

Jet splitting functions in the vacuum and QCD medium

Hai Tao Li
Los Alamos National Laboratory

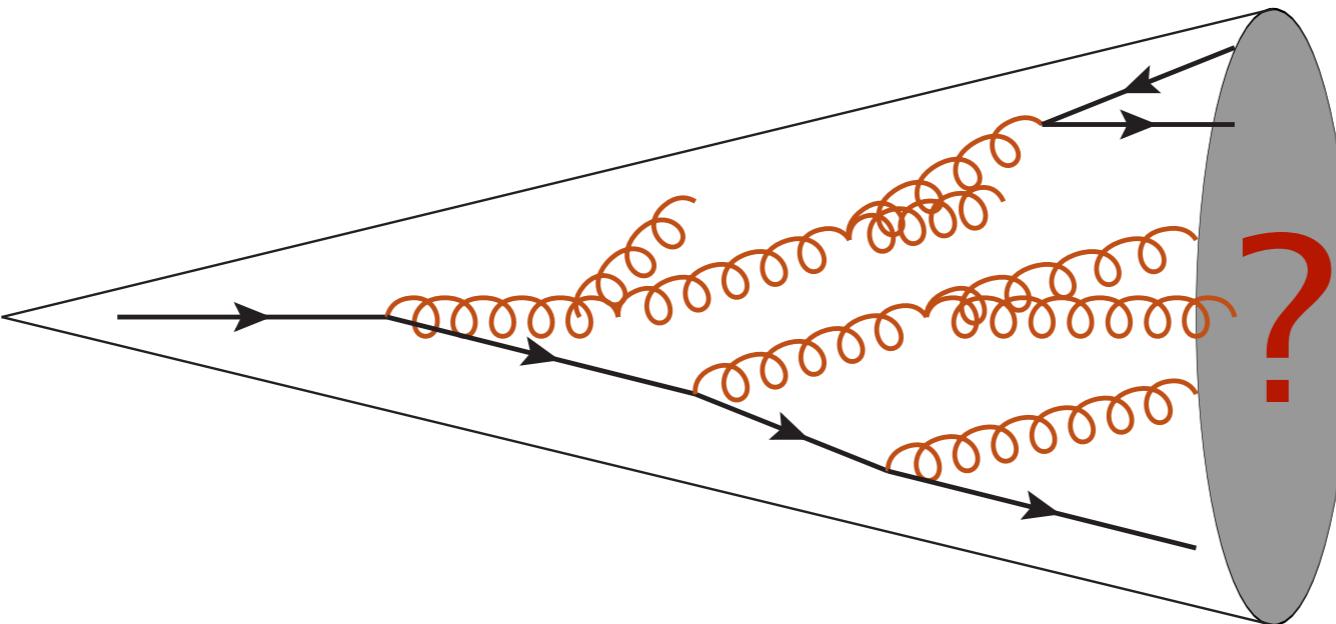


In collaboration with Ivan Vitev

Based on the work arXiv:1801.00008

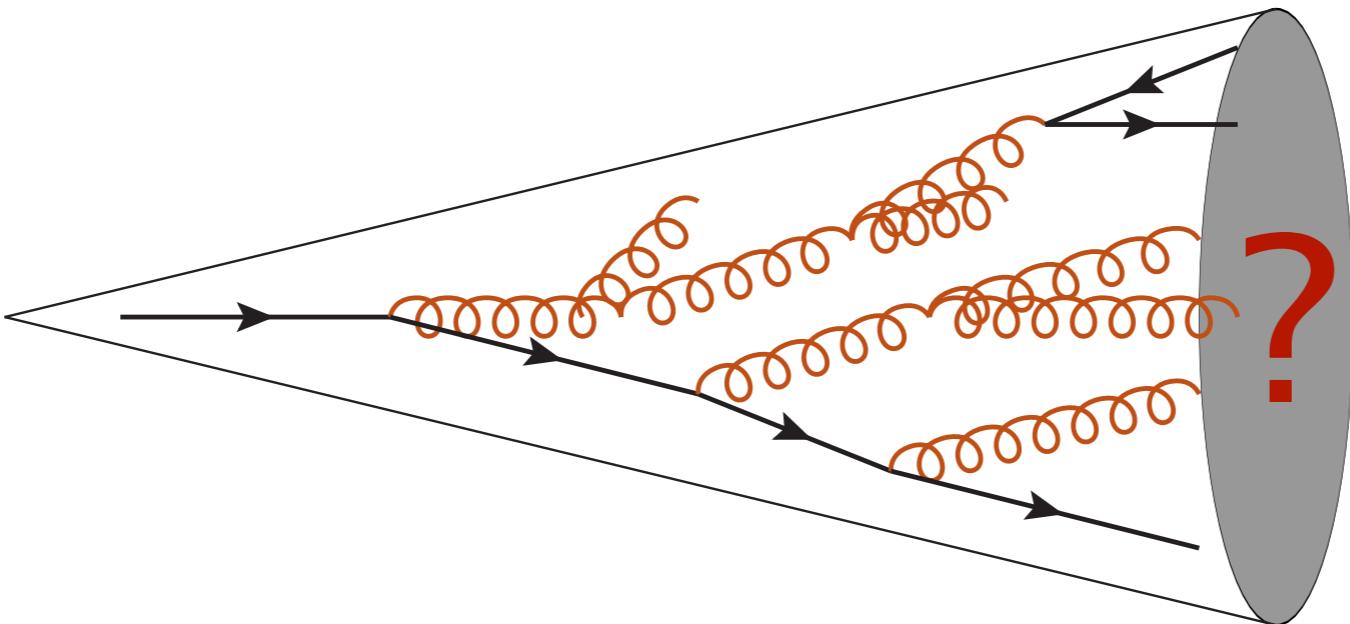
Hard Probes, Aix-Les-Bains
October 02, 2018

Jets



The study of jets has been used to test perturbative QCD, to probe proton structure and to search for New Physics

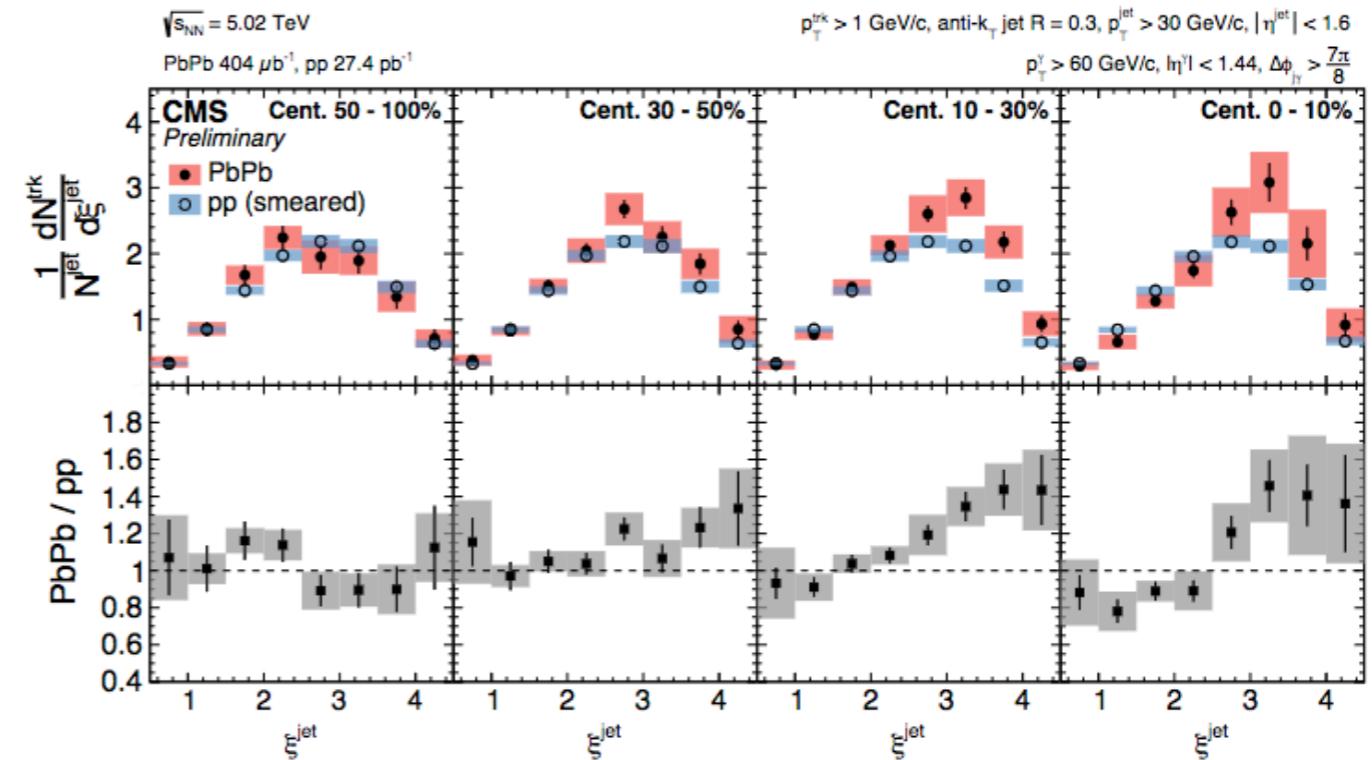
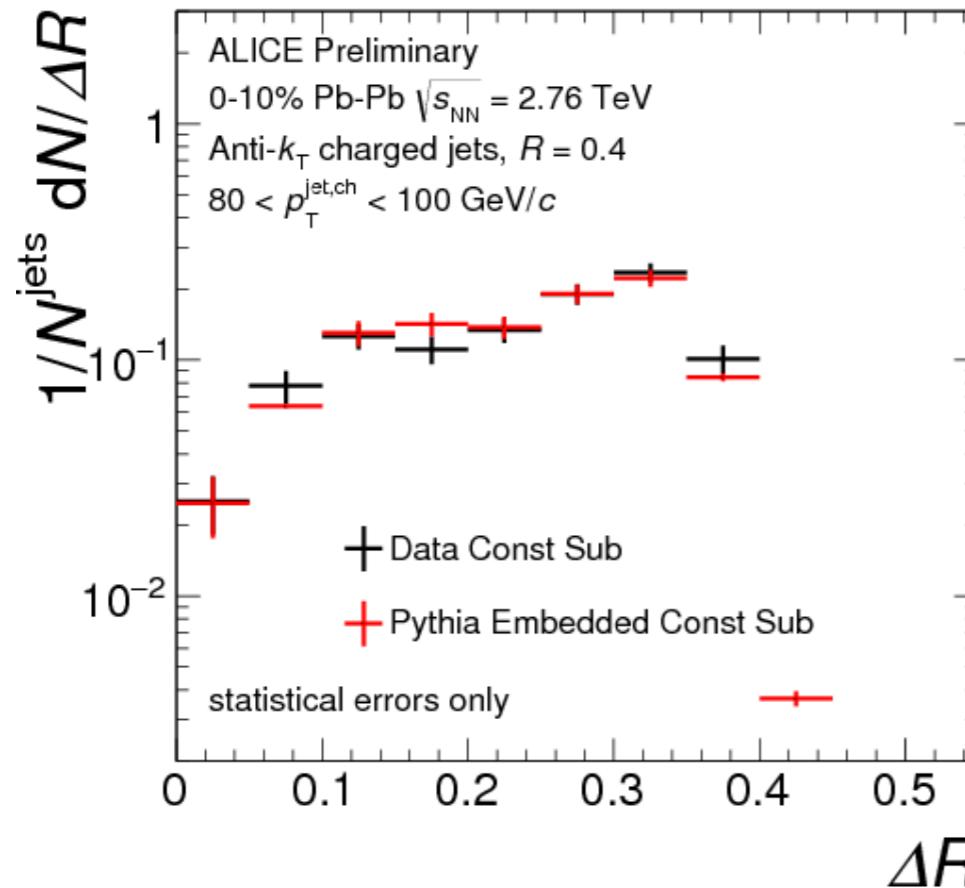
Jets



The study of jets has been used to test perturbative QCD, to probe proton structure and to search for New Physics

How about the jet substructure in heavy-ion collisions?

Jets

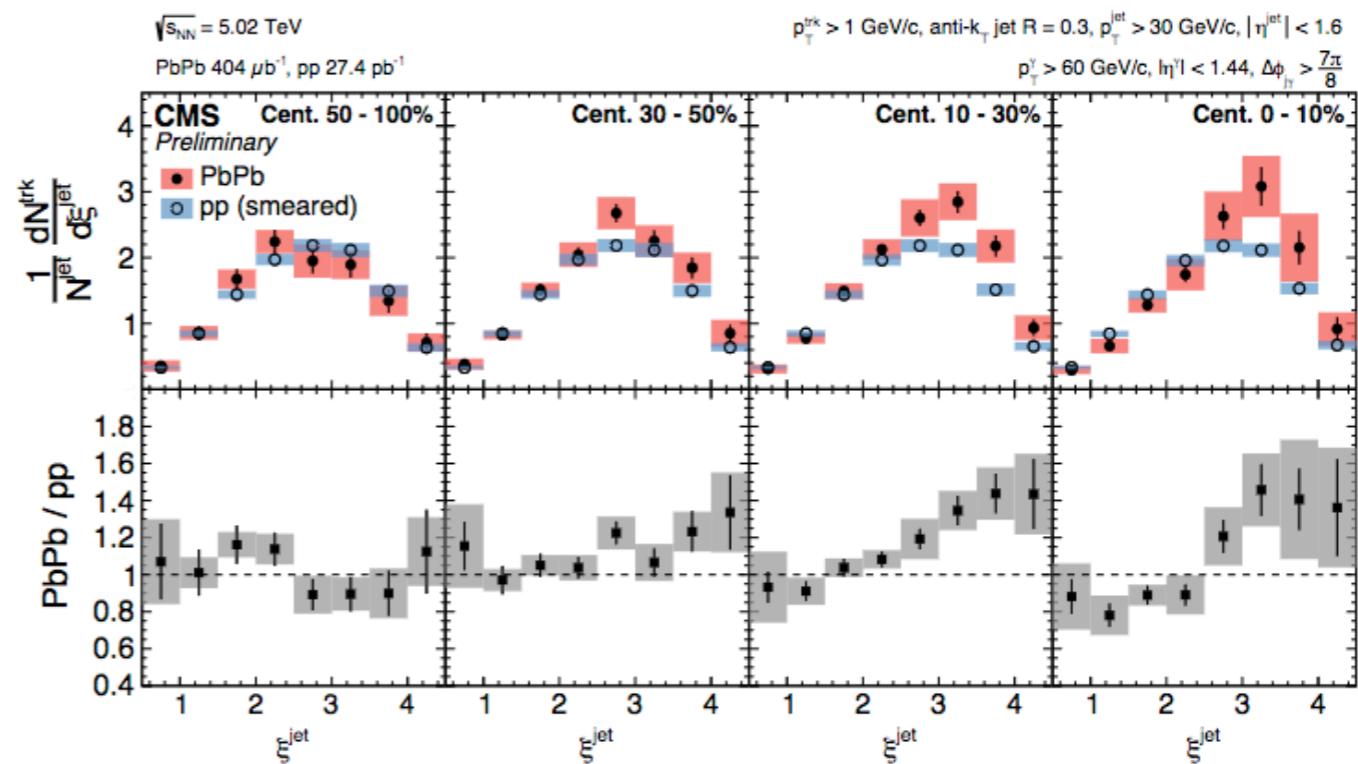
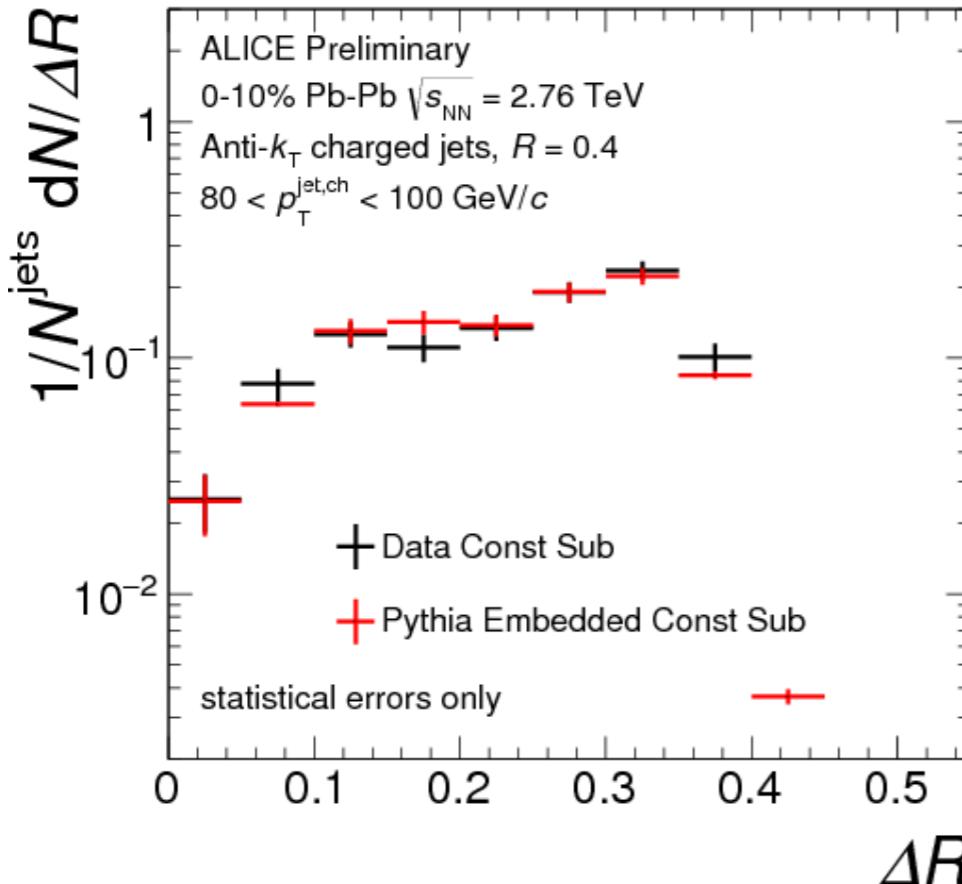


Measurements of fragmentation functions $\xi^{\text{jet}} = \ln \frac{|p_{T}^{\text{jet}}|^2}{p_{T}^{\text{trk.}} p_{T}^{\text{jet}}}$

Open angle between the two 2-subjettiness

ALI-PREL-127420

Jets



Measurements of fragmentation functions $\xi_{\text{jet}} = \ln \frac{|p_{\text{jet}}|^2}{p_{\text{trk}, p_{\text{jet}}}}$

Open angle between the two 2-subjettiness

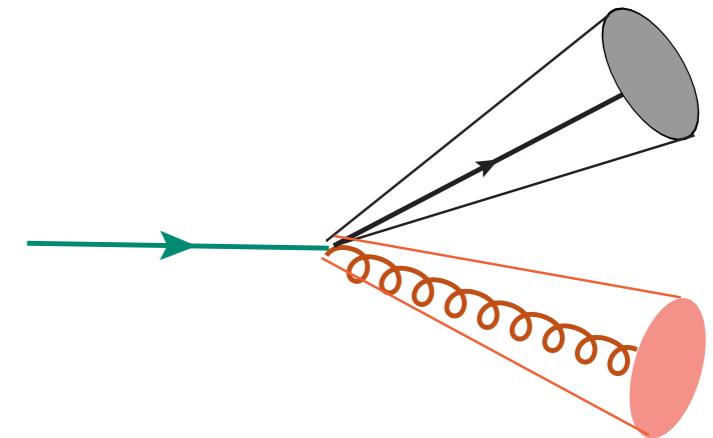
Our work provided

- the first predictions for the modification of the resumed substructure for light jet
- the first predictions for the jet substructure of heavy-flavor tagged jet in the vacuum and medium
- unique results for the mass dependence of b-jet and a novel way to study the b-quark mass effect in heavy ion collisions.

Jet Splitting Function

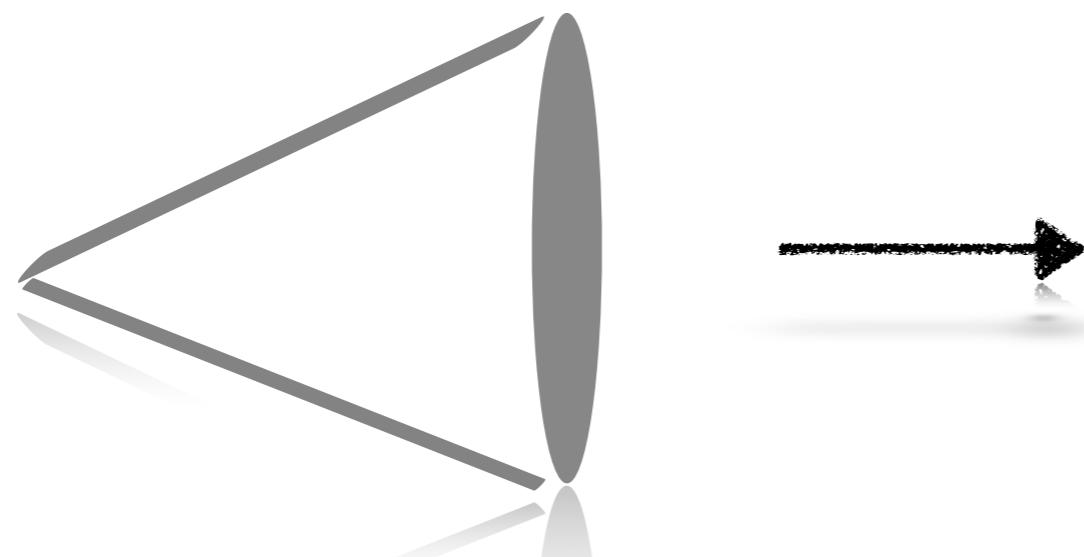
Defined as a two-prong substructure

- ▶ An early hard splitting will result in two partons with high transverse momentum.



One way to do this is to use Soft-Drop declustering

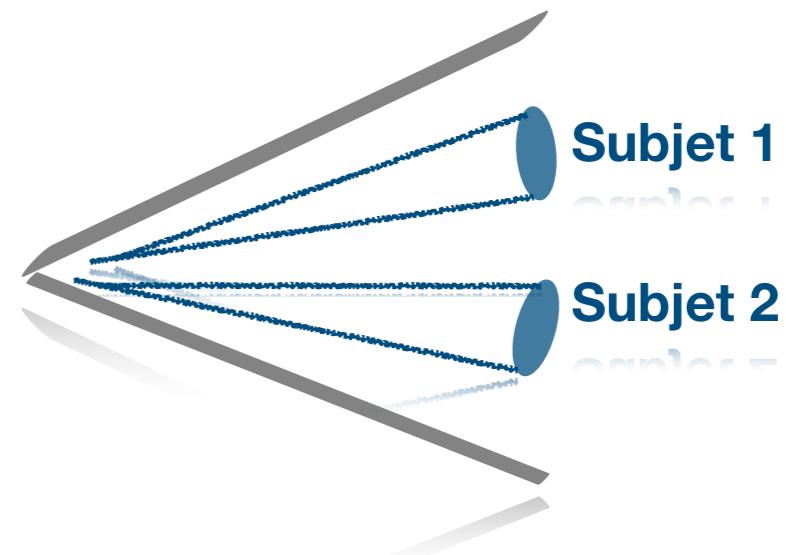
$1 \rightarrow 2$ splitting process



Original jet with radius R_0

Undo last stage of C/A clustering

Define $z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$

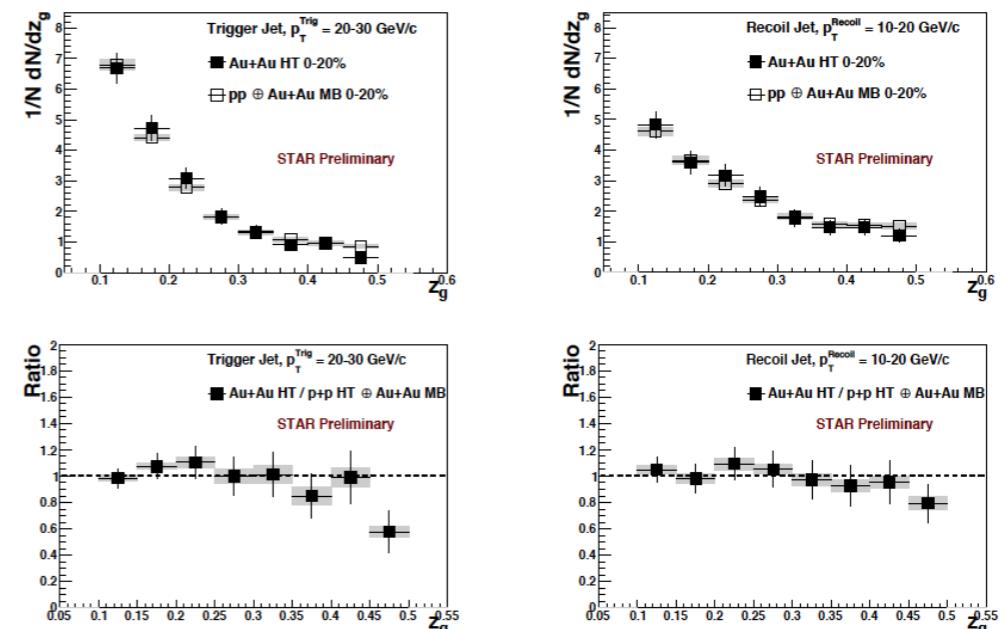
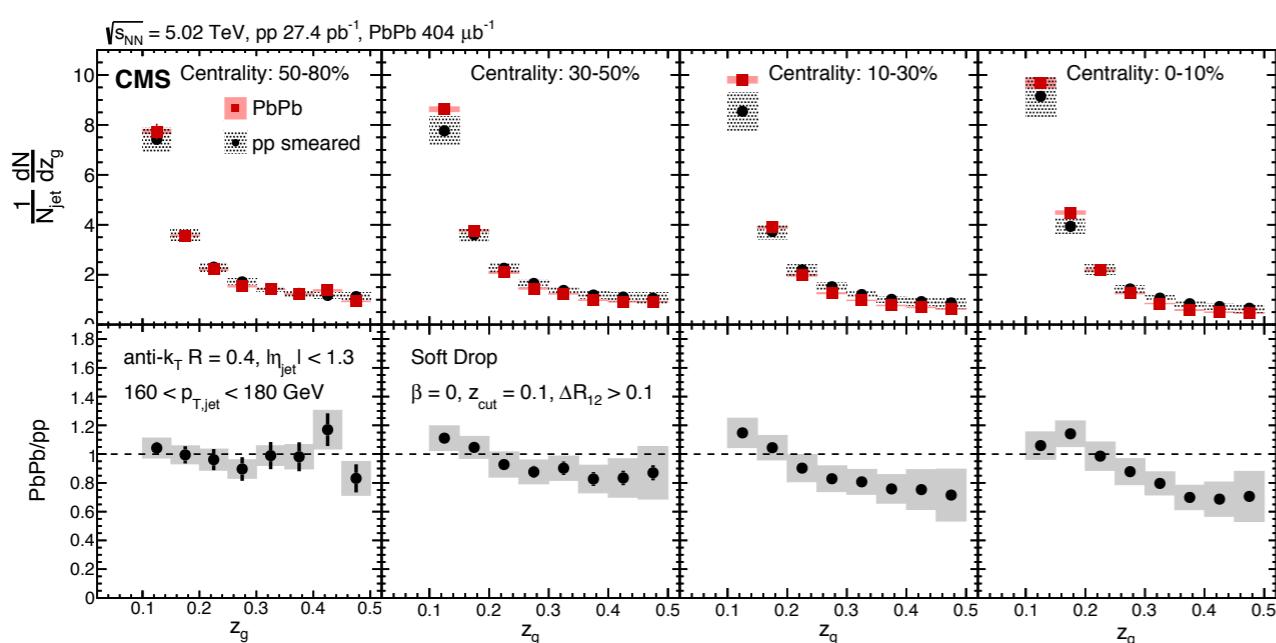


If $z_g < z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^\beta$ redefine j to be the harder one, else we have the two-prong subjets

Splitting functions in medium

The interactions of the outgoing partons with the hot and dense QCD medium, may change the jet splitting functions relative to the simpler proton-proton case

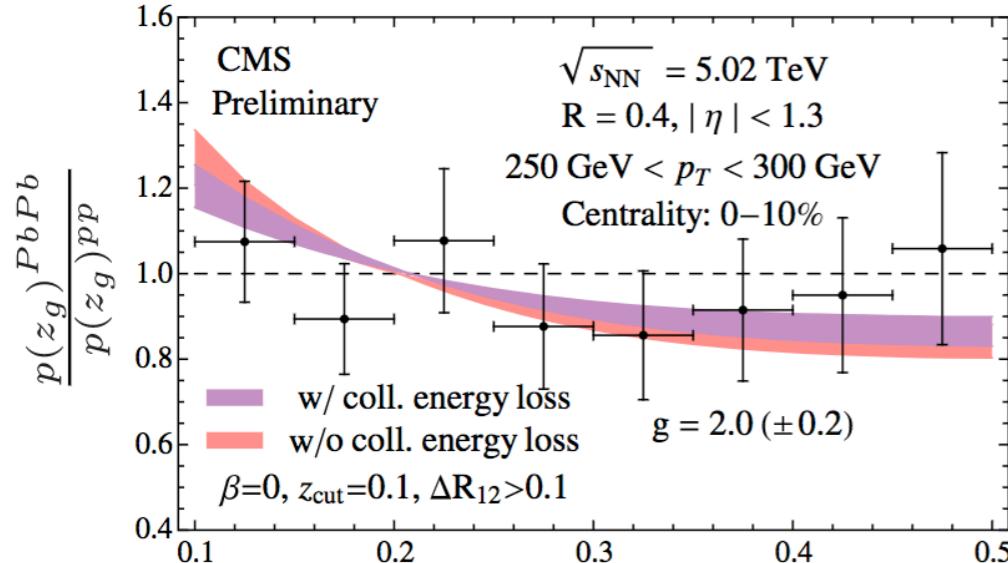
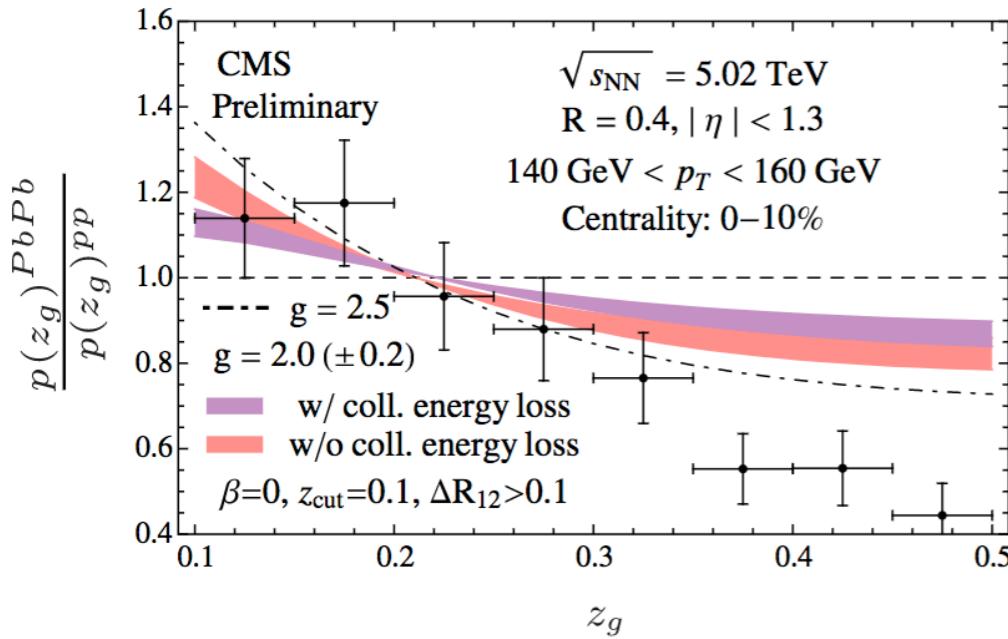
The modification of z_g distribution in heavy ion collisions has been measured at the LHC and RHIC



CMS Collaboration 2017

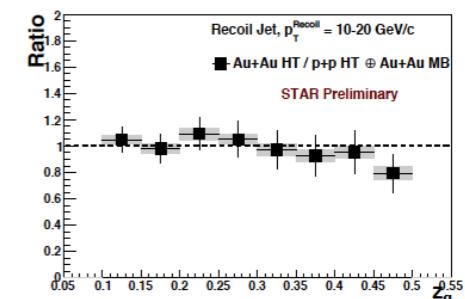
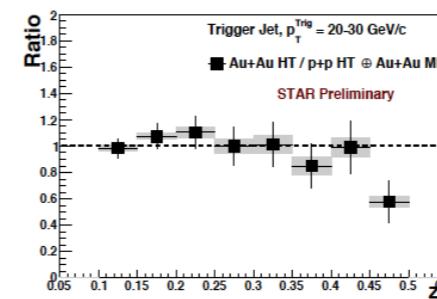
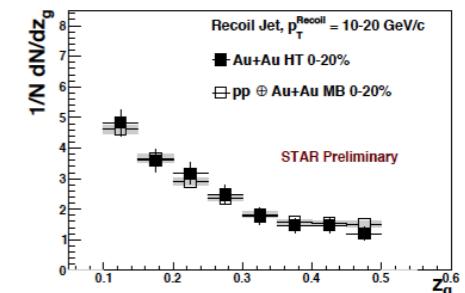
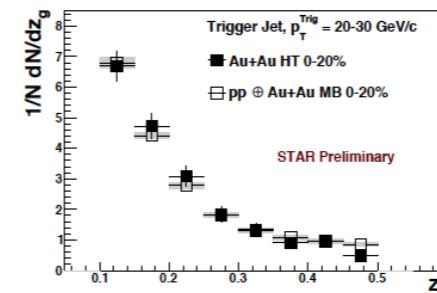
STAR Collaboration 2107

Splitting functions in medium



In the hot and dense QCD medium, may be simpler proton-proton case

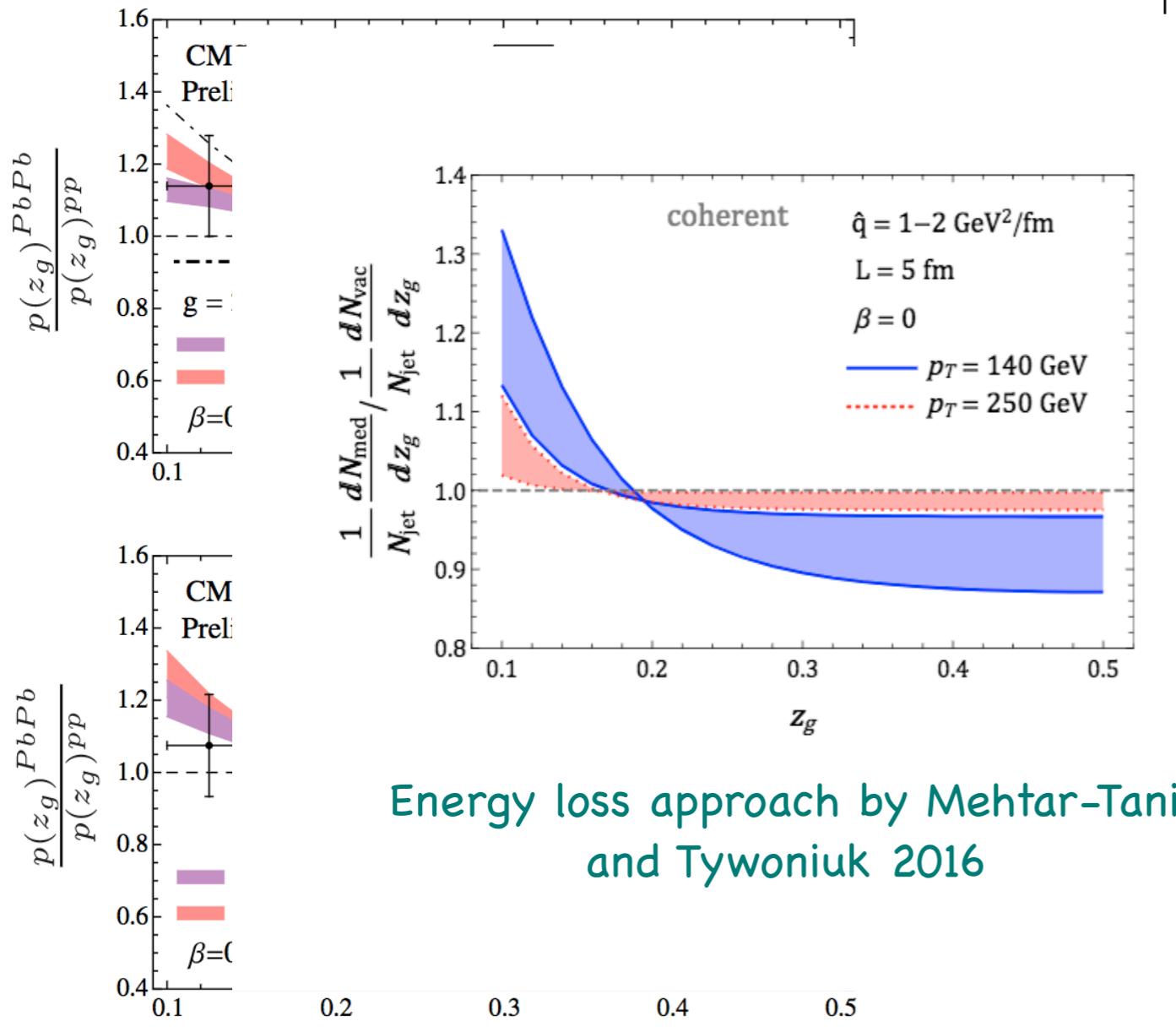
In collisions has been measured at the



STAR Collaboration 2107

A LO study for light jet (Chian, Vitev, 2016)

Splitting functions in medium

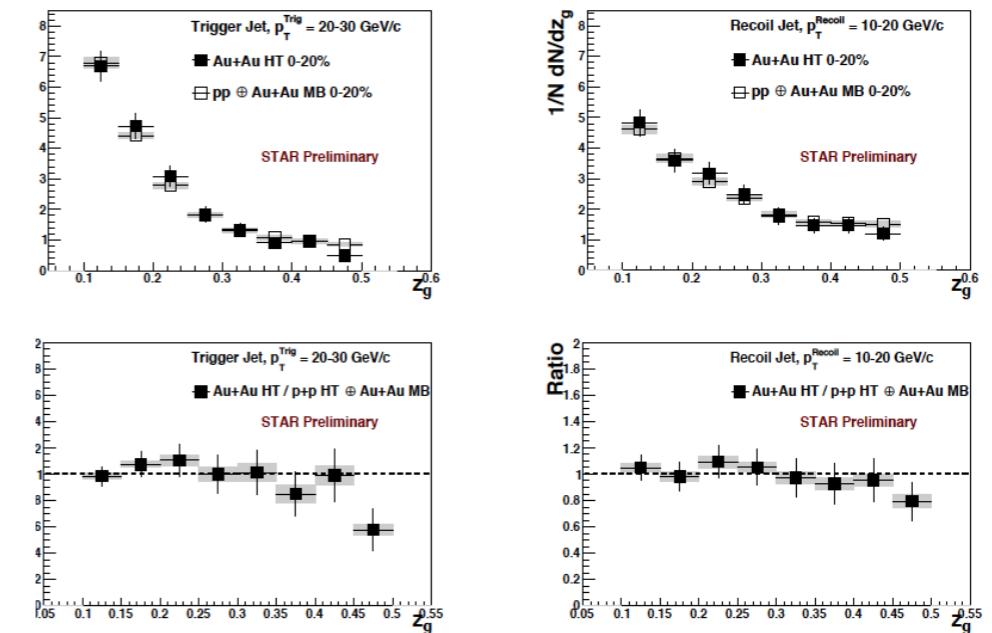


Energy loss approach by Mehtar-Tani and Tywoniuk 2016

A LO study for light jet (Chian, Vitev, 2016)

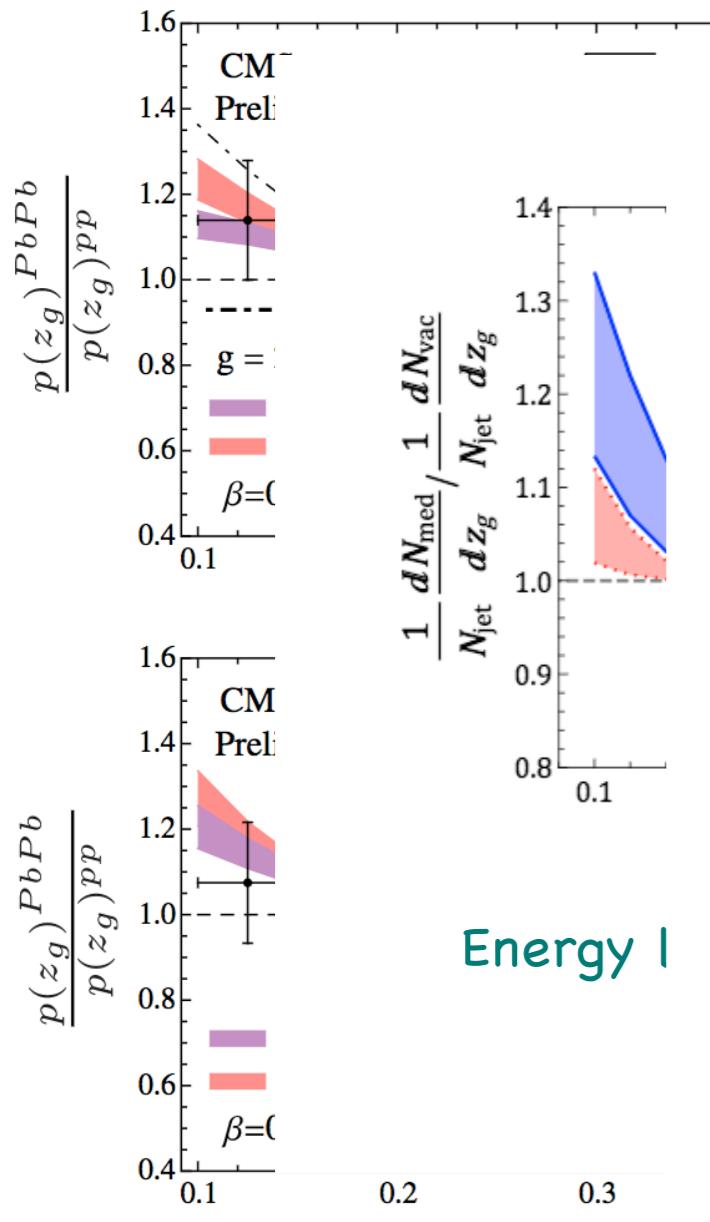
the hot and dense QCD medium, may alter proton-proton case

ions has been measured at the

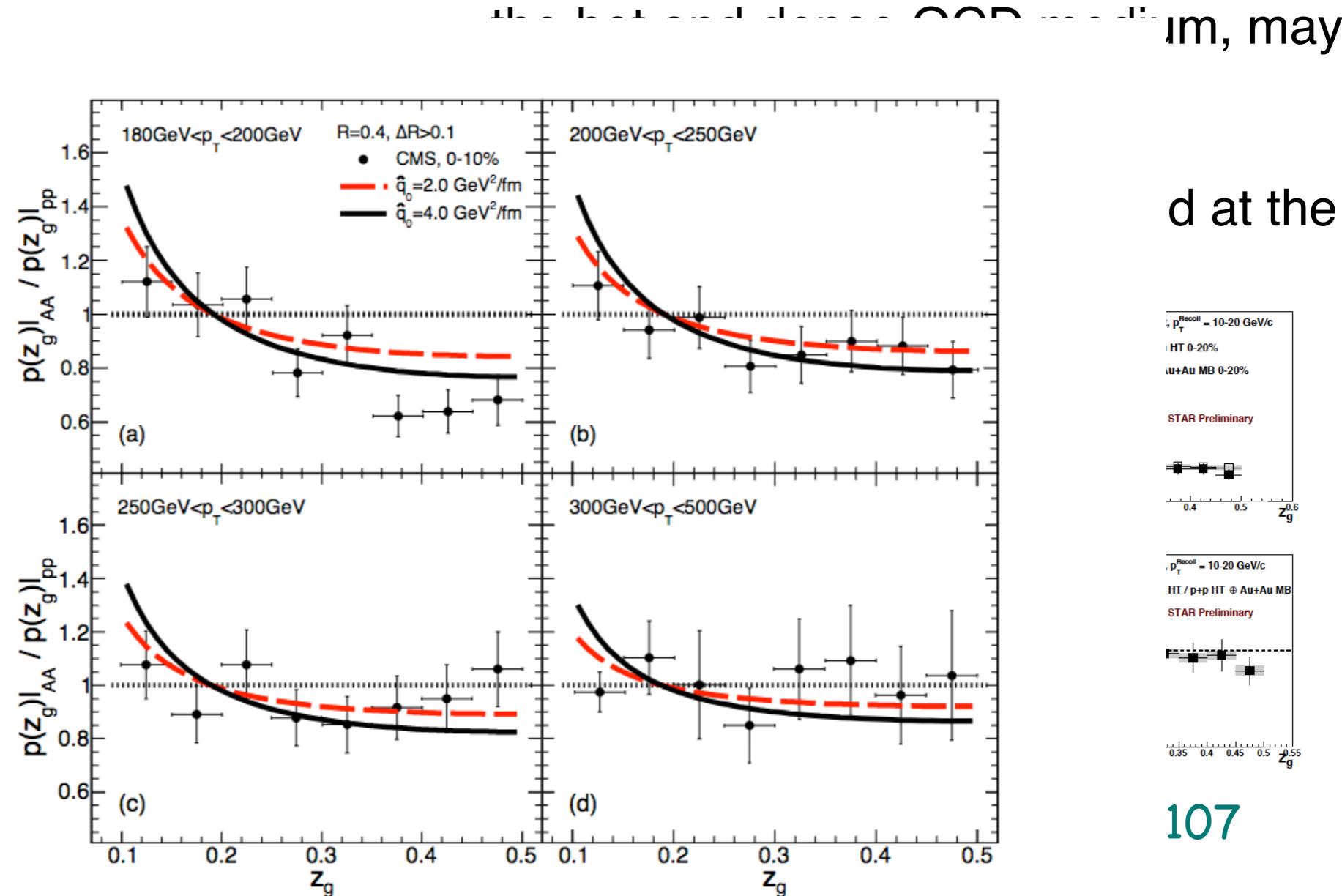


STAR Collaboration 2107

Splitting functions in medium



A LO study for light jet
 2016)



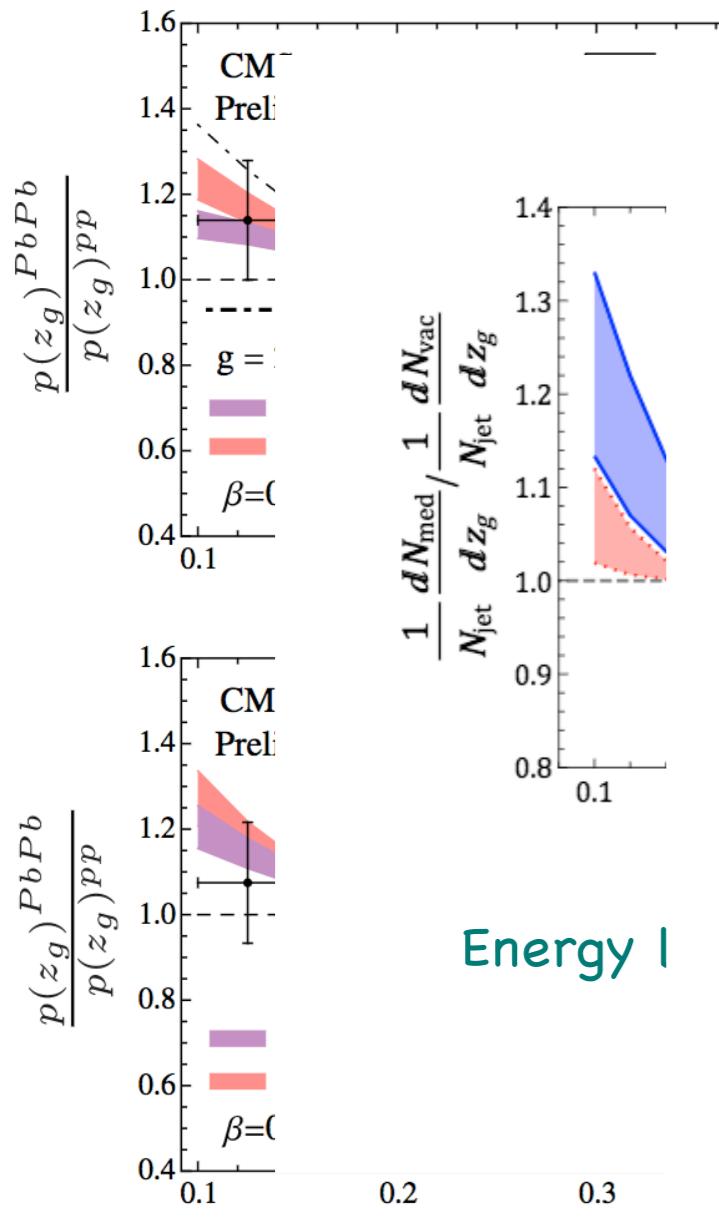
Based on the higher twist formalism (Chang et al 2017)

OOD, may

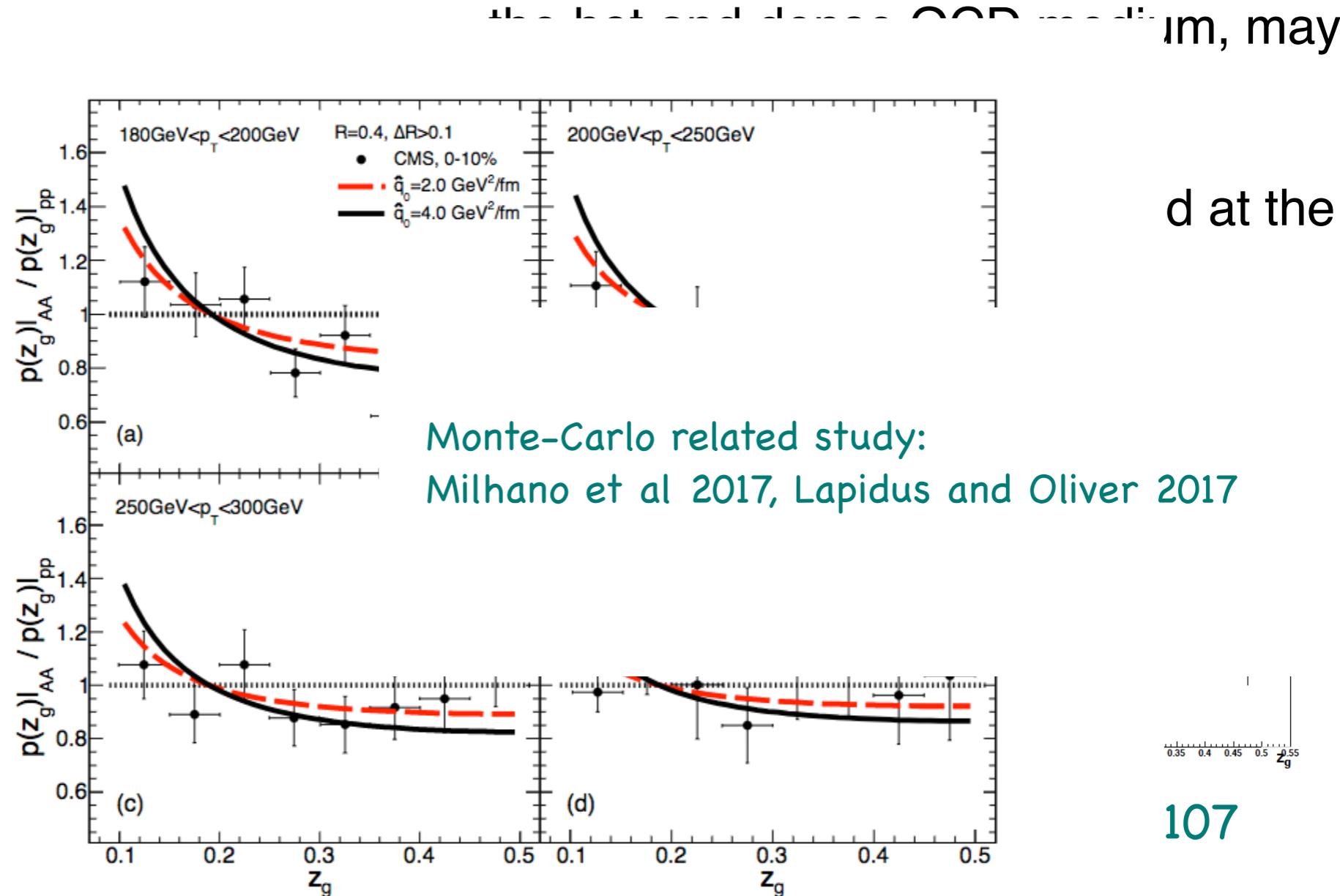
d at the

107

Splitting functions in medium



A LO study for light jet
2016)



Based on the higher twist formalism (Chang et al 2017)

OOD, may

d at the

107

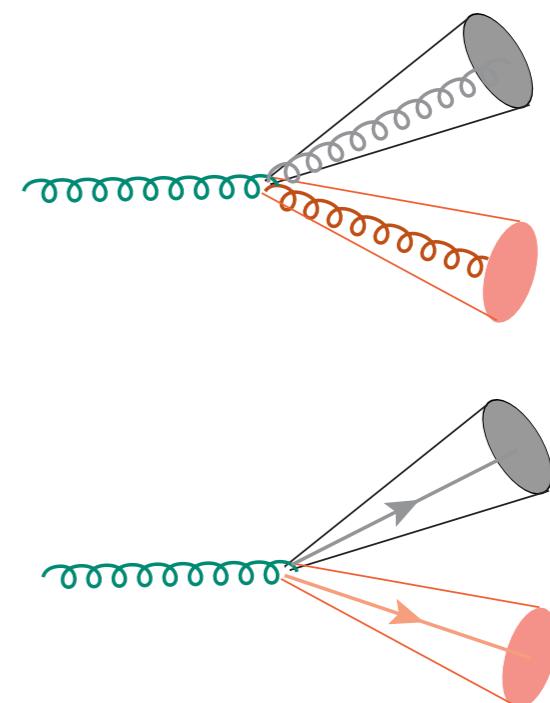
Resummation

Why resummation

- ▶ Jet splitting function is not IR safe. We have to resum the logs or place a cut on the distance of two subjets
- ▶ Resummation will change the distribution, especially for gluon splitting into massive quarks

Why heavy flavor

- ▶ Predominantly produced in the initial hard scatterings of partons in the incoming nuclei
- ▶ Hard probes to study the full evolution of the medium created by relativistic heavy ion collisions
- ▶ Interaction between the heavy quarks and the medium is sensitive to the medium dynamics

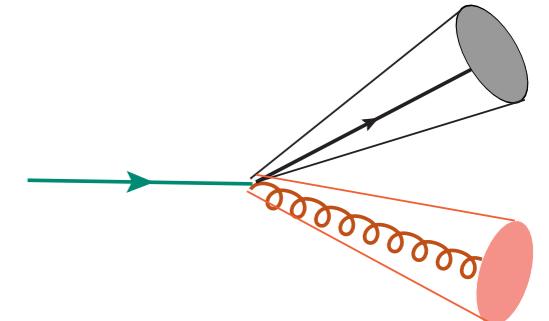


Gluon evolution

Vacuum splitting functions

The soft-drop groomed joint distribution is dominant by the first splitting

$$\left(\frac{dN^{\text{vac}}}{dz_g d\theta_g} \right)_j = \frac{\alpha_s}{\pi} \frac{1}{\theta_g} \sum_i P_{j \rightarrow i\bar{i}}^{\text{vac}}(z_g) . \quad 0 < \theta_g = \frac{\Delta R_{12}}{R_0} < 1$$

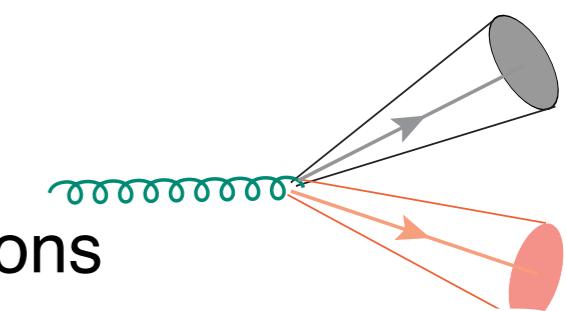
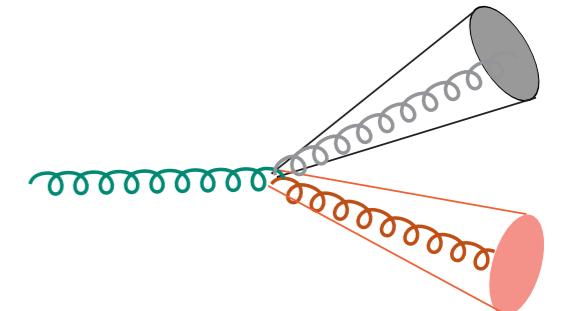


At the lowest non-trivial order the splitting functions are

$$P_{q \rightarrow qg}^{\text{vac}}(z) = C_F \frac{1 + (1 - z)^2}{z} ,$$

$$P_{g \rightarrow gg}^{\text{vac}}(z) = 2C_A \left(\frac{1 - z}{z} + \frac{z}{1 - z} + z(1 - z) \right) ,$$

$$P_{g \rightarrow q\bar{q}}^{\text{vac}}(z) = T_R (z^2 + (1 - z)^2) ,$$



These splitting functions have been widely used in many applications

$$\left(\frac{dN^{\text{vac}}}{dz d^2 \mathbf{k}_\perp} \right)_{Q \rightarrow Qg} = \frac{\alpha_s}{2\pi^2} \frac{C_F}{\mathbf{k}_\perp^2 + z^2 m^2} \left(\frac{1 + (1 - z)^2}{z} - \frac{2z(1 - z)m^2}{\mathbf{k}_\perp^2 + z^2 m^2} \right)$$

$$\left(\frac{dN^{\text{vac}}}{dz d^2 \mathbf{k}_\perp} \right)_{g \rightarrow Q\bar{Q}} = \frac{\alpha_s}{2\pi^2} \frac{T_R}{\mathbf{k}_\perp^2 + m^2} \left(z^2 + (1 - z)^2 + \frac{2z(1 - z)m^2}{\mathbf{k}_\perp^2 + m^2} \right)$$

The dependence on z and \mathbf{k}_\perp does not factorize.

Medium corrections to splitting functions

Calculated in the framework of soft-collinear effective theory with Glauber gluon interactions

$$\frac{dN}{dx} \sim \left| \frac{dN^{\text{med}}}{dxd^2\mathbf{k}_\perp} \right|_q \Big|_{q \rightarrow qg}^2 + 2\text{Re} \left[\frac{dN^{\text{med}}}{dxd^2\mathbf{k}_\perp} \Big|_{q \rightarrow qg} \times \frac{dN^{\text{med}}}{dxd^2\mathbf{k}_\perp} \Big|_{q \rightarrow qg} \right]$$

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

Massless partons: Ovanesyan and Vitev 2011

Medium corrections to splitting functions

Calculated in the framework of soft-collinear effective theory with Glauber gluon interactions

$$\frac{dN}{dx} \sim \left| \left(\text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3} \right) \right|^2 + 2\text{Re} \left[\left(\text{Diagram 4} + \text{Diagram 5} \right) \times \text{Diagram 6} \right]$$

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

$$\begin{aligned} \left(\frac{dN^{\text{med}}}{dxd^2\mathbf{k}_\perp} \right)_{Q \rightarrow Qg} &= \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{med}}}{d^2\mathbf{q}_\perp} \left\{ \left(\frac{1 + (1-x)^2}{x} \right) \left[\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \right. \right. \\ &\quad \times \left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} - \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} \cdot \left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \right. \\ &\quad \left. - \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_3)\Delta z]) + \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \cdot \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} (1 - \cos[(\Omega_2 - \Omega_3)\Delta z]) \\ &\quad + \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \cdot \left(\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2 + \nu^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \right) (1 - \cos[\Omega_4 \Delta z]) - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \cdot \frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2 + \nu^2} (1 - \cos[\Omega_5 \Delta z]) \\ &\quad \left. + \frac{1}{N_c^2} \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \cdot \left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} - \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) \right] \\ &\quad \left. + x^3 m^2 \left[\frac{1}{\mathbf{B}_\perp^2 + \nu^2} \cdot \left(\frac{1}{\mathbf{B}_\perp^2 + \nu^2} - \frac{1}{\mathbf{C}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \dots \right] \right\} \end{aligned}$$

$$\nu = x m \quad (Q \rightarrow Qg),$$

$$\nu = (1-x) m \quad (Q \rightarrow gQ),$$

$$\nu = m \quad (g \rightarrow Q\bar{Q}),$$

$\mathbf{A}_\perp = \mathbf{k}_\perp$, $\mathbf{B}_\perp = \mathbf{k}_\perp + x\mathbf{q}_\perp$, $\mathbf{C}_\perp = \mathbf{k}_\perp - (1-x)\mathbf{q}_\perp$, $\mathbf{D}_\perp = \mathbf{k}_\perp - \mathbf{q}_\perp$,
Massive partons: Kang et al 2016

Medium corrections to splitting functions

Calculated in the framework of soft-collinear effective theory with Glauber gluon interactions

$$\frac{dN}{dx} \sim \left| \left(\text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3} \right) \right|^2 + 2\text{Re} \left[\left(\text{Diagram 4} + \text{Diagram 5} \right) \times \text{Diagram 6} \right]$$

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

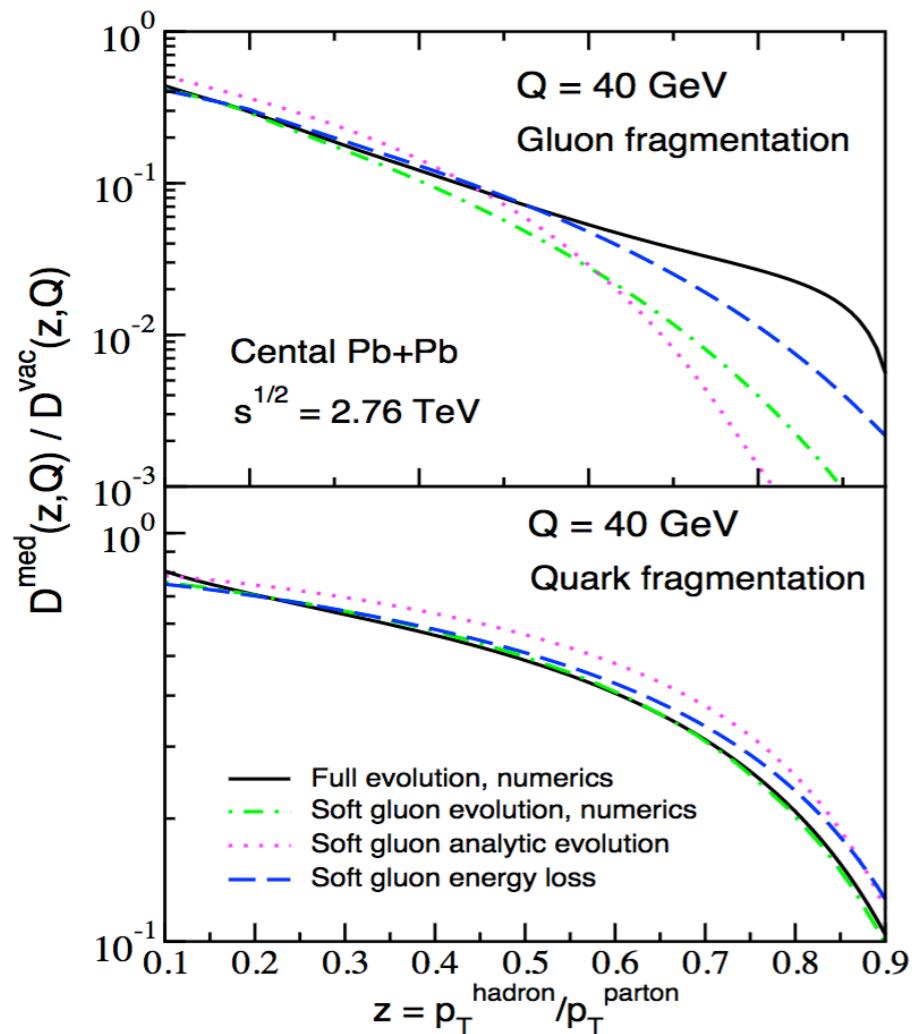
$$\begin{aligned} \left(\frac{dN^{\text{med}}}{dxd^2\mathbf{k}_\perp} \right)_{Q \rightarrow Qg} &= \frac{\alpha_s}{2\pi^2} C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{med}}}{d^2\mathbf{q}_\perp} \left\{ \left(\frac{1 + (1-x)^2}{x} \right) \left[\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \right. \right. \\ &\quad \times \left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} - \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} \cdot \left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \right. \\ &\quad \left. - \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_3)\Delta z]) + \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \cdot \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2 + \nu^2} (1 - \cos[(\Omega_2 - \Omega_3)\Delta z]) \\ &\quad + \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \cdot \left(\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2 + \nu^2} - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \right) (1 - \cos[\Omega_4 \Delta z]) - \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} \cdot \frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2 + \nu^2} (1 - \cos[\Omega_5 \Delta z]) \\ &\quad \left. + \frac{1}{N_c^2} \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \cdot \left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2 + \nu^2} - \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) \right] \\ &\quad \left. + x^3 m^2 \left[\frac{1}{\mathbf{B}_\perp^2 + \nu^2} \cdot \left(\frac{1}{\mathbf{B}_\perp^2 + \nu^2} - \frac{1}{\mathbf{C}_\perp^2 + \nu^2} \right) (1 - \cos[(\Omega_1 - \Omega_2)\Delta z]) + \dots \right] \right\} \end{aligned}$$

$\mathbf{A}_\perp = \mathbf{k}_\perp, \mathbf{B}_\perp = \mathbf{k}_\perp + x\mathbf{q}_\perp, \mathbf{C}_\perp = \mathbf{k}_\perp - (1-x)\mathbf{q}_\perp, \mathbf{D}_\perp = \mathbf{k}_\perp - \mathbf{q}_\perp,$

Massive partons: Kang et al 2016

See the work arXiv:1807.03799 for the method for the calculation up to any order of opacity.

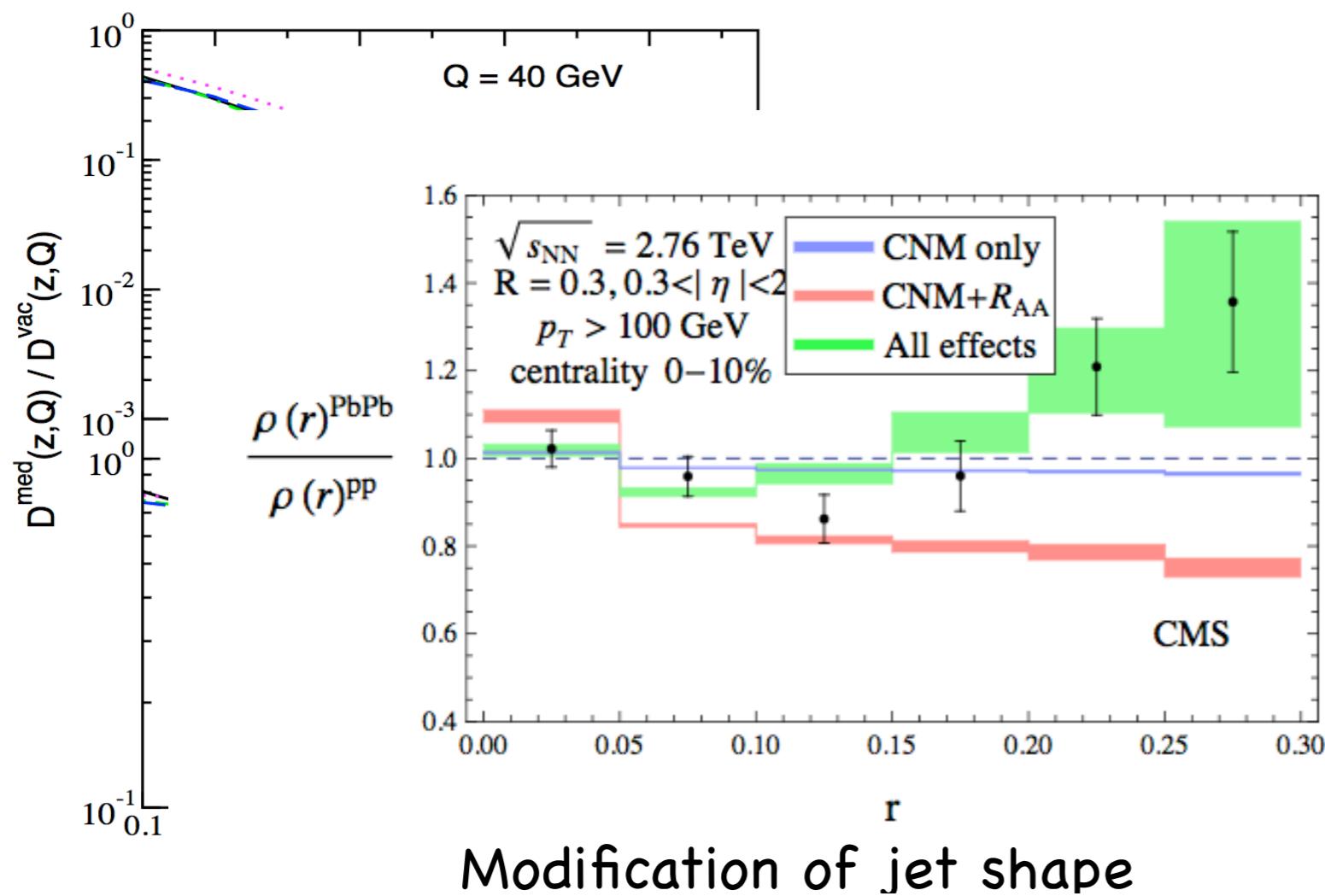
Applications



Modification of fragmentation functions for gluon and quark

Kang et al 2014

Applications

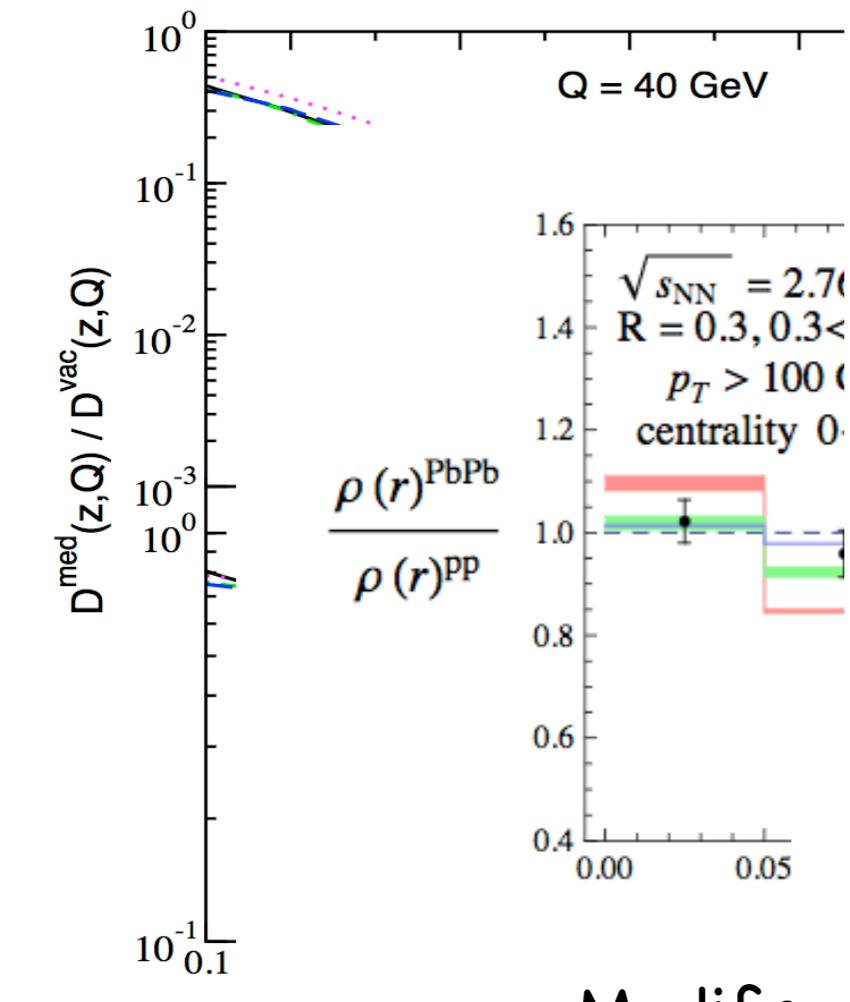


Modification
functions fo

Chien et al 2015

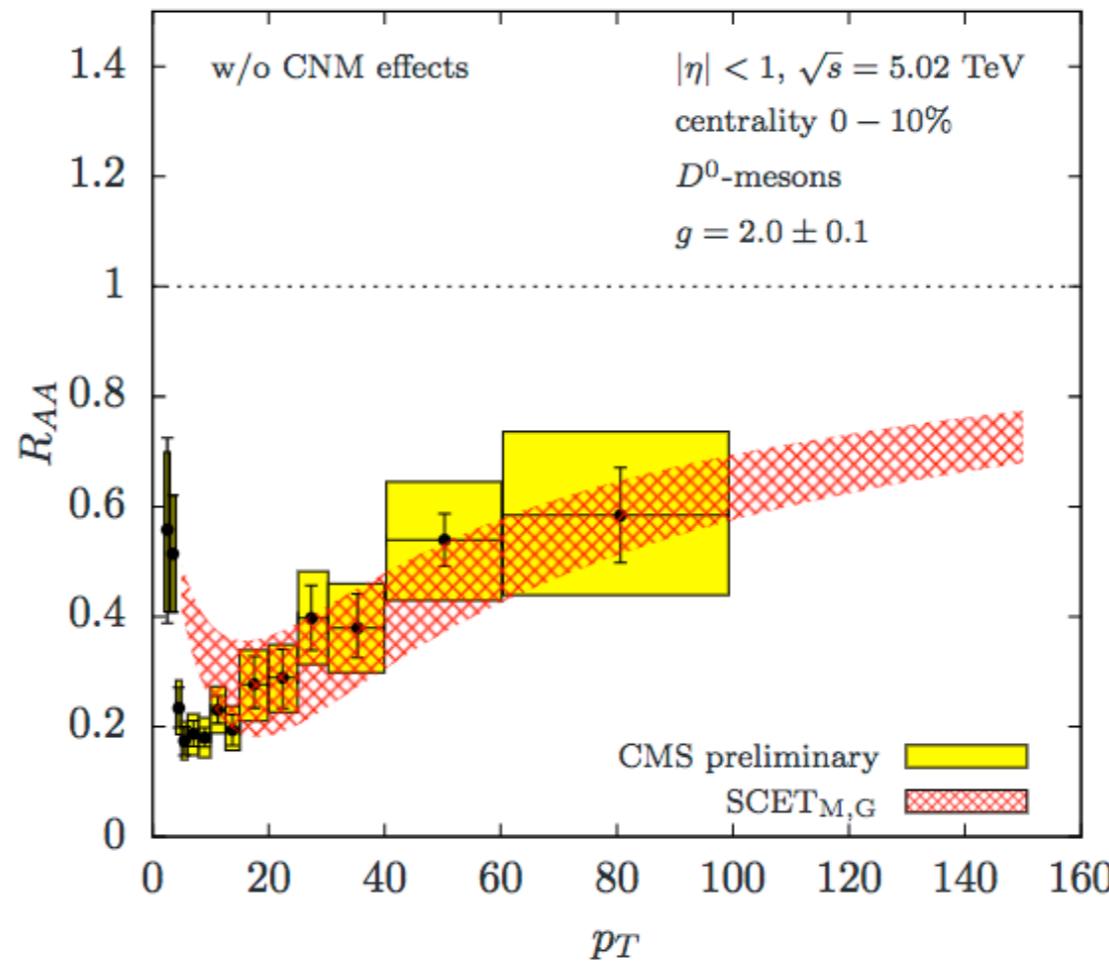
Kang et al 2014

Applications



Modification functions for η .

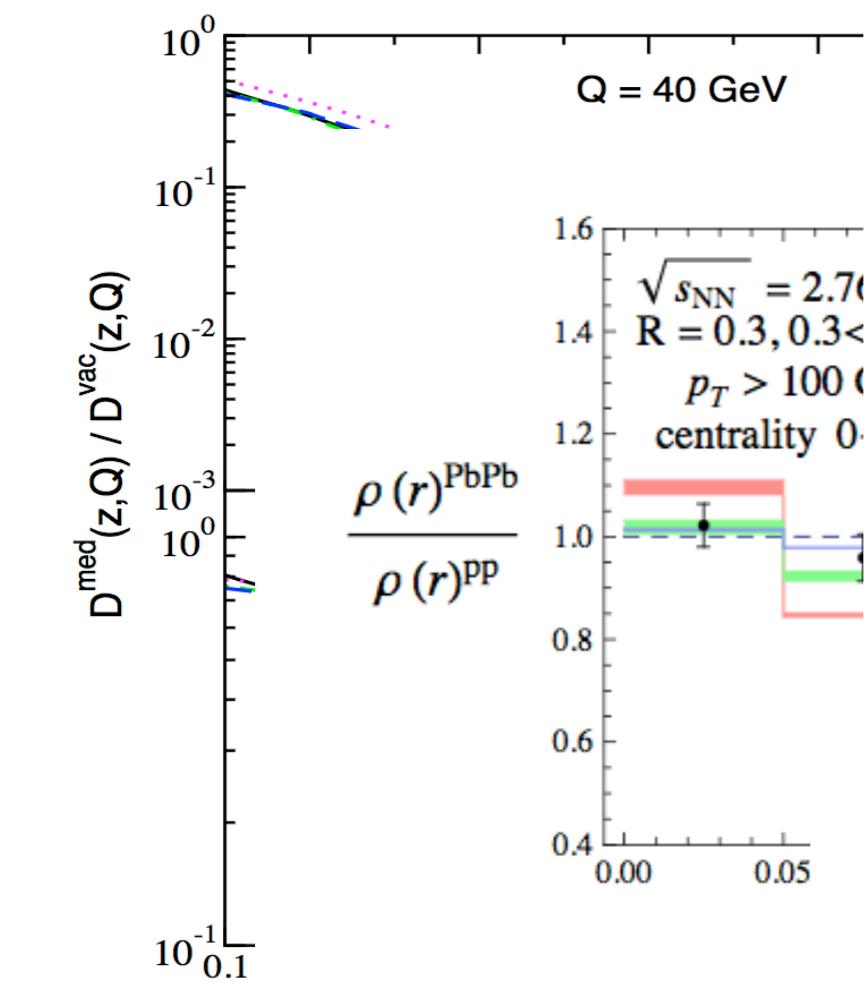
Kang et al 2014



Nuclear modification factor RAA
for D^0 meson (massive)

Kang et al 2016

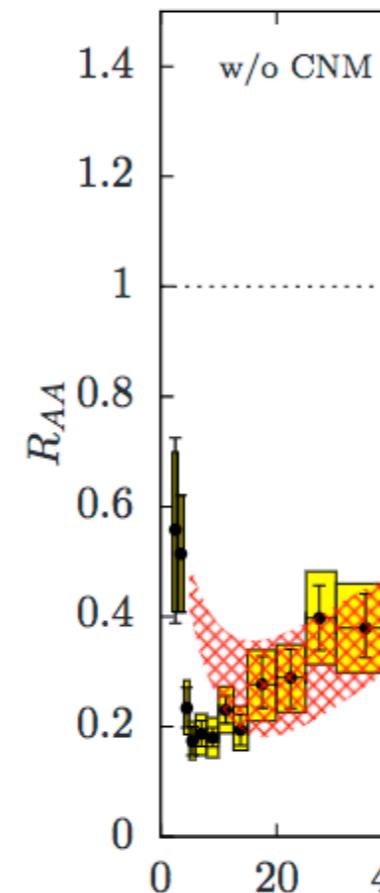
Applications



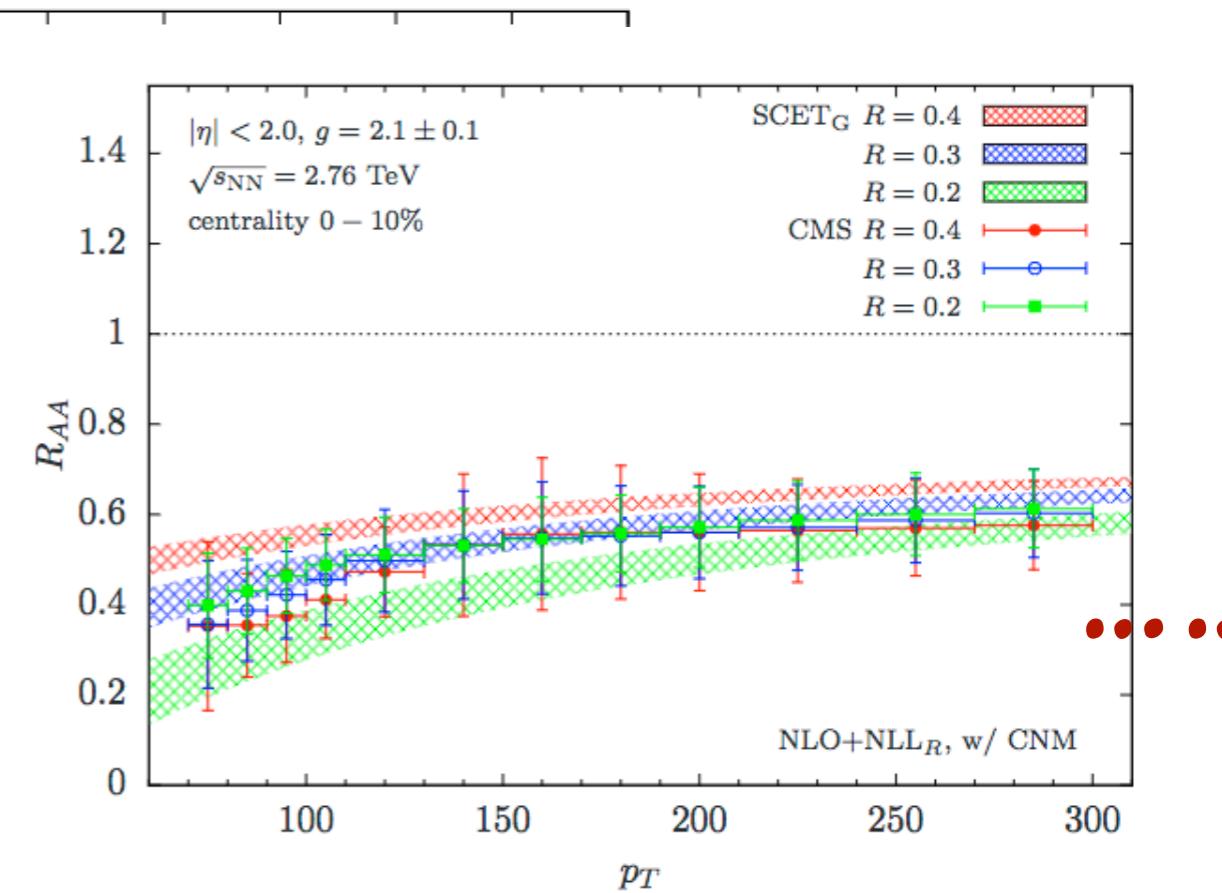
Modification functions for χ^2

Kang et al 2014

Modific
Chi



Nuclear
for D0 π



The nuclear modification factor RAA

Kang et al 2017

Resummation formalism

Resummed splitting kernels in the vacuum Larkoski et al 2015

$\frac{dN_j^F}{dz_g d\theta_g}$ is divergent when $\theta_g \rightarrow 0$

Collinear singularities

$\frac{dN_j^F}{dz_g}$ is not well-defined at any fixed perturbative order
but is well defined if we resum logs to all order

The MLL resummation for light jet to modified leading-logarithmic (MLL) accuracy,

$$\frac{dN_j^{\text{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\text{vac}}}{dz_g d\theta_g} \right)_{j \rightarrow i\bar{i}} \underbrace{\exp \left[- \int_{\theta_g}^1 d\theta \int_{z_{\text{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\text{vac}}}{dz d\theta} \right)_{j \rightarrow i\bar{i}} \right]}_{\text{Sudakov Factor}}$$

MLL includes running coupling effects and subleading terms in the splitting functions compared to LL resummation.

Theoretical formalism

Resummed splitting kernels for heavy flavors

Suppose that we can distinguish the splitting process involving heavy flavor

For $b \rightarrow bg$ $c \rightarrow cg$ formula is the similar with massless quark

$$\frac{dN_j^{\text{vac,MLL}}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\text{vac}}}{dz_g d\theta_g} \right)_{j \rightarrow i\bar{i}} \underbrace{\exp \left[- \int_{\theta_g}^1 d\theta \int_{z_{\text{cut}}}^{1/2} dz \sum_i \left(\frac{dN^{\text{vac}}}{dz d\theta} \right)_{j \rightarrow i\bar{i}} \right]}_{\text{Sudakov Factor}}$$

For $g \rightarrow b\bar{b}$ $g \rightarrow c\bar{c}$ the resummed distribution is

$$p(\theta_g, z_g) \Big|_{g \rightarrow Q\bar{Q}} = \frac{\left(\frac{dN^{\text{vac}}}{dz_g d\theta_g} \right)_{g \rightarrow Q\bar{Q}} \Sigma_g(\theta_g)}{\int_0^1 d\theta \int_{z_{\text{cut}}}^{1/2} dz \left(\frac{dN^{\text{vac}}}{dz d\theta} \right)_{g \rightarrow Q\bar{Q}} \Sigma_g(\theta)} ,$$

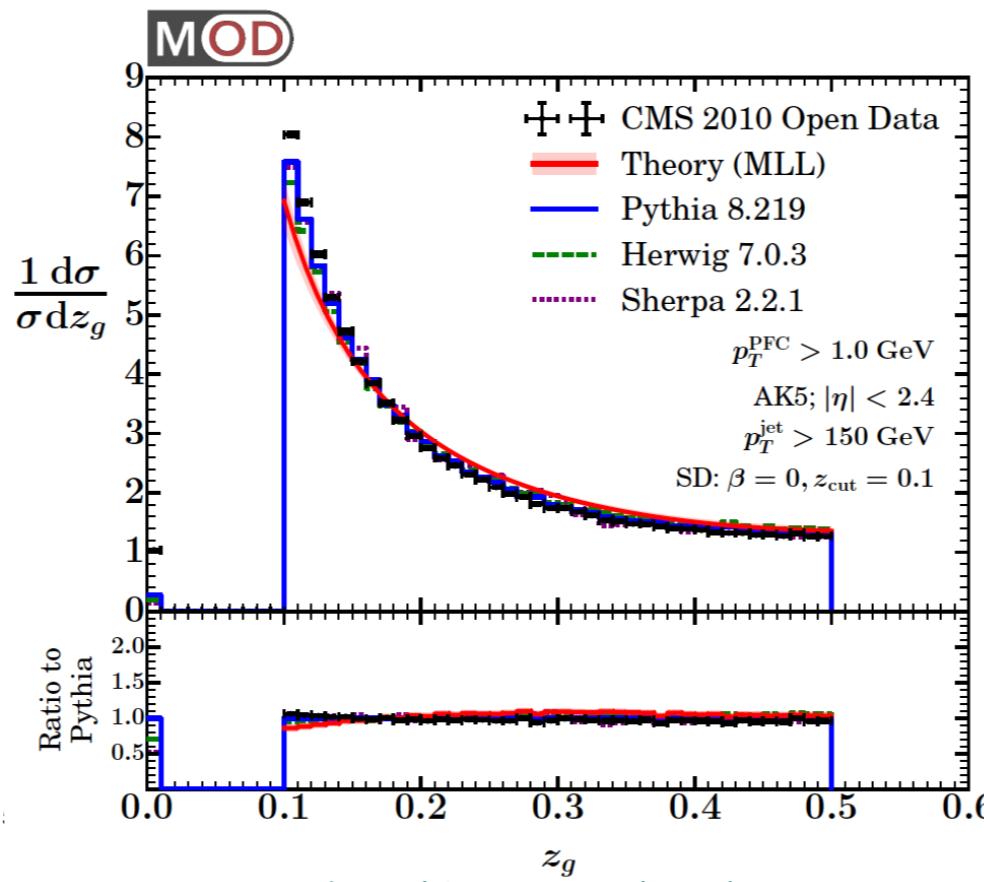
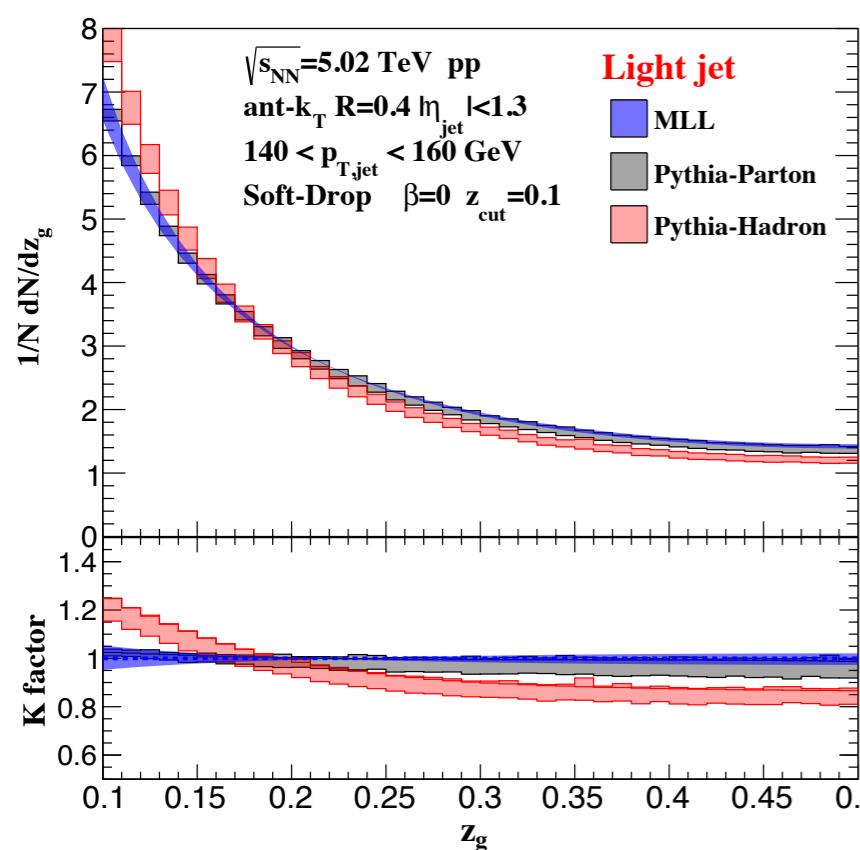
Exponentiate all the possible contributions for gluon evolution

Resummation changes the distribution a lot compared to LO results

Results for light jet

In pp collisions uncertainties are generated **by varying scales**

In heavy-ion collisions uncertainties are generated **by varying scales and coupling (between medium and jet)** independently.

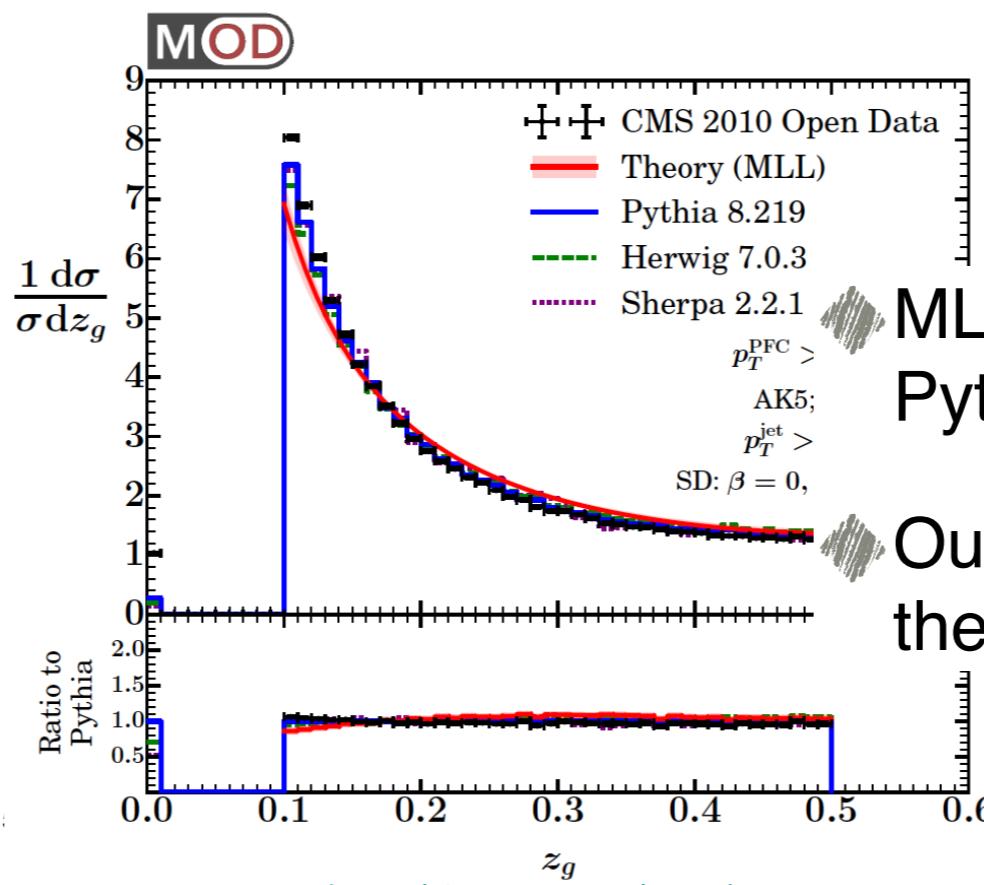
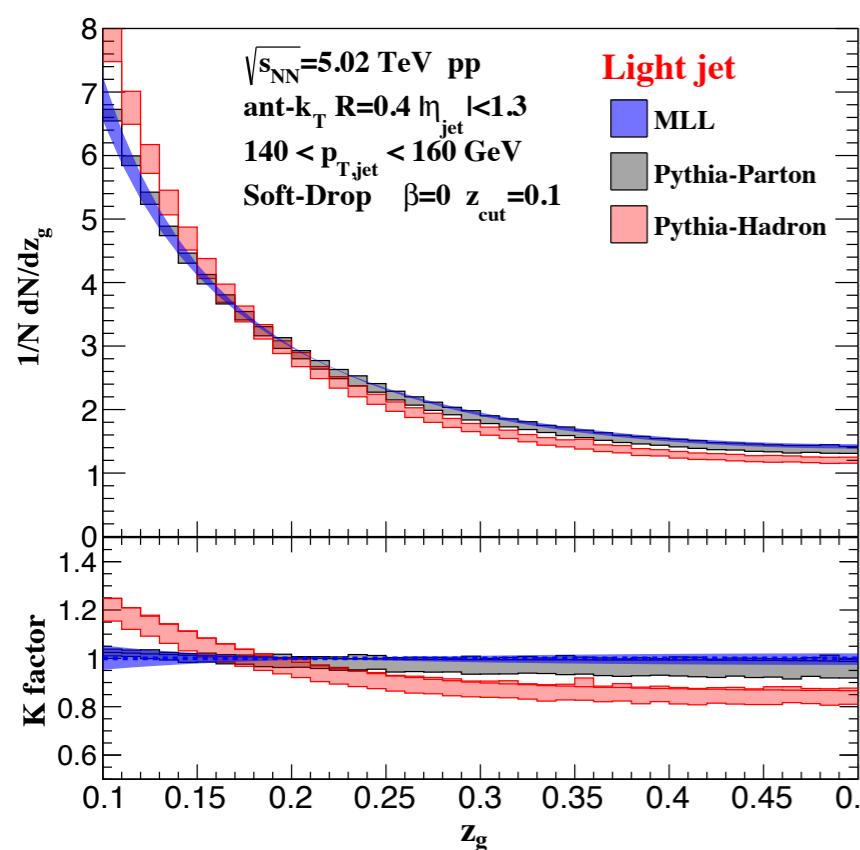


Tripathee, et al 2017

Results for light jet

In pp collisions uncertainties are generated **by varying scales**

In heavy-ion collisions uncertainties are generated **by varying scales and coupling (between medium and jet)** independently.



MLL is slightly less steep than Pythia with hadronization

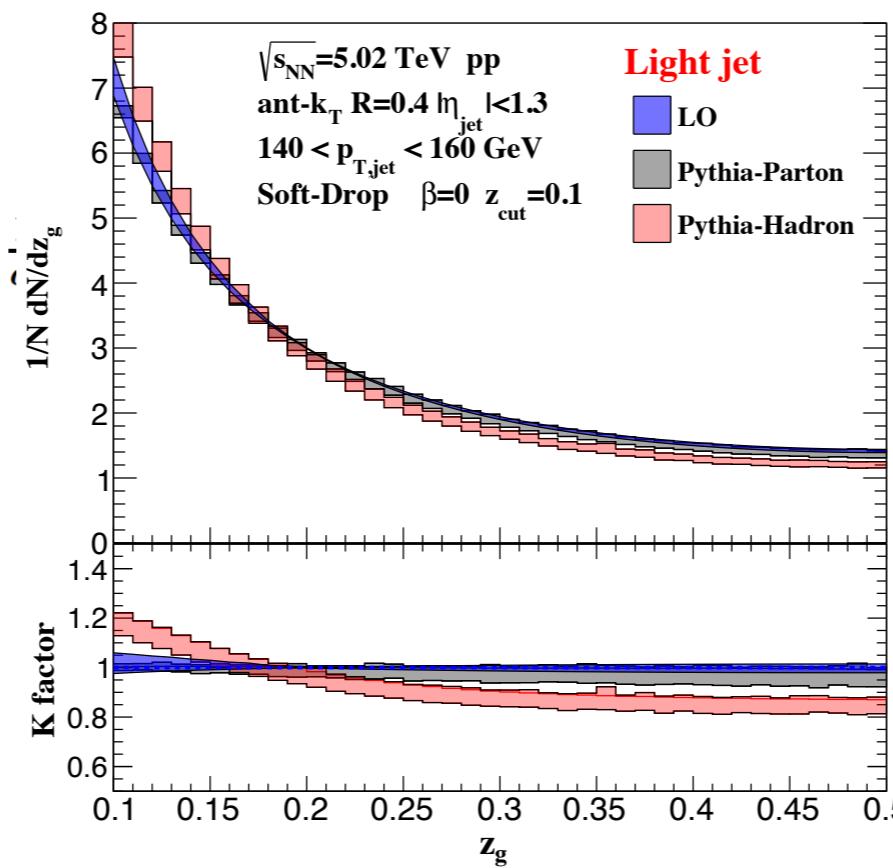
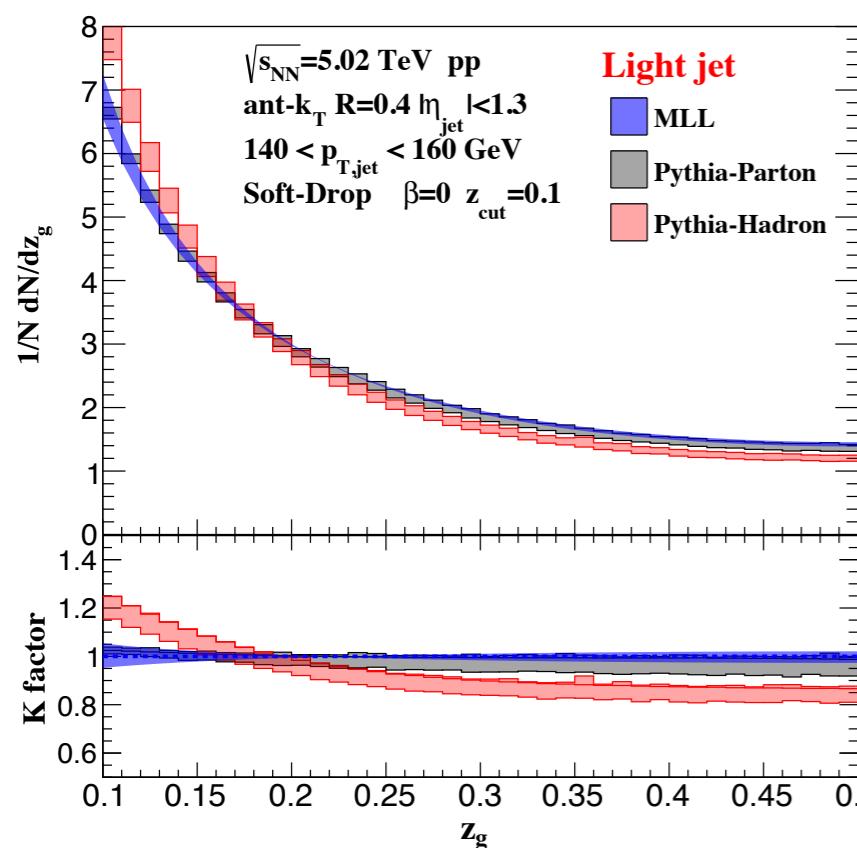
Our results are consistent with the ones from literature

Tripathee, et al 2017

Results for light jet

In pp collisions uncertainties are generated **by varying scales**

In heavy-ion collisions uncertainties are generated **by varying scales and coupling (between medium and jet)** independently.



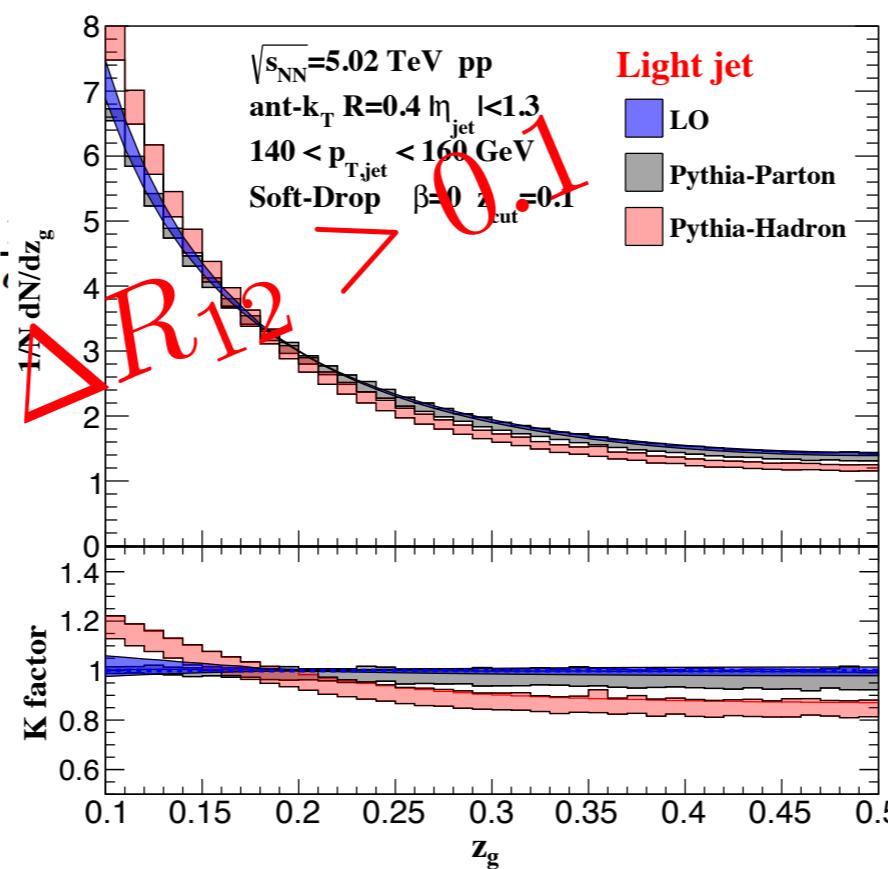
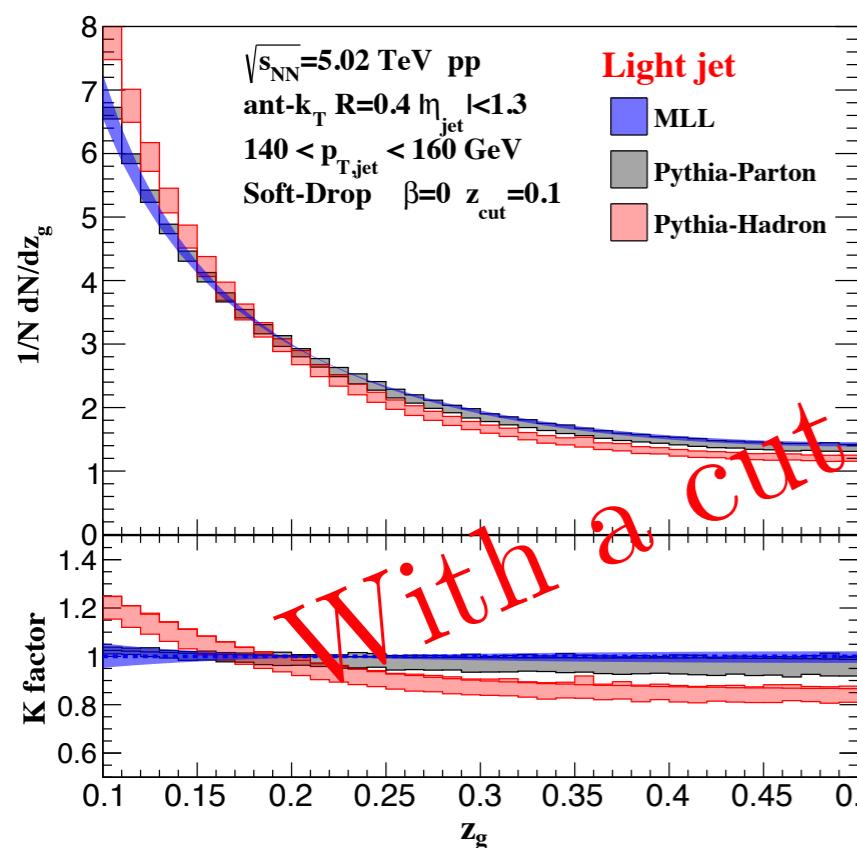
L is slightly less steep than
Pythia with hadronization

Our results are consistent with
ones from literature

Results for light jet

In pp collisions uncertainties are generated **by varying scales**

In heavy-ion collisions uncertainties are generated **by varying scales and coupling (between medium and jet)** independently.

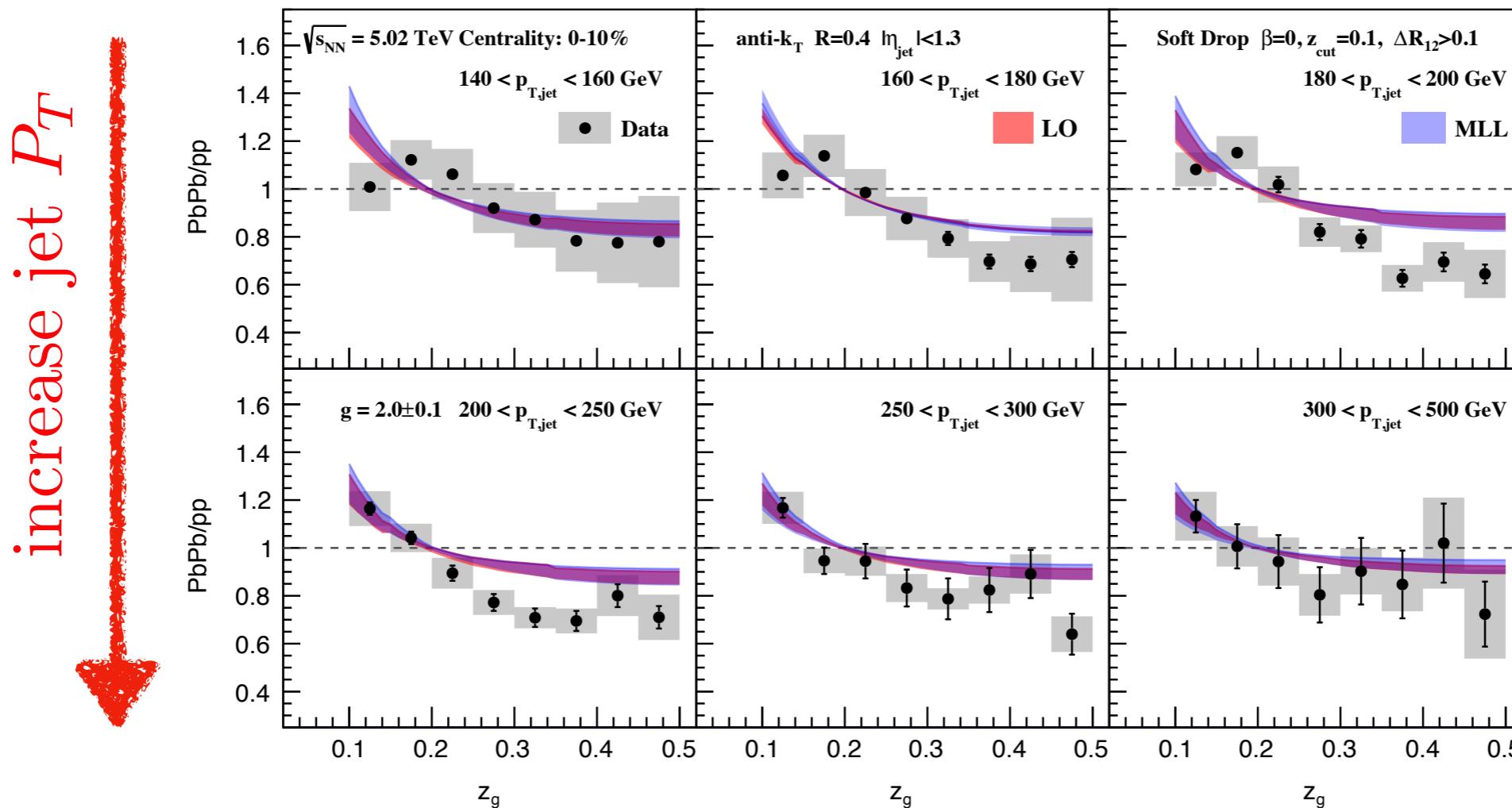


L is slightly less steep than
Pythia with hadronization

Our results are consistent with
ones from literature

Results for light jet

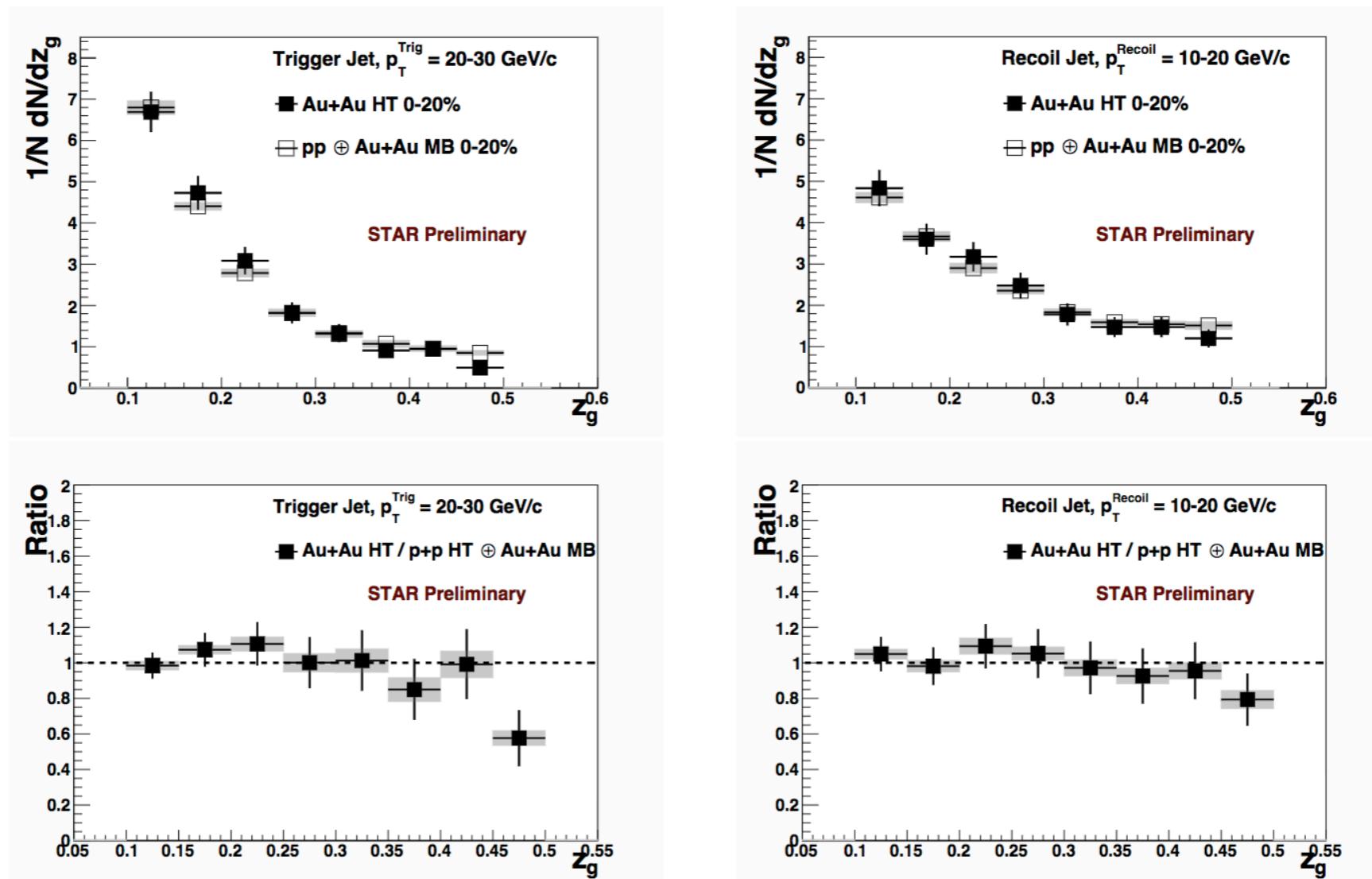
increase jet P_T



- ▶ The splitting function in the medium becomes steeper
- ▶ MLL changes the modification by a few percent
- ▶ The modification is larger for small jet P_T
- ▶ The theoretical predictions are consistent with the measurements

Results for light jet

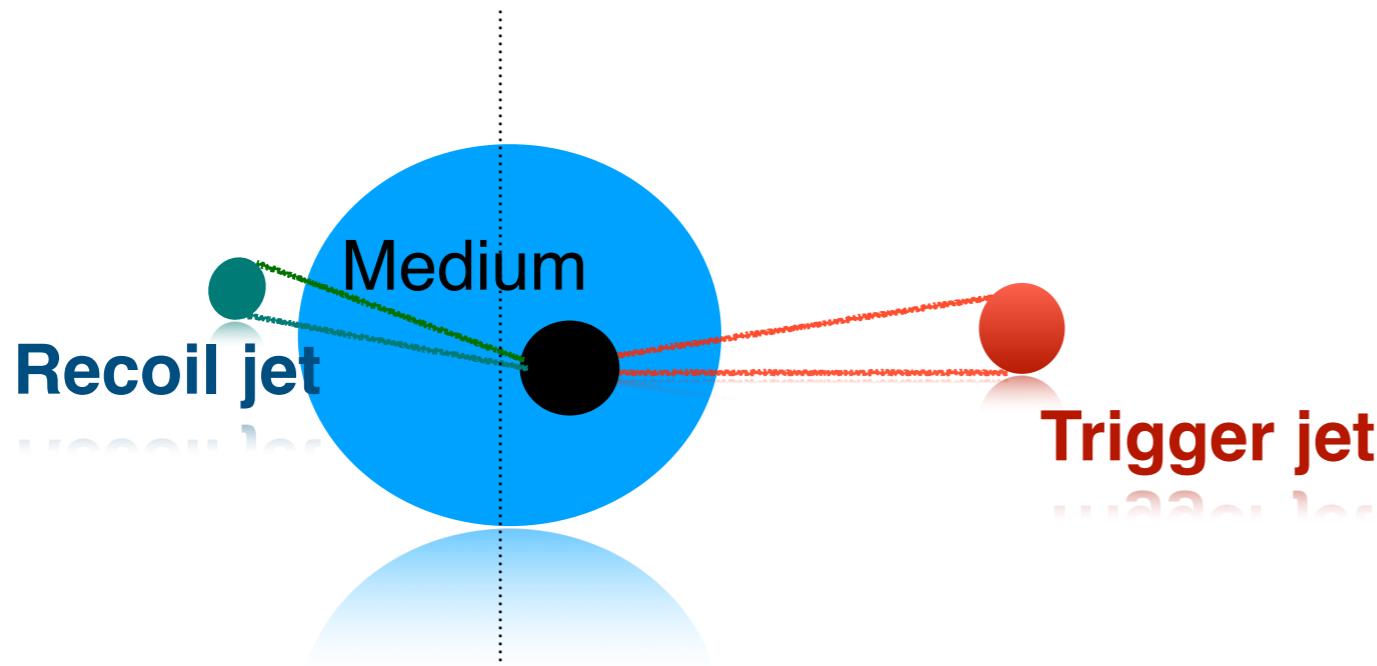
Modification at the RHIC



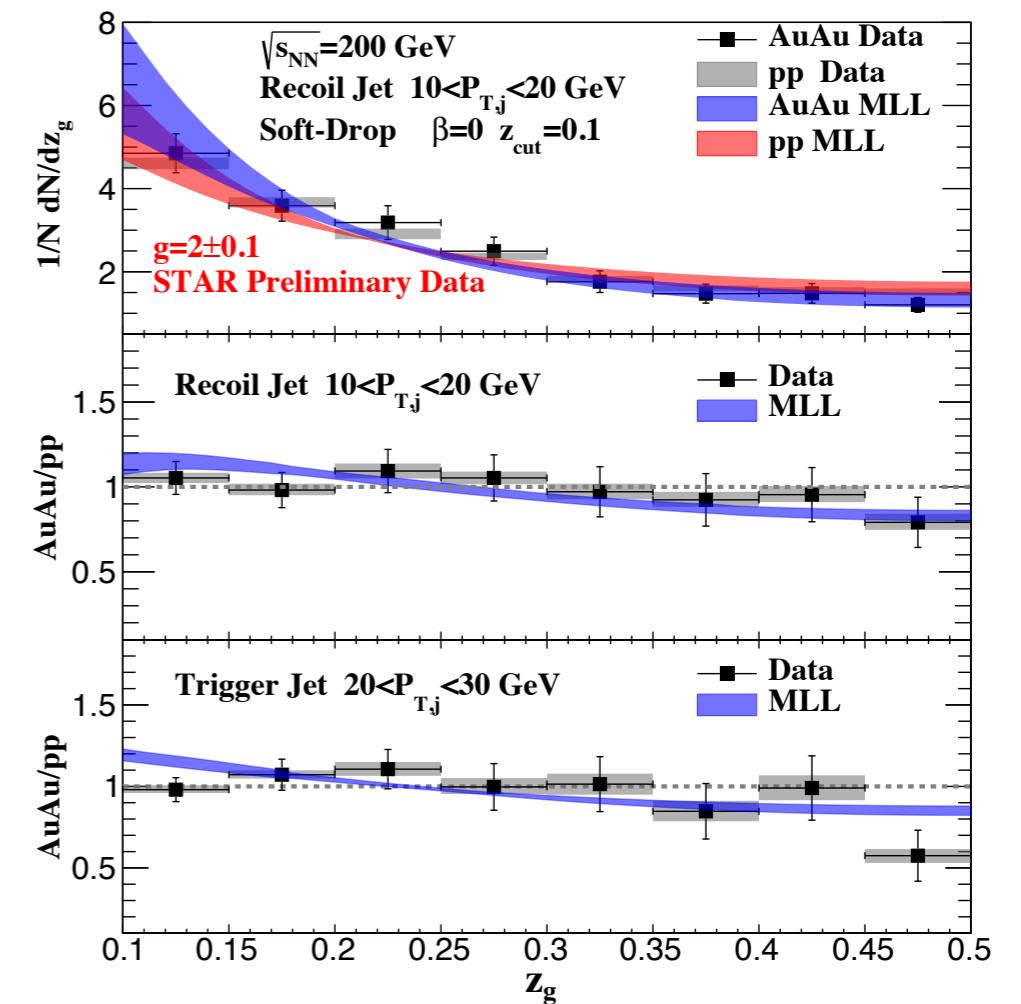
The triggered and recoiled jets in dijet production were used to measure the z_g distribution in Au+Au collision at RHIC

Results for light jet

Modification at the RHIC

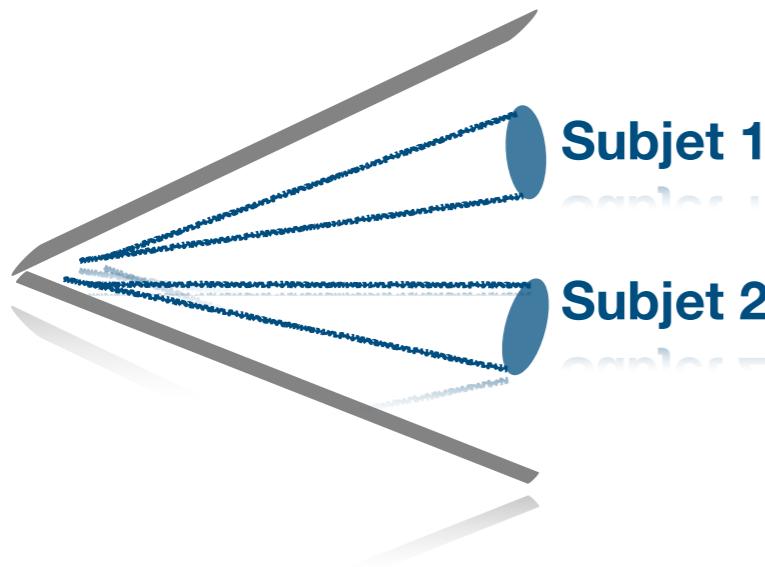


In general the path for recoil jet in the medium is longer than the one for trigger jet. To compare with data this effect is included in our splitting functions.



Results for heavy flavor tagged jet

In order to compare with the predictions from PYTHIA



- ▶ Label two subjets (n_1^c, n_2^c) (n_1^b, n_2^b)
- ▶ If there is no b-quark or b-hadron
$$(n_1^c, n_2^c) = \begin{cases} (1, 0) \text{ or } (0, 1) & c \rightarrow cg \\ (1, 1) & g \rightarrow c\bar{c} \end{cases}$$
- ▶ If there is no c-quark or c-hadron
$$(n_1^b, n_2^b) = \begin{cases} (1, 0) \text{ or } (0, 1) & b \rightarrow bg \\ (1, 1) & g \rightarrow b\bar{b} \end{cases}$$

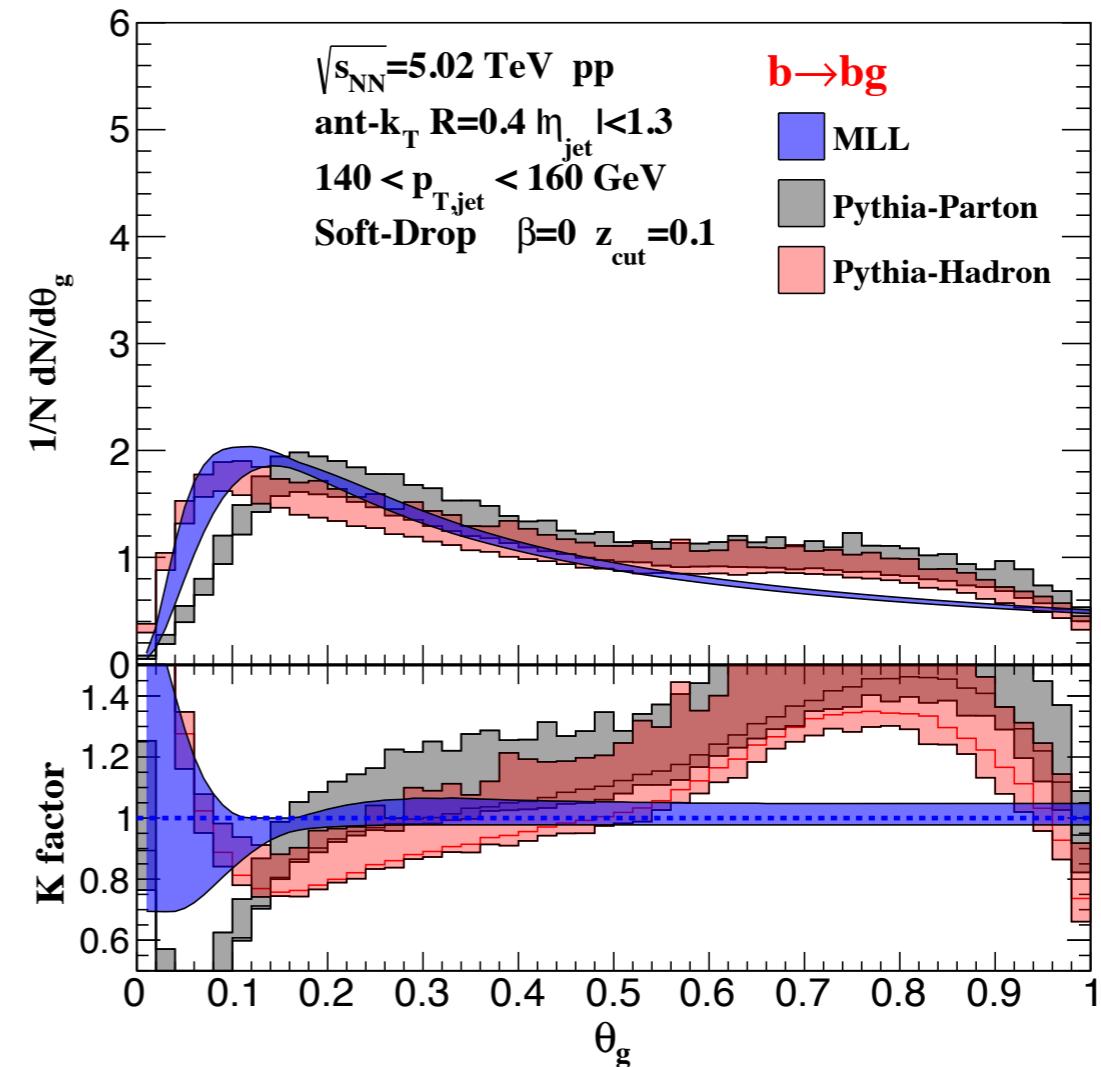
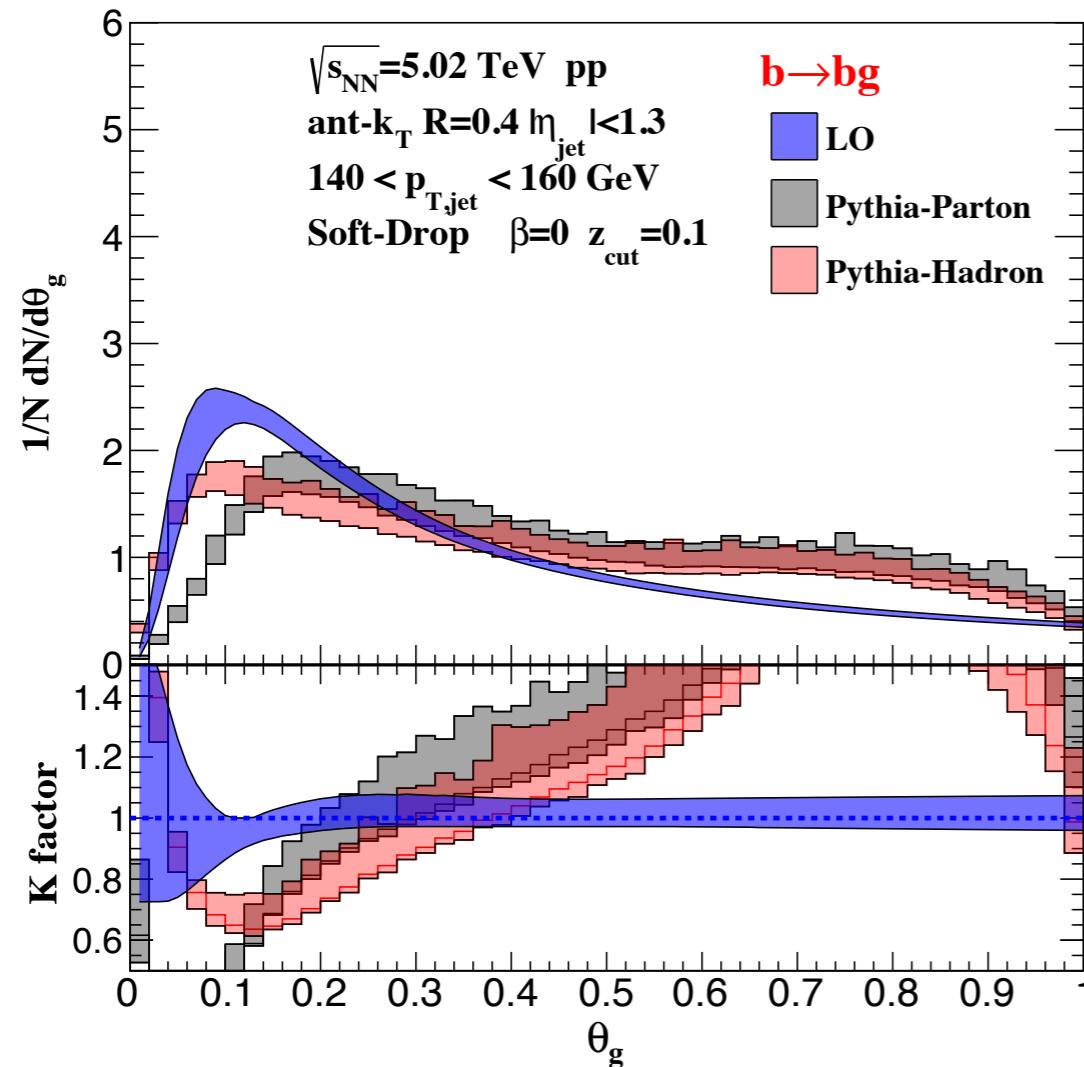
A recent study for charm and beauty quarks at colliders using Monte Carlo event generators

see the work for details: Ilten et al 2017

The other cases are ignored in the analysis during comparing with Pythia

Results for heavy flavor tagged jet

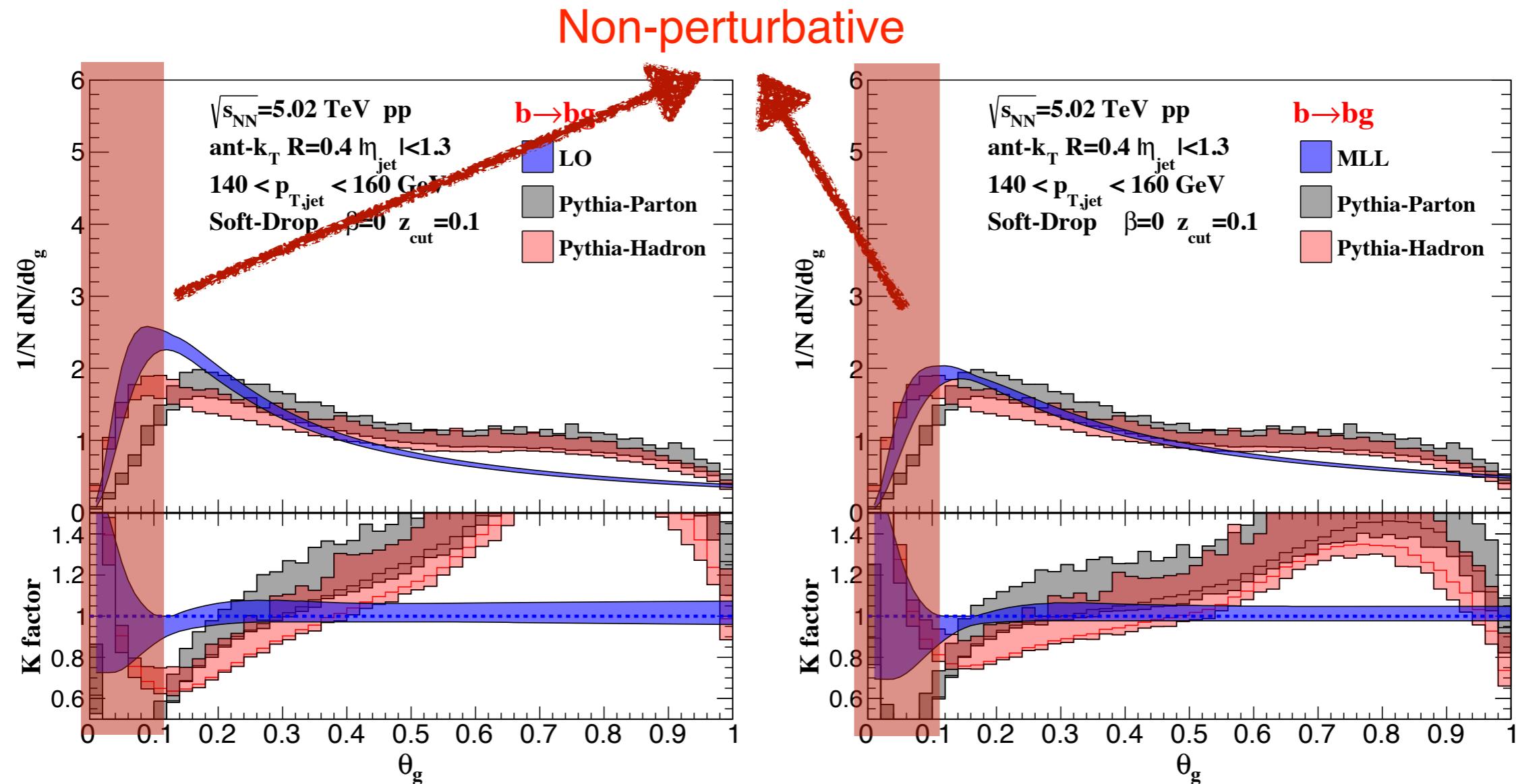
LO and MLL predictions for b-tagged jet



The splitting kernel $C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_\perp^2 + x^2 m^2}$ is zero after integration when k_T is zero

Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet

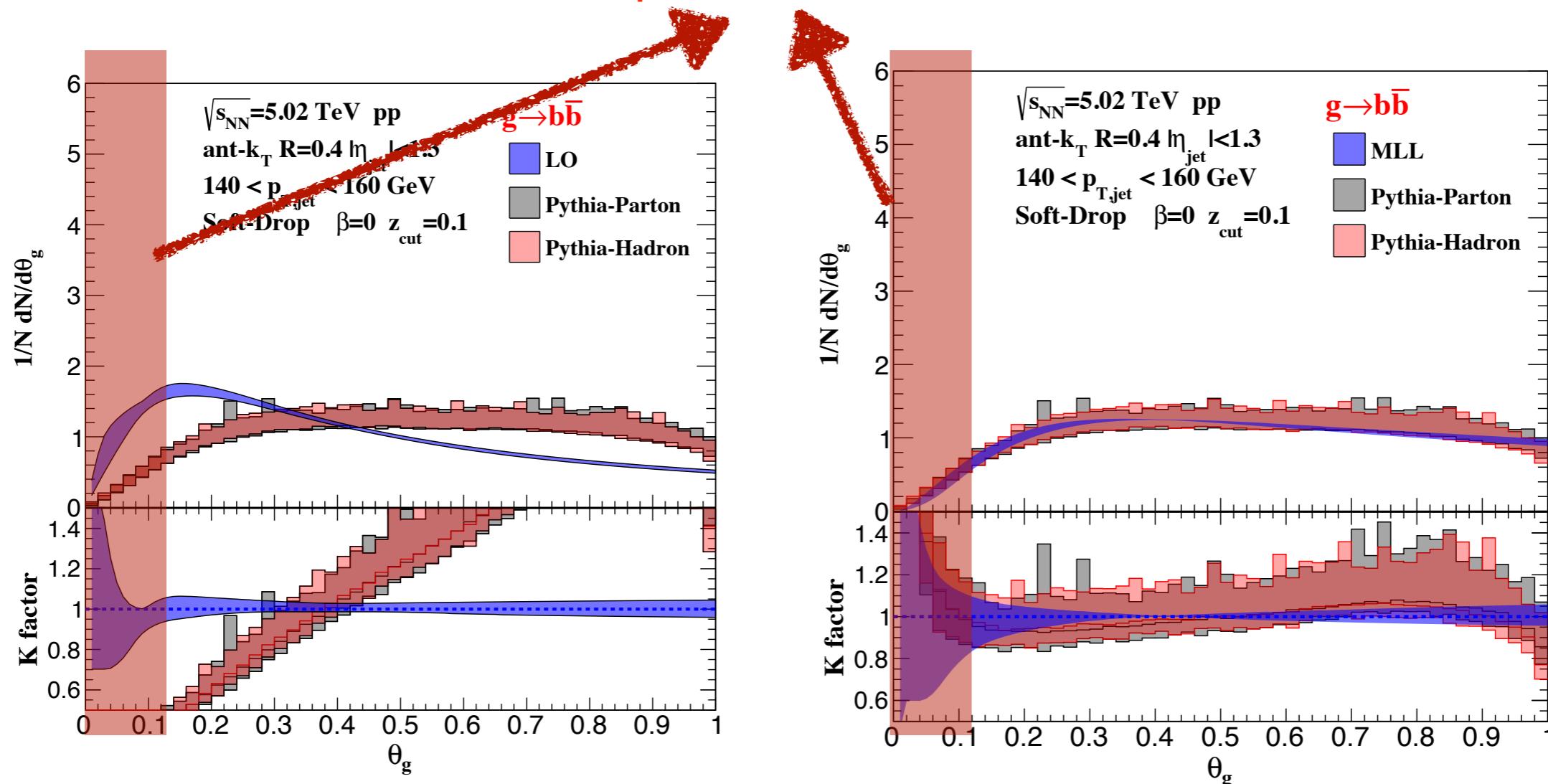


The splitting kernel $C_F \frac{\alpha_s}{\pi^2} \frac{1}{k_\perp^2 + x^2 m^2}$ is zero after integration when k_T is zero

Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged subjets

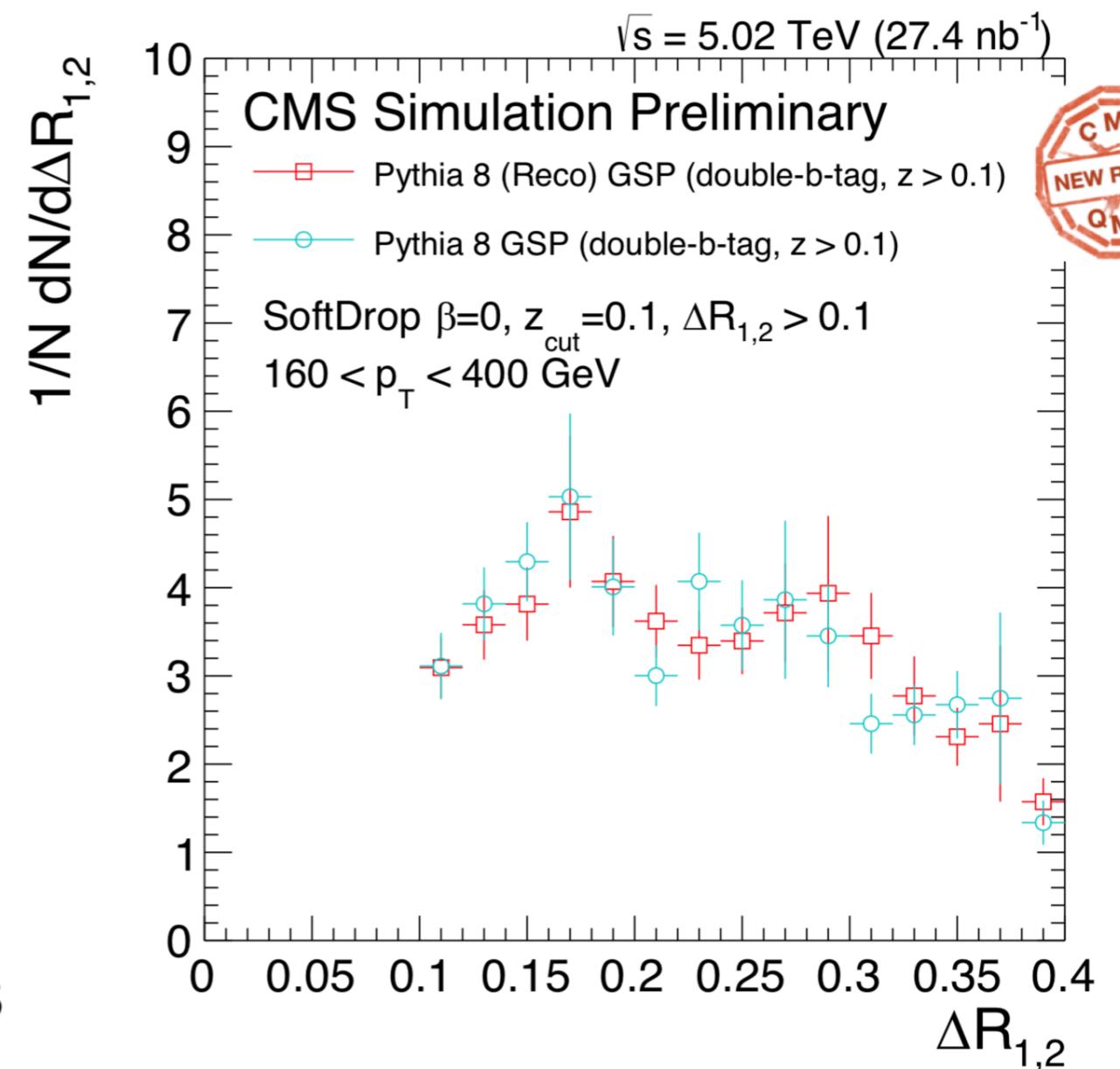
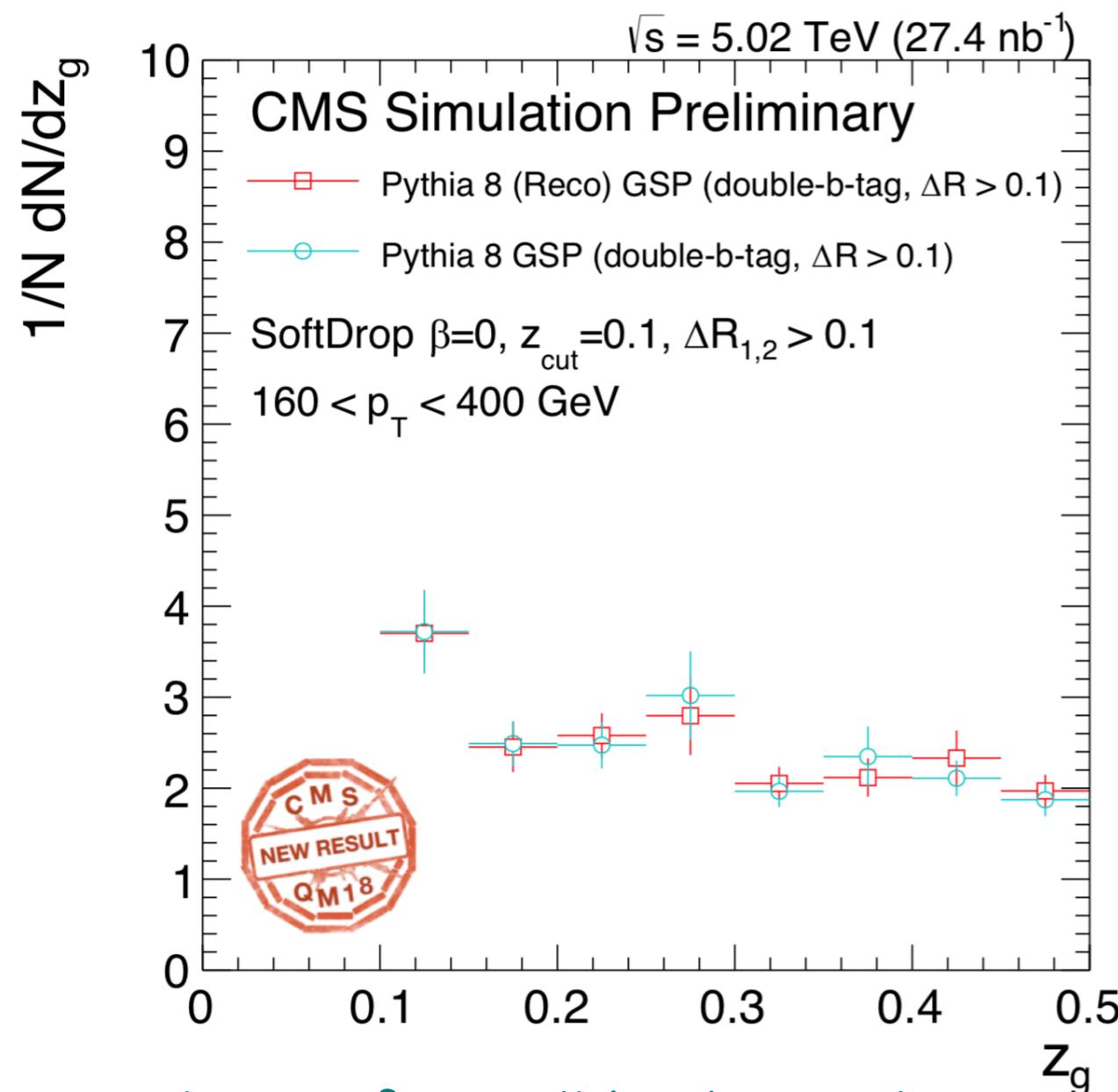
Non-perturbative corrections



- ▶ Huge Sudakov suppression in the small angle region
- ▶ Dominated by wide-angle gluon splittings

Future Measurement

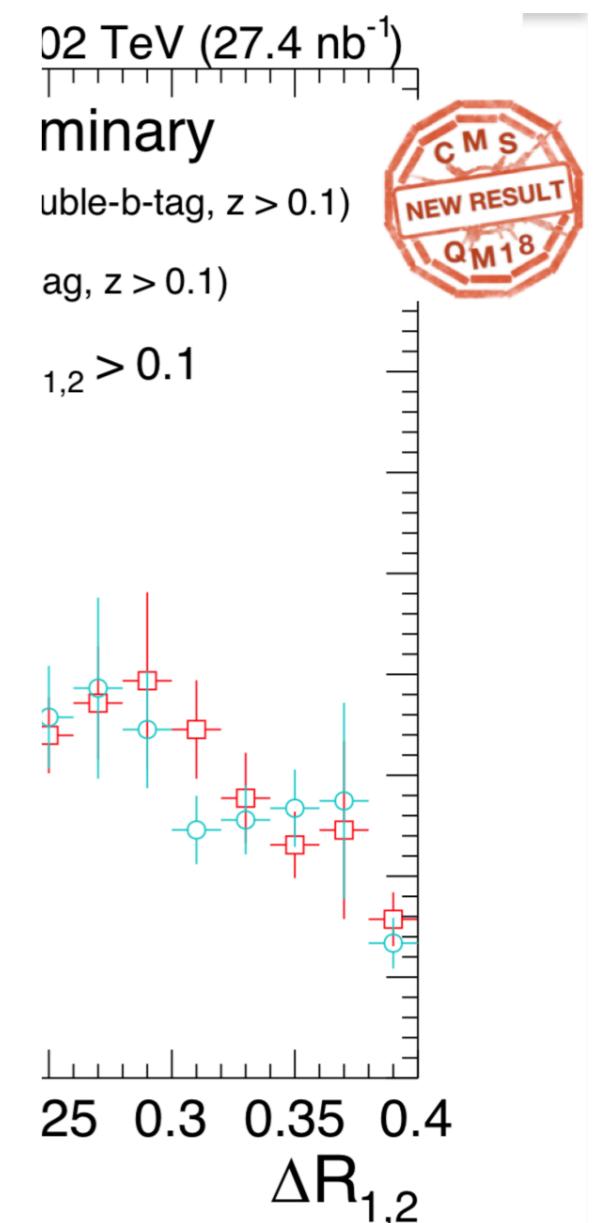
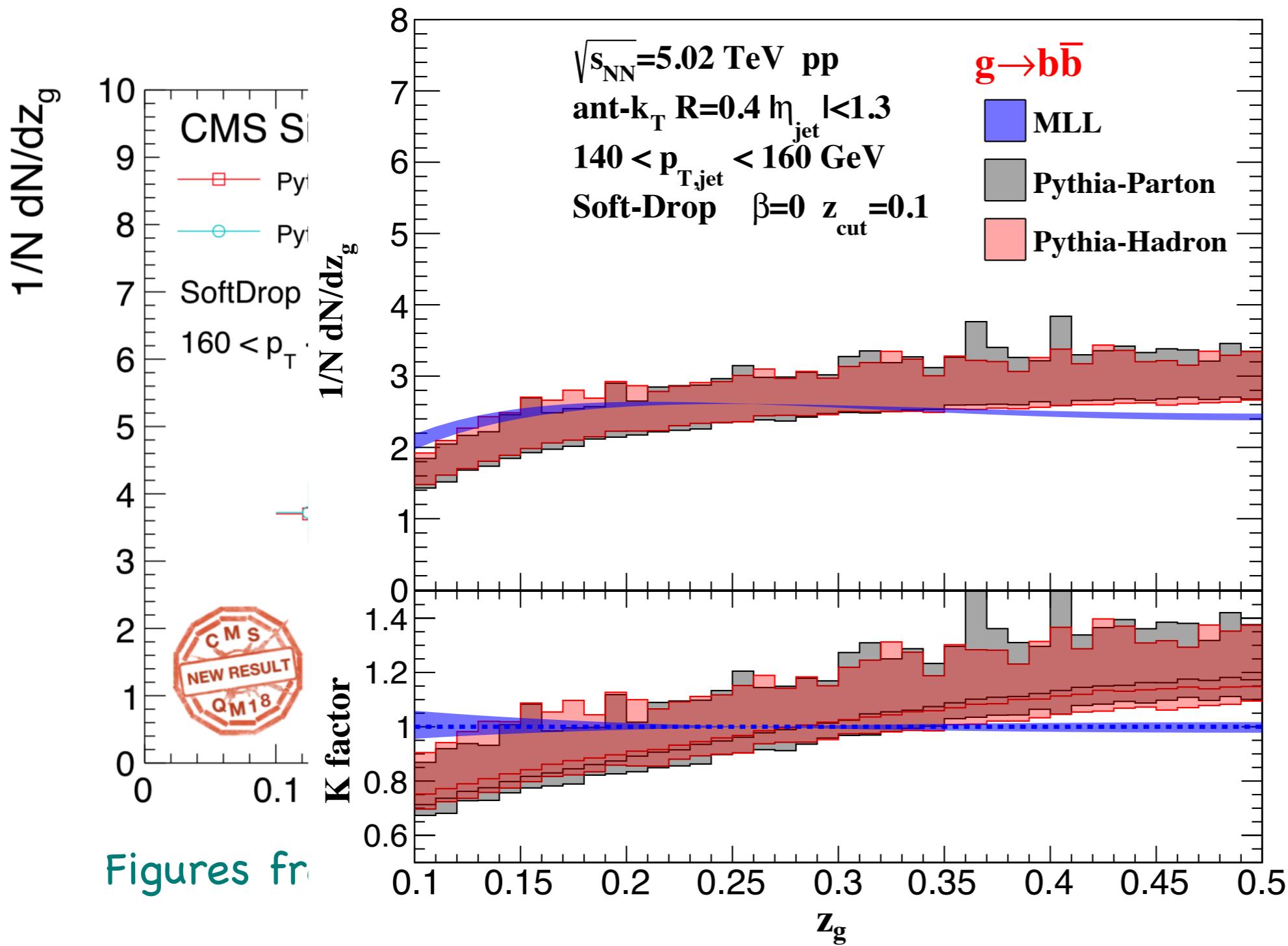
CMS is preparing to measure the double-b-taged gluon splittings



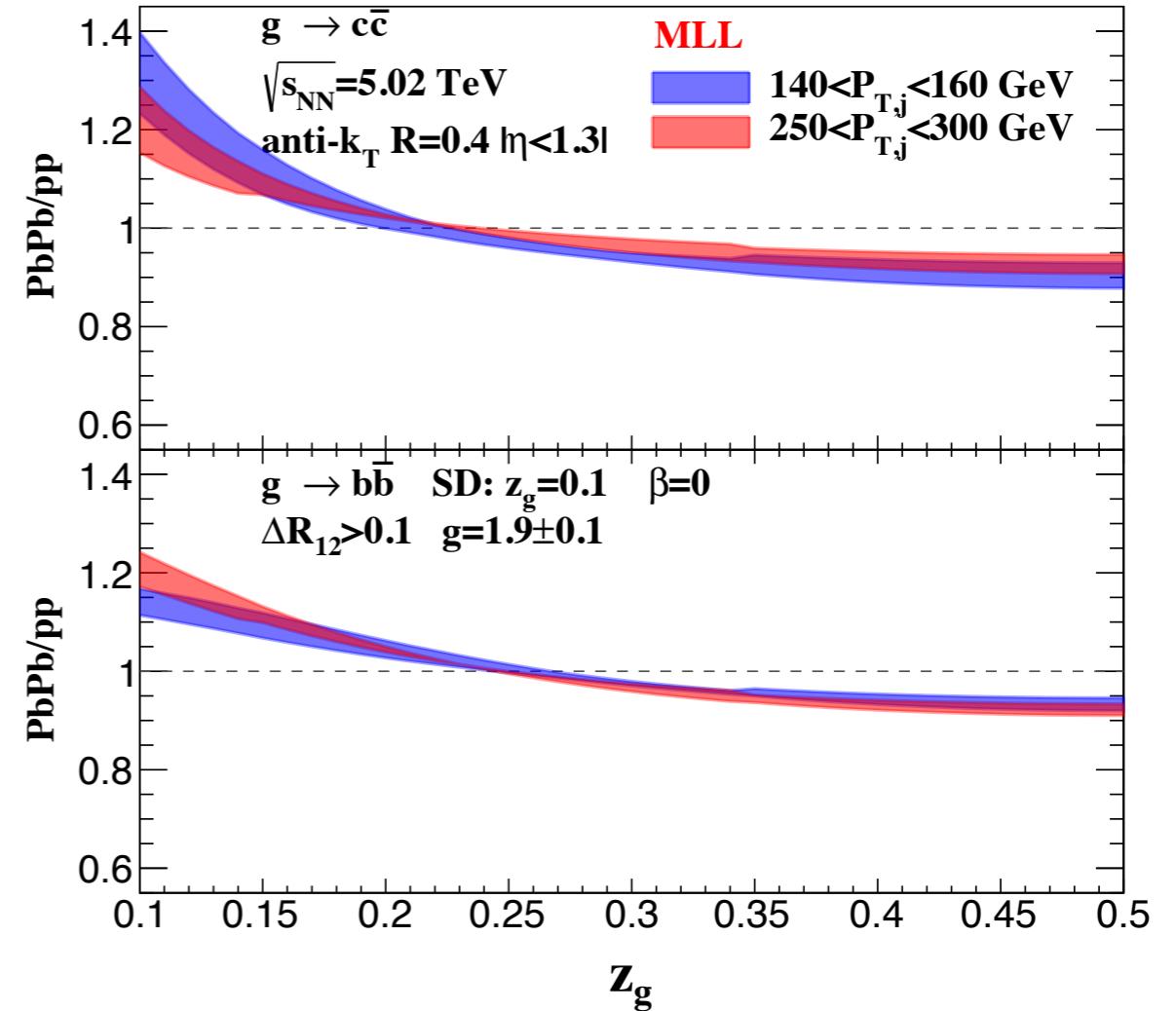
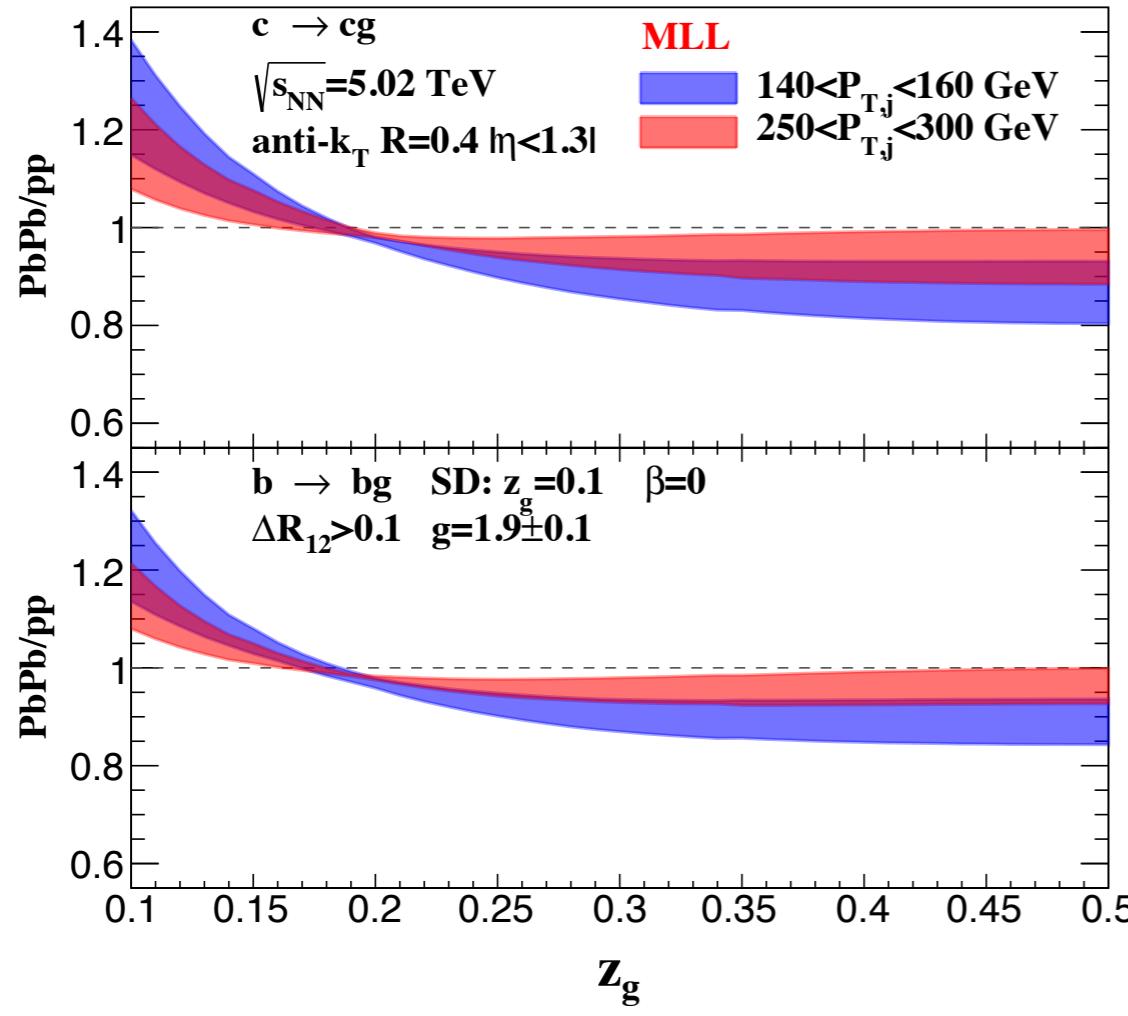
Figures from Slides by Kurt Jung at Quark matter 2018

Future Measurement

CMS is preparing

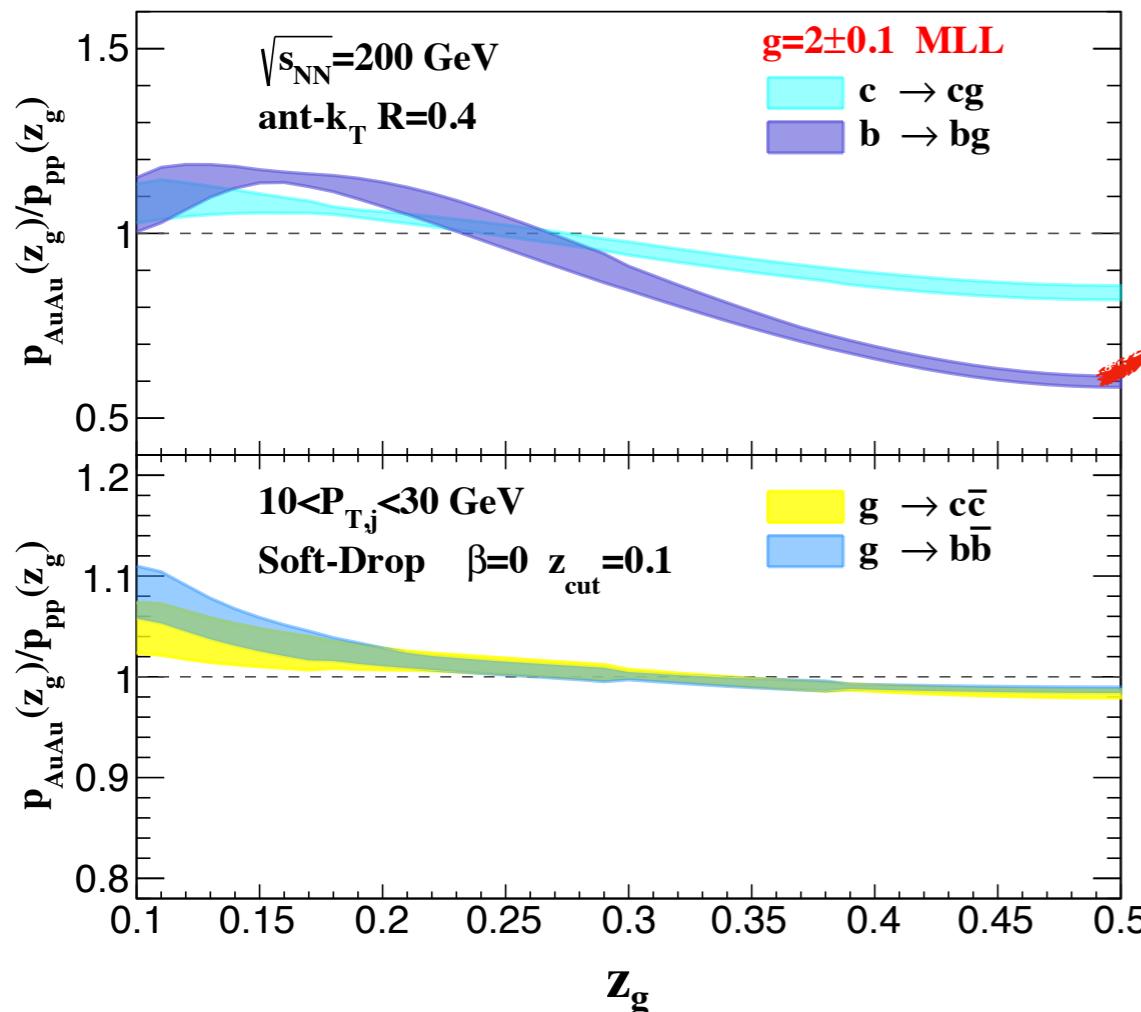


Results for heavy flavor tagged jet



When the jet energy is high the mass effect is small. The heavy flavor tagged jet behaves similar to the light jet in the medium.

Results for heavy flavor tagged jet



Inverting the mass hierarchy in

Splitting function in the vacuum

$$\left(\frac{dN^{\text{vac}}}{dz d^2 k_\perp} \right)_{Q \rightarrow Qg} = \frac{\alpha_s}{2\pi^2} \frac{C_F}{k_\perp^2 + z^2 m^2} \left(\frac{1 + (1-z)^2}{z} - \frac{2z(1-z)m^2}{k_\perp^2 + z^2 m^2} \right)$$

$$\left(\frac{dN^{\text{vac}}}{dz d^2 k_\perp} \right)_{g \rightarrow Q\bar{Q}} = \frac{\alpha_s}{2\pi^2} \frac{T_R}{k_\perp^2 + m^2} \left(z^2 + (1-z)^2 + \frac{2z(1-z)m^2}{k_\perp^2 + m^2} \right)$$

$b \rightarrow bg$

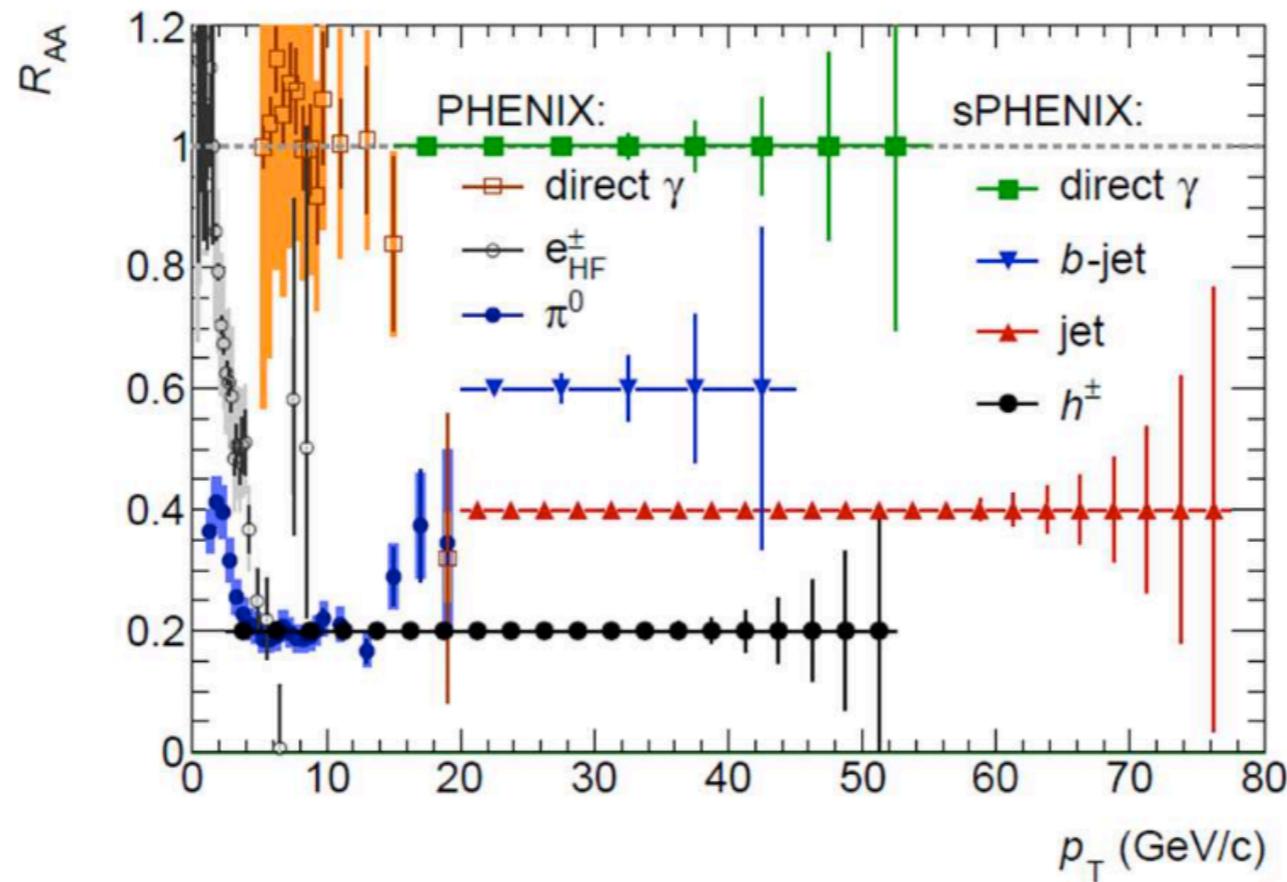
$$\left(\frac{1}{k_\perp^2 + z^2 m^2} \right) \times \left(\frac{1}{k_\perp^2 + z^2 m^2} \right) \times c \quad \xrightarrow{k_\perp \rightarrow 0} \quad \frac{1}{z^4 m^4} \times c \quad \left(\frac{1}{k_\perp^2 + m^2} \right) \times \left(\frac{1}{k_\perp^2 + m^2} \right) \times c \quad \xrightarrow{k_\perp \rightarrow 0} \quad \frac{1}{m^4} \times c$$

$g \rightarrow b\bar{b}$

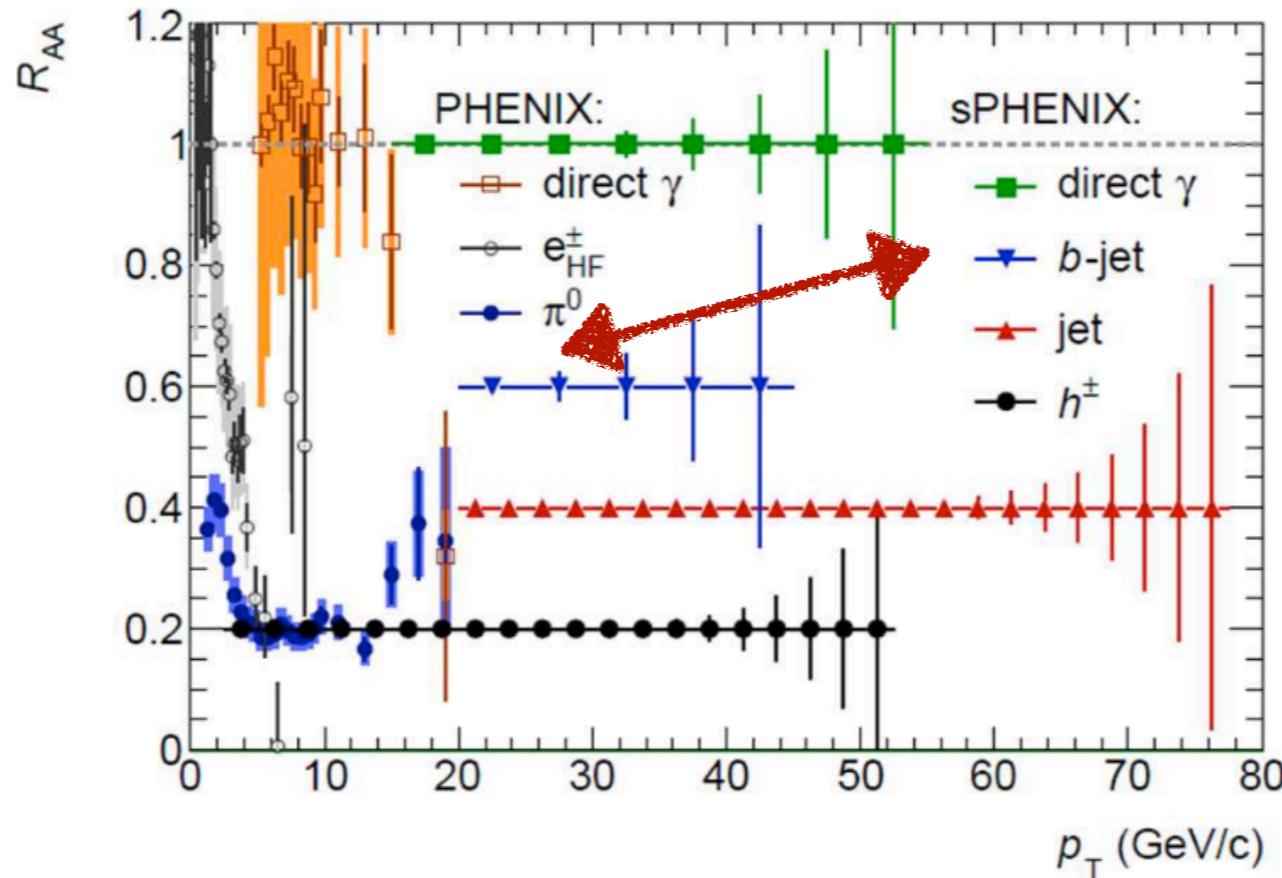
Predict stronger jet momentum sharing distribution modification than light jets

Predict almost no jet momentum sharing distribution modification

Mass versus Energy

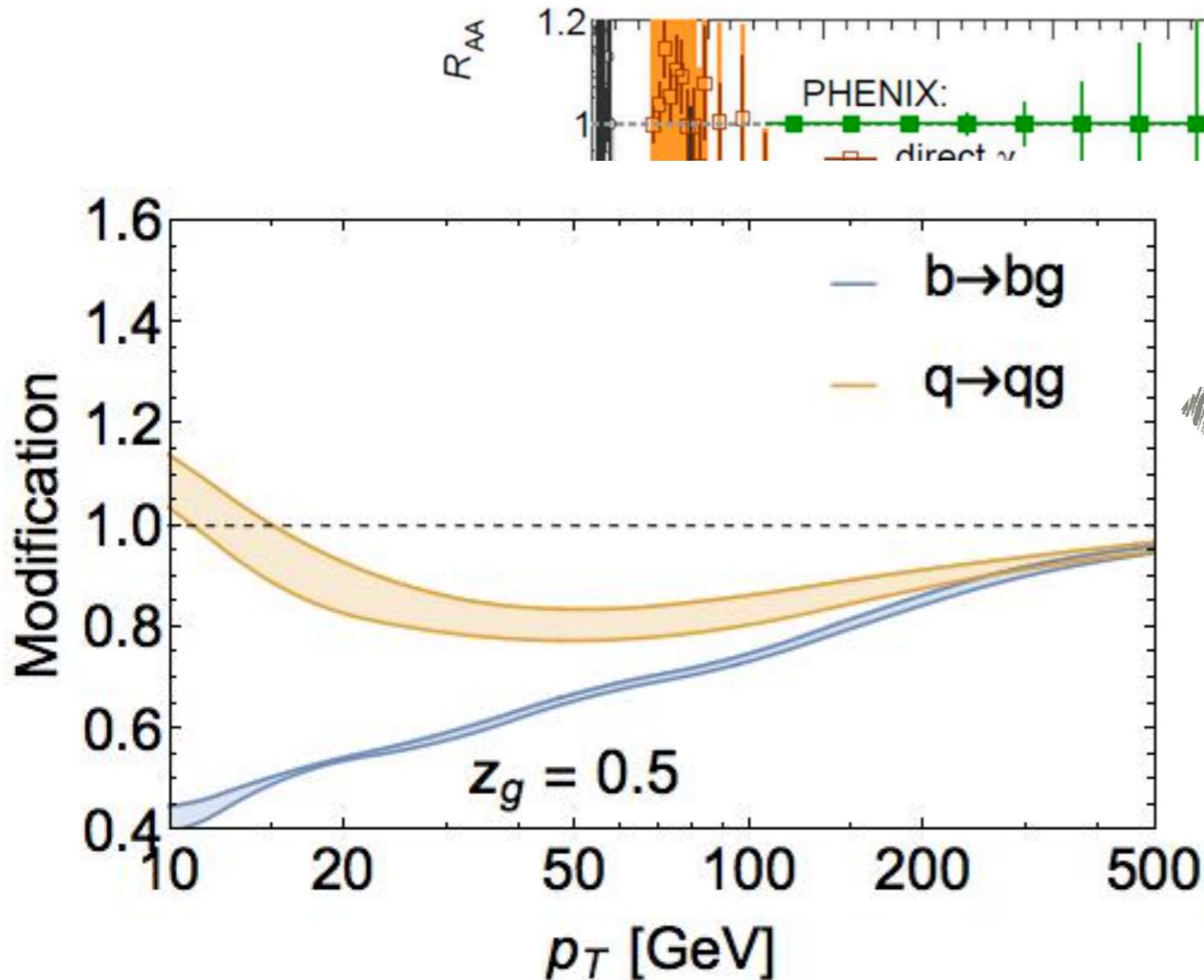


Mass versus Energy



It is measurable at RHIC

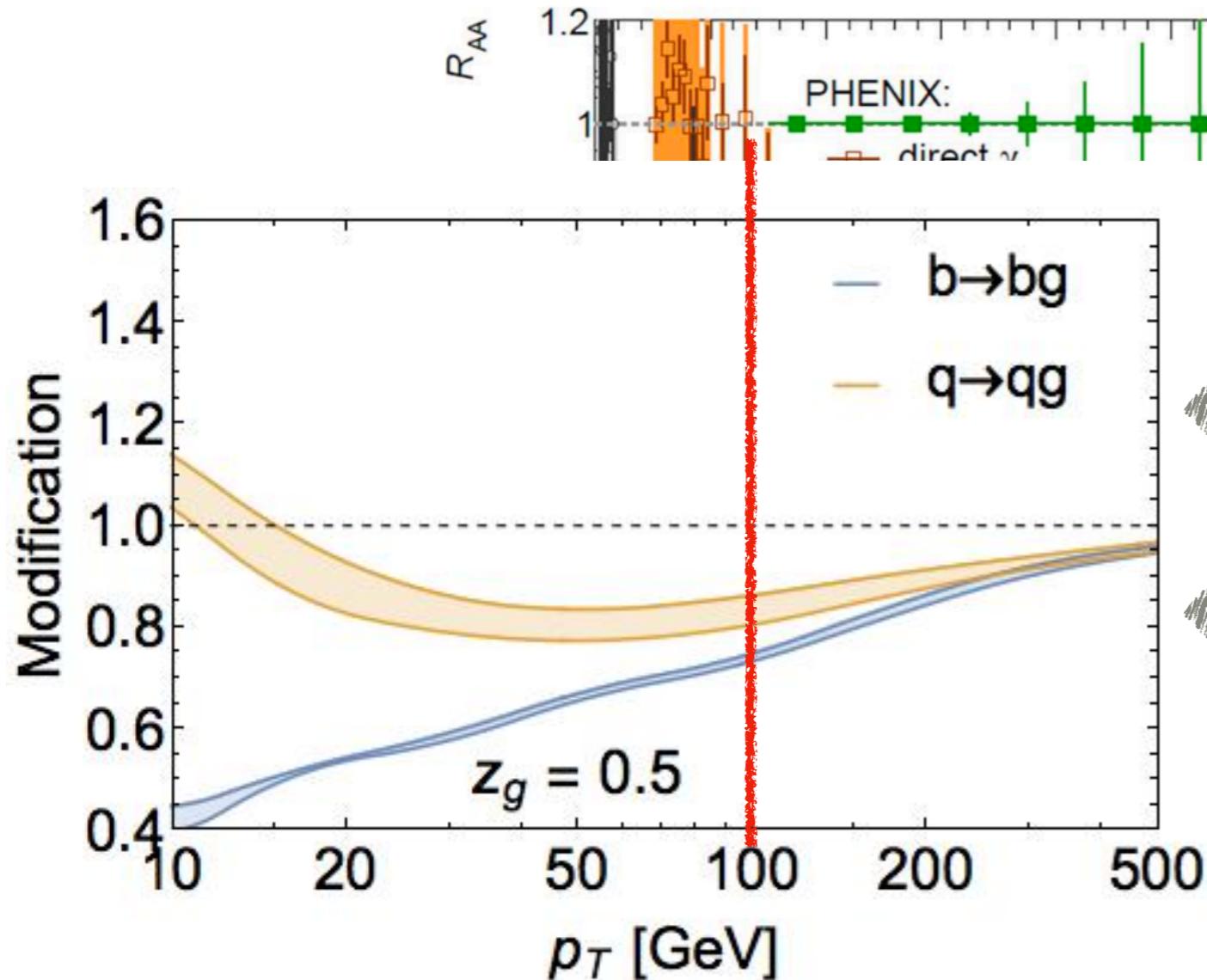
Mass versus Energy



As expected the mass effect goes away when the jet energy is really high.

It is measurable at RHIC

Mass versus Energy



- As expected the mass effect goes away when the jet energy is really high.
- Even when $p_T \sim 100$ GeV, there is sizable difference between the quark jet and b-jet

It is measurable at RHIC

It is measurable at LHC

Conclusions

- ▶ Presented **the first predictions for jet splitting function** in QCD medium
- ▶ Compared the MLL predictions with Pythia8 at pp collider
- ▶ Compared the MLL modifications for light jet with measurements from CMS and STAR and found a good agreement within all the uncertainties
- ▶ Found **an unique phenomenon about the mass effect** in heavy ion collisions
- ▶ **This mass effect is measurable at both the RHIC and LHC**

Conclusions

- ▶ Presented **the first predictions for jet splitting function** in QCD medium
- ▶ Compared the MLL predictions with Pythia8 at pp collider
- ▶ Compared the MLL modifications for light jet with measurements from CMS and STAR and found a good agreement within all the uncertainties
- ▶ Found **an unique phenomenon about the mass effect** in heavy ion collisions
- ▶ **This mass effect is measurable at both the RHIC and LHC**

Heavy flavor tagged-jet may be better probes of the QGP properties than light jet.

Conclusions

- ▶ Presented **the first predictions for jet splitting function** in QCD medium
- ▶ Compared the MLL predictions with Pythia8 at pp collider
- ▶ Compared the MLL modifications for light jet with measurements from CMS and STAR and found a good agreement within all the uncertainties
- ▶ Found **an unique phenomenon about the mass effect** in heavy ion collisions
- ▶ **This mass effect is measurable at both the RHIC and LHC**

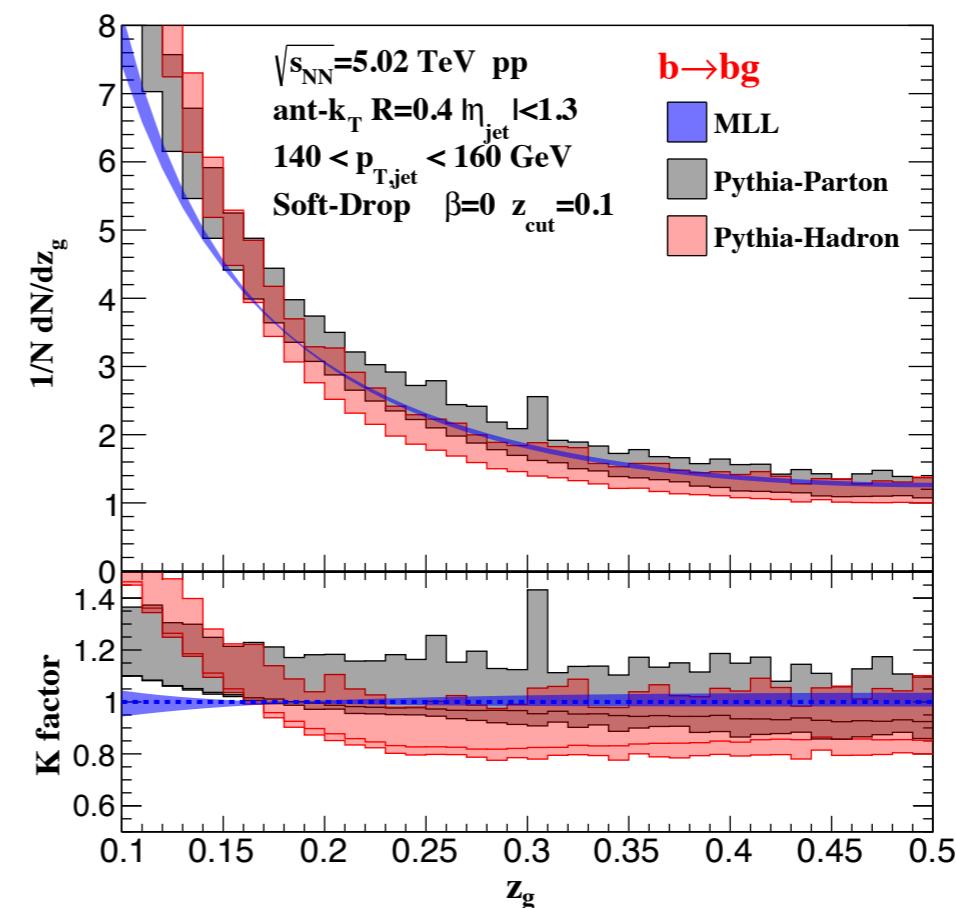
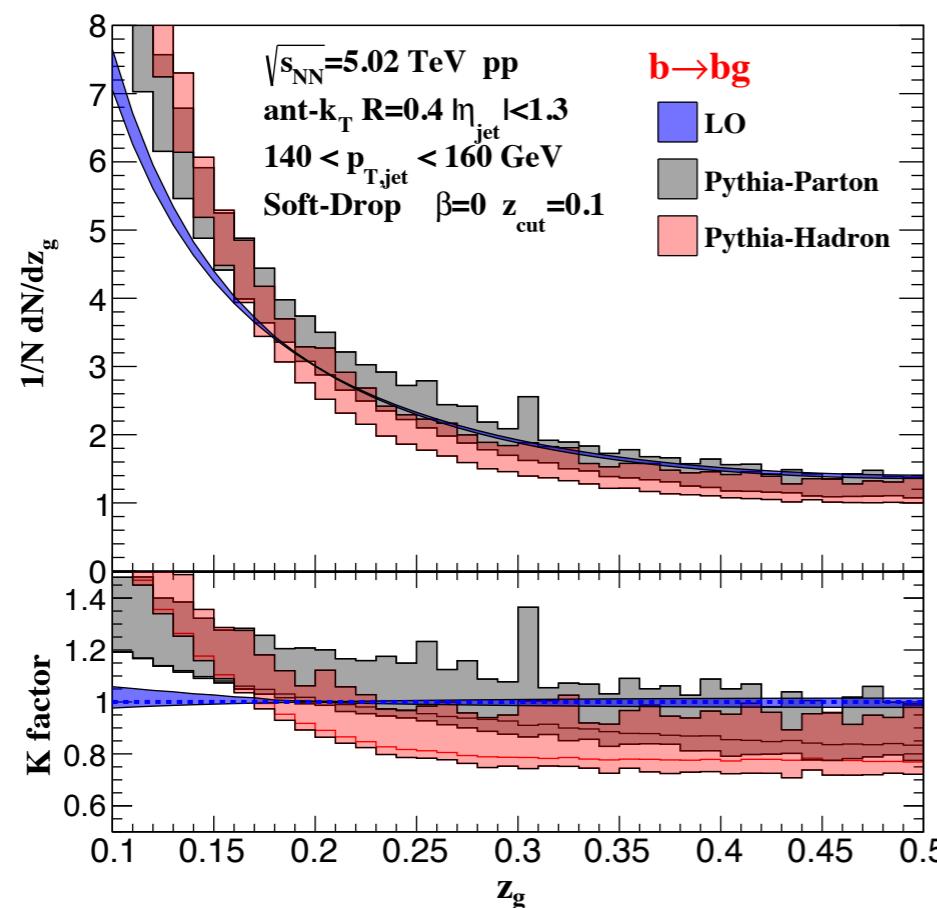
Heavy flavor tagged-jet may be better probes of the QGP properties than light jet.

Thank you

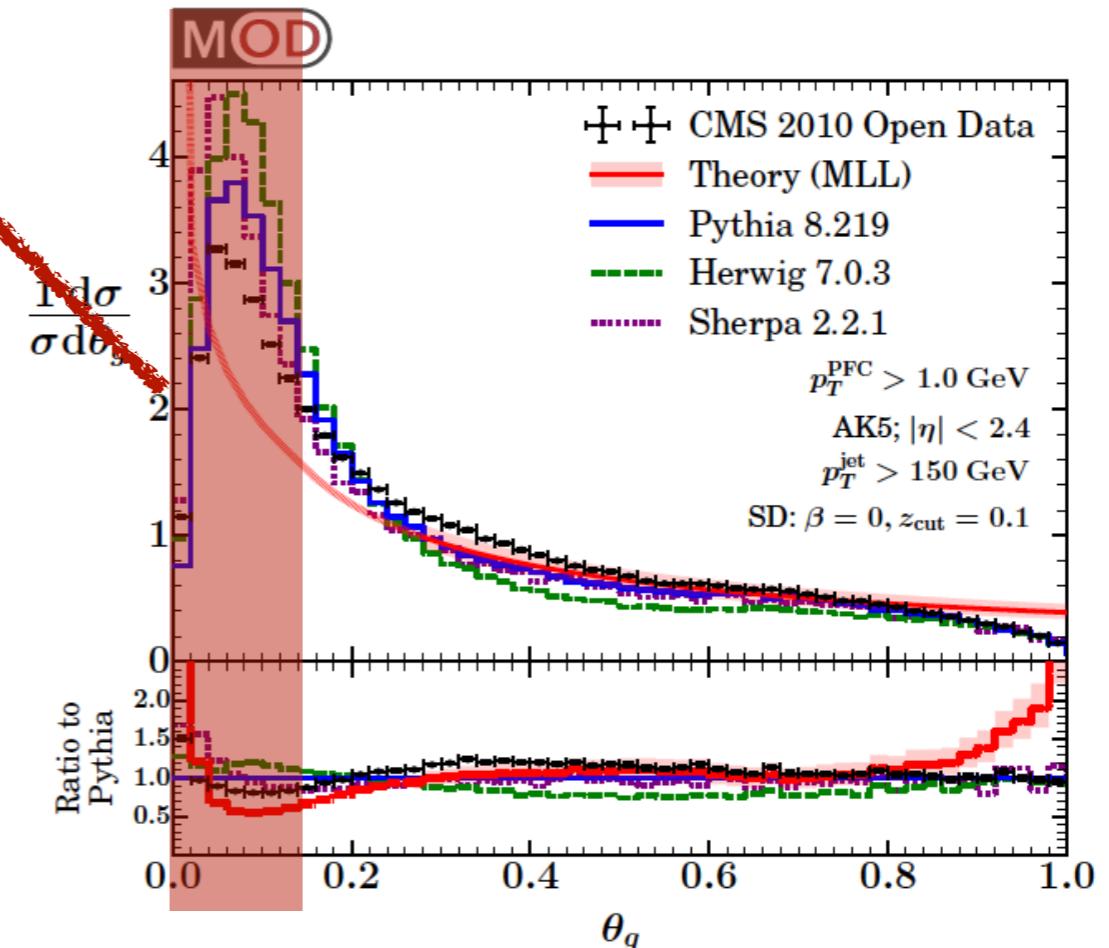
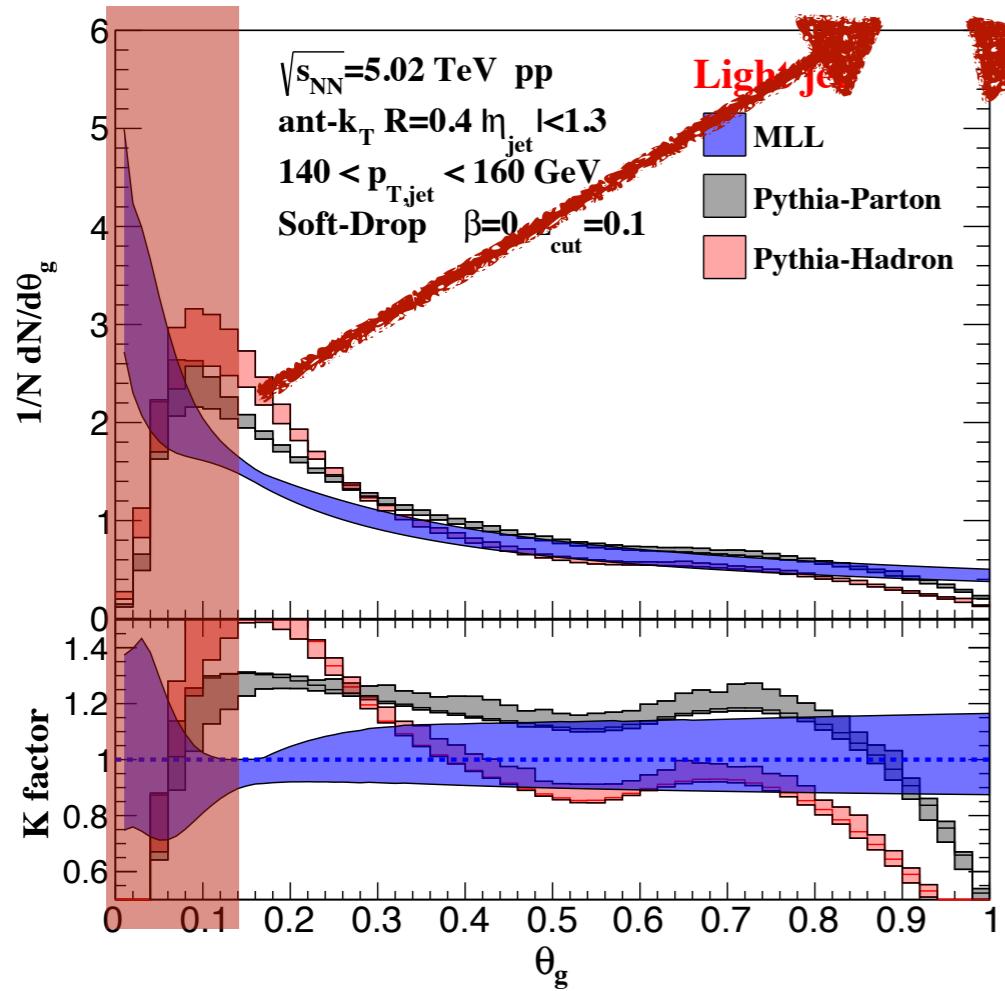
Back up

Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet

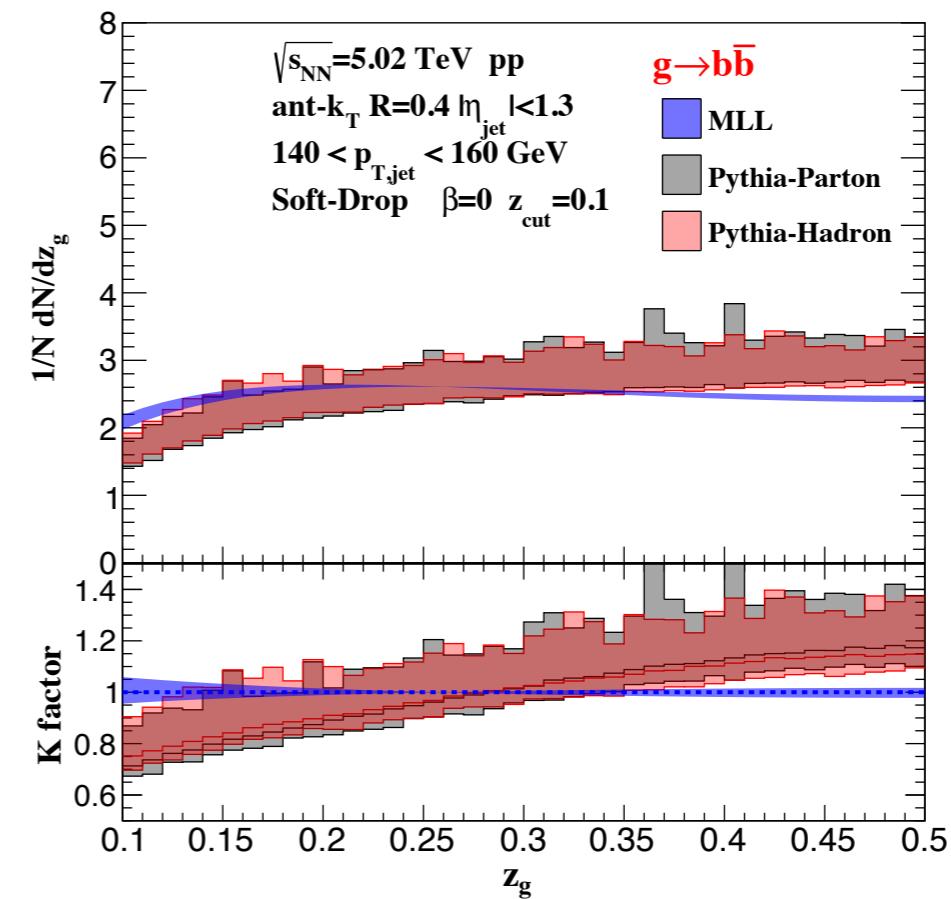
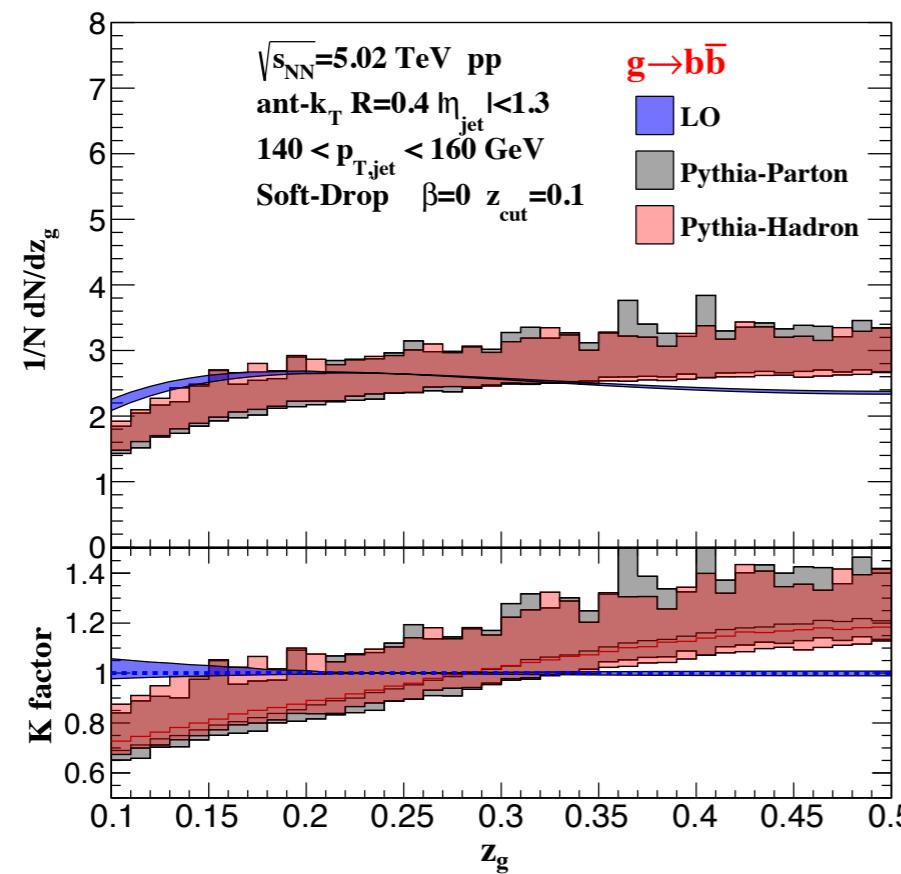


Non-perturbative



Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet



Back up

