Some Thoughts on Long-Lived Particles (etc.)

at LHCbeyond

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Something is Fishy at LHC… *(fish-flavored?)*

The **rougheye rockfish** (*Sebastes aleutianus*) are probably among the longest-lived marine fishes on Earth, living as old as 205 years. The name *aleutianus* refers to the Aleutian Islands, where this species was first discovered. The rougheye is also known as the blackthroat or blacktip rockfish in the fishing industry. The name rougheye refers to the 2-10 spines that are common along the lower rim of their eyes, though some have been known not to have these spines. This absence can add to the difficulty of identifying the rougheye from the shortraker rockfish, which have one or no spines. The rougheye is also identified by appearing pink, tan, or brownish with loose patches of brown or bronze when viewed underwater. A darker blotch usually appears on the rear of the operculum, and the posterior area of the lateral line is often pinkish in color. These fish are bright red or pink with black or gray patches after capture, which distinguishes them from the orange-pink or bright reddish-orange color of the shortraker. Another difference is that the rougheye has long, thin gill rakers on the first arch, while the shortraker's are short with knobby ends. These fish usually grow to 32 in. (80 cm), and have been

Why Long-Lived Particles?

Where do known long-lived particles come from?

- QCD gives us a wide variety whose lifetimes are extended for many different reasons.
- EW part of Standard Model does too

Examples:

- Approximate Symmetries violated by higher-dimension operators
  - Weak interaction decays suppressed by $G_F^2\ m^5$
- Weak dimensionless couplings
  - Positronium decay suppressed by five factors of α
  - Bottom quark decay suppressed: as $V_{cb} \rightarrow 0$, 3rd generation # is conserved.
- Small masses and Lorentz invariance
  - Pion decay has helicity suppression
- Naturally small mass splittings
  - Neutron

Realized in Supersymmetry, For Example

Symmetry: R-parity

Weak Coupling: Standard Model to non-Standard Model

- Small Splitting for Wino LSP: Chargino → Neutralino + soft pion
  - Track Stub
- Dim-6 Operators in Split SUSY: with high-mass sfermions, gluino/wino/bino # each almost conserved
  - Long-lived gluinos/winos/binos
- Dimensionless R-parity violation:
  - Small parameter violates R-parity → LSP decays, typically to SM fermions
- Weak coupling: Beyond MSSM with R-parity conserved:
    - Add gravitino: coupling is very weak
    - SM singlets – no SU(3)xSU(2)xU(1) interactions
  - SM LSP decays to SM particle(s) + invisible

REMEMBER: in both cases, SM LSP need not be color/charge neutral

Beyond Supersymmetry

- New particles carry a *(nearly)* exact global charge has a new *(nearly)* stable particle
  - Extra Dimensions with a symmetry
  - Non-anomalous Little Higgs
- New physics with SU(3)xSU(2)xU(1)-singlet particles may have very slow decays
  - RH neutrinos
  - Hidden Valley (e.g. various Dark Matter models, Stealth SUSY, Twin Higgs)
- Near-degeneracies may occur among SU(2) multiplets and other approximate symmetry multiplets

New particle may be stable on detector timescales

- If charged, observe as muon-like track [but with special properties]
- If colored, observe as R-hadron
- If neutral, "observe" as MET [with no special properties]

LHCb is probably not competitive with ATLAS and CMS here

Or it may decay in flight

- But why should lifetime lie between 10^{-12} and 10^{-7} seconds?
  - Well, must lie above 10^{-25} seconds – so why not?
  - However, there's another good reason

LHCb may be competitive with or better than ATLAS and CMS here

Hidden Valley Scenario

This IS The Grain Of Salt

Self-interacting SM singlets ---

- Motivated by dark matter, string theory model building
  - No dramatic constraints from precision EW, Z boson decays or cosmology
- Potentially as complicated as QCD or EW lepton sector
  - Like QCD and like EW lepton sector, multiple particles, multiple lifetimes, multiple symmetries/couplings
  - The more particles the sector has, the more likely it is to have a long-lifetime in the magic zone
- We'll consider a couple of examples later…

Getting Organized

What do we know from LHC so far:

- [almost] No high-rate colored particles below 1 TeV, medium rate below 800 GeV [LLP effects?!]
- At least one Higgs boson, at 125 GeV
- Not much about colorless electroweak multiplets; nothing about SM singlets

My view -- Highest Long-Lived Particles priority for LHCb: Higgs boson decays

- We know at least one exists!
  - Must develop comprehensive knowledge of this particle
- The Higgs decays via weak couplings/loops/off-shell W/Z and is very sensitive to new particles.
- Tough Target: Many final states difficult for ATLAS/CMS
  - If you can do it, your Higgs-related searches will exclude many other models too

Getting Organized

- Other priorities:
  - Top squarks and other low-rate low-mass colored objects
  - New colorless electroweak particles like charginos/neutralinos, other Higgs partners
    - Especially Higgsinos which must be light in natural models
  - Rare Z, W, top decays
  - Very rare bottom, charm decays

Note many of the possibilities are excluded now!

Higgs searches will cover many of these cases too

Fundamental Challenge:

- Many possibilities for process and lifetime
- Many searches required

What Your Competition Has Done On Decays In Flight

- Everybody does displaced photons
- D0
  - Displaced muon pair + MET
  - Displaced jet pairs with 1 embedded muon
- CDF
  - Displaced jet pairs at short lifetime
- CMS
  - Displaced lepton pair
  - Displaced jet pair [2 almost trackless jets with p_T >60 GeV]
- ATLAS
  - Displaced vertex with muon and many tracks
  - Displaced low-mass dilepton resonance (400 MeV only; muonic ``lepton-jet''; four muons in one jet)
  - Particles with m > 20 GeV with meter-long lifetimes decaying to jets

Where Does LHCb Have an Advantage?

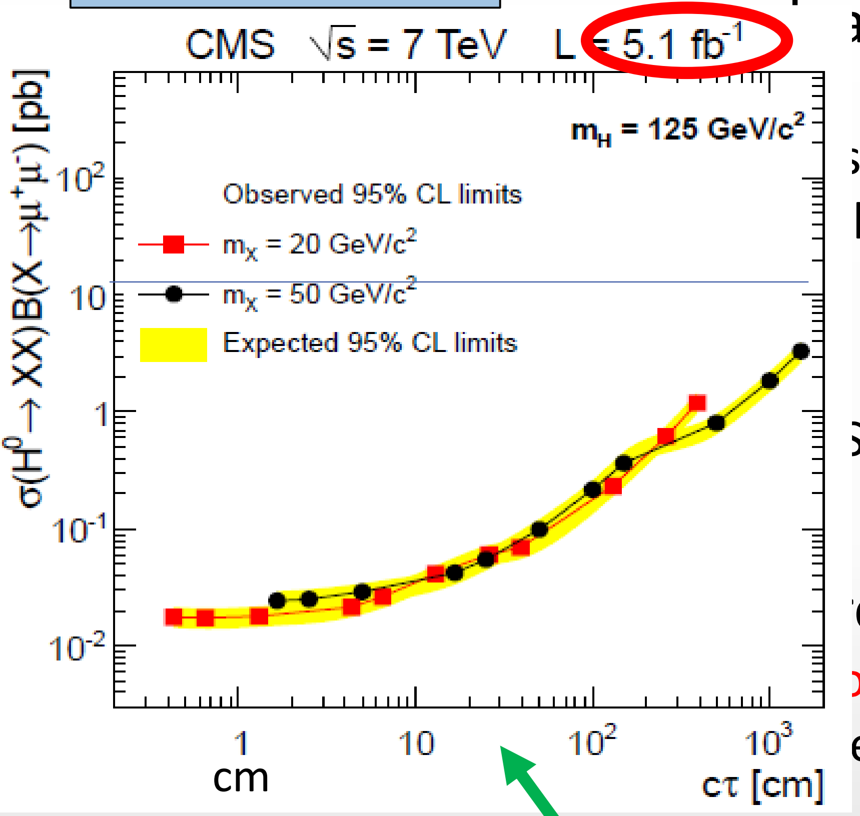
- Low-energy processes
    - Very hard triggering problems for ATLAS/CMS
  - Higgs decays
  - Decays among particles with smallish Δm

- Multiple clustered vertices
  - Confusing for ATLAS/CMS

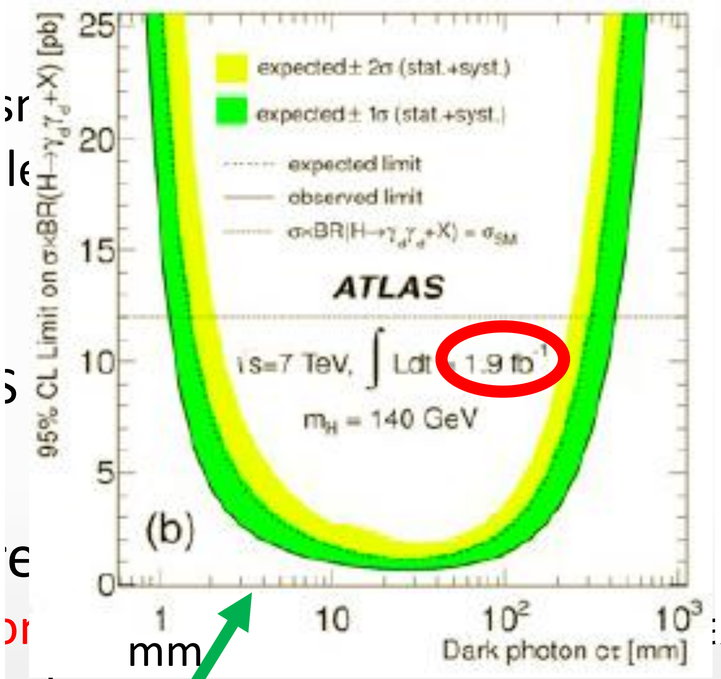
- Complex ``lepton-jets’’ that include hadrons as well as leptons
  - 2 or 4 muons + multiple hadrons from same vertex or from nearby vertices
  - Interesting even if not displaced

Where Does LHCb Have an Advantage?

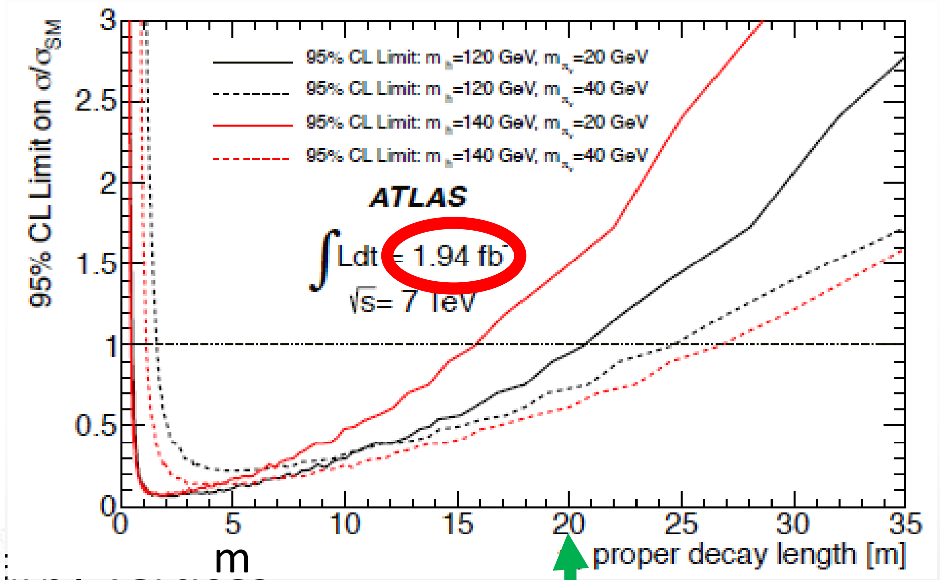
H → X X, X → ℓℓ



H → X X, X → jet of 2-4 muons



H → X X, X → bb



- No advantage
  - Pair of isolated leptons or all-lepton jets – (good for ATLAS/CMS) [exceptions?]
  - Meter-long lifetimes (good for ATLAS)
  - Gluinos (rates are huge or events are spectacular – good for ATLAS/CMS)
  - Weird tracks (?)

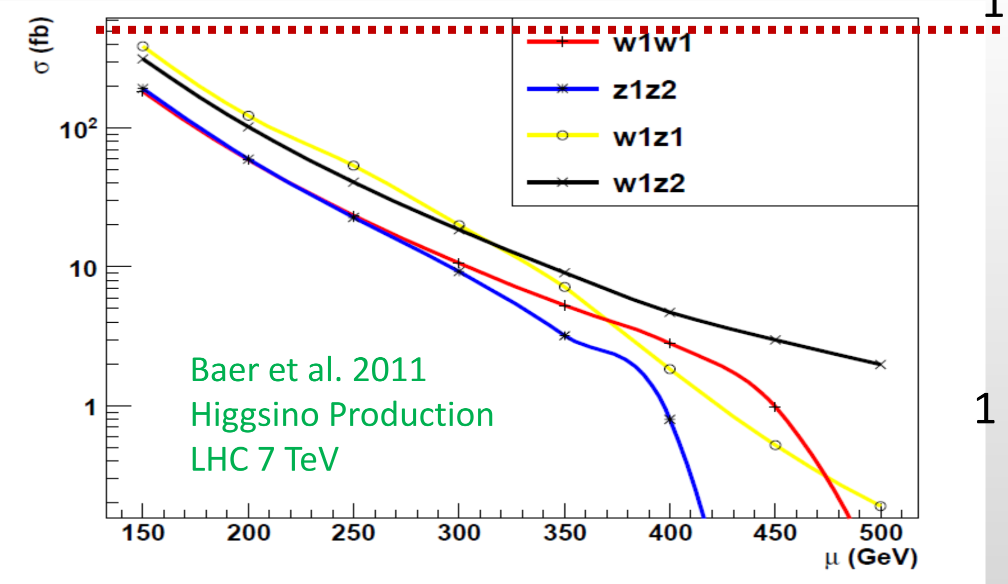
Natural SUSY: Higgsinos Should Be There

- This is a well-motivated target
    - *Just a pair of SU(2) doublets*
  - At 200 GeV, ~ 600 events so far at LHCb
  - At 300 GeV, ~ 120 events so far at LHCb

- Suppose these are long-lived but decay in flight
  - Or decay to other long-lived particles
- Many cases ruled out already by CMS/ATLAS

CMS constrains similar signal

R → X X, X → jj



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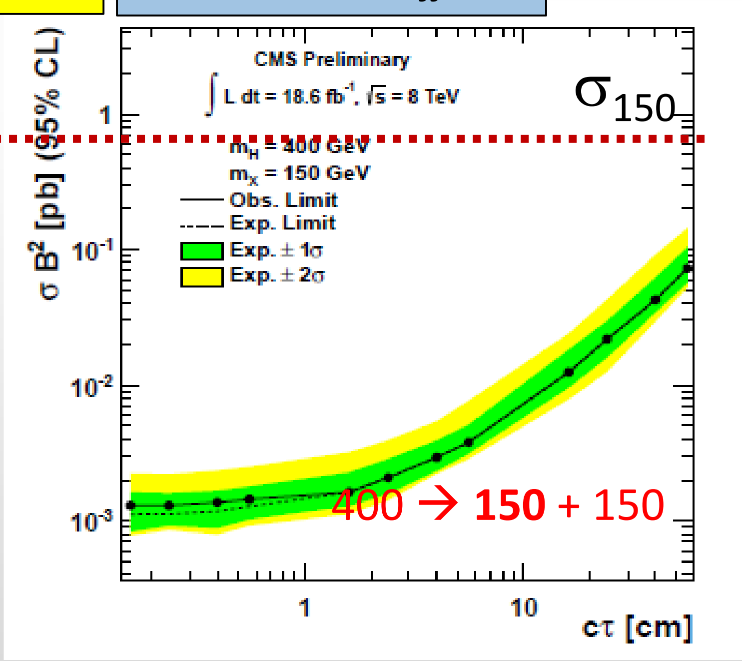

LHCb can still seek Higgsinos that decay to

Low energy + MET

Or high vertex multiplicity

Where Does LHCb Have an Advantage?

- Low-energy processes
    - Very hard triggering problems for ATLAS/CMS
  - Higgs decays
  - Decays among particles with smallish Δm

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- No advantage
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LHCb So Far

- 35 pb^{-1}: H → X X
  - X → jjj
    - RPV SUSY *hep-ph/0607204*
  - X → bb
    - HV models *hep-ph/0605193*

Bodes Well for Future Results

But Very Limited Sensitivity for m_X < 30 GeV
CAN THIS BE IMPROVED?

- In prep: X → jjμ
  - M ~ 50-100 GeV

LHCb-CONF-2012-014

h^0 decaying to Long-Lived Particles

Results:

- No candidate found in 36 pb^{-1} dataset
- Upper limits on $\sigma(h^0) \times BR(h^0 \to X^0X^0)$ in these 2 tables (in pb)
  - For the BV48 point:

    $\sigma(h^0) \times BR(h^0 \to X^0X^0) < 32$ pb @ 95% CL

LLP lifetime = 10 ps

m_{LLP}	30	35	40	48	55
m_{h^0}	(pb)				
100	101	58	44	58	
105	100	75	44	39	
110	132	75	56	34	
114	128	91	47	32	46
120	148	93	58	34	31
125	179	90	61	41	29

Higgs mass = 114 GeV/c^2

m_{LLP}	30	35	40	48	55
τ_{LLP}	(pb)				
3	210	156	136	168	410
5	145	101	68	58	137
10	129	91	47	32	46
15	155	90	49	31	33
20	131	93	63	32	31
25	142	100	61	34	25

Requirement	ϵ (%)
One LLP in acceptance (generator cut)	29.4
LLP preselection	44.1
Trigger	35.5
Fiducial volume	95.8
LLP selection	66.4
Two LLP found	19.1
$\|\Delta\phi\|$ cut	68.4
Total	0.384
Total without trigger	0.589

and Higgs-like particles at LHCb 15/21

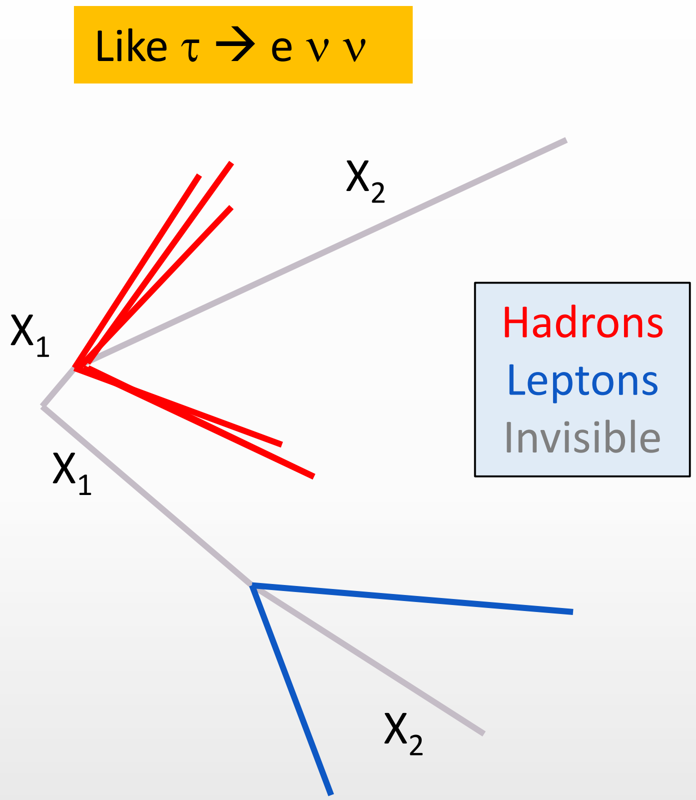
Weakly-Interacting EW-like HV

- Fermions X_1, X_2 with $m_1 > m_2$
- Very heavy U(1) gauge boson Z' weakly mixing with Z
- Perhaps Dark Matter: X_2

- H → X_1 X_1 (prompt)
- X_1 → X_2 q q or X_2 $\ell\,\ell$ via off-shell Z'

- Just like weak interactions except $g_W{}^4 m_f{}^5/m_W{}^4 \rightarrow g'^4 m_X{}^5/m_{Z'}{}^4$

- Result:
  - low-mass lepton pairs appearing from nowhere
  - low-mass low-multiplicity (di)jets appearing from nowhere (possibly just di-pions)



Weakly-Interacting EW-like HV

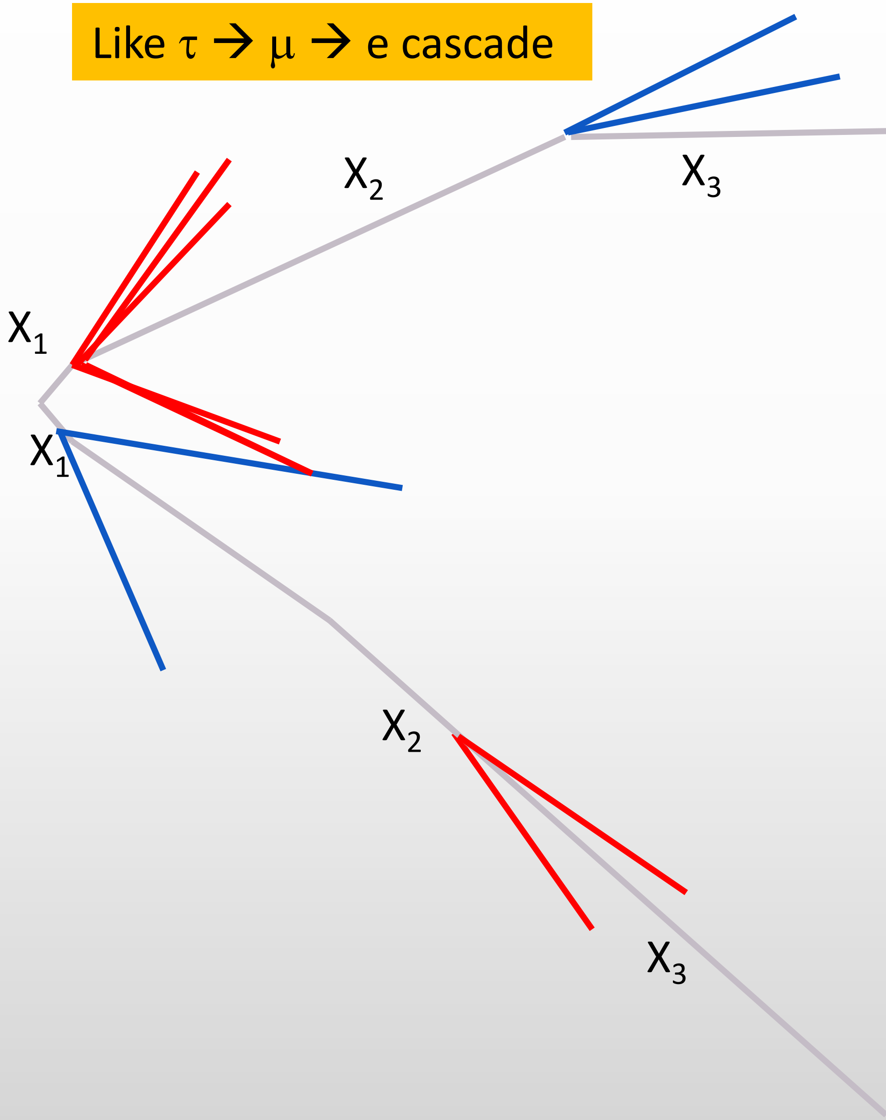
- Fermions X_1, X_2, X_3 with $m_1 > m_2 > m_3$
- Very heavy U(1) gauge boson Z' weakly mixing with Z
- Perhaps Dark Matter: X_3

- $H \rightarrow X_1 X_1$ (prompt)
- $X_1 \rightarrow X_2\, q\, q$ or $X_2\, \ell\, \ell$ via off-shell Z'
- $X_2 \rightarrow X_3\, q\, q$ or $X_3\, \ell\, \ell$ via off-shell Z'

- Just like weak interactions except $m_f^5/m_W^4 \rightarrow m_X^5/m_{Z'}^4$

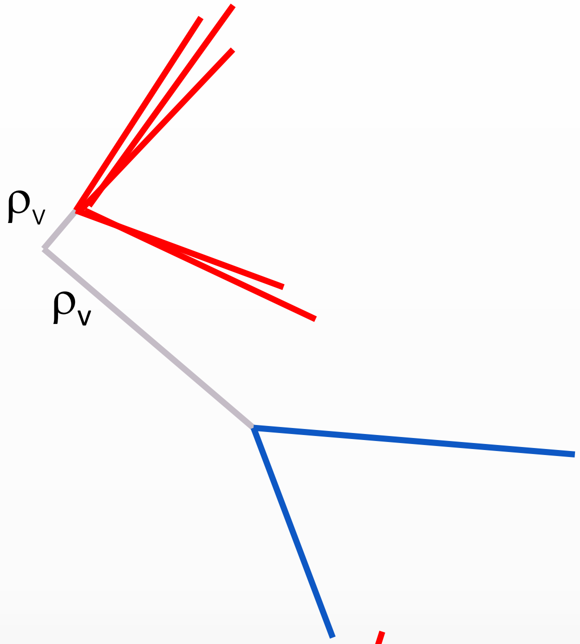
- Result: low-mass fermion pairs appearing from nowhere
  - May be aligned in space by kinematics
  - Not considered in most existing searches
    - Insufficient vertex mass, # tracks, lepton-pair isolation

Like $\tau \rightarrow \mu \rightarrow e$ cascade

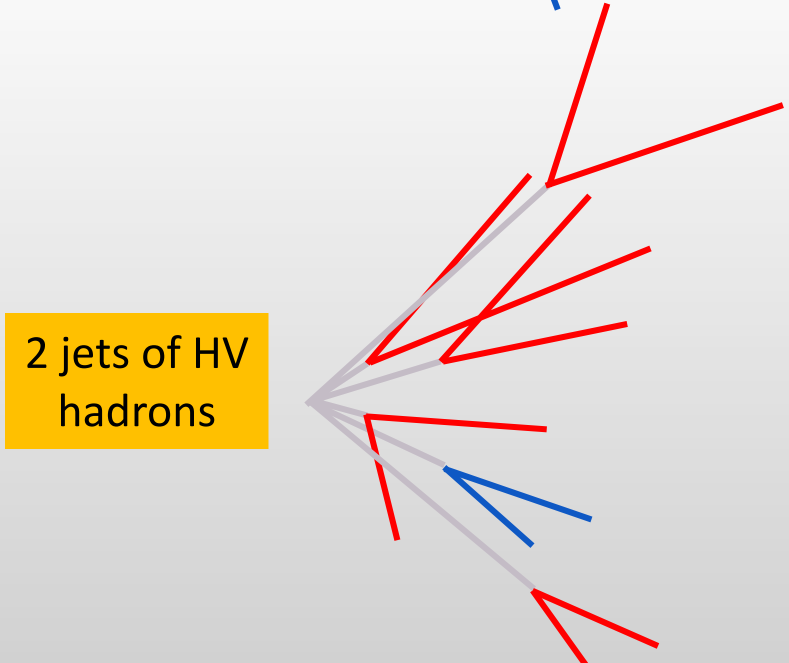


Strongly Interacting QCD-(un)like HV

- QCD-like spectrum:
  - (Meta)stable pseudoscalars (v-pions), spin ½ baryons
  - Flavor structure with cascade decays (as in B meson decays)
- QCD-unlike spectrum: e.g. 1-light quark flavor QCD
  - (Meta)stable pseudoscalar, vector, pseudovector, spin ½ and 3/2 baryons
- QCD-very-unlike spectrum: Yang-Mills glueballs
  - Metastable scalar, tensor, pseudoscalar, pseudovector,



- Any of these states may be able to decay in flight
  - Though lifetime vs. mass formula depends strongly on details
  - Vast array of signals are possible
- Examples
  - H → (bb)(bb), $(\tau\tau)(\tau\tau)$, $(\ell\ell)(\ell\ell)$, $(\ell\ell)$(jj), $(\ell\ell)(\pi\pi)$
  - H → jets of new particles → 2 clusters of vertices
  - H → large number of new particles → widely distributed vertices



Organizational Strategy for Searches?

- Dilepton vertex (ee, $\mu\mu$, $\tau\tau \rightarrow e\mu$ also)
  - Plus additional hadrons at the same vertex
  - Or plus another dilepton vertex
  - Or plus a di-pion or few-hadron vertex
    - Possibly with same invariant mass as dilepton
  - Or plus ditau vertex
    - Lepton + track
    - 1+3 tracks
  - Or plus multiple vertices
    - Not necessarily isolated from dilepton vertex

- Hadronic vertices (possibly with muon, not necessarily high-p_T or isolated)
  - 1 with many tracks [plus muon if necessary] (possibly clustered in 2 jets)
  - 2 with several tracks (can the 2^{nd} be looser?)
  - Many with 2-4 tracks (possibly with equal invariant mass)

Problem of Reinterpretation

It appears very difficult to characterize the efficiency of a long-lived particle analysis

- Too much dependence on too many variables
- Simple detector simulations are probably useless given the sensitivity to detector specifics

Therefore it is very difficult to apply the results for one benchmark to another model.

Probably very important to run a large number of benchmark models through the analysis chain to give current/future physicists a way to understand what has been excluded.

Also helps avoiding too much bias toward a particular model.

Ideally a small number of measurements can be used to put powerful constraints on a wide range of possibilities.

A Couple of Weird Opportunities (but benchmarks?)

- Particles that decay to many soft unclustered leptons are not impossible;
  - will curl up in ATLAS/CMS magnetic field and end up in forward region
  - At LHCb, very different!

Possibly prompt, possibly not

- Jets full of Kaons (from something coupling to strangeness)
  - Measure rate for 1; look for pairs
  - Look on tail and plot di-kaon masses

Cases Not Covered

LHCb has no obvious (to me) advantage for

- Stopped particles
- Particles with |charge| < 1
- Single tracks with kinks
- Other particles with strangely shaped tracks (e.g. macroscopic quirks, monopoles)

Conclusions

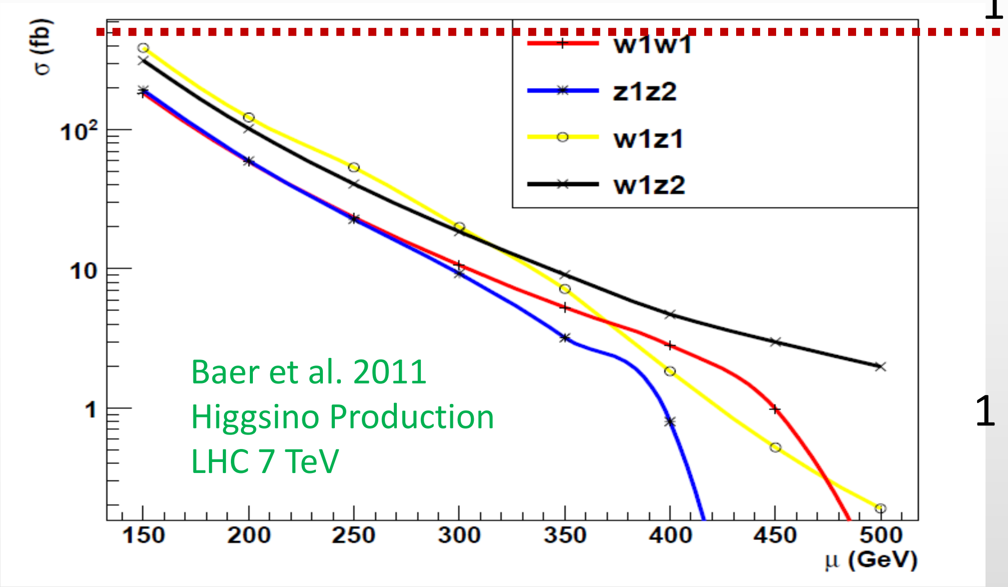
- For long-lived particles, LHCb has a niche
  - Low masses (0.1? – 100? GeV)
  - Short lifetimes (ps – few ns)
  - Everything from one vertex with many tracks to many (possibly clustered) vertices with two tracks
  - Final states with 0, 1, or few leptons and many hadrons
- Fortunately this is an **extremely interesting** niche
  - because it is where some Higgs boson BSM decays sit
- Every reason to expect LHCb can make measurements that no one else can make well
- Your competition is doing very well outside this niche
- So perhaps best to maximally exploit opportunity within the niche.
  - Perhaps a few, broad, carefully-designed searches targeting ATLAS/CMS weak points

σ_{50}

CMS constrains similar signal

R → X X, X → jj

1 pb



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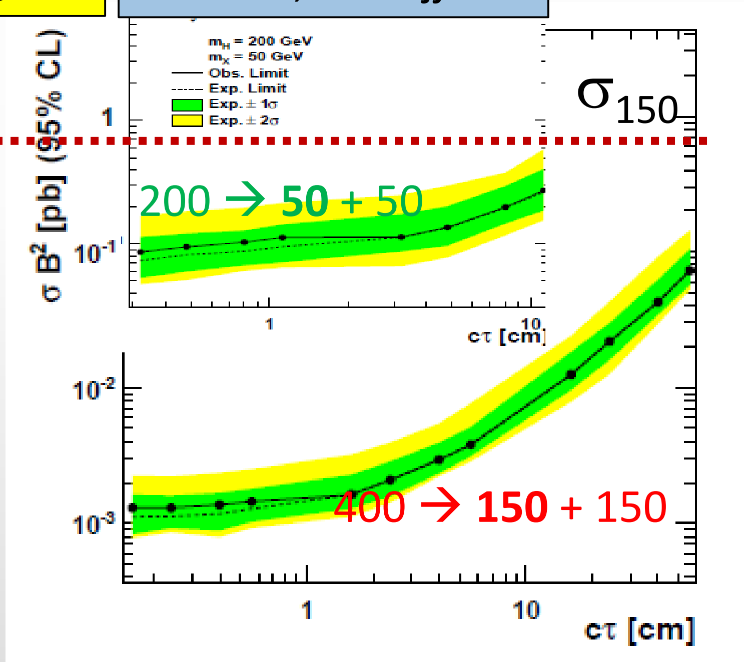

σ_{150}