Lepton jets in hadron colliders

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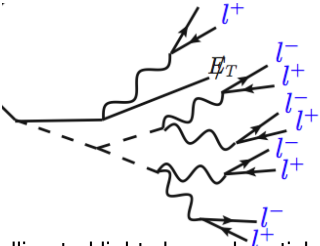
CERN, le 1 Septembre 2011

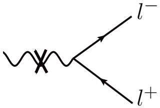
Who are lepton jets?



- 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
- 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.
- 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 (the hidden valley, Strassler,Zurke [hep-ph/0604261] ,Han et al [0712.2041])

Dark matter via the hypercharge portal

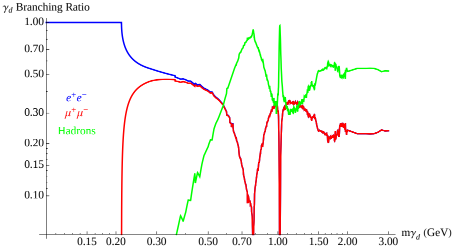
- One way to explain PAMELA is to introduce "dark photon" z_μ that mixes with hypercharge, Arkani-Hamed et al [0810.0713] , Holdom [1985]



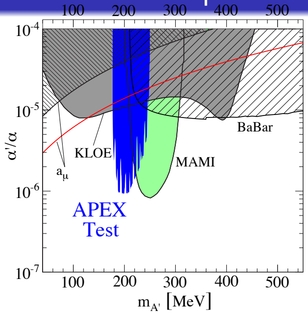
$$\mathcal{L} \sim -(\gamma^d_{\mu\nu})^2 + m^2_{\gamma_d}(\gamma^d_\mu)^2 + \epsilon\gamma^d_{\mu\nu}B_{\mu\nu} \qquad \epsilon \leq 10^{-3}$$

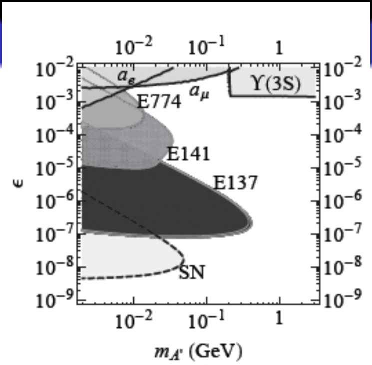
After field redefinition, $A_\mu \to A_\mu + \epsilon z_\mu$, dark photon mili-couples to the electromagnetic current, $\epsilon z_\mu Q_i \overline{\psi}_i \gamma^\mu \psi_i$

- 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

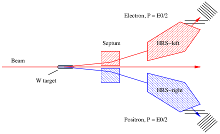


Constraints on dark photons





- Limits from e+e- colliders, $(g-2)_{\mu,e}$, beam dump, and supernovae, see Bjorken et al [0906.0580] for review
- $m_A \gtrsim 100$ MeV allowed if mixing small enough, typically $\epsilon < 10^{-3}$
- More parameter space currently probed by APEX in JLAB, Abrahamyan et al [1108.2750], and by A1 in MaMi Merkel et al [1101.4091]



- 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`

How to produce hidden sector particles in colliders

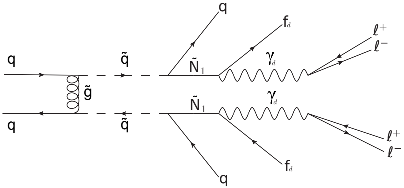
One possibility: from the MSSM to the hidden sector via the bino portal
Baumgart et al [0901.0283]

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

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

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

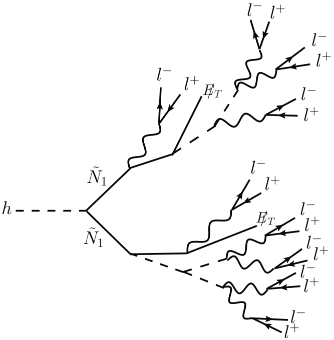
- Effects of bino mass mixing resulting from the shift are down by another m_{γ_d}/m_Z and can be neglected
- Lightest SM superpartner no longer stable but decays into hidden sector!



Every susy particle produced could lead to one more lepton jets

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

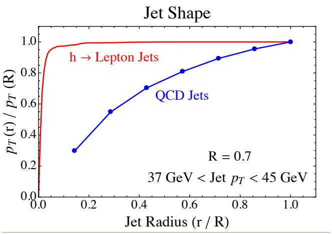


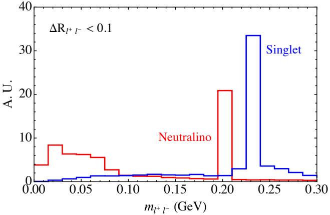
Higgs portal is another possible efficient source of LJs at the Tevatron and the LHC

Search strategies

Spectacular and relatively easy signatures, but new methods/IDs needed to discover LJs at colliders. Some handles (model dependent):

- Soft lepton multiplicity
- Jet shapes (lepton jets more narrow than QCD jets)
- Invariant mass peaks for close lepton pairs
- Missing energy from escaping hidden sector particles
- Large ECAL/HCAL for electron jets





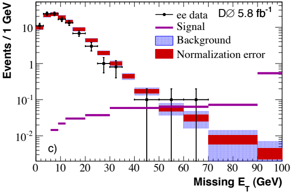
Existing searches

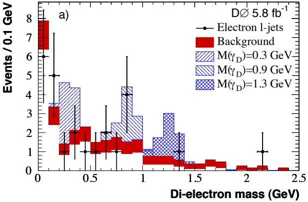
- LJ + MET search in D0, D0 [1008.3356] , see also D0 [0905.1478]
  - Targets narrowness, MET, and resonances
- CDF search for V+ H to LJs, S.Wilbur talk at Boost'11
  - Targets soft lepton multiplicity
- CMS search for LJs, CMS [1106.2375]
  - Targets dimuon resonances inside LJs
- ATLAS search for LJs, ATLAS-CONF-2011-076
  - Targets narrowness of LJs

D0 Lepton Jet Search

LJ + MET search at D0 with 5.8 fb-1, D0 [1008.3356] ,

- 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
- Most events pass single- or di-lepton trigger
- Isolation in the $0.2 < \Delta R < 0.4$ annulus around the seed
- Require two such LJ candidates separated by $\Delta R > 0.8$
- For $H \to LJs$. we estimate D0 puts a constraint on the Higgs mass up to $\lesssim 150$ GeV in a subclass of models producing narrow LJs with a small multiplicity of leptons

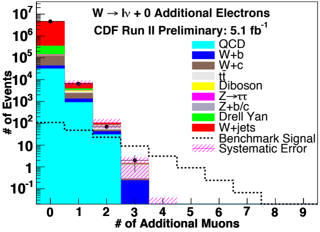


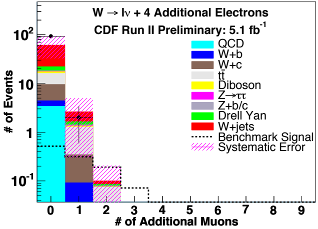


CDF Lepton Jet Search

W/Z + Higgs to LJs search at CDF with 5.1 fb-1

- Trigger on W/Z associated with the Higgs
- Identifies leptons with pT down to 1 GeV for electrons, 3 GeV for muons
- Good sensitivity to muons, worse to electrons due to photon conversion background
- For a benchmark with $m_{\gamma_D} = 0.3$ MeV the constraint $\sigma(p\bar{p} \to VH)\mathrm{Br}(H \to LJ) < 0.06\sigma(p\bar{p} \to VH)_{SM}$

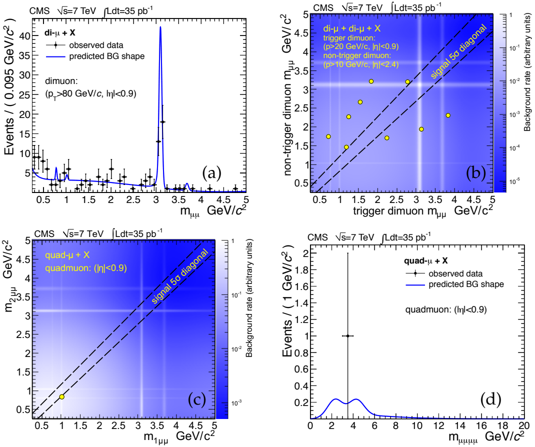




CMS Lepton Jet Search

CMS LJ search with 35 pb-1

- Triggers on a muon with $p_T > 15$ GeV and looks for additional muons with $p_T > 5$ GeV
- Clusters oppositely charged muons with $m_{\mu+\mu-} < 9$ GeV into jets
- Looks for coincident $m_{\mu+\mu-}$ in one event



ATLAS Lepton Jet Search

ATLAS LJ search with 35 pb-1

- Triggers on dimuons with $p_T > 6$ GeV
- Iteratively clusters muons within $\Delta R < 0.1$
- Demands at least 4 muons in at least 2 isolated LJs

	≥ 2 muon	≥ 4 muons	≥ 4 muons w/ ≥ 3 HQ	2 LJets	2 Isolated LJets
data	174450	246	84	3	0
all bkg	200000 ± 15000	200 ± 50	81 ± 20	1.74 ± 0.48	0.20 ± 0.19
QCD	160000 ± 14000	188 ± 50	73 ± 20	1.46 ± 0.42	0.19 ± 0.19
Υ	2100 ± 120	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
J/Ψ	22100 ± 3700	3.4 ± 1.9	0.95 ± 0.43	0.24 ± 0.23	0.00 ± 0.00
W+Jet	332 ± 11	0.40 ± 0.40	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Z+Jet	14420 ± 42	2.00 ± 0.50	1.37 ± 0.41	0.00 ± 0.00	0.00 ± 0.00
$t\bar{t}$	357 ± 1.4	4.31 ± 0.16	3.47 ± 0.14	0.041 ± 0.016	0.012 ± 0.008
Diboson	16.577 ± 0.070	1.640 ± 0.013	1.557 ± 0.013	0.00033 ± 0.00019	0.00033 ± 0.00019
Squark Signal Samples					
$\alpha_d = 0.0$, $m_a = 300$	8.26 ± 0.27	3.52 ± 0.18	2.38 ± 0.15	1.76 ± 0.12	1.38 ± 0.11
$\alpha_d = 0.0$, $m_a = 500$	6.90 ± 0.25	2.62 ± 0.15	1.87 ± 0.13	1.35 ± 0.11	1.04 ± 0.10
$\alpha_d = 0.1$, $m_a = 300$	15.16 ± 0.37	9.14 ± 0.28	7.58 ± 0.26	4.77 ± 0.21	2.90 ± 0.16
$\alpha_d = 0.1$, $m_a = 500$	15.97 ± 0.38	8.38 ± 0.27	6.99 ± 0.25	4.08 ± 0.19	2.33 ± 0.14
$\alpha_d = 0.3$, $m_a = 300$	9.60 ± 0.38	6.89 ± 0.32	5.99 ± 0.30	3.28 ± 0.22	1.25 ± 0.14
$\alpha_d = 0.3$, $m_a = 500$	11.75 ± 0.32	7.88 ± 0.26	7.01 ± 0.25	3.29 ± 0.17	1.11 ± 0.10

LJs: the story so far

- Several classes of LJ models targeted
- For models predicting narrow lepton jets, or LJs with dimuon resonances, or LJs with high multiplicity of muons, the LHC cross section constrained to be less than $\sim 0.1 - 0.5$ pb
- Purely electron LJs less constrained, unless accompanied by large missing energy

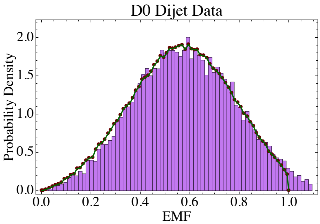
Another idea

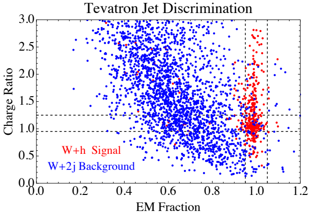
AA,Ruderman,Volansky,Zupan [1007.3496] : using electromagnetic fraction (EMF) and charge ratio (CR) to target electron LJs

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

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

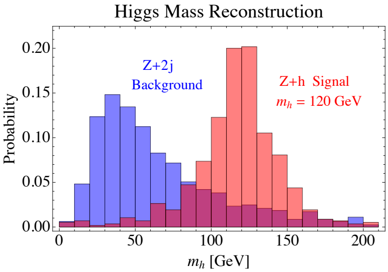
Analysis and Cuts

- 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.

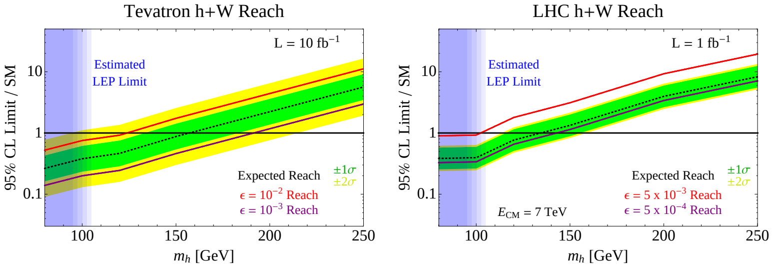
Results

$m_h = 120$ 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

- Experimental searches for purely electron lepton jets
- Largely hadronic lepton jets (may occur e.g for dark photon mass close to ρ resonance). Hopeless?
- Lepton jets with displaced vertices

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
- Searching for electron lepton jets using EMF and CR gives a good sensitivity to a wide class of models with lepton jets.