Hadron-in-Jet in EIC: Factorization and Resummation

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Supported by:

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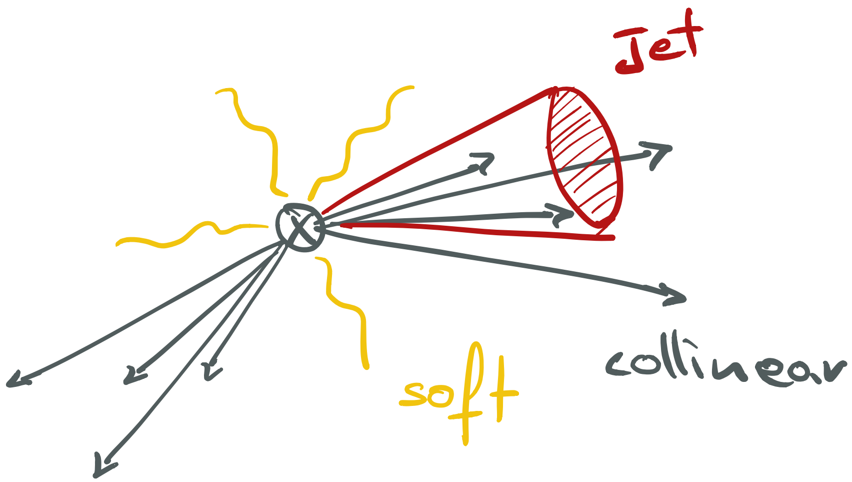
Outline

- Types of jets (semi-inclusive, exclusive, jet-axis, e.t.c)
- Phenomenology - Observables
  - Hadron-in-jet / Angularities / Energy fractions
  - TMDs + Groomed-jets
  - Heavy mesons in jets (threshold-logs)
- Factorization in EIC

Types of jets (exclusive vs semi-inclusive)

Semi-Inclusive

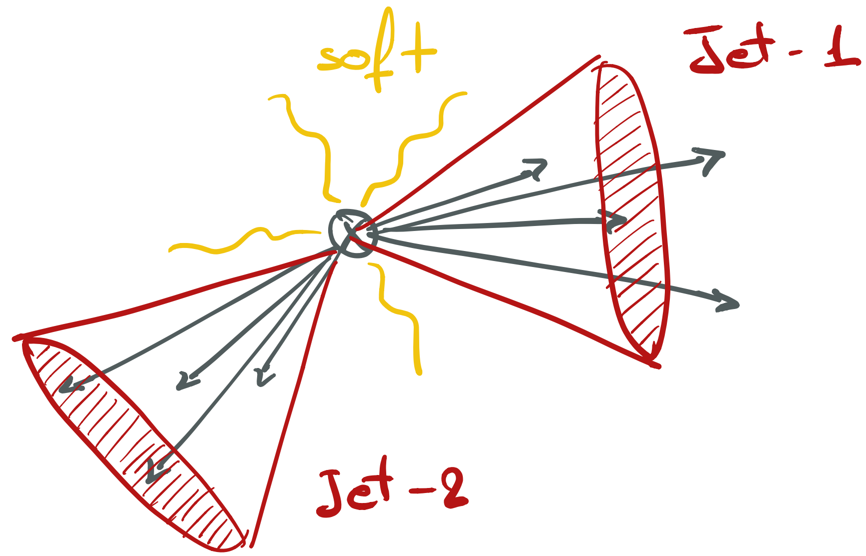


Example. $\ell + p \rightarrow \ell + \text{jet} + X$

Energetic radiation close to the jet axis can escape the jet.

Appropriate for small-R

Exclusive



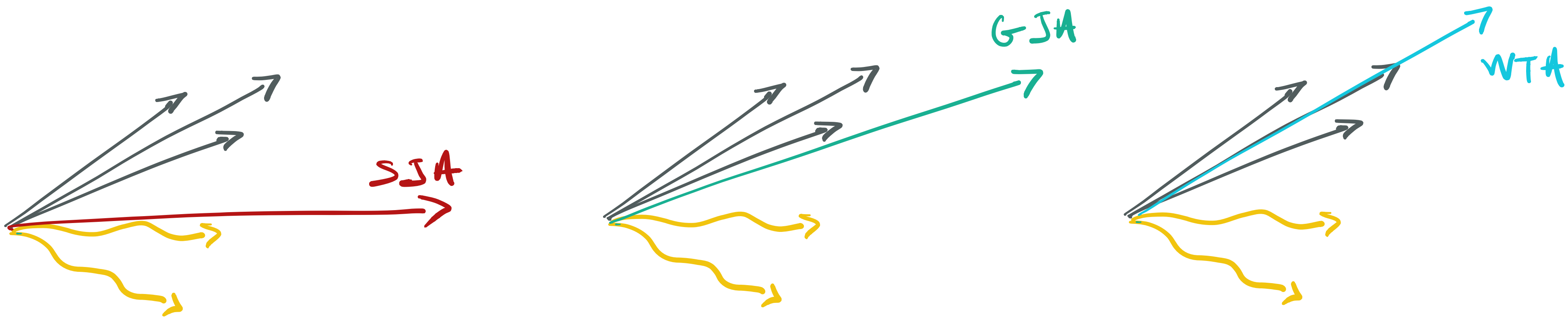
$\ell + p \rightarrow \ell + N\text{-jets} + X_{soft}$

$N = 1, 2, 3 \ldots$

Captures all energetic radiation

Works well with large-R

Types of jets (Modified vs Standard)



Particularly relevant for TMDs

Standard jet axis (SJA)

- located at the center of the jet and is given by the sum of all radiation in the jet

* Event-based axis: Thrust axis

Modified axis

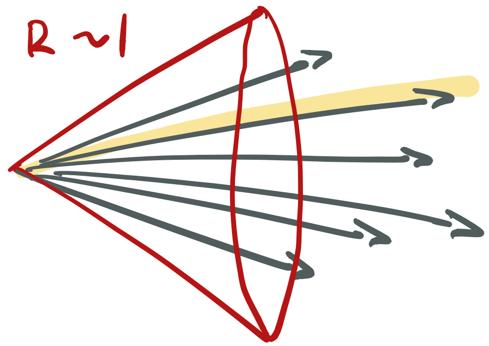
- Examples: Groomed jet axis (GJA)
  Jet broadening axis
  Winner-Take-All (WTA)

- Probes collinear radiation and is given by a sub-set of particles

Observables

Hadron-in-jet at EIC:

$\ell + p \to \ell + \text{jet}(h) + X$

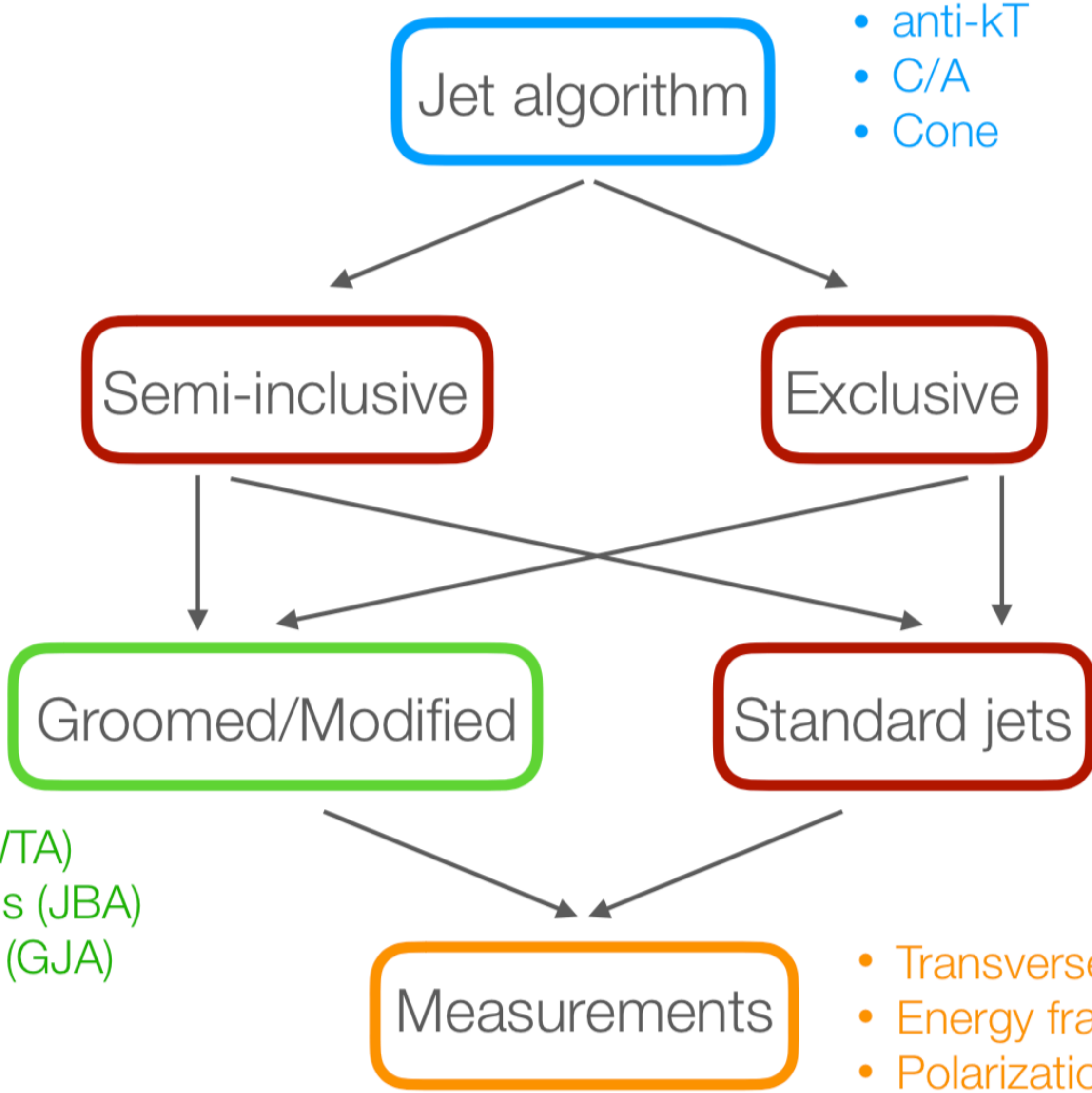


identified hadron (h)

The hadron is member of the jet

Measurments on the hadron w.r.t. the jet	Measurments on the jet substructure
Energy fractions (e.g. $z = E_h / E_{jet}$)	Jet energy
Transverse momentum w.r.t. jet ↳ choice of axis	Angularities / Thrust / jet mass
Polarization	Other jet substructure observablos

Definition of jets

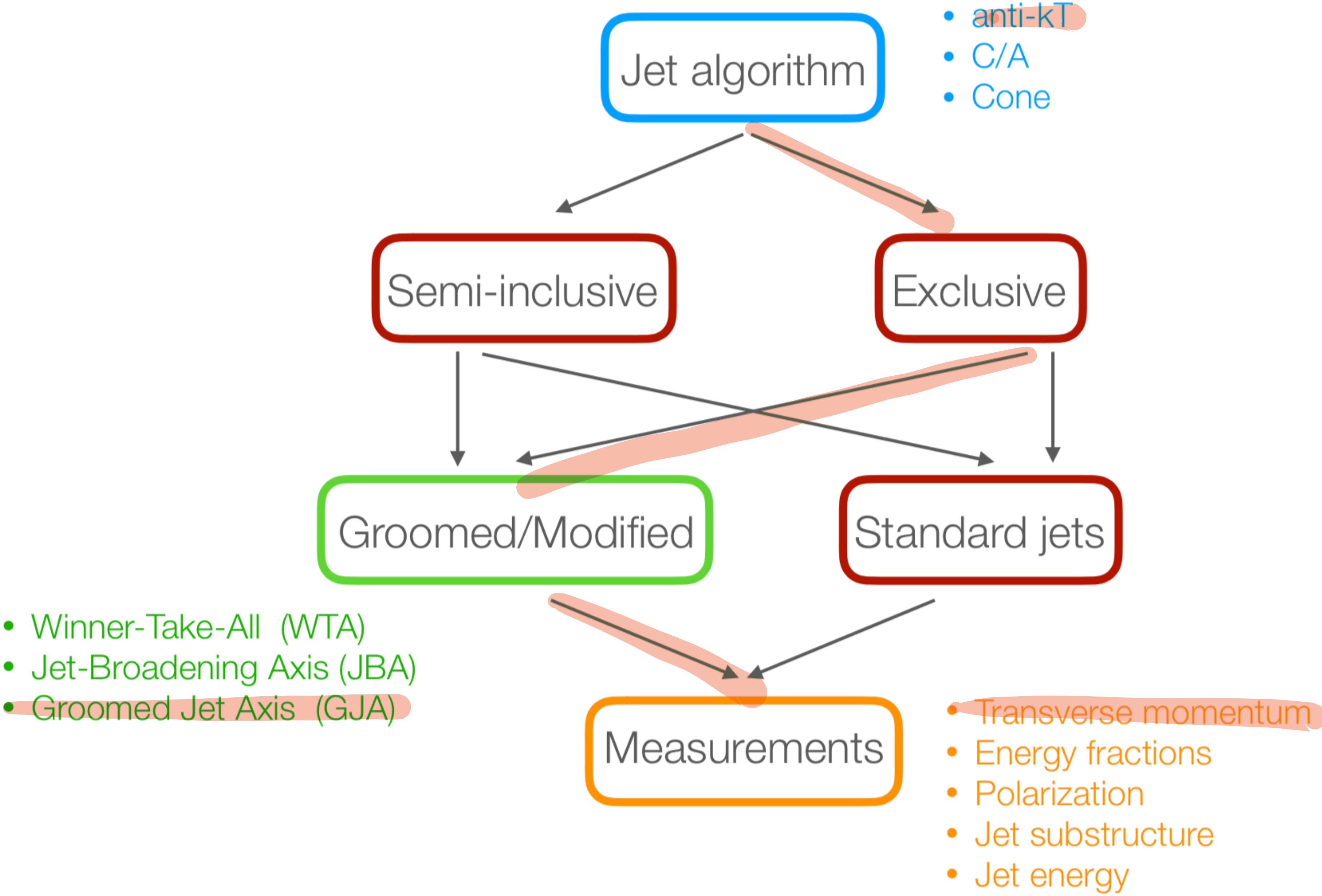


- anti-kT
- C/A
- Cone

- Winner-Take-All (WTA)
- Jet-Broadening Axis (JBA)
- Groomed Jet Axis (GJA)

- Transverse momentum
- Energy fractions
- Polarization
- Jet substructure
- Jet energy

Definition of jets



Factorization at EIC

Fragmenting-Jet-Functions (Measurment dependent Functions)

Exclusive jets

$$\frac{d\sigma}{dz\,dM} = \boxed{H_{ij}(Q;\mu)\, S(\Lambda;\mu)\, B_{i/p}(Q,M;\mu)}\; \mathcal{G}^{E}_{j/h}(z,Q,M;\mu)$$

Semi-Inclusive jets

$$\frac{d\sigma}{dz\,dM} = \boxed{\frac{d\sigma}{dz\,dM}(\ell p \to j)} \otimes \mathcal{G}^{S.I.}_{j/h}(z,Q,M,\mu)$$

- process specific part of the factorization

Univesal functions

The formalism for lepton-lepton colliders can be easily incorporated for EIC!

Re-Factorization of FJFs

Refactorization is important for resumming large logarithms

Exclusive

matching coefficient

$$\boxed{\mathcal{G}^{E}_{i/h} = C_S \otimes_M \mathcal{J}_{i/j} \otimes_z D_{j/h}(z, p)}$$

collinear fragmentation functions

collinear-soft matrix element

Semi-Inclusive

$$\boxed{\mathcal{G}^{S.I.}_{i/h} = H_i \times C_S \otimes_M \tilde{\mathcal{J}}_{i/j} \otimes_z D_{j/h}(z, h)}$$

additional matching term

Energy fractions (only)

** Mass corrections: Dai, Kim, Leibovich arXiv:1805.06014

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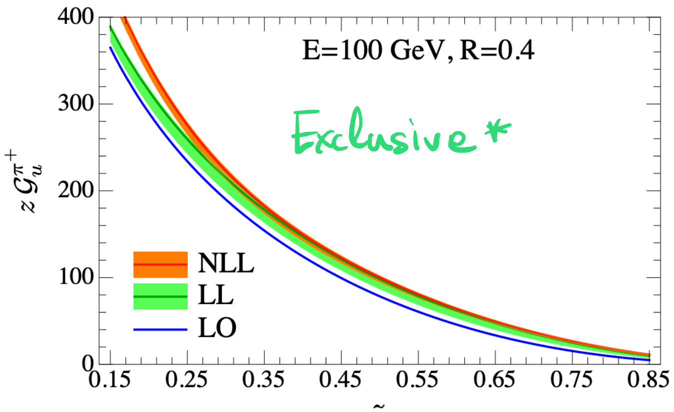
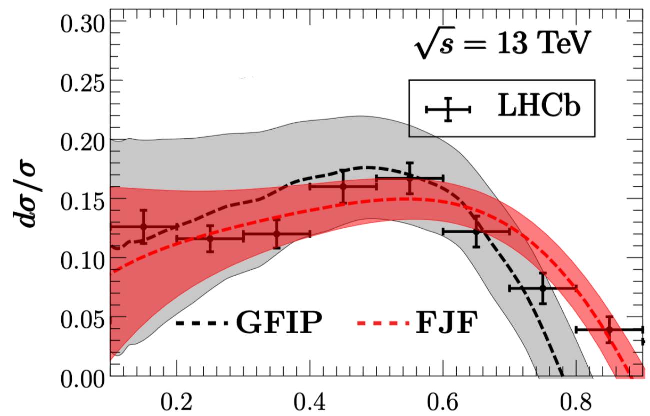
The simplest observable is to measure the energy fraction of the hadron w.r.t. the jet

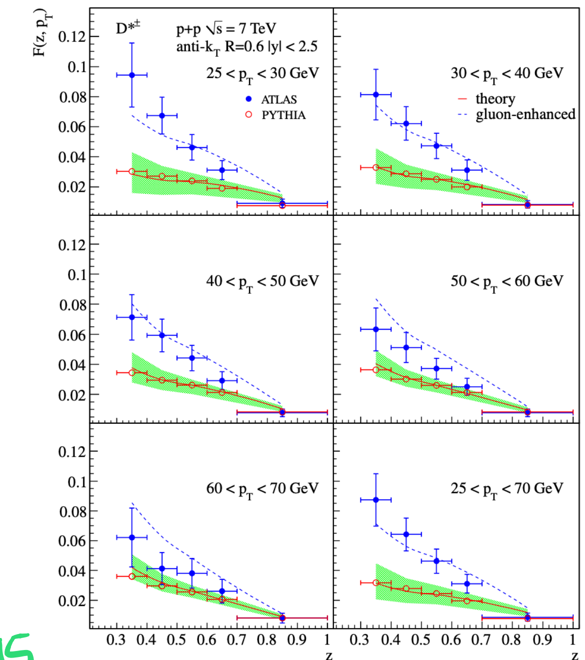
Light mesons (π) | Quarkonia (J/ψ) | Heavy mesons (D) **



Procura, Waalewijn arXiv: 1111.6605



Bain et.al arXiv: 1702.05525



Chien et.al. arXiv: 1512.06851

* For semi-inclusive jets: Kaufmann et.al. arXiv: 1506.01415

Threshold effects: Kaufmann et.al. arXiv 1910.11746

Thrust and Angularities

* full mass dependence by Bauer, Mereghetti arXiv: 1312.5605

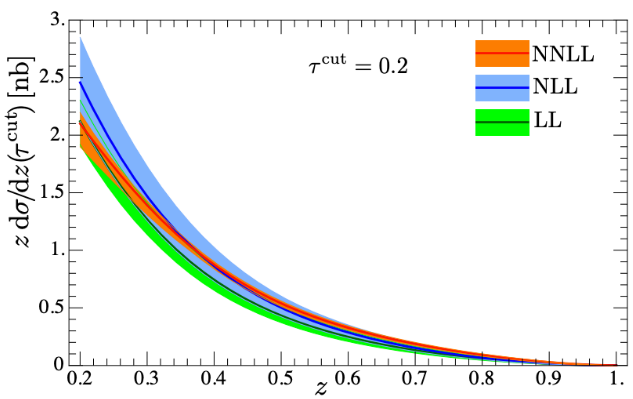
$$\boxed{\tau(a) = \frac{1}{2E_{jet}} \sum_{i \in jet} (p_i^+)^{1-a/2} (p_i^-)^{a/2}}$$

← Sensitive to all radiation in the jet

$a < 2$ $\qquad \tau(a=0) \sim$ thrust (jet)

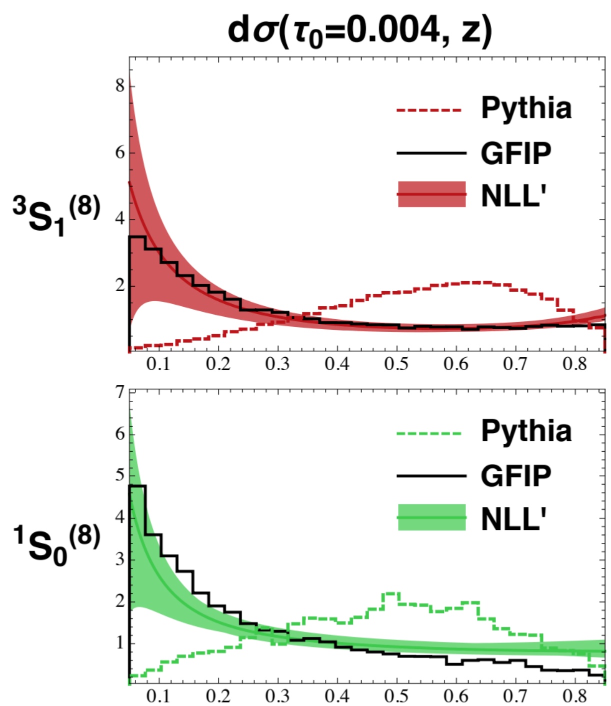
Angularities + Hadron-in-jet observables

Light mesons (π)



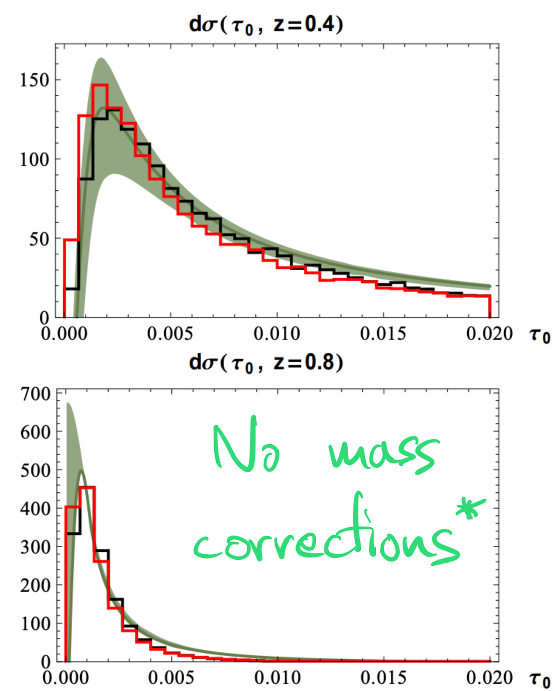
Jain, Procura, Waalewijn arXiv: 1101.4953

Quarkonia (J/ψ)



Bain et. al. arXiv: 1603.06981

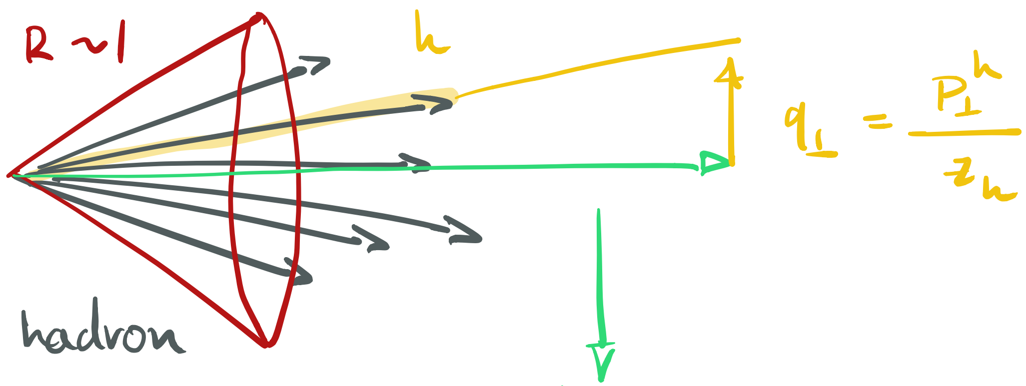
Heavy Mesons (B)



No mass corrections*

Transverse momentum dependent observables

Measurment :



the transverse momentum of the hadron is measured w.r.t. to the jet and rescaled by the energy fraction.

jet axis (SJA, GJA, WTA, ...)

Exclusive (SJA) : Bain et.al. arXiv:1610.06508

Semi-inclusive (SJA) : Kang et.al. arXiv : 1705.08443/1707.00913

Groomed -jets : Makris et.al. arXiv : 1712.07653/1807.09805

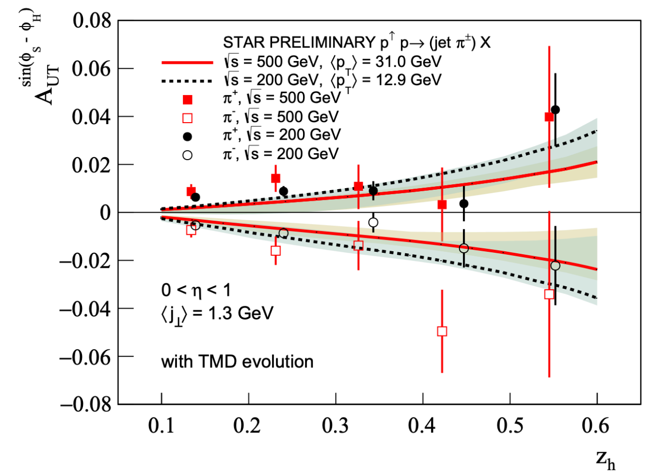
Winner - take - all : Neil et.al. arXiv: 1612.04817/1810.12915

What have we learned from these studies?

① Hadron-in-jet can provide a TMD-factorization in isolation

$$\frac{d\sigma}{dz\,dM} = \boxed{\frac{d\sigma}{dz\,dM}(pp \to j)} \otimes \mathcal{G}^{\text{S.I.}}_{j/h}(z, Q, M, \mu)$$

collinear factorization TMD factorization.



Kang et. al.

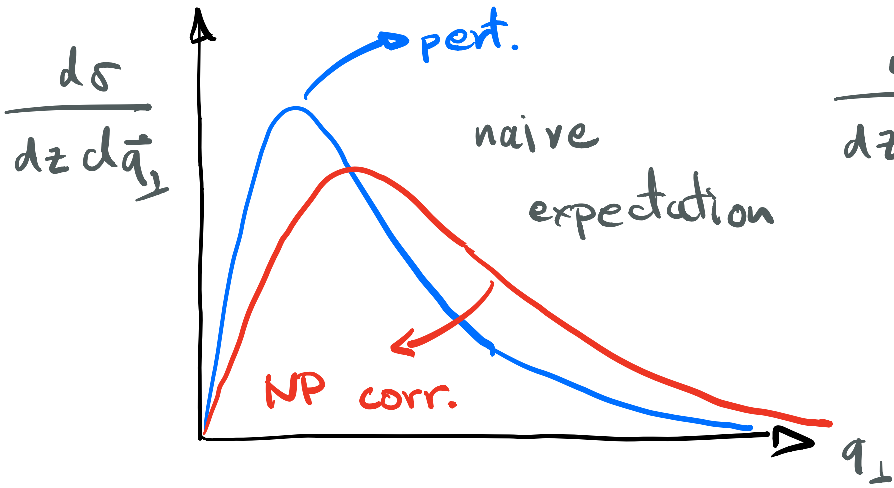
arXiv: 1707.00913

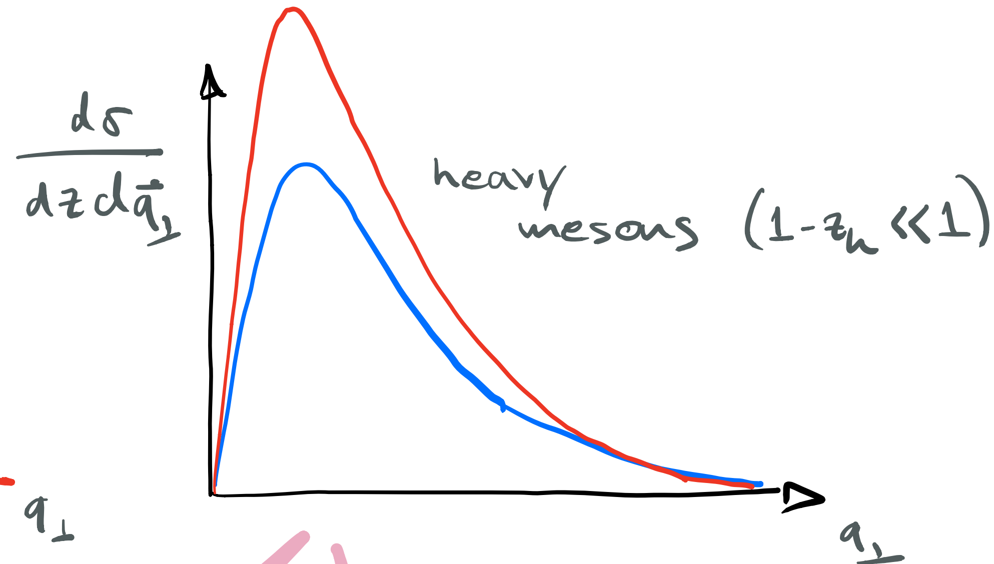
② Small z_h coming from underlying event can generate $q_\perp$ contribution in the TMD region

hard cutoff grooming

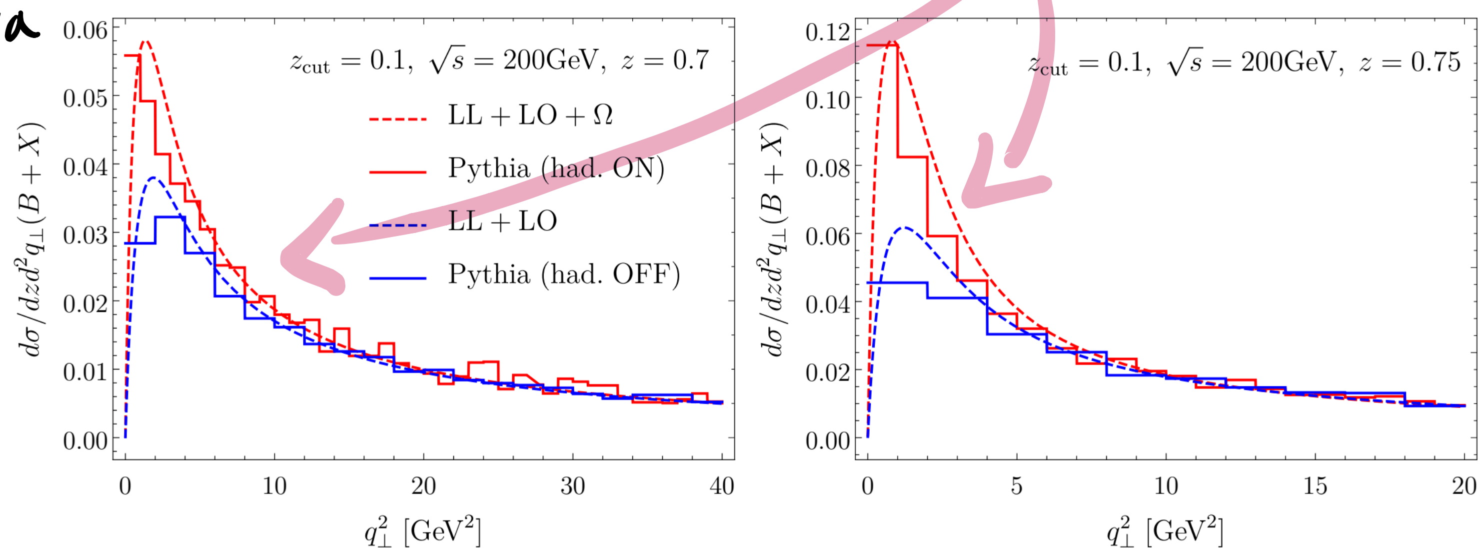
$z_{cut} \ll 0.1$ $z_{cut} \sim 0.1$

3 A more carefull look at the heavy meson production at threshold is needed. Heavy mesons in jet could provide a novel aproach to hadronization studies.





Makris, Vaidya arXiv: 1807.09805



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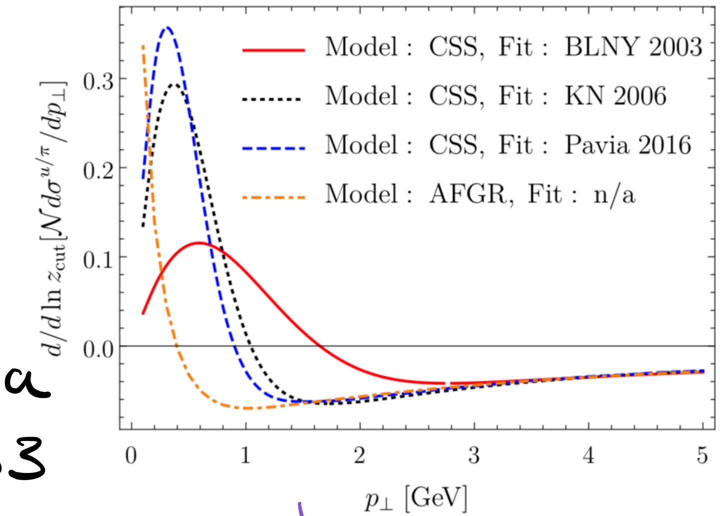
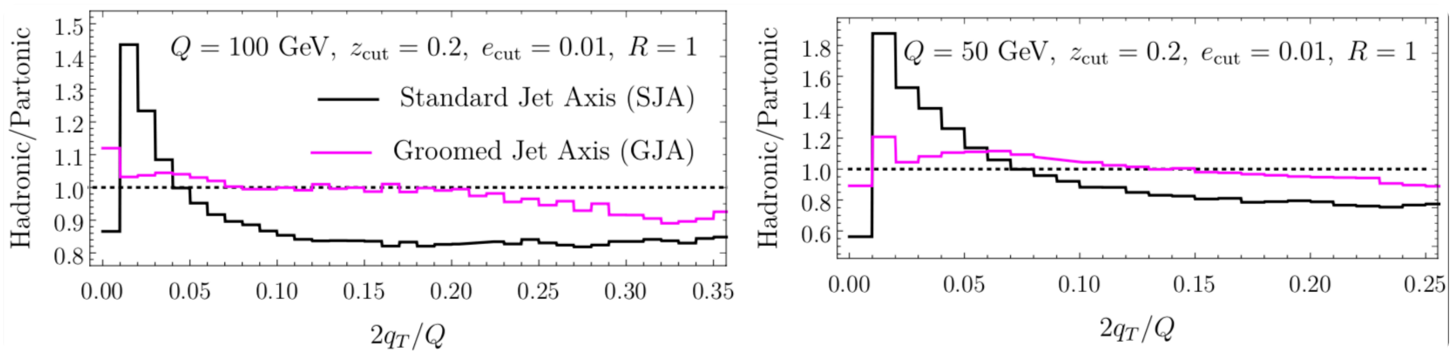
4) Grooming for light mesons can provide new observables for studying TMD-evolution



Makris, Neil, Vaidya
arXiv: 1712.07653

5) Warning! Jet-algorithm dependent matrix elements introduce new non-perturbative corrections. No jet axis is insensitive to hadronization.

Reyes et. al
arXiv: 1907.05896

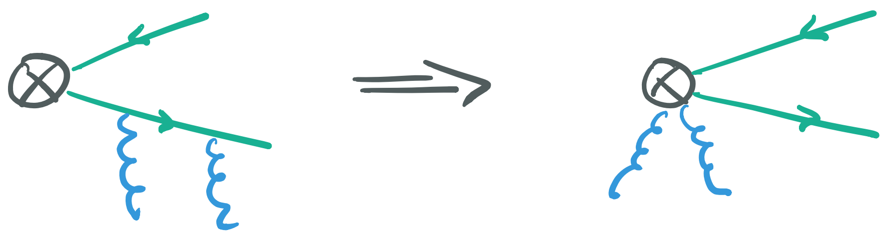


6) Not all hadron-in-jet $q_\perp$ measurements result in TMD-like factorization. Examples are WTA and heavy mesons ($z_h \to 1$)

TMDs - Quarkonia

Quarkonia studies in soft background:

$SCET_Q$: Real-soft radiation

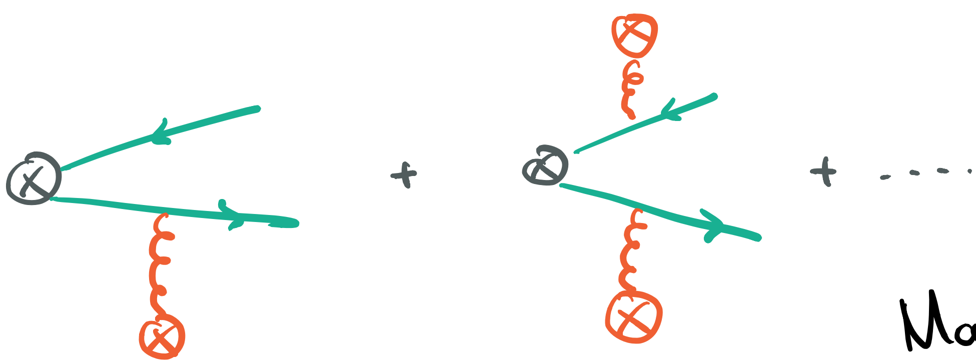


$\int -i/t$

Fleming, Makris, Mehen

arXiv:1910.03586

$NRQCD_G$: Virtual-soft interactions.



$\int -i/t$

Makris, Vitev

arXiv:1906.04186

1 Medium induced transitions (Ivan V.)

2 Quarkonium photo/lepto-production (Sean F., Thomas M.)

3 Quarkonium TMD-fragmentation (Ignazio S. Miguel E.)

(in-jet TMDs)

Summary

1. Rapid evolution of the topic hadron-in-jet

2. Better understanding of the possibilities and limitations

3. YR is a good reason to collaborate: categorize these limitations and to identify the key processes.

hadrons-in-jet

Nuclear matter effects

Hadronic structure

Hadronization