Long-Lived Exotica at the LHC

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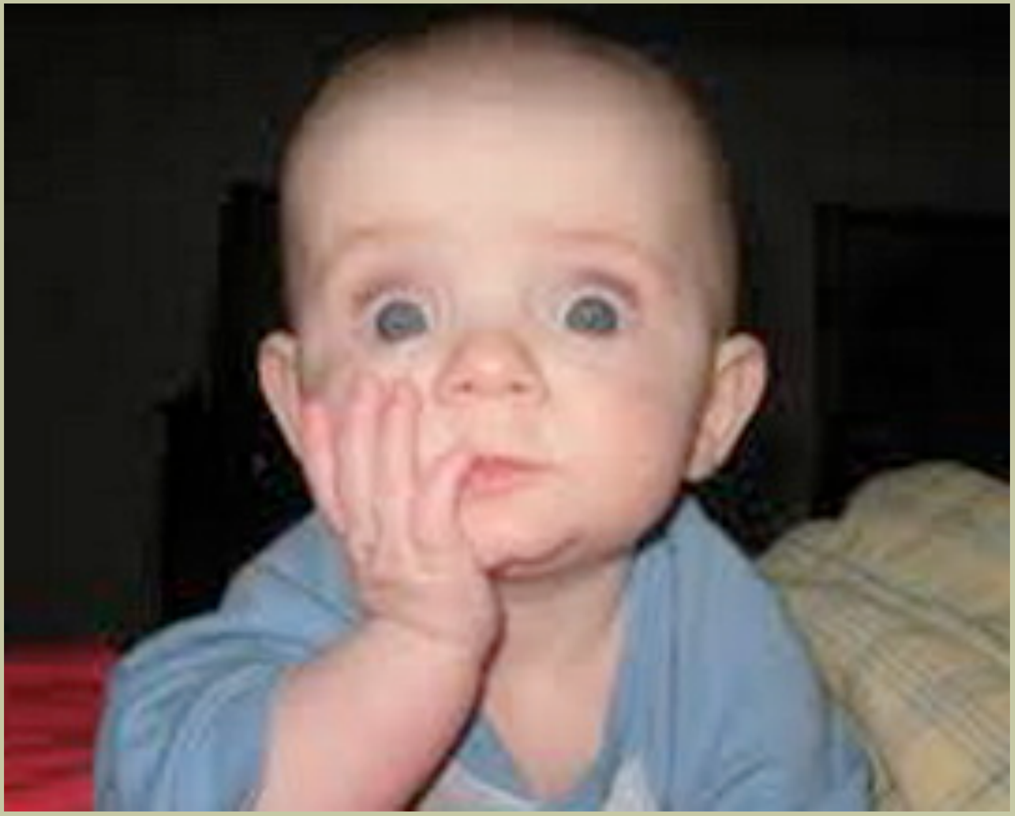
Why exotica??

Why exotica??

This is what the average theorist will look like a year from now, if only the SM Higgs will be discovered..



Why exotica??

Nothing very exciting (beyond the SM) at the LHC

Standard scenarios feel the tension

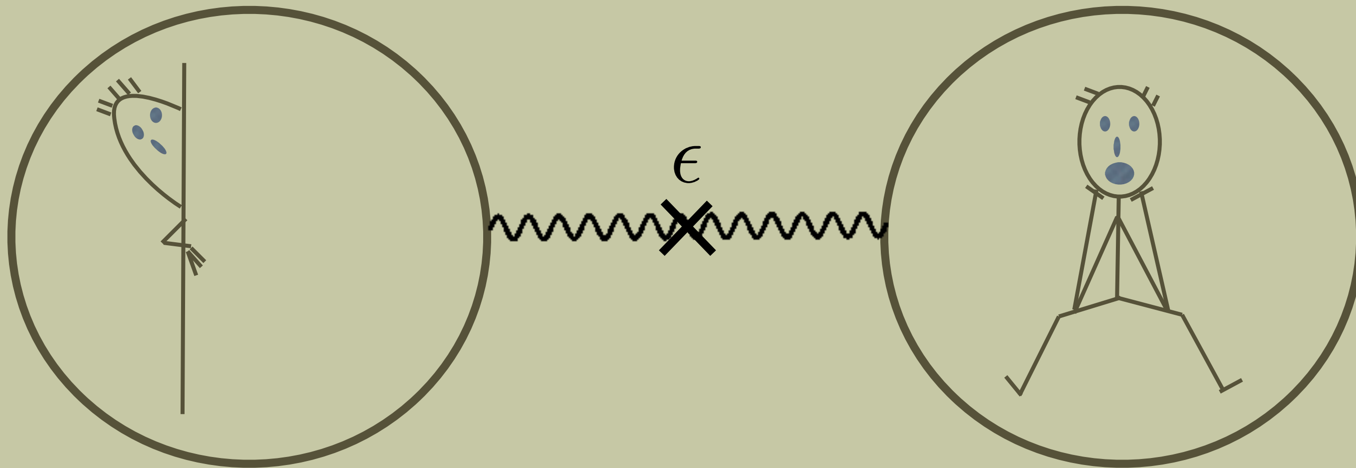
Theoretical prejudice is dangerous!

Long Lived Particles

- Many examples:
    - GMSB
    - AMSB
    - Split SUSY
    - RPV
    - Hidden Sectors
    - ...
- Several existing searches at the LHC:
    - ATLAS: Charged long-lived heavy particles (https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-022/)
    - ATLAS: AMSB [Arxiv: 1202.4847]
    - ATLAS: Stopped Gluinos [Arxiv: 1201.5595]
    - CMS: GMSB (https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11067)
    - CMS: Higgs to displaced leptons (https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11004)

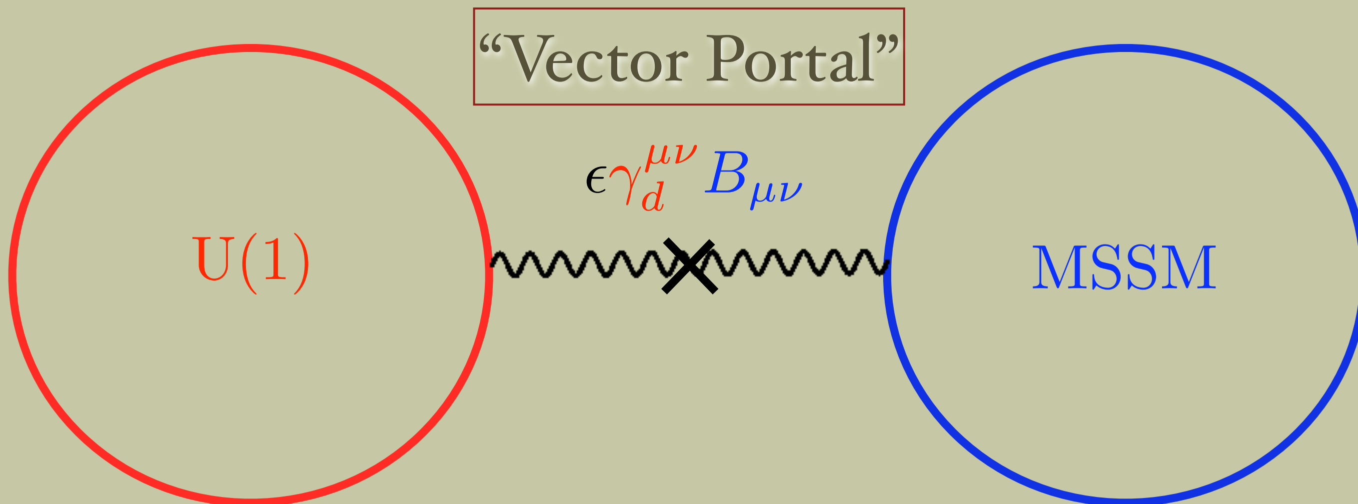
Hidden Valleys:
Decays in the Muon Spectrometer

A Hidden Sector

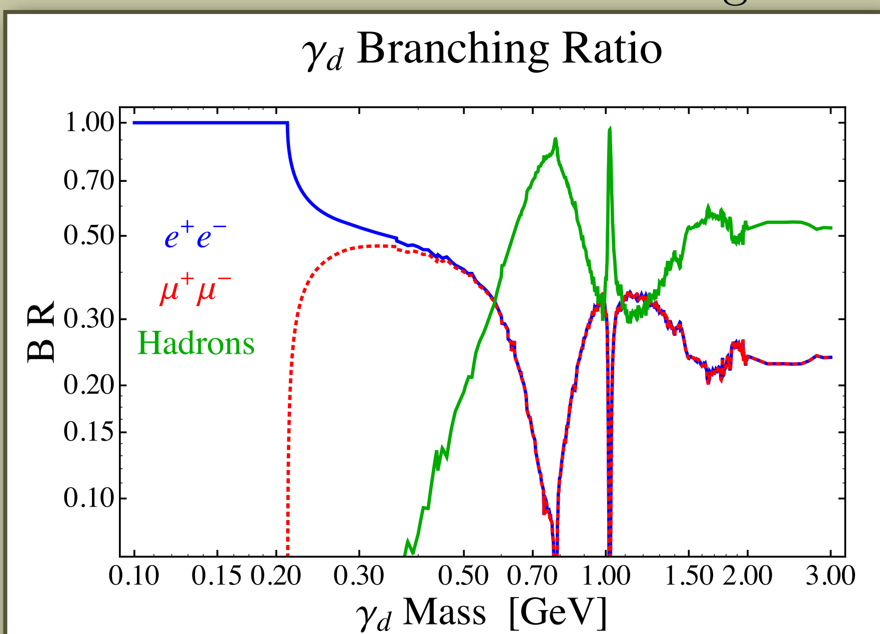


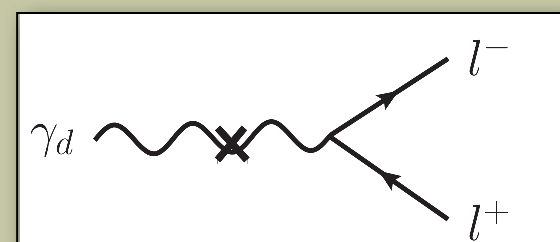
- Could be a weakly or strongly coupled version of "Hidden Valleys". [Strassler, Zurek, 2006]
- Simple and plausible extension of the SM.
- Mixing can be naturally generated at high scale, $\varepsilon \lesssim 10^{-3}$.
- Phenomenology vary with hidden sector structure, *which we know nothing about*!

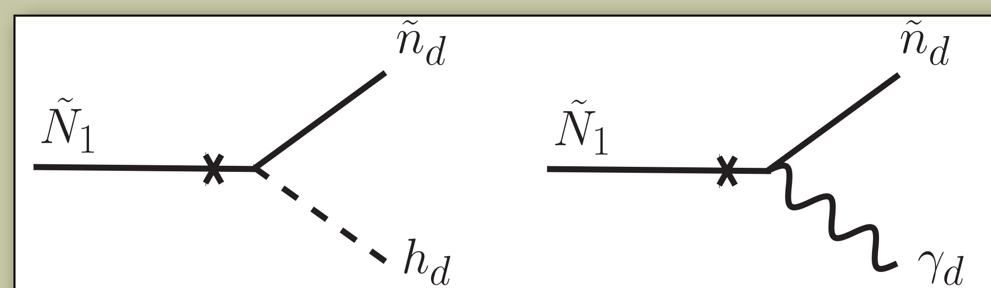
A Hidden Sector



$$\mathcal{L}_{mix} = \underbrace{\frac{1}{2}\epsilon\, \gamma_d^{\mu\nu} B^{\mu\nu}}_{\text{Gauge}} \underbrace{- i\epsilon\, \tilde{\gamma}_d^\dagger\, \bar{\sigma}^\mu \partial_\mu \tilde{B} + i\epsilon\, \tilde{B}^\dagger\, \bar{\sigma}^\mu \partial_\mu \tilde{\gamma}_d}_{\text{Gaugino}}$$

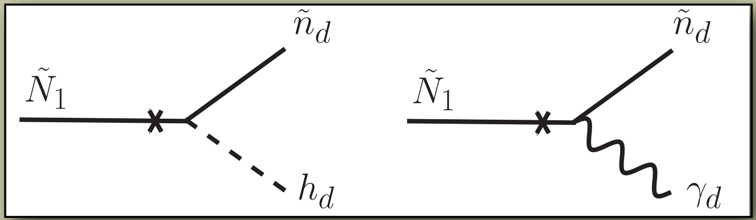






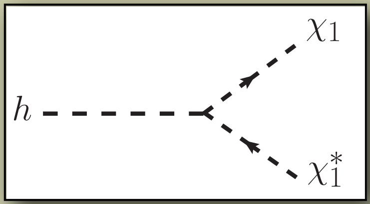
Production of Hidden Sector Particles

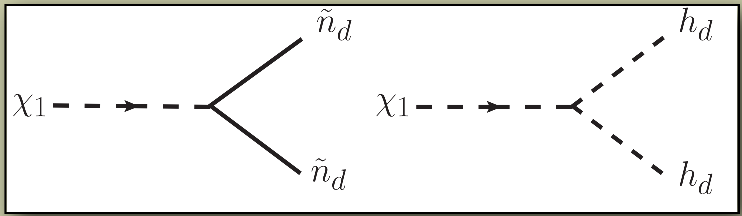
- Production may occur in various ways, e.g.:
    - In supersymmetric models, NLSP will decay to hidden sector.



    - Scalar particles may couple to visible and hidden sector.

$$W_{\mathrm{singlet}} = S\,(y\,\chi\,\bar{\chi} + \lambda\,H_u H_d) + \kappa_1\,\bar{\chi}\,h_1^2 + \kappa_2\,\chi\,h_2^2\,.$$



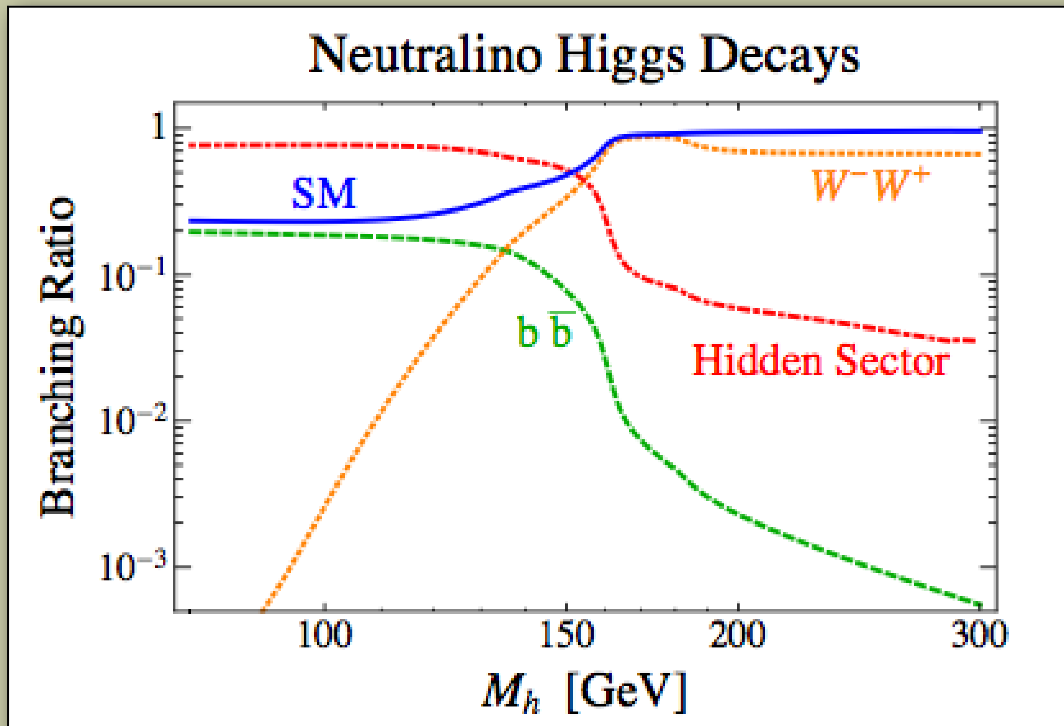


- Let's consider the case where the Higgs or some other scalar field decays to the hidden sector.

[Falkowski, Ruderman, TV, Zupan, 2010]

Production of Hidden Sector Particles

- In the case where the Higgs decays, it can predominantly decay to hidden sector.

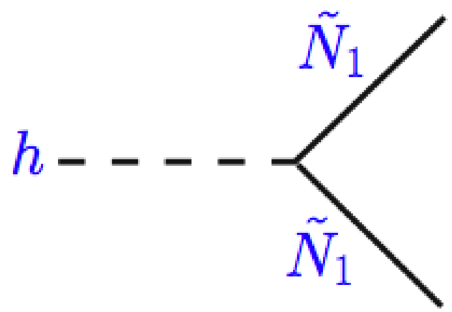


[Falkowski, Ruderman, TV, Zupan, 2010]

- Instead of a Higgs this can be a singlet scalar, *Z'*, etc.

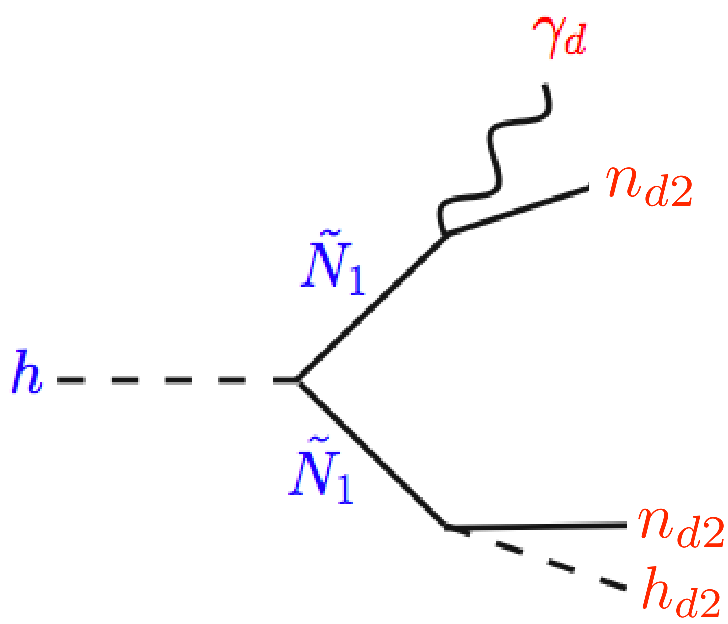
Example: Lepton Jet Topology

Higgs decays...



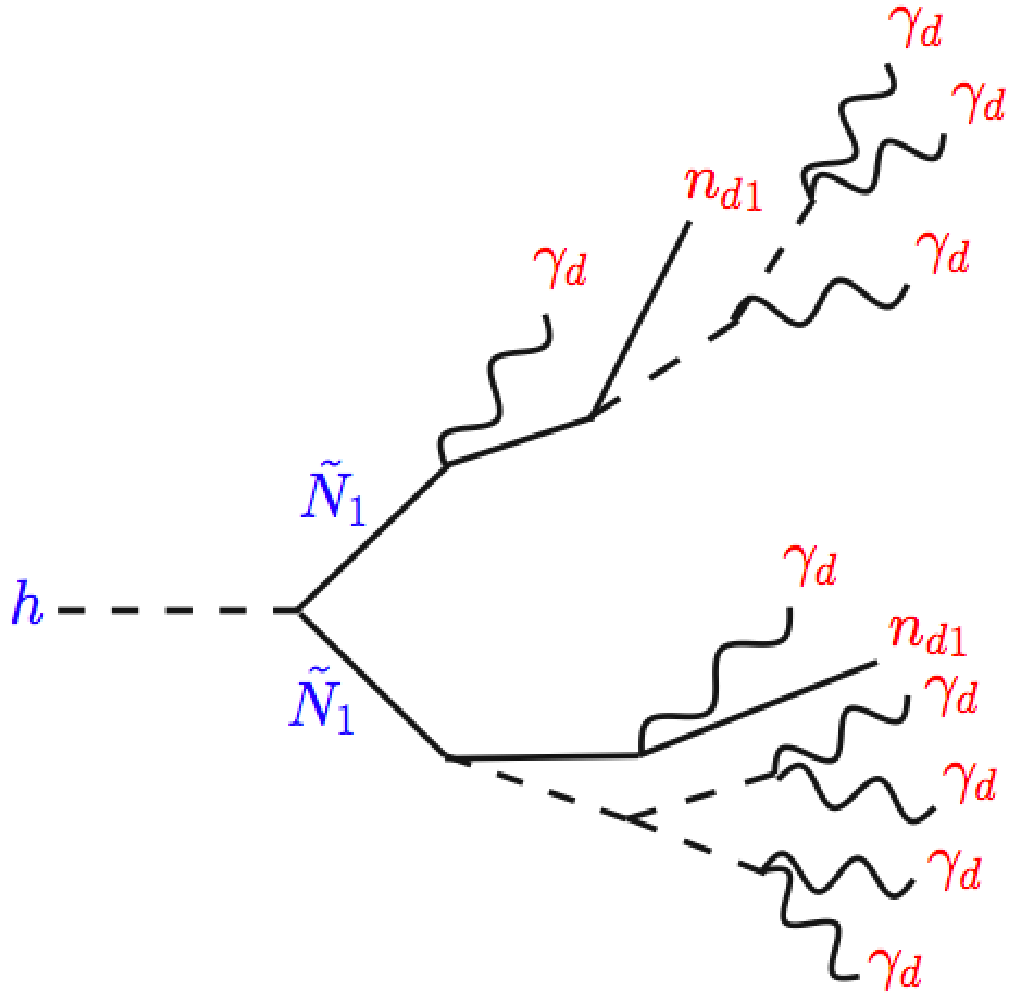
Example: Lepton Jet Topology

Into the Hidden Sector...



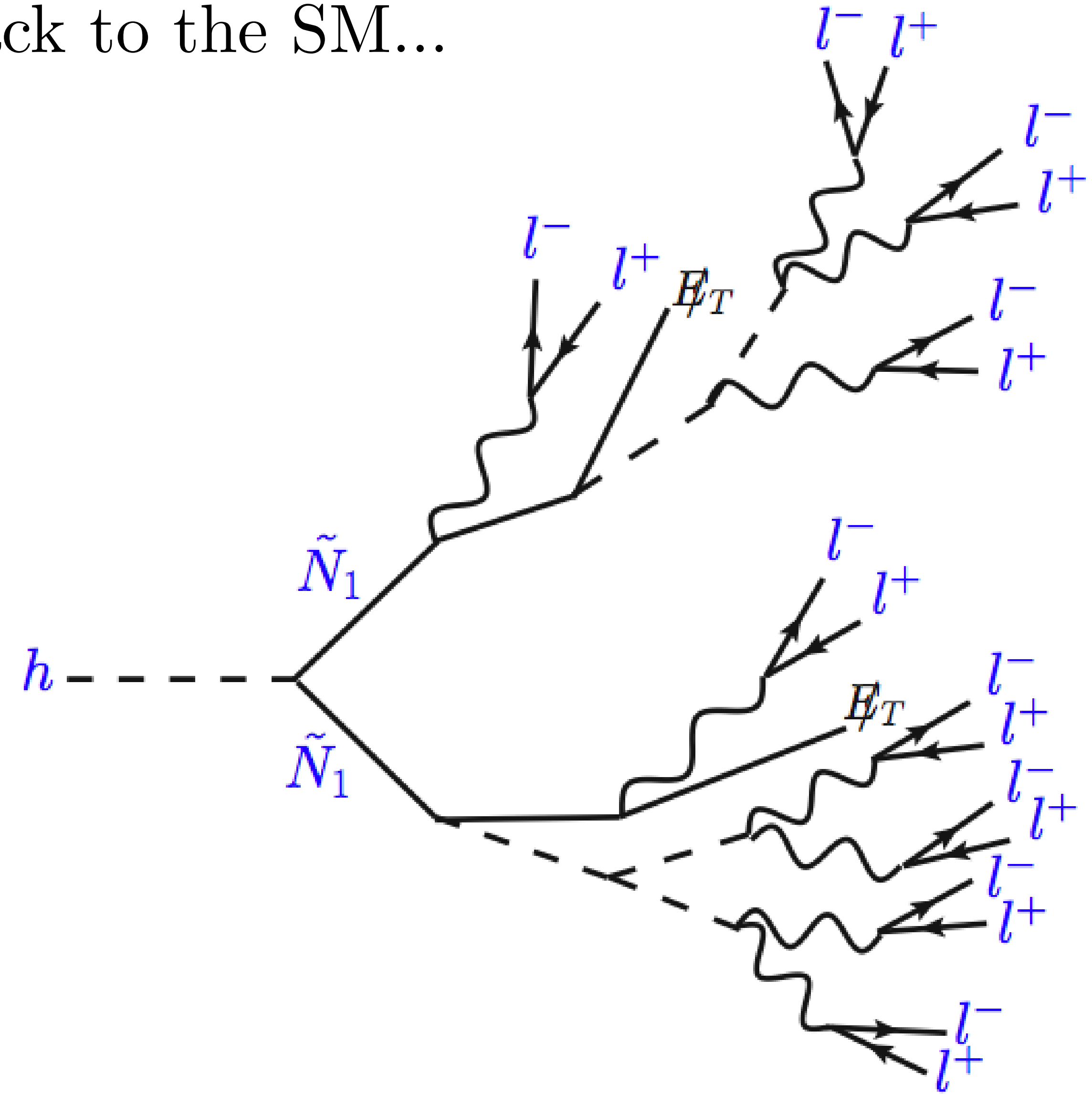
Example: Lepton Jet Topology

Hidden cascade...

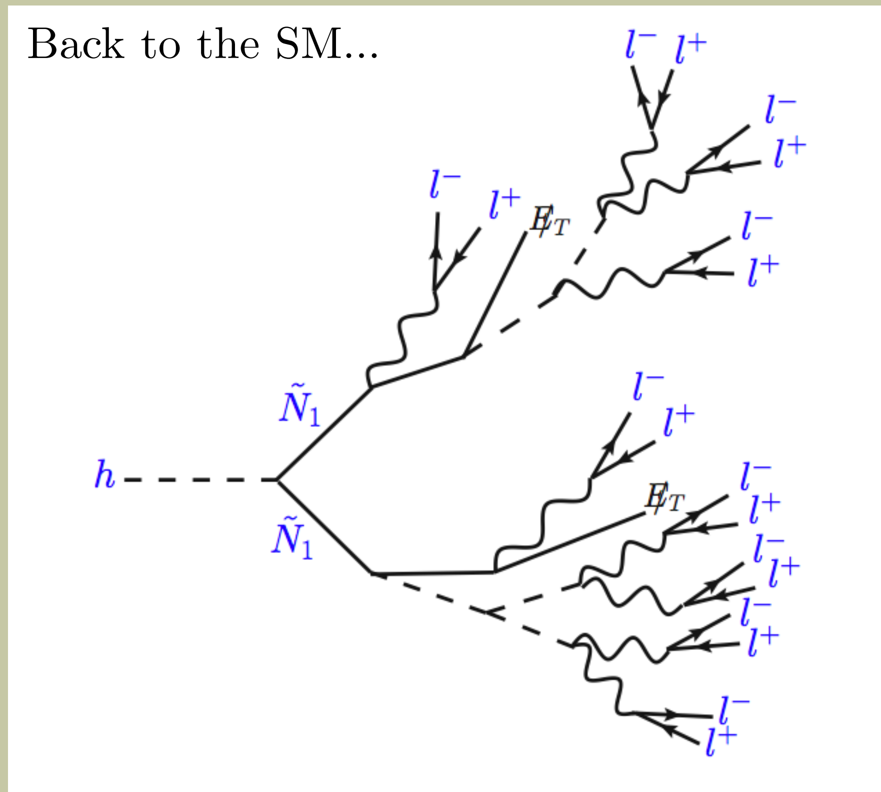


Example: Lepton Jet Topology

Back to the SM...



Example: Lepton Jet Topology



The final states are high-multiplicity clusters of boosted and collimated leptons:

Lepton Jets

[Arkani-Hamed, Weiner; Cheung, et al.; , Baumgart, et al.]

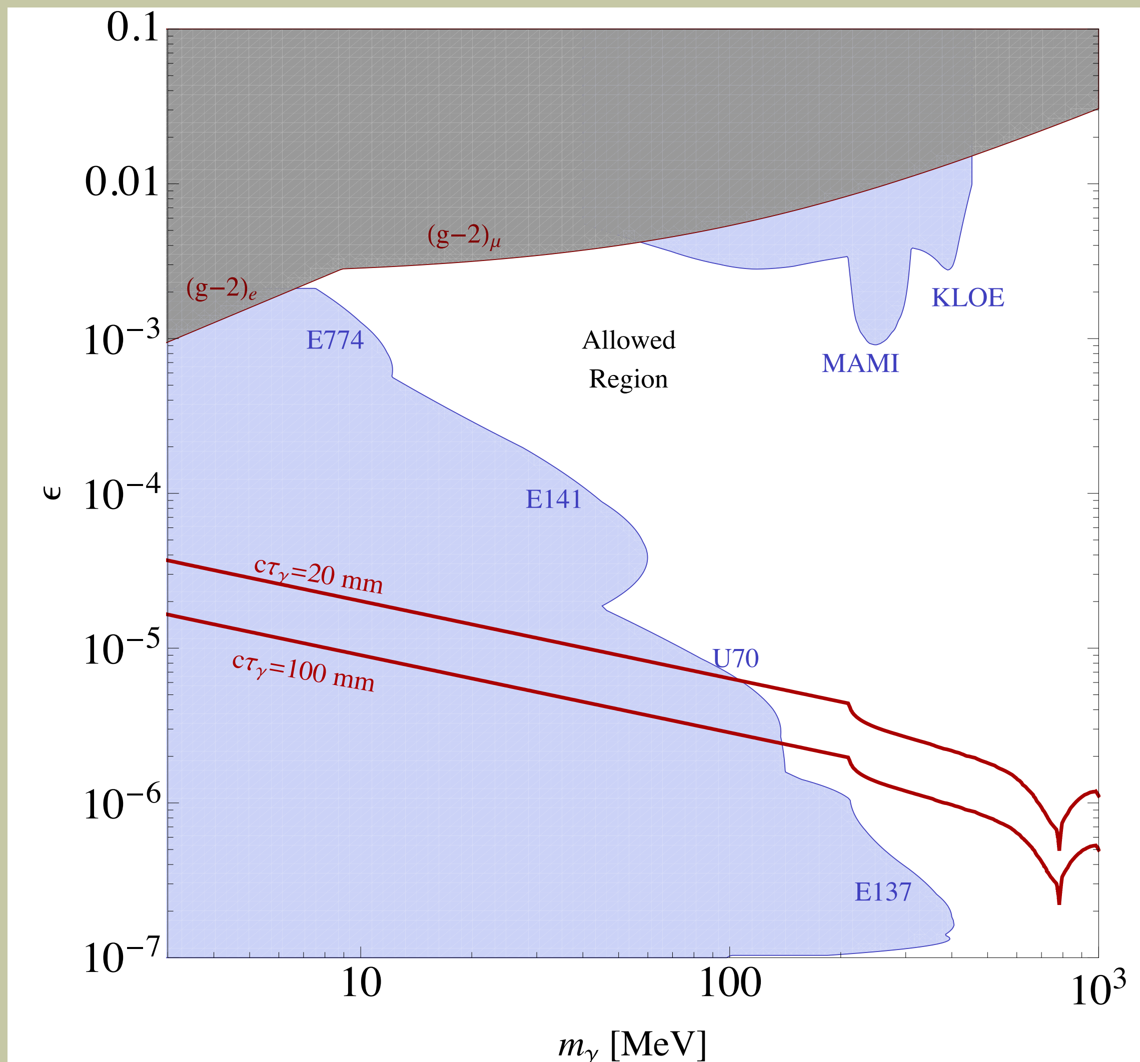
Lots of ongoing experimental efforts..

- **LEP-2**
  - L3: H $\rightarrow$ LJs (Princeton?)
  - ALEPH: H $\rightarrow$ LJs (RECAST)
- **Tevatron**
  - D0: SUSY $\rightarrow$ LJs (Rutgers and SLAC)
  - CDF: H $\rightarrow$ LJs (Chicago, see Azeddine's talk)
- **LHC**
  - CMS: H $\rightarrow$ displaced LJs (Princeton)
  - ATLAS: H $\rightarrow$ displaced LJs (Seattle/Rome)
  - CMS: SUSY $\rightarrow$ muonic LJs (Princeton, Texas A&M)
  - CMS: SUSY $\rightarrow$ LJs (Rutgers)
  - ATLAS: H $\rightarrow$ LJs (Ljubljana)

Lifetime

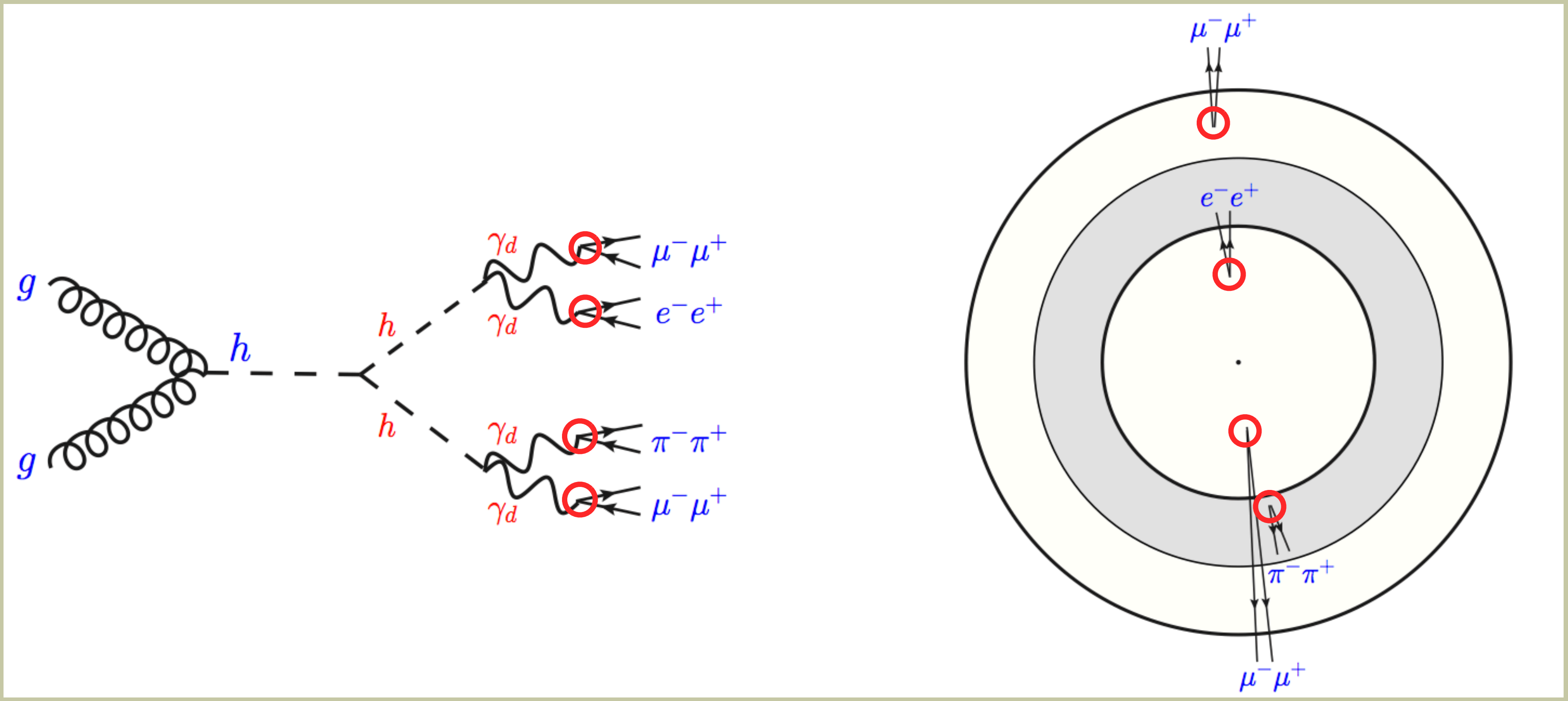
- The lifetime of both the γ_d and $\tilde{N}_1$ is controlled by ϵ.

$$\tau_{\gamma_d} \sim \left(\epsilon^2 \alpha_{\rm EM} m_{\gamma_d}\right)^{-1} \simeq 10^{-12}\ \text{sec} \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{\text{MeV}}{m_{\gamma_d}}\right)$$



[Bjorken, Essig, Schuster, Toro 2009; Blumlein, Brunner 2011]

Long Lived Higgs



Hidden Valley Triggers

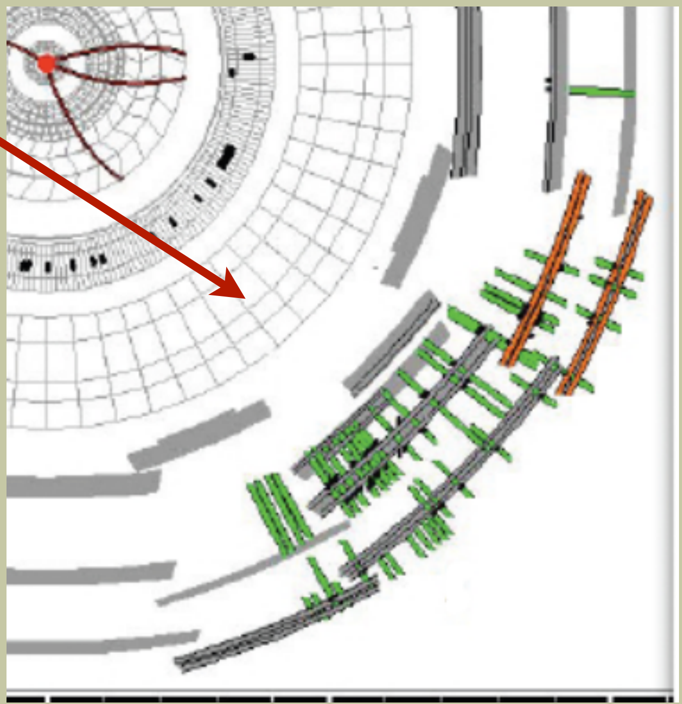
- Late decays would not be picked up with standard triggers.
- Three dedicated triggers were designed.

1. **MUON ROI CLUSTER TRIGGER**

   Developed for decays in the MS.

   L2 requires:
   - 3 muon RoI's in $\Delta R<0.4$
   - No calorimeter jets with $E_T>30$ GeV and $\Delta R<0.7$
   - No ID tracks with $p_T>5$ GeV and $\Delta\eta\times\Delta\phi=0.2\times0.2$

   Typical decays: Little energy in calorimeter



Hidden Valley Triggers

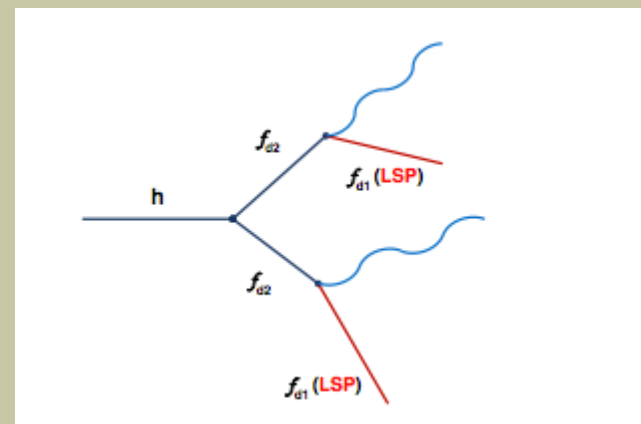
- Late decays would not be picked up with standard triggers.
- Three dedicated triggers were designed.

1. Muon RoI Cluster Trigger
2. Calorimeter Ratio Trigger
3. Trackless Jet + Muon Trigger

ATLAS h→LJs Search (preliminary)

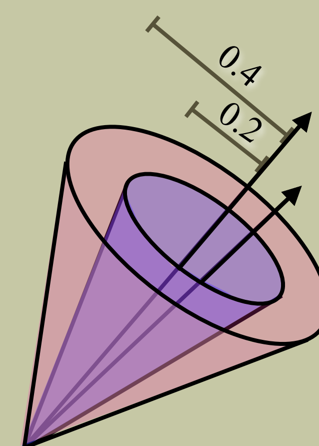
- Study muon-reach samples.
- Tune lifetime so that 80% of the decays occur inside the detector.

Higgs mass (GeV)	$m_{f_{d2}}$ (GeV)	m_{LSP} (GeV)	$\gamma_d$mass (GeV)	$c\tau$ (mm)
100.	5.0	2.0	0.4	47.
140.	5.0	2.0	0.4	36.



- Main event selection cuts:
  - Pick all muons in MS within an isolated cone in calorimeter and tracker:

    $E_{T,iso}$<5 GeV for 0.2<ΔR<0.4 and Σp_T<3 GeV for ΔR<0.4
  - At least two oppositely charged muons in each LJ
  - Require 2 LJs with |Δϕ|>2



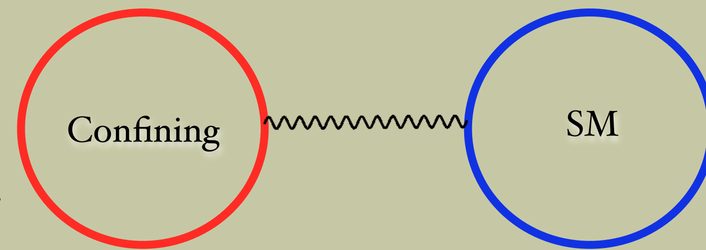
ATLAS h→LJs Search (preliminary)

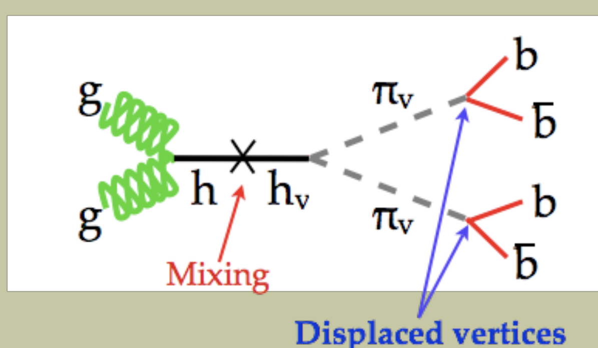
Results coming very soon...

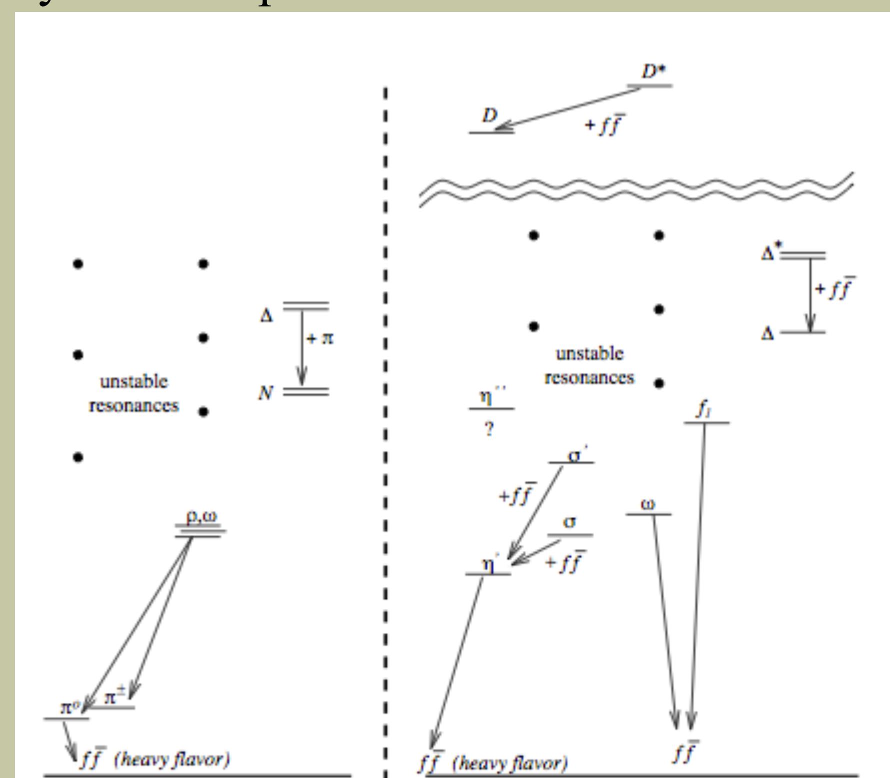
ATLAS $h \to \pi_v \pi_v \to 4b$ Search

[arXiv:1203.1303]

- Above I described a weakly coupled hidden sector, with decays to leptons.
- The hidden sector can be strongly coupled instead.
- Hidden pions decay predominantly to b-bar, $\pi_v \to bb^*$.
- Lifetime can easily be large, very similar to the previous case.
- Of course, this complicated strong-coupling story is not important - in the end we always model our ignorance with a weakly-coupled Lagrangian and this is what we look for.







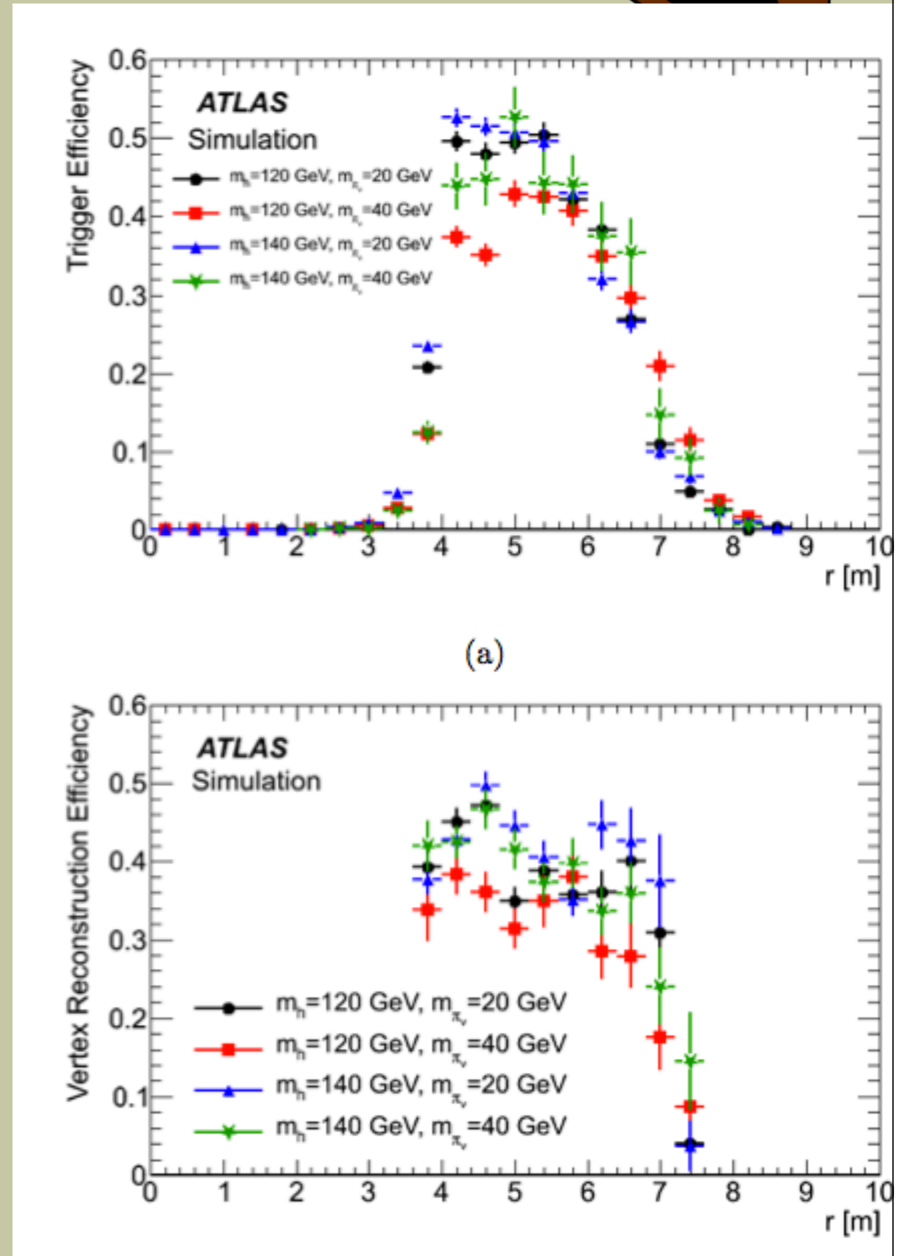
[Strassler and Zurek, 2006]

ATLAS $h \to \pi_v \pi_v \to 4b$ Search

[arXiv:1203.1303]

- Study: m_h=120 GeV and 140 GeV
  m_π=20 GeV and m_π=40 GeV
- Utilize Muon RoI Cluster Trigger implying one π_v must decay in barrel and one may decay in the forward spectrometer.
- Systematic uncertainty for trigger eff. (14%) extracted from punch-through and MC events.
- Specialized tracking and vertex reconstruction employed in MS. Requires at least 3 tracklets that point to IP and $|\eta|<2.2$.
- Isolation cuts: MS vertex separated from

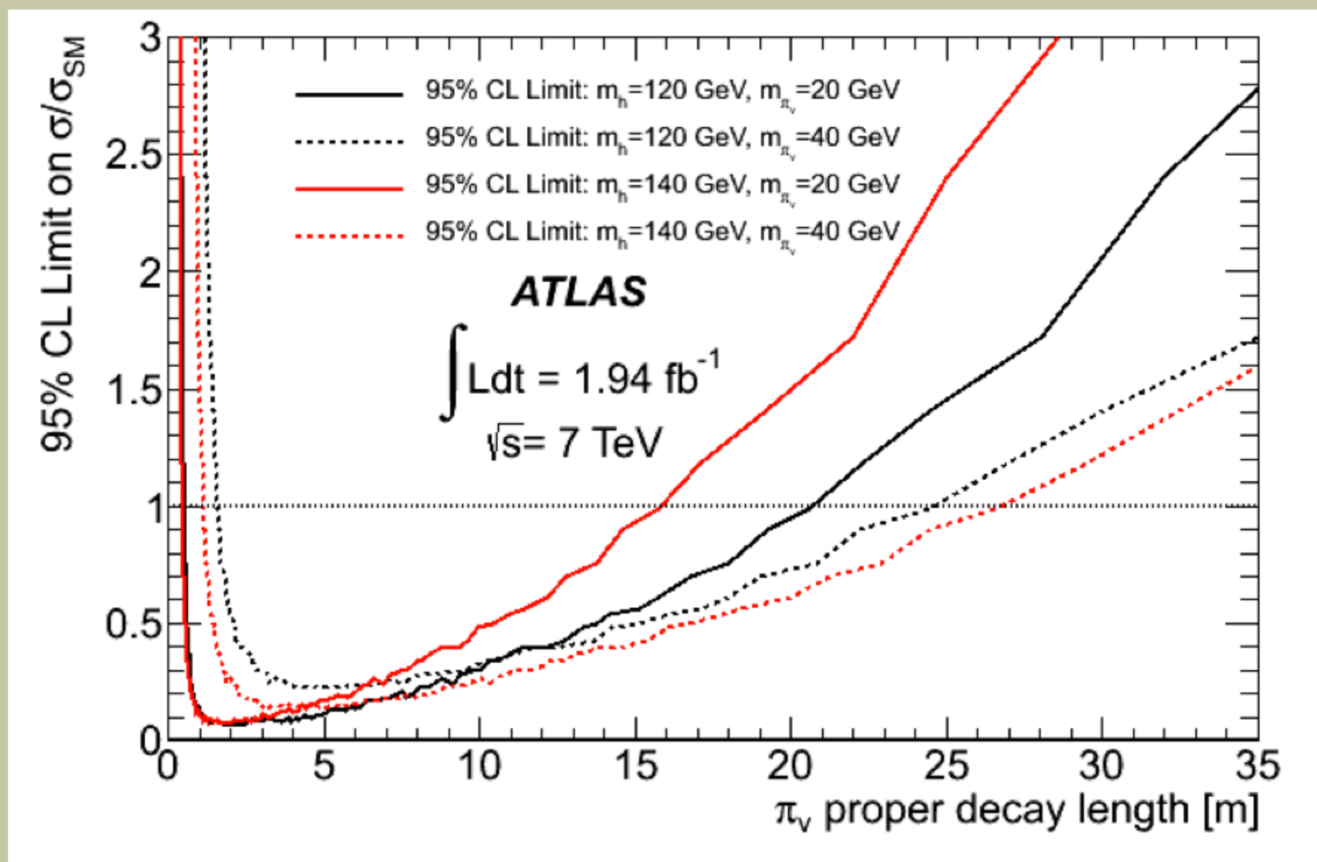
  ID tracks with $p_T > 5$ GeV, $\Delta R<0.4$
  Jets with $E_T>15$ GeV, $\Delta R<0.7$
- Require 2 good MS vertices with $\Delta R>2$.



ATLAS $h \rightarrow \pi_v \pi_v \rightarrow 4b$ Search

[arXiv:1203.1303]

- Expected background: 0.03±0.02 events.
- No events found.



Decays in the Tracker

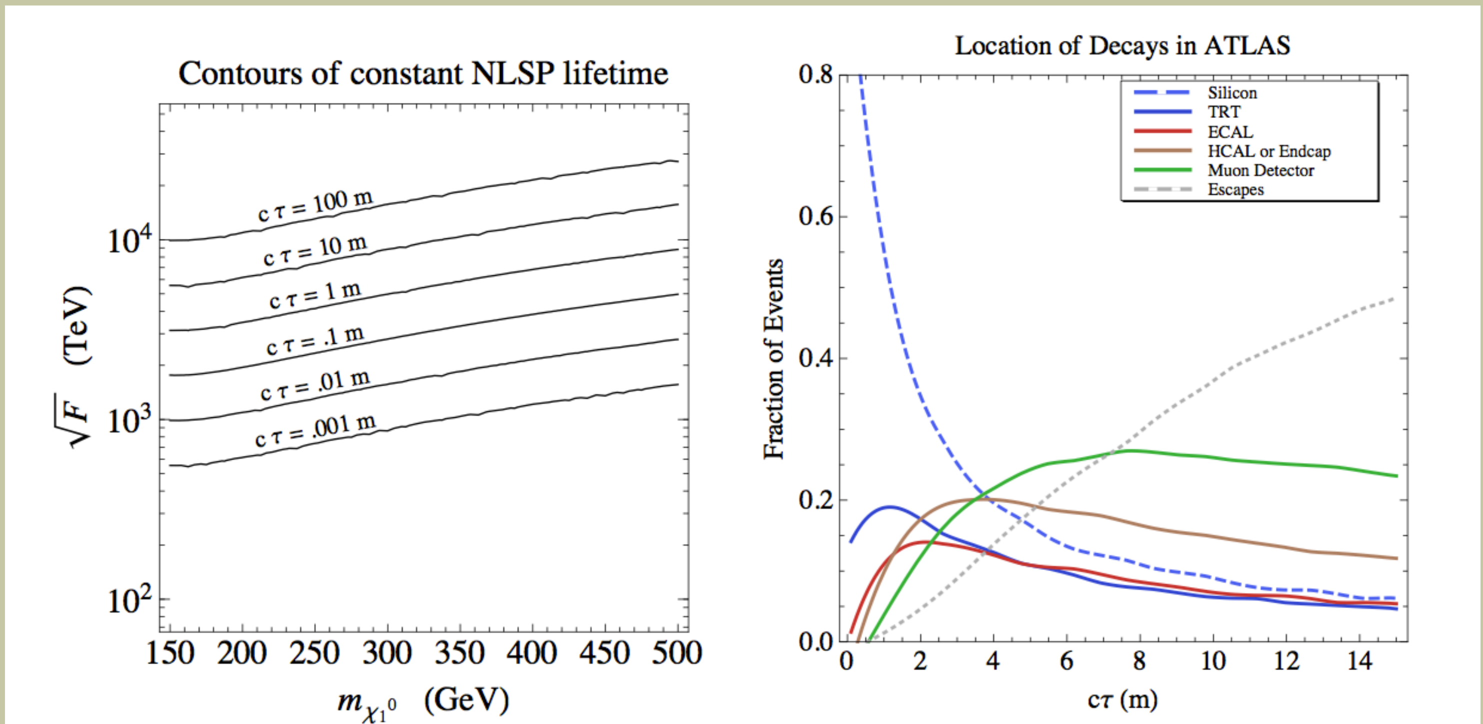
Why Look at the Tracker?

- It is likely that many of the possible NP models will be discovered even without dedicated searches.

- Nonetheless, models can be identified and further information can be obtained by studying decays in the tracker.

- For instance SUSY. In some models one can have late decays, e.g. GMSB:

$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi F^2} \approx \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{100\ \mathrm{TeV}}{\sqrt{F}}\right)^4 \frac{1}{0.1\ \mathrm{mm}}.$$



[Meade, Reece, Shih, 2010]

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  - Identifying these decays can help pin-pointing on the model.

  - It can also provide additional information, for example, by reconstructing a kink, the gravitino mass may be reconstructed (if heavy enough),

$$M_{\text{Recon}}^2 = m_{\tilde{l}}^2 + m_l^2 - 2E_{\tilde{l}}E_l + 2|\vec{p}_{\tilde{l}}||\vec{p}_l|\text{Cos}\theta_k$$

    and thus allow to distinguish between standard GMSB and one with multiple SUSY-breaking sectors.

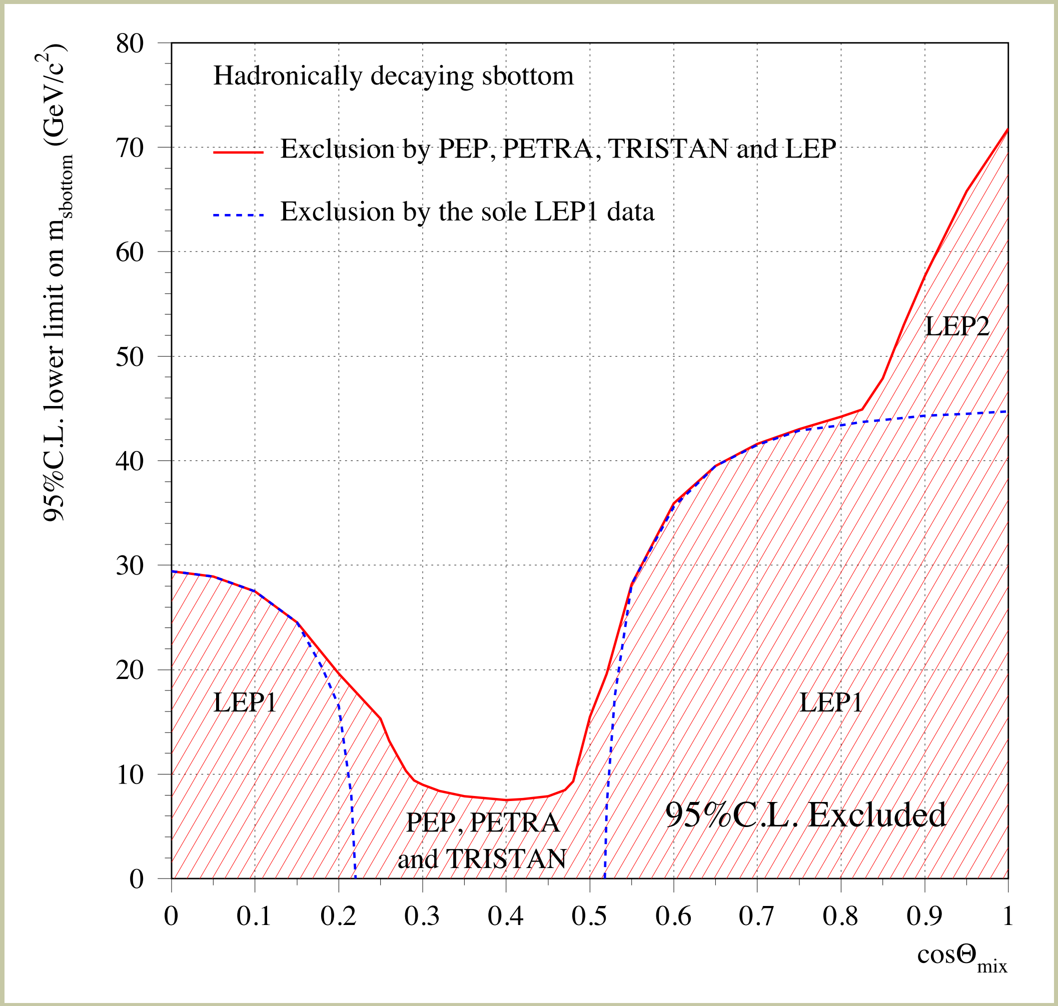
[C. Cheung, Y. Nomura, J. Thaler [arXiv:1002.1967]]

[C. Cheung, J. Mardon, Y. Nomura, J. Thaler [arXiv:1004.4627]]

[Elor, Meade, Papucci, TV, in progress]

Why Look at the Tracker?

- There are however, examples for models that will never be discovered without dedicated searches.
- One example: Hadronically decaying **light sbottoms** via RPV.



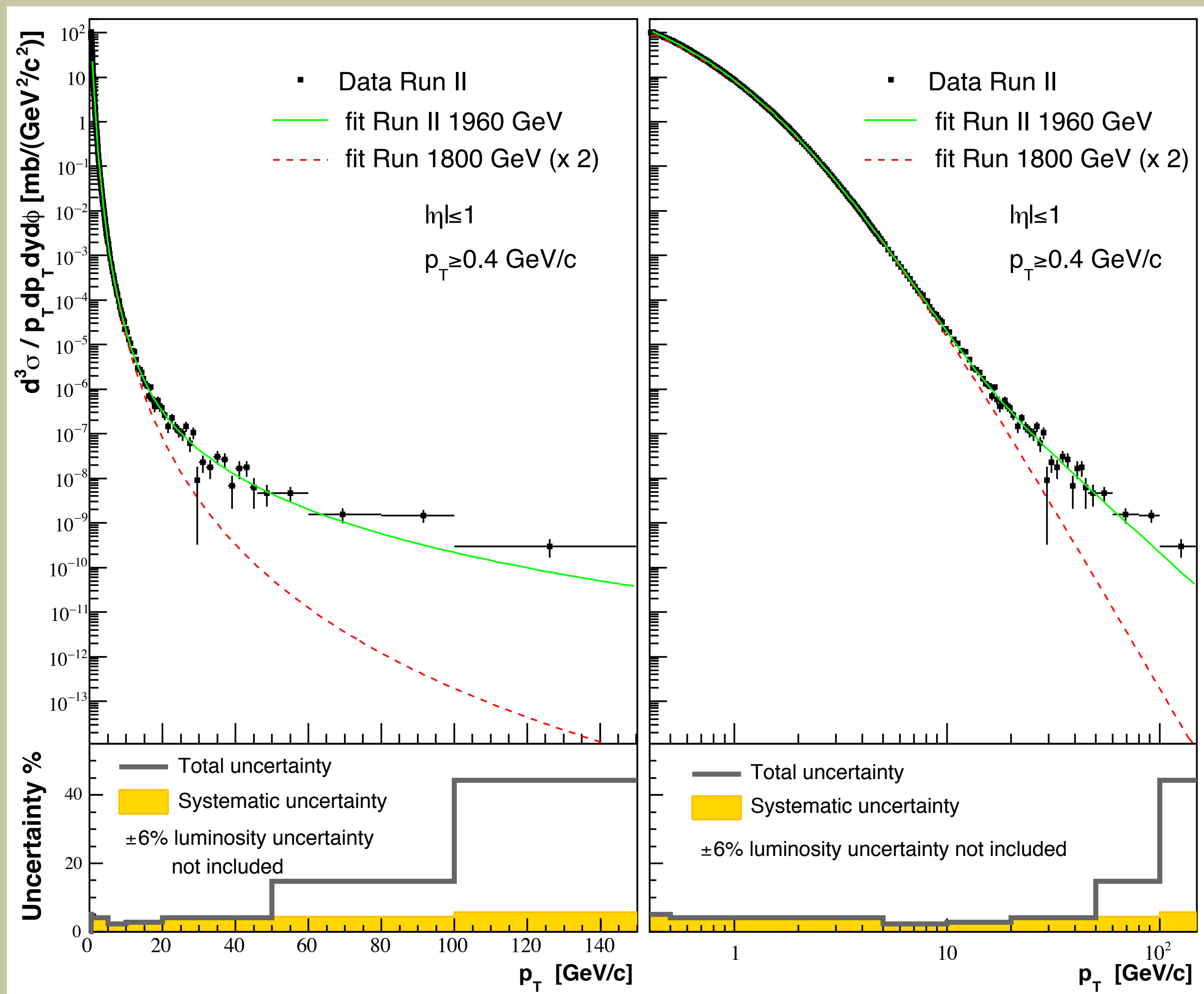
[Janot, 2004]

Why Look at the Tracker?

- There are however, examples for models that will never be discovered without dedicated searches.
- One example: Hadronically decaying **light sbottoms** via RPV.
- Production rate is huge.
- If sbottoms decay in tracker, they would produce a poor χ^2 and their p_T could be mismeasured.
- While the light sbottom window has been around for a while, I am not aware of a way to close it at the LHC.
- Ideas?

The XY Model [Papucci, Meade, TV, 2011]

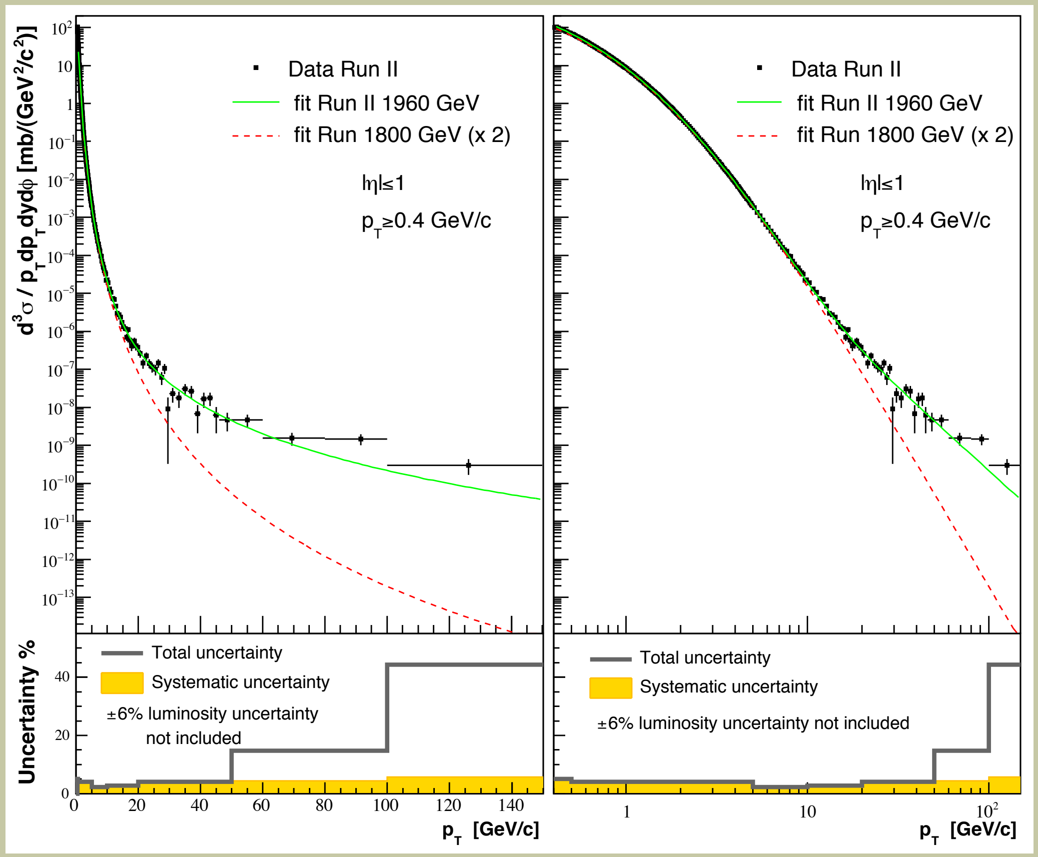
- There are even more exotic models with huge rates that will not be easily discovered.
- Motivation: CDF Anomaly - charged track distribution in MB events.



[CDF, 0904.1098]

The XY Model [Papucci, Meade, TV, 2011]

- ATLAS and CMS do not see this!
- Difference between CDF and ATLAS/CMS: track quality cuts.
- If true, anomaly indicates breakdown of QCD factorization or NP. [Albino et al.; Arleo et al.; Cacciari et al.]
- Difficulty in NP explanation: $p_T \lesssim M$ but for $M \simeq 100$ GeV, rate is too low.



The XY Model [Papucci, Meade, TV, 2011]

- Solution?
- Of course, this measurement is almost certainly wrong.
- But what kind of NP can explain it?
- Whatever it is, its momentum must be mismeasured.
- Consider adding a new vector-like particle,

$$X + \bar{X} \sim (3,1)_0 + (\bar{3},1)_0 \qquad\qquad m_X \sim 10\,\mathrm{GeV}$$

- When produced, X hadronizes into fractionally charged mesons.
- The p_T that will be measured is enhanced:

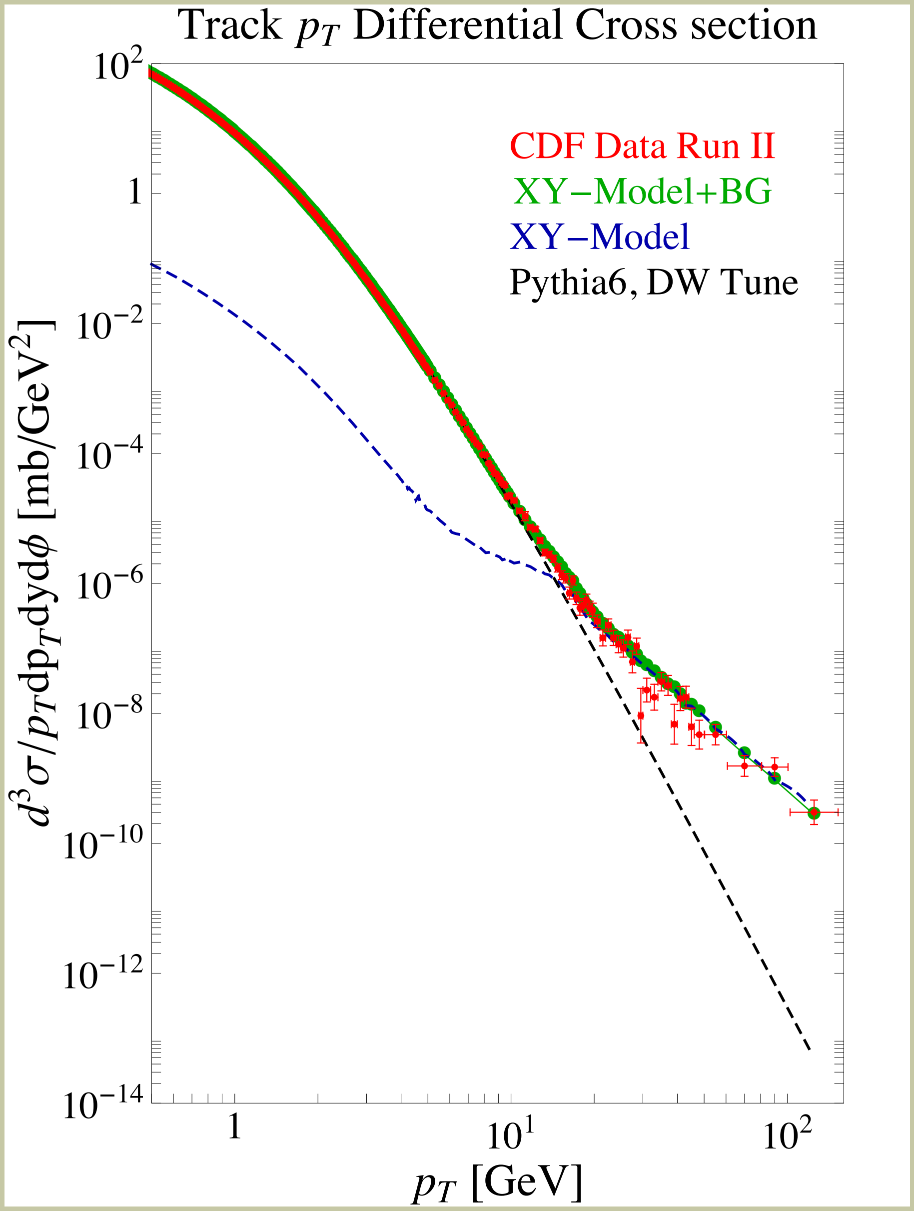
$$p_{T,\mathrm{measured}} = p_T \,/\, q$$

- But stable fractionally charged particles are very constrained (e.g. CHAMP searches), so X must decay inside the tracker:

$$\frac{1}{\Lambda} X \bar{d}_R Y^2$$

The XY Model [Papucci, Meade, TV, 2011]

- Since these are fractionally charged particles the don't have many hits in the silicon tracker or COT.
- Tracks systematically biased to high p_T.



Take Home Message:

Tracks can be strange enough to be missed.

Irregular tracks should be search for!

NOTs -- New Odd Tracks

- Irregular tracks can come in many forms.
- In many cases, peculiar properties may lead to a systematic mis-reconstruction of their tracks by the standard algorithms.
- Consequently, particles of this kind may evade detection.
- Refer to such particles as NOTs and classify signatures: [Meade, Papucci, TV, 20011]
  - Kinks.
  - Displaced vertices.
  - Anomalous dE/dx.
  - Anomalous timing.
  - Intermittent hits.
  - Anomalous curvature.
  - Stub Tracks.

Long Lived Particles

NOTs -- New Odd Tracks

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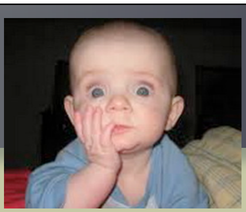
Model	Displaced Vertex	dE/dx	Timing	Curvature	Stub Tracks	Kinks
GMSB	✓	✓	✓			✓
AMSB					✓	✓
RPV	✓	✓	✓			✓
Quirks		✓		✓		✓
Fractionally Charged Particles		✓	✓		✓	✓

What do we do the morning after?



- If the SM Higgs is discovered and nothing else, there will only be a few games left in town:
  - Flavor physics
  - Higgs precision measurements
  - Exotic searches to ensure we missed nothing!

How to deal with unknown unknowns?

- **Stage 1:** We think through examples - so come up with as many as we can.
  (Often motivated by unsubstantiated rumors and weak anomalies...)

- **Stage 2:** Figure out triggering.
  Very crucial to understand in advance!!

- **Stage 3:** Experimental searches - keep general.
  Better do a signature-based search.
  Can be done more systematically.

Very important - work with simplified/pseudo models. When the unknowns are unknown, constraining one specific model is almost meaningless...

- **Stage 4:** Provide as much information as possible when presenting results so that the implication for other scenarios can be evaluated.

Extras

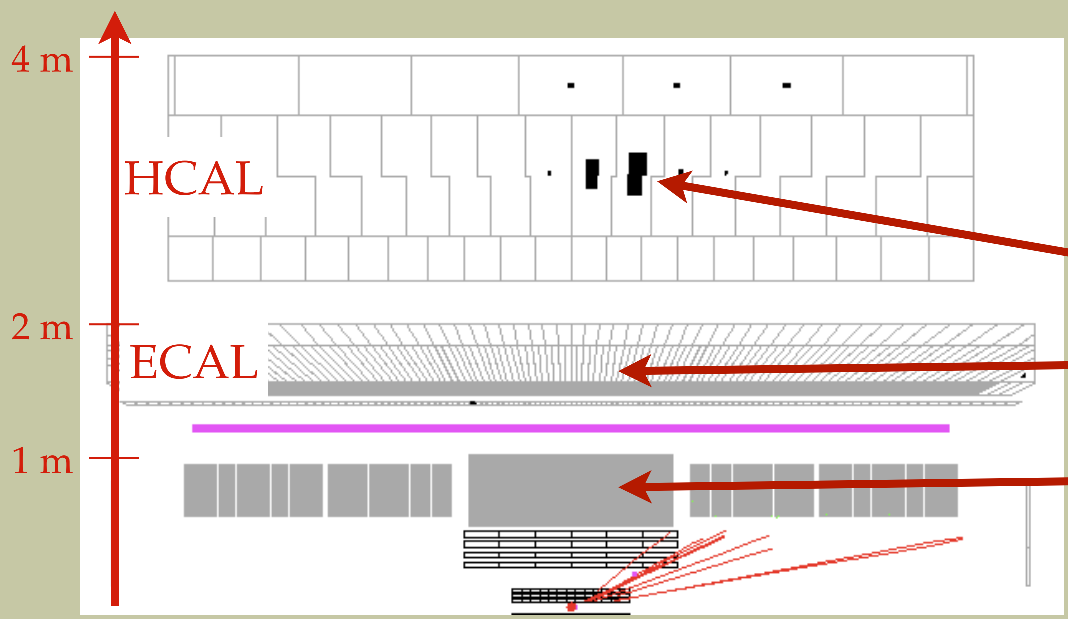
Hidden Valley Triggers

- Late decays would not be picked up with standard triggers.
- Three dedicated triggers were designed.

1. Muon RoI Cluster Trigger
2. Calorimeter Ratio Trigger

Developed for decays in the HCAL.

L2 requires: - A Jet with $E_T > 30$ GeV and $\mathrm{Log}_{10}(E_{HAD}/E_{EM}) > 1$
- No Inner Detector tracks in $\Delta\eta\times\Delta\phi<0.2\times0.2$ around the jet axis



Typical decays:

Narrow jets ($\Delta R < 0.1$)

Little/No Energy in the ECAL

No related tracks.

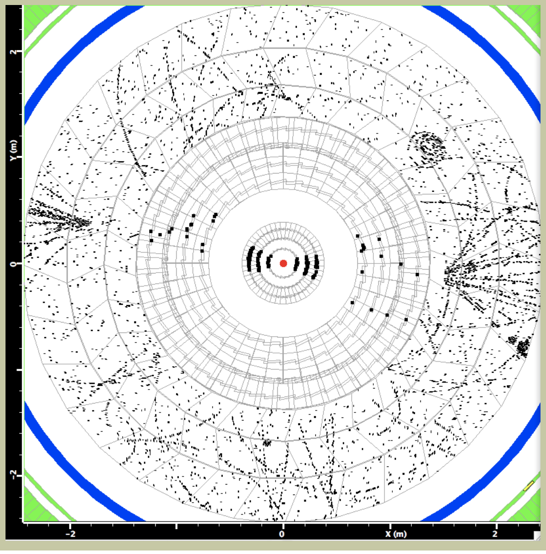
Hidden Valley Triggers

- Late decays would not be picked up with standard triggers.
- Three dedicated triggers were designed.

1. Muon RoI Cluster Trigger
2. Calorimeter Ratio Trigger
3. Trackless Jet + Muon Trigger

Developed for decays in the tracker.

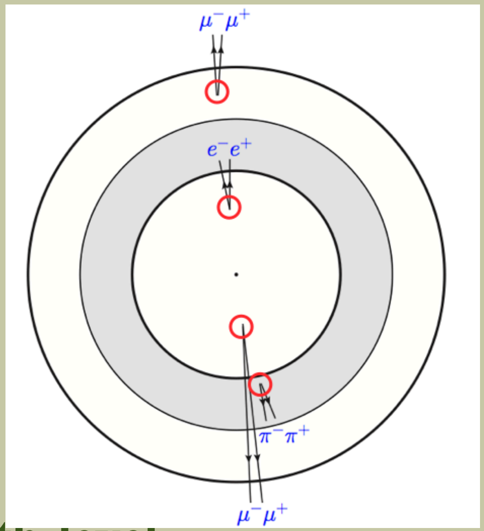
L2 requires: - A Jet ($E_T > 30$ GeV)
- No tracks (pT > 1 GeV) connecting to the IP
- Muon inside of the jet cone



Presentation of Results

How should we present constraints?

- Consider a search for long lived hidden particles (more details from Dan..)
- Limits can be placed on any given pseudo model with a specific topology, BRs, lifetime, masses, etc.



- How do we provide more information that can be used to to constrain other pseudo-models?
- Idea:
  Present efficiencies for **global** and **LJ-specific** properties, at **truth-level**.
  Try to (partly) disentangle the dependence on the various properties.
- What are the relevant parameters?
  - Composition.
  - p_T distributions.
  - Lifetime.
  - MET.
  - Number of LJs.
  - $\Delta\phi$(LJs,MET,..)
  - Isolated leptons (relevant for associated production)

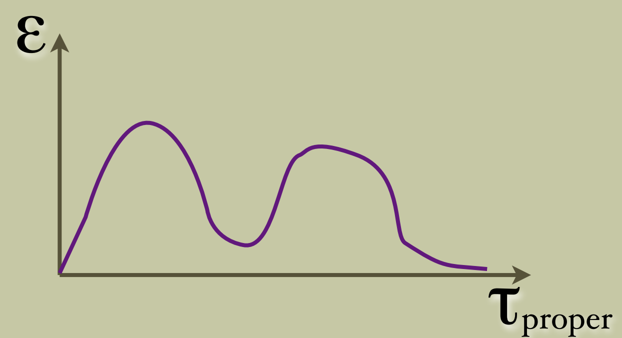
Useful plots for long-lived searches..

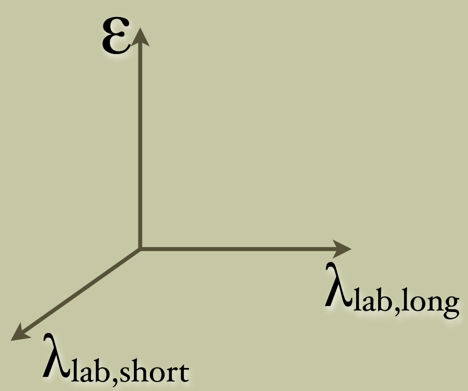
Present efficiencies at truth-level
(significantly more useful for theorists)

Present efficiencies per LJ
(provides information on the hidden structure)

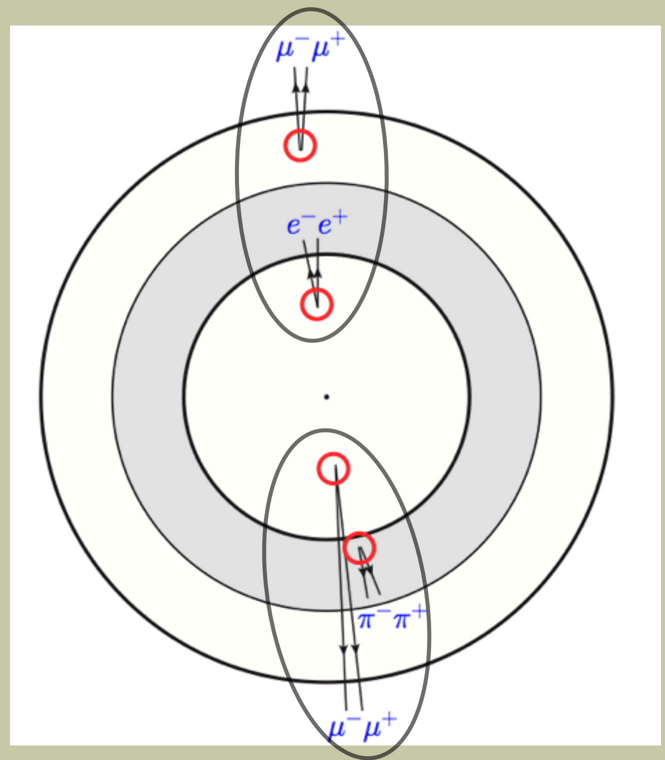
Useful plots for long-lived searches..

- **Lifetime:**



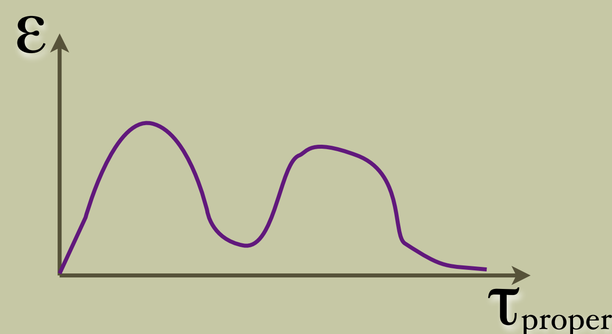


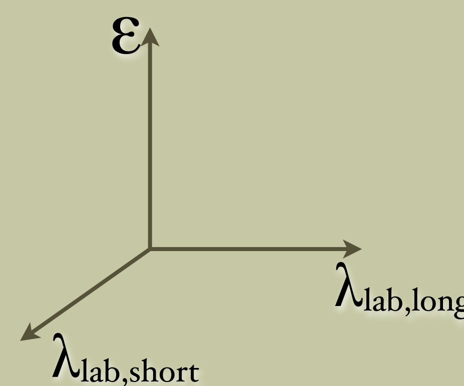
More information for models with several lifetimes and multiple decays.



Useful plots for long-lived searches..

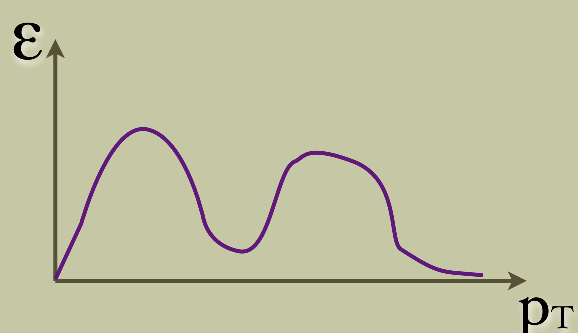
- **Lifetime:**

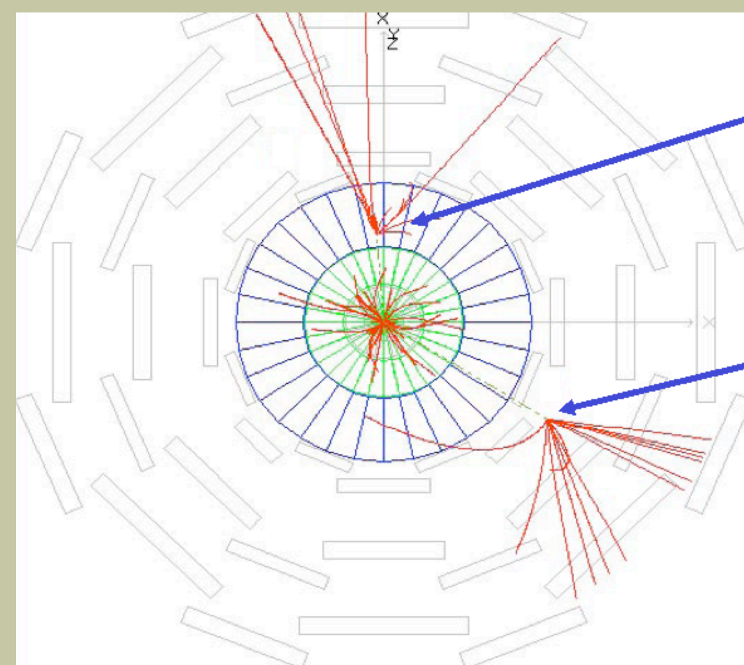




- **p_T:** Can disentangle dependence from lifetime

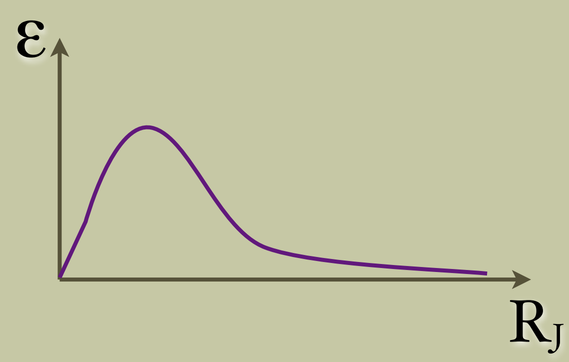
  Plot for each region of the detector: tracker, calorimeter, muon chamber.

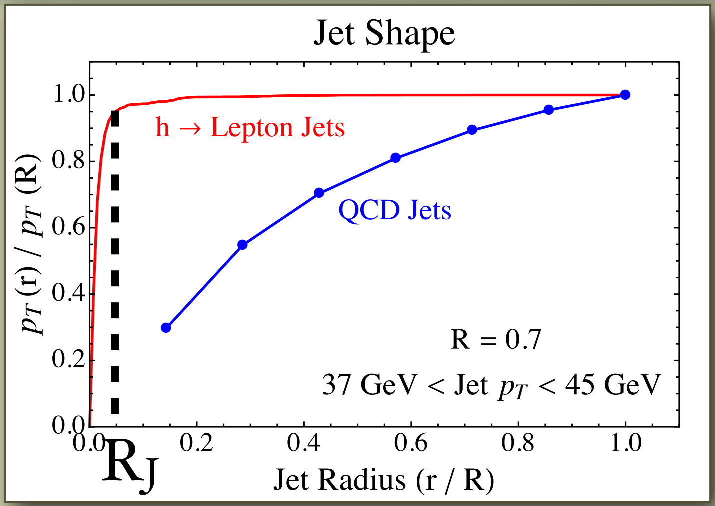




Useful plots for long-lived searches..

- **Collimation:**





Useful plots for long-lived searches..

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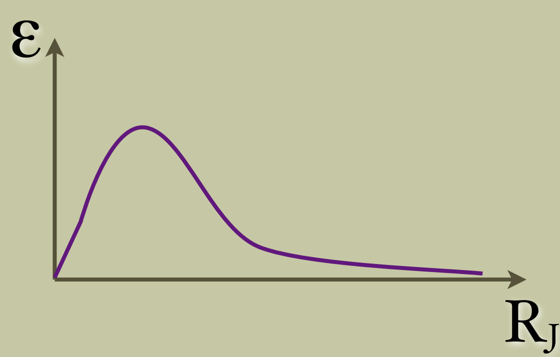
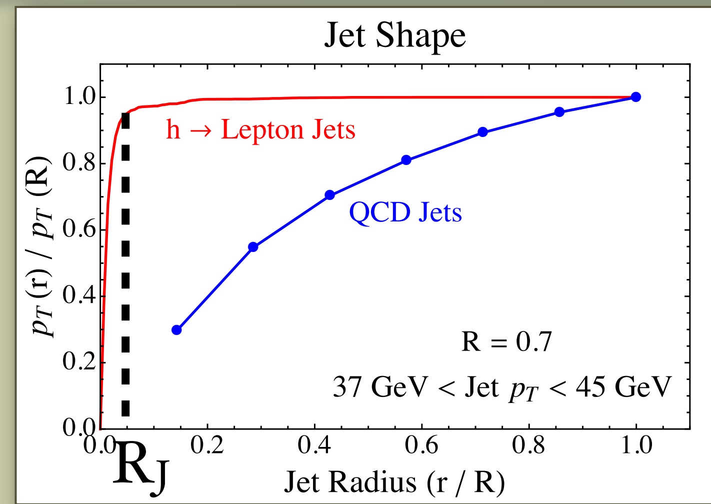
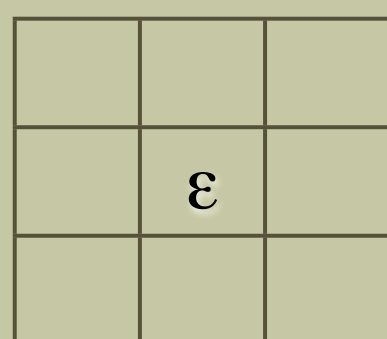




- **Composition:** 2D tables for efficiencies as function of composition on event-by-event basis.

e composition



μ composition

Pseudo Models

- A wide range of parameters can be captured with a small set of pseudo-models.
- Assume N-step cascade.
- Tunable parameters:
    - **Topology**: number of cascade steps (multiplicity and pT).
    - **Composition**: BR's of last step to SM (composition and MET distribution).
    - **Masses**: Higgs (rate) and hidden mass (number and width of LJ).
    - **Lifetime**.