Dead-cone effect in the production of heavy flavours at high-energy colliders

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work in progress with Andrea Ghira, Oleh Fedkevych, Simone Marzani and Gregory Soyez

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CSIC
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European Commission
Marie Skłodowska-Curie Actions

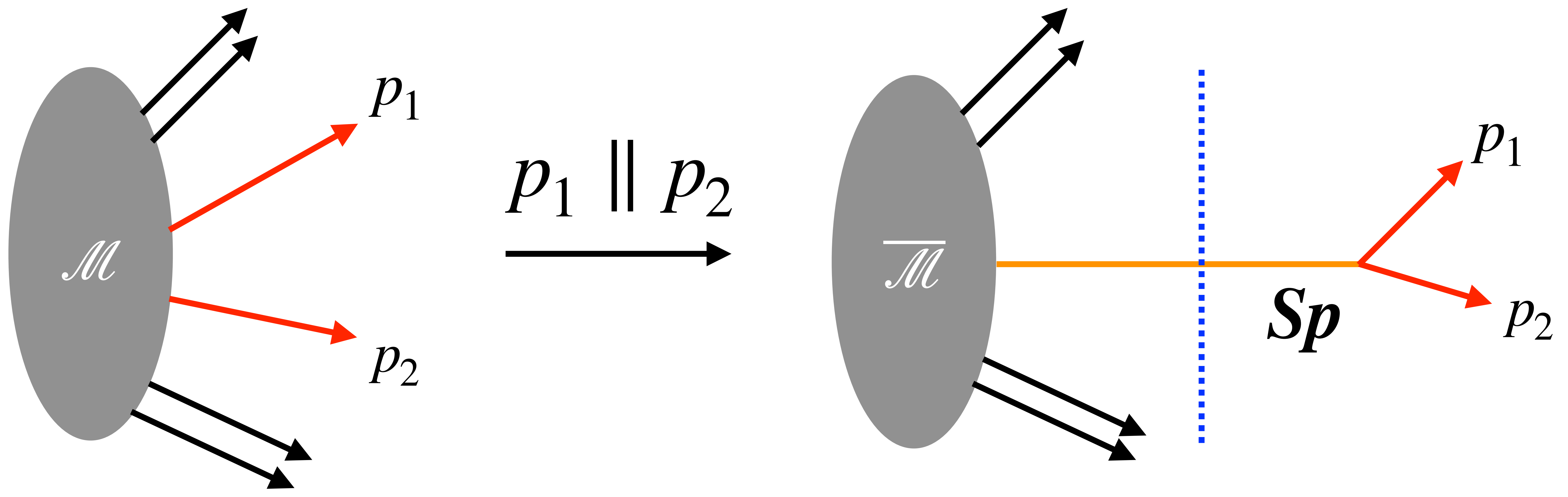
- Introduction: Collinear Factorization in QCD

  Massless Vs Massive

- Recent Measurement of Dead-Cone Effect by ALICE

- Heavy Flavour Jet Sub-Structure

- Summary



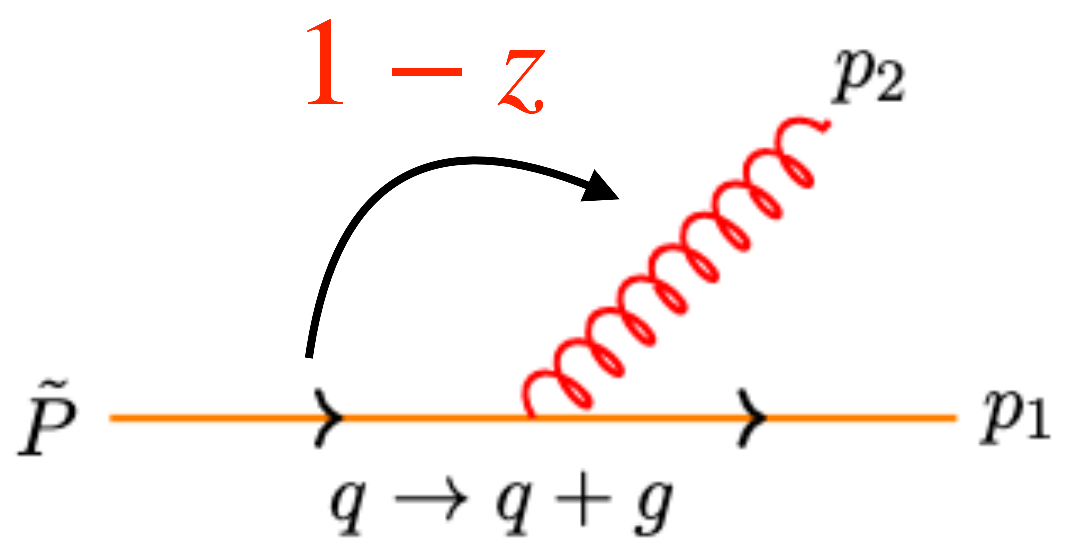
$$|\mathcal{M}_{a_1,a_2,\ldots}(p_1,p_2,\ldots)|^2 = \frac{8\pi\alpha_S^u\mu_0^{2\epsilon}}{s_{12}}\mathcal{I}^{ss'}_{a,\ldots}(\tilde{P},\ldots)\widehat{P}^{ss'}_{a_1a_2}$$

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

$$(p_1+p_2)^2 = 2p_1\cdot p_2 = 2p_1^0p_2^0(1-\cos\theta) \simeq p_1^0p_2^0\theta^2$$

Final state splitting

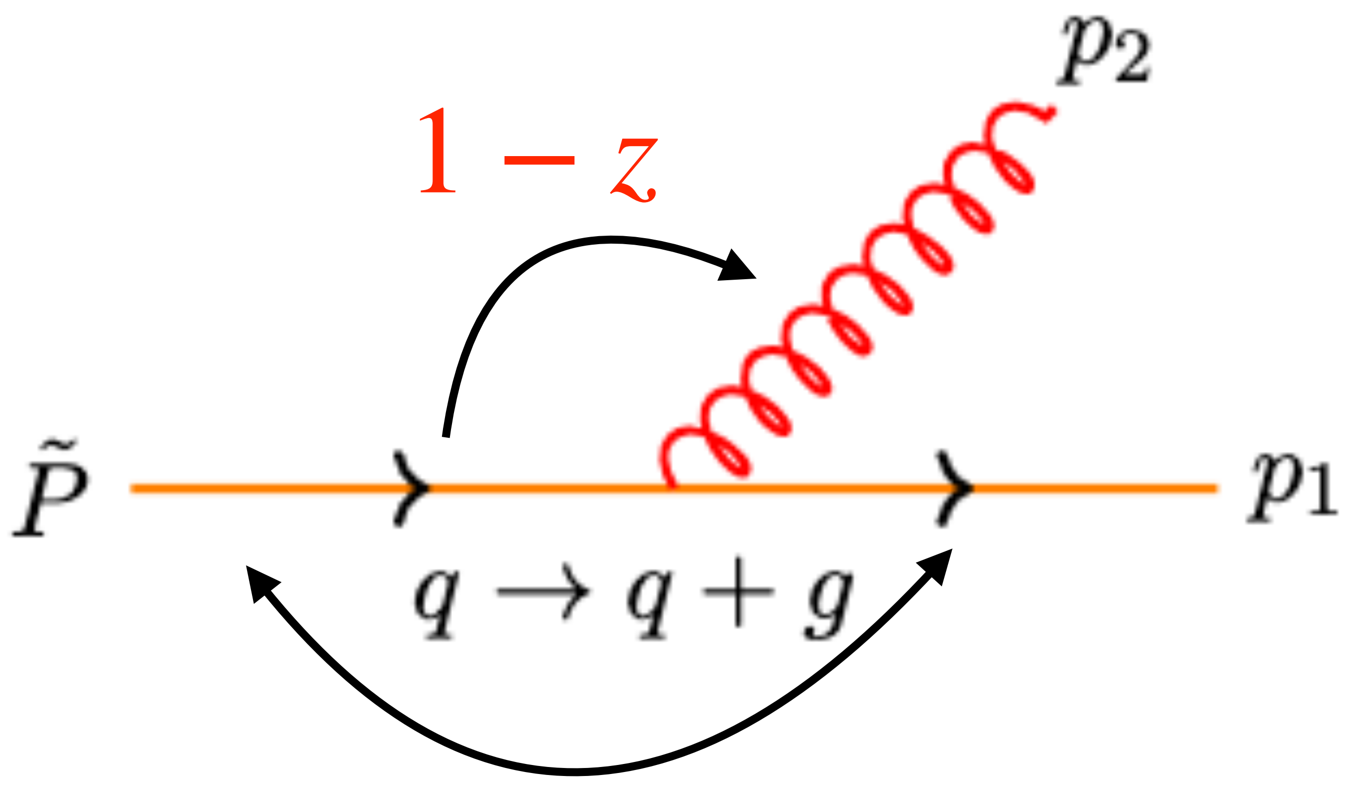
$$\widehat{P}^{\mathrm{TL}}_{qq} = C_F\left[\frac{1+z^2}{1-z} - \epsilon(1-z)\right]$$



$$|\mathcal{M}_{a_1,a_2,\ldots}(p_1,p_2,\ldots)|^2 = \frac{8\pi\alpha_S^u\mu_0^{2\epsilon}}{\tilde{s}_{12}}\mathcal{I}^{ss'}_{a,\ldots}(\tilde{P},\ldots)\widehat{P}^{ss'}_{a_1a_2}$$

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

$$2p_1\cdot p_2 = 2p_1^0p_2^0\left(1-\frac{|\vec{p}_1|}{p_1^0}\cos\theta\right) \simeq p_1^0p_2^0\left(\theta^2+\frac{m_Q^2}{(p_1^0)^2}\right)$$



massive quark

$$\widehat{P}^{\,\mathrm{TL}}_{QQ} = C_F\left[\frac{1+z^2}{1-z}-\epsilon(1-z)-2\frac{m_Q^2}{\tilde{s}_{12}}\right]$$

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN

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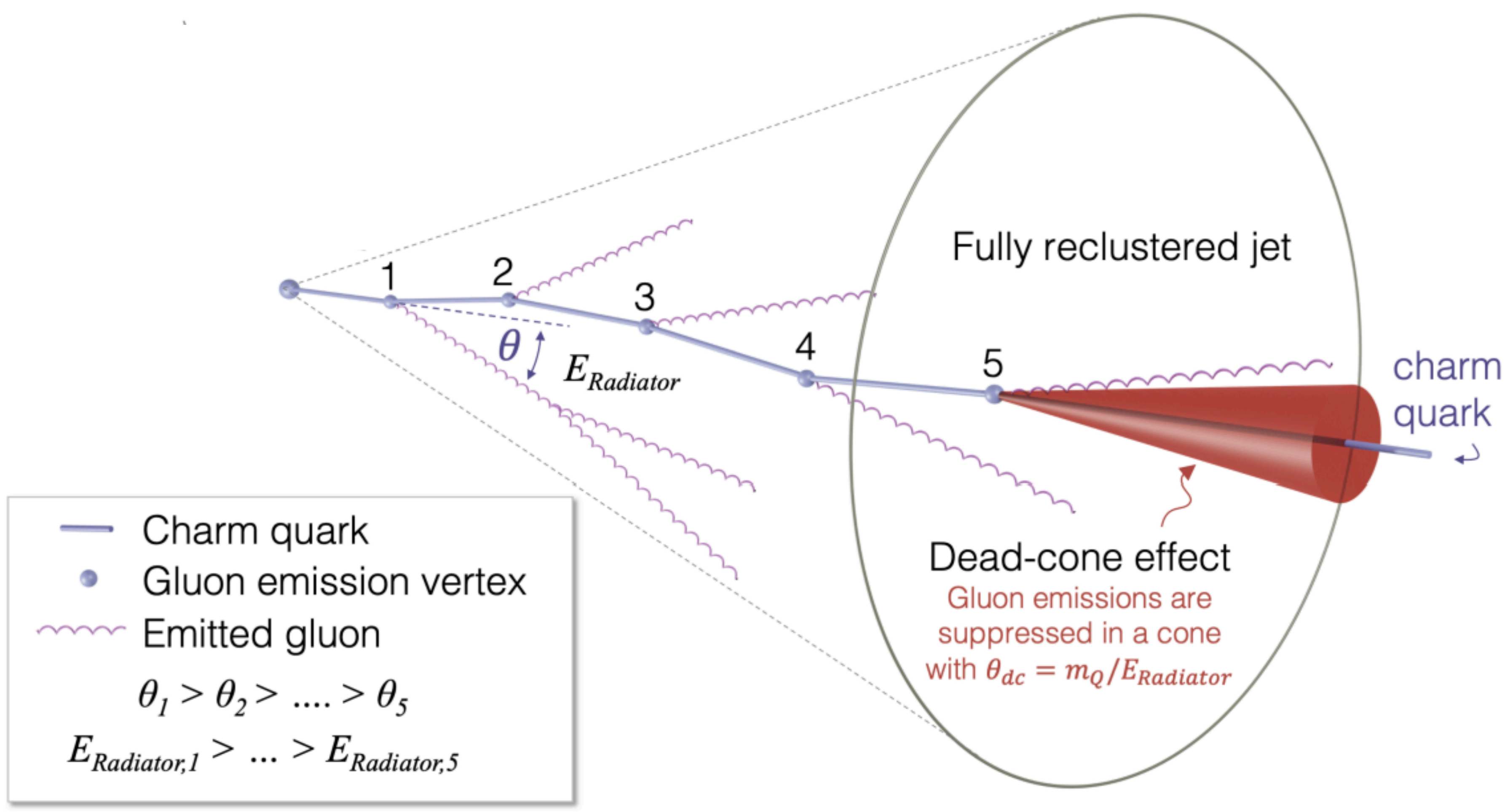
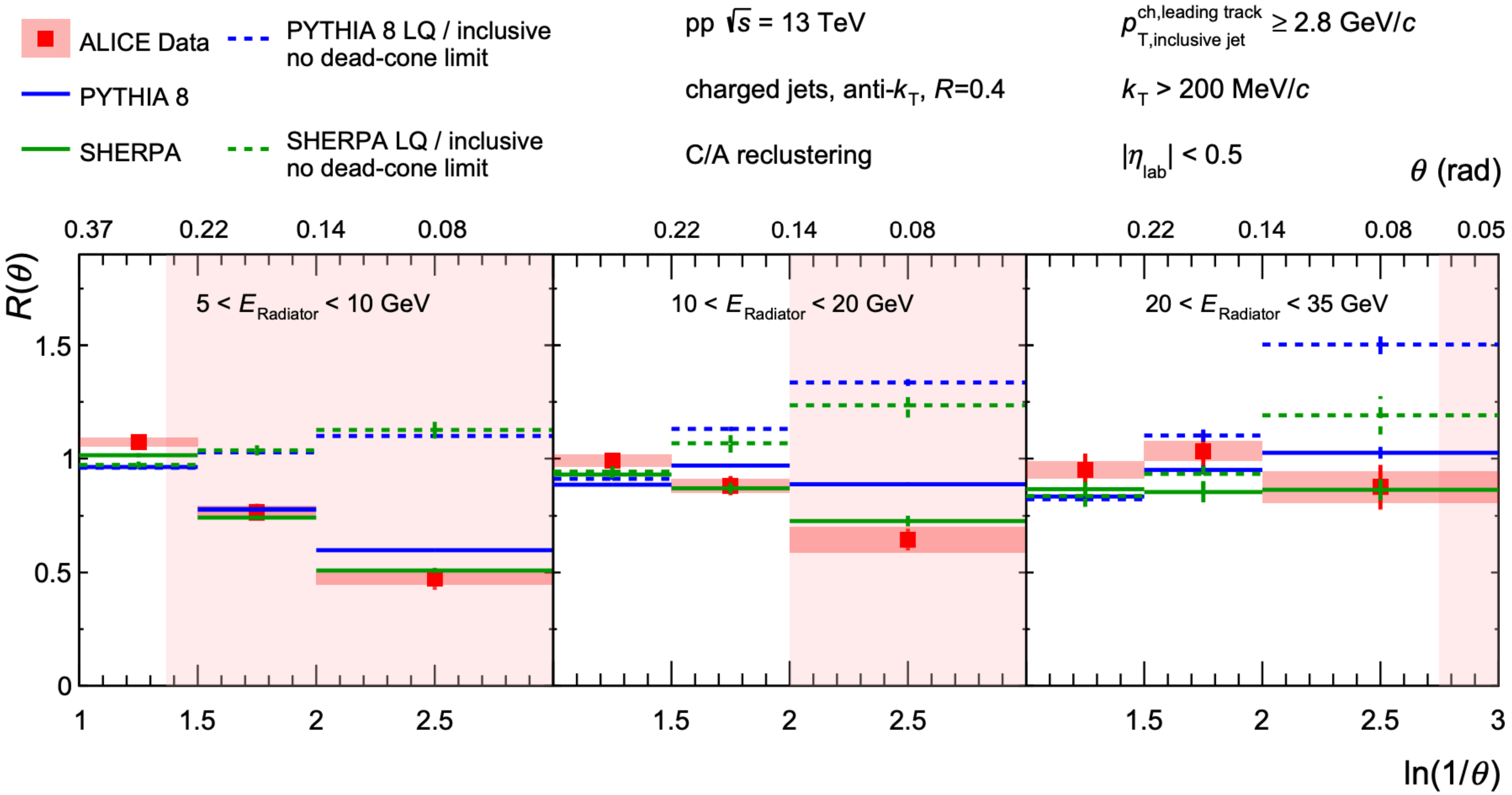
Direct observation of the dead-cone effect in quantum chromodynamics

ALICE Collaboration*

Abstract

In particle collider experiments, elementary particle interactions with large momentum transfer produce quarks and gluons (known as partons) whose evolution is governed by the strong force, as described by the theory of quantum chromodynamics (QCD) [1]. These partons subsequently emit further partons in a process that can be described as a parton shower [2] which culminates in the formation of detectable hadrons. Studying the pattern of the parton shower is one of the key experimental tools for testing QCD. This pattern is expected to depend on the mass of the initiating parton, through a phenomenon known as the dead-cone effect, which predicts a suppression of the gluon spectrum emitted by a heavy quark of mass m_Q and energy E, within a cone of angular size m_Q/E around the emitter [3]. Previously, a direct observation of the dead-cone effect in QCD had not been possible, owing to the challenge of reconstructing the cascading quarks and gluons from the experimentally accessible hadrons. We report the direct observation of the QCD dead cone by using new iterative declustering techniques [4, 5] to reconstruct the parton shower of charm quarks. This result confirms a fundamental feature of QCD. Furthermore, the measurement of a dead-cone angle constitutes a direct experimental observation of the non-zero mass of the charm quark, which is a fundamental constant in the standard model of particle physics.





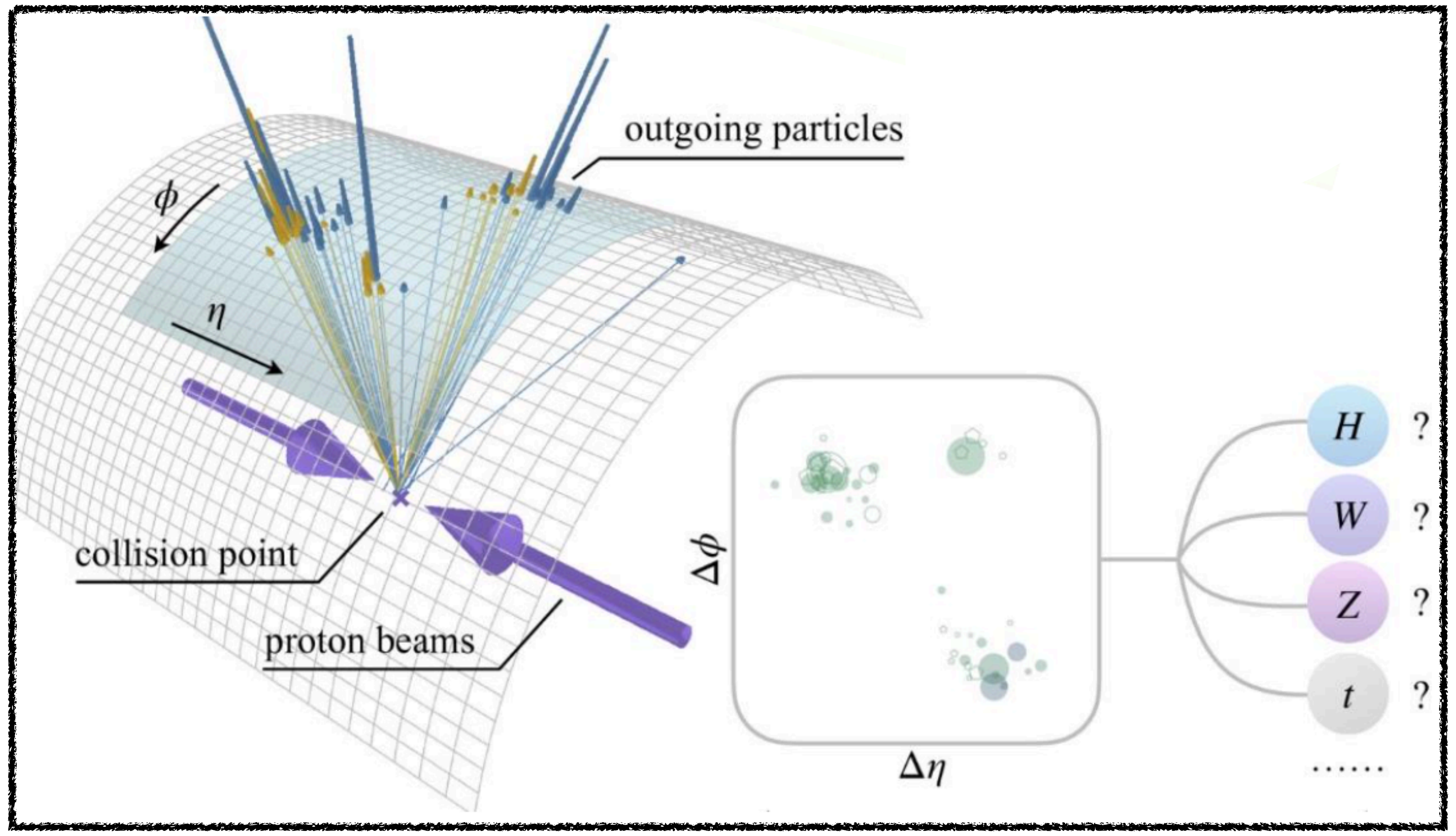
Dead Cone effect: the radiation emitted off a heavy flavour is suppressed inside a cone of opening angle $\theta \sim m/E$ [Dokshitzer, Khoze, Troian (J. Phys. G 17 (1991) 1602-1604, 9506425)]

Observable: $$R(\theta) = \frac{1}{N^{D^0 \text{jets}}} \frac{dn^{D^0 \text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\text{Radiator}}}$$

High energy collisions result in collimated sprays of particles called jets

↓

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



The collinear emission is enhanced:

$$\alpha_S \int \frac{d\theta^2}{\theta^2} \gg 1 \qquad \alpha_S \int \frac{d\theta^2}{\theta^2 + \frac{m^2}{E^2}} \simeq \alpha_S \log \frac{m^2}{E^2}$$

- Given an observable V, we consider the resummation of its cumulative distribution i.e. the probability for the observable V to be smaller than some given value v

$$\Sigma_V(v) = \frac{1}{\sigma_0}\int_0^v dv' \frac{d\sigma_V}{dv'}$$

- V is a function of momenta that vanishes when no emission occur (Born level)

- V must be Infrared-Collinear-Safe

- We begin studying the case of a single gluon emission off a massive quark

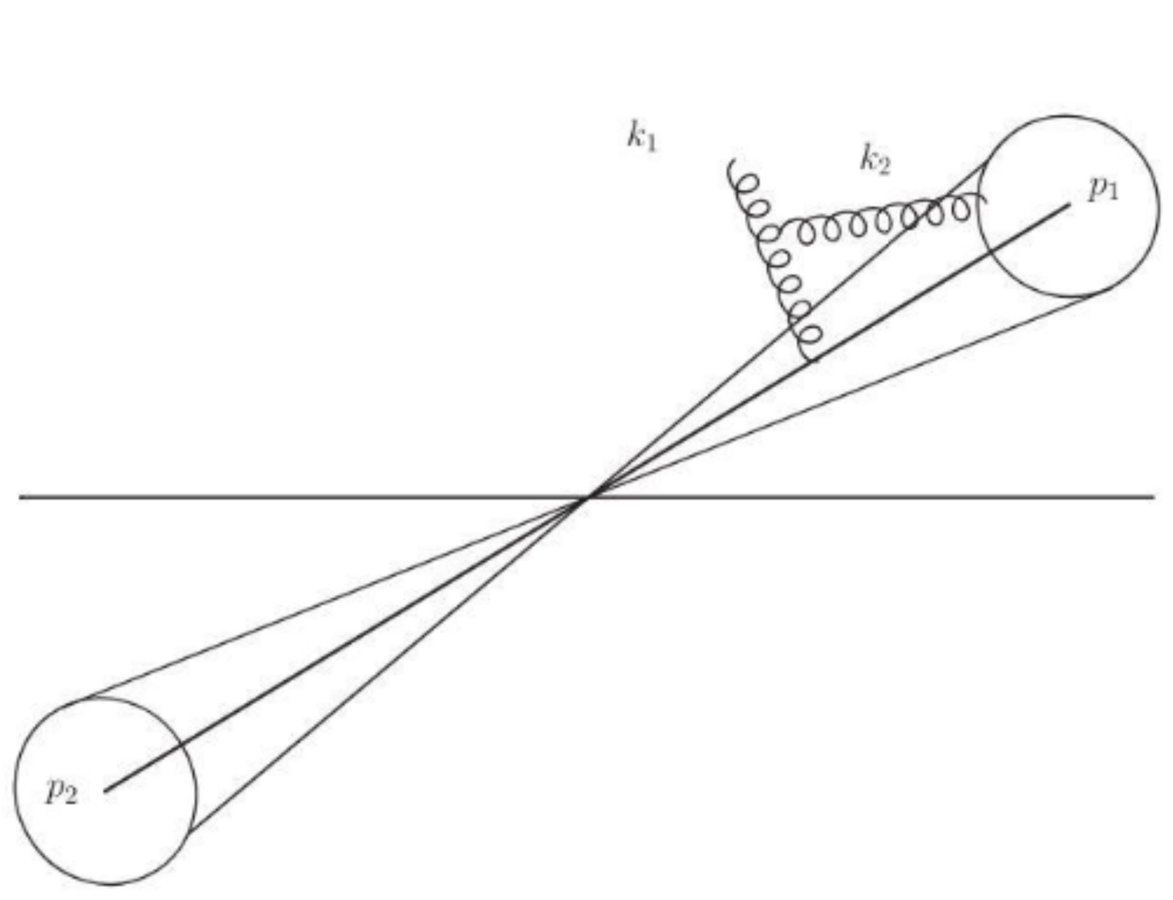
- The corresponding scattering amplitude squared factorises in the quasi-collinear limit, thus we can write the cumulative cross section as follows

$$\Sigma_V(v) = 1 - \frac{\alpha_S(\mu^2)}{2\pi} \int_0^{Q^2} \frac{dk_t^2}{k_t^2 + z^2 m^2} \int_0^1 dz\, P_{QQ}(z, k_t^2)\Theta\left(V\left(k_t^2, \eta\right) - v\right)$$

- $V(k_t^2, \eta)$ represents the soft and collinear limits of the observable and in general it can be parametrised as

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

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



multiple emission effects

$$\Sigma_{\rm res}(v) = e^{-R(v)}\mathscr{F}\,\mathcal{S}$$

non-global effects

[Dasgupta and Salam (0104277)]

$$\mathscr{F} = \frac{e^{-\gamma_E R'}}{\Gamma(1+R')}$$

with $R' = \frac{\partial R}{\partial L}$, $L = \log\frac{1}{v}$

with R the radiator defined as

$$R_b(v) = \int_{z^2m^2}^{Q^2}\frac{dk_t^2}{k_t^2}\int_0^1 dz\, P_{QQ}(z, k_t^2 - z^2m^2)\frac{\alpha_S^{\rm CMW}(k_t^2)}{2\pi}\Theta\left(V\left(k_t^2,\eta\right) - v\right)$$

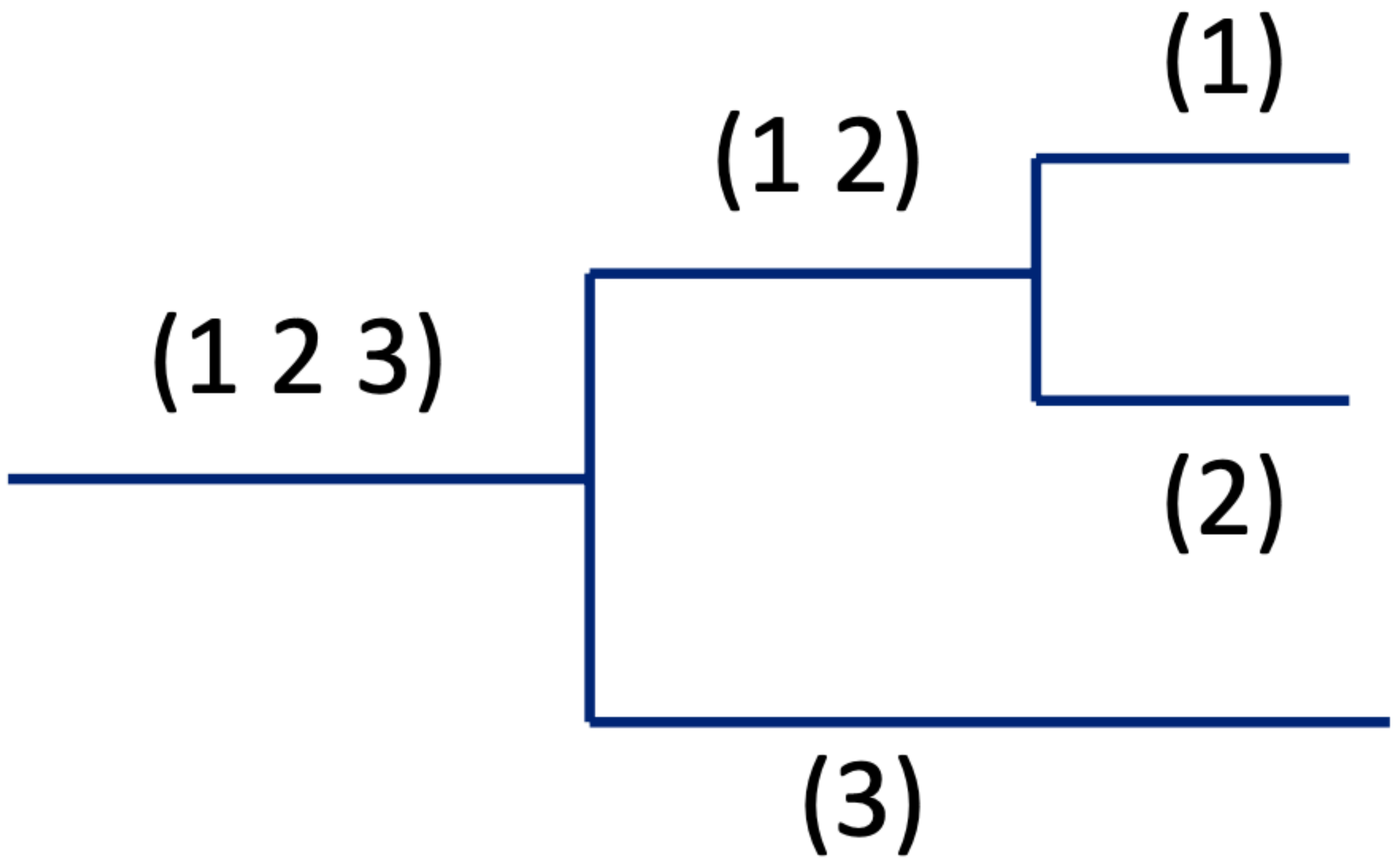
$$\alpha_s^{\rm CMW}(k_t^2) = \alpha_s(k_t^2)\left(1 + \alpha_s(k_t^2)\frac{K^{(n_f)}}{2\pi}\right)$$

$$K^{(n_f)} = C_A\left(\frac{67}{18} - \frac{\pi^2}{6}\right) - \frac{5}{9}n_f$$

Decoupling scheme

$$\alpha_S(k_t^2) = \alpha_S^{(5)}(k_t^2)\Theta(k_t^2 - m^2) + \alpha_S^{(4)}(k_t^2)\Theta(m^2 - k_t^2)$$

The SD algorithm consistently removes soft emissions at large angle



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

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

The jet constituents of an anti-k_t jet are reclustered according to Cambridge-Aachen to form an angular ordered tree. The de-clustering is then applied.

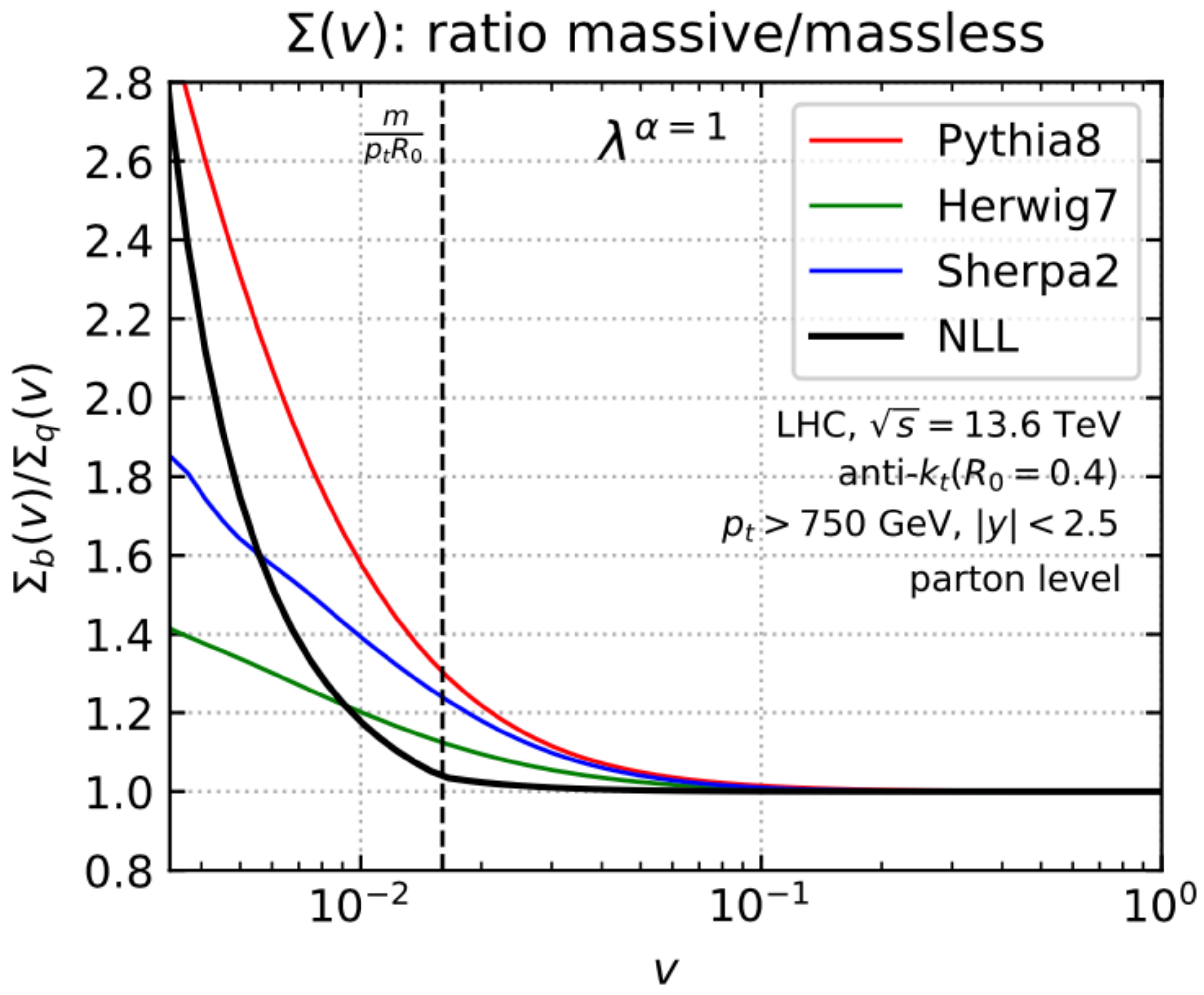
Energy-energy correlation functions

$$e_2^\alpha = \sum_{i \neq j \in \mathrm{Jet}} \frac{p_{t_i} p_{t_j}}{p_t^2} \left(\frac{\Delta R_{ij}}{R_0} \right)^\alpha \qquad \Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$

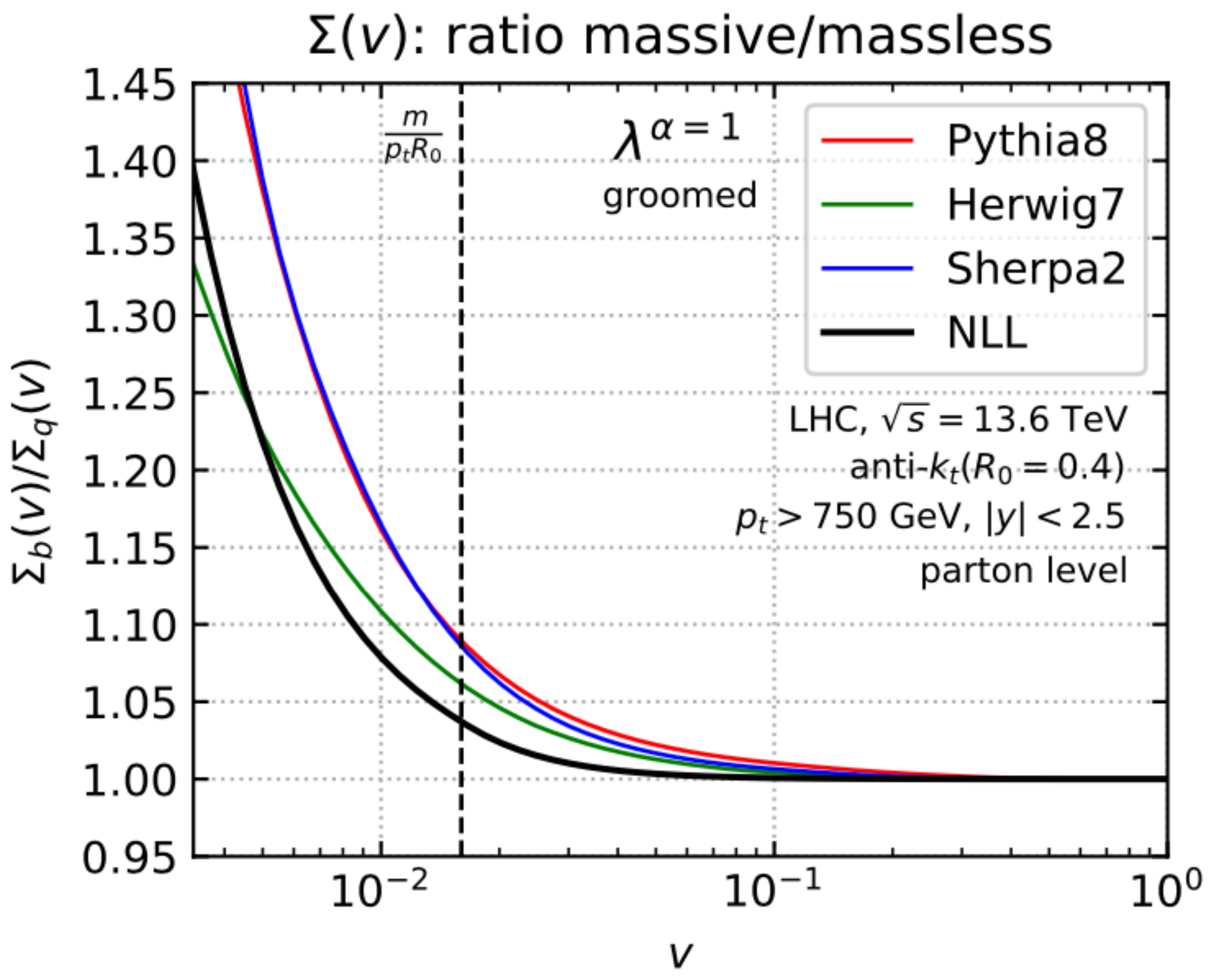
- Other definitions of EEC are equally interesting to study. [Lee, Shrivastava and Vaidya (1901.09095)]

Jet Angularity

$$\lambda^\alpha = \sum_{i \in \mathrm{Jet}} \frac{p_{t_i}}{p_t} \left(\frac{\Delta R_i}{R_0} \right)^\alpha \qquad \Delta R_i = \sqrt{(y - y_i)^2 + (\phi - \phi_i)^2}$$



Ungroomed



Soft-Drop with $\beta = 0$

- Plot showing the ratio of the cumulative distribution: massive/massless
- It appears that the dead cone effect manifests earlier in MC than predicted by theoretical calculations

- Jet sub-structure techniques provide a systematic method to understand the origin of various splittings that constitute a jet

- We have considered jet angularity to explore quark mass effects and understand recent measurement of dead-cone effect by ALICE collaboration

- Other related observables are under study

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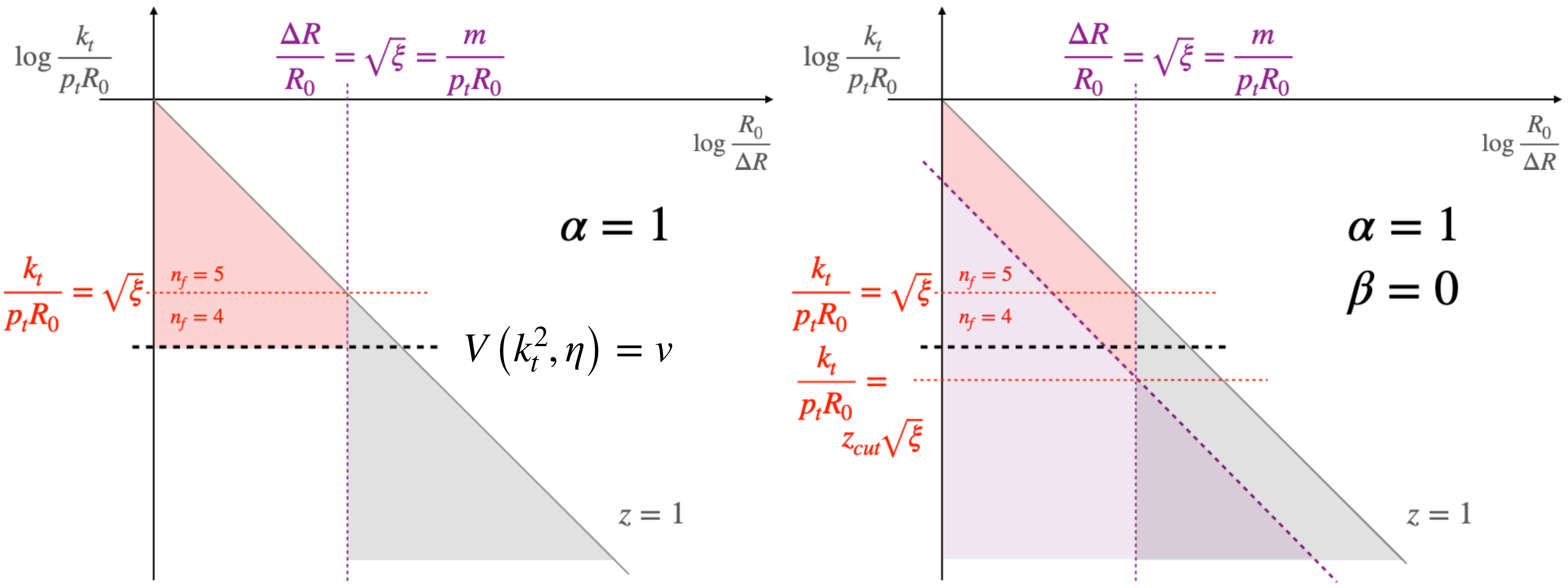
Thank You Very Much!



- To smooth the transition point, we also incorporate fixed order contribution
- These are beyond NLL contributions, which depend on the specific definition of the observable