A Subleading Operator Basis and Matching for $gg \to H$

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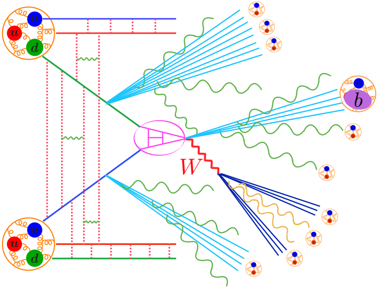
Outline

- Introduction to SCET and motivation for this work
- Operator basis
- Matching
- Conclusion and Outlook

Soft Collinear Effective Theory [Bauer, Fleming, Pirjol, Stewart]

SCET very powerful for treating multiscale processes in QCD



Light cone coord.: $p^\mu = \frac{\bar{n}^\mu}{2} n\cdot p + \frac{n^\mu}{2}\bar{n}\cdot p + p_\perp^\mu \equiv (n\cdot p,\, \bar{n}\cdot p,\, p_\perp)$

n-collinear: $p_n \sim Q(\lambda^2,\, 1,\, \lambda)$

$\bar{n}$-collinear: $p_{\bar{n}} \sim Q(1,\, \lambda^2,\, \lambda)$

(ultra)soft: $p_s \sim Q(\lambda^2,\, \lambda^2,\, \lambda^2)$

hard scale: Q , expansion: $\lambda \ll 1$

Allows for a factorized description: Hard, Jet, Beam, Soft radiation

Introduction

- A large class of observables τ (p_T, threshold, event shapes, etc.) exhibit singularities in perturbation theory for small τ:

$$\frac{d\sigma}{d\tau} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{m=0}^{2n-1} c_{nm}^{(0)} \left(\frac{\log^m \tau}{\tau}\right)_+ + \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{m=0}^{2n-1} c_{nm}^{(2)} \log^m \tau + \cdots$$

SCET: relate observable τ to power counting parameter λ

- p_T resummation in SCET: $\frac{p_T^2}{Q^2} \sim \lambda$
- Threshold in SCET: $(1-z)^2 \sim \lambda$
- Event shapes in SCET: $\tau \sim \lambda^2$

So that SCET is the EFT that describes the physics of the relevant degrees of freedom at small τ.

Application of SCET

For F.O. calculation:

- Only relevant d.o.f. involved $\Longrightarrow$ simpler calculation
- collinear and soft limits at the integrand level
- expansion by regions in loop integrals for free

For resummation:

- Prove factorization theorems

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \sigma_0 H(Q,\mu) \otimes J(Q,\tau,s,\mu) \otimes S(s,\mu) + p.c.$$

- Perform resummation by solving the RGE

$$\frac{1}{2}\gamma_H + \gamma_J + \gamma_S = 0$$

$$\frac{\mathrm{d}\sigma_{(\text{res})}}{\mathrm{d}\tau} = H(Q,\mu_H)\mathcal{U}_H(Q,\mu_H,\mu_S)J(Q,\tau,\mu_J)\otimes\mathcal{U}_J(\mu_J,\mu_S)\otimes S(\mu_S)$$

For example:

- Event shapes/Thrust
- Drell-Yan Threshold
- N-Jettiness
- Jet substructure
- Boosted t, W, Z physics
- Jet radius resummation
- Higgs p_T resummation (SCET$_{II}$)
- Jet broadening (SCET$_{II}$)
- Small-x resummation (Glauber)

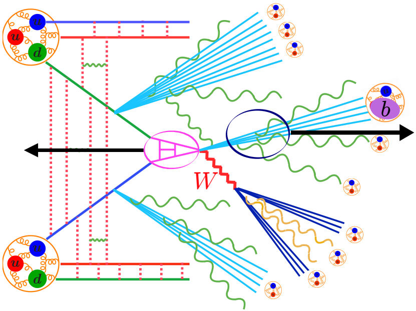
From SM to SCET

$$\mathcal{L}_{SM} \to \mathcal{L}_{\text{SCET}} = \mathcal{L}_{\text{hard}} + \mathcal{L}_{\text{dyn}}$$

$\mathcal{L}_{\text{hard}}$ describes the hard scattering/the partonic interaction.

e.g. how to go from gg to $H + 2$ partons.

Note: it can come from non-QCD interactions



$\mathcal{L}_{\text{dyn}}$ describes the evolution of the strongly interacting final/initial states

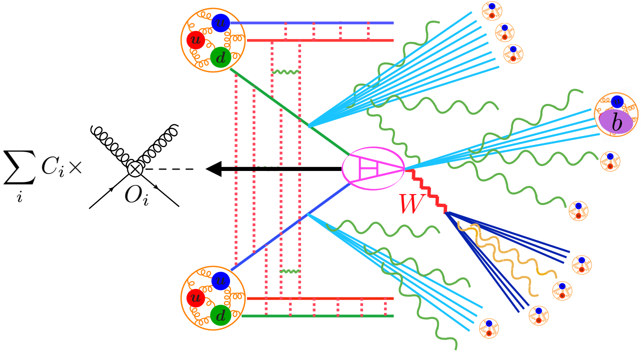
e.g. how to go from 2 partons to 2 jets/ how the jets evolve

EFT of pure QCD

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} \sim \sigma_0 H(Q,\mu) \otimes J(Q,\tau,s,\mu) \otimes S(s,\mu)$$

Hard scattering

- $\mathcal{L}_{\text{hard}}$ is made by hard scattering operators O_i made by incoming/outgoing fields.



- C_i are Wilson coefficients: computed via matching to SM (not only QCD), they encode physics of hard modes at scale Q. Analogue to 4 Fermi theory.

Hard scattering

- Fields/Lagrangians have a definite power counting in λ.

Operator	$\mathcal{B}^{\mu}_{n_i\perp}$	χ_{n_i}	$\mathcal{P}^{\mu}_{\perp}$	ψ_{us}	$\mathcal{B}^{\mu}_{us}$	∂^{μ}_{us}
Power Counting	λ	λ	λ	λ^3	λ^2	λ^2

therefore, the Lagrangians can be expanded in λ

$$\mathcal{L}_{\text{SCET}} = \mathcal{L}_{\text{hard}} + \mathcal{L}_{\text{dyn}} = \sum_{i\geq 0} \mathcal{L}^{(i)}_{\text{hard}} + \sum_{i\geq 0} \mathcal{L}^{(i)}$$

- $\mathcal{L}^{(i+k)}$ suppressed by λ^k w.r.t. $\mathcal{L}^{(i)}$
- $\mathcal{L}^{(0)}$ is called Leading Power Lagrangian
- $\mathcal{L}^{(1)}$ is Subleading Power Lagrangian
- $\mathcal{L}^{(2)}$ is Sub-Subleading Power Lagrangian
- etc ...

Note: Often no $\mathcal{O}(\lambda)$ at σ level, so Sub-Subleading Power (which is λ^2 suppressed) is called Next to Leading Power (first non vanishing).

Hard scattering in SCET: some definitions

$\mathcal{L}_{\rm hard}$ can be expanded:

- in powers of power counting parameter λ: $\mathcal{L}_{\rm hard} = \sum_i \mathcal{L}^{(i)}_{\rm hard}$
- on the operator basis: $\mathcal{L}^{(i)}_{\rm hard} = \sum_j C^{(i)}_j O^{(i)}_j$

A list of independent hard scattering operators $\{O^{(i)}_j\}$ for a given process is called a basis of hard scattering operators.

Hard scattering: Operator basis vs Wilson coefficients

$$\mathcal{L}^{(i)}_{\mathrm{hard}} = \sum_j C_j^{(i)} O_j^{(i)}$$

- Wilson coefficients $C_j^{(i)}$ depend on process (e.g. $gg \to H$) and power counting

- Operator basis $O_j^{(i)}$ depends on spin of non-QCD part and power counting $\implies$ more general (same basis for all $gg \to$ spin-0 at $\mathcal{O}(\lambda^i)$)

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A Subleading Operator Basis and Matching for $gg \to H$

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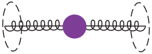
Note that, by definition, hard scattering operator basis is: at all orders in α_s, finite by power counting and fixed order in EW (typically LO)

Operator basis

- Include all operators with smallest power of λ, compatible with symmetries:
  - Collinear and u.s. gauge invariance (encoded in building blocks $\mathcal{B}_n^\mu, \mathcal{B}_{us}^\mu, \chi_n, \psi_{us}$)
  - Spin of the final state (use helicity building blocks $\mathcal{B}_n^\pm, J_{n\bar{n}}^\pm$)
  - Reparametrization Invariance (physics doesn't change if I change n^μ def. by $\mathcal{O}(\lambda^2)$)
- Lot of symmetries $\implies$ lot of constraints

For processes with only 2 collinear directions $(n, \bar{n})$ at leading power, operator basis is trivial: e.g. for $gg \to H$

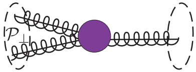
$\boldsymbol{g_n g_{\bar{n}}}$ **:**  $= -2\omega_1\omega_2\delta^{ab}\mathcal{B}^a_{\perp\bar{n},\omega_2} \cdot \mathcal{B}^b_{\perp n,\omega_1} H$

Operator basis at subleading powers

Order	Category	Operators (equation number)	$\sigma_{2j}^{\mathcal{O}(\lambda^2)} \neq 0$
$\mathcal{O}(\lambda^0)$	Hgg	$O^{(0)ab}_{\mathcal{B}\lambda_1\lambda_1} = \mathcal{B}^a_{n\lambda_1} \mathcal{B}^a_{\bar{n}\lambda_1} H$	✓
$\mathcal{O}(\lambda)$	$Hq\bar{q}g$	$O^{(1)a\,\bar{\alpha}\beta}_{\mathcal{B}n\lambda_1(-\lambda_1)} = \mathcal{B}^a_{n\lambda_1} J^{\bar{\alpha}\beta}_{n\bar{n}\,-\lambda_1} H$	✓
$\mathcal{O}(\lambda^2)$	$Hq\bar{q}Q\bar{Q}$	$O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ1(\lambda_1;\lambda_2)} = J^{\bar{\alpha}\beta}_{(q)n\lambda_1} J^{\bar{\gamma}\delta}_{(Q)\bar{n}\lambda_2} H$ $O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ2(\lambda_1;\lambda_1)} = J^{\bar{\alpha}\beta}_{(q\bar{Q})n\lambda_1} J^{\bar{\gamma}\delta}_{(Q\bar{q})\bar{n}\,\lambda_1} H$ $O^{(2)\bar{\alpha}\beta\bar{\gamma}\delta}_{qQ3(\lambda_1;-\lambda_1)} = J^{\bar{\alpha}\beta}_{(q)n\bar{n}\lambda_1} J^{\bar{\gamma}\delta}_{(Q)n\bar{n}-\lambda_1} H$	
	$Hq\bar{q}gg$	$O^{(2)ab\,\bar{\alpha}\beta}_{\mathcal{B}1\lambda_1\lambda_2(\lambda_3)} = \mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} J^{\bar{\alpha}\beta}_{n\,\lambda_3} H$ $O^{(2)ab\,\bar{\alpha}\beta}_{\mathcal{B}2\lambda_1\lambda_2(\lambda_3)} = \mathcal{B}^a_{\bar{n}\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} J^{\bar{\alpha}\beta}_{n\,\lambda_3} H$	✓
	$Hgggg$	$O^{(2)abcd}_{4g1\lambda_1\lambda_2\lambda_3\lambda_4} = S\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{n\lambda_2} \mathcal{B}^c_{\bar{n}\lambda_3} \mathcal{B}^d_{\bar{n}\lambda_4} H$ $O^{(2)abcd}_{4g2\lambda_1\lambda_2\lambda_3\lambda_4} = S\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} \mathcal{B}^c_{\bar{n}\lambda_3} \mathcal{B}^d_{\bar{n}\lambda_4} H$	 ✓
	$\mathcal{P}_\perp$	$O^{(2)a\,\bar{\alpha}\beta}_{\mathcal{P}\chi\lambda_1(\lambda_2)[\lambda_\mathcal{P}]} = \mathcal{B}^a_{n\lambda_1} \{J^{\bar{\alpha}\beta}_{\bar{n}\,\lambda_2} (\mathcal{P}^{\lambda_\mathcal{P}}_\perp)^\dagger\} H$ $O^{(2)abc}_{\mathcal{P}\mathcal{B}\lambda_1\lambda_2\lambda_3[\lambda_\mathcal{P}]} = S\,\mathcal{B}^a_{n\lambda_1} \mathcal{B}^b_{\bar{n}\lambda_2} \left[\mathcal{P}^{\lambda_\mathcal{P}}_\perp \mathcal{B}^c_{\bar{n}\lambda_3}\right] H$	✓ ✓
	Ultrasoft	$O^{(2)a\,\bar{\alpha}\beta}_{\chi n(us)0:(\lambda_1)} = \mathcal{B}^a_{us(n)0} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_1} H$ $O^{(2)\;\bar{\alpha}\beta}_{\partial\chi n(us)\lambda_1:(\lambda_2)} = \{\partial_{us(n)\lambda_1} J^{\bar{\alpha}\beta}_{n\bar{n}\,\lambda_2}\} H$ $O^{(2)abc}_{\mathcal{B}n(us)\lambda_1:\lambda_2\lambda_3} = \mathcal{B}^a_{us(n)\lambda_1} \mathcal{B}^b_{n\,\lambda_2} \mathcal{B}^c_{\bar{n}\,\lambda_3} H$ $O^{(2)ab}_{\partial\mathcal{B}n(us)\lambda_1:\lambda_2\lambda_3} = \left[\partial_{us(n)\lambda_1} \mathcal{B}_{n\,\lambda_2}\right] \mathcal{B}_{\bar{n}\,\lambda_3} H$	 ✓ ✓

Matching

Matching: a straightforward example

$(g)_n(gg\,\mathcal{P}_\perp)_{\bar{n}}$: 

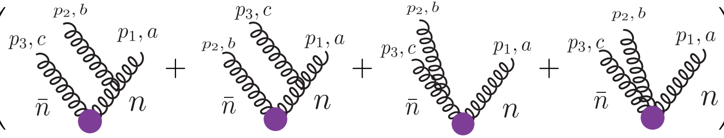
$$O^{(2)}_{\mathcal{P}\mathcal{B}1} = \mathcal{B}^a_{n\perp,\omega_1} \cdot \left[\mathcal{P}_\perp \mathcal{B}^b_{\bar{n}\perp,\omega_2} \cdot\right] \mathcal{B}^c_{\bar{n}\perp,\omega_3} H$$

$$O^{(2)}_{\mathcal{P}\mathcal{B}2} = \left[\mathcal{P}_\perp \cdot \mathcal{B}^a_{\bar{n}\perp,\omega_3}\right] \mathcal{B}^b_{n\perp,\omega_1} \cdot \mathcal{B}^c_{\perp\bar{n},\omega_2} H$$

- Assign kinematics with overlap to the operator:

$$p_1^\mu = \omega_1 \frac{n^\mu}{2}\,, \quad p_2^\mu = \omega_2 \frac{\bar{n}^\mu}{2} + p_\perp^\mu + p_2^r \frac{n^\mu}{2}\,, \quad p_3^\mu \sim \omega_3 \frac{\bar{n}^\mu}{2} - p_\perp^\mu + p_3^r \frac{n^\mu}{2}$$

- Expand full theory[1] diagrams at $\mathcal{O}(\lambda^2)$:



$$\left(\ldots\right)\Big|_{\mathcal{O}(\lambda^2)} =$$

$$=4gf^{abc}\left(2+\frac{\omega_3}{\omega_2}+\frac{\omega_2}{\omega_3}\right)\left(\epsilon_{2\perp}\cdot\epsilon_{3\perp}p_\perp\cdot\epsilon_{1\perp} - \epsilon_{1\perp}\cdot\epsilon_{2\perp}p_\perp\cdot\epsilon_{3\perp} + \right.$$
$$\left. - \epsilon_{1\perp}\cdot\epsilon_{3\perp}p_\perp\cdot\epsilon_{2\perp}\right).$$

[1] QCD with pointlike gluon fusion Higgs production

Matching: a straightforward example

- Extract Wilson Coefficient of the operators

$$C^{(2)}_{\mathcal{P}\mathcal{B}1} = -\left(\frac{1}{2}\right) 4ig\left(2+\frac{\omega_3}{\omega_2}+\frac{\omega_2}{\omega_3}\right) \qquad O^{(2)}_{\mathcal{P}\mathcal{B}1} = f^{abc}\mathcal{B}^a_{n\perp,\omega_1}\cdot\left[\mathcal{P}_\perp \mathcal{B}^b_{\bar{n}\perp,\omega_2}\cdot\right]\mathcal{B}^c_{\bar{n}\perp,\omega_3} H\,,$$

$$C^{(2)}_{\mathcal{P}\mathcal{B}2} = 4ig\left(2+\frac{\omega_3}{\omega_2}+\frac{\omega_2}{\omega_3}\right) \qquad O^{(2)}_{\mathcal{P}\mathcal{B}2} = f^{abc}\left[\mathcal{P}_\perp\cdot \mathcal{B}^a_{\bar{n}\perp,\omega_3}\right]\mathcal{B}^b_{n\perp,\omega_1}\cdot\mathcal{B}^c_{\perp\bar{n},\omega_2} H$$

- Matching onto Helicity basis

$$\mathcal{O}^{(2)}_{\mathcal{P}\mathcal{B}+++[-]} = 4gif^{abc}\left(2+\frac{\omega_3}{\omega_2}+\frac{\omega_2}{\omega_3}\right)\mathcal{B}^a_{n+,\omega_1}\,\mathcal{B}^b_{\bar{n}+,\omega_3}\,\left[\mathcal{P}^-_\perp \mathcal{B}^c_{\bar{n}+,\omega_2}\right] H\,,$$

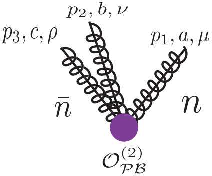
$$\mathcal{O}^{(2)}_{\mathcal{P}\mathcal{B}---[+]} = 4gif^{abc}\left(2+\frac{\omega_3}{\omega_2}+\frac{\omega_2}{\omega_3}\right)\mathcal{B}^a_{n-,\omega_1}\,\mathcal{B}^b_{\bar{n}-,\omega_3}\,\left[\mathcal{P}^+_\perp \mathcal{B}^c_{\bar{n}-,\omega_2}\right] H\,,$$

$$\mathcal{O}^{(2)}_{\mathcal{P}\mathcal{B}++-[+]} = -2gif^{abc}\left(2+\frac{\omega_3}{\omega_2}+\frac{\omega_2}{\omega_3}\right)\mathcal{B}^a_{n+,\omega_1}\,\mathcal{B}^b_{\bar{n}-,\omega_3}\,\left[\mathcal{P}^+_\perp \mathcal{B}^c_{\bar{n}+,\omega_2}\right] H\,,$$

$$\mathcal{O}^{(2)}_{\mathcal{P}\mathcal{B}-+-[-]} = -2gif^{abc}\left(2+\frac{\omega_3}{\omega_2}+\frac{\omega_2}{\omega_3}\right)\mathcal{B}^a_{n-,\omega_1}\,\mathcal{B}^b_{\bar{n}-,\omega_3}\,\left[\mathcal{P}^-_\perp \mathcal{B}^c_{\bar{n}+,\omega_2}\right] H\,.$$

Matching: Feynman Rule

In this way we get the Feynman rule in the EFT:



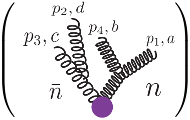
$$= 4 g f^{abc} \left(2 + \frac{\omega_2}{\omega_3} + \frac{\omega_3}{\omega_2}\right) \Big[p_\perp^\mu g_\perp^{\nu\rho} - p_\perp^\nu g_\perp^{\mu\rho} - p_\perp^\rho g_\perp^{\mu\nu} + \frac{p_\perp^2}{\omega_2 \omega_3} \left(\omega_3 n^\nu g_\perp^{\mu\rho} - \omega_2 n^\rho g_\perp^{\mu\nu} + p_\perp^\mu n^\nu n^\rho \right) \Big] .$$

Gauge invariant collinear gluon building block:

$$g\mathcal{B}^\mu_{n\perp} = g \left(A^{\mu a}_{\perp k} T^a - k_\perp^\mu \frac{\bar{n} \cdot A^a_{nk} T^a}{\bar{n} \cdot k} \right) + \mathcal{O}(g^2)$$

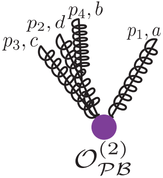
Matching: a less straightforward example

- EFT has non localities only at the hard scale $Q \sim \omega \sim \lambda^0$
- Some full theory diagrams have non localities also at the soft scale λ^2 (eg. $(p_2+p_3)^2 \sim p_2^r\omega_3 + p_3^r\omega_2 + p_\perp^2 \sim \lambda^2$)



$$\Big|_{\mathcal{O}(\lambda^2)} = \underbrace{\frac{4ig^2 f^{aeb} f^{dce}}{\omega_4}}_{\text{hard non locality}} \left[\underbrace{\frac{2(\omega_2+\omega_3)}{(p_2+p_3)^2}}_{\text{soft non locality}} p_\perp \cdot \epsilon_{1\perp} p_\perp \cdot \epsilon_{2\perp} \epsilon_{3\perp} \cdot \epsilon_{4\perp} + \right.$$
$$\left. -(2\omega_3+\omega_4)\epsilon_{1\perp}\cdot\epsilon_{4\perp}\epsilon_{2\perp}\cdot\epsilon_{3\perp} \right].$$

- Need to cancel with EFT contributions (SCET diagrams with same final states) e.g.



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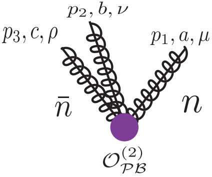
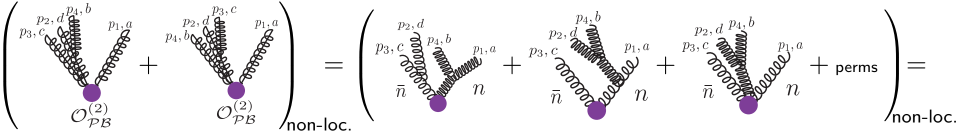


$\times$ collinear gluon splitting in SCET

Matching: cancellation of soft non localities

- Cancellation of soft non localities gives a strong cross check on matching of operators (both $3g$ and $4g$ operators involved)



$$= 8ig^2 p_\perp \cdot \epsilon_{1\perp} p_\perp \cdot \epsilon_{2\perp} \epsilon_{3\perp} \cdot \epsilon_{4\perp} \left(\frac{f^{abe} f^{ecd}}{(p_2 + p_3)^2} \frac{(\omega_2 + \omega_3 + \omega_4)^2}{(\omega_3 + \omega_2)\omega_4} + [3 \leftrightarrow 4, b \leftrightarrow c] \right) .$$

- Resulting Wilson Coefficient is free of soft non localities

$$C^{(2)}_{4g} = 16\pi\alpha_s \left(3 + \frac{\omega_j^3 + \omega_k^3 + \omega_\ell^3 + \omega_j \omega_k \omega_\ell}{(\omega_j + \omega_k)(\omega_j + \omega_\ell)(\omega_k + \omega_\ell)} \right) .$$

What is subleading power good for?

Leading Power

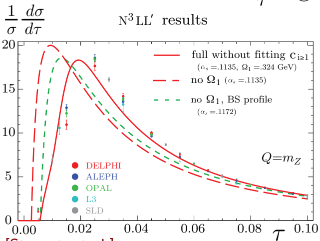
- Observables can be organized in an expansion in τ.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \frac{\mathrm{d}\sigma^{(0)}}{\mathrm{d}\tau} + \underbrace{\frac{\mathrm{d}\sigma^{(2)}}{\mathrm{d}\tau} + \frac{\mathrm{d}\sigma^{(4)}}{\mathrm{d}\tau} + \dots}_{\text{power corrections}}$$

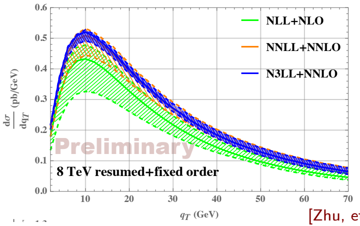
- Leading power well understood for a wide variety of observables.

$$\frac{\mathrm{d}\sigma^{(0)}}{\mathrm{d}\tau} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{m=0}^{2n-1} c_{nm}^{(0)} \left(\frac{\log^m \tau}{\tau}\right)_+ =$$

$$= H^{(0)} J_\tau^{(0)} \otimes J_\tau^{(0)} \otimes S_\tau^{(0)} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q\tau}\right)$$



[Stewart, et al.]



[Zhu, et al.]

Subleading Power

- Subleading powers much less well understood.
- Are there factorization theorems at each power?

$$\frac{\mathrm{d}\sigma^{(n)}}{\mathrm{d}\tau} = \sum_j H_j^{(n_{Hj})} \otimes J_j^{(n_{Jj})} \otimes S_j^{(n_{Sj})}$$

- What is the degree of universality?

- Start by looking at Next-to-Leading Power (NLP):

$$\frac{\mathrm{d}\sigma^{(2)}}{\mathrm{d}\tau} = \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{m=0}^{2n-1} c_{nm}^{(2)} \log^m \tau$$

Applications

- Goal: Understand all orders structure of NLP logs. Derive RG, etc.
- Fixed order is first step in understanding this.
- Already at fixed order NLP logs have interesting applications.

Application to N-jettiness Subtractions

- NNLO calculations require cancellation of real/virtual poles.
- Use a physical resolution variable to slice phase space.
- Recently a general method allowing for jets in final state, based on N-jettiness (see also Andrea Isgrò's talk)

[Boughezal, Focke, Petriello, Liu]

[Gaunt, Stahlhofen,Tackmann, Walsh]

$$\sigma(X) = \int_0 d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} = \int_0^{\mathcal{T}_N^{\text{cut}}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} + \int_{\mathcal{T}_N^{\text{cut}}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N}$$

N-jettiness Subtractions

$$\sigma(X) = \int_0 d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} = \int_0^{\mathcal{T}_N^{\mathrm{cut}}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} + \int_{\mathcal{T}_N^{\mathrm{cut}}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N}$$

$$\int_0^{\mathcal{T}_N^{\mathrm{cut}}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N}$$

Compute using factorization in soft/collinear limits:

$$\frac{d\sigma}{d\tau_N} = H\, B_a \otimes B_b \otimes S \otimes J_1 \otimes \cdots \otimes J_{N-1}$$

$$\int_{\mathcal{T}_N^{\mathrm{cut}}} d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N}$$

Additional jet resolved. Use NLO subtractions.

Power Corrections

- Current subtractions use leading power result in singular region.
- Power corrections are dropped $\implies$ small values of $\mathcal{T}_N^{\rm cut}$ necessary.

$$\frac{d\sigma}{d\tau} = \sum_{n=0}^{n=\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{n=0}^{2n-1} c_{nm}^{(0)} \left(\frac{\log^m \tau}{\tau}\right)_+$$

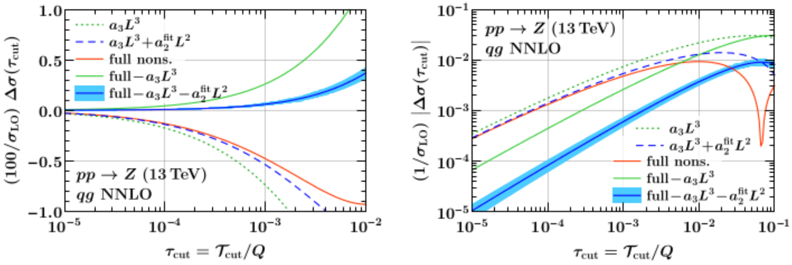
$$+ \sum_{n=0}^{n=\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{n=0}^{2n-1} c_{nm}^{(2)} \log^m \tau$$

$$+ \sum_{n=0}^{n=\infty} \left(\frac{\alpha_s}{\pi}\right)^n \sum_{n=0}^{2n-1} c_{nm}^{(2)} \tau \log^m \tau$$

$$+ \cdots$$

- Use of a physical resolution variable $\implies$ power corrections analytically tractable. [Gaunt, Stahlhofen,Tackmann, Walsh], see also Andrea's Talk [Boughezal, Petriello, Liu, et al.]

N-jettiness Subtractions



[Ian Moult, Lorena Rothen, Iain W. Stewart, Frank J. Tackmann, and Hua Xing Zhu1- arXiv:1612.00450v1]

Outlook

- Understand factorization beyond leading power
  - Systematic study of subleading Lagrangian insertions (Subleading Power Radiative Functions)
  - Combine subleading hard scattering operator and Radiative Functions
- Extend it to SCET$_{II}$
- Apply universal subleading SCET pieces to many observables to "automatize" NNLO FO calculations
- Perform resummation of subleading logarithms (next to leading power, next to eikonal)

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Thank you!

Backup slides

Helicity building blocks: definition

$$\mathcal{B}^a_{i\pm} = -\varepsilon_{\mp\mu}(n_i, \bar{n}_i)\, \mathcal{B}^{a\mu}_{n_i\perp,\omega_i}\,,$$

$$\chi^\alpha_{i\pm} = \frac{1 \pm \gamma_5}{2}\chi^\alpha_{n_i,-\omega_i}\,, \qquad \bar{\chi}^{\bar{\alpha}}_{i\pm} = \bar{\chi}^{\bar{\alpha}}_{n_i,-\omega_i}\frac{1 \mp \gamma_5}{2}\,.$$

$$\varepsilon^\mu_+(p,k) = \frac{\langle p+|\gamma^\mu|k+\rangle}{\sqrt{2}\langle kp\rangle}\,, \qquad \varepsilon^\mu_-(p,k) = -\frac{\langle p-|\gamma^\mu|k-\rangle}{\sqrt{2}[kp]}\,,$$

- Helicity currents where the quarks are in opposite collinear sectors,

$$h = \pm 1: \quad J^{\bar{\alpha}\beta}_{n\bar{n}\pm} = \mp\sqrt{\frac{2}{\omega_n\,\omega_{\bar{n}}}}\,\frac{\varepsilon^\mu_\mp(n,\bar{n})}{\langle \bar{n}\mp|n\pm\rangle}\,\bar{\chi}^{\bar{\alpha}}_{n\pm}\,\gamma_\mu\chi^\beta_{\bar{n}\pm}\,,$$

$$h = 0: \quad J^{\bar{\alpha}\beta}_{n\bar{n}0} = \frac{2}{\sqrt{\omega_n\,\omega_{\bar{n}}}\,[n\bar{n}]}\bar{\chi}^{\bar{\alpha}}_{n+}\chi^\beta_{\bar{n}-}\,, \quad (J^\dagger)^{\bar{\alpha}\beta}_{n\bar{n}0} = \frac{2}{\sqrt{\omega_n\,\omega_{\bar{n}}}\langle n\bar{n}\rangle}\bar{\chi}^{\bar{\alpha}}_{n-}\chi^\beta_{\bar{n}+}$$

- as well as where the quarks are in the same collinear sector,

$$h = 0: \quad J^{\bar{\alpha}\beta}_{i0} = \frac{1}{2\sqrt{\omega_{\bar{\chi}}\,\omega_\chi}}\,\bar{\chi}^{\bar{\alpha}}_{i+}\,\bar{n}\!\!\!/_i\,\chi^\beta_{i+}\,, \qquad J^{\bar{\alpha}\beta}_{i\bar{0}} = \frac{1}{2\sqrt{\omega_{\bar{\chi}}\,\omega_\chi}}\,\bar{\chi}^{\bar{\alpha}}_{i-}\,\bar{n}\!\!\!/_i\,\chi^\beta_{i-}\,,$$

$$h = \pm 1: \quad J^{\bar{\alpha}\beta}_{i\pm} = \mp\sqrt{\frac{2}{\omega_{\bar{\chi}}\,\omega_\chi}}\,\frac{\epsilon^\mu_\mp(n_i,\bar{n}_i)}{\left(\langle n_i\mp|\bar{n}_i\pm\rangle\right)^2}\,\bar{\chi}^{\bar{\alpha}}_{i\pm}\,\gamma_\mu\bar{n}\!\!\!/_i\,\chi^\beta_{i\mp}\,.$$

Helicity building blocks: power counting

Field:	$\mathcal{B}^a_{i\pm}$	$J^{\bar\alpha\beta}_{ij\pm}$	$J^{\bar\alpha\beta}_{ij0}$	$J^{\bar\alpha\beta}_{i\pm}$	$J^{\bar\alpha\beta}_{i0}$	$J^{\bar\alpha\beta}_{i\bar 0}$	$\mathcal{P}^\perp_\pm$
Power counting:	λ	λ^2	λ^2	λ^2	λ^2	λ^2	λ

Field:	$\mathcal{B}^a_{us(i)\pm}$	$\mathcal{B}^a_{us(i)0}$	$\partial_{us(i)\pm}$	$\partial_{us(i)0}$	$\partial_{us(i)\bar 0}$
Power counting:	λ^2	λ^2	λ^2	λ^2	λ^2