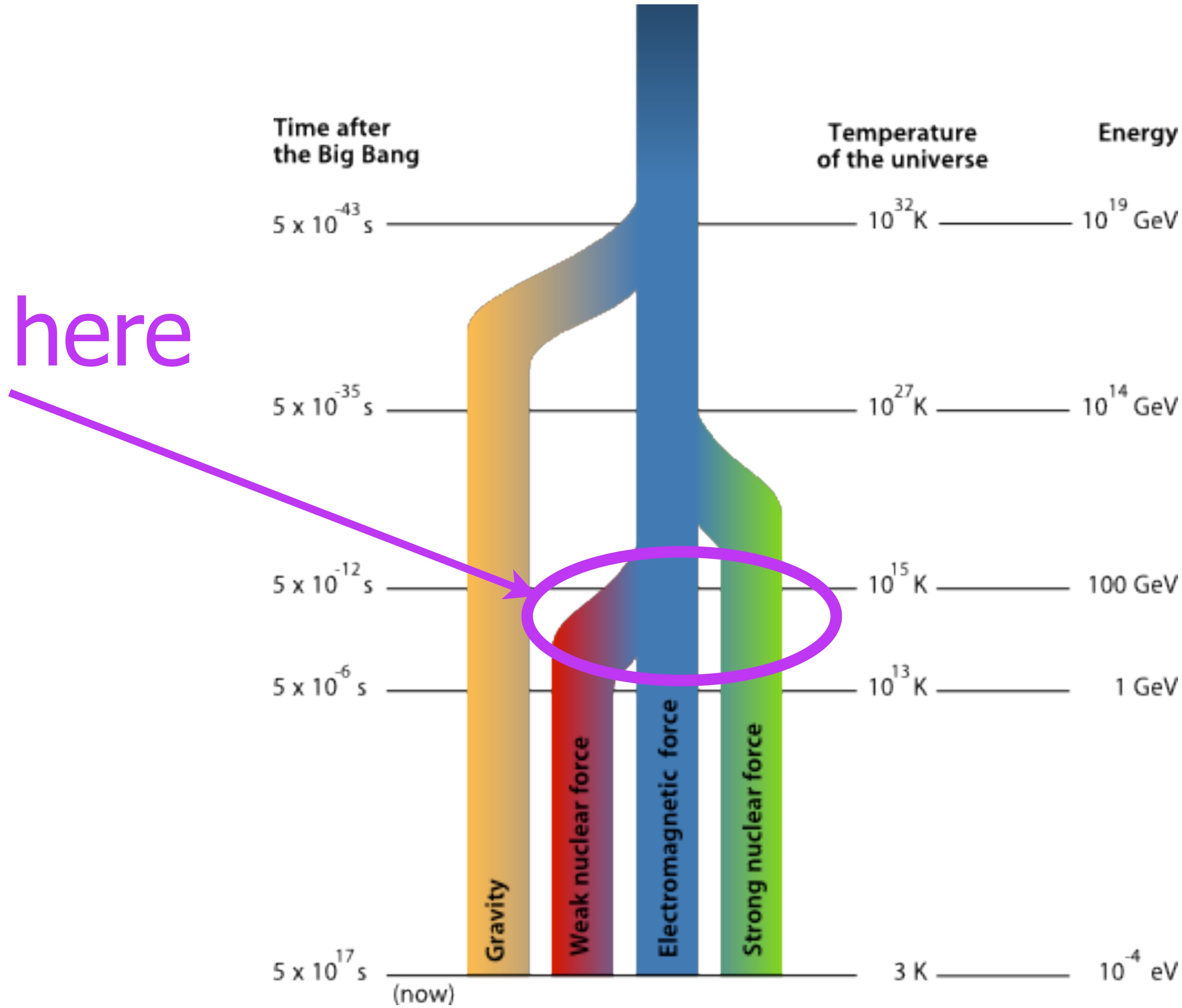
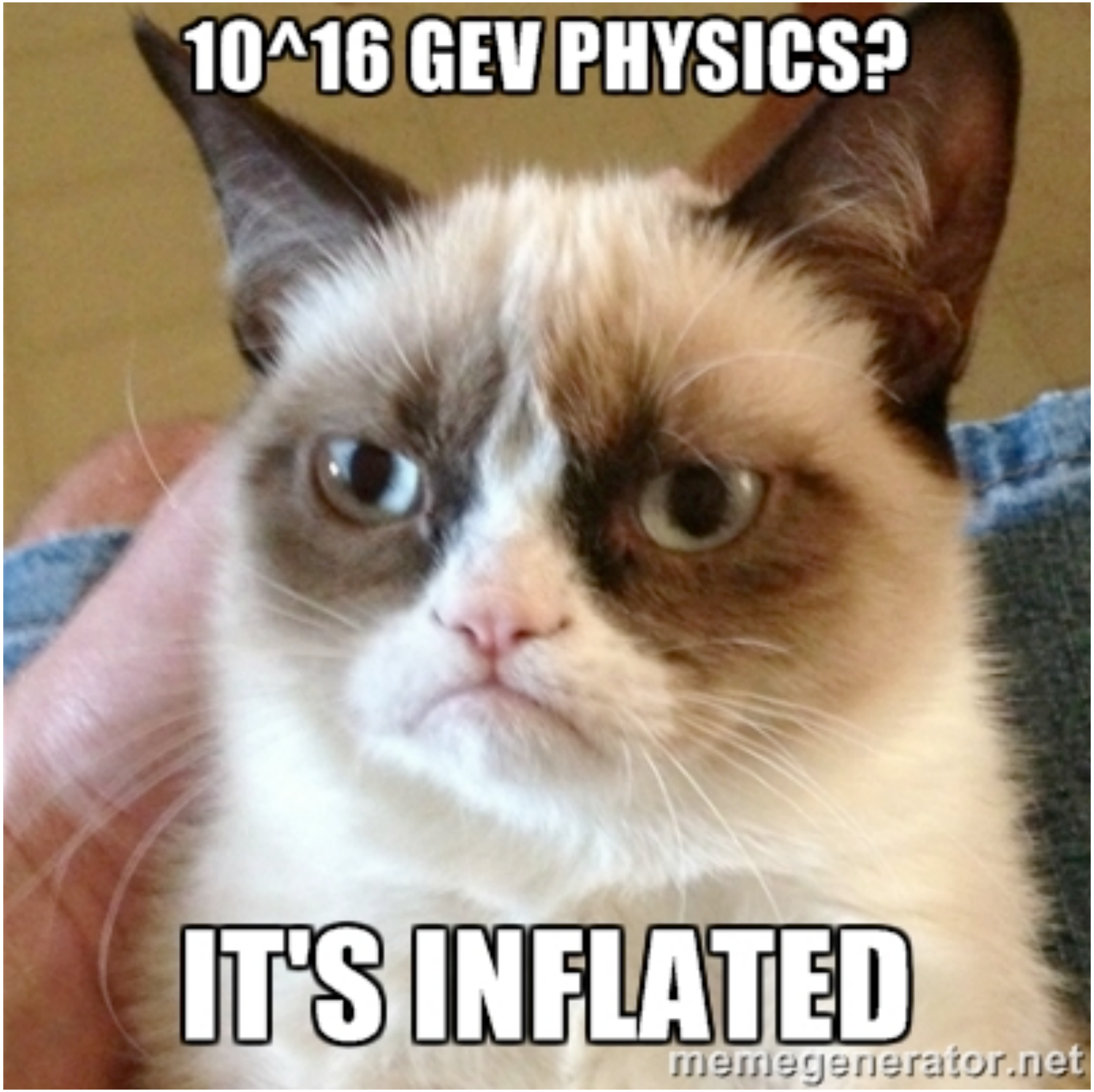
Non-Higgs BSM Searches

Yuri Gershtein

LHC is exploring Electroweak Scale

We are here





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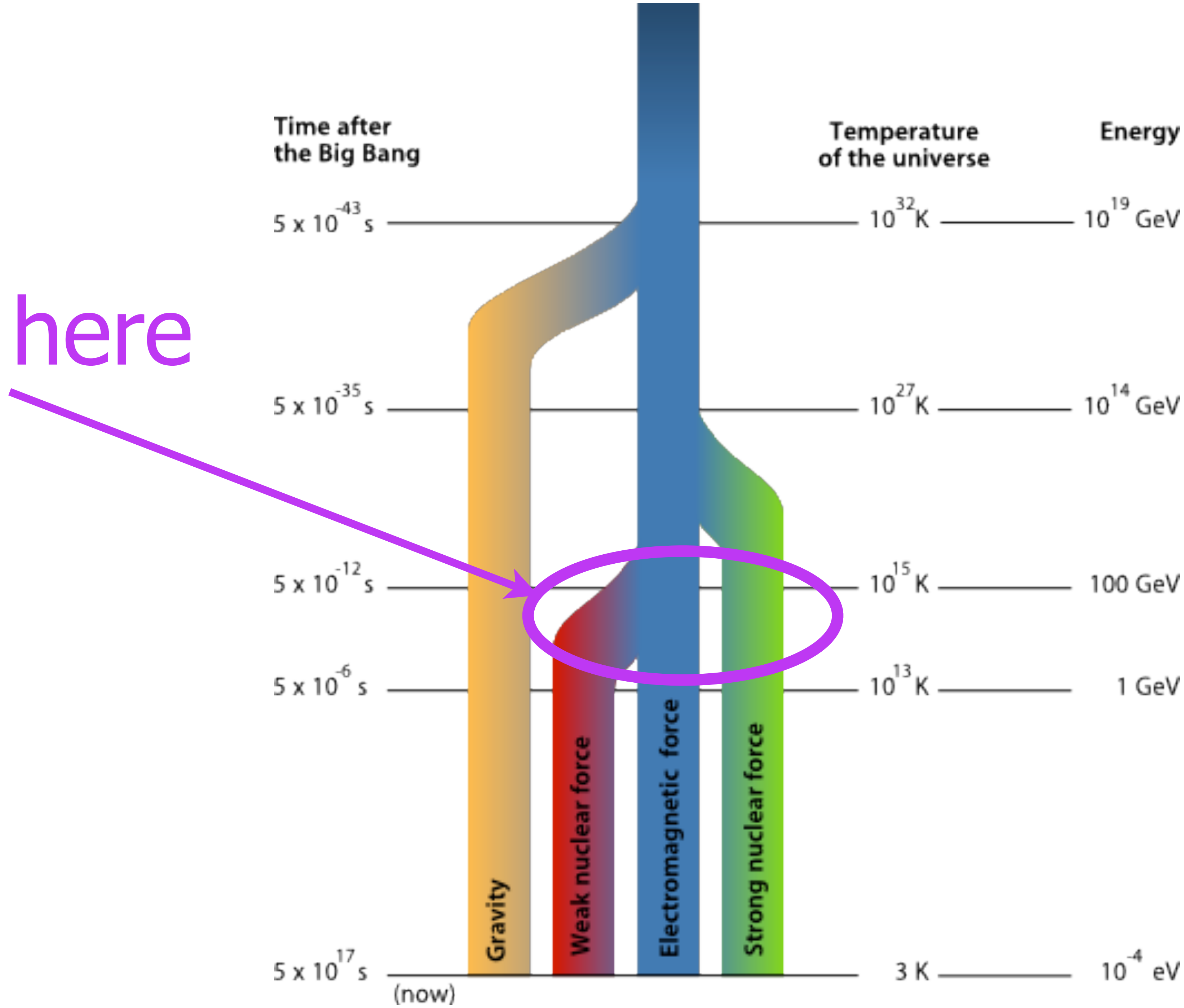

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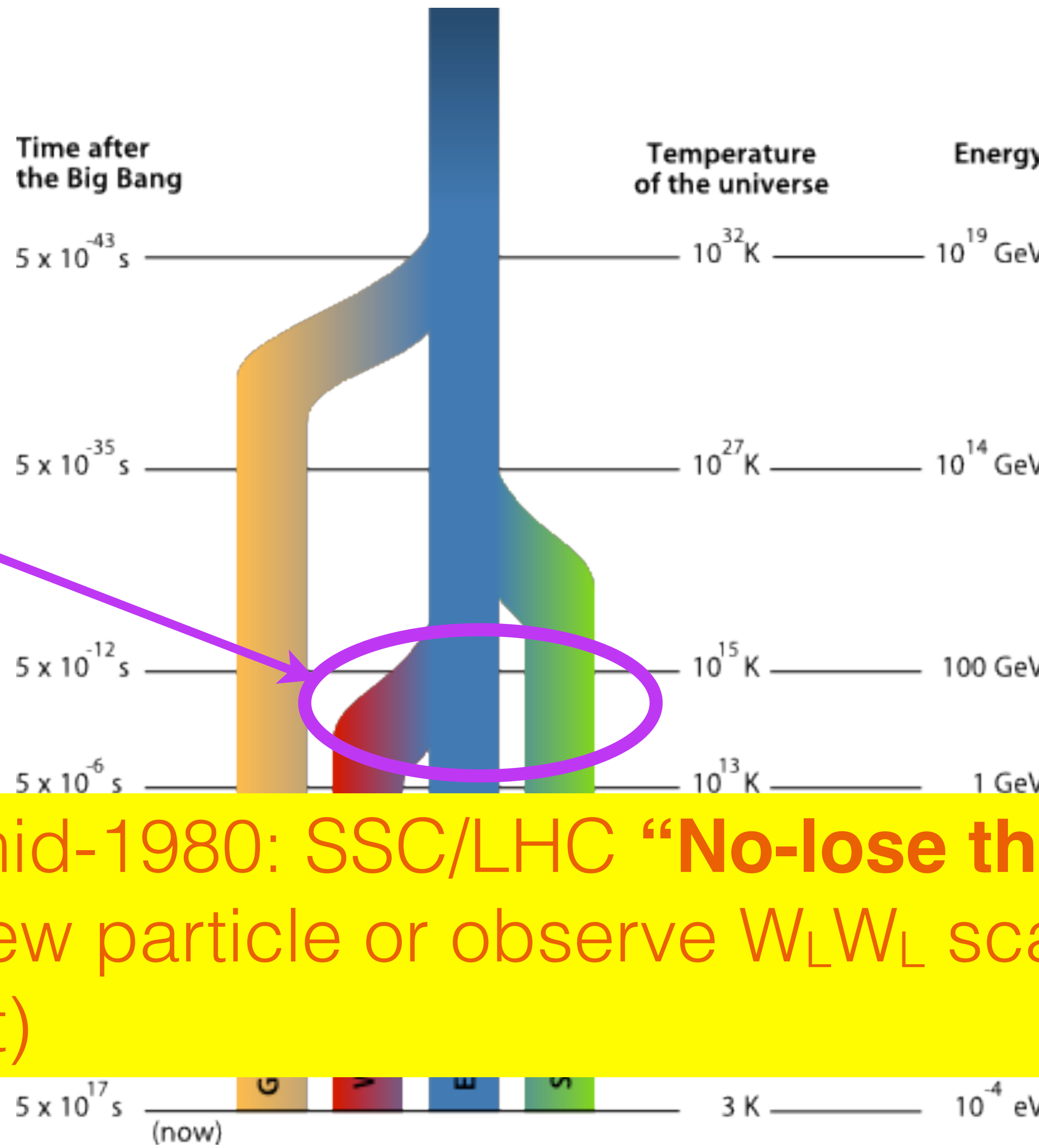

Spoiling us since mid-1980: SSC/LHC **"No-lose theorem"** either discover a new particle or observe $W_L W_L$ scattering violate unitarity (not)

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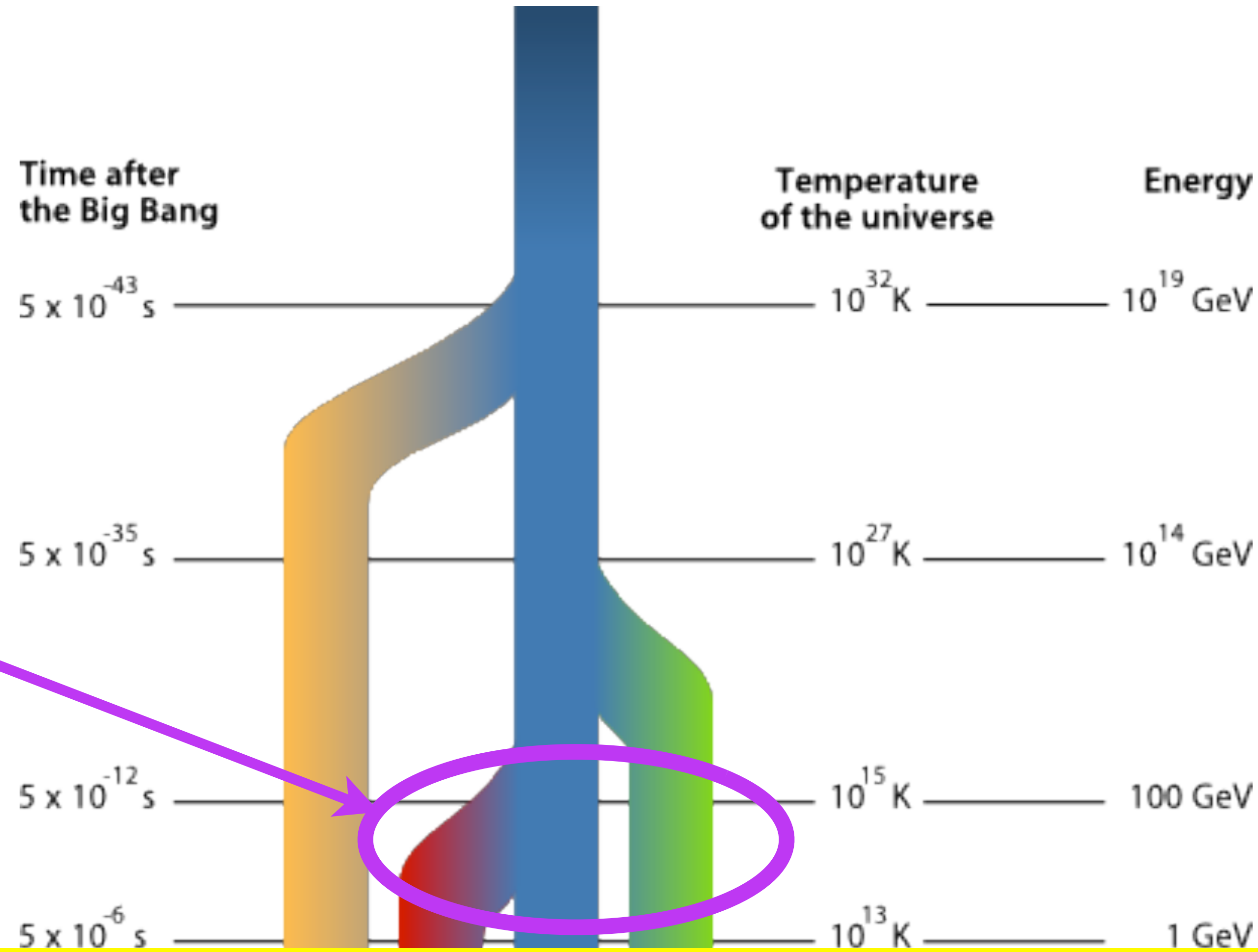


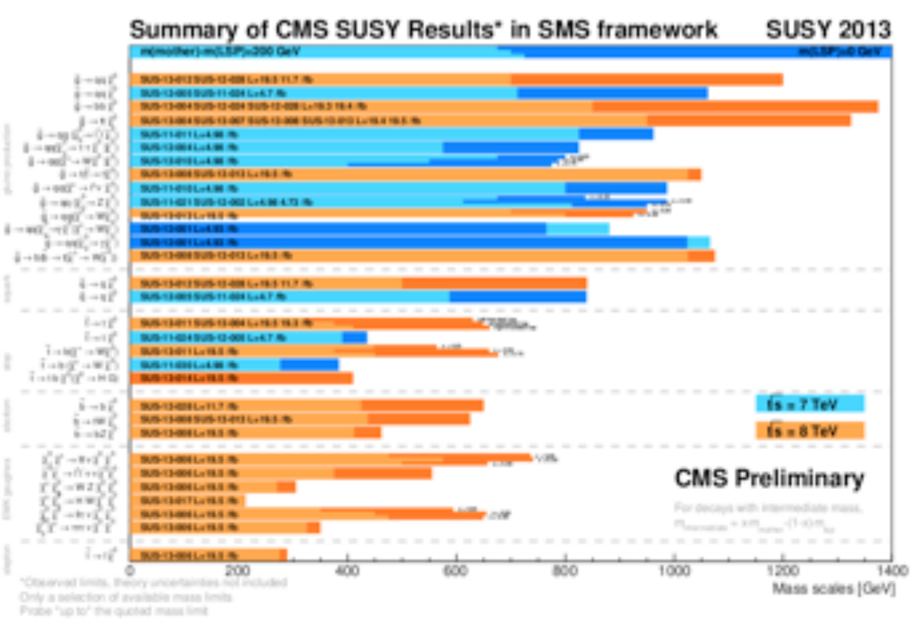
Spoiling us since mid-1980: SSC/LHC **"No-lose theorem"** either discover a new particle or observe $W_L W_L$ scattering violate unitarity (not)

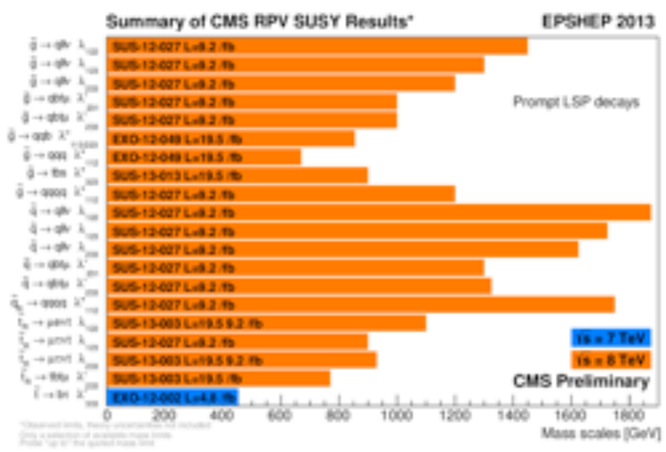
No such thing for the LHC any more - but that does not mean that the program is not is well motivated

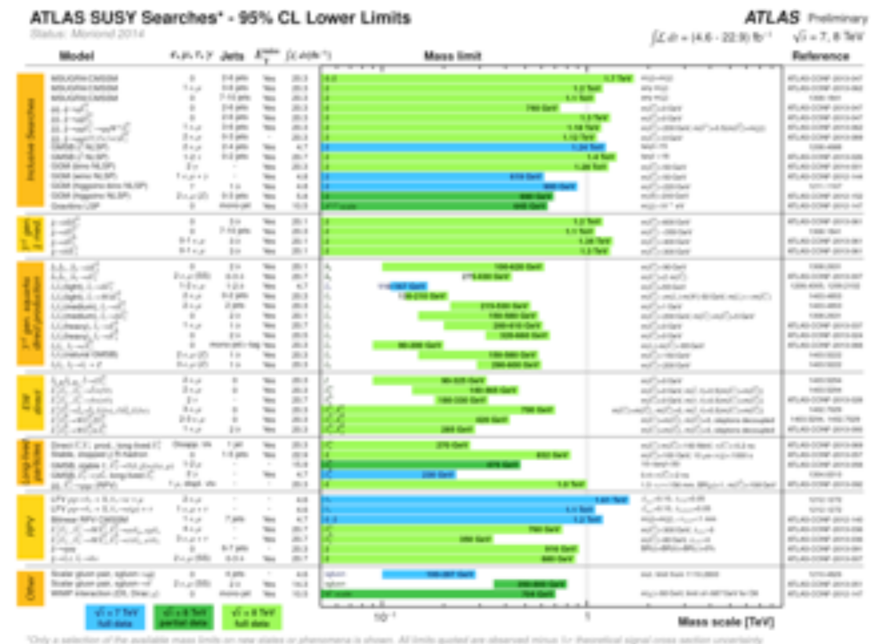
Torrential Details of No BSM

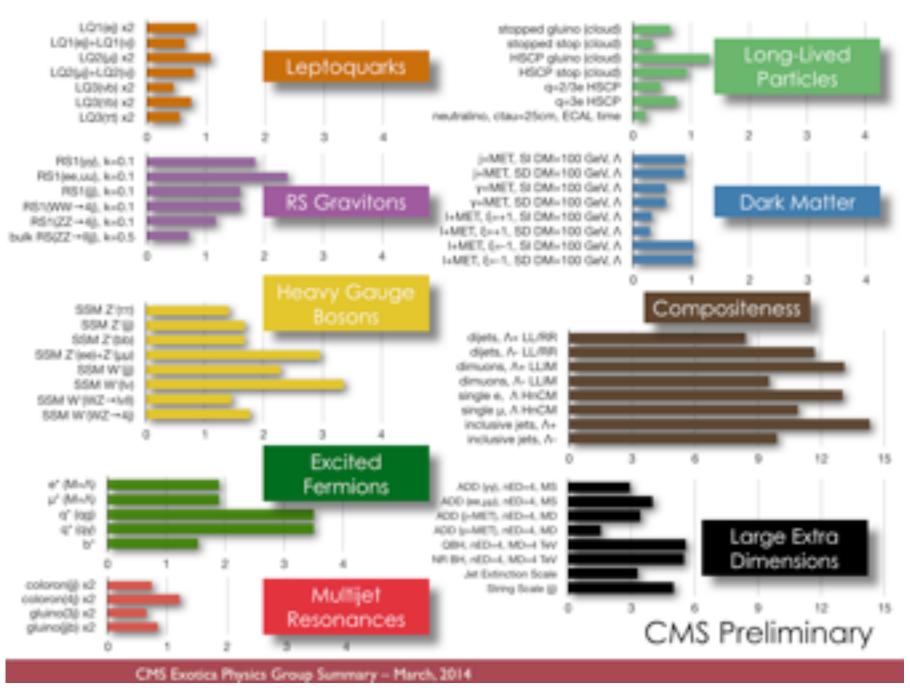
For the full picture see

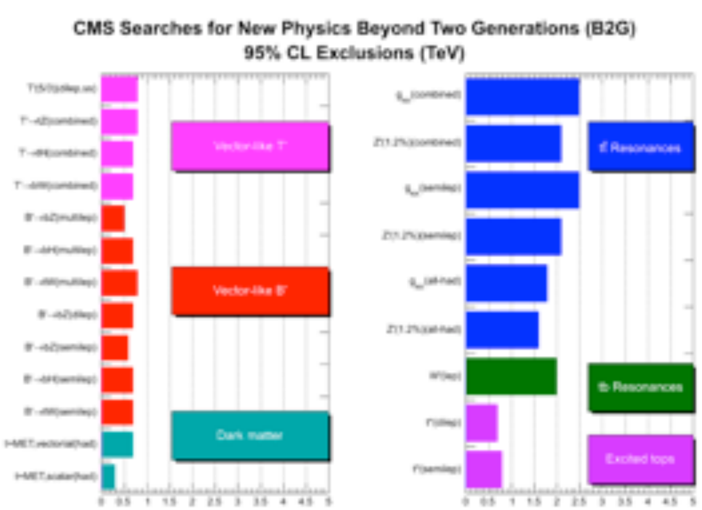
- SUSY and Exotics at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
- SUS, EXO and B2G at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

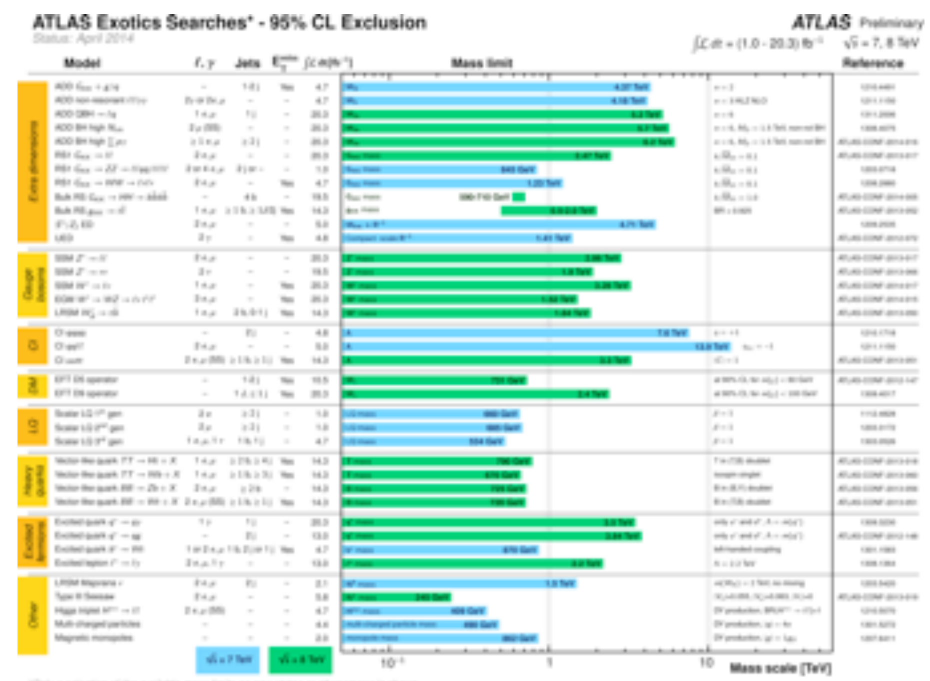












Lt. Cmdr. Albert A Michelson

“The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.”

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1894, seven years after his experiment disproving existence of aether

We've discovered what appears to be a fundamental spin 0 particle, a quantum of a scalar field with non-zero v.e.v.

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Aether is back!

Higgs boson is not the first “fundamental” spin zero particle we have discovered!

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“The present form of meson theory is not free from the diverging difficulties... We shall probably have to go through another change of theory, before we shall be able to arrive at the complete understanding of the ... various phenomena, which will occur in high energy regions”

Yukawa’s Nobel Lecture, 1949

What's so Exciting

- Exploring Electroweak Symmetry Breaking Scale
  - had to find something - and already have
    - something that looks a lot like a **fundamental scalar** - is the small Higgs mass anthropic or a consequence of some new symmetry? The answer is likely to lie at O(EWSB scale)
  - every time we produce a Higgs (or a W, or a Z at large $\sqrt{s}$) at the LHC we learn more about EWSB
- Are there more fundamental scalars?
  - *cMSSM is dead, but SUSY never looked more attractive*
- Can we produce Dark Matter at the LHC?
  - *especially given hints of indirect detection of DM with preferential coupling to the third generation*
- LHC probes Unknown territory - have to watch out for new things: ***Occama razor has a terrible record in our field***

In this talk

- *Will not go into details of most "staple" searches*
  - *i.e. jets + MET, di-electron resonances, etc - it's a very well motivated program with well-designed analyses that will get done very soon after the start of Run 2*

- Higgs and BSM
- Long-lived particles
- "Jet" substructure
- mono-X searches
- Summary / Outlook

will concentrate on promising methods tried in Run 1 to build on and gaps in search strategies

well-motivated scenarios that theorists told us about a while ago but we do not talk about very often

BSM in Higgs couplings (loops)

- **Example : Precision for Higgs couplings** P. Janot
  - **Maximal deviations with respect to SM couplings, as a function of new physics scale**
    - **SUSY** $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\text{ TeV}}{m_A}\right)^2$ **, for tanβ = 5** H. Baer, M. Peskin et al.
    - **Composite Higgs** $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\text{ TeV}}{f}\right)^2$
    - **Top partners** $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\text{ TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\text{ TeV}}{m_T}\right)^2$
    - **Other models may give up to 5% deviations with respect to the Standard Model**
  - **Maximal deviations for the new physics scale still allowed by LHC results**

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	$10\%^a$, $100\%^b$

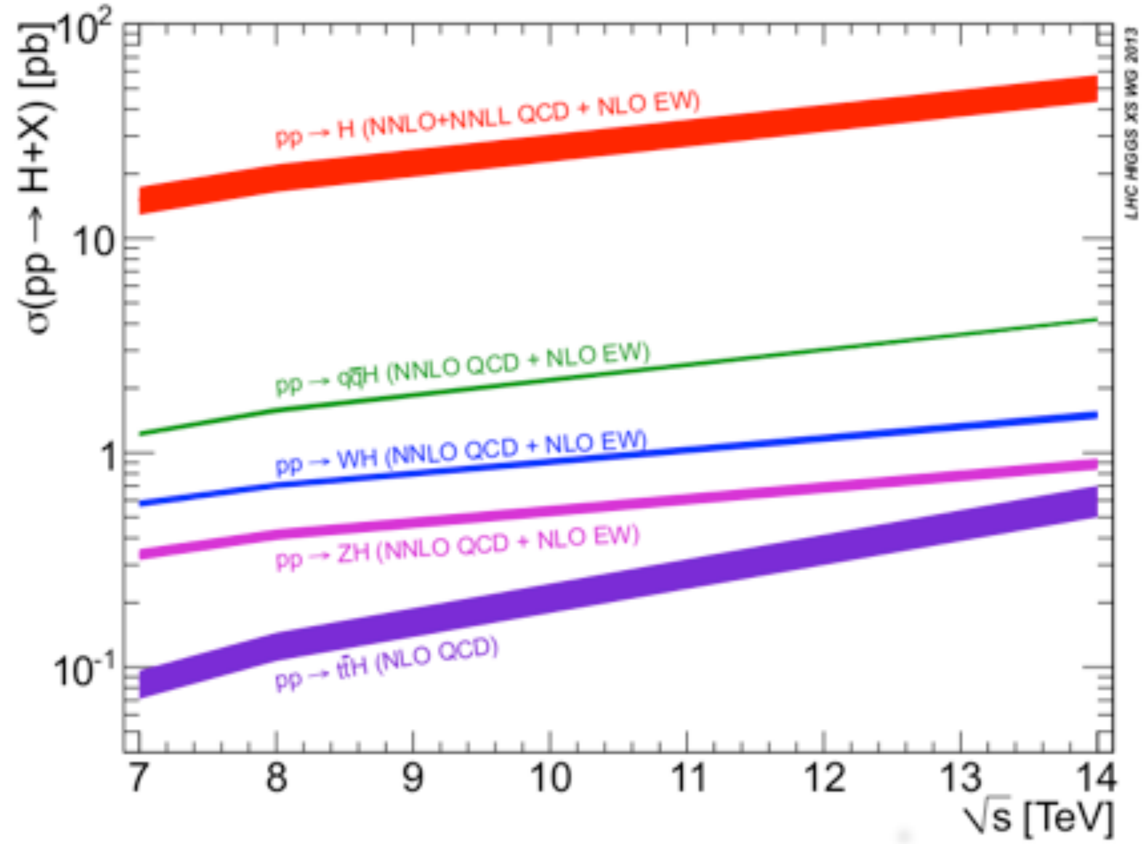
J.D. Wells et al.

- **Strongly influences the strategy for Higgs factory projects**
  - **Need at least a per-cent accuracy on couplings for a 5σ "observation"**
    - **And sub-percent precision if new physics is at the (multi-)TeV scale**

- With ~5-10% precision on couplings one is better off looking directly for new particles
  - some areas of 2HDM inaccessible at the LHC can be found with ILC-precision measurements
  - **important failsafe - if those new particles are escaping our triggers / searches**

Higgs as New Physics Tag

- New physics (SUSY?) cascades may produce higgses as copiously as W's and Z's - but the SM Higgs cross section is tiny compared to W/Z
  - single W: 10^5 pb
    - W+lots of jets (aka top): 10^3 pb
  - single h: 20 (50) pb
    - h + lots of jets (tth): 0.1 (0.6) pb
  - ***requiring higgs production is a New Physics booster***
  - even paying $2\cdot10^{-3}$ penalty for $\gamma\gamma$ branching one gets ~reasonable number of events
    - $5/\text{fb}\cdot1\text{pb}\cdot2\cdot10^{-3}$ = 10 events



- Impact way beyond just SUSY - every time you produce a Higgs you explore EWSB: SUSY here is just a great way to "generate signatures" with Higgs + stuff.

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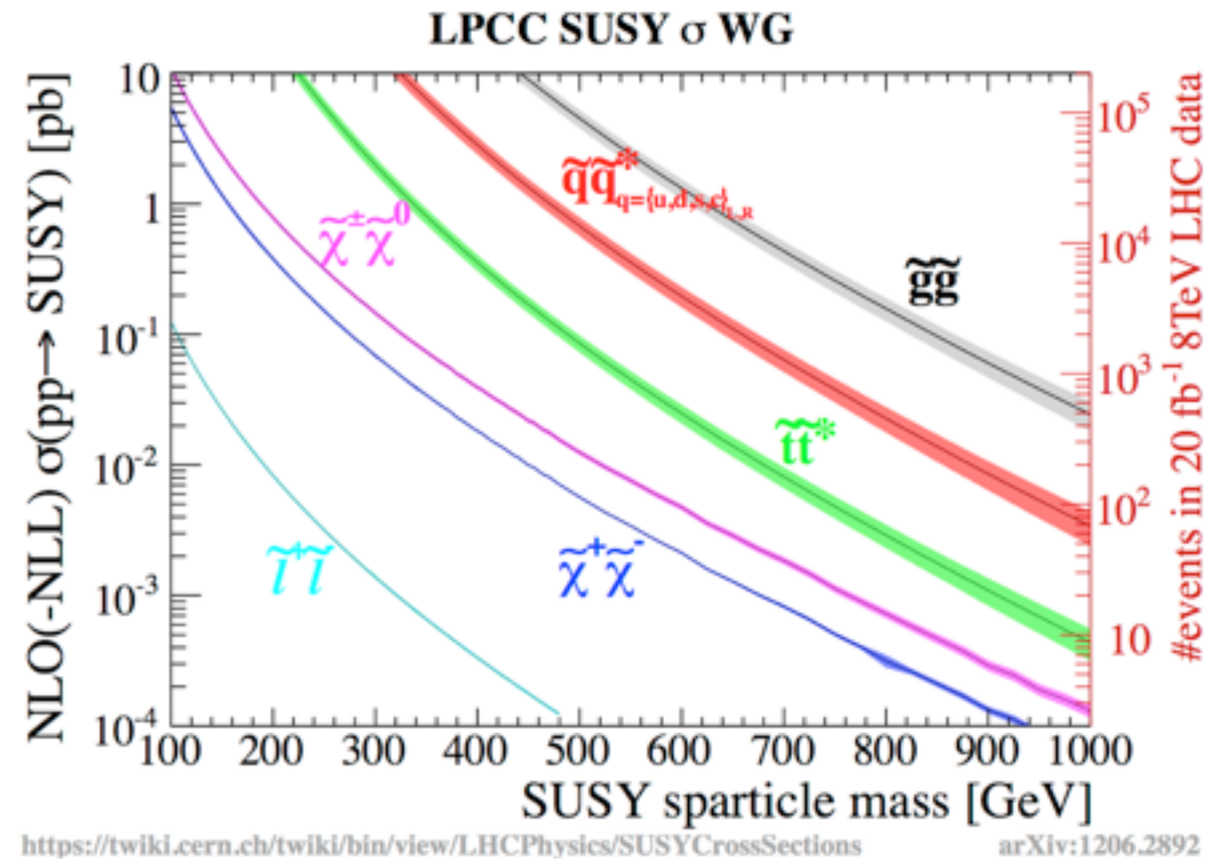

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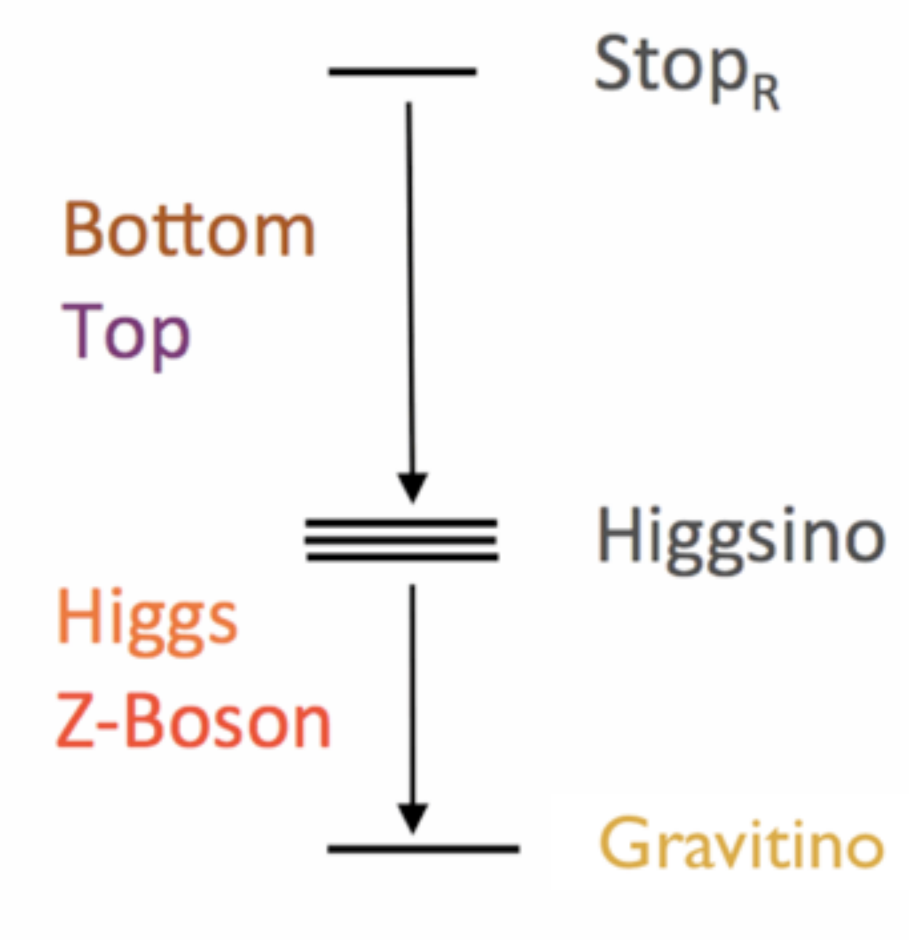
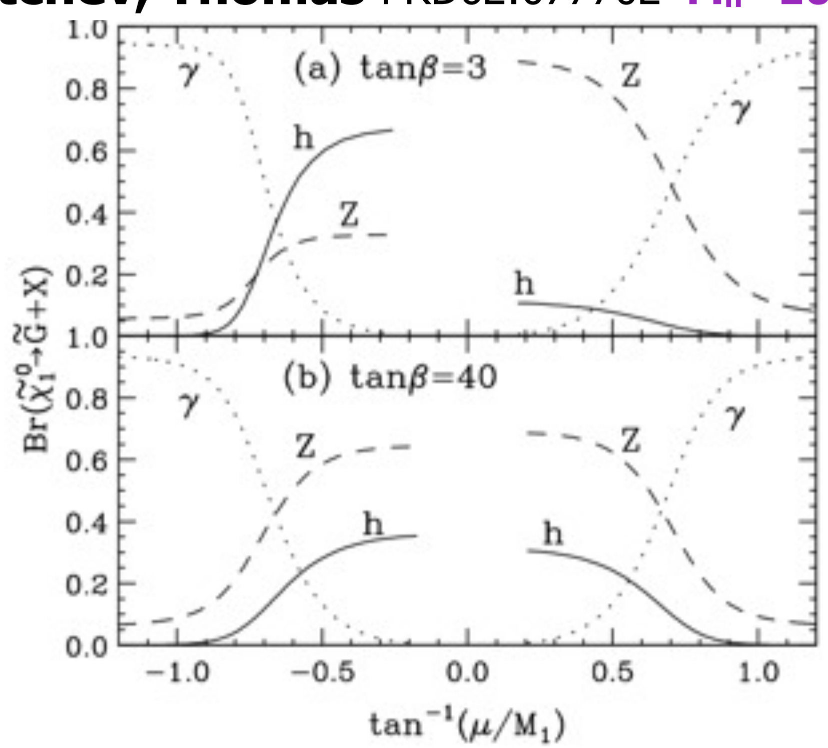
Example: "Natural"-ish SUSY



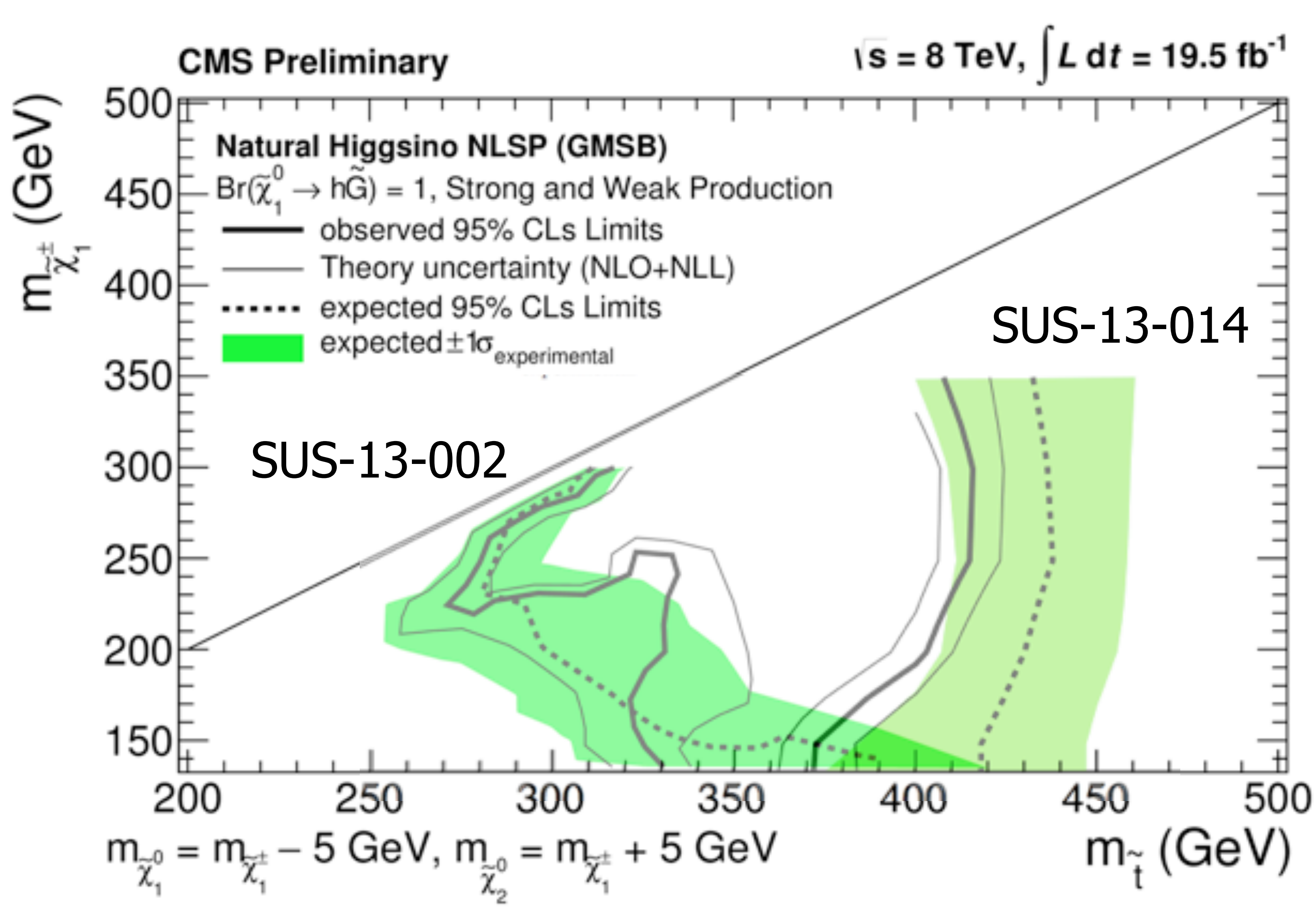
Matchev, Thomas PRD62:077702 M_h=105 GeV

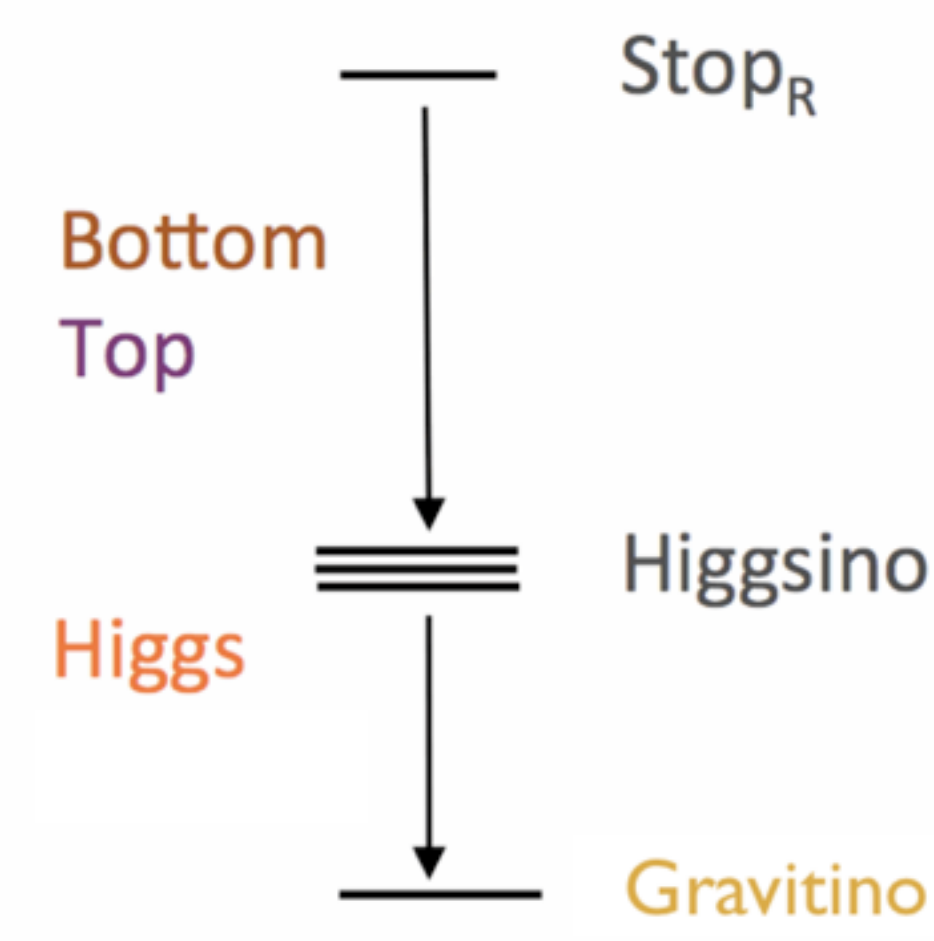


- In GM, lightest higgsino decays not to photons but to Z's and higgses - more higgses at low tan β
- can be quite stealthy
  - if higgsino just a little heavier then Higgs - almost no MET
- if $M_{\tilde{t}_R} - M_{\tilde{\chi}^0}$ is below top mass the decay is mostly to chargino and b
- chargino decays into soft pion(s) and lightest neutralino
  - final state is hh + maybe softish b's plus soft MET

Example: "Natural"-ish SUSY

- Two main channels - multileptons and di-photons
  - bb is tough due to low MET
  - di-photons win despite tiny branching





Hidden (Dark) Sectors

- New particles that are weakly coupled to SM
  - appear in abundance in GUT models
  - can be part of DM, contribute to astrophysical anomalies, etc.
- Appear at the LHC if there is a portal
  - **Z’** or some other heavy particle that couples to both SM and HV particles
  - if SUSY with R-parity, then LSP becomes **LSOP, decays into HV**
  - can appear in **rare Higgs decays** (thanks to its small natural width)
  - very rare Z decays - LHC now has more then 10 times number of Z’s then LEP!
    - only helps for rare Z decays that one can trigger on
- May or may not give rise to long-lived particles
- A lot of relevant searches had been done but large gaps remain

Hidden (Dark) Sectors

Strassler, Zurek (2006)

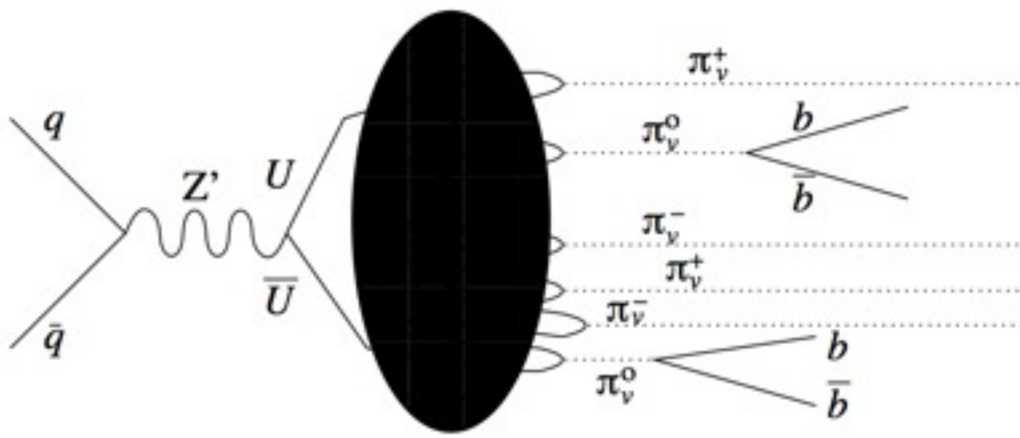
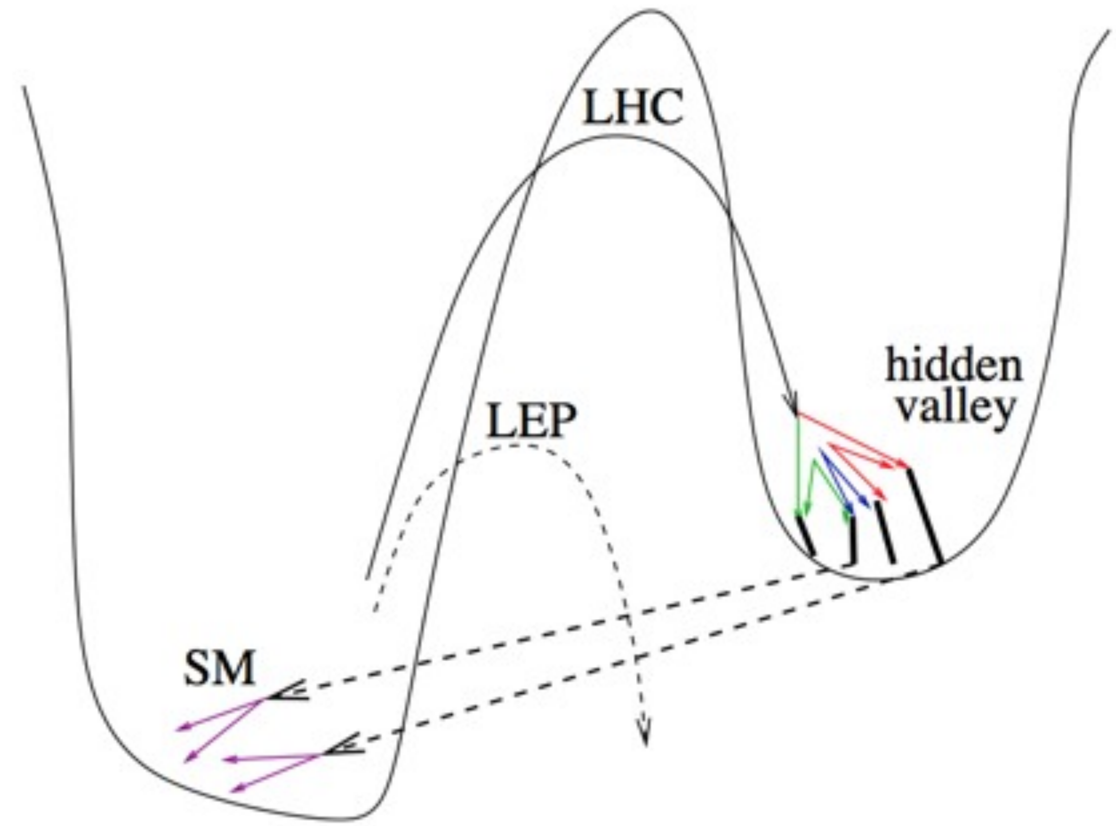


FIG. 3: A possible event in the two-light-flavor regime; note $\pi_v^\pm$ is electrically neutral and invisible.



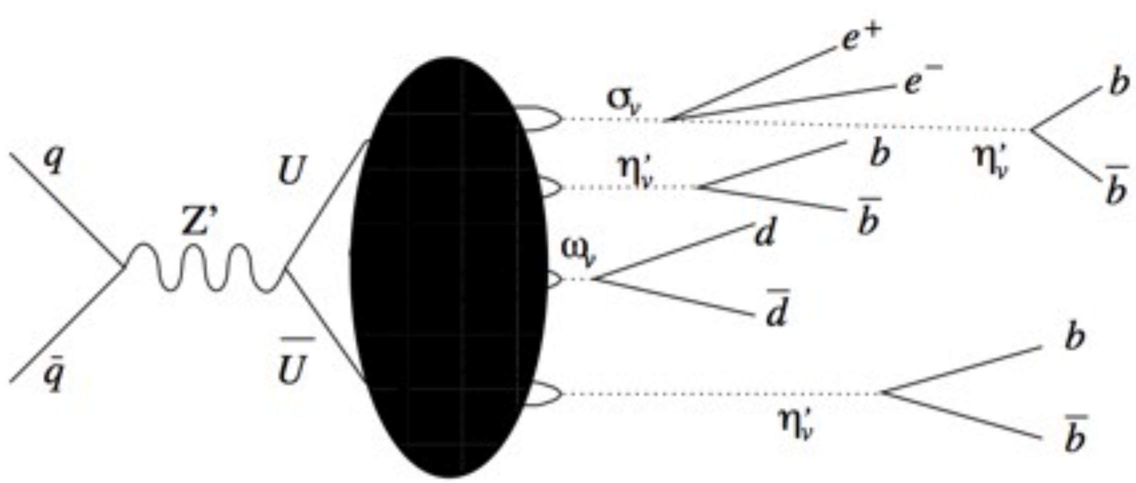


FIG. 4: A possible event in the one-light-flavor regime.

Looks like a strange dijet event

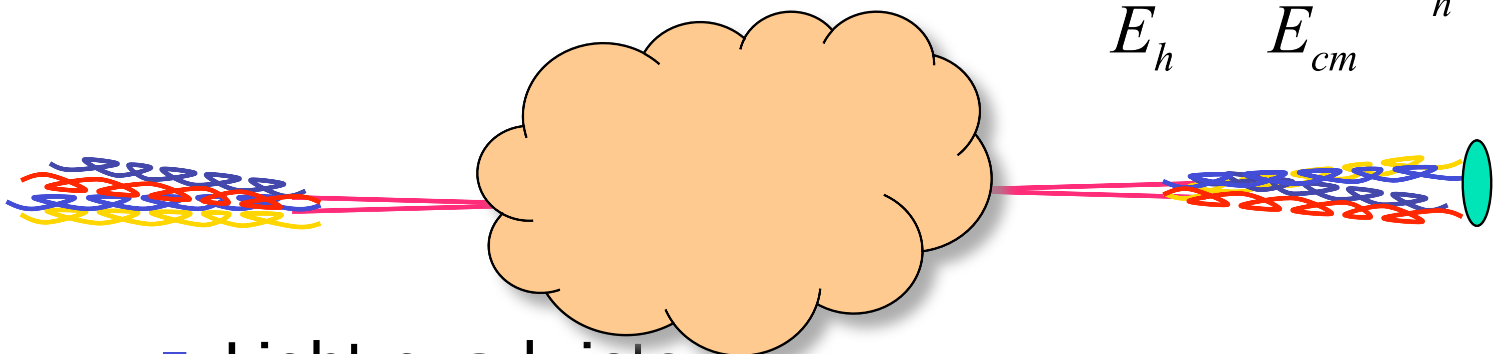
- *may have a lot of particles staying in the dark sector (MET) - Z' may be heavy, but visible ST can be small!!*
- *may have some long-lived particles inside the jets*
- *more massive particles - shorter lifetime, but that results in different event shape*

Hidden Valleys without LLP

Zurek (2006)

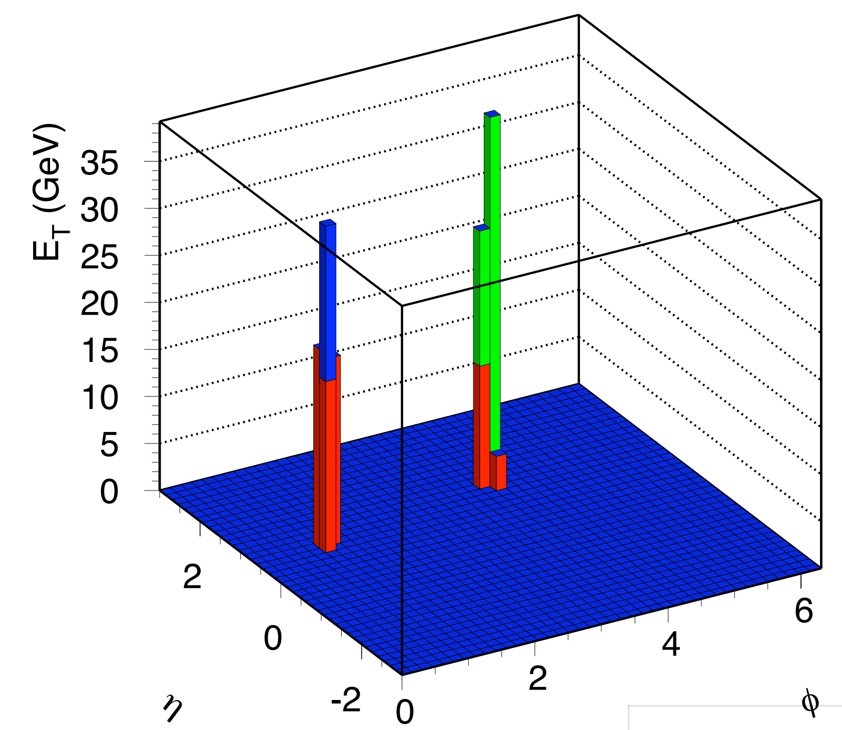
- Shape of event set by v-hadron mass

$$\theta \sim \frac{p_\perp}{E_h} \sim \frac{p_\perp}{E_{cm}} N_h$$

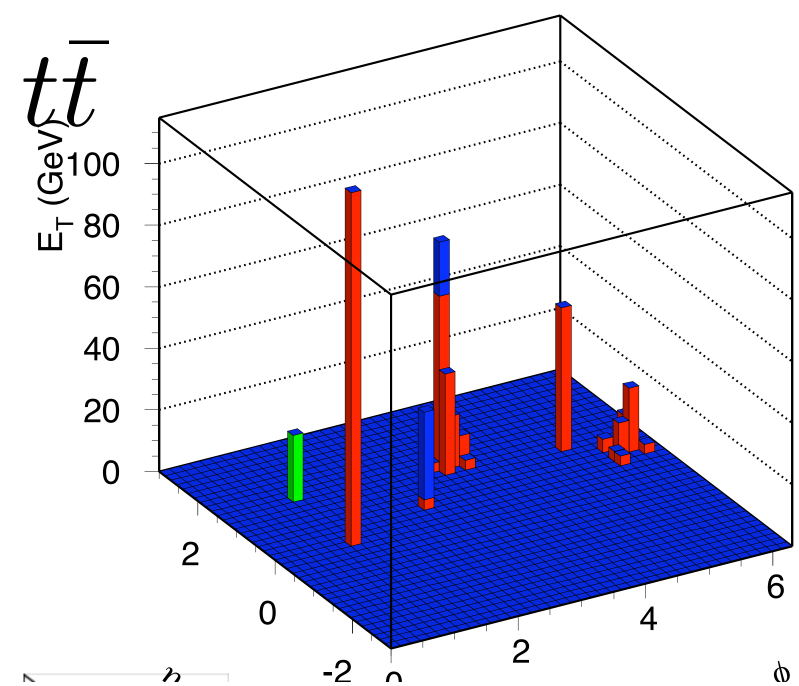


- Light quark jets
- vs. Hidden valley jets--larger opening angles due to higher mass v-hadrons

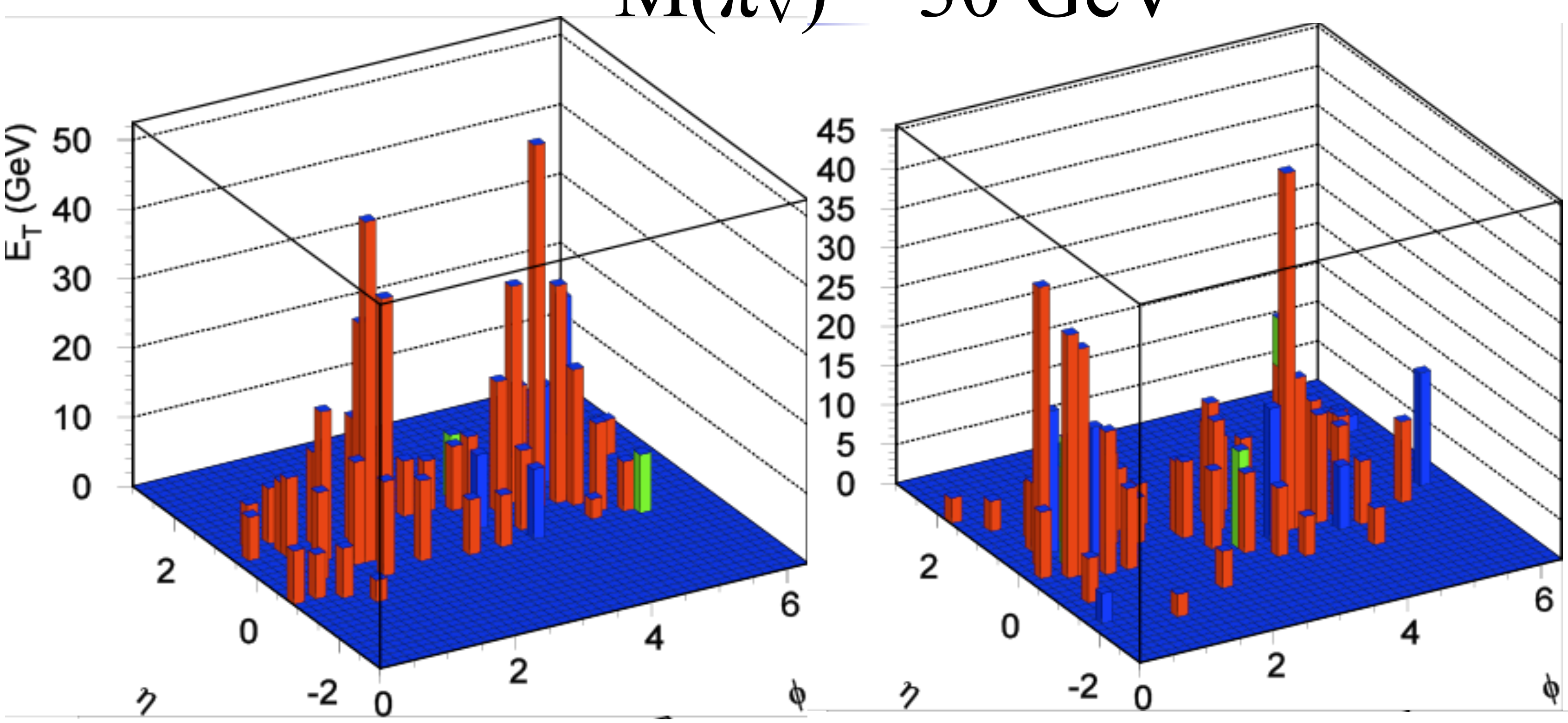
$b\bar{b}$



$t\bar{t}$

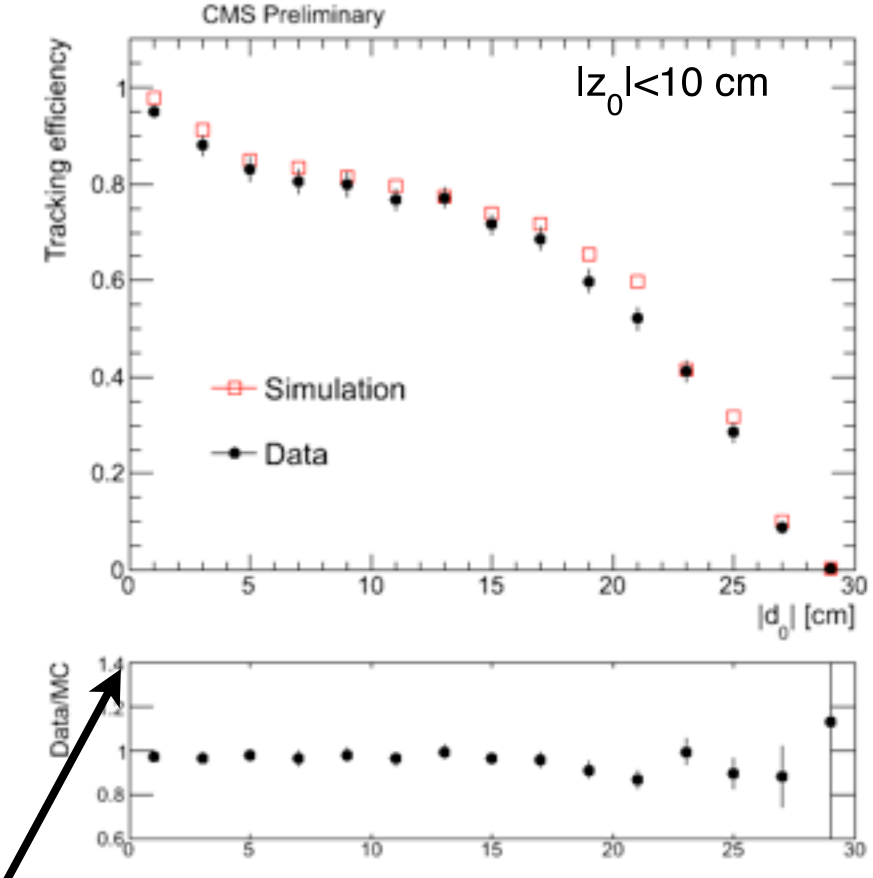


$M(\pi_V) = 30$ GeV

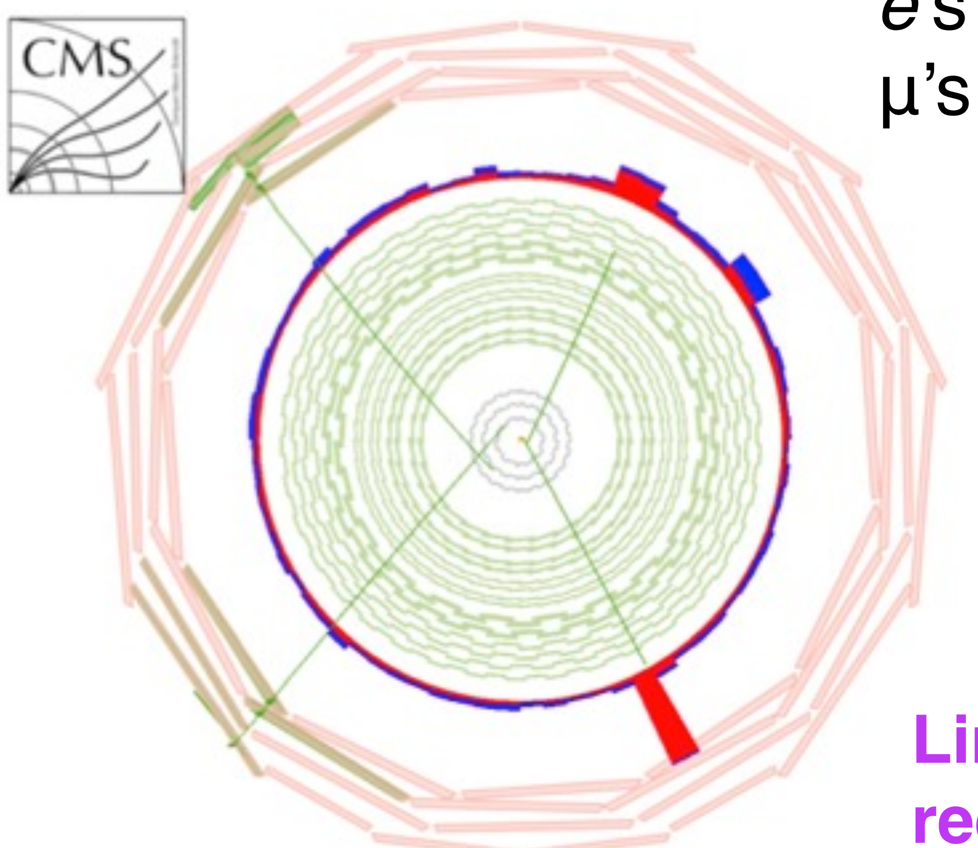


Long-lived particles

- Large number of well-motivated scenarios predict long-lived particles
  - here: leptonic decays
  - rare Higgs decays (the one at 125 GeV or a new one) - if there are HVs, Higgs may be the particle that senses them most: $H \to XX, \quad X \to f\bar{f}$
  - RPV SUSY $\tilde{q} \to q\chi^0(\to \ell^+\ell^-\nu)$ (or H cascade)

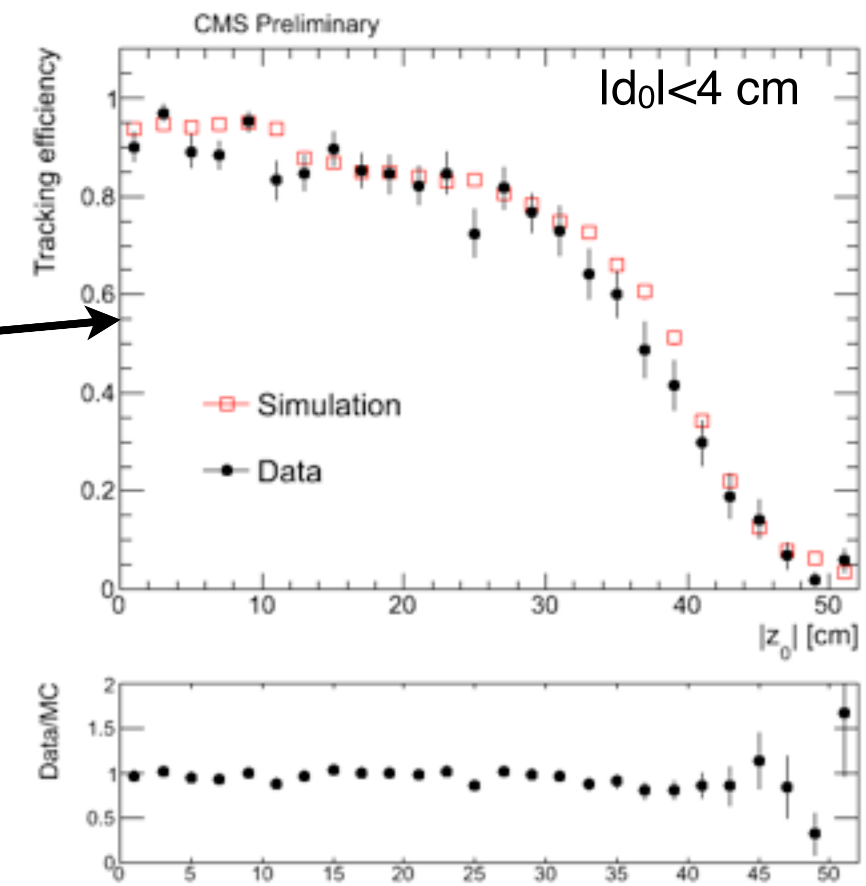


EXO-12-037



Trigger:
e's → photons
μ's: no central track

Offline:
dedicated tracking iterations for high IP track reconstruction

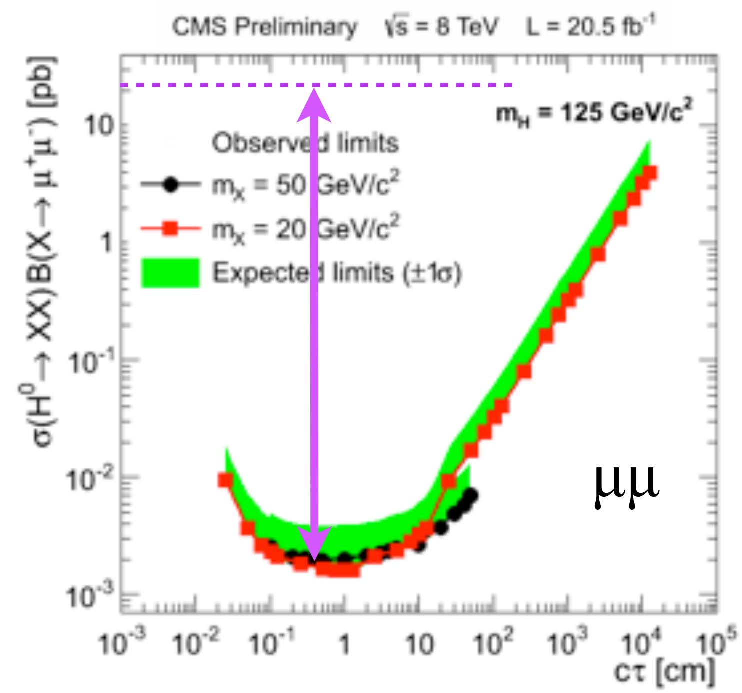


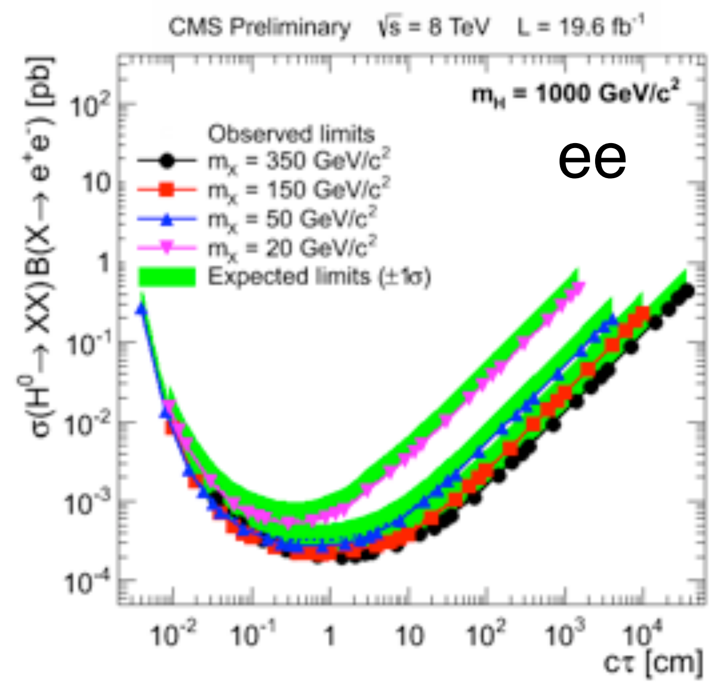
Limitation: leptons required to be isolated

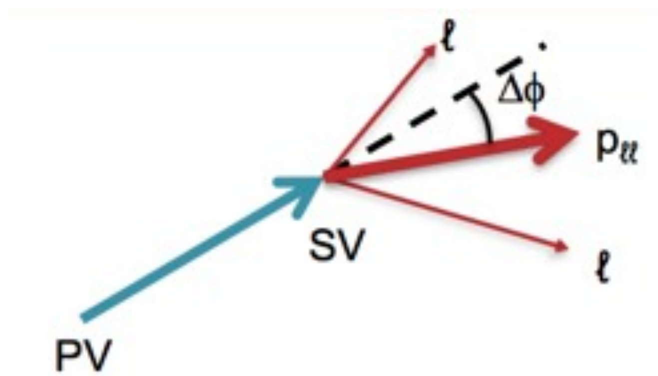
Long-Lived Particles decaying into leptons

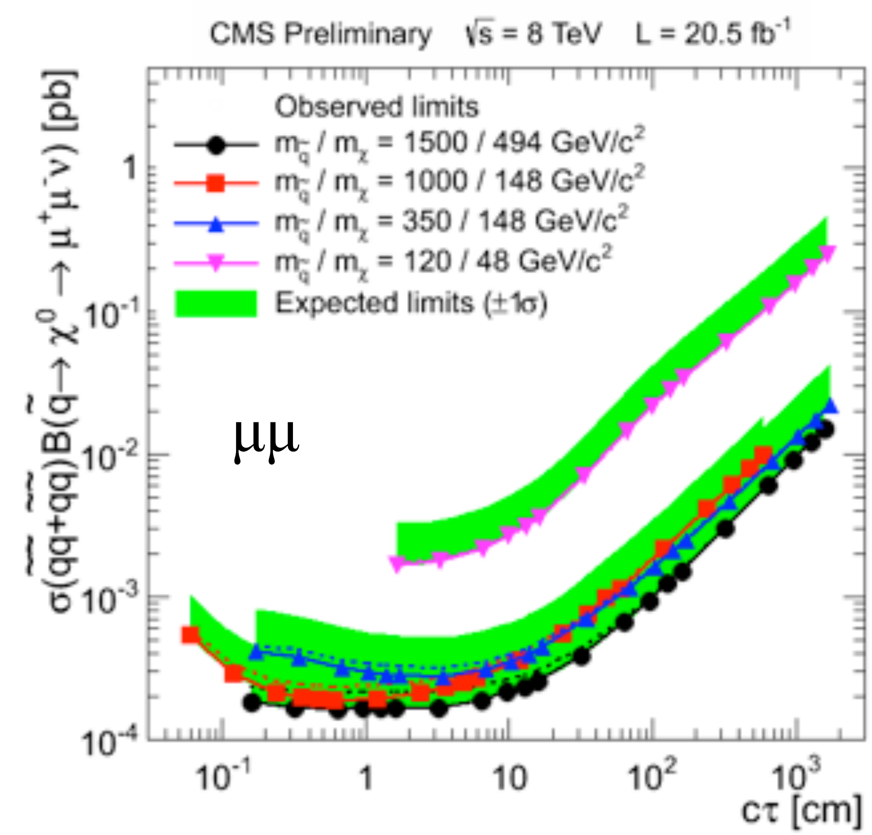
- observe no events for IP significance > 12σ, set limits

Sensitive to H(125) branchings of $\sim 10^{-4}$









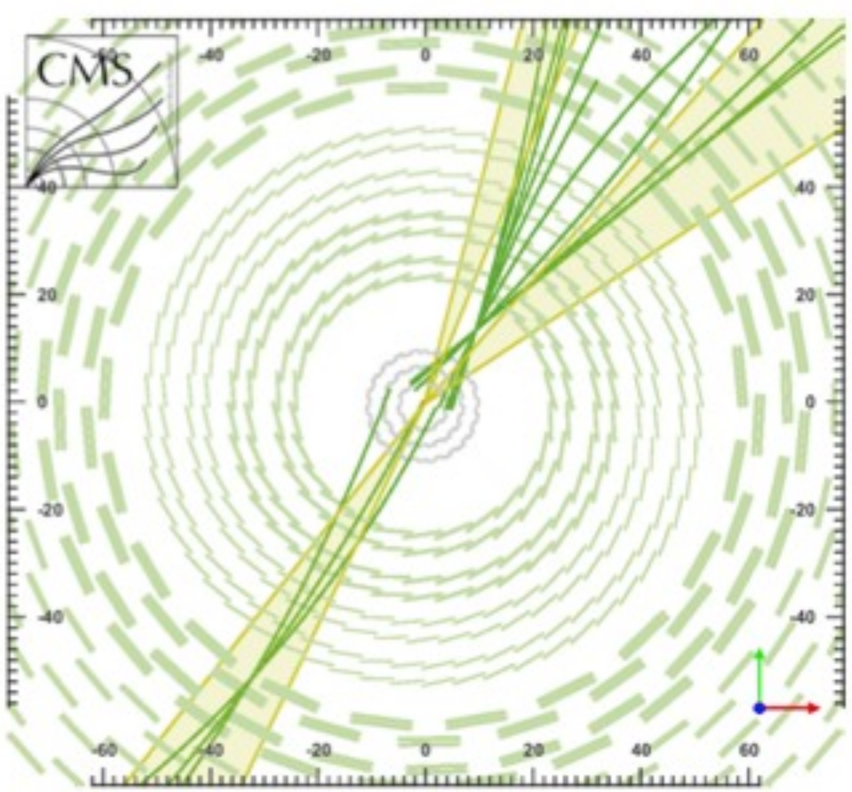
do not require tight pointing: $|\Delta\phi|<\pi/2$

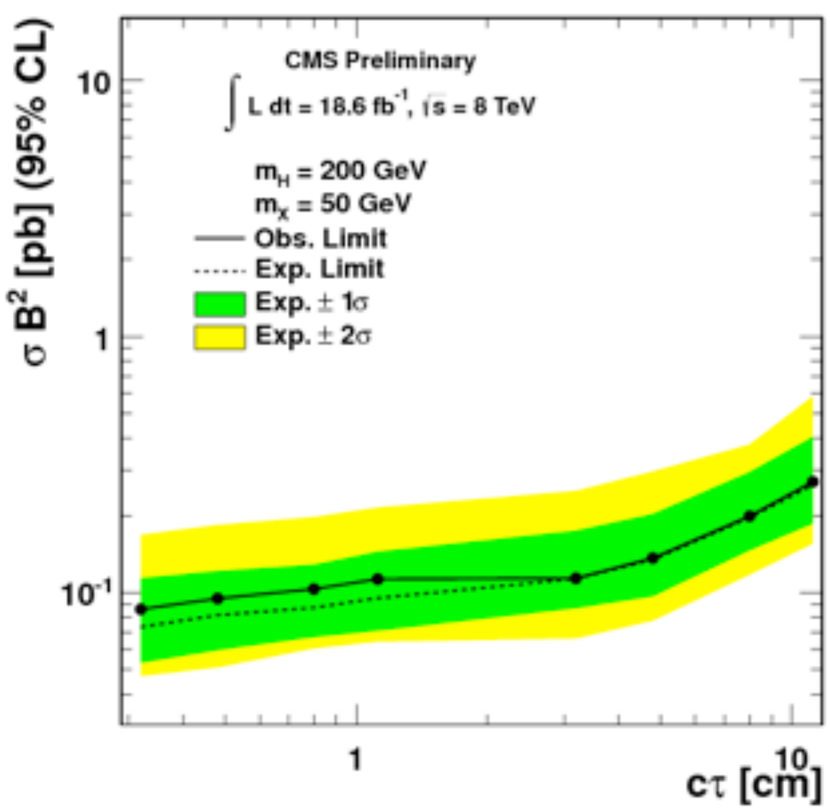
excludes ~0.1-0.3 fb - i.e. tiny squark branching fractions

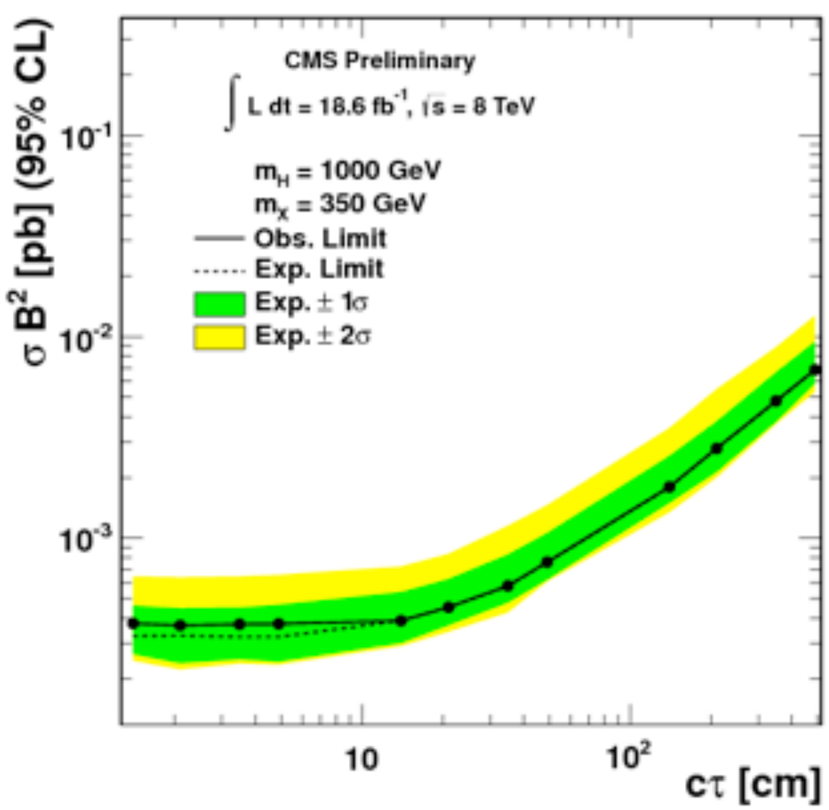
Long-Lived Particles decaying into jets

- decays into jets is much tricker - at least for decay products of the H(125)
  - triggering is the main challenge
  - both CMS and ATLAS have dedicated triggers based on specific range on decay lengths
- CMS: HLT trigger on jets with no prompt tracks
  - offline: vertex made out of the two displaced jets (limits generality)
  - no sensitivity for H(125), but wipes out huge fraction of RPV, etc

EXO-12-038







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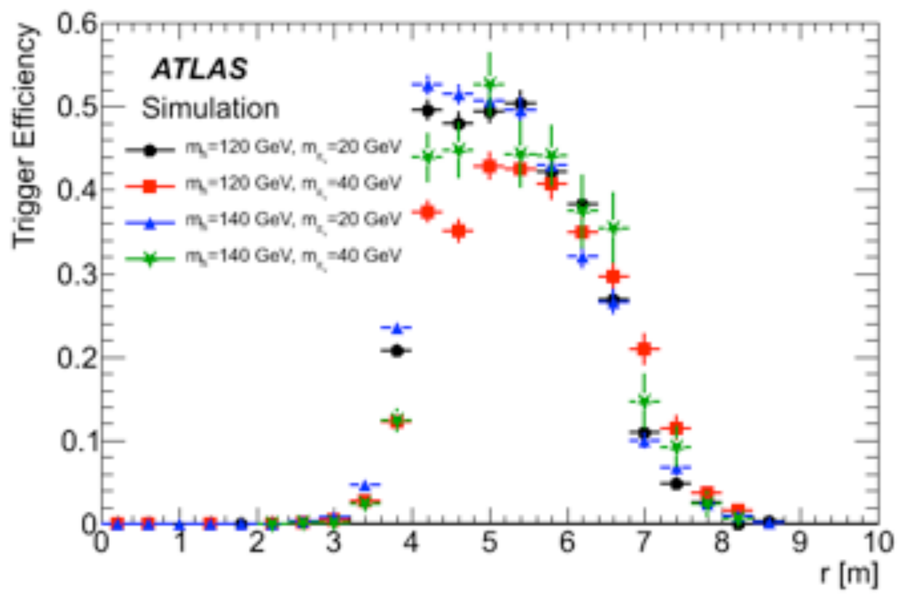
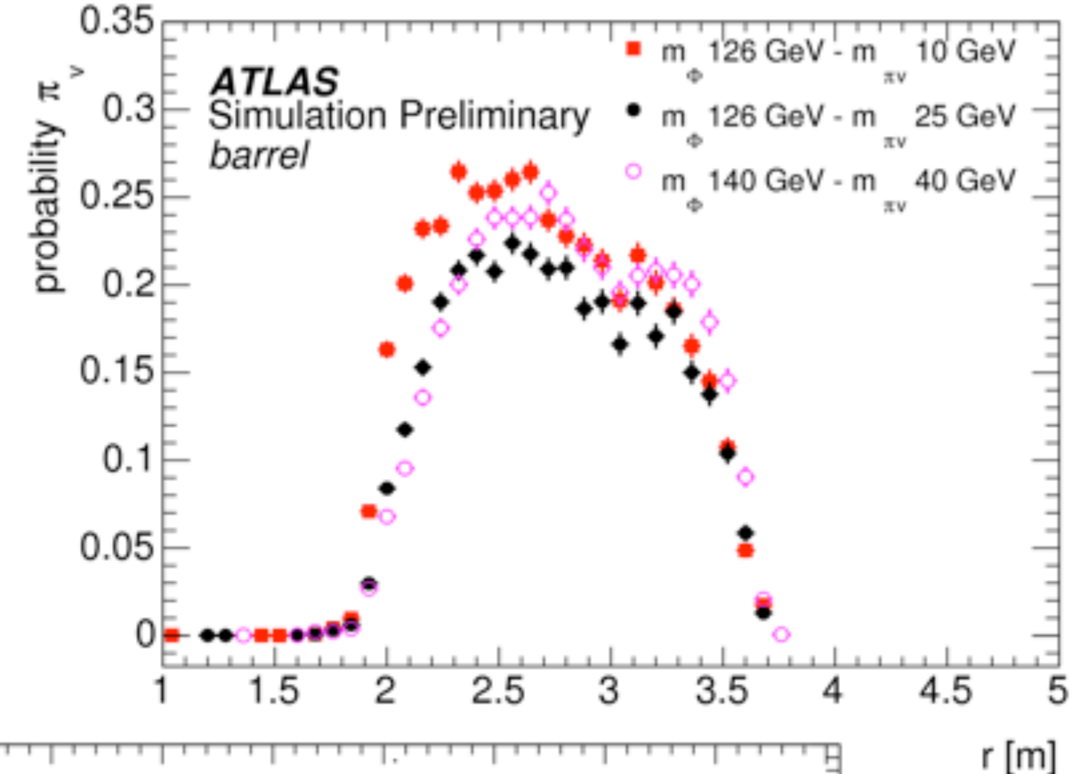
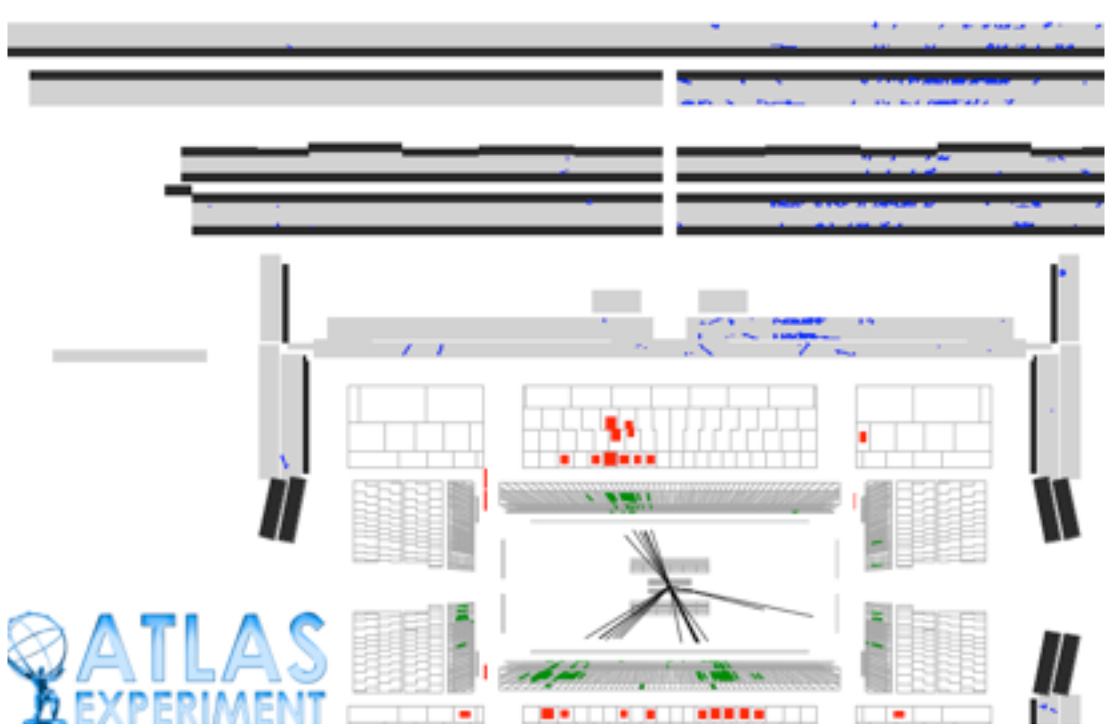
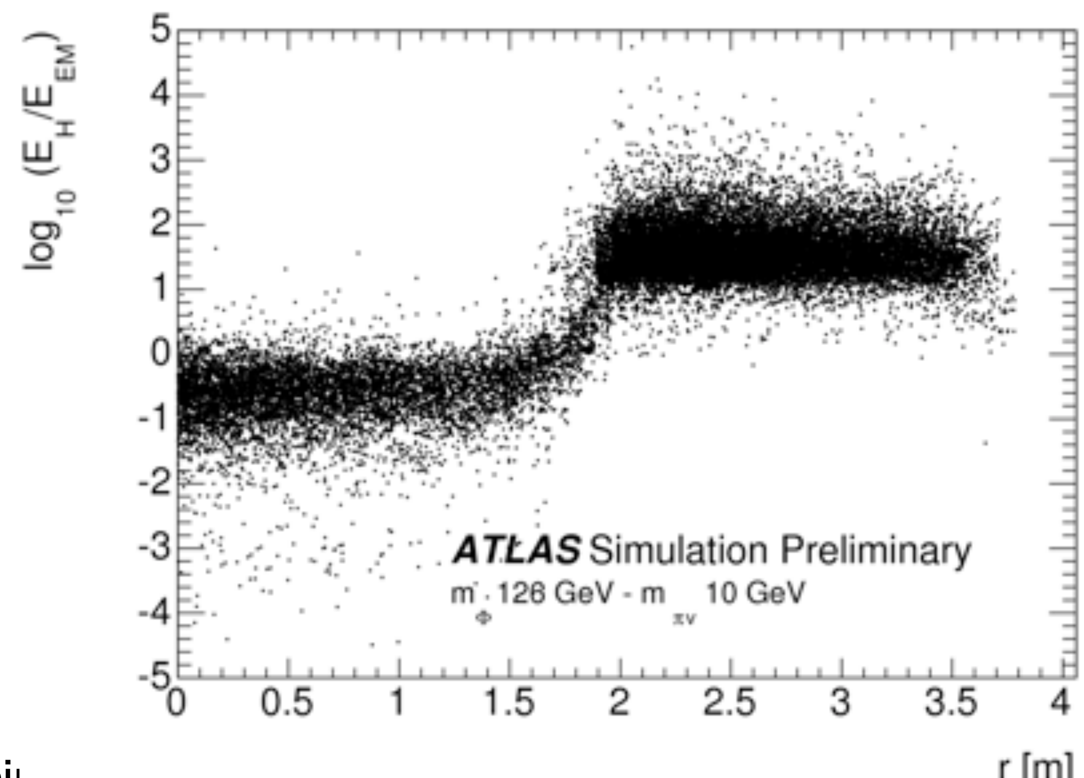
Long-Lived Particles decaying into jets

- ATLAS has focused on utilization of more unusual objects
  - decays in HCAL (no signals in ECAL)
  - decays outside HCAL (vertex in a muon system)
  - extra muon in the event

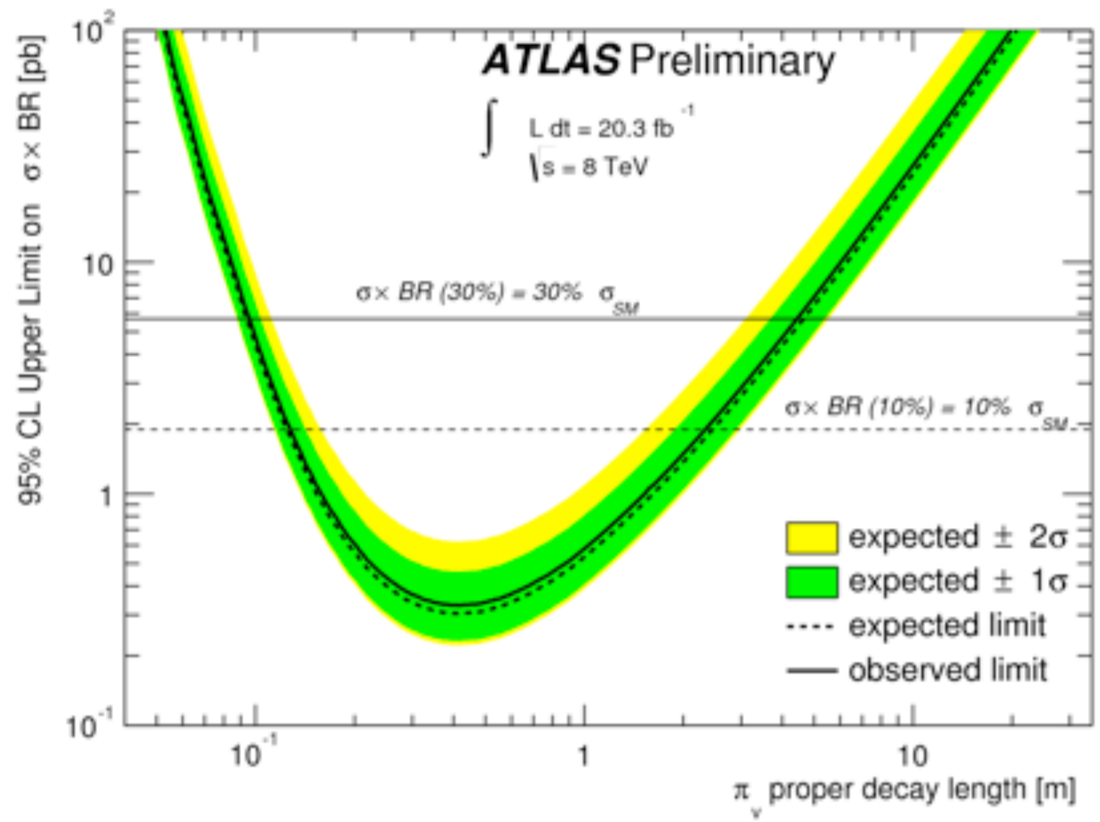


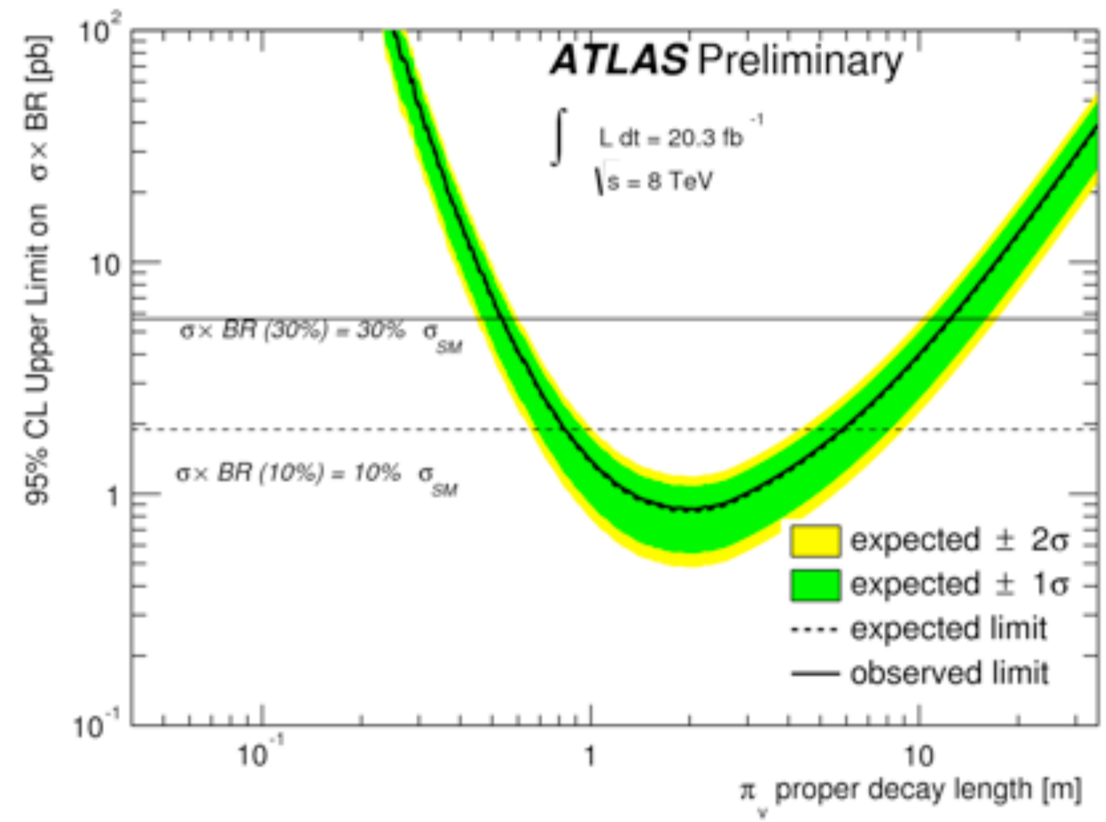


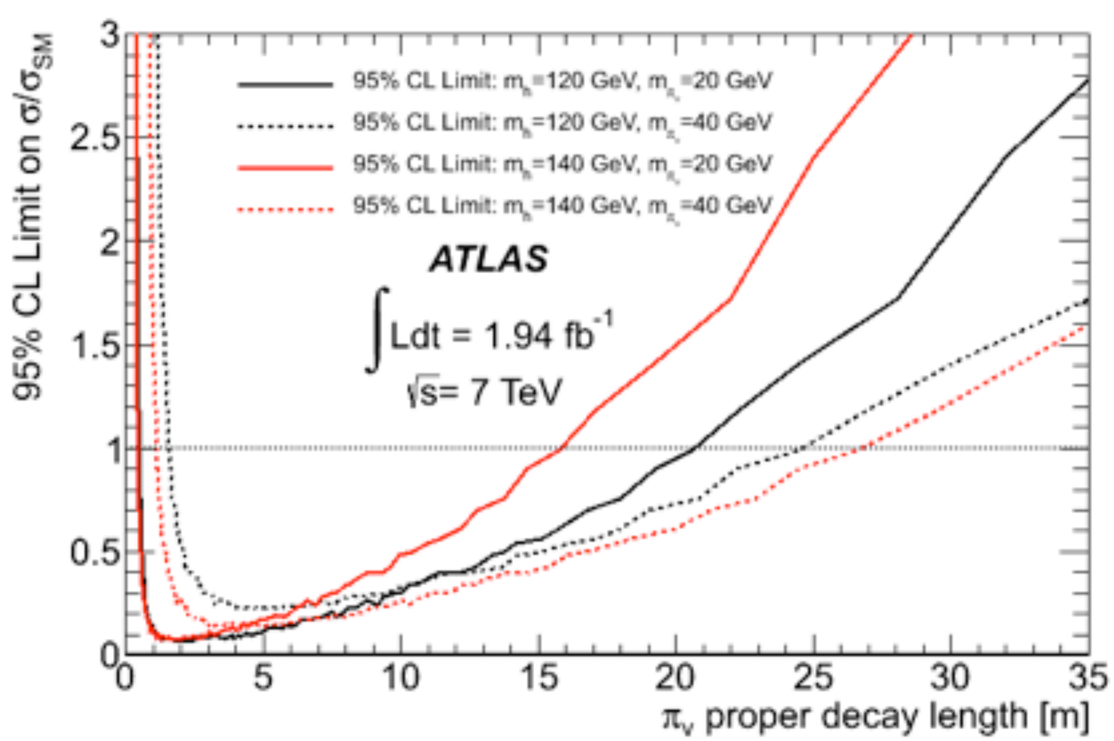




Long-Lived Particles decaying into jets







- Require two long-lived particles per event
- Most sensitivity at cτ around 100 cm and Br ~ few %
- extending sensitivity to low lifetimes is paramount

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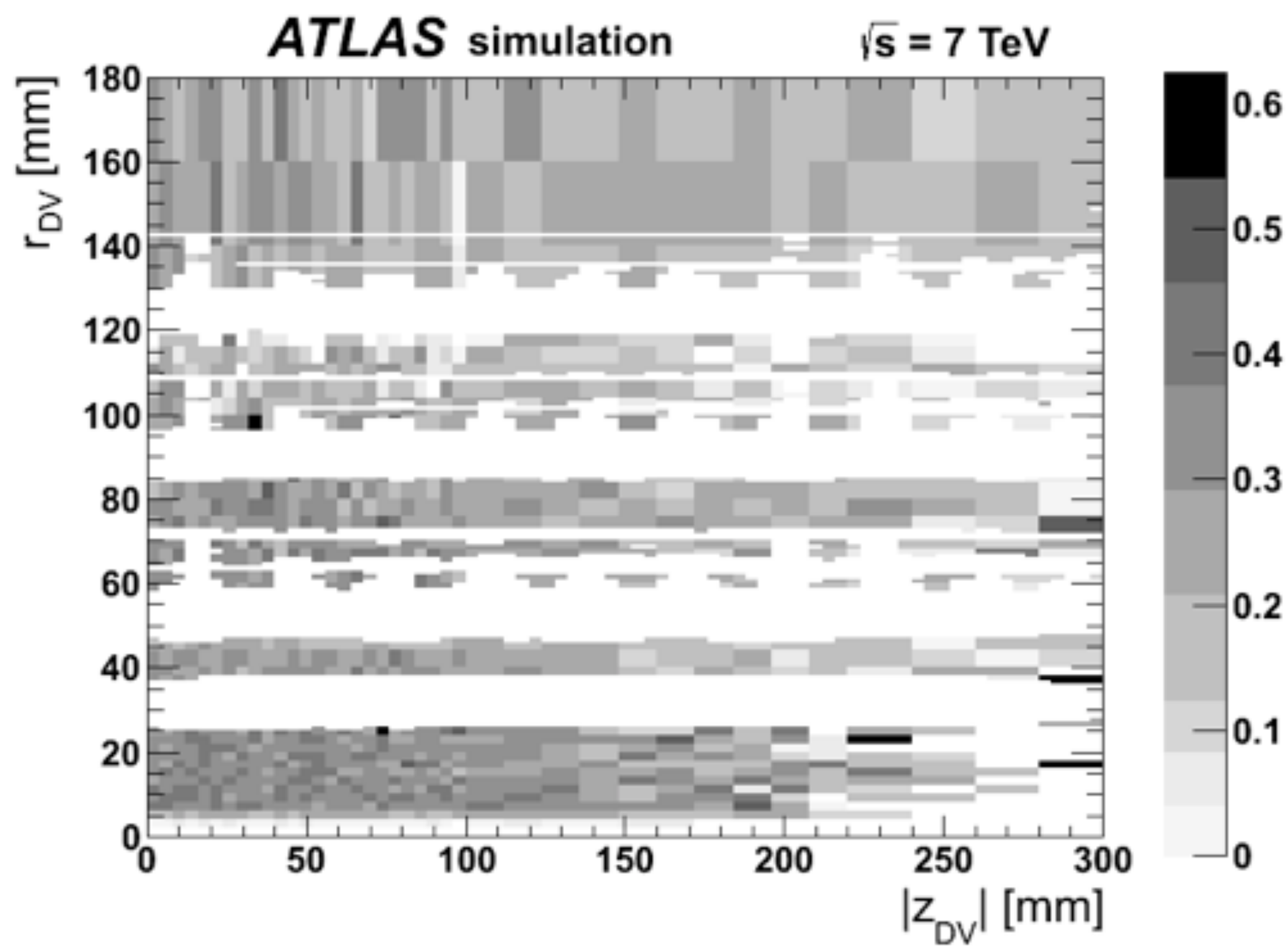
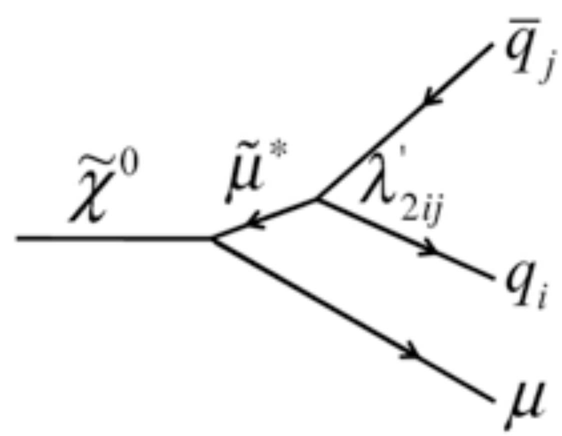
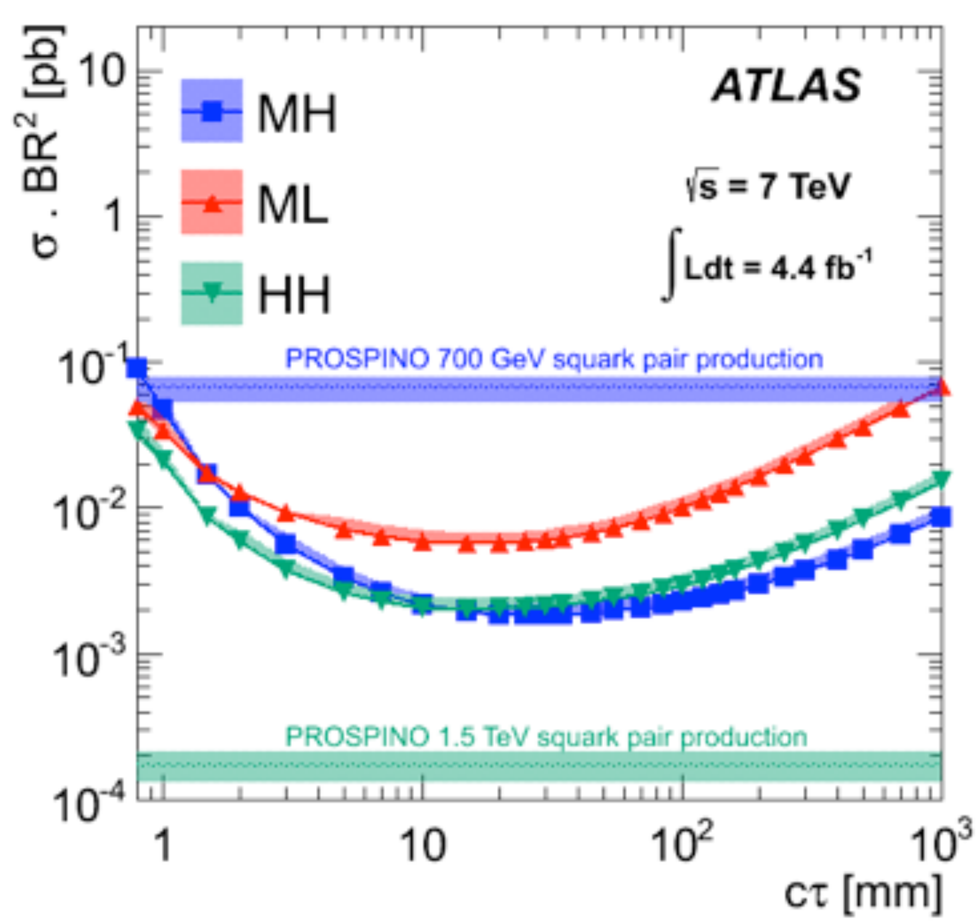
Monday, August 4, 14

Long-Lived Particles decaying into jets

- Lower E_T's and dijet masses - hadronic interactions in the material become a problem
  - have to make a material veto map



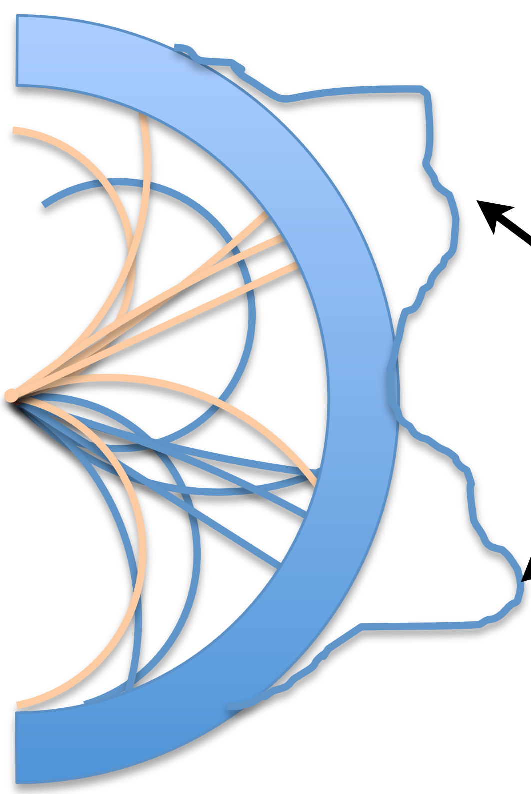




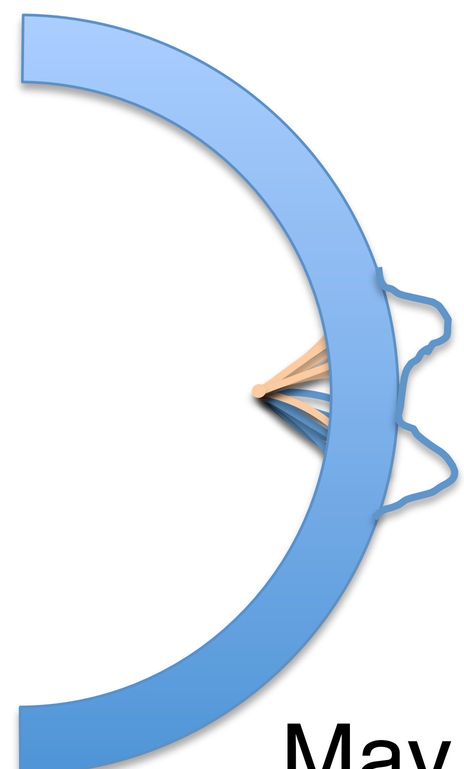
Limitation: requires the muon to originate from the same displaced vertex

Long-Lived Particles decaying into jets

- Decays in tracker volume tough to trigger on
  - would be easier with a L1 track trigger!
- More comprehensive cross-trigger strategy?
- More HLT / offline tricks to lower E_T thresholds?



Diffuse energy pattern, QCD-like

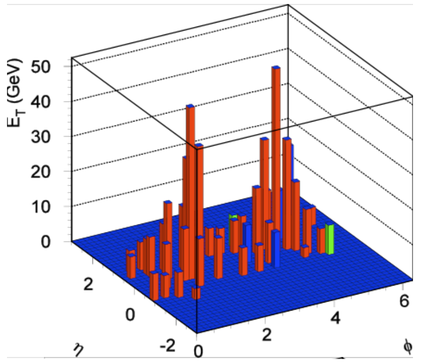


Same dijet, if displaced, now gives a very tight energy clusters

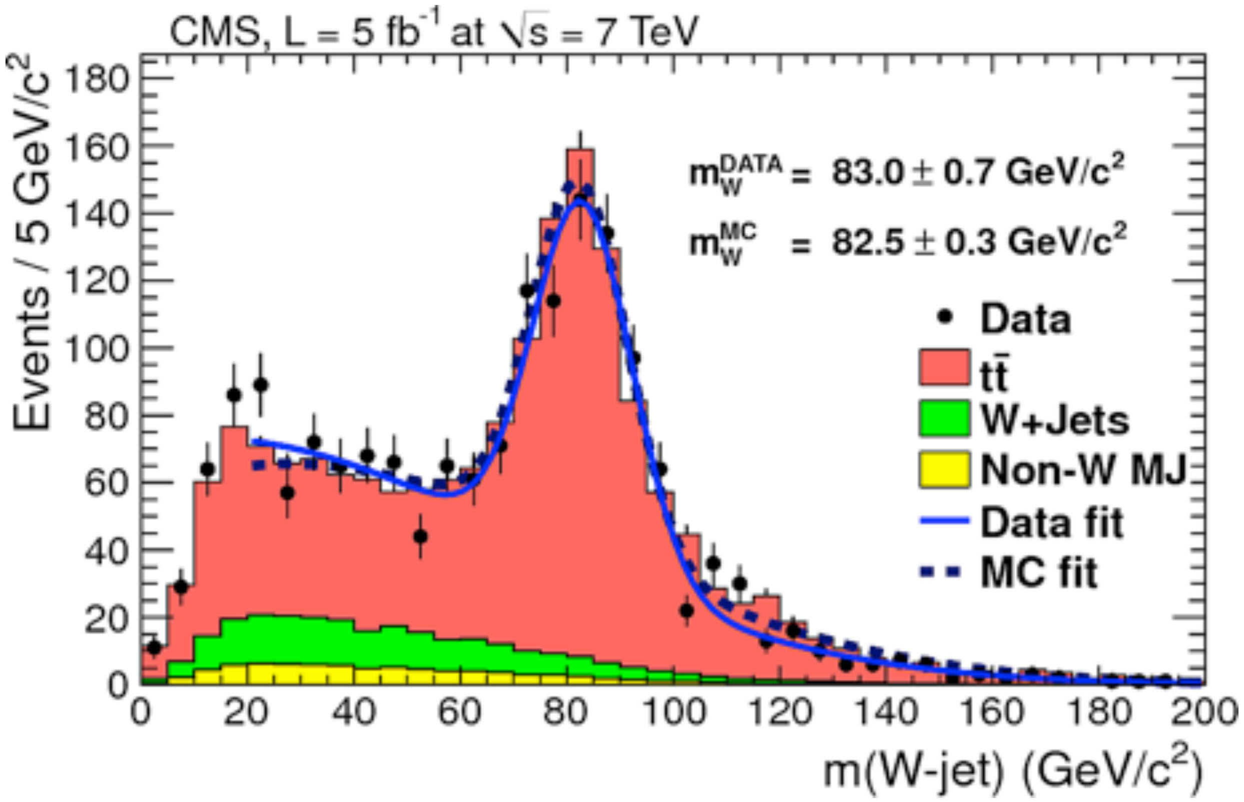
May be a good candidate for jet substructure tools

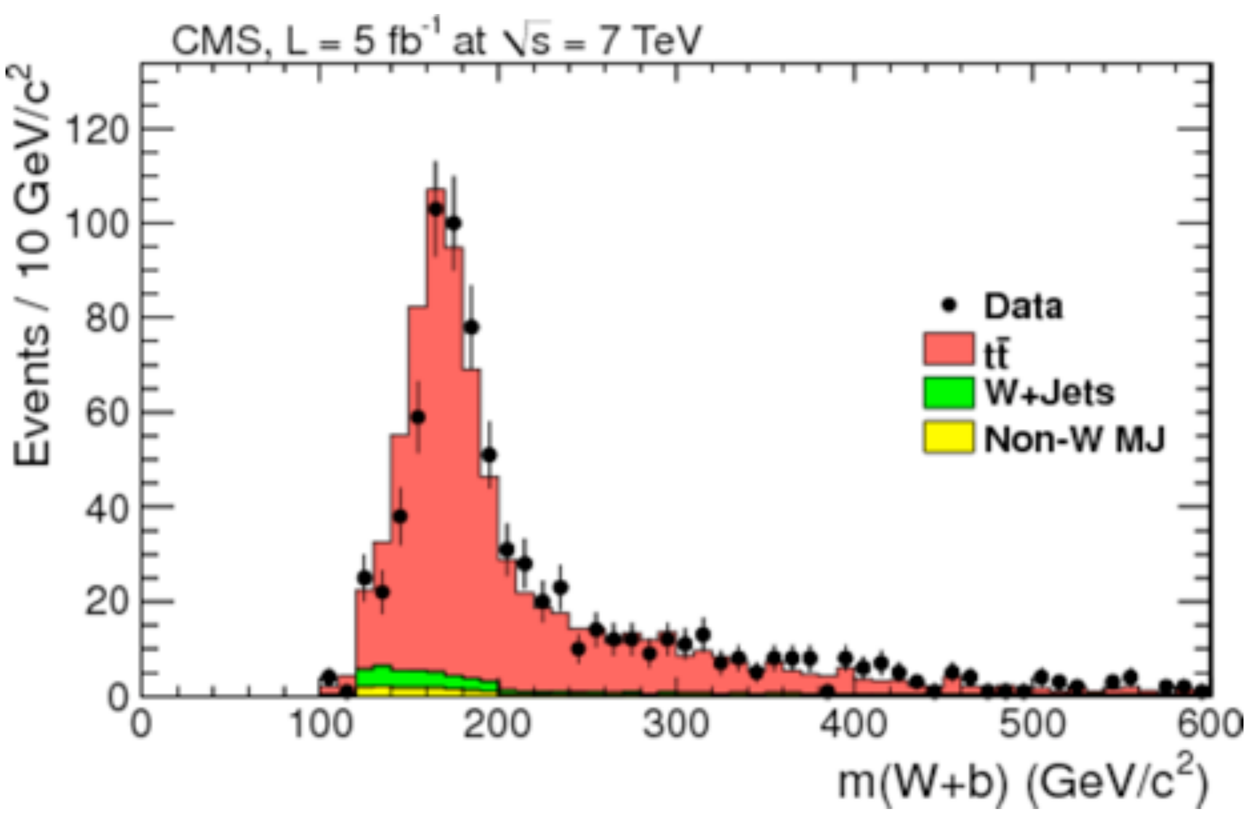
Jet Substructure

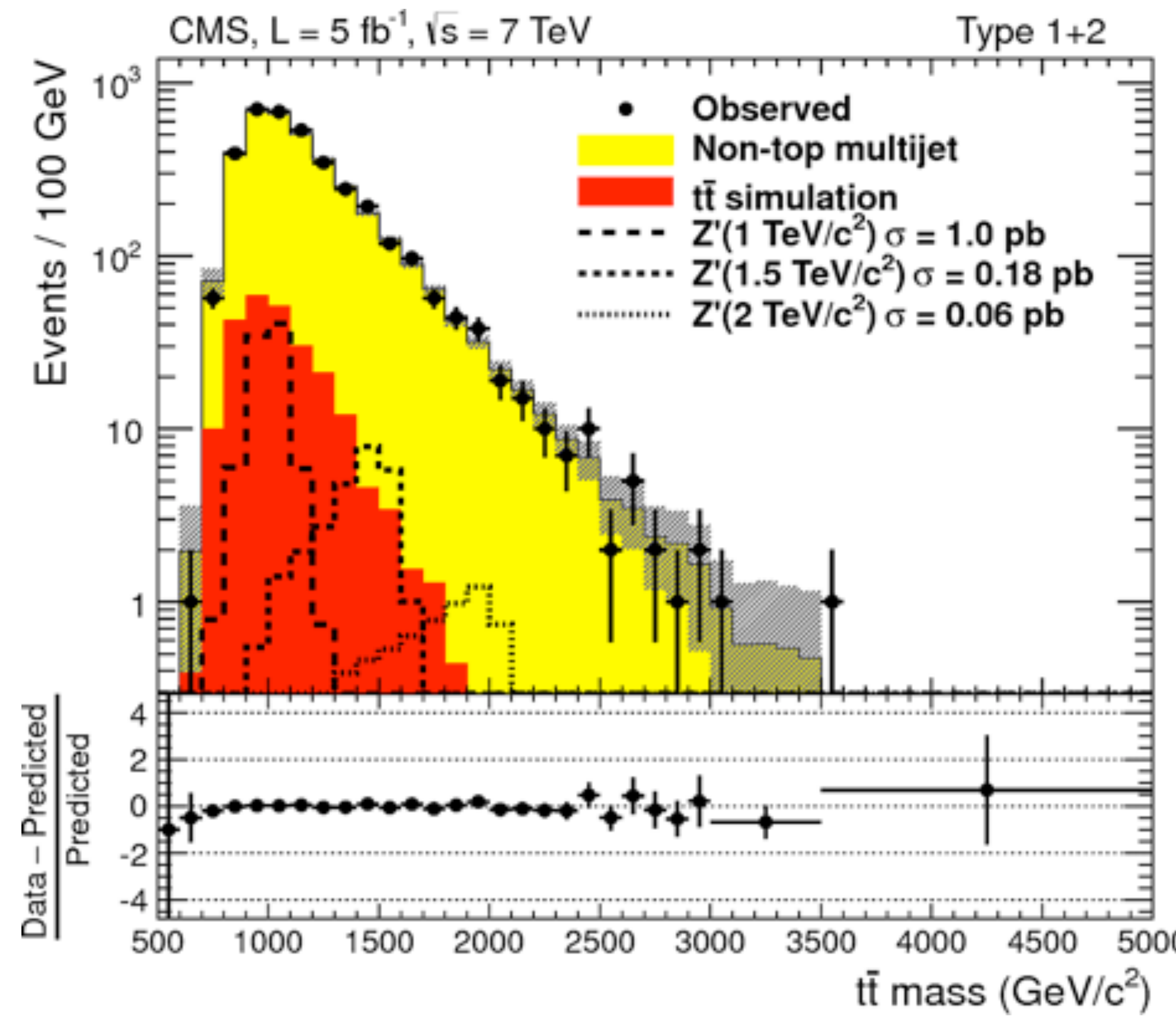
- Boosted objects
  - LHC13 is sensitive to colored particles with masses of ~2 TeV
  - LHC8 limits on electroweak particles are generally weak, not far above W/Z/H/top
  - If colored particles decay to electroweak particles (SM or non-SM) a huge boost for the latter is a general feature
- Accidental substructure
  - a way for BSM to hide from us is through long cascades - that means ~spherical events with lots of particles and accidental overlaps
  - technically easier to deal with few fat jets with substructure then O(10) regular objects
  - Strategy may need some adjustment for HV



Highly boosted top

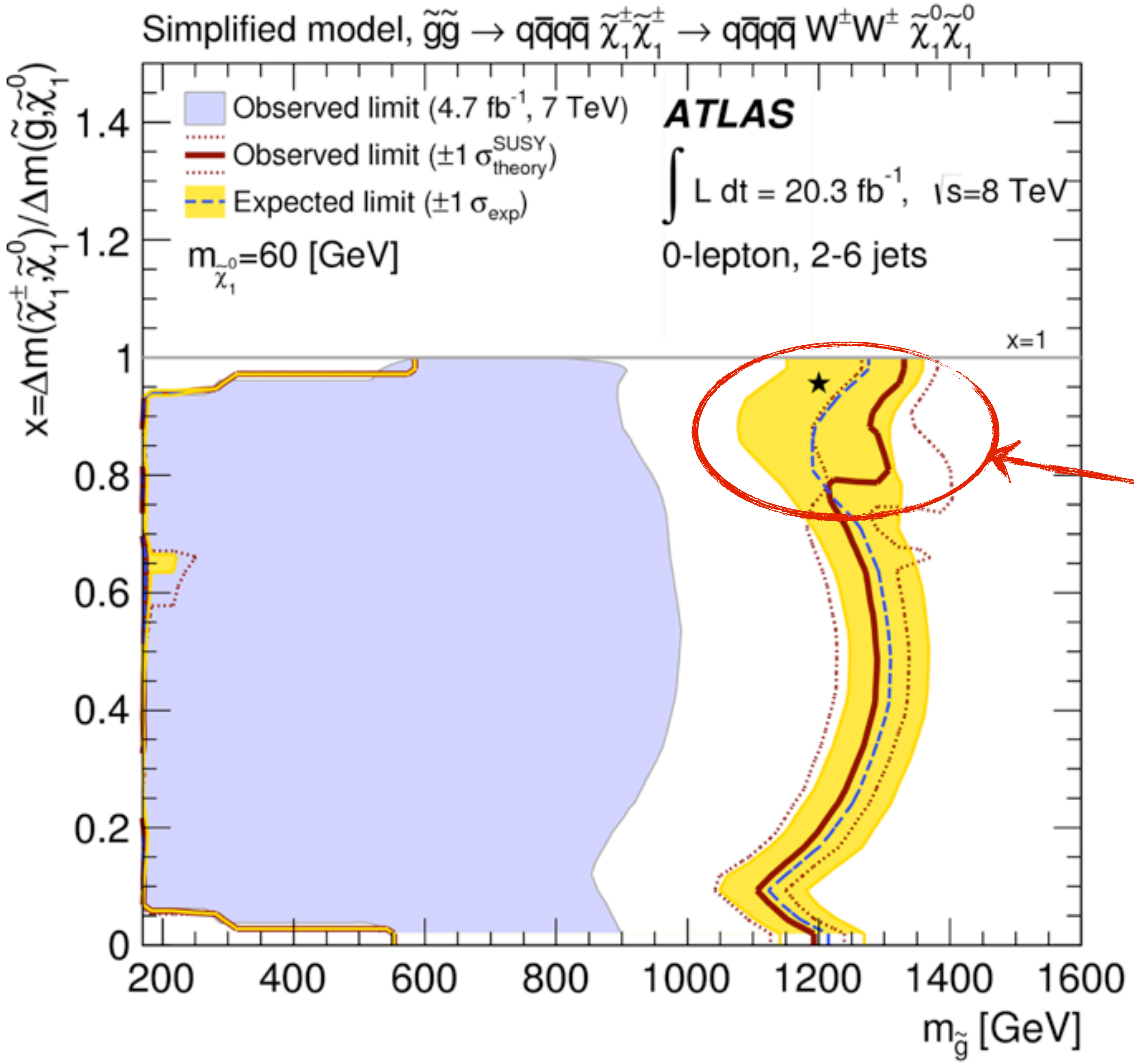


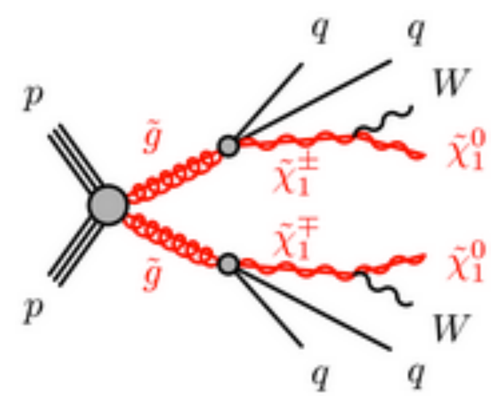




Yuri Gershtein

Boosted W in SUSY

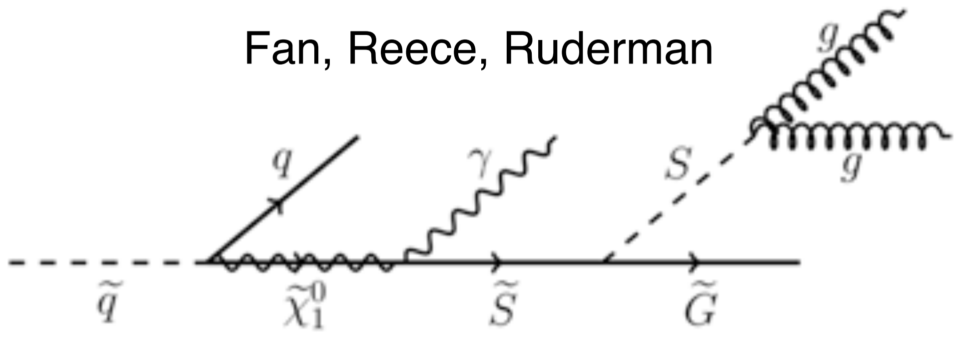




Monday, August 4, 14

How about boosting non-SM particles?

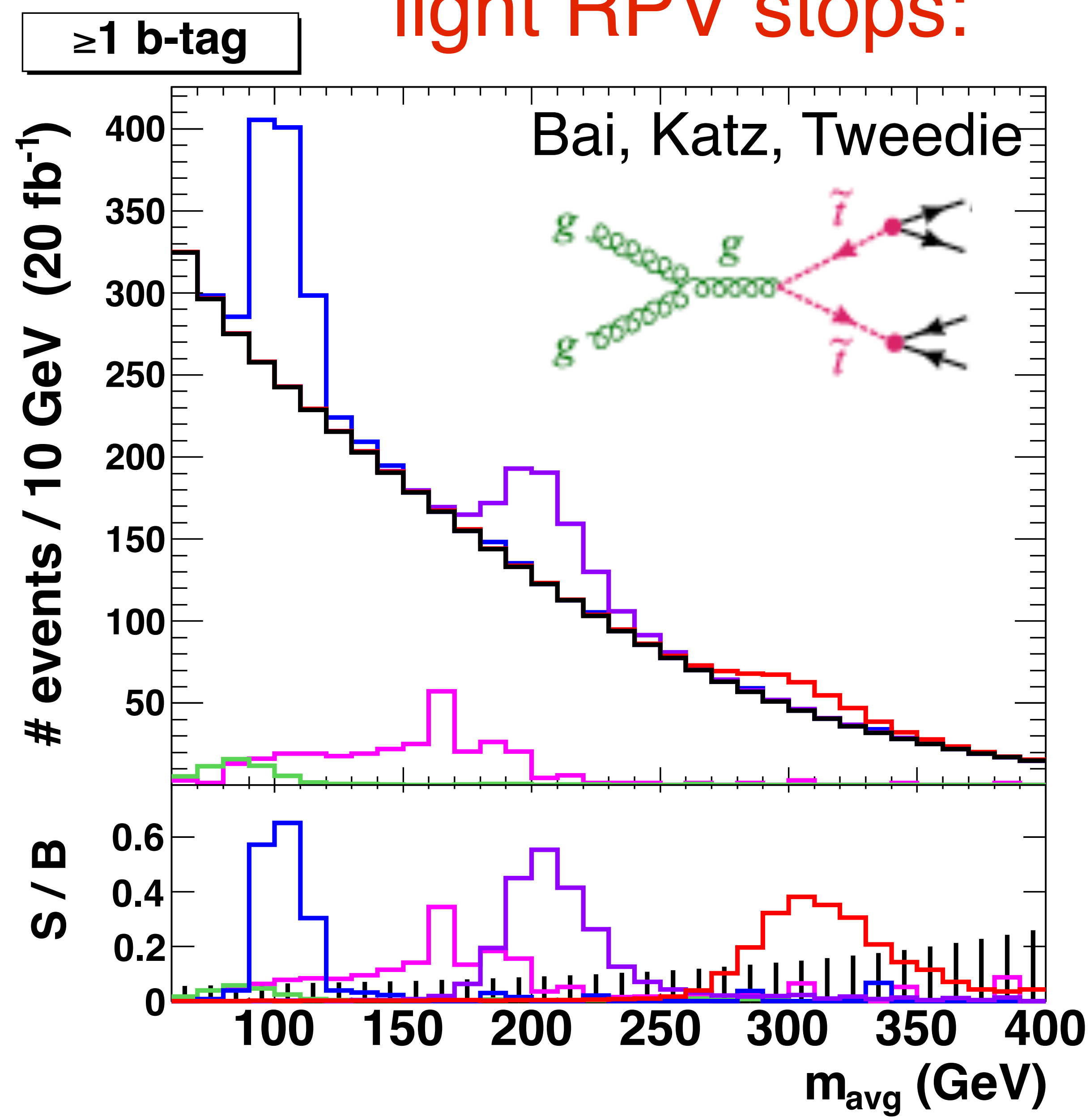
Stealth SUSY:



as M_{squark} limits are pushed much higher then M_S

- di-gluon resonances
- Sγ pseudo-resonances

light RPV stops:



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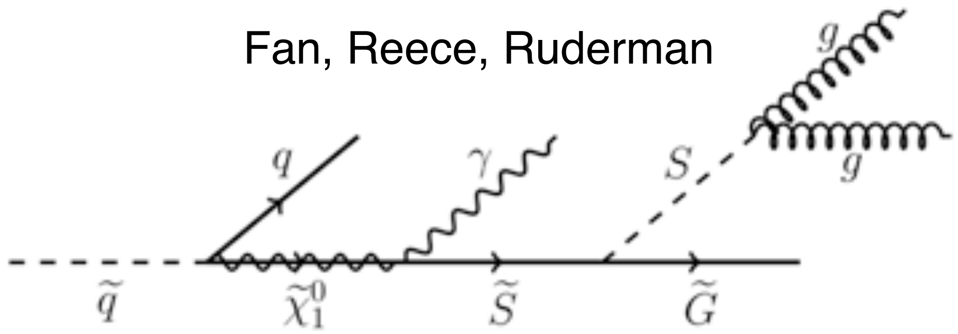

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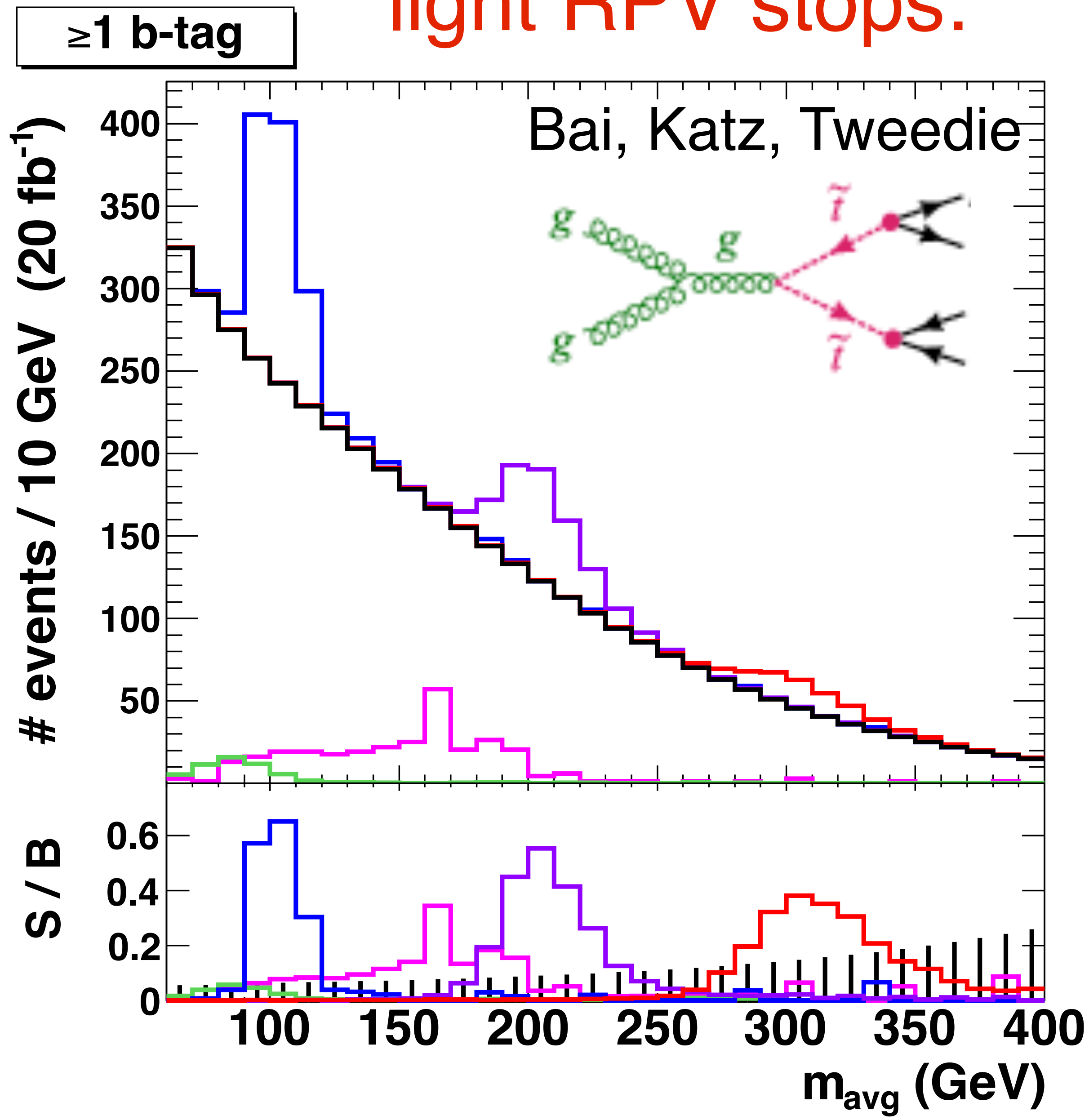
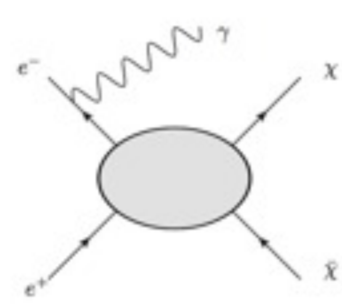
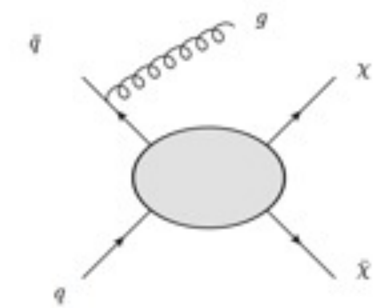


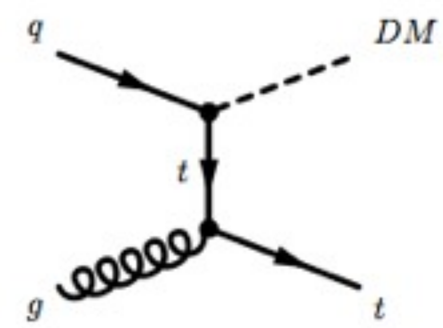
- Are we ready to believe we discovered a new particle if we see a bump in a fat jet mass at 110 GeV? Or we would think that PU cleaning and kinematical cuts we make move QCD/Z/W/h/t around?

Dark Matter Searches

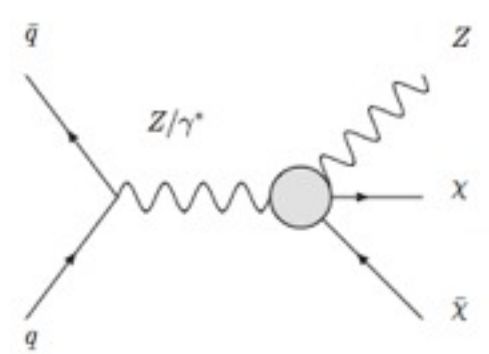
- If DM interacts more then gravitationally, it could be made in perceptible numbers at the LHC
- To be observable at the LHC, it has to be associated production with SM particles (that would also tell us about the DM couplings)
  - mono-jet / mono-photon
  - mono W/Z
  - mono top / top pairs
  - ...

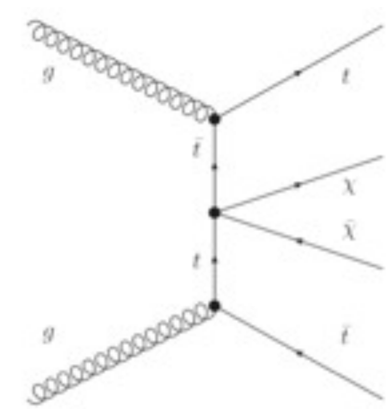


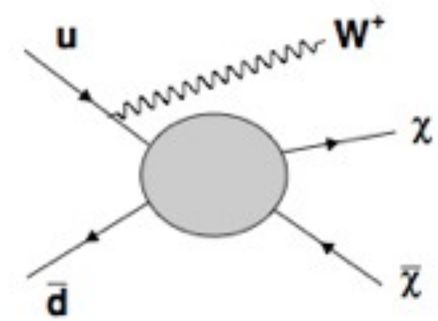




- Interpretation
  - model independent cross section times acceptance measurement / limits
  - Effective Field Theory approach for heavy DM force mediator
  - Specific model (i.e. Higgs portal, etc)







Dark Matter Searches

- Very important to remember that "mono"-X does not mean that there's nothing else in the event!
- Dark sector is not necessarily just one particle
  - $X + Y^1_{dark} + Y^2_{dark}$
  - Some of the dark cascade can produce SM particles
  - Examining "mono"-X candidates for extra stuff (especially unusual stuff) can help reduce SM sources of MET (i.e. $Z \rightarrow \nu\nu$)

- Even true in SUSY:
  - "natural" scenario - only higgsino is light enough to be accessible at the LHC
  - 3 higgsinos are almost mass degenerate - soft leptons / pions from cascades, short track stubs, etc

inelastic DM

spherical excess of photons from positronium annihilation seen by INTEGRAL

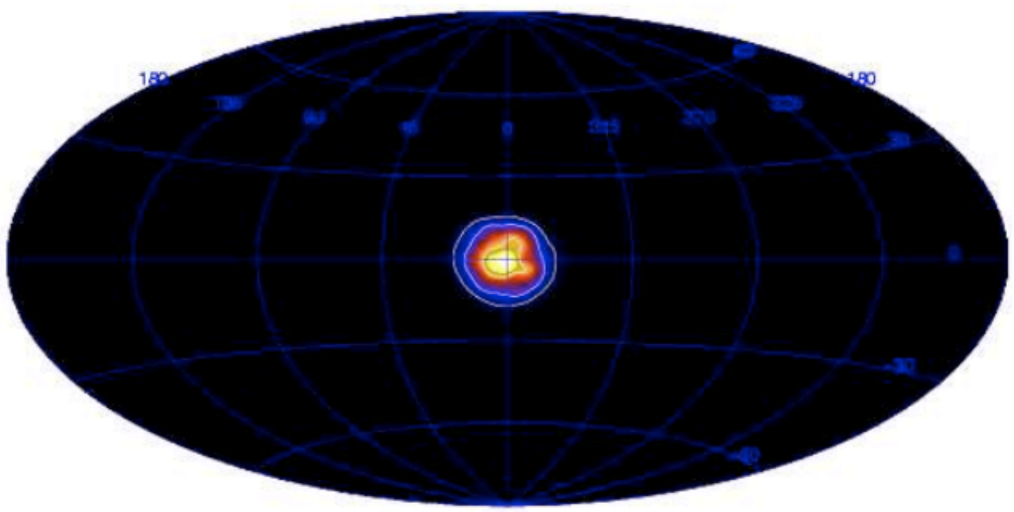
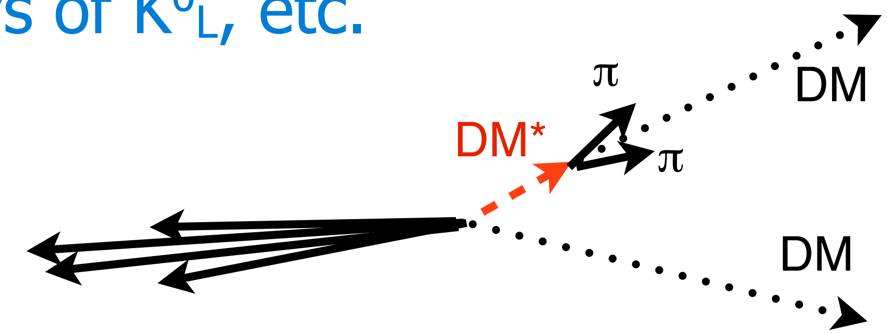


Fig. 1. A Richardson-Lucy sky map of extended emission in the summed Ps analysis intervals (the combination of the intervals 410–430, 447-465, and 490–500 keV). The contour levels indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2} s^{-1} sr^{-1}. Details are given in the text.

arXiv:astro-ph/0601673v1

Finkbeiner, Weiner: low energy positrons are coming from $DM^* \rightarrow DM$ transitions

- At the LHC: a $\pi^+\pi^-$ vertex opposite the jet
  - interactions in tracker material
  - decays of K^0_L, etc.



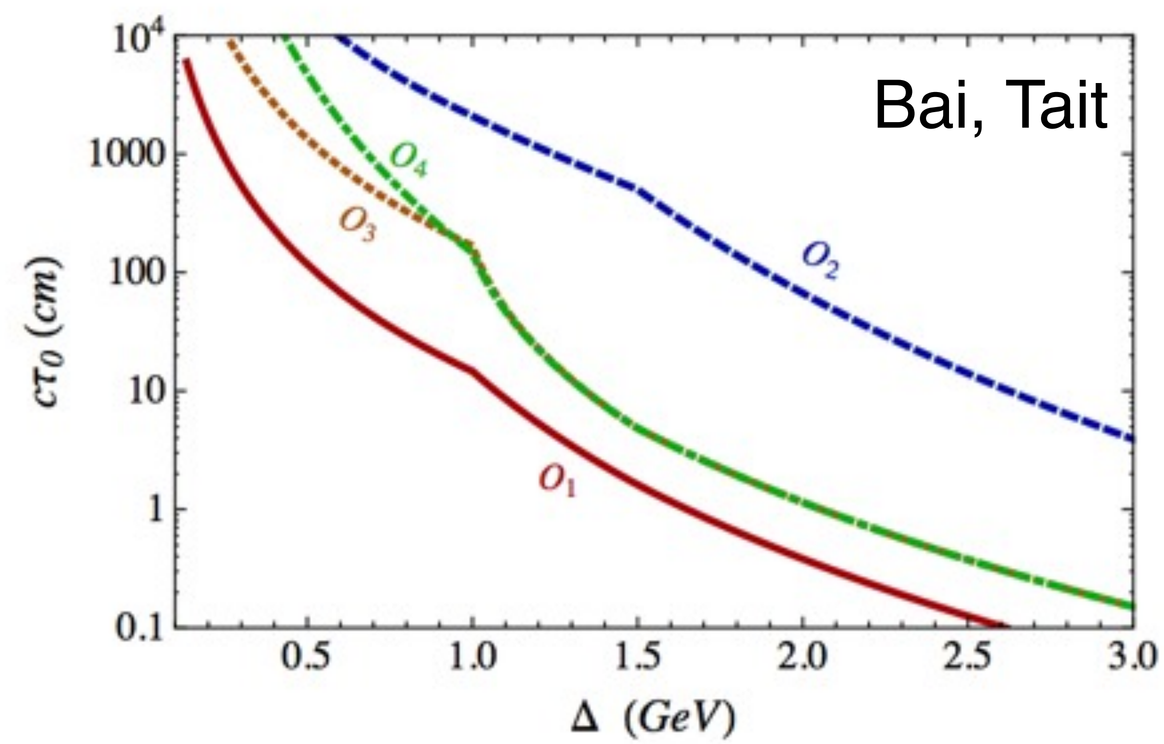
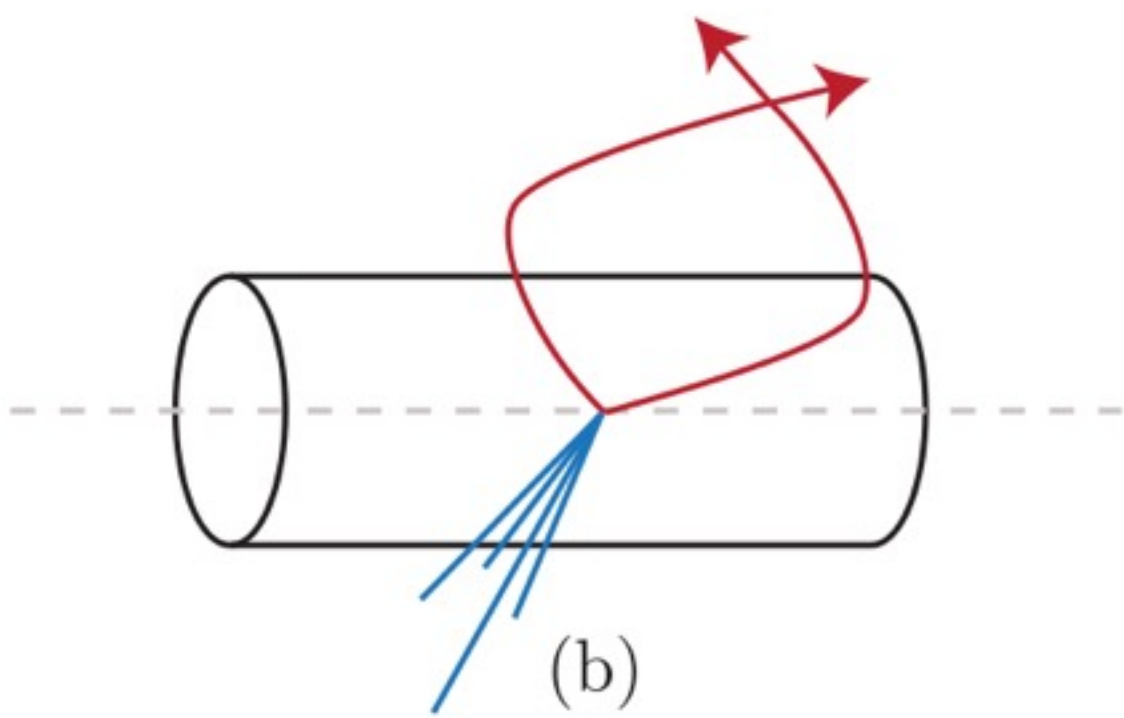


FIG. 1: Decay lengths of the excited dark matter state at rest as a function of mass splitting for different operators with $\Lambda_i = 1$ TeV and a dark matter mass of 5 GeV.

Quirks

- New fermion Q and new QCD-like force with very small Λ (infra-color) - the infra-color string does not have enough energy to pop $Q\bar{Q}$ pair
  - like two balls connected with a rubber band

Kang, Luty



- The tracks may be invisible but the infra-charges are going to radiate
  - huge number of ~soft pions may be radiated
    - not necessarily from the primary vertex
  - mono-jet events with anomalous track multiplicity

Summary and Outlook

- No lack of motivation for BSM
  - Dark Matter
  - Hierarchy problem
- No clear way to know how it manifests at the LHC
  - need to keep biases and prejudices in check
- We barely scratched the surface with the LHC8 run - even in terms of excluding fine tunings of 10% or so
  - sure, some of us wanted low scale phenomenologically rich Supersymmetry

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  - sure, some of us wanted low scale phenomenologically rich Supersymmetry
  - we may still get what we want
  - but if not - it's quite possible that we'll get what we need


C.M. Tholens

There is nothing like looking, if you want to find something.

You certainly usually find something, if you look, but it is not always quite the something you were after

J.R.R. Tolkien