Production of heavy quark dijets in forward directions

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Introduction

- k_t-factorization gives good description of inclusive D-meson distributions (Maciula-Szczurek). Higher orders are needed in collinear approach.
- k_t-factorization gives good description of $D^0 - \bar{D}^0$ correlation observables (Maciula-Szczurek).
- Such calculations involve hadronization which is not fully under control, especially in forward directions.
- Heavy quark dijets are therefore interesting alternative.
- LHCb measured recently some dijet observables for $b\bar{b}$ and $c\bar{c}$. The second for the first time. $\sqrt{s} = 13$ TeV, $2.2 < \eta_{jet} < 4.2$, $p_{t,jet} > 20$ GeV.
- R. Maciula, R. Pasechnik and A. Szczurek, arXiv:2202.07585.

k_t-factorization approach

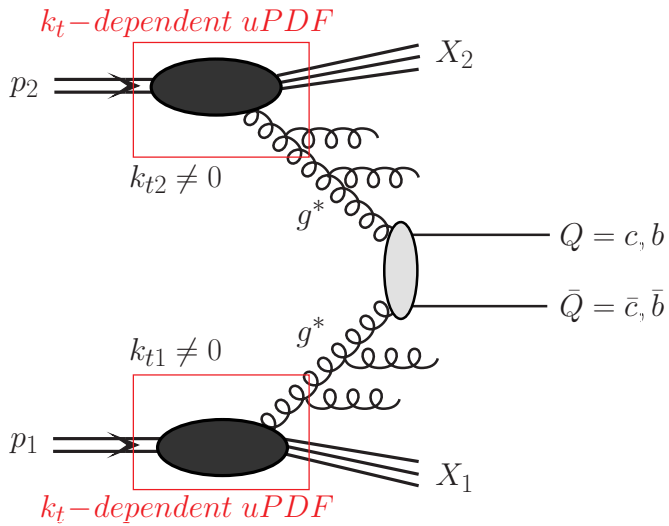


Figure: A diagramatic representation of the leading-order mechanism of heavy flavoured dijet production in the k_T-factorization approach.

k_t-factorization approach

$$\frac{d\sigma(pp \to Q\bar{Q}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}^{\text{off-shell}}_{g^*g^* \to Q\bar{Q}}|^2}$$
$$\times \delta^2\left(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \mathcal{F}_g(x_1, k_{1,t}^2, \mu_F^2)\, \mathcal{F}_g(x_2, k_{2,t}^2, \mu_F^2)\,,$$

where $\mathcal{F}_g(x_1, k_{1,t}^2, \mu_F^2)$ and $\mathcal{F}_g(x_2, k_{2,t}^2, \mu_F^2)$ are the gluon uPDFs for both colliding hadrons and $\mathcal{M}^{\text{off-shell}}_{g^*g^* \to Q\bar{Q}}$ is the off-shell matrix element for the hard subprocess. The gluon uPDF depends on gluon longitudinal momentum fraction x, transverse momentum squared k_t^2 of the gluons entering the hard process, and in general also on a (factorization) scale of the hard process μ_F^2.

k_t-factorization approach

The extra integration is over transverse momenta of the initial partons. Here, one keeps exact kinematics from the very beginning and additional hard dynamics coming from transverse momenta of incident partons. Explicit treatment of the transverse momenta makes the approach very efficient in studies of correlation observables. The two-dimensional Dirac delta function assures momentum conservation. The gluon uPDFs must be evaluated at longitudinal momentum fractions:

$$x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$$
$$x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2)$$

where $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$ is the quark/antiquark transverse mass.

The off-shell matrix elements are known explicitly only in the LO and only for limited types of $2 \to 2$ QCD processes (see *e.g.* heavy quark (Catani1990), dijet (Nefedov2013), Drell-Yan (Nefedov) mechanisms). Recently, higher multiplicity processes ($2 \to 3$ and $2 \to 4$) with off-shell partons were also calculated at tree level in the context of $c\bar{c}+$ jets (Maciula-Szczurek), $\gamma + \mathrm{c\text{-}jet}$ (Bednyakov2017), $Z^0 + \mathrm{c/b\text{-}jet}$ (Lipatov2018), 4-jets (Kutak2016) and double charm (vanHameren:2015wva) production. Some first steps to calculate NLO corrections in the k_T-factorization framework have been made for diphoton production (Nefedov2016).

The hybrid model

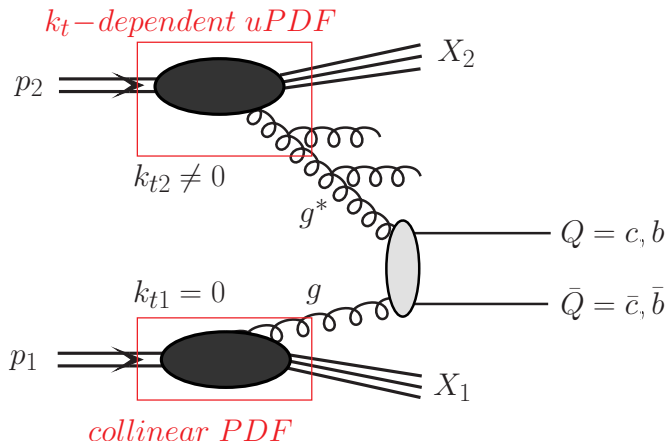


Figure: A diagramatic representation of the leading-order mechanism of heavy flavoured dijet production in the hybrid model.

The LHCb measurement of the $c\bar{c}$- and $b\bar{b}$-dijets is performed within the asymmetric kinematical configuration. Under the assumption that $x_1 \gg x_2$ the cross section for the processes can be also expressed in the so-called hybrid factorization aproach motivated by earlier works (Deak2009,Kutak2012).

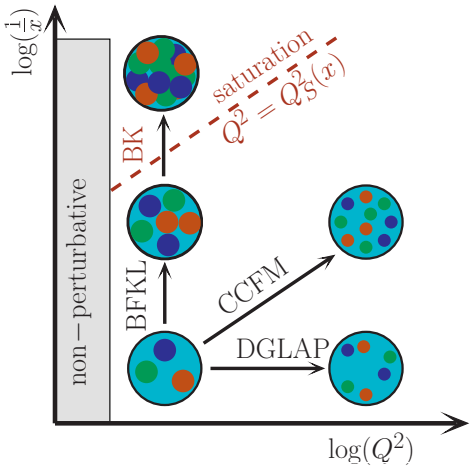
The hybrid model

the differential cross section for $pp \to Q\bar{Q}X$ via $g^*g \to Q\bar{Q}$ mechanism reads:

$$d\sigma_{pp\to Q\bar{Q}X} = \int d^2k_t \int \frac{dx_1}{x_1} \int dx_2 \; g(x_1,\mu^2)\, \mathcal{F}_{g^*}(x_2,k_t^2,\mu^2)\, d\hat{\sigma}_{g^*g\to Q\bar{Q}} \; ,$$

where $g(x_1,\mu^2)$ is a collinear PDF in one proton and $\mathcal{F}_{g^*}(x_2,k_t^2,\mu^2)$ is the unintegrated gluon distribution in the second one. The $d\hat{\sigma}_{g^*g\to Q\bar{Q}}$ is the hard partonic cross section obtained from a gauge invariant tree-level off-shell amplitude. In the present paper we shall not discuss the validity of the hybrid model on the theoretical level and concentrate only on its phenomenological application in forward production. A derivation of the hybrid factorization from the dilute limit of the Color Glass Condensate approach (Kotko2015).

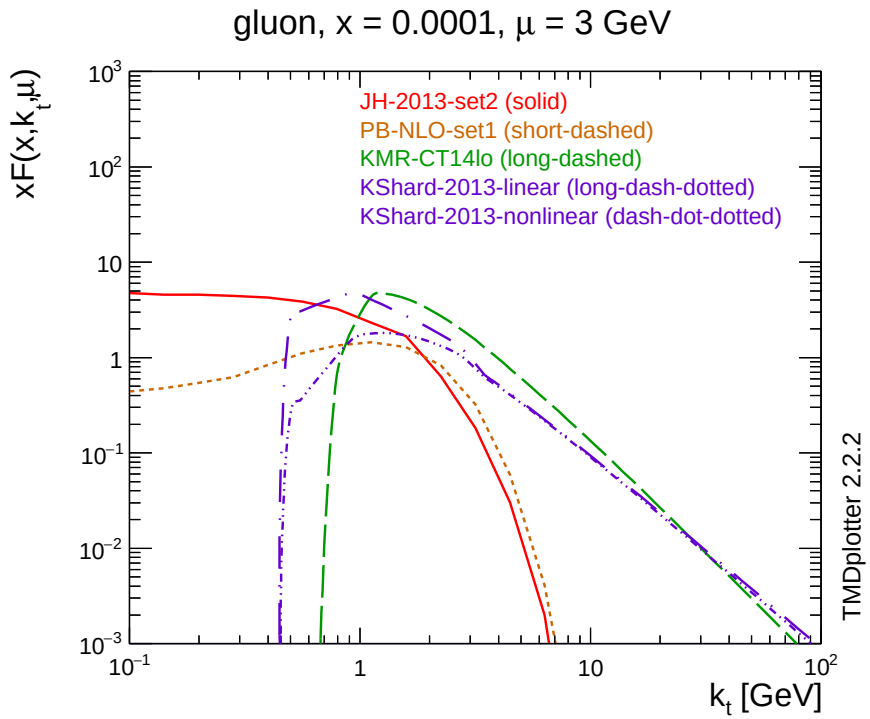
Unintegrated parton distribution functions (uPDFs)



Transverse momentum dependent PDFs: $\mathcal{F}_g(x, k_t^2, \mu)$

- CCFM evolution: Jung-Hautmann (JH2013)
- Parton Branching + DGLAP: Bermudez Martinez-Connor-Jung-Lelek-Zlebcik
- linear/nonlinear BK (saturation): Kutak-Sapeta (KS)
- modified DGLAP-BFKL: Kimber-Martin-Ryskin-Watt (KMR, MRW)

- CCFM: JH-2013-set1, JH-2013-set2, Jung-setA0
- Parton Branching: PB-NLO-set1, PB-NLO-set2
- KMR/MRW: from CT14 PDF
- Kutak Sapeta: KS-2013-linear, KS-2013-nonlinear (with hard scale)
- saturation effects possible to be studied within the KS uPDF
- Heavy Flavour dijets at the LHCb: both small-x and large-x behaviour probed



k_t-factorization, $c\bar{c}$ dijets

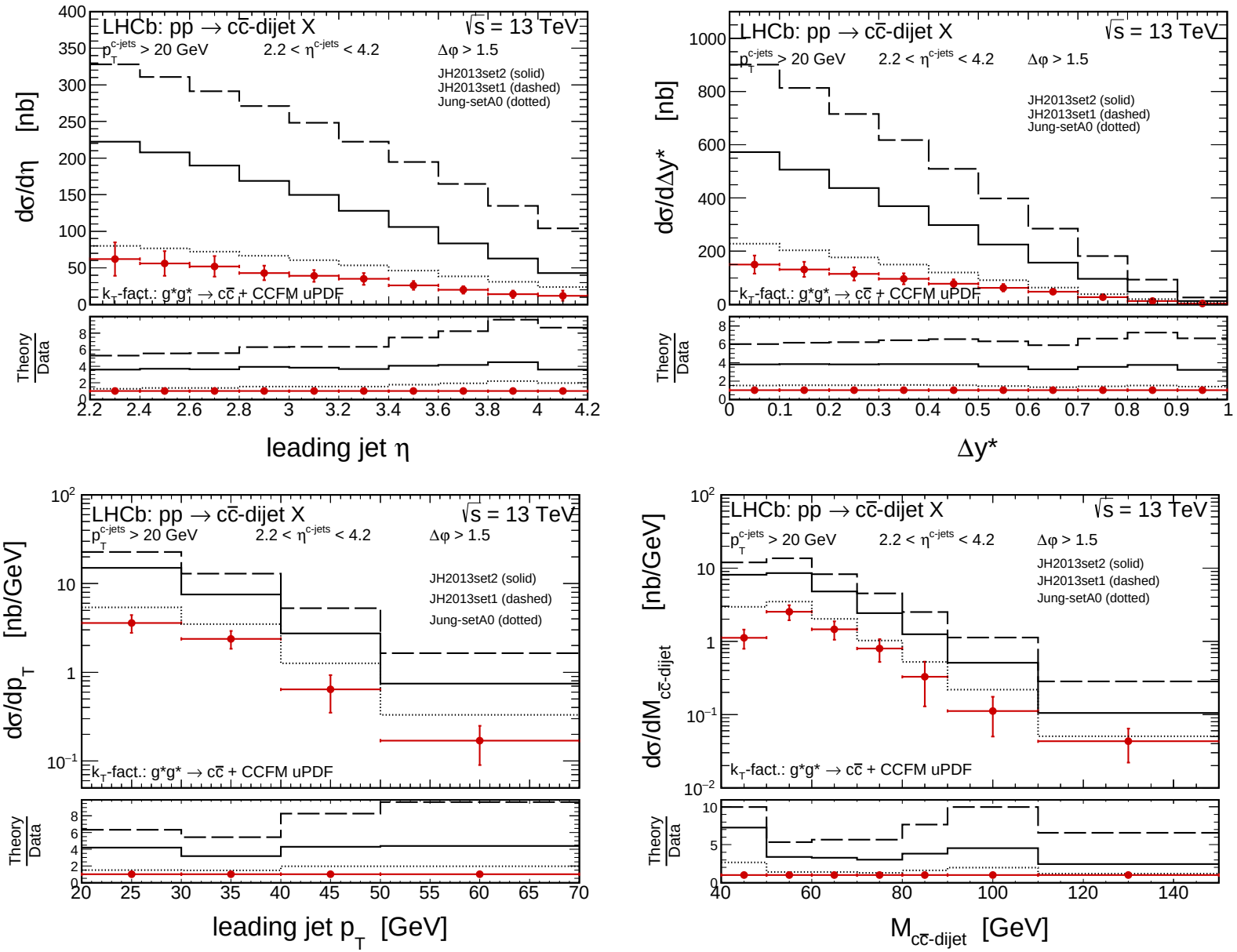


Figure: CCFM uPDF

k_t-factorization, $c\bar{c}$ dijets

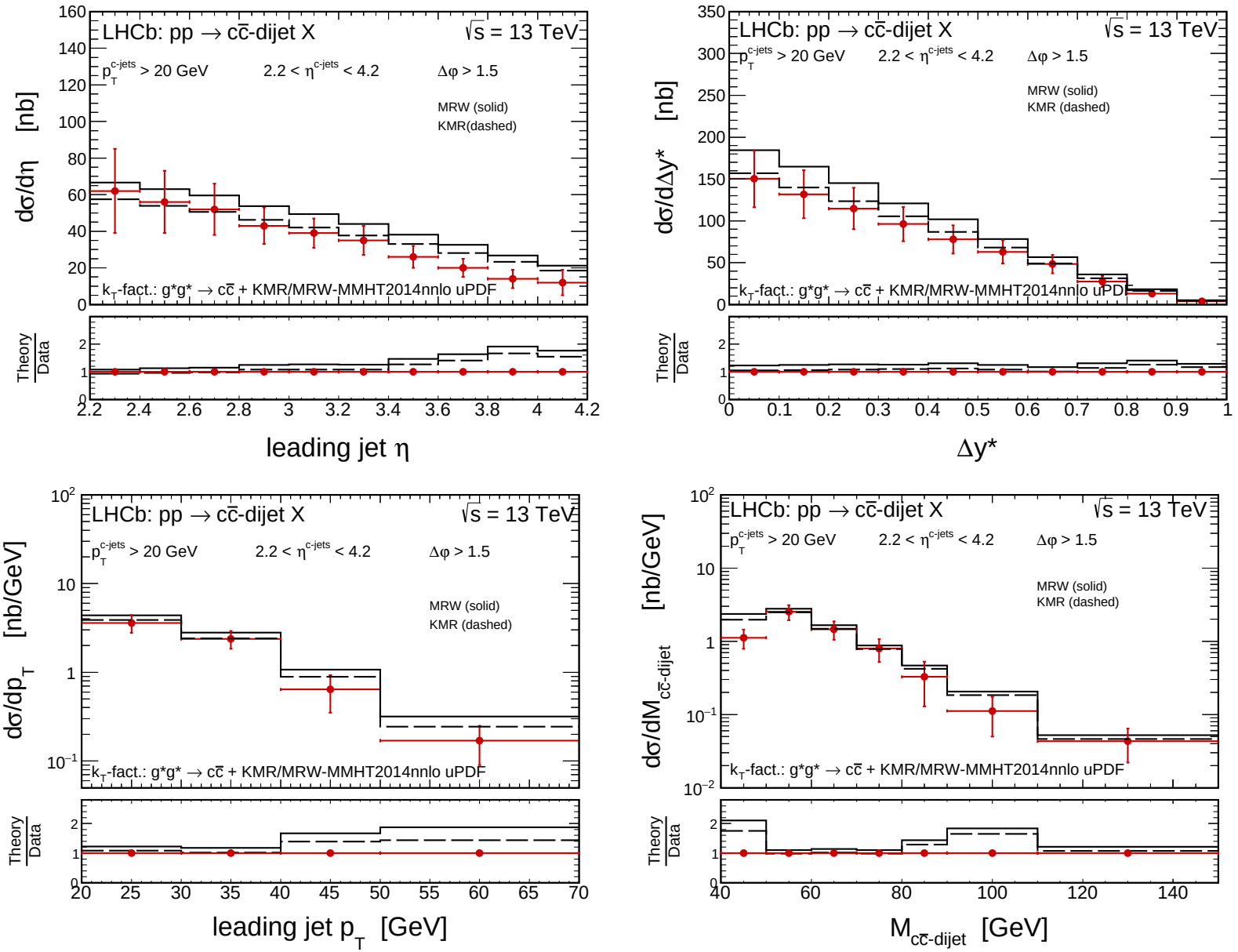


Figure: KMR and the MRW uPDFs are used.

k_t-factorization, $c\bar{c}$ dijets

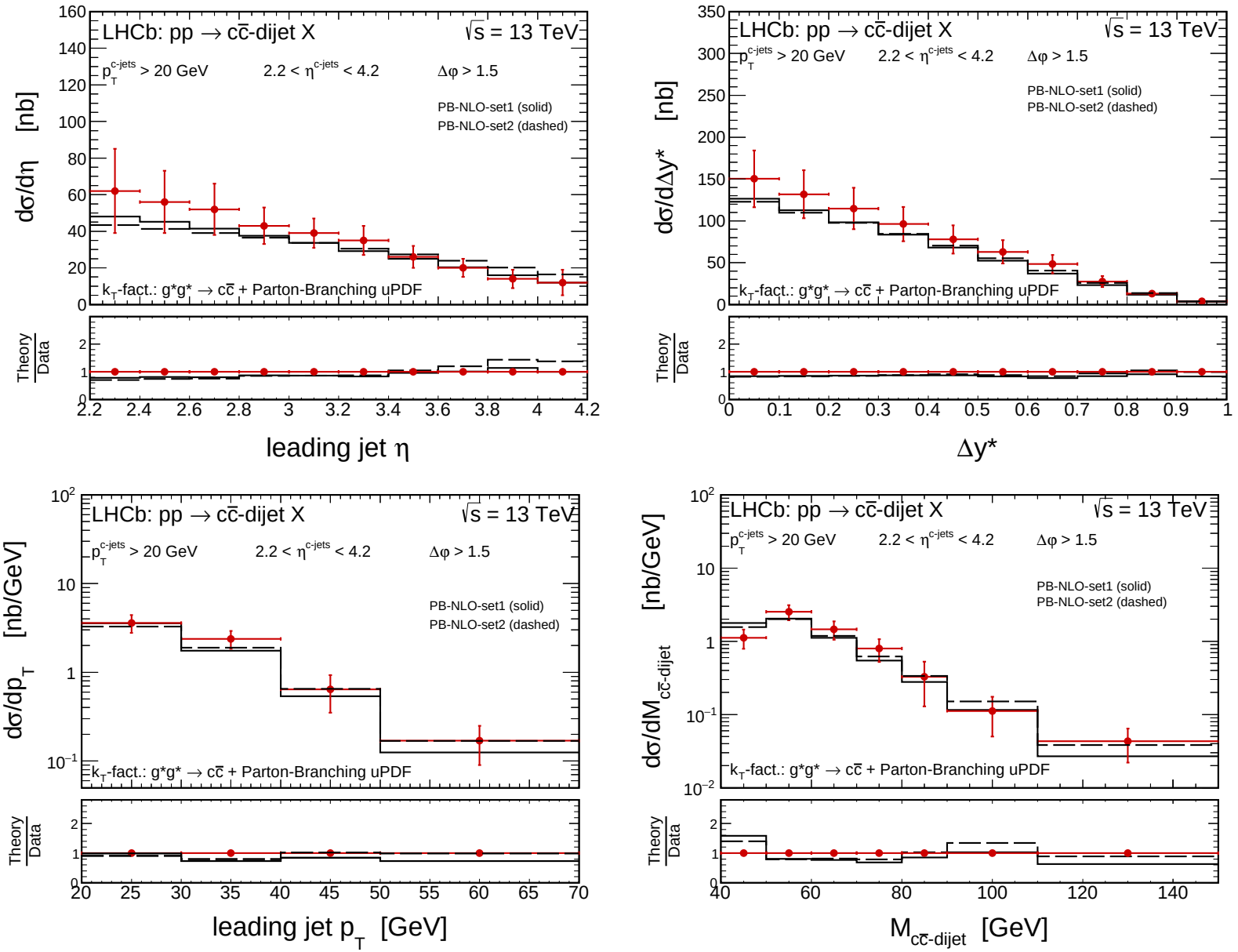
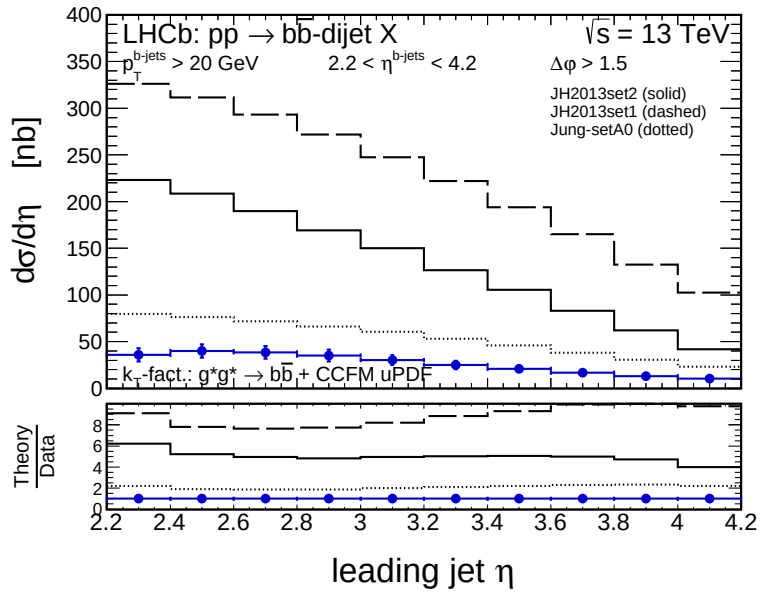
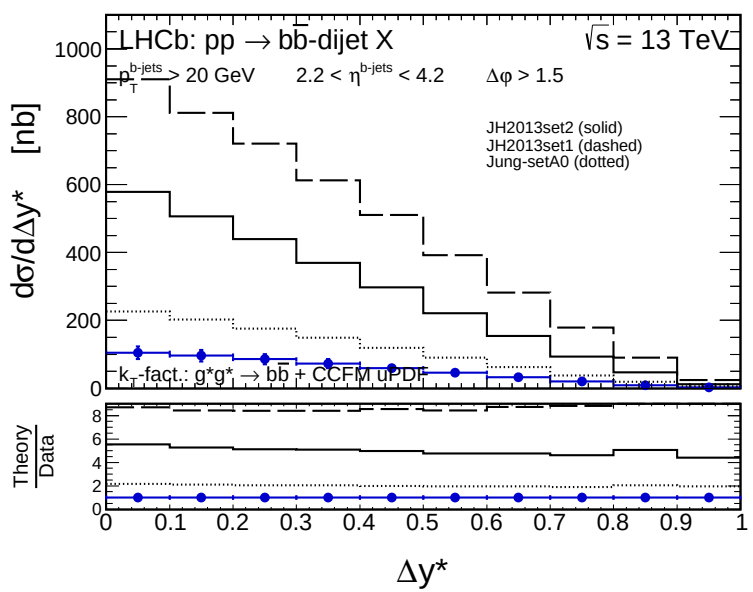
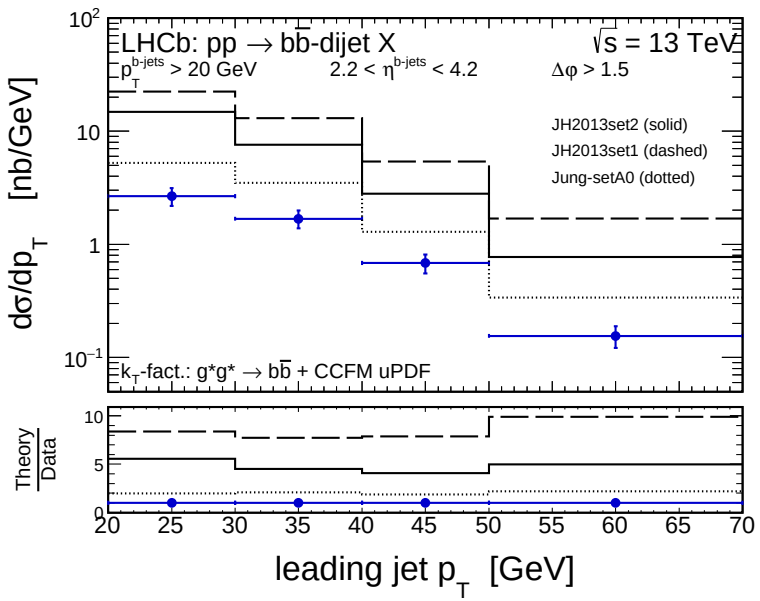


Figure: Parton Branching uPDFs are used.

k_t-factorization, $b\bar{b}$ dijets







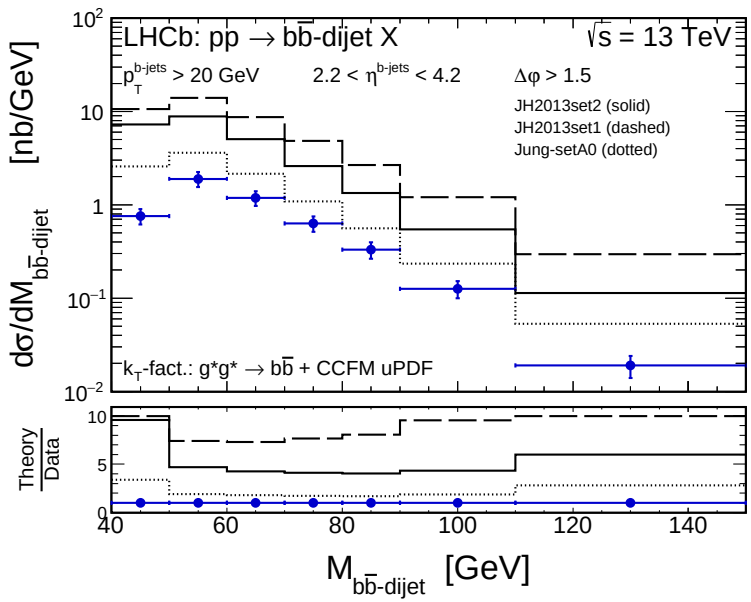


Figure: CCFM uPDFs are used.

k_t-factorization, $b\bar{b}$ dijets

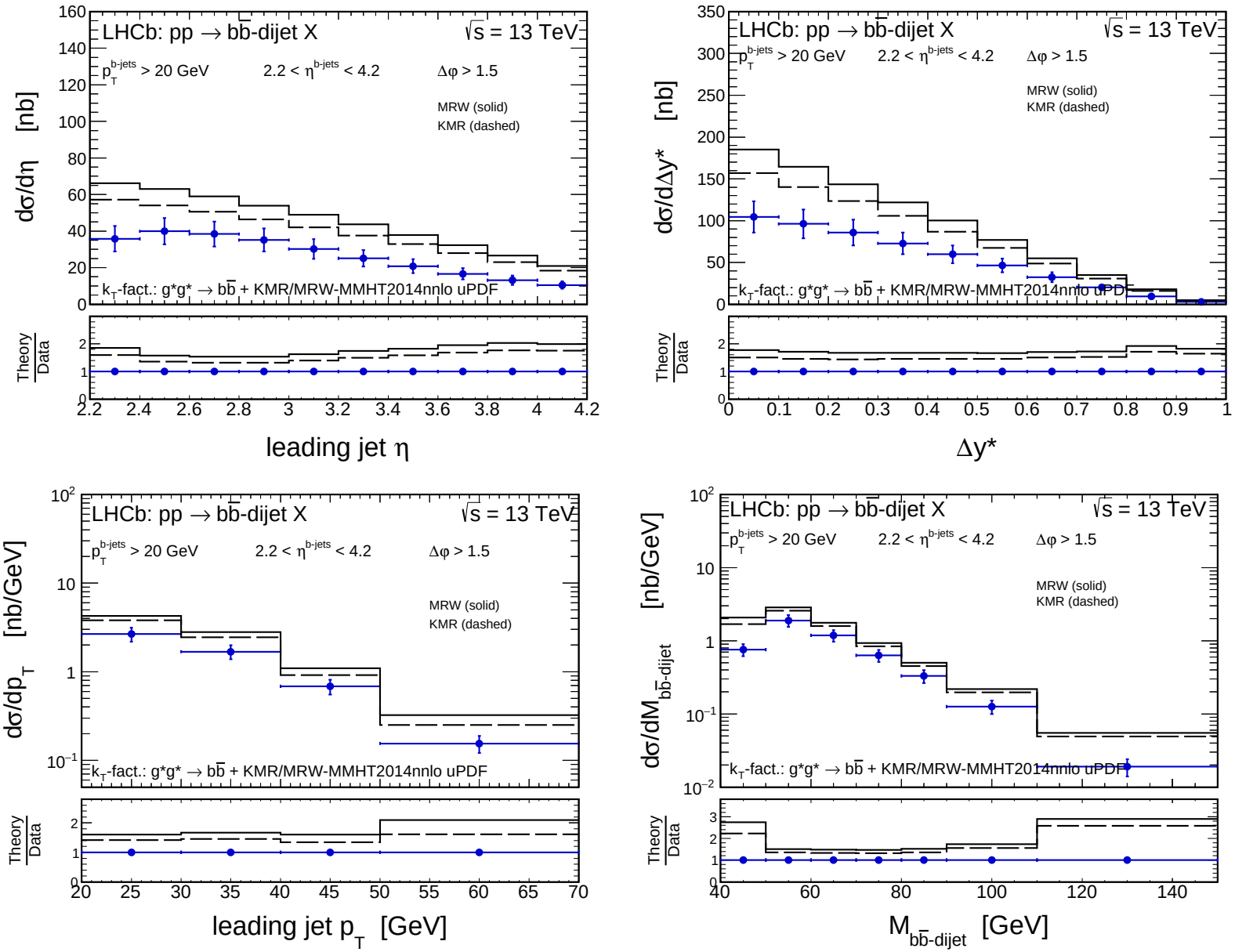


Figure: Here the KMR and the MRW uPDFs are used.

k_t-factorization, $b\bar{b}$ dijets

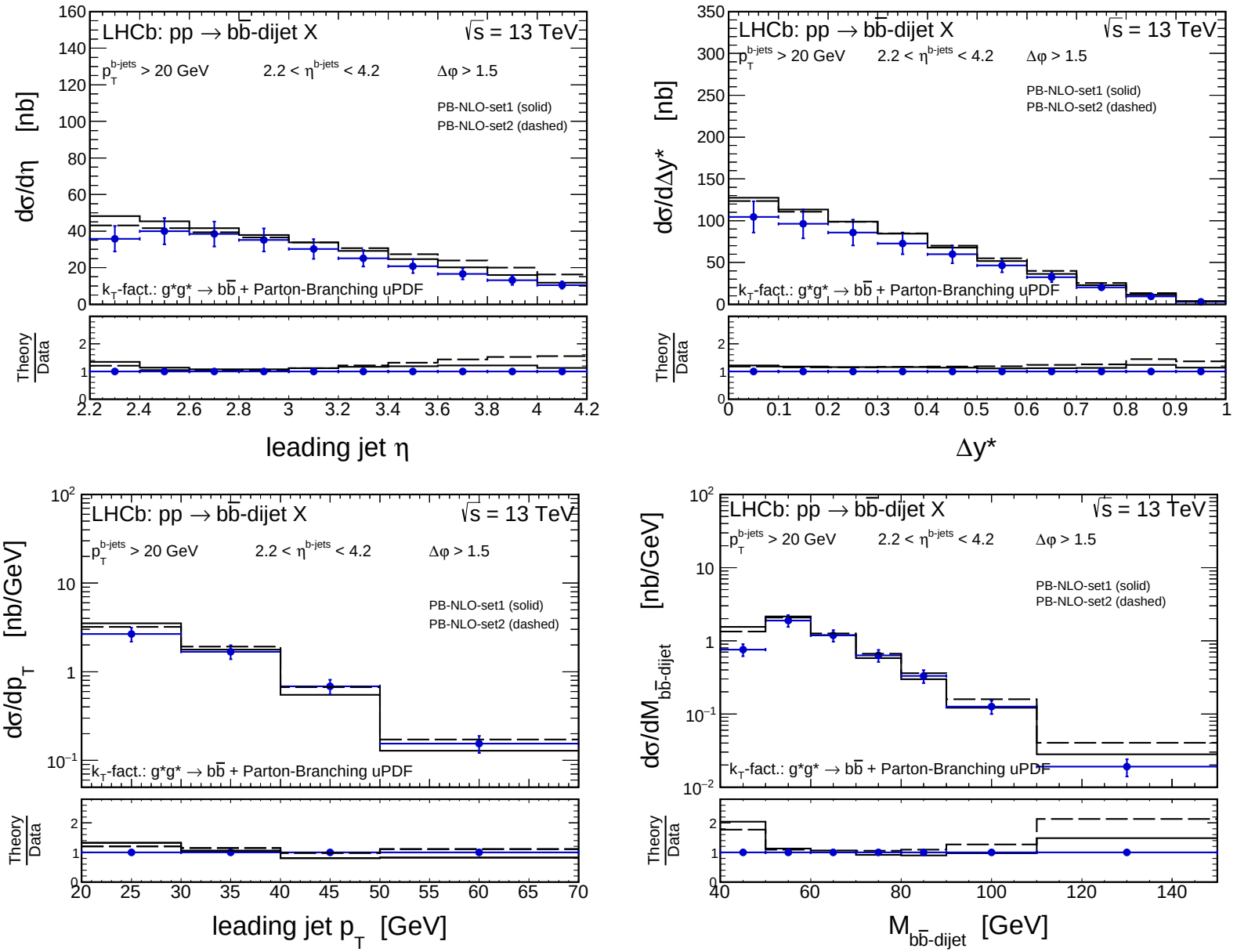
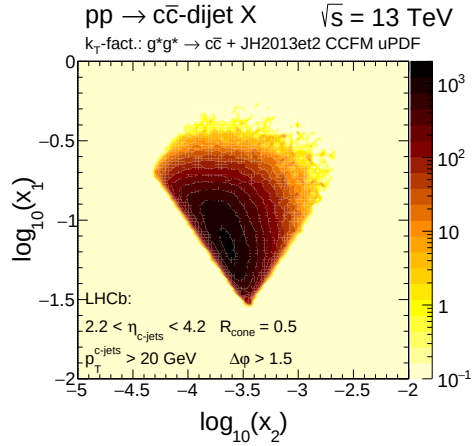
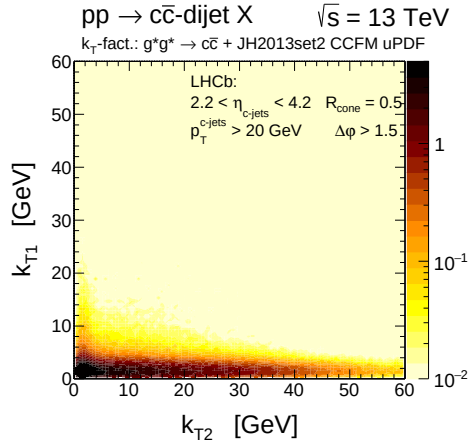
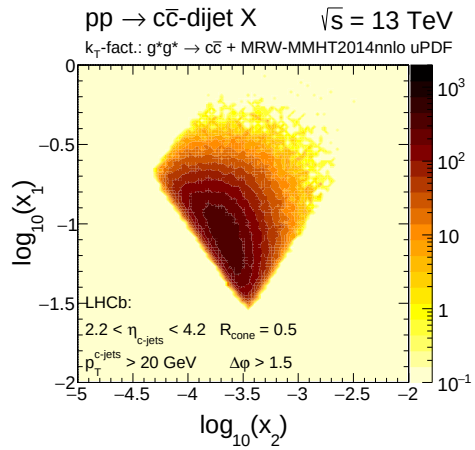


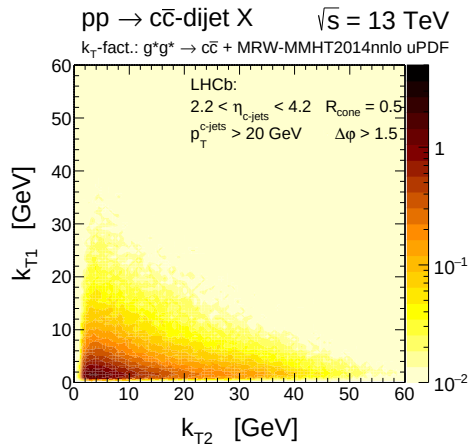
Figure: Here the Parton Branching uPDFs are used.

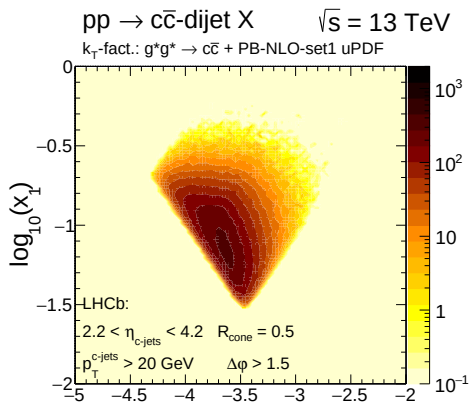
Kinematics of the process probed by LHCb

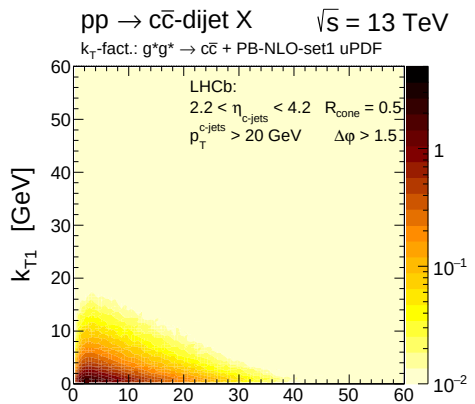




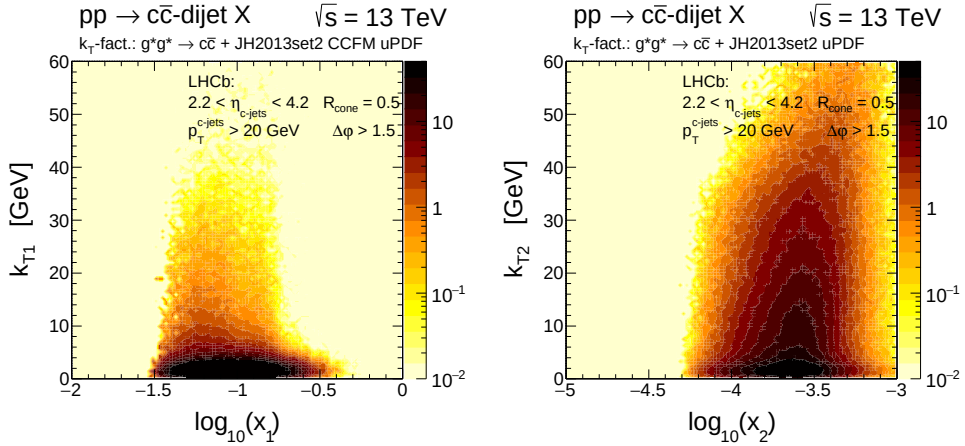


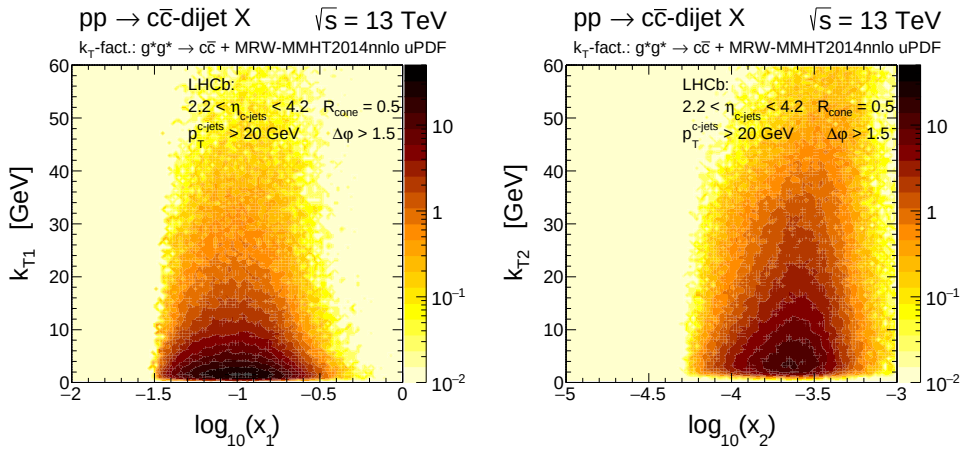


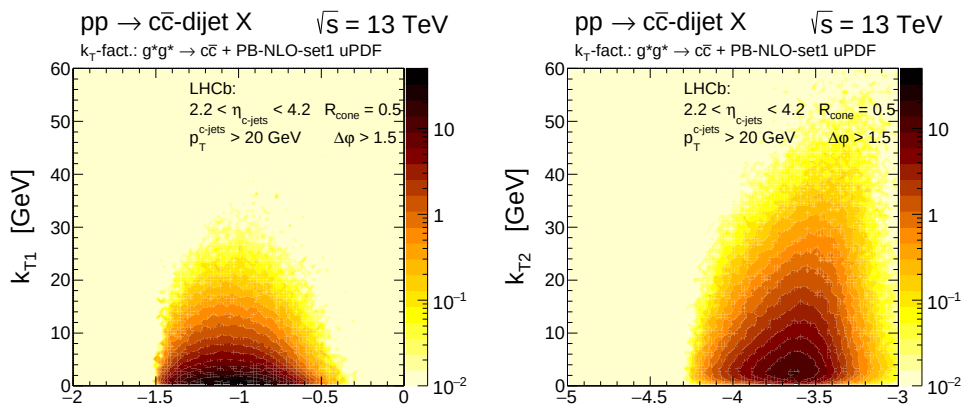




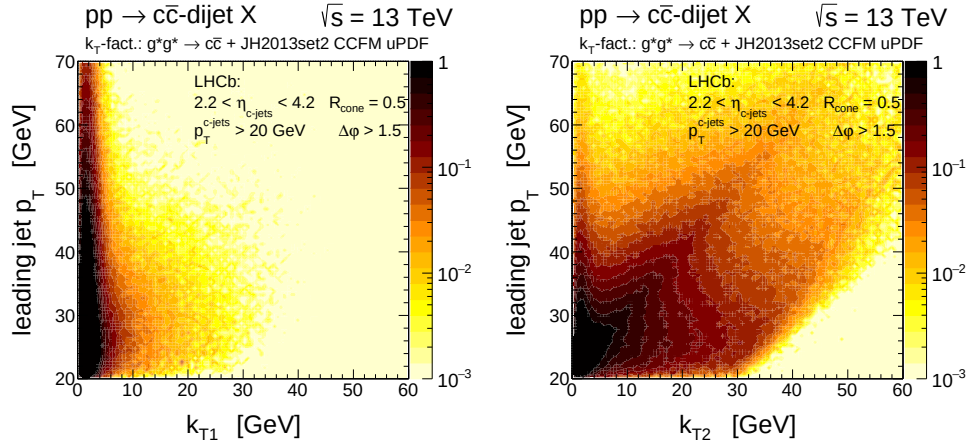
Kinematics of the process probed by LHCb

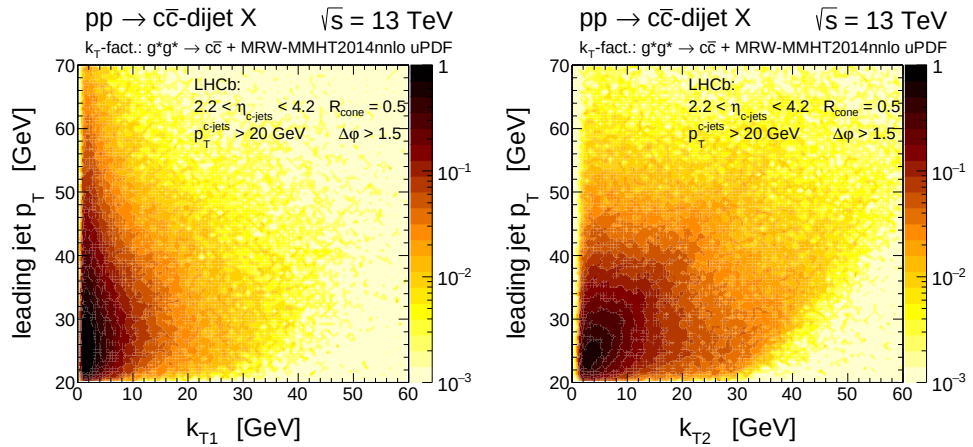


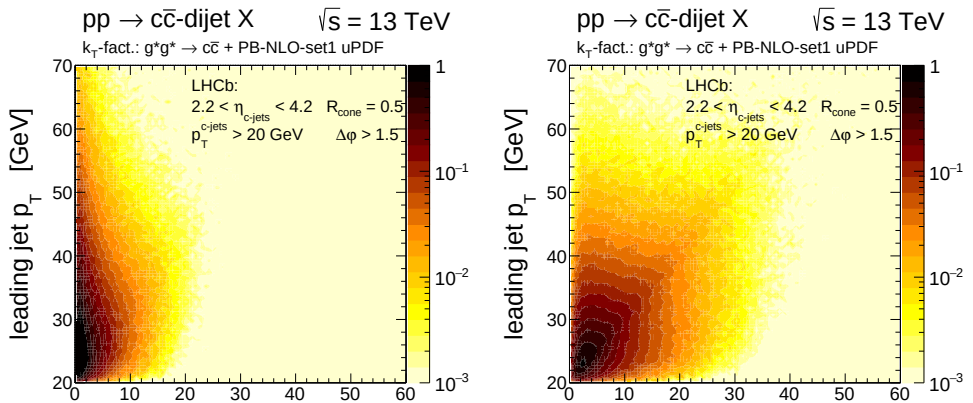




Kinematics of the process probed by LHCb







The large-x behaviour of the gluon uPDFs

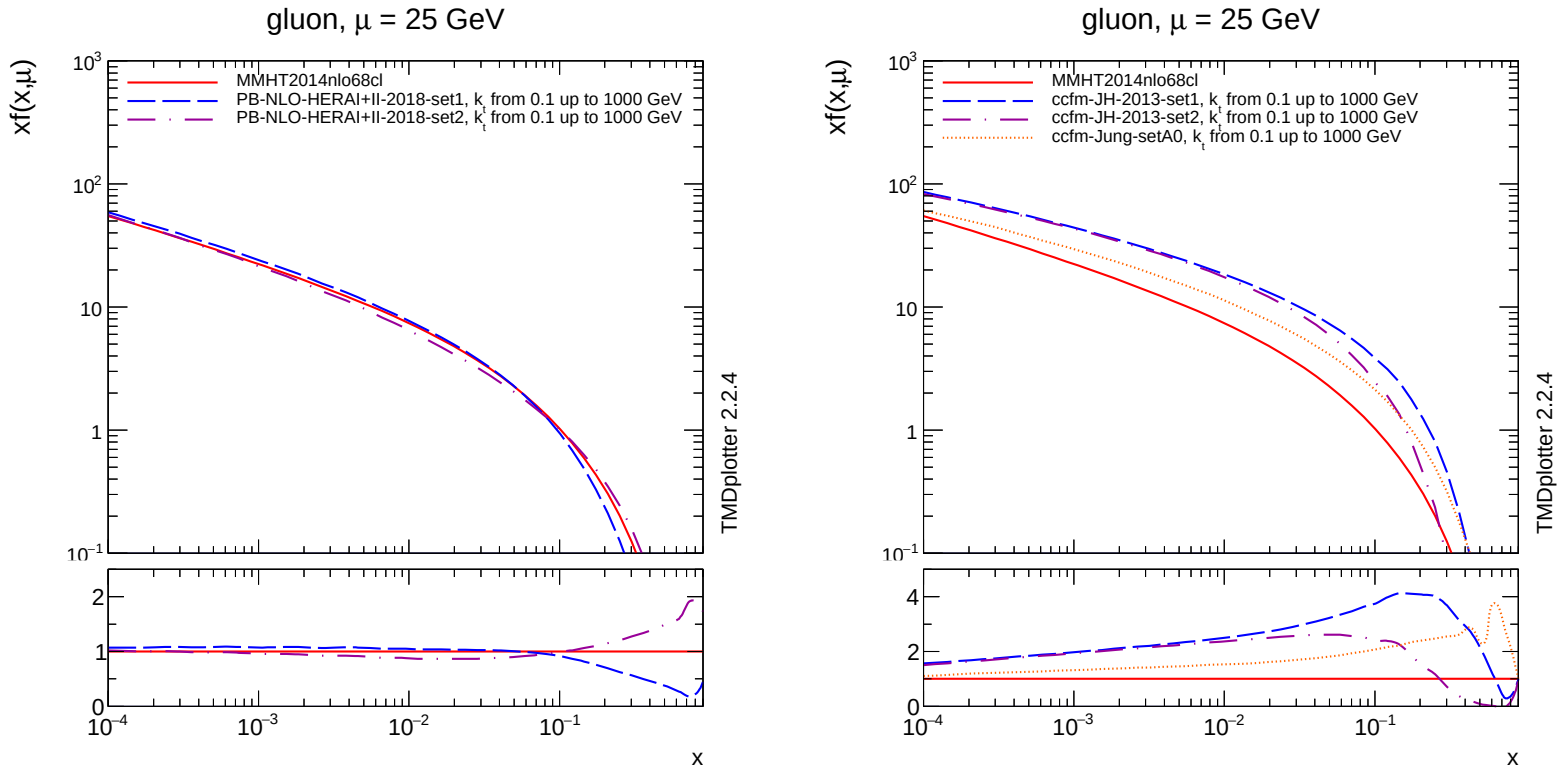
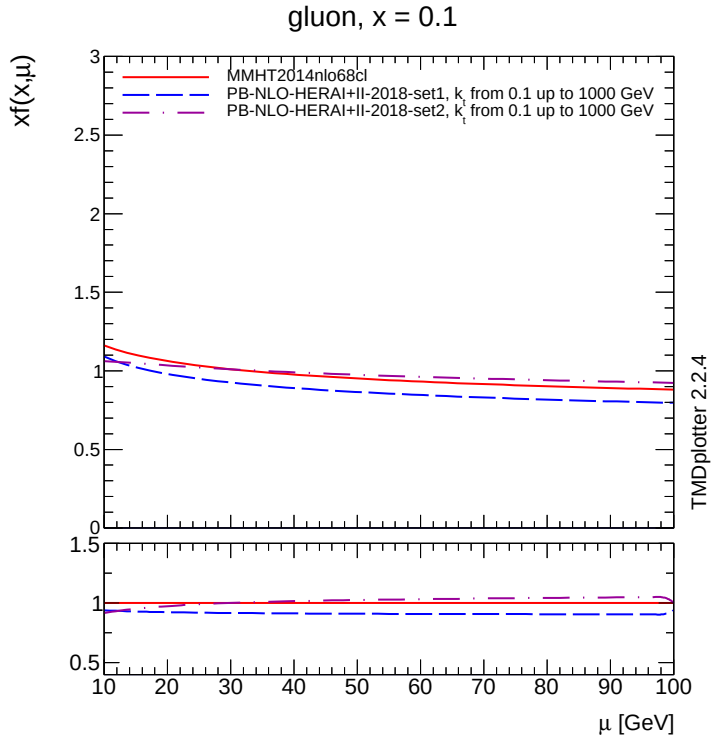
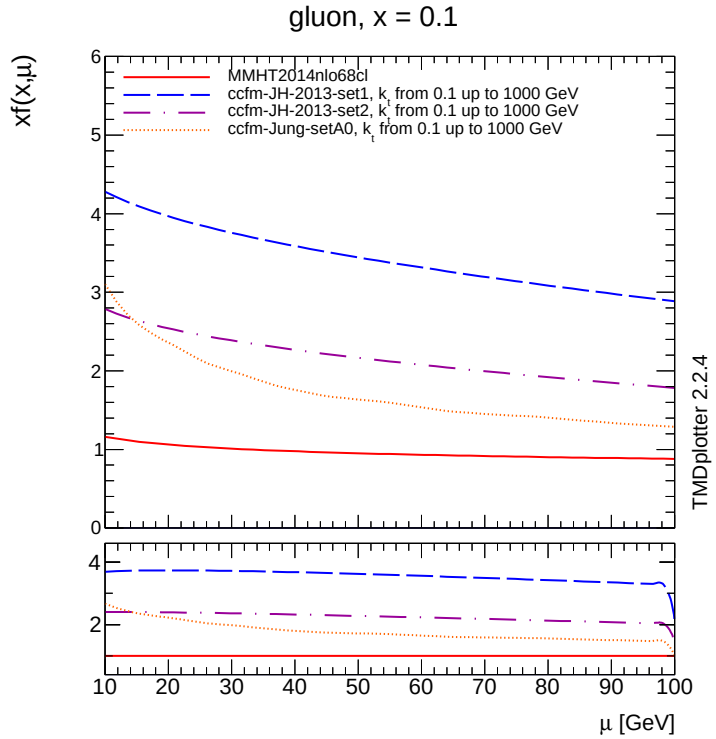
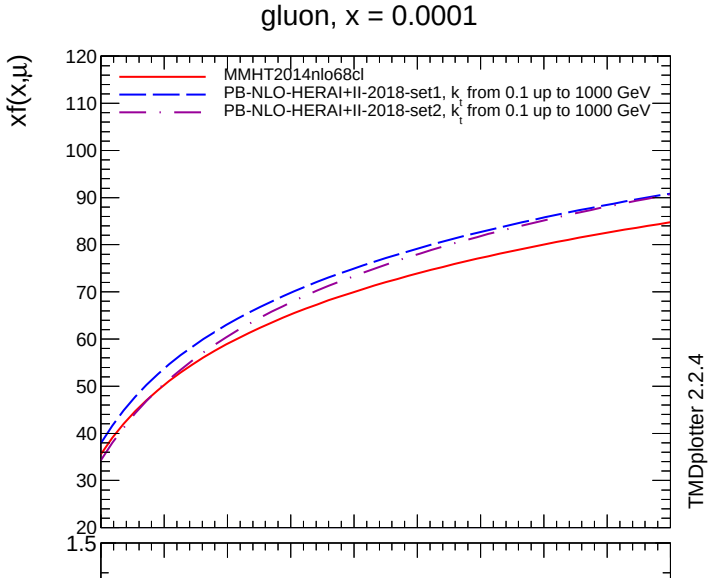


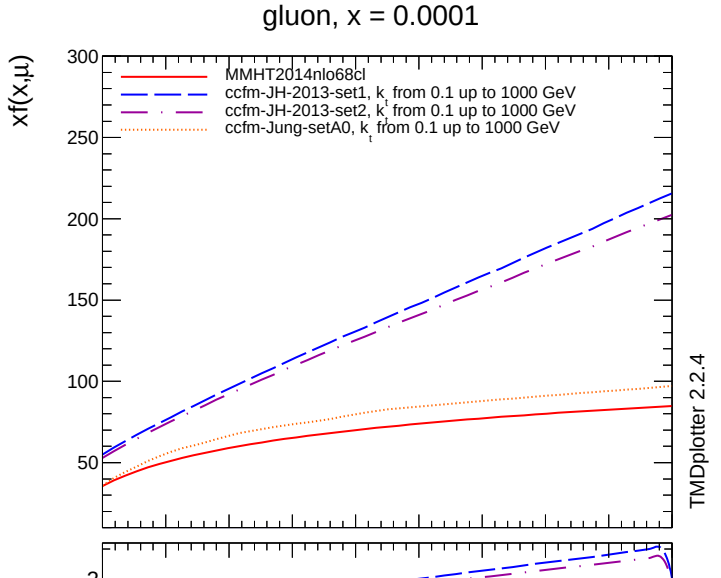
Figure: The gluon uPDFs (integrated over the transverse momentum k_t) as a function of the longitudinal momentum fraction x at a given scale $\mu = 25$ GeV. The left and right panels correspond to the Parton-Branching and the CCFM gluon uPDFs, respectively. As a reference the collinear MMHT2014nlo68cl gluon PDF.

The large-x behaviour of the gluon uPDFs

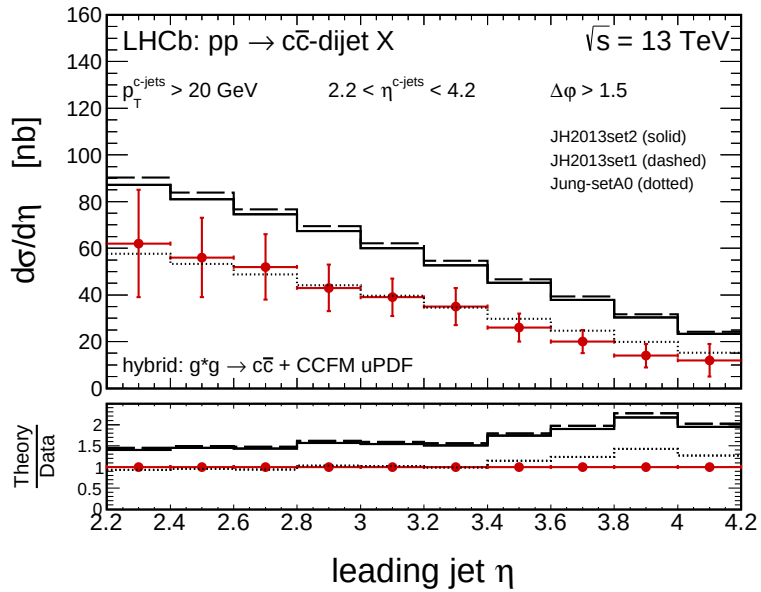


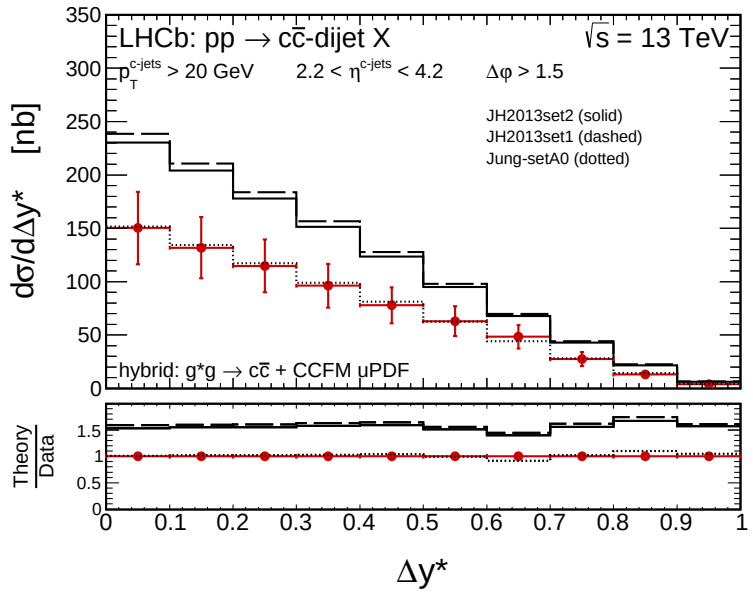


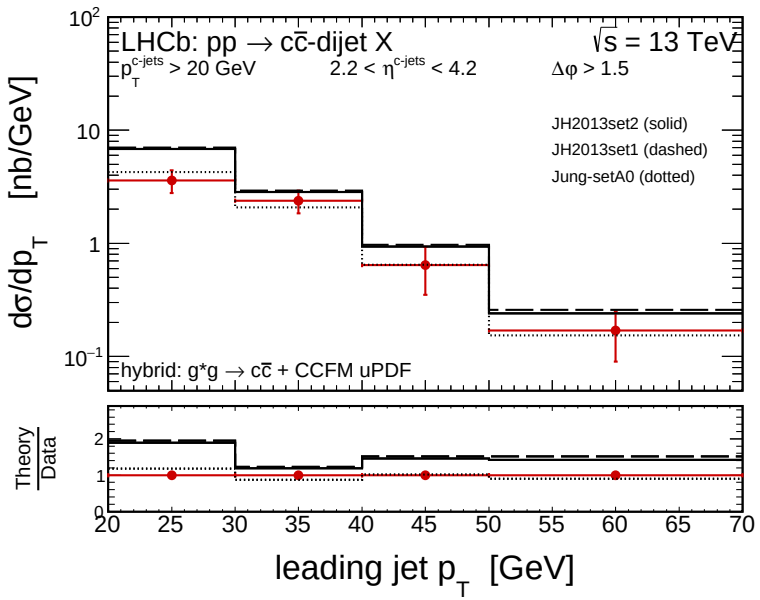




hybrid, $c\bar{c}$ dijets







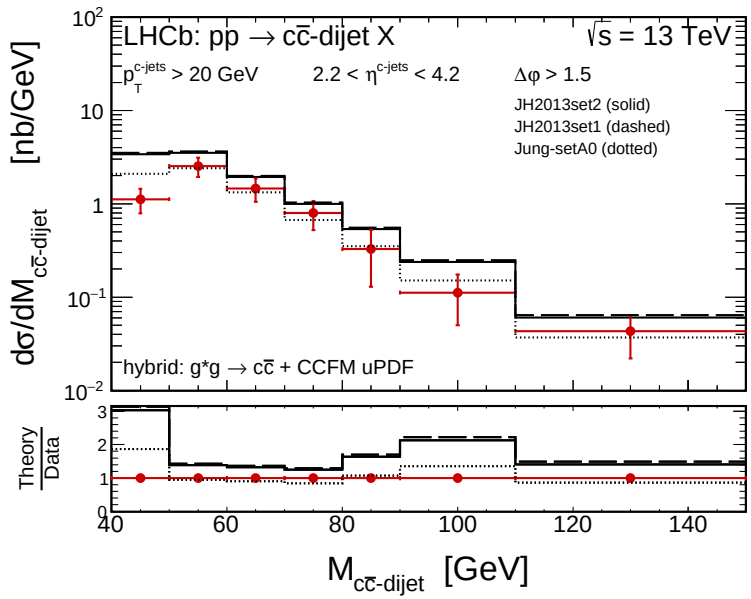


Figure: Here CCFM uPDFs

hybrid, $c\bar{c}$ dijets

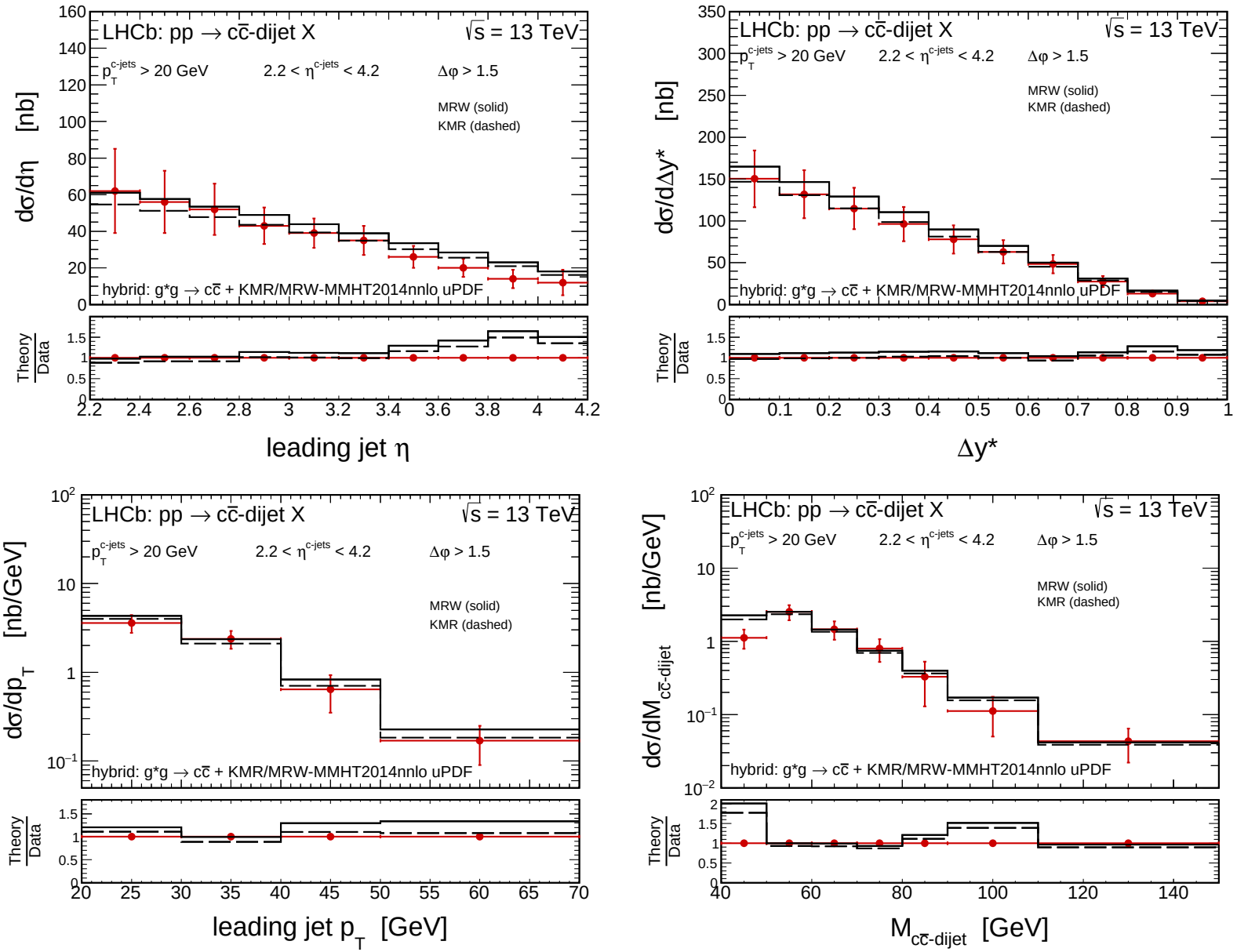


Figure: Here the KMR and the MRW uPDFs are used.

hybrid, $c\bar{c}$ dijets

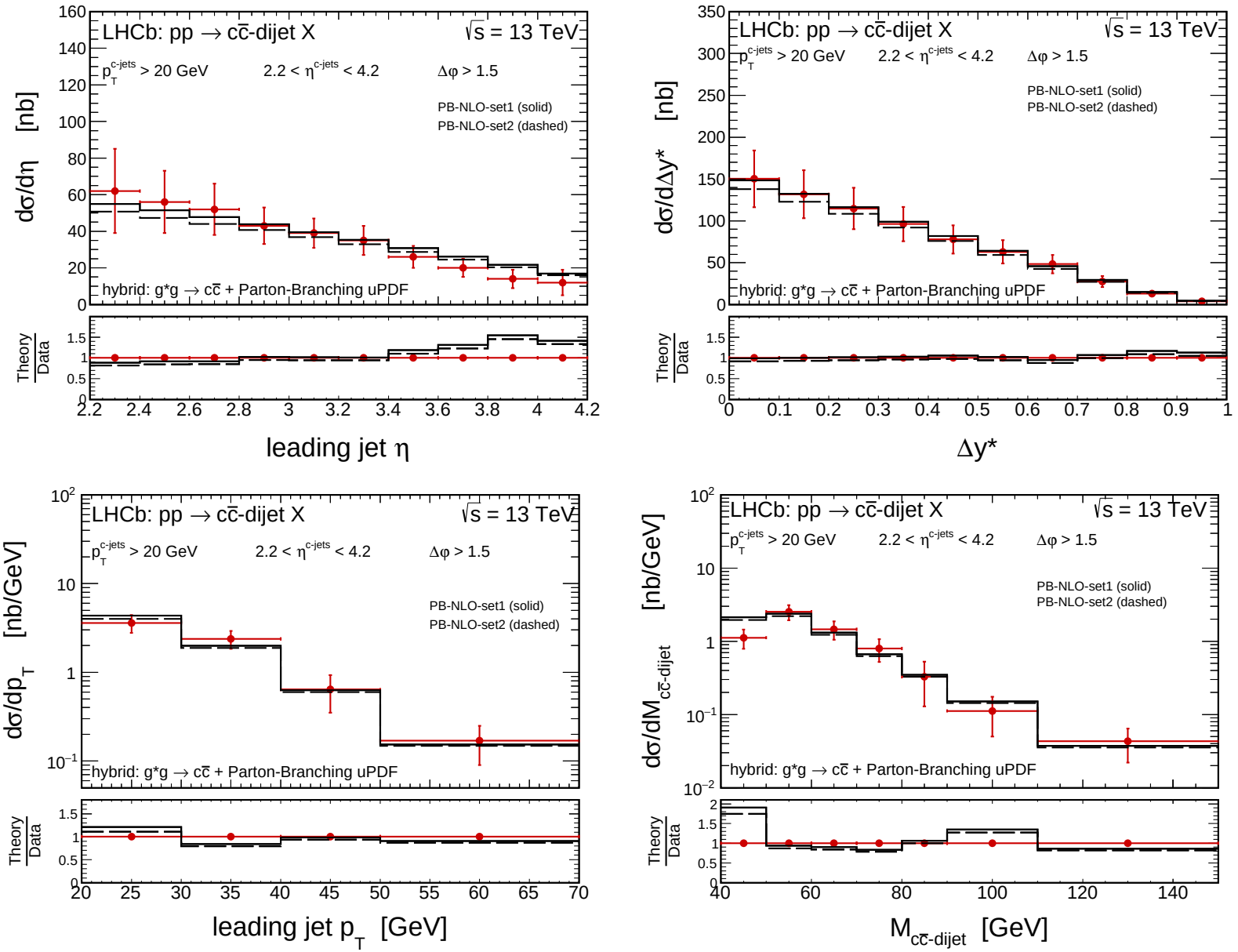
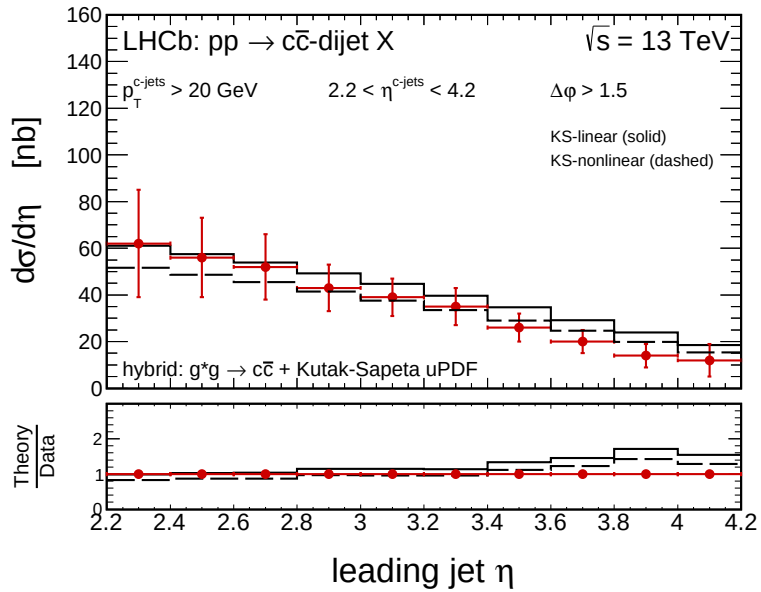
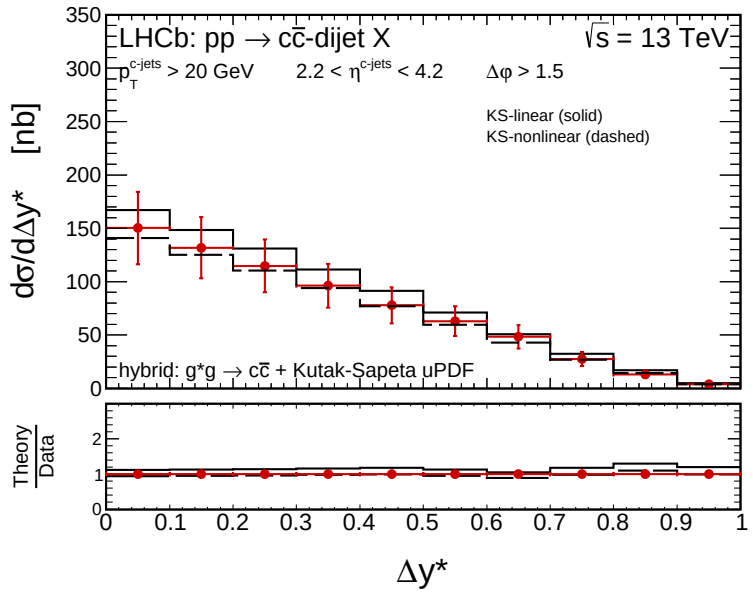
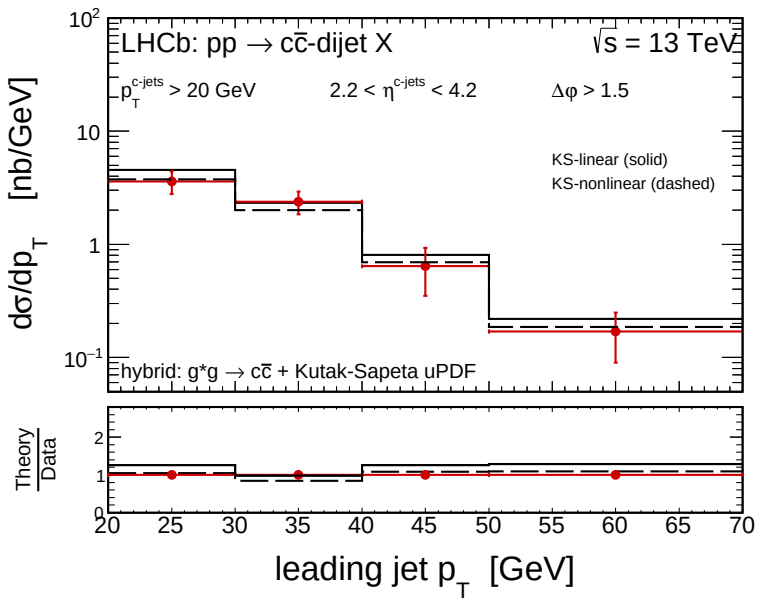


Figure: Here the Parton Branching uPDFs are used.

hybrid, $c\bar{c}$ dijets







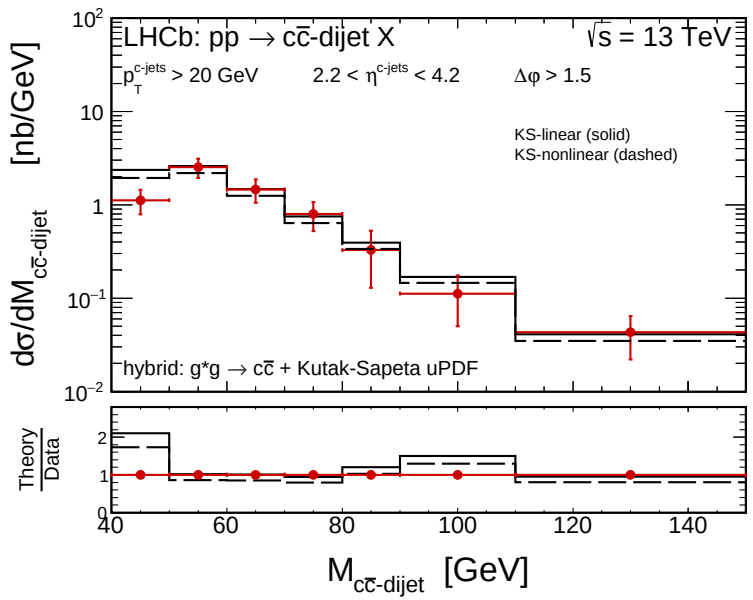
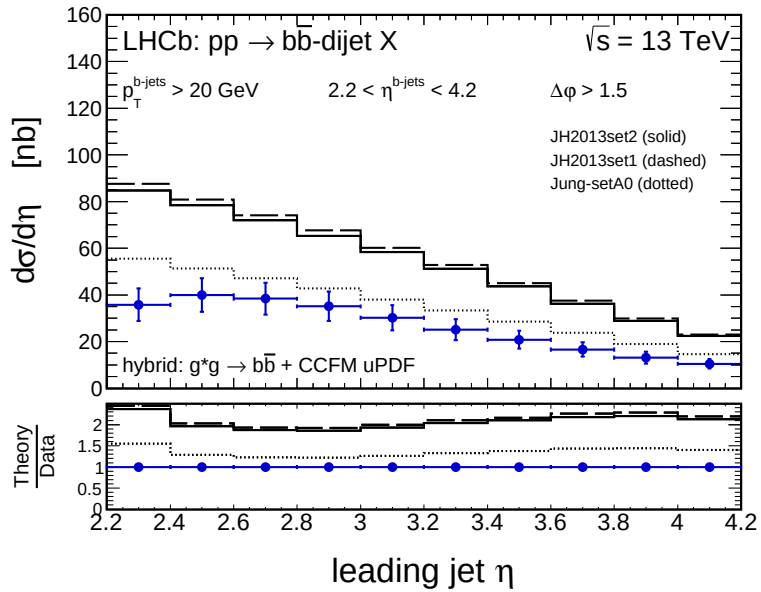
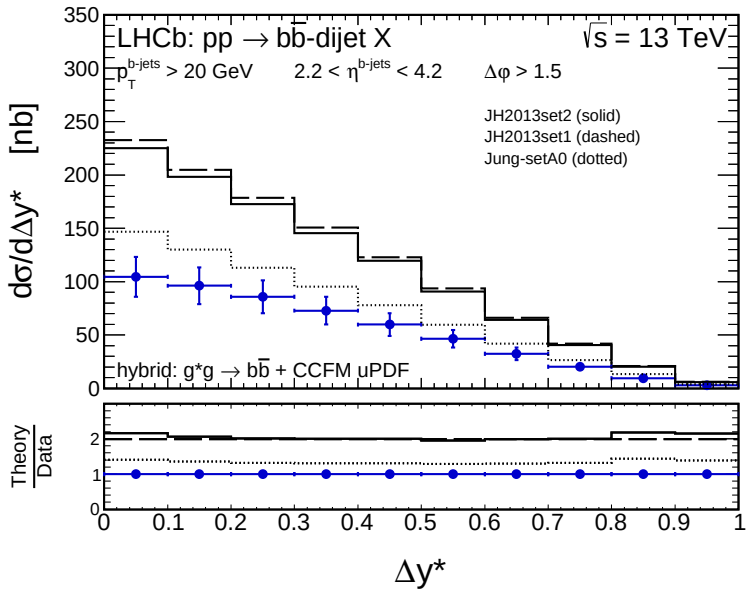
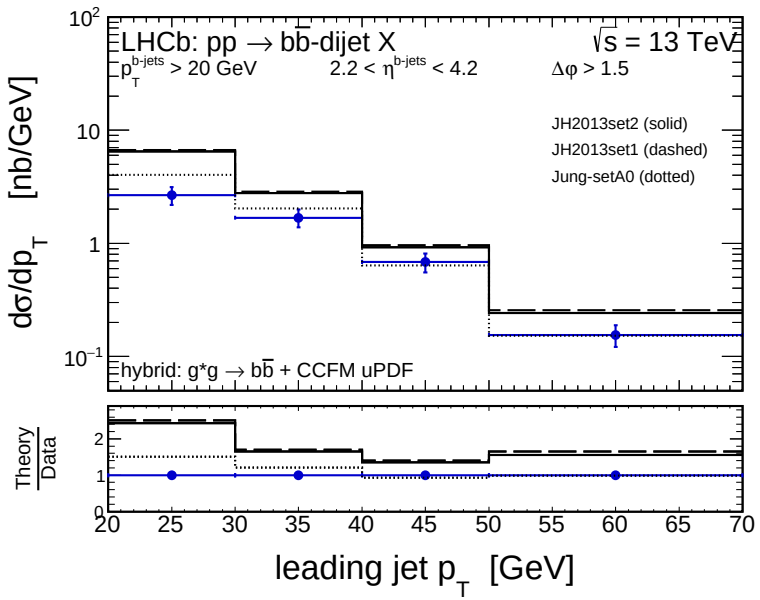


Figure: Here the Kutak-Sapeta uPDFs are used.

hybrid, $b\bar{b}$ dijets







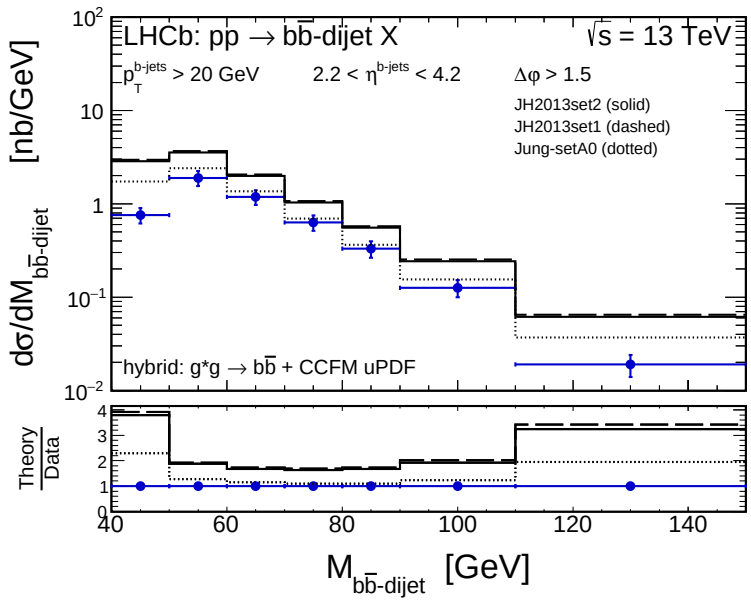
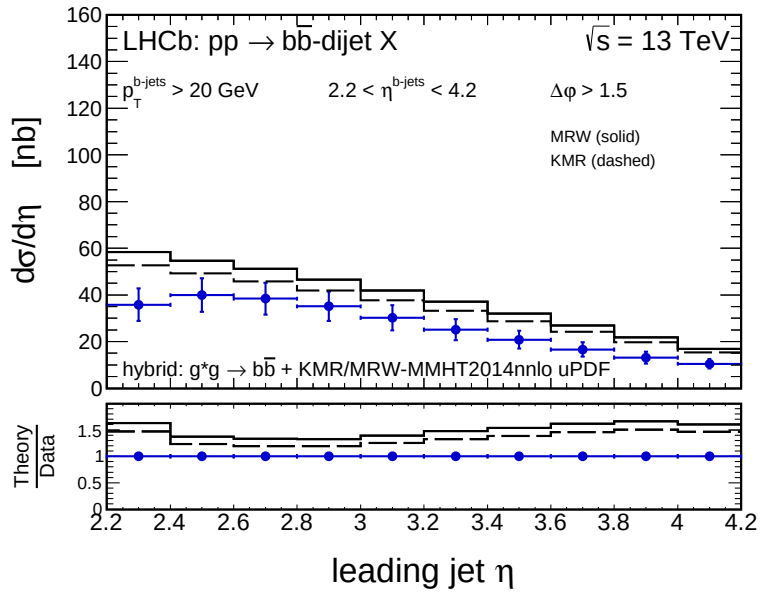
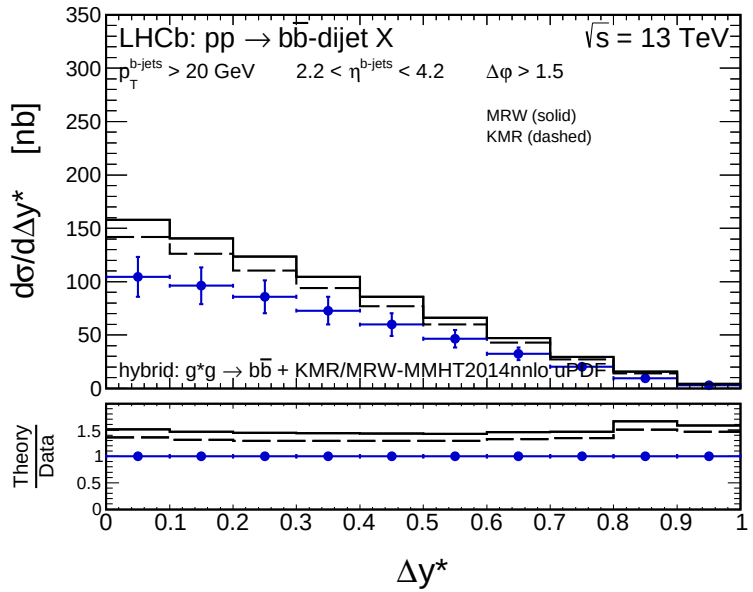
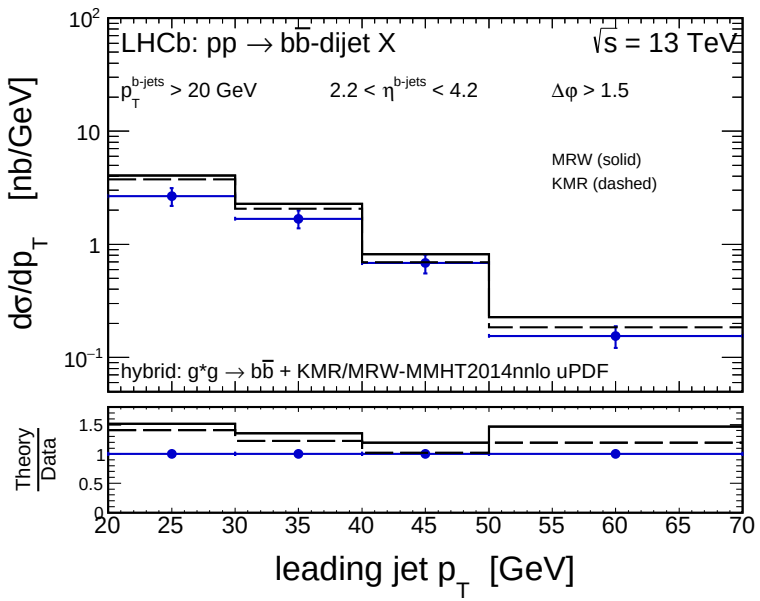


Figure: Here CCFM uPDFs.

hybrid, $b\bar{b}$ dijets







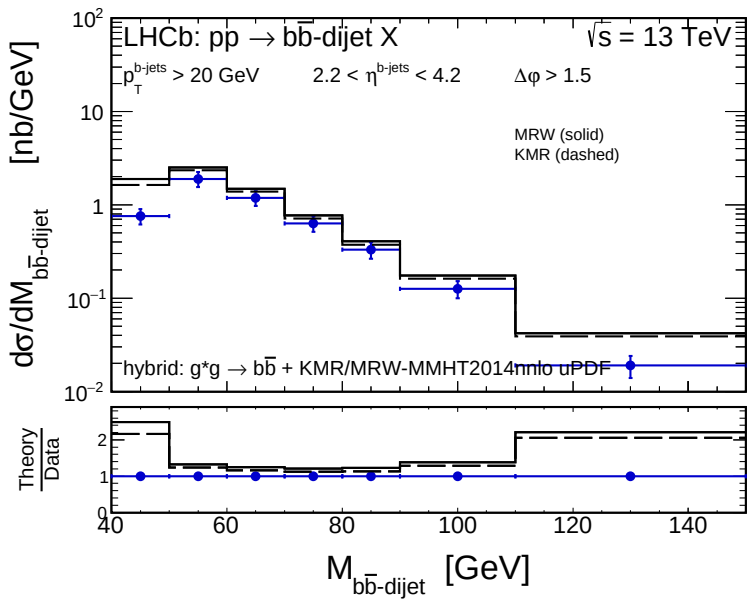


Figure: Here the KMR and the MRW uPDFs are used.

hybrid, $b\bar{b}$ dijets

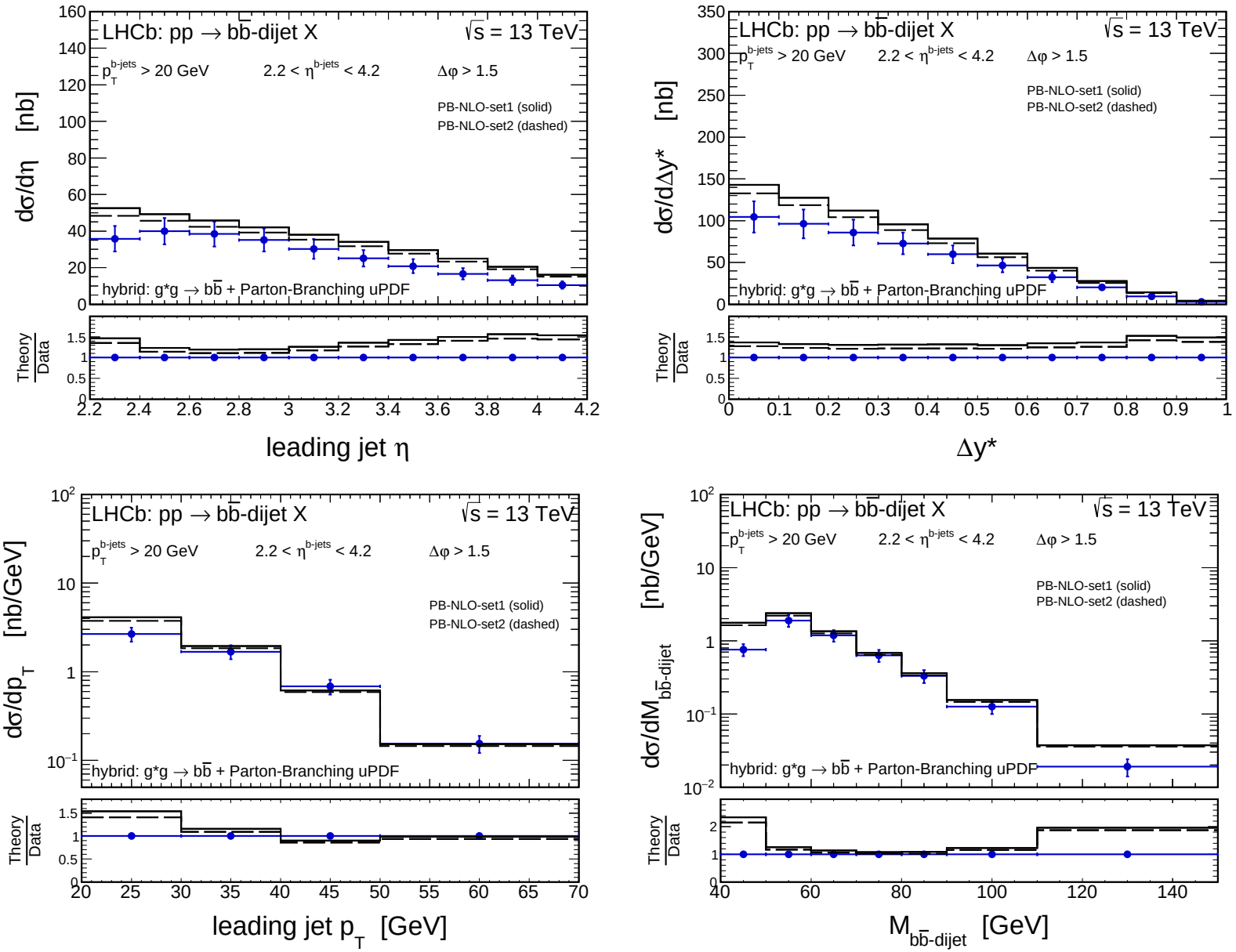
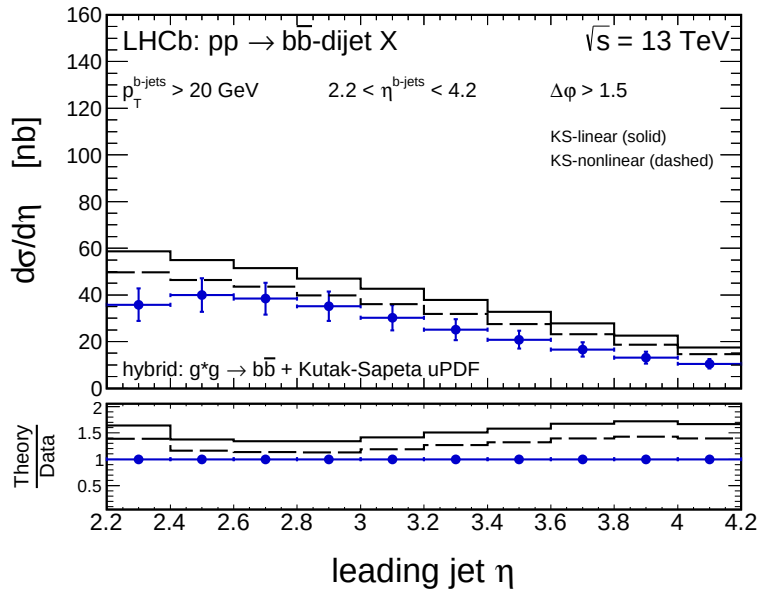
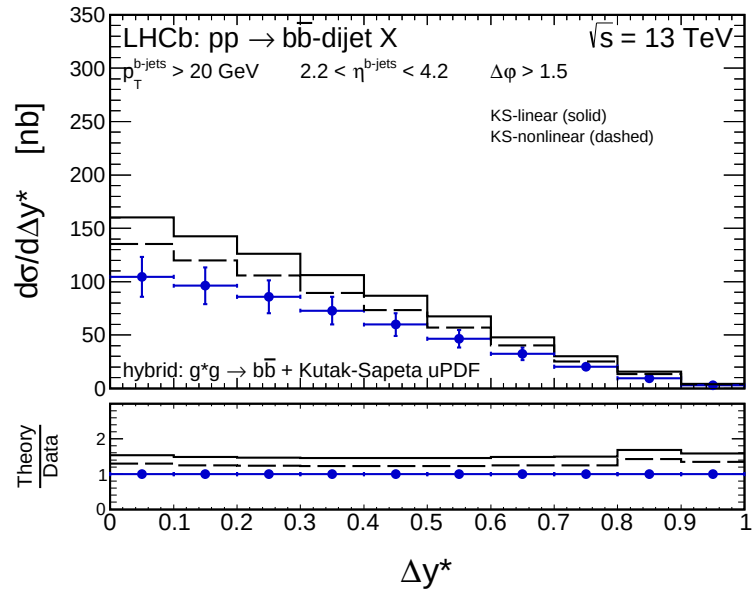
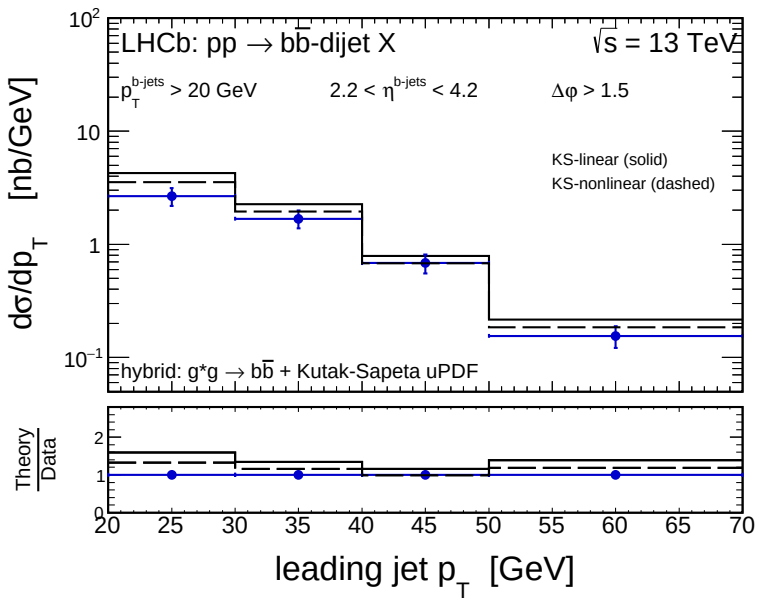


Figure: Here the Parton-Branching uPDFs are used.

hybrid, $b\bar{b}$ dijets







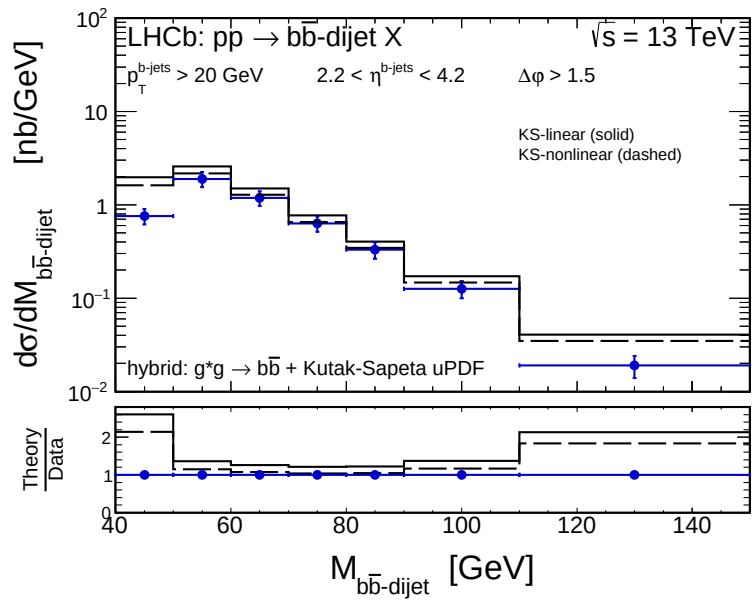
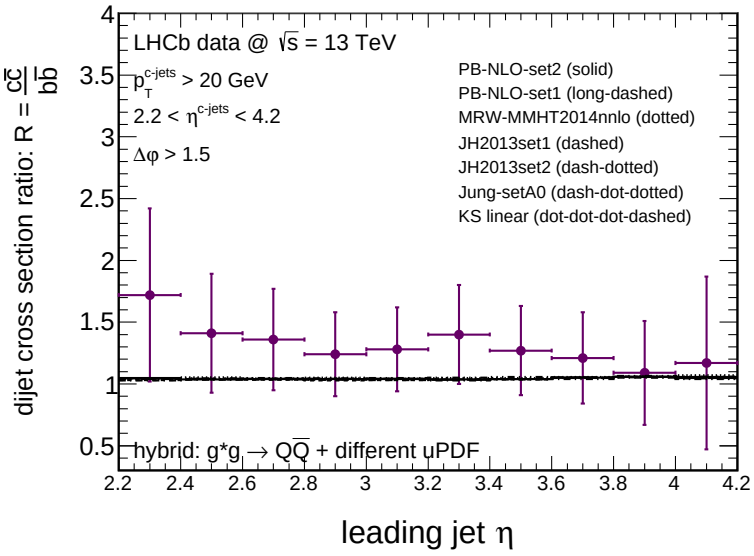
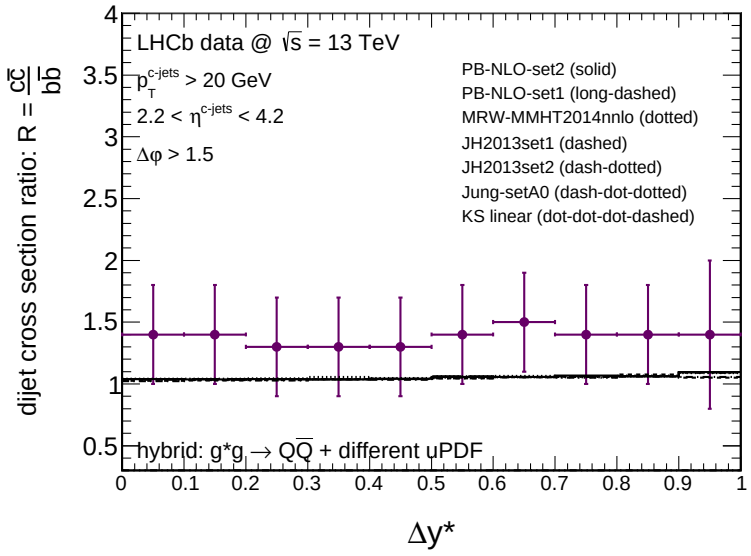
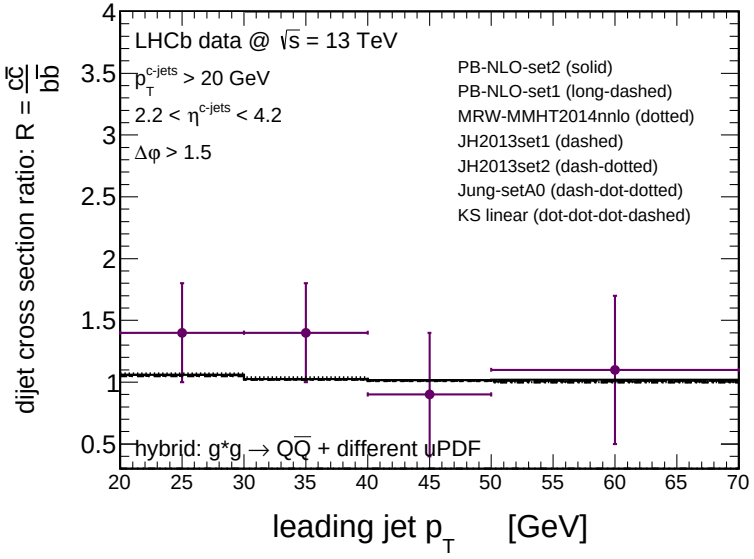


Figure: Here the Kutak-Sapeta uPDFs are used.

The charm/bottom dijet ratio







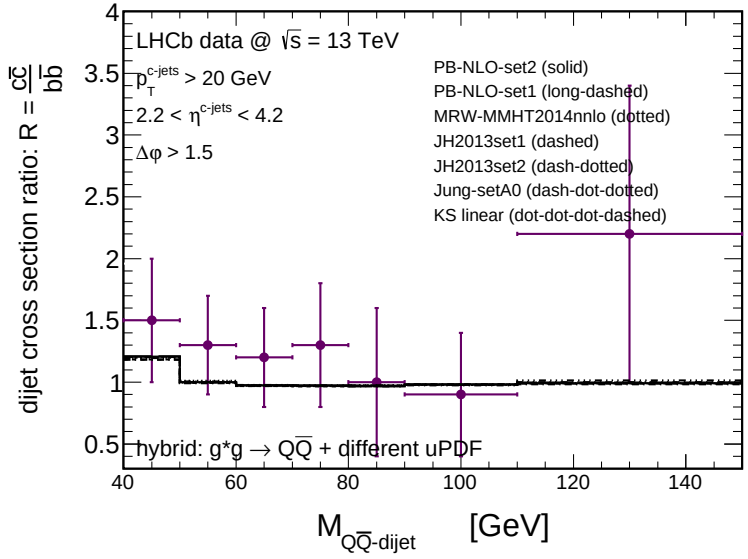
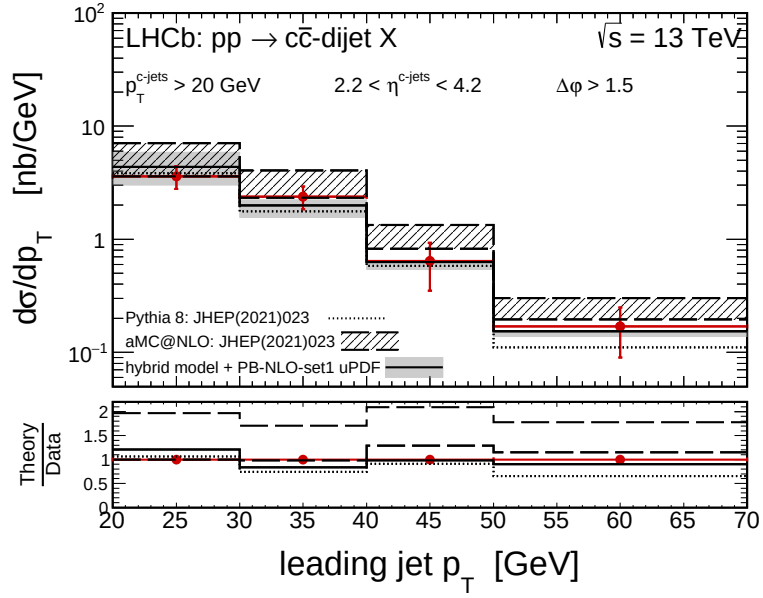
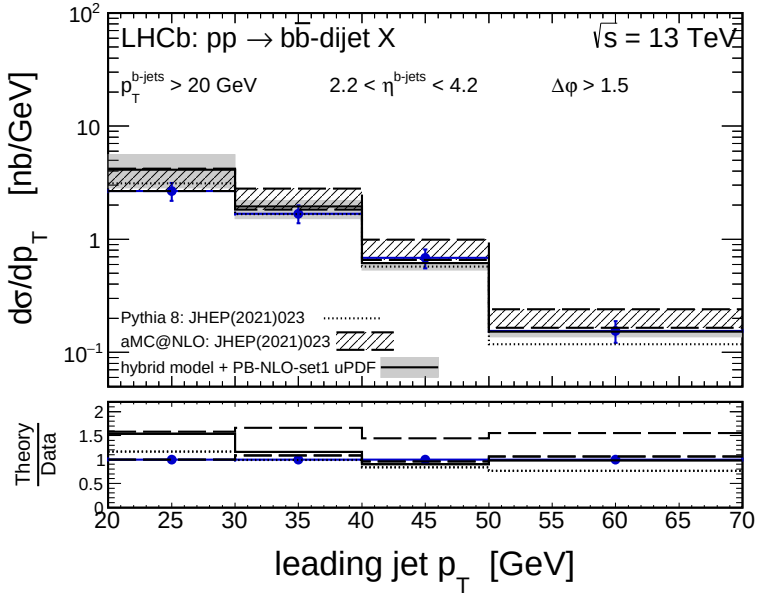
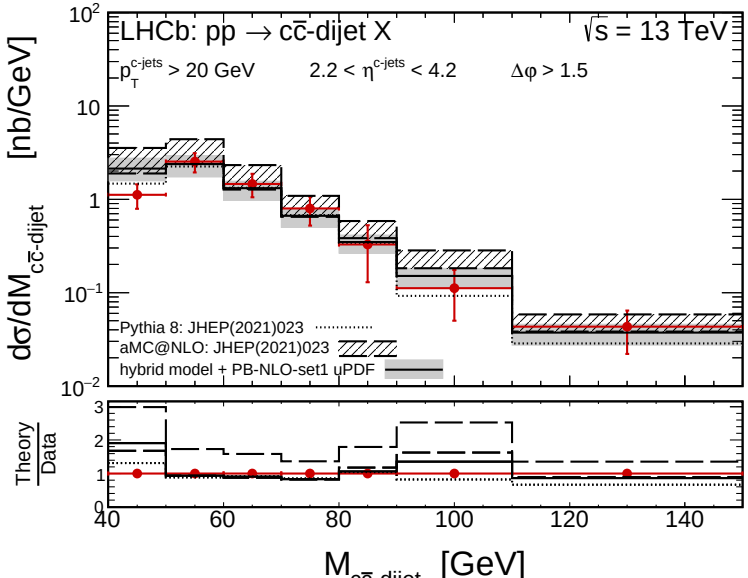


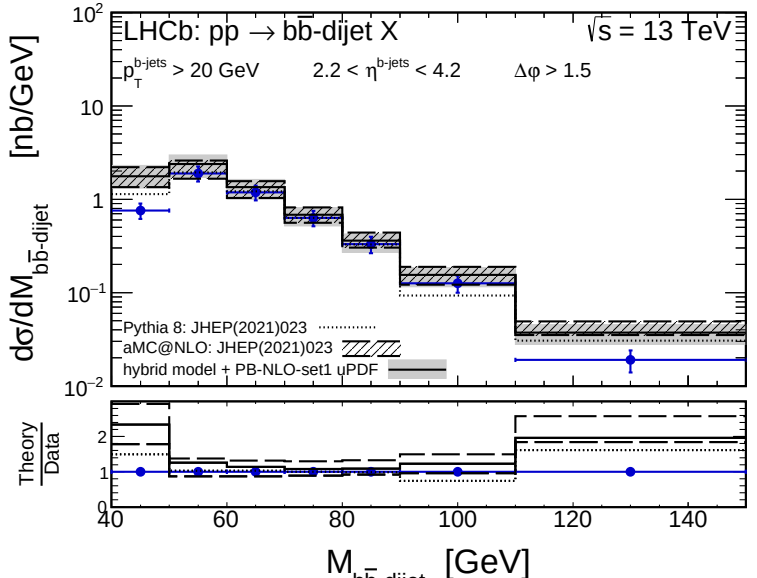
Figure: The ratio $R = \frac{c\bar{c}}{b\bar{b}}$ of the dijet differential cross sections in

A comparison with the results of the collinear approach

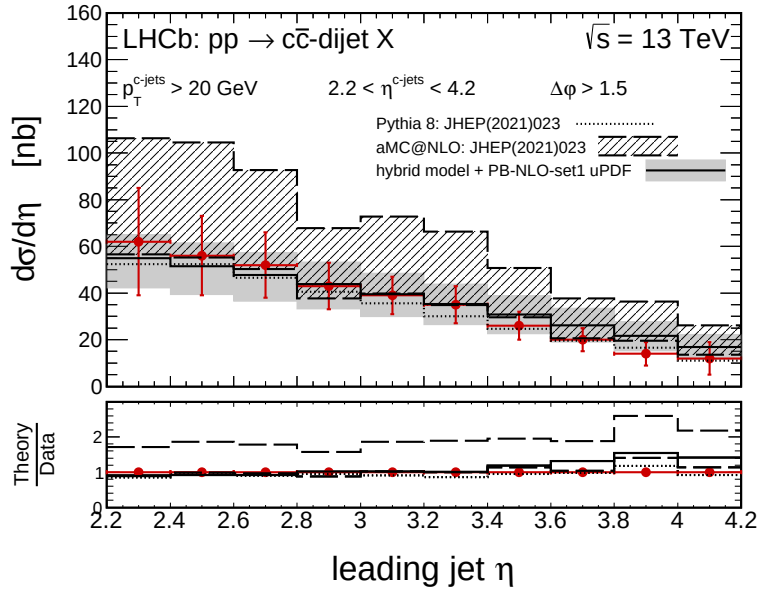


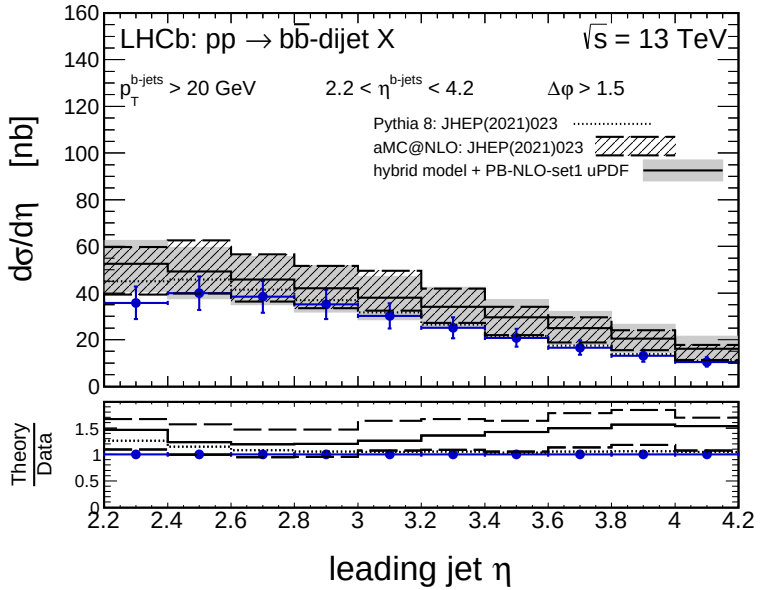


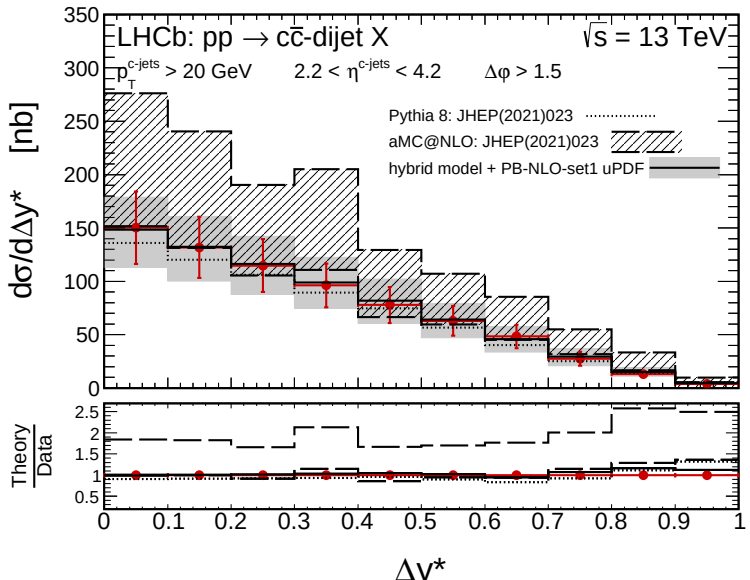


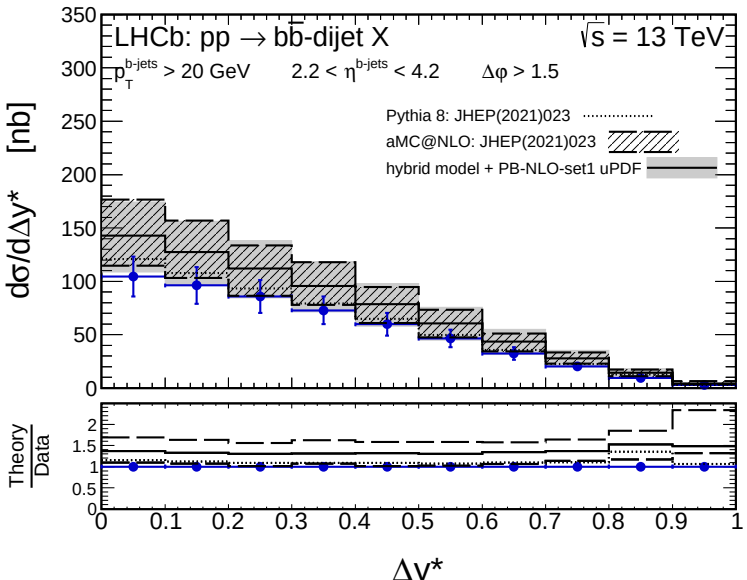


A comparison with the results of the collinear approach

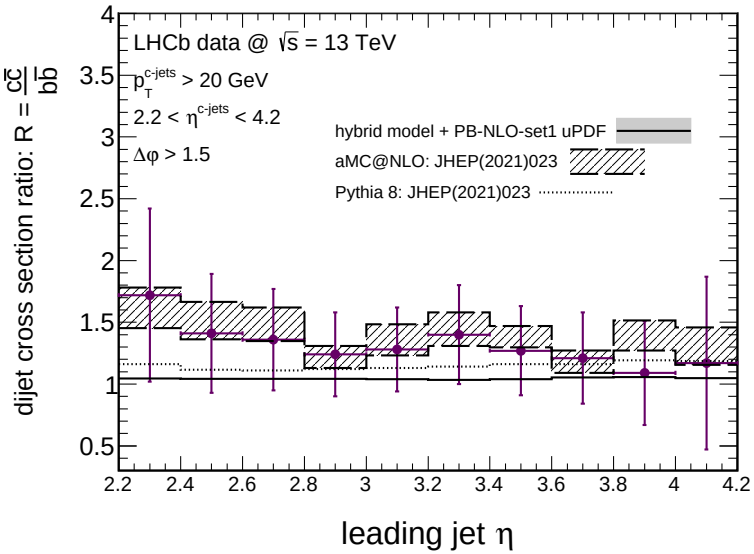


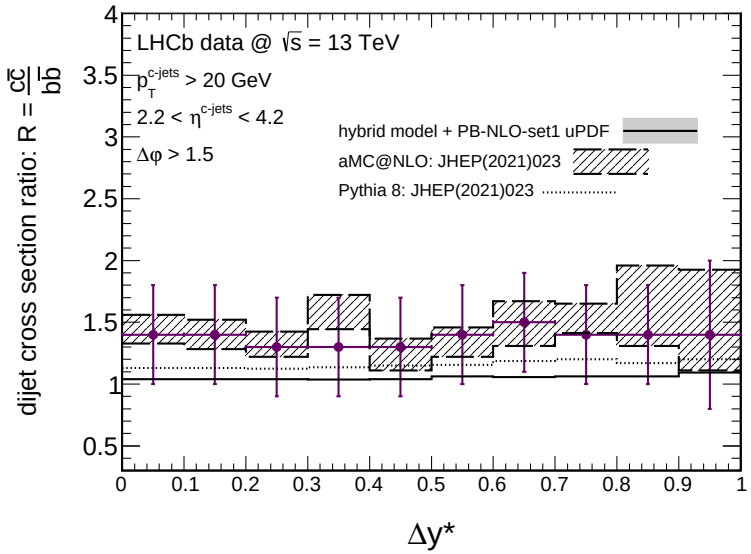


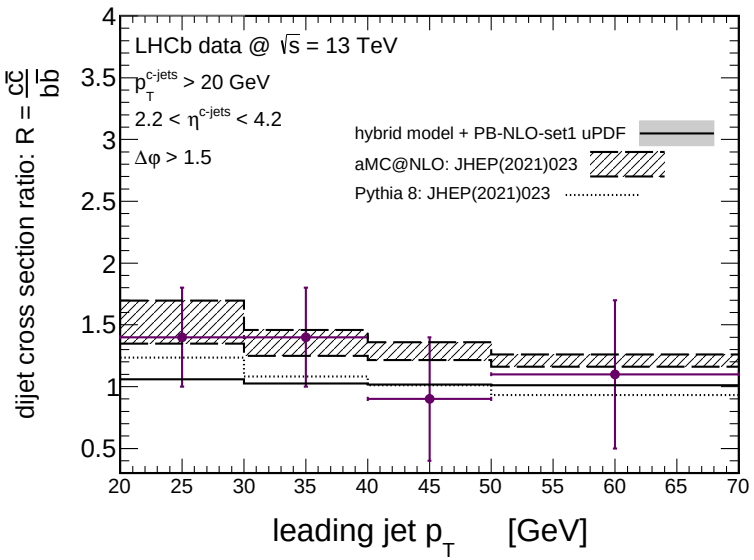


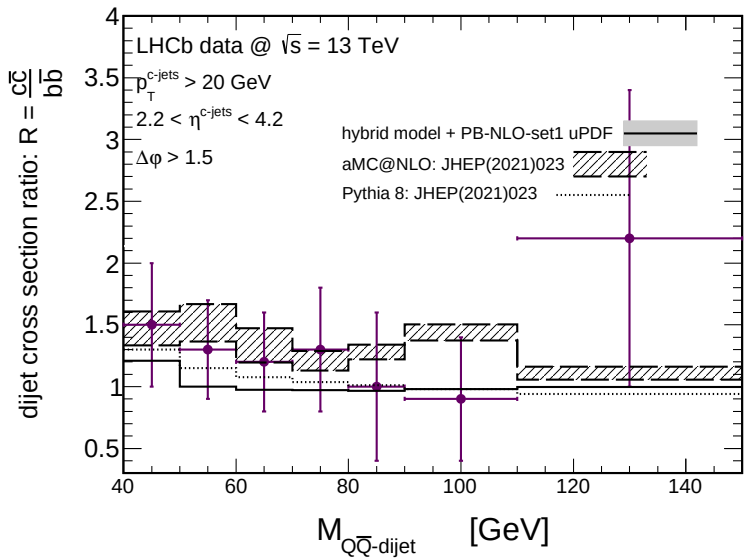


A comparison with the results of the collinear approach









A comment on finite jet size effects

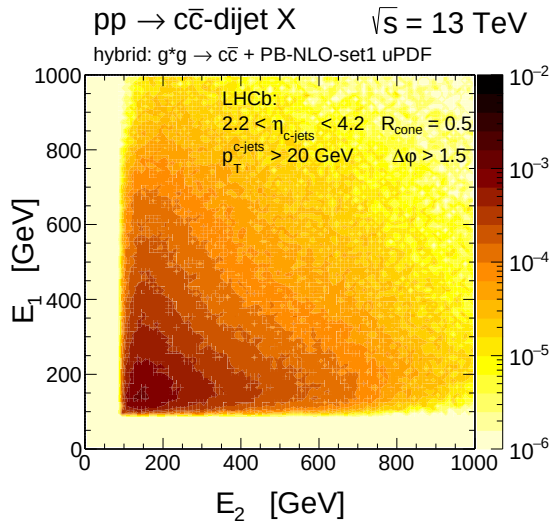


Figure: The double differential cross sections in energies of both jets for forward production of $c\bar{c}$-dijets in pp-scattering at $\sqrt{s} = 13$ TeV probed in the LHCb experiment

A comment on finite jet size effects

The typical jet energies are relatively large $E_1, E_2 > 200$ GeV. In the approach from Goncalves et al. the basic ingredient is $dE_g/dxdk^2$ where E_g is energy of the emitted gluon, x is its longitudinal momentum fraction and k^2 is transverse momentum squared of the gluon with respect to the heavy quark (c or b in our case). This quantity depends on the mass of the emitting quark. In principle, one can expect even a spectacular effect known under the name dead cone. The dead cone effect was observed experimentally recently for the first time by the ALICE collaboration. Energy loss due to emission outside of the jet cone can be then written as

$$\Delta E_g = \int \frac{dE_g}{dxdk^2} \theta\left(\theta > \theta_{\mathrm{open}}(R_{\mathrm{cone}})\right) \ , \tag{2}$$

where $\theta_{\mathrm{open}}(R_{\mathrm{cone}})$ is jet openning angle corresponding to a given jet radius R_{cone}. The distribution $\frac{dE_g}{dxdk^2}$ is obtained from a generalization of the Gunion-Bertsch formula for the gluon number distribution $\frac{dn_g}{dxdk^2}$.

A comment on finite jet size effects

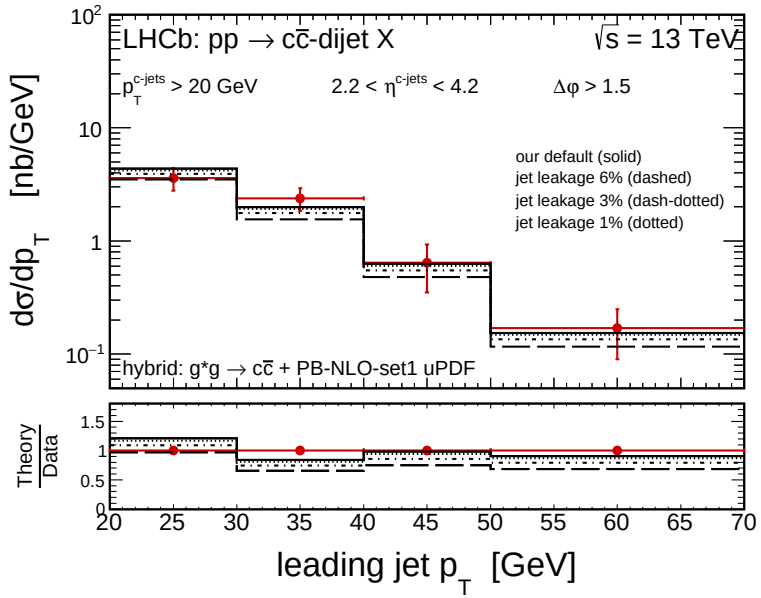


Figure: The differential cross sections for forward production of $c\bar{c}$-dijets in pp-scattering at $\sqrt{s} = 13$ TeV as a function of the leading jet p_T for three different values of the jet leakage effect.

Conclusions

- We have calculated differential distributions for heavy quark dijet production within k_t and hybrid factorization and compared our results to recent data of the LHCb collaboration
- The naive use of the k_t-factorization leads to overestimation of the experimental data for some uGDFs. The large x-region was identified to be a problem for CCFM UGDFs.
- The hybrid factorizations results are much better both for $c\bar{c}$ and $b\bar{b}$ dijets.
- The ratio of the $b\bar{b}$ to $c\bar{c}$ was calculated. We get the ratio very close to 1 while the experimental ratio seems larger.
- A comment on finite size ($R < ...$) was made. A simplified calculation does not allow to describe the ratio as the effect seems small. Such effects do not improve the ratios. In future a Monte Carlo simulation of the c and b jets would be welcomed.