Jets at the Electron Ion Collider

Duff Neill
LANL

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Nuclear Physics is Toddler Science

When presented with a nucleon or nucleus or neutron star:

- **Static: What is it?**
- **Dynamics: What happens when I hit or smash it?**

The Electron Ion Collider

So for EIC,
whence the static and dynamic properties of hadrons,
in terms of their underlying partonic degrees of freedom?

$$\mathcal{L}^{\mathrm{QCD}} = \frac{1}{4}\mathrm{tr}\Big[F_{\mu\nu}F^{\mu\nu}\Big] + \sum_i \bar{\psi}_i\Big(i\not{D} - m_i\Big)\psi_i$$

Understanding QCD

Two approaches to QCD manifestly use partons:*

- **Lattice QCD:** Evaluate hadron static properties with local Quark and Gluon Matrix Elements.
- **Factorization:** Describe dynamic cross-sections as products of Non-Local Quark and Gluon Matrix Elements.

Both claim model-independent all-orders or non-perturbative accuracy.

*As opposed to χ-PT.

To discusss Jets, we must discuss Factorization.

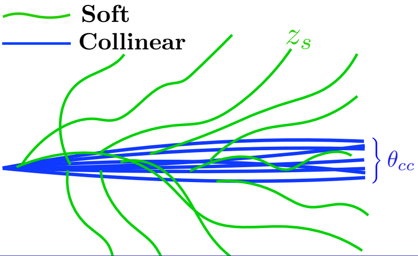
Factorization and The "States" of Perturbation Theory

- High energies, no intrinsic scale, except hard interaction at Q^2.
- (Most) Quarks and gluons are massless when on-shell: $p_g^2 = p_q^2 = 0$.
- Continuous spectrum and long range-interactions.

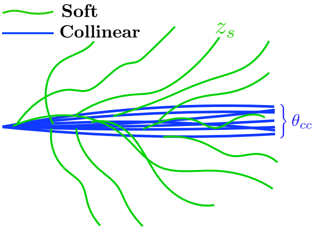
$$m_{ab}^2 = (p_a + p_b)^2 = 4E_a E_b \sin^2\frac{\theta_{ab}}{2} \sim Q^2 z_a z_b \theta_{ab}^2$$

Close to on-shell:

- Soft: $\left(\sum p_s\right)^2 \sim Q^2 z_s^2 \ll Q^2$
- Collinear: $\left(\sum p_c\right)^2 \sim Q^2 \theta_{cc}^2 \ll Q^2$



Power Counting The "States" of Perturbation Theory



$$p = (\bar{n}\cdot p, n\cdot p, p_\perp)$$

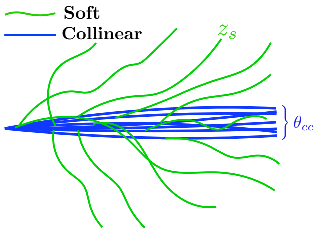
$$p_c \sim Q(1, \theta_{cc}^2, \theta_{cc}) \qquad\qquad p_s \sim Q(z_s, z_s, z_s)$$

Close to on-shell:

- Soft: $\left(\sum p_s\right)^2 \sim Q^2 z_s^2 \sim n\cdot p_s \bar{n}\cdot p_s - \vec{p}_{s\perp}^{\,2}$
- Collinear: $\left(\sum p_c\right)^2 \sim Q^2\theta_{cc}^2 \sim n\cdot p_c \bar{n}\cdot p_c - \vec{p}_{c\perp}^{\,2}$

Why do jets form?

Soft and Collinear regions are prefered.



Relating n to $n+1$ parton cross-sections:

$$d\sigma_{n+1} \sim \alpha_s(Qz\theta)\frac{d\theta}{\theta}\frac{dz}{z}d\sigma_n$$

Once we probe with a Q^2 with tens of GeV, jets will form.

Factorization:

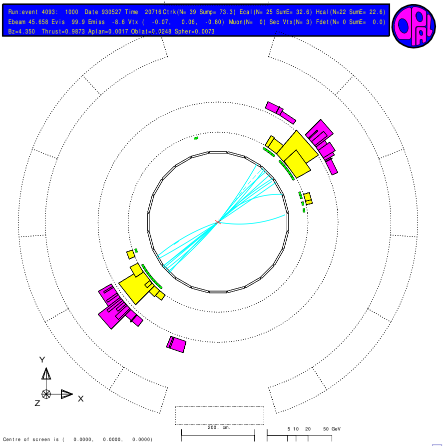
- Distinct Collinear Regions do not interact.
- Soft radiation resolves directions and total color charge.
- High energy processes arrange themselves into jets.

This encompasses much more than
PDFs, TMD-PDFs, FFs, TMD-FFs.

Factorization Intuition

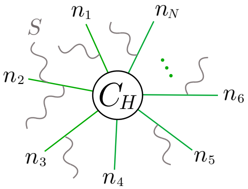
At a large Q^2:

- Short-distance physics perturbative: asympotic freedom.
- Fast moving partons quickly out of casual contact.
- Bulk momentum flow set by perturbative dynamics.



Questions of Jet Physics

Hard Scattering sets bulk momentum flow.

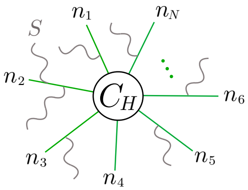


- What are the momentum fluctuations about this bulk flow?
- How are spin, color, flavor transported to the infra-red?
- How do the partonic fields become hadrons?
- Does the measurement respect the jet decomposition?
- When do media change the transport?

Factorization as a Theorem

Factorization:
Separating a cross-section into a finite product of non-trivial distributions, with support in distinct momentum regions.

$$\frac{d\sigma}{d\tau} = \mathrm{tr}[C_H(Q^2,\mu)S(\tau,\mu)C_H^\dagger(Q^2,\mu)] \otimes J_{n_1}(\tau,\mu) \otimes J_{n_2}(\tau,\mu) \otimes ... + O\left(\frac{\tau^2}{Q^2}\right)$$



- τ observable specifying N-jets.
- J energetic jets or beams contribution to τ.
- S soft radiation contribution to τ.
- Resummation with renormalization group.
- Universality of Asymptotics of QCD (Reusability of H, J, S)

Factorized Form of Q_T Spectrum, or 0-jet Cross-Section

Factorized Momentum Spectrum (Drell-Yan):

$$\frac{d\sigma}{dy d^2\vec{Q}_T dQ^2} = \sigma_0 \int \frac{d^4q}{(2\pi)^3}\delta^+(n\cdot q\,\bar{n}\cdot q - Q^2)\delta\Big(y - \frac{1}{2}\ln\frac{n\cdot q}{\bar{n}\cdot q}\Big)\delta^{(2)}(\vec{Q}_T - \vec{q}_\perp)$$

$$\int d^4b e^{ib\cdot q} H_{q\bar{q}}(Q) B_{n,q/N_A}(0, n\cdot b, \vec{b}_\perp) B_{\bar{n},\bar{q}/N_B}(\bar{n}\cdot b, 0, \vec{b}_\perp) S(0,0,\vec{b}_\perp)$$

$$+ \mathrm{q} \leftrightarrow \bar{\mathrm{q}} + O\left(\frac{Q_T^2}{Q^2}\right).$$

$$B_n(b^+, b^-, \vec{b}_\perp) = \mathrm{tr}\langle N(P)|\bar{\chi}_n(b)\frac{\bar{\not{n}}}{2}\chi_n(0)|N(P)\rangle\,,$$

$$S(b^+, b^-, \vec{b}_\perp) = \frac{1}{d_a}\mathrm{tr}\langle 0|\mathrm{T}\{S^\dagger_{\bar{n}}(0)S_n(0)\}\bar{\mathrm{T}}\{S^\dagger_n(b)S_{\bar{n}}(b)\}|0\rangle\,,$$

$$\chi_n(x) = W_n^\dagger(-\infty, x)\psi_n(x)$$

$$W_n(x) = \mathrm{P}\exp\Big(ig\int_{-\infty}^0 ds\,\bar{n}\cdot A(x+s\bar{n})\Big)\,,$$

$$S_n(x) = \mathrm{P}\exp\Big(ig\int_{-\infty}^0 ds\,n\cdot A(x+sn)\Big)\,.$$

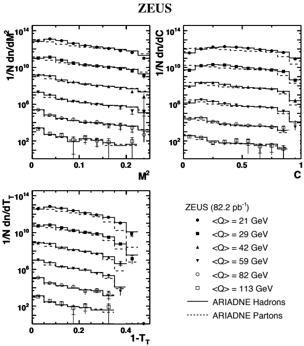
Jets at Colliders

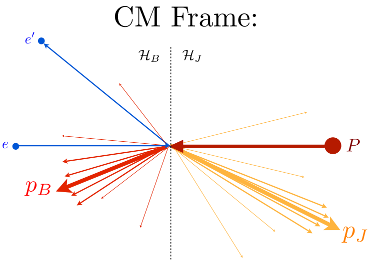
What has been done with jets at e^+e^- and $e-p$ machines?

- Inclusive jet production at R, p_T
- Fragmentation
- Event shapes

Main reasons: History and α_s.

Jets in $e-p$ at HERA





[**ZEUS: hep-ex/0604032**],

See also [H1: hep-ex/0512014],

Factorization:

$$\frac{d\sigma}{de} = HB \otimes J \otimes S$$

Specific convolution structure depends on jet definition:

[Kang, Lee, Stewart 1303.6952]

Jets at Colliders

LHC juiced study of jets:

- What does the pattern of radiation in a jet reveal about its origin?

Review of Jet Substructure, with approx. 450 references:
[Larkoski, Moult, Nachman, 1709.04464]

See talks from last weeks' Brookhaven conference:
"Probing Quark and Gluon Matter with Jets"

What about EIC?

Back to Toddler Science?

Observations:

- **Factorization:** Jets are the direct manifestation of parton dynamics.
- **Confinement:** Hadrons are “bags” of strongly bound-partons

So why not hit the nucleus or nucleon with a jet?!
This is something the EIC can do, no-one else has done with $e - A$*

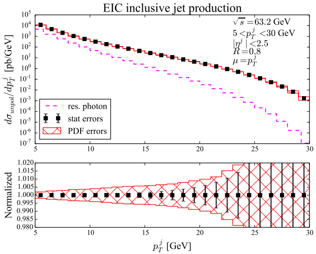
*Except maybe Fermilab E665, 1994

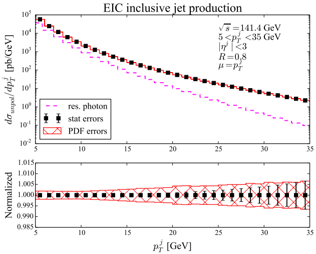
Toddler Science!

This is reason enough to think about jet physics at EIC.

Issue: Low Q^2

The EIC can make jets, but low multiplicity and Energy.





[Boughezal, Petriello, Xing 1806.07311]

This will limit how much jet substructure can be studied.

- Multiplicity
- Fragmentation
- Thrust, Angularities, Mass, Broadening...
- Jet axes, Jet Shape

Issue: Low Q^2

Therefore Jets at EIC will test the limits of the factorized description of jet cross-section.

However, compared to LHC.

- Little Underlying Event

New testing ground for

- Local Parton-Hadron Duality?
- String Fragmentation?
- Breakdown of Coherence?
- Substructure?
- α_s?

Mind the $O\left(\frac{\tau^2}{Q^2}\right)$ at the EIC

.

Given the low energies, are changes to jet spectra from:

- $e-A$ and $e-p$: non-perturbative components of B, J, S?
- $e-A$: changes in evolution
  [Mehtar-Tani, Salgado, Tywoniuk 1102.4317], **[Sievert, Vitev 1807.03799]** ?
- Subleading power factorization?
  [Boughezal et. al. 1802.00456], **[Ebert et. al. 1807.10764]**

Ultimately, how and whether these questions will be answered depends on the reach of the kinematic scan of the EIC.