Jet and Heavy Flavor Production from Soft Collinear Effective Theory

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Hard Probes `16, Wuhan

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Outline

- Open heavy flavor production
- Inclusive jet observables
- Conclusions

Kang, FR, Vitev `16 arXiv:1609.04908
Kang, FR, Vitev `16 arXiv:1606.06732

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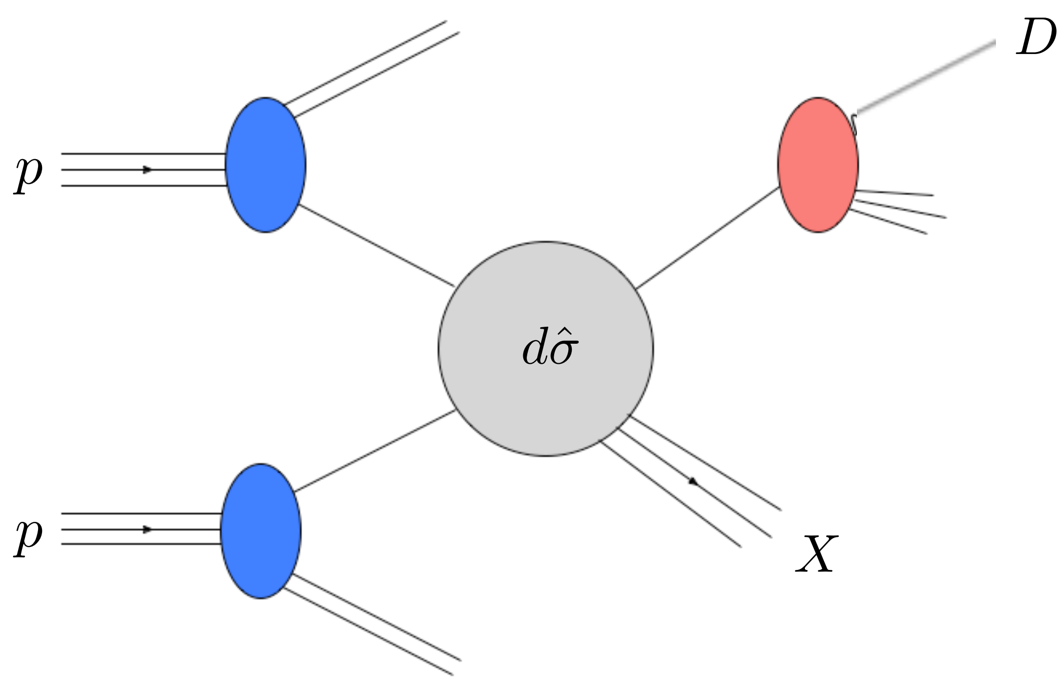
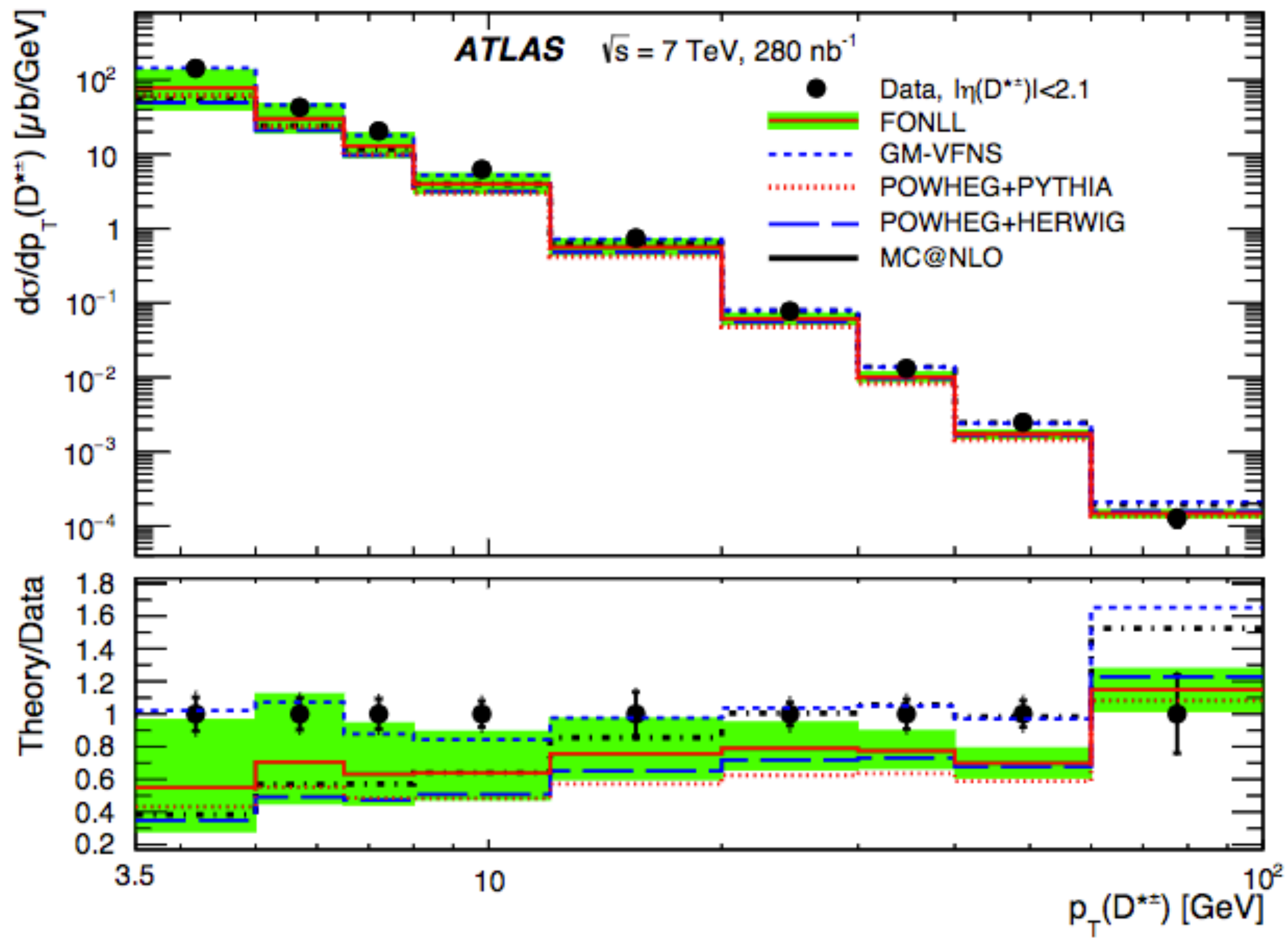
D and B-meson production $pp \to HX$

Inclusive D-meson data taken at the LHC





Nucl. Phys. B 907 (2016) 717

Similarly CMS, ALICE

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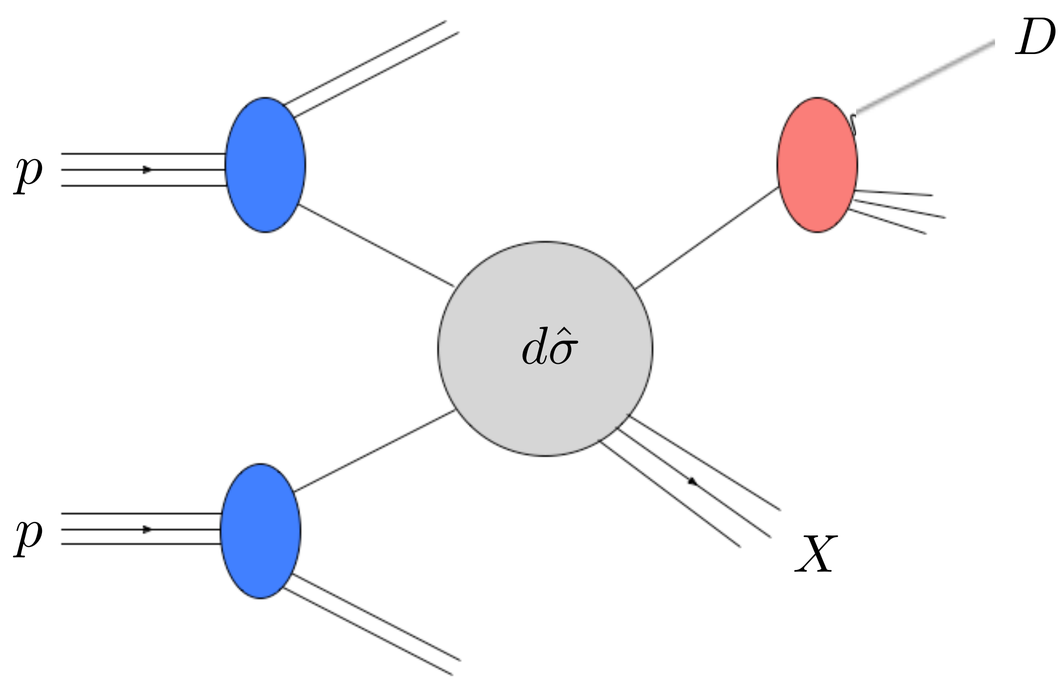
D and B-meson production $pp \to HX$

Next-to-leading order in QCD

Jäger, Stratmann, Vogelsang `02

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



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

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D and B-meson production $pp \to HX$

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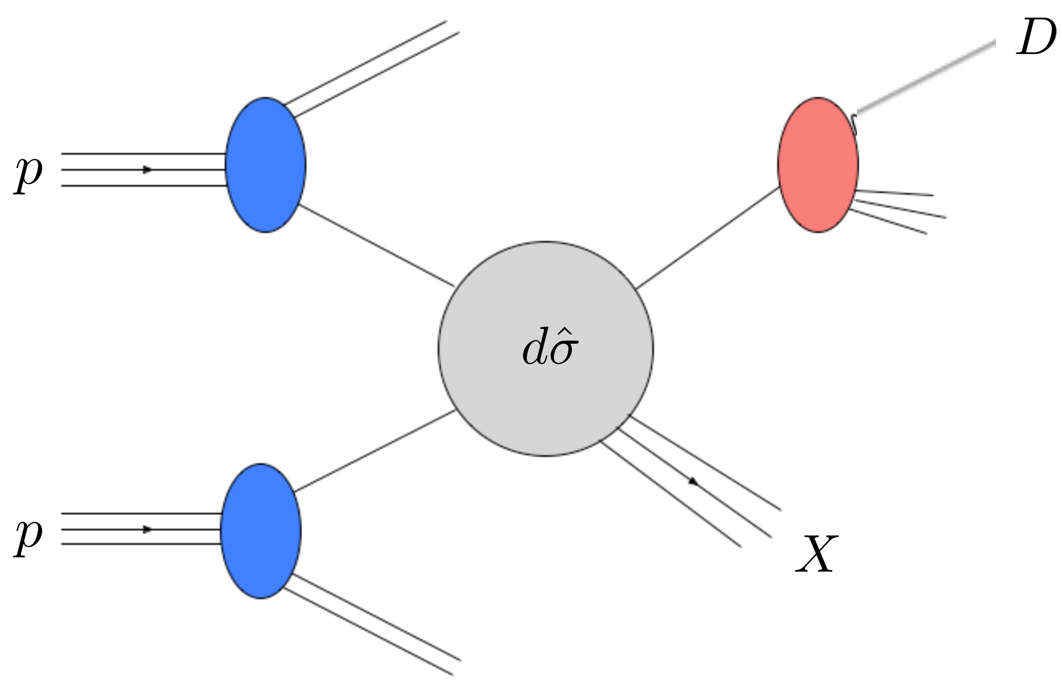


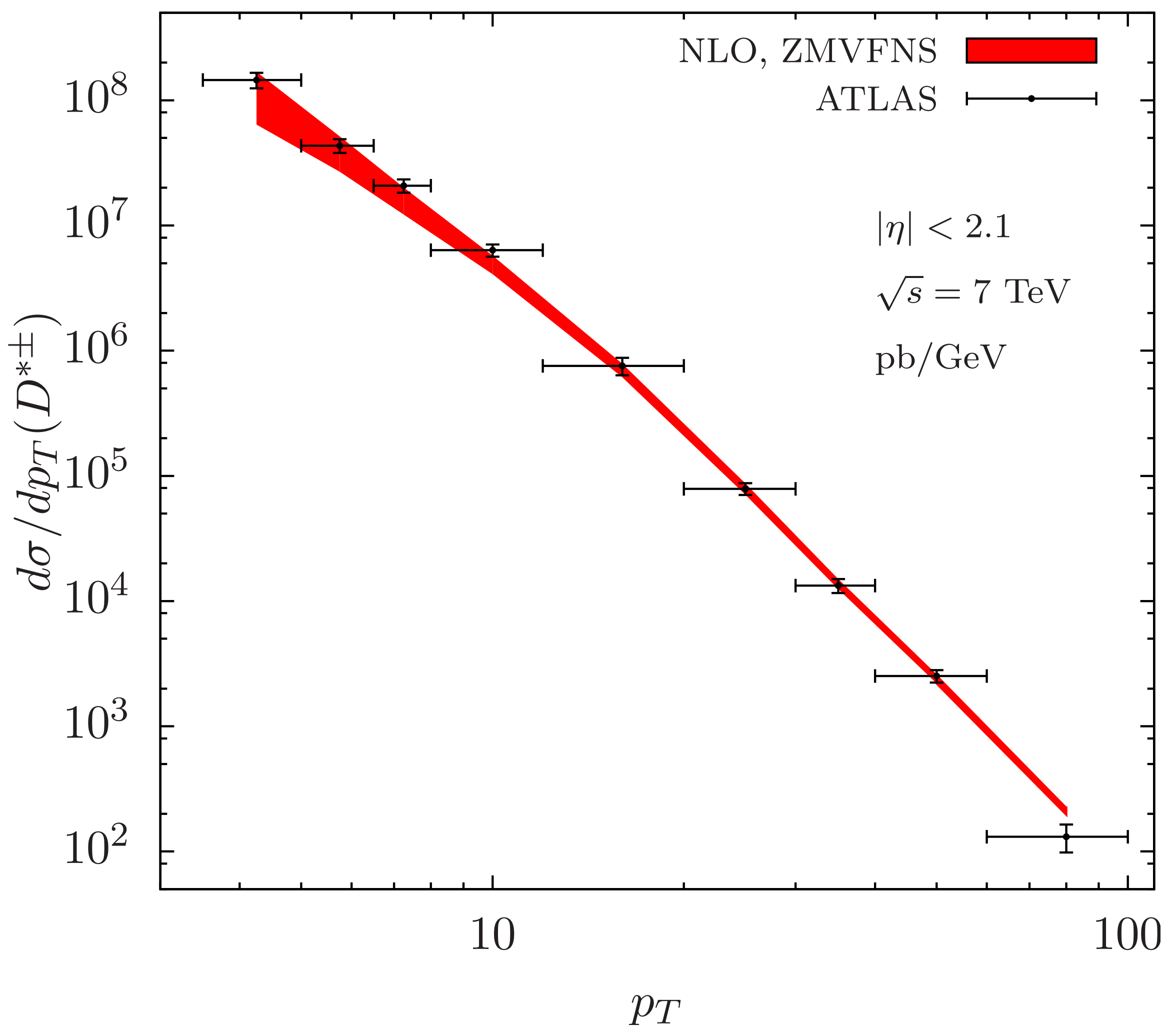
Using FFs from

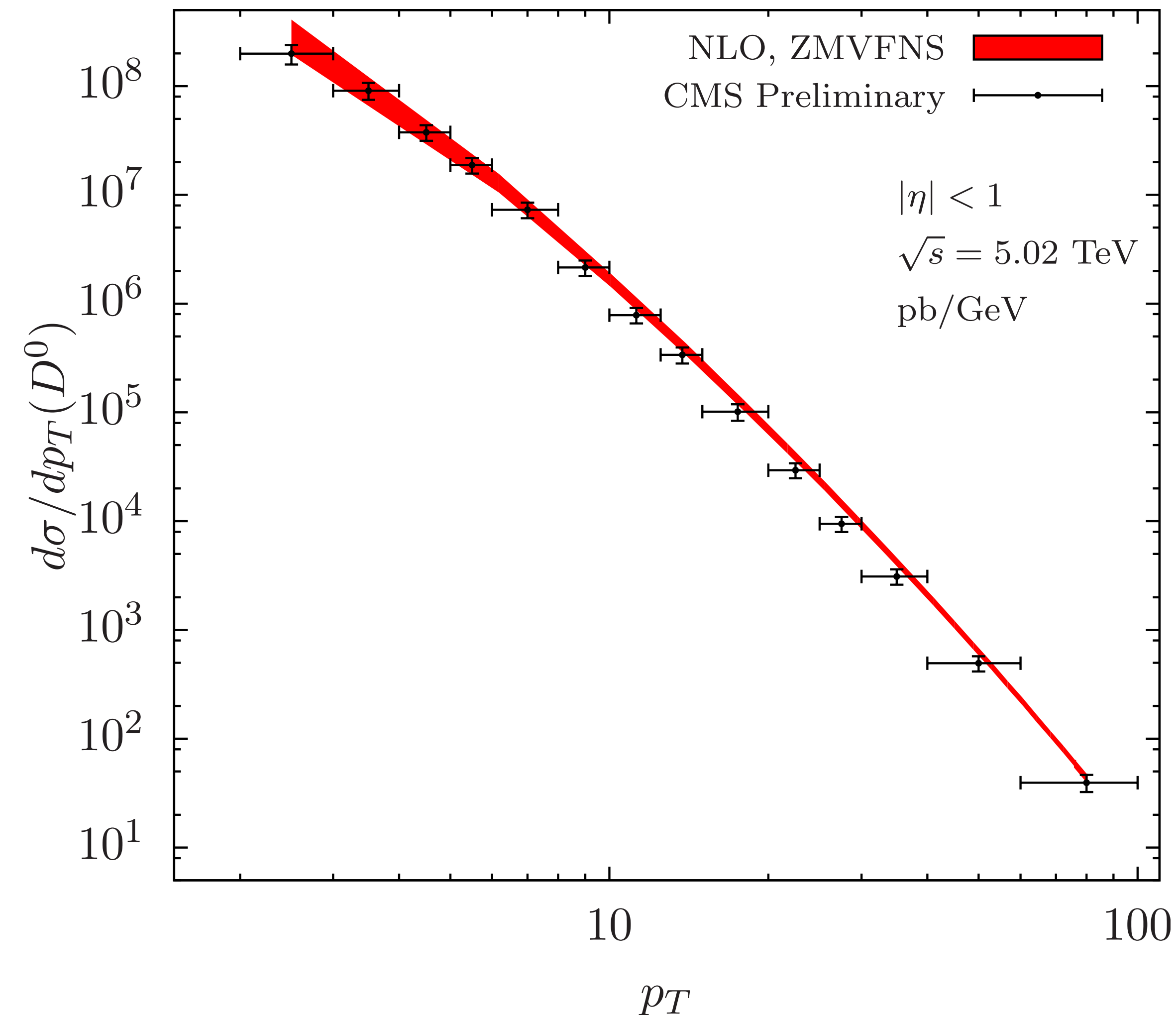
Kneesch, Kniehl, Kramer, Schienbein '08

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

D-meson production $pp \to HX$

Data taken at the LHC





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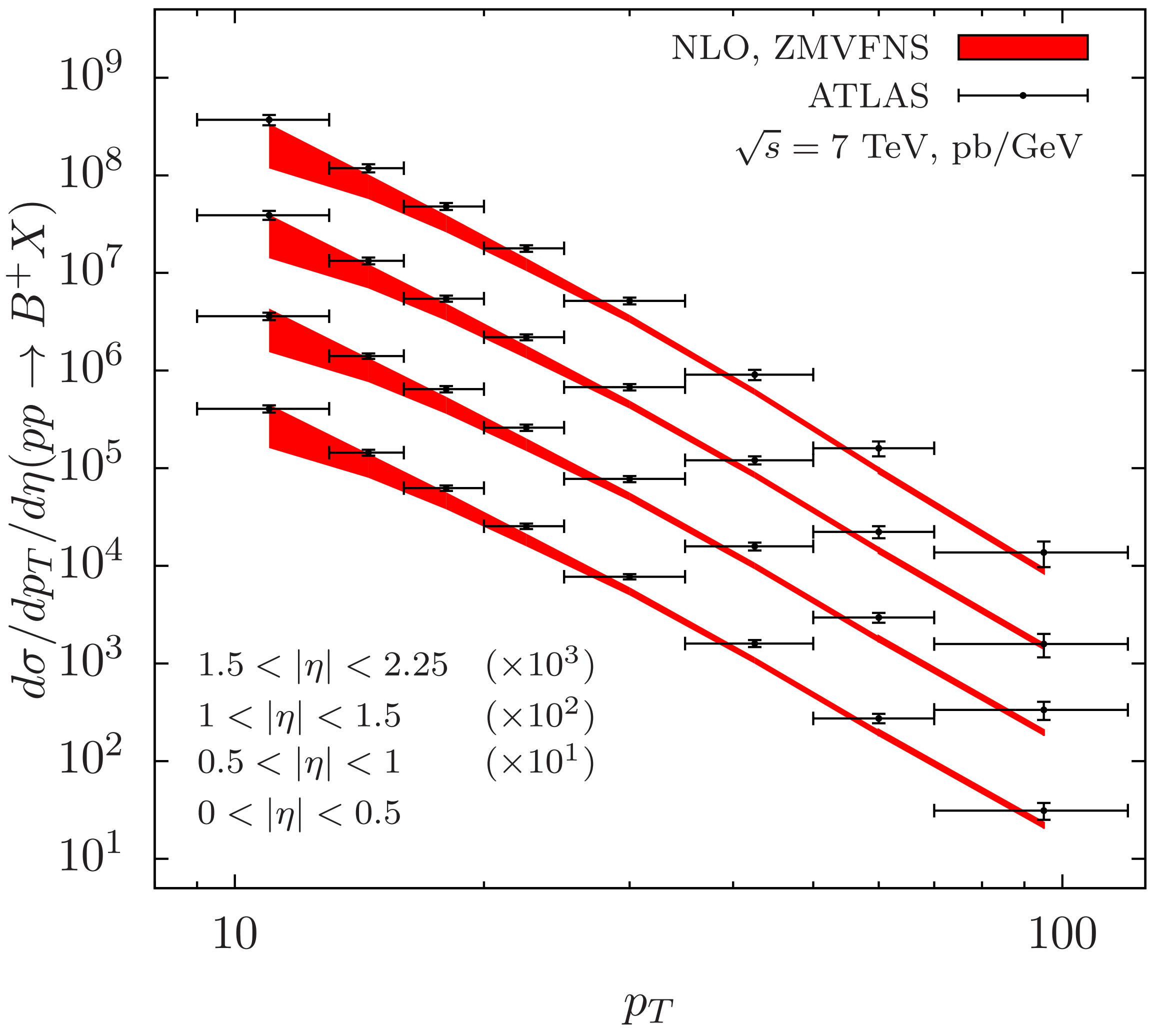
CMS-PAS-HIN-16-010

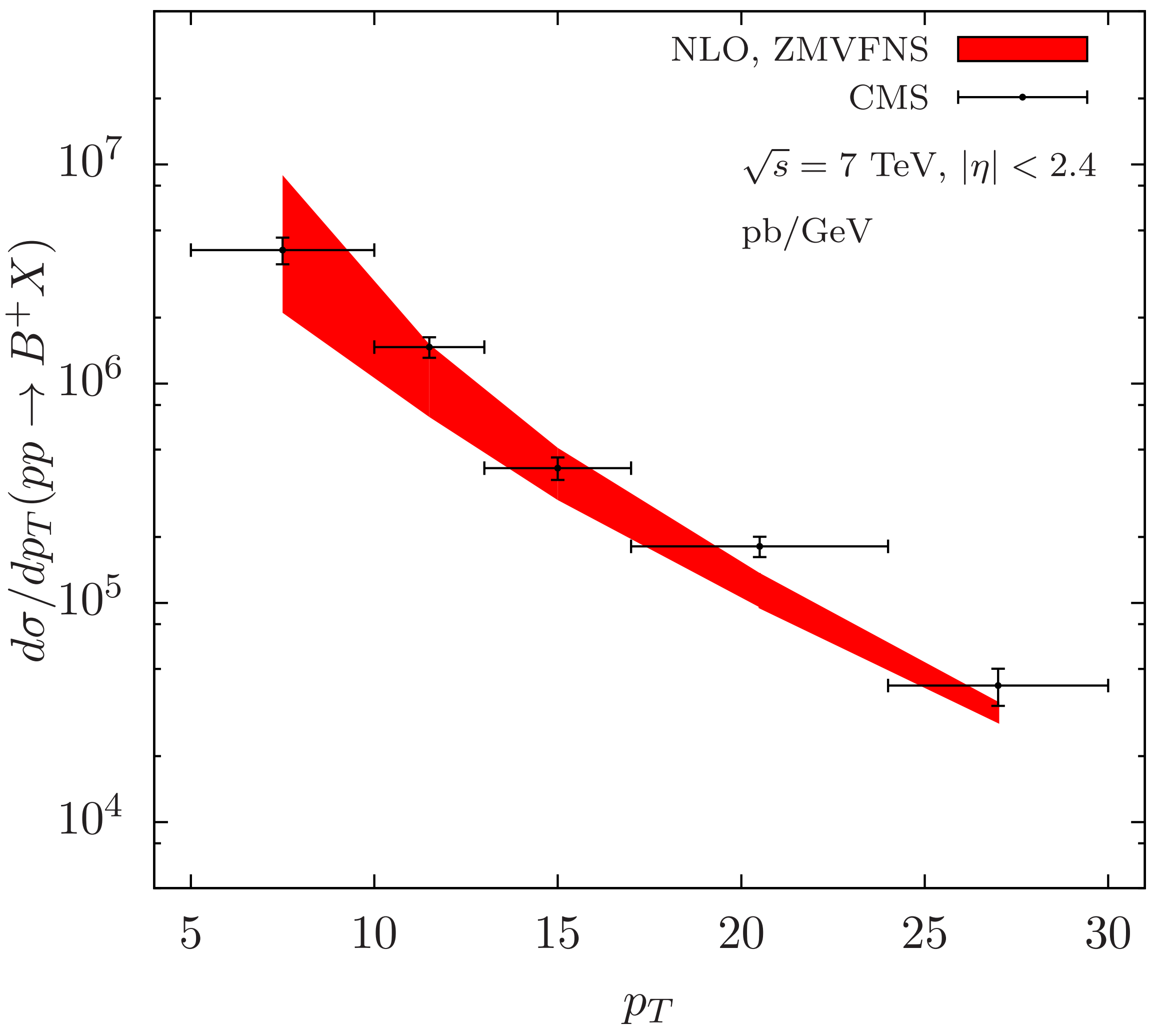
Jäger, Stratmann, Vogelsang `02

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

B-meson production $pp \to HX$

Data taken at the LHC





JHEP 10 (2013) 042

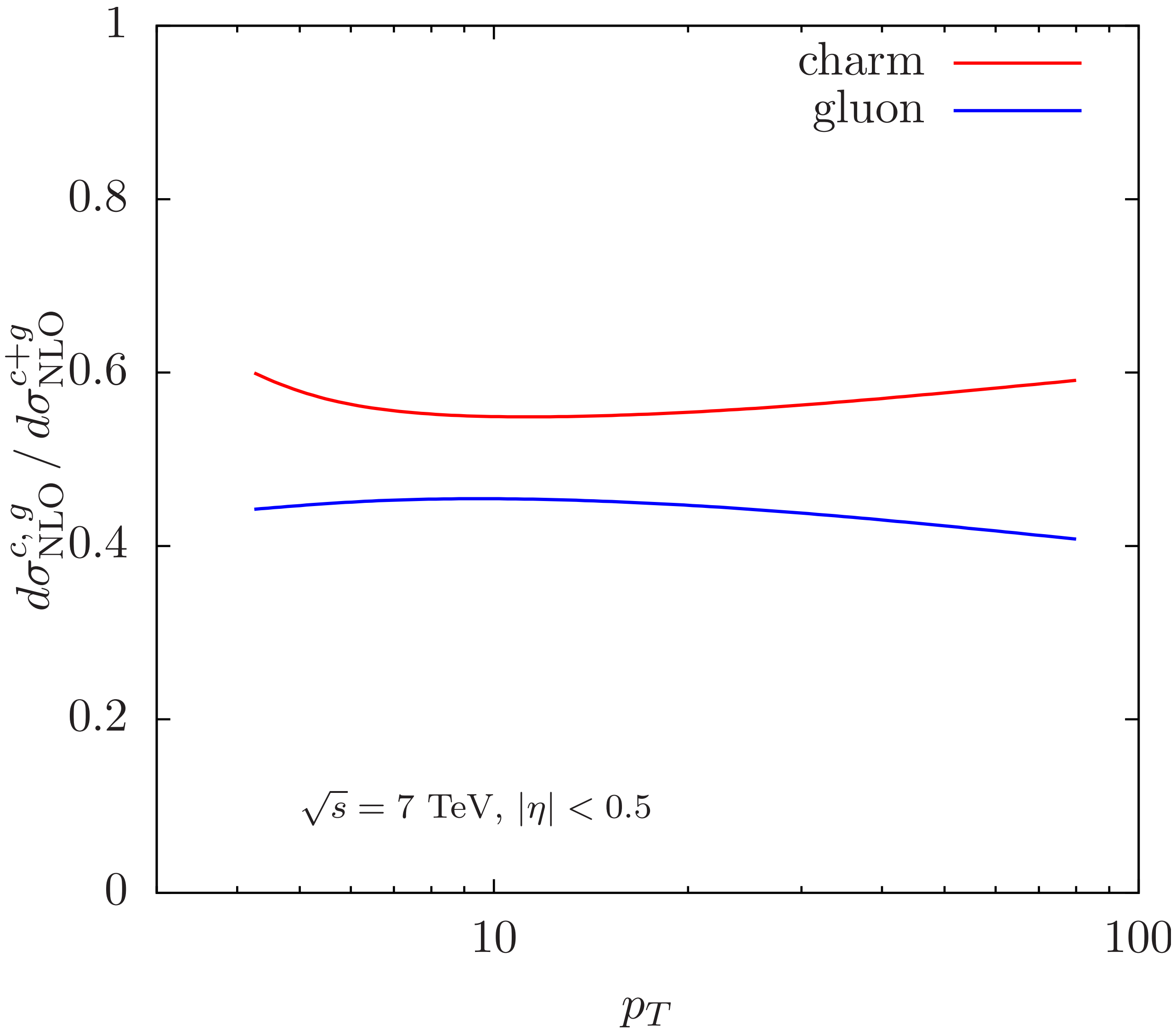
Phys. Rev. Lett 106 (2011) 112001

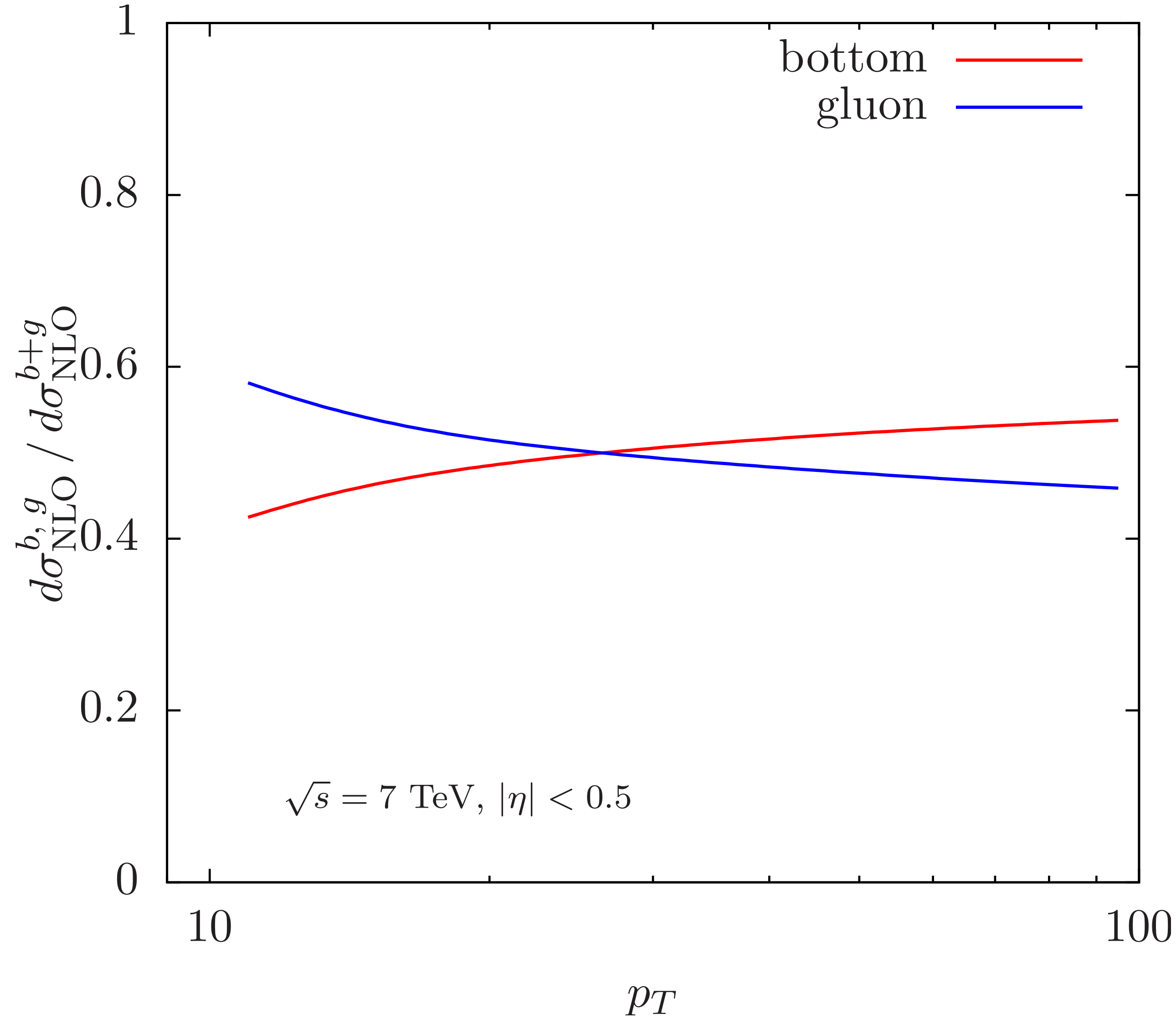
Jäger, Stratmann, Vogelsang `02

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

D and B-meson production $pp \to HX$

Heavy quark-gluon contribution





Jäger, Stratmann, Vogelsang `02

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

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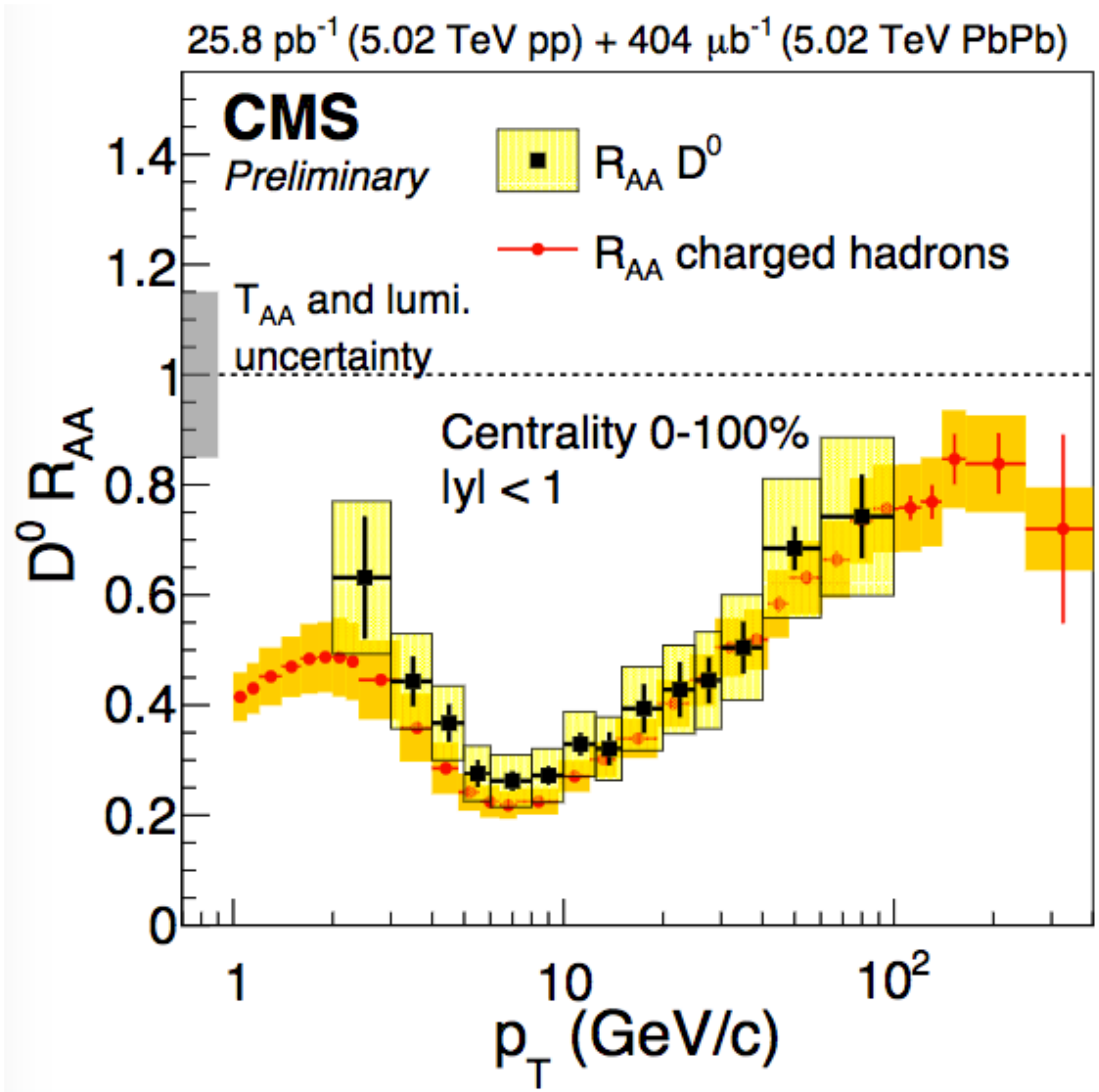
D-meson suppression in PbPb



CMS-PAS-HIN-16-001

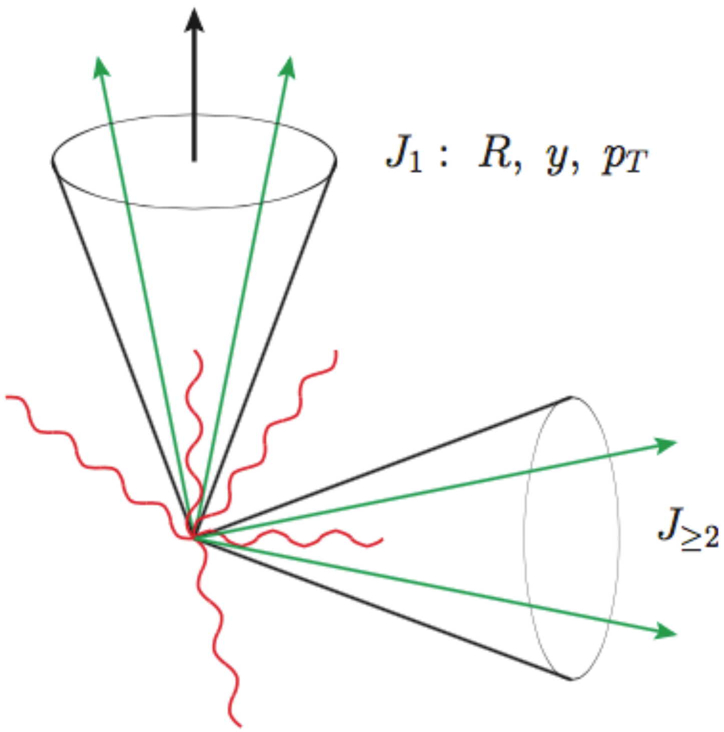
Soft Collinear Effective Theory

- Invaluable tool for high precision LHC phenomenology
- Identify collinear, soft and hard modes at the level of the Lagrangian
- Factorization
- Resummation for multi-scale problems

Bauer, Fleming, Luke, Pirjol, Rothstein, Stewart `00-`02

- Include medium interaction via Glauber gluon exchange
- Full in-medium splitting functions

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



$$d\sigma \sim H(p_T,\mu)\, J_1(z,\mu) \ldots J_N(\mu) S_{n_1 \ldots n_N}(\mu)$$

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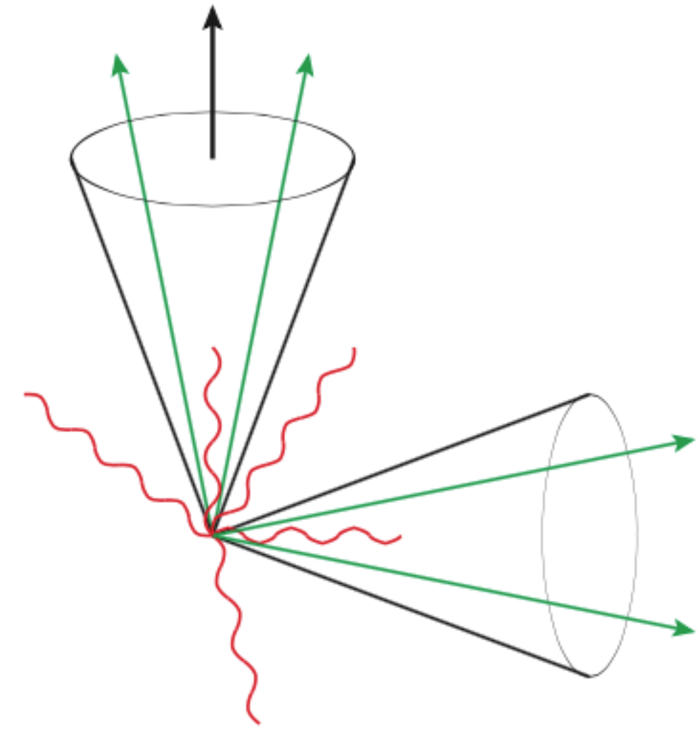
SCET$_{\mathrm{M,G}}$



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

Kang, FR, Vitev `16

- $$\mathcal{L}_{\mathrm{SCET_M}} = \bar{\xi}_{n,p'}\left\{in\cdot\partial + (\mathcal{P}\!\!\!/_\perp + gA\!\!\!/^\perp_{n,q})W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger(\mathcal{P}\!\!\!/_\perp + gA\!\!\!/^\perp_{n,q'})\right\}\frac{\bar{n}\!\!\!/}{2}\xi_{n,p}$$
$$+\; m\,\bar{\xi}_{n,p'}\left[(\mathcal{P}\!\!\!/_\perp + gA\!\!\!/^\perp_{n,q}), W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger\right]\frac{\bar{n}\!\!\!/}{2}\xi_{n,p} - m^2\,\bar{\xi}_{n,p'}W_n\frac{1}{\bar{\mathcal{P}}}W_n^\dagger\frac{\bar{n}\!\!\!/}{2}\xi_{n,p}$$

Leibovich, Ligeti, Wise `03

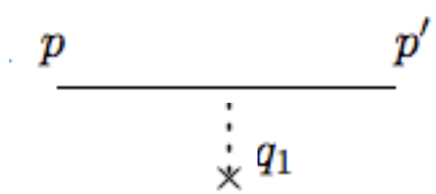
- $$\mathcal{L}_{\mathrm{G}}(\xi_n, A_n, A_G) = \sum_{p,p'} \mathrm{e}^{-i(p-p')x}\left(\bar{\xi}_{n,p'}\Gamma^{\mu,a}_{\mathrm{qqA_G}}\frac{\bar{n}\!\!\!/}{2}\xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}}\left(A^c_{n,p'}\right)_\lambda\left(A^b_{n,p}\right)_\nu\right)A_{\mathrm{G}\,\mu,a}(x)$$

Ovanesyan, Vitev '12

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

Bauer, Fleming, Luke, Pirjol, Rothstein, Stewart `00-`02

Idilbi, Majumder `08, D'Eramo, Liu, Rajagopal `10



$$= i\,v(q_{1\perp})\,(b_1)_R\,(b_1)_{T_i}\frac{\bar{n}\!\!\!/}{2}$$

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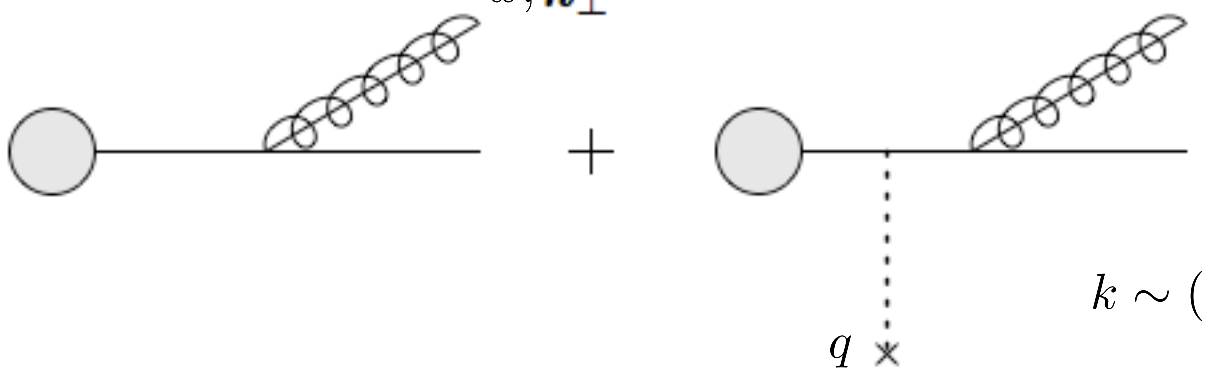
$\text{SCET}_{\text{M, G}}$ splitting kernels

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.

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

$$\times (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} \cdot \left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_3)\Delta z])$$

$$+ \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2} (1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \right) (1-\cos[\Omega_4\Delta z])$$

$$- \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} \cdot \frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2} (1-\cos[\Omega_5\Delta z]) + \frac{1}{N_c^2} \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) \Bigg],$$

$$\left.\left. + x^3 m^2 \left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} \cdot \left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2} - \frac{1}{\boldsymbol{C}_\perp^2+\nu^2} \right) (1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \ldots \right] \right\}$$

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

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

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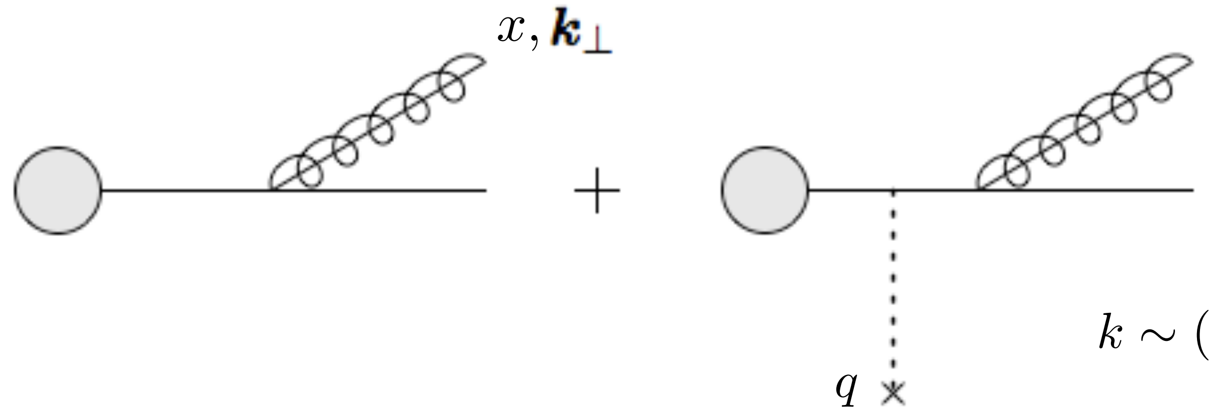

$k \sim (1, \lambda^2, \lambda)$

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

- medium: e.g.

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

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

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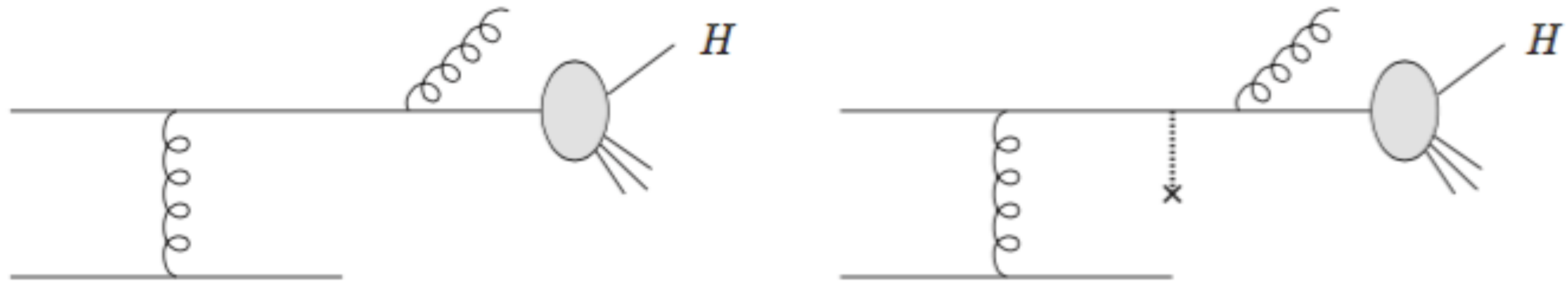
Application of in-medium splitting functions

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



$$\sum_j \hat{\sigma}_i^{(0)} \otimes \mathcal{P}_{i\to jk} \otimes D_j^H$$

vacuum + medium splitting function

$$\mathcal{P}_{i\to jk}(z,\mu) = \mathcal{P}^{\rm vac}_{i\to jk}(z,\mu) + \mathcal{P}^{\rm med}_{i\to jk}(z,\mu)$$

$$d\sigma^H_{\rm PbPb} = d\sigma^{H,\rm NLO}_{pp} + d\sigma^{H,\rm med}_{\rm PbPb}$$

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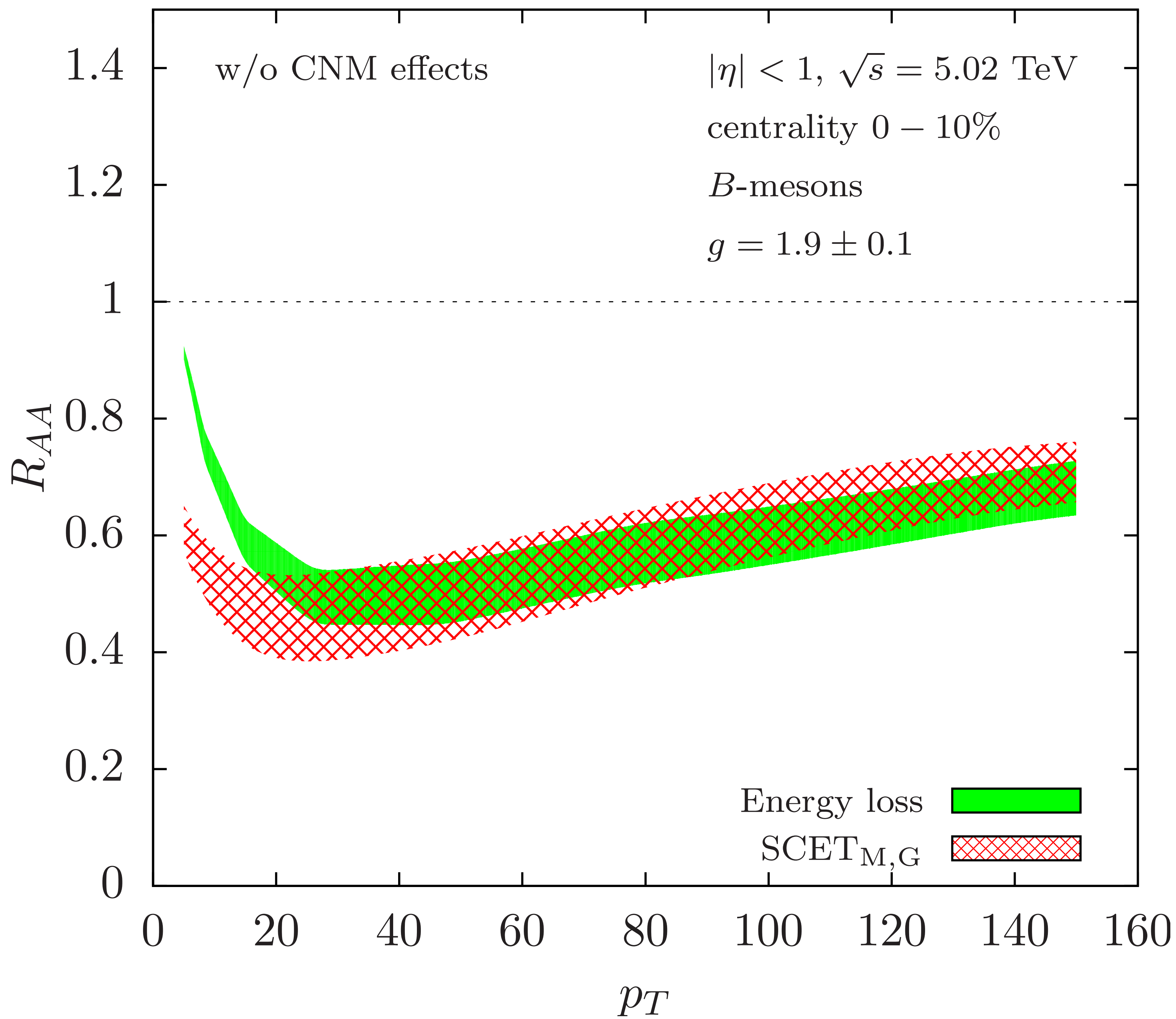
Traditional energy loss and $\mathrm{SCET}_{\mathrm{M,G}}$

B-mesons



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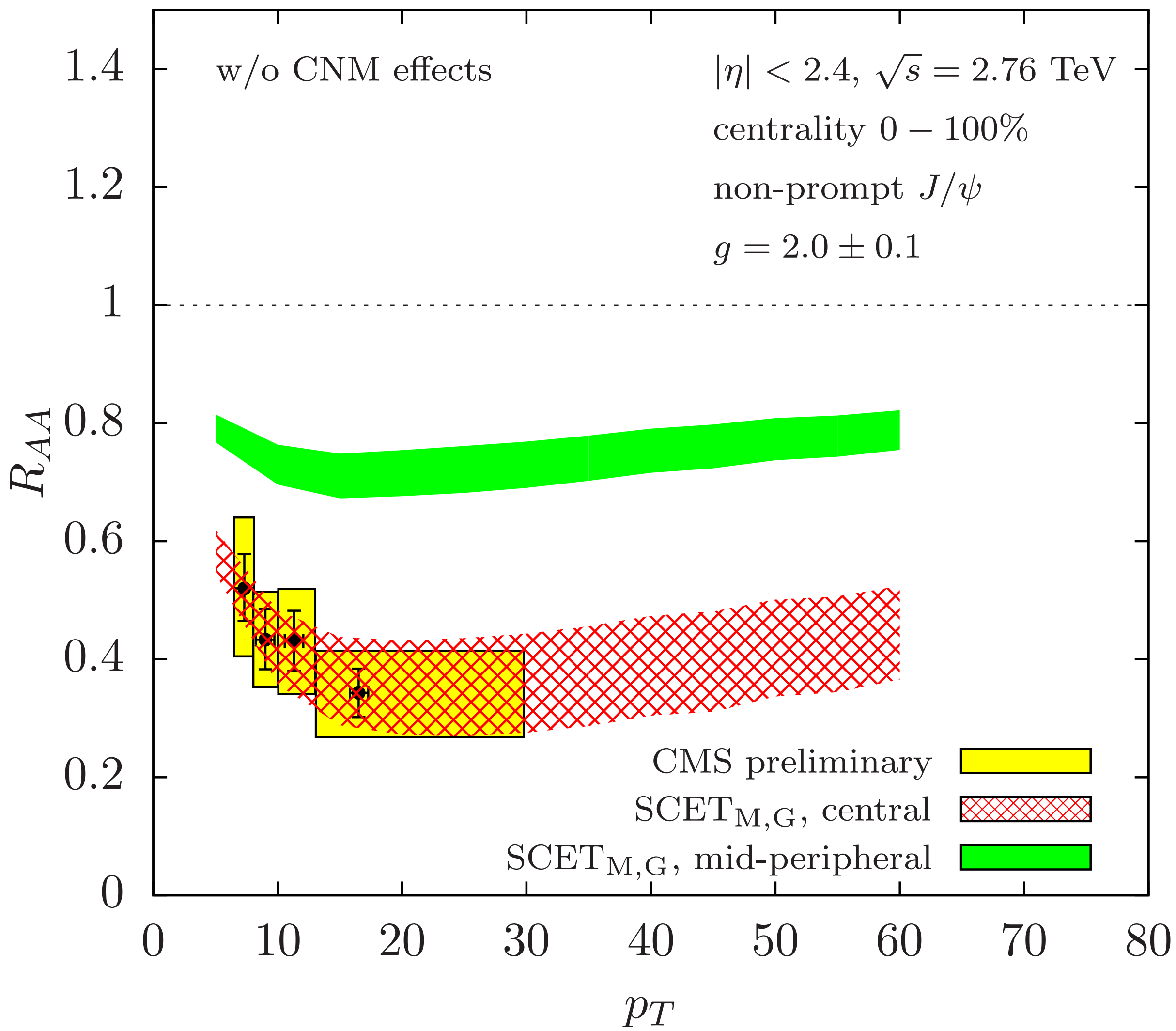
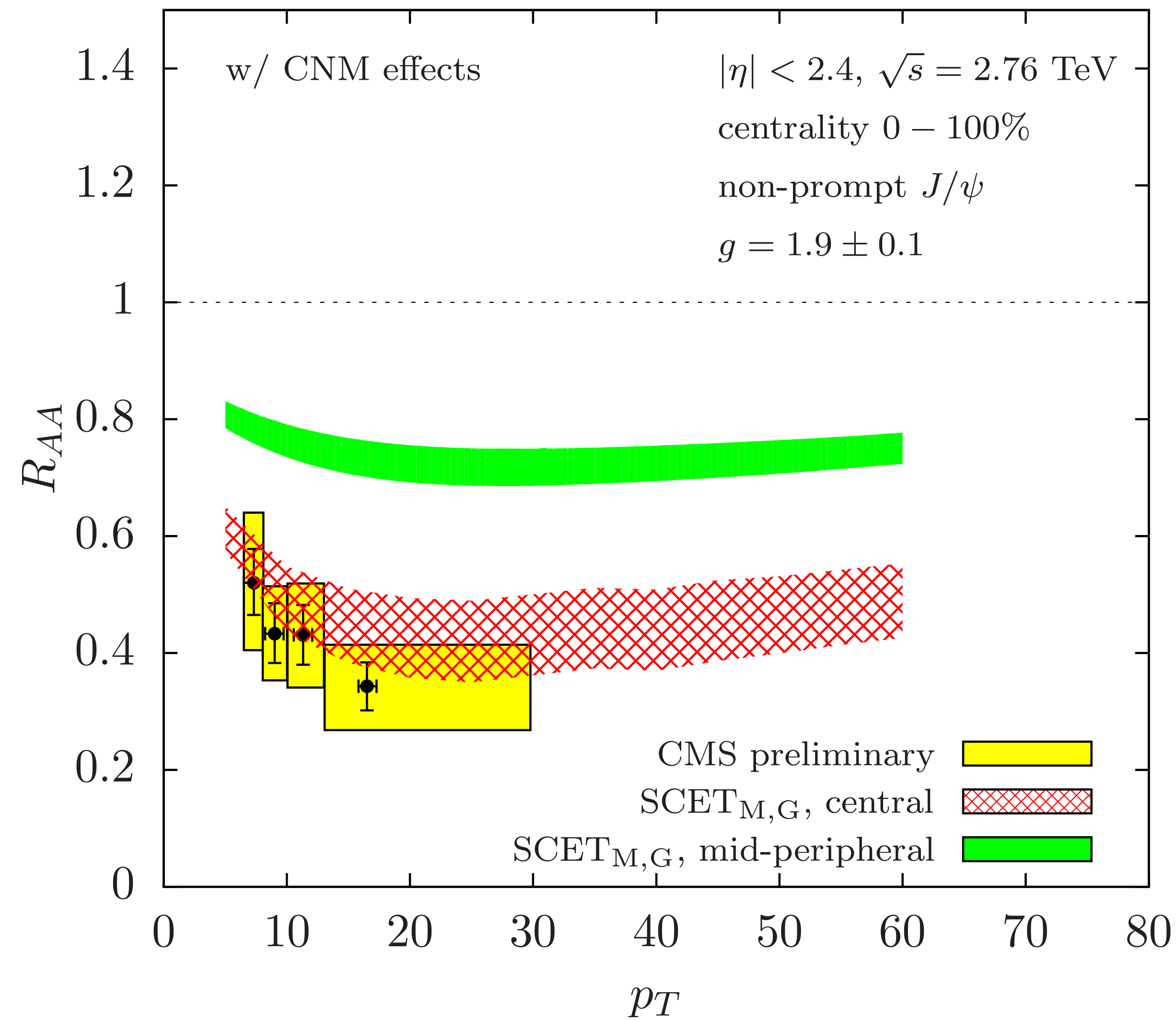
Comparison to LHC data

non-prompt J/ψ, from B-meson decays
minimum bias data



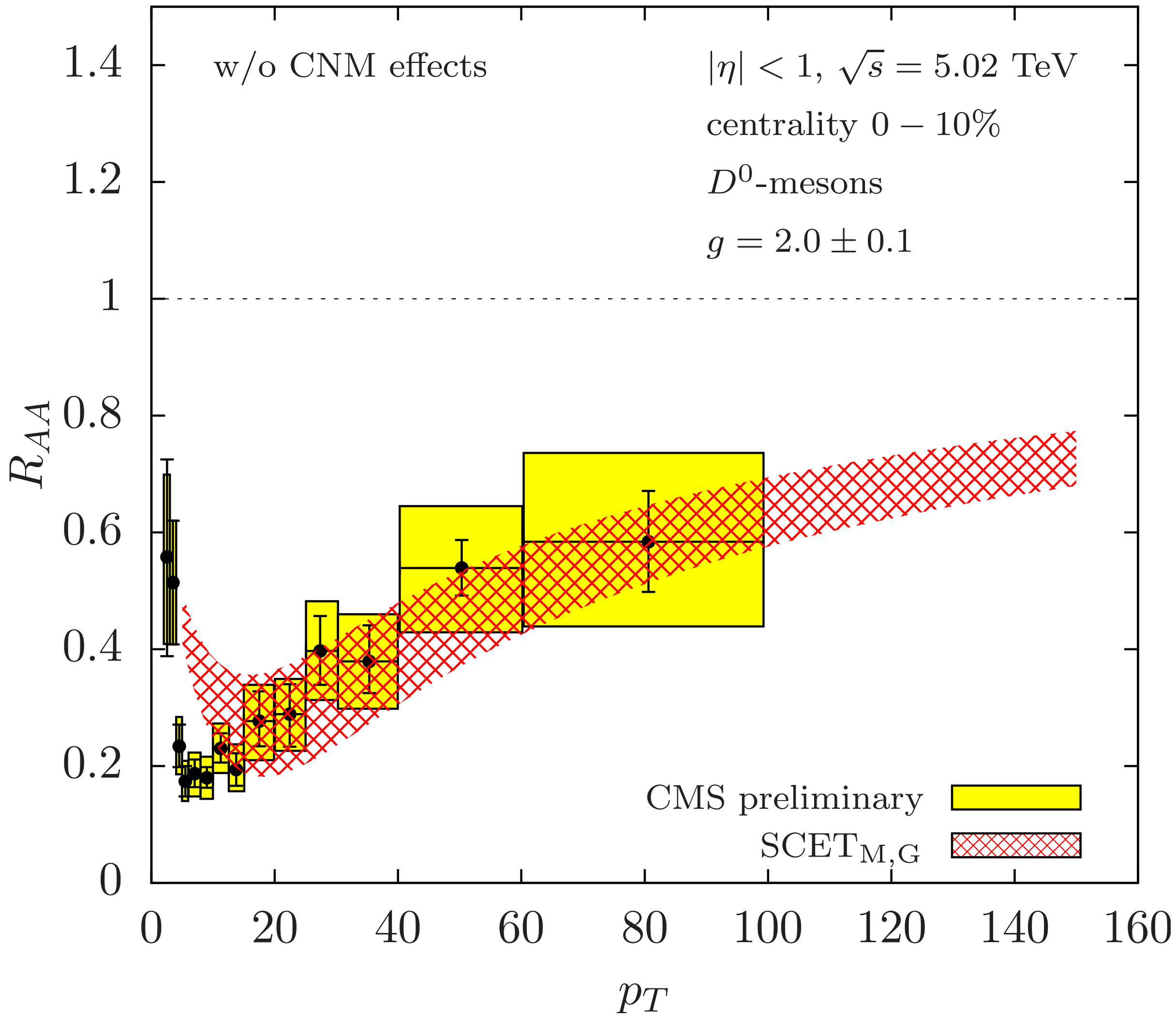


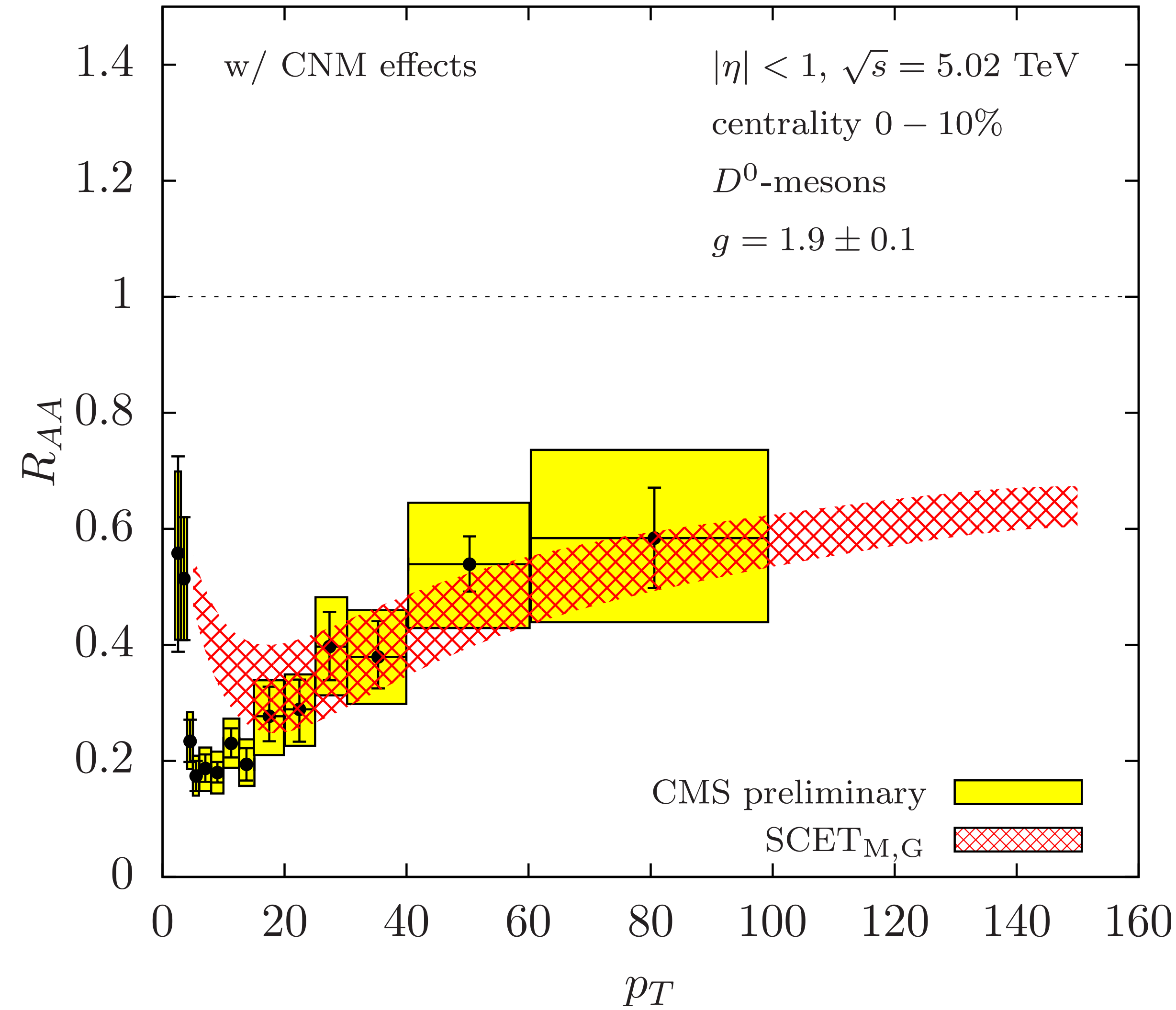
CNM here: Cold nuclear matter energy loss, Cronin and isospin effects

CMS-PAS-HIN-12-014

Comparison to LHC data

D-mesons





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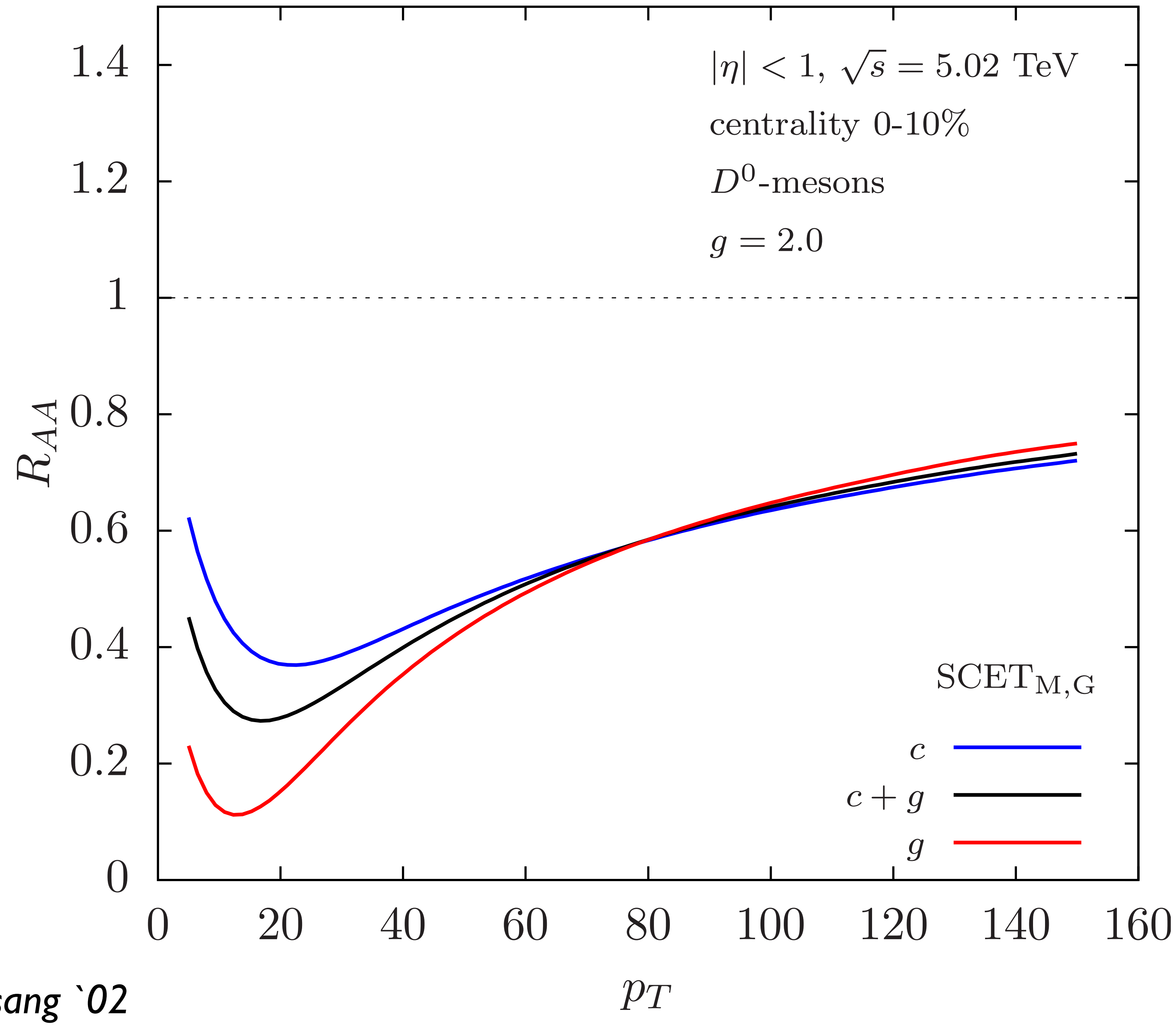
D-meson R_{AA}

Heavy quark-gluon suppression



Jäger, Stratmann, Vogelsang `02

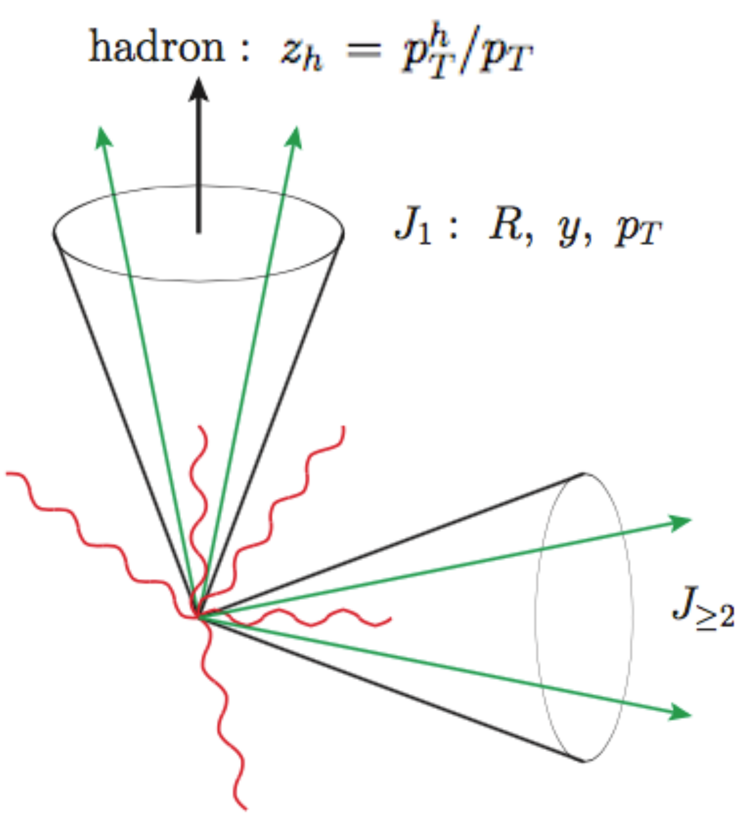
ZMVFS *Kneesch, Kniehl, Kramer, Schienbein - '08*
Kniehl, Kramer, Schienbein, Spiesberger - '08

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

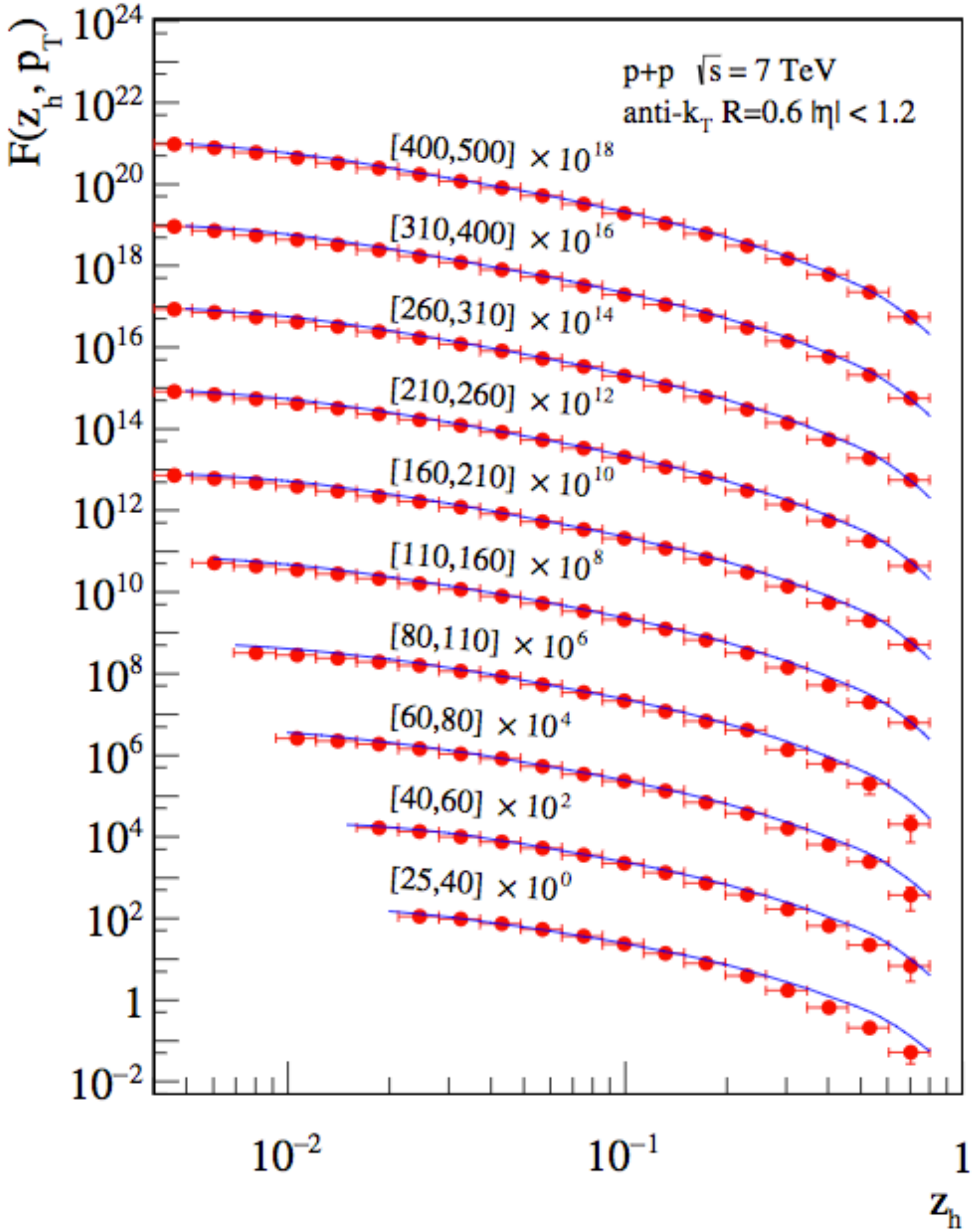
Chien, Kang, FR, Vitev, Xing `15
Kang, FR, Vitev `16, `16

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

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. $\text{NLO} + \text{NLL}_R$



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

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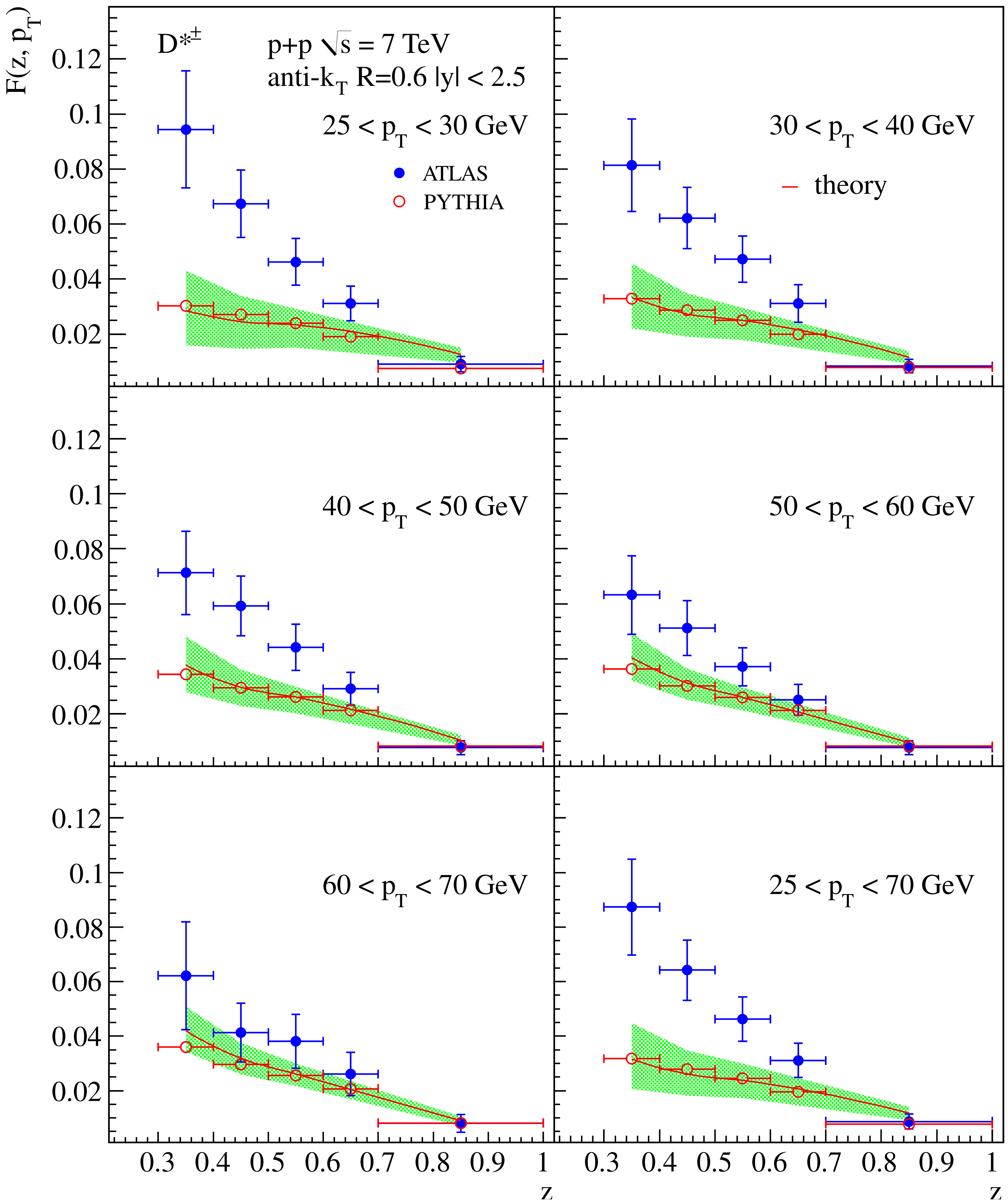

Chien, Kang, FR, Vitev, Xing `15

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

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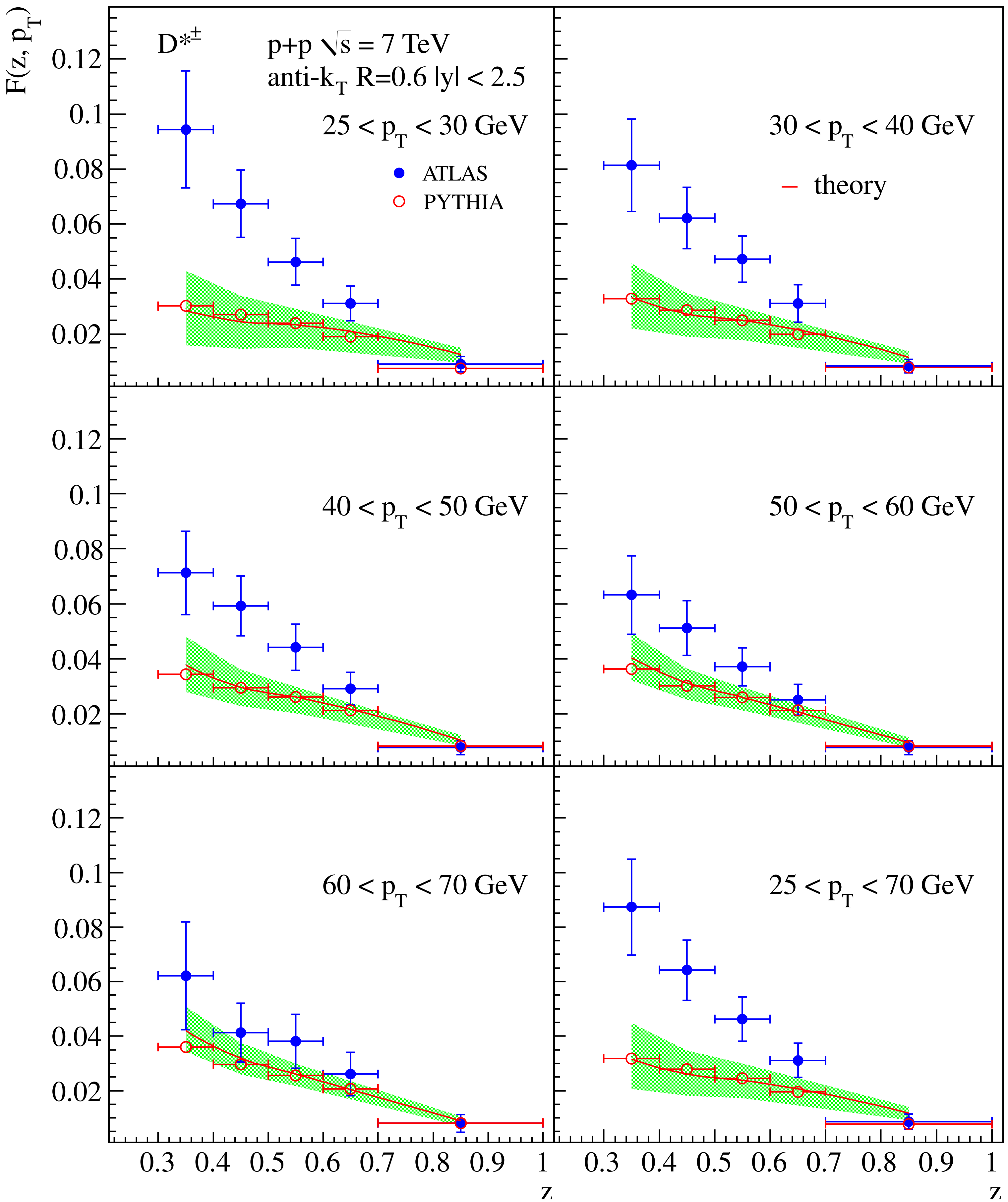


Chien, Kang, FR, Vitev, Xing `15

D-meson
jet fragmentation function

Motivates the need for global fits of heavy meson fragmentation functions!

Outline

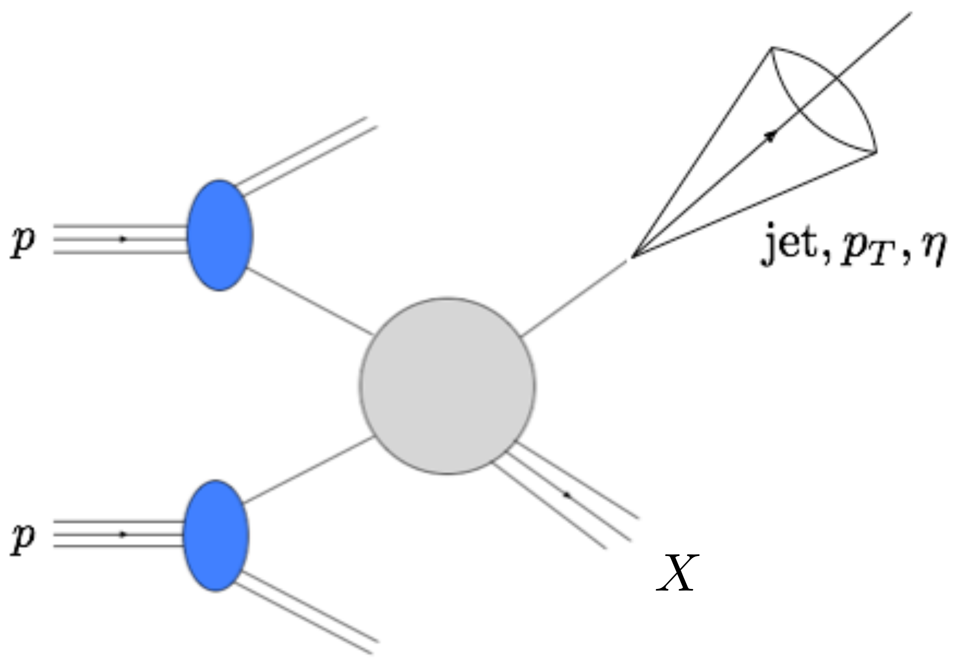
- Open heavy flavor production
- Inclusive jet observables
- Conclusions

Kang, FR, Vitev `16 arXiv:1609.04908
Kang, FR, Vitev `16, `16 arXiv:1606.06732

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

see also:

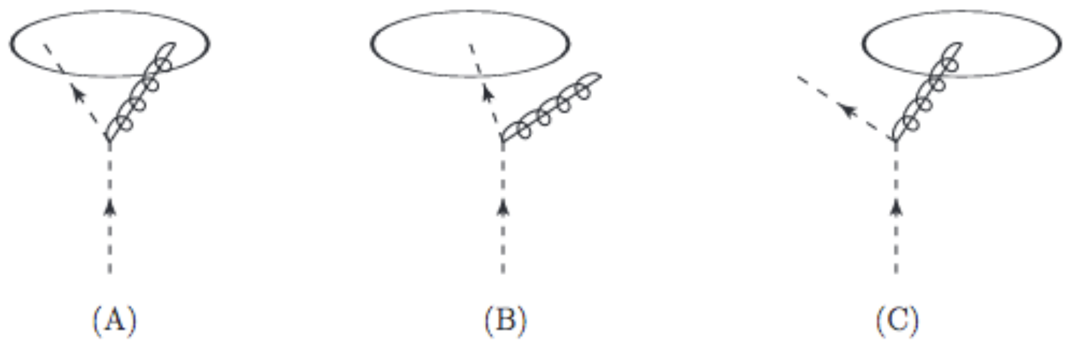
Jäger, Stratmann, Vogelsang `04, Mukherjee, Vogelsang `12, Kaufmann, Mukherjee, Vogelsang `15, Dasgupta, Dreyer, Salam, Soyez `14, `16

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

Kang, FR, Vitev `16, `16

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

Definition similar to FFs
but perturbatively calculable:



Jet cross section at NLO: $d\sigma \sim \mathcal{A}\ln R + \mathcal{B} + \mathcal{O}(R^2)$

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

Kang, FR, Vitev `16, `16

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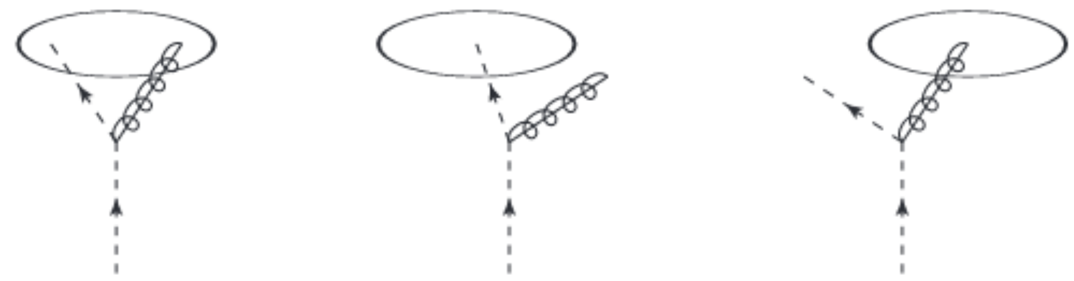

Follows standard timelike DGLAP

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

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

Especially relevant for heavy-ion phenomenology!

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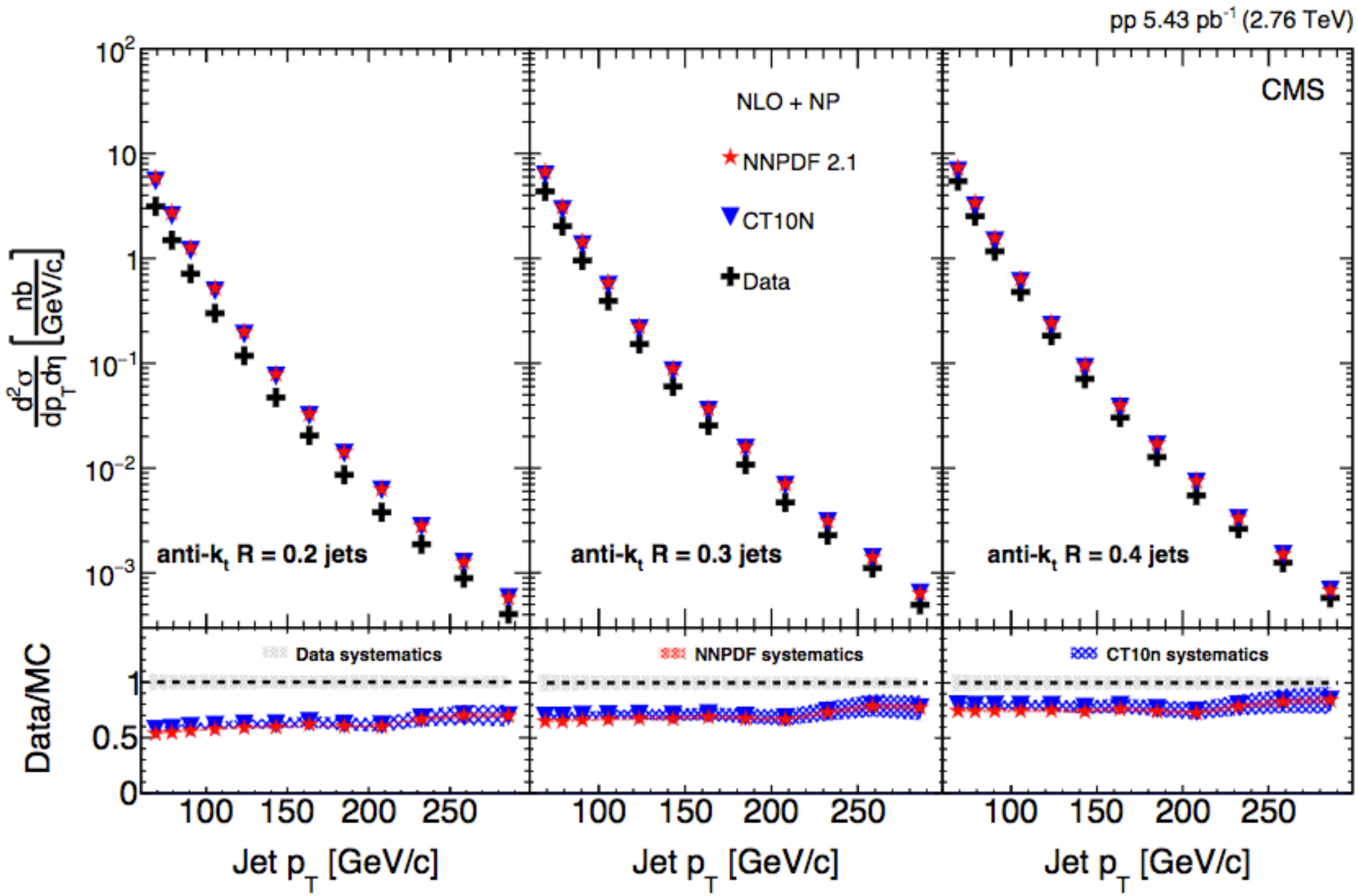
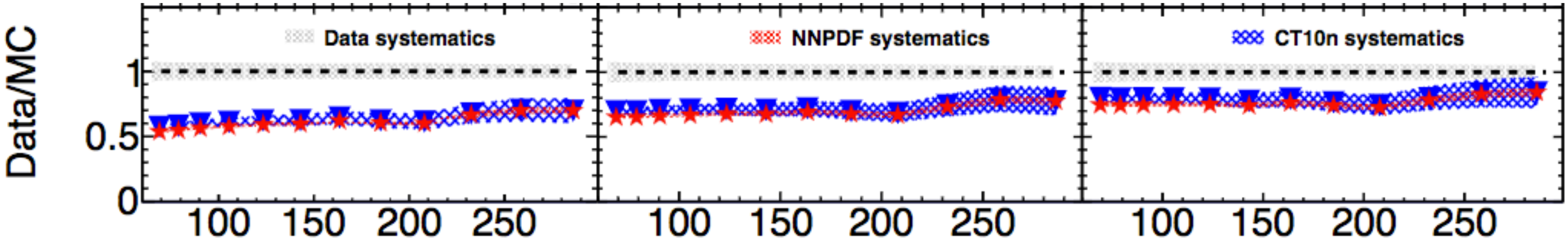
Inclusive Jet Production in SCET $pp \to \text{jet}X$



arXiv:1609.05383

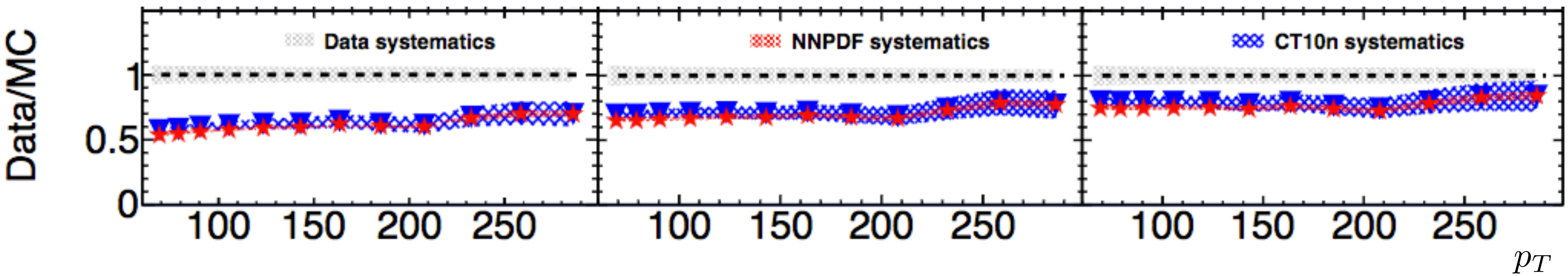
Inclusive Jet Production in SCET $pp \to \text{jet} X$

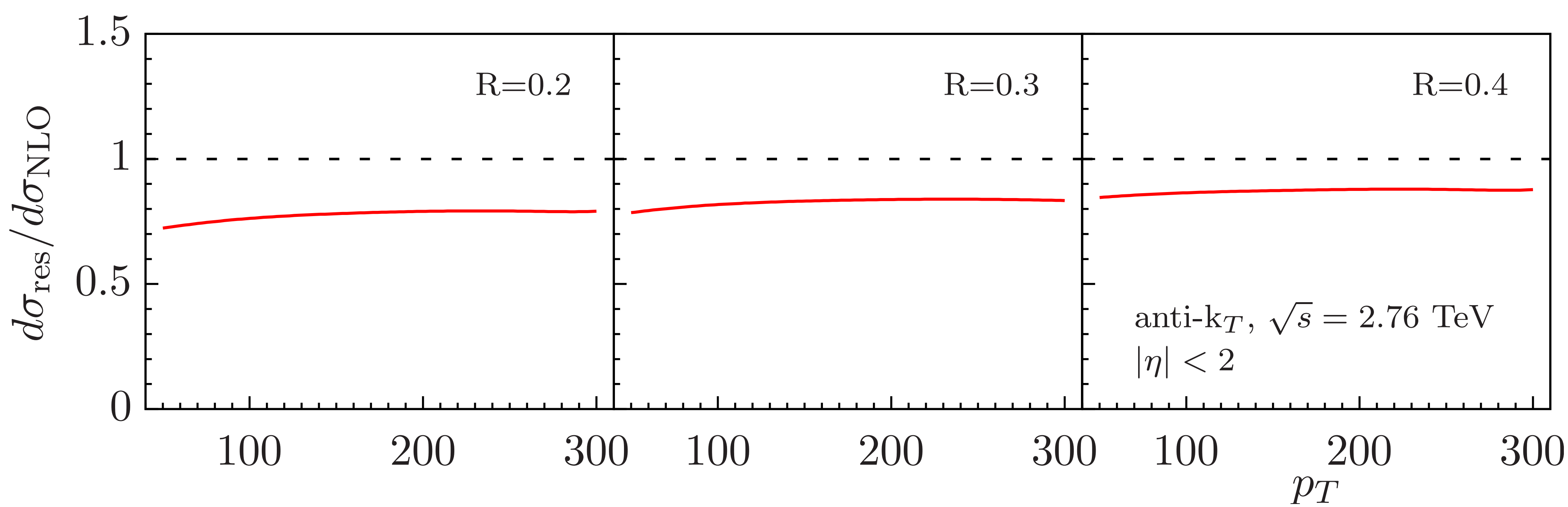


arXiv:1609.05383

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

Kang, FR, Vitev `16, `16





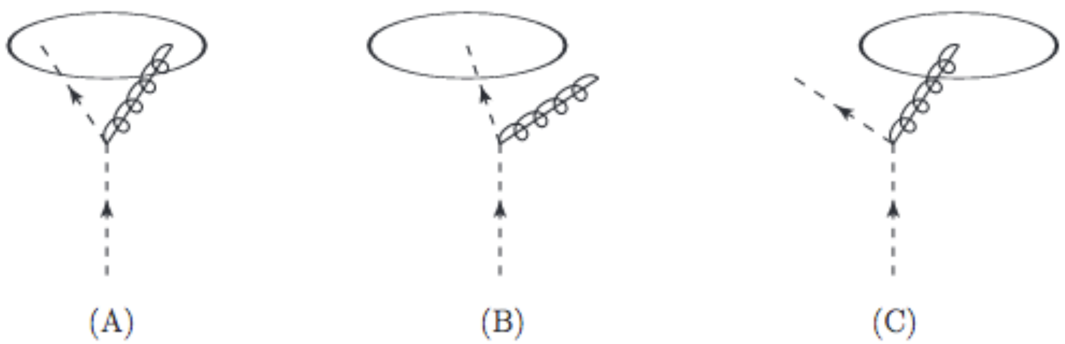
arXiv:1609.05383

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

Kang, FR, Vitev `16, `16

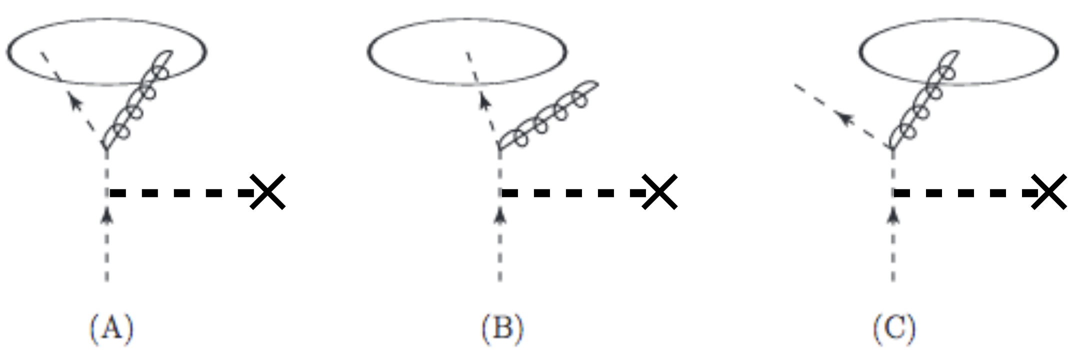
$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \frac{2p_T}{s} \sum_{a,b,c} \int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu) \int_{z_c^{\min}}^1 \frac{dz_c}{z_c^2} \frac{d\hat{\sigma}^c_{ab}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{dvdz} J_c(z_c,\omega_J,\mu)$$

vacuum



$$J_c^{\mathrm{vac}}(z,\omega_J) + J_c^{\mathrm{med}}(z,\omega_J)$$

medium



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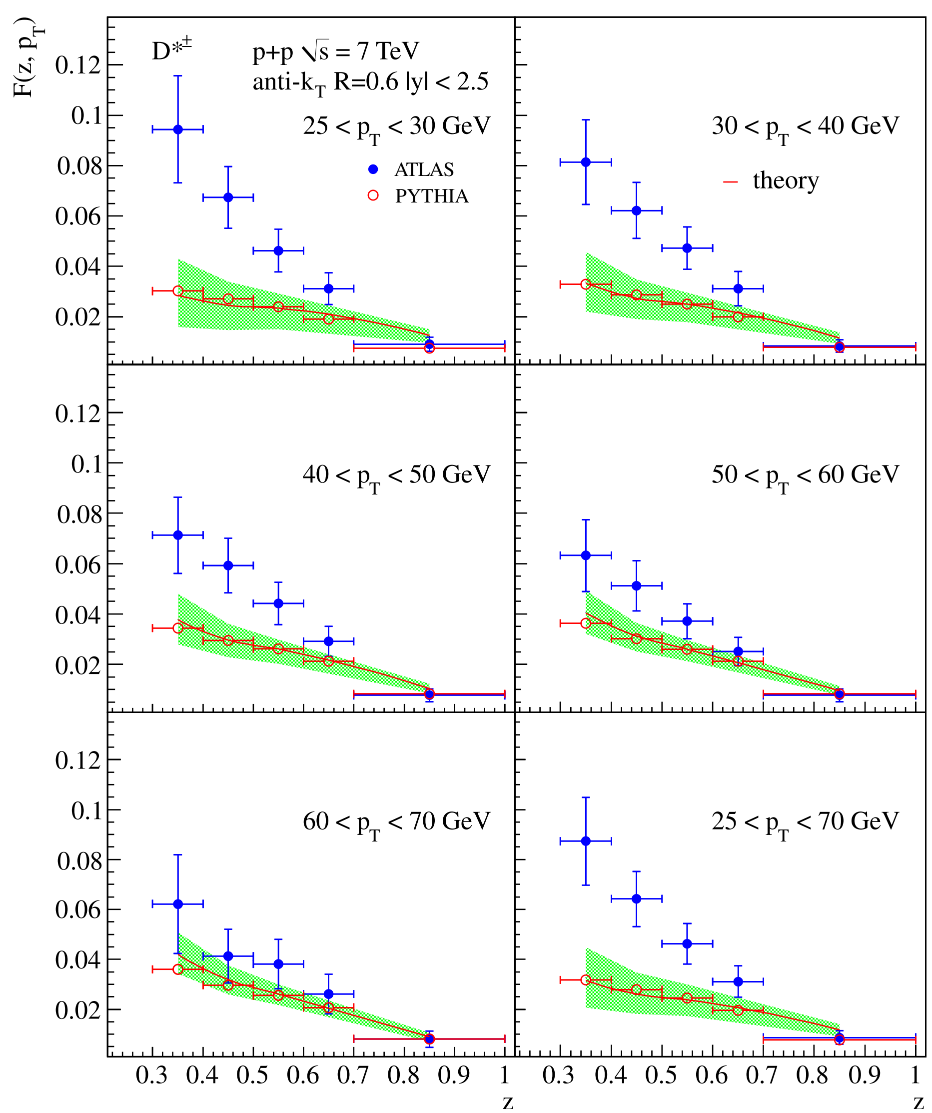
Jet substructure within SCET

e.g. the jet fragmentation function

Kang, FR, Vitev `16, `16
Chien, Kang, FR, Vitev, Xing `15

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

semi-inclusive fragmenting jet function



- More differential probe of the fragmentation process
- study modification in the medium

Outline

- Open heavy flavor production
- Inclusive jet observables
- Conclusions

Kang, FR, Vitev `16 arXiv:1609.04908
Kang, FR, Vitev `16, `16 arXiv:1606.06732

Conclusions

- Soft Collinear Effective Theory is an invaluable tool for heavy-ion physics
- New massive in-medium splitting functions
- Good description of D- and B-meson R_{AA}
- Results motivate global fits of heavy meson FFs
- $\ln R$ resummation for inclusive jet spectra
- Consistent treatment at NLO in QCD for inclusive hadron and jet observables

… please stay tuned!

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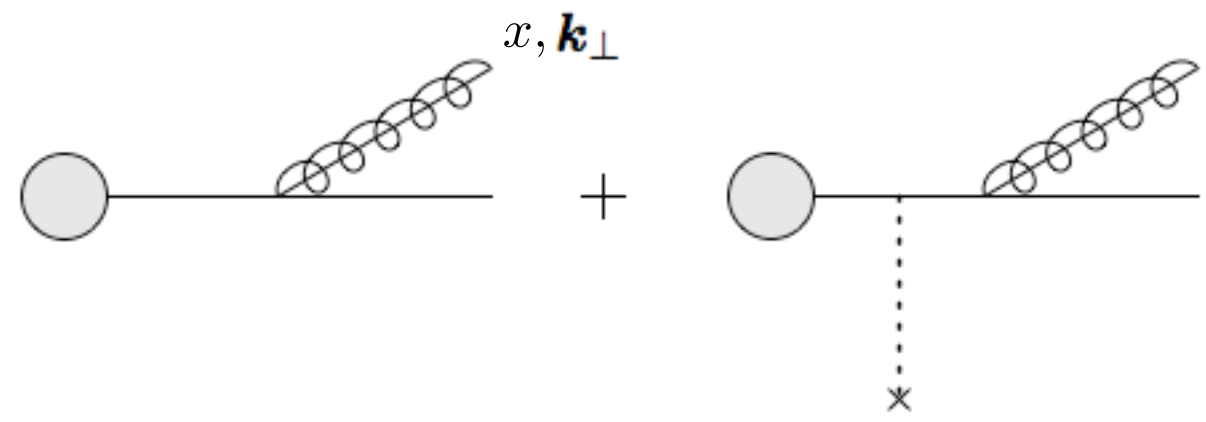
SCET$_{\mathrm{M,\,G}}$ splitting kernels

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



Final state - massive

- medium: Soft gluon approximation

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

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

Numerical results