Hidden Valleys in PYTHIA

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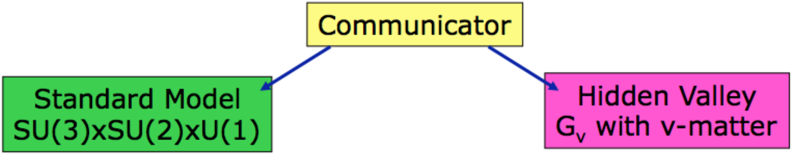
Based on L. Carloni & TS, JHEP 1009 (2010) 105
and L. Carloni, J. Rathsman & TS, JHEP 1104 (2011) 091

Hidden Valleys: motivation

M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374; . . .

Many BSM models contain new sectors
(= new gauge groups and matter content).
These new sectors may decouple from our own at low energy:

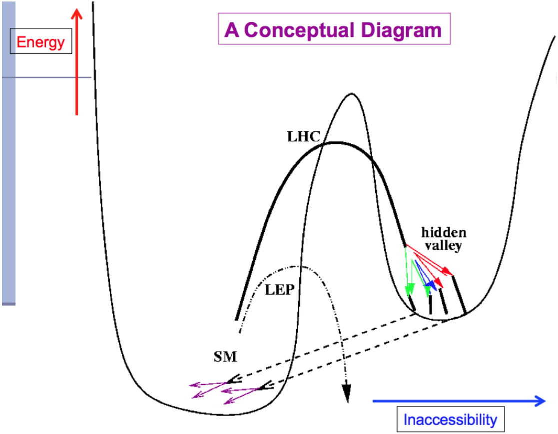


Hidden Valley = Secluded Sector ≈ Dark Sector

May provide the cosmologically required Dark Matter,
but motivation is not (only) fine-tuning to total DM content.

Here: no attempt to construct a specific model,
but to set up a reasonably generic framework.

Experimental relevance



Courtesy
M. Strassler

Hidden Valleys experimentally interesting if

- coupling not-too-weakly to our sector, and
- containing not-too-heavy particles.

so that they can give observable consequences at the LHC!

Production

Either of two gauge groups,

1. Abelian $U(1)$, unbroken or broken (massless or massive γ_v),
2. non-Abelian $SU(N)$, unbroken ($N^2 - 1$ massless g_v's),

with matter q_v's in fundamental representation.

Three alternative production mechanisms

1. massive Z': $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{Z}' \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
2. kinetic mixing: $\mathrm{q}\overline{\mathrm{q}} \to \gamma \to \gamma_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$,
3. massive F_v charged under both SM and hidden group, so e.g. $\mathrm{gg} \to \mathrm{F}_v\overline{\mathrm{F}}_v$. Subsequent decay $\mathrm{F}_v \to \mathrm{f}\mathrm{q}_v$.

Question: MadGraph vs. PYTHIA

- If both are run for the same model, at Leading Order, they should give same result. Useful check!
- MadGraph can do LO + visible multijet emission, with any shower for matching&merging (M&M).
- MadGraph can do LO + visible + invisible emission, but then only PYTHIA shower can provide M&M?
- Pure PYTHIA more reliable/stable within its framework, but less precise for hard emissions.
- MadGraph_aMC@NLO can do NLO, but only in visible sector? Should give bulk of NLO corrections to total cross section. Could be approximated by simple multiplicative factor.

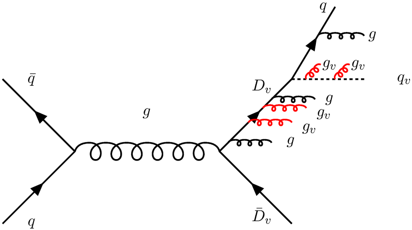
Showers

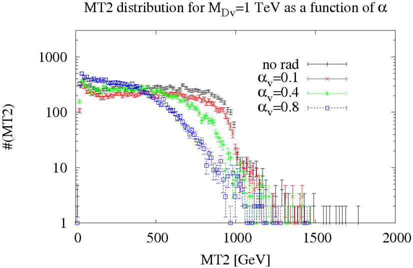
Interleaved shower in QCD, QED and HV sectors:
emissions arranged in one common sequence of decreasing emission $p_{\perp}$ scales.

HV $U(1)$: add $\mathrm{q}_v \to \mathrm{q}_v \gamma_v$ and $\mathrm{F}_v \to \mathrm{F}_v \gamma_v$.

HV $SU(N)$: add $\mathrm{q}_v \to \mathrm{q}_v \mathrm{g}_v$, $\mathrm{F}_v \to \mathrm{F}_v \mathrm{g}_v$ and $\mathrm{g}_v \to \mathrm{g}_v \mathrm{g}_v$.

By default fixed α_v, but running as option.





Recoil effects in visible sector also of invisible emissions!

Questions: Shower Structure

In Dark QCD the dark gluons are massless.
Thus almost exact copy of QCD, with soft and collinear divergences as handled in a normal dipole picture.
As in QCD, a massive quark has no collinear singularity.
Higher HV masses than in SM would imply less radiation.

In Dark QED a massless γ_v is again equivalent to a γ,
but a massive γ_v would have no soft singularity.

Note 1: decays $\gamma_v \to \mathrm{f\bar{f}}$ and $\mathrm{q}_v\overline{\mathrm{q}}_v \to \mathrm{f\bar{f}}$ are essentially isotropic,
so different structure even if all energy leaks back,
a bit like QCD with enhanced $\mathrm{g} \to \mathrm{q\overline{q}}$ rate.

Note 2: such $\mathrm{f\bar{f}}$ systems are colour singlets, so separated from each other, likely giving lower multiplicity and more separated hadron clusters.

Hadronization and Decays

Hidden Valley particles may remain invisible, or

- Broken $U(1)$: γ_v acquire mass, radiated γ_vs decay back, $\gamma_v \to \gamma \to \mathrm{f\bar{f}}$ with BRs as photon ($\Rightarrow$ lepton pairs!)
- $SU(N)$: hadronization in hidden sector, with full string fragmentation setup, permitting up to 8 different q_v flavours and 64 $\mathrm{q}_v\overline{\mathrm{q}}_v$ mesons, but for now assumed degenerate in mass, so only distinguish
  - off-diagonal, flavour-charged, stable & invisible
  - diagonal, can decay back $\mathrm{q}_v\overline{\mathrm{q}}_v \to \mathrm{f\bar{f}}$.

Allows visible, invisible or semi-visible jets.

Allows displaced vertices, by adjusting particle lifetimes.

Question: Stable Baryons

In an $SU(N)$ model a baryon consists of N quarks:

- $N = 2$ profuse baryon production, $\sim 50\%$.
- $N = 3$ as SM, $\sim 10\%$ baryons, or less if $m_{\mathrm{q}_v} \gg \Lambda_v$.
- $N = 4$ baryons likely negligible, $< 1\%$.

If baryon is stable and invisible, how distinguish it from scenario with more different q_v flavours, where diagonal fraction drops?

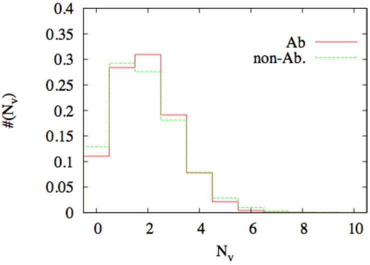
The class `HVStringFlav` in `HiddenValleyFragmentation.cc`

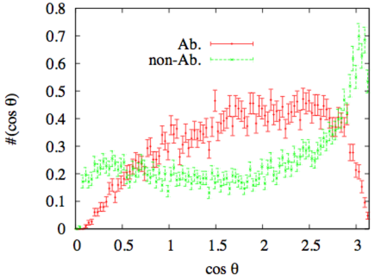
- `picks` new HV flavour and
- `combines` old with new to give HV meson.

Easy to extend with probability to pick HV diquark and combine to HV baryon.
(Should be enough, but some reservation about kinematics limits when more disparate HV hadron mass scales involved.)

Results

Even when tuned to same average activity,
hope to separate $U(1)$ and $SU(N)$:





and several other studies in the two articles.

Appendix 1: Particle Content

name	`name`	identity	comment
D_v	`Dv`	4900001	partner to the d quark
U_v	`Uv`	4900002	partner to the u quark
S_v	`Sv`	4900003	partner to the s quark
C_v	`Cv`	4900004	partner to the c quark
B_v	`Bv`	4900005	partner to the b quark
T_v	`Tv`	4900006	partner to the t quark
E_v	`Ev`	4900011	partner to the e lepton
ν_{E_v}	`nuEv`	4900012	partner to the ν_e neutrino
M_v	`MUv`	4900013	partner to the μ lepton
ν_{M_v}	`nuMUv`	4900014	partner to the ν_μ neutrino
T_v	`TAUv`	4900015	partner to the τ lepton
ν_{T_v}	`nuTAUv`	4900016	partner to the ν_τ neutrino
g_v	`gv`	4900021	the v-gluon in an $SU(N)$ scenario
γ_v	`gammav`	4900022	the v-photon in a $U(1)$ scenario
Z', Z_v	`Zv`	4900023	massive gauge boson linking SM- and v-sectors
q_v	`qv`	4900101	matter particles purely in v-sector
π_v^{diag}	`pivDiag`	4900111	flavour-diagonal spin 0 v-meson
ρ_v^{diag}	`rhovDiag`	4900113	flavour-diagonal spin 1 v-meson
π_v^{up}	`pivUp`	4900211	flavour-nondiagonal spin 0 v-meson
ρ_v^{up}	`rhovUp`	4900213	flavour-nondiagonal spin 1 v-meson
	`ggv`	4900991	glueball made of v-gluons

Appendix 2: Parameters

parameter	def.	meaning
		Scenario
HiddenValley:Ngauge	3	1 for $U(1)$, N for $SU(N)$
HiddenValley:spinFv	1	0, 1 or 2 for F_v spin 0, 1/2 and 1
HiddenValley:spinqv	0	q_v spin 0 or 1 when $s_{F_v} = 1/2$
HiddenValley:kappa	1.	F_v anomalous magnetic dipole moment
HiddenValley:doKinMix	off	allow kinetic mixing
HiddenValley:kinMix	1.	strength of kinetic mixing, if on
		Showers in secluded sector
HiddenValley:FSR	off	allow final-state radiation
HiddenValley:alphaFSR	0.1	constant coupling strength
HiddenValley:pTminFSR	0.4	lower cutoff of shower evolution
		Hadronization in secluded sector
HiddenValley:fragment	off	allow hadronization
HiddenValley:nFlav	1	N_{flav}, number of distinct q_v species
HiddenValley:probVector	0.75	fraction of spin-1 v-mesons
HiddenValley:aLund	0.3	a parameter in eq. (A.1)
HiddenValley:bmqv2	0.8	$b' = bm_{q_v}^2$ parameter in eq. (A.1)
HiddenValley:rFactqv	1.0	r parameter in eq. (A.1)
HiddenValley:sigmamqv	0.5	σ', such that $\sigma = \sigma' m_{q_v}$

`HiddenValley:alphaOrder = 1` and `HiddenValley:Lambda` added for running α_v.