TMDs with groomed jets

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JHEP 1908 (2019) 161
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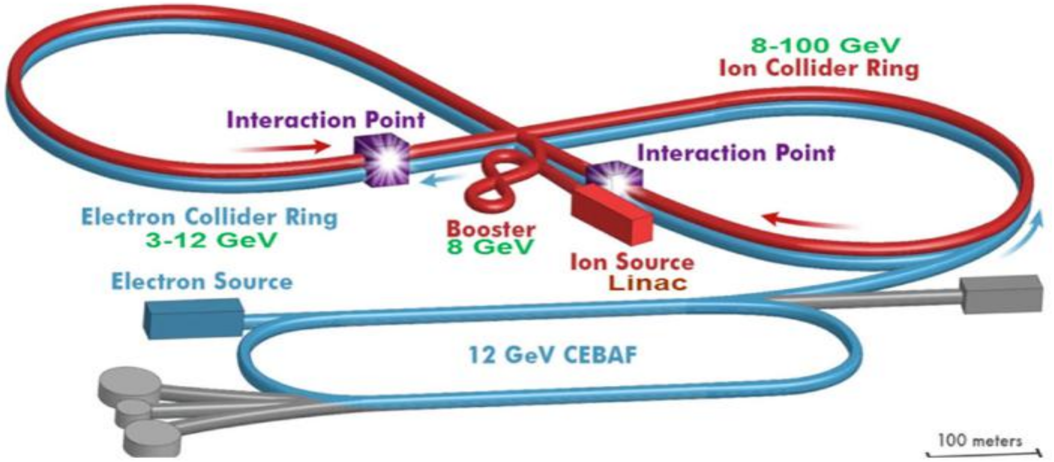
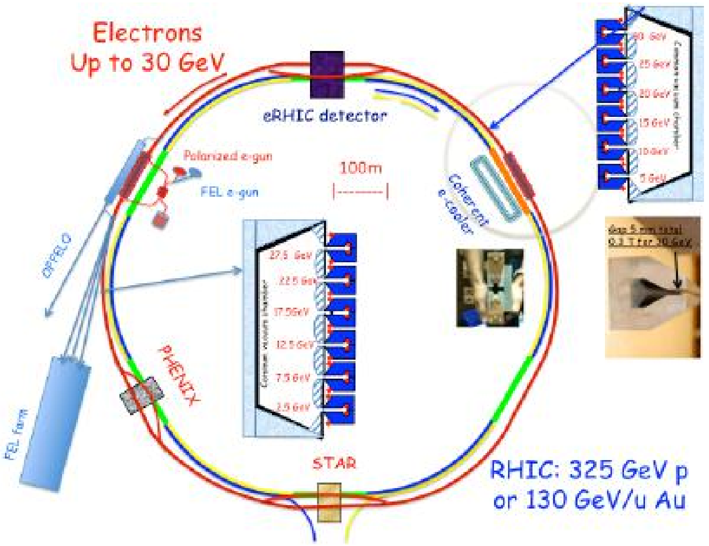
CONTENTS





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TMDPDF at the EIC

The goal

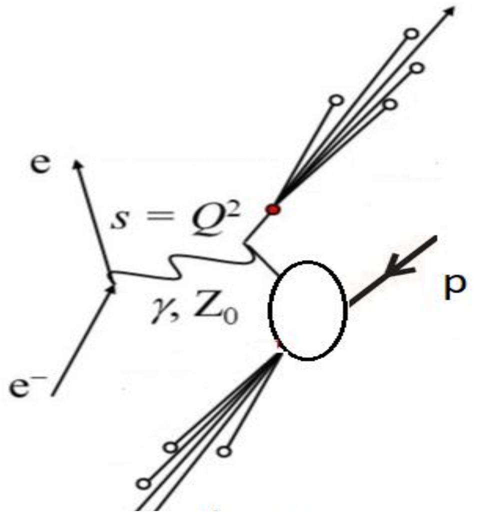
- Use Deep Inelastic Scattering(DIS) on the proton to probe its three dimensional structure.

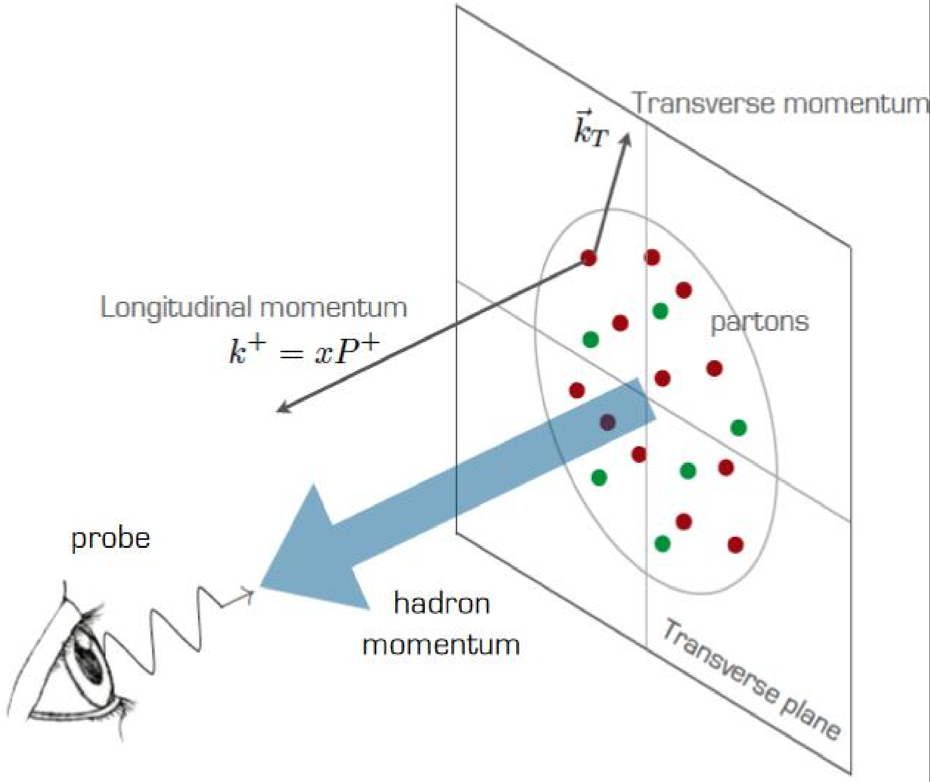
$$\frac{d\sigma}{dxdk_T} \sim H(Q^2)TMDPDF(k_T, x) \otimes FSTMD(k_T) + O\left(\frac{k_T^2}{Q^2}\right)$$

Encodes three dimensional momentum distrbution of partons inside the incoming hadron

Encodes transverse momentum distribution of final state radiation

What q_T observable can we measure on the final state that gives us the cleanest access to the TMDPDF at the EIC?

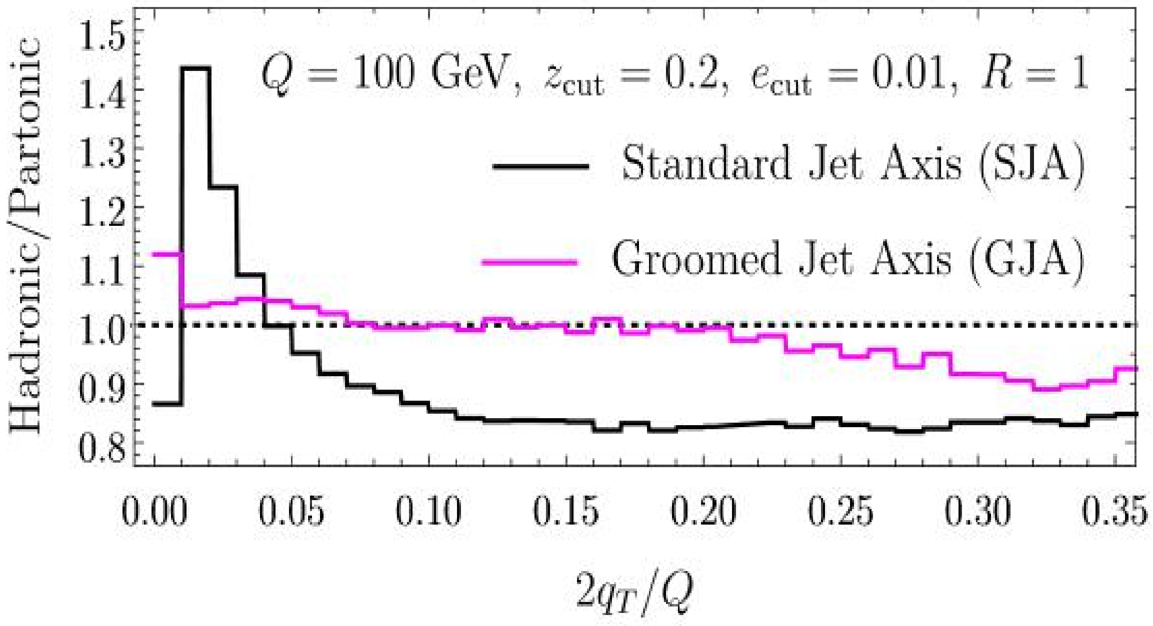




The constraints

- Work with large radius jets that include sufficient number of particles.
- Minimize Non-perturbative effects from every source other than the TMDPDF
- Universality of non -TMDPDF related non-perturbative effects so that they can be extracted from other experiments
- Systematically improvable parton level calculation that can match experimental precision.

The strategy



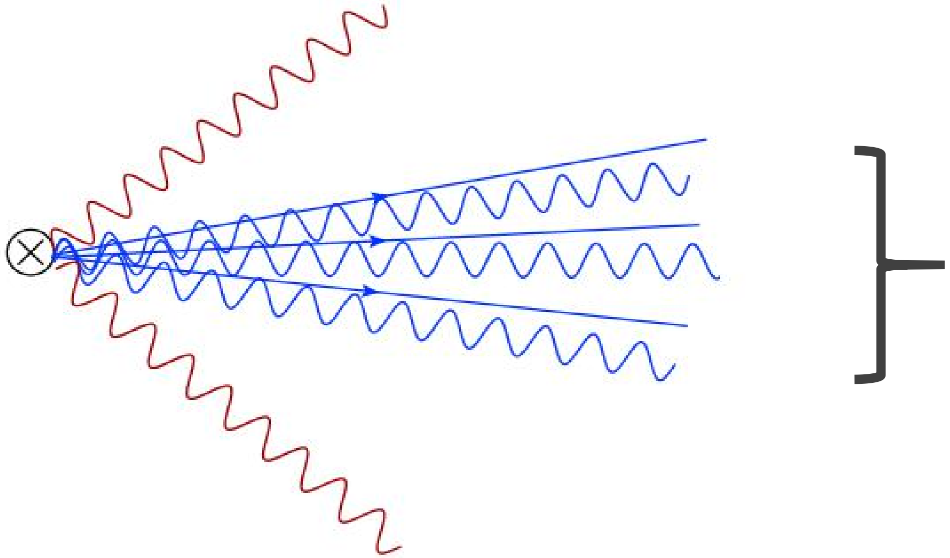
e+e- $\longrightarrow$ dijets

- Use transverse momentum observables computed directly on full jets instead of a single hadron.
- Use grooming procedure to allow for large radius jets free from effects of non-global logarithms, minimize non-perturbative effects.
- Use e+e- to dijets as a proxy for extracting final state non-perturbative effects.

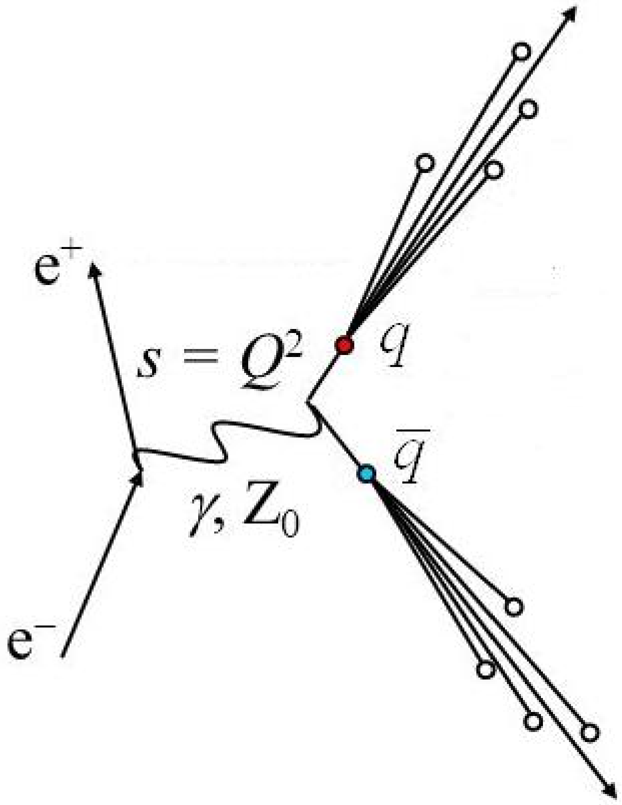
Soft Drop Jet Grooming

- Mitigate the effects of Non-Gobal logarithms and MPI by removing wide angle soft radiation

$$\frac{\min\{E_i, E_j\}}{E_i + E_j} > z_{cut}$$



Observable only sensitive to collinear radiation



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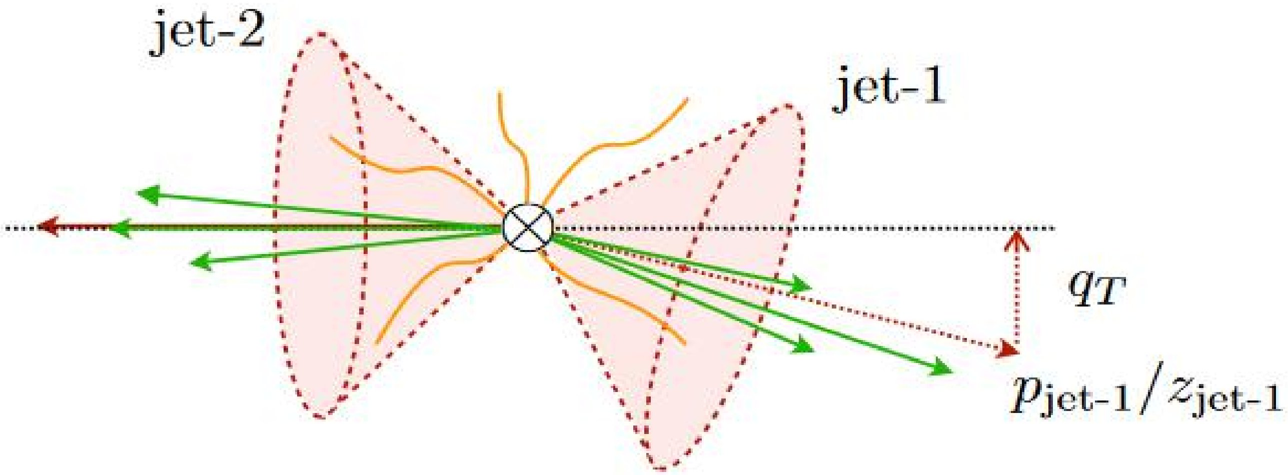
e+e- ⟶ dijets

The observable

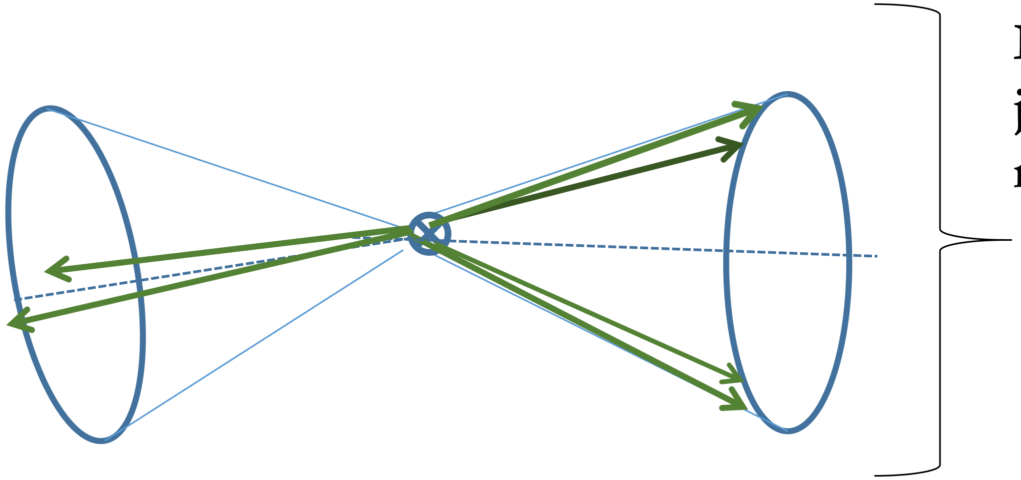
e+e- → dijets

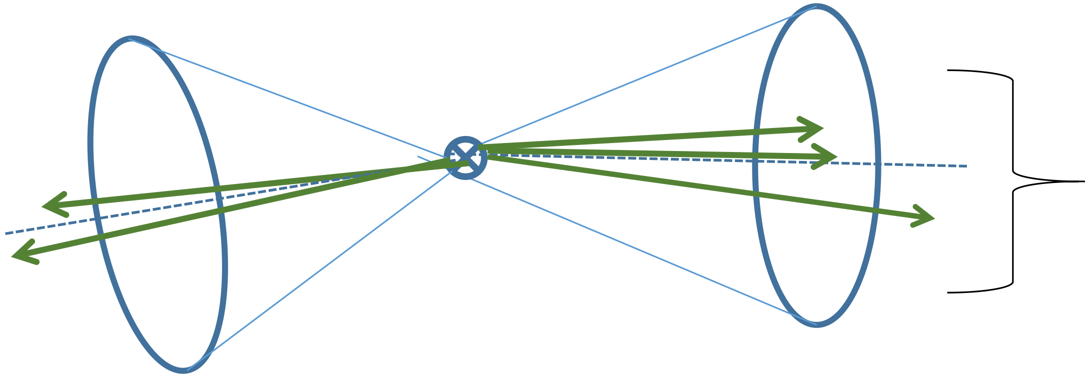


$$\vec{q}_T = \frac{\vec{p}_{t,jet1}}{z_{jet1}} + \frac{\vec{p}_{t,jet2}}{z_{jet2}}$$

- Grooming is implemented using a Soft drop algorithm, with a parameter z_{cut}.
- Measure the transverse momentum imbalance between the two groomed jets .
- This is basically the transverse momentum contribution from all the radiation that lies outside the jets

Factorization for large radius jets





- Wide angle energetic radiation can contribute to small transverse momentum imbalance

- Impose a jet mass measurement on groomed jet to ensure radiation collimated along the jet axis

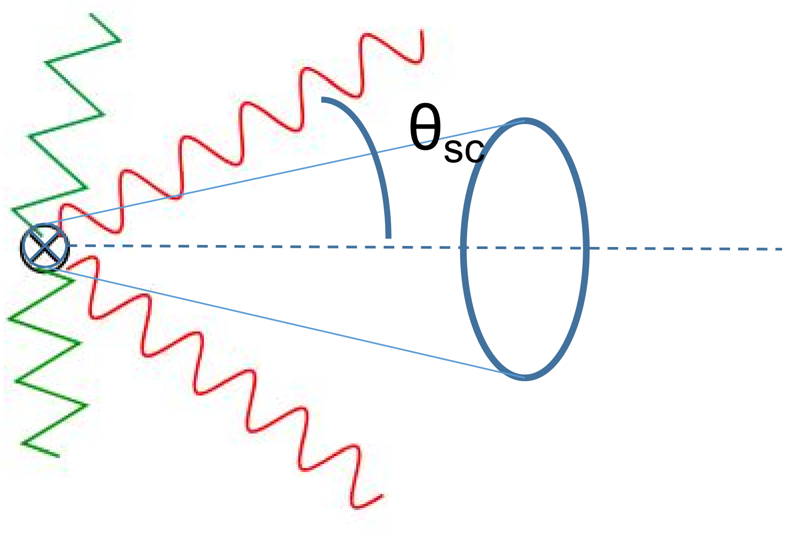
$$\frac{d\sigma}{de_1 de_2 d^2 q_T}, e_i = \left(\frac{m_i}{2E_i}\right)^2$$

$$\frac{d\sigma}{d^2 q_T} = \int_0^{e_{cut}} \int_0^{e_{cut}} \frac{d\sigma}{de_1 de_2 d^2 q_T}$$

- Allows factorization in terms of Universal Soft function with 2 Wilson lines

Factorization in SCET

$$Q >> Qz_{cut} >> q_T \geq Q\sqrt{e}$$



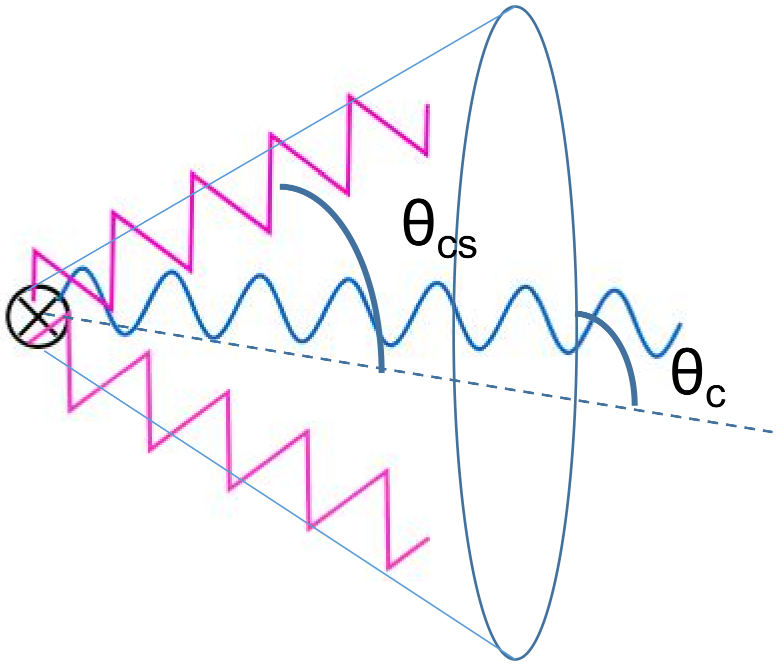
Carving up phase space by momentum scaling

$$p_s^\mu \sim q_T(1,1,1)$$

$$p_{sc}^\mu \sim Qz_{cut}(1,\theta_{sc}^2,\theta_{sc}) \qquad \theta_{sc} = \frac{q_T}{Qz_{cut}}$$

- These modes fail soft drop and contribute to the transverse momentum.
- $z_{cut} << 1 \sim 0.1 - 0.2$

Factorization in SCET



$$Q >> Qz_{cut} >> q_T \geq Q\sqrt{e}$$

Carving up phase space by momentum scaling

$$p_c^\mu \sim Q(1, \theta_c^2, \theta_c) \qquad \theta_c = \sqrt{e}$$

$$p_{cs}^\mu \sim Qz_{cut}(1, \theta_{cs}^2, \theta_{cs}) \qquad \theta_{cs} = \sqrt{\frac{e}{z_{cut}}}$$

These modes pass soft drop and contribute to the groomed jet mass.

Factorization in SCET

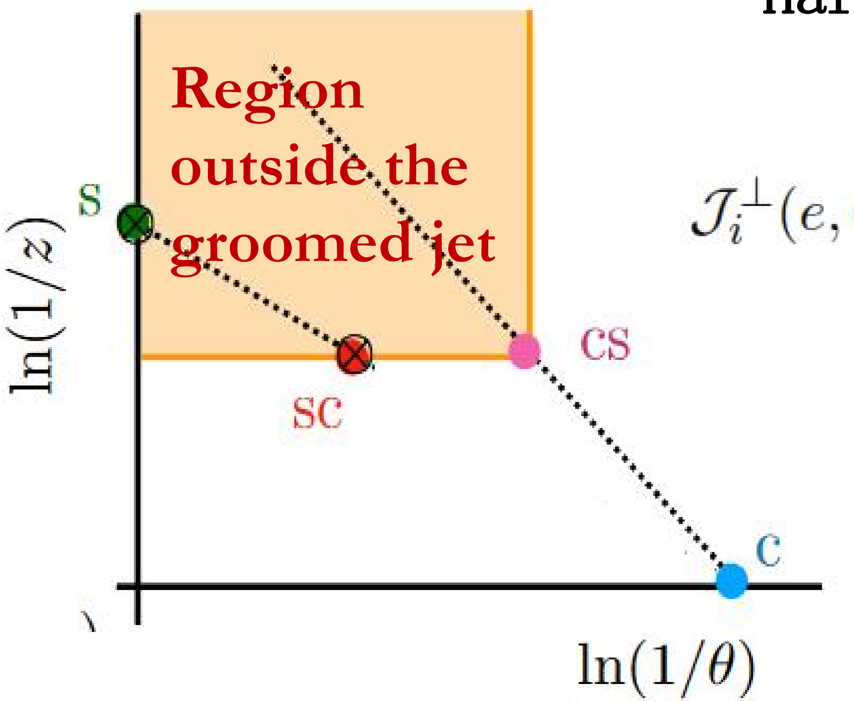
$$Q >> Qz_{cut} >> q_T \geq Q\sqrt{e}$$

$$\frac{d\sigma}{de_1 de_2 d\boldsymbol{q}_T} = H_2^{ij}(Q;\mu) \times S(\boldsymbol{q}_T) \otimes \mathcal{J}_i^{\perp}(e_1, Q, z_{\rm cut}, \boldsymbol{q}_T) \otimes \mathcal{J}_j^{\perp}(e_2, Q, z_{\rm cut}, \boldsymbol{q}_T)$$

Hard Soft

$$\mathcal{J}_i^{\perp}(e, Q, z_{\rm cut}, \boldsymbol{q}_T) = S_{sc,i}^{\perp}(Qz_{\rm cut}, \boldsymbol{q}_T) \times \int de' \, S_{cs,i}(e - e', Qz_{\rm cut}) J_i(e', Q)$$

Soft-Collinear Collinear-Soft Collinear



The jet mass dependent piece only acts as an overall normalization!

A note on definitions

$$\frac{d\sigma}{de_1 de_2 d\boldsymbol{q}_T} = H_2^{ij}(Q;\mu) \times S(\boldsymbol{q}_T) \otimes \mathcal{J}_i^{\perp}(e_1, Q, z_{\rm cut}, \boldsymbol{q}_T) \otimes \mathcal{J}_j^{\perp}(e_2, Q, z_{\rm cut}, \boldsymbol{q}_T)$$

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Unsubtracted jet TMD

$$\mathcal{J}_i^{\perp}(e, Q, z_{\rm cut}, \boldsymbol{b}, \mu, \zeta) = \sqrt{S(\boldsymbol{b})}\mathcal{J}_i^{\perp}(e, Q, z_{\rm cut}, \boldsymbol{b})$$

$$\frac{d\sigma}{de_1 de_2 d\boldsymbol{q}_T} = H_2^{ij}(Q;\mu) \times \mathcal{J}_i^{\perp}(e_1, Q, z_{\rm cut}, \boldsymbol{q}_T; \mu, \zeta_A) \otimes \mathcal{J}_j^{\perp}(e_2, Q, z_{\rm cut}, \boldsymbol{q}_T; \mu, \zeta_B)$$

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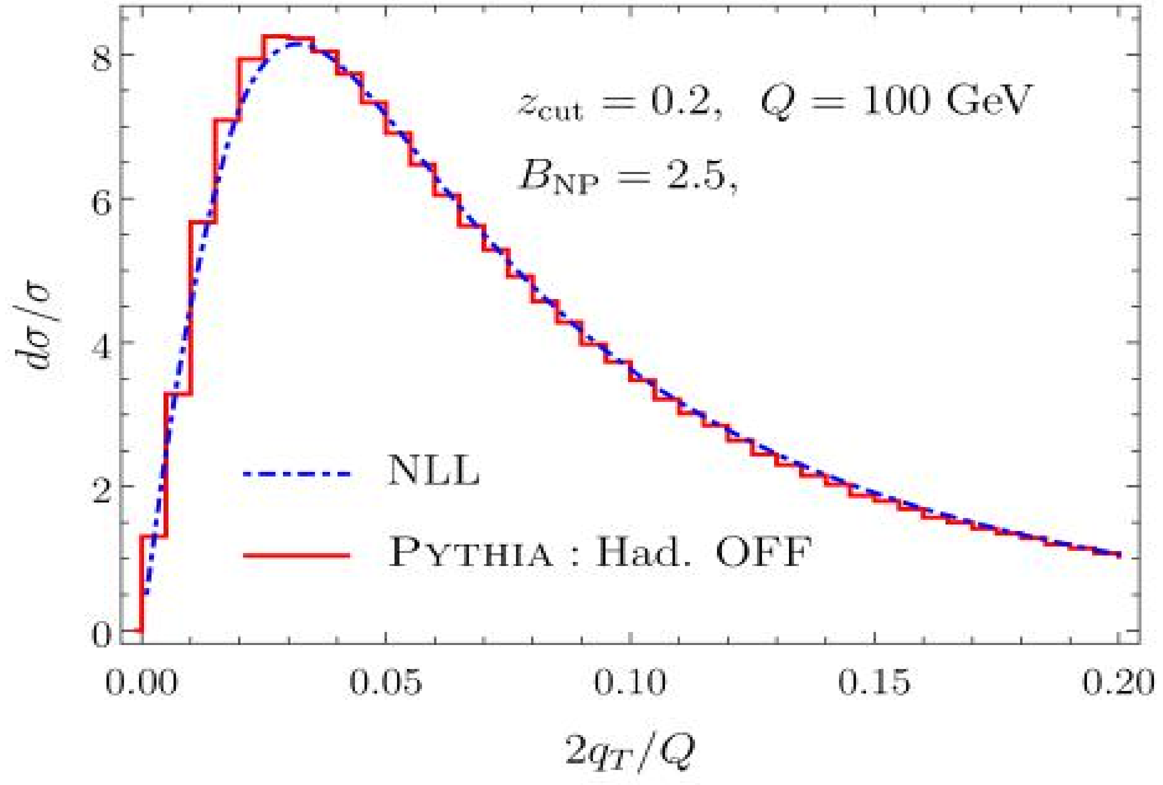
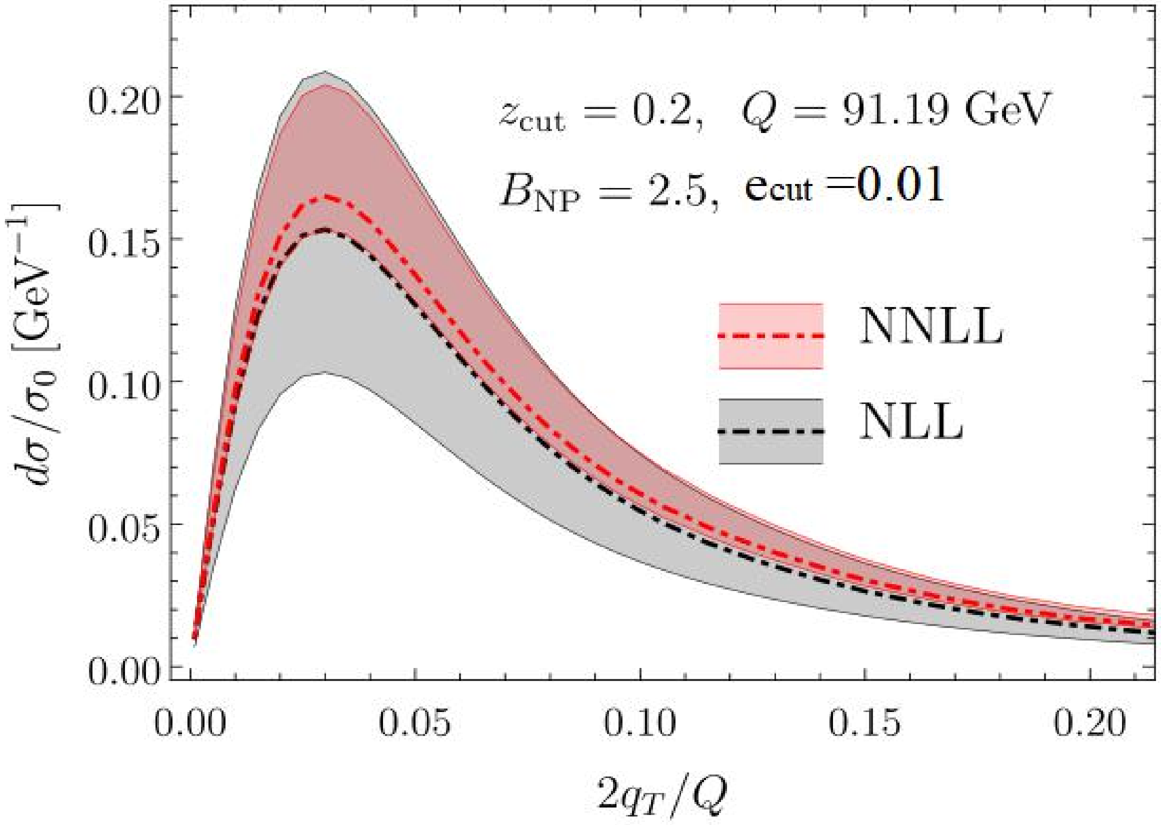
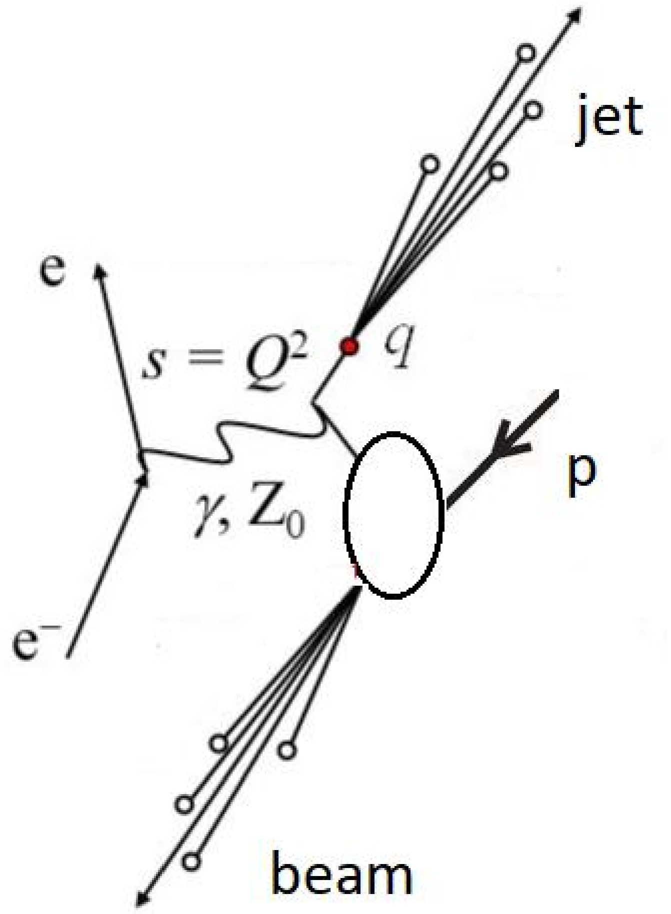
Subtracted jet TMD

Results for e^+e^- to dijets







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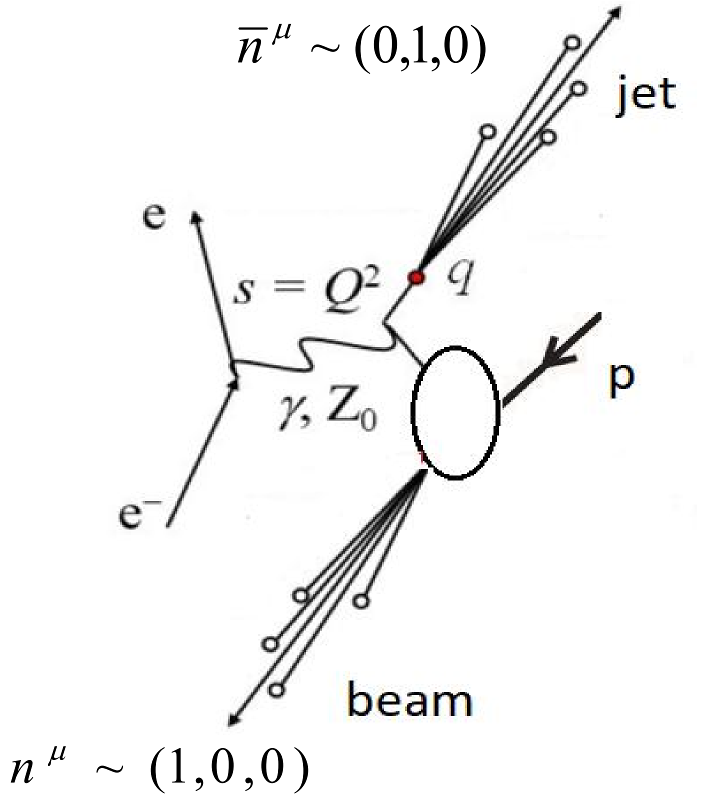
$e^- + p \longrightarrow e^- + \text{jet}$

Working in the Breit frame



- The photon has space-like momentum only in the z direction

$$q^\mu = \frac{Q}{2}(n^\mu - \bar{n}^\mu)$$

- Measure the transverse momentum of the final state jet with respect to the direction of the photon 3 momentum.

- We get a contribution from all the radiation that fails soft drop as well as initial state radiation that forms the TMDPDF

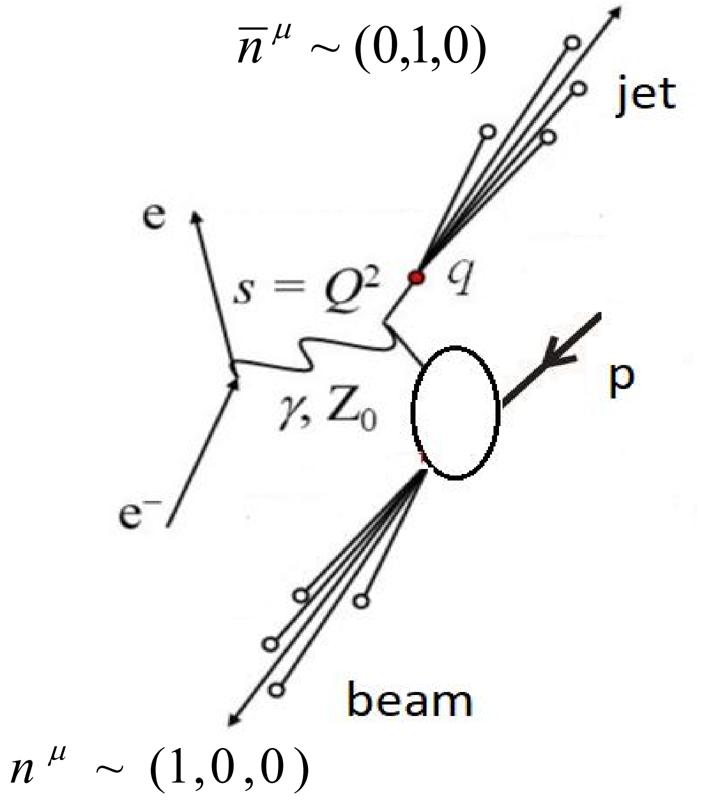
Working in the Breit frame

$$\frac{d\sigma}{dx dQ^2 d\boldsymbol{q}_T} = \mathcal{N}(x,Q) H_2(Q,\mu) \times S(\boldsymbol{q}_T) \otimes B_{i\leftarrow h}(x,Q,\boldsymbol{q}_T) \otimes \mathcal{J}_j^{\perp}(e_{\text{cut}},Q,z_{\text{cut}},\boldsymbol{q}_T)$$

Same soft function as in e^+e^-

Unsubtracted TMDPDF

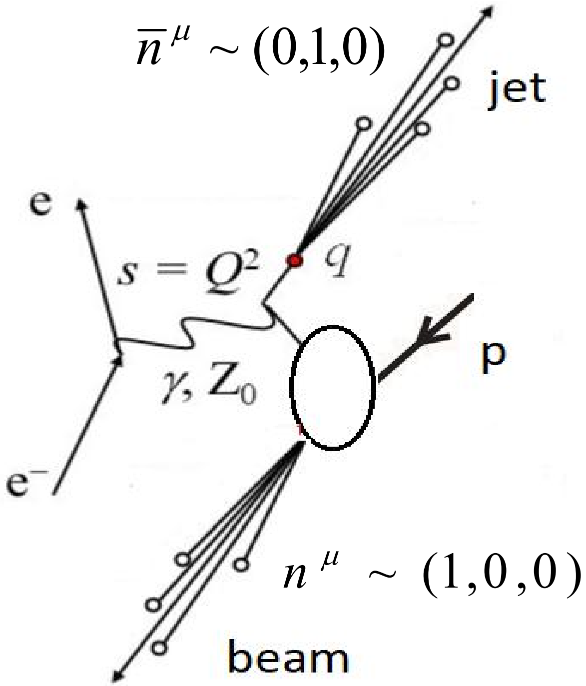
Unsubtracted jet TMD , same as in e^+e^-



- Working the Breit frame is crucial to get universality for the soft function.

$$S(\boldsymbol{q}_T) = \frac{1}{N_R} \text{tr} \, \langle [S_n^\dagger S_{\bar{n}}](0) \delta^{(2)}(\boldsymbol{q}_T - \boldsymbol{\mathcal{P}}_\perp) [S_{\bar{n}}^\dagger S_n](0) \rangle$$

Working in the Breit frame

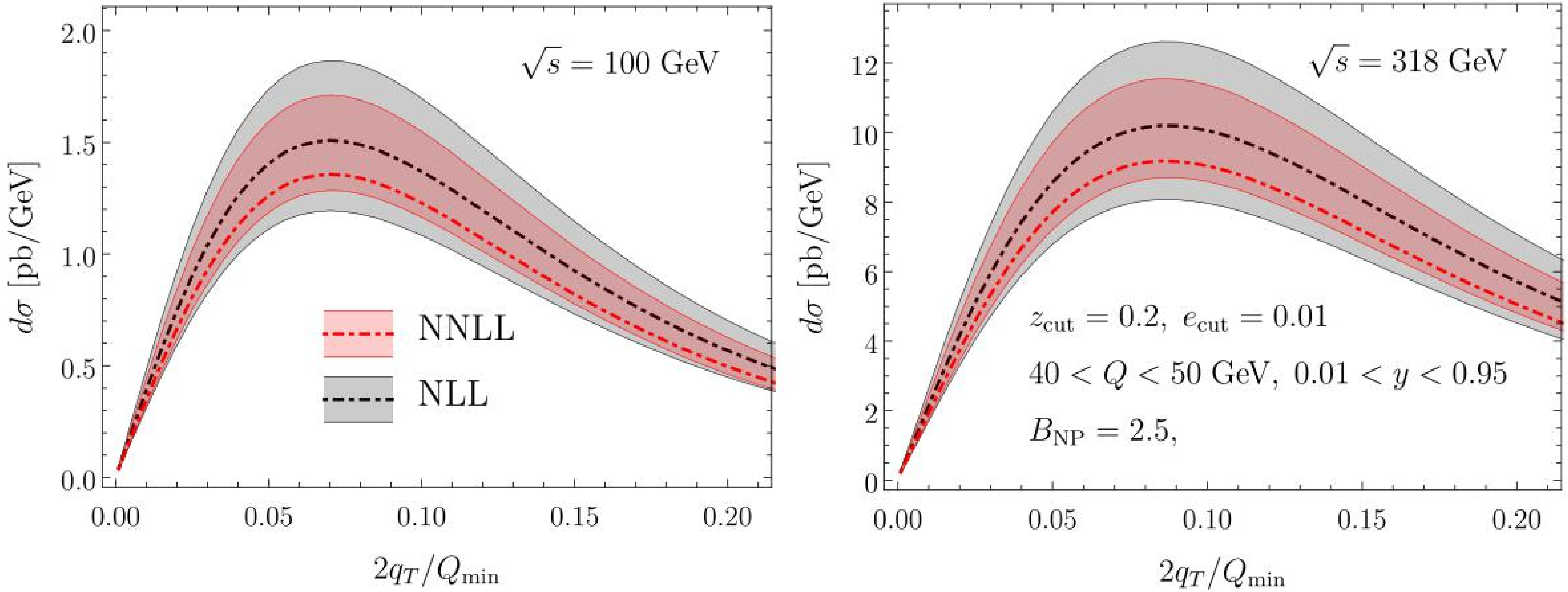


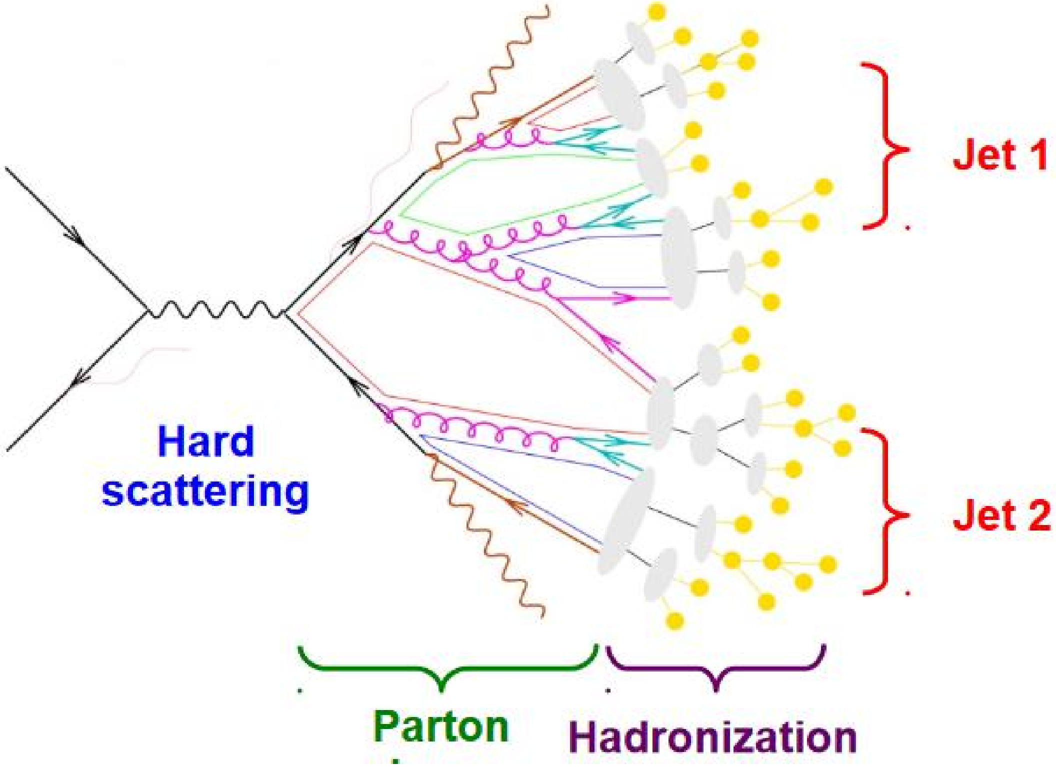
$$F_{i\leftarrow h}(x, \boldsymbol{b}; \mu, \zeta) = \sqrt{S(\boldsymbol{b})} B_{i\leftarrow h}(x, Q, \boldsymbol{b})$$

$$\mathcal{J}_i^{\perp}(e, Q, z_{\text{cut}}, \boldsymbol{b}, \mu, \zeta) = \sqrt{S(\boldsymbol{b})} \mathcal{J}_i^{\perp}(e, Q, z_{\text{cut}}, \boldsymbol{b})$$

$$\frac{d\sigma}{dx dQ^2 d\boldsymbol{q}_T} = \mathcal{N}(x, Q) H_2(Q, \mu) \int \frac{d\boldsymbol{b}}{4\pi^2} e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T} F_{i\leftarrow h}(x, Q, \boldsymbol{b}, \mu, \zeta_A) \mathcal{J}_j^{\perp}(e_{\text{cut}}, Q, z_{\text{cut}}, \boldsymbol{b}; \mu, \zeta_B)$$

Results for DIS





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Hadronization effects

Extracting the jet TMD Non-perturbatives effects

- To get to the TMDPDF we need to have a good handle on the (small) non-perturbative effects that appear in the final state jet TMD.

- After suitable parametrization, we can extract the Hadronization effects from e^+ e^- to dijets which contains two copies of the jet TMD

$$\frac{d\sigma}{de_1 de_2 d\boldsymbol{q}_T} = H_2^{ij}(Q;\mu) \times \mathcal{J}_i^{\perp}(e_1, Q, z_{\text{cut}}, \boldsymbol{q}_T; \mu, \zeta_A) \otimes \mathcal{J}_j^{\perp}(e_2, Q, z_{\text{cut}}, \boldsymbol{q}_T; \mu, \zeta_B)$$

- Then we can simply use those paramters for the case of DIS where one of the jet TMDs is replaced by the TMDPDF

$$\frac{d\sigma}{dx dQ^2 d\boldsymbol{q}_T} = \mathcal{N}(x, Q) H_2(Q, \mu) \int \frac{d\boldsymbol{b}}{4\pi^2} e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T} F_{i\leftarrow h}(x, Q, \boldsymbol{b}, \mu, \zeta_A) \mathcal{J}_j^{\perp}(e_{\text{cut}}, Q, z_{\text{cut}}, \boldsymbol{b}; \mu, \zeta_B)$$

A qualitative picture of final state hadronization effects for groomed jets

- Parametrize power corrections at leading power in Λ_{QCD}/q_T

  A. Shift power corrections

  hadronization corrections that do not affect the partonic Soft drop condition.

$$\langle 0|T[S_n S_{\bar{n}}^\dagger(\boldsymbol{b})]\bar{T}[S_{\bar{n}} S_n^\dagger(0)]|0\rangle = \tilde{S}(b)\Big(1 + b^2\, C_i^{(s)}(b)\langle 0|O^i|0\rangle\Big)$$

$$\tilde{S}_{sc}^\perp(b, z_{\rm cut})|_{\rm hadr.} = \tilde{S}_{sc}^\perp(b, Q z_{\rm cut})\Big(1 + b^2 C_i^{(sc)}(b, z_{\rm cut})\ \langle 0|O^i|0\rangle\Big)$$

$$SS_{sc}^\perp|_{\rm hadr.} = (1 + b^2(\Omega_s + \Omega_{sc}))SS_{sc}^\perp|_{\rm pert.}$$

→ **produces a shift in the TMD**

A qualitative picture of final state hadronization effects for groomed jets

B. Boundary power corrections

hadronization corrections that affect the partonic Soft drop condition -> only affects modes that sit on the boundary of SD -> Sc and Cs modes.

Only the Sc mode contributes to qT

1. The partonic sc mode fails SD but passes after hadronization.

2. The partonic sc mode passes SD but fails after hadronization.

A systematic analysis of these corrections is detailed in I.Stewart et. al. 1906.11843

Summary

- A proposal for measuring the transverse momentum imbalance for groomed jets as a probe of the TMDPDF

- Grooming allows for large radius jets without suffering from NGLs, also have very small hadronization effects.

- Final state NP effects can be systematically parametrized and extracted from e+e-.

- Ongoing work on obtaining operator definitions for leading NP effects for groomed jets.

THANK YOU