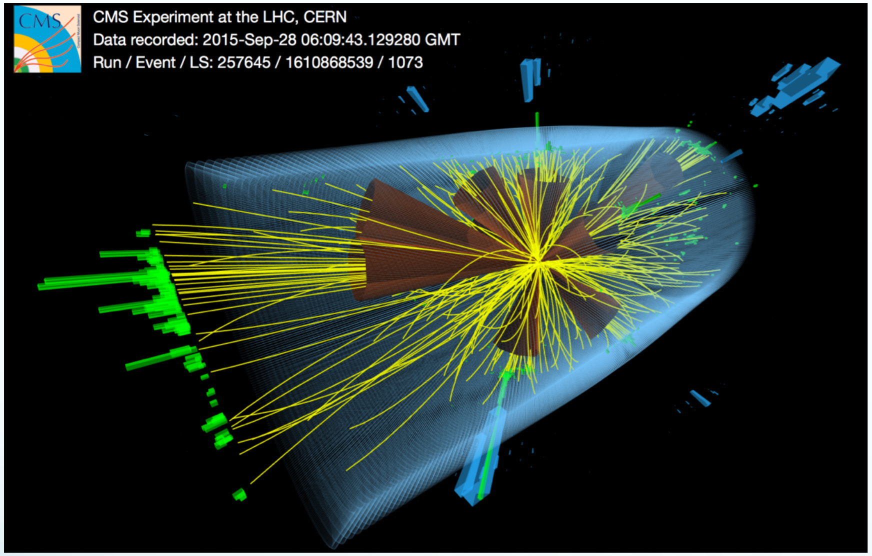
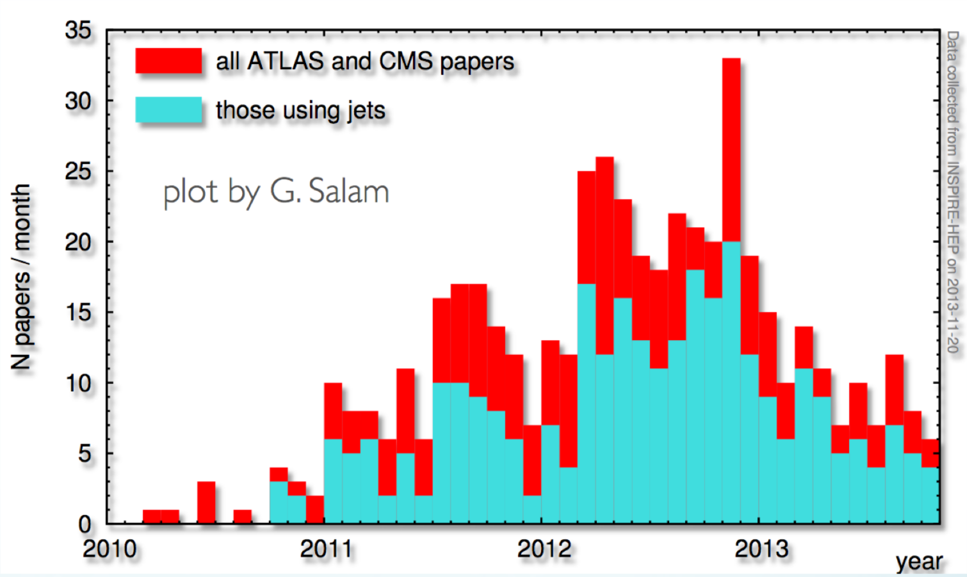
Recent developments in jet substructure theory

Zhongbo Kang
UCLA

7th Edition of the Large Hadron Collider Physics Conference
May 20 - 25, 2019

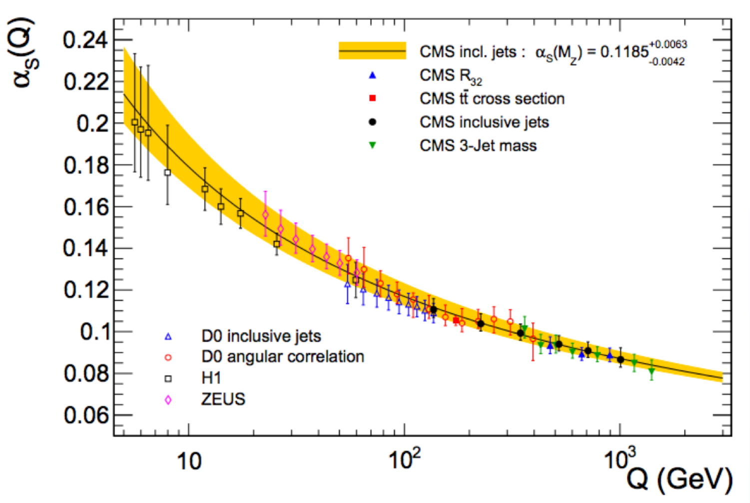
Jets are everywhere at the LHC

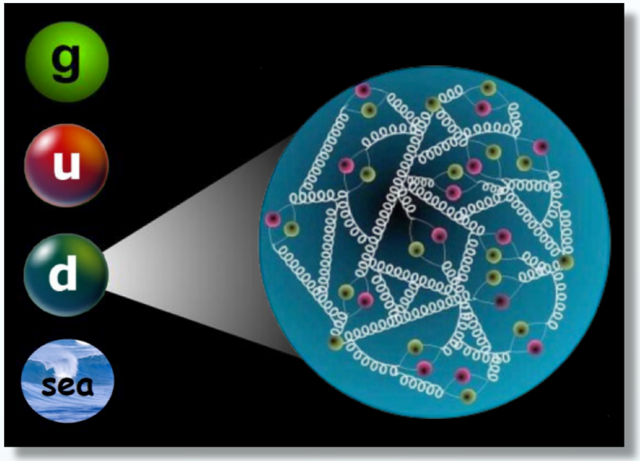




Why do we care about jets?

- Jets are inherently interesting
  - They are emergent phenomena and can teach us about QFT
- Extract fundamental QCD parameters
  - e.g., strong coupling constant

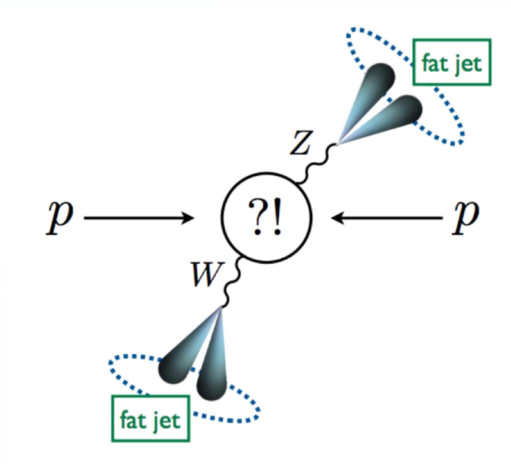




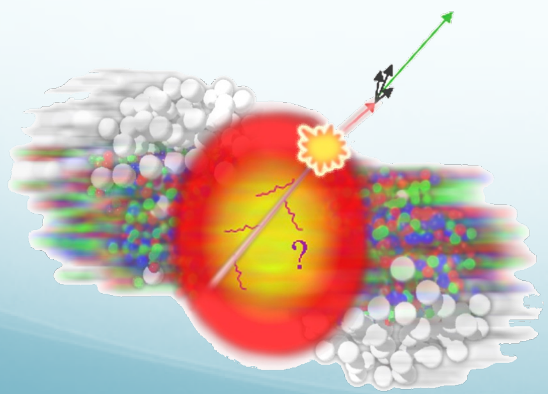
- Constrain non-perturbative quantities
  - Parton distribution functions
  - Fragmentation functions

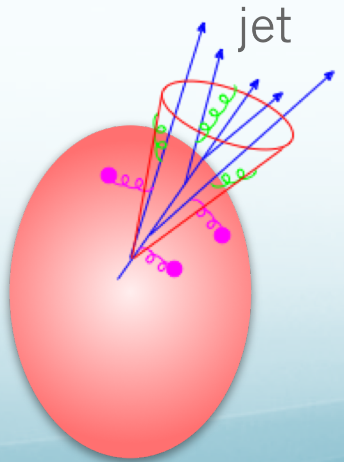
Jets for BSM and heavy ion physics

- Jet substructure: radiation pattern to distinguish BSM particle jet from QCD jets



- Jets as probes of quark-gluon plasma

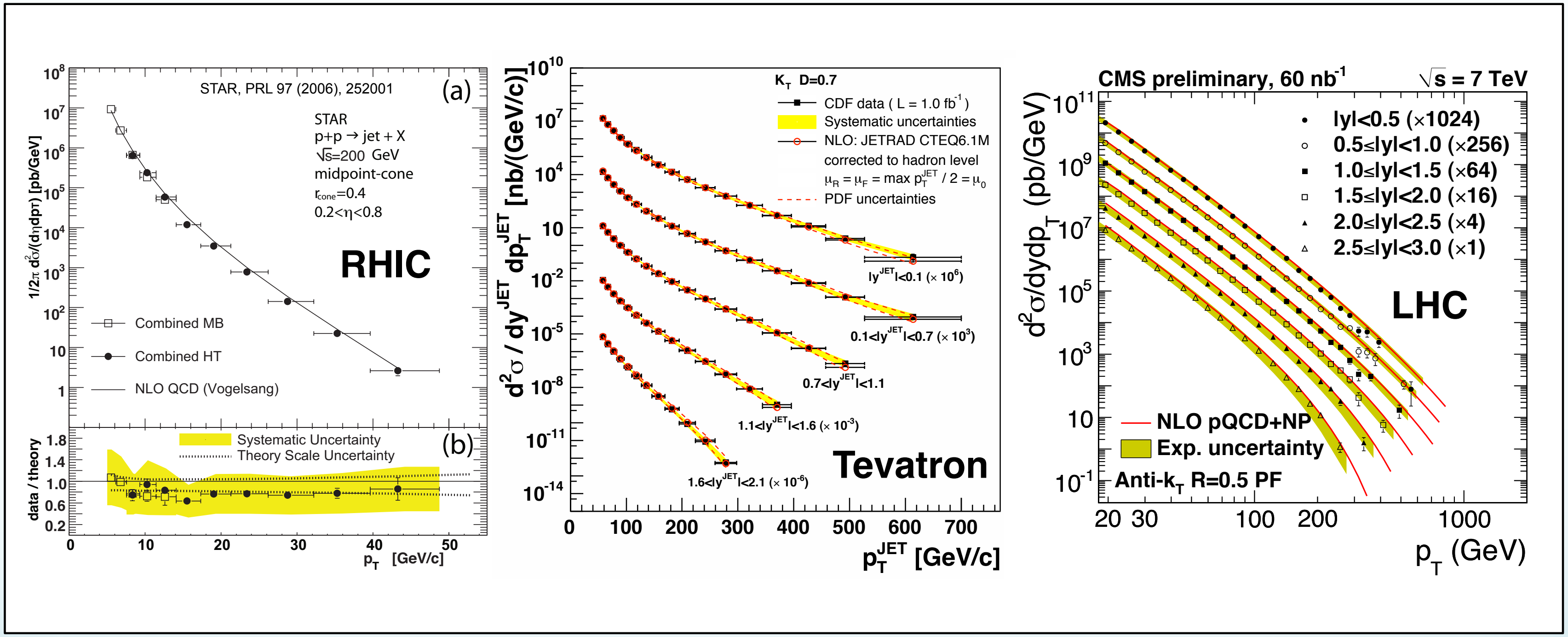




Lots of data: inclusive jet cross section

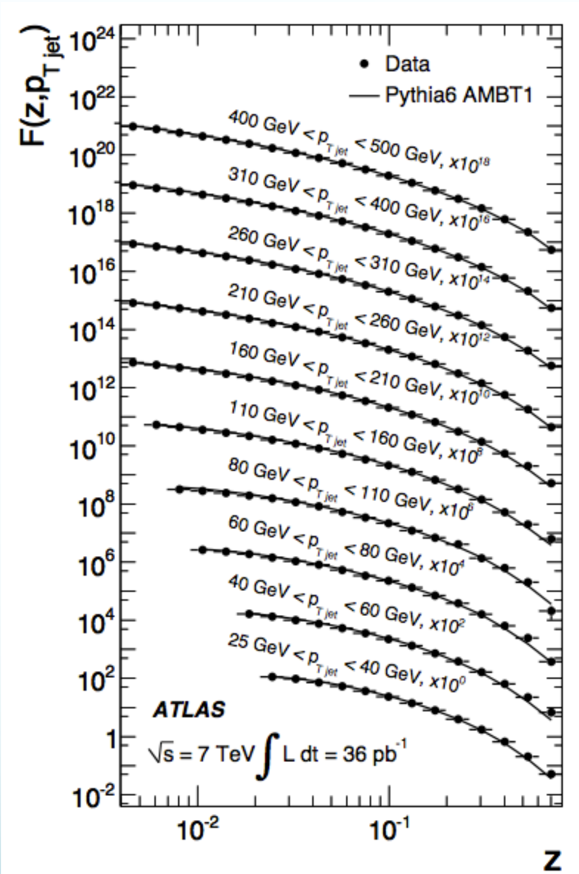
- Single inclusive jet cross sections

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

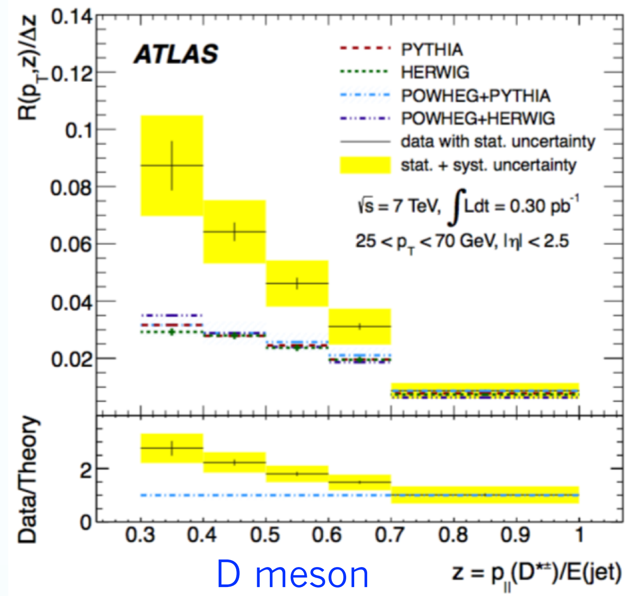


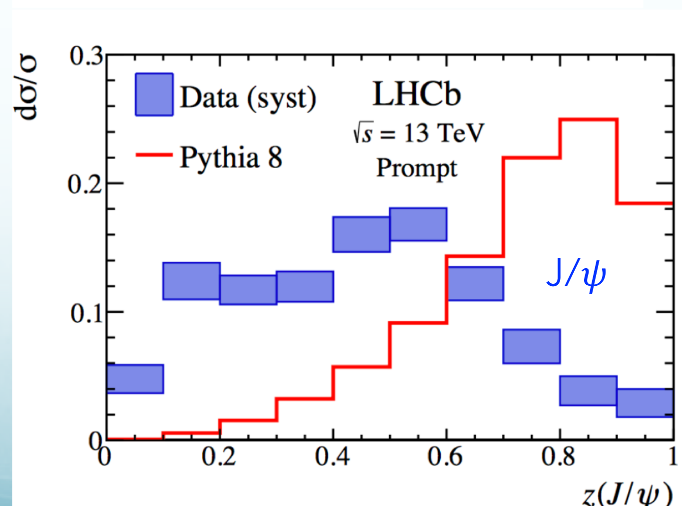
Lots of data: jet fragmentation function

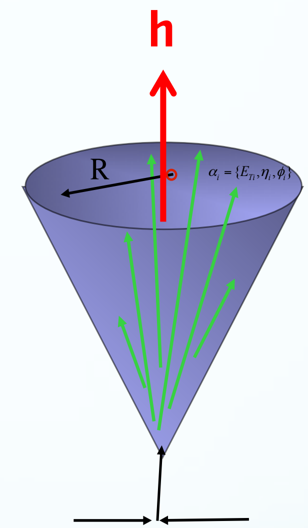
- Hadron distribution inside a jet $p + p \to \text{jet}\,(h) + X$



Light charged hadrons



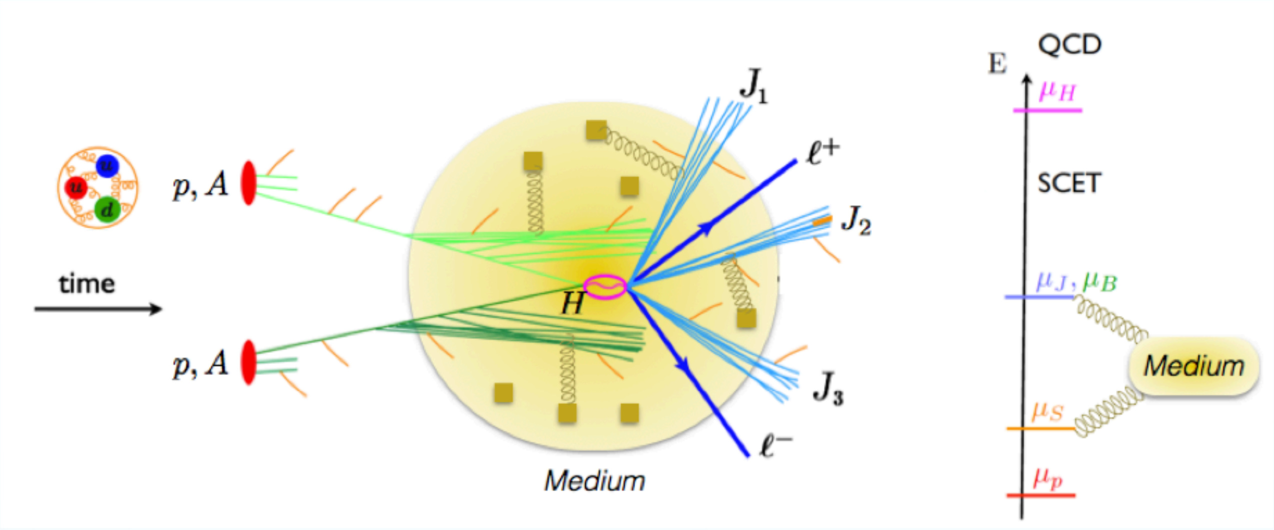




$$z_h = \frac{E_h}{E_{\text{jet}}}$$

Theory: jet substructure in p+p

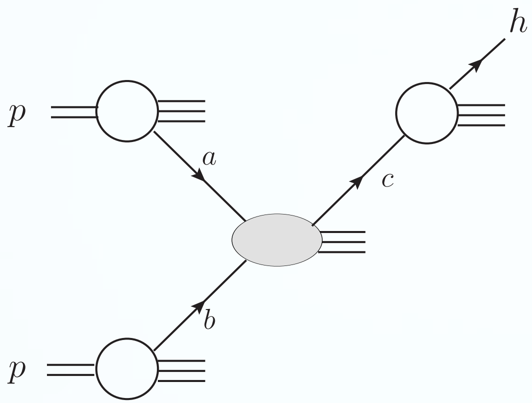
- Studying jet substructure in QCD is generally a complicated problem, due to its multi-scale nature
  - Fixed-order computation usually fails

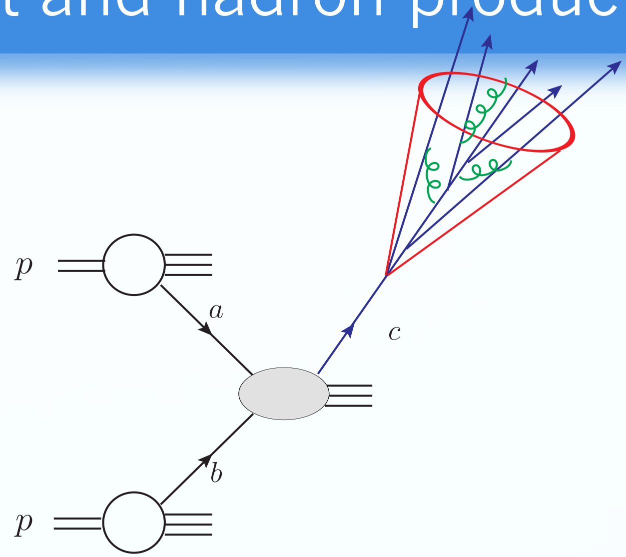


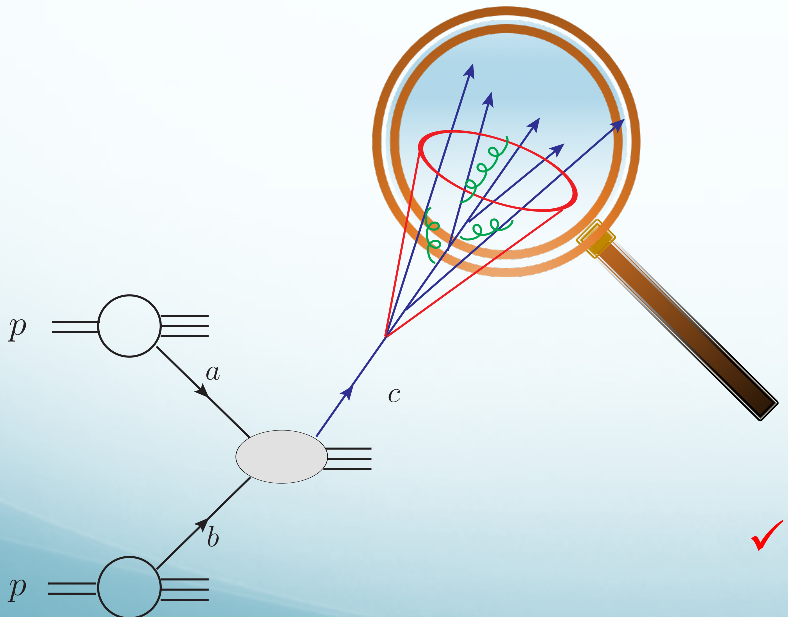
- Modern effective field theory (e.g., SCET) is here to rescue
  - Hard mode $p^\mu \sim Q(1,1,1)$
  - Collinear mode $p^\mu \sim Q(1,\lambda^2,\lambda)$ $p^\mu = (p^+, p^-, p_\perp)$
  - Soft mode $p^\mu \sim Q(\lambda,\lambda,\lambda)$

$$\sigma = H \otimes S \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j$$

A unified framework for jet and hadron production







$$\frac{d\sigma^{pp\to hX}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h(z,\mu)$$

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(z, p_T R, \mu)$$

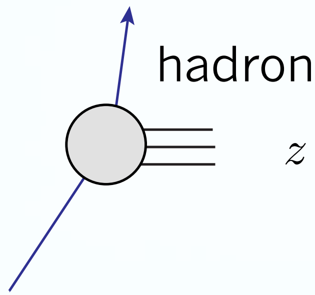
$$\frac{d\sigma^{pp\to \text{jet}(\tau)X}}{dp_T d\eta} \sim f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c(z, p_T R, \tau, \mu)$$

✓ Same hard functions, telling us the quark and gluon jet ratios order by order in pQCD

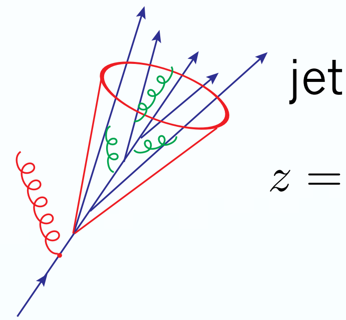
Kang, Ringer, Vitev, 1606.06732, 1606.07063, Dai, Kim, Leibovich, 1606.07411, see also, Kaufmann, Mukherjee, Vogelsang, 1506.01415

What are these jet functions?

- They are usually referred to as “semi-inclusive jet function”



$$z = \frac{p_{\rm h}^{+}}{p_{\rm parton}^{+}}$$



$$z = \frac{p_{\rm jet}^{+}}{p_{\rm parton}^{+}}$$

- They follow DGLAP evolution equation
  - All jet substructures are contained in these functions

$$\mu\frac{d}{d\mu}D_i^h(z,\mu) = \sum_j P_{ji}\otimes D_j^h(z,\mu)$$

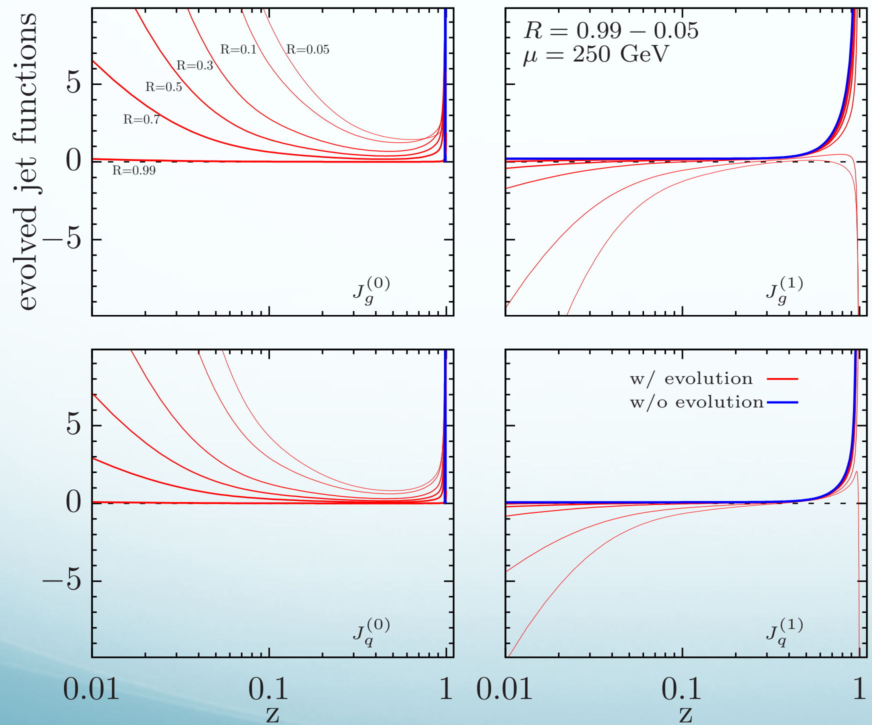
$$\mu\frac{d}{d\mu}J_i(z,p_T R,\mu) = \sum_j P_{ji}\otimes J_j(z,p_T R,\mu)$$

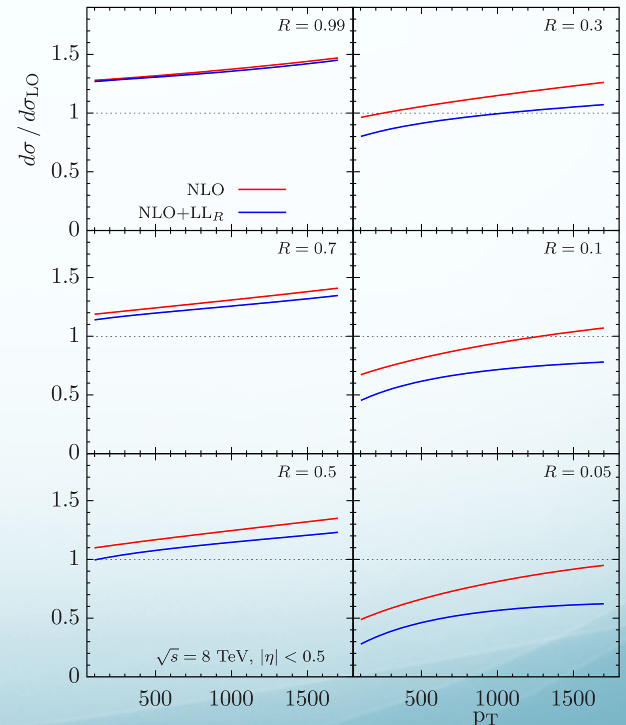
$$\mu\frac{d}{d\mu}\mathcal{G}_i(z,p_T R,\tau,\mu) = \sum_j P_{ji}\otimes \mathcal{G}_j(z,p_T R,\tau,\mu)$$

Ln(R) resummation

- Natural scale for jet functions: p_T*R
- Jet radius resummation: $(\alpha_s \ln R)^n$

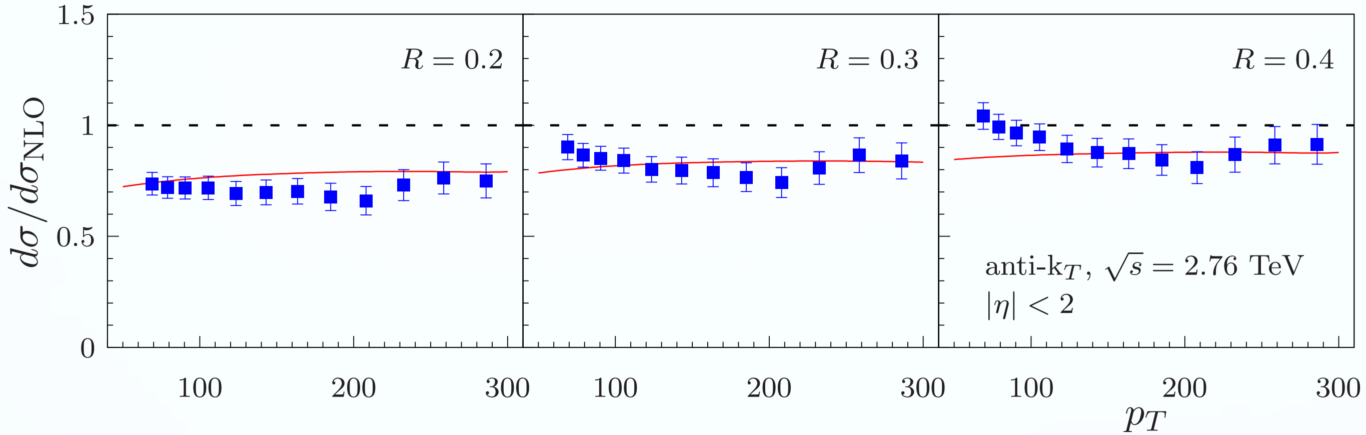
Kang, Ringer, Vitev, 1606.06732





Effect of ln(R) resummation

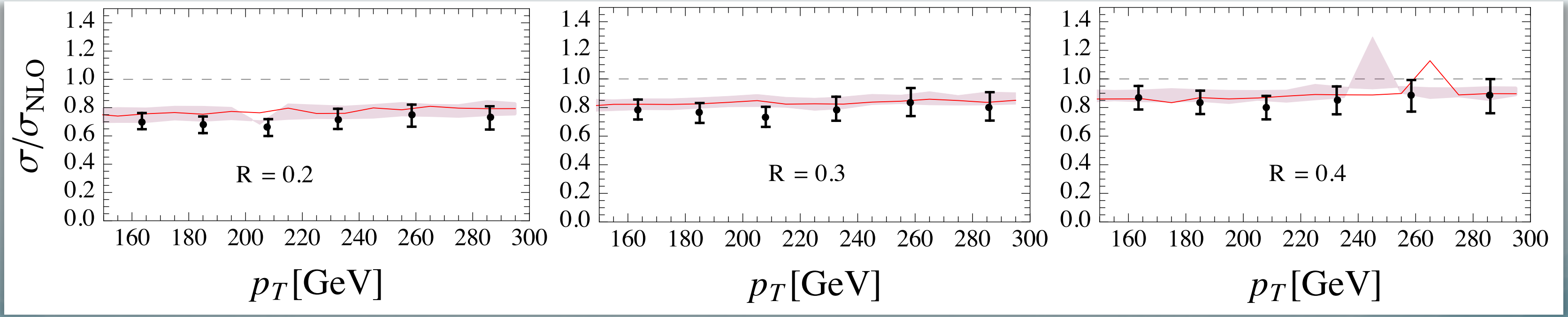
- The ln(R) is the main source for the discrepancy:



CMS, 1609.05383

Kang, Ringer, Vitev, PLB 2017

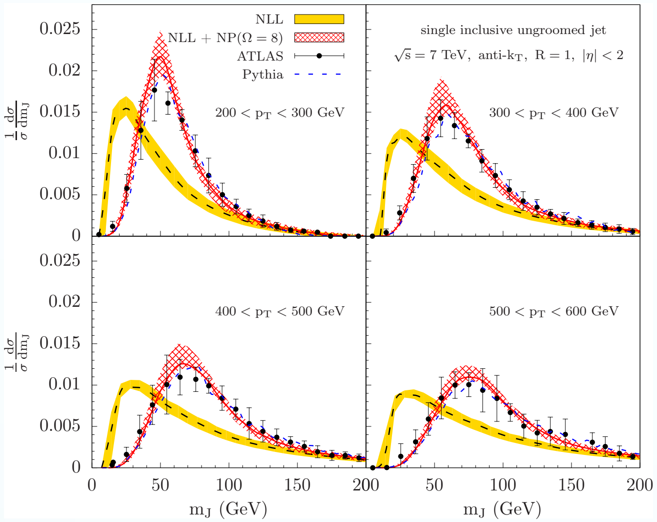
- Threshold resummation further improve the agreement

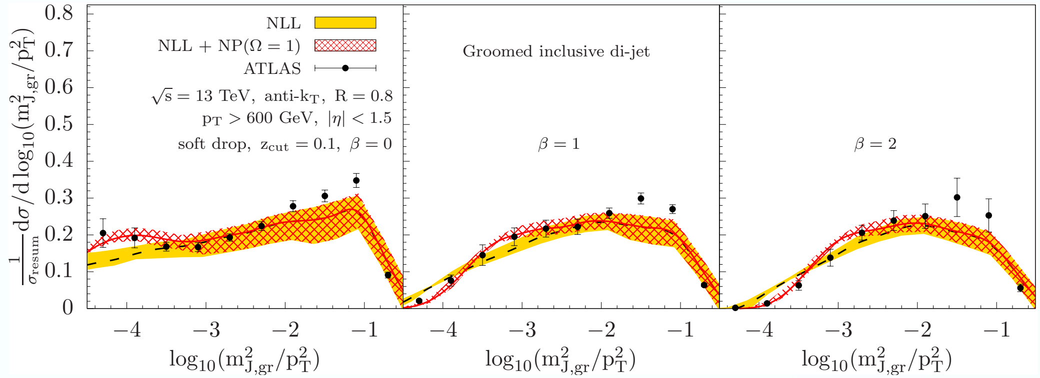


Liu, Moch, Ringer, PRL 2017

Many jet substructures: just mentioning

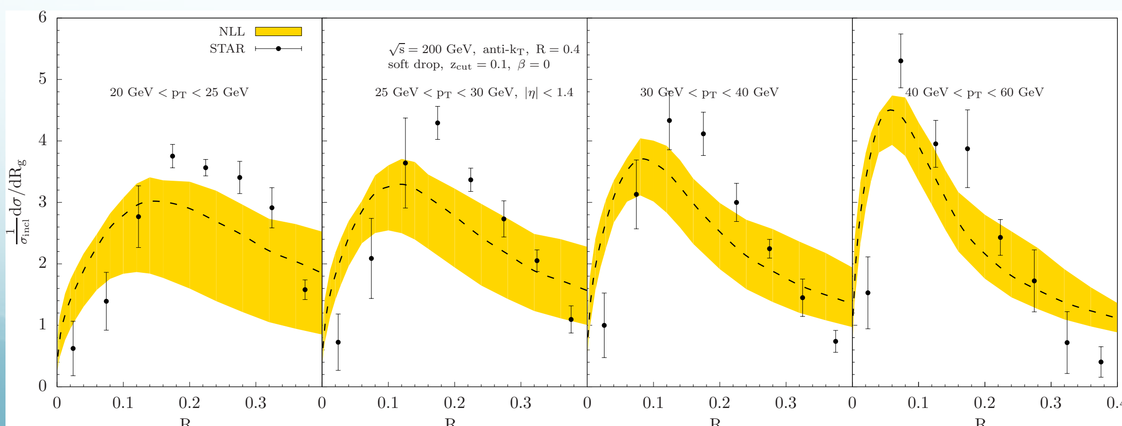
- Jet mass with and without grooming (angularity, shape, ...)

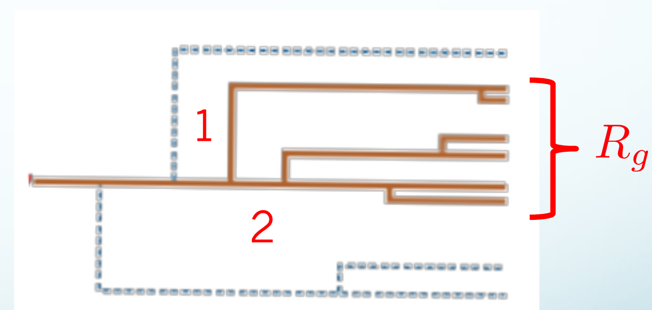




Kang, Lee, Liu, Ringer, 1803.03645

- Soft-drop groomed jet radius (z_g, ...)

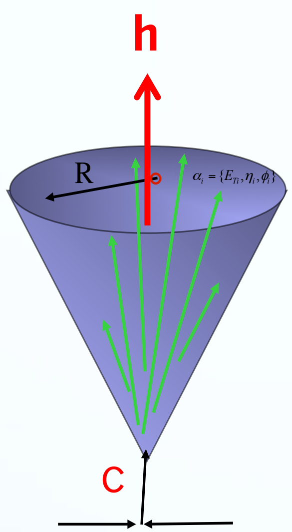




Kang, Lee, Liu, Ringer, in preparation

Jet fragmentation function

- First produce a jet, and then further look for a hadron inside the jet



$$F(z_h, p_T) = \frac{d\sigma^h}{dy dp_T dz_h} \Big/ \frac{d\sigma}{dy dp_T}$$

$$z_h = p_T^h / p_T$$

$$z = p_T / p_T^c$$

Kang, Ringer, Vitev, JHEP 2016

- Just like the single inclusive jet production, we have
  - Semi-inclusive fragmenting jet function

$$\frac{d\sigma}{dy dp_T dz_h} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, R, \mu)$$

Two DGLAPs

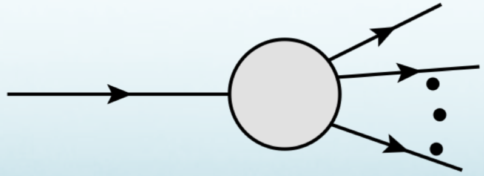
- Again DGLAP evolution: evolution is for variable z

$$\mu \frac{d}{d\mu} \mathcal{G}_i^h(z, z_h, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}\right) \mathcal{G}_j^h(z', z_h, \mu)$$

- Relation to standard FFs: relevant to variable z_h

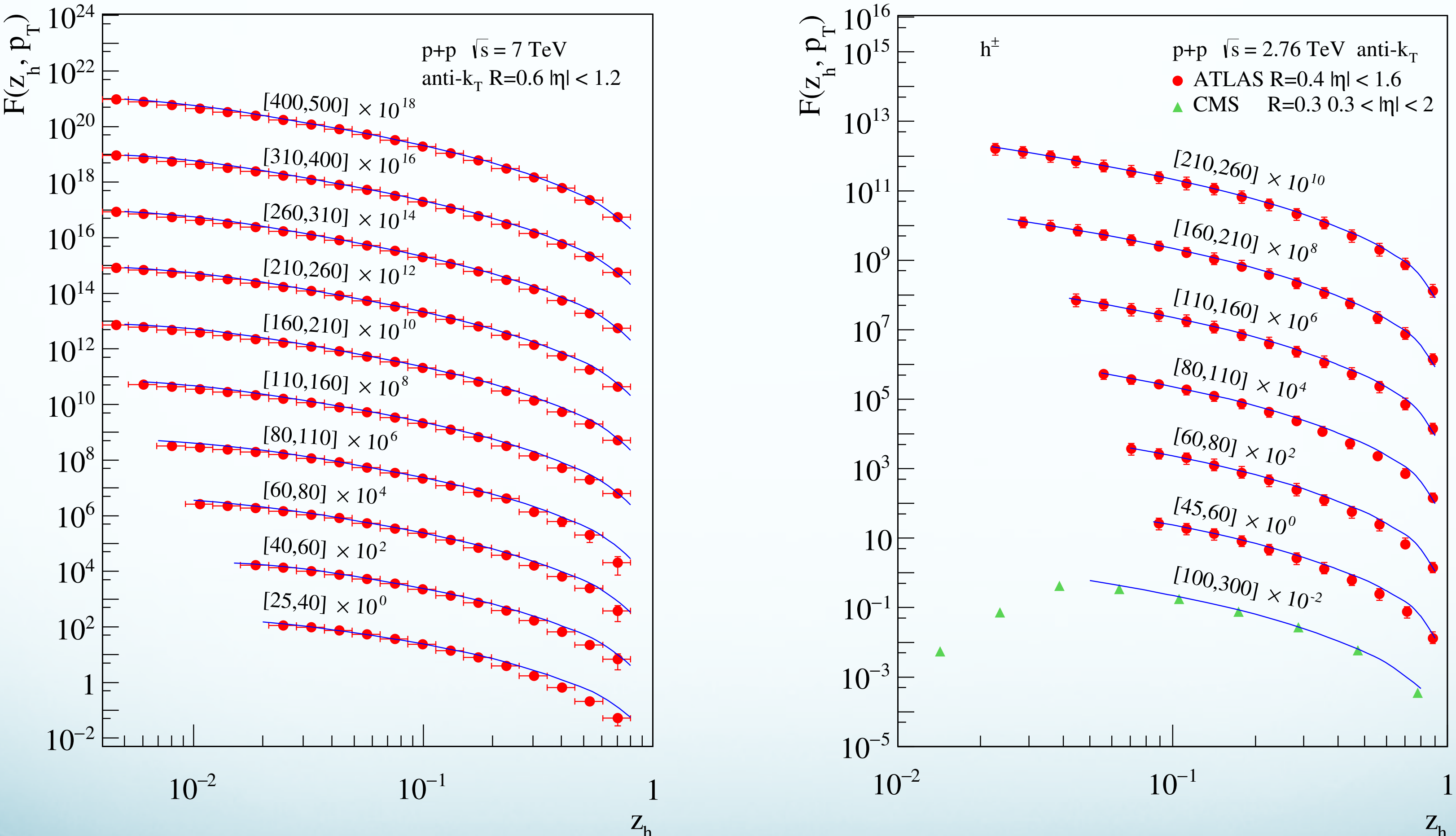
$$\mathcal{G}_i^h(z, z_h, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h', \mu) D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$

- Fragmentation function: probability for a quark/gluon converted itself into a hadron



Some interesting phenomenology

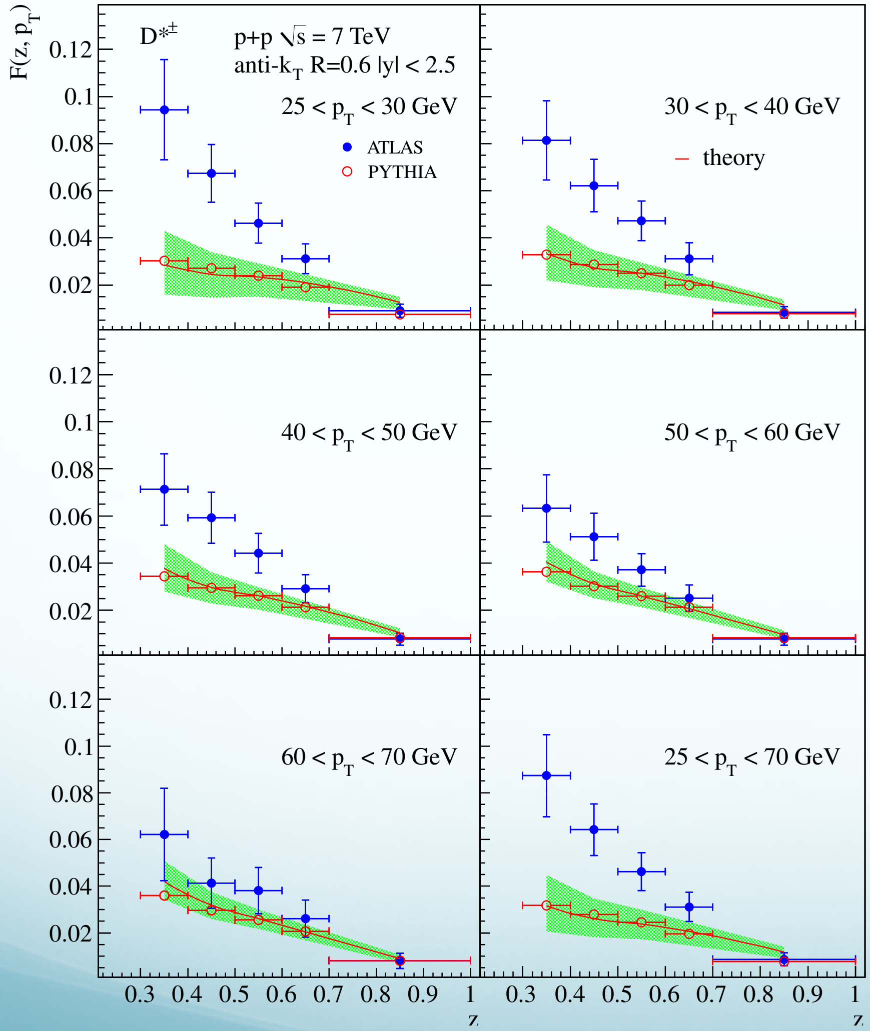
- Works pretty well in comparison with experimental data



Kang, Ringer, Vitev, arXiv:1606.07063

Jet fragmentation function for heavy meson

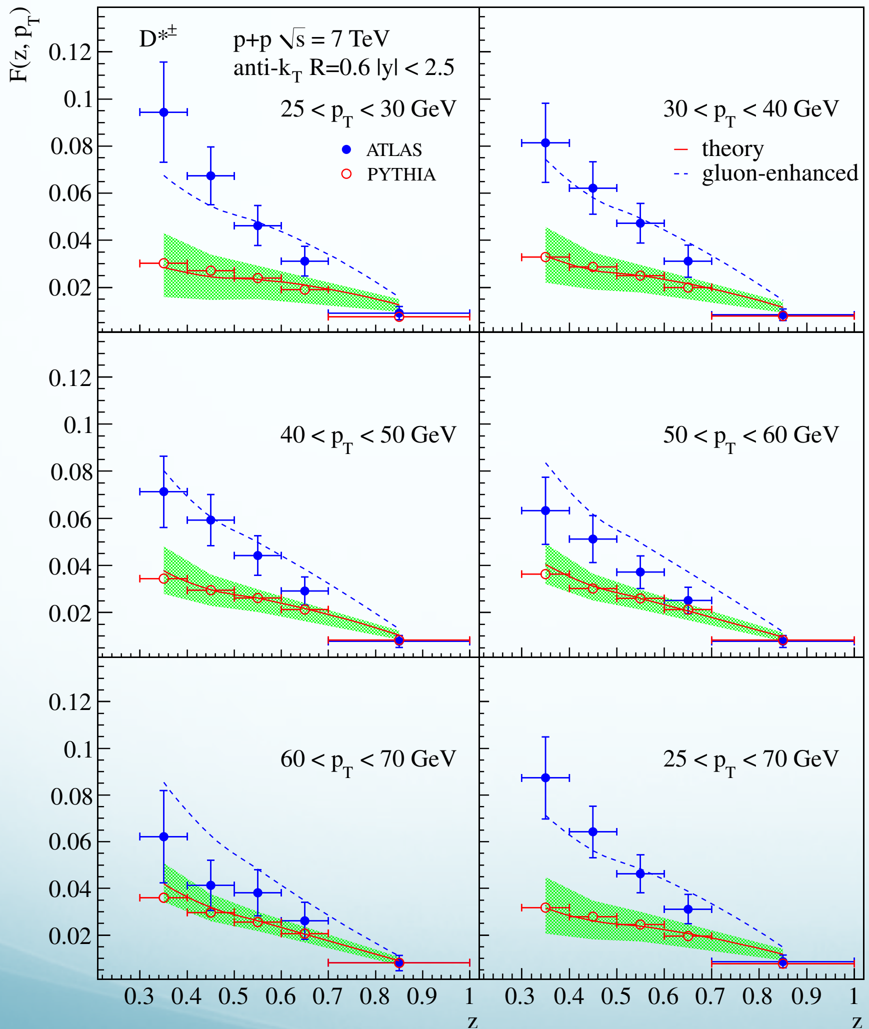
- Using D meson FFs fitted from e+e- data Kneesch, Kniehl, Kramer, Schienbein, 08



Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing, 1512.06851, JHEP 16

Jet fragmentation function for heavy meson

- Using D meson FFs fitted from e+e- data Kneesch, Kniehl, Kramer, Schienbein, 08



Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing, 1512.06851, JHEP 16

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

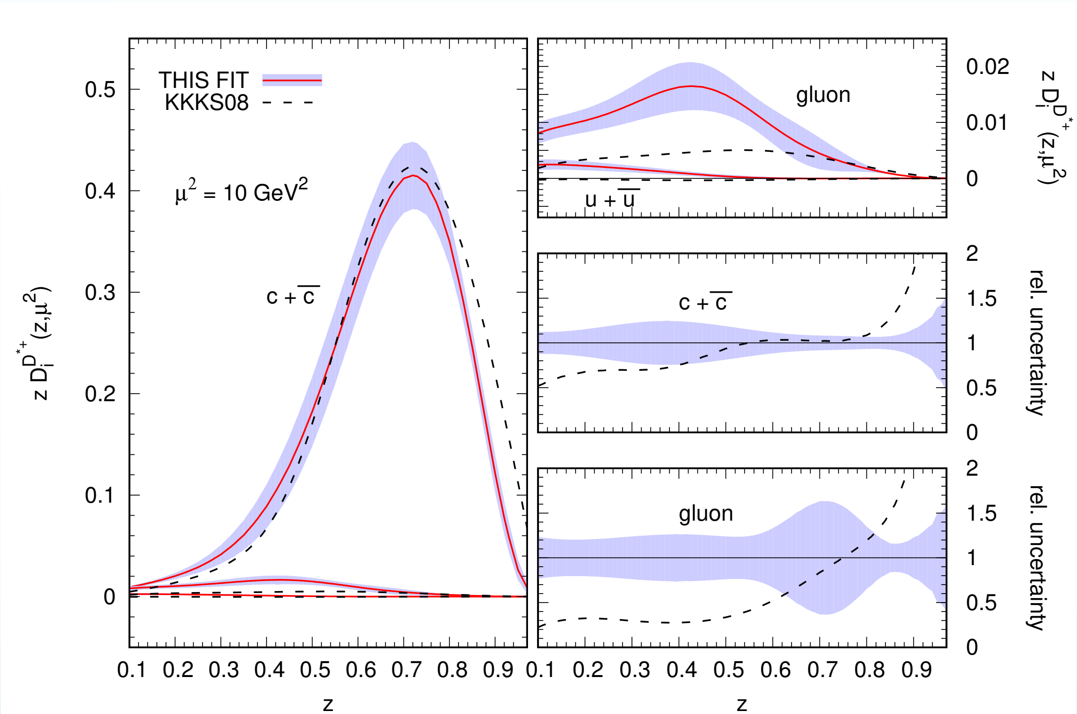
New fit of D-meson FFs needed

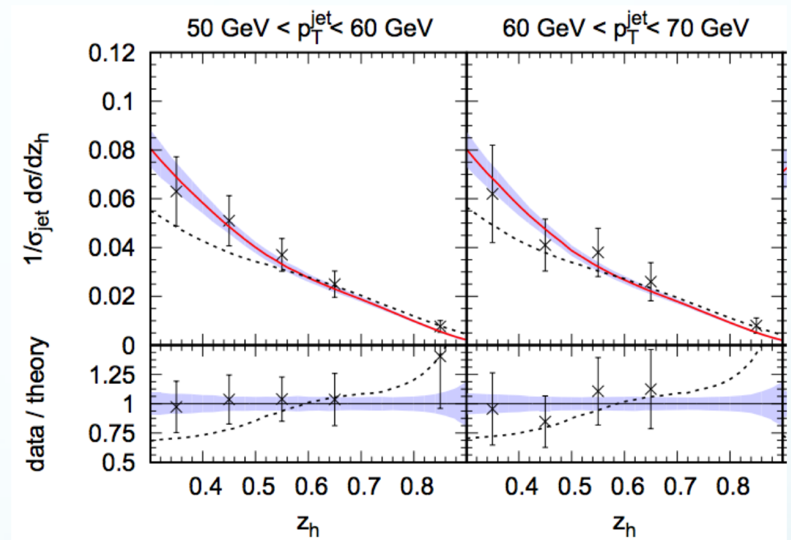
MC event generator can NOT completely replace analytical type theory calculations, they are complimentary to each other

A new global analysis of FFs

- New fit of D-meson FFs

New fit of D-meson FFs:
Stratmann, et.al., PRD 2017



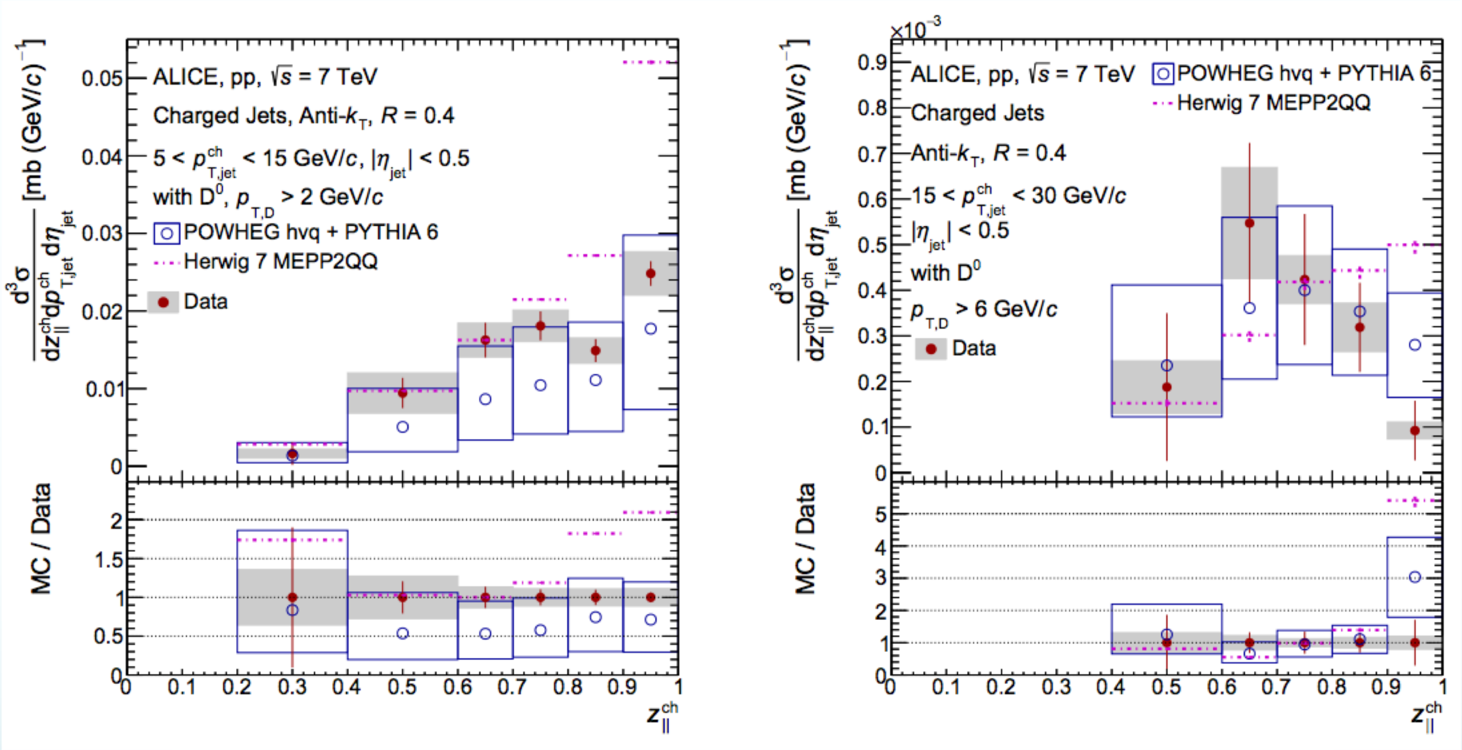


Confirms our earlier guess

D meson in charmed jets

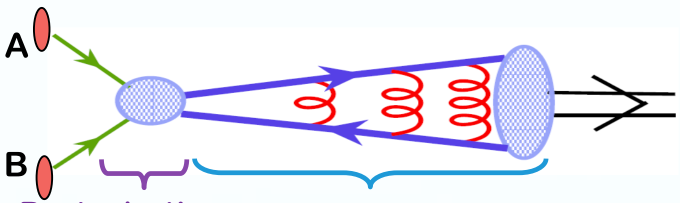
- Another opportunity for charm-to-D fragmentation functions

ALICE, 1905.02510

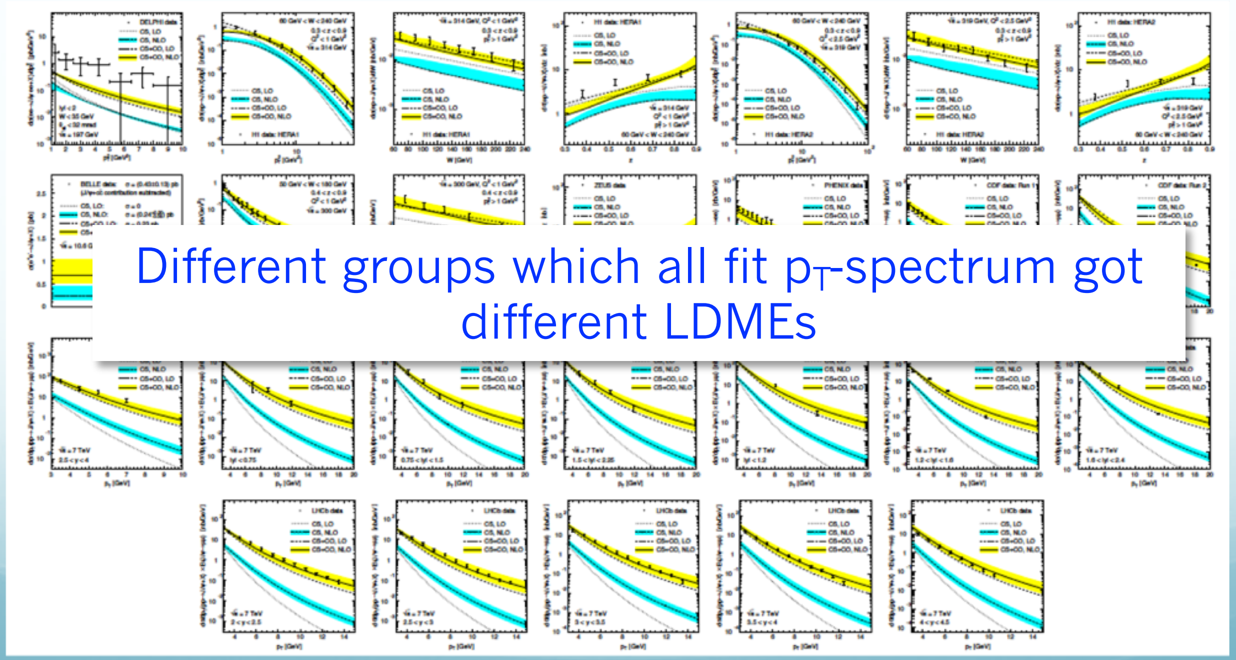


Quarkonium puzzle

- Non-relativistic QCD (NRQCD) theory for quarkonium production
  - Long-distance matrix elements (LDMEs)



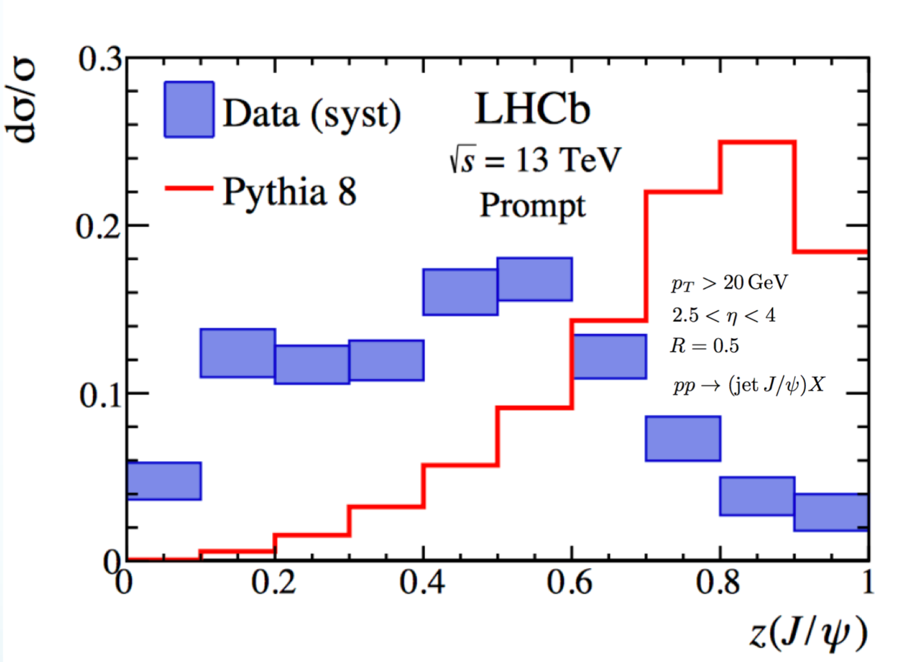
$$\sigma(gg \to J/\psi + X) = \sum_n \sigma(gg \to c\bar{c}(n) + X)\langle \mathcal{O}^{J/\psi}(n) \rangle$$

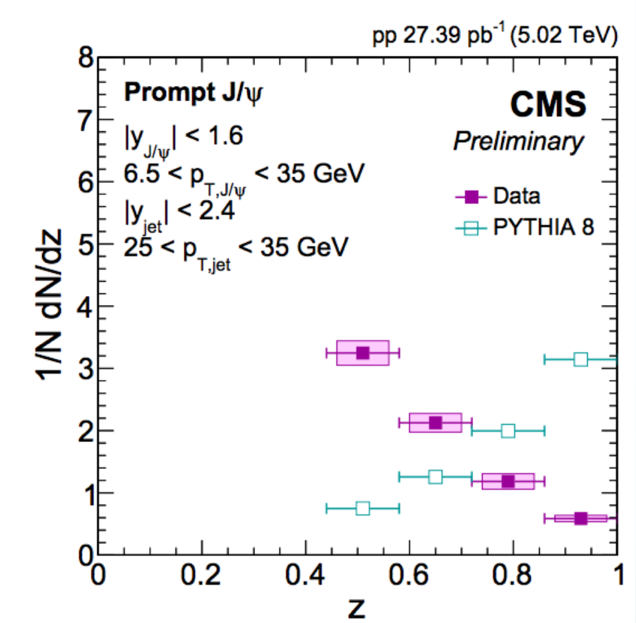


Different groups which all fit p_T-spectrum got different LDMEs

Quarkonium production in the jet

- J/ψ-in-jet measurement at LHC
  - It is better to be normalized by jet cross section (not inclusive J/ψ one)





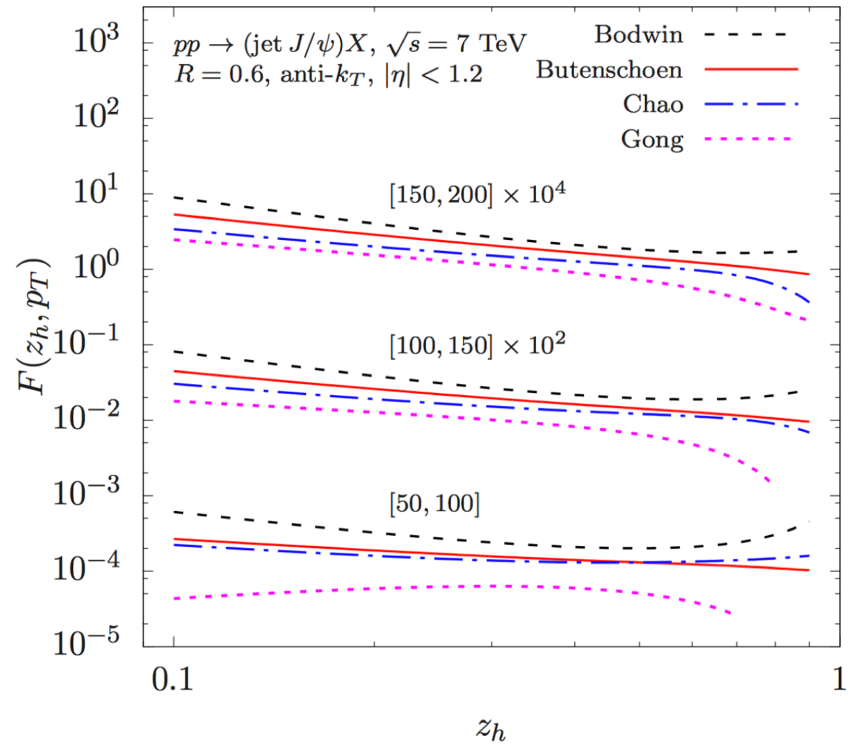
Production: Baumgart, Leibovich, Mehen, Rothstein, JHEP 14, PRL17
Polarization: Kang, Ringer, Xing, et.al., PRL17

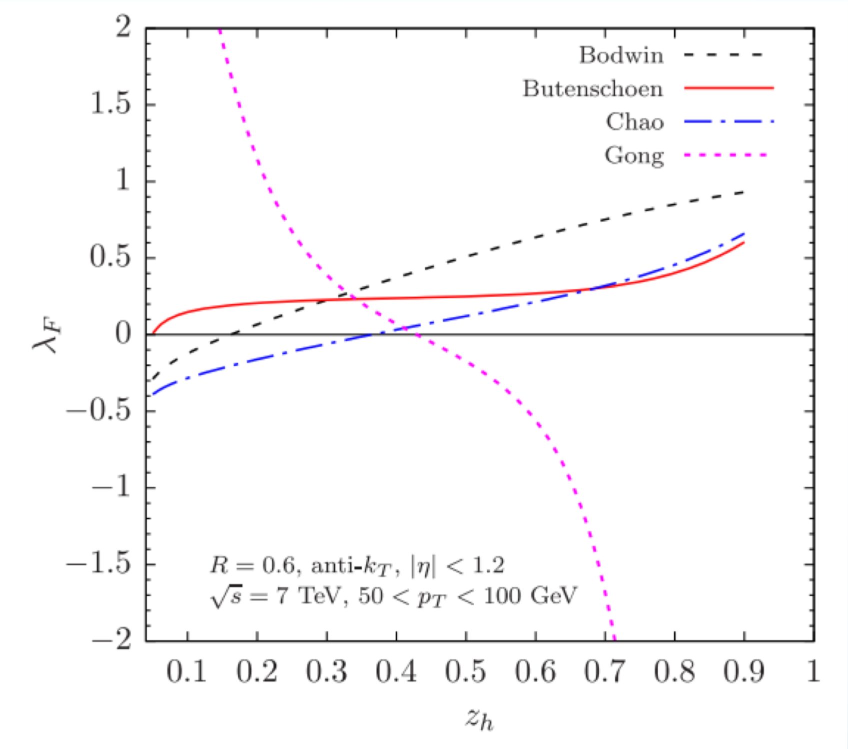
$$\frac{d\sigma^{J/\psi(\to\ell^+\ell^-)}}{d\cos\theta} \propto 1 + \lambda_F \cos^2\theta$$

$$\lambda_F = \begin{cases} +1, & \text{transversely polarized} \\ -1, & \text{longitudinally polarized} \end{cases}$$

J/ψ production and polarization in jets

- More differential than inclusive J/ψ p_T spectrum, and can discriminate different NRQCD parameterizations
  - p_T distribution alone cannot reliably fix all 3 CO LDMEs





Kang, Qiu, Ringer, Xing, Zhang, PRL 2017
See also the study by Bain, Dai, Leibovich, Makris, Mehen, PRL 2017

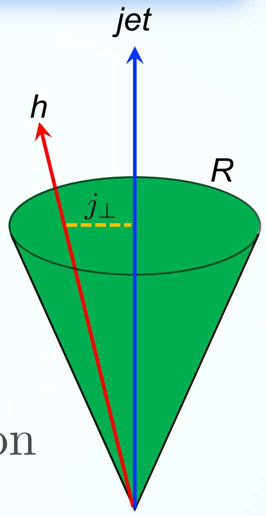
TMD hadron distribution inside the jet?

- Definition

$$F(z_h, j_\perp; p_T) = \frac{d\sigma^h}{dp_T d\eta dz_h d^2 j_\perp} \Big/ \frac{d\sigma}{dp_T d\eta}$$

$$z_h = p_T^{\rm h}/p_T^{\rm jet}$$

$j_\perp$: hadron transverse momentum with respect to the jet direction



- Factorization formalism

Kang, Liu, Ringer, Xing, 1705.08443

$$\frac{d\sigma}{dp_T d\eta dz_h d^2 j_\perp} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, \omega_J R, j_\perp, \mu)$$

- Related to transverse momentum dependent (TMD) fragmenting function

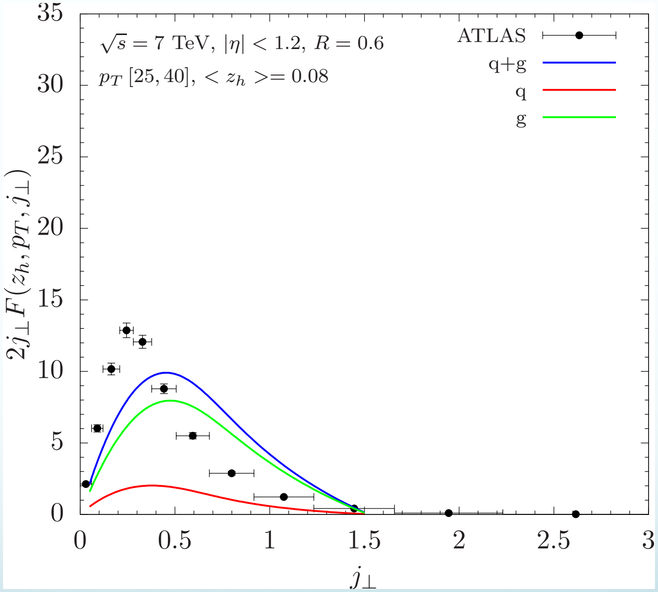
$$\mathcal{G}_c^h(z, z_h, \omega_J R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, \omega_J R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^2\left(z_h \boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp\right)$$
$$\times D_{h/i}(z_h, \boldsymbol{k}_\perp, \mu, \nu) S_i(\boldsymbol{\lambda}_\perp, \mu, \nu R)$$

Problem in comparison with LHC data

- Currently the LHC data integrate over entire z_h region: [0,1]
  - Fragmentation function is only constrained for z > 0.05
  - At both small *z* and large *z*, there are logarithm of ln(*z*) or ln(*1-z*), which has to be resumed to have a better convergence

- Inclusive jet is more sensitive to gluon TMD fragmentation functions

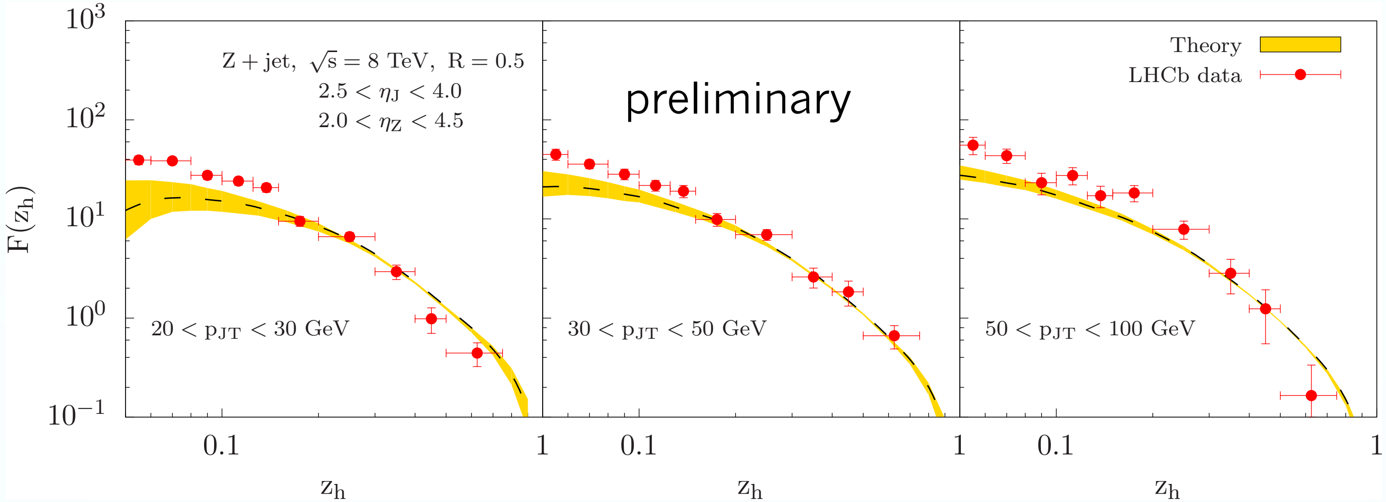
- What about quark TMD FFs?
  - Photon+jet
  - Z+jet



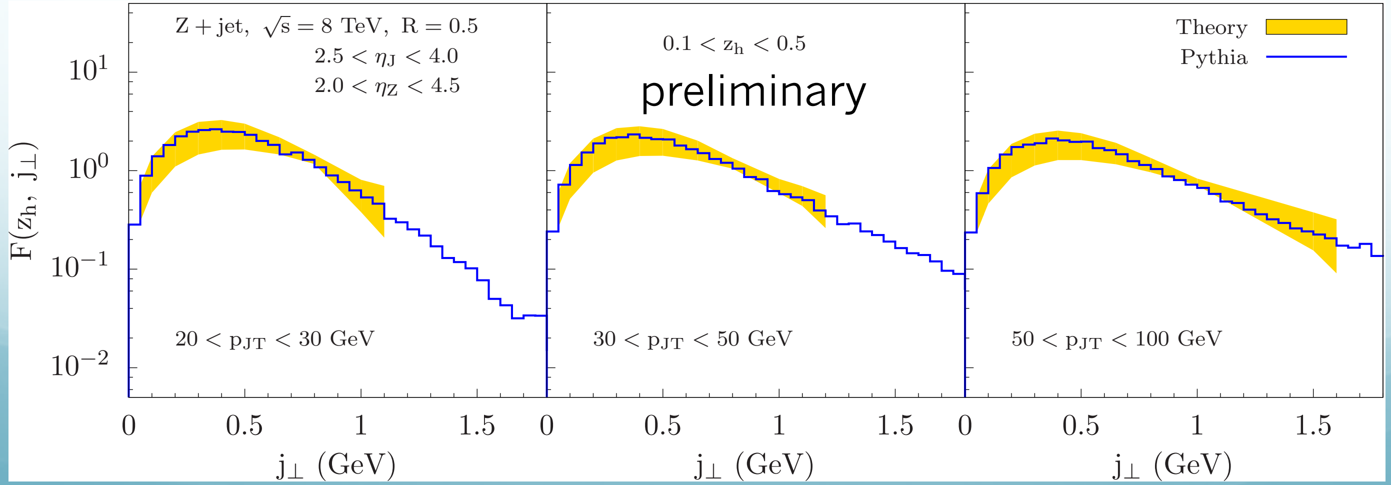
Jet fragmentation functions in Z+jet

- z_h distribution

Kang, Lee, Xing, in preparation, base on Buffing, Kang, Lee, Liu, 1812.07549, see also Chien, Shao, Wu, 1905.01335



- For the reason mentioned, a direct comparison with LHCb data on j_T distribution does now work well



Summary

- Jet physics presents great opportunities for QCD and strong interactions
- Jets and jet substructure are exciting research topics
  - Whether you study them as background or as signal
- Jet fragmentation functions provide new insights on the standard fragmentation functions

Thank you!