Not-quite mainstream Run 2 physics

Yuri Gershtein

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
- in some cases: no MC
- in all cases: theorists have to continuosly apply pressure on experimentalists

~now is when the Phase 2 trigger systems choices are being made

BSM in Higgs couplings (loops)

P. Janot

- **Example : Precision for Higgs couplings**
  - **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	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$

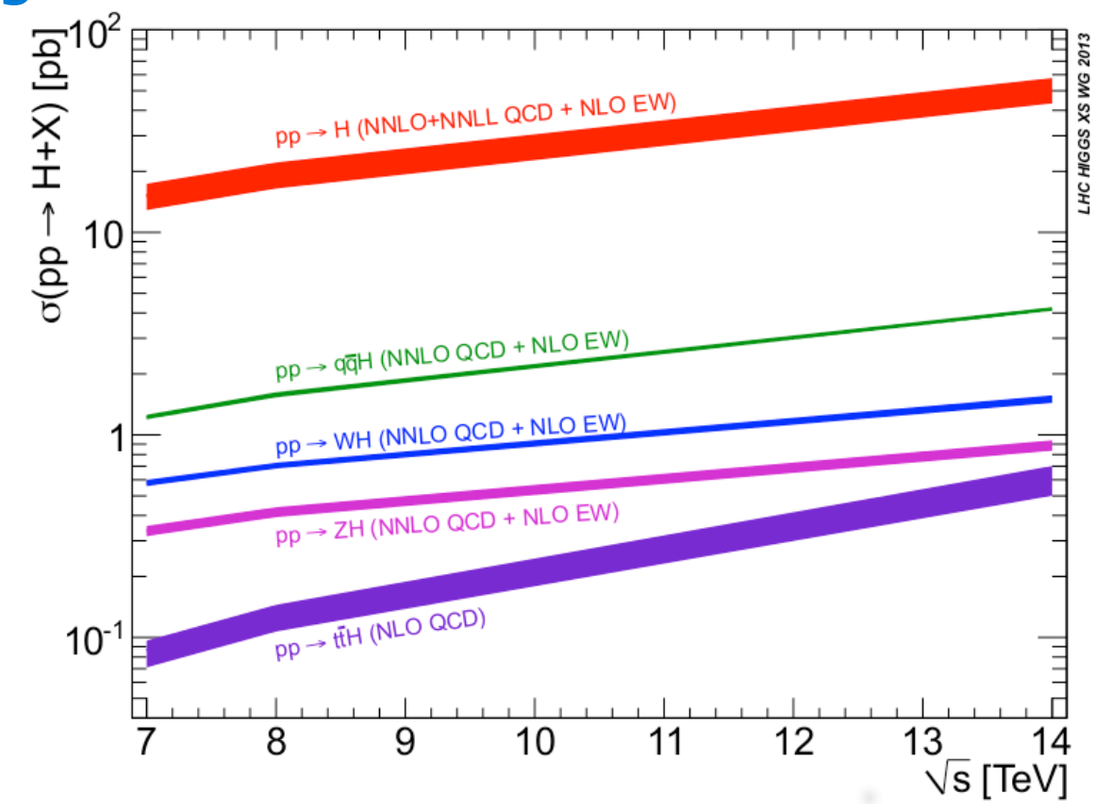
J.D. Wells et al.

- **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
- Main roles of the Higgs for Run 2:
  - portal into hidden sector (rare decays) and production in BSM cascades

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 $2 \cdot 10^{-3}$ penalty for $\gamma\gamma$ branching one gets ~reasonable number of events
    - $5/\text{fb} \cdot 1\text{pb} \cdot 2 \cdot 10^{-3} =$ 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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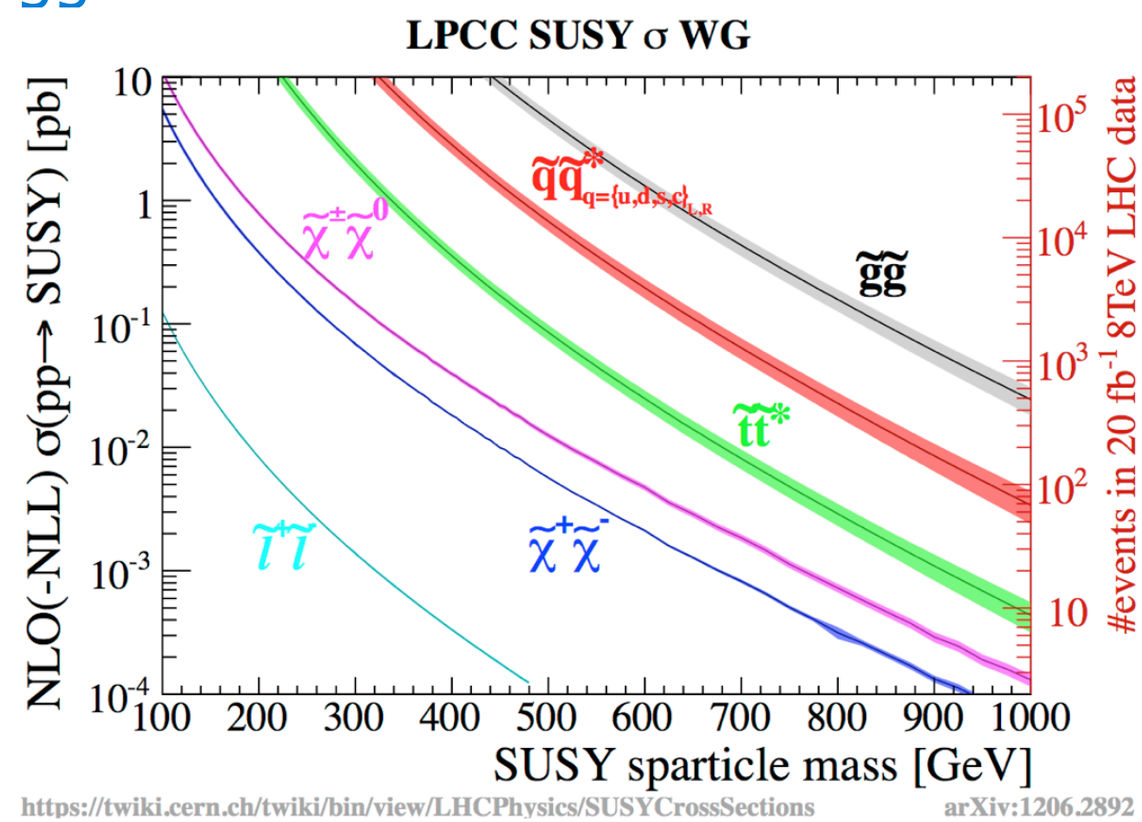

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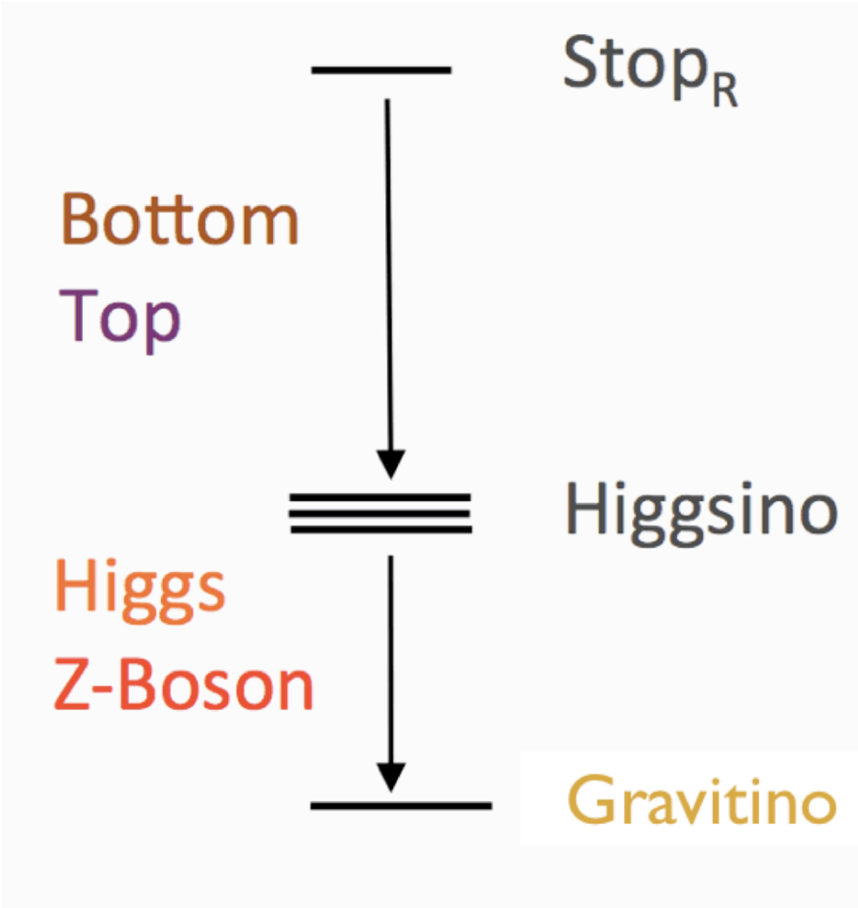
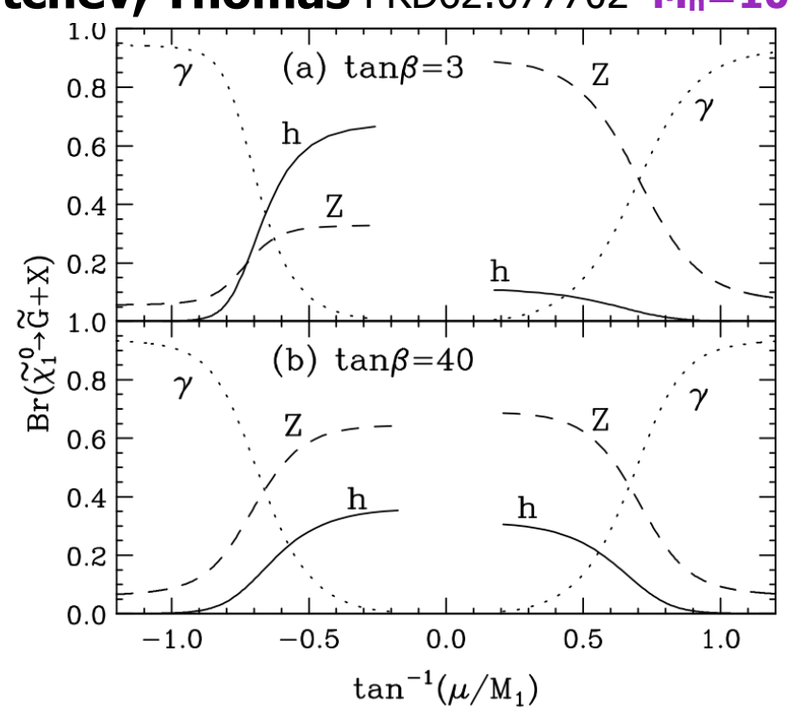
Example: "Natural"-ish SUSY



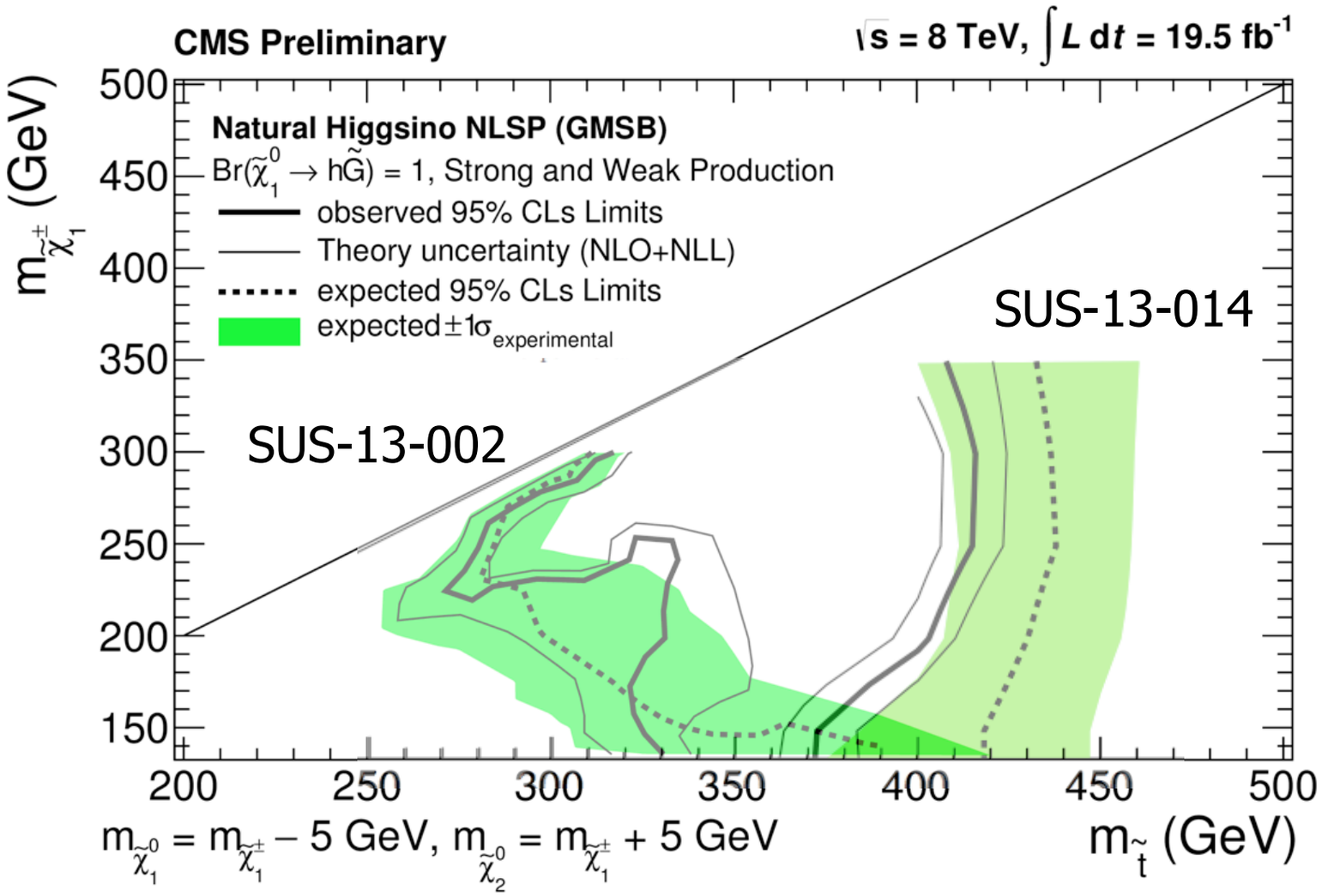
Matchev, Thomas PRD62:077702 **M_h=105 GeV**

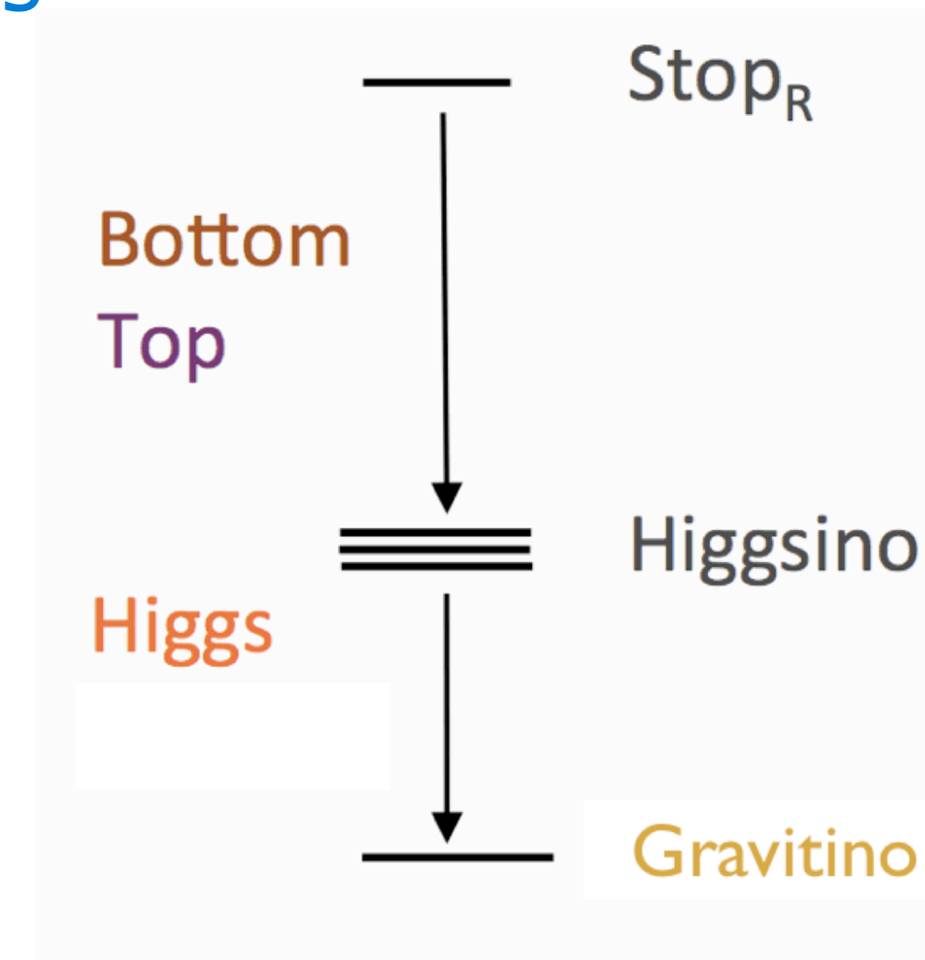


- In GM, lightest higgsino decays not to photons but to Z's and higgses - more higgses at low tan β
- can be quite stealthy
  - if higgsino just a little heavier then Higgs - almost no MET
- if $M_{\tilde{t}_R} - M_{\tilde{\chi}^0}$ is below top mass the decay is mostly to chargino and b
- chargino decays 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)
Extra U(1)xSU(n_v) - hidden sector with Z' portal

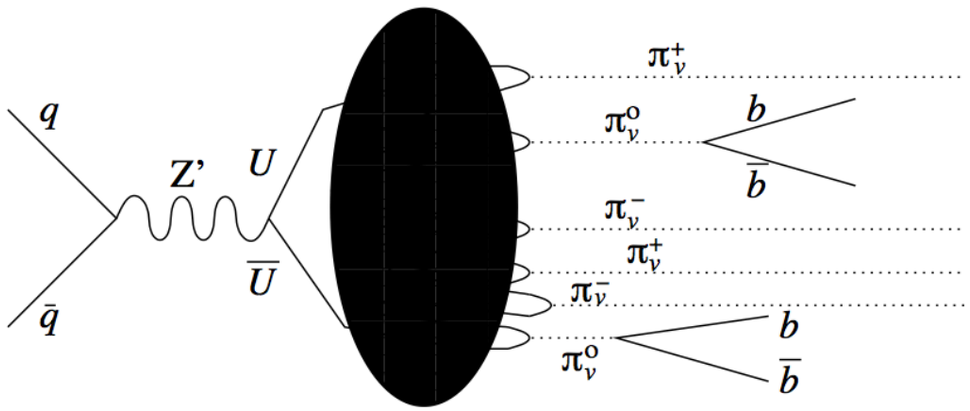
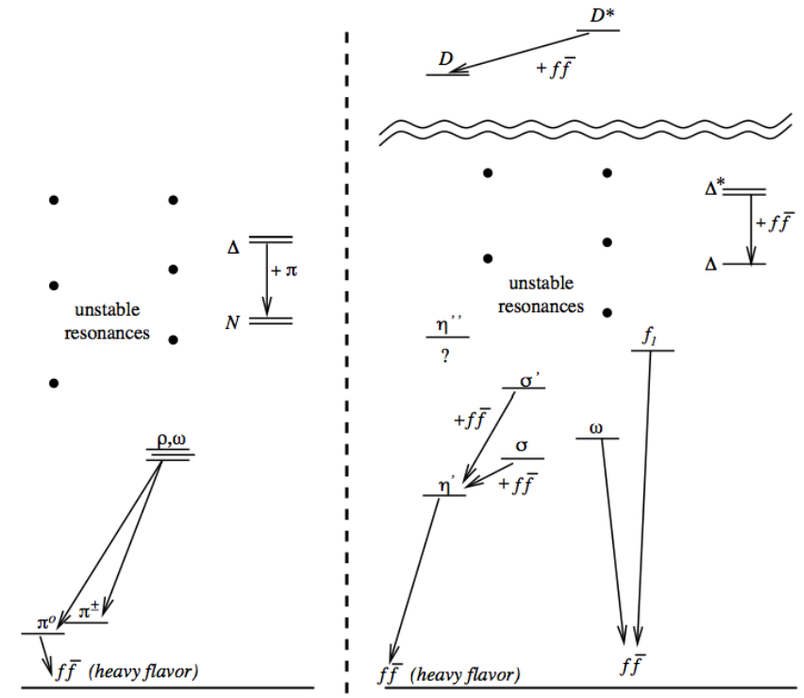


FIG. 3: A possible event in the two-light-flavor regime; note $\pi_v^{\pm}$ is electrically neutral and invisible.



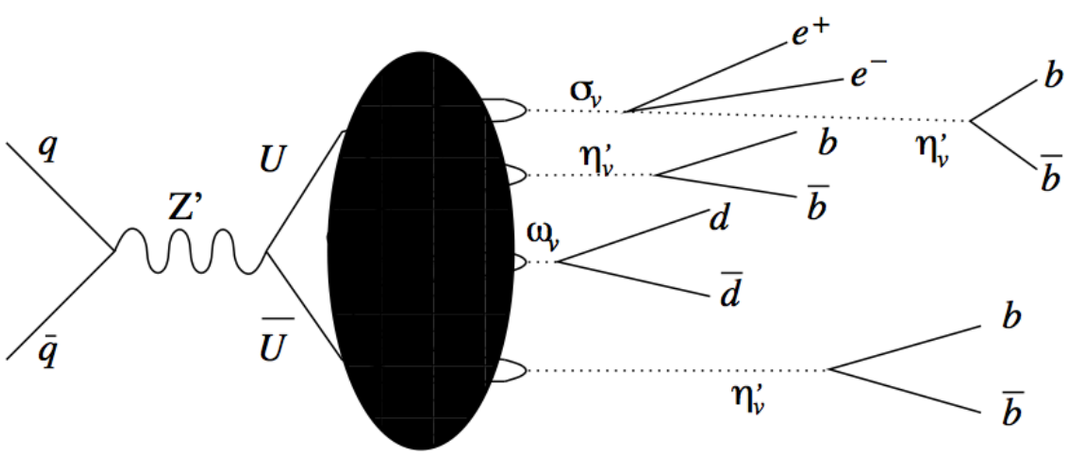


FIG. 4: A possible event in the one-light-flavor regime.

Looks like a strange dijet event

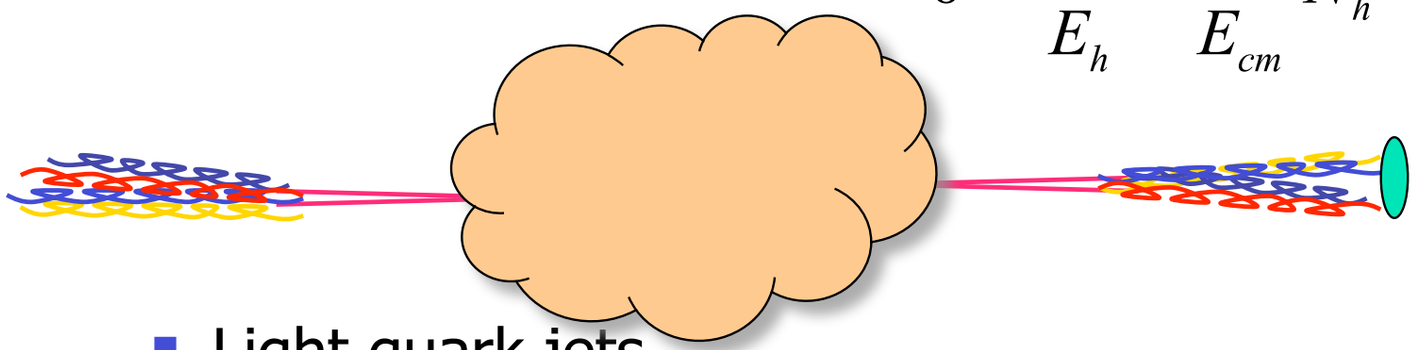
- *may have a lot of particles staying in the dark sector (MET) - Z' may be heavy, but visible ST can be small!!*
- *may have some long-lived particles inside the jets*
- *more massive particles - shorter lifetime, but that results in different event shape*

Hidden Valleys without LLP

Zurek (2006)

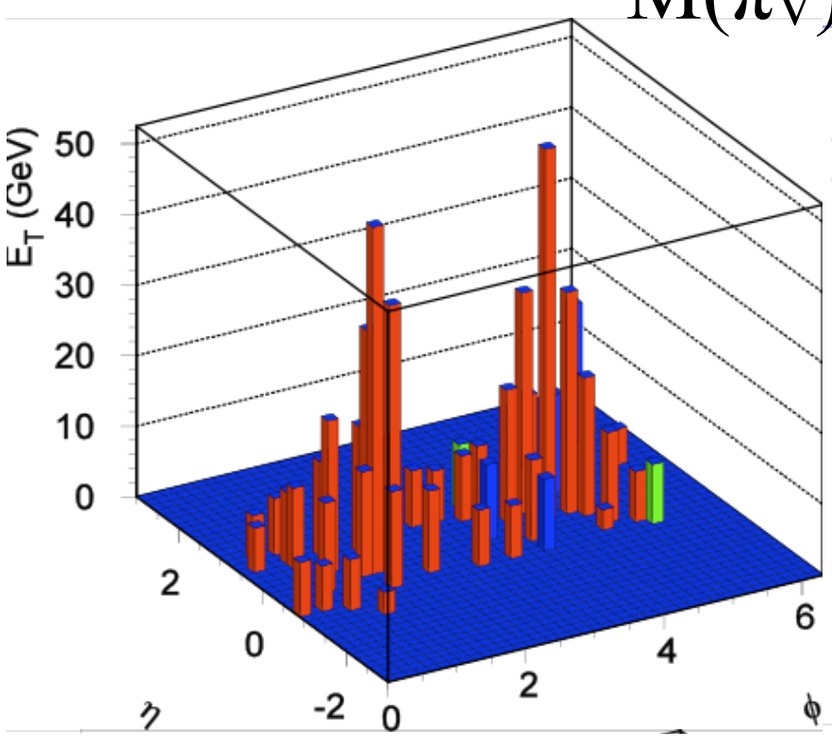
- Shape of event set by v-hadron mass

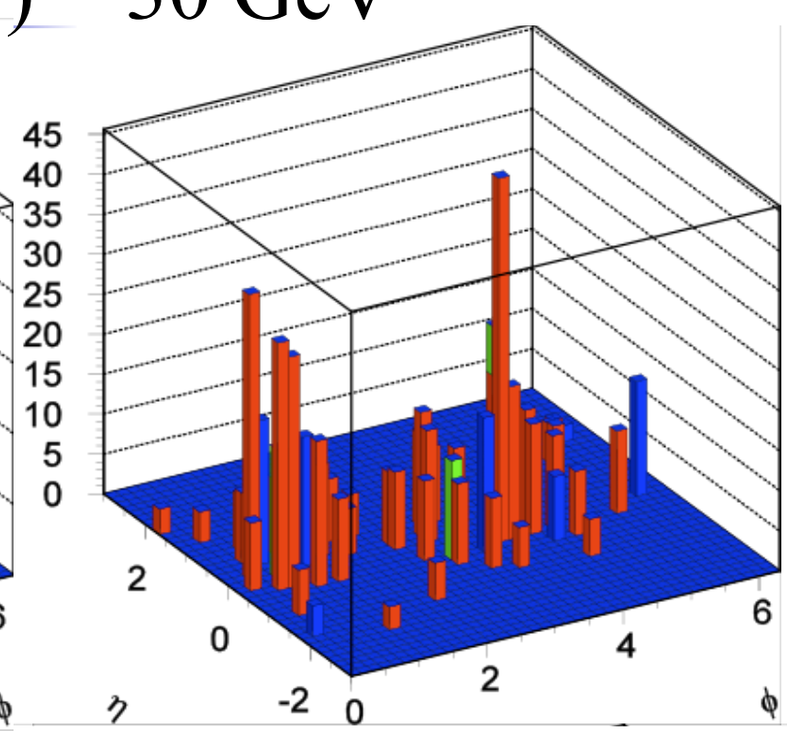
$$\theta \sim \frac{p_\perp}{E_h} \sim \frac{p_\perp}{E_{cm}} N_h$$



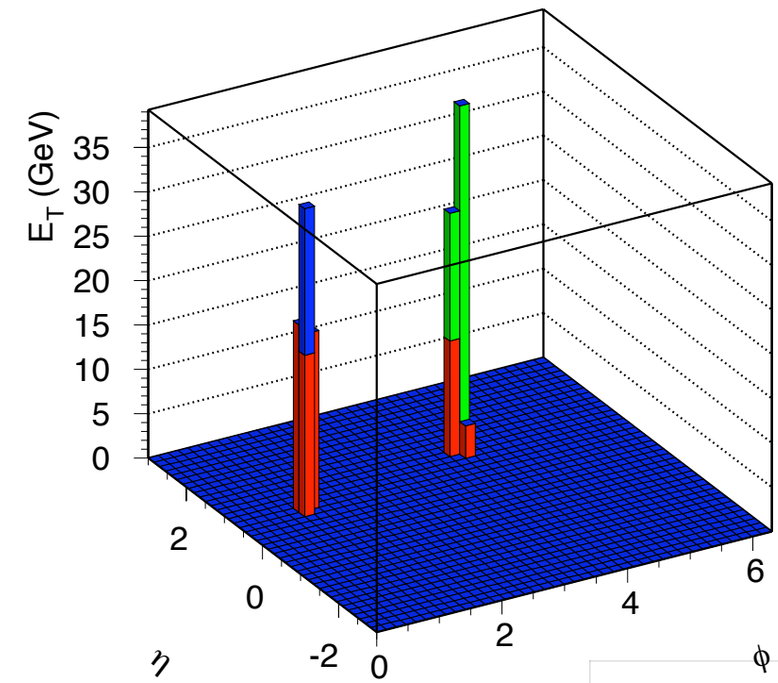
- Light quark jets
- vs. Hidden valley jets--larger opening angles due to higher mass v-hadrons

$M(\pi_V) = 30$ GeV





$b\bar{b}$



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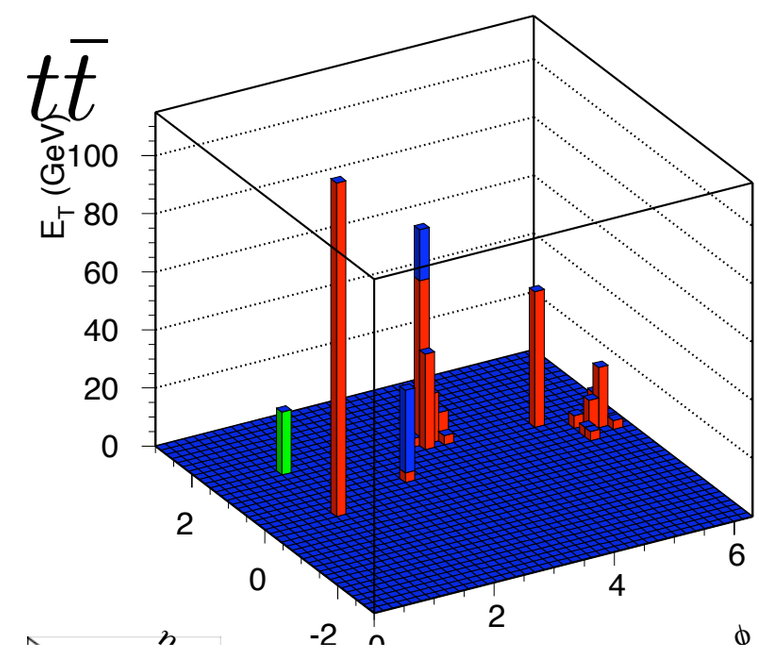
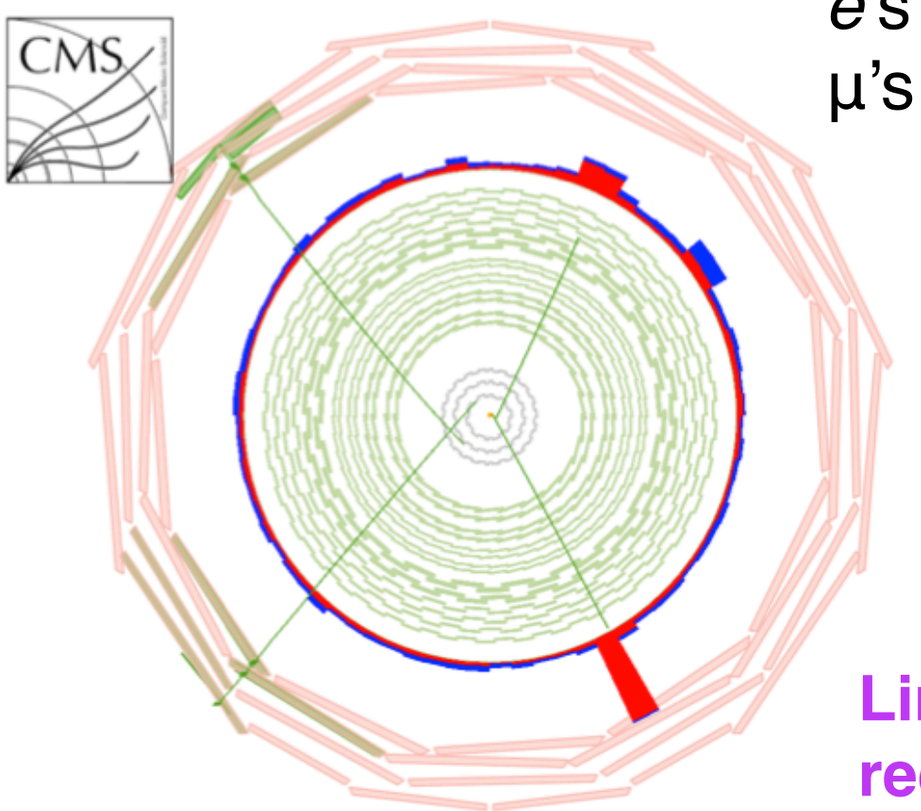


Long-lived particles

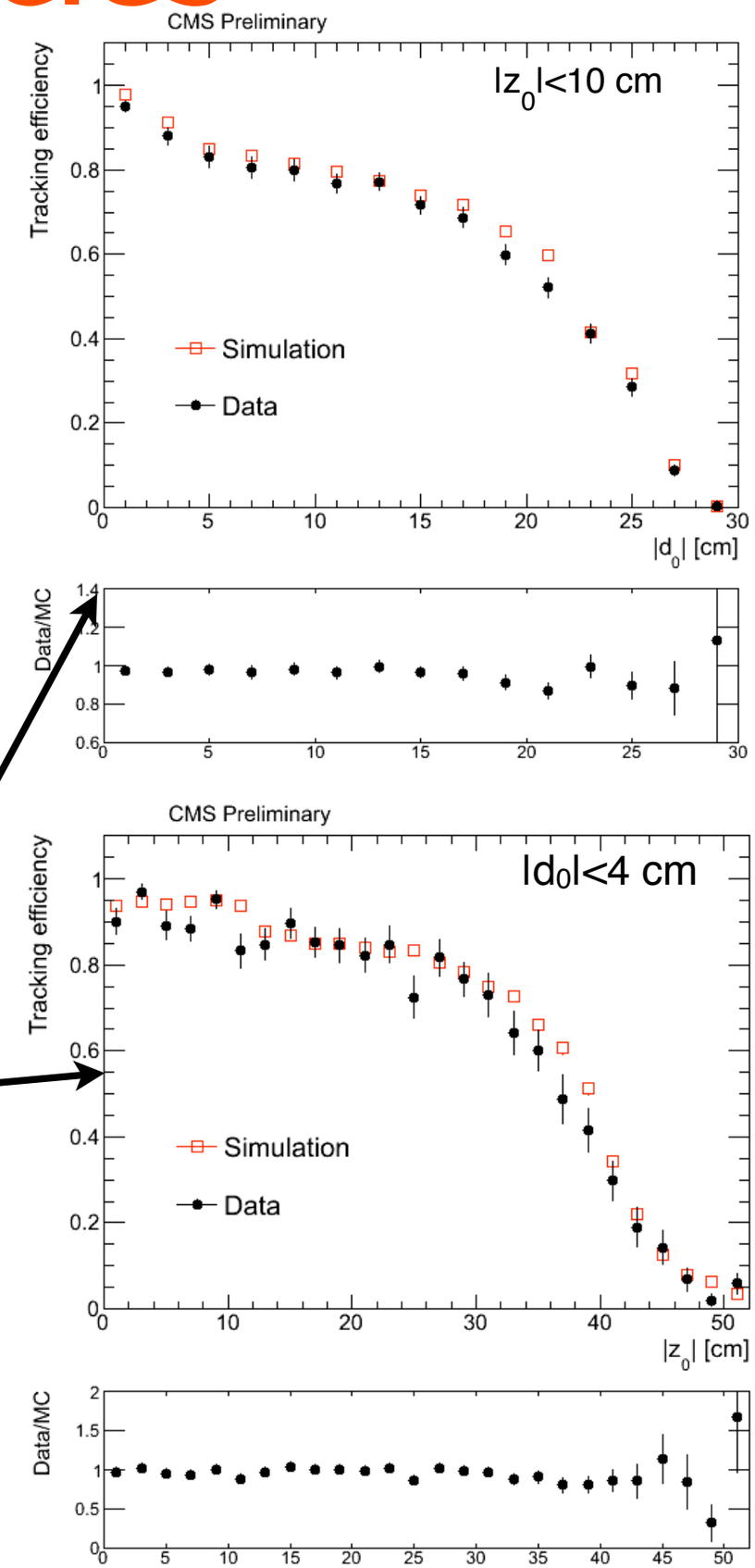
- Large number of well-motivated scenarios predict long-lived particles
  - here: leptonic decays
  - rare Higgs decays (the one at 125 GeV or a new one) - if there are HVs, Higgs may be the particle that senses them most: $H \to XX, \quad X \to f\bar{f}$
  - RPV SUSY $\tilde{q} \to q\chi^0(\to \ell^+\ell^-\nu)$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

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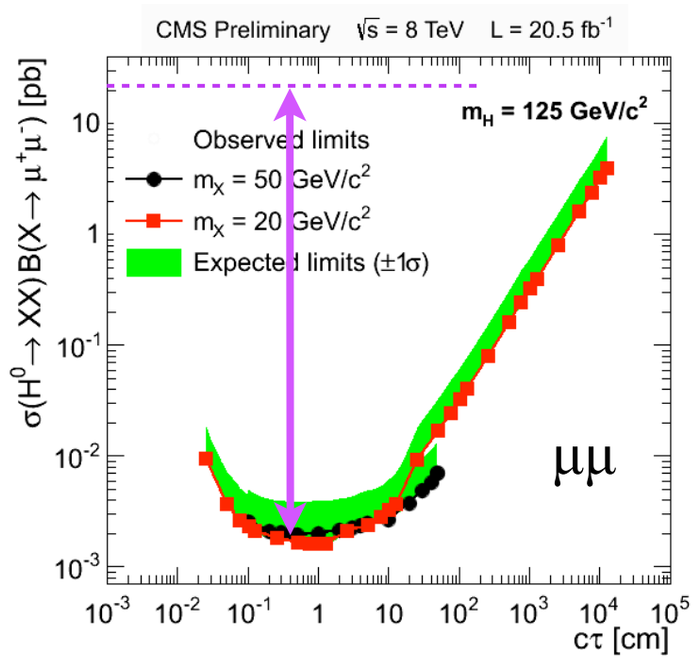
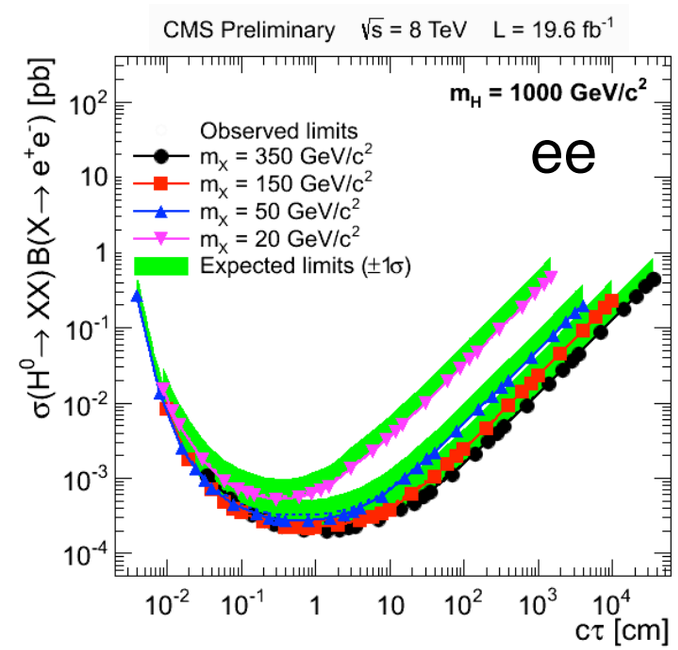
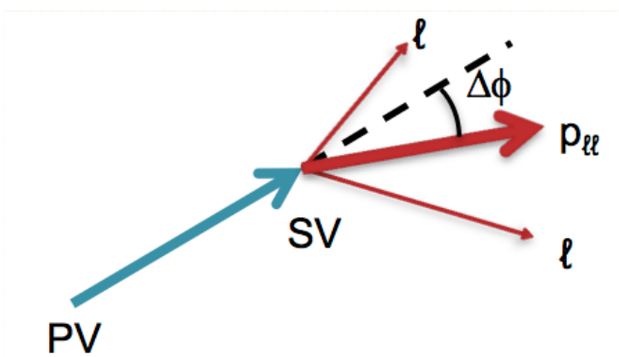
Long-Lived Particles decaying into leptons

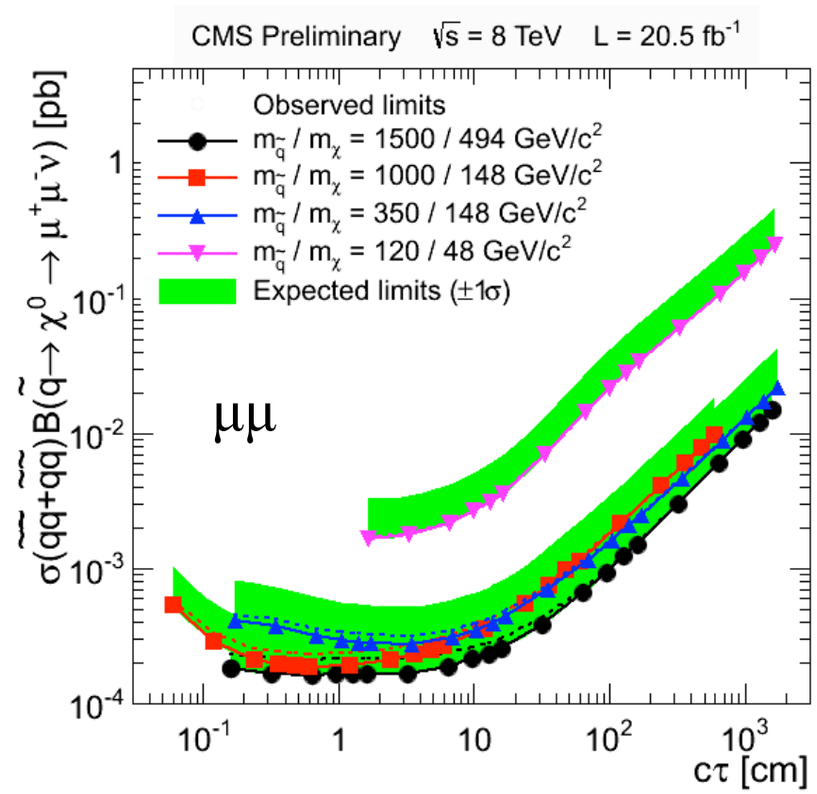
- observe no events for IP significance > 12σ, set limits

Sensitive to H(125) branchings of ~10^{-4}







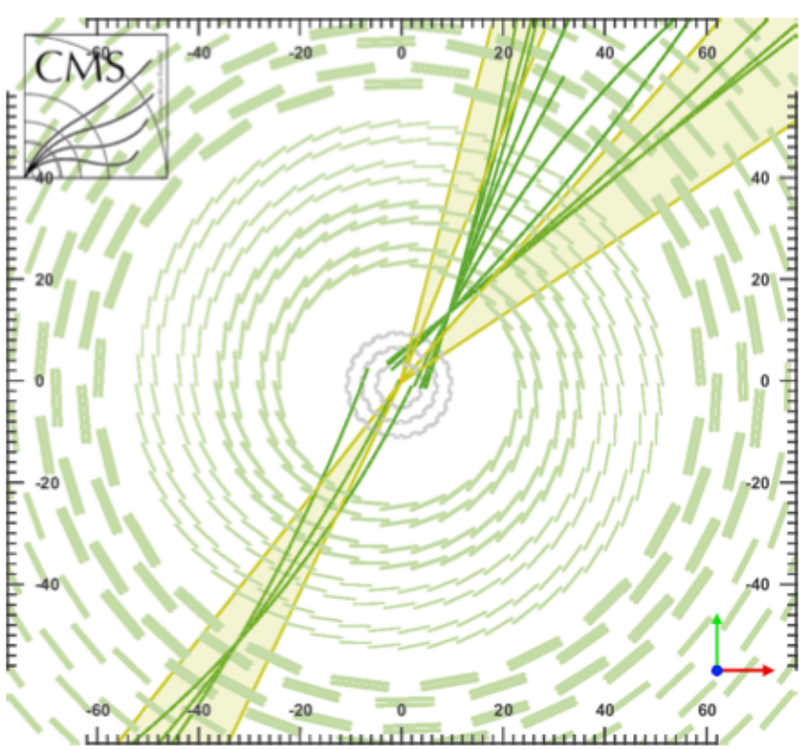


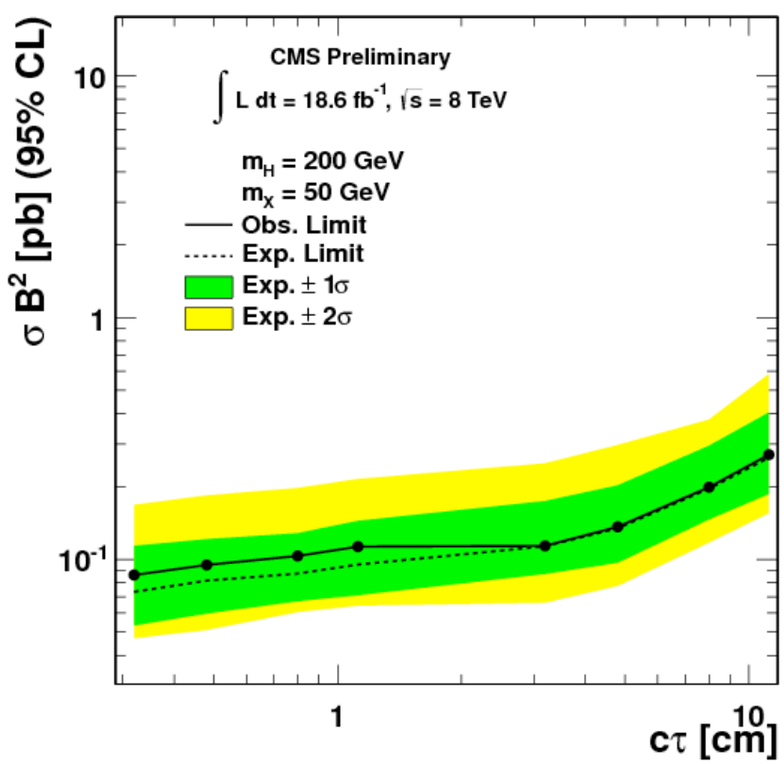
do not require tight pointing: $|\Delta\phi|<\pi/2$
excludes ~0.1-0.3 fb - i.e. tiny squark branching fractions

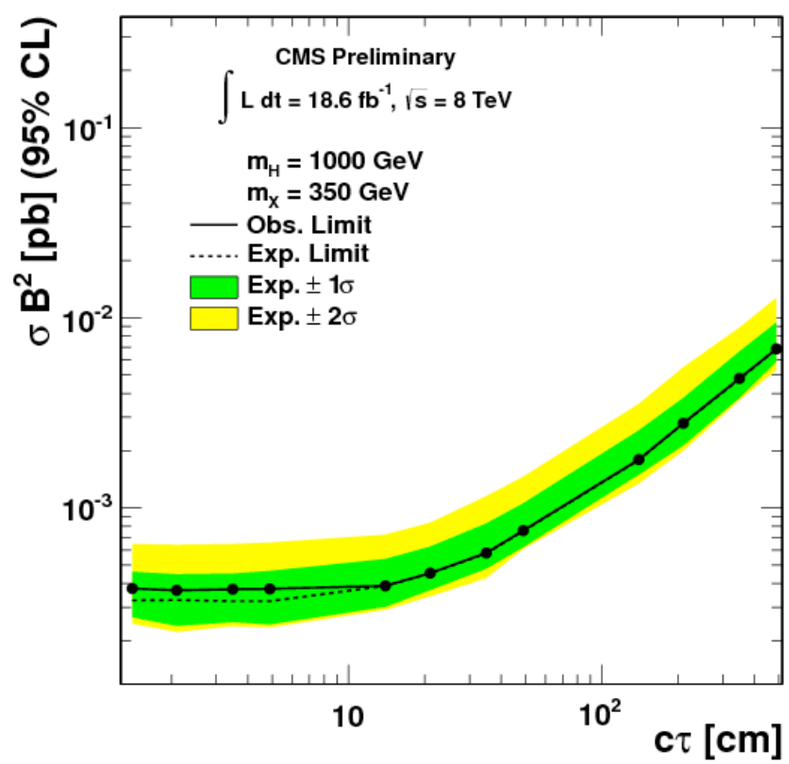
Long-Lived Particles decaying into jets

- 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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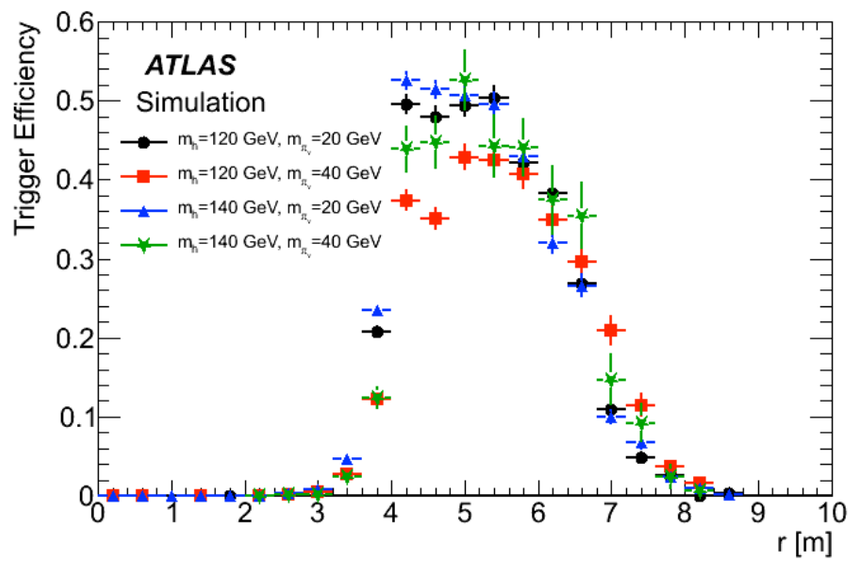
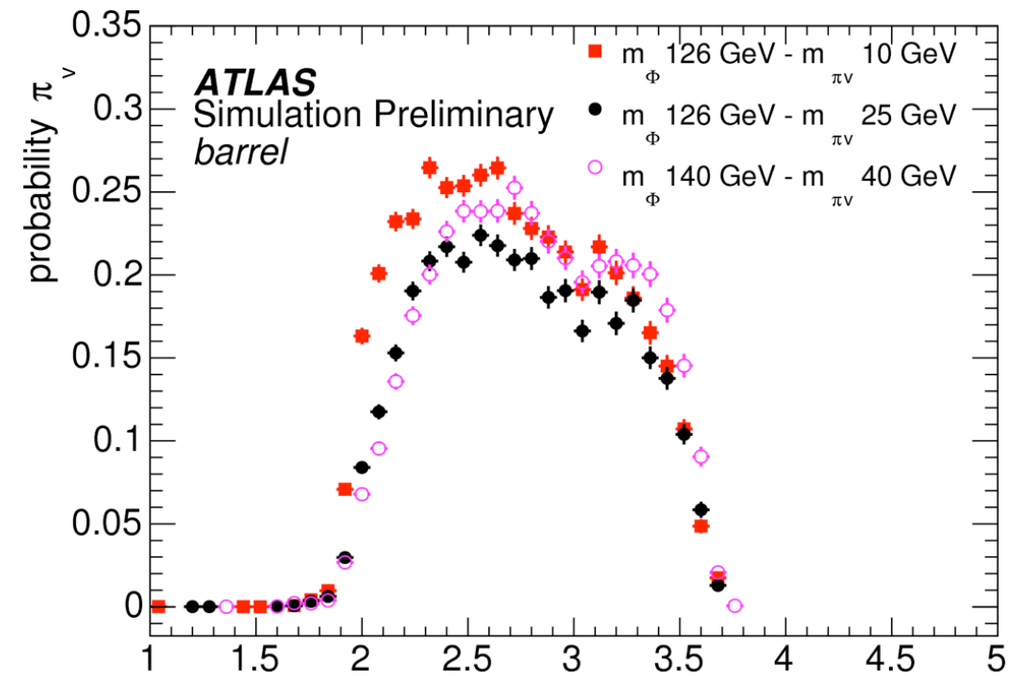
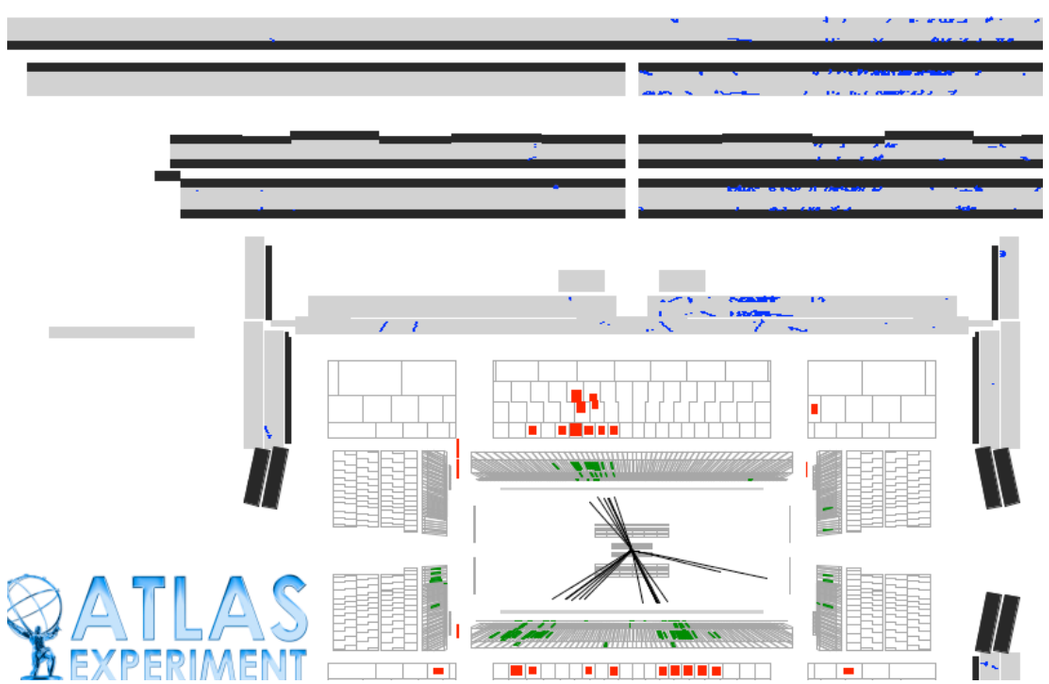
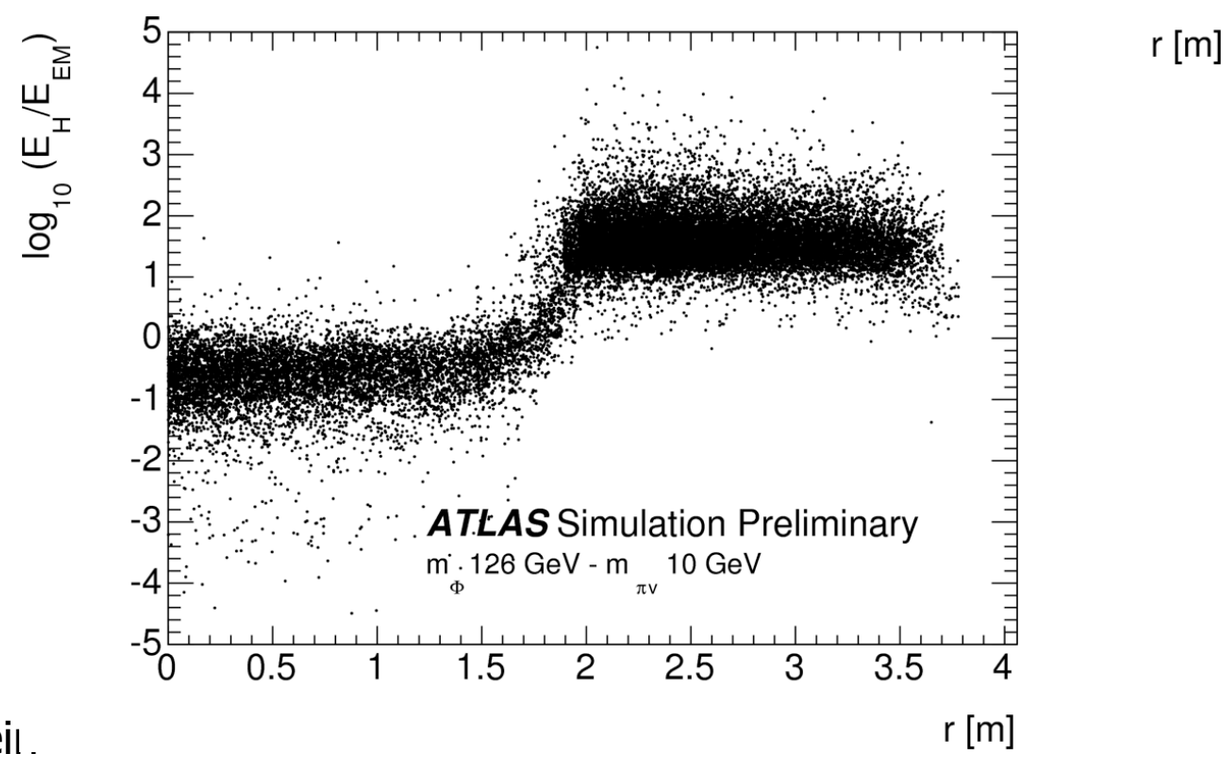
Long-Lived Particles decaying into jets

- 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

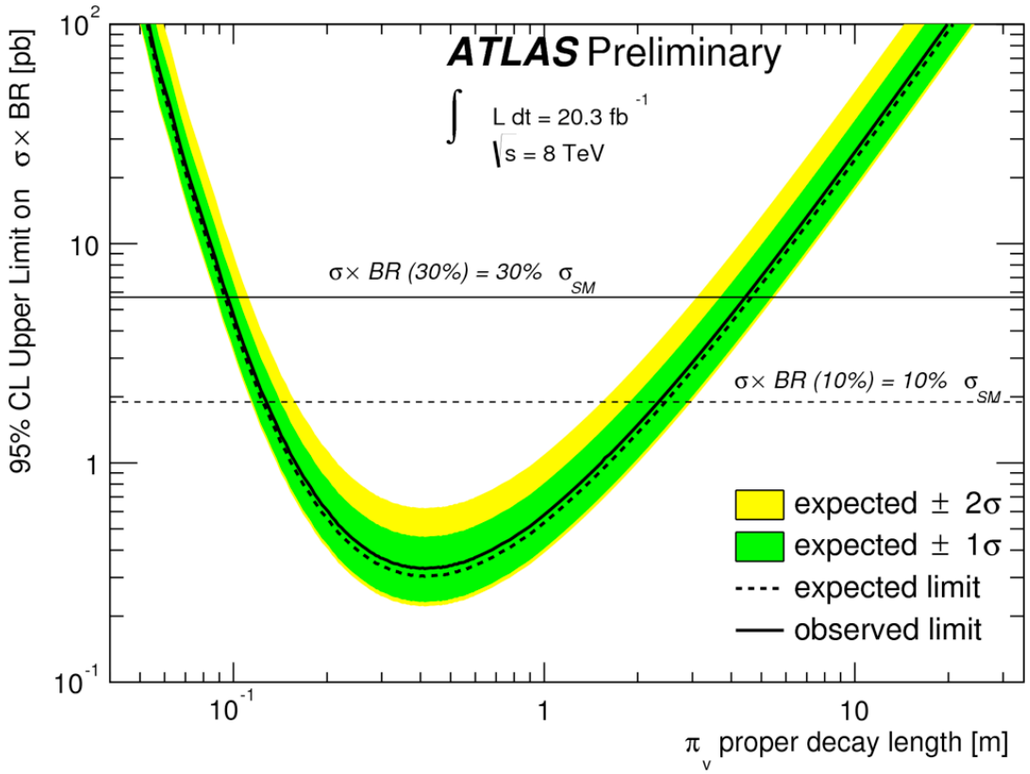


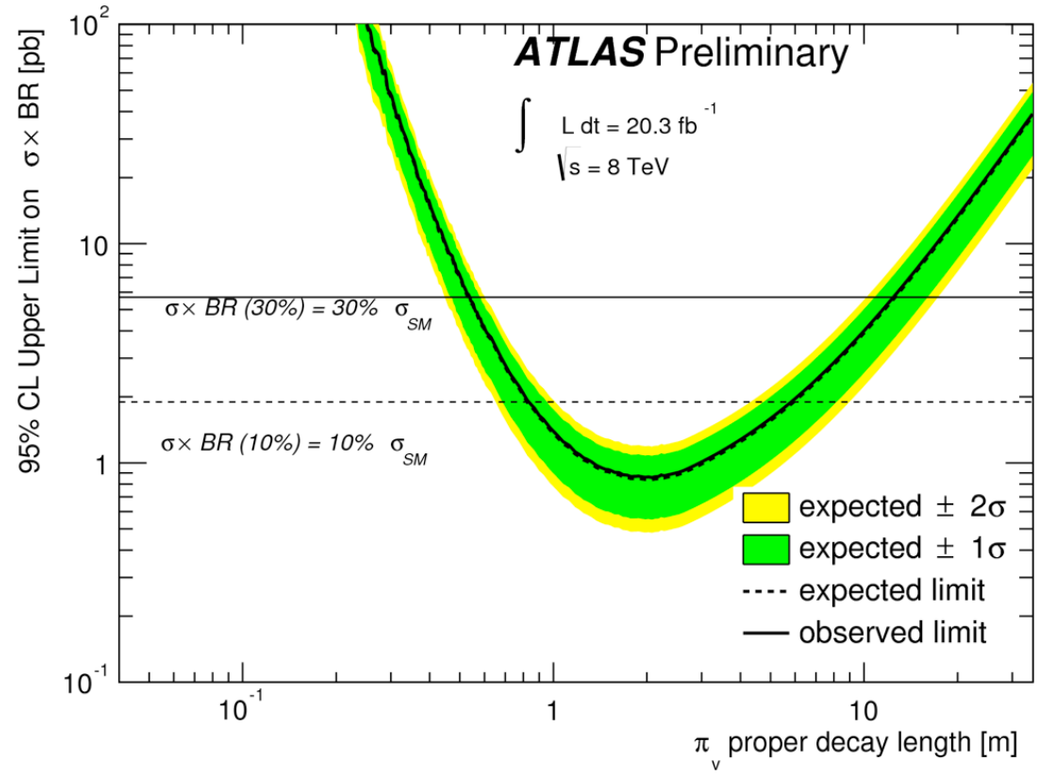


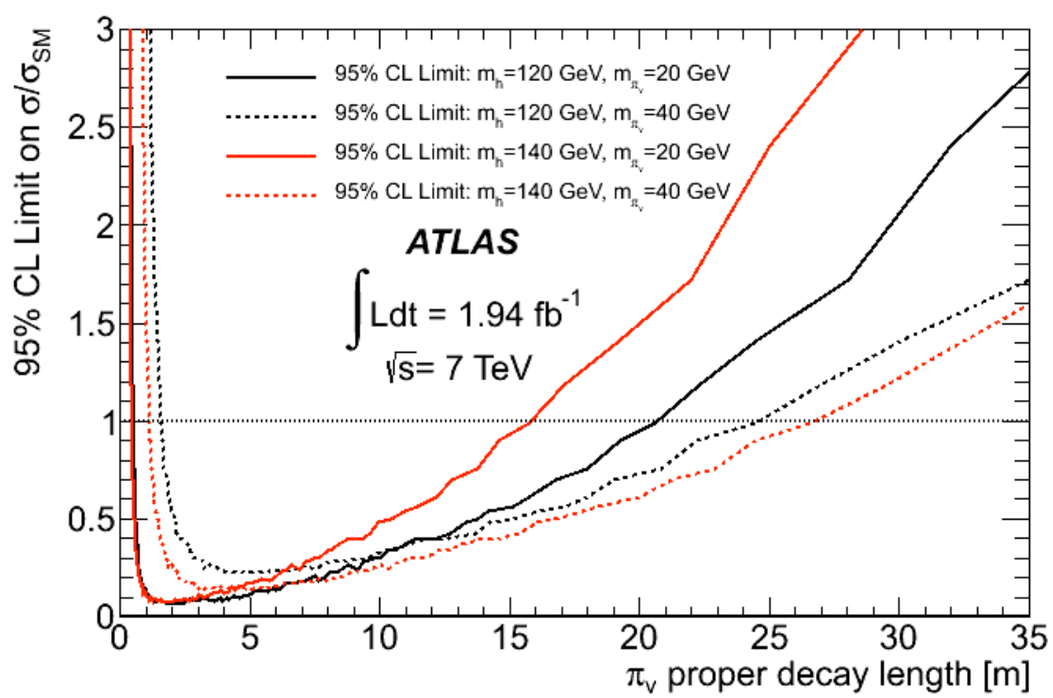




Long-Lived Particles decaying into jets





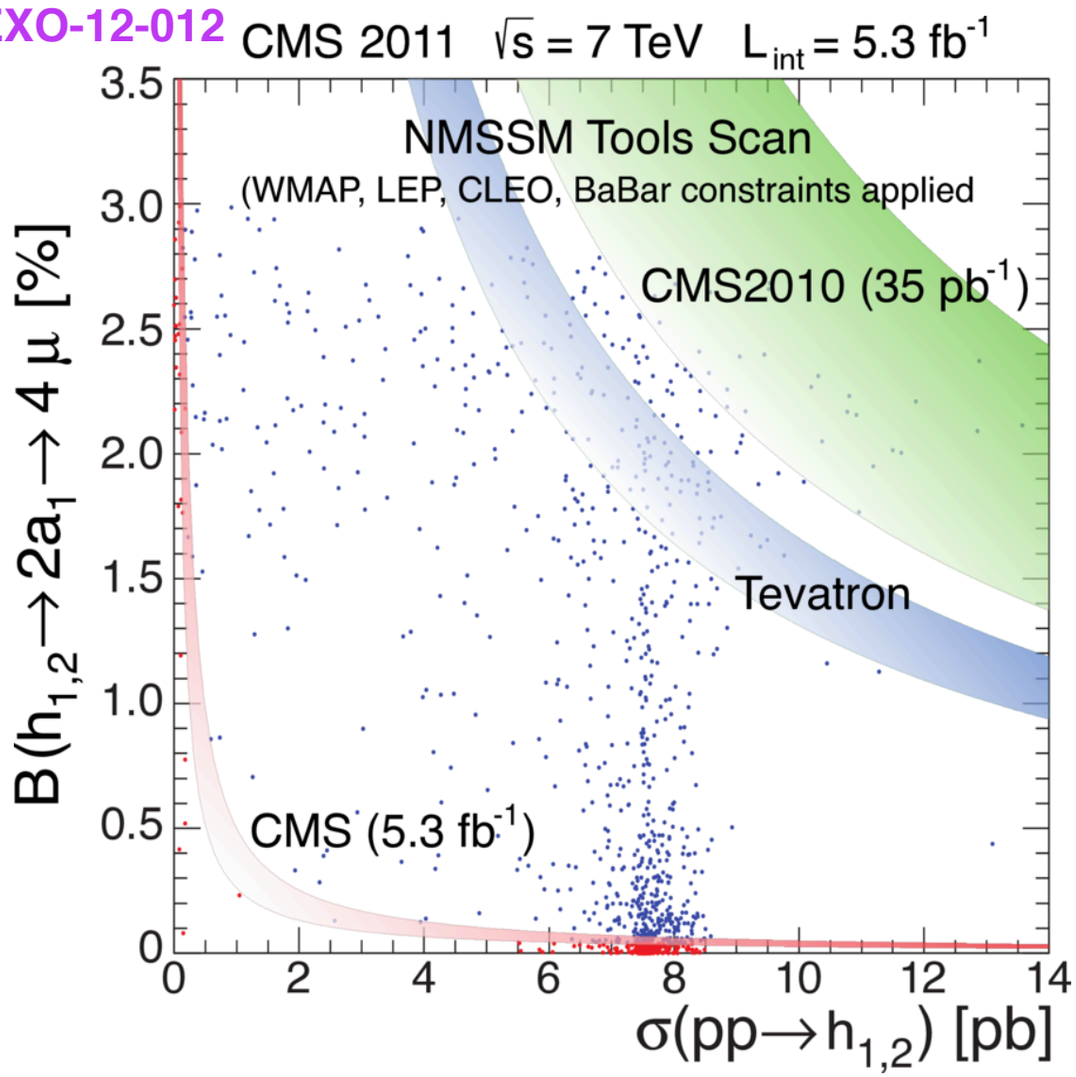


- Require two long-lived particles per event
- Most sensitivity at cτ around 100 cm and Br ~ few %
- extending sensitivity to low lifetimes is paramount

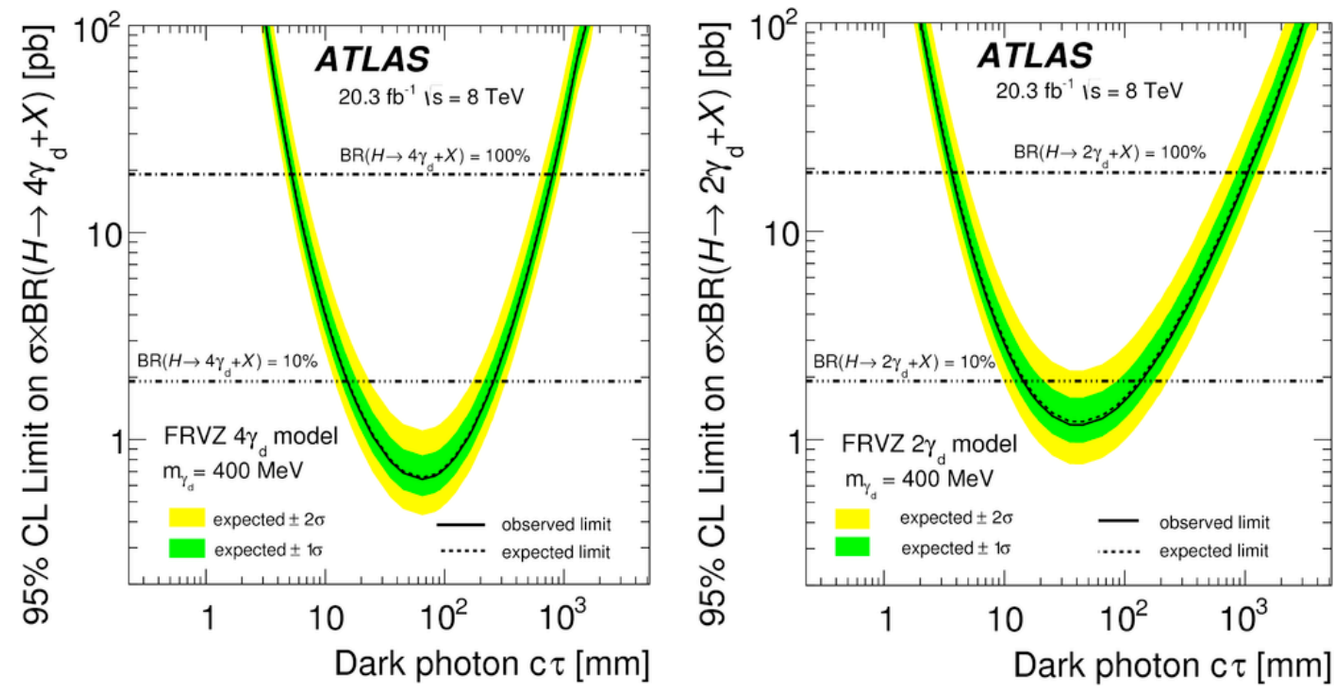
Leptonic jets

- Trigger is hard: multimuons or low EMfraction jets for long-lived dark photons decaying into electrons

EXO-12-012



arXiv:1409.0746

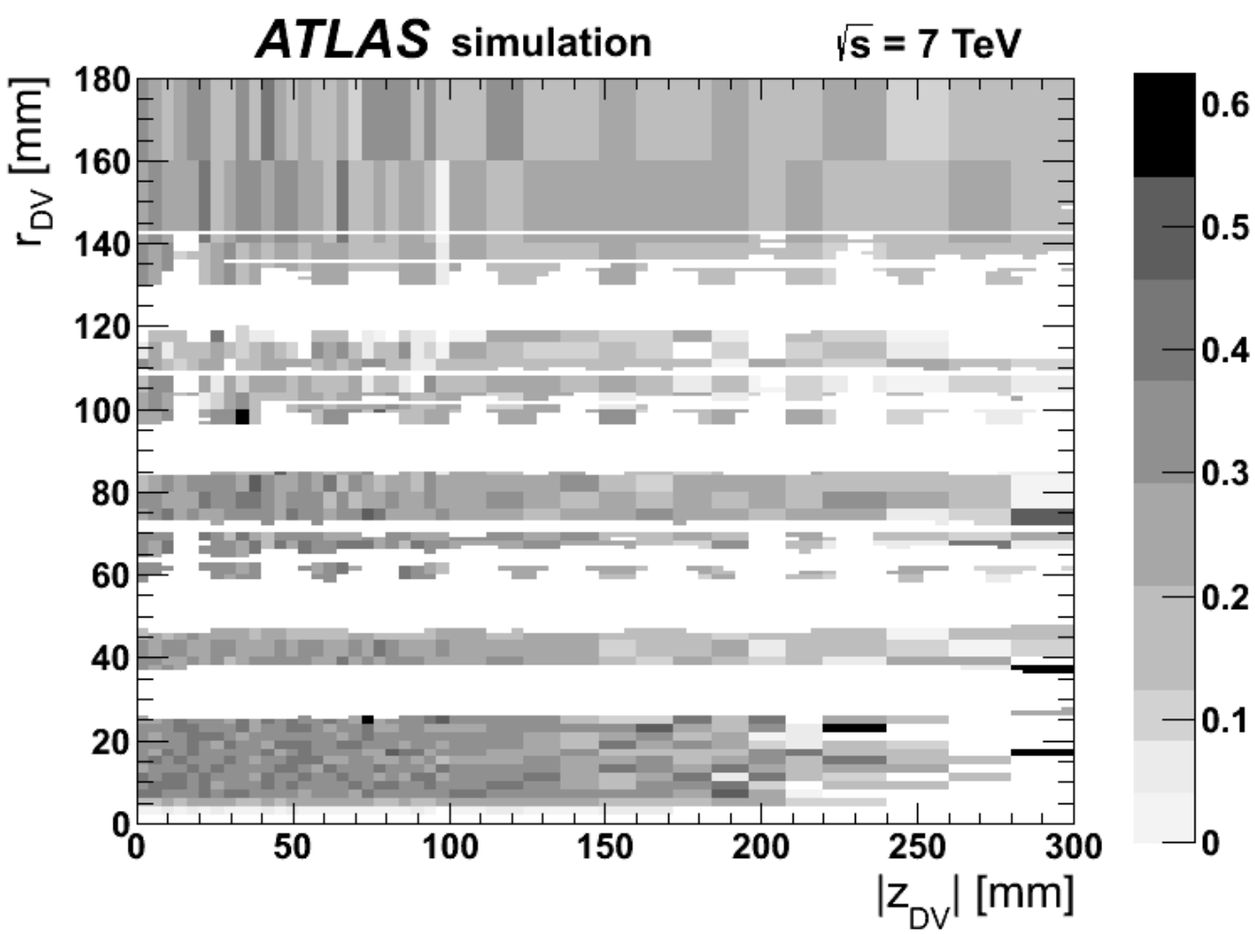


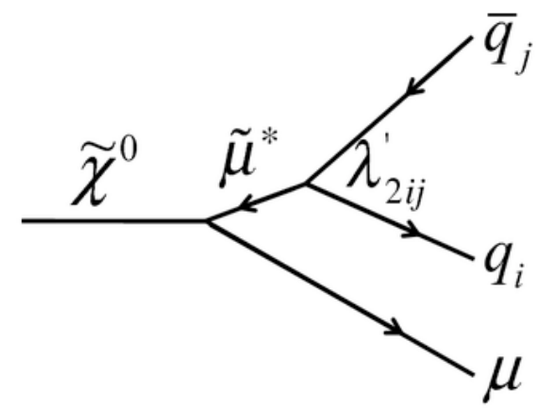
Isolated dimuons only
cτ ≤ few mm
For H(125), BR~5%

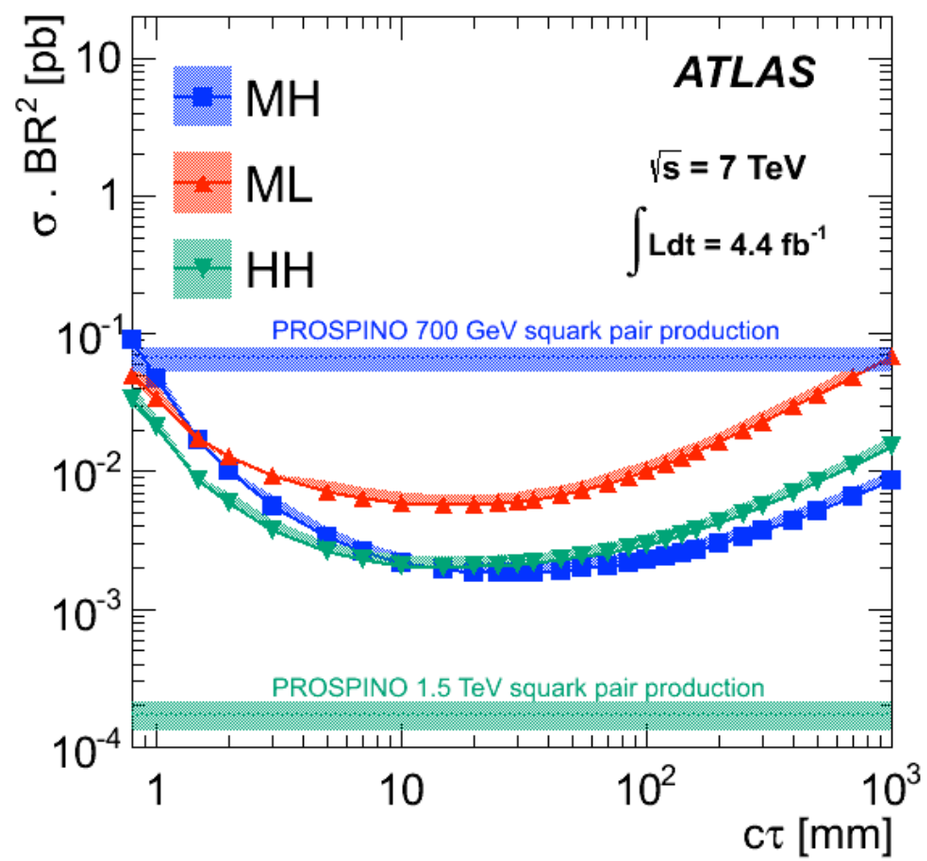
Long-lived LJ - isolated at vertex
no displaced track or SV reco
~5% BR limits at cτ ~50cm
~ little or no sensitivity to dark photon masses < 2μ threshold

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

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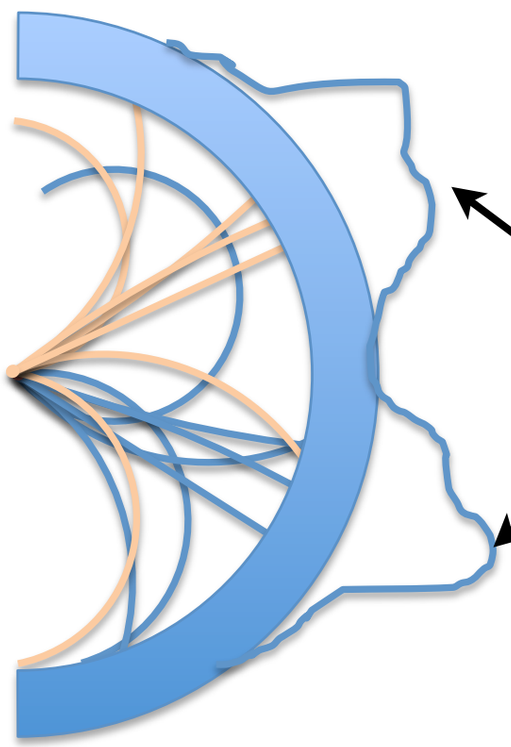
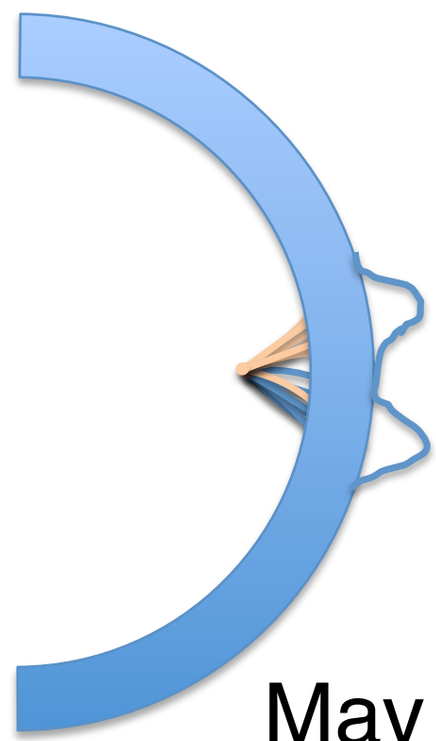
Long-Lived Particles decaying into jets

- 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

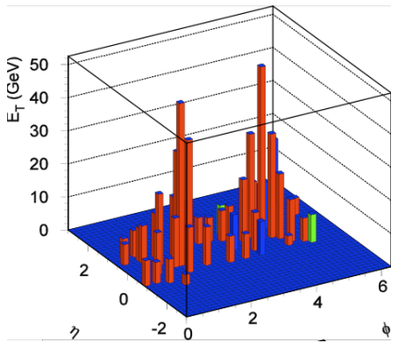


Same dijet, if displaced, now gives a very tight energy clusters

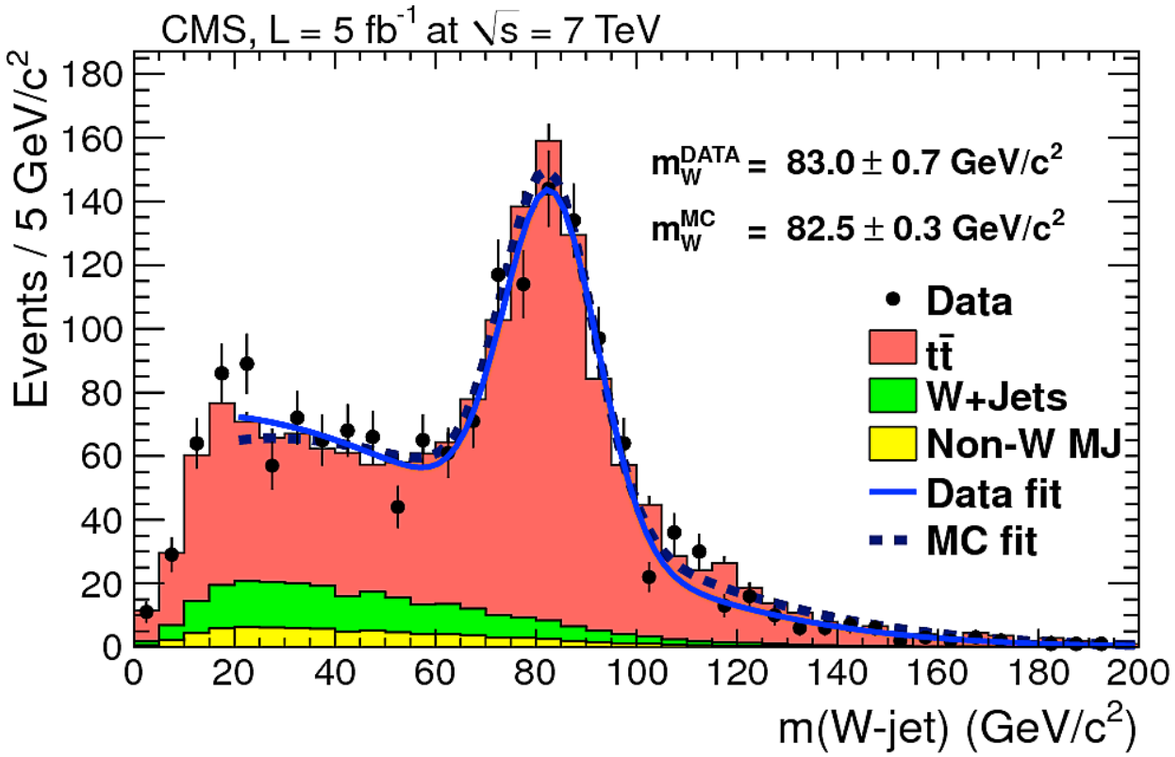
May be a good candidate for jet substructure tools

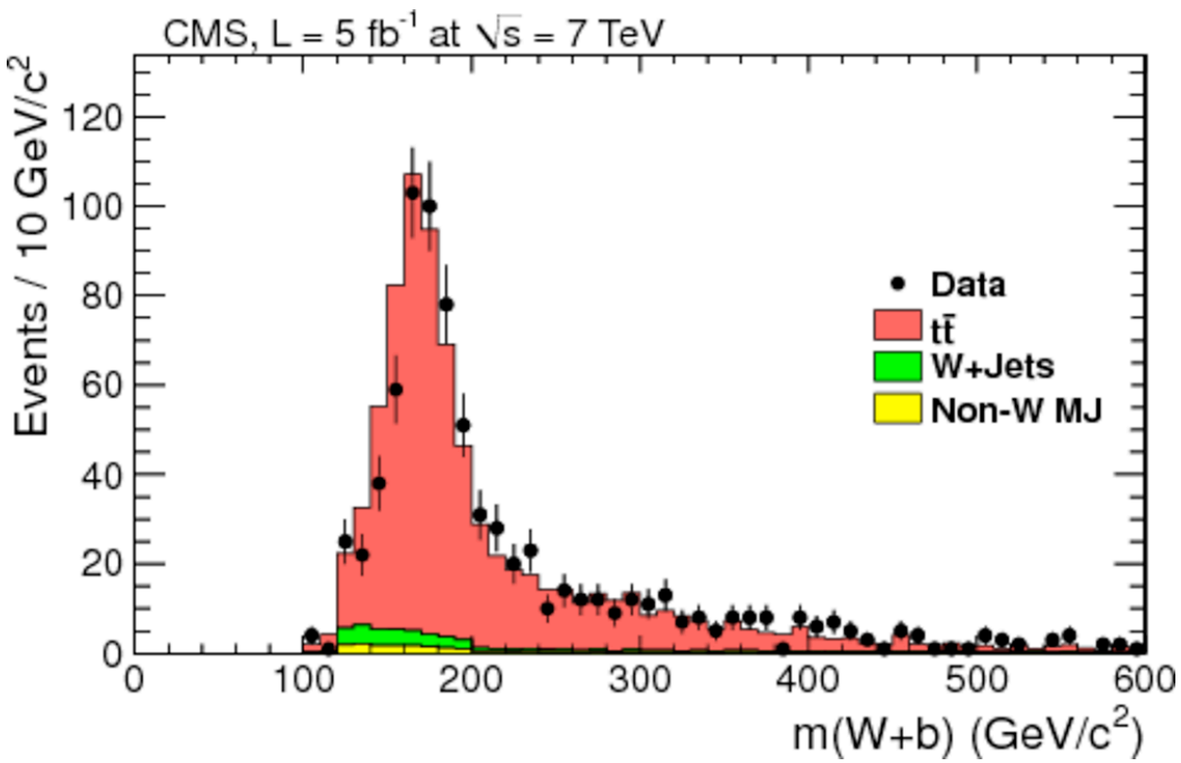
Jet Substructure

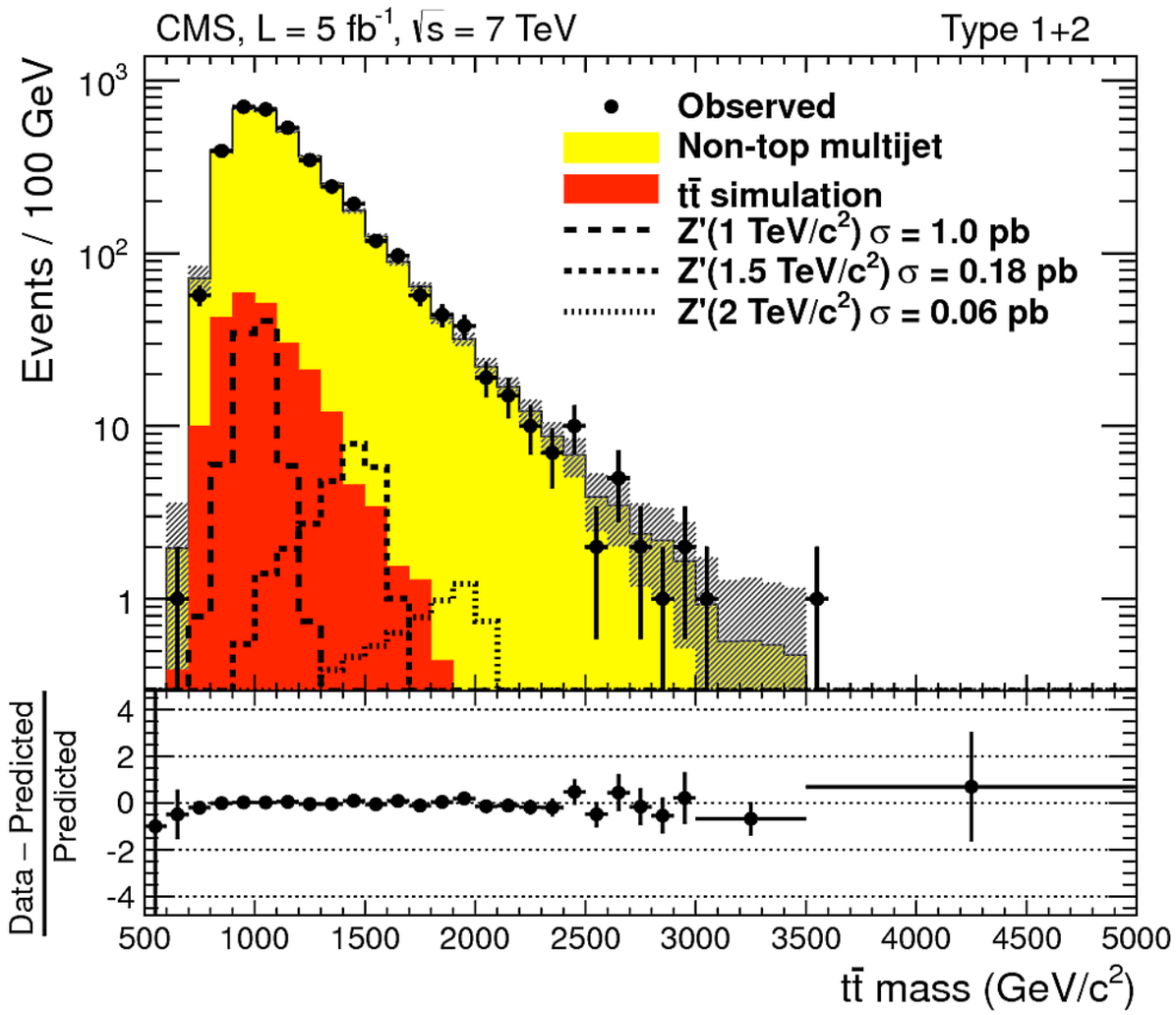
- Boosted objects
  - LHC13 is sensitive to colored particles with masses of ~2 TeV
  - LHC8 limits on electroweak particles are generally weak, not far above W/Z/H/top
  - If colored particles decay to electroweak particles (SM or non-SM) a huge boost for the latter is a general feature
- Accidental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



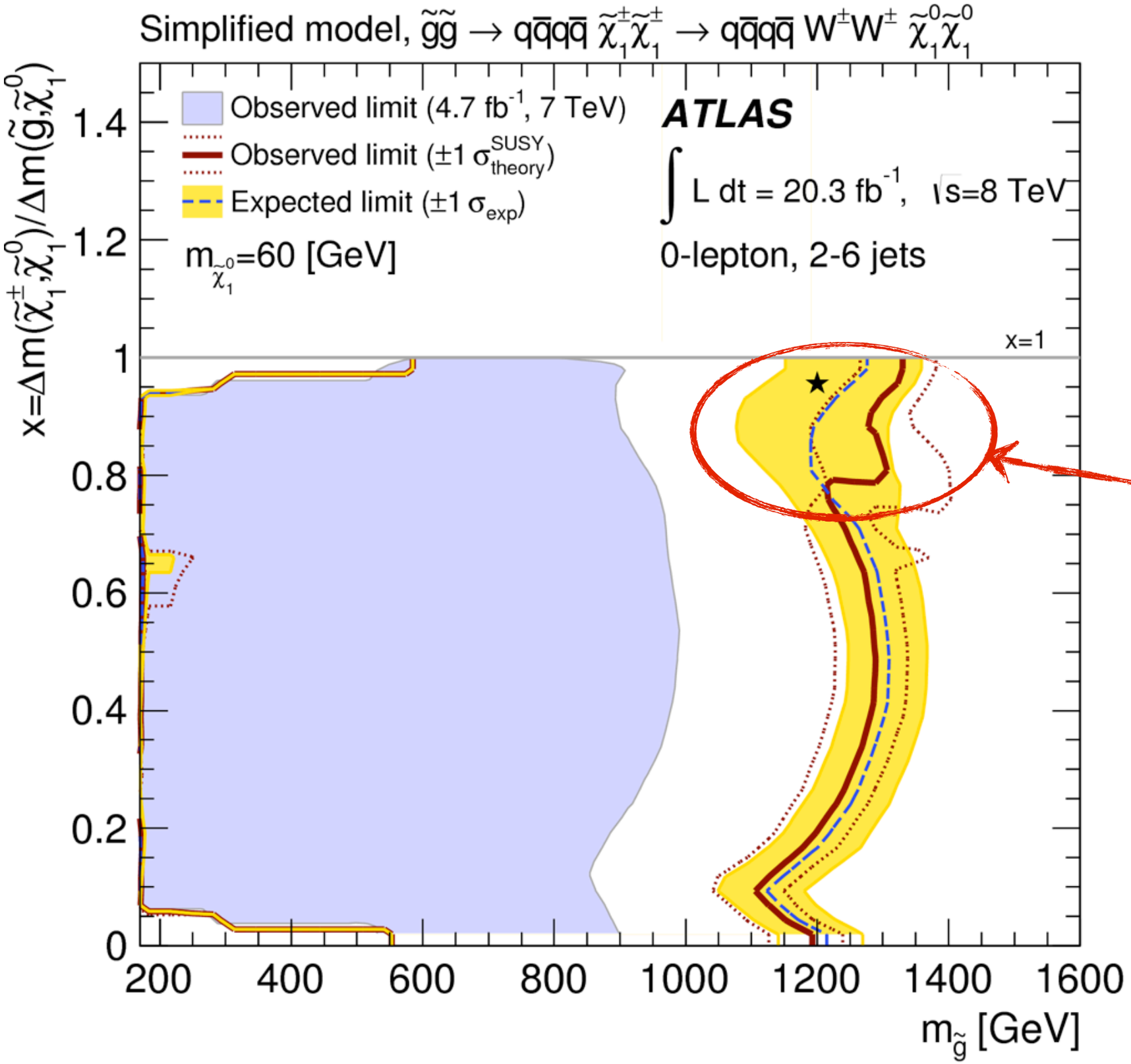
Highly boosted top

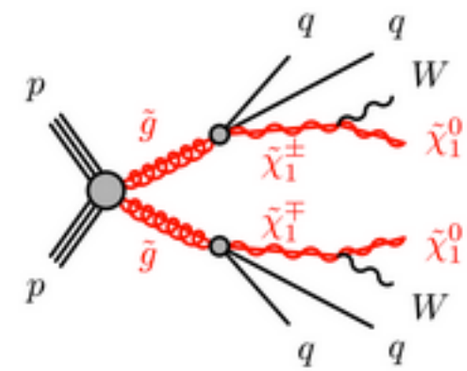






Boosted W in SUSY

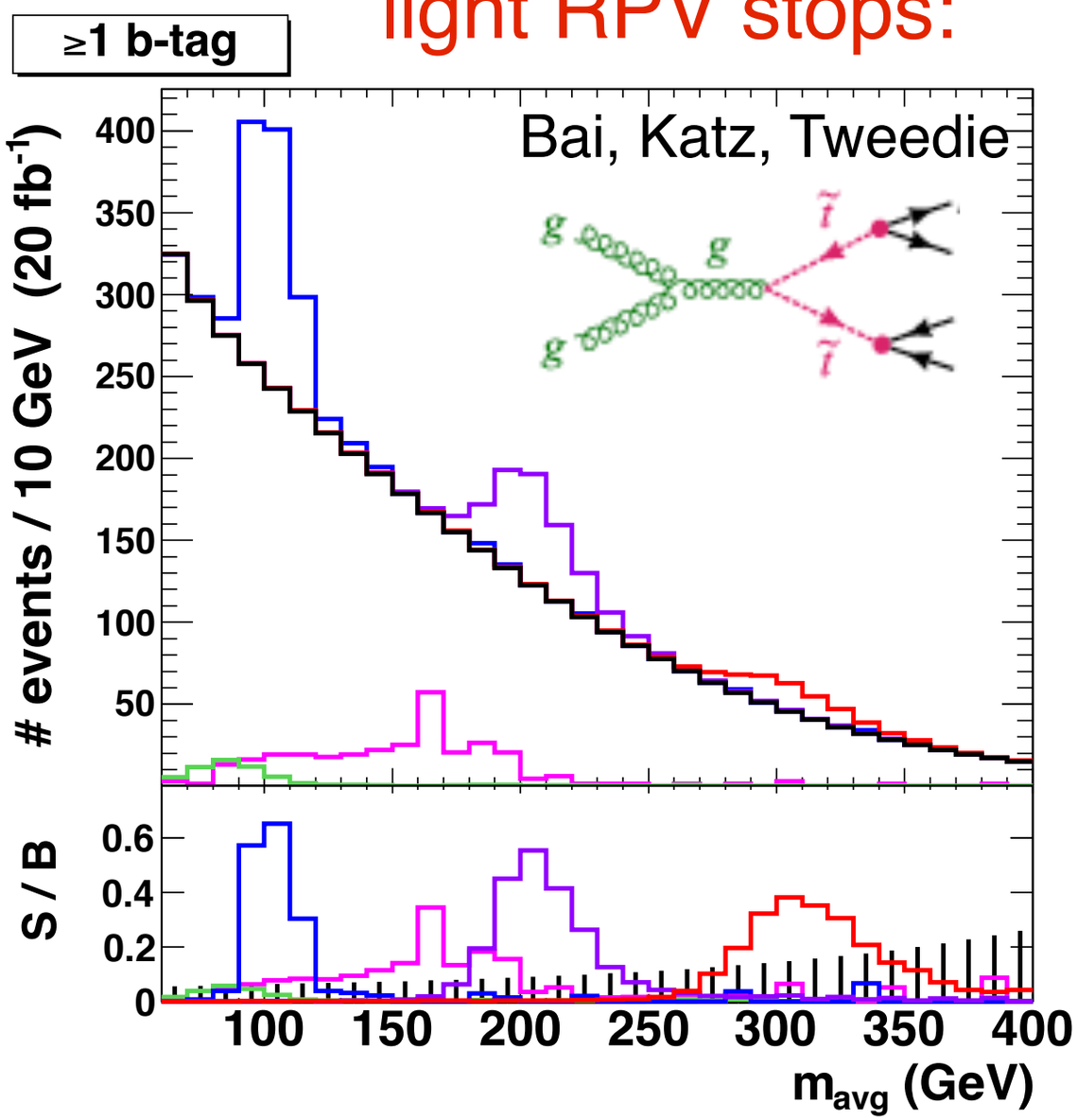




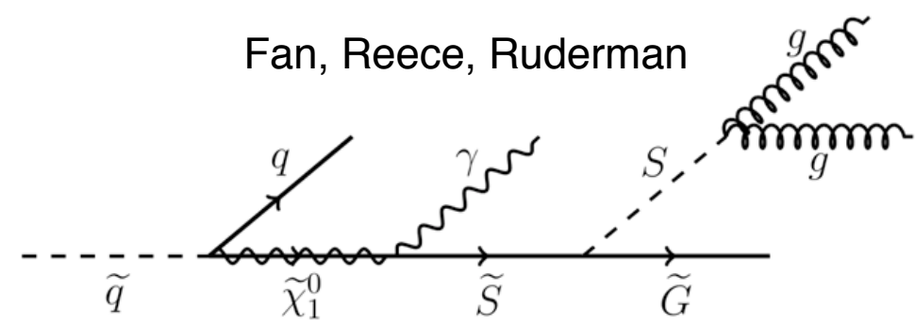
Boosted W→ jj region

How about boosting non-SM particles?

light RPV stops:



Stealth SUSY:

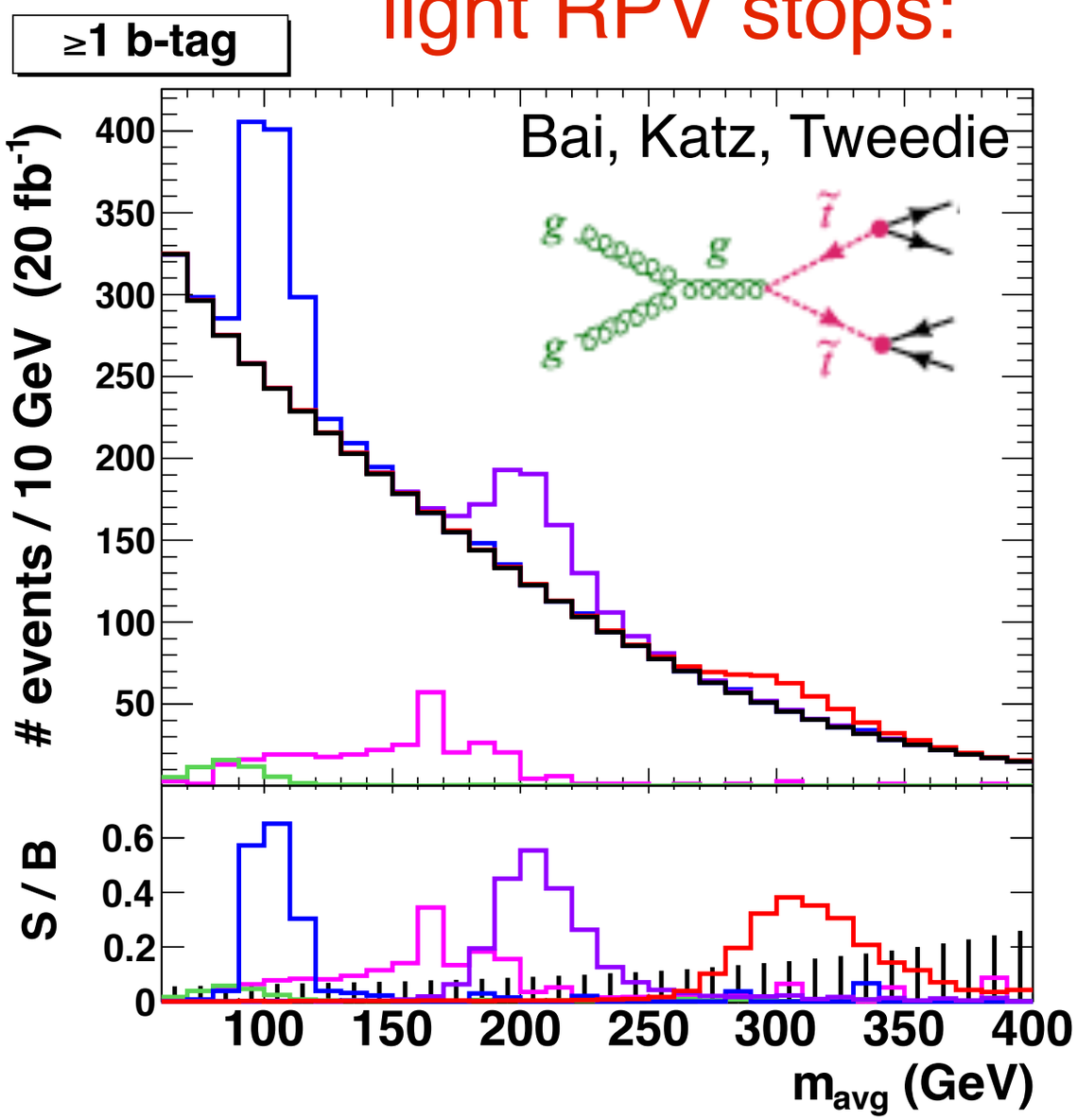


as M_{squark} limits are pushed much higher then M_S

- di-**gluon** resonances
- $S\gamma$ pseudo-resonances

How about boosting non-SM particles?

light RPV stops:



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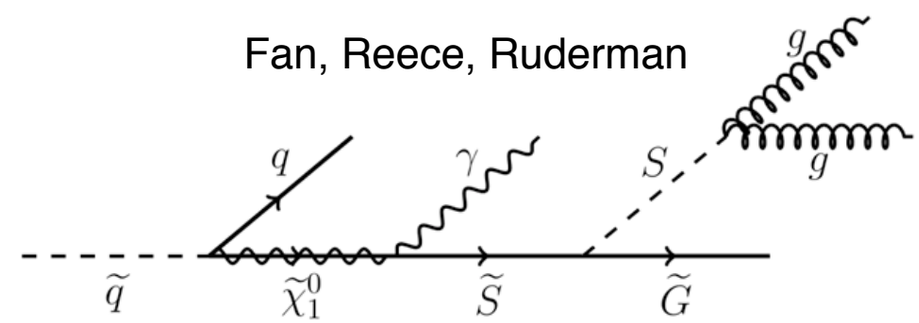

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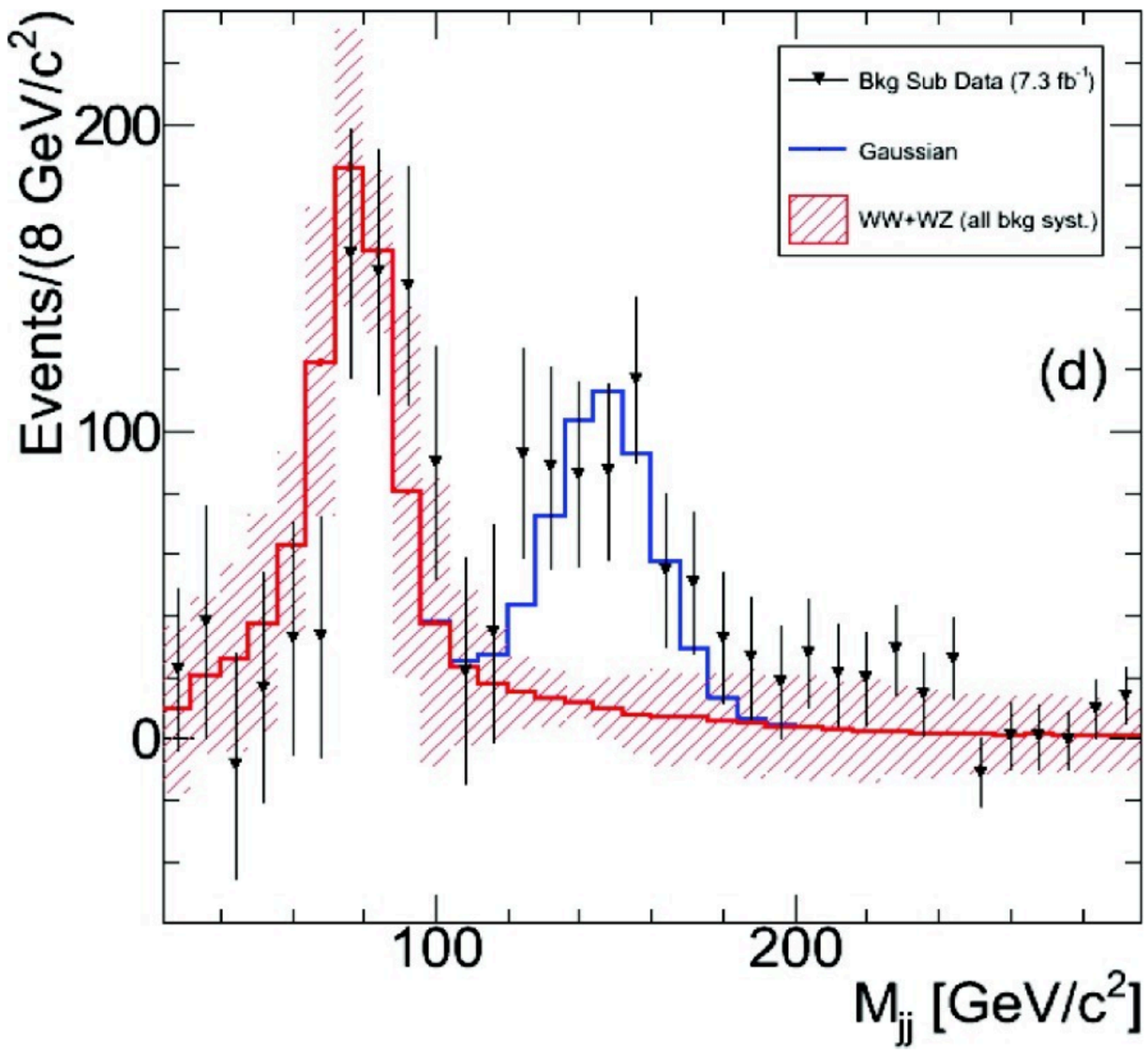
- Are we ready to believe we discovered a new particle if we see a bump in a fat jet mass at 110 GeV? Or we would think that PU cleaning and kinematical cuts we make move QCD/Z/W/h/t around?

How about boosting non-SM particles?

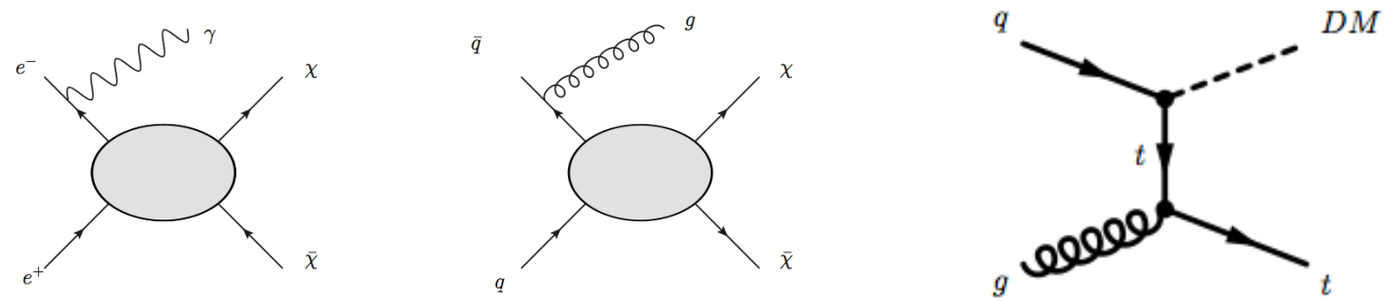


Real bump - but not new physics...

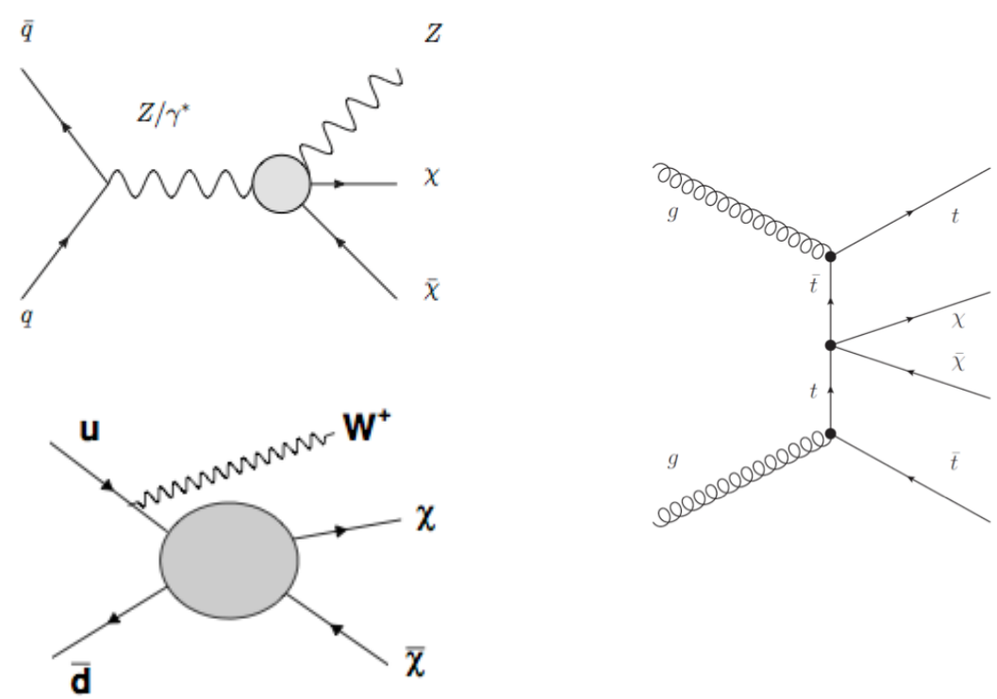
- Are we ready to believe we discovered a new particle if we see a bump in a fat jet mass at 110 GeV? Or we would think that PU cleaning and kinematical cuts we make move QCD/Z/W/h/t around?

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. $Z \to \nu\nu$)
- 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

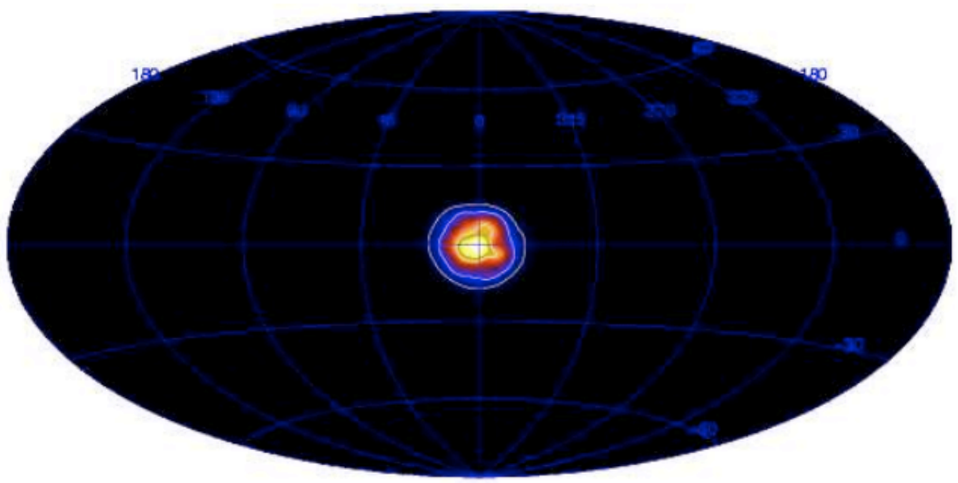
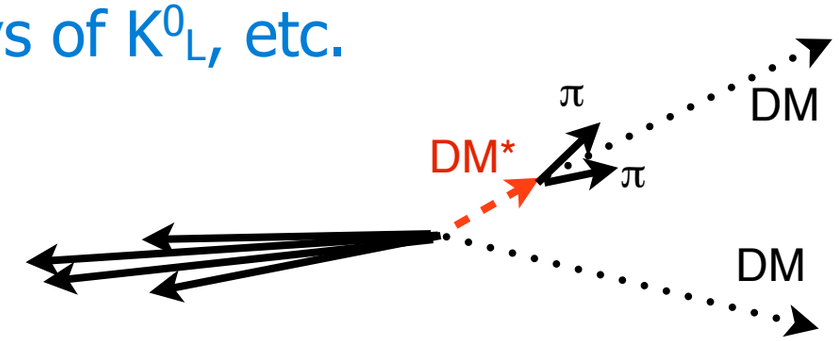


Fig. 1. A Richardson-Lucy sky map of extended emission in the summed Ps analysis intervals (the combination of the intervals 410–430, 447-465, and 490–500 keV). The contour levels indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2} s^{-1} sr^{-1}. Details are given in the text.

arXiv:astro-ph/0601673v1

Finkbeiner, Weiner: low energy positrons are coming from DM*→DM transitions

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



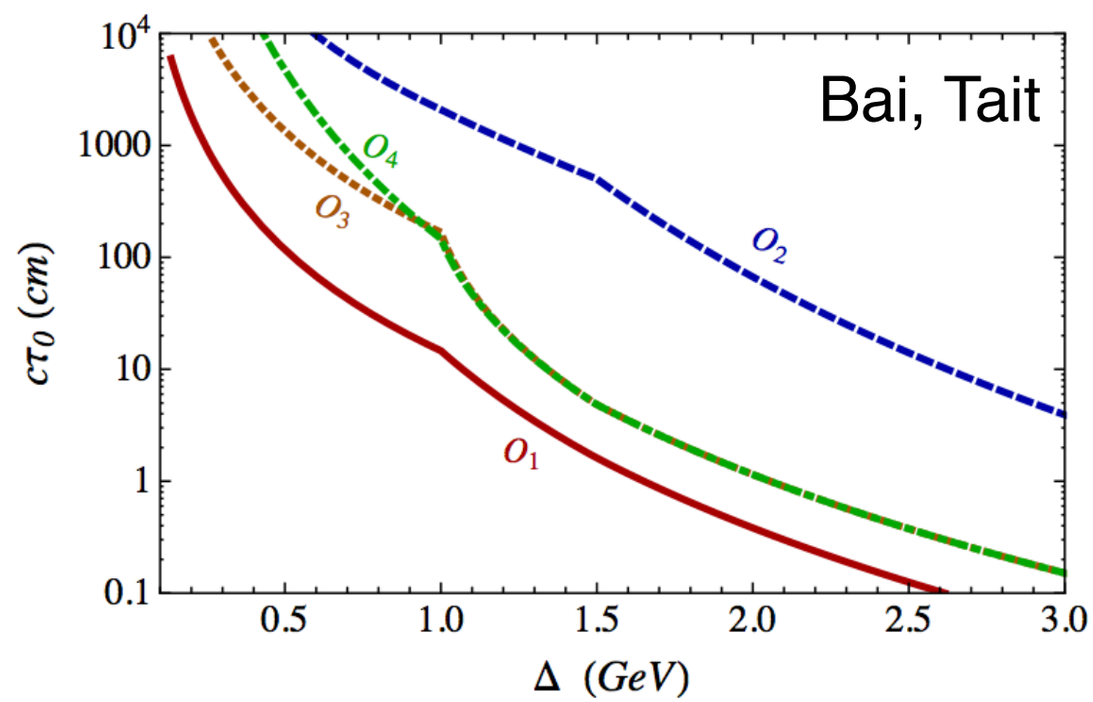
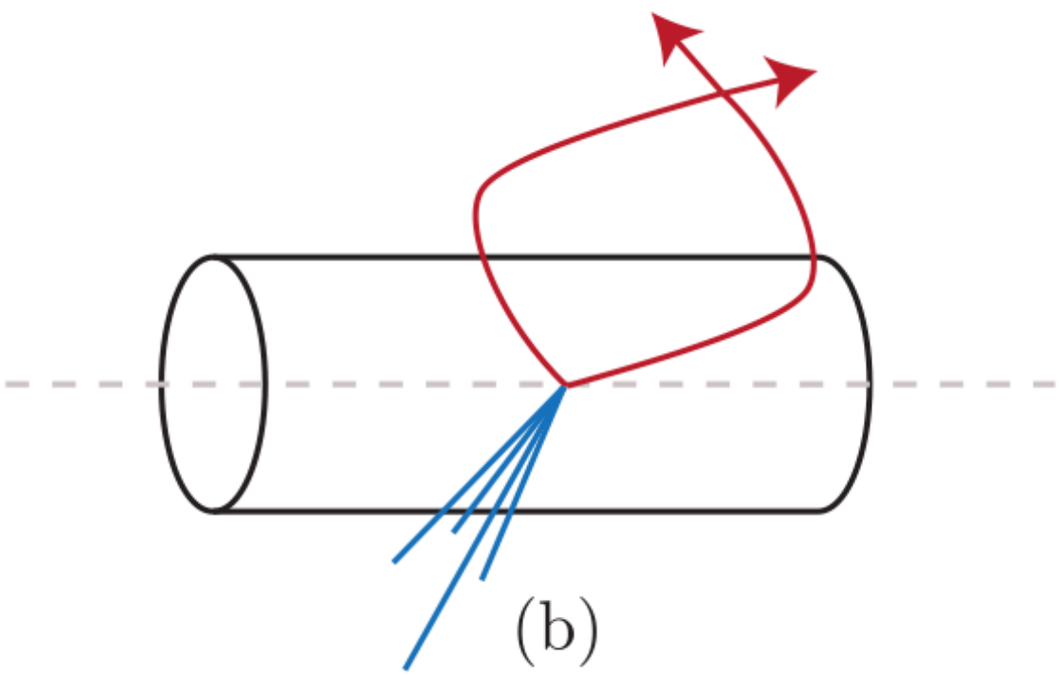


FIG. 1: Decay lengths of the excited dark matter state at rest as a function of mass splitting for different operators with $\Lambda_i = 1$ TeV and a dark matter mass of 5 GeV.

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
  - More satisfying explanation for EWSB then $\mu^2<0$
- 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
  - we may still get what we want
  - but if not - it's quite possible that we'll get what we need

Summary and Outlook

- No lack of motivation for BSM
  - Dark Matter
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  - More satisfying explanation for EWSB then $\mu^2<0$
- No clear way to know how it manifests at the LHC
  - need to keep biases and prejudices in check
- Still, it would be prudent to think about trigger strategy for HL LHC:
  - do we continue as is, with a goal of getting as much $h\rightarrow hh$ and ISR off compressed spectrum higgsinos or can **a broad program** for "not quite usual" searches be developed?
  - HL-LHC trigger upgrades are being finalized - time to design big expensive changes is running out