Inclusive Jets and their substructure in pp and heavy-ion collisions

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Bangalore, 01/26/17

Outline

Proton-proton

- Inclusive jets — *Kang, FR, Vitev `16*
- The jet fragmentation function — *Kang, FR, Vitev `16*

Heavy-ion

- $\mathrm{SCET}_{\mathrm{G}}$
- Inclusive jets — *Kang, FR, Vitev `17*
- The jet fragmentation function — *Chien, Kang, FR, Vitev, Xing - in preparation*

Conclusions

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Heavy-ion

- $SCET_G$
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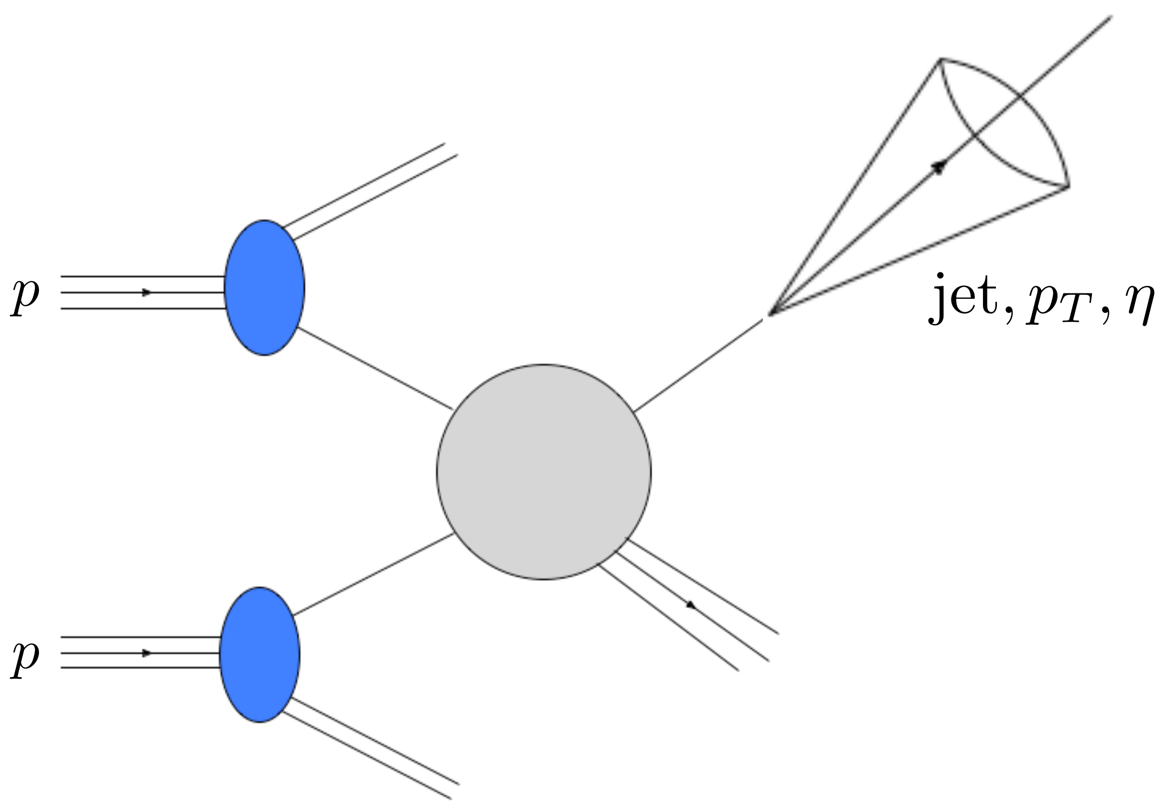
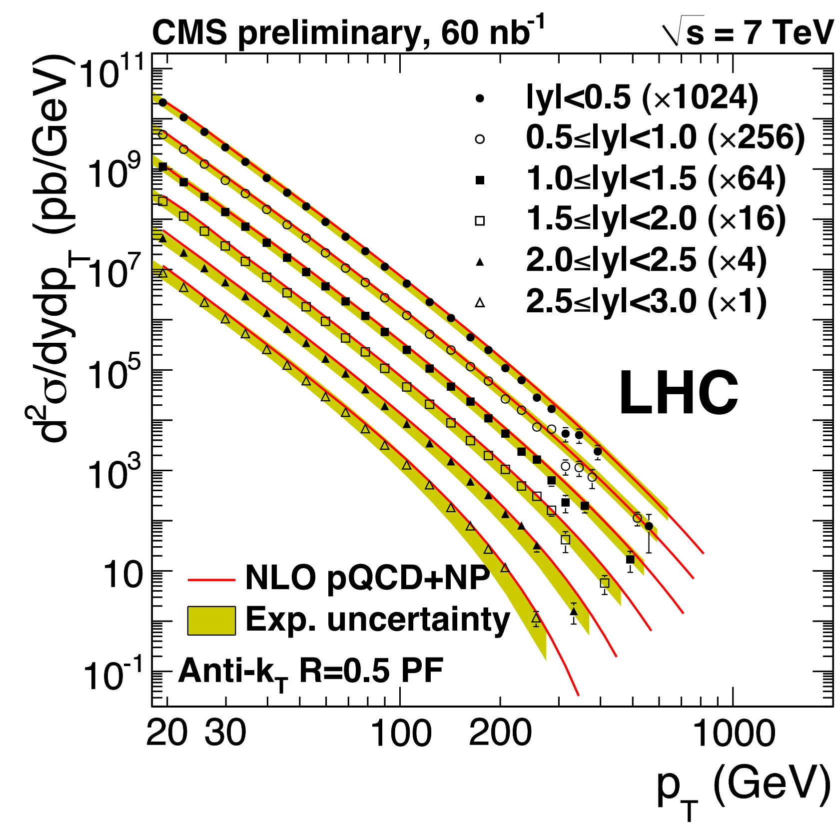
Conclusions

Inclusive Jet Production $pp \to \mathrm{jet}X$

- Large theoretical uncertainties especially at high p_T
- PDFs are constrained by collider jet data, especially $g(x), \Delta g(x)$
- Determination of α_s
- High p_T jets are a promising observable for the search of BSM physics at the LHC
- Jet quenching studies in heavy-ion collisions
- …





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Inclusive Jet Production $pp \to \text{jet} X$

pQCD MC or NJA $\text{NLO} \sim \mathcal{A} \ln R + \mathcal{B} + \mathcal{O}(R^2)$

Ellis, Kunszt, Soper `90, Aversa, Chiappetta, Greco, Guillet `90,
Jäger, Stratmann, Vogelsang `04,
Mukherjee, Vogelsang `12,
de Florian, Hinderer, Mukherjee, FR, Vogelsang `14
Dasgupta, Dreyer, Salam, Soyez `15, `16
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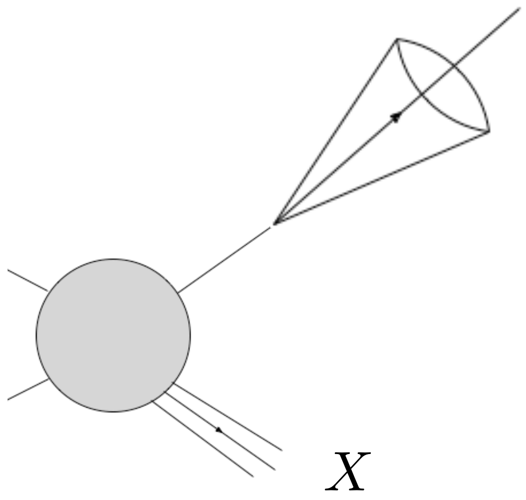

$\sim \alpha_s^n \ln^n R$

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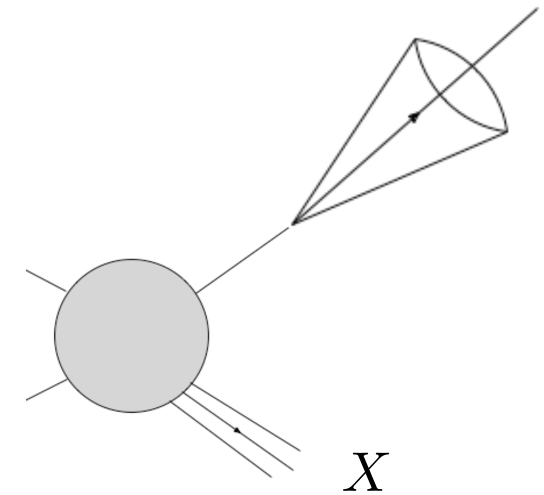
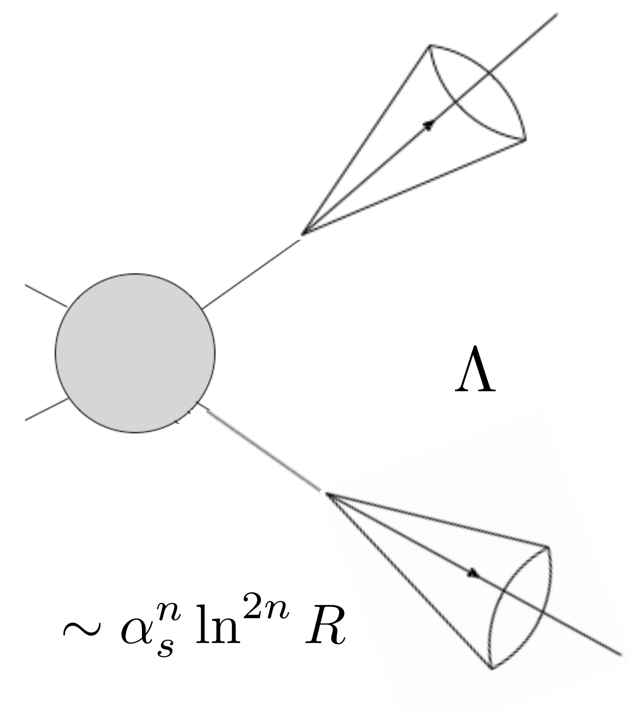


$\sim \alpha_s^n \ln^n R$

SCET for exclusive jet production $e^+e^- \to \mathrm{di-jets}, \quad pp \to Z + \mathrm{jet}$

Ellis, Vermilion, Walsh, Hornig, Lee `10,
Chien, Hornig, Lee `15
Becher, Neubert, Rothen, Shao `16
Kolodrubetz, Pietrulewicz, Stewart, Tackmann, Waalewijn `16
Frye, Larkoski, Schwartz, Yan `16
$\ldots$



$\sim \alpha_s^n \ln^{2n} R$

Inclusive vs. exclusive jets

- Few jet substructure calculations so far
  Kaufmann, Mukherjee, Vogelsang `15,
  Dai, Kim, Leibovich `16,
  Neill, Scimemi, Waalewijn `16

- Many substructure observables have been calculated. High precision calculations for e^+e^-, often MC methods for pp

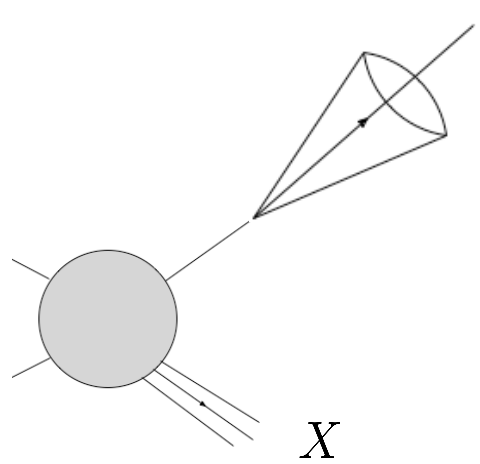
- Rather insensitive to non-global logarithms, # of jets. E.g. soft function in threshold limit
  de Florian, Hinderer, Mukherjee, FR, Vogelsang `14,
  Dai, Kim, Leibovich `17

$$\alpha_s \left(\frac{\ln(1-z)}{1-z}\right)_+$$

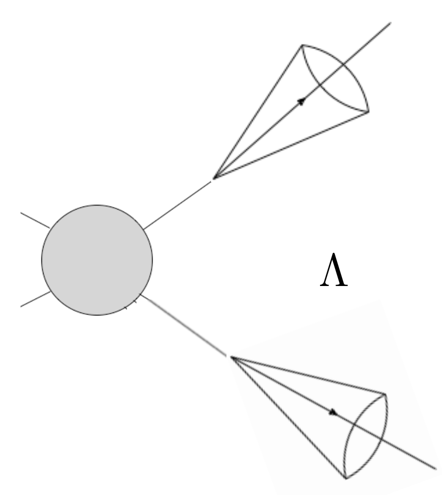
- Sensitivity to non-global logarithms, # of jets in the event
  Dasgupta, Salam `01, Larkoski, Moult, Neill `15 …

$$\ln(\Lambda/p_T) \qquad \mathcal{O}(\Lambda/p_T)$$

- e.g. jet quenching in heavy-ion collisions



- e.g. search for BSM physics



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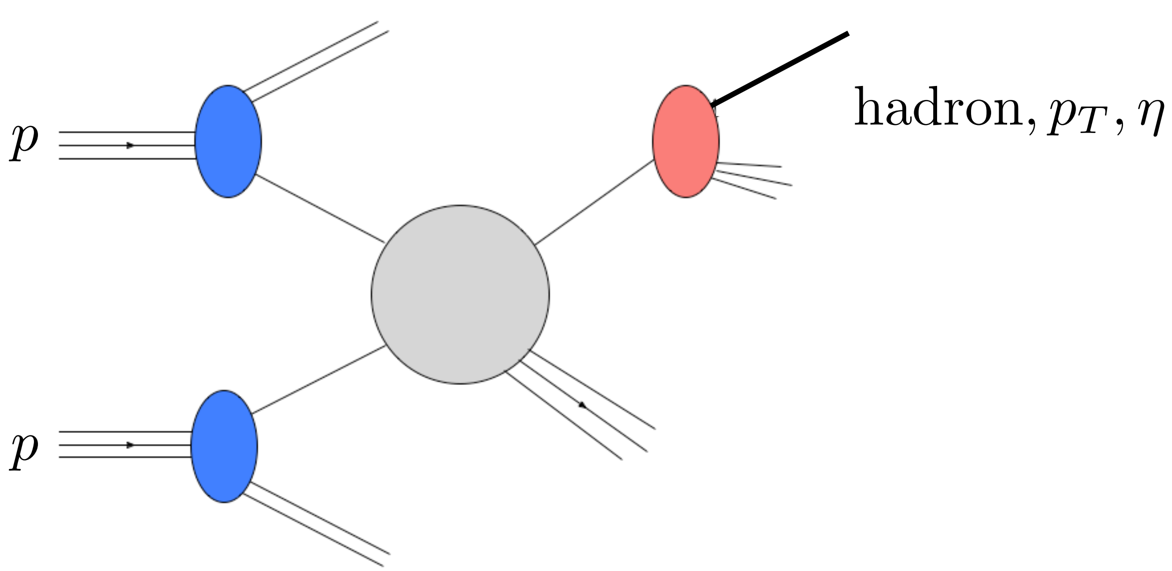
Recall Inclusive Hadron Production $pp \to hX$

Factorization

$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu)\int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2}\frac{d\hat{\sigma}^c_{ab}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz} D_c^h(z_c,\mu)$$

timelike DGLAP for FFs

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



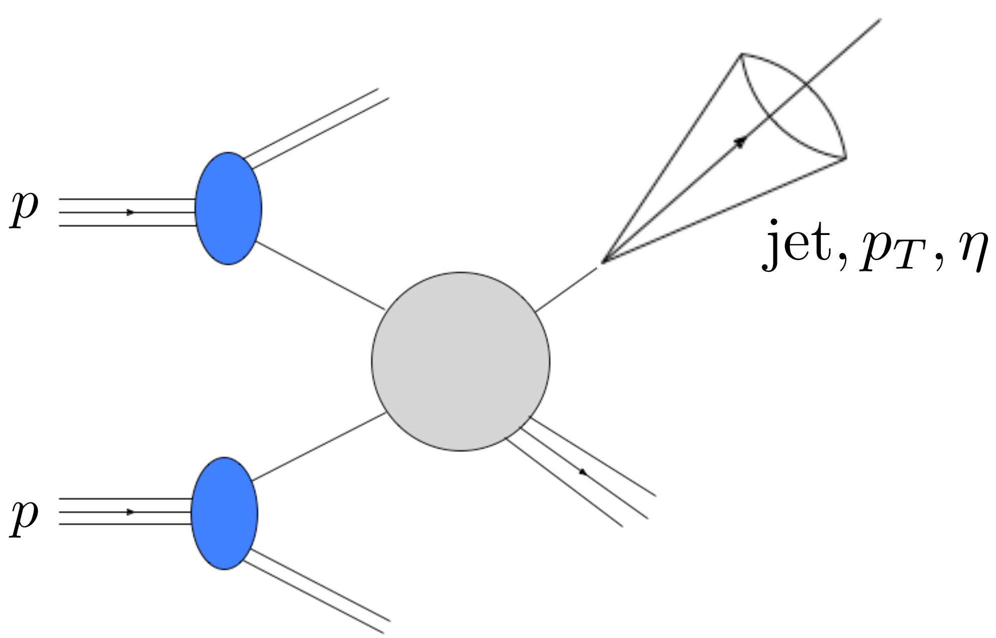
Aversa, Chiappetta, Greco, Guillet `89,
Jäger, Schäfer, Stratmann, Vogelsang `04

Inclusive Jet Production $pp \to \text{jet}X$

Factorization

Kang, FR, Vitev `16

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu)\int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu)\int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^c(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dv dz}\boxed{J_c(z_c,\omega_J,\mu)}$$



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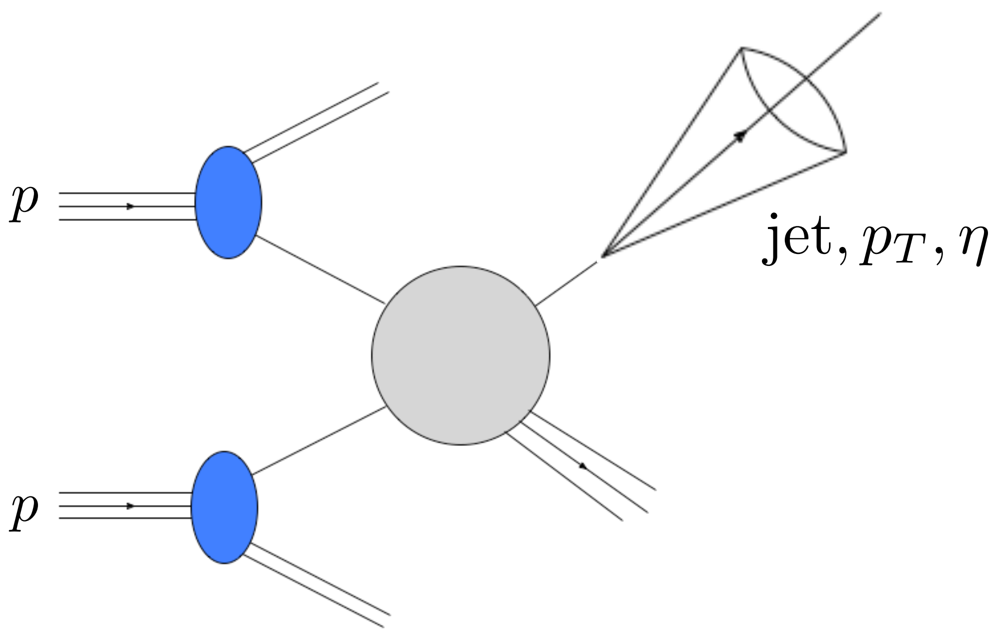
timelike DGLAP for semi-inclusive jet function

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



$\longrightarrow$ resummation of $\sim (\alpha_s \ln R)^n$

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Operator definition in SCET

Semi-inclusive jet function:

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

$$J_g(z = \omega_J/\omega, \omega_J, \mu) = -\frac{z\,\omega}{2(N_c^2-1)} \langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|JX\rangle\langle JX|\mathcal{B}_{n\perp}^{\mu}(0)|0\rangle$$

Fragmentation functions:

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

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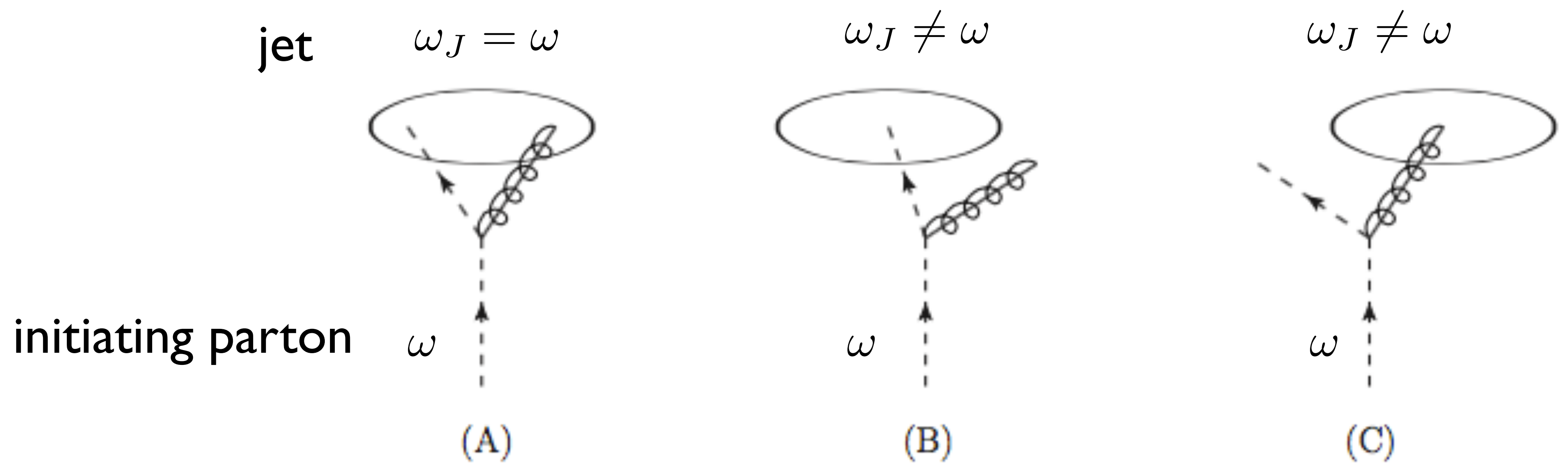
Semi-inclusive jet function in SCET at NLO

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



where $z = \omega_J/\omega$

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

Semi-inclusive jet function in SCET at NLO

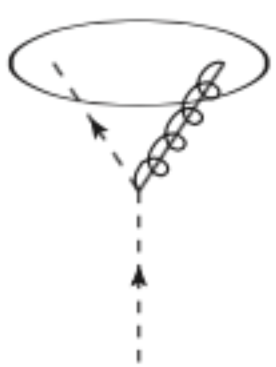
Leading order $J_q^{(0)}(z, \omega_J) = \delta(1 - z)$

Semi-inclusive jet function in SCET at NLO

Leading order $\quad J_q^{(0)}(z,\omega_J) = \delta(1-z)$

Next-to-leading order

(A) (B) (C) (D)



(A)

$$J_q(z,\omega_J) = \delta(1-z)\frac{\alpha_s}{\pi}\left(\frac{\mu^2 e^{\gamma_E}}{4\pi}\right)^{\epsilon}\int_0^1 dx \hat{P}_{qq}(x,\epsilon)\int \frac{dq_\perp}{q_\perp^{1+2\epsilon}}\Theta_{\rm alg}$$

where: anti-k$_T$: $\Theta_{\text{anti-k}_T} = \theta\left(x(1-x)\omega_J \tan\frac{R}{2} - q_\perp\right)$

$$\hat{P}_{qq}(x,\epsilon) = C_F\left[\frac{1+x^2}{1-x} - \epsilon(1-x)\right]$$

$$x = \frac{\ell^- - q^-}{\ell^-}$$

Semi-inclusive jet function in SCET at NLO

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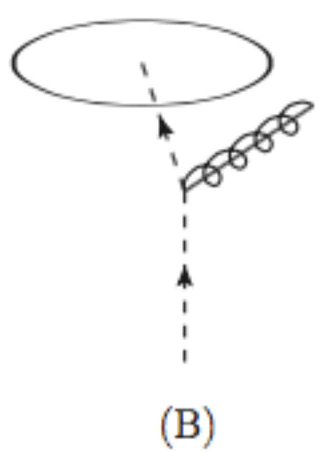
Next-to-leading order

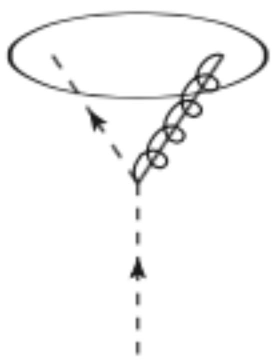


$$J_{q\to q(g)}(z,\omega_J) = \frac{\alpha_s}{\pi}\left(\frac{\mu^2 e^{\gamma_E}}{4\pi}\right)^{\epsilon} \hat{P}_{qq}(z,\epsilon)\int \frac{dq_\perp}{q_\perp^{1+2\epsilon}}\Theta_{\rm alg}$$

where: $$\Theta_{\text{anti-k}_{\rm T}} = \theta\left(q_\perp - (1-z)\omega_J \tan\frac{R}{2}\right)$$

Semi-inclusive jet function

$\overline{\text{MS}}$ scheme, anti-$\mathrm{k_T}$



(A)

$$J_q(z,\omega_J) = \delta(1-z)\frac{\alpha_s}{2\pi}C_F\left[\frac{1}{\epsilon^2}+\frac{3}{2\epsilon}+\frac{1}{\epsilon}L+\frac{1}{2}L^2+\frac{3}{2}L+\frac{13}{2}-\frac{3\pi^2}{4}\right]$$

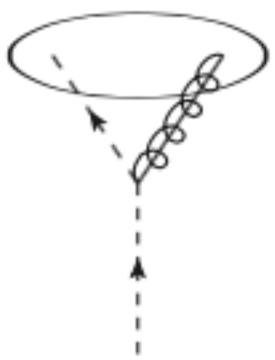
Essentially the same result as in the exclusive case

Ellis, Vermilion, Walsh, Hornig, Lee `10

where $L = \ln\left(\dfrac{\mu^2}{\omega_J^2\tan^2(R/2)}\right)$

Semi-inclusive jet function

$\overline{\text{MS}}$ scheme, anti-k_T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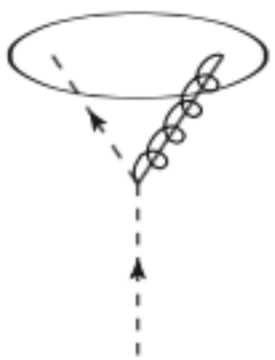
Exclusive cross section: double logarithmic dependence $\ln^2 R$

multiplicative renormalization

Semi-inclusive jet function

$\overline{\mathrm{MS}}$ scheme, $\mathrm{anti}\text{-}k_T$



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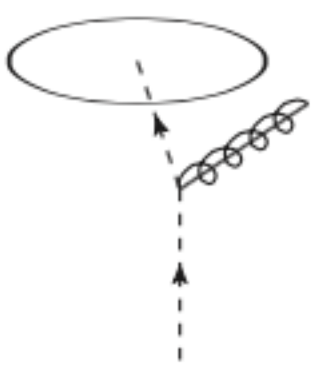


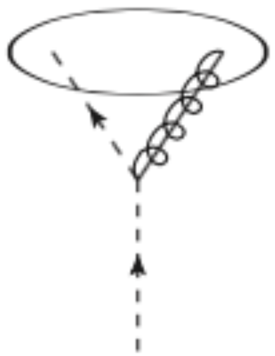
(B)

$$J_q(z,\omega_J) = \frac{\alpha_s}{2\pi}\delta(1-z)\left[-\frac{1}{\epsilon^2}-\frac{1}{\epsilon}L-\frac{1}{2}L^2+\frac{\pi^2}{12}\right]$$
$$+\frac{\alpha_s}{2\pi}\left[\left(\frac{1}{\epsilon}+L\right)\frac{1+z^2}{(1-z)_+}-2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+-(1-z)\right]$$

(C) …

Semi-inclusive jet function

$\overline{\mathrm{MS}}$ scheme, $\mathrm{anti}\text{-}\mathrm{k_T}$



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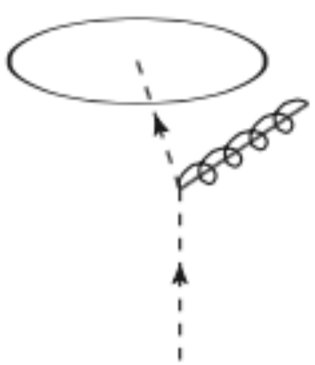
where $\quad L = \ln\left(\frac{\mu^2}{\omega_J^2\tan^2(R/2)}\right)$



(B)

$$J_q(z,\omega_J) = \frac{\alpha_s}{2\pi}\delta(1-z)\left[-\frac{1}{\epsilon^2}-\frac{1}{\epsilon}L-\frac{1}{2}L^2+\frac{\pi^2}{12}\right] + \frac{\alpha_s}{2\pi}\left[\left(\frac{1}{\epsilon}+L\right)\frac{1+z^2}{(1-z)_+}-2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+-(1-z)\right]$$

(C) ... $\longrightarrow$ only a single logarithmic $\ln R$ remains

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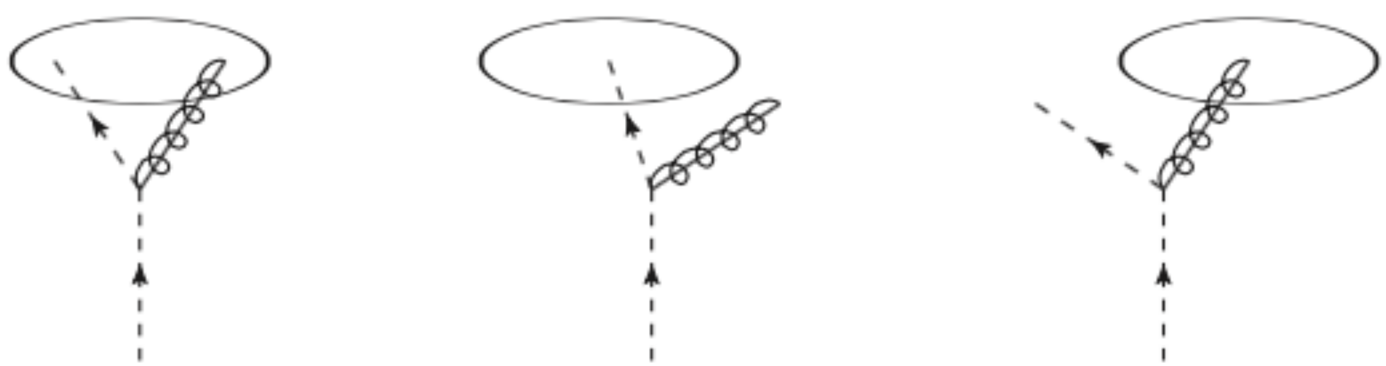
Semi-inclusive jet function in SCET at NLO

$\overline{\mathrm{MS}}$ scheme, anti-$\mathrm{k_T}$

$$J_q^{(1)}(z,\omega_J) = J_{q\to qg}(z,\omega_J) + J_{q\to q(g)}(z,\omega_J) + J_{q\to (q)g}(z,\omega_J)$$

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

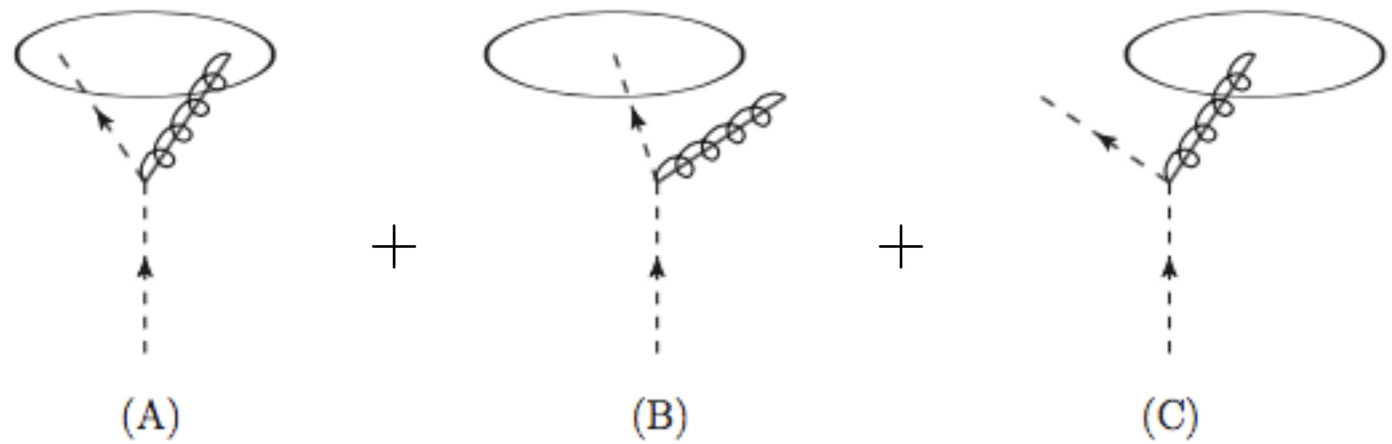
where $d_J^{q,\mathrm{anti\text{-}k_T}} = C_F\left(\frac{13}{2} - \frac{2\pi^2}{3}\right)$



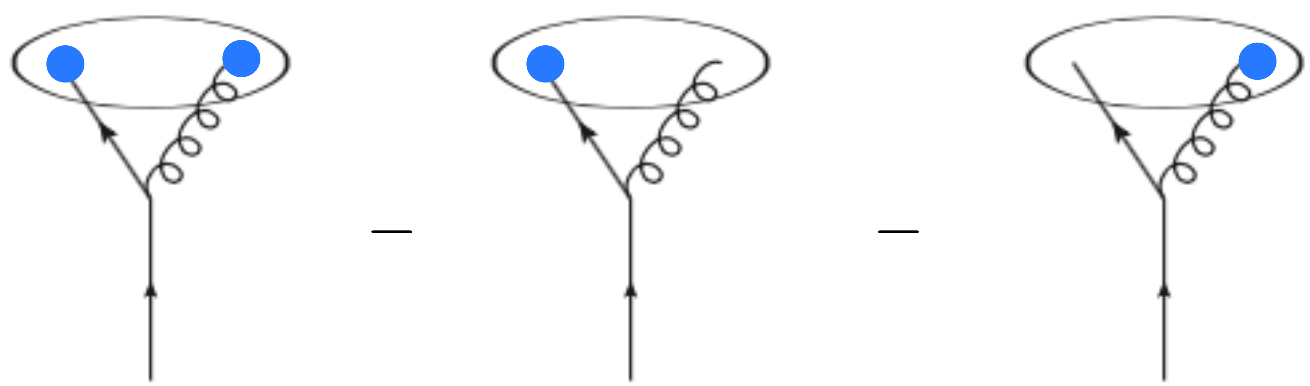
(A) (B) (C)

SCET vs. pQCD

SCET:



pQCD:



NJA: using a collinear splitting

Renormalization and RG evolution

Bare - renormalized semi-inclusive jet function

$$J_{i,\mathrm{bare}}(z,\omega_J) = \sum_j \int_z^1 \frac{dz'}{z'} Z_{ij}\left(\frac{z}{z'},\mu\right) J_j(z',\omega_J,\mu)$$

RG equation

$$\mu\frac{d}{d\mu}J_i(z,\omega_J,\mu) = \sum_j \int_z^1 \frac{dz'}{z'} \gamma_{ij}^J\left(\frac{z}{z'},\mu\right) J_j(z',\omega_J,\mu)$$

Anomalous dimension

$$\gamma_{ij}^J(z,\mu) = -\sum_k \int_z^1 \frac{dz'}{z'} (Z)_{ik}^{-1}\left(\frac{z}{z'},\mu\right) \mu\frac{d}{d\mu} Z_{kj}(z',\mu)$$

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Renormalization and RG evolution

We find

$$\gamma_{ij}^{J}(z,\mu) = \frac{\alpha_s(\mu)}{\pi} P_{ji}(z)$$

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

DGLAP evolution equation like for FFs. Resums single $\ln R$: LL_R, NLL_R

see also
Dasgupta, Dreyer, Salam, Soyez `15, `16

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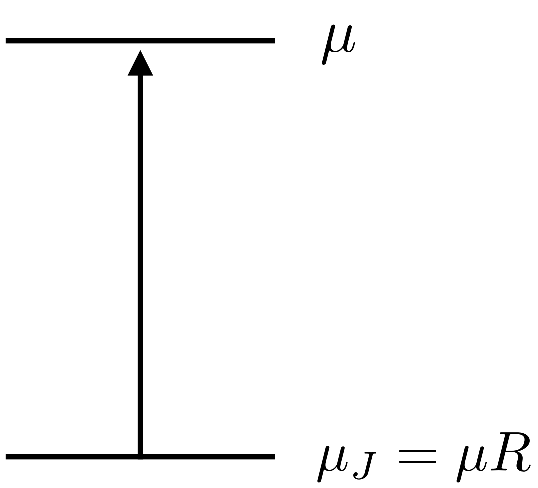
Jet function evolution

$$\frac{d}{d\log\mu^2}\begin{pmatrix} J_S(z,\omega_J,\mu) \\ J_g(z,\omega_J,\mu) \end{pmatrix} = \frac{\alpha_s(\mu)}{2\pi}\begin{pmatrix} P_{qq}(z) & 2N_f P_{gq}(z) \\ P_{qg}(z) & P_{gg}(z) \end{pmatrix} \otimes \begin{pmatrix} J_S(z,\omega_J,\mu) \\ J_g(z,\omega_J,\mu) \end{pmatrix}$$



initial condition contains distributions in $1-z$

where $J_S(z,\omega_J,\mu) = \sum_{q,\bar{q}} J_q(z,\omega_J,\mu) = 2N_f J_q(z,\omega_J,\mu)$ (singlet jet function)

Jet function evolution

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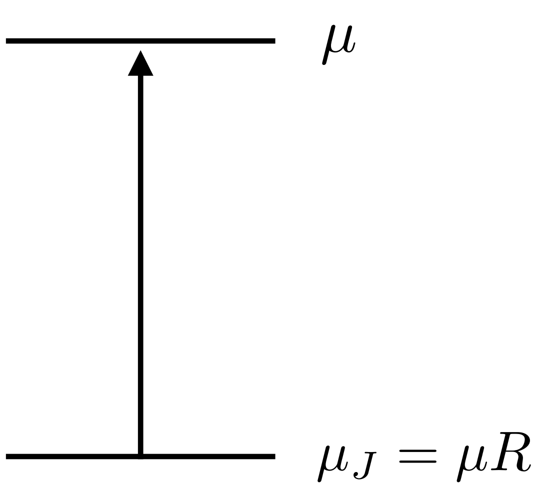

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solve in Mellin space: $f(N) = \int_0^1 dz\, z^{N-1} f(z)$

$$(f\otimes g)(N) = f(N)\, g(N)$$

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Jet function evolution

solve in Mellin space to LL_R

$$\begin{pmatrix} J_S(N,\omega_J,\mu) \\ J_g(N,\omega_J,\mu) \end{pmatrix} = \left[e_+(N) \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_J)} \right)^{-r_-(N)} + e_-(N) \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_J)} \right)^{-r_+(N)} \right] \begin{pmatrix} J_S(N,\omega_J,\mu_J) \\ J_g(N,\omega_J,\mu_J) \end{pmatrix}$$

where $$e_\pm(N) = \frac{1}{r_\pm(N) - r_\mp(N)} \begin{pmatrix} P_{qq}(N) - r_\mp(N) & 2N_f P_{gq}(N) \\ P_{qg}(N) & P_{gg}(N) - r_\mp(N) \end{pmatrix}$$

$$r_\pm(N) = \frac{1}{2\beta_0} \left[P_{qq}(N) + P_{gg}(N) \pm \sqrt{(P_{qq}(N) - P_{gg}(N))^2 + 4P_{qg}(N)P_{gq}(N)} \right]$$

see
Vogt `04 (Pegasus),
Anderle, FR, Stratmann `15

Jet function evolution

solve in Mellin space to LL_R

$$\begin{pmatrix} J_S(N,\omega_J,\mu) \\ J_g(N,\omega_J,\mu) \end{pmatrix} = \left[e_+(N) \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_J)}\right)^{-r_-(N)} + e_-(N) \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_J)}\right)^{-r_+(N)} \right] \begin{pmatrix} J_S(N,\omega_J,\mu_J) \\ J_g(N,\omega_J,\mu_J) \end{pmatrix}$$

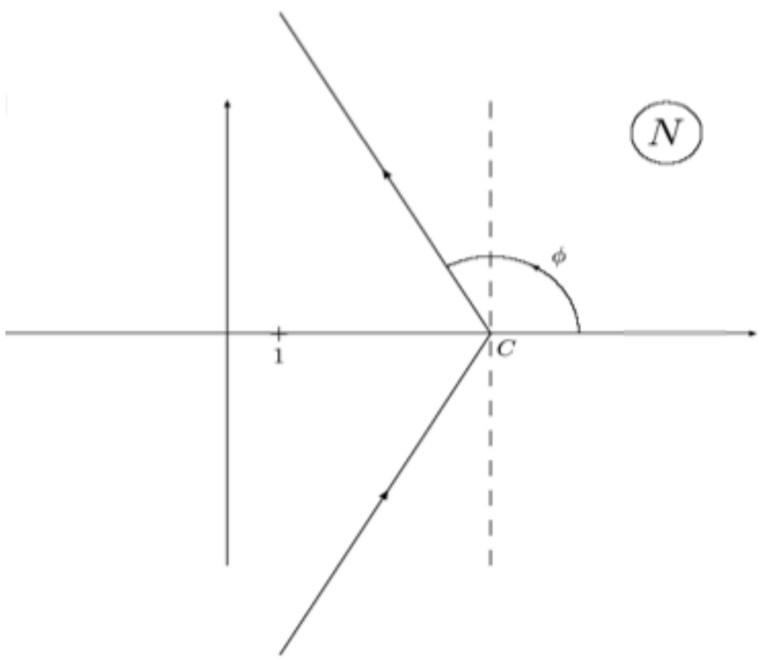
where $$e_\pm(N) = \frac{1}{r_\pm(N) - r_\mp(N)} \begin{pmatrix} P_{qq}(N) - r_\mp(N) & 2N_f P_{gq}(N) \\ P_{qg}(N) & P_{gg}(N) - r_\mp(N) \end{pmatrix}$$

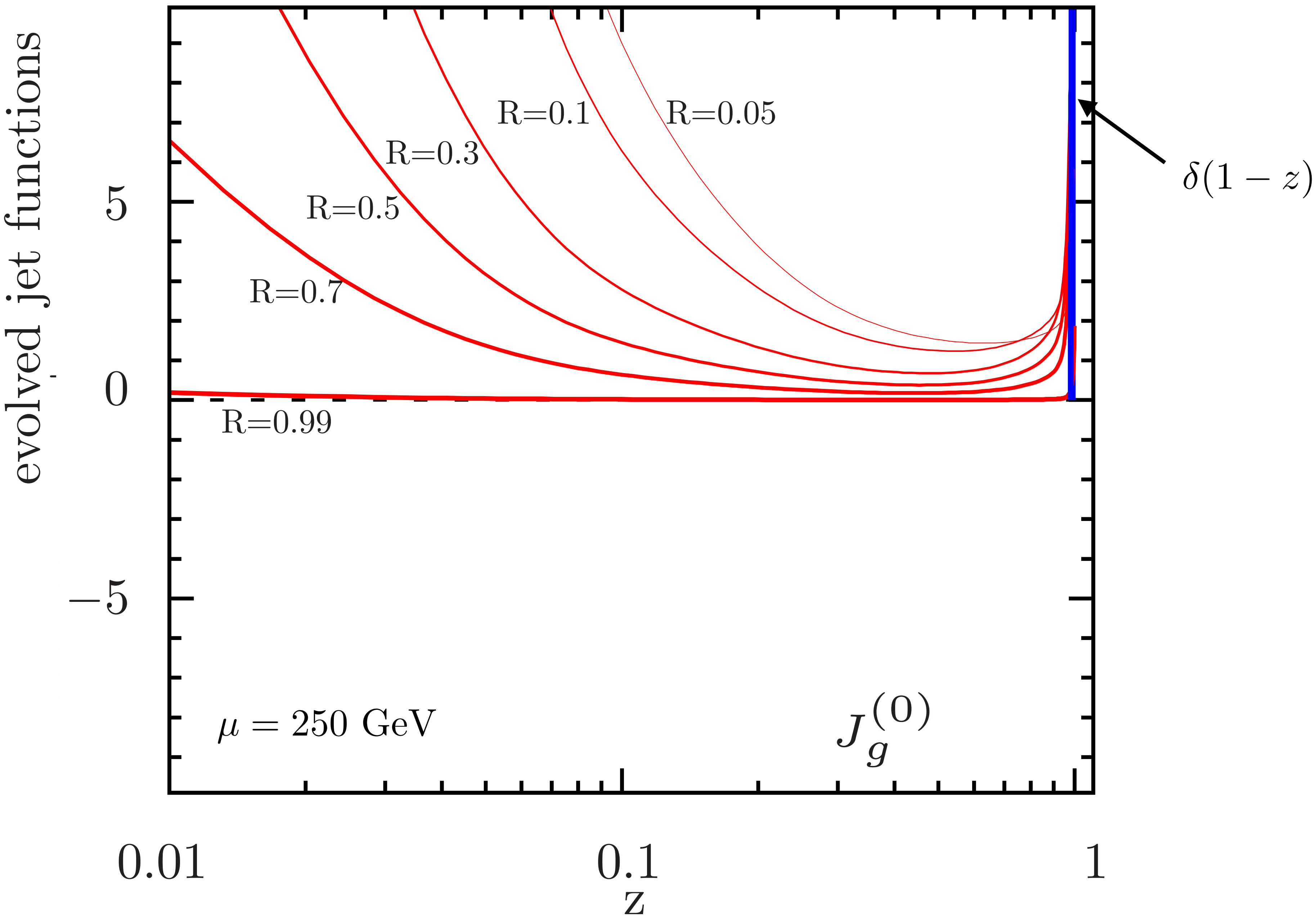
$$r_\pm(N) = \frac{1}{2\beta_0}\left[P_{qq}(N) + P_{gg}(N) \pm \sqrt{(P_{qq}(N) - P_{gg}(N))^2 + 4P_{qg}(N)P_{gq}(N)} \right]$$

see
Vogt `04 (Pegasus),
Anderle, FR, Stratmann `15

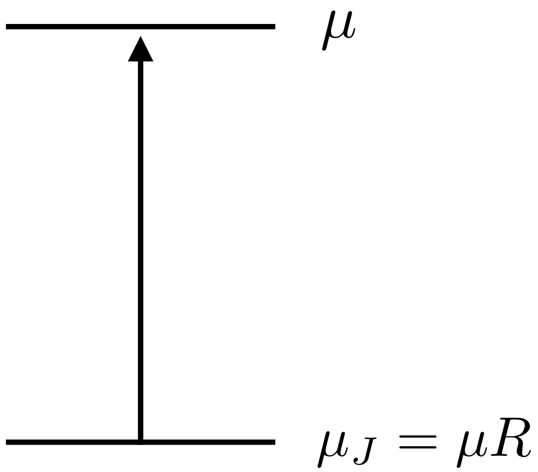
Mellin inverse

$$J_{S,g}(z,\omega_J,\mu) = \frac{1}{2\pi i}\int_{\mathcal{C}_N} dN\, z^{-N} J_{S,g}(N,\omega_J,\mu)$$

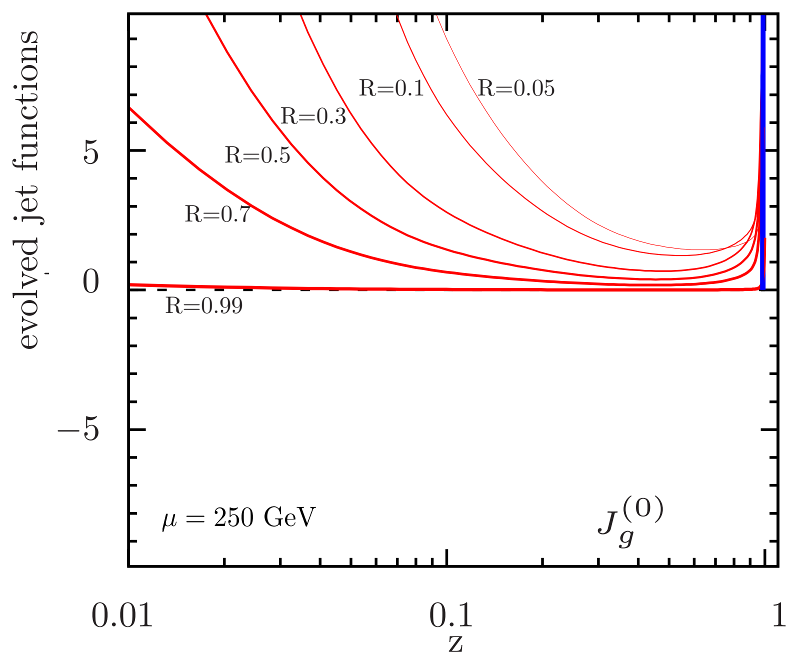




LL_R DGLAP evolution



see
Vogt `04 (Pegasus),
Anderle, FR, Stratmann `15

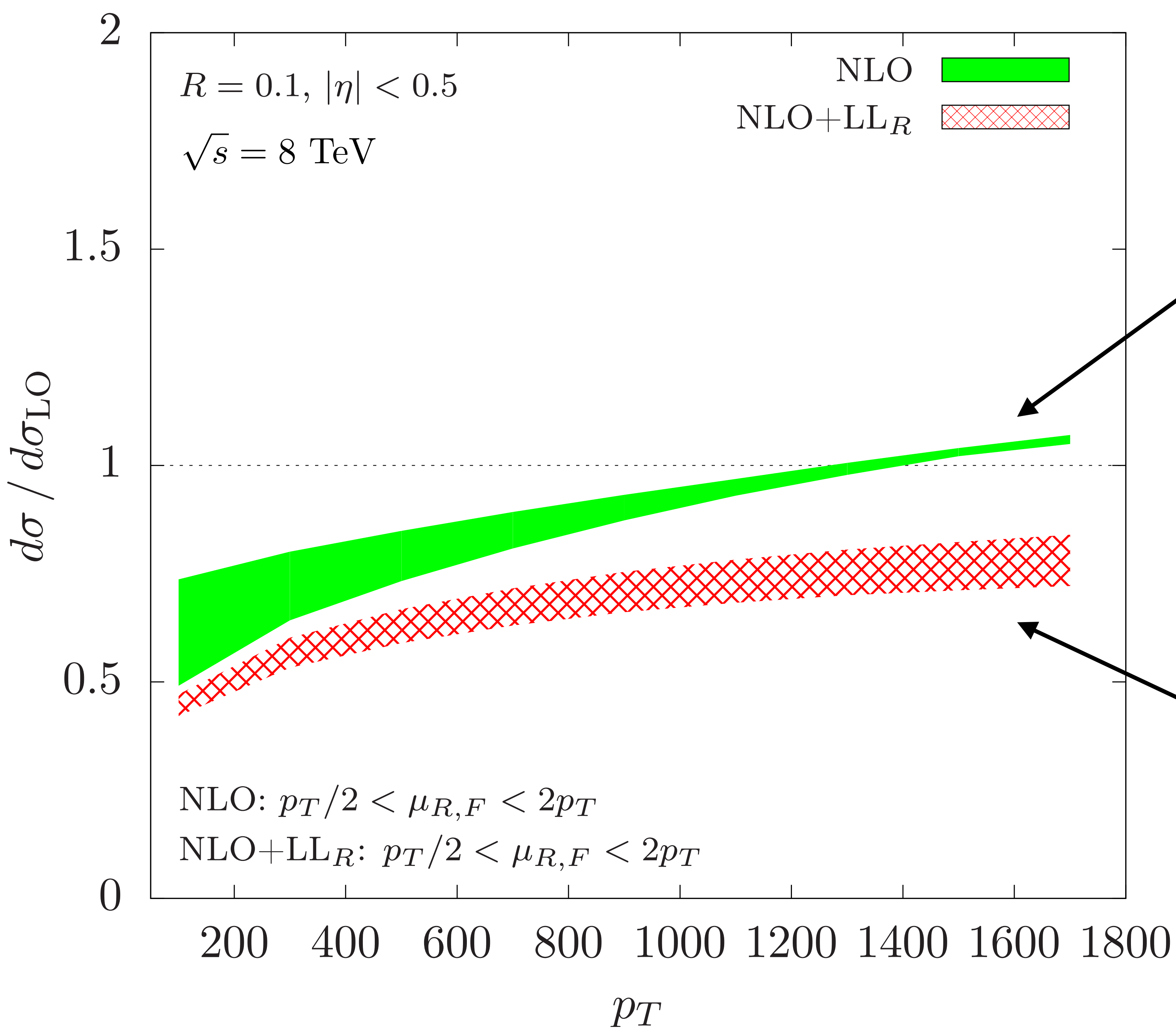


$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

- Resummation of $\alpha_s^n \ln^n R$
- Adopt a prescription used for quarkonium fragmentation functions

  Bodwin, Chao, Chung, Kim, Lee, Ma `16

LL_R DGLAP evolution

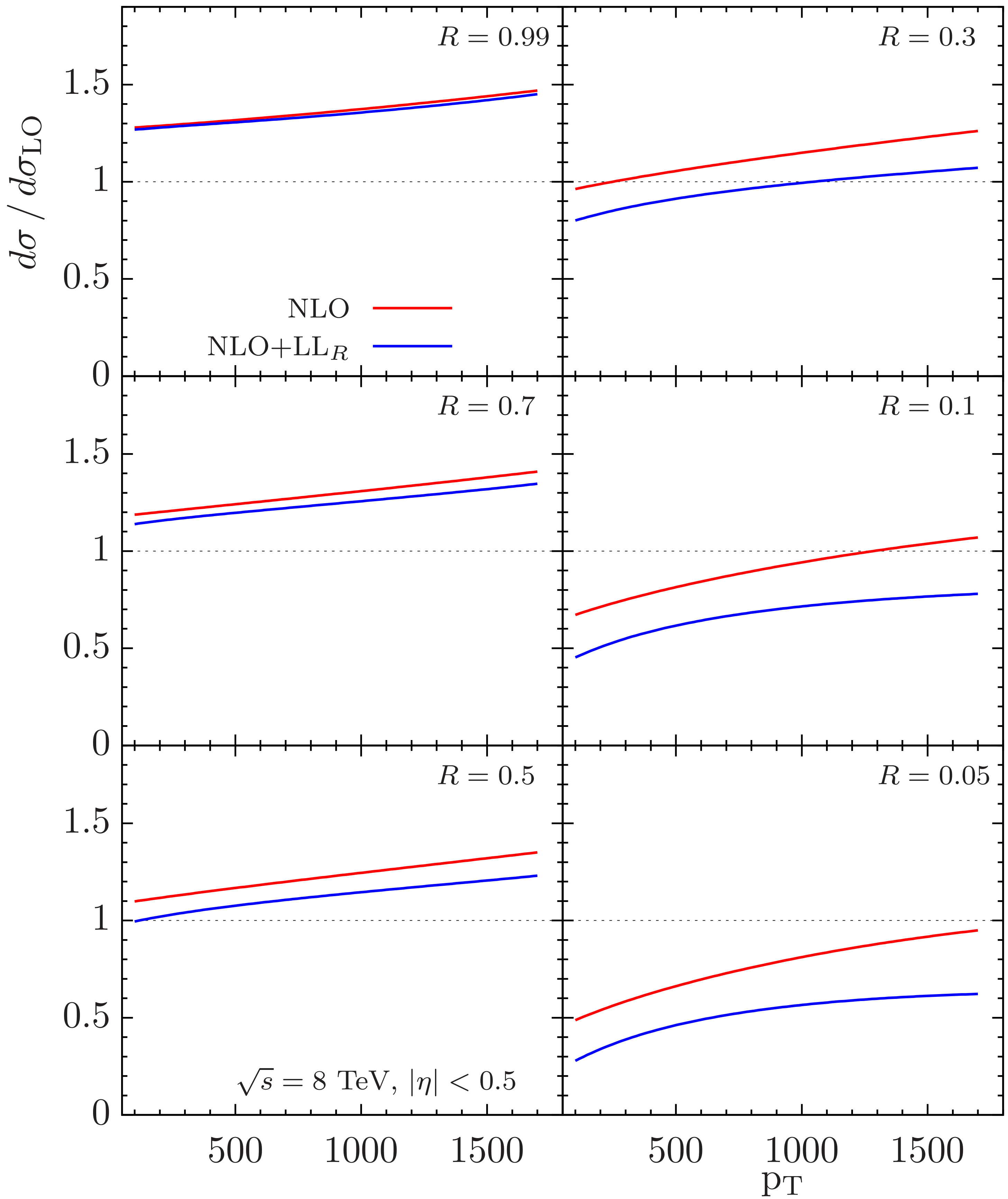


Vanishing, unphysical scale dependence

Note: same at NNLO (large-N_c)
Currie, Glover, Pires `16

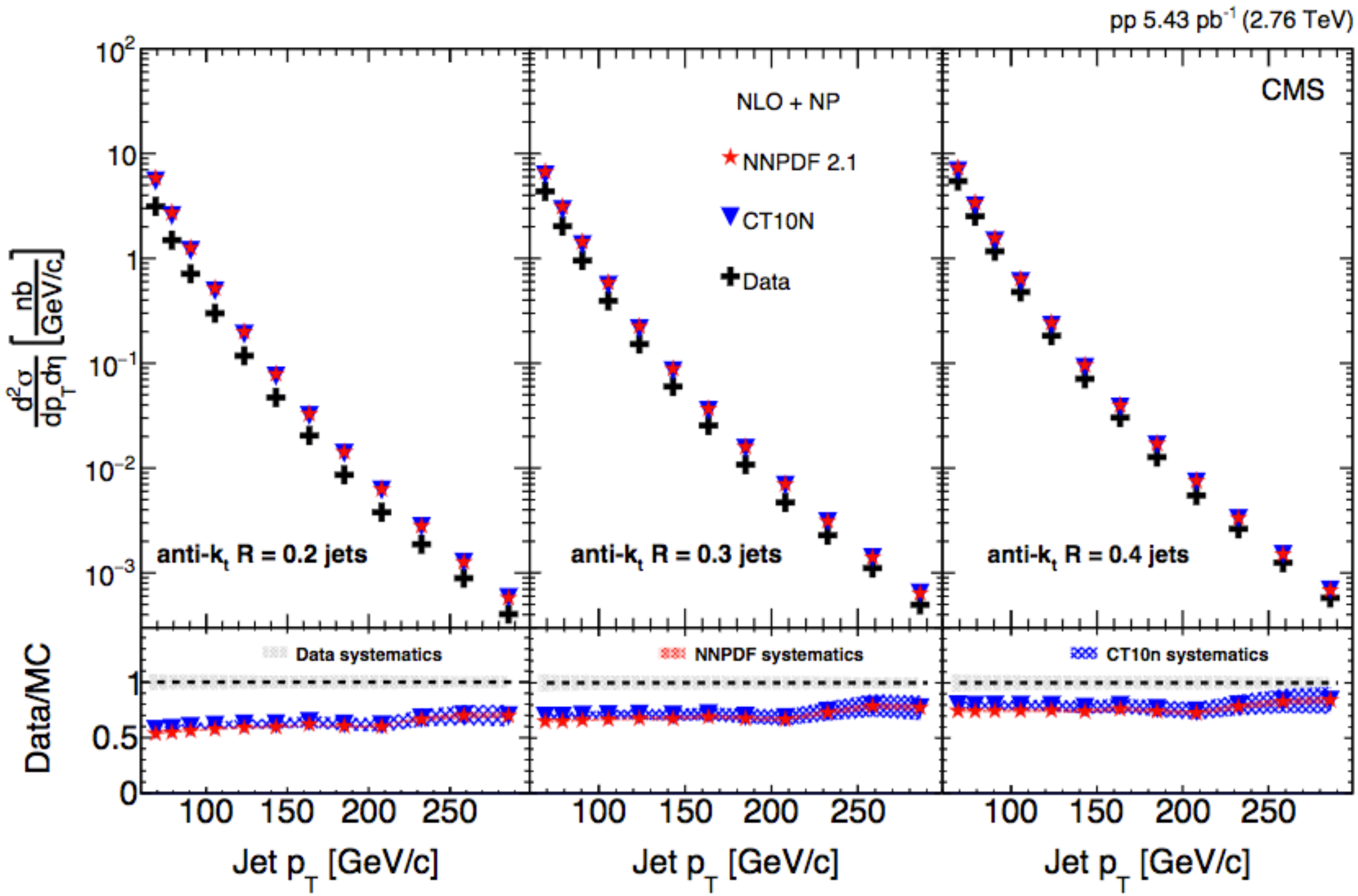
Additional final state factorization

see also
Dasgupta, Dreyer, Salam, Soyez `15, `16



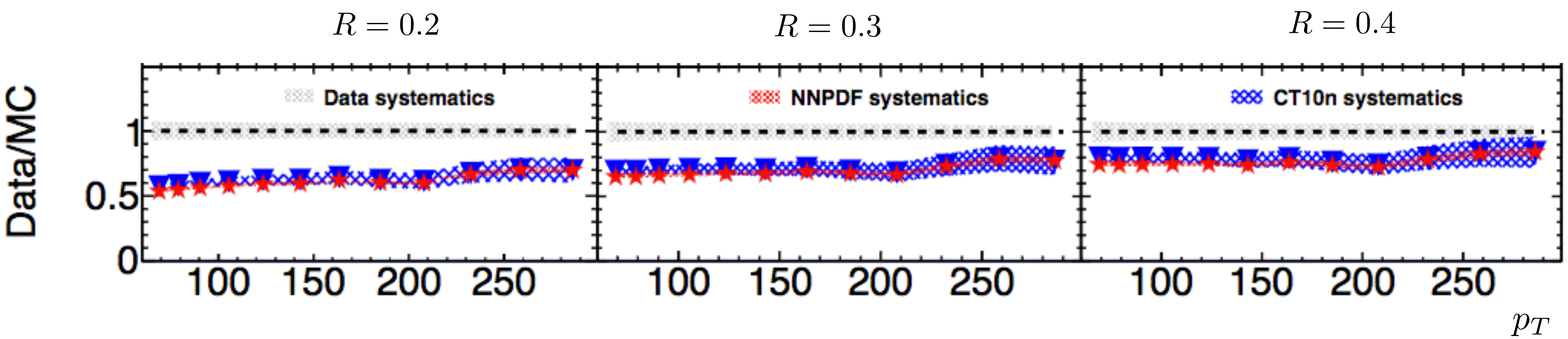
LL$_R$ DGLAP evolution

Inclusive Jet Production in SCET $pp \to \mathrm{jet}X$



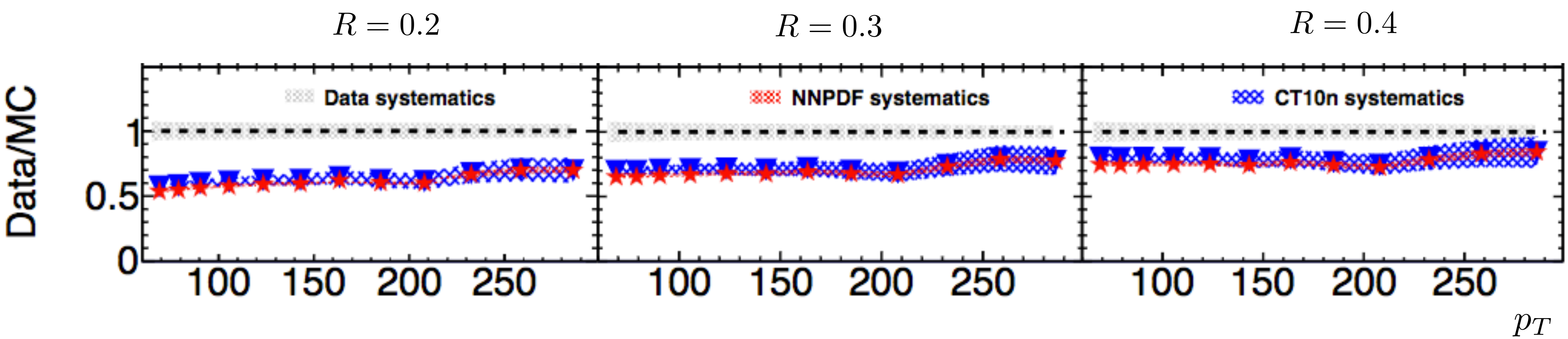
CMS data arXiv:1609.05383

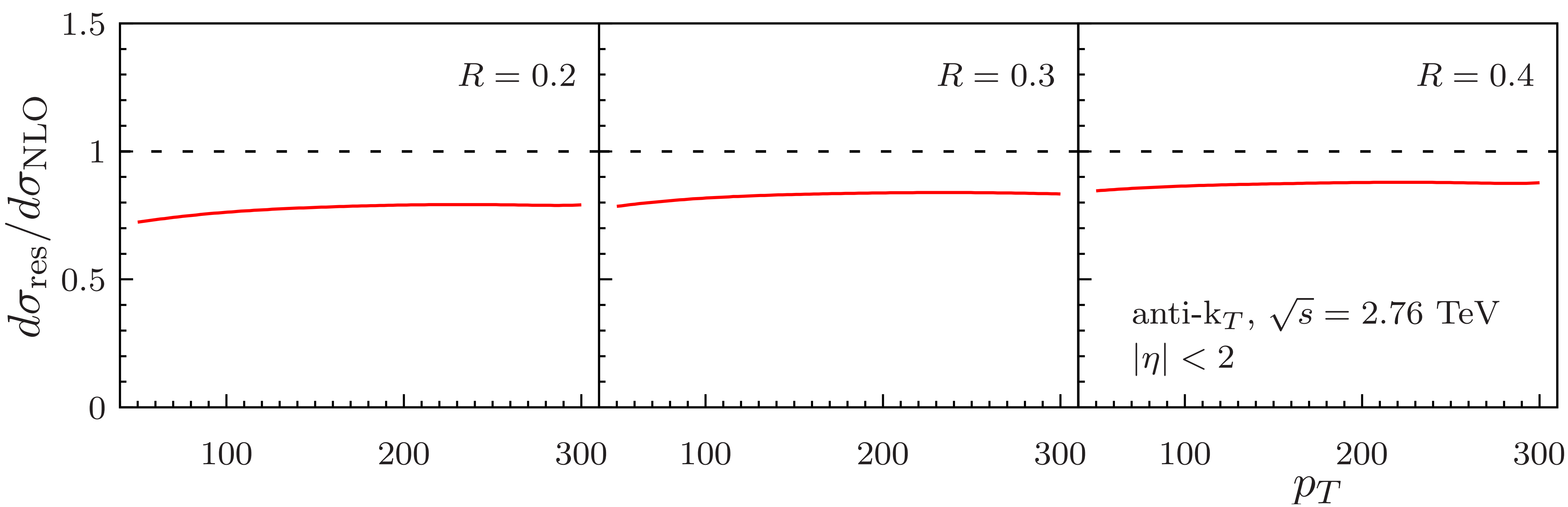
Inclusive Jet Production in SCET $pp \to \mathrm{jet}X$



CMS data arXiv:1609.05383

Inclusive Jet Production in SCET $pp \to \text{jet}X$





CMS data arXiv:1609.05383

Outline

Proton-proton

- Inclusive jets *Kang, FR, Vitev `16*
- The jet fragmentation function *Kang, FR, Vitev `16*

Heavy-ion

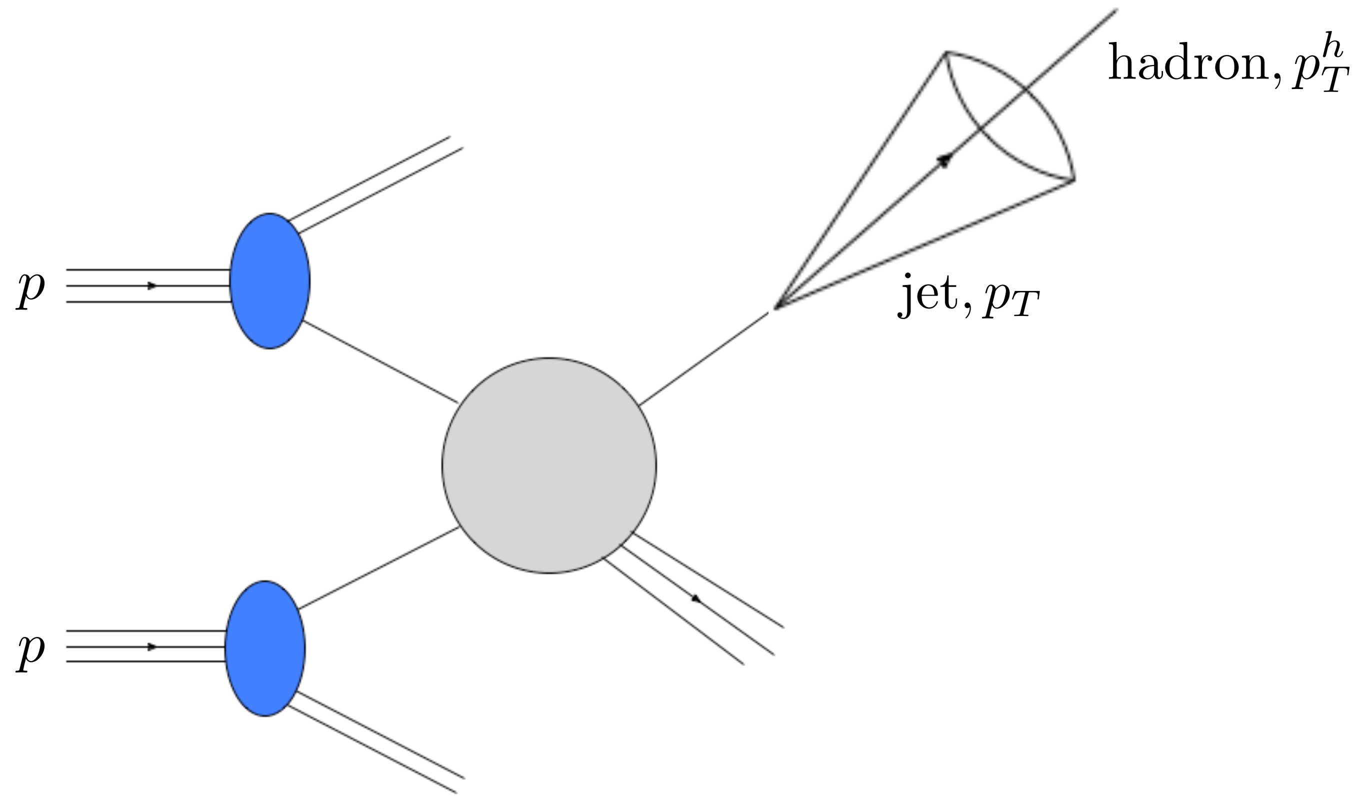
- SCET$_G$
- Inclusive jets *Kang, FR, Vitev `17*
- The jet fragmentation function *Chien, Kang, FR, Vitev, Xing - in preparation*

Conclusions

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

- Jet substructure observable studying the distribution of hadrons inside a jet

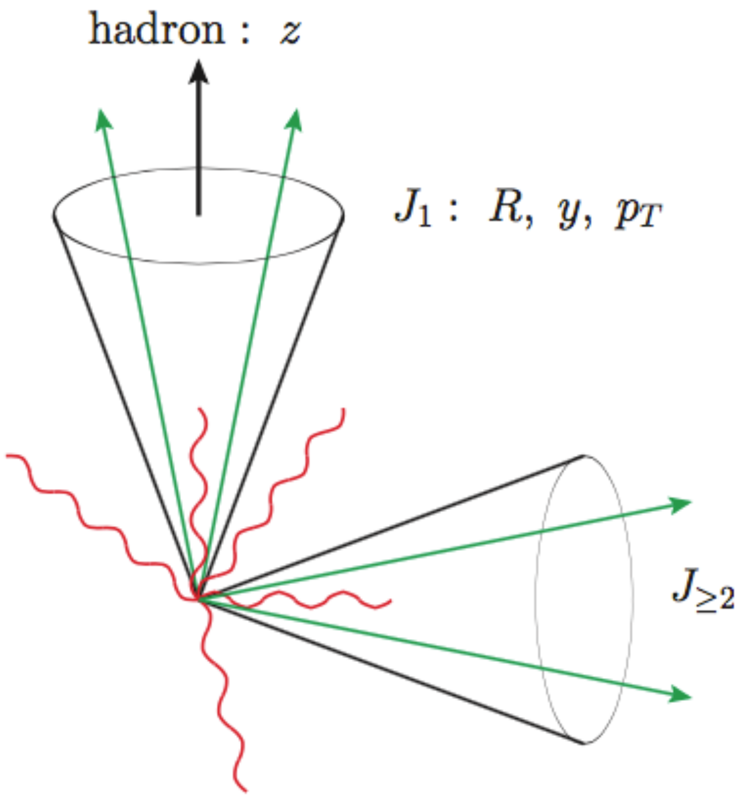
- Provides further constraints for fits of fragmentation functions
- Possible studies include spin correlations and TMDs
- Differential probe for the modification of jets in AA and eA



Jet fragmentation function

Definition: $$F(z, p_T) = \frac{d\sigma^h}{dy dp_T dz} \Big/ \frac{d\sigma}{dy dp_T}$$

where $$z \equiv p_T^h / p_T$$



It describes the longitudinal momentum distribution of hadrons inside a reconstructed jet

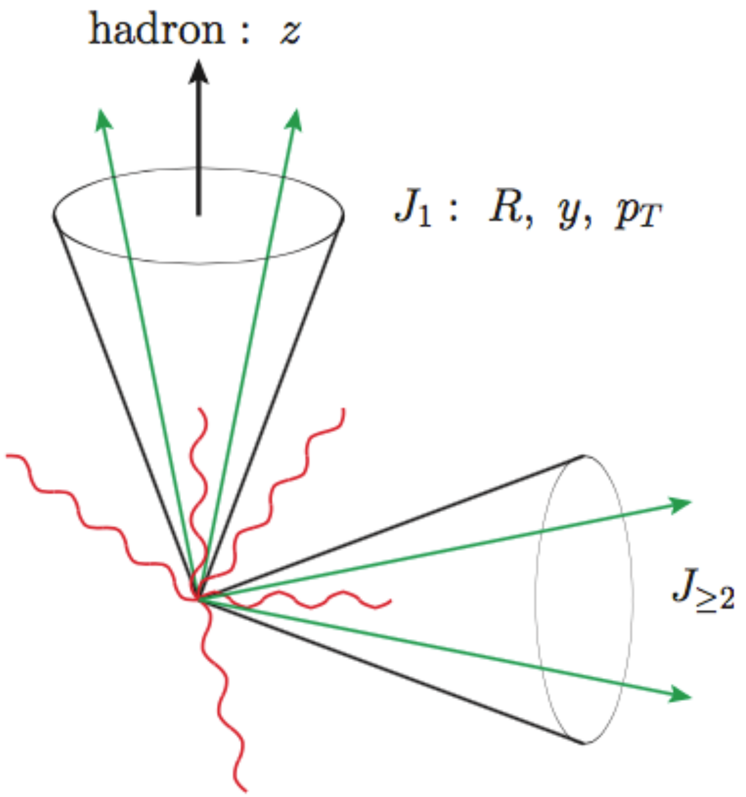
Jet fragmentation function in pp

- Fragmenting jet function studies within SCET

  Procura, Stewart `10; Liu `11; Jain, Procura, Waalewijn `11 and '12; Procura, Waalewijn `12; Bauer, Mereghetti `14; Baumgart, Leibovich, Mehen, Rothstein `14, Chien, Kang, FR, Vitev, Xing `15, Bain, Dai, Hornig, Leibovich, Makris, Mehen `16, Bain, Makris, Mehen `16 …

- Jet fragmentation function studies at NLO for pp

  Arleo, Fontannaz, Guillet, Nguyen `14, Kaufmann, Mukherjee, Vogelsang `15



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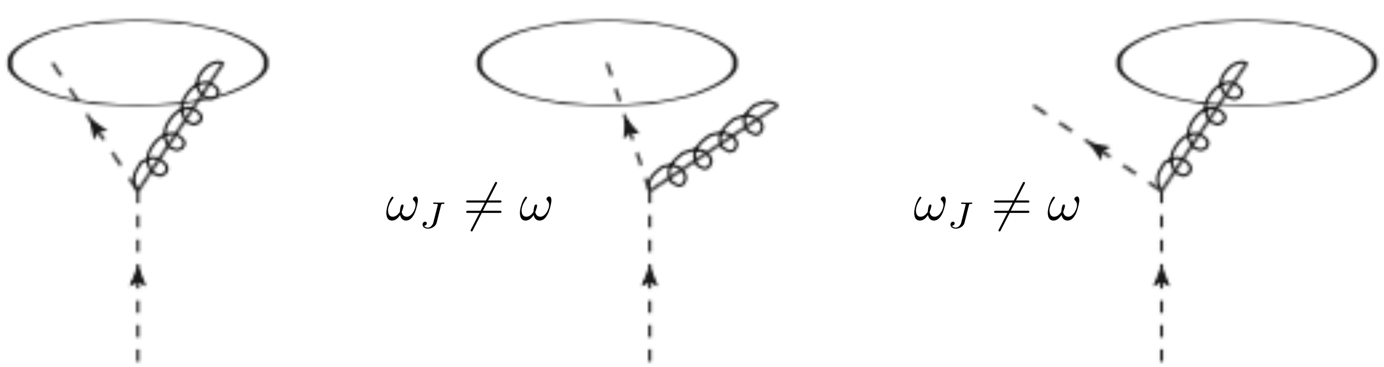
Semi-inclusive fragmenting jet function

$$\mathcal{G}_q(z, z_h, \omega_J) \qquad \text{where} \qquad z = \frac{\omega_J}{\omega}, \quad z_h = \frac{\omega_h}{\omega_J}$$

Leading-order, e.g. $\mathcal{G}_q^{q,(0)}(z, z_h, \omega_J) = \delta(1-z)\delta(1-z_h)$

NLO

• fragmenting parton	$\omega_h \neq \omega_J$	$\omega_h = \omega_J$	$\omega_h = \omega_J$
• jet	$\omega_J = \omega$	$\omega_J \neq \omega$	$\omega_J \neq \omega$
• initiating parton	ω	ω	ω



Semi-inclusive jet function

(A) (B) (C) (D)

quark-quark:

$$\begin{aligned}\mathcal{G}^q_{q,\mathrm{bare}}(z, z_h, \omega_J, \mu) =& \, \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\left(-\frac{1}{\epsilon} - L\right) P_{qq}(z_h)\delta(1-z) \\ &+ \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + L\right) P_{qq}(z)\delta(1-z_h) \\ &+ \delta(1-z)\frac{\alpha_s}{2\pi}\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + 2P_{qq}(z_h)\ln z_h\right] \\ &- \delta(1-z_h)\frac{\alpha_s}{2\pi}\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right],\end{aligned}$$

$\overline{\mathrm{MS}}$ scheme, $\mathrm{anti}{-}k_T$

Semi-inclusive jet function

(A) (B) (C) (D)

quark-quark:

$$
\begin{aligned}
\mathcal{G}^q_{q,\mathrm{bare}}(z, z_h, \omega_J, \mu) = &\, \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi} \overset{\text{IR}}{\left(-\frac{1}{\epsilon} - L\right)} P_{qq}(z_h)\delta(1-z) \\
& + \frac{\alpha_s}{2\pi} \overset{\text{UV}}{\left(\frac{1}{\epsilon} + L\right)} P_{qq}(z)\delta(1-z_h) \\
& + \delta(1-z)\frac{\alpha_s}{2\pi}\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + 2P_{qq}(z_h)\ln z_h\right] \\
& - \delta(1-z_h)\frac{\alpha_s}{2\pi}\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right],
\end{aligned}
$$

$\overline{\mathrm{MS}}$ scheme, $\mathrm{anti}{-}k_T$

Renormalization and RG evolution

Bare - renormalized:

$$\mu\frac{d}{d\mu}\mathcal{G}_i^j(z,z_h,\omega_J,\mu)=\sum_j\int_z^1\frac{dz'}{z'}\gamma_{ik}^{\mathcal{G}}\left(\frac{z}{z'},\mu\right)\mathcal{G}_k^j(z',z_h,\omega_J,\mu)$$

where

$$\gamma_{ij}^{\mathcal{G}}(z,\mu)=\frac{\alpha_s(\mu)}{\pi}P_{ji}(z)$$

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

… same DGLAP RG equations as before, resums $\ln R$

$$\longrightarrow\qquad \frac{d}{d\log\mu^2}\begin{pmatrix}\mathcal{G}_S^h(z,z_h,\omega_J,\mu)\\ \mathcal{G}_g^h(z,z_h,\omega_J,\mu)\end{pmatrix}=\frac{\alpha_s(\mu)}{2\pi}\begin{pmatrix}P_{qq}(z) & 2N_fP_{gq}(z)\\ P_{qg}(z) & P_{gg}(z)\end{pmatrix}\otimes\begin{pmatrix}\mathcal{G}_S^h(z,z_h,\omega_J,\mu)\\ \mathcal{G}_g^h(z,z_h,\omega_J,\mu)\end{pmatrix}$$

+ non-singlet evolution

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Matching

- onto standard collinear fragmentation functions

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

FFs:

$$D_i^j(z, \mu) = \delta_{ij}\delta(1-z) + \frac{\alpha_s}{2\pi} P_{ji}(z)\left(-\frac{1}{\epsilon}\right)$$

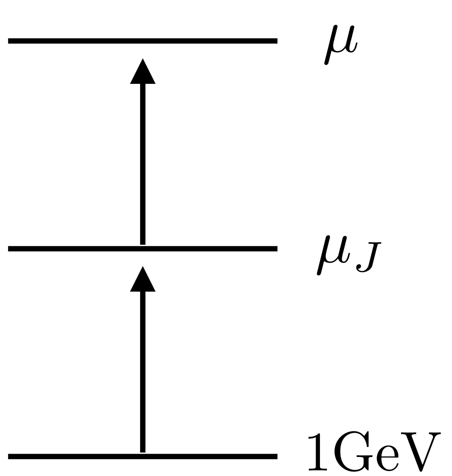
$$\begin{aligned}\mathcal{J}_{qq}(z, z_h, \omega_J, \mu) = \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\Big\{ & L\left[P_{qq}(z)\delta(1-z_h) - P_{qq}(z_h)\delta(1-z)\right] \\ & + \delta(1-z)\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + \mathcal{I}_{qq}^{\mathrm{alg}}(z_h)\right] \\ & - \delta(1-z_h)\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right]\Big\},\end{aligned}$$

$\overline{\mathrm{MS}}$ scheme, $\mathrm{anti}-k_T$

pQCD: *Kaufmann, Mukherjee, Vogelsang `15*

Matching

- onto standard collinear fragmentation functions



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

FFs: $$D_i^j(z, \mu) = \delta_{ij}\delta(1-z) + \frac{\alpha_s}{2\pi} P_{ji}(z)\left(-\frac{1}{\epsilon}\right)$$

… 2 DGLAPs now

$$\begin{aligned}\mathcal{J}_{qq}(z, z_h, \omega_J, \mu) = \delta(1-z)\delta(1-z_h) + \frac{\alpha_s}{2\pi}\Big\{ & L\left[P_{qq}(z)\delta(1-z_h) - P_{qq}(z_h)\delta(1-z)\right] \\ & + \delta(1-z)\left[2C_F(1+z_h^2)\left(\frac{\ln(1-z_h)}{1-z_h}\right)_+ + C_F(1-z_h) + \mathcal{I}_{qq}^{\mathrm{alg}}(z_h)\right] \\ & - \delta(1-z_h)\left[2C_F(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + C_F(1-z)\right]\Big\},\end{aligned}$$

$\overline{\mathrm{MS}}$ scheme, $\mathrm{anti}{-}k_T$

pQCD: *Kaufmann, Mukherjee, Vogelsang `15*

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Matching

- onto standard collinear fragmentation functions

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

- at the hard scale

$$\frac{d\sigma^{pp\to(\text{jet}h)X}}{dp_T d\eta dz_h} = \frac{2p_T}{s} \sum_{a,b,c} \int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a, \mu) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b, \mu) \int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}_{ab}^c(\hat{s}, \hat{p}_T, \hat{\eta}, \mu)}{dvdz} \boxed{\mathcal{G}_c^h(z_c, z_h, \omega_J, \mu)}$$

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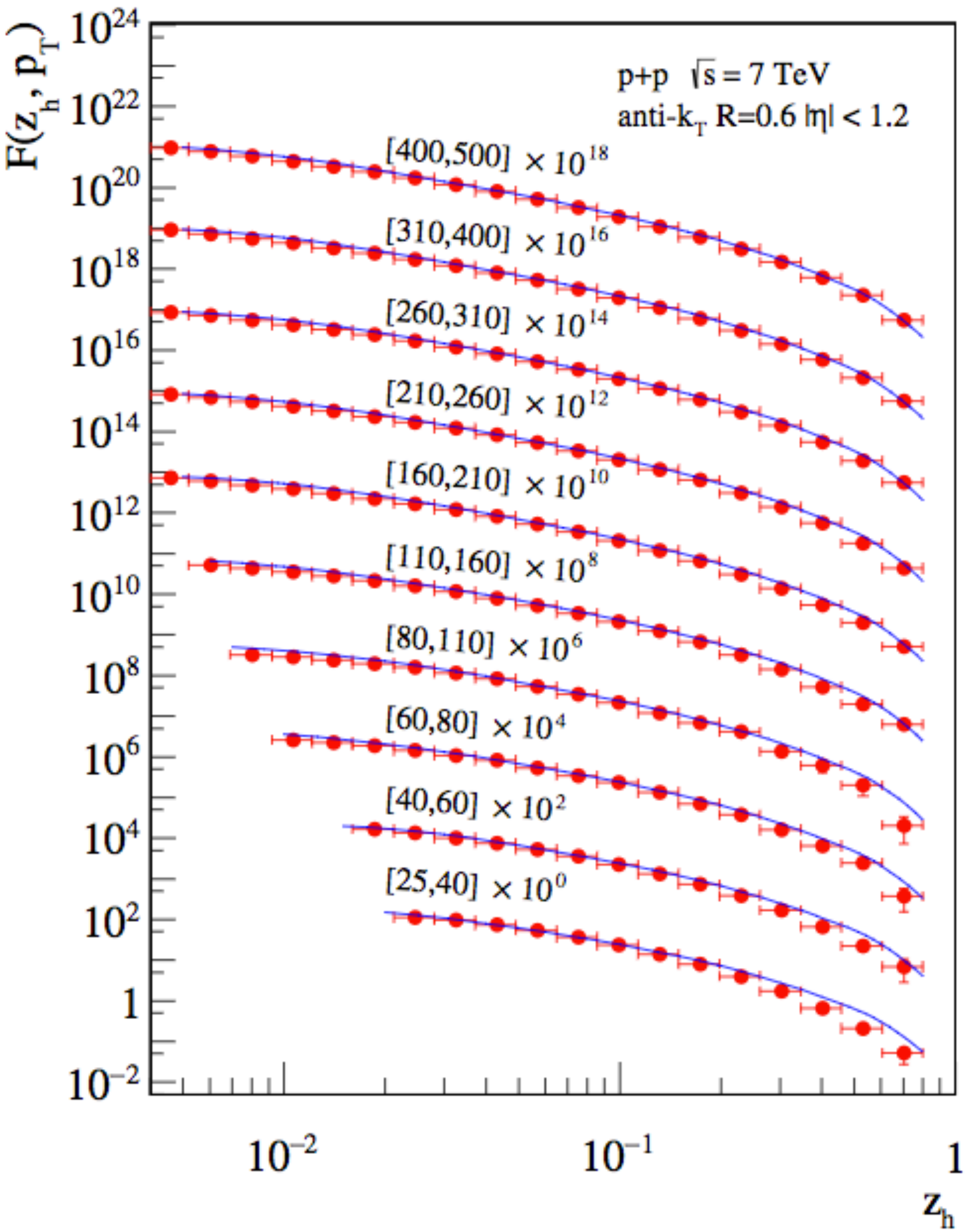
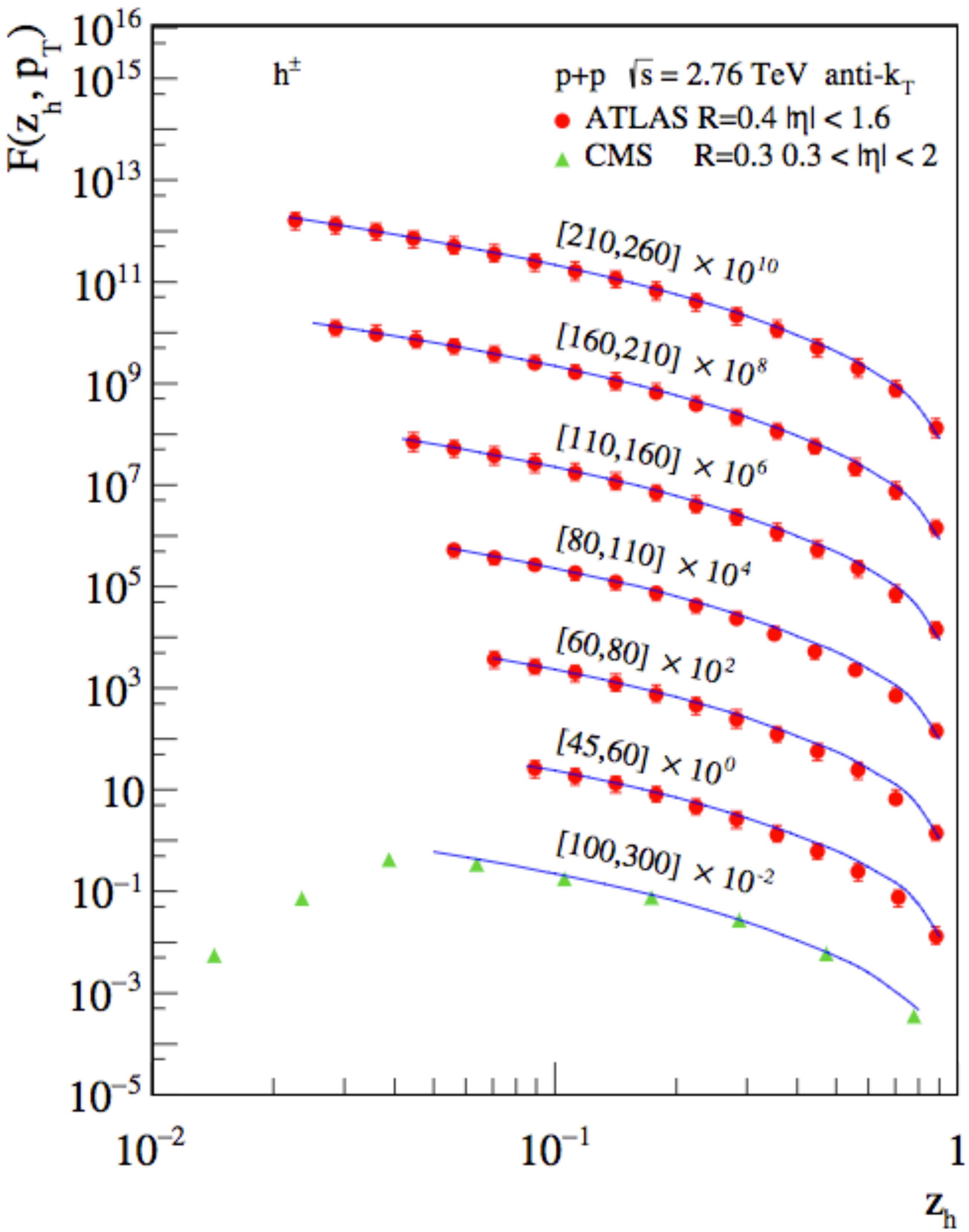


Comparison to ATLAS data at $\sqrt{s} = 7\,\mathrm{TeV}$

Light charged hadrons $h = \pi + K + p$

Using DSS FFs

de Florian, Sassot, Stratmann - '07



Comparison to ATLAS and CMS data at $\sqrt{s} = 2.76\,\mathrm{TeV}$

Light charged hadrons $h = \pi + K + p$

Using DSS FFs

de Florian, Sassot, Stratmann - '07

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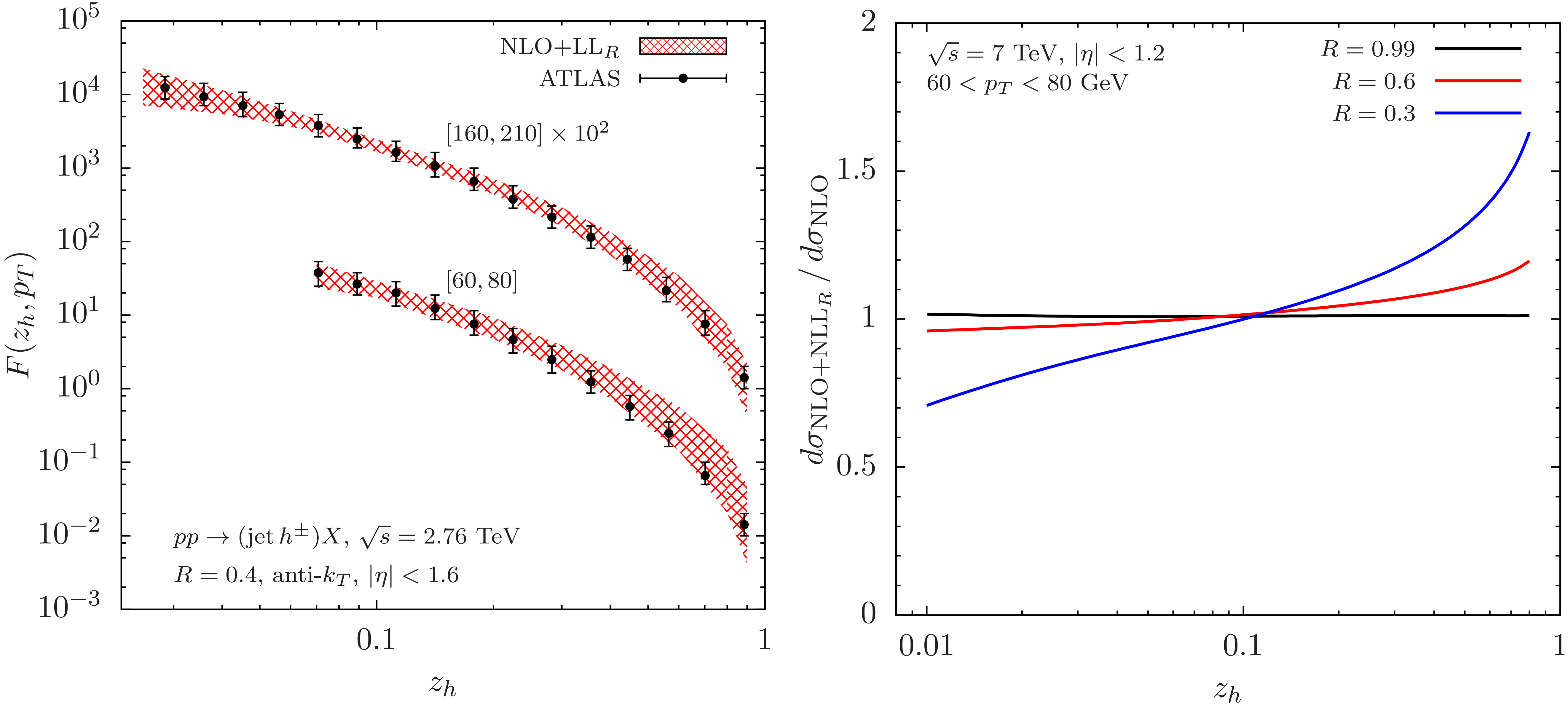

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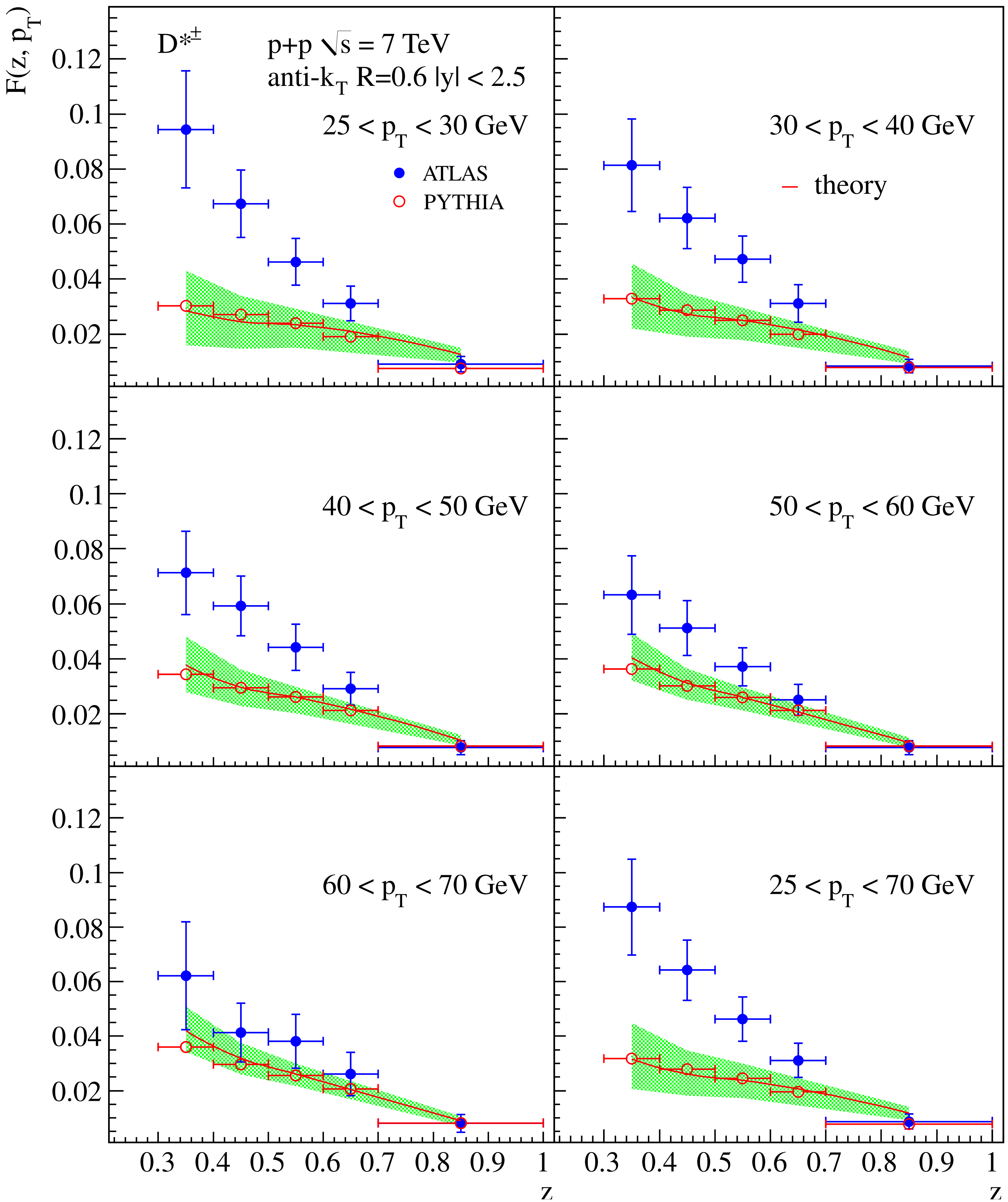


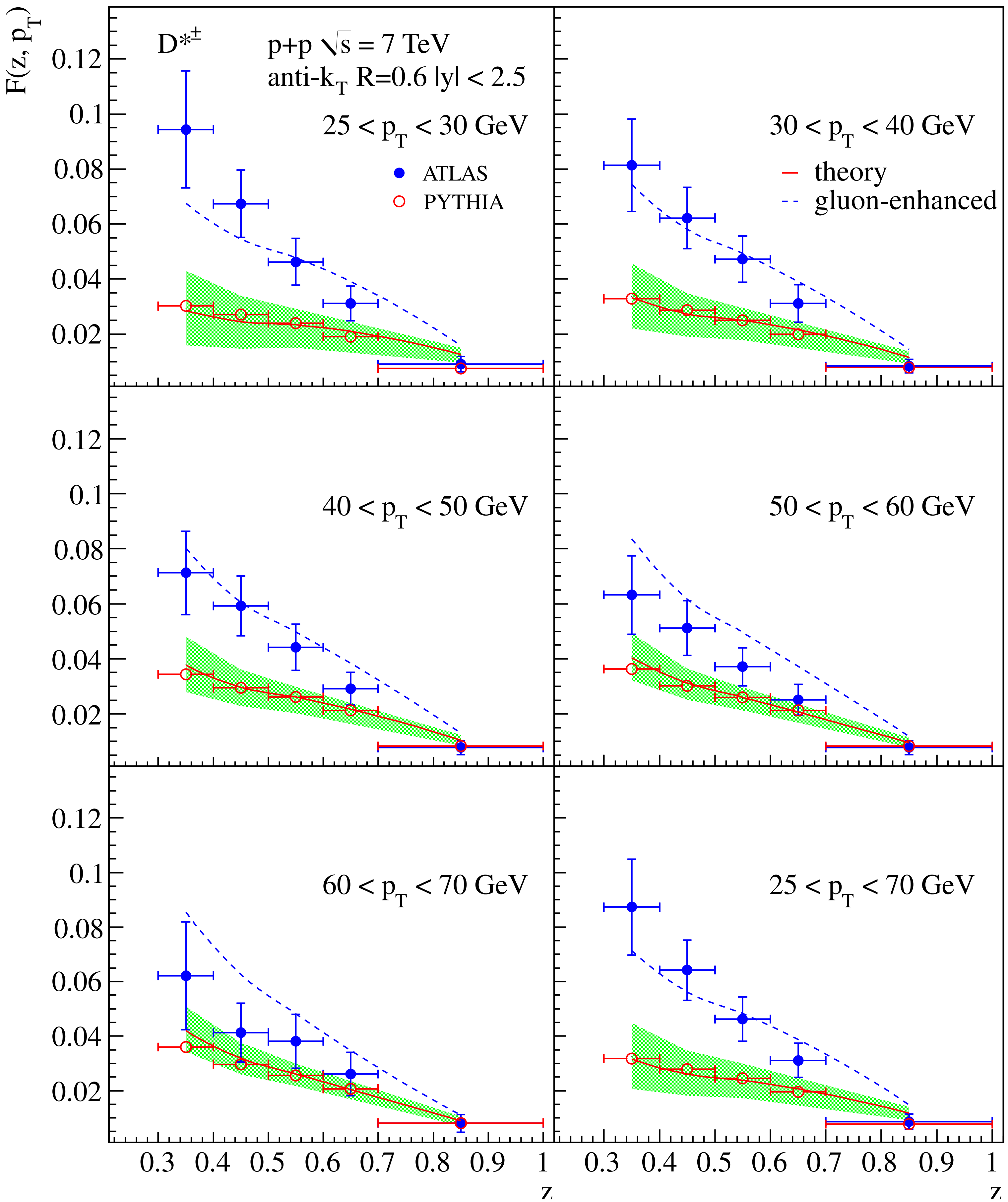
D-meson
jet fragmentation function

Comparison to ATLAS data
and PYTHIA simulations
at $\sqrt{s} = 7\,\mathrm{TeV}$

Using FFs from
Kneesch, Kniehl, Kramer, Schienbein - '08

ZMVNFS, $e^+e^- \to DX$
$\mu,\ \mu_J,\ \mu_G \gg m_Q$

Chien, Kang, FR, Vitev, Xing `15 (exclusive FJF)



Chien, Kang, FR, Vitev, Xing `15 (exclusive FJF)

D-meson
jet fragmentation function

$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$

Comparison to ATLAS data and PYTHIA simulations at $\sqrt{s} = 7\,\mathrm{TeV}$

Using FFs from
Kneesch, Kniehl, Kramer, Schienbein - '08

ZMVNFS, $e^+e^- \to DX$
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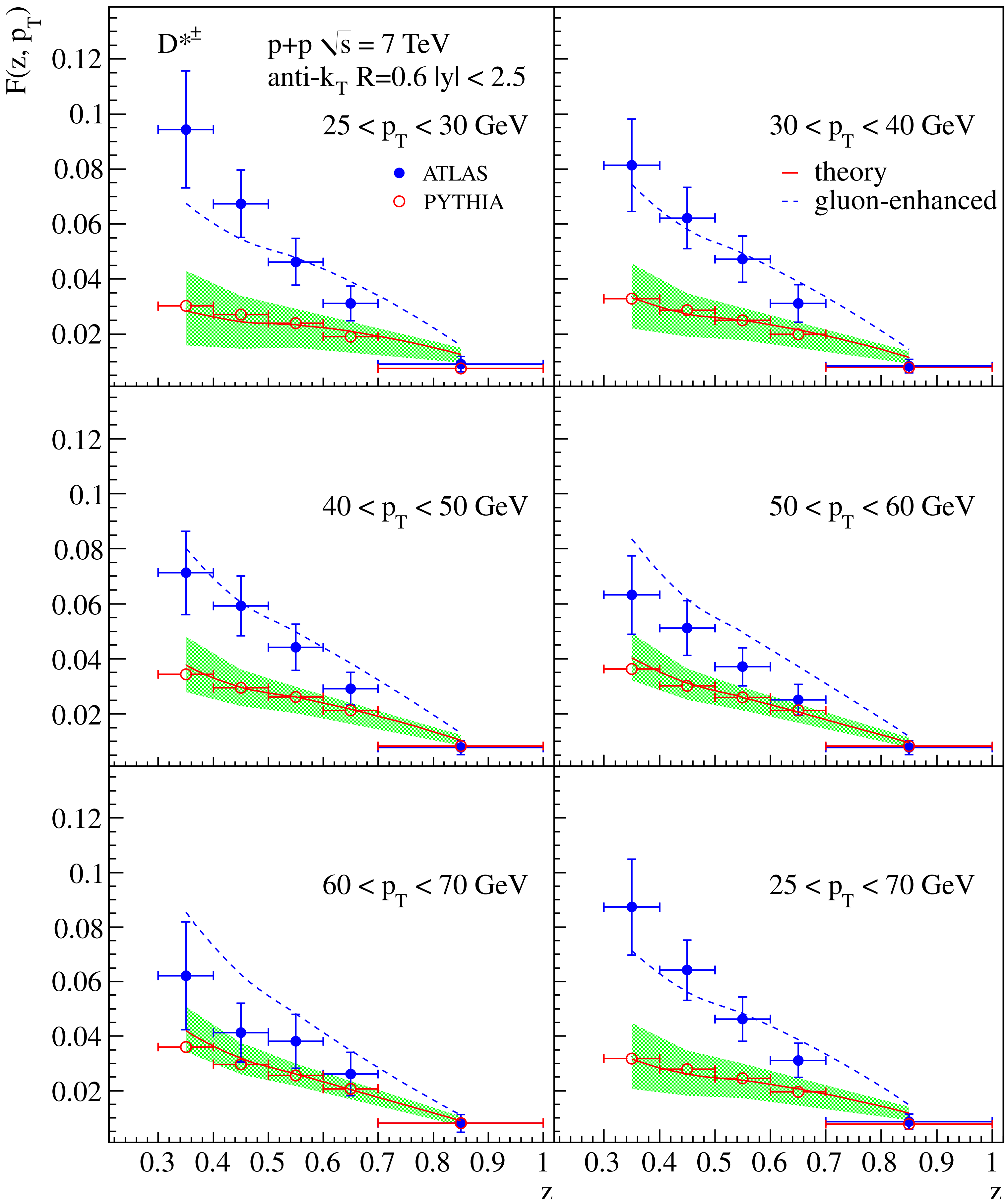


Chien, Kang, FR, Vitev, Xing `15 (exclusive FJF)

D-meson
jet fragmentation function

$$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$$

Comparison to ATLAS data and PYTHIA simulations at $\sqrt{s} = 7\,\mathrm{TeV}$

New fit of D-FFs:

Anderle, Kaufmann, FR, Stratmann, Vitev - in preparation

Outline

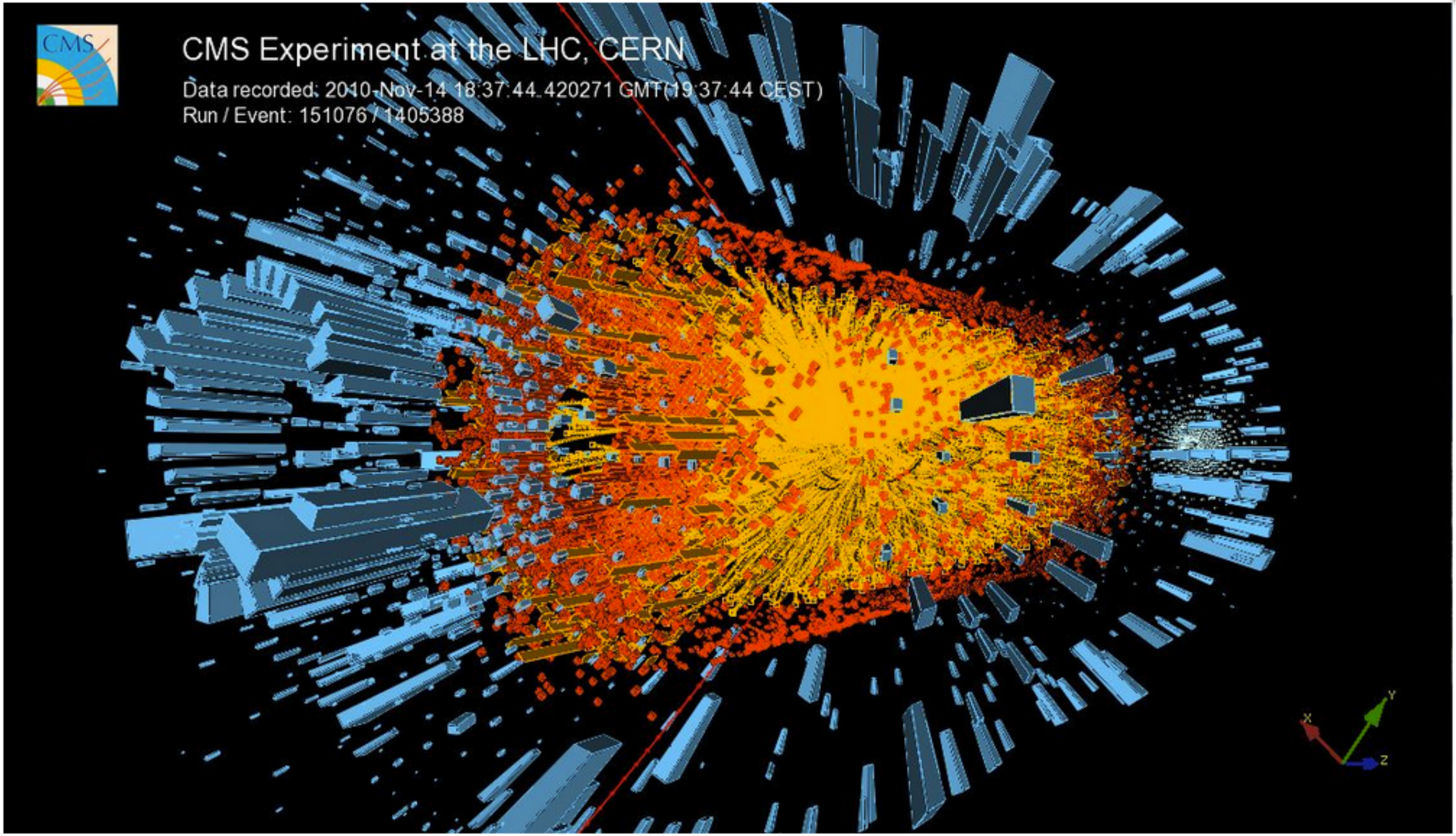
Proton-proton

- Inclusive jets — *Kang, FR, Vitev `16*
- The jet fragmentation function — *Kang, FR, Vitev `16*

Heavy-ion

- SCET$_G$
- Inclusive jets — *Kang, FR, Vitev `17*
- The jet fragmentation function — *Chien, Kang, FR, Vitev, Xing - in preparation*

Conclusions


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST)
Run / Event: 151076 / 1405388
X
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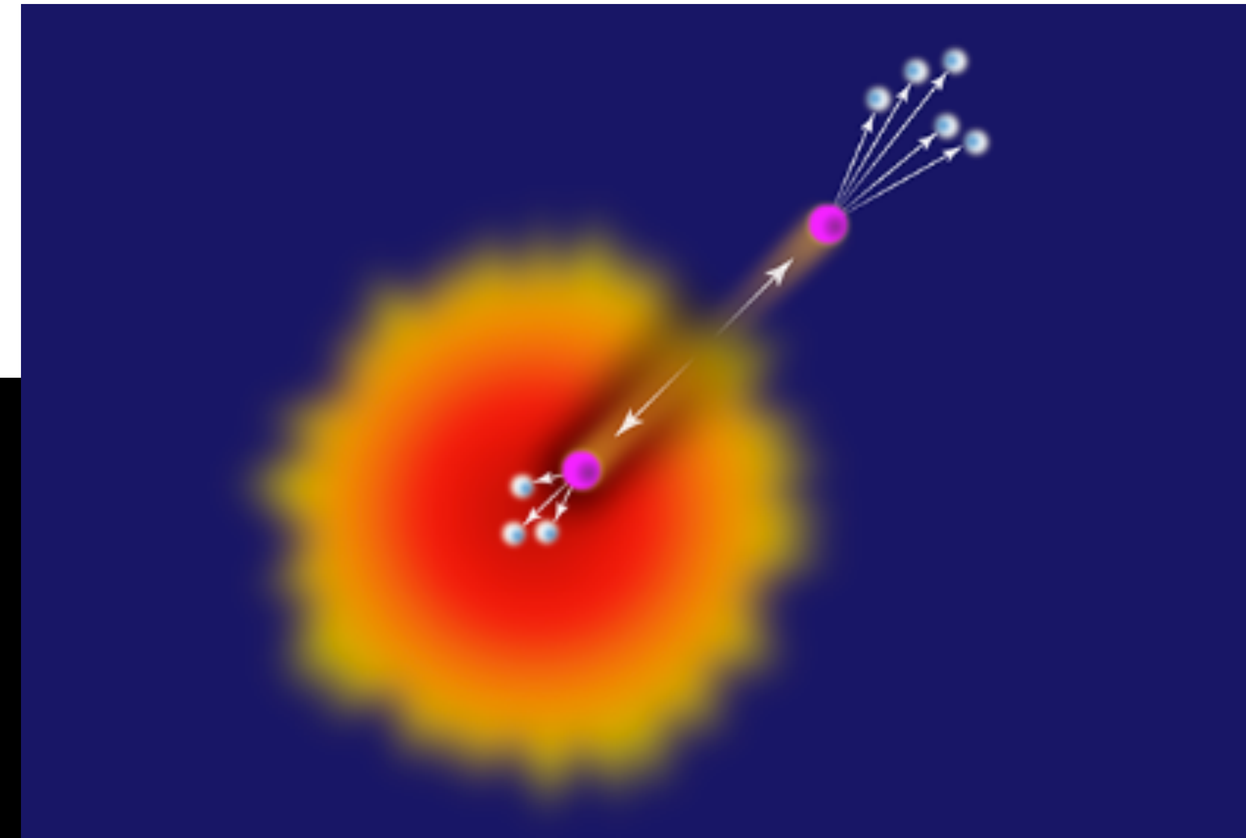
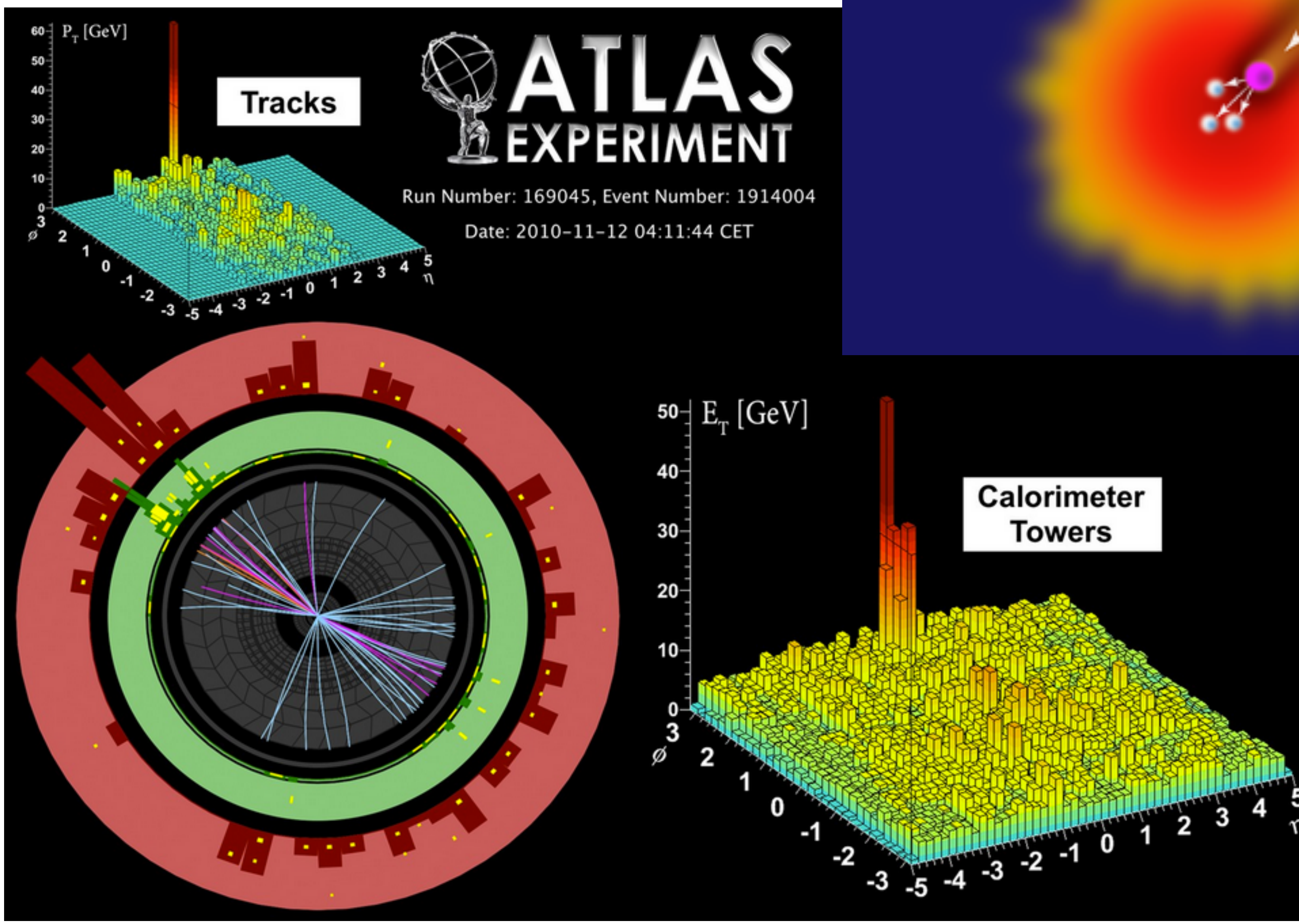
Z





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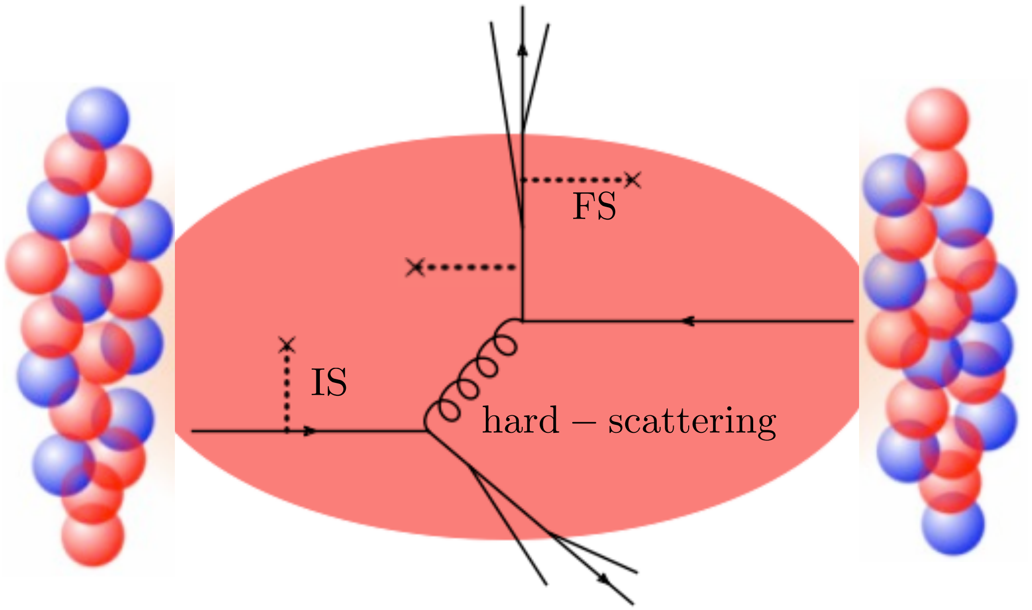
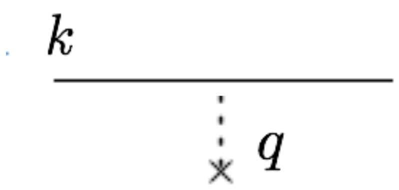
SCET$_G$ - an effective theory for medium interactions

- Add medium interaction terms at the level of the SCET Lagrangian: SCET$_G$ *Idilbi, Majumder `09*

$$\mathcal{L}_{\mathrm{SCET_G}}(\xi_n, A_n, A_G) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + \mathcal{L}_{\mathrm{G}}(\xi_n, A_n, A_G)$$





$$k \sim (1, \lambda^2, \lambda)$$

$$q \sim (\lambda^2, \lambda^2, \lambda)$$

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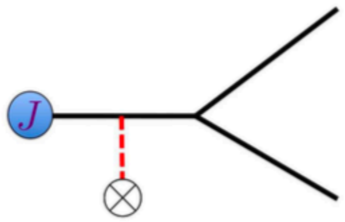

Gyulassy, Levai, Vitev `00

SCET$_G$ - an effective theory for medium interactions

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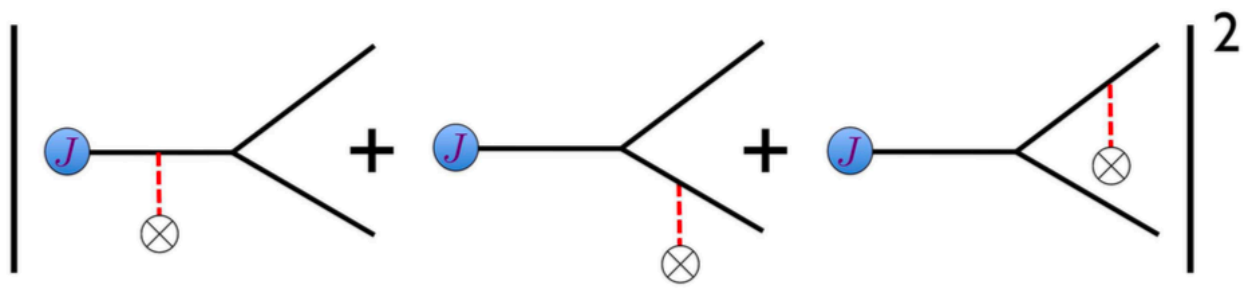
$$\mathcal{L}_{\mathrm{SCET_G}}(\xi_n, A_n, A_G) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + \mathcal{L}_{\mathrm{G}}\,(\xi_n, A_n, A_G)$$

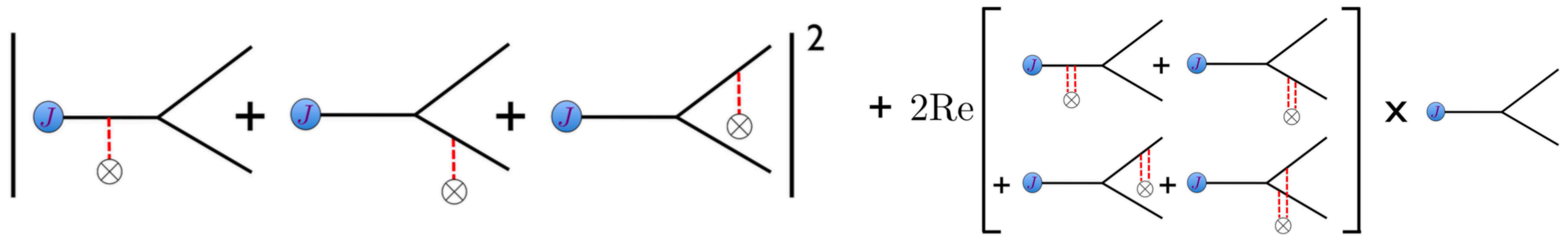


Gyulassy, Levai, Vitev `00

SCET$_G$ - an effective theory for medium interactions

- Add medium interaction terms at the level of the SCET Lagrangian: SCET$_G$ *Idilbi, Majumder `09*

$$\mathcal{L}_{\mathrm{SCET_G}}(\xi_n, A_n, A_G) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + \mathcal{L}_{\mathrm{G}}(\xi_n, A_n, A_G)$$



Gyulassy, Levai, Vitev `00

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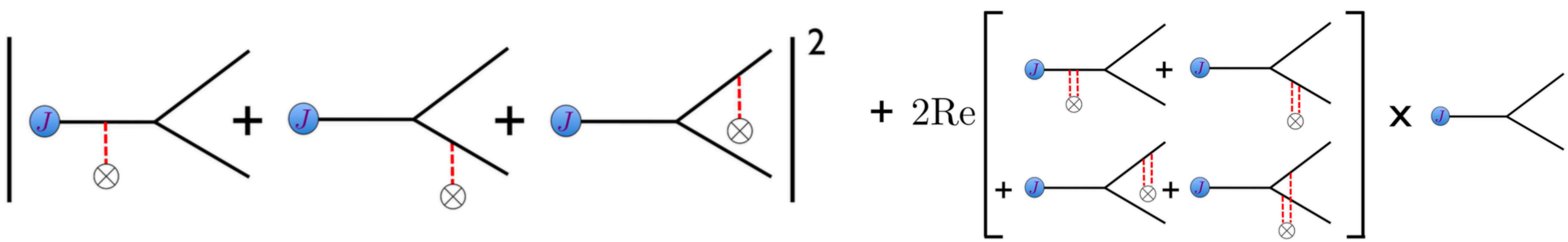


Soft in-medium splitting function:

Gyulassy-Levai-Vitev (GLV) opacity expansion

$$P_{qq}^{\mathrm{med}}(x, k_\perp) = \frac{\alpha_s}{2\pi} C_F \frac{1}{1-x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2 q_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\mathrm{med}}}{d^2 q_\perp} \frac{2 k_\perp \cdot q_\perp}{k_\perp^2 (k_\perp - q_\perp)^2} \left[1 - \cos \frac{(k_\perp - q_\perp)^2}{(1-x) p_0^+} \Delta z \right]$$

Gyulassy, Levai, Vitev `00

model dependence

SCET$_G$ - an effective theory for medium interactions

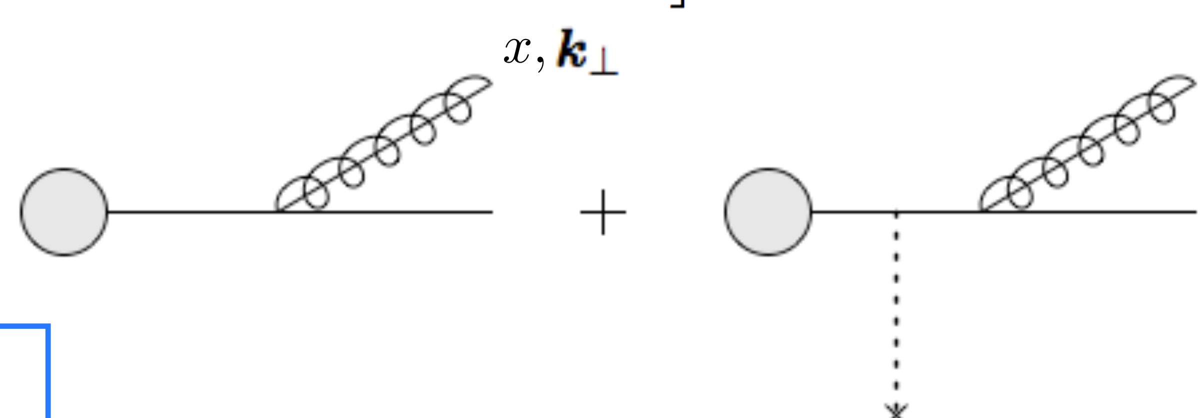
- Add medium interaction terms at the level of the SCET Lagrangian: SCET$_G$ *Idilbi, Majumder `09*

$$\mathcal{L}_{\mathrm{SCET_G}}(\xi_n, A_n, A_G) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + \mathcal{L}_{\mathrm{G}}\,(\xi_n, A_n, A_G)$$

Ovanesyan, Vitev `12

- Use collinear sector of SCET$_G$ to derive *collinear* in-medium splitting functions *Ovanesyan, FR, Vitev `15* *Kang, FR, Vitev `16*

$$P_{qq}^{\mathrm{med}}(x,k_\perp) = \frac{\alpha_s}{2\pi} C_F \frac{1+x^2}{1-x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\mathrm{medium}}}{d^2\mathbf{q}_\perp} \Bigg[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right)$$
$$\times\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)$$
$$+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)\left(1-\cos[\Omega_4\Delta z]\right)$$
$$-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\left(1-\cos[\Omega_5\Delta z]\right) + \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\Bigg]$$



$$\boxed{P_{qq}^{\mathrm{med}}(x,k_\perp) = P_{qq}(x,k_\perp)\, f_{qq}(x,k_\perp;\beta)}$$

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SCET$_G$ - an effective theory for medium interactions

- Add medium interaction terms at the level of the SCET Lagrangian: SCET$_G$ — *Idilbi, Majumder `09*

$$\mathcal{L}_{\mathrm{SCET_G}}(\xi_n, A_n, A_G) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + \mathcal{L}_{\mathrm{G}}\,(\xi_n, A_n, A_G)$$

- Use collinear sector of SCET$_G$ to derive *collinear* in-medium splitting functions — *Ovanesyan, Vitev `12*; *Ovanesyan, FR, Vitev `15*; *Kang, FR, Vitev `16*

- Factorization theorems for proton-proton observables derived within SCET
  Pieces in factorization theorem written in terms of collinear splitting functions

- Applications: light hadrons, open heavy flavor, jets — *Kang, Lashof-Regas, Ovanesyan, Saad, Vitev `14*; *Chien, Vitev `15*; *Kang, FR, Vitev `16*; *Kang, FR, Vitev `17*

Outline

Proton-proton

- Inclusive jets — *Kang, FR, Vitev `16*
- The jet fragmentation function — *Kang, FR, Vitev `16*

Heavy-ion

- SCET$_G$
- Inclusive jets — *Kang, FR, Vitev `17*
- The jet fragmentation function — *Chien, Kang, FR, Vitev, Xing - in preparation*

Conclusions

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Jet quenching in AA

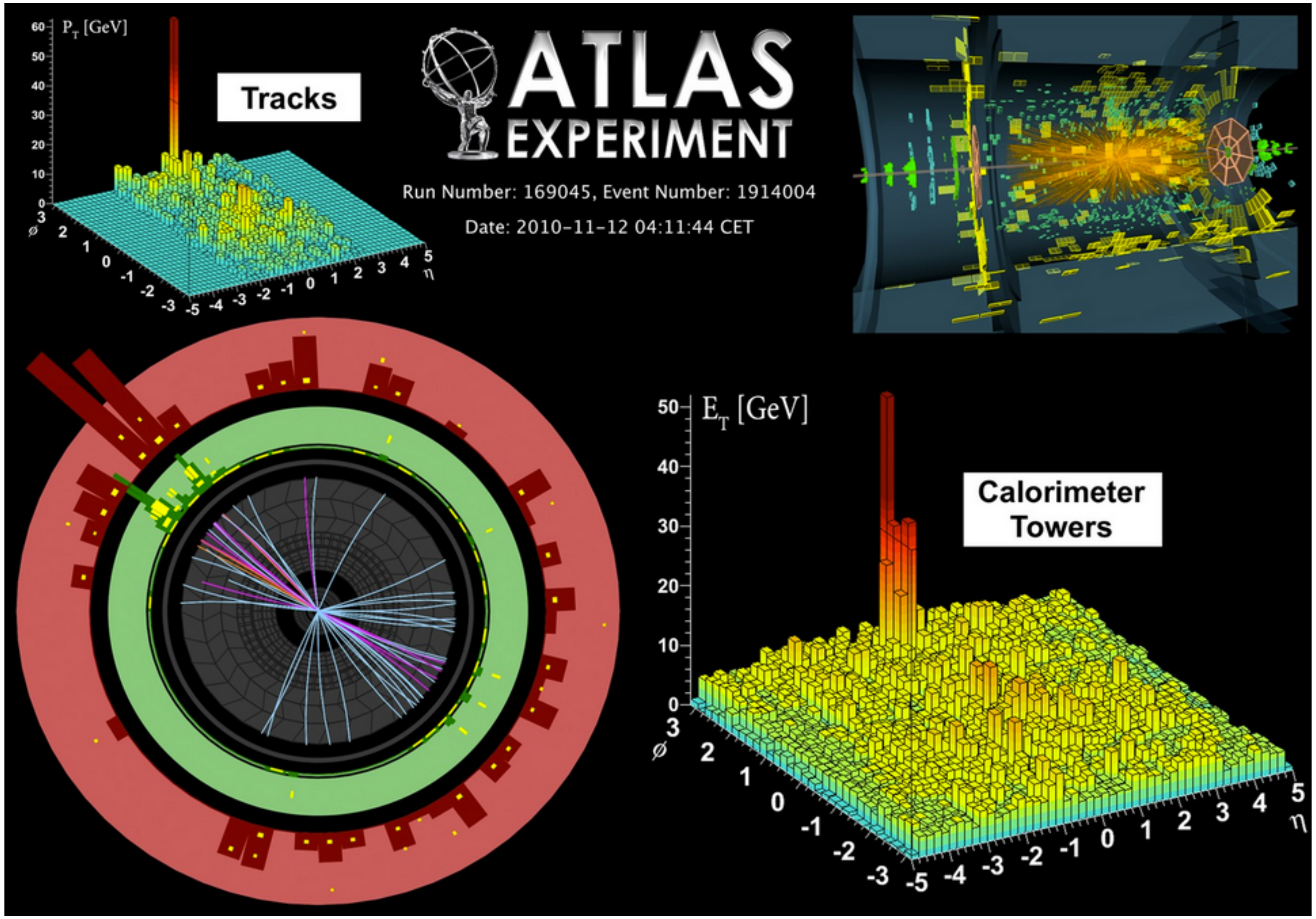
Jets as hard probes of the QGP

Nuclear modification factor

$$R_{AA} = \frac{d\sigma^{\mathrm{PbPb}\to\mathrm{jet}X}}{\langle N_{\mathrm{coll}}\rangle\, d\sigma^{pp\to\mathrm{jet}X}}$$

Heavy-ion cross section

using in-medium siJFs



Jet quenching in AA

- One of the most frequently studied hard probes of the QGP

  More sensitive to medium properties than hadrons, constrain QGP models (e.g. hydrodynamics)

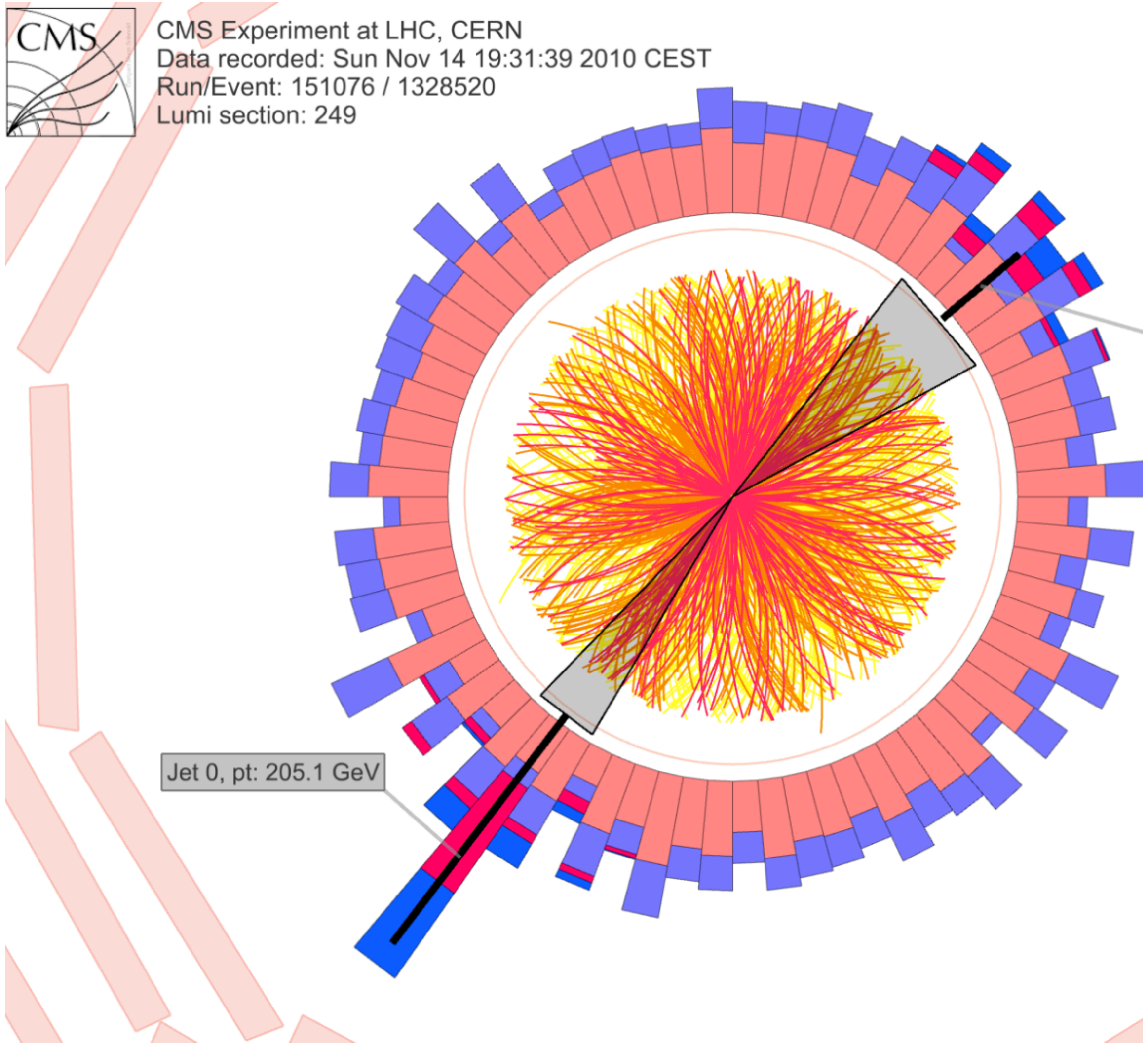
- Disentangle in-medium effects:

  radiative and collisional energy loss, CNM effects …

- Mostly LO calculations available so far in AA

- Jet size parameter typically R ~ 0.4 - 0.2

  consistent description of pp and AA



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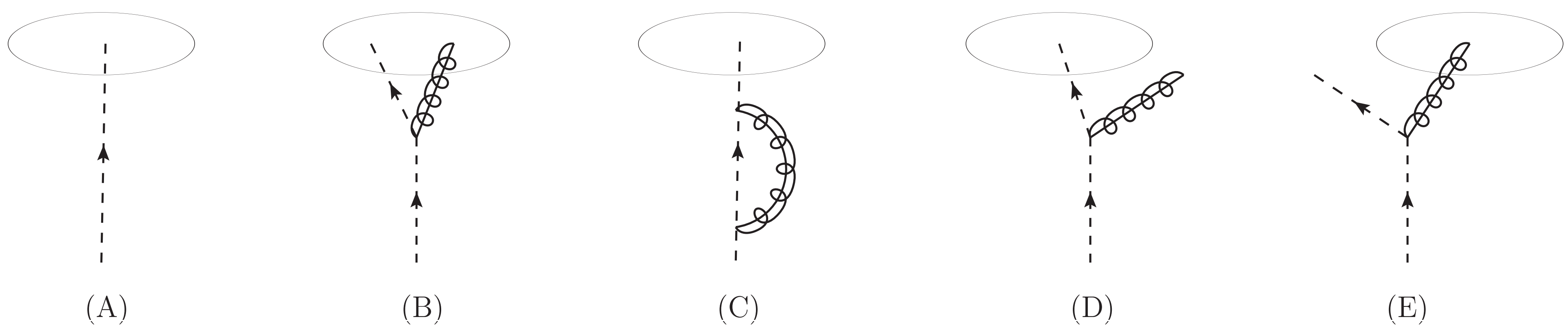
Jet quenching in AA

Kang, FR, Vitev `17

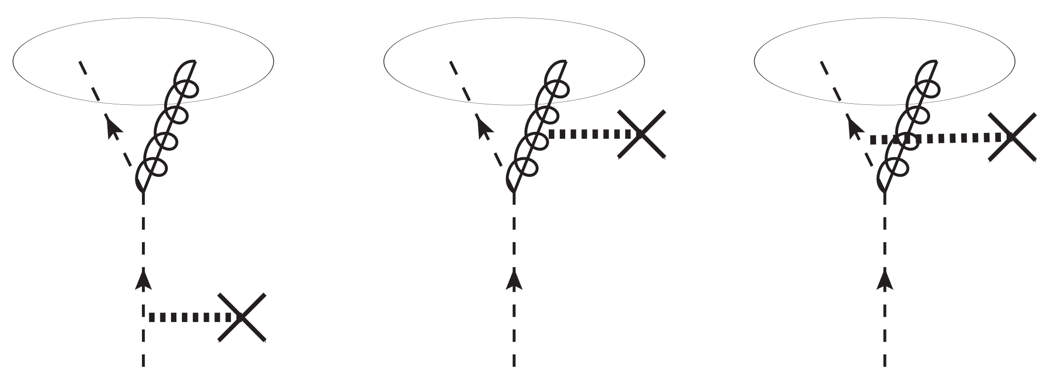
$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$

$$J_i \to J_i^{\text{vac}} + J_i^{\text{med}}$$

vacuum siJF:



in-medium siJF: e.g. single-Born

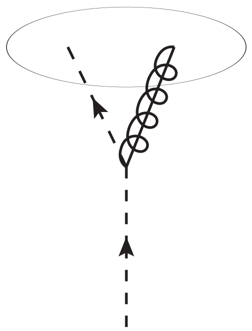


Jet quenching in AA

Kang, FR, Vitev `17

Numerical evaluation of in-medium siJF: cut-off scheme

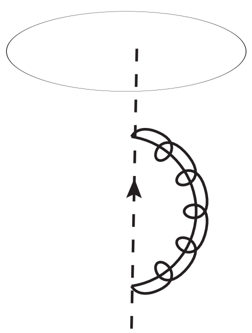
in-jet



(B)

$$\delta(1-z)\int_0^1 dx \int_0^{x(1-x)\omega\tan(R/2)} dq_\perp P_{qq}(x, q_\perp)$$

virtual corr.



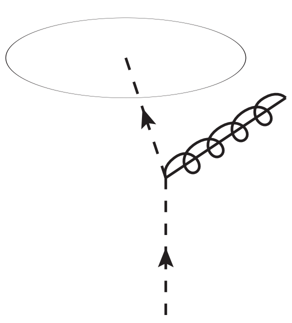
(C)

vacuum: $$P_{qq}(x, q_\perp) = \frac{\alpha_s}{\pi} C_F \frac{1+x^2}{1-x}\frac{1}{q_\perp}$$

medium: (SCET$_G$) $$P_{ji}^{\rm med}(z, q_\perp) = P_{ji}(z, q_\perp)\, f_{ji}(z, q_\perp; \beta)$$

collinear, not *soft* splitting functions needed

out-of-jet



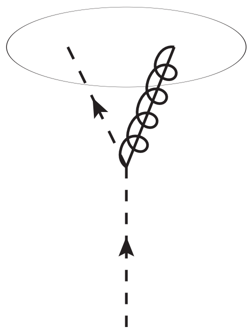
(D)

Jet quenching in AA

Kang, FR, Vitev `17

Numerical evaluation of in-medium siJF: cut-off scheme

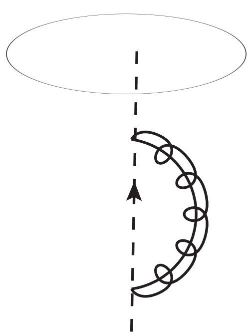
in-jet



(B)

$$\delta(1-z)\int_0^1 dx \int_0^{x(1-x)\omega\tan(R/2)} dq_\perp P_{qq}(x,q_\perp)$$

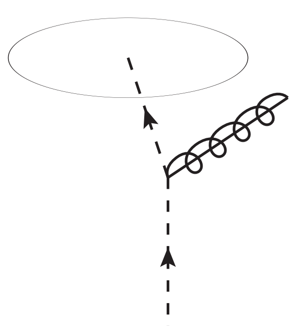
virtual corr.



(C)

$$-\delta(1-z)\int_0^1 dx \int_0^{\mu} dq_\perp P_{qq}(x,q_\perp)$$

out-of-jet



(D)

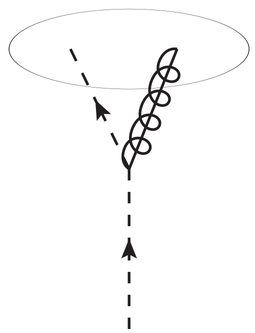
$$\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)$$

Jet quenching in AA

Kang, FR, Vitev `17

Numerical evaluation of in-medium siJF

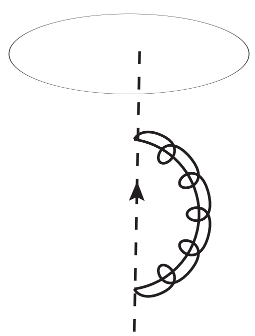
in-jet



(B)

$$(\mathrm{B})+(\mathrm{C})+(\mathrm{D})=\left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)\right]_+$$

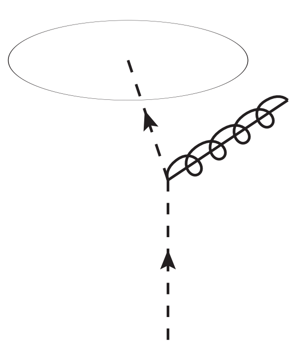
virtual corr.



(C)

$$d\sigma_{\mathrm{PbPb}}^{\mathrm{jet,med}}=\sum_{i=q,\bar{q},g}\sigma_i^{(0)}\otimes J_i^{\mathrm{med}}$$

out-of-jet

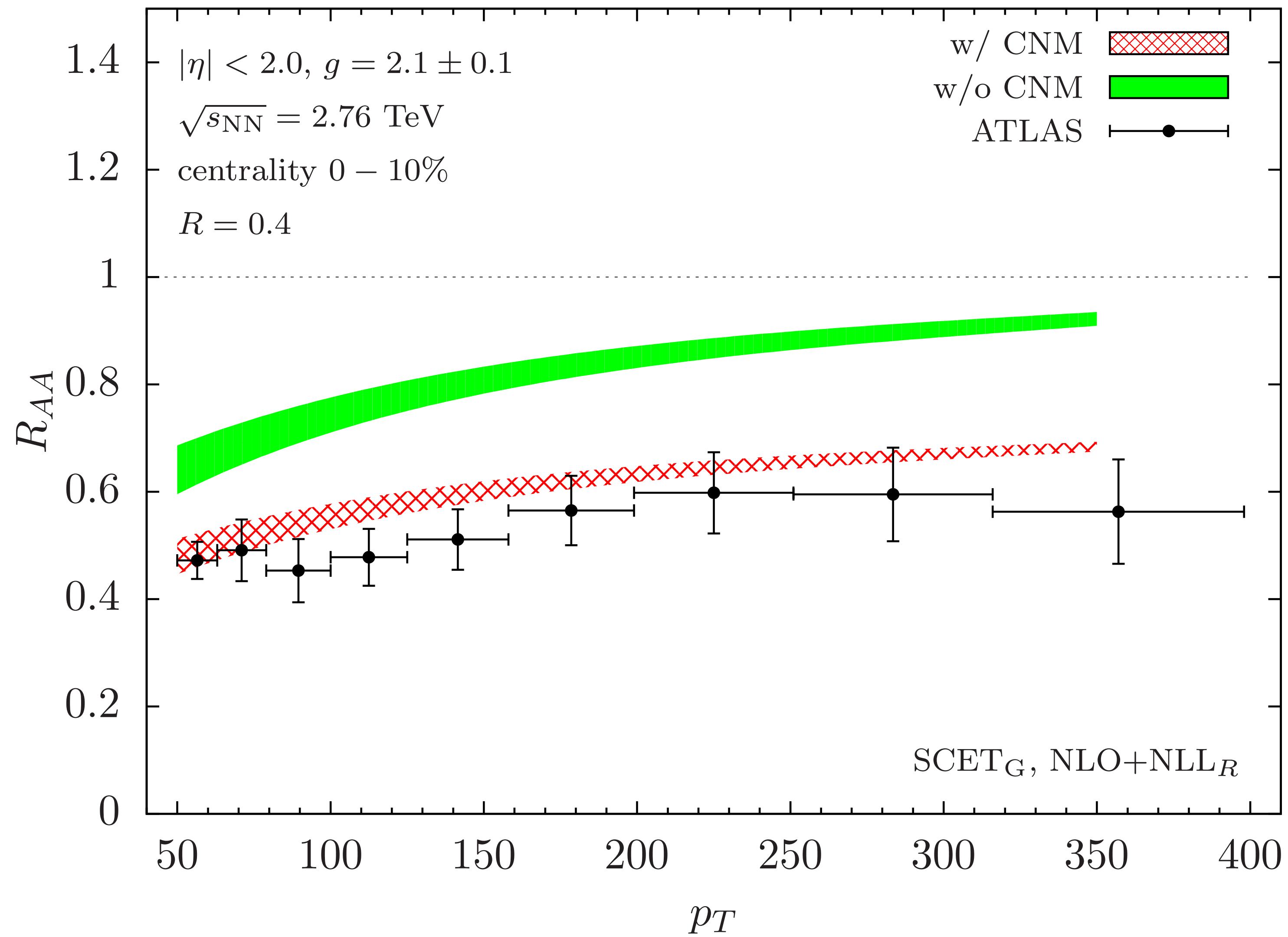


(D)

where

$$\int_0^1 dz\, f(z)[g(z)]_+\equiv\int_0^1 dz(f(z)-f(1))g(z)$$

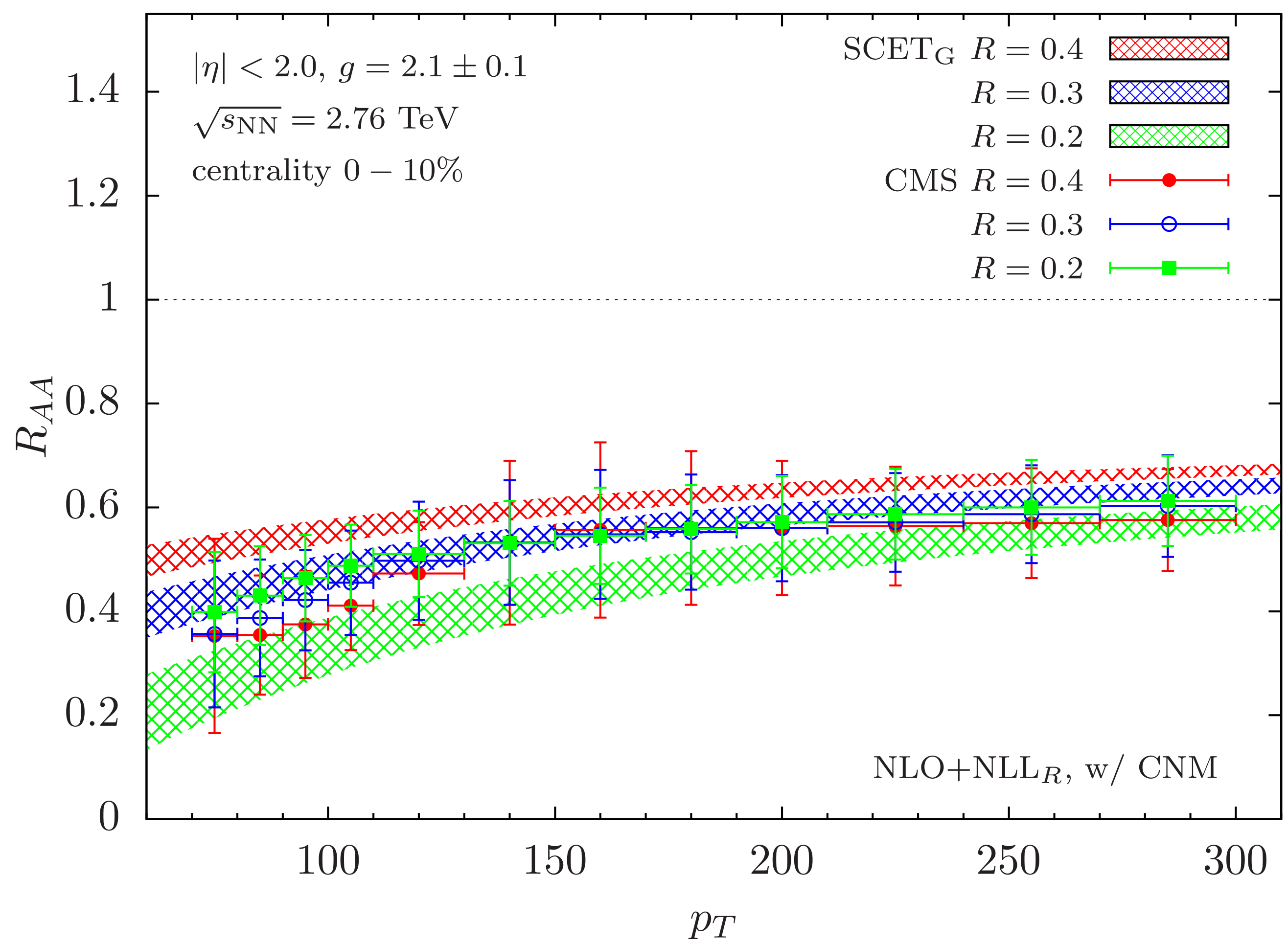
Jet quenching in AA

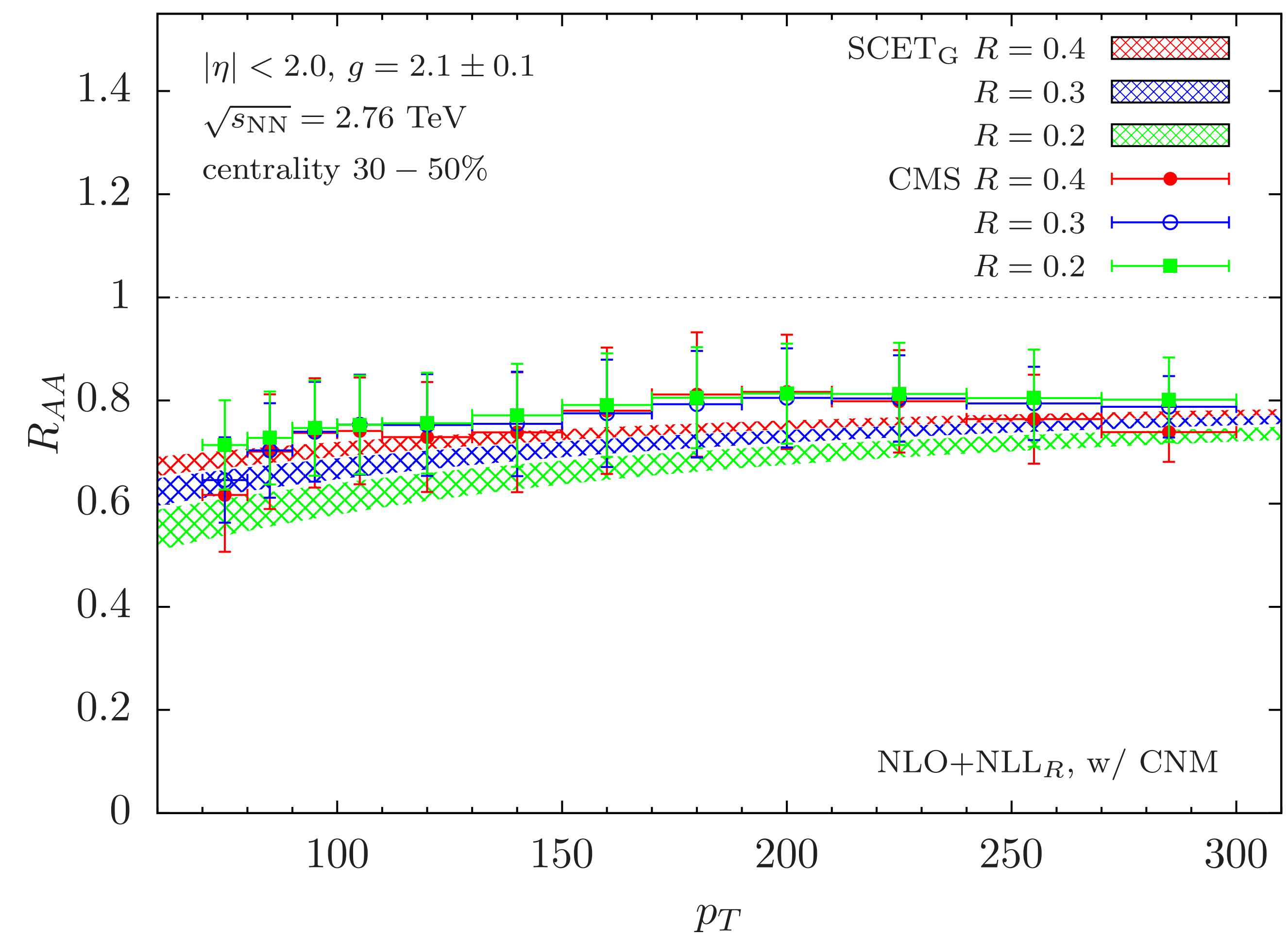


ATLAS data arXiv:1208.1967

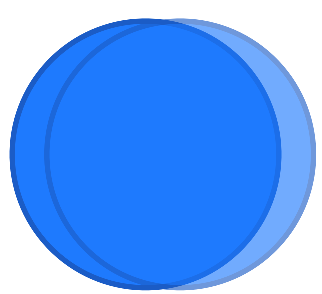
Jet quenching in AA

CMS data arXiv:1609.05383

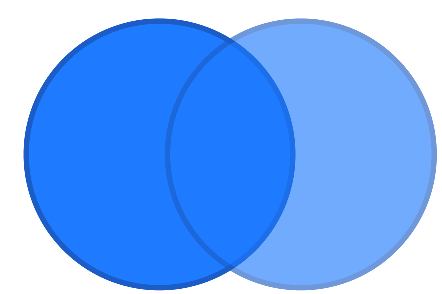




central



mid-peripheral



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Outline

Proton-proton

- Inclusive jets *Kang, FR, Vitev `16*
- The jet fragmentation function *Kang, FR, Vitev `16*

Heavy-ion

- SCET_G
- Inclusive jets *Kang, FR, Vitev `17*
- The jet fragmentation function *Chien, Kang, FR, Vitev, Xing - in preparation*

Conclusions

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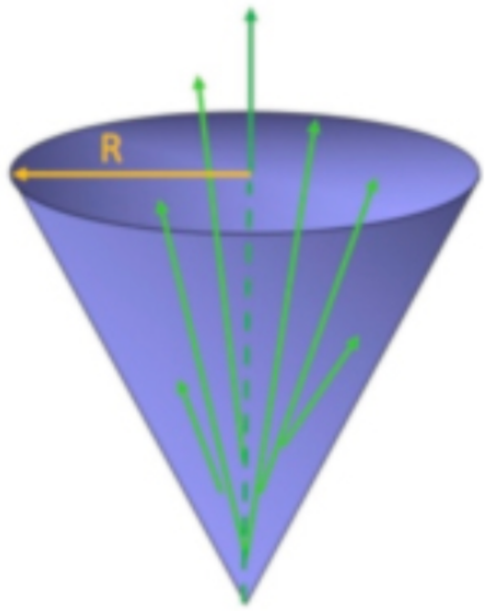
Jet substructure in AA

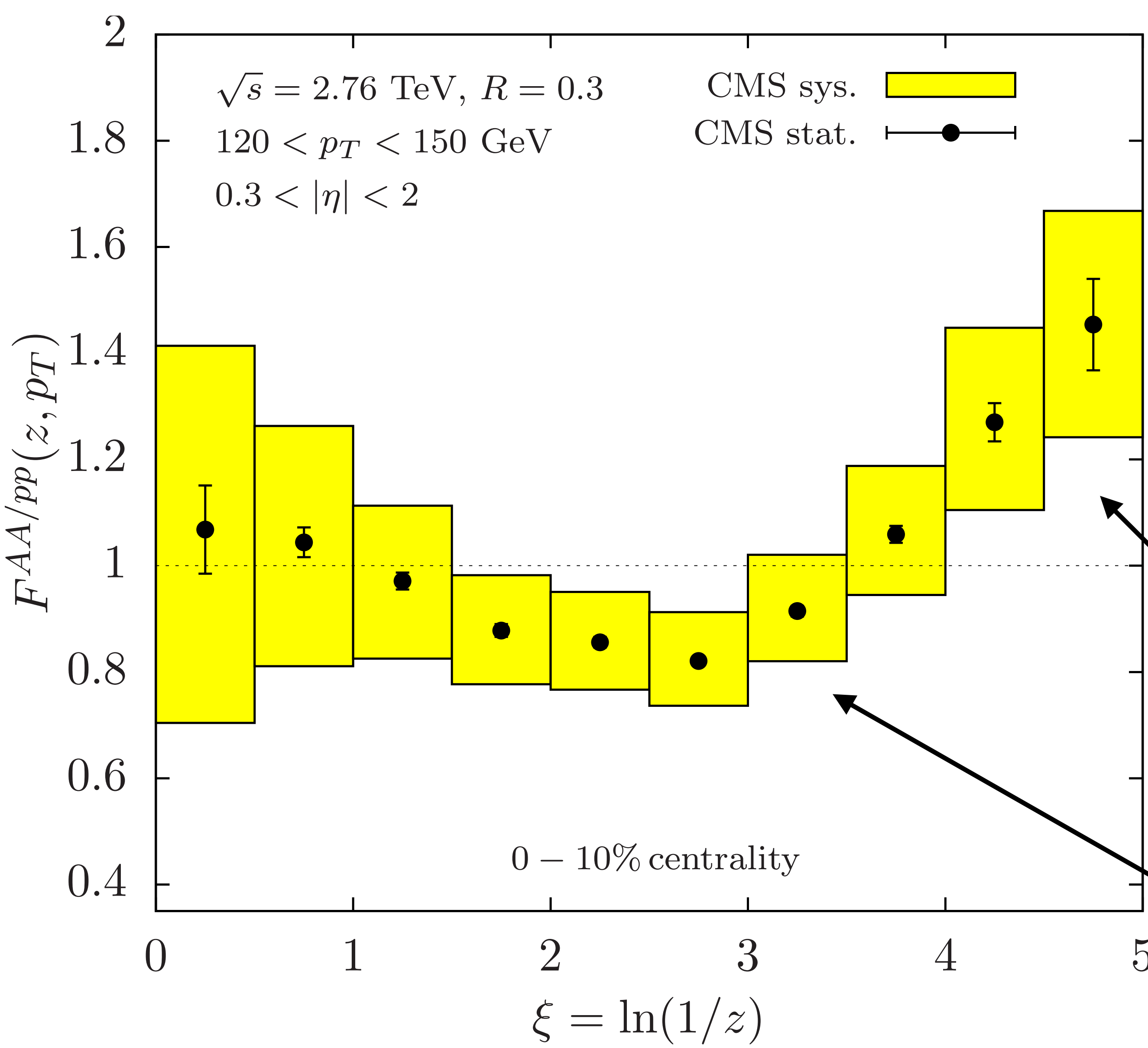


- Lots of experimental results but only few theory calculations
- More differential probe of the QGP than inclusive cross sections
- Disentangle in-medium effects:

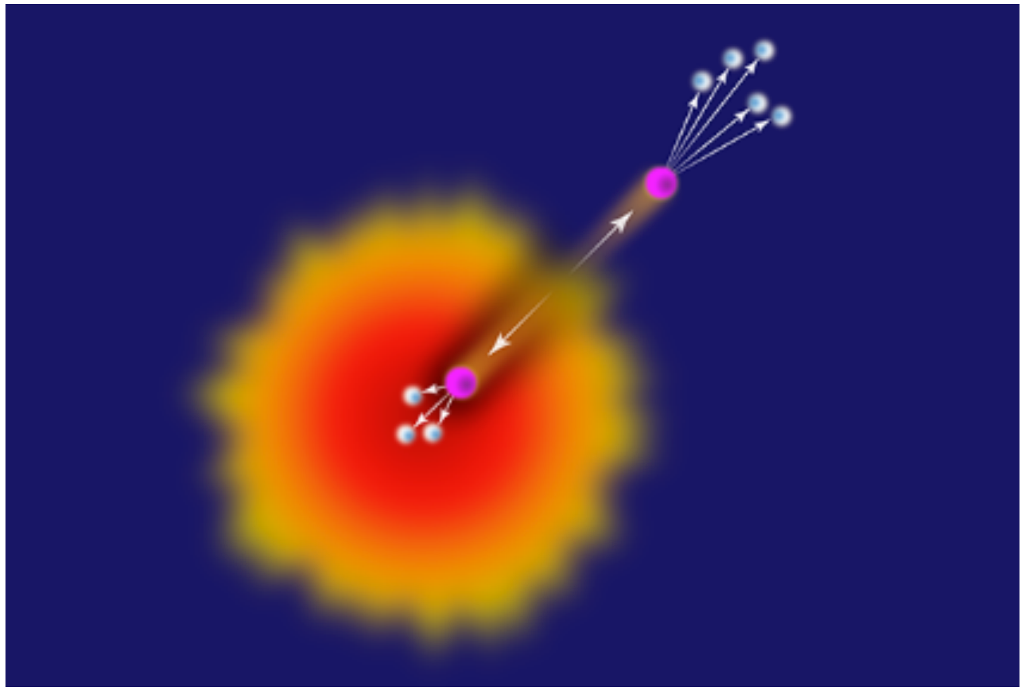
  CNM effects are expected to be negligible

- Ideally one would like to understand both the longitudinal and the transverse energy distribution of jets in AA

The jet fragmentation function in AA



CMS data arXiv:1406.0932



enhancement of soft particles, small-z region

attenuation of particles in the large-z region

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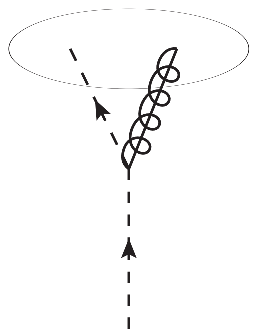
The jet fragmentation function in AA

Chien, Kang, FR, Vitev, Xing - in preparation

Numerical evaluation of in-medium siFJF

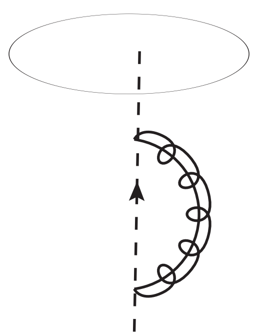
in-jet



(B)

$$\delta(1-z)\int_{\mu_0}^{z_h(1-z_h)\omega\tan(R/2)} dq_\perp P_{qq}(z_h,q_\perp)$$

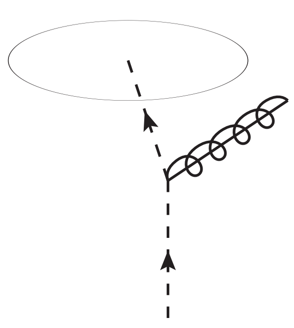
virtual corr.



(C)

$$-\delta(1-z)\delta(1-z_h)\int_0^1 dx\int_{\mu_0}^{\mu} dq_\perp P_{qq}(x,q_\perp)$$

out-of-jet



(D)

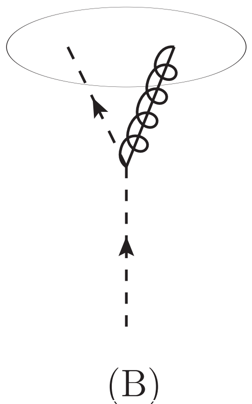
$$\delta(1-z_h)\int_{z(1-z)\omega\tan(R/2)}^{\mu} P_{qq}(z,q_\perp)$$

The jet fragmentation function in AA

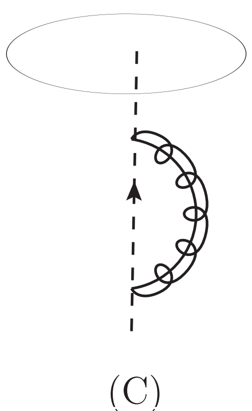
Numerical evaluation of in-medium siFJF

Chien, Kang, FR, Vitev, Xing - in preparation

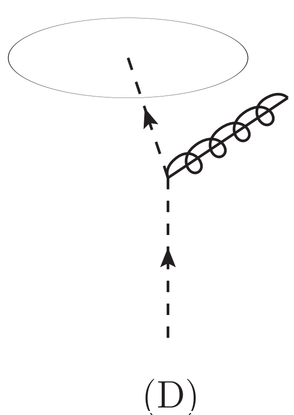
in-jet



virtual corr.



out-of-jet



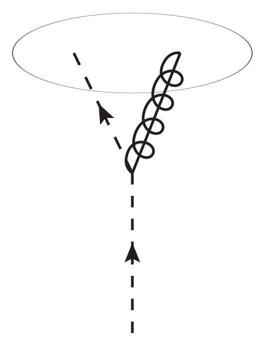
$$(\mathrm{B})+(\mathrm{C})+(\mathrm{D})=\delta(1-z_h)\left[\int_{z(1-z)\omega\tan(R/2)}^{\mu}P_{qq}(z,q_\perp)\right]_+ +\delta(1-z)\left[\int_{\mu_0}^{z_h(1-z_h)\omega\tan(R/2)}dq_\perp P_{qq}(z_h,q_\perp)\right]_+$$

The jet fragmentation function in AA

Numerical evaluation of in-medium siFJF

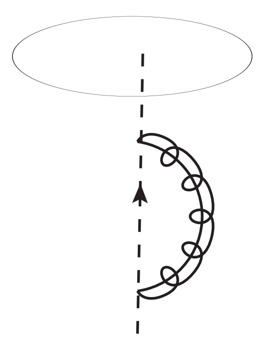
Chien, Kang, FR, Vitev, Xing - in preparation

in-jet



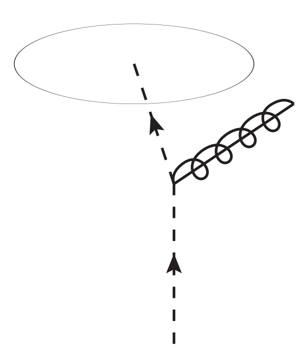
(B)

virtual corr.



(C)

out-of-jet



(D)

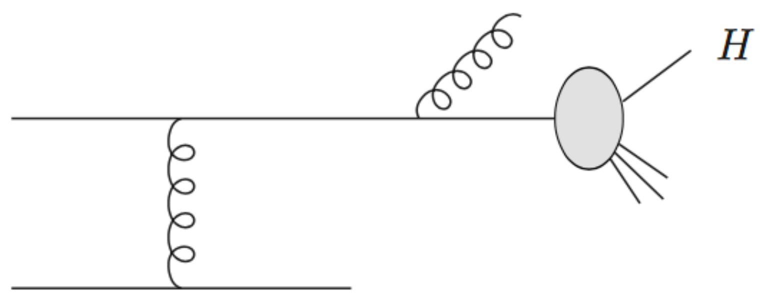
$$(\mathrm{B})+(\mathrm{C})+(\mathrm{D}) = \delta(1-z_h)\left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} P_{qq}(z,q_\perp)\right]_+ + \delta(1-z)\left[\int_{\mu_0}^{z_h(1-z_h)\omega\tan(R/2)} dq_\perp P_{qq}(z_h,q_\perp)\right]_+$$

$$d\sigma_{\mathrm{PbPb}}^{\mathrm{jet}h} = d\sigma_{pp}^{\mathrm{jet}h,\mathrm{vac}} + d\sigma_{\mathrm{PbPb}}^{\mathrm{jet}h,\mathrm{med}}$$

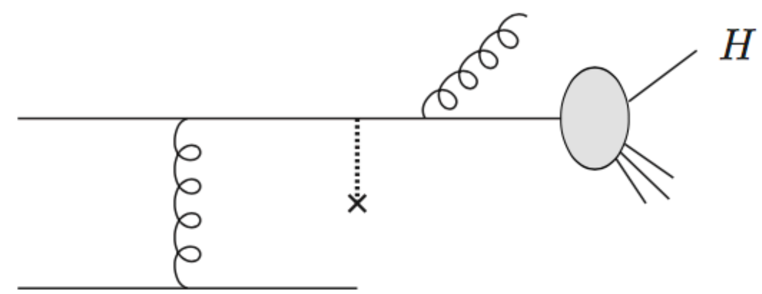
$$d\sigma^{\mathrm{jet}h,\mathrm{med}} = \sum_{ij} d\sigma_i^{(0)} \otimes \mathcal{G}_i^{j,\mathrm{med}} \otimes D_j^h$$

vacuum FFs
(hadronization outside the medium)

The jet fragmentation function in AA



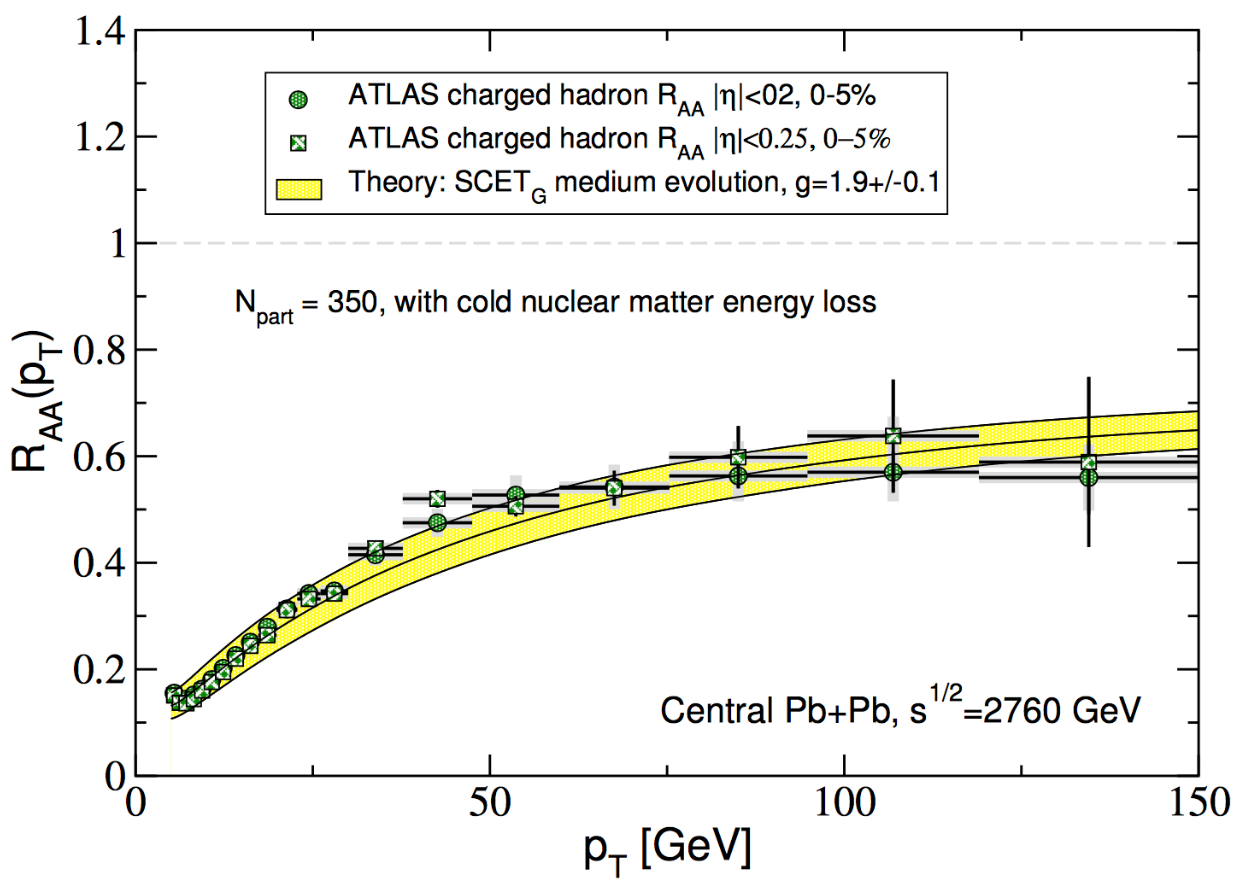
vacuum



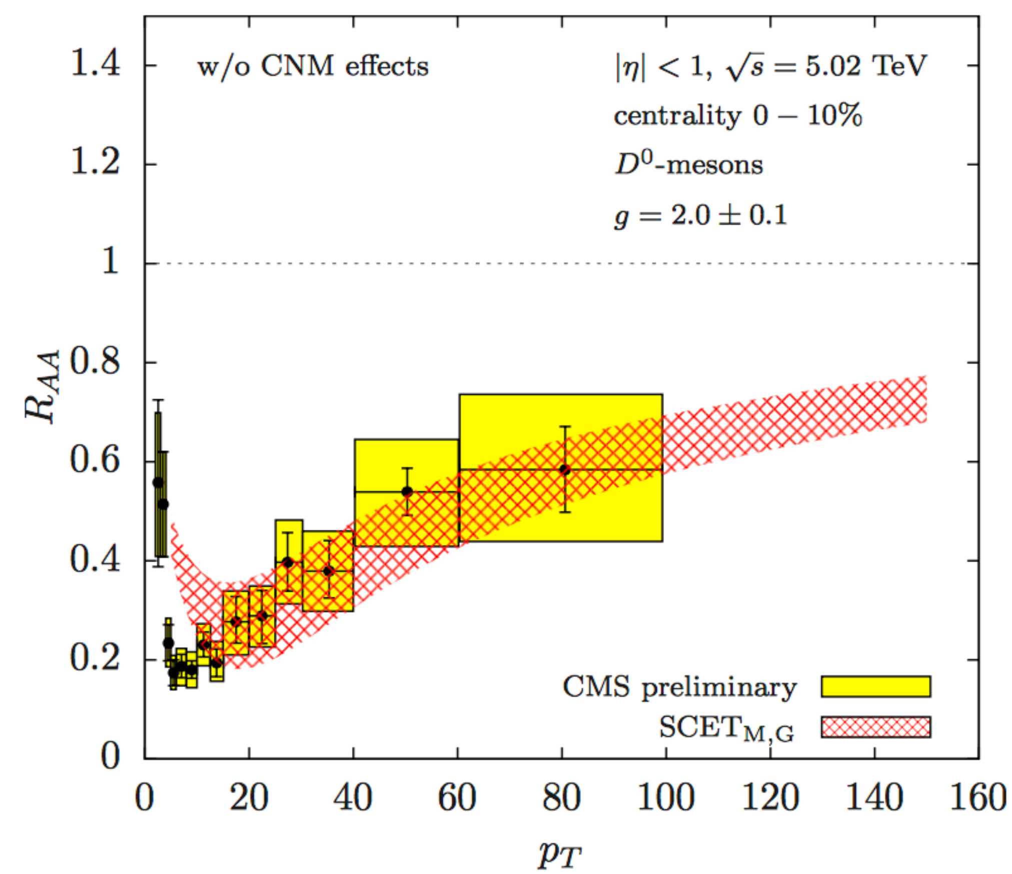
medium

Chien, Emerman, Kang, Ovanesyan, Vitev `16

Kang, FR, Vitev `16



light charged hadrons



D-mesons

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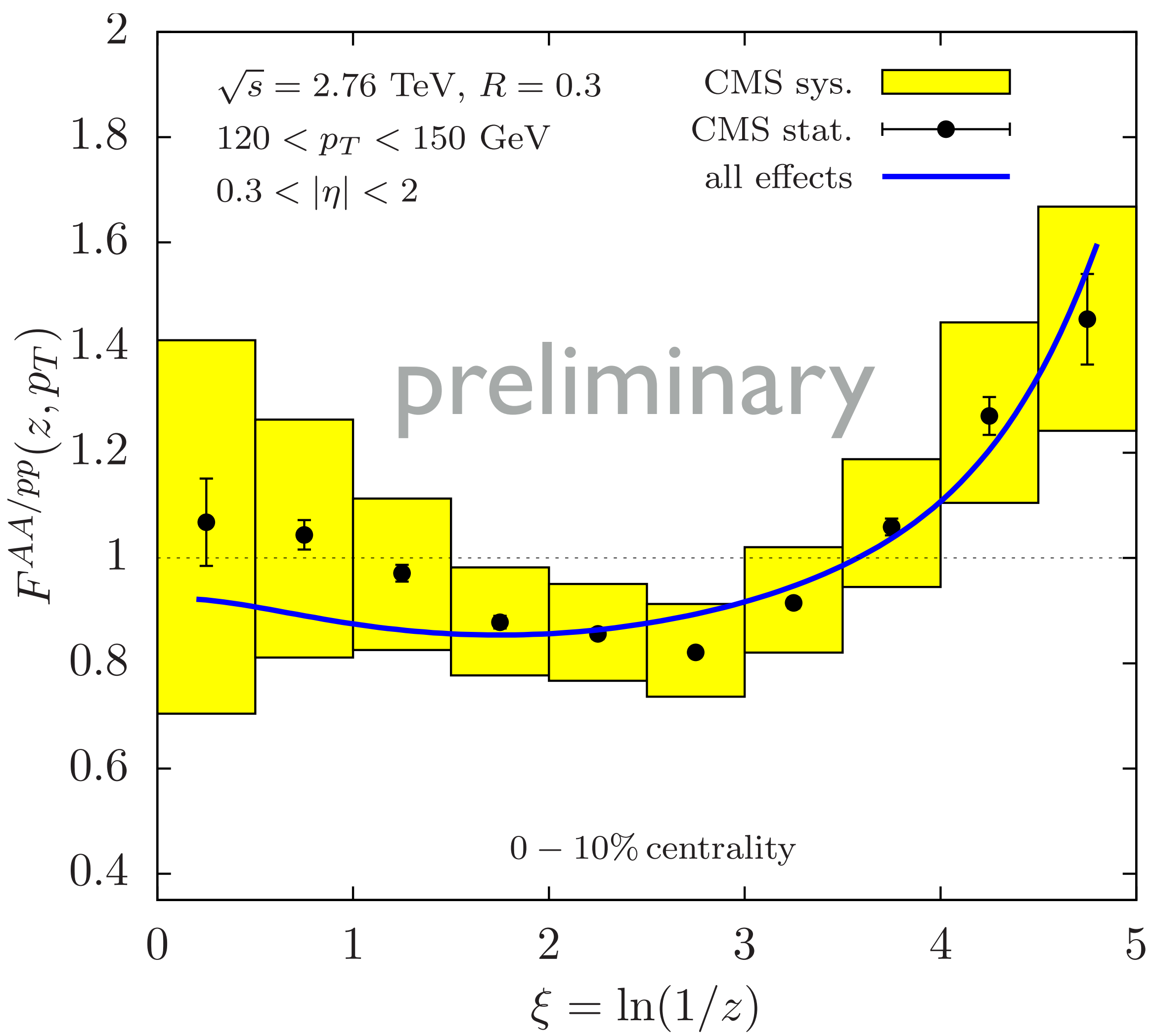
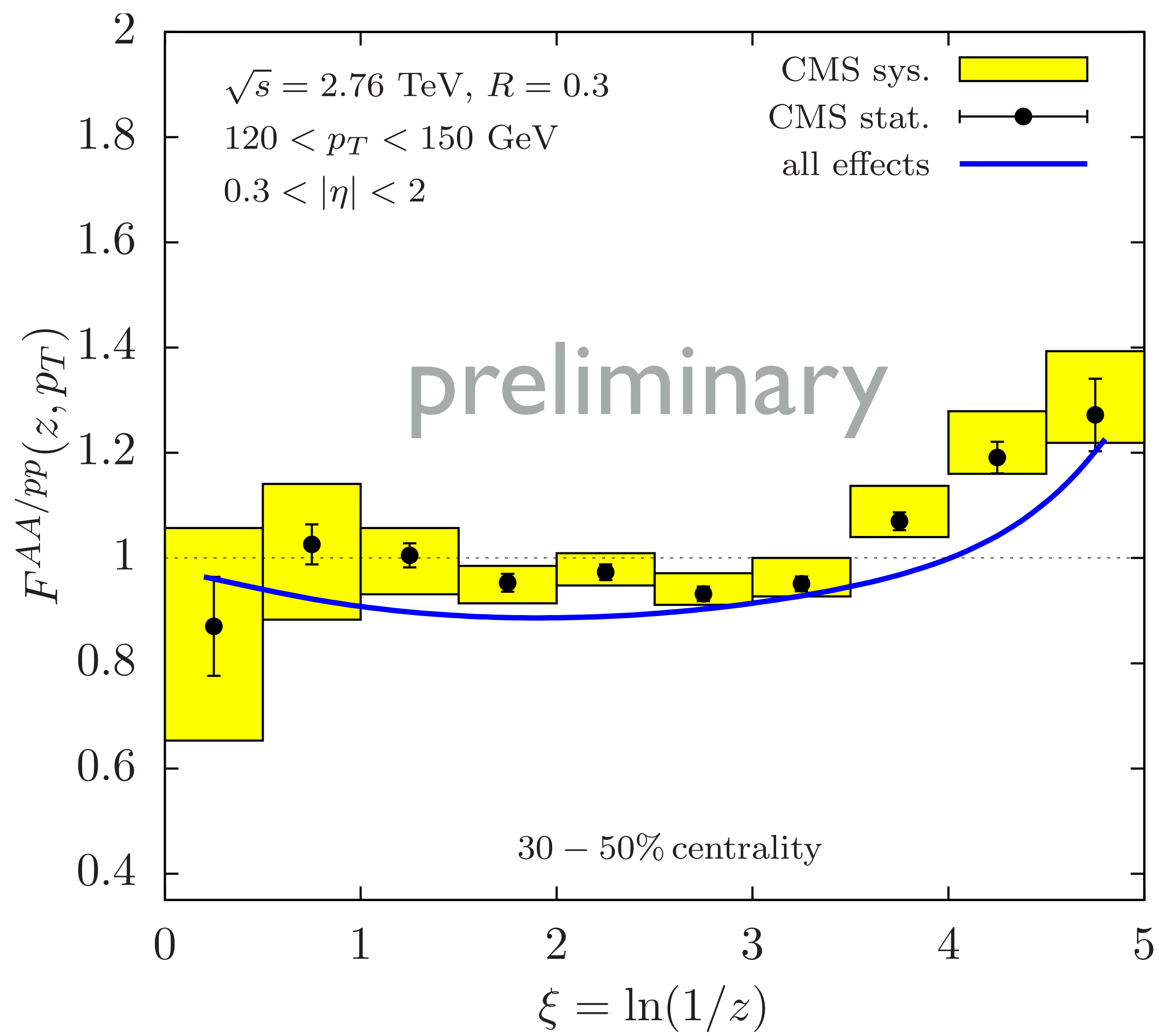
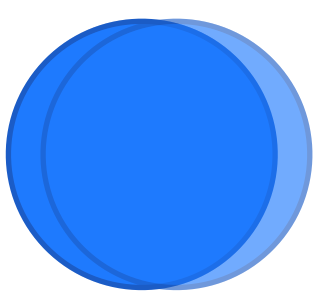
The jet fragmentation function in AA

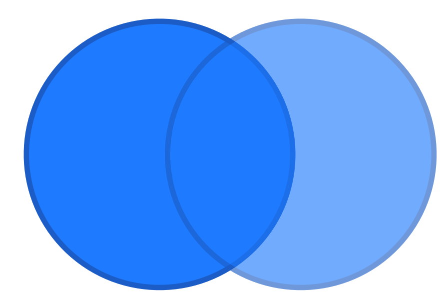




central



mid-peripheral



CMS data arXiv:1406.0932

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Outline

Proton-proton

- Inclusive jets *Kang, FR, Vitev `16*
- The jet fragmentation function *Kang, FR, Vitev `16*

Heavy-ion

- SCET_G
- Inclusive jets *Kang, FR, Vitev `17*
- The jet fragmentation function *Chien, Kang, FR, Vitev, Xing - in preparation*

Conclusions

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Conclusions

- (Semi-) inclusive jet observables in SCET
- Longitudinal hadron-in-jet distribution

- $\mathrm{SCET_G}$ splitting functions and siJFs allow consistent treatment of hadrons and jets
- Jet substructure observables with hard-collinear factorization theorems

- Disentangle: radiative and collisional energy loss as well as CNM effects
- Develop soft sector of $\mathrm{SCET_G}$ to address in-medium soft functions