Hadron in Jet Fragmentation

Felix Ringer

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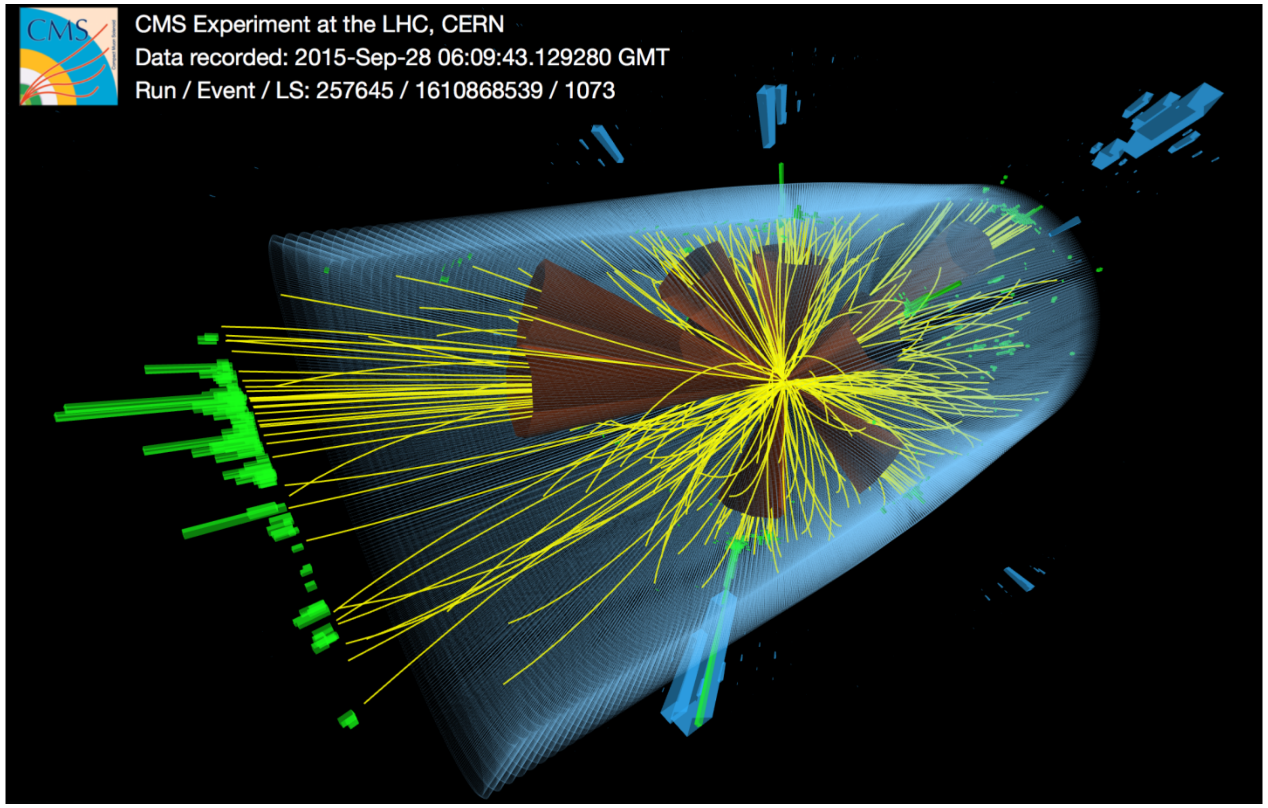
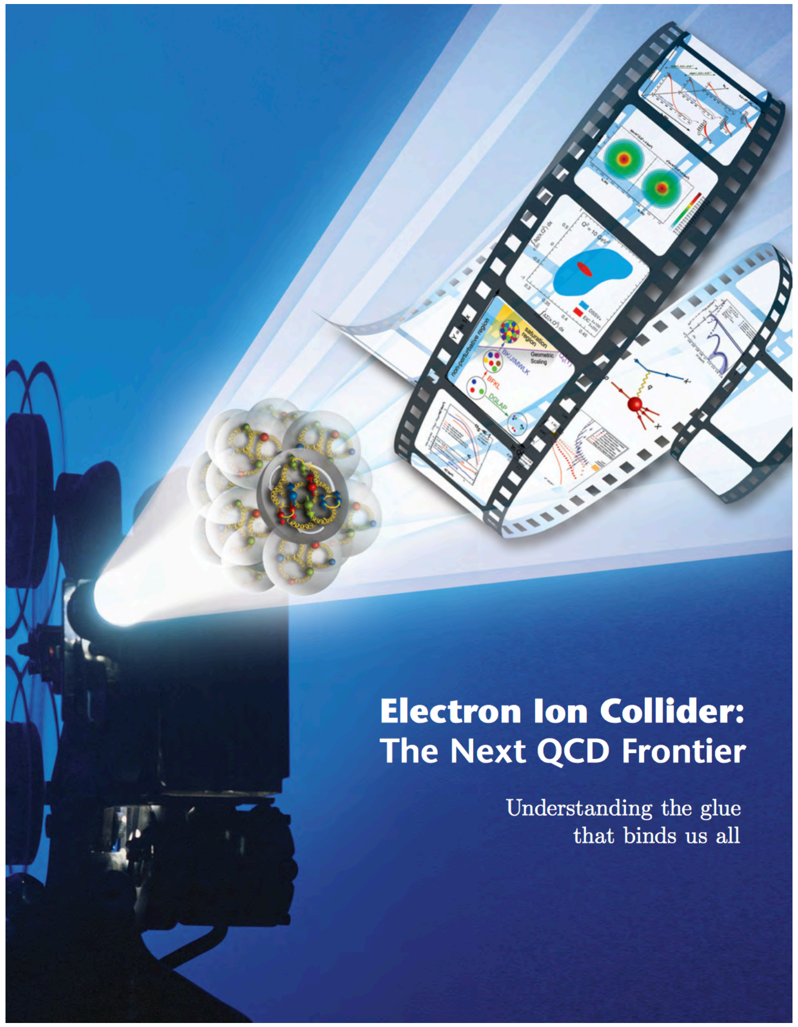
CIPANP 18, Palm Springs, 05/30/18

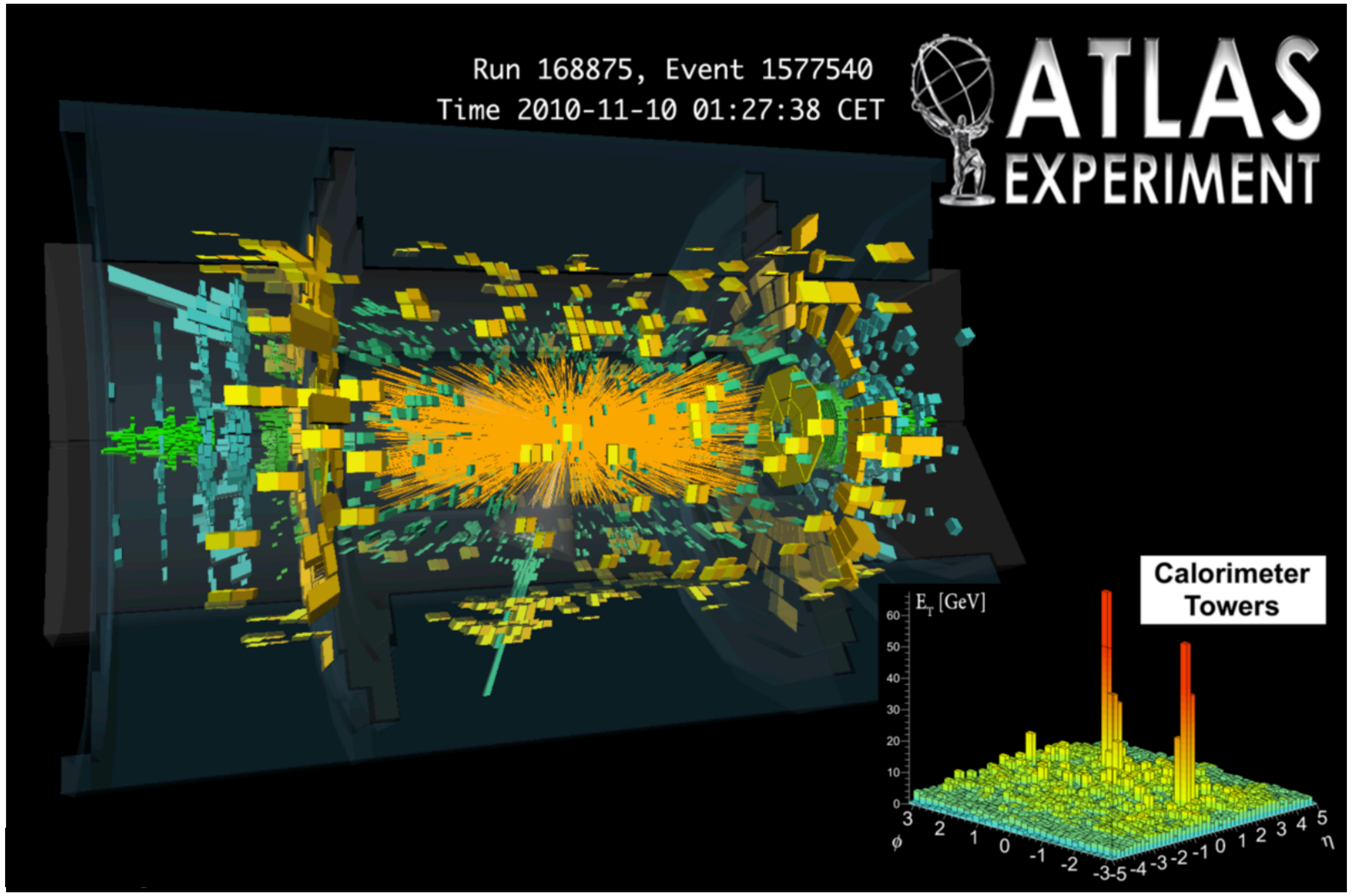
BERKELEY LAB



Jets and their substructure at

- LHC, RHIC
- HERA
- EIC
- BELLE



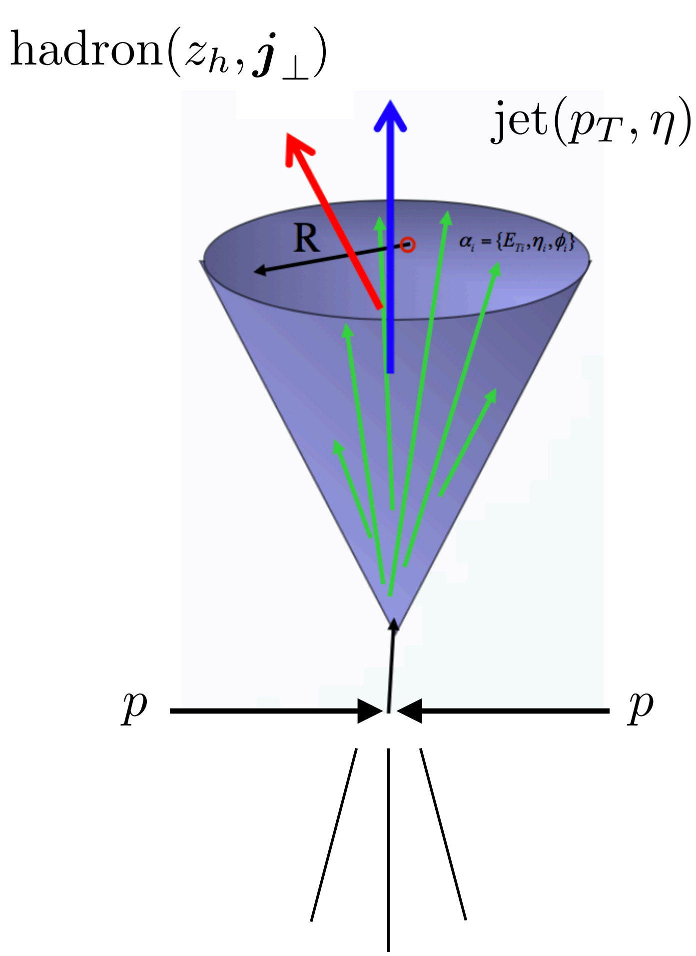


Hadron in jet fragmentation

Inclusive production of jets p_T, η

- Identify the hadrons in the jet and measure additional two variables:
  - Longitudinal momentum fraction $z_h = p_T^h / p_T$
  - Relative transverse momentum wrt. to a predetermined axis $\boldsymbol{j}_\perp$

$$F(z_h, \boldsymbol{j}_\perp; \eta, p_T, R) = \frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} \Bigg/ \frac{d\sigma^{pp\to\text{jet}X}}{dp_T d\eta}$$



- Constrain (gluon) fragmentation function
- Test of universality and (TMD) evolution

Outline

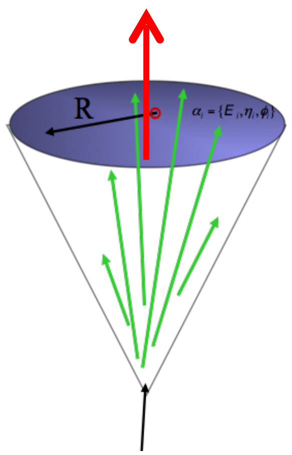
- Introduction
- Hadron-in-jet: Longitudinal case
  - proton-proton
  - Heavy-ion
- Hadron-in-jet: Transverse case
- Conclusions

The jet fragmentation function $pp \to (\text{jet}h)X$

Kang, FR, Vitev `16

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

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



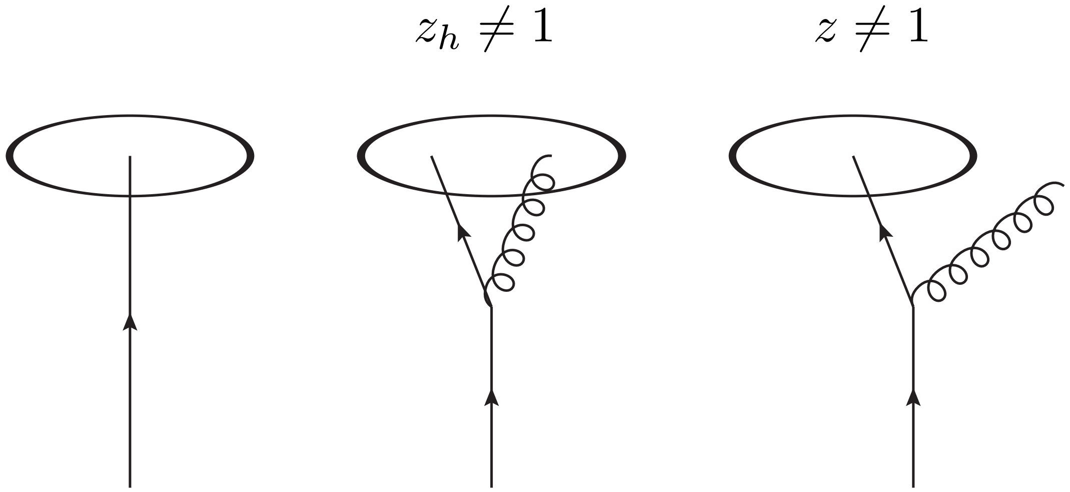
- Factorization for inclusive jet production

$$\frac{d\sigma^{pp\to(\text{jet }h)+X}}{d\eta dp_T dz_h} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^h$$

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

matching coefficients

standard collinear FFs



see also: Procura, Stewart `10, Jain, Procura, Waalewijn `11, Arleo et al. `14, Kaufmann, Mukherjee, Vogelsang `15

The jet fragmentation function $pp \to (\text{jet}h)X$

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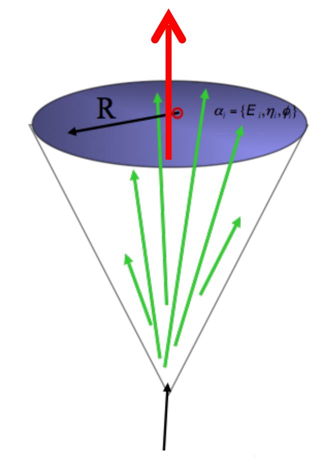

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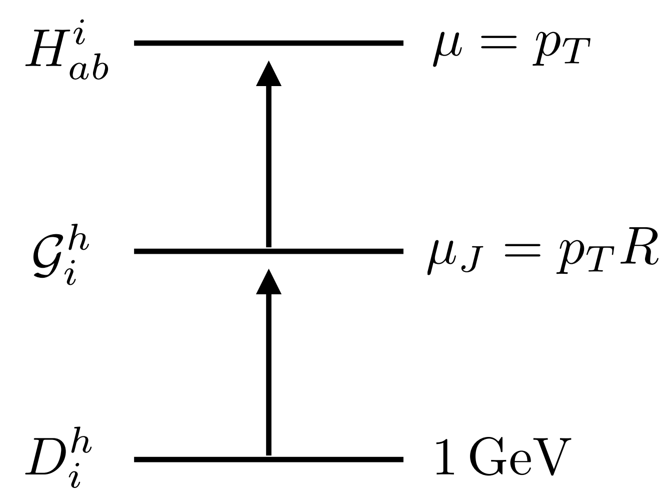
matching coefficients

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

see also: *Procura, Stewart `10, Jain, Procura, Waalewijn `11, Arleo et al. `14, Kaufmann, Mukherjee, Vogelsang `15*

Phenomenology

- Light charged hadrons
  - *Arleo, Fontannaz, Guillet, Nguyen `14*
  - *Kaufmann, Mukherjee, Vogelsang `15*
  - *Kang, FR, Vitev `16*
  - *Neill, Scimemi, Waalewijn `16*
  - *Makris, Neill, Vaidya `17*

- 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*
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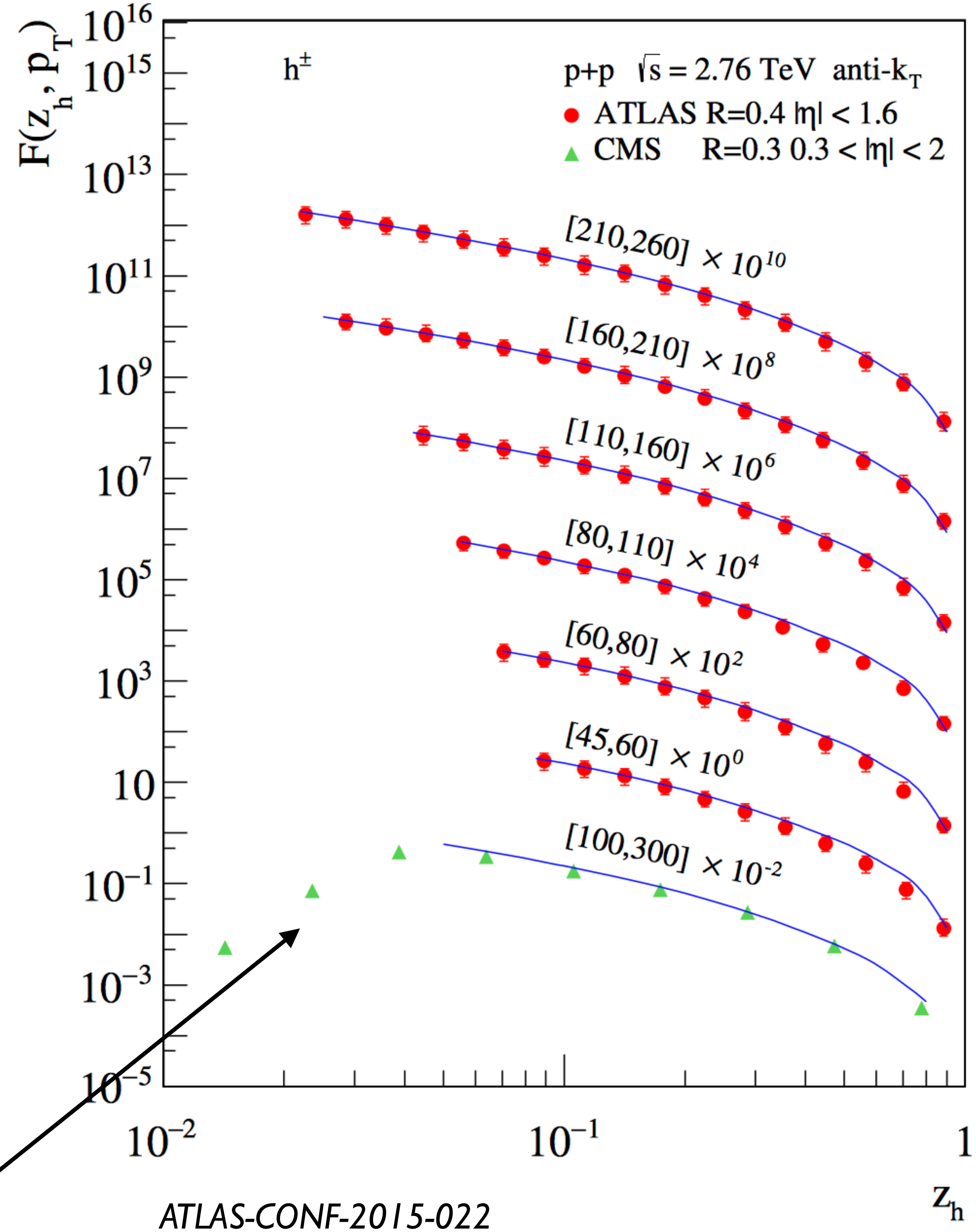
- Photons
  - *Kaufmann, Mukherjee, Vogelsang `16*



small-z requires additional resummation
see Anderle, Kaufmann, FR, Stratmann `16

ATLAS-CONF-2015-022
CMS, JHEP 10 (2012) 087
Kang, FR, Vitev `16

Phenomenology

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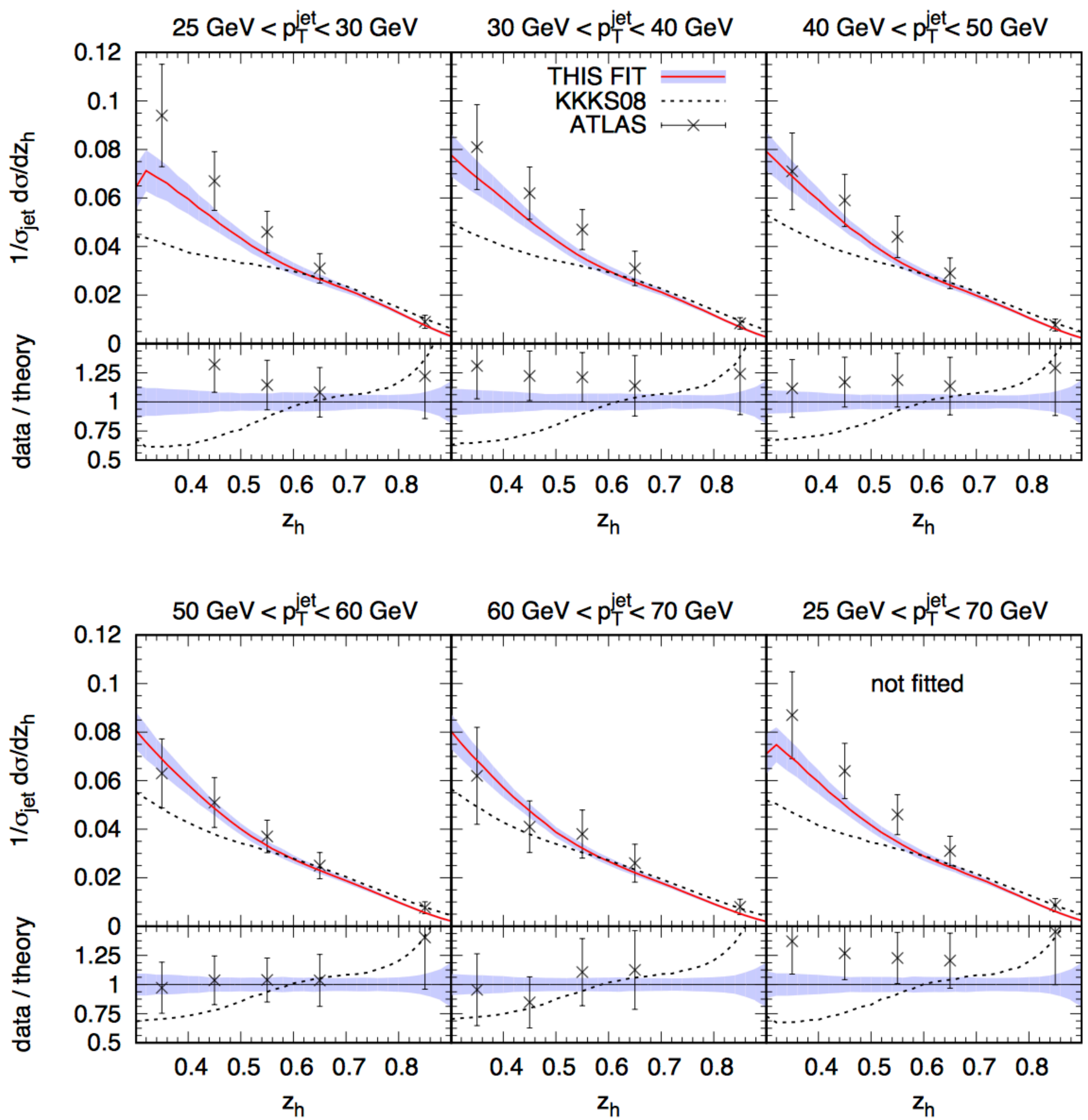

New global D-meson fragmentation function fit
Anderle, Kaufmann, Stratmann, FR, Vitev `17

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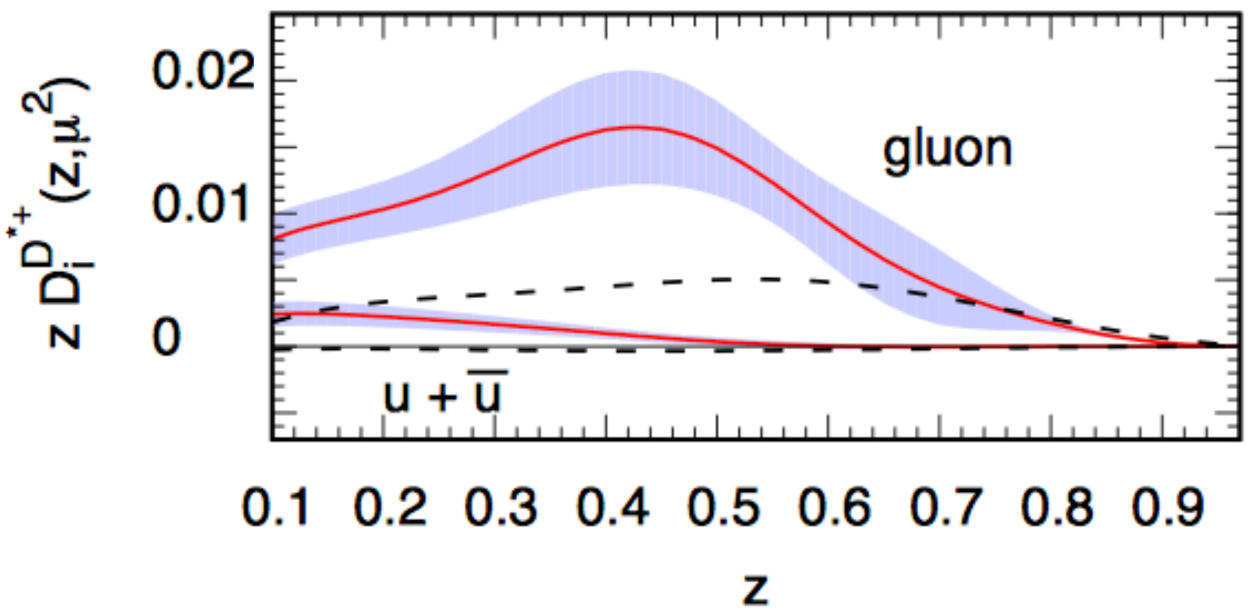

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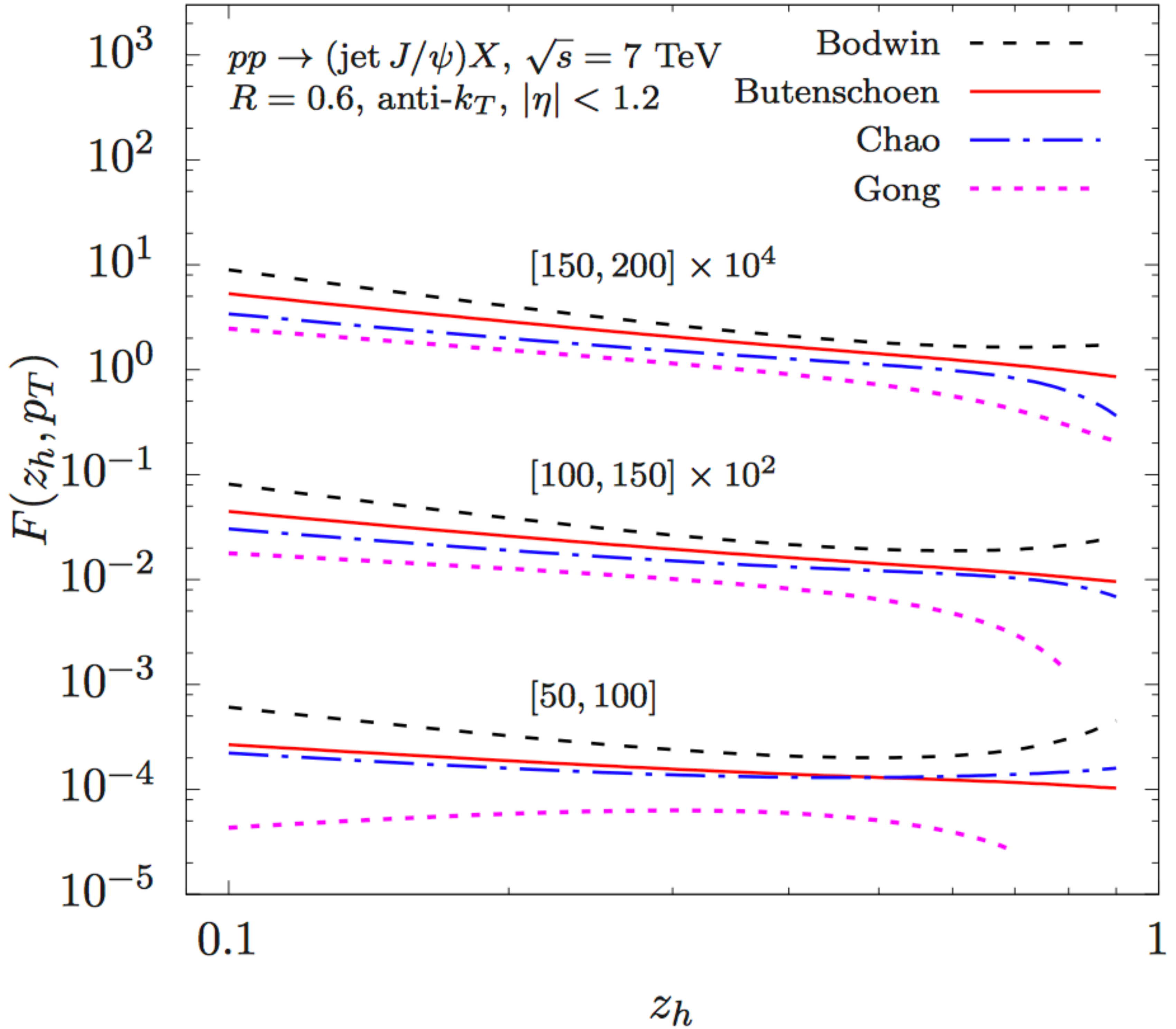

Kang, Qiu, FR, Xing, Zhang `17

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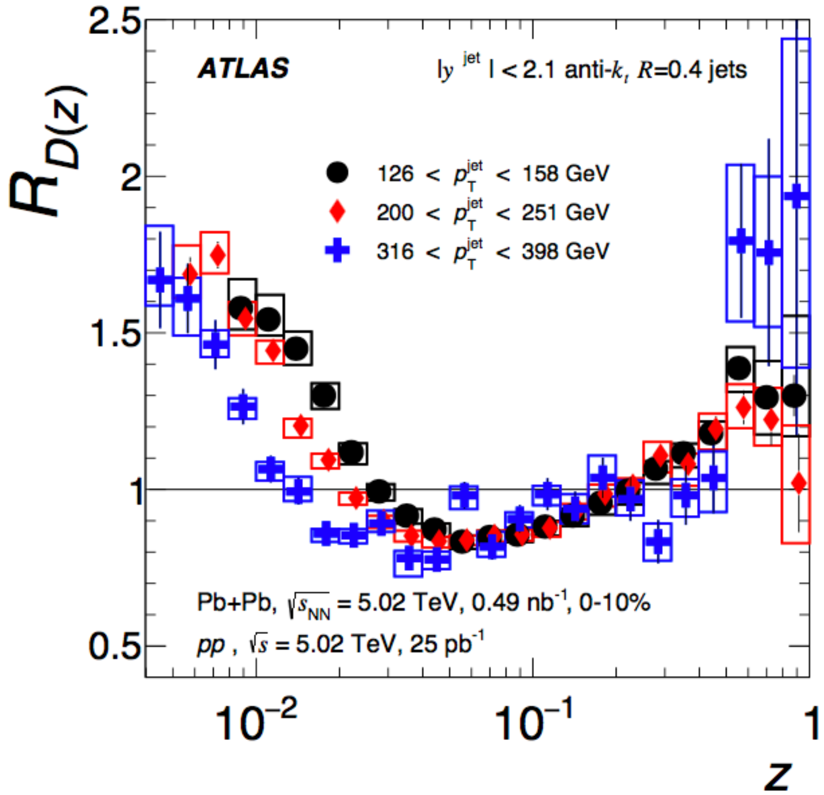
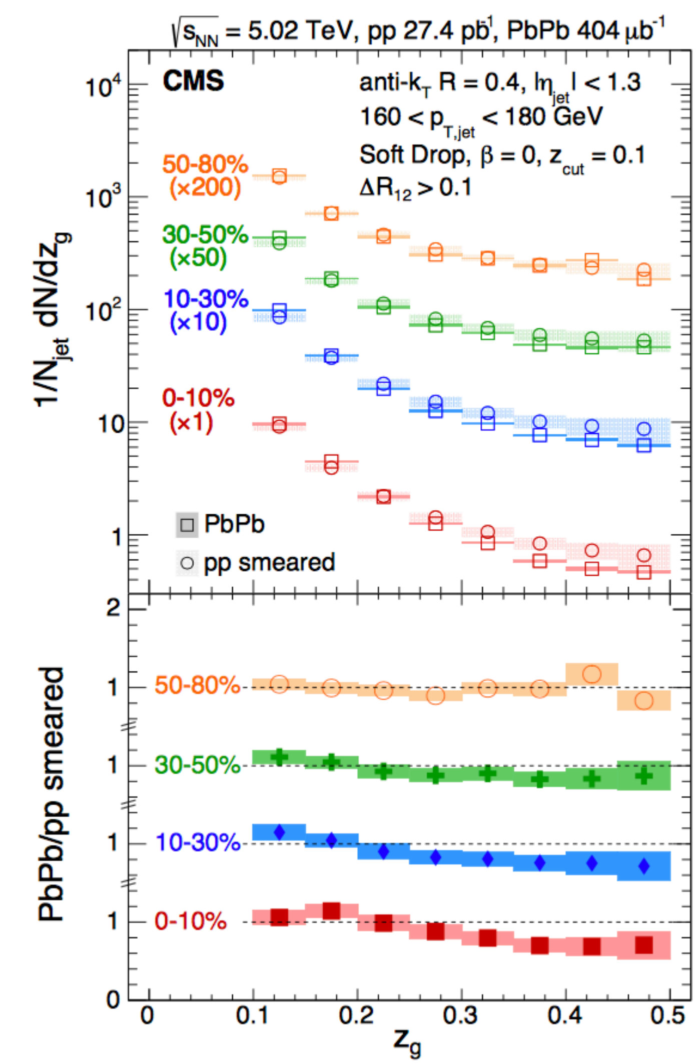
Jet substructure in heavy-ion collisions

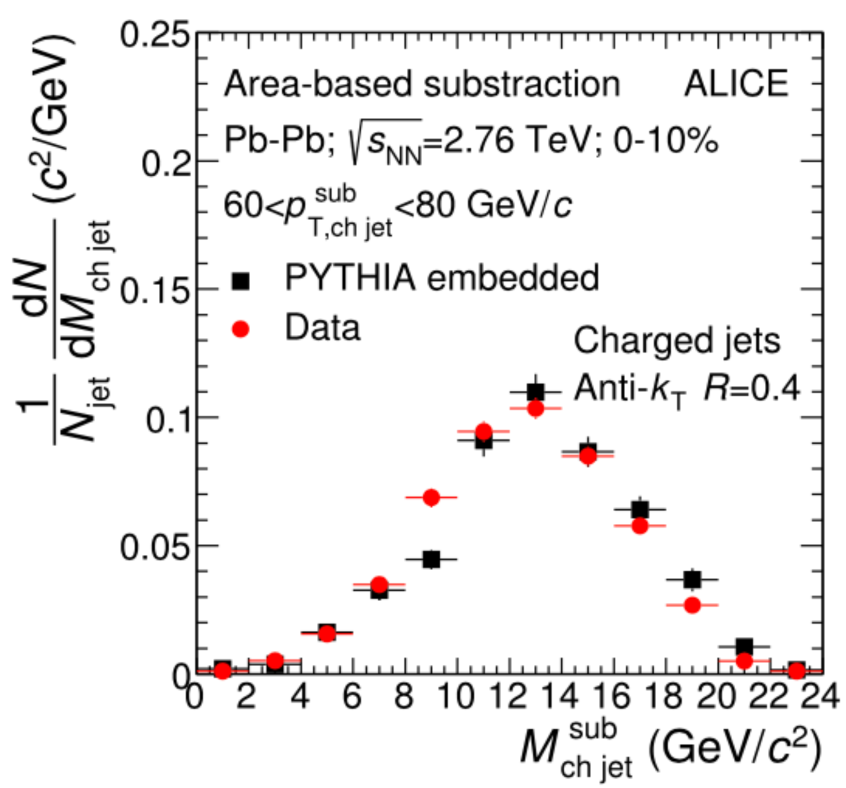


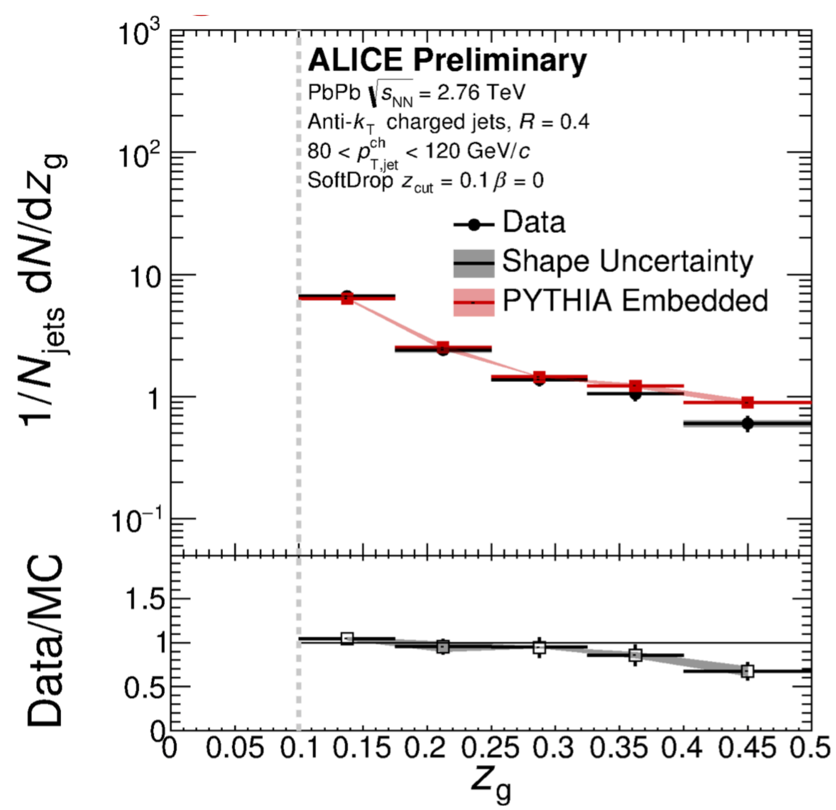
Hadron in jet fragmentation
ATLAS, arXiv:1805.05424

Momentum sharing z_g



Jet mass *ALICE, PLB 776 (2018) 249*





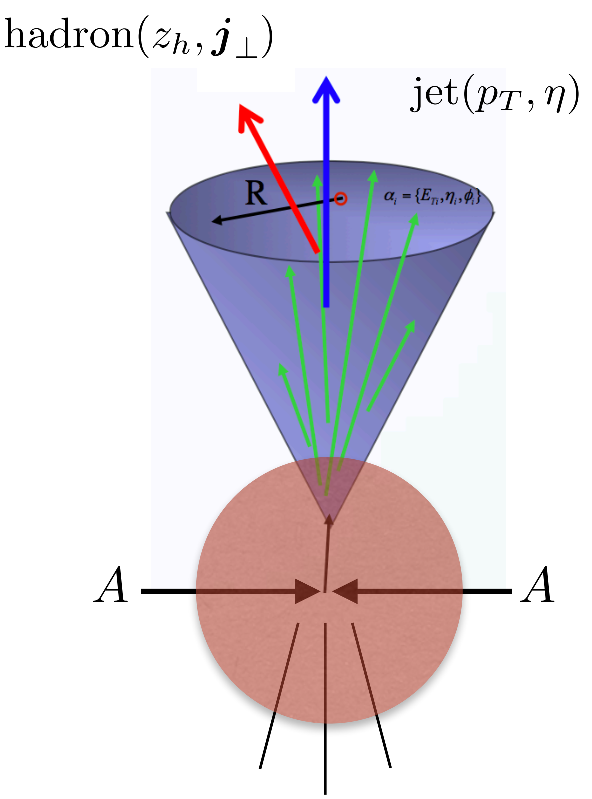
Harry Andrews, ALICE, QM18

CMS, PRL 120 (2018) 142302

Hadron in jet fragmentation in heavy-ion collisions

Chien, Kang, FR, Vitev - in preparation

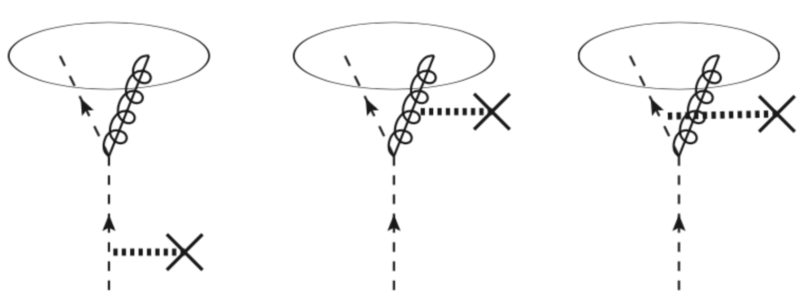
- Differential probe of the longitudinal momentum structure of jets in HI
- Baseline well understood using collinear factorization



- Medium modified jet functions *Kang, FR, Vitev `17*

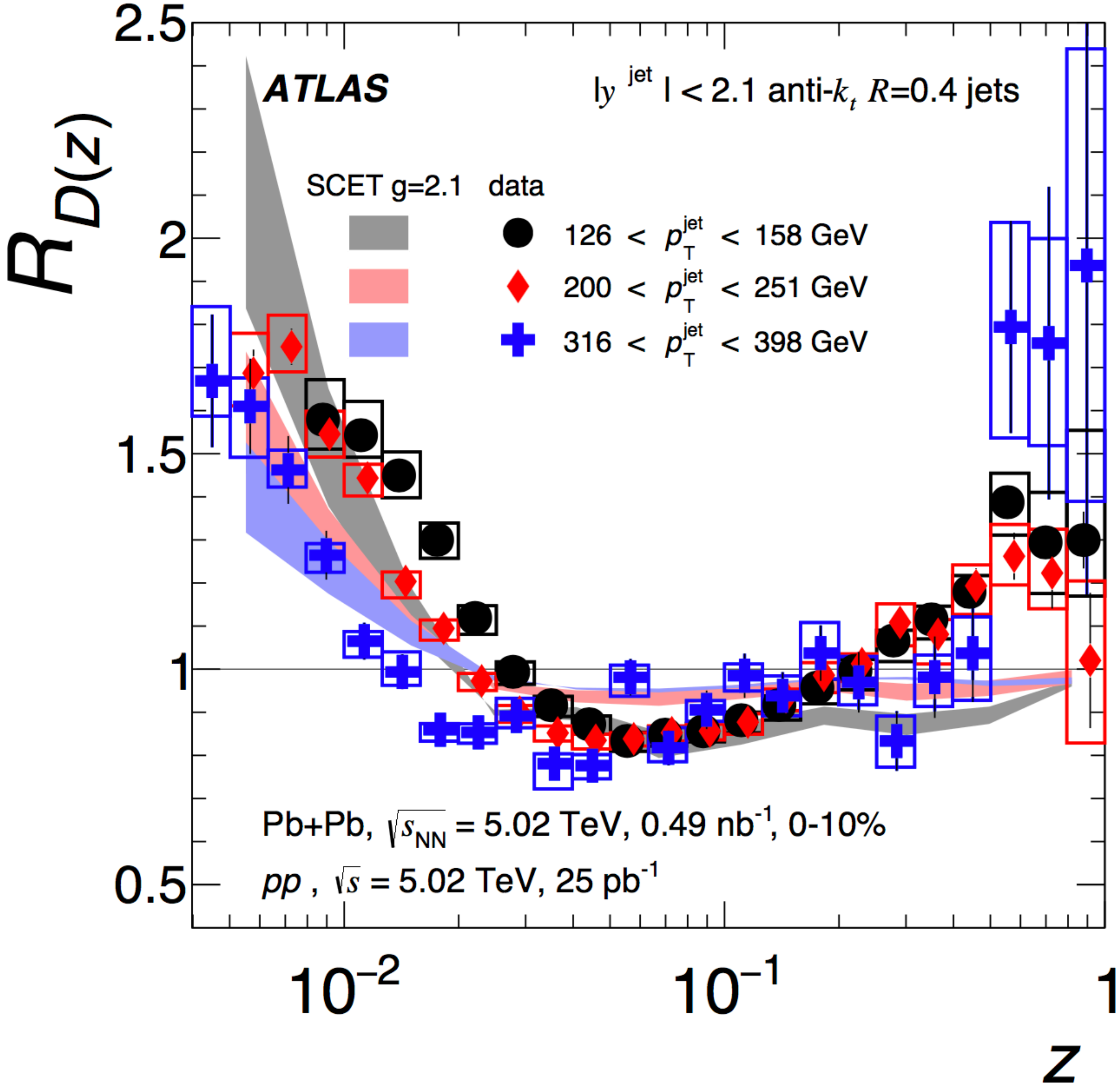
$$\frac{d\sigma^{pp\to(\text{jet }h)+X}}{d\eta\, dp_T\, dz_h} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^h$$

$$\mathcal{G}_q^{q,\text{med}}(z, z_h, p_T R, \mu) = D_q(z_h)\left[\int_{z(1-z)p_T R}^{\mu} P_{qq}(z, q_\perp)\right]_+$$
$$+\,\delta(1-z)\left[\int_{\mu_0}^{z_h(1-z_h)p_T R} dq_\perp P_{qq}(z_h, q_\perp)\right]_+ \otimes D_q(z_h)$$



Written in terms of medium modified splitting functions - SCET$_G$ *Idilbi, Majumder`09, Ovanesyan, Vitev `12*

Comparison to ATLAS data



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

Powerful probe of the QGP

↓

Constrain model calculations

ATLAS, arXiv:1805.05424

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

see also: Hybrid model Hulcher, Pablos, Rajagopal `17, EQ model Cole, Spousta `16

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TMD in jet fragmentation

Kang, Liu, FR, Xing `17
Kang, Prokudin, FR, Yuan `17

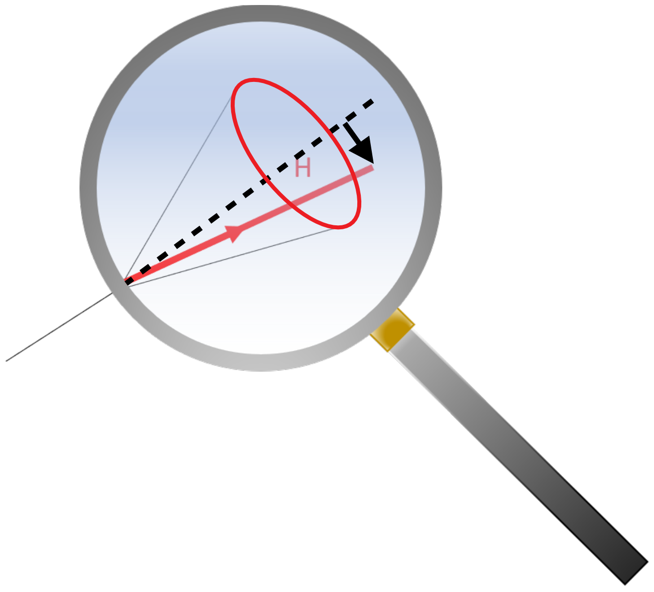
- Measure the relative transverse momentum of the hadron wrt. to the jet axis

$$F(z_h, \boldsymbol{j}_\perp; \eta, p_T, R) = \frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} \Bigg/ \frac{d\sigma^{pp\to\text{jet}X}}{dp_T d\eta}$$

longitudinal and transverse momentum z_h, $\boldsymbol{j}_\perp$

$$\mathcal{G}_c^h(z, z_h, p_T R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, p_T R, \mu) \times D_{h/i}(z_h, \boldsymbol{j}_\perp, \mu) \otimes S_i(\boldsymbol{j}_\perp, R, \mu)$$

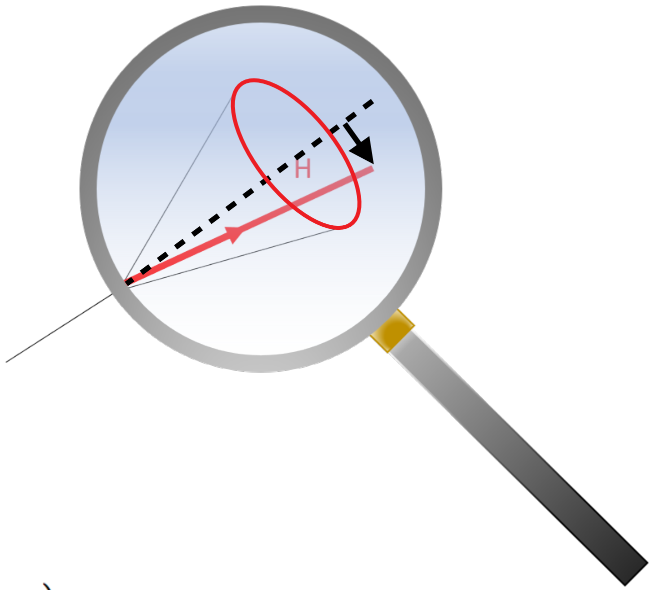
standard TMD fragmentation functions as for SIDIS and e^+e^-



- Test of universality and TMD evolution
- Constrain gluon TMD fragmentation function
- Azimuthal asymmetries at RHIC - Collins effect

see also: Bain, Makris, Mehen `16, Neill, Scimemi, Waalewijn `17
Makris, Neill, Vaidya `17

TMD in jet fragmentation



$$\mathcal{G}_c^h(z, z_h, p_T R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, p_T R, \mu) \times D_{h/i}(z_h, \boldsymbol{j}_\perp, \mu) \otimes S_i(\boldsymbol{j}_\perp, R, \mu)$$

- Proper TMD evaluated at the jet scale

$$\hat{D}_{h/i}(z_h, \boldsymbol{j}_\perp; \mu_J) = \frac{1}{z_h^2} \int \frac{b\, db}{2\pi} J_0(j_\perp b/z) C_{j\leftarrow i} \otimes D_{h/j}(z_h, \mu_{b_*}) e^{-S^i_{\rm pert}(b_*,\mu_J) - S^i_{\rm NP}(b,\mu_J)}$$

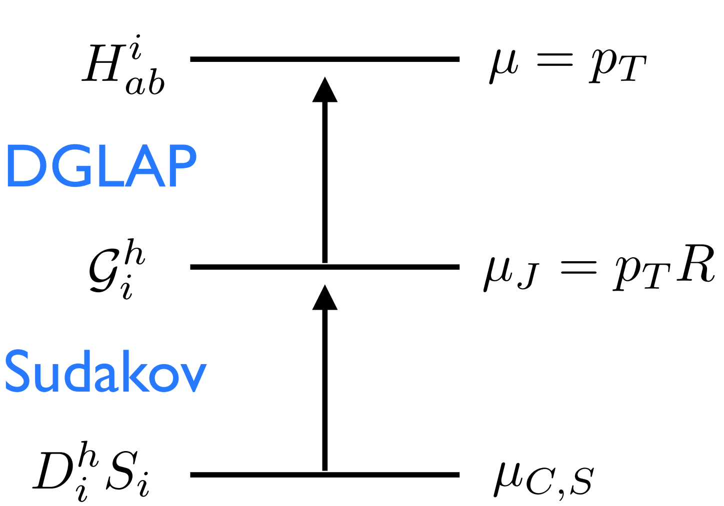
- The usual perturbative Sudakov factor

$$S^i_{\rm pert}(b_*, \mu_J) = \int_{\mu_{b_*}}^{\mu_J} \frac{d\mu'}{\mu'} \left(\Gamma^i_{\rm cusp} \ln\left(\frac{\mu_J^2}{\mu'^2}\right) + \gamma^i \right)$$

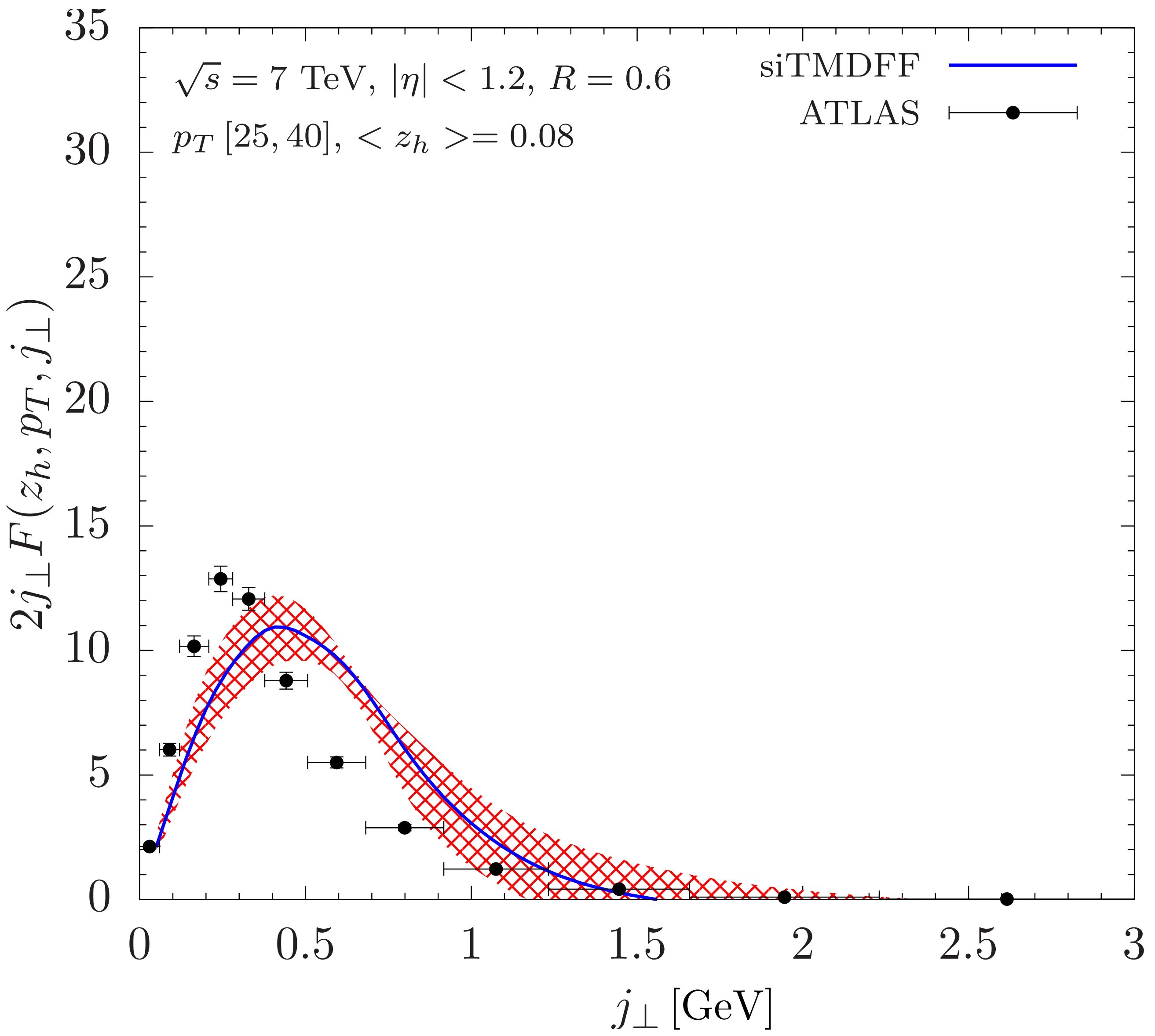
Collins, Soper, Sterman `85

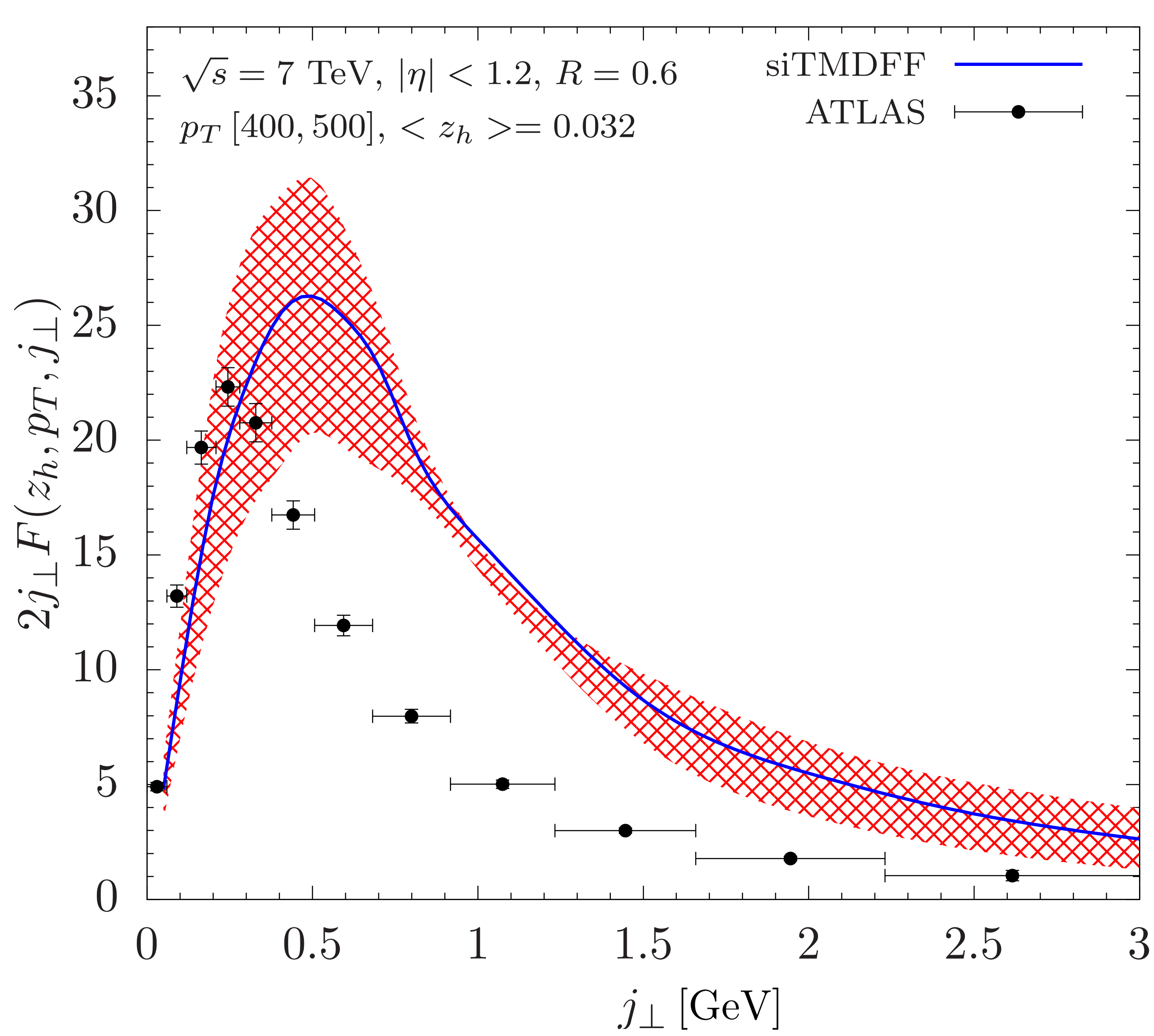
- Non-perturbative input from *Sun, Isaacson, Yuan, Yuan `14*

RG evolution



Comparison to ATLAS data





- Problematic comparison since the data is not double differential
- Varying μ, μ_J by factors of 2

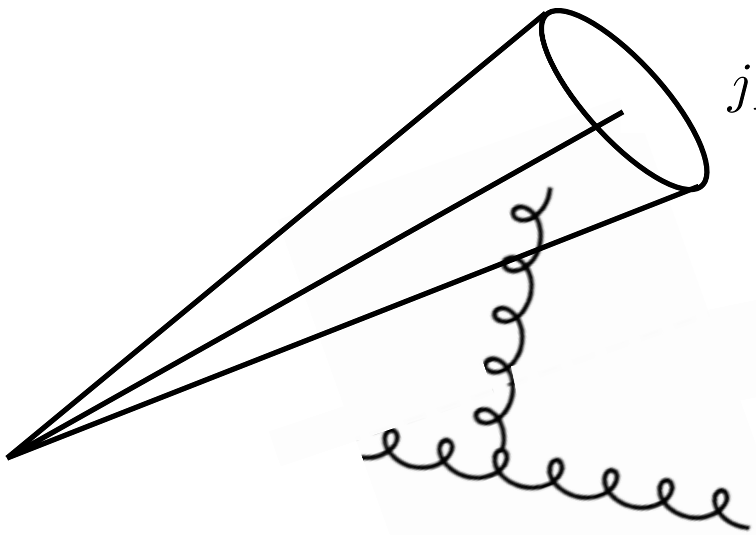
ATLAS, Eur. Phys. J C71 (2011) 1795

Non-global logarithms

Dasgupta, Salam `01,
Banfi, Marchesini, Smye `02
Larkoski, Moult, Neill `15
Becher, Rahn, Shao `17 …

- $pp \to \text{jet} + X$ at small jet radii
  Banfi, Dasgupta `04

$\alpha_s^2 \ln^2(j_\perp/(p_T R))$ contribution obtained in the strongly ordered limit



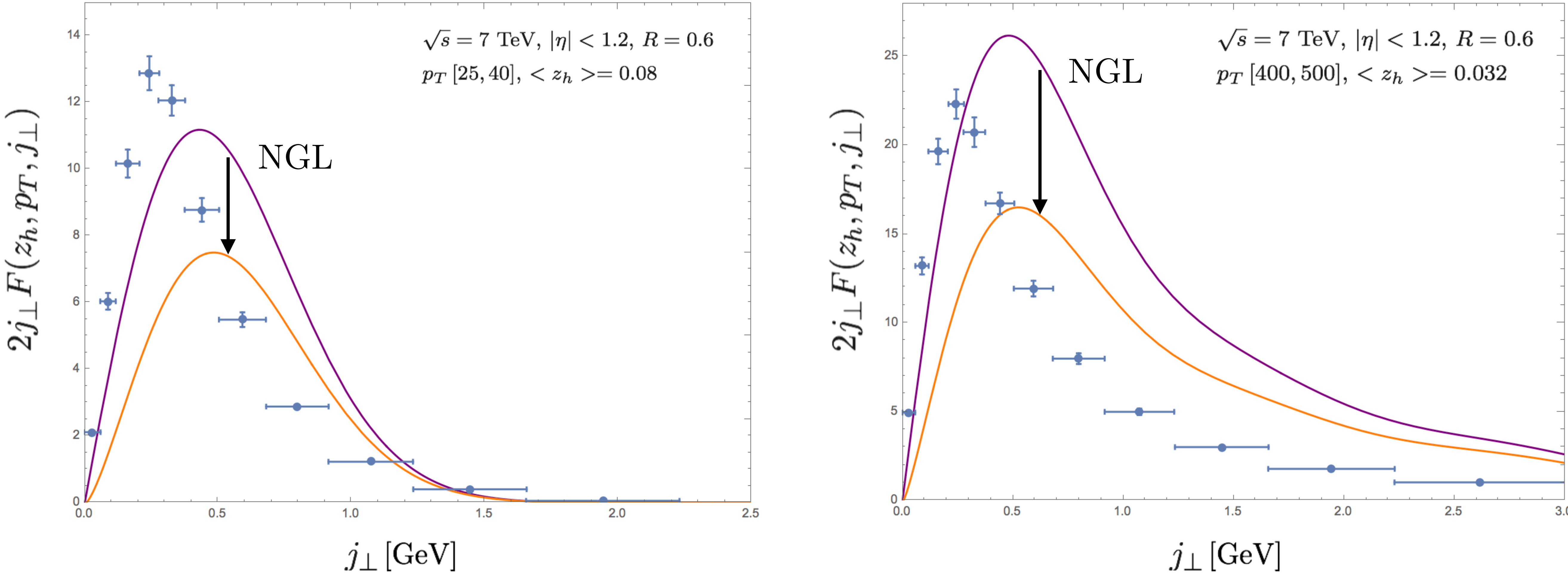
- Include higher order corrections $\alpha_s^n \ln^n(j_\perp/(p_T R))$
  Leading logarithmic, leading color accuracy
  - Monte-Carlo *Dasgupta, Salam `01*
  - BMS equation *Banfi, Marchesini, Smye `02*
  - Fixed order expansions *Schwartz, Zhu `14*
  - Beyond leading color *Hatta, Ueda `13*

boosted version of the e^+e^- hemisphere jet mass case
Dasgupta, Salam `01

$$d\sigma = \sum_{abcd} f_a\, f_b\, H_{ab}^c\, \mathcal{H}_{cd}\, \hat{\mathcal{D}}_d \times S_{d,\mathrm{NGL}}$$

Non-global logarithms

ATLAS, Eur. Phys. J C71 (2011) 1795



- NGLs included using the MC method
- Important to have results from other experiments like RHIC and BELLE

Kang, Lee, Liu, Neill, FR - in preparation

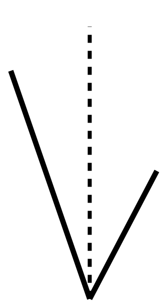
In-jet TMD distributions

- Overview of in-jet TMD distributions with respect to a given axis

Standard jet axis

Bain, Makris, Mehen `16
Kang, Liu, FR, Xing `17

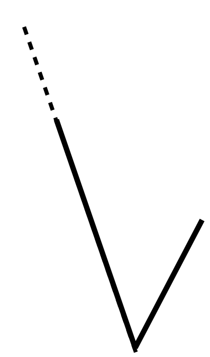
Soft sensitivity,
related to standard TMDs



Recoil free axis
e.g. Winner-take-all

Neill, Scimemi, Waalewijn `17

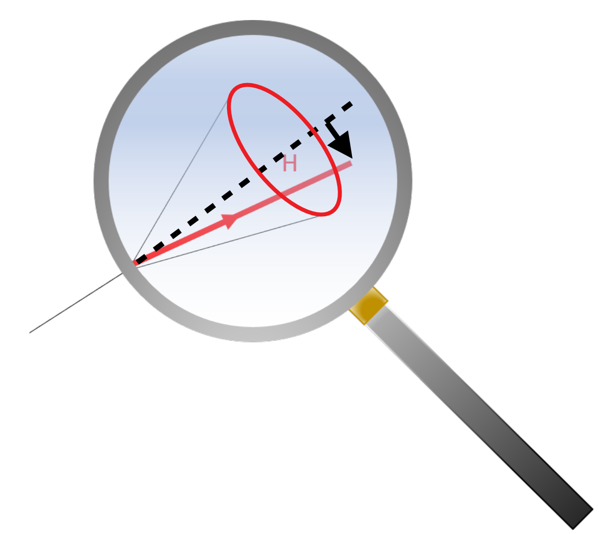
Collinear factorization only



Standard jet axis

Makris, Neill, Vaidya `17

grooming (soft drop)



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Conclusions

- Longitudinal and transverse energy distribution of jets
- New constraints on fragmentation functions
- Non-global logarithms
- Relevant for the LHC, RHIC, HERA, EIC
- Polarization
- Probe of the QGP