Inverting the mass hierarchy of jet quenching with b-jet substructure

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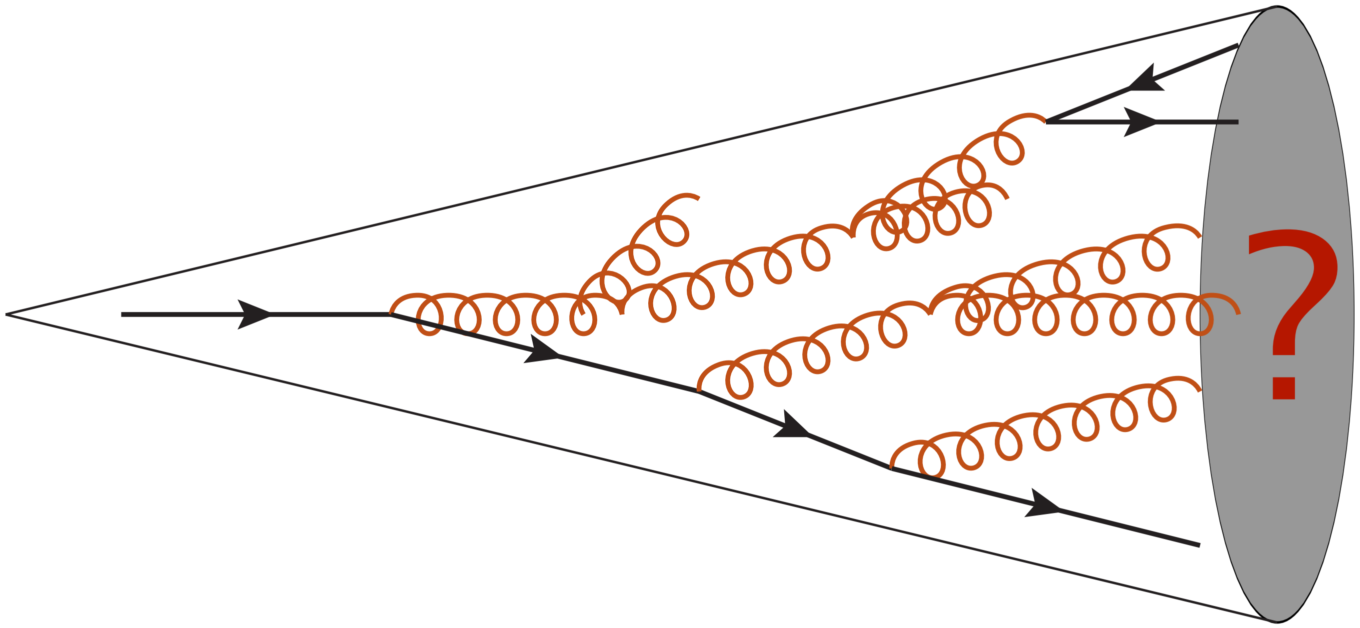
Los Alamos National Laboratory

In collaboration with Ivan Vitev
Based on the work arXiv:1801.00008

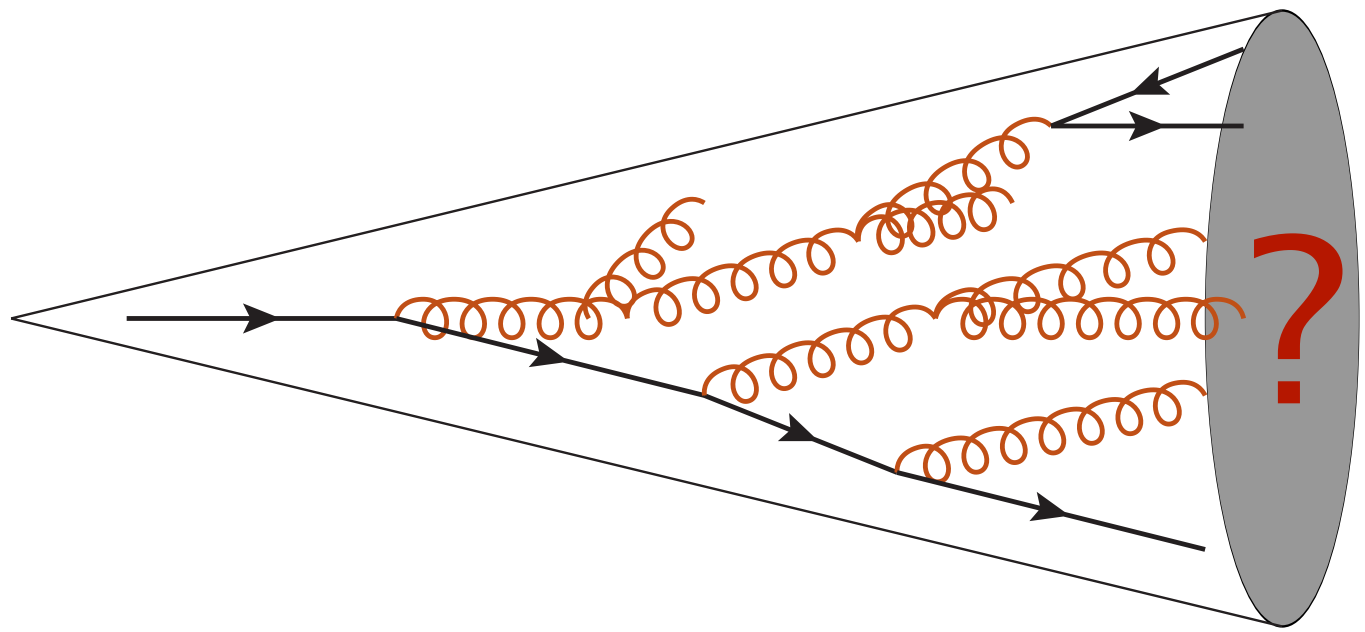
QCD Evolution, Santa Fe
May 23, 2018

Jets



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

Jets



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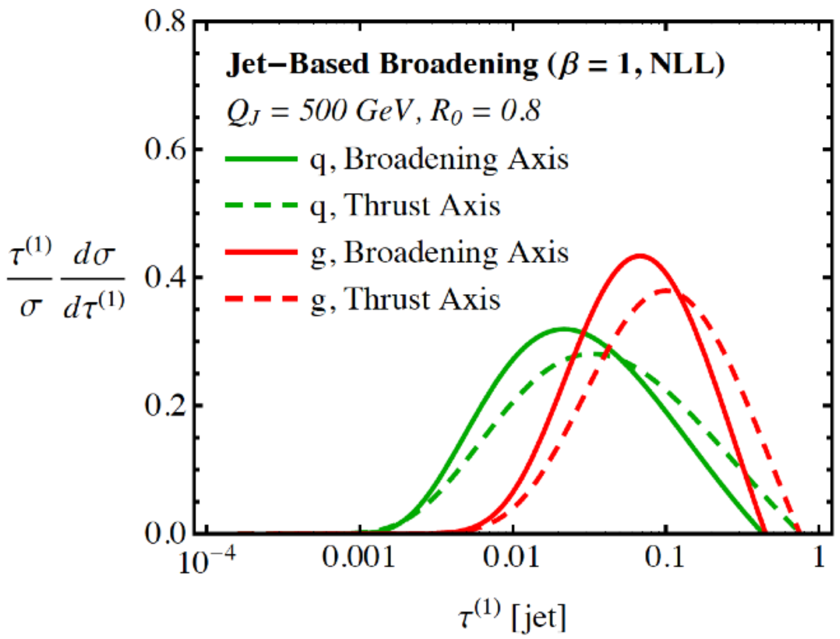
Where do jets come from, quark, gluon or decaying product of other particles ?

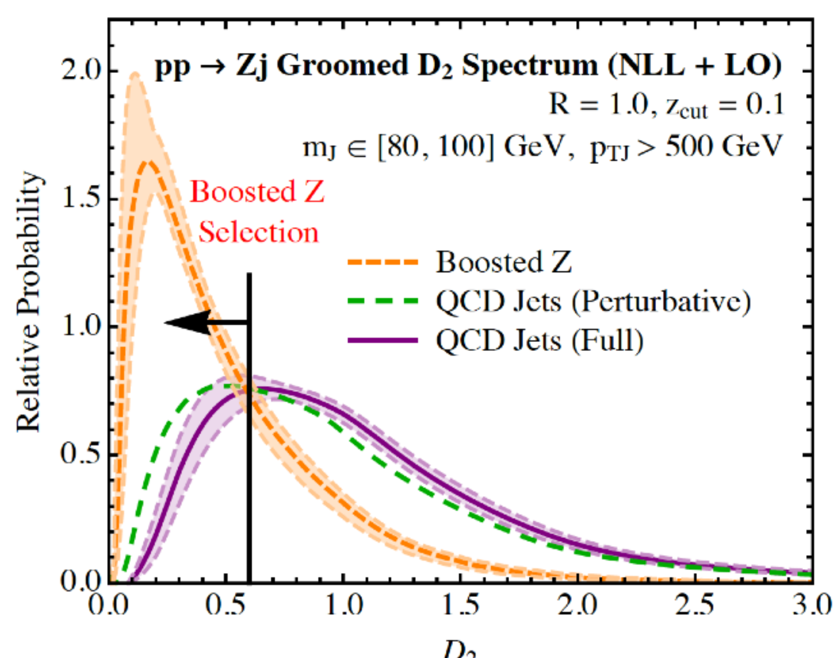
Jet substructures

Jet substructures at the LHC

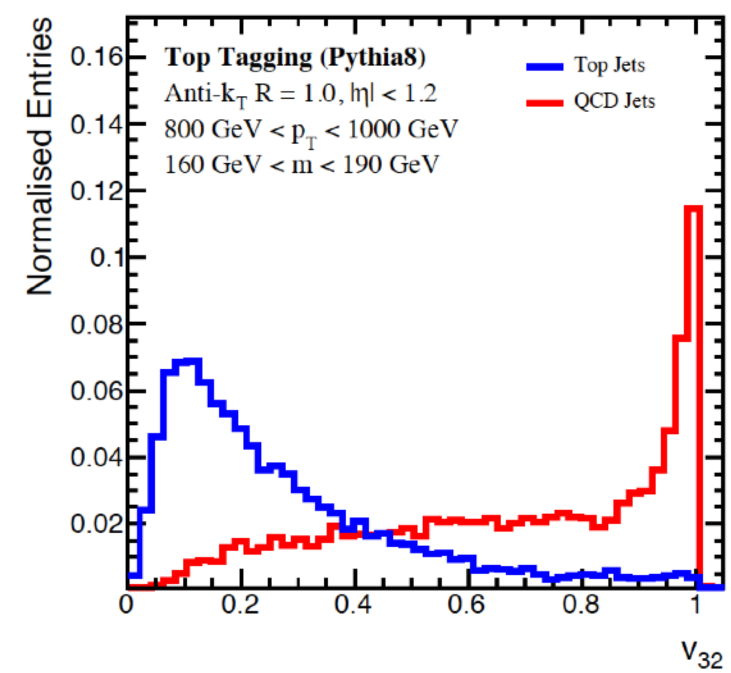
Jet Substructures provide new ways to search for new physics and to probe the Standard Model in extreme regions of phase space.



1-prong jet:
Larkoski et al 2014



groomed multi-prong observables
Larkoski et al 2017

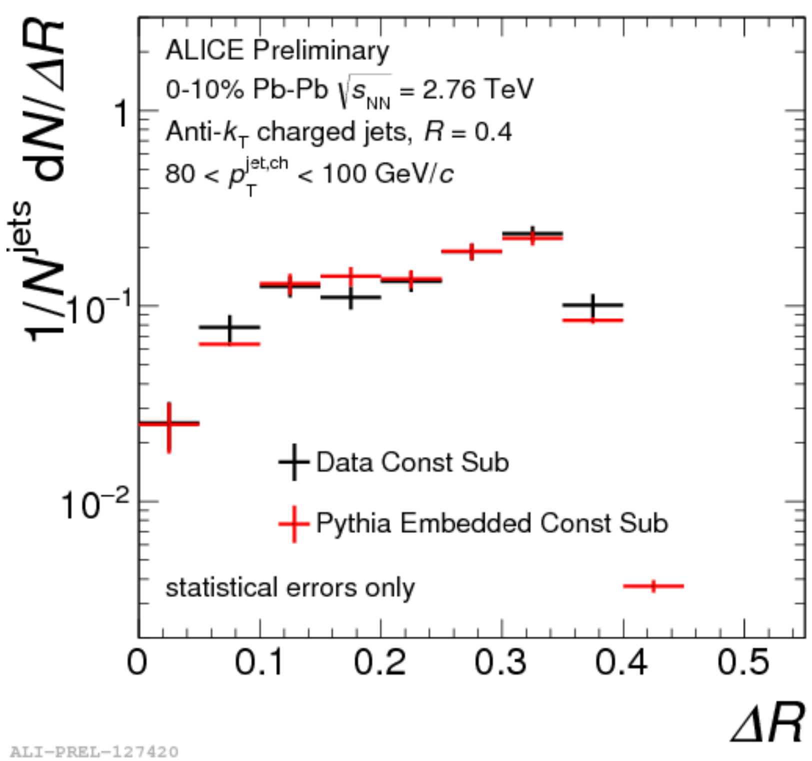


ratio of 2-prong and 3-prong:
Chien et al 2017

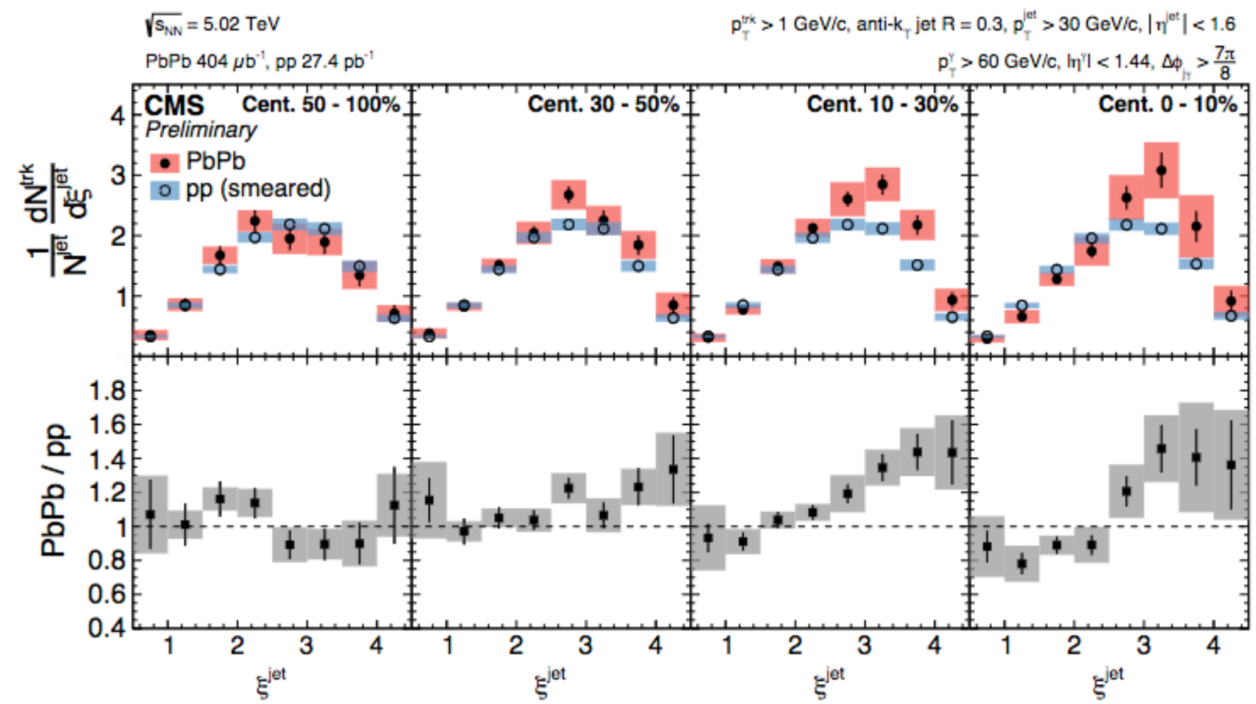
See Varun's talk for Energy-Energy correlator and Kyle's talk for jet mass
for a recent review see arXiv:1709.04464

Jet in Heavy ion collisions

For example recent measurements



Open angle between the two 2-subjettiness



$$\xi^{jet} = \ln \frac{|\mathbf{p}^{jet}|^2}{\mathbf{p}^{trk} \cdot \mathbf{p}^{jet}}$$

Measurements of fragmentation functions for jets

The observable we are interested is Jet splitting function

Jet Splitting Function

Defined as a two-prong substructure

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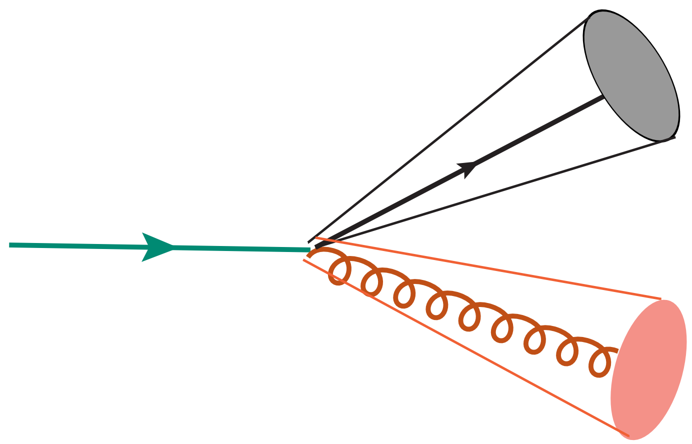
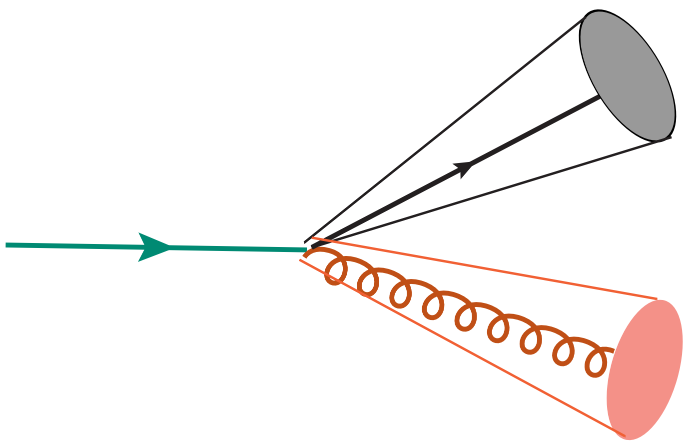


$1 \to 2$ splitting process

Jet Splitting Function

Defined as a two-prong substructure

- An early hard splitting will result in two partons with high transverse momentum.
- Information about these leading partonic components can be obtained by removing the softer wide-angle radiation contributions
- This is done through the use of jet grooming algorithms that attempt to split a single jet into two subjets, a process referred to as "declustering"



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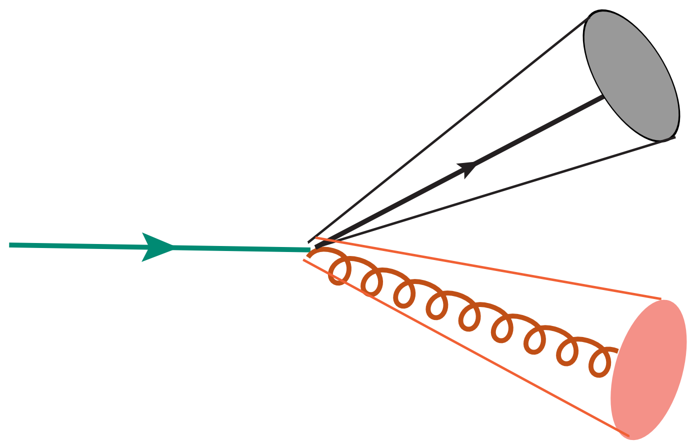
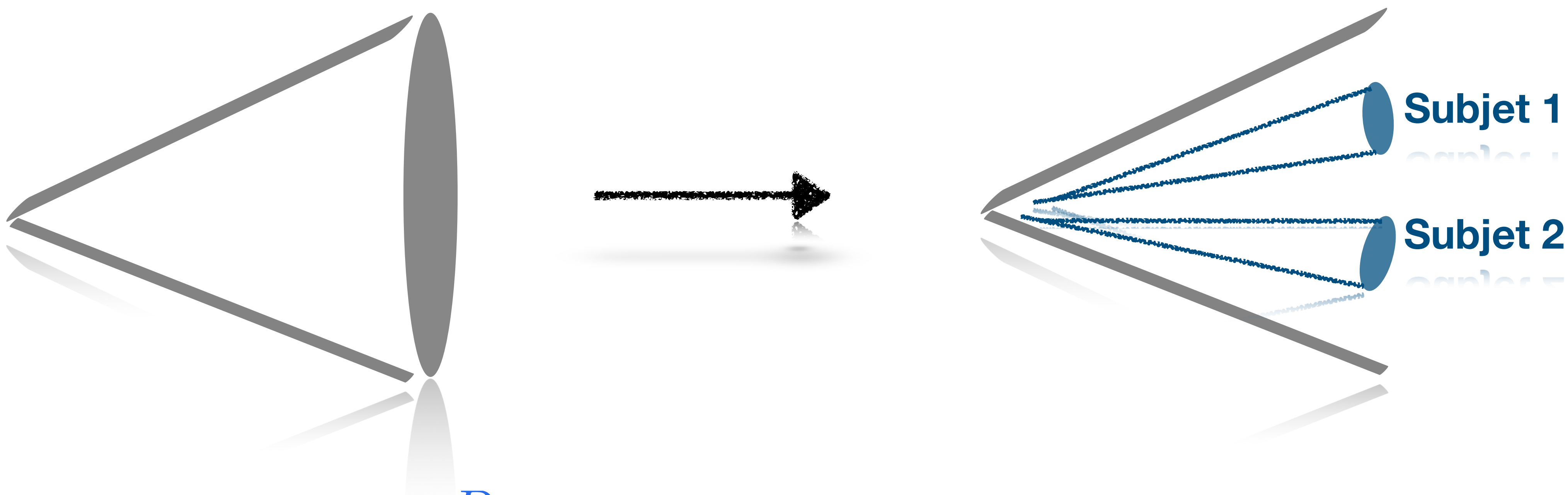


$1 \to 2$ splitting process

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

Soft drop decluttering



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

- Drop soft divergences systematically
- All remaining particles in the jet must be collinear

See Varun, Felix and Kyle's talks

Larkoski et al 2014

Jet Splitting Function

The QCD splitting function

- Fundamental property of pQCD
- Heart to the collinear universality, DGLAP evolutions
- Most of Parton shower Models are generated by LO splitting functions

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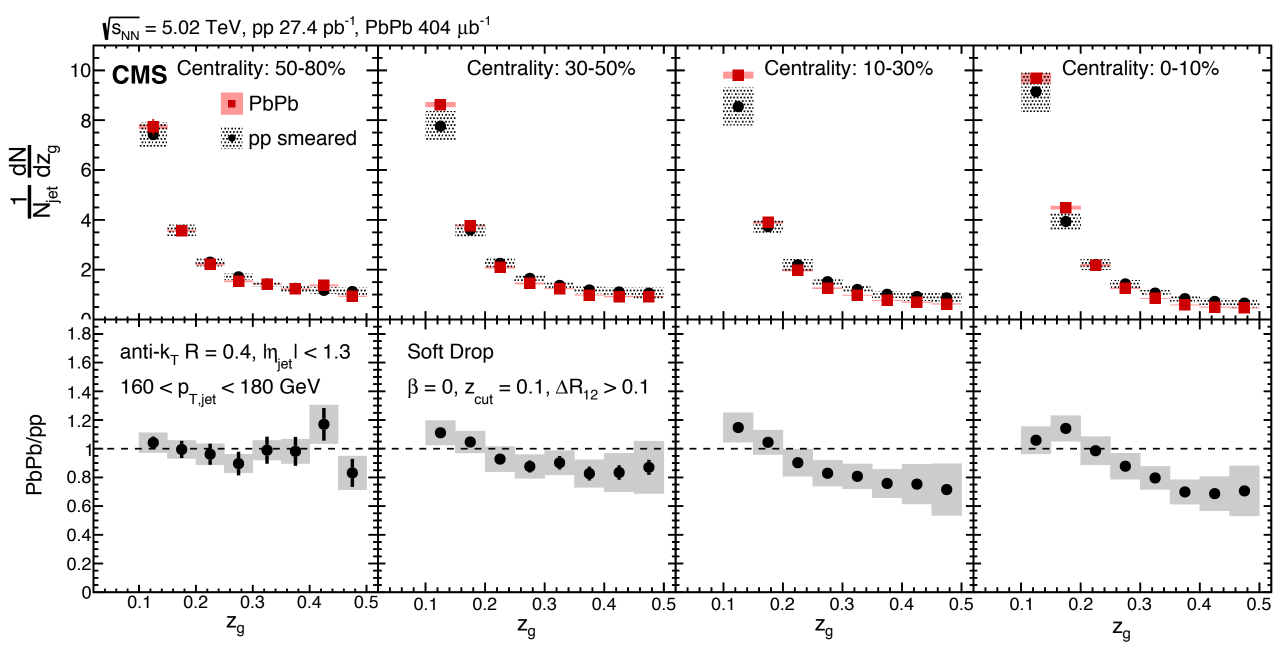
Splitting functions in QCD medium

- Test the in-medium splitting functions.
- Study early stage of the in-medium parton shower evolution.

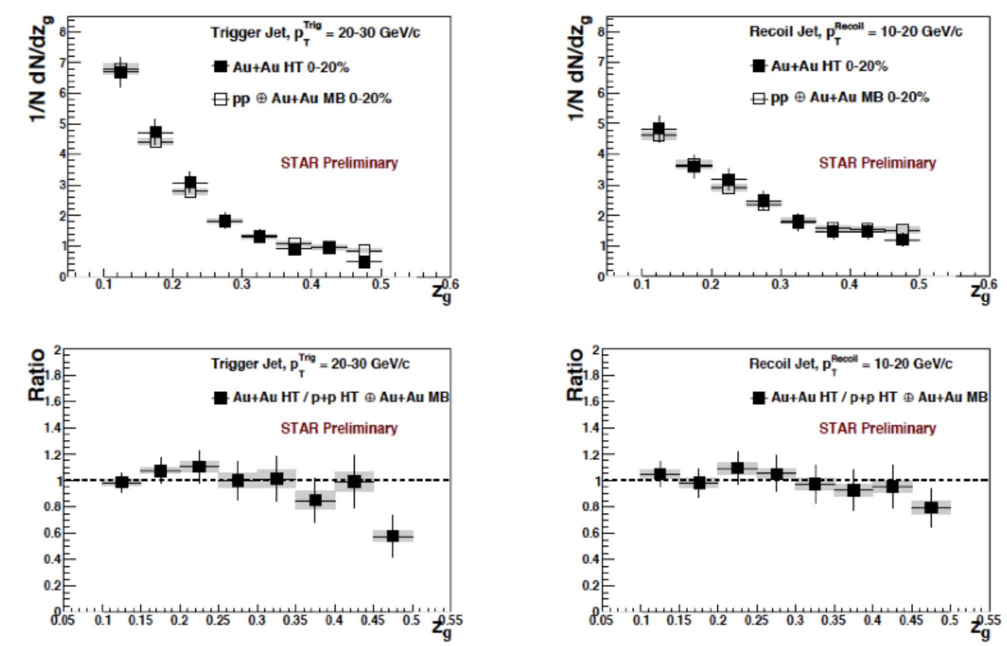
Splitting functions in medium

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

- the predictions for the modification of **the resumed substructure** for light jet
- the predictions for the jet substructure of **heavy-flavor tagged jet** in the vacuum and medium

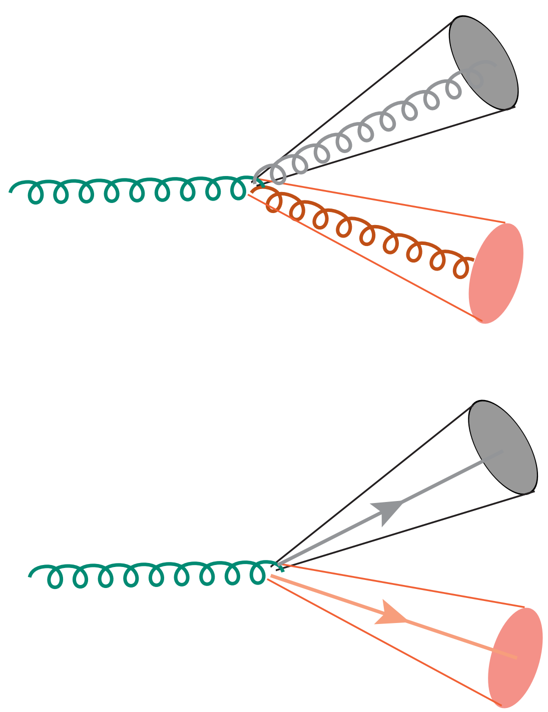
Resummation

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

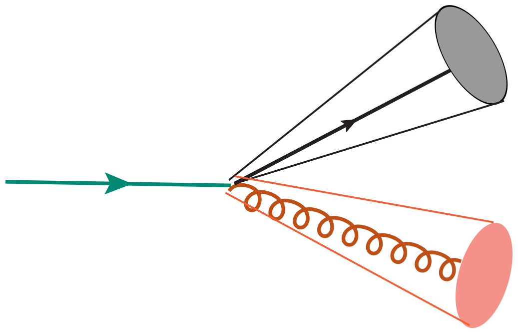


Gluon evolution

Vacuum splitting functions

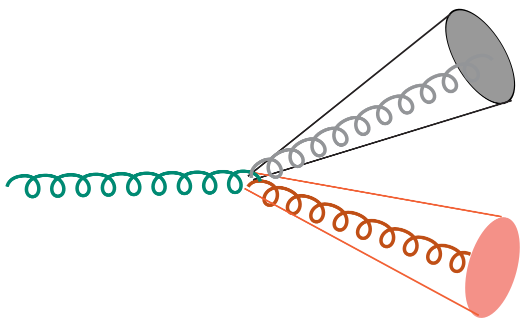
The soft-drop groomed joint distribution is dominant by the first splitting

$$\left(\frac{dN^{\rm vac}}{dz_g d\theta_g}\right)_j = \frac{\alpha_s}{\pi}\frac{1}{\theta_g}\sum_i P^{\rm vac}_{j\to i\bar{i}}(z_g)\ . \qquad 0 < \theta_g = \frac{\Delta R_{12}}{R_0} < 1$$



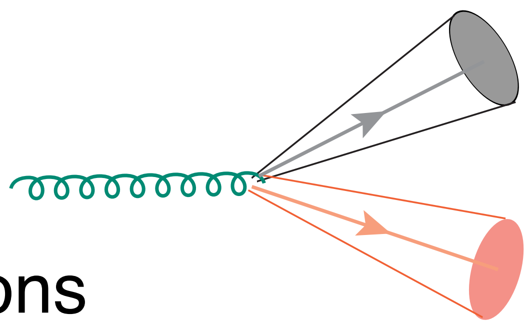
At the lowest non-trivial order the splitting functions are

$$P^{\rm vac}_{q\to qg}(z) = C_F\frac{1+(1-z)^2}{z}\ ,$$



$$P^{\rm vac}_{g\to gg}(z) = 2C_A\left(\frac{1-z}{z}+\frac{z}{1-z}+z(1-z)\right)\ ,$$

$$P^{\rm vac}_{g\to q\bar{q}}(z) = T_R\left(z^2+(1-z)^2\right)\ ,$$



These splitting functions have been widely used in many applications

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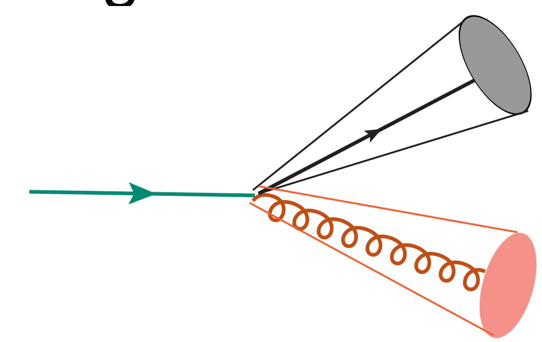

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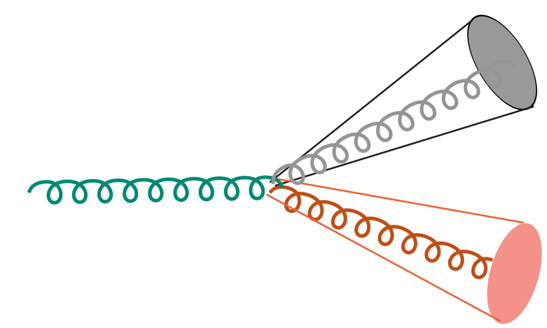
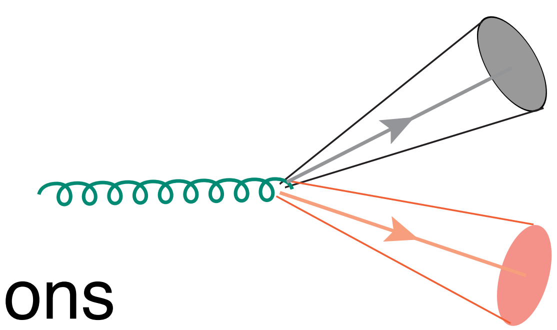
$$P^{\rm vac}_{g\to q\bar{q}}(z) = T_R\left(z^2+(1-z)^2\right)\ ,$$





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

The dependence on z and kT does not factorize.

Medium corrections to splitting functions

The Glauber modes are included using background filed method

Ovanesyan and Vitev 2011

$$\mathcal{L}_{\mathrm{SCET_G}}\left(\xi_n, A_n, A_G\right) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + \mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, A_G\right)$$

$$\mathcal{L}_{\mathrm{G}}\left(\xi_n, A_n, A_G\right) = \sum_{p,p'} \mathrm{e}^{-i(p-p')x} \left(\bar{\xi}_{n,p'} \Gamma^{\mu,a}_{\mathrm{qqA_G}} \frac{\bar{\not{n}}}{2} \xi_{n,p} - i\Gamma^{\mu\nu\lambda,abc}_{\mathrm{ggA_G}} \left(A^c_{n,p'}\right)_\lambda \left(A^b_{n,p}\right)_\nu\right) A_{\mathrm{G}\,\mu,a}(x)$$

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This framework was extended by including the finite quark mass

Kang, Ringer and Vitev 2016

$$\mathcal{L}_0 = \sum_{\tilde{p},\tilde{p}',\tilde{q}} e^{-ix\cdot\mathcal{P}}\, \bar{\xi}_{n,p'} \left[in\cdot D + (\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q}) W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger (\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q'}) \right] \frac{\bar{\not{n}}}{2} \xi_{n,p} + \mathcal{L}_m$$

$$\mathcal{L}_m = \sum_{\tilde{p},\tilde{p}',\tilde{q}} e^{-ix\cdot\mathcal{P}} \left[m\,\bar{\xi}_{n,p'} \left[(\not{\mathcal{P}}_\perp + g\not{A}^\perp_{n,q}), W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger \right] \frac{\bar{\not{n}}}{2} \xi_{n,p} - m^2\, \bar{\xi}_{n,p'} W_n \frac{1}{\bar{\mathcal{P}}} W_n^\dagger \frac{\bar{\not{n}}}{2} \xi_{n,p} \right]$$

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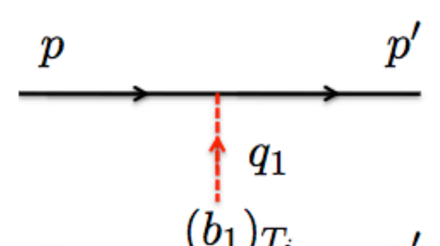
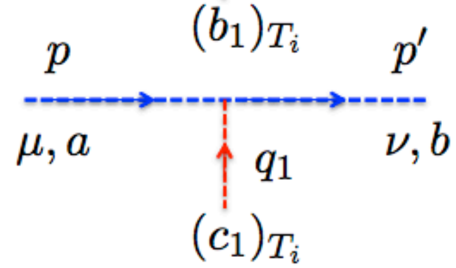
Feynman Rules are derived directly from the Lagrangian



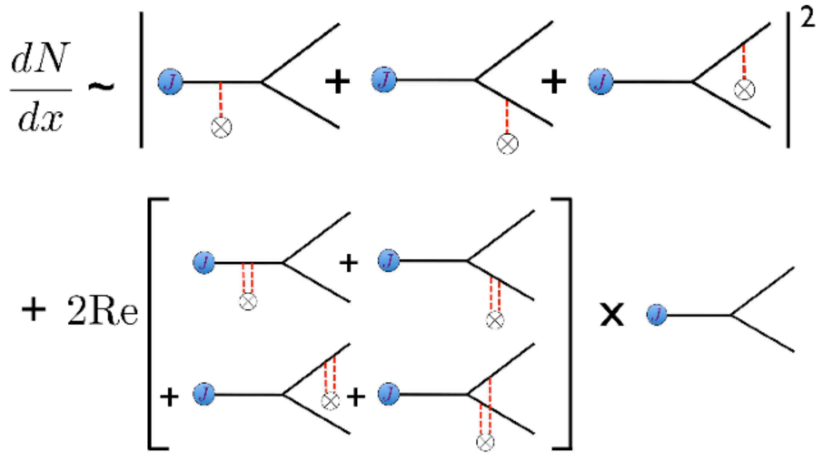
$$= i\, v(q_{1\perp})\, (b_1)_R\, (b_1)_{T_i} \frac{\bar{\not{n}}}{2}$$



$$= v(q_{1\perp})\, f^{abc_1}\, (c_1)_{T_i}\, g_\perp^{\mu\nu}\, \bar{n}\cdot p$$

Medium corrections to splitting functions

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



$$
\left(\frac{dN^{\rm med}}{dx\,d^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2} - \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right) \right.
$$
$$
\times \left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)
$$
$$
+ \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2} - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)\left(1-\cos[\Omega_4\Delta z]\right)
$$
$$
\left. - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\left(1-\cos[\Omega_5\Delta z]\right) + \frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2} - \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\right].
$$

Massless partons: Ovanesyan and Vitev 2011

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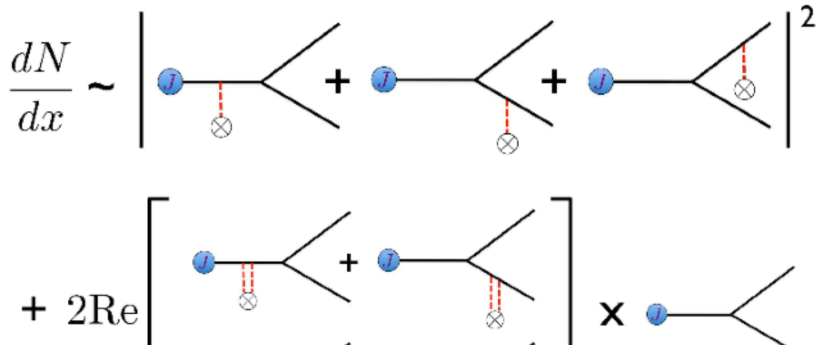

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$$\times\,(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])$$

$$+\,\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z]) + \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)(1-\cos[\Omega_4\Delta z])$$

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$$\times\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.$$

$$\left.-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])$$

$$+\,\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])$$

$$+\,\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\Bigg]$$

$$+\,x^3m^2\left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\ldots\right]\Bigg\}$$

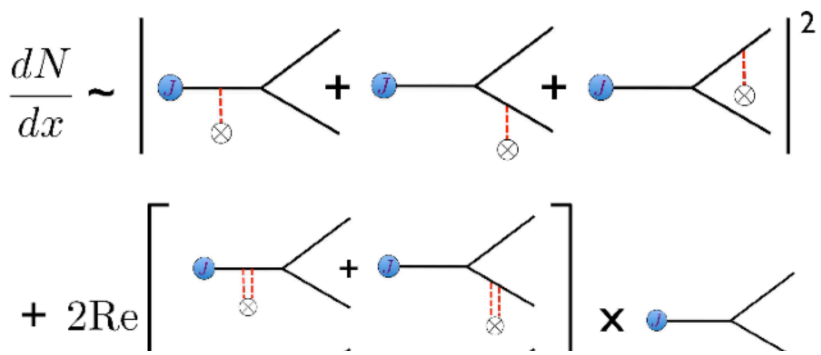
$$\nu = x\,m \qquad (Q\to Qg)\,,$$
$$\nu = (1-x)\,m \qquad (Q\to gQ)\,,$$
$$\nu = m \qquad (g\to Q\bar{Q})\,,$$

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

Massive partons: Kang et al 2016

Medium corrections to splitting functions

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



$$\left(\frac{dN^{\rm med}}{dx\, d^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x}\int \frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\mathbf{q}_\perp}\left[\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2}\cdot\left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2}-\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2}\right)\right.$$

$$\times\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right) + \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2}\cdot\left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2}-\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)$$

$$+\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2}\cdot\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right) + \frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2}\cdot\left(\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2}\right)\left(1-\cos[\Omega_4\Delta z]\right)$$

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$$\times\left(\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}-\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right) + \frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\cdot\left(2\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\right.$$

$$\left.-\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right) + \frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\frac{\mathbf{C}_\perp}{\mathbf{C}_\perp^2+\nu^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right)$$

$$+\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2}-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\right)\left(1-\cos[\Omega_4\Delta z]\right)-\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}\cdot\frac{\mathbf{D}_\perp}{\mathbf{D}_\perp^2+\nu^2}\left(1-\cos[\Omega_5\Delta z]\right)$$

$$\left.+\frac{1}{N_c^2}\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{\mathbf{A}_\perp}{\mathbf{A}_\perp^2+\nu^2}-\frac{\mathbf{B}_\perp}{\mathbf{B}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\right]$$

$$\left.+x^3m^2\left[\frac{1}{\mathbf{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\mathbf{B}_\perp^2+\nu^2}-\frac{1}{\mathbf{C}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)+\ldots\right]\right\}$$

$$\nu = x\, m \qquad (Q\to Qg)\,,$$
$$\nu = (1-x)\, m \qquad (Q\to gQ)\,,$$
$$\nu = m \qquad (g\to Q\bar{Q})\,,$$

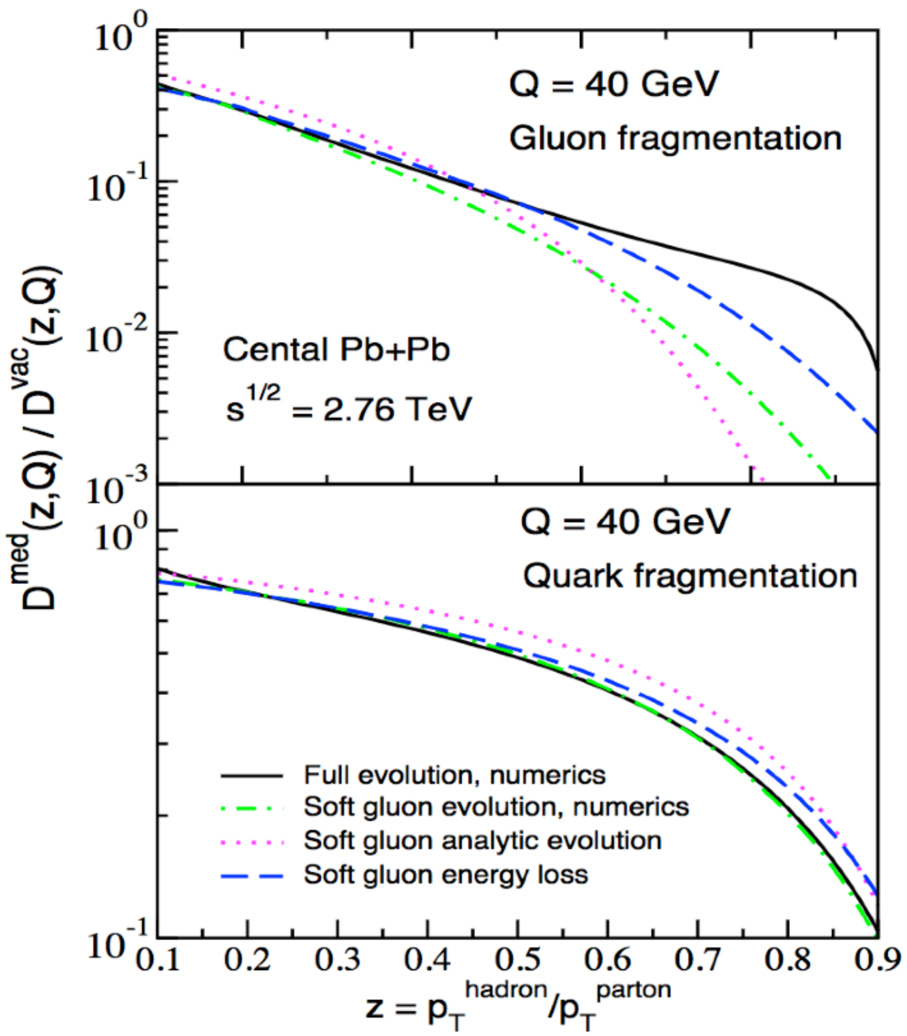
$$\mathbf{A}_\perp=\mathbf{k}_\perp,\ \mathbf{B}_\perp=\mathbf{k}_\perp+x\mathbf{q}_\perp,\ \mathbf{C}_\perp=\mathbf{k}_\perp-(1-x)\mathbf{q}_\perp,\ \mathbf{D}_\perp=\mathbf{k}_\perp-\mathbf{q}_\perp,$$

Massive partons: Kang et al 2016

See Matt Sievert's talk on Sunday for the all opacity results

Applications

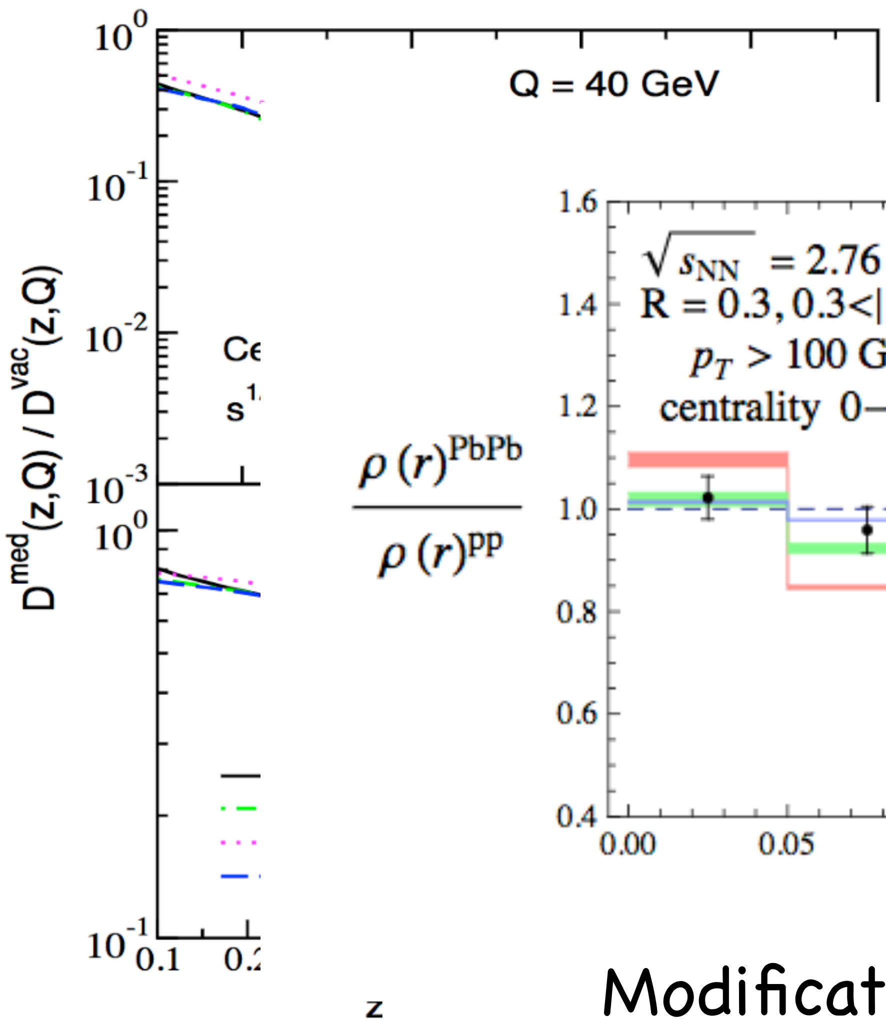
Applications

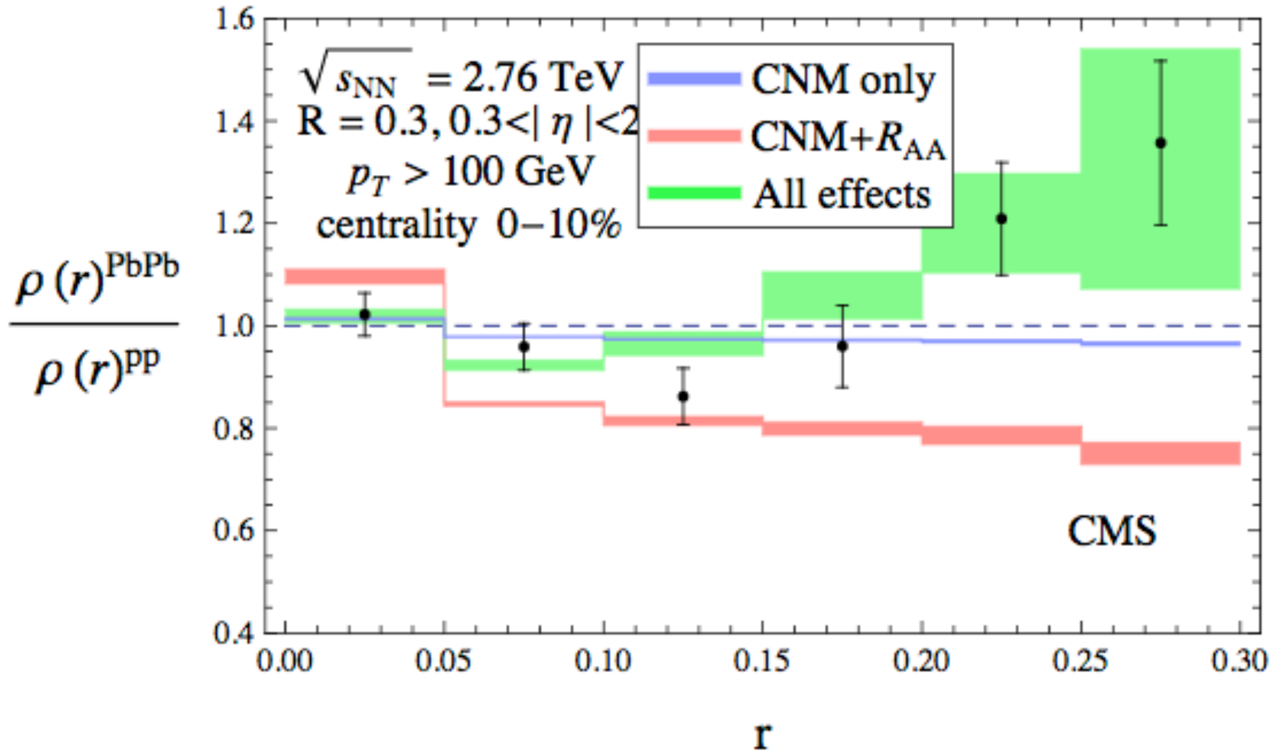


Modification of fragmentation functions for gluon and quark

Kang et al 2014

Applications





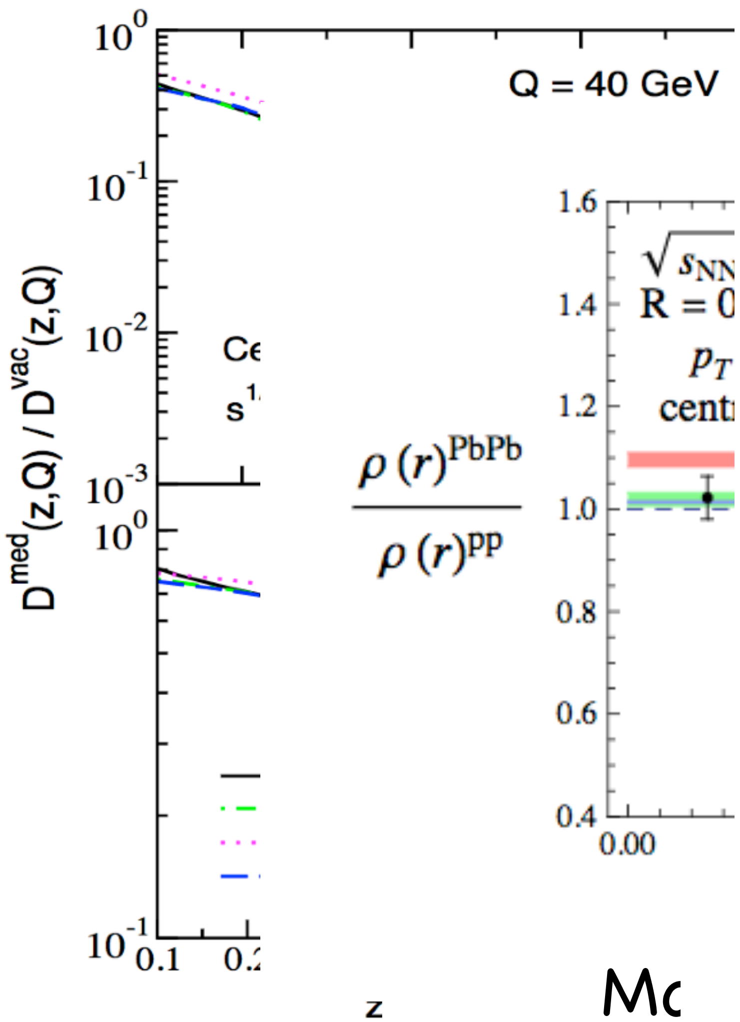
Modification of jet shape

Chien et al 2015

Modification o
functions for g... and quark

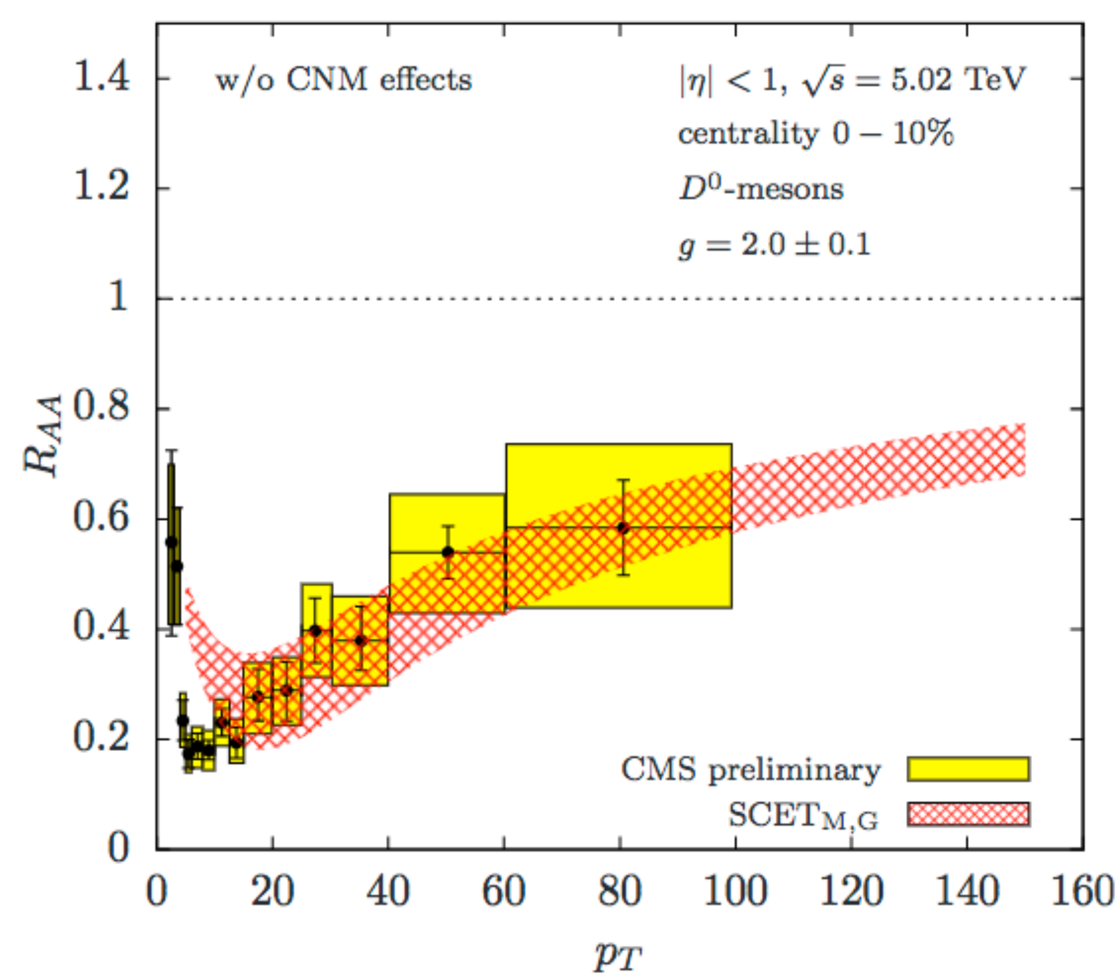
Kang et al 2014

Applications



Modification o
functions for

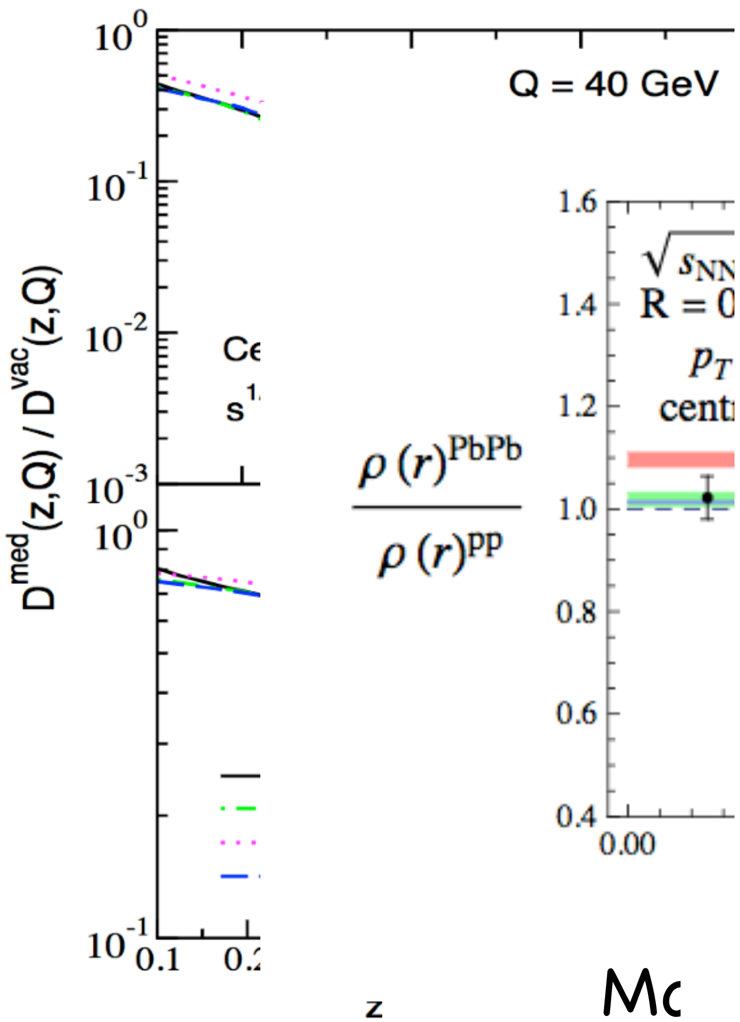
Kang et al 2014

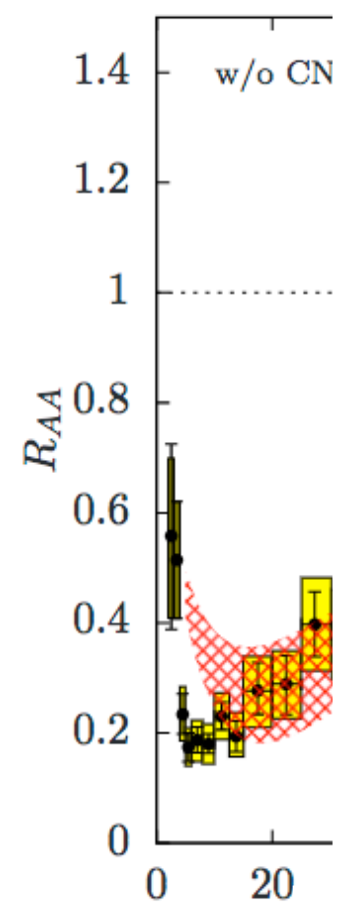


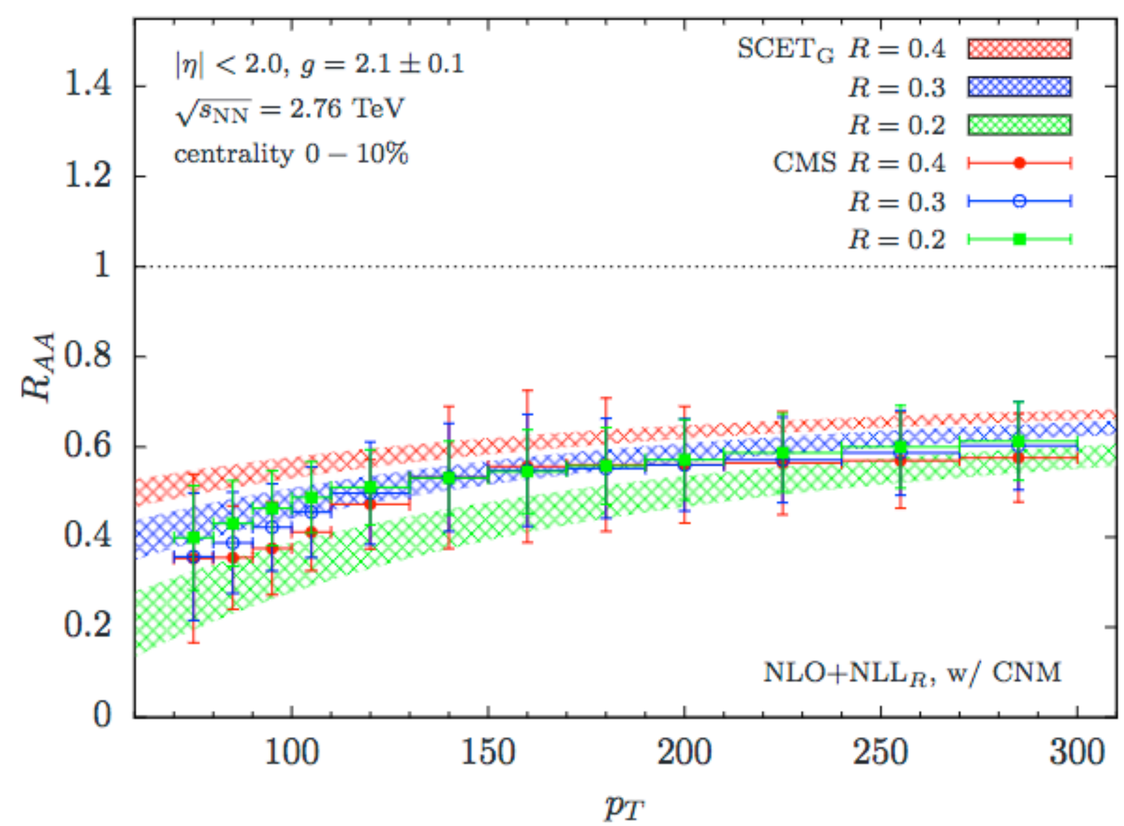
Nuclear modification factor RAA
for D0 meson (massive)

Kang et al 2016

Applications







Modification o
functions for g...

Kang et al 2014

Nuclear
for D0

The nuclear modification factor RAA for heavy-ion collisions at

Kang et al 2017

Resummation formalism

Resummed splitting kernels in the vacuum   Larkoski et al 2015

Resummation formalism

Resummed splitting kernels in the vacuum

Larkoski et al 2015

$\frac{dN_j^{FO}}{dz_g d\theta_g}$ is divergent when $\theta_g \to 0$

Collinear singularities

$\frac{dN_j^{F}}{dz_g}$ is not well-defined at any fixed perturbative order

Resummation formalism

Resummed splitting kernels in the vacuum

Larkoski et al 2015

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but is well defined if we resum logs to all order

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

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

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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 $\begin{matrix} b \to bg \\ c \to cg \end{matrix}$ formula is the similar with massless quark

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

For $\begin{matrix} g \to b\bar{b} \\ g \to c\bar{c} \end{matrix}$ the resumed distribution is

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

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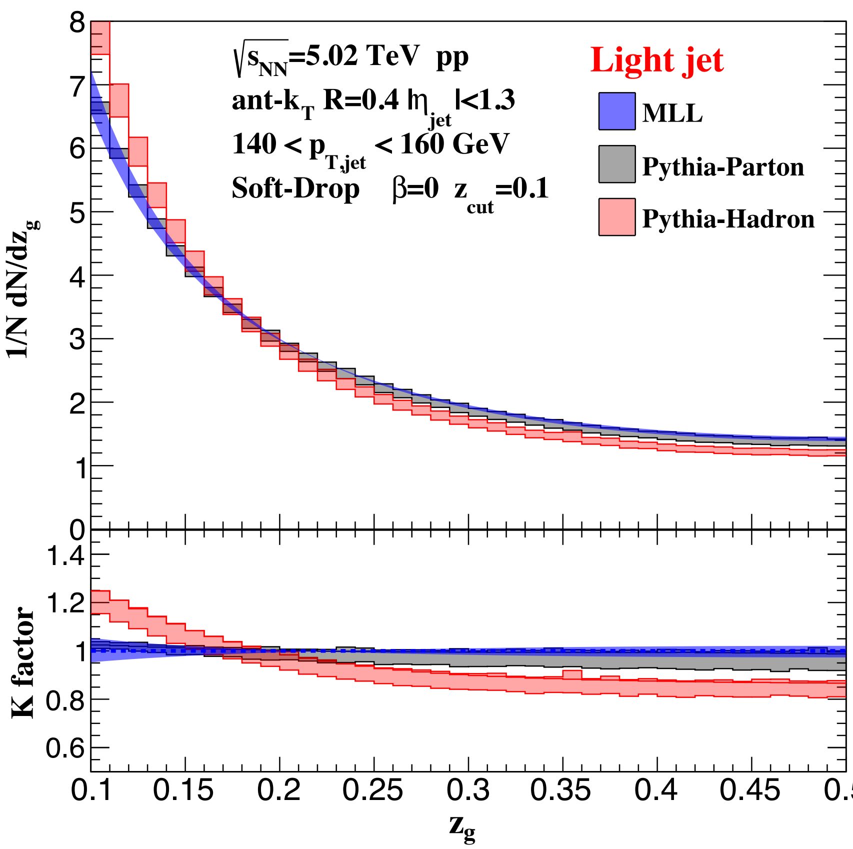
Exponentiate all the possible contributions for gluon evolution

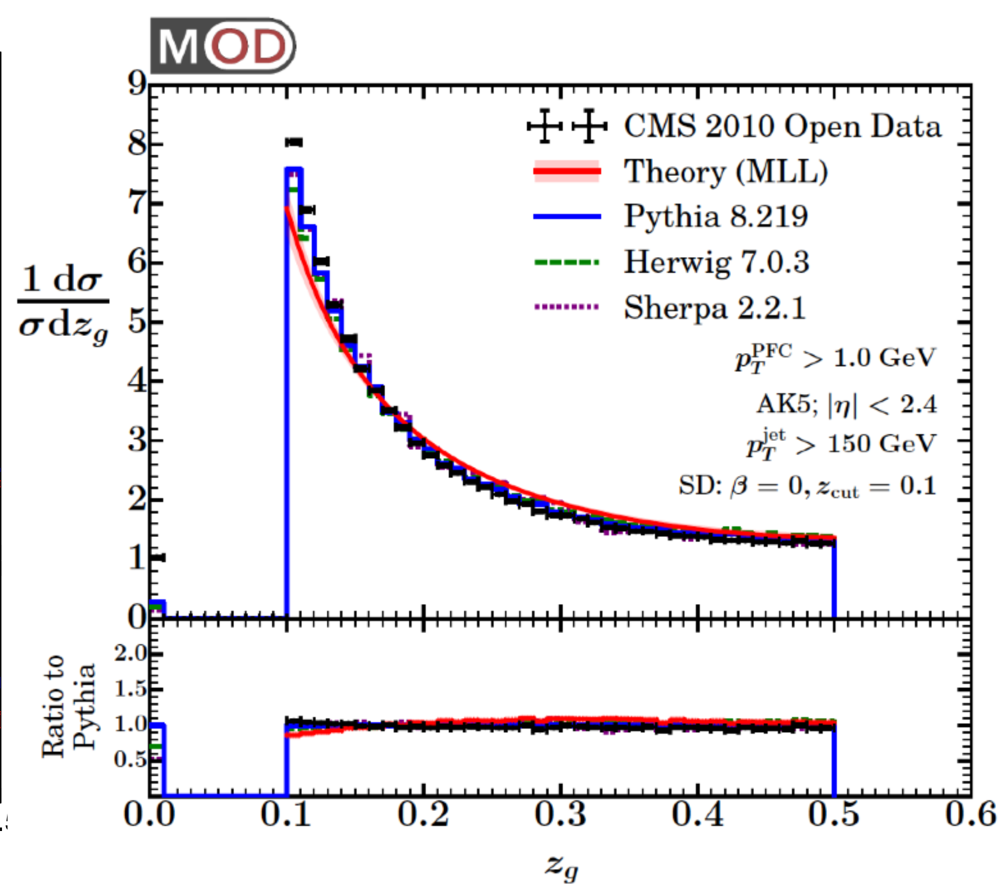
Resummation changes the distribution a lot compared to LO results

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

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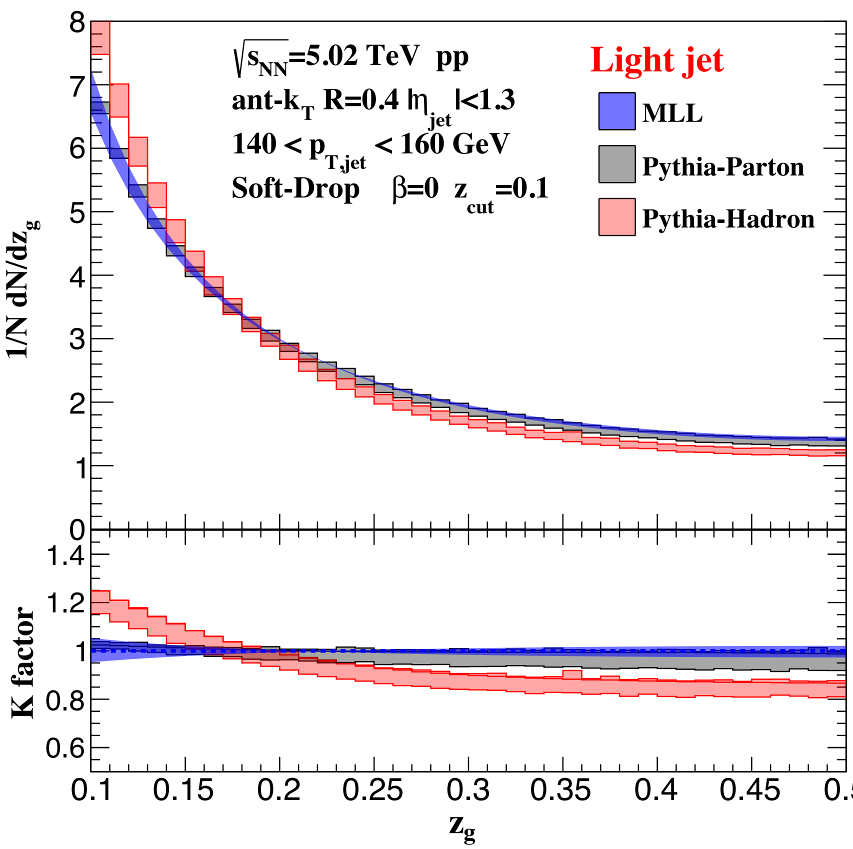

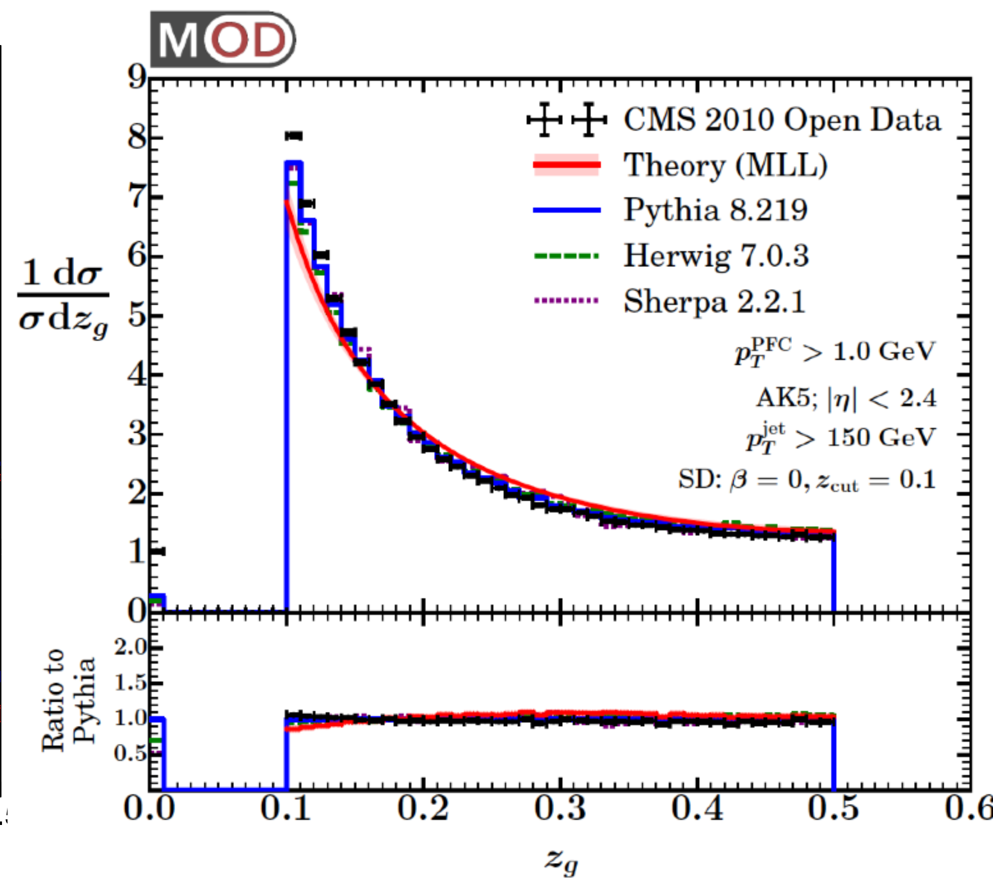

Tripathee, et al 2017

- MLL is less steep than Pythia with hadronization
- Our results are consistent with the ones from literature

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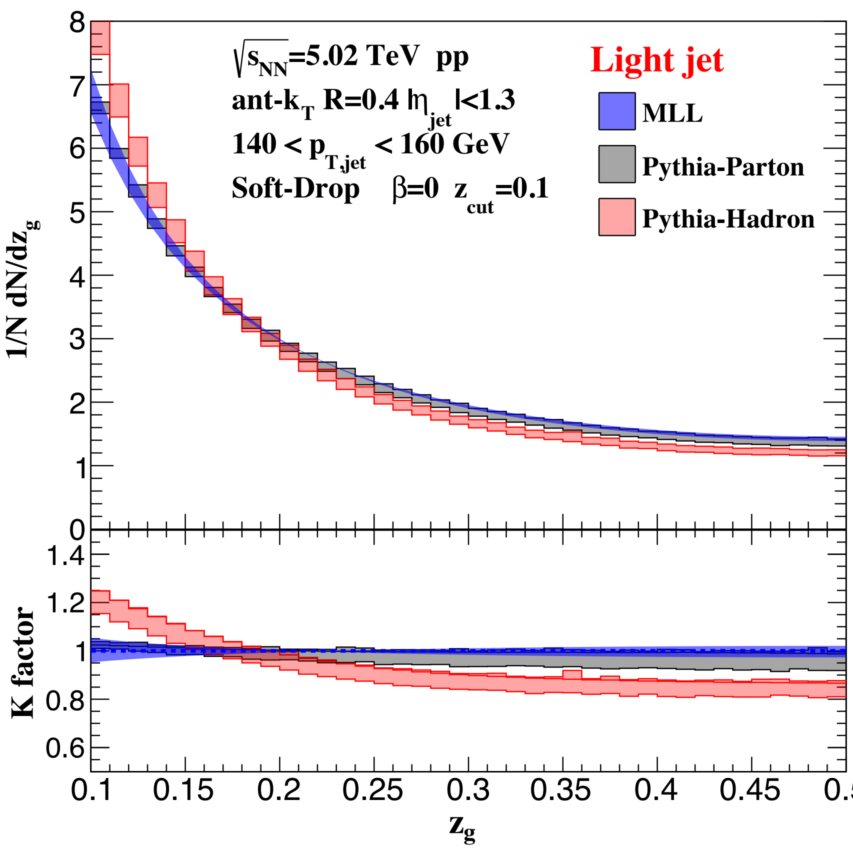

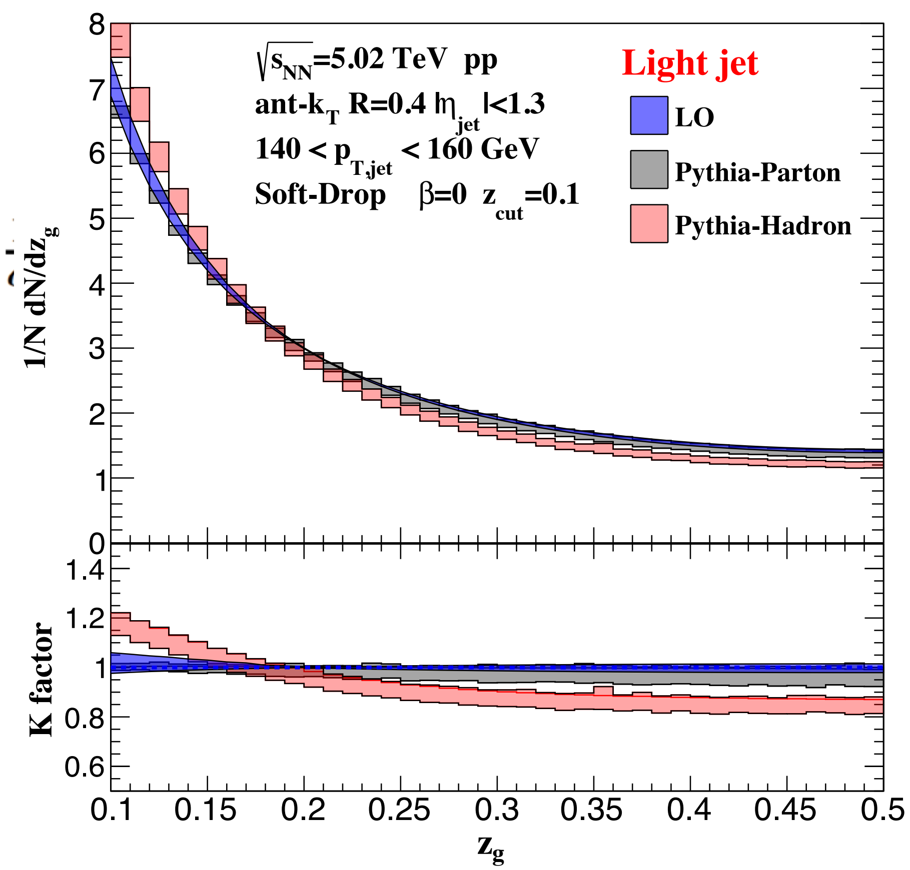

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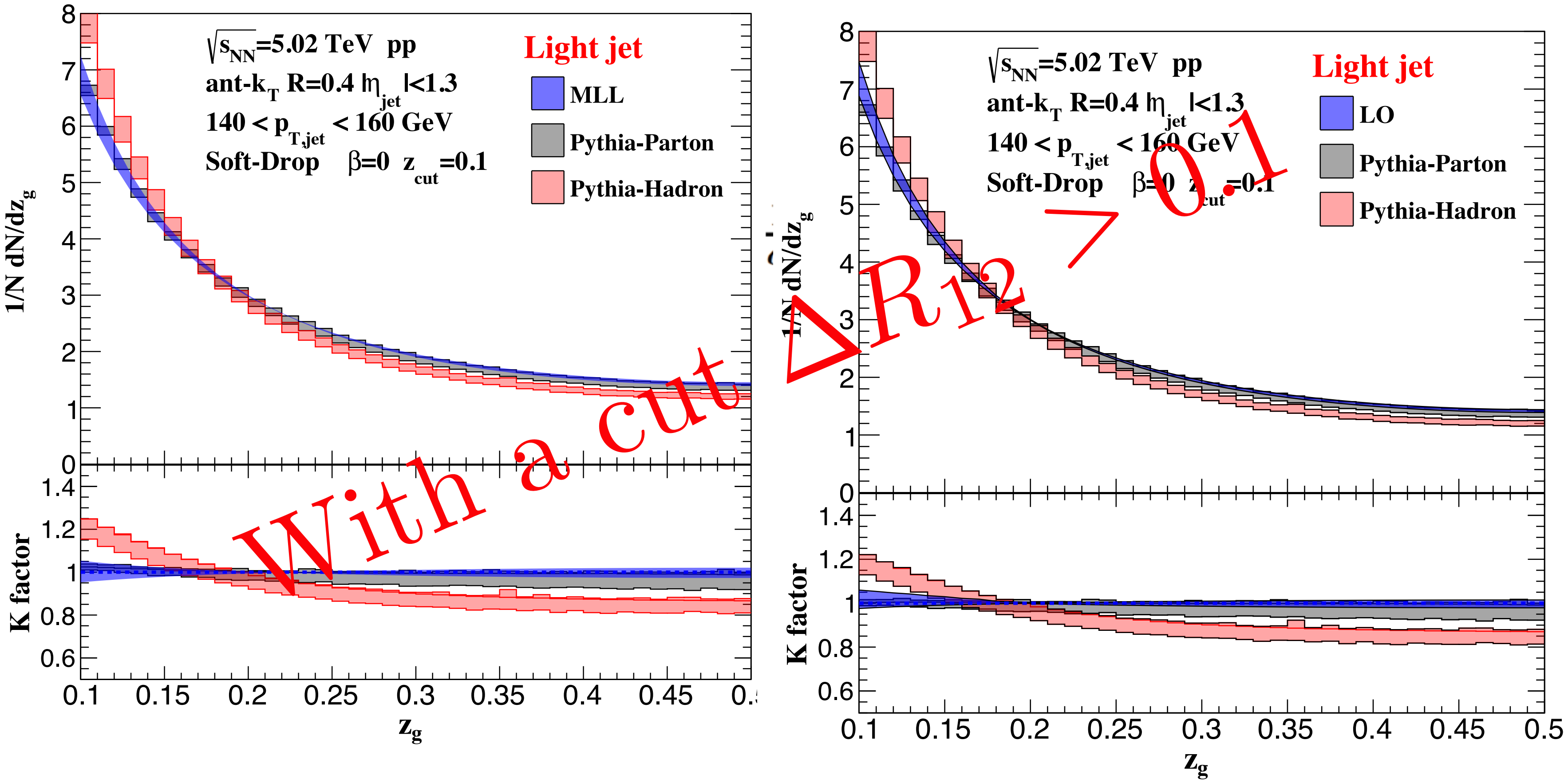

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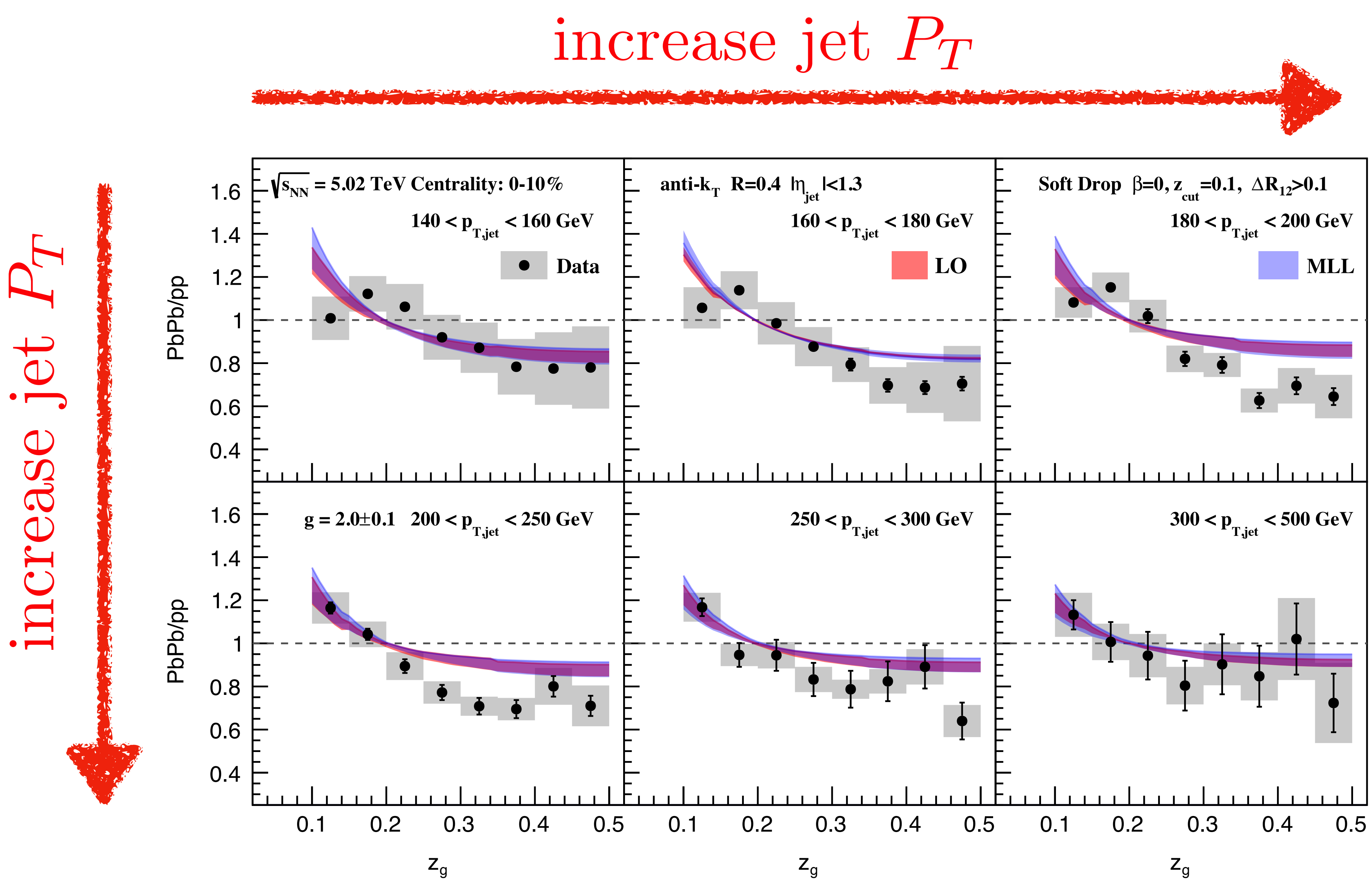
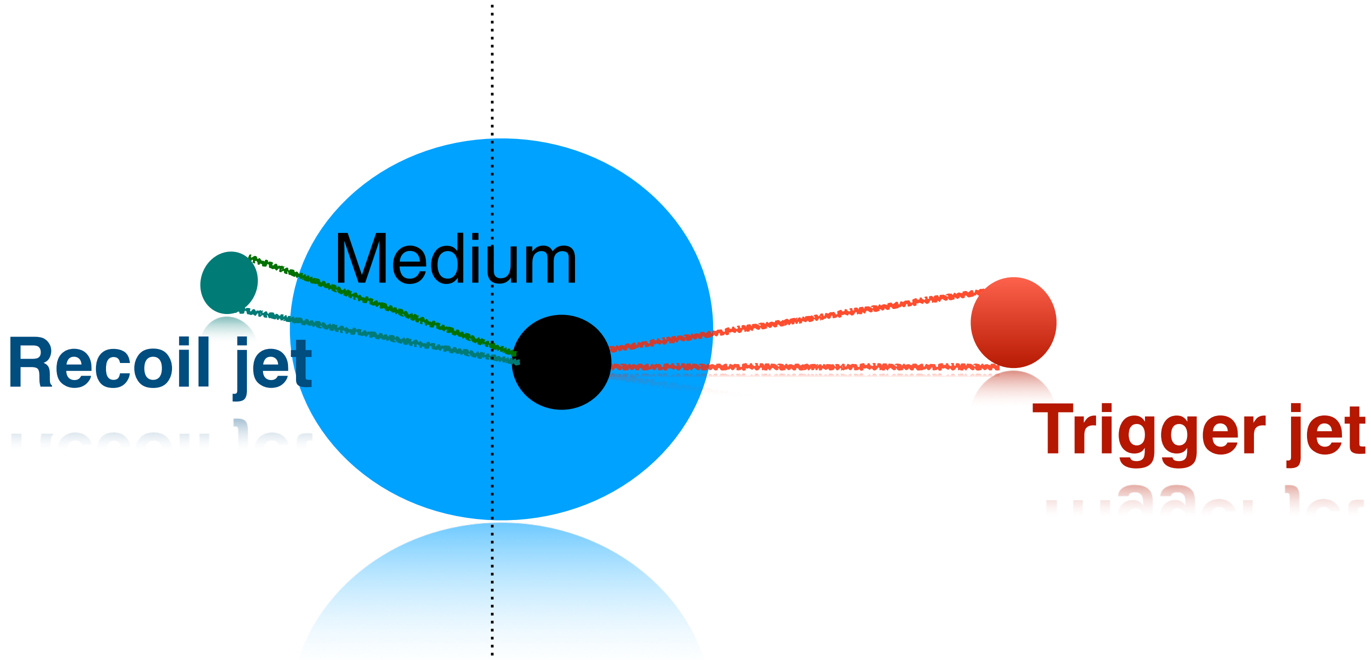
Results for light jet

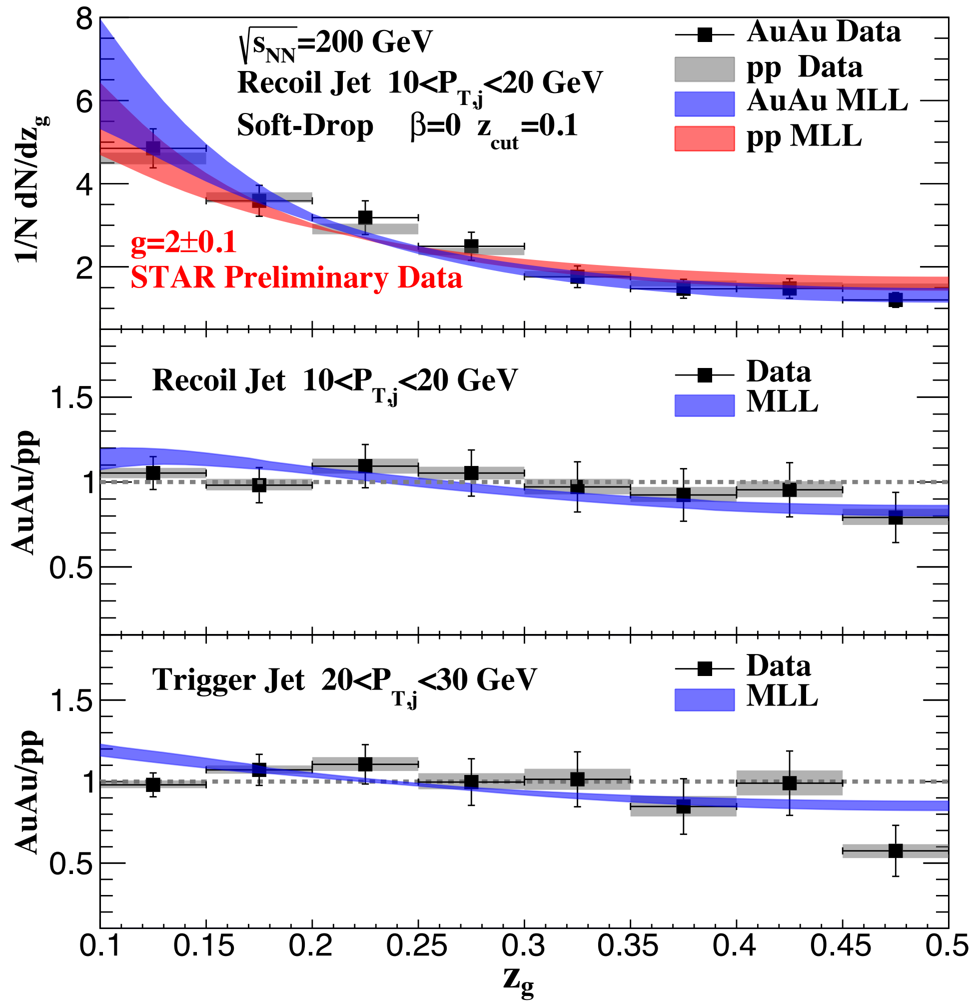


- The splitting function in the medium becomes steeper
- MLL changes the modification by a few percent
- The modification is larger for small jet P_T
- The theoretical predictions are consistent with the measurements

Results for light jet

Modification at the RHIC



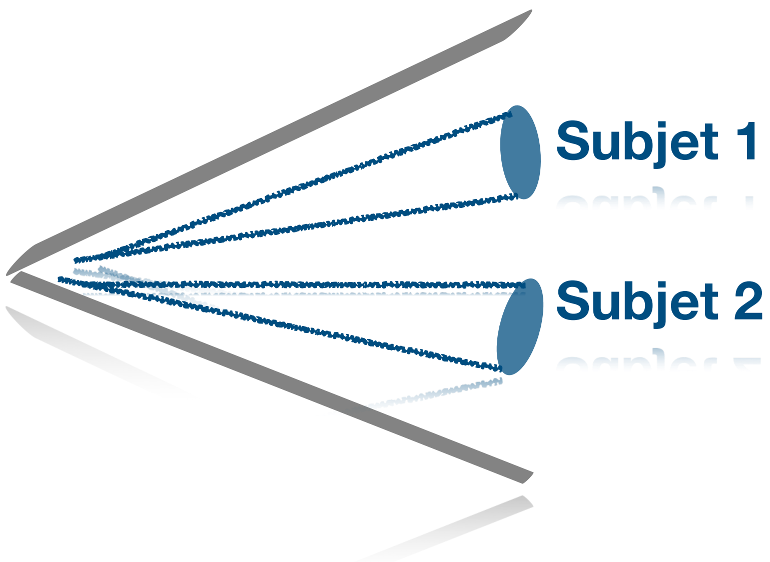


In general the path for recoil jet in the medium is longer than the one for trigger jet.

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)

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

see the work for details: Ilten et al 2017

Results for heavy flavor tagged jet

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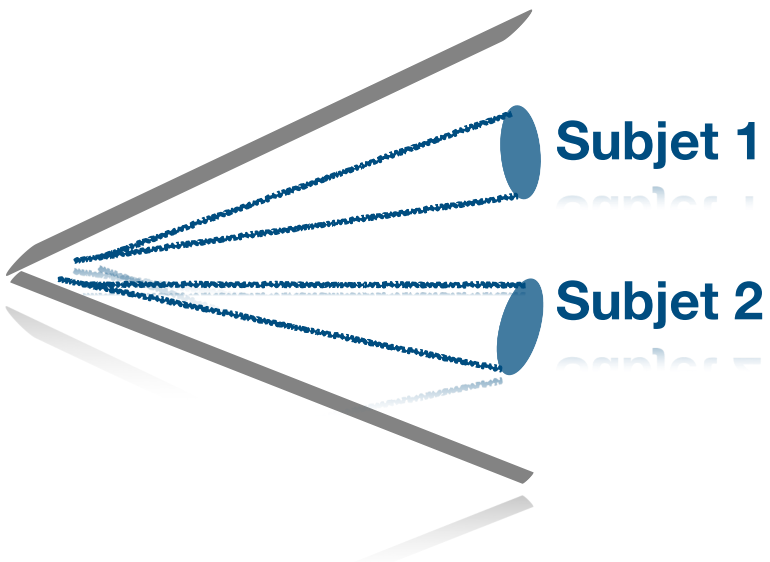

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- If there is no b-quark or b-hadron

$$(n_1^c, n_2^c) = \begin{cases} (1,0) \text{ or } (0,1) & c \to cg \\ (1,1) & g \to c\bar{c} \end{cases}$$

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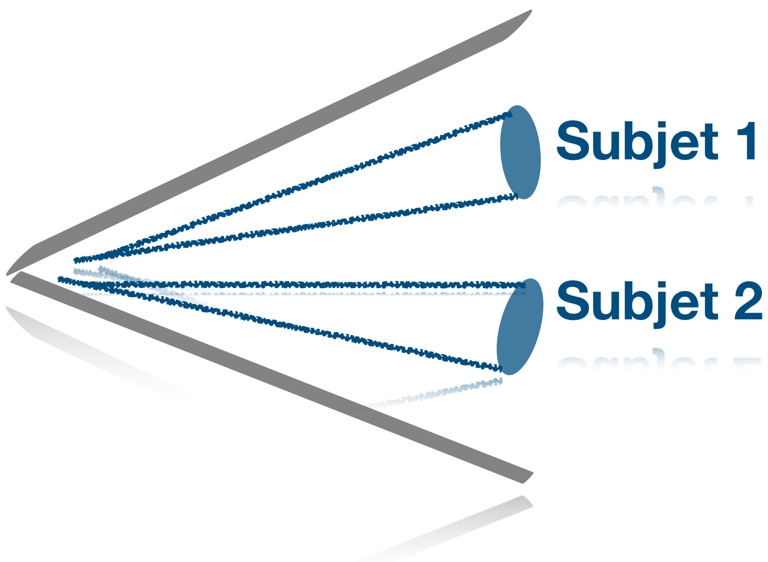

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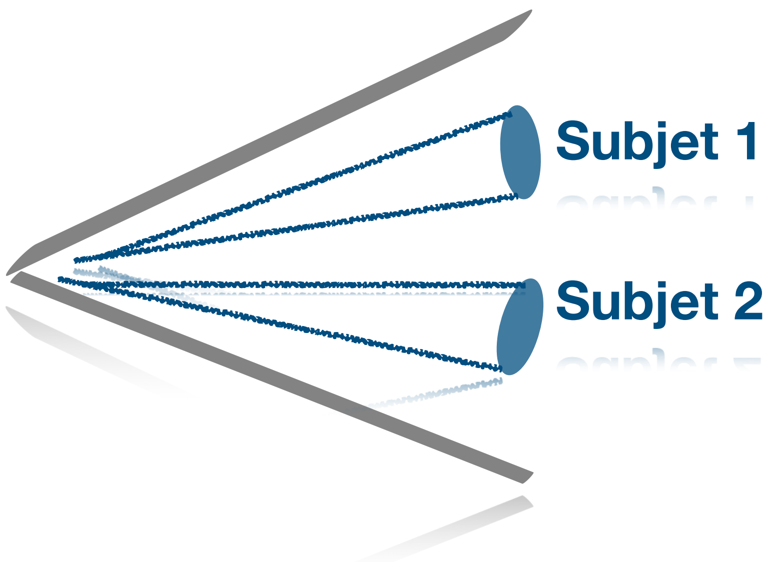

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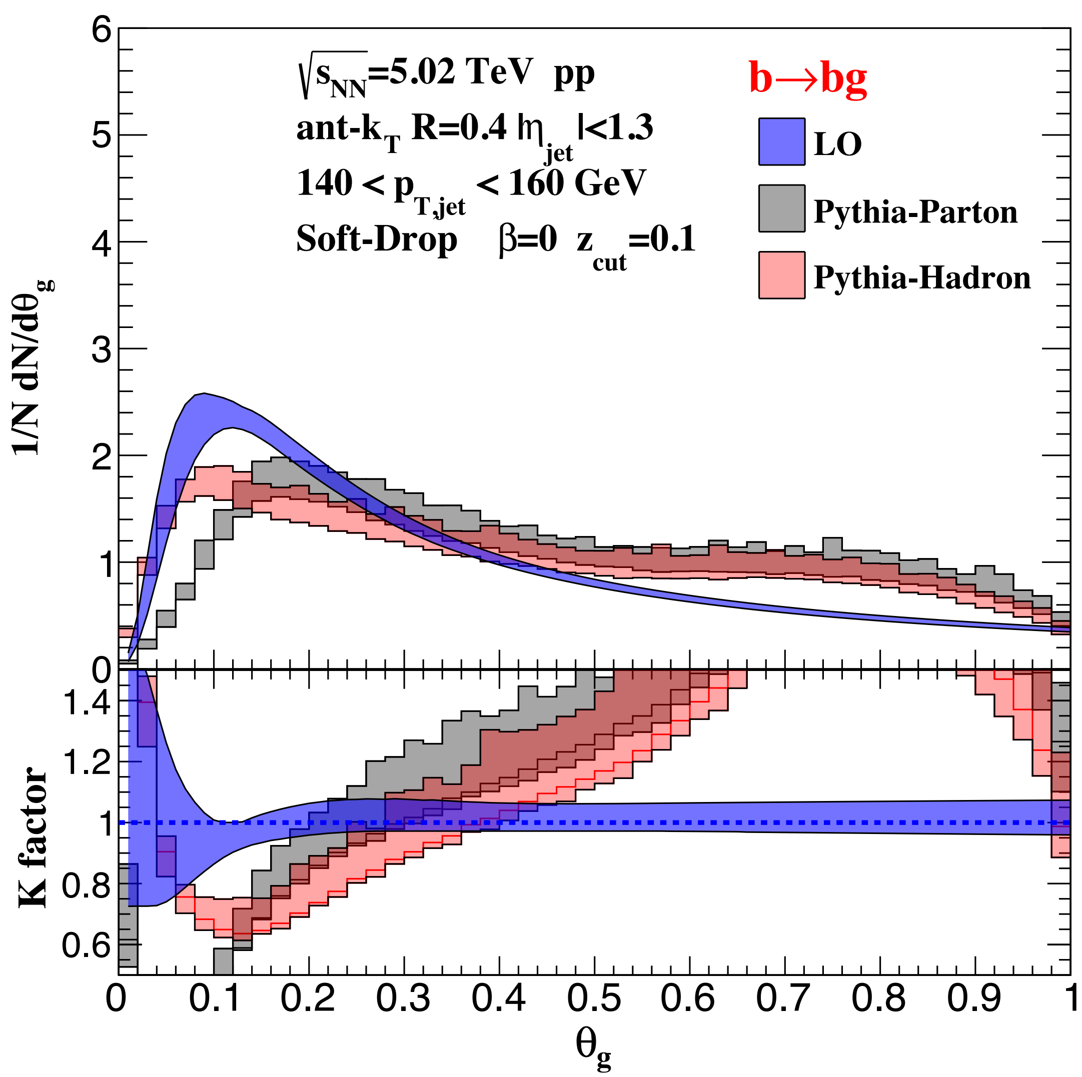
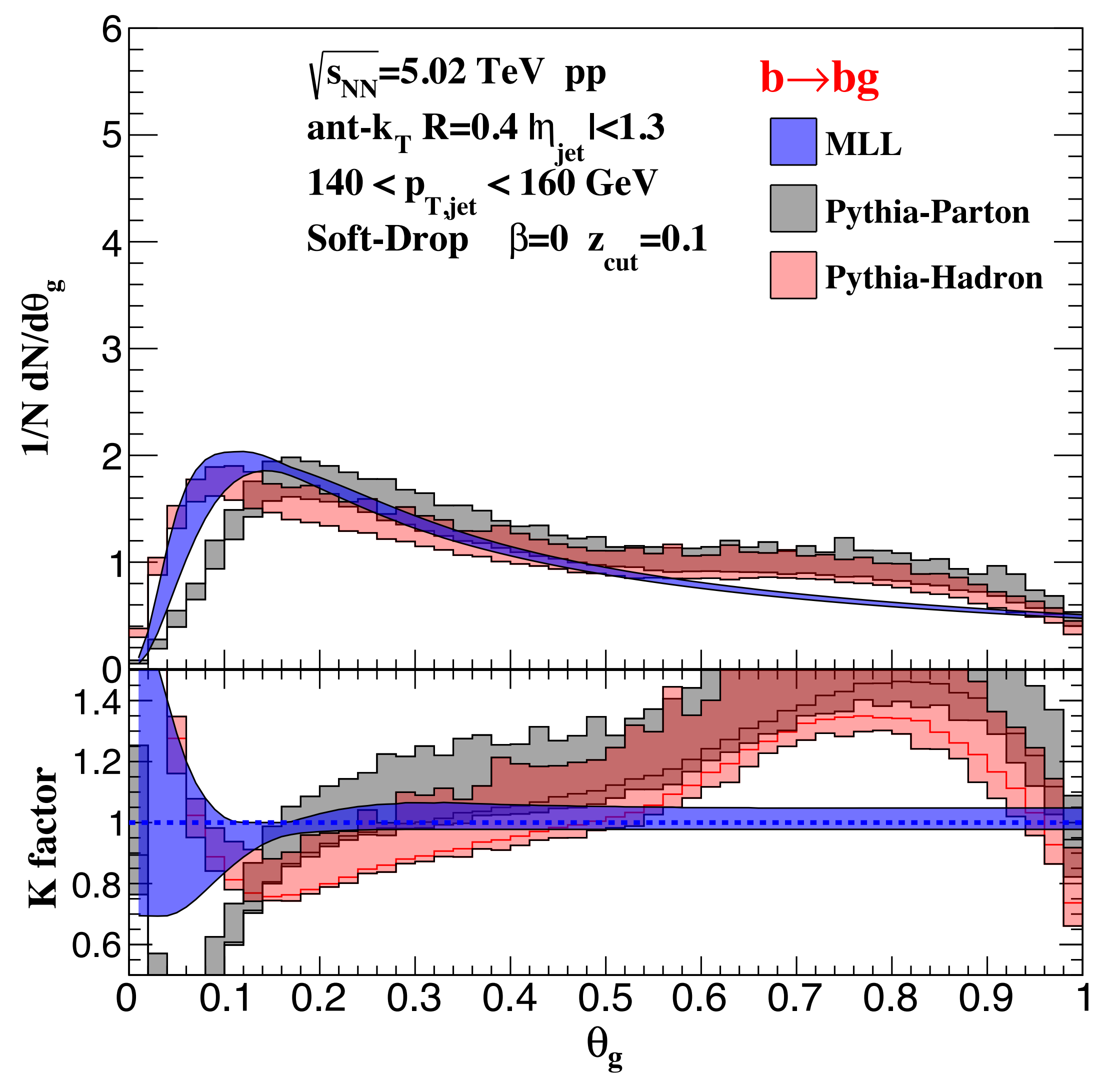
The other cases are ignored in the analysis during comparing with Pythia

Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet

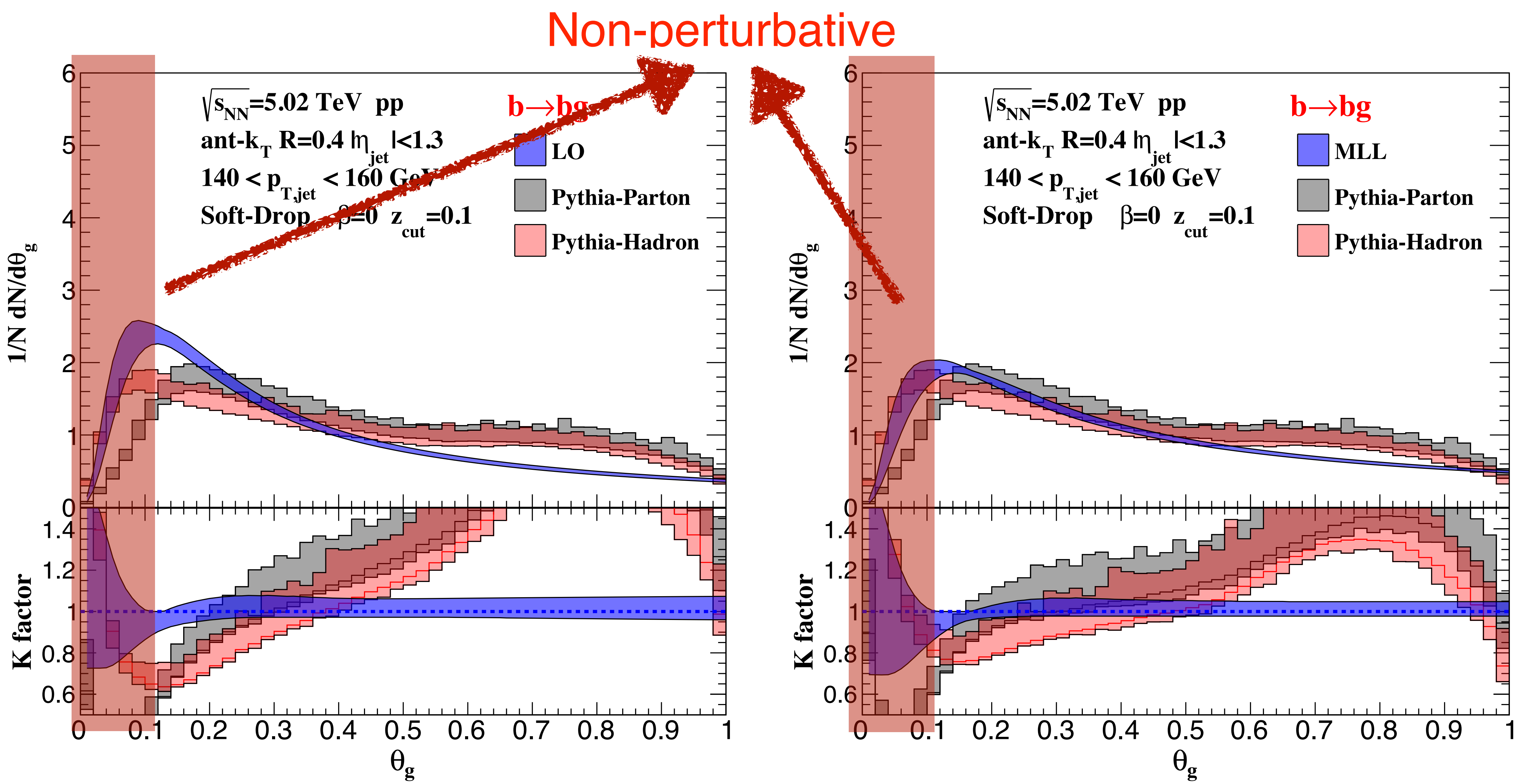




The splitting kernel $C_F \frac{\alpha_s}{\pi^2} \frac{1}{\boldsymbol{k}_\perp^2 + x^2 m^2}$ is zero after integration when k_T is zero

Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet



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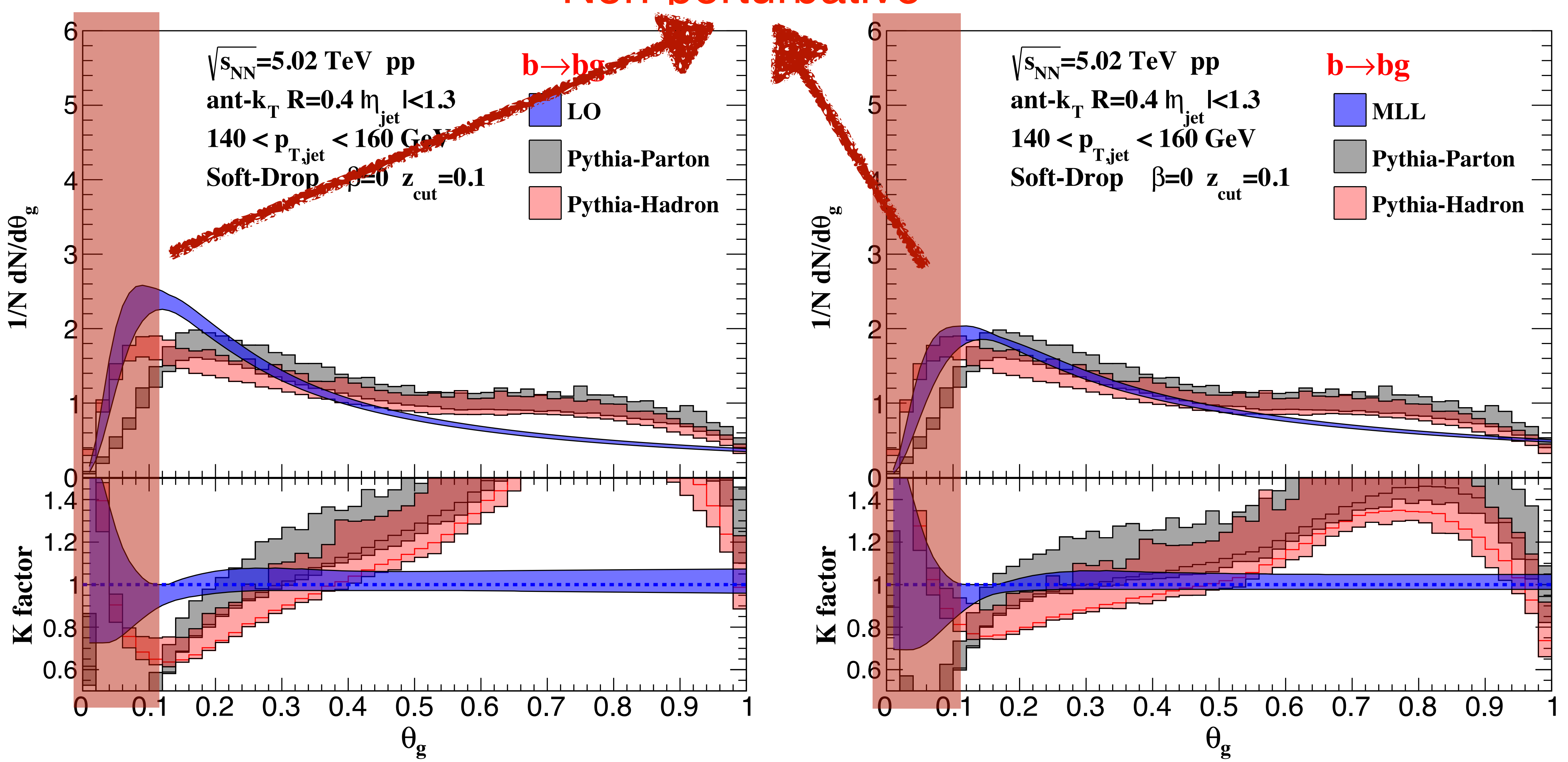
Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet

Non-perturbative



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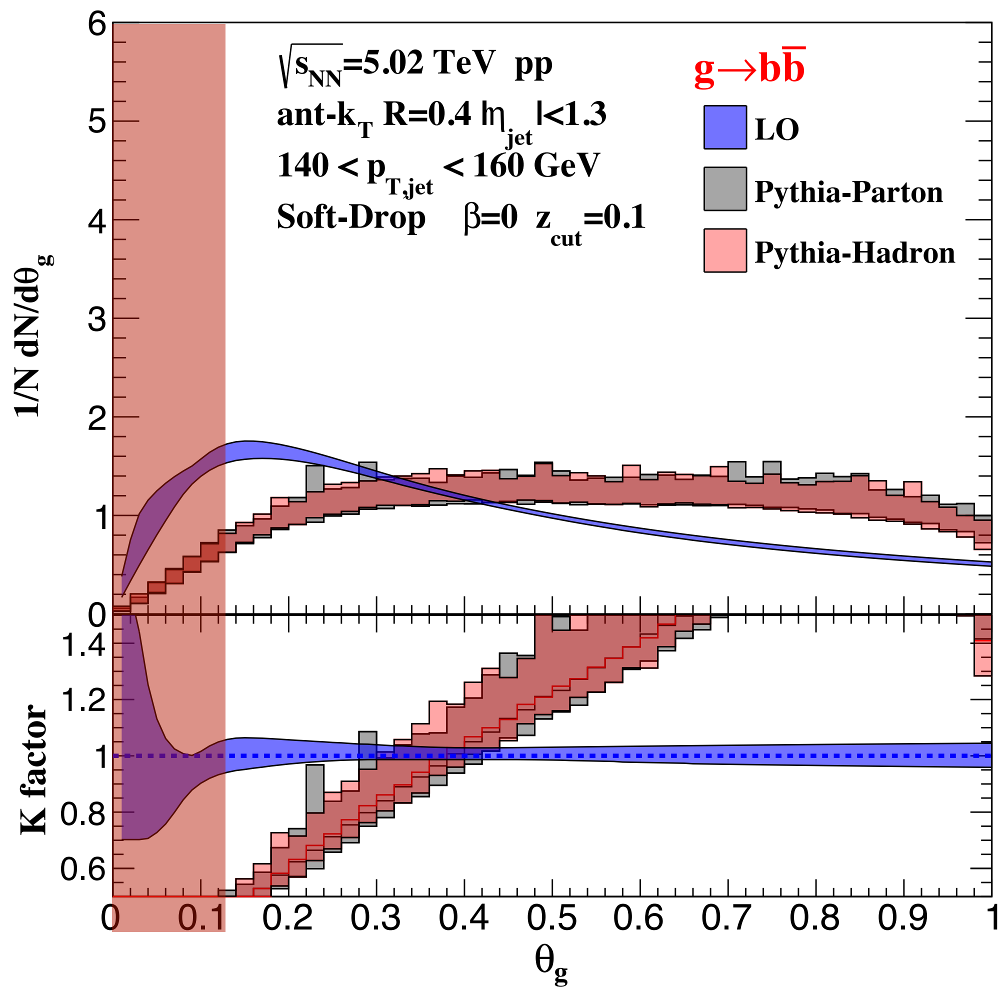
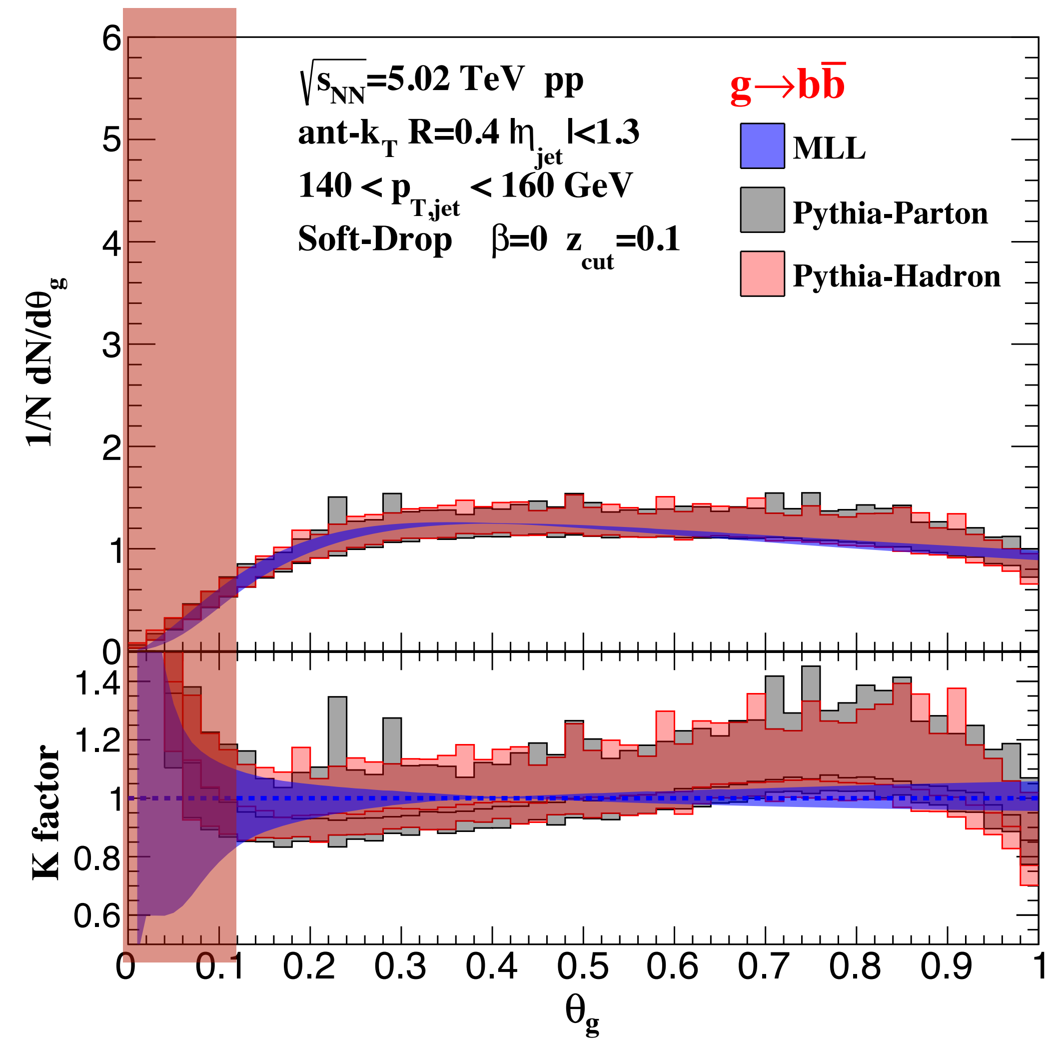
Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged subjets



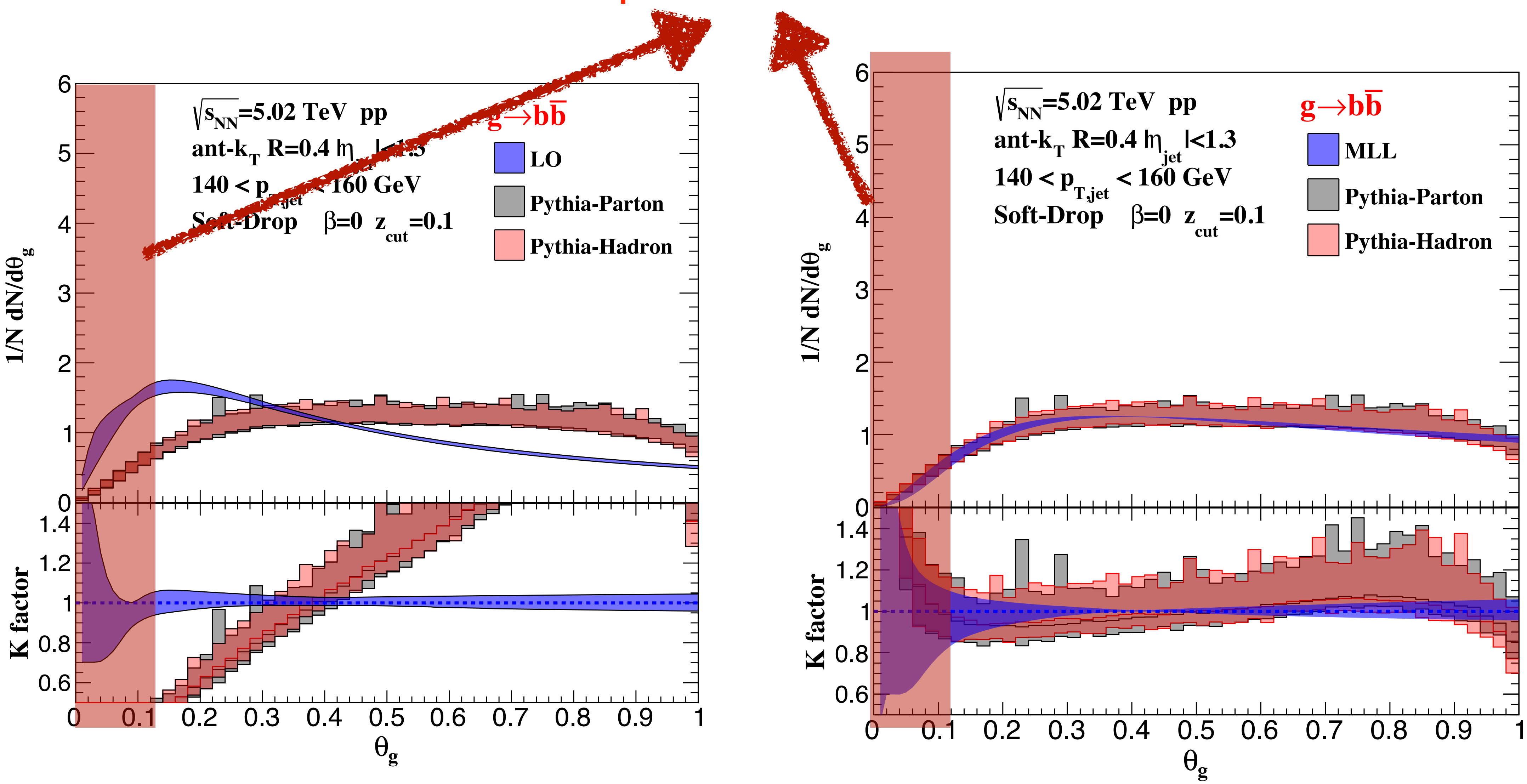


- Huge Sudakov suppression in the small angle region
- Wide-angle gluon splittings

Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged subjets

Non-perturbative corrections



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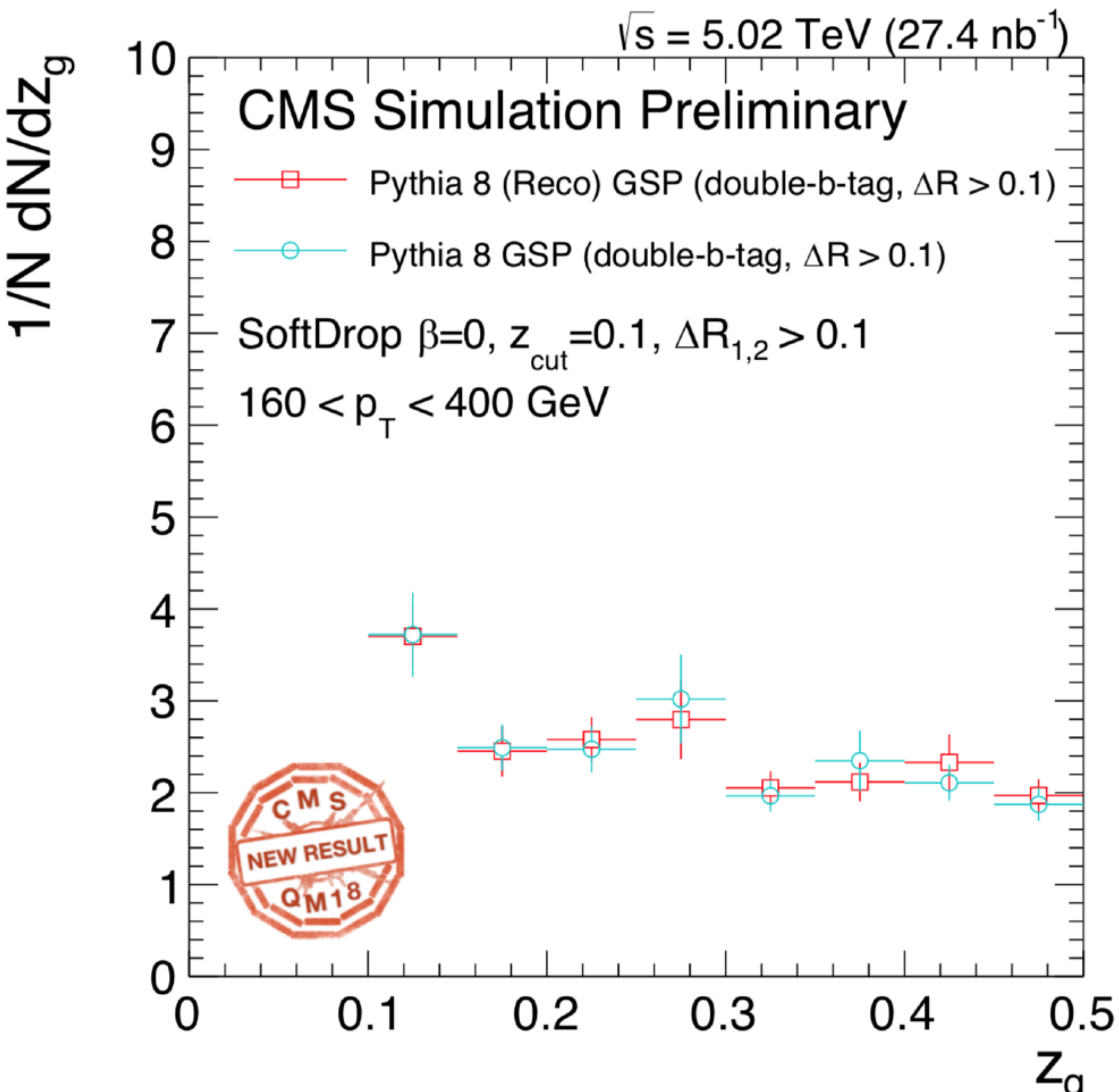
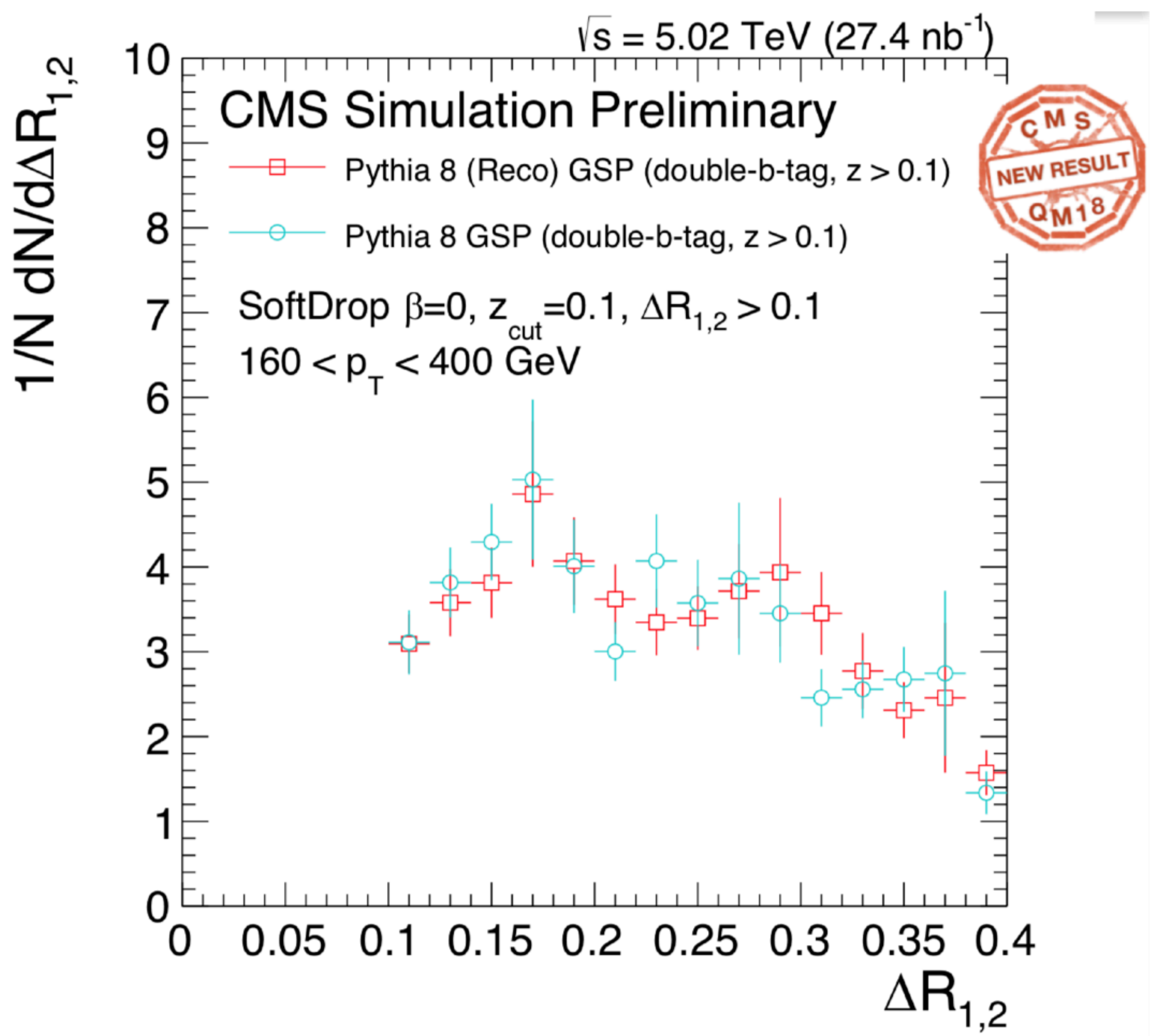
Future Measurement

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





Figures from Slides by Kurt Jung at Quark matter 2018

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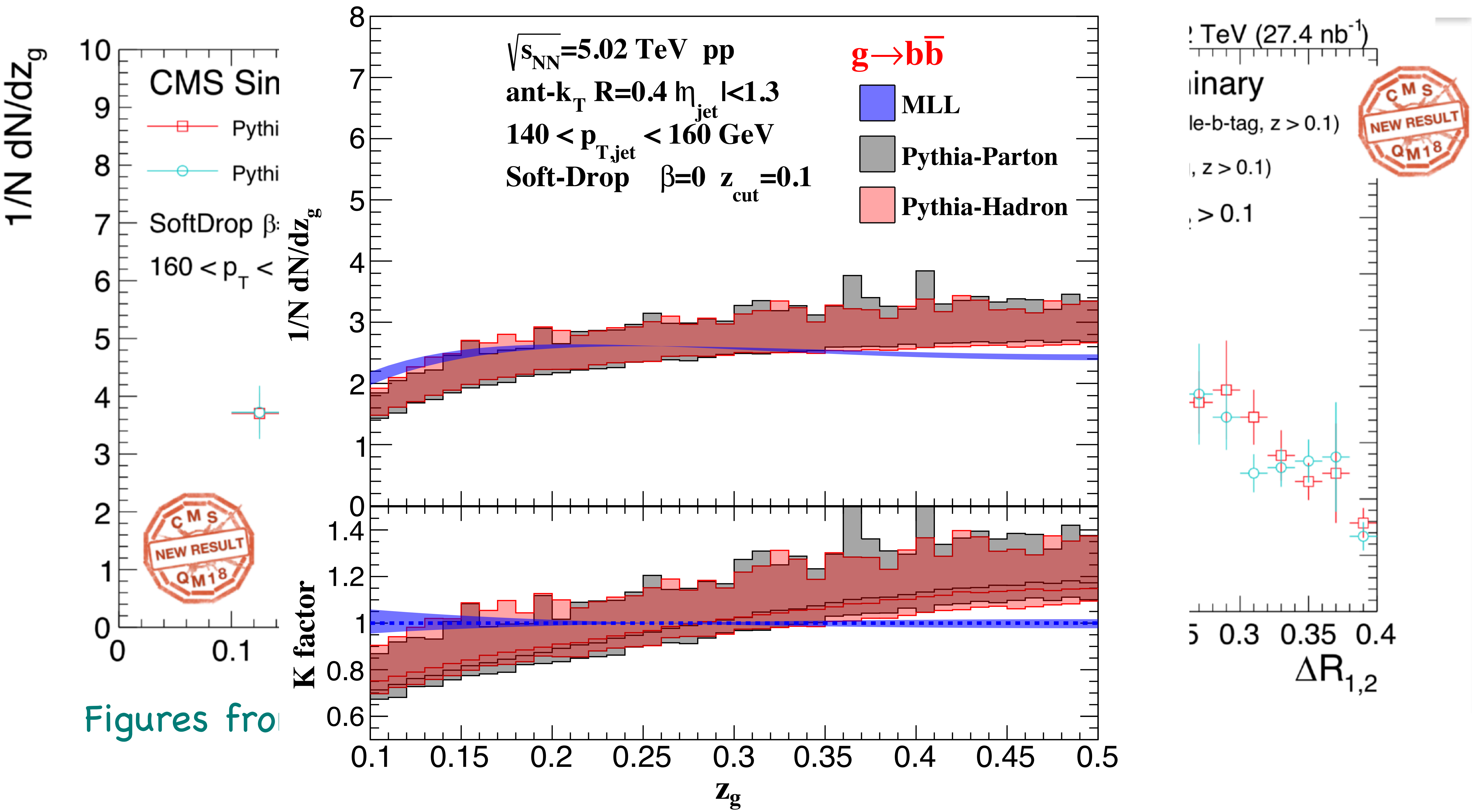
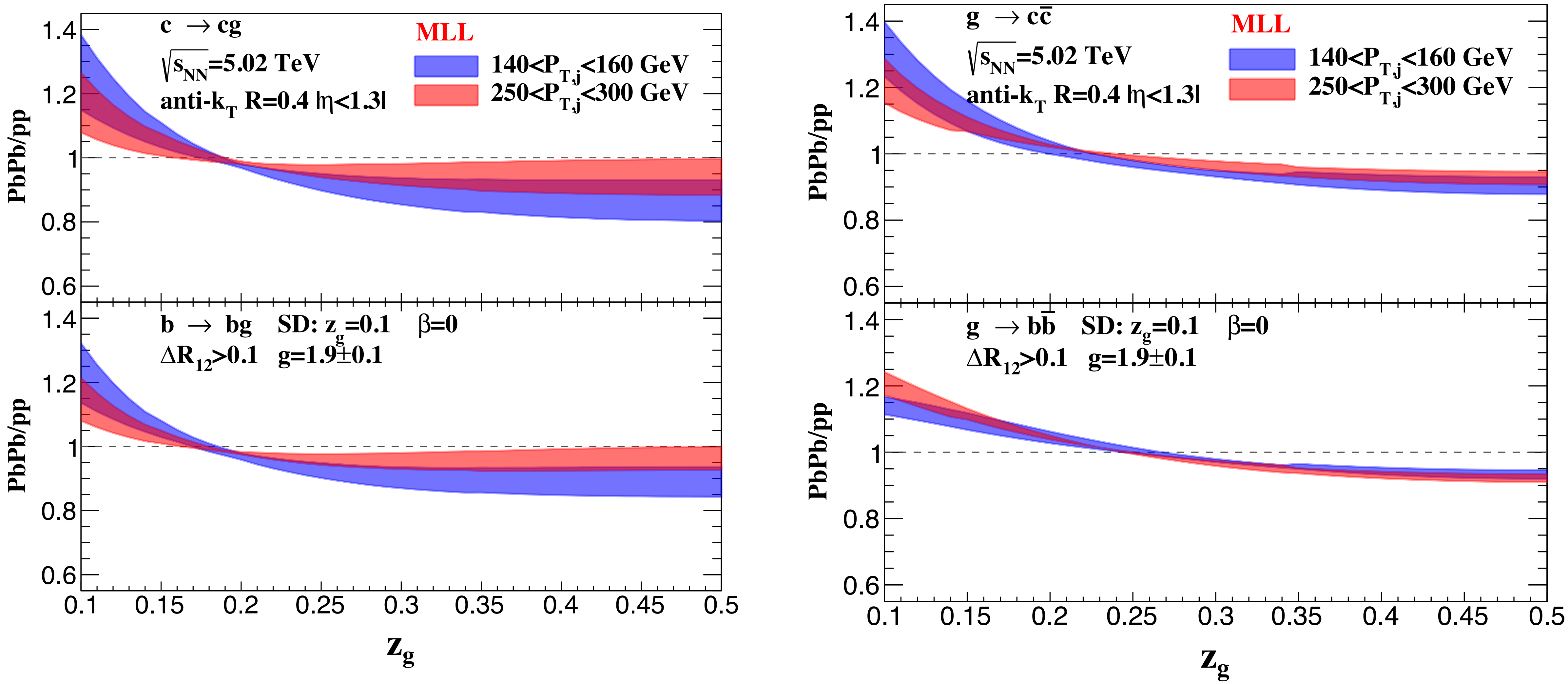
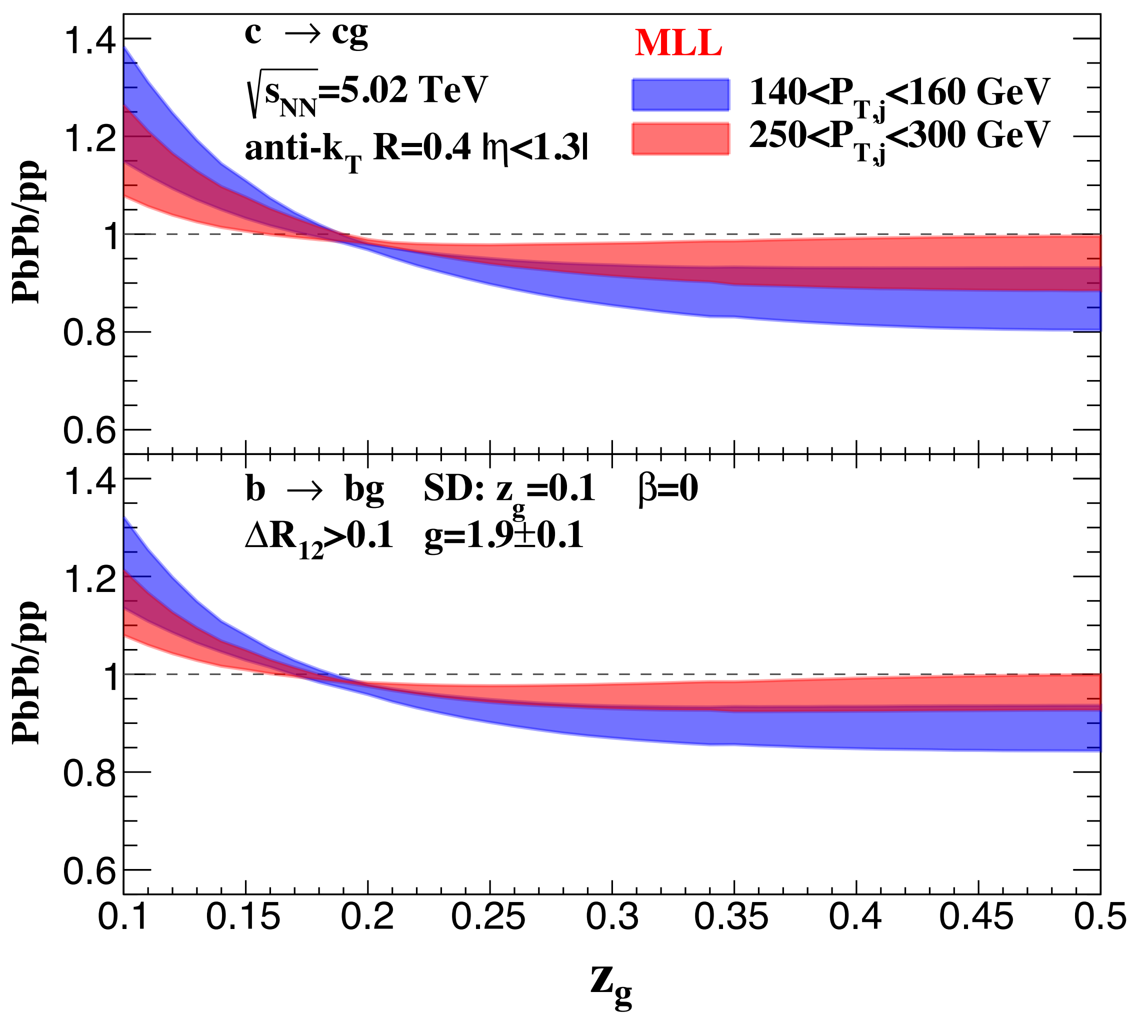
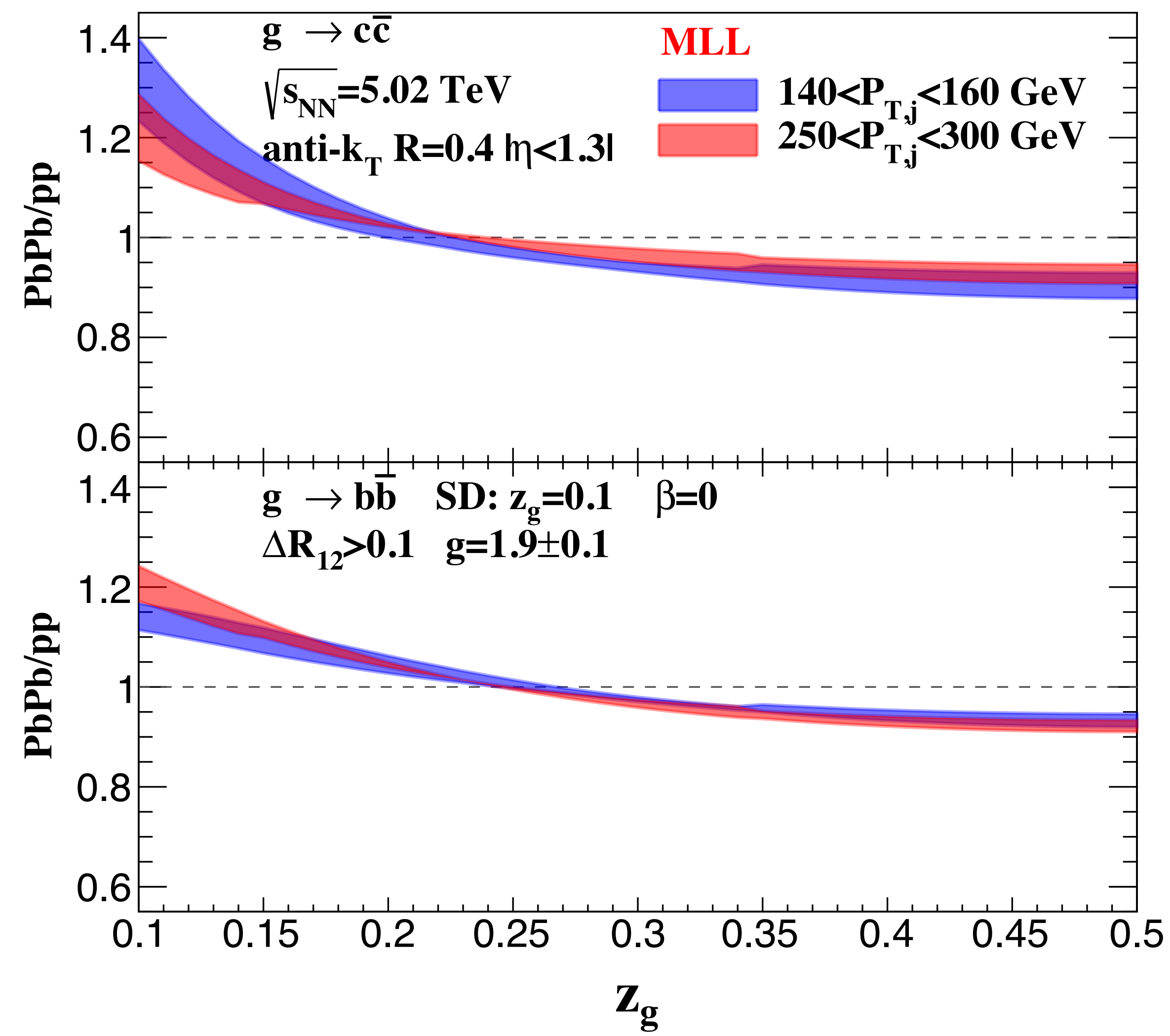


Results for heavy flavor tagged jet



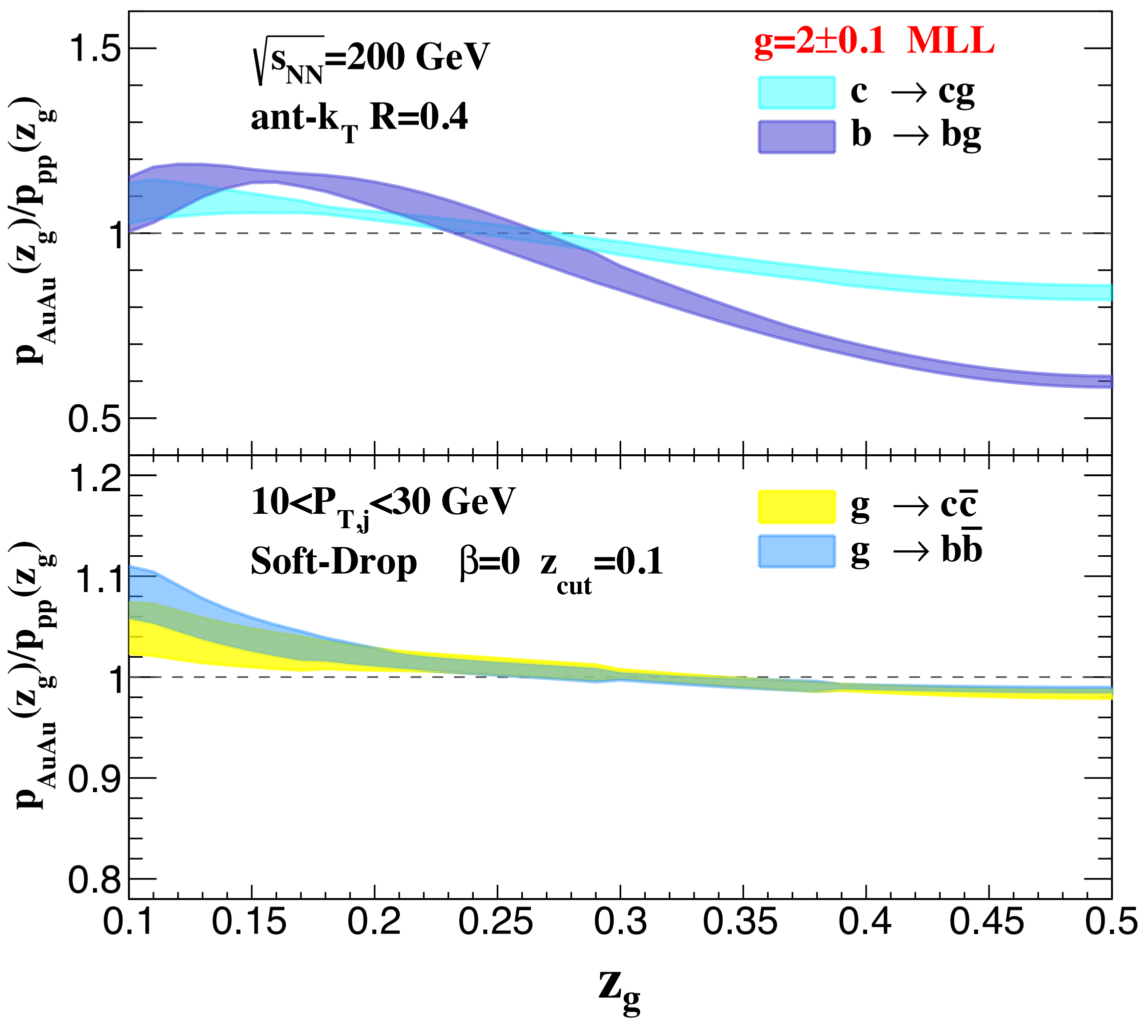
Results for heavy flavor tagged jet





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



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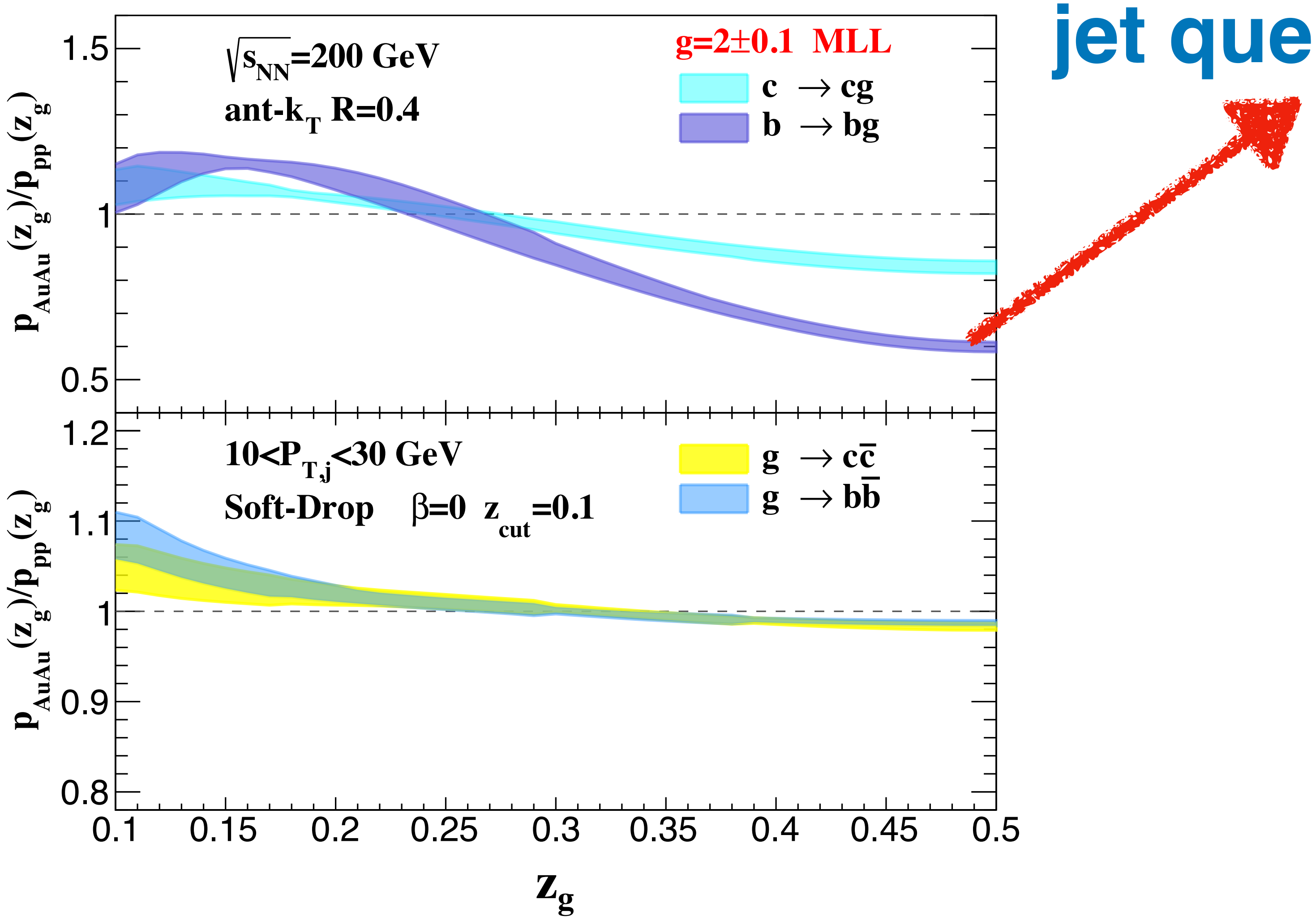
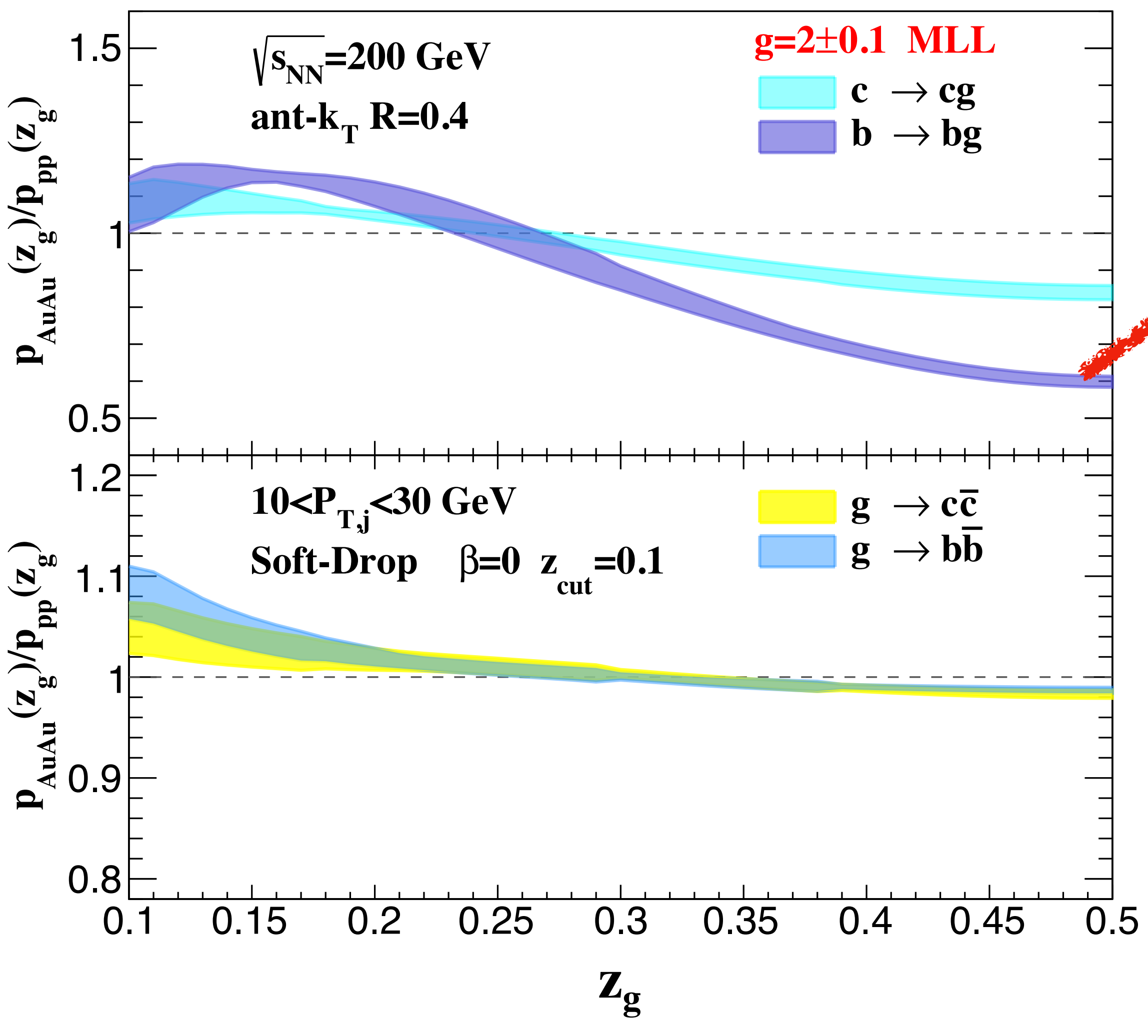


Inverting the mass hierarchy in jet quenching effects

Results for heavy flavor tagged jet



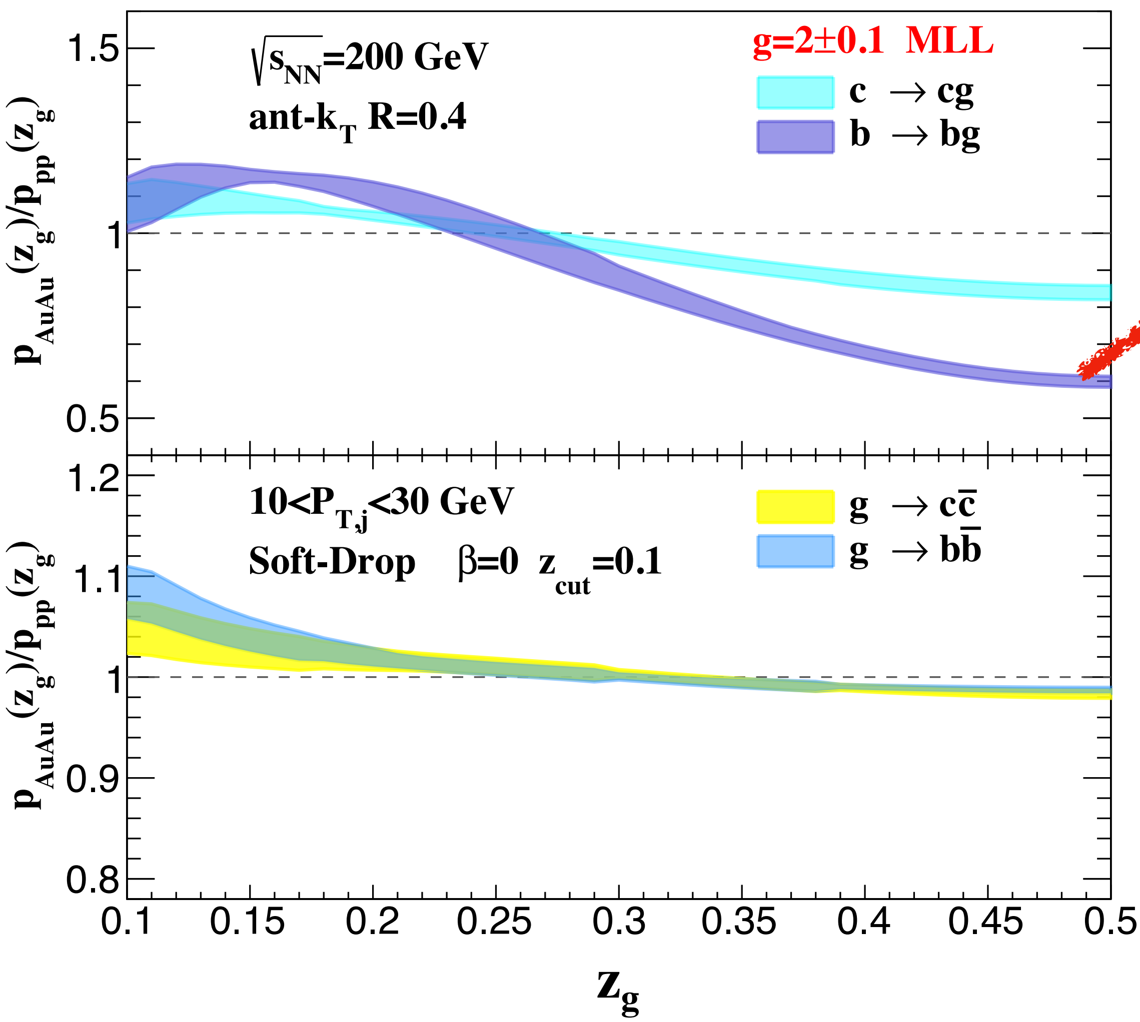
Inverting the mass hierarchy in jet quenching effects

Splitting function in the vacuum

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

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

Results for heavy flavor tagged jet



Inverting the mass hierarchy in jet quenching effects

Splitting function in the vacuum

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

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

Corrections in QCD medium contain terms such as

$$\left(\frac{1}{k_\perp^2+z^2m^2}\right)^2 \times f(k_\perp, z) \qquad \text{for} \qquad Q\to Qg$$

$$\left(\frac{1}{k_\perp^2+m^2}\right)^2 \times f'(k_\perp, z) \qquad \text{for} \qquad g\to Q\bar{Q}$$

Conclusions

- Presented the resummation formula for jet splitting function in vacuum and QCD medium
- Compared the MLL predictions with Pythia8 at pp collider
- Compared the MLL modifications with measurements from CMS and STAR and found a good agreement within all the uncertainties
- Presented the modifications of the momentum sharing distributions for heavy flavor tagged jet

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

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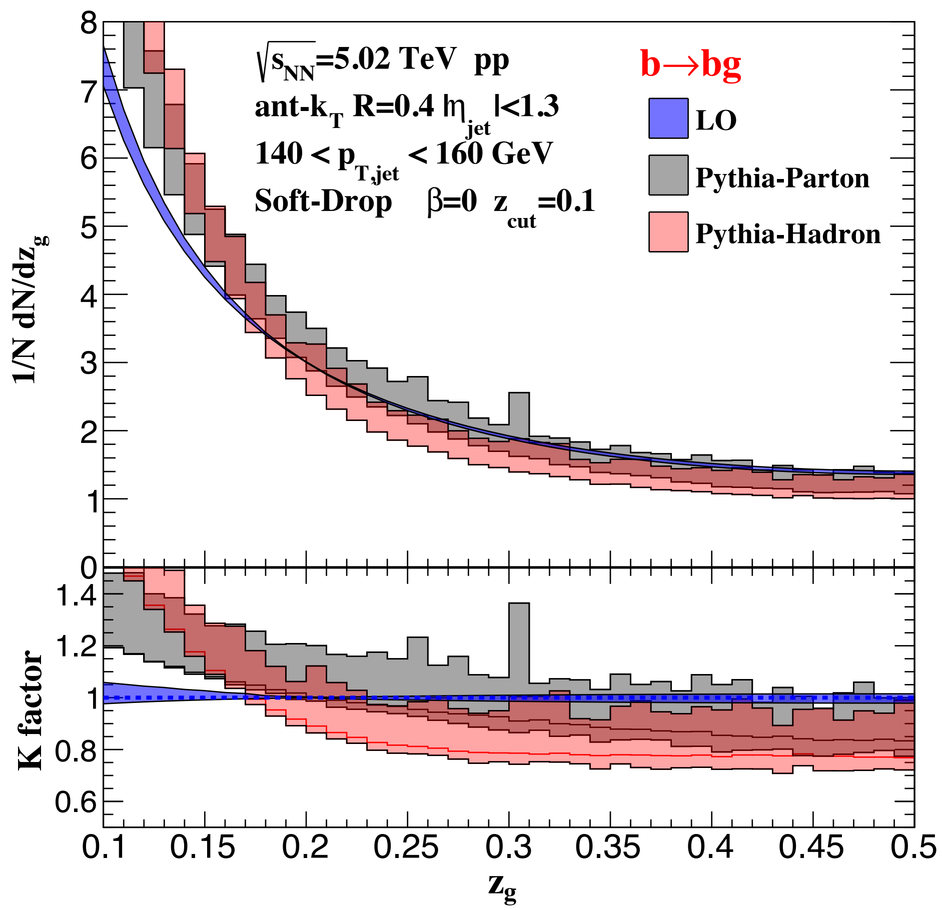
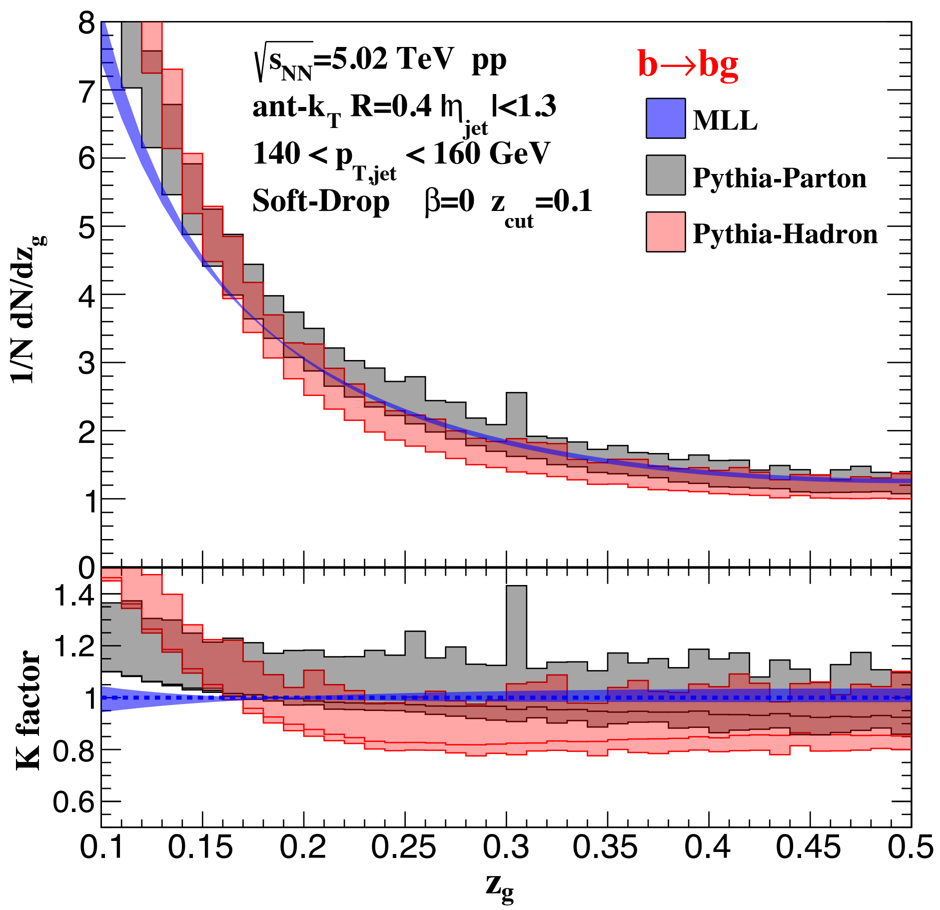
Thank you

Back up

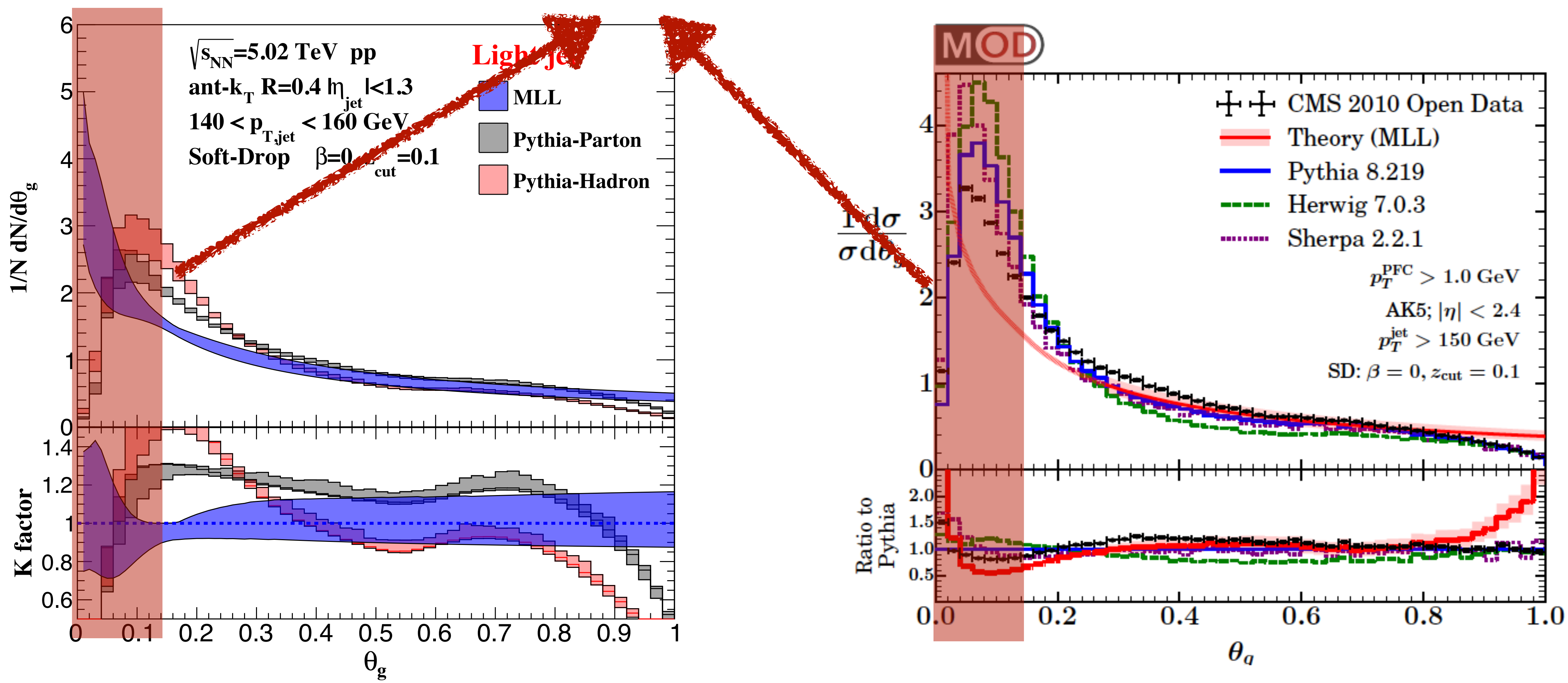
Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet



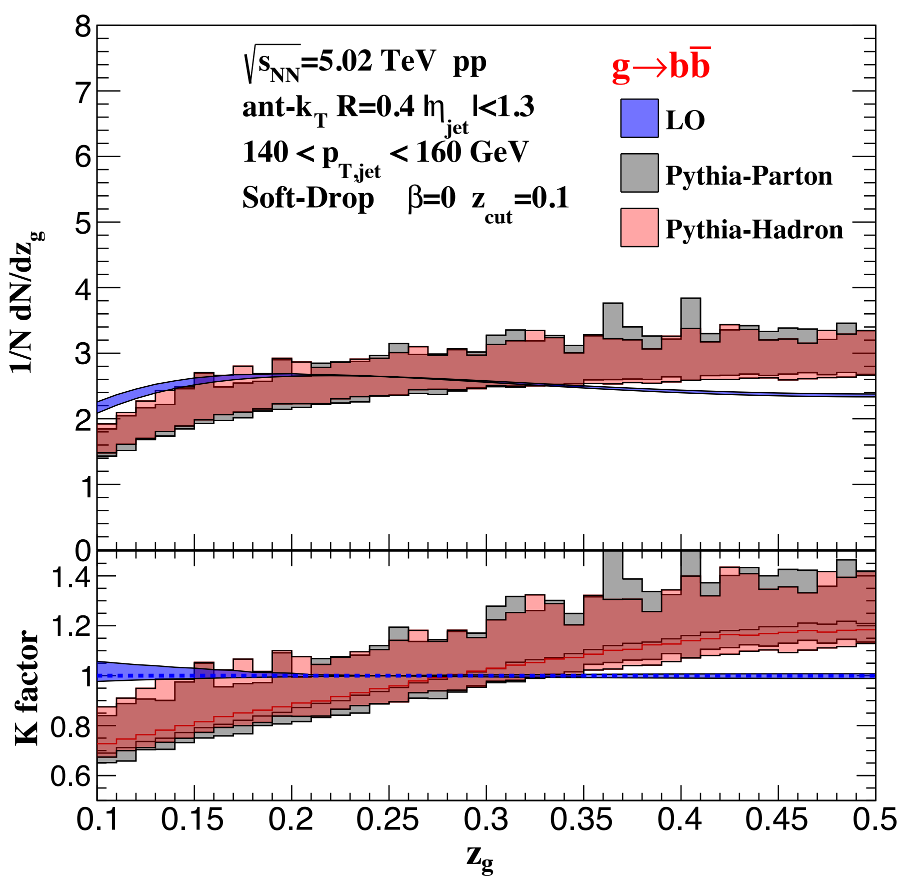


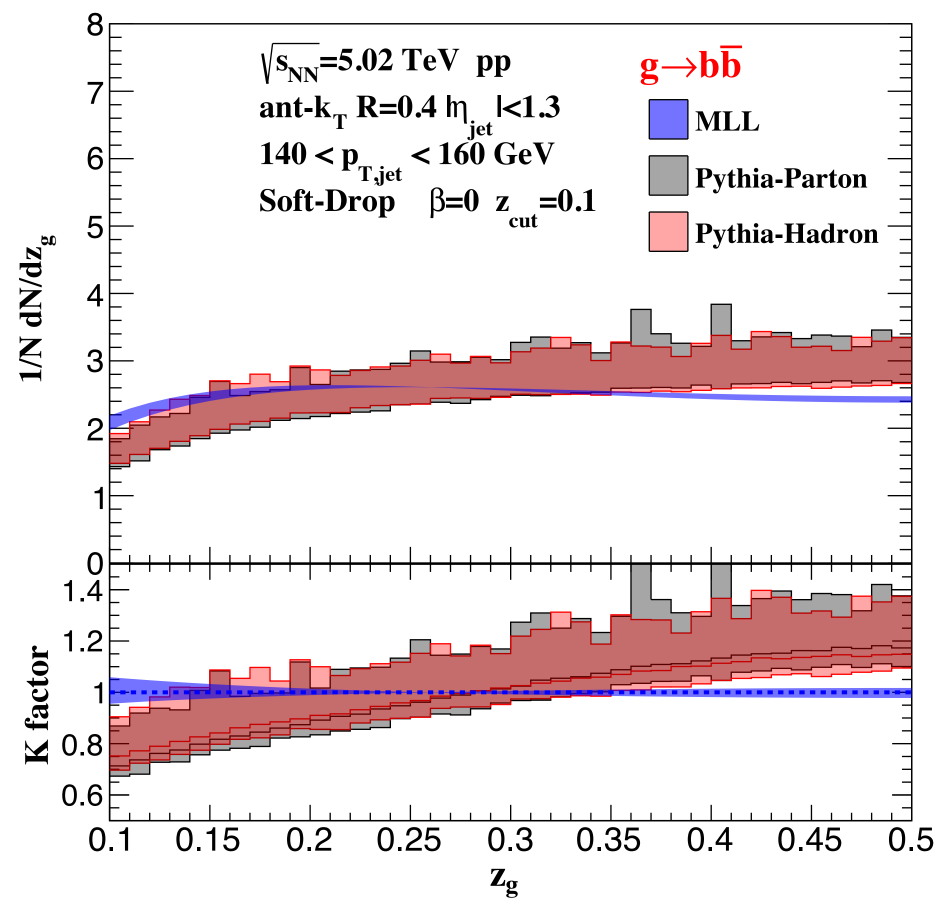
Non-perturbative



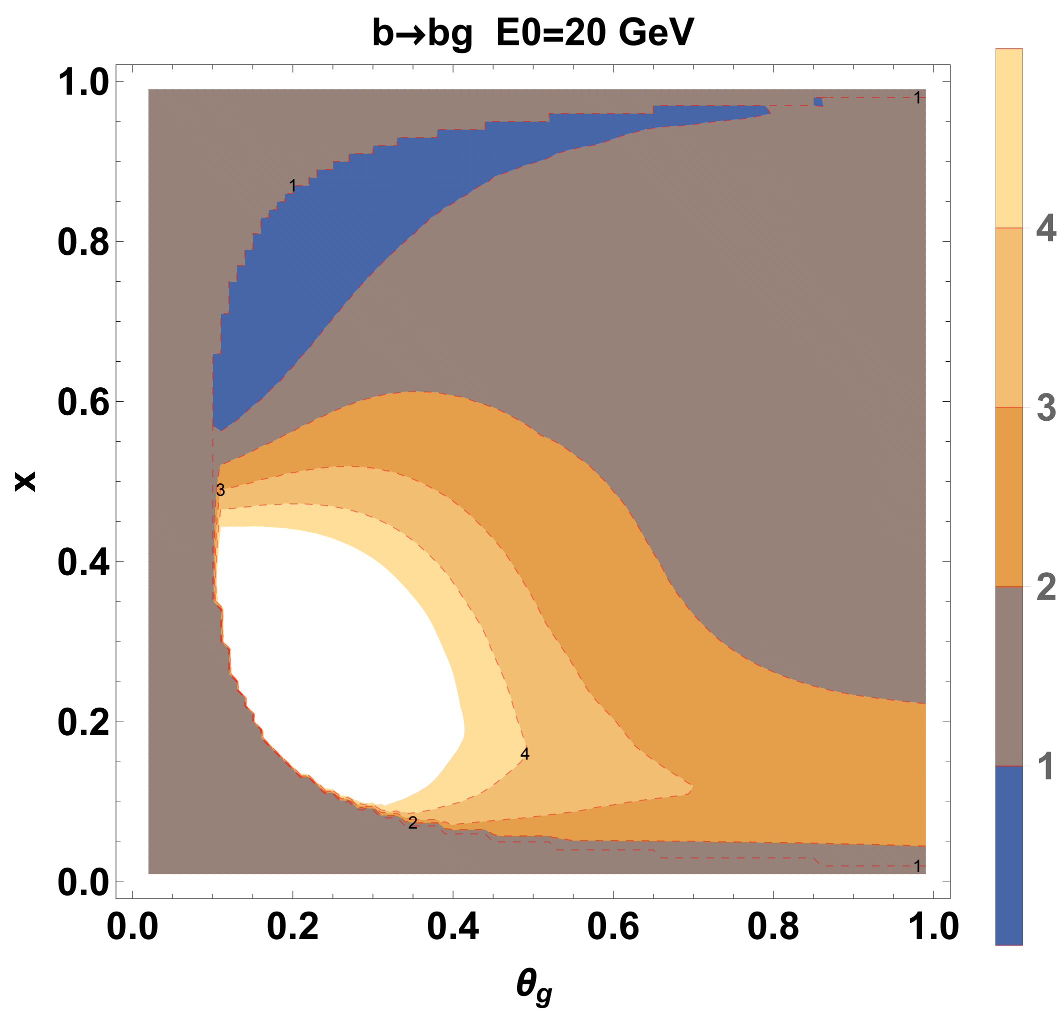
Results for heavy flavor tagged jet

LO and MLL predictions for b-tagged jet





Back up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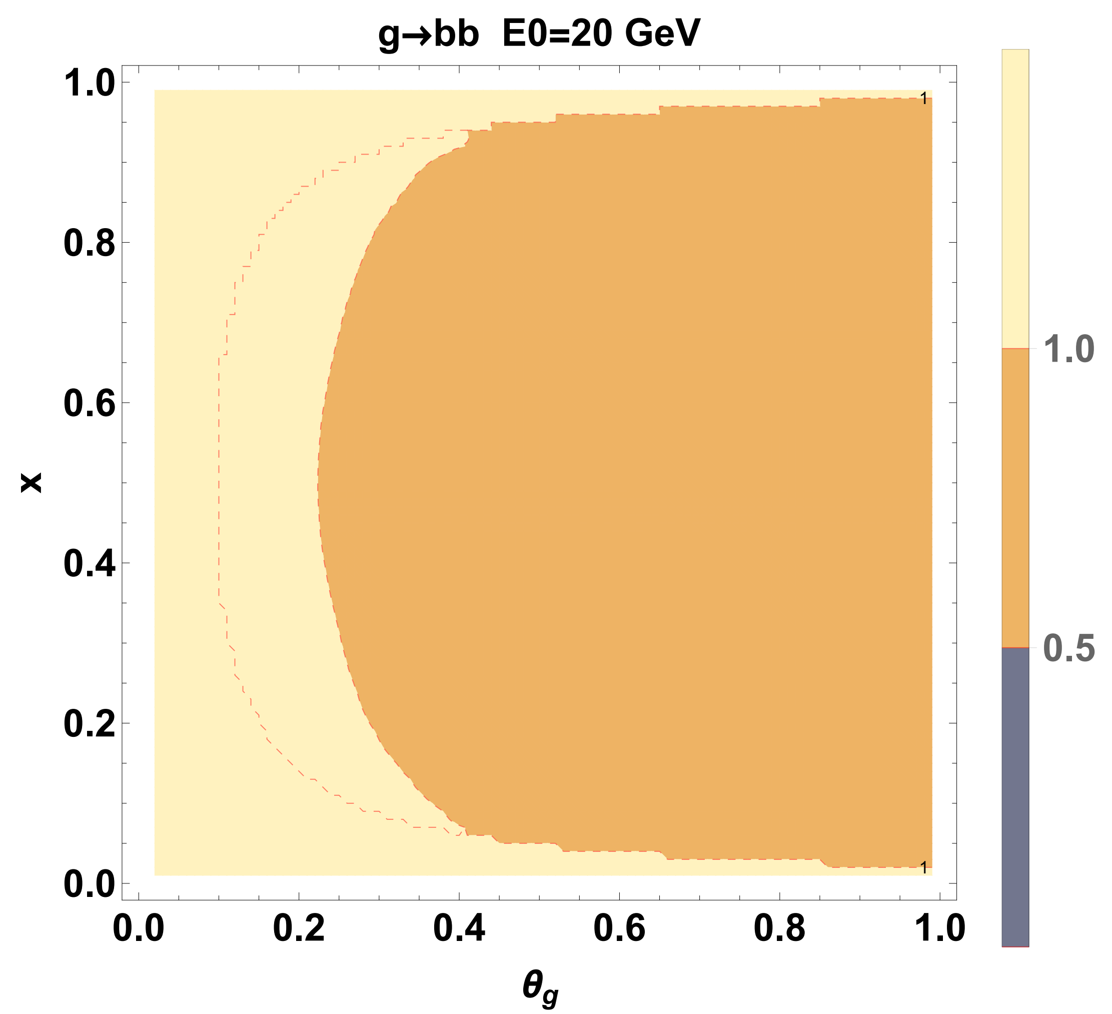
0.6
0.4
0.2
0.0
x
0.0 0.2 0.4 0.6 0.8 1.0
θg
1
2
3
4


g→bb E0=20 GeV
1.0
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0.6
0.4
0.2
0.0
x
0.0 0.2 0.4 0.6 0.8 1.0
θg
1.0
0.5