Characterising dark jets: Implications of theory scenarios for experimental signatures

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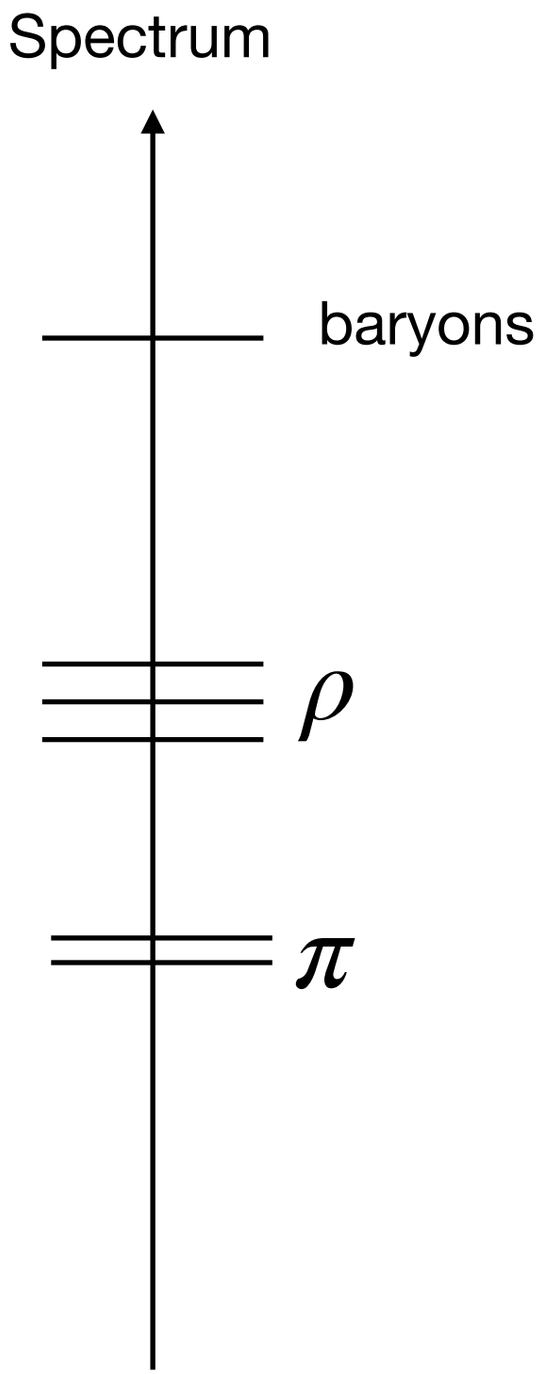
Strongly interacting dark matter



- What if dark matter is a composite particle arising from non-Abelian dynamics?
- Theory under consideration: SU(N_D) gauge theory - confines at some scale Λ_D
- Low energy theory: bound states of mesons and baryons, masses computed by lattice
- Free parameters: $N_D, N_f, \alpha_D, M_{q_D}$ (technically Λ_D is not a free parameter, fixed by RGE running)
- Mediator mechanisms: vector portal/scalar portal
- Low energy theory: masses and decay rates of bound states, string tension (for hadronization) [Derived from lattice simulations]
- Low energy Lagrangian: Chiral perturbation theory, heavy quark theory… something else?
- **Central question**: how do each of these parameters affect distribution of final state particles and kinematic distributions for s-channel processes?

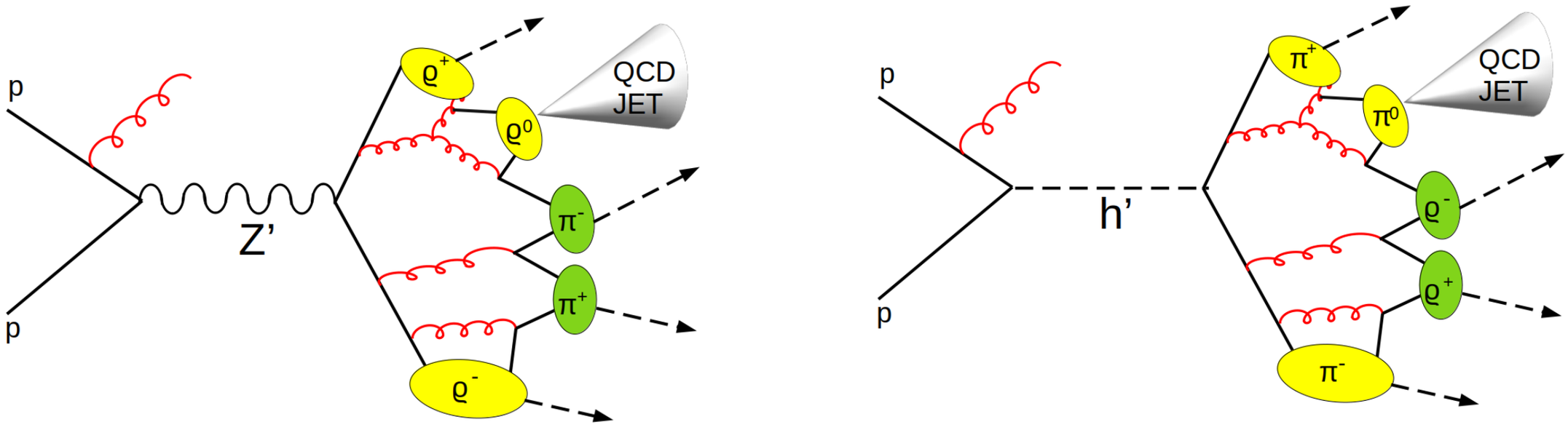
Two mediators, two portals, one signature

- Mass degenerate, vector dark quarks with flavour and parity conservation and use expectations of chiral perturbation theory
- Consequence: off-diagonal rho and pions are stable due to dark flavour number. Flavour diagonal (neutral rho and pion) are NOT stable. All pions (rhos) are mass degenerate, however generically rhos are heavier than pions.
- Regime of interest: $\sqrt{s} \gg \Lambda_D, M_{q_D}$ hard process includes direct production of dark quarks
- **Two portals**
  - Scalar portal: leads to unstable neutral dark pion via mixing with scalar
  - Vector portal: leads to unstable neutral dark rho via mixing with vector
- **Two mass hierarchies**
  - Rho to pion decay mode is open
  - Rho to pion decay mode is closed
- In either case, the final signature at the LHC is semi-visible jet
- We will systematically illustrate effect of $N_f, N_c, \alpha_D, \Lambda, M_{q_D}, \frac{m_\rho}{m_\pi}$

For heavier composite DM scenarios featuring SM measurements see L. Corpe's talk from yesterday
Also see talks by T. Binder and Y. Gouttenoire

LHC phenomenology

See also: Cohen et al. arXiv:1707.05326,arXiv:1503.00009



- Reconstructed level studies using HL-LHC settings via PYTHIA8, DELPHES
- All following distributions are reconstructed level
- No cuts applied (will need at least lead jet pT cut)
- Configurations considered: s-channel resonance mass 2 TeV, N_c = 2, 3, 5, 8; N_f = 2, 8
  - Need to be careful with N_c = 8 scenarios, starts to touch SUEP regime

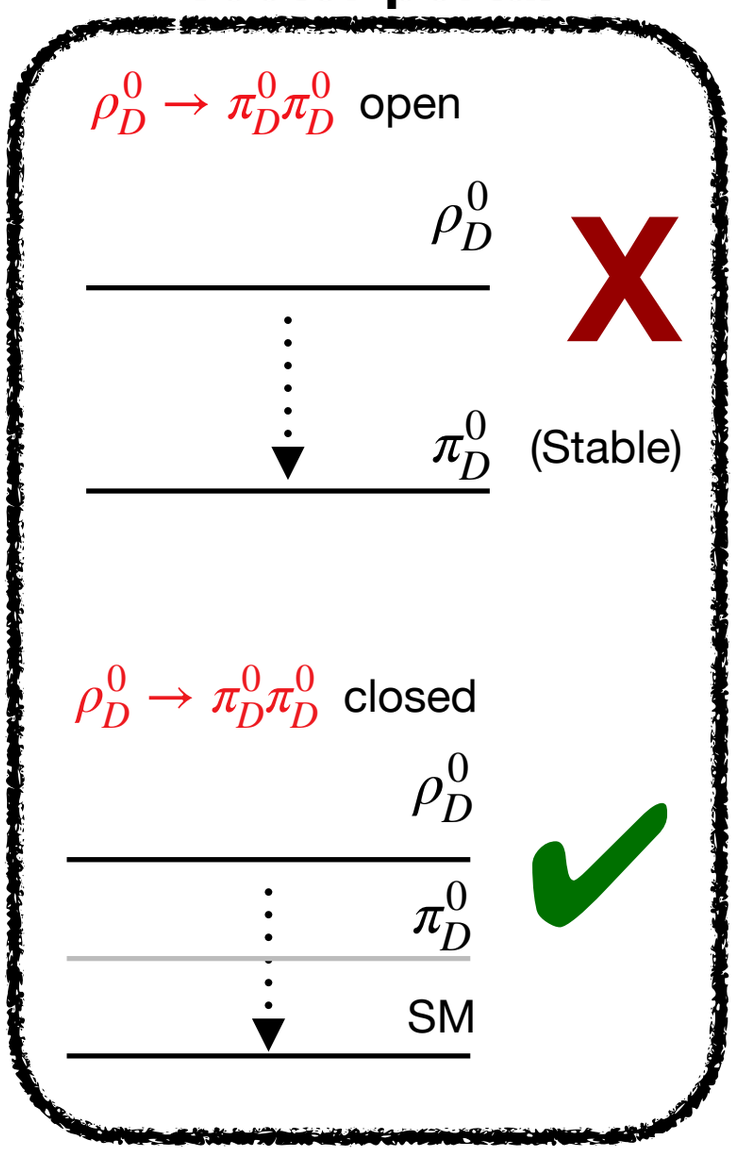
For SUEP studies see e.g. Cesarotti et. al. arXiv:2004.06125, Knapen et. al. arXiv:1612.00850

- Pythia cards generated using this tool *(Knapen et al. arXiv:2103.01238)*

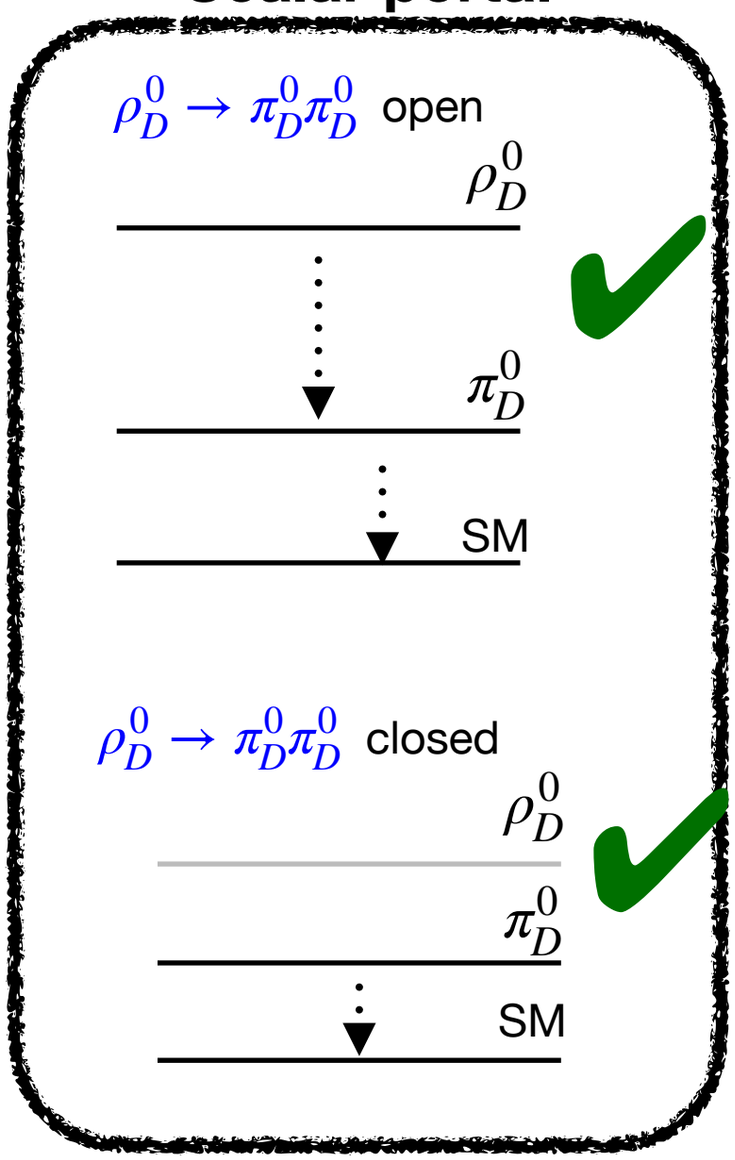
N.B. it is also possible to generate emerging jets see e.g. Schwaller et. al. arXiv:1502.05409

Invisible jet fraction

Vector portal



Scalar portal



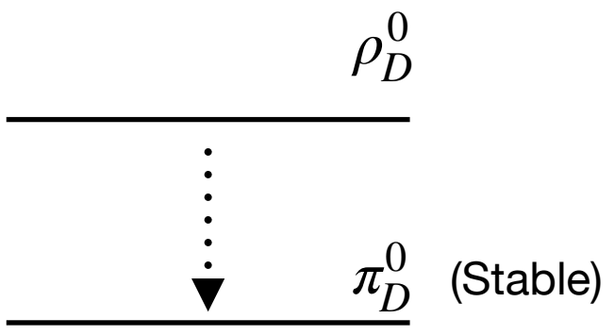
$$\Pi = \begin{bmatrix} \pi_D^0 & \pi_D^{\pm} & \cdots \\ \vdots & \ddots & \\ \pi_D^{\pm} & & \pi_D^0 \end{bmatrix}$$

- For a theory with N_f flavours, number of pions are $N_f^2 - 1$
- Mass degenerate quarks imply mass degenerate pions (and rho)
- Out of these $N_f - 1$ are diagonal pions and $N_f(N_f-1)/2$ off-diagonal pions
- As N_f increases the number of pions increase, and number of off-diagonal pions increase faster than diagonal pions
- In general fraction of off-diagonal pions produced = $1/N_f$

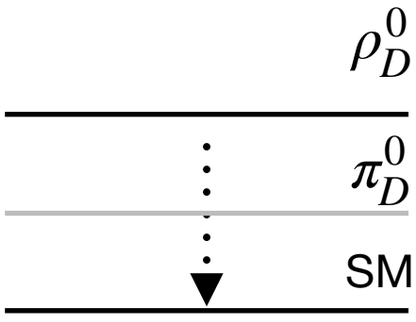
Invisible jet fraction

Vector portal

$\rho_D^0 \to \pi_D^0\pi_D^0$ open

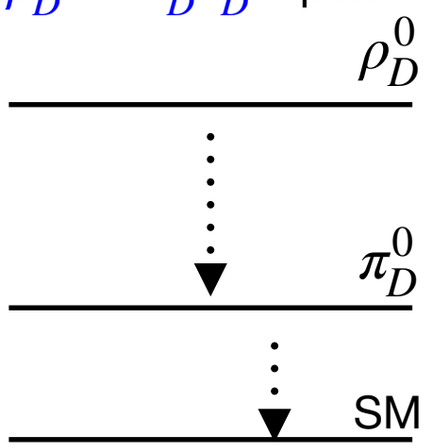


$\rho_D^0 \to \pi_D^0\pi_D^0$ closed

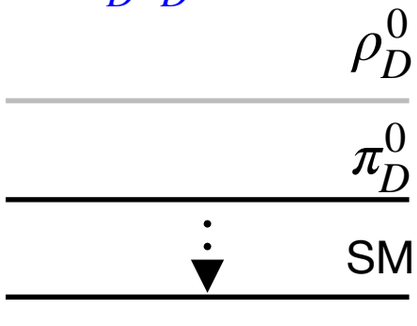


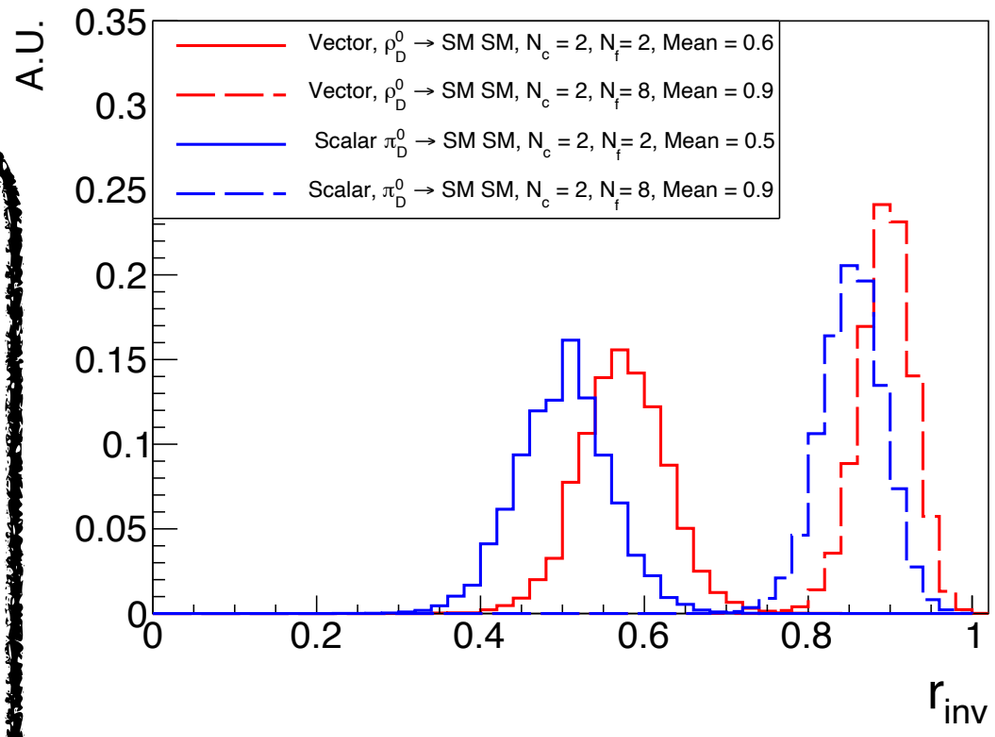
Scalar portal

$\rho_D^0 \to \pi_D^0\pi_D^0$ open



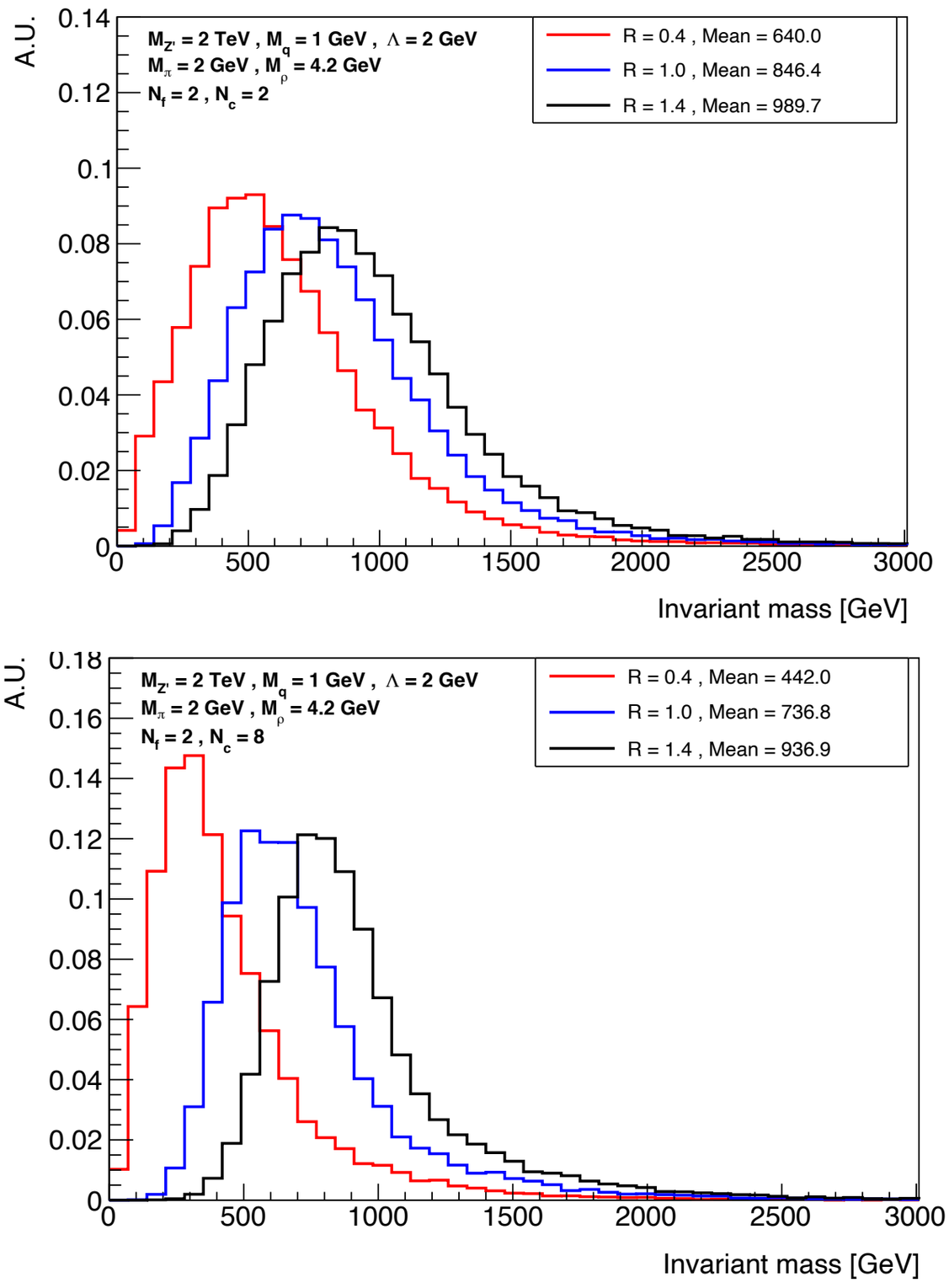
$\rho_D^0 \to \pi_D^0\pi_D^0$ closed

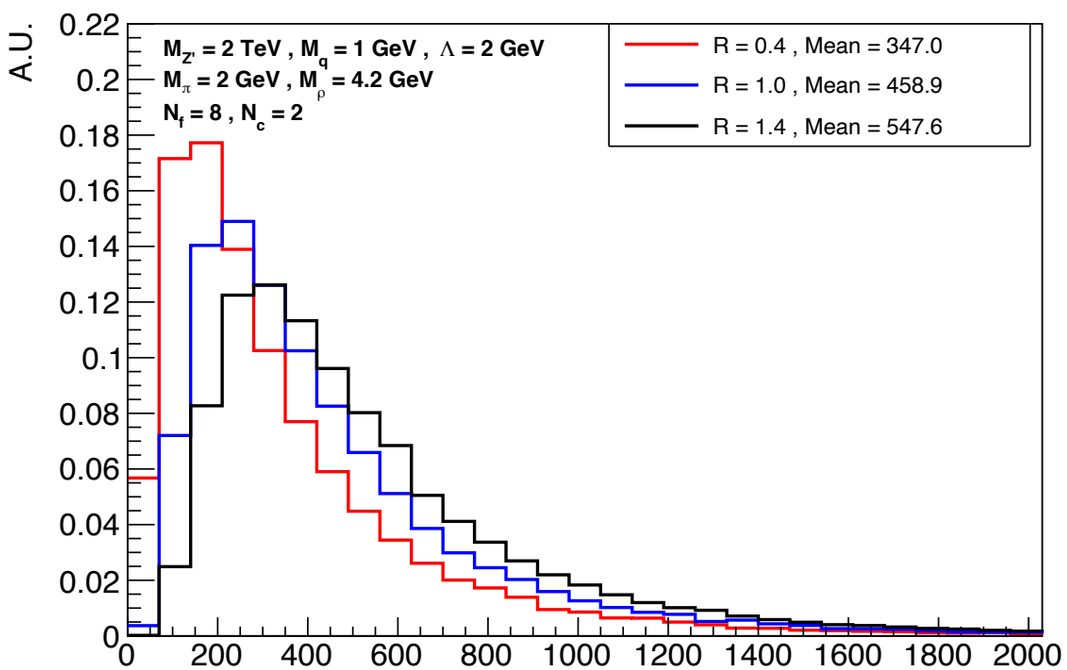




- R_{inv} increases when more stable particles in jets (as expected)
- R_{inv} comparable between scalar and vector portal when rho can not and can decay to pions

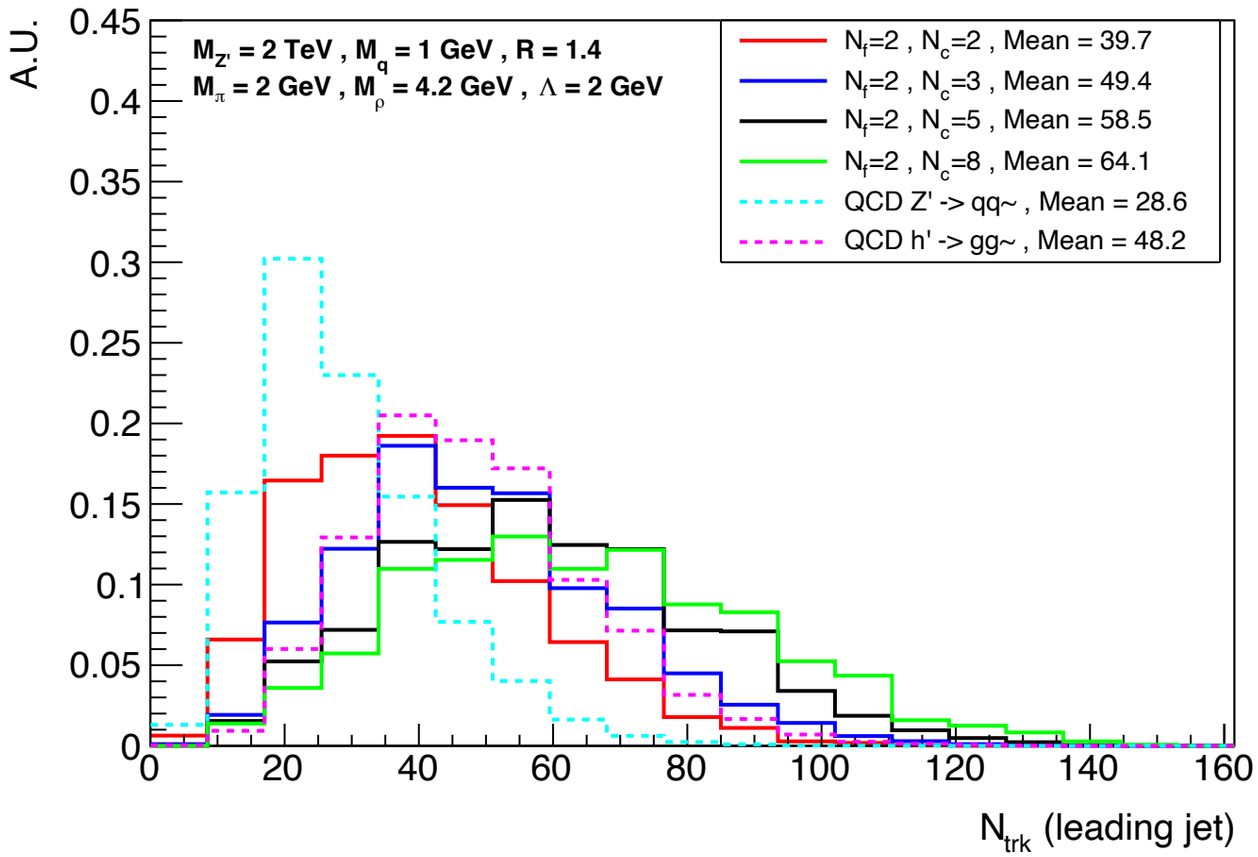
Invariant mass - dependence on R

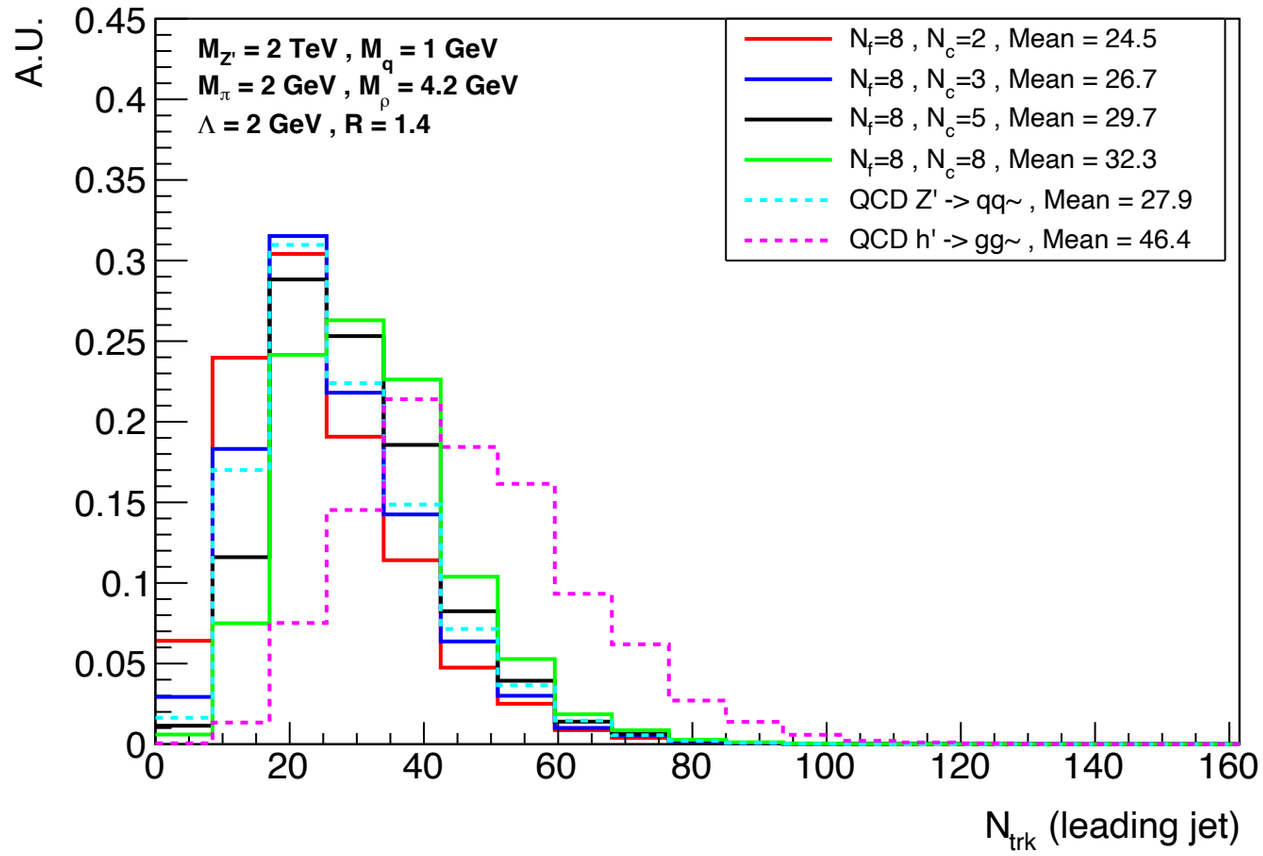




- Jet clustering radius makes a difference while looking for invariant mass peaks
- Invariant mass better reconstructed with large R (R = 1.4) jets
- We will use R = 1.4 for further studies

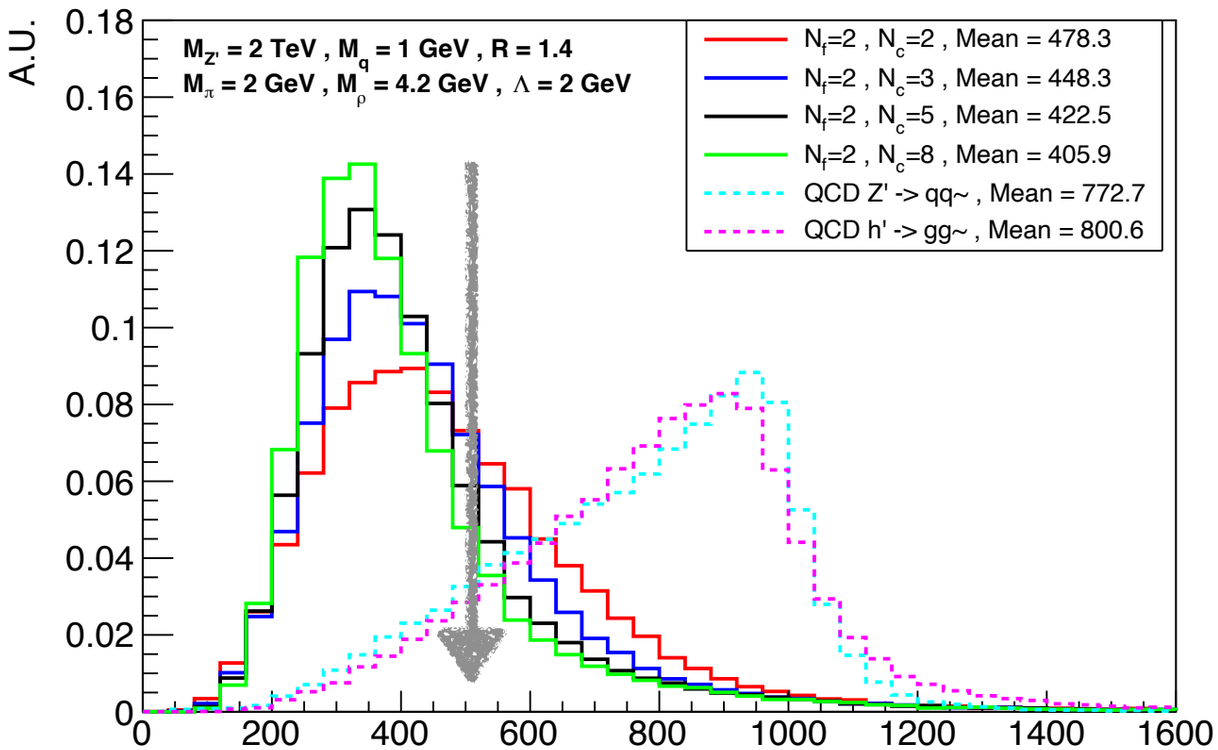
Number of tracks

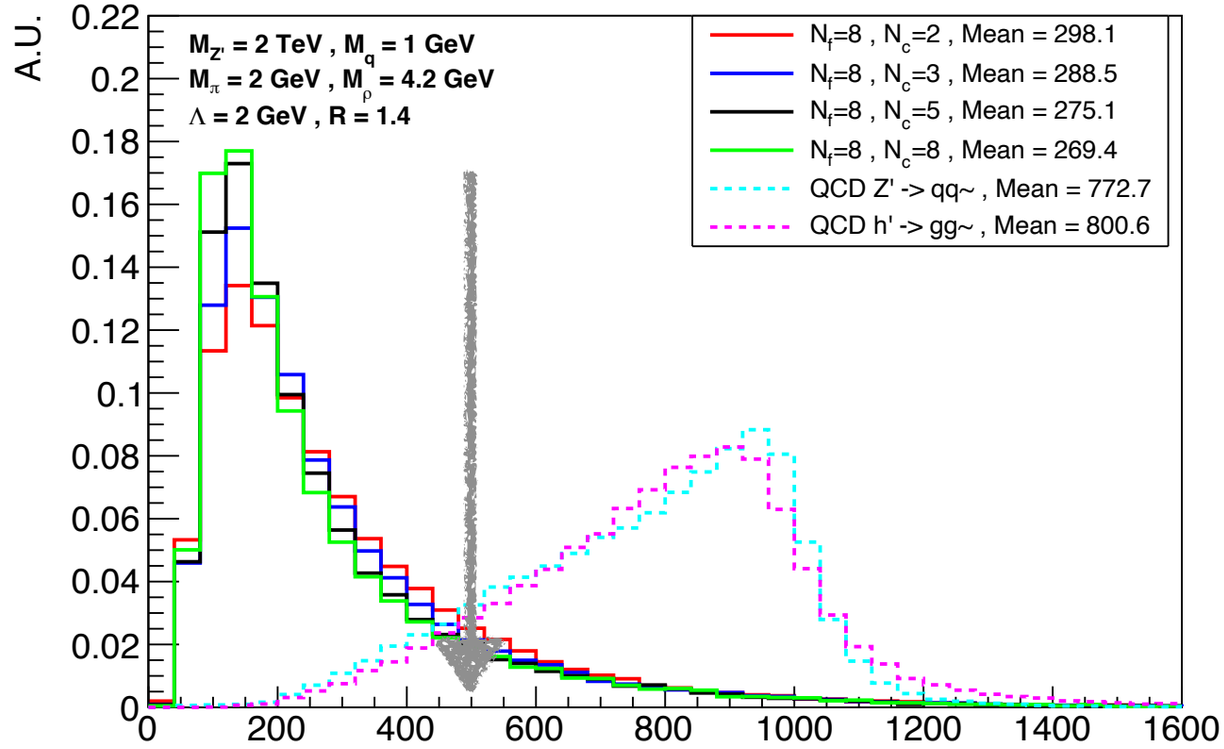




- For given N_c, number of tracks in jets decrease with increase N_f
  - This is because fraction of off-diagonal (stable) mesons increases
- For given N_f number of tracks in jets increase with N_c
  - This is because of increased splitting during hadronization which leads to more particles
- Large N_c, small N_f scenarios predict larger number of tracks

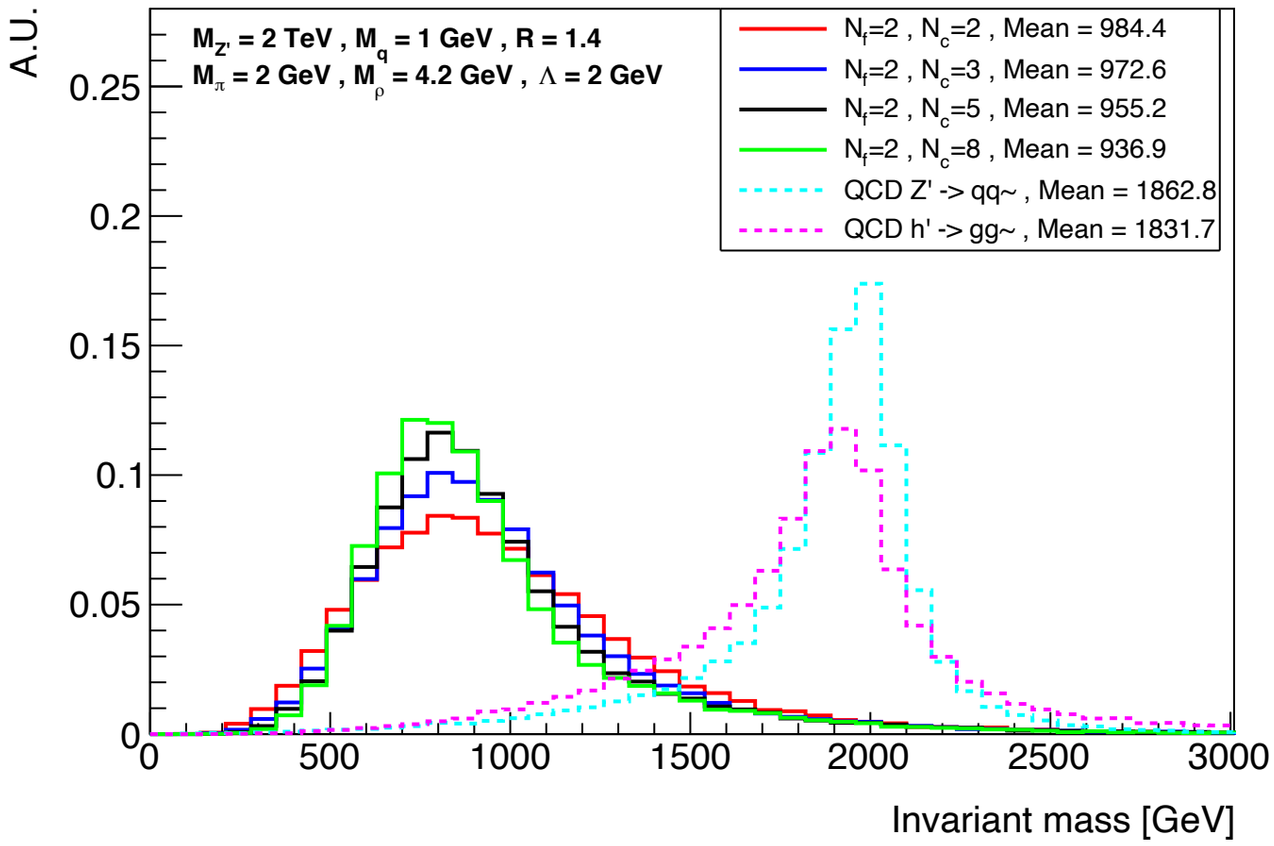
Jet p_T

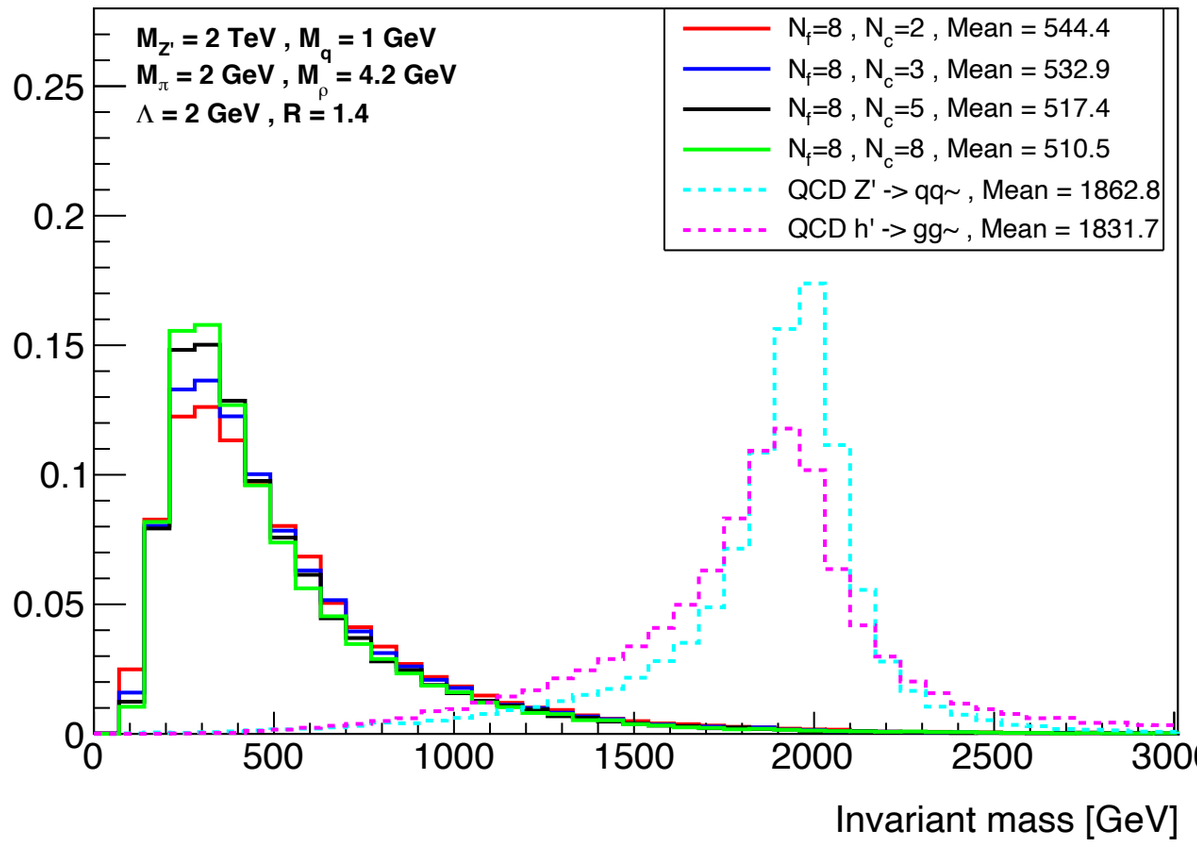




- For given N_c, increasing N_f decreases the p_T of the jet
- For given N_f, increasing N_c decreases p_T of jet, this is because more dark radiation splits the energy making tracks softer (the event would become spherical with increasing N_c)
- For triggering purposes, a cut on jet p_T would be necessary will affect models with large N_f and N_c
  - Searches in the tails should be carried out carefully as changes in N_f, N_c affect jet kinematics

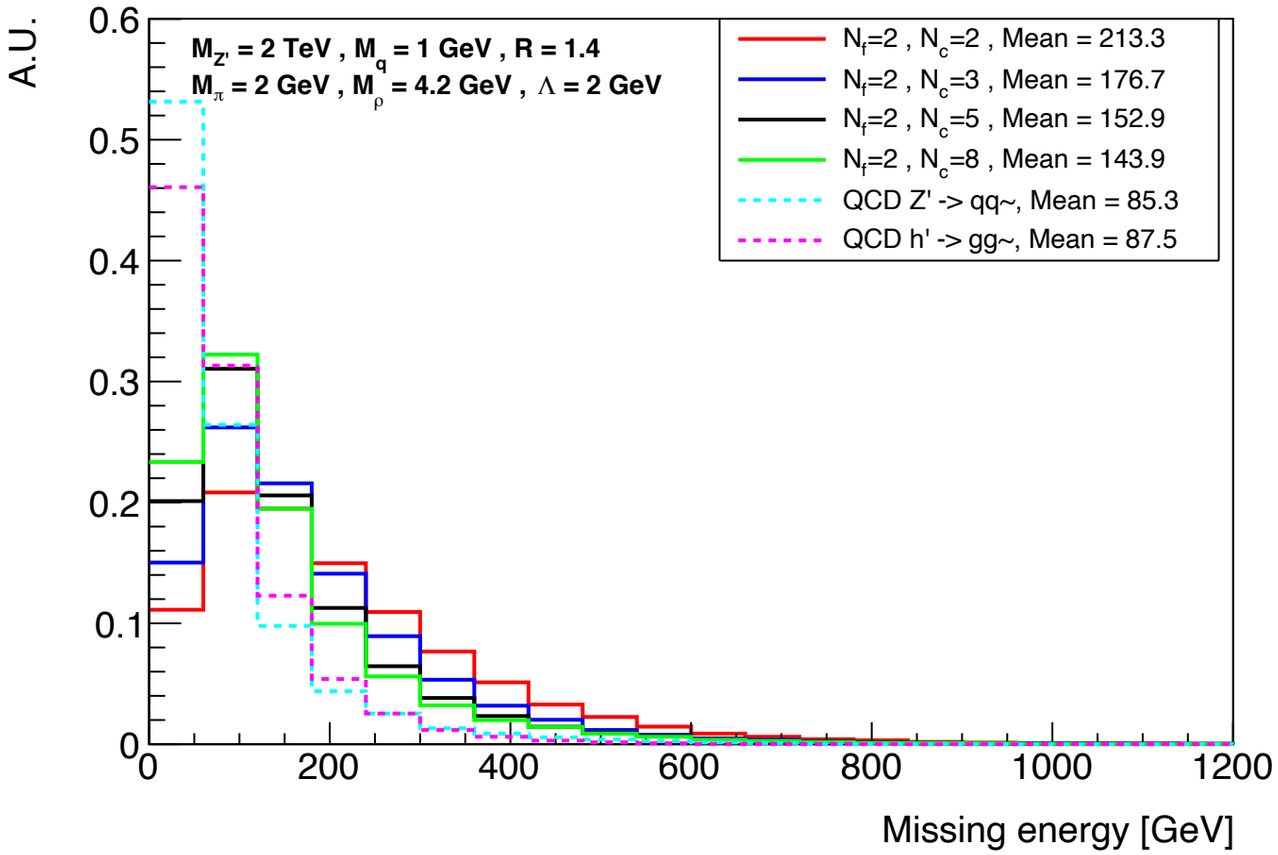
Invariant mass - dependence on N_c, N_f

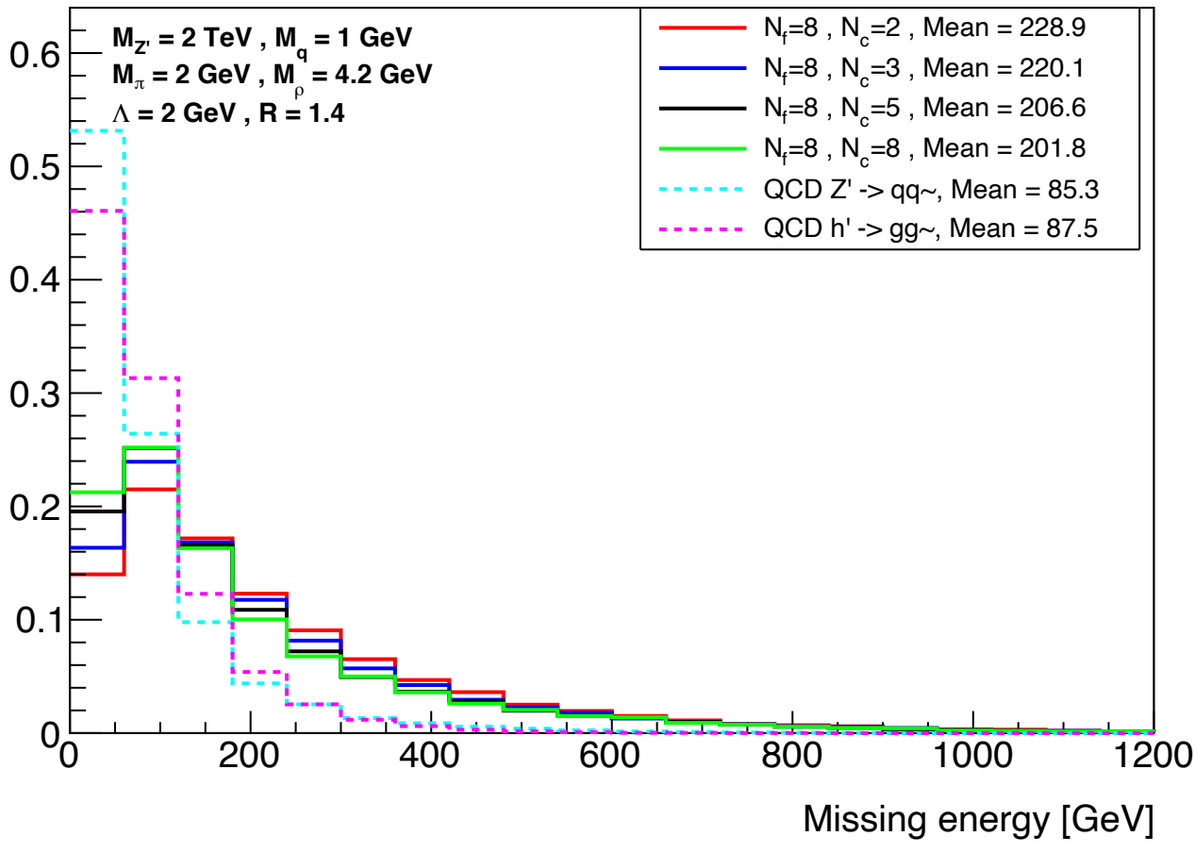




- Usually invariant mass is washed out due to presence of missing energy in the same direction as the jet
- Better mass reconstruction is possible with optimised event selection
  - A peak will be visible, however it will be difficult to reconstruct the invariant mass
- In variant mass decreases with increase in N_f, N_c due to previously seen behaviour of jet p_T

Missing energy





- For a given N_c, increase in N_f, increases the missing energy significantly
  - This is due to presence of larger number of off-diagonal stable mesons
- Increasing N_c also decreases missing energy
- Large missing energy tail - a very sharp feature for semi-visible jets in contrast to ‘fully visible’ signature

Conclusions

1. We considered vector mass degenerate dark quarks with various number of dark flavours and colours and analysed their LHC phenomenology when $\sqrt{s} \gg \Lambda_D, M_{q_D}$, leading to semi-visible jets
2. Considered two different portals vector and scalar portals, in vector portal only flavour neutral dark rho can decay to SM, in scalar portal the flavour neutral dark pions can decay to SM. If dark rho can decay to dark pion, then in scalar portal more visible particles are produced in final states as compared to vector case
3. The number of off-diagonal stable mesons have a non-trivial impact on the LHC signatures in terms of number of tracks and jet p_T, invariant mass and missing energy
4. Large R jets in general reconstruct resonance mass better
5. For fixed (N_c), if number of flavours (N_f) are increased, off-diagonal stable mesons carry away significant amount of energy in terms of missing energy decreasing the number of tracks, jet pT and invariant mass
6. Increasing number of colours while fixing flavours leads to more splitting, thus larger number of (softer) tracks and fatter jets
7. Conclusions qualitatively similar for both portals, decreasing α_D decreases effects of N_f, N_c variations. No appreciable impact of Λ_D, m_{q_D} so long as $\sqrt{s} \gg \Lambda_D, M_{q_D}$

Dark showers snowmass effort

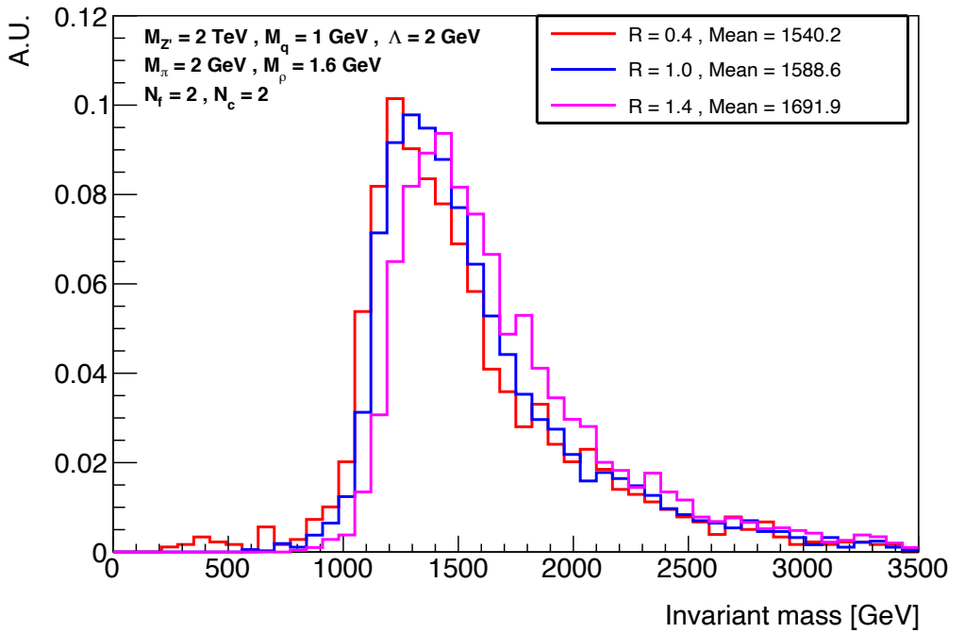
1. For more on dark showers studies, discussions between experiments and theory, join us at the snowmass dark showers effort
2. LOI: link
3. Meetings held so far (with recordings and google doc notes): https://indico.cern.ch/category/12893/
4. Mailing list: dark-showers-snowmass21@cern.ch (sign up for e-group with CERN/ lightweight account)

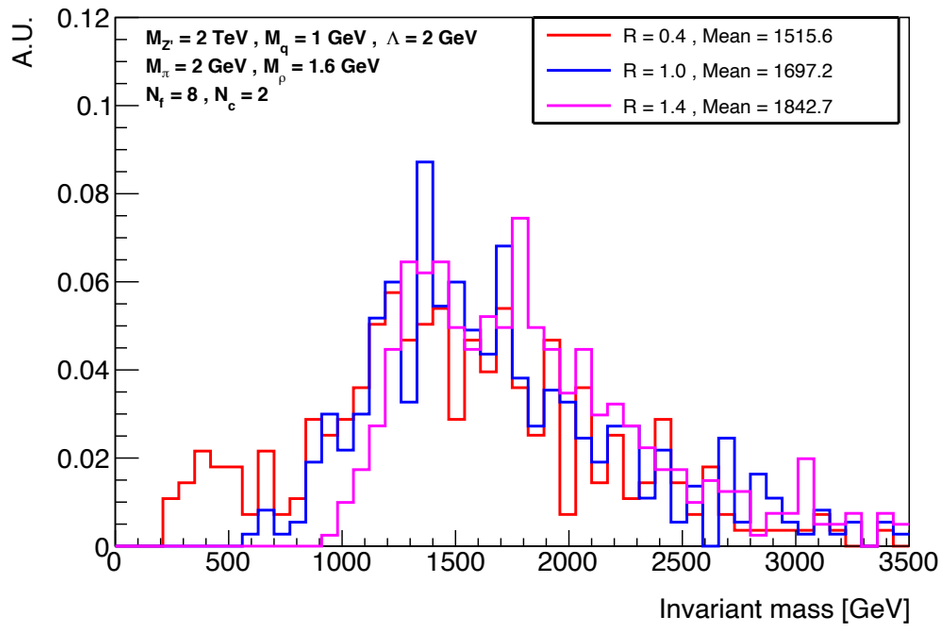
Yes, we have a very creative logo!

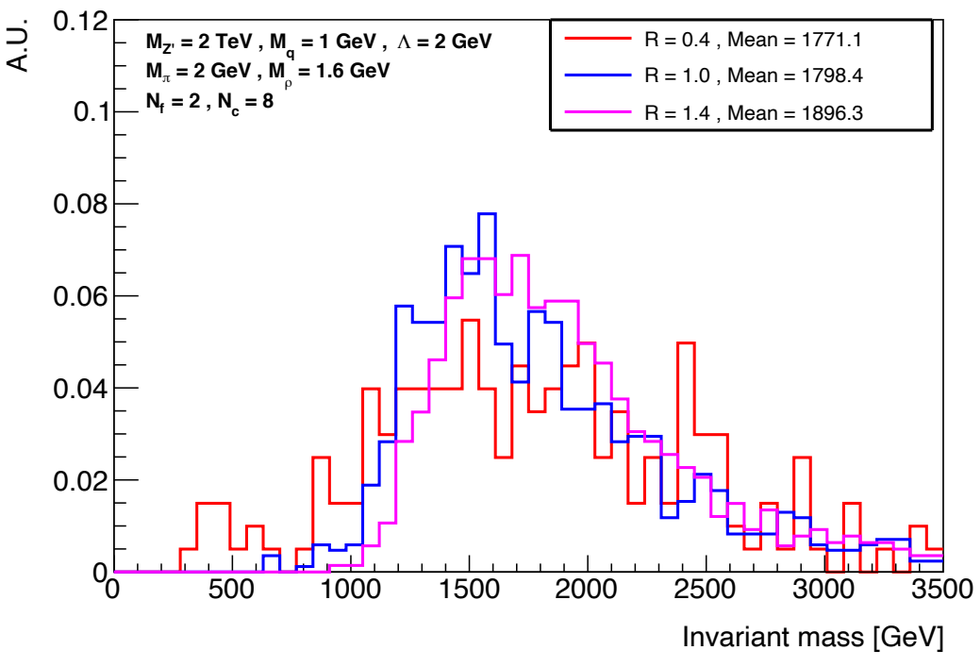
Backup

Impact of cuts

1. $p_T(j_1) > 500\,\mathrm{GeV}, \mathrm{p_T(j_2)} > 500\,\mathrm{GeV}, |\eta(\mathrm{j_1})| < 2.5, |\eta(\mathrm{j_2})| < 2.5$
2. Note we are now sensitive to fluctuations in the tail

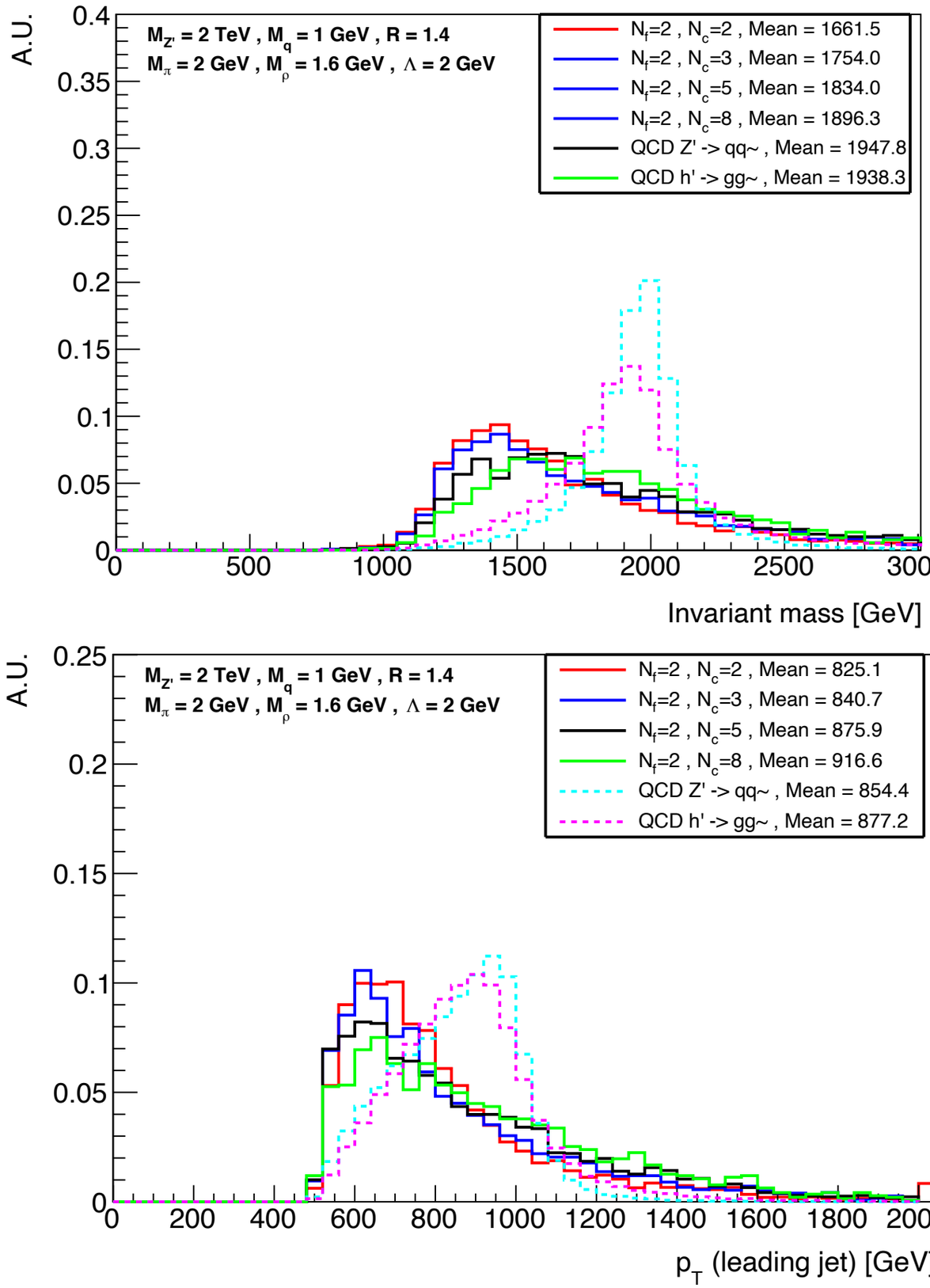


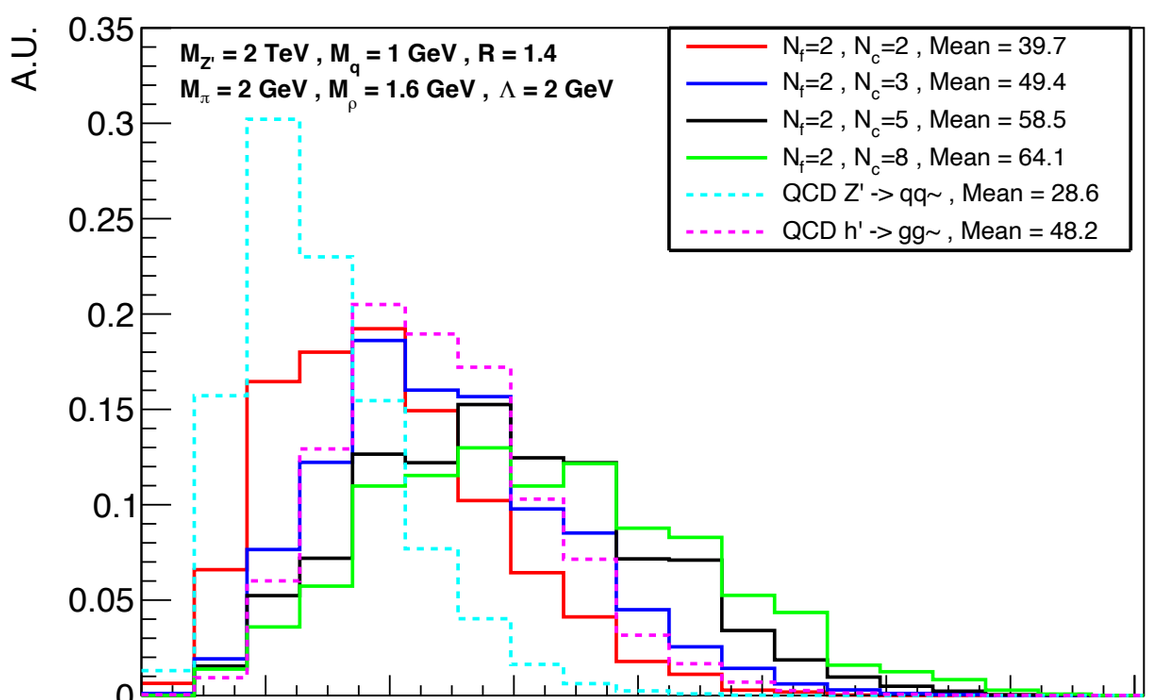




Large R jets still perform better

Impact of cuts





1. Quantities of interest for collider searches seem to increase with N_c, N_f (N_f variation not shown)
2. Somewhat counter intuitive however consistent with observation of searches in the tails