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

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.

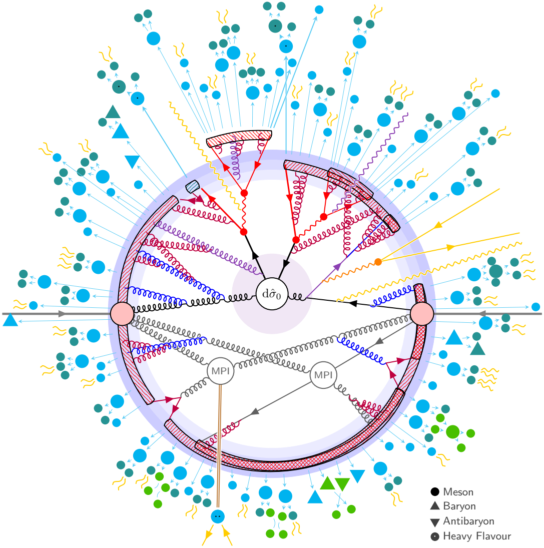
Hidden Valleys experimentally interesting
if they can give observable consequences at the LHC:

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

Here: no attempt to construct a specific model,
but to set up a reasonably generic framework,
to allow the simulation of a variety of experimental signatures.

Commonly used by theorists and experimentalists.

PYTHIA and the structure of an LHC pp collision



- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium

- Multiparton Interactions

- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

(: incoming lines are crossed)*

From PYTHIA 8.3 guide, arXiv:2203.11601, 315 pp

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.
Number of colours and number of quarks are key parameters.

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 $\mathrm{F}_v \to \mathrm{f}\mathrm{q}_v$. F_v spin either 0, 1/2 or 1 and matching q_v either 1/2 or 0.
4. (No Higgs portal, but doable. Qualitatively similar to Z'.)

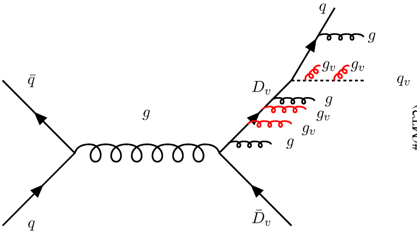
Shower intro

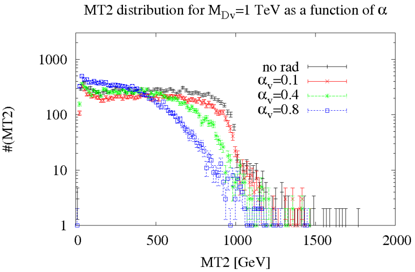
Interleaved shower in QCD, QED and HV sectors:
emissions arranged in one common sequence of decreasing emission $p_\perp$ scales.

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 first-order running as recommended option.





Recoil effects in visible sector also of invisible emissions!

Shower details

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.
A massive quark has no collinear singularity, as in QCD.
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.

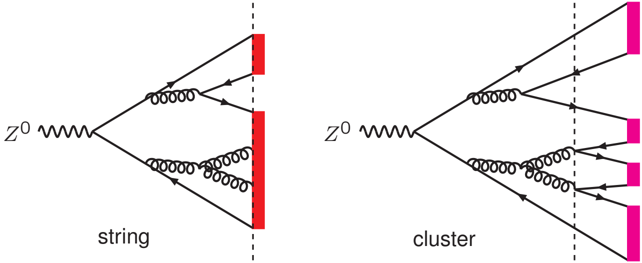
Note 1: decays $\gamma_v \to \mathrm{f}\overline{\mathrm{f}}$ and $\mathrm{q}_v\overline{\mathrm{q}}_v \to \mathrm{f}\overline{\mathrm{f}}$ are essentially isotropic, so different structure than shower even if all energy leaks back, a bit like QCD with enhanced $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$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

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

Shower splittings

QCD allows branchings $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$, and similarly $\mathrm{g}_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$.
No soft singularity is involved, so small rate.

In (HERWIG/SHERPA) cluster all gluons are forced to split, $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$, giving more but smaller colour singlets.



Low-mass strings more difficult to hadronize, notably if $m_{\mathrm{string}} < 2m_{\mathrm{hadron}}$. ($\Rightarrow$ Forbidden shower history?)
$\Rightarrow$ Currently no $\mathrm{g}_v \to \mathrm{q}_v\overline{\mathrm{q}}_v$ in PYTHIA.

Avoided in cluster if $m_{\mathrm{g}_v} > 2m_{\mathrm{q}_v}$ and $m_{\mathrm{q}_v} > m_{\mathrm{lightest\ hadron}}$.

Simple 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 2×64 $\mathrm{q}_v\overline{\mathrm{q}}_v$ mesons. Simple setup assumes mass degeneracy, so only distinguish
  • off-diagonal, flavour-charged, stable & invisible
  • diagonal, can decay back $\mathrm{q}_v\overline{\mathrm{q}}_v \to \mathrm{f\bar{f}}$.
  (Extended setup after this.)

Allows visible, invisible or semi-visible jets.
Diagonal fraction is $1/n_{\mathrm{q}_v}$.

Allows displaced vertices, by adjusting particle lifetimes.

Simple baryons

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

- $N = 2$ profuse "baryon" production, $\sim 50\%$, but unclear mass spectra and production.
- $N = 3$ 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 limited number of HV baryons.

Simple 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
$\mathrm{Z}', \mathrm{Z}_v$	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
Δ_v	Deltav	4901114	a single v-baryon
	ggv	4900991	glueball made of v-gluons

Simple parameters

parameter	def.	meaning
HiddenValley:Ngauge	3	1 for $U(1)$, N for $SU(N)$
HiddenValley:nFlav	1	N_{flav}, number of distinct q_v species
	Production	
HiddenValley:spinFv	0	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	
HiddenValley:FSR	off	allow final-state radiation
HiddenValley:alphaOrder	0	order of running α_v
HiddenValley:alphaFSR	0.1	constant coupling strength
HiddenValley:Lambda	0.4	scale for running α_v
HiddenValley:pTminFSR	0.44	lower cutoff of shower evolution
	Hadronization	
HiddenValley:fragment	off	allow hadronization
HiddenValley:probVector	0.75	fraction of spin-1 v-mesons
HiddenValley:probDiquark	0.	fraction of $\mathrm{q}_v\mathrm{q}_v - \overline{\mathrm{q}}_v\overline{\mathrm{q}}_v$ string breaks
HiddenValley:aLund	0.3	a in Lund fragmentation function
HiddenValley:bmqv2	0.8	$b' = bm_{q_v}^2$ in ditto
HiddenValley:rFactqv	1.0	r in ditto
HiddenValley:sigmamqv	0.5	σ', such that $\sigma = \sigma' m_{q_v}$

Extended hadronization

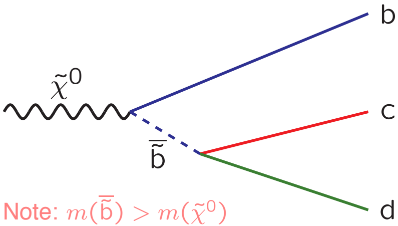
Extension available from PYTHIA 8.307 (25 February 2022)
Thanks to Matt Strassler and Suchita Kulkarni.

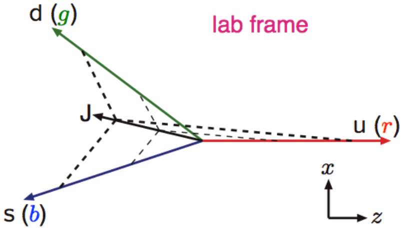
- Up to 8 q_v with separate masses and production rates. Assume $m(4900101) \leq m(4900102) \leq m(4900103) \ldots$.
- Up to 2×64 $\mathrm{q}_v\overline{\mathrm{q}}_v$ mesons with separate masses and decay patterns (modulo particle–antiparticle symmetry).
- Optional suppression of η_1 flavour state.
- Only one 4901103 "lightest diquark" state (cf ud_0 in QCD), giving up to 8 "baryon" states classified by heaviest flavour (instead of $168 + 120$).
- Also a few minor improvements and bug fixes since 8.306.

parameter	def.	meaning
`HiddenValley:separateFlav`	off	switch on extended handling
`HiddenValley:probFlav`	$8 \times 1.$	relative flavour hadronization suppression
`HiddenValley:probKeepEta1`	1.	suppression of η_1 production

Alternative 1: Baryon number violation

Baryon number violation (BNV) is allowed in SUSY superpotential.
BNV couplings should not be too big, or else large loop corrections
$\Rightarrow$ long-lived LSP (Lightest Supersymmetric Particle).





Two nontrivial issues addressed in PYTHIA:

- Parton showers as half-strength dipoles between all q pairs, to give normal quark radiation split between two recoilers.
- Junction fragmentation: 3 strings stretched in Y-shape, from common junction that carries the baryon number.

Alternative 2: *R*-hadron formation

Conventional SUSY: LSP is neutralino, sneutrino, or gravitino.
Coloured are unstable and decay to LSP, e.g. $\tilde{\mathrm{g}} \to \tilde{\mathrm{q}}\overline{\mathrm{q}} \to \mathrm{q}\tilde{\chi}\overline{\mathrm{q}}$.

Alternative SUSY: gluino LSP, or long-lived for another reason.
E.g. Split SUSY (Dimopoulos & Arkani-Hamed):
scalars are heavy, including squarks $\Rightarrow$ gluinos long-lived.

More generally, many BSM models contain colour triplet or octet particles that can be (pseudo)stable: extra-dimensional excitations with odd KK-parity, leptoquarks, excited quarks, ...

$\Rightarrow$ PYTHIA allows for hadronization of 3 generic states:

- colour octet uncharged, like $\tilde{\mathrm{g}}$, giving $\tilde{\mathrm{g}}\mathrm{u}\overline{\mathrm{d}}$, $\tilde{\mathrm{g}}\mathrm{uud}$, $\tilde{\mathrm{g}}\mathrm{g}$, . . . ,
- colour triplet charge $+2/3$, like $\tilde{\mathrm{t}}$, giving $\tilde{\mathrm{t}}\overline{\mathrm{u}}$, $\tilde{\mathrm{t}}\mathrm{ud}_0$, . . . ,
- colour triplet charge $-1/3$, like $\tilde{\mathrm{b}}$, giving $\tilde{\mathrm{b}}\overline{\mathrm{c}}$, $\tilde{\mathrm{b}}\mathrm{su}_1$, ...

Interesting detector simulation: slow-moving,
charge- and baryon-number-exchange reactions.

Outlook

12 year old framework recently extended for more flexibility.
Already allows wide array of scenarios.

Possible future extensions (largely input from Matt Strassler):

- Implement Higgs portal.
- Relate Λ_v in running α_v to string tension κ, and relations to other hadronization parameters.
- Update defaults, e.g. to running α_v.
- How model chiral limit $m_{q_v} \to 0$ for fixed Λ_v?
- How model "baryon" production in $SU(2)$?
- Physics in non-SU groups.
- Longer model writeup, with default value motivations.
- ...