Probing collinear and TMD fragmentation functions through hadron distribution inside the jet

Zhongbo Kang
UCLA

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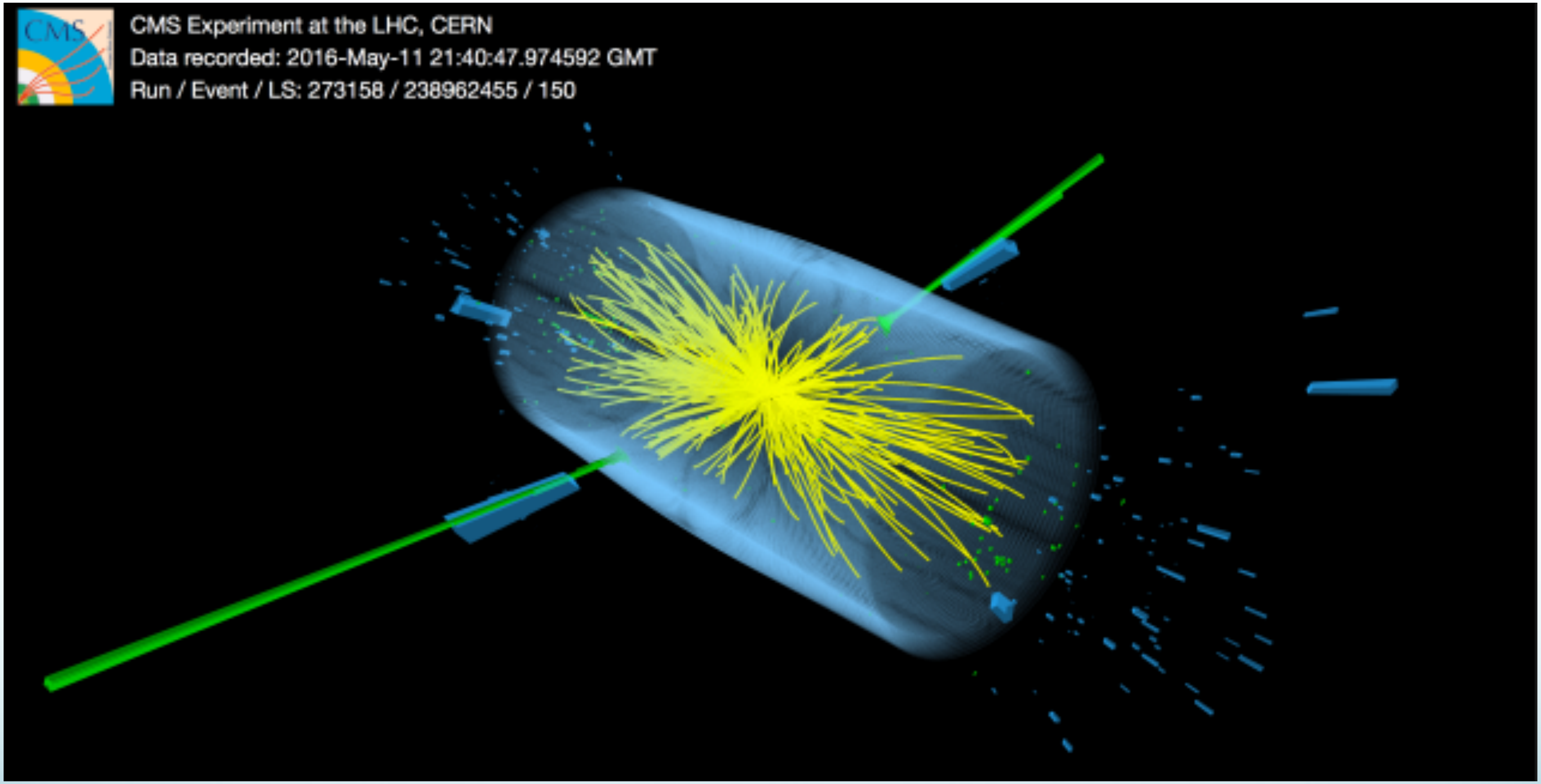
Jets are abundantly produced at the LHC

- They are most common at the LHC



Jets and its internal substructure as new tools

- Jesse Thaler, 2015

Jets as a Tool for (B)SM Physics

Importance/relevance of jet radius variation, multiple jet algorithms
Making jet substructure part of everyday analyses (e.g. pileup mitigation, jet shapes)
Improved VBF tagging, jet vetoes for Higgs physics
...

Jets as a Precision Probe of QCD

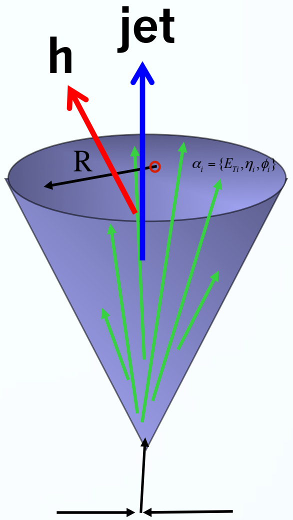
Wishlist of jet shape measurements (e.g. angularities)
Interplay between fixed order and resummation for jet observables (esp. PS/ME matching)
IRC Unsafe but Sudakov Safe observables where resummation is essential
Analytic handles on soft QCD (e.g. underlying event, hadronization)
...

Many points of contact with other working groups

Hadron distribution inside the jet

- Study a hadron distribution inside a fully reconstructed jet

$$p + p \to \text{jet}\,(h) + X$$



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

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

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

j_T : hadron transverse momentum with respect to the jet direction

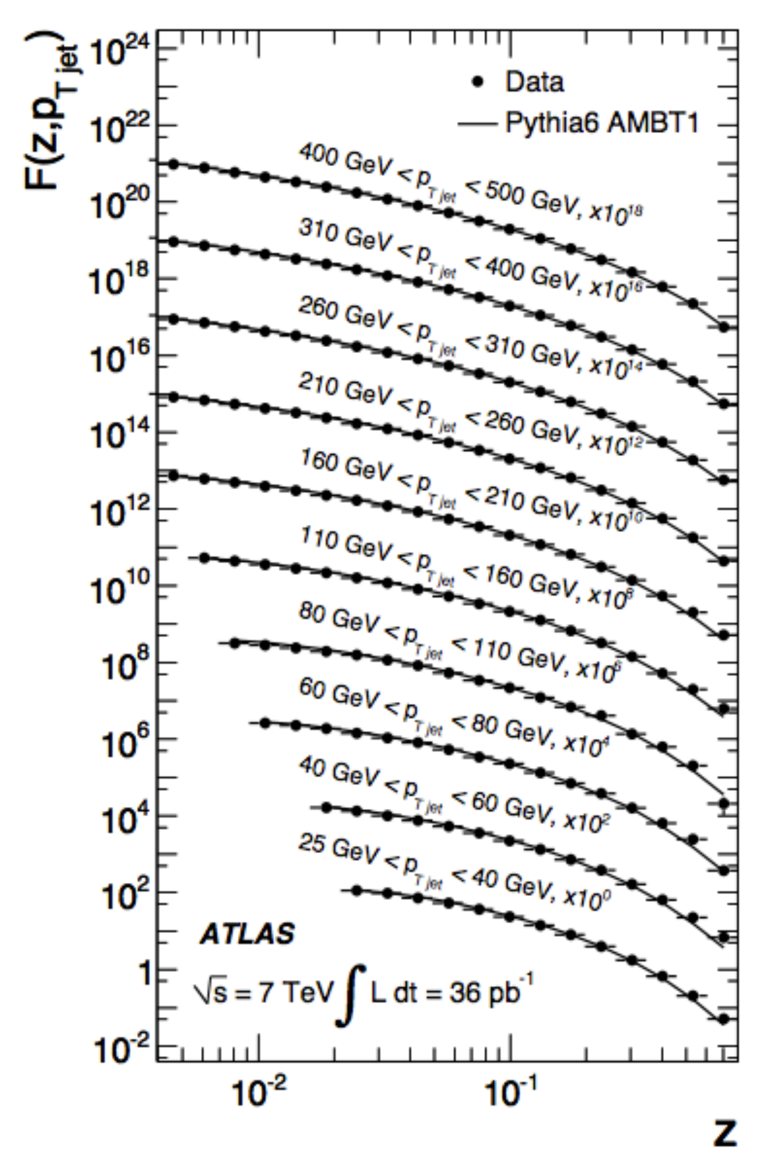
- The 1st observable is like collinear fragmentation function, while the 2nd observable is more like a TMD fragmentation function

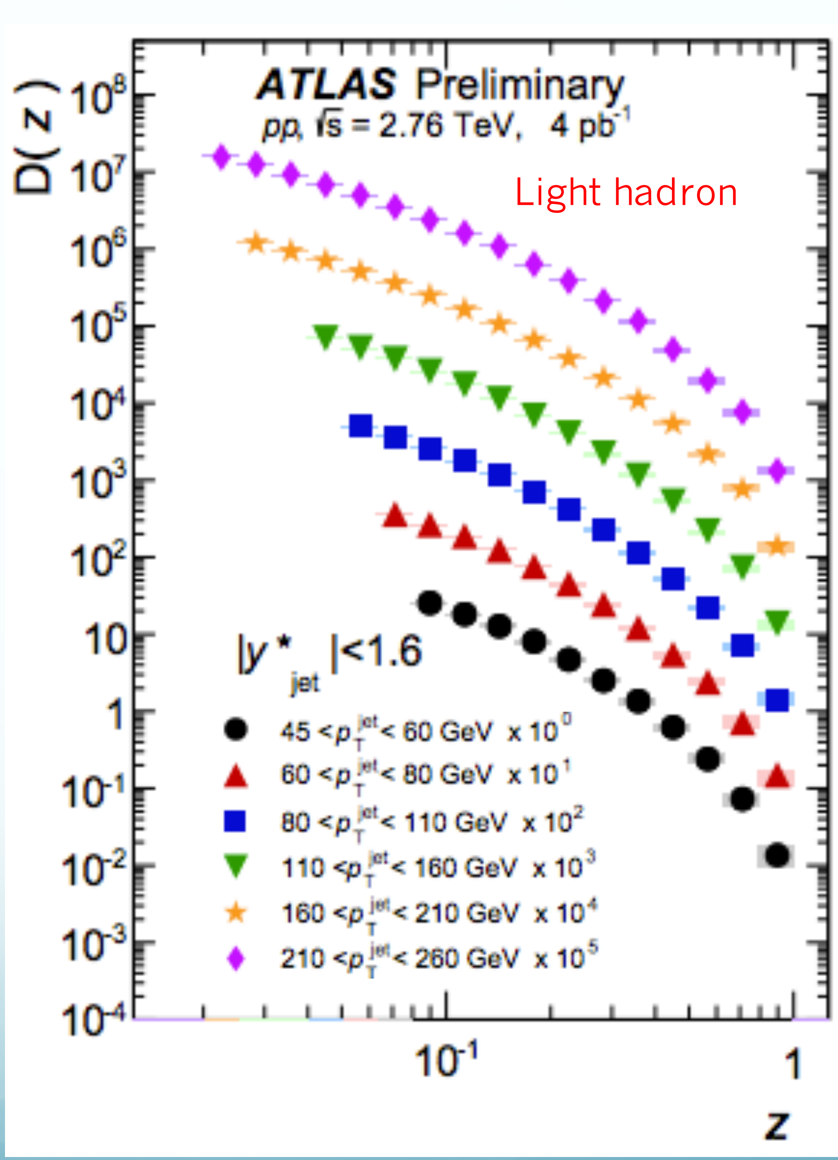
- LHC did a great deal of all kinds of measurements, and compared with Pythia simulation

Collinear z-dependence: light hadron

- ATLAS measurements at 7 TeV and 2.76 TeV

1109.5816, ATLAS-CONF-2015-022

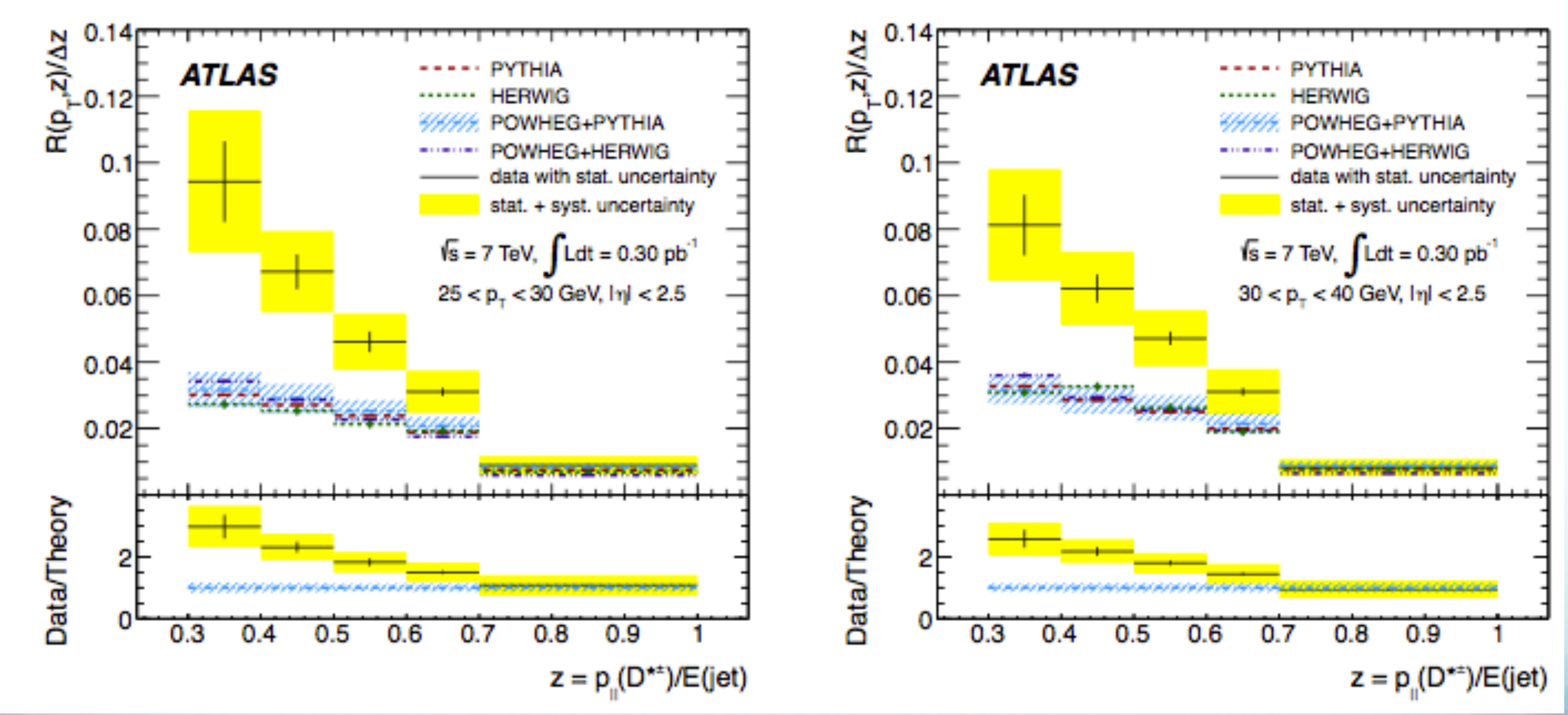




Collinear z-dependence: heavy meson

- D meson production inside a jet

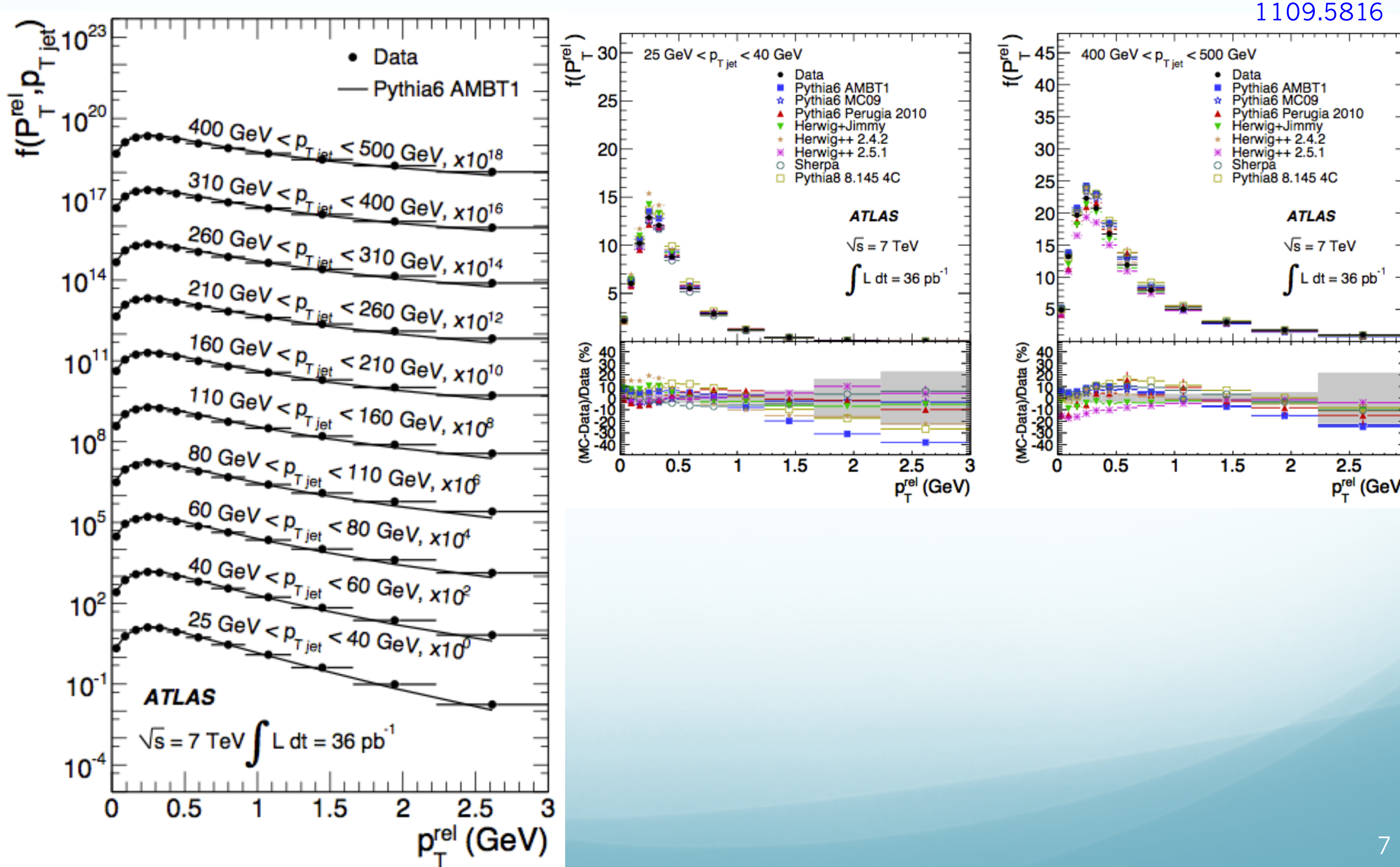
ATLAS, arXiv:1112.4432



Relative momentum j_T dependence

- j_T shape does not change much: how to link to TMD evolution

1109.5816



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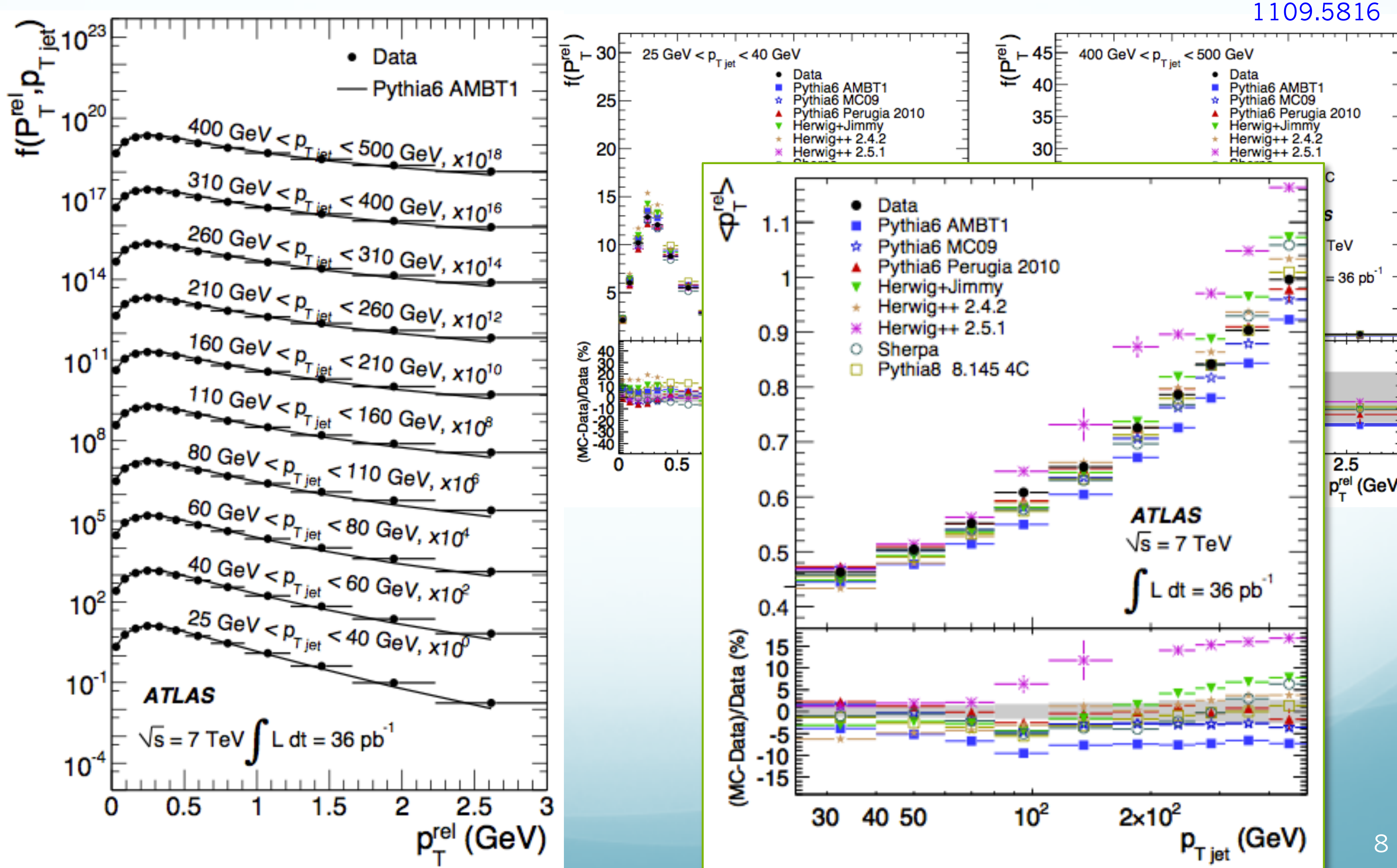
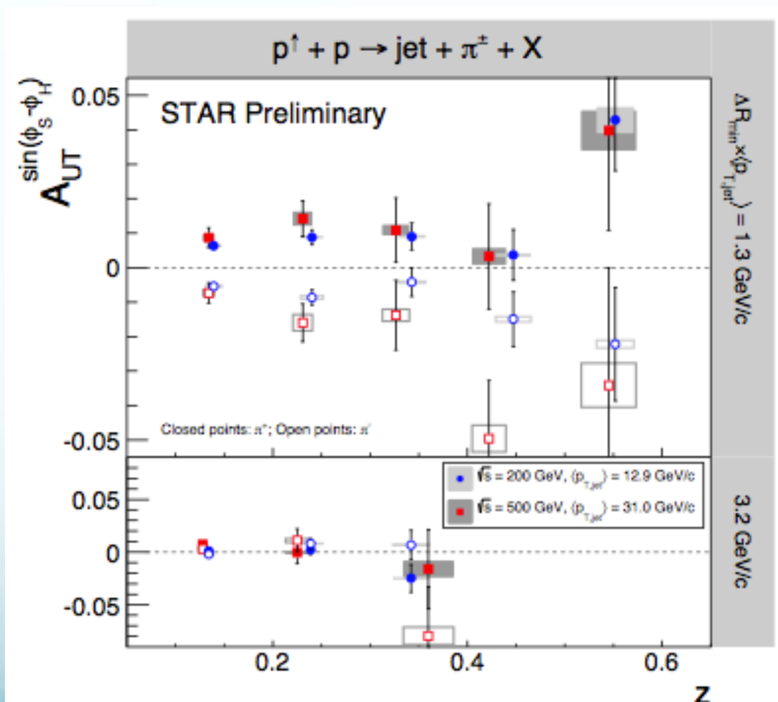


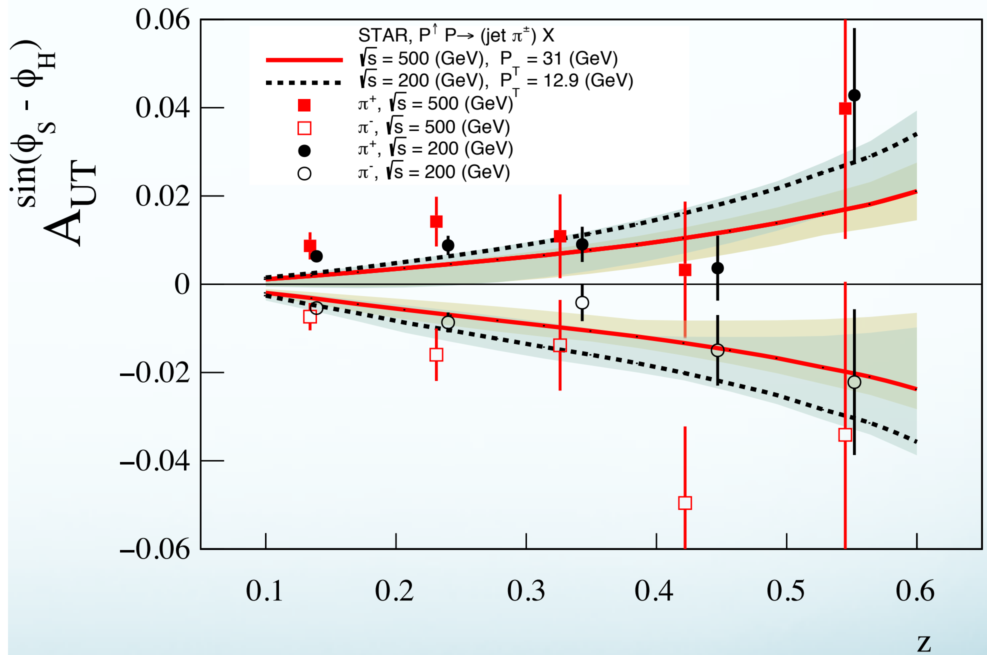
RHIC measurements

- Hadron azimuthal distribution inside the jet in transversely polarized p+p collisions: spin dynamics

$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right] + p \to [\text{jet}\, h(\phi_H)] + X$$

STAR, in arXiv:1501.01220





See Prokudin's talk on Wednesday
Kang, Prokudin, Ringer, Yuan, to appear

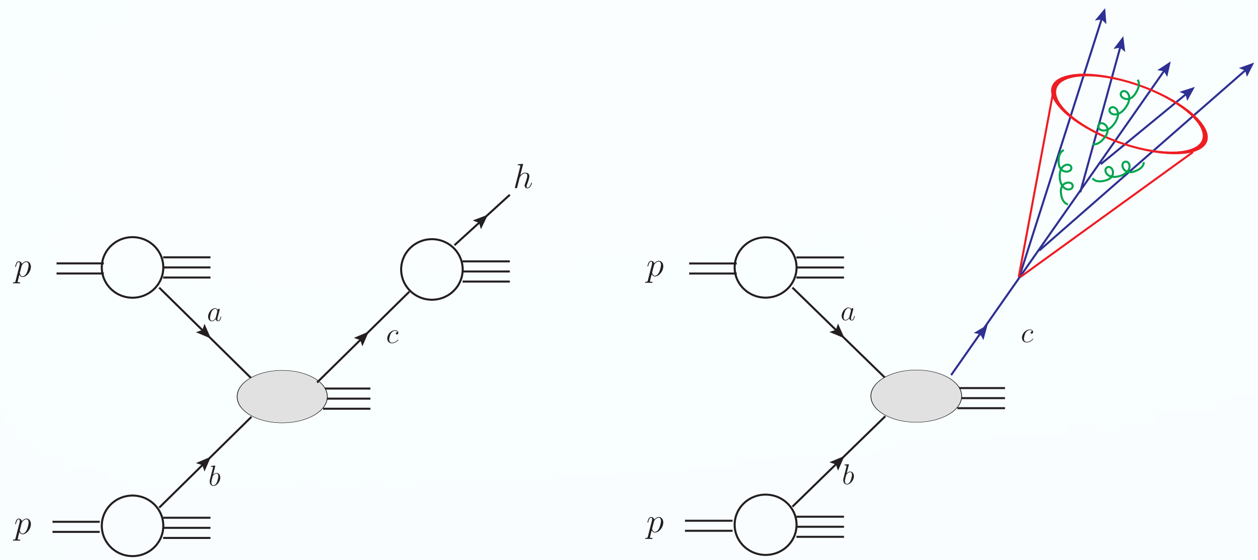
Questions

- How does the factorization formalism look like?
- How is the collinear z-distribution of hadrons in the jet related to the standard collinear fragmentation function?
- How is the transverse momentum dependent j_T-distribution of hadrons in the jet related to the usual TMD fragmentation function as measured in SIDIS and e+e-?

Lots of work have been performed along these directions recently, and very active developments
e.g., Kaufmann, Mukherjee, Vogelsang; Bain, Makris, Mehen, Leibovich;
Kang, Ringer, Vitev; Neill, Scimenmi, Waalewijn; ...

A further re-factorization for jet and jet substructure

- For cross section or substructure of single **inclusive** jet production



$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h$$

$$\frac{d\sigma^{pp\to \text{jet}(v)X}}{dp_T d\eta dv} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c(\mu \sim p_T R, v)$$

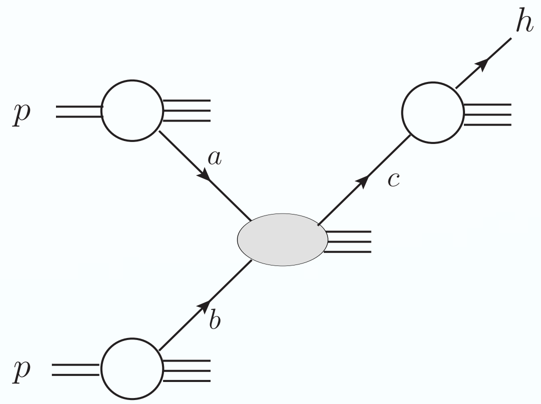
Fragmentation function — Semi-inclusive jet function

$$D_c^h \Rightarrow \mathcal{G}_c(\mu \sim p_T R, v)$$

Kang, Ringer, Vitev, arXiv:1606.06732, 1606.07063, JHEP

Recall single hadron production

- Illustration of single hadron production: $p + p \to h + X$

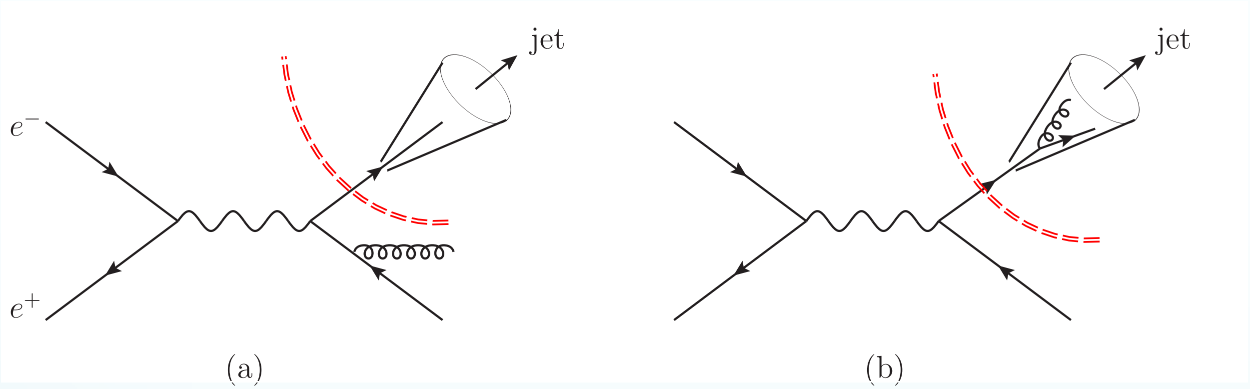


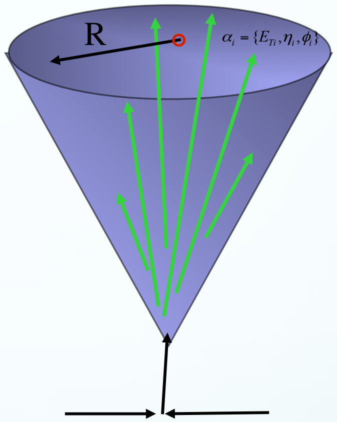
$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h$$

- QCD factorization can be reviewed from the spirit of the effective field theory: physics at very different scales do not affect each other
  - Hard collision happens at scale ~ pT
  - Hadronization/fragmentation happens at a much lower scale ~ mh
  - The interference between these two scales should be suppressed by mh/pT

QCD factorization makes things simple

- Think of QCD factorization using the spirit of effective field theory
  - What are the relevant scales for single jet production?
  - Two momenta: (1) hard collision: pT (2) jet radius can build one: pT*R
  - In the small-R limit, one can actually factorizes the jet cross section into two steps, just like single hadron production





$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(\mu \sim p_T R)$$

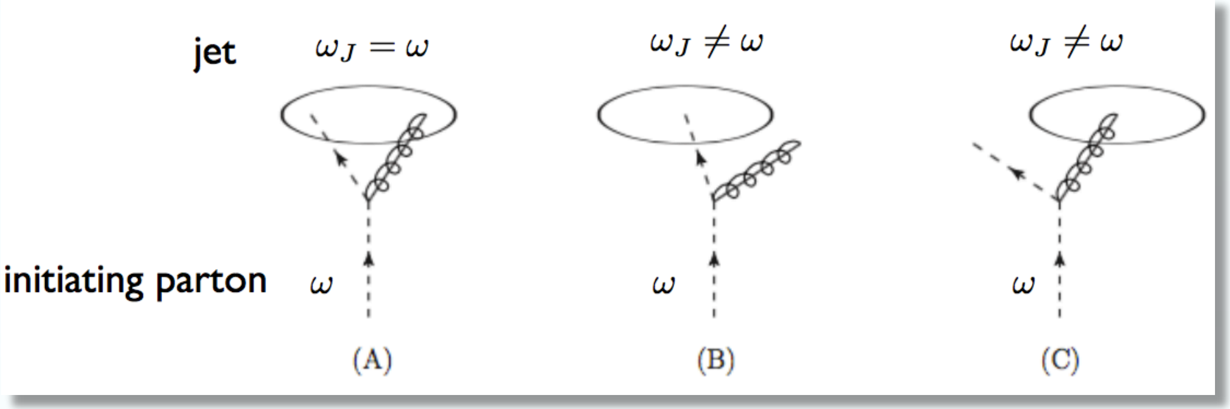
- Good thing: semi-inclusive jet function $J_{q,g}(z, R, w)$ are purely perturbative

Kang, Ringer, Vitev, arXiv:1606.06732, Dai, Kim, Leibovich, 1606.07411, see also, Kaufmann, Mukherjee, Vogelsang, 1506.01415

Semi-inclusive jet function

- Describe how a parton (q or g) is transformed into a jet (with a jet radius R) and energy fraction z

$$J_q(z,\omega_J,\mu) = \frac{z}{2N_c}\mathrm{Tr}\left[\frac{\bar{\not n}}{2}\langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\chi_n(0)|JX\rangle\langle JX|\bar{\chi}_n(0)|0\rangle\right] \qquad z=\omega_J/\omega$$



Semi-inclusive quark/gluon jets follow DGLAP evolution equation, just like hadron fragmentation functions

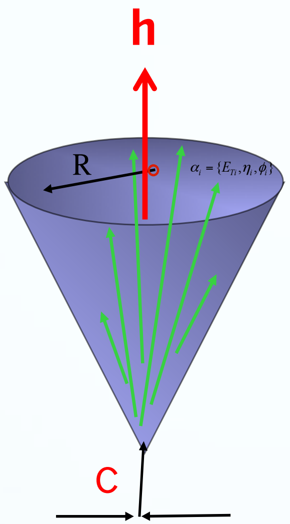
$$\mu\frac{d}{d\mu}J_i(z,\omega_J,\mu) = \frac{\alpha_s(\mu)}{\pi}\sum_j\int_z^1\frac{dz'}{z'}P_{ji}\left(\frac{z}{z'},\mu\right)J_j(z',\omega_J,\mu)$$

Kang, Ringer, Vitev, arXiv:1606.06732, JHEP

Collinear hadron distribution inside the jet

- First produce a jet, and then further look for a hadron inside the jet

Kang, Ringer, Vitev, arXiv:1606.07063, JHEP



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

$$z_h = p_T^h / p_T$$

- Just like the single inclusive jet production, we have
  - Semi-inclusive fragmenting jet function

$$z = p_T / p_T^c$$

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

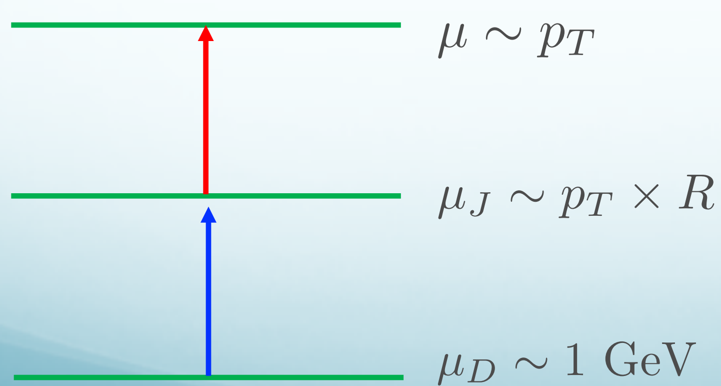
Two DGLAPs

- Parton-to-jet part: evolution is for variable z

$$\mu \frac{d}{d\mu} \mathcal{G}_i^h(z, z_h, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}\right) \mathcal{G}_j^h(z', z_h, \mu)$$

- Substructure of the jet: collinear hadron distribution in the jet, relevant to variable z_h

$$\mathcal{G}_i^h(z, z_h, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h', \mu) D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$

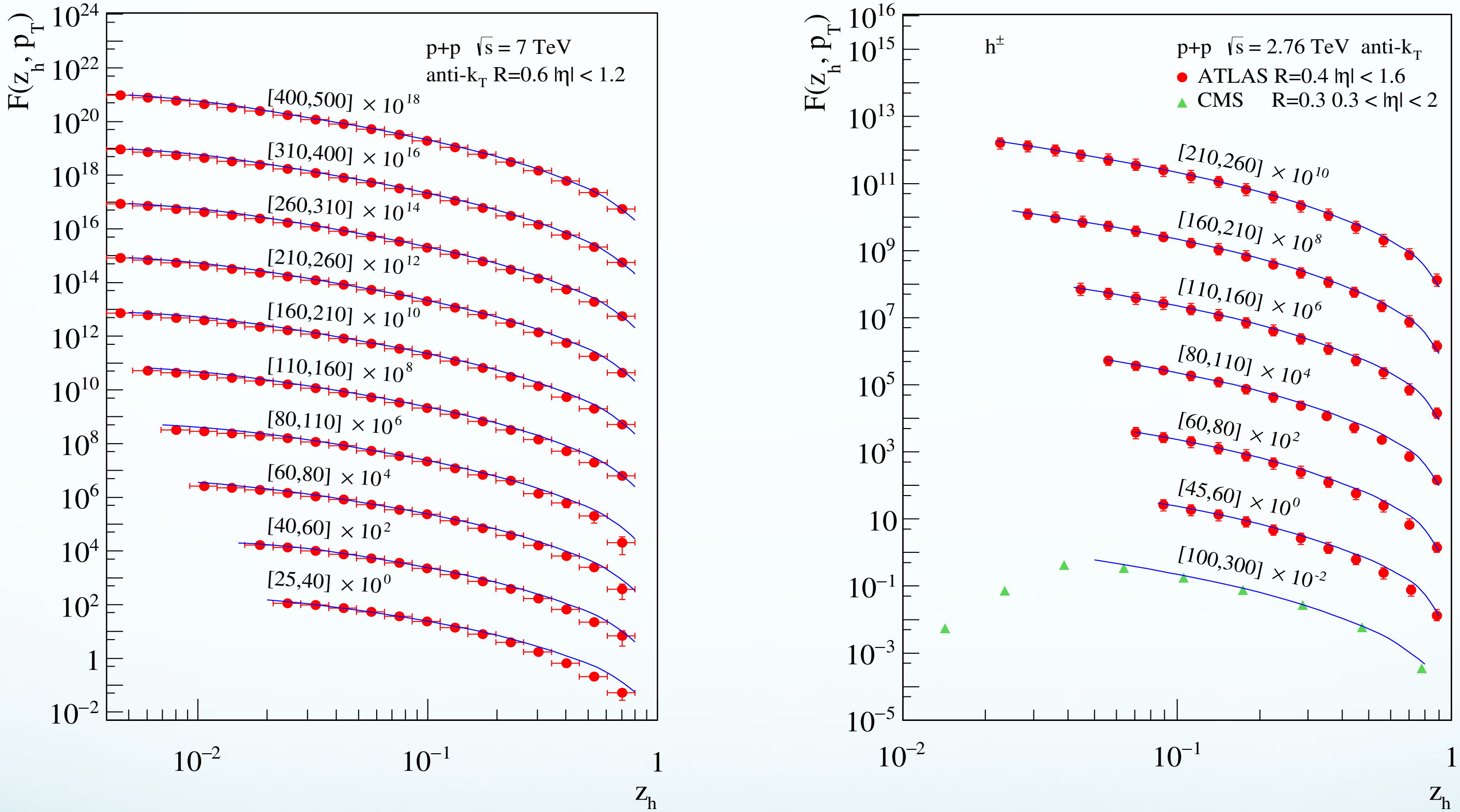


Resum ln(R)

Evolve standard FFs from 1 GeV to pT*R

Great probe for collinear FFs

- Works pretty well in comparison with experimental data



- Could be used for better constraining gluon-to-hadron FFs, large-z region and etc

Kang, Ringer, Vitev, arXiv:1606.07063

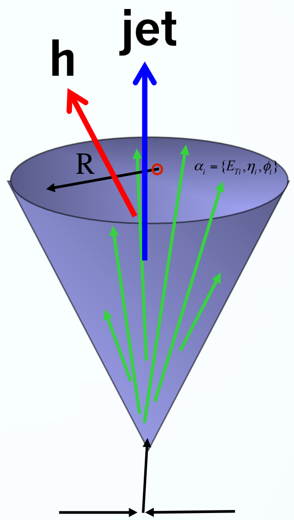
What about TMD FFs?

- TMD hadron distribution inside the jet

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

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

j_T : hadron transverse momentum with respect to the jet direction



- Factorization formalism

Kang, Liu, Ringer, Xing, in preparation

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

- Re-factorization of semi-inclusive fragmenting jet function

$$\mathcal{G}_c^h(z, z_h, j_T, \mu) = \mathcal{C}_{c\to d}(z, R) \int d^2\lambda_T d^2 k_T \delta^2(j_T - \lambda_T - k_T) S(\lambda_T, R) D_d^h(z_h, k_T)$$

A couple of main points

- One soft function + one TMD FFs
  - How do the rapidity divergences cancel between them?
  - Recall: standard TMD factorization for SIDIS, DY, e+e-, which always involve one soft function + TWO TMDs

- What sets the scale for the TMD evolution of TMD FFs?

TMD factorization for DY: $p+p\to[\gamma^*\to\ell^+\ell^-]+X$

- Factorized form and mimic "parton model"

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

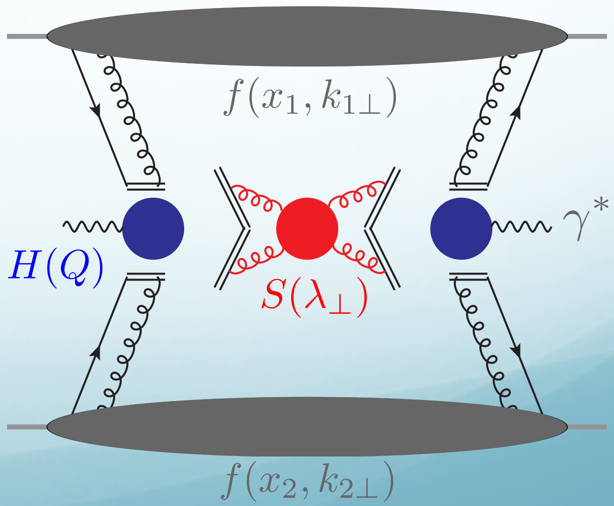
$$=\int\frac{d^2b}{(2\pi)^2}e^{iq_\perp\cdot b}H(Q)f(x_1,b)f(x_2,b)S(b)$$

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

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

- Rapidity divergences cancel between

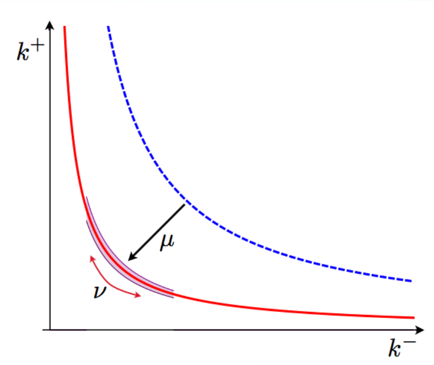
$$F(x,b)=f(x,b)\sqrt{S(b)}$$



TMDs in b-space at NLO

- Quark TMD at one loop

$$f_{q/q}(x,b) = \frac{\alpha_s}{2\pi} C_F \left\{ \left[\frac{2}{\eta}\left(\frac{1}{\epsilon} + \ln\frac{\mu^2}{\mu_b^2}\right) + \frac{2}{\epsilon}\ln\frac{\nu}{p^+} + \frac{3}{2}\frac{1}{\epsilon}\right]\delta(1-x) + \left(-\frac{1}{\epsilon} - \ln\frac{\mu^2}{\mu_b^2}\right) P_{qq}(x) + \left[2\ln\frac{\mu^2}{\mu_b^2}\ln\frac{\nu}{p^+} + \frac{3}{2}\ln\frac{\mu^2}{\mu_b^2}\right]\delta(1-x) + (1-x) \right\}$$



- Soft factor

$$S(b) = \frac{\alpha_s}{2\pi} C_F \left\{ \frac{4}{\eta}\left(-\frac{1}{\epsilon} - \ln\frac{\mu^2}{\mu_b^2}\right) + \frac{2}{\epsilon^2} + \frac{2}{\epsilon}\left(\ln\frac{\mu^2}{\mu_b^2} - \ln\frac{\nu^2}{\mu_b^2}\right) + \left[-2\ln\frac{\mu^2}{\mu_b^2}\ln\frac{\nu^2}{\mu_b^2} + \ln^2\frac{\mu^2}{\mu_b^2} - \frac{\pi^2}{6}\right] \right\}$$

$$\mu_b = 2e^{-\gamma_E}/b$$

- Interesting features
  - Rapidity divergence cancels in $F^{\text{sub}}_{q/q}(x,b) = f_{q/q}(x,b)\sqrt{S(b)}$
  - $f_{q/q}(x, b)$ and $S(b)$ lives in the same $\mu \sim \mu_b$, but different rapidity scale $\nu \sim p^+, \mu_b$

Kang, Spin 2016 conference

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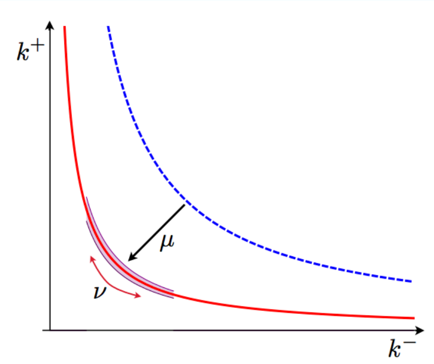

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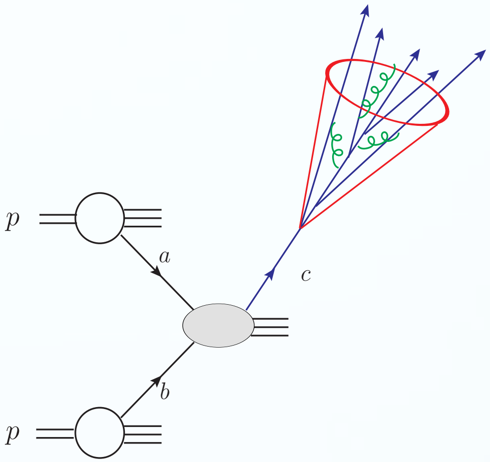
Kang, Spin 2016 conference

What's different for hadron in the jet?

- Soft radiation has to happen inside the jet
  - For single inclusive jet production, first we produce a high-pt jet
  - This process only involves hard-collinear factorization, and such a process is not sensitive to any soft radiation
  - This is the usual standard "collinear factorization"

$$\int_0^\infty \frac{dy}{y} \Rightarrow \int_0^{\tan^2 \frac{R}{2}} \frac{dy}{y}$$

$$y \sim \frac{\ell^+}{\ell^-}$$



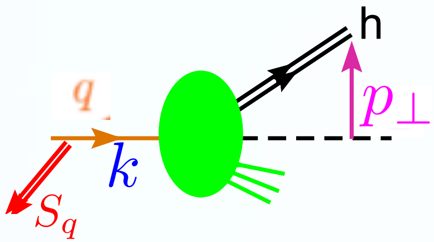
  - Once such a high-pt jet is produced, we further observe a hadron inside the jet
  - At this step, we measure the relative transverse momentum of hadron w.r.t the jet. For such a step, soft radiation matters
  - However, only those soft radiation that happens inside the jet matters
  - Restricts soft radiation to be within the jet: cuts half of the rapidity divergence

- Rapidity divergence cancel between restricted "soft factor" and TMD FFs
  - At least up to this order, the combined evolution is the same as the usual TMD evolution in SIDIS, DY, e+e-; justify the use of same TMD evolution here

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

Collins function: universal

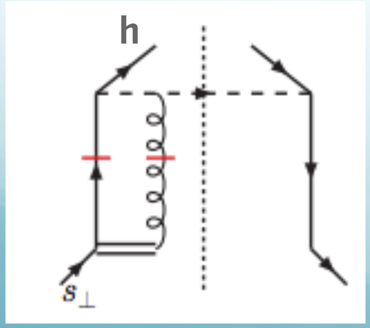
- Collins function: unpolarized hadron from a transversely polarized quark



$$D_{h/q}(z,p_\perp) = D_1^q(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\vec{S}_q \cdot \left(\hat{k} \times p_\perp\right)$$

Spin-independent Spin-dependent

- ✓ 2002: A. Metz studied the universality property of Collins function in a model-dependent way – very subtle – finally found it is universal between SIDIS and e+e-
- ✓ 2004: Collins and Metz have general arguments
- ✓ 2008: Yuan generalizes to pp
- ✓ Collins function is universal: concern on collinear gauge link (unsubtracted TMDs)
- ✓ Now soft function seems to be fine, too

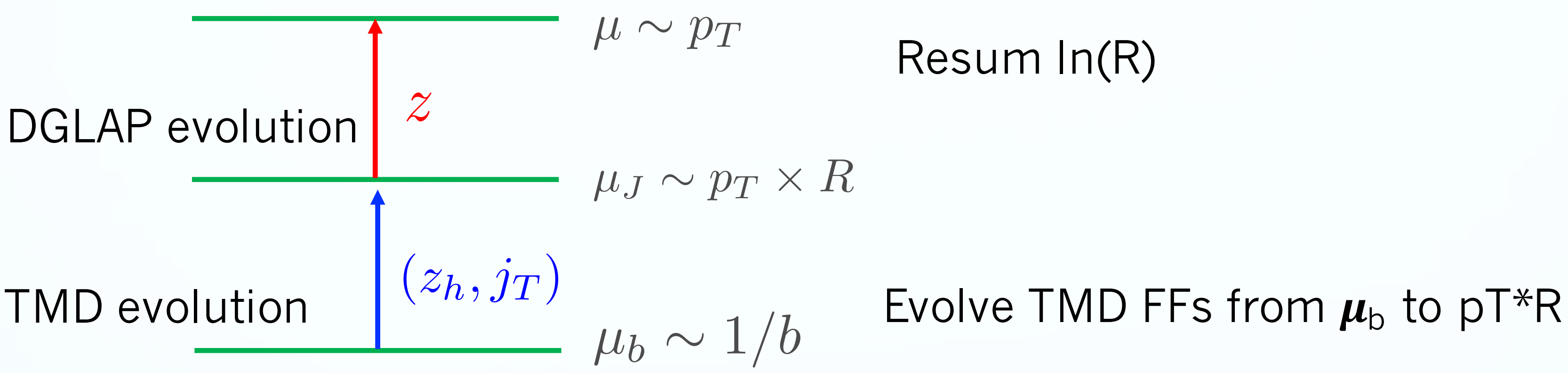


$$H_1^{\perp \mathrm{SIDIS}}(z,p_\perp^2) = H_1^{\perp e^+e^-}(z,p_\perp^2) = H_1^{\perp \mathrm{pp}}(z,p_\perp^2)$$

Metz 02, Collins, Metz 04, Yuan 08,
Gamberg, Mulders, 10,
Boer, Kang, Vogelsang, Yuan, 10, ...

TMD + DGLAP evolution

- Evolution structure



- TMD FFs thus are related to the usual TMD FFs in SIDIS at scale pT*R
- Thus hadron TMD distribution inside the jet could be used to test the universality of TMD FFs from SIDIS, e+e- processes

Summary

- jet cross section and jet substructure for inclusive jet production follow a two-step factorization
  - First step: parton-to-jet production
  - Second step: jet internal substructure
- The hard function associated with the 1st step is the same as that for single inclusive hadron production
- For jet substructure, one could then concentrate on the 2nd step
- Collinear and TMD distribution of hadron in a jet are great processes to probe collinear and/or TMD FFs
  - Factorization seems to be okay

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Thank you!