Precision Jet (Event) Substructure

Yang-Ting Chien

YITP-CFNS Fellow, Stony Brook University (since September, 2019)

In collaboration with George Sterman

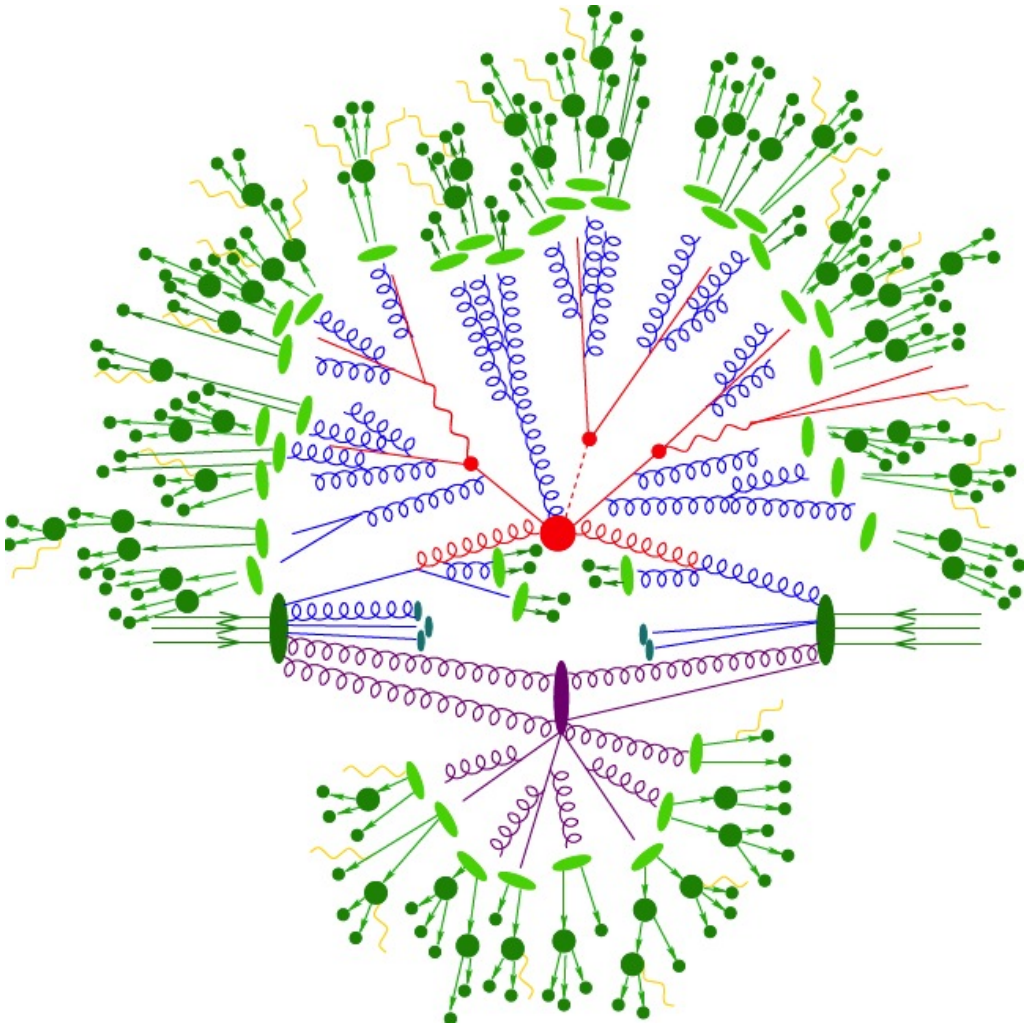
December 5, 2019

Outline

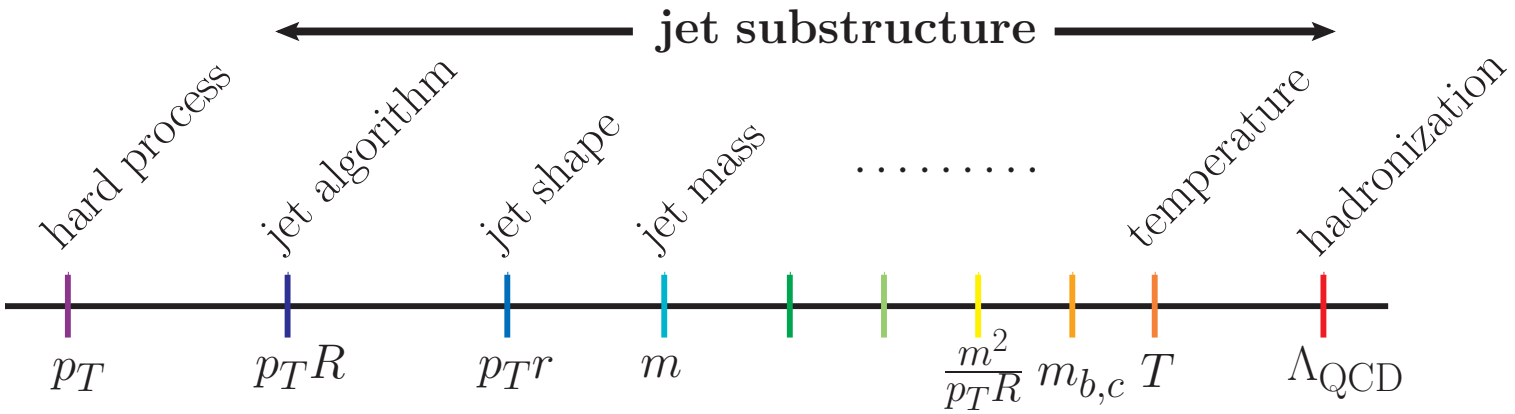
- Jet substructure
  - New observables and precise theory understanding
  - New techniques for signal searches
- collinear drop (arXiv: 1907.11107)
- two-particle correlation neural network (2PCNN) (arXiv:1911.02020)
- Future plans for the EIC
  - flattened jet angularity (work in progress with George)
  - quantum jet classification (work in progress)
  - polarization in jet substructure
  - ...
- Recent publications and talks

Challenge and opportunity in nuclear and particle physics simulations

- pp event simulation paradigm
  - parton shower
  - underlying events
  - hadronization
- Burning issues
  - quark-gluon plasma signature in pp, pA and AA collisions
  - hydrodynamics and collectivity
  - understanding initial state dependence from EIC studies is essential
- Concrete strategy to study any stage of collider event $\equiv$ jet substructure



Precision jet (event) substructure



- Different observables are sensitive to physics at different energy scales
- Essential to exploit all types (quantum numbers) of probes in all collision systems: quark jet, gluon jet, heavy flavors, boosted bosons, bound states... in e^+e^-, ep, eA, pp, pA, AA, ... (proposal: $\bar{p}p$ and $\bar{p}A$ are also useful. $\bar{A}A$ is too hard at the moment)

Precise QCD calculations using soft-collinear effective theory (SCET)

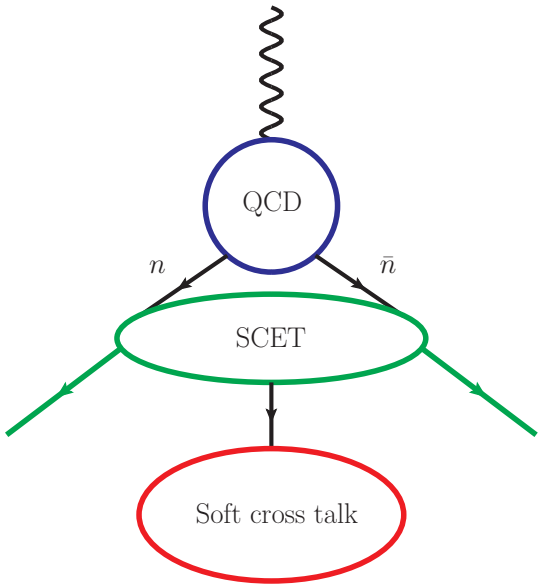
LARGE LOGS

- Large logarithms of scale ratios (e.g. $\log \text{mass}/\text{energy}$) appear in perturbative calculations and fixed-order calculations break down
  - All-order resummation is necessary

RESUM USING RG

- Large logarithms can be resummed using renormalization group evolution between characteristic scales in effective field theories
  - Factorization and evolution = resummation

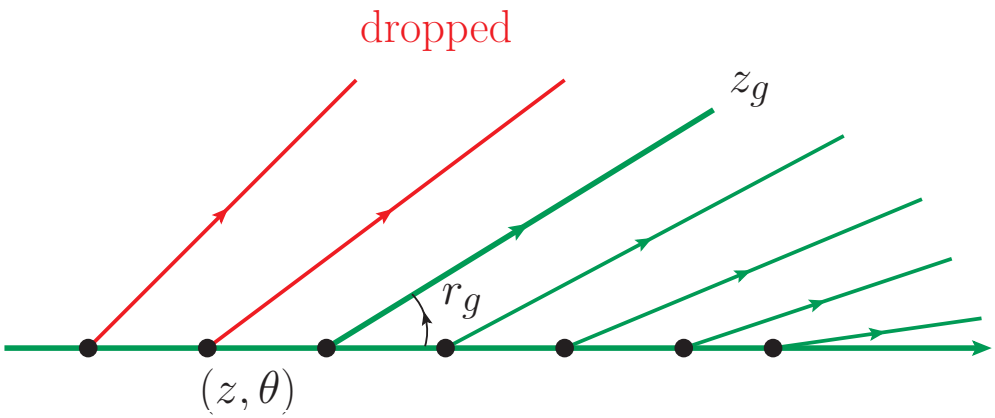
- SCET factorizes hard, jet and soft radiation
  - Hard matching coefficients describe hard scattering processes
  - Collinear Wilson lines describe radiation in the collinear limit
  - Soft Wilson lines along jet directions describe soft radiation in all angles

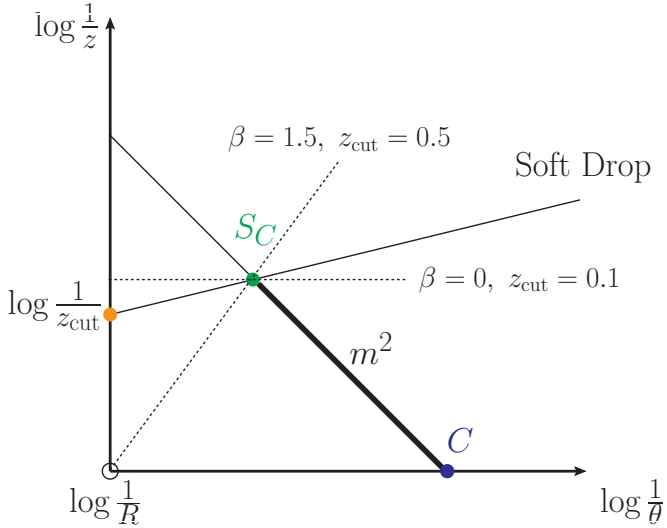


Soft Drop

Dasgupta, Fregoso, Marzani, Salam, JHEP09(2013)029

Larkoski, Marzani, Soyez, Thaler, JHEP05(2014)146

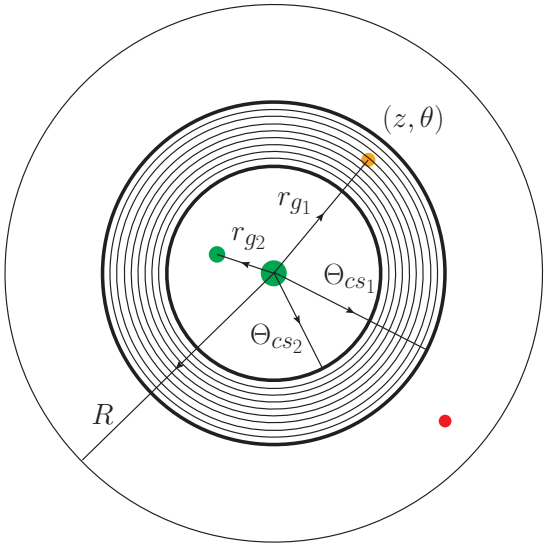


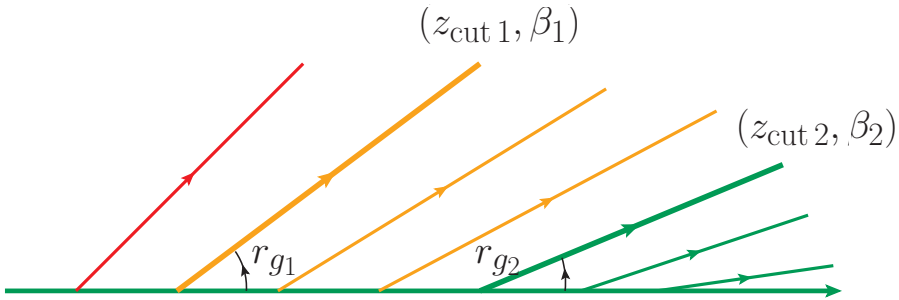


- Tree-based procedure to drop soft radiation
  - Recluster a jet using Cambridge-Aachen algorithm into an angular-ordered tree
  - For each branching, consider the p_T of each branch and the angle θ between branches
  - Soft drop condition: drop the soft branch if $z < z_{\rm cut}\ (\theta/R)^\beta$, where z is the momentum fraction of the soft branch

Collinear Drop using soft drop + anti soft drop

Chien, Stewart, 1907.11107





- $\Delta m^2 = m^2_{\text{SD}_1} - m^2_{\text{SD}_2}$ probes the soft radiation within the ring
- Phase space constraints on soft emissions with $(\text{z}, \theta) = (\text{momentum fraction}, \text{angle})$,

$$z\theta^2 \approx \frac{\Delta m^2}{E_J^2}\,, \qquad z_{\text{cut}\,1}\left(\frac{\theta}{R}\right)^{\beta_1} \lesssim z \lesssim z_{\text{cut}\,2}\left(\frac{\theta}{R}\right)^{\beta_2}$$

- Relevant degrees of freedom have characteristic energies E_{cs_i} and angles Θ_{cs_i}.

Highlighted in Barbara Jacak's Quark Matter 2019 opening talk

- Progress is made with expertise in both nuclear and particle physics

When to groom jets, use soft-drop?

- Pioneered by HEP – search for W, other hard stuff
- In QGP studies soft-drop is good for:
  - Isolating the first gluon splitting
    - *is it well enough calibrated?*
  - Reducing the underlying event
    - *are we grooming away the right particles?*
- In QGP soft-drop is terrible for:
  - parton-plasma interactions & medium response
  - …groom away the interesting soft stuff…
- Proposal:
  - ***Use a jet-grooming algorithm - "soft-keep"****
  - 1st step: Look at what is groomed away
  - parton-plasma interaction vs. underlying event

*e.g. collinear drop *arXiv:1907.11107*

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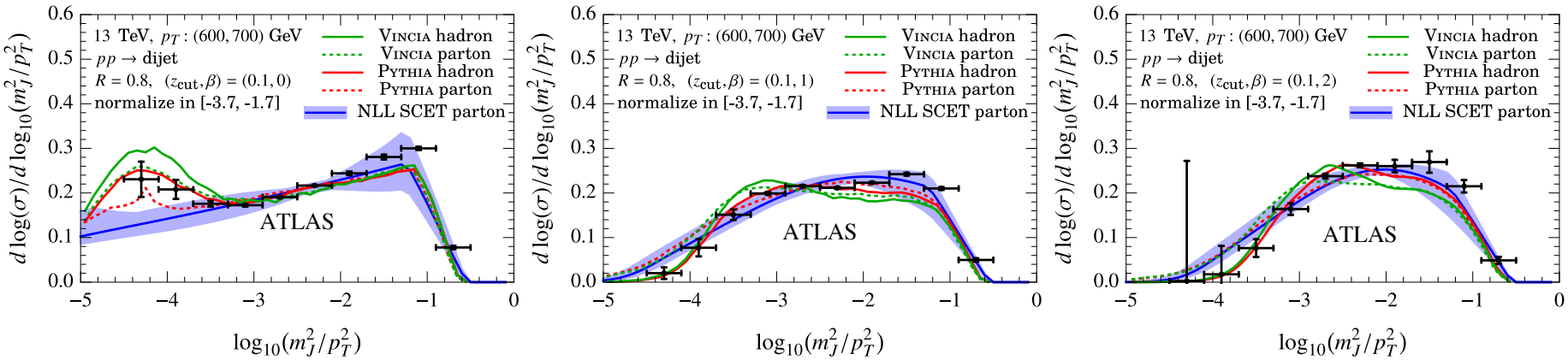
Soft drop by turning off collinear drop

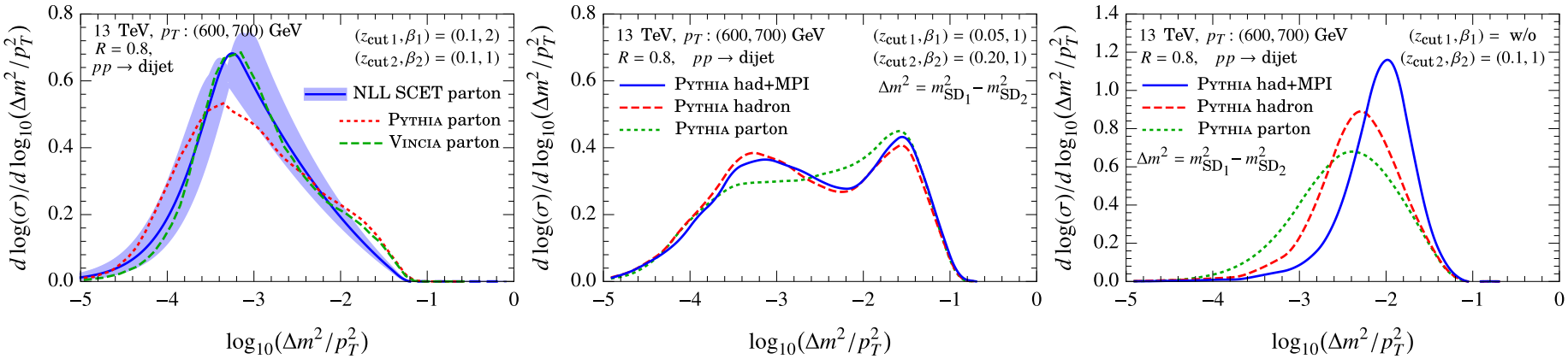
Previous soft drop work: Larkoski et al '16, Marzani et al '17, Kang et al '18

ATLAS: PRL 121.092001, CMS: JHEP11(2018)113



- Soft drop reduces sensitivity to soft physics
- Bands correspond to next-to-leading log (NLL) calculation with uncertainty estimated by scale variation. Good agreement with data and theory precision needs to be improved.

Disentangling effects from hadronization and underlying events

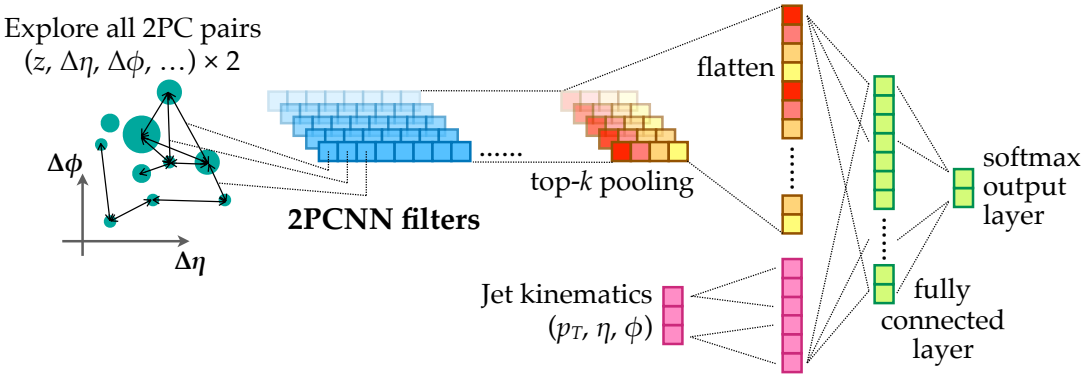


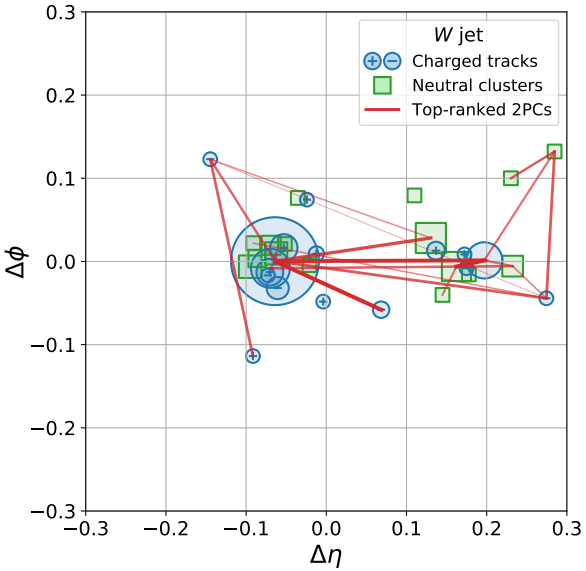
- Significant difference between Pythia and Vincia is observed
- Impressive agreement between Vincia and analytic calculation
- Underlying event effects can be suppressed while keeping sensitivity to hadronization
- Or, one can enhance the sensitivity to underlying events

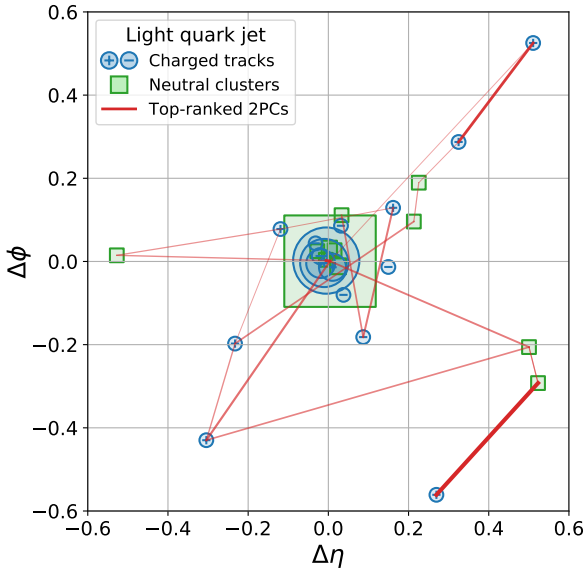
Promising applications for scrutinizing QCD phase space of EIC

Two-particle correlation neural network (2PCNN)

Chen, Chien, 1911.02020





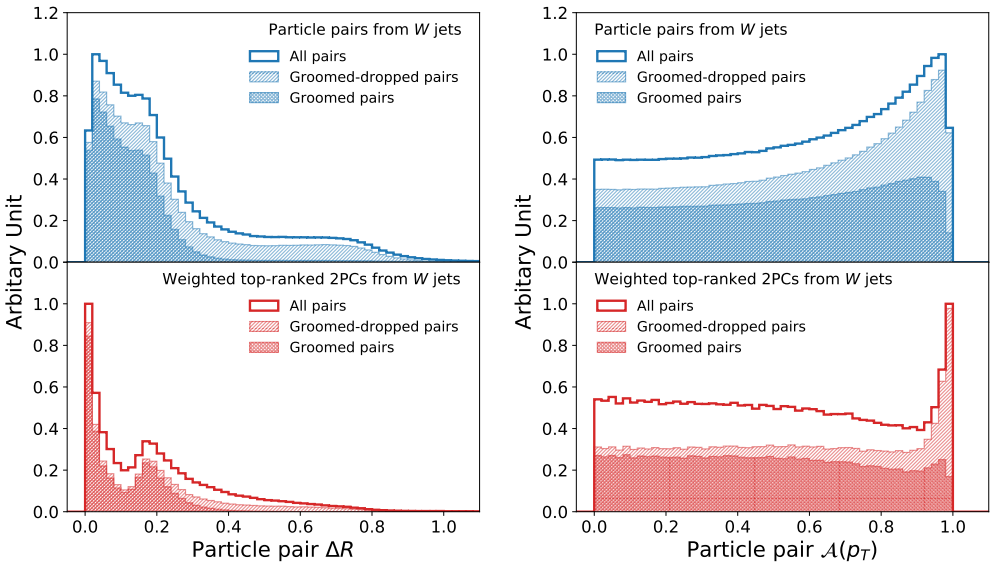


- Deciphering complex jet information requires a physical jet representation: we use two-particle correlation as basic information elements
- The rise of machine learning gives powerful tools for extracting physics features
- We construct a novel neural network model suitable for nuclear and particle physics studies

Machine learning works with (or, for) physical analysis

Promising applications for enhancing sensitivities to QCD effects at EIC

	2PCNN(E-flow)		2PCNN(full)		T-jet model	
Task	ACC	AUC	ACC	AUC	ACC	AUC
W vs quark	0.881	0.945	0.881	0.946	0.880	0.945
Higgs vs quark	0.873	0.939	0.959	0.993	0.866	0.934
top vs quark	0.900	0.962	0.929	0.978	0.900	0.963
W^+ vs W^-	0.505	0.502	0.757	0.839	0.502	0.502
quark vs gluon	0.738	0.810	0.748	0.823	0.732	0.802



- The practical: excellent classification performance and feature extraction quantified by AUC (area under ROC curves) and ACC (accuracy)
- The conceptual: neural network model combined with physical analysis allows us to identify key physics observables
- 2PCNN identifies the two-prong structure and color-singlet isolation of W jets as shown in the relative angle ΔR and p_T asymmetry $\mathcal{A} = \Delta p_{Ti} / \sum p_{Ti}$ of 2PCs and the relation to energy-energy correlators

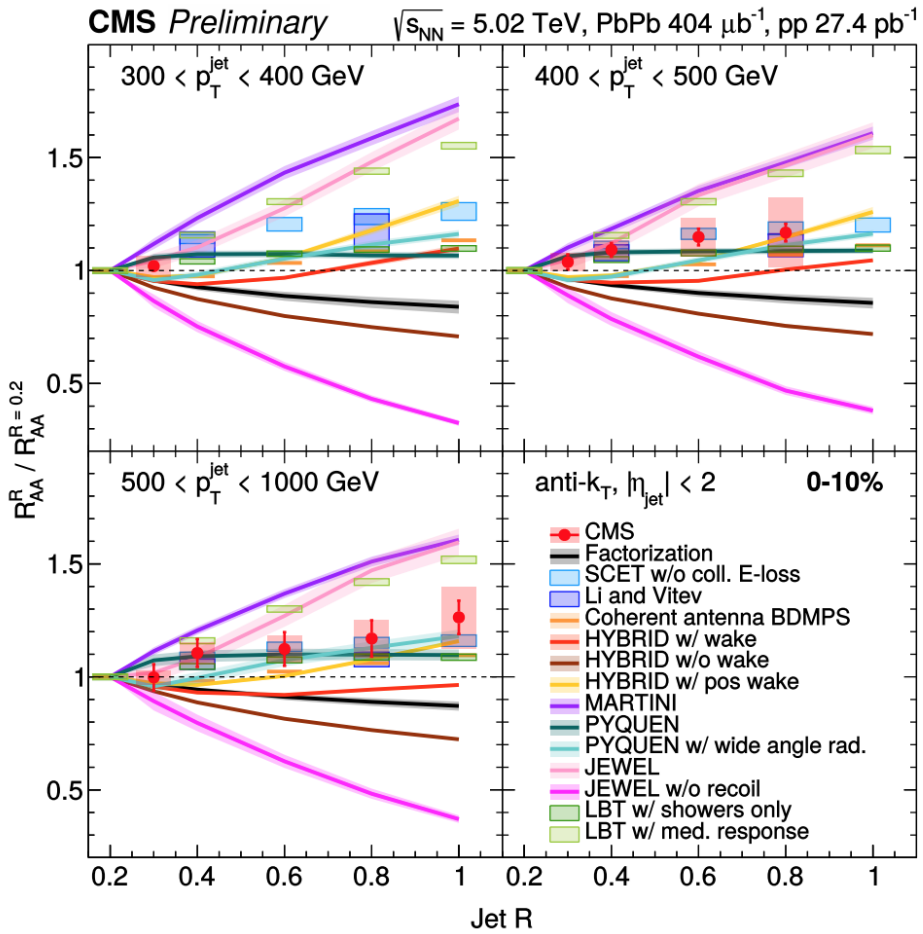
Recent publications

- K. -F. Chen and Y. -T. Chien, "Deep learning jet substructure from two-particle correlation," arXiv:1911.02020
- Y. -T. Chien and I. Stewart, "Collinear drop," arXiv:1907.11107
- Y. -T. Chien, D. Shou and B. Wu, "Resummation of boson-jet correlation at hadron colliders," JHEP **1911**, 025 (2019)
- Y. -T. Chien, "Confronting jet quenching with jet grooming: jet mass distributions in heavy ion collisions," PoS HardProbes2018 (2019) 098
- Y. -T. Chien, "Heavy ion jet physics studies using precision jet substructure and quark-gluon jet classification," PoS HardProbes2018 (2019) 097
- Y. -T. Chien, D. Kang, K. Lee and Y. Makris, "Subtracted cumulants: mitigating large background in jet substructure," Phys. Rev. D **100**, no. 7, 074030 (2019)

Jet quenching predictions for different jet radii

- Great agreement with CMS data announced at Quark Matter 2019

Jet R_{AA}: jet radius scan



$SCET_G$ w/o coll. energy loss:

- $SCET_G$ models interaction of hard partons with soft gluons
- Great agreement with data

Recent and future talks

- "Deep Learning Jet Substructure from Two Particle Correlation", ML4Jets workshop, 01/13/2020, New York University.
- "Deep Learning Jet Substructure from Two Particle Correlation", Particle Physics in Computing Frontiers, 12/11/2019, Institute for Basic Science, Daejeo, Korea. **Invited talk**.
- "Collinear Drop", XLIX International Symposium on Multiparticle Dynamics, 09/09/2019, Hotel Santa Fe, New Mexico. **Invited talk**.
- "Latest Development in Jet Substructure Techniques", Meeting of the Division of Particles & Fields of the American Physical Society, 07/30/2019, Northeastern University. **Invited talk**.
- "Collinear Drop", 11th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches (BOOST 2019), 07/25/2019, MIT.
- "Collinear Drop Quark/Gluon Jet Substructure", 13th Particle Physics Phenomenology workshop (PPP13), 06/04/2019, National Taiwan Normal University, Taipei, Taiwan.
- "Probing Heavy Ion Collisions Using Precision Jet Substructure", High Energy Physics Seminar, 05/30/2019, National Taiwan Normal University, Taipei, Taiwan. **Invited talk**.
- "Collinear Drop", 16th Annual Workshop on Soft-Collinear Effective Theory (SCET2019), 03/26/2019, UC San Diego. **Invited talk**.
- "Searching for New QCD Signatures in Soft Jet Substructure", Joint BNL and CFNS seminar, February 7th, 2019, Brookhaven National Laboratory. **Invited talk**.
- "Collinear Drop", 4th Santa Fe Jets and Heavy Flavor Workshop, 01/30/2019, UC Los Angeles.