Effective field theories for precision b-jet substructure

Christopher Lee
T-2

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.

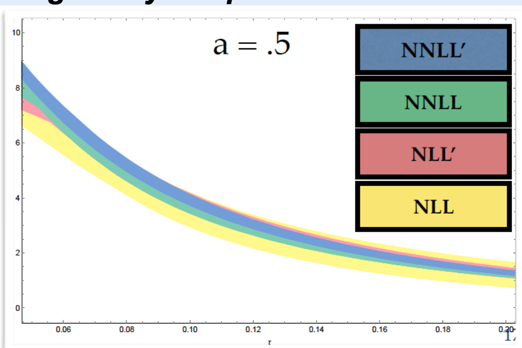
Affiliated LANL scientists: Duff Neill (Feynman Fellow), Yiannis Makris (postdoc)

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

SCET and precision jet structure

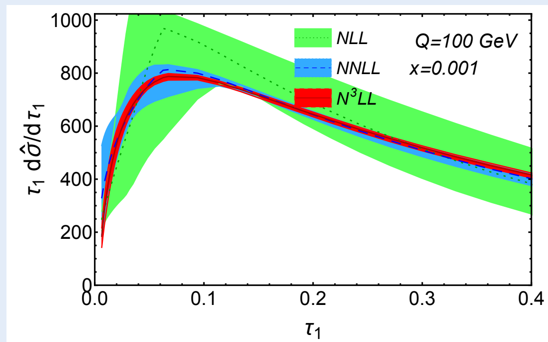
Powerful EFT methods (Soft Collinear Effective Theory = SCET) developed in 2000s leading to *vast improvements* in accuracy of jet cross sections in e+e-, ep, and pp collisions:

Angularity shapes in e⁺e⁻ to NNLL'



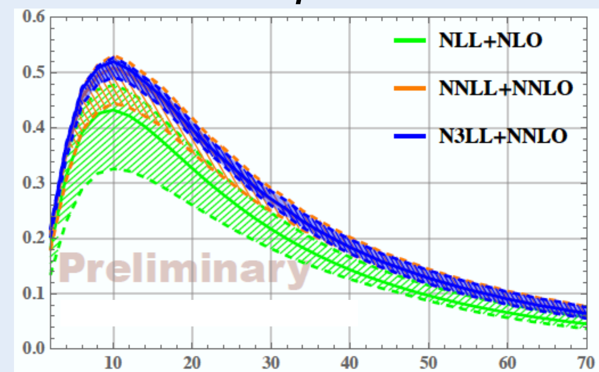
A. Hornig, C. Lee (LANL), G. Bell, J. Talbert (2017)

1-jettiness shapes in ep to NNNLL



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

Drell-Yan qT distribution

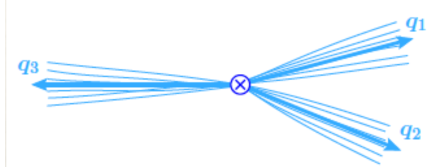


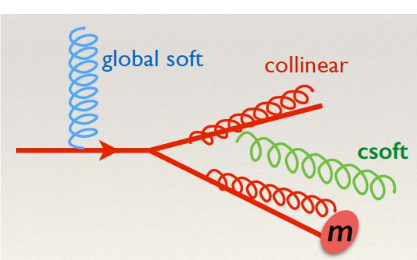
Y. Li, D. Neill (LANL), et al. (2016)

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

SCET₊ Bauer et al. (2011)

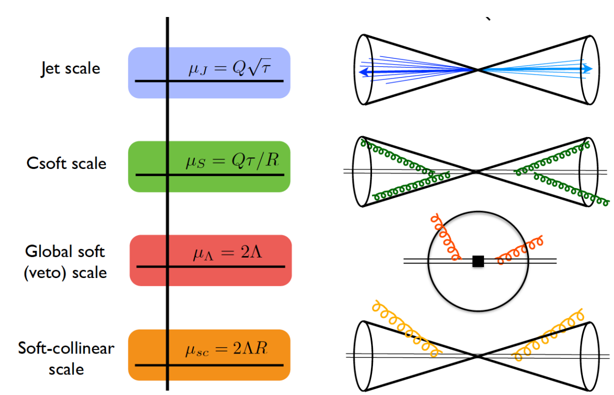
for subjets and jet substructure





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

for jet cones and algorithms



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:

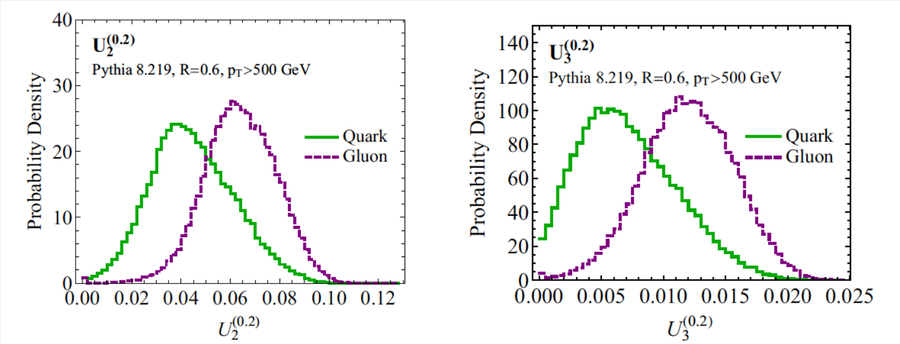
Energy correlation functions:

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

Moult, Necib, Thaler (2016)

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

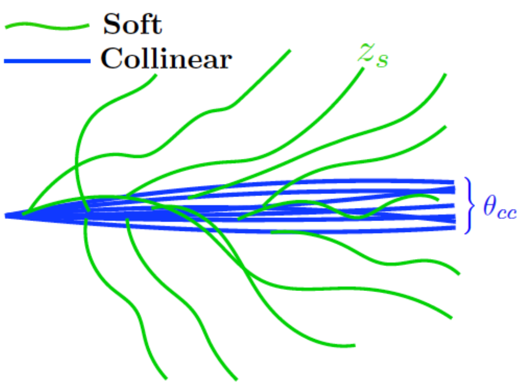
shown to be excellent light quark jet vs. gluon jet discriminants:



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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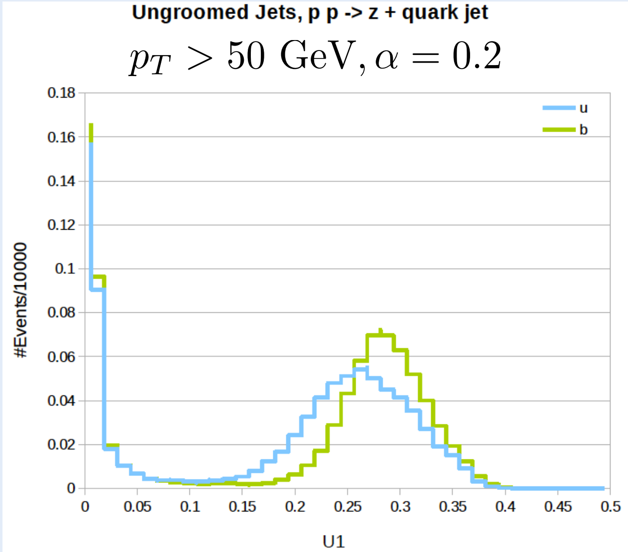
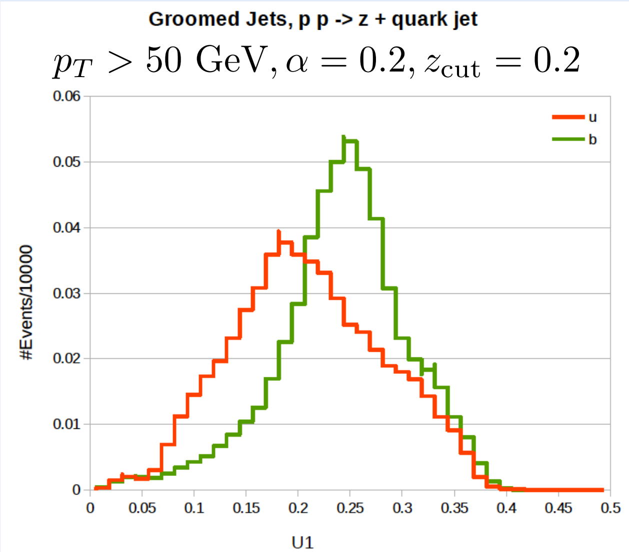
Performance on b-jets in Monte Carlo

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

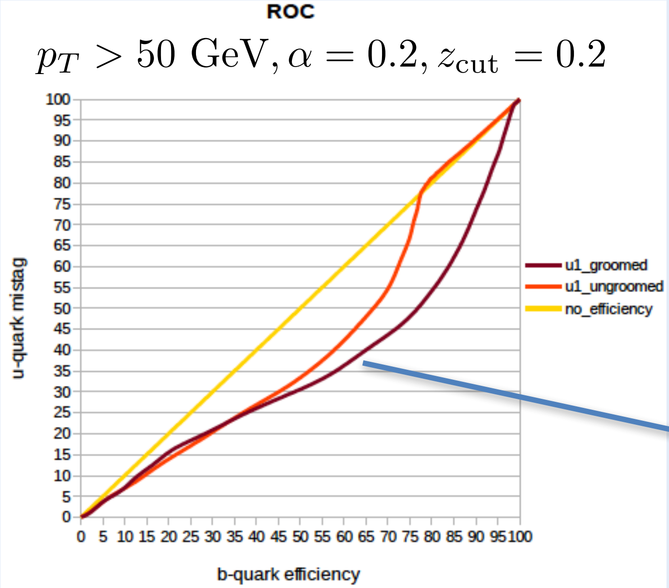
$$U_1^\alpha = \sum_{1 \le i < j < n_J} z_i z_j \theta_{ij}^\alpha$$





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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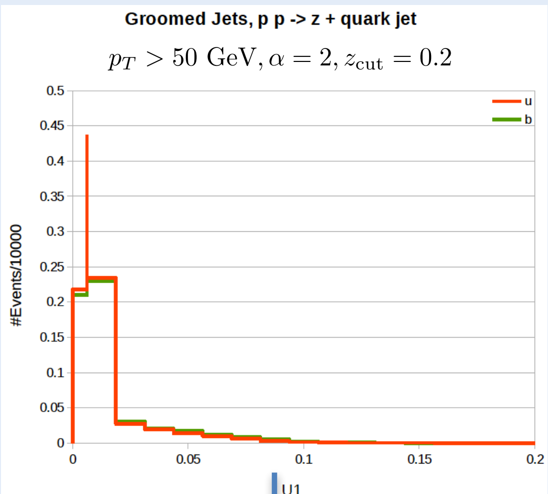
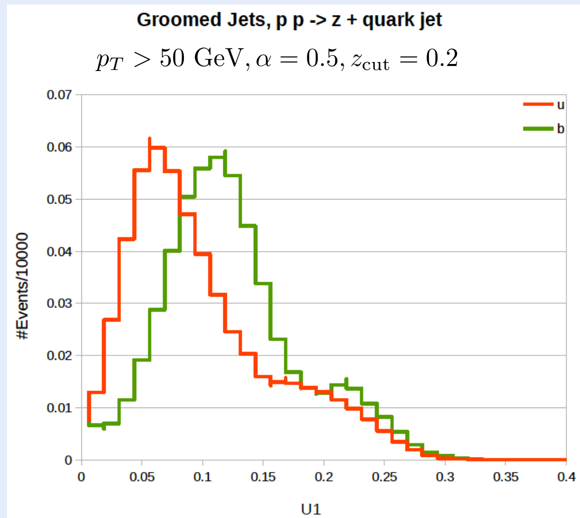
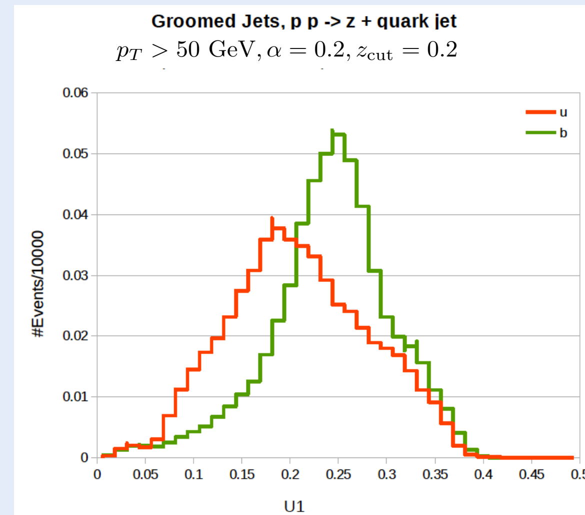
Performance on b-jets in Monte Carlo

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







Little to no discriminating power

improved discriminating power

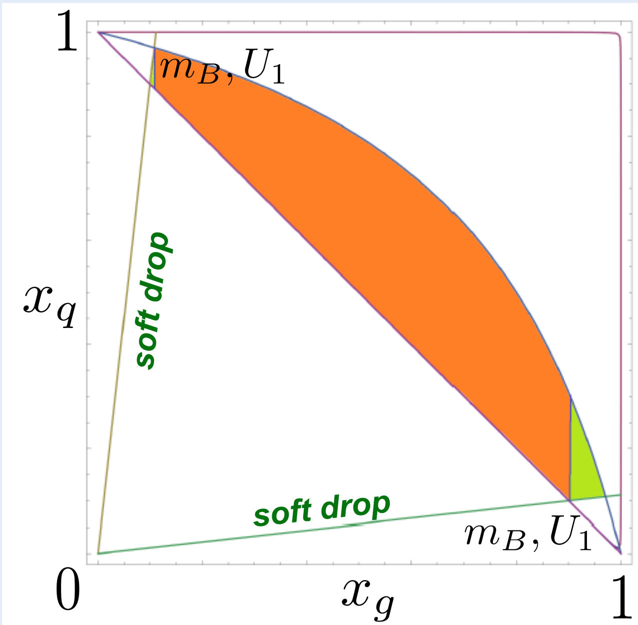
Motivates theoretical calculations:

predict groomed U_1 distributions using EFT

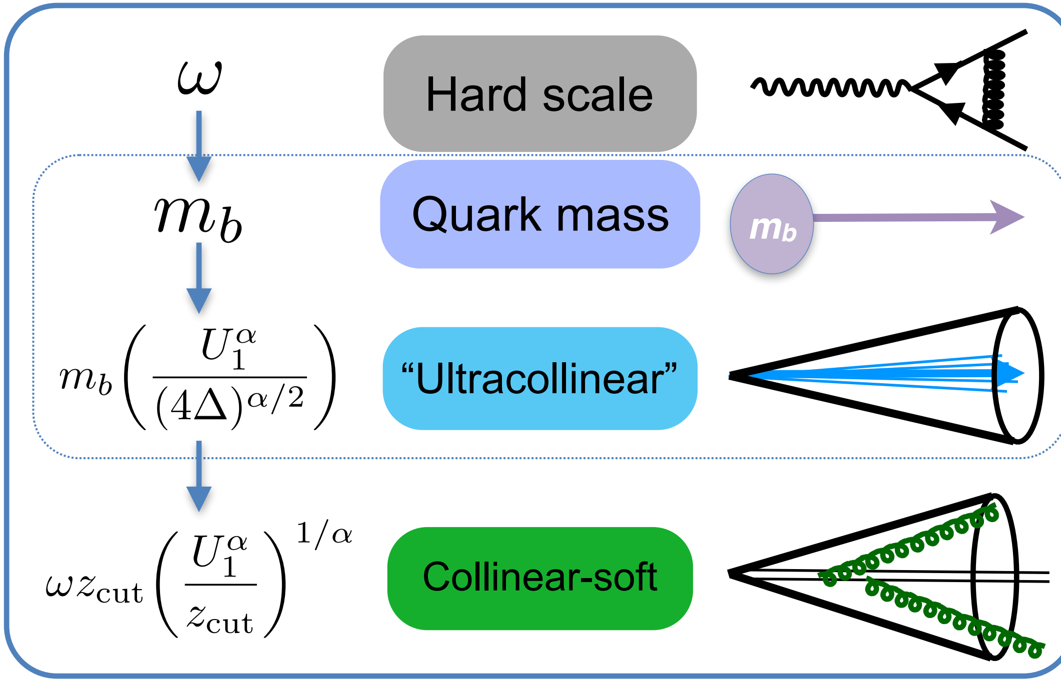
Progress on analytic EFT predictions

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:

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

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

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

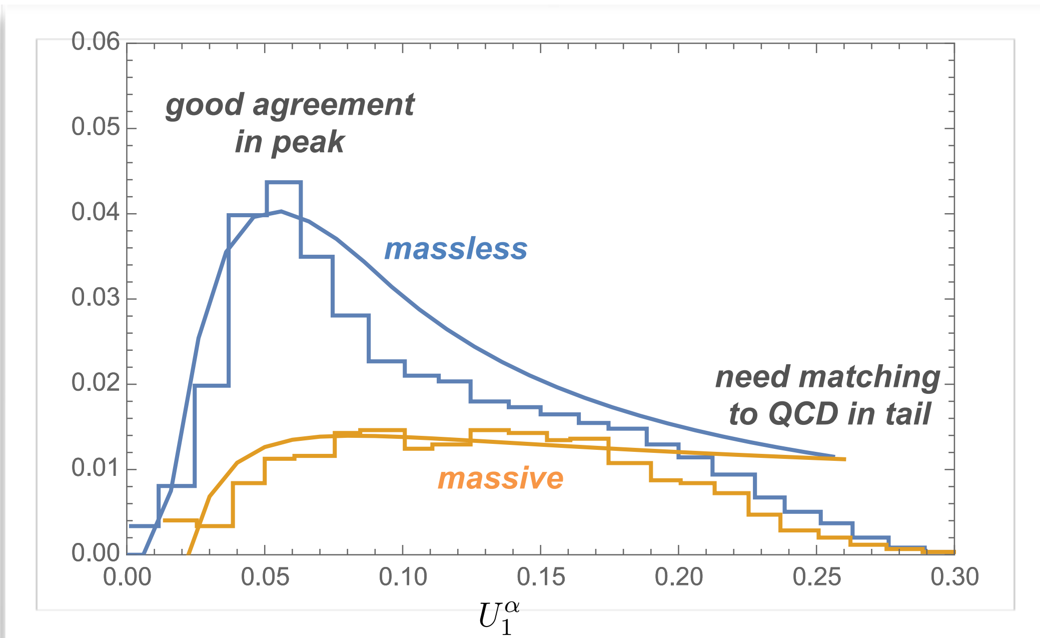
Progress on analytic EFT predictions

Los Alamos NATIONAL LABORATORY EST. 1943

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

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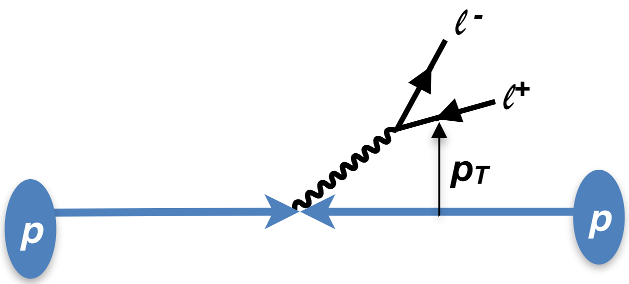
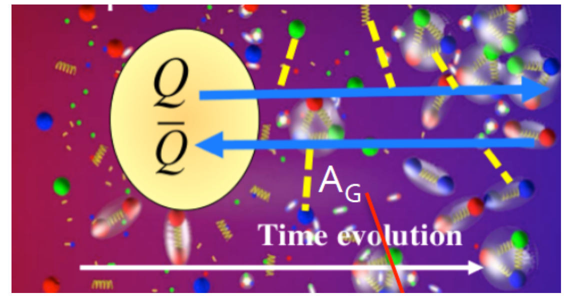
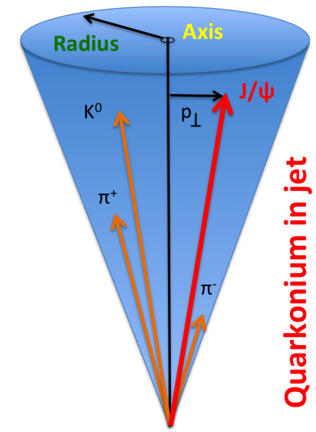
Related publications advancing TMD phenomenology

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





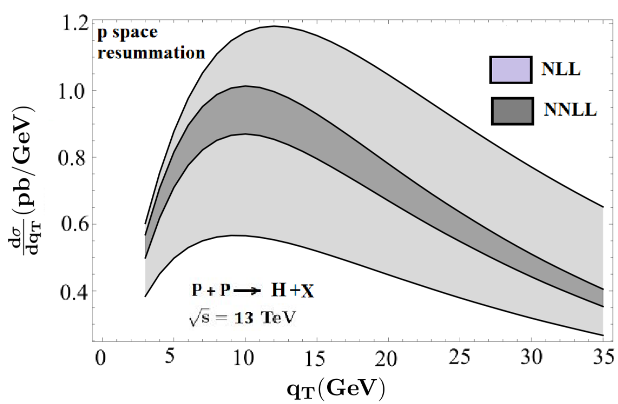


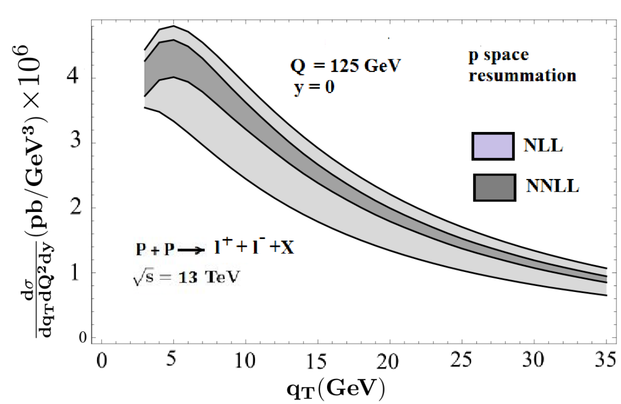
New EFT method for *analytic* resummation of transverse-momentum-dependent (TMD) cross sections:

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

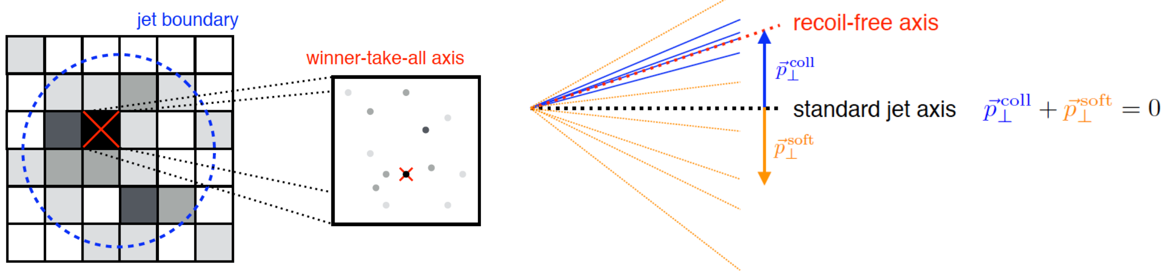
Invited talks at APS (VV 2/17), SF Jets (DK 2/17), SCET (VV 3/17), and UCLA (CL, 5/17)





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

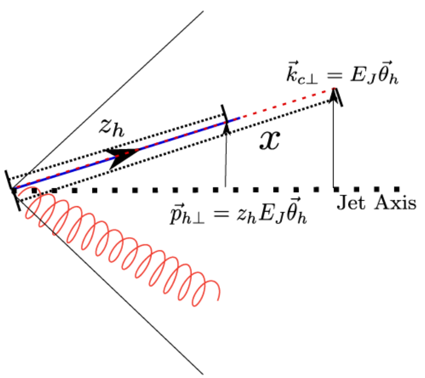
D. Neill, I. Scimemi, W. Waalewijn, *"Jet axes and universal transverse-momentum-dependent fragmentation,"* JHEP 1704 (2017) 020 [arXiv:1612.04817]



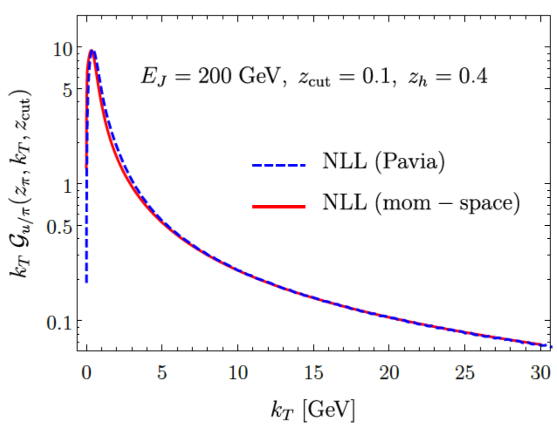
Jet axis insensitive to recoil of soft radiation

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

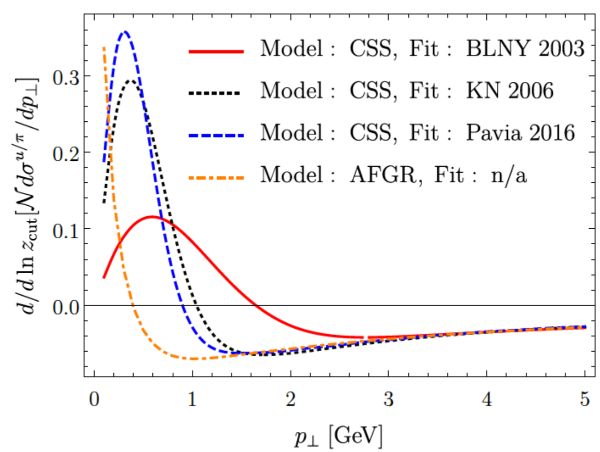
Y. Makris, D. Neill, V. Vaidya, "*Probing transverse-momentum dependent evolution with groomed jets,*" under review by JHEP, LA-UR-17-31338 [arXiv:1712.07653] + Invited talk at SF Jets (YM 1/18)



Hadron identified inside a jet



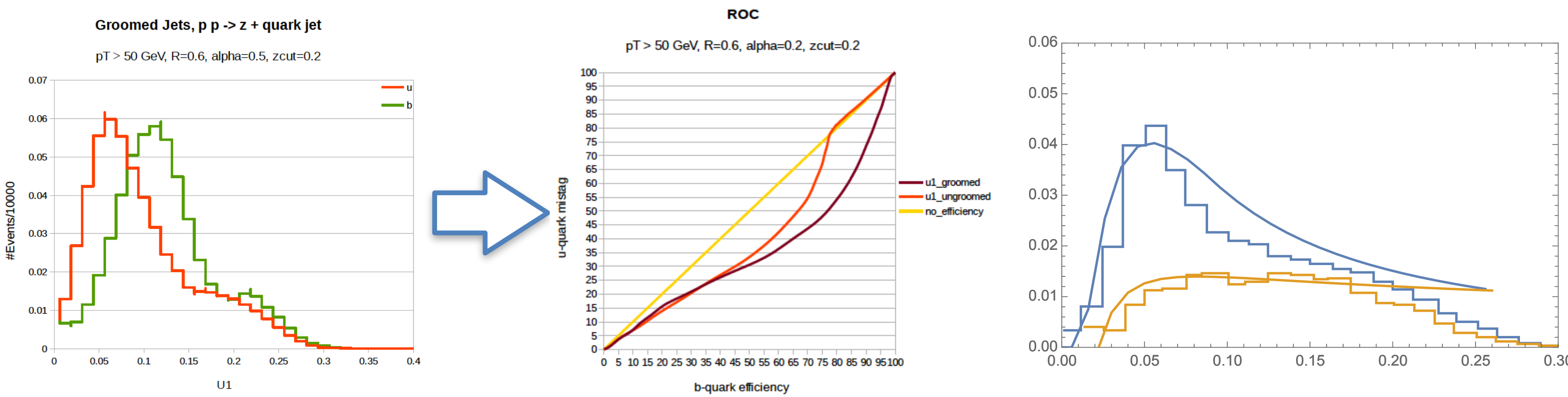
Perturbative TMD cross section vs. Monte Carlo



Distinguishing nonperturbative model predictions at low p_T

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