Searching for lepton jets at hadron colliders

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Heavy Particles at the LHC, Zurich, 07January 2011

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

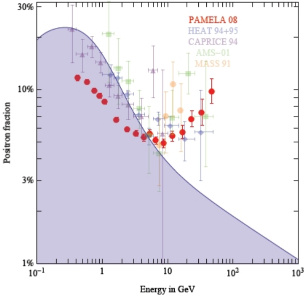
Outline

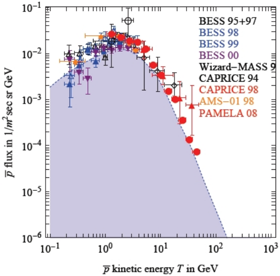
Who are lepton jets?

- LJ is a cluster of highly collimated light charged particles: electrons., muons, etc.
- LJs arise in models with a light hidden sector composed of unstable particles with masses in the MeV to GeV range decaying to SM particles
- In that mass range of hidden sector particles, only the lightest SM states (neutrinos, electrons, maybe muons, pions, kaons) are kinematically available
- 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.

PAMELA saw hints of hidden sector?

- The concept of lepton jets was motivated by models aiming to explain cosmic ray anomalies





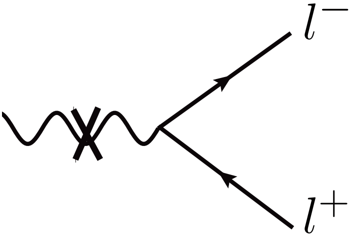
- PAMELA sees an excess in positrons but not in antiprotons
- Also, no clear signs of dark matter in gamma rays
- If dark matter annihilation or decay is the source, one needs to find mechanism why it populates cosmic electrons only

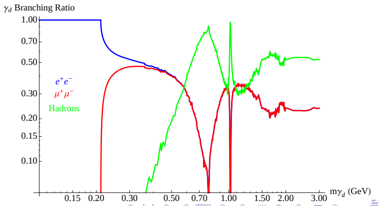
Dark matter via the hypercharge portal

- One way to explain PAMELA is to introduce "dark photon" z_μ that mixes kinetically with the SM hypercharge, Arkani-Hamed, Finkbeiner, Slatyer, Weiner [0810.0713]

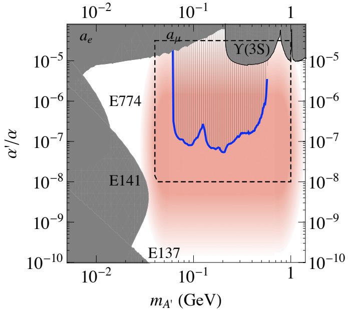
$$\mathcal{L} \sim -z_{\mu\nu}^2 + m_z^2 z_\mu^2 + \epsilon z_{\mu\nu} B_{\mu\nu} \qquad \epsilon \leq 10^{-3}$$

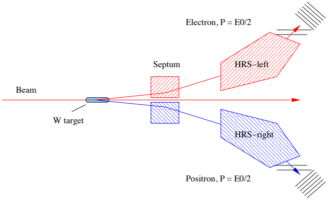
  After field redefinition, $A_\mu \rightarrow A_\mu + \epsilon z_\mu$, dark photon mili-couples to the electromagnetic current, $\epsilon z_\mu Q_i \overline{\psi}_i \gamma^\mu \psi_i$
- Dark matter could annihilate into dark photons
- Dark photon then decay into a pair of charged kinematically available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





Constraints on dark photons





- $m_A \gtrsim 100$ MeV allowed if the mixing parameter is small enough, typically $\epsilon < 10^{-3}$
- More parameter space soon probed by the APEX experiment in JLAB , Essig et al [1001.2557]

- For the rest of this talk, forget astrophysics motivation and ask the question 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 poorly studied signatures are predicted.
- OK, but how to produce many of those particles in colliders, given that the coupling is necessarily so small?
- Simplest possibility: from decay of weak scale particles that have large (strong, electroweak, ..) couplings to the SM
- That possibility almost automatically realized, when supersymmetry is present at the weak scale

Supersymmetric dark photon

- Supersymmetry is a natural extension that stabilizes the GeV scale
- Minimal framework based on hidden U(1), with dark photon z + dark bino $\tilde{b}$ + 2 dark higgs multiplets $h_{u,d}$ Cheung,Ruderman,Wang,Yavin [0902.3246]
- After electrodark symmetry breaking,
  - One massive dark photon z_μ,
  - Three dark neutralinos $\tilde{n}_d$, who are mixtures of the hidden bino and higgsinos,
  - Three dark scalars h_d, two CP-even h_d, H_d and one CP-odd A_d.
- Playing with soft and mu terms in the hidden sector, various mass patterns leading to various cascade decay chains can be obtained

How to produce hidden sector particles in colliders

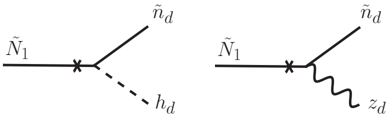
Portal from the MSSM to the hidden sector via bino

$$-i\epsilon\tilde{b}^{\dagger}\bar{\sigma}_{\mu}\partial_{\mu}\tilde{B} - i\epsilon\tilde{B}^{\dagger}\bar{\sigma}_{\mu}\partial_{\mu}\tilde{b}$$

- Induces dark bino shift $\tilde{b} \to \tilde{b} + \epsilon\tilde{B}$, that leads visible bino mili-coupling to hidden sector

$$\epsilon\sqrt{2}g_d\tilde{B}\left(h_u^{\dagger}\tilde{h}_u - h_d^{\dagger}\tilde{h}_d\right)$$

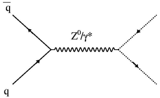
- Effects of bino mass mixing resulting from the shift are down by another m_z/m_Z and can be neglected
- The lightest SM superpartner is no longer stable but decays into hidden sector!



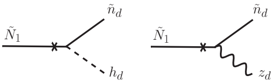
Every susy particle produced could lead to one more lepton jets

Into and out of hidden sector

- Collider processes produce the lightest SM superpartner $\tilde{N}_1$



- ...who decays into hidden sector



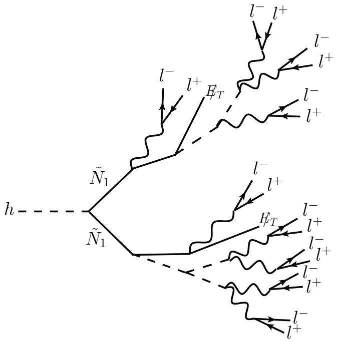
- Hidden cascade follows

- Dark photons decay to visible leptons; hidden neutralino carries off ET

Thus, the lightest "visible" neutralino decays into collimated leptons (lepton jets) plus missing energy, rather than pure missing energy as in the MSSM

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



Higgs decays to Neutralino

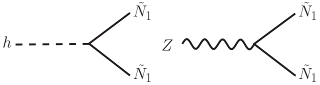
- In the MSSM the lightest Higgs boson can decay into neutralinos when $m_N < m_h/2$

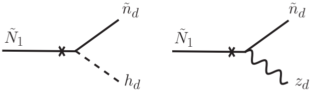
$$g_{h11}\, h \tilde{N}_1 \tilde{N}_1 + \mathrm{h.c.} \qquad g_{h11} = \frac{1}{2}\left(g c_W - g' c_B\right)\left(s_\gamma c_U - c_\gamma c_D\right)$$

$$H_u^0 = (s_\beta v + s_\gamma h + \ldots)/\sqrt{2},\; H_d^0 = (c_\beta v + c_\gamma h + \ldots)/\sqrt{2}$$

$$\Gamma(h \to \tilde{N}_1 \tilde{N}_1) \approx \frac{g_{h11}^2 m_h}{4\pi}$$

- A large branching fraction only when neutralino is *mixture* of bino/wino and higgsino
- A light neutralino has to be mostly bino to evade detection at LEP
- Branching fraction into neutralinos is above 75% when $c_{U,D} \gtrsim 1/5$
- That implies $BR(Z \to \tilde{N}_1 \tilde{N}_1) \sim 10^{-3} - 10^{-4}$, so that $m_{N1} < m_Z/2$ NOT excluded by Z width





Uncovering Higgs

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

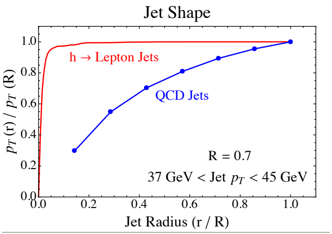
- Order 100 Higgs to lepton jets decay per experiment at LEP2
- Order 10000 Higgs to lepton jets decay per experiment at Tevatron and counting
- Order 1000 Higgs to lepton jets decay per experiment at the LHC and counting

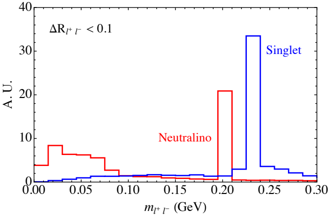
all waiting to be uncovered by a clever analysis...

Search strategies

Closely spaced leptons do not satisfy usual isolation criteria and will not reconstruct as leptons. Still 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
- Large ECAL/HCAL for electron jets





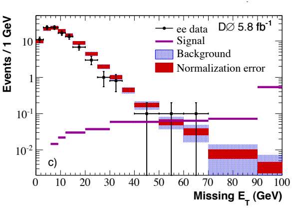
Published Searches

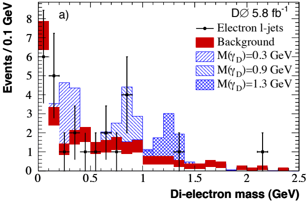
- Search for a dark photon produced in association with a photon at Tevatron's D0, D0 [0905.1478] (sensitive to certain susy models with gauge mediation, not discussed here)
- LJ + Missing Energy search at Tevatron's D0, D0 [1008.3356] (sensitive to a wide class of lepton jets)

D0 Lepton Jet Search with 5.8 fb-1

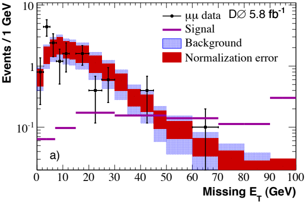
- Seed track of $p_T > 10$ GeV matching to EM cluster or to hits in outer muon system
- At least one companion track of pT > 4 GeV within $\Delta R \leq 0.2$ of the seed
- Isolation in the $0.2 < \Delta R < 0.4$ annulus around the seed
- Require two such LJ candidates separated by $\Delta R > 0.8$
-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

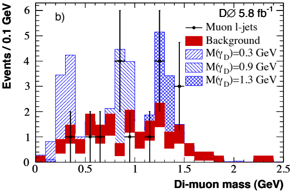
Electron channel





Muon channel





Constraints on H $\to$ 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

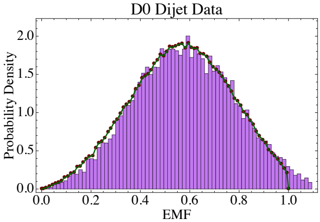
Another idea

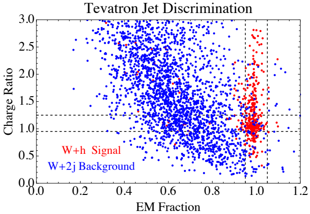
AA,Ruderman,Volansky,Zupan [1007.3496] : using electromagnetic fraction (EMF) and charge ratio (CR) to target electron LJs

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

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 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

Calorimeter simulation

- 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

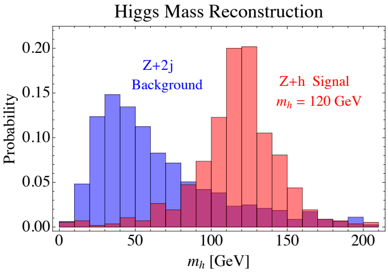
Analysis and Cuts

- 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.

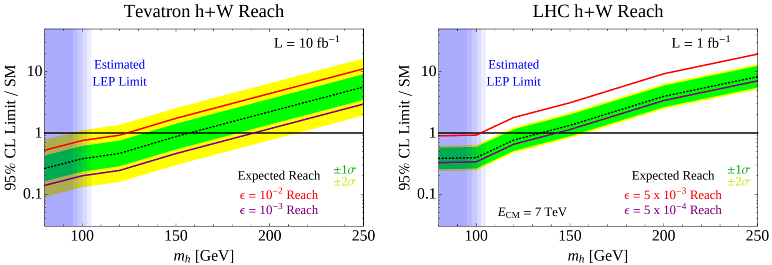
Results

$m_h = 120$ GeV		$W+h$ Signal(Eff.)	$W+h$ Bckg	$Z+h$ Signal(Eff.)	$Z+h$ Bckg
Tevatron (10 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 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
95% CL Limit / SM
10
1
0.1
100
150
200
250
m_h [GeV]
Expected Reach
±1σ
±2σ
ϵ = 10^{-2} Reach
ϵ = 10^{-3} Reach
LHC h+W Reach
L = 1 fb^{-1}
Estimated
LEP Limit
95% CL Limit / SM
10
1
0.1
E_{CM} = 7 TeV
100
150
200
250
m_h [GeV]
Expected Reach
±1σ
±2σ
ϵ = 5 x 10^{-3} Reach
ϵ = 5 x 10^{-4} Reach

To do before the LHC data come

- Purely muonic lepton jets (no ECAL to HCAL handle, but should be piece of cake for experimentalists)
- Purely pionic lepton jets ???
- Lepton jets with displaced vertices

Ongoing experimental efforts

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

Last Words

- 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