

Precision boson-jet azimuthal decorrelation at hadron colliders

Bin Wu

IGFAE, Universidade De Santiago De Compostela
April 10, 2024

DIS 2024, Grenoble, FRANCE

JHEP 02 (2023), 256 with Y. T. Chien, R. Rahn, D. Y. Shao, W. J. Waalewijn



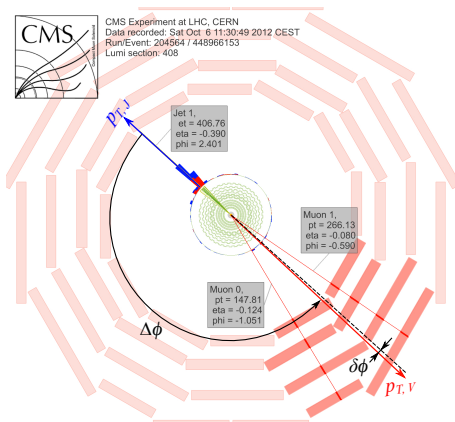
Motivations

Boson-jet azimuthal decorrelation

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



CMS Experiment at LHC, CERN
Data recorded: Sat Oct 6 11:30:49 2012 CEST
Run/Event: 204564 / 448966153
Lumi section: 408



Precise predictions rely on

1. Fixed-order calculations

NLO, NNLO, ...

2. Resummation of $\ln \delta\phi$

▶ Parton branching method

▶ Pythia, Herwig, ...

▶ TMD factorization

▶ SCET

3. Validity of factorization

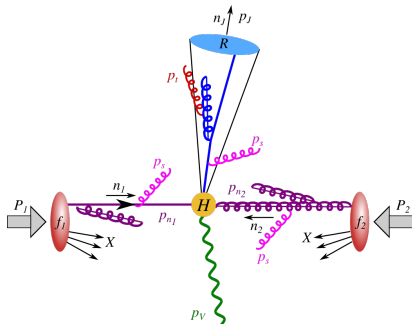
Is it broken by Glauber modes?

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: $\mathcal{H}_{ij \rightarrow \nu k}$

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

Soft function: $\mathcal{S}_{ij \rightarrow \nu k}$

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

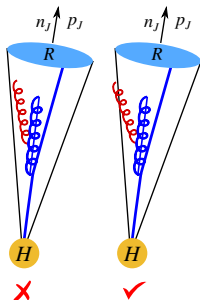
$$\frac{d\sigma}{d^2 p_T^J d^2 p_T^V d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2 x_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{x}_T} \mathcal{S}_{ij \rightarrow \nu k}(\vec{x}_T, \epsilon) \mathcal{B}_{i/N_1}(\xi_1, x_T, \epsilon) \mathcal{B}_{j/N_2}(\xi_2, x_T, \epsilon) \\ \times \mathcal{H}_{ij \rightarrow \nu k}(\hat{s}, \hat{t}, m_V, \epsilon) \mathcal{J}^k(p_J^2, \vec{x}_T, \epsilon)$$

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

SJA



For $\delta\phi > 0$

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

$$\Rightarrow \text{NGL} \propto \alpha_S C_A \alpha_S C_k L^2$$

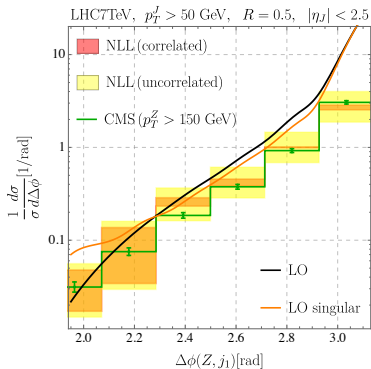
starting as NLL terms with $\alpha_S L \sim 1$.

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

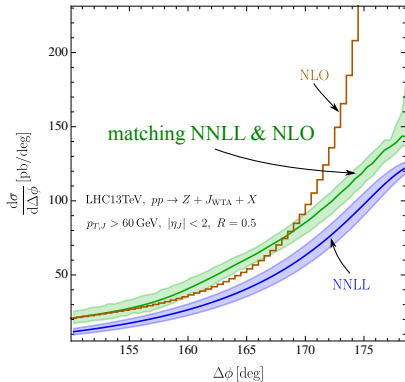


Y. T. Chien, D. Y. Shao and BW, JHEP **11**, 025 (2019) [arXiv:1905.01335 [hep-ph]].

precision predictions \Leftrightarrow going beyond NLL

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

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?

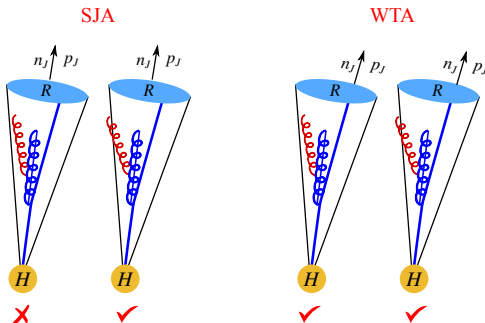
WTA- p_T scheme:

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

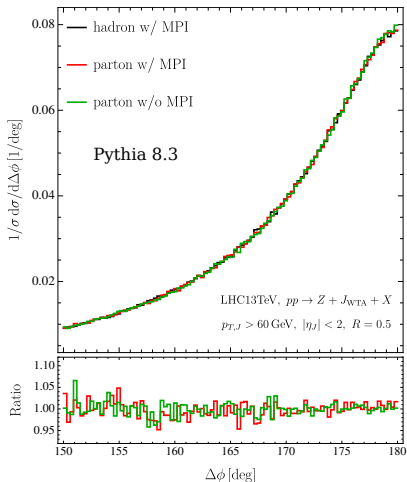
Salam, " E_t^∞ Scheme." unpublished; Bertolini, Chan and Thaler, JHEP **04**, 013 (2014) [arXiv:1310.7584 [hep-ph]].

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

The WTA axis eliminates NGLs: insensitive to soft radiation



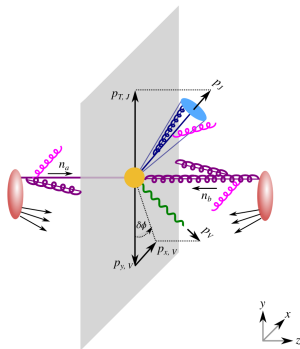
Another advantage of WTA



Very robust to hadronization and the underlying event

Factorization formula

An all-order resummation formula using the WTA axis:



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

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

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

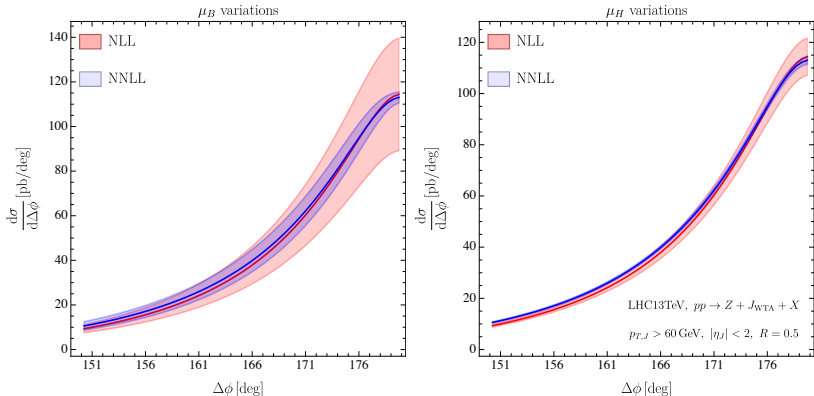
Jet function: \mathcal{J}_k does NOT contain NGLs!

$$\frac{d\sigma}{dq_x dp_{T,V} dy_V d\eta_J} = \int \frac{db_x}{2\pi} e^{b_x q_x} \sum_{ijk} \mathcal{H}_{ij \rightarrow vk}(p_{T,V}, y_V - \eta_J) \mathcal{B}_i(x_a, b_x) \mathcal{B}_j(x_b, b_x) \mathcal{J}_k(b_x) S_{ijk}(b_x, \eta_J)$$

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:

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

where

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

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:

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

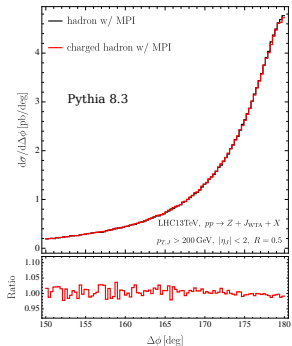
- ▶ LHC trackers have superior angular resolution

In theory, for track-based jets using WTA

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

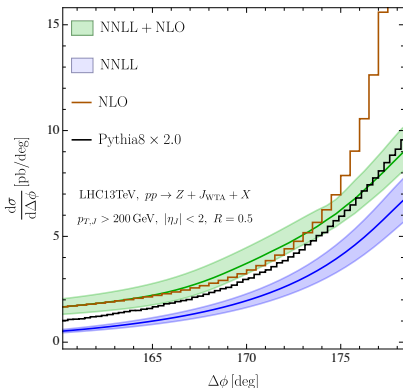
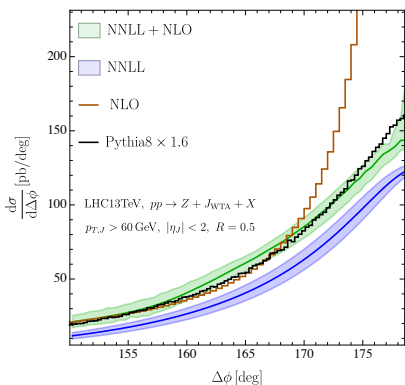
Pythia simulations: using tracks has a minimal effect on $\Delta\phi$ distribution!

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



Theoretical predictions

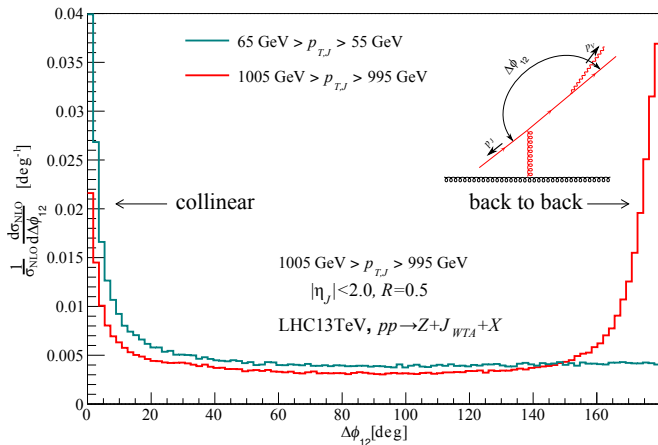
At NNLL + NLO accuracy



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 N³LL 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
Florian Cougoulic's talk at 5:20pm today.
2. Resummation and QGP effects in high-energy nuclear collisions

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

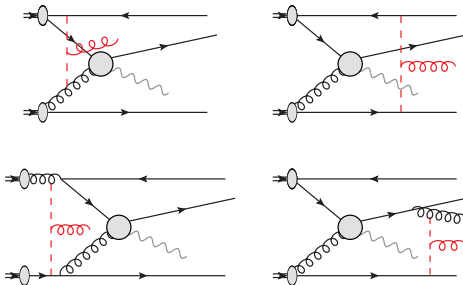
Backup slides

Factorization breaking?

Glauber exchange: instantaneous interaction

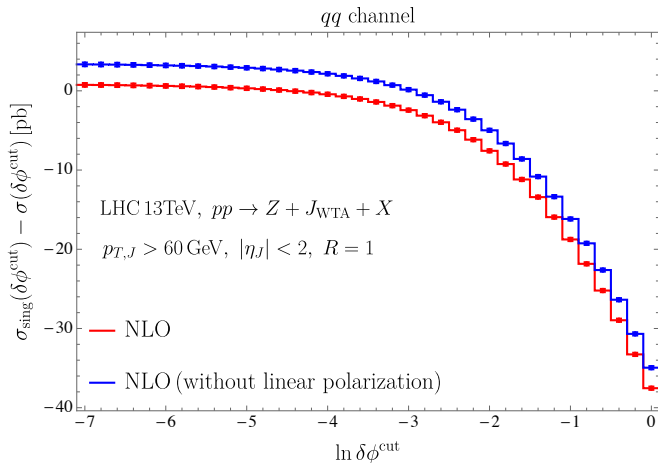
$$\text{---} \xrightarrow{k} \text{---} \propto \frac{1}{k_{\perp}^2}$$

Glauber topologies:



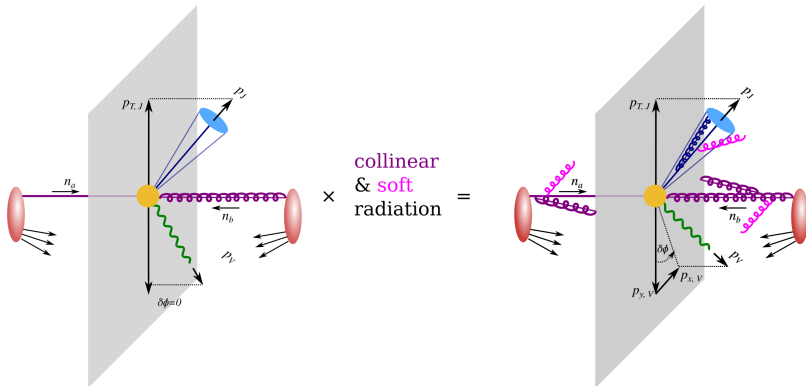
Don't spoil factorization up to and including $O(\alpha_s^3)$

Confirmation of linearly-polarized contribution



Factorization formula

An all-order resummation formula using the WTA axis:

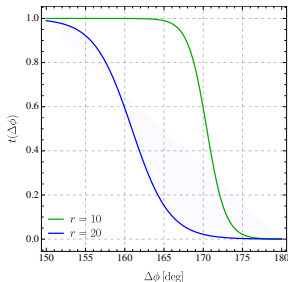


$$\Rightarrow \ln \Sigma(\delta\phi) \equiv \ln \left(\int_0^{\delta\phi} \frac{d\sigma}{d\delta\phi} \right) \sim \underbrace{L(\alpha_s L)}_{LL} + \underbrace{(\alpha_s L)}_{NLL} + \dots + \underbrace{\alpha_s^{i-1}(\alpha_s L)}_{N^i LL}$$

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

Matching to the fixed-order cross section

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



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

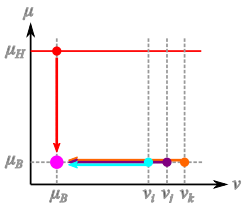
where $t(\Delta\phi) = \frac{1}{2} - \frac{1}{2} \tanh\left[4 - \frac{240(\pi - \Delta\phi)}{r}\right]$ with $r = 20(10)$ for $p_{T,J} > 60(200)$ GeV.

Resummation

All-order resummation formula by RG running

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

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



Natural momentum scales:

$$\mu_H = \sqrt{m_V^2 + p_{T,V}^2}, \quad \nu_a = \bar{n}_a \cdot p_a,$$

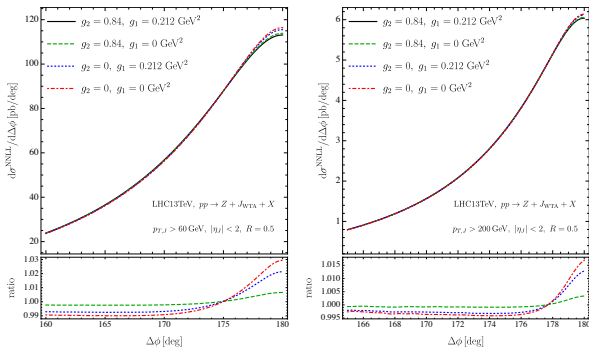
$$\mu_B = \nu_S = 2e^{-\gamma_E} \sqrt{1 + b_x^2/b_{\text{max}}^2} |b_x|$$

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!)

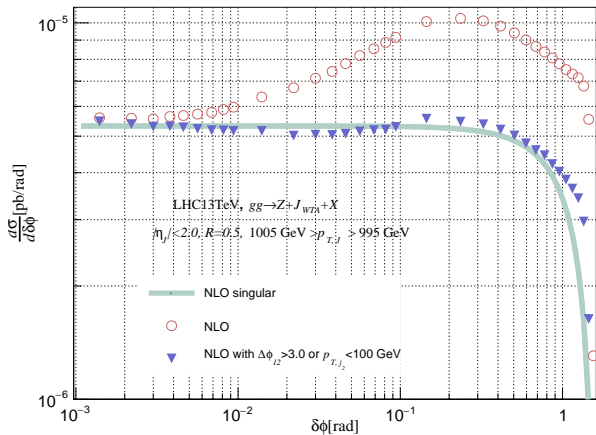
NP corrections is included as a multiplicative function $e^{-S_{\text{NP}}(b)}$

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

Uncertainties due to NP corrections are not large!

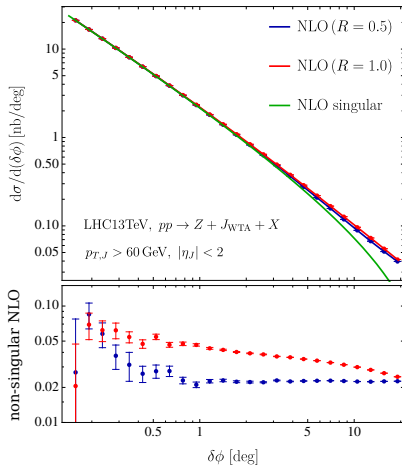
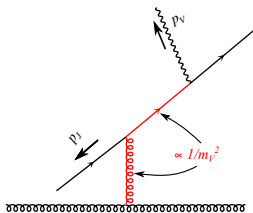
Z isolation

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

