PROJECT B2A:

AUTOMATED CALCULATIONS IN SOFT-COLLINEAR EFFECTIVE THEORY

[GUIDO BELL]

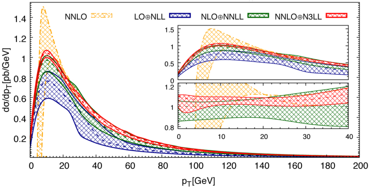
UNIVERSITÄT SIEGEN

Scope

Precision resummations for collider observables

[Chen et al 18]

- large Sudakov logs in corners of phase space
- beyond (N)NLO+PS for simple observables
- threshold, p_T, jet-veto resummations etc.

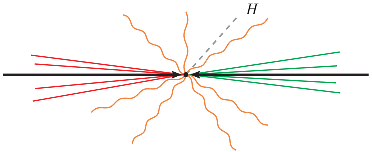


Infrared counterterms for fixed-order calculations

- SCET ingredients contain information on IR singularities
- q_T slicing, N-jettiness slicing [Catani, Grazzini 07; Boughezal et al 15; Gaunt et al 15]
- interplay with other slicing / subtraction techniques?

Resummations in SCET

Scale separation: $p_T \ll m_H$



$$\frac{d\hat{\sigma}}{dp_T} \simeq H(m_H, \mu)\, J(p_T, \mu) \otimes J(p_T, \mu) \otimes S(p_T, \mu)$$

Resum Sudakov logarithms by solving RG equations

$$\frac{dH(m_H, \mu)}{d \ln \mu} = \left[2\, \Gamma_{\rm cusp}(\alpha_s)\, \ln \frac{m_H^2}{\mu^2} + 4\gamma_H(\alpha_s) \right] H(m_H, \mu)$$

- anomalous dimensions: $\Gamma_{\rm cusp}, \gamma_H, \gamma_J, \gamma_S$
- matching corrections: c_H, c_J, c_S

Counting logs

Accuracy	Γ_{cusp}	$\gamma_H, \gamma_J, \gamma_S$	c_H, c_J, c_S
LL	1-loop	–	–
NLL	2-loop	1-loop	tree
NNLL	3-loop	2-loop	1-loop
N^3LL	4-loop	3-loop	2-loop

Precision resummations require observable-dependent 2-loop ingredients

- so far analytic calculations on a case-by-case basis

$\Rightarrow$ develop generic method for automated computations

Work program

Project B2a:

- automated calculation of NNLO soft functions – on-going –
- automated calculation of NNLO jet and beam functions – on-going –
- extending and improving SCET subtraction techniques
- development of an automated resummation code

$\Rightarrow$ I will present preliminary work / first results for points 1+2 today

Soft functions

Definition

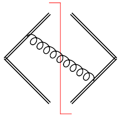
$$S(\tau,\mu) = \sum_{i\in X} \mathcal{M}(\tau;\{k_i\})\ \langle 0|(S_{n_1}S_{n_2}S_{n_3}\dots)^\dagger|X\rangle\langle X|S_{n_1}S_{n_2}S_{n_3}\dots|0\rangle$$

- soft Wilson lines S_{n_i} with $n_i^2 = 0$
- soft function is a matrix in colour space
- generic measurement function $\mathcal{M}(\tau;\{k_i\})$

Status

- formalism exists for two light-like directions [GB, Rahn, Talbert 18]
- numerical implementation: `SoftSERVE`
- first results for $N > 2$ light-like directions [GB, Dehnadi, Mohrmann,Rahn in progress]

In a nutshell



Consider NLO calculation for simplicity

- find phase-space parametrisation that factorises all divergences

$$k_T = \sqrt{k_+ k_-} \qquad y_k = \frac{k_+}{k_-} \qquad t_k = \frac{1-\cos\theta_k}{2}$$

- find generic parametrisation of measurement function

$$\mathcal{M}_1(\tau; k) = \exp\Big(-\tau\, k_T\, y_k^{n/2}\, f(y_k, t_k)\Big)$$

- perform all observable-independent integrations

$$S^{(1)}(\tau,\mu) \sim \Gamma(-2\varepsilon) \int_0^1 dy_k\; y_k^{-1+n\varepsilon} \int_0^1 dt_k\; (4t_k\bar{t}_k)^{-1/2-\varepsilon}\;\; f(y_k,t_k)^{2\varepsilon}$$

$\Rightarrow$ soft ($k_T \to 0$) and collinear ($y_k \to 0$) singularities are factorised

SoftSERVE

[GB, Rahn, Talbert 18]

Publically available at `https://softserve.hepforge.org`

- uses Divonne integrator from Cuba library
- supports multi-precision variables (`boost`, `GMP/MPFR`)
- scripts for automated renormalisation

e^+e^- event shapes

- Thrust
- C-parameter
- Jet broadening
- Angularities
- Hemisphere masses

Hadron-collider observables

- Threshold resummation
- p_T resummation
- Jet veto resummation
- Soft-drop jet groomer
- Transverse thrust

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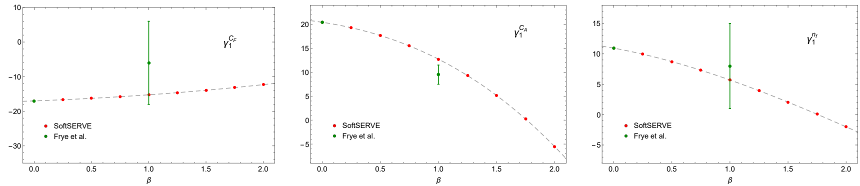
Two-loop soft anomalous dimension as a function of the grooming parameter β



[Frye, Larkoski, Schwartz, Yan 16]

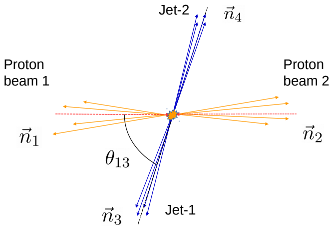
Beyond two light-like directions

N-jettiness [Stewart, Tackmann, Waalewijn 10]

$$\mathcal{T}_N(\{k_i\}) = \sum_i \min_j (n_j \cdot k_i) \qquad j = \underbrace{1,2}_{\text{beams}},\underbrace{3,\ldots,N+2}_{\text{jets}}$$

- 1-jettiness soft function known to NNLO [Boughezal, Liu, Petriello 15; Campbell, Ellis, Mondini, Williams 17]
- 2-jettiness soft function appeared recently [GB, Dehnadi, Mohrmann, Rahn 18; Jin, Liu 19]

Simplified kinematics for illustration



$$n_{12} \equiv n_1 \cdot n_2 = n_3 \cdot n_4 = 2$$

$$n_{13} \equiv n_1 \cdot n_3 = n_2 \cdot n_4 = 1 - \cos\theta_{13}$$

$$n_{14} \equiv n_1 \cdot n_4 = n_2 \cdot n_3 = 1 + \cos\theta_{13}$$

Beyond two light-like directions

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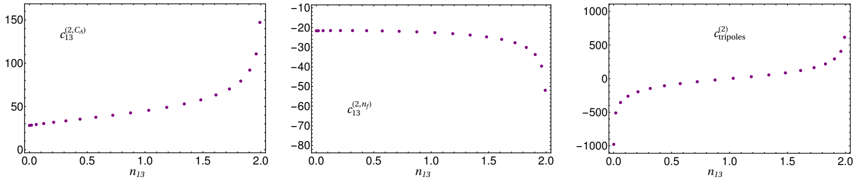
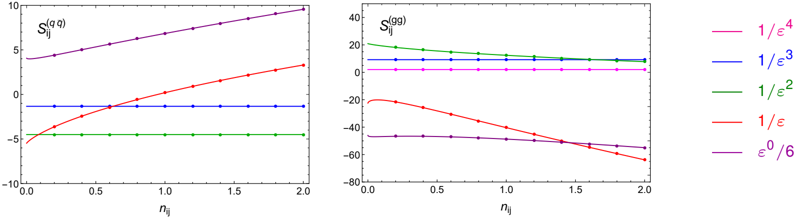
Two-loop matching correction as a function of the kinematic variable n_{13}



Connections within the CRC

Double-soft integral for nested soft-collinear subtractions [Caola, Delto, Frellesvig, Melnikov 18]



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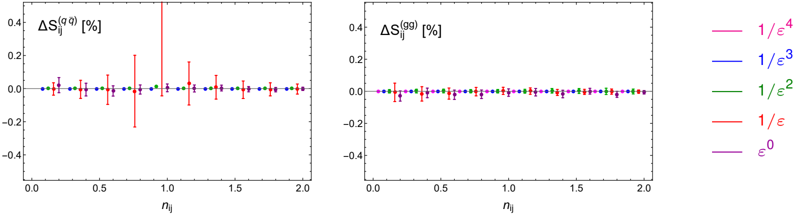

NNLO soft function for $t\bar{t}$ production at small p_T [Angeles-Martinez, Czakon, Sapeta 18]

- requires extension for time-like Wilson lines with $n_i^2 \neq 0$
- matrix elements more complicated, but less divergent
- slicing techniques for $t\bar{t}\gamma$, $t\bar{t}H$ or $t\bar{t}$ + jet calculations?

Jet functions

Definition

$$J_q(\tau,\mu) \sim \sum_{i\in X} \delta(Q - \textstyle\sum_i n\cdot k_i)\, \delta^{(d-2)}(\sum_i k_i^\perp)\, \mathcal{M}(\tau;\{k_i\})\, \langle 0|\chi|X\rangle\langle X|\bar\chi|0\rangle$$

$$J_g(\tau,\mu) \sim \sum_{i\in X} \delta(Q - \textstyle\sum_i n\cdot k_i)\, \delta^{(d-2)}(\sum_i k_i^\perp)\, \mathcal{M}(\tau;\{k_i\})\, \langle 0|\mathcal{A}_\perp^\mu|X\rangle\langle X|\mathcal{A}_{\perp,\mu}|0\rangle$$

- collinear field operators $\chi = W^\dagger \frac{\not{n}\not{\bar{n}}}{4}\psi,\ \mathcal{A}_\perp^\mu = W^\dagger[iD_\perp^\mu W]$
- generic measurement function $\mathcal{M}(\tau;\{k_i\})$
- similar definition for beam functions ($\rightarrow$ proton matrix elements)

Status

- formalism exists for NLO calculation [Brune Master thesis]
- currently looking at NNLO real-virtual interference

NLO calculation

In analogy to soft function calculation

- use splitting variable instead of rapidity measure

$$k_T = \sqrt{k_+ k_-} \qquad z_k = \frac{k_-}{Q} \qquad t_k = \frac{1 - \cos\theta_k}{2}$$

- collinear measurement function must fall back to soft one as $z_k \to 0$

$$\mathcal{M}_1(\tau; k) = \exp\Big(- \tau\, k_T \Big(\frac{k_T}{z_k Q}\Big)^n f(z_k, t_k)\Big)$$

- similar master formula with all singularities factorised

$$J_q^{(1)}(\tau,\mu) \sim \Gamma\Big(\frac{-2\varepsilon}{n+1}\Big) \int_0^1 dz_k\, z_k^{-1-\frac{2n}{n+1}\varepsilon} \, \big(z_k P_{qg}^{(0)}(z_k)\big) \int_0^1 dt_k\, (4 t_k \bar{t}_k)^{-1/2-\varepsilon} \;\; f(z_k, t_k)^{\frac{2\varepsilon}{n+1}}$$

splitting function $P_{qg}^{(0)}(z_k) \sim \frac{1+(1-z_k)^2}{z_k} - \varepsilon\, z_k$

Projections

Next steps

- NLO splitting functions required for NNLO real-virtual interference
- LO $1 \to 3$ splitting functions required for NNLO double real-emission contribution
- find suitable parametrisation of double-emission measurement function
- numerical integrations probably not more expensive than for soft functions
- develop generic formalism for quark / gluon jet and beam functions
- implement in a similar code to `SoftSERVE`

New postdoc will join this project in October (G. Das from DESY)

Summary

Automation of NNLO computations for SCET calculations

- formalism and numerical implementation exists for soft functions
- first steps for computation of quark jet functions

Possible interactions with the CRC

- further development of NNLO slicing / subtraction techniques
- precision resummations in Higgs, top, electroweak and BSM physics