Higgs decays to lepton jets at hadron colliders

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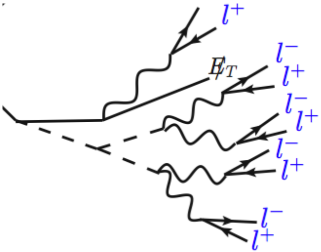
Based on AA,Ruderman,Volansky,Zupan [1002.2952] and AA,Ruderman,Volansky,Zupan [1007.3496]

Who are lepton jets?



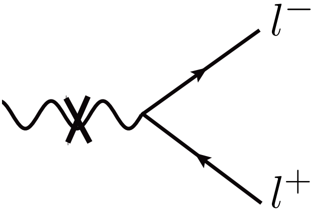
- LJ is a cluster of collimated light charged particles: $e^{\pm}$, $\mu^{\pm}$ etc.
- LJs arise in models with a hidden sector composed of unstable particles with the masses in the MeV to GeV range decaying to SM particles. For light hidden sector particles only the lightest SM states (neutrinos, electrons, maybe muons, pions, kaons) are available
- Motivation for those models was recently provided by certain astrophysical anomalies (PAMELA, Fermi), but the existence of light hidden sectors is a more general possibility that can be tested in colliders
- At high energy colliders (LEP, Tevatron and LHC) light hidden particles are produced with large boosts, causing their visible decay products to form jet-like structures.

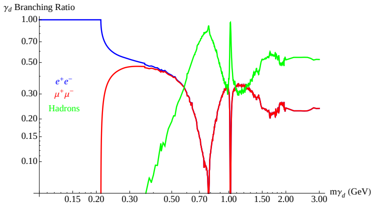
Dark matter via the hypercharge portal

- One way to explain PAMELA is to introduce "dark photon" z_μ that mixes with hypercharge, Arkani-Hamed et al [0810.0713] , Holdom [1985]

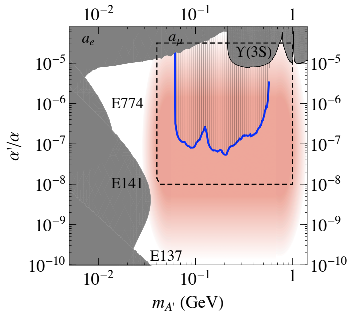
$$\mathcal{L} \sim -z_{\mu\nu}^2 + m_z^2 z_\mu^2 + \epsilon z_{\mu\nu} B_{\mu\nu} \qquad \epsilon \leq 10^{-3}$$

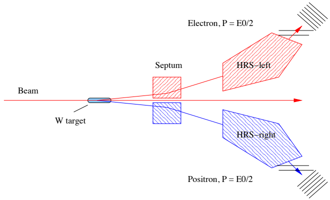
  After field redefinition, $A_\mu \to A_\mu + \epsilon z_\mu$, dark photon mili-couples to the electromagnetic current, $\epsilon z_\mu Q_i \overline{\psi}_i \gamma^\mu \psi_i$
- Dark photon decays into a pair of charged SM states
- Roughly the same coupling to electrons, muons, pions (except at threshold or vector-meson resonance) so roughly democratic decay





Constraints on dark photons



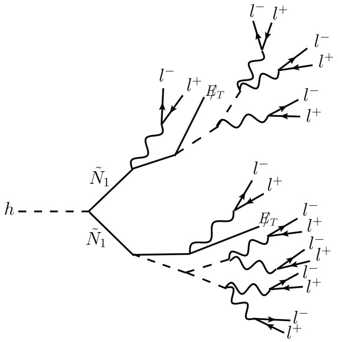


- $m_A \gtrsim 100$ MeV allowed if mixing small enough, typically $\epsilon < 10^{-3}$
- More parameter space soon probed by the APEX experiment in JLAB, Essig et al [1001.2557] , and in MAMI experiment in Mainz
- Other interaction portals possible (e.g. Higgs portal) leading to slightly different signatures than dark photon

- The rest of this talk: how to search for hidden photons at colliders
- If light dark sector particles are produced in colliders and decay promptly (or at least within detector) to SM states, then spectacular though not sufficiently studied signatures are predicted
- OK, but is it possible th particles in colliders, given that the coupling to the hidden sector is necessarily so small?
- Simplest possibility: from decay of weak scale particles that have a charge (strong, electroweak, ..) under the SM
- The charged particles that can decay to the hidden sector include SUSY particles and the `Higgs`

Higgs to lepton jets

- AA,Ruderman,Volansky,Zupan [1002.2952] proposal: Higgs decays into lepton jets and missing energy, in the MSSM + light hidden sector

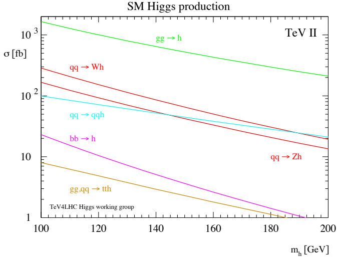


Uncovering Higgs

Higgs is another possibly efficient production portal of lepton jets in colliders
For $m_{Higgs} \sim 100$ GeV,

- Order 10000 Higgs to lepton jets decay per experiment at Tevatron and counting
- Order 1000 Higgs to lepton jets decay per experiment at the LHC and counting

all waiting to be uncovered by a clever analysis...

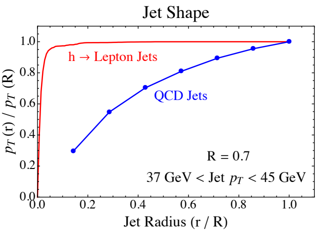


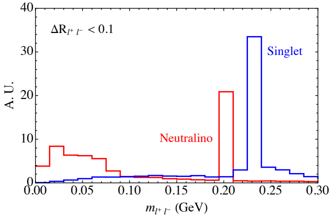
But: Leptons in LJs fail isolation criteria, they won't show in usual multilepton searches. Unorthodox search strategies needed!

Search strategies

Spectacular signatures and relatively easy search, but new methods and IDs have to be developed to discover LJs at colliders.
Some handles (model dependent):

- Jet shapes (lepton jets more narrow than QCD jets, if large mass drop and weakly coupled dark sector)
- Invariant mass peaks for close lepton pairs
- Missing energy from escaping hidden sector particles
- Large ECAL/HCAL for electron jets

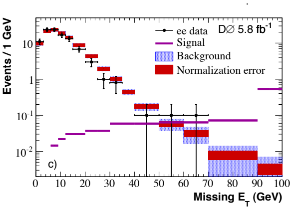


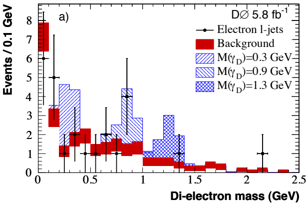


D0 Lepton Jet Search with 5.8 fb-1

LJ + MET search at Tevatron's D0, D0 [1008.3356] , sensitive to a wide class of lepton jets signatures, see also D0 [0905.1478]

- Seed track of $p_T > 10$ GeV matching to EM cluster or to hits in outer muon system
- At least one companion track of pT > 4 GeV within $\Delta R \leq 0.2$ of the seed
- Isolation in the $0.2 < \Delta R < 0.4$ annulus around the seed
- Require two such LJ candidates separated by $\Delta R > 0.8$
- Background from jets and photon conversions becomes marginal at large missing ET





Constraints on H $\rightarrow$ LJ

- Higgs decaying to LJs was not specifically targeted by D0, but the search is inclusive enough to constrain our idea as well
- We estimate D0 puts a constraint on the Higgs mass in a subclass of models up to $\lesssim$ 150 GeV
- Models that produce narrow LJs with a small multiplicity of leptons in jets are severely constrained
- However in certain models LJs can be
  - wider than $\Delta R \sim 0.2$ (so that isolation criteria not satisfied), and/or
  - have a large multiplicity of leptons (so that there's no high p_T tracks to serve as seeds), and/or
  - contain little missing energy,

  in which case they would not be picked by D0 search
- This subclass of models is not constrained by any search so far, and allows the Higgs as light as $\sim$ 100 GeV

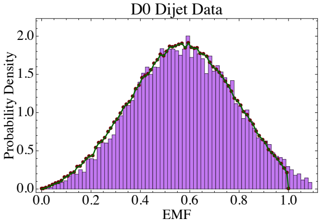
Another idea

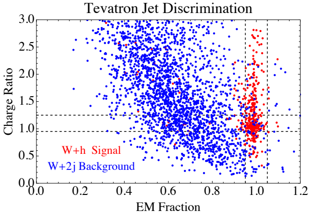
AA,Ruderman,Volansky,Zupan [1007.3496] : using electromagnetic fraction (EMF) and charge ratio (CR) to target electron LJs

$$EMF = \frac{E_{EM}(j)}{E_{tot}(j)} \qquad CR = \frac{\sum p_T(j)}{E_{EM}(j)}$$

Obviously, for lepton jets we expect EMF $\sim$ 1 and CR $\sim$ 1...

- QCD jets consist mostly of $\pi^{\pm}$ (who deposit in ECAL and HCAL) and π^0's (who promptly decay to photons, therefore deposit mostly in ECAL)
- Precise particle content of jets varies wildly on event-to-event basis
- EMF distribution further broadens by fluctuations of EM and Hadronic cascade and detector smearing
- Jets with high π^0 content can have EMF $\sim$ 1, much like LJs
- But those jets have few charged particles, therefore CR $\ll$ 1, unlike LJs





Methodology

- Concentrate on W+h and Z+h Higgs production channels ($gg \to h$ swamped by dijet background) at Tevatron's D0 and LHC's ATLAS
- Main background from $W + 2j$, $Z + 2j$.
- Signal and background generated at parton level in MadGraphv4 and BRIDGE, then showered and hadronized in Pythia 6.4.21
- Track p_T simulated in PGS4.
- PGS is too simplistic for simulating EMF and CR; instead we used a private MC (`tomersim`), taking into account parametrization for EM and hadronic showers in detector material, non-compensating effects (e/h) and detector smearing
- Simulation is tuned to D0 and ATLAS using dijet EMF data

Simulation of calorimeter deposits

- In ECAL, energy losses of electron and photons due to bremsstrahlung, pair production, and photoelectric absorption
- Longitudinal shower development well approximated by gamma distribution, depends on energy and radiation length proper to the detector material
- Other particles (muons and pions) can be treated as MIPs in the ECAL
- Bock parametrization of hadronic cascades,
- Different detection efficiency of hadronic and EM energy (the non-compensation parameter h/e)
- Detector smearing effects (stochastic, noise,)

$$\sigma_E/E = a/\sqrt{E} + b/E + c$$

- At the end, tune h/e to fit to experimental data

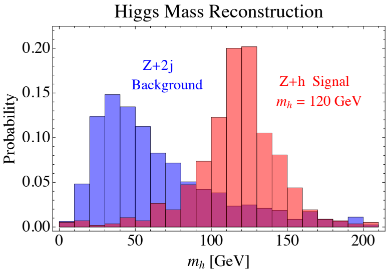
Analysis and Cuts

- Exactly two jets $\Delta R(j_1, j_2) > 0.7$
- **Z+h:** 2 opposite sign same flavor isolated leptons (l = e, μ): $p_T(l) > 10$ GeV, $|m(l_+, l_-) - m_Z| < 10$ GeV
- **W+h:** 1 lepton and missing p_T : $p_T(l) > 20$ GeV, $p_{T,miss} > 20$ GeV
- $N_{track}(j) \geq 4$ (to cut down photon conversions in tracker)
- EMF cut: $0.95 < EMF < 1.05$ for D0, while for ATLAS $0.99 < EMF < 1$
- CR cut: $0.9 < CR < 1.9$ for Z+h and $0.95 < CR < 1.25$ for W+h.

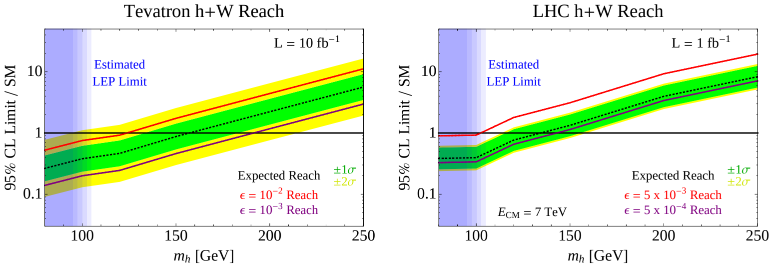
Results

$m_h = 120$ GeV		$W+h$ Signal(Eff.)	$W+h$ Bckg	$Z+h$ Signal(Eff.)	$Z+h$ Bckg
Tevatron ($10\ \mathrm{fb}^{-1}$)	Kinematic	87 (18%)	4.4×10^5	10.6 (18%)	2.8×10^4
	EMF+CR	14.4 (3%)	5.9	3.5 (6%)	1.4
LHC ($1\ \mathrm{fb}^{-1}$)	Kinematic	35(17%)	4.9×10^5	5.2 (25%)	3.6×10^4
	EMF+CR	4.9 (2%)	0.7	1.5 (7%)	0.7

In Z+h Higgs mass can be reconstructed assuming missing energy aligned with the jets (much as in $H \to \tau\tau$)



Reach


Tevatron h+W Reach
L = 10 fb^{-1}
Estimated
LEP Limit
Expected Reach
±1σ
±2σ
ϵ = 10^{-2} Reach
ϵ = 10^{-3} Reach
95% CL Limit / SM
10
1
0.1
100
150
200
250
m_h [GeV]
LHC h+W Reach
L = 1 fb^{-1}
Estimated
LEP Limit
Expected Reach
±1σ
±2σ
ϵ = 5 x 10^{-3} Reach
ϵ = 5 x 10^{-4} Reach
E_{CM} = 7 TeV
95% CL Limit / SM
10
1
0.1
100
150
200
250
m_h [GeV]

Some work left to do

- Purely muonic lepton jets (no ECAL to HCAL handle, but should be piece of cake)
- Largely hadronic lepton jets (may occur e.g for dark photon mass close to ρ resonance). Hopeless?
- Lepton jets with displaced vertices

Ongoing experimental efforts

- CDF search for H $\to$ LJs (Chicago)
- CMS search for LJs + MET (Rutgers)
- CMS search for muonic LJs (Princeton and Texas)
- ATLAS search for $H \to$ LJs (Ljubljana)
- ATLAS search for hadronic LJ production (SLAC)
- ATLAS triggering on displaced LJs (Seattle)
- ...

Summary

- Light hidden sectors could be around. They can be probed via astrophysics, atomic physics, high luminosity colliders. High energy colliders provide another possible road to a discovery
- Lepton jets produce a new class signatures in hadron colliders: easy when you're prepared, but easily missed if not specifically targeted
- Higgs decaying to lepton jets is a possibility that has not been experimentally explored to date - thousands of events possible in Tevatron and 1st year LHC data
- Searching for lepton jets using EMF and CR gives a good sensitivity to a wide class of models with lepton jets.