Precision boson-jet azimuthal decorrelation at hadron colliders

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DESY Parton Branching discussion meeting

arXiv: 2205.05104 with Y. T. Chien, R. Rahn, D. Y. Shao, W. J. Waalewijn

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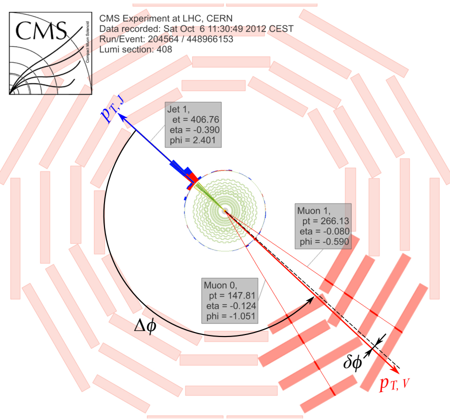
Motivations

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

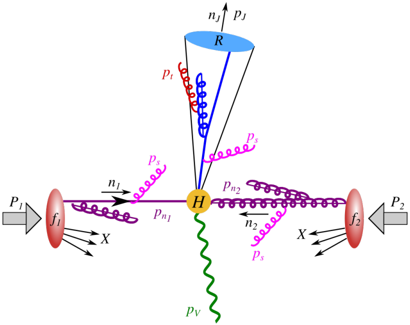
   Is it broken by Glauber modes?

Main topics: resummation using SCET and (very briefly) factorization breaking

Resummation using standard jet axis

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

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!

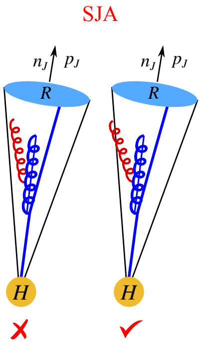
$$\frac{d\sigma}{d^2p_T^J d^2p_T^V d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2x_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{x}_T} \mathcal{S}_{ij\to Vk}(\vec{x}_T,\epsilon)\mathcal{B}_{i/N_1}(\xi_1,x_T,\epsilon)\mathcal{B}_{j/N_2}(\xi_2,x_T,\epsilon)$$

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

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

Non-global logarithm and SJA

An non-global observable:



For $\delta\phi > 0$

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

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

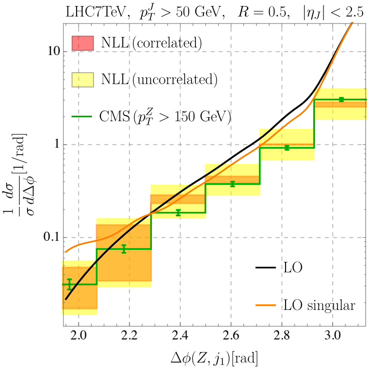
starting as NLL terms with $\alpha_s L \sim 1$.

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

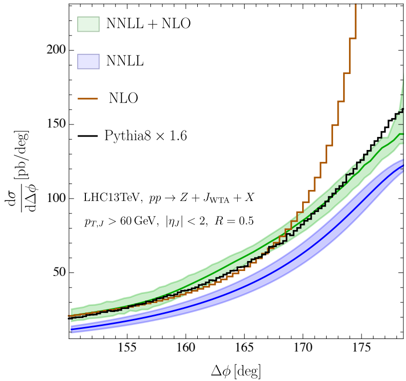


Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

precision predictions $\Leftrightarrow$ going beyond NLL

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

NNLL resummation in $\delta\phi$



The "minor" change: SJA → Winner-Take-All (WTA) axis

N^3LL resummation is also possible!

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, [arXiv:2205.05104 [hep-ph]].

Resummation using the WTA axis

What is WTA?

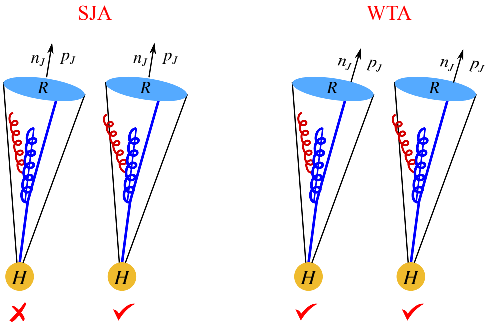
WTA-p_T scheme:

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

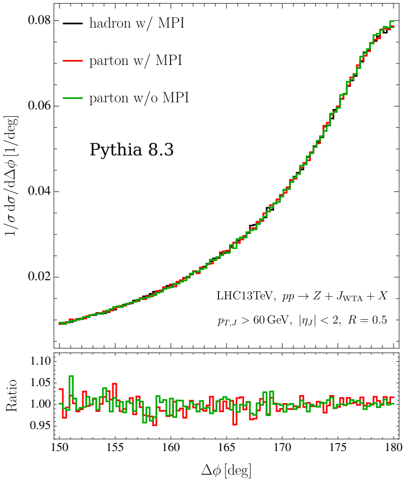
Salam, "E_t^∞ Scheme." unpublished; Bertolini, Chan and Thaler, JHEP **04**, 013 (2014) [arXiv:1310.7584 [hep-ph]].

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

The WTA axis eliminates NGLs: insensitive to soft radiation



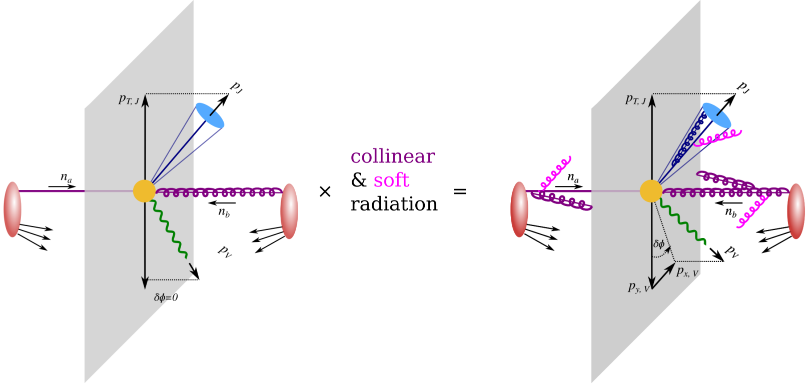
Another advantage of WTA



Very robust to hadronization and the underlying event

Factorization formula

An all-order resummation formula using the WTA axis:

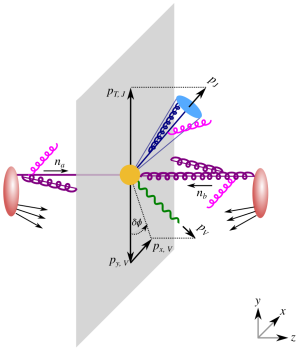


$$\Rightarrow \ln \Sigma(\delta\phi) \equiv \ln \left(\int_0^{\delta\phi} \frac{d\sigma}{d\delta\phi} \right) \sim \underbrace{L(\alpha_s L)}_{LL} + \underbrace{(\alpha_s L)}_{NLL} + \cdots + \underbrace{\alpha_s^{i-1}(\alpha_s L)}_{N^i LL}$$

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

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

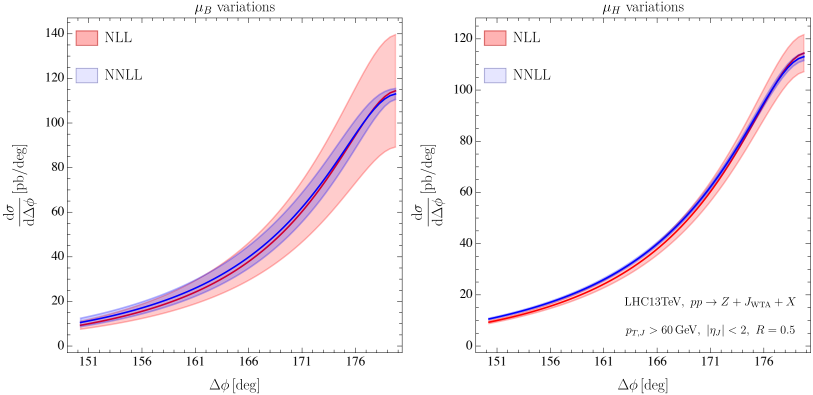
Jet function: $\mathcal{J}_k$ does NOT contain NGLs!

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

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, [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

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

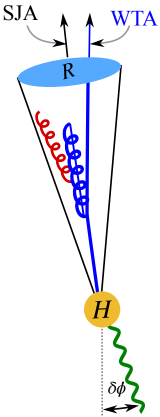
with

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

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]].

TMD in jets



TMD jet function: offset of the WTA axis w.r.t SJA

Gutierrez-Reyes, Scimemi, Waalewijn and Zoppi, Phys. Rev. Lett. **121**, 162001 (2018).

Linearly-polarized TMD jet function starts to contribute

$$\mathcal{J}_g^T = \frac{-g_\perp^{\mu\nu}}{d-2}\mathcal{J}_{g\,\mu\nu} = 1 + \mathcal{O}(\alpha_s),$$

$$\mathcal{J}_g^L = \frac{1}{(d-2)(d-3)}\left[g_\perp^{\alpha'_J\alpha_J} + (d-2)\frac{b_\perp^{\alpha'_J} b_\perp^{\alpha_J}}{\vec{b}_\perp^2}\right]\mathcal{J}_{g\,\mu\nu}$$

$$= \frac{\alpha_s}{4\pi}\left(-\frac{1}{3}C_A + \frac{2}{3}T_F n_f\right) + O(\alpha_s^2)$$

with

$$\mathcal{J}_g^{\mu\nu} = \frac{2(2\pi)^{d-1}}{N_c^2-1}\bar{n}\cdot p_J \langle 0|\mathcal{B}_{n\perp}^{a\mu}(0)e^{\delta_x b_x}\delta(\bar{n}\cdot p_J - \bar{n}\cdot p_c)\delta^{(d-2)}(\vec{p}_{\perp,c})\mathcal{B}_{n\perp}^{a\nu}(0)|0\rangle$$

and $\delta_x \equiv p_{x,c} - p_{x,J}$.

TMD in jets contributes to $\delta\phi$ using WTA!

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, [arXiv:2205.05104 [hep-ph]].

Track-based measurements

In experiments:

- Limitation of (calorimeter) jet measurements:

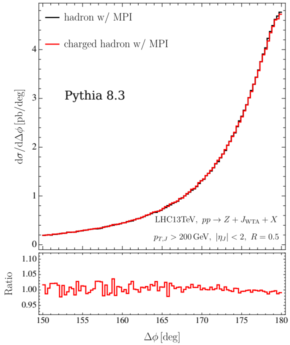
$$\text{granularity} \sim 0.1 \text{ rad} \approx 6^\circ$$

- 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

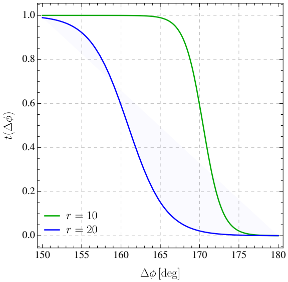


Pythia simulations: using tracks has a minimal effect on $\Delta\phi$ distribution!

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

Matching to the fixed-order cross section

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

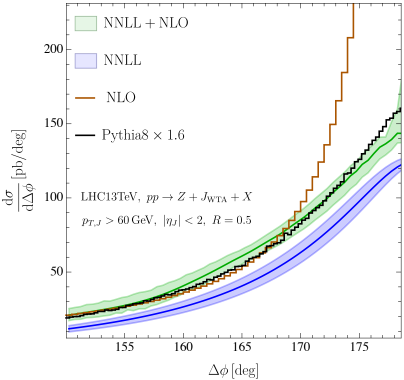


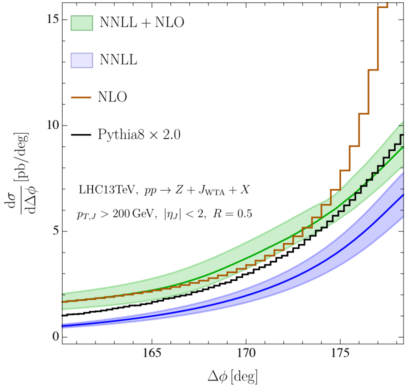
$$\boxed{\mathrm{d}\sigma(\mathrm{NLO}+\mathrm{NNLL}) = [1 - t(\Delta\phi)] \times (\mathrm{NNLL} + \text{nonsingular part of NLO}) + t(\Delta\phi) \times (\mathrm{NLO})}$$

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.

Theoretical predictions

At NNLL + NL0 accuracy

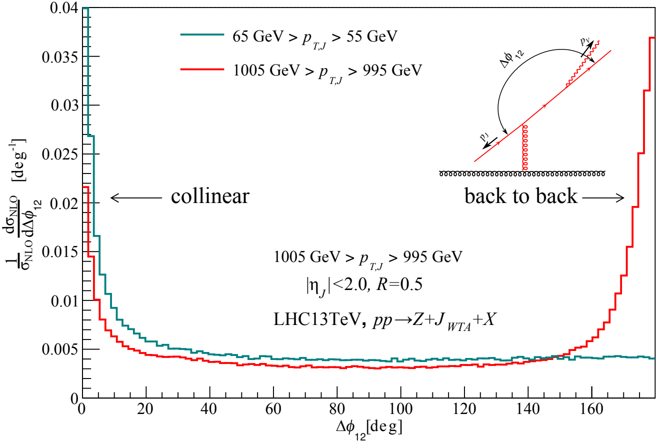




Large nonsingular corrections are not accounted for in Pythia simulations!

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

Matching: emission of boson off dijets

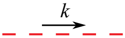


- For $p_{T,J} \gg m_V$: Large contribution for $\delta\phi \gtrsim m_V/p_{T,J}$
- For $p_{T,J} \ll m_V$: finite corrections independent of $\delta\phi$

Can be removed by Z isolation!

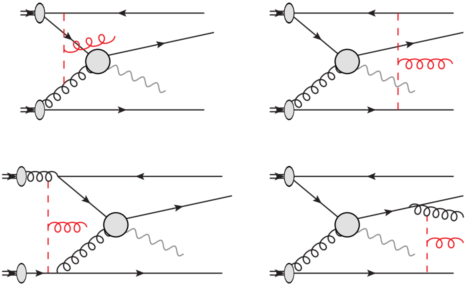
Factorization breaking?

Glauber exchange: instantaneous interaction



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

Glauber topologies:



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

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
   - Reveal TMD in jets using azimuthal decorrelation
2. Potentially large corrections from boson emission of dijets from matching

   They can be removed by introducing boson isolation
3. All these discussions can be generalized to p_T^n recombination scheme:

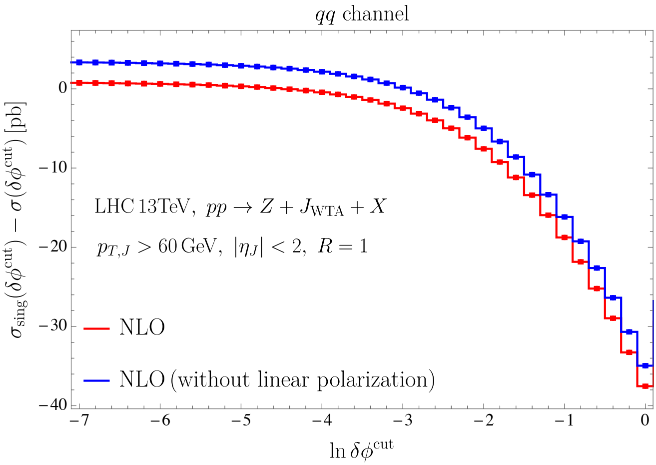
$$
\begin{aligned}
p_{T,r} &= p_{T,i} + p_{T,j}, \\
\phi_r &= (p_{T,i}^n \phi_i + p_{T,j}^n \phi_j)/(p_{T,i}^n + p_{T,j}^n), \\
y_r &= (p_{T,i}^n y_i + p_{T,j}^n y_j)/(p_{T,i}^n + p_{T,j}^n)
\end{aligned}
$$

with $n > 1$. WTA corresponds to the limit $n \to \infty$.

4. No factorization breaking up to and including $O(\alpha_s^3)$

Backup slides

Confirmation of linearly-polarized contribution

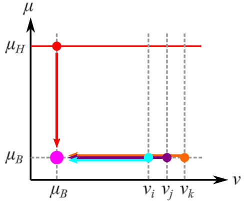


Resummation

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:

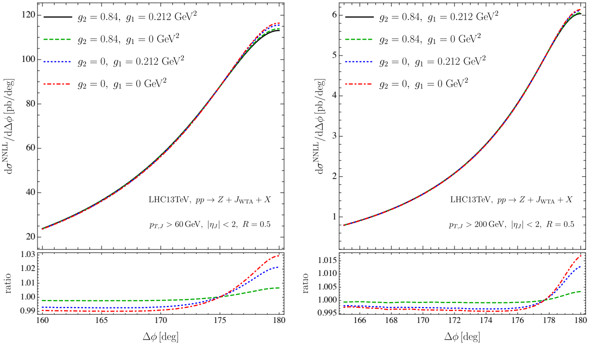
$$\mu_H = \sqrt{m_V^2 + p_{T,V}^2}\,, \quad \nu_a = \bar{n}_a \cdot p_a\,,$$
$$\mu_B = \nu_S = 2e^{-\gamma_E}\sqrt{1 + b_x^2/b_{\text{max}}^2}/|b_x|$$

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

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!)

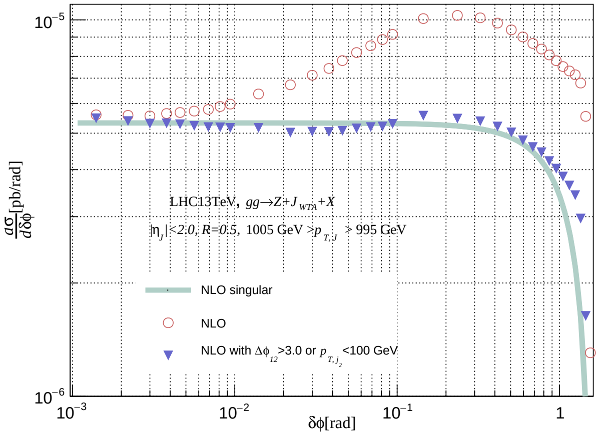
NP corrections is included as a multiplicative function $e^{-S_{\mathrm{NP}}(b)}$

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

Uncertainties due to NP corrections are not large!

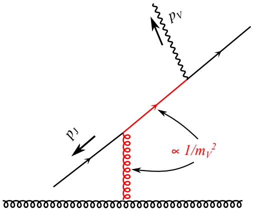
Z isolation

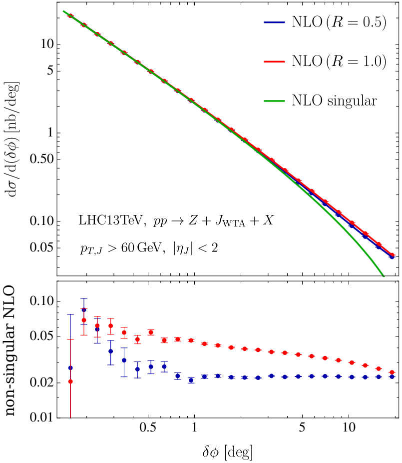
An illustration using the gg channel



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