Jet substructure observables involving hadrons and subjets

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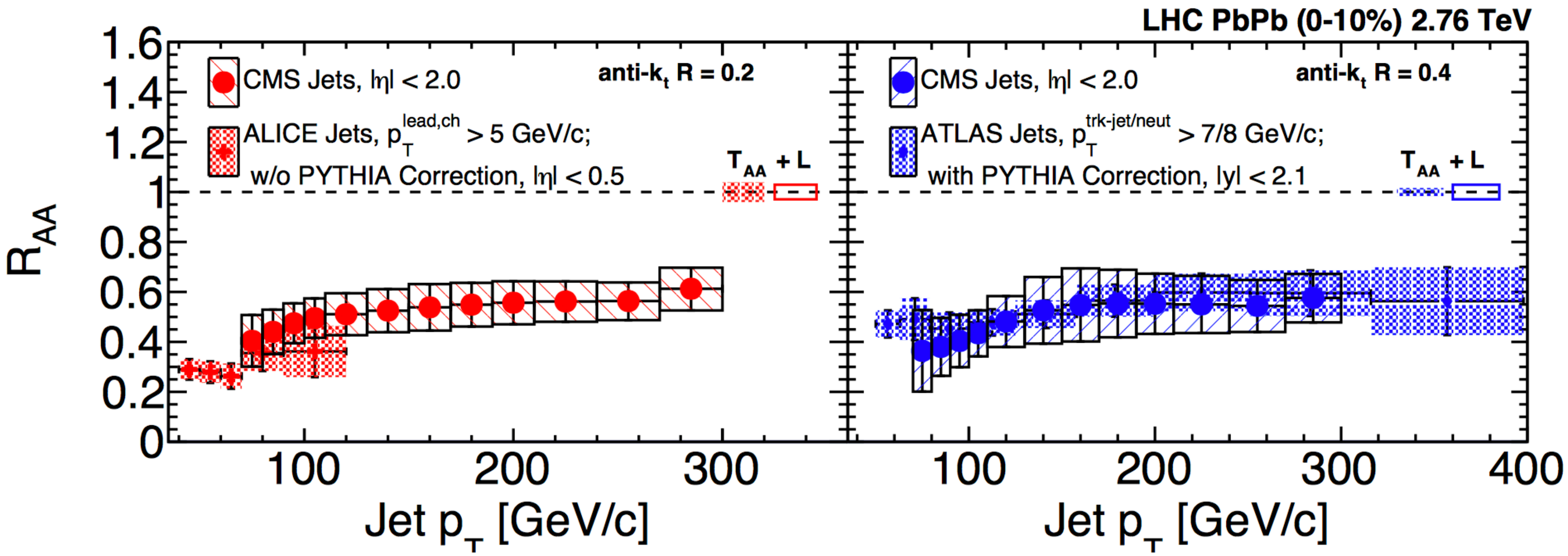
CCNU, Wuhan, 06/09/18



Inclusive jet production

$pp \to \text{jet} + X$

CMS, PRC 015202 (2017)

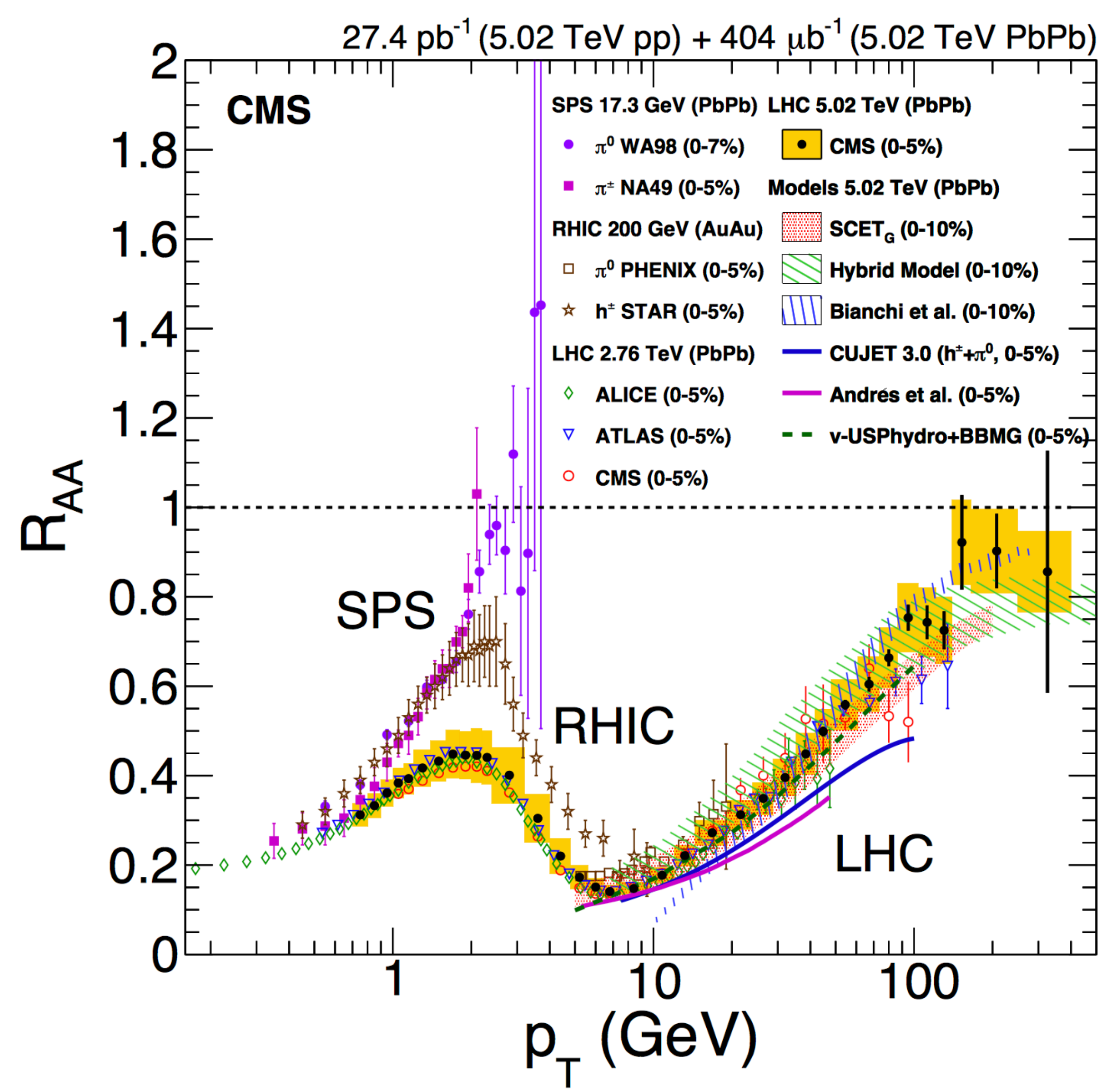
Nuclear modification factor

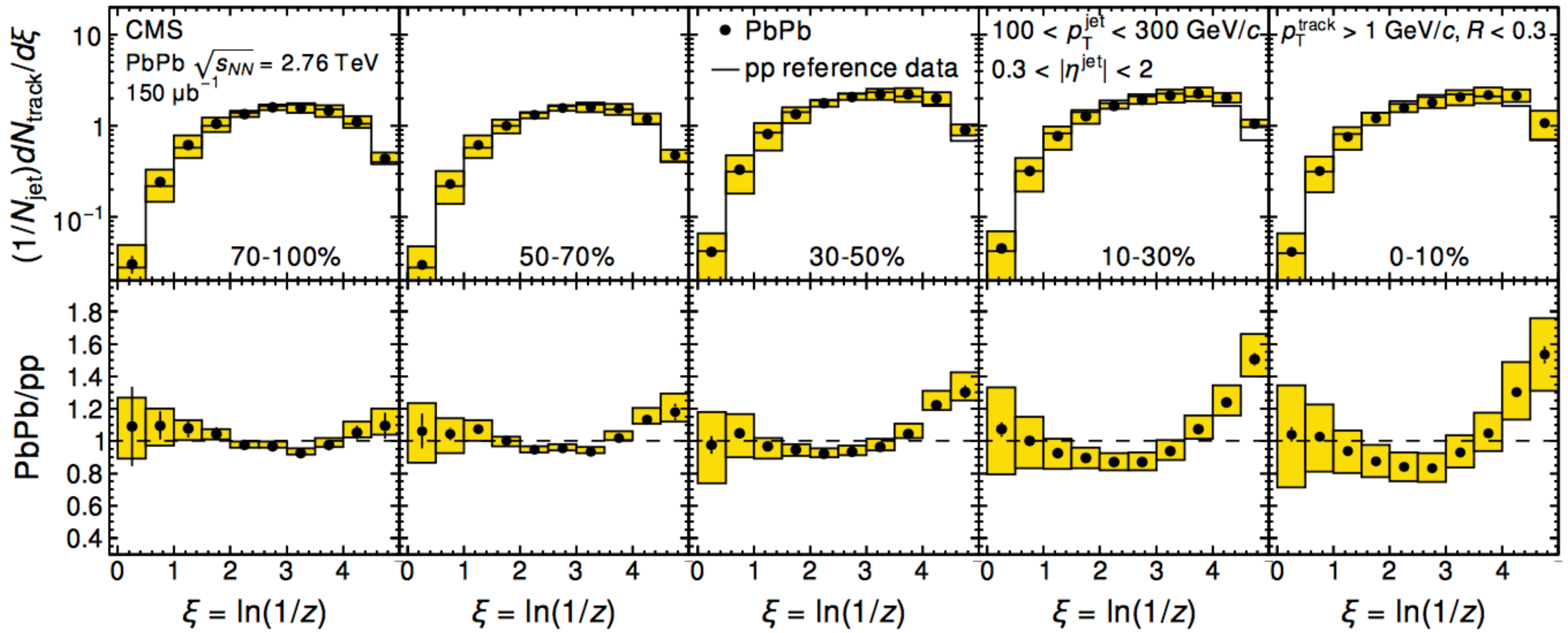
$$R_{AA} = \frac{d\sigma_{\text{PbPb}}/d\eta dp_T}{\langle N_{\text{bin}}\rangle\, d\sigma_{pp}/d\eta dp_T}$$

Inclusive hadron production

$pp \to h + X$

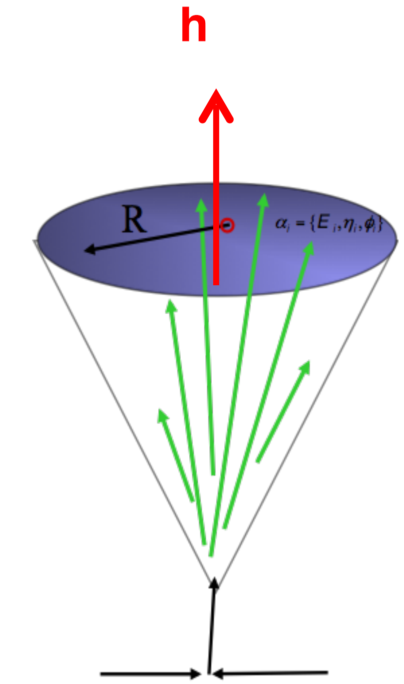
e.g. CMS, JHEP 04 (2017) 039

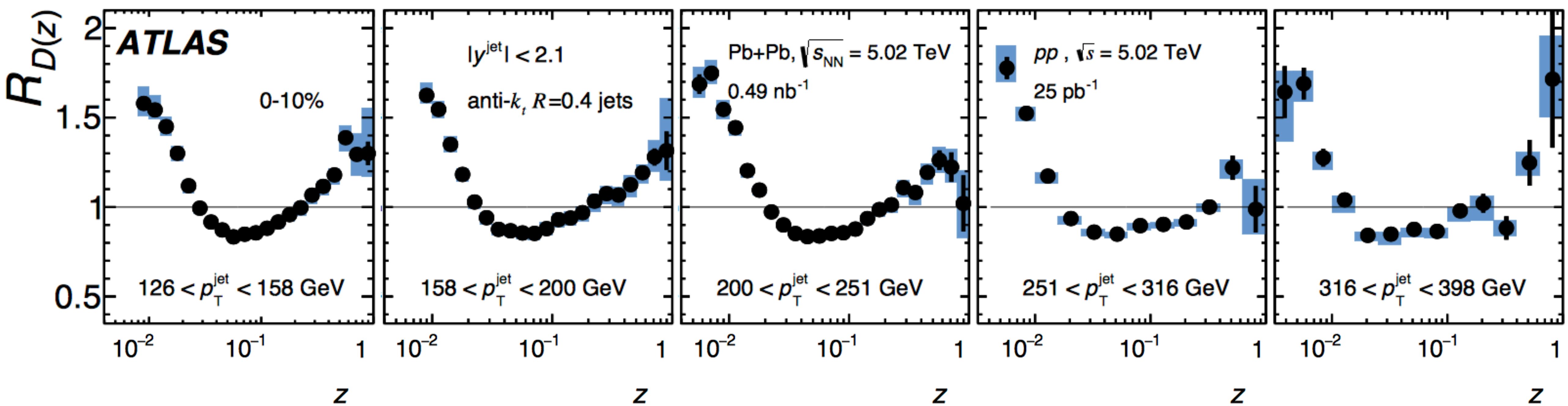




CMS, Phys. Rev. C 90 (2014) 024908

In-jet fragmentation of hadrons





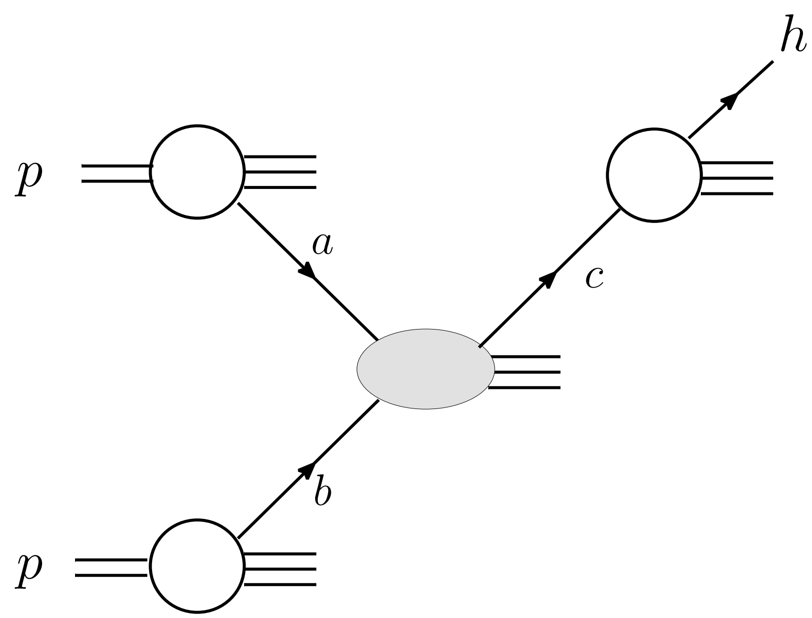
ATLAS, arXiv:1805.05424

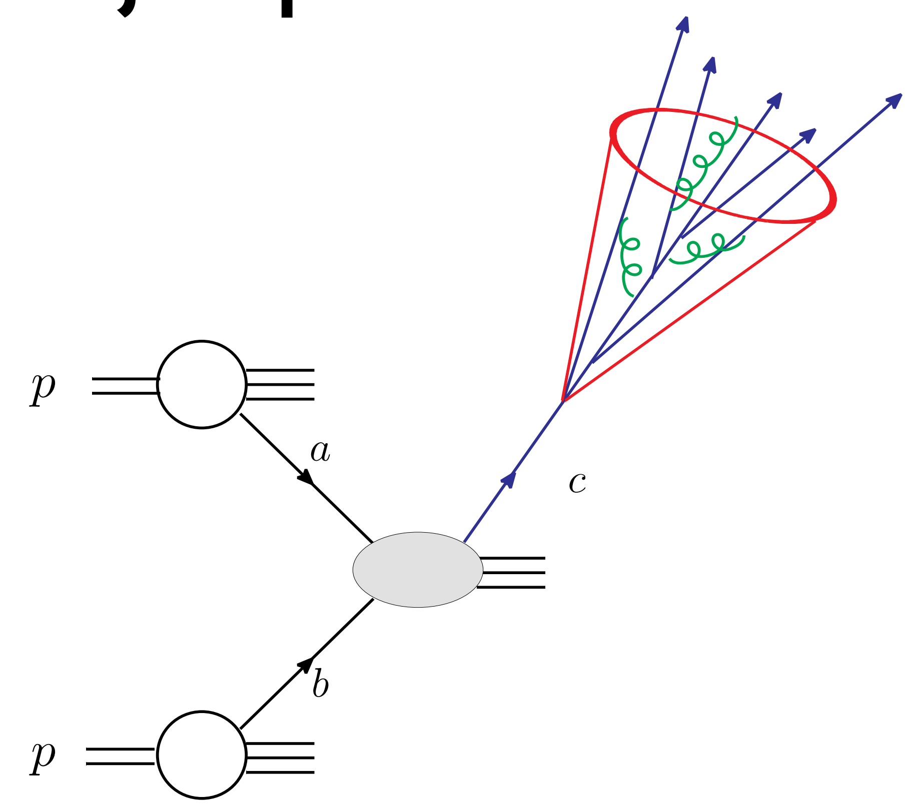
Requires a consistent description within collinear factorization (and SCET$_G$)

Outline

- Collinear factorization in pp collisions
- Jets and their substructure in AA collisions
- Inclusive subjets
- Conclusions

Factorization for hadron and jet production





Factorization

Hadron

$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes \boxed{D^h_c}$$

Jet

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes \boxed{J_c} + \mathcal{O}(R^2)$$

Jet functions

Evolution

$$\mu\frac{d}{d\mu}D^h_i = \sum_j P_{ji} \otimes D^h_j$$

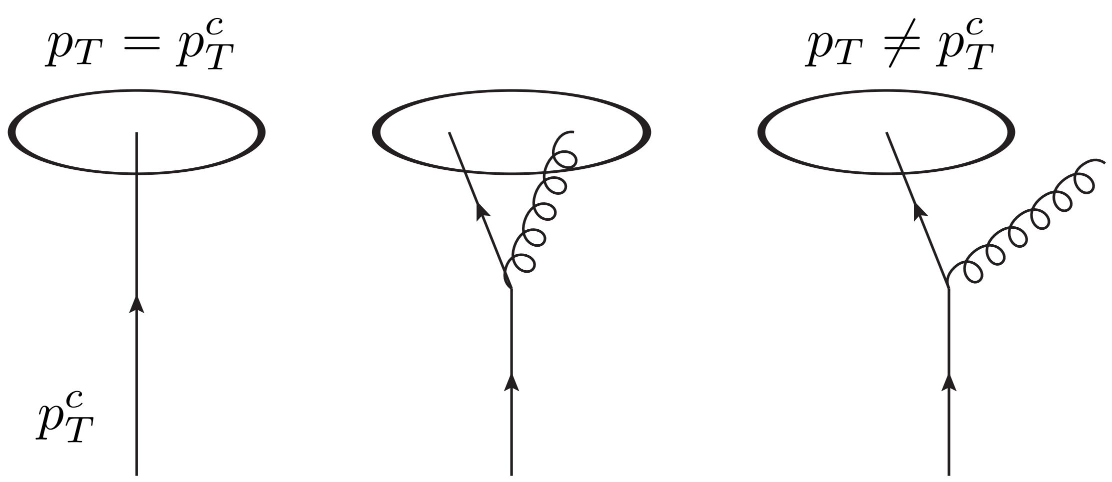
$$\mu\frac{d}{d\mu}J_i = \sum_j P_{ji} \otimes J_j$$

Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16

The semi-inclusive jet function

Kang, FR, Vitev `16

- The siJF $J_c(z, p_T R, \mu)$ describes how a parton is transformed into a jet with radius R and carrying an energy fraction z



where $\boxed{z = p_T / p_T^c}$

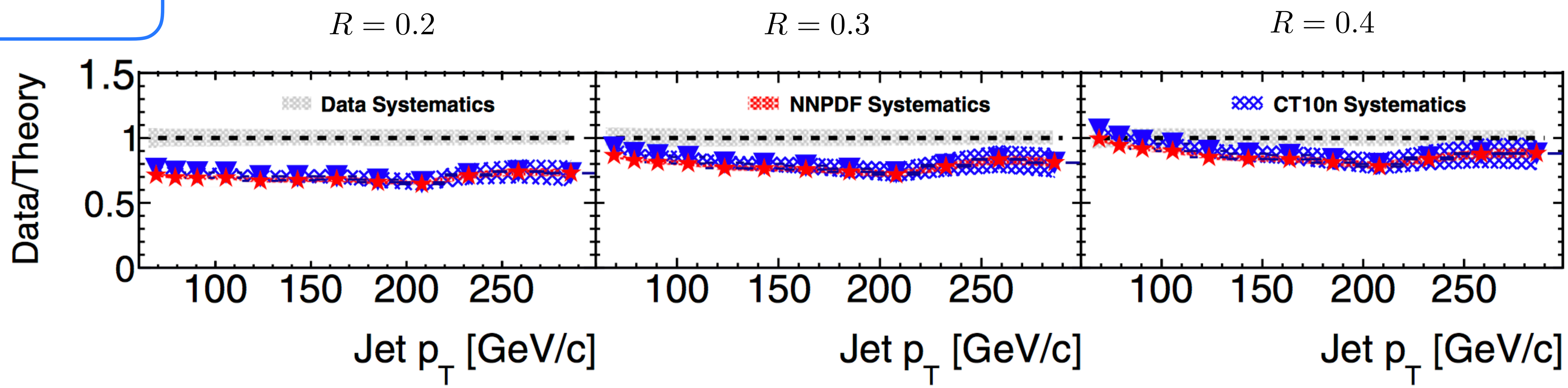
$$\int_0^1 dz\, z J_i(z, \omega R, \mu) = 1$$

- NLO result

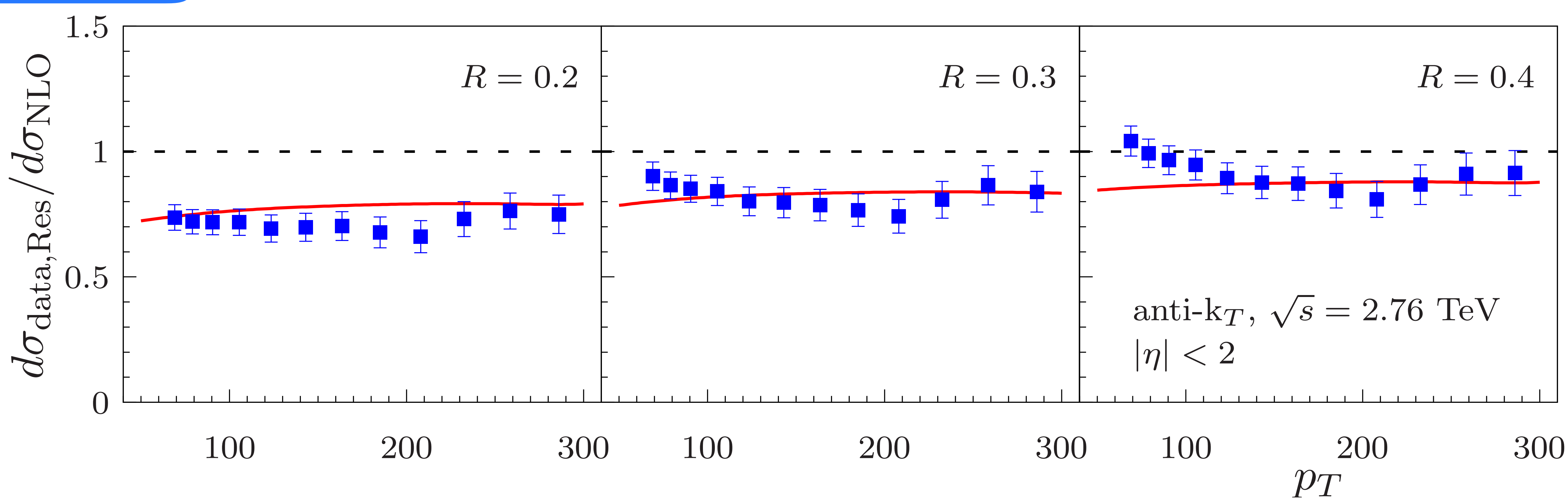
$$J_q^{(1)}(z, p_T R, \mu) = \frac{\alpha_s}{2\pi} \boxed{\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{p_T^2 R^2}\right)\right)} [P_{qq}(z) + P_{gq}(z)]$$
$$- \frac{\alpha_s}{2\pi}\left\{ C_F \left[2\left(1+z^2\right)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right] - \delta(1-z) d_J^{q,\mathrm{alg}}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

Comparison to LHC data

$$\sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}$$

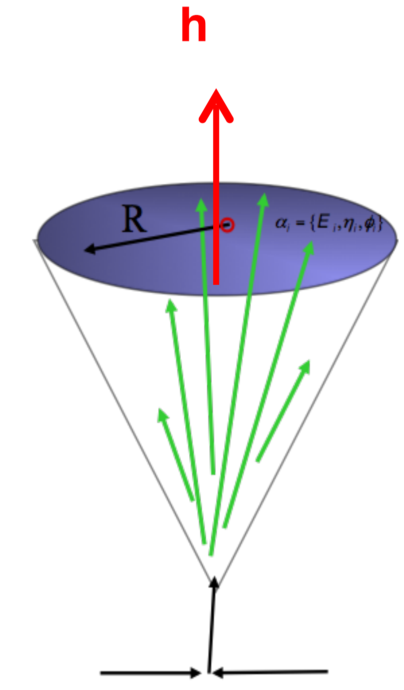


$$\sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c$$



Kang, FR, Vitev `16

The jet fragmentation function

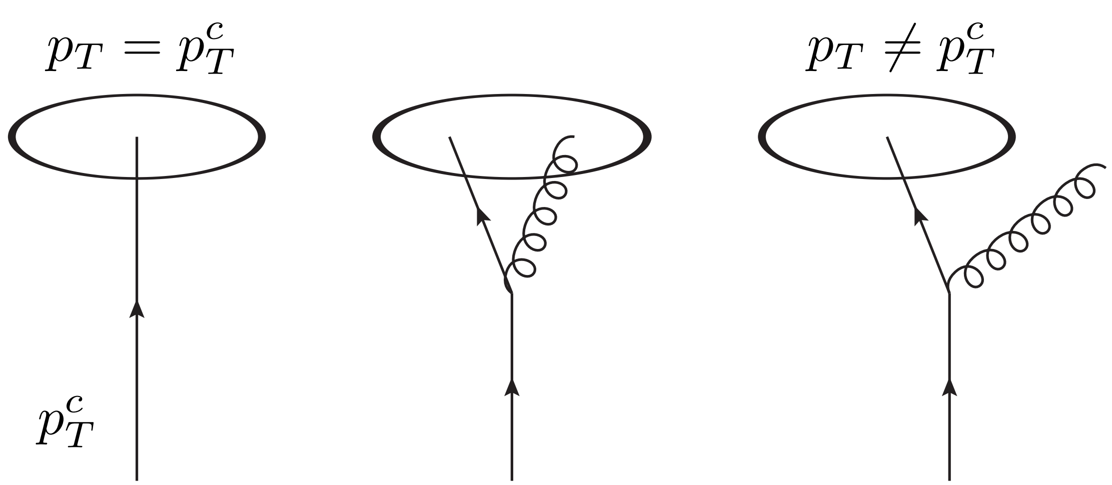


- First reconstruct a jet and then identify the hadrons inside the jet

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

$$J_i(z, p_T R, \mu) \longrightarrow \mathcal{G}_q^h(z, z_h, p_T R, \mu) = \sum_j \mathcal{J}_{ij}(z, z_h, p_T R, \mu) \otimes D_j^h(z_h, \mu)$$

matching coefficients | standard collinear FFs



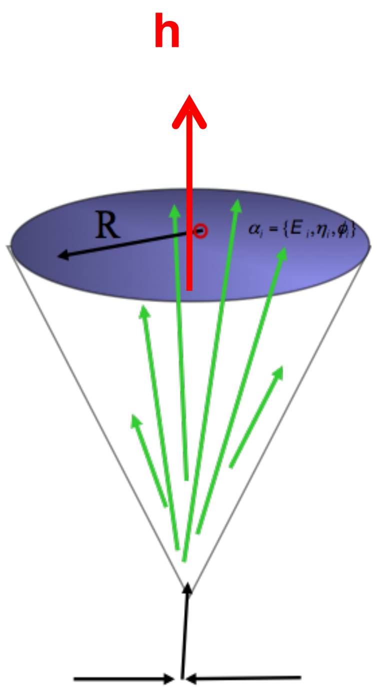
Two step process

$$z = p_T/p_T^c$$

$$z_h = p_T^h/p_T$$

Procura, Stewart `10, Liu `11, Arleo, Fontannaz, Guillet, Nguyen `14, Kaufmann, Mukherjee, Vogelsang `15, Kang, FR, Vitev `16, …

The jet fragmentation function



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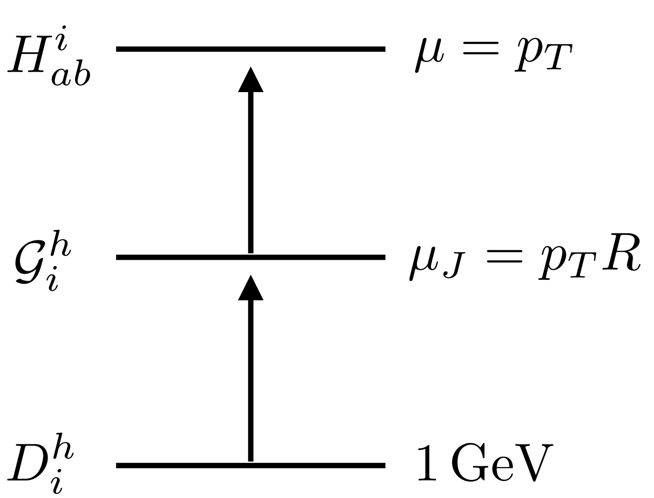
$$J_i(z, p_T R, \mu) \quad \longrightarrow \quad \mathcal{G}_q^h(z, z_h, p_T R, \mu) = \sum_j \mathcal{J}_{ij}(z, z_h, p_T R, \mu) \otimes D_j^h(z_h, \mu)$$

matching coefficients

standard collinear FFs

- $\alpha_s^n \ln^n R$ resummation again via DGLAP

$$\mu \frac{d}{d\mu} \mathcal{G}_i^h(z, z_h, p_T R, \mu) = \sum_j P_{ji}(z) \otimes \mathcal{G}_j^h(z, z_h, p_T R, \mu)$$



2x DGLAP

Procura, Stewart `10, Liu `11, Arleo, Fontannaz, Guillet, Nguyen `14, Kaufmann, Mukherjee, Vogelsang `15, Kang, FR, Vitev `16, …

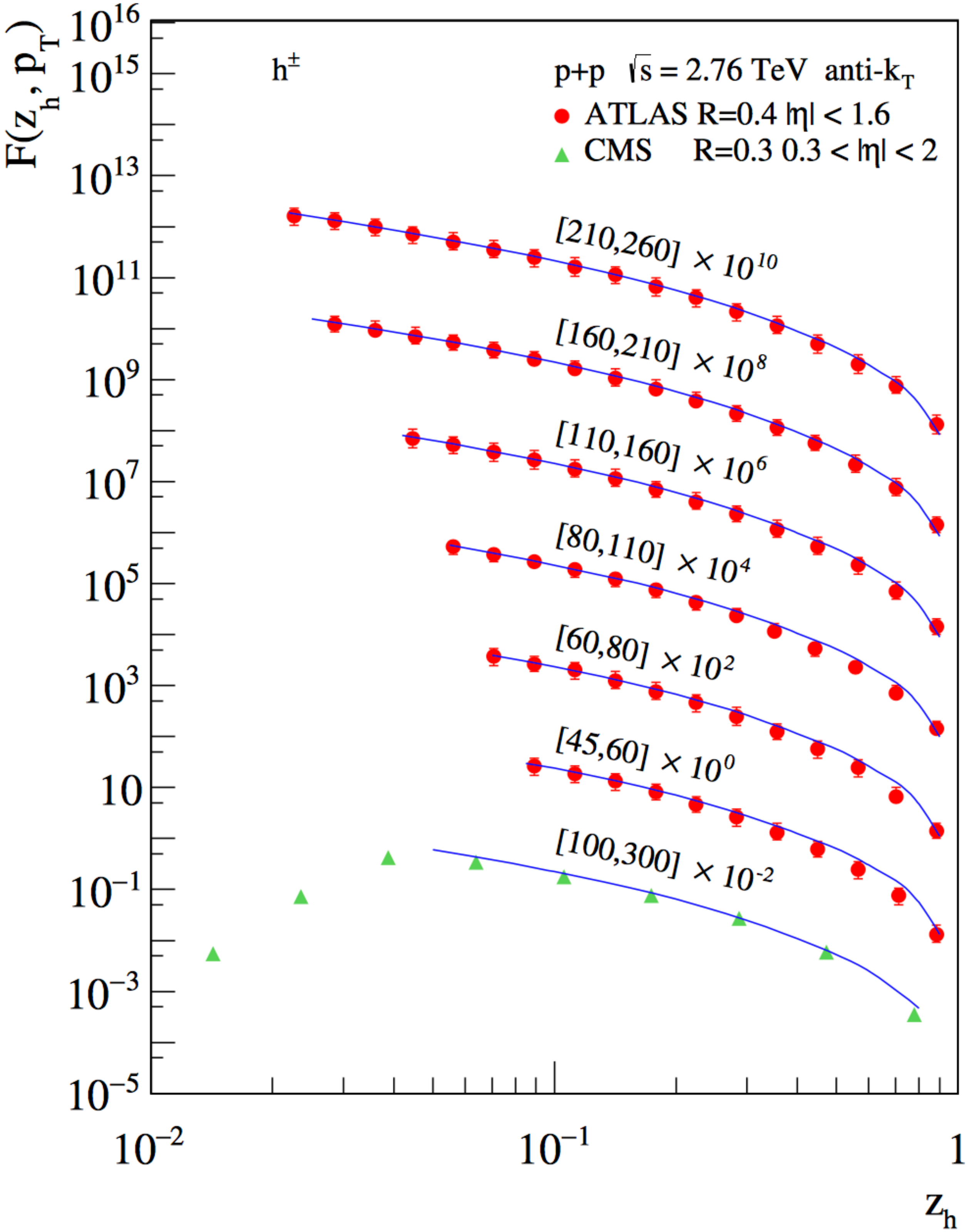
Comparison to LHC data

- Light charged hadrons
  Arleo, Fontannaz, Guillet, Nguyen `14
  Kaufmann, Mukherjee, Vogelsang `15
  Kang, FR, Vitev `16
  Neill, Scimemi, Waalewijn `16

- Heavy flavor mesons
  Chien, Kang, FR, Vitev, Xing `15
  Bain, Dai, Hornig, Leibovich, Makris, Mehen `16
  Anderle, Kaufmann, Stratmann, FR, Vitev `17

- Quarkonia
  Baumgart, Leibovich, Mehen, Rothstein `14
  Bain, Dai, Hornig, Leibovich, Makris, Mehen `16
  Kang, Qiu, FR, Xing, Zhang `17
  Bain, Dai, Leibovich, Makris, Mehen `17

- Photons
  Kaufmann, Mukherjee, Vogelsang `16



Kang, FR, Vitev `16

Comparison to LHC data

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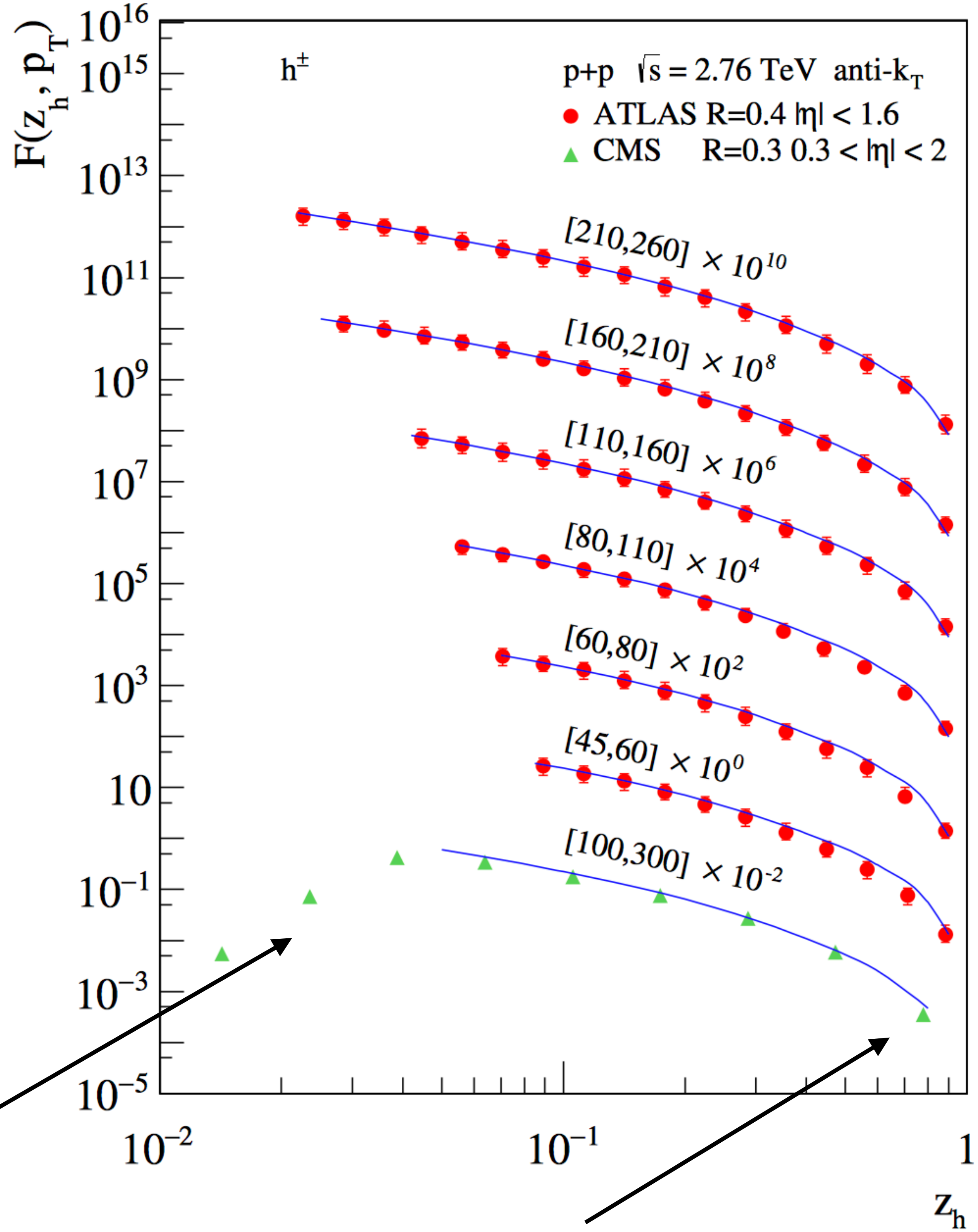


Requires endpoint resummation:
small-z and threshold

Anderle, Kaufmann, FR, Stratmann `17

Kang, FR, Vitev `16

Outline

- Proton-proton baseline
- Jets and their substructure in heavy-ion collisions
- Inclusive subjets
- Conclusions

SCET$_G$

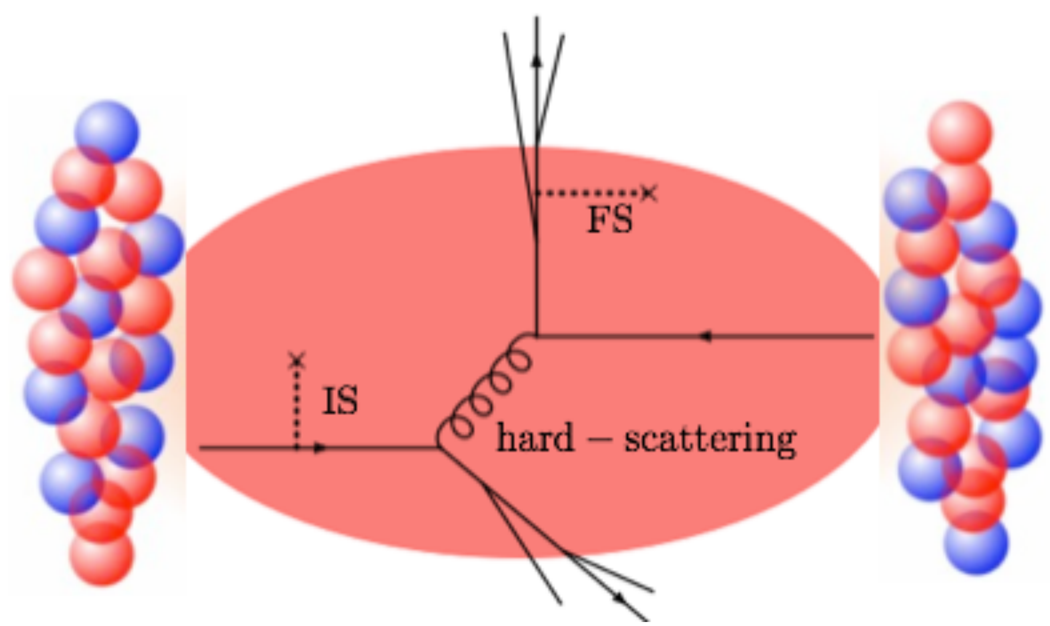
Idilbi, Majumder `08, D'Eramo, Liu, Rajagopal `10
Ovanesyan, Vitev `12, Kang, FR, Vitev `16

- Soft Collinear Effective Theory with Glauber gluons
- An effective field theory approach to jet propagation in dense QCD matter

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

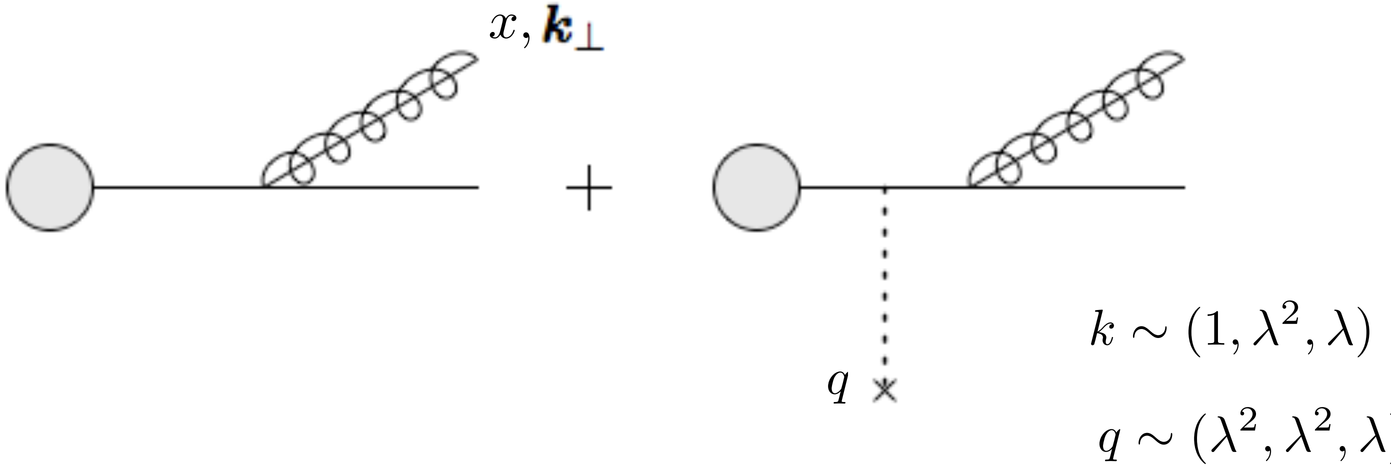
- Include medium interaction via Glauber gluon exchange
- Derive Feynman rules and collinear in-medium splitting functions
- Related to the GLV approach to parton energy loss

Gyulassy, Levai, Vitev `00



SCET$_G$ splitting functions

- Basic ingredients for jet calculations



- Collinear in-medium splitting function

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

where:

$$\boldsymbol{A}_\perp=\boldsymbol{k}_\perp,\ \boldsymbol{B}_\perp=\boldsymbol{k}_\perp+x\boldsymbol{q}_\perp,\ \ldots$$

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

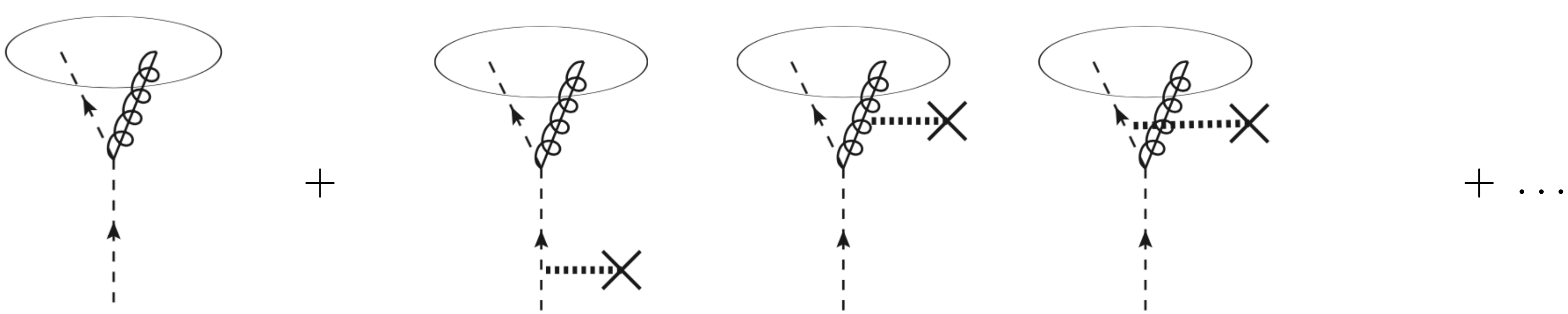
- Vacuum analogue

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

Ovanesyan, Vitev `12, Kang, FR, Vitev `16

Jet production in heavy-ion collisions

- Assume that collinear factorization holds (approximately) in pp and AA
  - Establish phenomenologically
  - Require universality
- Jet functions can be written in terms of collinear splitting functions
- Include vacuum and in-medium terms



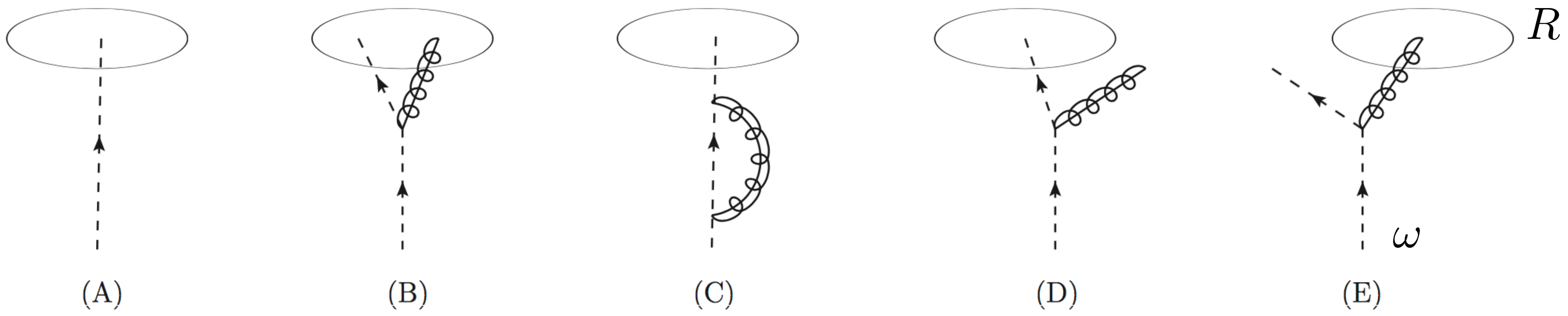
e.g. single medium exchange

$$P_{ji}^{\mathrm{med}}(z, q_\perp) = P_{ji}(z, q_\perp)\, f_{ji}(z, q_\perp; \beta)$$

Kang, FR, Vitev `17

Jet production in heavy-ion collisions

- Jet functions can be written in terms of collinear splitting functions $pp \to \text{jet} + X$



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

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

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

Kang, FR, Vitev `17

Jet production in heavy-ion collisions

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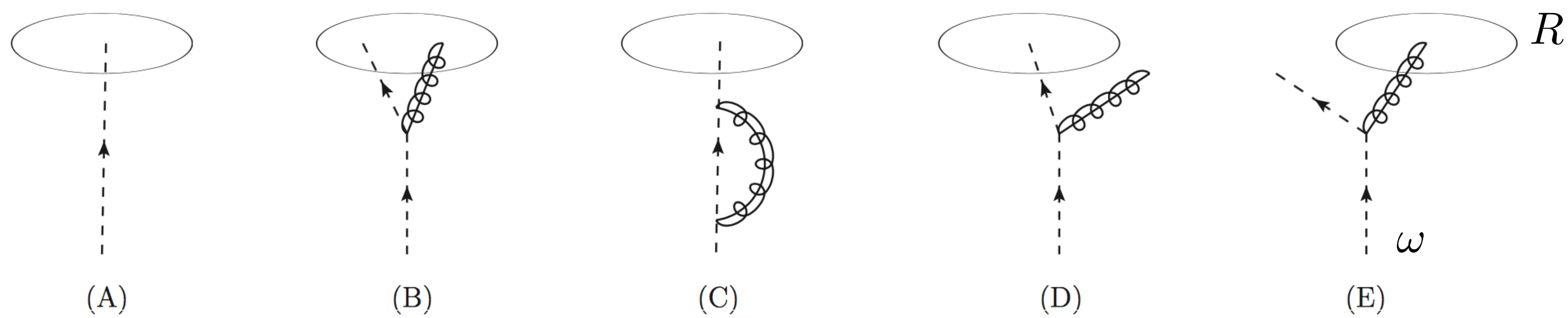


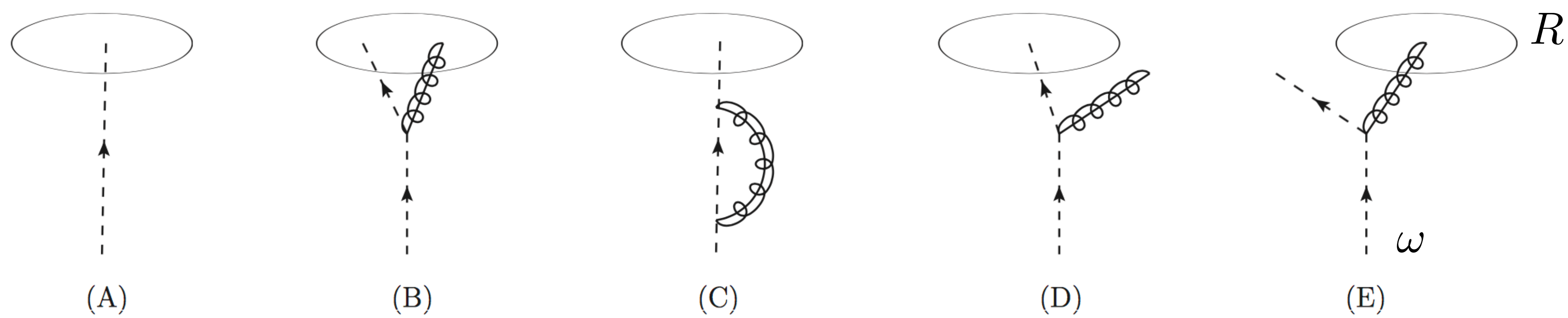
$$(\mathrm{B}) + (\mathrm{C}) = -\,\delta(1-z)\int_0^1 dx \int_{x(1-x)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(x, q_\perp)$$

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

Kang, FR, Vitev `17

Jet production in heavy-ion collisions

- Jet functions can be written in terms of collinear splitting functions $pp \to \text{jet} + X$



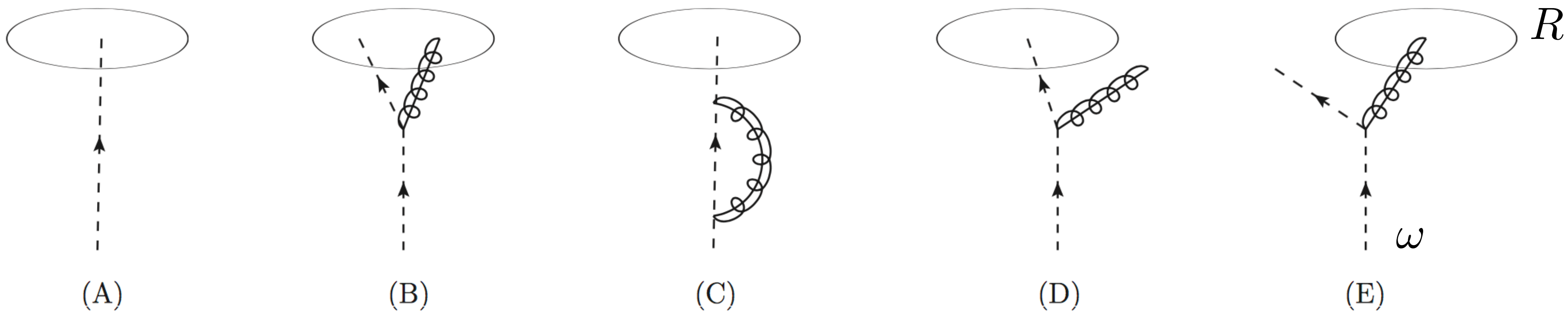
$$(\mathrm{B}) + (\mathrm{C}) + (\mathrm{D}) = \left[\int_{z(1-z)\omega \tan(R/2)}^{\mu} dq_\perp P_{qq}(z, q_\perp) \right]_+$$

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

Kang, FR, Vitev `17

Jet production in heavy-ion collisions

- Jet functions can be written in terms of collinear splitting functions $pp \to \text{jet} + X$



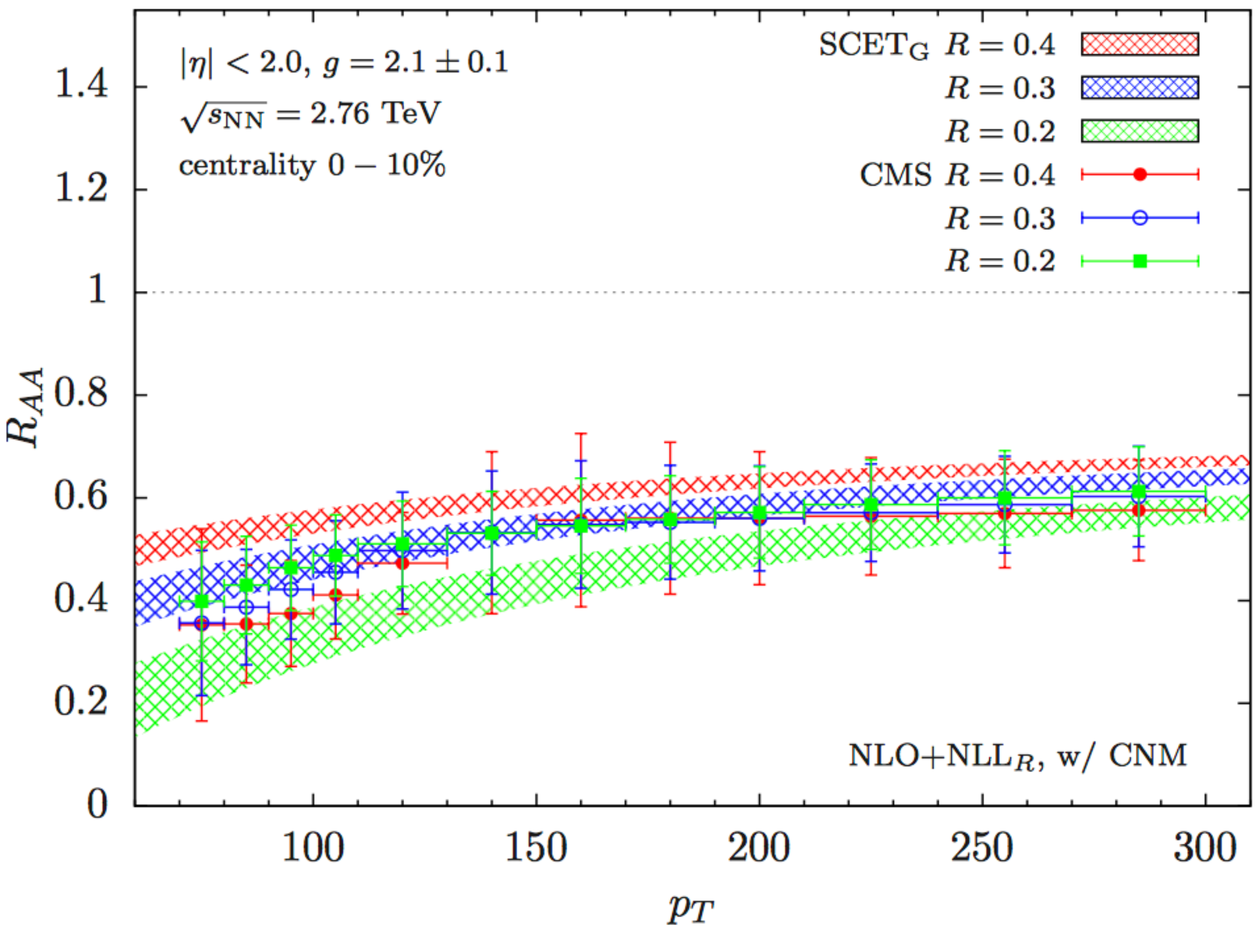
$$(\mathrm{B}) + (\mathrm{C}) + (\mathrm{D}) = \left[\int_{z(1-z)\omega \tan(R/2)}^{\mu} dq_\perp P_{qq}(z, q_\perp) \right]_+$$

⟶ Integrable and can be evaluated numerically $d\sigma_{\mathrm{PbPb}}^{\mathrm{jet,med}} = \sum_{i=q,\bar{q},g} \sigma_i^{(0)} \otimes J_i^{\mathrm{med}}$

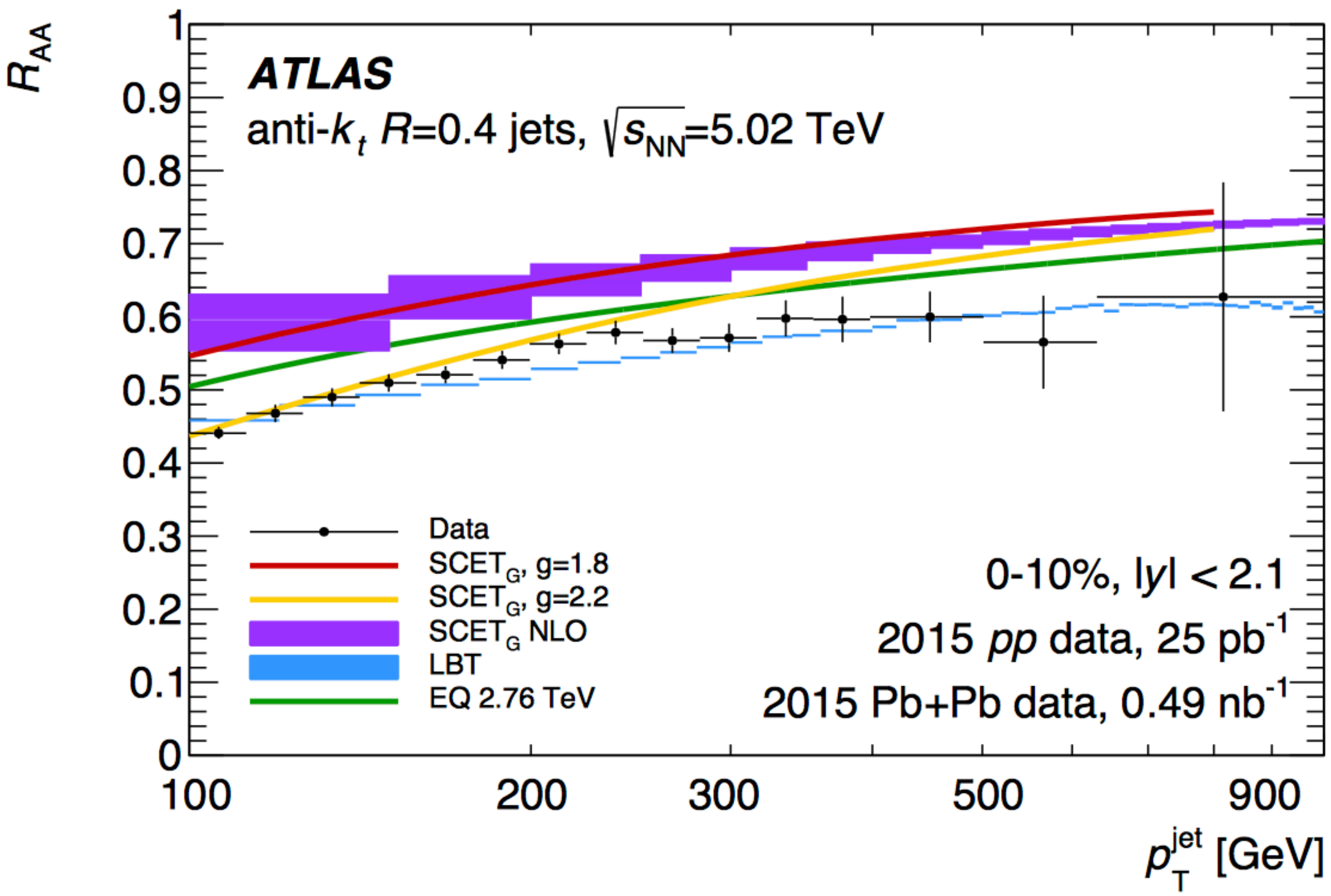
⟶ $d\sigma_{\mathrm{PbPb}}^{\mathrm{jet}} = d\sigma_{pp}^{\mathrm{jet,vac}} + d\sigma_{\mathrm{PbPb}}^{\mathrm{jet,med}}$

Kang, FR, Vitev `17

Jet production in AA



CMS, PRC 015202 (2017)

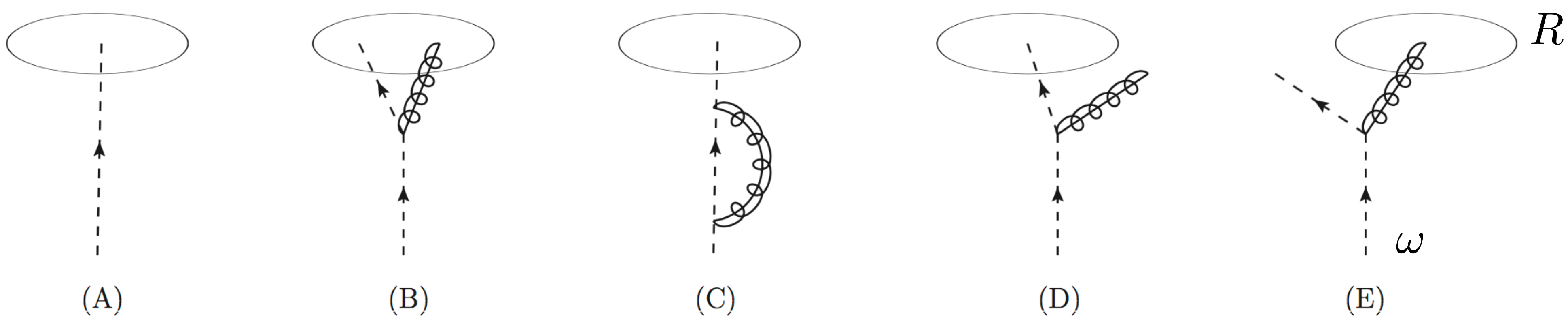


ATLAS, arXiv:1805.05424

Kang, FR, Vitev `17

Jet production in heavy-ion collisions

- Jet functions can be written in terms of collinear splitting functions $pp \to (\text{jet}\, h) + X$



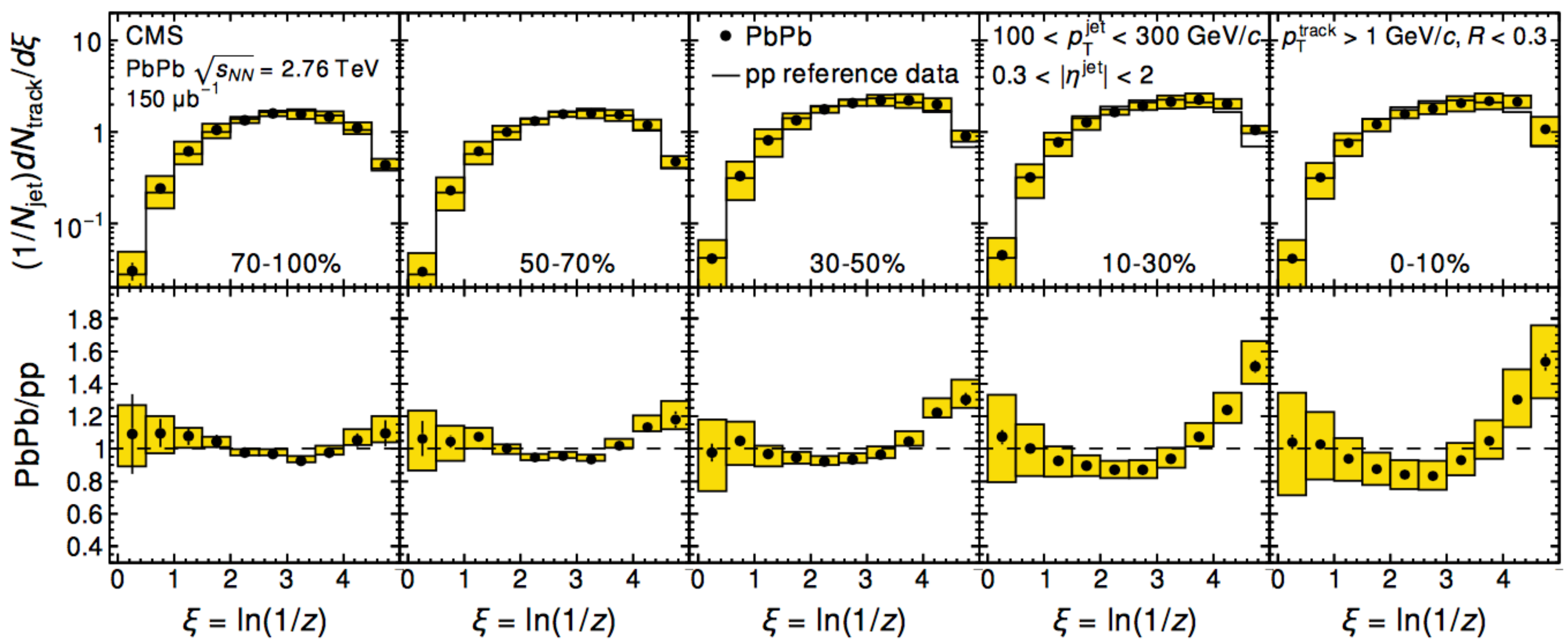
Similar analysis gives

$$\mathcal{G}_q^{q,(1)}(z, z_h, \omega R, \mu) = D_q(z_h)\left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{qq}(z, q_\perp)\right]_+$$

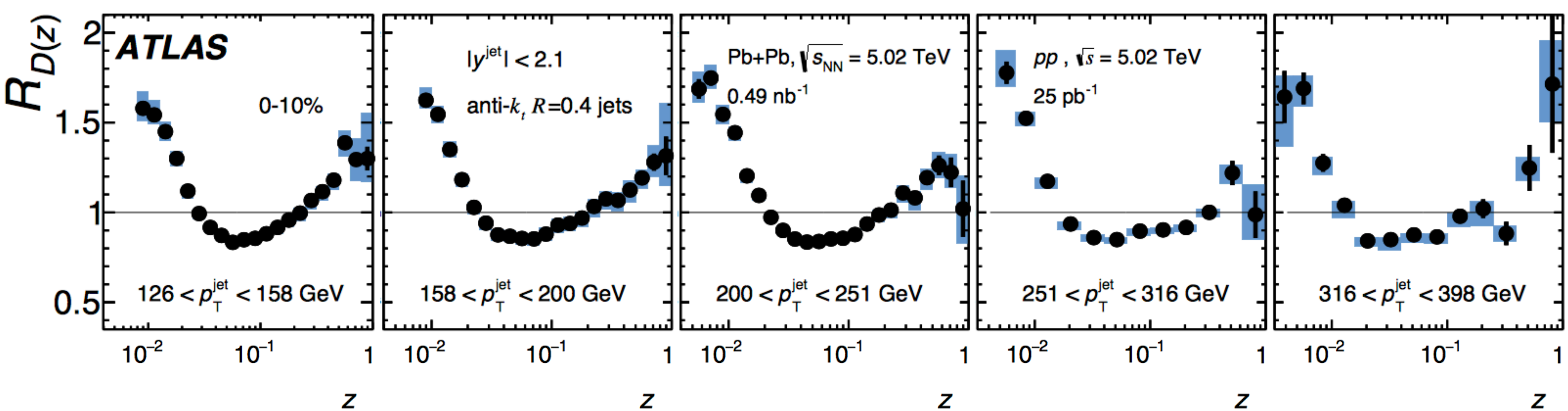
$$+\,\delta(1-z)\left[\int_{\mu_0}^{z_h(1-z_h)p_T R} dq_\perp P_{qq}(z_h, q_\perp)\right]_+ \otimes D_q(z_h)\,.$$

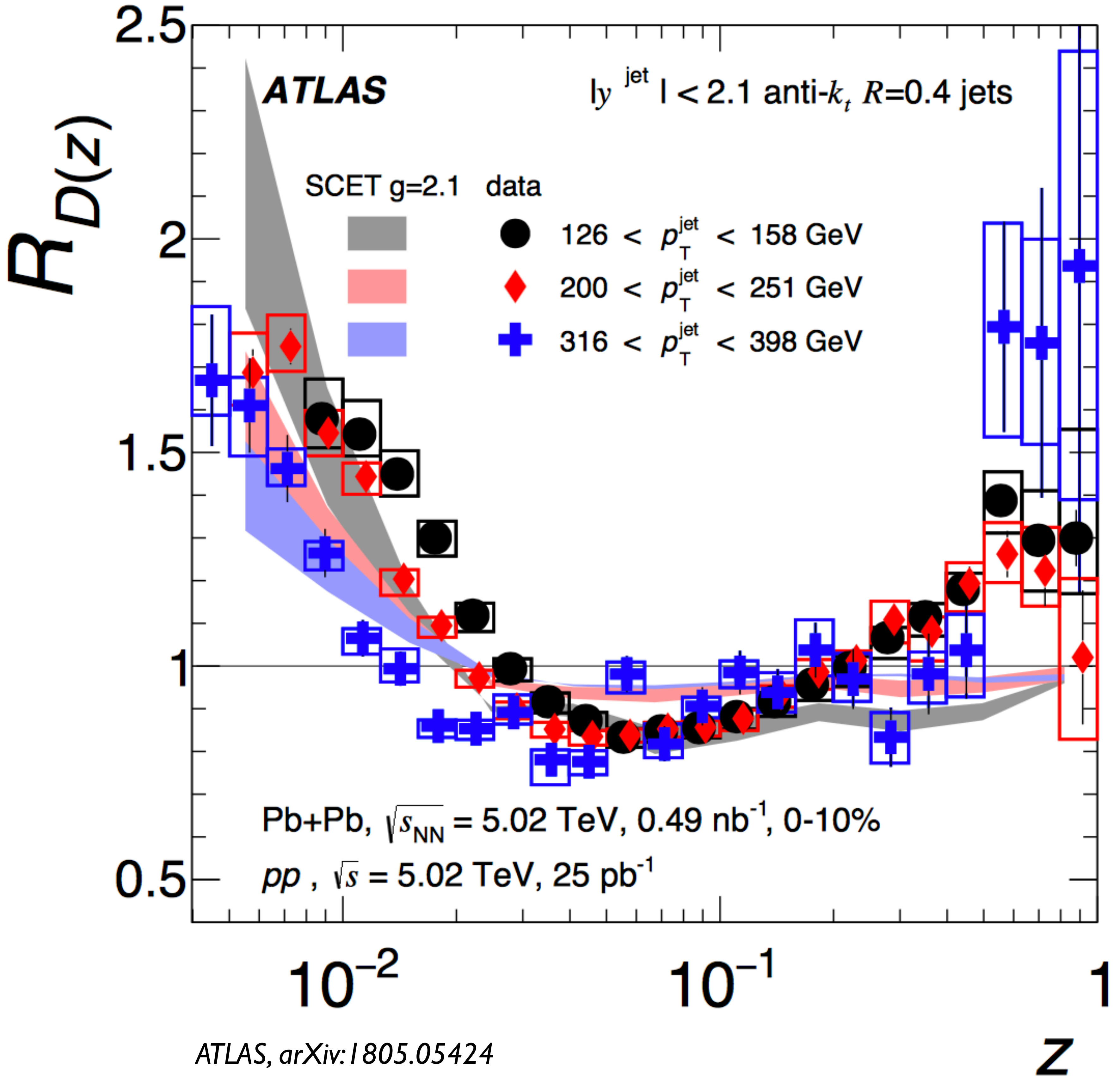
Chien, Kang, FR, Vitev - in preparation

Phys. Rev. C 90 (2014) 024908



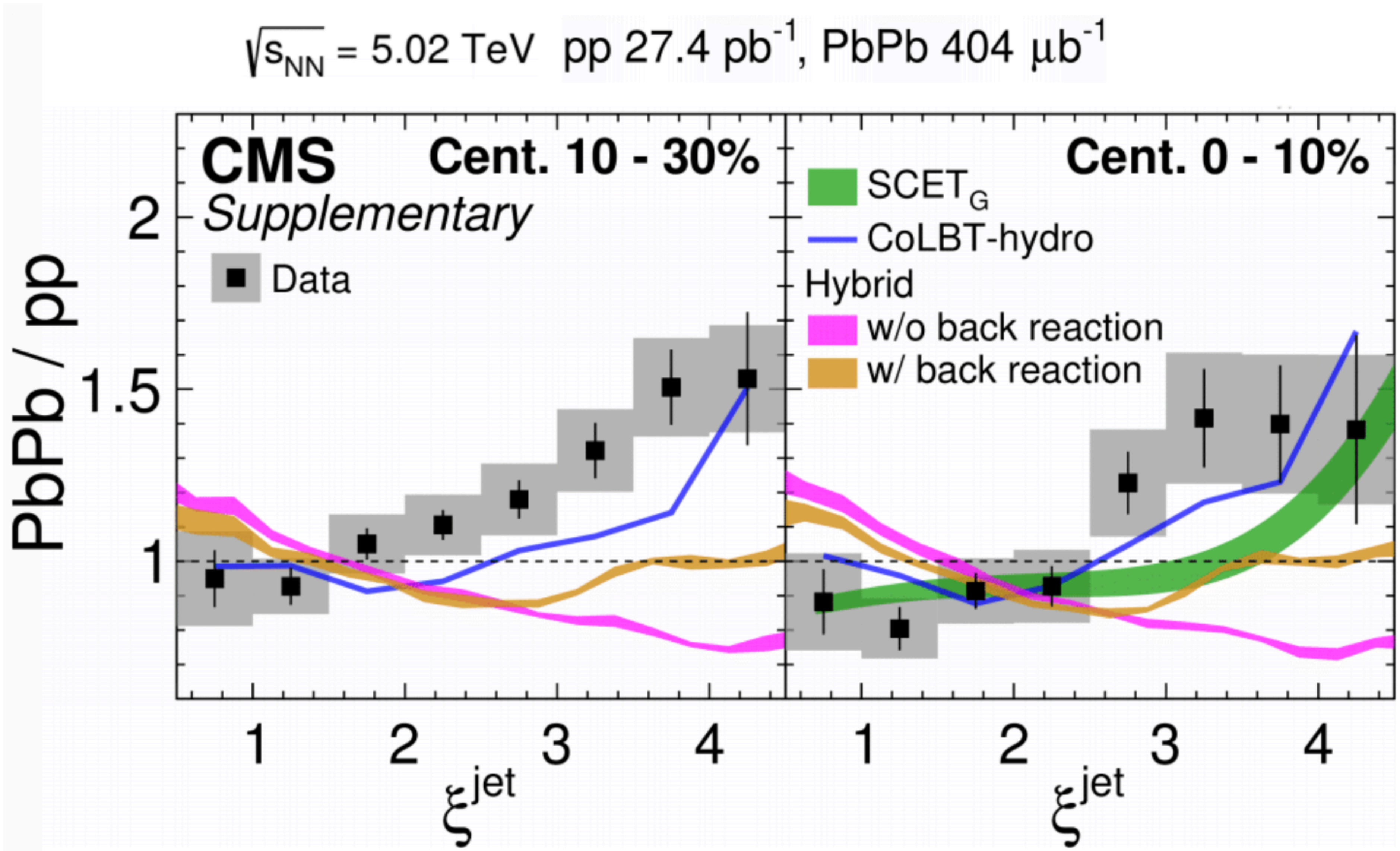
ATLAS, arXiv:1805.05424





ATLAS, arXiv:1805.05424

Photon tagged jets



Kaya Tatar, CMS, QM18

Outline

- Proton-proton baseline
- Jets and their substructure in heavy-ion collisions
- Inclusive subjets
- Conclusions

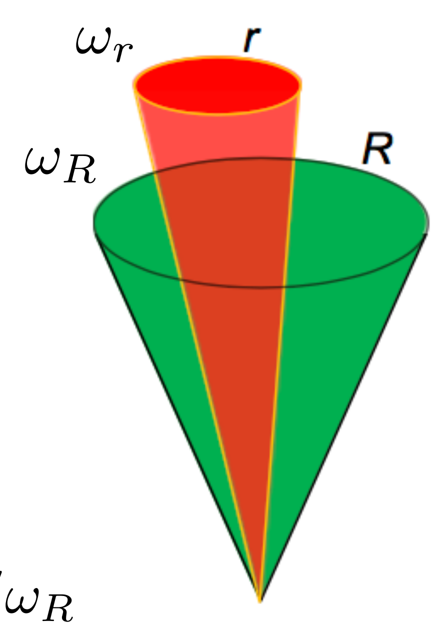
Inclusive subjets

Kang, FR, Waalewijn `17

- Recluster particles inside the jet with a smaller jet parameter $r < R$
- Measure the energy fraction of the subjets
- Requires resummation of $\ln R,\ \ln(r/R)$

$$pp \to (\text{jet}\, j_r) + X$$

$$F(z_r, r; \eta, p_T, R) = \frac{\mathrm{d}\sigma}{\mathrm{d}\eta\, \mathrm{d}p_T\, \mathrm{d}z_r} \bigg/ \frac{\mathrm{d}\sigma}{\mathrm{d}\eta\, \mathrm{d}p_T}$$



$$z_r = \omega_r / \omega_R$$

see also: *Krohn, Thaler, Wang `10*
Dai, Kim, Leibovich `16

Inclusive subjets

Kang, FR, Waalewijn `17

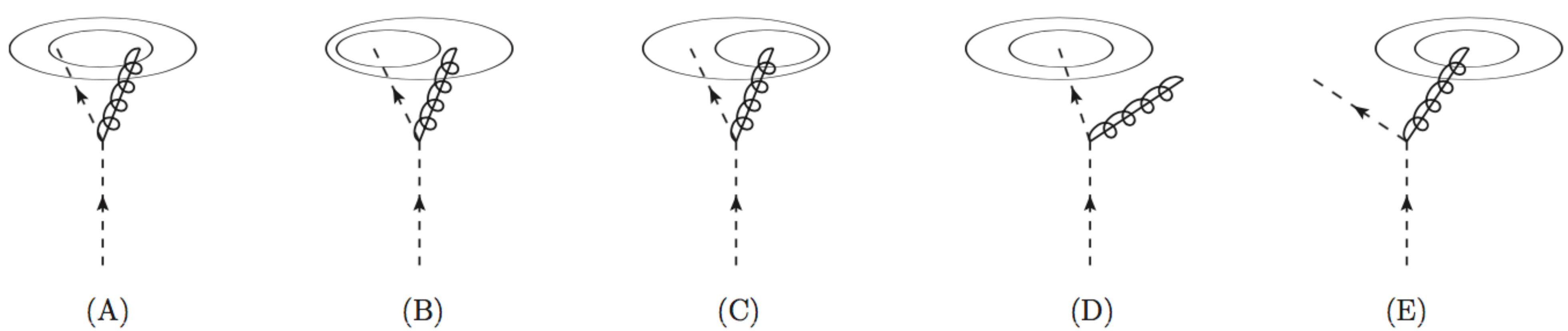
- Factorization for $R \ll 1$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta\,\mathrm{d}p_T\,\mathrm{d}z_r} = \sum_{a,b,c} f_a(x_a,\mu) \otimes f_b(x_b,\mu) \otimes H_{ab}^c(x_a,x_b,\eta,p_T/z,\mu) \otimes \mathcal{G}_c^{\mathrm{jet}}(z,z_r,\omega_R,\mu)$$

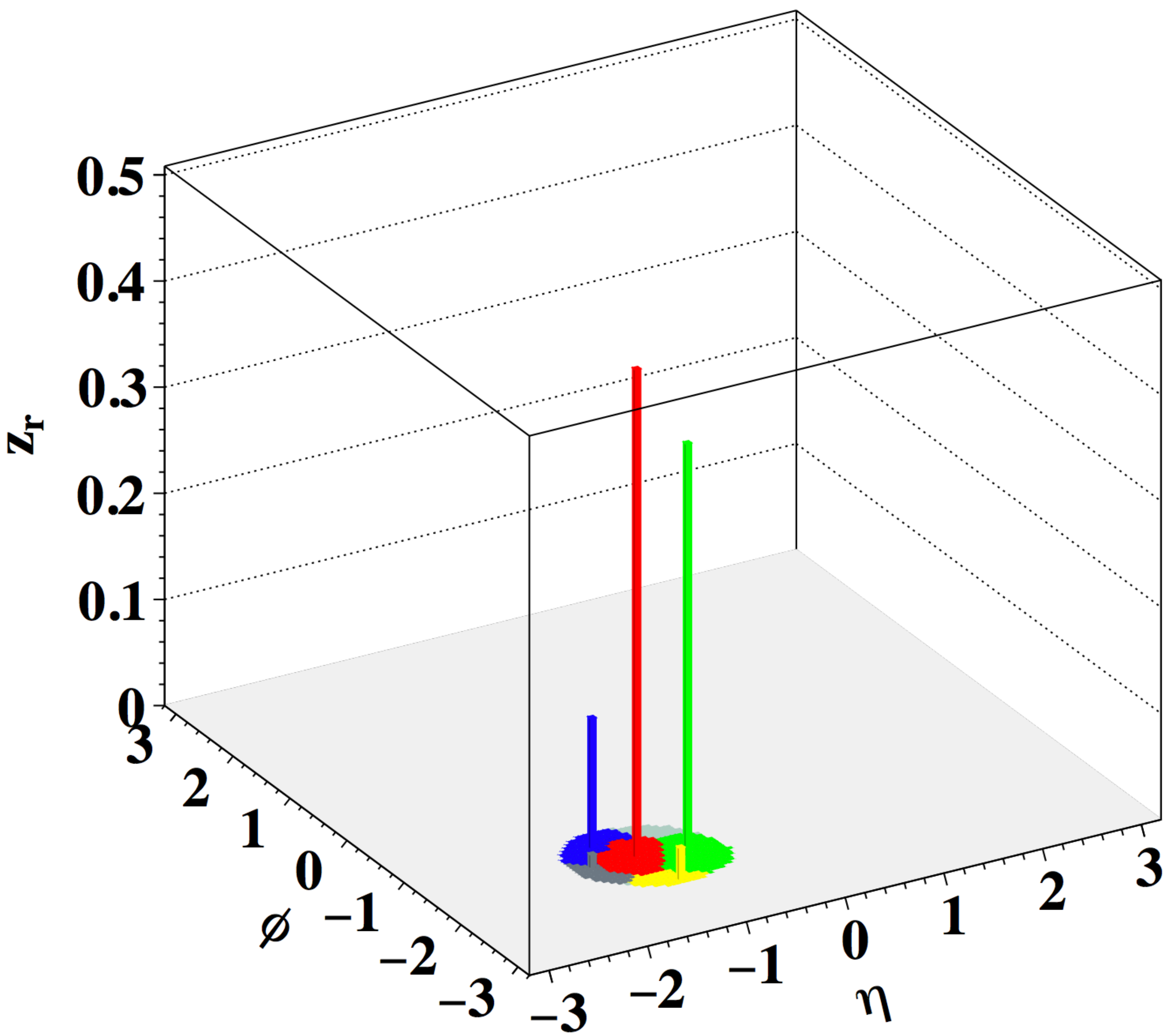
same hard functions as before ↑

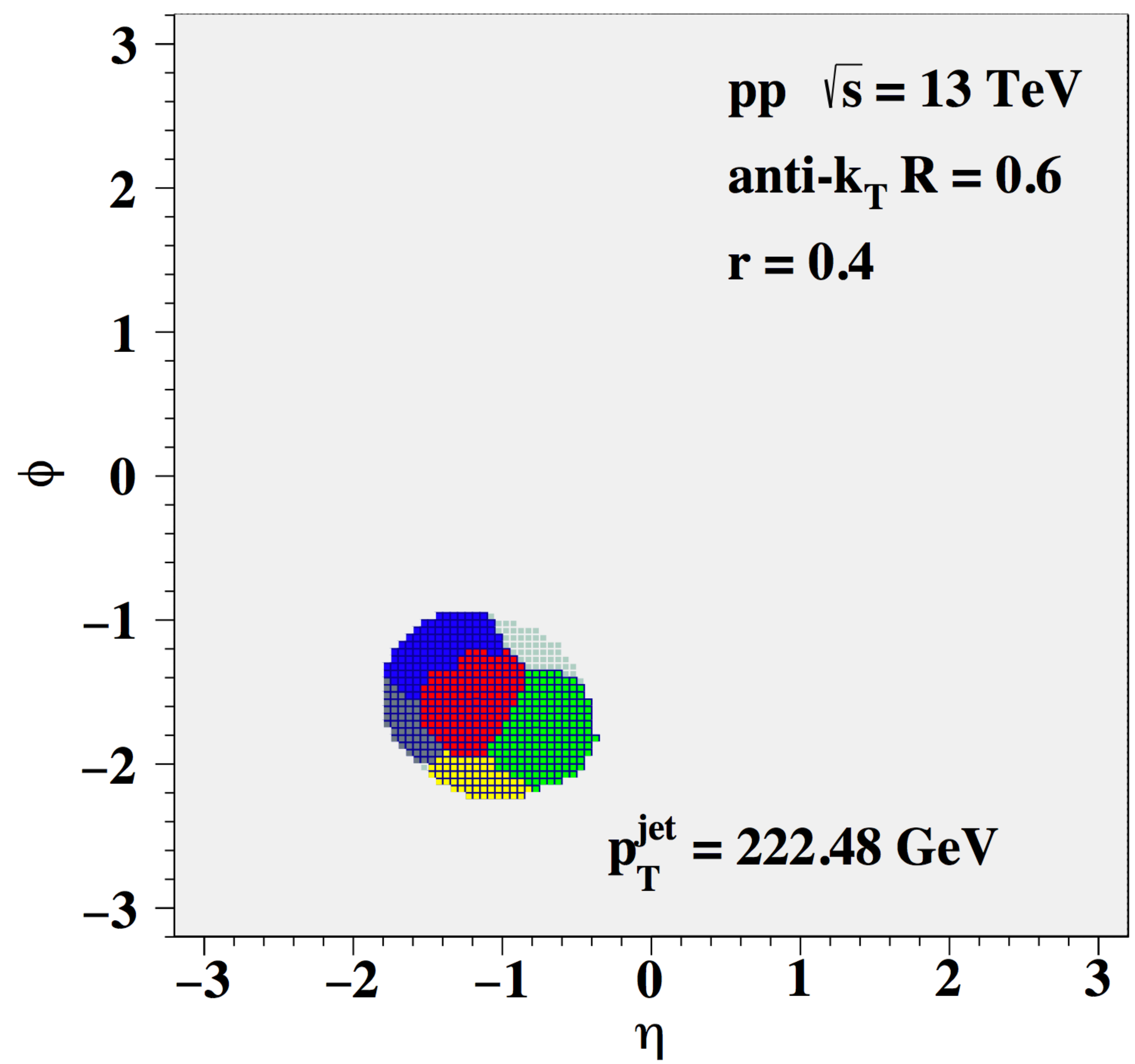
↑ semi-inclusive subjet function (siSJF)

- The quark siSJF at NLO



Pythia simulation





$0.1 < z_r < 0.2$ trigger

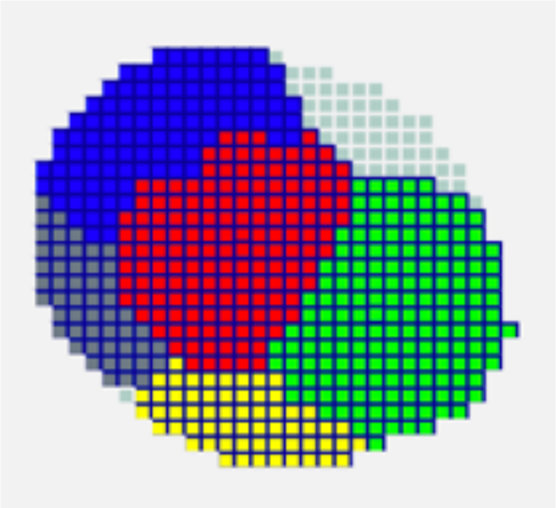
courtesy of Yayun He

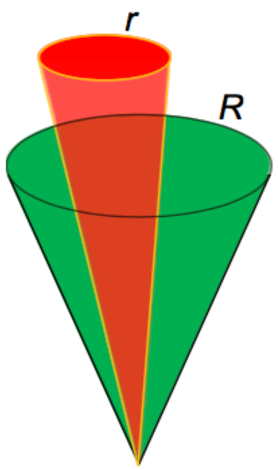
Inclusive subjets

- Direct access to the QCD the splitting functions $r \sim R$

Kang, FR, Waalewijn `17

$$\mathcal{G}_q^{\text{jet}}(z, z_r < 1, \omega_R, \mu) = \frac{\alpha_s}{2\pi}\,\delta(1-z)\,\ln\left(\frac{R^2}{r^2}\right)\left[P_{qq}(z_r) + P_{gq}(z_r)\right]$$





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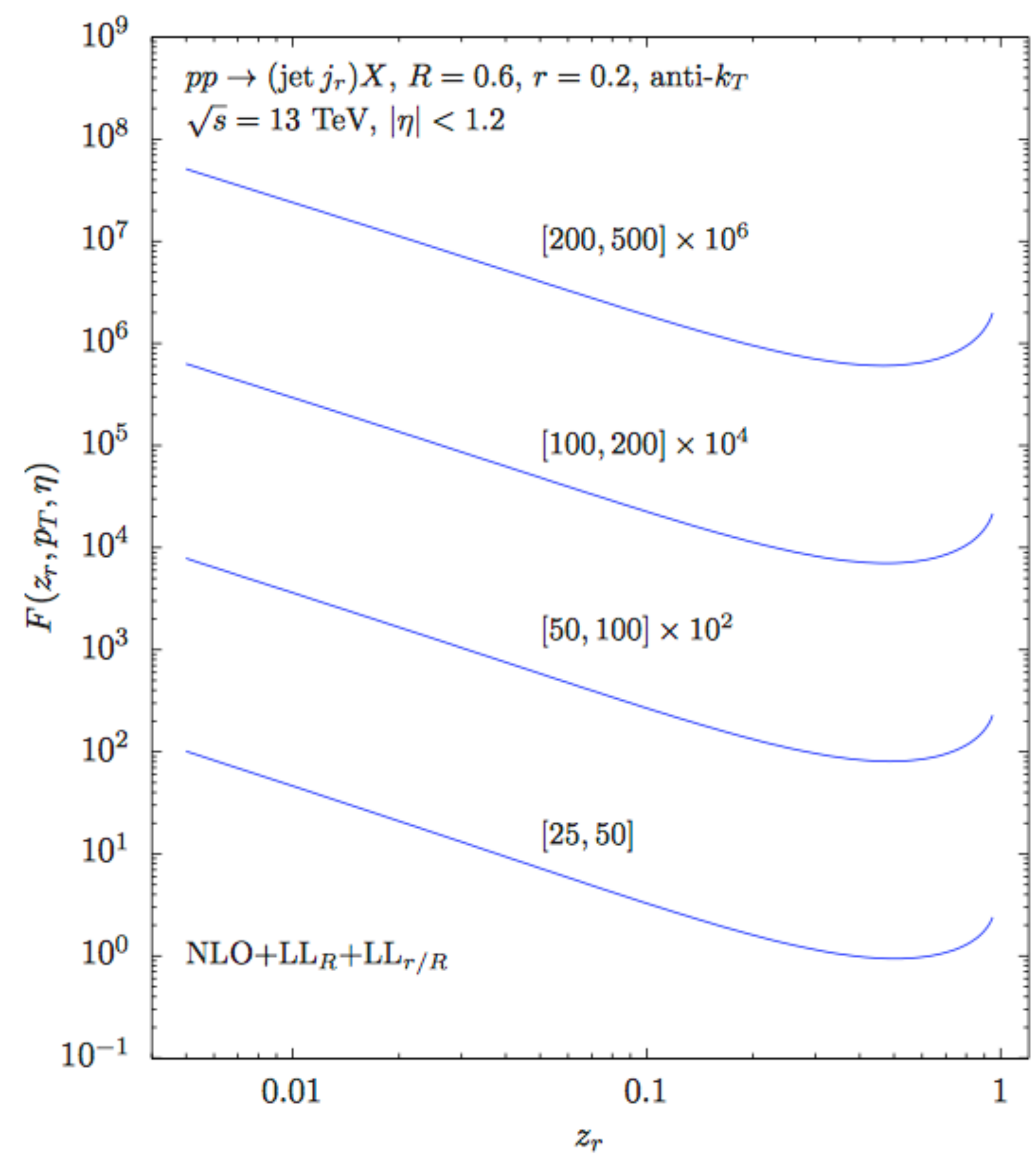

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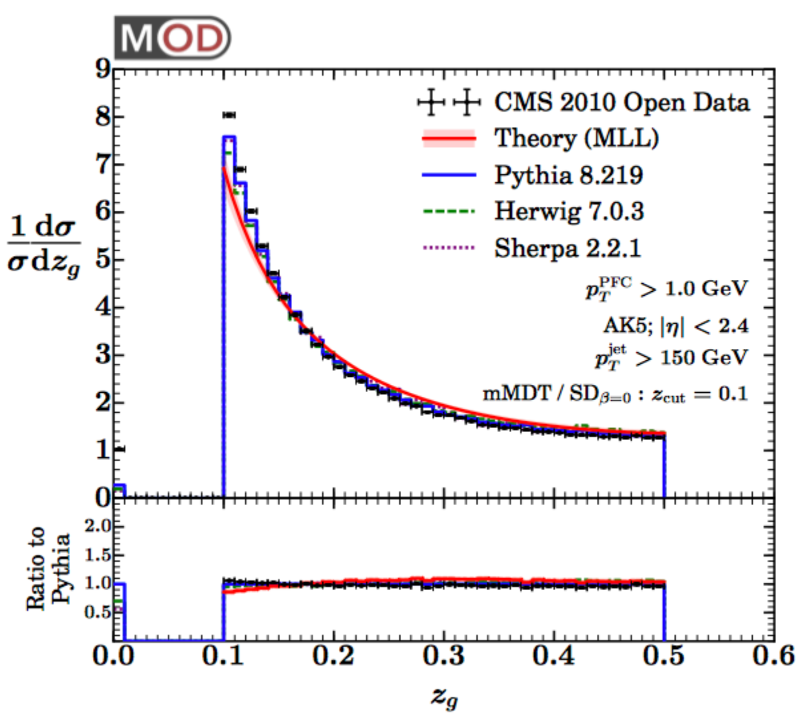
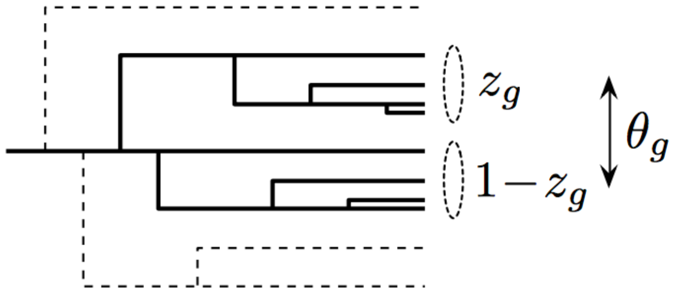
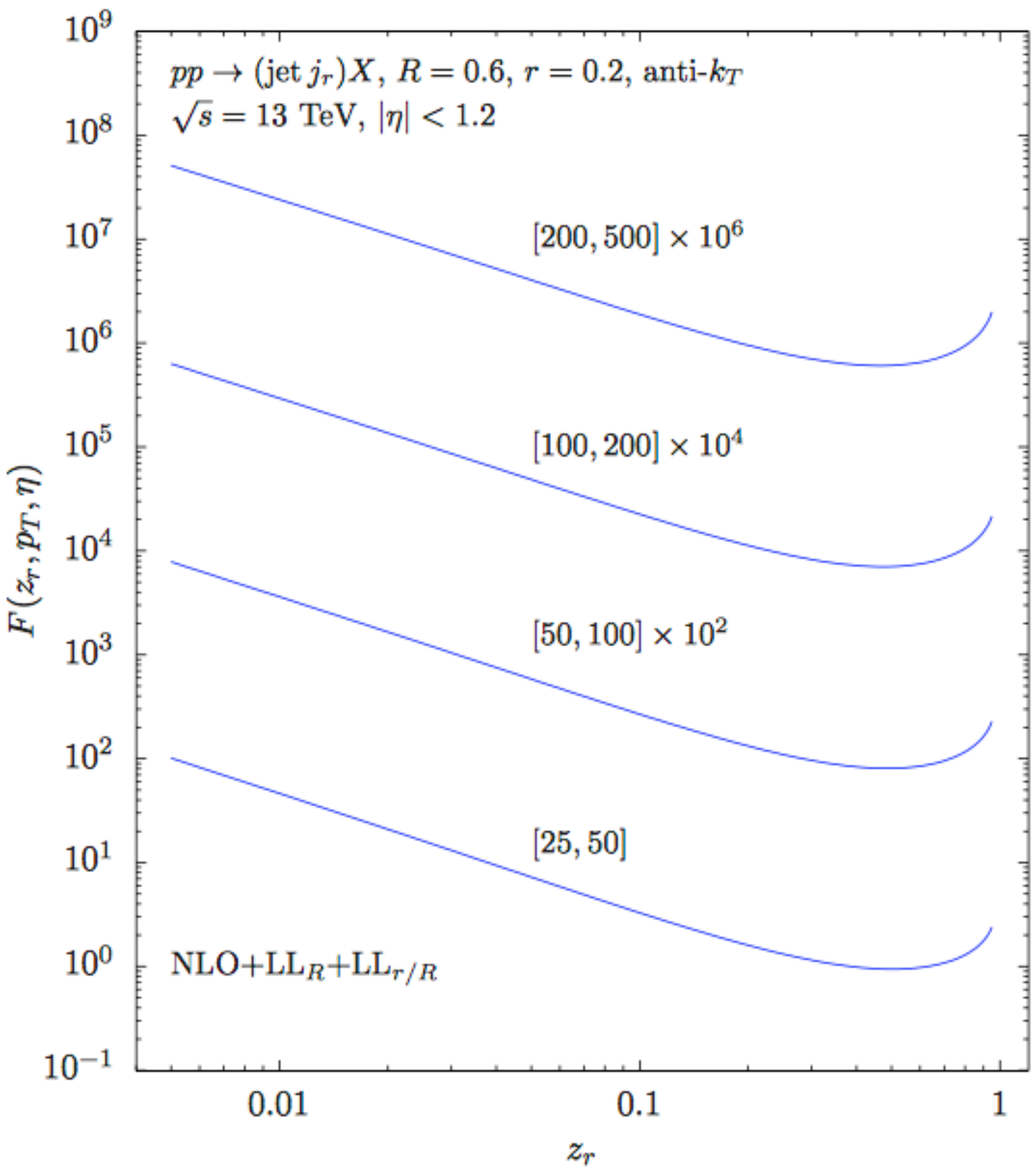
see also soft drop declustering, $z_g = \dfrac{\min[p_{T1}, p_{T2}]}{p_{T1}+p_{T2}}$

Larkoski, Marzani, Soyez, Thaler `14





Tripathee, Xue, Larkoski, Marzani, Thaler `17



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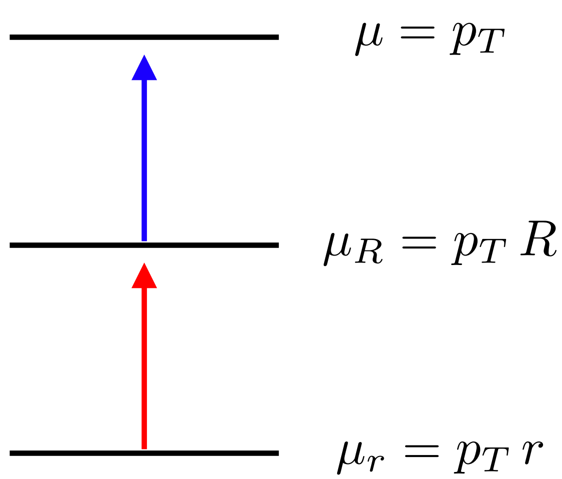
- Direct access to the semi-inclusive jet functions $r \ll R$

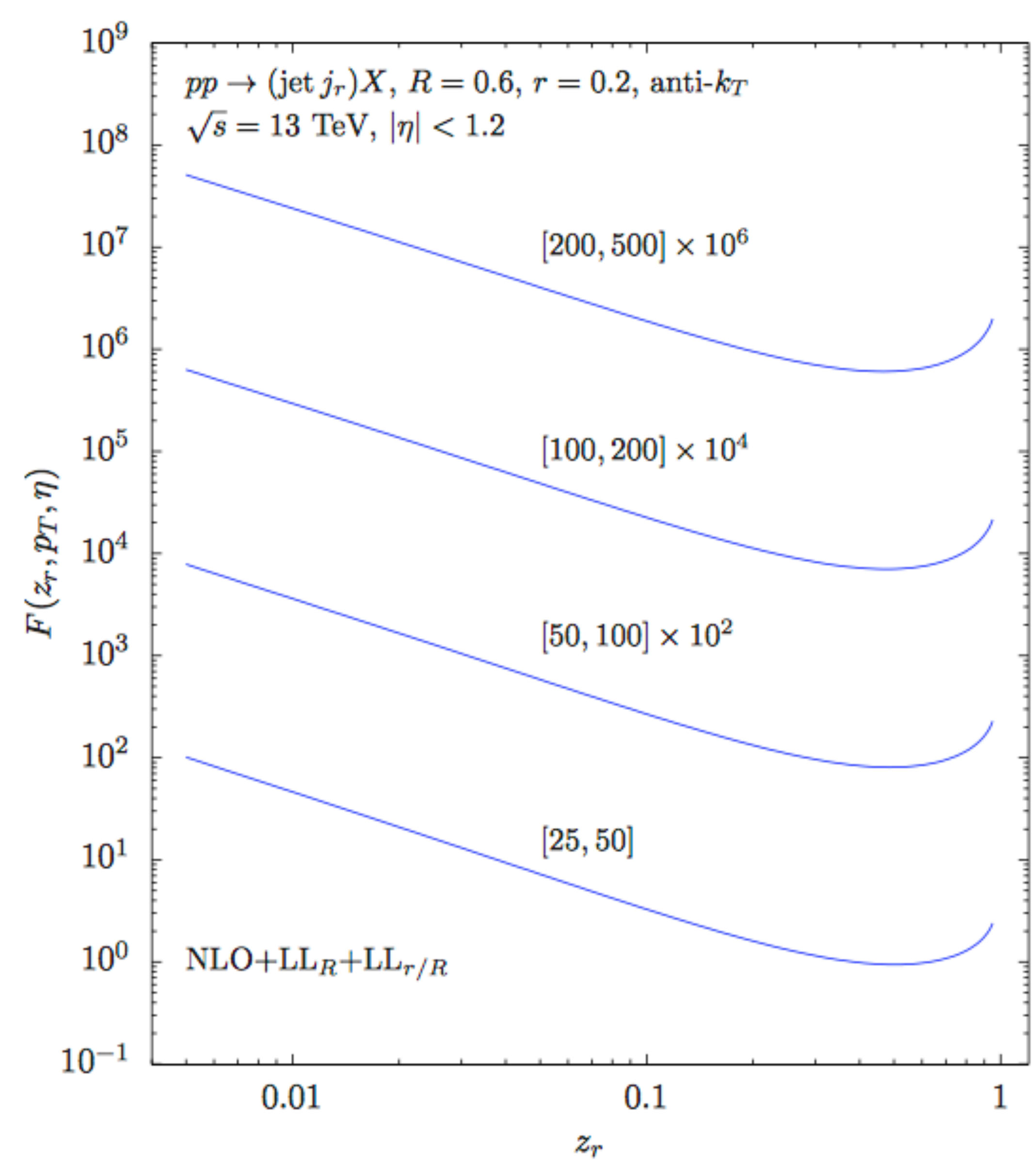
$$\mathcal{G}_i^{\text{jet}}(z, z_r, \omega_R, r, R, \mu) = \sum_j \int_{z_r}^1 \frac{\mathrm{d}z_r'}{z_r'}\,\mathcal{J}_{ij}(z, z_r', \omega_R, R, \mu)\, J_j\left(\frac{z_r}{z_r'}, \omega_r, r, \mu\right)$$

matching coefficients same as for hadron-in-jet

siJF for subjet of size r



2x DGLAP



Inclusive subjets

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Kang, FR, Waalewijn `17

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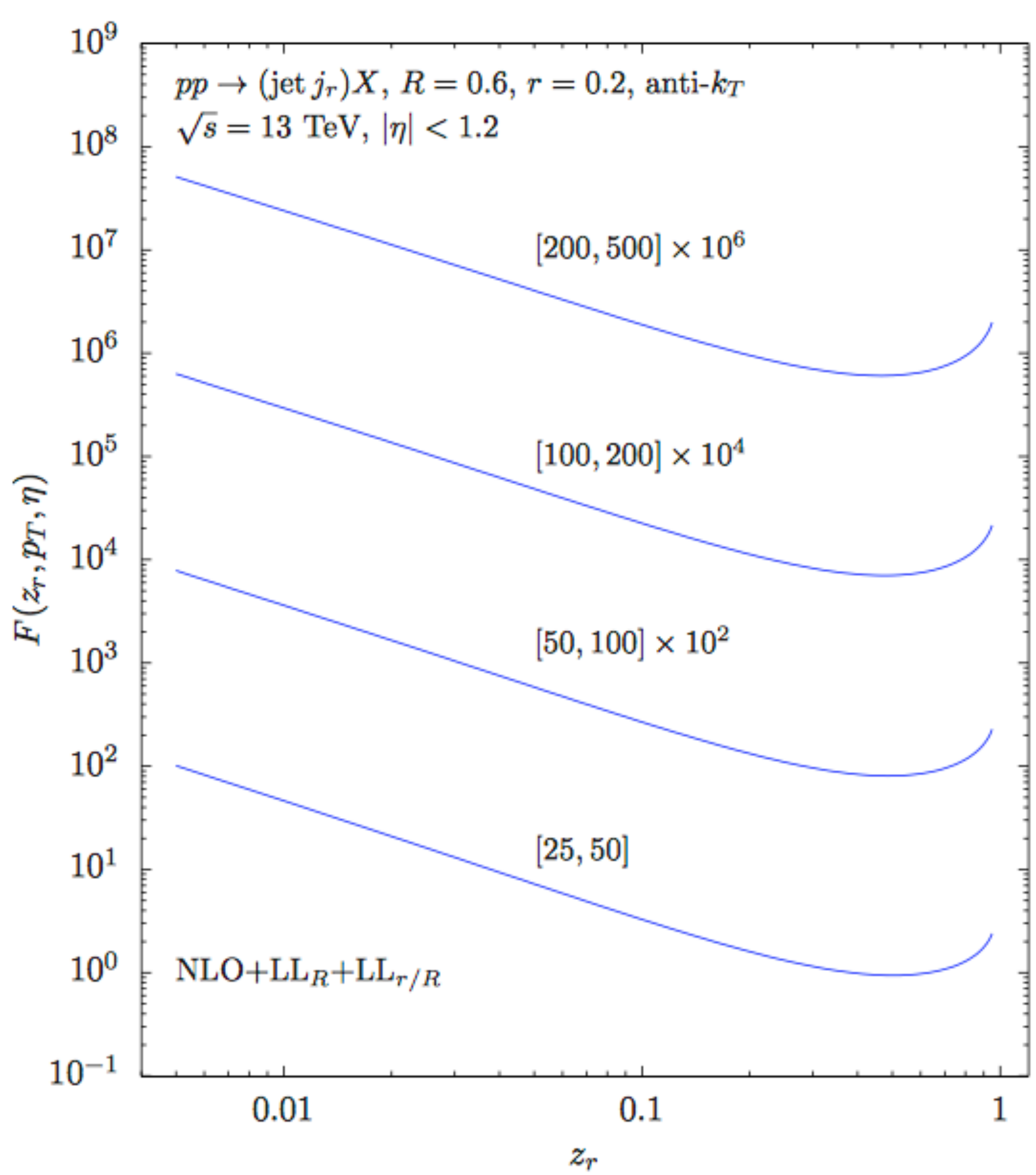
siJF for subjet of size r

- Two endpoint resummations required



Inclusive subjets

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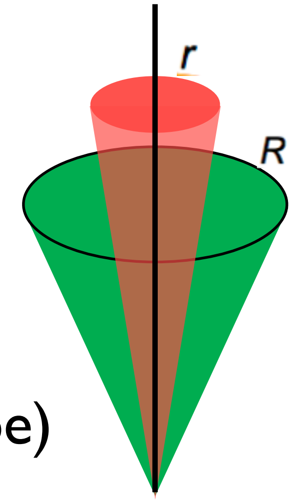
matching coefficients same as for hadron-in-jet

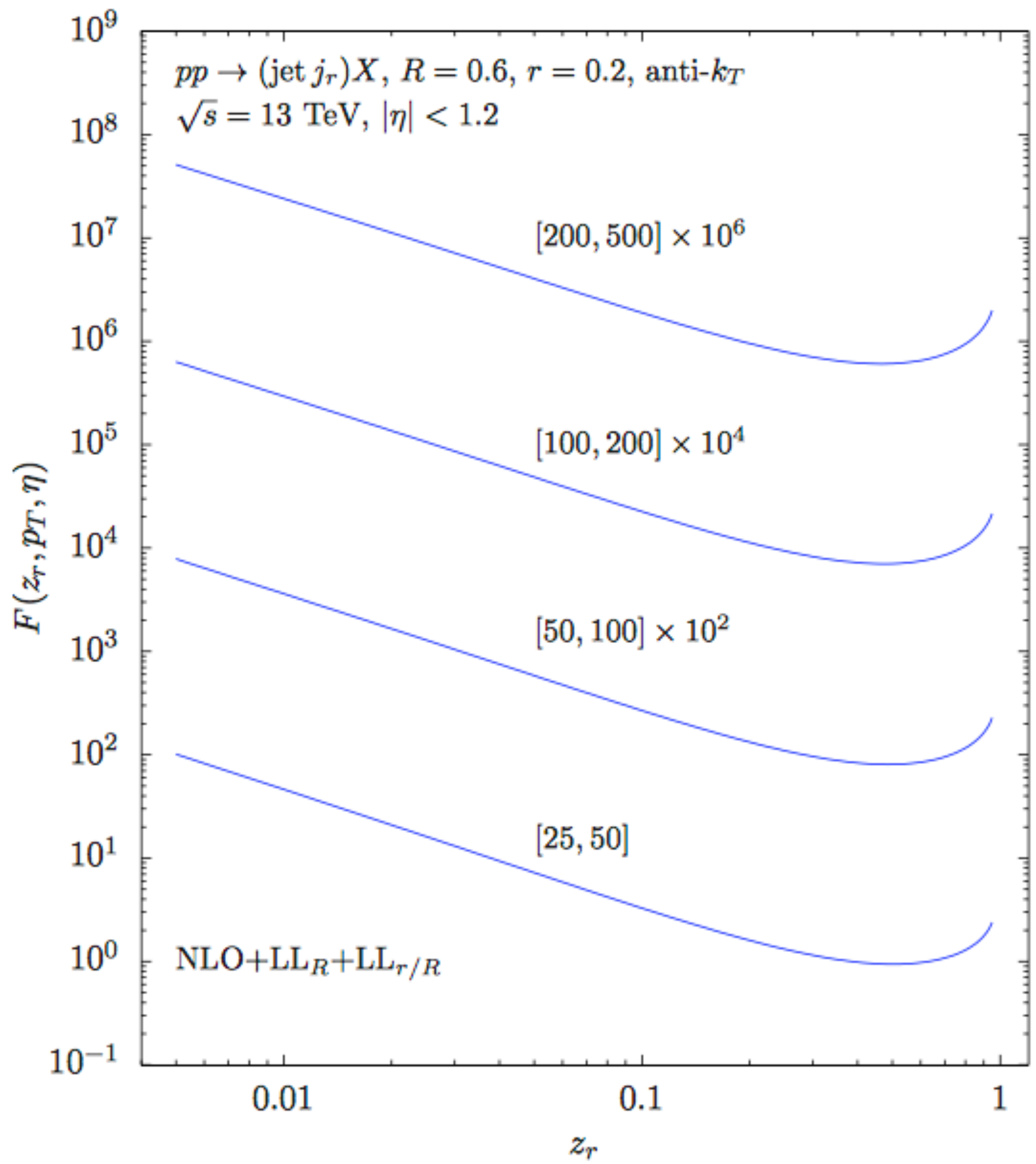
siJF for subjet of size r

- Two endpoint resummations required

- Energy profile in the transverse direction

choose central subjets (similar to the jet shape)



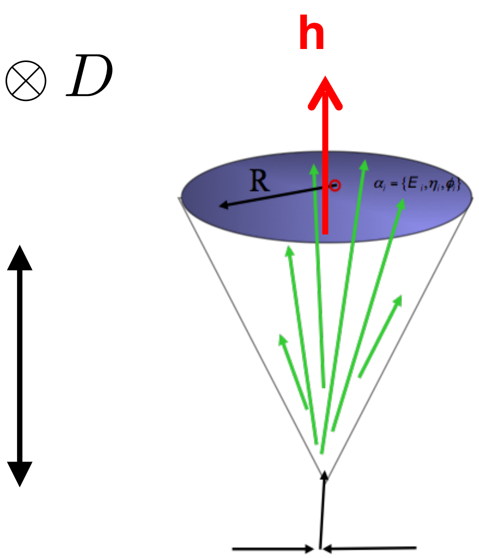


Jet substructure within collinear factorization

Inclusive hadron production

$pp \to h + X$

$$d\sigma \sim H \otimes D$$



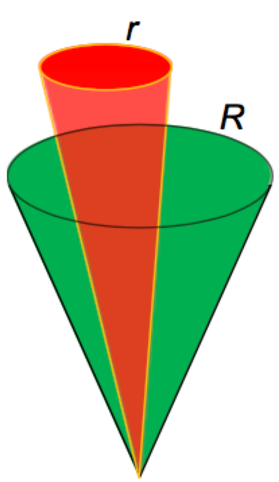
Hadron in jet

$$\frac{d\sigma}{dz_h} \sim H \otimes \mathcal{J} \otimes D(z_h)$$

Inclusive jet production

$pp \to \text{jet} + X$

$$d\sigma \sim H \otimes J$$



Subjet in jet

$$\frac{d\sigma}{dz_r} \sim H \otimes \mathcal{J} \otimes J(z_r)$$

Outline

- Proton-proton baseline
- Jets and their substructure in heavy-ion collisions
- Inclusive subjets
- Conclusions

Conclusions

- First results for the jet fragmentation function within $\mathrm{SCET}_{\mathrm{G}}$
- Consistent within collinear factorization for pp and AA

- Higher orders in the opacity series
- Inclusive subjets
- Transverse momentum spectra

$$\frac{d\sigma}{dp_T d\eta\, dz_h dj_\perp}$$