Resummation for Jet Veto and Cone Jet Cross Sections

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DESY theory: Fellow's meeting

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T. Becher, M. Neubert and LR, JHEP 1310 (2013) 125
T. Becher, R. Frederix, M. Neubert and LR, Eur.Phys.J. C75 (2015) 4, 154
T. Becher, M. Neubert, LR and D. Y. Shao arXiv:1508.06645

Resummation for Jet Veto Cross Sections

Jet Veto Cross Sections

Production cross section of one or several **weak bosons** at the LHC

$$Z,\, W^+,\, W^-,\;\, H$$

to test the electroweak sector of SM.

Challenges:

- We collide only light, strongly interacting particle
  - Most common reaction will be just a pure QCD interaction with QCD final states.
  - Huge backgrounds

Impose a **jet veto** (only allow for jets with low transverse momentum)

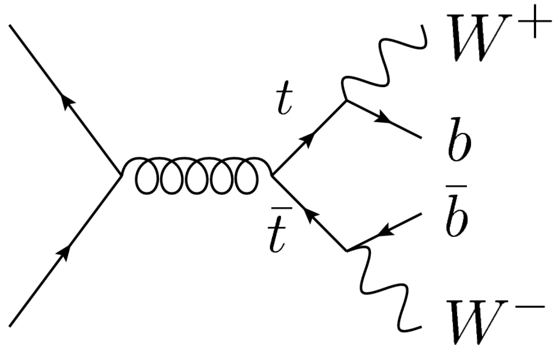
$$p_T^{\mathrm{Jet}} < p_T^{\mathrm{Veto}} \sim 15 - 30\ \mathrm{GeV}$$

(Analysis is done in jet bins, needs precise prediction of the 0-jet bin.)

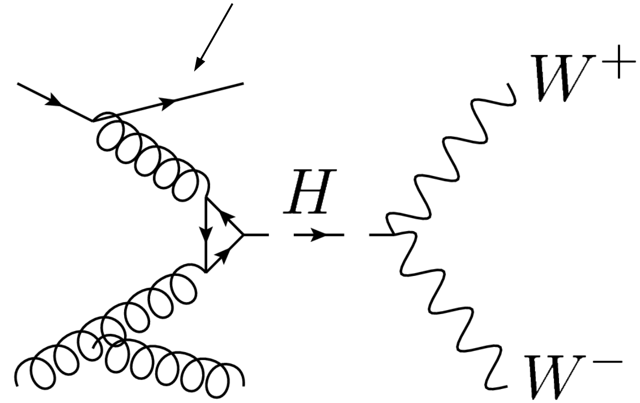
Role of the Jet Veto

Suppression of top-quark background in processes involving *W* bosons

- For example in $H \to W\,W^*$



Initial state radiation



Multiple scales ⇨ **enhancement by large Sudakov logarithms**

$$\alpha_s^n \ln\left(\frac{p_T^{\text{veto}}}{Q}\right)^k \qquad k \le 2n$$

Q Invariant mass of the boson system

⇨ **Resummation**

Resummation and SCET

Resummation in general can be achieved using Soft-Collinear Effective Theory (SCET) or QCD based resummation techniques.

SCET framework:

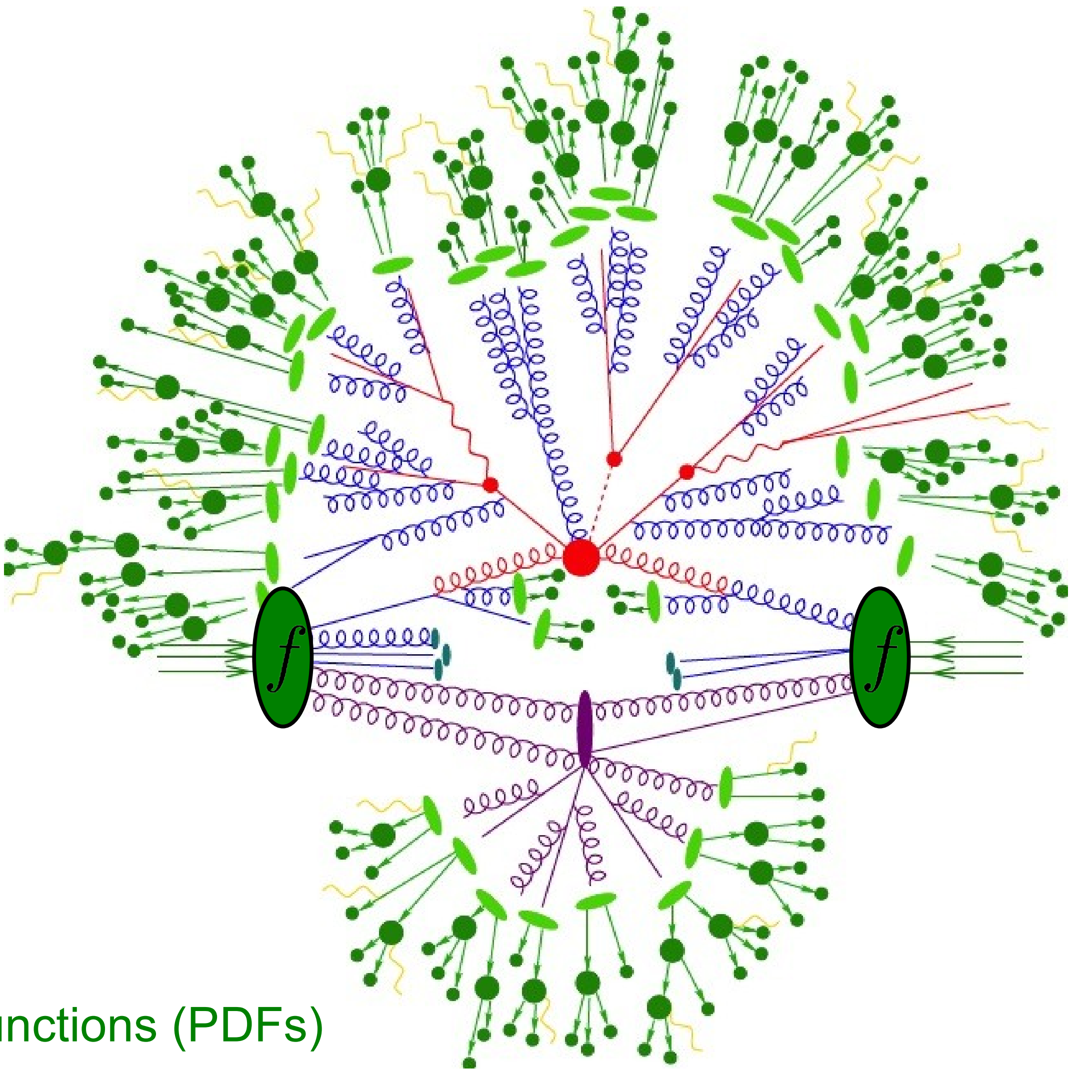
- Low-energy degrees of freedom: **Soft** and **Collinear** fields
- Off-shell modes are integrated out. Hard-scattering encoded in the **Wilson coefficents** of the operators.

- Advantages:
  - Operator definition (manifest gauge invariance).
  - Systematic scale separation. Resummation by **renormalization group (RG) evolution.**
  - **Power corrections** can be included.

Collider Physics

Typical multi-scale problem!

- Hard collision
- Proton structure (non-perturbative long distance physics)
- Collinear & soft radiation



sciencenode.org/feature/sherpa-and-open-science-grid-predicting-emergence-jets.php

All LHC calculation rely on the factorization

$$d\sigma = d\hat{\sigma} \otimes f\, f$$

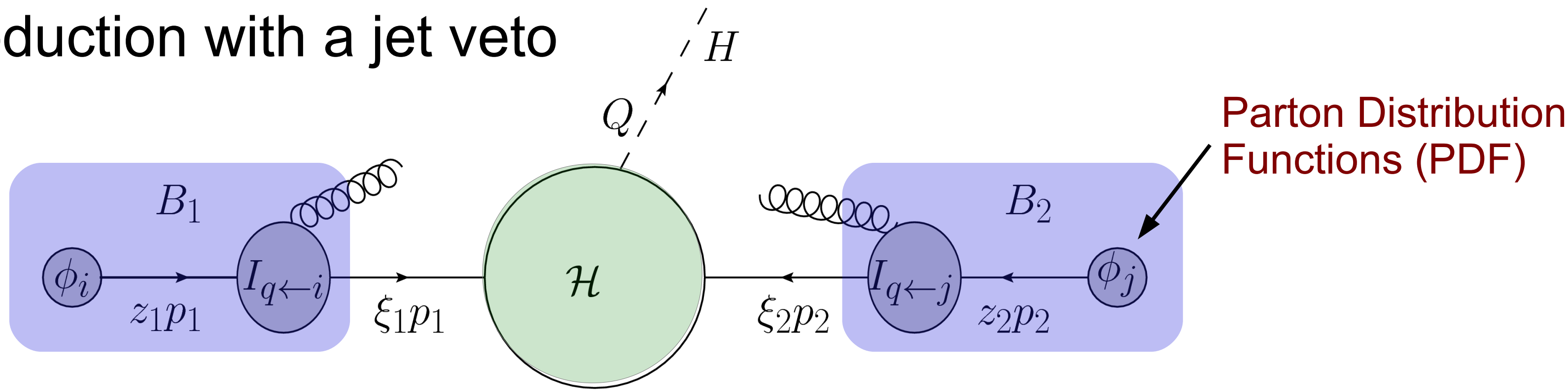
partonic cross section

parton distribution functions (PDFs)

SCET used to further factorize the physics at different scales in the partonic cross section.

All-Order Factorization Theorem from SCET

For Higgs production with a jet veto



Born CS | Hard function | Collinear Anomaly

$$\frac{d\sigma(p_T^{\text{veto}})}{dy} = \sigma_0(\mu) C_t^2(m_t^2,\mu)|C_S(-m_H^2,\mu)|^2 \left(\frac{m_H}{p_T^{\text{veto}}}\right)^{-2F_{gg}(p_T^{\text{veto}},\mu)}$$

$$\times \sum_{i,j} I_{g\leftarrow i}(p_T^{\text{veto}},\mu)\otimes\phi_{i/P}(\mu)\; I_{g\leftarrow j}(p_T^{\text{veto}},\mu)\otimes\phi_{j/P}(\mu)$$

perturbative | PDF

Beam-jet functions $B_1 \cdot B_2$

Sources of Log(m_H /p_T): Anomaly and RG evolution of the hard function.

Valid up to **first order** power corrections p_T^{veto}/Q and nonperturbative effects Λ_{QCD}/p_T^{veto}

Resummation of Large Logarithms

Factorization theorem together with **RG evolution** now allow for resummed predictions for the cross section with a Jet Veto.

$$\begin{aligned}\sigma \sim \sigma_0 \big(1 + \alpha_s &(L^2 + L + c1) && \text{NLO}\\ +\alpha_s^2 &(L^4 + L^3 + L^2 + L + c2) && \text{NNLO}\\ +\alpha_s^3 &(\vdots + \vdots + \vdots + \vdots + \dots) && \text{NNNLO}\end{aligned}$$

LL NLL NNLL

$$L = \ln\left(\frac{p_T^{\text{veto}}}{Q}\right)$$

Resummed Order	Γ_{cusp}	γ	$I_{g\leftarrow i}$	F_{gg}	Matching to:
LL	1-loop	tree	-	tree	-
NLL	2-loop	1-loop	tree	1-loop	LO
NNLL	3-loop	2-loop	1-loop	2-loop	NLO
N^3LL	4-loop	3-loop	2-loop	3-loop	NNLO

Parton shower → LL

Padé approximation → N^3LL 4-loop

Matching to fixed order results includes power suppressed terms (p_T^{veto}/m_H)

Computed 2-loop anomaly coefficient in SCET and extracted 2 loop beam functions numerically:

N^3LL_p+NNLO for Higgs production cross section with a jet veto.

Automated Resummation for Jet Veto Cross Sections

All-order Factorization Theorem from SCET

Similar analysis can be done for any weak boson production with a jet veto!

Born-level CS | Hard function | Evolution factor

$$\frac{d^3\sigma(p_T^{\rm veto})}{dy\, dQ^2\, d\hat{t}} = \sigma_0(Q^2,\hat{t},\mu)\, \mathcal{H}_{q\bar{q}}(Q^2,\hat{t},\mu_h) U_q(Q^2,\mu_h,\mu)$$

$$\times \left(\frac{Q}{p_T^{\rm veto}}\right)^{-2F_q(p_T^{\rm veto},\mu)} B_q(\xi_1,\mu,p_T^{\rm veto})\, B_{\bar{q}}(\xi_2,\mu,p_T^{\rm veto})$$

Collinear Anomaly | Beam-jet functions

Hard function is the only process dependent ingredient!
For NNLL resummation, one loop hard function needed → NLO computations have been automated over the past years.

⇒ Automated jet veto resummation (NNLL+NLO) in SCET.
Used the event generator MadGraph5_aMC@NLO.

Advantages of an Automated Resummation

- Much more efficient and less error prone.

- Straightforward to **include decays** and **cuts** on the decay products.
  - Complicated in analytic computations.

- Code publicly available (recent MadGraph5_aMC@NLO release).

Cone Jet Cross Sections

Effective Theory for Jet Processes

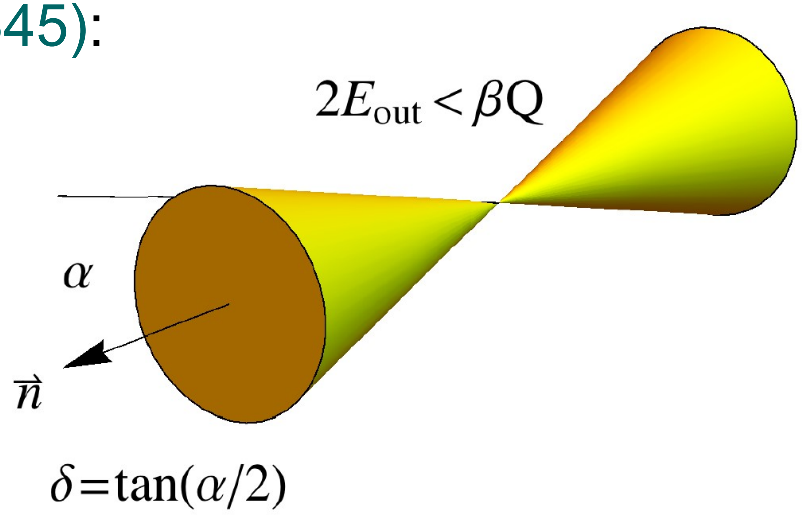
- SCET successfully applied to many collider processes.
- Jet processes: Exclusive observables that involve some kind of jet definition:
  - Cone algorithms
  - Sequential recombination algorithms
- SCET (and also traditional QCD resummation techniques) has not been very successful for such observables:
  - Problem of so-called **non-global logarithms (NGLs)**.
- Usual factorization into hard, jet and soft functions

$$\sigma = \mathcal{H}_2 \cdot \mathcal{J} \cdot \overline{\mathcal{J}} \cdot \mathcal{S}_2$$

  does not achieve complete scale separation.
  - Soft function suffer from large logarithms itself.
- Despite recent progress of various groups, no fully factorized form has been available so far.

Effective Theory for Jet Processes

- In Becher, Neubert, LR, Shao (1508.06645):
  EFT analysis of cone-jet cross sections:
  - $e^+e^- \to 2$ jets
  - Sterman-Weinberg jet definition
  - Find additional mode besides soft and collinear.
    Describes soft small angle radiation.
  - Factorized form (full scale separation).



$$\widetilde{\sigma}(\tau) = \sigma_0\, H(Q)\, \widetilde{S}(Q\tau) \left[\sum_{m=1}^{\infty} \left\langle \mathcal{J}_m(Q\delta) \otimes \widetilde{\mathcal{U}}_m(Q\delta\tau) \right\rangle \right]^2$$

  - Solving the associated (highly non-trivial) RG equations resums all large logs (also NGLs). Framework not limited to leading logs or leading color.