Jet fragmentation functions in proton and heavy ion collisions

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Outline

- Jet Fragmentation functions in pp collisions

Chien, Kang, FR, Vitev, Xing - '15

- Modification in AA

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

- Conclusions

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- Jet Fragmentation functions in pp collisions

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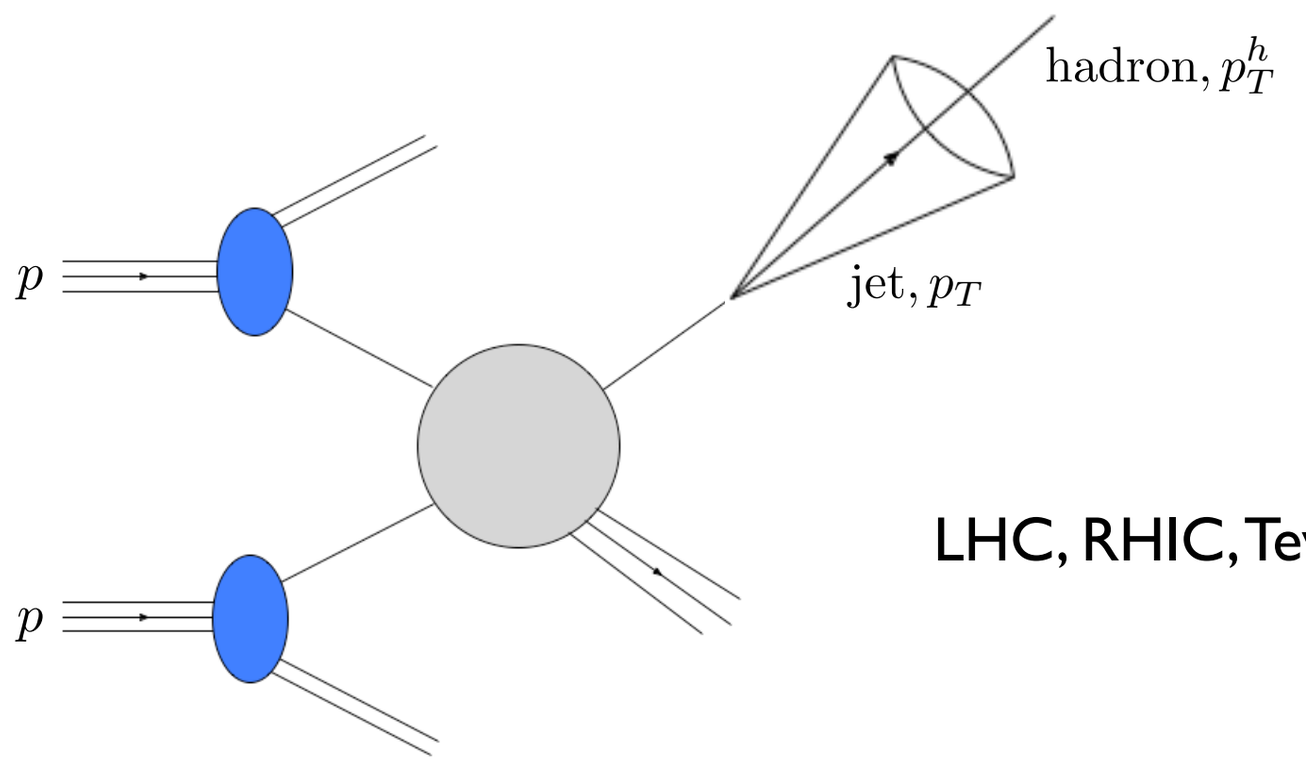
- Conclusions

Jet fragmentation function

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

- Probes jet dynamics at a more differential level
- Provides further constraints for fits of fragmentation functions

- Possible studies include spin correlations and
- the modification in heavy ion collisions

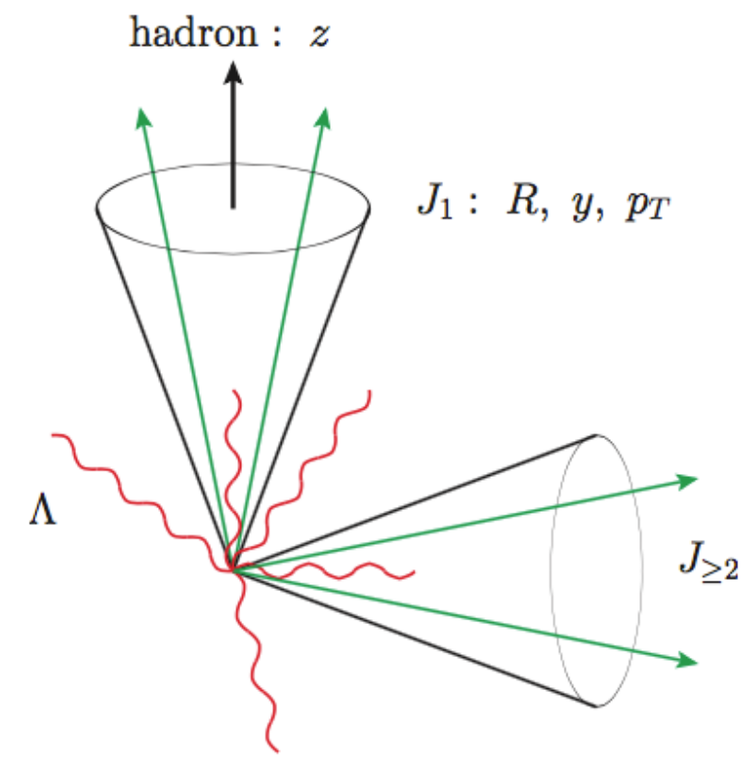


LHC, RHIC, Tevatron

Jet fragmentation function

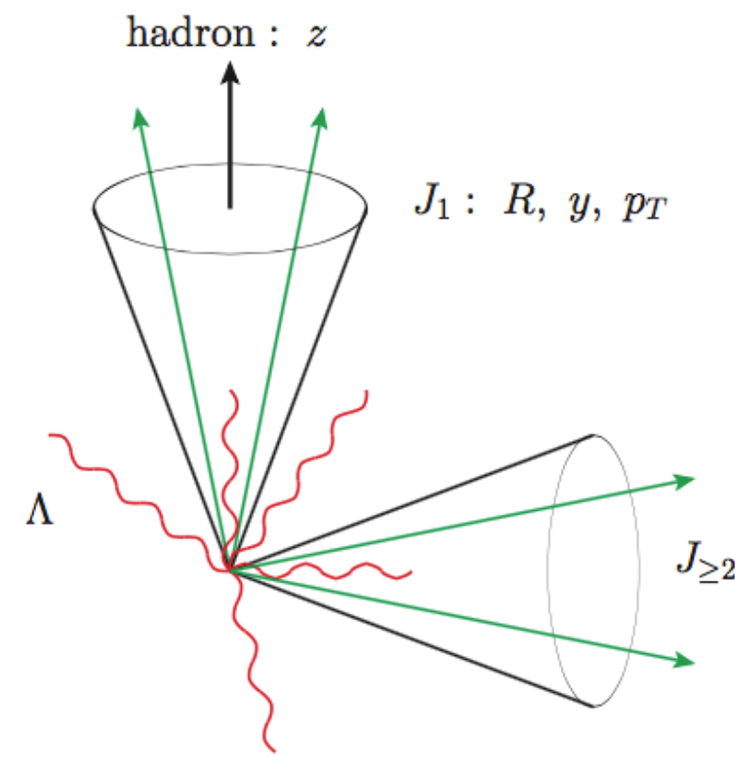
Definition: $$F(z, p_T) = \frac{d\sigma^h}{dy dp_T dz} \Big/ \frac{d\sigma}{dy dp_T}$$

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, Bain, Dai, Hornig, Leibovich, Makris, Mehen `16 …

- Jet fragmentation function studies at NLO for pp

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

Jet fragmentation function in pp

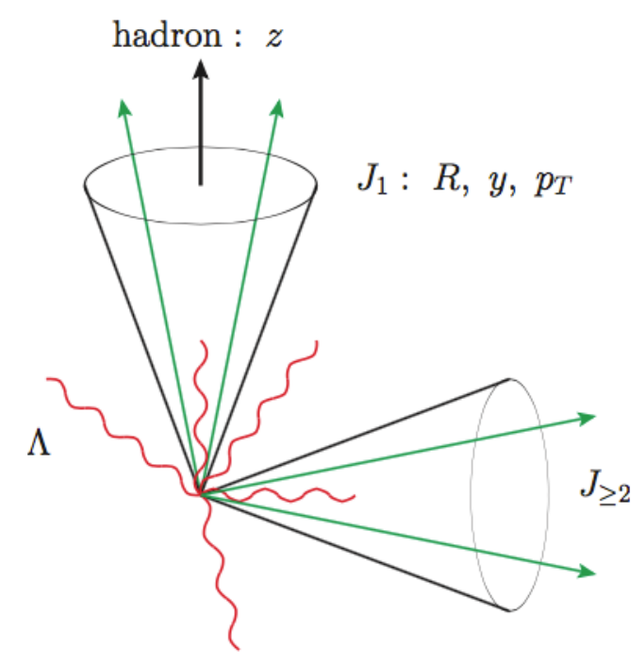
Factorization

$$\frac{\dfrac{d\sigma^h}{dy_i dp_{T_i} dz}}{\dfrac{d\sigma}{dy_i dp_{T_i}}} = \frac{H(y_i, p_{T_i}, \mu)\, \mathcal{G}^h_{\omega_1}(z,\mu) J_{\omega_2}(\mu) \cdots J_{\omega_N}(\mu) S_{n_1 n_2 \cdots n_N}(\Lambda, \mu)}{H(y_i, p_{T_i}, \mu) J_{\omega_1}(\mu) \cdots J_{\omega_N}(\mu) S_{n_1 n_2 \cdots n_N}(\Lambda, \mu)} = \frac{\mathcal{G}^h_{\omega_1}(z,\mu)}{J_{\omega_1}(\mu)}$$

Li, Li, Yuan `13
Chien, Vitev `15

$$\omega_i = 2p_{T_i}$$

$$\longrightarrow \quad F(z, p_T) = \frac{1}{\sigma_{\rm tot}} \sum_{i=q,g} \int_{\rm PS} dy\, dp'_T \frac{d\sigma^i}{dy\, dp'_T} \frac{\mathcal{G}^h_i(\omega, R, z, \mu)}{J^i(\omega, R, \mu)}$$



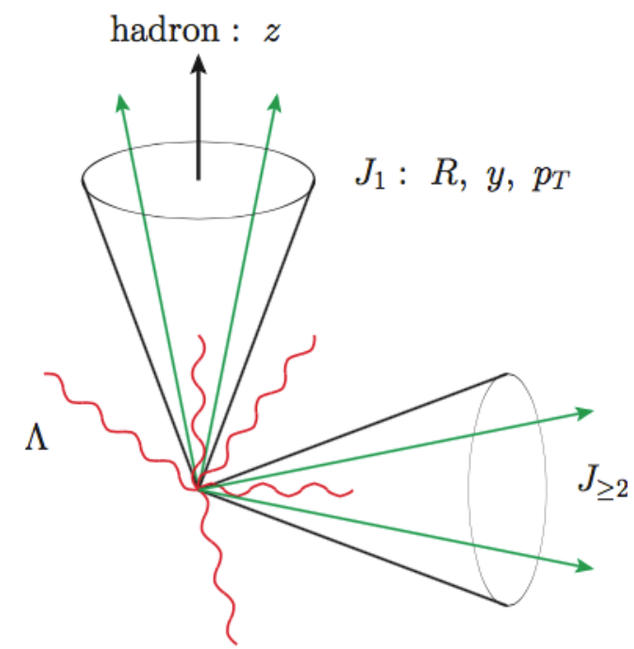
Fragmenting jet function

$$\mathcal{G}^{j}_{i,\mathrm{bare}}(\omega, R, z, \mu) = \int \frac{dk_\perp^2}{(k_\perp^2)^{1+\epsilon}} \frac{\alpha_s}{2\pi} \frac{(e^{\gamma_E}\mu^2)^\epsilon}{\Gamma(1-\epsilon)} P_{ji}(z,\epsilon)\delta_{\mathrm{alg}}$$

- where:

$$\delta_{\mathrm{anti}-k_T} = \theta(k_\perp^2)\,\theta(z^2(1-z)^2\omega^2\tan^2(R/2) - k_\perp^2)$$

e.g. $P_{qq}(z,\epsilon) = C_F\left[\frac{1+z^2}{1-z} - \epsilon(1-z)\right]$



$\overline{\mathrm{MS}}$, pure dim reg, $\mathcal{O}(\alpha_s)$

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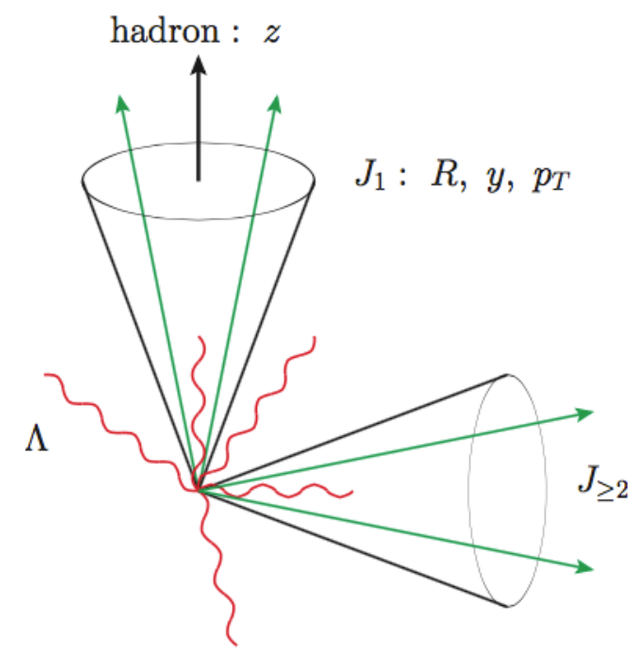

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$\overline{\text{MS}}$, pure dim reg, $\mathcal{O}(\alpha_s)$

- matching onto standard FFs $D_j^h(z,\mu)$ for $\mu_{\mathcal{G}} \gg \Lambda_{\text{QCD}}$

$$\mathcal{G}_i^h(\omega, R, z, \mu) = \sum_j \int_z^1 \frac{dx}{x} \mathcal{J}_{ij}(\omega, R, x, \mu)\, D_j^h(\frac{z}{x}, \mu) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{\omega^2\tan^2(R/2)}\right)$$

Matching coefficients

standard collinear fragmentation functions

Fragmenting jet function

Quark FJF at 1-loop:

$$\mathcal{J}_{qq}(\omega, R, z, \mu) = \delta(1-z) + \frac{\alpha_s}{\pi} C_F \left[\delta(1-z) \left(\ln^2 \left(\frac{\omega \tan(R/2)}{\mu} \right) - \frac{\pi^2}{24} \right) + \hat{P}_{qq} \ln \left(\frac{\omega \tan(R/2)}{\mu} \right) \right.$$
$$\left. + \hat{P}_{qq}(z) \ \ln \ z + (1+z^2) \left(\frac{\ln(1-z)}{1-z} \right)_+ \right]$$

Jain, Procura, Waalewijn `11, Waalewijn `12

where $\hat{P}_{qq}(z) = \frac{1+z^2}{(1-z)_+}$

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

Fragmenting jet function

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Jain, Procura, Waalewijn `11, Waalewijn `12

$$J_q(\omega, R, \mu) = 1 + \frac{\alpha_s}{\pi} C_F \left[\ln^2 \left(\frac{\omega \tan(R/2)}{\mu} \right) - \frac{3}{2} \ln \left(\frac{\omega \tan(R/2)}{\mu} \right) + \frac{13}{4} - \frac{3\pi^2}{8} \right]$$

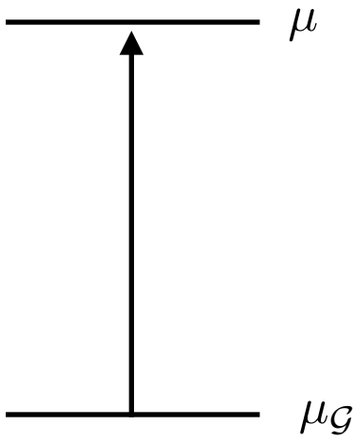
Ellis, Vermilion, Walsh, Hornig, Lee `10

where $\hat{P}_{qq}(z) = \dfrac{1+z^2}{(1-z)_+}$

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

Resummation

- solve RG equation $\mu \frac{d}{d\mu} \mathcal{G}_i^h(\omega, R, z, \mu) = \gamma_{\mathcal{G}}^i(\mu)\, \mathcal{G}_i^h(\omega, R, z, \mu)$



$$\mathcal{G}_i^h(\omega, R, z, \mu) = \mathcal{G}_i^h(\omega, R, z, \mu_{\mathcal{G}}) \exp\left[\int_{\mu_{\mathcal{G}}}^{\mu} \frac{d\mu'}{\mu'} \gamma_{\mathcal{G}}^i(\mu')\right]$$

where

$$\gamma_{\mathcal{G}}^i(\mu) = \Gamma_{\text{cusp}}^i(\alpha_s) \ln \frac{\mu^2}{\omega^2 \tan^2(R/2)} + \gamma^i(\alpha_s)$$

anomalous dimensions:

$$\Gamma_{\text{cusp}}^i = \sum_n \Gamma_{n-1}^i \left(\frac{\alpha_s}{4\pi}\right)^n$$

$$\gamma^i = \sum_n \gamma_{n-1}^i \left(\frac{\alpha_s}{4\pi}\right)^n$$

$\longrightarrow$ Resummation of $\ln R$

Resummation

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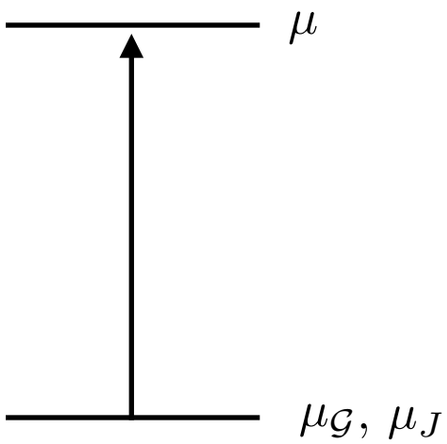
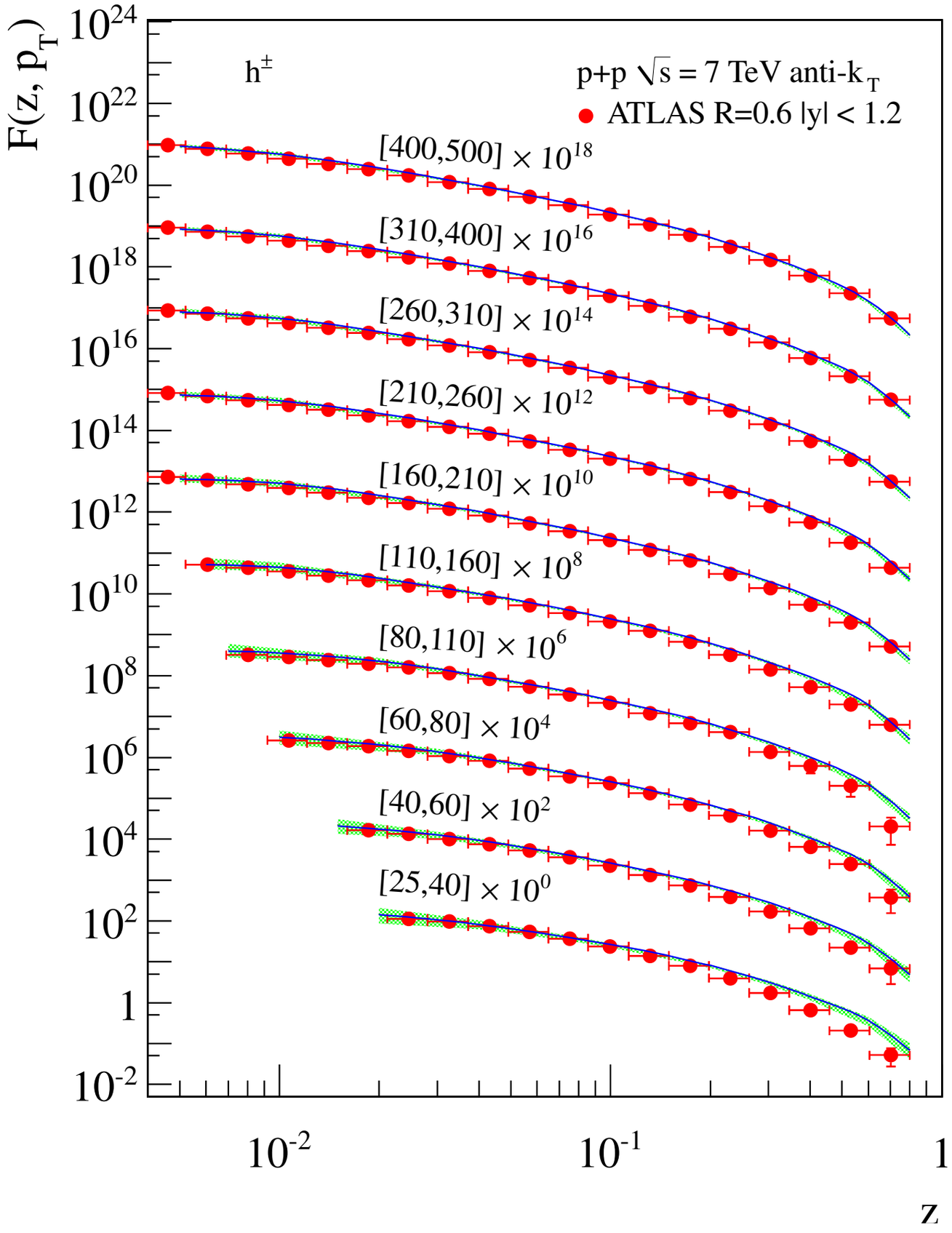


$$\mathcal{G}_i^h(\omega, R, z, \mu) = \mathcal{G}_i^h(\omega, R, z, \mu_{\mathcal{G}}) \exp\left[\int_{\mu_{\mathcal{G}}}^{\mu} \frac{d\mu'}{\mu'} \gamma_{\mathcal{G}}^i(\mu')\right]$$

- same for the unmeasured jet function $J_{\omega_1}(\mu)$

$\longrightarrow$ $F_{\omega_1}(z, p_{T_i}) = \dfrac{\mathcal{G}_{\omega_1}^h(z, \mu)}{J_{\omega_1}(\mu)}$ is RG-invariant for $\mu_{\mathcal{G}} = \mu_J = p_{TR} = \omega \tan(R/2)$



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

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

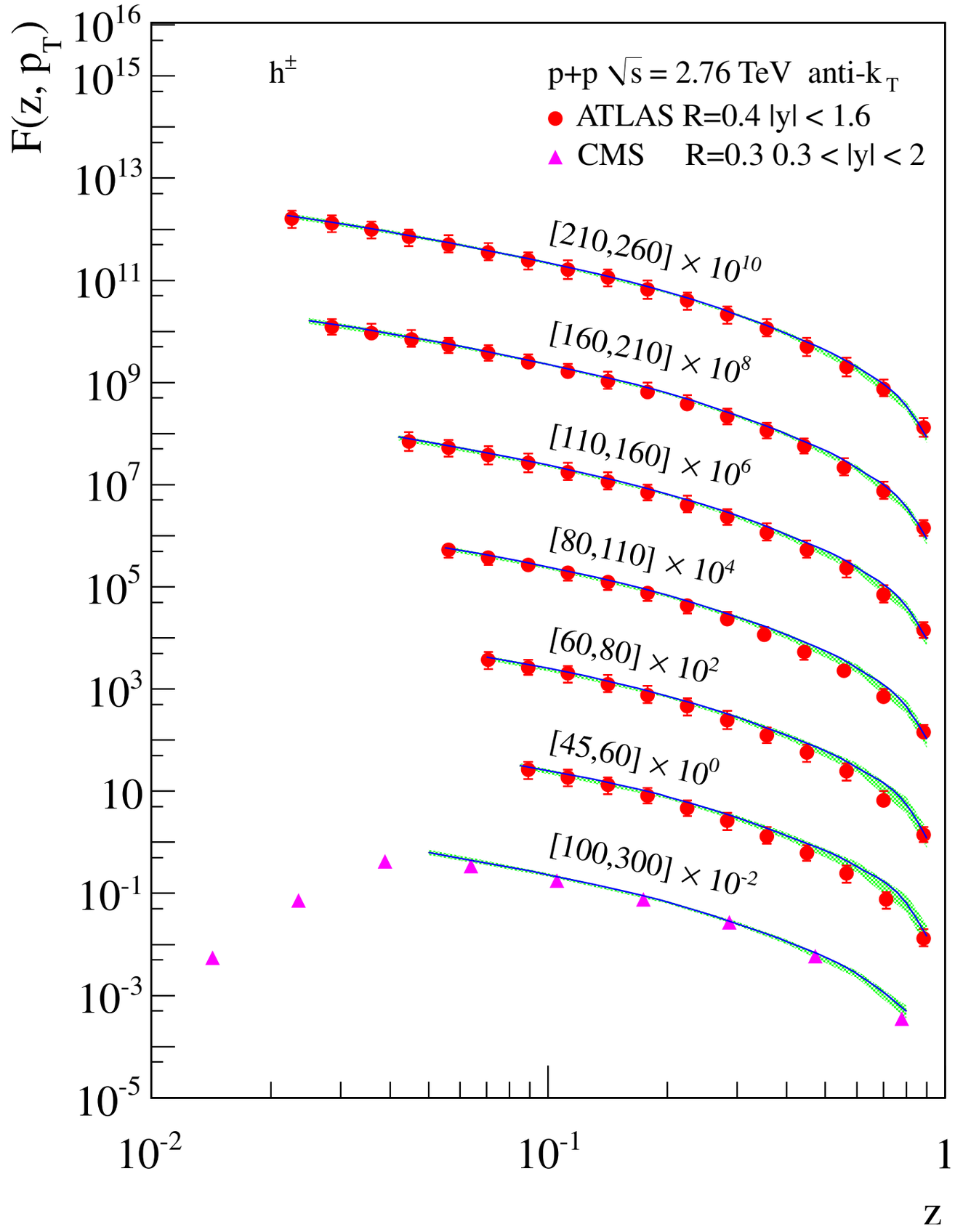
QCD scale uncertainty

$$\mu \in [p_T/2, 2p_T],$$
$$\mu_J \in [p_{TR}/2, 2p_{TR}],$$
$$\mu_{\mathcal{G}} \in [p_{TR}/2, 2p_{TR}]$$

$$p_{TR} = 2p_T \tan(R/2)$$

Using DSS FFs

de Florian, Sassot, Stratmann - '07



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

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Resummation of large logarithms

Convolution structure:

$$\mathcal{G}_i^h(\omega, R, z, \mu) = \sum_j \int_z^1 \frac{dx}{x} \mathcal{J}_{ij}(\omega, R, x, \mu) D_j^h(\frac{z}{x}, \mu) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}^2}{\omega^2 \tan^2(R/2)}\right)$$

Threshold logarithms $\left(\frac{\ln(1-x)}{1-x}\right)_+$ become large at the partonic threshold $x \to 1$

Procura, Waalewijn `12

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Threshold logarithms $\left(\frac{\ln(1-x)}{1-x}\right)_+$ become large at the partonic threshold $x \to 1$

$$\longrightarrow \quad \mathcal{G}_q^h(\omega, R, z, \mu) = \left\{1 + \frac{\alpha_s}{\pi} C_F \left[\ln^2\left(\frac{\omega \tan(R/2)(1-z)}{\mu}\right) - \frac{\pi^2}{24}\right]\right\} D_q^h(z, \mu) + \cdots$$

Choosing $\mu = \omega \tan(R/2)(1-z)$ resums logarithms of R and $(1-z)$

Procura, Waalewijn `12

Both $\ln R$ and $\ln(1-z)$ are simultaneously resummed

Hadronic threshold $z \to 1$

QCD scale uncertainty

$$\mu \in [p_T/2, 2p_T],$$
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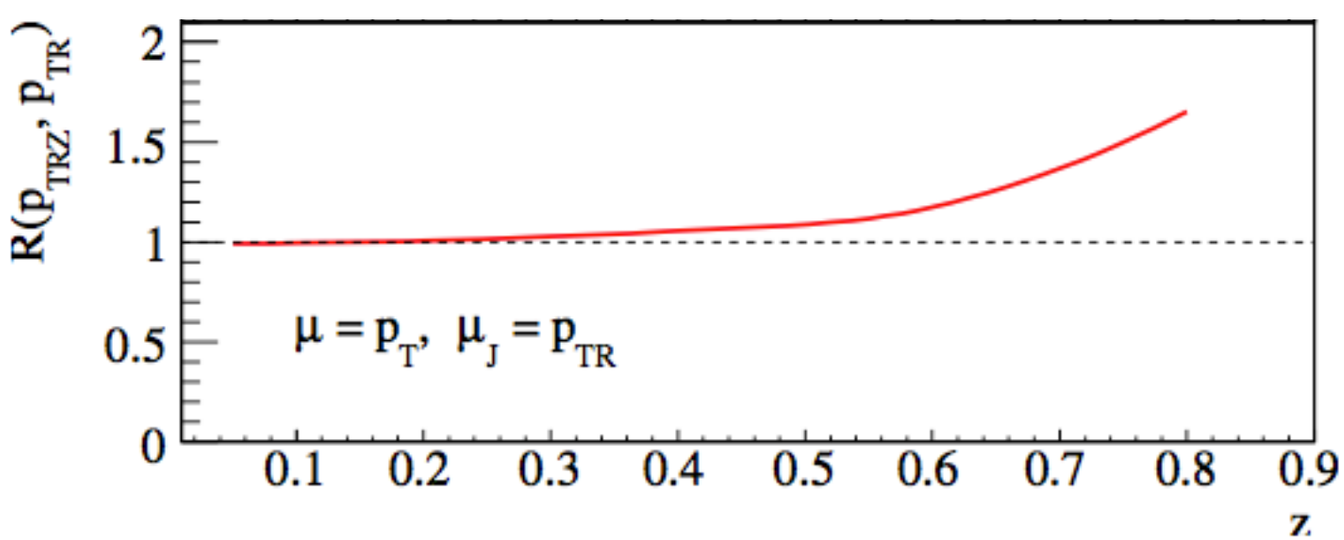
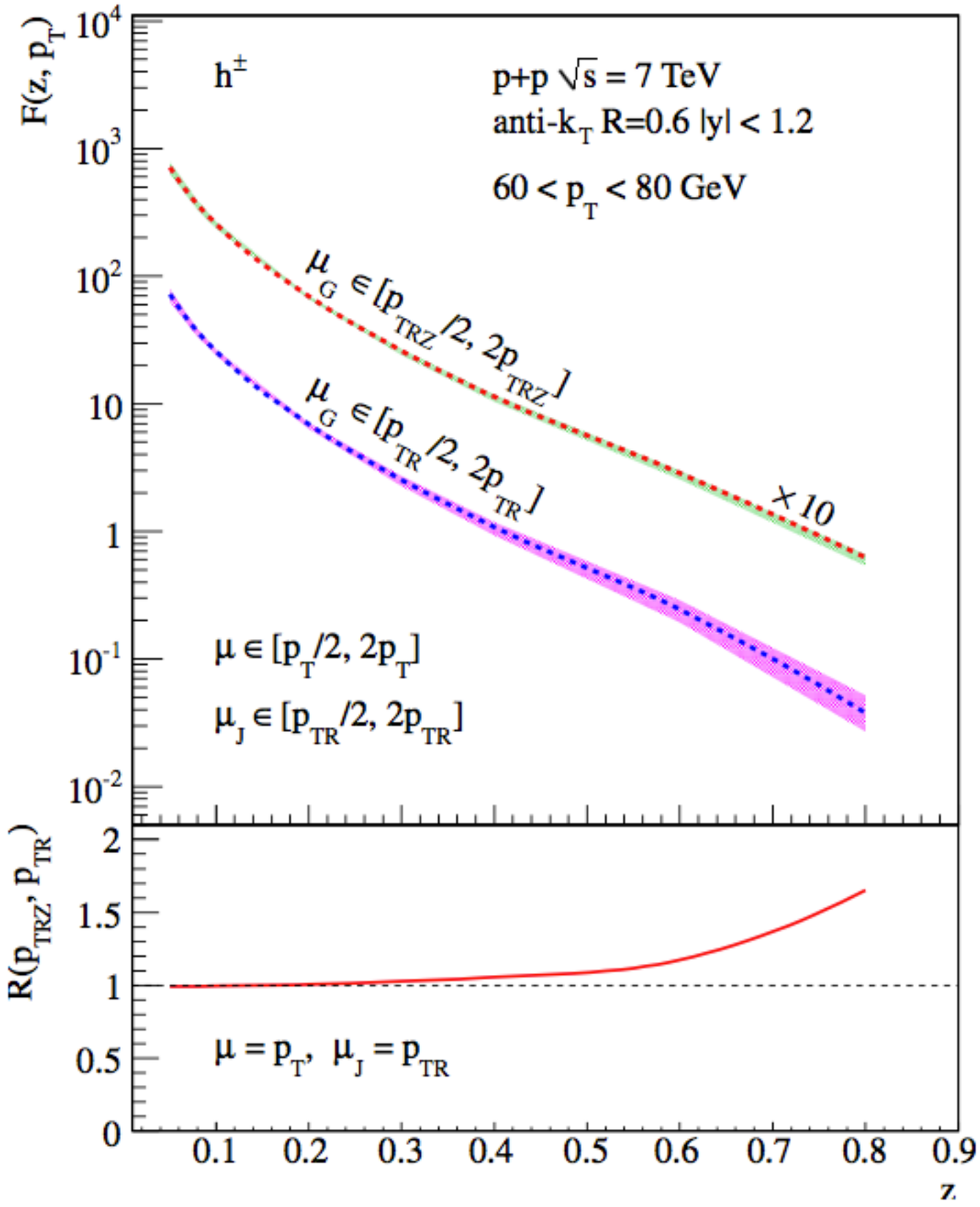
$$p_{TRZ} = 2p_T \tan(R/2)\,(1-z)$$





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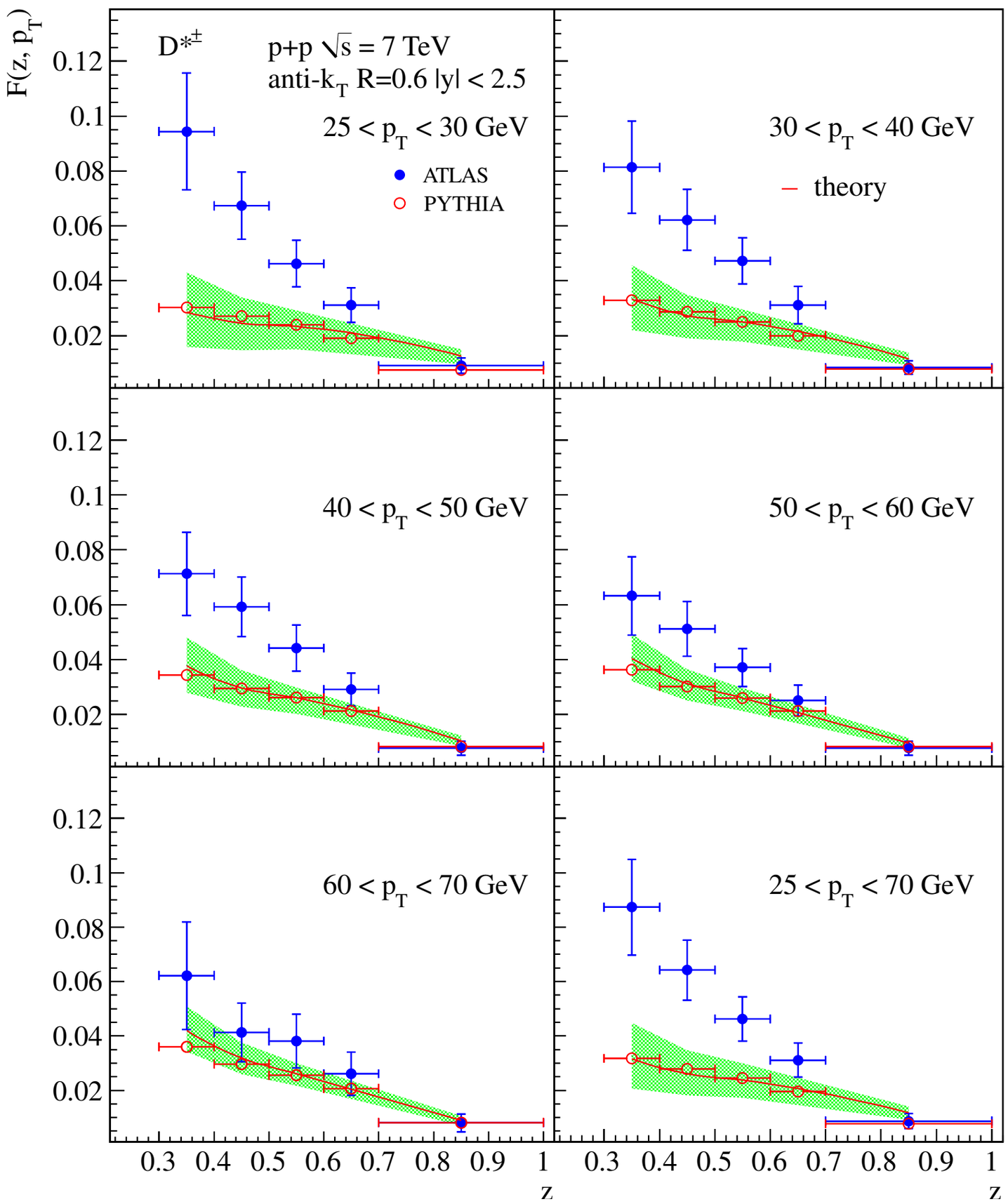
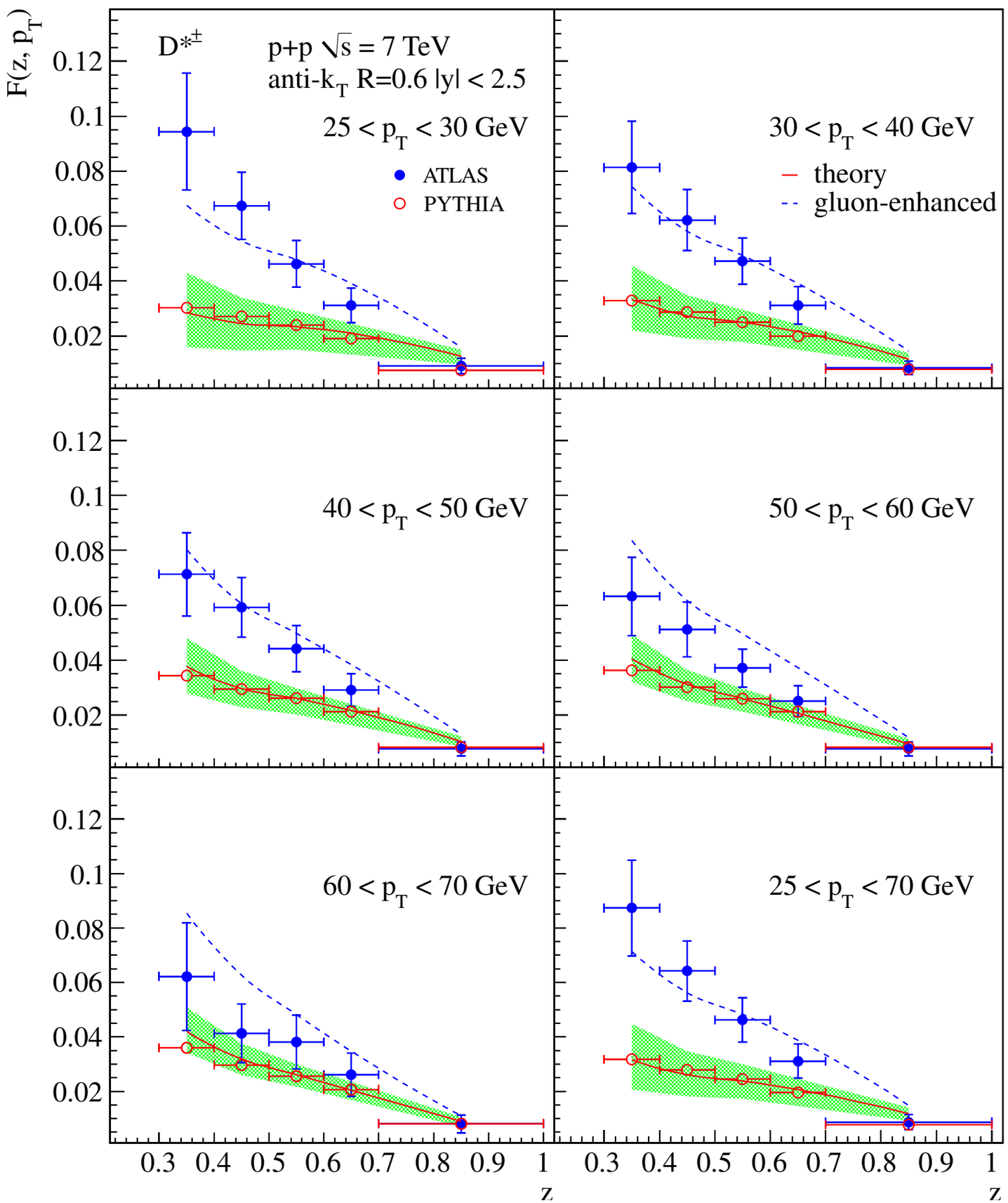


D-meson
jet fragmentation function

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

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

ZMVNFS, $e^+e^- \to DX$
$\mu,\ \mu_J,\ \mu_{\mathcal{G}} \gg m_Q$



D-meson
jet fragmentation function

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

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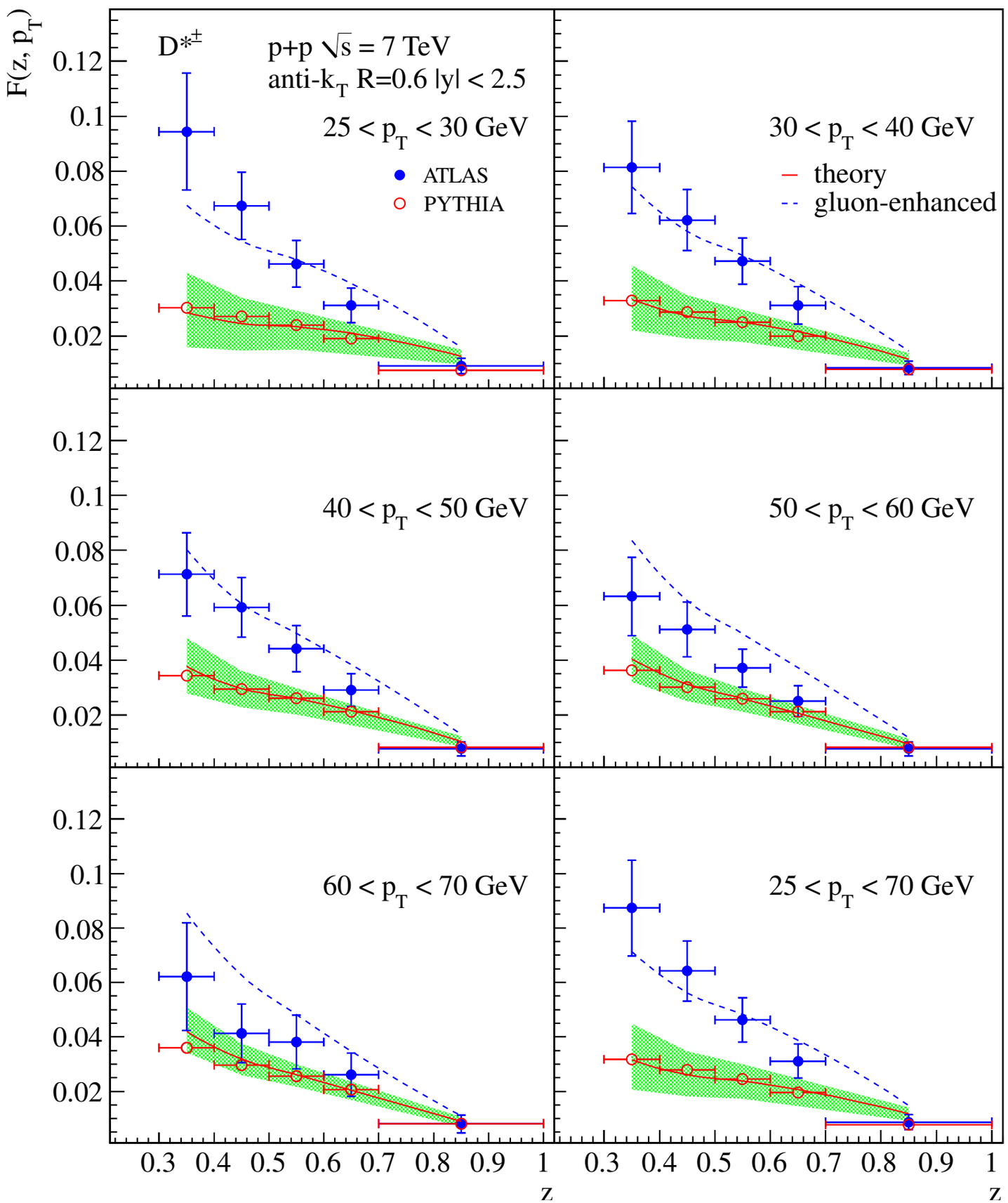

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Comparison to ATLAS data
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New fit of D-FFs:

Anderle, Kang, FR, Stratmann, Vitev
- work in progress

Outline

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Chien, Kang, FR, Vitev, Xing - '15

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- Conclusions

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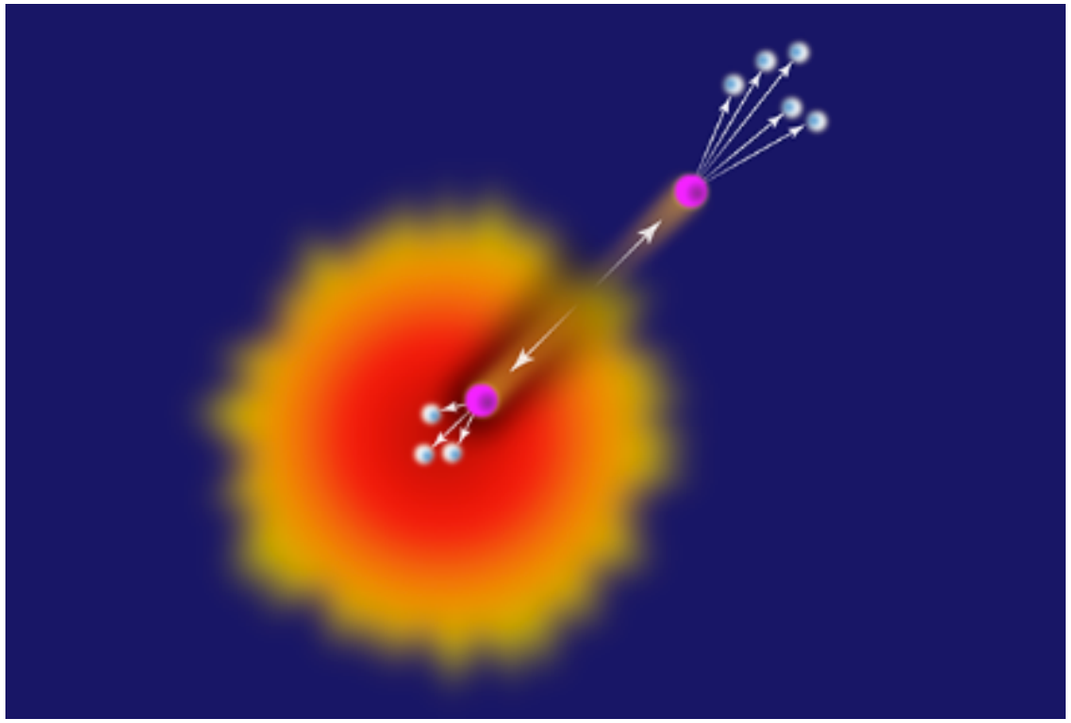
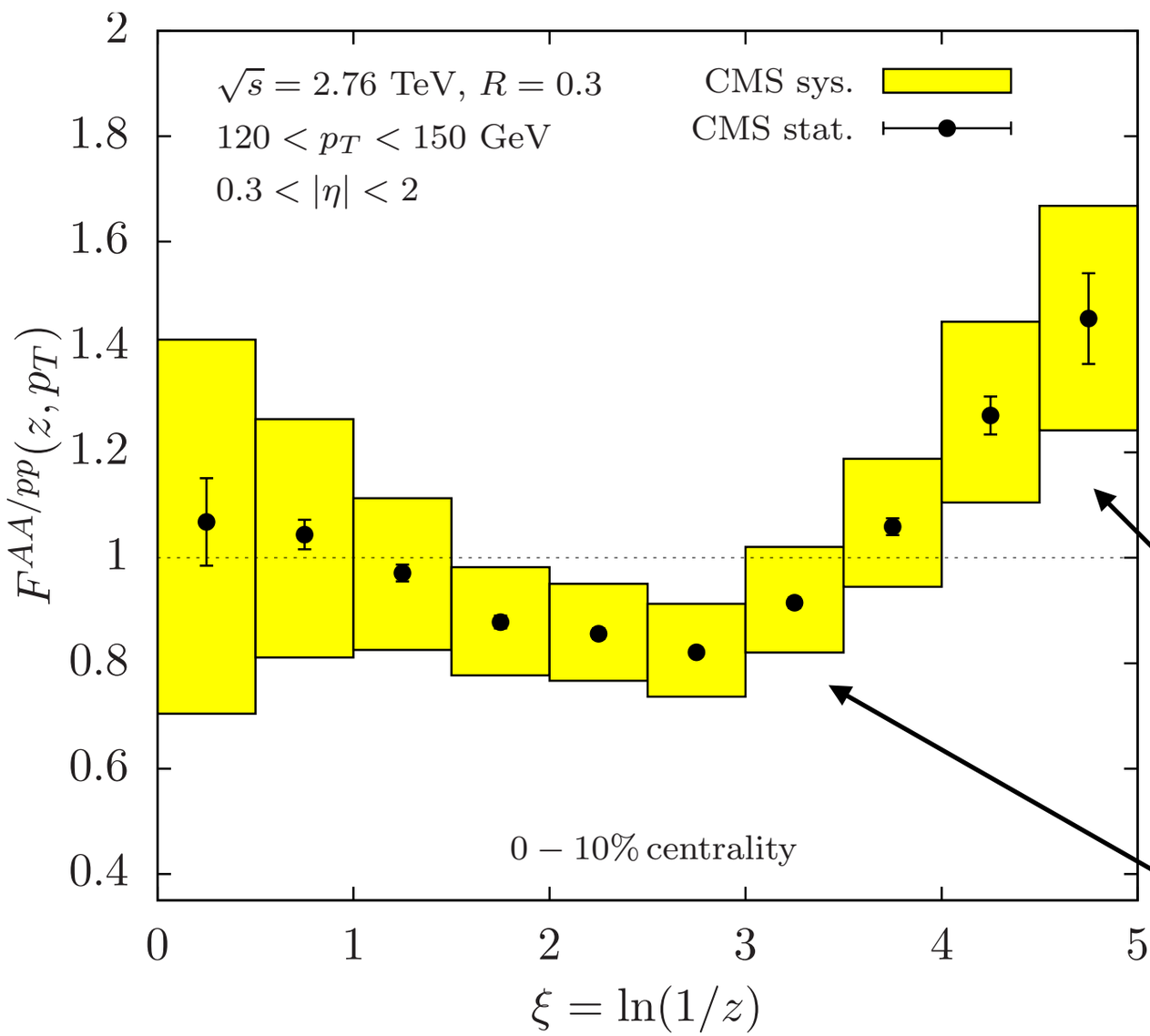
$$\frac{\frac{d\sigma_{AA}}{dydp_T}}{\langle N_{\rm bin}\rangle \frac{d\sigma_{pp}}{dydp_T}}$$





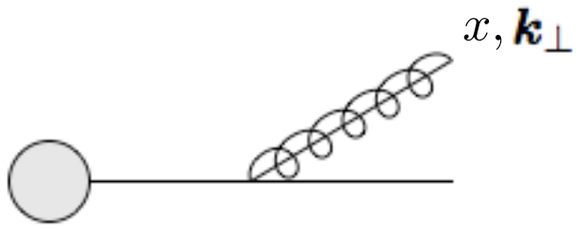
enhancement of soft particles, small-z region

attenuation of particles in the large-z region

$\mathrm{SCET_G}$ splitting kernels

Basic ingredients for the calculation of the modification in AA collisions:

1. Final state



vacuum:

$$\left(\frac{dN^{\mathrm{vac}}}{dx\, d^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \frac{1}{\mathbf{k}_\perp^2}$$

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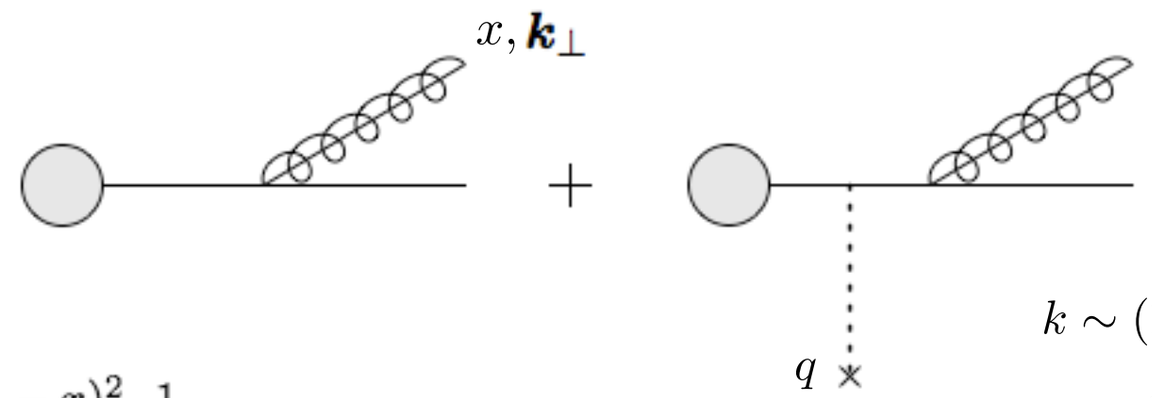

$k \sim (1, \lambda^2, \lambda)$

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

vacuum: $$\left(\frac{dN^{\mathrm{vac}}}{dx\, d^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \frac{1}{\mathbf{k}_\perp^2}$$

medium: *Ovanesyan, Vitev '12* *Idilbi, Majumder `08, D'Eramo, Liu, Rajagopal `10*

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

$\mathrm{SCET_G}$ splitting kernels

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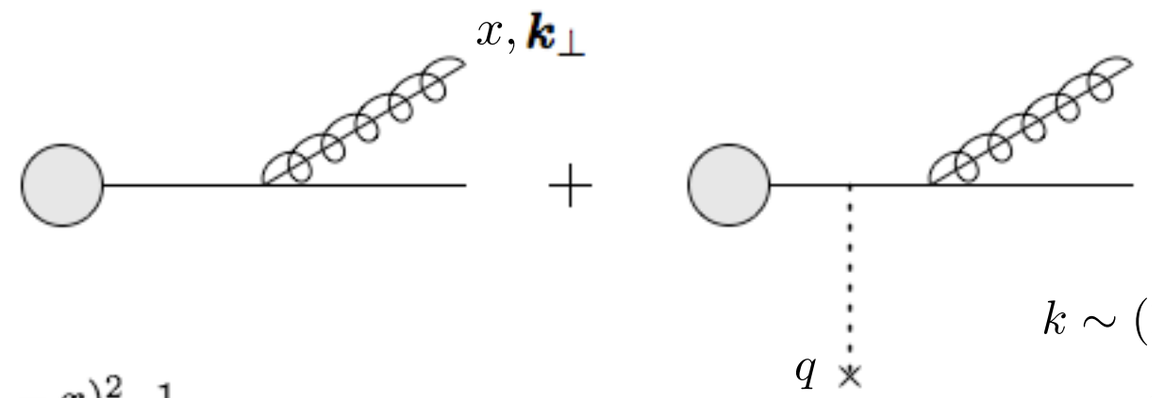


$k \sim (1, \lambda^2, \lambda)$

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

vacuum: $$\left(\frac{dN^{\rm vac}}{dx\, d^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \frac{1}{\mathbf{k}_\perp^2}$$

medium: *Ovanesyan, Vitev '12* *Idilbi, Majumder `08, D'Eramo, Liu, Rajagopal `10*

$$\left(\frac{dN^{\rm med}}{dx d^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm medium}}{d^2\mathbf{q}_\perp} \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} \cdot \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2} \right) \left(1 - \cos[(\Omega_1 - \Omega_2)\Delta z]\right) + \ldots \right]$$

model dependence of the medium

Soft gluon limit is consistent with traditional energy loss approach

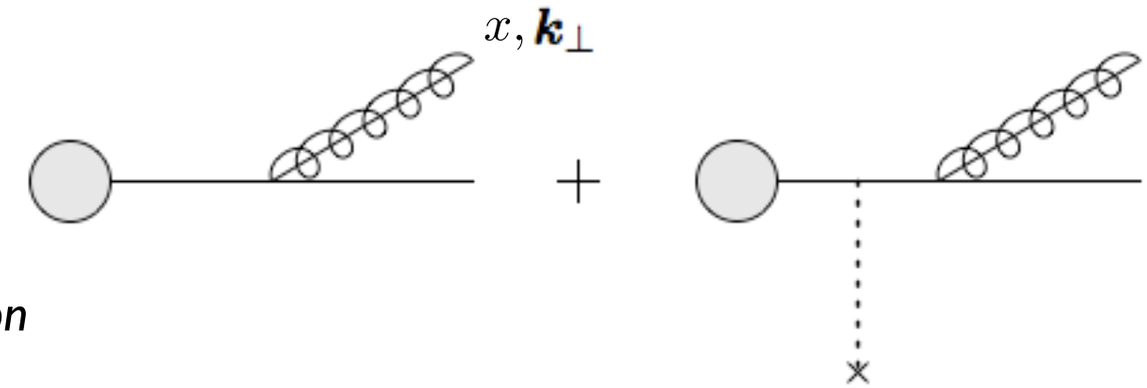
Gyulassy, Levai, Vitev '00

$\mathrm{SCET_G}$ splitting kernels

Basic ingredients for the calculation of the modification in AA collisions:

1. Final state *Ovanesyan, Vitev '12*

2. Final state - massive *FR, Vitev - in preparation*



e.g. vacuum

$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2}\frac{1}{\boldsymbol{k}_\perp^2 + x^2 m^2}\left[\frac{1-x+x^2/2}{x} - \frac{x(1-x)m^2}{\boldsymbol{k}_\perp^2 + x^2 m^2}\right]$$

$\mathrm{SCET_G}$ splitting kernels

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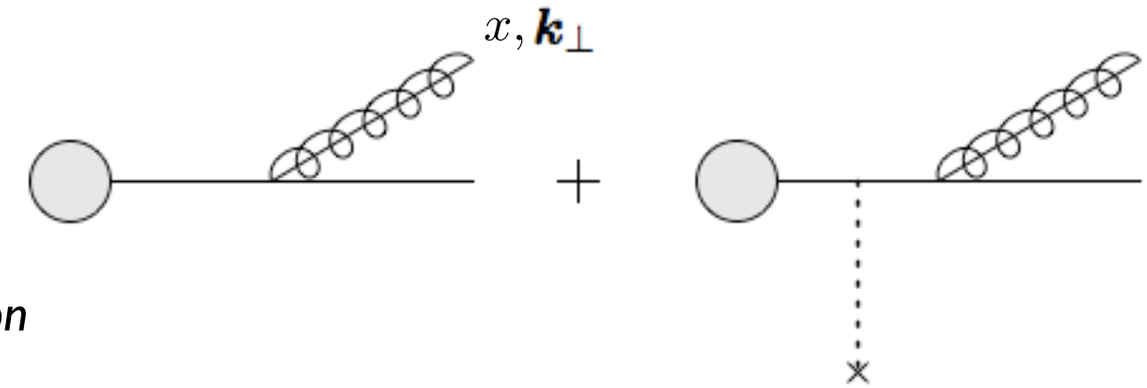
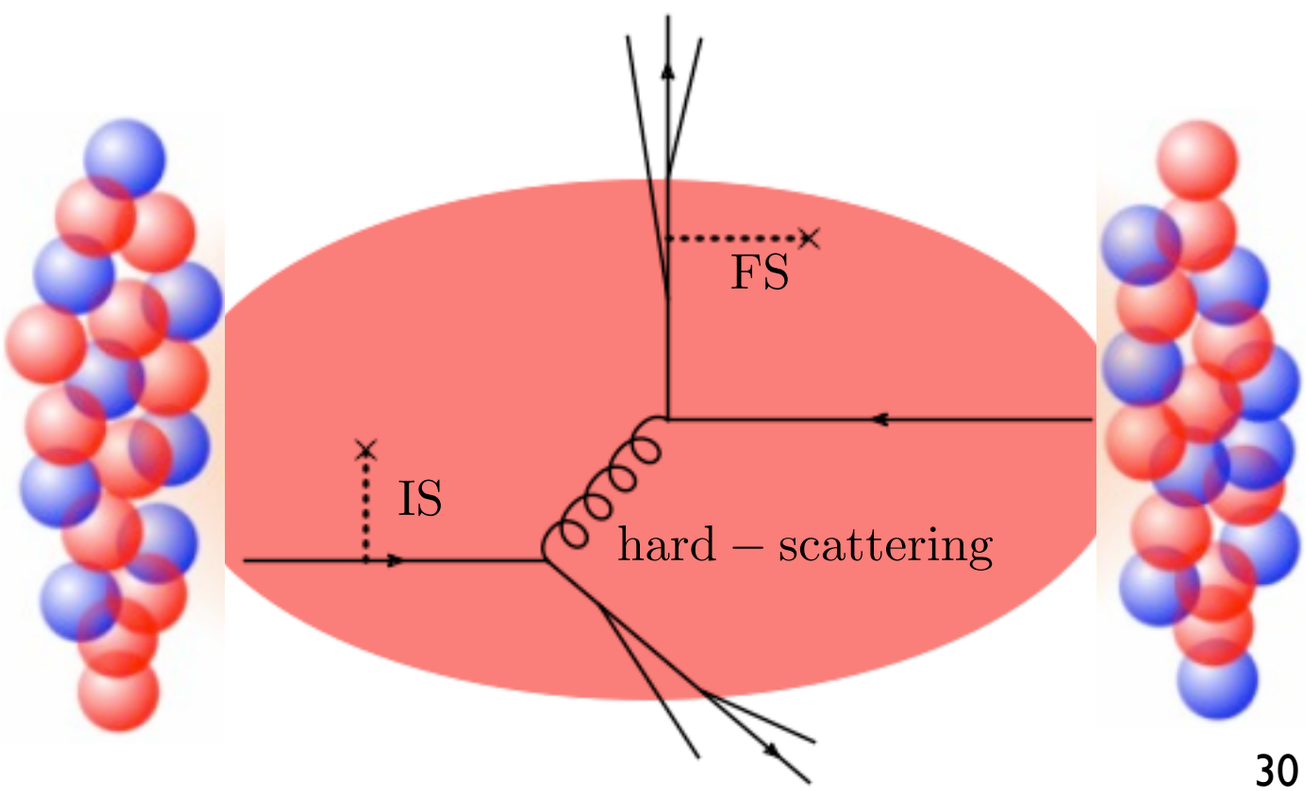
2. Final state - massive *FR, Vitev - in preparation*

3. Initial state *Ovanesyan, FR, Vitev - '15*



1. Initial state - Cold Nuclear Matter (CNM)



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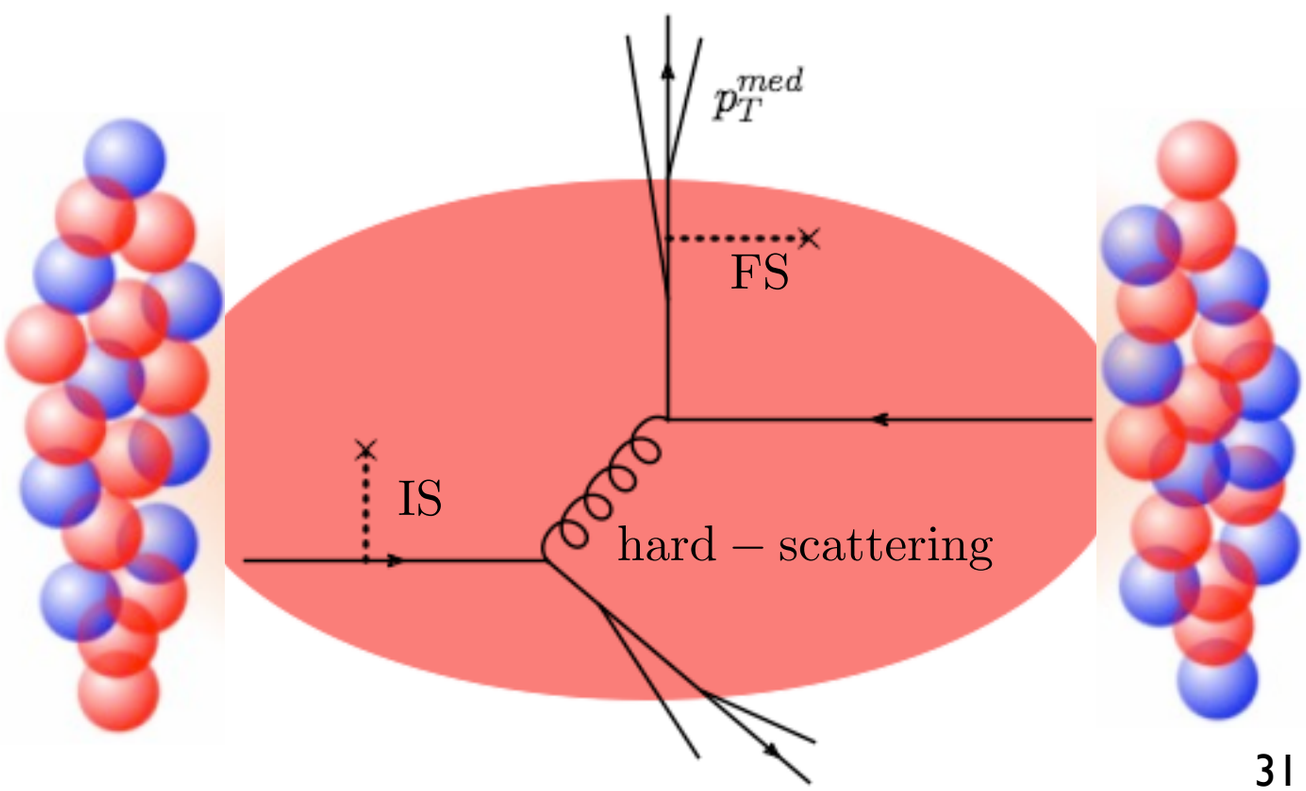
1. Initial state - Cold Nuclear Matter (CNM)

$$\sum_{i=q,g} \frac{d\sigma^i_{\rm AA}}{d\eta dp_T} \frac{\mathcal{G}_i^{j,\rm AA}}{J_i^{\rm AA}}$$

2. Final state - jet energy loss



Chien, Vitev `15

He, Vitev, Zhang `12

Dasgupta, Dreyer, Salam, Soyez `15

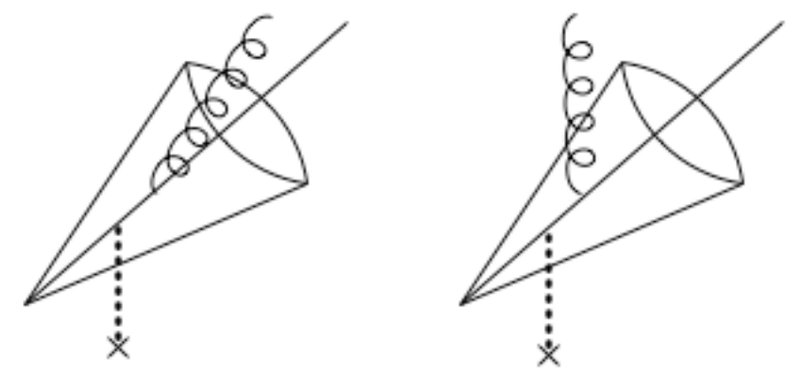
1. Initial state - Cold Nuclear Matter (CNM)

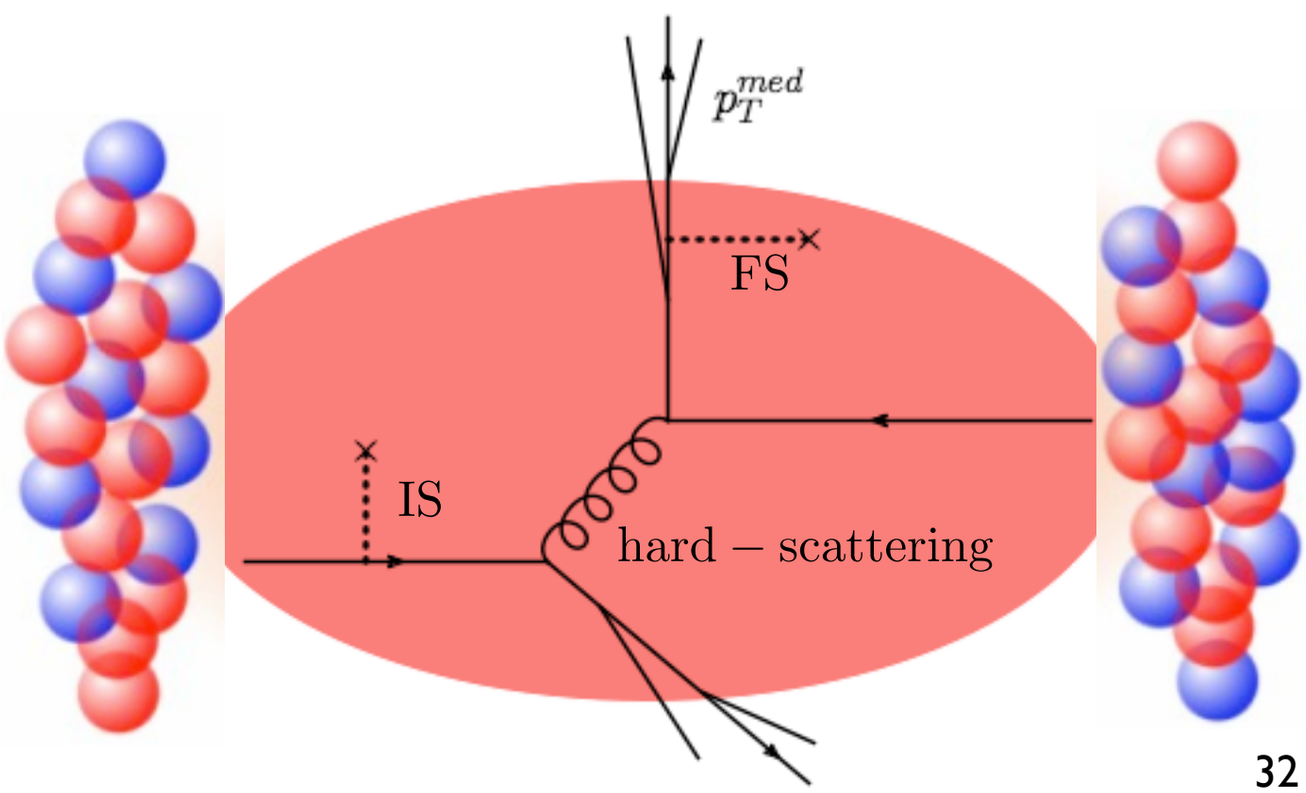
$$\sum_{i=q,g} \frac{d\sigma^i_{\rm AA}}{d\eta dp_T} \frac{\mathcal{G}_i^{j,\rm AA}}{J_i^{\rm AA}}$$

2. Final state - jet energy loss

$$p_T^{med} = p_T^{vac} \times (1-\epsilon) \longrightarrow \frac{1}{\sigma_0}\frac{d\sigma^i_{\rm AA}}{dydp_T}\bigg|_{p_T} = \frac{1}{\sigma_0}\frac{d\sigma^i_{pp}}{dydp_T}\bigg|_{\frac{p_T}{1-\epsilon_i}} \frac{1}{1-\epsilon_i}$$

$\longrightarrow$ Inclusive jet R_{AA}





Chien, Vitev `15

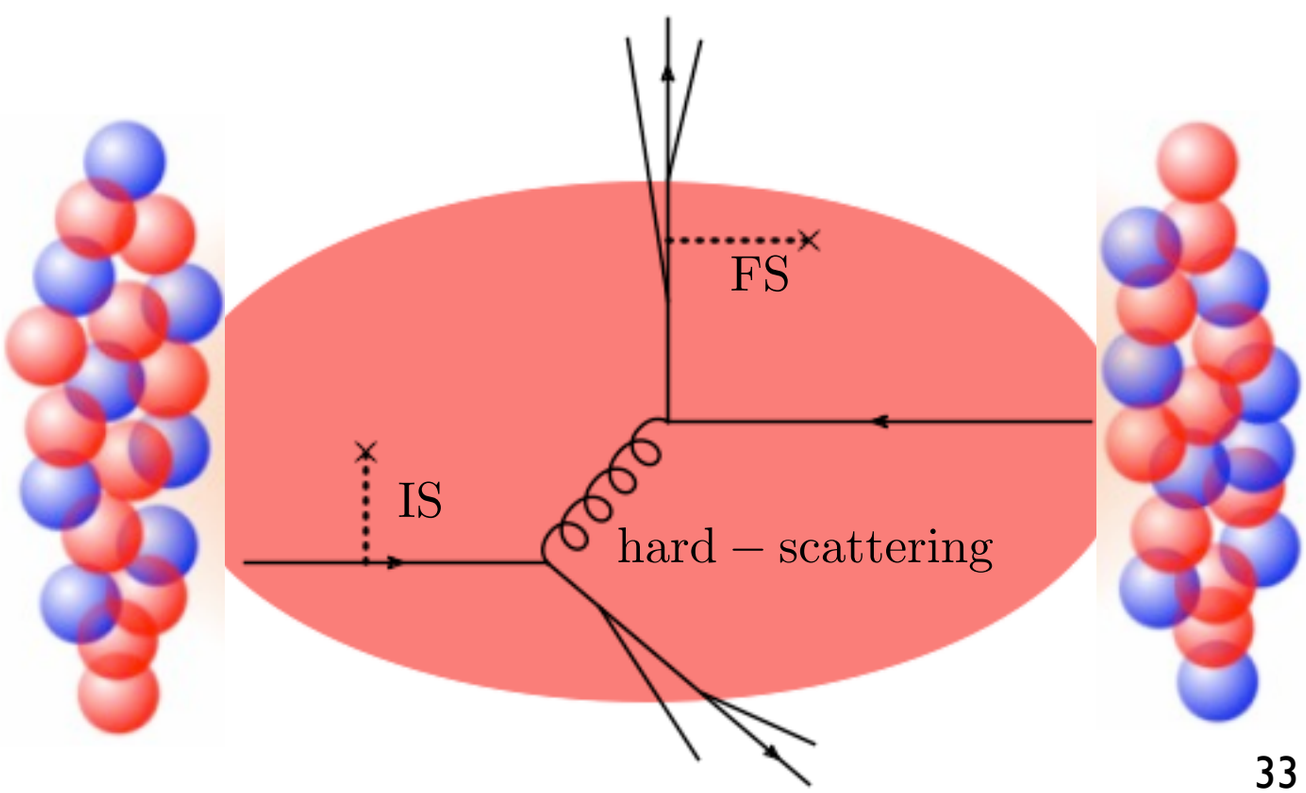
He, Vitev, Zhang `12

Dasgupta, Dreyer, Salam, Soyez `15

1. Initial state - Cold Nuclear Matter (CNM)
2. Final state - jet energy loss
3. Final state - jet substructure

$$\mathcal{G}^j_{i,\mathrm{bare}}(\omega, R, z, \mu) = \int dk_\perp^2 \frac{(e^{\gamma_E}\mu^2)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{dN^{\mathrm{vac}}}{dx dk_\perp^2}\right)_{i\to jk} \delta_{\mathrm{alg}} \qquad (x \to 1-z)$$

$$\left(\frac{dN^{\mathrm{vac}}}{dx dk_\perp^2}\right)_{q\to qg} = \frac{\alpha_s}{2\pi} C_F \frac{1+(1-x)^2}{x} \frac{1}{(k_\perp^2)^{1+\epsilon}}$$

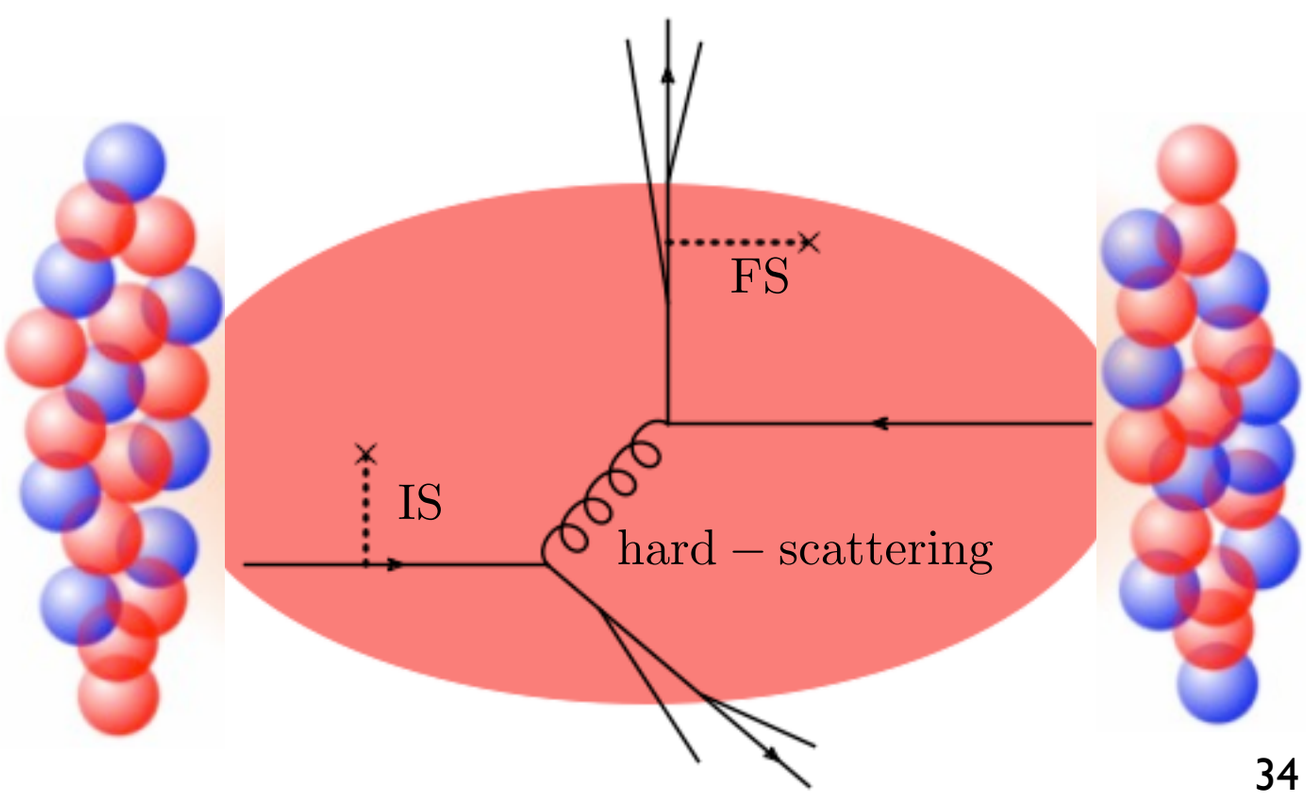


1. Initial state - Cold Nuclear Matter (CNM)
2. Final state - jet energy loss
3. Final state - jet substructure

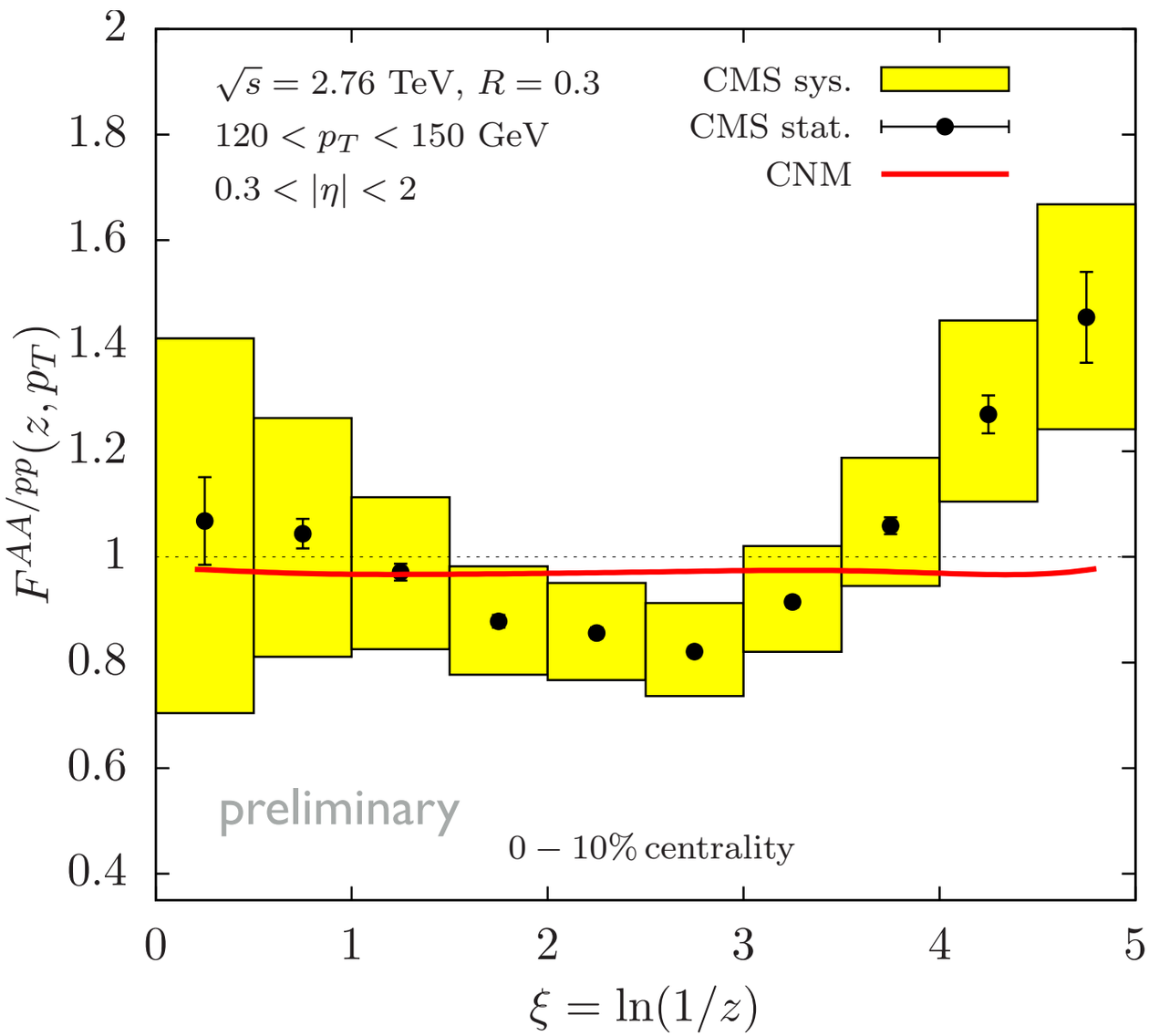
$$\mathcal{G}^{j}_{i,\mathrm{bare}}(\omega, R, z, \mu) = \int dk_\perp^2 \frac{(e^{\gamma_E}\mu^2)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{dN^{\mathrm{vac}}}{dx dk_\perp^2}\right)_{i\to jk} \delta_{\mathrm{alg}} \qquad (x \to 1-z)$$

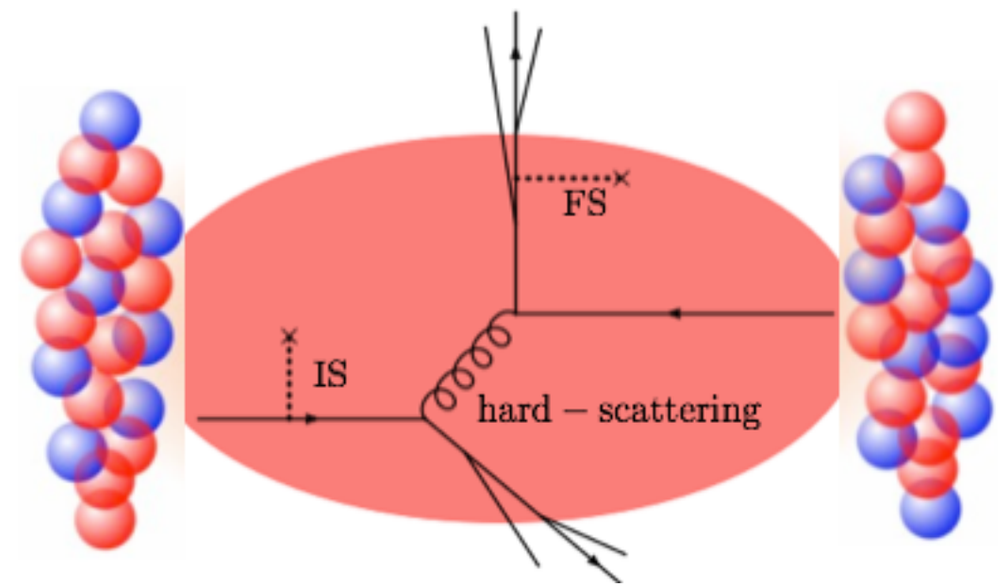
$$\left(\frac{dN^{\mathrm{vac}}}{dx dk_\perp^2}\right)_{q\to qg} = \frac{\alpha_s}{2\pi} C_F \frac{1+(1-x)^2}{x} \frac{1}{(k_\perp^2)^{1+\epsilon}}$$

$$\longrightarrow \quad \mathcal{G}^{j,\mathrm{AA}}_{i,\mathrm{bare}}(\omega, R, z, \mu) = \int dk_\perp^2 \frac{(e^{\gamma_E}\mu^2)^\epsilon}{\Gamma(1-\epsilon)} \left[\left(\frac{dN^{\mathrm{vac}}}{dx dk_\perp^2}\right)_{i\to jk} + \left(\frac{dN^{\mathrm{med}}}{dx dk_\perp^2}\right)_{i\to jk}\right] \delta_{\mathrm{alg}}$$



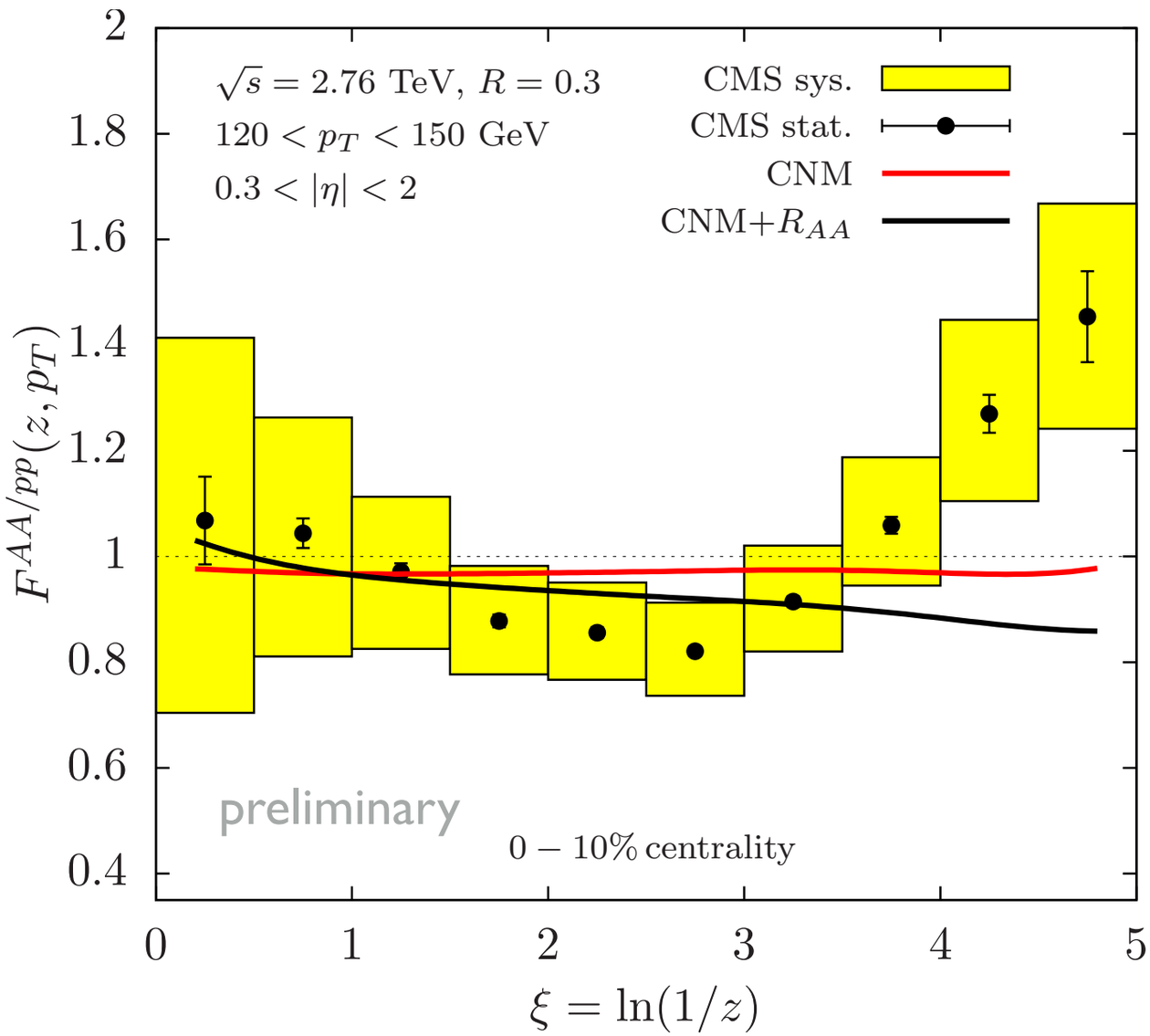
Similarly: $J_i^{\mathrm{AA}}(\mu) = J_i^{\mathrm{vac}}(\mu) + J_i^{\mathrm{med}}(\mu)$



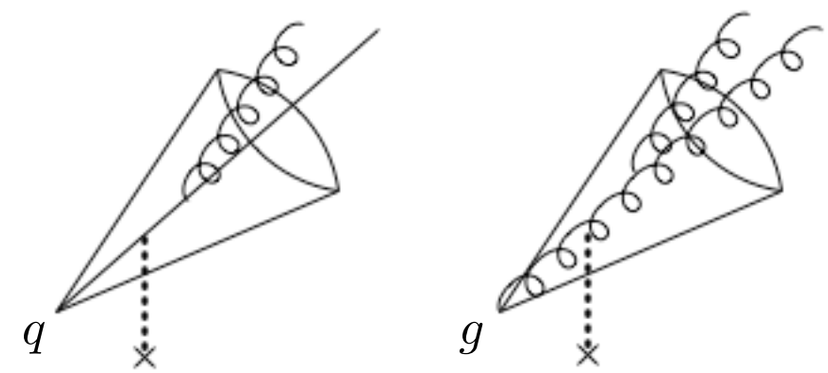


Using Kretzer FFs

Kretzer - '00

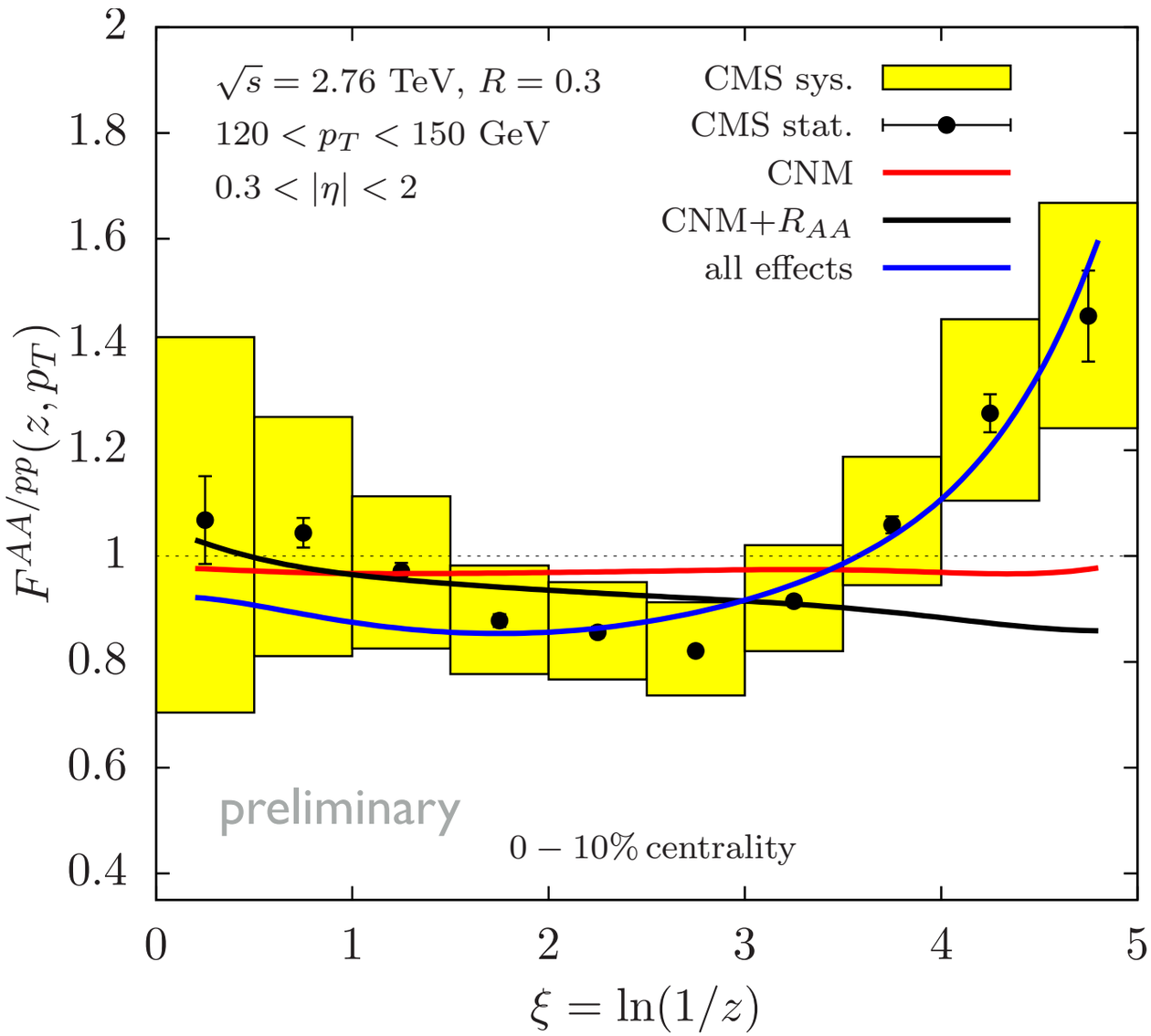


$$\sum_{i=q,g} \frac{d\sigma^i_{\rm AA}}{d\eta dp_T}$$

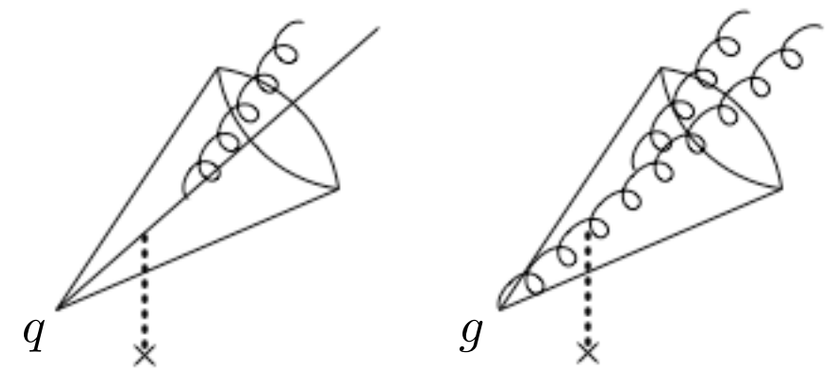


Using Kretzer FFs

Kretzer - '00



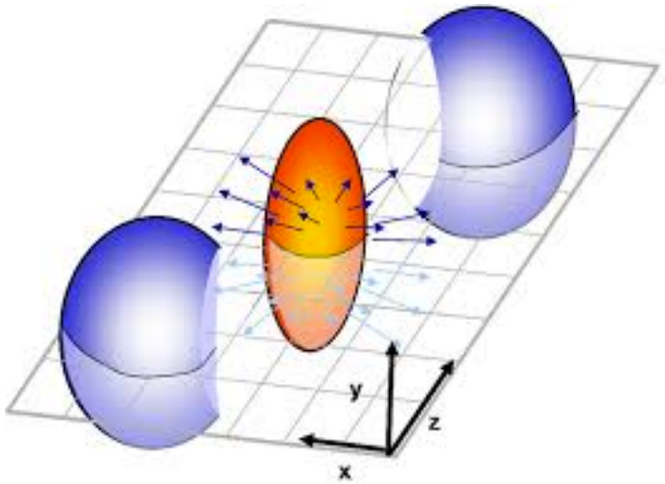
$$\sum_{i=q,g} \frac{d\sigma^i_{\rm AA}}{d\eta dp_T} \frac{\mathcal{G}_i^{j,\rm AA}}{J_i^{\rm AA}}$$

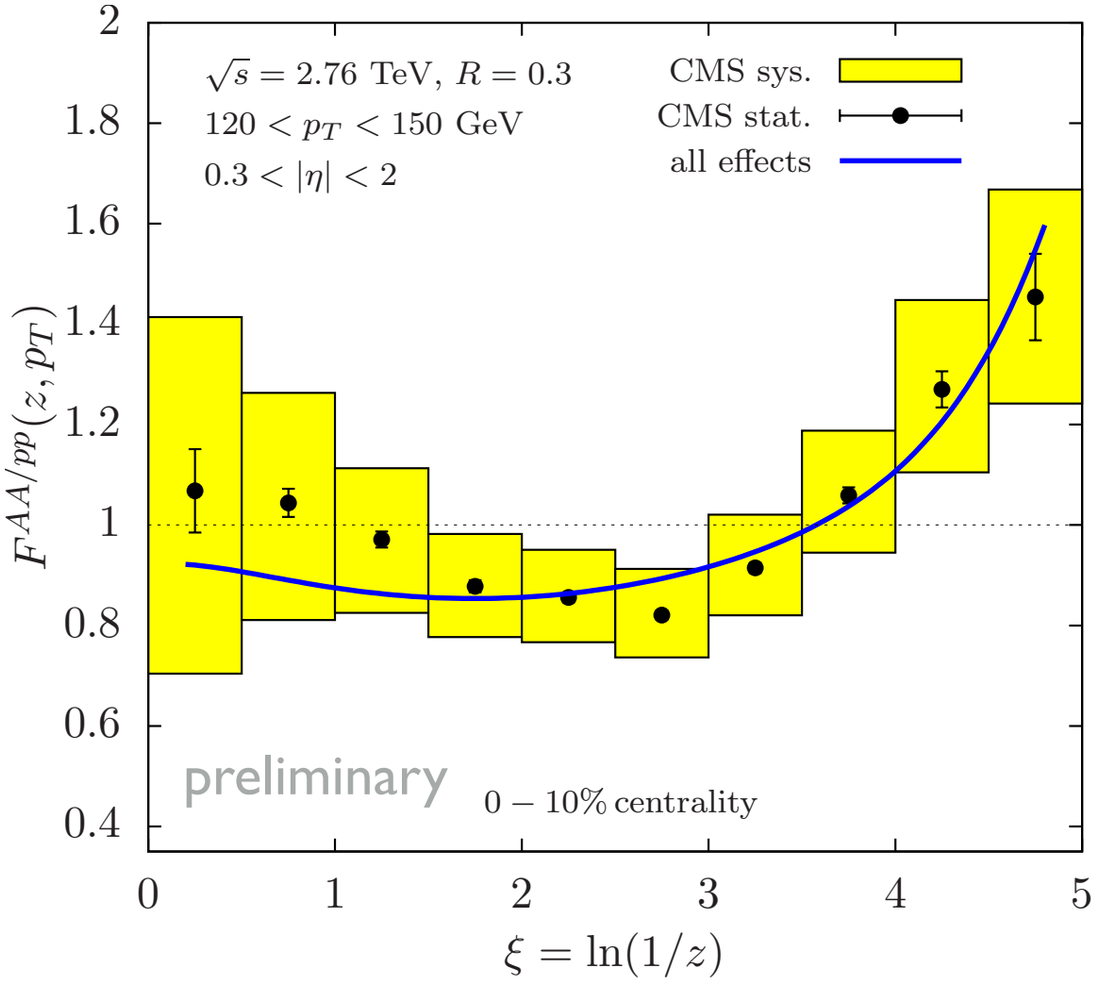


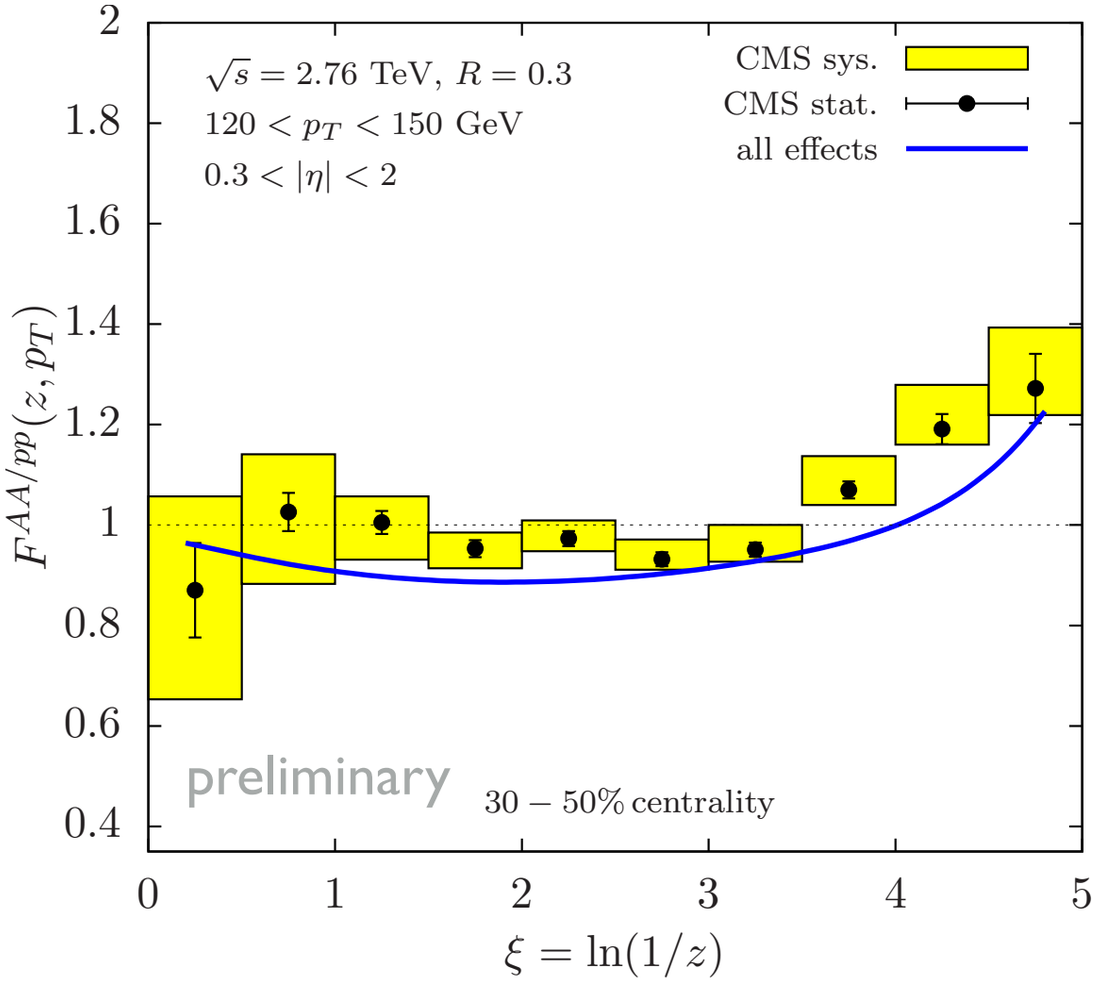
Using Kretzer FFs

Kretzer - '00

Centrality dependence

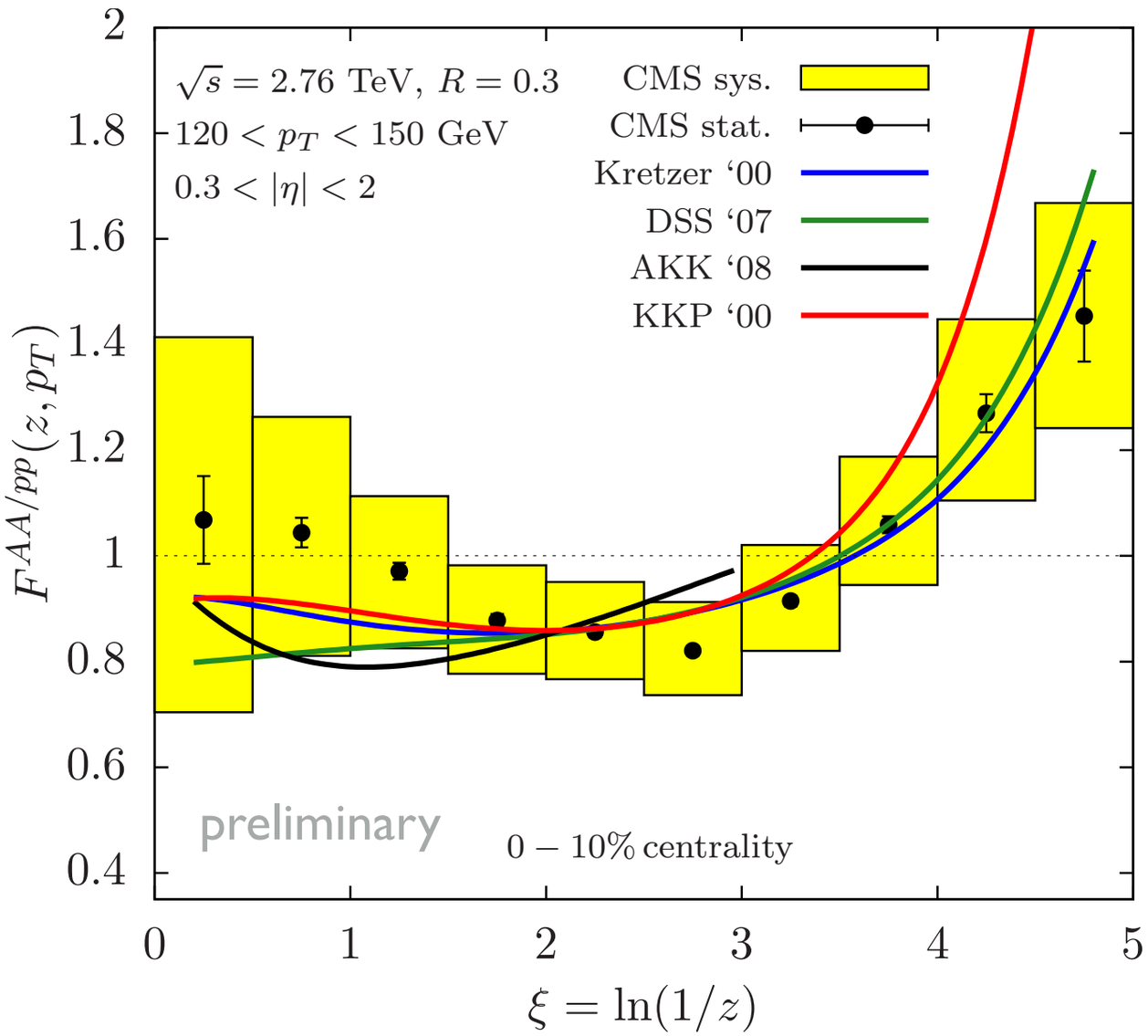






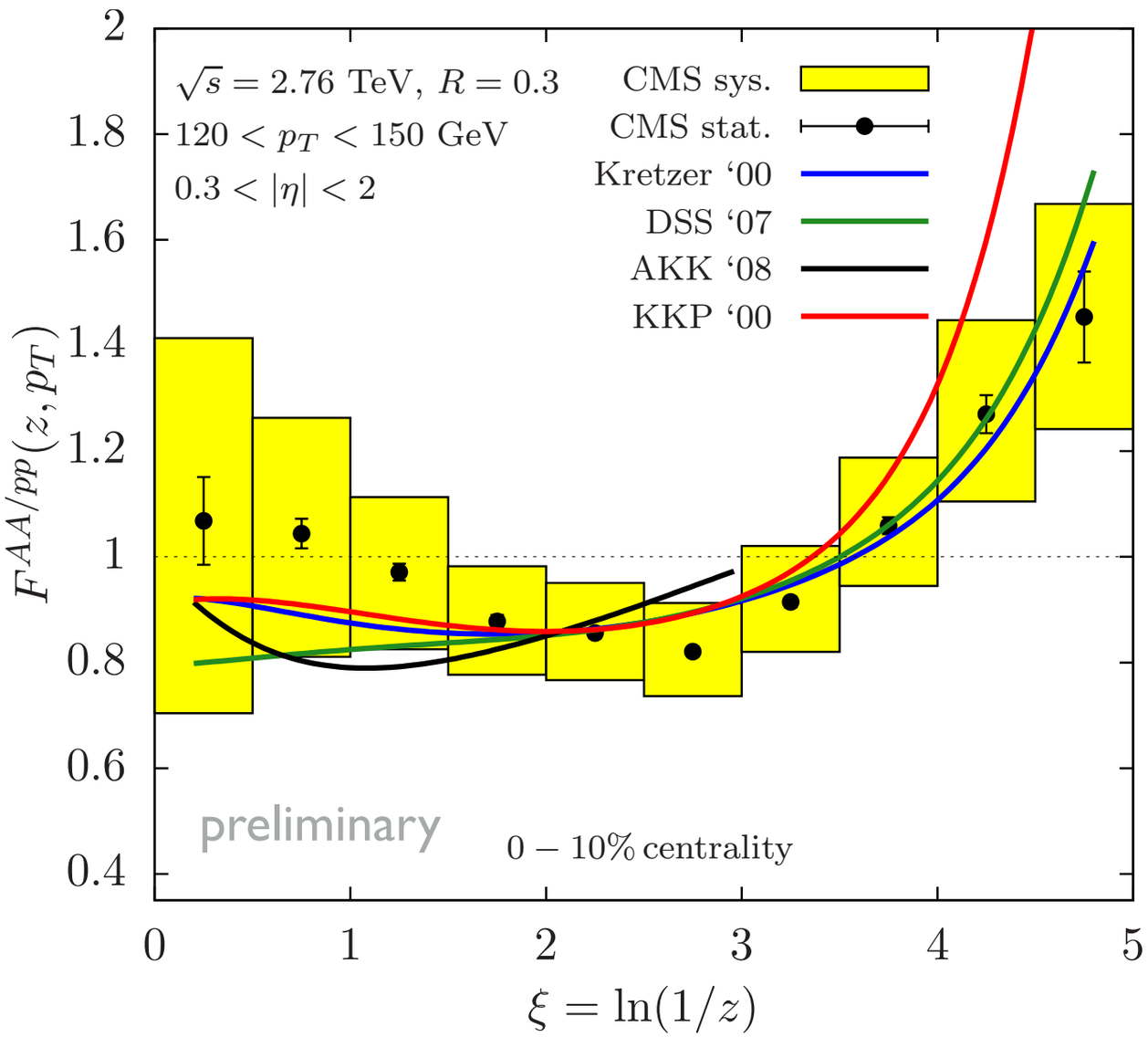
Uncertainties

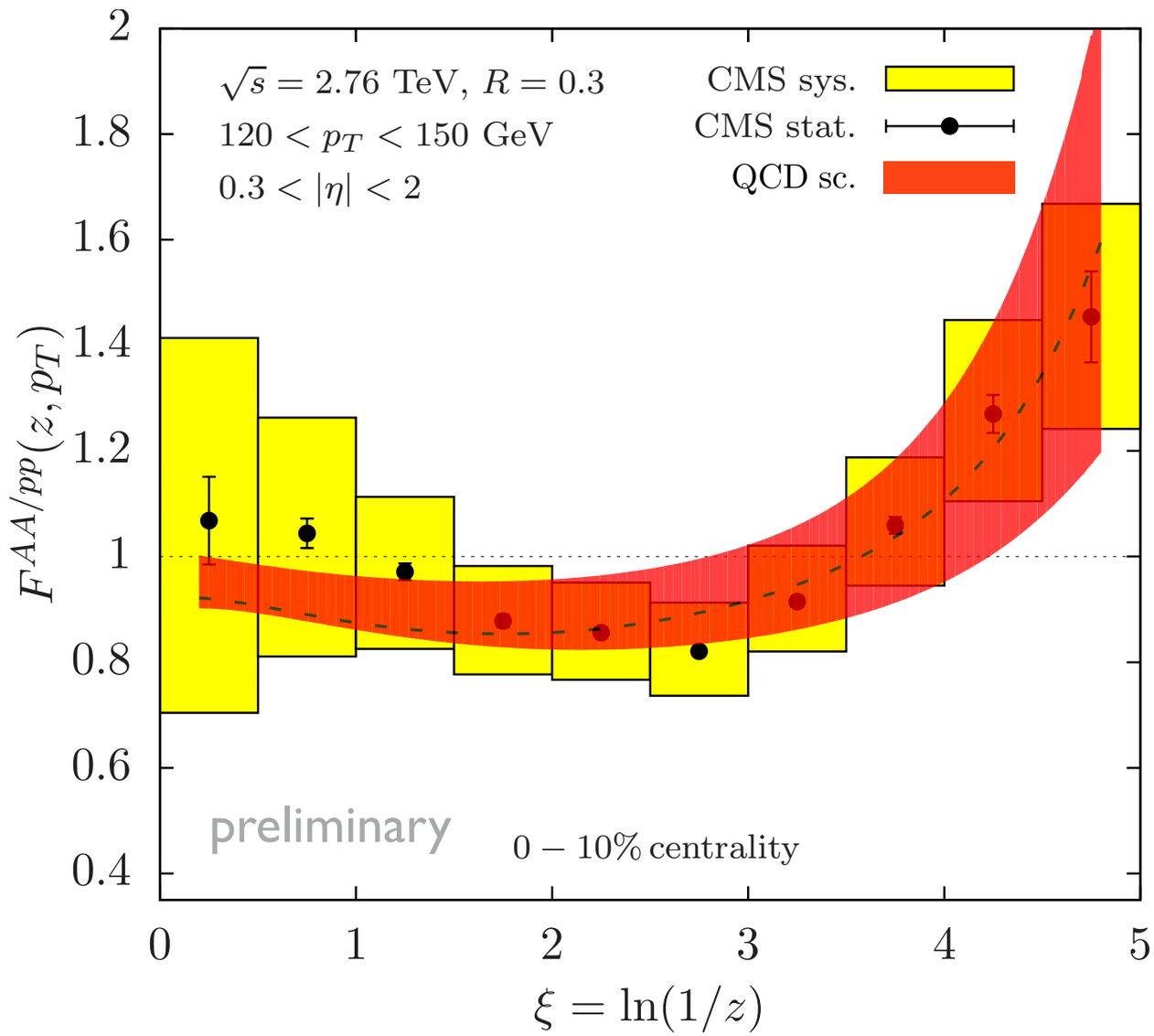
- fragmentation functions



Uncertainties

- fragmentation functions
- QCD scale uncertainty $\mu, \mu_{\mathcal{G}}, \mu_J$





Outline

- Jet Fragmentation functions in pp collisions

Chien, Kang, FR, Vitev, Xing - '15

- Modification in AA

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

- Conclusions

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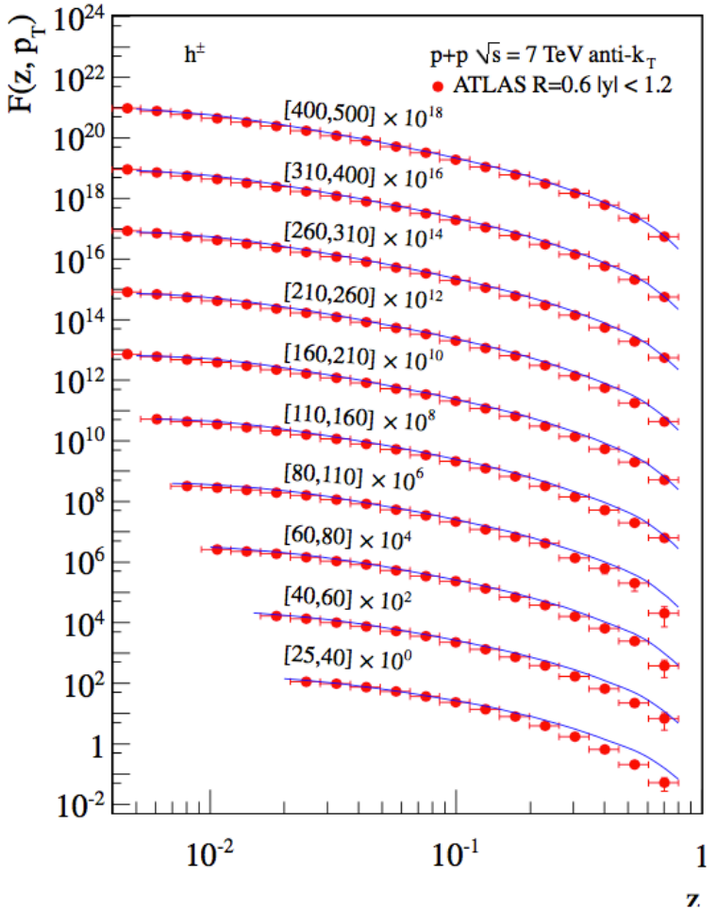
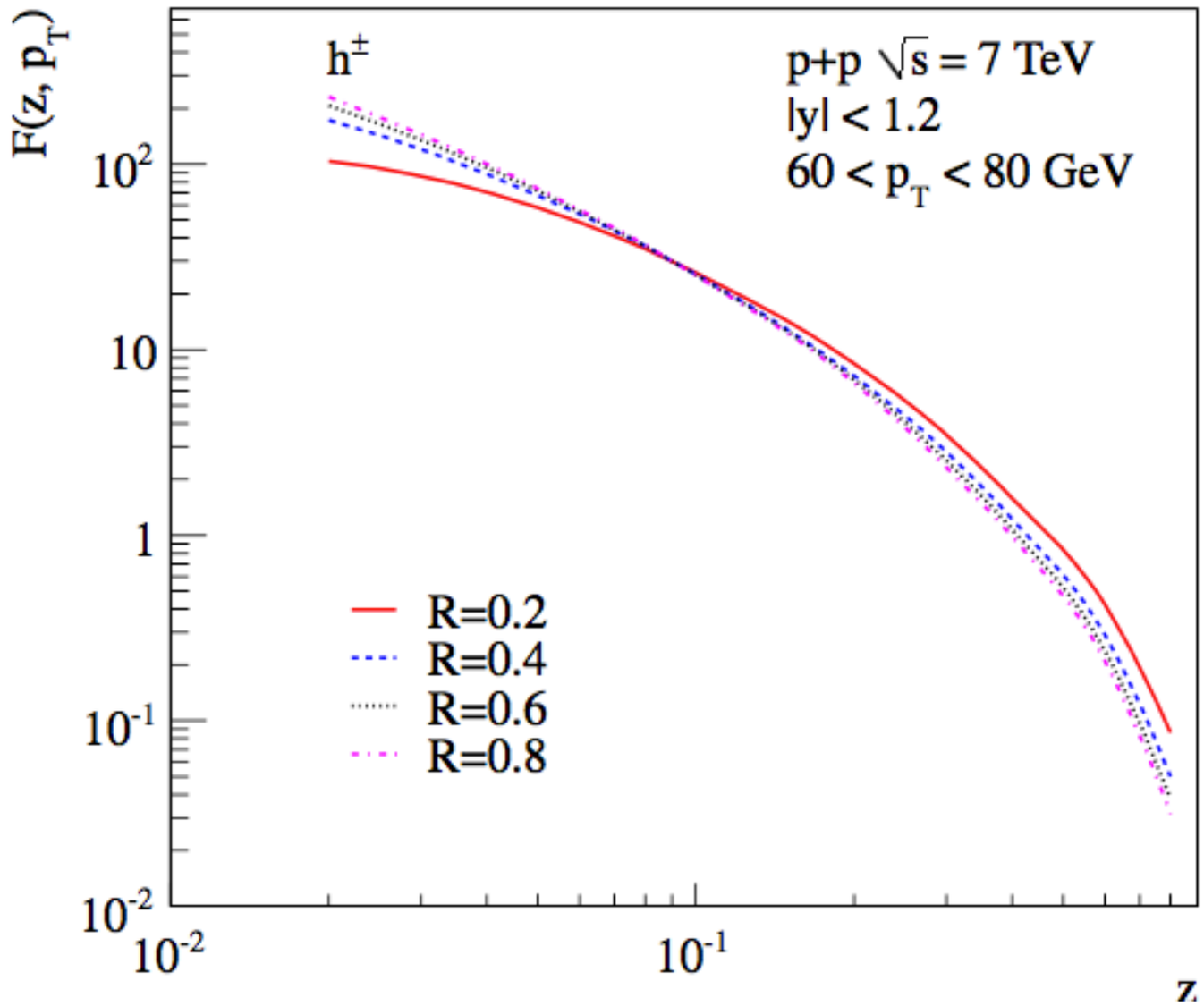
Conclusions

- Jet fragmentation function for light hadrons and heavy mesons
- Modification in heavy-ion collisions

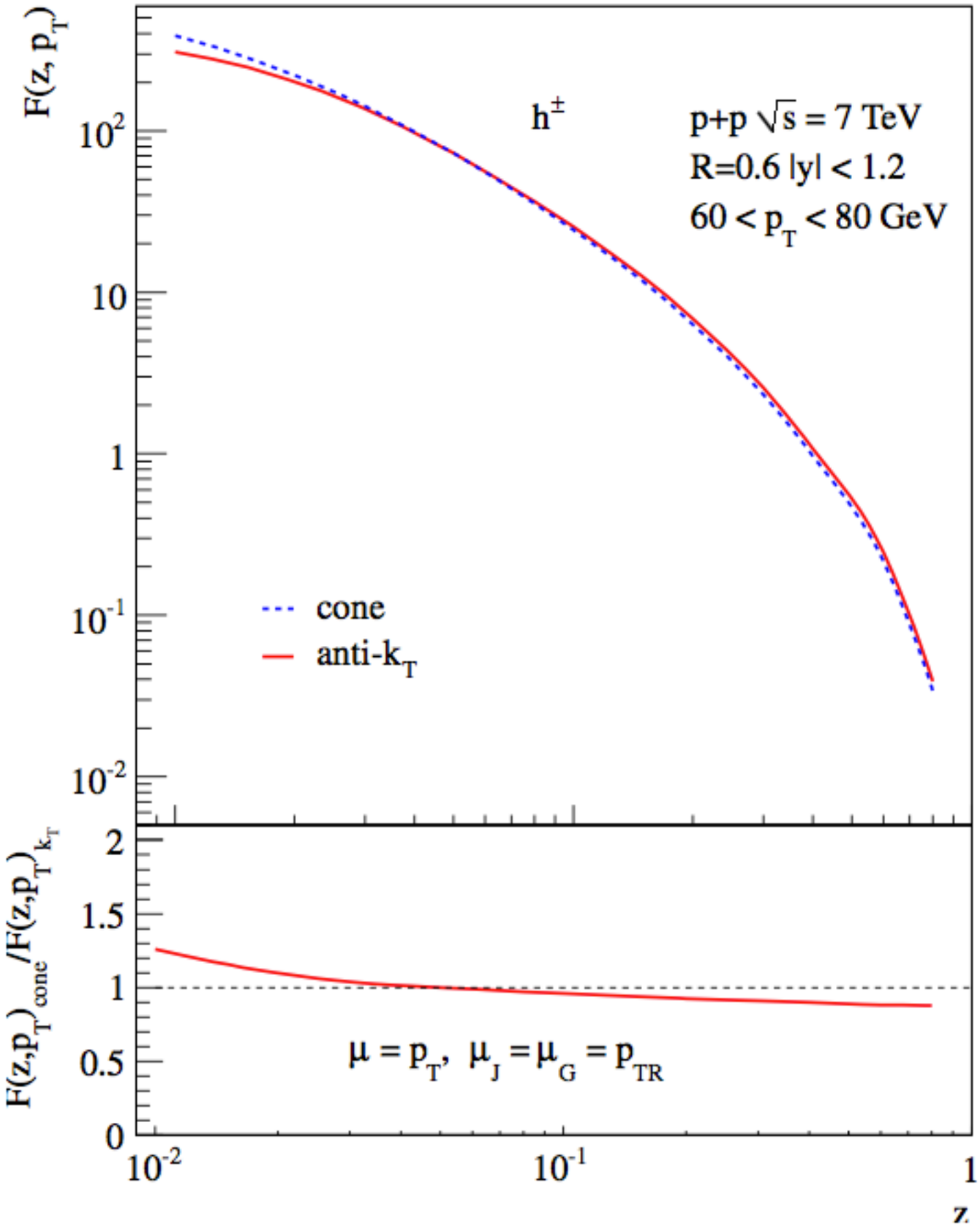


- Threshold and small-z resummation
- Heavy quarks pp and AA
- e.g. hadron+jet back-to-back
- Extension to eA for the EIC

backup



Jet parameter R dependence



Jet algorithm dependence: cone, $\mathrm{anti}-k_T$

Accuracy of Resummation

$$\mathcal{O}(\alpha_s^k): \qquad C_{kn} \times \alpha_s^k \ln^n \bar{N}, \quad \text{where } n \leq 2k$$

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

$L = \ln \bar{N}$

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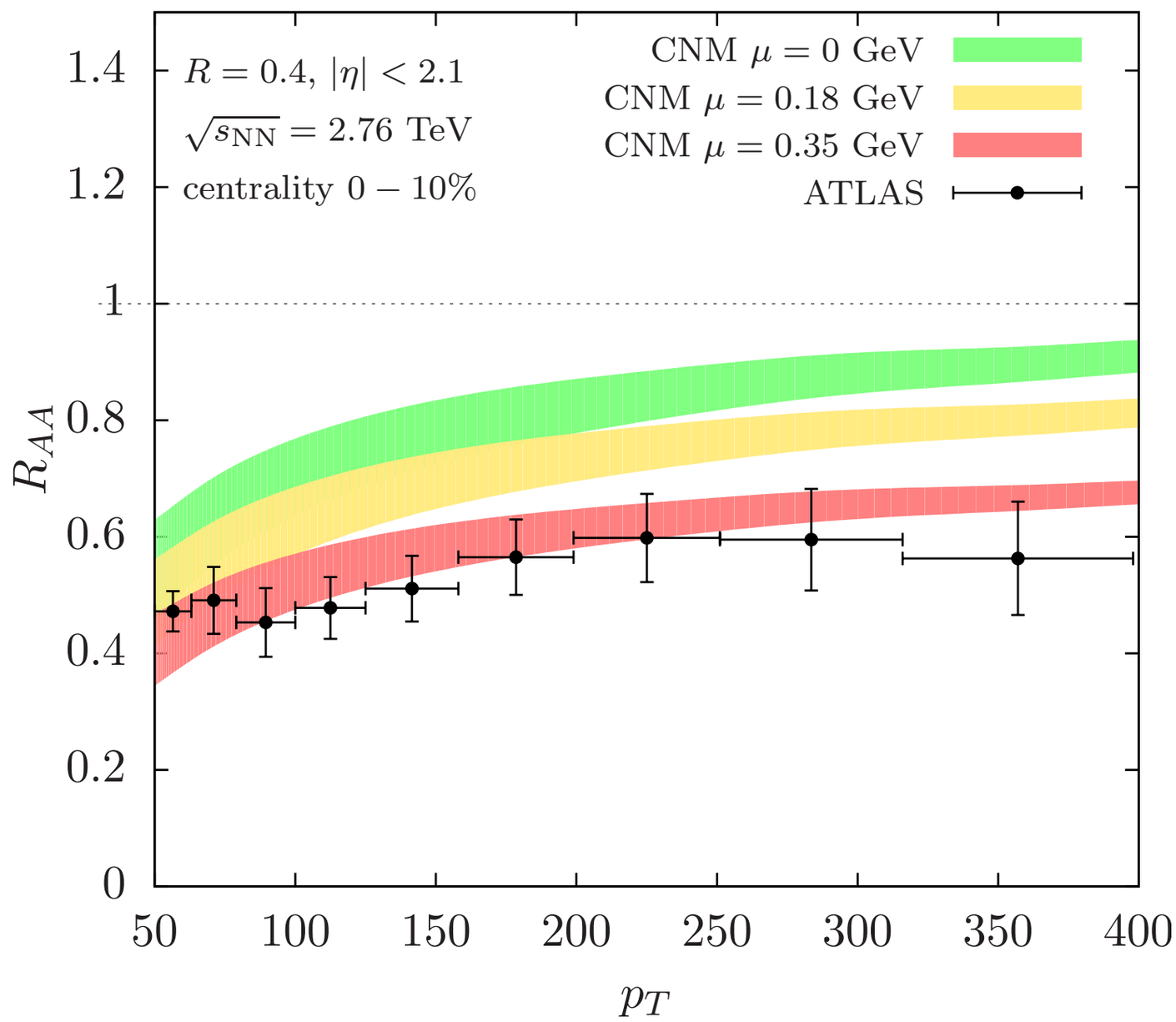
1. Initial state - Cold Nuclear Matter (CNM)

2. Final state - jet energy loss

Inclusive jet R_{AA}



Chien, Vitev `15