Fragmentation of hadrons and photons inside jets

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- Introduction
- NLO
- Resummation

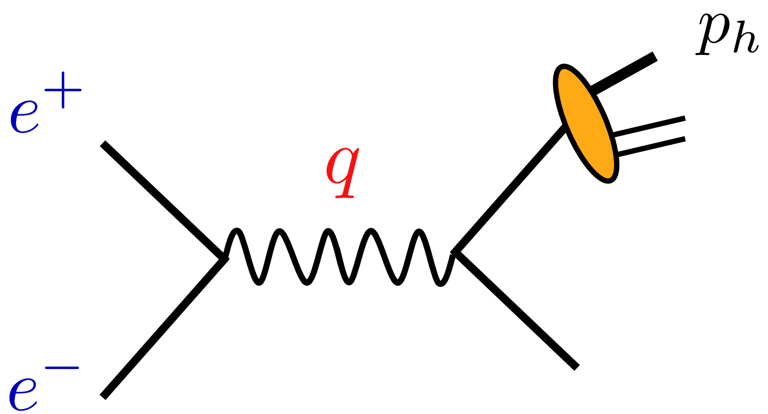
mostly based on work with T. Kaufmann & A. Mukherjee

Introduction

Wide range of applications of fragmentation functions:

spin effects, nuclear effects, hadronization

Prime source of information:



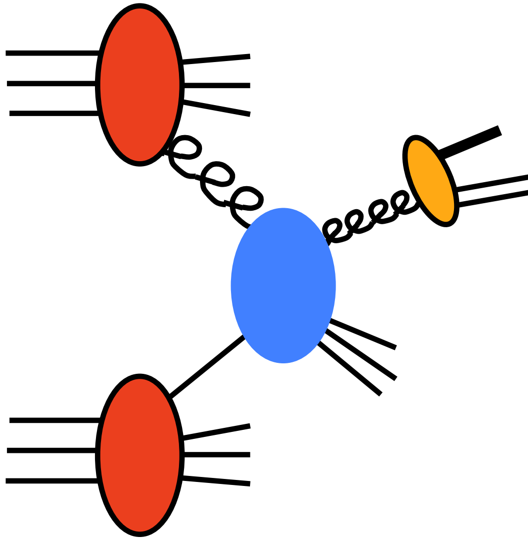
$$z = \frac{2\, p_h \cdot q}{q^2}$$

direct scan of z-dependence: at LO

$$\sigma \leftrightarrow D_c(z, q^2)$$

little sensitivity to gluon FF

pp→πX



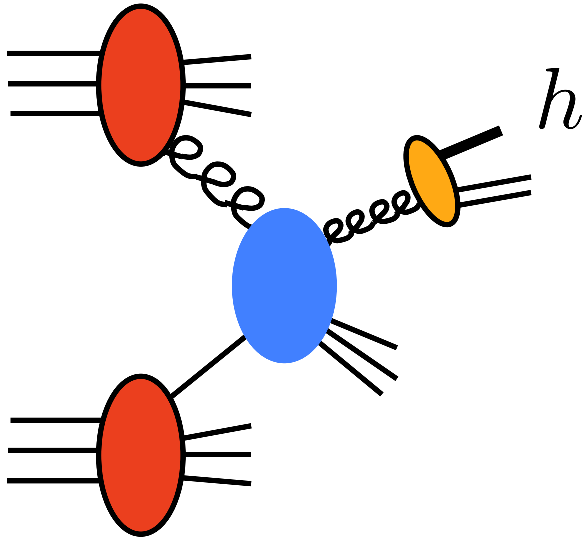
(p_T, η)

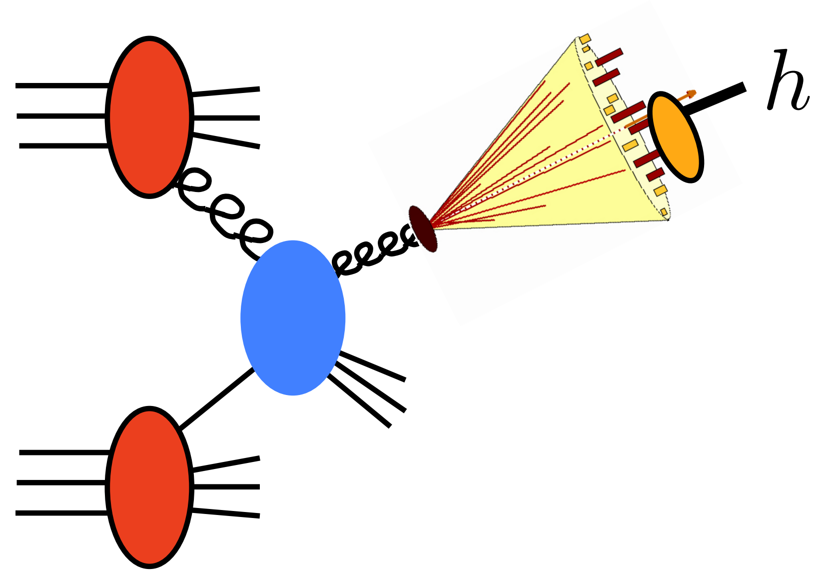
$$d\sigma = \sum_{abc} f_a \otimes f_b \otimes d\hat{\sigma}^{ab\to c} \otimes D_c$$

$$\int_{\frac{2p_T}{\sqrt{s}}\cosh\eta}^{1} dz_c D_c(z_c, \mu)$$

sensitivity to gluon FF

samples broad range in z_c





$$z_h \equiv \frac{p_T^h}{p_T^{\text{jet}}}$$

LO:

$$\frac{d\sigma^{\text{jet}/h}}{dp_T^{\text{jet}} d\eta^{\text{jet}} dz_h} \propto \sum_c \Omega^c(p_T^{\text{jet}}, \eta^{\text{jet}})\, D_c(z_h, \mu)$$

$$\Omega^c = \sum_{a,b} \int dx_a\, f_a(x_a, \mu) \int dx_b\, f_b(x_b, \mu)\, \frac{d\hat{\sigma}^{ab\to c}}{dp_T^{\text{jet}} d\eta^{\text{jet}}}$$

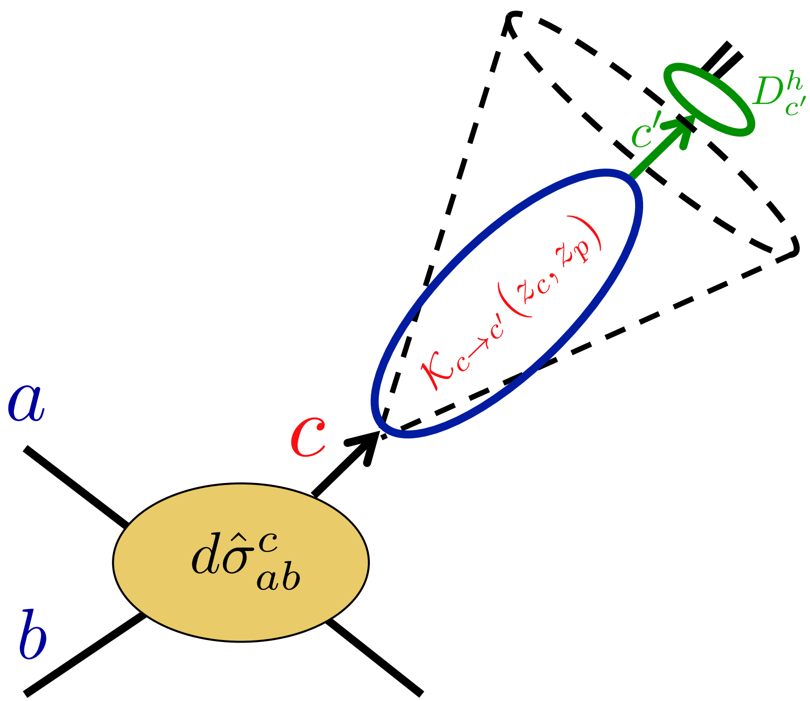
Next-to-leading order

NLO result (analytic for "narrow" jets):

$$\frac{d\sigma^{\mathrm{jet}/h}}{dp_T^{\mathrm{jet}}\,d\eta^{\mathrm{jet}}\,dz_h} = \sum_{a,b,c} \int \frac{dx_a}{x_a} f_a(x_a,\mu) \int \frac{dx_b}{x_b} f_b(x_b,\mu) \int \frac{dz_c}{z_c} \frac{d\hat{\sigma}^{ab\to c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{d\hat{p}_T\,d\hat{\eta}}$$

$$\times \sum_{c'} \int_{z_h}^{1} \frac{dz_p}{z_p} \mathcal{K}_{c\to c'}\left(z_c, z_p; \mathcal{R}\, p_T^{\mathrm{jet}}/\mu\right) D_{c'}\left(\frac{z_h}{z_p},\mu\right)$$

"fragmenting jet functions"



Procura, Waalewijn
Procura, Stewart
Jain, Procura, Waalewijn
Kaufmann, Mukherjee, WV
Thaler et al.
Chien, Kang, Ringer, Vitev, Xing
Arleo, Fontannaz, Guillet, Nguyen

For example,

$$\mathcal{K}_{q\to q}\left(z_c, z_p, \mathcal{R}\, p_T^{\rm jet}/\mu\right) = \underbrace{\delta(1-z_c)\delta(1-z_p)}_{\rm LO}$$

$$+\frac{\alpha_s(\mu)}{2\pi}\Bigg[-\delta(1-z_p)\left\{2C_F(1+z_c^2)\left(\frac{\log(1-z_c)}{1-z_c}\right)_+ + 2\,P_{qq}(z_c)\log\left(\frac{\mathcal{R}\,p_T^{\rm jet}}{\mu}\right)+C_F(1-z_c)\right\}$$

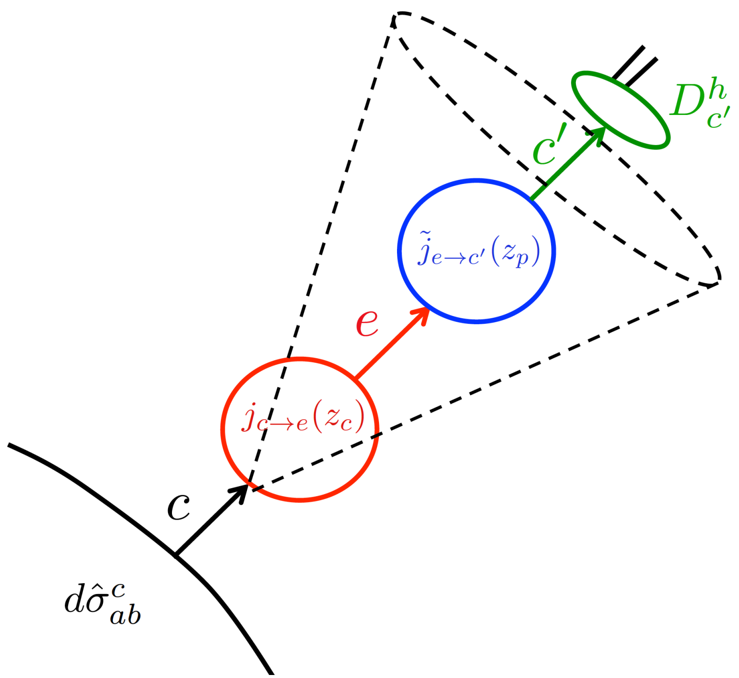
$$+\delta(1-z_c)\left\{2C_F(1+z_p^2)\left(\frac{\log(1-z_p)}{1-z_p}\right)_+ + 2\,P_{qq}(z_p)\log\left(\frac{\mathcal{R}\,p_T^{\rm jet}}{\mu}\right)+C_F(1-z_p)+\mathcal{I}_{qq}^{\rm algo}(z_p)\right\}\Bigg]$$

$$= j_{q\to q}\left(z_c, \mathcal{R}\, p_T^{\rm jet}/\mu\right) \times \tilde{j}_{q\to q}\left(z_p, \mathcal{R}\, p_T^{\rm jet}/\mu\right) + \mathcal{O}(\alpha_s^2)$$

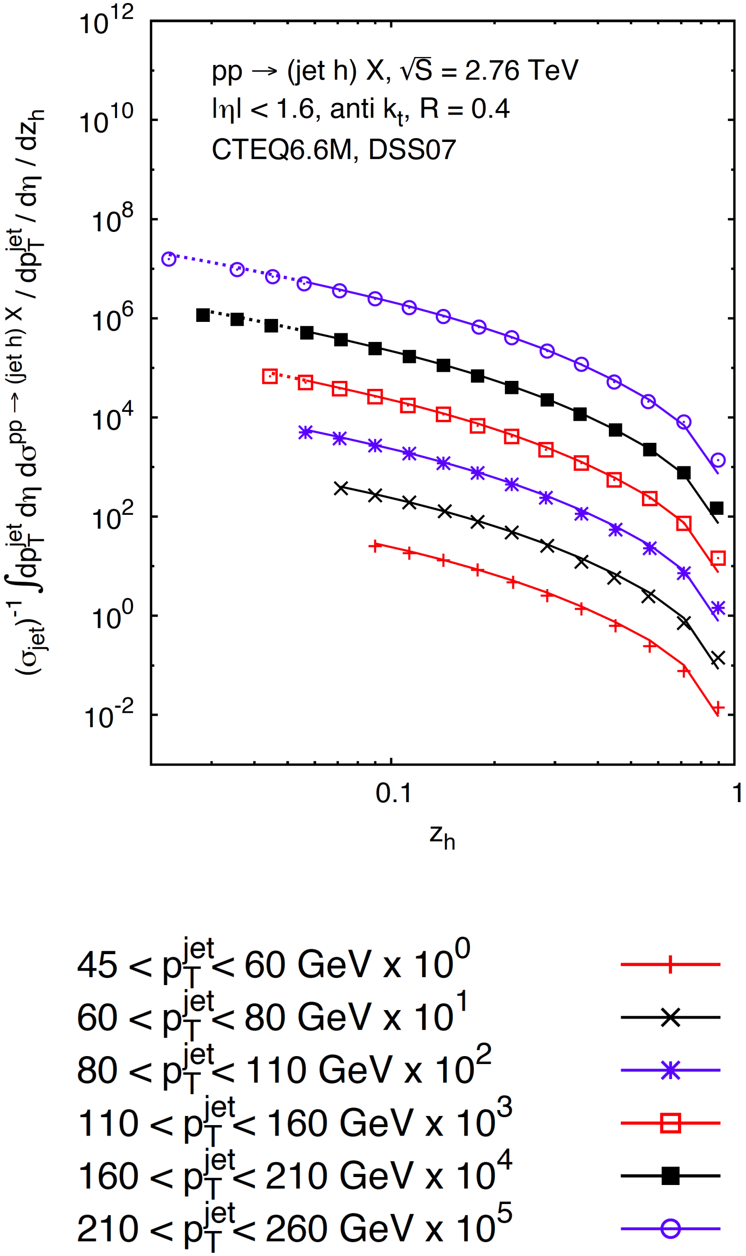
In the end, at NLO:

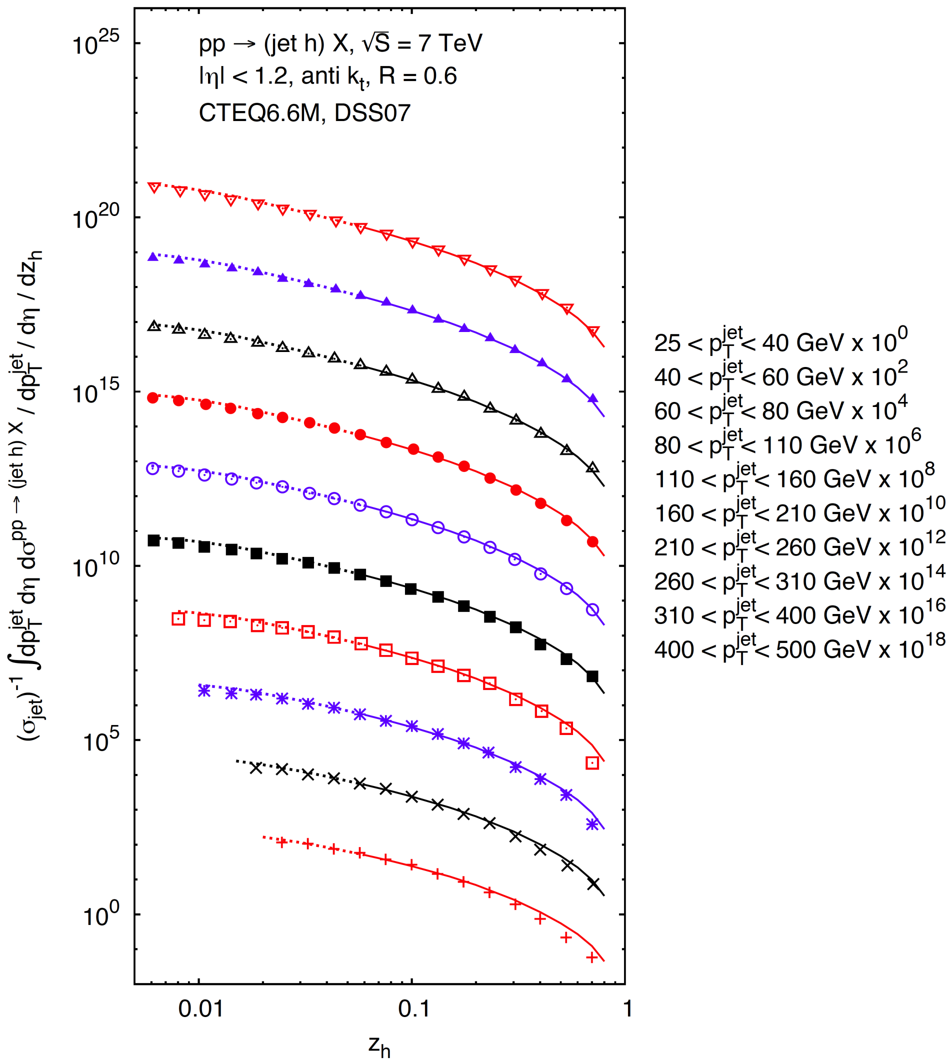
$$\frac{d\sigma^{\mathrm{jet}/h}}{dp_T^{\mathrm{jet}}\, d\eta^{\mathrm{jet}}\, dz_h} = \sum_{a,b,c} \int \frac{dx_a}{x_a} f_a(x_a,\mu) \int \frac{dx_b}{x_b} f_b(x_b,\mu) \int \frac{dz_c}{z_c} \frac{d\hat{\sigma}^{ab\to c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{d\hat{p}_T\, d\hat{\eta}}$$

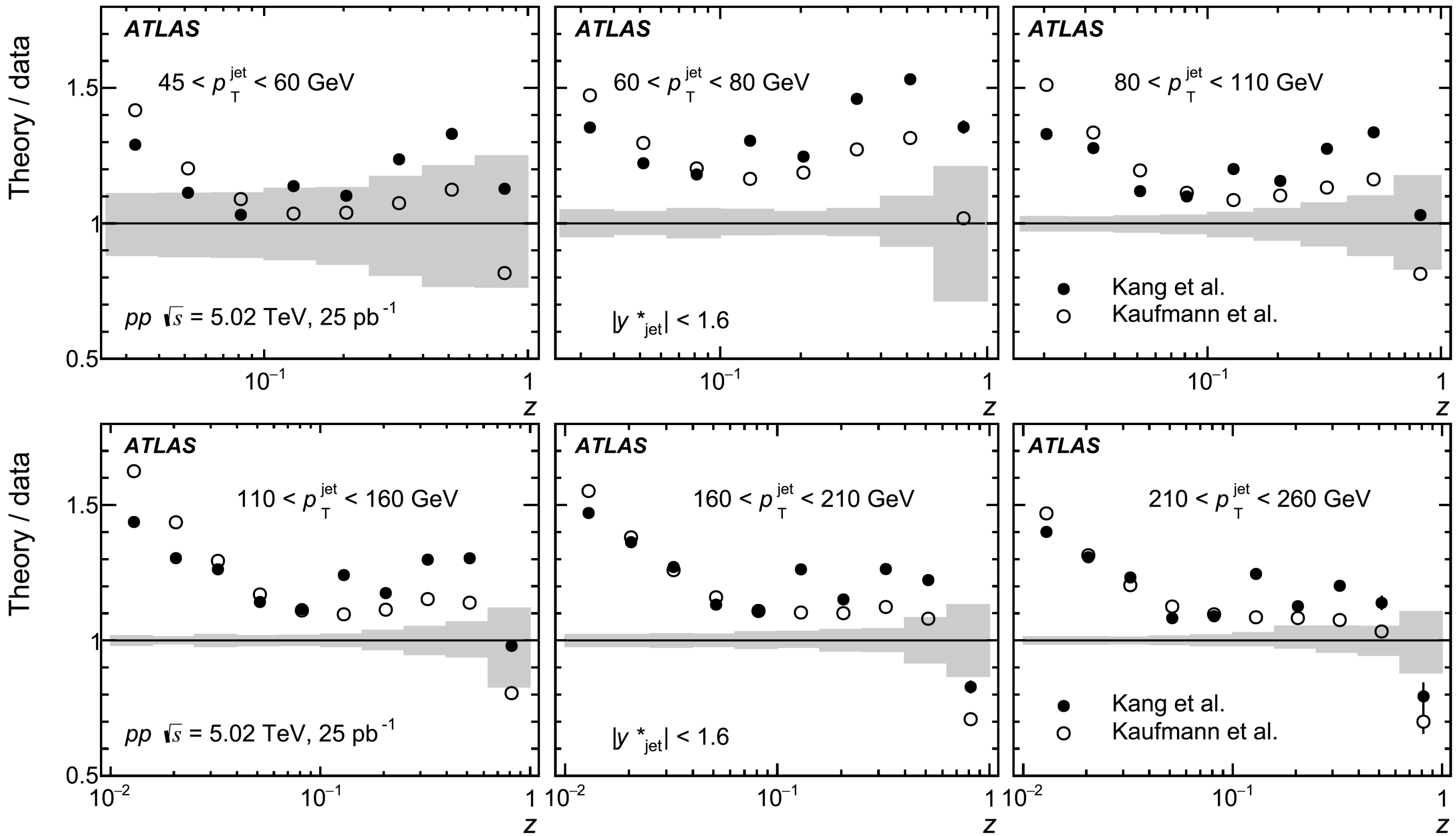
$$\times \sum_e j_{c\to e}\left(z_c, \mathcal{R}\, p_T^{\mathrm{jet}}/\mu\right) \sum_{c'} \int_{z_h}^{1} \frac{dz_p}{z_p} \tilde{j}_{e\to c'}\left(z_p, \mathcal{R}\, p_T^{\mathrm{jet}}/\mu\right) D_{c'}\left(\frac{z_h}{z_p}, \mu\right)$$



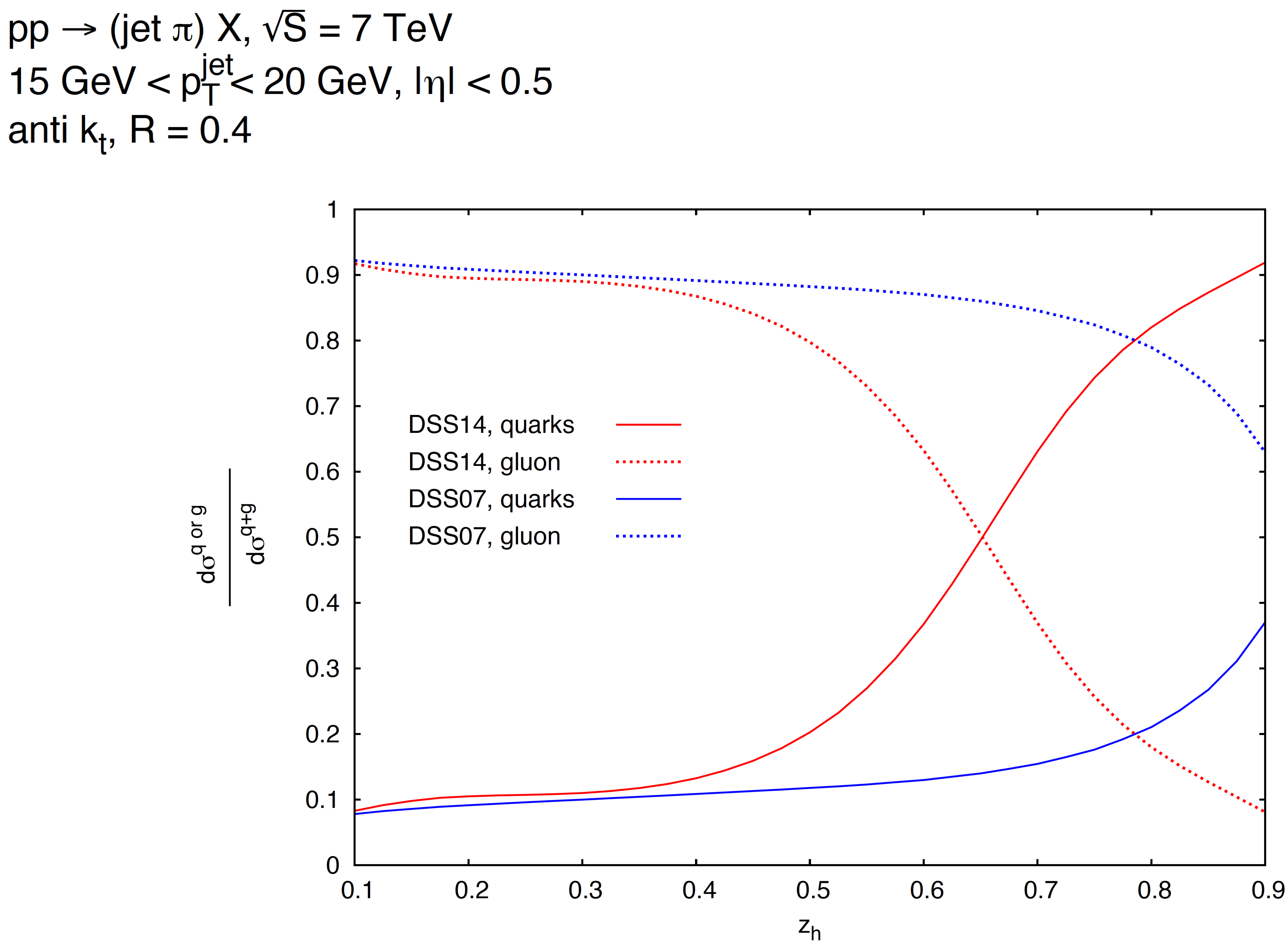
data: ATLAS


pp → (jet h) X, √S = 2.76 TeV
|η| < 1.6, anti k_t, R = 0.4
CTEQ6.6M, DSS07
$(\sigma_{jet})^{-1} \int dp_T^{jet} d\eta \, d\sigma^{pp \to (jet\, h)\, X} / dp_T^{jet} / d\eta / dz_h$
z_h
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
0.1
1
$45 < p_T^{jet} < 60$ GeV x 10^0
$60 < p_T^{jet} < 80$ GeV x 10^1
$80 < p_T^{jet} < 110$ GeV x 10^2
$110 < p_T^{jet} < 160$ GeV x 10^3
$160 < p_T^{jet} < 210$ GeV x 10^4
$210 < p_T^{jet} < 260$ GeV x 10^5


pp → (jet h) X, √S = 7 TeV
|η| < 1.2, anti k_t, R = 0.6
CTEQ6.6M, DSS07
$(\sigma_{jet})^{-1} \int dp_T^{jet} d\eta \, d\sigma^{pp \to (jet\, h)\, X} / dp_T^{jet} / d\eta / dz_h$
z_h
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
0.01
0.1
1
$25 < p_T^{jet} < 40$ GeV x 10^0
$40 < p_T^{jet} < 60$ GeV x 10^2
$60 < p_T^{jet} < 80$ GeV x 10^4
$80 < p_T^{jet} < 110$ GeV x 10^6
$110 < p_T^{jet} < 160$ GeV x 10^8
$160 < p_T^{jet} < 210$ GeV x 10^{10}
$210 < p_T^{jet} < 260$ GeV x 10^{12}
$260 < p_T^{jet} < 310$ GeV x 10^{14}
$310 < p_T^{jet} < 400$ GeV x 10^{16}
$400 < p_T^{jet} < 500$ GeV x 10^{18}



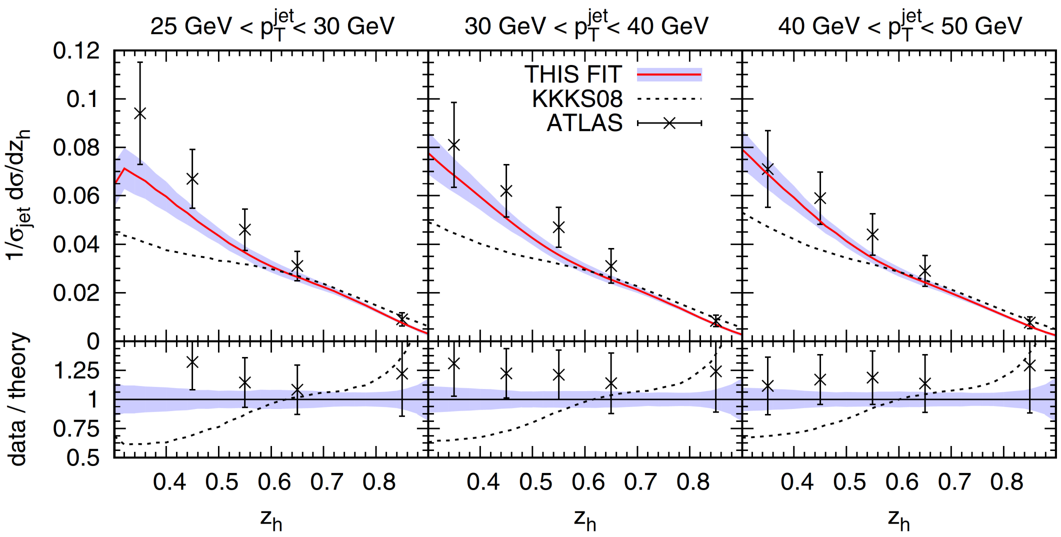
ATLAS
$45 < p_T^{jet} < 60$ GeV
$pp\ \sqrt{s}$ = 5.02 TeV, 25 pb^{-1}
$60 < p_T^{jet} < 80$ GeV
$|y^*_{jet}| < 1.6$
$80 < p_T^{jet} < 110$ GeV
$110 < p_T^{jet} < 160$ GeV
$160 < p_T^{jet} < 210$ GeV
$210 < p_T^{jet} < 260$ GeV
Kang et al.
Kaufmann et al.
Theory / data
z



pp → (jet π) X, √S = 7 TeV
15 GeV < p_T^{jet} < 20 GeV, |η| < 0.5
anti k_t, R = 0.4
DSS14, quarks
DSS14, gluon
DSS07, quarks
DSS07, gluon
$\frac{d\sigma^{q\ or\ g}}{d\sigma^{q+g}}$
z_h
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Anderle, Kaufmann, Stratmann, Ringer, Vitev

Application to D* mesons produced in jets:



Full global analysis of

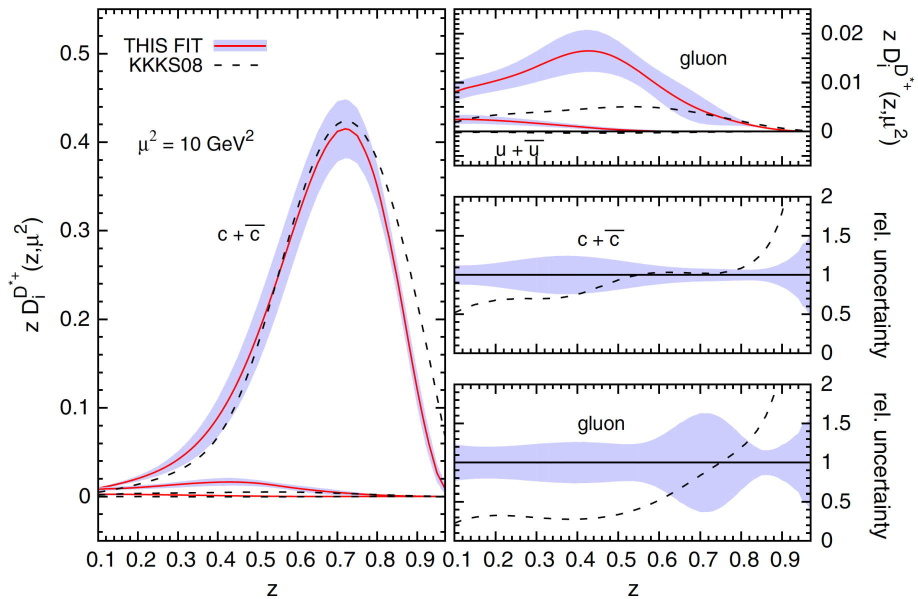
$$e^+e^- \to D^* + X$$

$$pp \to D^* + X$$

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

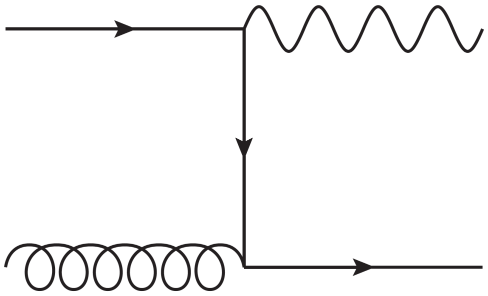
$$pp \to \text{jet}(D^*) + X$$

puts constraint on gluon FF

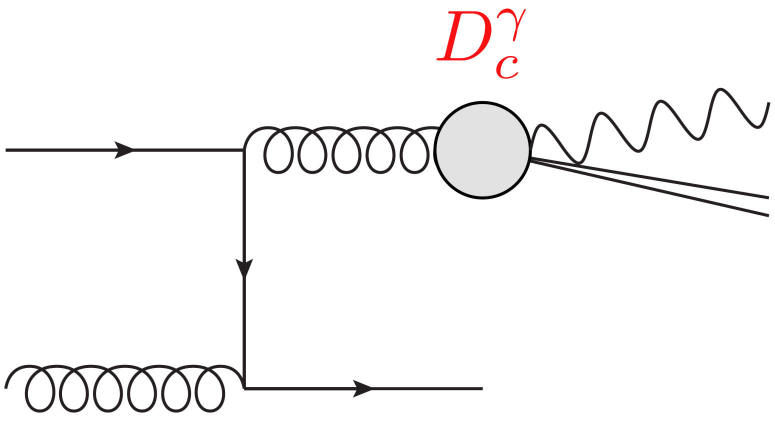


also applicable to photon production inside jets:

Kaufmann, Mukherjee, WV



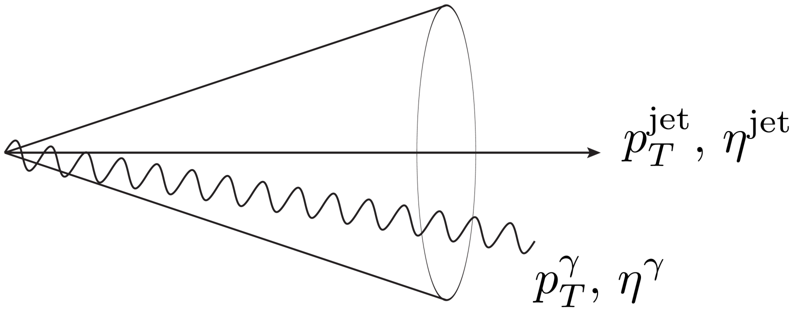
“direct”



“fragmentation”

poorly known

“democratic” jet algorithm



$$z_\gamma \equiv \frac{p_T^\gamma}{p_T^{\rm jet}} \quad \begin{cases} = 1 & \text{direct part} \\ < 1 & \text{fragmentation part} \end{cases}$$

LO:

$$\left.\frac{d\sigma^{pp\to(\text{jet}\,\gamma)X}}{dp_T^{\rm jet}\,d\eta^{\rm jet}\,dz_\gamma}\right|_{\rm LO} \propto \sum_{\substack{a,b,c\in\\ \{q,\bar{q},g,\gamma\}}} f_a\otimes f_b\otimes d\hat{\sigma}_{ab}^{c,{\rm LO}}\times\Big[\delta(1-z_\gamma)\delta_{c\gamma}+D_c^\gamma(z_\gamma,\mu^2)(1-\delta_{c\gamma})\Big]$$

- at NLO, suitable fragmenting jet functions for photons

(beware of background from $\pi^0 \to \gamma\gamma$!)

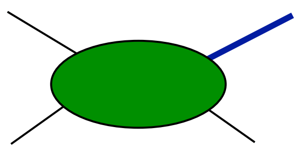
QCD resummation for pp→(jet h)X

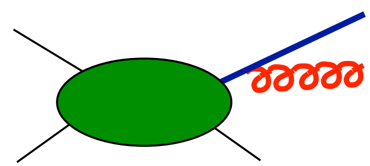
$$\frac{d\sigma^{\text{jet}/h}}{dp_T^{\text{jet}}\,d\eta^{\text{jet}}\,dz_h} = \sum_{a,b,c} \int \frac{dx_a}{x_a} f_a(x_a,\mu) \int \frac{dx_b}{x_b} f_b(x_b,\mu) \int \frac{dz_c}{z_c} \frac{d\hat{\sigma}^{ab\to c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{d\hat{p}_T\,d\hat{\eta}}$$

$$\times \sum_e j_{c\to e}\left(z_c, \mathcal{R}\,p_T^{\text{jet}}/\mu\right) \sum_{c'} \int_{z_h}^{1} \frac{dz_p}{z_p} \tilde{j}_{e\to c'}\left(z_p, \mathcal{R}\,p_T^{\text{jet}}/\mu\right) D_{c'}\left(\frac{z_h}{z_p}, \mu\right)$$

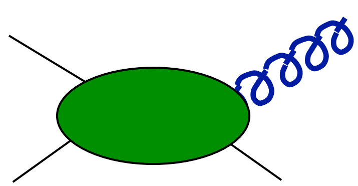
Near $z_p = 1$:

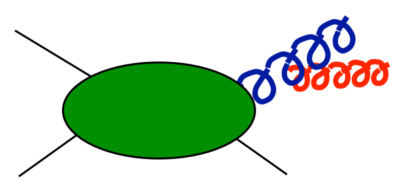
$$\tilde{j}_{q\to q}(z_p) = \delta(1-z_p) + \frac{\alpha_s(\mu)}{2\pi}\left[4C_F\left(\frac{\log(1-z_p)}{1-z_p}\right)_+ + \ldots\right]$$



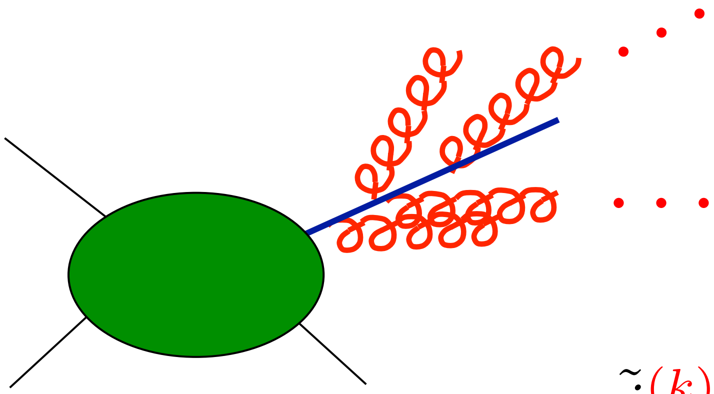


$$\tilde{j}_{g\to g}(z_p) = \delta(1-z_p) + \frac{\alpha_s(\mu)}{2\pi}\left[4C_A\left(\frac{\log(1-z_p)}{1-z_p}\right)_+ + \ldots\right]$$





- higher orders:



$$\tilde{j}^{(k)}_{q\to q}(z_p) \;\propto\; \alpha_s^k \left(\frac{\log^{2k-1}(1-z_p)}{1-z_p} \right)_+$$

"double logarithms"

- for $z_p \to 1$ real gluon radiation inhibited
- with Mellin moments $\int_0^1 dz_p \, z_p^{N-1} \, \tilde{j}_{q\to q}(z_p)$

$$\left(\frac{\log^{2k-1}(1-z_p)}{1-z_p} \right)_+ \quad \longleftrightarrow \quad \log^{2k}(N)$$

Large logs can be resummed to all orders

Catani, Trentadue; Sterman; …

Fixed Order →

Resummation ↓

LO	1					
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s			
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
...	...	...	...	...	...	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$\alpha_s^k L^{2k-4}$	...

LL NLL NNLL

$$L = \log(N)$$

Kaufmann, Liu, Mukherjee, Ringer, WV (in progr.)

$\overline{\text{MS}}$ scheme

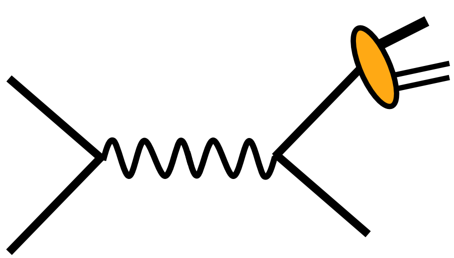
$$\tilde{j}^{\text{resum}}_{q\to q}(N) \sim \exp\left\{\int_0^1 dz\, \frac{z^N-1}{1-z} \int_{\mu^2}^{\mathcal{R}^2 p_T^2 (1-z)^2} \frac{dk^2}{k^2} A_q\left(\alpha_s(k^2)\right)\right\}$$

$$A_q(\alpha_s) = C_F \left\{\frac{\alpha_s}{\pi} + \left(\frac{\alpha_s}{\pi}\right)^2 \left[\frac{C_A}{2}\left(\frac{67}{18} - \zeta(2)\right) - \frac{5}{9} T_R n_f\right] + \ldots\right\}$$

leading logs:

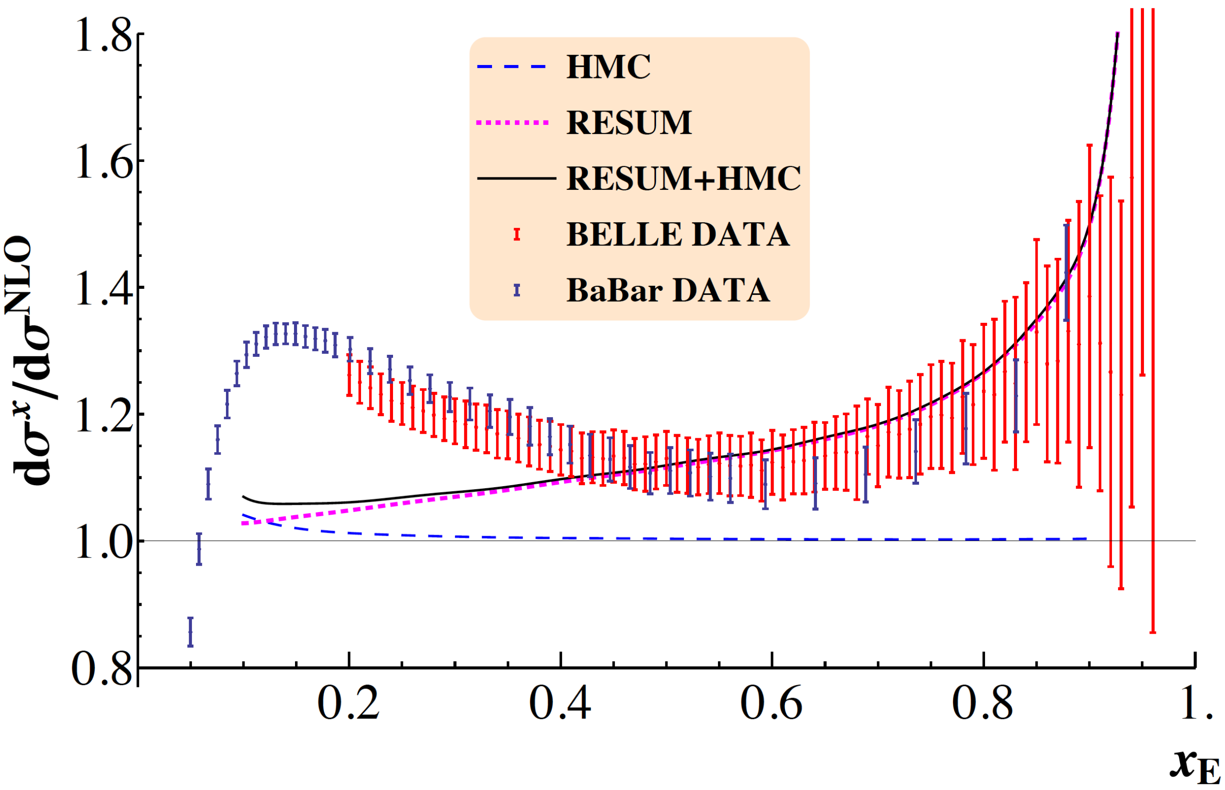
$$\tilde{j}^{\text{resum}}_{q\to q}(N) \sim \exp\left[\frac{C_F}{\pi}\alpha_s \log^2(N)\right]$$

compare $e^+e^- \to hX$: Anderle, Ringer, WV



$$\sigma^{\text{resum}}(N) \sim \exp\left[\frac{C_F}{2\pi}\alpha_s \log^2(N)\right]$$

Accardi, Anderle, Ringer



Conclusions and outlook:

$pp \to (\text{jet}/h) + X$: probe of fragmentation fcts.

Future avenues:

- use in full global analysis with LHC/RHIC data
- further improve theory framework: resummation at large (and small) z_h
- transverse momentum dependence in fragmentation (spin effects)
- longitudinal polarization (Λ baryons)
- dihadron production