Lepton Jets

Itay Yavin

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M. Baumgart, C. Cheung, J. T. Ruderman, L. T. Wang and I. Y. 0901.0283 [hep-ph]

C. Cheung, J. T. Ruderman, L. T. Wang and I. Y. 0902.3246[hep-ph]

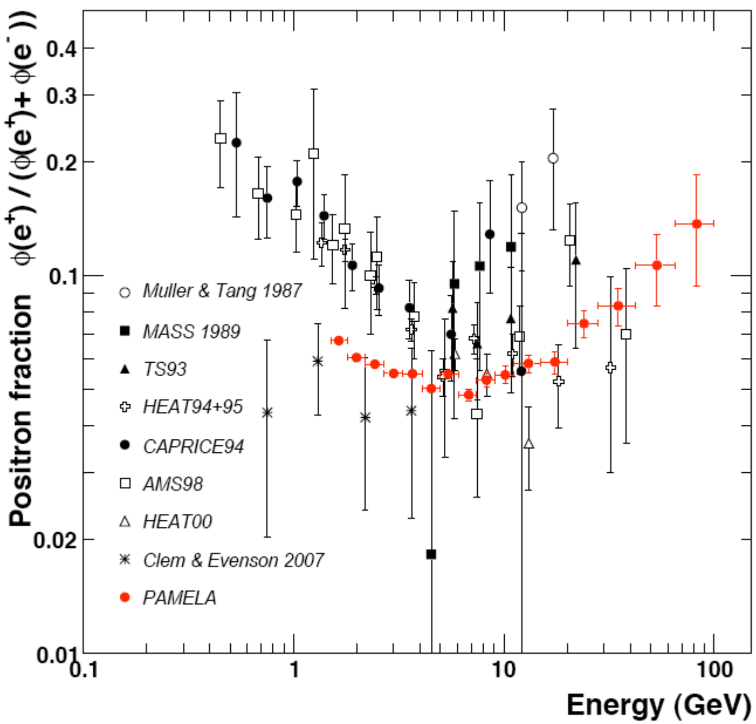
C. Cheung, J. T. Ruderman, L. T. Wang and I. Y. tomorrow and tomorrow and tomorrow, creeps in this petty pace…

Contents

- Motivation
  - New observations may be interpreted as an extended dark sector.
  - A light (~ GeV) sector weakly coupled to the SM.
- Production of Dark States
  - Different operators that couple the SM to the DS.
  - Survey of channels at high energy colliders.
- Lepton Jets
  - What are lepton jets - qualitative definition and examples.
  - Searching for lepton jets - quantitative definition . . .

Part I

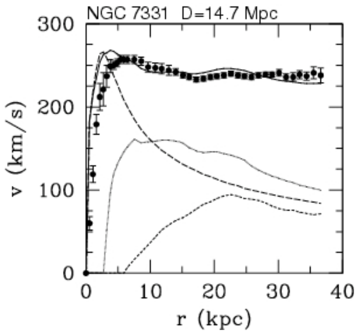
A Light Dark Sector



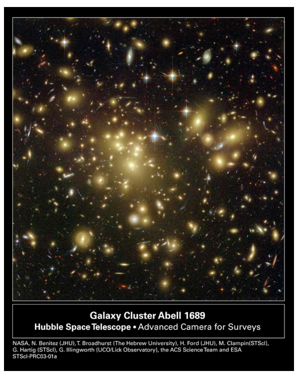
Dark Matter

Dark Matter

Rotation curves



Lensing Effect



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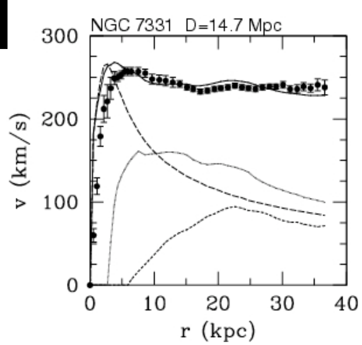
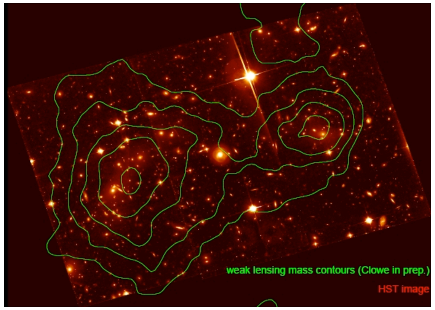


Bullet Cluster



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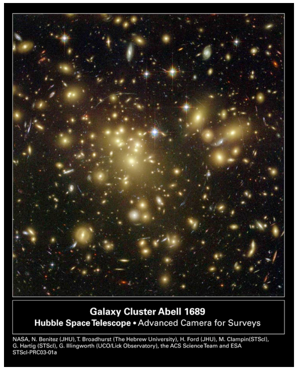

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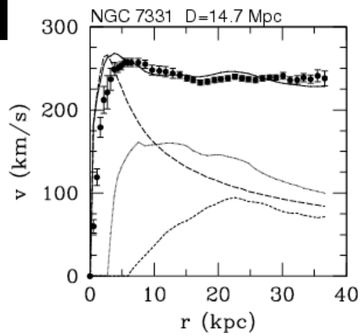
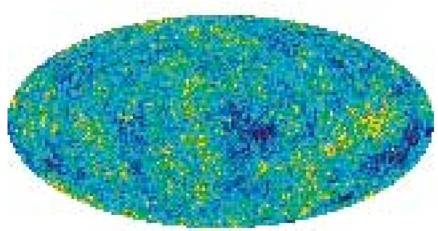


WMAP



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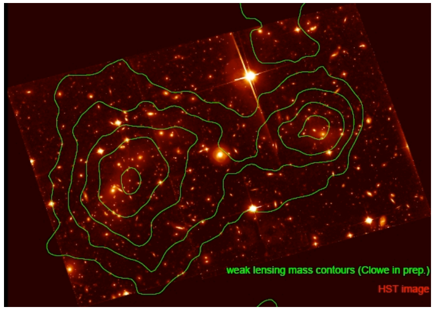

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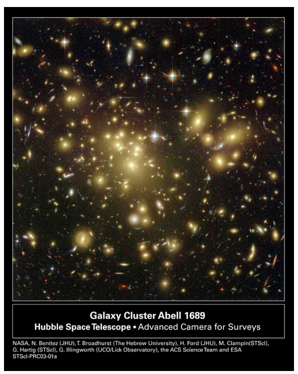
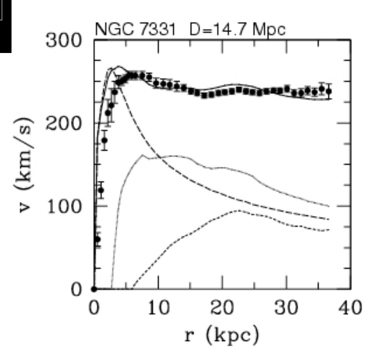


Rotation curves



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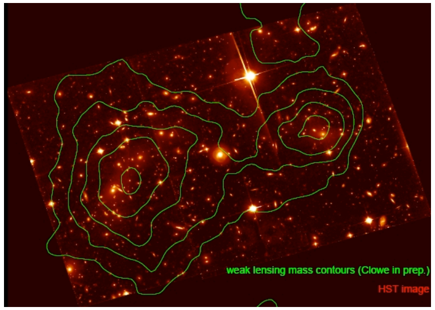

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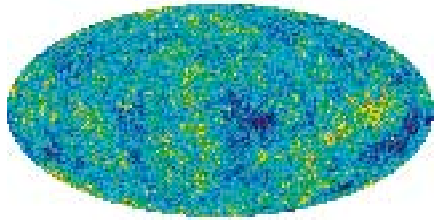
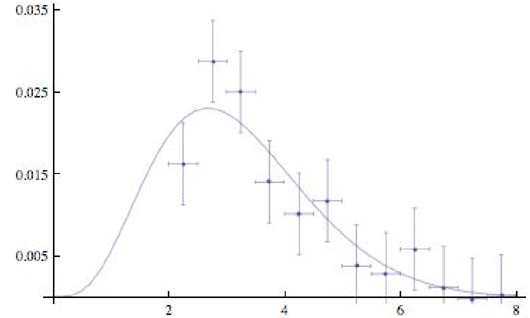


Direct Detection



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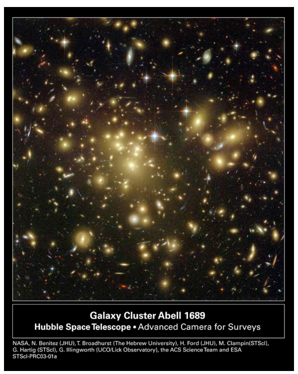

Dark Matter

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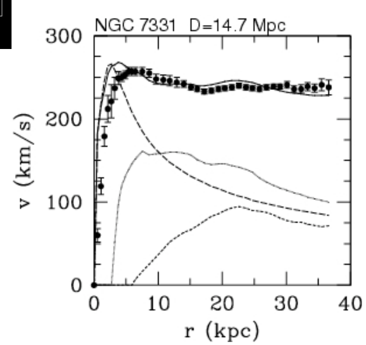
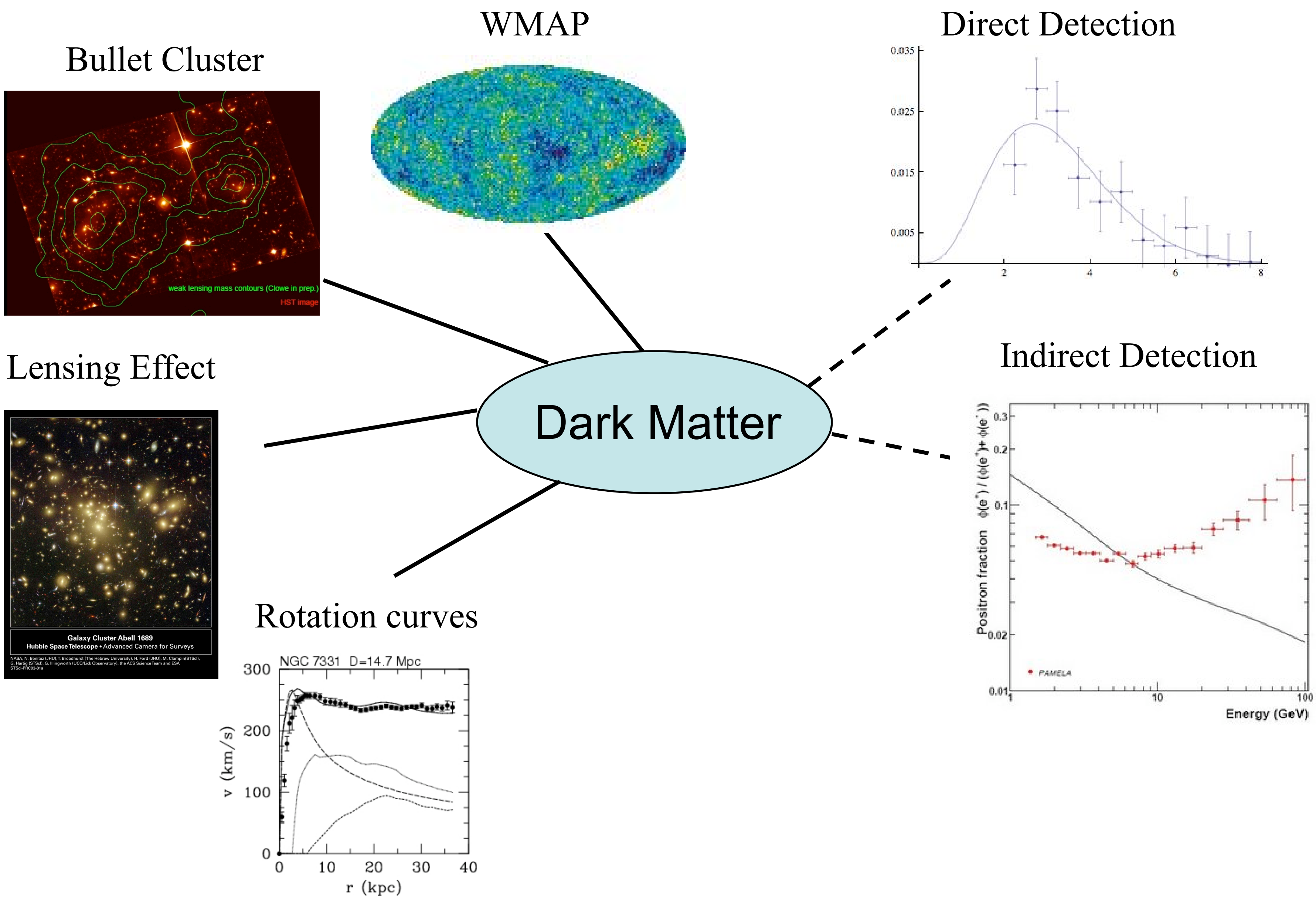
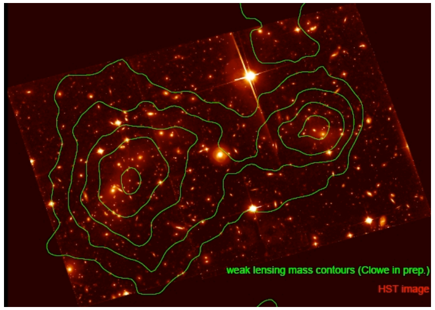




WMAP
Direct Detection
Bullet Cluster
weak lensing mass contours (Clowe in prep.)
HST image
Lensing Effect
Dark Matter
Indirect Detection
Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys
Rotation curves
NGC 7331 D=14.7 Mpc
v (km/s)
r (kpc)
Positron fraction φ(e+) / (φ(e+)+ φ(e-))
PAMELA
Energy (GeV)

Bullet Cluster



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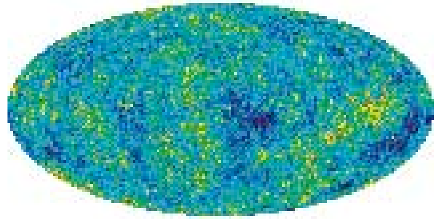

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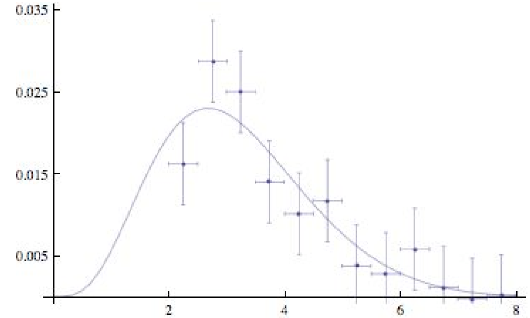

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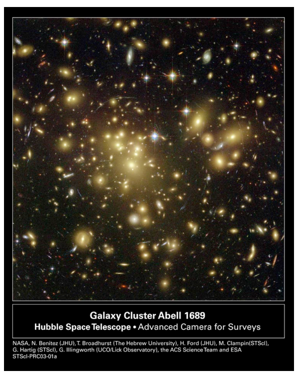
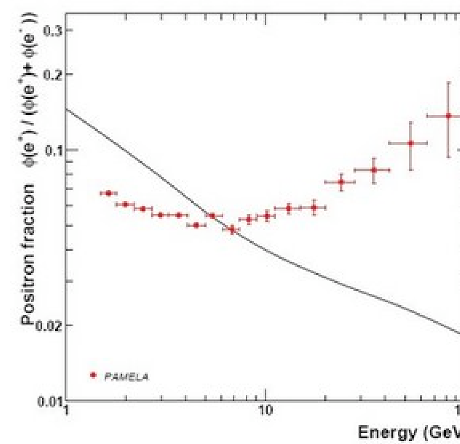
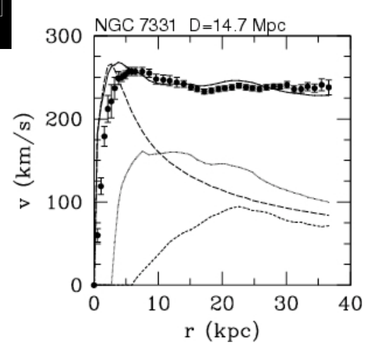


Dark Matter

Indirect Detection



Rotation curves



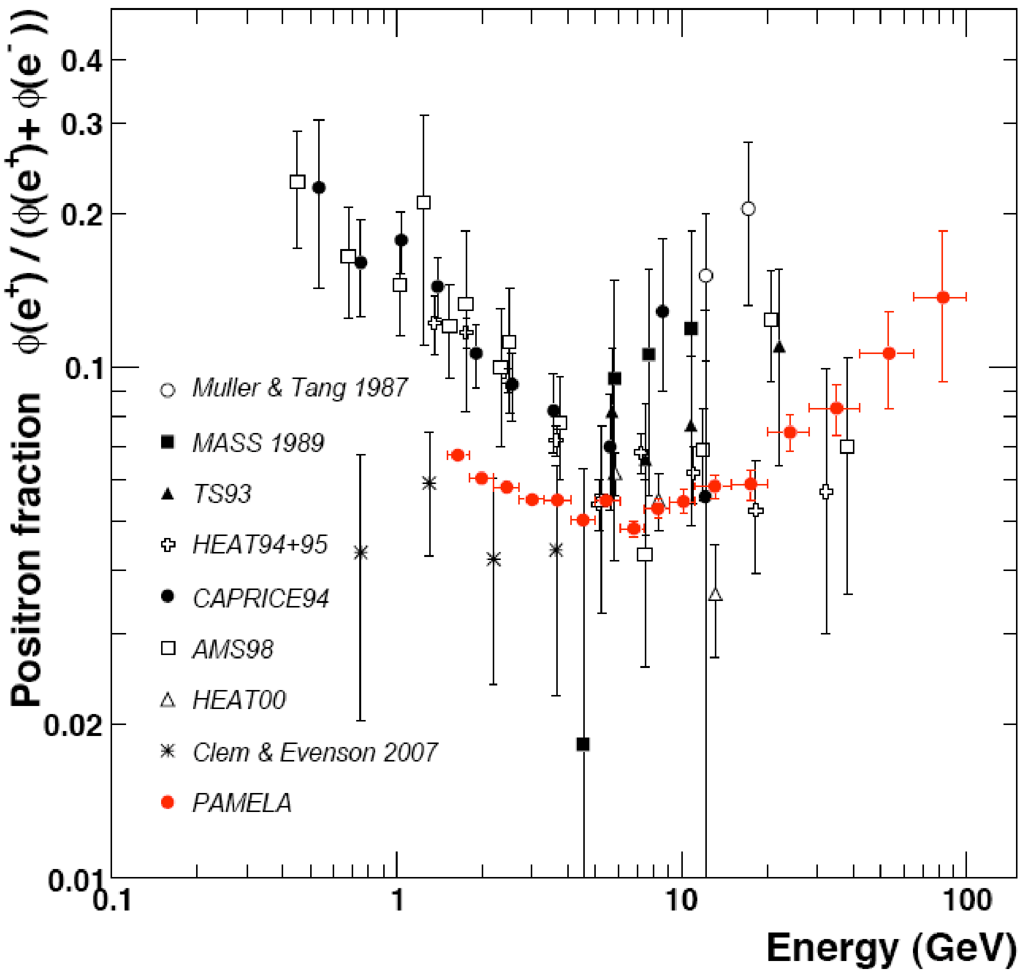
Direct Production

???

Indirect Detection

PAMELA

In Oct. 2008, the Payload for Anti-Matter Exploration and Light-nuclei Astrophysics reported a sharp raise in the positron content of cosmic rays from 10-50 GeV.



1) No anti-protons excess observed!!!

2) Very sharp rise.

3) Demands a large ann. Cross-section

Similar results have been seen by ATIC and FERMI, extending to higher energies.

Dark Matter Interactions

Arkani-Hamed, Finkbeiner, Slatyer, and Weiner (0810.0713) suggested a heavy relic (~ TeV) which couples to a new abelian gauge-group,

$$\mathcal{L}_{\rm SM} = \ldots$$

http://pdg.lbl.gov

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$$\mathcal{L}_{\rm DS} \supset i\bar{\chi}\gamma^{\mu}D_{\mu}\chi + M\bar{\chi}\chi - \frac{1}{4}f_{\mu\nu}f^{\mu\nu} + \frac{1}{2}m^2 b_{\mu}b^{\mu} + |D_{\mu}h_i|^2 - V(h_i)$$

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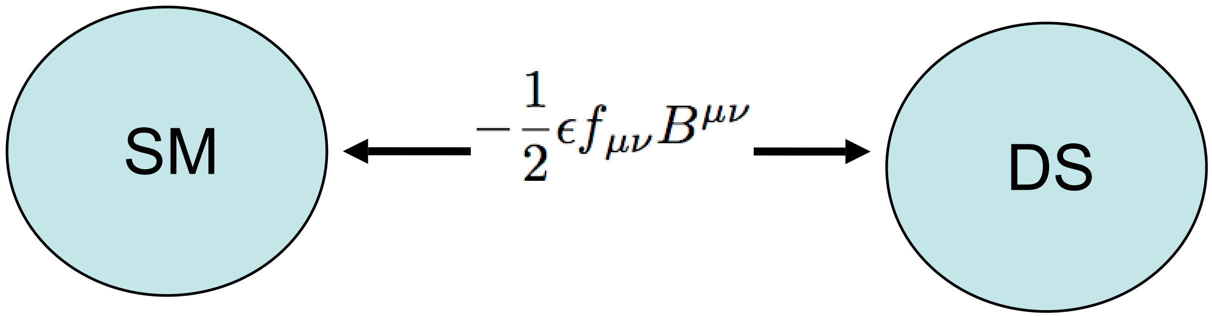

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Dark Spectrum

TeV

$M_{\bar{\chi}\chi}$

Dark Spectrum

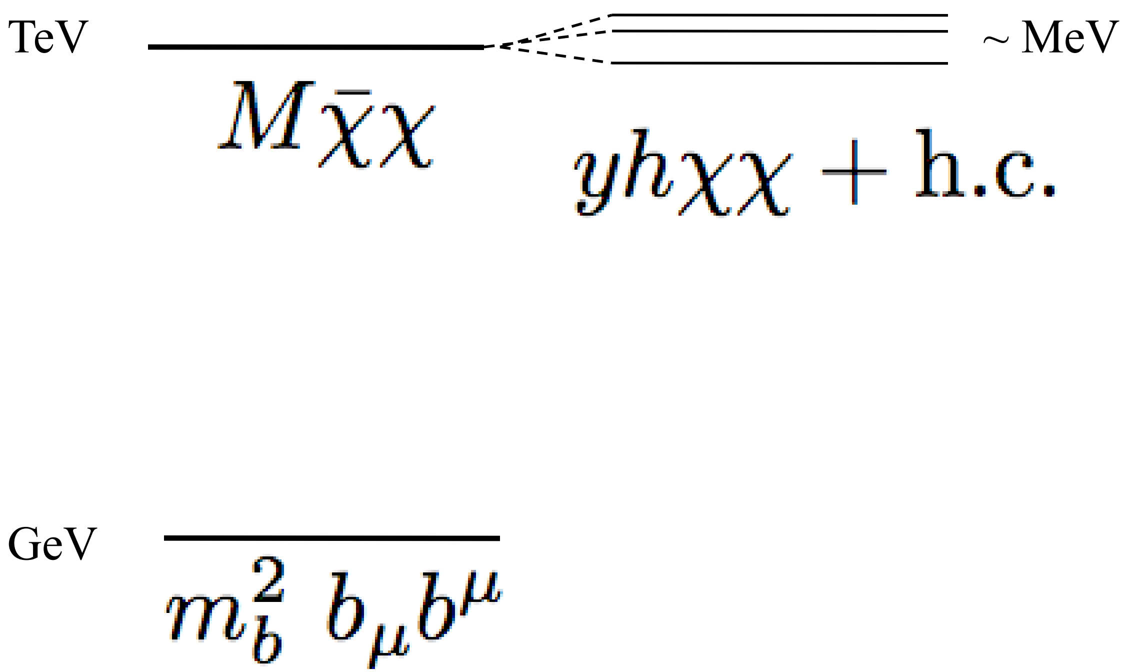
TeV

$$M\bar{\chi}\chi$$

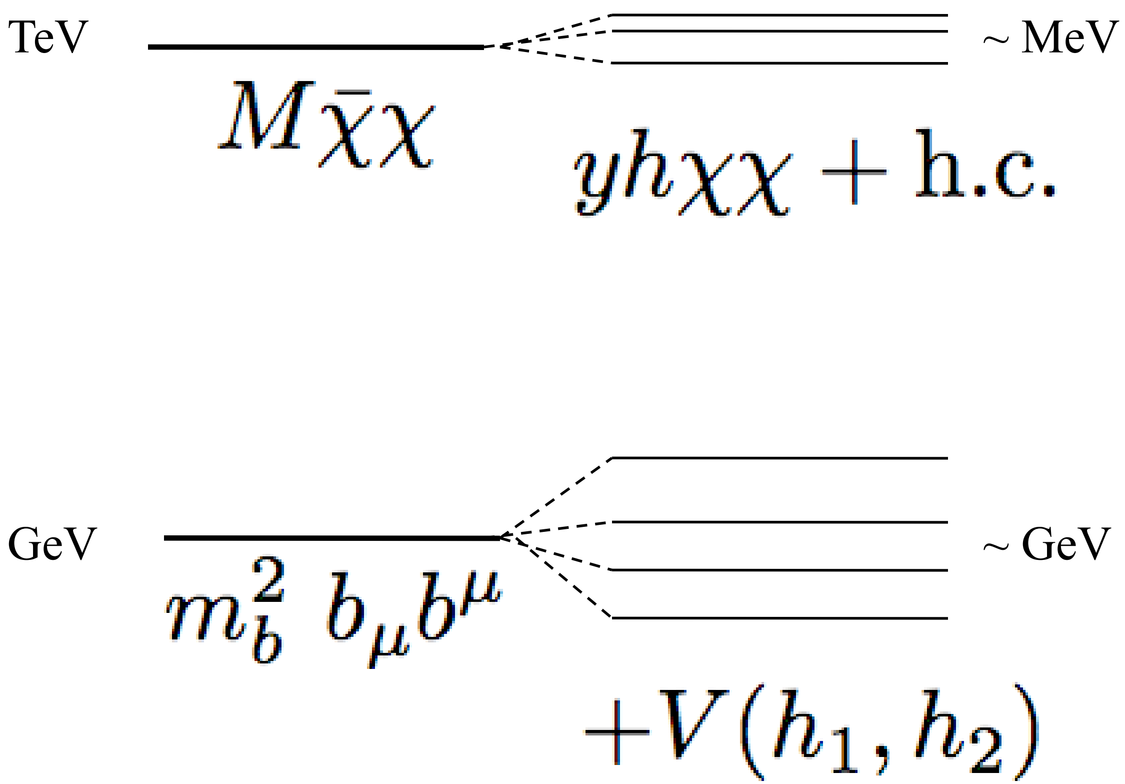
GeV

$$m_b^2\ b_\mu b^\mu$$

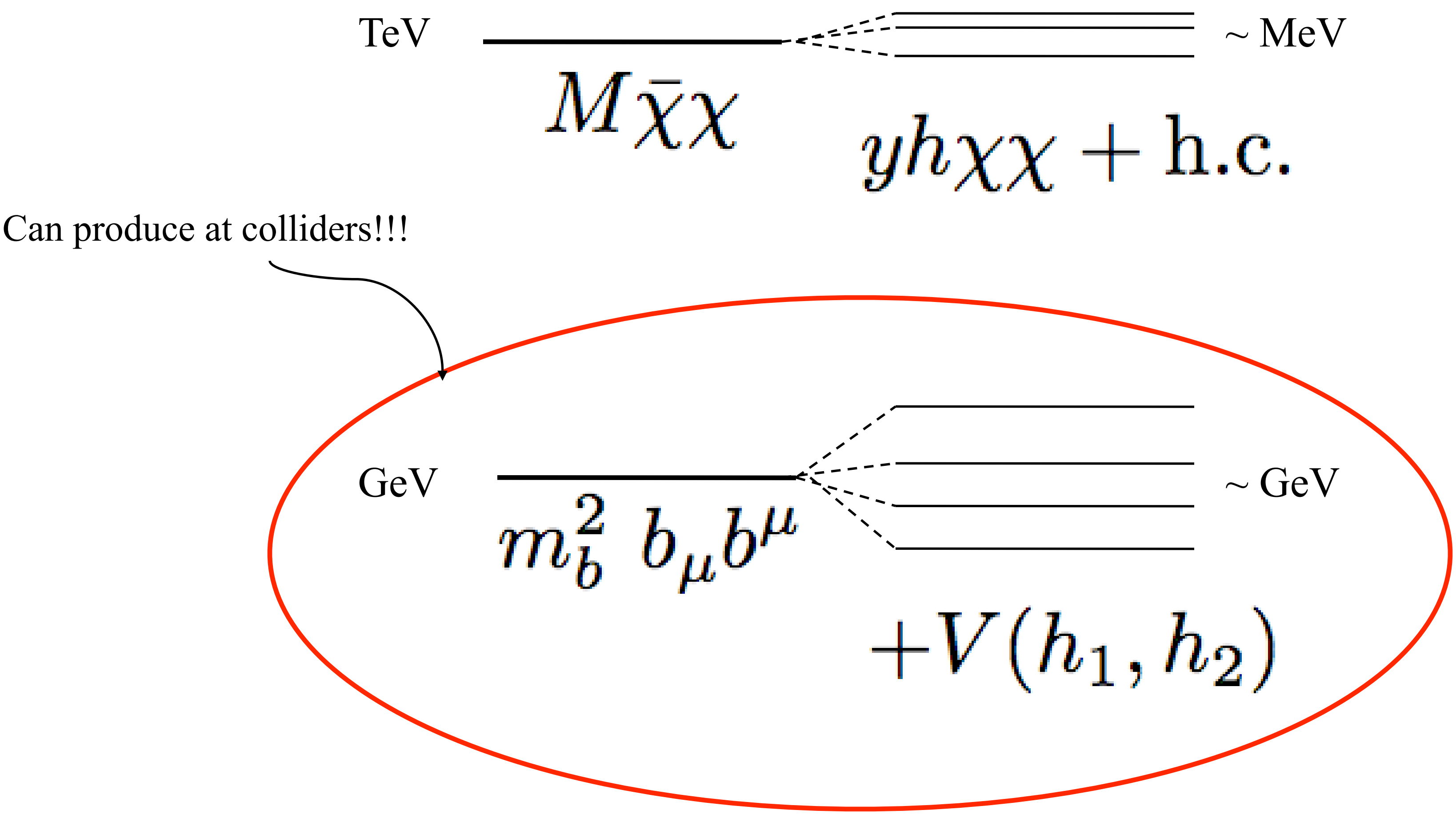
Dark Spectrum



Dark Spectrum

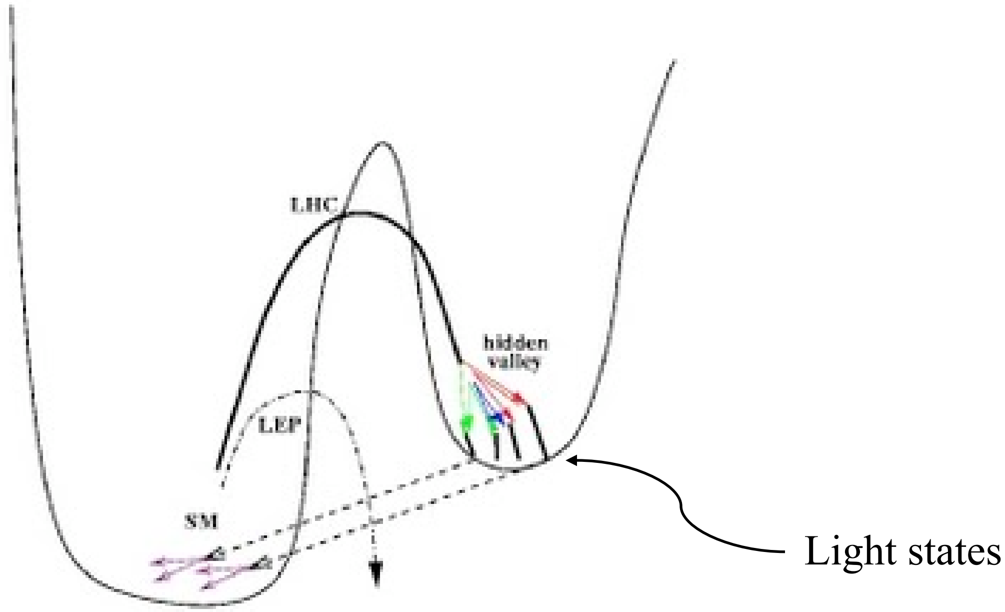


Dark Spectrum



Hidden Valleys

Strassler and Zurek's proposal of hidden valleys share some of the phenomenology and Lepton Jet searches can in principle be sensitive to these type of models as well,



* Taken from Strassler's talk.

Coupling to the Standard Model

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In general the dark gauge-boson can mix with both the photon and the Z^0,

$$\begin{aligned}\mathcal{L}_{\text{gauge mix}} &= -\frac{1}{2}\epsilon_1 b_{\mu\nu} A^{\mu\nu} - \frac{1}{2}\epsilon_2 b_{\mu\nu} Z^{\mu\nu} \\ &= -\frac{1}{2}\epsilon_1' b_{\mu\nu} B^{\mu\nu} - \frac{1}{2}\epsilon_2' b_{\mu\nu} W_3^{\mu\nu}\end{aligned}$$

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If supersymmetry is only softly broken in the dark sector, then there is also an important mixing of the electroweak gauginos with the dark gaugino:

$$\mathcal{L}_{\text{gaugino mix}} = -2i\epsilon_1' \tilde{b}^\dagger \bar{\sigma}^\mu \partial_\mu \tilde{B} - 2i\epsilon_2' \tilde{b}^\dagger \bar{\sigma}^\mu \partial_\mu \tilde{W}_3 + \text{h.c.}$$

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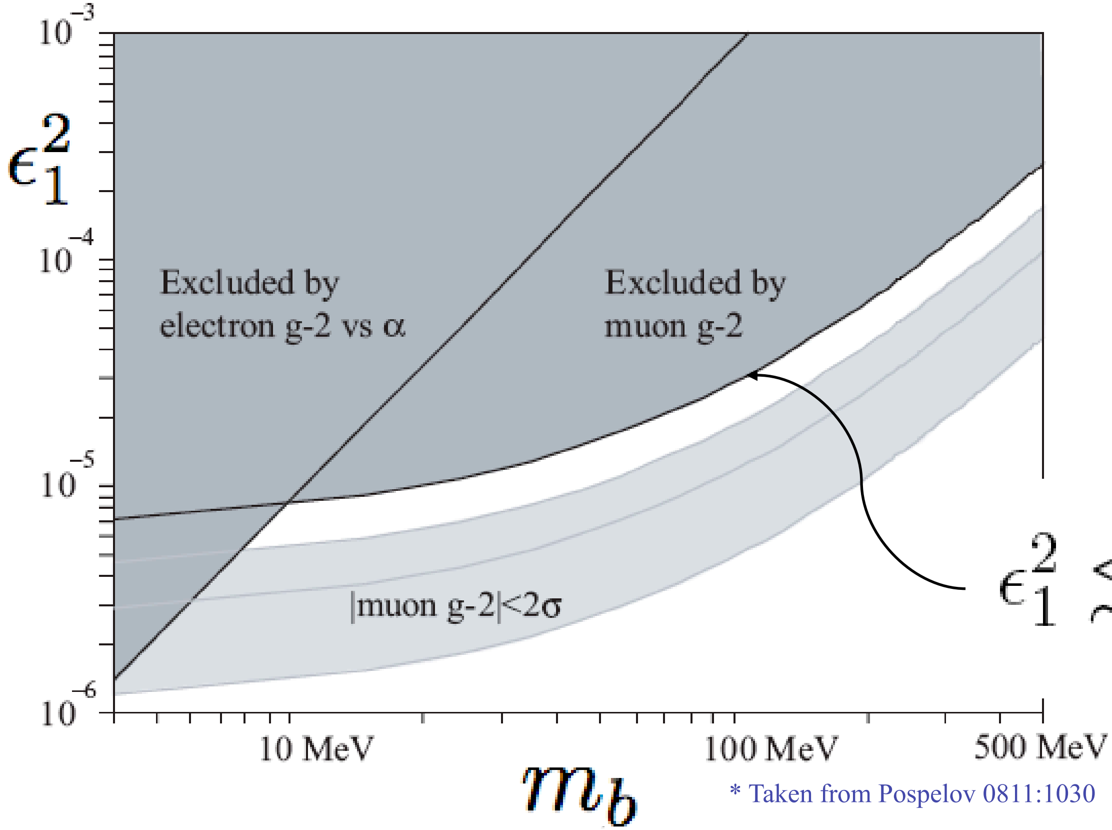
All in all we have the following couplings (after diagonalization and etc.), which act as a portal to the dark sector

$$\mathcal{L}_{\text{portal}} = \epsilon_1 b_\mu J^\mu_{\text{EM}} + \epsilon_2 Z_\mu J_b + \epsilon'_1\tilde{B}\tilde{J}_{\tilde{b}} + \epsilon'_2\tilde{W}_3\tilde{J}_{\tilde{b}}$$

Limits on Kinetic Mixing

The kinetic mixing with the photon is bounded by low energy experiments, in particular the muonic g-2 ratio (Pospelov 0811:1030):



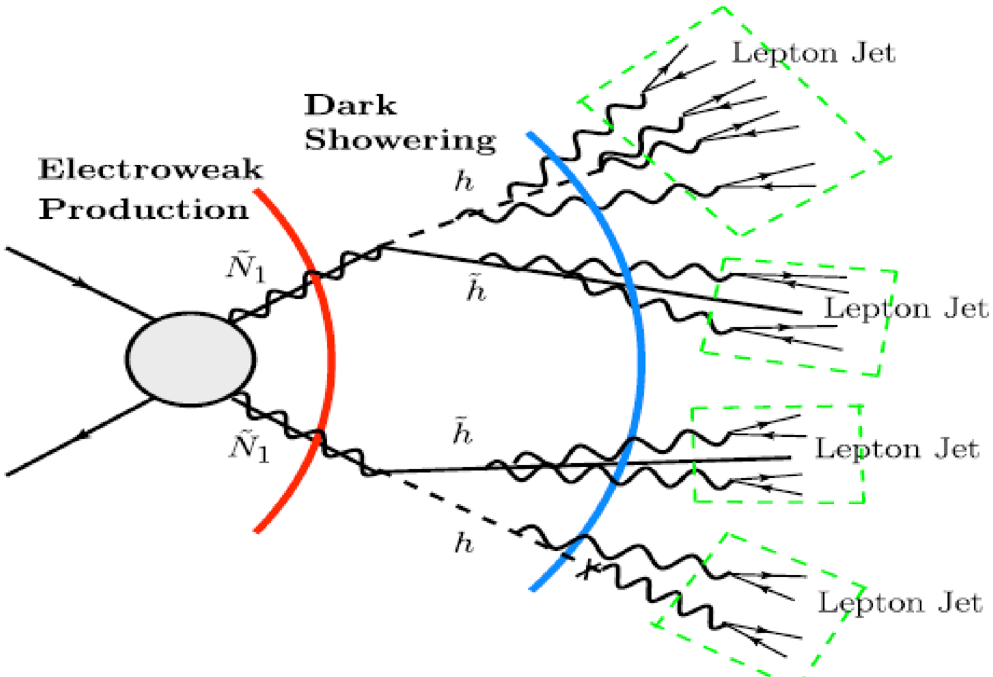
$$\epsilon_1^2 \lesssim 3 \times 10^{-5} \frac{m_b}{100\ \mathrm{MeV}}$$

* Taken from Pospelov 0811:1030

Notice that this measurement does not bound ϵ_2

Part II

Production and Evolution of Dark States



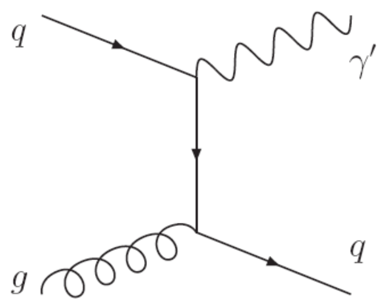
Origin of a Species

Production:

Origin of a Species

Production:

Prompt Dark Photon



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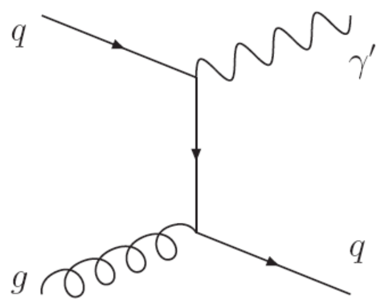
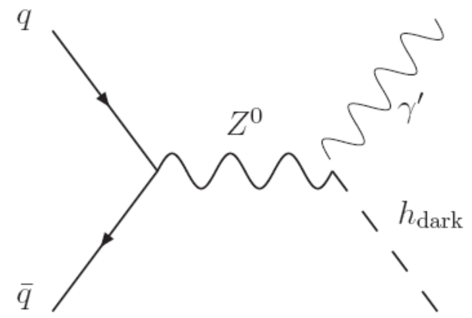


Rare Z^0 decays



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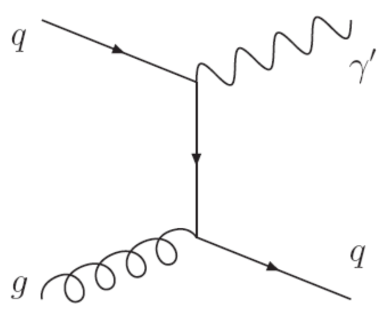

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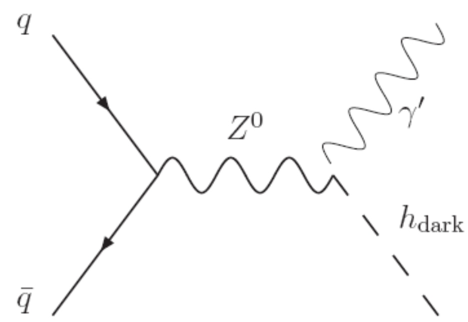
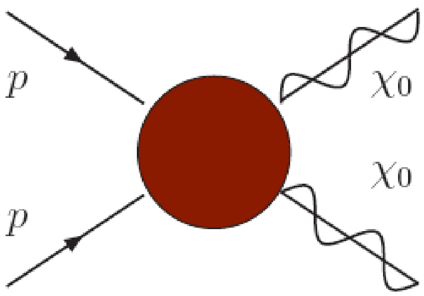


Gaugino Pair Prod



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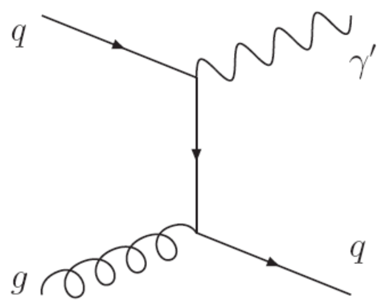

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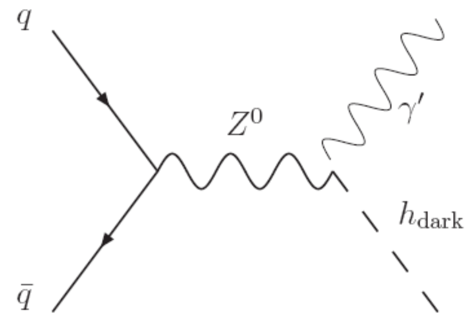

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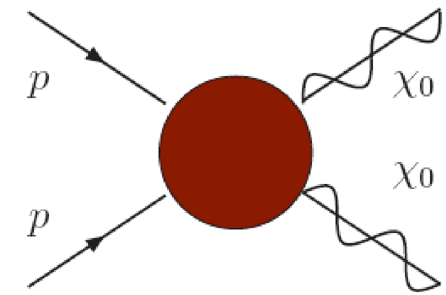


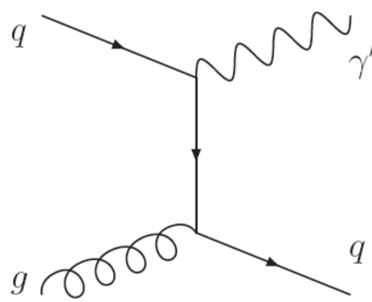
Evolution:

Dark Radiation

Origin of a Species

Production:

Prompt Dark Photon



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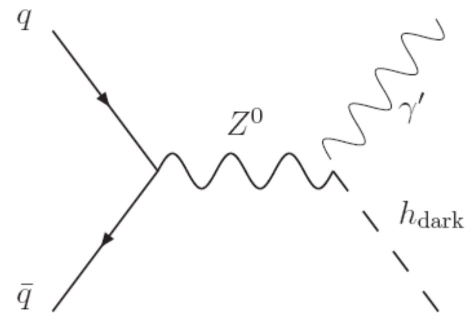

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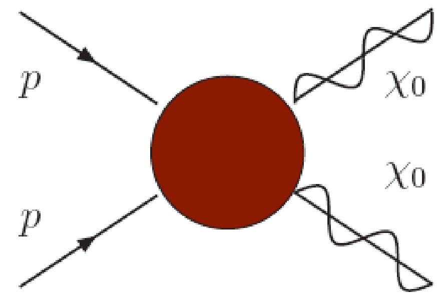
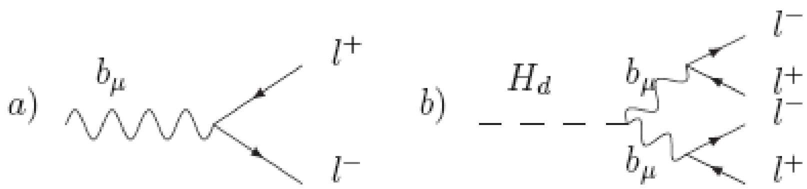


Evolution:

Dark Radiation

Dark Cascades and Lepton Jets



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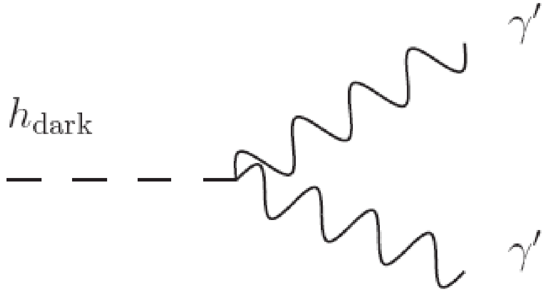

The dark higgs is unstable, but it's decay width depends on its mass relative to the dark photon!

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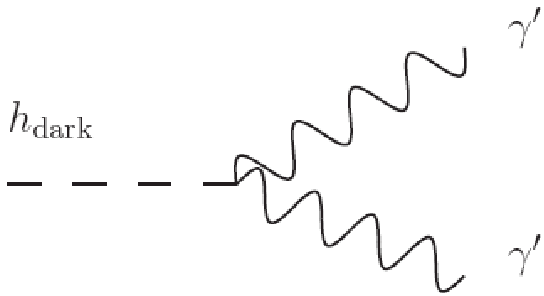

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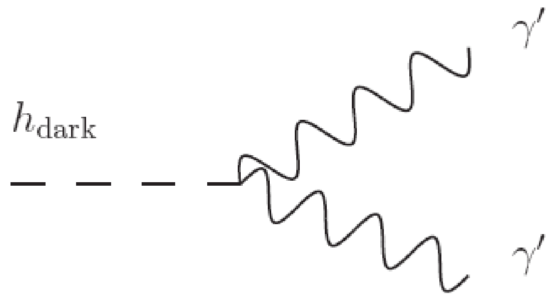

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Prompt decay
(Many leptons)

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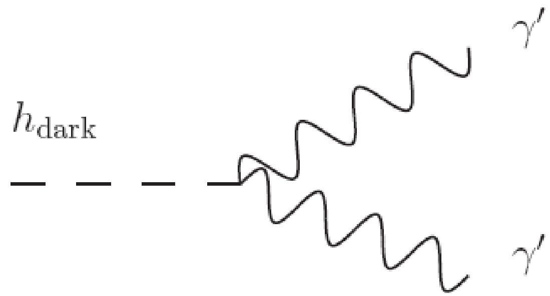

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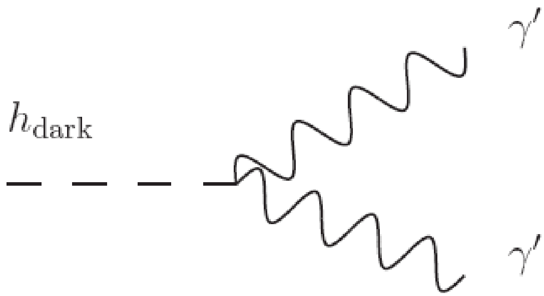

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Dark Radiation

Since the dark state are extremely boosted, they will radiate dark gauge-bosons,

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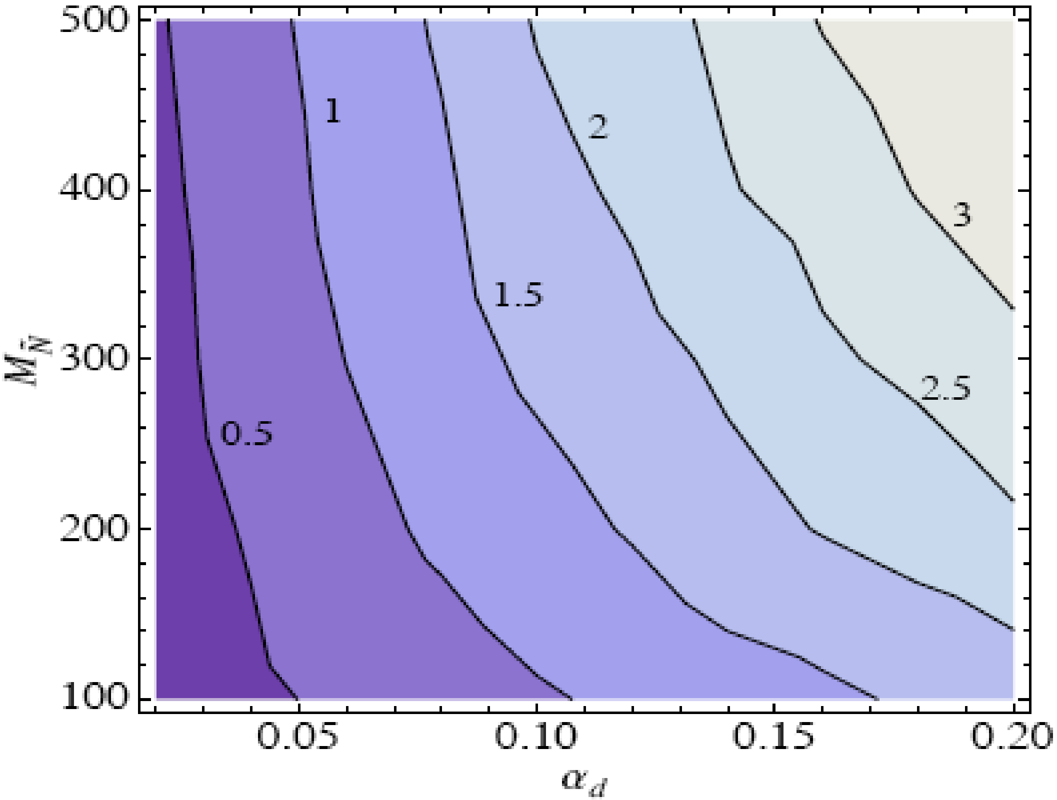

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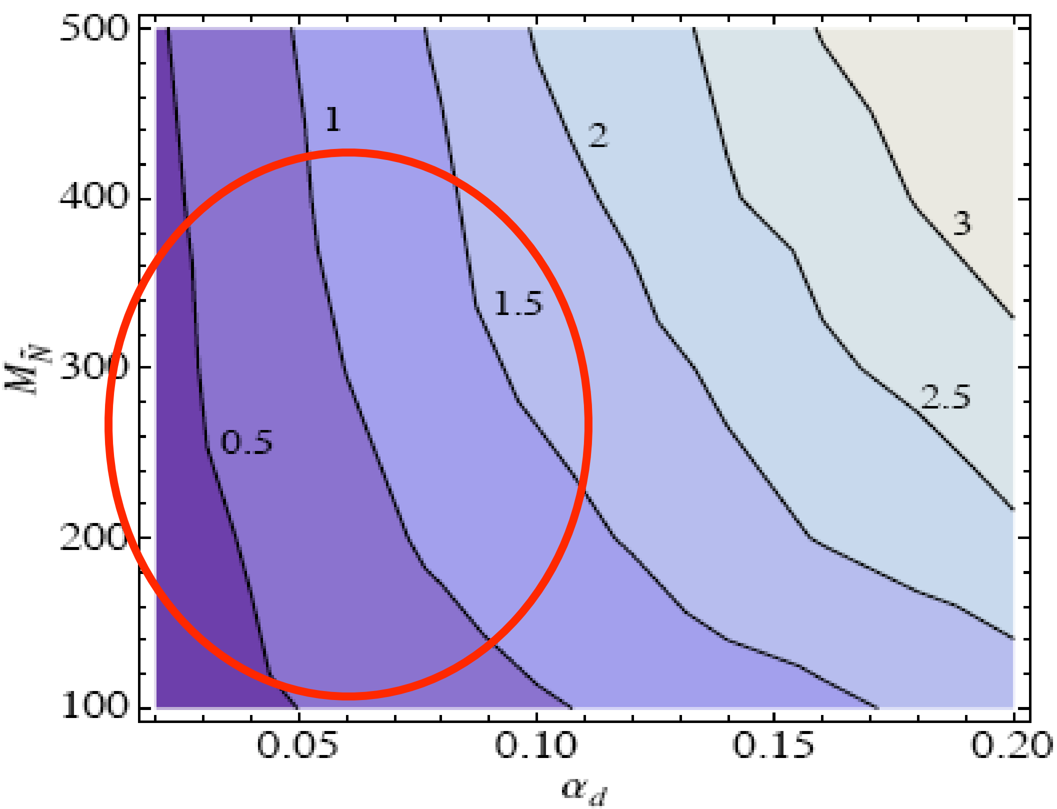

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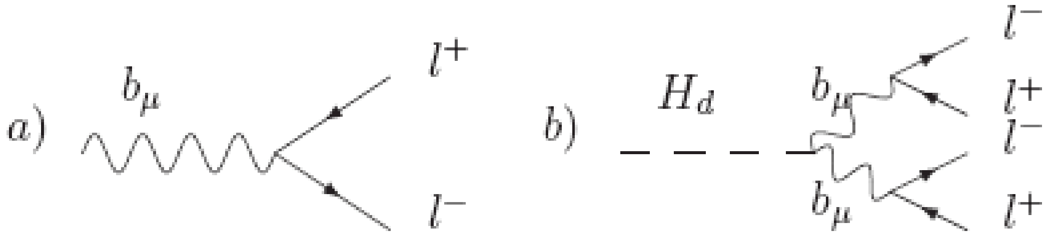

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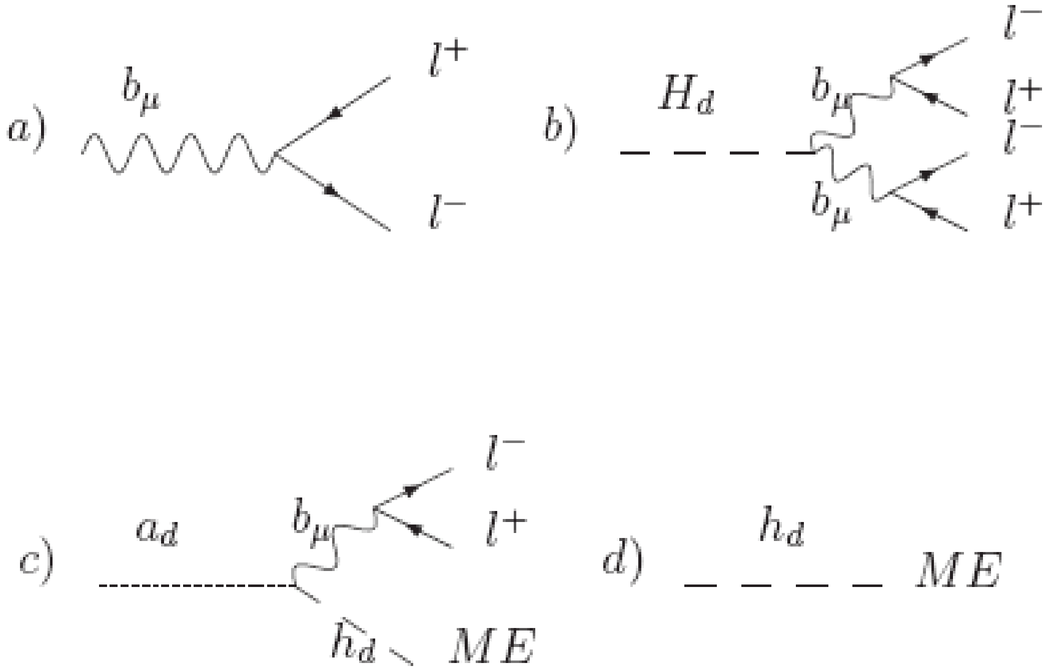

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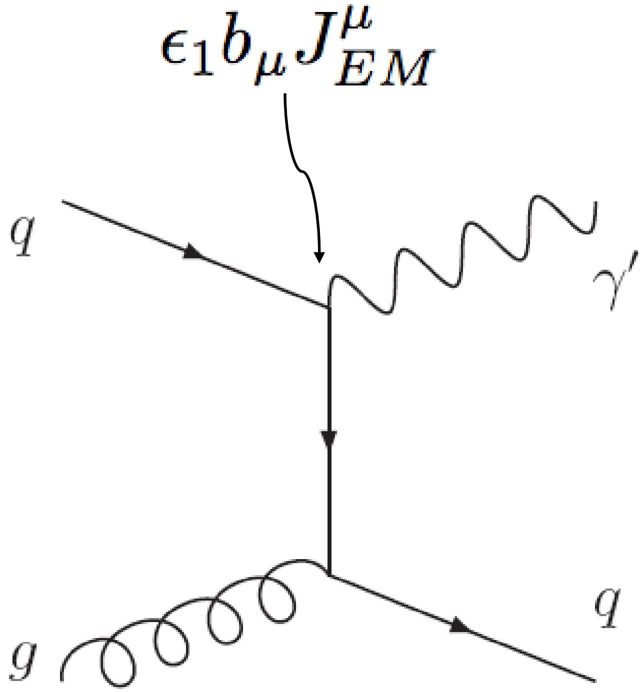

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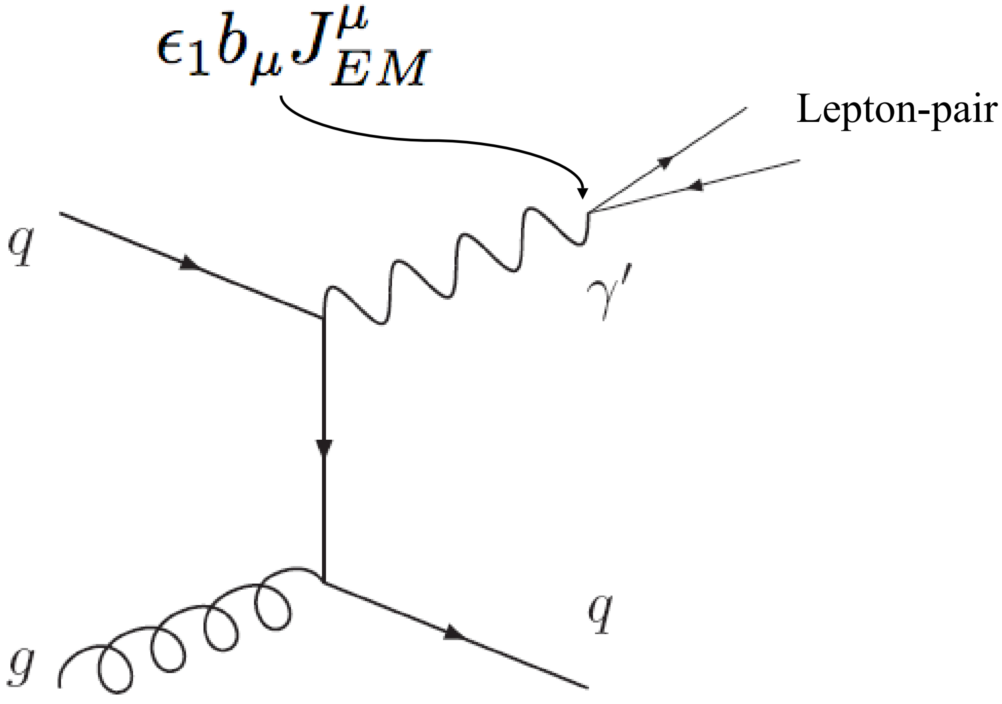

Too much background!!!

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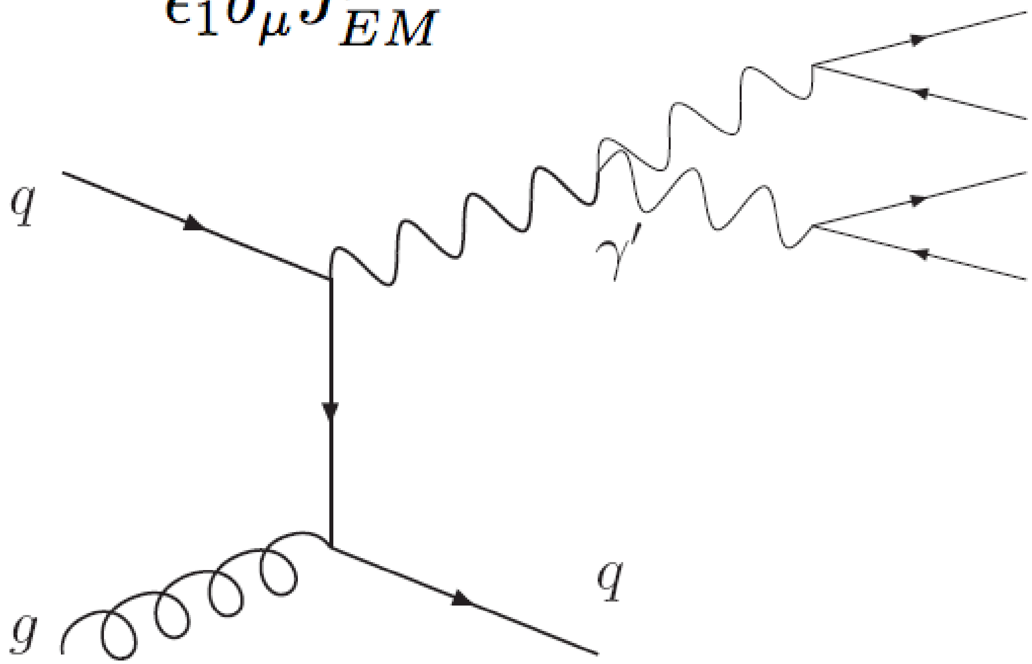

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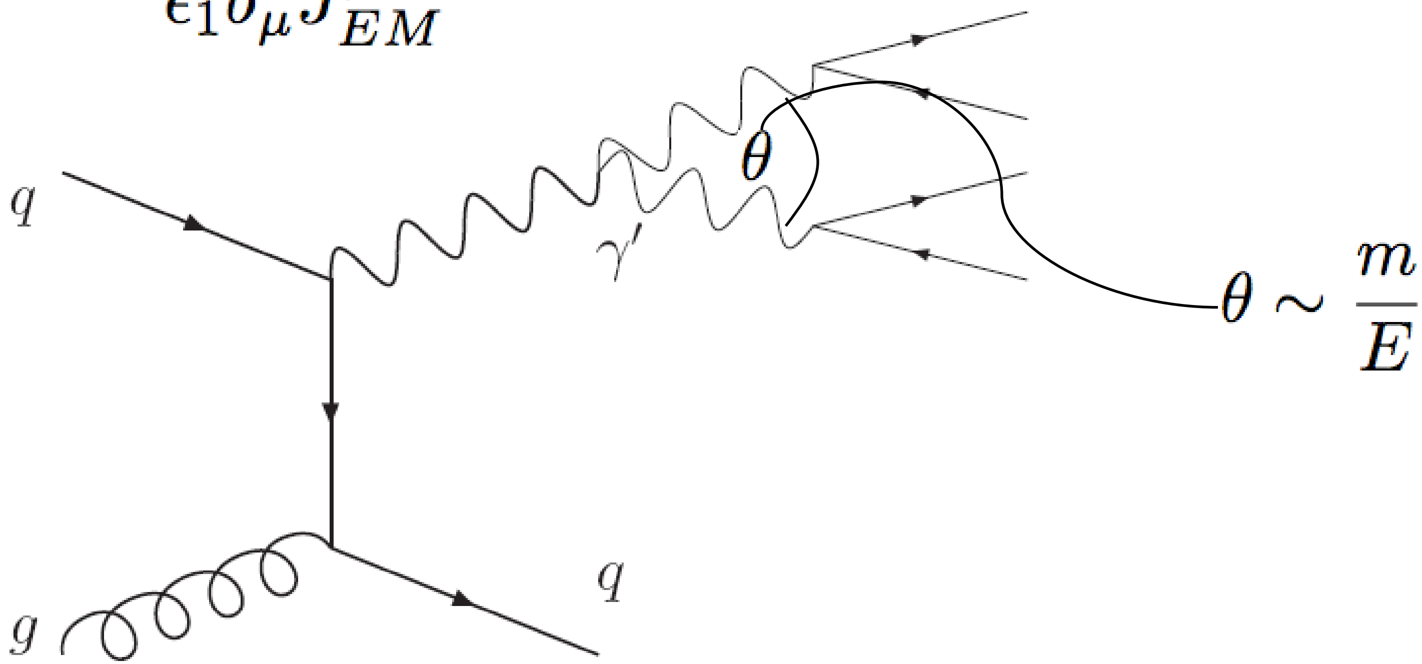

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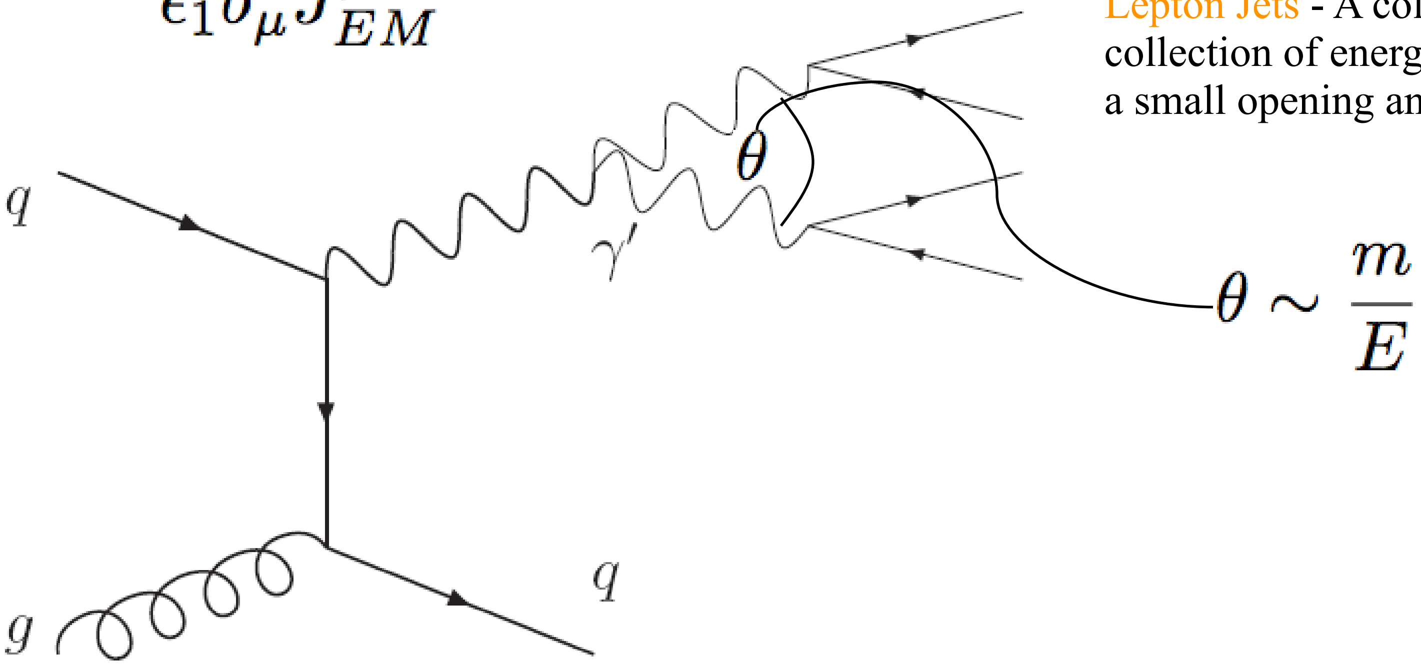

Lepton Jets - A collimated collection of energetic leptons with a small opening angle.

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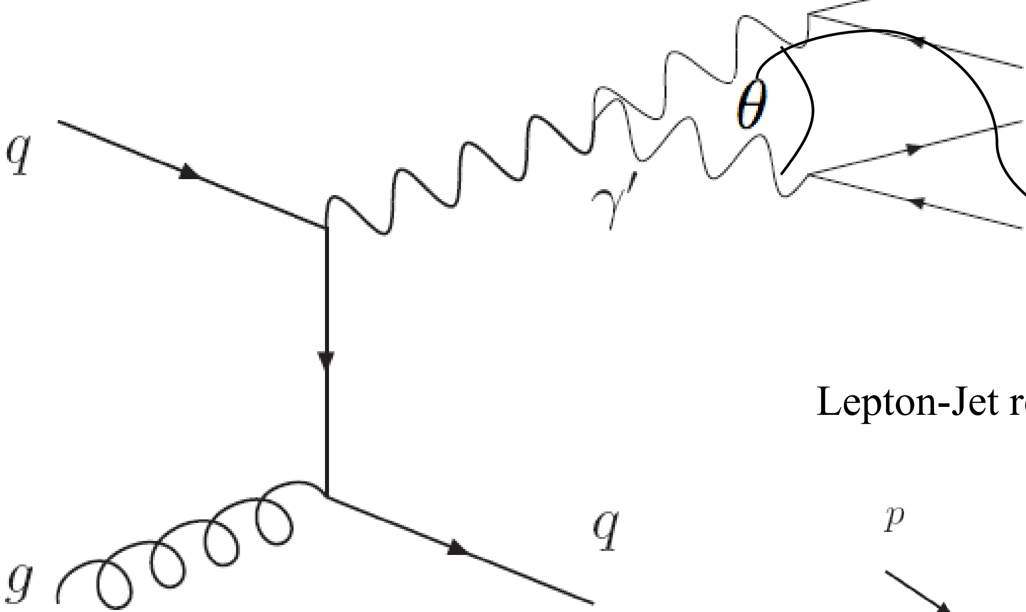
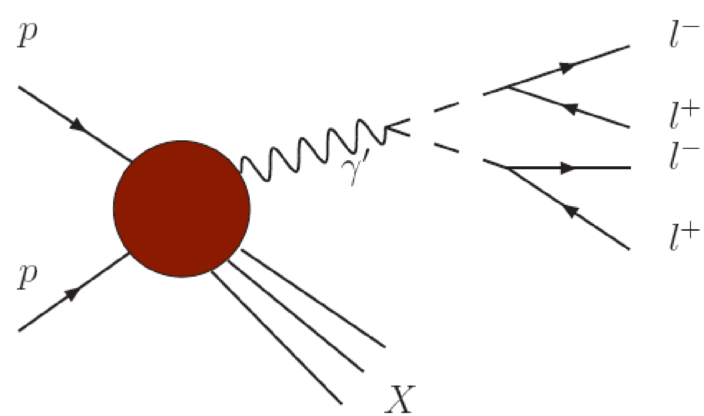


$$\theta \sim \frac{m}{E}$$

Lepton Jets - A collimated collection of energetic leptons with a small opening angle.

Lepton-Jet recoiling against a QCD jet:



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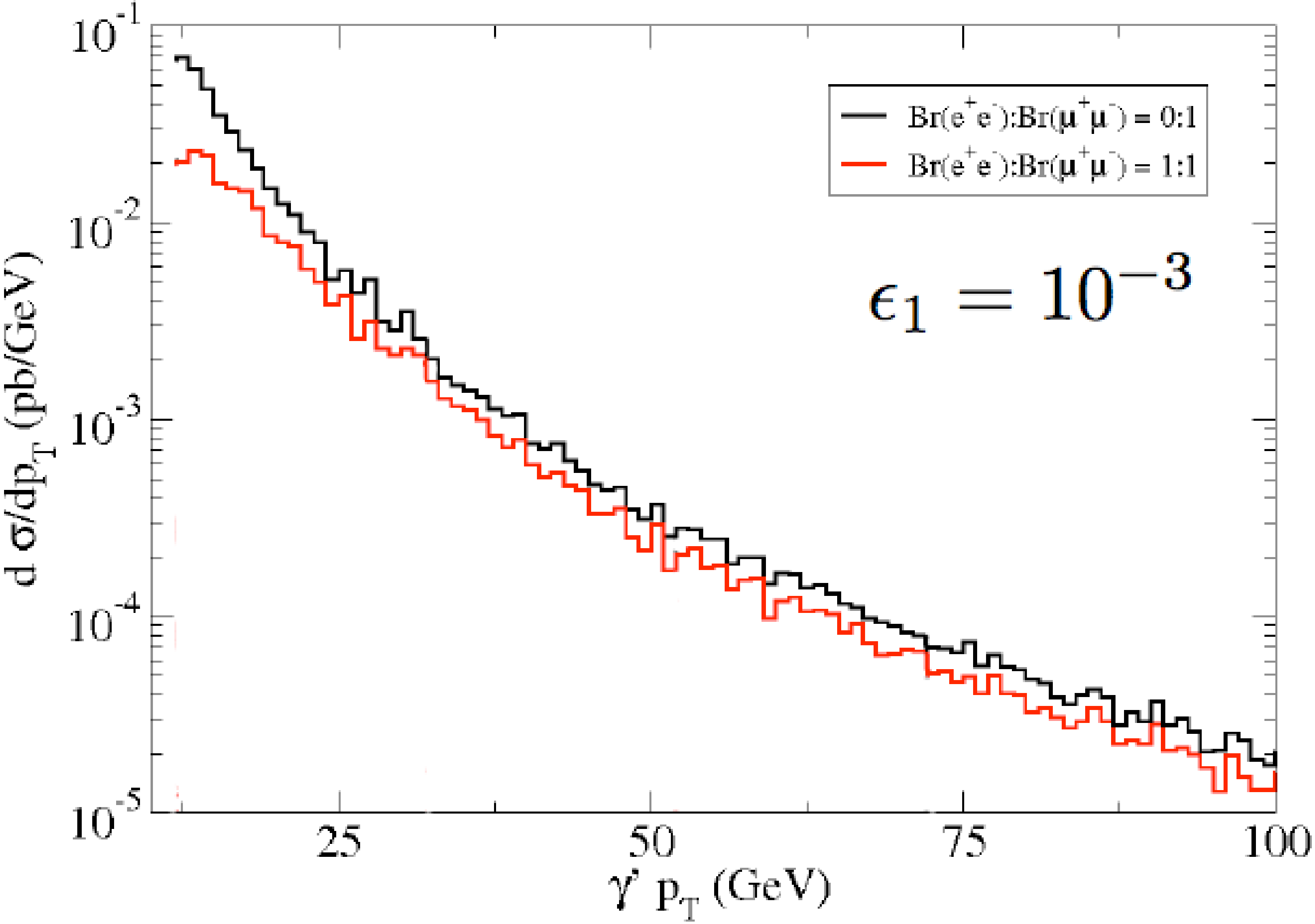

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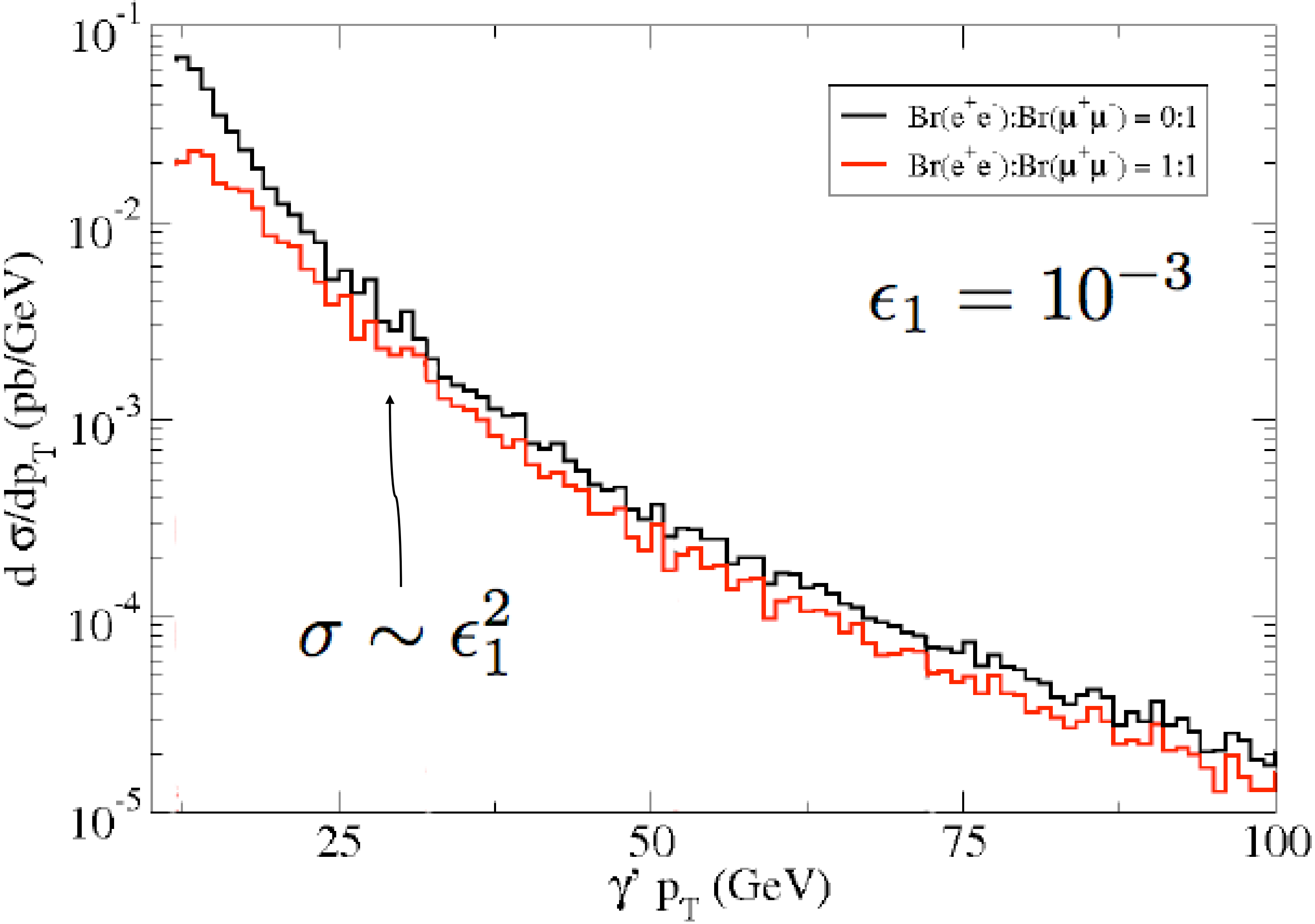
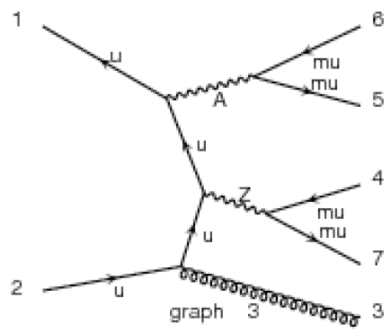


Standard Model Background

The SM can give 2 muon pairs recoiling against a jet and that is an irreducible background. Simulation with Madgraph suggest that this is not going to be a serious obstacle:



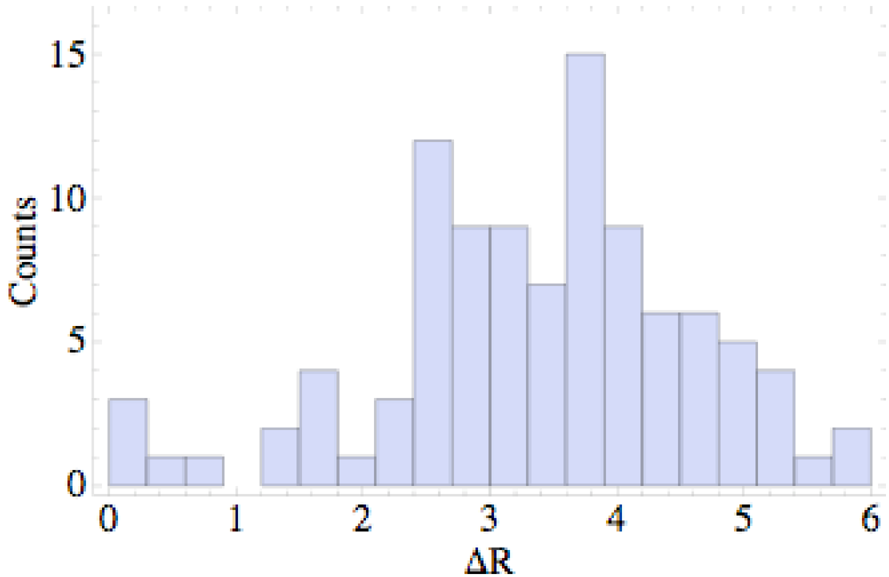
… and many more . . .

$$\sigma = 37 \text{ fb}$$

This can be reduced to **< 1 fb** by requiring:

ΔR < 0.1
pT > 3 GeV

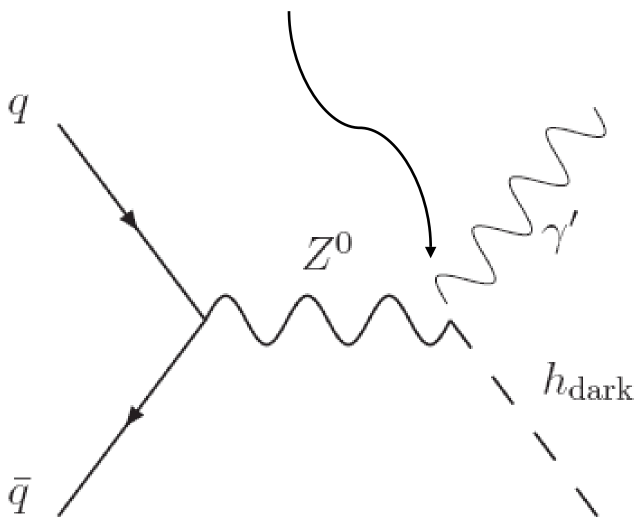
For all 4 muons.



Rare Z Decay

The neutral vector-boson couples directly to the dark current. Therefore, the dark higgses and can be directly produced:

$$\epsilon_2 Z_\mu J^\mu_{dark}$$



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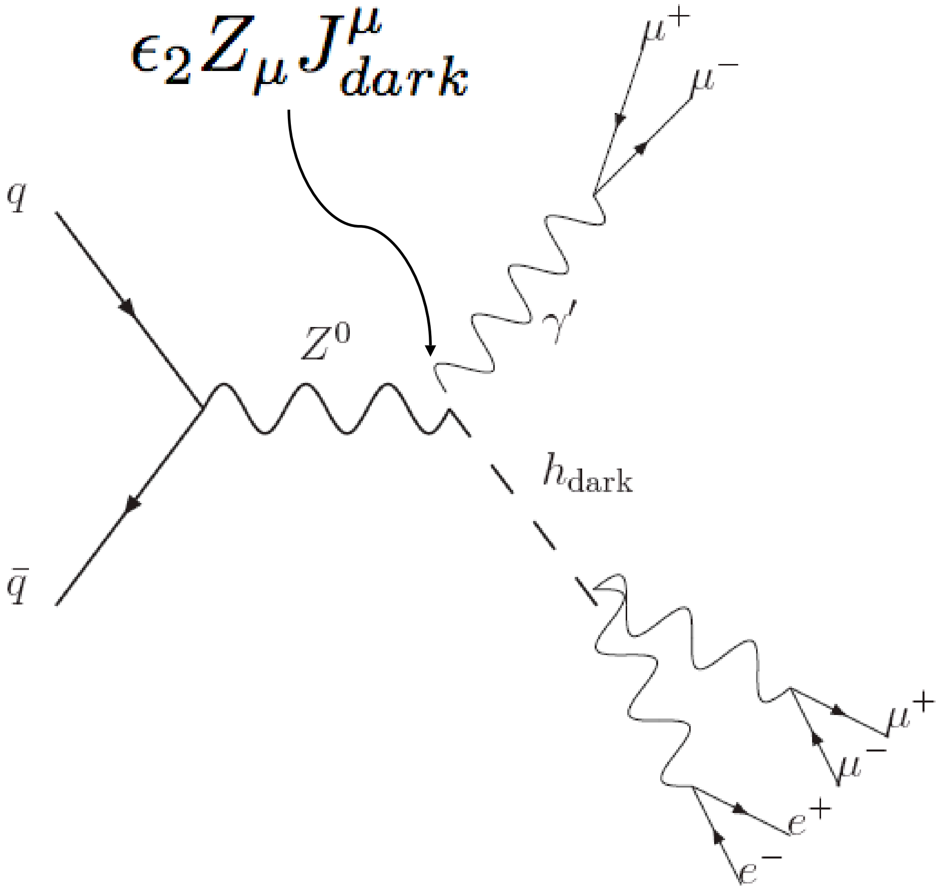

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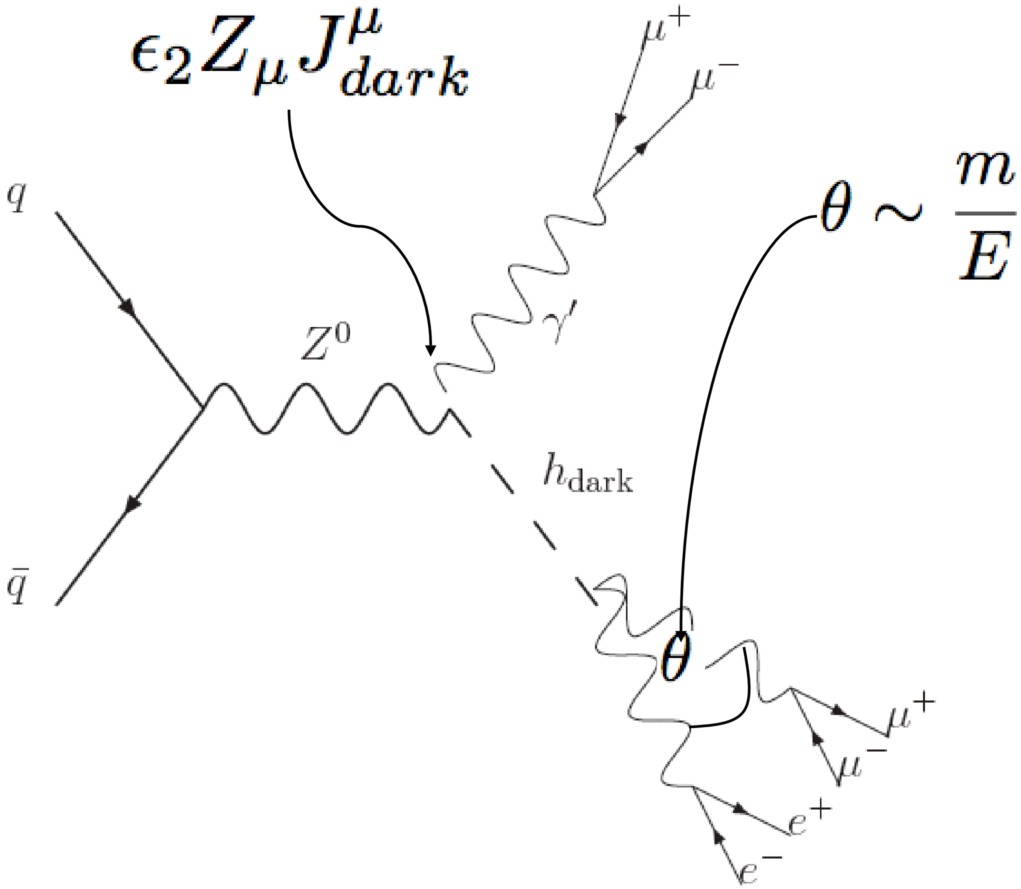
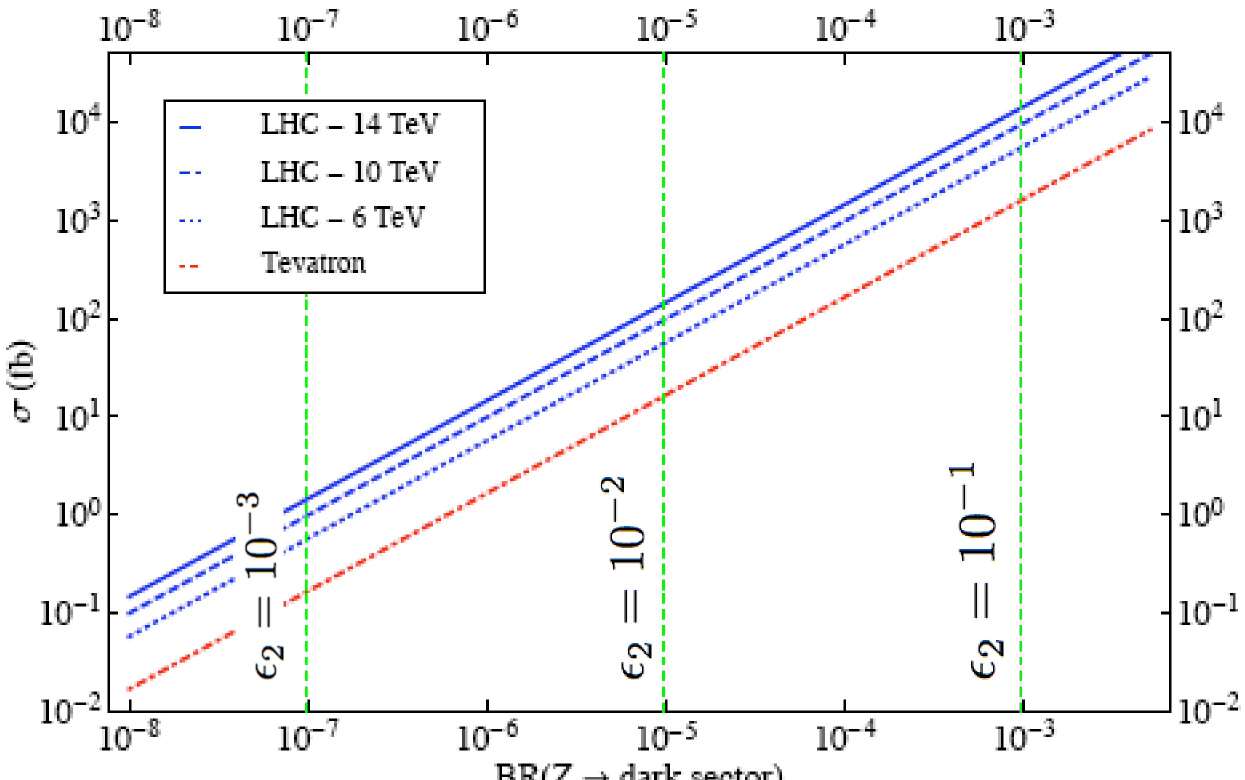


Lepton Jets - A collimated collection of energetic leptons with a small opening angle.

Rare Z^0 Decay

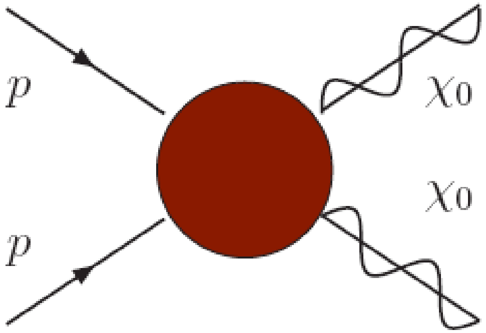
At LEP : $\mathrm{BR}\left(Z \to f\bar{f}\right) = \frac{\epsilon_2^2 g_{\mathrm{dark}}^2}{12\pi} \frac{M_{Z^0}}{\Gamma_{Z^0}}$ ➡ $\mathcal{O}(100)$ events for $\epsilon_2 = 10^{-2}$

At Tevatron and LHC :



Neutralino Decay

The bottom of the SUSY cascade is no longer stable. It will decay into the dark dark sector.



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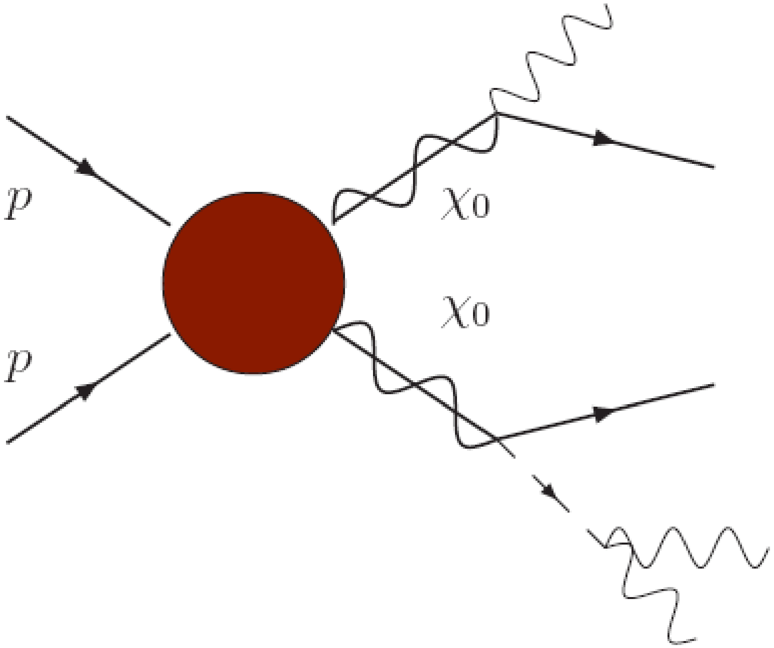
$$+\,\epsilon_1' \tilde{B} \tilde{J}_{\tilde{b}} + \epsilon_2' \tilde{W}_3 \tilde{J}_{\tilde{b}}$$



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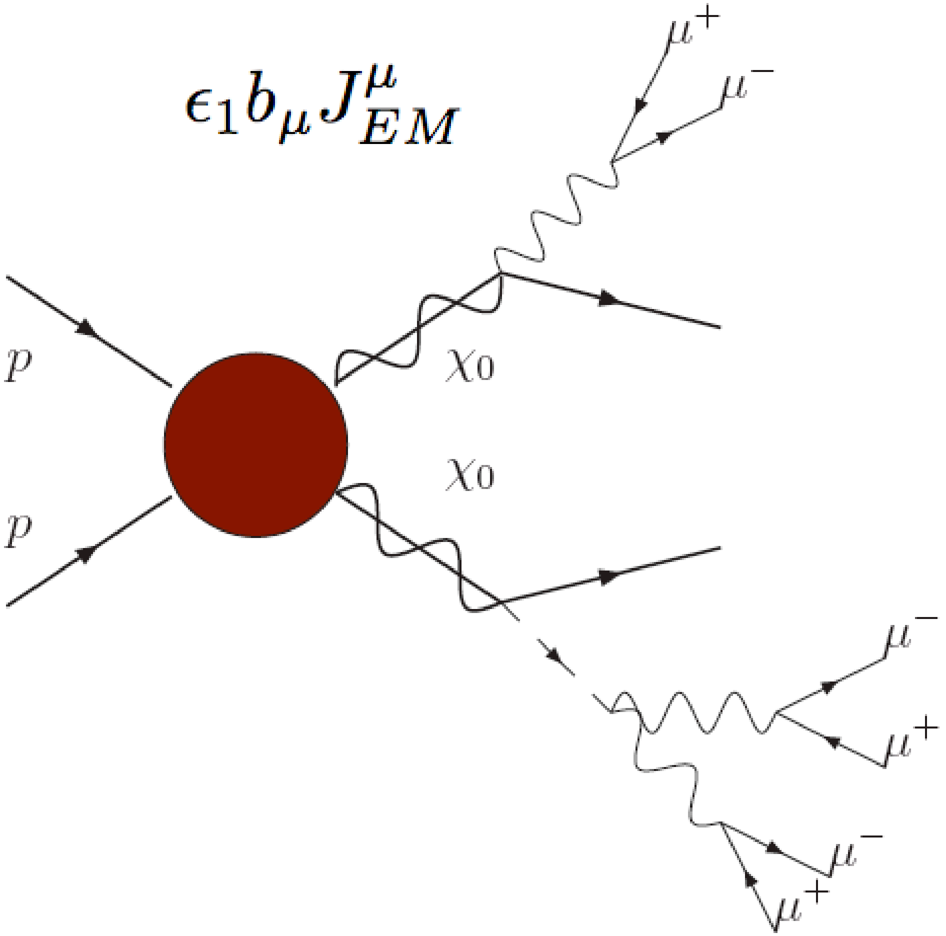

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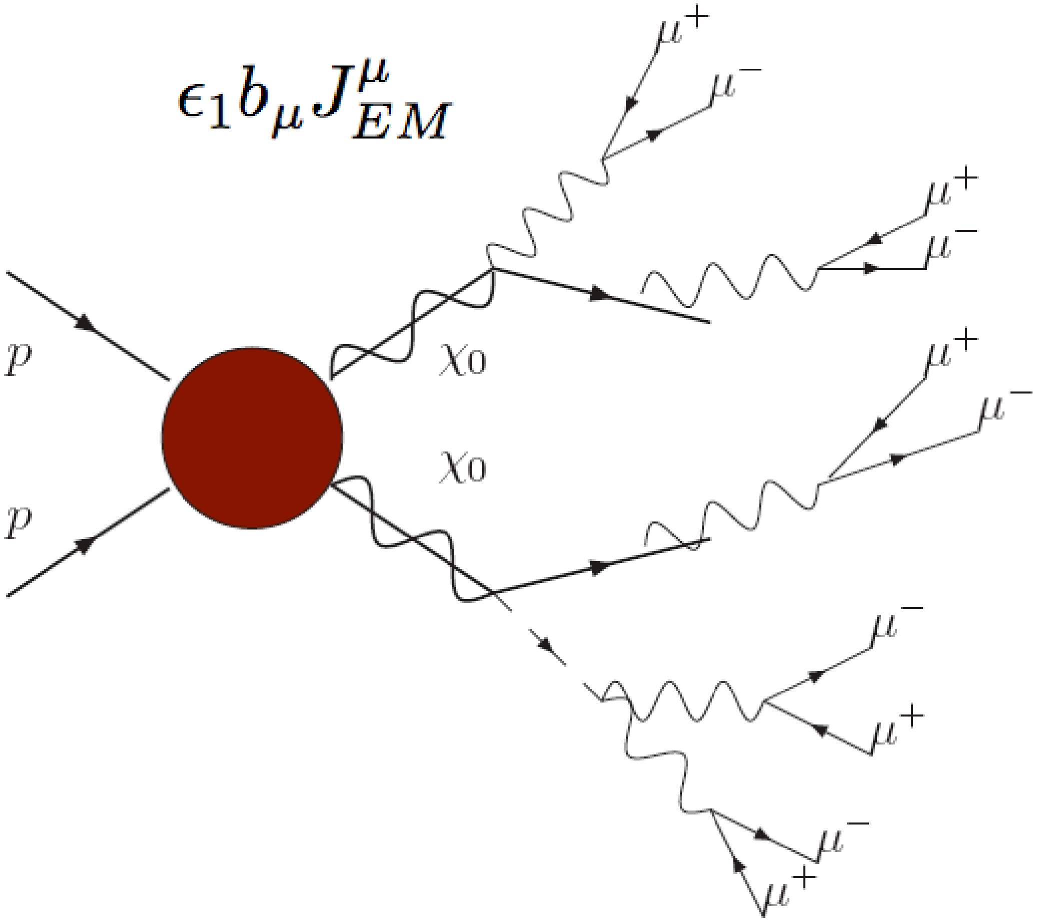

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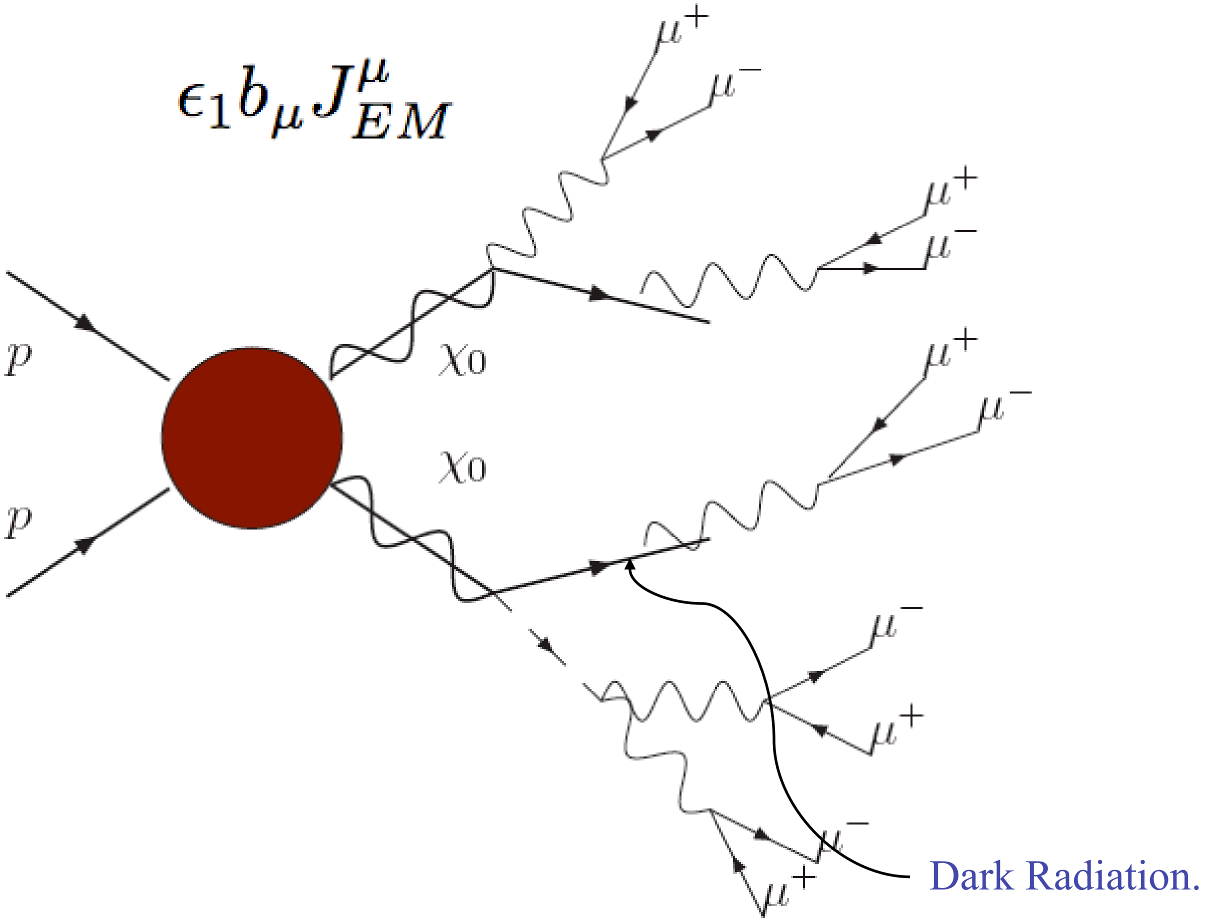

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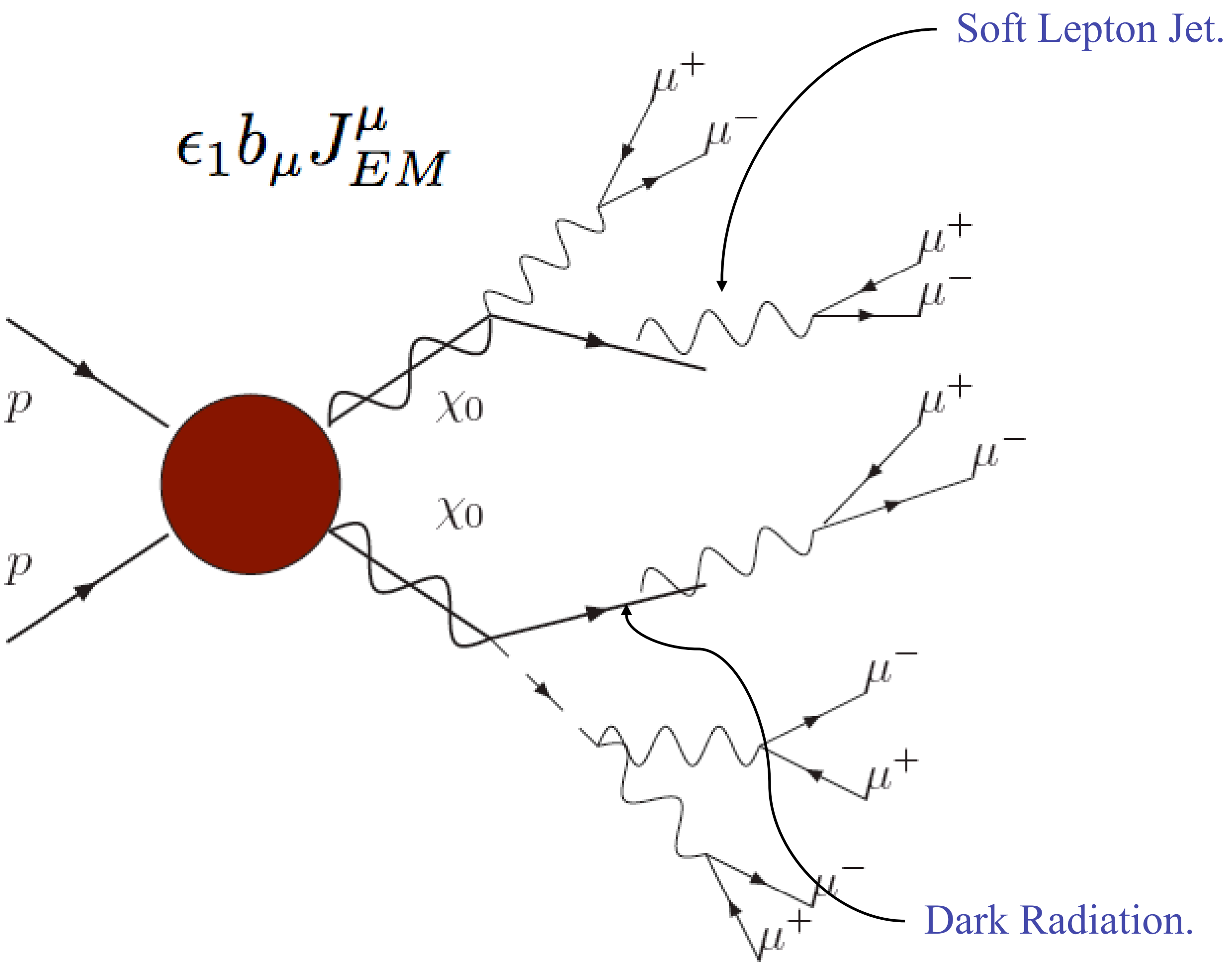

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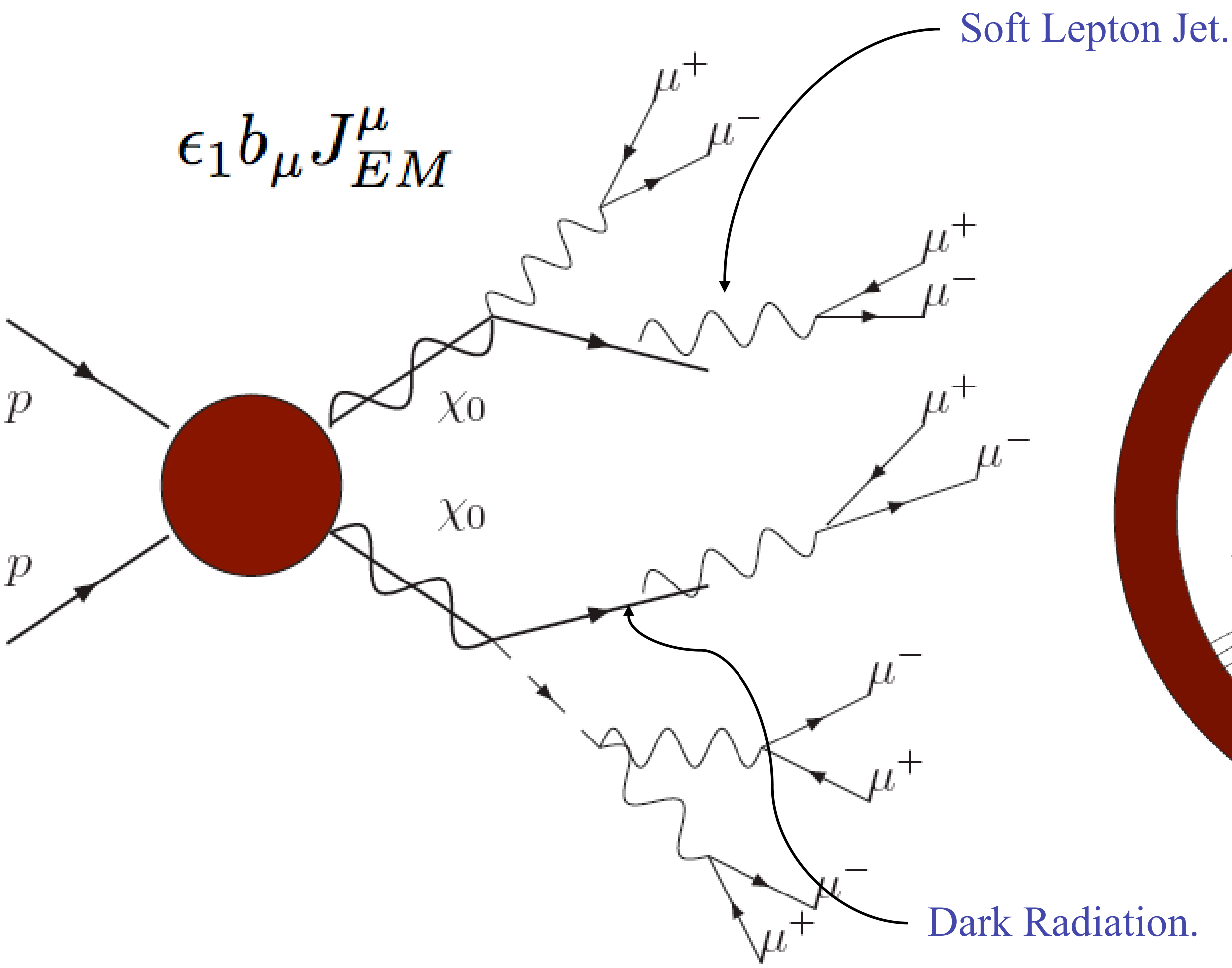
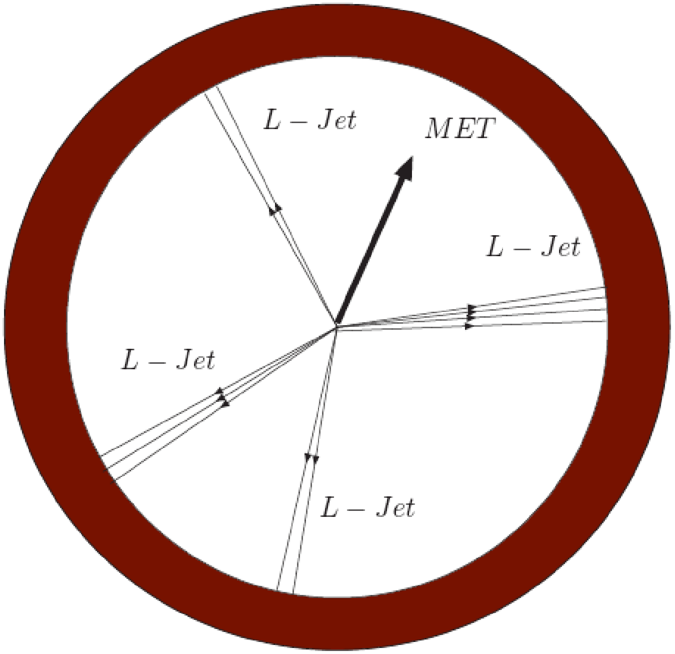
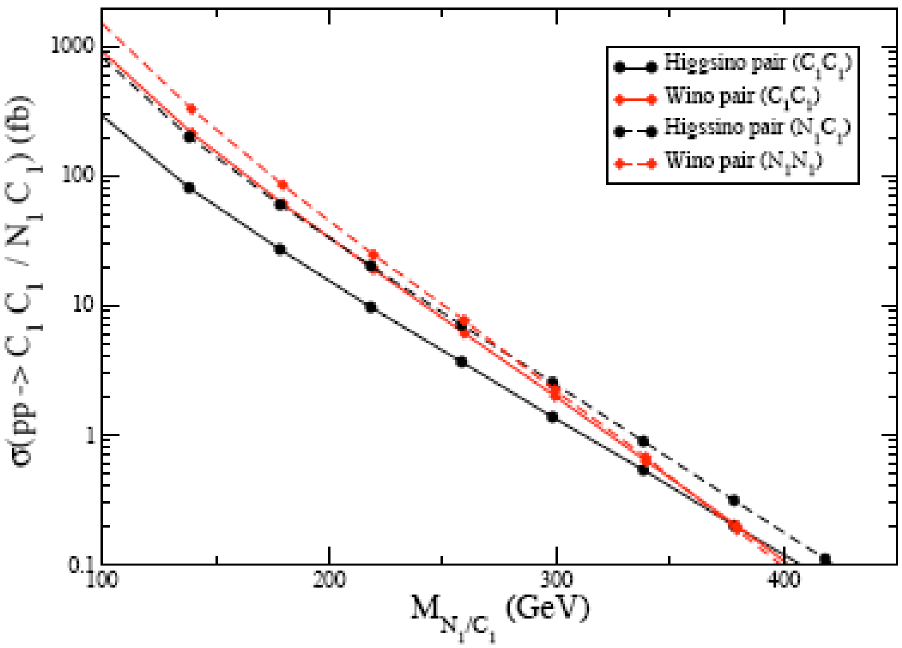
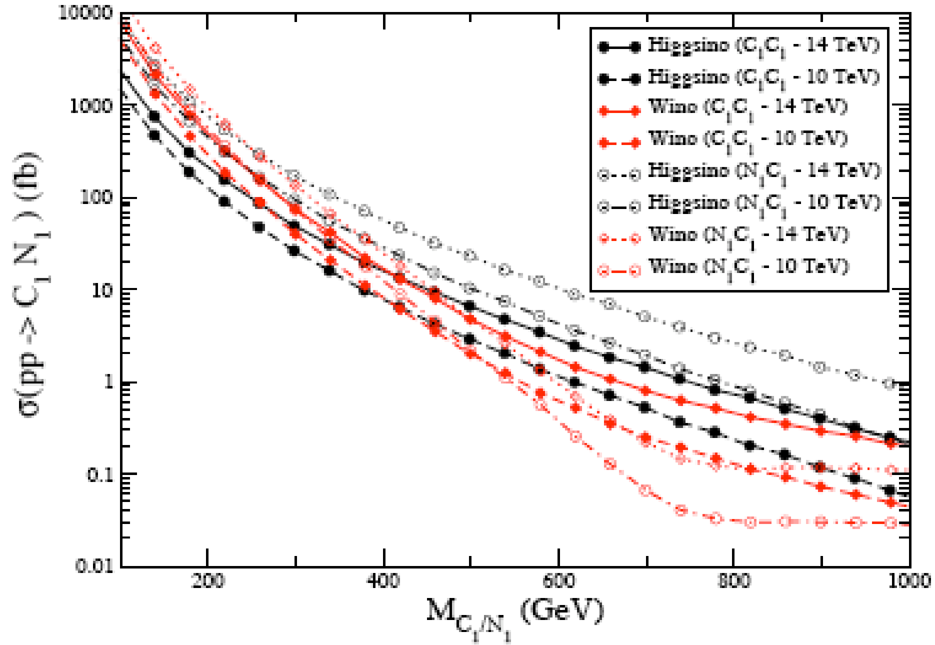




LHC/Tevatron Reach



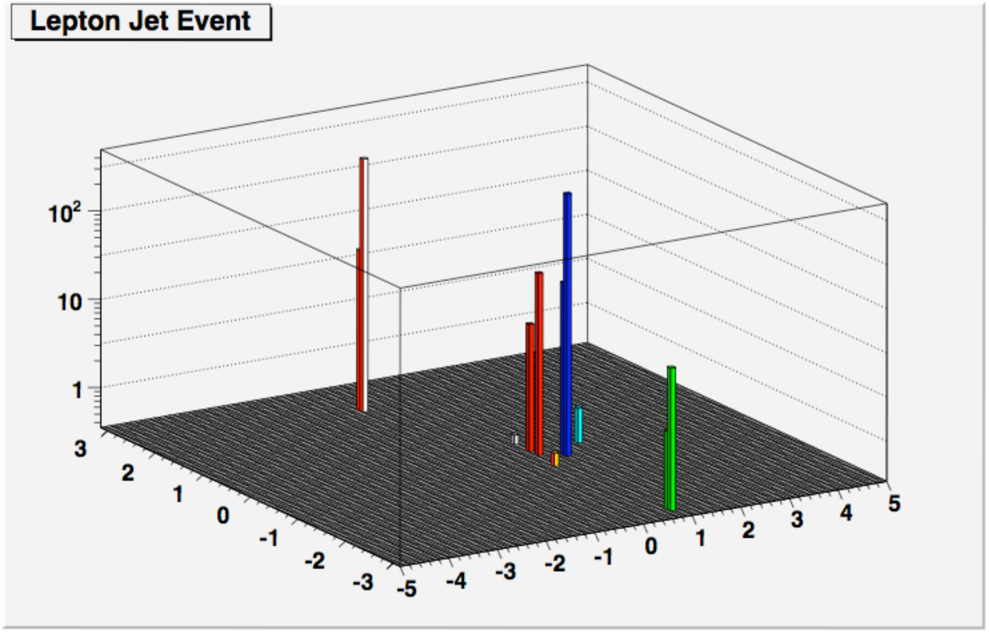


* This is for a squark mass of 750 GeV.

These are large cross-sections.
Some of the parameter space can already be excluded by Tevatron searches.

Part III

Lepton Jets



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Two or more leptons with $p_T > 10$ GeV *inside a cone of* $\Delta R < 0.1$ *with hadronic/leptonic isolation cut of* $p_T < 3$ GeV *in an annulus of* $0.1 < \Delta R < 0.4$ *around the leptons.*

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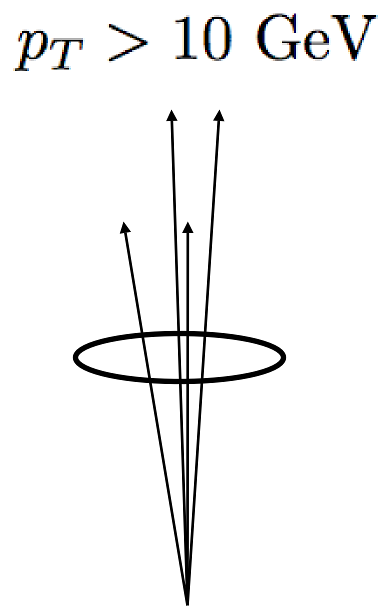

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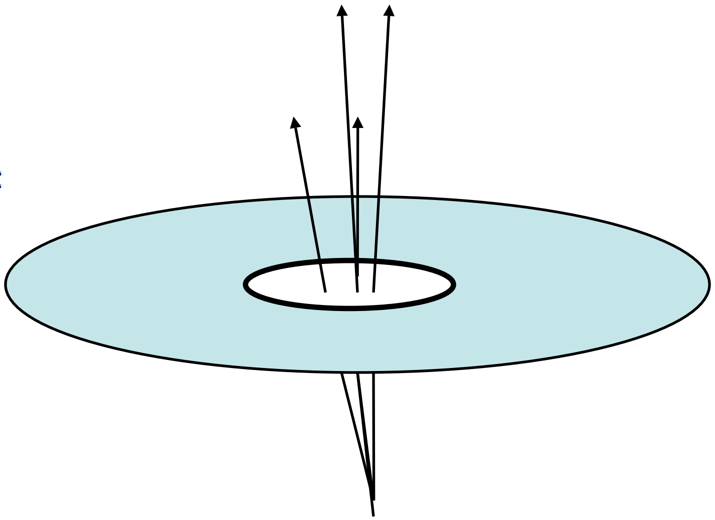

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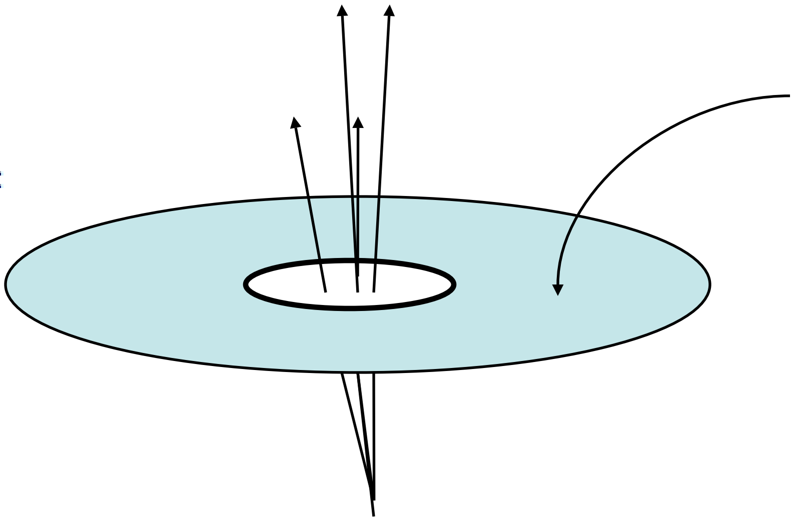
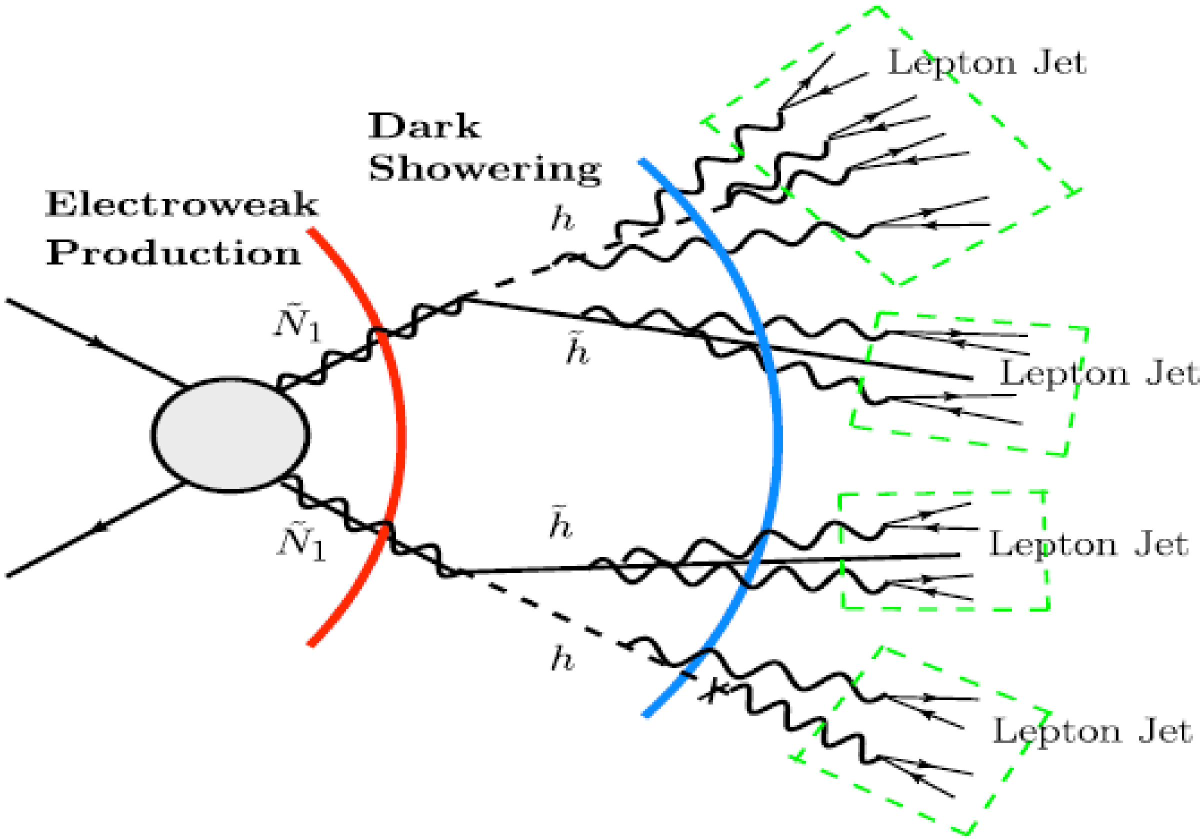


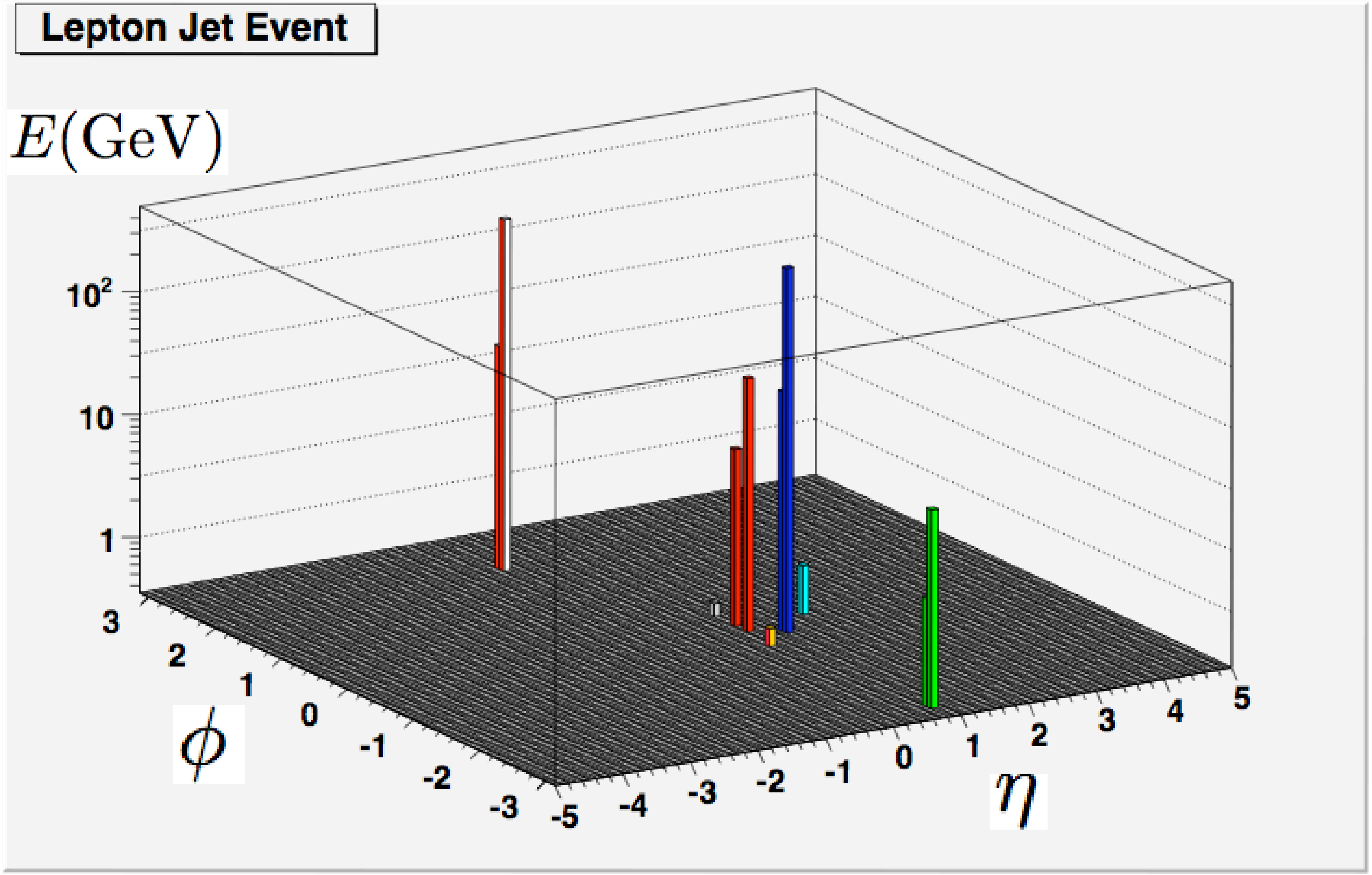
$$\sum p_T < 3 \text{ GeV}$$

Full Evolution



Lego Plots

For a 500 GeV LSP pair production, the event looks like:



Experimental Discovery

When looking for lepton-jets, it is important to attempt inclusive searches:

1) Isolation cuts around the hard lepton(s) should exclude hadronic activity, but if possible allow for other leptonic activity (a lepton bunch may contain more than 2).

2) Looking for a very particular final state is probably too exclusive and usually involve too much theory-bias. . .

3) By defining "Lepton-Jet" objects (as inclusive as possible), searches can be designed to look for events containing "Lepton-Jet"s in the final state (and possibly additional stuff).

4) While a resonance structure is probably present, since we don't know the mass, it may not very useful to implement mass-window cuts and etc.

Sources of Lepton Jets

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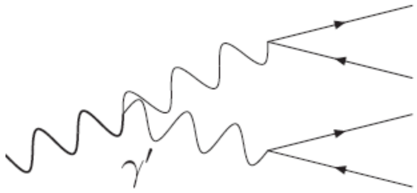
There are different possibilities for obtaining lepton-jets:



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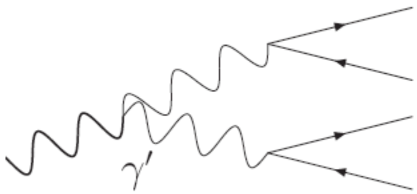

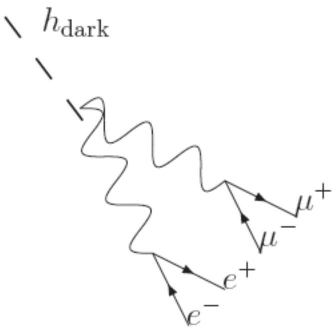

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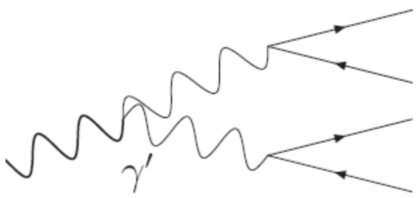
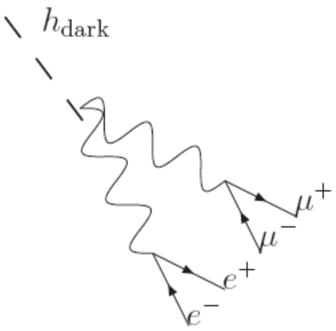


2) Dark higgs(es) decay



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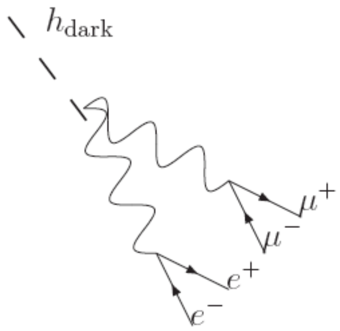
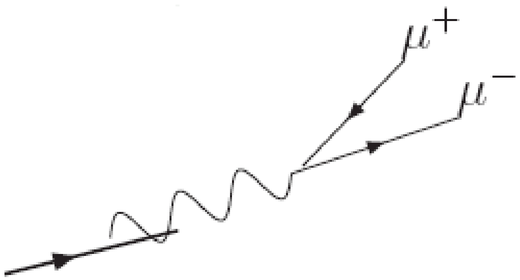


3) Dark radiation



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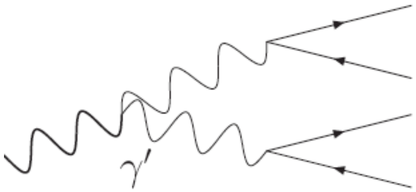

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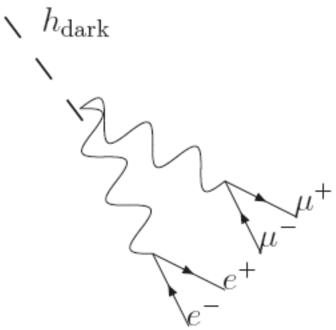

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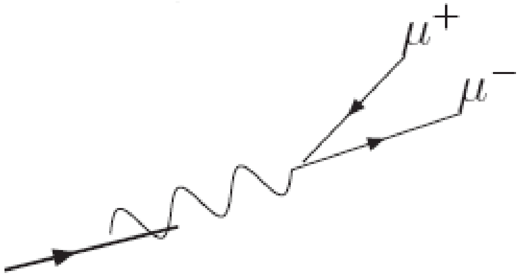

There are different ways of producing dark states:

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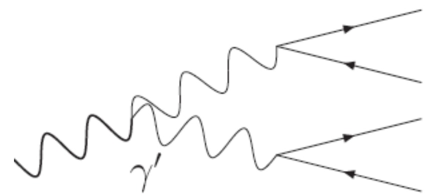

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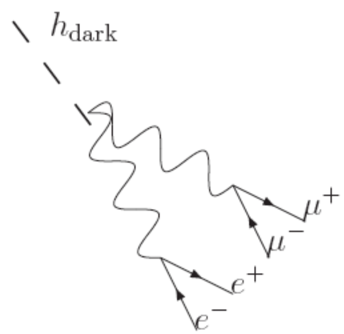

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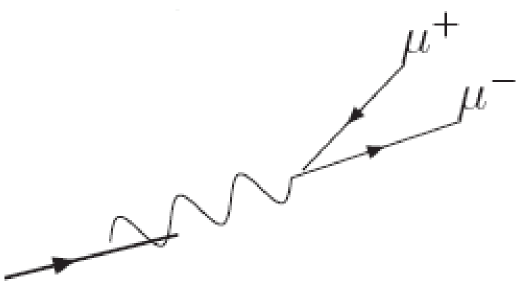

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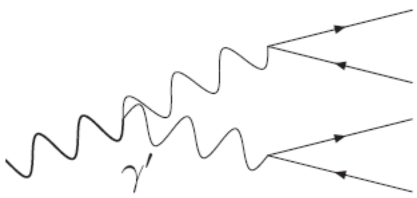

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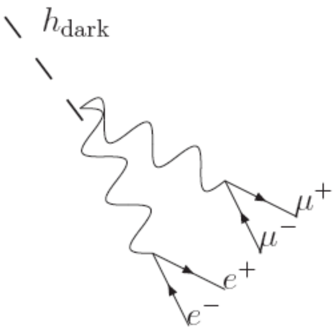

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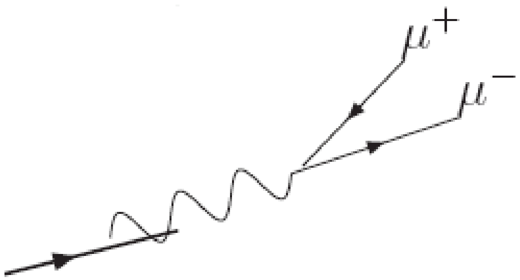

There are different ways of producing dark states:

1) Prompt dark photon

2) Rare Z decays

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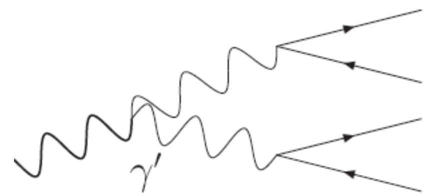
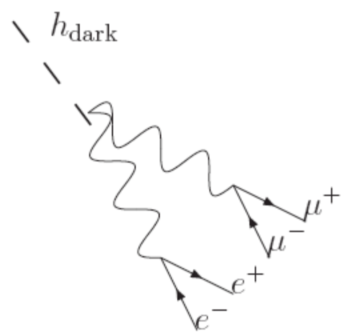
There are different possibilities for obtaining lepton-jets:

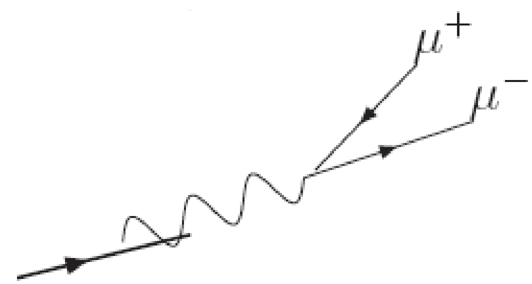
1) A non-abelian structure in the dark sector



2) Dark higgs(es) decay



3) Dark radiation

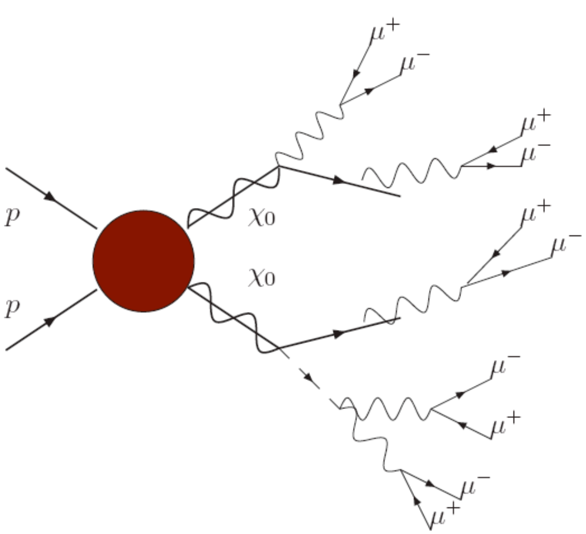


There are different ways of producing dark states:

1) Prompt dark photon

2) Rare Z decays

3) Susy cascades



Future Directions

- Searches at LEP and Tevatron.
- Searches at BaBar/Belle (see Essig, Schuster, and Toro) .
- Tune and modify triggers (see Demirkoz and Moore).
- Lepton-Jet observables?
- Other scenarios with similar signatures? (see Strassler and Zurek).

Motivation 2

Aside from the recent astrophysical observations, there can be another motivation for looking for such objects.

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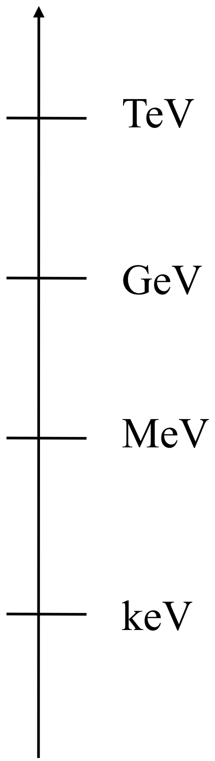

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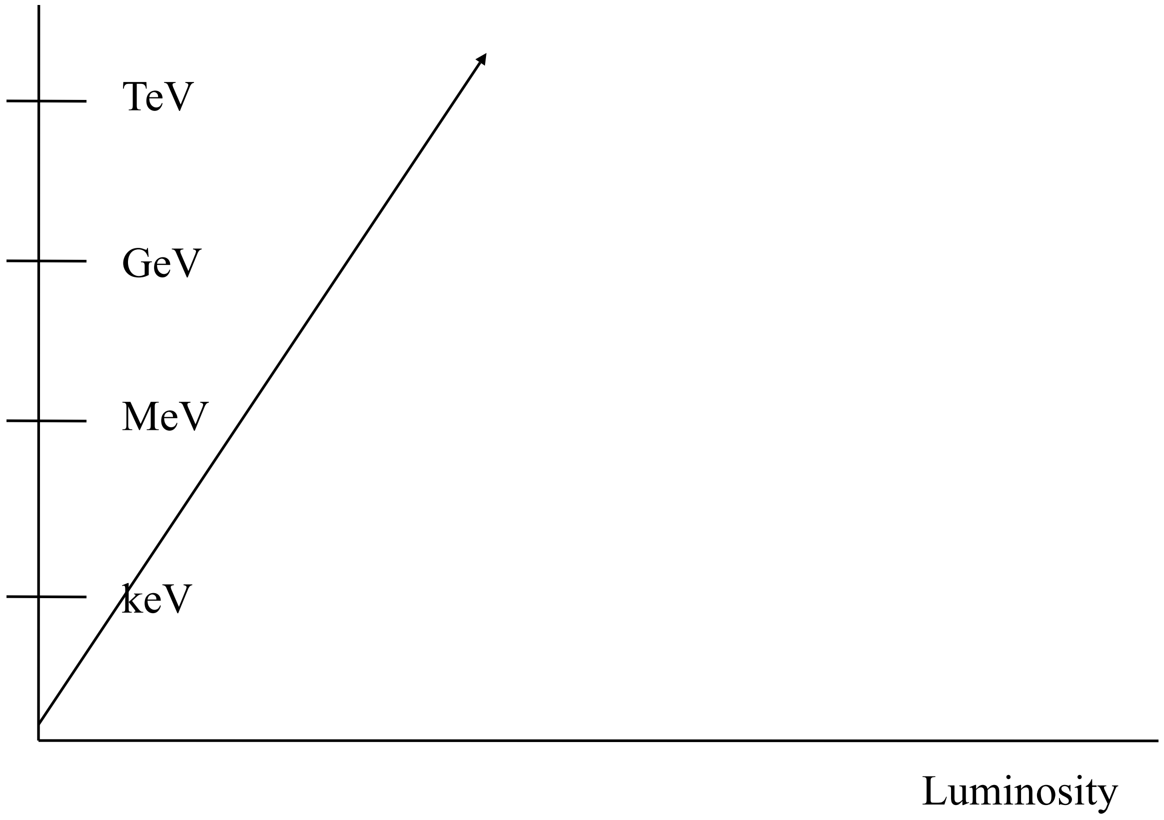

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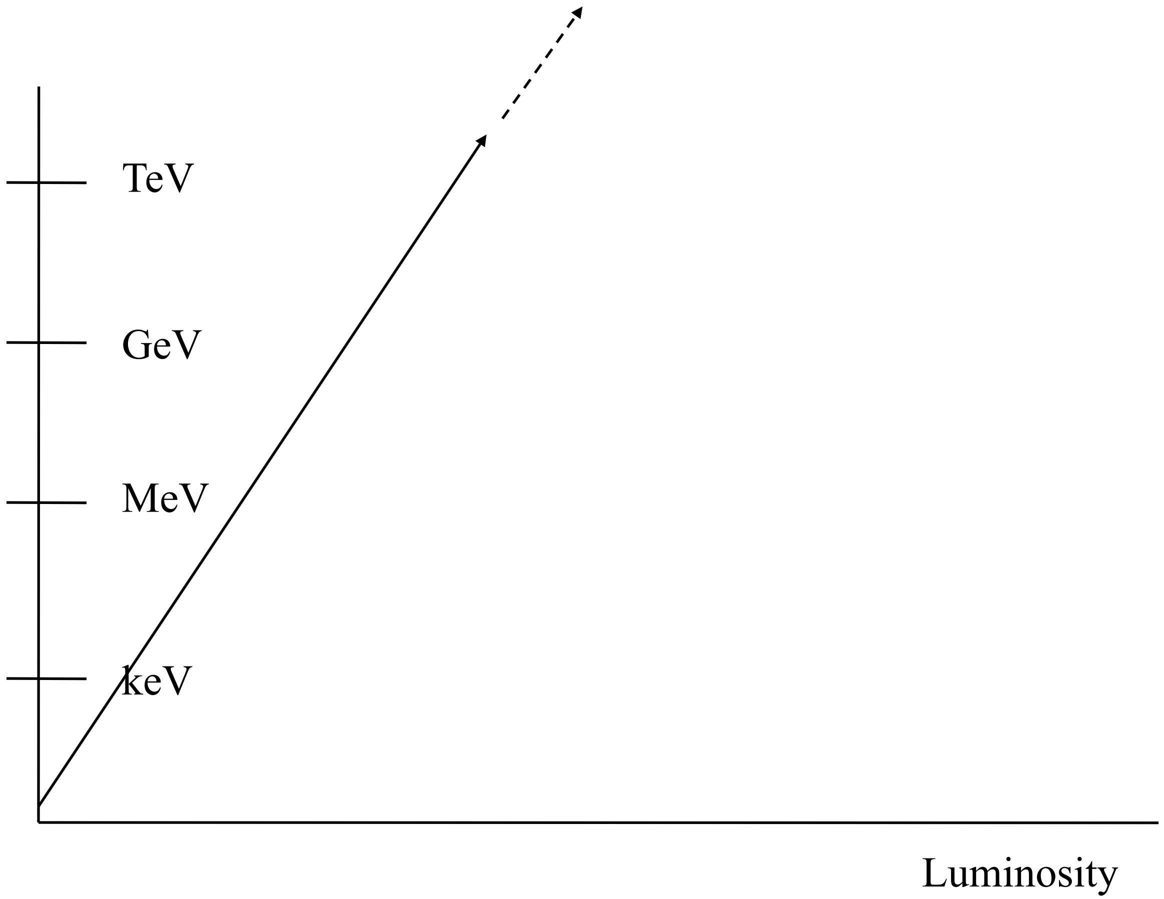

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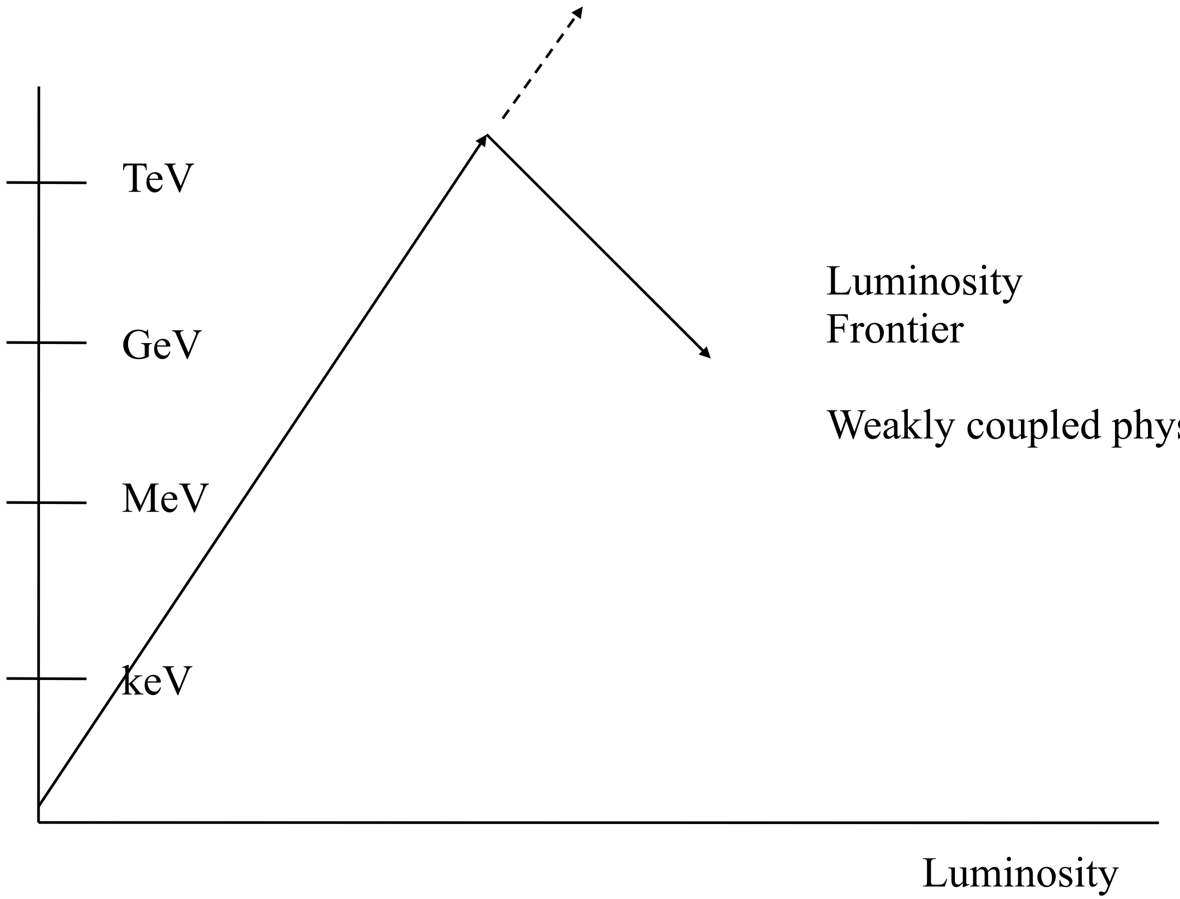
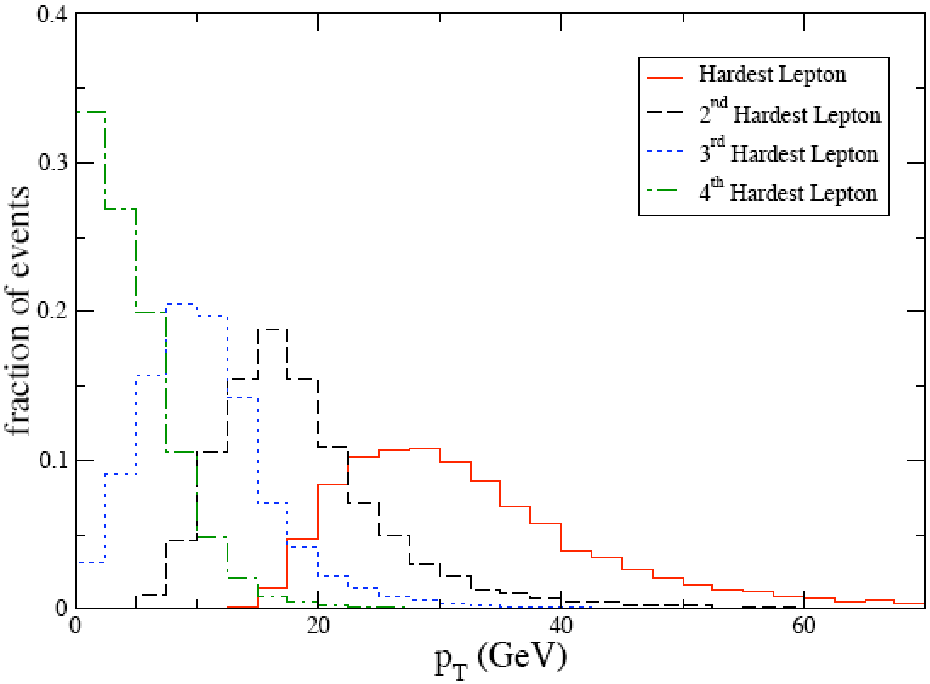
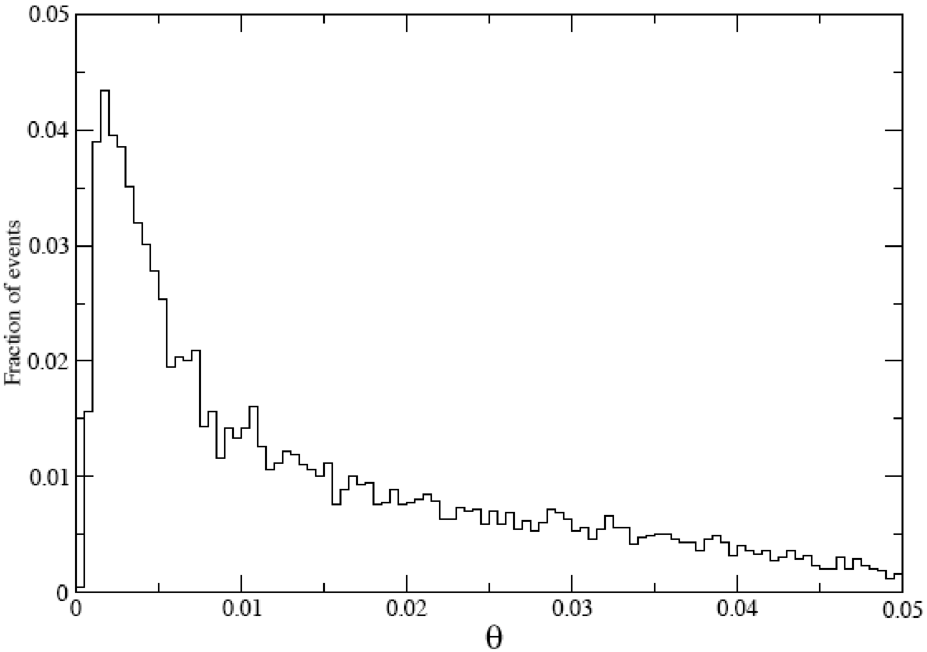


Luminosity
Frontier

Weakly coupled physics be there

Detector Performance





Bilge Demirkoz and Roger Moore investigated ATLAS performance using the prompt dark photon production as a benchmark.

Bilge Demirkoz also implemented new triggers to help improve the efficiency associated with such events.

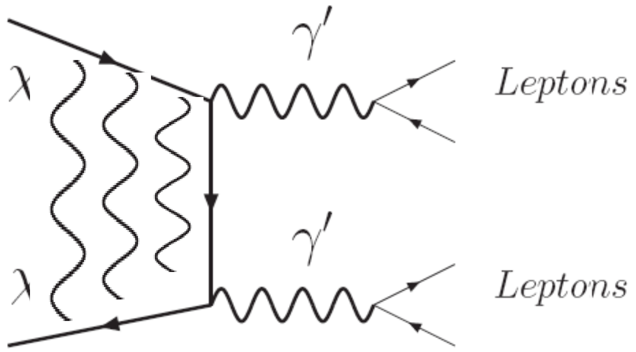
Lepton Jet Efficiency

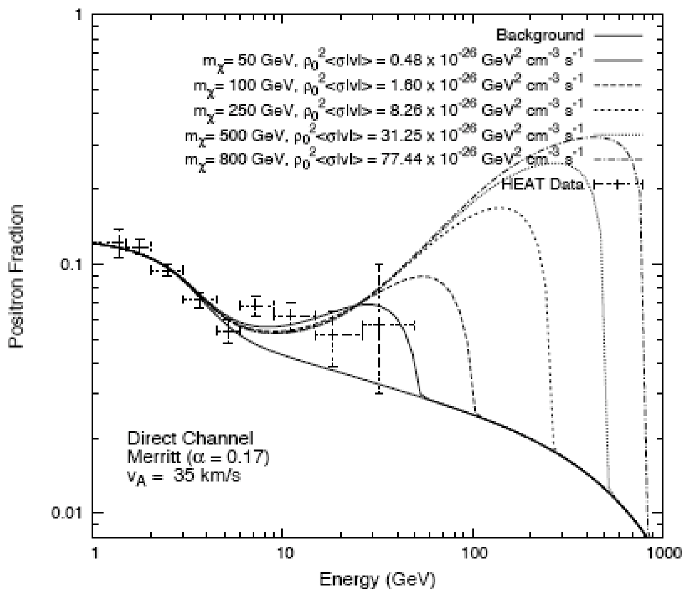
Lepton Jet Efficiencies						
	1 Lepton-Jet			2 Lepton-Jet		
$Br_{b \to \pi\pi}$	1/7	1/3	3/5	1/7	1/3	3/5
α_d						
0	0.49 (0.49)	0.47 (0.47)	0.31 (0.31)	0.28 (0.28)	0.14 (0.15)	0.05 (0.05)
0.01	0.47 (0.47)	0.44 (0.45)	0.31 (0.32)	0.3 (0.31)	0.16 (0.16)	0.04 (0.04)
0.03	0.43 (0.41)	0.47 (0.48)	0.3 (0.3)	0.27 (0.3)	0.14 (0.16)	0.04 (0.05)
0.1	0.43 (0.39)	0.41 (0.44)	0.29 (0.32)	0.23 (0.3)	0.13 (0.18)	0.05 (0.07)
0.3	0.38 (0.32)	0.34 (0.36)	0.25 (0.34)	0.16 (0.3)	0.11 (0.22)	0.05 (0.09)

Table 1: Clean lepton jet efficiencies for different values of the dark gauge-coupling and $Br(b \to \pi^+\pi^-)$. The neutralino mass was set to $\tilde{M} = 300$ GeV. For $\alpha_d = 0$ dark radiation was switched off. The number of lepton jets increases with α_d as radiation becomes more likely. The requirement for "clean" lepton jets, as described in the text, results in a decrease in efficiency with the growth of the branching ratio into pion. In brackets are efficiencies for the case where only hadronic isolation is required in the $0.1 < \Delta R < 0.4$ annulus.

Resolution of PAMELA

So dark matter annihilates to dark photons first. The dark photons then decay into leptons.





1) Protons are kinematically disallowed.

2) The leptons are direct products of the annihilations.

3) Sommerfeld enhancement of the cross-section due to light particle exchange.