Mass effects on jet angularities at hadron colliders

Andrea Ghira

Genova, 30th July 2024

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

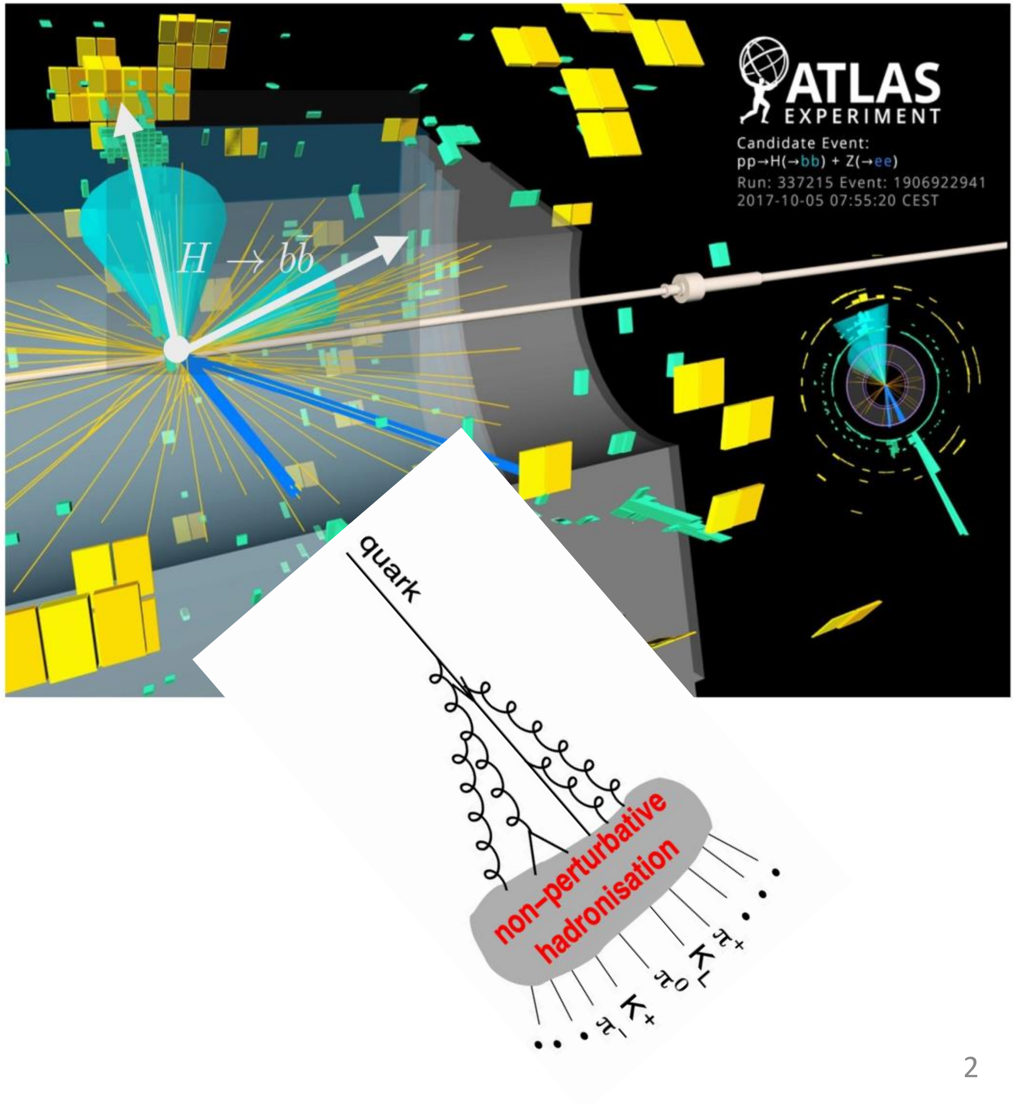
Jet substructure in a nutshell

High energy collisions result in collimated sprays of particles

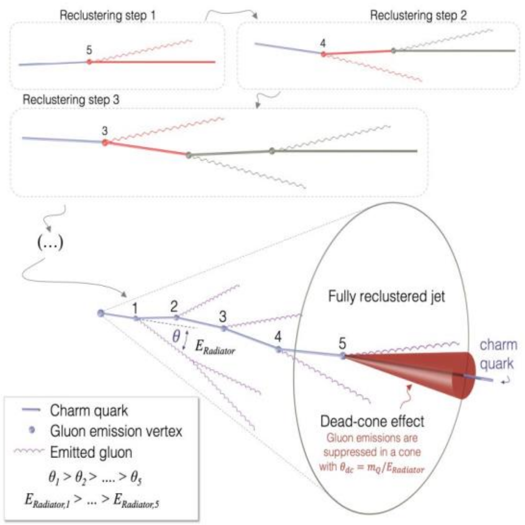
Internal structure of jets gives an insight on the originating splitting process

In a massless theory, the collinear emission is enhanced:

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

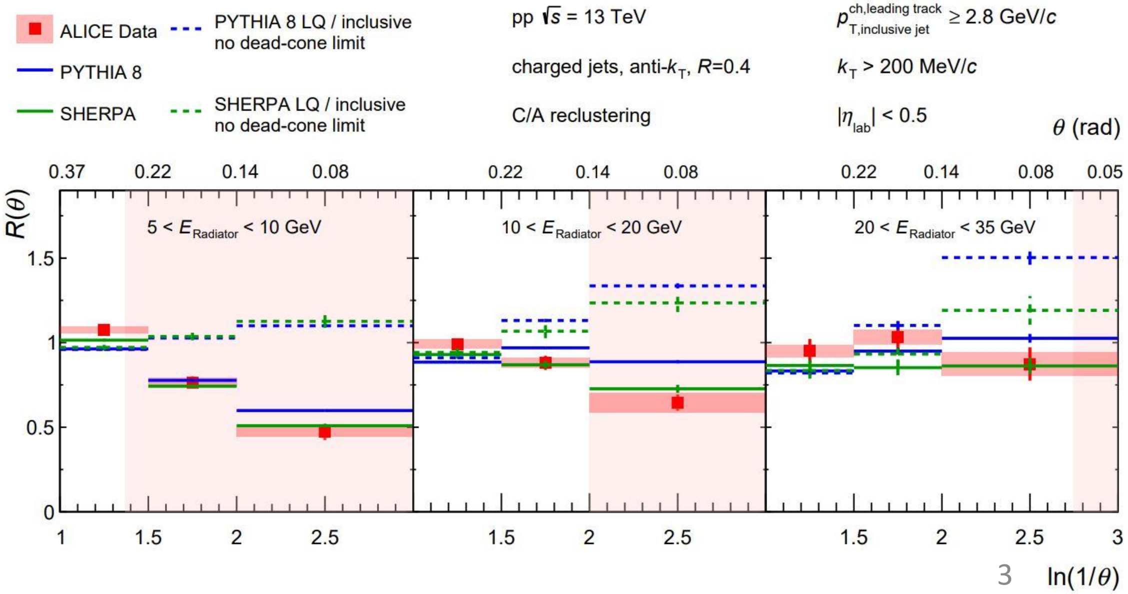


Jets to probe heavy flavours



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

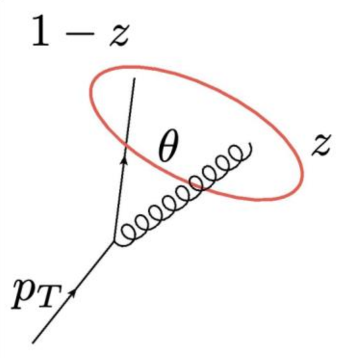
the radiation emitted off a heavy flavour is suppressed inside a cone of opening angle $\theta \sim m/E$ (ALICE)

Jet angularities

We study jet angularities λ^{α} (see backup slides for energy-correlation functions (ECFs) e_2^{α})

In a massless theory, considering only one emission:

$$\lambda^{\alpha} \simeq z\theta^{\alpha}$$



Many possible choices in the case of massive particles within the jet
(C. Lee, P. Shrivastava, V. Vaidya)

Which one is more sensitive to the dead-cone effect?

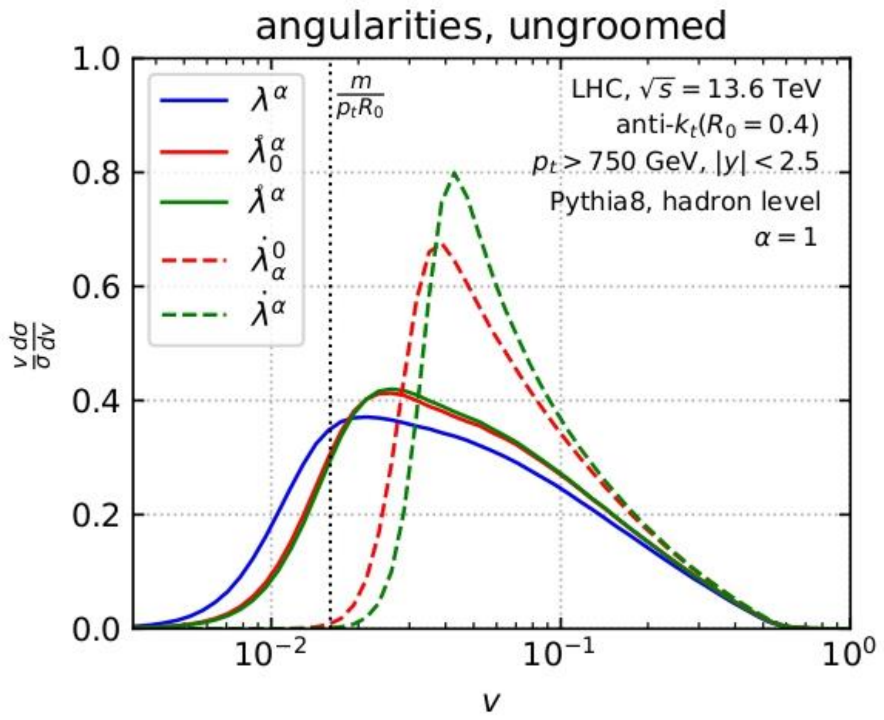
Possible definitions in $\boldsymbol{pp}$ collisions

$$\dot{\lambda}_0^{\alpha} = \sum_i \frac{p_{t_i}}{p_t}\left(\frac{2p_i\cdot\bar{n}}{p_{t_i}R_0^2}\right)^{\frac{\alpha}{2}}, \quad \dot{\lambda}^{\alpha} = \sum_i \frac{p_{t_i}}{p_t}\left(\frac{2p_i\cdot n}{p_{t_i}R_0^2}\right)^{\frac{\alpha}{2}}$$

$$\lambda^{\alpha} = \sum_i \frac{p_{t_i}}{p_t}\left(\frac{\Delta R_i}{R_0}\right)^{\alpha}, \quad \mathring{\lambda}_0^{\alpha} = \sum_{i\neq n} \frac{p_{t_i}}{p_t}\left(\frac{2p_i\cdot\bar{n}}{p_{t_i}R_0^2}\right)^{\frac{\alpha}{2}}, \quad \mathring{\lambda}^{\alpha} = \sum_{i\neq n} \frac{p_{t_i}}{p_t}\left(\frac{2p_i\cdot n}{p_{t_i}R_0^2}\right)^{\frac{\alpha}{2}}$$

- The cumulative distribution associated to the dotted variable cannot be computed in resummed perturbation theory (does not vanish at Born level)
- All these variables do not coincide when one take the quasi-collinear limit

Monte Carlo analysis (ungroomed case)



$$\lambda^\alpha = \sum_i \frac{p_{t_i}}{p_t}\left(\frac{\Delta R_i}{R_0}\right)^\alpha$$

$$\mathring{\lambda}_0^\alpha \simeq \sum_{i\neq n} \frac{p_{t_i}}{p_t}\left(\frac{m_i^2}{p_{t_i}^2 R_0^2} + \frac{\Delta R_i^2}{R_0^2}\right)^{\frac{\alpha}{2}},$$

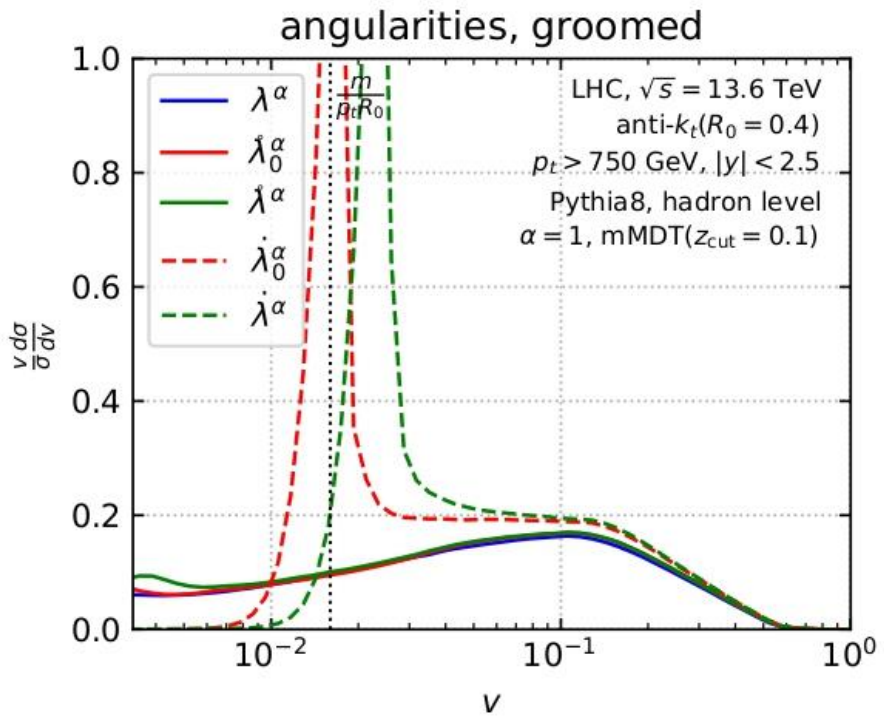
$$\mathring{\lambda}^\alpha \simeq \sum_{i\neq n} \frac{p_{t_i}}{p_t}\left(\frac{m_i^2}{p_{t_i}^2 R_0^2} + \frac{m_n^2}{p_t^2 R_0^2} + \frac{\Delta R_i^2}{R_0^2}\right)^{\frac{\alpha}{2}}$$

$$\dot{\lambda}_0^\alpha \simeq \sum_{i\neq n} \frac{p_{t_i}}{p_t}\left(\frac{m_i^2}{p_{t_i}^2 R_0^2} + \frac{\Delta R_i^2}{R_0^2}\right)^{\frac{\alpha}{2}} + \left(\frac{m_n^2}{p_t^2 R_0^2}\right)^{\frac{\alpha}{2}},$$

$$\dot{\lambda}^\alpha \simeq \sum_{i\neq n} \frac{p_{t_i}}{p_t}\left(\frac{m_i^2}{p_{t_i}^2 R_0^2} + \frac{m_n^2}{p_t^2 R_0^2} + \frac{\Delta R_i^2}{R_0^2}\right)^{\frac{\alpha}{2}} + \left(\frac{2m_n^2}{p_t^2 R_0^2}\right)^{\frac{\alpha}{2}}$$

- Huge peak in the differential distribution associated to the dotted observables: they do not vanish at Born level.
- The circled observables exhibits a larger peak than λ^α : “kinematical” effect.
- The mass contribution in on λ^α distribution is only “dynamical”

Monte Carlo analysis (groomed case)



$$\mathring{\lambda}^\alpha \simeq \sum_{i \neq n} \frac{p_{t_i}}{p_t} \left(\frac{m_i^2}{p_{t_i}^2 R_0^2} + \frac{m_n^2}{p_t^2 R_0^2} + \frac{\Delta R_i^2}{R_0^2} \right)^{\frac{\alpha}{2}},$$

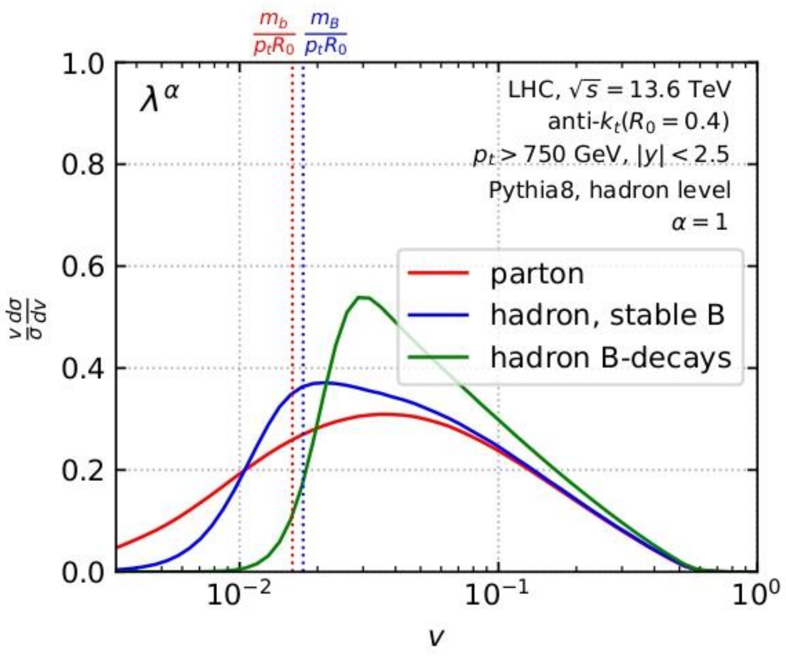
$$\frac{\min(p_{t1}, p_{t2})}{p_{t1} + p_{t2}} > z_{\rm cut}$$

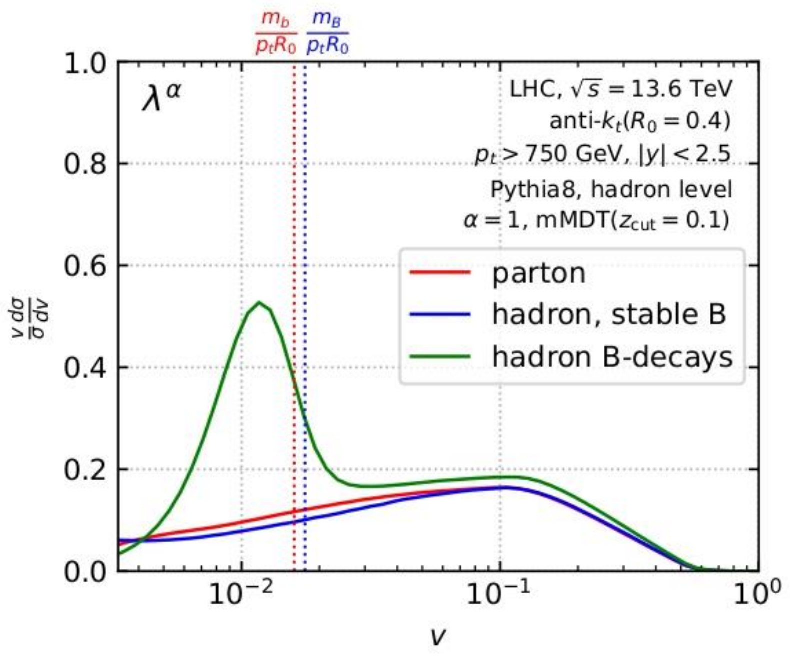
Soft Drop with $\beta = 0$, mMDT

- Even more marked peak in the dotted observables.
- Also the solid green curve starts to exhibit a small peak in the tail of the distribution

➡ we cannot have an arbitrarily soft emission

B decay effects





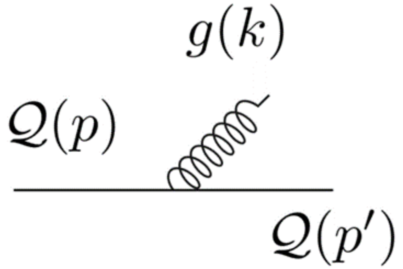
- Change in the radiation pattern due to B decay effect: the decay product contribute non trivially to the distribution (C. Lee, P. Shrivastava, V. Vaidya)
- Need to reconstruct the B kinematics to disentangle the spurious effect and to have a distribution more sensitive to the dead-cone effect.

Analytic calculation

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

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

$$\Sigma(v) = 1 - \frac{\alpha_{\mathrm{s}}}{2\pi}\int_0^{Q^2}\frac{\mathrm{d}k_t^2}{k_t^2 + z^2 m^2}\int_0^1 \mathrm{d}z P_{\mathcal{Q}g}\Theta\left(\mathcal{V}(k_t^2,\eta) - v\right)$$



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

$$\mathcal{V}(k_t^2,\eta) = d\left(\frac{k_t^2}{Q^2}\right)^{\frac{a}{2}} e^{-b\eta}$$

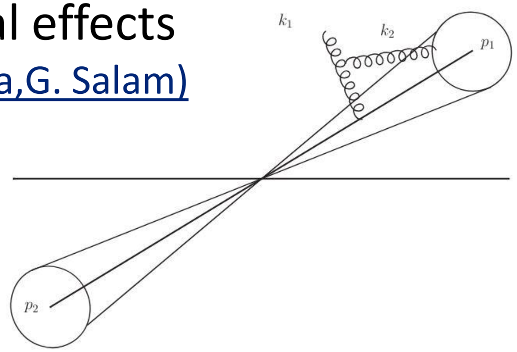
Going to all orders

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)



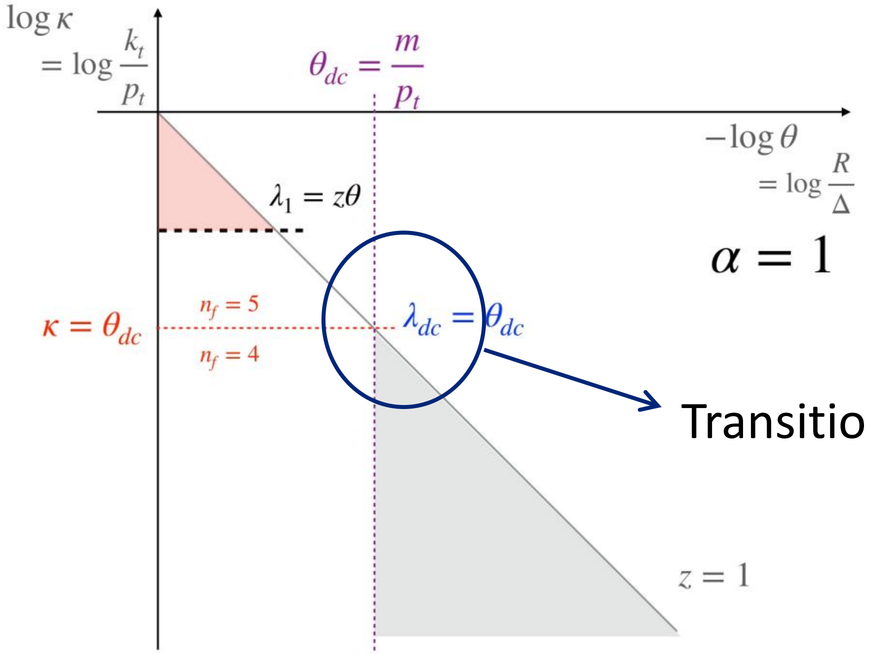
with R the radiator defined as:

$$R(v) = \int_{z^2m^2}^{Q^2}\frac{\mathrm{d}k_t^2}{k_t^2}\int_0^1 \mathrm{d}z P_{\mathcal{Q}g}\frac{\alpha_\mathrm{s}^{\mathrm{CMW}}(k_t^2)}{2\pi}\Theta(\mathcal{V}(k_t^2,\eta)-v)$$

Resummation of jet angularities

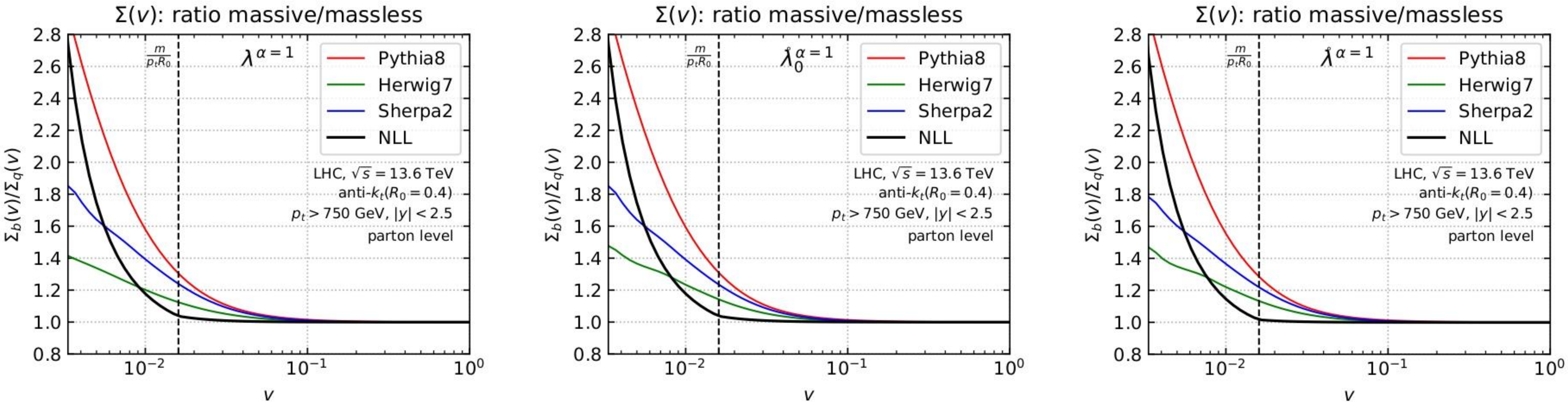
From analytical point of view, all the cumulative distribution resum in the same way at NLL. However, the differential distribution is discontinuous.

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



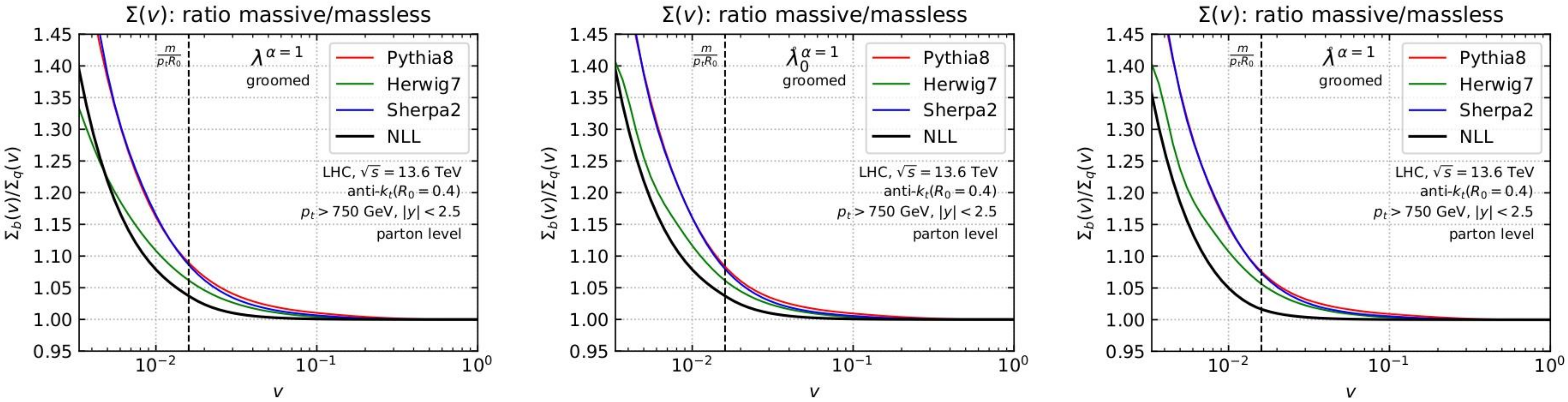
Transition point

Comparison analytics and Monte Carlo (ungroomed case)



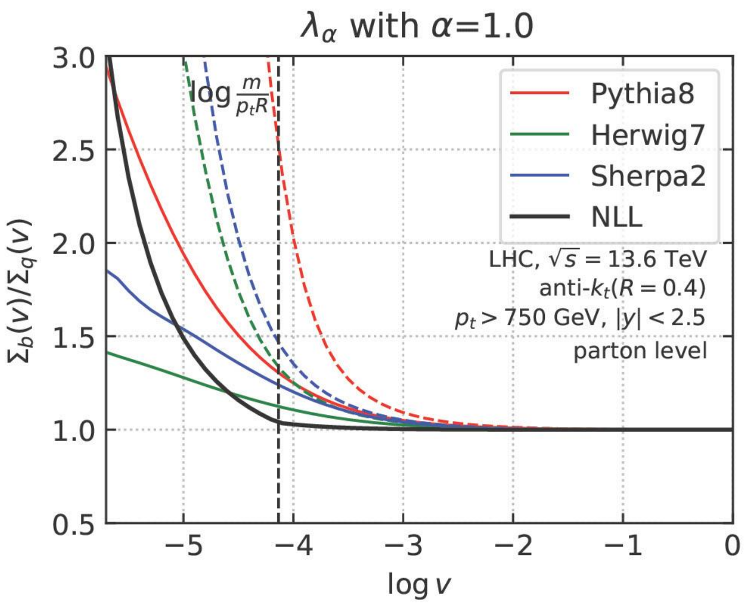
- Plot of the ratio of the cumulative distribution massive/massless
- It appears that the dead cone effect manifests earlier than predicted by theoretical calculations ($v \simeq \frac{m^\alpha}{p_T^\alpha R_0^\alpha}$).

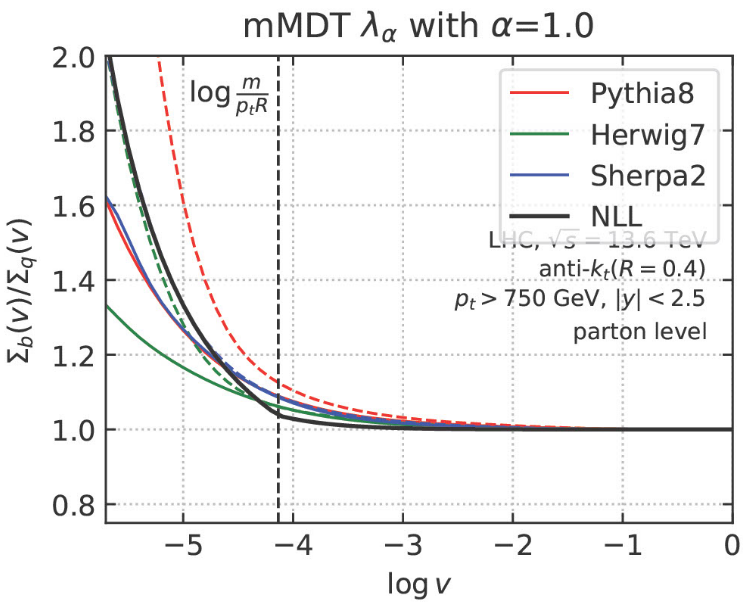
Comparison Analytics and Monte Carlo (groomed case)



- Plot of the ratio of the cumulative distribution massive/massless (NGL are absent in the groomed case)
- Closer to MC, soft radiation at large angle is removed by the soft drop algorithm

Non perturbative effects on groomed distributions (preliminary results)





- The dashed line are the ratio $\frac{\Sigma_b^{hadron}}{\Sigma_q^{hadron}}$
- λ^α more stable against the inclusion of non perturbative effects
- The scalar product observable are far more sensitive to non perturbative-correction

Conclusions & outlook

- The angularities defined with the scalar products are more sensitive to mass effects. Mass dependence both in the definition of the observable and at amplitude level.
- Importance of grooming to have control on NP physics, reconstruction on B kinematics.

- The distribution associated to λ^{α} depends on the mass only through the square matrix element, thus all the mass effects that we see are related to a dynamical suppression of the radiation: $\lambda^{\alpha=1}$ $\longleftrightarrow$ best way to probe the dead-cone
- Next step: phenomenological study (resummation plugin and matching to fixed order)

Thanks for your attention !!

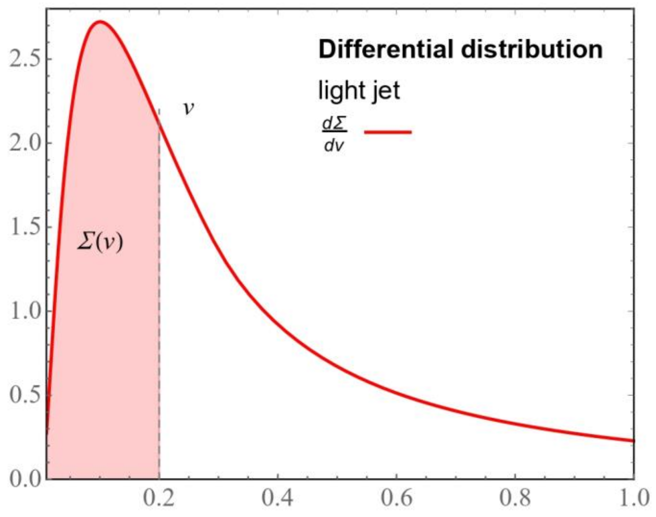
Backup slides

Andrea Ghira

Genova, 30th July 2024

Theoretical Framework for heavy quark jet

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

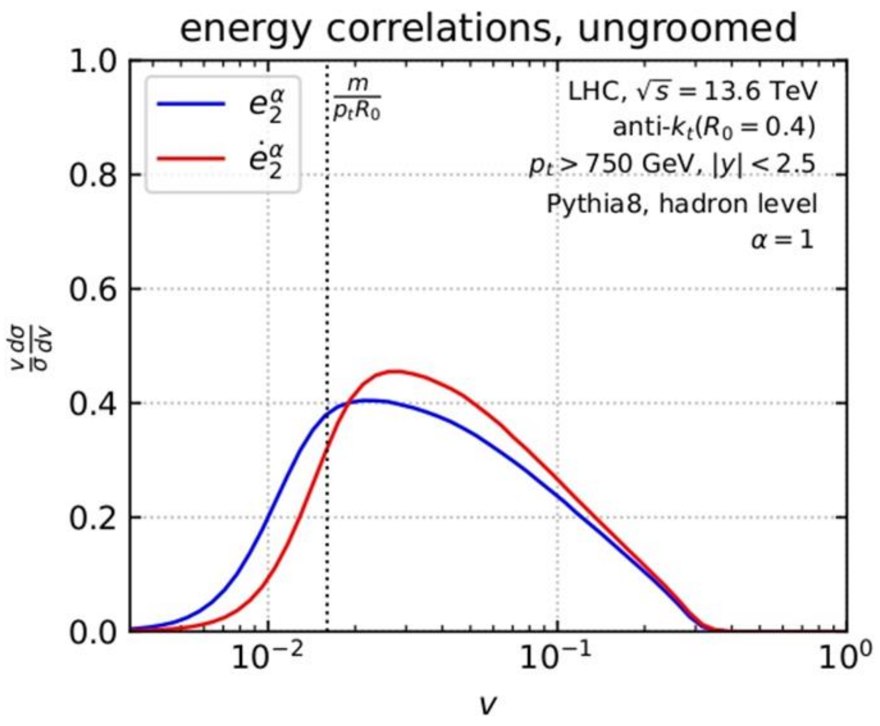


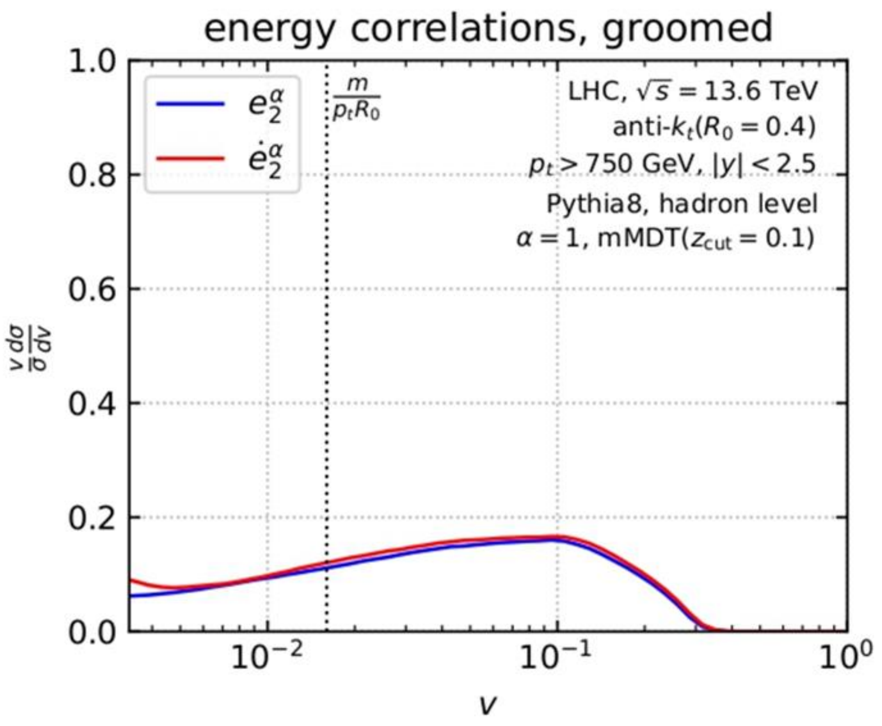
$$\Sigma(v) = \frac{1}{\sigma_0} \int_0^v \mathrm{d}v' \frac{\mathrm{d}\sigma}{\mathrm{d}v'}$$

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

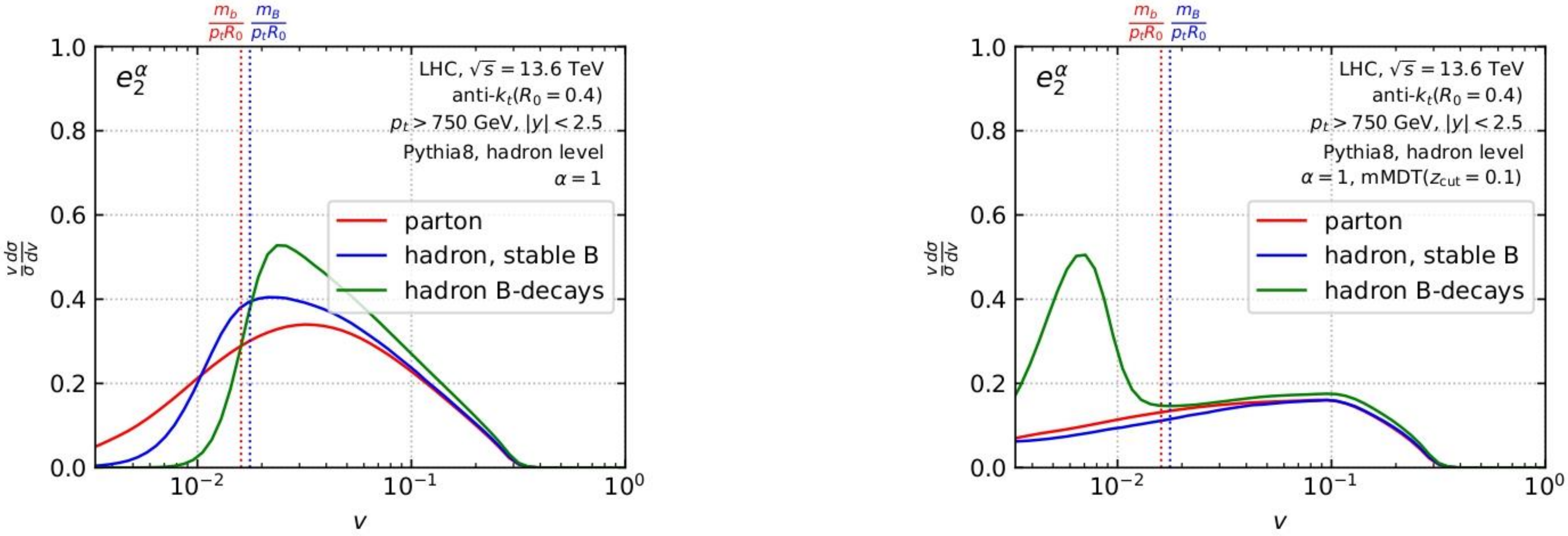
Energy-energy correlation functions (EEFCs)

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

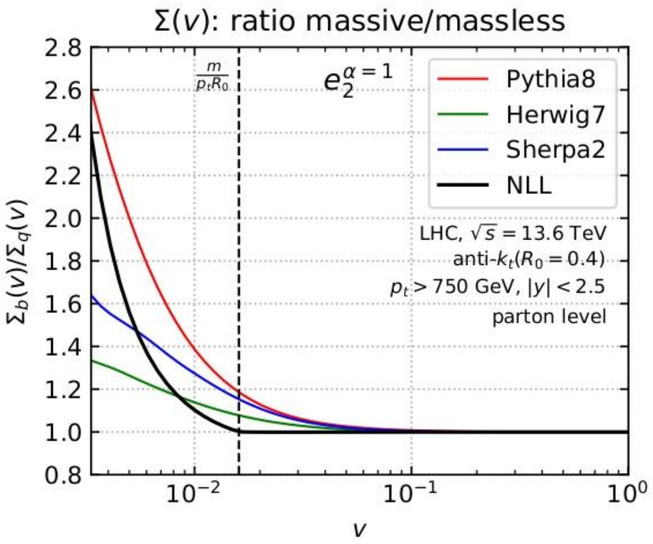


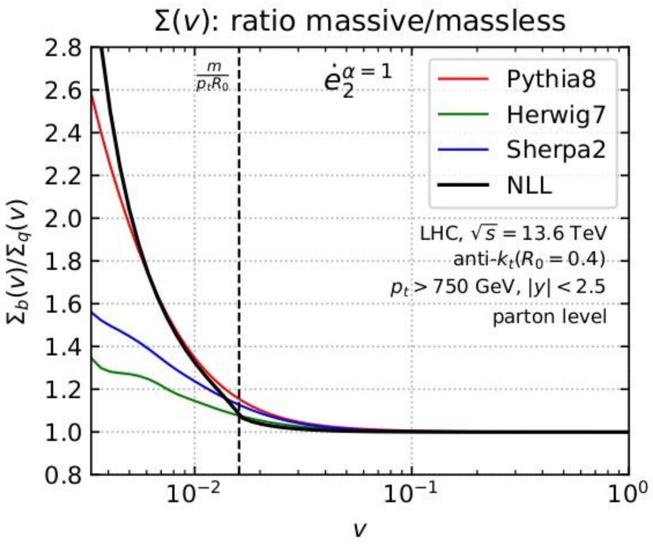


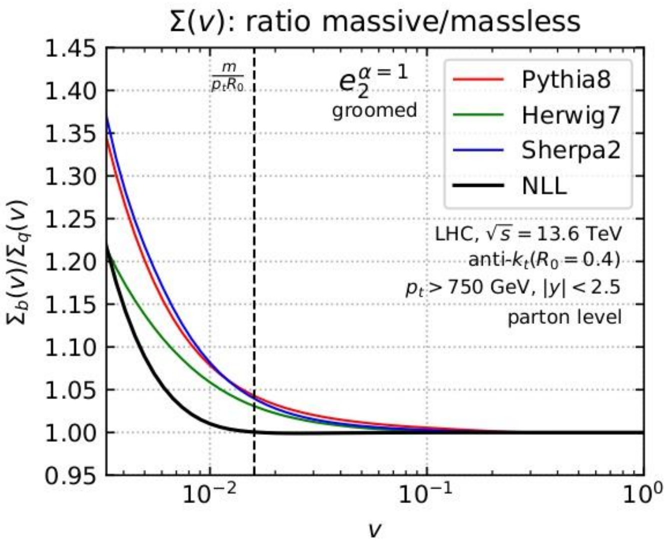
B decays effects on EECFs

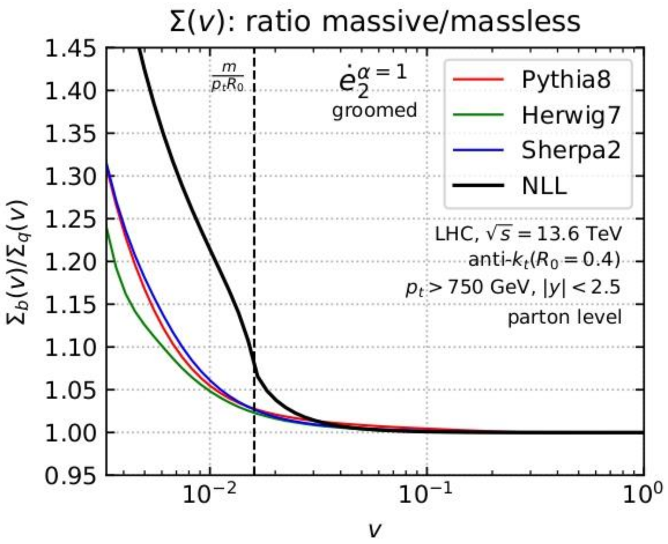


Comparison between MC and analytics









Non-perturbative effects in the ungroomed distributions for angularities