Running in the Hidden Valley

(To appear!)

Exploring near-conformal dark sector theories

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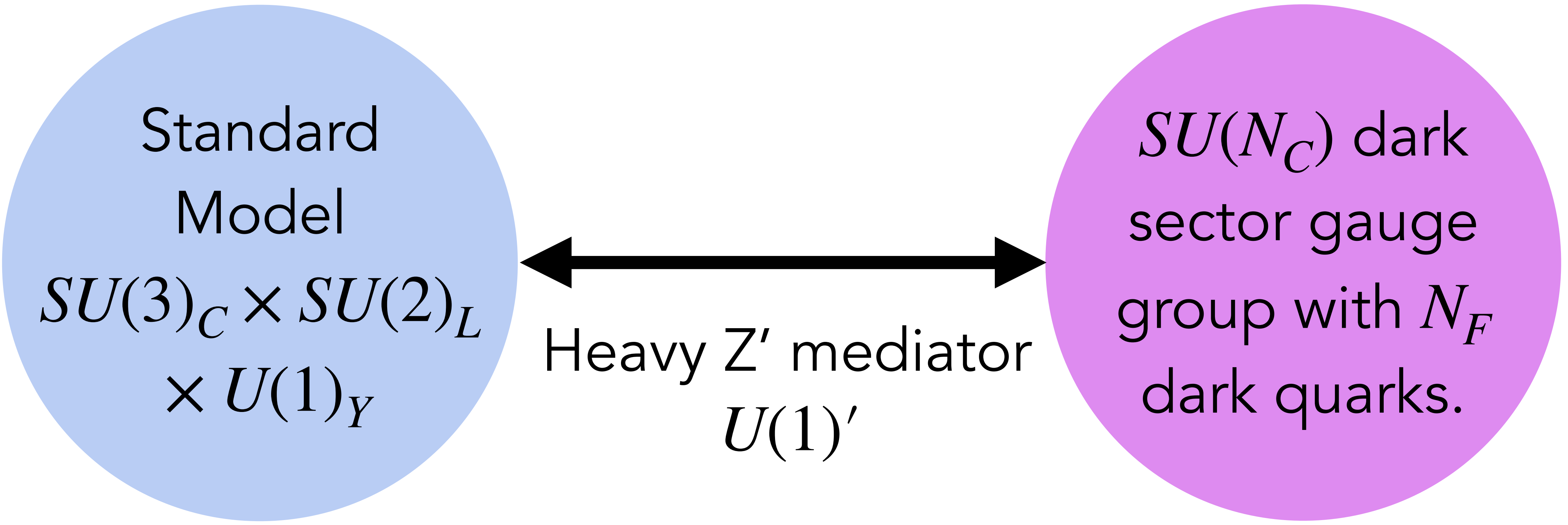
Confining Hidden Valley models

arXiv:0604261, M.J. Strassler et al.

arXiv:1502.05409, P. Schwaller et al.

arXiv:1503.00009, T. Cohen et al.

arXiv:0712.2041, T. Han et al.

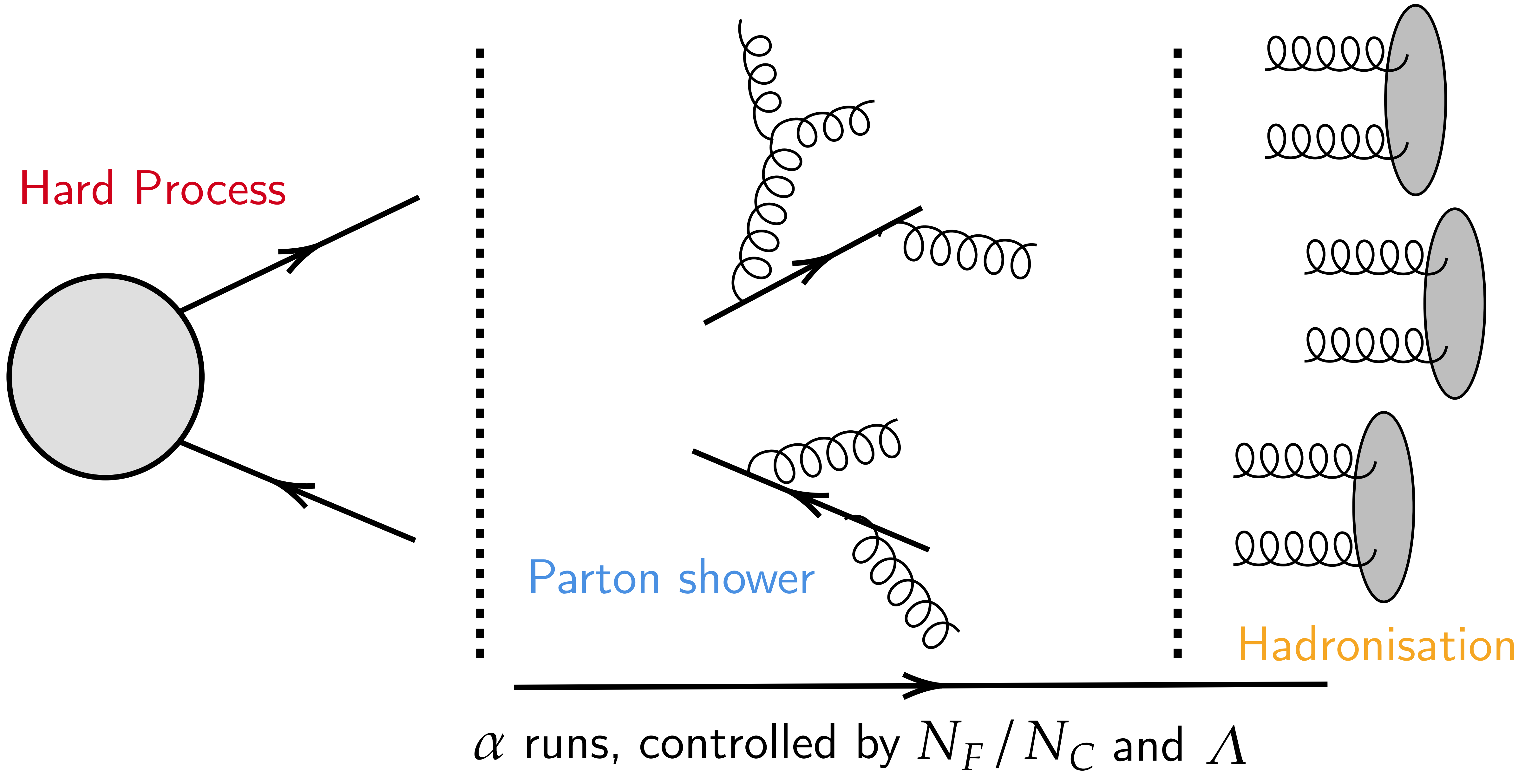


- Hidden Valley models that extend the SM with a new confining dark sector resembling QCD present exciting opportunities for new physics discovery. For now, we focus on dark quarks which are light Dirac fermions in the fundamental representation of $SU(N_C)$.
- At colliders, these dark quarks undergo parton showering, hadronisation and decay giving rise to anomalous jet signatures e.g. emerging or semi-visible jets that are well-known at small N_F/N_C. Large N_F/N_C dark sectors are a largely undeveloped area of theory space and could give rise to distinct signatures.
- There is a plethora of work focused on the non-perturbative structure and the low-energy effective descriptions of large N_F/N_C theories; can be leveraged to build up near-conformal dark sector models in the future.

arXiv:2306.07236, A. Hasenfratz et al. arXiv:2305.03665, T. Appelquist et al. arXiv:2312.13761, R. Zwicky

arXiv:1610.01752, M. Golterman et al. arXiv:2312.08332, A. Pomarol et al. arXiv:2404.07601, T. Appelquist et al.

Dark parton showering



$$\mu^2 \frac{d\alpha}{d\mu^2} = \beta(\alpha) = -\,\alpha^2\left(\beta_0 + \beta_1\alpha\right) \qquad \text{(at 2-loop)}$$

$$N_C\,\alpha = f(N_F/N_C, \mu/\Lambda) \;+\; \mathcal{O}(N_F/N_C^3) \text{ corrections}$$

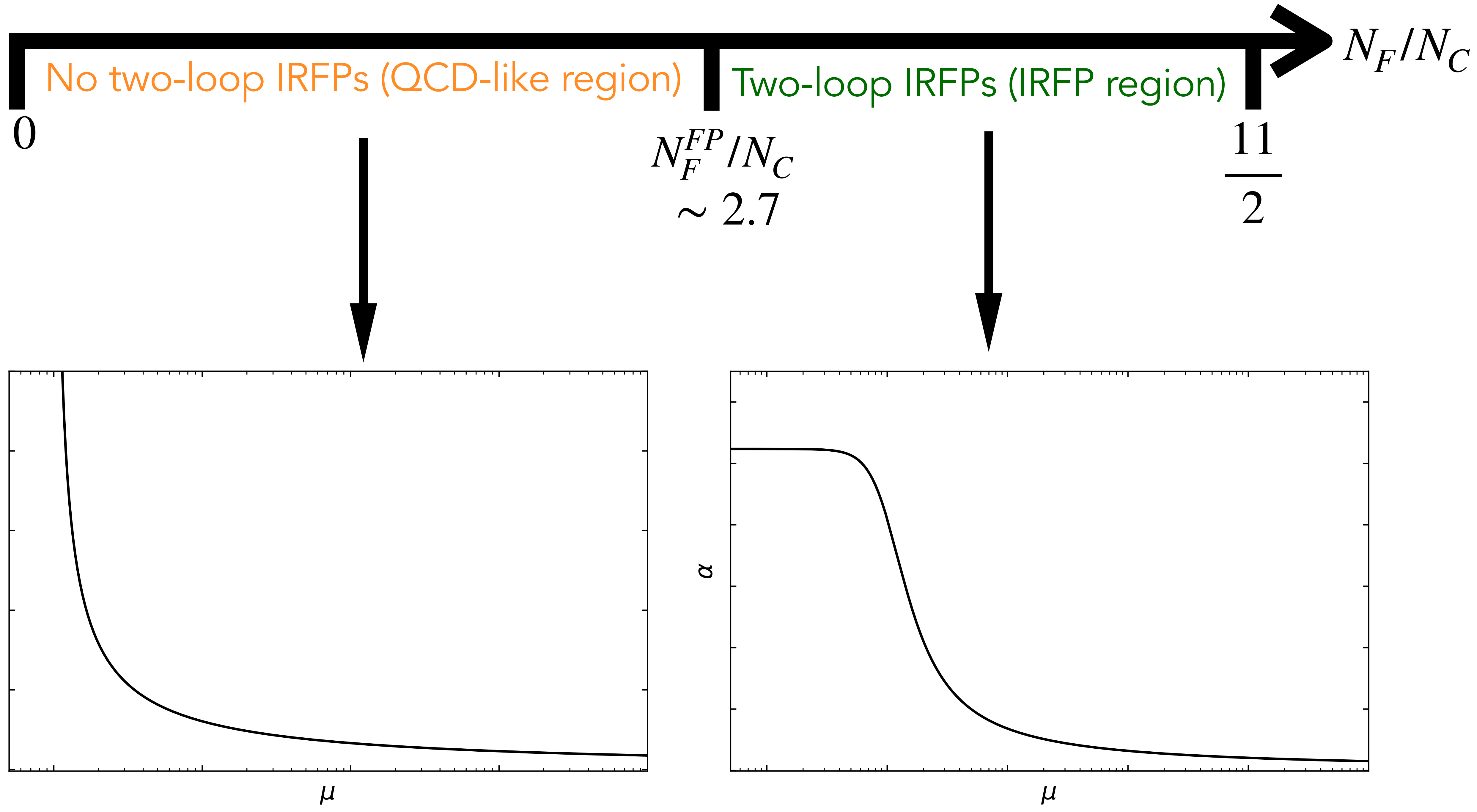
Non-trivial fixed point: $\alpha_* = -\dfrac{\beta_0}{\beta_1}$; > 0 for $N_F/N_C \gtrsim 2.7$

- For now, focus on dark parton showering; hadronisation details not yet fully understood. Dark parton showering is governed by the t' Hooft gauge coupling, $N_C\,\alpha$ with α in turn being governed by the Renormalisation Group Equations (RGE). G. 't Hooft Nucl. Phys. B ('74)
- Parton shower ends near scale Λ, which characterises breakdown of perturbative expansion of α, thus scaling α as $\alpha(\mu/\Lambda)$. To a good approximation, the t' Hooft gauge coupling is governed solely by N_F/N_C and μ/Λ.
- At two-loop, for $N_F/N_C \gtrsim 2.7$, α flows to a non-trivial infra-red fixed point (IRFP); as N_F/N_C increases α begins to slow down. New procedures are needed to understand parton showering within this region. T. Banks., A. Zaks, Nucl.Phys.B 196 ('82)

Near-conformal dark sector models

arXiv:2008.12223, J.W. Lee

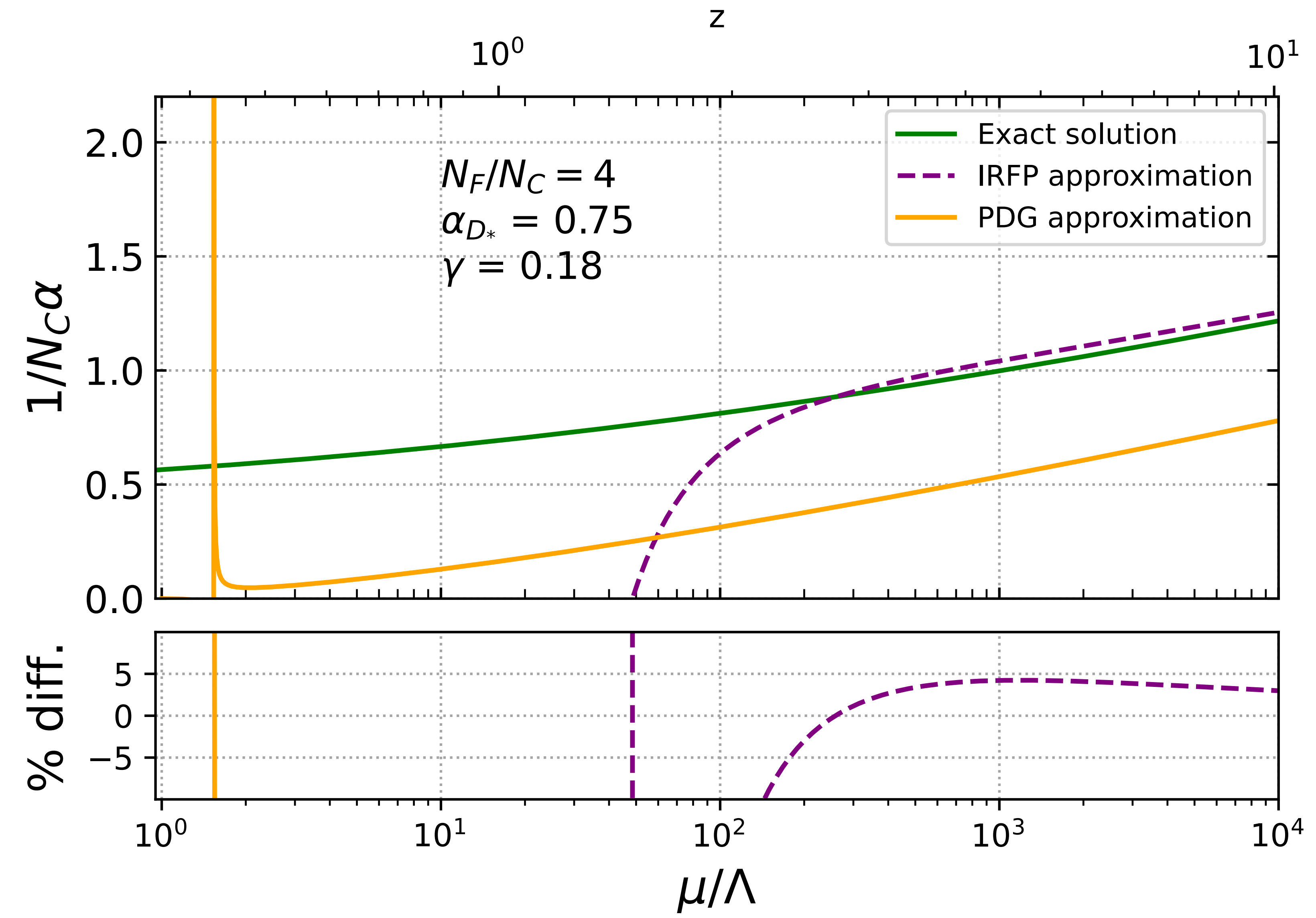
Two-loop perturbative description

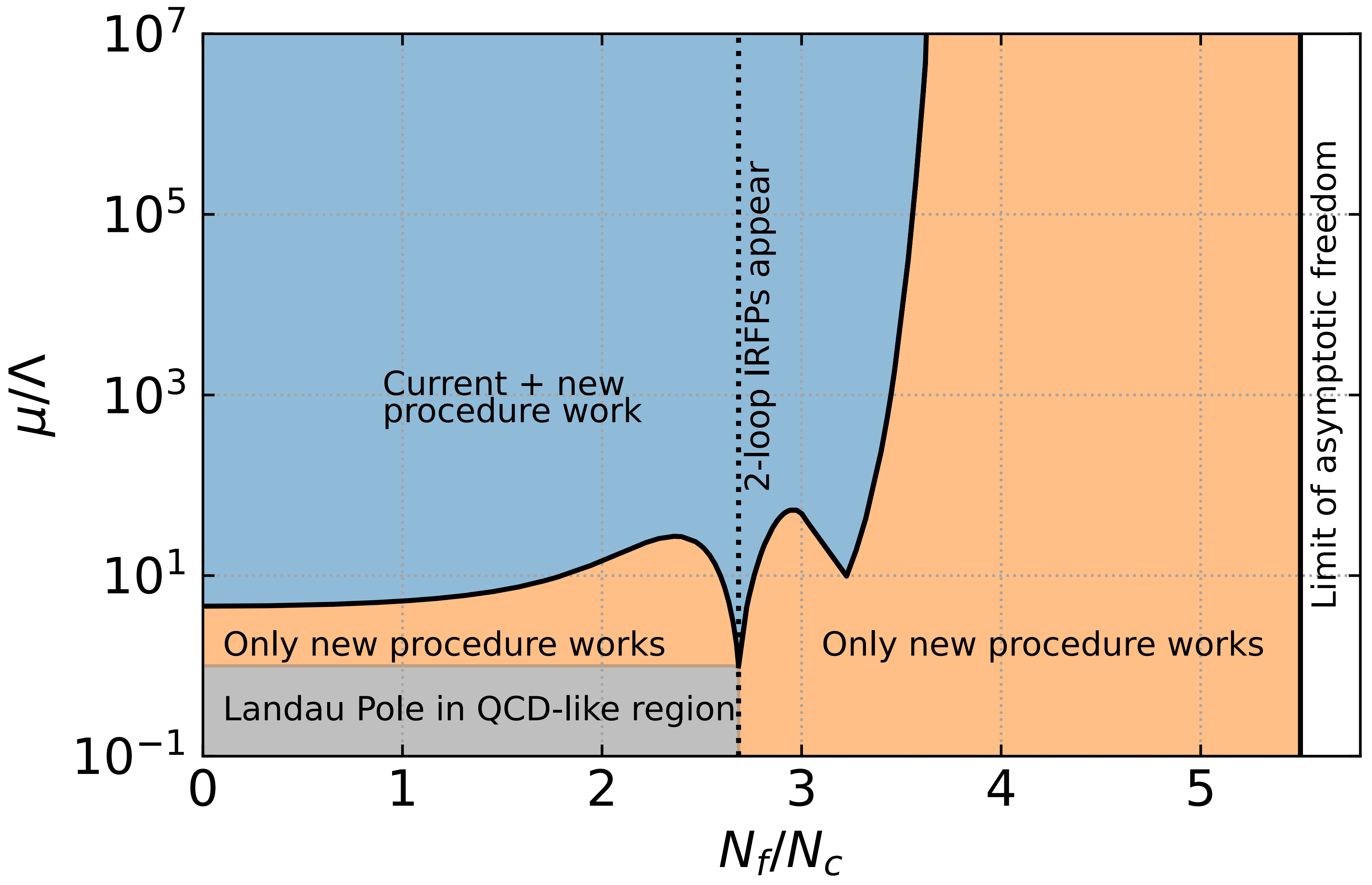


Non-perturbative description

- Within the conformal window, chiral symmetry is restored and the infra-red theory is conformal, having no associated scale. Lattice calculations suggest N_F^c/N_C = 3 — 4. arXiv:2004.00754, A. Hasenfratz et al.
- Since the dark quarks are light but massive ($m_q \ll \Lambda$), this deforms the IR conformal symmetry and provides a scale - thus ensuring the signature is not purely missing energy.

Modelling of dark parton showers





- The current approximation used within event generators (the PDG formula) is insufficient to describe two-loop α for high N_F/N_C since it neglects effects of the IRFP.
- By taking this IRFP into account, we establish a framework of two solutions to the RGE that allow for parton showering to be simulated across a wide range of parameter space.

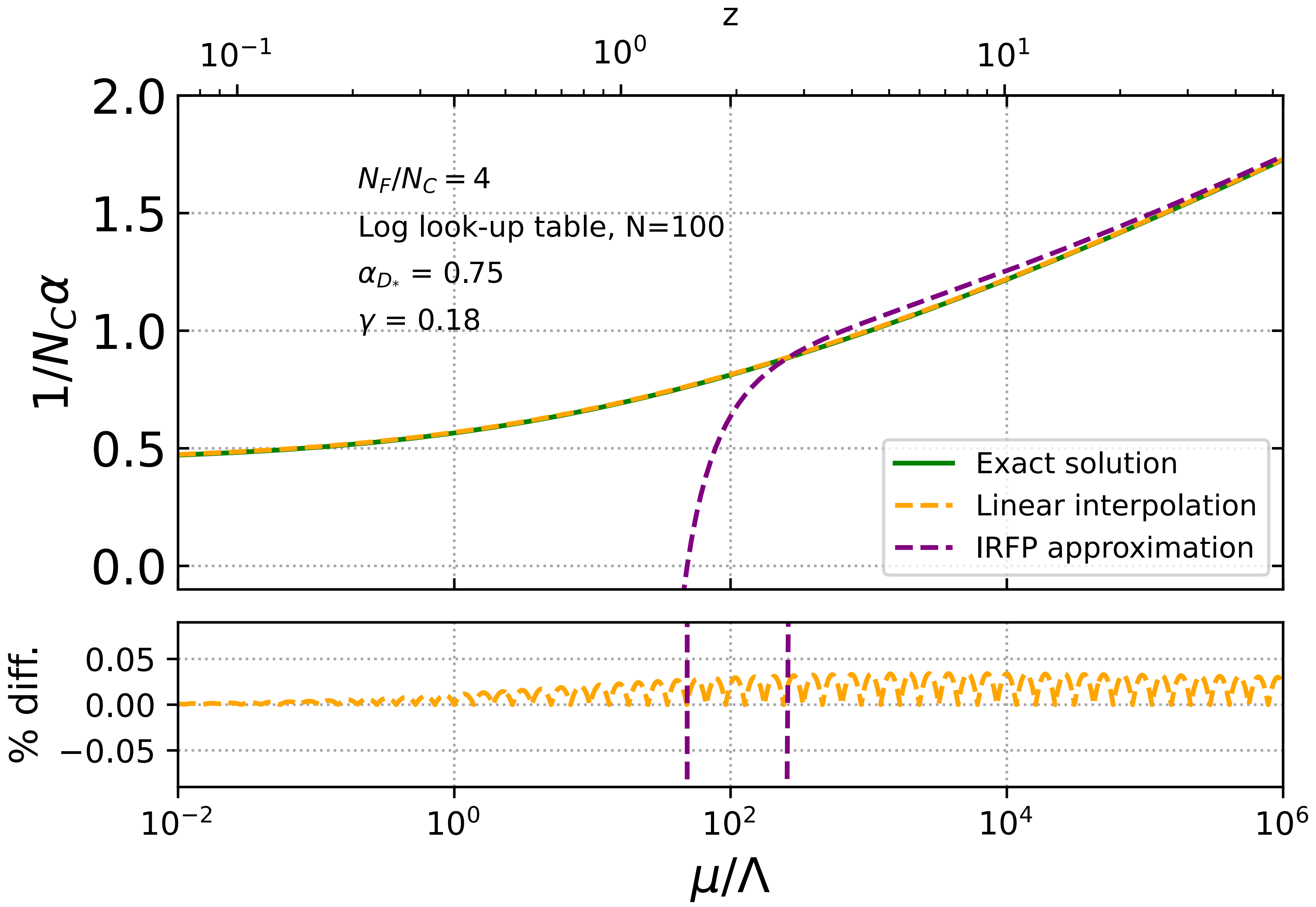
$$\alpha = \alpha_* \left[W_{-1}\left(-\frac{1}{e}\left(\frac{\mu^2}{\Lambda^2}\right)^{\beta_0\alpha_*} \right) + 1 \right]^{-1} \quad ; \quad \alpha = \alpha_* \left[W_0\left(\frac{1}{e}\left(\frac{\mu^2}{\Lambda^2}\right)^{\beta_0\alpha_*} \right) + 1 \right]^{-1}$$

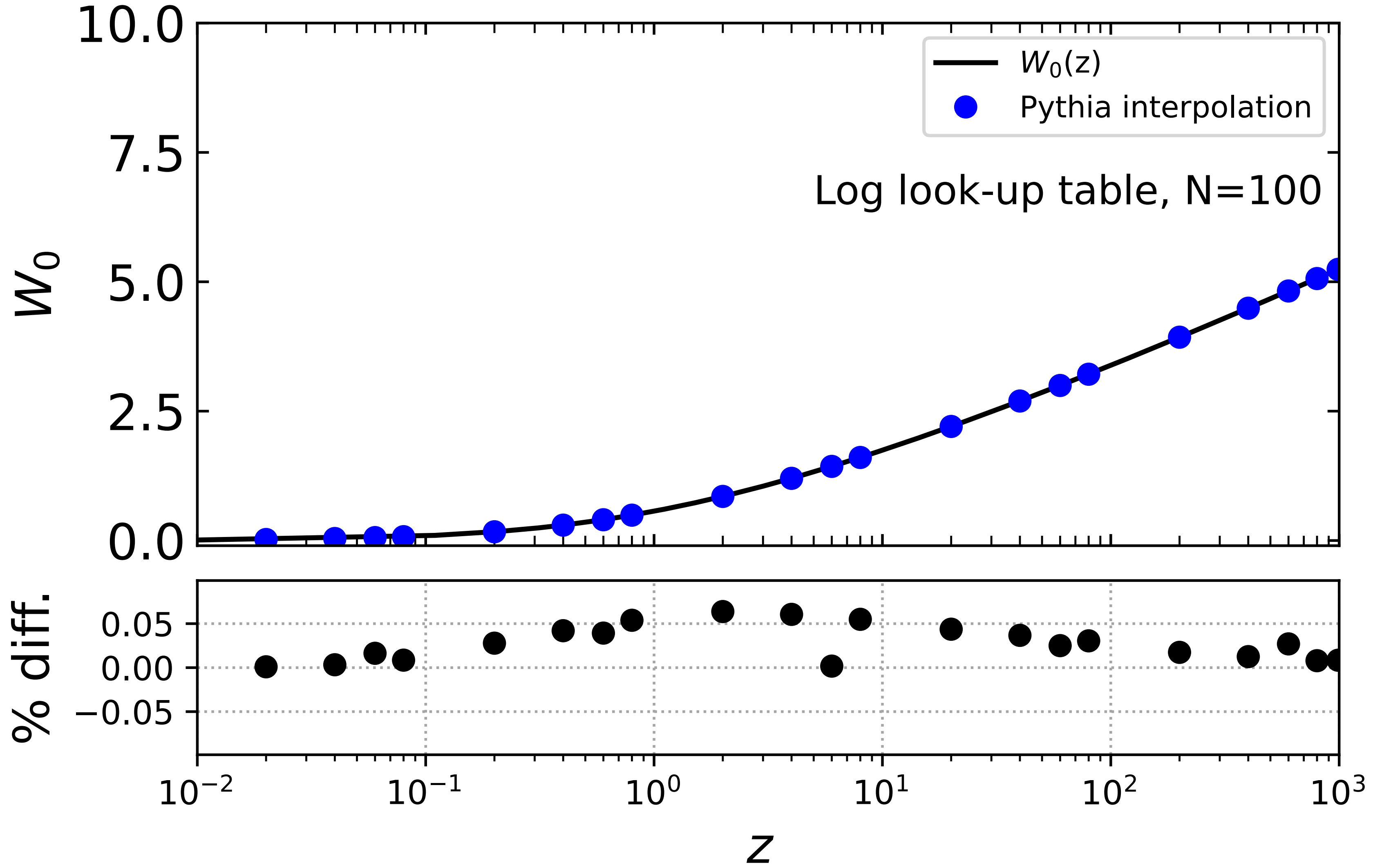
QCD-like (no IRFP) — IRFP-region

- This procedure defines Λ within the IRFP region as the scale at which power-law running takes over from logarithmic running.

arXiv:9602385, T. Appelquist et al. arXiv:1406.2337, D. Litim et al. arxiv:9810192 - E. Gardi et al.

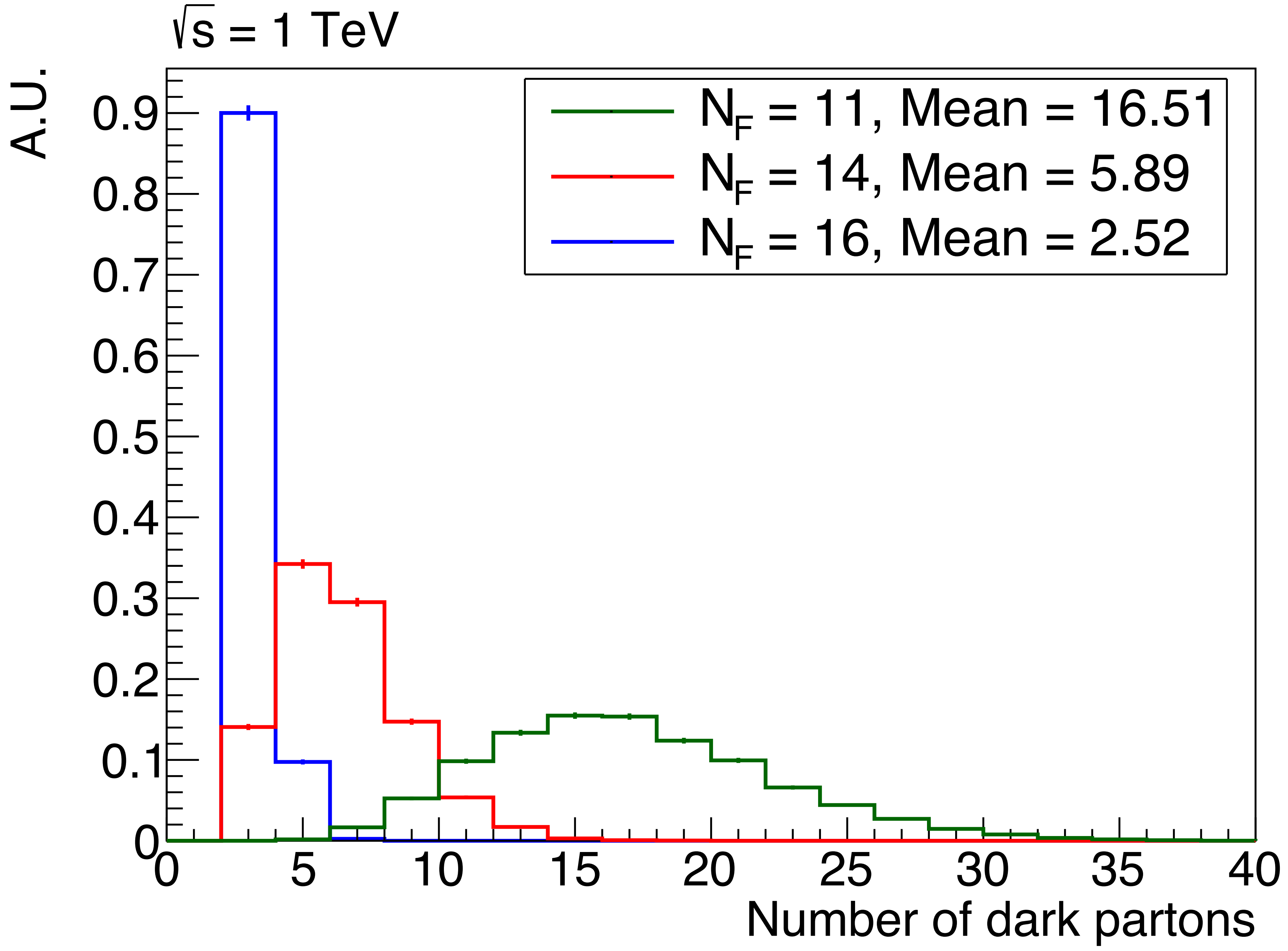
Modelling of dark parton showers

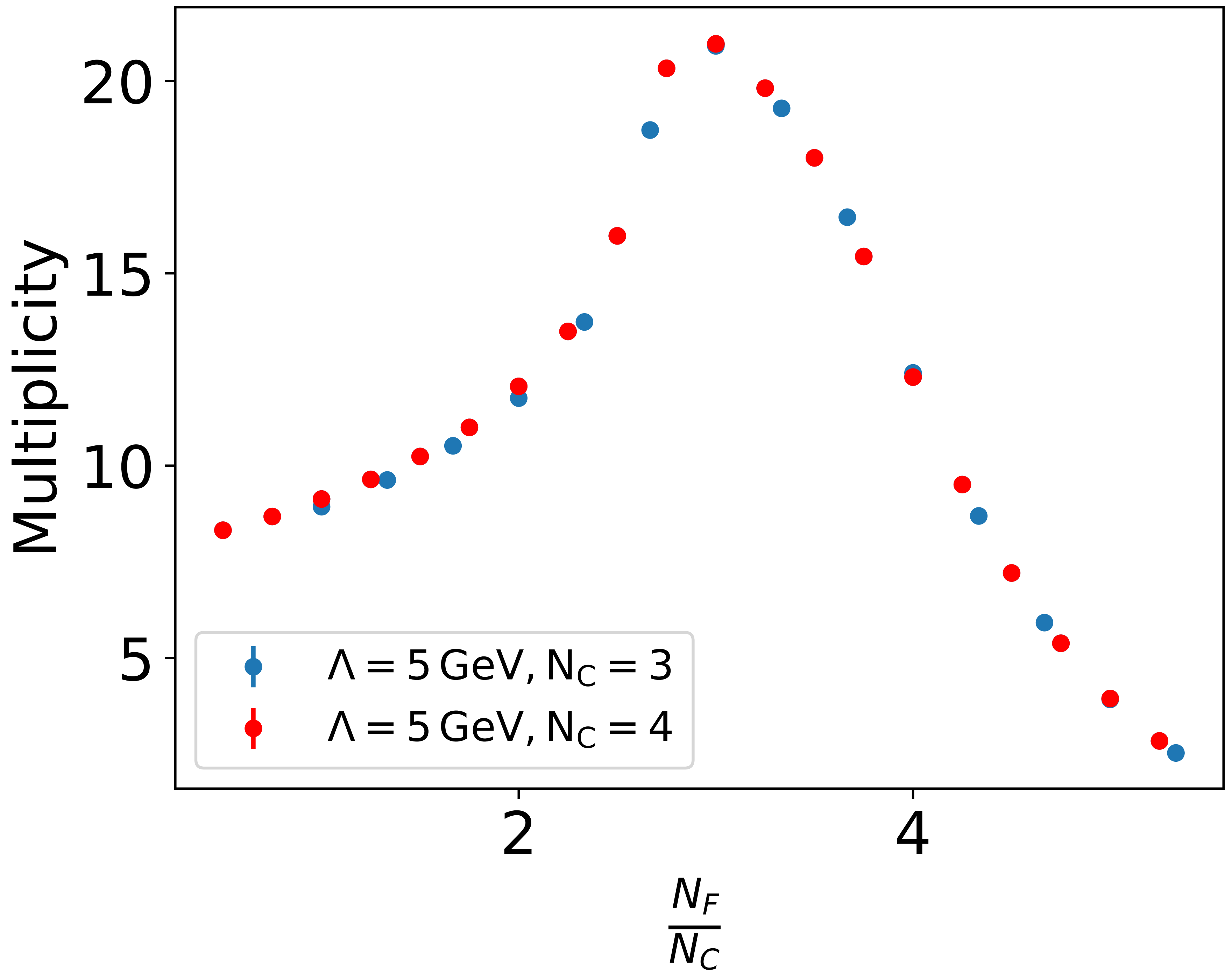




- Entire implementation makes use of the parameter $z = \frac{1}{e}\left(\frac{\mu^2}{\Lambda^2}\right)^{\beta_0\alpha_*}$ as it allows for scaling between different values of N_F/N_C.
- Within the QCD-like region, the implementation of the running coupling suffices with a large μ/Λ approximation for all $\mu/\Lambda > 1$.
- Within the IRFP region, the implementation also requires a large μ/Λ approximation, however this expansion can not model behaviour near the IRFP.
- Within this region, an interpolation routine is instead used. This was taken over z between a range of 10^{-2} and 10^{3} using 100 data points.
- The upper boundary of this interpolation is determined by when the large μ/Λ approximation deviates from the exact solution by 0.1%.

Simulation of dark parton showers

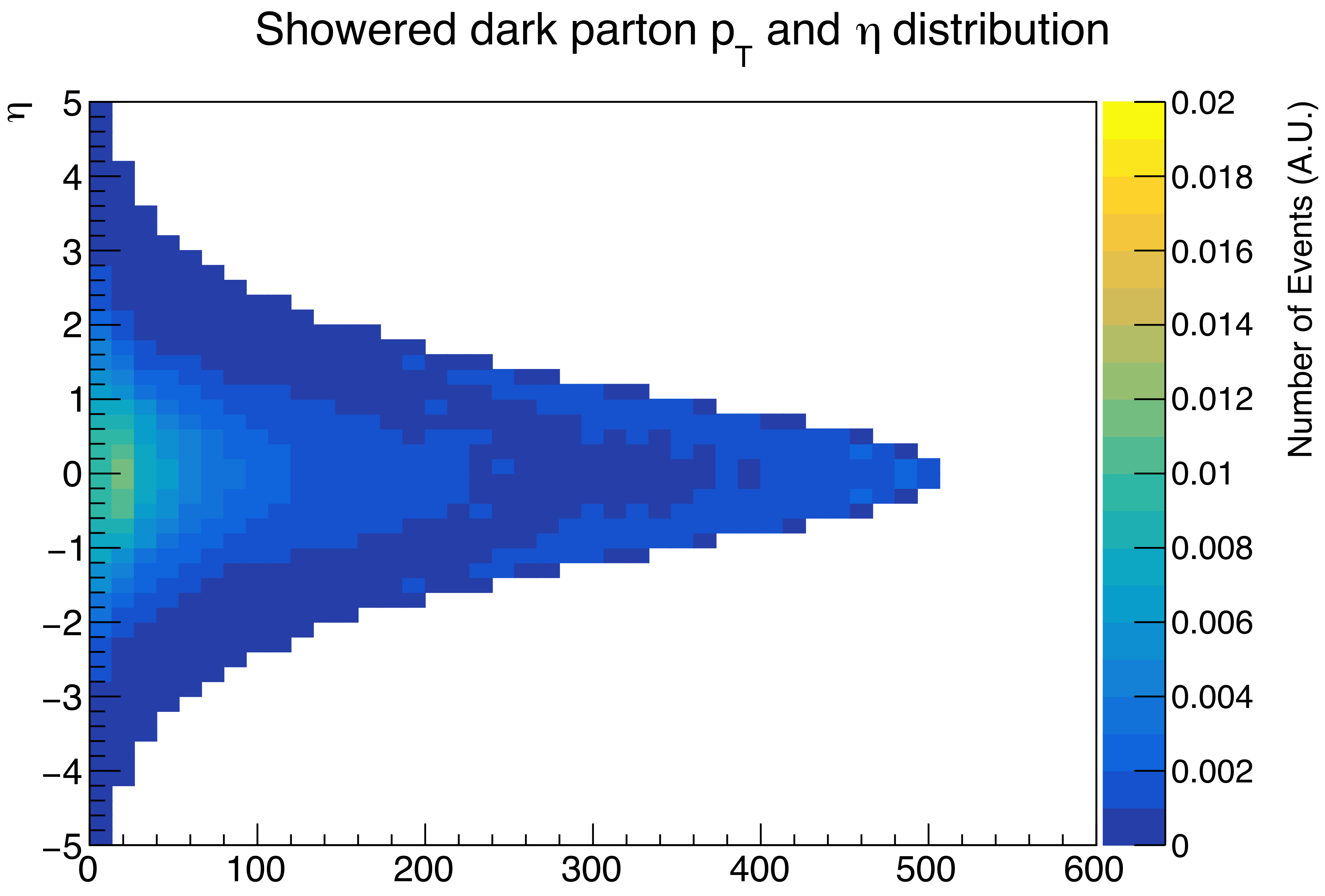




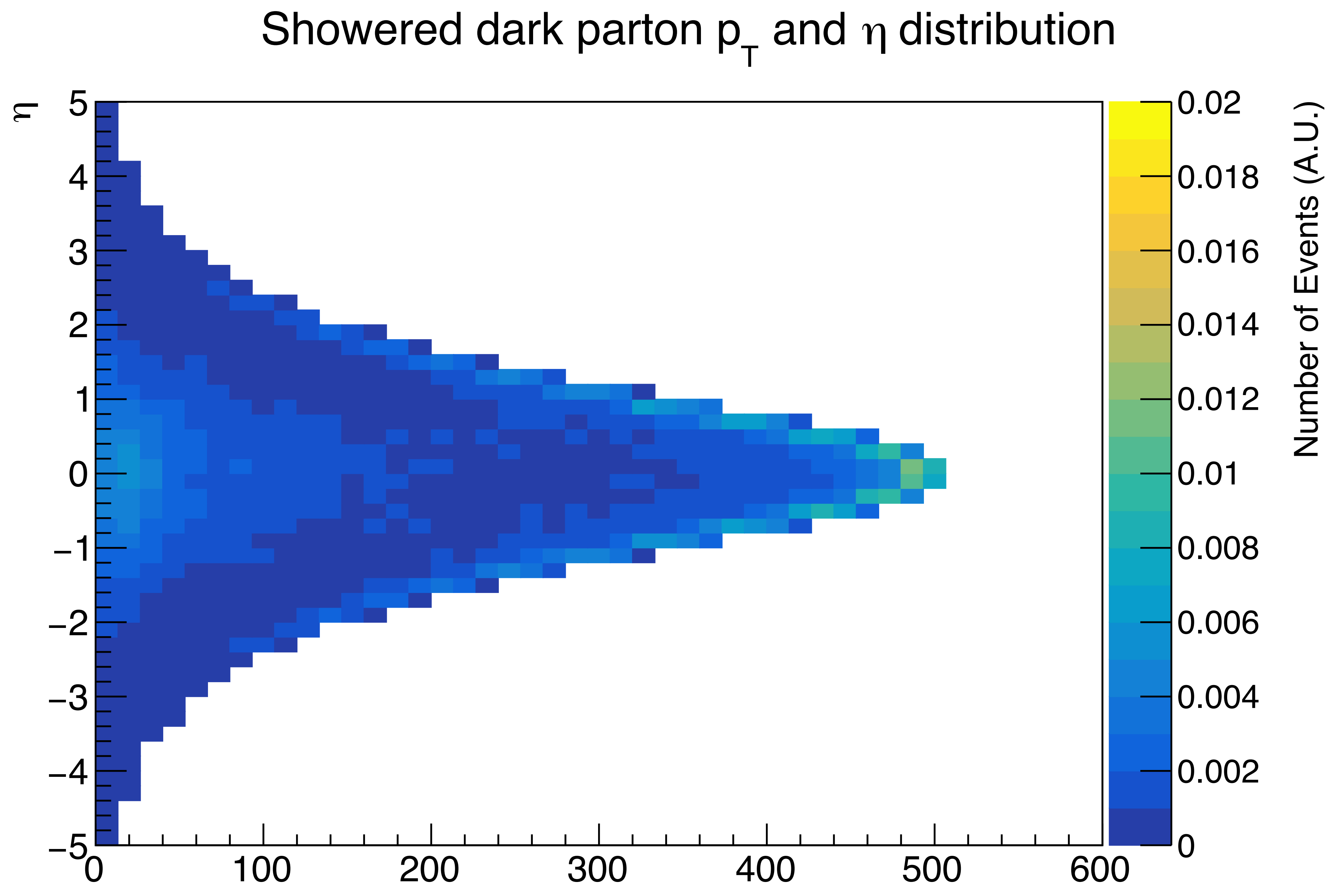
Simulated with a custom Pythia 8.307 with benchmark: $e^+e^- \to Z' \to q_D\overline{q_D}$, $\sqrt{s} = M_{Z'} = 1$ TeV , hadronisation off , $\Lambda = 5$ GeV , $N_C = 3$.

- Theories with large IRFPs ($\alpha_* \gg 1$) (around N_F/N_C ~3) have similar parton showering behaviour to those without IRFPs, having a overall large multiplicity of soft partons. Theories with small IRFPs ($\alpha_* \ll 1$) (around N_F/N_C ~5) have both hard and soft partons; having an overall small multiplicity of hard partons.
- Since parton splitting probability is proportional to α, it thus vanishes as $N_F/N_C \to 5.5$. Hence there is very little splitting at N_F/N_C ~5 and average parton multiplicity is almost 2 - the 2 initial dark quarks.

Simulation of dark parton showers



$\Lambda = 5$ GeV , $N_F = 14$



$\Lambda = 5$ GeV , $N_F = 16$

Simulated with a custom Pythia 8.307 with benchmark:
$e^+e^- \to Z' \to q_D\overline{q_D}$,
$\sqrt{s} = M_{Z'} = 1$ TeV ,
hadronisation off ,
$\Lambda = 5$ GeV , $N_C = 3$.

- At around N_F/N_C ~5, there is a transition in the p_T — η plane from the majority of partons being soft to a majority being hard, reflecting how branching probability is negligible and the majority of partons are initial dark quarks.
- This new procedure allows for the simulation of the anomalous jets signatures of near-conformal Hidden Valley theories. Motivates further investigations into the hadronisation and subsequent decay of near-conformal bound states, as this could have an additionally large influence on the dark shower phenomenology.

Thank you!
Questions?