Resummation for Jet Veto and Cone Jet Cross Sections

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DESY Fellow 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

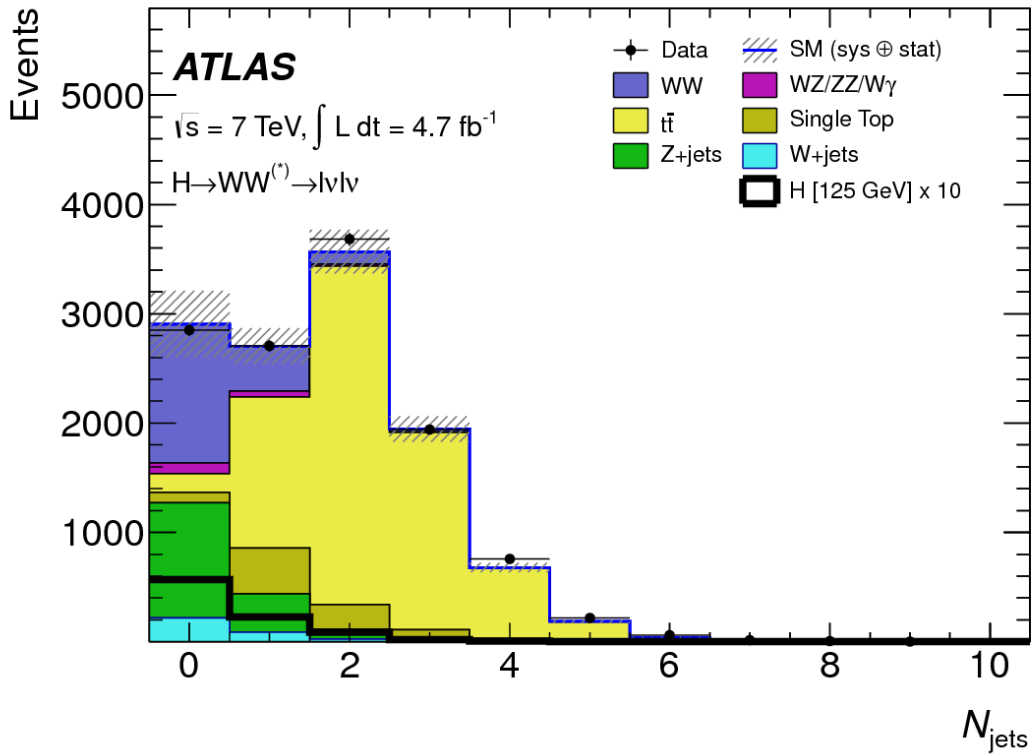
$$Z,\ W^+,\ W^-,\ H$$

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

Reduction of $t\,\bar{t}$ Background by imposing a Jet Veto



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

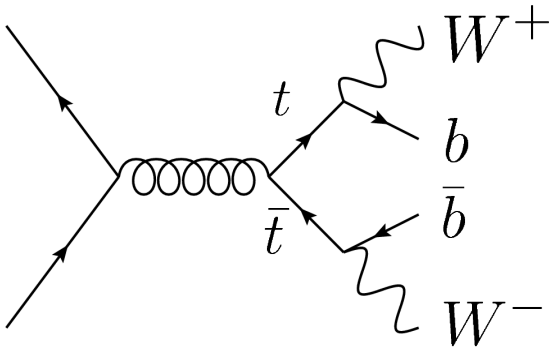
$$p_T^{\mathrm{Jet}} < p_T^{\mathrm{Veto}} \sim 15 - 30\ \mathrm{GeV}$$

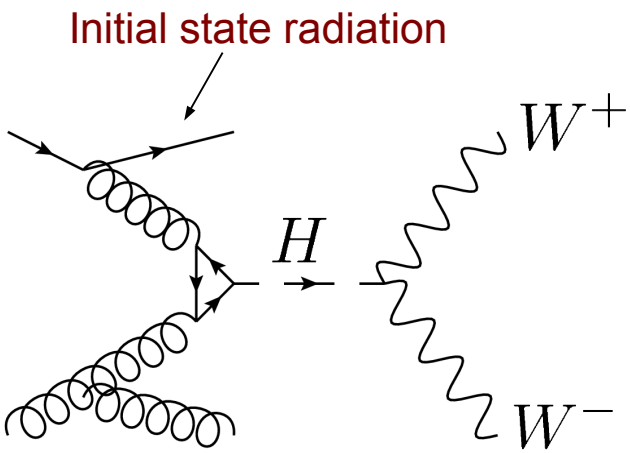
(Analysis is done in jet bins, needs precise prediction of the 0-jet bin.)

Reduction of $t\,\bar{t}$ Background by imposing a Jet Veto

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

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





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

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

Q Invariant mass of the boson system

⇨ **Resummation**

Resummation and SCET

Parton Showers resum only leading-log terms.

Higher accuracy resummation can be achieved using QCD based resummation techniques or Soft-Collinear Effective Theory (SCET).

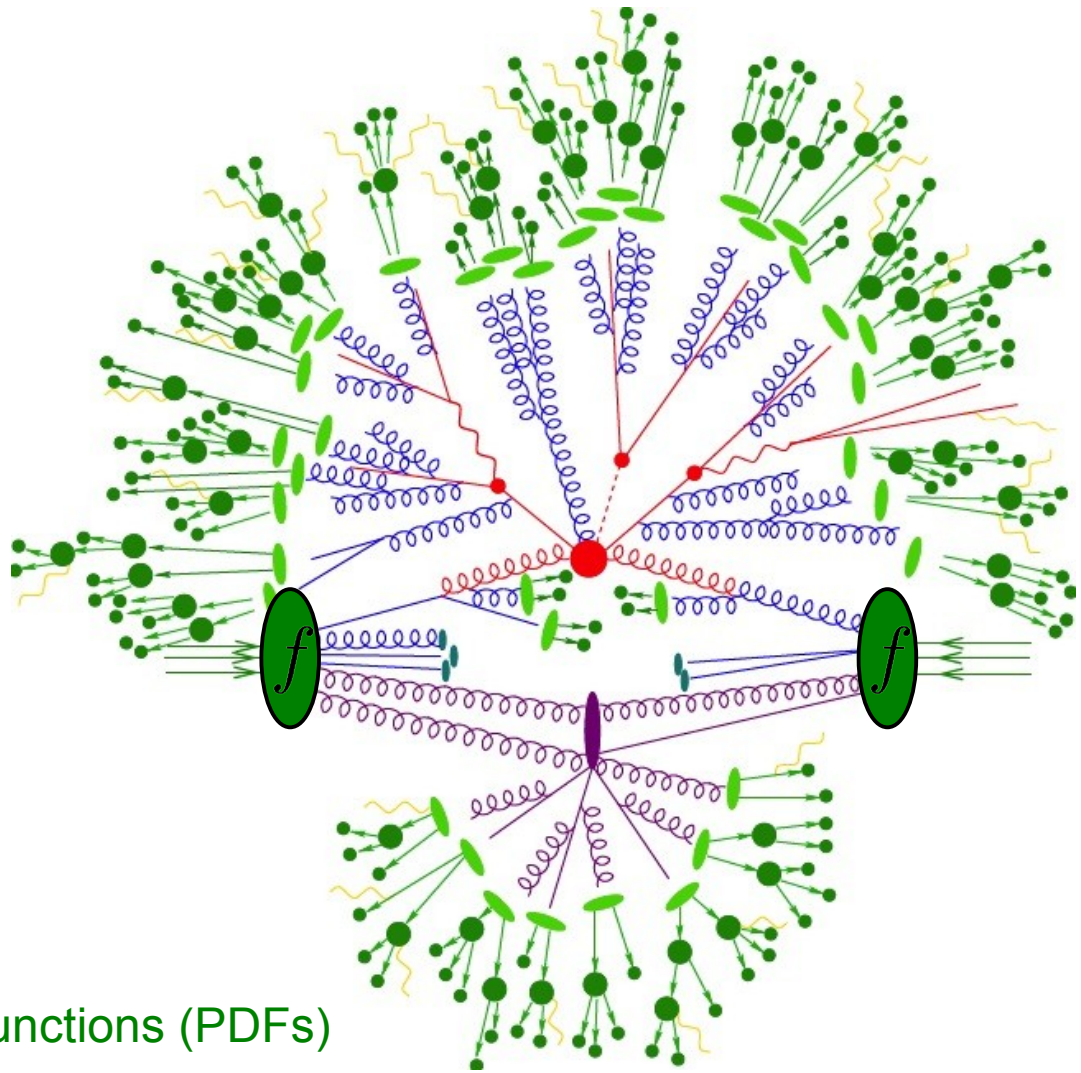
SCET framework:

- Off-shell modes are integrated out. Hard-scattering encoded in the **Wilson coefficents** of the operators.
- Low-energy degrees of freedom: **Soft** and **Collinear** fields
- Advantages:
  - Operator definition (manifest gauge invariance).
  - Systematic scale separation: **Factorization.**
  - 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

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

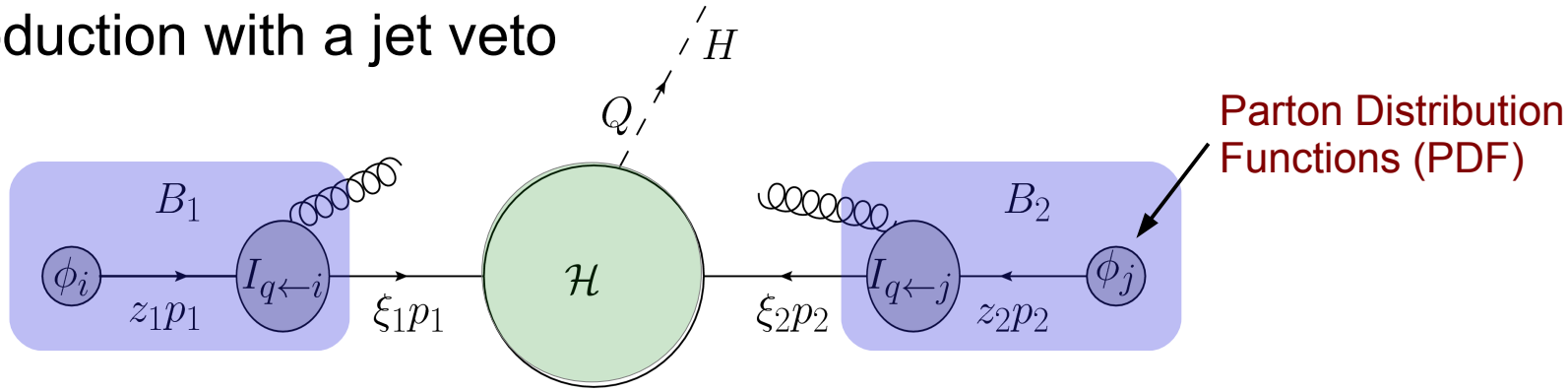
partonic cross section

parton distribution functions (PDFs)

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

All-Order Factorization Formula from SCET

For Higgs production with a jet veto



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

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

Born CS | Hard function | Collinear Anomaly

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

$$\sigma \sim \sigma_0 \big(1 + \alpha_s (L^2 + L + c1) \qquad \text{NLO}$$
$$+\alpha_s^2 (L^4 + L^3 + L^2 + L + c2) \qquad \text{NNLO}$$
$$+\alpha_s^3 (\vdots + \vdots + \vdots + \vdots + \ldots) \qquad \text{NNNLO}$$

LL NLL NNLL

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

Parton shower

Padé approximation

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
N³LL	4-loop	3-loop	2-loop	3-loop	NNLO

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

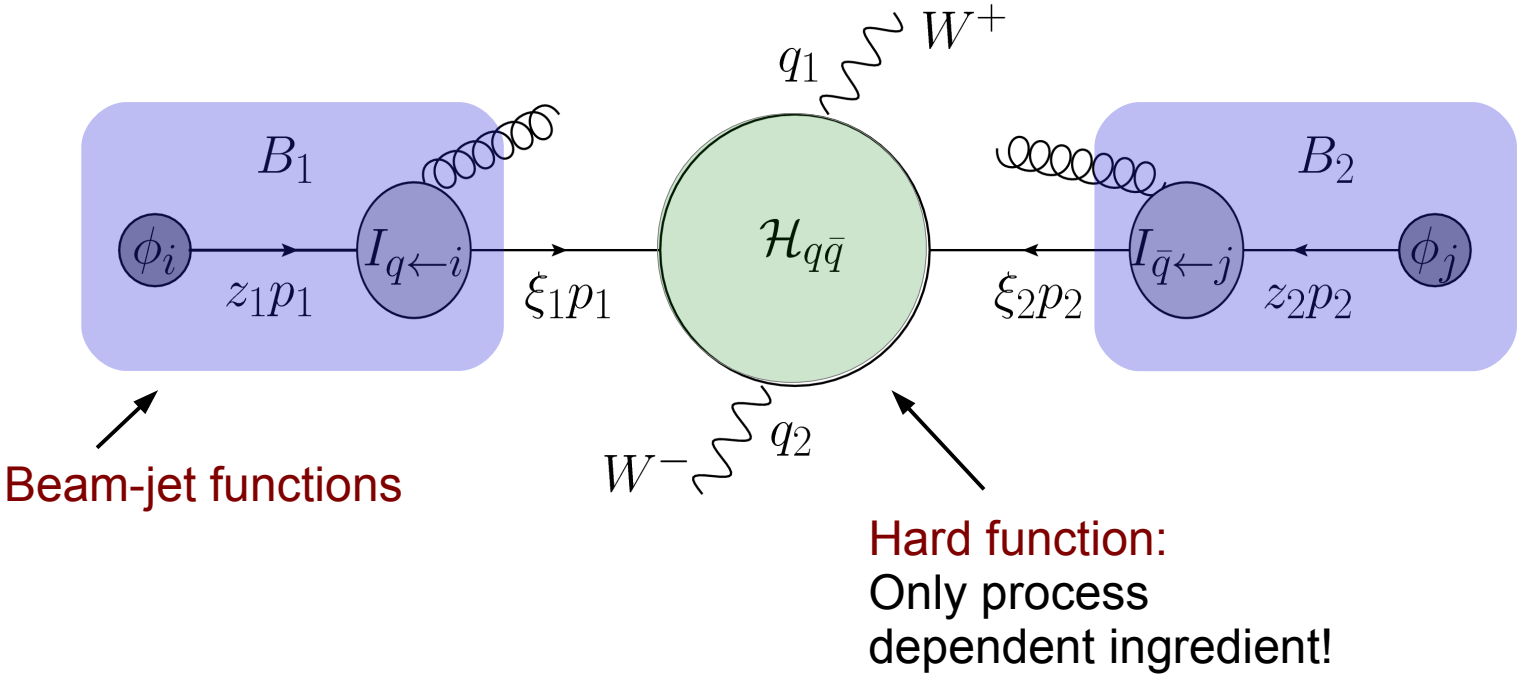
Computed 2-loop anomaly coefficient in SCET and extracted 2 loop beam functions numerically:

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

Automated Resummation for Jet Veto Cross Sections

All-order Factorization Formula from SCET

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



For NNLL resummation, one loop hard function needed →
NLO computations have been automated over the past years!

⇨ Automated jet veto resummation (NNLL+NLO) using 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:

  MadGraph5_aMC@NLO 2.3 (set `ickkw=-1`)

Cone Jet Cross Sections

Effective Theory for Jet Processes

- SCET successfully applied to many collider processes.

- Non-global observables (e.g. jet cross sections):
  - Only a certain region of phase-space is probed
  - Problem of so-called **non-global logarithms (NGLs)**.

- Usual factorization into hard, jet and soft functions

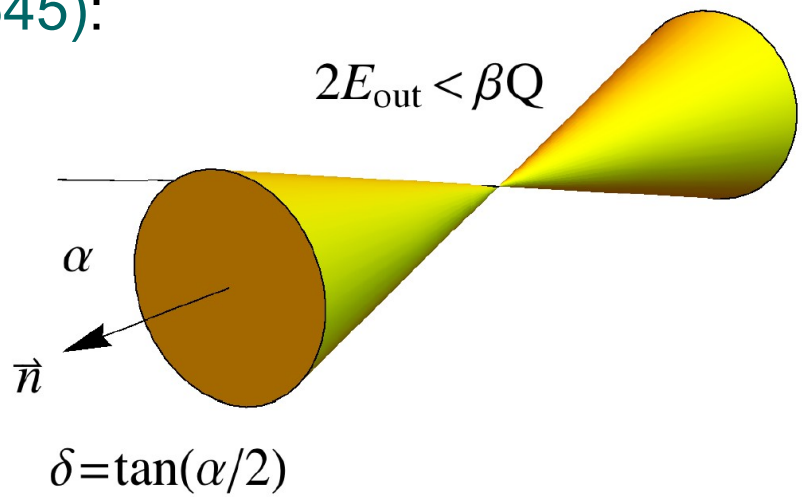
$$\sigma = \mathcal{H}_2 \cdot \mathcal{J} \cdot \overline{\mathcal{J}} \cdot \mathcal{S}_2$$

  does not achieve complete scale separation (no exponentiation).
  - Soft function suffer from large logarithms itself.

- Despite recent progress of various groups, no systematic,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
  - 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.