu '07, Rogers & Mulders '10, ……)
  - Glauber gluon
  - Lipatov vertex
  - superleading logs



Jet radius and q_T joint resummation for boson-jet correlation

(Chien, DYS & Wu '19)

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



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

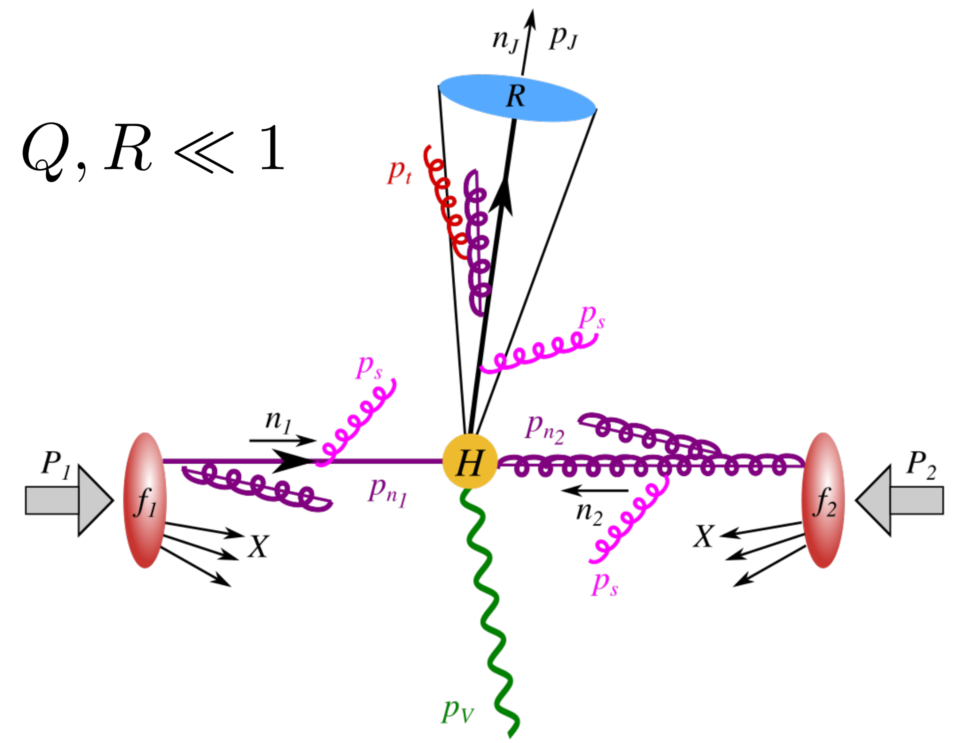
$p_{n_J} \sim p_T^J\,(R^2, 1, R)_{n_J \bar{n}_J}$

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

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

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

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



Construction of the theory formalism

- **Multiple scales in the problem**
- **Rely on effective field theory: SCET + Jet Effective Theory** (Becher, Neubert, Rothen, DYS '15)

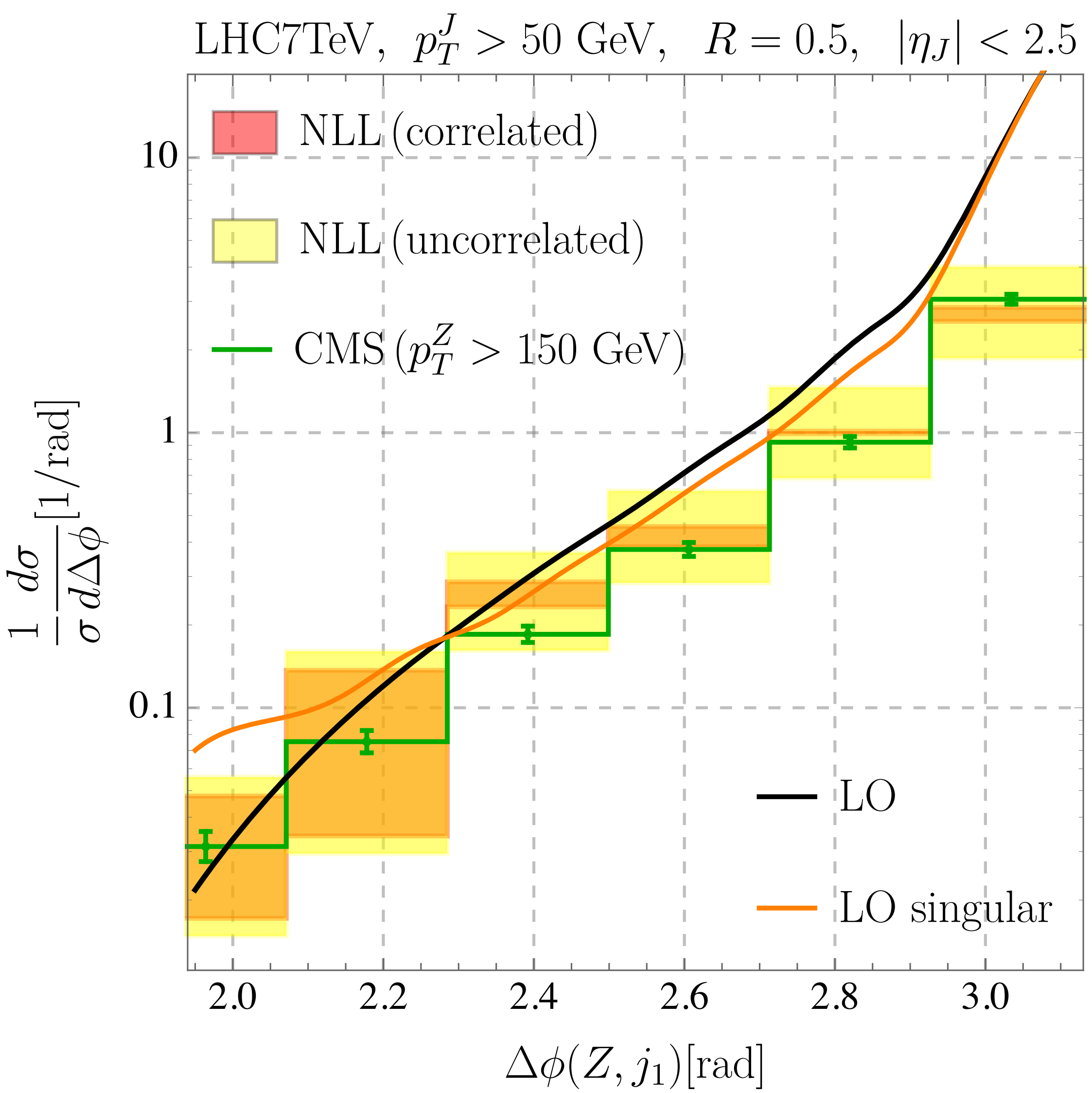
$$\frac{d\sigma}{d^2q_T d^2p_T d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2x_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{x}_T} \mathcal{S}_{ij\to Vk}(\vec{x}_T,\epsilon)\mathcal{B}_{i/N_1}(\xi_1, x_T,\epsilon)\mathcal{B}_{j/N_2}(\xi_2, x_T,\epsilon)$$

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

(also see Sun,Yan,Yuan,Yuan '18; Buffing,Kang,Lee,Liu '18,...)

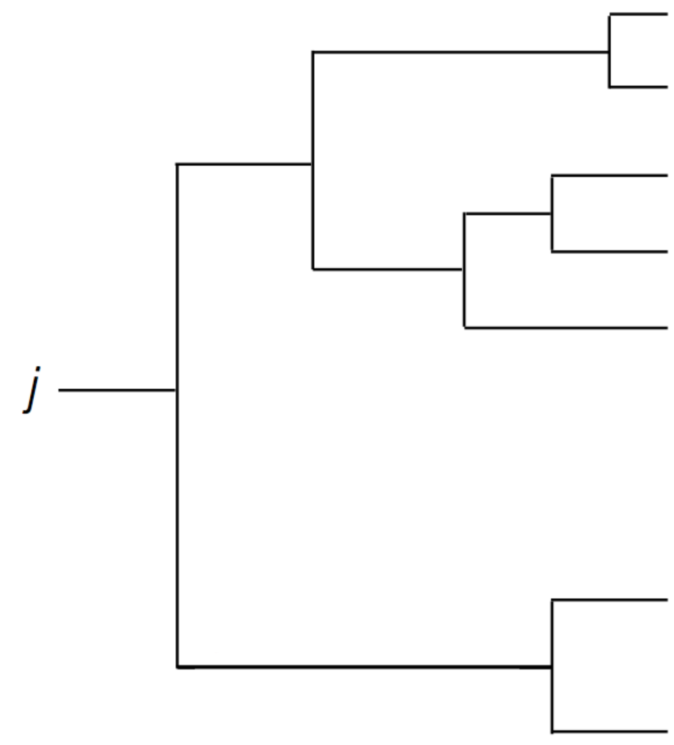
Numerical results

(Chien, DYS & Wu ’19)



- **All-order resummation result is consistent with CMS data**
- **Next-to-leading logarithms result has 20-30% scale uncertainties.**
- **Higher-order resummation is necessary**
  - **Two-loop kernels are known** (Caron-Huot ’15)
  - **Non-linear evolution equation, new Monte-Carlo algorithms**
  - **NLO matching has been included** (Balsiger, Becher, DYS ’19)
  - **Two-loop kernels + NLO matching -> NNLL**
  - **N^3LL ?**

Jet definition



Which particles get put together?

Jet algorithm

How to combine their momenta?

Recombination scheme

Jet TMDs and recombination scheme

Recombination schemes in jet definitions:

E-scheme: add the four vectors $p_r^\mu = p_i^\mu + p_j^\mu$ **Non-Global; non-linear RG**

Non-global in jet TMD resummation **(Banfi, Dasgupta & Delenda '08)**

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

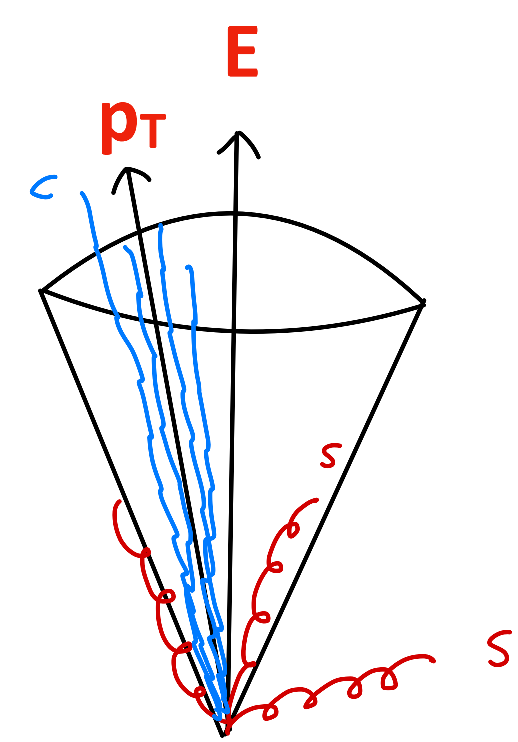
sum over all soft partons not combined with hard jets

deviation from q_T=0 are only caused by particle flow outside the jet regions

p_T-scheme: (Ellis, Soper '93)

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

Global; linear RG



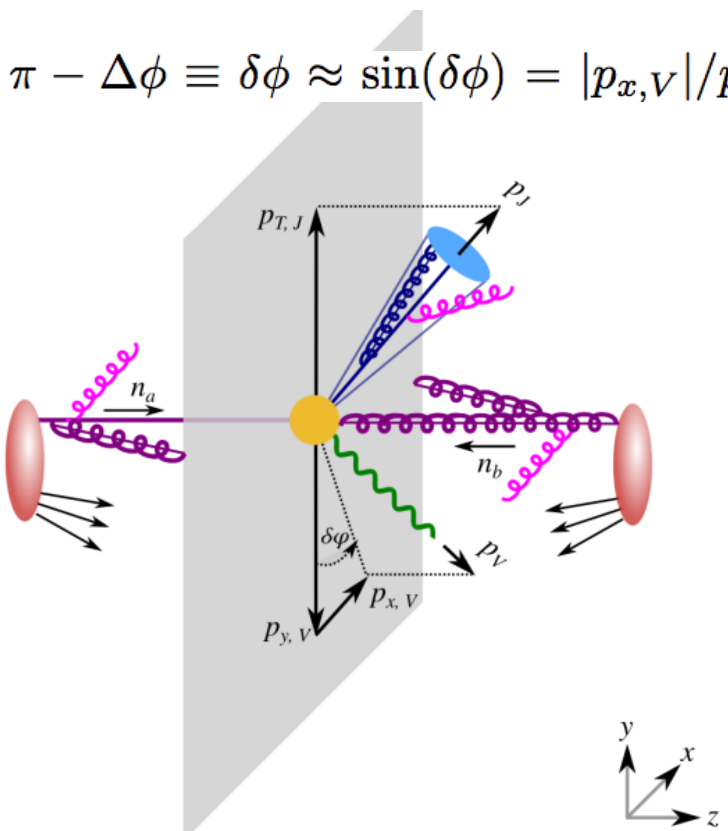
$n \to \infty$ **(Winner-take-all scheme)**

(Bertolini, Chan, Thaler '13)

Recoil-free azimuthal angle for boson-jet correlation

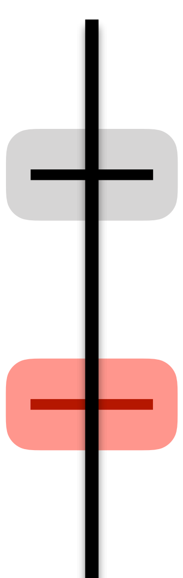
(Chien, Rahn, Schrignder, DYS, Waalewijn & Wu '20)

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



$$\frac{d\sigma}{dp_{x,V}\, dp_{T,J}\, dy_V\, d\eta_J} = \int \frac{db_x}{2\pi}\, e^{ip_{x,V} b_x} \sum_{i,j,k} B_i(x_a, b_x) B_j(x_b, b_x) S_{ijk}(b_x, \eta_J) \times \mathcal{H}_{ij\to Vk}(p_{T,V}, y_V - \eta_J)\, \mathscr{J}_k(b_x) \left[1 + \mathcal{O}\left(\frac{p_{x,V}^2}{p_{T,V}^2}\right)\right]$$

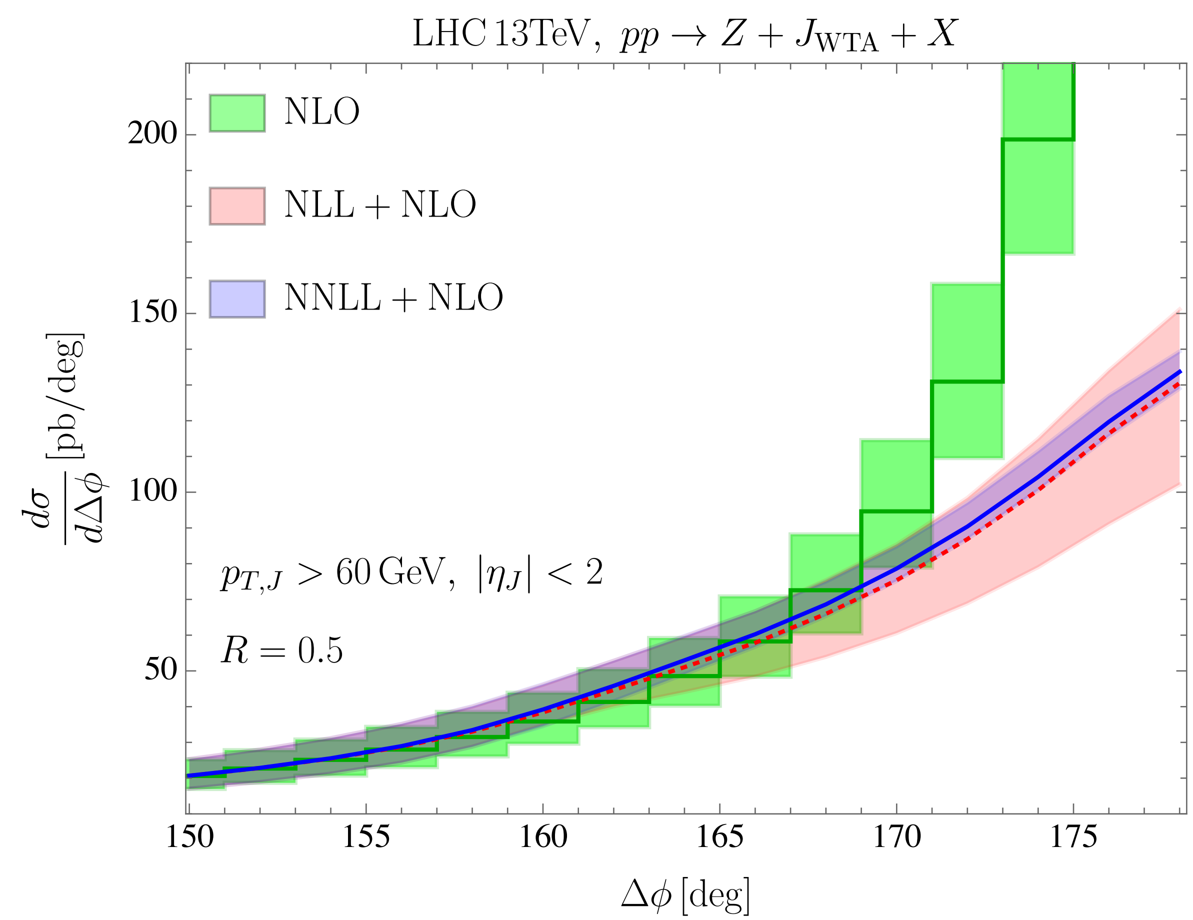
Standard SCET₂



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

$p_n \sim (p_x^2/Q, Q, p_x)_{n\bar{n}}$

$p_s \sim (p_x, p_x, p_x)$



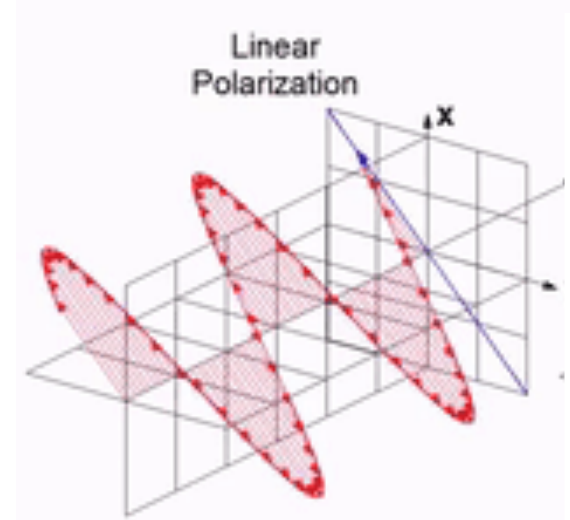
first N²LL resummation

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

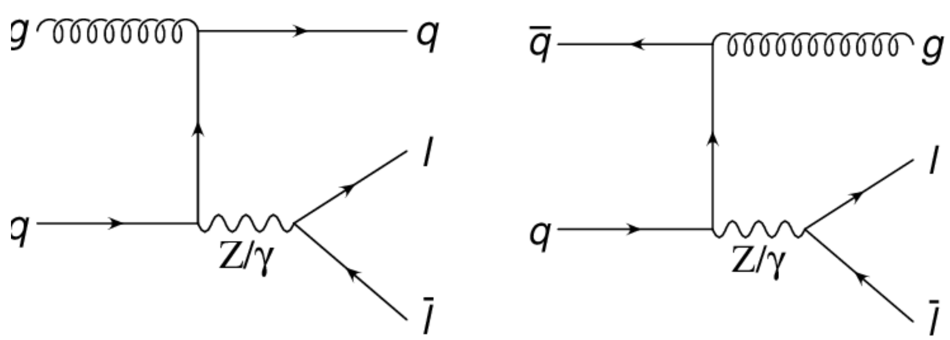
Linearly-polarized gluon jets

(Chien, Rahn, Schrignder, DYS, Waalewijn & Wu ’20)

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



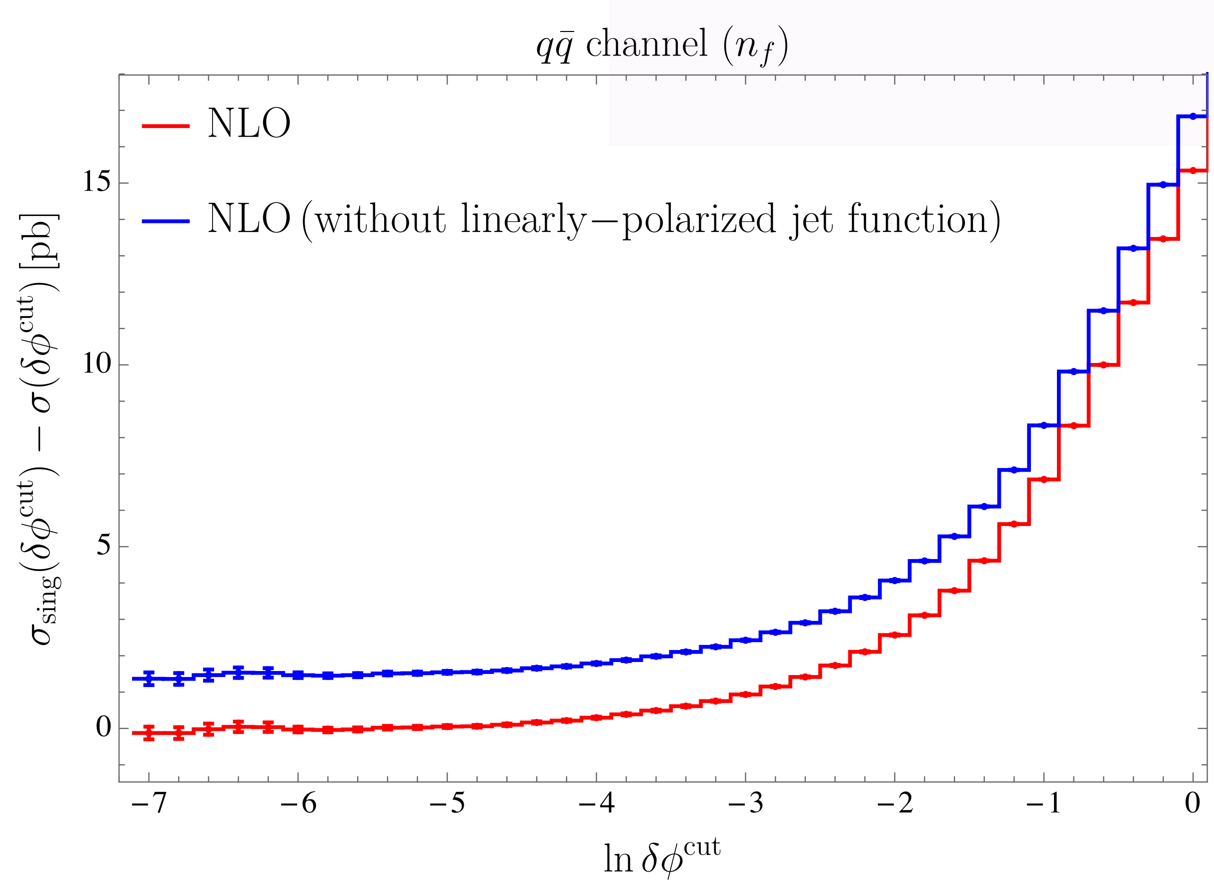
Boson-jet correlation can be used to probe linear-polarized gluon TMDs inside the proton (Boer, Mulders, Pisano, Zhou ’16)



Linear-polarized gluon jets:

$$\mathscr{J}_g^L(\vec{b}_\perp, \mu, \nu) = \left[\frac{1}{d-3}\left(\frac{g_\perp^{\mu\nu}}{d-2} + \frac{b_\perp^\mu b_\perp^\nu}{\vec{b}_\perp^2}\right)\right]\frac{2(2\pi)^{d-1}\omega}{N_c^2-1}$$

$$\times \langle 0|\delta(\omega - \bar{n}\cdot\mathcal{P})\delta^{d-2}(\mathcal{P}_\perp)\mathcal{B}^a_{n\perp\mu}(0)e^{i\vec{b}_\perp\cdot\hat{\vec{k}}_\perp}\mathcal{B}^a_{n\perp\nu}(0)|0\rangle$$



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

Track-based jet definition

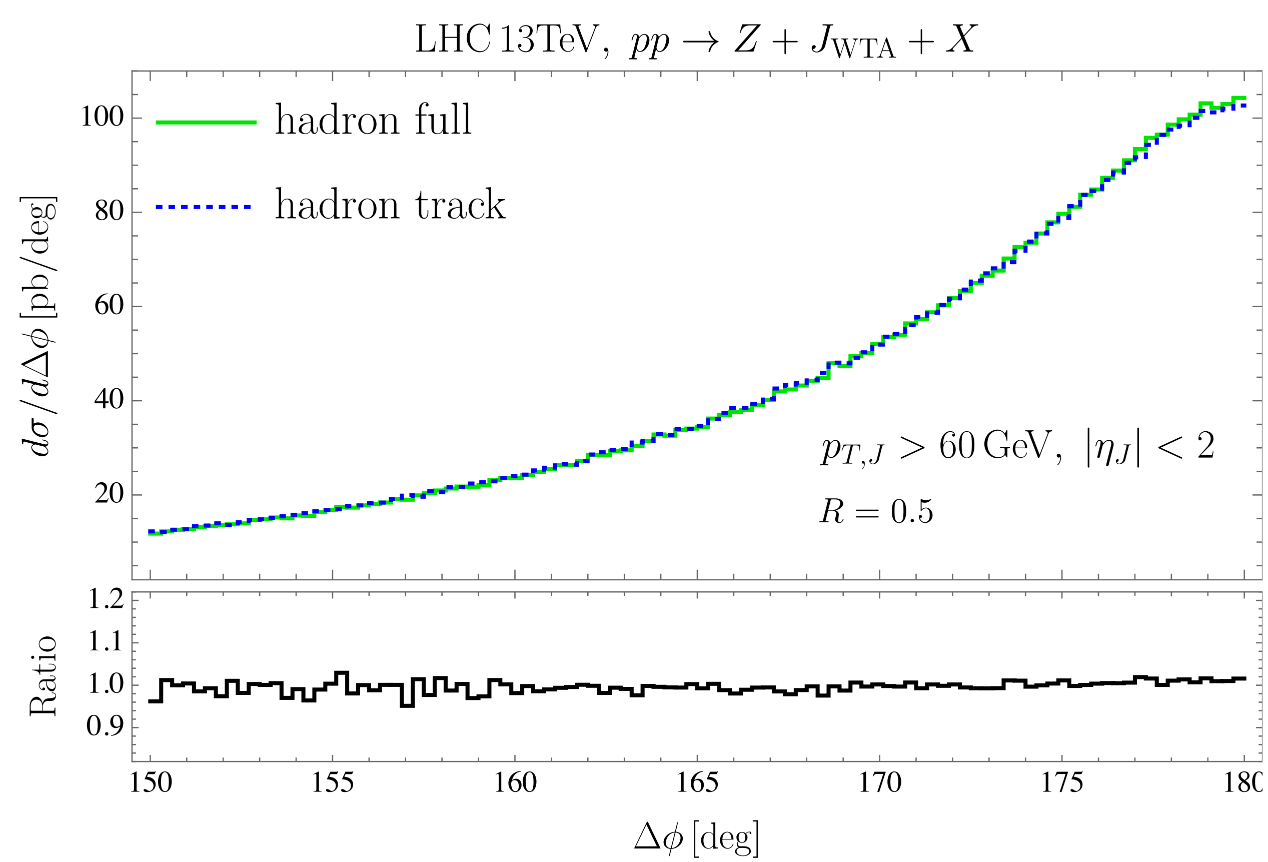
(Chien, Rahn, Schrignder, DYS, Waalewijn & Wu '20)

- **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:

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

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



Conclusion

- **Jet offers a rich physics program at the LHC**
- **The boson-jet azimuthal decorrelation with the winner-take-all axis makes the observable robust in the presence of a large background.**
- **The effective field theory approach enables us to achieve very precise predictions(the first N^2LL resummation, no theoretical obstacles for N^3LL).**
- **We show that if this observable is measured using only charged particle tracks the effect on our theory predictions is minimal.**
- **Our TMD factorization formula presents an excellent opportunity to shed light on the 3-D structure of the proton.**
- **The recoil-free axis can suppress effects from the huge underlying background in the heavy-ion collision, and thus our work serves as a baseline for pinning down the inner-workings of the QCD medium.**

Thank you