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Jet TMDs and Jet Axes

Most recent results in collaboration with
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Wouter Waalewijn

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Outline & Issues

- **Transverse Momentum Distributions (TMD) have a clear experimental meaning in DY**
- **How should we measure transverse momentum of hadrons in final states?**
- **In most cases the measure of hadrons is related to axes definitions and/or jets**
- Does evolution of TMD depend on the these choices?

….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
(renormalon analysis in Scimemi,Vladimirov 2016)

The latest and more elegant formulation of this in Echevarria, Scimemi, Vladimirov 2015-16:

The NNLO era is just started! (see the talk of A. Vladimirov and D. Gutiérrez Reyes)

Factorization formulas for Jet TMDs

Starting point:

Sum over partons

Kang, Ringer, Vitev; Dai, Kim, Leibovich

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

Hard factor

Fragmenting Jet Function

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

$$\begin{aligned} x &= \text{fraction of parton momentum that goes in the jet} \\ z_h\mathbf{k} &= \text{transverse momentum of the hadron in the jet} \\ k_A &= \text{component of } \vec{k} \text{ along the jet axis } \vec{A}_J \end{aligned}$$

Operator matrix element definition:

The phase space of the hadron is not included in J

$$\mathcal{G}_{q\to h}(x, p_T R, \mathbf{k}, z_h) = \frac{1}{4xN_c}\sum_X \sum_{J/h} \int \frac{d\xi^+}{4\pi}\, e^{-ip_J^-\xi^+/(2x)}\, \delta\left(z_h - \frac{p_h^-}{p_J^-}\right) \int dk_A\, \delta^{(3)}\left(\vec{k} - \frac{\vec{p}_h}{z_h}\right)$$

$$\times \langle 0|T\left[\tilde{W}^\dagger_{Tn} q_j\right]_a \left(\frac{\xi^+}{2}\right)|X, h\in J\rangle\, \gamma^-_{ij}\, \langle X, h\in J|\bar{T}\left[\bar{q}_i\, \tilde{W}_{Tn}\right]_a \left(-\frac{\xi^+}{2}\right)|0\rangle$$

This depends on several physical scales $p_T R,\ k_T,\ \Lambda_{QCD}$ Can we recover some TMD-like functions?

Factorization formulas for Jet TMDs

A very interesting limit!!

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

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

JET TMD!!!

AXIS DEPENDENCE

$$D_{q\to h}(\mathbf{k}, z_h) = \frac{1}{4 z_h N_c} \sum_X \int \frac{d\xi^+}{4\pi} e^{-i p_h^- \xi^+/(2z_h)} \int dk_A\, \delta^{(3)}\left(\vec{k} - \frac{\vec{p}_h}{z_h}\right)$$
$$\times \langle 0 | T \left[\tilde{W}^\dagger_{Tn} q_j\right]_a \left(\frac{\xi^+}{2}\right) |X, h\rangle \gamma^-_{ij} \langle X, h| \bar{T} \left[\bar{q}_i\, \tilde{W}_{Tn}\right]_a \left(-\frac{\xi^+}{2}\right) |0\rangle$$

TMDs in fragmentation…jets

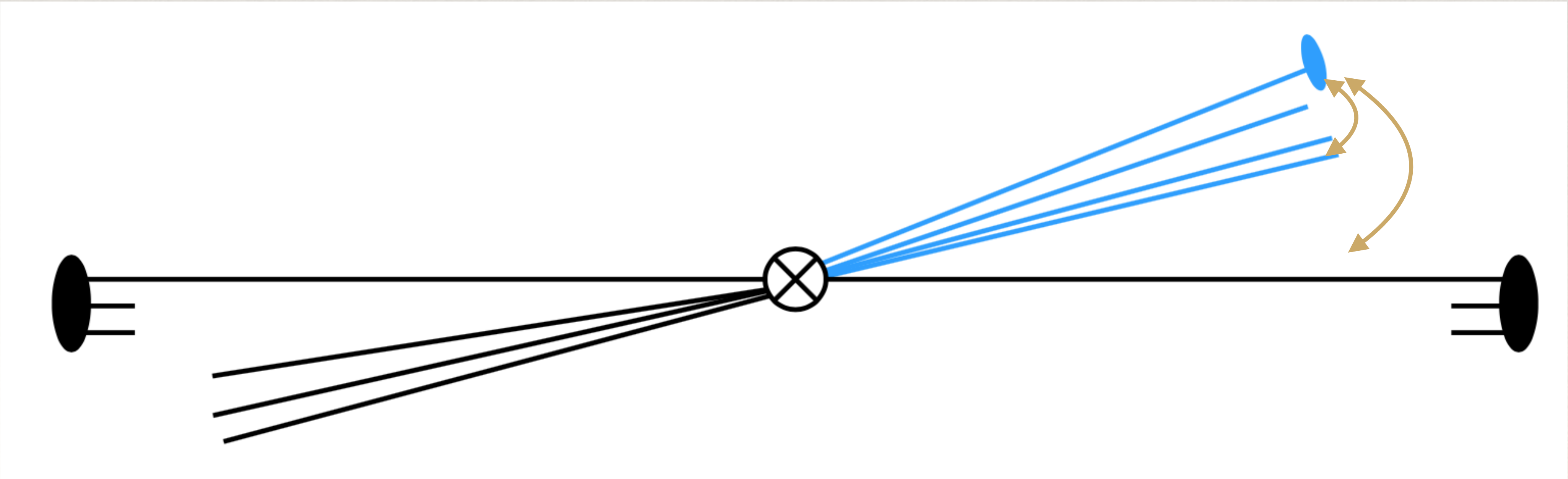
The main difference with respect to the standard definition is the axis with respect to which we measure the **TMD FRAGMENTATION**

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

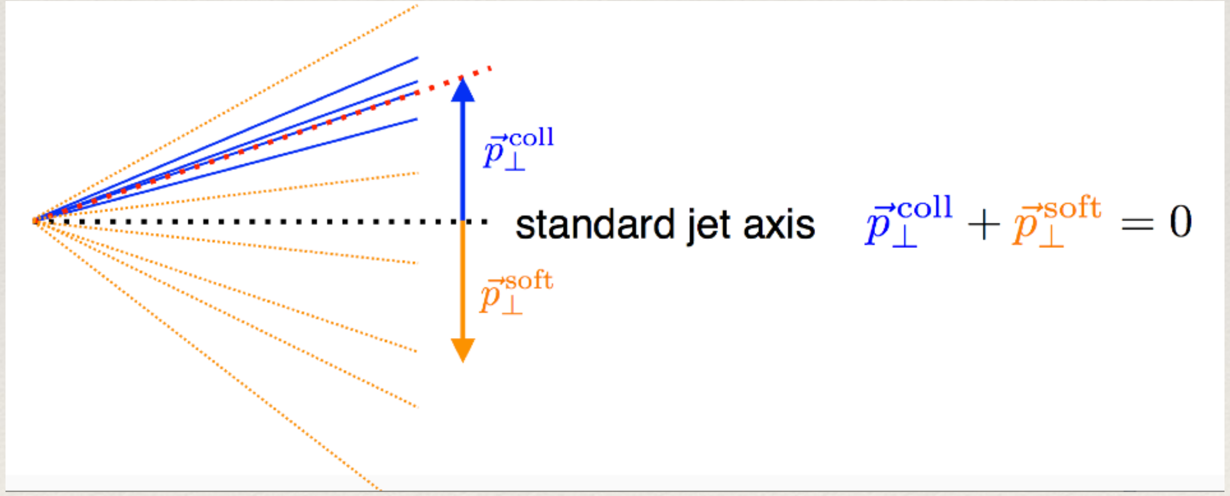
The definition and evolution of TMDs depend on the choice of jet axis

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)
Standard jet axis in 1705.08443 (Kang,Liu, Ringer,Xing)



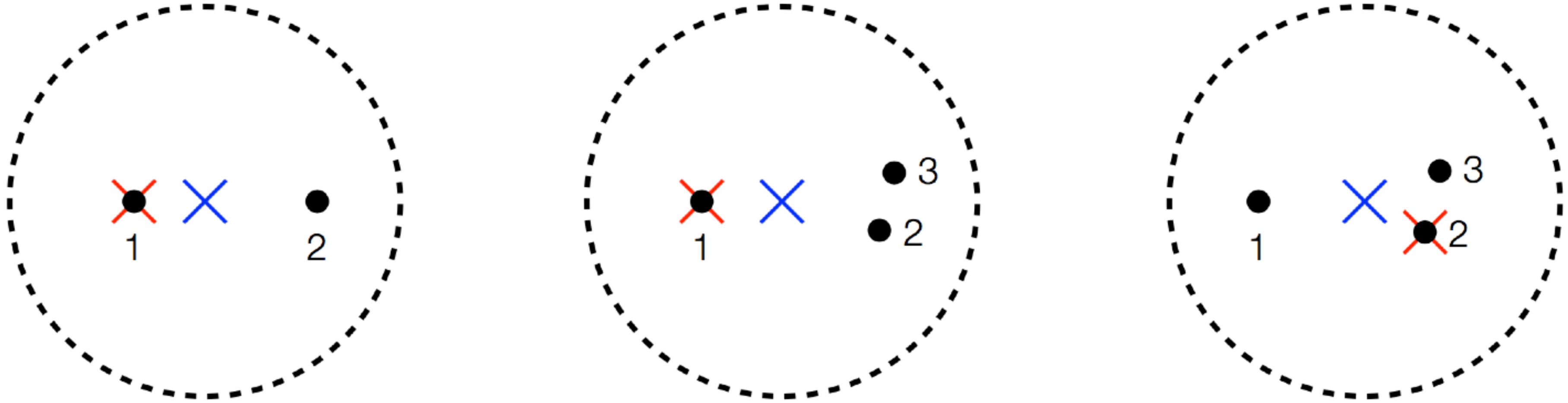
Recoil-free axis: Winner -Take-All (WTA) axis

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]



$E_1 > E_2$ $\qquad$ $E_1 > E_2 + E_3$ $\qquad$ $E_2 + E_3 > E_1$, $E_1 > E_2 > E_3$

Re-factorization limits

We can find several predictable asymptotic behaviors..

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

$$\mathcal{G}_{i\to h}(x, p_T R, \mathbf{k}, z_h, \mu) = \sum_j \int \frac{dz}{z} \mathcal{J}_{ij}\Big(x, p_T R, \mathbf{k}, \frac{z_h}{z}, \mu\Big) d_{j\to h}(z,\mu) \Big[1 + \mathcal{O}\left(\frac{\Lambda^2_{QCD}}{\mathbf{k}^2}\right)\Big]$$

..in this limit we can recover a classical separation in coefficients and fragmentation functions..

$\mathcal{J}_{ij}$ describes the formation of a jet with momentum fraction x of the initial parton i, containing a parton j with momentum fraction z_h/z and transverse momentum $\mathbf{k}$.

Re-factorization limits

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

$$\mathcal{J}_{ij}(x, p_T R, \mathbf{k}, z, \mu) = \sum_k \int \frac{dy}{y} B_{ik}(x, p_T R, y, \mu)\, C_{kj}\Big(\mathbf{k}, \frac{z}{y}, \mu\Big)\Big[1 + \mathcal{O}\Big(\frac{\mathbf{k}^2}{p_T^2 R^2}\Big)\Big]$$

..and all non-perturbative effects should be power suppressed..

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JetTMDs with WTA axis

$p_T R \gg k_T \sim \Lambda_{QCD}$

For small hadron transverse momentum the border effects can be perturbatively extracted and we can obtain Jet TMDs

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

Consistency with previous limits requires that for $k_T \gg \Lambda_{QCD}$

$$D_{k\to h}(\mathbf{k}, z_h, \mu) = \sum_j \int \frac{dz}{z} C_{kj}\Big(\mathbf{k}, \frac{z_h}{z}, \mu\Big)\, d_{j\to h}(z, \mu)\Big[1 + \mathcal{O}\Big(\frac{\Lambda_{QCD}^2}{\mathbf{k}^2}\Big)\Big]$$

JTMD evolution with WTA axis

Standard fragmentation evolution…

$$d_{i\to h}^{\rm bare}(z_h) = \sum_j \int \frac{dz}{z}\, Z_{ij}\Big(\frac{z_h}{z},\mu\Big)\, d_{j\to h}(z,\mu)$$

$$\mu\frac{d}{d\mu} d_{i\to h}(z_h,\mu) = \sum_j \int \frac{dz}{z}\, \gamma_{ij}\Big(\frac{z_h}{z},\mu\Big) d_{j\to h}(z,\mu)\,,$$

$$\gamma_{ij}(z_h,\mu) = -\int \frac{dz}{z}\, Z^{-1}_{ik}\Big(\frac{z_h}{z},\mu\Big)\, \mu\frac{d}{d\mu} Z_{kj}(z,\mu)$$

…is the same as for fragmenting jet function…

$$\mathcal{G}_{i\to h}^{\rm bare}(x, p_T R, \mathbf{k}, z_h, \mu) = \sum_j \int \frac{dx'}{x'}\, Z_{ij}\Big(\frac{x}{x'},\mu\Big)\, \mathcal{G}_{j\to h}(x', p_T R, \mathbf{k}, z_h, \mu)$$

..and is similar (but not the same!!) for fragmenting jet function…

DGLAP Splitting functions

$$D_{i\to h}^{\rm bare}(\mathbf{k}, z) = \sum_j \int \frac{dz'}{z'}\, Z'_{ij}\Big(\frac{z}{z'},\mu\Big)\, D_{j\to h}(\mathbf{k}, z', \mu)$$

$$\gamma_{ij}(z,\mu) = P_{ji}(z,\mu)\,,$$

$$\gamma'_{ij}(z,\mu) = \theta\Big(z \geq \frac{1}{2}\Big)\, P_{ji}(z,\mu)$$

All this checked at NLO

Summary: scales and factorization

- Factorization depends on relevant hierarchy:

fat jet $\bar{\sigma}(p_T, \eta)$

partonic xsec — jet boundary — TMD fragmentation $D(\mathbf{k})$

$$\frac{d\sigma_h}{dp_T\, d\eta\, d^2\mathbf{k}\, dz_h} = \hat{\sigma}(p_T, \eta) \otimes B(p_T R) \otimes C(\mathbf{k}) \otimes D(\Lambda_{\rm QCD})$$

$\mathcal{J}(p_T R, \mathbf{k})$

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

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

Evolution and resummation

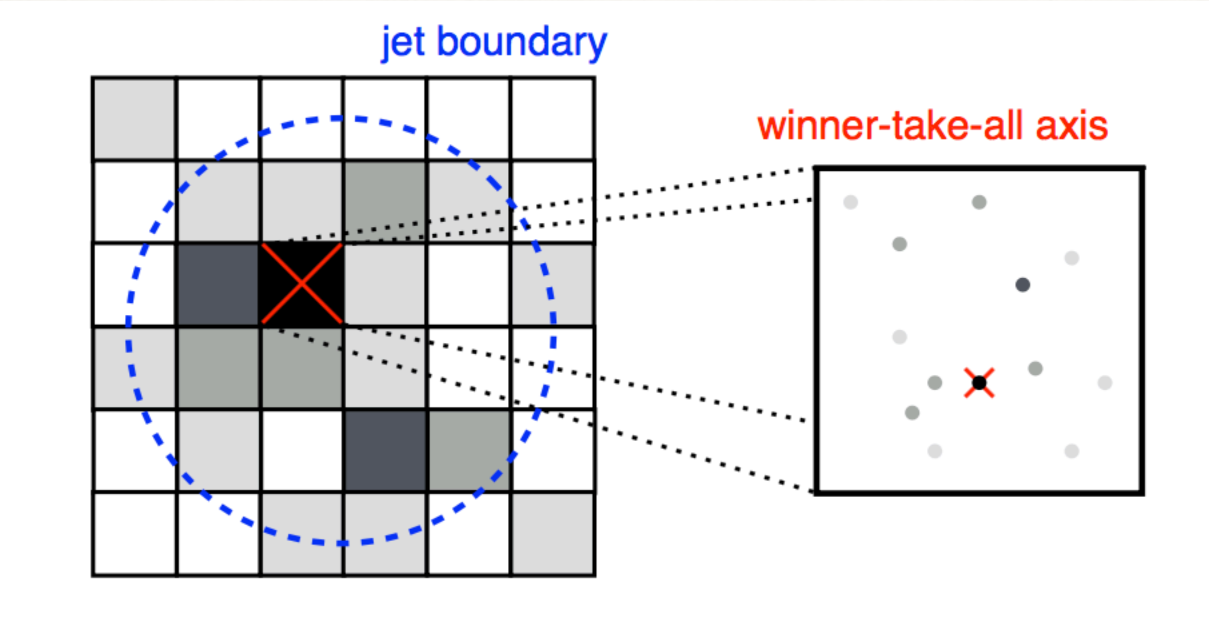
- Single logarithms resummed by renormalization group evolution

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

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

Jet Algorithms and JTMDs with WTA axis

The WTA axis is always aligned with the most energetic parton in the jet.
If r is the distance of the hadron from jet axis we want $r \ll R$



We can pixelate the jet and look at the energy released in each pixed of radius $r \ll R$.
The most energetic pixel fixes the axis.
Boundary effects are power suppressed by r/R

Jet Algorithm requirements:

- radiation within the pixel that contains the jet axis will be preferentially clustered together first
- the configuration of the radiation outside of this pixel does not interfere with the constituents of the pixel
- anti-kT and Cambridge/Aachen do the job

Conclusions

The possibility to define jets allows a connection between Tevatron/LHC and future experiments.

Jets allow a definition of new types of TMD which are relevant for our understanding of confinement

WTA axis analysis offer an example of these possibilities:

Jet TMDs with respect to WTA axis have a simpler evolution equation…
they can be an opportunity for new studies

Back up

REF 2017

November 13-16
Madrid, Spain

For any question ask Daniel or me!

You can see the web page
http://jacobi.fis.ucm.es/REF2017/

Also you can send an email to
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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,…)