Fragmentation in Jets

Felix Ringer

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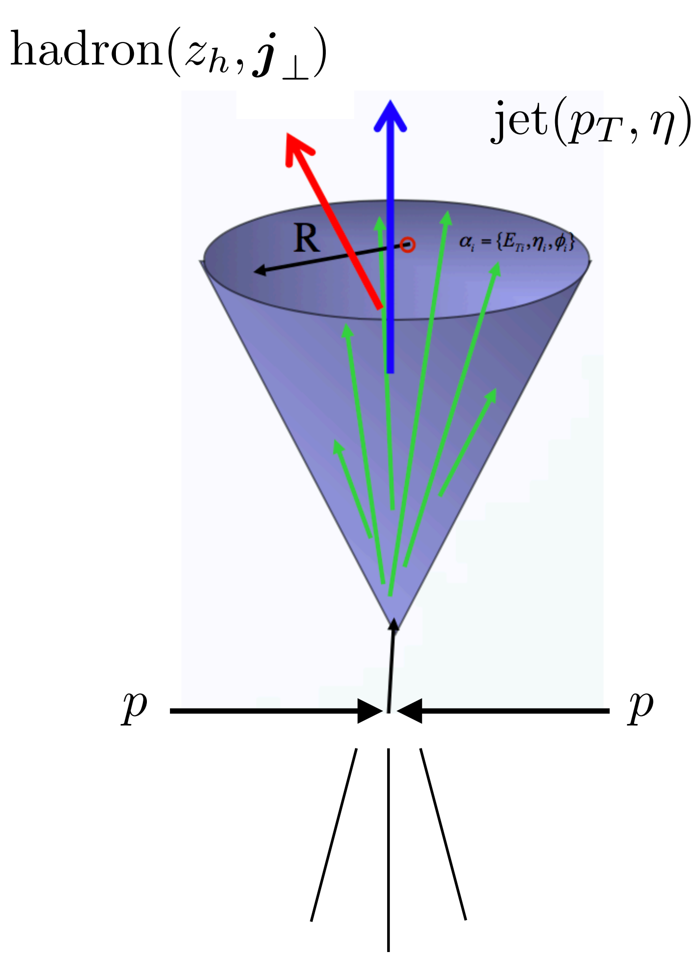
Duke University, 03/15/19

Hadron in jet fragmentation

Inclusive production of jets p_T, η

- Identify the hadrons in the jet and measure additional two variables:
  - Longitudinal momentum fraction $z_h = p_T^h / p_T$
  - Relative transverse momentum wrt. to a predetermined axis $\boldsymbol{j}_\perp$

$$F(z_h, \boldsymbol{j}_\perp; \eta, p_T, R) = \frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} \bigg/ \frac{d\sigma^{pp\to\text{jet}X}}{dp_T d\eta}$$



- Constrain (gluon) fragmentation function
- Test of universality and (TMD) evolution

The longitudinal and transverse structure of jets

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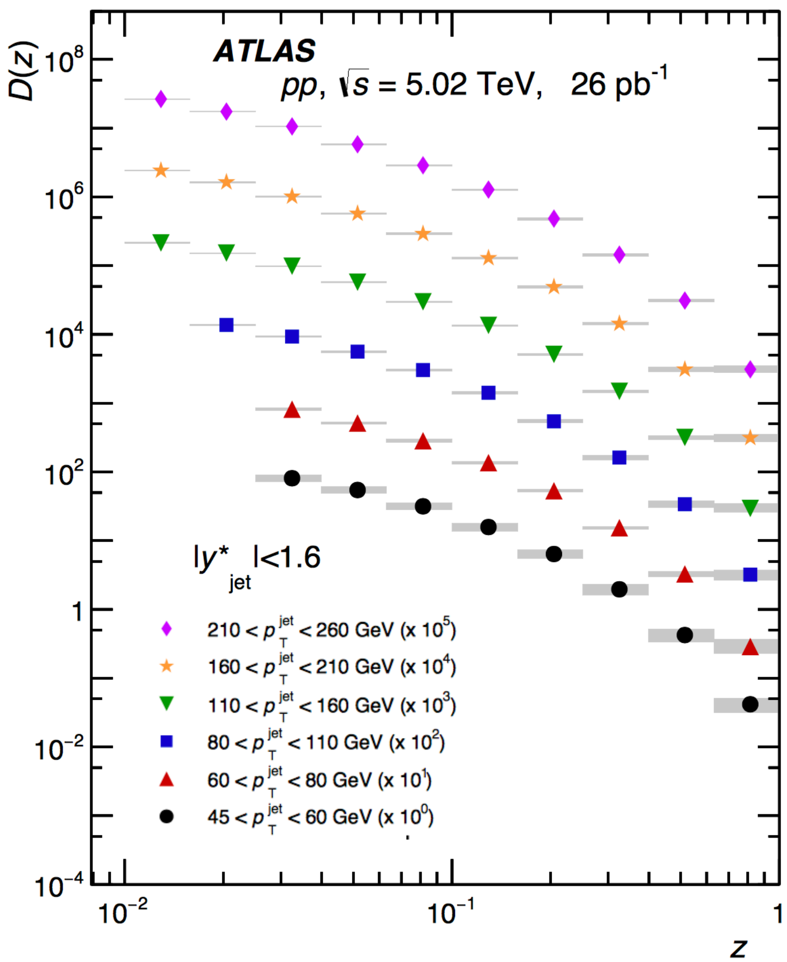
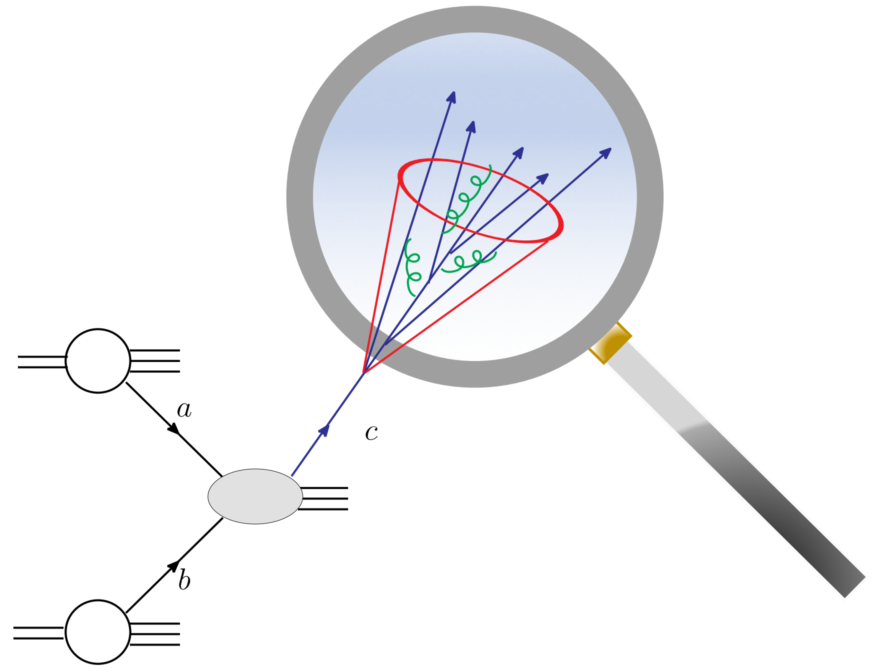
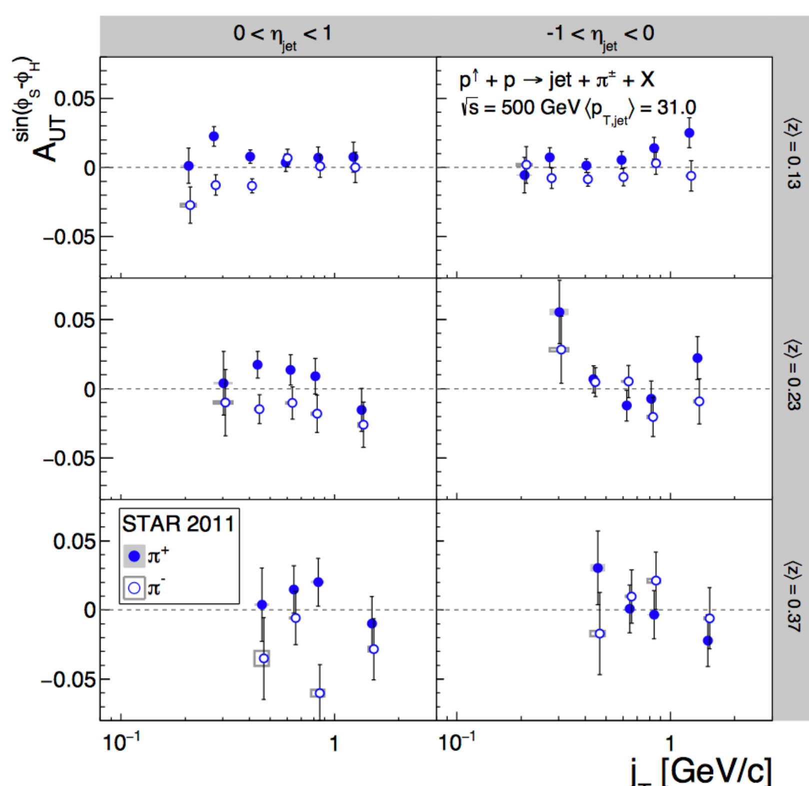
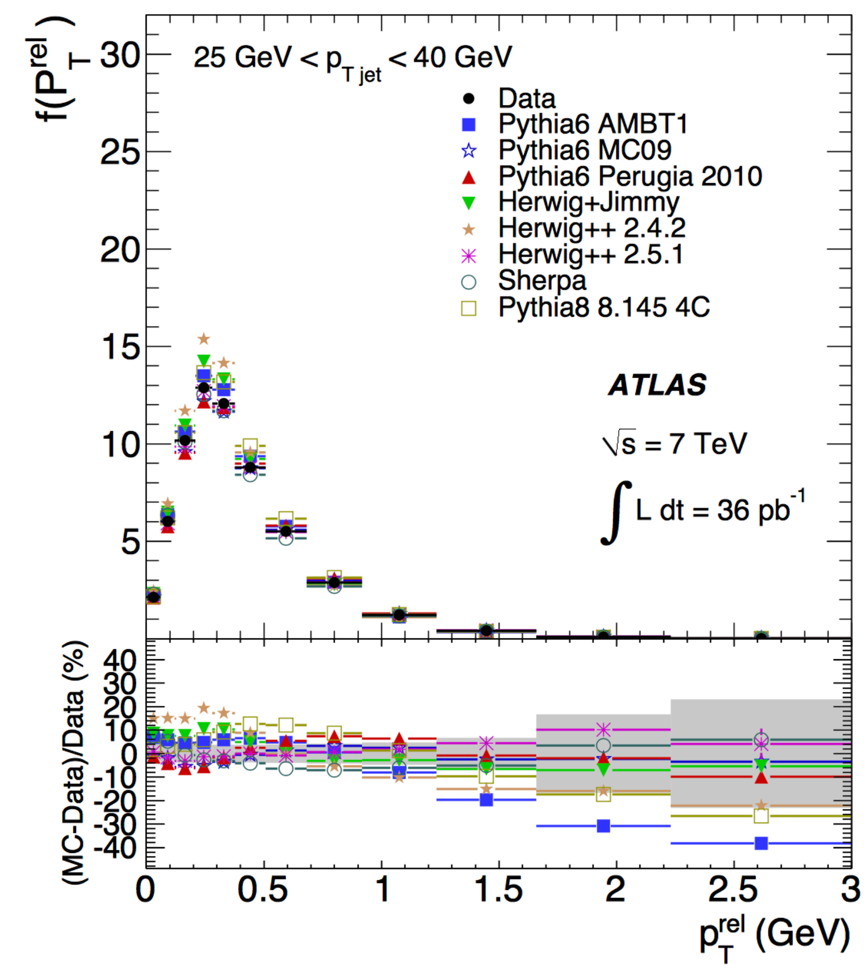






STAR, Phys. Rev. D 97 (2018) 032004

ATLAS, Eur. Phys. J C71 (2011) 1795



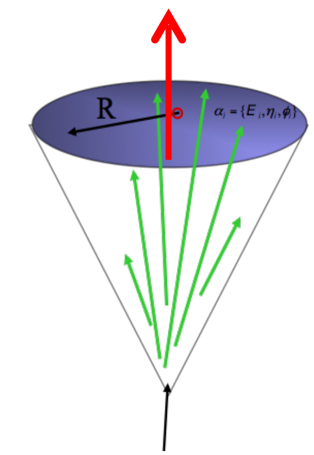
Outline

- Introduction
- Collinear FFs in jets
- TMD FFs in jets
- The jet shape
- Conclusions

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

Kang, FR, Vitev `16

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



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

- Factorization for inclusive jet production

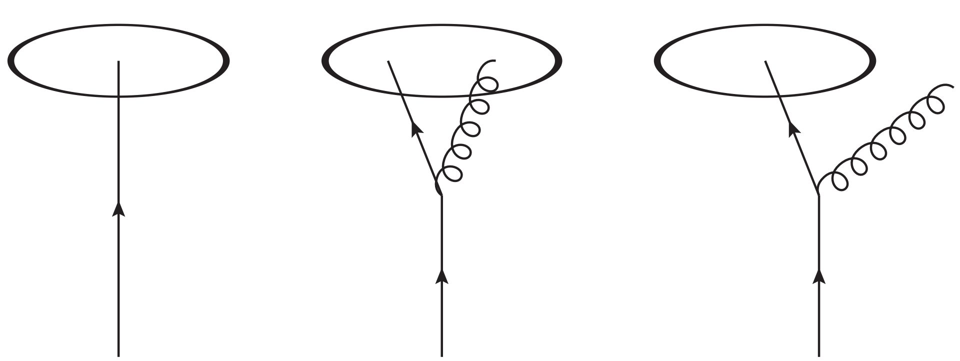
$$\frac{d\sigma^{pp\to(\text{jet }h)+X}}{d\eta dp_T dz_h} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^h$$

where $\quad \mathcal{G}_q^h(z, z_h, p_T R, \mu) = \sum_j \mathcal{J}_{ij}(z, z_h, p_T R, \mu) \otimes D_j^h(z_h, \mu)$

matching coefficients

standard collinear FFs

$z_h \neq 1 \qquad z \neq 1$



see also: Procura, Stewart `10, Jain, Procura, Waalewijn `11, Arleo et al. `14, Kaufmann, Mukherjee, Vogelsang `15

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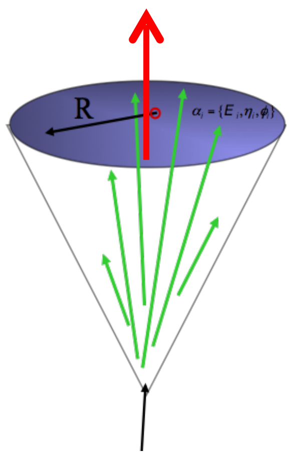

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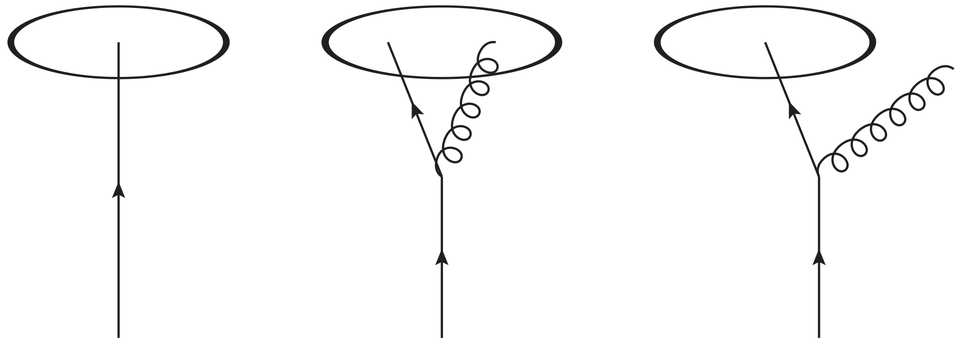
where $$\mathcal{G}_i^h(z, z_h, p_T R, \mu) = \sum_j \mathcal{J}_{ij}(z, z_h, p_T R, \mu) \otimes D_j^h(z_h, \mu)$$

$$= \sum_{jk} j_{ij}(z, p_T R, \mu) \times \tilde{j}_{jk}(z_h, p_T R, \mu) \otimes D_k^h(z_h, \mu) + \mathcal{O}(\alpha_s^2)$$

$z_h \neq 1$ $\qquad$ $z \neq 1$



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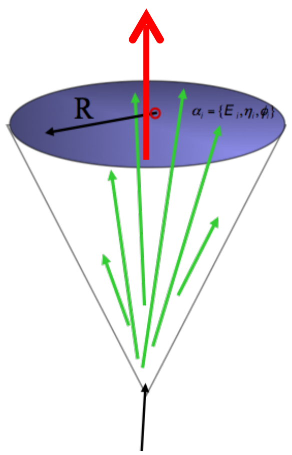


$$\frac{d\sigma^{pp\to(\mathrm{jet}\,h)+X}}{d\eta dp_T dz_h} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^h$$

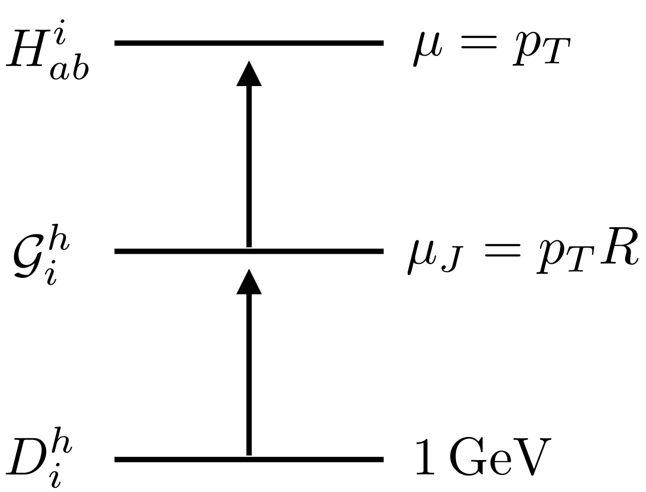
where $$\mathcal{G}_q^h(z, z_h, p_T R, \mu) = \sum_j \mathcal{J}_{ij}(z, z_h, p_T R, \mu) \otimes D_j^h(z_h, \mu)$$

matching coefficients

standard collinear FFs

- $\alpha_s^n \ln^n R$ resummation again via DGLAP

$$\mu \frac{d}{d\mu}\mathcal{G}_i^h(z, z_h, p_T R, \mu) = \sum_j P_{ji}(z) \otimes \mathcal{G}_j^h(z, z_h, p_T R, \mu)$$



2x DGLAP

see also: *Procura, Stewart `10, Jain, Procura, Waalewijn `11, Arleo et al. `14, Kaufmann, Mukherjee, Vogelsang `15*

Phenomenology

- Light charged hadrons

  Arleo, Fontannaz, Guillet, Nguyen `14
  Kaufmann, Mukherjee, Vogelsang `15
  Kang, FR, Vitev `16
  Neill, Scimemi, Waalewijn `16
  Makris, Neill, Vaidya `17

- Heavy flavor mesons

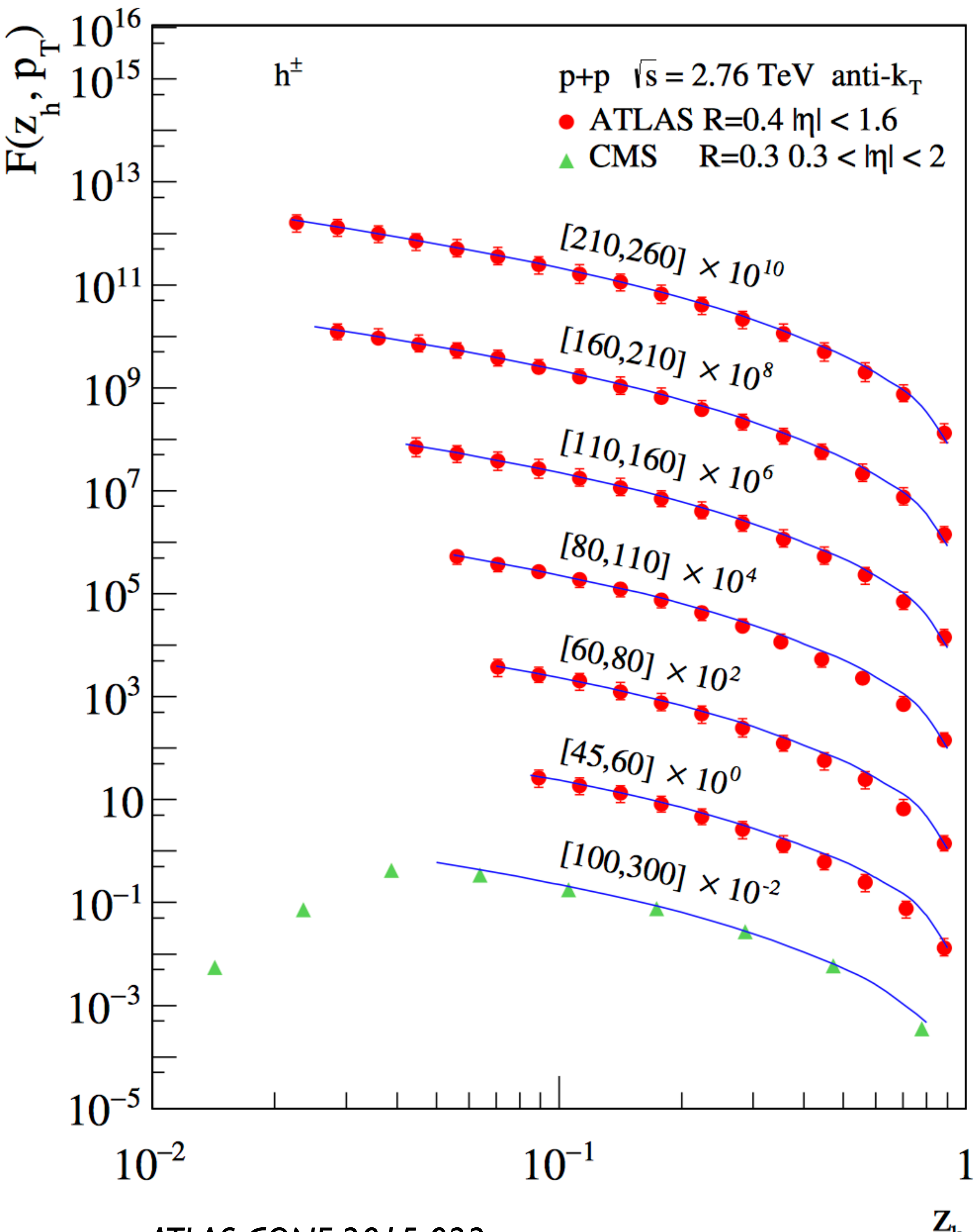
  Chien, Kang, FR, Vitev, Xing `15
  Bain, Dai, Hornig, Leibovich, Makris, Mehen `16
  Anderle, Kaufmann, Stratmann, FR, Vitev `17

- Quarkonia

  Baumgart, Leibovich, Mehen, Rothstein `14
  Bain, Dai, Hornig, Leibovich, Makris, Mehen `16
  Kang, Qiu, FR, Xing, Zhang `17
  Bain, Dai, Leibovich, Makris, Mehen `17

- Photons

  Kaufmann, Mukherjee, Vogelsang `16



ATLAS-CONF-2015-022
CMS, JHEP 10 (2012) 087
Kang, FR, Vitev `16

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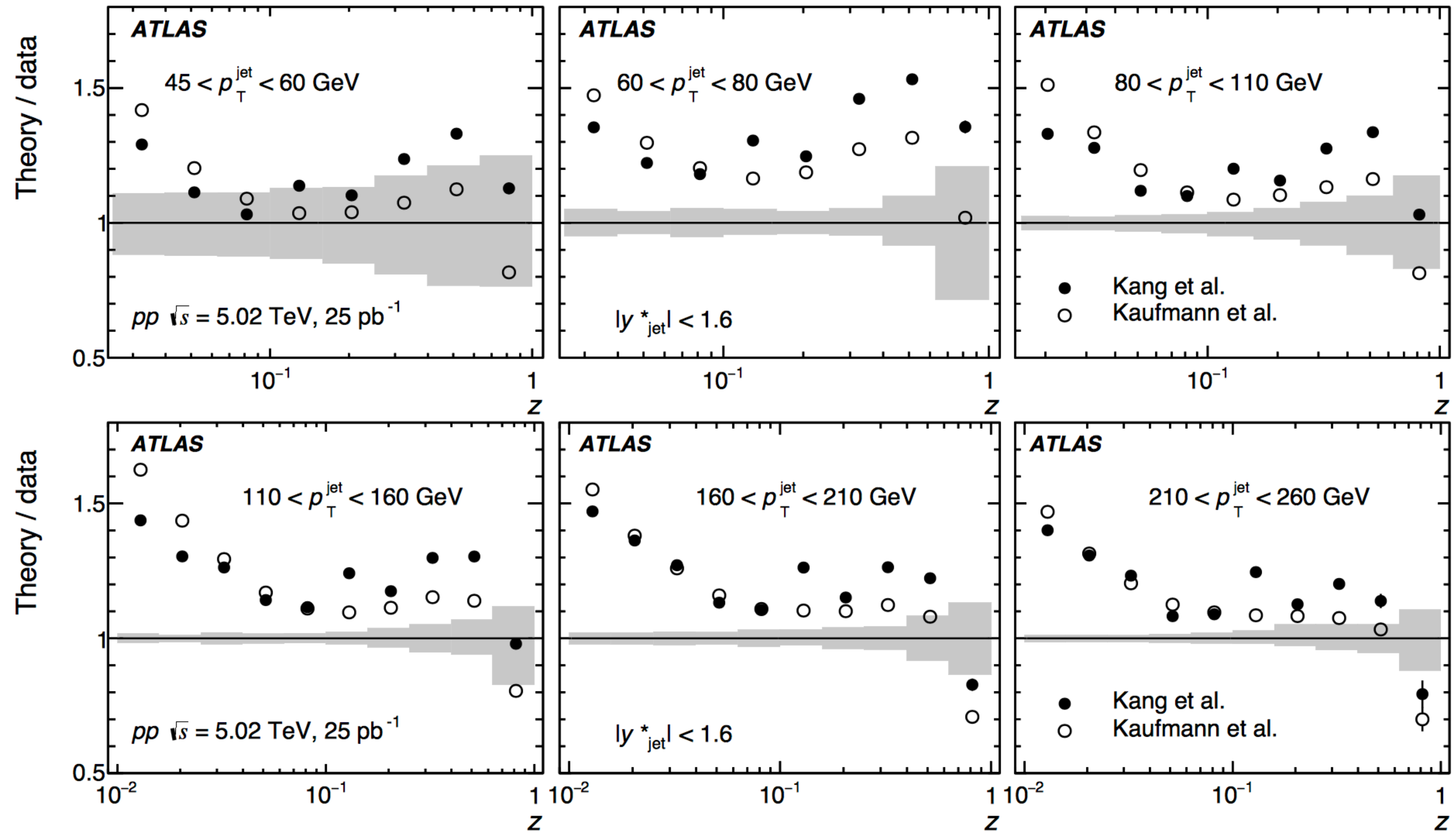

Kaufmann, Mukherjee, Vogelsang `15* *Kang, FR, Vitev `16

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In-jet TMD distributions

- Overview of in-jet TMD distributions with respect to a given axis

Standard jet axis

Bain, Makris, Mehen `16

Kang, Liu, FR, Xing `17

Kang, Lee, Liu, Neill, FR - in preparation

Recoil free axis
e.g. Winner-take-all

Neill, Scimemi, Waalewijn `17

Neill, Papaefstathiou, Waalewijn, Zoppi `18

Standard jet axis

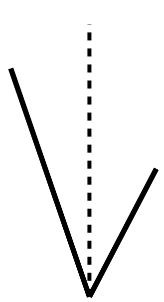
Makris, Neill, Vaidya `17

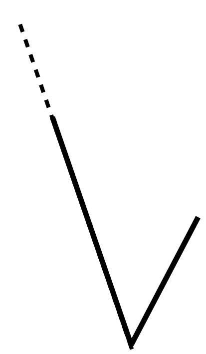
→ *see Yianni's talk*

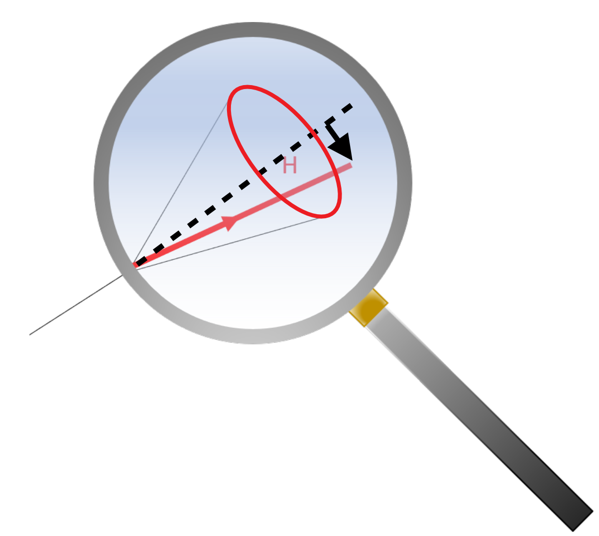
Soft sensitivity,
related to standard TMDs

Collinear factorization only

Grooming (soft drop)







TMD in jet fragmentation

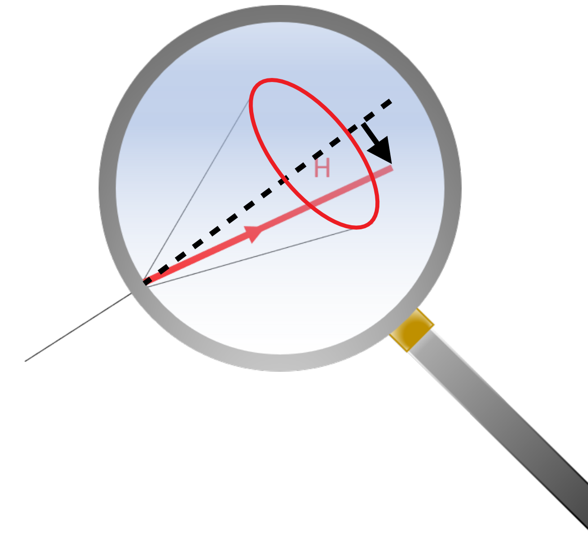
Kang, Liu, FR, Xing `17
Kang, Prokudin, FR, Yuan `17

- Measure the relative transverse momentum of the hadron wrt. to the jet axis

$$F(z_h, \boldsymbol{j}_\perp; \eta, p_T, R) = \frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} \Bigg/ \frac{d\sigma^{pp\to\text{jet}X}}{dp_T d\eta}$$

longitudinal and transverse momentum z_h, $\boldsymbol{j}_\perp$

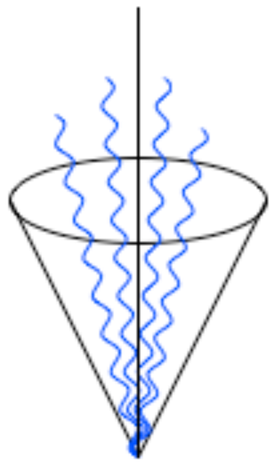
$$0 \ll z_h \ll 1$$



$$\mathcal{G}_c^h(z, z_h, p_T R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, p_T R, \mu) \times D_{h/i}(z_h, \boldsymbol{j}_\perp, \mu) \otimes S_i(\boldsymbol{j}_\perp, R, \mu)$$

Out-of-jet radiation
cf. $j_{ij}(z, p_T R, \mu)$
Jet algorithm dependent

Standard TMD fragmentation functions as for SIDIS and e^+e^-



- Test of universality and TMD evolution
- Azimuthal asymmetries at RHIC - Collins effect → *see James' talk*

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

The soft function

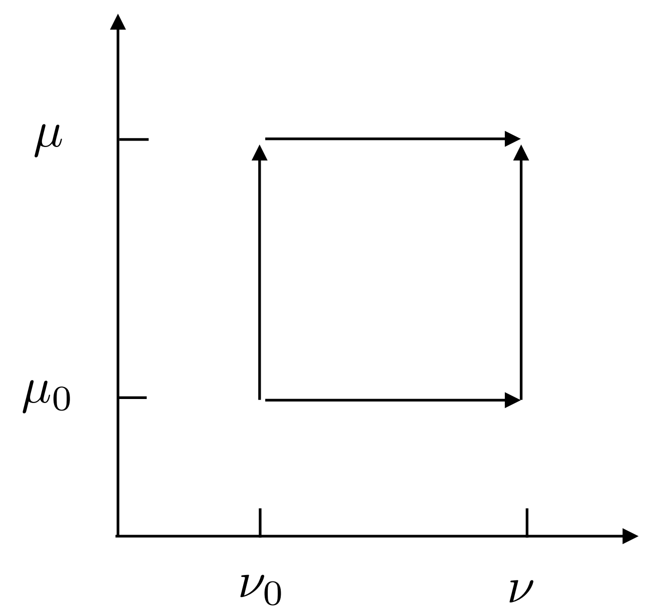
- Global soft function

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

$$\Big\downarrow \times\frac{1}{2},\ \nu \to \nu R\tan(R/2)$$

- Soft function in the jet (b-space):

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



Chiu, Jain, Neill, Rothstein `11

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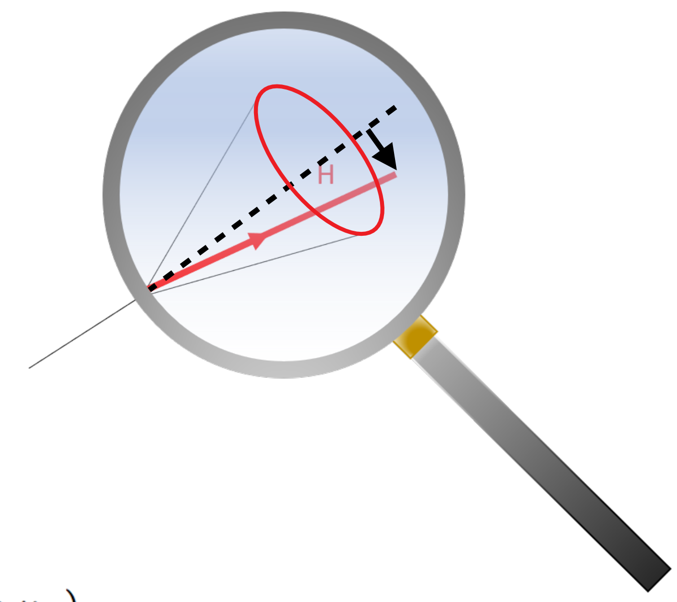
- Proper TMD definition
  - SIDIS and e^+e^-: $\hat{\mathcal{D}}_{h/i}(z_h,\boldsymbol{b};\mu_b) \equiv D_{h/i}(z_h,\boldsymbol{b},\mu_D,\nu_D)\sqrt{\hat{S}_i(\boldsymbol{b},\mu_{\hat{S}},\nu_{\hat{S}})}$
  - In-jet TMD $\mathcal{D}^R_{h/i}(z_h,\boldsymbol{b};\mu_b) \equiv D_{h/i}(z_h,\boldsymbol{b},\mu_D,\nu_D)S_i(\boldsymbol{b},\mu_S,\nu_S R)$

Canceled by evolution of $\mathcal{H}_{c\to i}$

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

TMD in jet fragmentation

$$\mathcal{G}_c^h(z, z_h, p_T R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, p_T R, \mu) \times D_{h/i}(z_h, \boldsymbol{j}_\perp, \mu) \otimes S_i(\boldsymbol{j}_\perp, R, \mu)$$



- Proper TMD evaluated at the jet scale

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

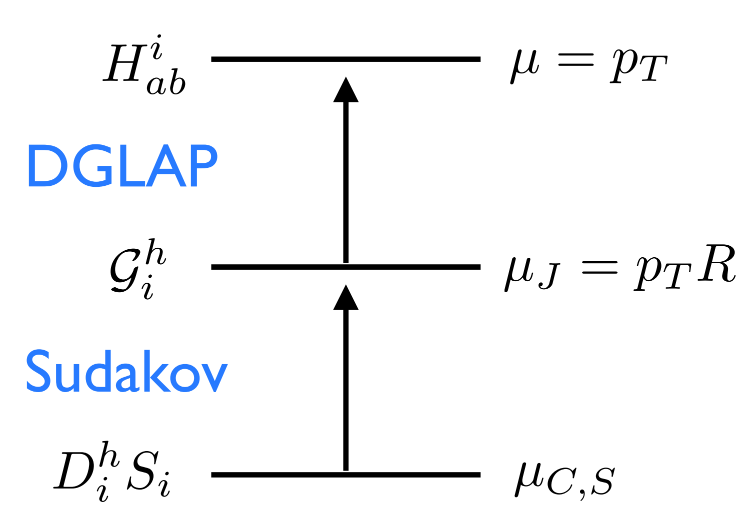
- The usual perturbative Sudakov factor

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

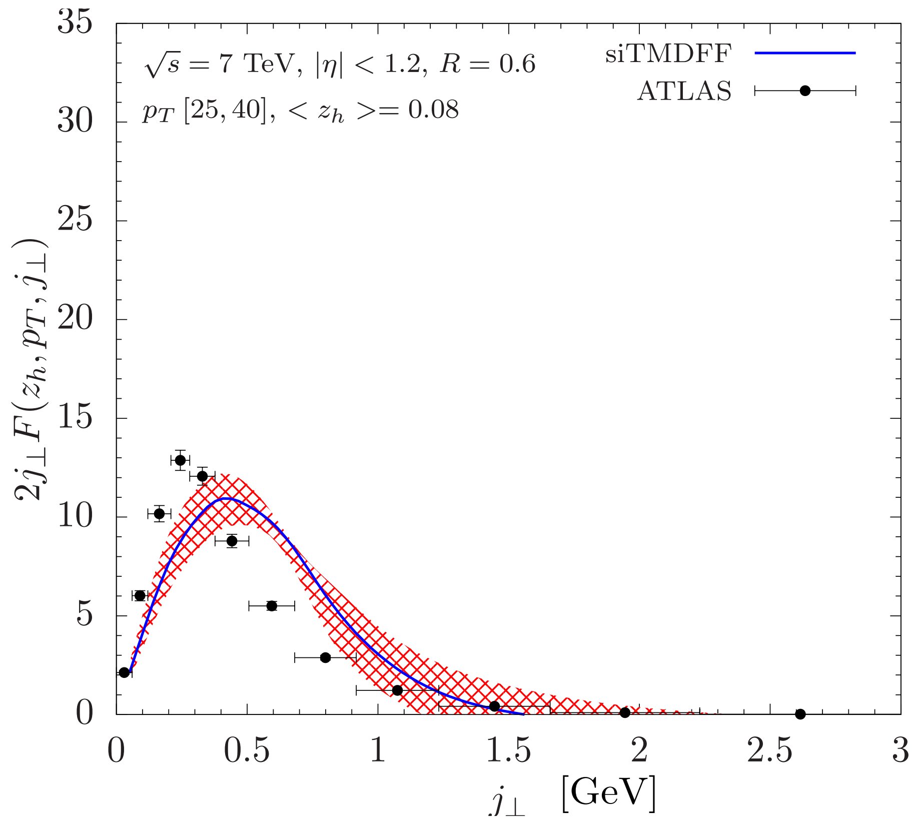
Collins, Soper, Sterman `85

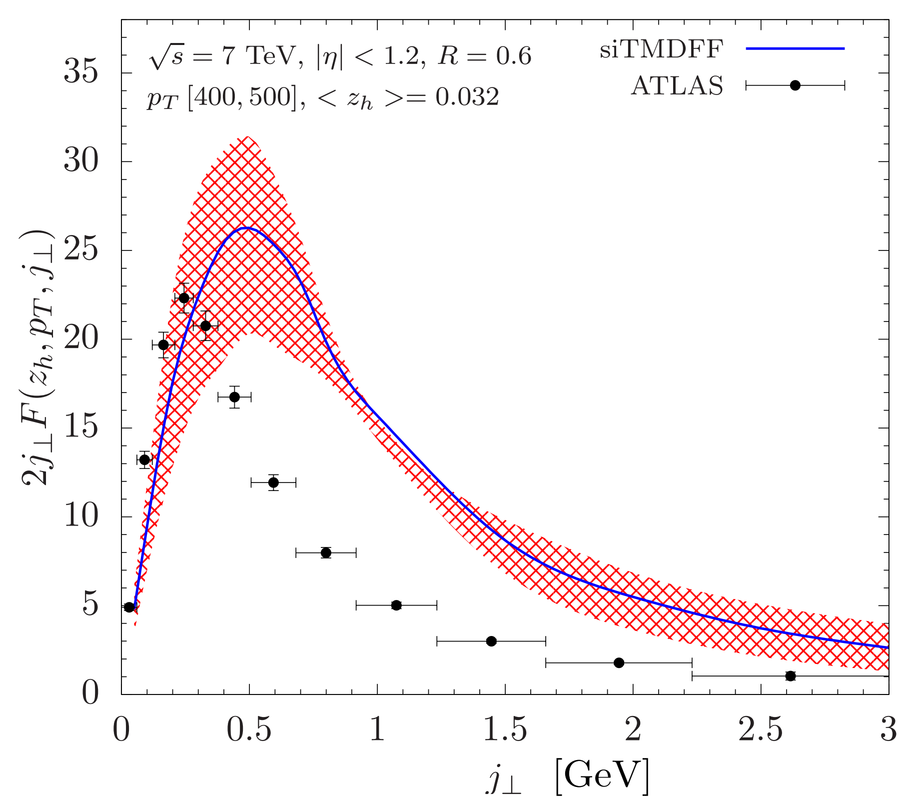
- Non-perturbative input from *Sun, Isaacson, Yuan, Yuan `14*

RG evolution



Comparison to ATLAS data





ATLAS, Eur. Phys. J C71 (2011) 1795

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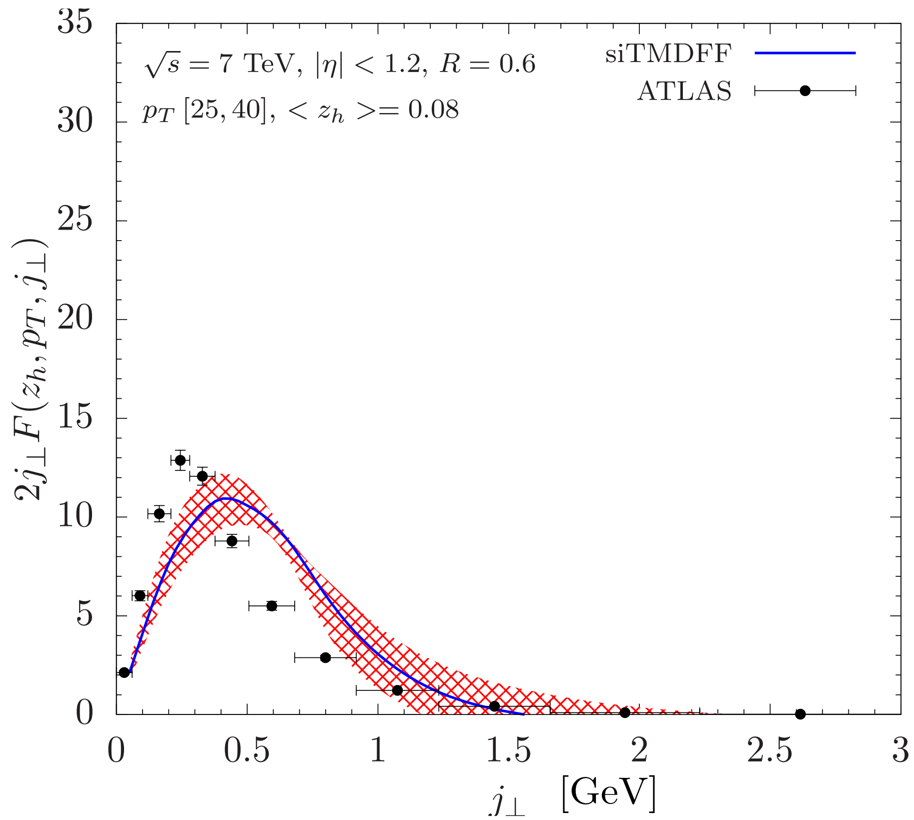

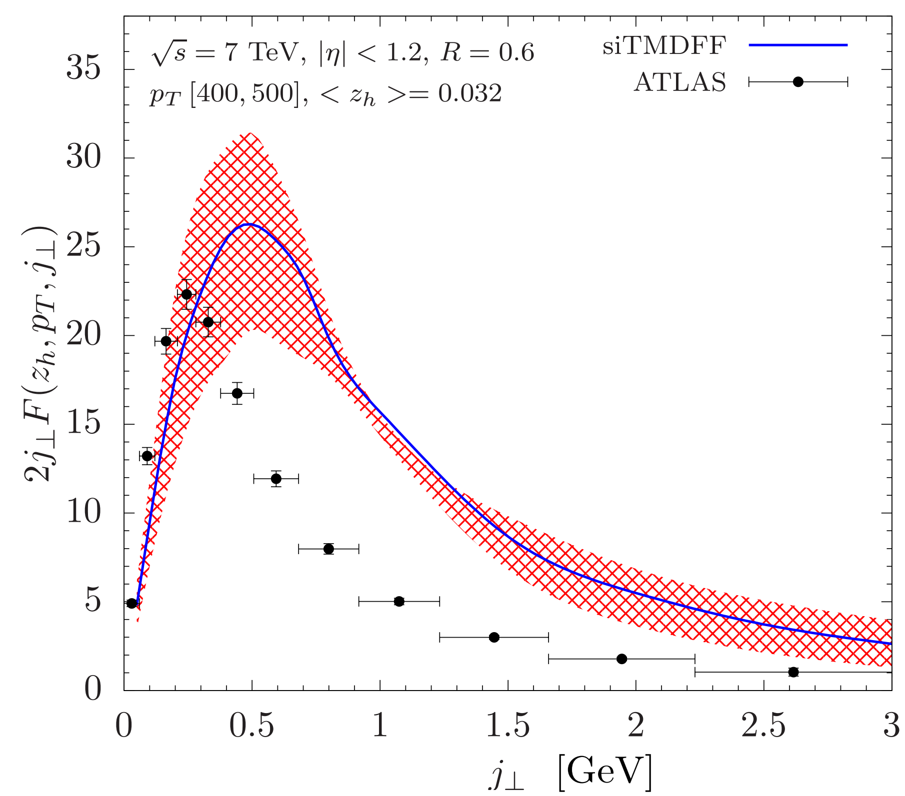

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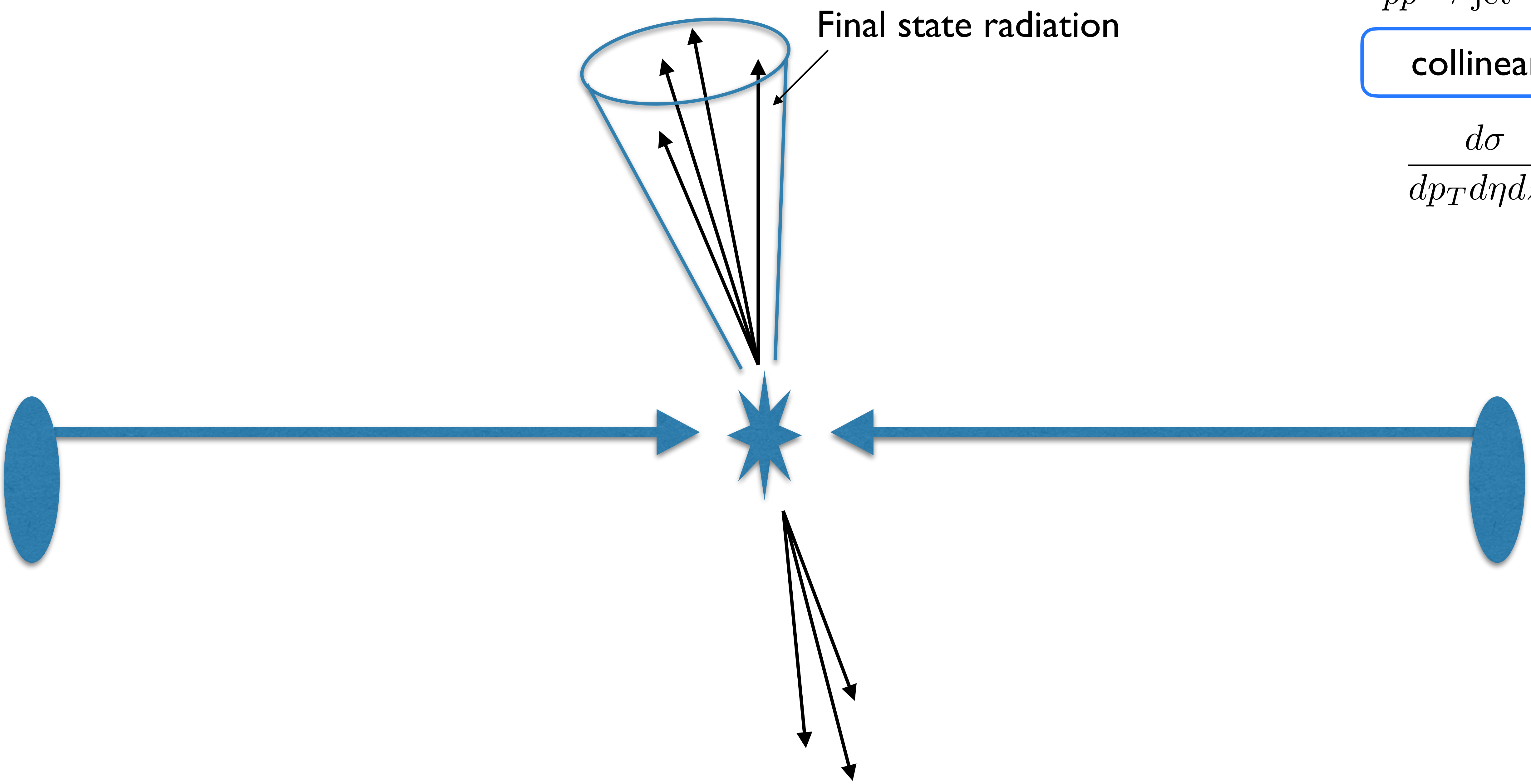
Where is the discrepancy coming from?

- z_h range of the ATLAS data $0 < z_h < 1$
- Underlying event, initial state radiation $\longrightarrow$ effective grooming $z_h > z_h^{\rm cut}$
- Matching at large $j_\perp$
- NLL $\longrightarrow$ NNLL accuracy *see Lee, Liu, Kang, FR `18*
- Non-global logarithms
- Fit of the nonperturbative component

$pp \to \mathrm{jet} + X$

$\boxed{\text{collinear}}$

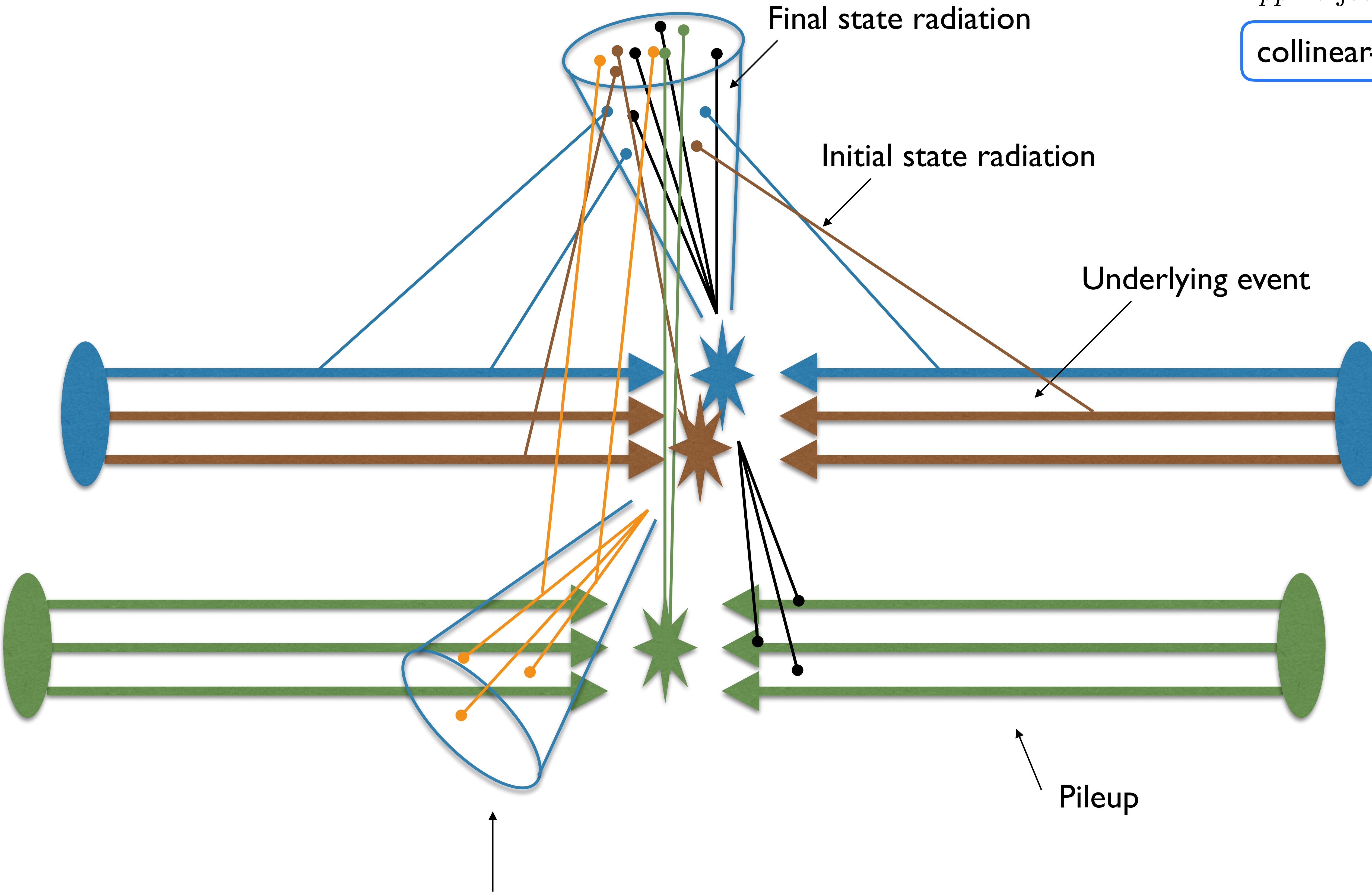
$$\frac{d\sigma}{dp_T d\eta dz_h}$$



adapted from M. Schwartz `17

$pp \to \text{jet} + X$

collinear-soft



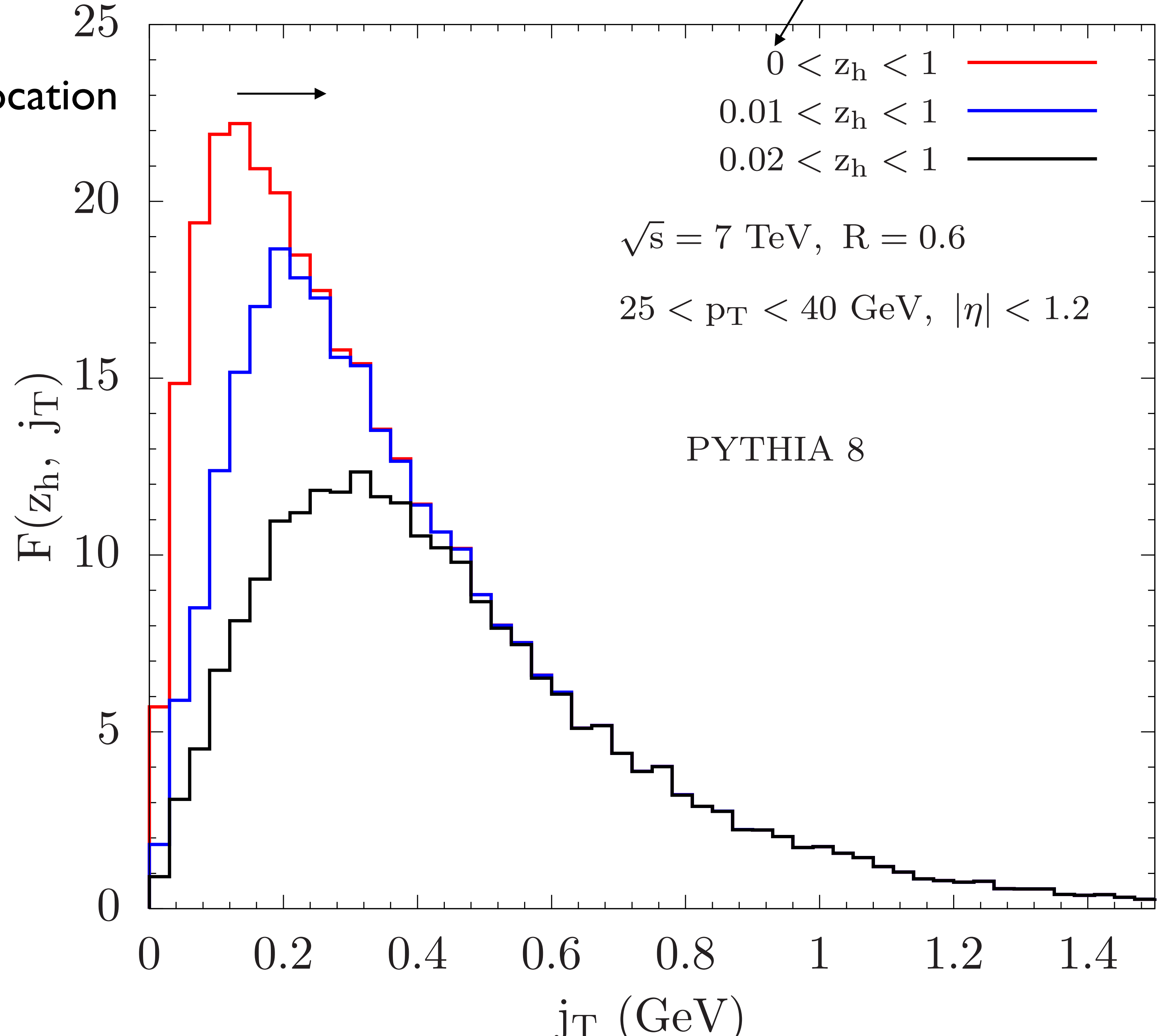
see Jet Shape results

adapted from M. Schwartz `17

Dependence on the longitudinal momentum fraction

Different $z_h^{\rm cut}$

Shift of the peak location



Preliminary

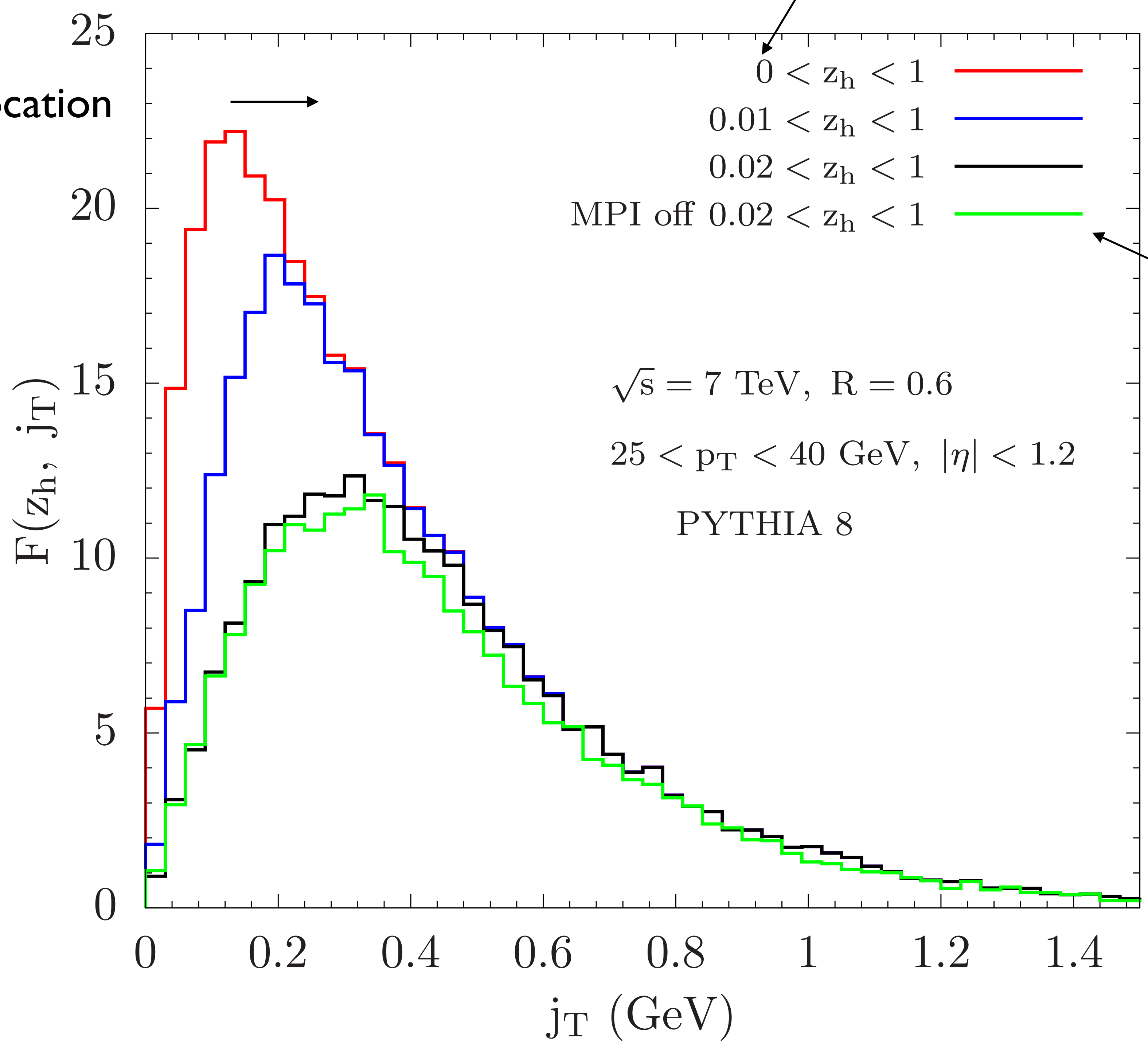
Effectively grooming the jet like trimming

Krohn, Thaler, Wang `10

Dependence on the longitudinal momentum fraction

Different z_h^{cut}

Shift of the peak location



Almost no sensitivity to the underlying event for $z_h^{\text{cut}} = 0.02$

Preliminary

Non-global logarithms

Dasgupta, Salam `01,
Banfi, Marchesini, Smye `02
Larkoski, Moult, Neill `15
Becher, Rahn, Shao `17 …

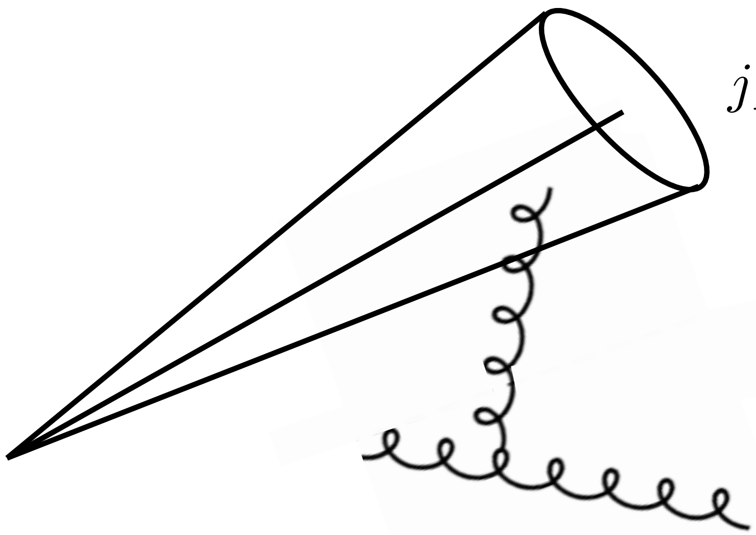
- $pp \to \mathrm{jet} + X$ at small jet radii
  Banfi, Dasgupta `04

  $\alpha_s^2 \ln^2(j_\perp/(p_T R))$ contribution obtained in the strongly ordered limit

- Include higher order corrections $\alpha_s^n \ln^n(j_\perp/(p_T R))$
  Leading logarithmic, leading color accuracy

  - Monte-Carlo *Dasgupta, Salam `01*
  - BMS equation *Banfi, Marchesini, Smye `02*
  - Fixed order expansions *Schwartz, Zhu `14*
  - Beyond leading color *Hatta, Ueda `13*

$$d\sigma = \sum_{abcd} f_a \; f_b \; H_{ab}^c \; \mathcal{H}_{cd} \; \hat{\mathcal{D}}_d \times S_{d,\mathrm{NGL}}$$



boosted version of the e^+e^- hemisphere jet mass case
Dasgupta, Salam `01

Non-global logarithms

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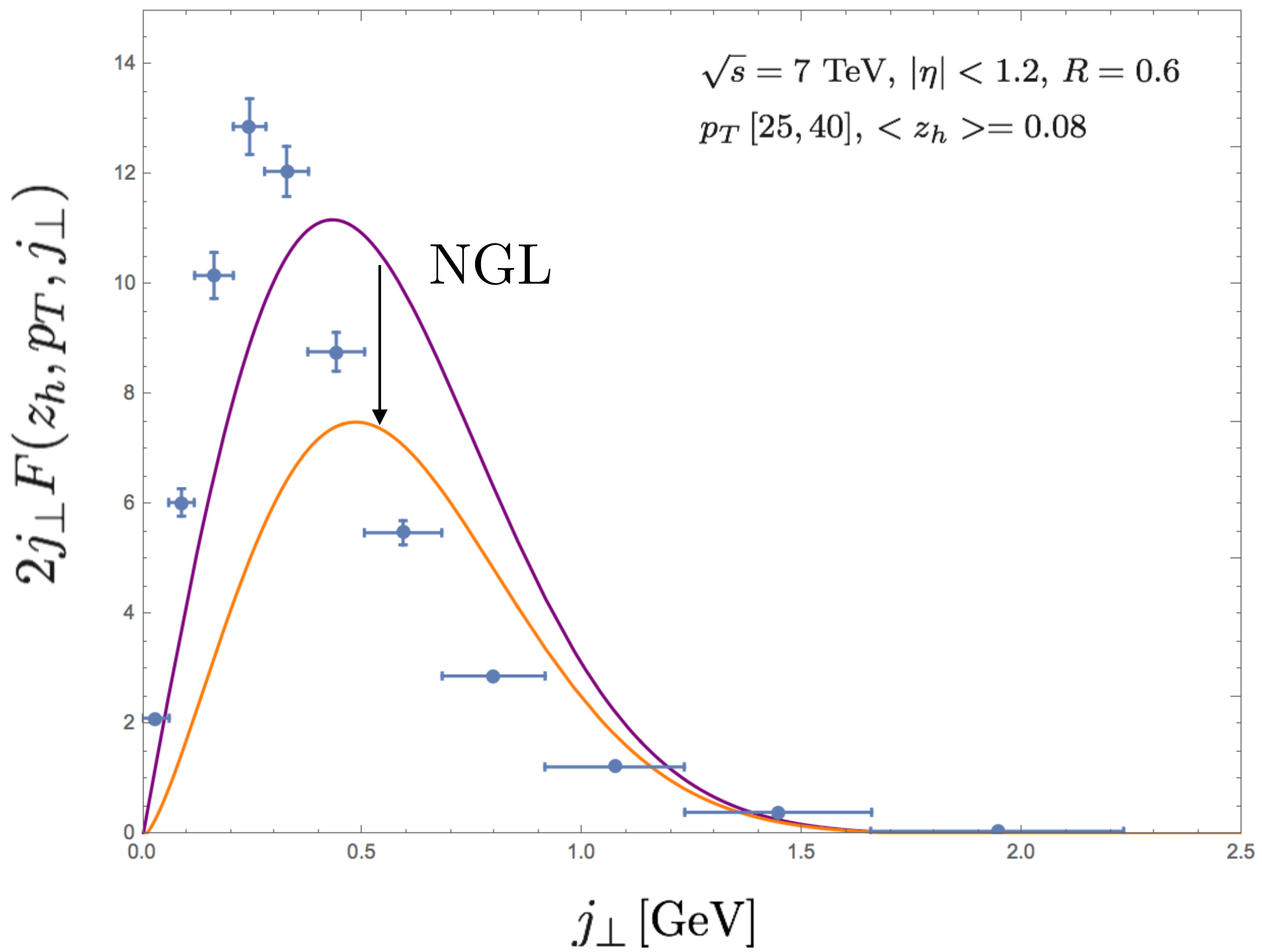

- NGL Monte-Carlo
  Dasgupta, Salam `01

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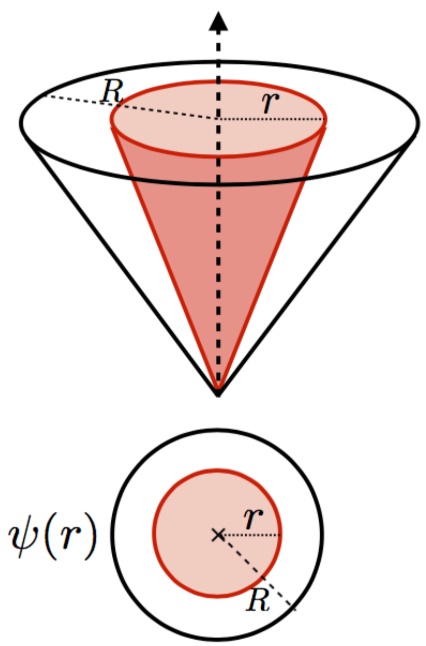
The jet shape

Integrated



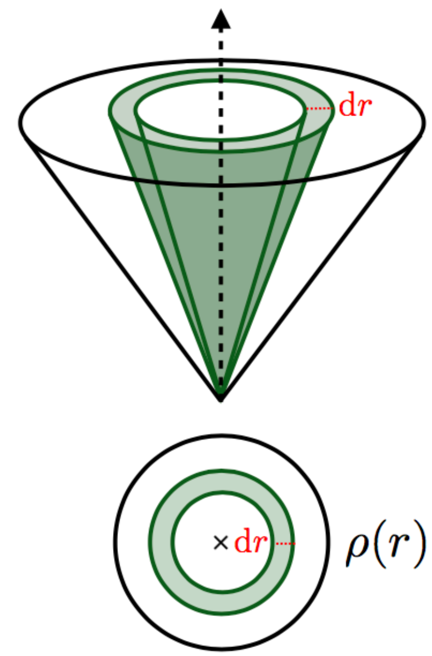
$$\psi(r) = \frac{\sum_{r_i<r} p_{Ti}}{\sum_{r_i<R} p_{Ti}}$$

$R = \text{Jet radius}$

$r = \text{Subjet radius}$

$$z_r = \frac{p_T^{\text{subjet}}}{p_T^{\text{jet}}}$$

Differential



$$\rho(r) = \frac{\mathrm{d}\psi(r)}{\mathrm{d}r}$$

- Data from

  LEP, HERA, Tevatron, LHC …

  $pp, p\bar{p}, e^+e^-, ep, AA$

- Constrain parton showers
- Quark/gluon discrimination
- BSM searches, heavy flavor

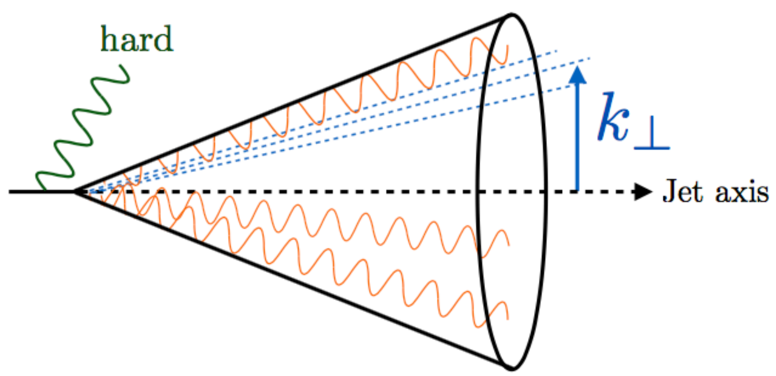
$$\psi(r) = \int_0^1 \mathrm{d}z_r\, z_r \frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}\eta \mathrm{d}z_r} \longrightarrow$$ Derive factorization for a central subjet

Factorization

Cal, FR, Waalewijn `19

- Relevant jet function

$$\mathcal{G}_c^{\rm jet}(z, z_r, p_T R, r/R, \mu) \overset{\rm NLL'}{=} \sum_d H_{cd}(z, p_T R, \mu) \int \mathrm{d}^2 k_\perp C_d(z_r, p_T r, k_\perp, \mu, \nu)$$
$$\times\, \underbrace{S_d^{\rm G}(k_\perp, \mu, \nu R)}_{\text{Global}} \underbrace{S_d^{\rm NG}\Big(\frac{r}{R}\Big)}_{\text{Non Global}} \Big[1 + \mathcal{O}\Big(\frac{r}{R}\Big)\Big]$$



Same as for TMD hadron-in-jet

- First extension beyond LO + LL. Previous work, see

Ellis, Kunszt, Soper `92
Seymour `98
Li, Li, Yuan `11
Chien, Vitev `14

Factorization

Cal, FR, Waalewijn `19

- Relevant jet function

$$\mathcal{G}_c^{\rm jet}(z, z_r, p_T R, r/R, \mu) \overset{\rm NLL'}{=} \sum_d H_{cd}(z, p_T R, \mu) \int {\rm d}^2 k_\perp\, C_d(z_r, p_T r, k_\perp, \mu, \nu)$$
$$\times\, \underbrace{S_d^{\rm G}(k_\perp, \mu, \nu R)}_{\text{Global}}\, \underbrace{S_d^{\rm NG}\Big(\frac{r}{R}\Big)}_{\text{Non Global}} \Big[1 + \mathcal{O}\Big(\frac{r}{R}\Big)\Big]$$

- Collinear function …

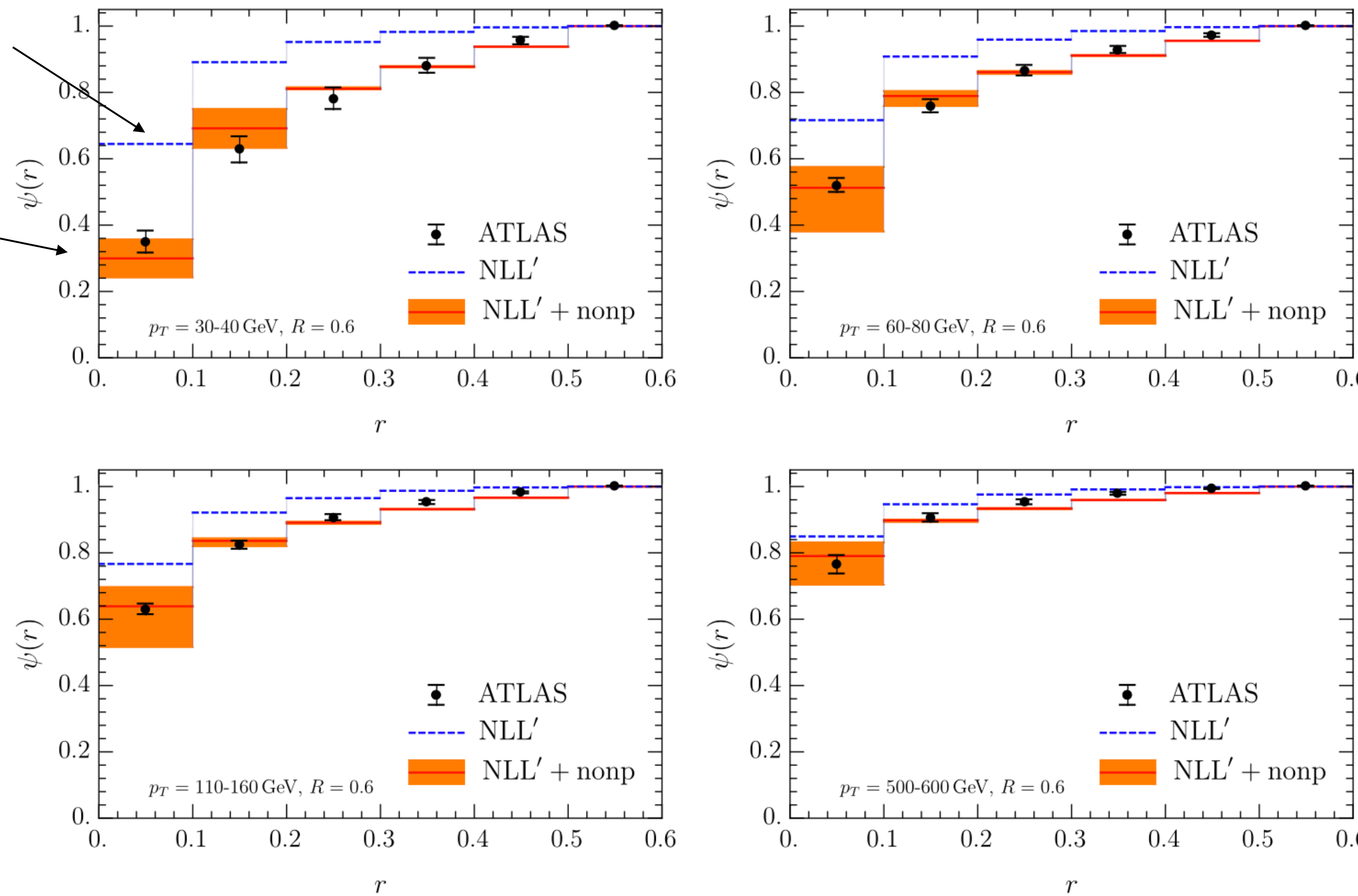
$$C_q^{(\theta<r)} = \frac{\alpha_s C_F}{2\pi^2} \int_0^{2\pi} {\rm d}\phi \,\Big\{ \delta(1-z_r)\Big[\frac{1}{\eta}\Big(\frac{1}{\epsilon} + L_1\Big) + \frac{1}{\epsilon}\Big(L_\nu + \frac{3}{4}\Big) + L_\nu L_1 + \frac{3L_1}{4}$$
$$- \ln^2(1-\widetilde{\beta}) + 2\ln\widetilde{\beta}\ln(1-\widetilde{\beta}) - \frac{3}{2}\ln\widetilde{\beta} + 2{\rm Li}_2(1-\widetilde{\beta}) - \frac{\widetilde{\beta}}{2} - \frac{\pi^2}{3} + 2\Big]$$
$$+ \Theta(z_r > \widetilde{\beta})\Big[-(1+z_r^2)\Big(\frac{\ln(1-z_r)}{1-z_r}\Big)_+ + \ln\Big(\frac{z_r(1-\widetilde{\beta})}{\widetilde{\beta}}\Big)\frac{1+z_r^2}{(1-z_r)}_+\Big]$$
$$+ \Theta(z_r > 1-\widetilde{\beta})\Big[\frac{1+(1-z_r)^2}{z_r}\ln\Big(\frac{z_r\widetilde{\beta}}{(1-z_r)(1-\widetilde{\beta})}\Big)\Big]\Big\},$$
$$C_q^{(\theta>r)} = \frac{\alpha_s C_F}{2\pi^2}\Big[\delta(1-z_r)\Big(\frac{2}{\eta} + 2L_\nu\Big) - \frac{1+z_r^2}{(1-z_r)_+} - \frac{1+(1-z_r)^2}{z_r}\Big] \int_{-\phi_{\max}}^{\phi_{\max}} {\rm d}\phi \ln\Big(\frac{\beta_2^{\min}}{\beta_2^{\max}}\Big)$$

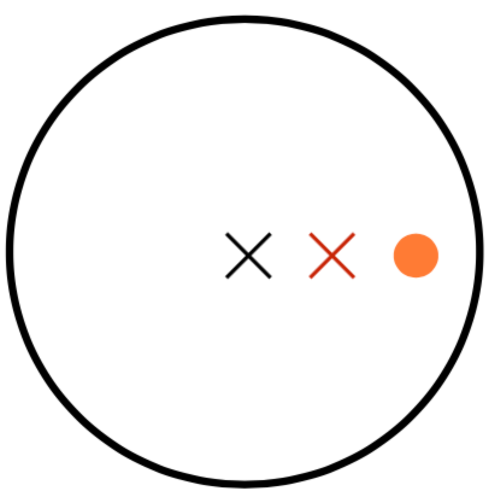
Comparison to LHC data

Cal, FR, Waalewijn `19

Purely perturbative result

Including a NP model



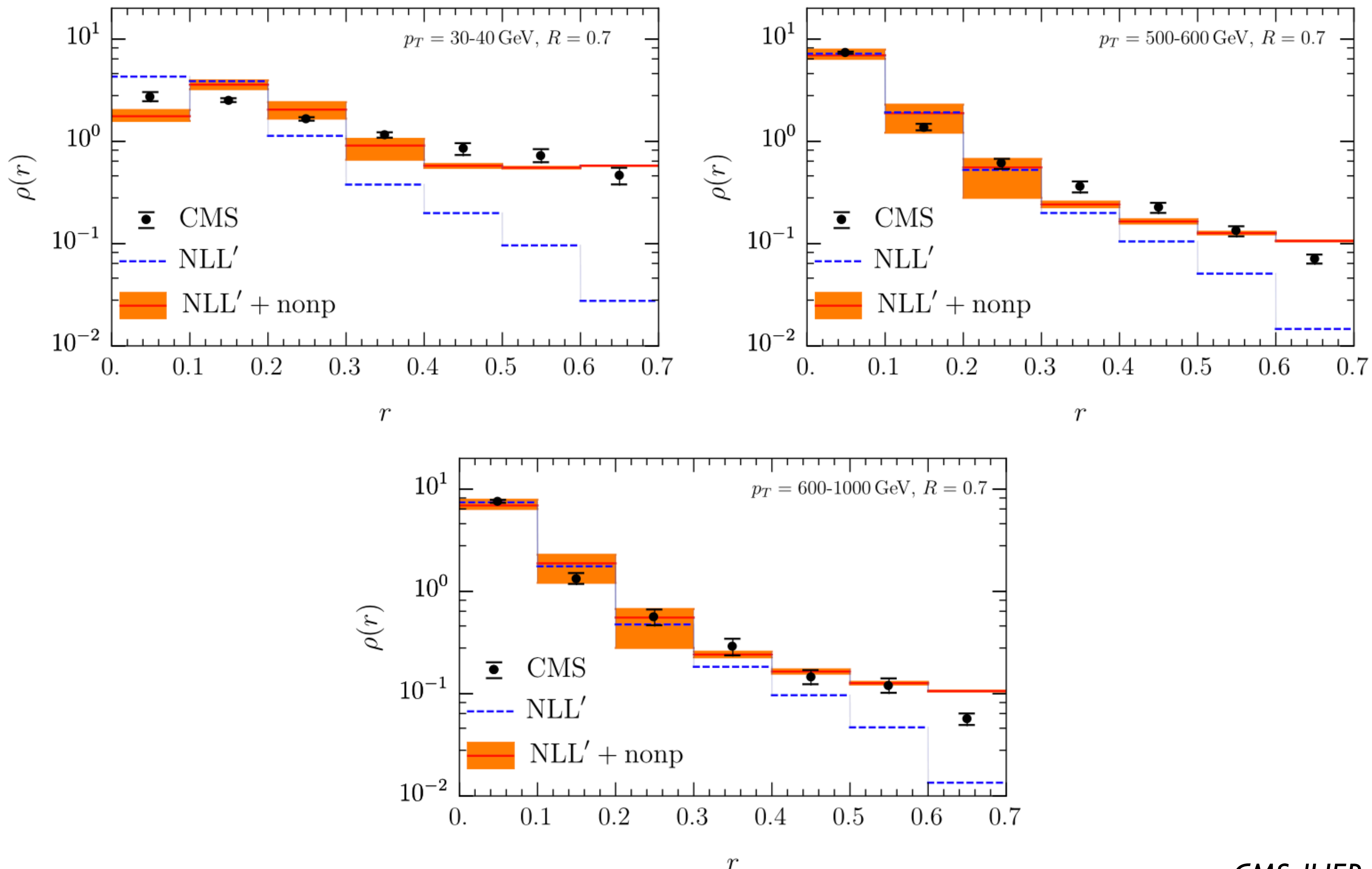


Include axis displacement

ATLAS, Phys. Rev. D 83 (2011) 052003

Comparison to LHC data

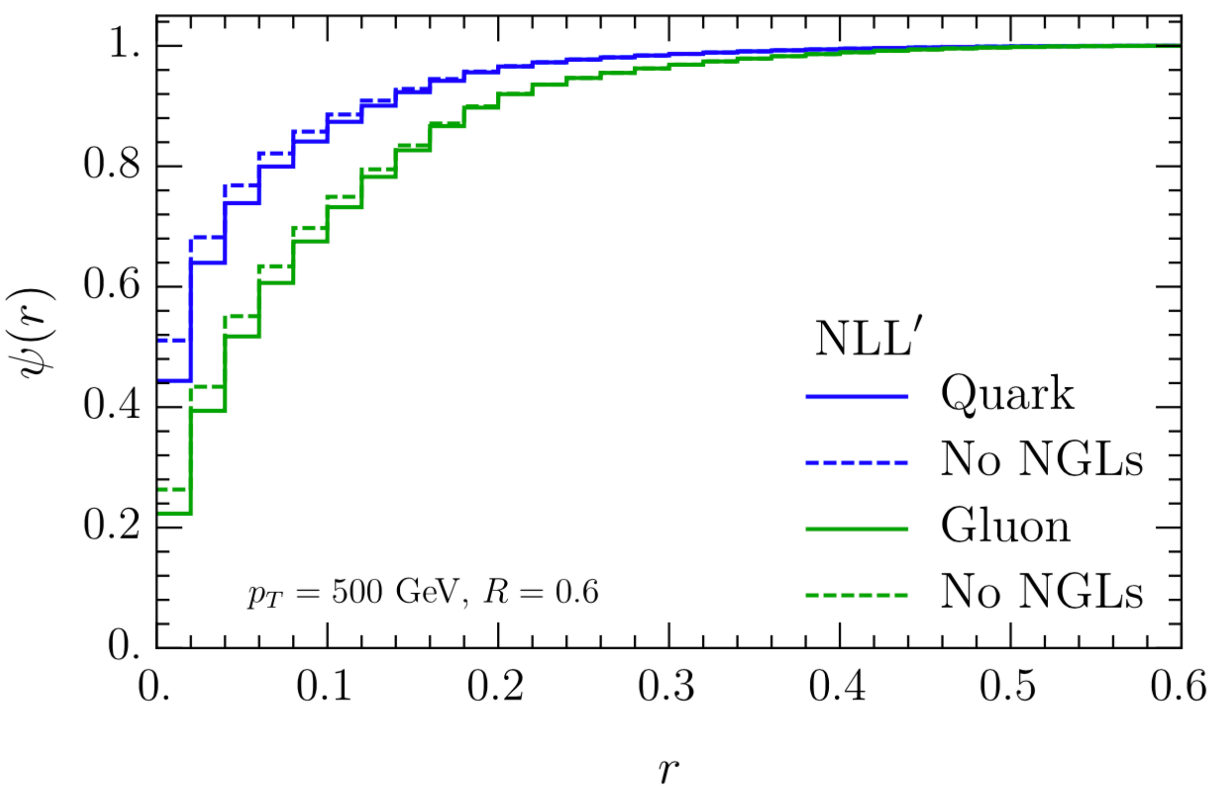
Cal, FR, Waalewijn `19

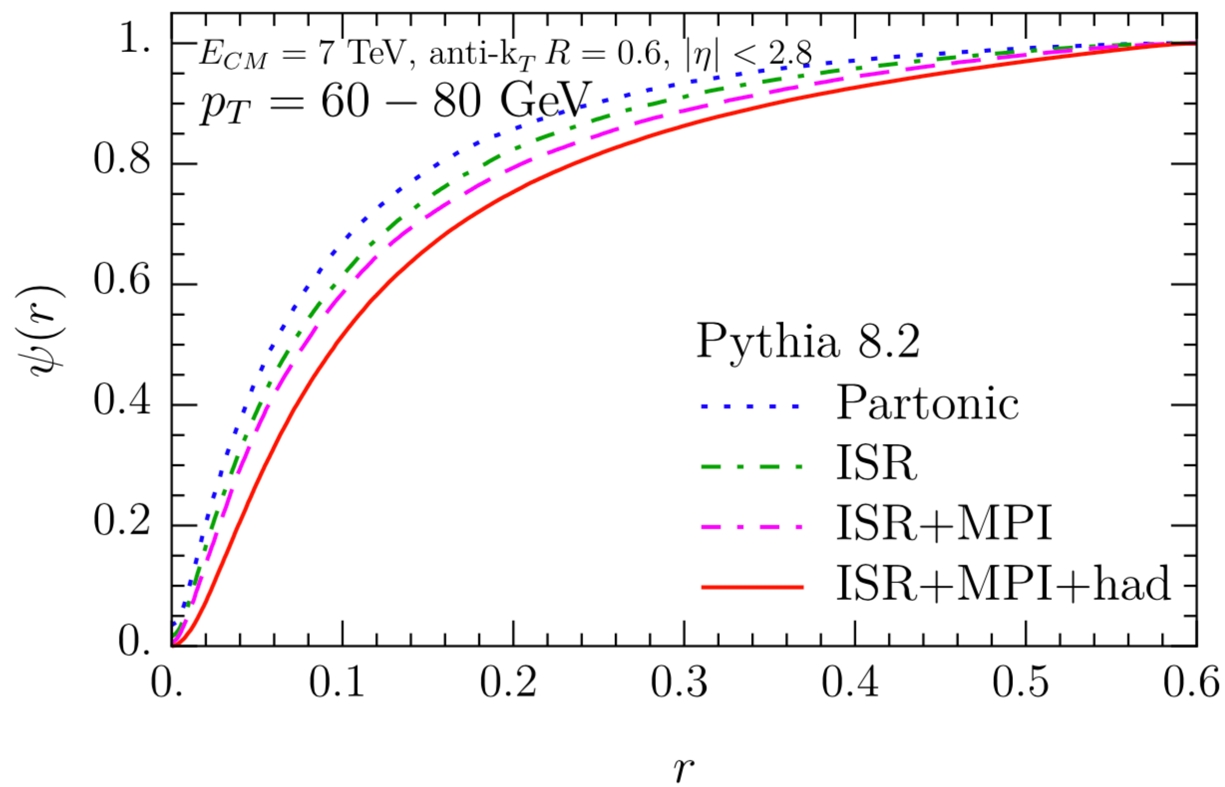


CMS, JHEP 06 (2012) 160

Non-global logarithms and Pythia comparisons

Cal, FR, Waalewijn `19





- Relatively small hierarchy of r, R

- Initial State Radiation
- Multi Parton Interactions/underlying event
- Hadronization

Outline

- Introduction
- Collinear FFs in jets
- TMD FFs in jets
- The jet shape
- Conclusions

Conclusions

- Longitudinal and transverse energy distribution of jets
- More work needed for one-to-one comparison
- Non-global logarithms
- Collins asymmetries in jets