Effective field theories for precision b-jet substructure

Christopher Lee
T-2

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T-2 Effort and Affiliated Scientists

Co-I Christopher Lee

Leading effective field theory (EFT) effort on *b*-jets in *pp* collisions

Postdoc Varun Vaidya

Constructing effective field theory and performing analytic calculations for *b*-jet substructure.

PhD student Prashant Shrivastava (CMU)

Monte Carlo simulations and EFT calculations to explore and test best variables to probe *b*-jet substructure. DR supported Summer 2017 visit to LANL, ongoing collaboration.

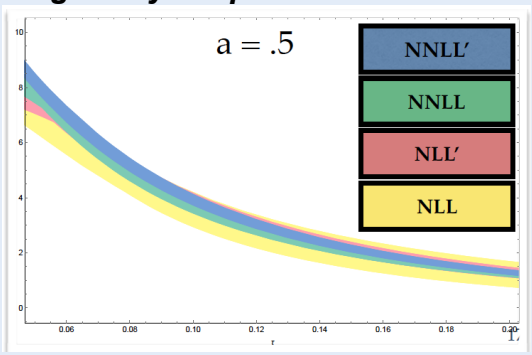
Affiliated LANL scientists: Duff Neill (Feynman Fellow), Yiannis Makris (postdoc)

Improved observables and EFT calculation for transverse-momentum-dependent jet phenomenology.

SCET and precision jet structure

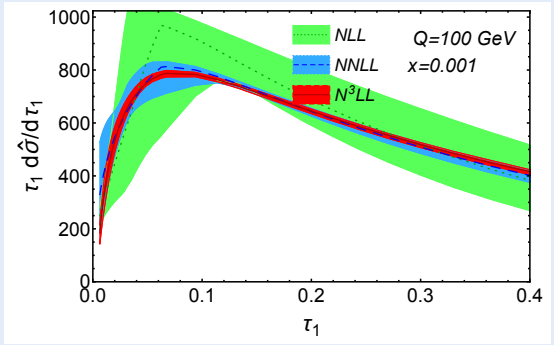
Powerful EFT methods (Soft Collinear Effective Theory = SCET) developed in 2000s leading to *vast improvements* in accuracy of jet cross sections in e+e-, ep, and pp collisions:

Angularity shapes in e⁺e⁻ to NNLL'



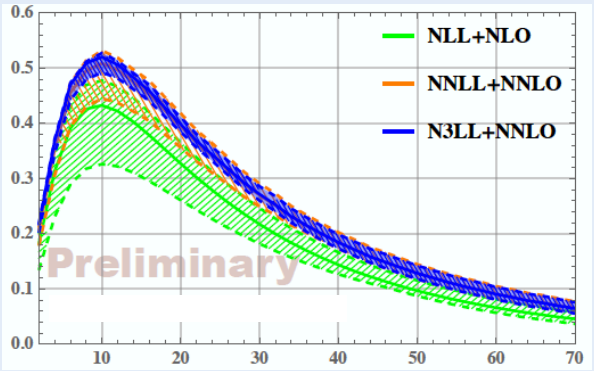
A. Hornig, C. Lee (LANL), G. Bell, J. Talbert (2017)

1-jettiness shapes in ep to NNNLL



D. Kang, C. Lee (LANL), I. Stewart (2016)

Drell-Yan qT distribution



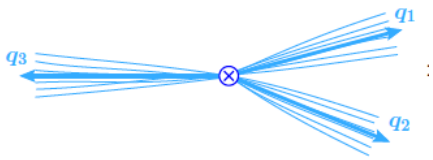
Y. Li, **D. Neill (LANL),** et al. (2016)

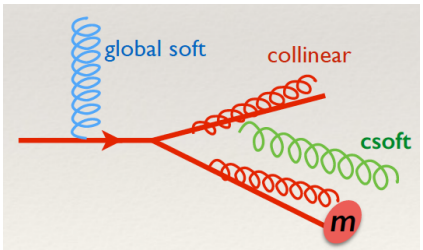
New versions of SCET introduced in 2010s applicable to more differential probes of jet *substructure*:

SCET+

Bauer et al. (2011)

for subjets and jet substructure

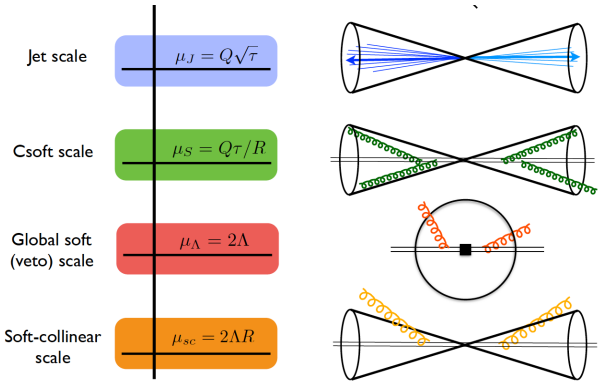




SCET++

for jet cones and algorithms

Y.-T. Chien, A. Hornig, C. Lee (LANL) (2015)



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New observables to probe jet substructure

C. Lee, P. Shrivastava, V. Vaidya formed collaboration to apply two recent theoretical ideas in jet physics to precision b-jet substructure:

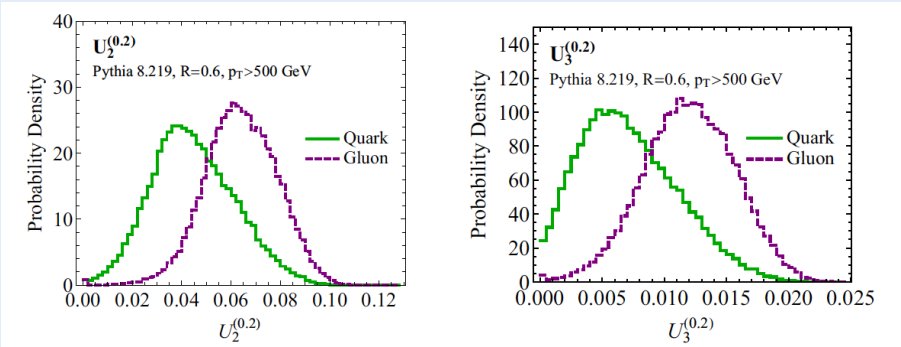
Energy correlation functions:

$$U_1^\alpha = \sum_{1\le i<j<n_J} z_i z_j \theta_{ij}^\alpha$$

Moult, Necib, Thaler (2016)

$$U_2^\alpha = \sum_{1\le <j<k<n_J} z_i z_j z_k \min\{\theta_{ij}^\alpha, \theta_{ik}^\alpha, \theta_{jk}^\alpha\}$$

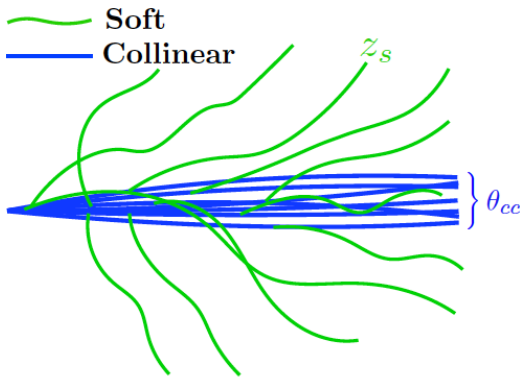
shown to be excellent light quark jet vs. gluon jet discriminants:



and designed to be well suited for analytic calculation using factorization and resummation in SCET

Jet Grooming:

"Soft Drop" algorithm: Larkoski, Marzani, Soyez, Thaler (2014)



Step through branching history of reclustered jet.

Remove branches failing **soft drop** condition:

$$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti} + p_{Tj}} > z_{\text{cut}}$$

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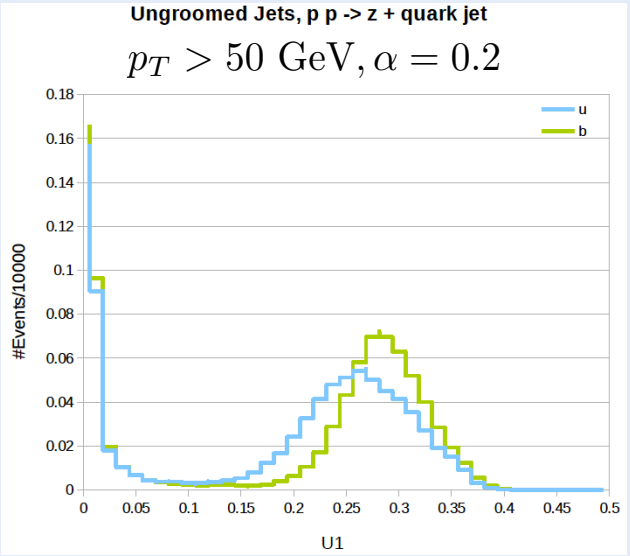
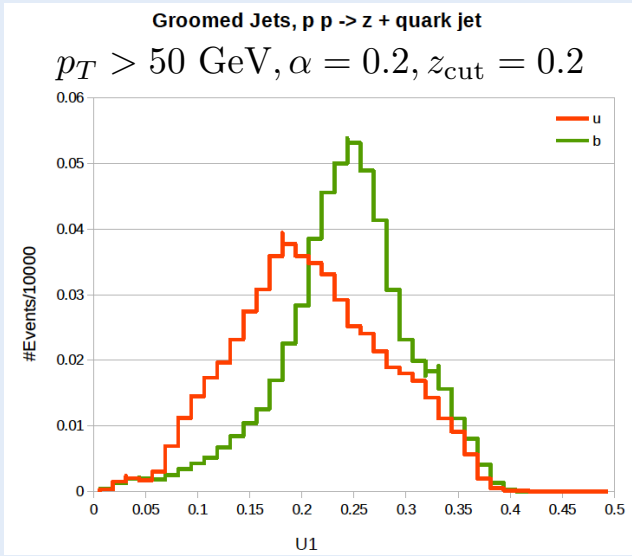
Performance on b-jets in Monte Carlo

***Combining* jet grooming with energy correlators provides cleaner distributions for light jets and *b* jets:**

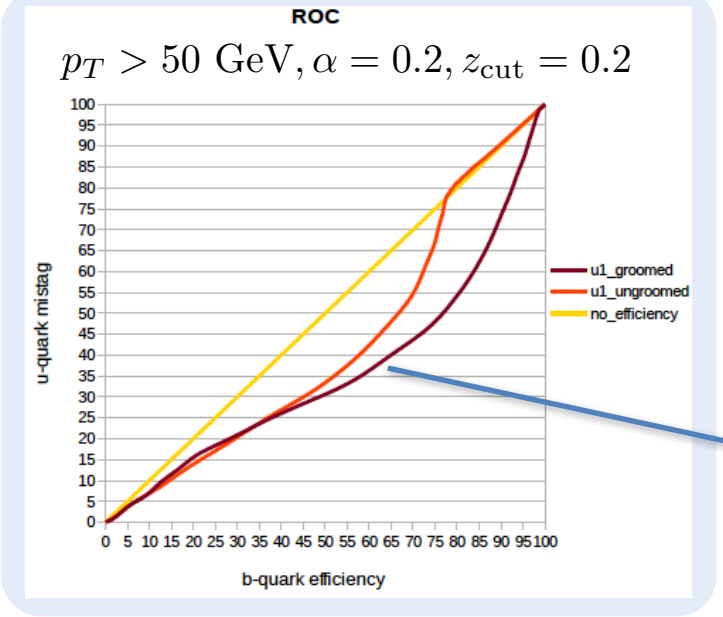
$$U_1^\alpha = \sum_{1 \le i < j < n_J} z_i z_j \theta_{ij}^\alpha$$





Performance in distinguishing light and heavy quark jets:

Better performance for groomed variable than ungroomed



e.g.
keep ~65% b-jets, ~35% light jets

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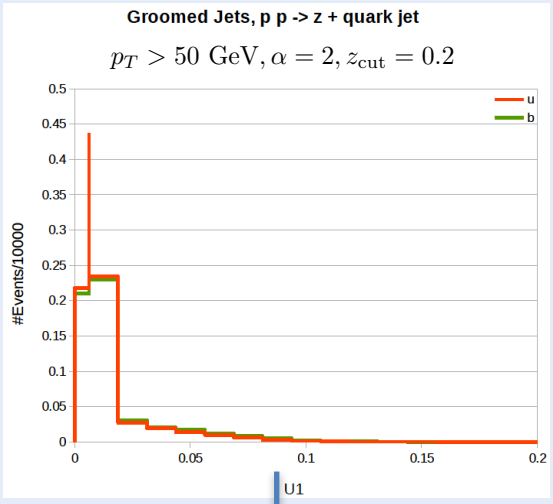
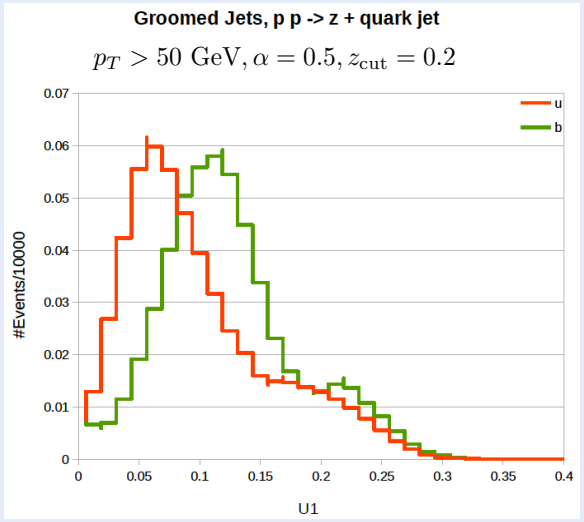
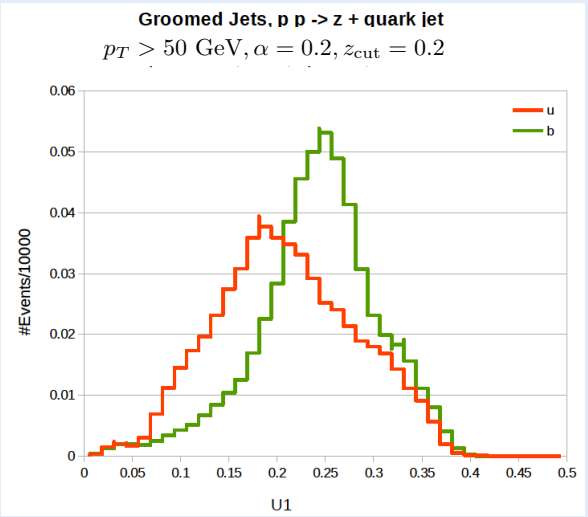
Performance on b-jets in Monte Carlo

Varying angular exponent in energy correlator can enhance discriminating power: $U_1^\alpha = \sum_{1 \le i < j << n_J} z_i z_j \theta_{ij}^\alpha$







Little to no discriminating power

improved discriminating power

Motivates theoretical calculations:

predict groomed U_1 distributions using EFT

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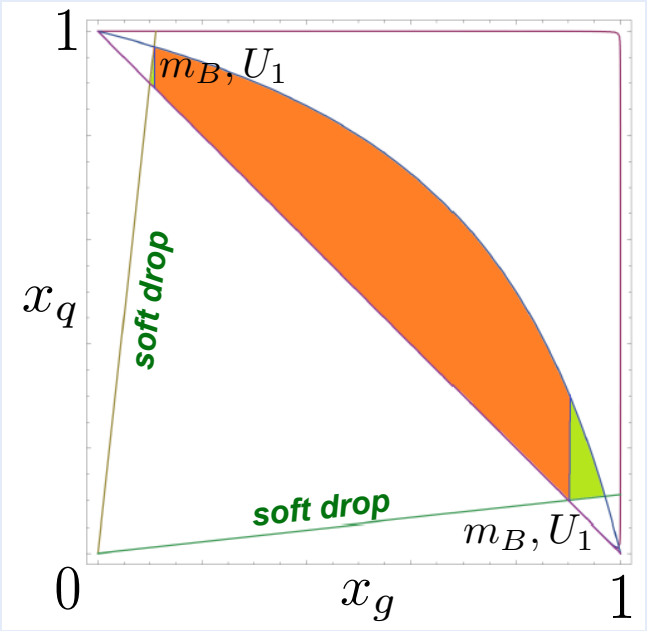
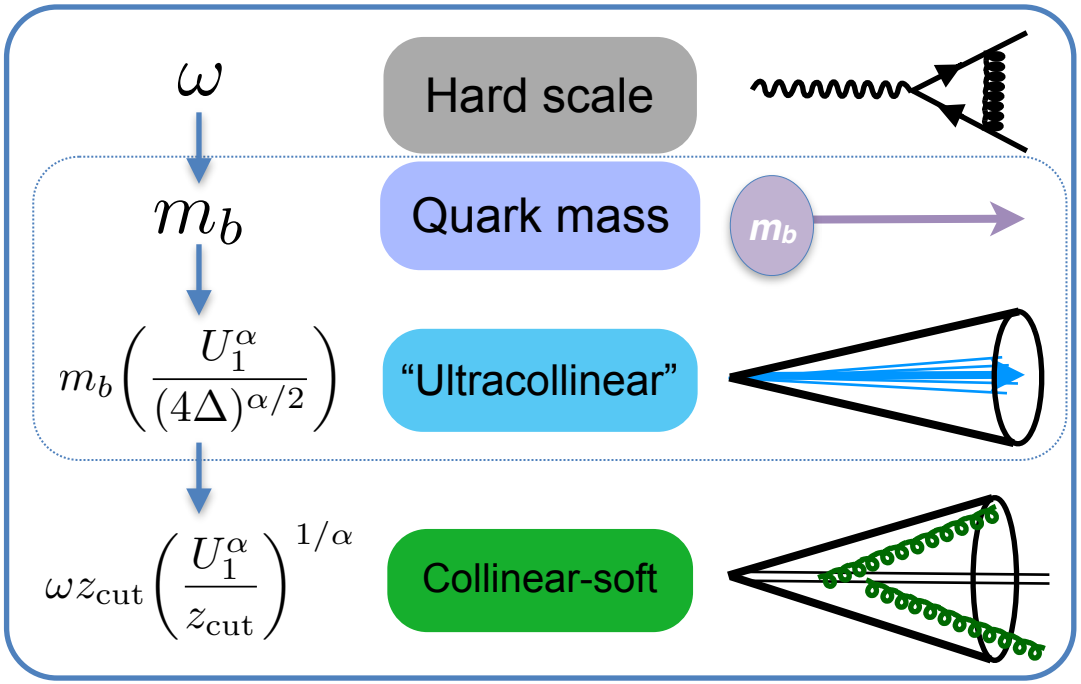
Progress on analytic EFT predictions

Performed one-loop (one-gluon emission) EFT calculation for massive quark U_1^α

Phase space in quark/gluon energy fraction



Hierarchy of scales defining EFT: **SCET$_+$ + HQET**



E.g. ordinary SCET jet functions, factors into separate "ultracollinear" and HQET matching functions:

$$J = \frac{\alpha_s C_F}{\pi}\left(\frac{1}{\alpha-1}L_C^2 + L_V^2 + L_C + \frac{1}{2}L_V\right)$$

$$L_C = \ln\left(\frac{\mu}{\omega U_1^\alpha}\right)\Delta^{\frac{\alpha-1}{2}} \qquad \Delta = \frac{m^2}{\omega^2}$$

$$L_V = \ln\frac{\mu}{m}$$

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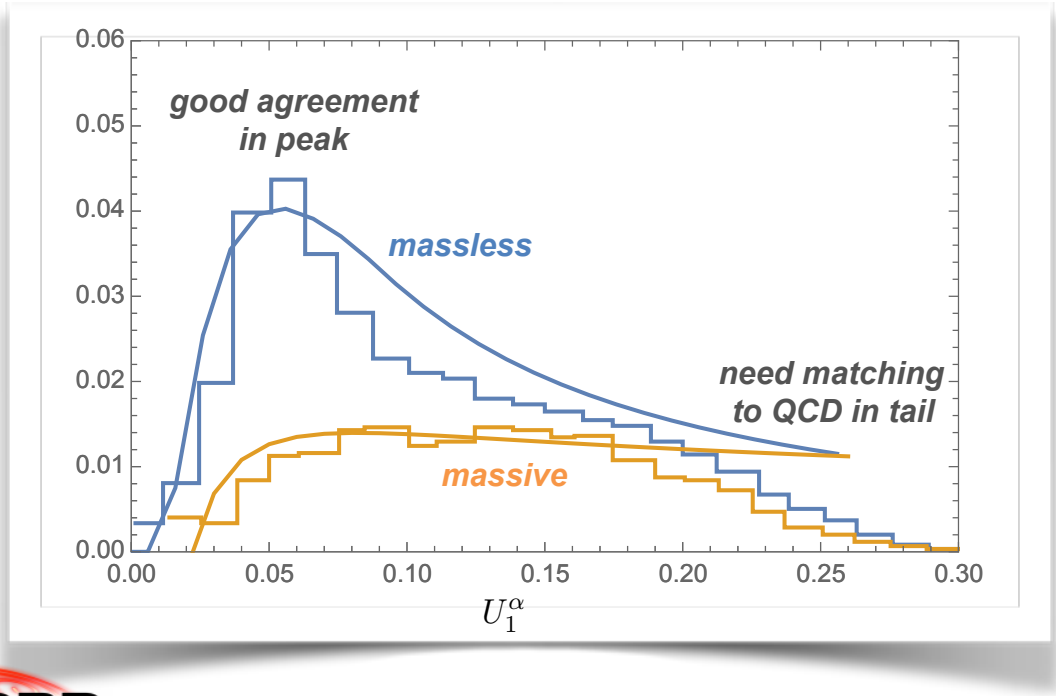
Progress on analytic EFT predictions

Computed all needed anomalous dimensions to one-loop accuracy, enough for NLL accuracy of resummed cross section:

$$\frac{1}{\sigma_0}\frac{d\sigma}{dU_1^\alpha} = \frac{1}{e_2^{(\alpha)}} Exp\left(K_{H_+}(\omega,\mu_0^{H_+}) + K_{CS}(\omega,\mu_0^{CS}) + K_{B_+}(\omega,\mu_0^{B_+})\right)\left[\Gamma\left(-\frac{2}{\alpha}\omega_{CS}(\omega,\mu_0^{CS}) - 2\omega_{B_+}(\omega,\mu_0^{B_+})\right)\right]^{-1}$$

shape of massless and massive quark jet distributions vs. Pythia Monte Carlo (partonic):



Timeline:

FY17: Monte Carlo tests of jet observables and grooming ✓

early FY18: NLL perturbative calculations of groomed jet observables ✓

Spring/Summer FY18:

- matching to fixed-order QCD in tail region
- model of nonperturbative effects, universality in endpoint region
- publication on EFT predictions of groomed heavy quark jet substructure

FY19:

- effects of modification in QGP medium

LDRD innovation for our nation

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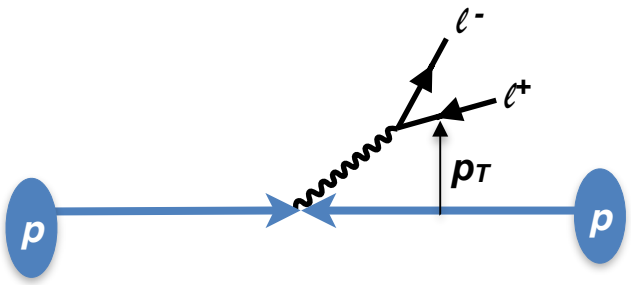
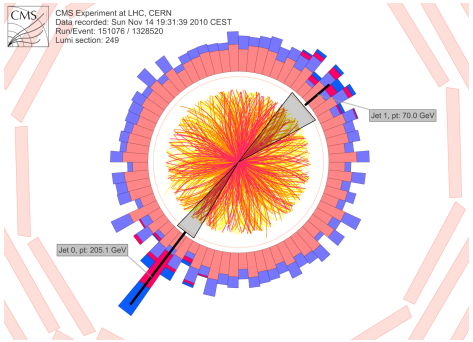
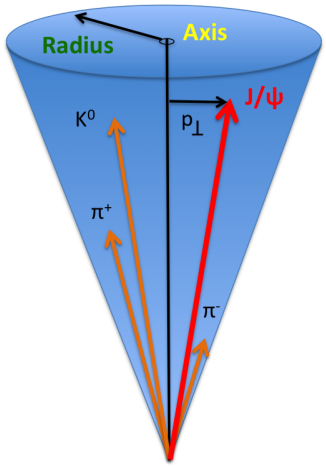
Related publications advancing TMD phenomenology

Transverse-momentum distributions of radiation within events and within jets play important role in probing QCD effects in *pp* and heavy-ion collisions:





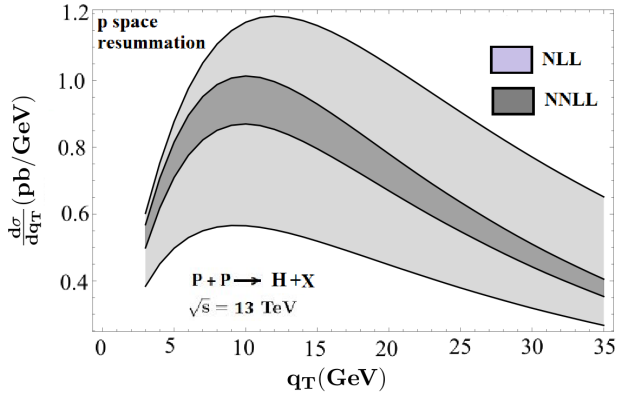


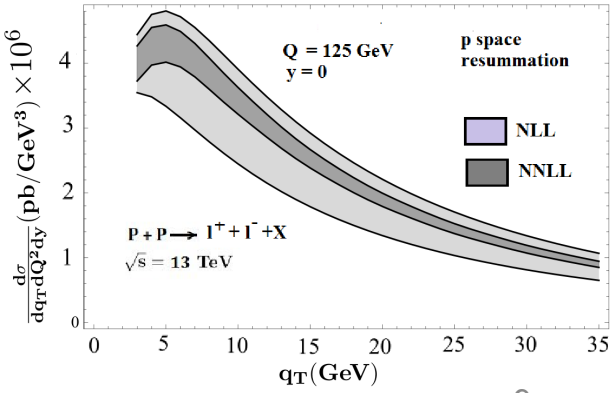
New EFT method for *analytic* resummation of transverse-momentum-dependent (TMD) cross sections:

D. Kang, C. Lee, V. Vaidya, *"A fast and accurate method for perturbative resummation of transverse momentum-dependent observables,"* under review by JHEP, LA-UR-17-27820 [arXiv:1710.00078]

Results shown for Drell-Yan processes; general method applicable to any TMD factorized observable

Invited talks at APS (VV 2/17), SF Jets (DK 2/17), SCET (VV 3/17), and UCLA (CL, 5/17)

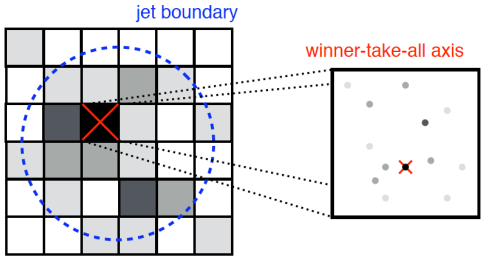


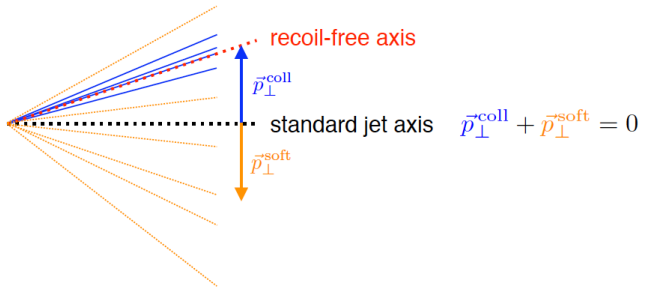


Related publications advancing TMD phenomenology

Improved definition of jet axes leading to more robust theoretical predictions and new *universal* TMD fragmentation functions

D. Neill, I. Scimemi, W. Waalewijn, *"Jet axes and universal transverse-momentum-dependent fragmentation,"* JHEP 1704 (2017) 020 [arXiv:1612.04817]



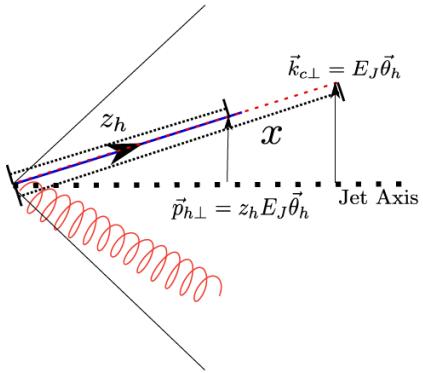


Jet axis insensitive to recoil of soft radiation

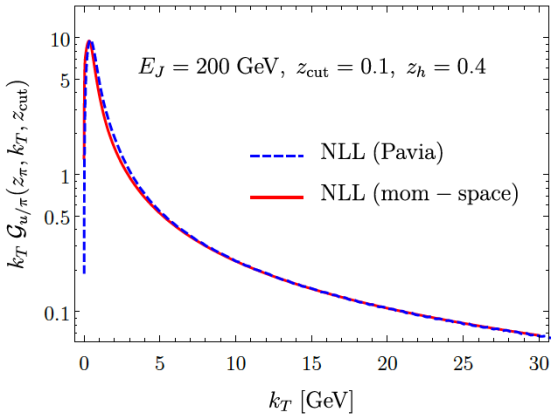
TMD Evolution of Groomed Jets providing sensitive probe of nonperturbative models of TMD hadron structure

Y. Makris, D. Neill, V. Vaidya, "*Probing transverse-momentum dependent evolution with groomed jets,*" under review by JHEP, LA-UR-17-31338 [arXiv:1712.07653]

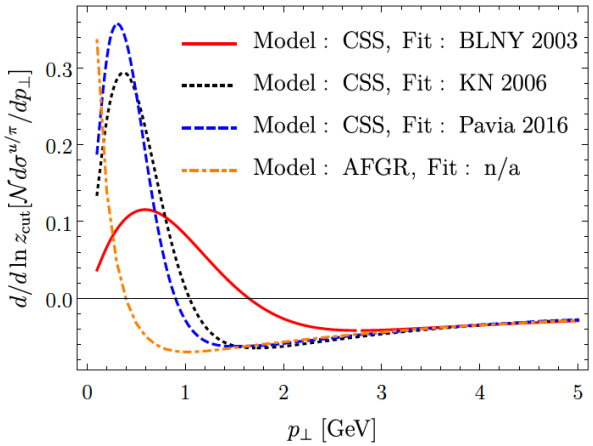
+ Invited talk at SF Jets (YM 1/18)



Hadron identified inside a jet



Perturbative TMD cross section vs. Monte Carlo

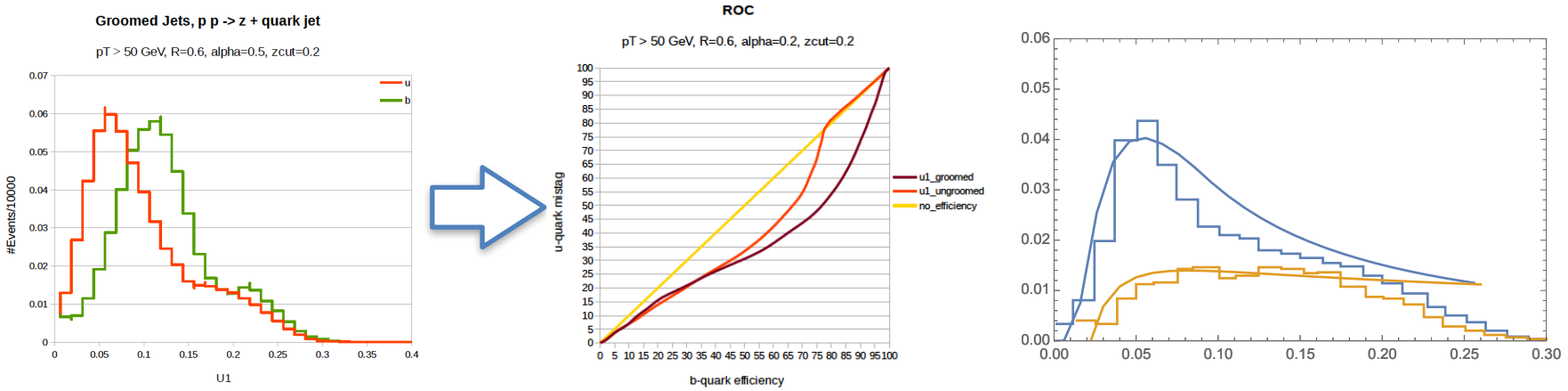


Distinguishing nonperturbative model predictions at low p_T

Summary of EFT Efforts

Advances on several fronts in applying EFT to precision jet phenomenology in hadron collisions

One paper on groomed *b*-jet substructure in preparation, **one talk** (VV) in preparation for SCET 2018.



Three papers submitted/published and **five invited talks** on TMD phenomenology in hadron collisions

Progress in FY18-19 will lead to more robust predictions for *b*-jet substructure in *pp* and heavy-ion collisions