Searching for Dark Matter with Semi-Visible Jets at CMS

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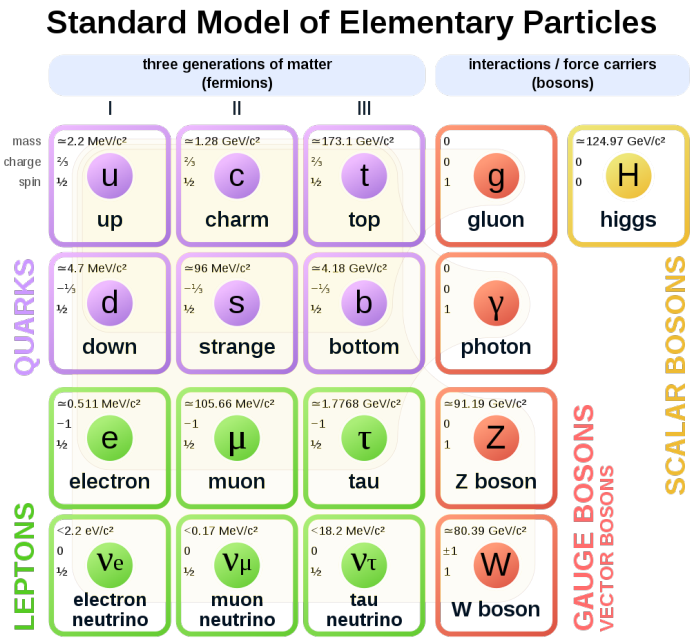
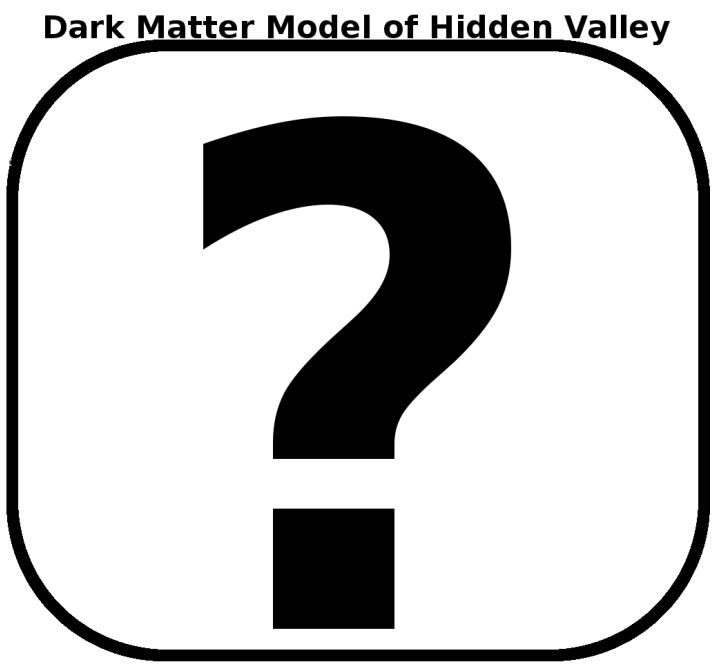
- A new gauge group exists independently of the SM gauge group.
- This Hidden Valley gauge contains the physics of Dark Matter.
- A messenger particle, M, is necessary to bridge the gap between the independent gauges, and it must be charged under both.

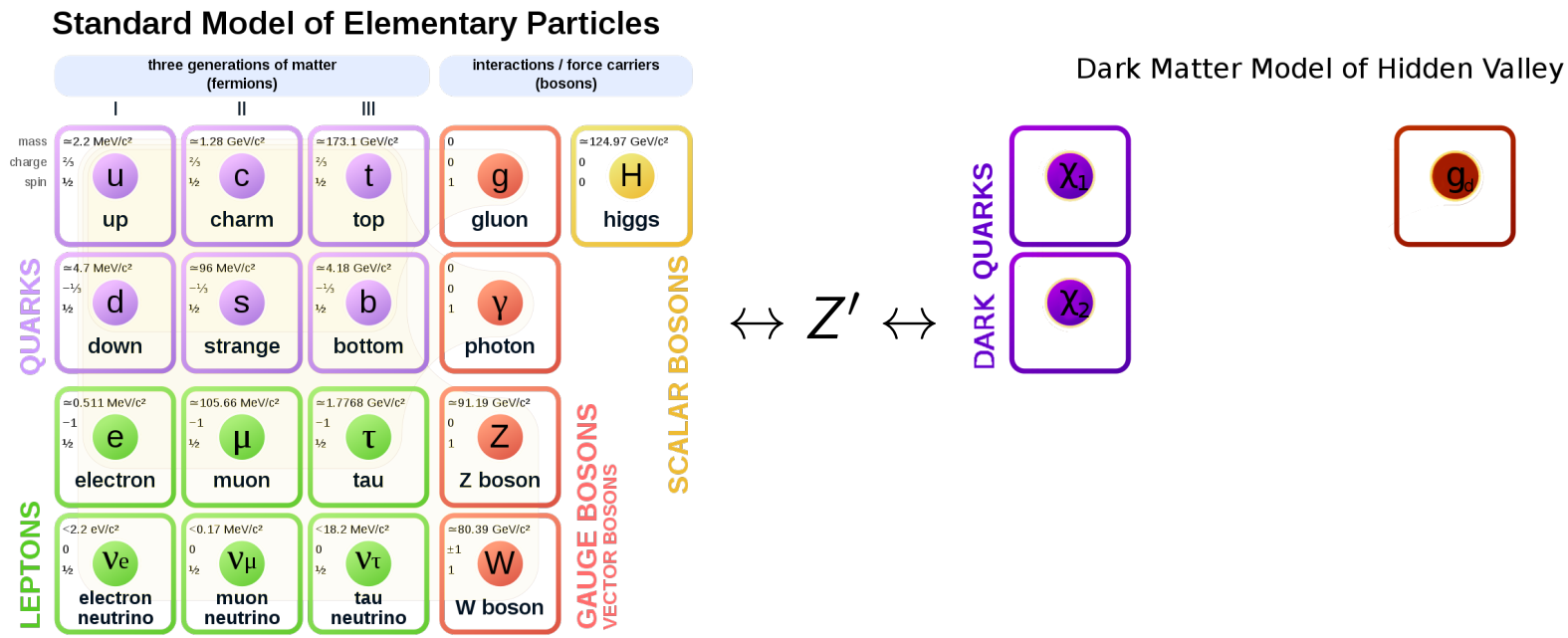


$\leftrightarrow M \leftrightarrow$



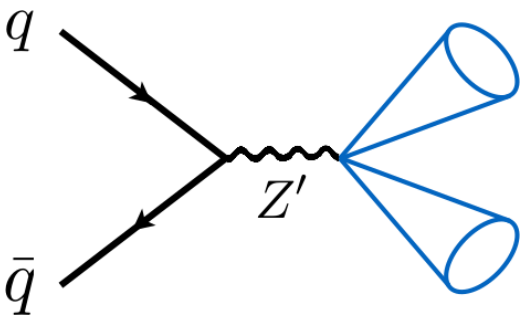
A group of theorists (Cohen, Lisanti, et al) investigated a form of the HV gauge that allows for some interesting physics to occur:

- The mediator is a leptophobic massive particle that is created as an s-channel resonance, called Z'.
  - There is also an alternate mediator that changes SM quarks into DM quarks via a t-channel mechanism[1].
- The Dark Sector is an SU(2) gauge that is QCD-like.
- The Dark Sector consists of two dark quarks and dark gluons.

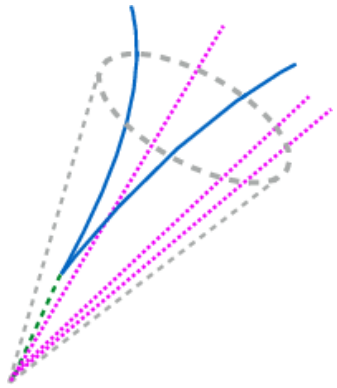


[1] Its the future.

- SM quarks produce an on-shell Z'.
- Z' decays into two HV quarks.
- The HV quarks hadronize into dark hadrons due to dark asymptotic freedom.
  - Each dark hadron formed can be stable or unstable.
- Any stable HV hadrons escape undetected.
- Any unstable HV hadrons decay via an off-shell Z' into SM hadrons.
- What is left is two jets of SM hadrons, both with an unknown quantity of invisible HV hadrons: *two Semi-Visible Jets!*
- See arXiv:1503.00009 and 1707.05326.



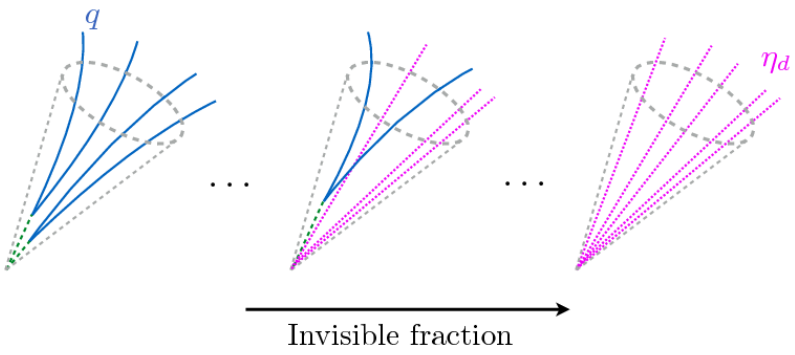
A small Feynman diagram showing a signal event.



A more in-depth view of a Semi-Visible Jet.

The phenomenology can be characterized by 5 free parameters:

- Mass of the Mediator: $m_{Z'}$
- Production Rate: $\sigma_{Z'} \times Br(Z' \to \chi\chi^{\dagger})$



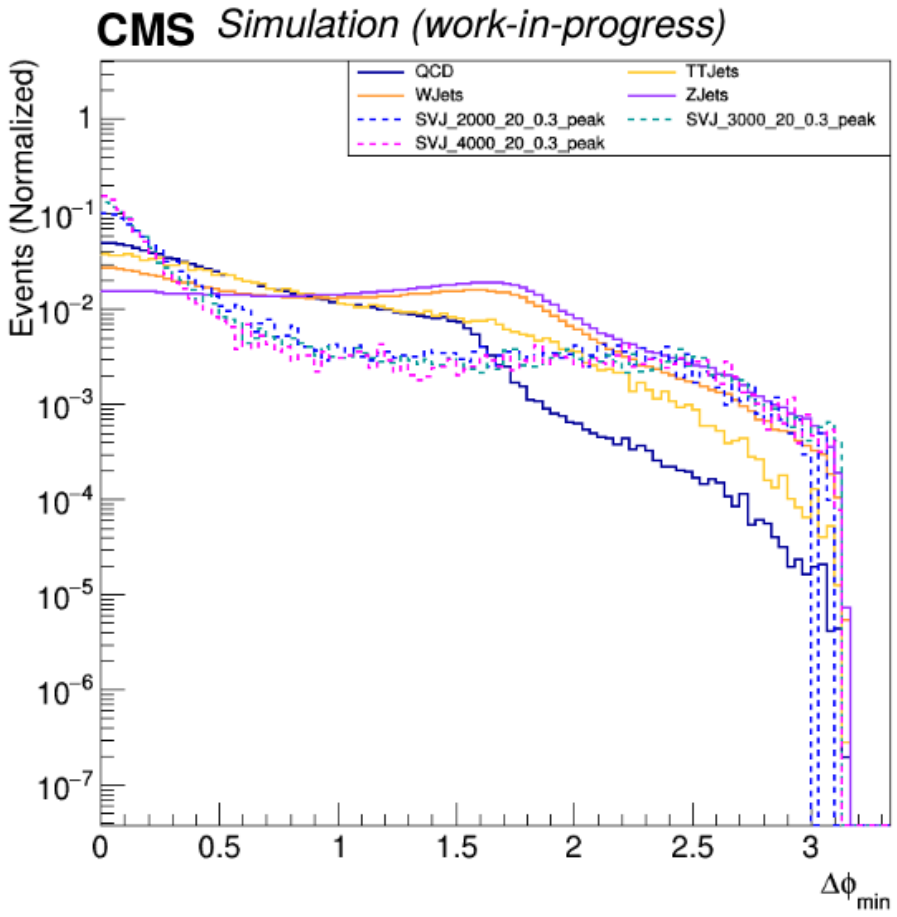
- Mass of the Dark Hadrons: m_{dark}
  - Dark Hadrons are mass degenerate.
  - Dark Quarks have half the mass of Dark Hadrons.
- Fraction of Dark Hadrons that are Stable: r_{inv}
  - $\left\langle \frac{N^{dark}_{stable}}{N^{dark}_{unstable}+N^{dark}_{stable}} \right\rangle$
  - Key parameter to distinguish this analysis from others.
- Coupling Strength of the Dark QCD Force: α_d

Composition of SVJs as the r_{inv} parameter varies.

- Main objects are Jets and Missing Transverse Energy.
  - Signal signature is "MET-within-Jets"
- Jets are clustered using the anti-k_T algorithm with a distance parameter of R = 0.8 (AK8 jets).
- Missing transverse energy, $\text{MET} = -\Sigma_j \vec{p}_{Tj} - \Sigma_i \vec{p}_{Ti}$
  - where the first sum is a sum over the jets, and the second is a sum over the particles not clustered into a jet.
  - This allows us to account for jet energy corrections in the MET.
- $M_T^2 = m_{jj}^2 + 2(\sqrt{m_{jj}^2 + p_{Tjj}^2}\not{E}_T - \vec{p}_{Tjj} \cdot \vec{\not{E}}_T)$
  - Used in lieu of m_{jj} as bump hunt search variable.
  - Signal has too broad a peak in dijet mass because of the MET.

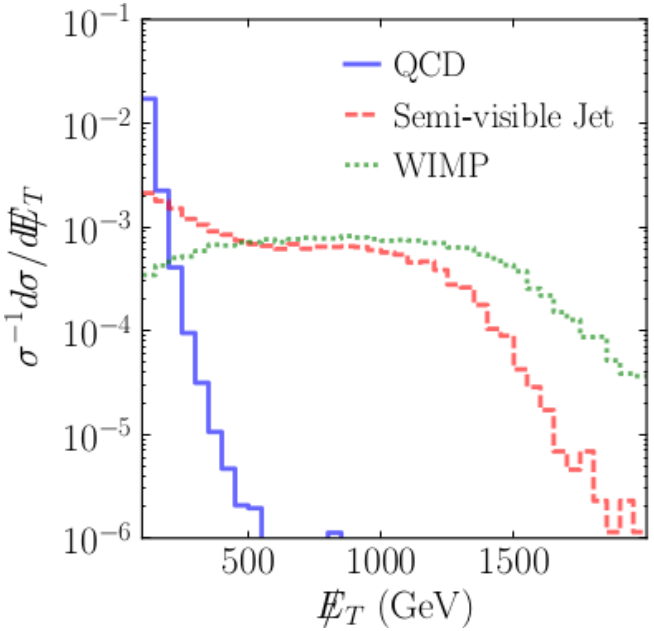
Four backgrounds:

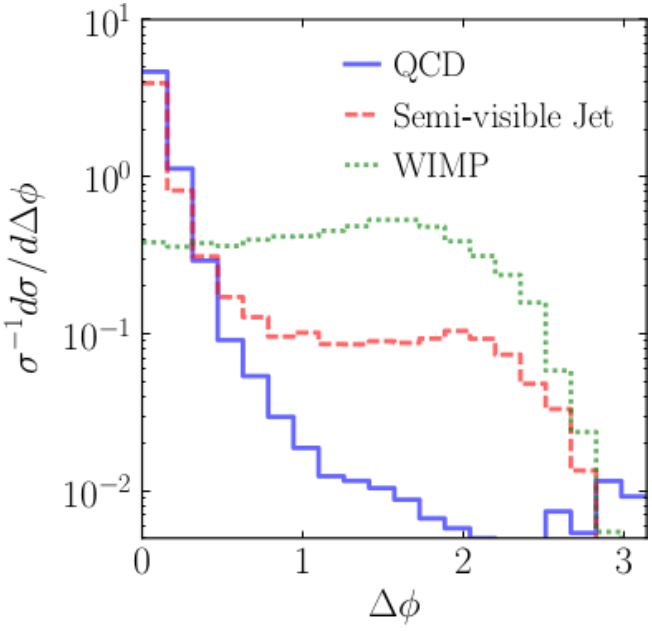
- Multijet QCD
- ttbar
- W($\ell\nu$) + Jets
- Z($\nu\nu$) + Jets



$\Delta\phi_{min}$ for four backgrounds and three signal sets. All datasets are MC.
$\Delta\phi_{min} = min(\Delta\phi(MET, j_1), \Delta\phi(MET, j_2))$

- SUSY searches often have similar backgrounds.
- But our signal region is a region that SUSY searches often cut out due to jet mis-modeling and lack of signal in that region.





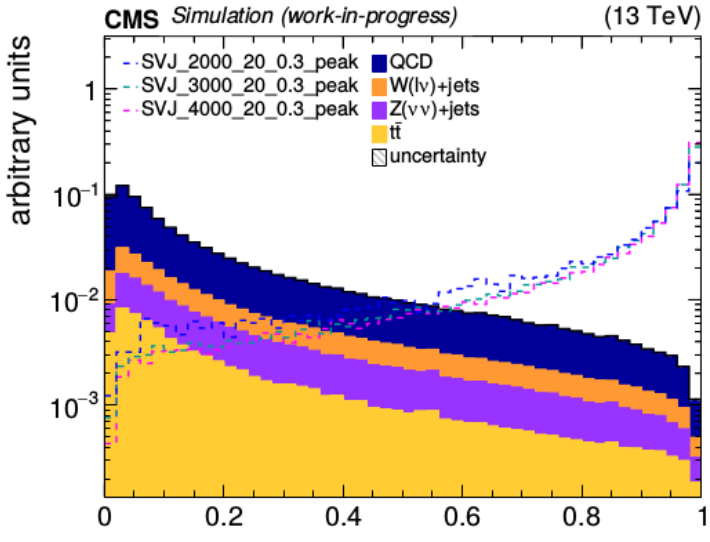
MET and min$\Delta\phi$ for QCD, SVJ, and WIMP signals. Plots are taken from the theory papers.

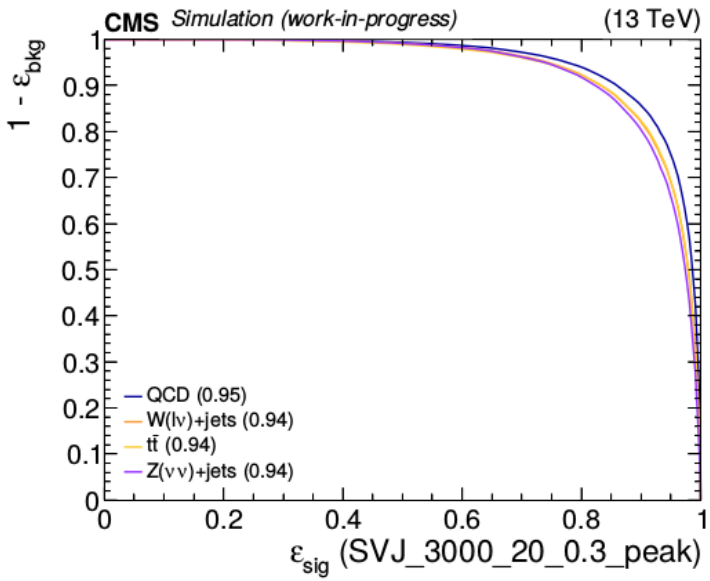
Event Selection:

- Leading two AK8 Jets satisfy $p_T > 200\text{GeV}$ and $|\eta| < 2.4$
- $\Delta\eta(j_1, j_2) < 1.5$, for trigger efficiency.
- $R_T = \frac{MET}{M_T} > 0.15$, removes $\approx 99\%$ t-channel multijet QCD events
- Isolated Lepton Veto, to remove electroweak events
- $M_T > 1500\text{GeV}$, for trigger efficiency.
- various MET filters, to remove mis-reconstructed jets
- $min(\Delta\phi(j_{1,2}, MET)) < 0.75$ to select for events with MET aligned to a jet[2]

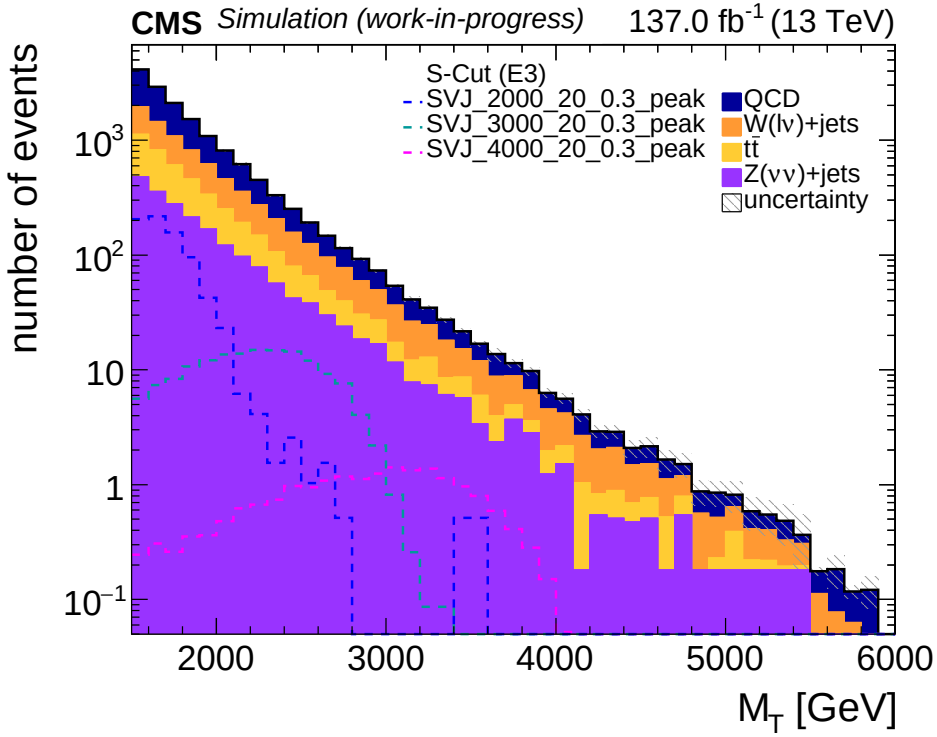
After these cuts, we still have a low signal-to-background ratio, so we gathered some jet substructure variables that individually have weak discriminating power between normal SM jets and SVJs, and combined them into a boosted decision tree.

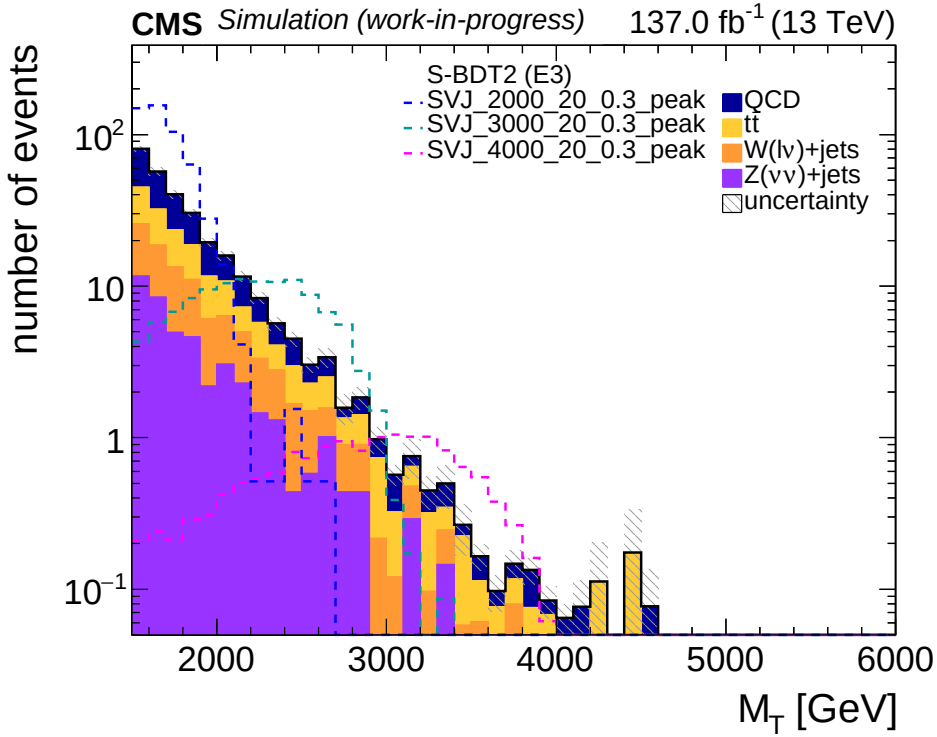
[2]Final selection cut. Currently, we're still blinded.





- Input Variables
  - N-subjettiness
  - Energy Correlation Functions
  - Softdrop Mass
  - Jet Girth
  - Major and Minor axes
  - Fragmentation Variable $p_T D$
  - Jet Parton Energy Fractions (charged and neutral hadrons, e, μ, and γ)
  - $\Delta\phi$(jet, MET)
- Trained on p_T flattened MC samples.
- Mixture of QCD and ttbar backgrounds.

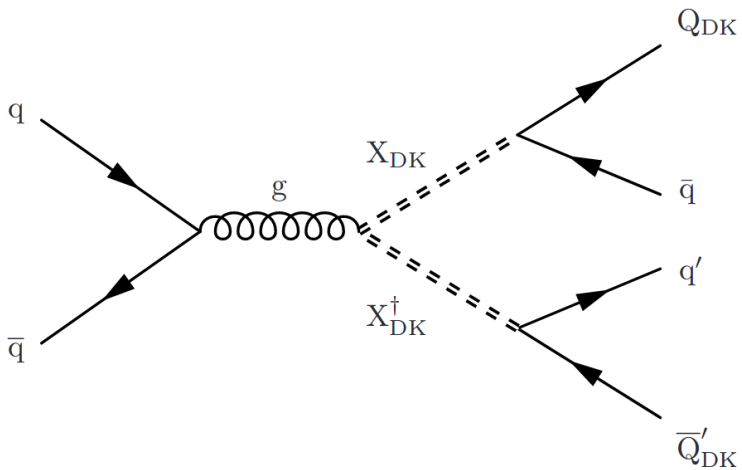


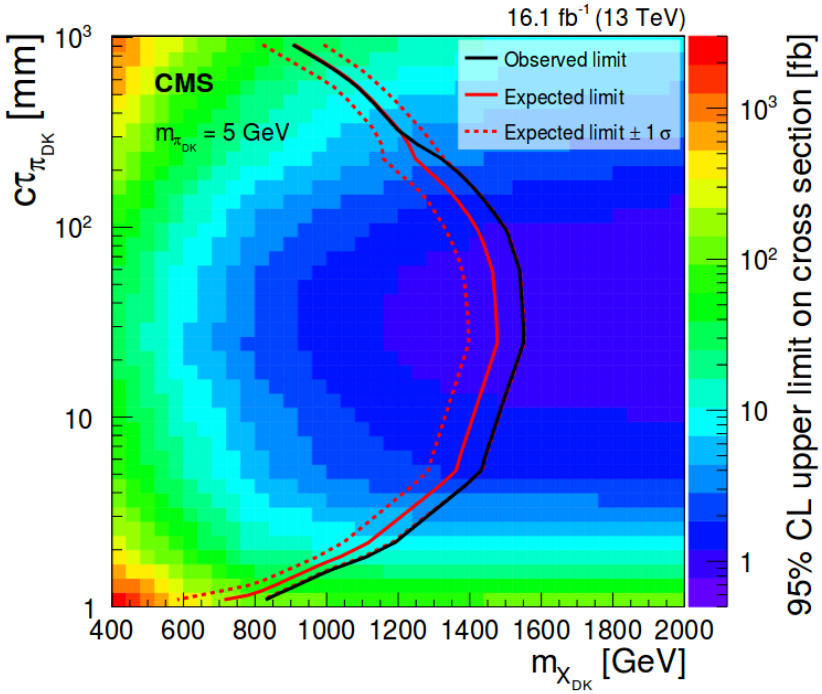


Left plot is our signal region without any help from the BDT ("S-Cut"). Right plot is our signal region in our tightest BDT region, requiring both leading AK8 jets to be tagged as SVJs ("S-BDT2").

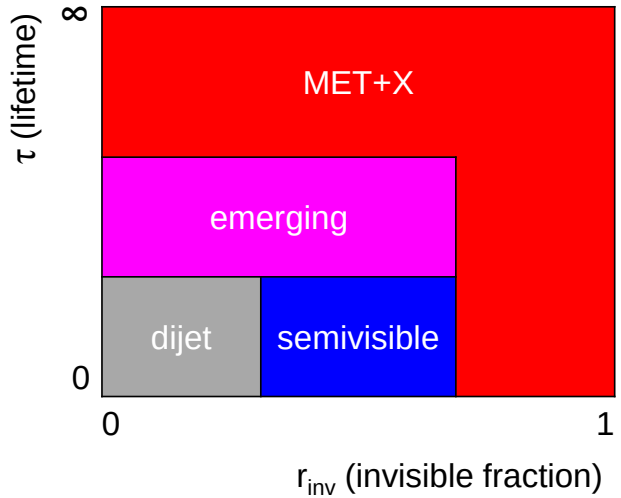
Emerging Jets are another exotic signal that HV can predict, given the right Hidden Valley:

- Electrically charged complex scalar, X_{DK}
- *Long-lived dark hadrons*
- See arXiv:1306.4676, 1502.05409, and 1810.10069 (CMS-EXO-18-001).





- Left: Feynman Diagram of Emerging Jet signal.
- Top: Exclusion plot of Emerging Jets. Signal has been excluded for dark pion decay lengths between 5 and 225 mm for dark mediators with masses between 400 and 1250 GeV. Decay lengths smaller than 5 and greater than 225 mm are also excluded in the lower part of this mass range



Future Goals:

- Publish Semi-Visible Jet analysis.
- Improve the BDT for SVJ tagging, perhaps more advanced ML techniques.
- Add in signal models of the *t*-channel production mechanism.

Thank you!