Medium modified jets, soft drop and leading hadrons in a single formalism

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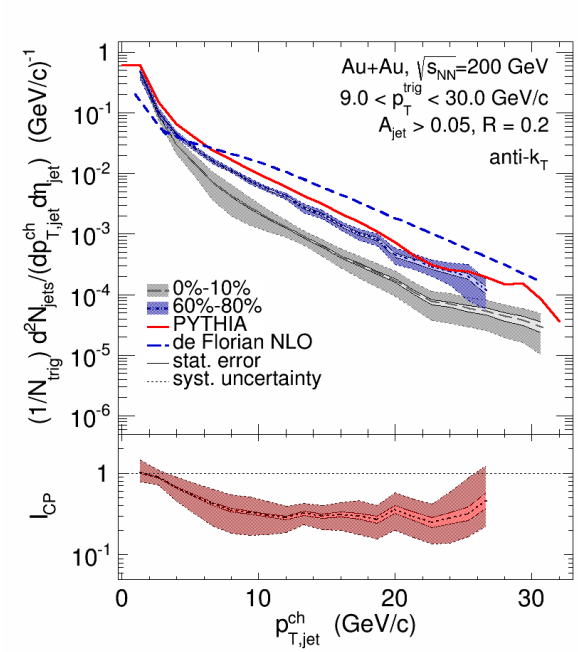
Outline

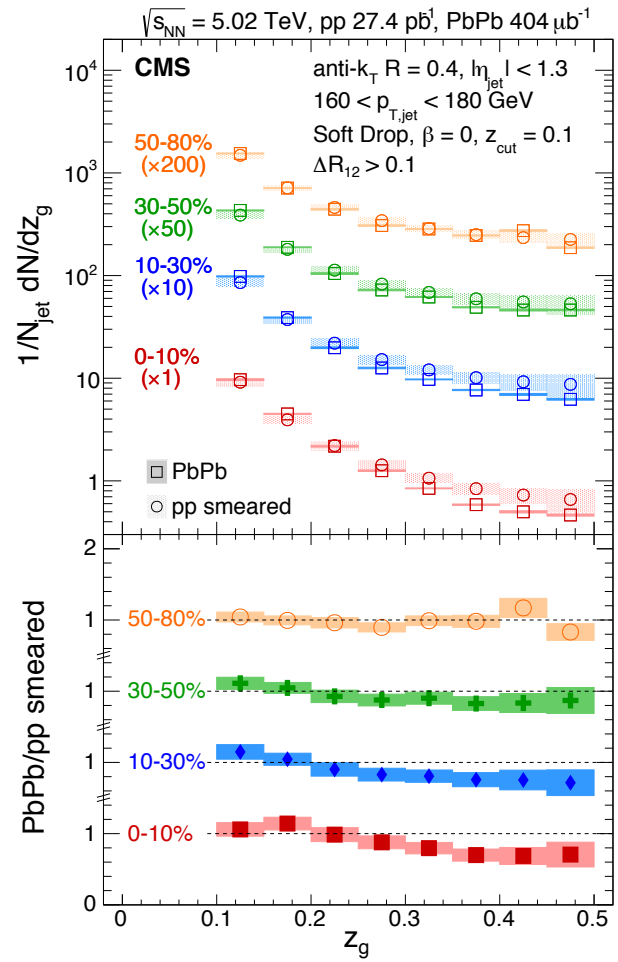
- Single hadron Fragmentation Function
- Jet Function
- Di-hadron Fragmentation Function
- Soft-Drop Function
- Summary and Future Goals

Motivation

- Heavy ion collision → large background → narrow jets
- Increasing interest into narrow jets and jet grooming
- Is it possible to calculate soft drop and narrow jets in one single formalism, that also includes leading hadron evolution?

Adamczyk et al, Phys.Rev. C96 (2017) no.2, 024905

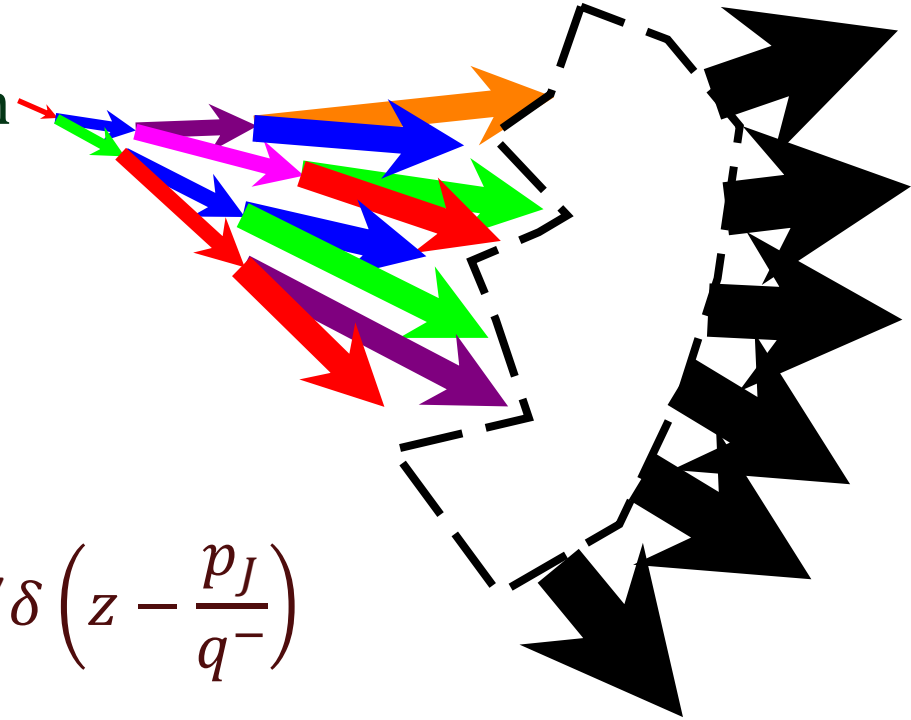




Sirunyan *et al.*, Phys. Rev. Lett. 120, 142302

Single Hadron Fragmentation Function

- The distribution of hadrons with momentum fraction z produced in the hadronization of the outgoing hard parton



- Non-perturbative
- Definition

$$D_q^h(z,Q\ ) = \frac{z^3}{2}\int d^4y \frac{d^4q}{(2\pi)^4} e^{-iq.y}\delta\left(z - \frac{p_J}{q^-}\right)$$

$$\times \sum_{S_{had}} Tr\left[\frac{\gamma^-}{2}\langle 0|\psi(0)|p_h, S_{had}\rangle\langle p_h, S_{had}|\bar{\psi}(y^+)|0\rangle\right]$$

- Factorized from hard scattering, evolution given by

$$\frac{dD_i(z,Q)}{dlog(Q^2)} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dz'}{z'} P_{i\to j}(z')D_j\left(\frac{z}{z'},Q\right)$$

Single Hadron Fragmentation Function

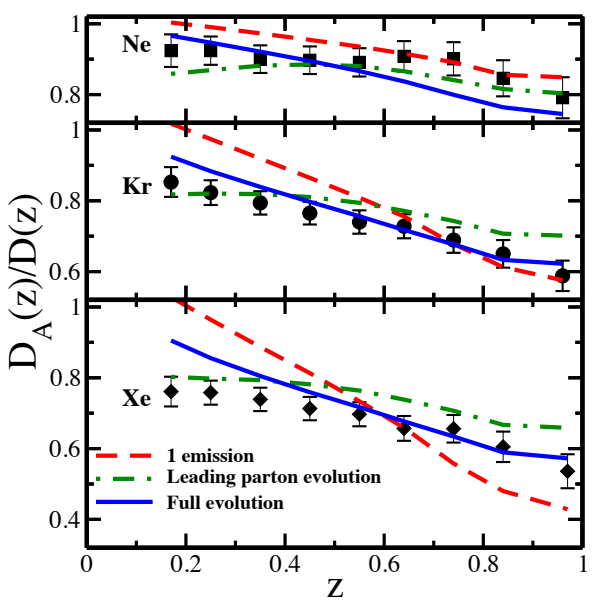
- Medium modified evolution equation, using Higher twist formalism.

$$\frac{\partial D_i^h(z,Q^2,q^-)|_{\xi_i}^{\xi_f}}{\partial log(Q^2)} = \int_z^1 dy \int_{\xi_i}^{\xi_f} d\xi K_{q^-,Q^2}(y,\xi)\, D_j^h\left(\frac{z}{y},Q^2,q^-\right)\Bigg|_{\xi}^{\xi_f}$$

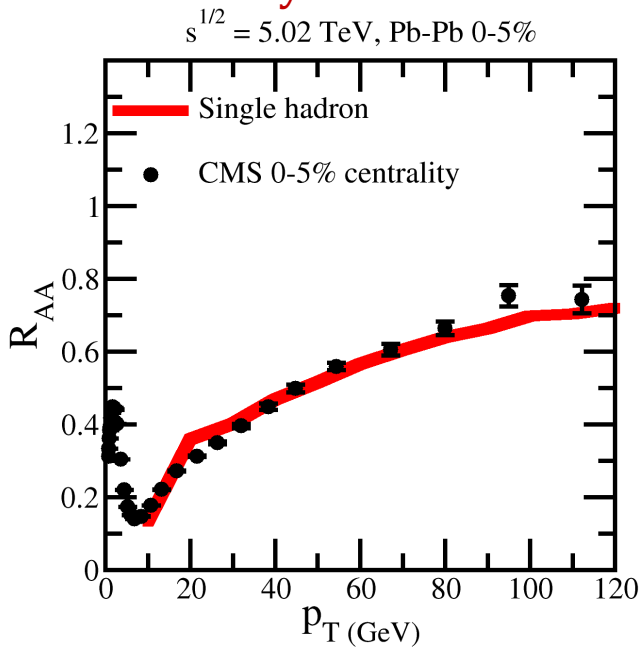
Where,

$$K_{q^-,Q^2}(y,\xi) = \frac{\alpha_s}{2\pi}\frac{\tilde{P}_{i\to j}(y)}{yQ^2}\hat{q}(\xi,x_T)\left[2-2\cos\left\{\frac{Q^2(\xi-\xi_i)}{2q^-y(1-y)}\right\}\right]$$

DIS on a large nucleus



Heavy-ion collisions



Single Jet Function

- Two lines of thought:
  - Kang, Ringer and Vitev, JHEP 1610 (2016) 155 (KRV)
  - Dasgupta, Dreyer, Salam and Soyez, JHEP 1504 (2015) 039 (DDSS)

- Definition of the Jet function by KRV

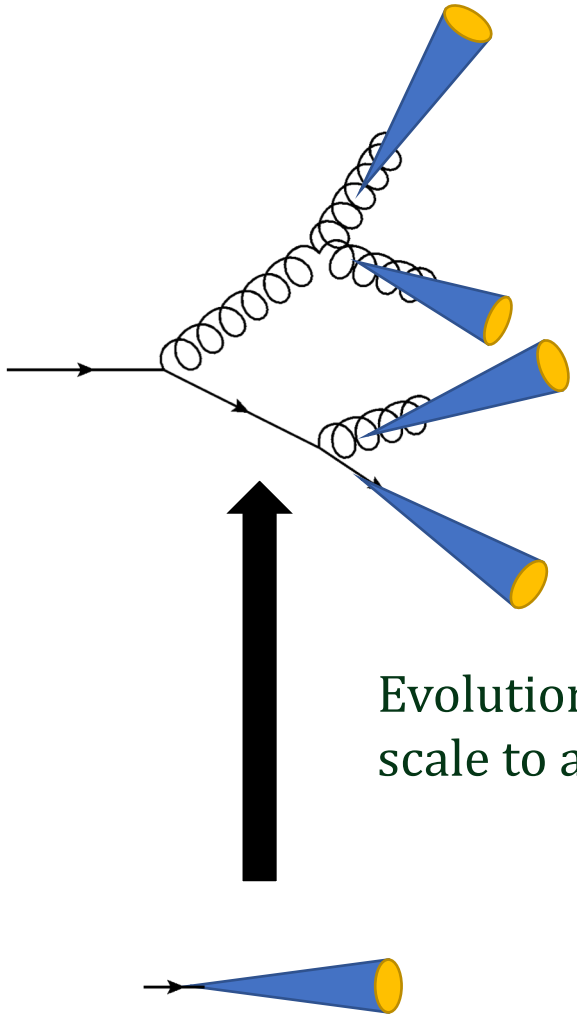
$$J_q(z,\omega_J,Q) = \frac{z}{2N_C} Tr\left[\frac{\bar{n}.\gamma}{2}\langle 0|\delta(\omega-\bar{n}.P)\chi_n(0)|JX\rangle\langle JX|\bar{\chi}_n(0)|0\rangle\right]$$

- $Q \sim E_J tan\frac{\theta}{2} \sim E\theta$ Factorization proved within $SCET_G$

- $$\frac{dJ_i(z,\omega_J,Q)}{dlog(Q^2)} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dz'}{z'} P_{i\to j}(z') J_j\left(\frac{z}{z'},\omega_J,Q\right)$$

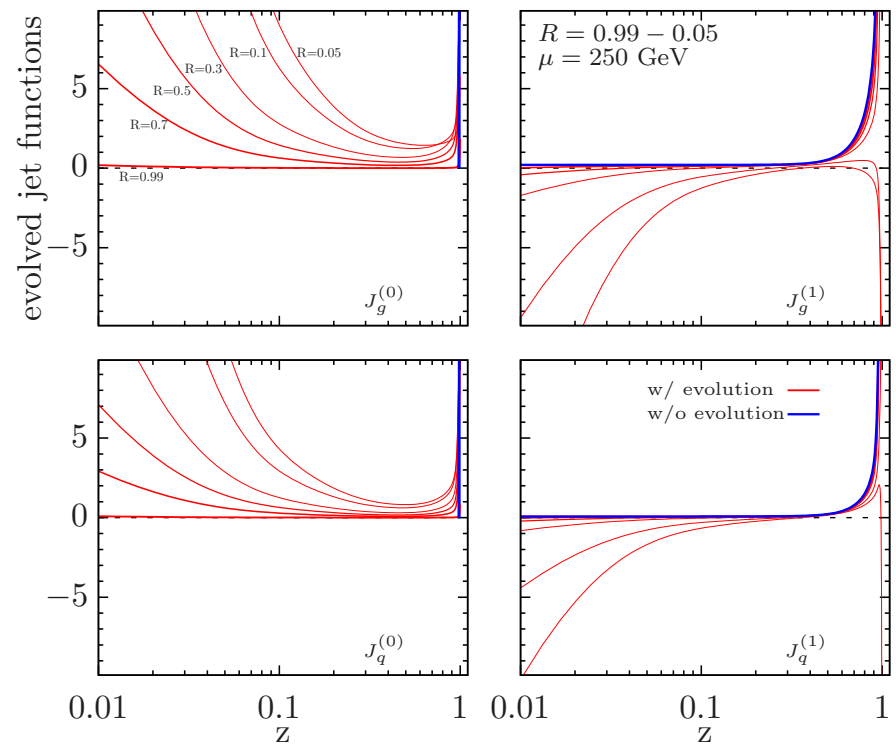
- Jet function at small angle is calculated perturbatively

Single Jet Function



Evolution from lower scale to a higher scale

Kang, Ringer and Vitev, JHEP 1610 (2016) 155



Single Jet Function

- Alternative method by DDSS
- Evolution variable,

$$\mathrm{t}(R, p_T) = \int_{R^2}^{1} \frac{d\theta^2}{\theta^2} \frac{\alpha_s(p_T\theta)}{2\pi}$$

- Initial jet function,

$$J_i(z, 0) = \delta(1 - z)$$

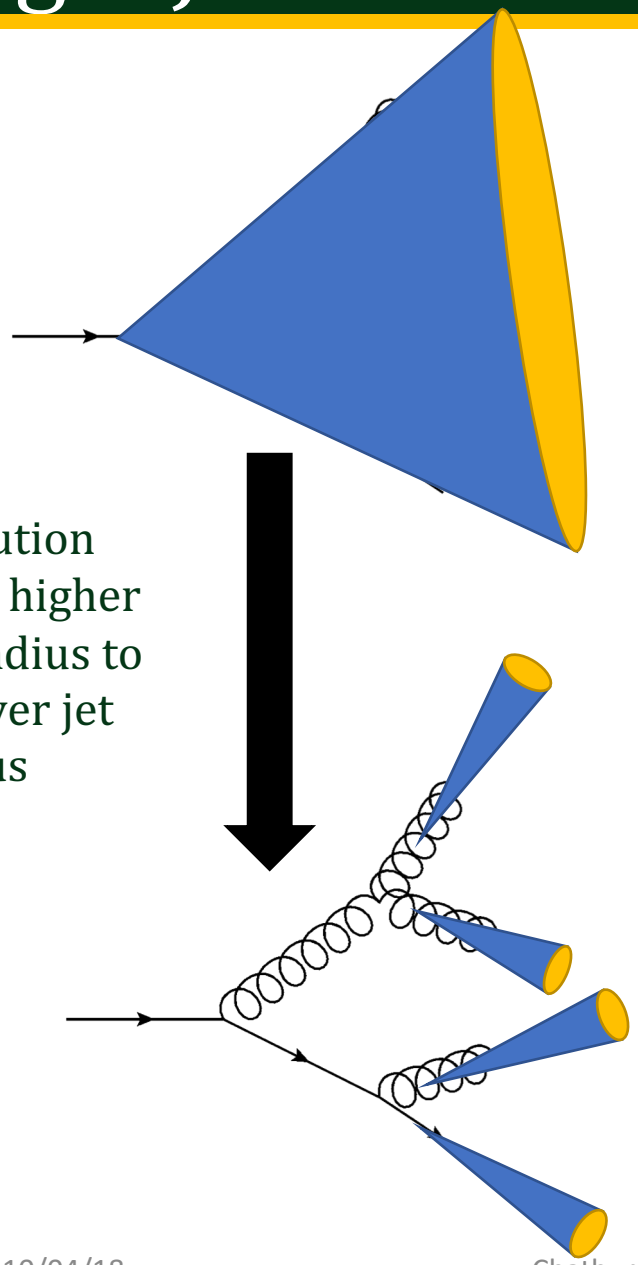
- Evolution equation:

$$\frac{dJ_i(z,t)}{dt} = \sum_k \int_z^1 \frac{dz'}{z'} P_{i\to k}(z') J_k\left(\frac{z}{z'}, t\right)$$

- Evolution in angle

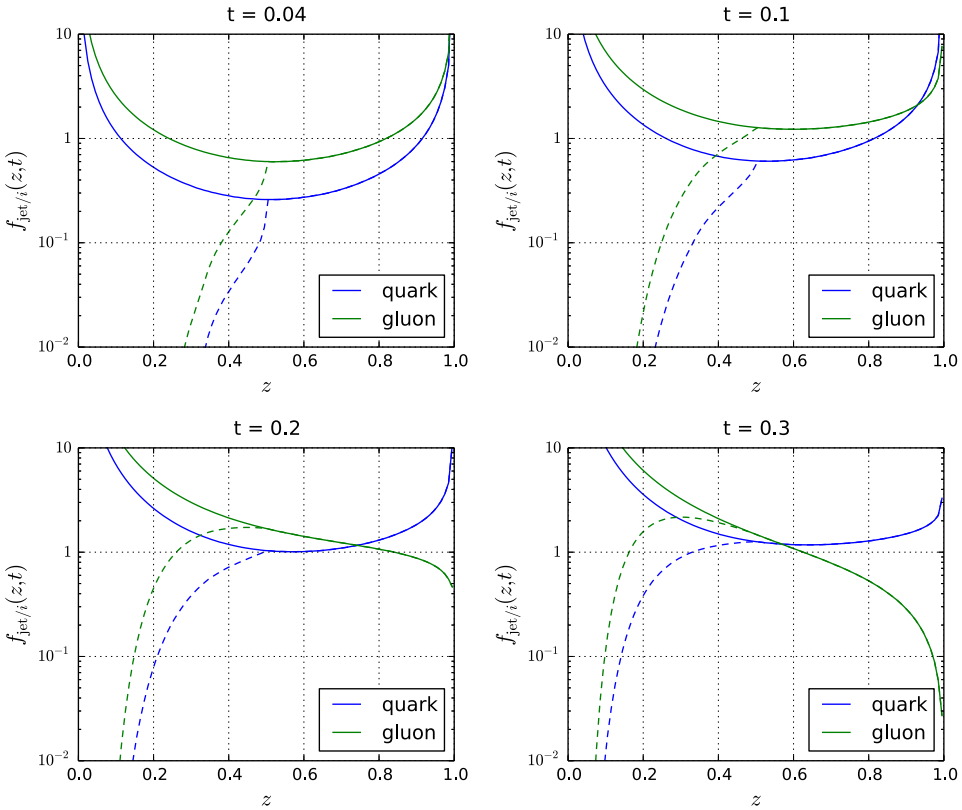
$$\frac{dJ_i(z, E, R)}{dlog(R^2)} = -\frac{\alpha_s}{2\pi} \int_z^1 \frac{dz'}{z'} P_{i\to j}(z') J_j\left(\frac{z}{z'}, E, R\right)$$

Single Jet Function



Evolution from higher jet radius to a lower jet radius

Dasgupta, Dreyer, Salam and Soyez, JHEP 1504 (2015) 039

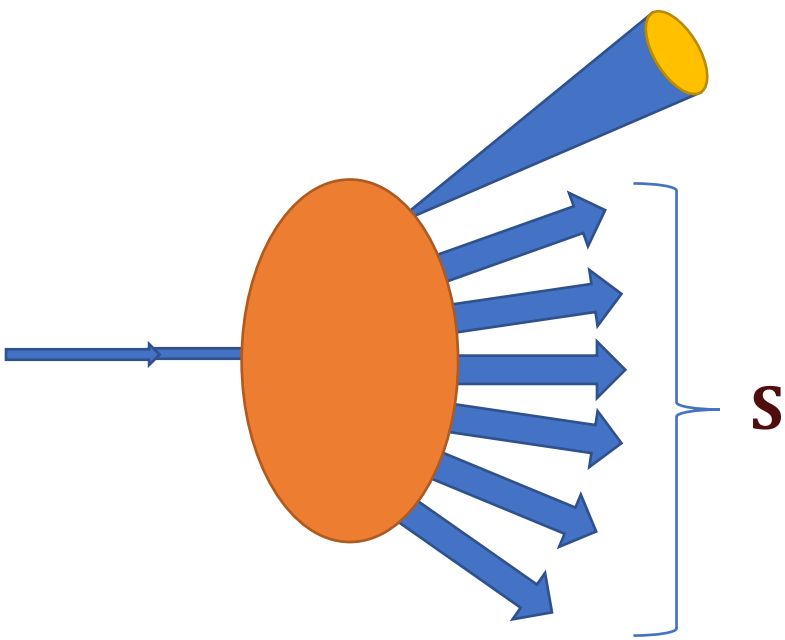


Our approach

- Modified definition of the Jet function

$$J_q\left(z, E_J, R, \mu = E_J R\right) = \frac{z^3}{2}\int d^4y \frac{d^4q}{(2\pi)^4} e^{-iq.y}\delta\left(z - \frac{p_J}{q^-}\right) \sum_{S_{had}} Tr\left[\frac{\gamma^-}{2}\langle 0|\psi(0)|p_J, S\rangle\langle p_J, S|\bar{\psi}(y^+)|0\rangle\right]$$

- $Q \sim E_J tan\frac{R}{2} \sim ER$ Equivalent to KRV definition

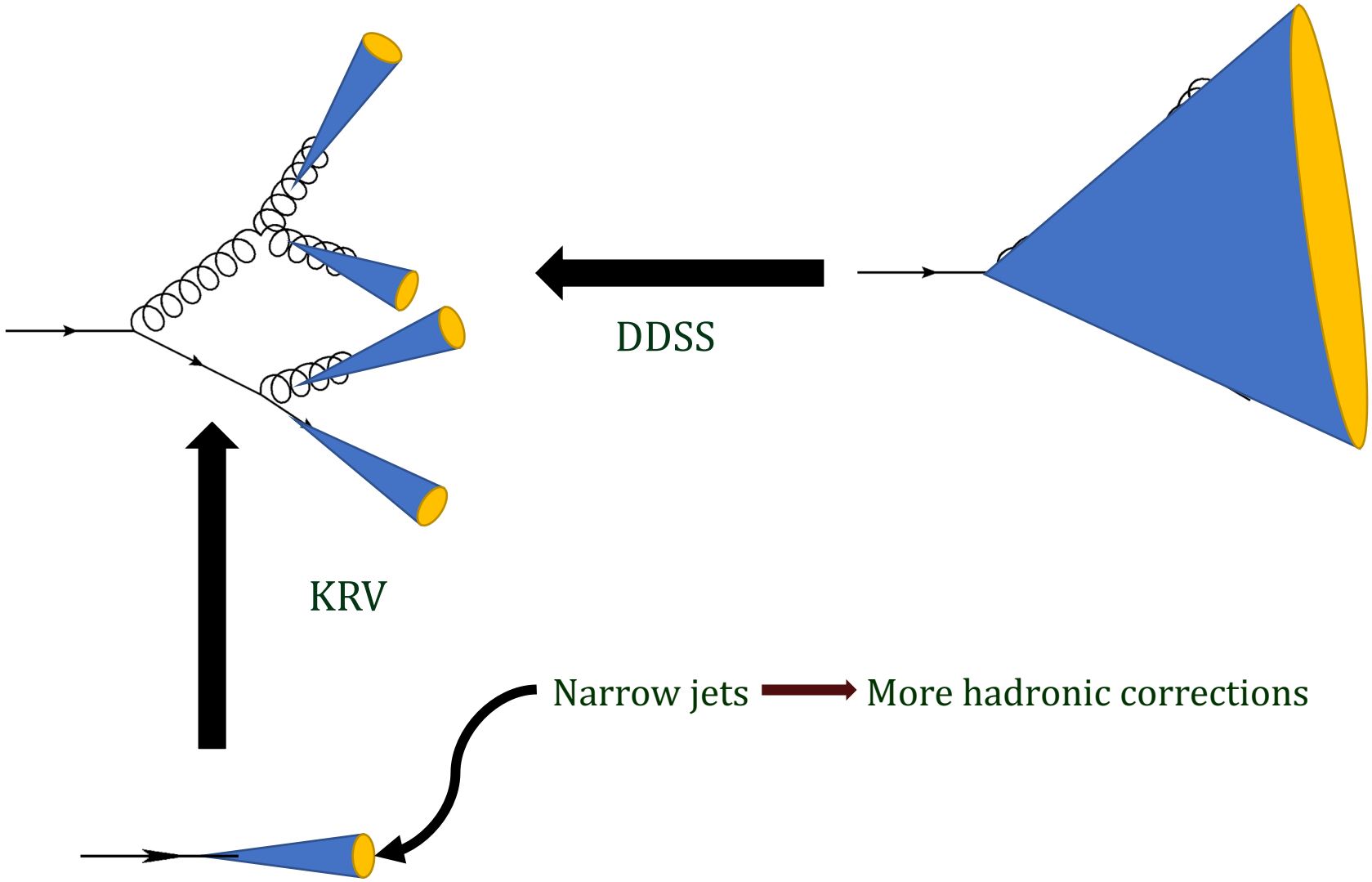


The distribution of jets with radius R, energy E_J and momentum fraction z

Our approach

- We measure Jet function $J_q\left(z, E_J, R, Q\right)$ at low energy and large radius
- Boost it up to a higher energy
  - Virtuality Q and z are boost invariant
  - Q~$E_J R$ ⟶ E_J ⟶ γE_J makes R ⟶ R/γ
  - i.e jets become narrower
- Evolve it up to a higher scale by using DGLAP evolution
- $\frac{dJ_i(z,E_J,R,Q)}{dlog(Q^2)} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dz'}{z'} P_{i\to j}(z') J_j\left(\frac{z}{z'}, E_J, R, Q\right)$

Summarize all approaches



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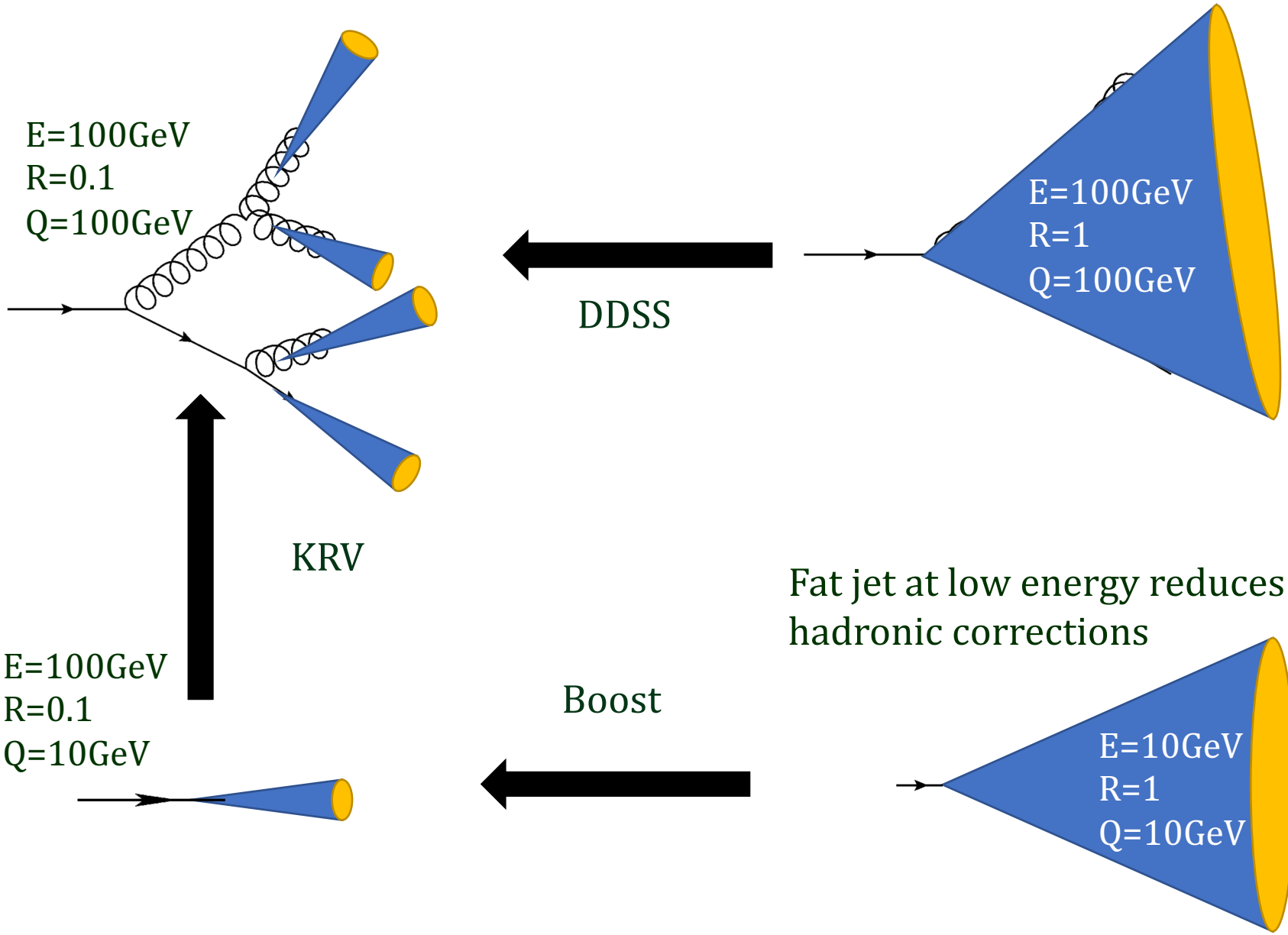
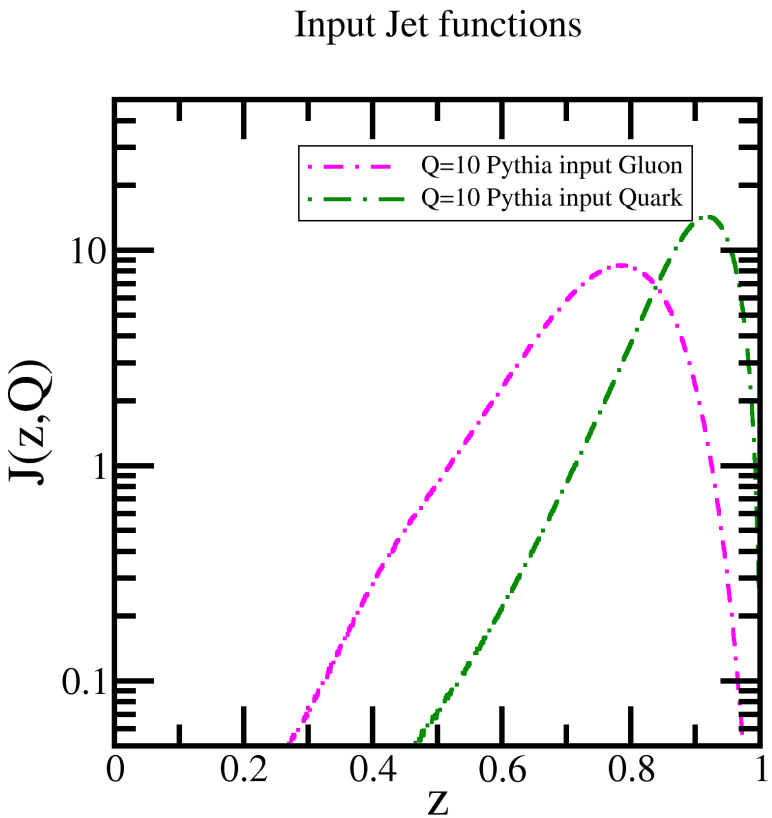
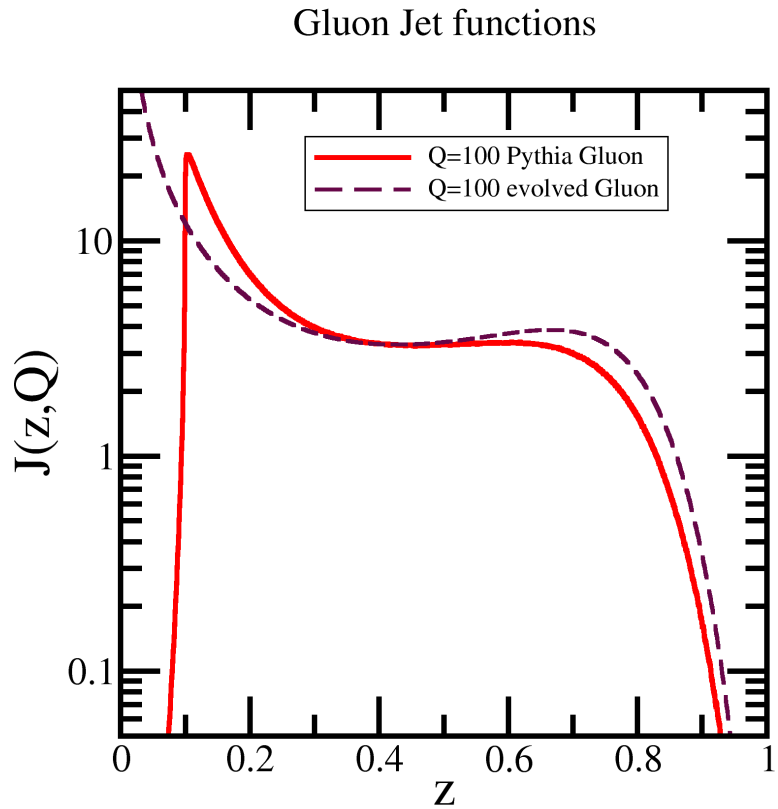


Compare with PYTHIA in lieu of data

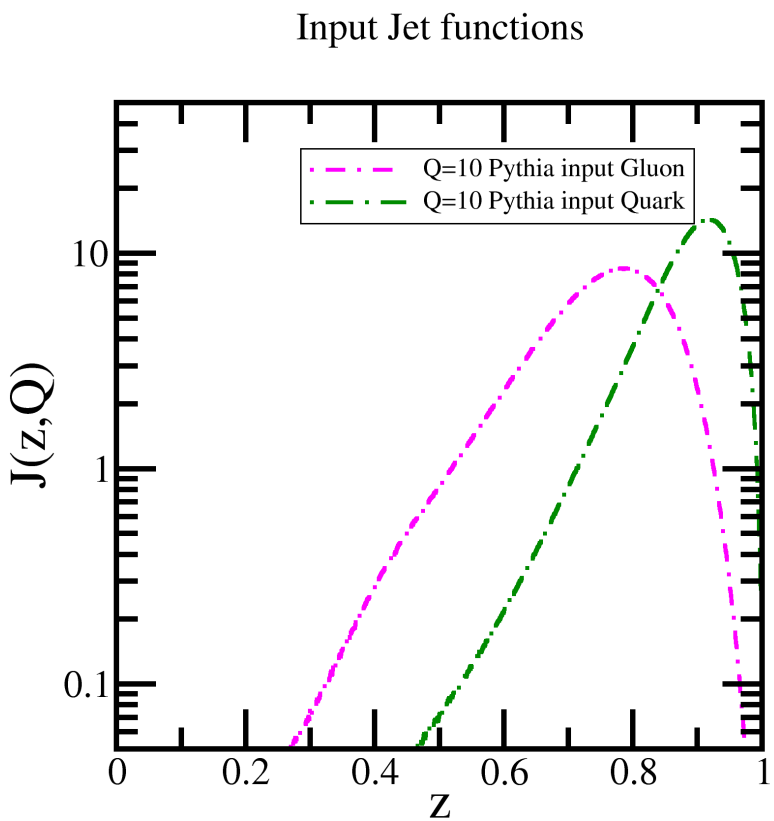


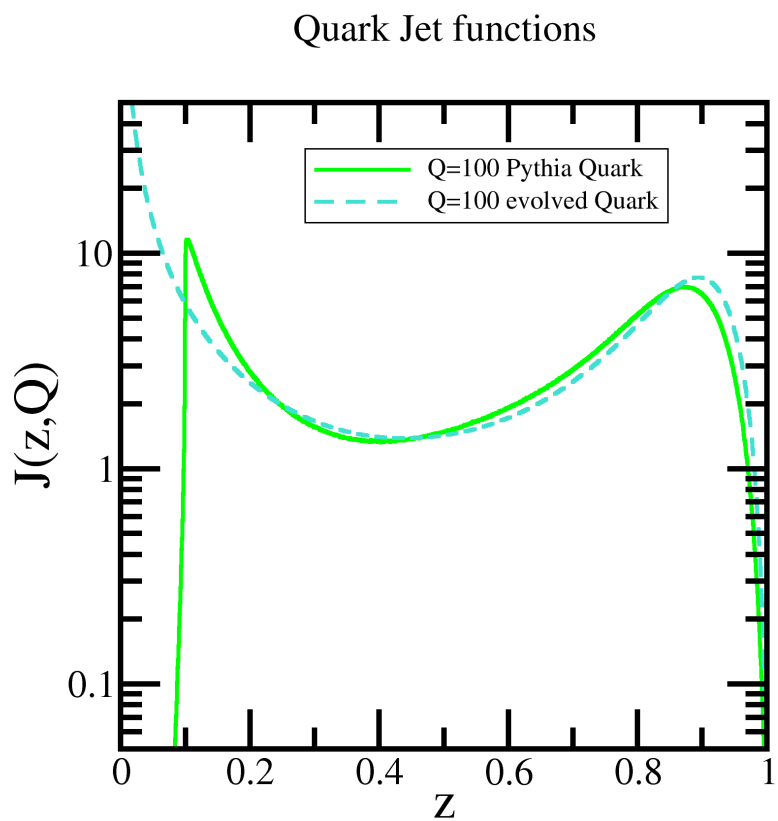


- E=10 GeV, R = 1 ➡ Q=10 GeV
- Boosted jet function is the same
- E=100 GeV, R=0.1 ➡ Q=10 GeV
- Measured using Pythia 8

- E=100 GeV, R = 0.1 ➡ Q=100 GeV
- Evolved function is similar to the measured function using Pythia8

Compare with PYTHIA in lieu of data





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- E=100 GeV, R = 0.1 ➡ Q=100 GeV
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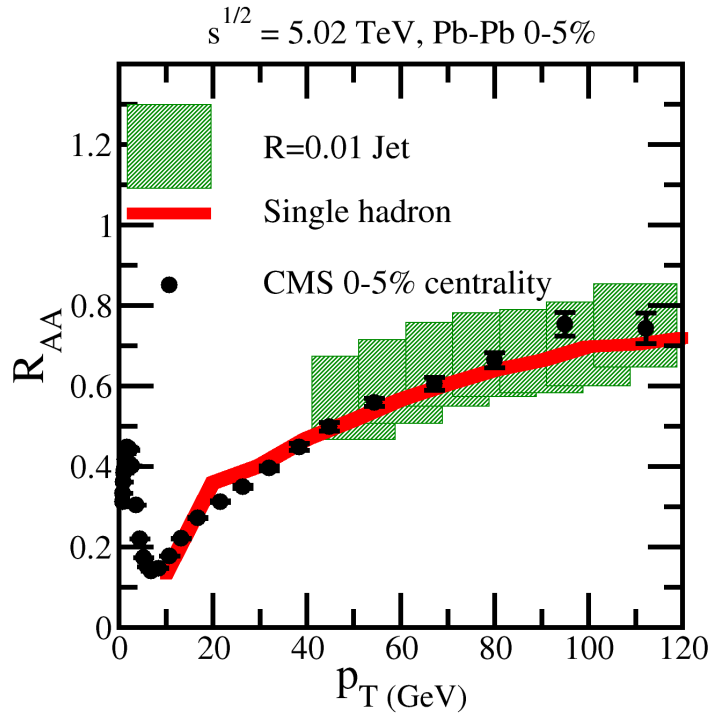
Medium Modified Single Jet Function

- Medium modified evolution equation

$$\frac{\partial J_i(z, E_J, R, Q^2)\big|_{\xi_i}^{\xi_f}}{\partial log(Q^2)} = \int_z^1 dy \int_{\xi_i}^{\xi_f} d\xi K_{q^-,Q^2}(y,\xi) J_j\left(\frac{z}{y}, E_J, R, Q^2\right)\Bigg|_{\xi}^{\xi_f}$$

Where,

$$K_{q^-,Q^2}(y,\xi) = \frac{\alpha_s}{2\pi}\frac{\tilde{P}_{i\to j}(y)}{yQ^2}\hat{q}(\xi, x_T)\left[2 - 2\cos\left\{\frac{Q^2(\xi-\xi_i)}{2q^- y(1-y)}\right\}\right]$$



This is an expected result

At some small angle the Jet R_{AA} should match the single hadron R_{AA}

This quite non-trivial: The jet function is not the same as the fragmentation function

Di-hadron Fragmentation Function

- The distribution of two hadrons combinations with momentum fractions z_1 and z_2 produced in the hadronization of the outgoing hard parton

- Motivation to calculate the Soft-Drop function

- Definition:

$$D_q^{h_1,h_2}(z_1,z_2) = \frac{z^4}{4z_1z_2}\int \frac{dq_\perp^2}{8(2\pi)^2}\int \frac{d^4l}{(2\pi)^4}\delta\left(z-\frac{p_h^+}{l^+}\right)$$

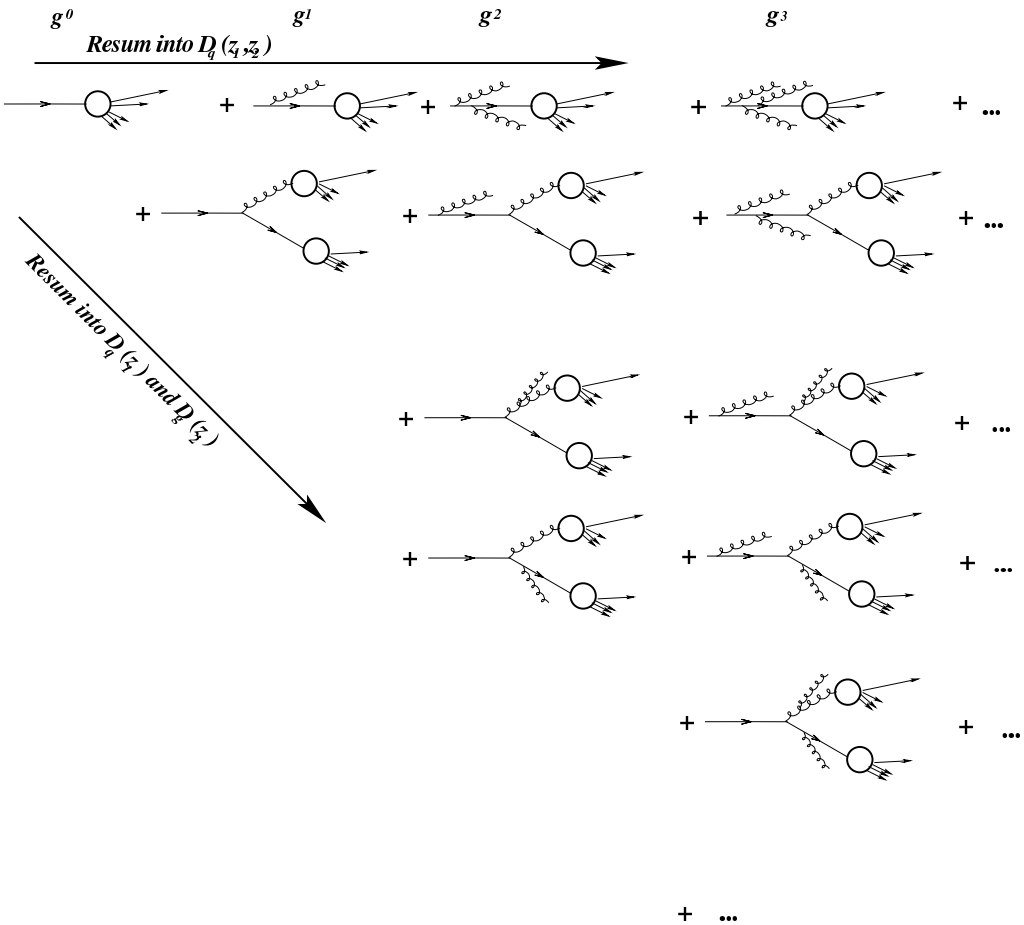
$$\times Tr\left[\frac{n.\gamma}{n.p_h}\int d^4x\, e^{-il.x}\sum_s \langle 0|\psi_q(x)|p_1,p_2,S\rangle\langle p_1,p_2,S|\bar{\psi}_q(0)|0\rangle\right]$$

- Evolution:

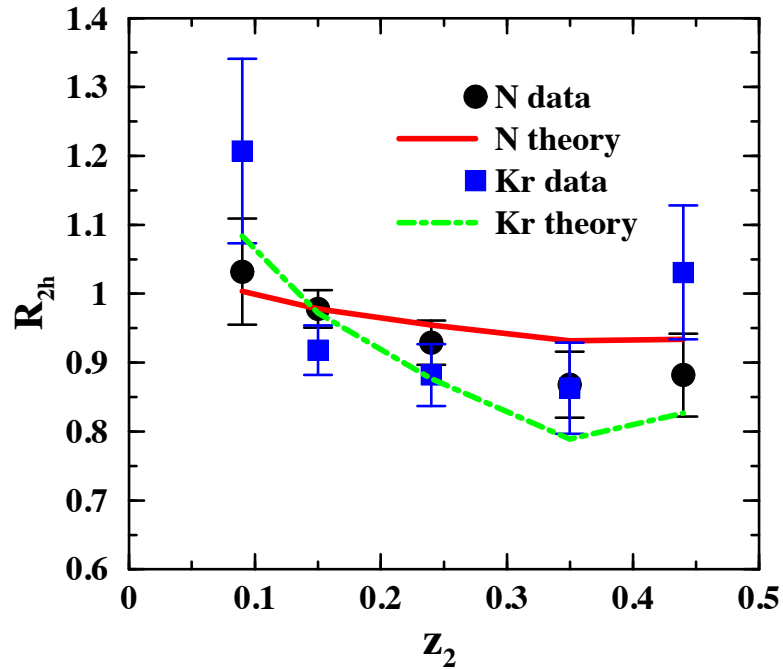
$$\frac{dD_q^{h_1,h_2}(z_1,z_2,\mu^2)}{dlog\mu^2} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dy}{y^2}P_{qk}(y)\,D_k^{h_1,h_2}(z_1,z_2,\mu^2)$$

$$+\frac{\alpha_s}{2\pi}\int_{z_1}^{1-z_2}\frac{dy}{y(1-y)}P_{qq}(y)\,D_q^h(z,\mu^2)D_q^h(z,\mu^2) + 1\rightarrow 2$$

Di-hadron Fragmentation Function



Majumder, E. Wang and X. N. Wang, Phys.Rev.Lett. 99 (2007) 152301



$$R_{2h} = \frac{D^A(h_1,h_2)/D^A(h_1)}{D^P(h_1,h_2)/D^P(h_1)}$$

Majumder and X. N. Wang,Phys.Rev. D70 (2004) 014007

Un-normalized Soft-Drop function

- Distribution of jets with Energy E_J, radius R and momentum fraction z, which contains two prongs with momentum fractions z_1 and z_2, in a parton with Energy E.

- Definition: This is the un-normalized soft-drop function

$$J_q(z_1, z_2, Q = E_J R, R) = \frac{z^4}{4 z_1 z_2} \int \frac{dq_\perp^2}{8(2\pi)^2} \int \frac{d^4 l}{(2\pi)^4} \delta\left(z - \frac{p_J^+}{l^+}\right)$$

$$\times Tr\left[\frac{n.\gamma}{n.p_h} \int d^4x\, e^{-il.x} \sum_s \langle 0|\psi_q(x)|p: p_1, p_2, S\rangle \langle p: p_1, p_2, S|\bar{\psi}_q(0)|0\rangle\right]$$

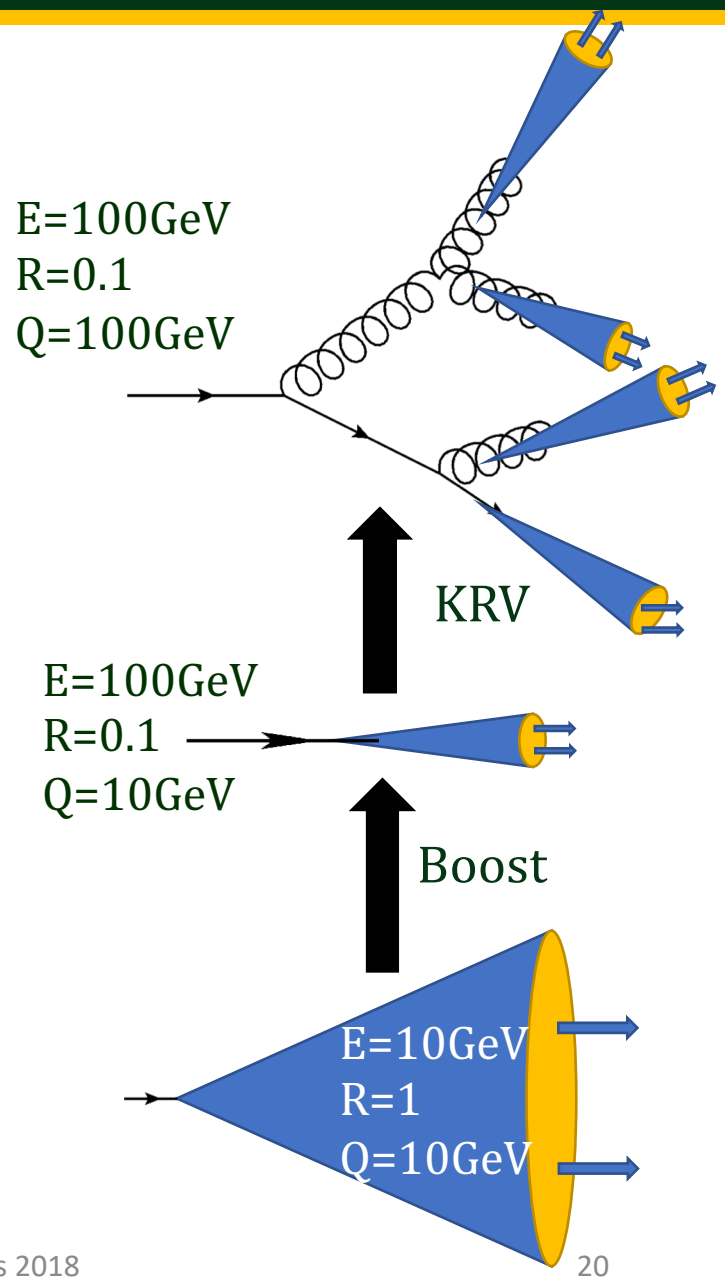
- Evolution:

$$\frac{dJ_q(z_1, z_2, Q, R)}{d\log Q^2} = \frac{\alpha_s}{2\pi} \int_z^1 \frac{dy}{y^2} P_{qk}(y) J_k\left(\frac{z_1}{y}, \frac{z_2}{y}, Q, R\right)$$

- Soft-Drop function evolution does not depend on the product of two single jet functions

Unnormalized Soft-Drop Function

- Quark and Gluon input at E=10 GeV
  - Soft-Drop function at R=1 and Q=10 GeV
- Boost them up to E=100 GeV
  - Soft-Drop function at R=0.1 and Q=10 GeV
  - Same as the previous Soft-Drop functions at E=10 GeV
- Evolve them up to E=100 GeV in scale
  - Soft-Drop function at R=0.1 and Q=100GeV



Unnormalized Soft-Drop Function

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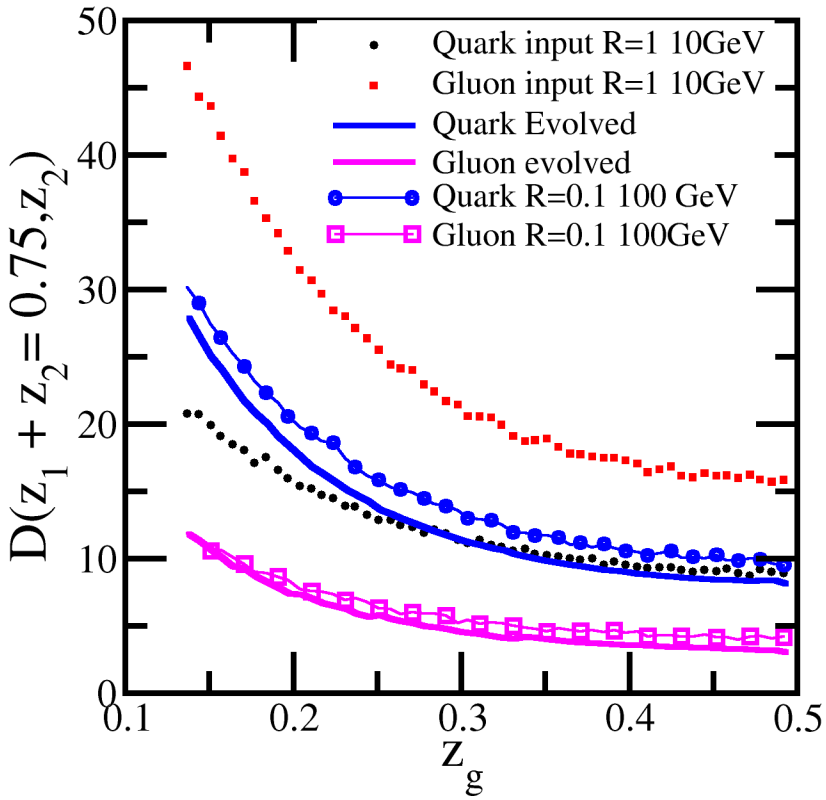

Summary

- In this talk, I discussed;
  - Single hadron Fragmentation Function and Di-hadron Fragmentation Function
  - Jet Function and Soft-Drop Function and their Evolution
    - They can be evolved by using similar evolution equations used for fragmentation functions
    - R_{AA} for extremely narrow jets is equivalent to single hadron R_{AA}
    - Scale evolution of Soft-Drop function does not depend on the single jet function

- Our Goals;
  - Extend this calculation using medium modification
  - Estimate LHC results by boosting and evolving RHIC results