Heavy Flavor Production from Soft Collinear Effective Theory

Felix Ringer

Los Alamos National Laboratory

in collaboration with Ivan Vitev et al.

SQM `16, Berkeley, 06/28/16

Los Alamos NATIONAL LABORATORY EST. 1943

Outline

- proton-proton baseline
- Medium Modification using SCET
- Conclusions

Chien, Kang, FR, Vitev `15
Kang, FR, Vitev `16, `16
FR, Vitev - in preparation

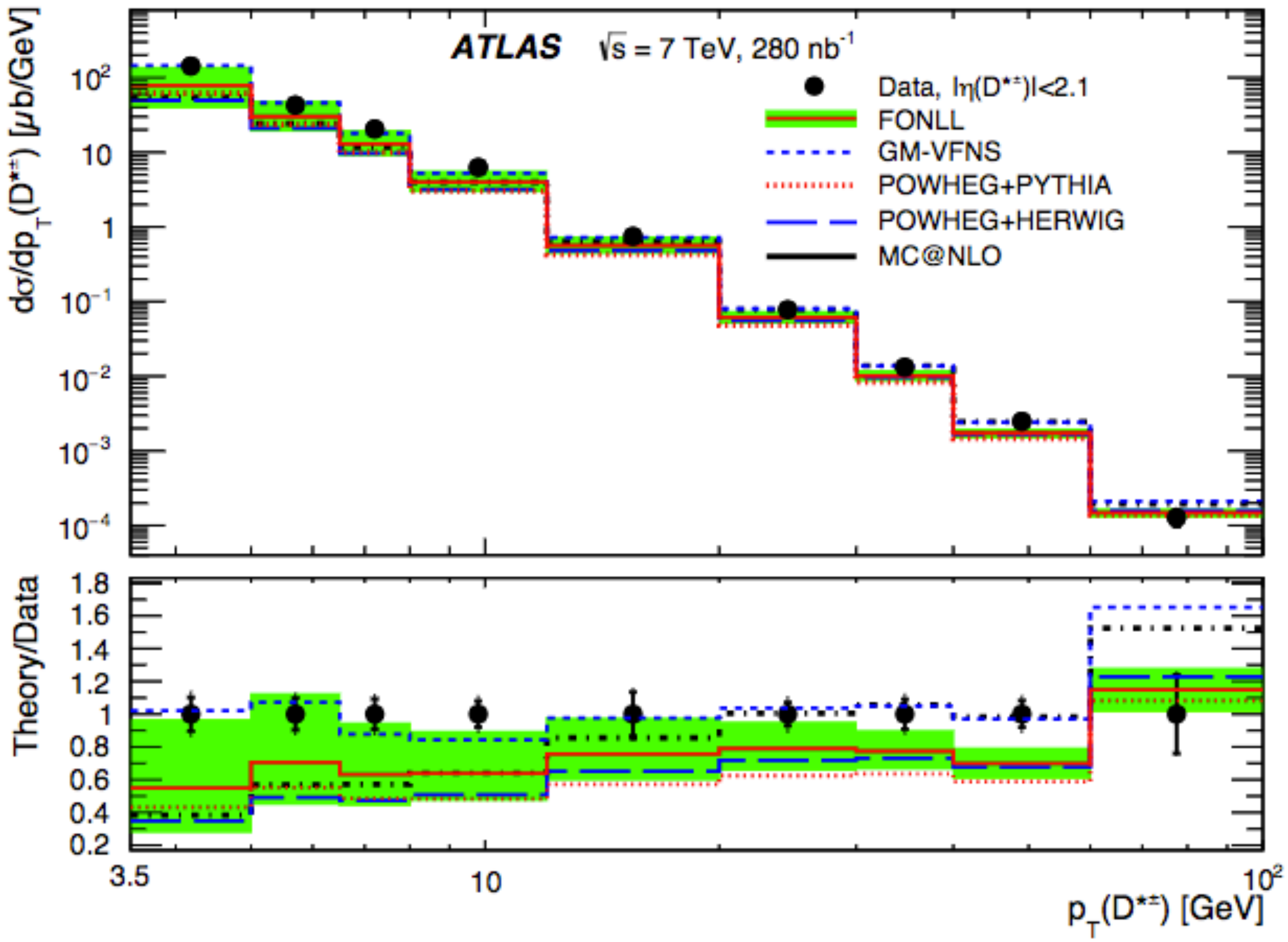
Outline

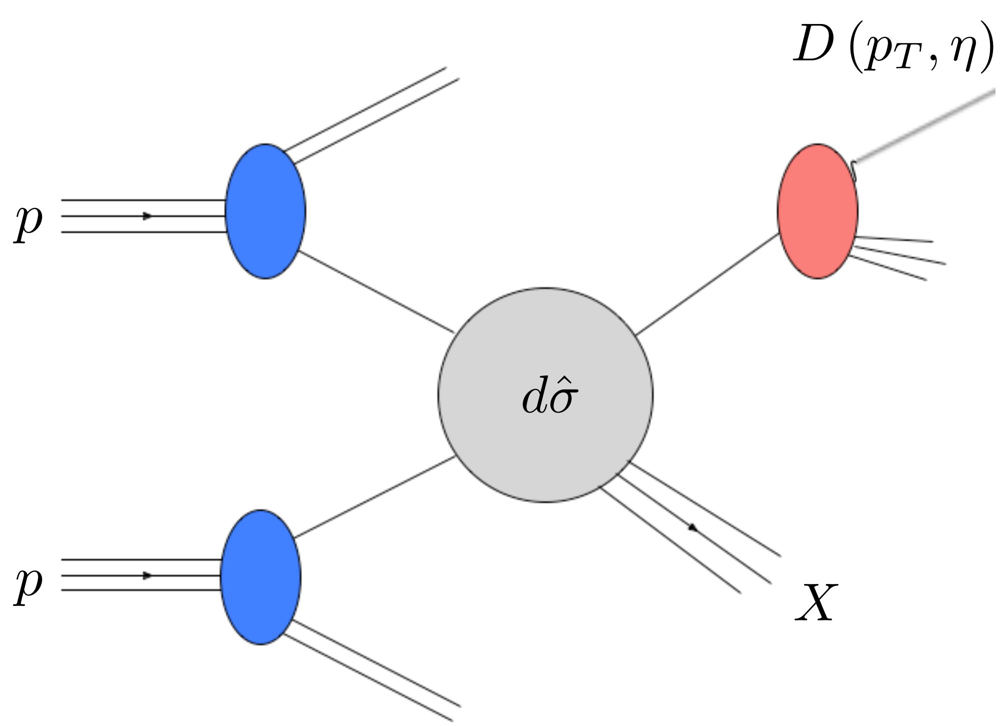
- proton-proton baseline
- Medium Modification using SCET
- Conclusions

Chien, Kang, FR, Vitev `15
Kang, FR, Vitev `16, `16
FR, Vitev - in preparation

D-meson production $pp \to DX$

Inclusive D-meson data taken at the LHC



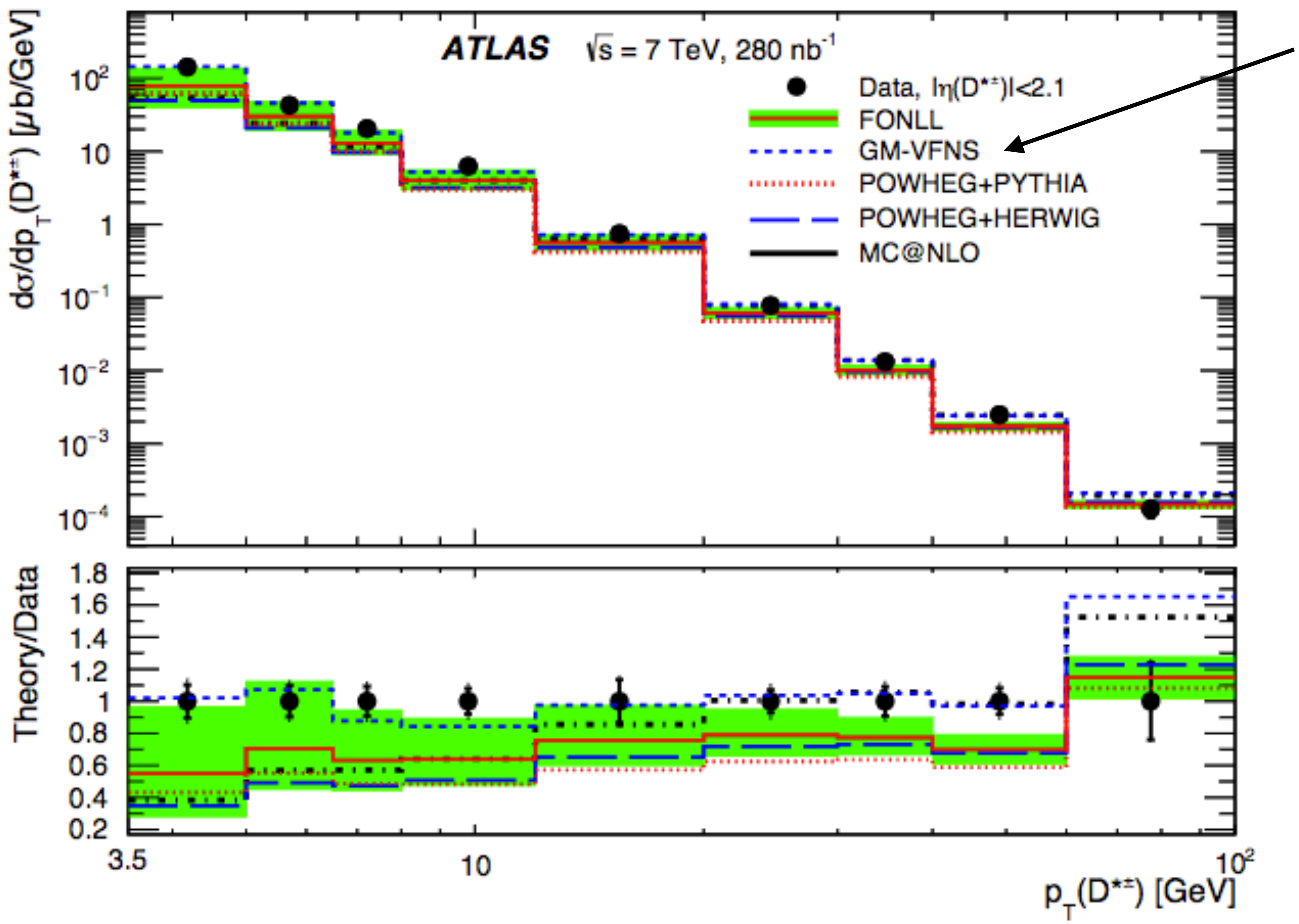


Nucl. Phys. B 907 (2016) 717

Similarly CMS, ALICE

D-meson production $pp \to DX$

Inclusive D-meson data taken at the LHC



Nucl. Phys. B 907 (2016) 717

Similarly CMS, ALICE

GM-scheme *Kneesch, Kniehl, Kramer, Schienbein - '08*

Meson and quark mass effects

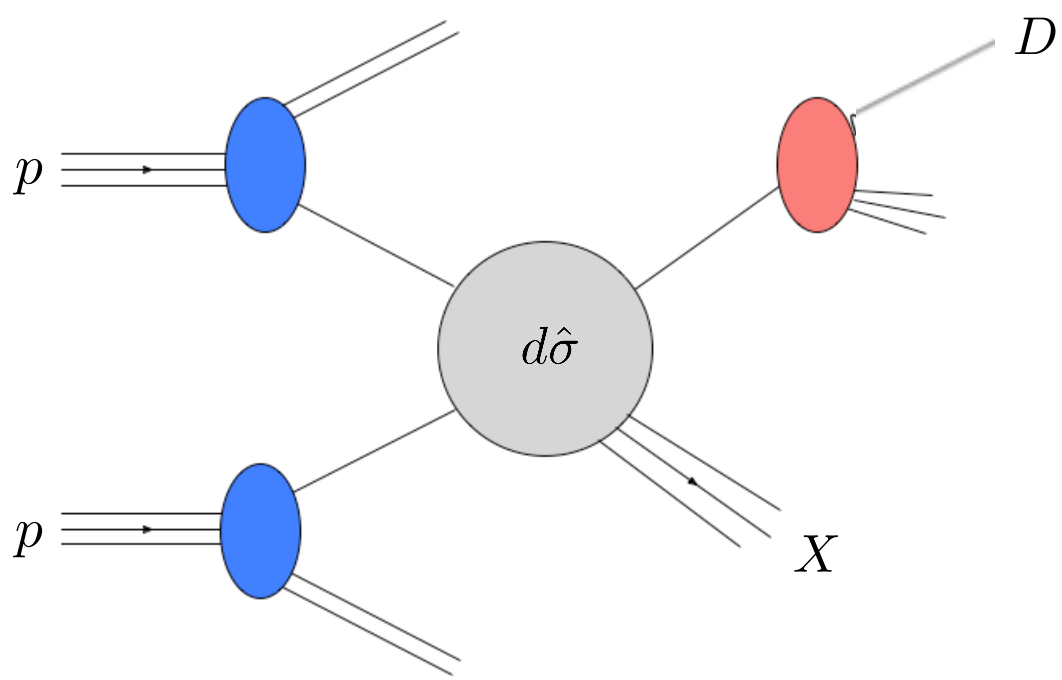
D-meson production $pp \to DX$

Next-to-leading order in QCD
Jäger, Stratmann, Vogelsang `02

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

where $v = 1 - \frac{2\hat{p}_T}{\sqrt{\hat{s}}}e^{-\hat{\eta}}, \qquad z = \frac{2\hat{p}_T}{\sqrt{s}}\cosh\hat{\eta}$

$$\hat{\eta} = \eta - \ln(x_a/x_b)/2$$



NLO: $\frac{d\hat{\sigma}_{ab}^{c}}{dvdz} = \frac{d\hat{\sigma}_{ab}^{c,(0)}}{dv}\delta(1-z) + \frac{\alpha_s(\mu)}{2\pi}\frac{d\hat{\sigma}_{ab}^{c,(1)}}{dvdz}$

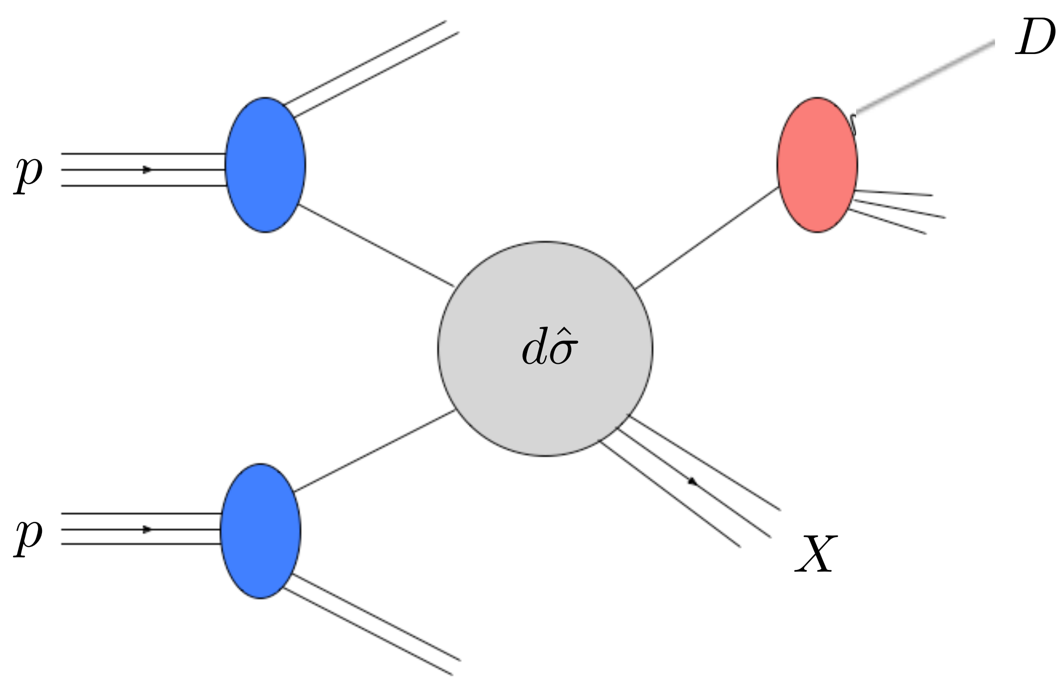
Los Alamos NATIONAL LABORATORY EST. 1943

D-meson production $pp \to DX$

Next-to-leading order in QCD

Jäger, Stratmann, Vogelsang `02

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



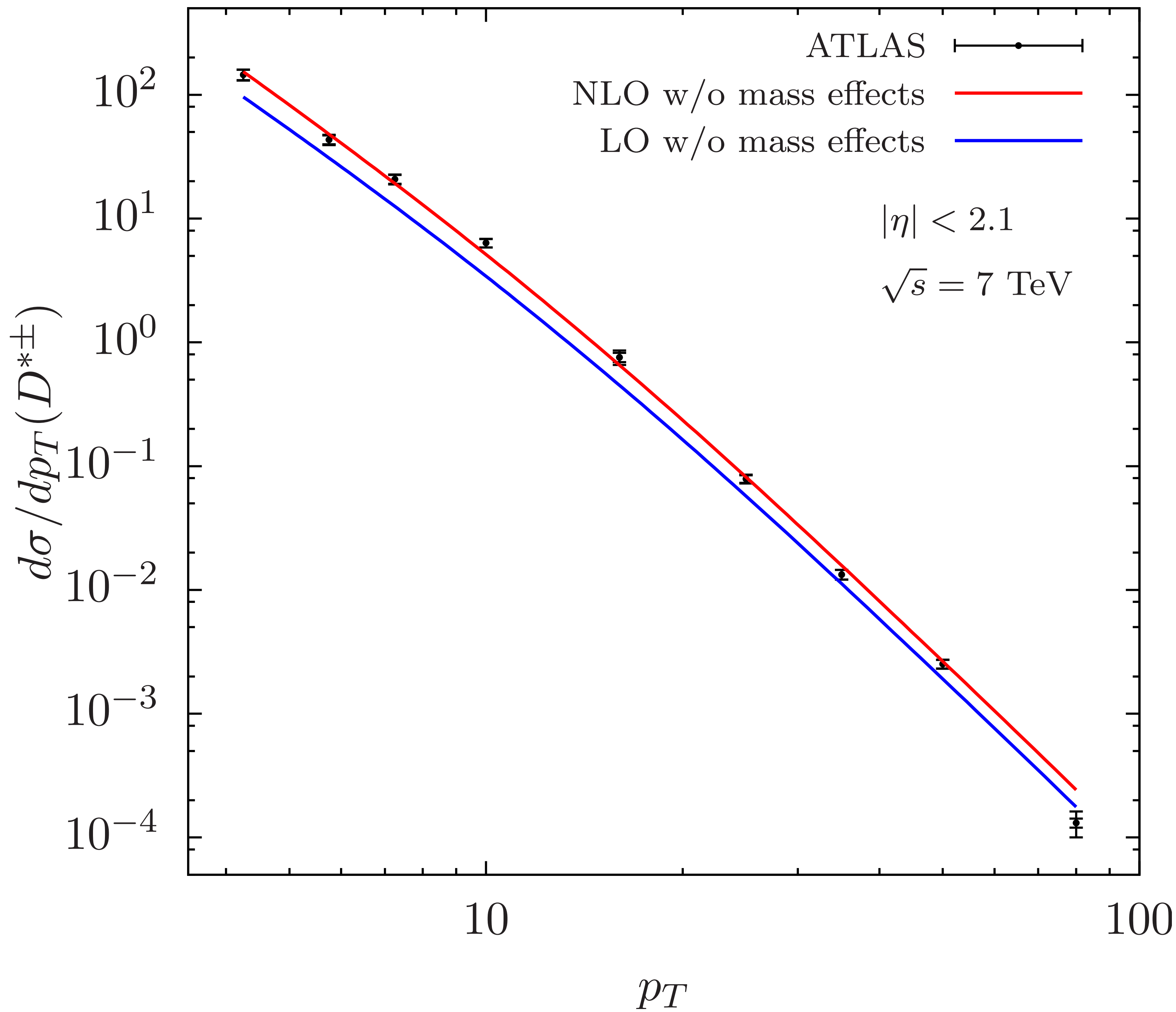
Using FFs from

Kneesch, Kniehl, Kramer, Schienbein '08

- Zero mass variable flavor scheme
- General mass scheme
- fit from $e^+e^- \to DX$ data

D-meson production $pp \to DX$

Data taken at the LHC



Nucl. Phys. B 907 (2016) 717

Similarly CMS, ALICE

Jäger, Stratmann, Vogelsang `02

ZMVFS *Kneesch, Kniehl, Kramer, Schienbein - '08*

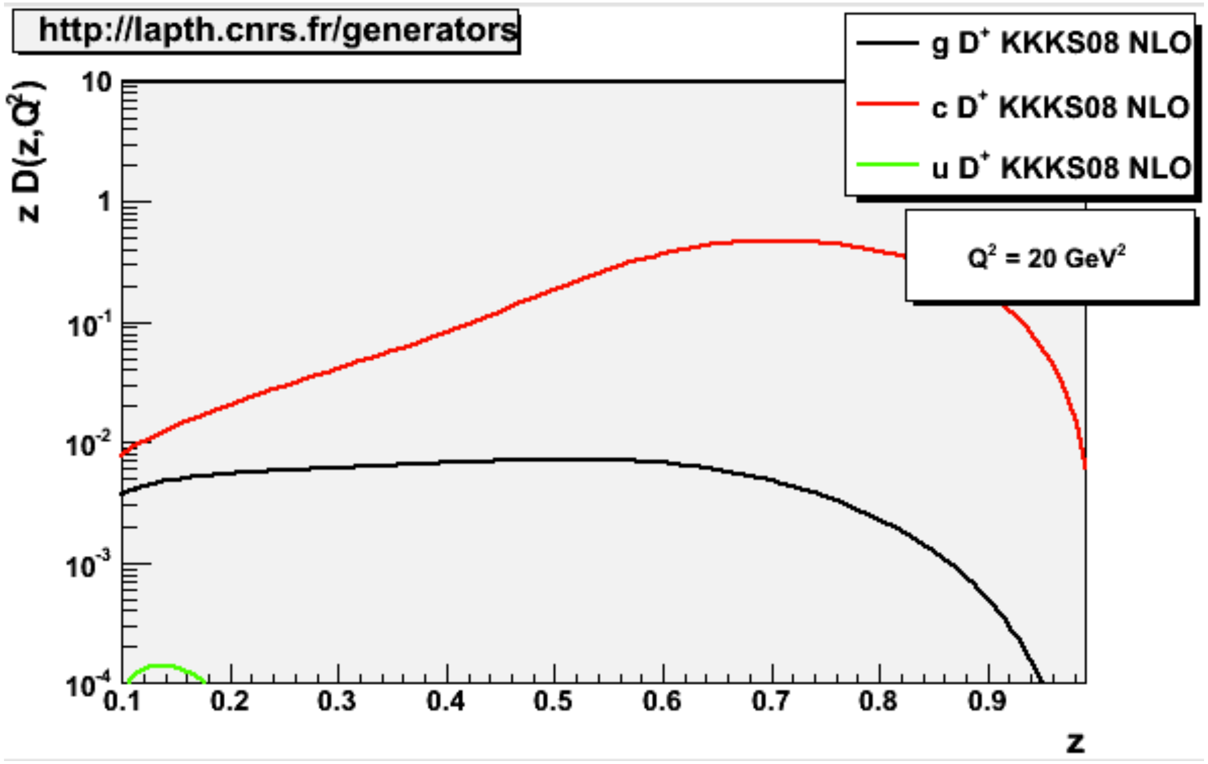
$Q \gg m_Q$

Los Alamos NATIONAL LABORATORY EST. 1943

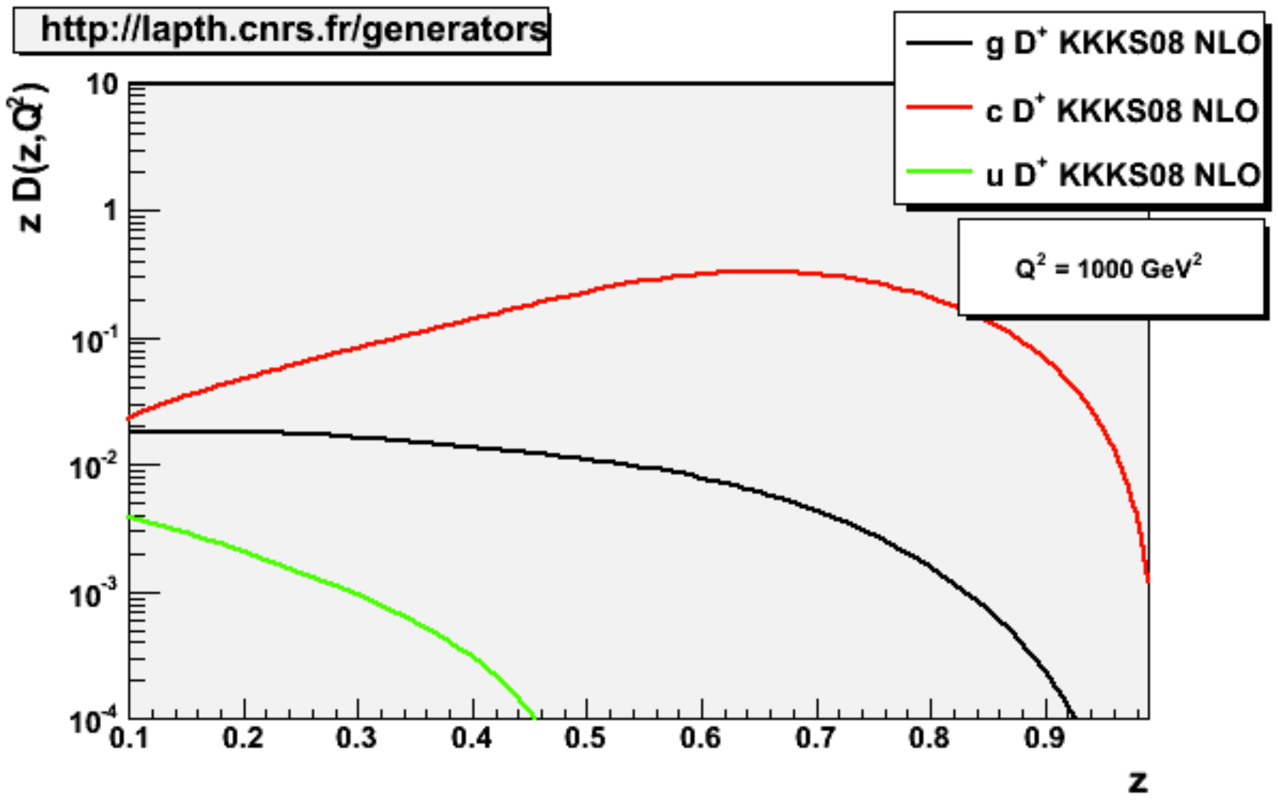
D-meson production $pp \to DX$

Charm-gluon-uds FFs

$Q^2 = 20\,\mathrm{GeV}^2$

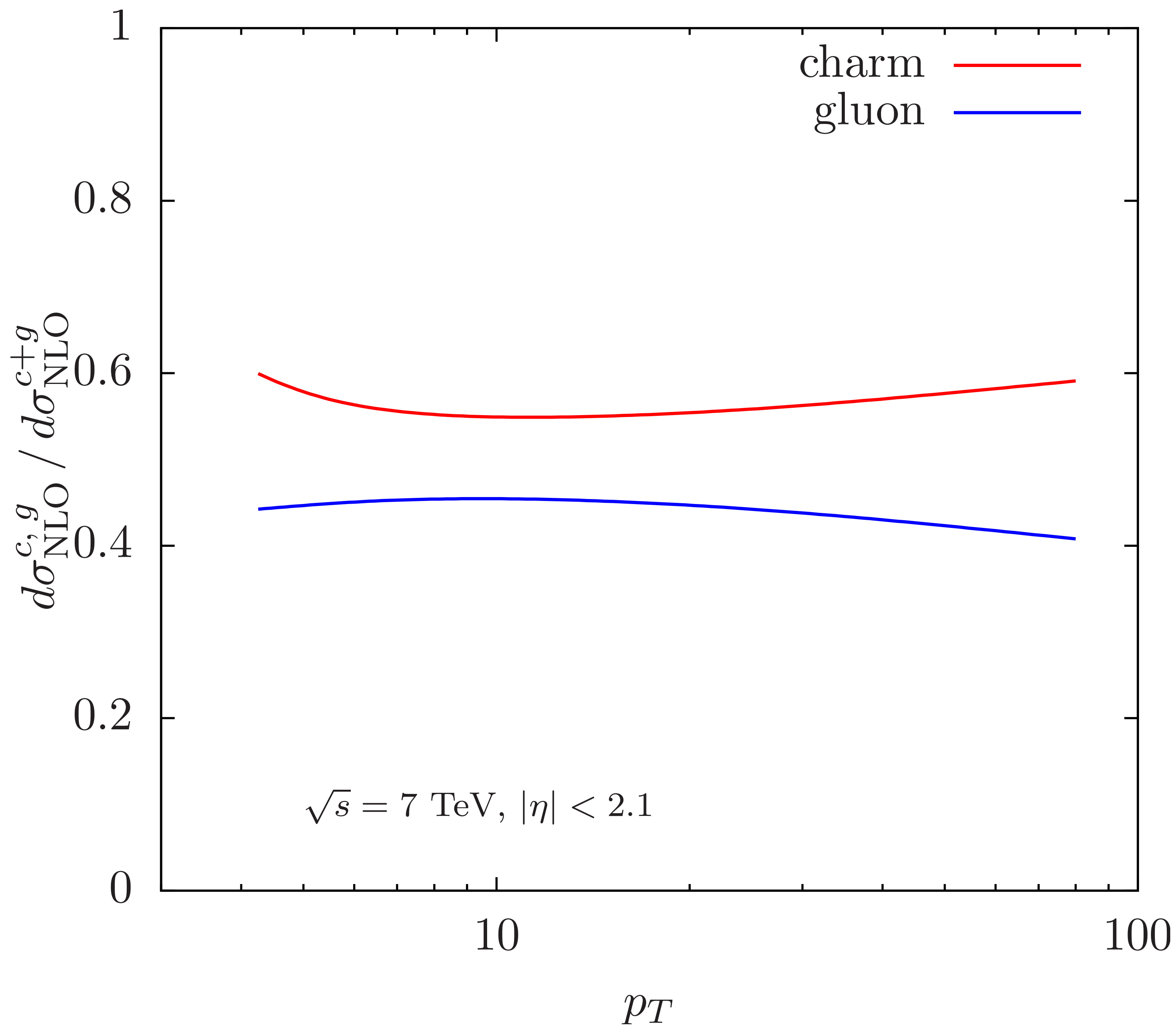


$Q^2 = 1000\,\mathrm{GeV}^2$



D-meson production $pp \to DX$

Charm-gluon contribution



Nucl. Phys. B 907 (2016) 717

Similarly CMS, ALICE

Jäger, Stratmann, Vogelsang `02

ZMVFS *Kneesch, Kniehl, Kramer, Schienbein - '08*

$Q \gg m_Q$

Los Alamos NATIONAL LABORATORY EST. 1943

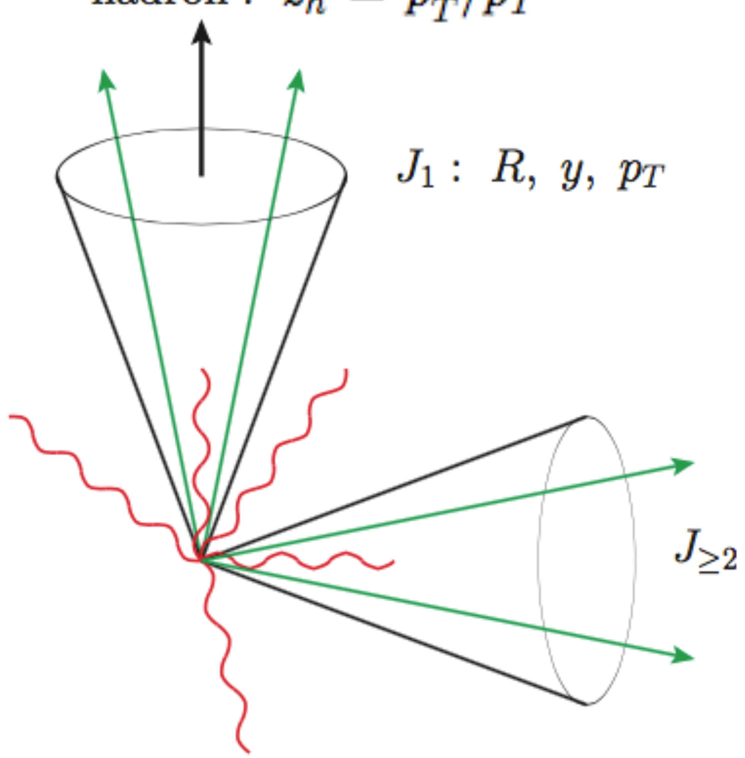
The Jet Fragmentation Function $pp \to (\text{jet}h)X$

Kang, FR, Vitev `16, `16

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

where

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

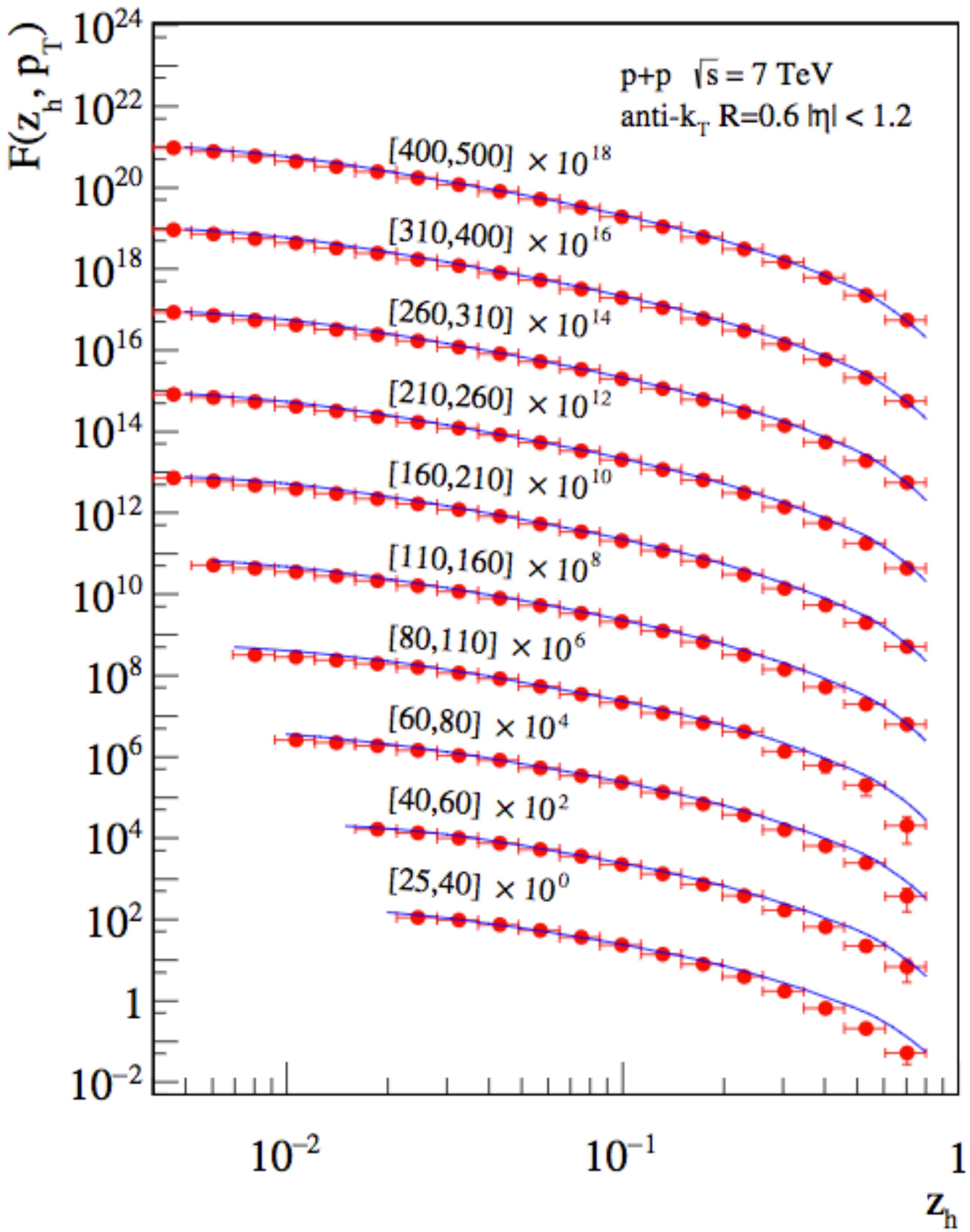


"semi-inclusive fragmenting jet function" in SCET

resummation of $\ln R$, i.e. $\text{NLO} + \text{NLL}_R$

see also:

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



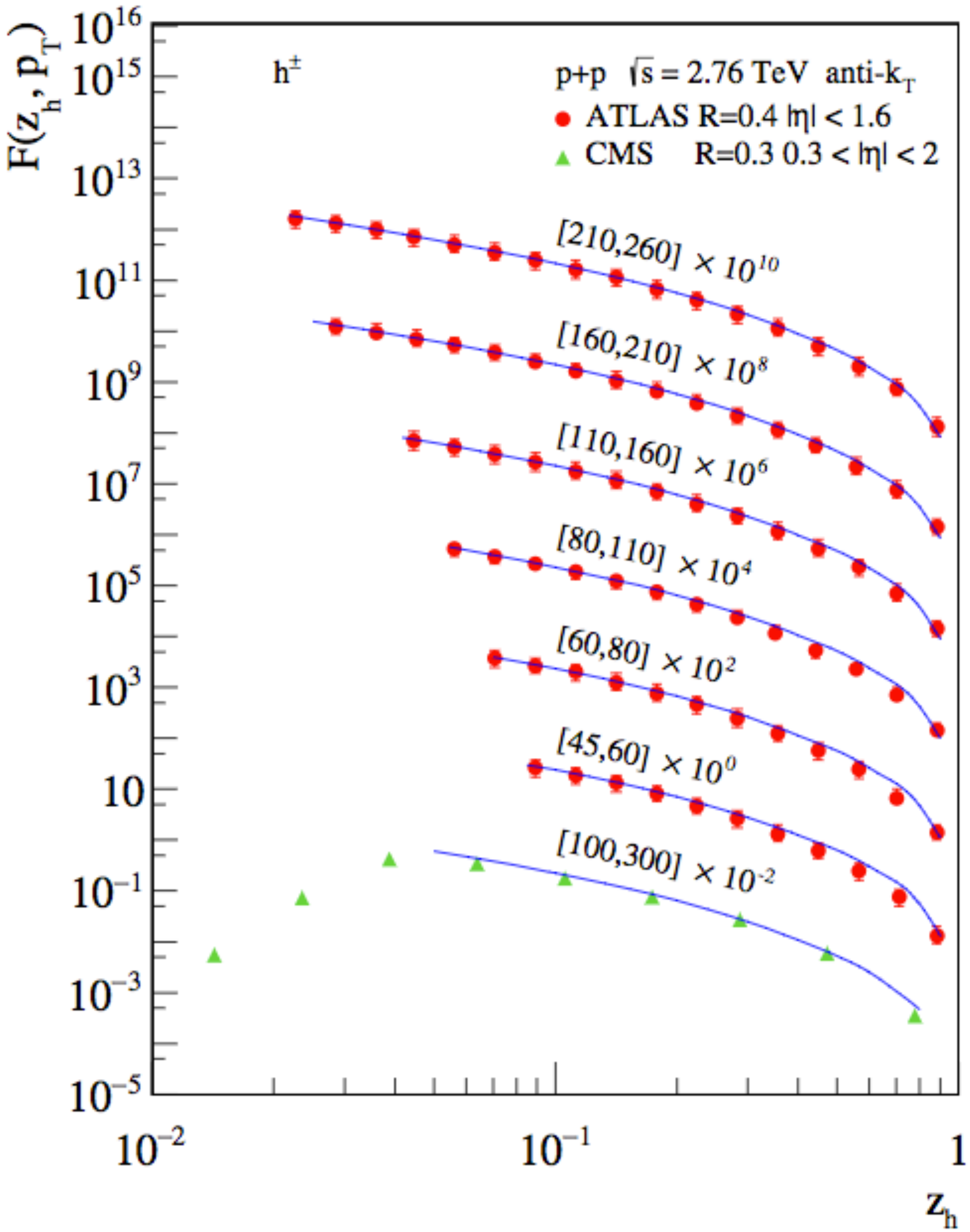
Comparison to ATLAS data at $\sqrt{s} = 7\,\mathrm{TeV}$

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

Using DSS FFs

de Florian, Sassot, Stratmann - '07

Los Alamos NATIONAL LABORATORY EST. 1943

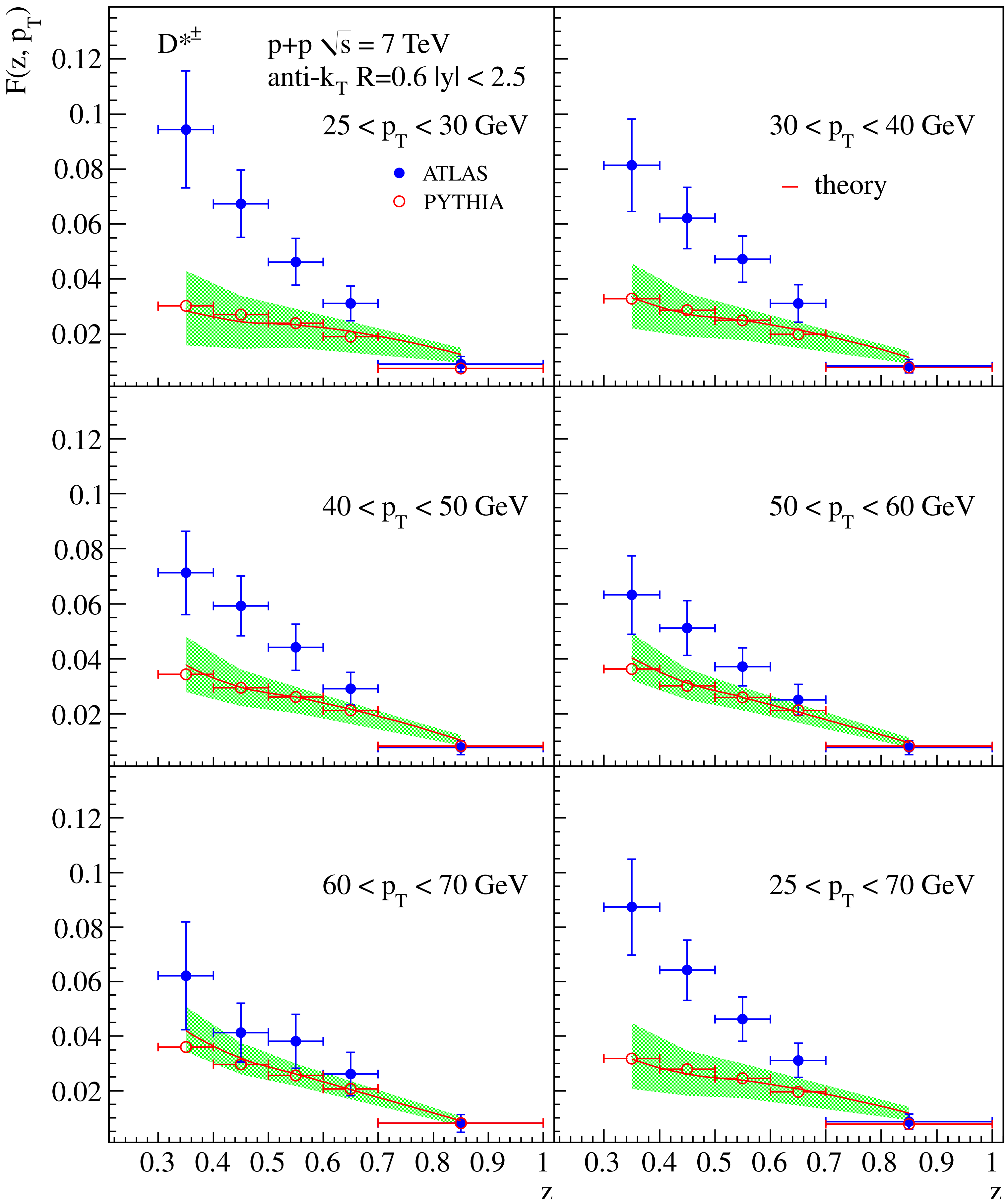


Comparison to ATLAS and CMS data at $\sqrt{s} = 2.76\,\mathrm{TeV}$

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

Using DSS FFs

de Florian, Sassot, Stratmann - '07



D-meson
jet fragmentation function

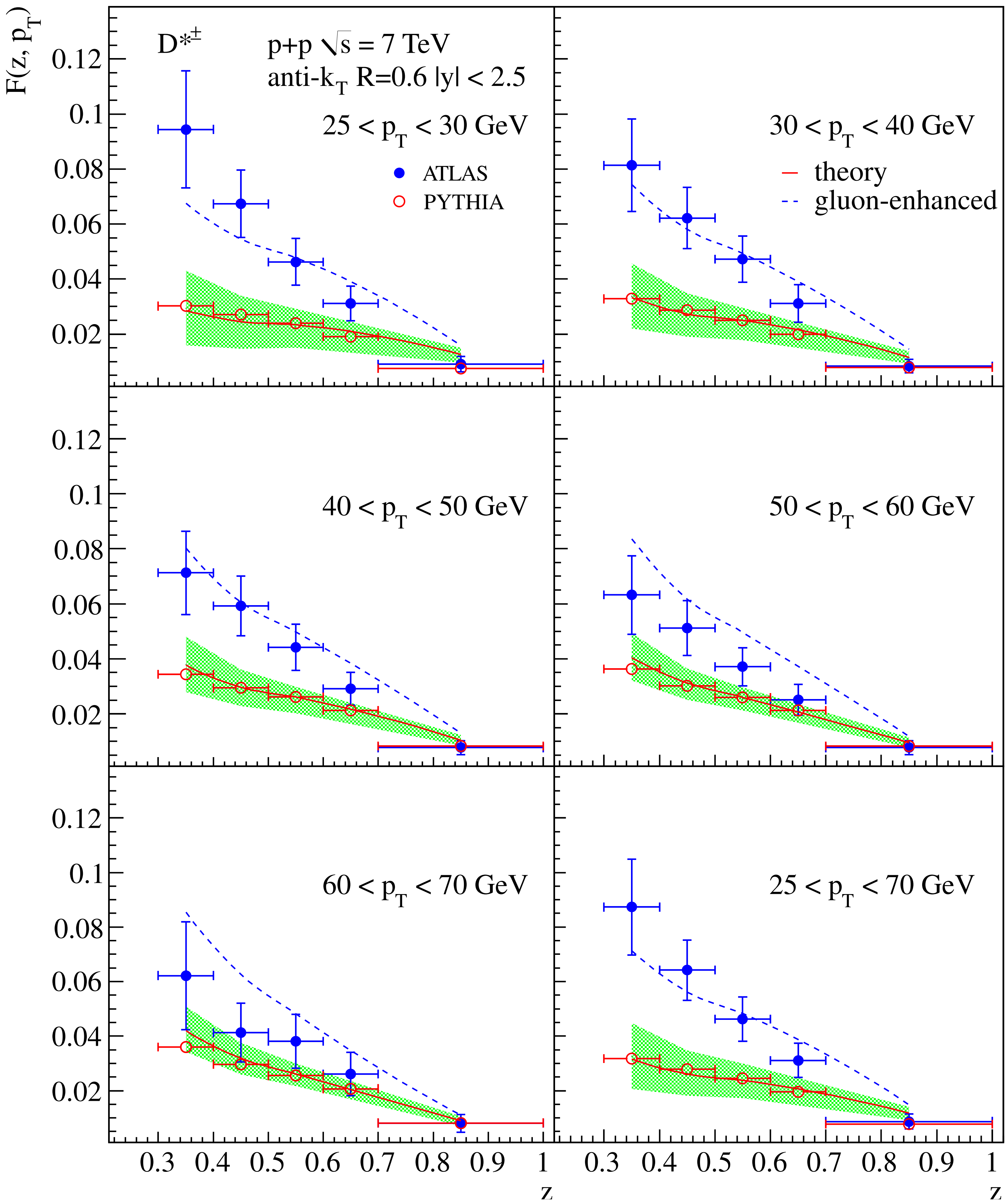
Comparison to ATLAS data and PYTHIA simulations at $\sqrt{s} = 7\,\mathrm{TeV}$

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

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

Los Alamos NATIONAL LABORATORY EST. 1943

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



D-meson
jet fragmentation function

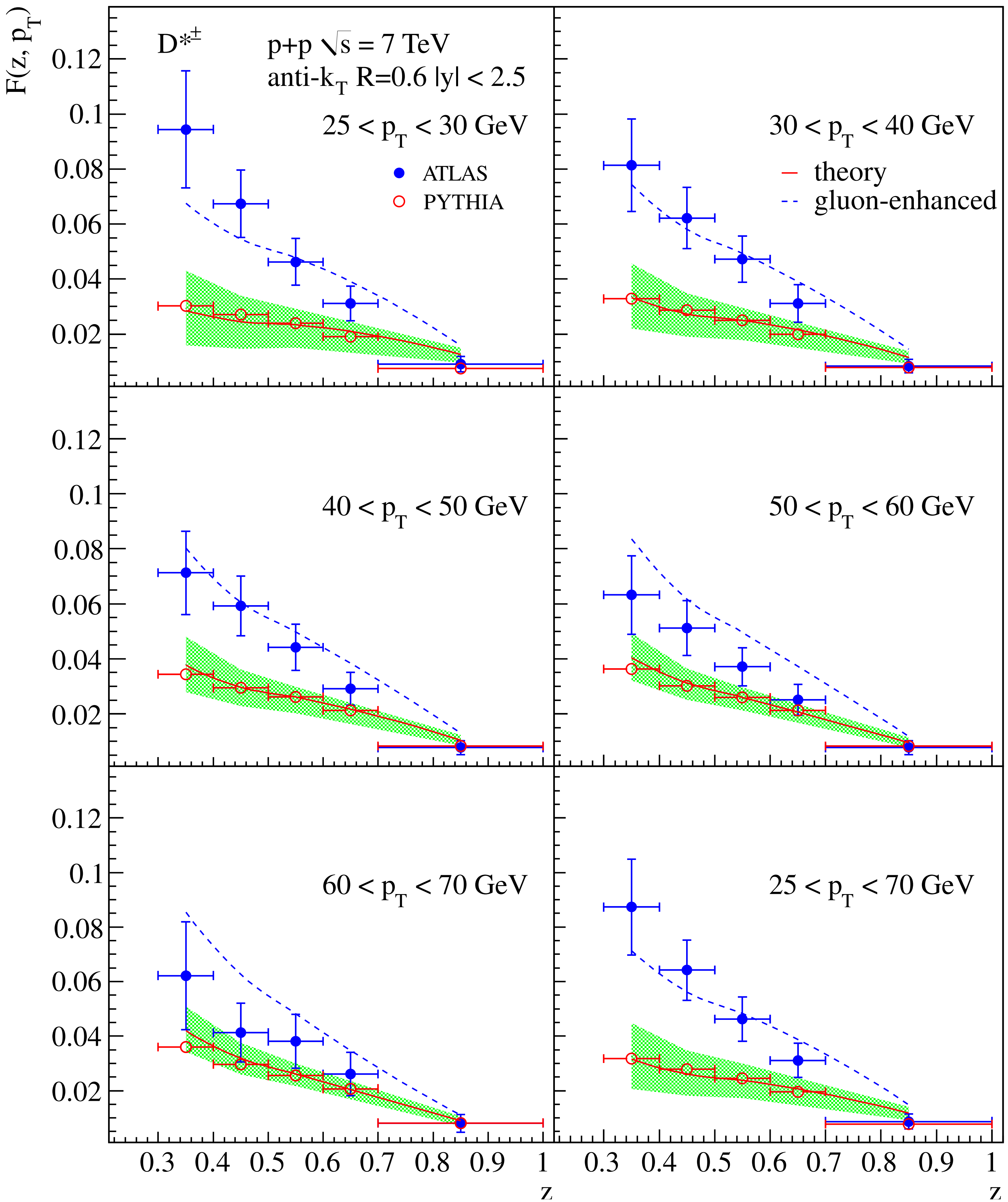
$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$

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

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

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

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 $\sqrt{s} = 7\,\mathrm{TeV}$

New fit of D-FFs:

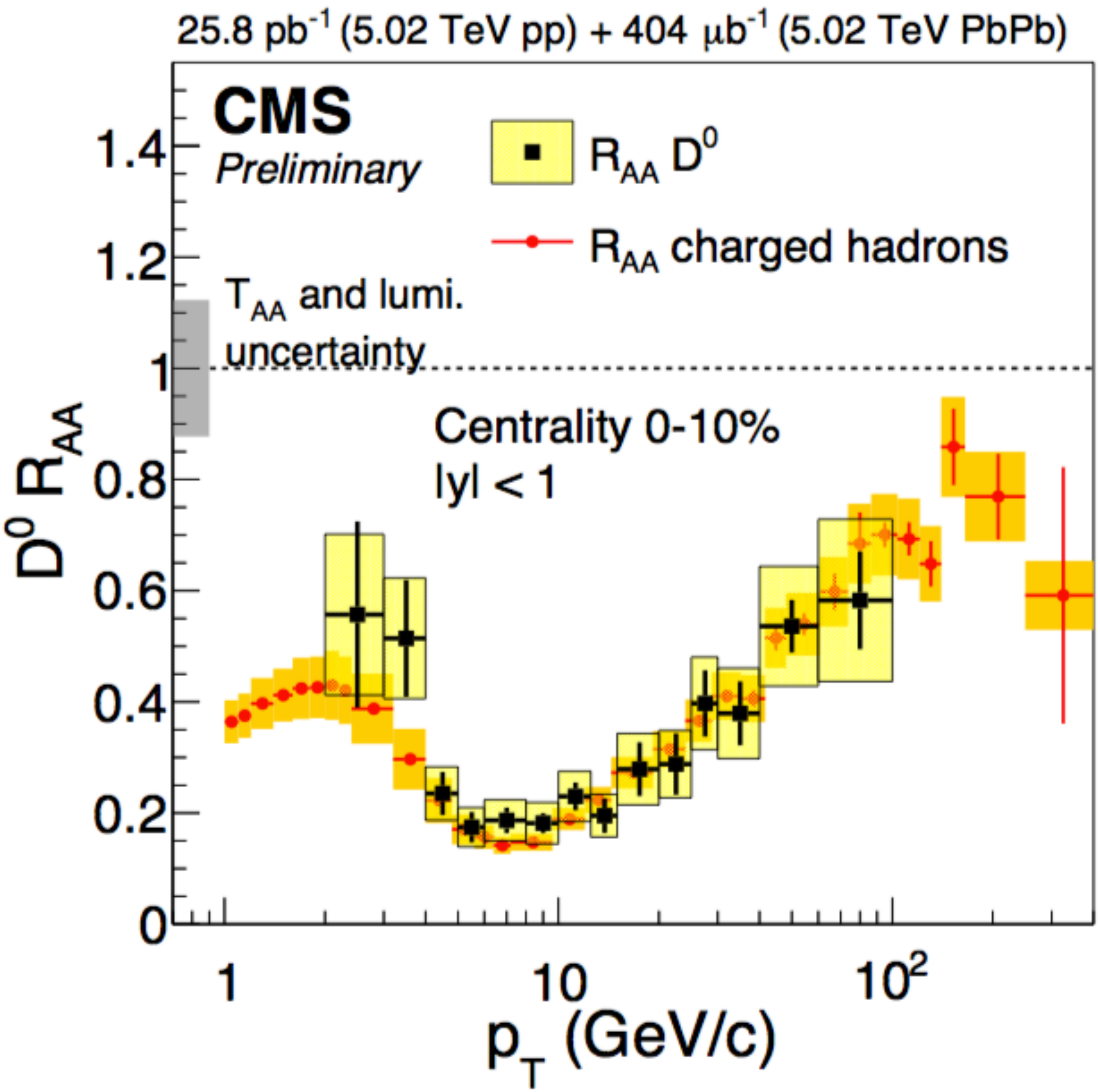
Anderle, Kang, FR, Stratmann, Vitev
- work in progress

Outline

- proton-proton baseline
- **Medium Modification using SCET**
- Conclusions

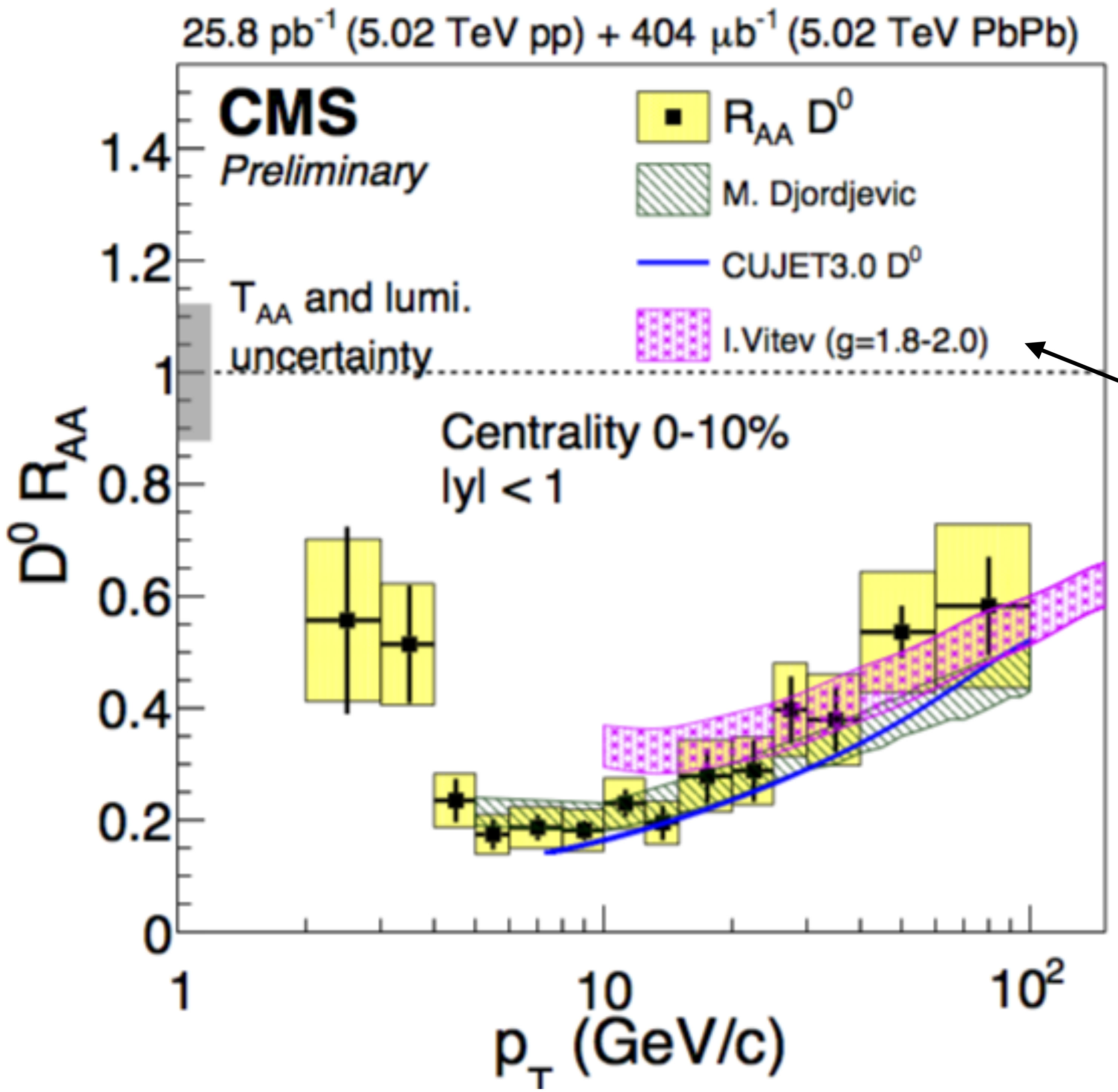
Chien, Kang, FR, Vitev `15
Kang, FR, Vitev `16, `16
FR, Vitev - in preparation

Hadron suppression in AA



taken from
Gian Michele Innocenti's talk (CMS)
at Initial Stages 2016

D-meson suppression in AA



taken from
Gian Michele Innocenti's talk (CMS)
at Initial Stages 2016

Energy loss, not $SCET_G$!

$\text{SCET}_{\mathrm{M,\,G}}$

$$\mathcal{L}_{\mathrm{SCET_{M,G}}} = \mathcal{L}_{\mathrm{SCET_M}} + \mathcal{L}_G(\xi_n, A_n, A_G)$$

FR, Vitev - in preparation

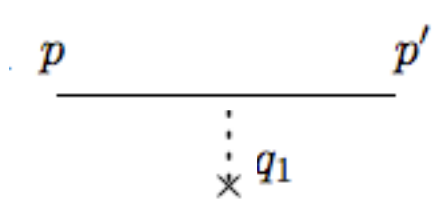
- $$\mathcal{L}_{\mathrm{SCET_M}} = \bar{\xi}_{n,p'} \left\{ in\cdot\partial + (\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q}) W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger (\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q'}) \right\} \frac{\not{\bar{n}}}{2}\, \xi_{n,p}$$
  $$+\ m\,\bar{\xi}_{n,p'} \left[(\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q}), W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger \right] \frac{\not{\bar{n}}}{2}\, \xi_{n,p} - m^2\, \bar{\xi}_{n,p'} W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger \frac{\not{\bar{n}}}{2}\, \xi_{n,p}$$

  Leibovich, Ligeti, Wise `03

- $$\mathcal{L}_{\mathrm{G}}(\xi_n, A_n, A_G) = \sum_{p,p'} \mathrm{e}^{-i(p-p')x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\mathrm{qqA_G}} \frac{\not{\bar{n}}}{2} \xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}} \left(A^c_{n,p'}\right)_\lambda \left(A^b_{n,p}\right)_\nu \right) A_{\mathrm{G}\,\mu,a}(x)$$

  Ovanesyan, Vitev '12

Feynman rules for interaction with the medium do not depend on the mass to leading-power!



$$= i\, v(q_{1\perp})\, (b_1)_R\, (b_1)_{T_i} \frac{\not{\bar{n}}}{2}$$

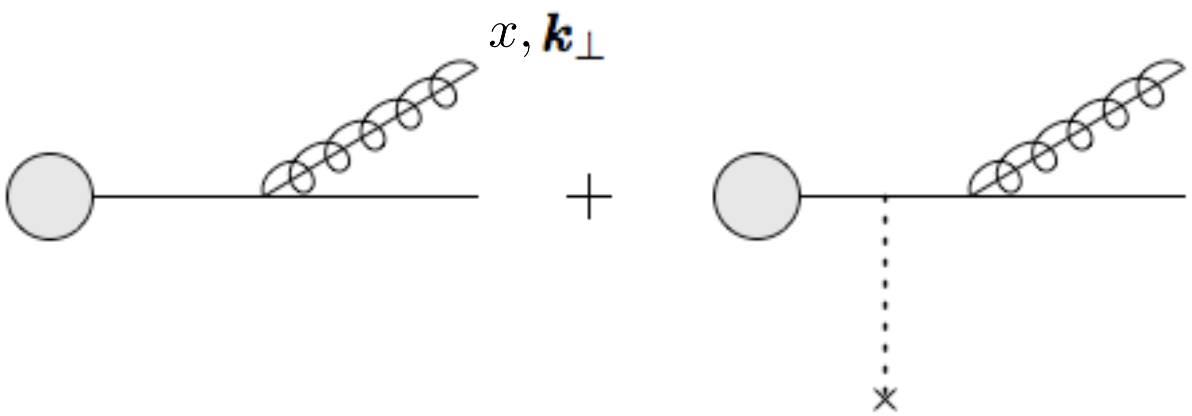
Bauer, Fleming, Luke, Pirjol, Rothstein, Stewart `00-`02
Idilbi, Majumder `08, D'Eramo, Liu, Rajagopal `10

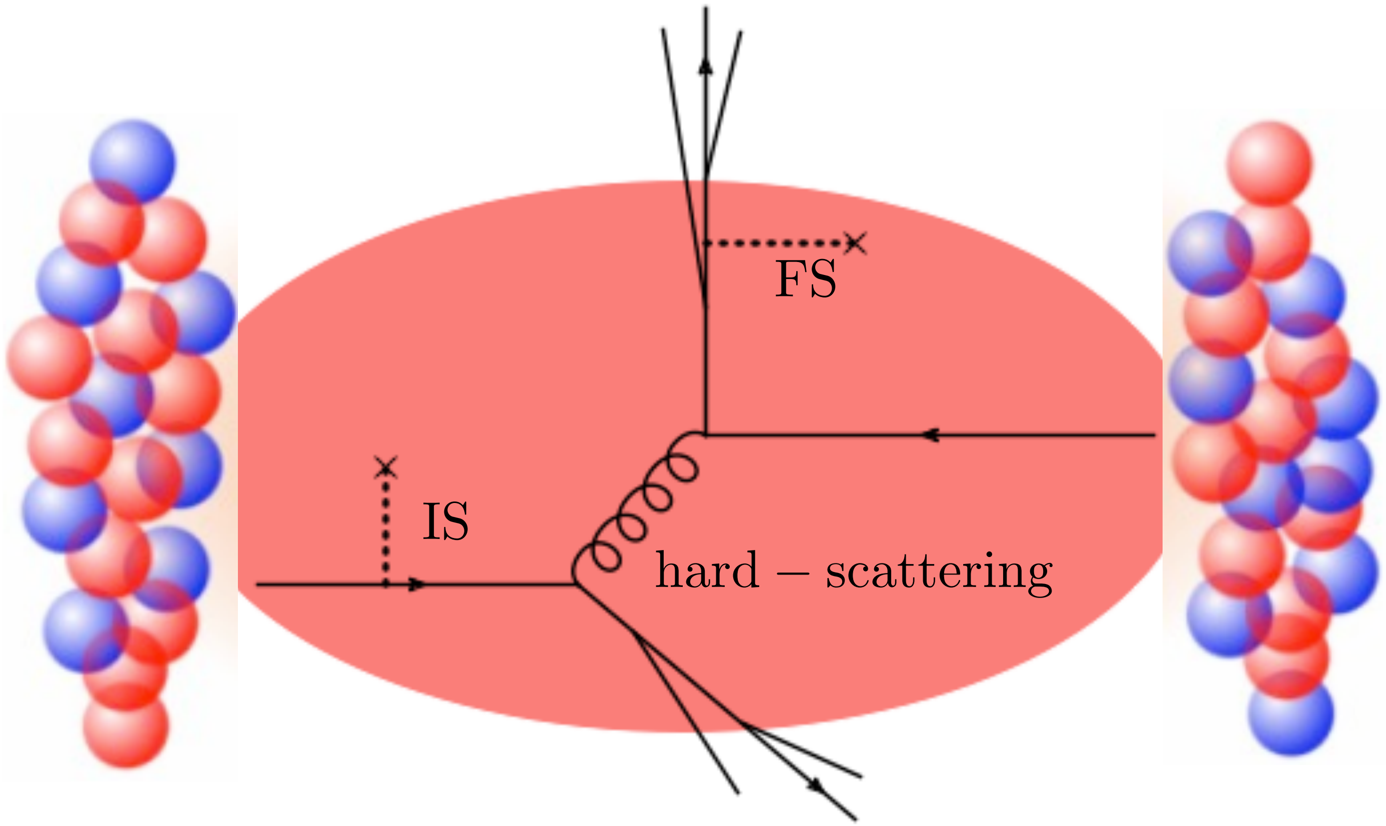
Los Alamos NATIONAL LABORATORY EST. 1943

$\mathrm{SCET_G}$ splitting kernels

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

1. Final state *Ovanesyan, Vitev '12*
2. Initial state *Ovanesyan, FR, Vitev - '15*

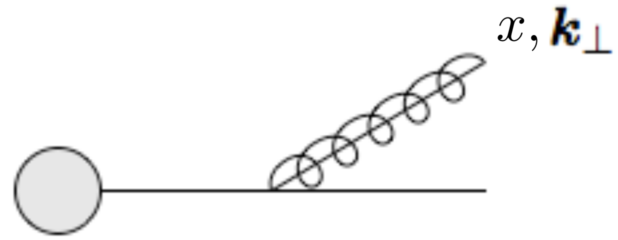




Los Alamos NATIONAL LABORATORY EST. 1943

SCET$_{\mathrm{M,\,G}}$ splitting kernels

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



Final state - massive

- vacuum:

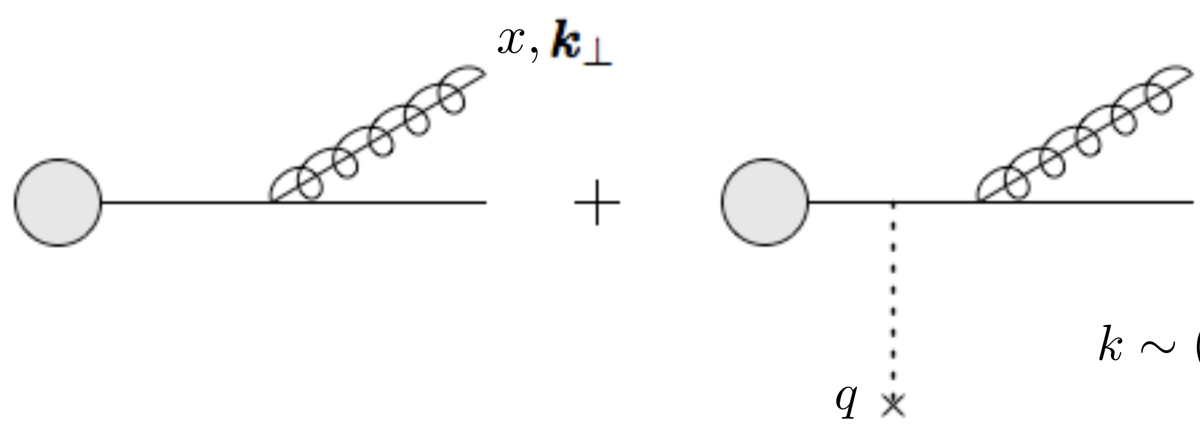
$$\left(\frac{dN}{dx\,d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2} \frac{1}{\boldsymbol{k}_\perp^2 + x^2 m^2} \left[\frac{1 - x + x^2/2}{x} - \frac{x(1-x)m^2}{\boldsymbol{k}_\perp^2 + x^2 m^2} \right]$$

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

$x, \boldsymbol{k}_\perp$ do not factorize

SCET$_{\mathrm{M,\,G}}$ splitting kernels

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



Final state - massive

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

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

- medium: e.g.

$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\,\mathrm{medium}}}{d^2\mathbf{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} \right) \right.\right.$$
$$\times (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} \cdot \left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_3)\Delta z])$$
$$+ \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} (1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \right) (1-\cos[\Omega_4\Delta z])$$
$$- \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} (1-\cos[\Omega_5\Delta z]) + \frac{1}{N_c^2} \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) \Bigg],$$
$$\left. + x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots \right] \right\}$$

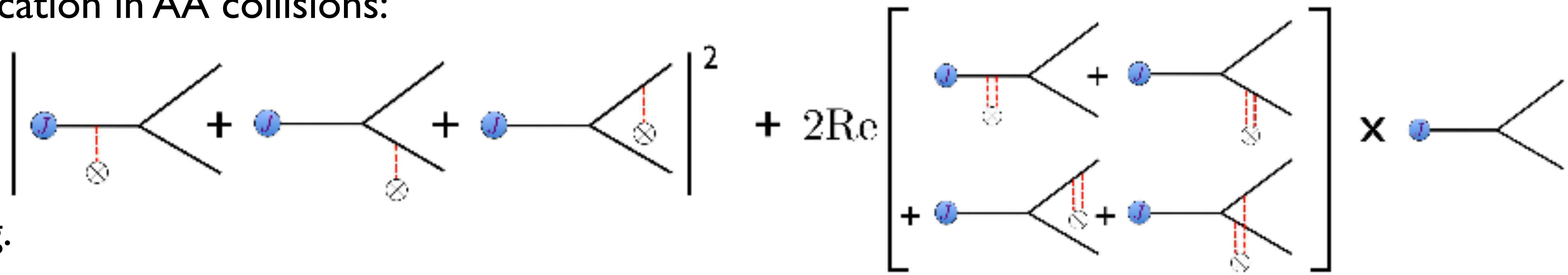
where: $\nu = x m$, $\quad \boldsymbol{A}_\perp = \boldsymbol{k}_\perp,\ \boldsymbol{B}_\perp = \boldsymbol{k}_\perp + x\boldsymbol{q}_\perp,\ \boldsymbol{C}_\perp = \boldsymbol{k}_\perp - (1-x)\boldsymbol{q}_\perp,\ \boldsymbol{D}_\perp = \boldsymbol{k}_\perp - \boldsymbol{q}_\perp$

$$\Omega_1 - \Omega_2 = \frac{\boldsymbol{B}_\perp^2+\nu^2}{p_0^+ x(1-x)},\ \Omega_1 - \Omega_3 = \frac{\boldsymbol{C}_\perp^2+\nu^2}{p_0^+ x(1-x)},\ \ldots$$

Los Alamos NATIONAL LABORATORY EST. 1943

$\mathrm{SCET}_{\mathrm{M,\,G}}$ splitting kernels

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



- medium: e.g.

$$\left(\frac{dN}{dx\,d^2\mathbf{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\,\mathrm{medium}}}{d^2\mathbf{q}_\perp}\Bigg\{\left(\frac{1+(1-x)^2}{x}\right)\Bigg[\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}-\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\right)$$
$$\times(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\cdot\left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}-\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])$$
$$+\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])+\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z])$$
$$-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])+\frac{1}{N_c^2}\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}-\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\Bigg],$$
$$+x^3m^2\left[\frac{1}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\mathbf{B}_\perp^2+\nu^2}-\frac{1}{\mathbf{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\ldots\right]\Bigg\}$$

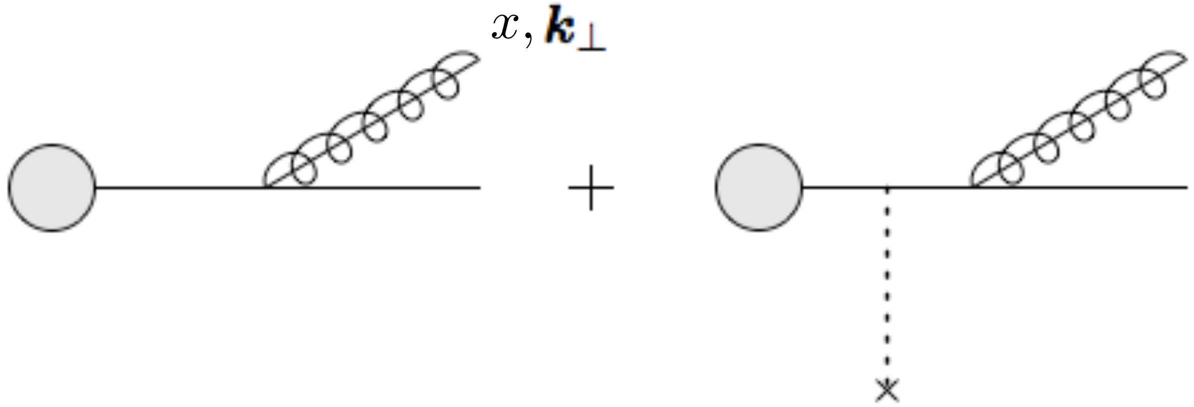
where: $\nu = x\,m$, $\quad \mathbf{A}_\perp=\mathbf{k}_\perp,\ \mathbf{B}_\perp=\mathbf{k}_\perp+x\mathbf{q}_\perp,\ \mathbf{C}_\perp=\mathbf{k}_\perp-(1-x)\mathbf{q}_\perp,\ \mathbf{D}_\perp=\mathbf{k}_\perp-\mathbf{q}_\perp$

$$\Omega_1-\Omega_2=\frac{\mathbf{B}_\perp^2+\nu^2}{p_0^+x(1-x)},\ \Omega_1-\Omega_3=\frac{\mathbf{C}_\perp^2+\nu^2}{p_0^+x(1-x)},\ \ldots$$

Los Alamos NATIONAL LABORATORY EST. 1943

SCET$_{\mathrm{M,\,G}}$ splitting kernels

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



Final state - massive

- medium: e.g.

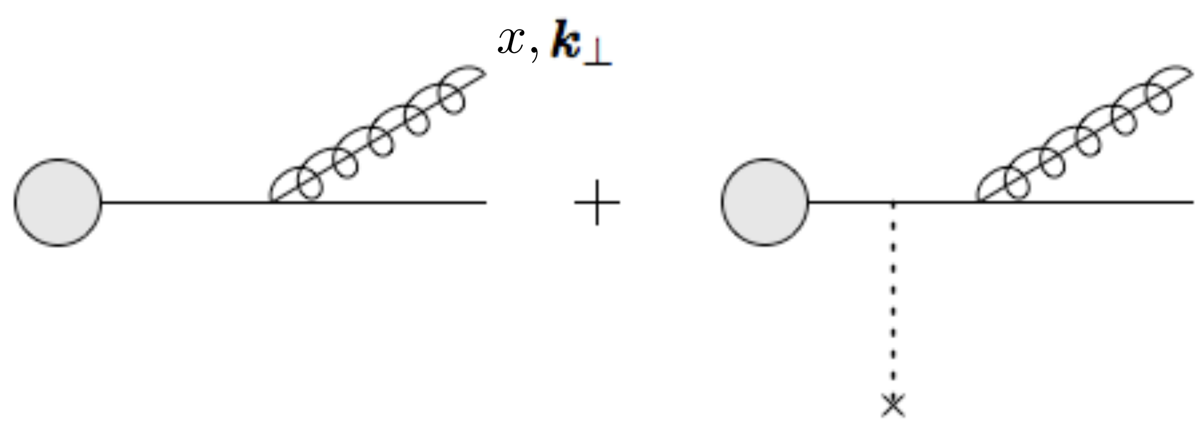
$$\left(\frac{dN}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp} \left\{ \left(\frac{1+(1-x)^2}{x}\right) \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} \right) \right.\right.$$
$$\times (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} \cdot \left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_3)\Delta z])$$
$$+ \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} (1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \right) (1-\cos[\Omega_4\Delta z])$$
$$\left. - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} (1-\cos[\Omega_5\Delta z]) + \frac{1}{N_c^2} \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) \right],$$
$$\left. + x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots \right] \right\}$$

where: $\nu = x m$, $\quad \boldsymbol{A}_\perp = \boldsymbol{k}_\perp,\ \boldsymbol{B}_\perp = \boldsymbol{k}_\perp + x\boldsymbol{q}_\perp,\ \boldsymbol{C}_\perp = \boldsymbol{k}_\perp - (1-x)\boldsymbol{q}_\perp,\ \boldsymbol{D}_\perp = \boldsymbol{k}_\perp - \boldsymbol{q}_\perp$

$$\Omega_1 - \Omega_2 = \frac{\boldsymbol{B}_\perp^2+\nu^2}{p_0^+ x(1-x)},\ \Omega_1 - \Omega_3 = \frac{\boldsymbol{C}_\perp^2+\nu^2}{p_0^+ x(1-x)}, \ldots$$

SCET$_{\mathrm{M,\,G}}$ splitting kernels

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



Final state - massive

- medium: Soft gluon approximation

$$x\left(\frac{dN}{dx}\right)_{Q\to Qg} = \frac{\alpha_s}{\pi^2} C_F \int d\Delta z \frac{1}{\lambda_g(z)} \int d^2\mathbf{k}_\perp d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\mathrm{medium}}}{d^2\mathbf{q}_\perp} \frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{[\boldsymbol{k}_\perp^2 + x^2m^2][(\boldsymbol{k}_\perp - \boldsymbol{q}_\perp)^2 + x^2m^2]} \left[1 - \cos\frac{(\boldsymbol{k}_\perp - \boldsymbol{q}_\perp)^2}{x p_0^+}\Delta z\right]$$

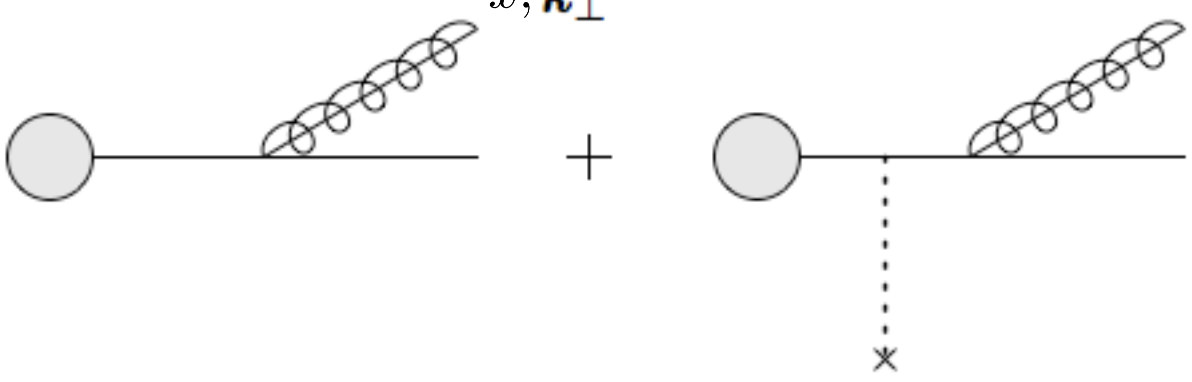
keeping only the first correction in the denominator, similarly

$$Q \to gQ \qquad \sim \quad \frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{[\boldsymbol{k}_\perp^2 + (1-x)^2m^2][(\boldsymbol{k}_\perp - \boldsymbol{q}_\perp)^2 + (1-x)^2m^2]}$$

$$g \to Q\bar{Q} \qquad \sim \quad \frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{[\boldsymbol{k}_\perp^2 + m^2][(\boldsymbol{k}_\perp - \boldsymbol{q}_\perp)^2 + m^2]}$$

SCET$_{\mathrm{M,\,G}}$ splitting kernels

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



Final state - massive

- medium: Soft gluon approximation

$$x\left(\frac{dN}{dx}\right)_{Q\to Qg} = \frac{\alpha_s}{\pi^2}C_F\int d\Delta z\frac{1}{\lambda_g(z)}\int d^2\mathbf{k}_\perp d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\,\mathrm{medium}}}{d^2\mathbf{q}_\perp}\;\frac{2\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp}{[\boldsymbol{k}_\perp^2+x^2m^2][(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2]}\left[1-\cos\frac{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2}{xp_0^+}\Delta z\right]$$

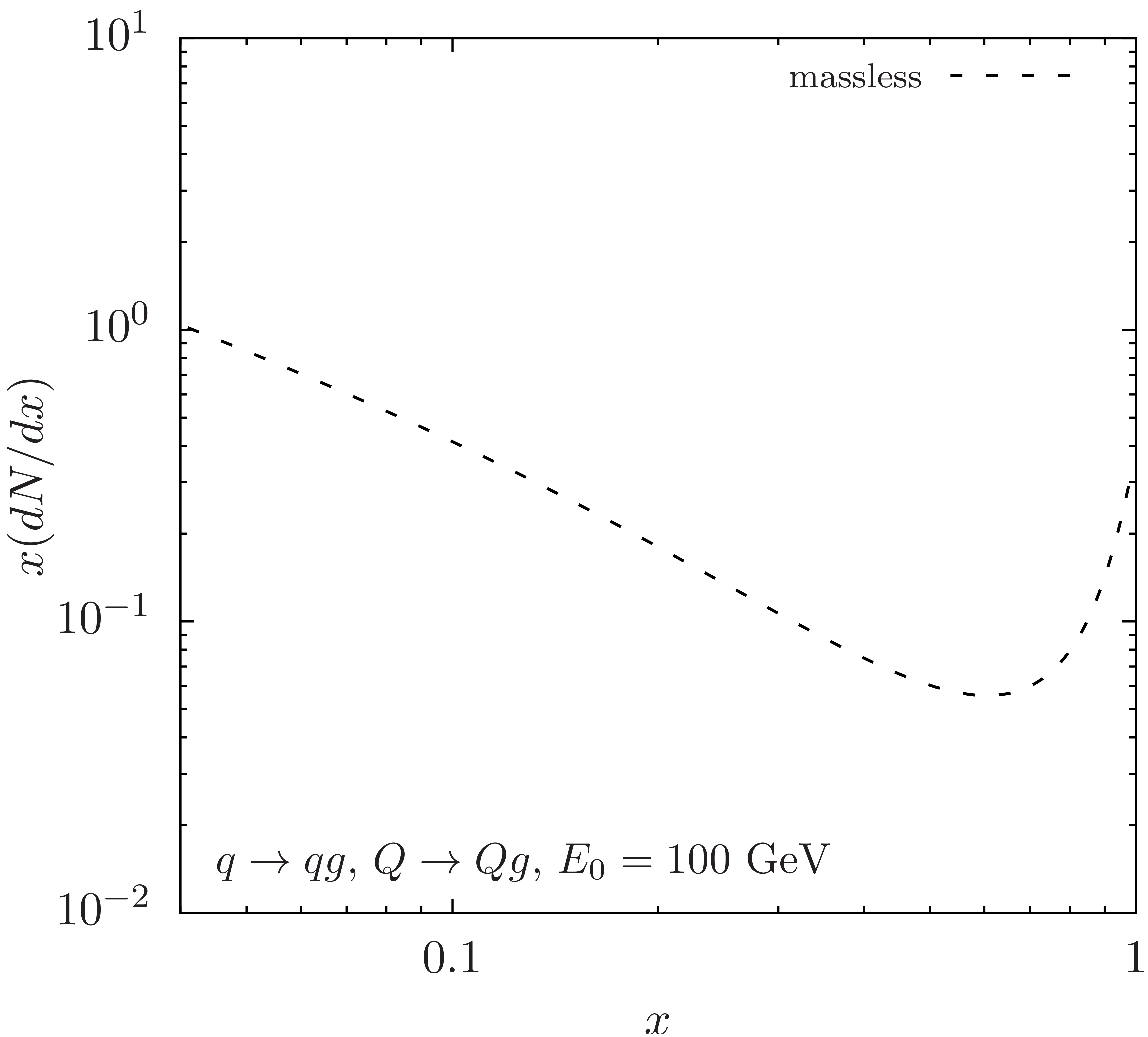
Instead

$$\frac{\boldsymbol{k}_\perp-\boldsymbol{q}_\perp}{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2}\left(\frac{\boldsymbol{k}_\perp-\boldsymbol{q}_\perp}{(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2}-\frac{\boldsymbol{k}_\perp}{\boldsymbol{k}_\perp^2+x^2m^2}\right)=\frac{\boldsymbol{k}_\perp\cdot\boldsymbol{q}_\perp(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2\boldsymbol{q}_\perp\cdot(\boldsymbol{q}_\perp-\boldsymbol{k}_\perp)}{[\boldsymbol{k}_\perp^2+x^2m^2][(\boldsymbol{k}_\perp-\boldsymbol{q}_\perp)^2+x^2m^2]^2}$$

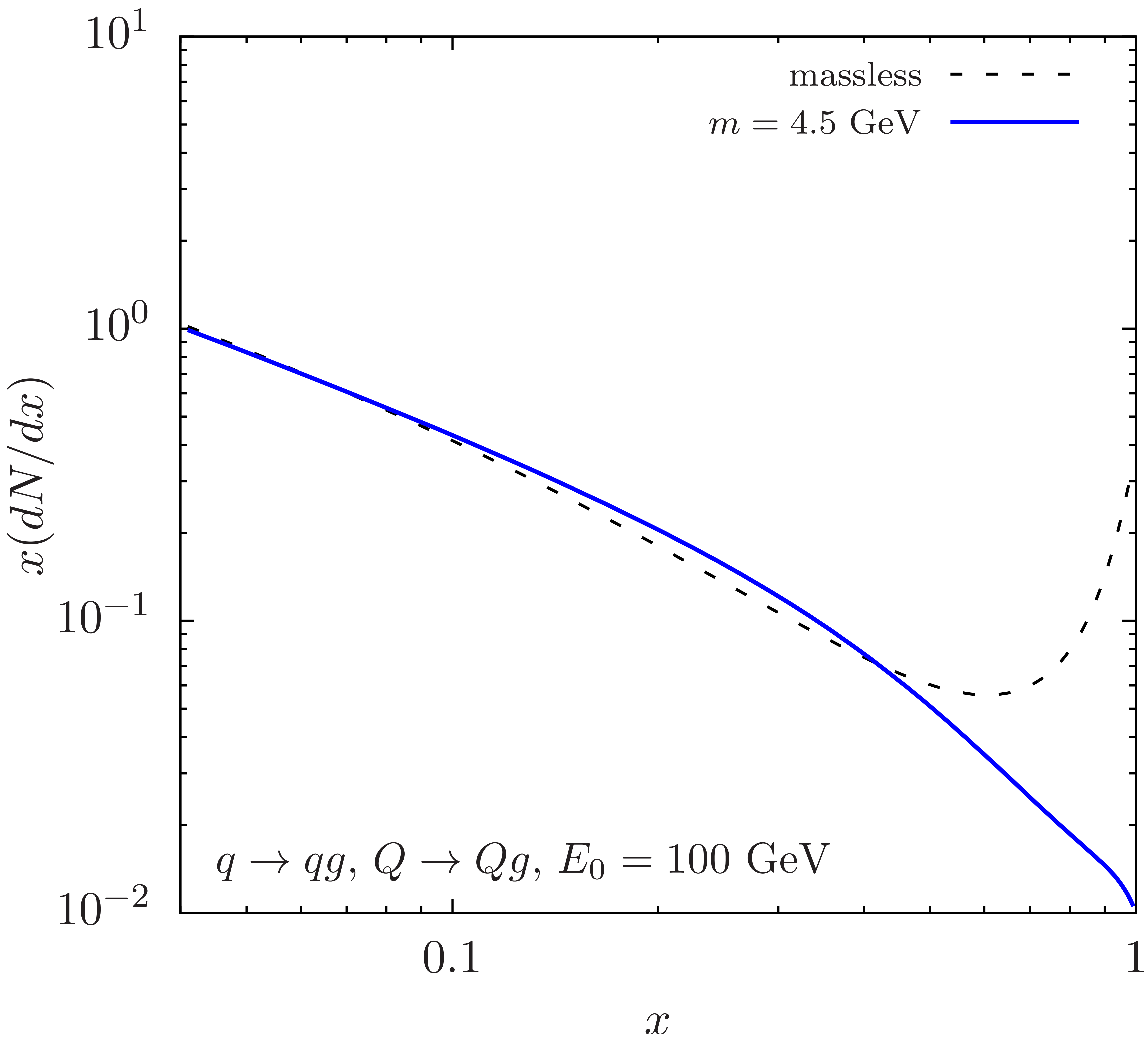
Soft gluon limit is consistent with *Gyulassy, Levai, Vitev `00*
Djordjevic, Gyulassy `03

Los Alamos NATIONAL LABORATORY EST. 1943

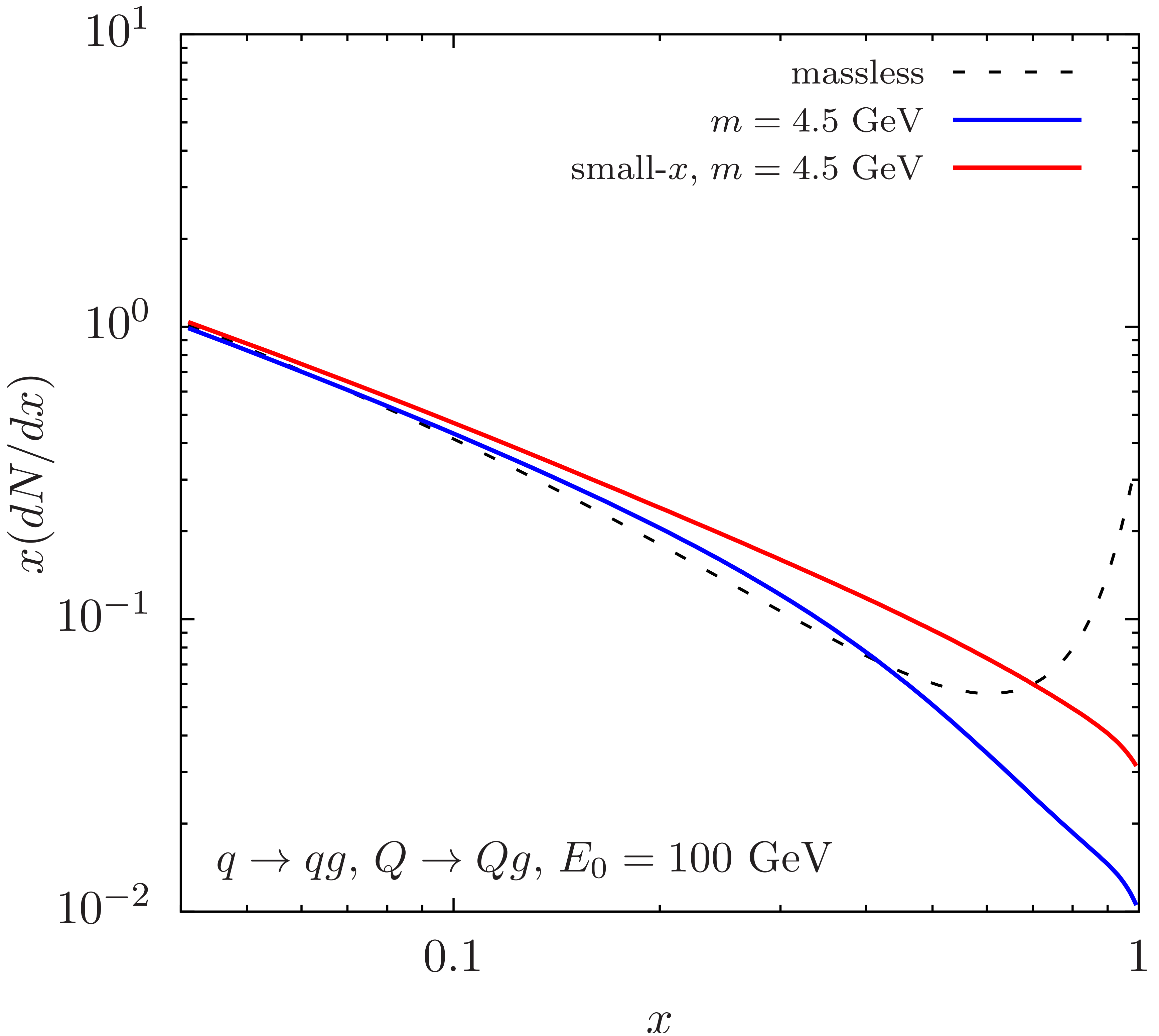
Numerical results



Numerical results



Numerical results



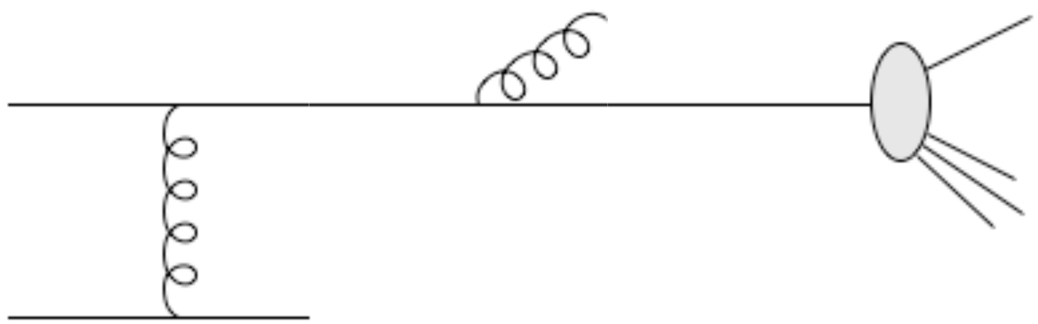
Los Alamos NATIONAL LABORATORY EST. 1943

Application of in-medium splitting functions

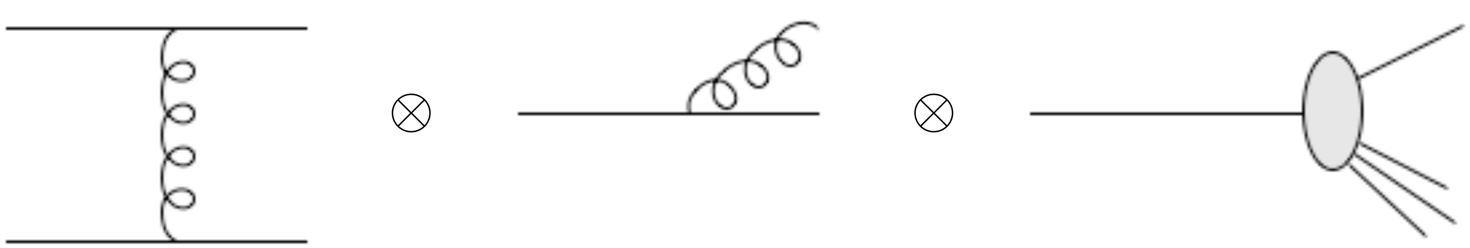
- SCET is an important tool to understand the structure of cross sections, e.g. jets *Kang, FR, Vitev `16, `16*
- Hadron cross sections

vaccum

$\mathcal{O}(\alpha_s)$



decompose as



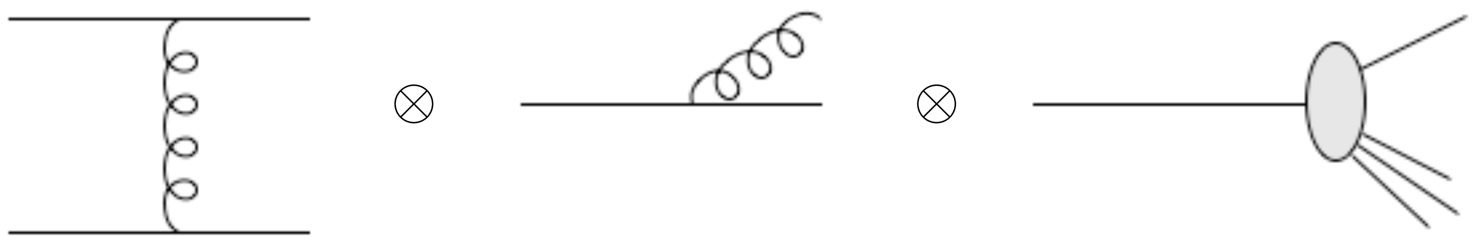
$\sigma^{(0)}_{qq}$ $\quad$ $P_{qq}(z)$ $\quad$ $D_q^h(z,\mu)$

Application of in-medium splitting functions

- SCET is an important tool to understand the structure of cross sections, e.g. jets *Kang, FR, Vitev \`16, \`16*
- Hadron cross sections

vaccum

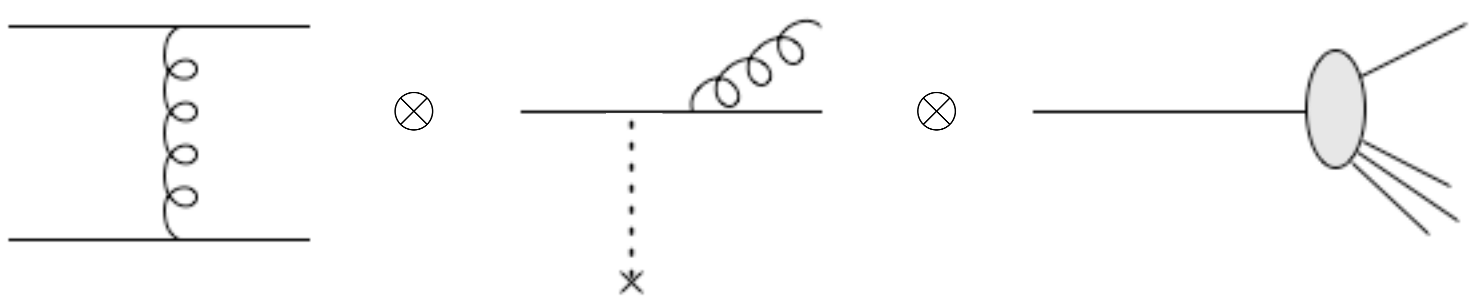
$\mathcal{O}(\alpha_s)$



$\sigma_{qq}^{(0)}$ $\otimes$ $P_{qq}(z)$ $\otimes$ $D_q^h(z,\mu)$

medium

$\mathcal{O}(\alpha_s)$



$\sigma_{qq}^{(0)}$ $\otimes$ $P_{qq}^{\rm med}(z)$ $\otimes$ $D_q^h(z,\mu)$

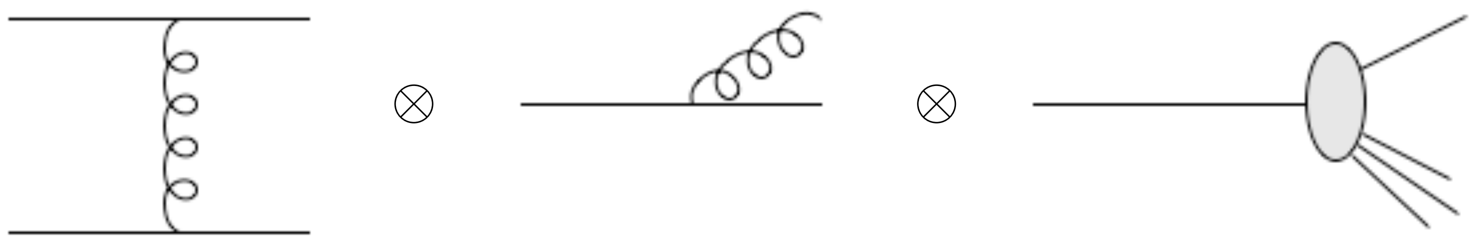
Los Alamos NATIONAL LABORATORY EST. 1943

Application of in-medium splitting functions

- SCET is an important tool to understand the structure of cross sections, e.g. jets *Kang, FR, Vitev `16, `16*
- Hadron cross sections

vaccum

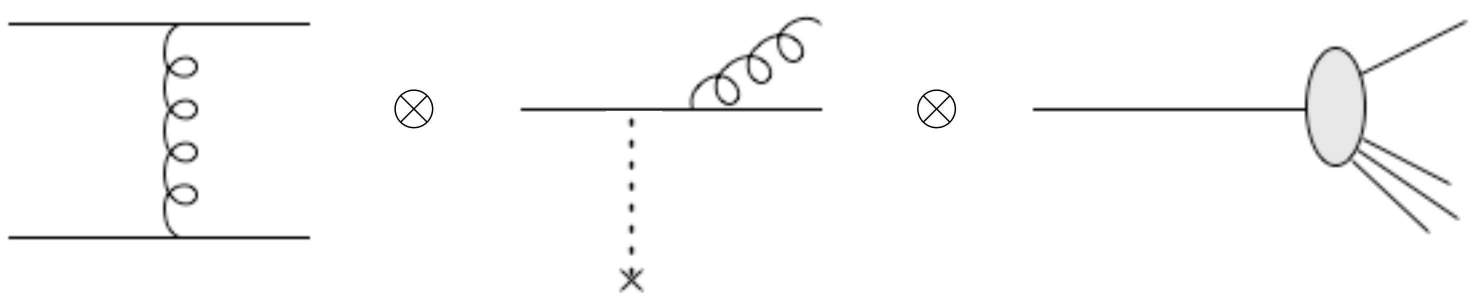
$\mathcal{O}(\alpha_s)$



$\sigma_{qq}^{(0)}$ $\otimes$ $P_{qq}(z)$ $\otimes$ $D_q^h(z,\mu)$

medium

$\mathcal{O}(\alpha_s)$



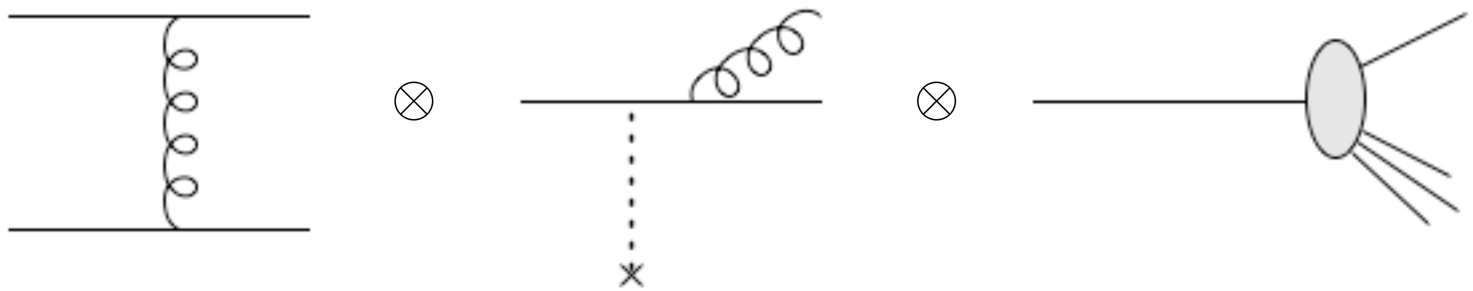
$\sigma_{qq}^{(0)}$ $\otimes$ $D_q^{h,\mathrm{med}}(z,\mu)$

Application of in-medium splitting functions

- Hadron cross sections

medium

$\mathcal{O}(\alpha_s)$



$\sigma_{qq}^{(0)}$ $\qquad$ $D_q^{h,\mathrm{med}}(z,\mu)$

vacuum

$$\frac{\alpha_s}{2\pi} C_F \int^{\mu^2} \frac{dk_\perp^2}{k_\perp^2} \frac{1+(1-z)^2}{z} - \delta(1-z) \frac{\alpha_s}{2\pi} C_F \int^{\mu^2} \frac{dk_\perp^2}{k_\perp^2} \int_0^1 dx \frac{1+(1-x)^2}{x}$$

real $\qquad$ virtual

medium

$$\frac{\alpha_s}{2\pi} C_F \int^{\mu^2} dk_\perp^2 P_{qq}^{\mathrm{med}}(z,k_\perp) - \delta(1-z) \frac{\alpha_s}{2\pi} C_F \int^{\mu^2} dk_\perp^2 \int_0^1 dx P_{qq}^{\mathrm{med}}(x,k_\perp)$$

cut-off scheme

Qiu, Collins `88

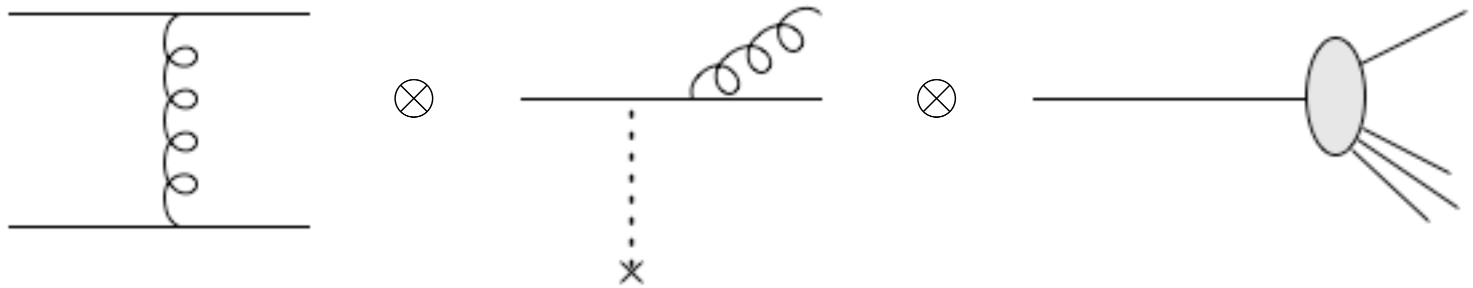
Los Alamos NATIONAL LABORATORY EST. 1943

Application of in-medium splitting functions

- Hadron cross sections

medium

$\mathcal{O}(\alpha_s)$



$\sigma_{qq}^{(0)}$ $\qquad$ $D_q^{h,\mathrm{med}}(z,\mu)$

vacuum

$$\frac{\alpha_s}{2\pi}C_F\int^{\mu^2}\frac{dk_\perp^2}{k_\perp^2}\frac{1+(1-z)^2}{z}-\delta(1-z)\frac{\alpha_s}{2\pi}C_F\int^{\mu^2}\frac{dk_\perp^2}{k_\perp^2}\int_0^1 dx\frac{1+(1-x)^2}{x}$$

real $\qquad$ virtual

medium

$$\frac{\alpha_s}{2\pi}C_F\int^{\mu^2}dk_\perp^2 P_{qq}^{\mathrm{med}}(z,k_\perp)-\delta(1-z)\frac{\alpha_s}{2\pi}C_F\int^{\mu^2}dk_\perp^2\int_0^1 dxP_{qq}^{\mathrm{med}}(x,k_\perp)$$

cut-off scheme

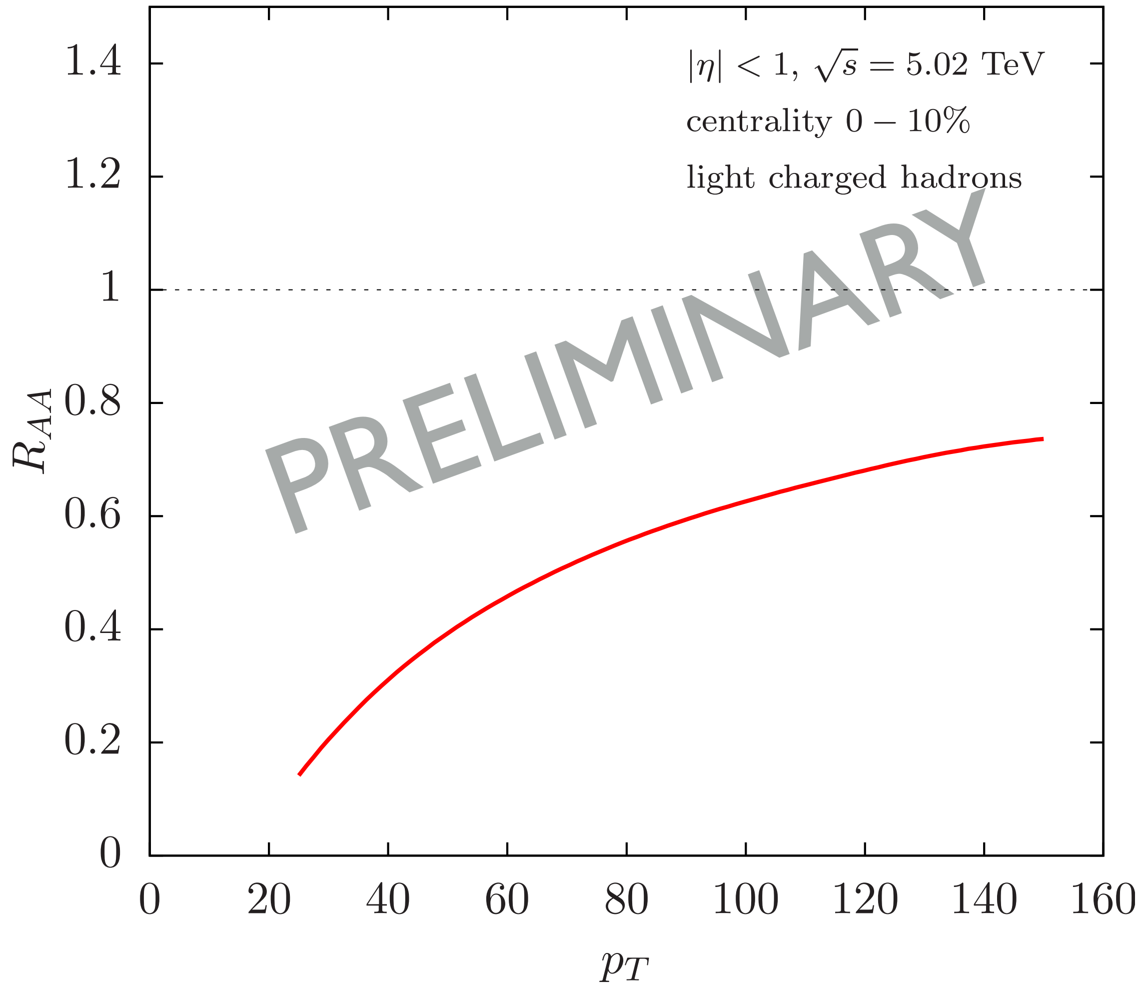
Qiu, Collins `88

- DGLAP formalism *Kang, Lashof-Regas, Ovanesyan, Saad, Vitev `14, Chien, Emerman, Kang, Ovanesyan, Vitev `15*

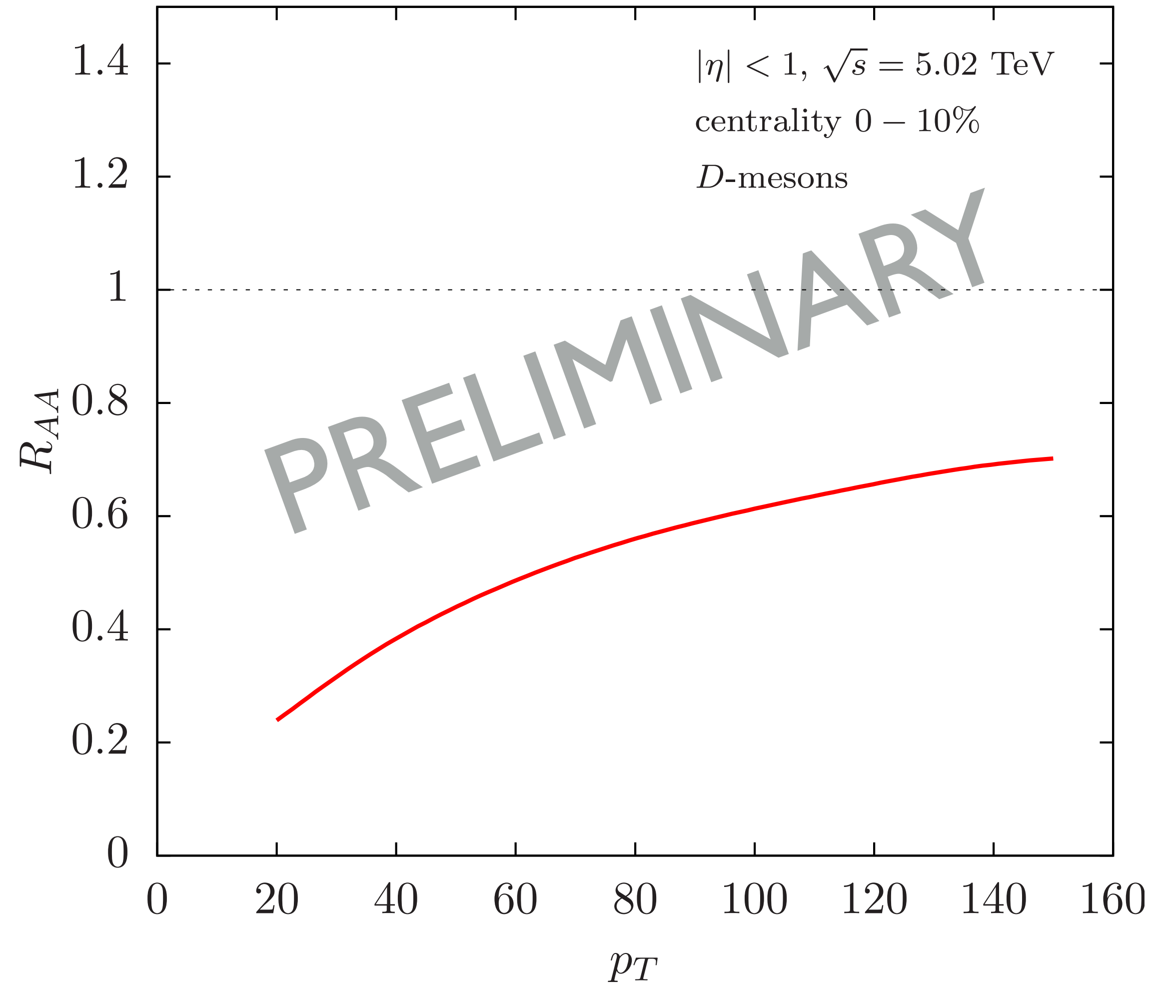
Los Alamos NATIONAL LABORATORY EST. 1943

Numerical results

Light charged hadrons



D-mesons



Outline

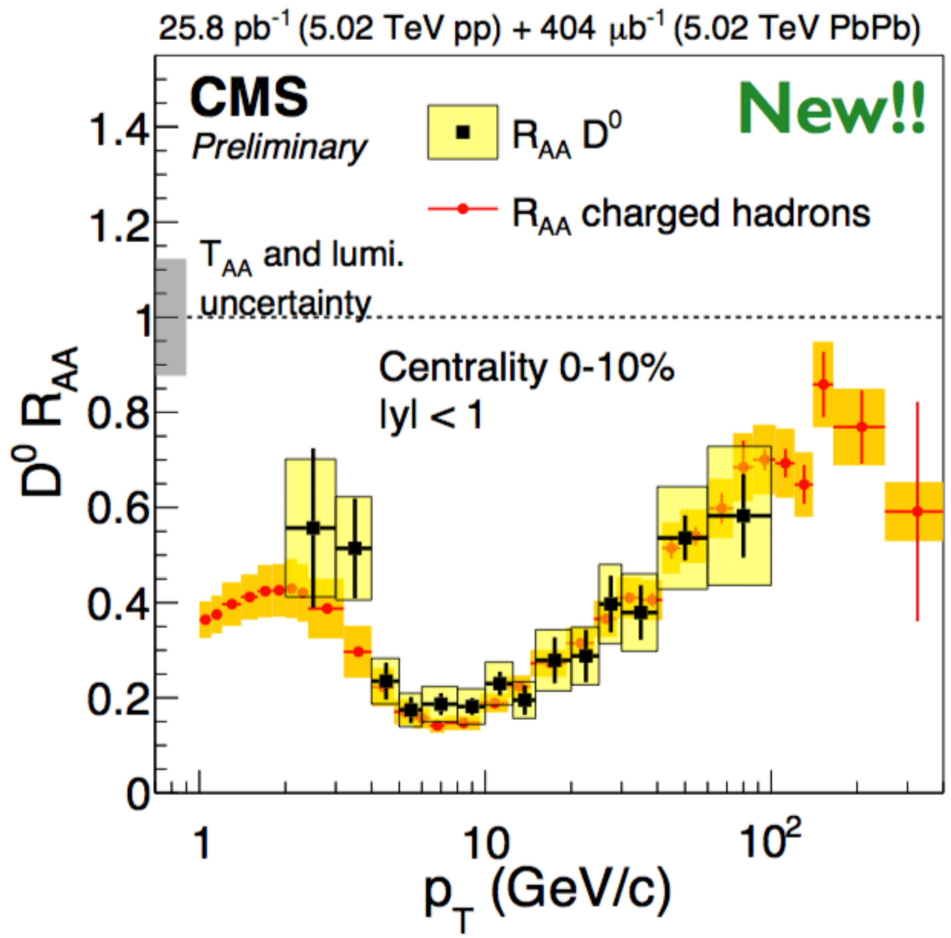
- proton-proton baseline
- Medium Modification using SCET
- Conclusions

Chien, Kang, FR, Vitev `15
Kang, FR, Vitev `16, `16
FR, Vitev - in preparation

Los Alamos NATIONAL LABORATORY EST. 1943

Conclusions

- NLO or resummed pp baseline
- Inclusive production and jet fragmentation functions
- Extension to $\mathrm{SCET}_{\mathrm{M,\,G}}$



- Consistent treatment for the modification of hadron and jet observables in the medium
- Light hadrons as well as D, B-meson suppression

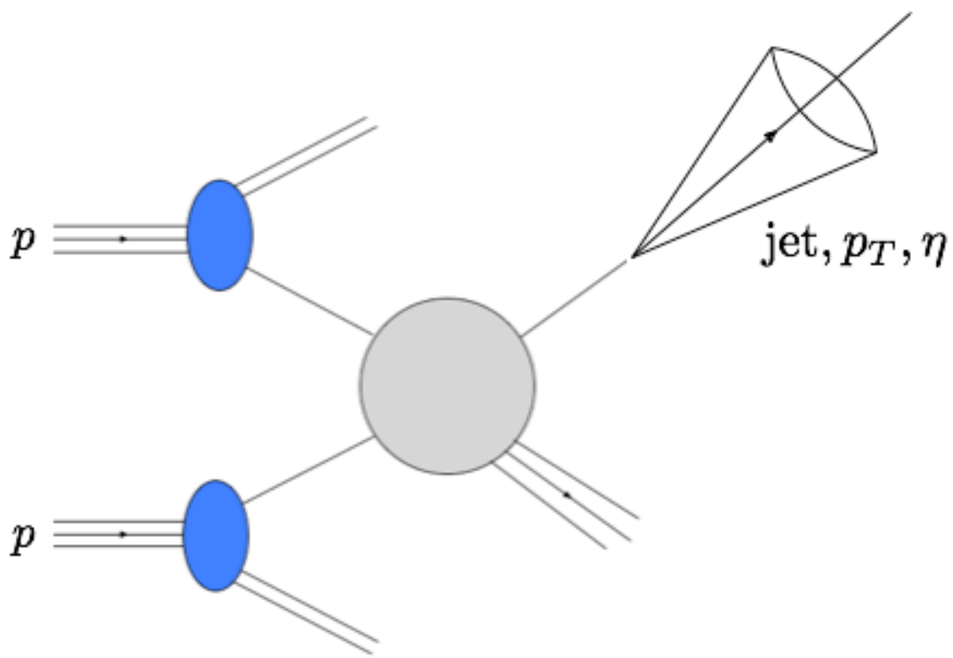
… please stay tuned!

backup

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

Kang, FR, Vitev `16, `16

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



"semi-inclusive jet function" in SCET (perturbatively calculable)

see also:

Jäger, Stratmann, Vogelsang `04, Mukherjee, Vogelsang `12, Kaufmann, Mukherjee, Vogelsang `15, Dasgupta, Dreyer, Salam, Soyez `14, `16

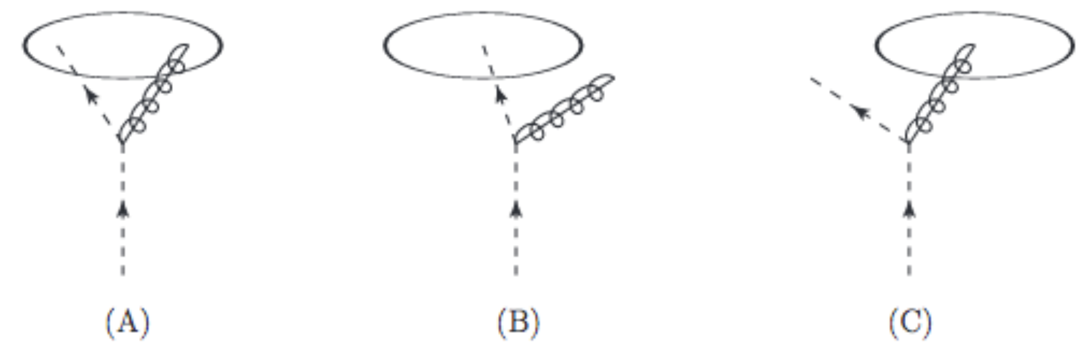
Los Alamos NATIONAL LABORATORY EST. 1943

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

Kang, FR, Vitev `16, `16

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

Definition similar to FFs
but perturbatively calculable:



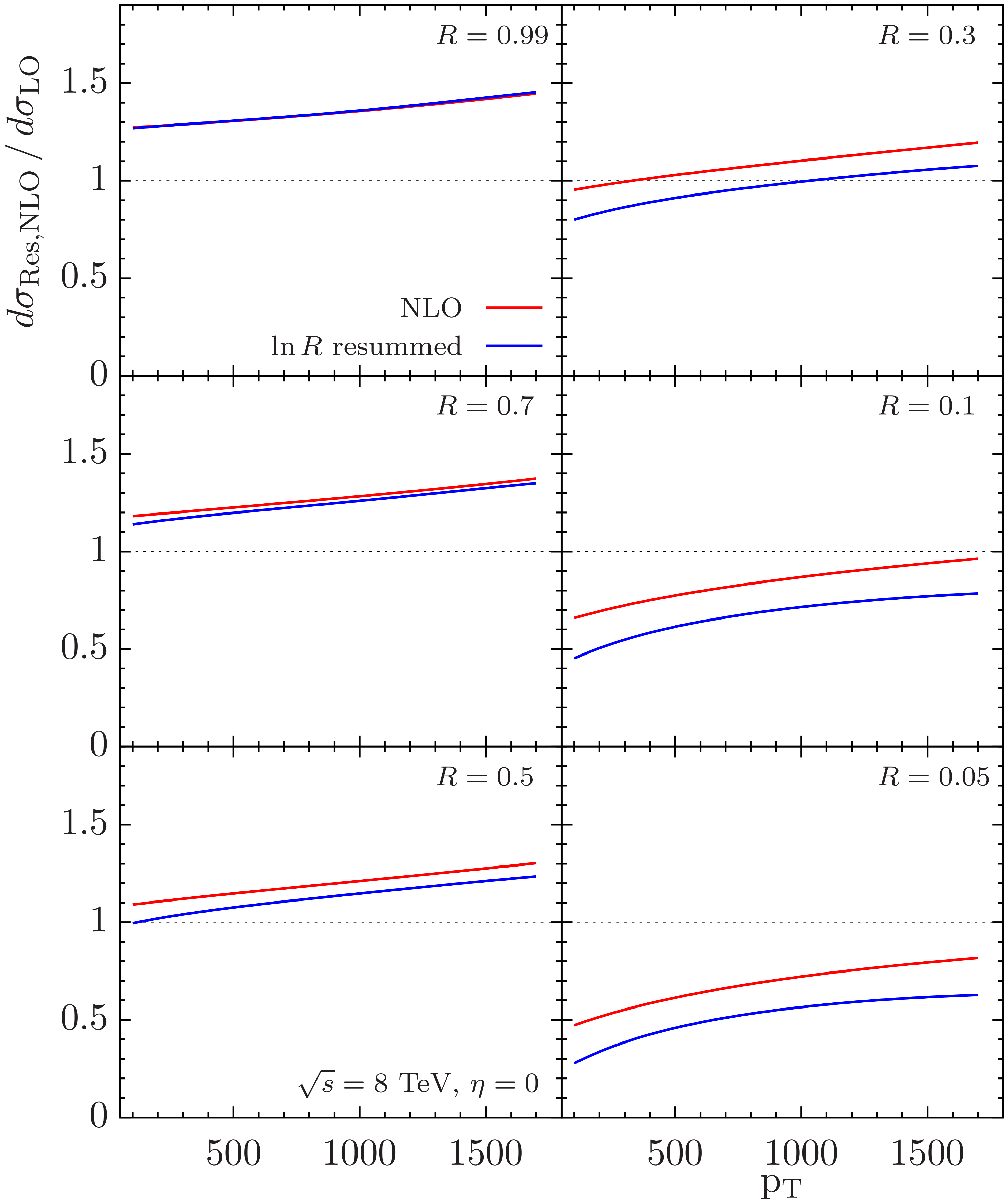
NLO:

$$J_q^{(0)}(z,\omega_J) = \delta(1-z) - \frac{\alpha_s}{2\pi}\left\{C_F\left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z) d_J^{q,\mathrm{alg}} + P_{gq}(z) 2\ln(1-z) + C_F z\right\}$$

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

→ resummation of $\ln R$, i.e. $\mathrm{NLO}+\mathrm{NLL}_R$

Especially relevant for heavy-ion phenomenology!



LL_R DGLAP evolution

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