Update on Snowmass Benchmarks for Semi-Visible Jets

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Introduction

Goal: create benchmarks for semi-visible jets

- Assure experimental coverage, provide diversity of targets
- Focus: s-channel production of a confining hidden valley (HV) dark sector
  - Theoretically consistent and experimentally relevant
  - A range of r_{inv} and diversity of substructure
- Constraints: able to simulate using validated Pythia 8 HV module
  - Advances in Pythia 8 have been achieved, see below

Note: Same issues important for t-channel production

Notation: will not put “D” or “v” indices on hidden hadrons;

- all hadrons in this talk are dark sector/hidden valley hadrons.

One Hidden Valley Sector (QCD-like)

Dark Sector consists of

- SU(N) gauge theory with F quarks q^v_r of equal (current) mass m_q
  - Use m_π rather than m_q as parameter
- "Confinement scale" Λ
  - $SU(F)_L \times SU(F)_R \times U(1)_B \rightarrow SU(F)_D \times U(1)_B$ spontaneous breaking
  - $U(1)_A$ broken explicitly by anomaly
- Spin-0 bosons
  - F^2-1 flavor-adjoint pseudo-Nambu-Goldstones π, mass m_π
  - 1 flavor singlet scalar η' with mass $m_{\eta'}$ determined by m_π and anomaly
- Spin-1 bosons
  - F^2-1 flavor-adjoint ρ , mass m_ρ (determined by m_π, Λ)
  - 1 flavor singlet vector φ with mass m_φ
- Baryons (available only for N=3 in simulations, small effect N>3)
- Other hadrons (neglected in simulations)

One Class of Couplings (Z')

Dark Sector consists of

- SU(N) gauge theory with F quarks q^v_r of equal (current) mass m_q
  - Use m_π rather than m_q as parameter
- "Confinement scale" Λ

Coupled to SM by **leptophobic** Z'

- To evade Z' constraints
- To assure all-hadronic final state *[otherwise different expt strategy.]*

- U(1)' charge Q_f of quark q^v_f , f = 1,…,F

The FxF matrix Q = diag(Q_1,Q_2,…,Q_F) controls all decays to SM

- Ex.: If **Q**=diag(1,-1, 2,-2) then ***3 diagonal*** mesons ➔ SM
- Ex. If **Q**= diag(1,-1, 1,-1) then ***only 1 diagonal meson*** ➔ SM
- Ex.: If **Q**=diag(1, 1, 1, 1) then ***only flavor-singlet*** meson ➔ SM

- *New version of Pythia 8 HV module can handle this* **separateFlav=on**

Update (beta) to Pythia 8

separateFlav=off

- Works as before (except for adjustment to soft π emission)
- Treats spin-0/1 diagonal/off-diagonal as four particle categories
  - Each category has one set of decay modes, lifetimes

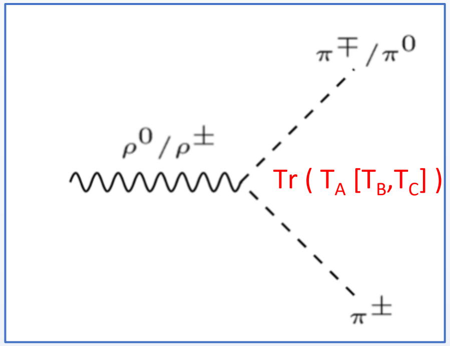
See cautions for usage in prior presentations!

separateFlav=on

- All F^2 spin-0 mesons π_{rs} and F^2 spin-1 mesons ρ_{rs} are now independent
  - Each can have its own mass, decay modes
    - Decay modes can vary, so accommodates many choices of **Q** matrix
    - We have only validated case with masses equal

- Updates to singlets, baryons later in the talk

$m_\pi < \frac{1}{2} m_\rho$



In this case Br(ρ → π π) = 100% (SM never competes)

- r_{inv} = 1 unless some π's can decay

- Depending on **Q**, some diag π's may decay
  - (via offshell Z') to heavy SM q q (*as in SM π → eν*)
- All off-diagonal π are stable (*unless additional flavor-violating physics)*

$$r_{inv} = 1 - r_{vis} \geq 1 - F / (F^2) = 1 - {}^{1}/_{F}$$

Substructure variables will depend on m_π/m_ρ.

- Does this impact efficiencies for SVJ identification?

Can r_{inv} be further reduced?

- Still under investigation but seems likely
  - Example: add an invisible axion a that allows π_{12} → a + q q

Benchmark Models ($m_\pi < \frac{1}{2} m_\rho$)

separateFlav=off

- Diag/off-diag ρ's decay to diag/off-diagonal π's
- Diagonal π assigned a decay to qq
- Off-diagonal π stable

Benchmarks are currently available

separateFlav=on

- ρ decays need to be kept proper track of (long decay table)
- Allows for **Q**-dependent details of diag π decay
- May be needed for certain flavor-changing decays of off-diag π's

Benchmarks under development

(long decay tables must be written, checked)
(possibly overkill for Snowmass but will be needed later)

$\rho_A \rightarrow \pi_B \pi_C$ proportional to $[\mathrm{Tr}\,(T_A\,[T_B,T_C]\,)\,]^2$

T_A the generator matrices $\rho_{fg} = \rho_A\,(T_A)_{fg}$

$m_\pi > \frac{1}{2} m_\rho$

In this case $\rho \rightarrow \pi\,\pi$ is kinematically impossible

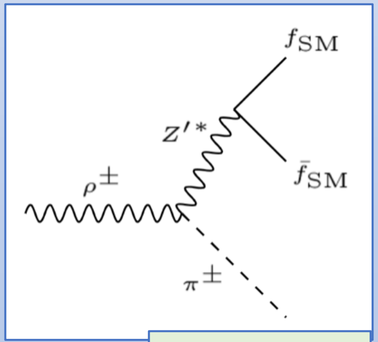
- All π's, ρ's decay to SM or are stable
  - All off-diag π stable
    - *(Assuming no other source of SU(F) breaking)*
  - All diagonal π may be set LHC-stable *(late decay via two offshell Z' to q q q q)*
  - All diagonal ρ decay (via offshell) Z' to q q
  - All off-diagonal ρ are stable (?)

$$r_{inv} = 1 - r_{vis} = 1 - F / (F^2 + F^2) = 1 - {}^{1}/_{2F}$$

$m_\pi > \frac{1}{2}\, m_\rho$

In this case $\rho \rightarrow \pi\,\pi$ is kinematically impossible

- All π's, ρ's decay to SM or are stable
  - All off-diag π stable
    - *(Assuming no other source of SU(F) breaking)*
  - All diagonal π may be set LHC-stable *(late decay via two offshell Z' to q q q q)*
  - All diagonal ρ decay (via offshell) Z' to q q
  - ~~All off-diagonal ρ are stable~~ Off-diag ρ may decay via anomaly
    - $\rho_{fg} \rightarrow \pi_{fg}$ + q q

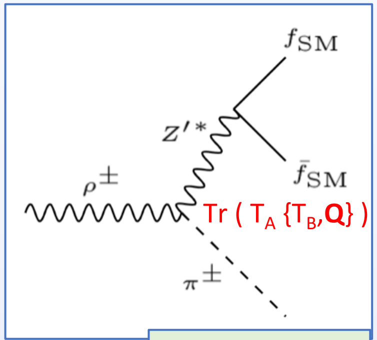


See for ex. Berlin et al. 1801.05805

$r_{inv} = 1 - r_{vis} =$ ~ 0.8 (if $m_\pi \sim \frac{1}{2}\, m_\rho$)

r_{inv} must be calculated by simulation

$m_\pi > \frac{1}{2} m_\rho$



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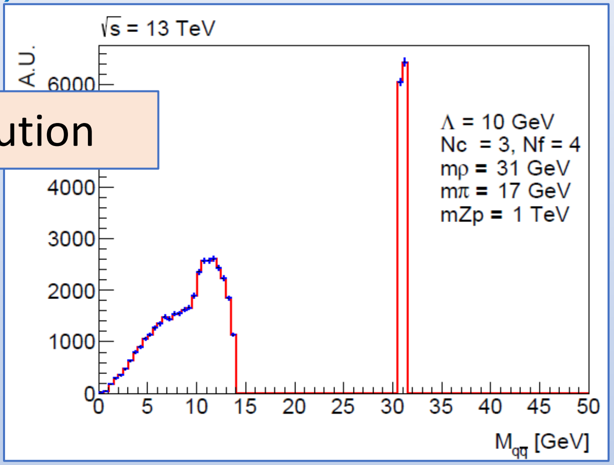
In this case $\rho \to \pi\,\pi$ is kinematically impossible

- All diagonal ρ decay (via offshell) Z' to q q
- Off-diag ρ may decay via anomaly
  - $\rho_{fg} \to \pi_{fg}$ + q q
- **LLPs** if m_ρ too small, $m_{Z'}$ too big (e.g. 10 GeV vs 1 TeV)
- **Change in substructure**:

q-qbar invt mass distribution



- r_{inv} now roughly 0.8 (if $m_\pi \sim \frac{1}{2} m_\rho$)
  - **Cannot avoid:** decays will occur for **some** off-diag ρ_{rs} for any F>2 .
    - If **Q = diag(Q_1,Q_2,…,Q_F)** is generic (no $|Q_r| = |Q_s|$) then **all** decay
    - For F>2, non-generic **Q,** some states may be stable

Examples in backup

Benchmark Models ($m_\pi > \frac{1}{2} m_\rho$)

separateFlav=off

- Set all π's stable
- Set diagonal $\rho \rightarrow qq$
- Set off-diagonal $\rho \rightarrow$ (qq + off-diag π) or invisible
  - Such as to obtain the correct fraction of off-diagonal ρ's that are stable

Benchmarks are newly available

separateFlav=on

- Can be explicit about pattern of stable/unstable diag/off-diag ρ

$\rho_A \rightarrow \pi_B (Z')^*$ prop to $[\, \mathrm{Tr}\, (T_A \{T_B, \mathbf{Q}\})\,]^2$

T_A the generator matrices $\rho_{fg} = \rho_A (T_A)_{fg}$

Benchmarks under development

(long decay tables must be written, checked)

Benchmark Models So Far

- Table of Parameters

separateFlav=off

Regime	N_c, N_f	Λ [GeV]	Q	m_π [GeV]	m_ρ [GeV]	Stable dark hadrons	Dark hadron decays
$m_\pi > 1/2\, m_\rho$	3,4	10	(-1,2,3,-4)	17	31.77	All π	$\rho^0 \to q\bar{q}$ $\rho^\pm \to \pi^0 q\bar{q}$
$m_\pi < 1/2\, m_\rho$	3,3	5	Various	3	12.55	0/1/2 π^0	$\rho^{0/\pm} \to \pi^{\pm/0}\pi^\mp$ $\pi^0 \to c\bar{c}$
	3,3	10	Various	6	26	0/1/2 π^0	$\rho^{0/\pm} \to \pi^{\pm/0}\pi^\mp$ $\pi^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	0/1/2 π^0	$\rho^{0/\pm} \to \pi^{\pm/0}\pi^\mp$ $\pi^0 \to c\bar{c}$

probVec = 0.58 (first row)

probVec = 0.5 (rows 2–4)

Various **Q** will stabilize different # of diag π:

<u>Ex: (1,1,-2)</u>
gives 2 stable, 1 not

Different **Q** will also have different Z' branching fractions, not treated correctly with separateFlav=off, but small effect

Not Covered (see backup)

- separateFlav=on has been validated, ran out of time for benchmarks
  - Degenerate masses: needed for singlets, for some decay patterns, LLPs
  - Non-degenerate masses
- Flavor-singlets (need separateFlav=on)
  - Especially spin-0
- Baryons (N=3 only, not used yet)
- Hadronization studies needed
  - Lund string parameters
  - probVec, probKeepEta1, probDiquark

Backup Slides

separateFlav=on

Degenerate masses – sometimes hard to mock up with separateFlav=off

- e.g. if a new particle can affect both ρ and π decays in a flavor-dependent way

Cannot treat flavor singlets without it; especially important for small F

Essential for LLP searches

- multiple LLP's with different lifetimes

Essential for non-degenerate masses

- cascade decays
- different masses

Hadronization studies needed

probVec parameter (probability that fragmented hadron is spin-1)

- Theory/data suggest 0.75 for $m_\pi \sim m_\rho$, 0.5 in QCD
- We take 0.58 in $m_\pi > ½\, m_\rho$ benchmarks, 0.5 in $m_\pi < ½\, m_\rho$ benchmarks
- Should be varied

Standard Lund-model hadronization parameters

- For now we take the defaults
- Further discussion & studies are needed to investigate the unknowns and unknowables
- Also, what parameter should they scale with? Currently easy to set them wrong.

probKeepEta1 parameter (for separateFlav=on) not much studied yet

- See below

Baryons: off for now

Treatment of singlet states

Singlet phi will have similar mass to other spin-one states (as in QCD)

Singlet eta' heavier than other spin-zero states unless N>>F.

But singlets have

- Different quantum numbers
- Different decay modes
- Different lifetimes

- Details depend on **Q** and on spectrum.
  - Often singlet-adjoint mixing makes the states more similar
  - But this is not always the case.
- Sometimes they can provide a separate signal.

More theory work needs to be done here.

Treatment of singlet spin-0 η'

This state is heavier than the spin-0 mesons because of the anomaly

- Our QCD analysis gives

$$(m_{\eta'})^2 \sim m_\pi^2 + {}^F/_N\,(3\,\Lambda)^2$$

though the coefficient of Λ depends on how it is defined, needs more theory work

Pythia 8

- Define singlet pseudoscalar to be the hadron π_{FF} .
  - Could be issues with diag hadron flavor mixing, needs consideration in some models.
- Use parameter `probKeepEta1` to suppress production in hadronization

- If heavy and suppressed (i.e. F ~ N or greater) then for $m_\pi < \frac{1}{2}\, m_\rho$

$$r_{inv} = 1 - {}^1/_F \Rightarrow 1 - {}^1/_{F+1}$$

Baryons

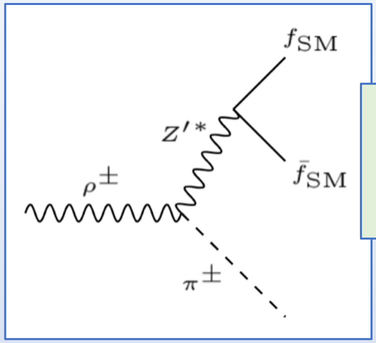
- Huge effect for N=2, Pythia cannot currently simulate it
  - F^2 mesons are degenerate with 2F(F-1) baryons and antibaryons
  - Form a larger multiplet of SU(2F)

- 10% effect for N=3; new version of Pythia **can** simulate
  - Increases effective r_{inv} by 10%?
  - Implementation in Pythia still crude; not validated

- Very limited effect for N>3
  - Baryons simply too heavy

How **Q** Affects ρ Decays

Diag state must have Tr(T^a Q) nonzero to decay to SM



See for ex. Berlin et al. 1801.05805

ρ_{rs} state's d^{abc} coeffs all vanish if $Q_r+Q_s=0$

- **Q** = (-2,-1,1,-2)
  - ρ_{14}, ρ_{23} stable, others decay
- **Q** = (-1,-1,1,1)
  - Any ρ_{rs} with r=1,2, s=3,4 is stable
  - Two diag ρ decay via 3-body because of preserved SU(2)xSU(2)
- **Q** = (-1,-3,2,2)
  - All off-diag can decay
  - One diag ρ decay via 3-body because of preserved SU(2)

Future Beyond Snowmass

Within Reach:

- Non-degenerate quarks (all with m < or ~ Λ)
- More study of flavor-changing interactions
- t-channel *(need to introduce SM flavor physics constraints?)*
- Scalar s-channel
- Herwig/Sherpa engagement?

Pipe Dream

- F=1 (need wider range of mesons)
- N=2 (need baryons degenerate with mesons)
- Both light and heavy hidden quarks (affects hadronization, spectrum)
- F=0 (pure-glue hadronization models) or all quarks heavy
- Sp(N), SO(N)
- Better theory of hadronization in new regimes (e.g. chiral limit)