Walking in the Hidden Valley

(Paper to appear!)

Exploring near-conformal dark sectors

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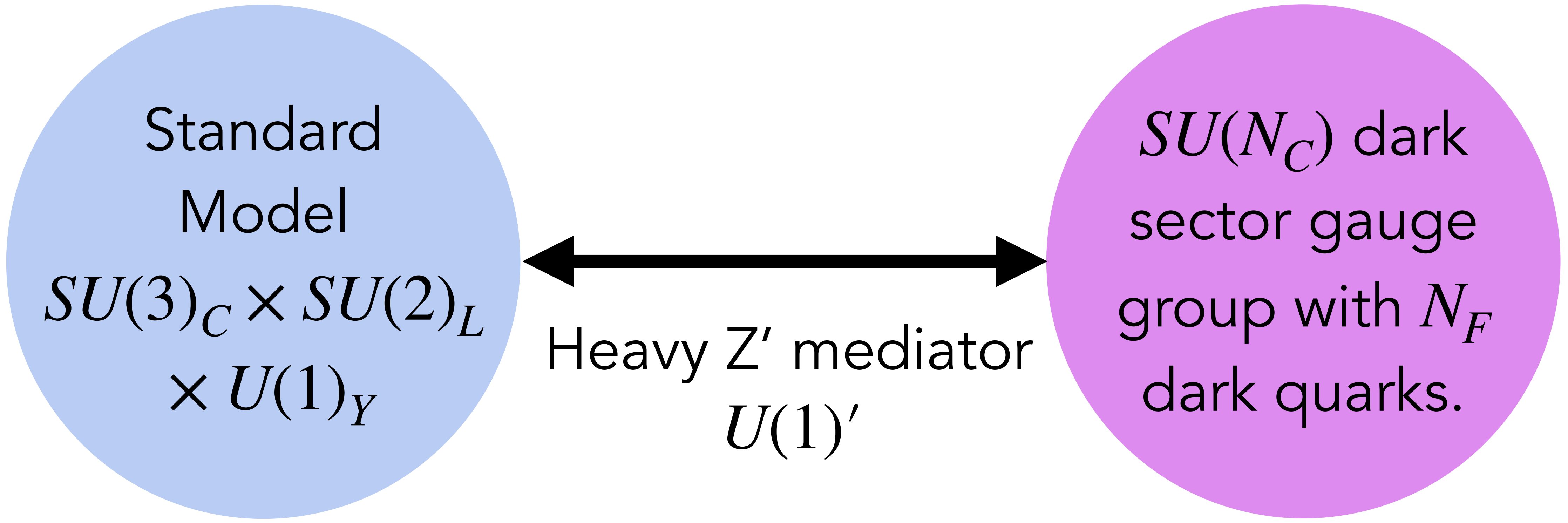
Confining dark sector models

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.

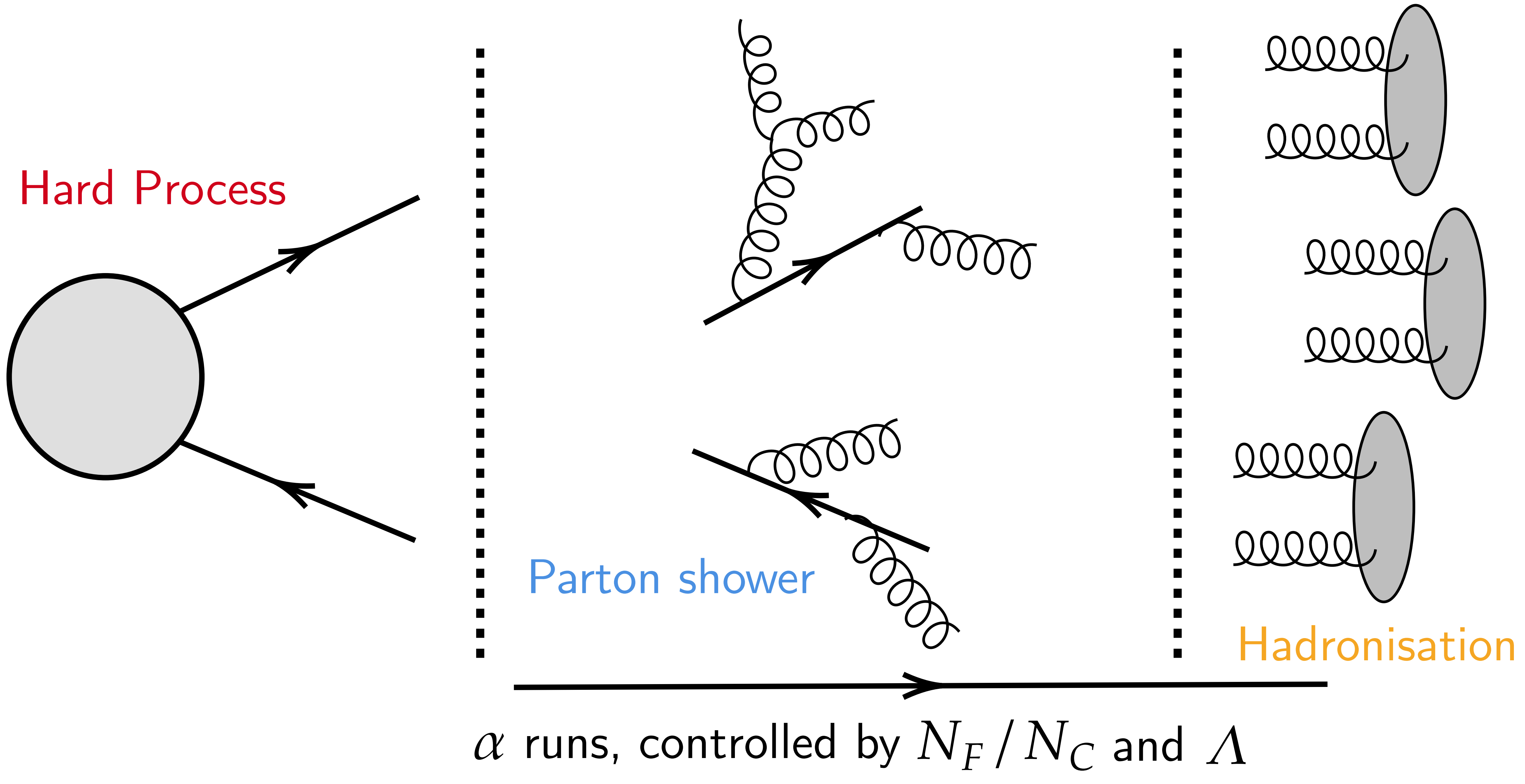


- Hidden Valley models that extend the SM with a new confining dark sector resembling QCD present exciting opportunities for new physics discovery. We will focus on light dark quarks; Dirac fermions in the fundamental representation of $SU(N_C)$.
- At colliders, these dark quarks undergo parton showering, 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 used 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



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

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

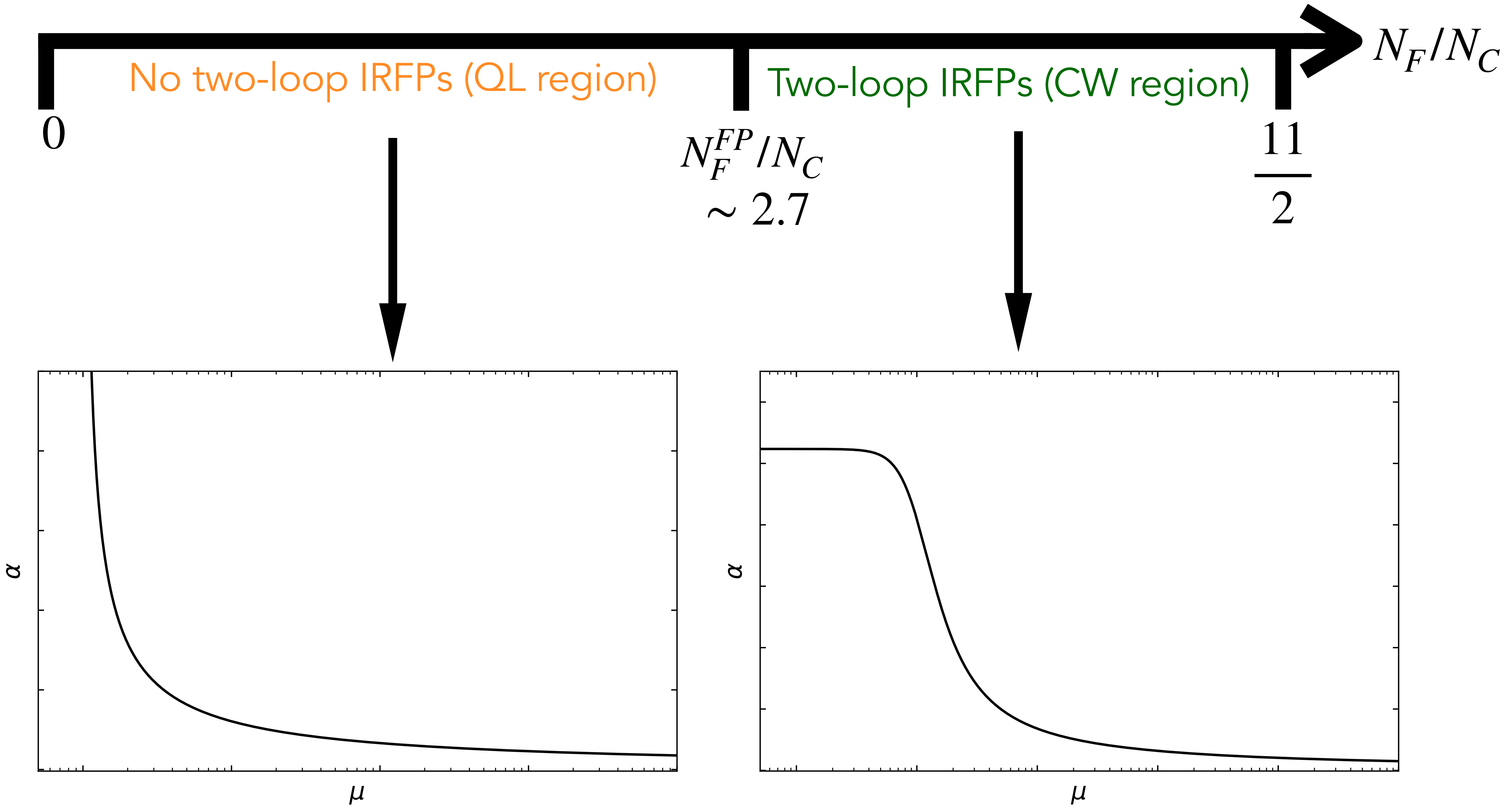
Non-trivial fixed point: $\alpha_* = -\,\dfrac{\beta_0}{\beta_1}$; > 0 for $N_F/N_C \gtrsim 2.7$

- First, we'll 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, this scale characterises the breakdown of the perturbative expansion of α and is a good proxy for the scale of the theory. Up to corrections, 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)

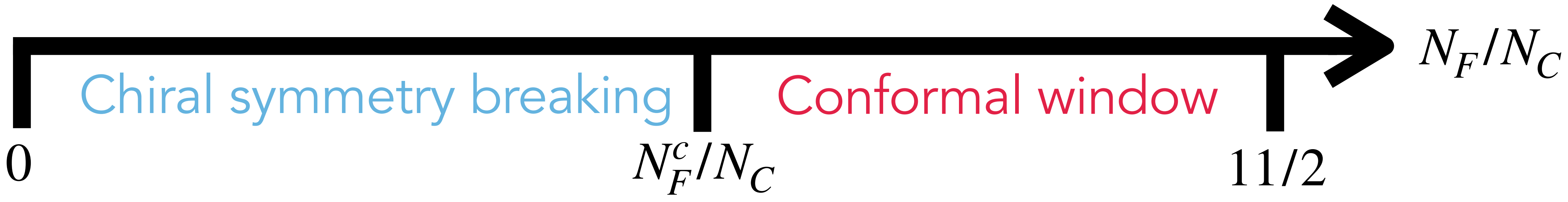
Near-conformal dark sector models

arXiv:2008.12223, J.W. Lee

Two-loop perturbative description

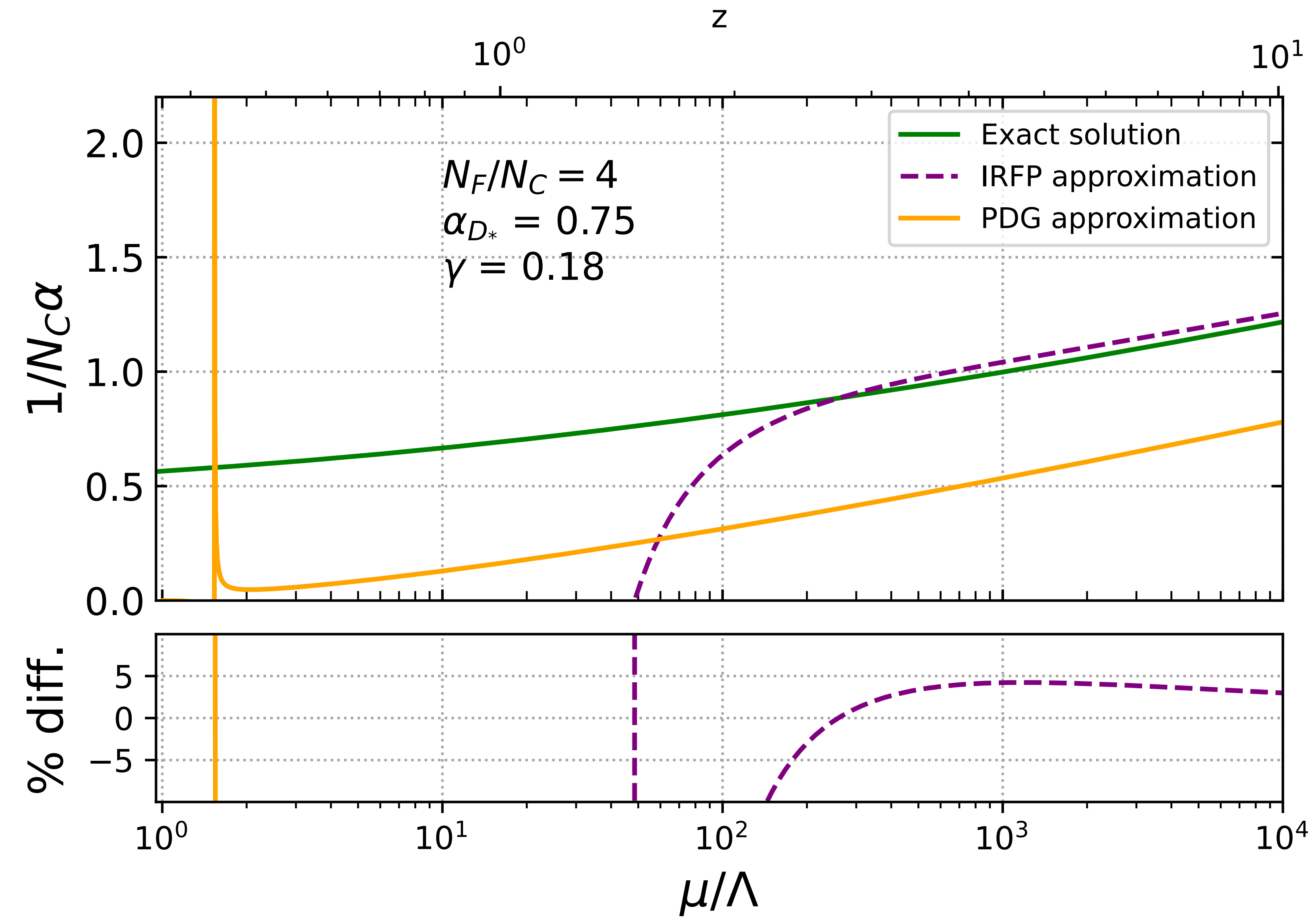


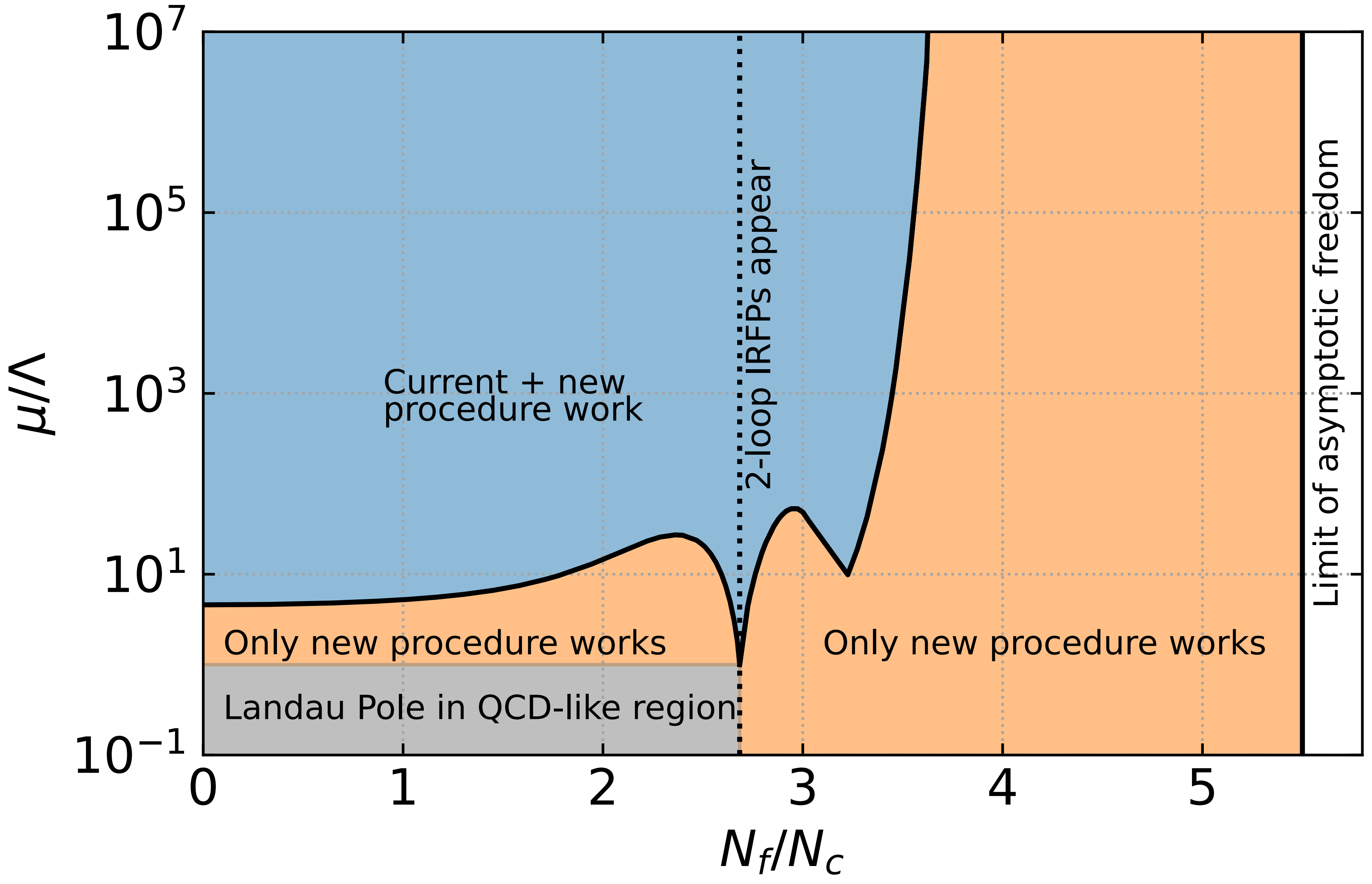
Non-perturbative description



- Within the conformal window, chiral symmetry is restored and the infra-red theory is conformal. Lattice calculations suggest N_F^c/N_C = 3 — 4. arXiv:2004.00754, A. Hasenfratz et al.
- Since α flows from a weakly coupled value in the UV, we automatically lose scale invariance. The dark quark mass (m_q) additionally deforms the IR conformal symmetry. These ensure any signatures are 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.

$$\alpha = \alpha_* \left[W_{-1}\left(-\frac{1}{e}\left(\frac{\mu^2}{\Lambda^2}\right)^{\beta_0\alpha_*} \right) + 1 \right]^{-1} \quad ; \quad \alpha = \alpha_* \left[W_{0}\left(\frac{1}{e}\left(\frac{\mu^2}{\Lambda^2}\right)^{\beta_0\alpha_*} \right) + 1 \right]^{-1}$$

QL region (no IRFPs) CW region (IRFPs)

- 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.

The Sudakov veto algorithm at two-loop

- To generate some scale Q_i^2 given some initial scale Q_{i-1}^2, Pythia generates a random number R_1 and solves for $\Delta\left(Q_i^2, Q_{i-1}^2\right) = R_1$. Δ is the Sudakov form factor, the probability of no parton emissions between Q_{i-1}^2 and Q_i^2.

arXiv:0603175 - T. Sjöstrand et al. arXiv:1102.2126 - W. Giele et al. arXiv:1101.2599 - A. Buckley et al. arXiv:1211.7204 - L. Lonnblad et al.

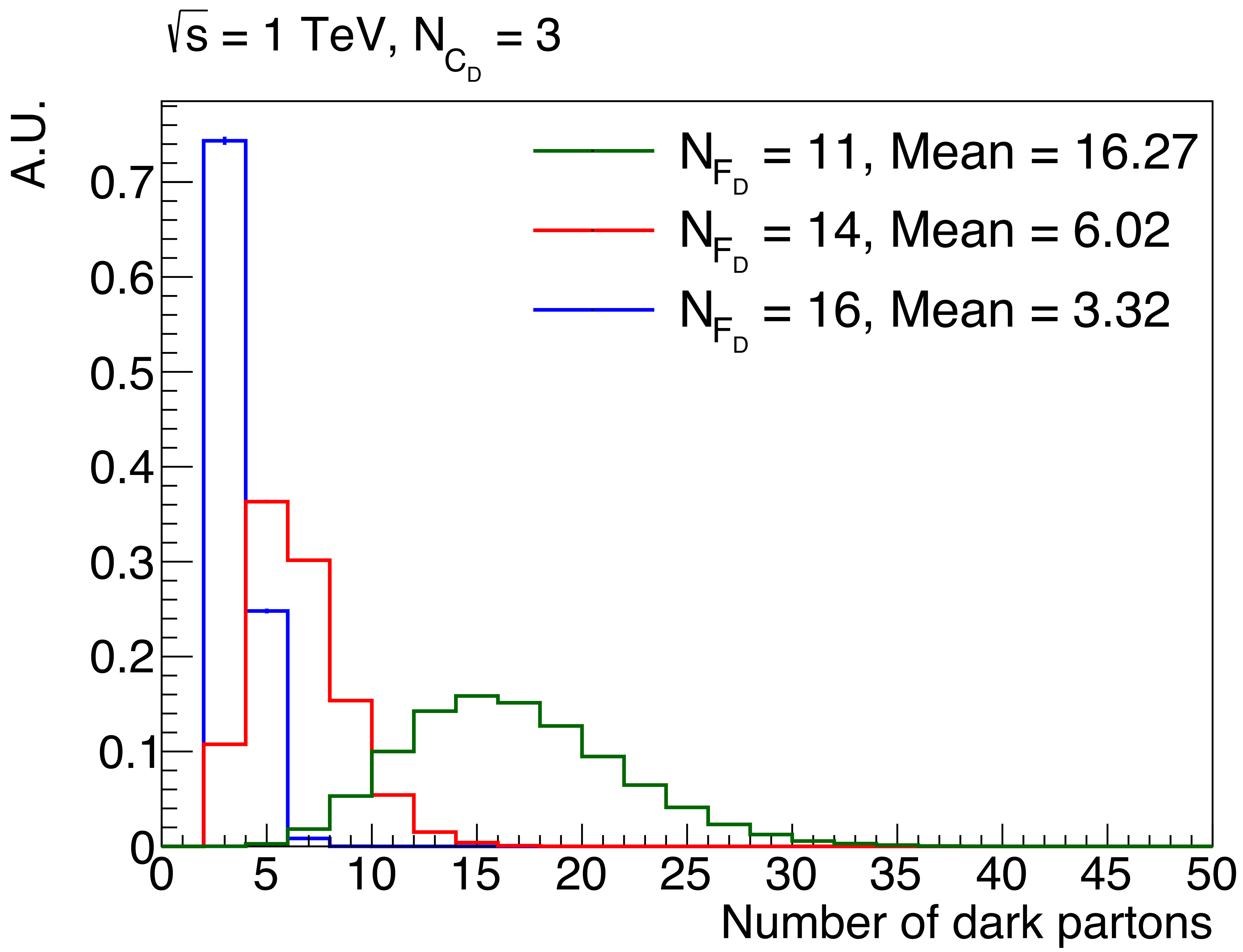
- This inversion is complicated, so Δ is usually overestimated with a much simpler $\tilde{\Delta}$. The overestimate is then corrected for through the Sudakov veto algorithm. At two-loop, the inverse can be performed exactly as,

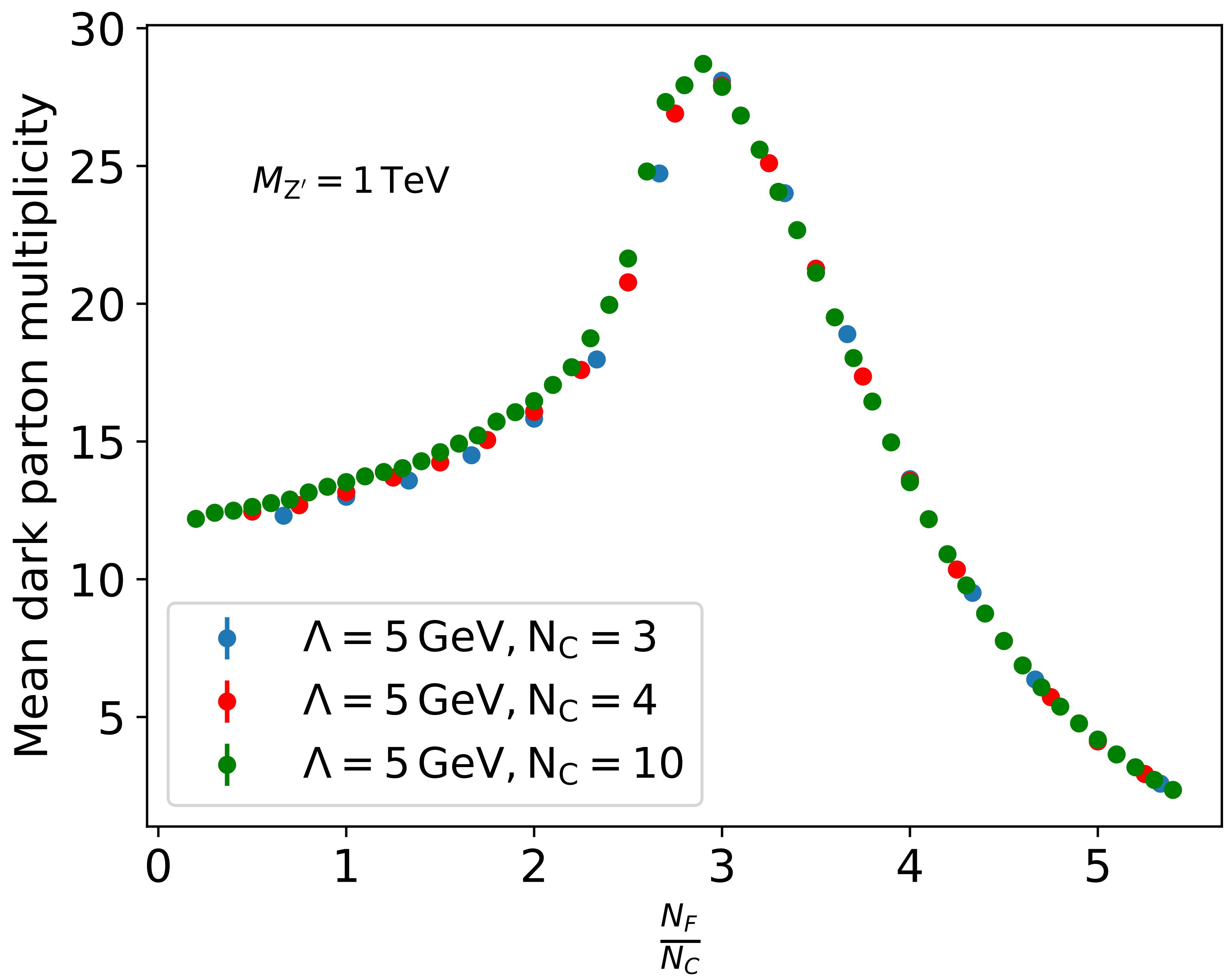
$$Q_i^2 = \Lambda^2 \left(\frac{Q_{i-1}^2}{\Lambda^2}\right)^{\tilde{\Delta}^{2\pi\beta_0/\epsilon}} \left[\tilde{\Delta}^{2\pi\beta_0/\epsilon}\left(\mp e W_n\left(\mp\frac{1}{e}\left(\frac{Q_{i-1}^2}{\Lambda^2}\right)^{\beta_0\alpha_*}\right)\right)^{1-\tilde{\Delta}^{2\pi\beta_0/\epsilon}}\right]^{1/\beta_0\alpha_*} ; \quad \epsilon = \int_{\tilde{\xi}_{min}}^{\tilde{\xi}_{max}} \tilde{P}_{a\to bc}(\xi')d\xi' \quad ; \mp, n = \begin{cases} -, -1 & \text{(QL region)} \\ +, 0 & \text{(CW region)} \end{cases}$$

- Previous two-loop efforts relied on a separate veto algorithm that corrected one-loop showering with two-loop effects - a method which did not converge for the entire N_F/N_C — μ/Λ space. The new implementation now even provides a way to simulate below $\mu/\Lambda = 1$ in the CW region.

- The Lambert W function is put within Pythia through a combination of approximation and interpolation.

Simulation of dark parton showers

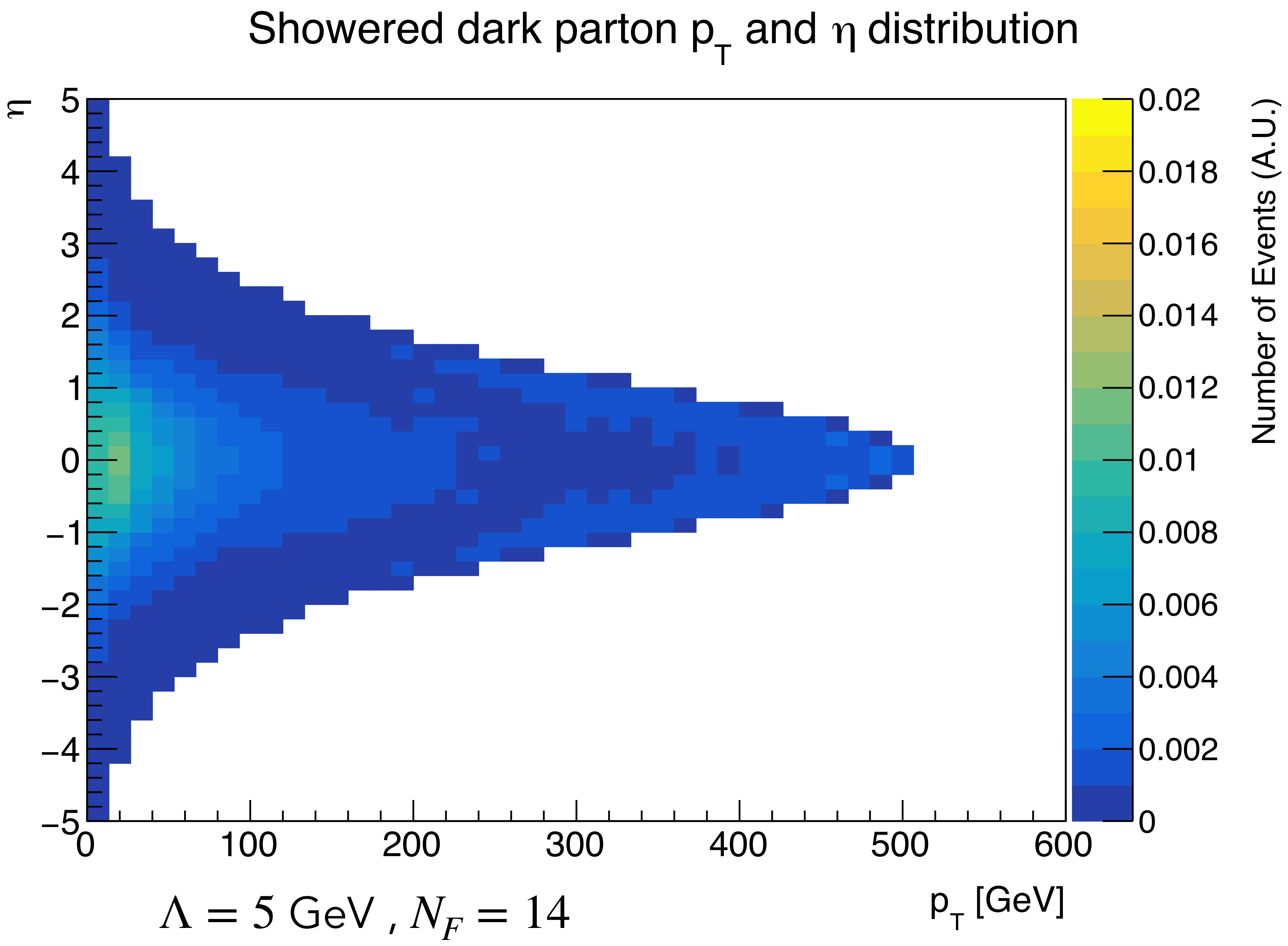


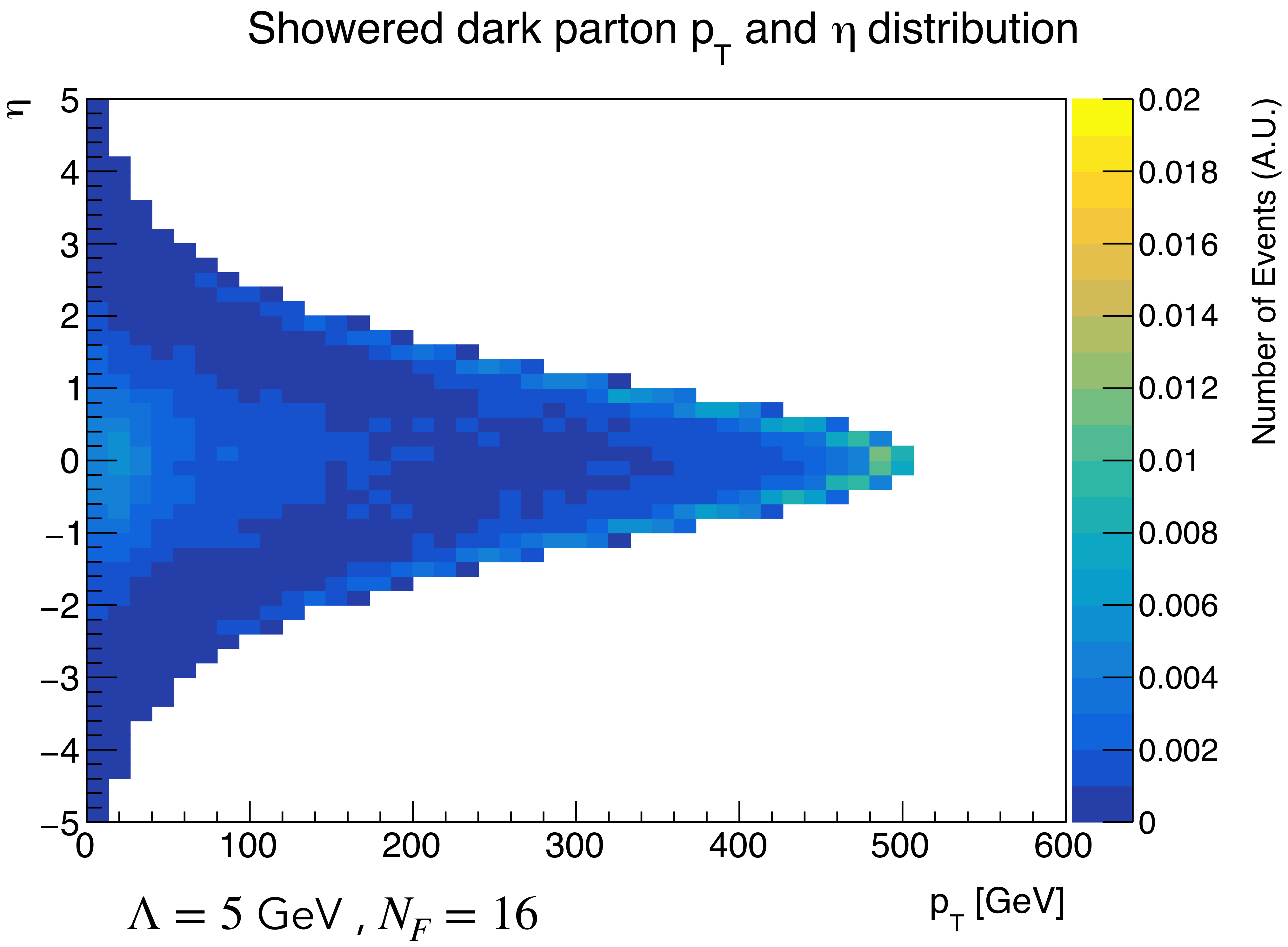


Simulated with a custom Pythia 8.307 with benchmark: $e^+e^- \to Z' \to q_D\overline{q_D}$, $\sqrt{s} = M_{Z'} = 1$ TeV , hadronisation off , $\Lambda = 5$ GeV , $N_C = 3$.

- 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





Simulated with a custom Pythia 8.307 with benchmark:
$e^+e^- \to Z' \to q_D\overline{q_D}$,
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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?