Jet functions

Zhongbo Kang
UCLA

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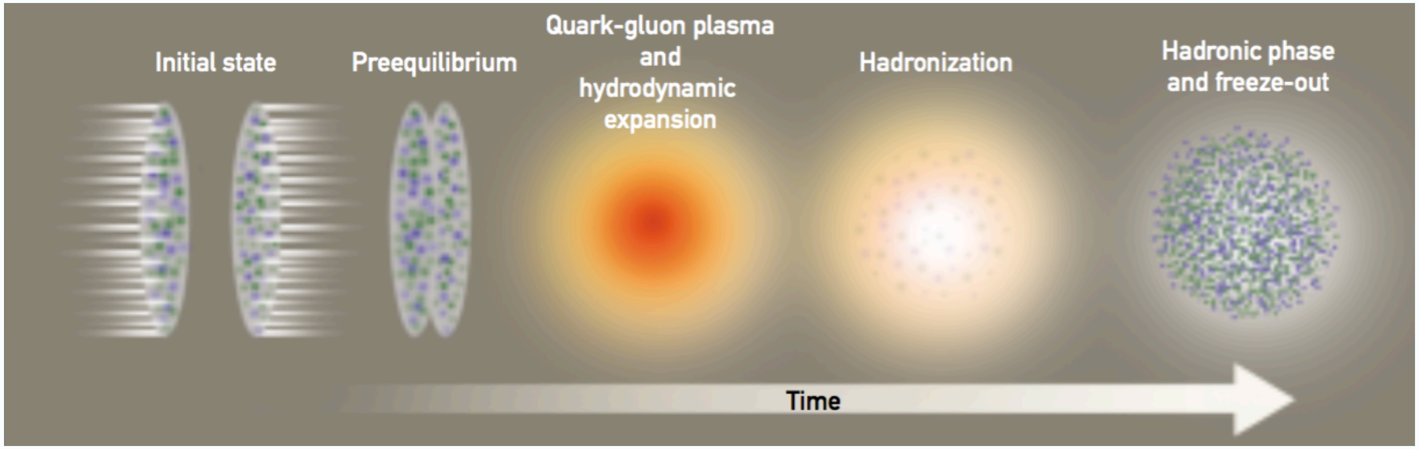
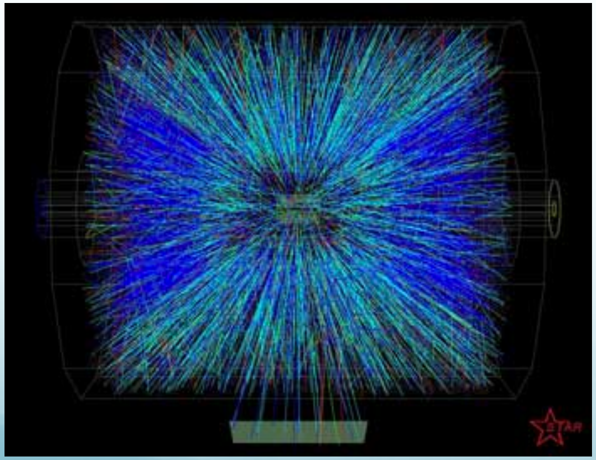
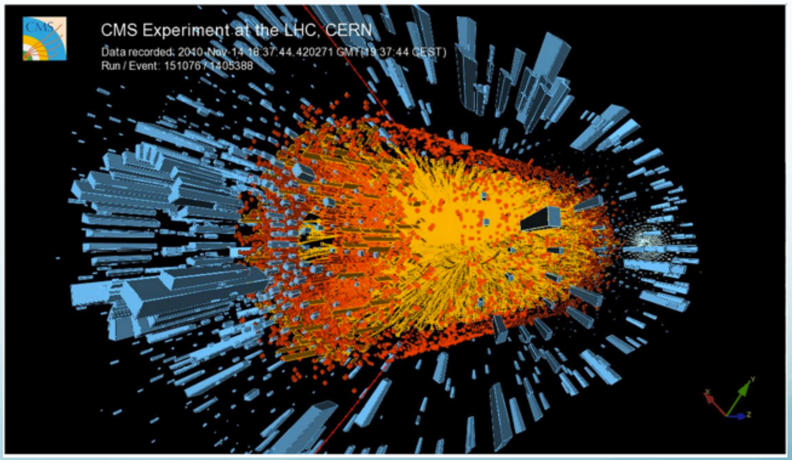
Heavy ion physics

- Recreate a new state of matter, the quark gluon plasma (QGP), which prevailed in early Universe in first few micro-seconds, study its properties





RHIC: Au+Au

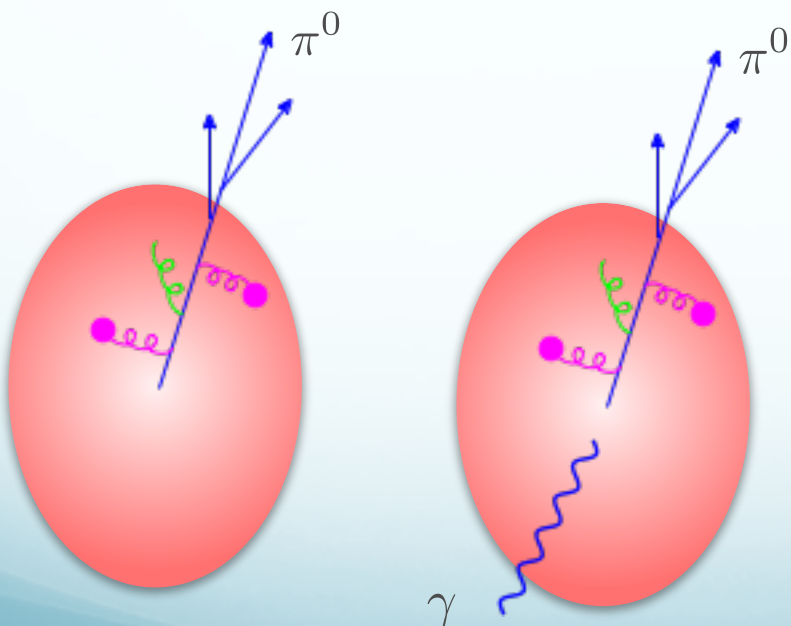


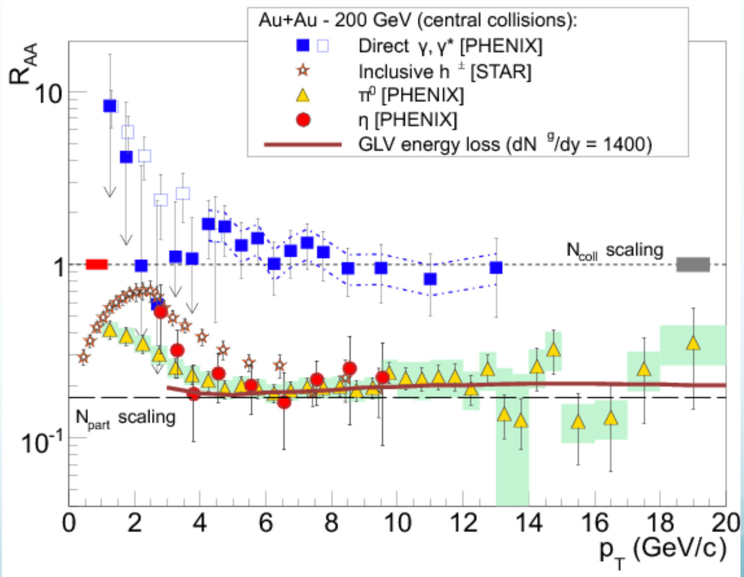
LHC: Pb+Pb

“Jet” tomography: really hadrons

- Early jet tomography is really using “inclusive hadron production”
  - (modified) fragmentation function in p+p (A+A)

Hadrons ⟷ Fragmentation functions

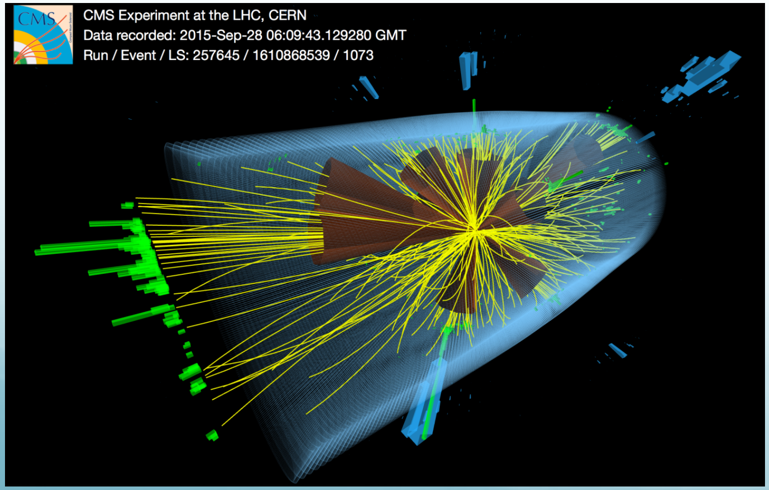


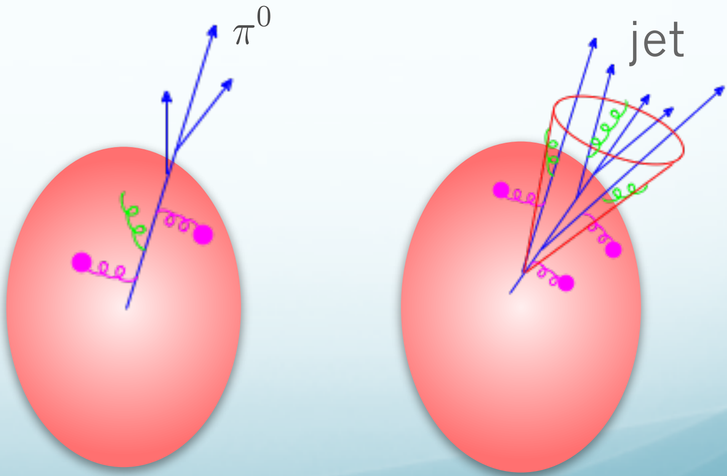


Jet tomography: true jets

- New opportunities: jets are abundantly produced at LHC (also future RHIC)
  - To describe jet production, we need jet functions

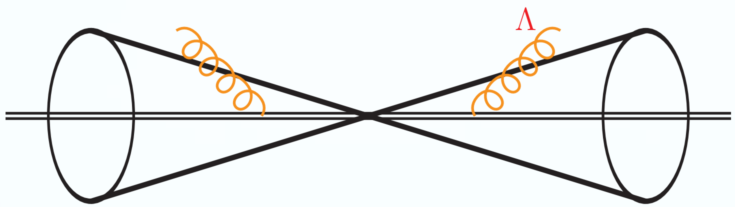
Jets ⟷ **Jet functions**



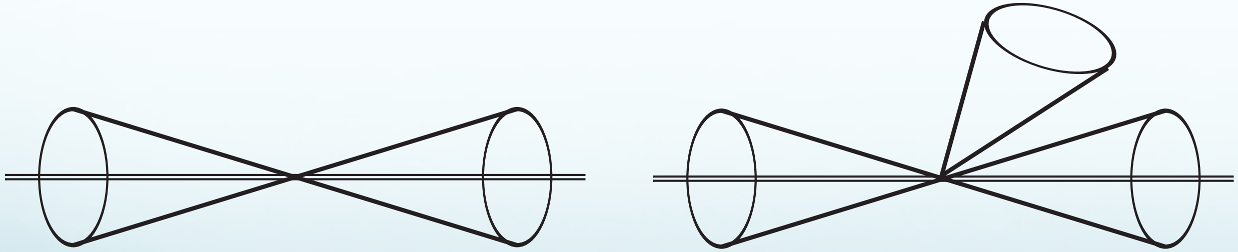


Jets: exclusive and inclusive measurements

- Exclusive jet production
  - Make sure one has fixed-number of jets (e.g., dijet), and veto any additional jets (e.g., through energy or p_T cut)



- Inclusive jet production
  - Sum over all particles in the final state besides the observed jets
  - Example: single inclusive jet production



Soft-Collinear Effective Theory (SCET)

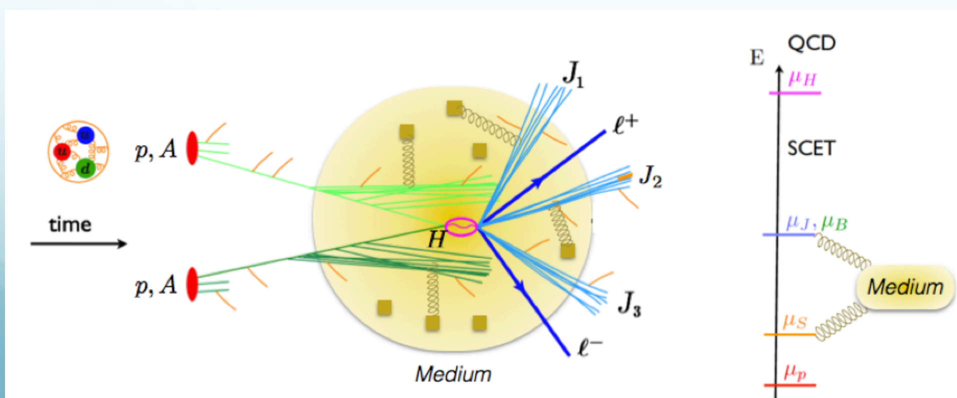
- SCET: an effective field theory of QCD — Bauer et al. 01, Pirjol et al. 04
  - Suitable for processes where there are energetic, nearly light-like (collinear) degrees of freedom interacting with one another via soft radiation

- Modes in SCET

Collinear quarks, antiquarks	$\xi_n,\ \bar{\xi}_n$
Collinear gluons, soft gluons	$A_n,\ A_s$

modes	$p^\mu = (+,-,\perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$

- Especially suited for jet physics: QCD factorization of modes



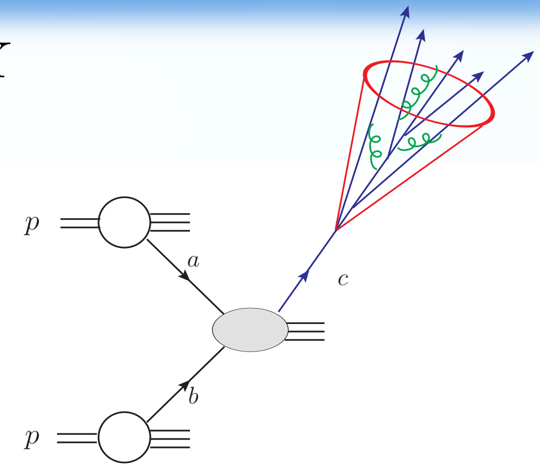
$$\sigma = H \otimes S \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j$$

Comments

- Most of SCET calculations are dealing with “exclusive” jet production
- Most of heavy ion measurements are performed for “inclusive” jet samples
- Jet functions involved in “exclusive” and “inclusive” cases are different, even follow different renormalization group equations
- What are the jet functions for inclusive jet production?

Tradition tools: QCD factorization

- Single inclusive jet production: $p + p \to \text{jet} + X$



$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}$$

↑ **partonic hard-scattering cross section**

$$H_{ab} = \alpha_s^2 \left(H_{ab}^{(0)} + \alpha_s H_{ab}^{(1)} + \alpha_s^2 H_{ab}^{(2)} + \ldots \right)$$

- The idea is simple: dynamics which happen in very different scales do not interfere with each other: **Λ_{QCD} vs P_T**

Tradition tools: QCD factorization

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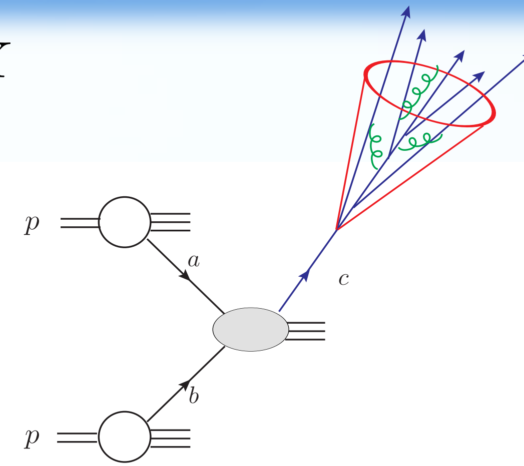

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}$$

partonic hard-scattering cross section

$$\ldots {}^{(2)}_{ab} + \ldots)$$

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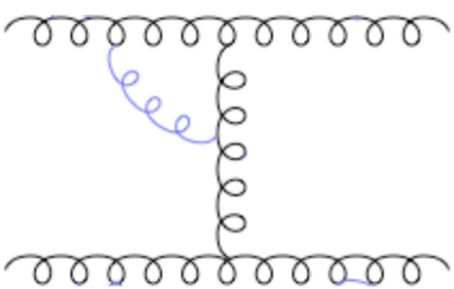
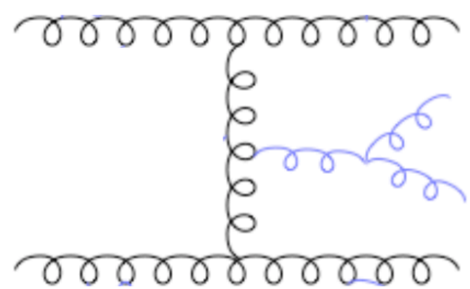


NLO 1990

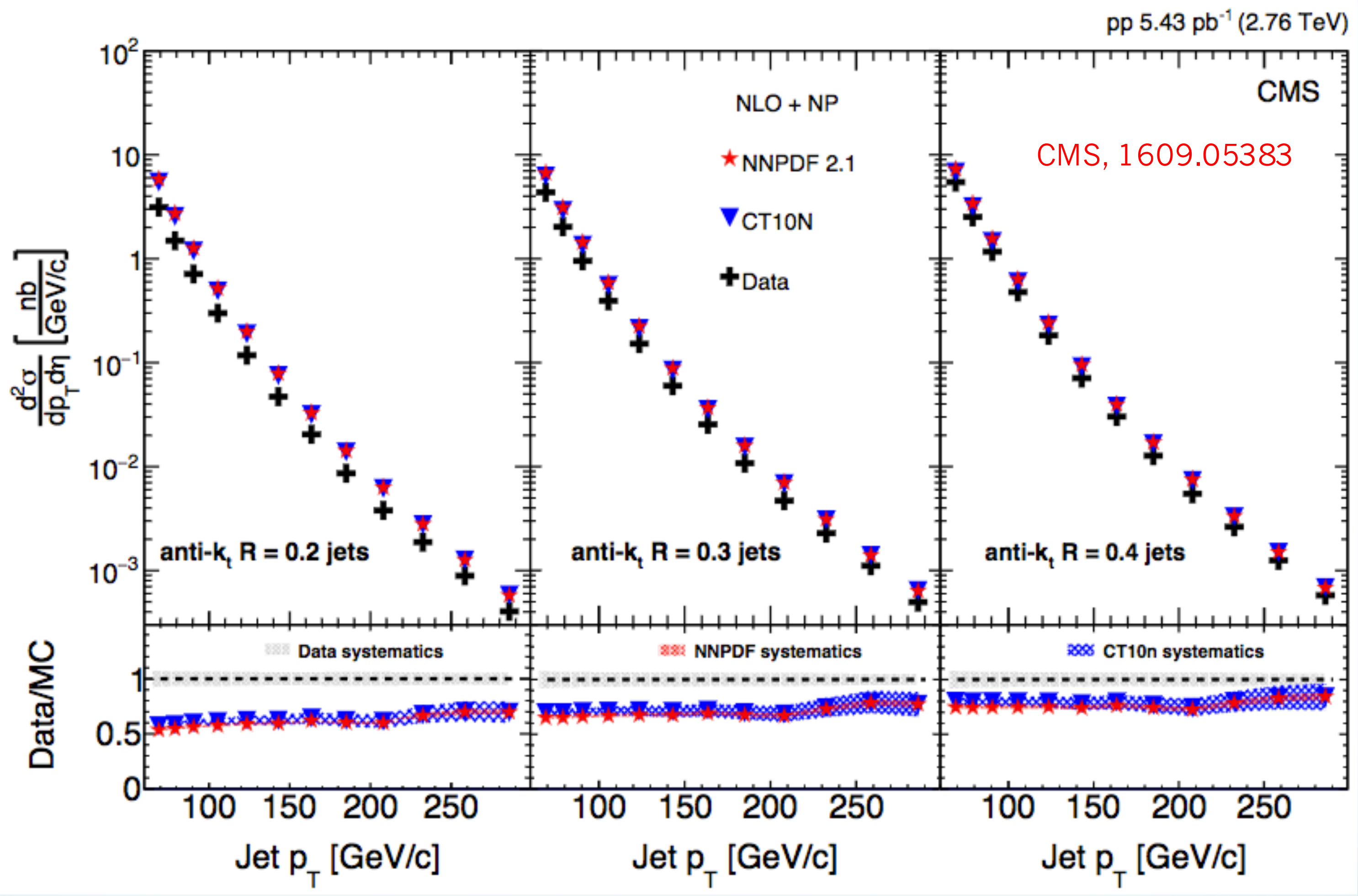
Ellis, Kunszt, Soper `90



NNLO 2016 …

Currie, Glover, Pires `16

Most recent jet measurements



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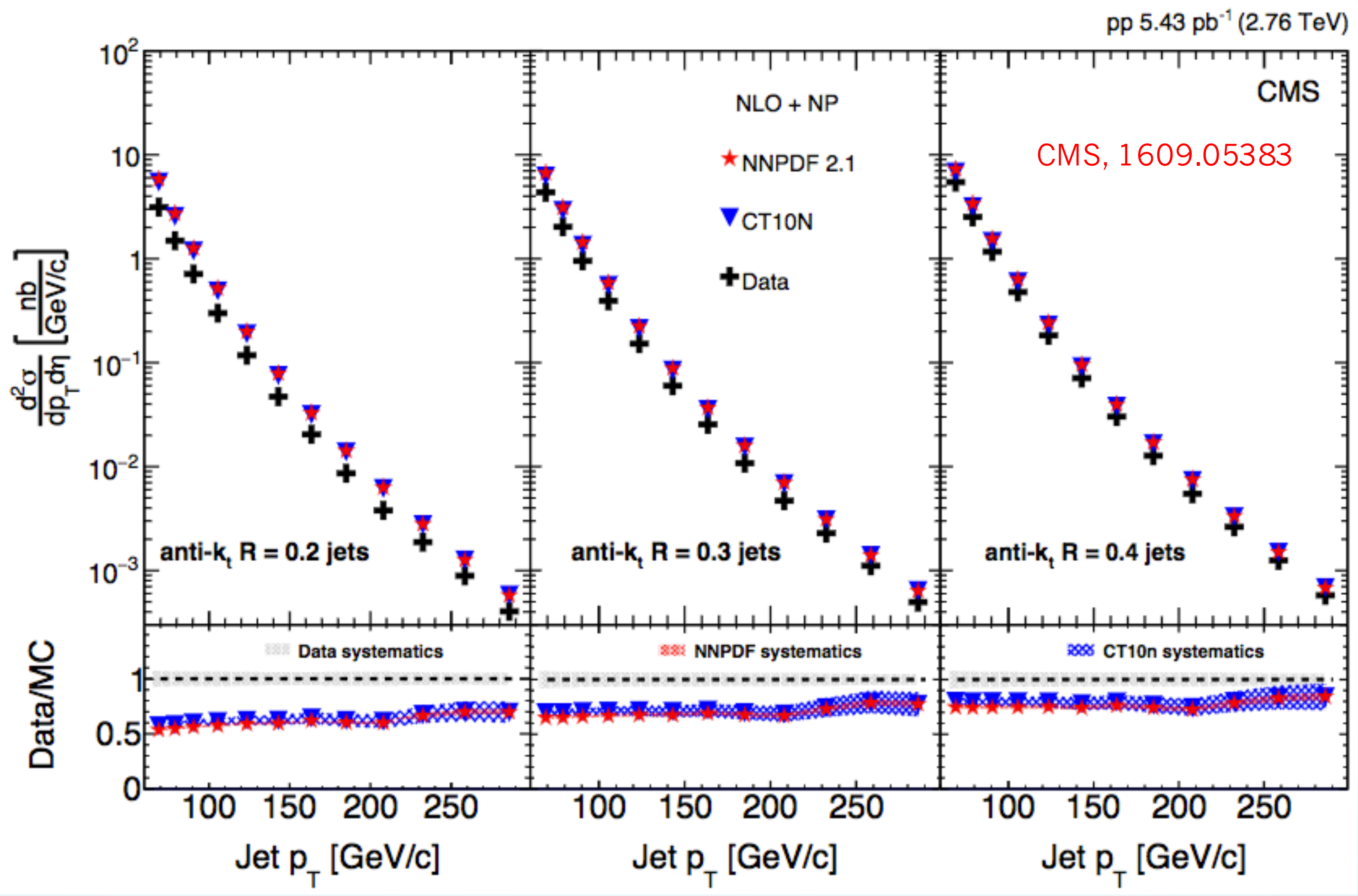

✓ **NNLO does not help: further increase, even worse**

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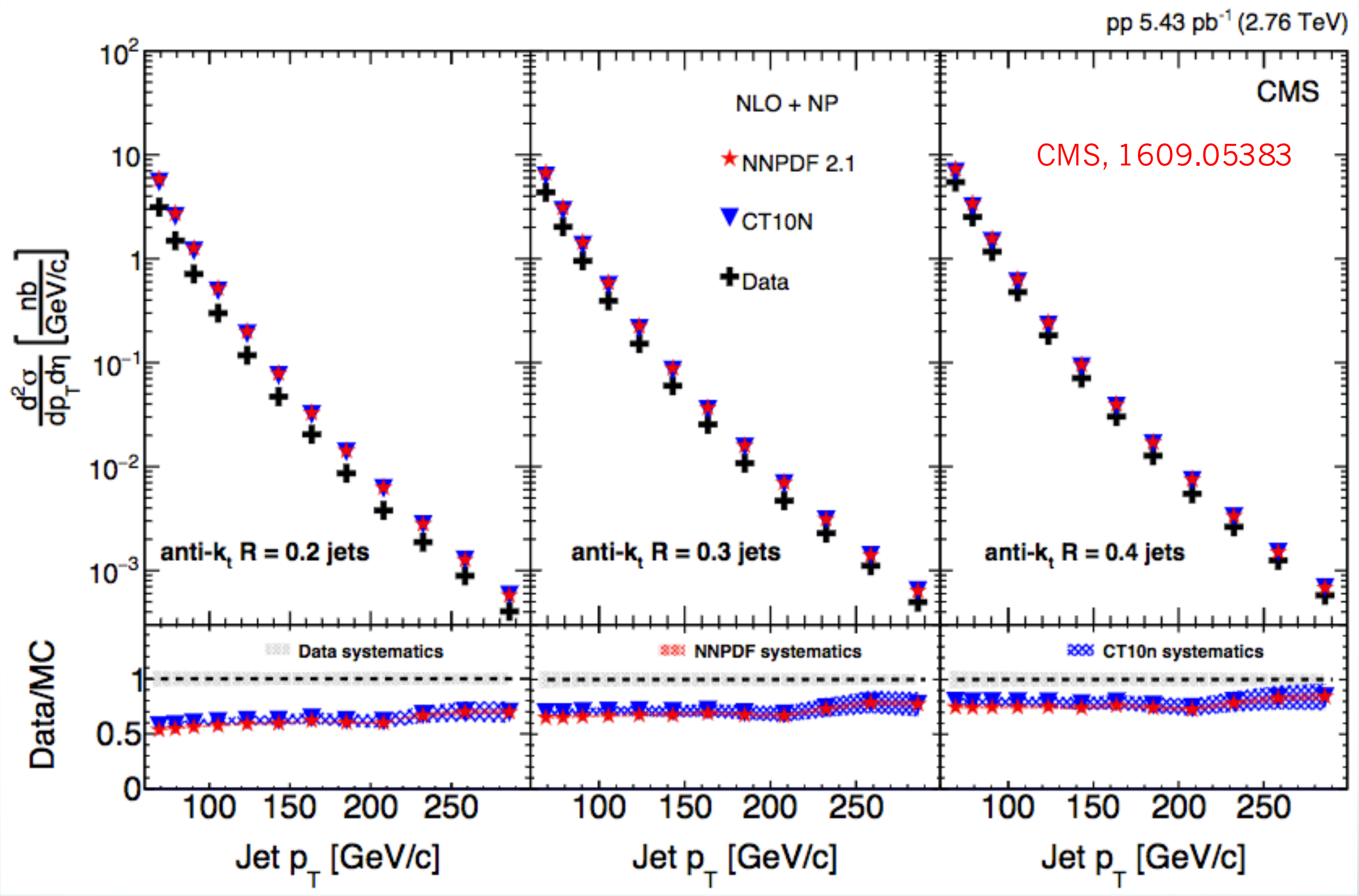
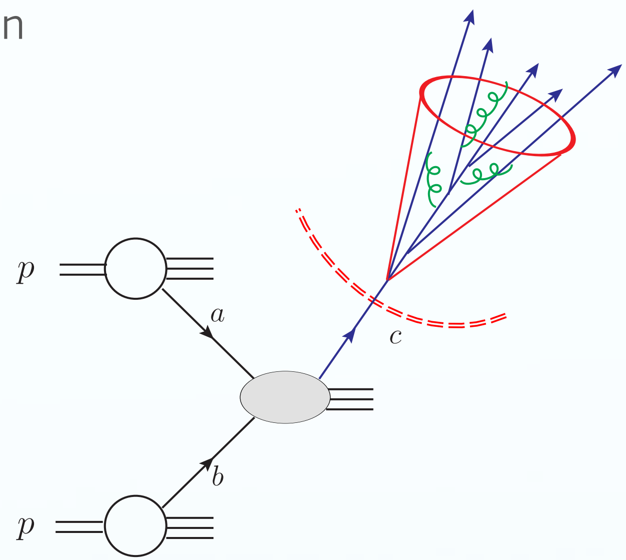


- ✓ **NNLO does not help: further increase, even worse**
- ✓ **Jet radius R is small: 0.2 – 0.4, $[\alpha_s \ln(R)]^n$ resummation?**

Refactorization: semi-inclusive jet function

- When R << 1, the relevant scales for single jet production
  - Two momenta: (1) hard collision: pT (2) jet radius can build one: pT*R
  - A further factorization



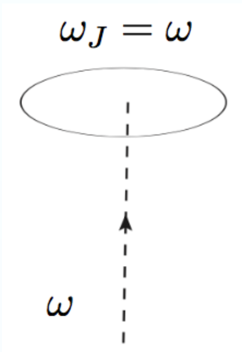
$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes J_c(z, \mu \sim p_T R)$$

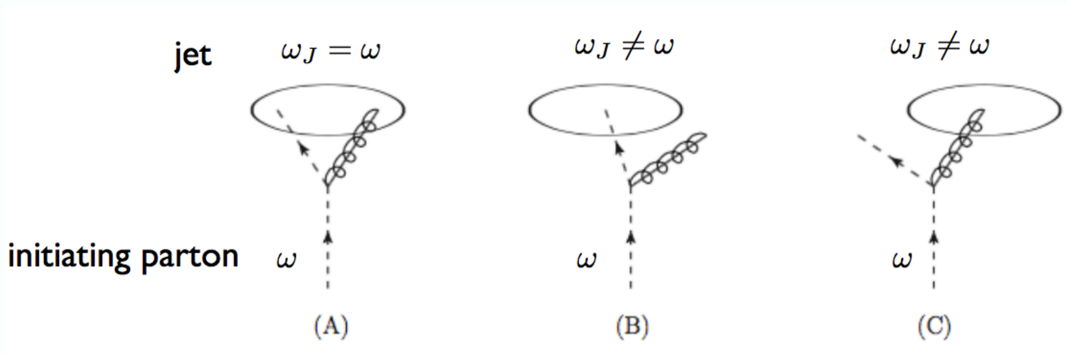
- Good thing: semi-inclusive jet function $J_{q,g}(z, R)$ are purely perturbative

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

Semi-inclusive jet functions

- Describe how a parton (q or g) is transformed into a jet (with a jet radius R) and energy fraction z





LO

$$J_q^{(0)}(z, \omega_J) = \delta(1-z)$$

NLO

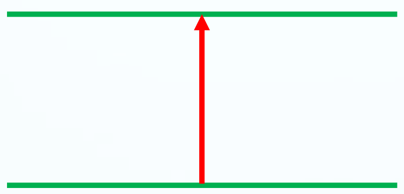
$$z = \omega_J/\omega$$

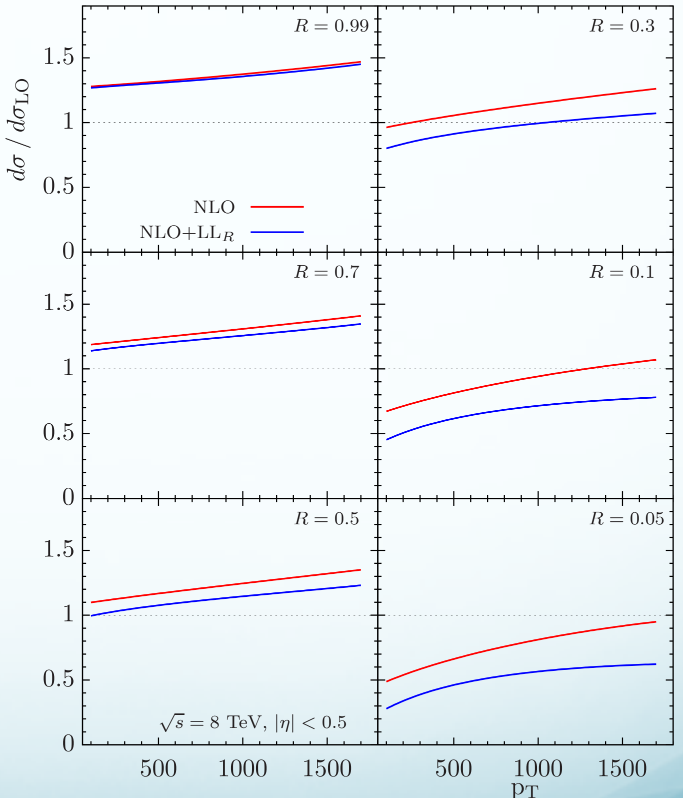
- Semi-inclusive quark/gluon jet functions follow DGLAP evolution equation, just like hadron fragmentation function

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

Ln(R) resummation

- Natural scale for jet functions: p_T*R
- Jet radius resummation: $(\alpha_s \ln R)^n$
  - Note: ln(R) < 0 when R < 1

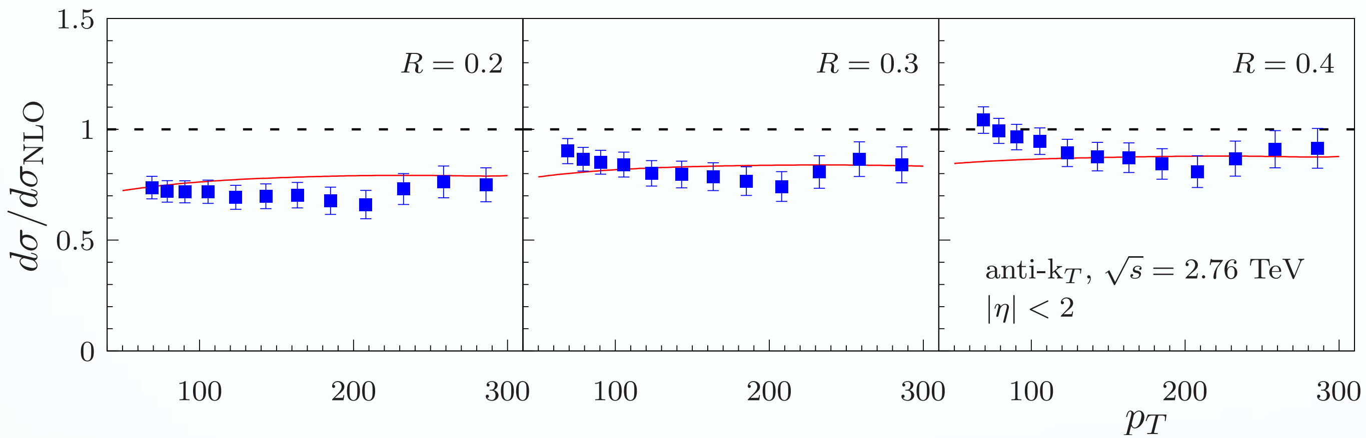




Kang, Ringer, Vitev, arXiv:1606.06732, JHEP 16

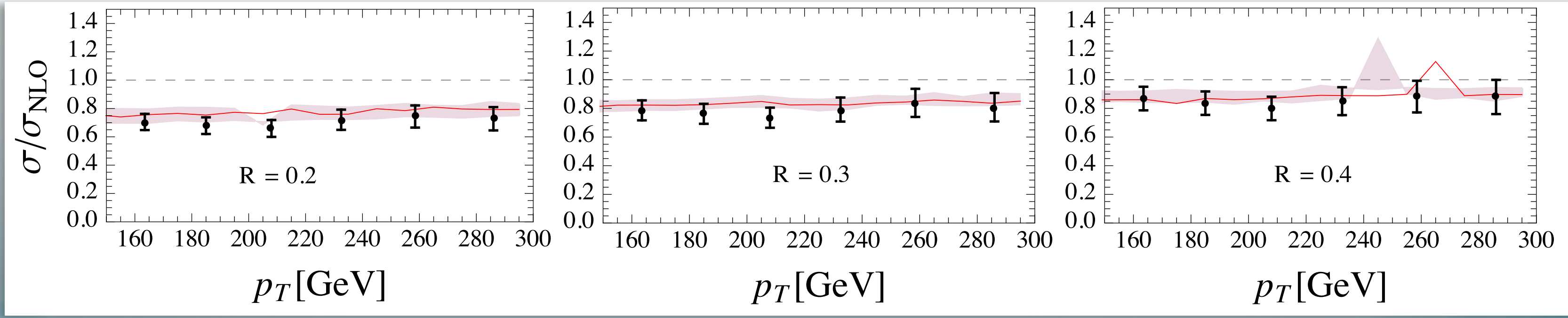
Effect of ln(R) resummation

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



Kang, Ringer, Vitev, 1707.00913, PLB 17

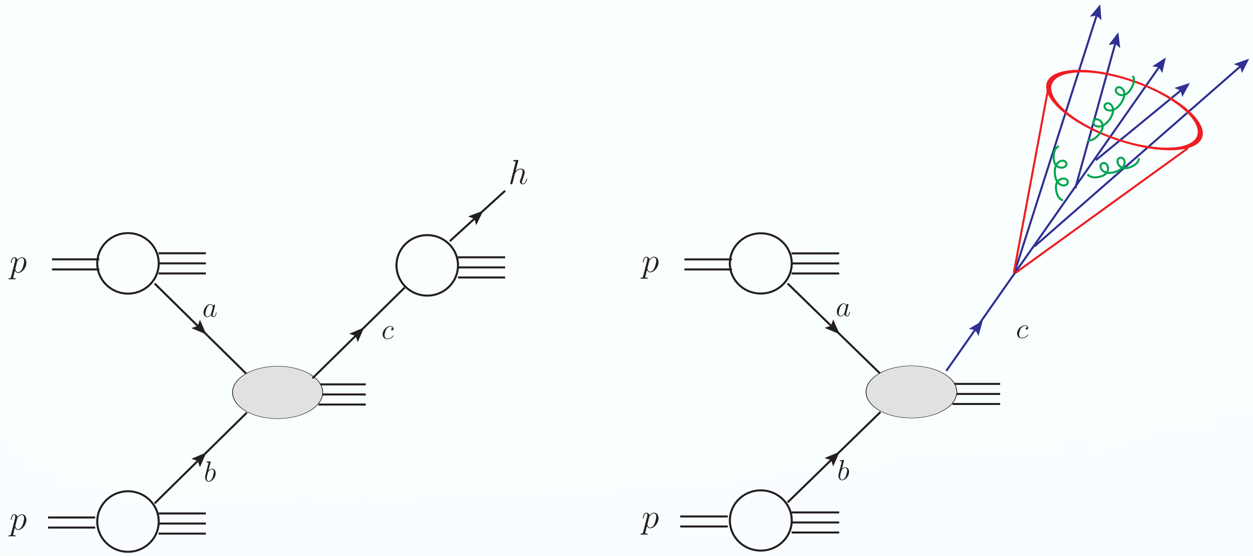
- Threshold resummation further improve the agreement



Liu, Moch, Ringer, PRL 2017

Features: unified formalism

- Unified factorization formalism for hadron and jet production



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

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

- Consistent definition of what are called quark/gluon jets at NLO
- Even though derived for small R, R = 0.7, the difference between small R approximation and full result is less than 5%

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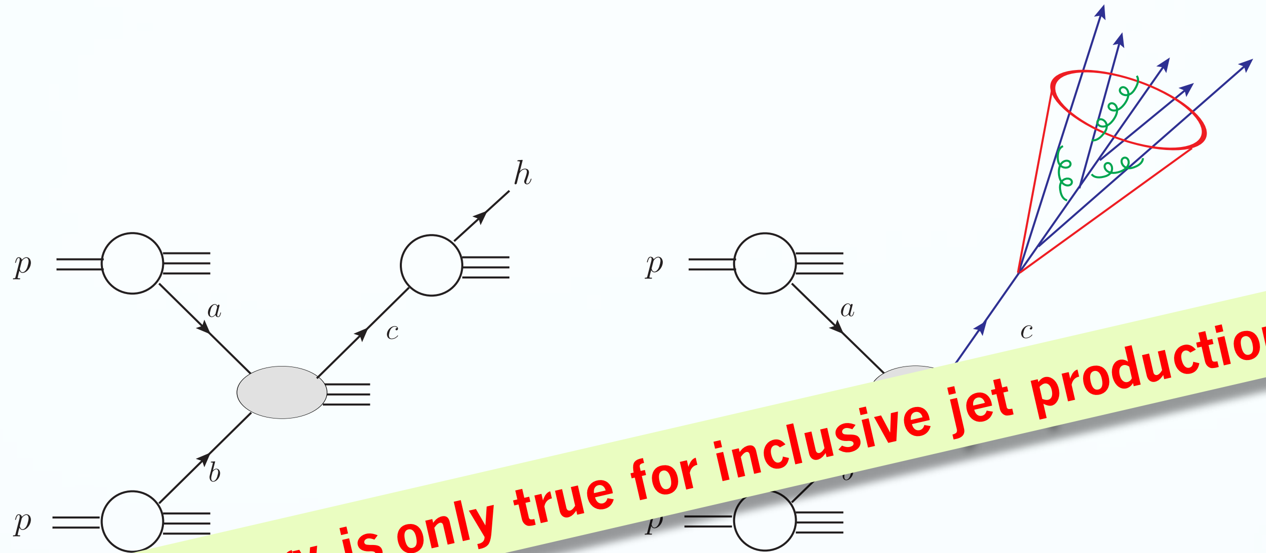
- Unified factorization formalism for hadron and jet production



Such analogy is only true for inclusive jet production

$$\frac{\ldots}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes D_c^h(z,\mu)$$

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

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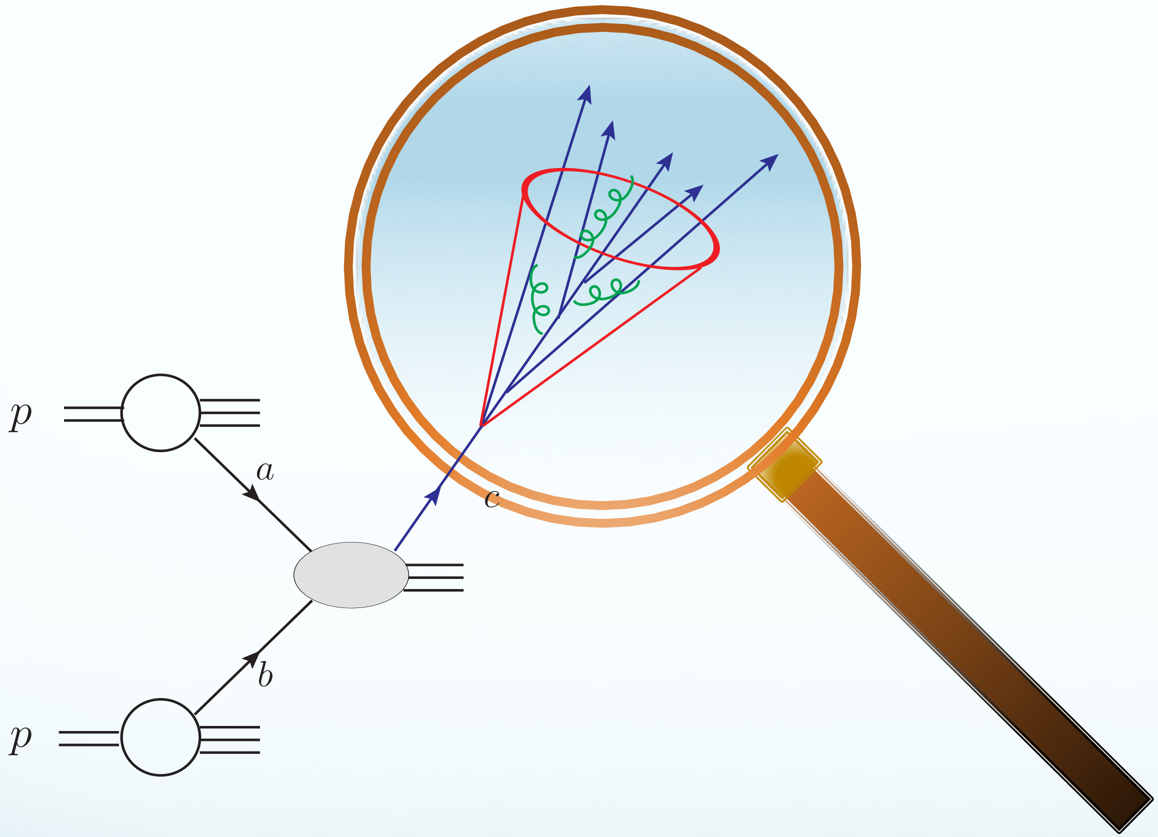
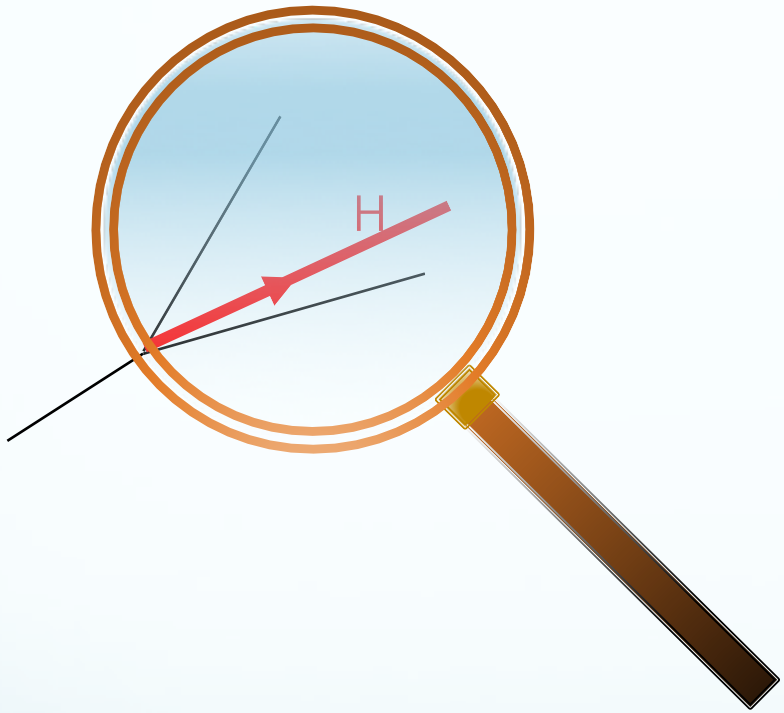
Jet substructure

- Look inside the jet



Simplest example: hadron inside the jet

- Jet fragmentation function

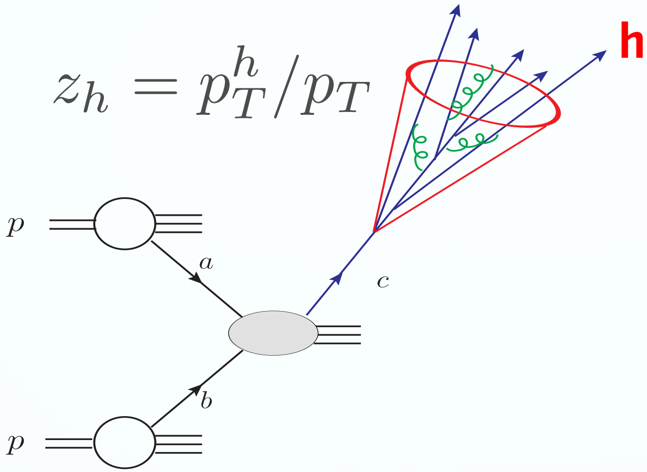


Semi-inclusive fragmenting jet function

- One needs a more complicated jet function

Kang, Ringer, Vitev, 1606.07063, JHEP 16

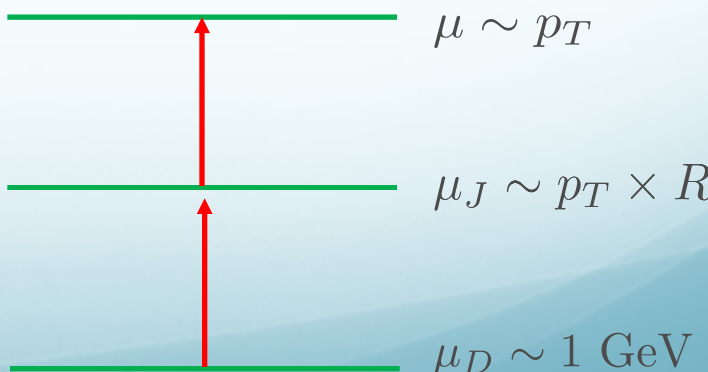
$$z_h = p_T^h / p_T$$



$$J_c(z, p_T R, \mu) \rightarrow \mathcal{G}_c^h(z, z_h, p_T R, \mu)$$

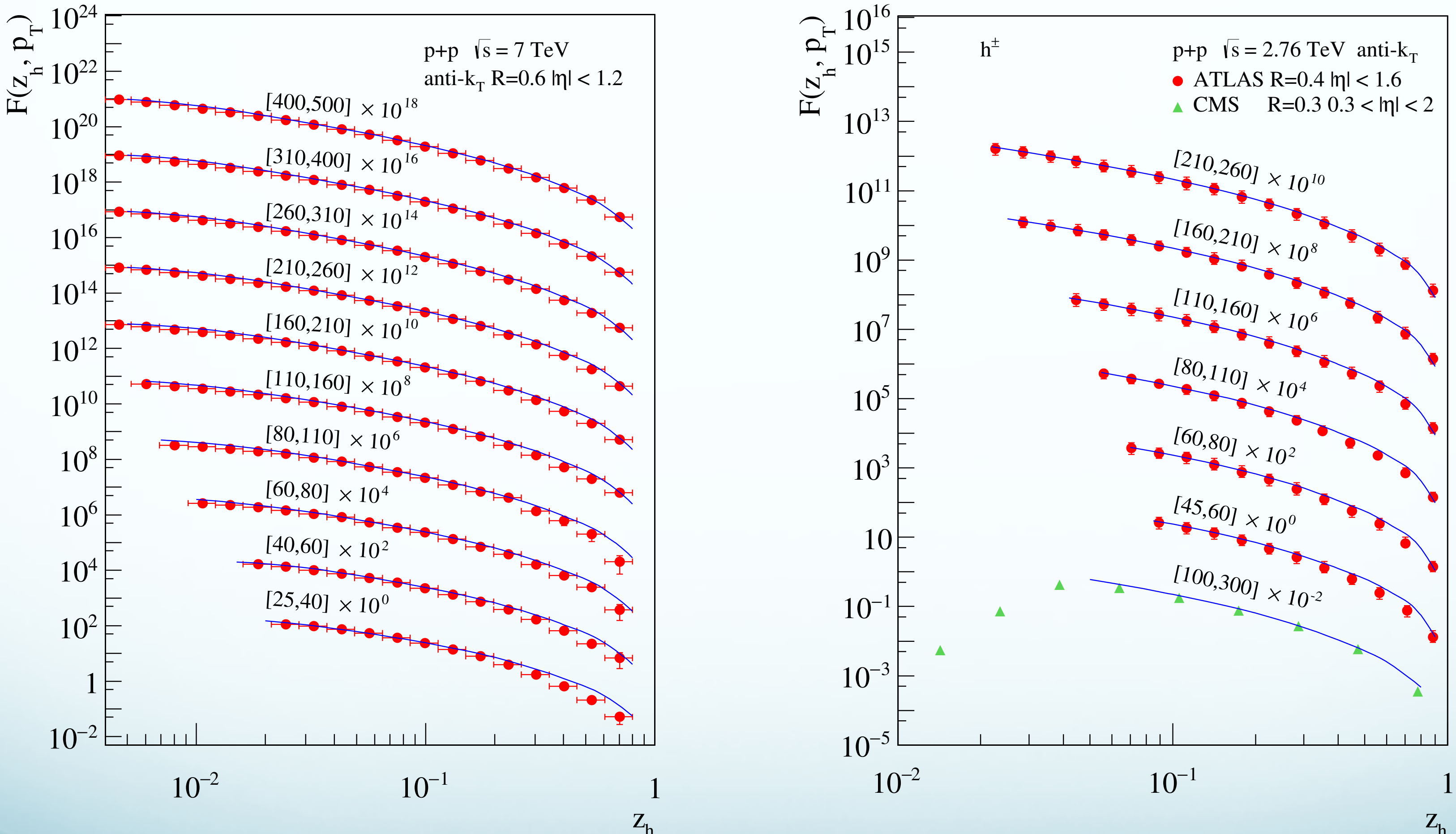
- Two DGLAPs: $$\mu \frac{d}{d\mu} \mathcal{G}_i^h(z, z_h, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}\right) \mathcal{G}_j^h(z', z_h, \mu)$$

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



Light hadrons: work well

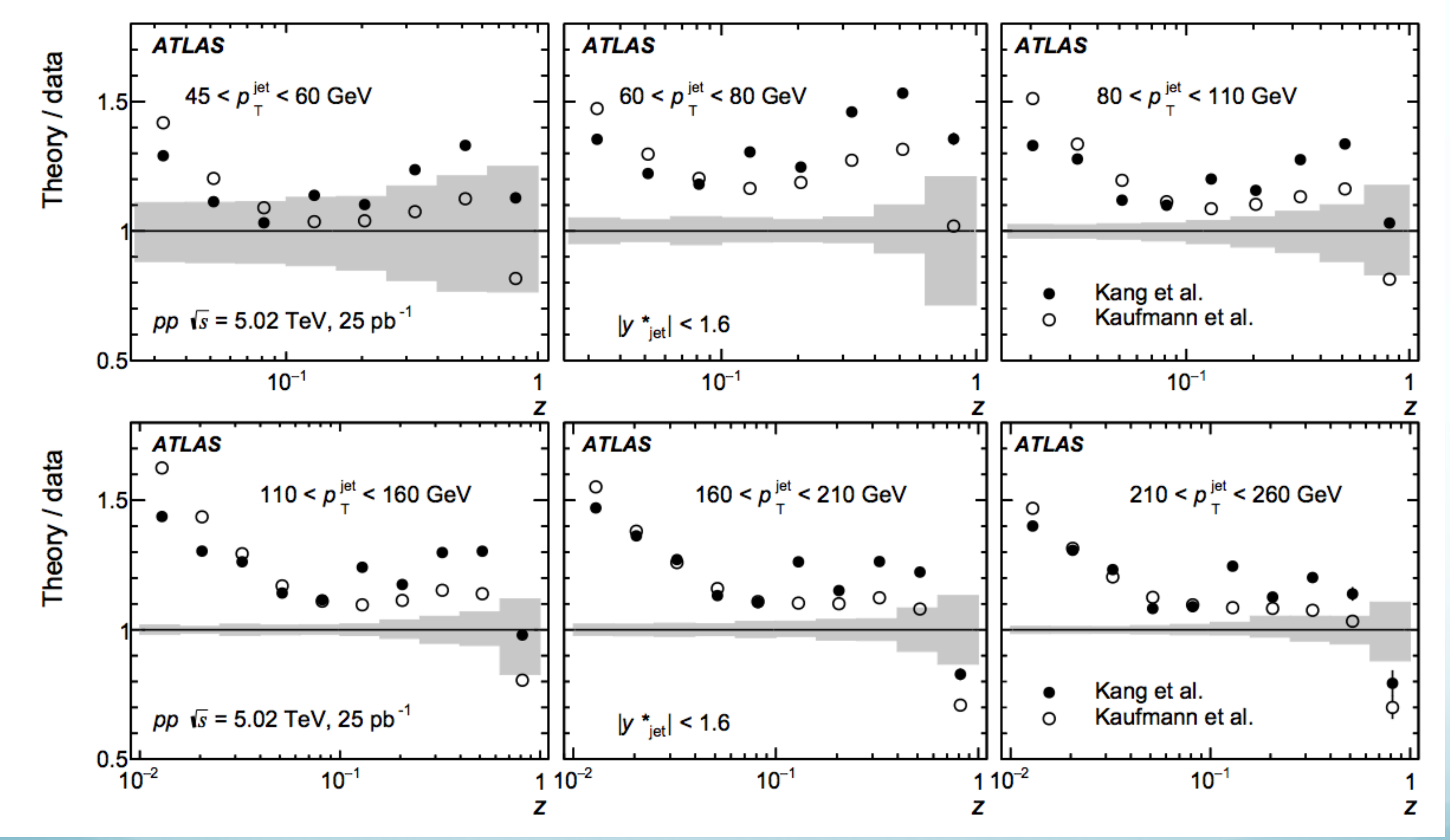
- Light charged hadrons



Kang, Ringer, Vitev, 1606.07063, JHEP, 16

Further improvement

- So far standard FFs is only constrain for z > 0.05
  - These data can constrain small-z
  - One might need threshold resummation for large z region



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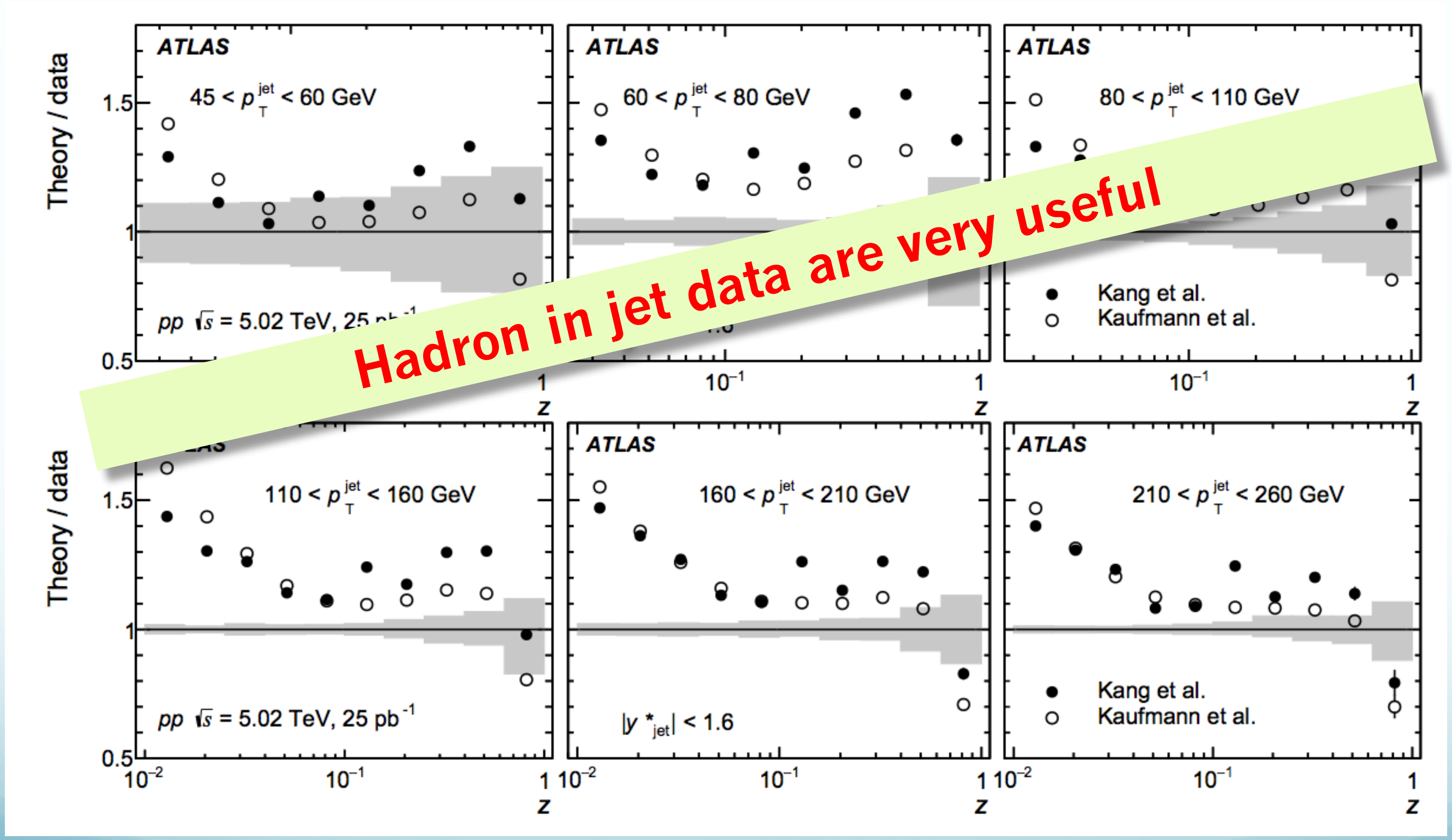
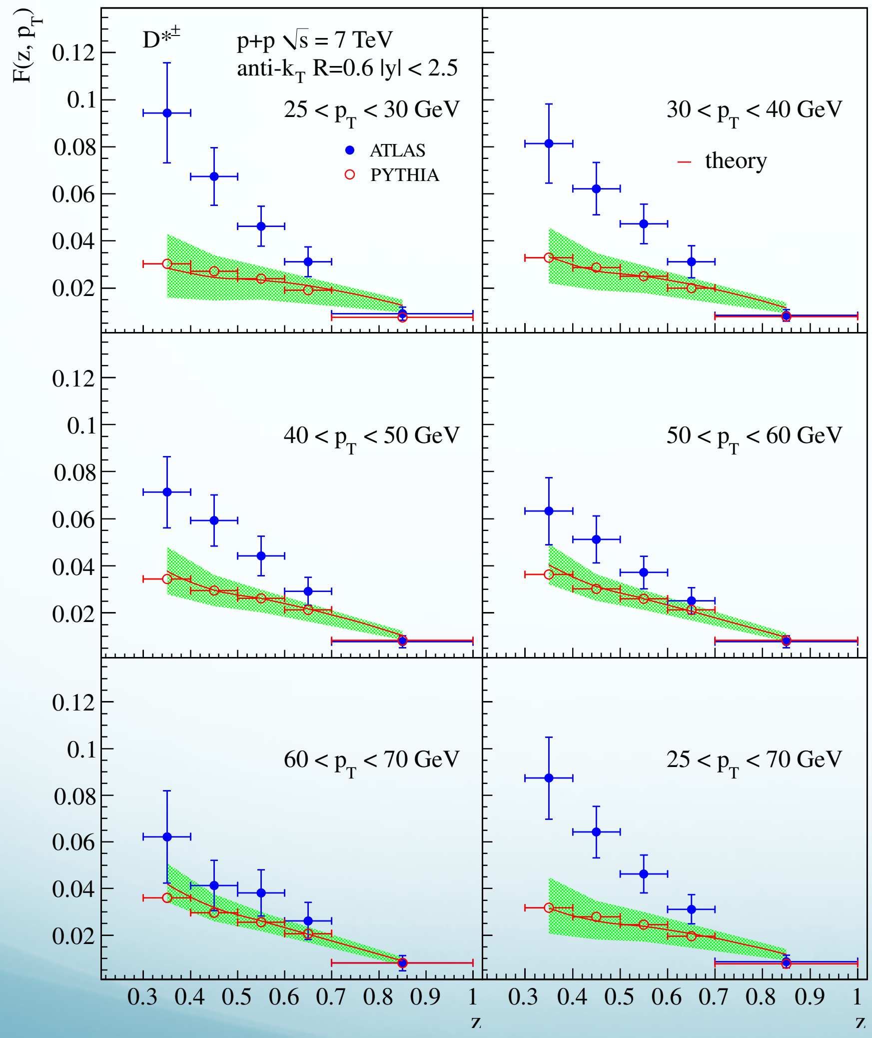


Jet fragmentation function for heavy meson

- 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

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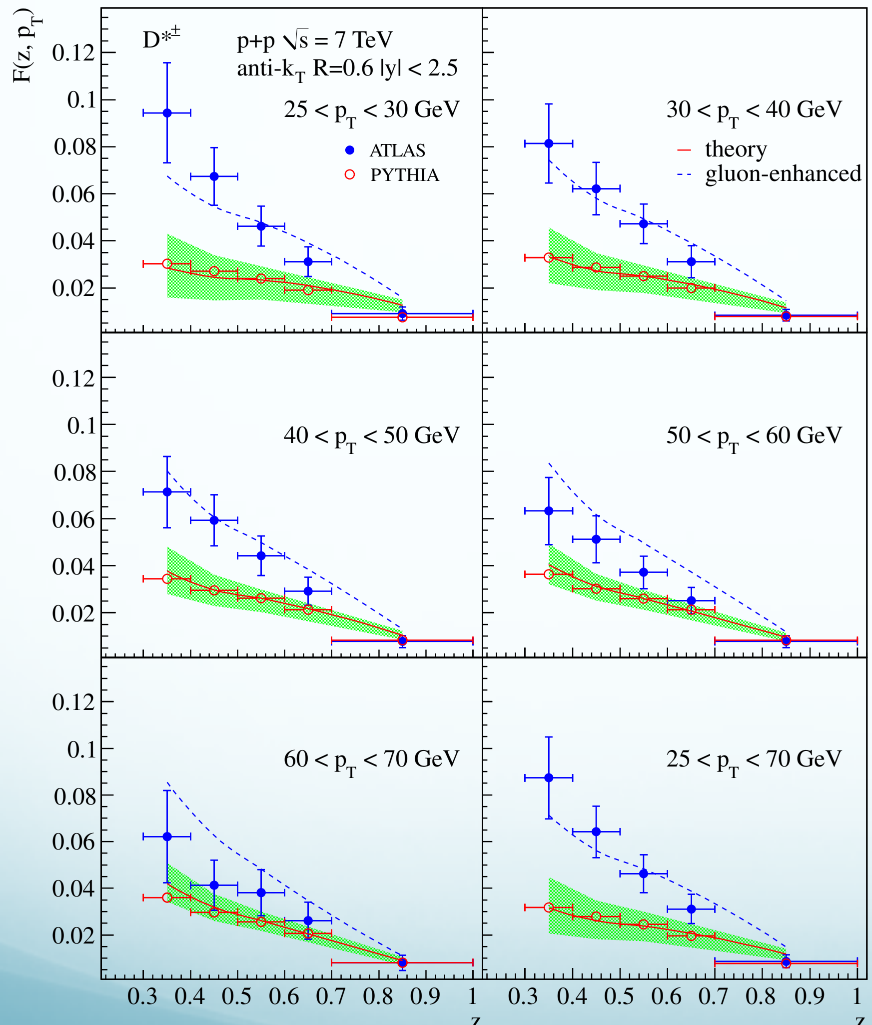


Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing, 1512.06851, JHEP 16

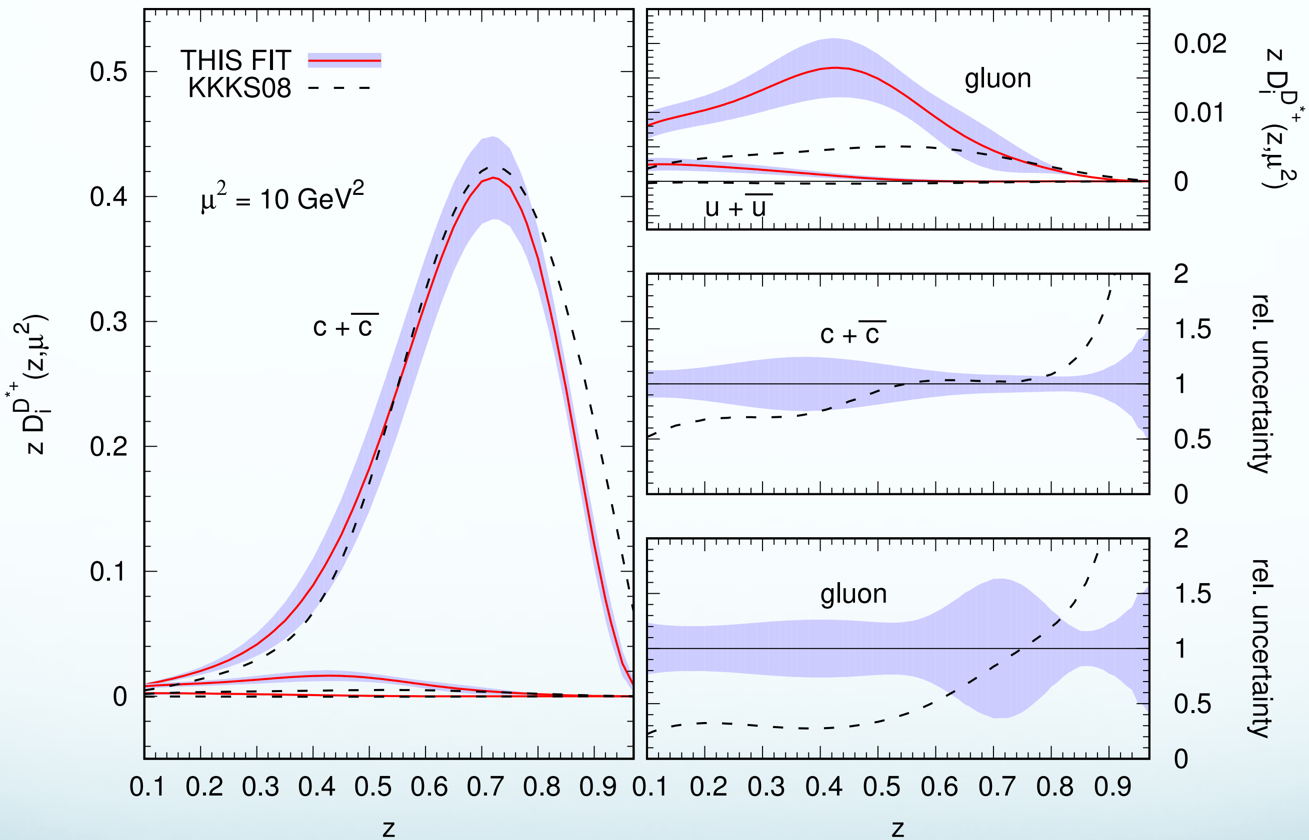
$$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$$

New fit of D-meson FFs needed

A new global analysis of FFs

- New fit of D-meson FFs

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



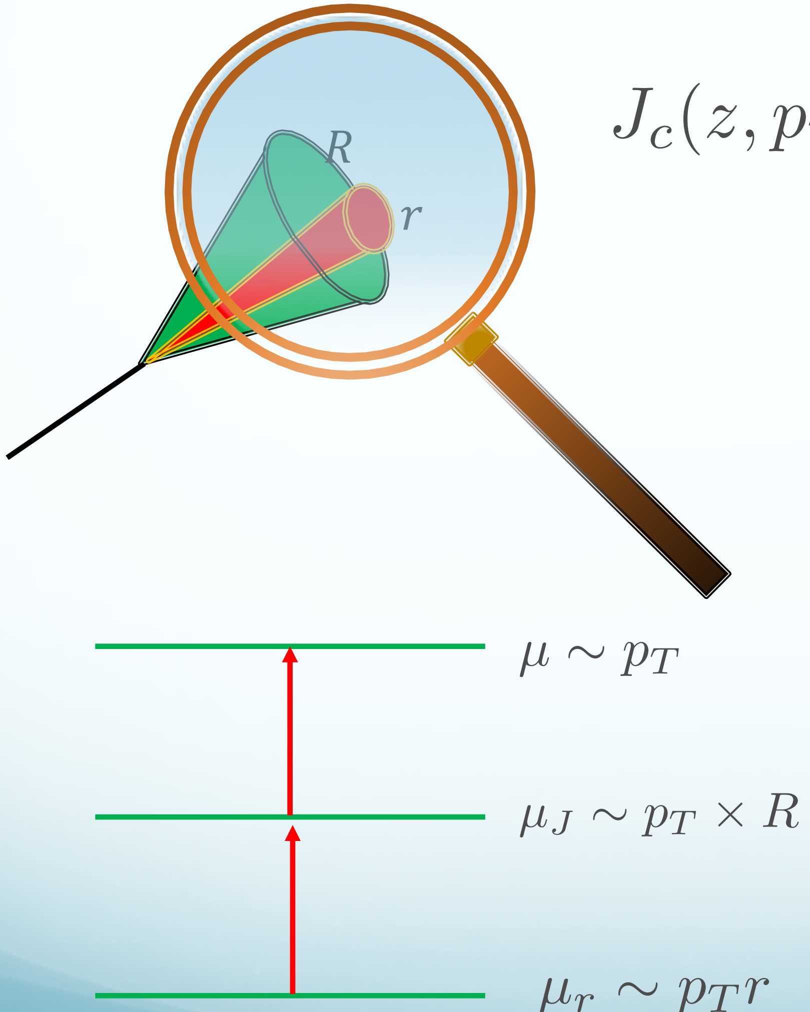
Confirms our earlier guess

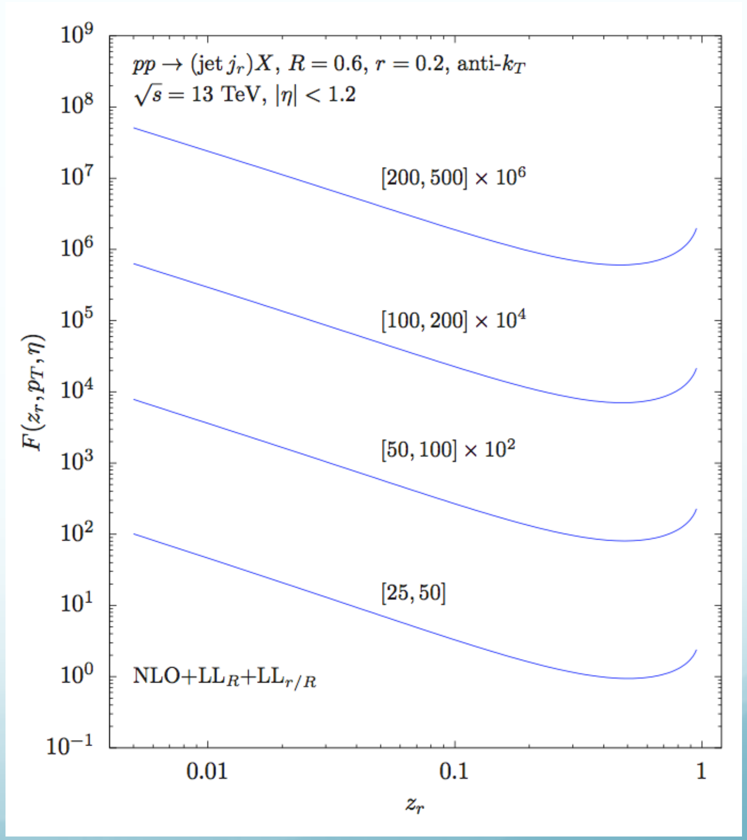
Subjet in jet: subjet function

- We may try to observe a subjet with radius r

Kang, Ringer, Waalewijn, 1705.05375, JHEP, 17

$$J_c(z, p_T R, \mu) \to \mathcal{G}_c^{\text{jet}}(z, z_r, p_T R, \mu)$$



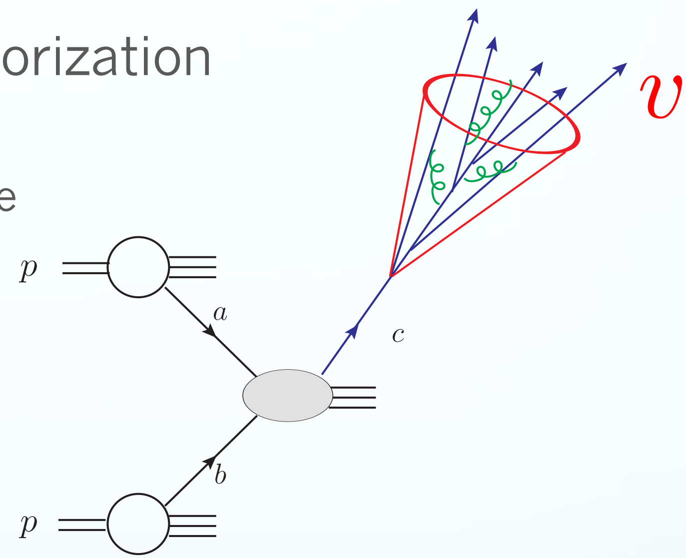


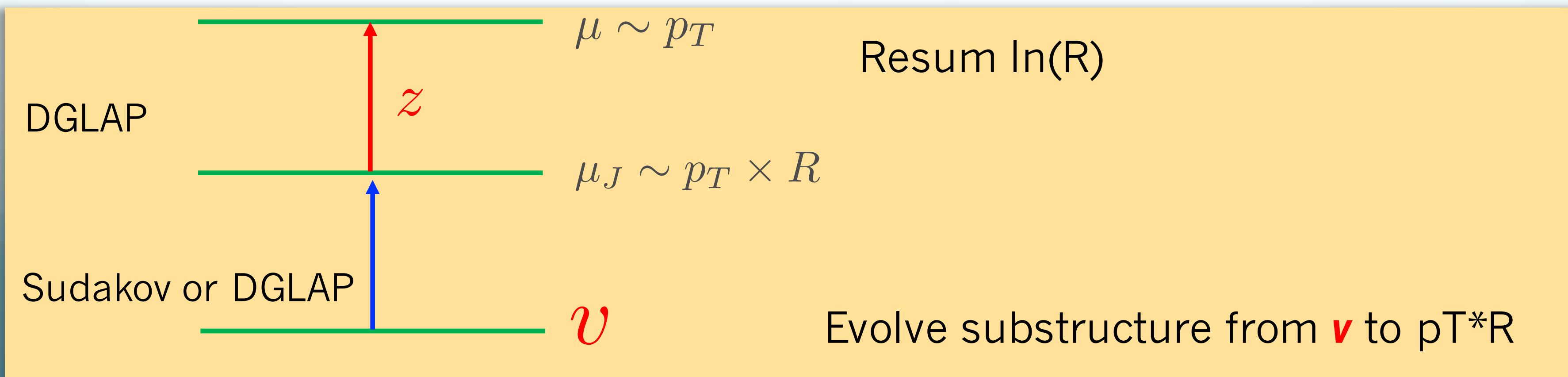
Pattern emerging for the evolution

- When we measure any jet substructure variable "v" from the jet, once we evolve to jet dynamaics scale p_T*R, the remaining evolution to hard scale p_T is given by DGLAP evolution

- Jet substructure: two-layer QCD factorization
  - Producing the jet
  - Concentrating on the internal substructure

$$\frac{d\sigma}{d\eta dp_T dv}$$





Jet angularity

- Trust was defined as an event shape parameter to understand radiation pattern

$$T = \frac{1}{Q}\max_{\mathbf{t}} \sum_{i \in X} |\mathbf{t} \cdot \mathbf{p}_i| = 1 - \tau_0$$

  - $\tau_0 \to 0$ is equivalent to dijet limit
  - A generalized class of IR safe observables, angularity (applied to jet)

$$\tau_a^{e^+e^-} = \frac{1}{E_J} \sum_{i \in J} E_i \, \theta_{iJ}^{2-a}$$

$$\tau_a^{pp} = \frac{1}{p_T} \sum_{i \in J} p_{Ti} \, (\Delta R_{iJ})^{2-a}$$

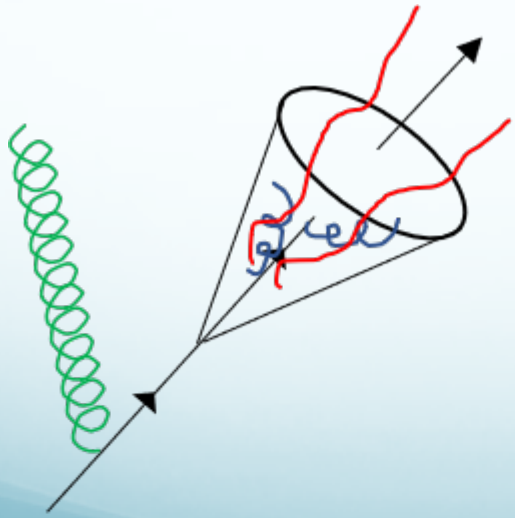
Sterman, et.al. 03, 08, C. Lee, et.al. 10
Hornig, Makris, Mehen, 16

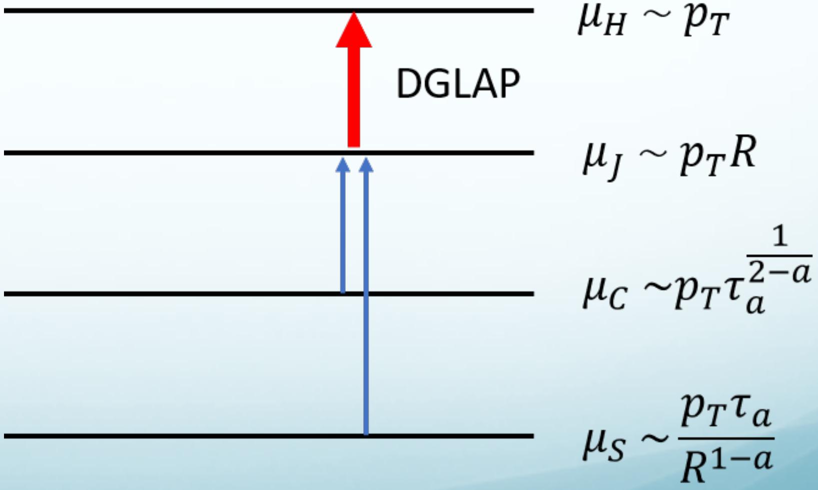
  - a=0 related to thrust (jet mass)
  - a=1 related to jet broadening

Semi-inclusive angularity jet function

- Similar replacement: $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- Refactorization

$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu) \times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu)$$



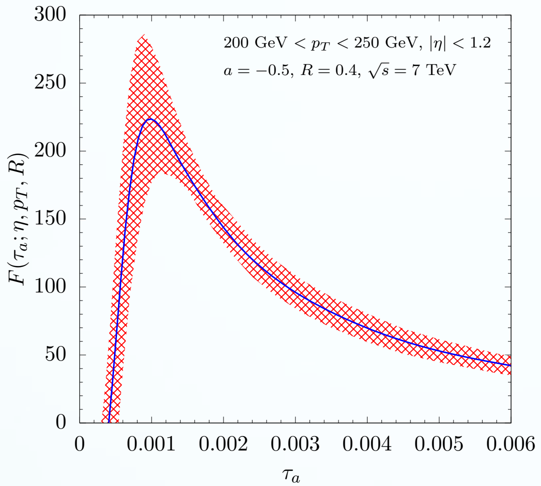


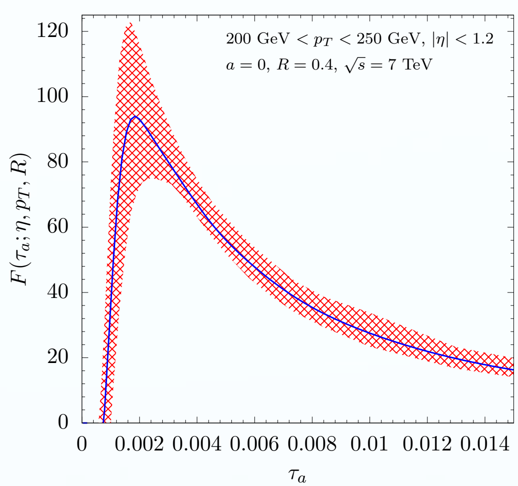
Kang, Lee, Ringer, 1801.00790

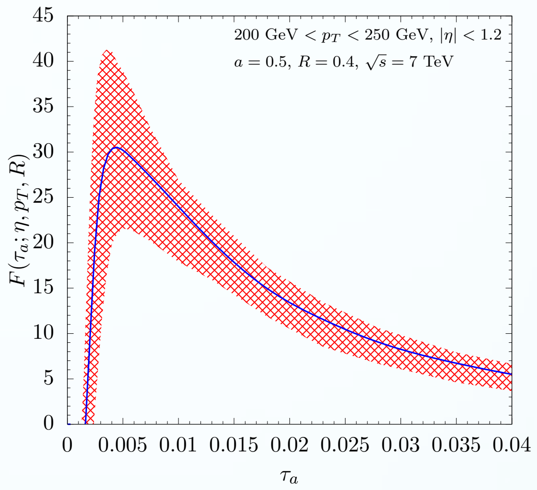
LHC phenomenology

- Prediction at the LHC

Kang, Lee, Ringer, 1801.00790

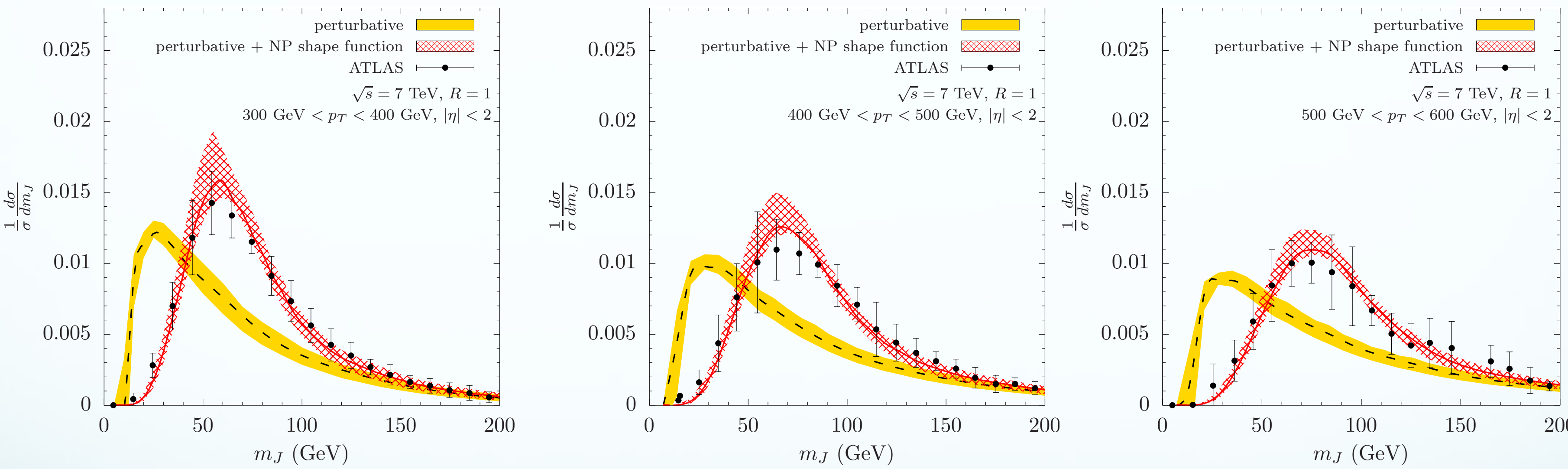






Jet mass: a = 0

- Comparison with jet mass measurements at the LHC



Compiled from Kang, Lee, Ringer, 1801.00790,
See also, C.S. Lee, et.al., 1412.1337, JHEP 15

Summary

- A consistent formalism for study inclusive jets and jet substructure is introduced, through so-called semi-inclusive jet functions
- For inclusive jet cross section, these novel semi-inclusive jet functions are purely perturbative, and follow the usual DGLAP evolution equations, which can be used to perform ln(R) resummation
- Jet substructure for inclusive jets can be computed similarly
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Thank you!