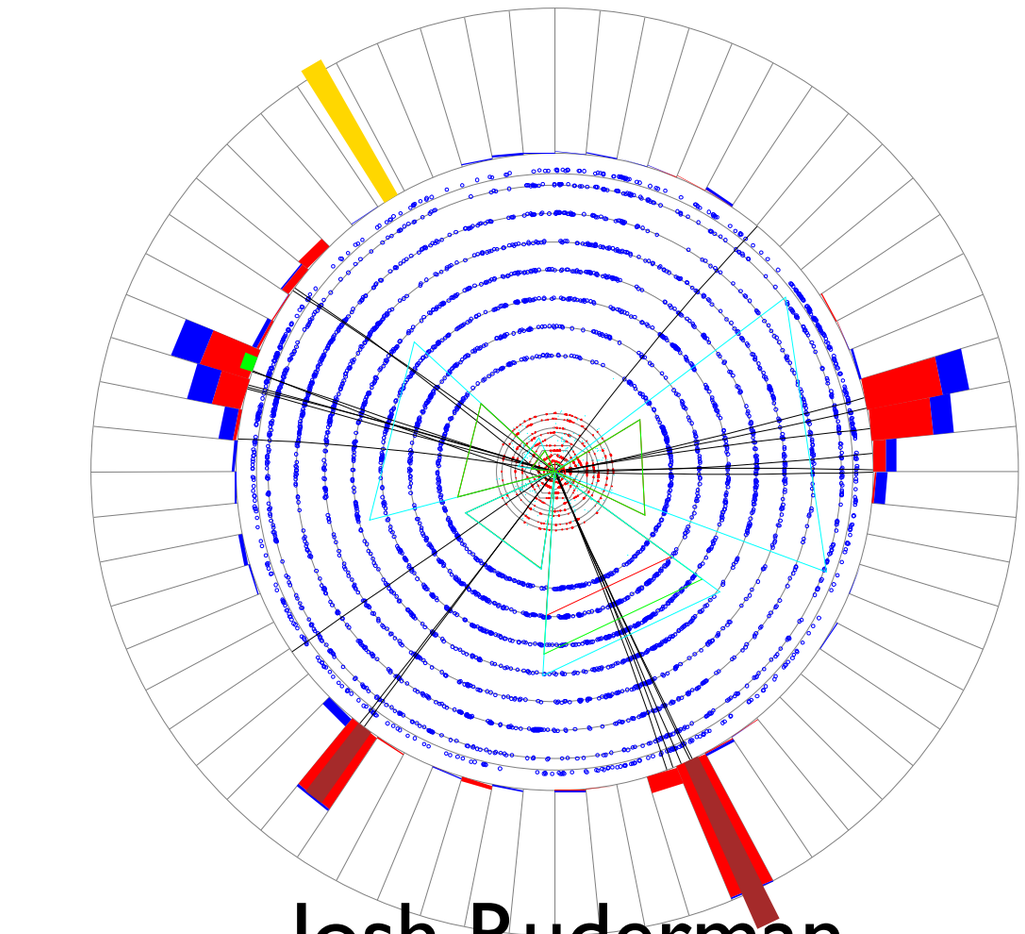
Lepton Jets
and their signature space

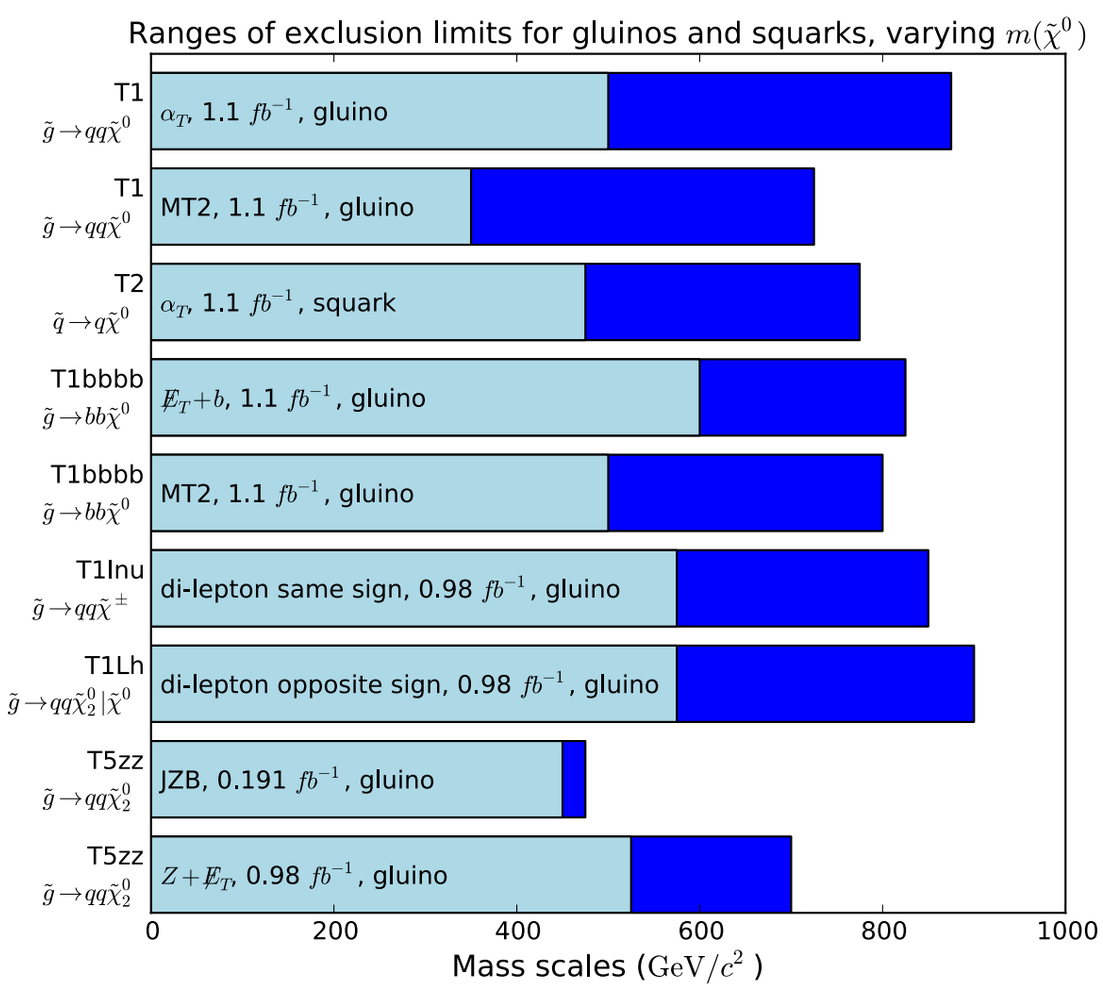


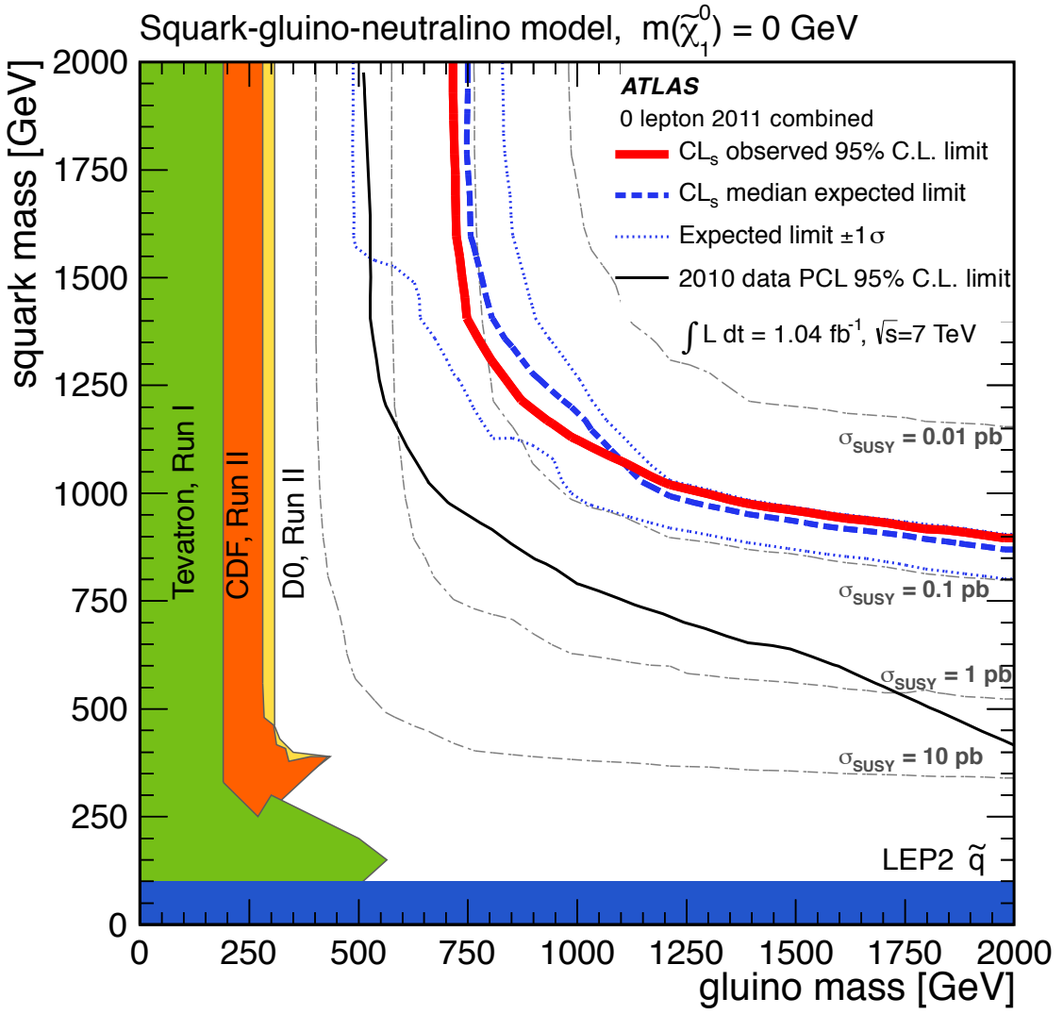
Josh Ruderman

Nov 15, 2011

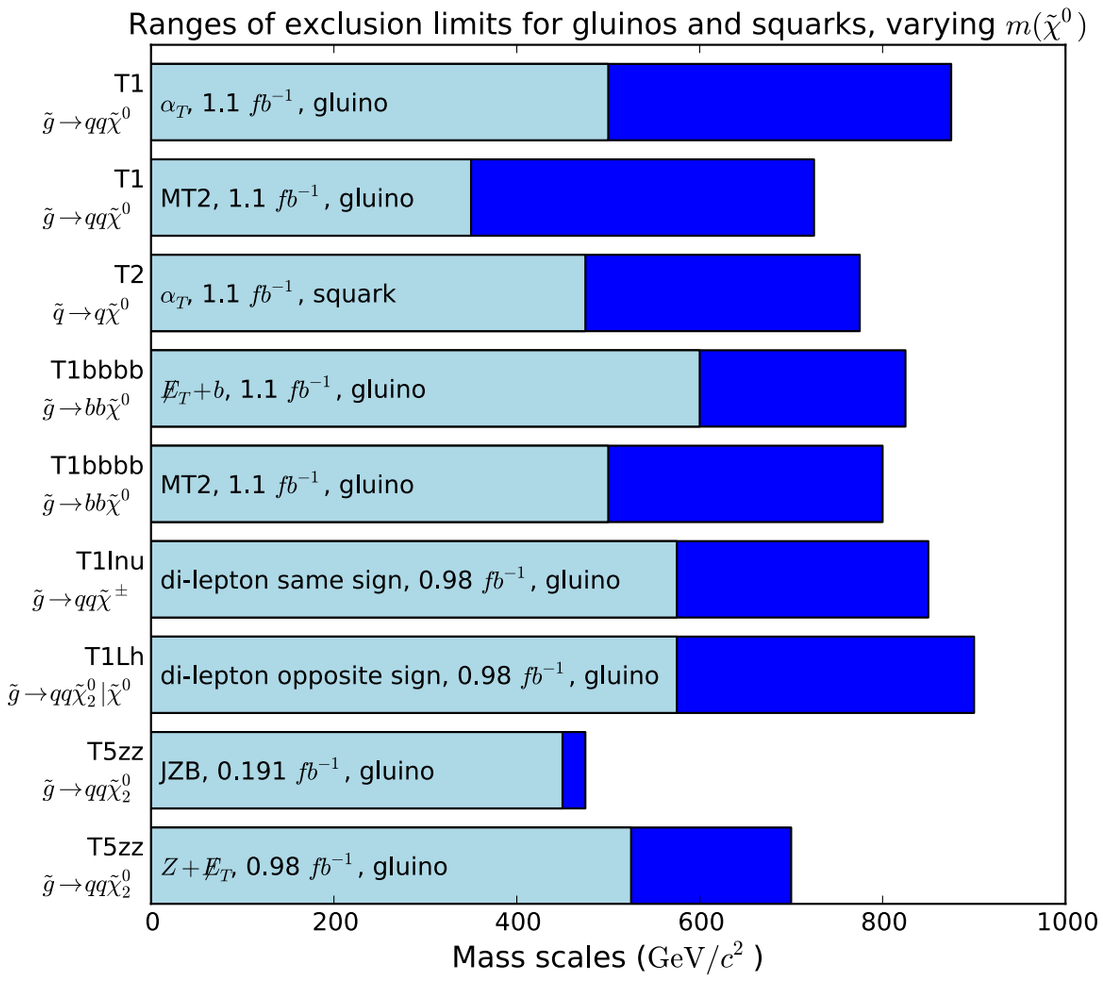
LPC at Fermilab

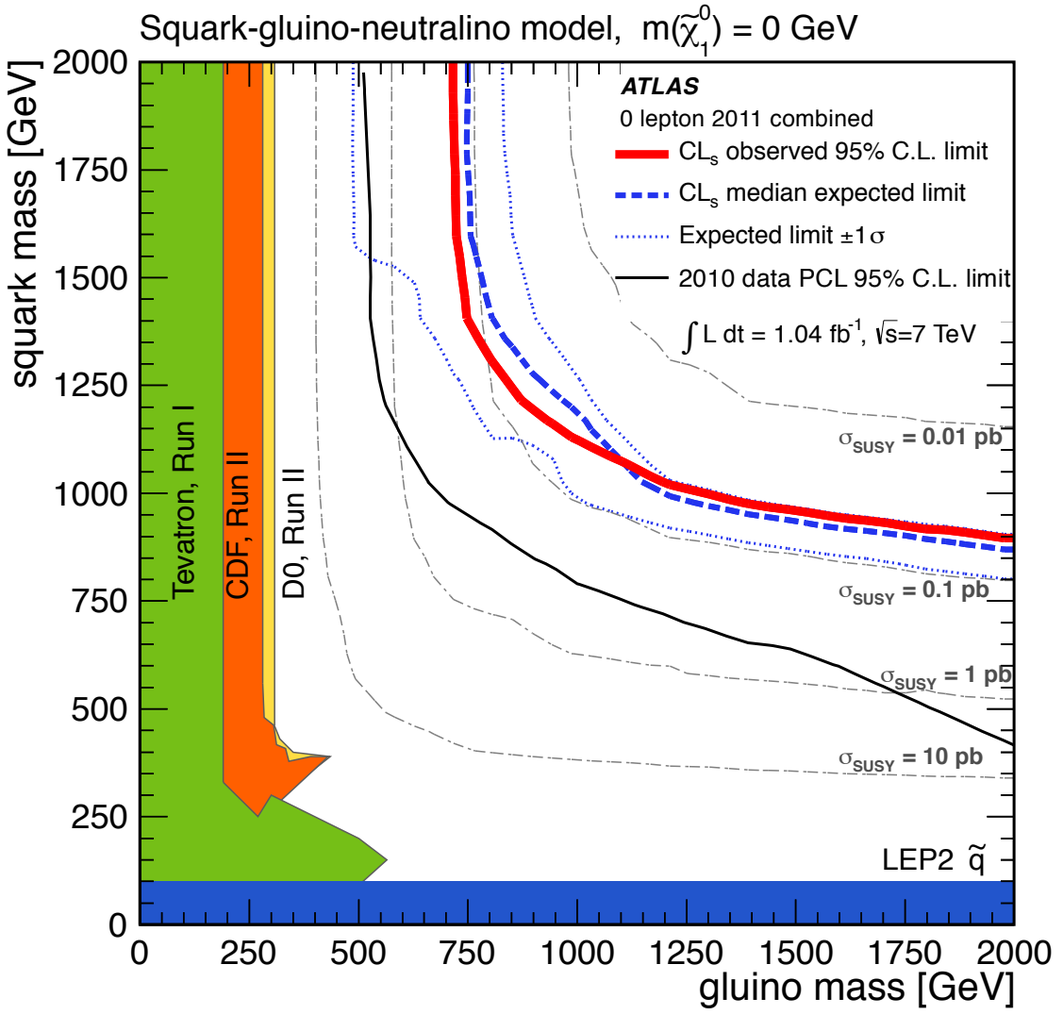
CMS and ATLAS have conducted an impressive set of searches for vanilla SUSY





CMS and ATLAS have conducted an impressive set of searches for vanilla SUSY

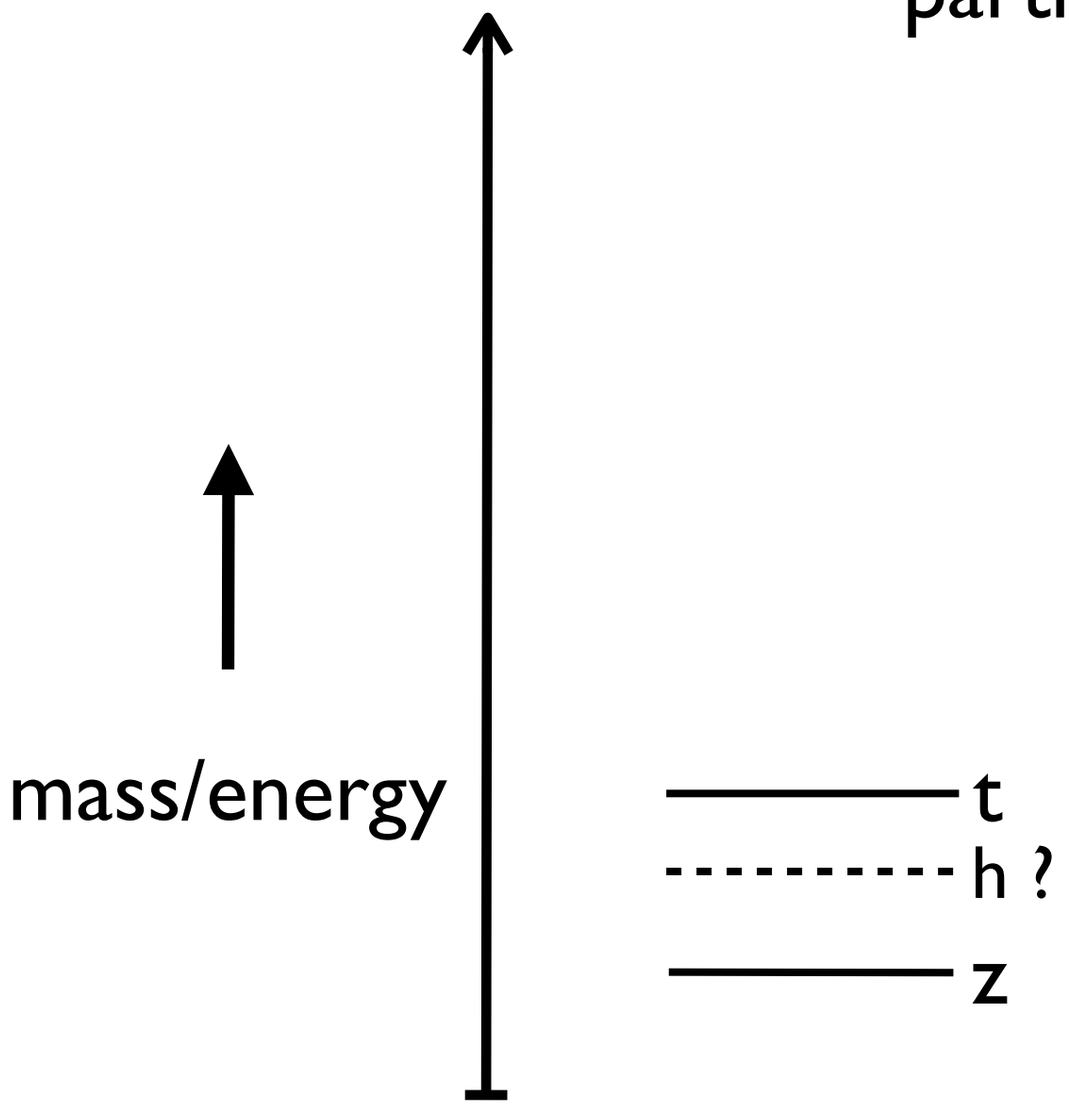




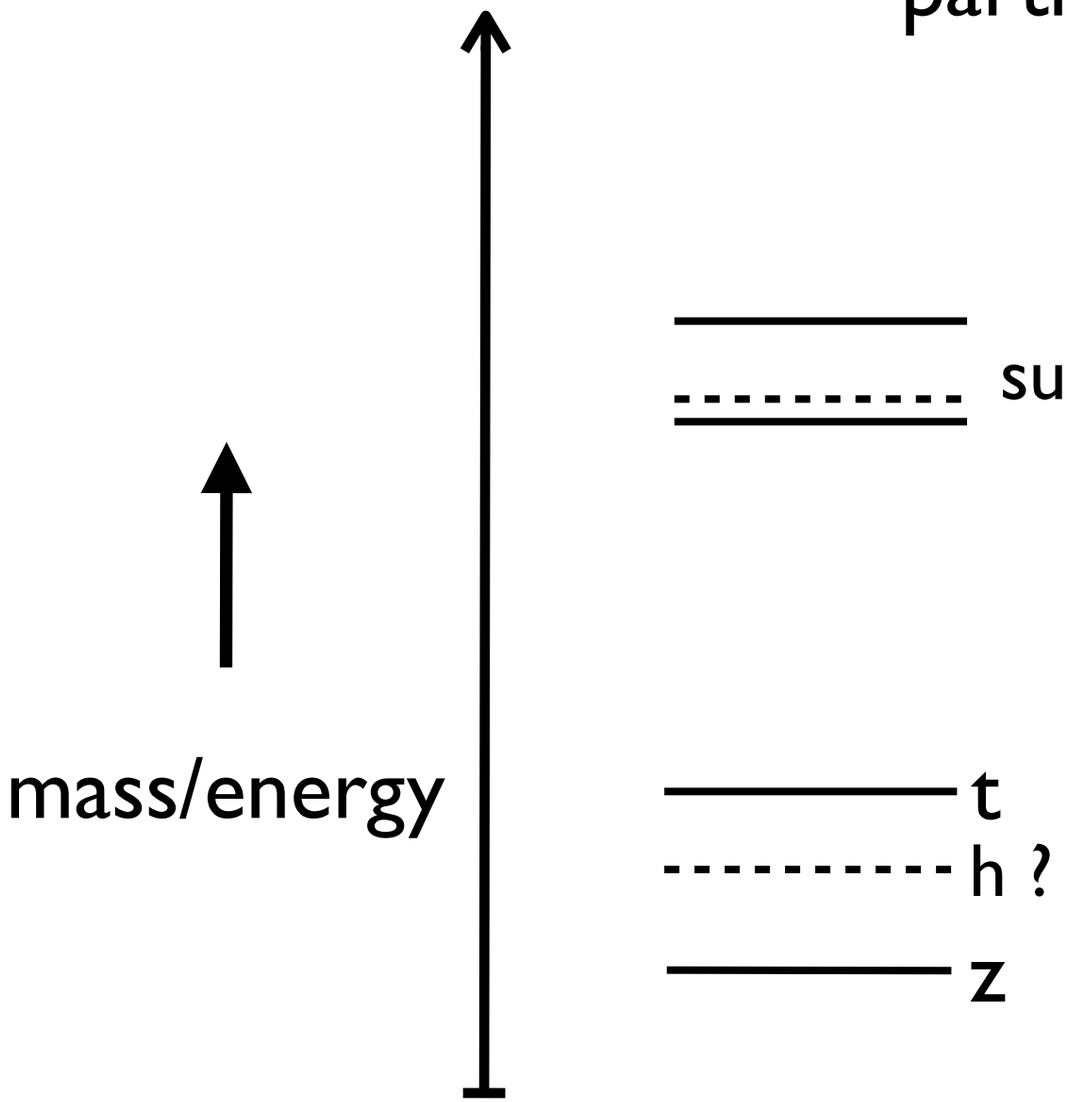
it'll be exciting to see these searches updated, but we may also want to broaden the scope...

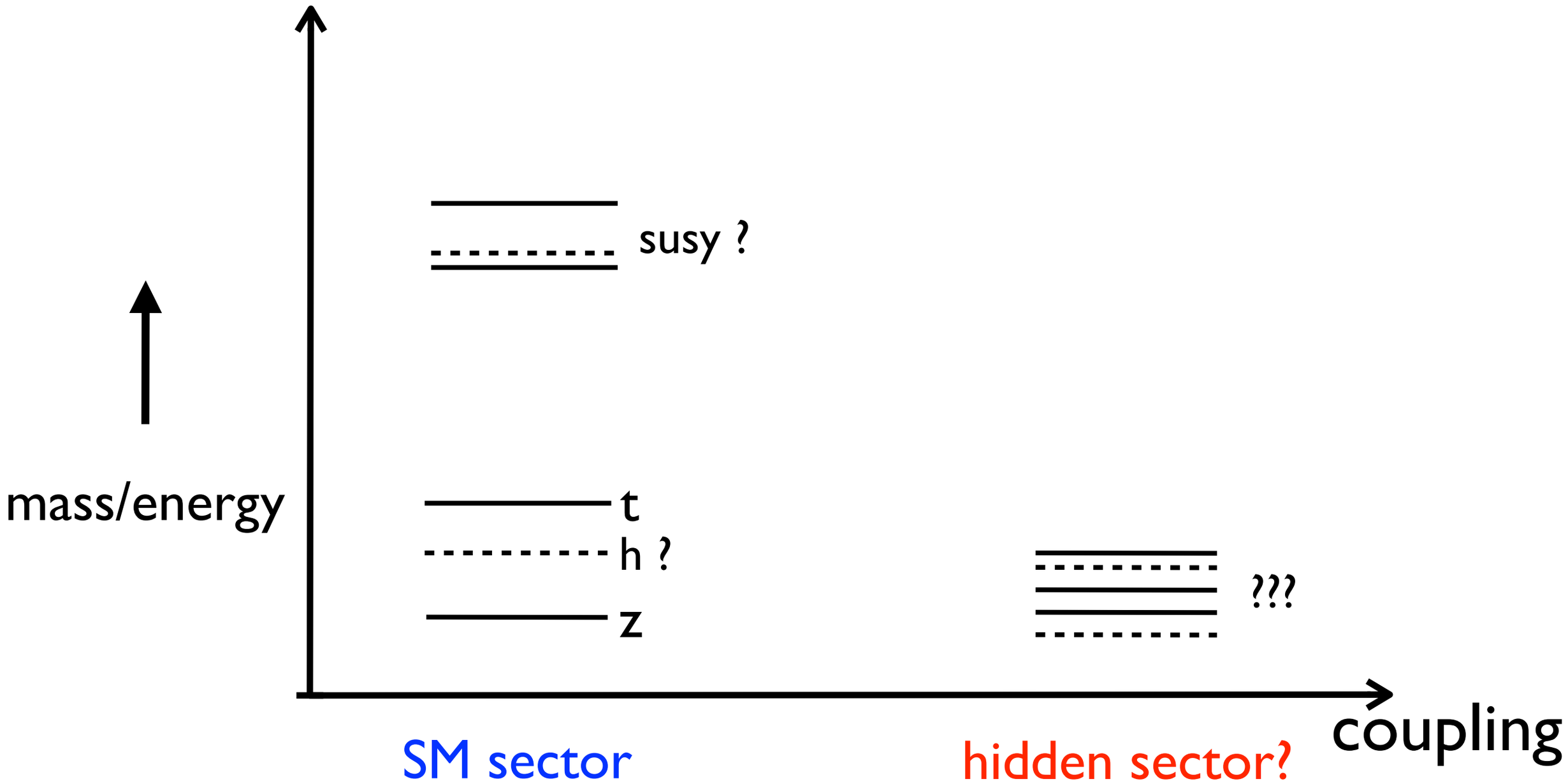
- 2011 is the year of susy (limits)
- 2012 will be the year of the higgs
- 2013, year of exotica?

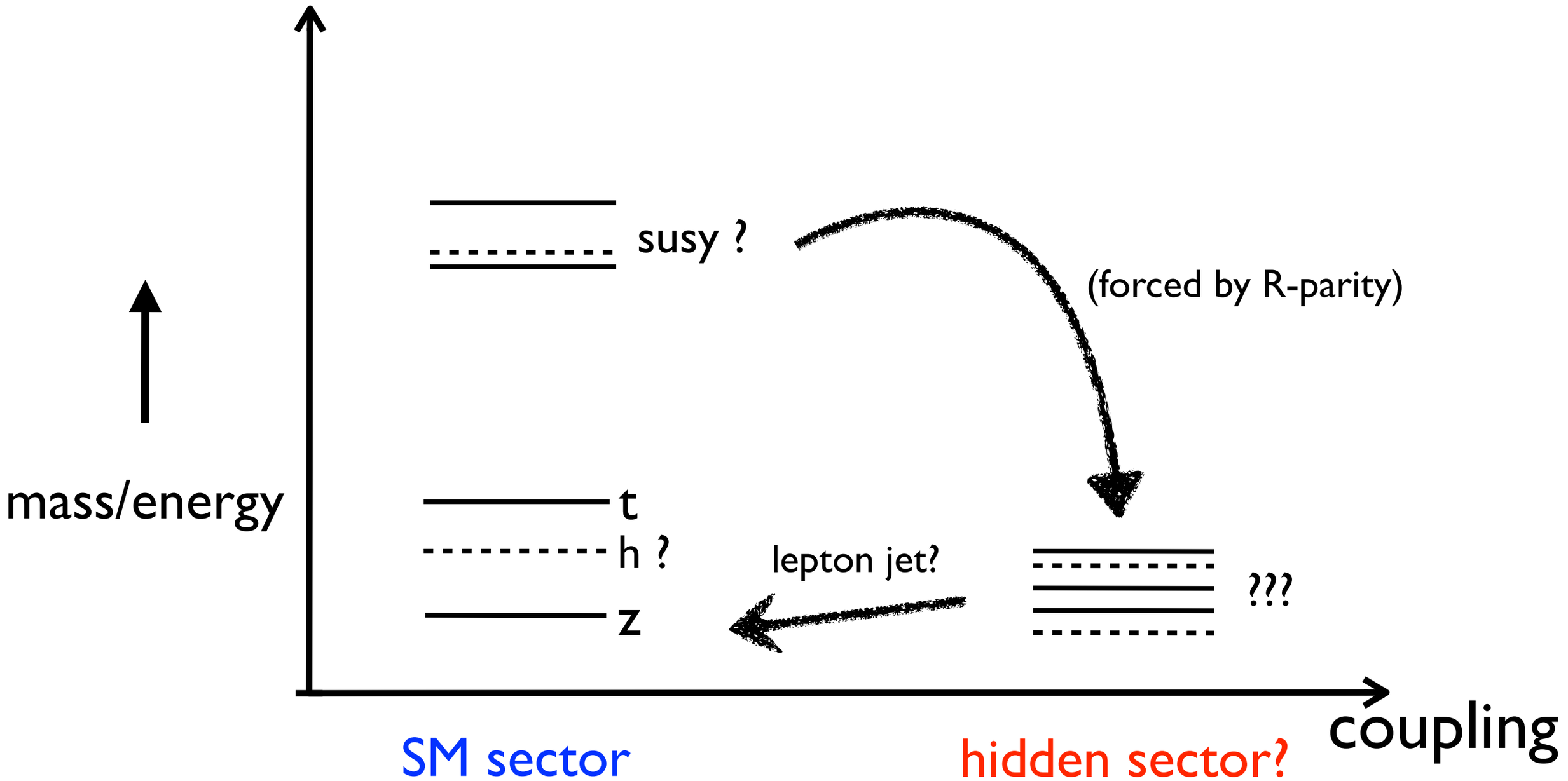
The usual way we think about particle physics:



The usual way we think about particle physics:




susy ?
mass/energy
t
h ?
z
???
coupling
SM sector
hidden sector?



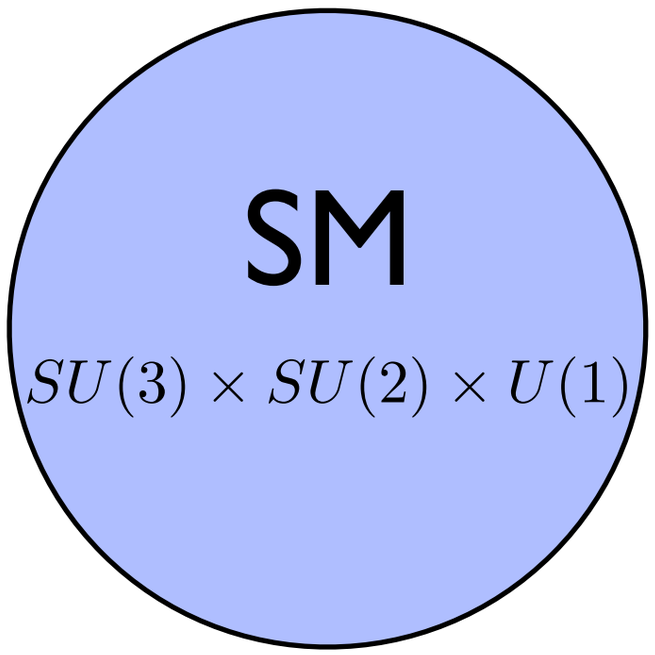
a light hidden sector could completely change
the way we need to look for heavy states

the plan

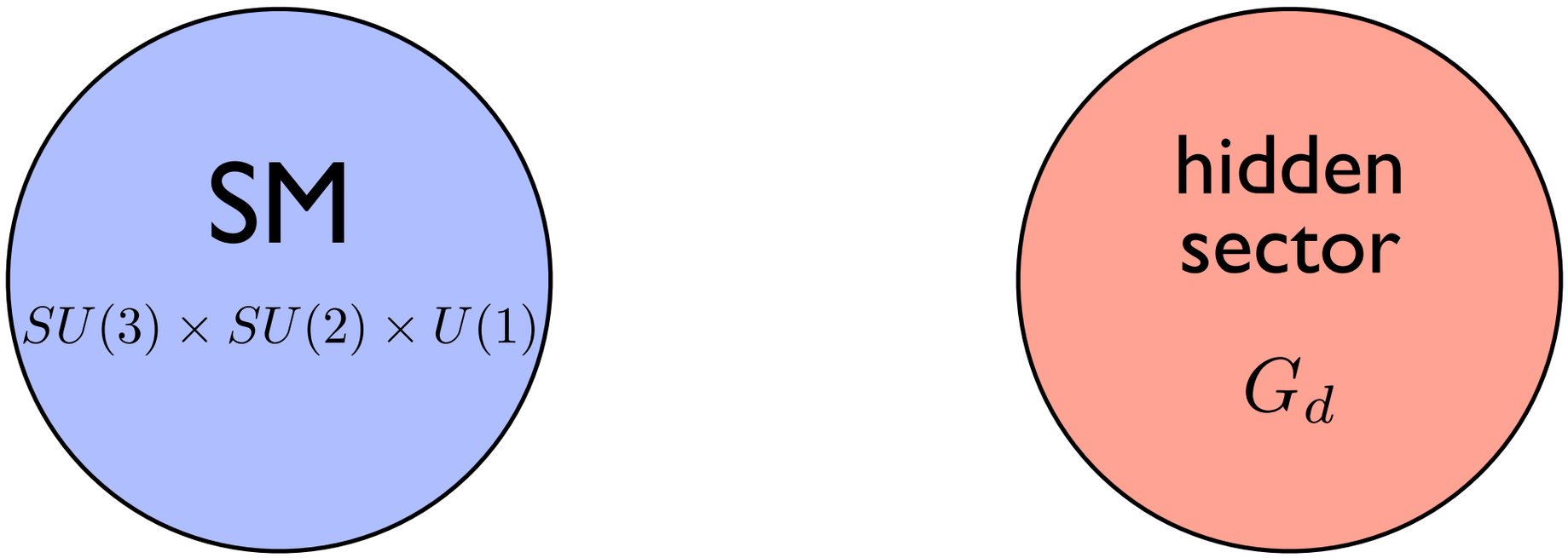
1. lepton jet primer
2. motivations for light hidden sectors
3. lepton jet signature space
4. searches so far (and how to evade them)

lepton jet primer

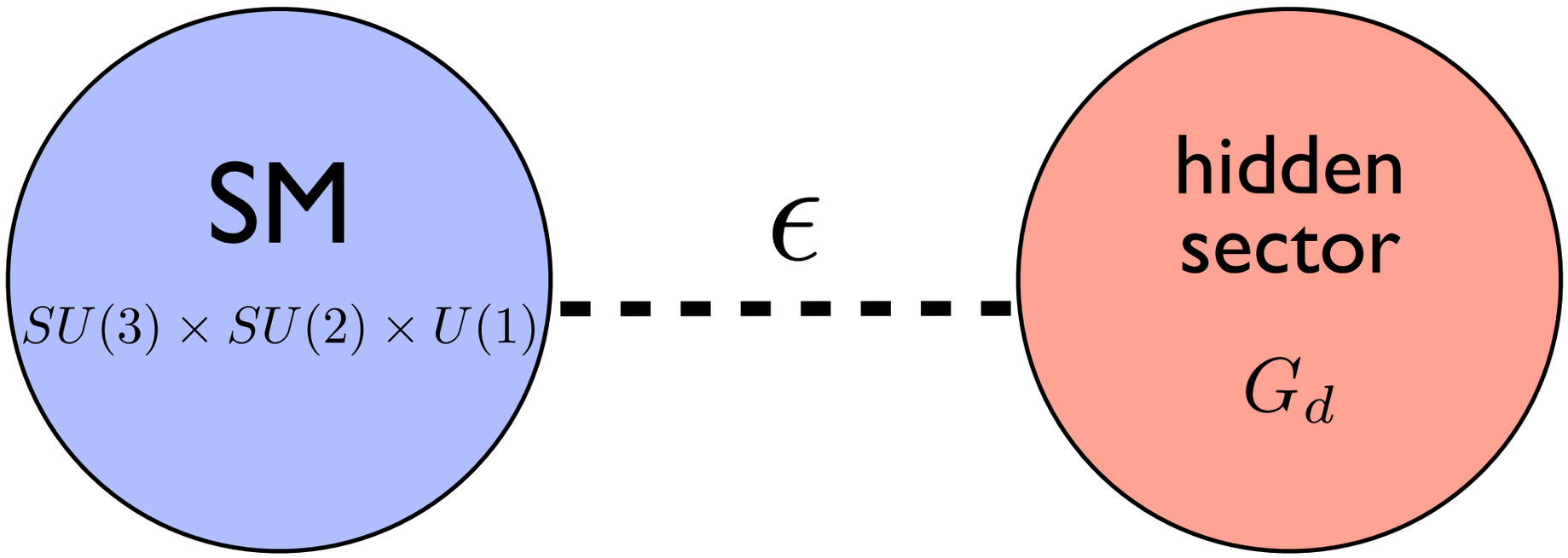
the scenario



the scenario



the scenario

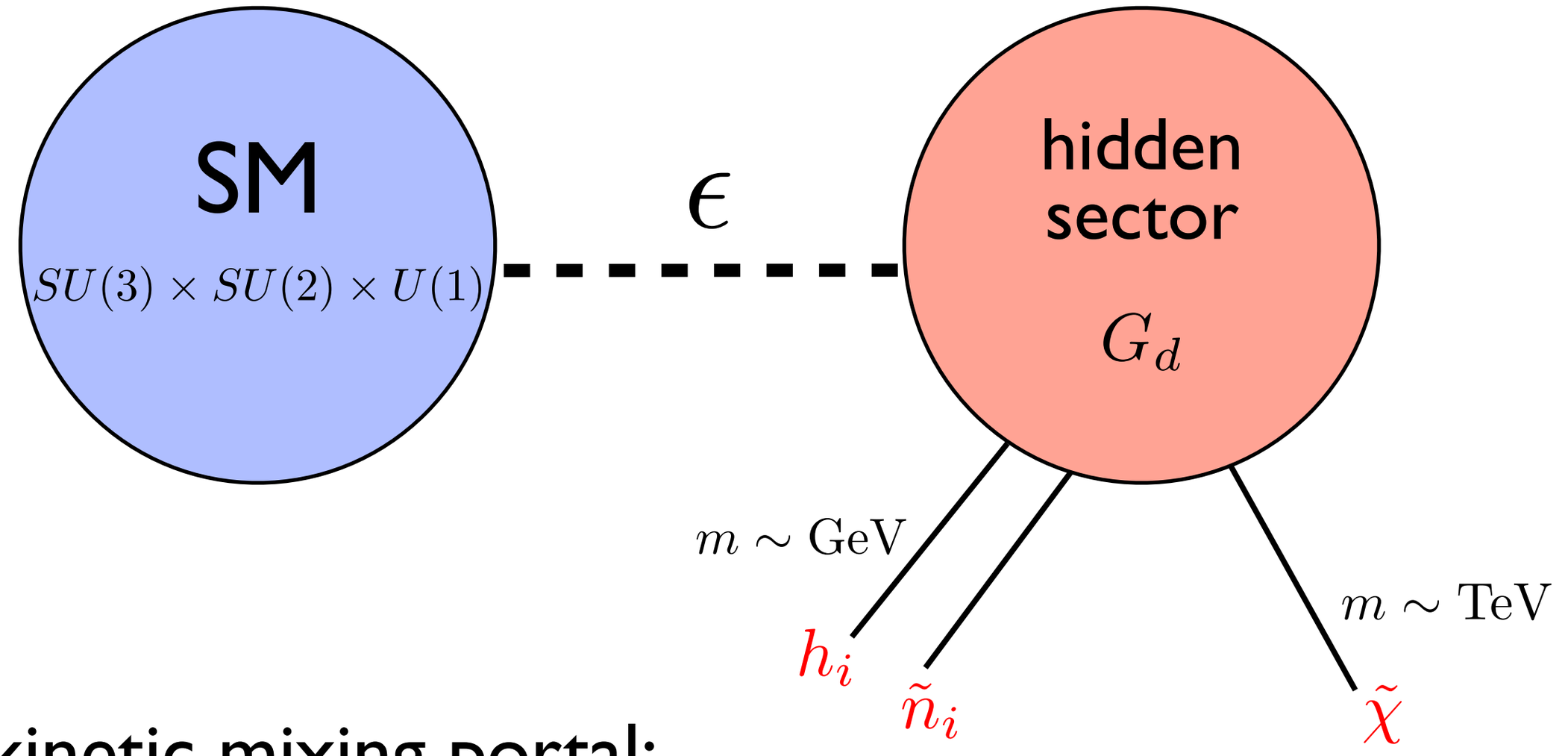


kinetic mixing portal:

$$\mathcal{L} \supset \frac{\epsilon}{2} b_{\mu\nu} F^{\mu\nu} \qquad \epsilon \lesssim 10^{-3}$$

Bob Holdom, 1986.

the scenario



kinetic mixing portal:

$$\mathcal{L} \supset \frac{\epsilon}{2} b_{\mu\nu} F^{\mu\nu} \qquad \epsilon \lesssim 10^{-3}$$

Bob Holdom, 1986.

kinetic mixing

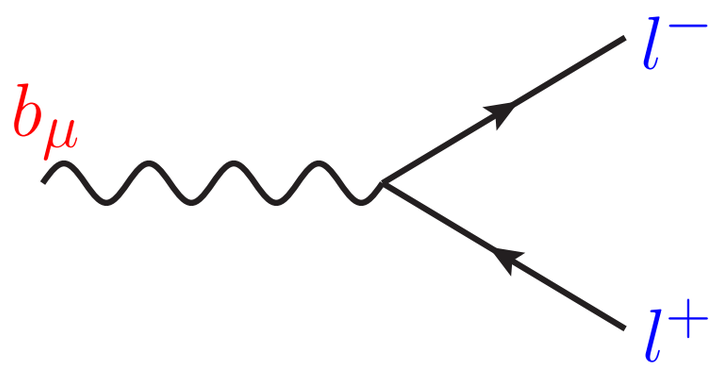
$$\mathcal{L} \supset -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} b^{\mu\nu} b_{\mu\nu} + \frac{\epsilon}{2} F^{\mu\nu} b_{\mu\nu}$$
$$+ \; m_b \, b^2 + A_\mu J^\mu_{EM} + b_\mu J^\mu_b$$

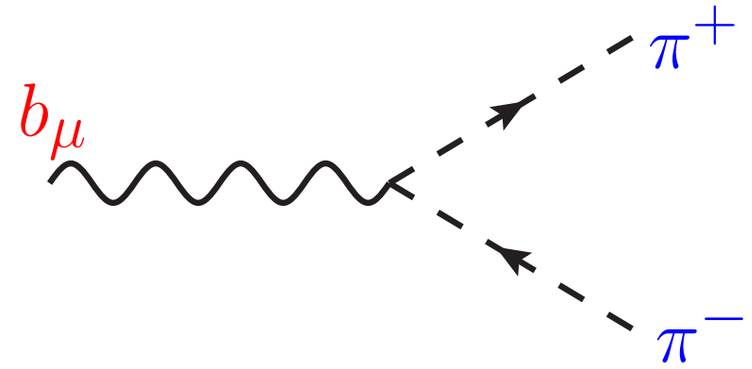
the simplest way to deal with kinetic mixing is to get rid of it,

$$A_\mu \to A_\mu + \epsilon \, b_\mu$$

leading to the interactions,

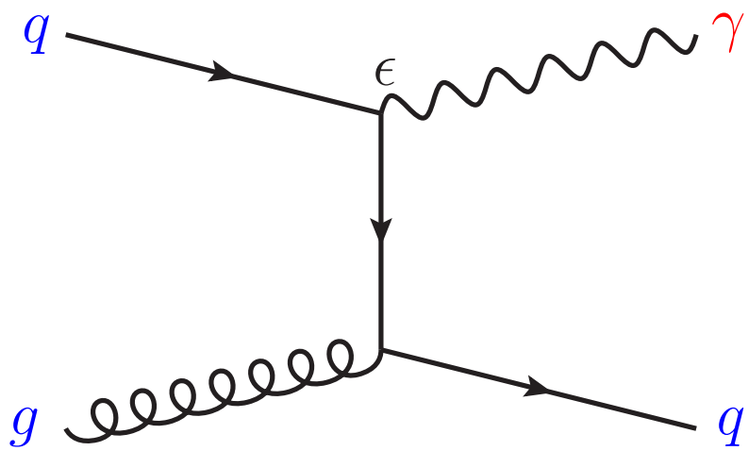
$\mathcal{L} \supset b_\mu J^\mu_{EM}$

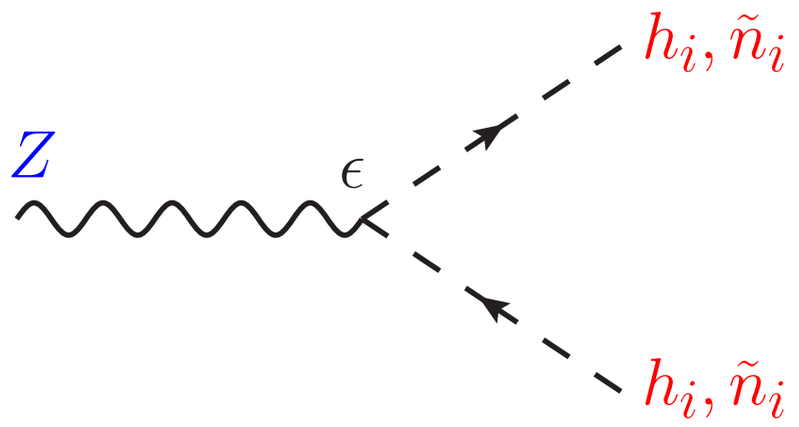




us to them

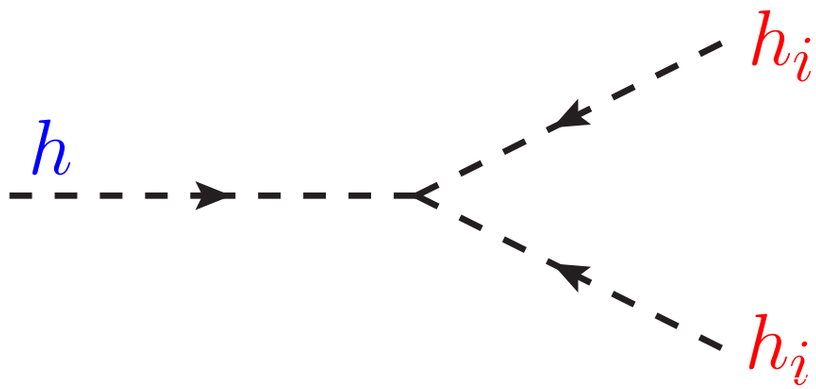
- through the kinetic mixing:





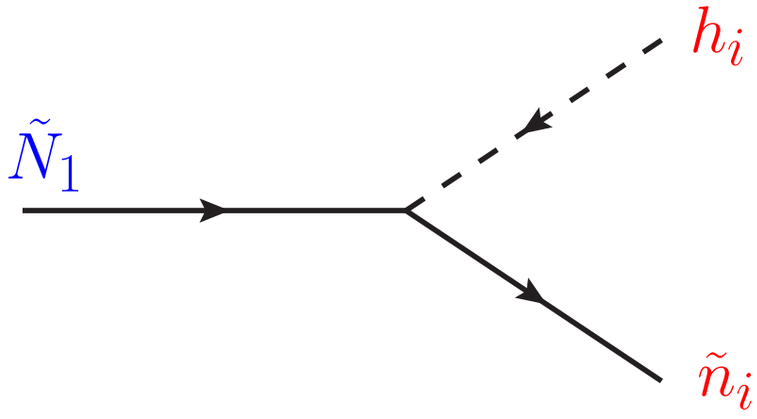
- through higgs portal:

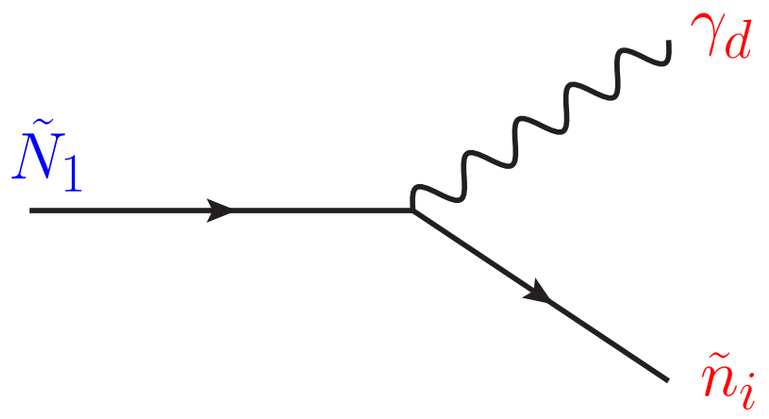
$$\mathcal{L} \supset |H|^2 \, |h_i|^2$$

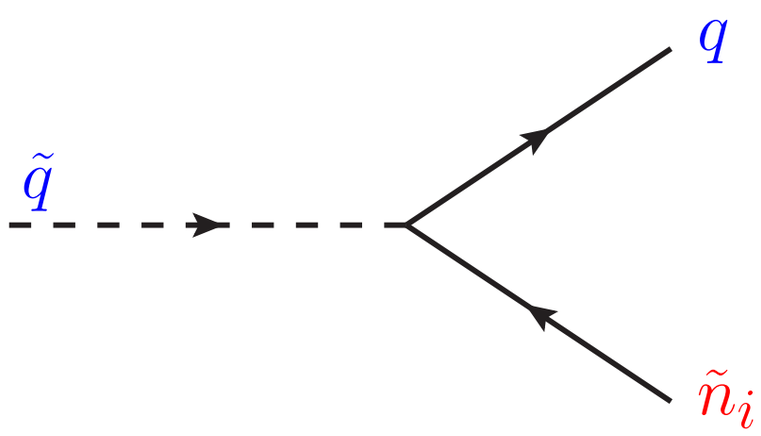


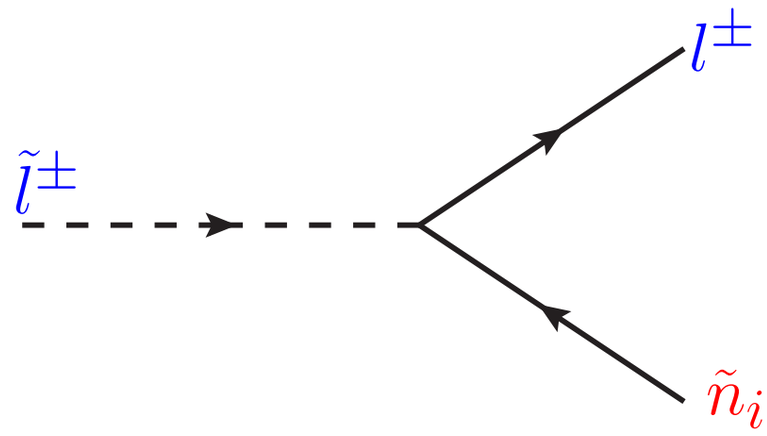
us to them

- with SUSY, R-parity forces decays into the hidden sector

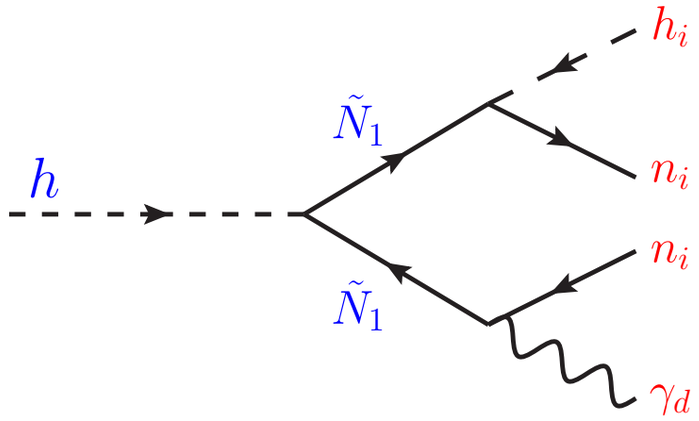






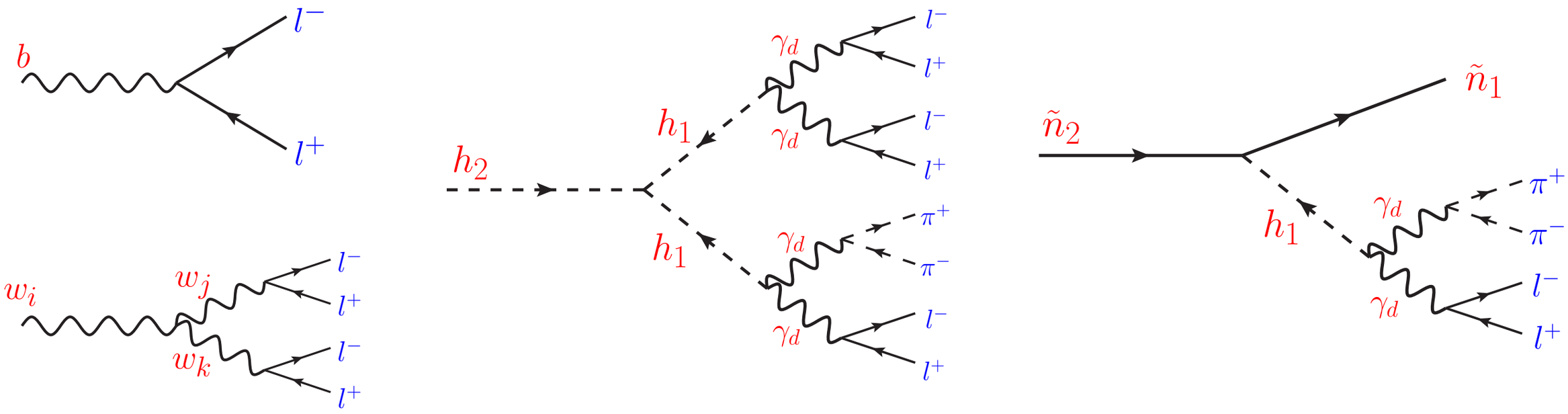


- the higgs can also decay through sparticles:



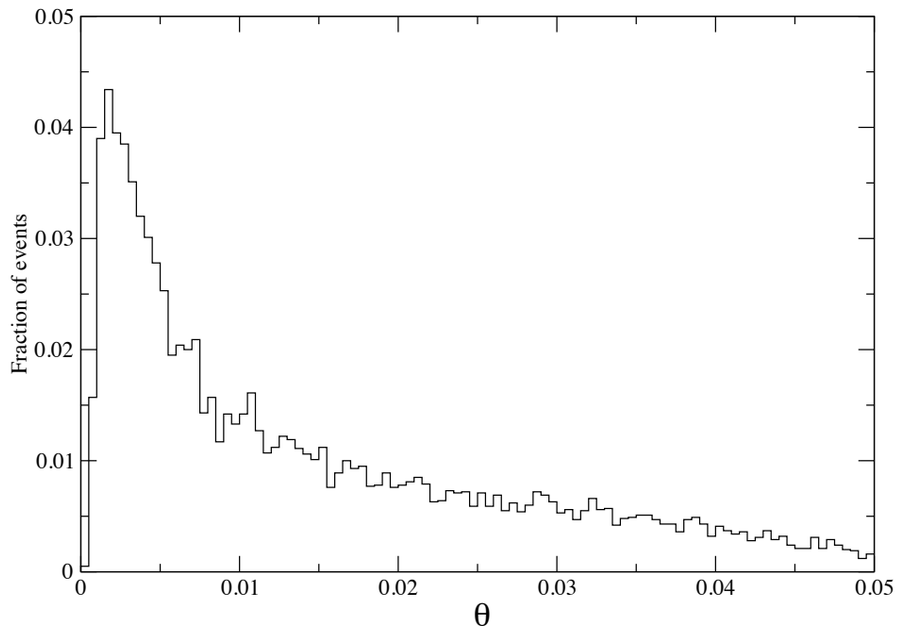
lepton jets

- hidden sector cascades will form bunches of leptons



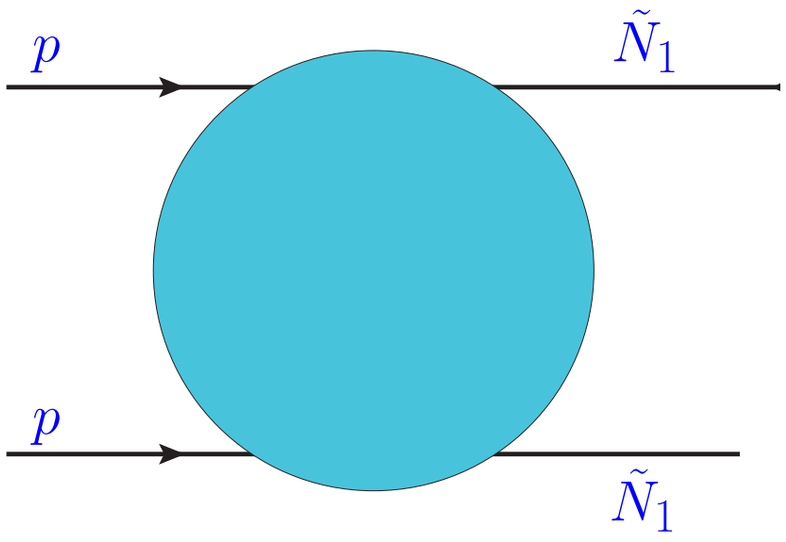
- the leptons are collimated because the hidden particles are boosted

$$\theta \sim \frac{m}{E} \sim 10^{-2}$$



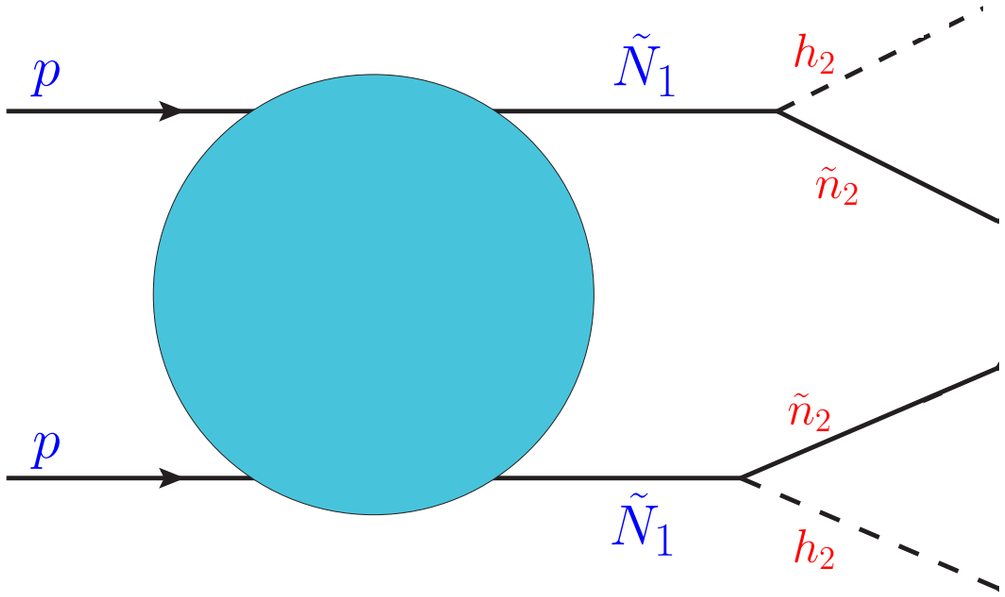
lepton jets

susy production



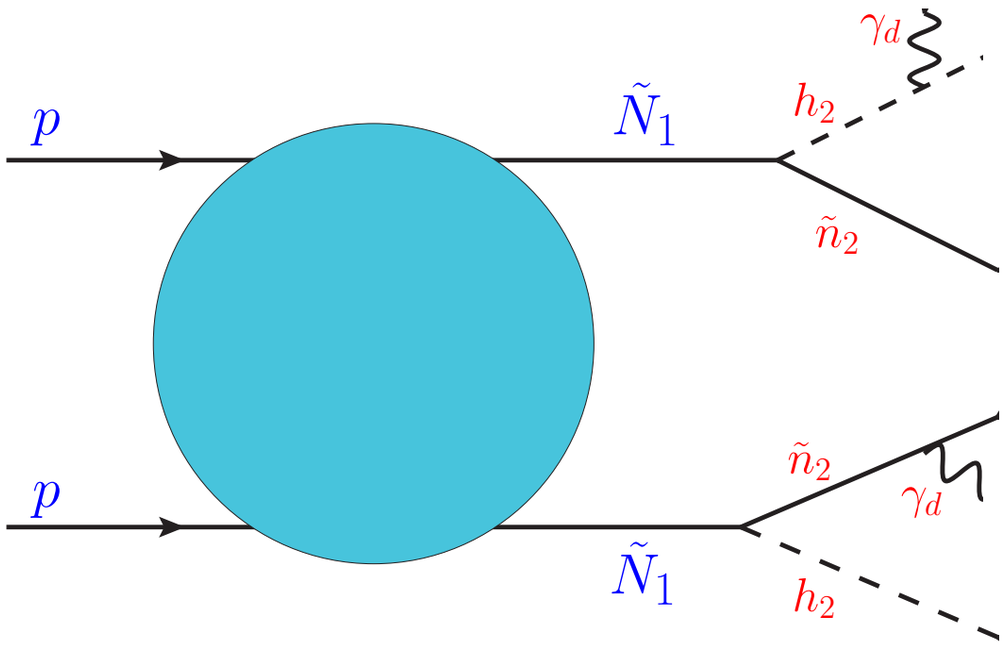
lepton jets

decay to hidden sector

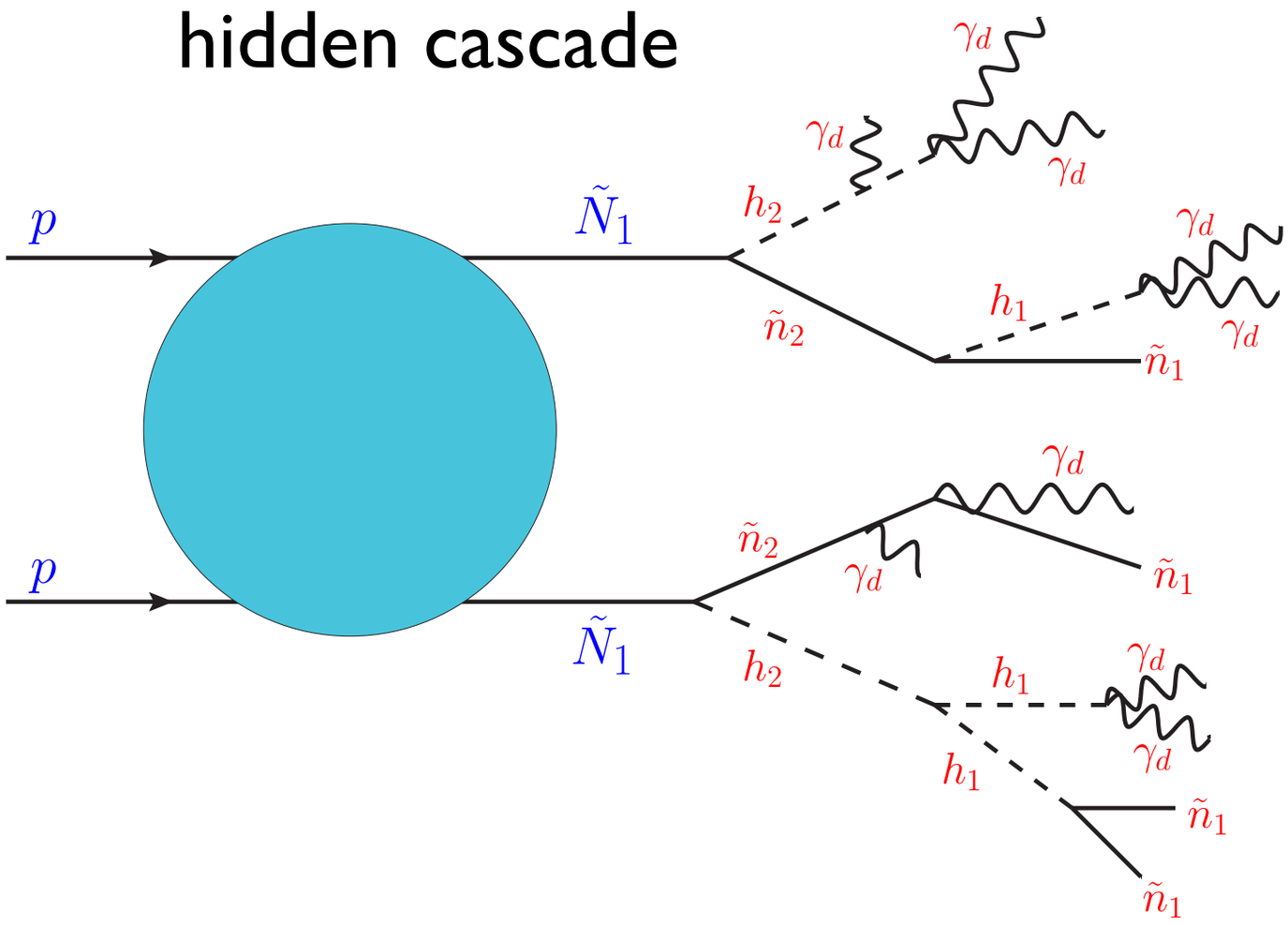


lepton jets

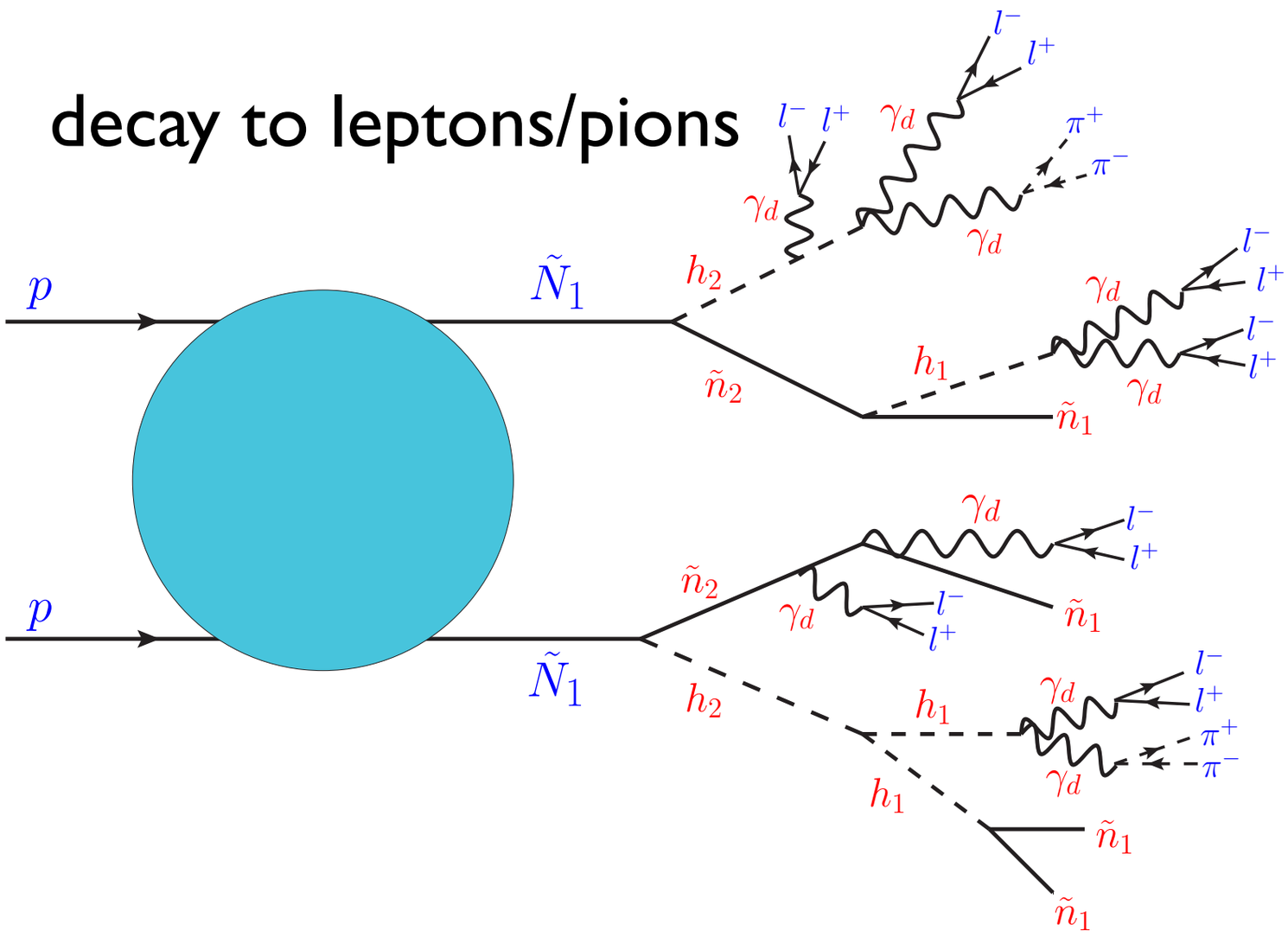
hidden showering



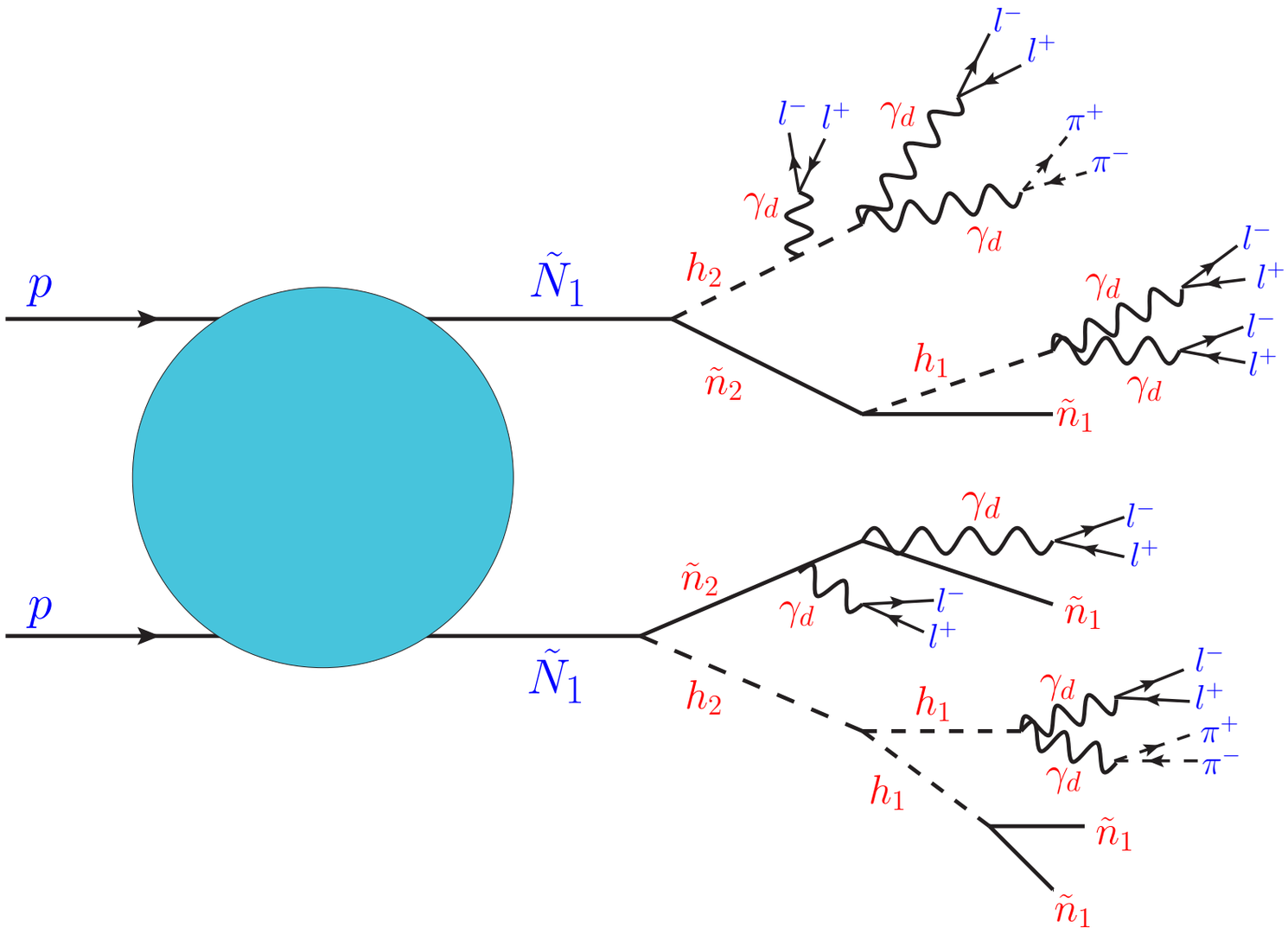
lepton jets

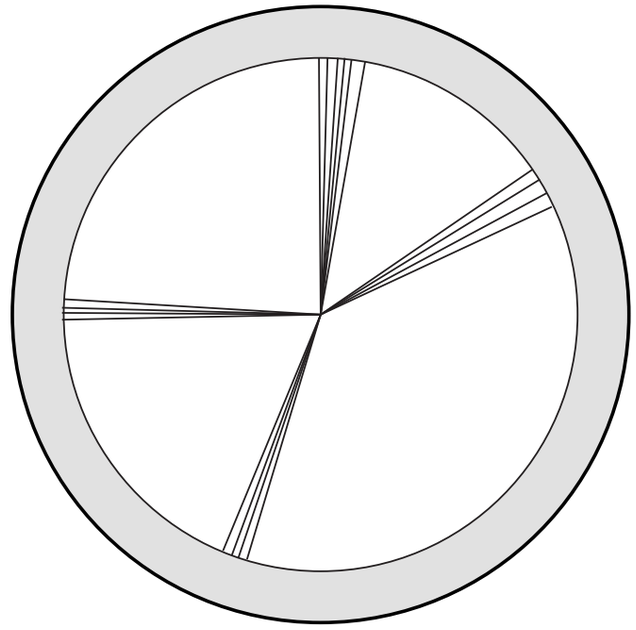

hidden cascade
p
p
$\tilde{N}_1$
$\tilde{N}_1$
h_2
γ_d
γ_d
γ_d
$\tilde{n}_2$
h_1
γ_d
$\tilde{n}_1$
γ_d
$\tilde{n}_2$
γ_d
$\tilde{n}_1$
h_2
h_1
γ_d
h_1
γ_d
$\tilde{n}_1$
$\tilde{n}_1$

lepton jets

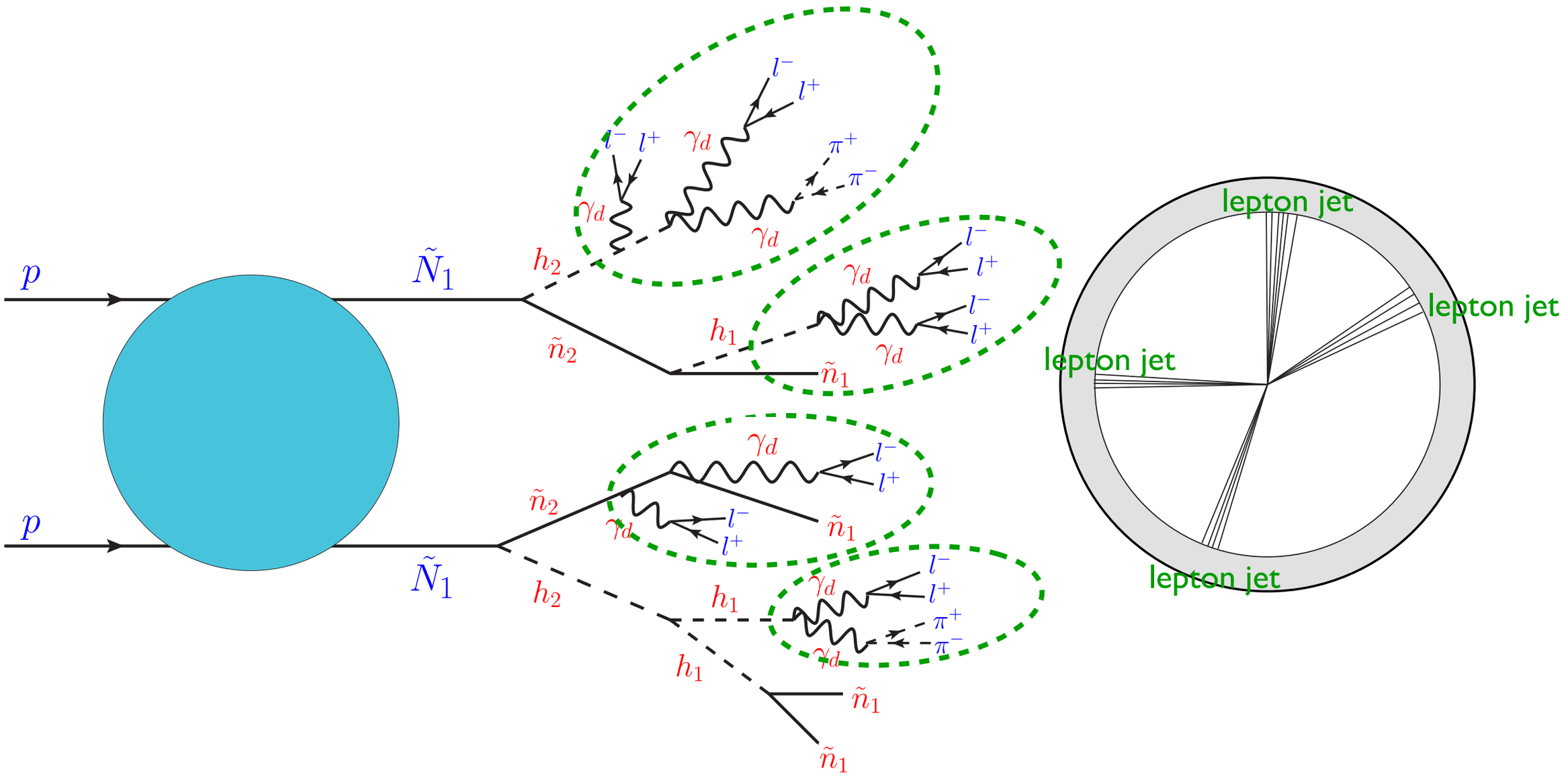

decay to leptons/pions
p
p
$\tilde{N}_1$
$\tilde{N}_1$
h_2
h_1
$\tilde{n}_2$
$\tilde{n}_1$
γ_d
l^-
l^+
π^+
π^-

lepton jets





lepton jets



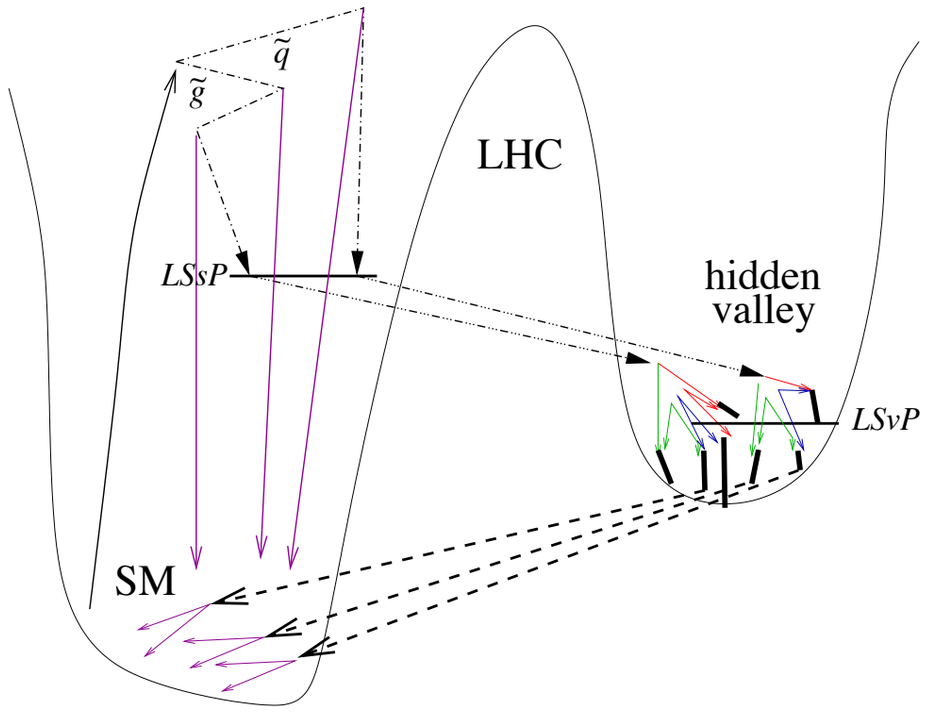
Arkani-Hamed and Weiner 0810.0714

motivations
for light hidden sectors

1. non-minimality
2. dark matter
3. natural in SUSY

1. non-minimality

- the SM is terribly non-minimal. (remember when we discovered the muon?)

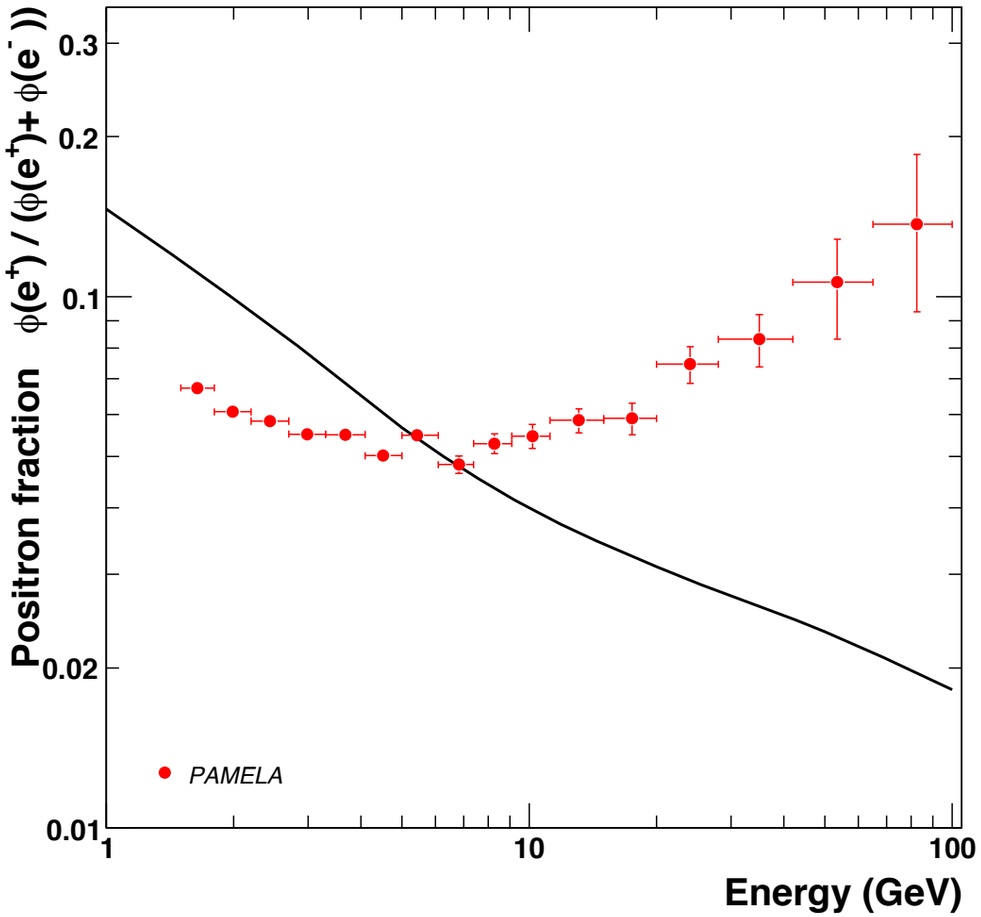


- new sectors of particles may exist, and may dramatically impact collider signals

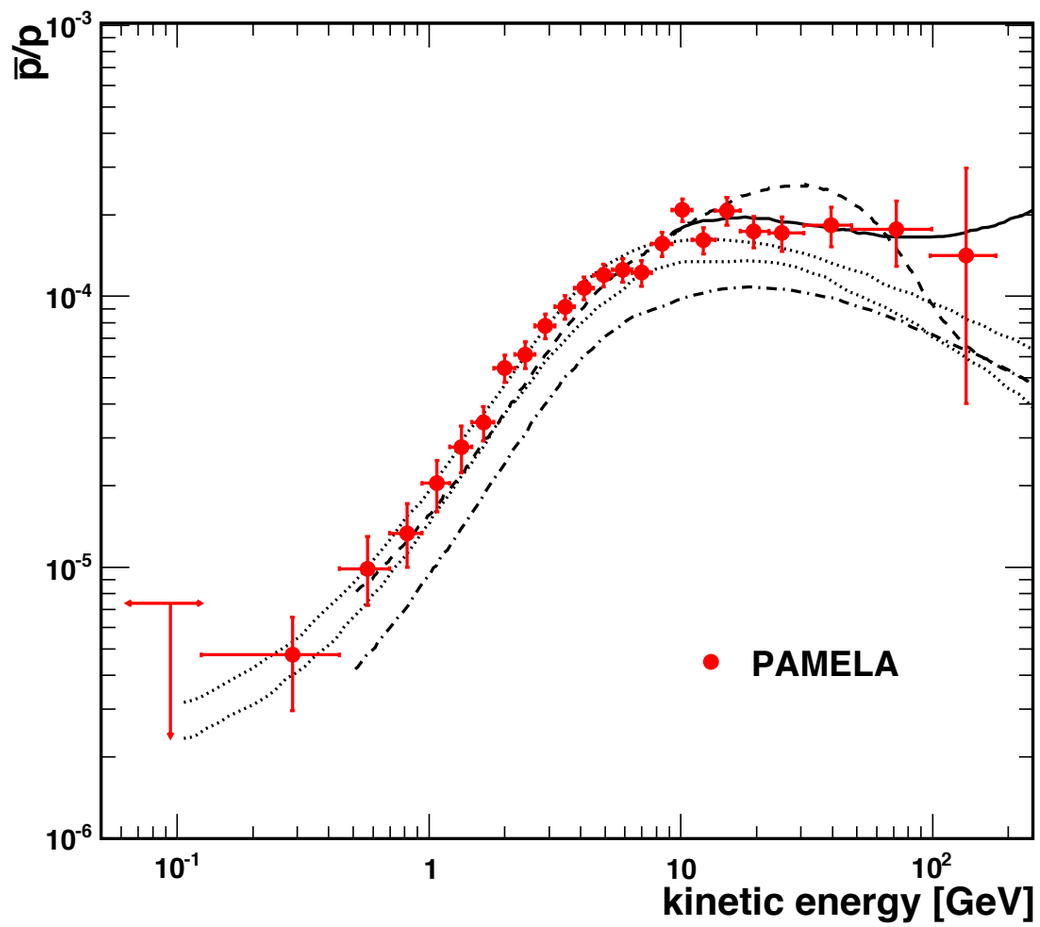
- emphasized by the "hidden valley" papers

M. Strassler and K. Zurek, 0604261, 0605193, 0607160

2. dark matter



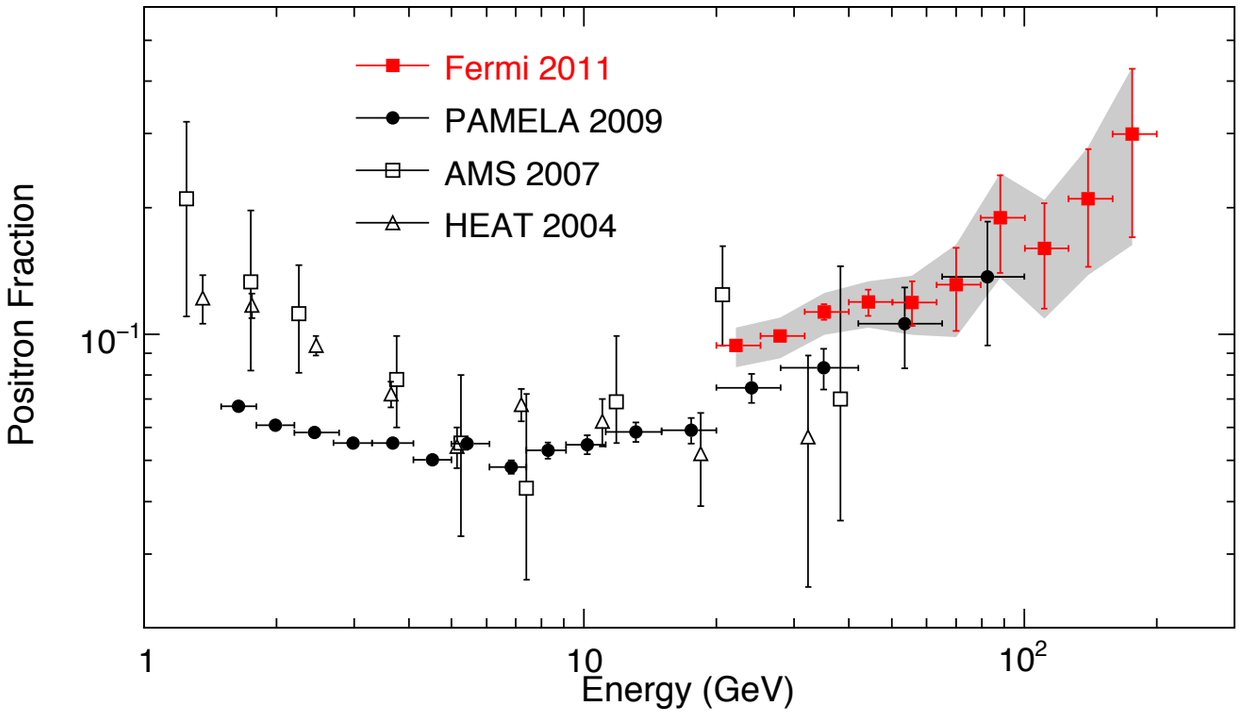
PAMELA 0810.4995



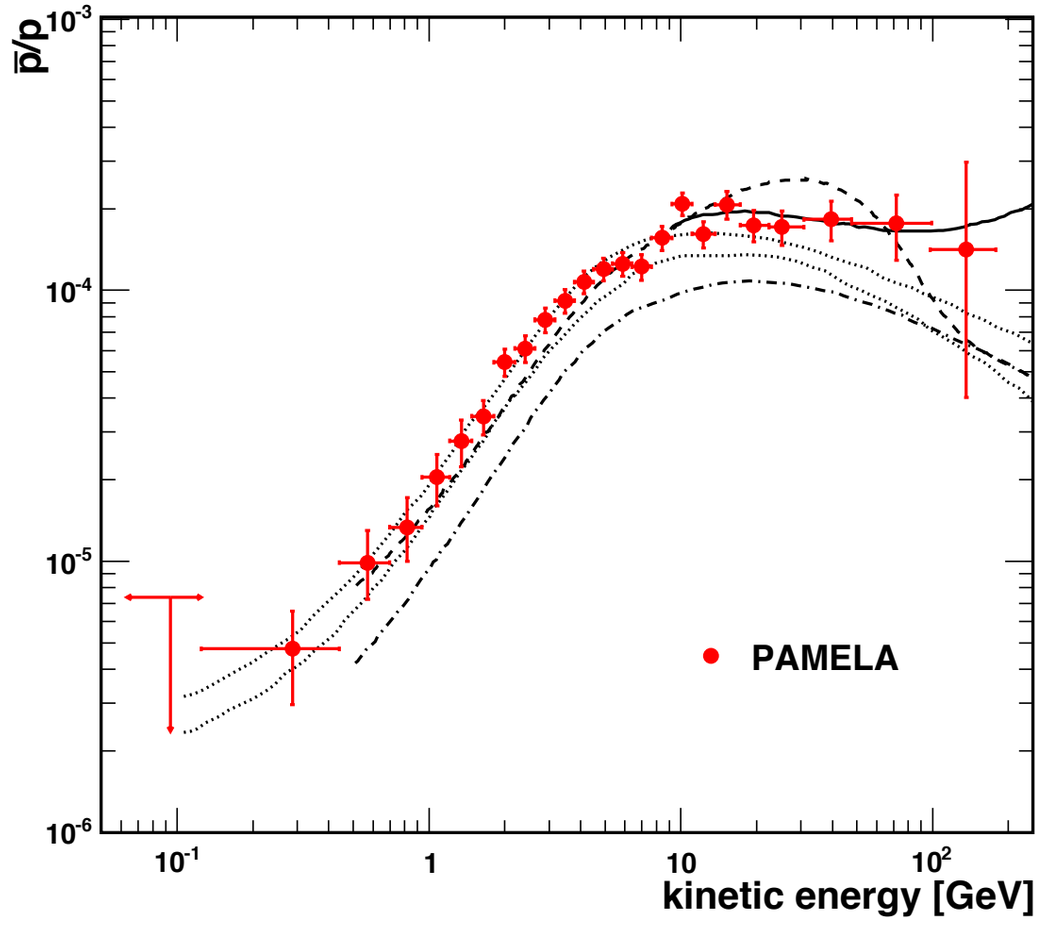
PAMELA 1007.0821

there is an excess in the positron, but not antiproton, fraction of cosmic rays

2. dark matter



PAMELA 0810.4995
FERMI 1109.0521



PAMELA 1007.0821

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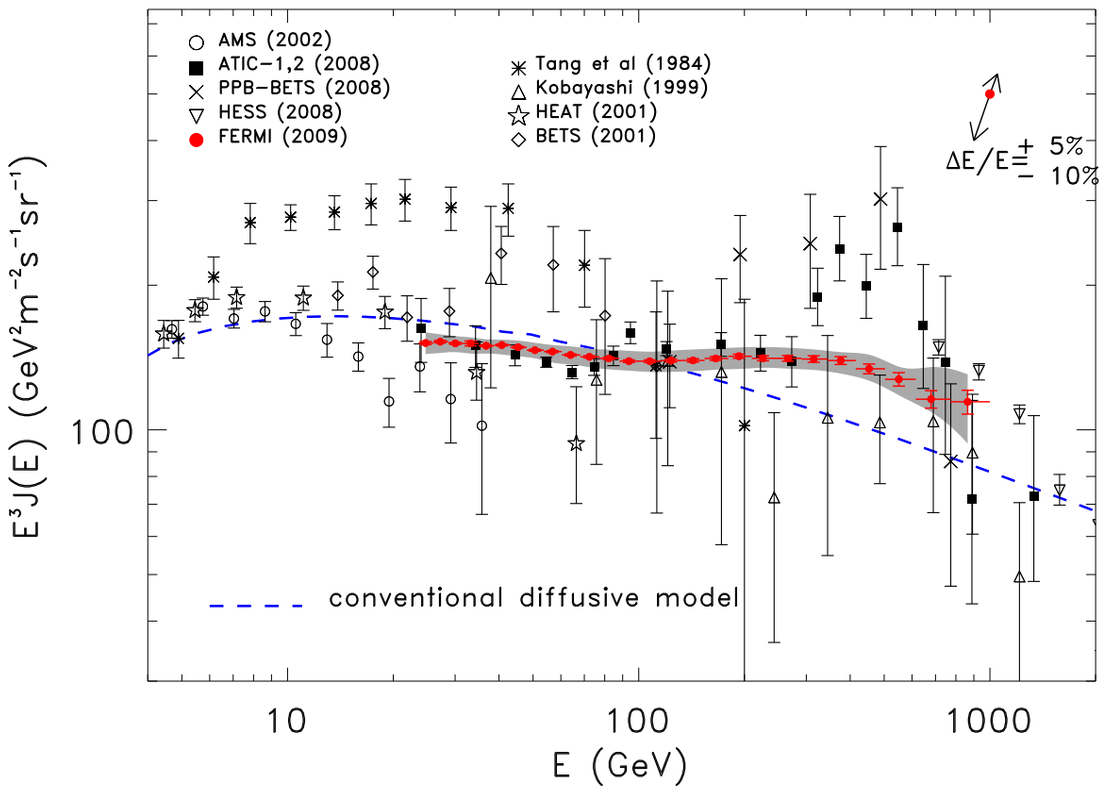
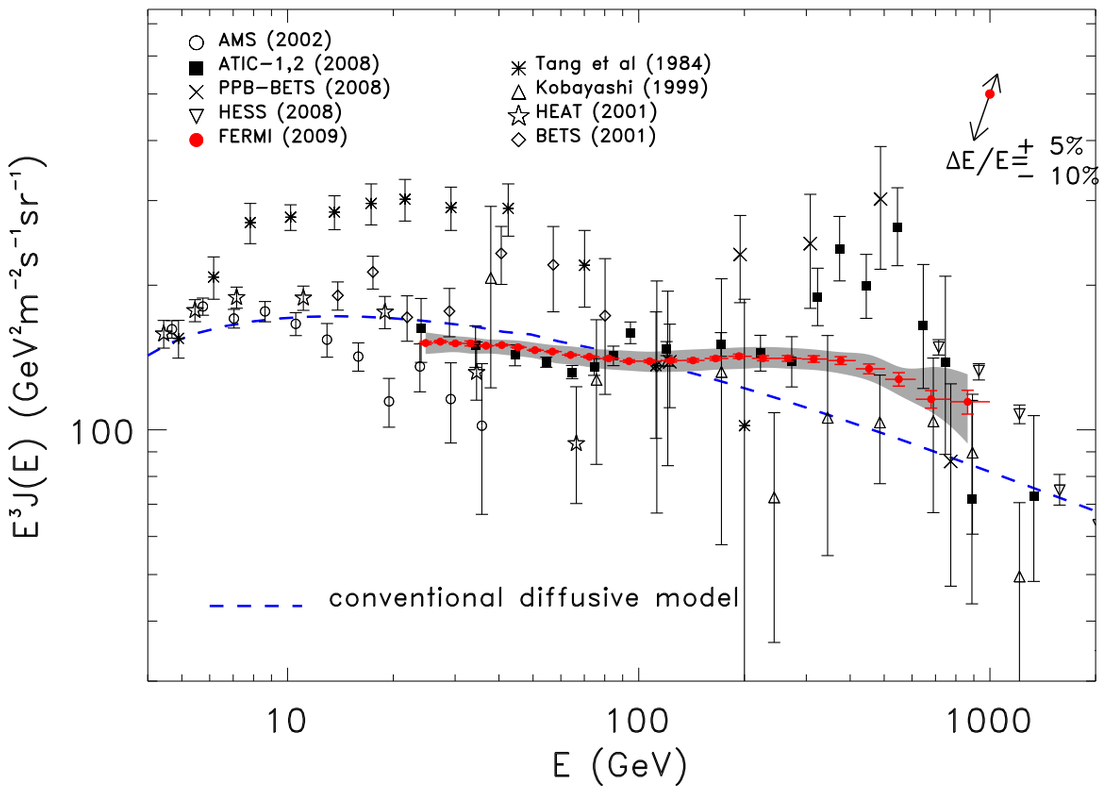
2. dark matter



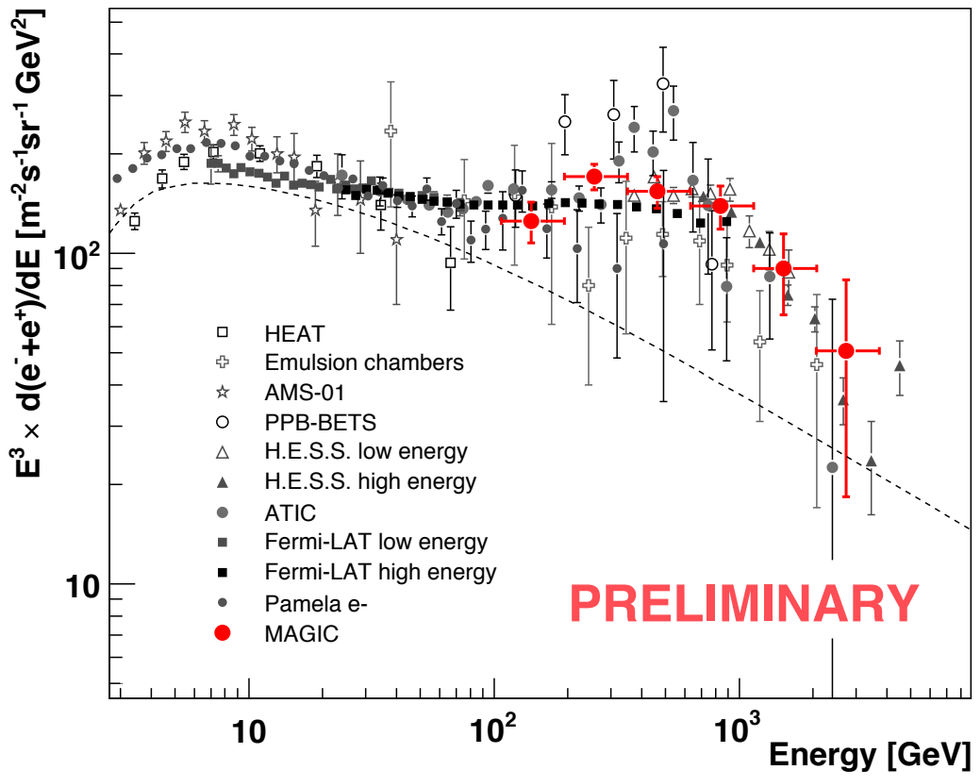
FERMI 0905.0025

there is also a broad excess in the electron + positron spectrum

2. dark matter



FERMI 0905.0025



MAGIC 1110.4008

there is also a broad excess in the electron
+ positron spectrum

2. dark matter

- the positron and total $e^- + e^+$ excesses are consistent with one new source

Meade, Papucci, Strumia, Volansky 0810.4995

- could be pulsars?

- could be dark matter, but not vanilla SUSY DM:

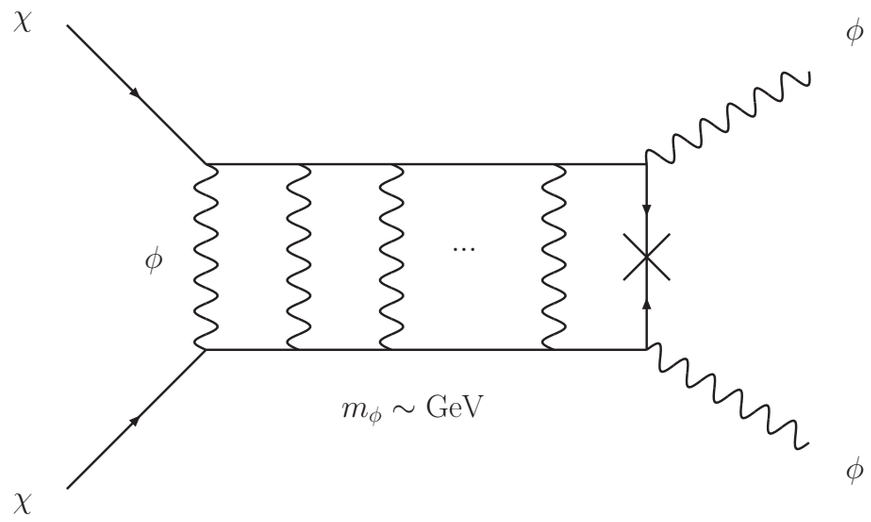
1. too large cross-section $\sigma \sim 10^{2-3}\, \sigma_{wimp}$
2. need leptons but not hadrons

The cosmic rays can be explained by dark matter charged under a light hidden sector.

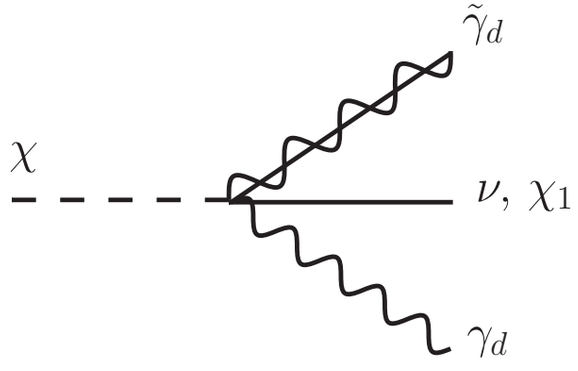
1. annihilate into hidden sector

- large rate from Sommerfeld enhancement
- leptons but not antiprotons from kinematics

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 0810.0713.



2. decay into hidden sector



- rate from higher dimension operator (ex. GUT scale)
- leptons but not antiprotons from kinematics

JTR, Volansky 0908.1570.

3. natural in SUSY

- why should the GeV scale appear, and does it introduce a new hierarchy problem?

- suppose you start with kinetic mixing

$$\mathcal{L} \supset \frac{\epsilon}{2} b_{\mu\nu} F^{\mu\nu}$$

- a typical size for ϵ is: $\epsilon \approx \frac{\alpha_{EM}}{4\pi} \frac{g_{dark}}{g_{SM}} \approx 10^{-4}$

- in SUSY theories the hidden photon automatically gets a mass from interacting with the SM

$$m_b \approx \sqrt{\epsilon}\, m_Z \sim \mathrm{GeV}$$

Baumgart, Cheung, JTR, Wang, Yavin, 0901.0283
Cheung, JTR, Wang, Yavin, 0902.3246

lepton jet signature space

Global Event Properties:

number of LJ's	other objects	MET

Lepton Jet Properties:

composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

Global Event Properties:

number of LJ's	other objects	MET

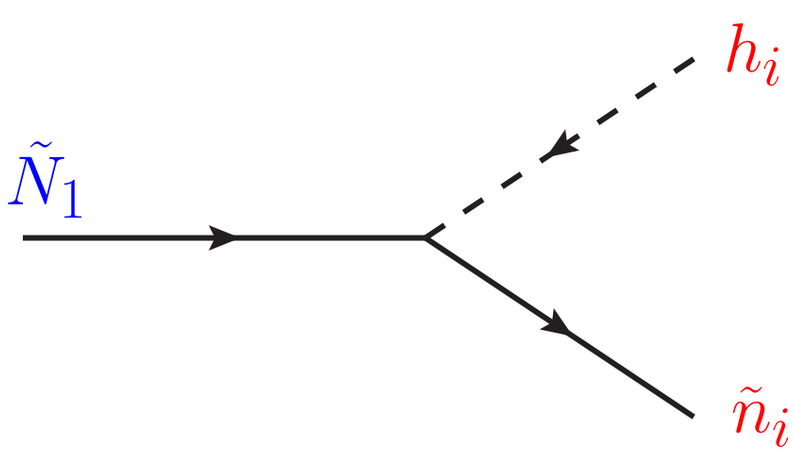
Lepton Jet Properties:

composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

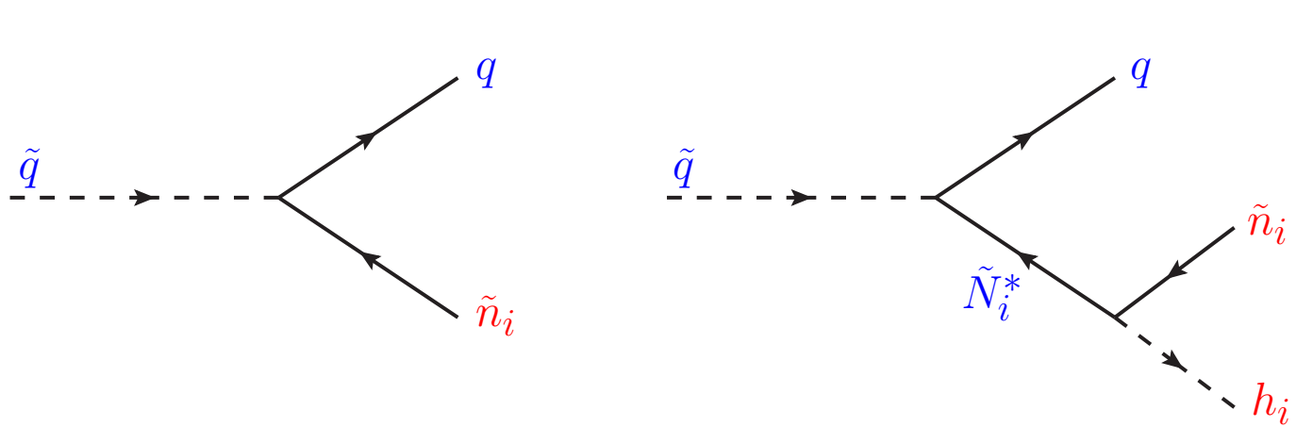
number of lepton jets

- depends on the production mode
- with SUSY, depends on the LSP

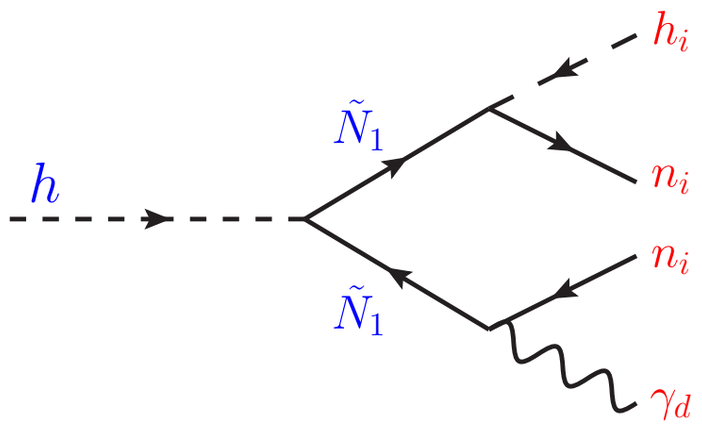
$\tilde{N}_1\tilde{N}_1 \to 4\,LJ$



$\tilde{q}\tilde{q}\ (\tilde{l}\tilde{l}) \to 2, 4\,LJ$



- higgs ⟶ 2 or 4 LJ
  depending on $m_{\tilde{N}_1}$



Global Event Properties:

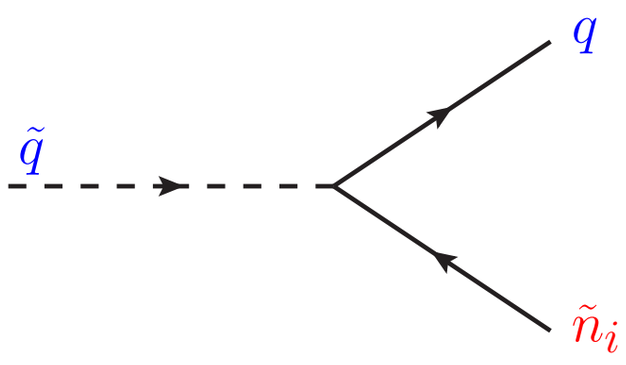
number of LJ's	other objects	MET

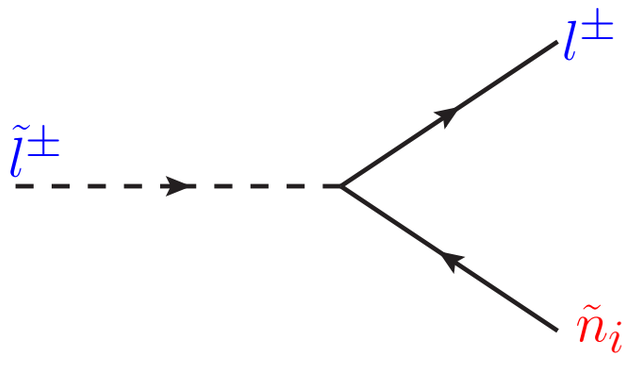
Lepton Jet Properties:

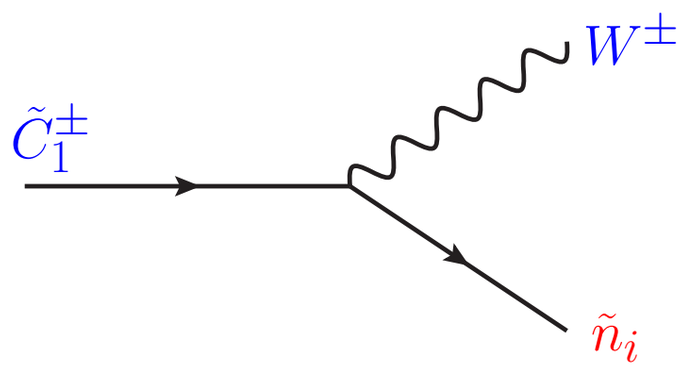
composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

other objects

- also depends on the production mode and SUSY spectrum
- jets/leptons can come from the susy cascade
- there can be associated objects depending on the LSP







Global Event Properties:

number of LJ's	other objects	MET

Lepton Jet Properties:

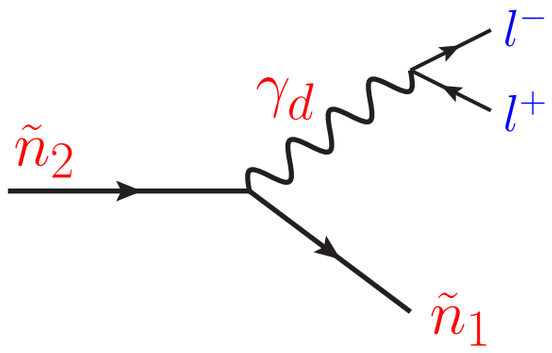
composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

missing energy

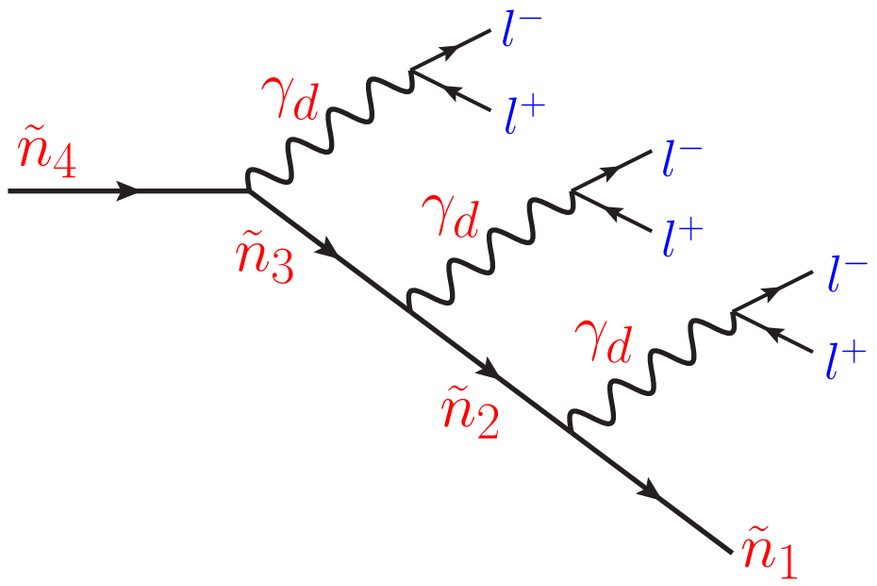
- with SUSY, the LSP of the hidden sector contributes to missing energy
- the amount of missing energy depends on the length of the hidden cascades

MET ~ 100%

MET ~ 50%



MET ~ 12.5%



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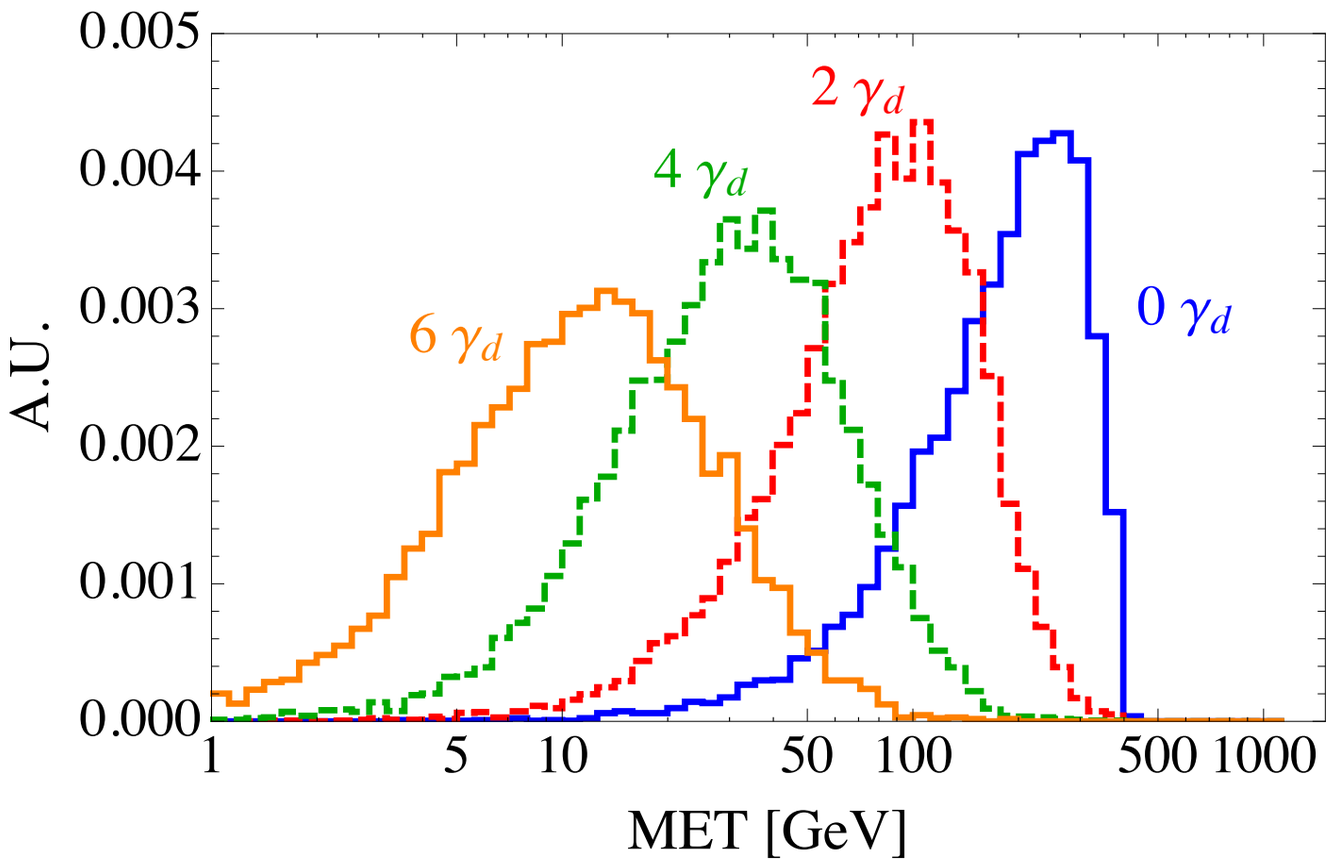
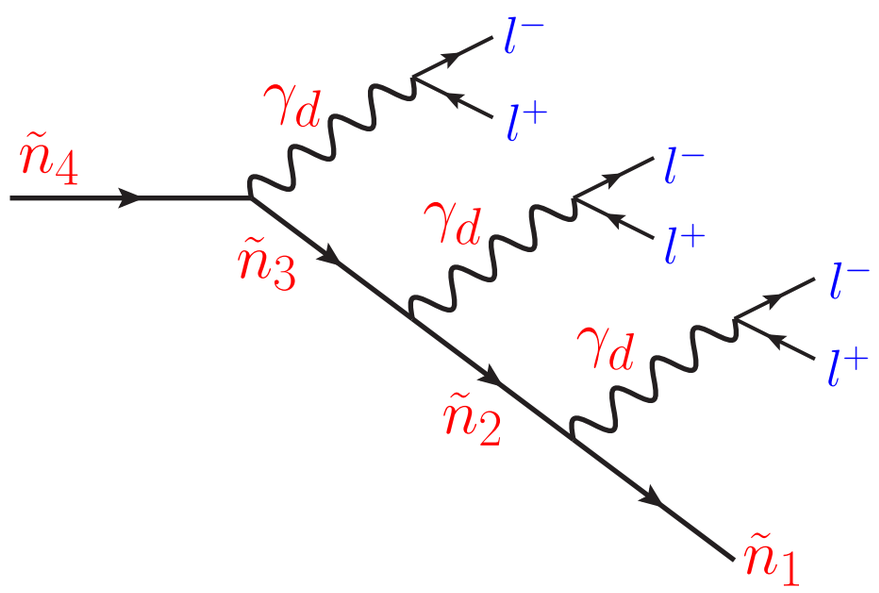


MET ~ 12.5%



Global Event Properties:

number of LJ's	other objects	MET

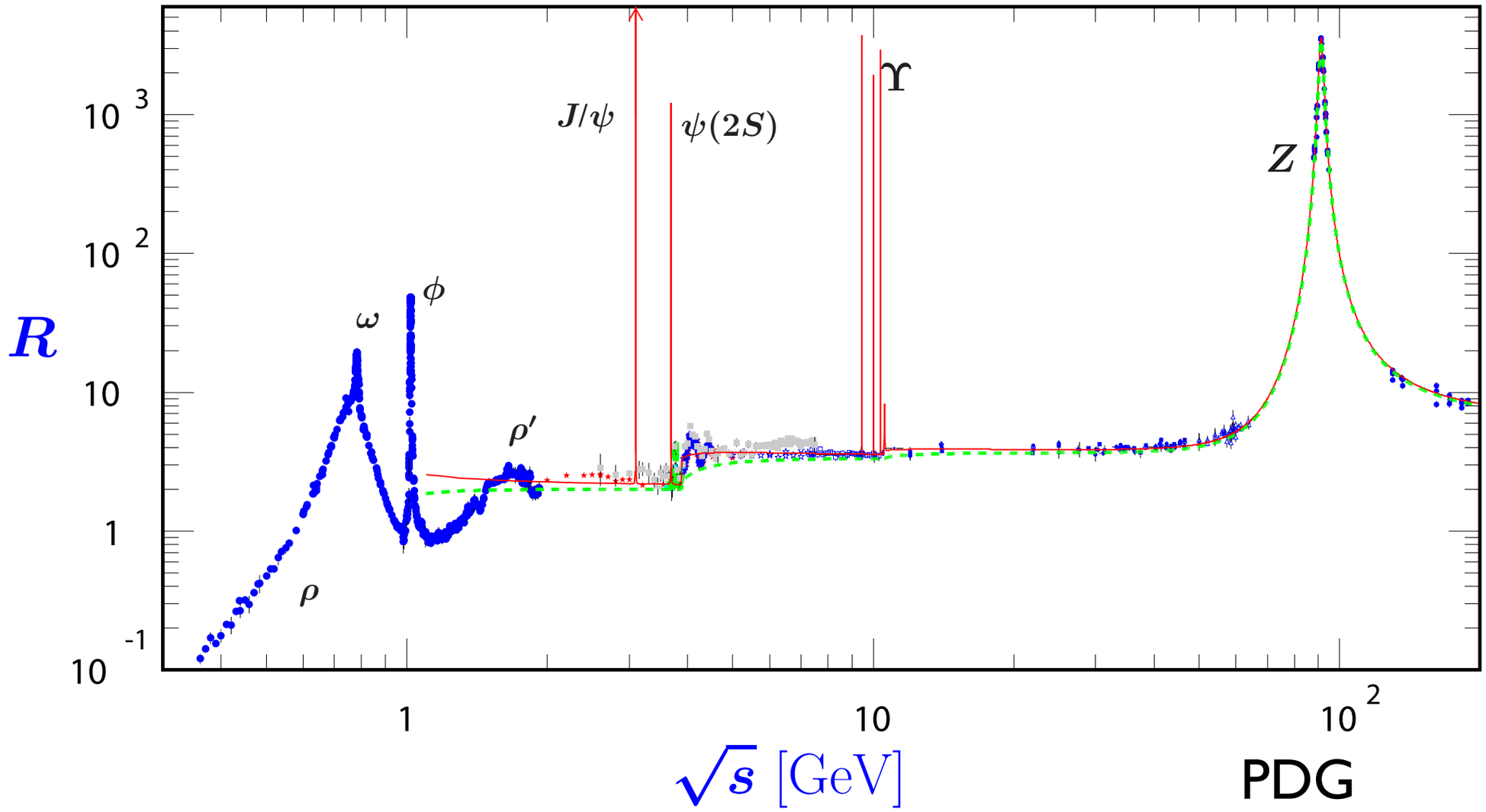
Lepton Jet Properties:

composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

composition

- branching ratio into $e/\mu/\pi$ depends on the hidden photon mass

determined by: $$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



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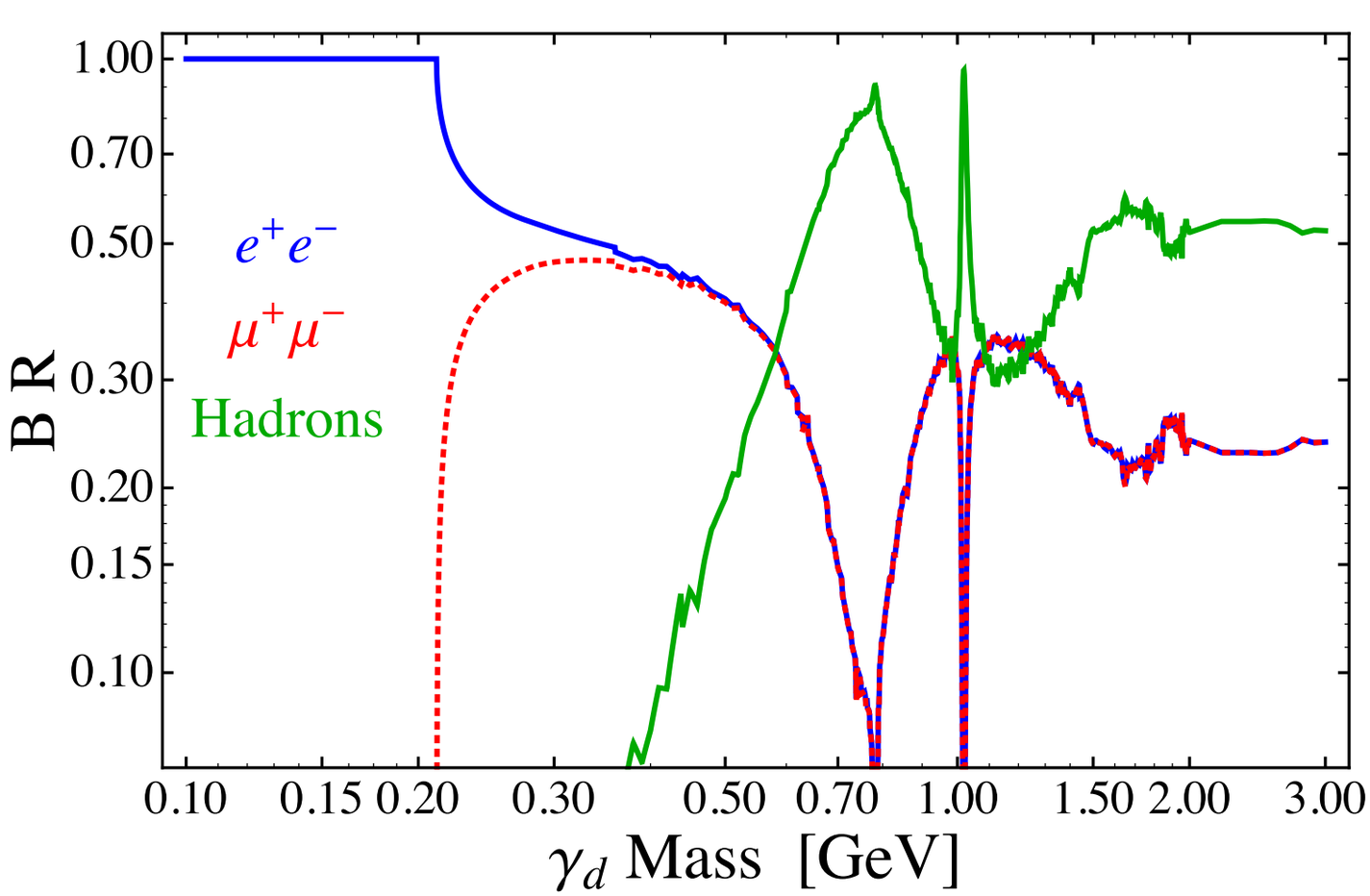
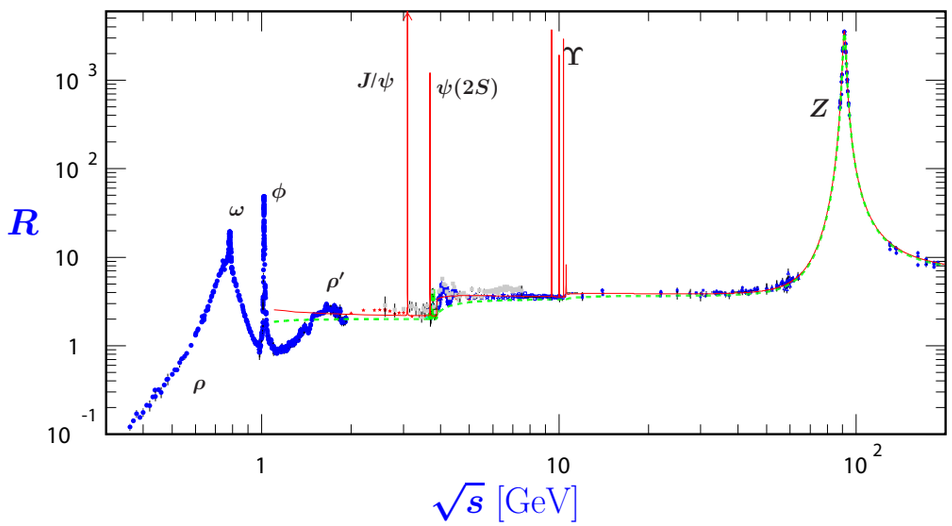


Falkowski, JTR, Volansky, Zupan 1002.2952

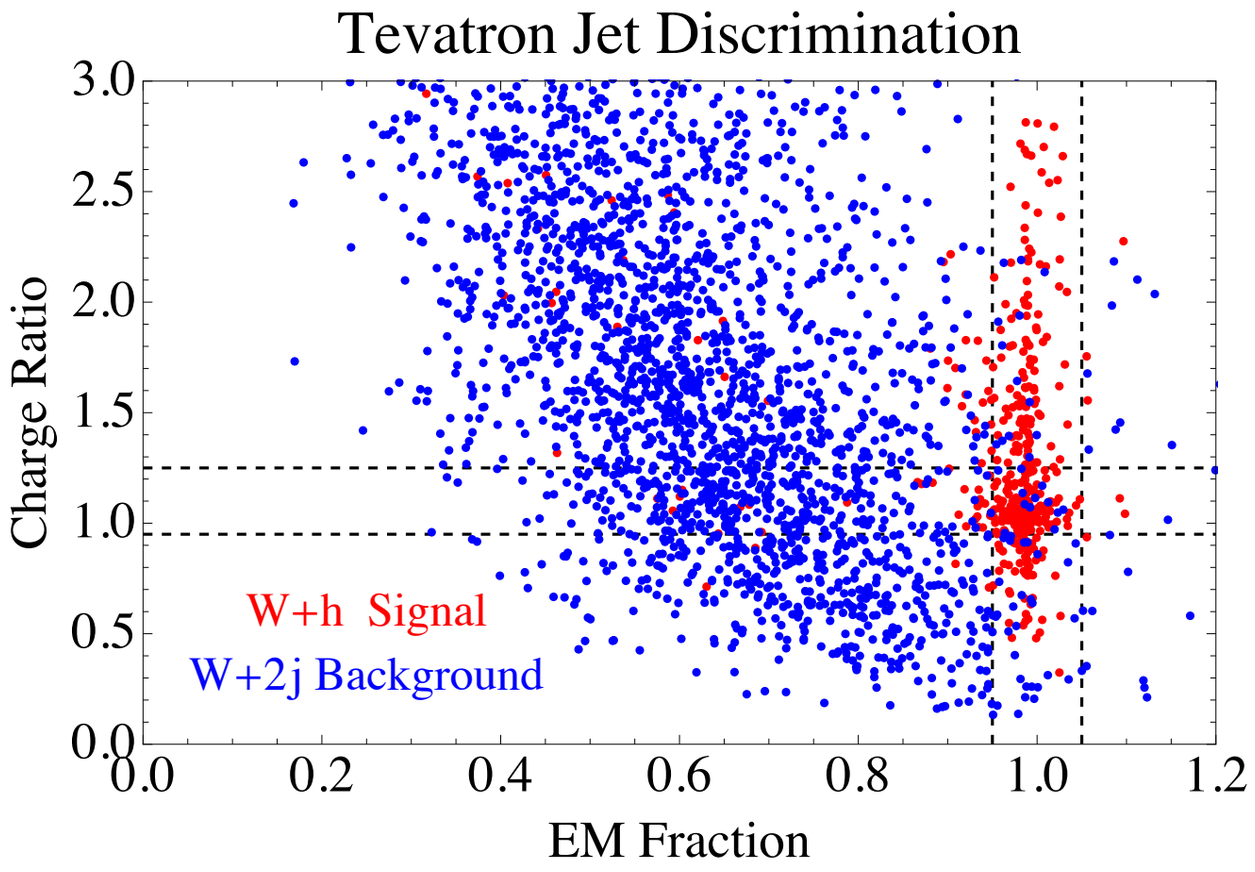


composition

- the LHC searches for lepton jets so far require muons
- but an interesting case is when the lepton jets are all-electron

$$m_{\gamma_d} < 2\, m_\mu$$

- it may be possible to identify electron-jets by looking for jets with high EMF



Falkowski, JTR, Volansky, Zupan, 1007.3496

we estimated a "fake rate" of

$$\mathcal{O}(10^{-3})$$

Global Event Properties:

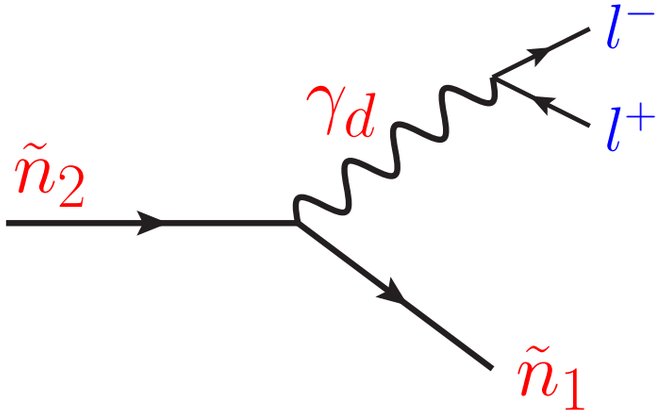
number of LJ's	other objects	MET

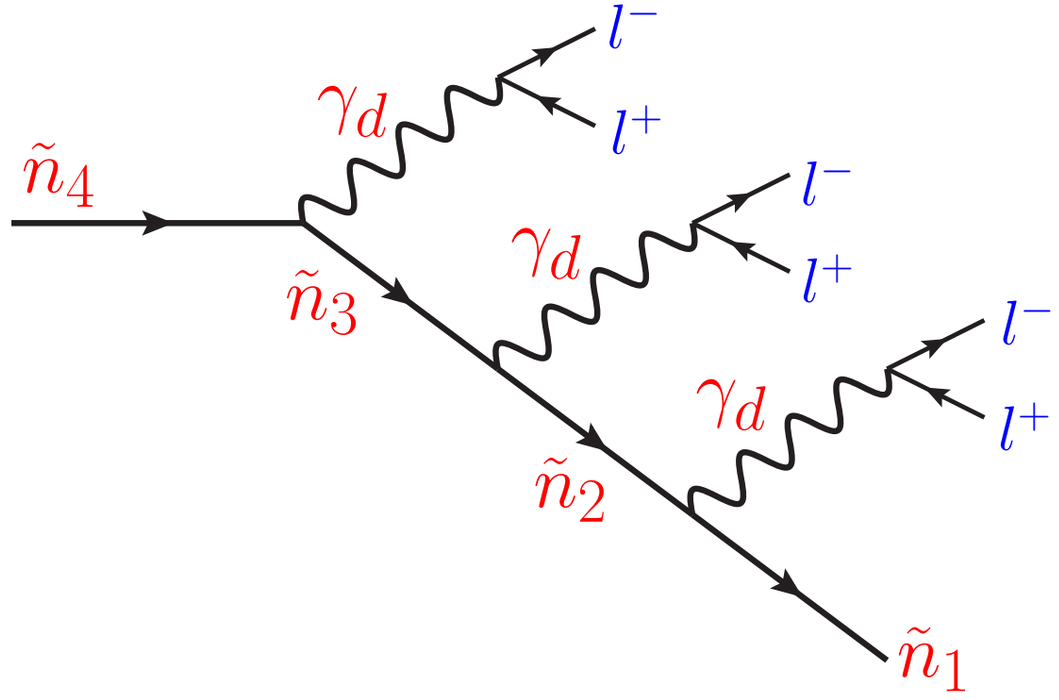
Lepton Jet Properties:

composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

lepton multiplicity

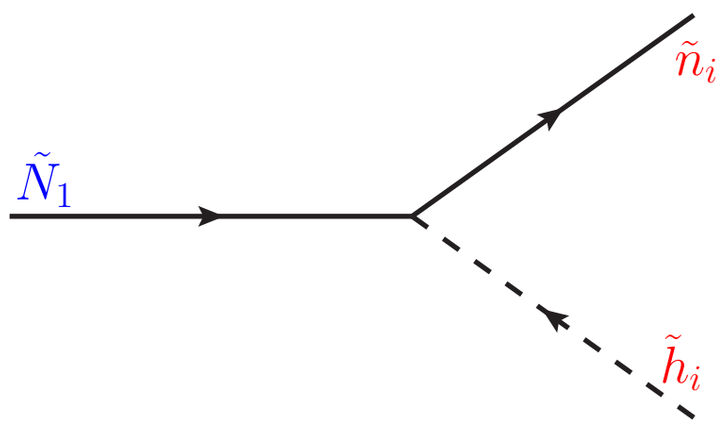
- the number of leptons per LJ depends on the length of the hidden cascades (which depends on the size of the hidden sector)





lepton multiplicity

- additional hidden photons (and leptons) can be produced by hidden showering



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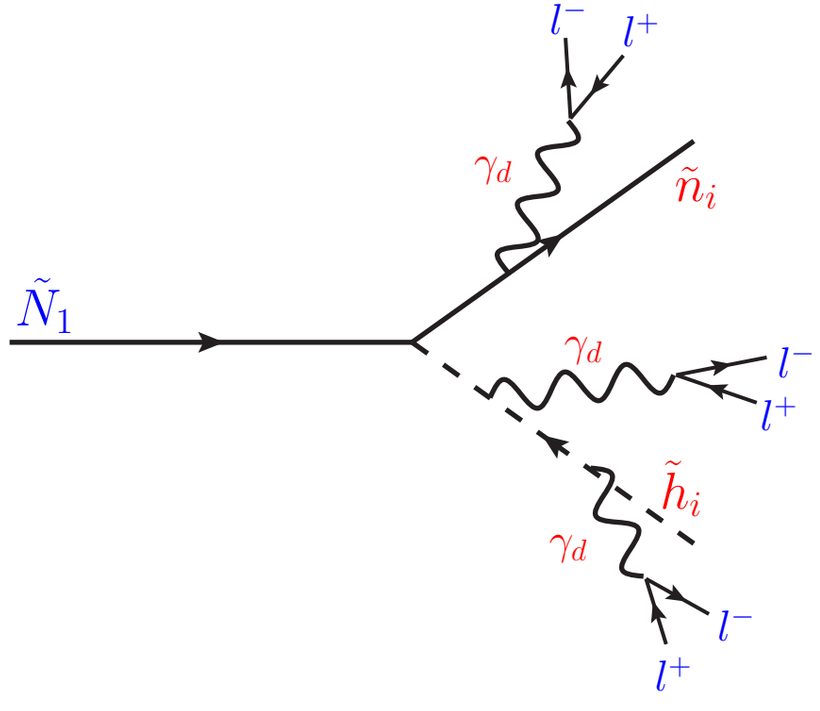
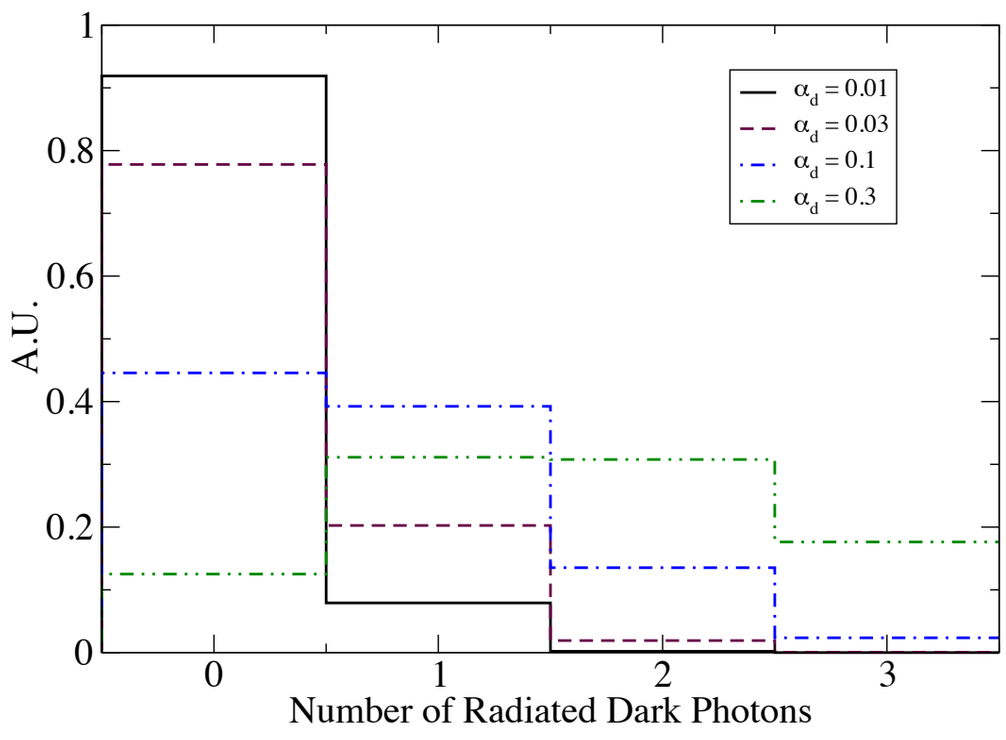
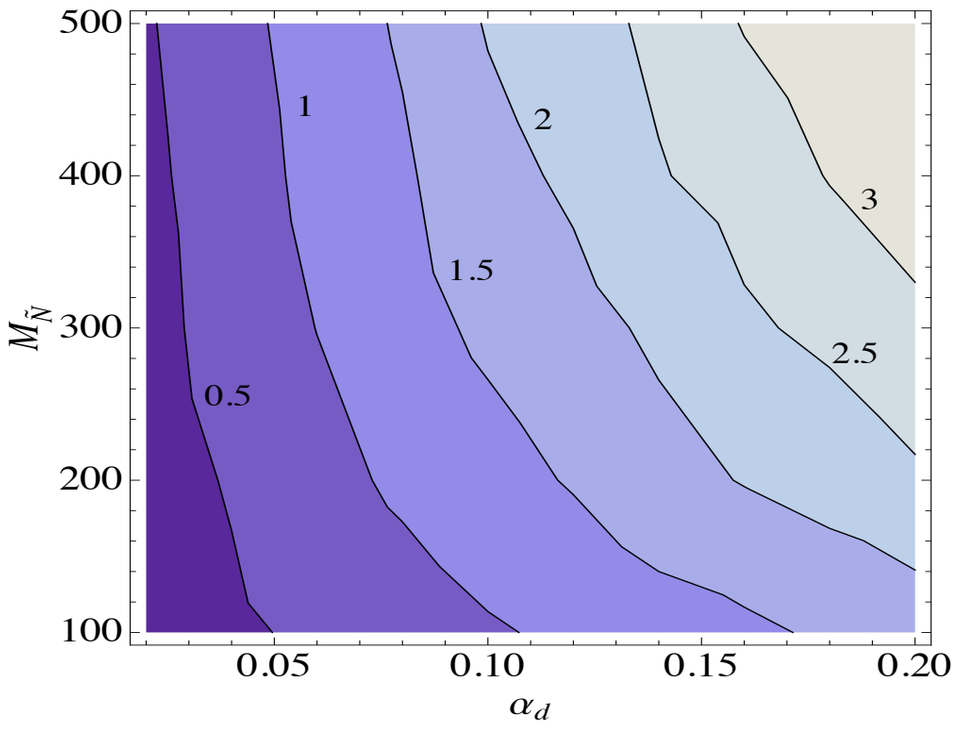


lepton multiplicity

- amount of showering depends on size of hidden gauge coupling

$$N_\gamma \approx \frac{\alpha_d}{2\pi} \log\left(\frac{M_{\rm EW}^2}{M_{\rm dark}^2}\right) \approx 1.4\left(\frac{\alpha_d}{0.1}\right)$$





Cheung, JTR, Wang, Yavin 0909.0290

Global Event Properties:

number of LJ's	other objects	MET

Lepton Jet Properties:

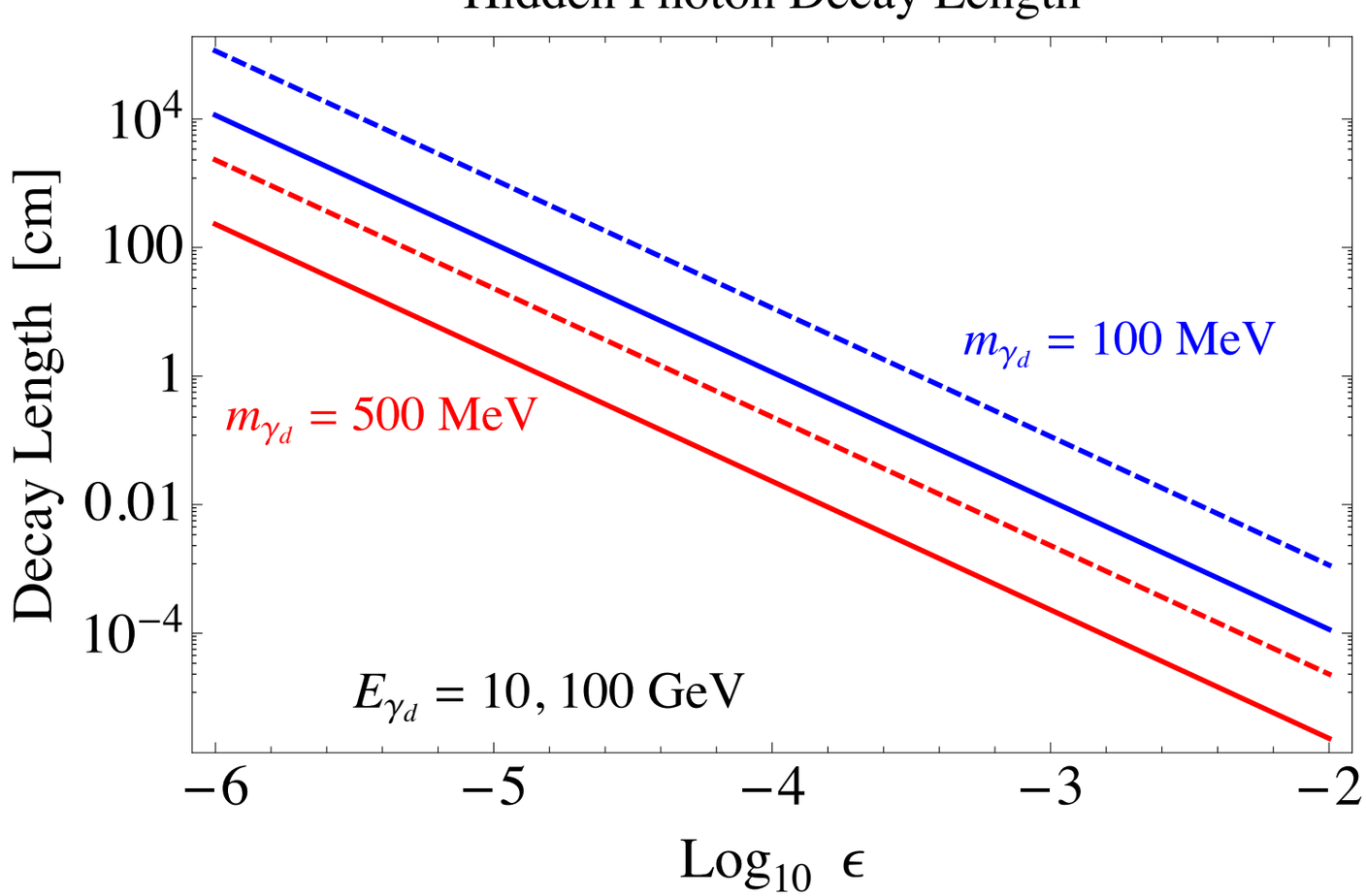
composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

lifetime

- depending on ϵ, the hidden photons can be prompt or displaced

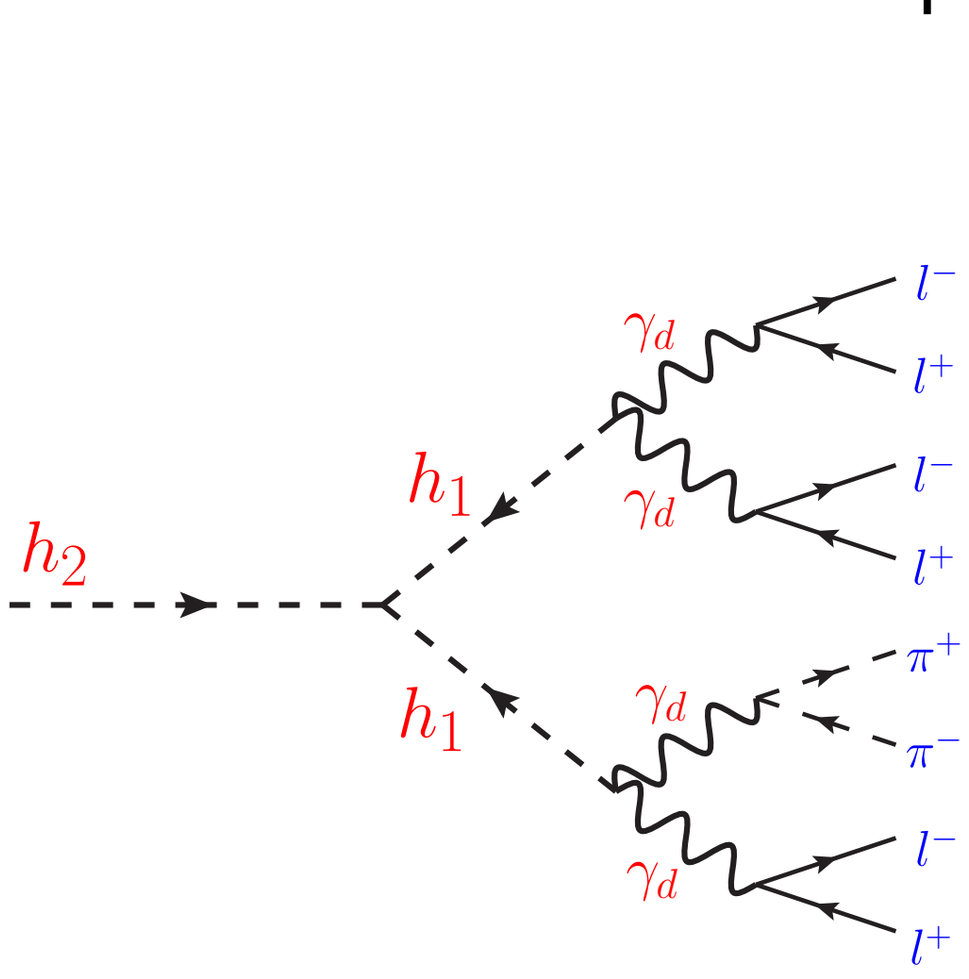
$$\Gamma = \frac{1}{3}\alpha\,\epsilon^2\,m_{\gamma_d}\sqrt{1-\frac{4m_l^2}{m_{\gamma_d}^2}}\left(1+\frac{2m_l^2}{m_{\gamma_d}}\right)$$

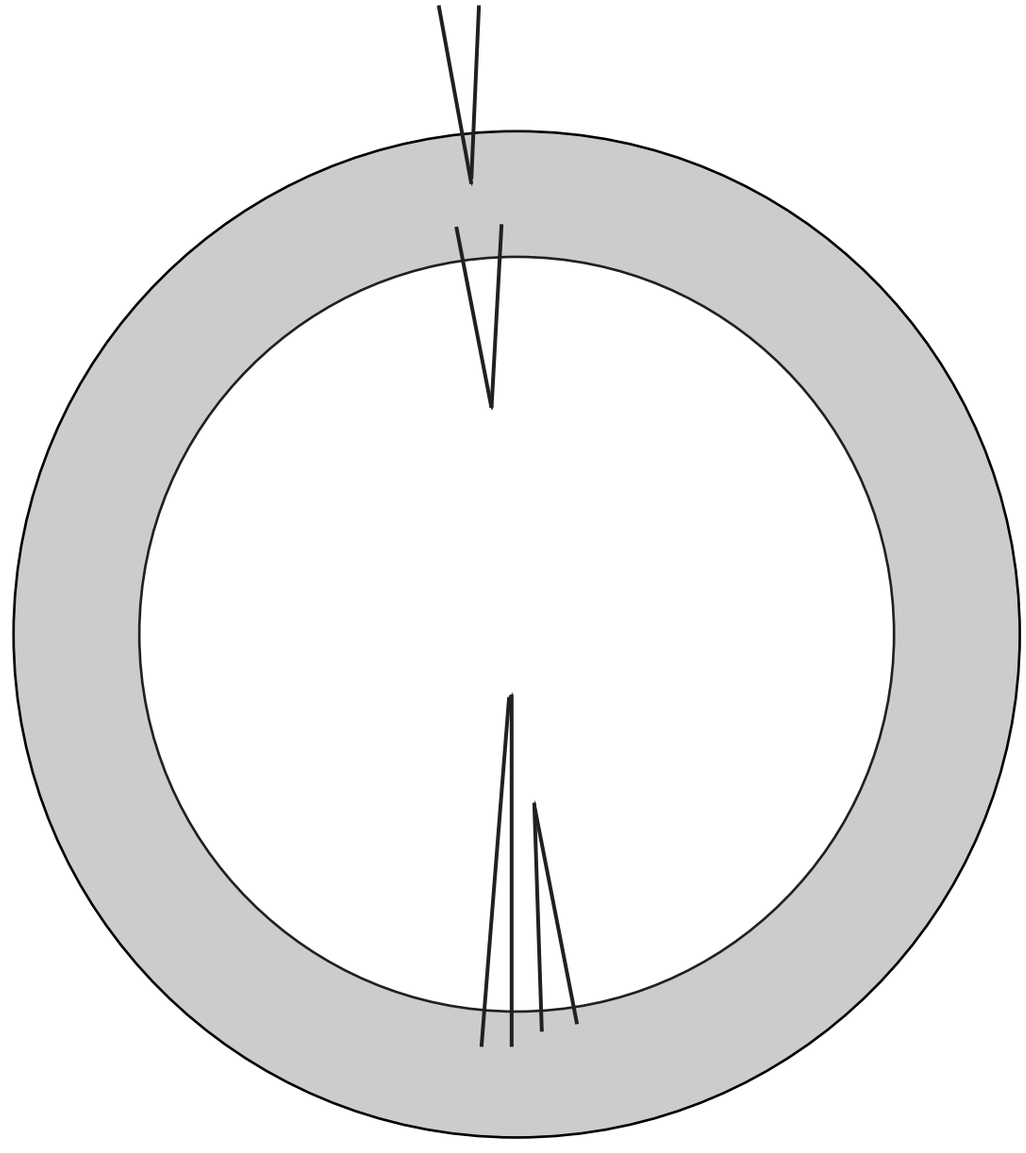
$$l = \gamma\, c\, \tau$$



lifetime

- displaced lepton jets give multiple collinear displaced vertices





lifetime

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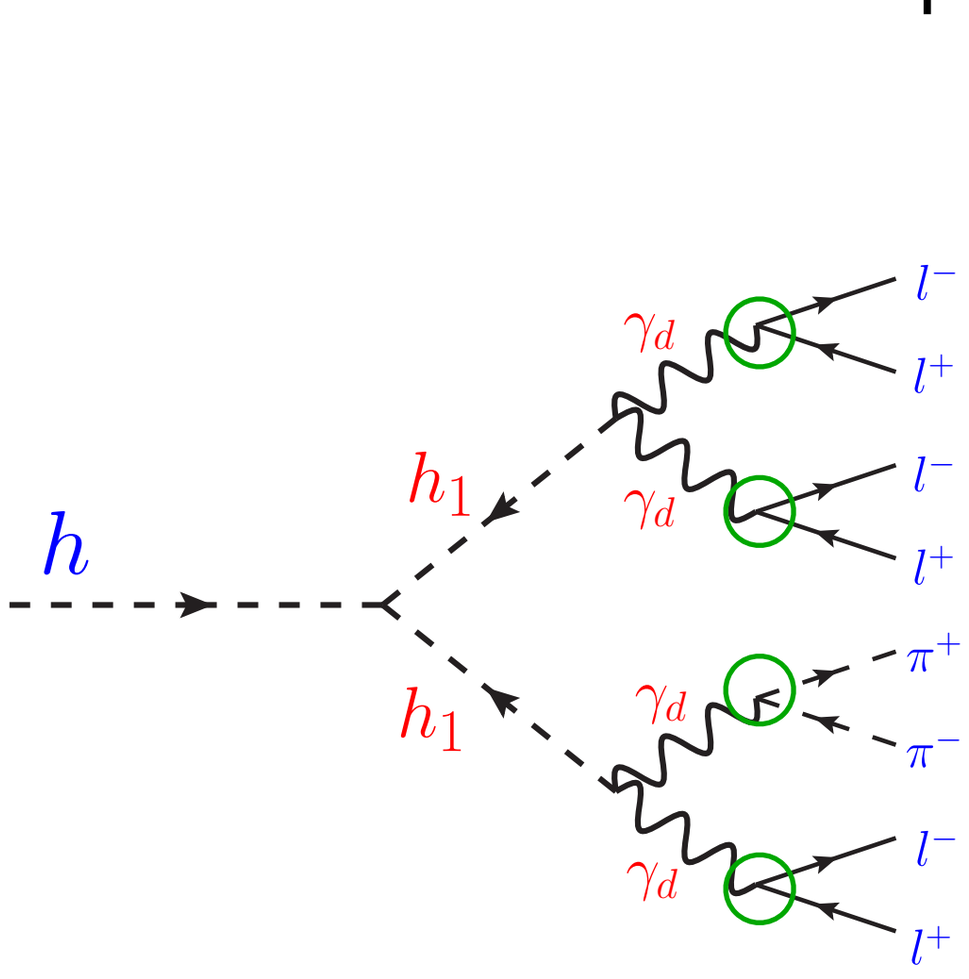
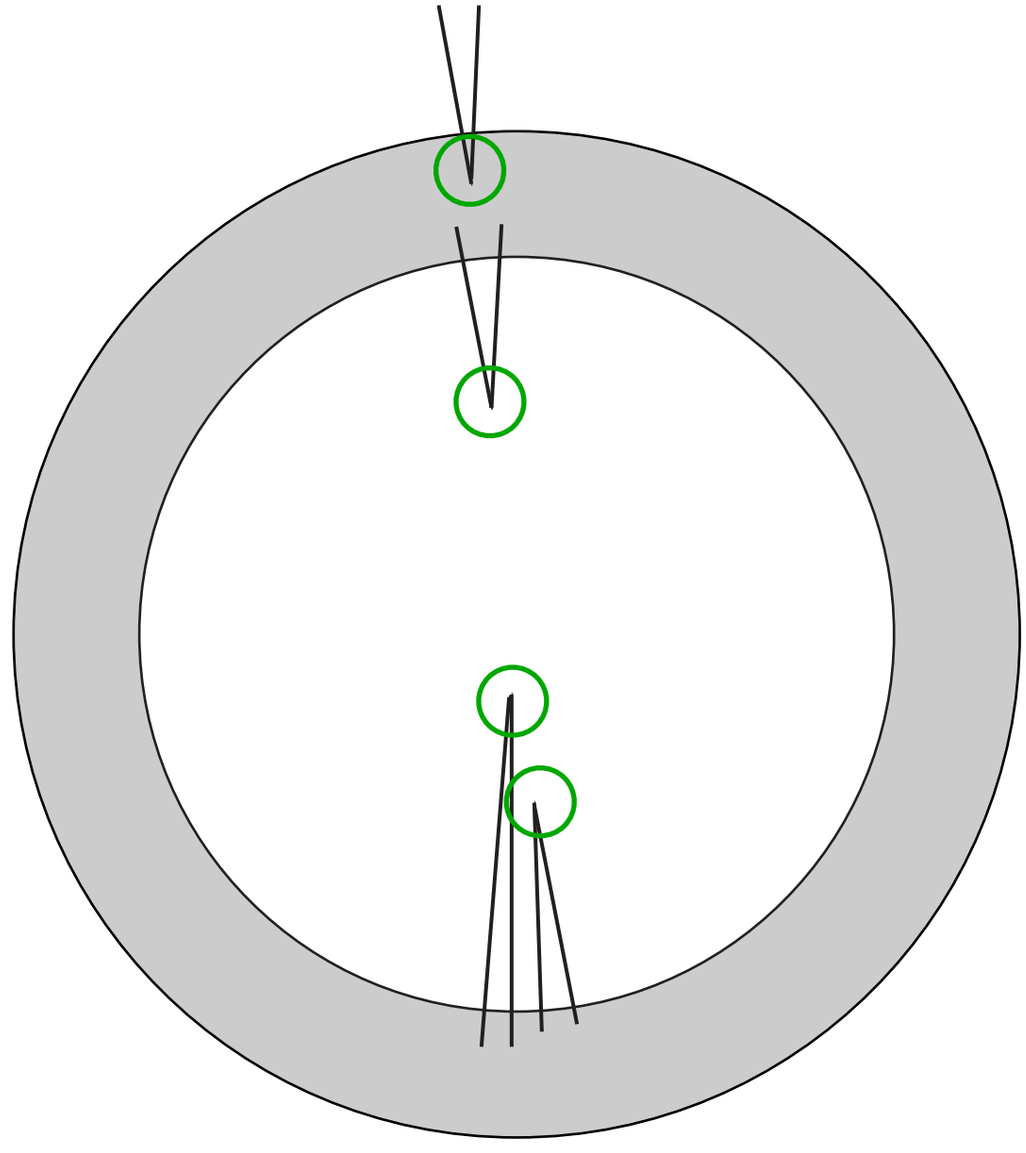
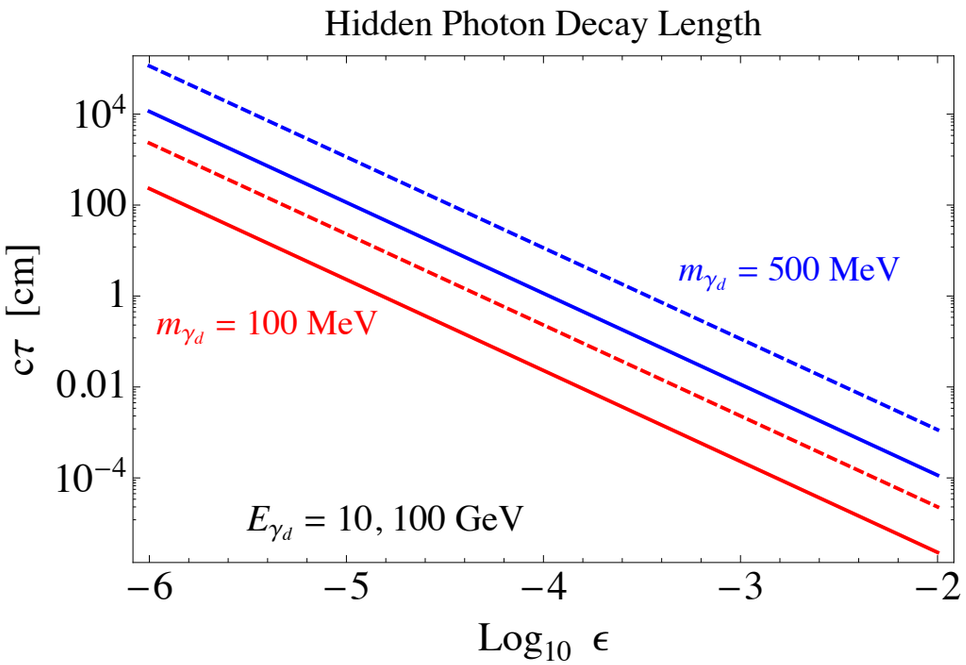
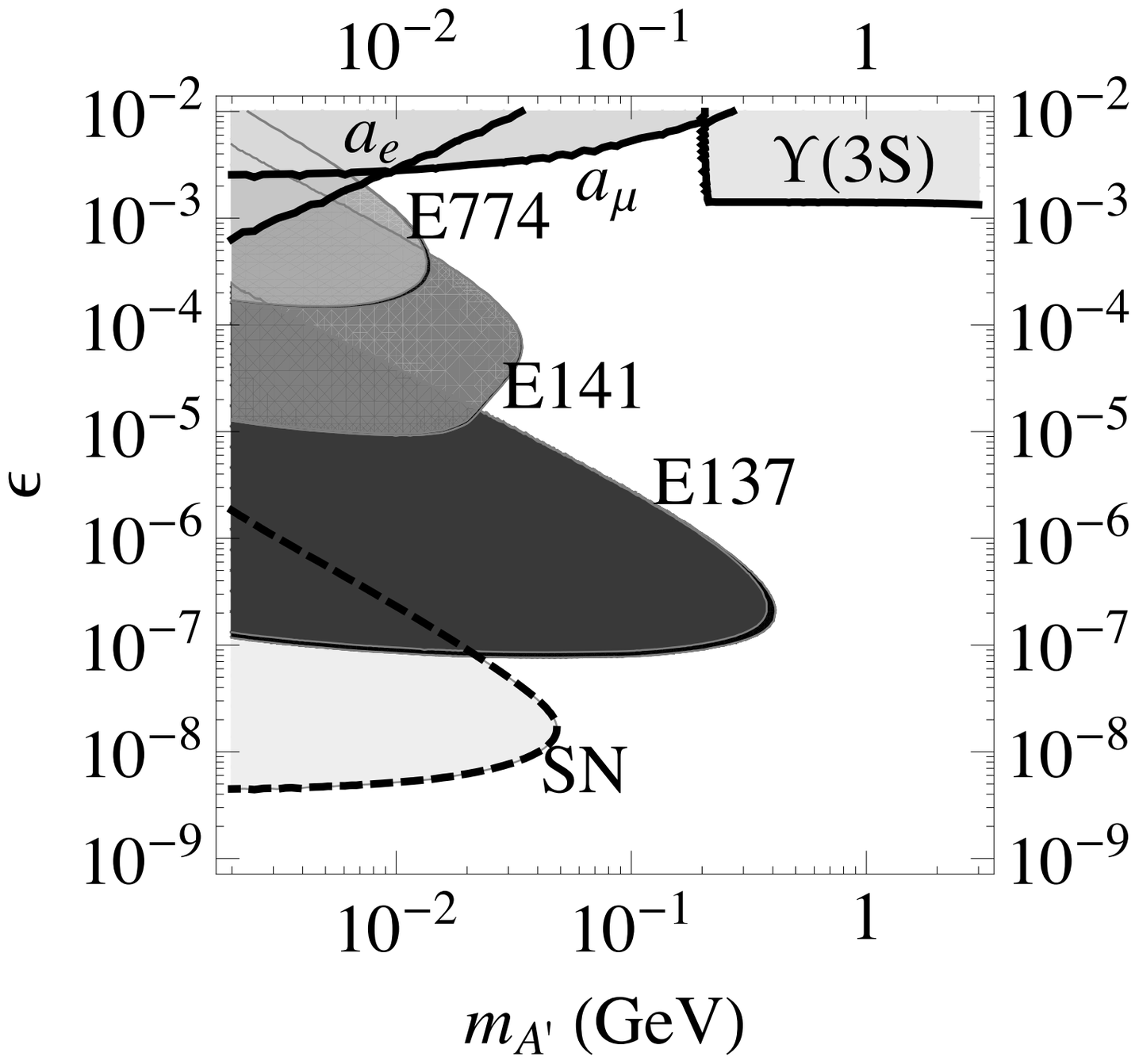




lifetime



direct limits:

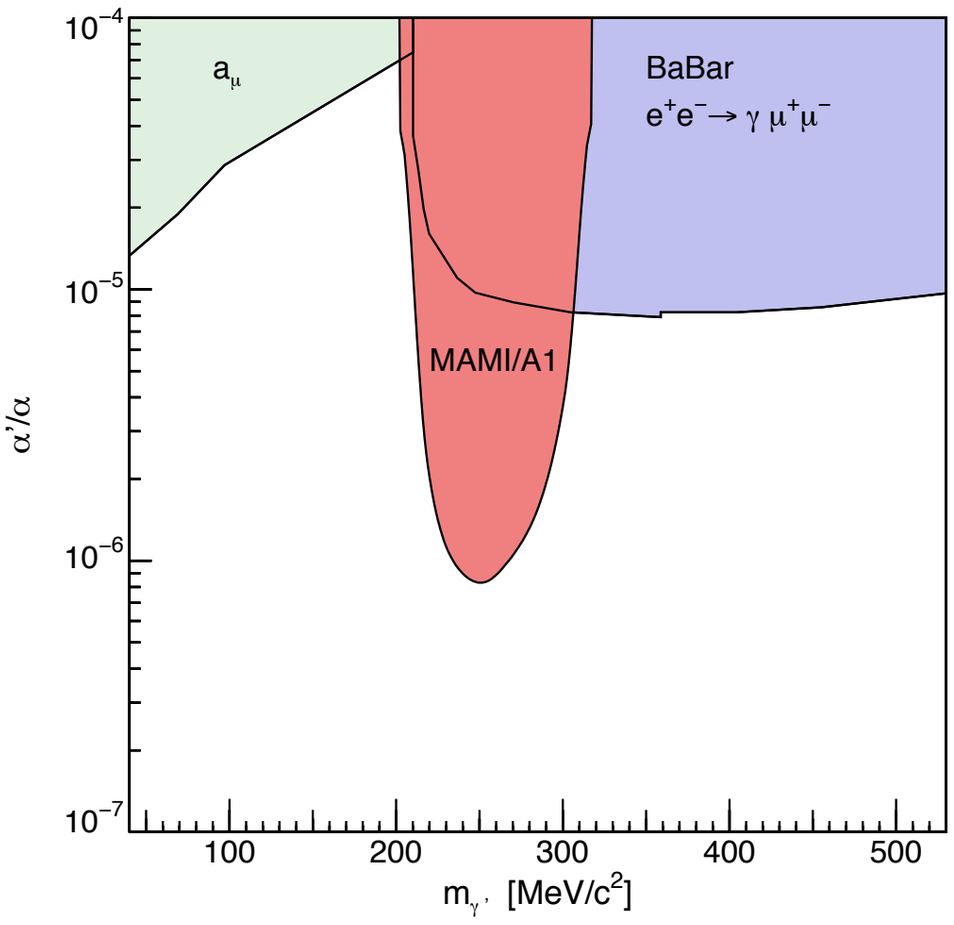


Bjorken, Essig, Schuster, Toro, 0906.0580

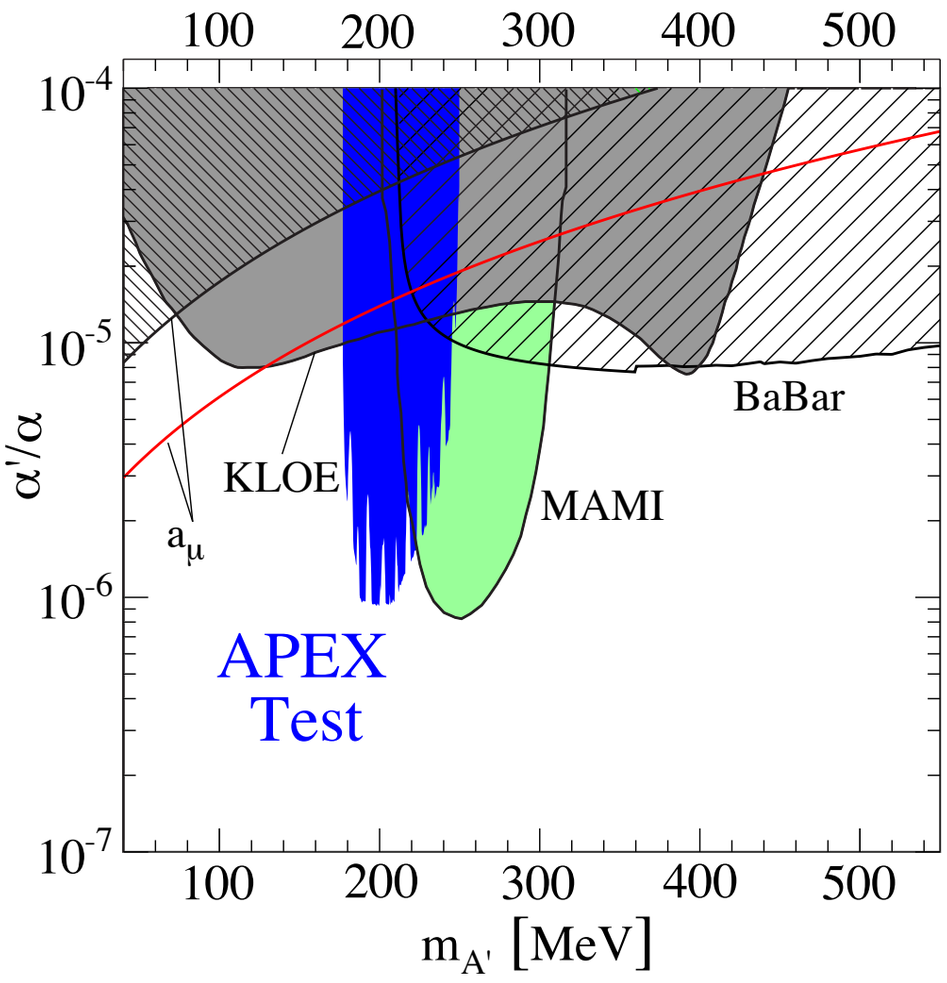
lifetime

recent progress in the $m - \epsilon$ plane!

$$\alpha' = \epsilon^2 \alpha$$



A1, 1101.4091



APEX, 1108.2750

KLOE, 1110.0411

Global Event Properties:

number of LJ's	other objects	MET

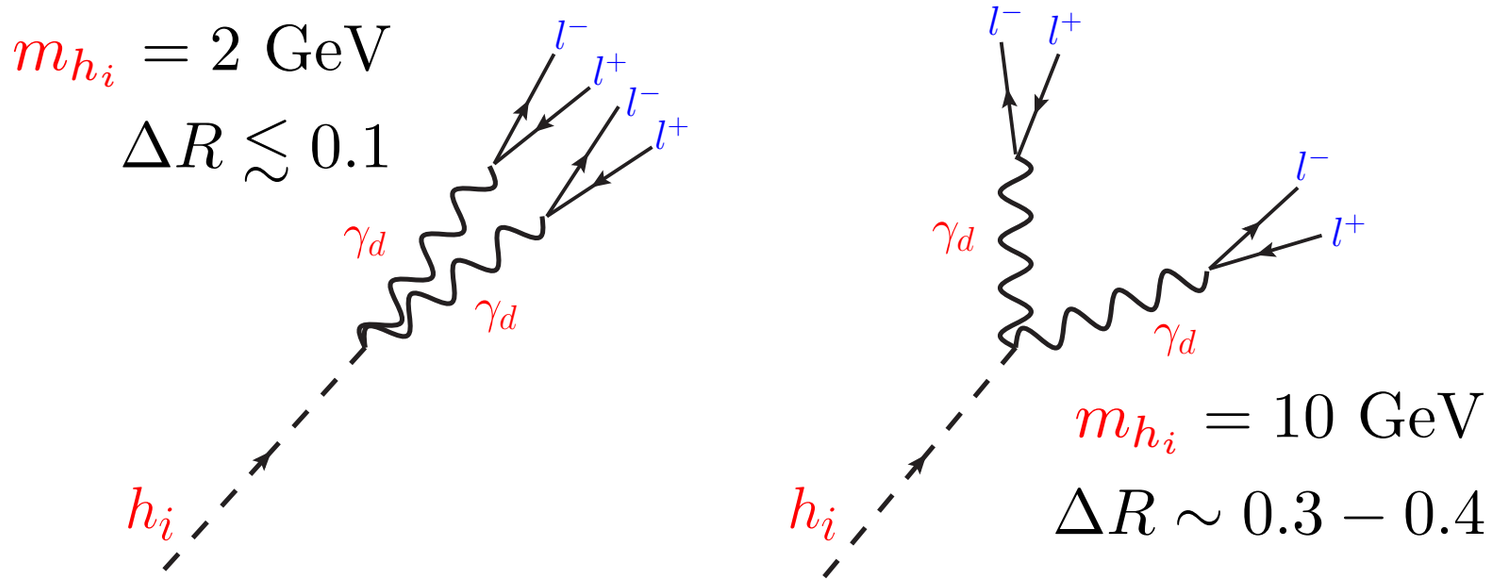
Lepton Jet Properties:

composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

jet shape

- depends on the masses of the hidden particles in the cascade
- heavier masses ⟶ less boost ⟶ wider jets

for example, fixing, $m_{\gamma_d} = 500\ \mathrm{MeV}$



- also note that showering tends to populate phase space differently than cascades, leading to fatter jets

Global Event Properties:

number of LJ's	other objects	MET

Lepton Jet Properties:

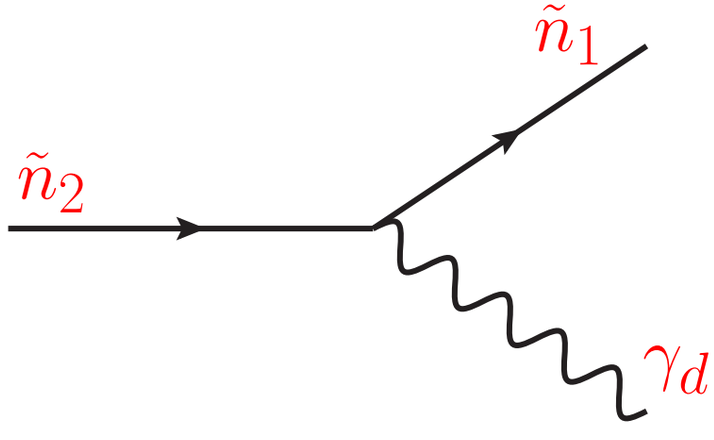
composition	lepton multiplicity	lifetime	jet shape	2 vs. 3 body

2 v. 3 body

- the hidden photon can be produced on or off-shell, depending on whether 2 or 3 body decays dominate

for example,

$m_{\tilde{n}_2} > m_{\tilde{n}_1} + m_{\gamma_d}$



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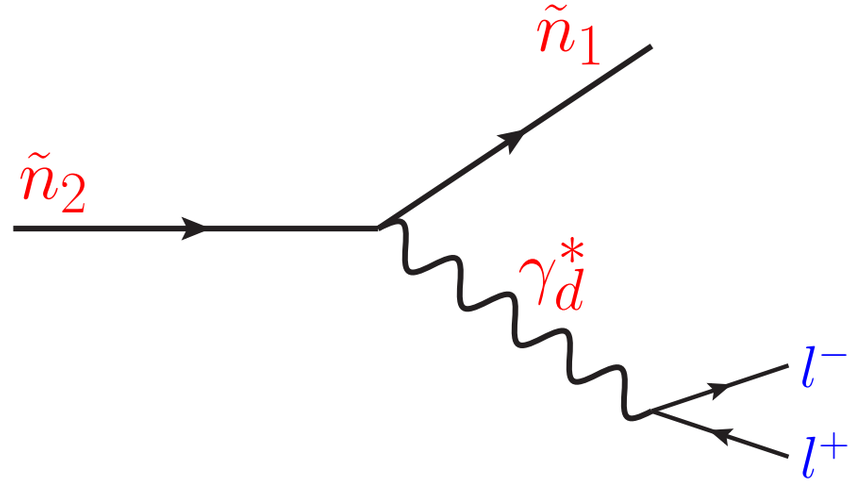


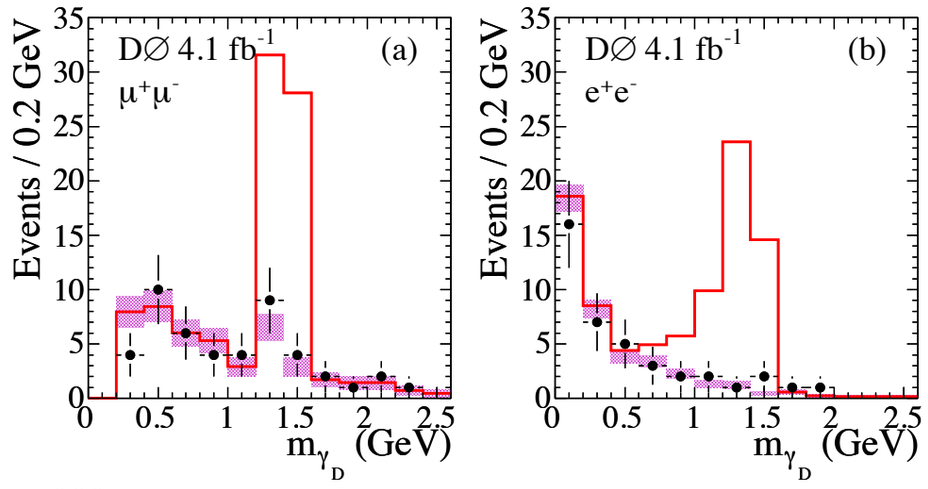
the current searches:
(and how to evade them)

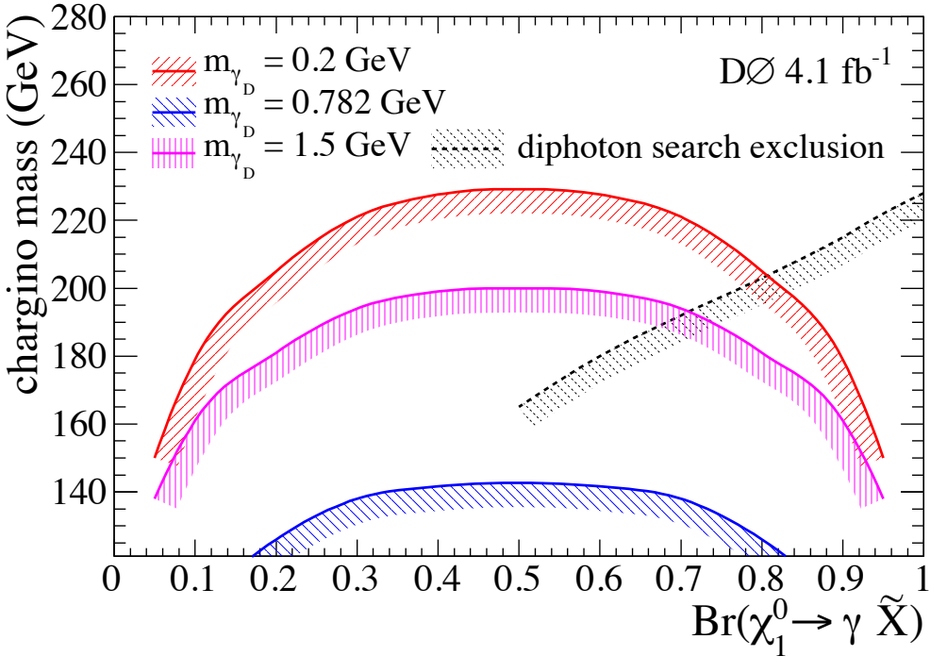
the current searches

collaboration	lum	final state	ref
D0	4.1/fb	γ + e/μ-jet	0905.1478
D0	5.8/fb	2 e/μ-jets	1008.3356
CDF	5.1/fb	soft lepton counting	note:10526
CMS	35/pb	μ-jets	1106.2375
ATLAS	40/pb	2 μ-jet	CONF-2011-076

D0: γ + e/μ-jet

- the search:
  - one gamma
  - one LJ with exactly 2 e or μ (extra tracks vetoed)





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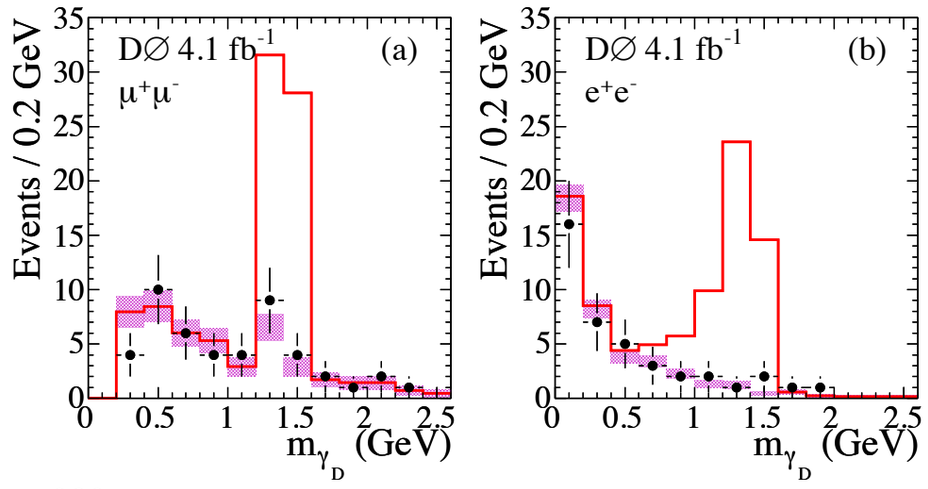
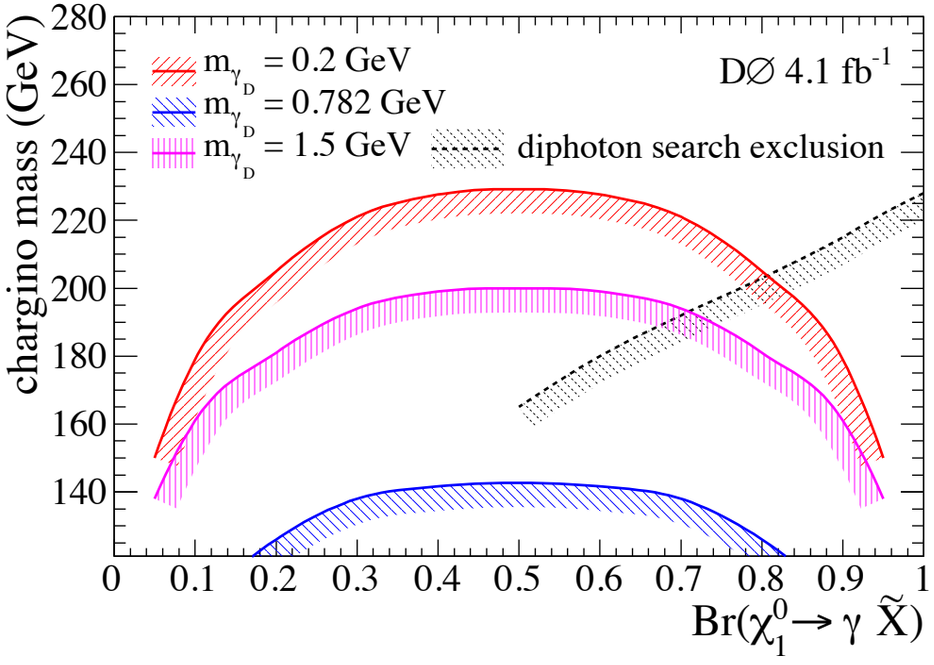


- models that evade it:
  - models without photons
  - high multiplicity (>2l) LJ



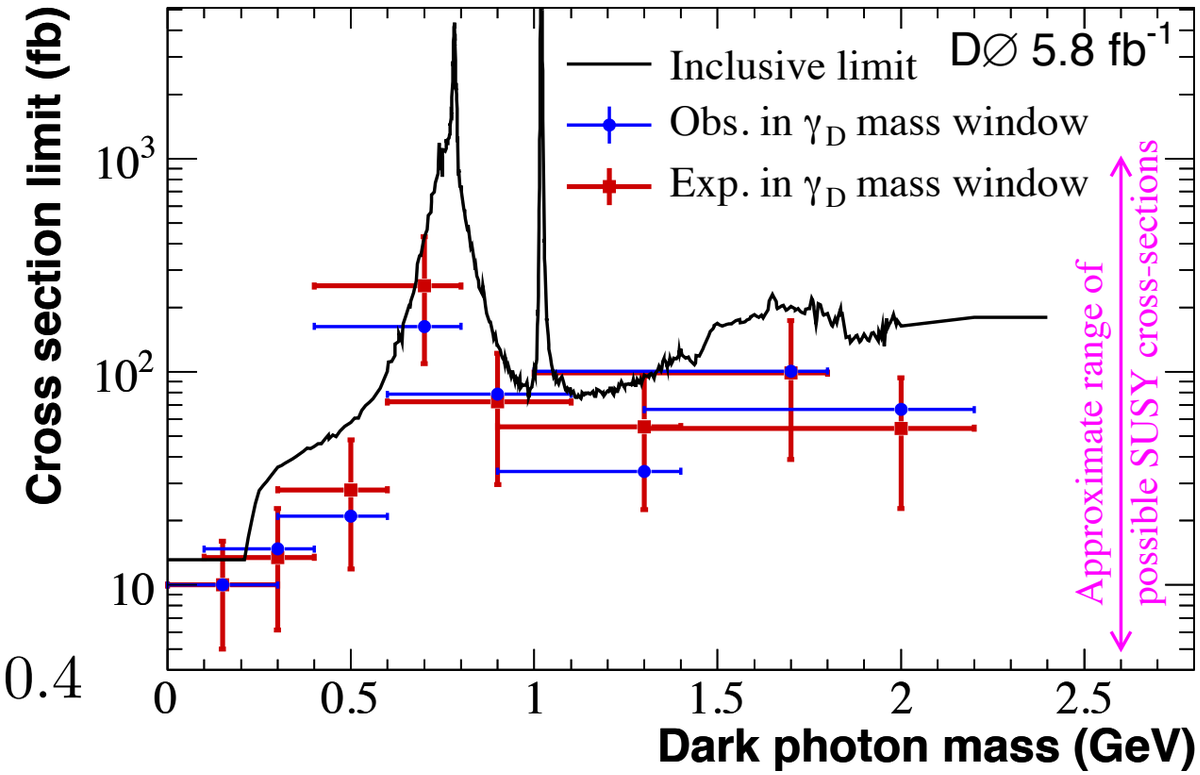
D0: 2 e/μ-jet

- the search:

- 2 LJ, each with e or μ seed and companion track $\Delta R < 0.2$

- $p_T > 10, 4$ GeV

- iso in annulus: $\Sigma_{trk}\ p_T < 2$ GeV in $0.2 < \Delta R < 0.4$



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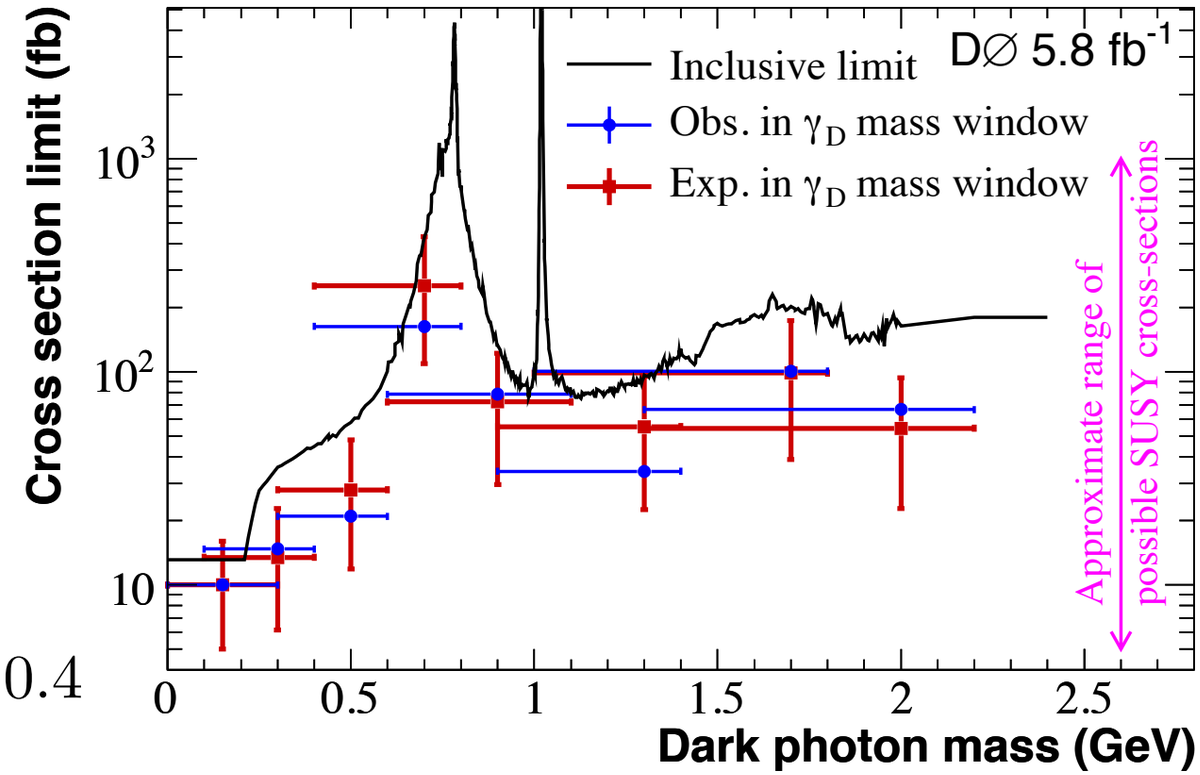
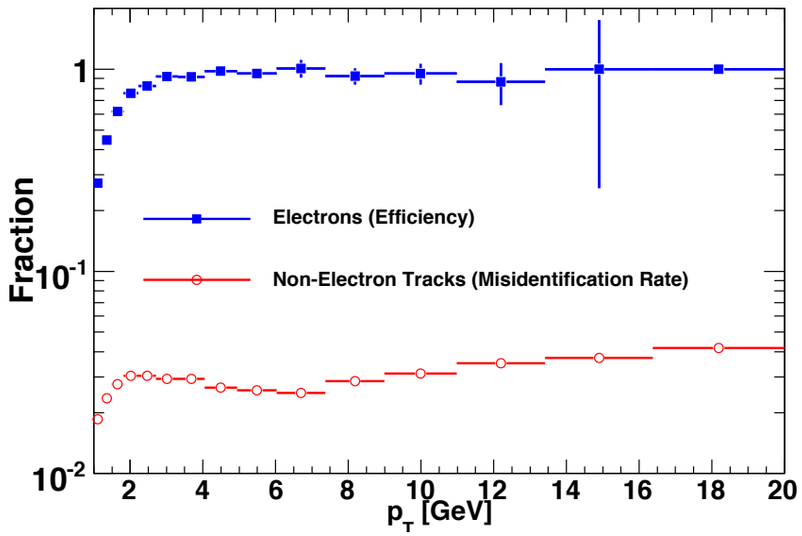


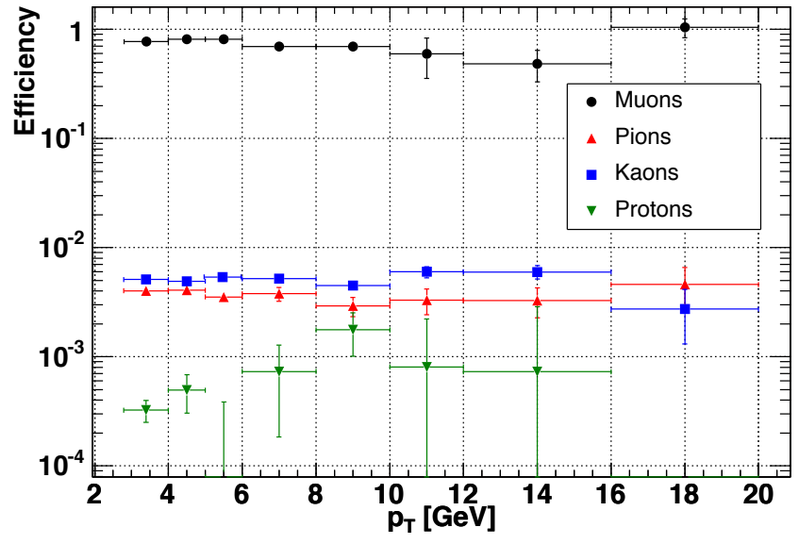
- models that evade it:

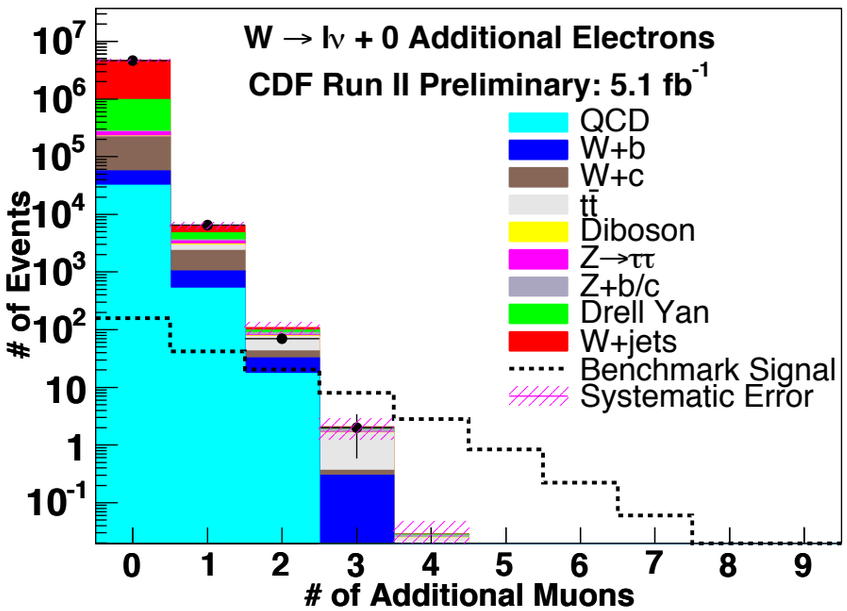
- fat lepton jets that spoil the iso, $\Delta R > 0.2$

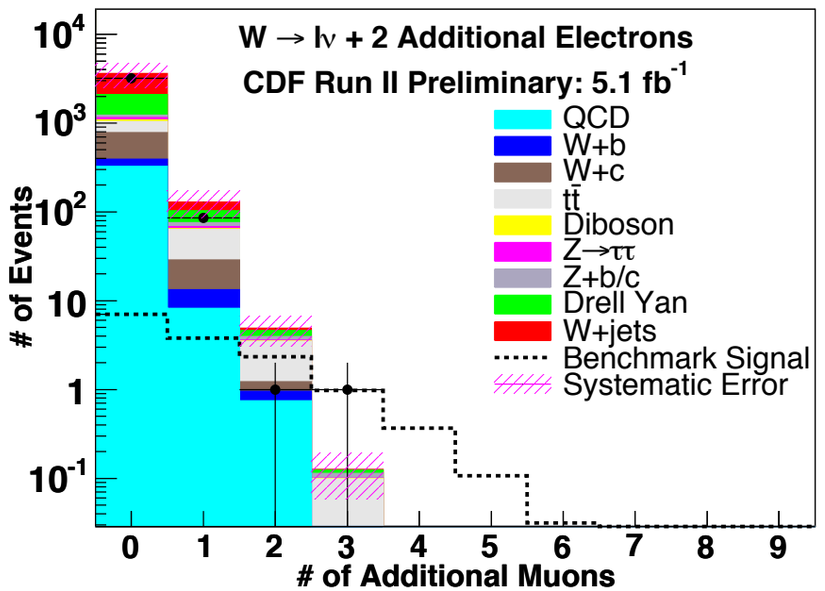
- high enough multiplicity to avoid the pT cut

CDF: soft lepton counting



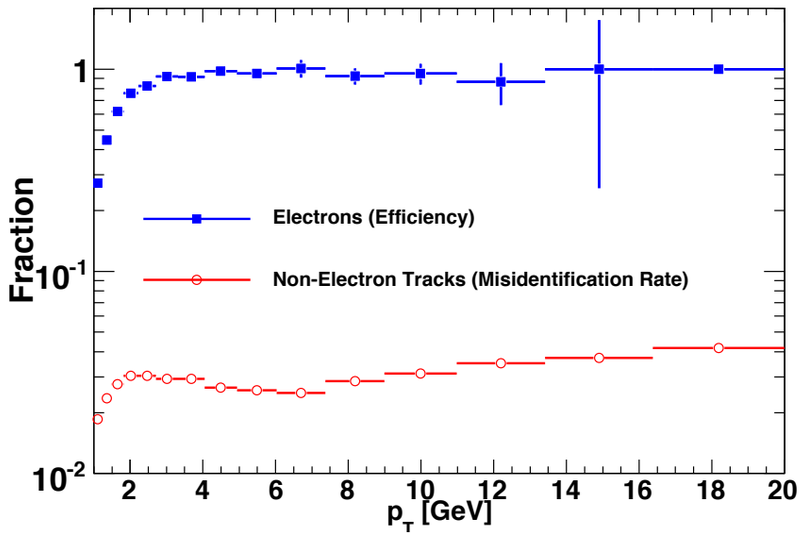


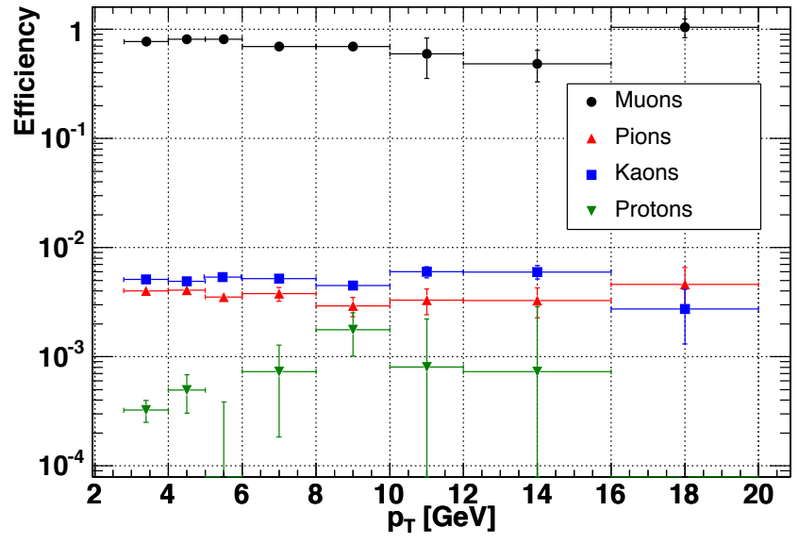


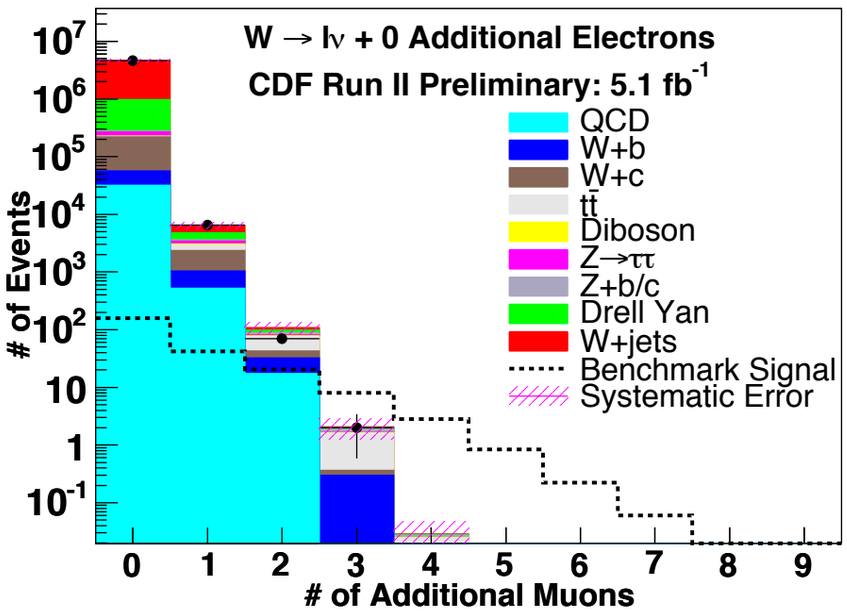


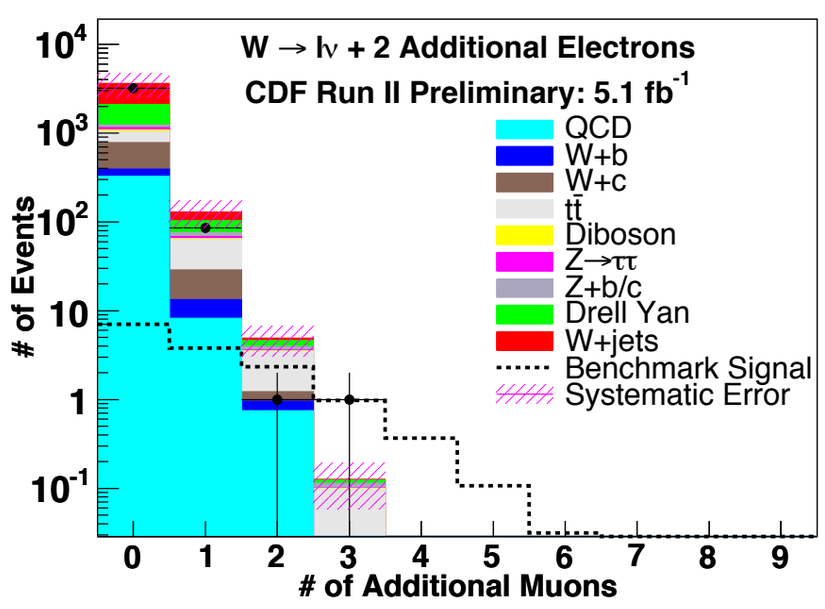
- the search:
  - identify leptonic Z/W
  - count soft e/μ

CDF: soft lepton counting









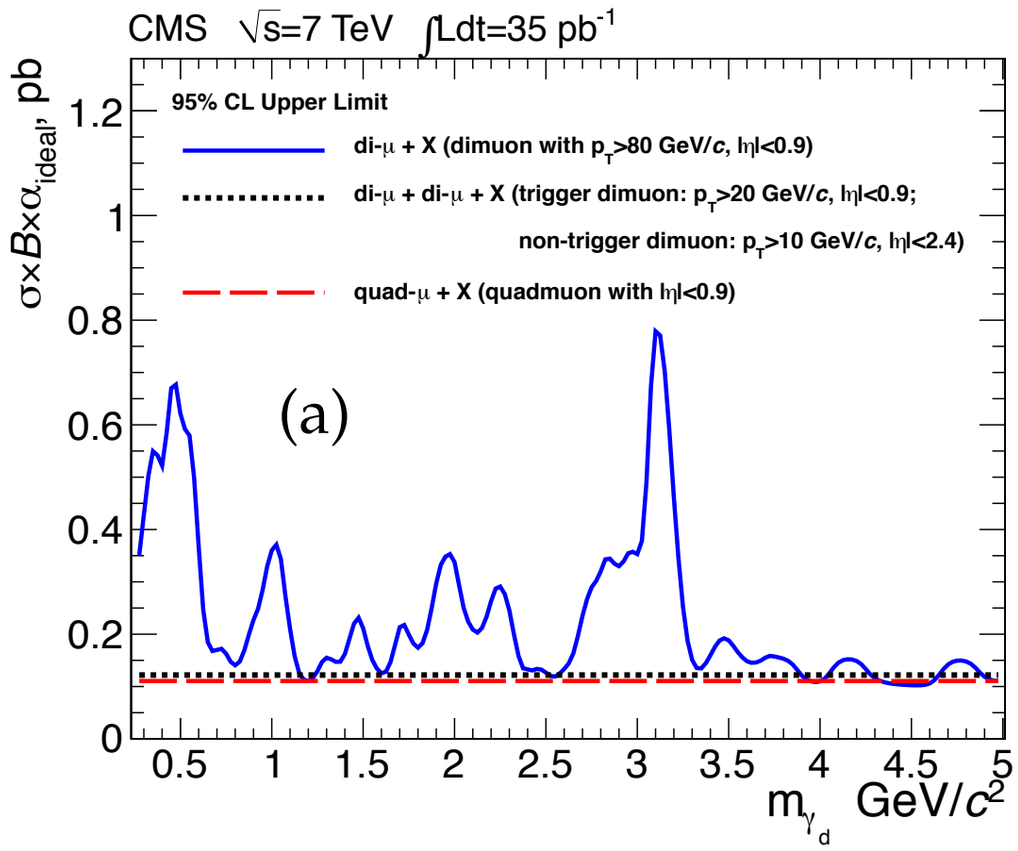
- the search:
  - identify leptonic Z/W
  - count soft e/μ
- models that evade it:
  - no leptonic Z/W
  - low lepton multiplicity

CMS μ-jets

- the search:

- cluster muons with $m_{\mu\mu} < 9$ GeV
- bump hunt in:

$$m_{\mu\mu}, m^n_{\mu\mu}, m_{\mu\mu\mu\mu}$$

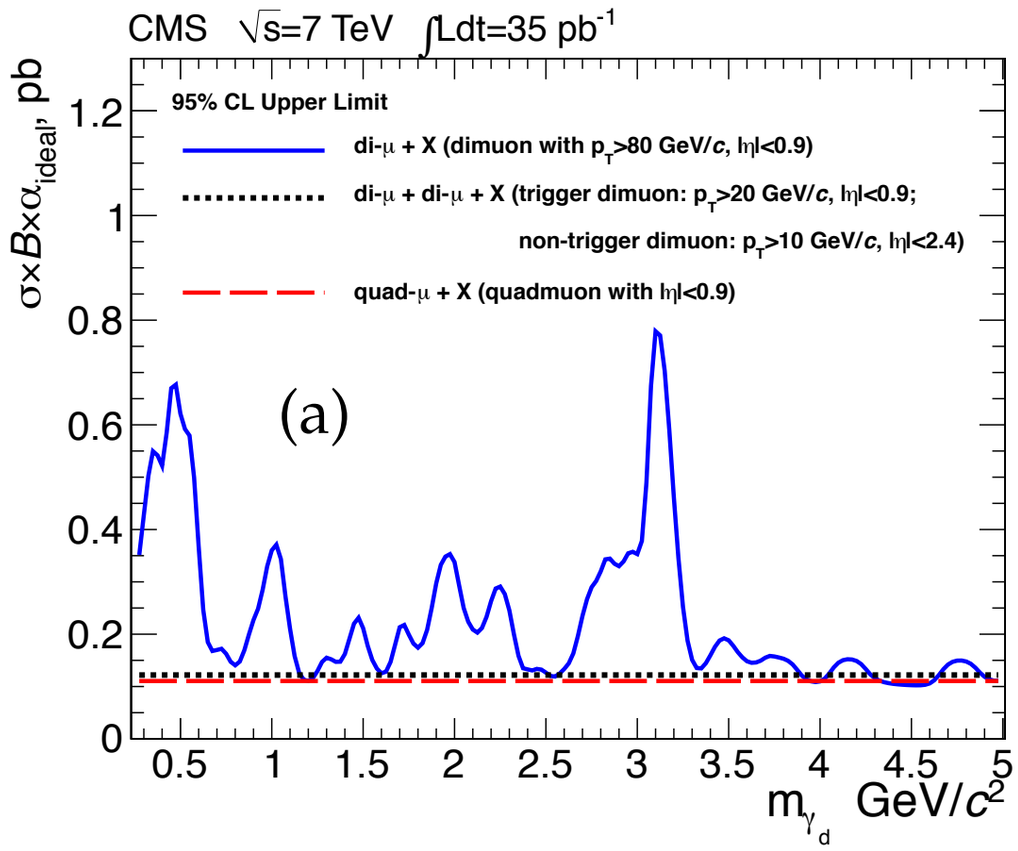


CMS μ-jets

- the search:

- cluster muons with $m_{\mu\mu} < 9\ \mathrm{GeV}$
- bump hunt in:

$$m_{\mu\mu}, m^{n}_{\mu\mu}, m_{\mu\mu\mu\mu}$$



- models that evade it:

  - $m_{\gamma_d} < 2\, m_\mu$

  - dominated by 3-body decays

ATLAS μ-jets

- the search:

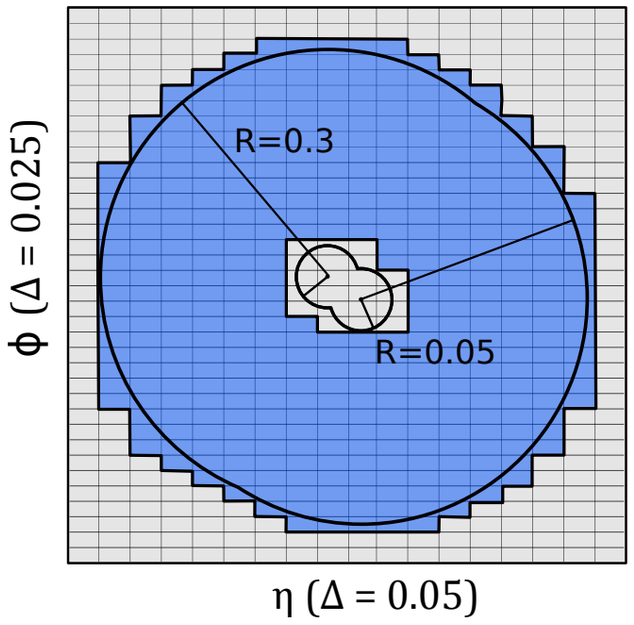
- cluster muons with:

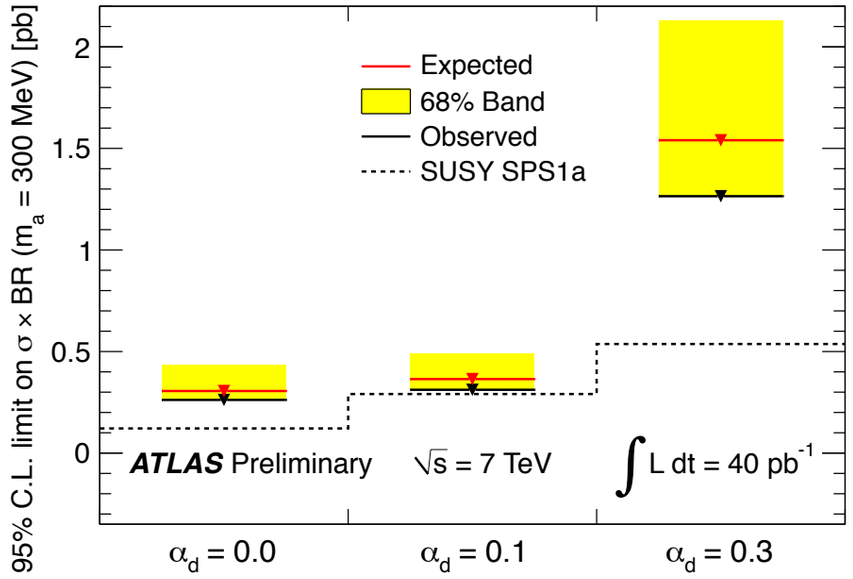
$$\Delta R < 0.1$$

- require 2 LJ with 2μ each

- cal iso in annulus,

$$E_T < 0.7\, p_T$$





ATLAS μ-jets

- the search:

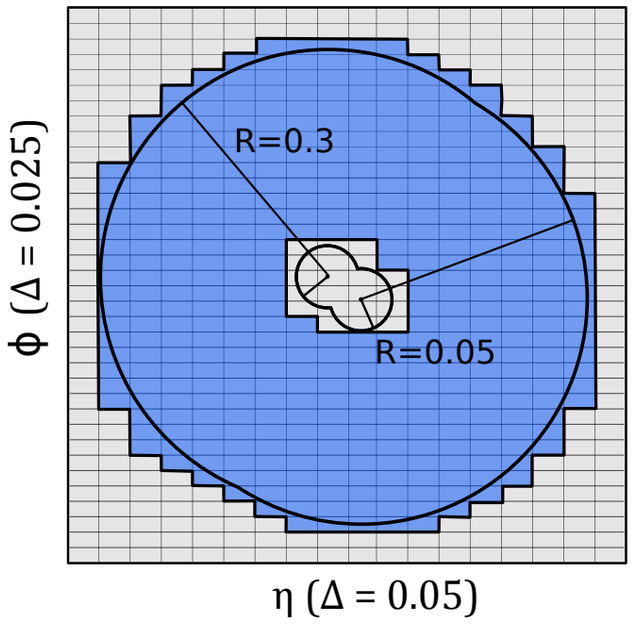
- cluster muons with:

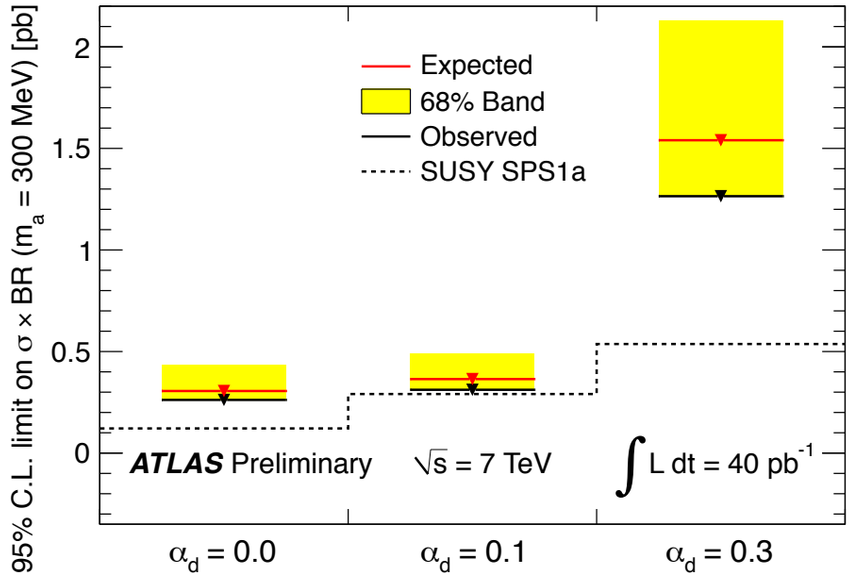
$$\Delta R < 0.1$$

- require 2 LJ with 2μ each

- cal iso in annulus,

$$E_T < 0.7\, p_T$$





- models that evade it:

- $m_{\gamma_d} < 2\, m_\mu$

- models that spoil the iso due to high multiplicity / fat jets

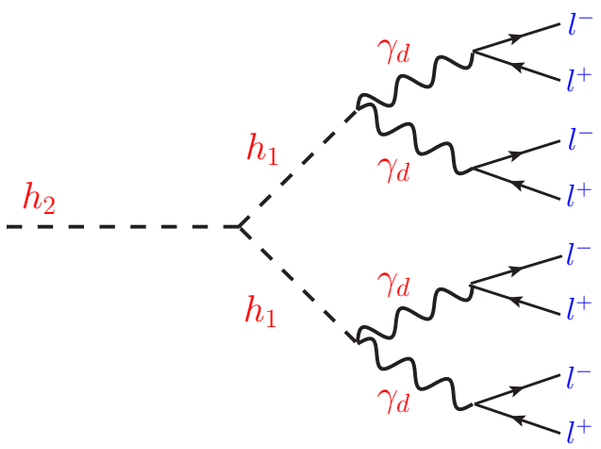
take away points

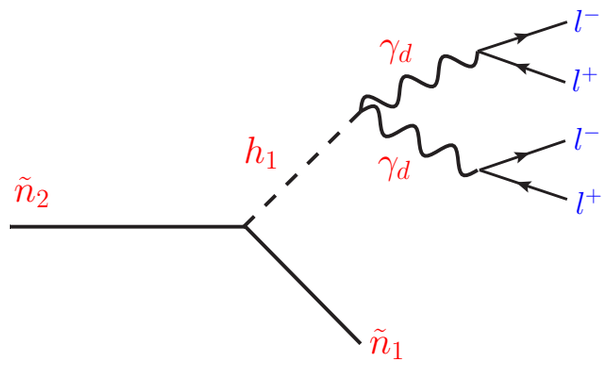
- lepton jets can be produced by a GeV-scale hidden sector and may accompany all SUSY events
- hidden sector models cover a large LJ signature space in terms of composition, lepton multiplicities, jet shape, lifetime, ...
- the two LHC searches (with 35/pb) rely on muons and are complementary (bump hunt vs iso)
- the electron-jet, pion-jet, and displaced scenarios are all untouched at the LHC (for now)

backup

LJ Simplified Model

- consider one process at a time
- specify production mode (SUSY spectrum)
- specify N steps and masses





lepton jet seed	parameters
γ_d	m_{γ_d}
h_N	N, m_{h_i}, $\mathrm{BR}(h_1 \to \tilde{n}_1\tilde{n}_1)$ m_{γ_d}
$\tilde{n}_2$	$m_{\tilde{n}_i}$ N, m_{h_i}, $\mathrm{BR}(h_1 \to \tilde{n}_1\tilde{n}_1)$ m_{γ_d}