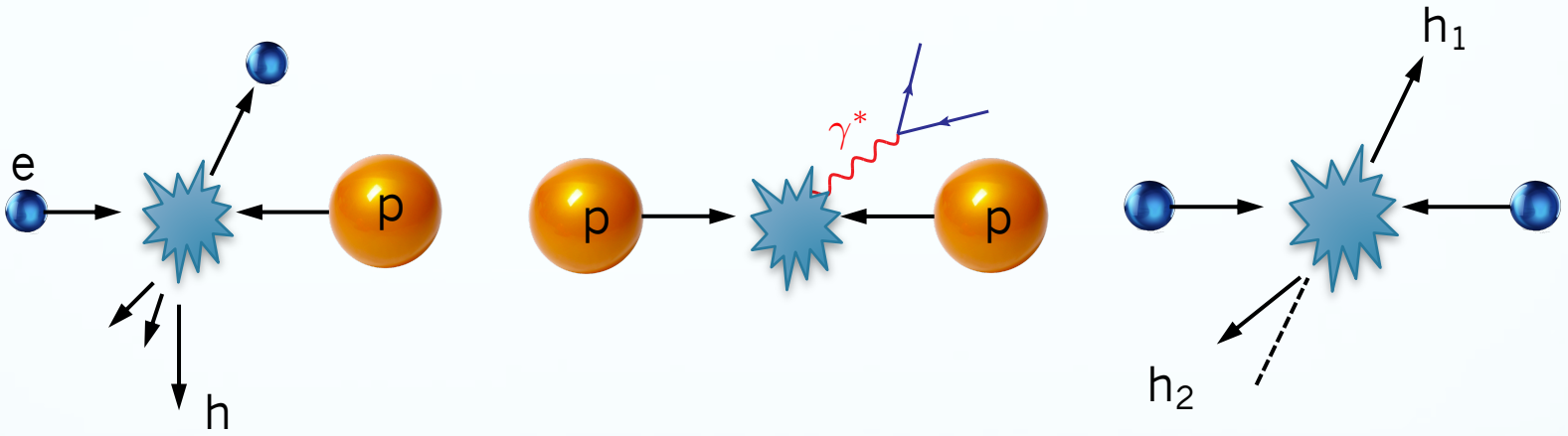
TMD opportunities at the LHC

Zhongbo Kang
UCLA

EF06/07 TMD jamboree
October 28, 2020

Processes to extract TMDs

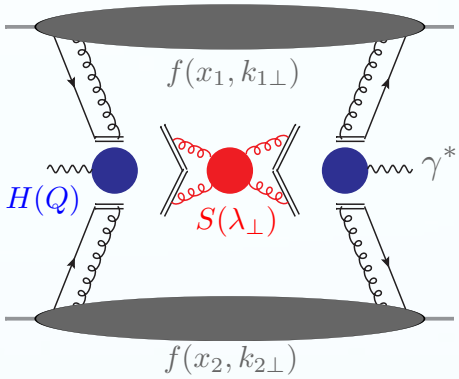
- SIDIS, Drell-Yan, dihadron in e^+e^-
  - Well-established TMD factorization
  - TMD PDFs and TMD FFs



- At the LHC, what are the TMD opportunities?
  - Especially, besides W/Z (quark TMD PDFs) and Higgs (gluon TMD PDF)

TMD contains soft function

- TMDs as studied in the TMD community generally include the soft function in their definition
- Drell-Yan: $p + p \to [\gamma^* \to \ell^+\ell^-] + X$



$$\frac{d\sigma}{dQ^2 dy d^2q_\perp} \propto \int d^2k_{1\perp}\, d^2k_{2\perp}\, d^2\lambda_\perp H(Q) f(x_1, k_{1\perp}) f(x_2, k_{2\perp}) S(\lambda_\perp) \delta^2(k_{1\perp} + k_{2\perp} + \lambda_\perp - q_\perp)$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) f(x_1, b) f(x_2, b) S(b)$$

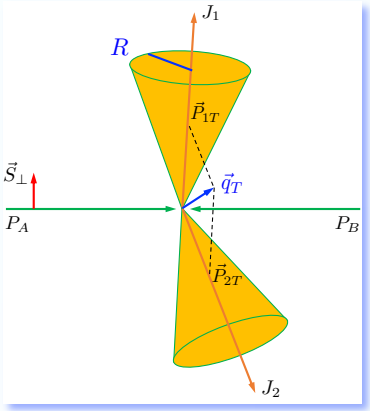
$$F(x,b) = f(x,b)\sqrt{S(b)}$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

mimic "parton model"

TMD PDFs: back-to-back jet correlation

- To be more sensitive to the *small* parton transverse motion, one has to further measure a small transverse momentum in the experiment, such as transverse momentum imbalance (q_T) in
  - dijet production, photon+jet, W/Z+jet, Higgs+jet



- Theory formalism is much more complicated
  - Easy to write down in SCET [ignore issue of Glauber modes]

$$\sigma \propto f_a(x_a, k_{aT}) \otimes f_b(x_b, k_{bT}) \otimes \mathrm{Tr}[\boldsymbol{S}_{ab}(q_T)\boldsymbol{H}_{ab\to cd}(P_T)] \otimes S_c^{\rm cs}(q_T R) S_d^{\rm cs}(q_T R) J_c(P_T R) J_d(P_T R)$$

Catani, Grazzini, et.al., heavy quark/top pair, 1408.4564, 1806.01601, 1901.04005
Li, Li, Shao, Zhu, top quark pair, 1307.2464
Shao, Li, Li, vector boson+jet, 1309.5015
Kang, Lee, Shao, Terry, dijet, 2008.05470, Buffing, **Kang**, Lee, Liu, photon+jet, 1812.07549, Chien, Shao, Wu, Z+jet, 1905.01335

  - Issue about TMD definition

$$\boldsymbol{S}_{ab\to cd}(b,\mu,\nu) = \tilde{\boldsymbol{S}}_{ab\to cd}(b,\mu) S_{ab}(b,\mu,\nu)$$
$$f_a^{\rm unsub}(x_a,b,\mu,\nu)\, f_b^{\rm unsub}(x_b,b,\mu,\nu)\, S_{ab}(b,\mu,\nu) = f_a(x_a,b,\mu)\, f_b(x_b,b,\mu)$$

Standard soft function as in Z boson or Higgs

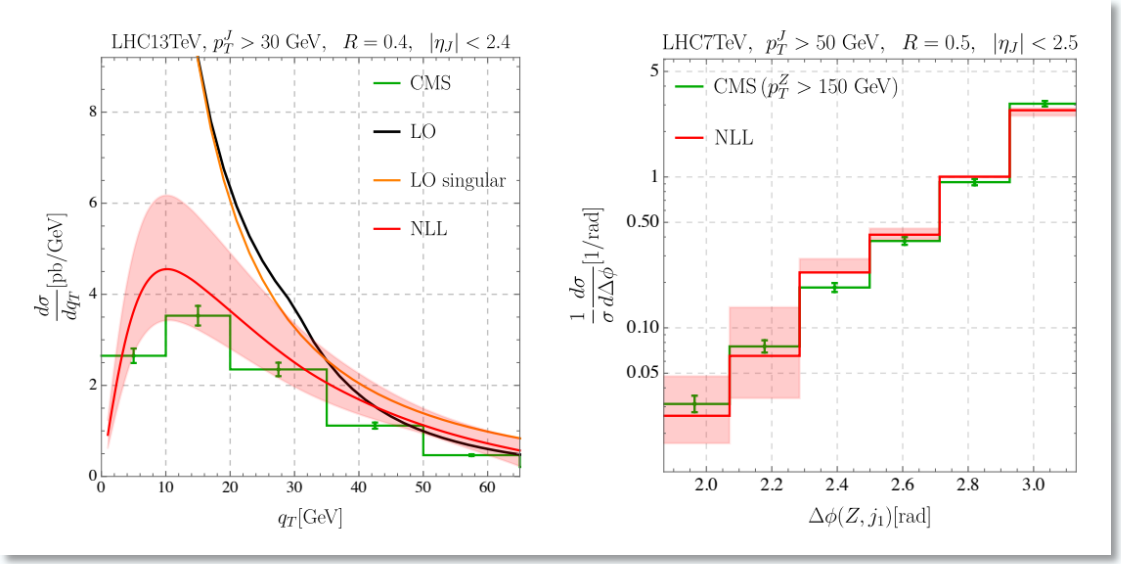
  - Glauber gluons lead to TMD factorization breaking
    - An outstanding theoretical question to explore
    - Phenomenology: likely small?

Rothstein, Stewart, 1601.04695,
or higher-order perturbative from H. X. Zhu, et.al.

Phenomenology: example

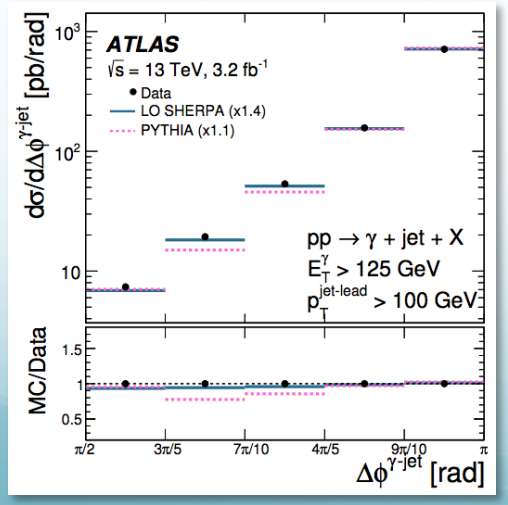
- Z+jet

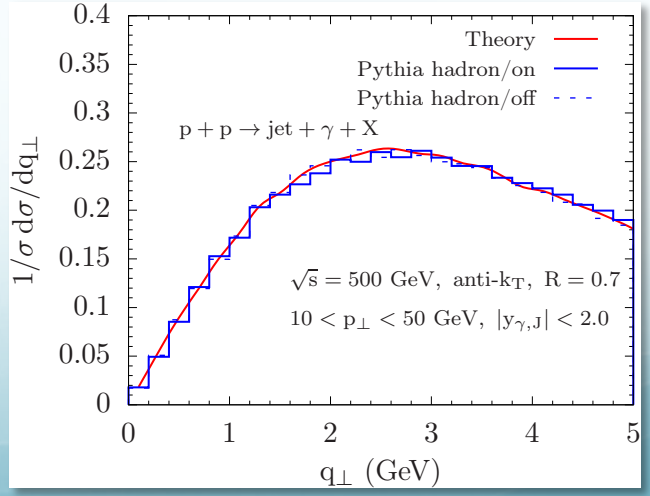
Chien, Shao, Wu, 1905.01335



- Photon+jet: good comparison with Pythia

Buffing, **Kang**, Lee, Liu, 1812.07549





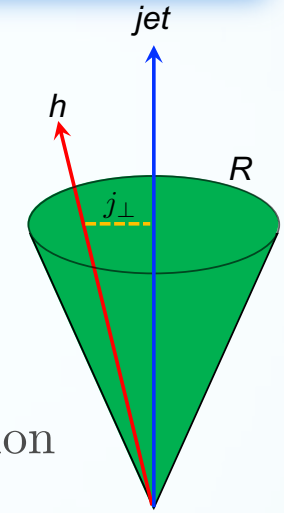
TMD FFs: via jet substructure

- Definition

$$F(z_h, j_\perp; p_T) = \frac{d\sigma^h}{dp_T d\eta dz_h d^2 j_\perp} \Big/ \frac{d\sigma}{dp_T d\eta}$$

$$z_h = p_T^{\mathrm{h}} / p_T^{\mathrm{jet}}$$

$j_\perp$: hadron transverse momentum with respect to the jet direction



- Factorization formalism

Kang, Liu, Ringer, Xing, 1705.08443
Makris, Neill, Vaidya, 1712.07653
Gutierrez-Reyes, Makris, Vaidya, Scimemi, Zoppi, 1907.05896
...

$$\frac{d\sigma}{dp_T d\eta dz_h d^2 j_\perp} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, p_T R, j_\perp, \mu)$$

- Related to transverse momentum dependent (TMD) fragmenting function

$$\mathcal{G}_c^h(z, z_h, \omega_J R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, \omega_J R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^2\left(z_h \boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp\right)$$
$$\times D_{h/i}(z_h, \boldsymbol{k}_\perp, \mu, \nu) S_i(\boldsymbol{\lambda}_\perp, \mu, \nu R)$$

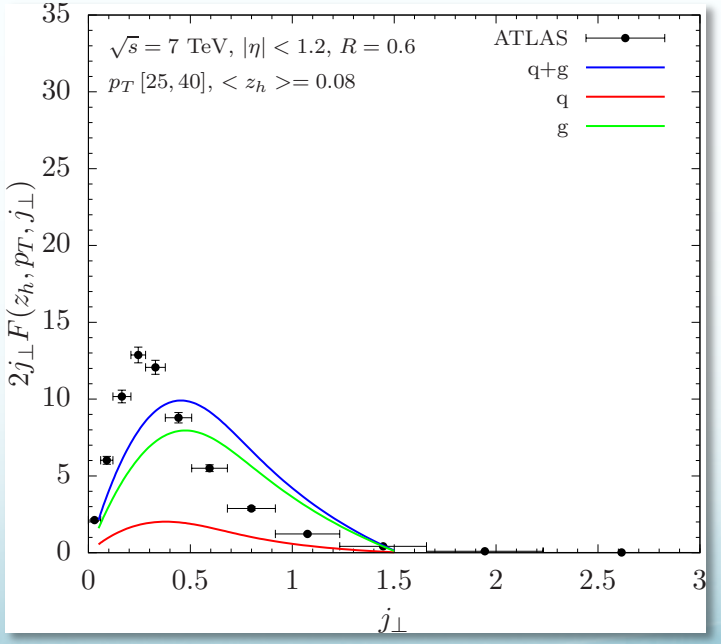
Some features

- Advantage
  - We only have TMD FFs in the formalism, not TMD PDFs as in SIDIS
- Connection to standard TMD FFs
  - Via a NLO calculation, one can verify that the combined evolution is the same as the usual TMD evolution in SIDIS and e+e-

$$\sqrt{S(b)}D_c^h(z_h,b)_{\mathrm{e^+e^-}} \Rightarrow S(b,R)D_c^h(z_h,b)_{\mathrm{pp}}$$

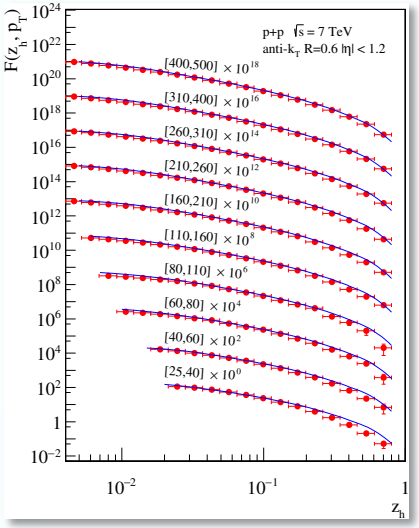
Problem in comparison with LHC data

- It is extremely important to be differential in z_h if we want to extract TMD FFs
  - Currently the LHC data integrate over entire z_h region: [0,1]
  - Thus the current comparison is not great: contamination from soft hadrons
- Inclusive jet is more sensitive to gluon TMD fragmentation functions

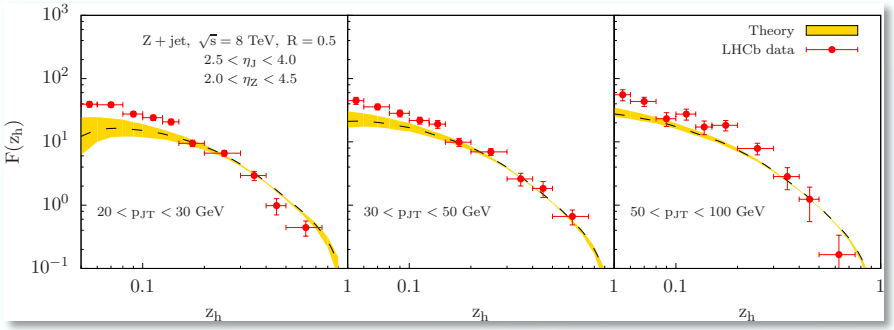


Lesson: differential in z_h and j_T

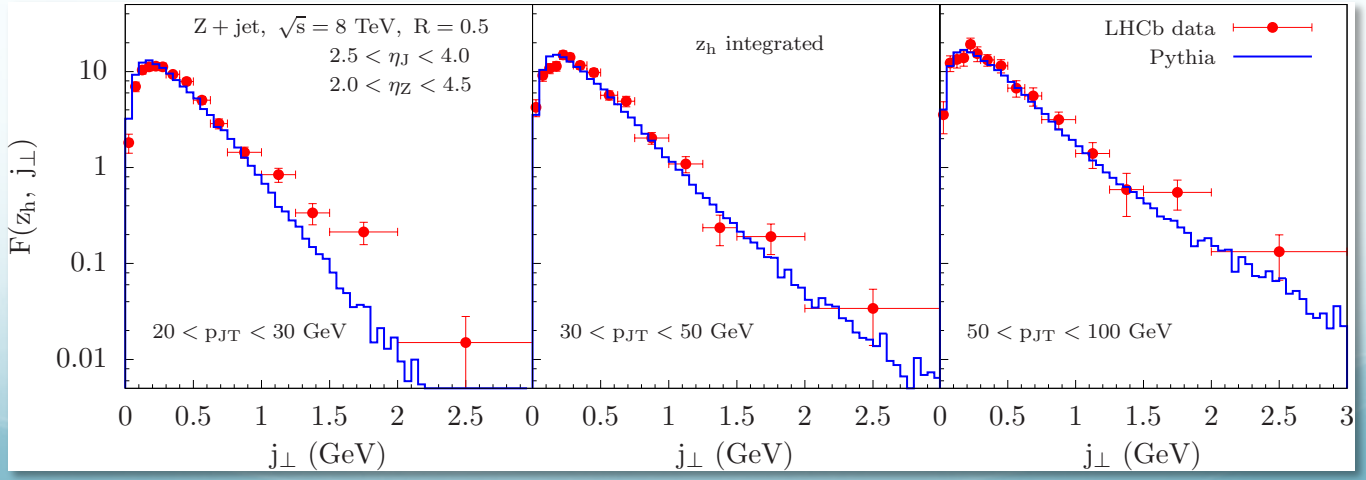
- z_h distribution: integrated j_T ⟶ collinear FFs



Kang, Ringer, Vitev, 1606.07063
Kang, Lee, Terry, Xing, arXiv:1906.07187

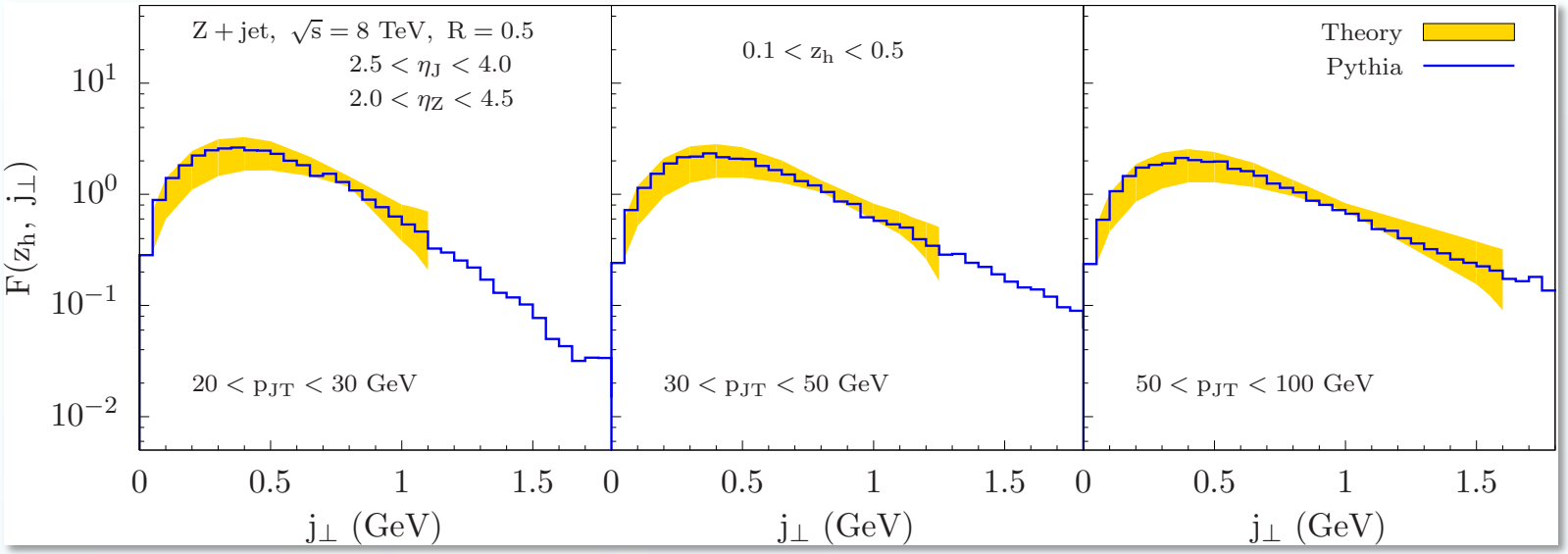


- Again, since zh integrated over [0,1], let us check with Pythia



For physical region zh: [0.1,0.5]

- For zh integrated [0.1,0.5]



- Works very well

TMD study at the LHC

- Lots of TMD opportunities at the LHC
  - Besides the usual W/Z boson, Higgs production
- TMD PDFs: back-to-back jet correlation
  - Dijet, W/Z+jet, photon+jet, Higgs+jet, etc
- TMD FFs: via jet substructure
  - Hadron TMD distribution inside the jet

Thank you!