Heavy flavour jet substructure

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Graz, 3rd July 2024

Based on 2312.11623 in collaboration with S. Caletti and S. Marzani, and on a work in progress with P. Dhani, O. Fedkevych, S.Marzani and G.Soyez

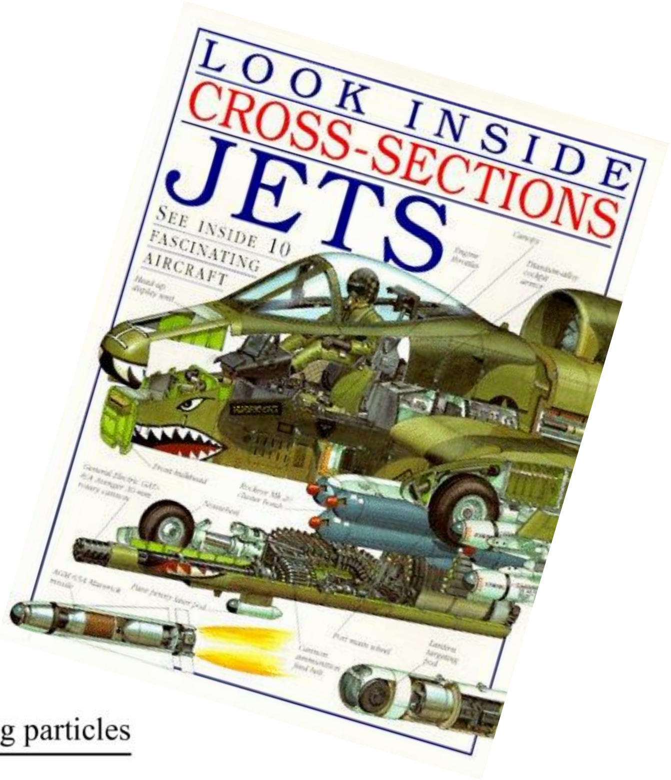
Jet substructure in a nutshell

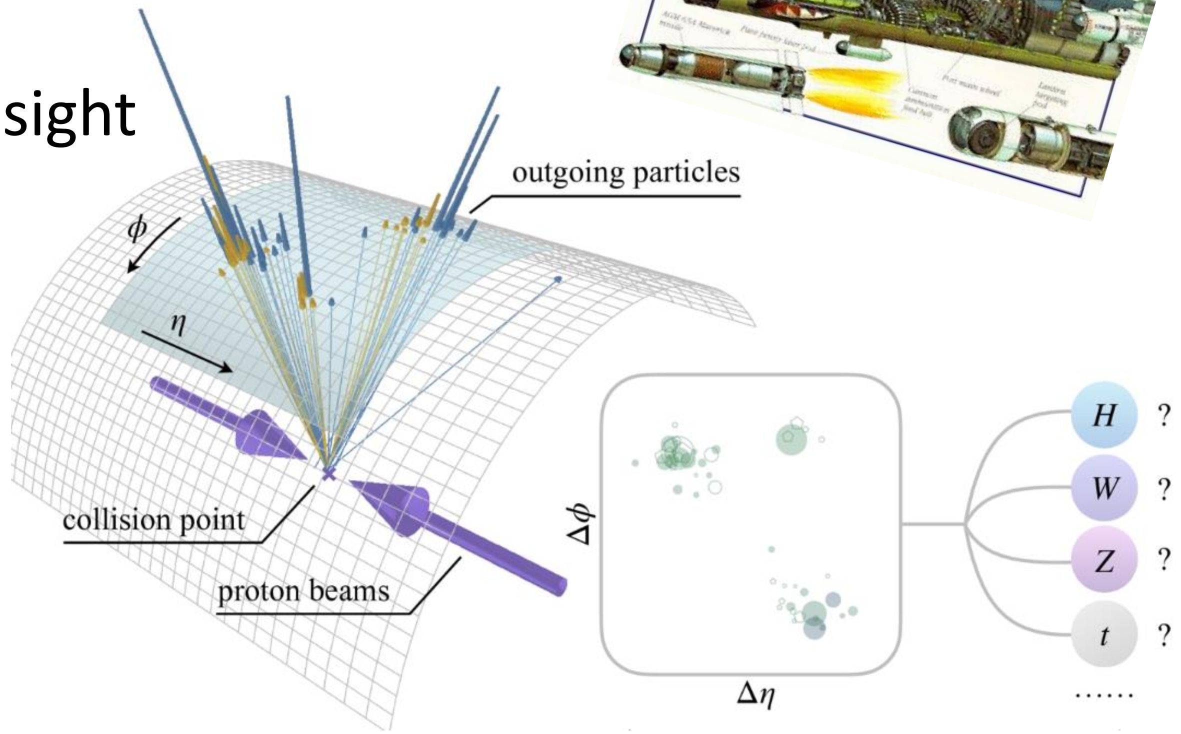
High energy collisions result in collimated sprays of particles

Internal structure of jets gives an insight on the originating splitting process

In a massless theory, the collinear emission is enhanced:

$$\alpha_S \int \frac{d\,\theta^2}{\theta^2} \gg 1$$





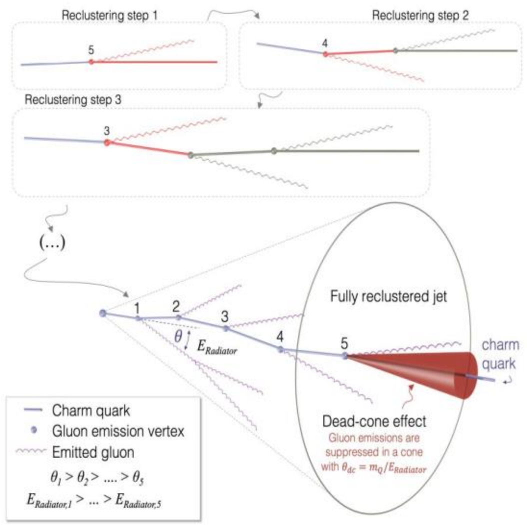
Jets to probe heavy flavours

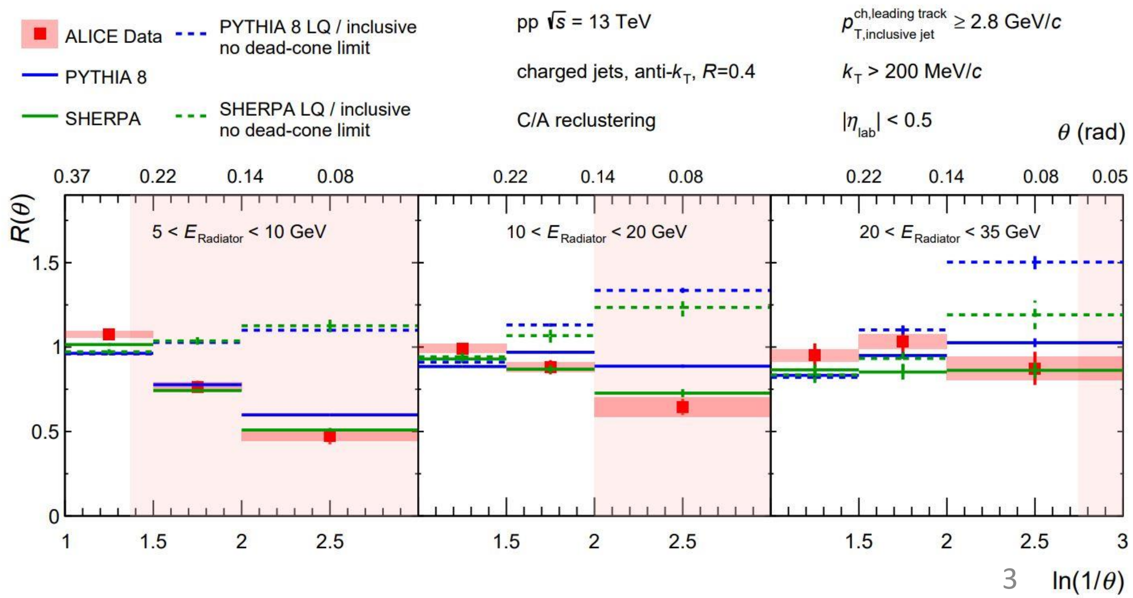
When jets are initiated by a heavy flavour, the quark mass shields the collinear singularity

$$\alpha_s \int \frac{d\,\theta^2}{\theta^2 + \frac{m^2}{E^2}} \simeq \alpha_s \log \frac{m^2}{E^2}$$

Dead Cone effect

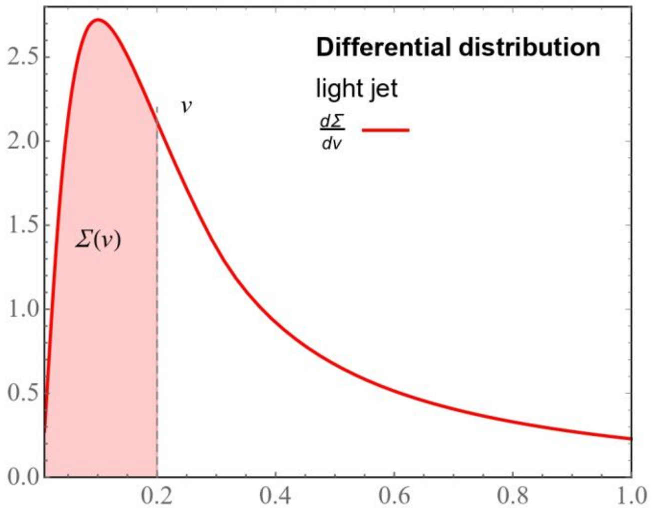
the radiation emitted off a heavy flavour is suppressed inside a cone of opening angle $\theta \sim m/E$ (ALICE)





Theoretical Framework: light jet

Given an observable v, from a theoretical point of view it is natural to compute the resummation of the cumulative distribution



$$\Sigma(v) = \frac{1}{\sigma_0} \int_0^v \mathrm{d}v' \, \frac{\mathrm{d}\sigma}{\mathrm{d}v'}$$

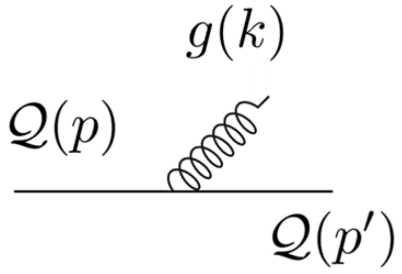
- v is a function of momenta that vanish when no emissions occur (Born level)
- v must be IRC safe

Collinear factorization

We begin studying the case of the single emission off a quark.

The matrix element factorizes in the collinear limit, thus we can write the cumulative as:

$$\Sigma(v) = 1 - \sum_{\ell} \int_0^{Q^2} \frac{\mathrm{d}k_t^2}{k_t^2} \int_0^1 \mathrm{d}z P_{\mathcal{Q}g}(z) \frac{\alpha_\mathrm{s}}{2\pi} \Theta\left(\mathcal{V}^\ell(k_{t_\ell}^2, \eta_\ell) - v\right)$$



$\mathcal{V}$ represents the soft and collinear limit of the observable and in general can be written (Banfi, Salam, Zanderighi)

$$\mathcal{V}^\ell\left(k_{t_\ell}^2, \eta\right) = d_\ell \left(\frac{k_{t_\ell}^2}{Q^2}\right)^{\frac{a_\ell}{2}} e^{-b_\ell \eta_\ell}$$

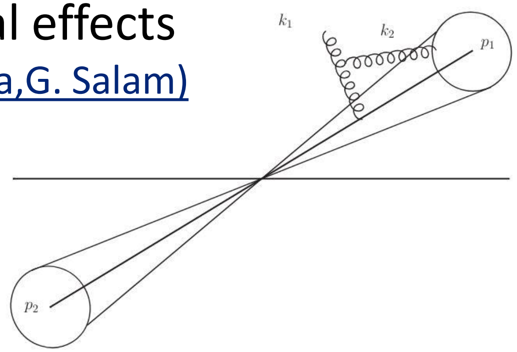
Going to all orders

Taking into account an infinite number of emissions, at NLL accuracy we have:

$$\Sigma(v) = e^{-R(v)}\mathcal{F}S$$

Multiple emission

Non-global effects
(M. Dasgupta,G. Salam)

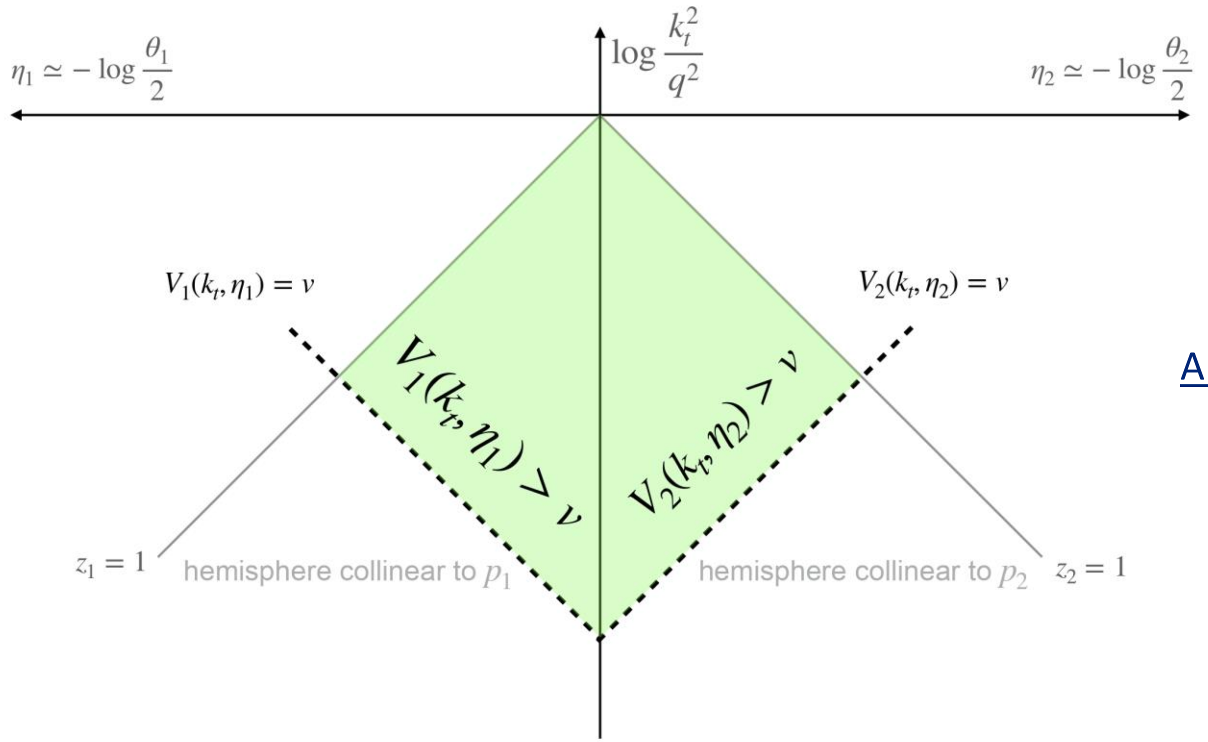


with R the radiator defined as:

$$R(v) = \sum_{\ell}\int_0^{Q^2}\frac{\mathrm{d}k_t^2}{k_t^2}\int_0^1 \mathrm{d}z P_{\mathcal{Q}g}(z)\frac{\alpha_s^{\mathrm{CMW}}(k_{t_\ell}^2)}{2\pi}\Theta\left(\mathcal{V}^\ell(k_{t_\ell}^2,\eta_\ell) - v\right)$$

Lund Plane geography for light quarks

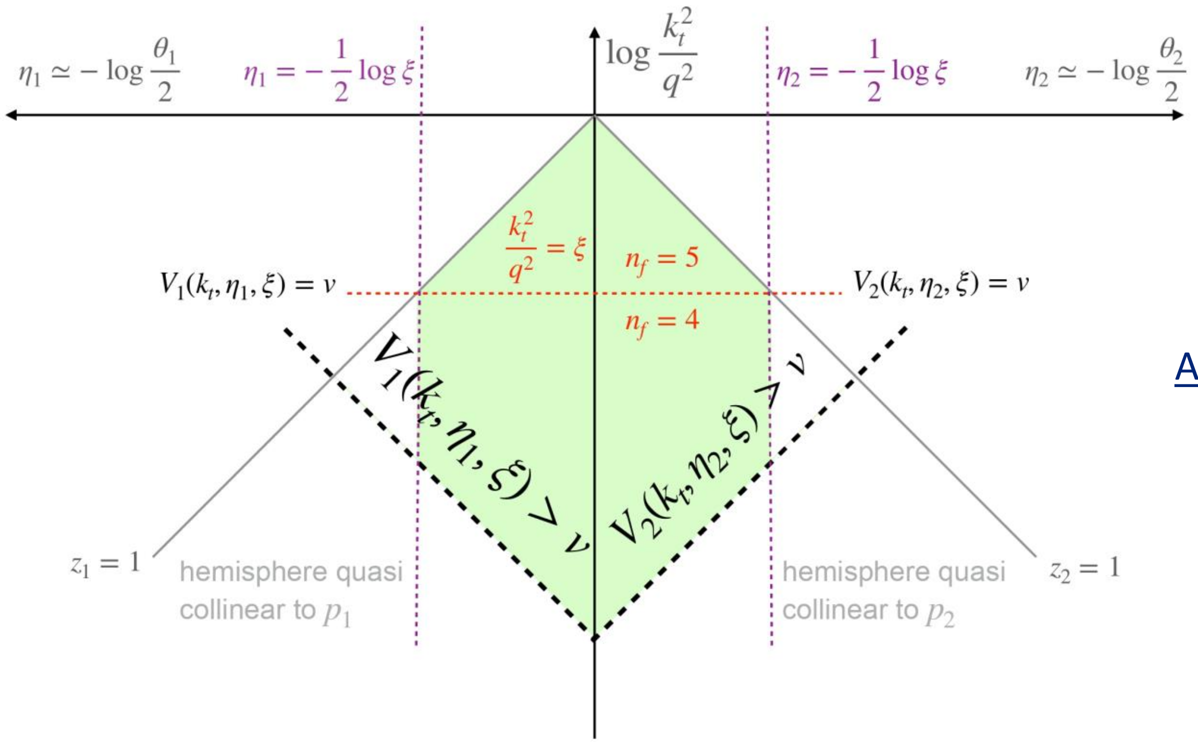
In order to perform the calculation of R, we exploit the Lund diagrams.



A.G., S. Marzani, G. Ridolfi

Differences with the massive case

- Threshold in the running of the coupling
- Dead-cone effect



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Mass effects on θ_g and z_g distribution

We want to examine observables which are sensitive to the dead cone.

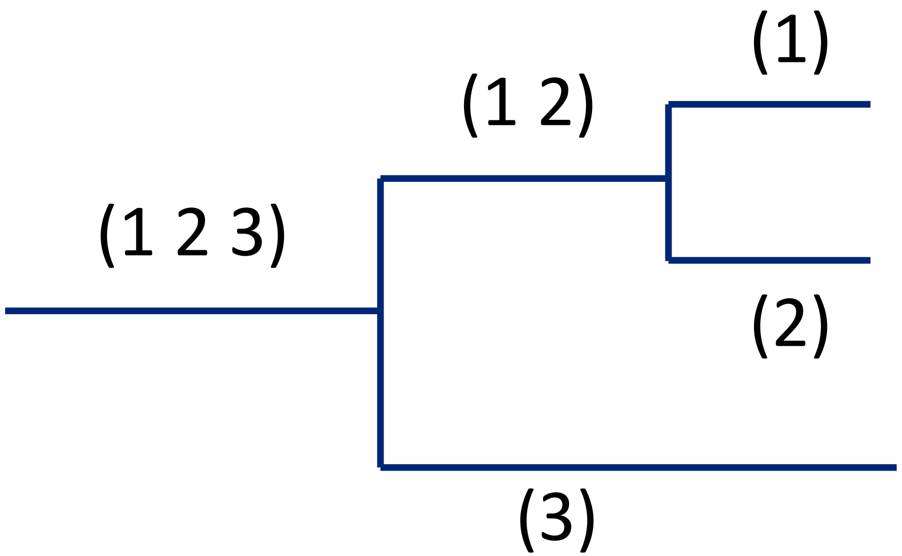
To start, we consider heavy-flavour initiated jets groomed with the Soft-Drop procedure (A. Larkoski, S. Marzani, G. Soyez, J. Thaler).

θ_g: angular opening of the groomed jet (access to the dead-cone)
z_g: allows us to probe the heavy quark splitting function

Recent measurement by ALICE of the SD observables on c-jets.

The Soft Drop Procedure

The SD algorithm removes consistently soft emission at large angle



$$\frac{\min\left(p_{t(12)}, p_{t(3)}\right)}{p_{t(12)} + p_{t(3)}} > z_{\rm cut} \left(\frac{\Delta_{(12)(3)}}{R_0}\right)^{\beta},$$

$$\Delta_{(12)(3)} = \sqrt{(y_{(12)} - y_{(3)})^2 + (\phi_{(12)} - \phi_{(3)})^2}.$$

The jet constituents of an anti-k_t are re-clustered according to C/A, to form an angular ordered tree. The declustering is then applied.

Definition of the observables

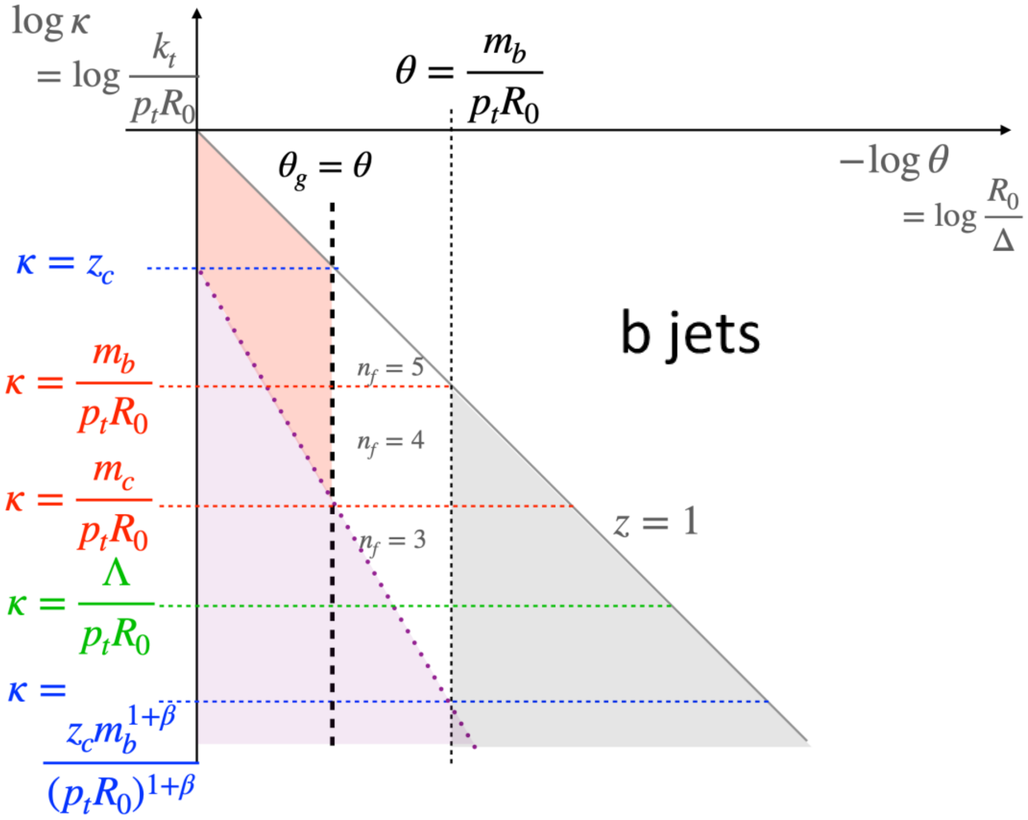
The first branching that passes the soft-drop procedure defines the groomed jet radius θ_g and the groomed fraction of momentum z_g

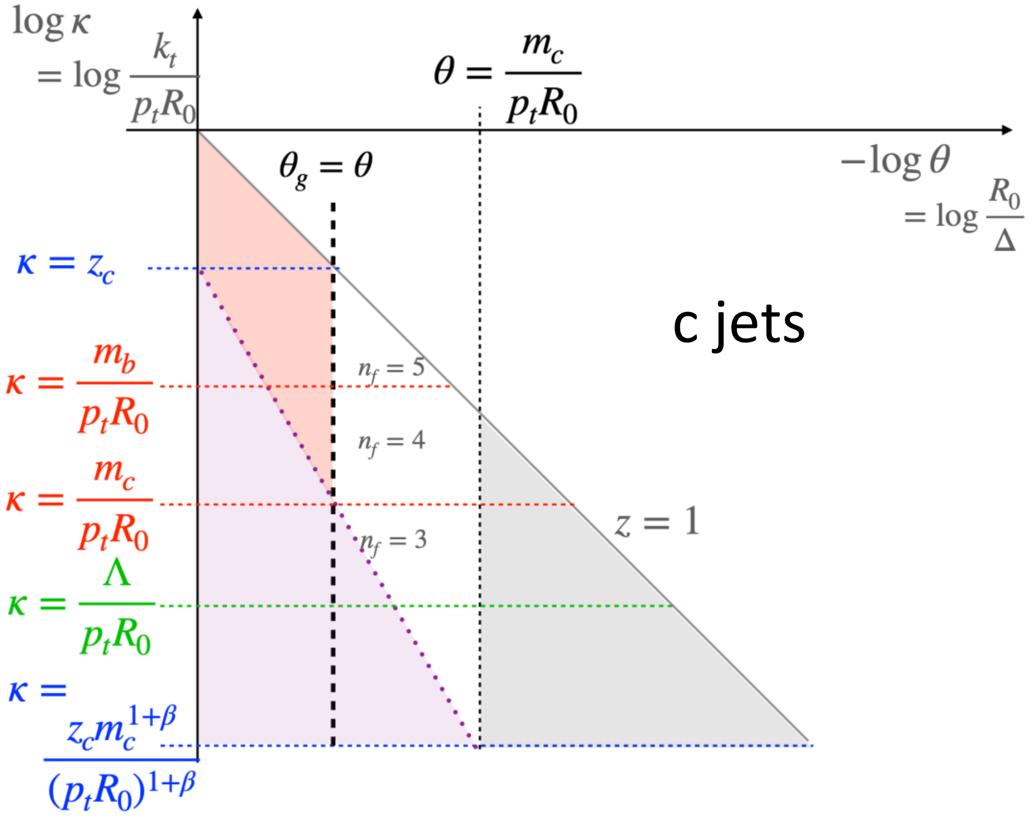
$$\theta_g = \frac{\Delta_{(12)(3)}}{R_0}, \qquad z_g = \frac{\min\left(p_{t(12)}, p_{t(3)}\right)}{p_{t(12)} + p_{t(3)}}.$$

- The θ_g distribution is IRC safe both for massive and massless particles.

- The z_g distribution is IRC safe for massless particles only for $\beta < 0$. Conversely, it is always IRC safe for massive particles.

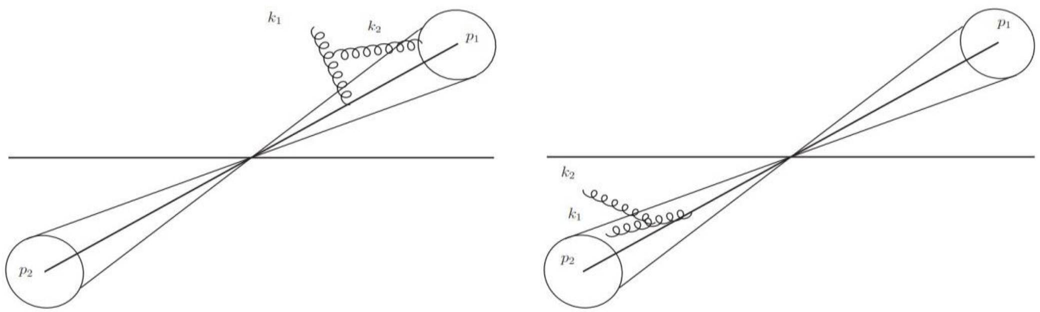
Analytic understandings of θ_g distribution





Non global Logs

- Non global logs represent correlated gluon emissions (M. Dasgupta, G. Salam and A. Banfi, M. Dasgupta, K. Khelifa-Kerfa, S. Marzani)



- Their contribution is reduced with the inclusion of clustering effects

(Z. Kang, K. Lee, X. Liu, D. Neill, F. Ringer)

$$S_0(\theta_g) = 1 + \left(\frac{\alpha_s}{\pi}\right)^2 \frac{\pi^2}{108} \left(C_F^2 - 4C_F C_A\right) \log\left(z_{\mathrm{cut}} \theta_g^\beta\right)^2 + \mathcal{O}(\alpha_s^3)$$

Mass effects on NGLs

The inclusion of the masses in the computation further reduce the effect of the NGLs.

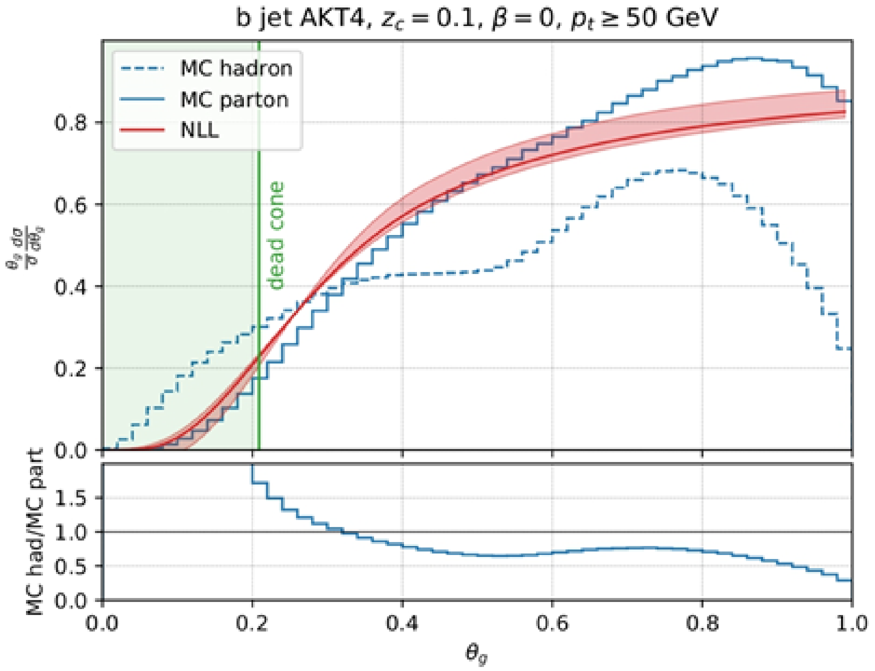
$$S(\theta_g,\theta_i) = 1 + \left(\frac{\alpha_\mathrm{s}}{\pi}\right)^2 \left(C_\mathrm{F}^2\mathcal{F}_1\left(\theta_g,\theta_i\right) + C_\mathrm{F}C_\mathrm{A}\mathcal{F}_2\left(\theta_g,\theta_i\right)\right)\log\left(z_\mathrm{cut}\theta_g^\beta\right)^2 + \mathcal{O}(\alpha_\mathrm{s}^3)$$

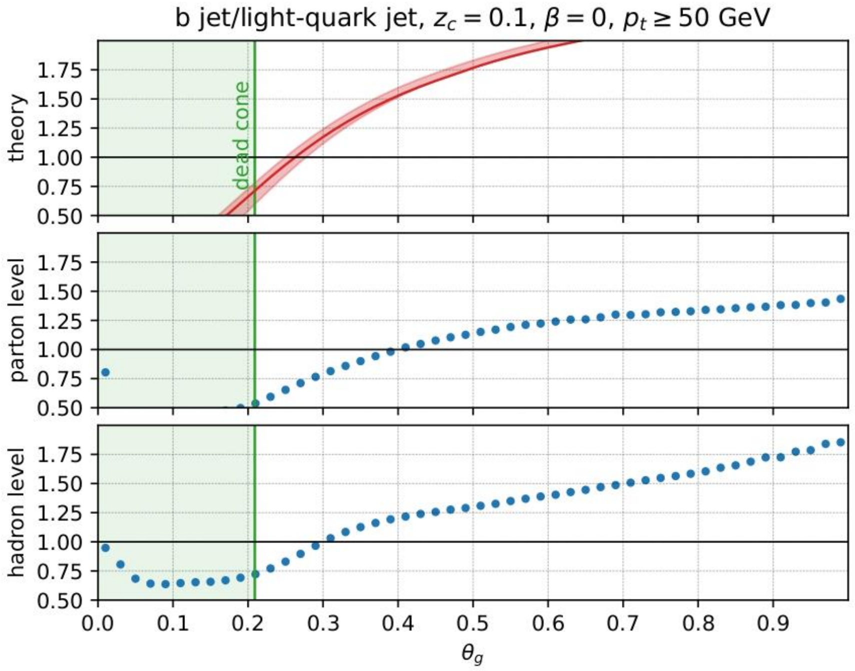
$$\lim_{\theta_g\to 0}\mathcal{F}_1(\theta_g,\theta_i) = \lim_{\theta_g\to 0}\mathcal{F}_2(\theta_g,\theta_i) = 0$$

- This result is related to the requirement that one of the two gluons is within the jet radius. Performing the small θ_g limit of such configuration $S \to 1$.

- The resumed expression is approximated by exponentiating the two-loop result with RC corrections

$\boldsymbol{\theta_g}$ distribution: Comparison with Monte Carlo





- Good agreement with Monte Carlo simulations (especially for $\beta = 0$).
- Sensitive to the dead-cone
- The two distributions (heavy and light) are normalized to have area 1 (tagging mode).

z_g distribution: Sudakov Safety

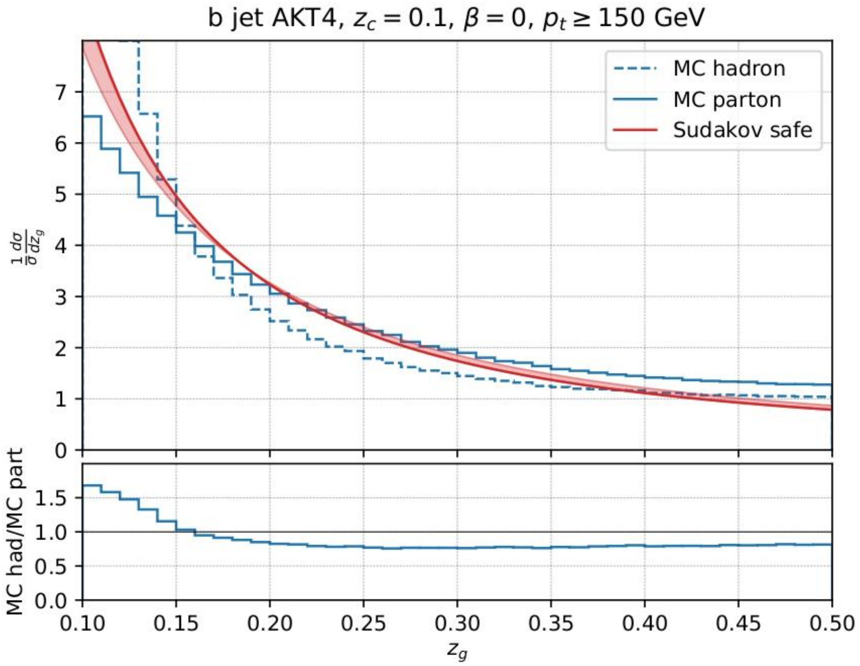
In the massless case z_g is not an IRC safe observable

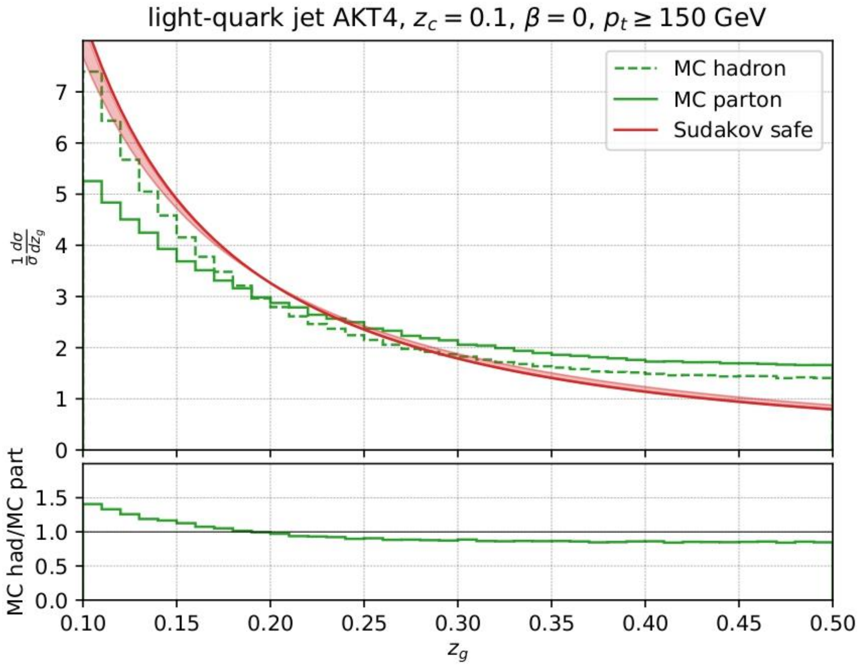
$\Rightarrow$ Sudakov Safety (A. Larkoski, S. Marzani, J. Thaler) .

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \int_0^1 \mathrm{d}\theta_g \left[\frac{p(z_g,\theta_g)}{p(\theta_g)}\right]^{\mathrm{F.O}} p(\theta_g)^{\mathrm{RES}}, \quad p(\theta_g) = \frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}\theta_g}$$

- In the massless case , this mechanism allows to obtain a finite expression of the differential cross section.
- The full resummation of the logs of z_g and z_{cut} is performed in (P. Cal, K. Lee, F. Ringer, W. Waalewijn), but not considered here

z_g distribution: Comparison with Monte Carlo





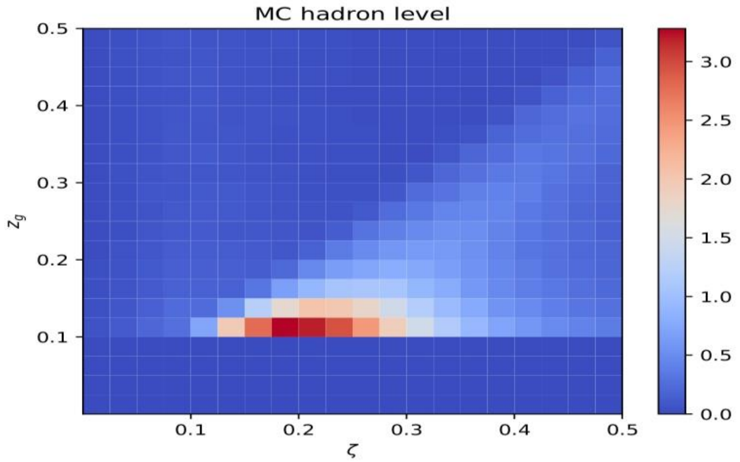
- Similar behaviour of the two differential distributions $\rightarrow$ same leading term in the splitting function $1/z_g$
- Lack of agreement in the large z_g region $\rightarrow$ missing symmetrization of the splitting function

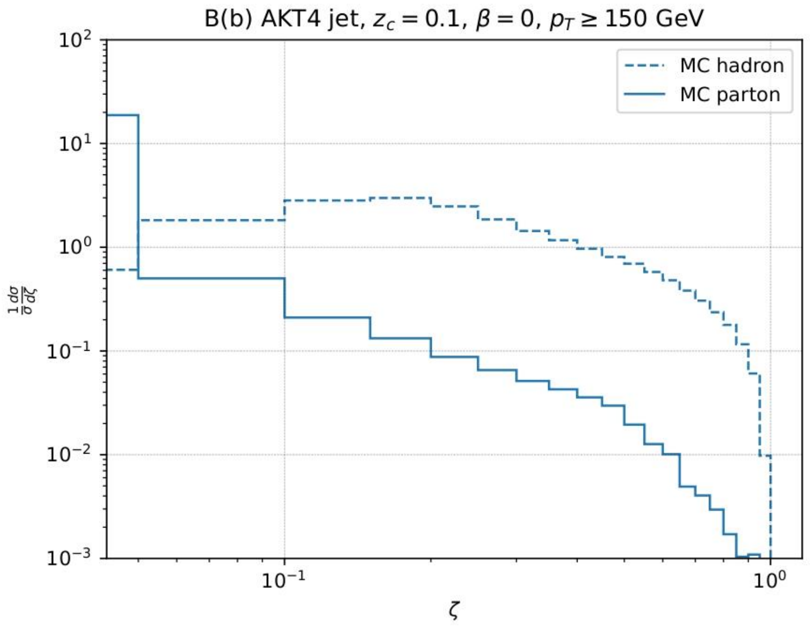
Correlation with fragmentation distribution

We study the correlation between the fragmentation variable $\zeta = 1 - \frac{p_{T,b}}{p_{T,J}}$ and z_g:

At order α_S: $$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma^{(\mathrm{f.o.})}}{\mathrm{d}\zeta} = -\frac{\alpha_s C_F}{\pi}\frac{\log\left(\frac{m_i^2}{p_t^2 R_0^2}\right)}{\zeta}$$

Identical to z_g distribution at this order!





- The spectrum of the b quark is strongly affected by hadronization.
- z_g distribution remains more stable with the inclusion of NP corrections

Mass effects on angularities and ECF

- We now study another class of observables: jet angularities and energy-correlation function (ECF).

- Many possible choices in the definition of observables sensitive to the dead-cone

  (C. Lee, P. Shrivastava, V. Vaidya)

Which one is more sensitive to dead-cone effect?

Example: ECF in pp collisions

Linked to the mass of the particles

$$e_\alpha = \sum_{i \neq j \in \mathrm{Jet}} \frac{p_{t_i} p_{t_j}}{p_t^2} \left(\frac{\Delta_{ij}}{R_0} \right)^\alpha , \quad \dot{e}_\alpha = \sum_{i \neq j \in \mathrm{Jet}} \frac{p_{t_i} p_{t_j}}{p_t^2} \left(\frac{2 p_i \cdot p_j}{p_{t_i} p_{t_j} R_0^2} \right)^{\frac{\alpha}{2}}$$

Massless theory

e_α coincides with $\dot{e}_\alpha$ in the collinear limit

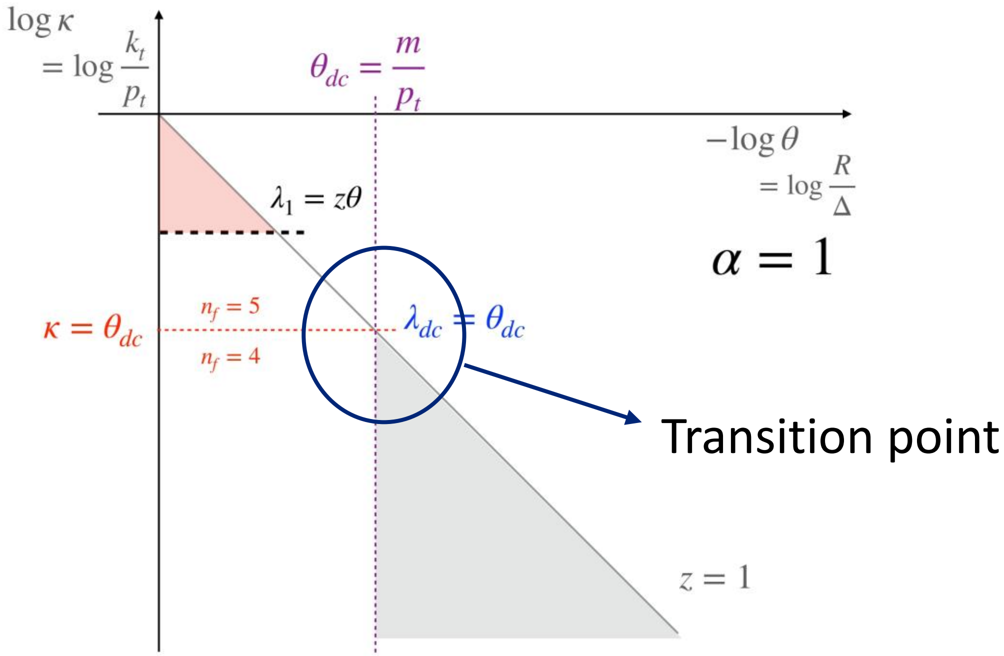
Massive theory

e_α does not coincide with $\dot{e}_\alpha$ in the quasi-collinear limit

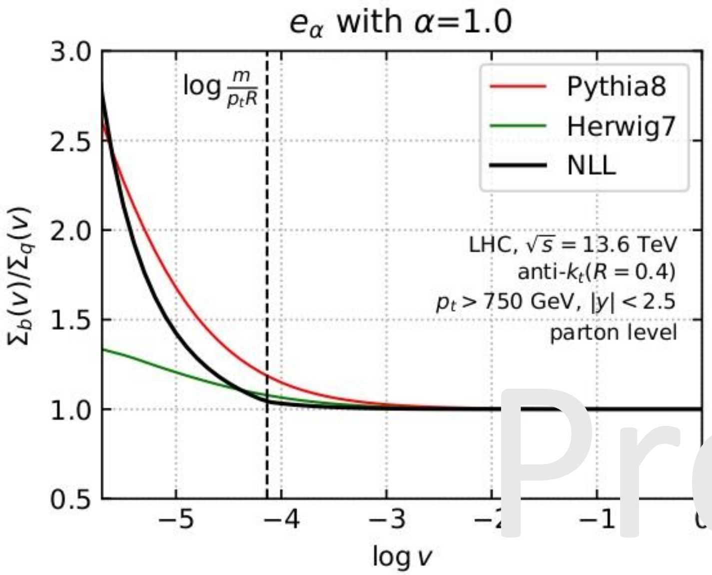
Transition from 5 to 4 flavours

Differential distribution exhibit discontinuity for any value of α in the transition

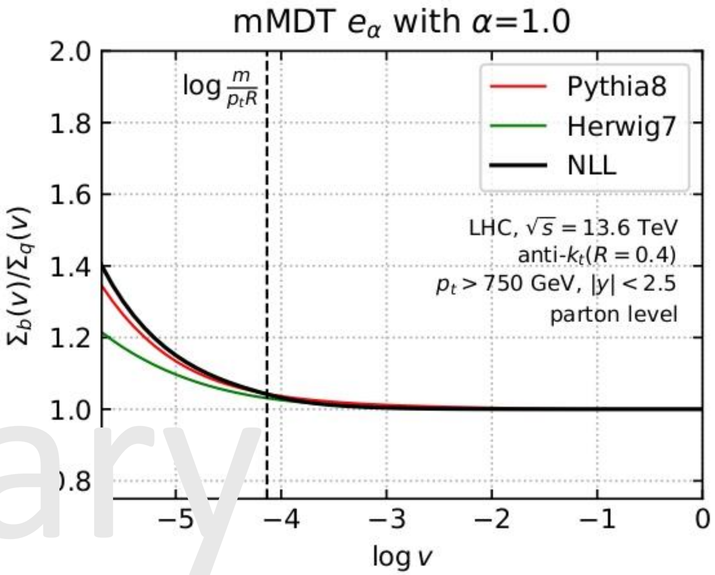
- To smooth the transition we decide to incorporate fixed order calculation
- These are NNLL contributions, which depend on the specific definition of the observable



Comparison Analytics and Monte Carlo



Ungroomed



Groomed ($\beta = 0$)

Preliminary

- Plot of the ratio of the cumulative distribution massive/massless (NGL simplify in the ungroomed case)
- It appears that the dead cone effect manifests earlier than predicted by theoretical calculations ($v \simeq \frac{m^\alpha}{p_T^\alpha R_0^\alpha}$).

Conclusions and Outlook

- We have discussed about mass effects on different types of variables
- Good agreement with Monte Carlo for θ_g and z_g distribution

- The situation for angularities and ECF is more complicated

$\longrightarrow$ need to access NNLL accuracy for heavy flavoured jets

- More observable to study: Lund plane density

Special acknowledgment to the Cost Action COMETA CA22130
(Comprehensive Multiboson Experiment Theory Action)

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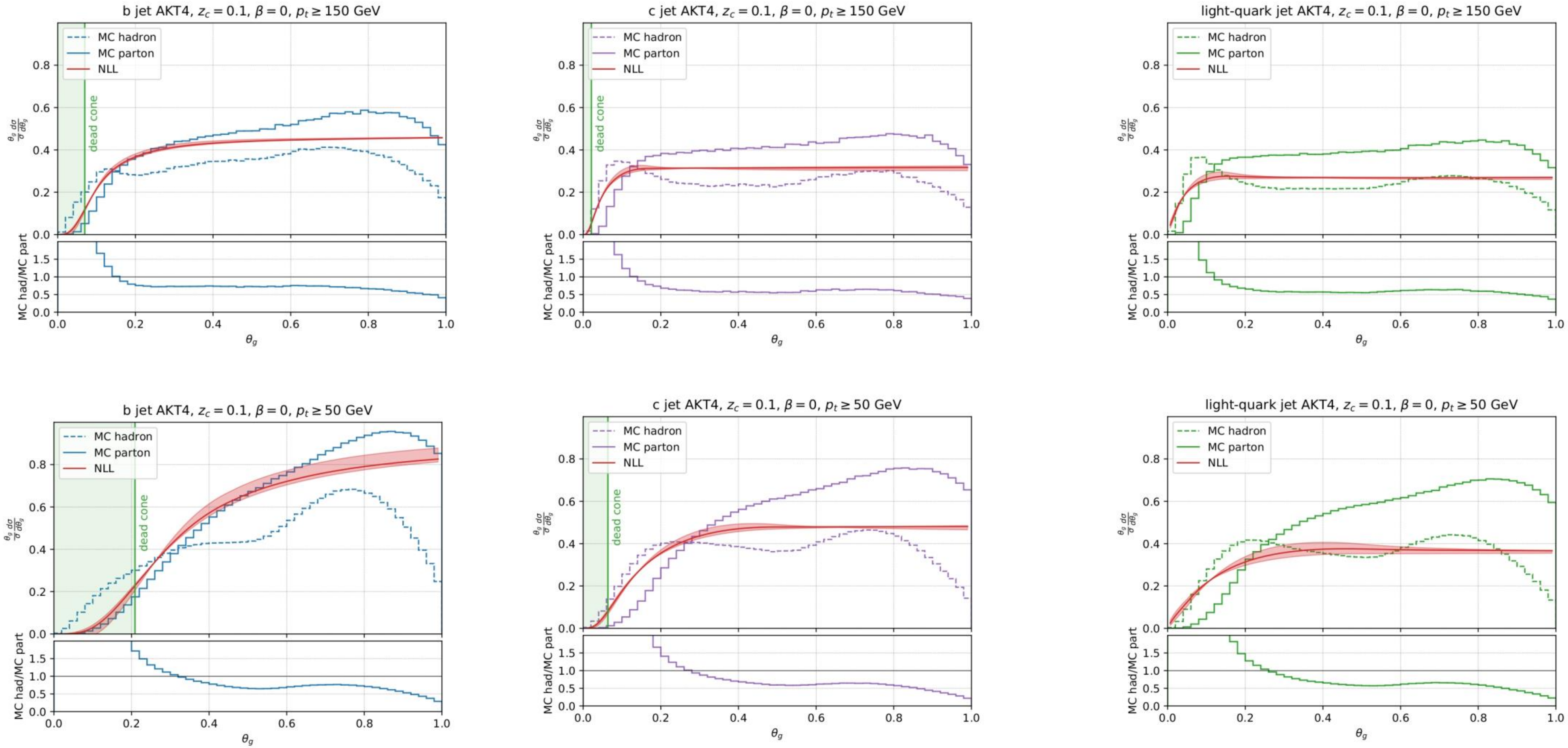
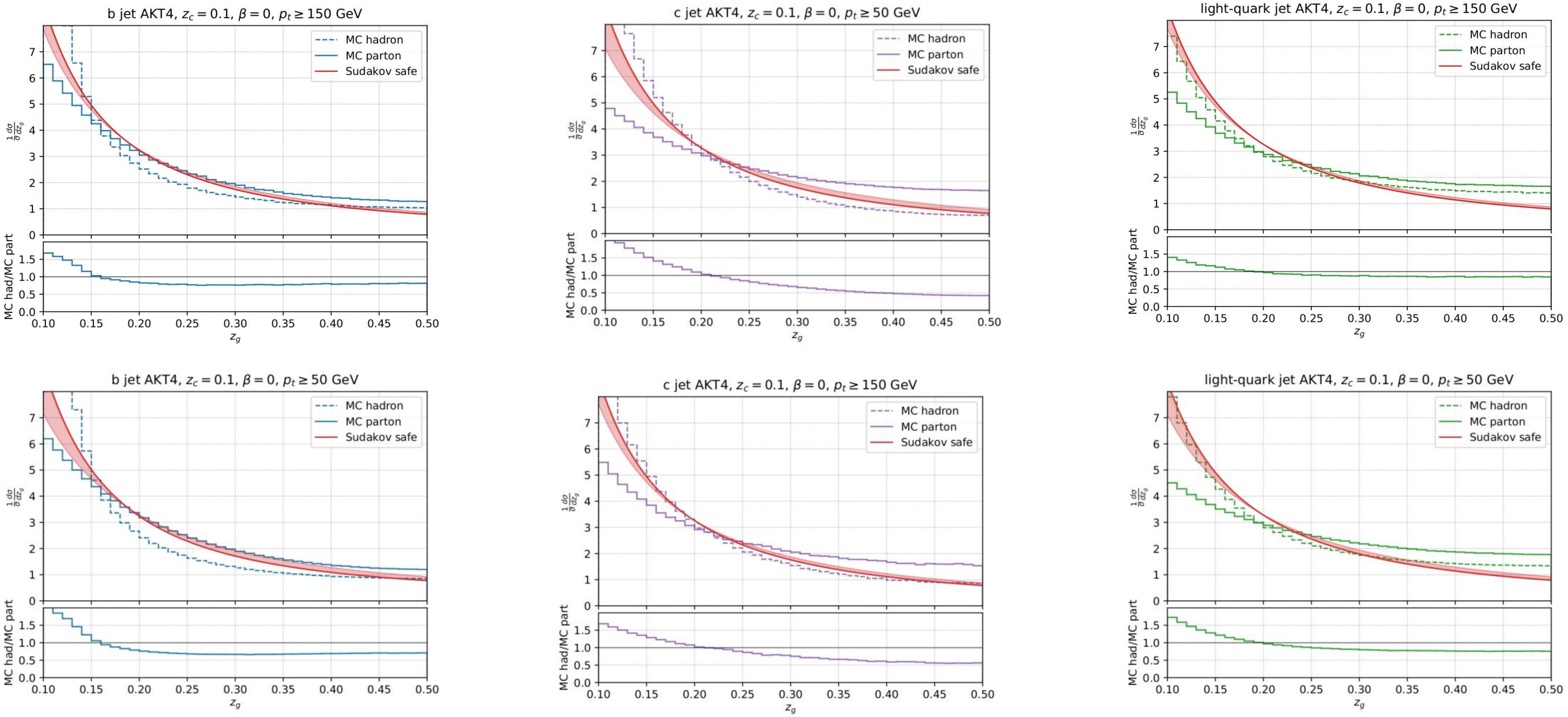
Thanks for your attention !!

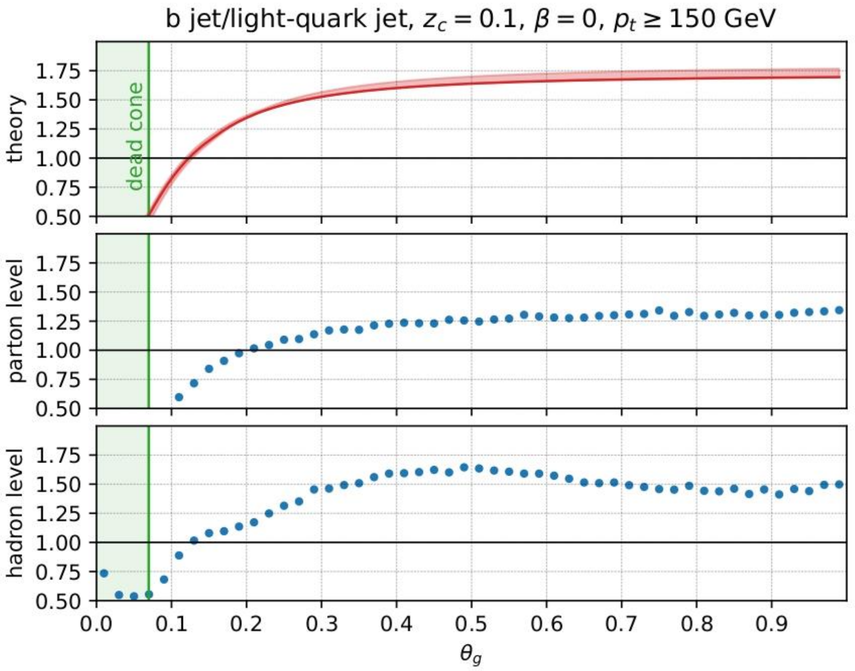
$\boldsymbol{\theta_g}$ distribution: Comparison with Monte Carlo

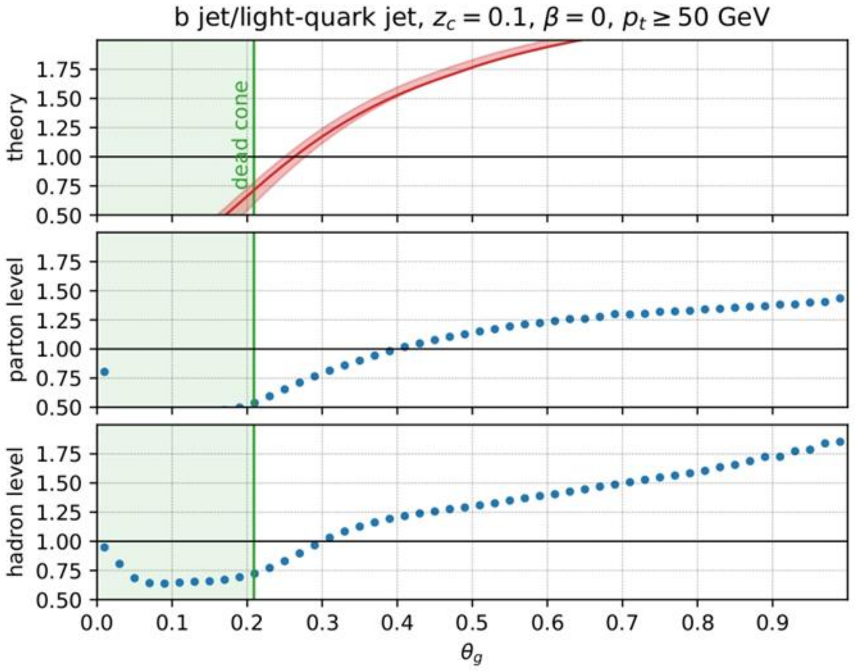


z_g distribution: Comparison with Monte Carlo

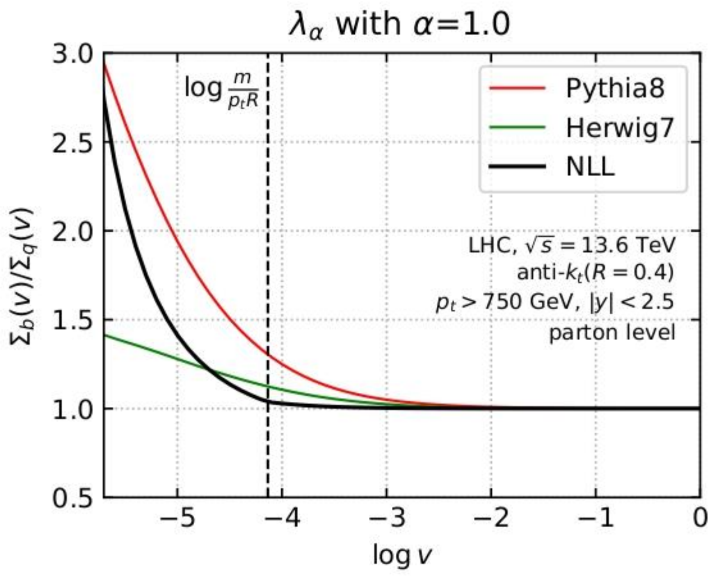


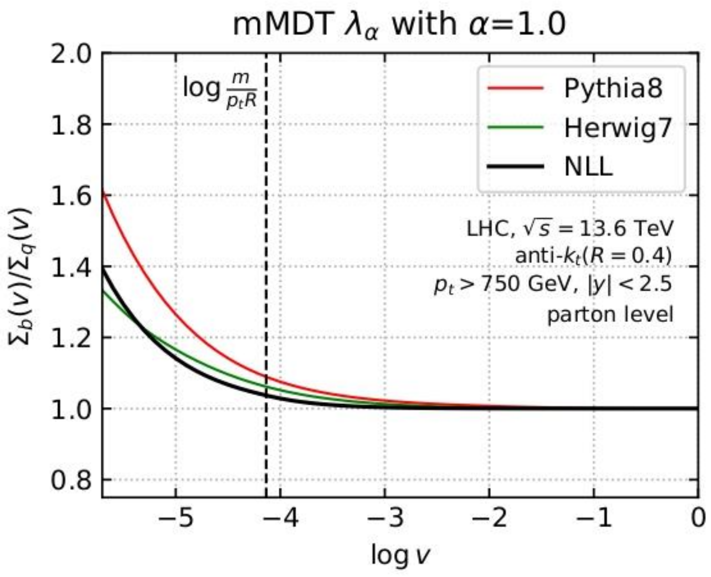
Ratio plots


b jet/light-quark jet, $z_c = 0.1$, $\beta = 0$, $p_t \geq 150$ GeV
theory
parton level
hadron level
dead cone
θ_g


b jet/light-quark jet, $z_c = 0.1$, $\beta = 0$, $p_t \geq 50$ GeV
theory
parton level
hadron level
dead cone
θ_g

Angularities: $\boldsymbol{\lambda_\alpha}$ for $\boldsymbol{pp}$ collisions





$$\lambda_\alpha = \sum_{i \in \mathrm{Jet}} \frac{p_{t_i}}{p_t} \left(\frac{\Delta R_i}{R_0} \right)^\alpha$$

Mass effects manifests earlier than predicted