Precision boson-jet azimuthal decorrelation at hadron colliders

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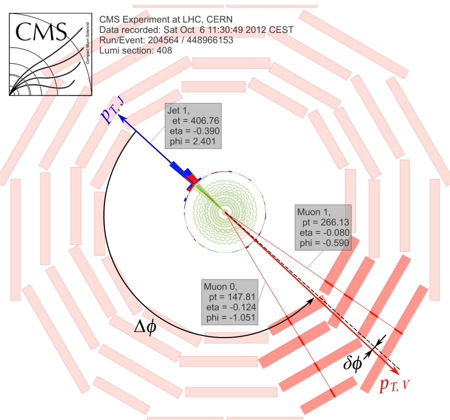
Motivations

Boson-jet azimuthal decorrelation

Definition: $\Delta\phi \equiv |\phi_V - \phi_J|$ ($\delta\phi \equiv \pi - \Delta\phi$): a stringent test of QCD



Precise predictions rely on

1. Fixed-order calculations

   NLO, NNLO,$\cdots$

2. Resummation of $\ln \delta\phi$
   - Parton branching method
   - Pythia, Herwig,$\cdots$
   - TMD factorization
   - SCET

3. Validity of factorziation

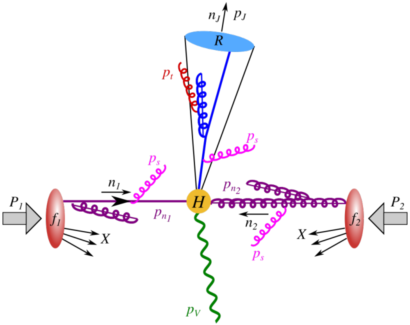
   Is it broken by Glauber modes?

Main topics: resummation using SCET

Resummation using standard jet axis

Standard jet axis (SJA): $p_J^\mu = \sum_{i\in \text{jet}} p_{J,i}^\mu$

An all-order resummation formula (with Glauber modes neglected):



Hard function: $\mathcal{H}_{ij\to Vk}$

Beam functions: $\mathcal{B}_{i/N_1}, \mathcal{B}_{j/N_2}$

Soft function: $\mathcal{S}_{ij\to Vk}$

Jet function: $\mathcal{J}^k$ contains NGLs!

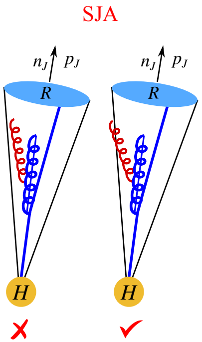
$$\frac{d\sigma}{d^2p_T^J d^2p_T^V d\eta_J dy_V} = \sum_{ijk}\int \frac{d^2x_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{x}_T} \mathcal{S}_{ij\to Vk}(\vec{x}_T,\epsilon)\mathcal{B}_{i/N_1}(\xi_1, x_T,\epsilon)\mathcal{B}_{j/N_2}(\xi_2,x_T,\epsilon)$$

$$\times\, \mathcal{H}_{ij\to Vk}(\hat{s},\hat{t},m_V,\epsilon)\mathcal{J}^k(p_J^2,\vec{x}_T,\epsilon)$$

Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

Non-global logarithm (NGL) and SJA

An non-global observable: sensitive to radiation in only a part of phase space



For $\delta\phi > 0$

- In-jet soft radiation does not contribute
- Only out-jet soft radiation contributes

$\Rightarrow$ NGL $\propto \alpha_S C_A \alpha_s C_k L^2$

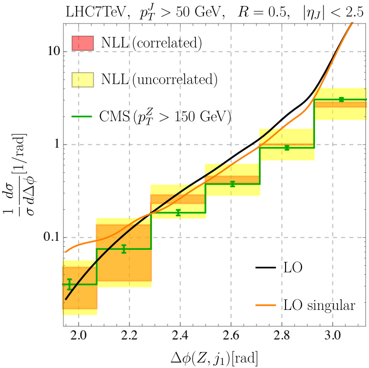
starting as NLL terms with $\alpha_s L \sim 1$.

M. Dasgupta and G. P. Salam, Phys. Lett. B **512**, 323-330 (2001) [arXiv:hep-ph/0104277 [hep-ph]].

Resummation of NGLs is very difficult

NLL resummation using SJA

NLL resummed results with NGLs: relatively large uncertainties

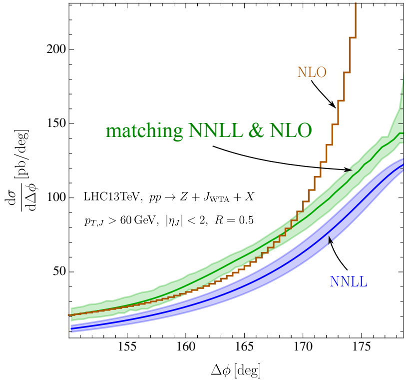


Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

precision predictions ⇔ going beyond NLL

NNLL resummation using SJA has not been achieved in any frameworks!

Main topic: NNLL resummation in $\delta\phi$



Two points to make:

1. The "minor" change: SJA $\rightarrow$ Winner-Take-All (WTA) axis
2. Matching to NLO cross section leads to a BIG shift

Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn and BW, Phys. Lett. B **815**, 136124 (2021) [arXiv:2005.12279 [hep-ph]].

Chien, Rahn, Shao, Waalewijn and BW, JHEP 02 (2023), 256 [arXiv:2205.05104 [hep-ph]].

Resummation using the WTA axis

What is WTA?

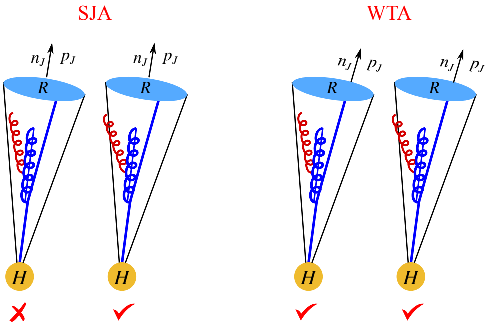
WTA-p_T scheme:

$$p_{T,r} = p_{T,i} + p_{T,j}, \qquad (y_r, \phi_r) = (y, \phi) \text{ of larger } p_T$$

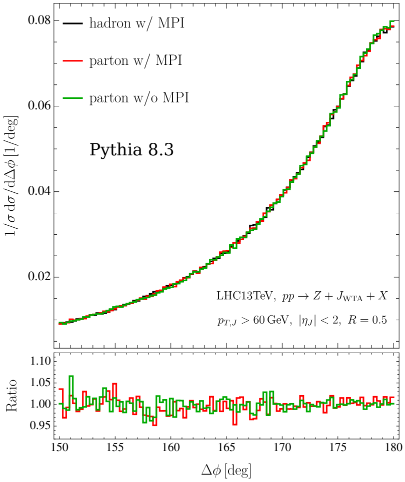
Salam, "E_t^∞ Scheme." unpublished; Bertolini, Chan and Thaler, JHEP **04**, 013 (2014) [arXiv:1310.7584 [hep-ph]].

Jet definition: anti-k_t algorithm with WTA-p_T scheme

The WTA axis eliminates NGLs: insensitive to soft radiation



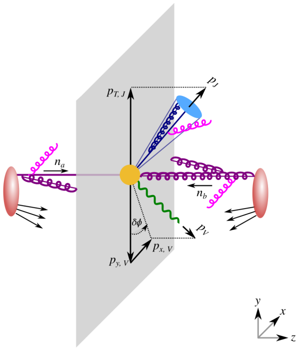
Another advantage of WTA



Very robust to hadronization and the underlying event

Factorization formula

An all-order resummation formula using the WTA axis:



Hard function: $\mathcal{H}_{ij\to Vk} \leftarrow$ parton-level $\hat{\sigma}$

Beam functions: $\mathcal{B}_i, \mathcal{B}_j \leftarrow$ TMDs in hadrons

Soft function: $S_{ijk} \leftarrow$ soft radiation

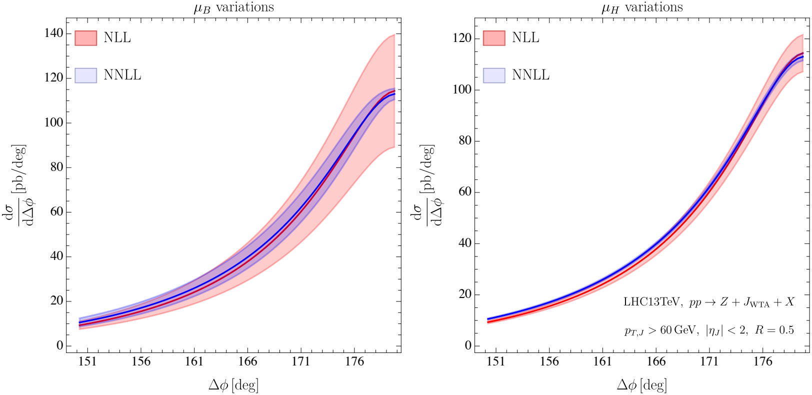
Jet function: $\mathcal{J}_k$ does NOT contain NGLs!

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_x\,\mathrm{d}p_{T,V}\,\mathrm{d}y_V\,\mathrm{d}\eta_J} = \int \frac{\mathrm{d}b_x}{2\pi} e^{b_x q_x} \sum_{ijk} \mathcal{H}_{ij\to Vk}(p_{T,V}, y_V - \eta_J) \mathcal{B}_i(x_a, b_x) B_j(x_b, b_x) \mathcal{J}_k(b_x) S_{ijk}(b_x, \eta_J)$$

Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn and BW, Phys. Lett. B **815**, 136124 (2021) [arXiv:2005.12279 [hep-ph]].

Chien, Rahn, Shao, Waalewijn and BW, JHEP 02 (2023), 256 [arXiv:2205.05104 [hep-ph]].

Theoretical uncertainties at NNLL



estimated by varying scales up and down by a factor of two.

Parton TMD distributions

Linearly-polarized beam functions start to contribute to $\delta\phi$ at NLO/NNLL:

$$B_g^L(x, b_x) = \frac{d-2}{d-3}\left(\frac{1}{d-2}g_T^{\alpha\alpha'} + \frac{b_T^\alpha b_T^{\alpha'}}{\vec{b}_T^2}\right)B_{\alpha\alpha'}(x, b_x)$$
$$= \mathcal{O}(\alpha_s),$$

where

$$\mathcal{B}^{\alpha'\alpha}(x, b_x) \equiv 2x\bar{n}\cdot P\int\frac{dt}{2\pi}e^{-i\xi t\bar{n}\cdot p}\langle P|\mathcal{B}_{n\perp}^{a\alpha'}(t\bar{n}+b_x)\mathcal{B}_{n\perp}^{a\alpha}(0)|P\rangle$$

with

$$\mathcal{B}_n^\alpha = \frac{1}{\bar{n}\cdot\mathcal{P}}W_n^\dagger i\bar{n}_\nu F^{\nu\mu}W_n$$

They contribute to Higgs production starting only at NNLO!

Gutierrez-Reyes, Leal-Gomez, Scimemi and Vladimirov, JHEP **11**, 121 (2019) [arXiv:1907.03780 [hep-ph]].

Track-based measurements

In experiments:

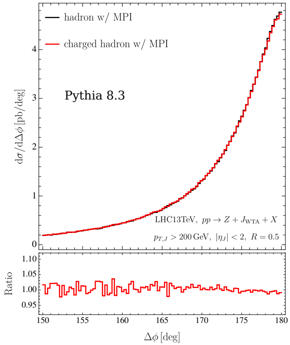
- Limitation of (calorimeter) jet measurements:

$$\text{granularity} \sim 0.1 \text{ rad} \approx 6^\circ$$

- LHC trackers have superior angular resolution

In theory, for track-based jets using WTA

- Only jet functions need to be modified!
- Naturally robust to pile-up

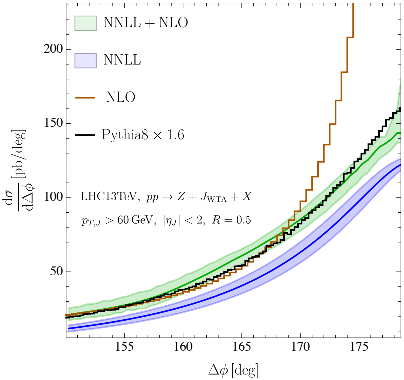


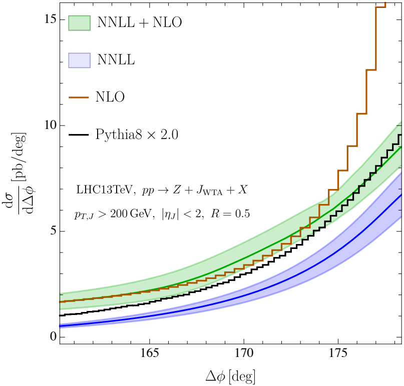
Pythia simulations: using tracks has a minimal effect on $\Delta\phi$ distribution!

Track-based jets: a means to access the resummation region!

Theoretical predictions

At NNLL + NL0 accuracy

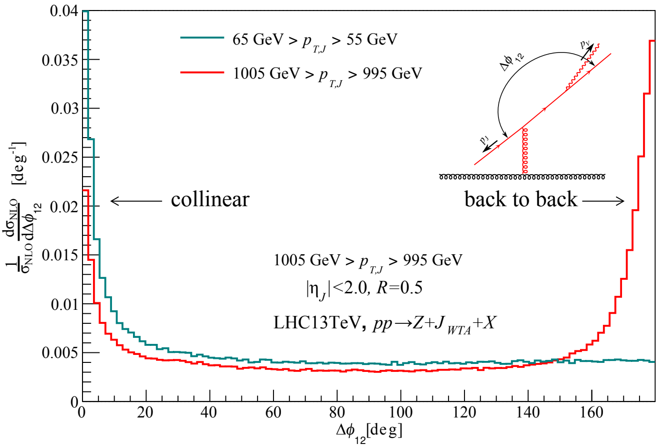




Large nonsingular corrections are not accounted for in Pythia simulations!

Large nonsingular corrections even at small $\delta\phi$?

Matching: emission of boson off dijets



- For $p_{T,J} \gg m_V$: Large contribution for $\delta\phi \gtrsim m_V/p_{T,J}$
- For $p_{T,J} \ll m_V$: finite corrections independent of $\delta\phi$

Can be removed by Z isolation!

Summary and Perspective

In summary:

1. The WTA axis has the following advantages
   - Amenable to NNLL, or even N^3LL resummation in $\delta\phi$
   - Insensitive to hadronization and the underlying event
   - Facilitates track-based jet definitions
2. Potentially large corrections from boson emission of dijets from matching

   They can be removed by introducing boson isolation

In the future:

1. Cold nuclear effects in high-energy nuclear collisions

   Nestor Armesto Perez, Florian Cougoulic and BW, to appear soon.

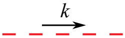
2. Resummation and QGP effects in high-energy nuclear collisions

   Chien, Rahn, Shao, Waalewijn and BW, work in progress.

Backup slides

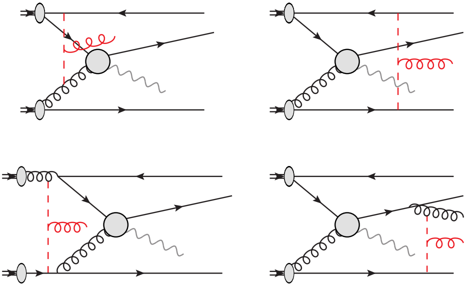
Factorization breaking?

Glauber exchange: instantaneous interaction



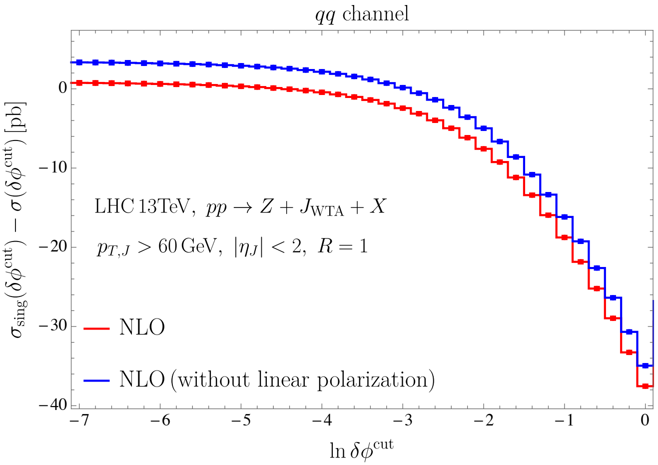
$$\propto \frac{1}{k_\perp^2}$$

Glauber topologies:



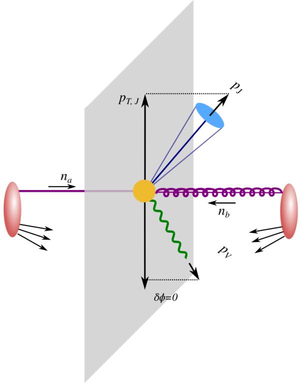
Don't spoil factorization up to and including $O(\alpha_s^3)$

Confirmation of linearly-polarized contribution

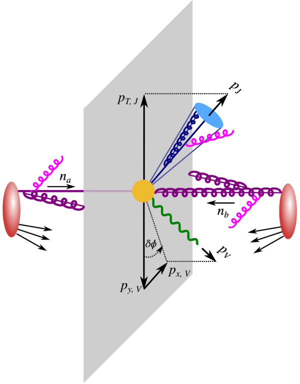


Factorization formula

An all-order resummation formula using the WTA axis:



× collinear & soft radiation =

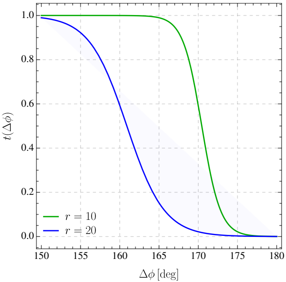


$$\Rightarrow \ln \Sigma(\delta\phi) \equiv \ln\left(\int_0^{\delta\phi} \frac{d\sigma}{d\delta\phi}\right) \sim \underbrace{L(\alpha_s L)}_{LL} + \underbrace{(\alpha_s L)}_{NLL} + \cdots + \underbrace{\alpha_s^{i-1}(\alpha_s L)}_{N^i LL}$$

with $L = \ln \delta\phi$ as $\delta\phi \to 0$.

Matching to the fixed-order cross section

The $O(\alpha_s)$ formula for a wide range of $\Delta\phi$:



$$\boxed{\mathrm{d}\sigma(\mathrm{NLO} + \mathrm{NNLL}) = [1 - t(\Delta\phi)] \times (\mathrm{NNLL} + \text{nonsingular part of NLO}) + t(\Delta\phi) \times (\mathrm{NLO})}$$

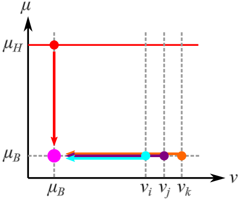
where $t(\Delta\phi) = \frac{1}{2} - \frac{1}{2}\tanh\left[4 - \frac{240(\pi - \Delta\phi)}{r}\right]$ with $r = 20(10)$ for $p_{T,J} > 60(200)$ GeV.

Resummation

All-order resummation formula by RG running

$$\frac{d\sigma_{\text{resum}}}{dq_x\, dp_{T,V} dy_V} = \sum_{ijk} \int_0^\infty \frac{db_x}{\pi} \cos(b_x q_x) \prod_{a=ijk} \left(\frac{\nu_S}{\nu_a}\right)^{\Gamma_\nu^{B_a}(\mu_B)} \exp\left(\int_{\mu_H}^{\mu_B} \frac{d\mu}{\mu} \Gamma_\mu^{\mathcal{H}_{ij\to Vk}}(\alpha_s)\right)$$
$$\times \mathcal{H}_{ij\to kV}(p_{T,V}, y_V - \eta_J, \mu_H) \mathcal{B}_i(x_1, b_x, \mu_B, \nu_i) \mathcal{B}_j(x_2, b_x, \mu_B, \nu_j)$$
$$\times \mathcal{J}_k(b_x, \mu_B, \nu_k) S_{ijk}(b_x, \mu_B, \nu_S)$$

with $\Gamma_\mu^{\mathcal{H}_{ij\to Vk}}$ anomalous dimension of the hard function.



Natural momentum scales:

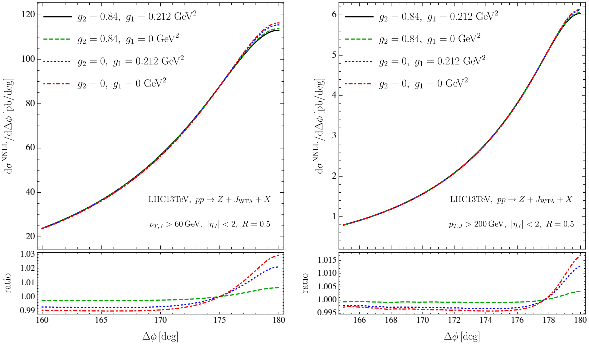
$$\mu_H = \sqrt{m_V^2 + p_{T,V}^2}\,, \quad \nu_a = \bar{n}_a \cdot p_a\,,$$
$$\mu_B = \nu_S = 2e^{-\gamma_E}\sqrt{1 + b_x^2/b_{\text{max}}^2}/|b_x|$$

with $b_{\text{max}} = 1.5$ GeV^{-1}.

Uncertainties are estimated by varying μ_H, μ_B and ν_S.

Does it make sense to go to small $\delta\phi$?

From non-perturbative (NP) corrections:



(Note: standard jet functions are used here!)

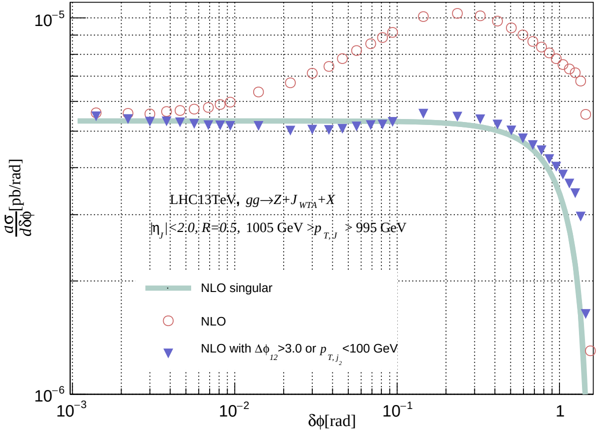
NP corrections is included as a multiplicative function $e^{-S_{\mathrm{NP}}(b)}$

$$e^{-S_{\mathrm{NP}}(b_x)} = e^{-g_1 b_x^2} \prod_{a=ijk} \exp\left(-\frac{C_a}{C_F}\frac{g_2}{2} \ln\frac{|b_x|}{b_*} \ln\frac{\omega_a}{Q_0}\right) \qquad \text{with } Q_0^2 = 2.4\ \mathrm{GeV}^2.$$

Uncertainties due to NP corrections are not large!

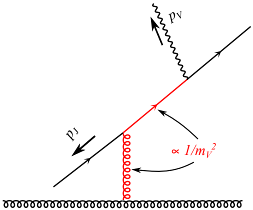
Z isolation

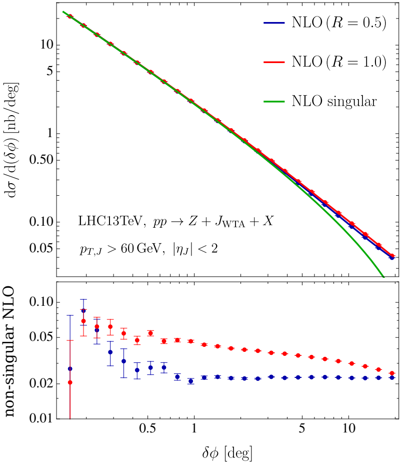
An illustration using the gg channel



Matching: emission of boson off dijets

Low $p_{T,J} \ll m_V$:





$\Rightarrow$ $\delta\phi$-independent terms in nonsingular part of the NLO cross section.

Choice of transition point