



Ignazio Scimemi (UCM)

Jet substructures and TMD

Most recent results in collaboration with
Miguel G. Echevarría,
Daniel Gutiérrez Reyes,
Duff Neill,
Alexey Vladimirov
Wouter Waalewijn

Resummation, Evolution, Factorization 2017



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Presentation

Dates: 13/11/2017-17/11/2017

REF 2017 is the 6th workshop in the series of workshops on Resummation, Evolution, Factorization. Previous discussion meetings and workshops were

7-10 November 2016 Antwerp (Belgium)

2-5 November 2015 DESY Hamburg (Germany)

1-3 June 2015 Amsterdam (The Netherlands)

8-11 December 2014 Antwerp (Belgium)

Outline & Issues

- ❖ Pure/entangled states in QCD? Factorization theorems for DY, DIS and semi-inclusive processes
- ❖ **Transverse Momentum Distributions (TMD):** definition, renormalization,...status
- ❖ Jets..a new frontier
- ❖ Conclusions

The non-perturbative part of TMDs is **not** included just in PDFs. Possible extraction from

- ❖ Lattice
- ❖ Experiment

.... TMD factorization

.. for DY and heavy boson production we have (Collins 2011, Echevarria, Idilbi, Scimemi (EIS) 2012)

$$\frac{d\sigma}{dQ^2 dq_T dy} = \sum_q \sigma_q^\gamma H(Q^2, \mu^2) \int \frac{d^2 \mathbf{b}}{4\pi} e^{-i \mathbf{q}_T \cdot \mathbf{b}} \Phi_{q/A}(x_A, \mathbf{b}, \zeta_A, \mu) \Phi_{q/B}(x_B, \mathbf{b}, \zeta_B, \mu)$$
$$\sqrt{\zeta_A \zeta_B} = Q^2$$

...and similar formulas are valid for SIDIS (EIC) and hadron production in ee colliders

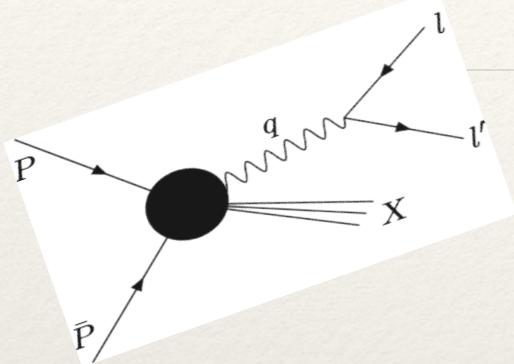
The pathological behavior is associated to a particular kind of divergences: rapidity divergences

The renormalization of the rapidity divergences is responsible for the new resummation scale

We have new nonperturbative effects which cannot be included in PDFs. (Scimemi,Vladimirov 2016)

The latest and more elegant formulation of this in Echevarria, Scimemi, Vladimirov 2015-16:
the NNLO era is just started!

TMD's factorization and Operator Product Expansion: general outlook



Factorized hadronic tensor

$$q^2 = Q^2 \gg q_T^2$$

$Q=M$ =di-lepton invariant mass

Factorization

$$q_T^2 \sim \Lambda_{QCD}^2 \rightarrow \tilde{M} = H(Q^2/\mu^2) \tilde{F}_n(x_n, b; Q^2, \mu^2) \tilde{F}_{\bar{n}}(x_{\bar{n}}, b; Q^2, \mu^2)$$

OPE

$$q_T^2 \gg \Lambda_{QCD}^2 \rightarrow \tilde{F}_n(x_n, b; Q^2, \mu^2) = \tilde{C}_{n/j}(x_n, (bQ)^2, (b\mu)^2) f_{j/h}(x_n; \mu^2) + \mathcal{O}(x_n b^2/B^2)$$

Very important

The factorization theorem predicts that each coefficient can be extracted on its own.

The evolution of TMD is universal (process independent)
Rennomalons: power corrections are x -dependent

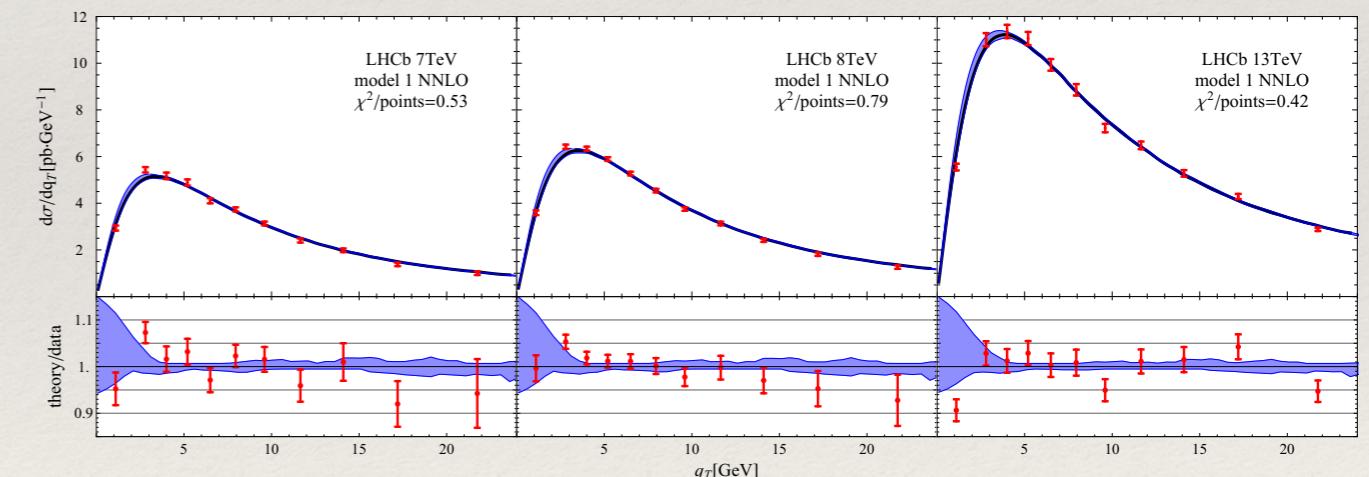
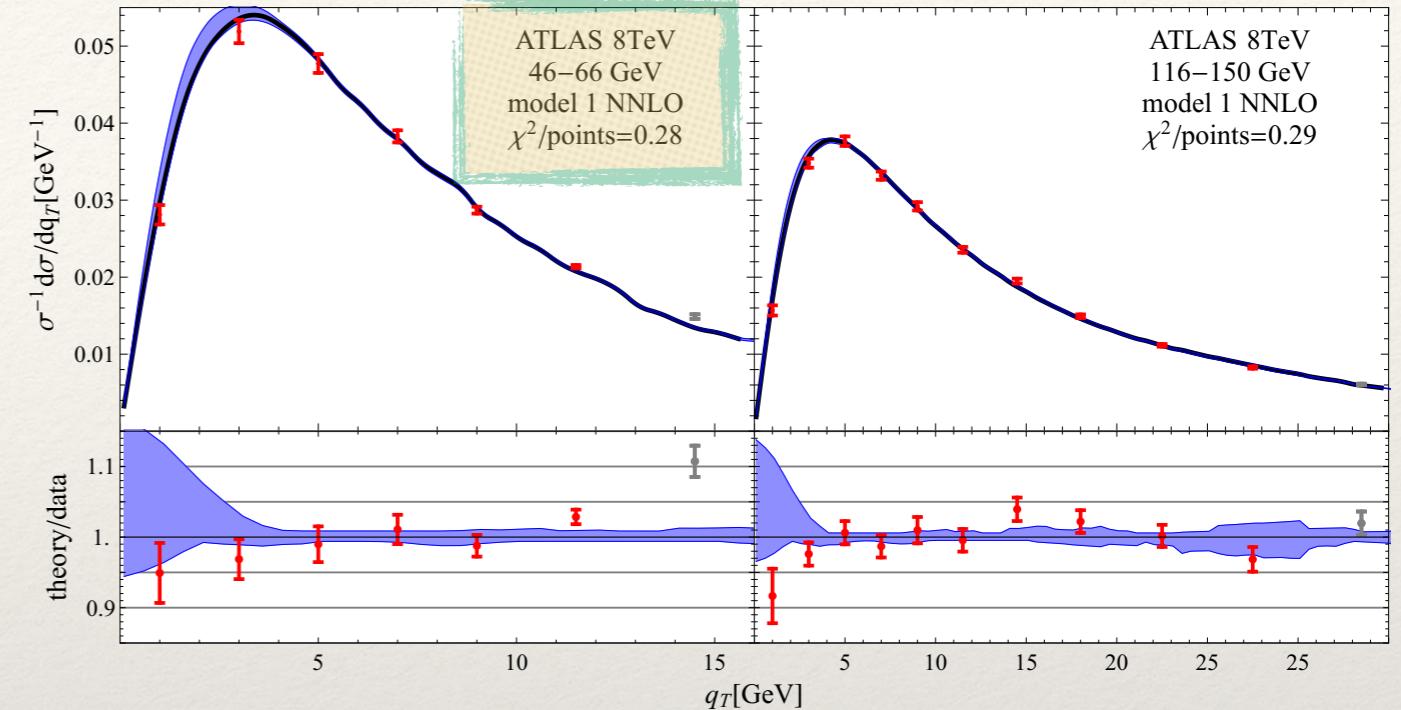
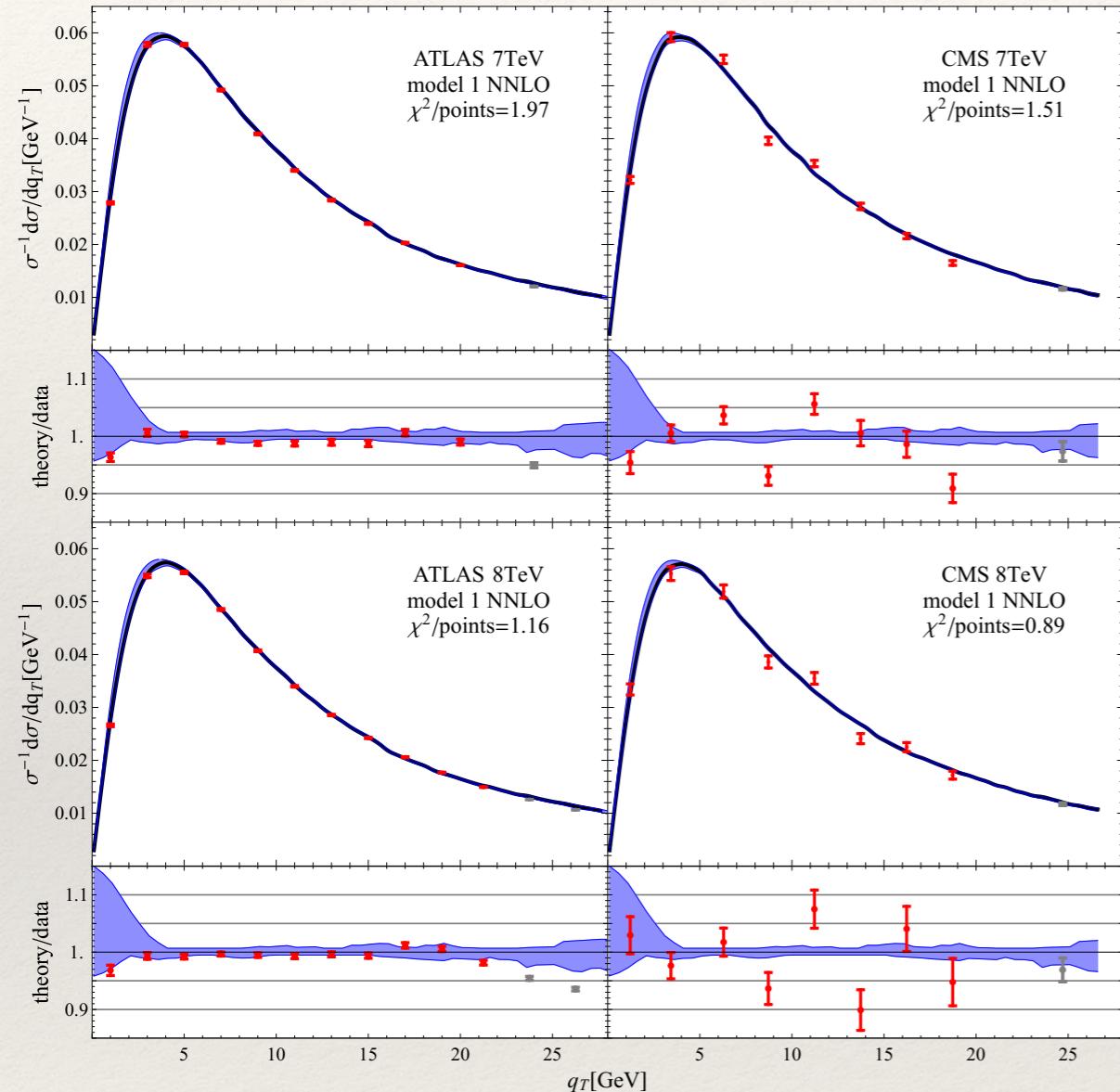
M.G. Echevarría, I.S., A. Vladimirov, arXiv:1509.06392, arXiv:1511.05590, arXiv:1604.07869

All these matchings on collinear functions are just the asymptotic expansion of a more complex structure: how can we explore it?



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results for LHC in Drell-Yan and Z-production



TMDs in fragmentation...jets

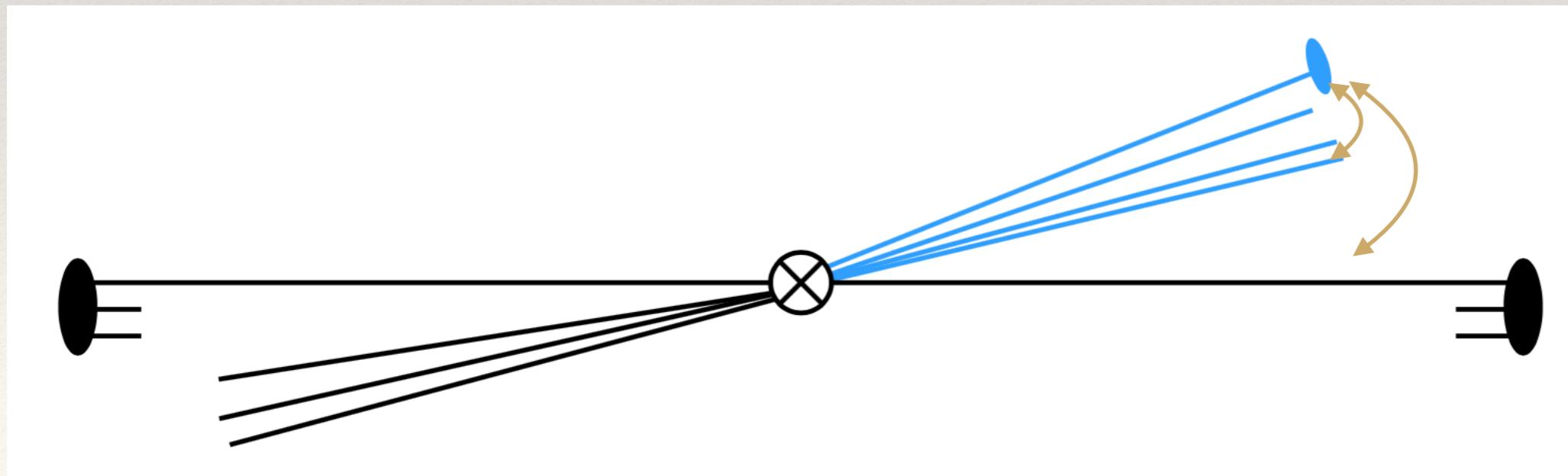
The formalism that we have developed works for fragmentation of partons into hadrons. But, in many experiments, in order to identify hadrons we need **JETS!**

There are several possibility to define a transverse momentum depending on the reference axes:

- beam axis
- jet axis
- ...

So we have a multiplicity of information that we can use!!

We want to study transverse momentum of hadrons inside a jet



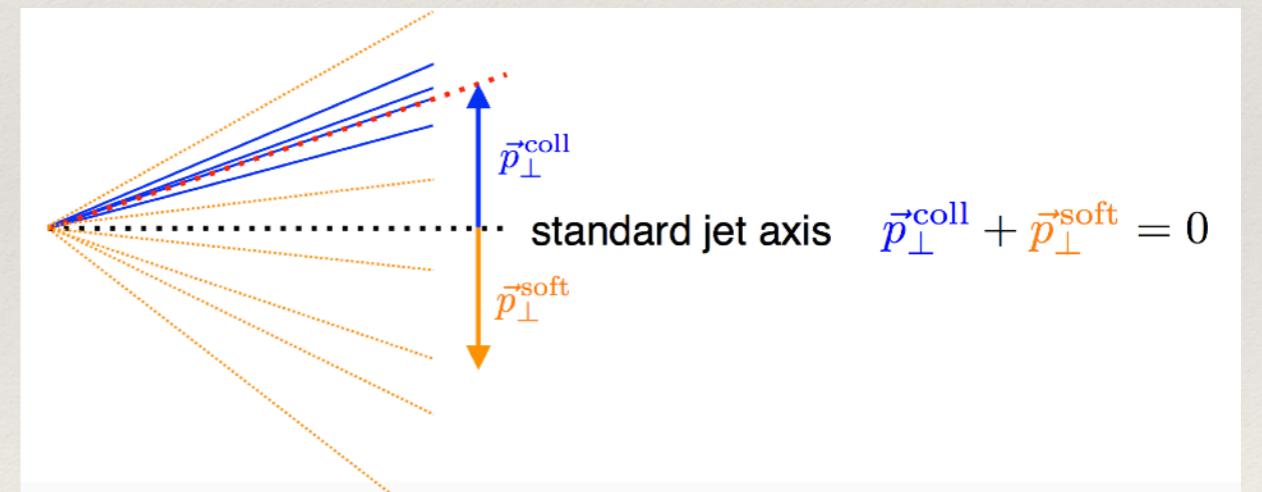
Recoil-free axis: Winner -Take-All axis

We have explored the possibility of recoil free axis to avoid:

- Non-global logs
- rapidity divergences

The price to pay is: the axis is not aligned with the standard jet momentum (standard jet axis)

The soft radiation recoil shifts the whole collinear sector coherently in Transverse Momentum:
We want an axis that shifts of the same amount: WTA axis (Larkoski, Neill, Thaler)



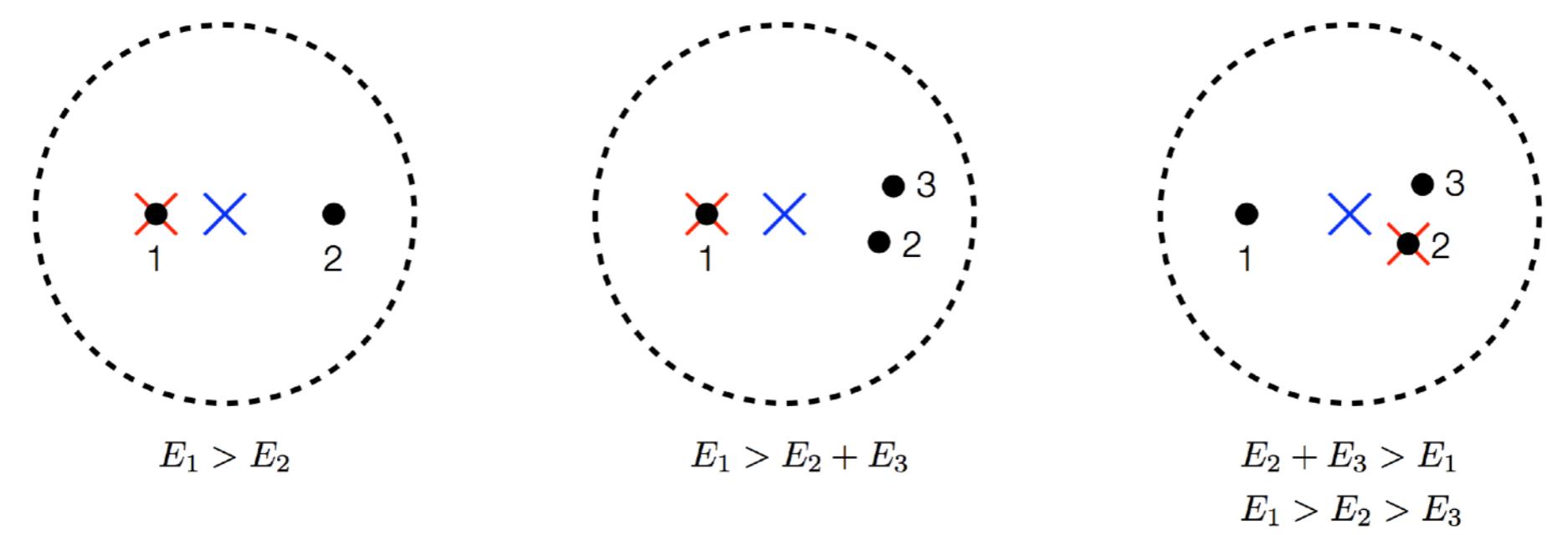
Recoil-free axis: Winner -Take-All (WTA) axis

Run clustering algorithm with following recombination scheme

$$E_r = E_1 + E_2$$

$$\hat{n}_r = \begin{cases} \hat{n}_1 & \text{if } E_1 > E_2 \\ \hat{n}_2 & \text{if } E_2 > E_1 \end{cases}$$

[Salam; Bertolini, Chan, Thaler]



Factorization formulas for Jet TMDs

Starting point:

$$\frac{d\sigma_h}{dp_T d\eta d^2\mathbf{k} dz_h} = \sum_i \int \frac{dx}{x} \hat{\sigma}_i\left(\frac{p_T}{x}, \eta, \mu\right) \mathcal{G}_{i \rightarrow h}(x, p_T R, \mathbf{k}, z_h) [1 + \mathcal{O}(R^2)]$$

Kang, Ringer, Vitev; Dai, Kim, Leibovich



$$z_h = \frac{p_h^-}{p_J^-}$$

x = fraction of parton momentum that goes in the jet

$z_h \mathbf{k}$ = transverse momentum of the hadron in the jet

A very interesting limit!! Suppose

$$p_T R \gg |\mathbf{k}| \sim \Lambda_{QCD}$$

JET TMD!!!

$$\mathcal{G}_{i \rightarrow h}(x, p_T R, \mathbf{k}, z_h, \mu) = \sum_k \int \frac{dy}{y} B_{ik}(x, p_T R, y, \mu) D_{k \rightarrow h}\left(\mathbf{k}, \frac{z_h}{y}, \mu\right) \left[1 + \mathcal{O}\left(\frac{\mathbf{k}^2}{p_T^2 R^2}\right)\right]$$

Summary: scales and factorization

- Factorization depends on relevant hierarchy:

$$\frac{d\sigma_h}{dp_T d\eta d^2\mathbf{k} dz_h} = \hat{\sigma}(p_T, \eta) \otimes \underbrace{B(p_T R) \otimes C(\mathbf{k}) \otimes D(\Lambda_{\text{QCD}})}_{\mathcal{J}(p_T R, \mathbf{k})} \cdot \underbrace{\frac{\text{fat jet } \bar{\sigma}(p_T, \eta)}{\text{partonic xsec}}}_{\text{jet boundary}} \cdot \underbrace{D(\mathbf{k})}_{\text{TMD fragmentation}}$$

fragmenting jet function $\mathcal{G}(p_T R, \mathbf{k})$

- Fragmentation scales: transverse momentum $|\mathbf{k}|$ and Λ_{QCD}
- Jet scales: transverse momentum p_T and radius R

Evolution and resummation

- Single logarithms resummed by renormalization group evolution



- $\mathcal{G}_{i \rightarrow h}(x, p_T R, \mathbf{k}, z_h, \mu)$ has standard DGLAP evolution in x
- $D_{i \rightarrow h}(z_h, \mu)$ satisfies DGLAP evolution in z_h
- $D_{i \rightarrow h}(\mathbf{k}, z_h, \mu)$ has modified **all-orders** evolution equation:

$$\mu \frac{d}{d\mu} D_{i \rightarrow h}(\mathbf{k}, z_h, \mu) = \sum_j \int \frac{dz}{z} \theta\left(z - \frac{1}{2}\right) P_{ji}(z, \mu) D_{j \rightarrow h}\left(\mathbf{k}, \frac{z_h}{z}, \mu\right)$$

Back up

The TMD program

- ❖ Recover/reformulate/understand QCD in the limit of high qT (NNLO, some 3-loop results):
M.G. Echevarría, I.S., A. Vladimirov, arXiv:1509.06392, arXiv:1511.05590, arXiv:1604.07869
T. Lübbert, J. Oredsson, M. Stahlhofen, arXiv:1602.01829, Y. Li, H.X. Zhu, arXiv:1604.01404 A. Vladimirov, arXiv:1610.05791

- ❖ Achieve NEW results in the limit of high qT :

- unpolarized fragmentation at NNLO M.G. Echevarría, I.S., A. Vladimirov, arXiv:arXiv:1604.07869
- double parton scattering factorization A. Vladimirov arXiv:1608.04920
- Twist -2 TMD matching (D. Gutierrez-Reyes, I.S., A. Vladimirov, arXiv:1702.06558)

- ❖ New inputs for the non-perturbative TMD structure:

- renormalons (I.S., A. Vladimirov, arXiv:arXiv:1609.06047)
- lattice (X. Ji, M. Engelhardt,...)
- fits and data analysis...
- jets (Kang, Ringer, Vitev, Leibovich, Mehen,Neill, I.S., Waalewijn,...)

RESUMING...

- ❖ The confinement frontier (experiment, theory, phenomenology):
- spin physics (EIC, AFTER, COMPASS, BABAR, BELLE,...)
- precision at LHC (Vector and Higgs Boson production, jets,...)

Spin Fun

TMDPDF

Nucleon
Polarization

| | | U | L | T |
|---|----------------|----------|---------------------|---|
| U | f_1 | | h_1^\perp | |
| L | | g_1 | h_{1L}^\perp | |
| T | f_{1T}^\perp | g_{1T} | h_1, h_{1T}^\perp | |

Quark Polarization

Similar structures for
Gluons as initial
states: in Higgs
production both f_1^g and $h_1^{\perp g}$

$$\begin{aligned}\tilde{F}_{f/N}^{[\gamma^+]}(x, \mathbf{b}_\perp, S; \zeta_F, \mu^2) &= \tilde{f}_1 - \frac{\epsilon_\perp^{ij} \mathbf{b}_{\perp i} \mathbf{S}_{\perp j}}{ib_T M_N} \tilde{f}_{1T}^{\perp(1)}, \\ \tilde{F}_{f/N}^{[\gamma^+ \gamma_5]}(x, \mathbf{b}_\perp, S; \zeta_F, \mu^2) &= \lambda \tilde{g}_{1L} + \frac{(\mathbf{b}_\perp \cdot \mathbf{S}_\perp)}{ib_T M_N} \tilde{g}_{1T}^{(1)}, \\ \tilde{F}_{f/N}^{[i\sigma^{i+} \gamma_5]}(x, \mathbf{b}_\perp, S; \zeta_F, \mu^2) &= \mathbf{S}_\perp^i \tilde{h}_1 + \frac{\lambda \mathbf{b}_\perp^i}{ib_T M_N} \tilde{h}_{1L}^{\perp(1)} \\ &\quad - \frac{(\mathbf{b}_\perp^i \mathbf{b}_\perp^j + \frac{1}{2} b_T^2 g_\perp^{ij}) \mathbf{S}_{\perp j}}{(i)^2 b_T^2 M_N^2} \tilde{h}_{1T}^{\perp(2)} - \frac{\epsilon_\perp^{ij} \mathbf{b}_{\perp i} \mathbf{S}_{\perp j}}{ib_T M_N} \tilde{h}_1^{\perp(1)}\end{aligned}$$

T-odd distributions

$$f_{1T,DIS}^\perp = -f_{1T,DY}^\perp$$

TMDFF

$$\begin{aligned}\tilde{D}_{h/f}^{[\gamma^-]}(z, \mathbf{b}_\perp, S_h; \zeta_D, \mu^2) &= \tilde{D}_1 - \frac{\epsilon_\perp^{ij} \mathbf{b}_{\perp i} \mathbf{S}_{h\perp j}}{(-ib_T) M_h} \tilde{D}_{1T}^{\perp(1)}, \\ \tilde{D}_{h/f}^{[\gamma^- \gamma_5]}(z, \mathbf{b}_\perp, S_h; \zeta_D, \mu^2) &= \lambda \tilde{G}_{1L} + \frac{(\mathbf{b}_\perp \cdot \mathbf{S}_{h\perp})}{(-ib_T) M_h} \tilde{G}_{1T}^{(1)}, \\ \tilde{D}_{h/f}^{[i\sigma^{i-} \gamma_5]}(z, \mathbf{b}_\perp, S_h; \zeta_D, \mu^2) &= \mathbf{S}_{h\perp}^i \tilde{H}_1 + \frac{\lambda \mathbf{b}_\perp^i}{(-ib_T) M_h} \tilde{H}_{1L}^{\perp(1)} \\ &\quad - \frac{(\mathbf{b}_\perp^i \mathbf{b}_\perp^j + \frac{1}{2} b_T^2 g_\perp^{ij}) \mathbf{S}_{h\perp j}}{(-ib_T)^2 M_h^2} \tilde{H}_{1T}^{\perp(2)} - \frac{\epsilon_\perp^{ij} \mathbf{b}_{\perp i} \mathbf{S}_{h\perp j}}{(-ib_T) M_h} \tilde{H}_1^{\perp(1)}\end{aligned}$$