SCET and Resummation

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Introduction.

Resummation.

Consider an observable or measurement that resolves or restricts the phase-space of additional real emissions

- Say it only allows real emissions up to momentum scales of $\sim p$
  (i.e. only allows soft and/or collinear emissions but no hard emissions)
- Virtual emissions unconstrained and contribute up to the hard scale $\sim Q$
- As a result the cancellation between real and virtual IR singularities only works up to the scale of the real emission, leaving remnant logs of p/Q

$$\int_0^p \mathrm{d}k_{\mathrm{real}}\,\frac{1}{k_{\mathrm{real}}} - \int_0^Q \mathrm{d}\ell_{\mathrm{virt}}\,\frac{1}{\ell_{\mathrm{virt}}} = \ln\frac{p}{Q}$$

Many examples of such IR-sensitive observables

- Low-p_T spectra ($p \simeq p_T$), production near threshold, jet substructure, ...
- More generally: When a problem/process involves several parametrically separate physical scales

Resummation.

Soft-collinear singularities can cause up to two logarithms at each α_s order

$$\begin{aligned}
\mathrm{d}\sigma = 1 &+ \alpha_s\big[\ln^2\tau + \ln\tau + 1 && + \mathcal{O}(\tau)\big] \\
&+ \alpha_s^2\big[\ln^4\tau + \ln^3\tau + \ln^2\tau + \ln\tau + 1 && + \mathcal{O}(\tau)\big] \\
&+ \quad \vdots \qquad \vdots \qquad \vdots \qquad \vdots \qquad \ddots && + \ldots\big] \\
= &\qquad \mathrm{d}\sigma^{(0)} && + \mathcal{O}(\tau)
\end{aligned}$$

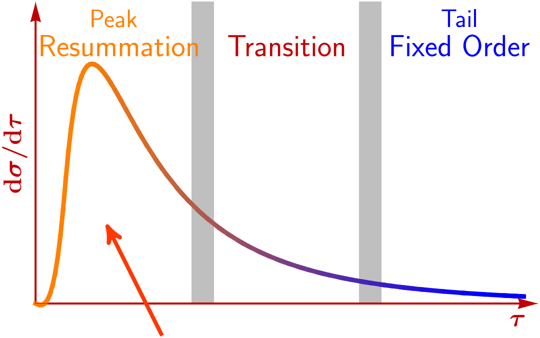
For $\tau \equiv p/Q \ll 1$ two related things happen

- Leading-power terms $\mathrm{d}\sigma^{(0)}$ ("singular") dominate over $\mathcal{O}(\tau)$ power corrections ("nonsingular")
- As τ decreases logarithms grow large deteriorating the α_s expansion

Resummation

- Sums up most important terms $\alpha_s^n \ln^{2n}\tau$, $\alpha_s^n \ln^{2n-1}\tau$, $\alpha_s^n \ln^{2n-2}\tau$, ... in $\mathrm{d}\sigma^{(0)}$ to all orders (for all n)

To Resum or Not to Resum.



$\tau \to 0$ (so $p \ll Q$):
only soft or collinear emissions

$\tau \sim 1$ (so $p \sim Q$):
additional hard emissions

Very small τ

- Fixed-order expansion breaks down
- Resummation is necessary to obtain meaningful predictions

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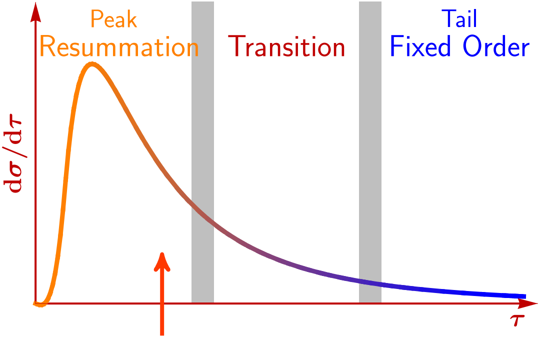

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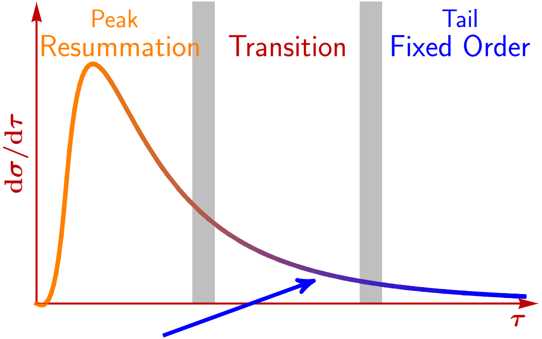
$\tau \sim 1$ (so $p \sim Q$):
additional hard emissions

Moderately small $\tau \sim 0.1 - 0.2$

- Typical use case, often experimentally relevant region of interest
- Motivation is not that one must resum, but rather that doing so makes sense and improves predictions as long as power corrections are subdominant

To Resum or Not to Resum.



$\tau \to 0$ (so $p \ll Q$):
only soft or collinear emissions

$\tau \sim 1$ (so $p \sim Q$):
additional hard emissions

Large $\tau \gtrsim 0.5$

- Power expansion in τ becomes meaningless
- Often large cancellations between formally leading and subleading power terms
- Resummation would spoil these cancellations in which case it must not be done

Soft-Collinear Effective Theory (SCET).

SCET is the effective field theory (EFT) that arises from expanding full QCD in powers of τ at the Lagrangian and operator level

$$\mathrm{QCD} = \underbrace{\mathrm{SCET}^{(0)}}_{\text{leading-power}} + \underbrace{\mathrm{SCET}^{(1)}}_{\text{next-to-leading power}} + \mathcal{O}(\tau^2)$$

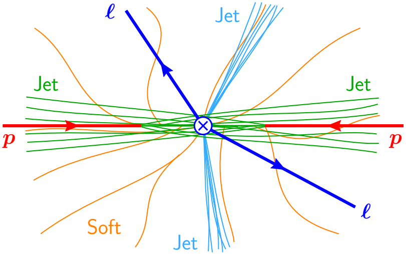
By definition/construction SCET reproduces the small-τ limit of full QCD. Hence, calculating the cross section with $\mathrm{SCET}^{(0)}$ we exactly get the leading-power result

$$\mathrm{d}\sigma^{(0)} = \langle \mathrm{SCET}^{(0)} \rangle$$

- Holds to all orders in α_s
  - Can use SCET to perform resummation with EFT methods
- Also holds nonperturbatively
  - E.g. PDFs defined in QCD and SCET are the same (in both cases the power expansion being the usual twist expansion)
  - Can also define and study other nonperturbative operator matrix elements, e.g. can include hadronization through nonperturbative soft functions

Soft-Collinear Effective Theory (SCET).

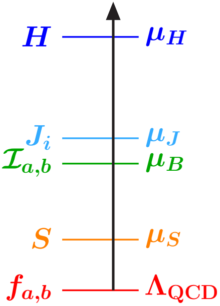
EFT systematically separates relevant momentum scales



Hard interaction

ISR and FSR
Collinear to incoming and outgoing primary partons

Soft radiation
no preferred direction



$$\mathrm{d}\sigma = \text{Hard} \otimes \text{PDFs} \otimes \text{ISR} \otimes \text{FSR} \otimes \text{Soft}$$

$$H(\mu) \times \Big[\big(f_{a,b}(\mu) \otimes \mathcal{I}_{a,b}(\mu)\big) \times \prod_j J_j(\mu)\Big] \otimes S(\mu)$$

- Factorization properties of QCD in soft/collinear limit are manifest in SCET at Lagrangian level
- All pieces are defined through renormalized operator matrix elements
- Resummation is performed by deriving associated RGEs and using their solution to run from one scale to the next

Simplest Case: Multiplicative RGE (Hard Function).

$$\mu \frac{\mathrm{d}H(Q,\mu)}{\mathrm{d}\mu} = \gamma_H(Q,\mu)\, H(Q,\mu)$$

- Formal solution

$$H(Q,\mu) = H(Q,\mu_0) \times \exp\biggl[\int_{\mu_0}^{\mu} \frac{\mathrm{d}\mu'}{\mu'} \gamma_H(Q,\mu')\biggr]$$
$$\equiv H(Q,\mu_0) \times U_H(\mu_0,\mu)$$

- Evolution factor $U_H(\mu_0,\mu)$ sums logarithms $\ln^n(\mu_0/\mu)$
  - A priori it only *shifts* logarithms from $\ln^n(Q/\mu_0)$ to $\ln^n(Q/\mu)$
- *Resummation* requires appropriate choice of $\mu_0 = \mu_H \simeq Q$

$$H^{\mathrm{resum}}(Q,\mu) = \underbrace{H^{\mathrm{FO}}(Q,\mu_H \simeq Q)}_{1+\alpha_s+\cdots} \times U_H(\mu_H \simeq Q,\mu)$$

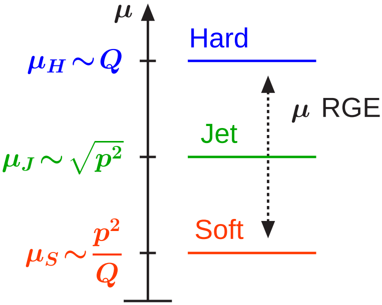
  - Boundary condition $H(Q,\mu_H)$ is free of logarithms (or we can neglect the effects of unresummed but now-small logarithms $\ln(Q/\mu_H)$)
  - Residual dependence on μ_H allows us to probe intrinsic resummation uncertainties by varying μ_H around its canonical value Q

Resummation Structure in SCET$_\mathrm{I}$

For observables that constrain invariant mass p^2 (or $p^+ = p^0 - |\vec{p}|$)

- e^+e^- event shapes: thrust, C-parameter
- mass-variables: jet mass, dijet invariant mass
- N-jettiness

$$\ln^2\frac{p^2}{Q^2} = 2\ln^2\frac{Q}{\mu} - \ln^2\frac{p^2}{\mu^2} + 2\ln^2\frac{p^2}{Q\mu}$$



- Arbitrary scale μ drops out, such that RGE sums logs of scale ratios

$$\ln\frac{\mu_J^2}{\mu_H^2}\,, \qquad \ln\frac{\mu_S^2}{\mu_J^2}\,, \qquad \ln\frac{\mu_S}{\mu_H}$$

- Logs $\ln(p^2/Q^2)$ are resummed with canonical boundary scale choices

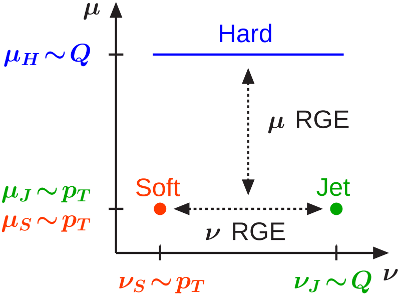
$$\mu_H = Q\,, \qquad \mu_J^2 = p^2 = \mu_H\mu_S\,, \qquad \mu_S = p^2/Q$$

Resummation Structure in SCET$_{\text{II}}$

For observables that constrain transverse momentum p_T

- Drell-Yan or Higgs q_T, jet-p_T
- N-jettiness with p_T-like measures (as used e.g. in N-subjettiness)

$$\ln^2 \frac{p_T}{Q} = 2\ln^2 \frac{Q}{\mu} + 2\ln\frac{p_T}{\mu}\ln\frac{\nu}{Q} + \ln\frac{p_T}{\mu}\ln\frac{\mu\, p_T}{\nu^2}$$



- Arbitrary scales μ and ν must drop out (RG consistency), such that RGE sums logs of scale ratios

$$\ln\frac{\mu_B}{\mu_H}\,, \qquad \ln\frac{\mu_S}{\mu_H}\,, \qquad \ln\frac{\nu_S}{\nu_B}$$

- Logs $\ln(p_T/Q)$ are resummed by canonical boundary scale choices

$$\mu_H = Q\,, \qquad \nu_B = Q\,, \quad \mu_B = p_T\,, \qquad \mu_S = \nu_S = p_T$$

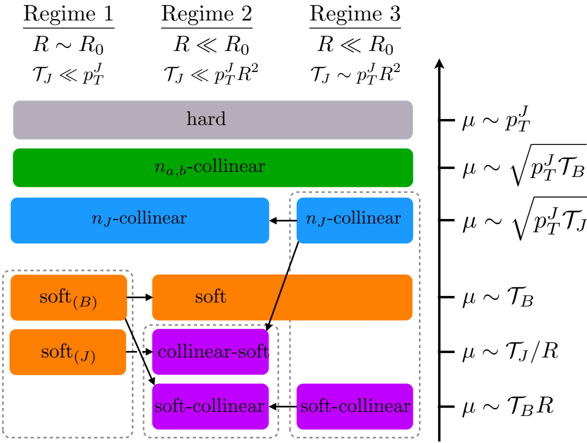
Multi-Scale Resummation.

Multi-scale problems with several power-counting parameters/expansions

- Can require sequence of EFTs

$$\text{QCD} \xrightarrow{\tau_1} \text{SCET}(\tau_1) \xrightarrow{\tau_2} \text{SCET}(\tau_2)$$

- Or more complicated SCET_+ setups accounting for additional intermediate scales



Resummation Orders.

- Fundamentally, resummation order is (or should be) strictly defined by perturbative input (fixed-order expansions) for the anomalous dimensions and boundary conditions
  - Counting logarithms as $\alpha_s \ln \sim 1$ in the Sudakov exponent maps directly onto this strict definition (only) when the RGE is multiplicative and its solution a pure exponential

	Boundary conditions (singular)	Anomalous dimensions $\gamma_{H,B,S,\nu}$	Γ_{cusp}, β	FO matching (nonsingular)
NLL	1	1-loop	2-loop	-
NLL′+NLO	α_s	1-loop	2-loop	α_s
NNLL+NLO	α_s	2-loop	3-loop	α_s
NNLL′+NNLO	α_s^2	2-loop	3-loop	α_s^2
N^{3}LL+NNLO	α_s^2	3-loop	4-loop	α_s^2
N^{3}LL′+N^{3}LO	α_s^3	3-loop	4-loop	α_s^3

Additional Remarks.

Analytical (RGE based) resummation

- System of RGEs encodes the all-order logarithmic structure
- Corresponding or equivalent evolution equations can be obtained directly by studying the soft-collinear limit of QCD
  - e.g. CSS formalism [Collins, Soper, Sterman '81-'85]
- Once the correct differential equations are known, resummation ultimately amounts to solving a coupled system of more-or-less complicated differential equations
- Different choices and approximations people make along the way should not be perceived as differences between SCET and "direct QCD"

Numerical (Monte-Carlo based) approaches

- Numerically sum up contributions from multiple soft-collinear emissions
- Parton showers matched to FO
  - Provide convenient lowest-order prediction across phase space
- Can also be applied at higher order for classes of observables
  [Banfi, Salam, Zanderighi '01-'04, Banfi, McAslan, Monni, Zanderighi '14]

($\rightarrow$ see talks by C. Bauer, Z. Nagy, D. Reichelt, ...)

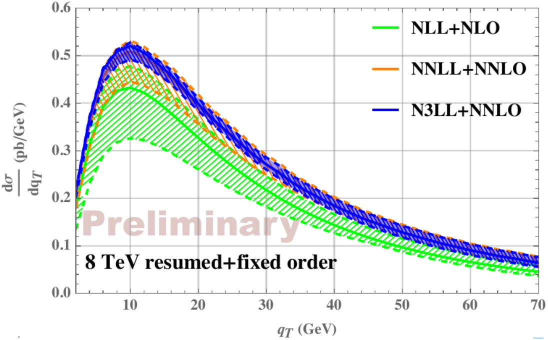
Some Recent Results.

q_T Resummation at N^{3}LL.

Required: 3-loop rapidity anomalous dimension [Li, Zhu, 1604.01404]

- Based on bootstrapping and new exponential regulator for rapidity divergences [Li, Neill, Zhu, 1604.00392]
- Result confirmed by [Vladimirov, 1610.05791, 1707.07606]
  - Maps rapidity divergences to UV divergences via conformal transformation, leading to all-order relation between soft and rapidity anomalous dimensions
  - Proof of factorization and renormalization of rapidity divergences

- Numerical results at N^{3}LL look promising [Li, Neill, Schulze, Stewart, Zhu, Advances in QCD 2016]
- Also used in [Bizon et al., 1705.09127] (→ see talk by P. Torrielli)



q_T Resummation in Momentum (Distribution) Space.

Essential nontrivial ingredient is the rapidity RGE [Chiu, Jain, Neill, Rothstein '12]

$$\nu \frac{\mathrm{d}S(\vec{p}_T, \mu, \nu)}{\mathrm{d}\nu} = \int \mathrm{d}^2\vec{k}_T\, \gamma_\nu(\vec{k}_T, \mu)\, S(\vec{p}_T - \vec{k}_T, \mu, \nu)$$

- Analogous evolution equation appears in all CSS or SCET based formulations
- Formal solution is easily obtained in either Fourier b-space or q_T-space

$$S(\vec{p}_T, \mu, \nu) = \int \frac{\mathrm{d}^2\vec{b}_T}{(2\pi)^2}\, e^{i\vec{p}_T\cdot\vec{b}_T}\, \tilde{S}(\vec{b}_T, \mu, \nu_0)\, \exp\Big[\ln\frac{\nu}{\nu_0}\tilde{\gamma}_\nu(\vec{b}_T, \mu)\Big]$$

$$= \int \mathrm{d}^2\vec{k}_T\, S(\vec{p}_T - \vec{k}_T, \mu, \nu_0)\Big[\delta(\vec{k}_T) + \sum_{n=1}^{\infty}\frac{1}{n!}\ln^n\frac{\nu}{\nu_0}\,(\gamma_\nu\otimes^n)(\vec{k}_T, \mu)\Big]$$

  - Both are exactly equivalent and correctly *shift* logs from ν_0 to ν (at fixed μ)
- Complication lies in correct treatment of boundary condition
  - Easy in b-space: $\tilde{S}(\vec{b}_T, \mu = \nu_0 = 1/b) = 1 + \alpha_s + \cdots$
  - Resummation in b space, resums conjugate logarithms $\ln(Qb)$

q_T Resummation in Momentum (Distribution) Space.

- Several previous attempts [Dokshitzer, Diakonov, Troian ’78-’80; Ellis, Veseli ’97; Frixione, Nason, Ridolfi ’98; Kulesza, Stirling ’99-’01]
  - Naive boundary choice $\nu_0 = q_T$ leads to spurious divergences (causes mistreatment of energetic emissions that balance to give small q_T)
  - One cannot count logarithms $\ln^n(q_T/Q)$ (in the spectrum or cumulant)

Complete momentum-space solution [Ebert, FT, 1611.08610]

- Directly resums $[\ln^n(q_T^2/Q^2)/q_T^2]_+$ in physical q_T distribution
- Valid to any desired resummation order (strictly defined via anom. dim.)
- Requires new distributional scale setting
- Analogous nonpert. sensitivity in rapidity evolution kernel as in b-space

Similar results based on coherent branching formalism

[Bizon, Monni, Re, Rottoli, Torrielli, 1604.02191, 1705.09127] ($\rightarrow$ see talk by P. Torrielli)

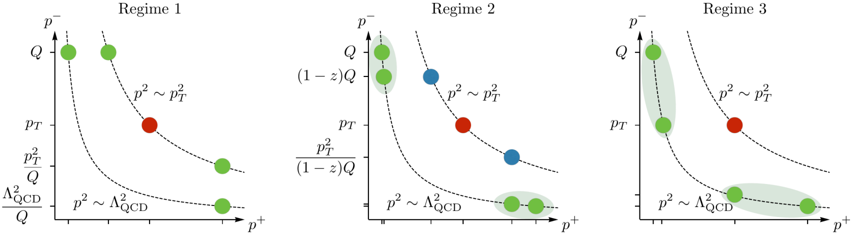
- Count and resum logs of k_T of hardest emission
- Differs from strict solution (by subleading logs and nonperturbative sensitivity), but allows for numerical implementation using Monte-Carlo methods

Joint q_T and Threshold Resummation Beyond NLL.

- Goal: simultaneously resum both q_T and threshold logs
  - Known before to NLL [Li '98; Banfi, Kulesza, Laenen, Sterman, Vogelsang '00-'04]

Extension to in principle any order [Lustermans, Waalewijn, Zeune, 1605.02740]

[see also Marzani, Theeuwes, 1612.01432; Muselli, Forte, Ridolfi, 1701.01464]



- Regime 1: $q_T/Q \ll 1-z \sim 1$: q_T resummation ($\mathrm{SCET_{II}}$)
- Regime 2: $q_T/Q \ll 1-z \ll 1$: joint resummation (SCET_+)
  - Similar to previous multi-differential (joint) resummations
    [Bauer, FT, Walsh, Zuberi '11; Procura, Waaelwijn, Zeune '14; Larkoski, Moult, Neill '15]
- Regime 3: $q_T/Q \sim 1-z \ll 1$: threshold resummation ($\mathrm{SCET_I}$)

$\Rightarrow$ All ingredients known for NNLL′ resummation

Form factor $H(q^2, \mu)$ contains $\ln^n[(-q^2 - \mathrm{i}0)/\mu^2]$

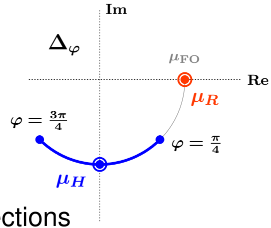
[Altarelli, Ellis, Martinelli '79; Parisi '80; Sterman '87; Magnea, Sterman '90; Eynck, Laenen, Magnea '03]

- For timelike $q^2 > 0$ and $\mu_{\rm FO} \simeq q^2$ contains large timelike logs $\ln^2(-1) = -\pi^2$
  - Can be resummed by evolving H from $\mu_H^2 \simeq -q^2$ to $\mu_{\rm FO}$
  - Applied to $gg \to H$ total cross section [Ahrens, Becher, Neubert, Yang '08]

Application to generic inclusive cross section differential in Born kinematics X [Ebert, Michel, FT, 1702.00794]

$$\sigma^{\rm FO}(X) = H(q^2, \mu_{\rm FO}) \times R(X, \mu_{\rm FO})$$

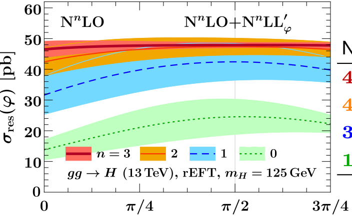
$$\Rightarrow \quad \sigma^{\rm resum}(X) = H(q^2, \mu_H)\, U_H(\mu_H, \mu_{\rm FO}) \times R(X, \mu_{\rm FO})$$



- In soft/collinear limit H factors out up to power corrections
- For inclusive cross sections, important to
  - consistently reexpand $H(\mu_H)R(\mu_{\rm FO})$ to avoid spurious higher-order terms and to recover FO result in the limit where $\mu_H \to \mu_{\rm FO}$
  - check that there are no large cancellations between H and R that might be spoiled by resummation

Resummation Improved Higgs Spectra.

[Ebert, Michel, FT, 1702.00794]



$\sigma^{\rm rEFT} + \delta\sigma^t$ [pb], $\sqrt{s} = 13$ TeV, $m_H = 125$ GeV

$\mathrm{N}^n\mathrm{LO}$ $\mu_{\rm FO} = m_H$	$\mu_{\rm FO} = m_H/2$	$\mathrm{N}^n\mathrm{LO}+\mathrm{N}^n\mathrm{LL}'_\varphi$
$46.3 \pm 2.5_\mu (5.5\%)$	$47.7 \pm 1.7_\mu (3.7\%)$	$47.7 \pm 0.8_\mu \pm 0.2_\varphi (1.7\%)$
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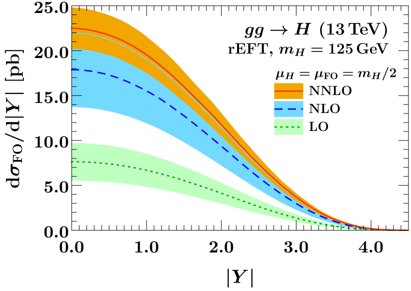

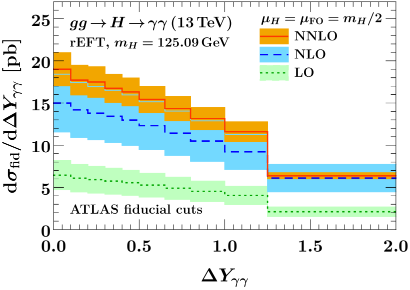

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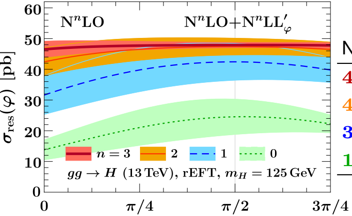

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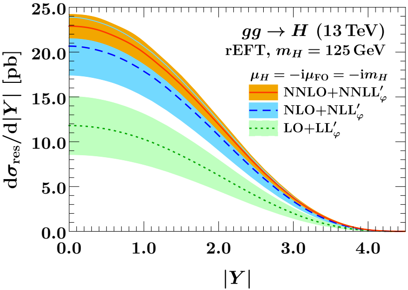

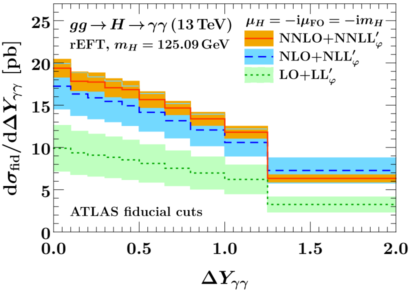

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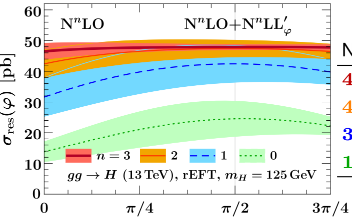

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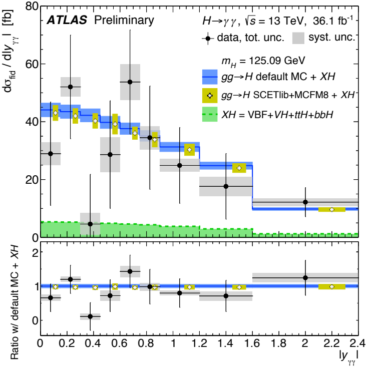
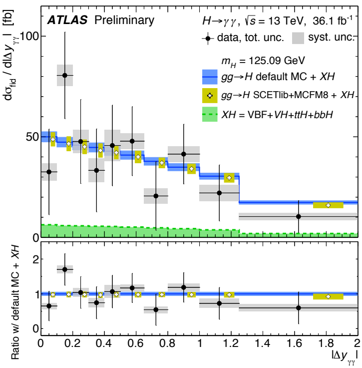
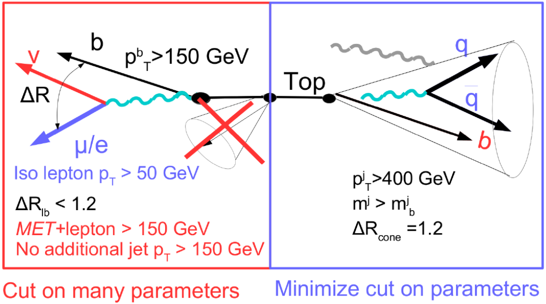
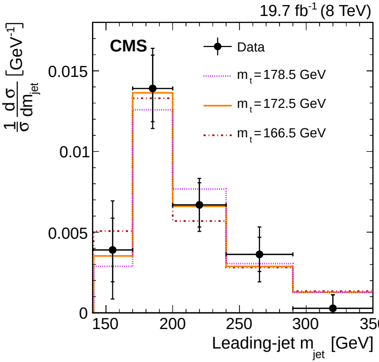




Top Mass from Boosted Top Jets.



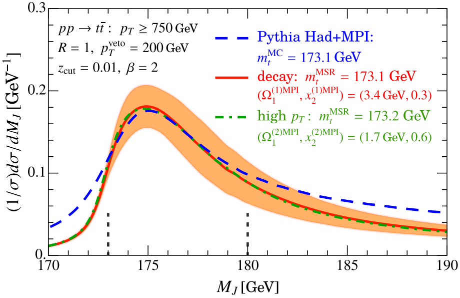


Boosted top production: $pp \to t\bar{t}$ at $p_T \gg m_t$

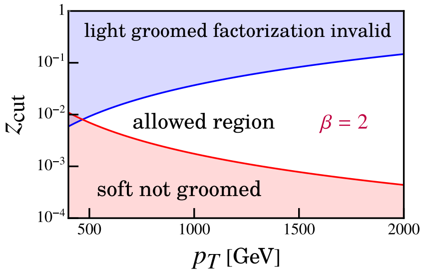
- Top quarks are boosted enough so they can be reconstructed as a single (fat) top jet
- Jet mass of the top-jet is directly sensitive to top quark mass
- Starting to get measured by experiments
  ($\to$ see talks by F. Stober, A. Buckley)

$$m_t = 170.8 \pm 6.0\text{(stat)} \pm 2.8\text{(syst)} \pm 4.6\text{(model)} \pm 4.0\text{(theo)}\ \mathrm{GeV}$$

Top Mass from Boosted Top Jets.



[Hoang, Mantry, Pathak, Stewart, 1708.02586]



Factorization-based resummed (so far NLL) hadron-level predictions

- Light soft-drop grooming [Larkoski, Marzani, Soyez, Thaler ’14]
  - Reduces MPI/UE effects while retaining explicit control of top mass scheme
- Can measure well-defined m_t by fitting to hadron-level theory predictions
- And/or calibrate Monte-Carlo mass by fitting MC to theory predictions
  - Pythia8 mass parameter is not the same as the pole mass
  - Consistent with earlier findings from $e^+e^- \to t\bar{t}$ [Butenschoen, Dehnadi, Hoang, Mateu, Preisser, Stewart, 1608.01318]

Resummation for groomed jet mass for light jets
[Frye, Larkoski, Schwartz, Yan, 1603.09338, Marzani, Schunk, Soyez, 1704.02210]

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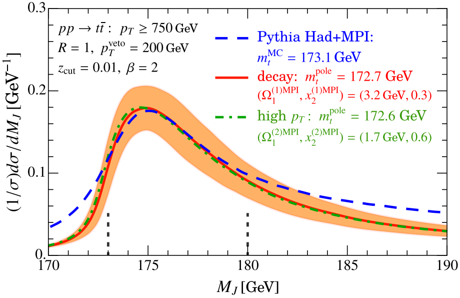

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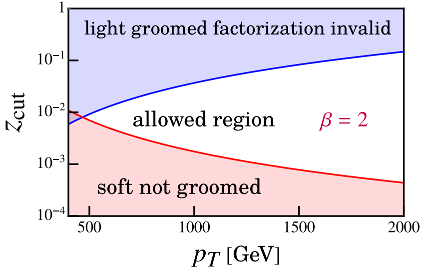

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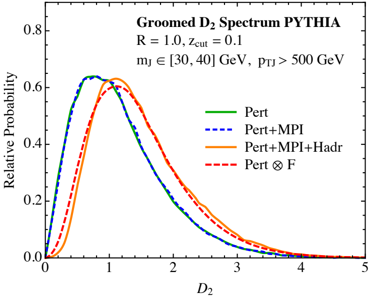
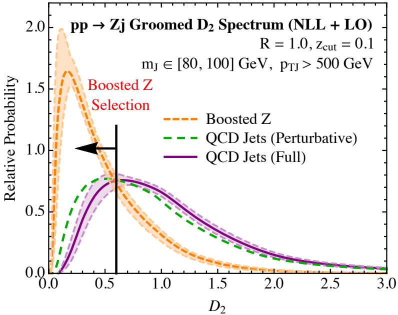
Analytic Predictions for Groomed Jet Substructure.

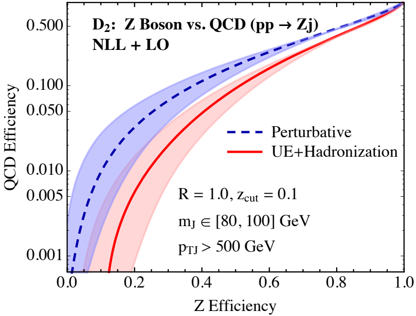
[Larkoski, Moult, Neill, 1708.06760]

Resummed hadron-level predictions for groomed 2-prong jet substructure variable D_2

- Based on multi-scale SCET_+ setup
- Grooming removes MPI effects
- Hadronization effects taken into account via nonperturbative shape function







N-Jettiness Subtractions.

[Boughezal, Focke, Liu, Petriello ’15; Gaunt, Stahlhofen, FT, Walsh ’15]

$$\sigma = \underbrace{\sigma^{\rm sub}(\tau_{\rm cut})}_{\text{NNLO}_N} + \underbrace{\int_{\tau_{\rm cut}} d\tau_N \frac{d\sigma}{d\tau_N}}_{\text{NLO}_{N+1}} + \underbrace{\sigma(\tau_{\rm cut}) - \sigma^{\rm sub}(\tau_{\rm cut})}_{\text{neglect}}$$

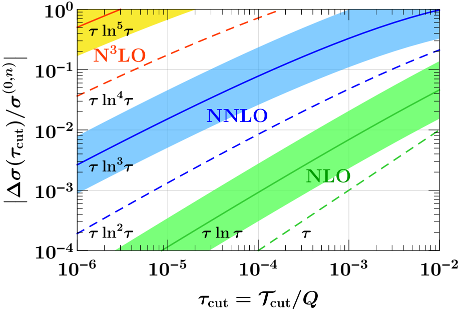
- Subtractions correspond to leading-power terms, which are obtained using N-jettiness factorization theorem in SCET [Stewart, FT, Waaelwijn ’09, ’10]

$$\sigma^{\rm sub}(\tau_{\rm cut}) = \sigma^{(0)}(\tau_{\rm cut})\,[1 + \mathcal{O}(\tau_{\rm cut})]$$

- Neglected terms are

$$\Delta\sigma(\tau_{\rm cut}) = \sigma(\tau_{\rm cut}) - \sigma^{\rm sub}(\tau_{\rm cut}) = \mathcal{O}(\tau_{\rm cut})$$

- However, power corrections also have up to two logs per α_s order
  - Knowing even the LL at next-to-leading power provides significant improvement

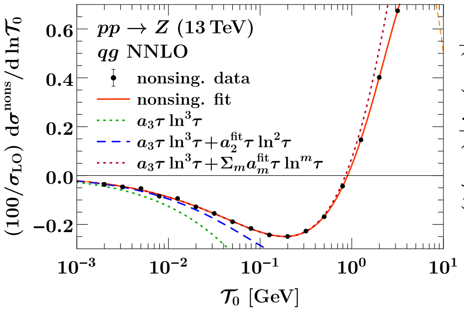


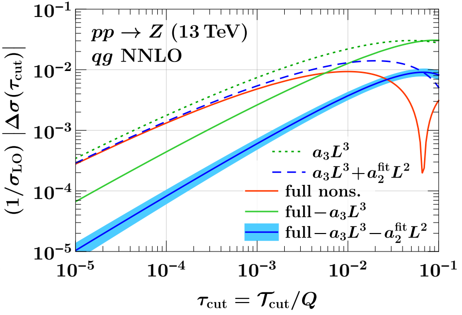
Power Corrections for N-Jettiness Subtractions.

[Moult, Rothen, Stewart, FT, Zhu, 1612.00450, 1709.sooon]

SCET provides the tools to systematically study power corrections

- Explicitly constructed to maintain manifest power counting
- Provides organization of different sources of power corrections
  - Insertions of subleading SCET Lagrangian
  - Subleading hard-scattering operators [Feige, Kolodrubetz, Moult, Stewart, Vita '17]
  - Subleading corrections to the measurement/observable





Alternative: Analytically expand NLO V+j calculation [Boughezal, Liu, Petriello '16]

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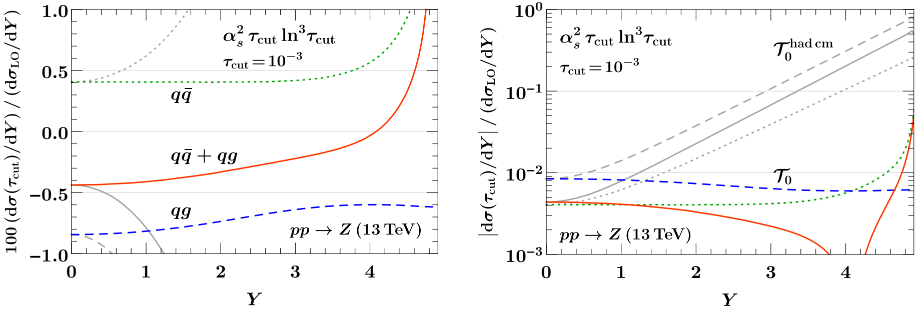
  - Subleading corrections to the measurement/observable
- It is crucial to use the right N-jettiness definition, otherwise power corrections can grow exponentially with rapidity



Summary.

Active field with many applications, really only gave you a glimpse

- Resummation is important whenever measurements are sensitive (directly or indirectly) to infrared QCD dynamics (happens more often than not)
  - Even when fixed-order predictions work, resummation can often add perturbative information and improve predictions (smaller and better understood uncertainties)
- SCET applies powerful EFT toolset to study infrared/soft-collinear regime of QCD
  - Includes systematic control of power corrections and nonperturbative effects
- Standard applications of resummation being pushed to higher precision
- Moving toward tackling multi-scale problems
  - Jet substructure, jet-radius logarithms, quark mass effects, ...
- Many things I could not cover (apologies ...)
  - Threshold resummation ($\to$ talks by A. Kulesza, A. Broggio, C. Schwinn)
  - heavy-ion, e^+e^- collisions ($\to$ talk by Z. Tulipánt)
  - Forward scattering, factorization breaking effects, nonglobal logs
  - ...