The transverse momentum distribution of hadrons inside jets

Felix Ringer

Lawrence Berkeley National Laboratory

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Outline

- Introduction
- In-jet TMDs *Kang, Liu, FR, Xing `17*
- Collins asymmetries *Kang, Prokudin, FR, Yuan `17*
- Conclusions

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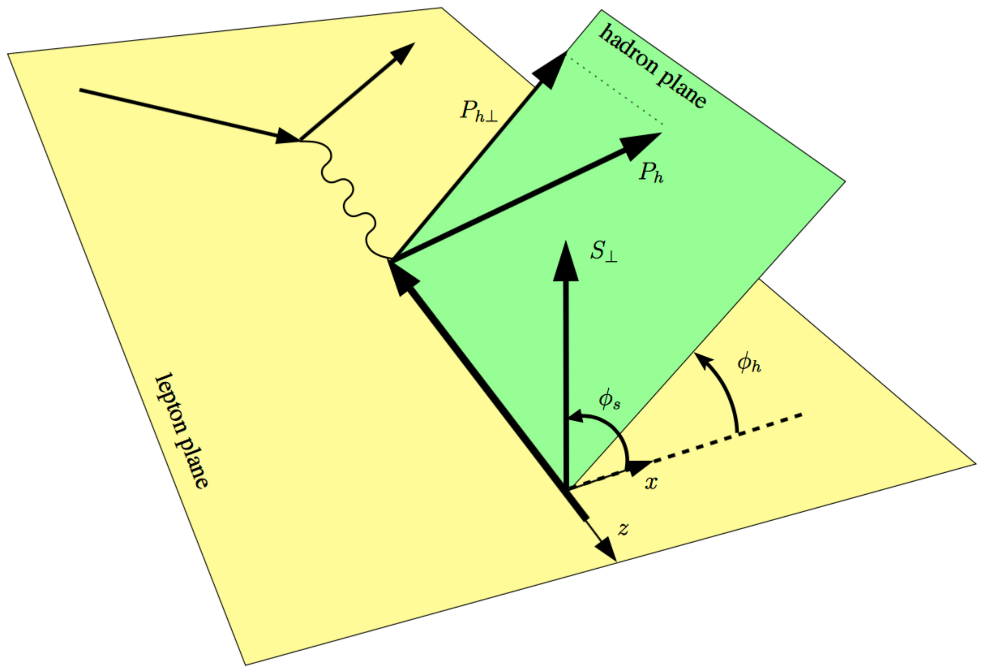
Accessing Transverse Momentum Distributions



- SIDIS: JLab, HERMES, COMPASS
- Drell-Yan
- Electron-positron: BELLE, BABAR

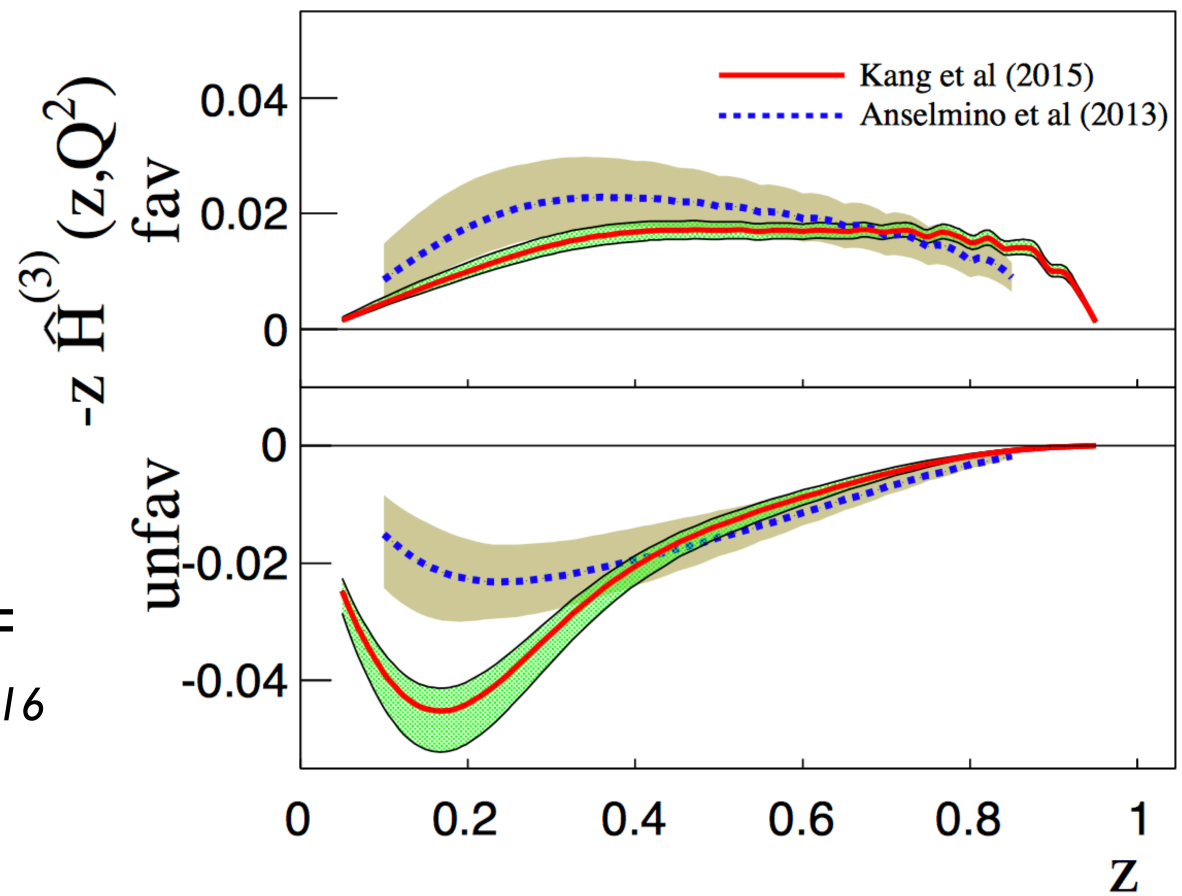
TMD extractions in global fits

Bacchetta et al. `17, Kang et al. `16, …

- Factorization *Boglione et al. `17*
- Test of universality
- TMD evolution

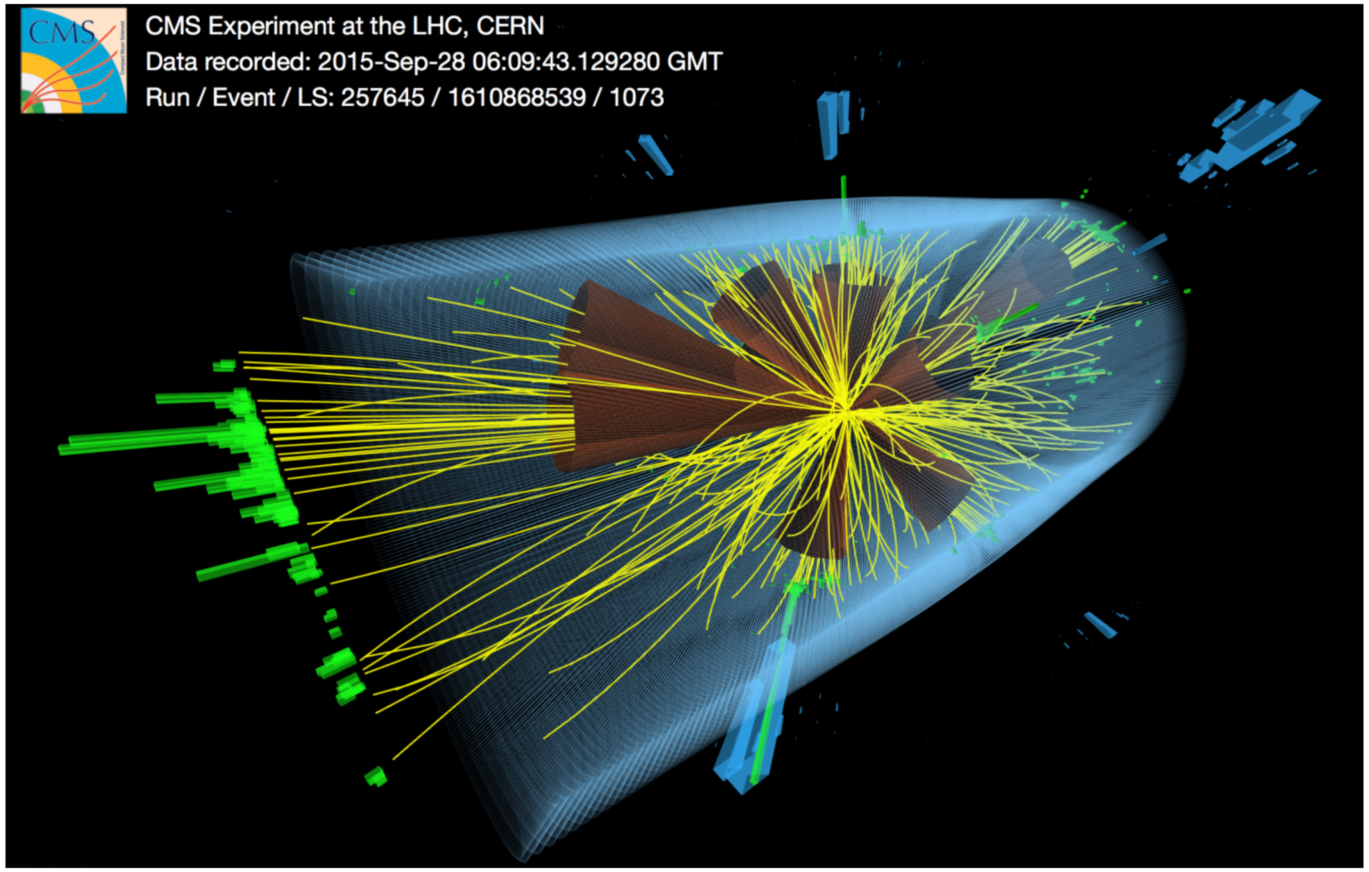
Collins FF

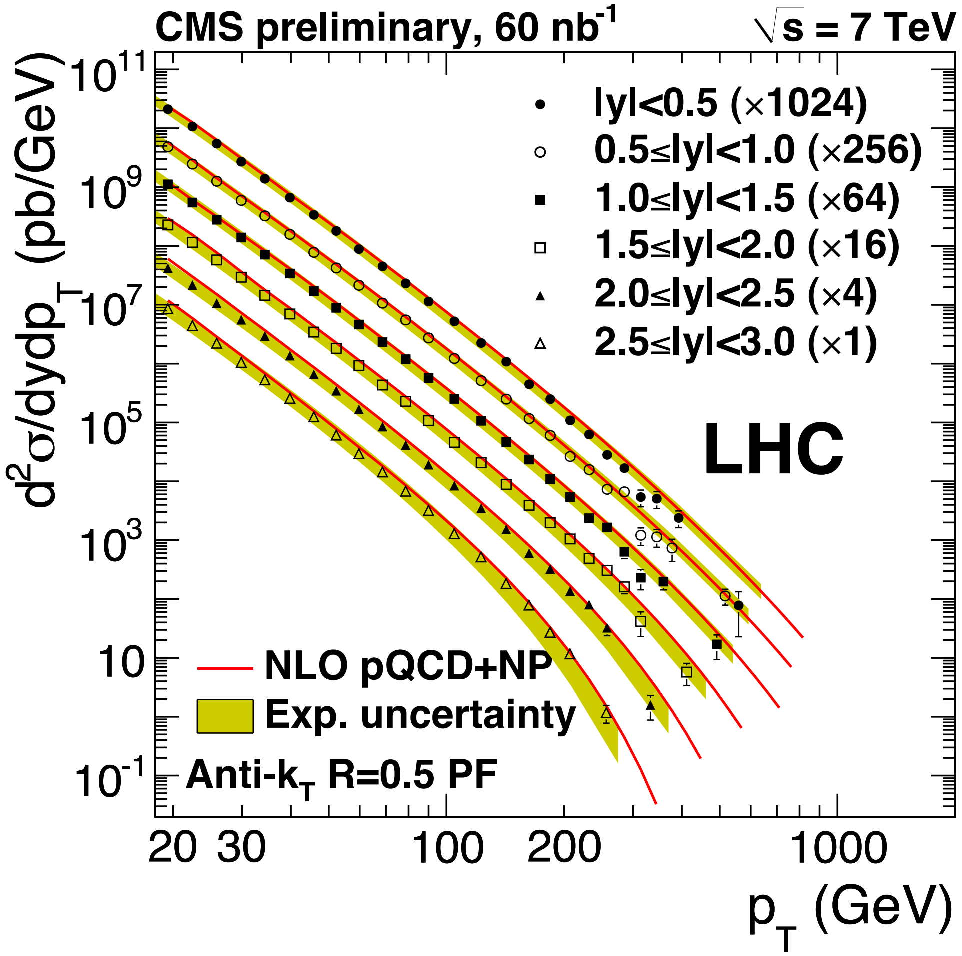
Kang et al. `16



Jets in proton-proton collisions

- PDFs and α_s are constrained by collider jet data
- High p_T jets are a promising observable for the search of BSM physics at the LHC
- Baseline for jet quenching in heavy-ion collisions
- Jet substructure



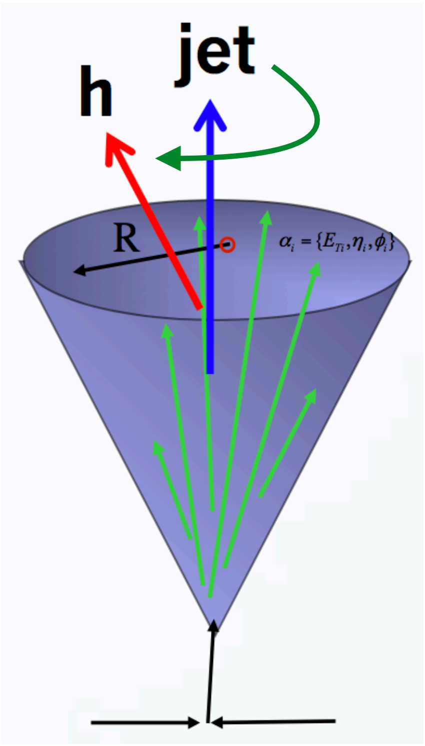


Hadron distributions inside jets

- Study hadron distributions inside a reconstructed jet

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

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



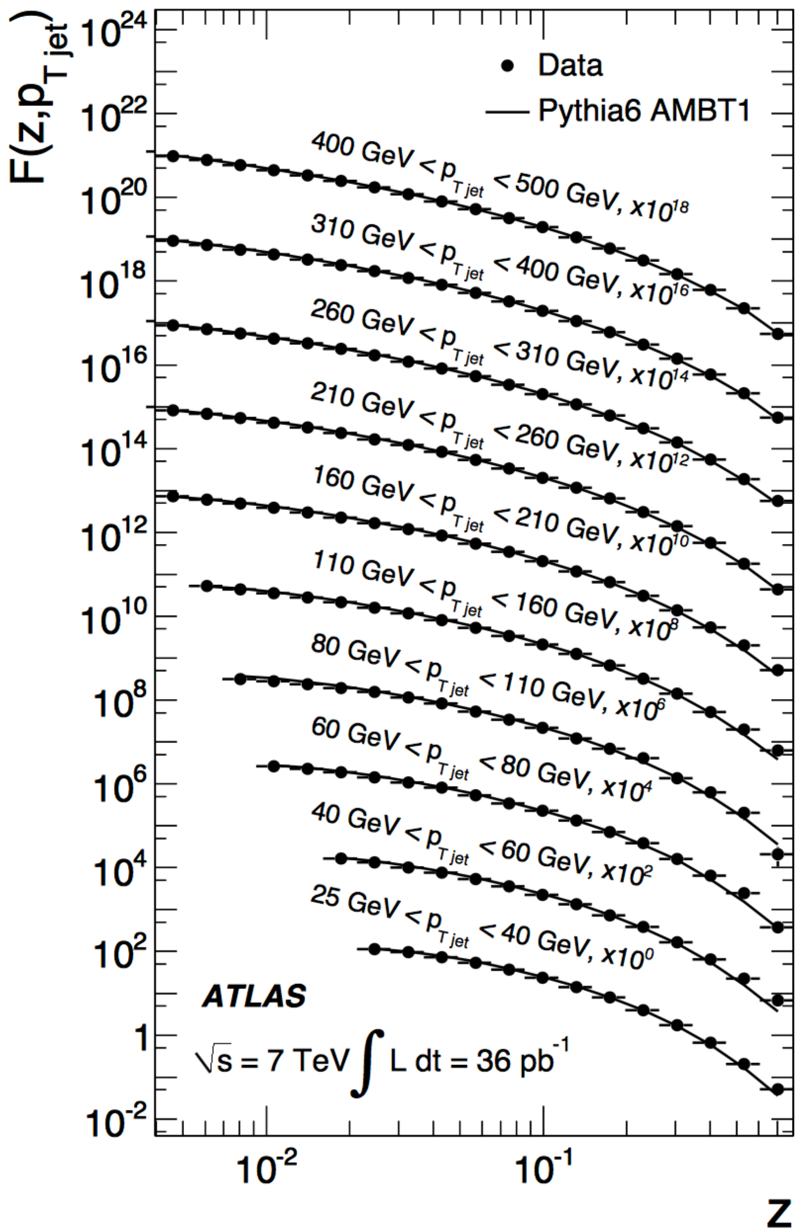
$$pp \to (\mathrm{jet}\, h) + X$$

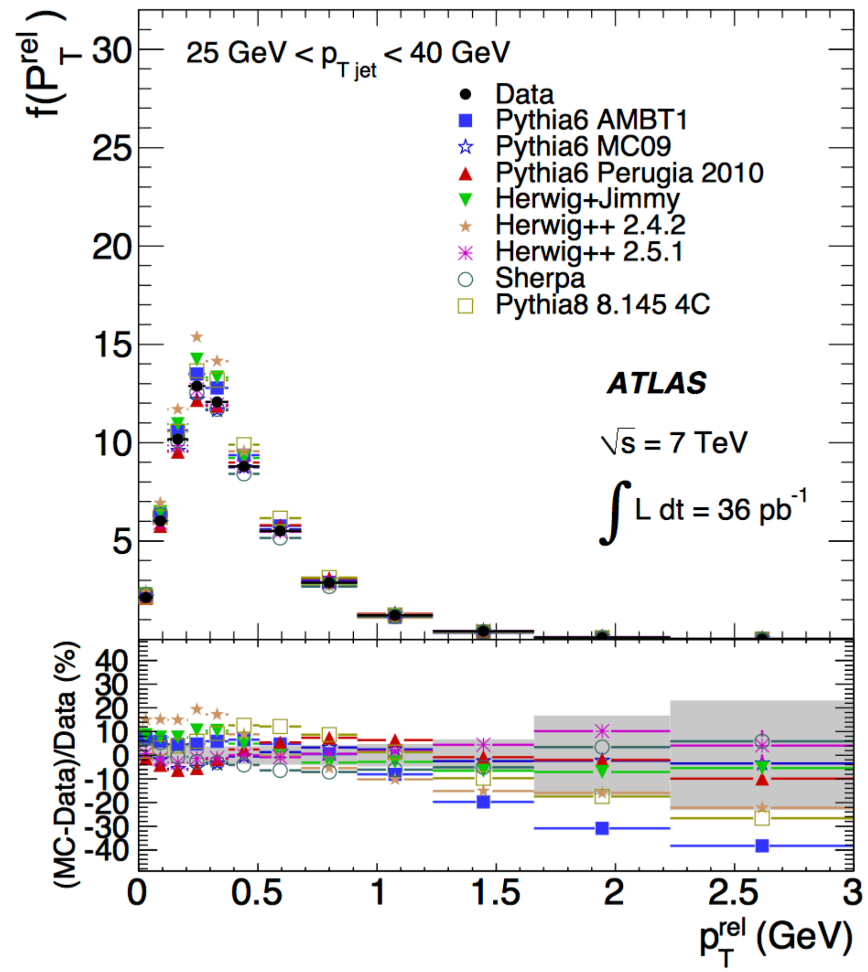
$z_h = p_T^h / p_T$

$j_\perp$: hadron transverse momentum with respect to the (standard) jet axis

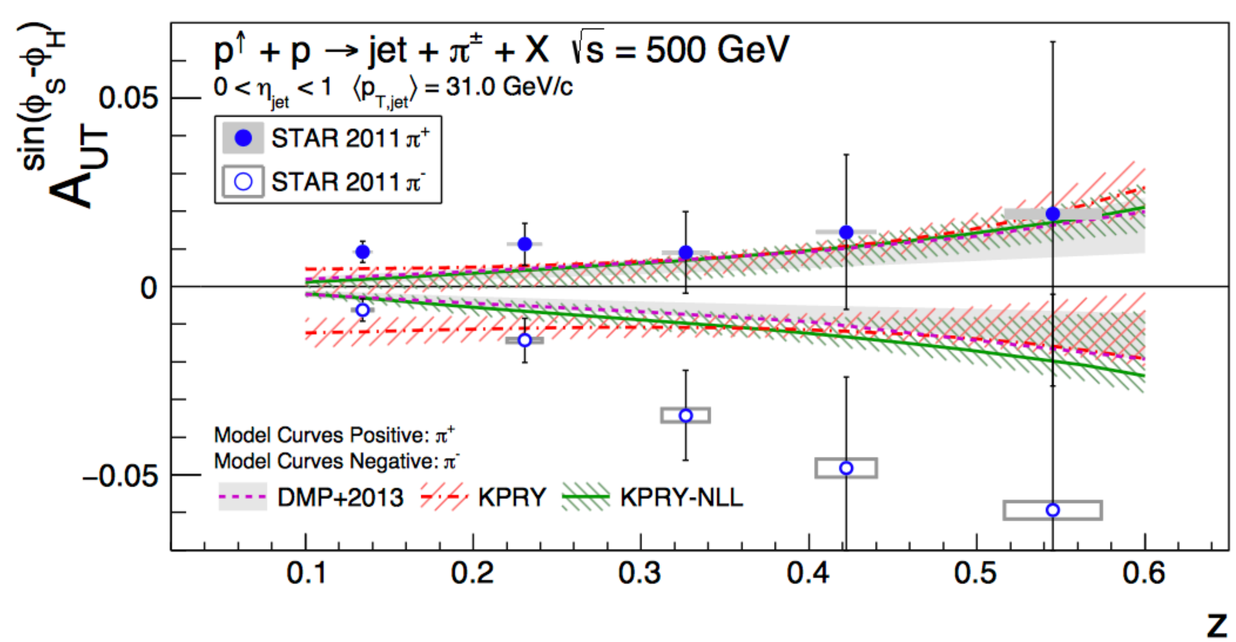
- Longitudinal momentum distribution probes collinear FFs
- Transverse momentum distribution probes TMD FFs
- Collins azimuthal asymmetries

Recent measurements at the LHC and RHIC



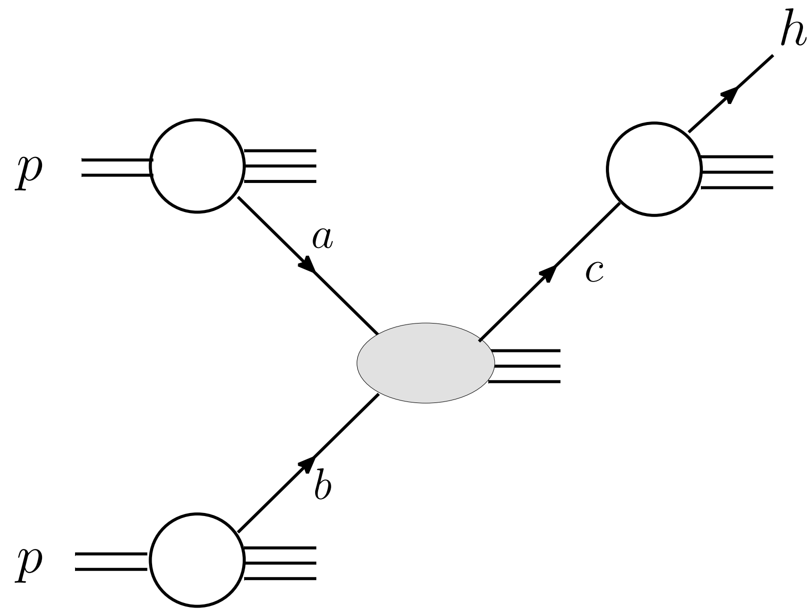


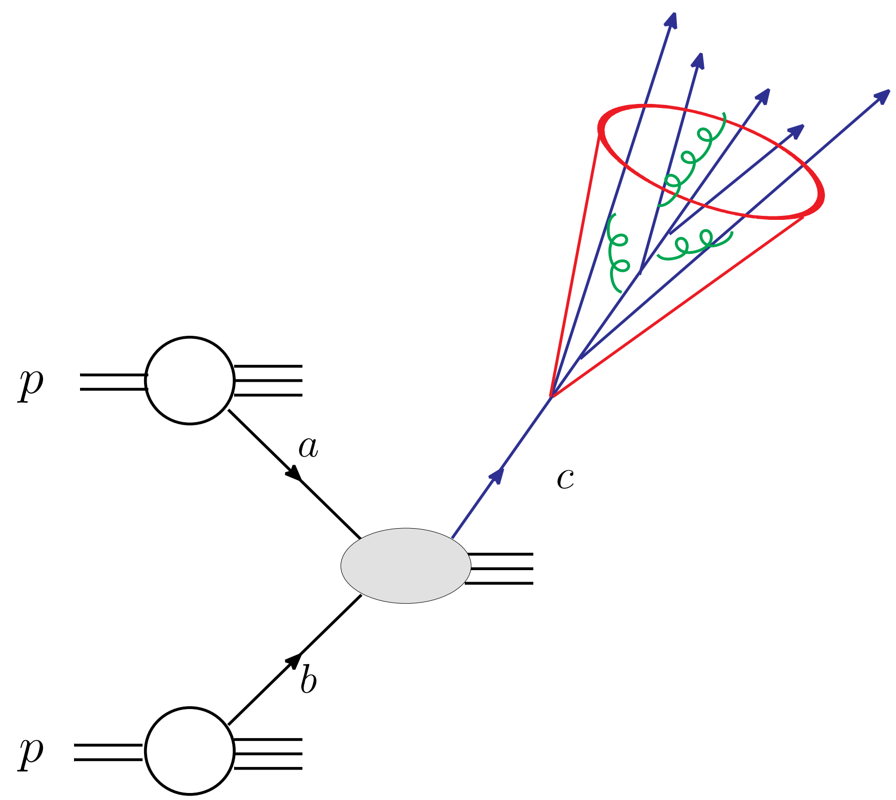
ATLAS Eur. Phys. J. C71 (2011) 1795
arXiv: 1109.5816



STAR Collaboration, arXiv: 1708.0708

Analogy of hadron and jet cross sections





Factorization

Jet

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

Hadron

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

Evolution

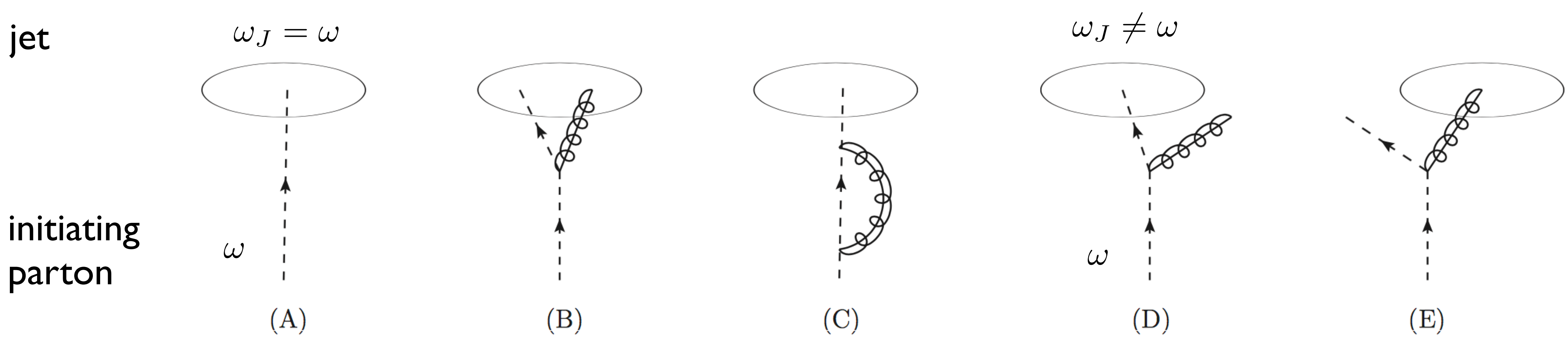
$$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$$

$$\mu \frac{d}{d\mu} D_i^h = \sum_j P_{ji} \otimes D_j^h$$

Kang, FR, Vitev `16

Semi-inclusive jet function in SCET

- The siJFs describe how a parton is transformed into a jet with radius R and carrying an energy fraction z



LO NLO

where $z = \omega_J/\omega$

momentum sum rule: $\int_0^1 dz\, z J_i(z, \omega R, \mu) = 1$

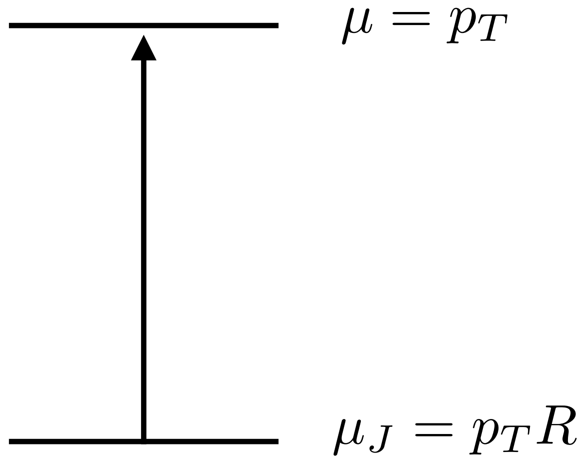
see also: Kaufmann, Mukherjee, Vogelsang `15
Dai, Kim, Leibovich `16

Semi-inclusive jet function in SCET

- NLO result

$$J_q^{(1)}(z,\omega_J) = \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon}+\ln\left(\frac{\mu^2}{p_T^2R^2}\right)\right)\left[P_{qq}(z)+P_{gq}(z)\right]$$
$$-\frac{\alpha_s}{2\pi}\left\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ +(1-z)\right]-\delta(1-z)d_J^{q,\mathrm{alg}}\right.$$
$$\left.+P_{gq}(z)2\ln(1-z)+C_F z\right\},$$

$\overline{\mathrm{MS}}$ scheme



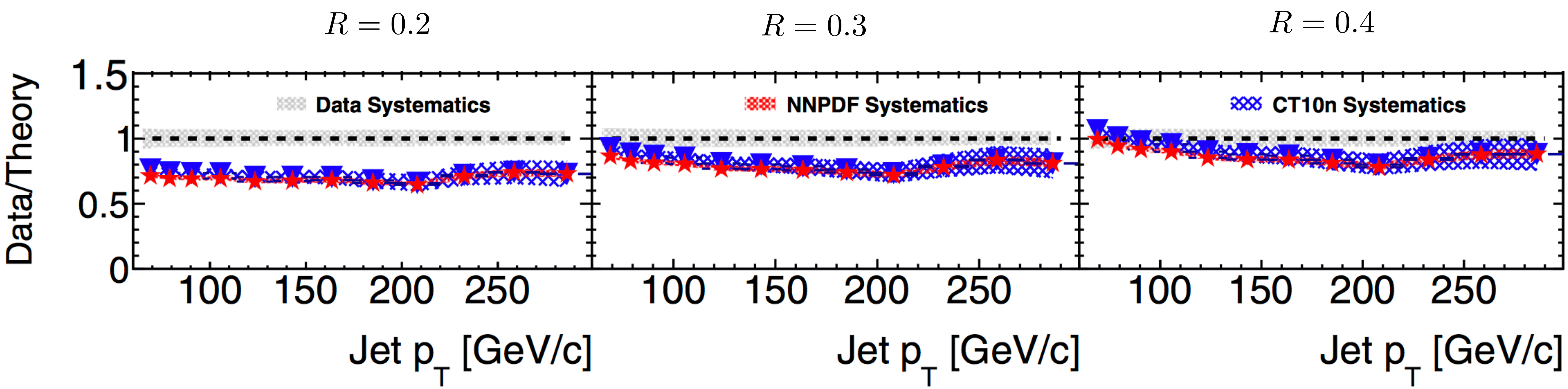
- RG equation
  timelike DGLAP for semi-inclusive jet function

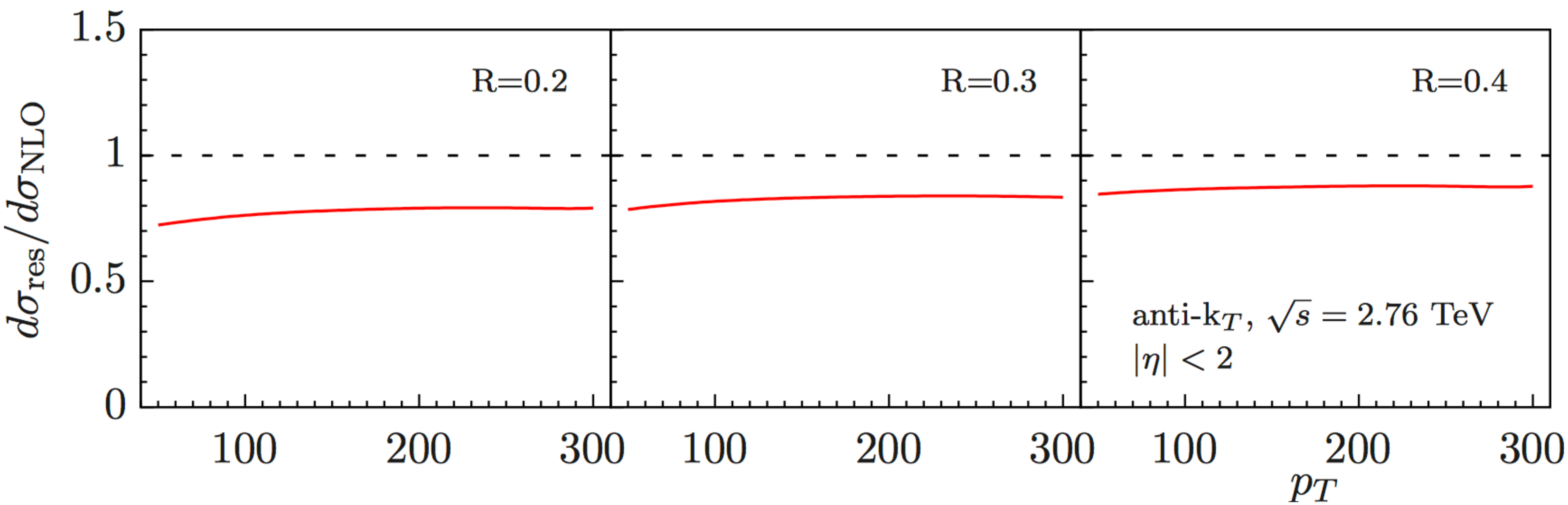
$$\mu\frac{d}{d\mu}J_i = \sum_j P_{ji}\otimes J_j$$

resummation of $\alpha_s^n \ln^n R$

see also: Dasgupta, Dreyer, Salam, Soyez `16

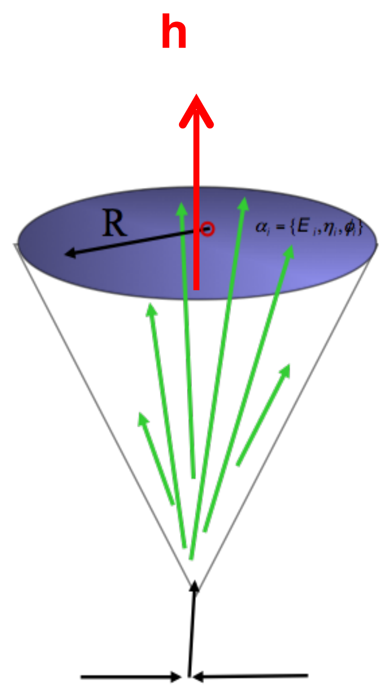
Comparison to LHC data





CMS Phys.Rev. C96 015202 (2017)

The jet fragmentation function $pp \to (\text{jet}h)X$



- First reconstruct a jet and then identify hadrons inside that jet

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

$$z_h = p_T^h / p_T$$

$$z = p_T / p_T^c$$

- Similar factorization to inclusive jet production

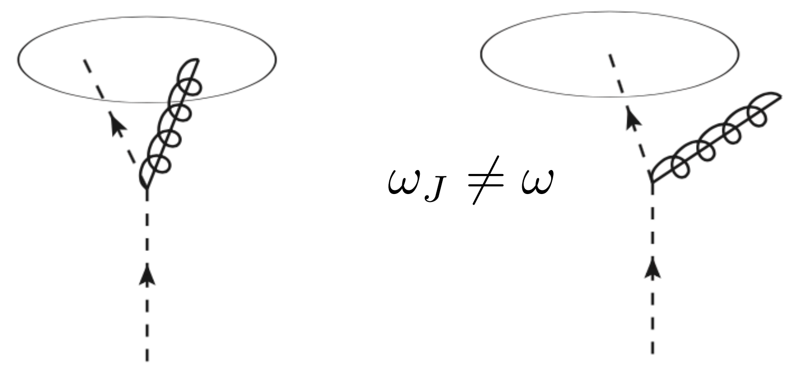
$$\frac{d\sigma^{pp\to(\text{jet }h)X}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a(x_a,\mu) \otimes f_b(x_b,\mu) \otimes H_{ab}^c(x_a,x_b,\eta,p_T/z,\mu) \otimes \mathcal{G}_c^h(z,z_h,\omega_J,\mu)$$

Semi-inclusive fragmenting jet function

Procura, Stewart `10, Liu `11, Jain, Procura, Waalewijn `11, Arleo, Fontannaz, Guillet, Nguyen `14, Kaufmann, Mukherjee, Vogelsang `15, Kang, FR, Vitev `16, …

Semi-inclusive fragmenting jet function

- Fragmenting parton: $\omega_h \neq \omega_J$ | $\omega_h = \omega_J$
- Jet: $\omega_J = \omega$ | $\omega_J \neq \omega$
- Initiating parton: ω | ω

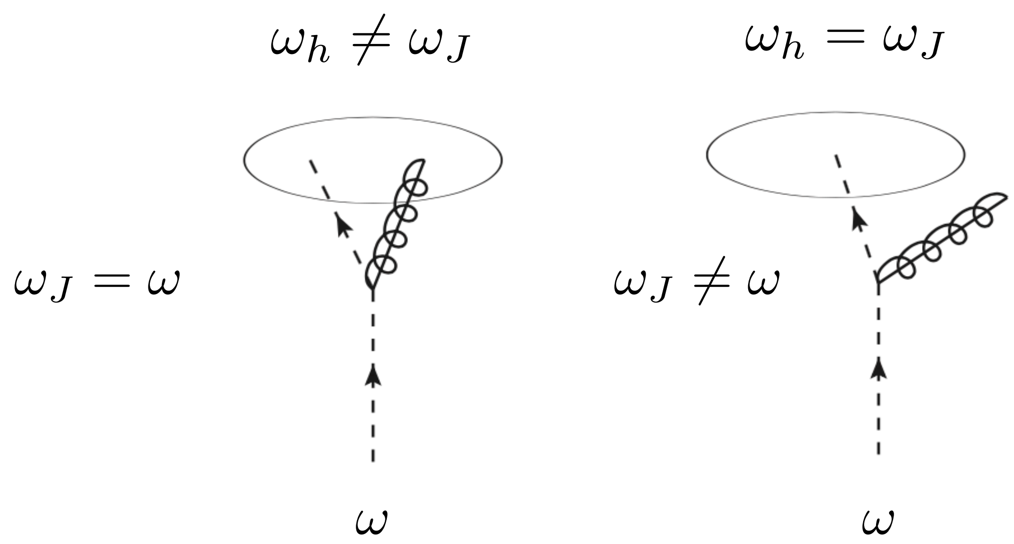


$$z_h = \omega_h / \omega_J$$

$$z = \omega_J / \omega$$

Semi-inclusive fragmenting jet function

- Fragmenting parton
- Jet
- Initiating parton



$$z_h = \omega_h/\omega_J$$

$$z = \omega_J/\omega$$

- Matching

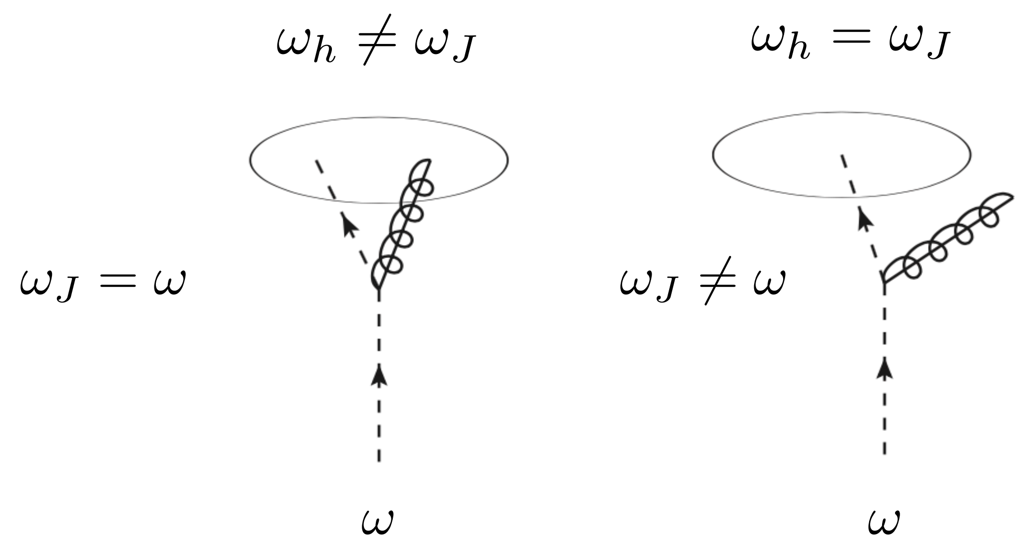
$$\mathcal{G}_i^h(z, z_h, \omega_J, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h}{z_h'} \mathcal{J}_{ij}(z, z_h', \omega_J, \mu) D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$

- $\ln R$ resummation

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

Semi-inclusive fragmenting jet function

- Fragmenting parton
- Jet
- Initiating parton



$z_h = \omega_h / \omega_J$

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- Matching

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

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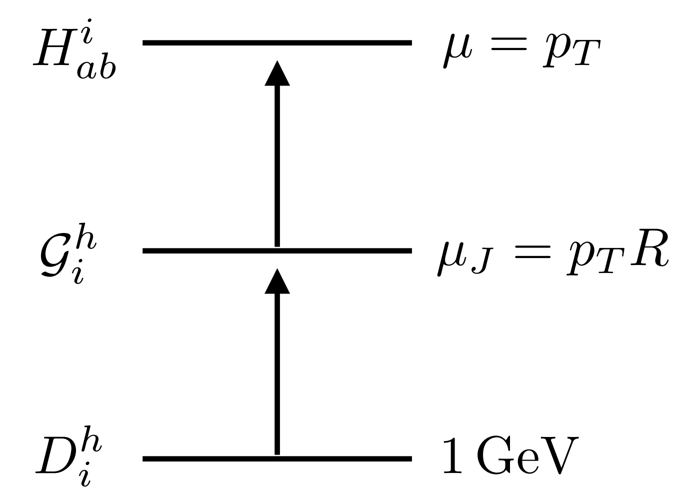
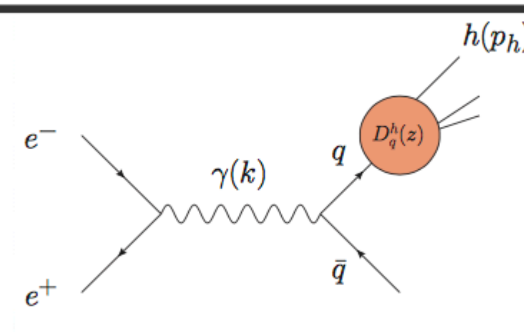
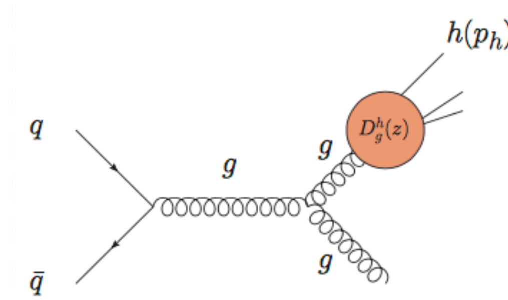
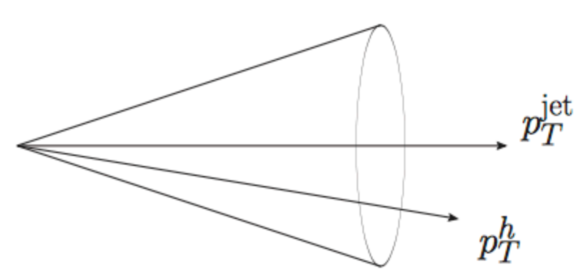


… 2 DGLAPs now

- The JFF is an ideal observable to constrain in particular gluon FFs

<table>
<tr><th>Process</th><th>D_g^h ?</th><th>Direct scan?</th></tr>
<tr><td>$e^+e^- \to hX$
$ep \to ehX$</td><td></td><td> 

$z = \frac{2p_h \cdot k}{k^2}$</td></tr>
<tr><td>$pp \to hX$</td><td></td><td> 

$\hat{p}_T = \frac{p_T^h}{z_c}$ $\quad z_c^{\min} = \frac{2p_T^h}{\sqrt{S}} \cosh\eta$
$d\sigma \propto \int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \left[f_a \otimes f_b \otimes d\hat{\sigma}_{ab}^c(\hat{p}_T, \dots)\right] D_c^h(z_c)$</td></tr>
<tr><td>$pp \to (\text{jet}\, h)\, X$</td><td></td><td> 

$z = z_h \equiv \frac{p_T^h}{p_T^{\text{jet}}}$</td></tr>
</table>

Slide courtesy of Tom Kaufmann

Phenomenology

- Light charged hadrons
  Arleo, Fontannaz, Guillet, Nguyen `14
  Kaufmann, Mukherjee, Vogelsang `15
  Kang, FR, Vitev `16
  Neill, Scimemi, Waalewijn `16

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- Heavy flavor mesons
  Chien, Kang, FR, Vitev, Xing `15
  Bain, Dai, Hornig, Leibovich, Makris, Mehen `16
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- Quarkonia
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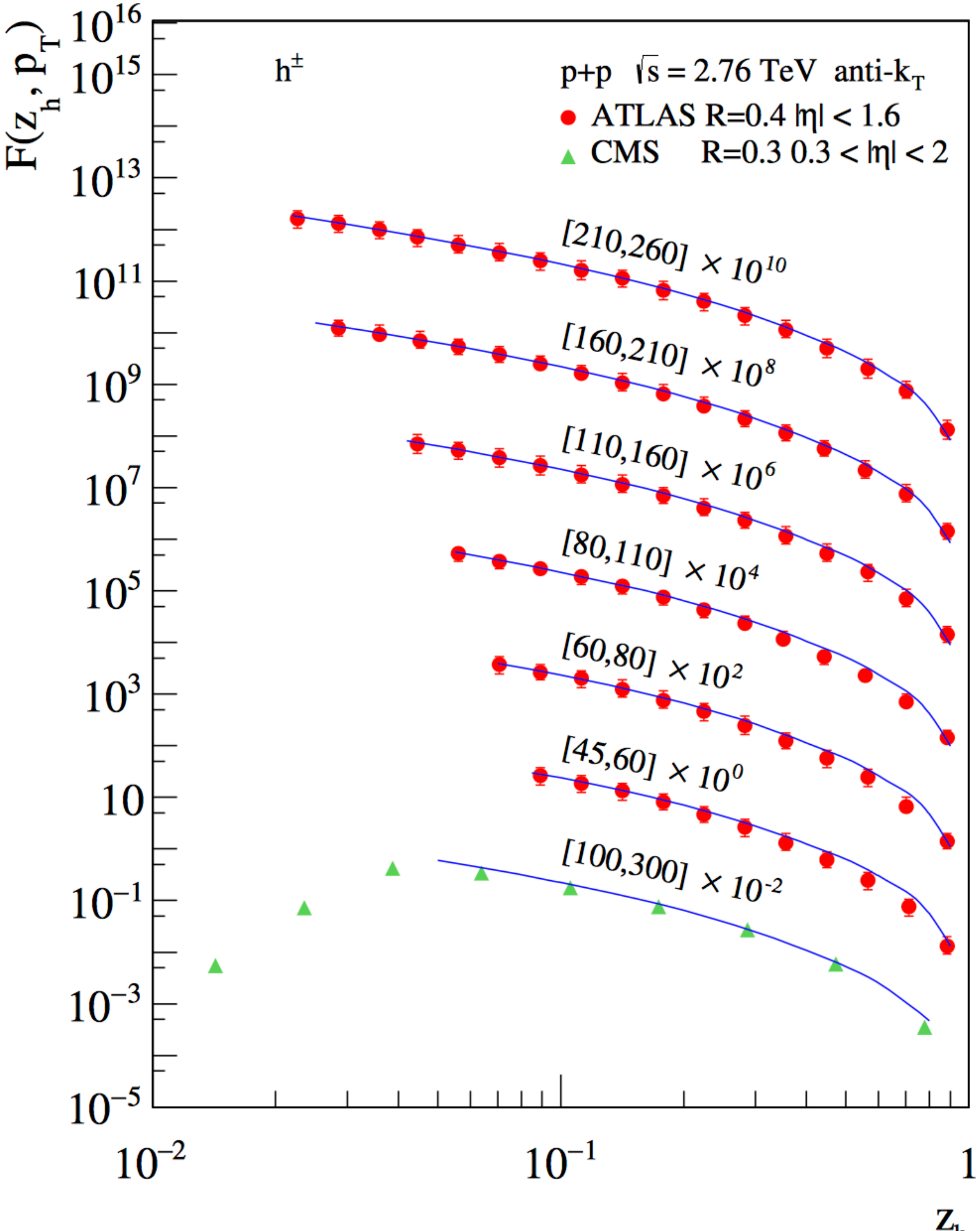

Kang, FR, Vitev `16

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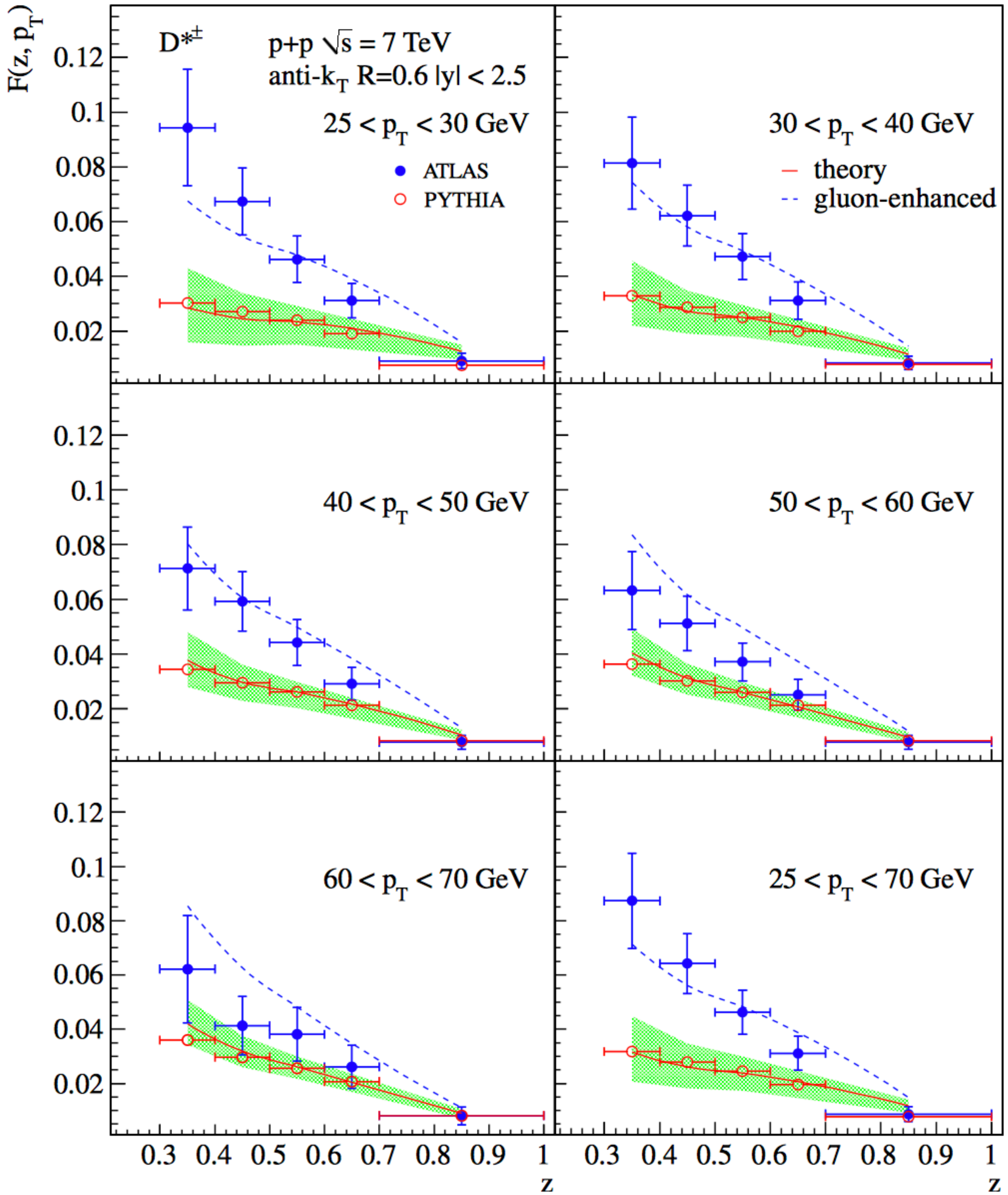

Chien, Kang, FR, Vitev, Xing `15

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$pp \to (\text{jet } D^*)X$

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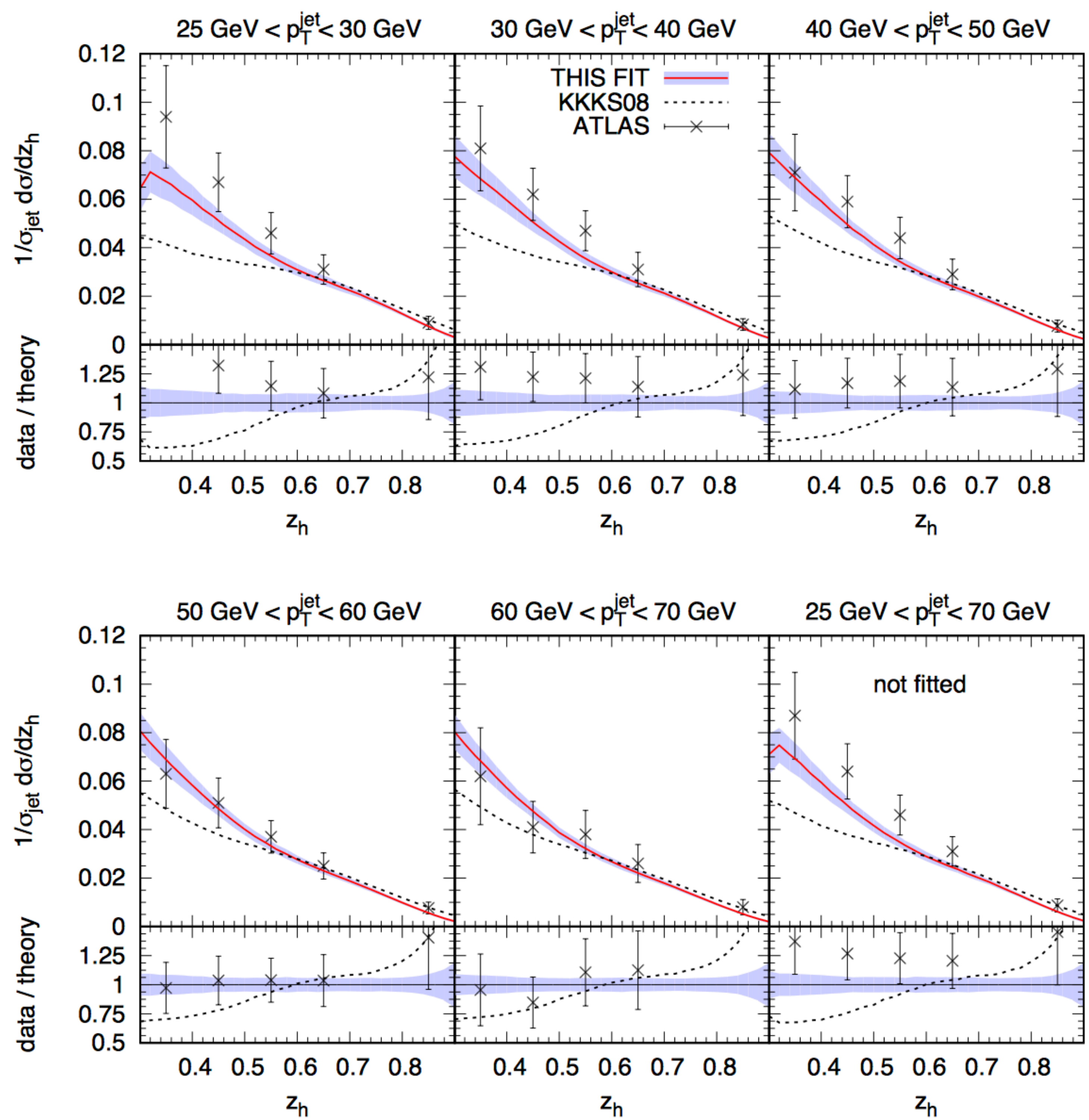

New global D*-meson FF fit
Anderle, Kaufmann, Stratmann, FR, Vitev `17

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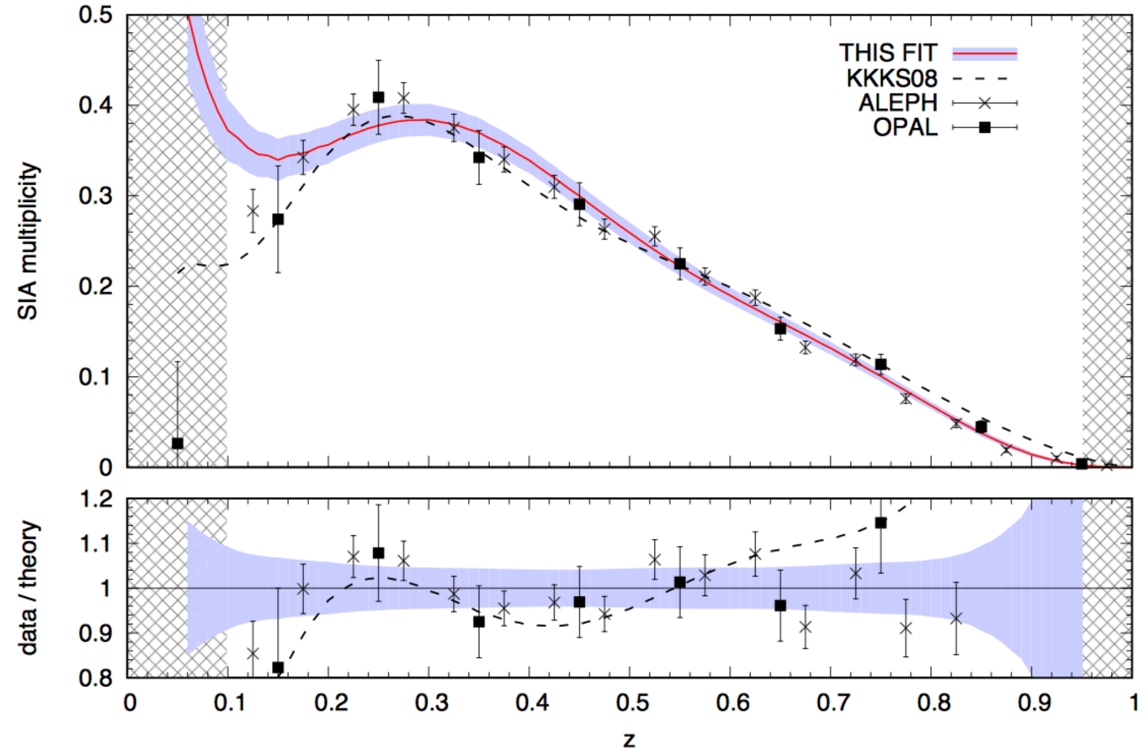

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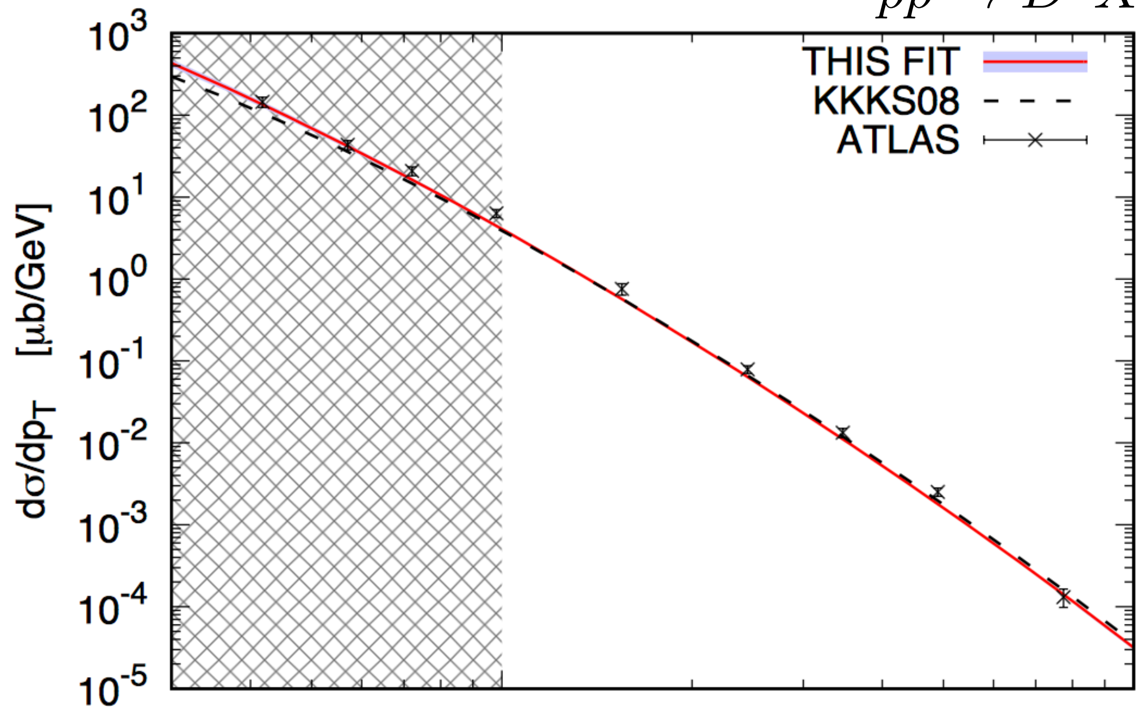

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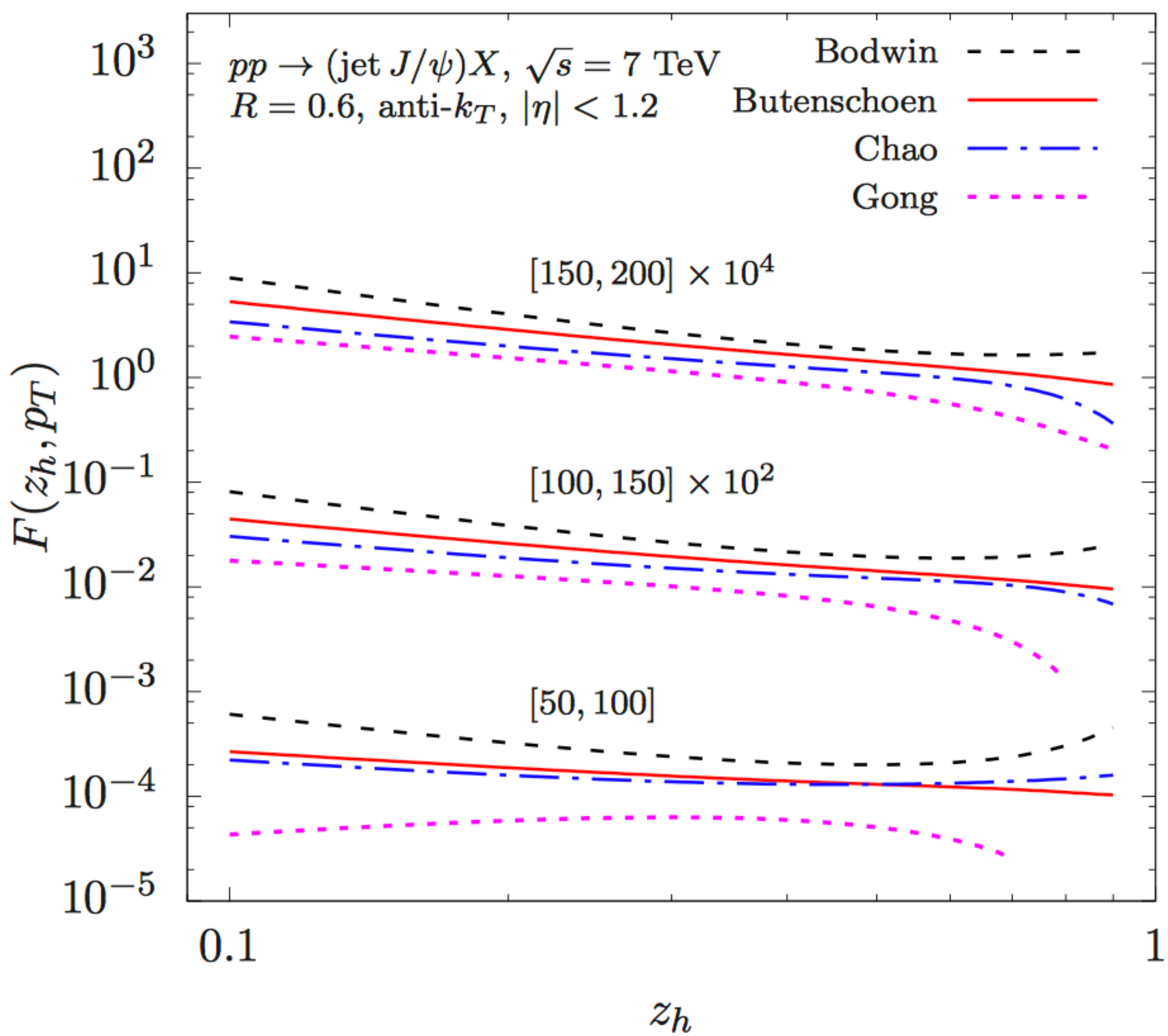

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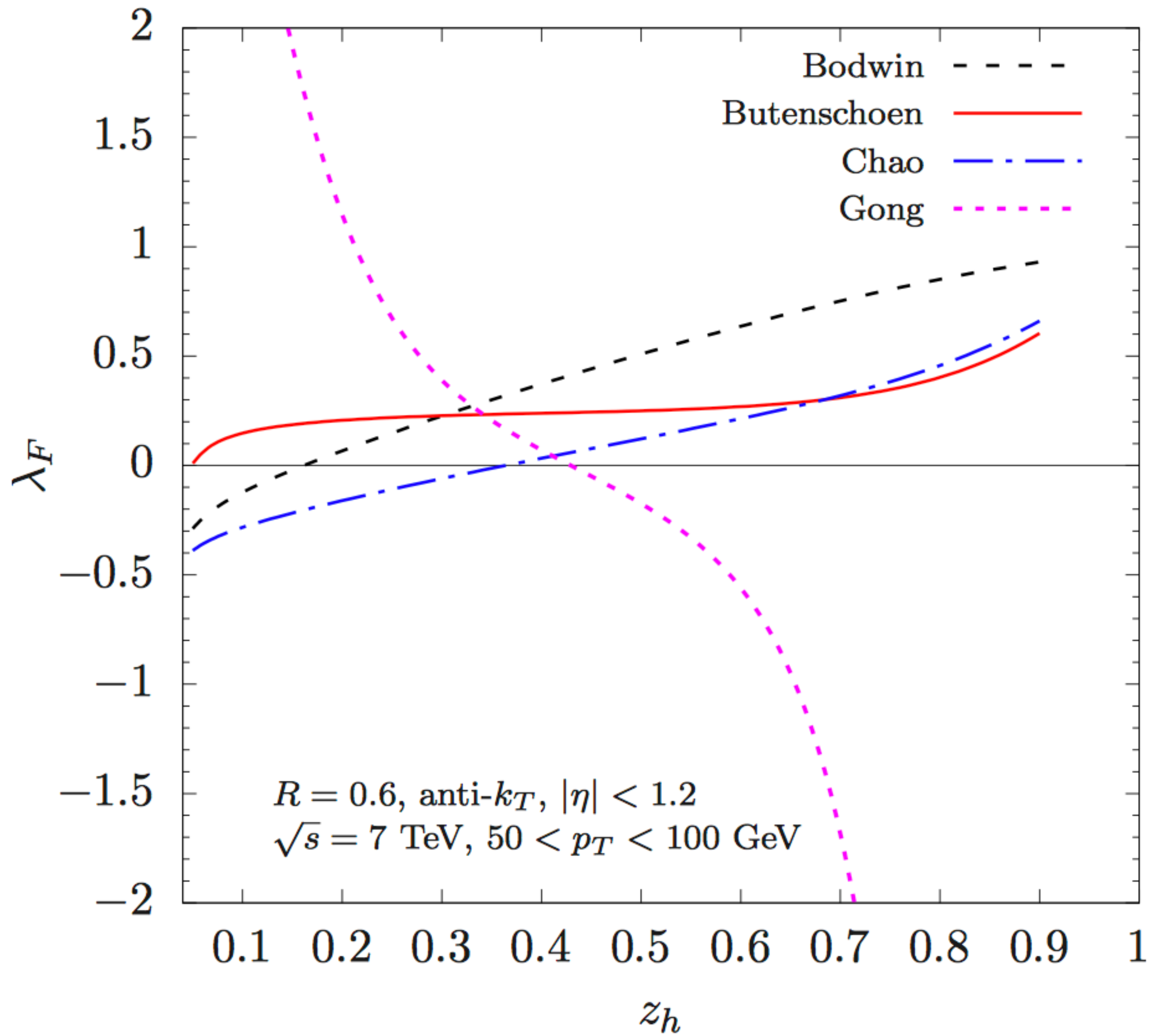

Kang, Qiu, FR, Xing, Zhang `17

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- Collins asymmetries *Kang, Prokudin, FR, Yuan `17*
- Conclusions

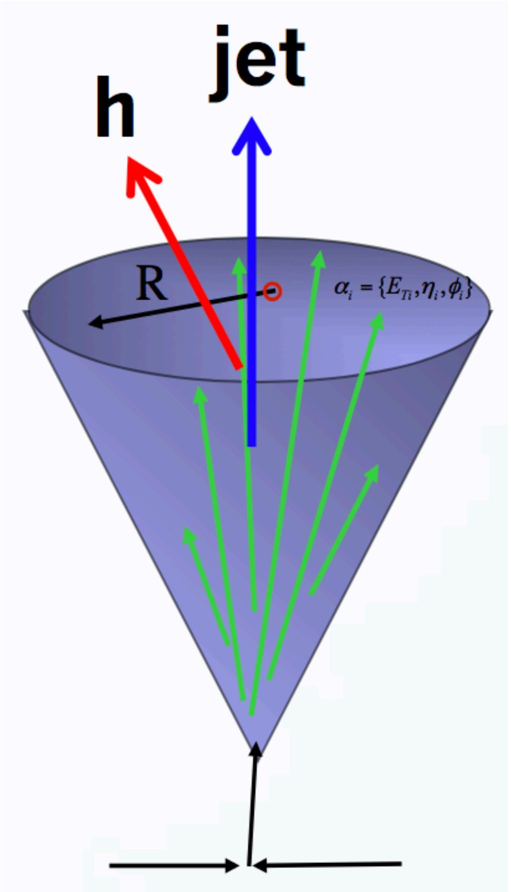
TMD sensitive jet substructure observables

Kang, Liu, FR, Xing `17

- Measure in addition the relative transverse momentum of the hadron wrt. to the (standard) jet axis

$$\frac{d\sigma^{pp\to(\text{jet } h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_a(x_a,\mu)\otimes f_b(x_b,\mu)\otimes H^c_{ab}(x_a,x_b,\eta,p_T/z,\mu)$$

$$\otimes\, \mathcal{G}^h_c(z,z_h,\boldsymbol{j}_\perp,\omega_J,\mu)$$



momentum fraction z_h

transverse momentum $\boldsymbol{j}_\perp$

- Standard jet axis
- Inclusive jet sample
- Relation to usual TMD evolution and fits
- Light charged hadrons

See also: Bain, Makris, Mehen `16
Neill, Scimemi, Waalewijn `17

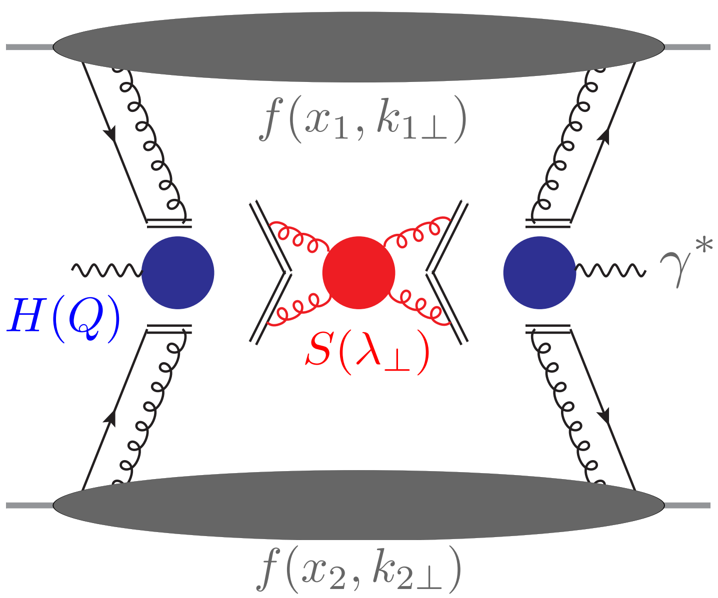
Drell-Yan $pp \to [\gamma^* \to \ell^+\ell^-]X$

Parton model interpretation

$$\frac{d\sigma}{dQ^2 dy d^2\boldsymbol{q}_\perp} \sim \int d^2\boldsymbol{k}_{1\perp}\, d^2\boldsymbol{k}_{2\perp}\, d^2\boldsymbol{\lambda}_\perp\, H(Q)\, f(x_1, \boldsymbol{k}_{1\perp})\, f(x_2, \boldsymbol{k}_{2\perp})\, S(\boldsymbol{\lambda}_\perp)\, \delta^2(\boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp} + \boldsymbol{\lambda}_\perp - \boldsymbol{q}_\perp)$$

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

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



Rapidity divergences cancel in redefined TMD

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

Jet fragmentation function $pp \to (\text{jet} h)X$

Factorization formalism

$$\frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_a(x_a,\mu)\otimes f_b(x_b,\mu)\otimes H^c_{ab}(x_a,x_b,\eta,p_T/z,\mu)\otimes \mathcal{G}^h_c(z,z_h,\boldsymbol{j}_\perp,\omega_J,\mu)$$

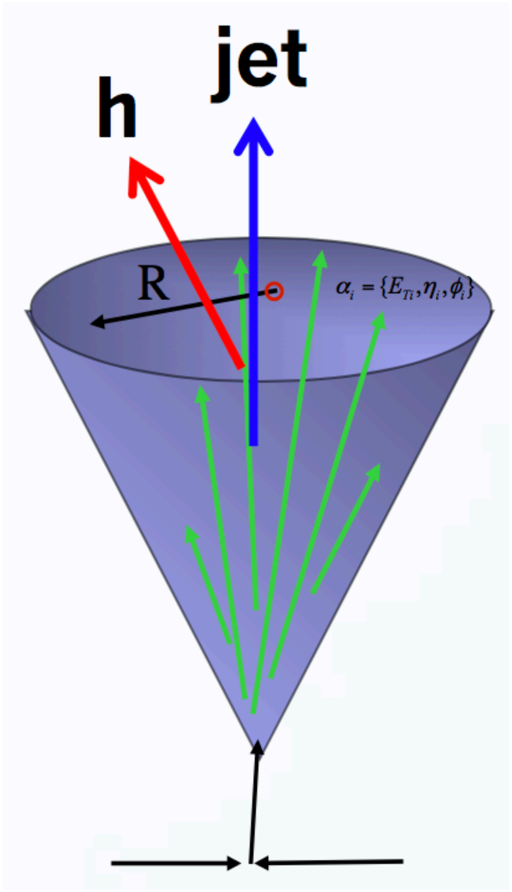
where for $|\boldsymbol{j}_\perp| \ll p_T R$

hard matching function

$$\mathcal{G}^h_c(z,z_h,\boldsymbol{j}_\perp,\omega_J,\mu) = \mathcal{H}_{c\to i}(z,\omega_J,\mu)\int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{\lambda}_\perp\, \delta^2(z_h\boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp)$$

$$\times\, D^h_i(z_h,\boldsymbol{k}_\perp,\mu,\nu)\; S_i(\boldsymbol{\lambda}_\perp,R,\mu,\nu)$$

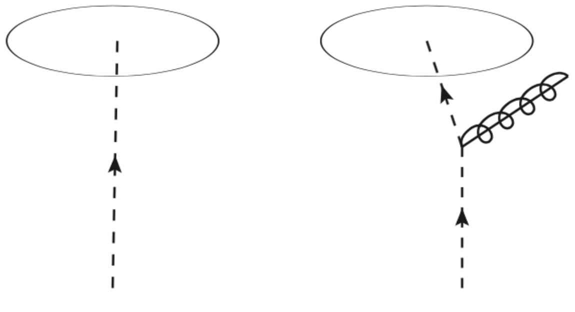
TMD FF — Soft function



Jet fragmentation function $pp \to (\text{jet}h)X$

- Hard matching functions

$$\mathcal{H}_{q\to q'}(z,\omega_J,\mu) = \delta_{qq'}\delta(1-z) + \delta_{qq'}\frac{\alpha_s}{2\pi}\Big[C_F\delta(1-z)\Big(-\frac{L^2}{2} - \frac{3}{2}L + \frac{\pi^2}{12}\Big) + P_{qq}(z)L - 2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ - C_F(1-z)\Big]$$



$$L = \ln\left(\frac{\mu^2}{p_T^2 R^2}\right)$$

- Evolution: modified DGLAP

$$\mu\frac{d}{d\mu}\mathcal{H}_{i\to j}(z,\omega_R,\mu) = \sum_k \int_z^1 \frac{dz'}{z'}\gamma_{ik}\left(\frac{z}{z'}\right)\mathcal{H}_{k\to j}(z',\omega_R,\mu)$$

where $\gamma_{ij}(z) = \delta_{ij}\delta(1-z)\Gamma_i + \frac{\alpha_s}{\pi}P_{ji}(z)$, $\quad \Gamma_q = \frac{\alpha_s}{\pi}C_F\left(-L - \frac{3}{2}\right)$

4 coupled equations with double logarithms. Characteristic scale $\mu_{\mathcal{H}} = p_T R$

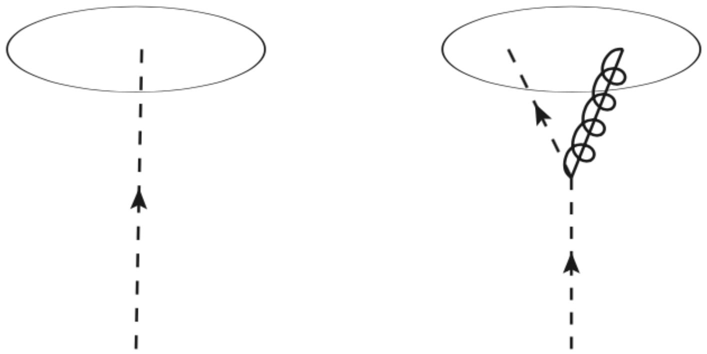
see also: Kang, FR, Waalewijn `17

Jet fragmentation function $pp \to (\text{jet}h)X$

- Rapidity regulator η , scale ν *Chiu, Jain, Neill, Rothstein `12*
- (In-jet) quark TMD

$$D_q^q(z_h, \boldsymbol{k}_\perp, \mu, \nu) = \delta(1-z_h)\delta^2(\boldsymbol{k}_\perp) + \frac{\alpha_s}{2\pi^2} C_F \Gamma(1+\epsilon) e^{\gamma_E \epsilon} \frac{1}{\mu^2}\left(\frac{\mu^2}{\boldsymbol{k}_\perp^2}\right)^{1+\epsilon}$$

$$\times \left[\frac{2z_h}{(1-z_h)^{1+\eta}}\left(\frac{\nu}{\omega_J}\right)^\eta + (1-\epsilon)(1-z_h)\right]$$

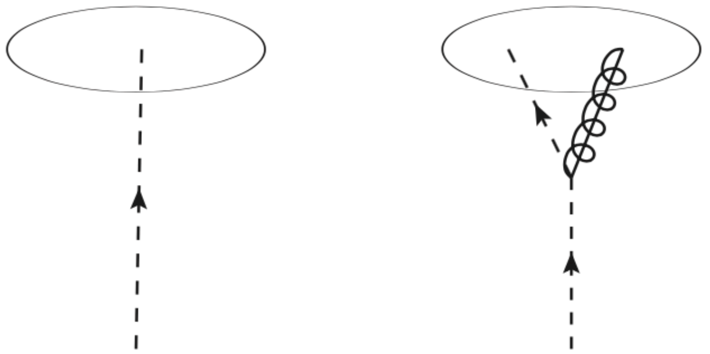


(A) (B)

Jet fragmentation function $pp \to (\mathrm{jet}h)X$

- Rapidity regulator η , scale ν *Chiu, Jain, Neill, Rothstein `12*
- (In-jet) quark TMD

$$D_q^q(z_h, \boldsymbol{k}_\perp, \mu, \nu) = \delta(1-z_h)\delta^2(\boldsymbol{k}_\perp) + \frac{\alpha_s}{2\pi^2} C_F \Gamma(1+\epsilon) e^{\gamma_E \epsilon} \frac{1}{\mu^2} \left(\frac{\mu^2}{\boldsymbol{k}_\perp^2}\right)^{1+\epsilon} \times \left[\frac{2z_h}{(1-z_h)^{1+\eta}} \left(\frac{\nu}{\omega_J}\right)^\eta + (1-\epsilon)(1-z_h)\right]$$



b-space and expansion in $\eta,\ \epsilon$:

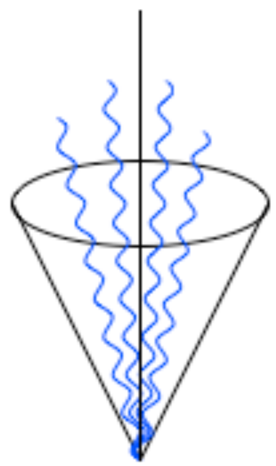
$$\begin{aligned} D_q^q(z_h, \boldsymbol{b}, \mu, \nu) = \frac{1}{z_h^2} \Bigg\{ & \delta(1-z_h) \\ & + \frac{\alpha_s}{2\pi} C_F \left[\frac{2}{\eta}\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{\mu_b^2}\right)\right) + \frac{1}{\epsilon}\left(2\ln\left(\frac{\nu}{\omega_J}\right) + \frac{3}{2}\right)\right] \delta(1-z_h) \\ & + \frac{\alpha_s}{2\pi} C_F \left[-\frac{1}{\epsilon} - \ln\left(\frac{\mu^2}{z_h^2 \mu_b^2}\right)\right] P_{qq}(z_h) \\ & + \frac{\alpha_s}{2\pi} C_F \left[\ln\left(\frac{\mu^2}{\mu_b^2}\right)\left(2\ln\left(\frac{\nu}{\omega_J}\right) + \frac{3}{2}\right)\delta(1-z_h) + (1-z_h)\right] \Bigg\} \end{aligned}$$

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

Jet fragmentation function $pp \to (\text{jet}h)X$

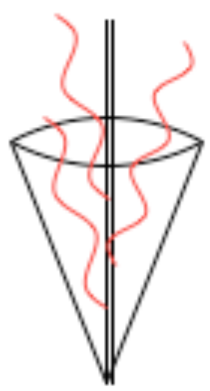
- Rapidity regulator η , scale ν *Chiu, Jain, Neill, Rothstein `12*
- (In-jet) quark TMD

$$D_q^q(z_h, \boldsymbol{b}, \mu, \nu) = \frac{1}{z_h^2}\Big\{\delta(1-z_h)$$
$$+ \frac{\alpha_s}{2\pi}C_F\left[\frac{2}{\eta}\left(\frac{1}{\epsilon}+\ln\left(\frac{\mu^2}{\mu_b^2}\right)\right)+\frac{1}{\epsilon}\left(2\ln\left(\frac{\nu}{\omega_J}\right)+\frac{3}{2}\right)\right]\delta(1-z_h)$$
$$+ \frac{\alpha_s}{2\pi}C_F\left[-\frac{1}{\epsilon}-\ln\left(\frac{\mu^2}{z_h^2\mu_b^2}\right)\right]P_{qq}(z_h)$$
$$+ \frac{\alpha_s}{2\pi}C_F\left[\ln\left(\frac{\mu^2}{\mu_b^2}\right)\left(2\ln\left(\frac{\nu}{\omega_J}\right)+\frac{3}{2}\right)\delta(1-z_h)+(1-z_h)\right]\Big\}$$



- In-jet soft function

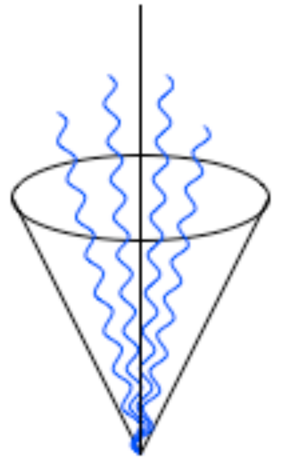
$$S_q(\boldsymbol{b}, R, \mu, \nu) = \int d^2\boldsymbol{\lambda}_\perp e^{-i\boldsymbol{\lambda}_\perp\cdot\boldsymbol{b}}\, S_q(\boldsymbol{\lambda}_\perp, R, \mu, \nu)$$
$$= 1 + \frac{\alpha_s}{2\pi}C_F\left[-\frac{2}{\eta}\left(\frac{1}{\epsilon}+\ln\left(\frac{\mu^2}{\mu_b^2}\right)\right)+\frac{1}{\epsilon^2}-\frac{1}{\epsilon}\ln\left(\frac{\nu^2\tan^2(R/2)}{\mu^2}\right)\right.$$
$$\left.-\ln\left(\frac{\mu^2}{\mu_b^2}\right)\ln\left(\frac{\nu^2\tan^2(R/2)}{\mu_b^2}\right)+\frac{1}{2}\ln^2\left(\frac{\mu^2}{\mu_b^2}\right)-\frac{\pi^2}{12}\right]$$



Jet fragmentation function $pp \to (\mathrm{jet}h)X$

- Rapidity regulator η , scale ν *Chiu, Jain, Neill, Rothstein `12*
- (In-jet) quark TMD

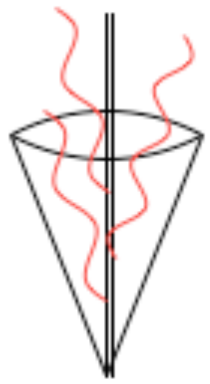
$$D_q^q(z_h, \boldsymbol{b}, \mu, \nu) = \frac{1}{z_h^2}\Bigg\{\delta(1-z_h) + \frac{\alpha_s}{2\pi}C_F\left[\frac{2}{\eta}\left(\frac{1}{\epsilon}+\ln\left(\frac{\mu^2}{\mu_b^2}\right)\right)+\frac{1}{\epsilon}\left(2\ln\left(\frac{\nu}{\omega_J}\right)+\frac{3}{2}\right)\right]\delta(1-z_h) + \frac{\alpha_s}{2\pi}C_F\left[-\frac{1}{\epsilon}-\ln\left(\frac{\mu^2}{z_h^2\mu_b^2}\right)\right]P_{qq}(z_h) + \frac{\alpha_s}{2\pi}C_F\left[\ln\left(\frac{\mu^2}{\mu_b^2}\right)\left(2\ln\left(\frac{\nu}{\omega_J}\right)+\frac{3}{2}\right)\delta(1-z_h)+(1-z_h)\right]\Bigg\}$$



- In-jet soft function

$$S_q(\boldsymbol{b}, R, \mu, \nu) = \int d^2\boldsymbol{\lambda}_\perp e^{-i\boldsymbol{\lambda}_\perp\cdot\boldsymbol{b}}\, S_q(\boldsymbol{\lambda}_\perp, R, \mu, \nu)$$

$$= 1 + \frac{\alpha_s}{2\pi}C_F\left[-\frac{2}{\eta}\left(\frac{1}{\epsilon}+\ln\left(\frac{\mu^2}{\mu_b^2}\right)\right)+\frac{1}{\epsilon^2}-\frac{1}{\epsilon}\ln\left(\frac{\nu^2\tan^2(R/2)}{\mu^2}\right) - \ln\left(\frac{\mu^2}{\mu_b^2}\right)\ln\left(\frac{\nu^2\tan^2(R/2)}{\mu_b^2}\right)+\frac{1}{2}\ln^2\left(\frac{\mu^2}{\mu_b^2}\right)-\frac{\pi^2}{12}\right]$$



Jet fragmentation function $pp \to (\text{jet}h)X$

- Renormalization

$$D_{i,\text{bare}}(z_h, \boldsymbol{b}, \mu, \nu) = Z_i^D(\boldsymbol{b}, \mu, \nu)\, D_{i,\text{ren}}(z_h, \boldsymbol{b}, \mu, \nu)$$

$$S_{i,\text{bare}}(\boldsymbol{b}, R, \mu, \nu) = Z_i^S(\boldsymbol{b}, R, \mu, \nu)\, S_{i,\text{ren}}(\boldsymbol{b}, R, \mu, \nu)$$

- Evolution

$$\mu \frac{d}{d\mu} S_i(\boldsymbol{b}, R, \mu, \nu) = \gamma_{i,\mu}^S(R, \mu, \nu)\, S_i(\boldsymbol{b}, R, \mu, \nu)$$

$$\nu \frac{d}{d\nu} S_i(\boldsymbol{b}, R, \mu, \nu) = \gamma_{i,\nu}^S(\boldsymbol{b}, \mu)\, S_i(\boldsymbol{b}, R, \mu, \nu)$$

$$\mu \frac{d}{d\mu} D_i(z_h, \boldsymbol{b}, \mu, \nu) = \gamma_{i,\mu}^D(\omega_J, \nu)\, D_i(z_h, \boldsymbol{b}, \mu, \nu)$$

$$\nu \frac{d}{d\nu} D_i(z_h, \boldsymbol{b}, \mu, \nu) = \gamma_{i,\nu}^D(\boldsymbol{b}, \mu)\, D_i(z_h, \boldsymbol{b}, \mu, \nu)$$

anomalous dimensions:

$$\gamma_{q,\mu}^S(R, \mu, \nu) = -\frac{\alpha_s}{\pi} C_F \ln\left(\frac{\nu^2 \tan^2(R/2)}{\mu^2}\right)$$

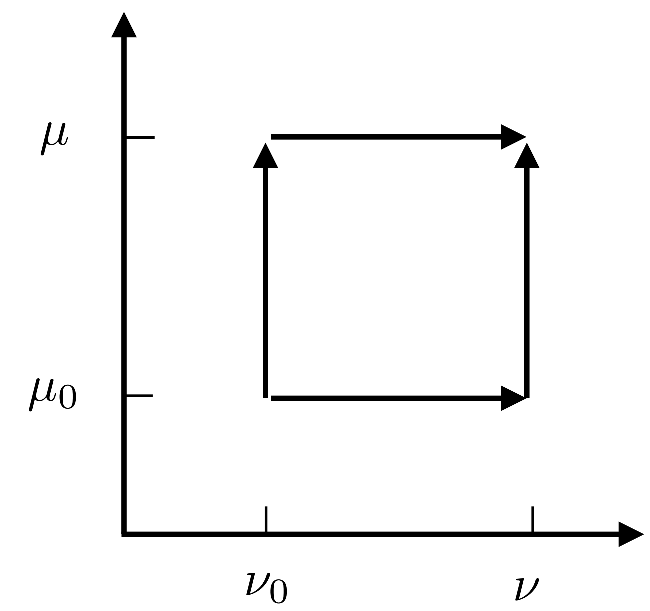
$$\gamma_{q,\nu}^D(\boldsymbol{b}, \mu) = -\gamma_{q,\nu}^S(\boldsymbol{b}, \mu) = \frac{\alpha_s}{\pi} C_F \ln\left(\frac{\mu^2}{\mu_b^2}\right)$$

$$\gamma_{q,\mu}^D(\omega_J, \nu) = \frac{\alpha_s}{\pi} C_F \left[\ln\left(\frac{\nu^2}{\omega_J^2}\right) + \frac{3}{2}\right]$$

Jet fragmentation function $pp \to (\mathrm{jet}h)X$

- Evolution

redefined TMD $\mathcal{D}^R_{h/i}$
and evolution to a common scale



$$\mathcal{D}^R_{h/i}(z_h, \boldsymbol{b}; \mu_b) \equiv D_{h/i}(z_h, \boldsymbol{b}, \mu_D, \nu_D) S_i(\boldsymbol{b}, \mu_S, \nu_S R)$$

$$= \mathcal{D}^R_{h/i}(z_h, \boldsymbol{b}; \mu_b) \exp\left[-\int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'}\left(\Gamma^i_{\mathrm{cusp}} \ln\left(\frac{\mu_J^2}{\mu'^2}\right) + \gamma^i\right)\right]$$

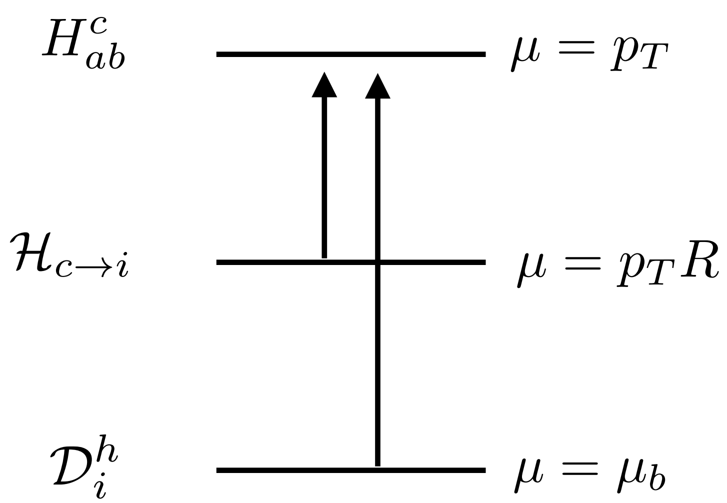
$$= \hat{\mathcal{D}}_{h/i}(z_h, \boldsymbol{b}; \mu_J) \exp\left[-\int_{\mu_J}^{\mu} \frac{d\mu'}{\mu'}\left(\Gamma^i_{\mathrm{cusp}} \ln\left(\frac{\mu_J^2}{\mu'^2}\right) + \gamma^i\right)\right]$$

Collins, Soper, Sterman `85

standard TMD at μ_J — extra evolution factor $\mu_J \to \mu$

Evolution

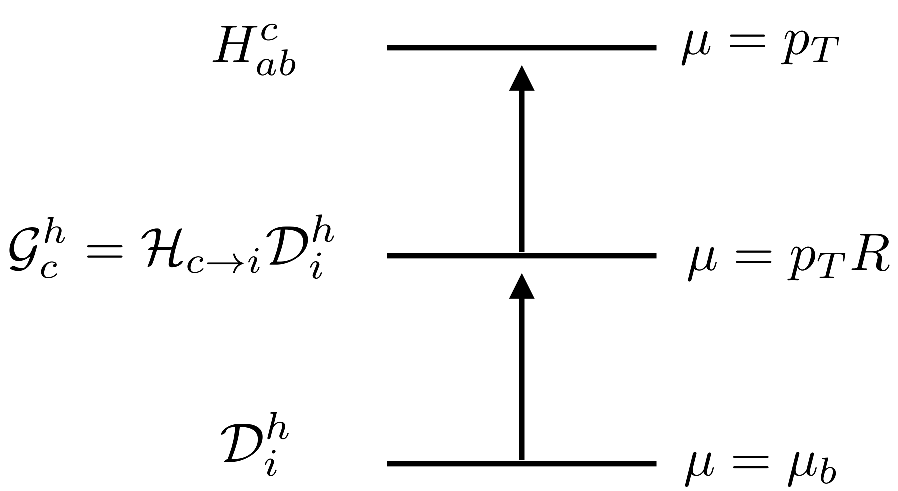
1.



using modified DGLAP for $\mathcal{H}_{c\to i}$

$$\mu \frac{d}{d\mu} \mathcal{H}_{c\to i} = \gamma_{ck} \otimes \mathcal{H}_{ki}$$

2.



using DGLAP for siFJFs $\mathcal{G}_c^h$

$$\mu \frac{d}{d\mu} \mathcal{G}_c^h = P_{ic} \otimes \mathcal{G}_i^h$$

$$\gamma_{ii}^{\Gamma_i} + \gamma_{i,\mu}^S + \gamma_{i,\mu}^D = 0$$

b* prescription

$$\hat{\mathcal{D}}_{h/i}(z_h, \boldsymbol{j}_\perp; \mu_J) = \frac{1}{z_h^2} \int \frac{b\, db}{2\pi} J_0(j_\perp b/z) C_{j\leftarrow i} \otimes D_{h/j}(z_h, \mu_{b_*}) e^{-S^i_{\rm pert}(b_*,\mu_J) - S^i_{\rm NP}(b,\mu_J)}$$

- perturbative Sudakov factor: $S^i_{\rm pert}(b_*, \mu_J) = \int_{\mu_{b_*}}^{\mu_J} \frac{d\mu'}{\mu'} \left(\Gamma^i_{\rm cusp} \ln\left(\frac{\mu_J^2}{\mu'^2}\right) + \gamma^i \right)$

where: $\mu_{b_*} = 2e^{-\gamma_E}/b_*\,,\quad b_* = b/\sqrt{1 + b^2/b^2_{\rm max}}\,,\quad b_{\rm max} < 1/\Lambda_{\rm QCD}$

Collins, Soper, Sterman `85

- non-perturbative Sudakov factor:

quark TMD $\quad S^q_{\rm NP} = g_2 \ln\left(\frac{b}{b_*}\right) \ln\left(\frac{\mu}{\mu_0}\right) + \frac{g_h}{z_h^2} b^2$

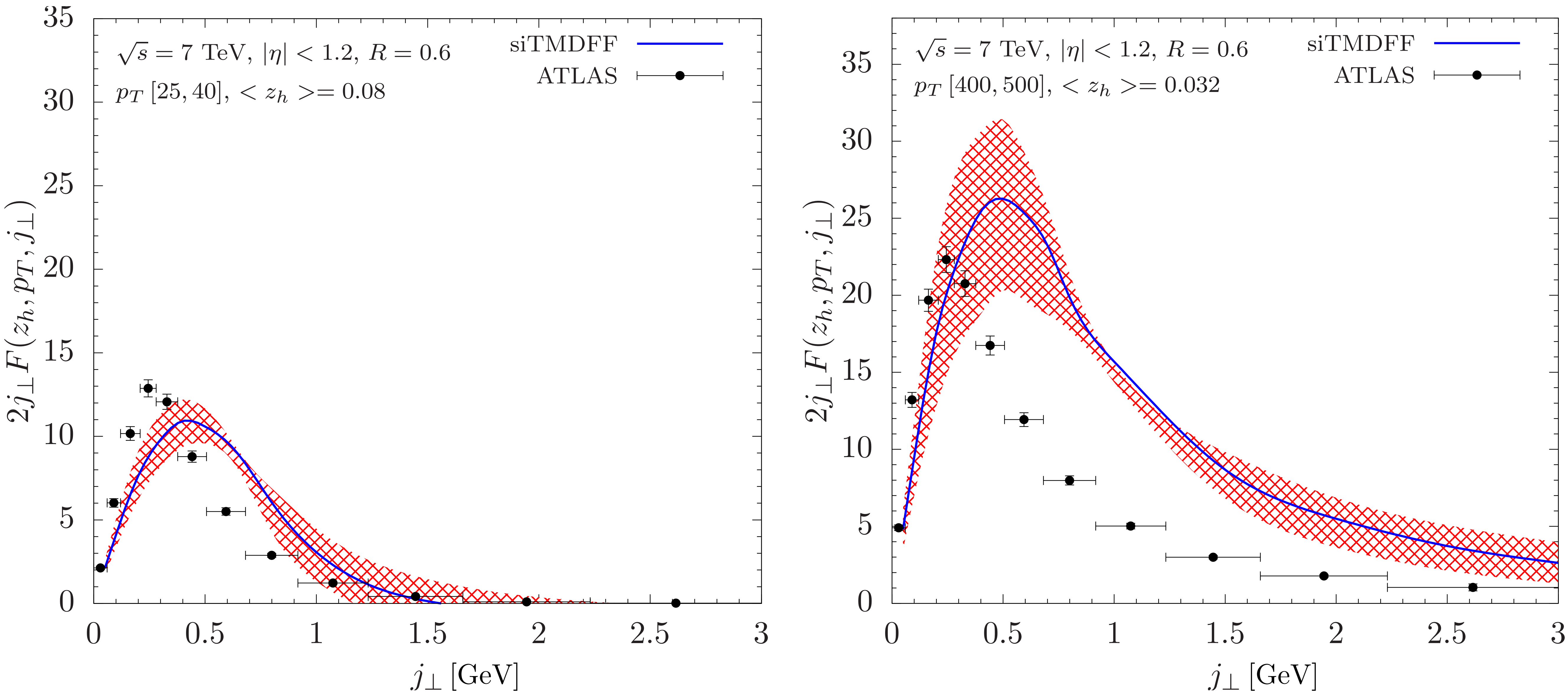
Sun, Isaacson, Yuan, Yuan `14

gluon TMD $\quad S^g_{\rm NP} = \frac{C_A}{C_F} g_2 \ln\left(\frac{b}{b_*}\right) \ln\left(\frac{\mu}{\mu_0}\right) + \frac{g_h}{z_h^2} b^2$

Balazs, Berger, Mrenna, Yuan `14
Balazs, Berger, Nadolsky, Yuan `14

Consistent with the fits of e.g. *Sun, Kang, Prokudin, Yuan `16*

Comparison to ATLAS data

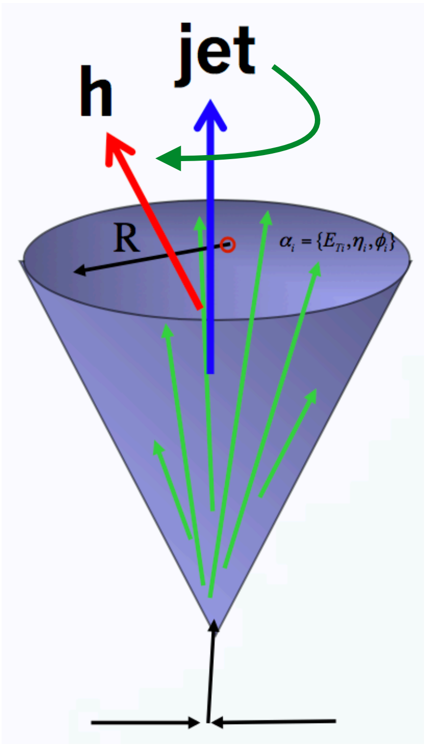


- Varying μ, μ_J by factors of 2
- Gluon contribution dominates at low p_T
- Still need to include NGLs

Outline

- Introduction
- In-jet TMDs *Kang, Liu, FR, Xing `17*
- Collins asymmetries *Kang, Prokudin, FR, Yuan `17*
- Conclusions

Collins azimuthal asymmetries inside jets



- Transversely polarized pp collisions

$$p^{\uparrow}(P_A, S_T, \phi_S) + p(P_B) \to \text{jet}(\eta, p_T)\, h(z_h, j_\perp, \phi_H) + X$$

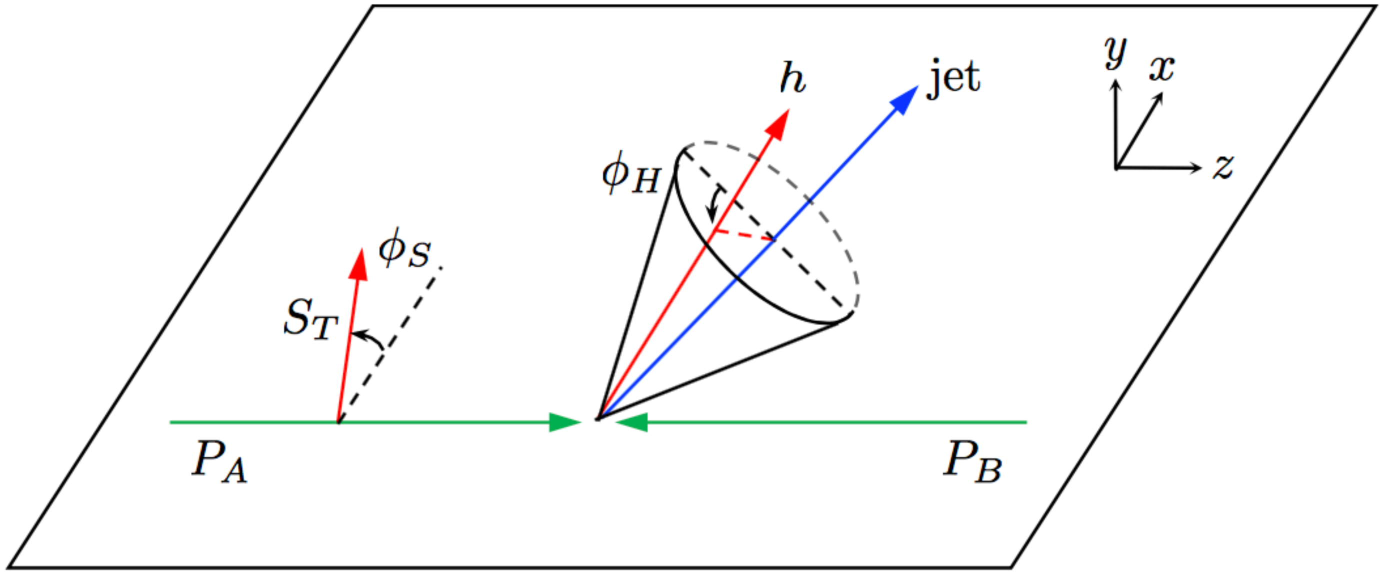
$$\frac{d\sigma}{d\eta d^2p_T dz_h d^2 j_\perp} = F_{UU} + \sin(\phi_S - \phi_H) F_{UT}^{\sin(\phi_S - \phi_H)}$$

- Test of the universality of the Collins FF
  as currently extracted in global fits to SIDIS and electron-positron data
- Test of TMD evolution effects

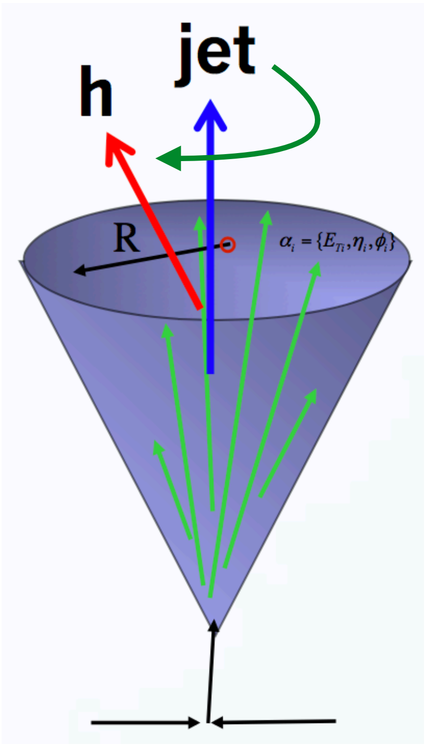
Collins azimuthal spin asymmetry

$$A_{UT}^{\sin(\phi_S-\phi_H)}(z_h, j_\perp; \eta, p_T) = \frac{F_{UT}^{\sin(\phi_S-\phi_H)}}{F_{UU}}$$

Yuan `08



Collins azimuthal asymmetries inside jets



$$A_{UT}^{\sin(\phi_S-\phi_H)}(z_h, j_\perp; \eta, p_T) = \frac{F_{UT}^{\sin(\phi_S-\phi_H)}}{F_{UU}}$$

where

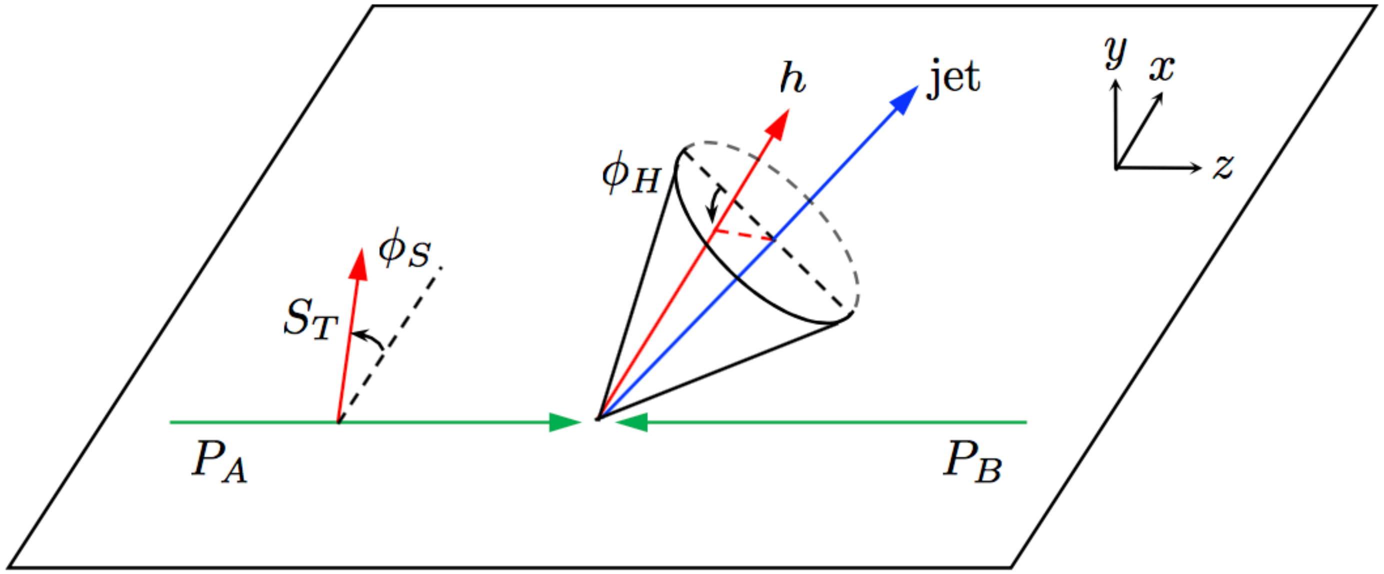
quark transversity distribution

$$F_{UT}^{\sin(\phi_S-\phi_H)}(z_h, j_\perp) = \frac{\alpha_s^2}{s}\sum_{a,b,c}\int_{x_{1\min}}^1 \frac{dx_1}{x_1} h_1^a(x_1,\mu)\int_{x_{2\min}}^1 \frac{dx_2}{x_2} f_{b/B}(x_2,\mu)\frac{j_\perp}{z_h M_h} H_{1\,h/c}^\perp(z_h, j_\perp^2; Q)$$
$$\times H_{ab\to c}^{\text{Collins}}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u})$$

Collins FF

Global fits used for our numerical studies

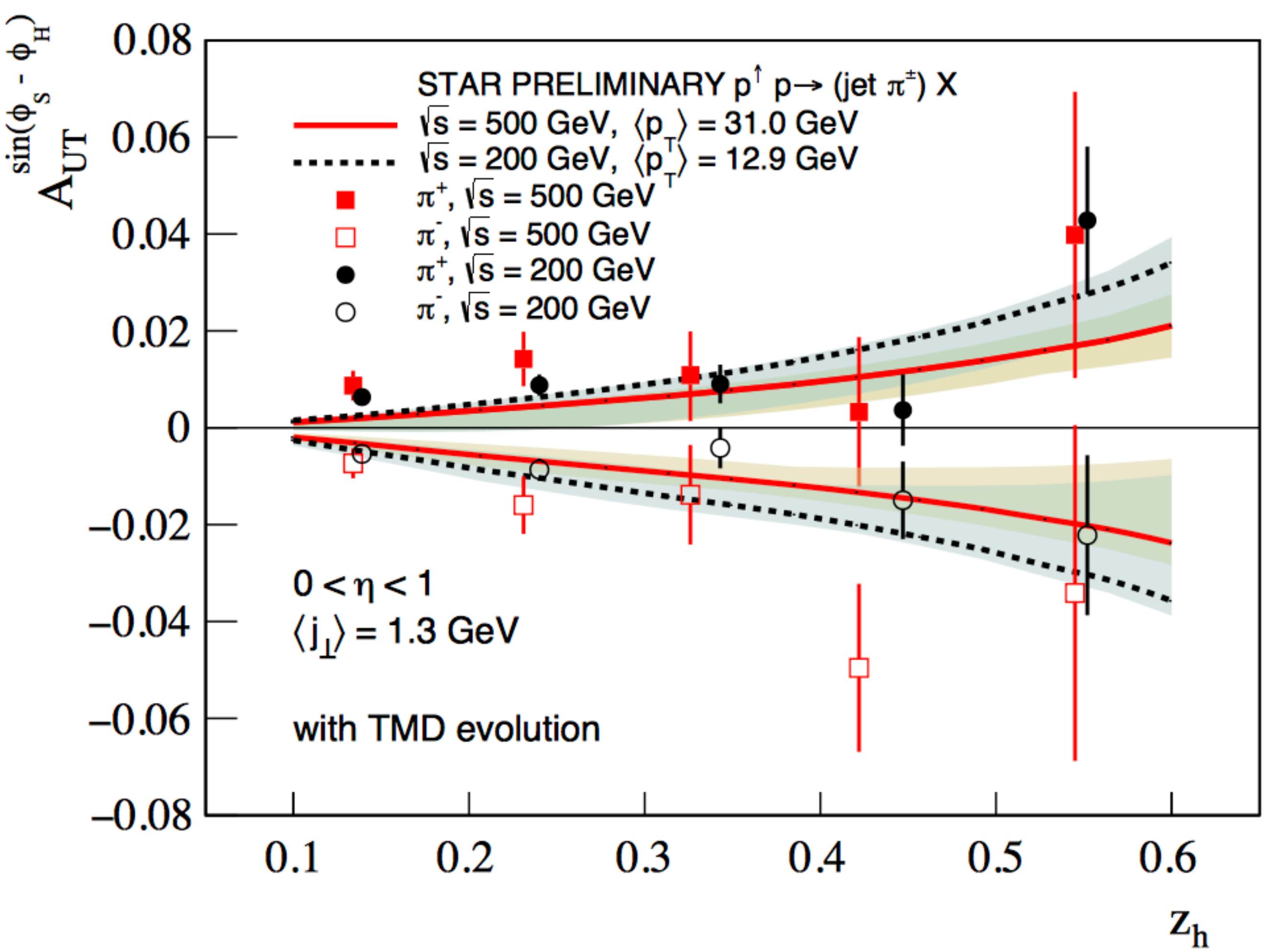
- with TMD evolution *Kang, Prokudin, Sun, Yuan `16*
- without *Anselmino, Boglione, D'Alesio, Hernandez, Melis, Murgia, Prokudin `15*



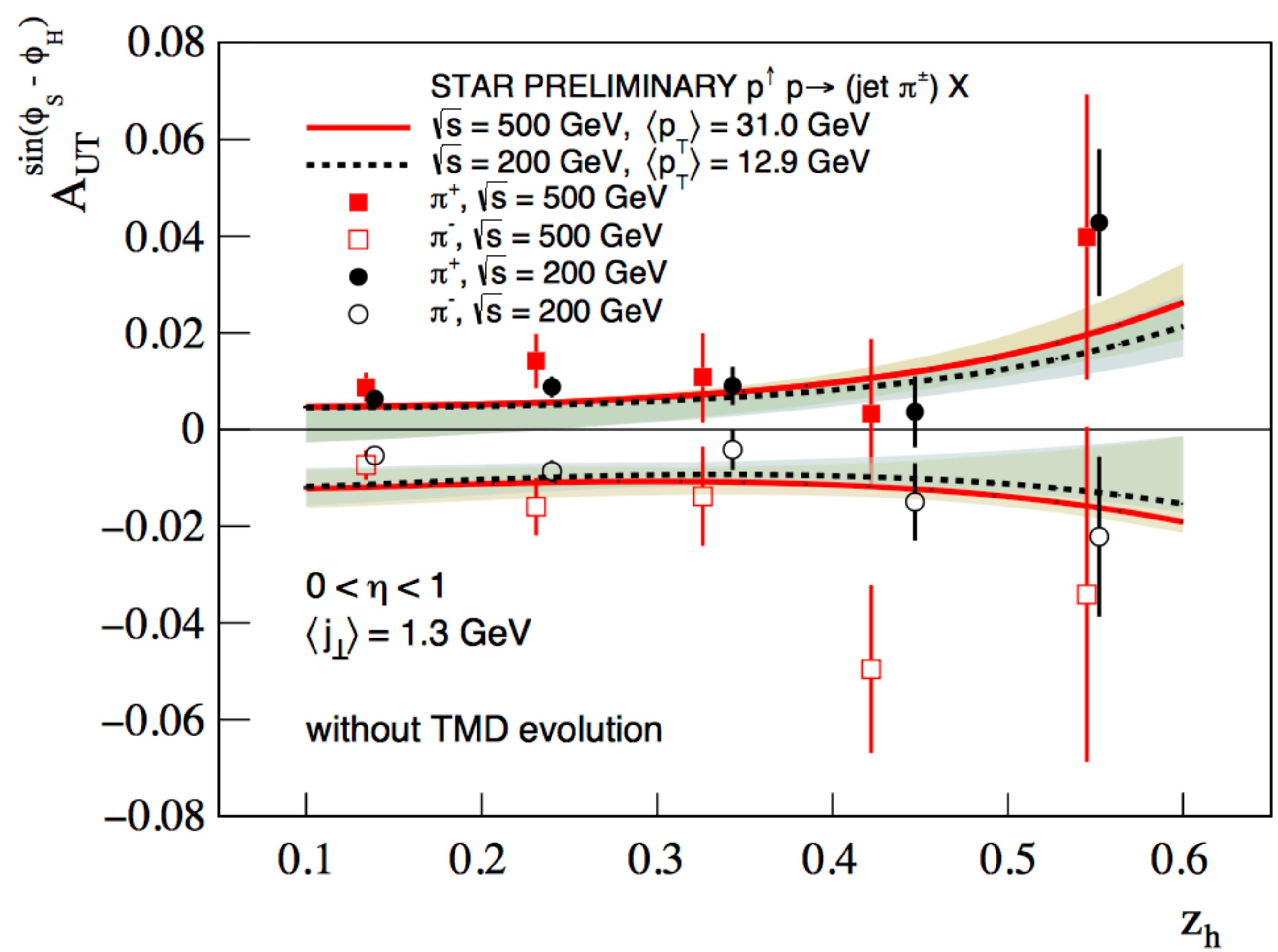
see also: generalized parton model
D'Alesio, Murgia, Pisano `11, `17

Comparison to RHIC data

with TMD evolution



without



$pp \to (\text{jet}\, \pi^{\pm})X$

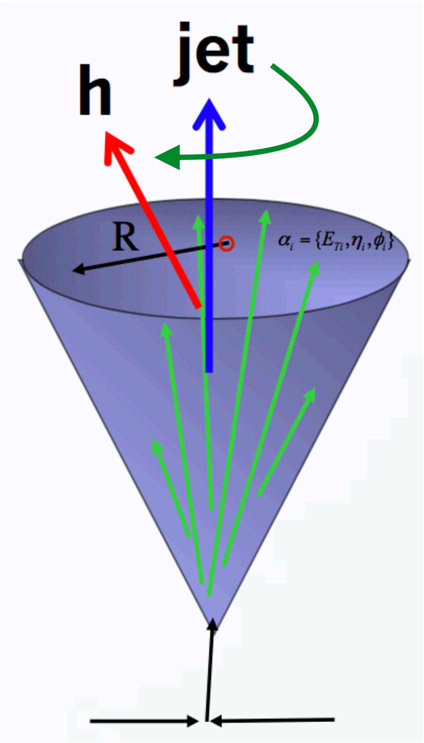
Outline

- Introduction
- In-jet TMDs *Kang, Liu, FR, Xing `17*
- Collins asymmetries *Kang, Prokudin, FR, Yuan `17*
- Conclusions

Conclusions

- Inclusive jets and their substructure
- Identified hadrons within jets:

  light hardrons, photons, open heavy flavor, quarkonia
- TMD FFs within jets



- Y-term, non-global logarithms, global fits
- $e^+e^- \to (\text{jet}h)X$