The Abdus Salam International Centre for Theoretical Physics

Are we ready for LHC Run 2?
(Selected, biased, musings on the topic)

Christopher S. Hill
The Ohio State University

Disclaimer: In this talk, CMS material is primarily used (solely for my convenience), this is not intended as a slight to ATLAS, nor does it indicate this is a CMS talk (it is not)

As far as LHC machine & Experiments' Detectors concerned, answer is "easy" … yes

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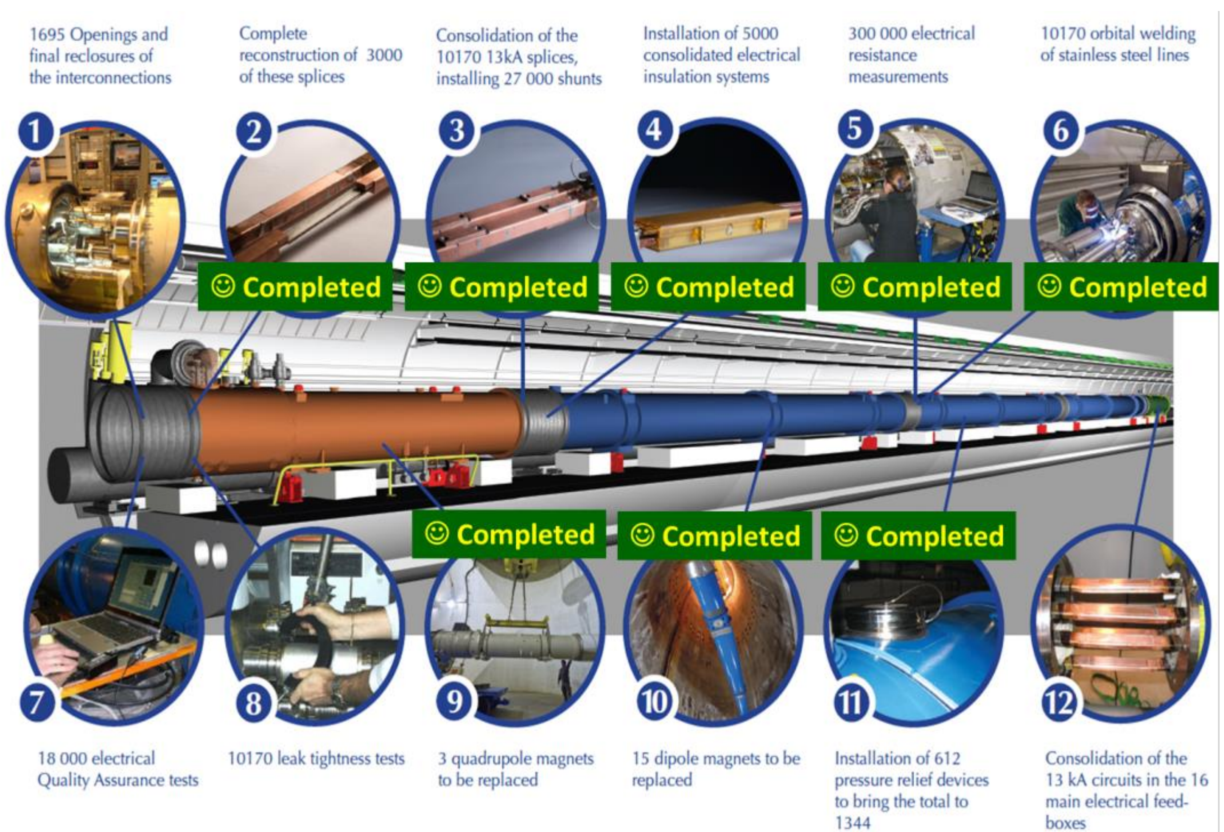
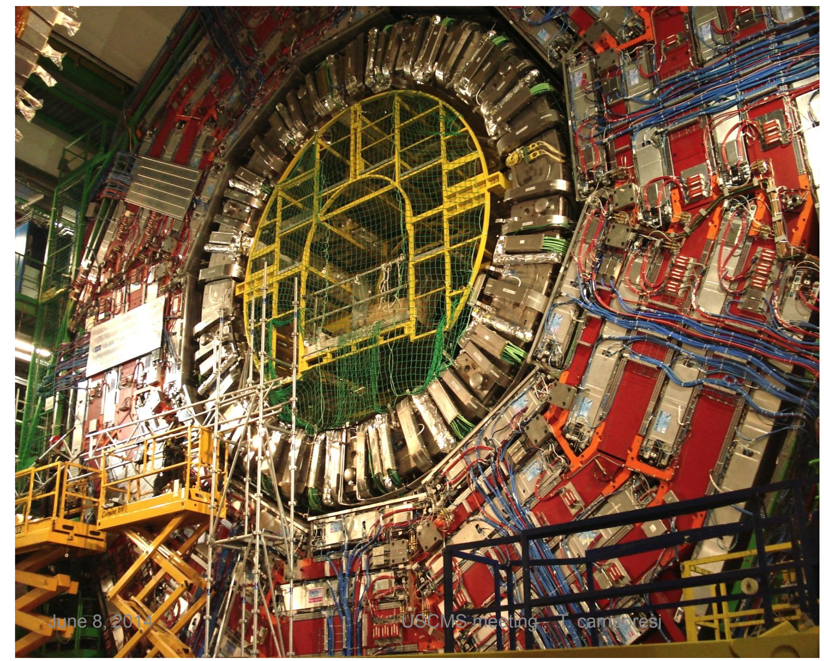
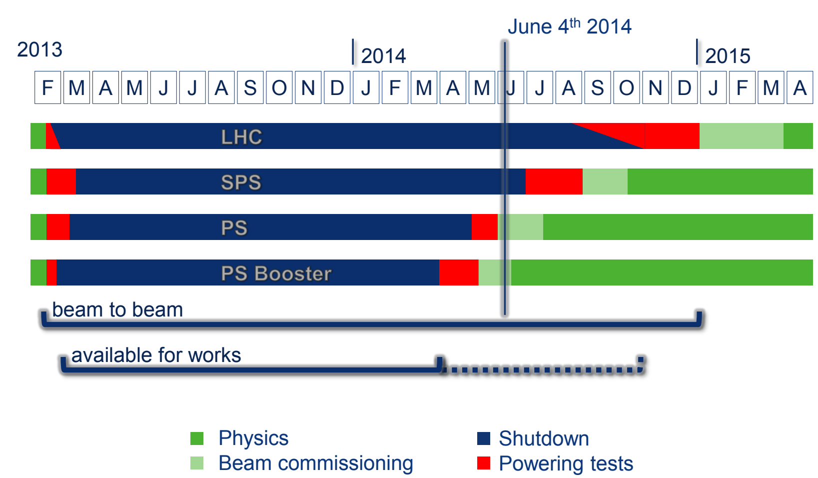
- Despite a lot of LS1 activity (not by any means easy) upgrades to both machine and detectors' are **on schedule**
- Can expect physics beams ~April 2015







But that wasn't what I meant. I meant are we ready for the data when it comes next April?

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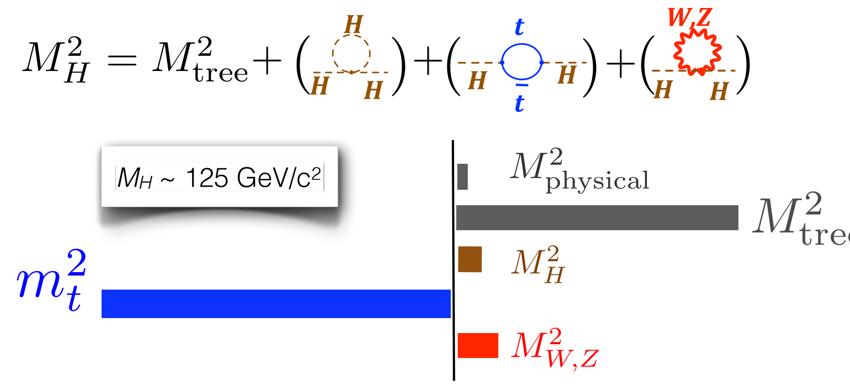
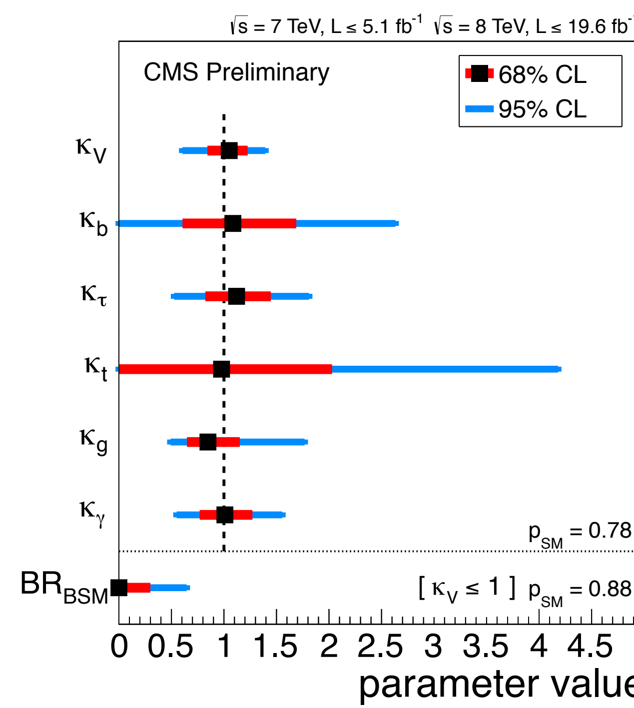
- So let me ask another question - what are the IMO the primary goal(s)* of LHC Run 2?
  - *Find the "natural" solution to the hierarchy problem*
    - **Direct evidence by observing BSM states**
    - **And/or increasingly precise measurements of Higgs properties**
  - *Conduct searches in a way that if do not find any such solution can draw (some) conclusions about correctness of naturalness arguments*
    - **No loop holes!**





*Note, for the purposes of this talk I am considering dark matter discovery a secondary goal

Look at each one of these goals a bit more

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- Precision Higgs physics
  - *We will "simply" repeat existing measurements with larger datasets*
    - **Some triggering challenges, but these have been/being addressed in LS1**
  - *So here we are basically ok*
  - *However, precision will not be particularly great until end of ~2030 and the end of HL-LHC, i.e 3000 fb^{-1} (see table below which lists the projected uncertainty on each of the couplings for Run 3 and Run 4/HL-LHC)*
    - **So by end of Run 2 (~100 fb^{-1}) which I don't have the numbers for, whether we see BSM effects in these measurements or not is far from a foolproof plan**

	L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$
Run 3	300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]
HL-LHC	3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]

Look at each one of these goals a bit more (cont.)

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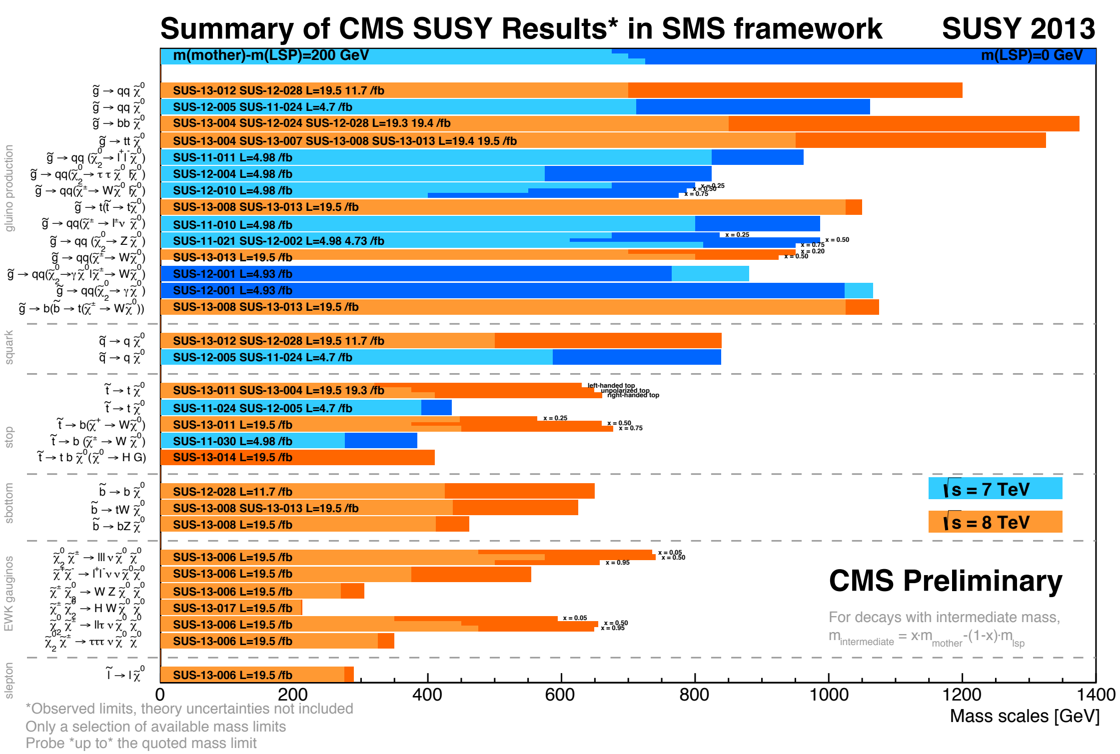
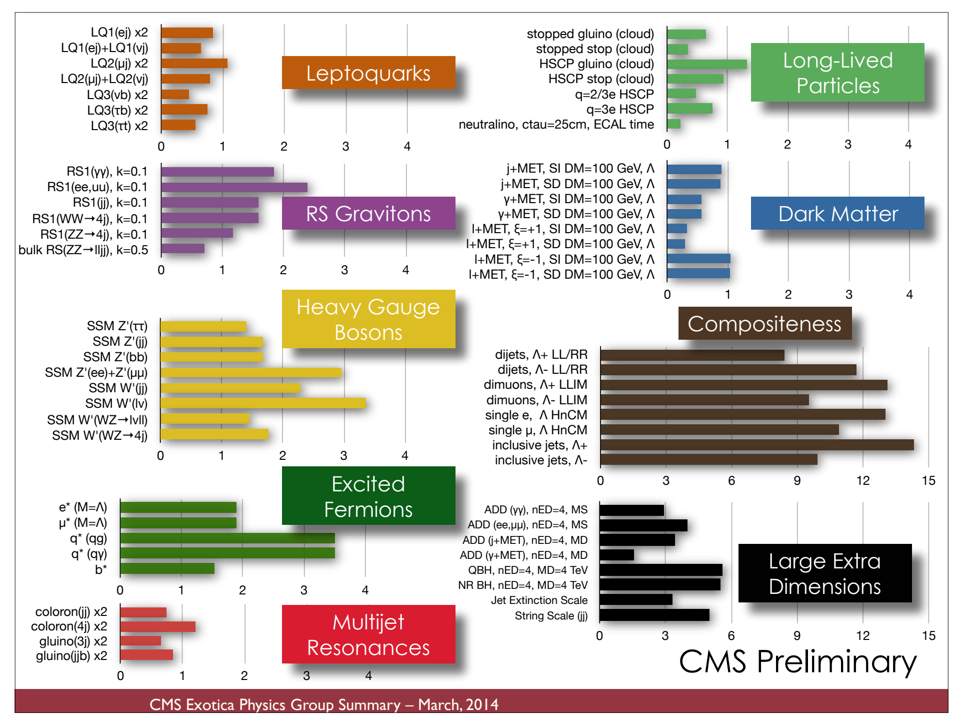
- Direct evidence for BSM particles
  - *Have performed many (unsuccessful) searches already in Run 1 - see below*
  - *Unsuccessful searches necessarily move the target, so **repeating it** in the same exact way is **not what you should do***
  - *So where is the target now?*



Gluinos >~ 1300 GeV, Stops >~ 600?



Exotics >~ 2 TeV?

Not so easy to tell from these summary plots …

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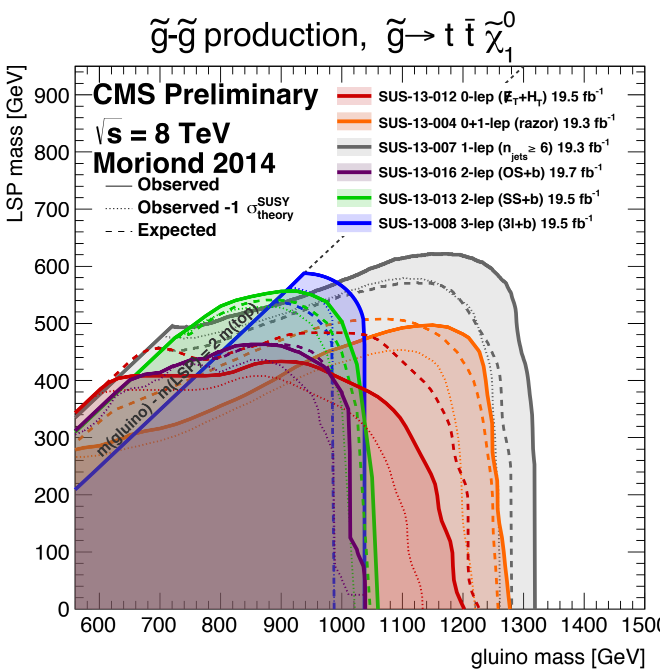
- Make a number of assumptions, e.g. for SUSY:
  - *Assumes an LSP mass*
    - **For some regions of phase space bounds degraded or do not apply ("compressed spectra")**
  - *Assume a BR (usually 100%)*
    - **For BR < 100% direct bounds are degraded, but**
    - **Indirect bounds from correlated BR into other states could increase constraints - but these are ignored**
  - *Assumes BSM particles decay promptly (no lifetime)*

But still not crystal clear what exactly has been completely, i.e. with no loopholes, excluded

Adding LSP mass as 2nd dimension helps a bit



Showing constraints in BR plane as triangle helps even more

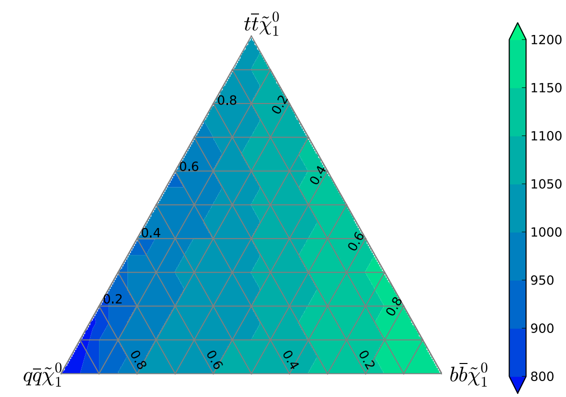


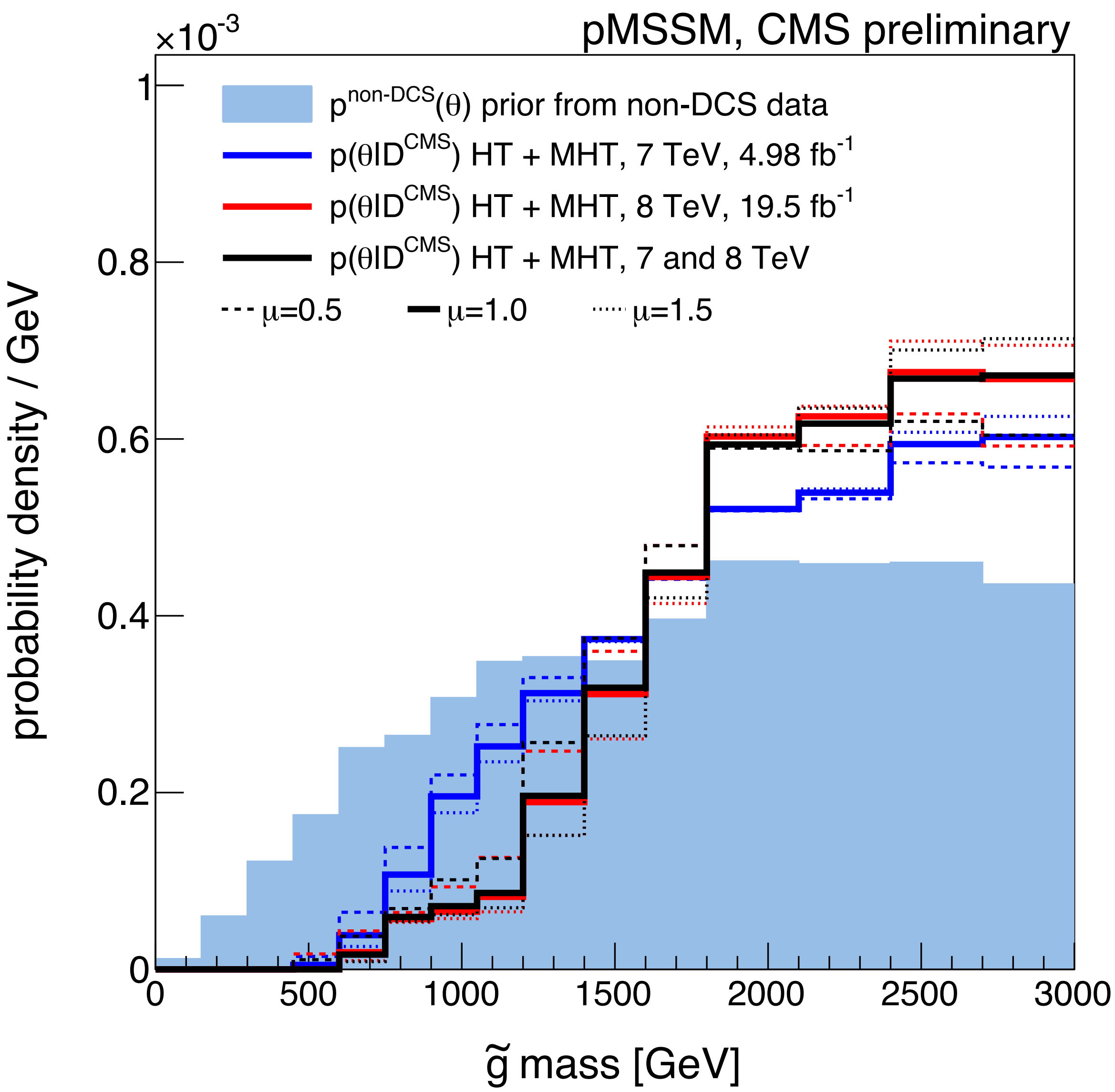
Figure 2: The interpretation of CMS analysis Ref. [6] for benchmark points with various combinations of decay branching fractions of the gluino to $b\bar{b}\tilde{\chi}^0$, $t\bar{t}\tilde{\chi}^0$ and $q\bar{q}\tilde{\chi}^0$. Each point in the above triangle has a unique combination of the three branching fractions and the vertices represent the simplified models with 100% branching fractions into the three final states.

http://arxiv.org/abs/arXiv:1403.4294

Another approach (pMSSM scans)

- Scan over LHC accessible (subspace) of pMSSM
- For each point, compute probability densities before and after CMS results
- Compare these distributions
    - *gluino masses disfavored below 1200*

$$-3\,\mathrm{TeV} \le M_1, M_2 \le 3\,\mathrm{TeV}$$
$$0 \le M_3 \le 3\,\mathrm{TeV}$$
$$-3\,\mathrm{TeV} \le \mu \le 3\,\mathrm{TeV}$$
$$0 \le m_A \le 3\,\mathrm{TeV}$$
$$2 \le \tan\beta \le 60$$
$$0 \le \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{D}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \le 3\,\mathrm{TeV}$$
$$-7\,\mathrm{TeV} \le A_t, A_b, A_\tau \le 7\,\mathrm{TeV},$$



These scans can reveal the loopholes

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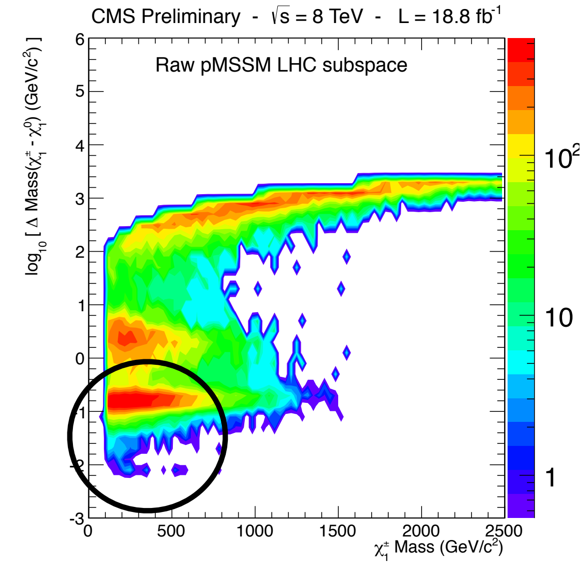
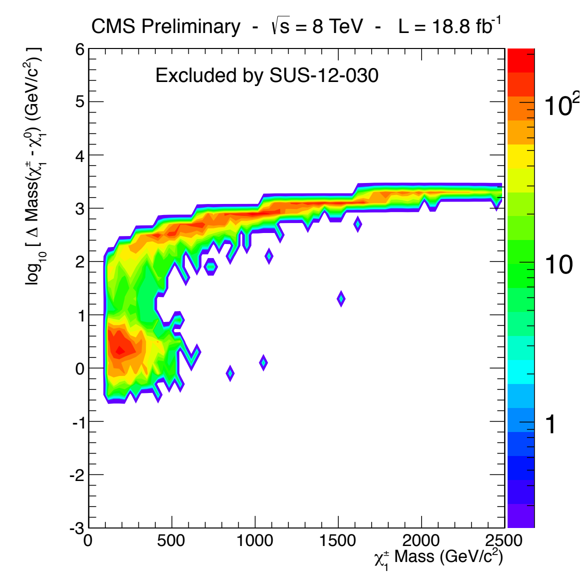
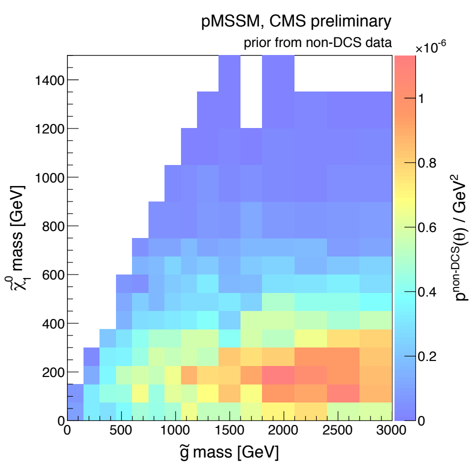
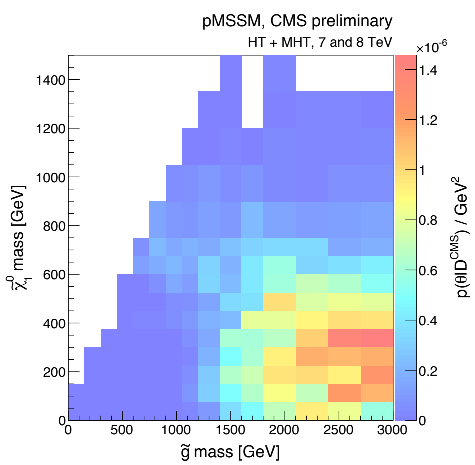
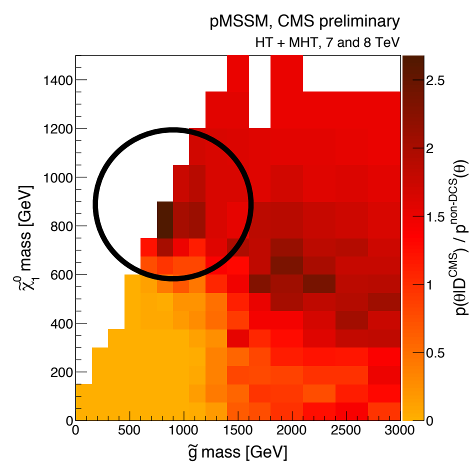
- While 1D plots are already useful, 2D plots can be even more useful
- Indicates areas (if you can decipher the colors) where we still have work to do
- As noted before, principal among these are:
    - *Compressed spectra (see below)*
        - **We have a number of strategies to deal with this loophole (I'll leave this to Maurizio's talk …)**
    - *Long-lived particles (see right)*











~Stable Long-lived Particles

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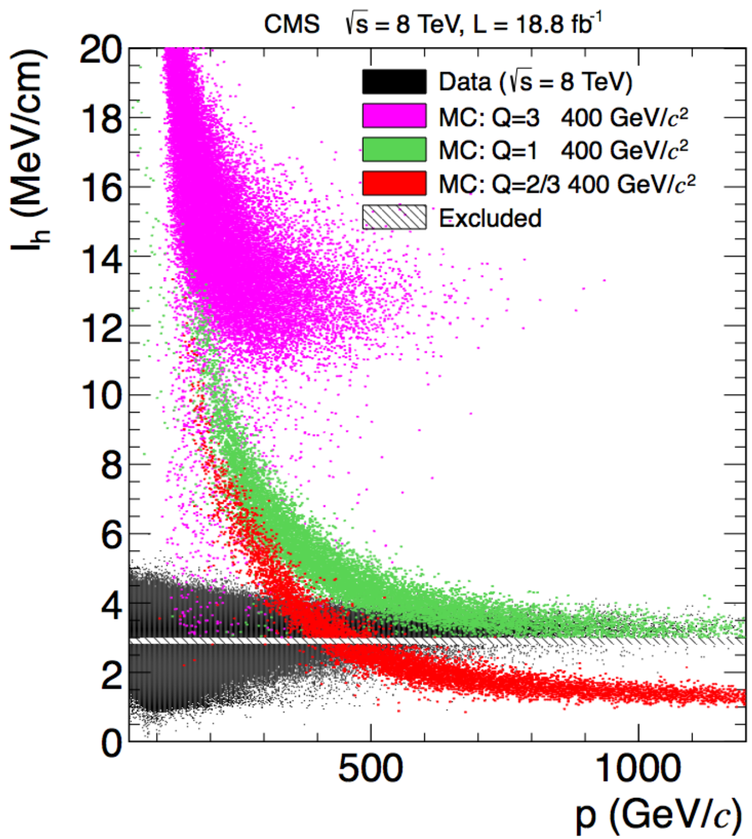
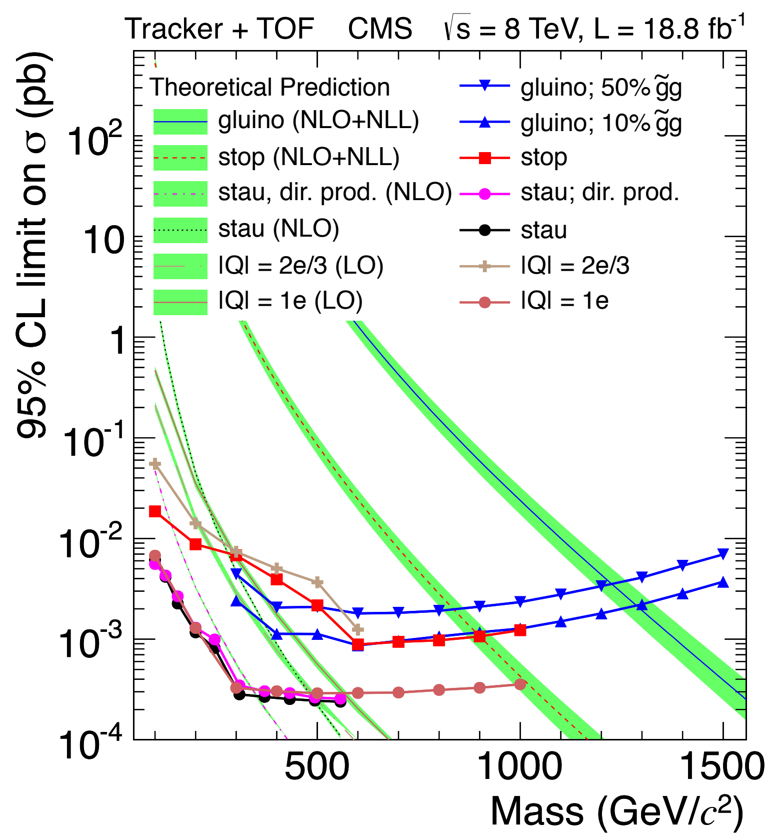
- For long-lived particles, we also have a number of strategies to deal with this loophole
    - *For ~stable particles, workhorse is search for slowly moving particles (heavy) particles - high dE/dx + long TOF*





- Such searches are robust and generic and excludes a variety of sufficiently long-lived particles
    - *e.g. gluinos < ~1250 GeV, stops < ~900 GeV*

Similarly, low dE/dx can isolate fractionally charged particles

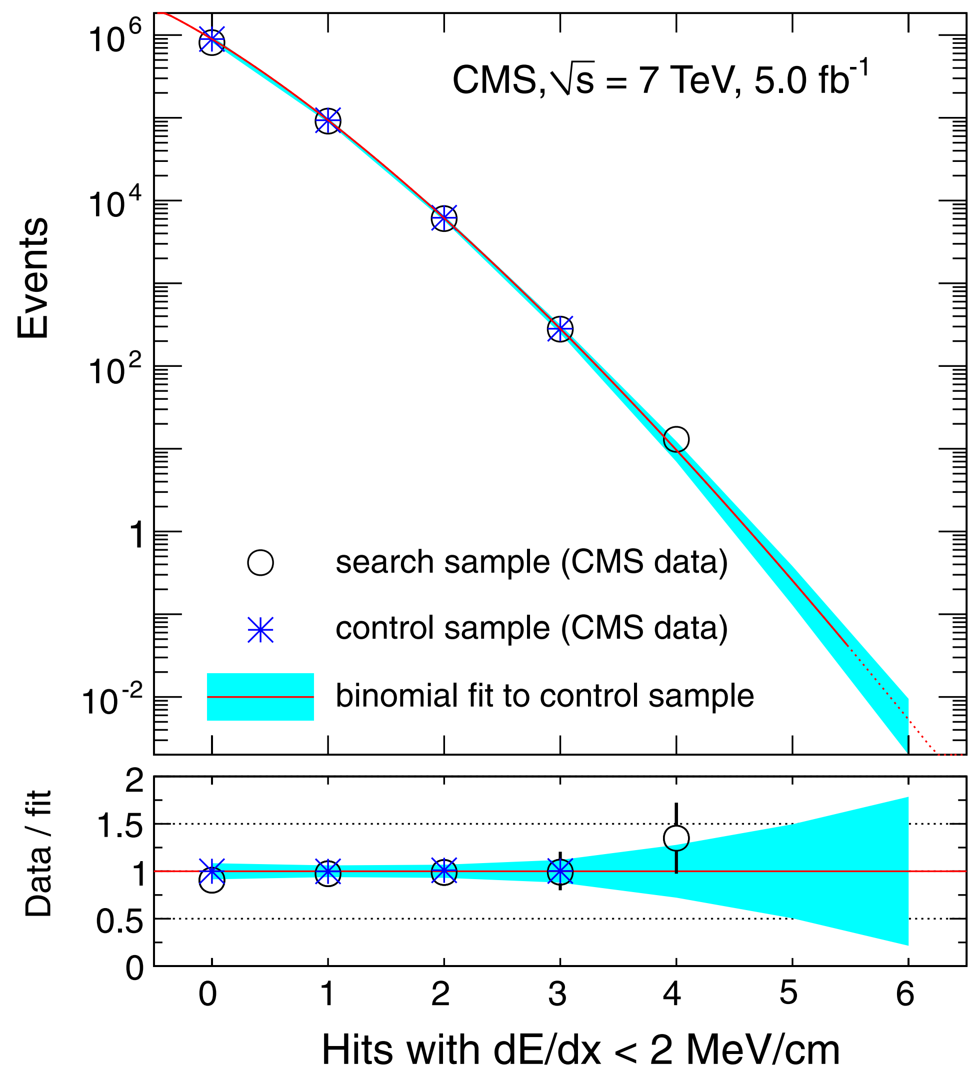
- Interestingly, noticed the following:
  - *Tracks have some probability to have a "low dE/dx" hit*
  - *If assume hits independent, data will follow binomial distribution (they will either be low dE/dx or not)*
  - *We found we can fit a signal depleted control sample for the probability, p2 and then apply the function to the search sample*

$$N = p_0 \binom{p_1}{n} p_2^n (1-p_2)^{p_1-n}$$

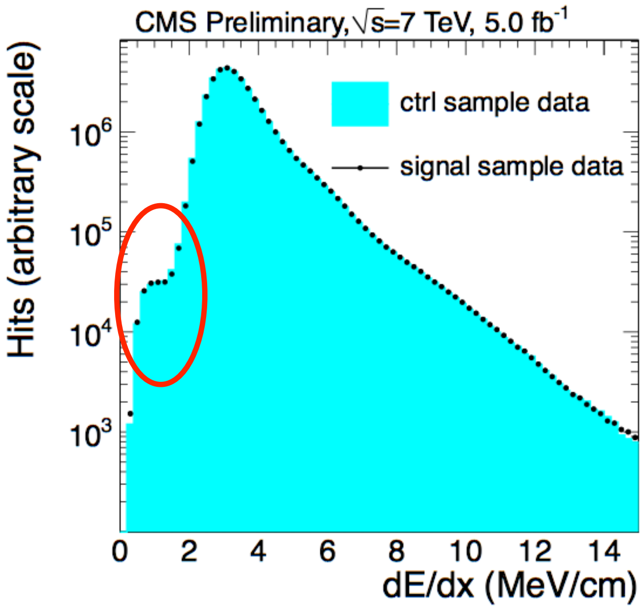
$$\binom{p_1}{n} = \frac{\Gamma(p_1+1)}{\Gamma(n+1)\Gamma(p_1-n+1)}$$

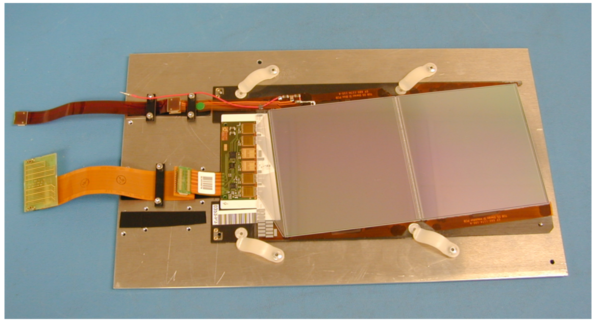
binomial coefficient in terms of continuous Gamma functions

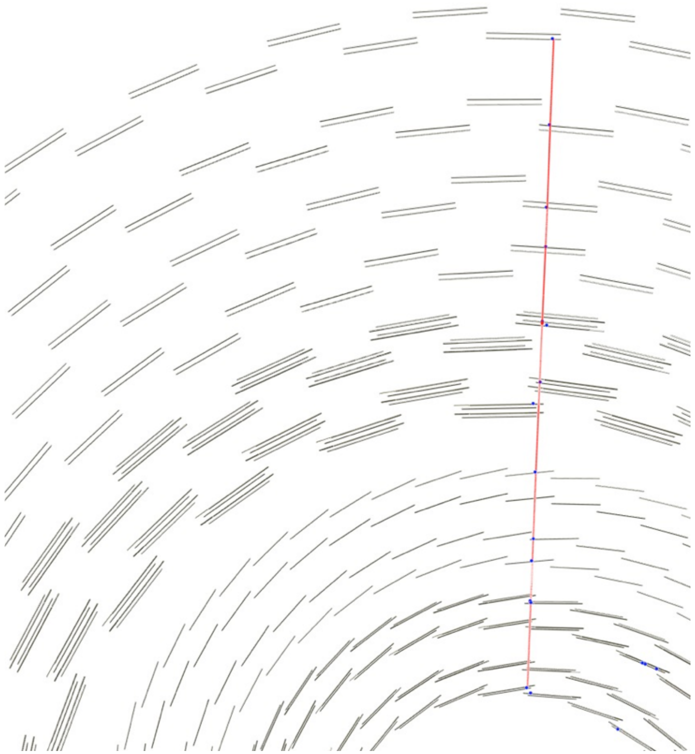
where n is the number of low dE/dx hits, p_1 is the total number of hits on a track, and N is the number of events containing at least one track with n low dE/dx measurements.



Aside (cont) - type of things you find …







A signal? No, it is due to hits which happen to come near the edge of physical sensor - some charge is lost, so "low dE/dx"

- For ~straight tracks, given CMS tracker geometry, it is possible therefore to violate the uncorrelated assumption
  - *Additional "correlated pp background"*

What can we expect from such searches in Run 2 (and beyond)?

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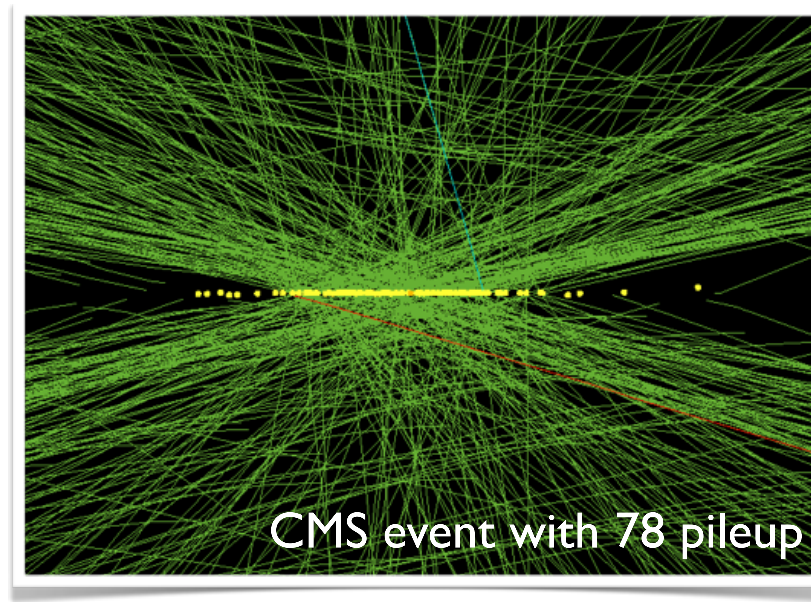
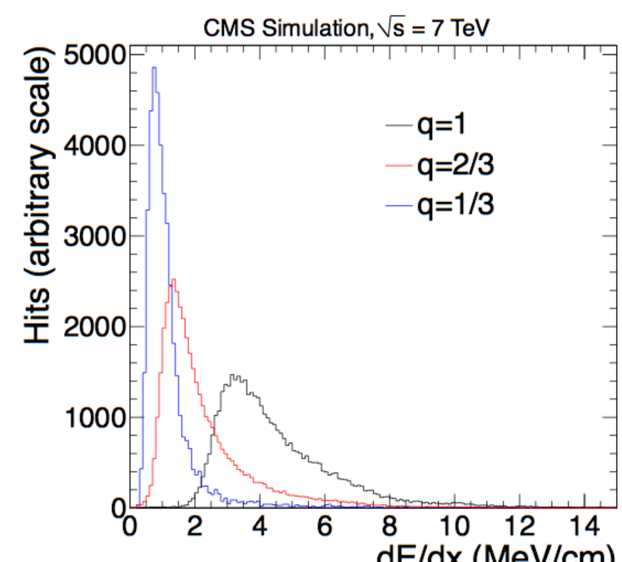
- dE/dx + TOF searches
  - *For q ≥ e, will remain effective, with early discovery potential*
    - **By the time we get to HL-LHC, will be more difficult (at least with CMS)**
    - **Outer tracker will use a binary chip, i.e. no dE/dx information unless re-designed …**
  - *For q ≤ e, will be challenging since (at least on CMS) minimum charge thresholds to register "hit" will be raised in an effort to combat pile-up*
    - **lower efficiency for q ≤ e particles**





If detect a signal with such a search, corroborate/ study it using “stopped particle” approach

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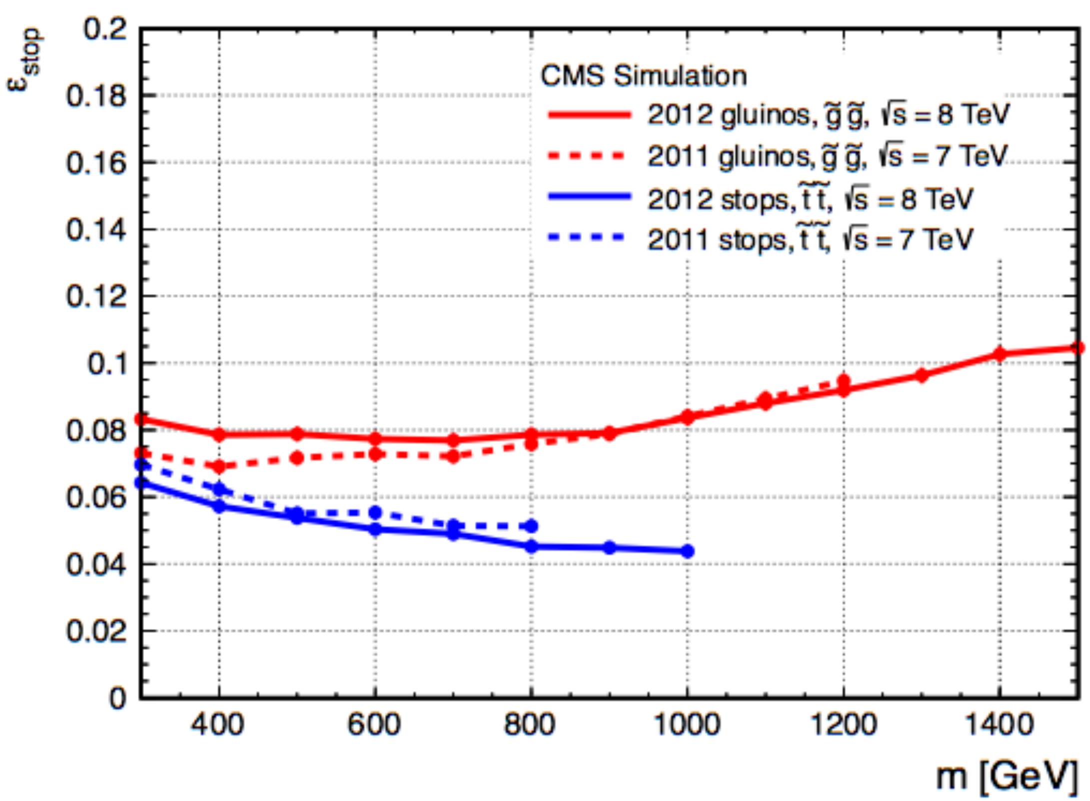
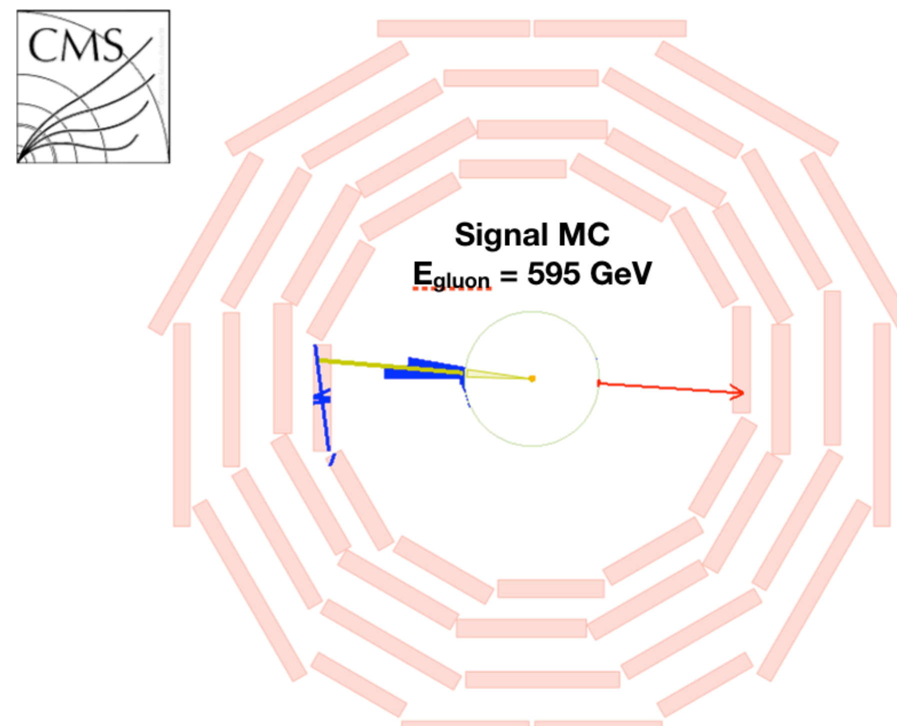
- If new particles have a low enough β, material interactions cause them to stop within the detector
  - *Stop if β ≲ 0.45 in CMS (mainly in HCAL and iron yoke)*
- Look for decays of stopped particles decay ns, seconds, minutes, or even days later
  - *Trigger on HCAL energy deposit when no collisions are expected*

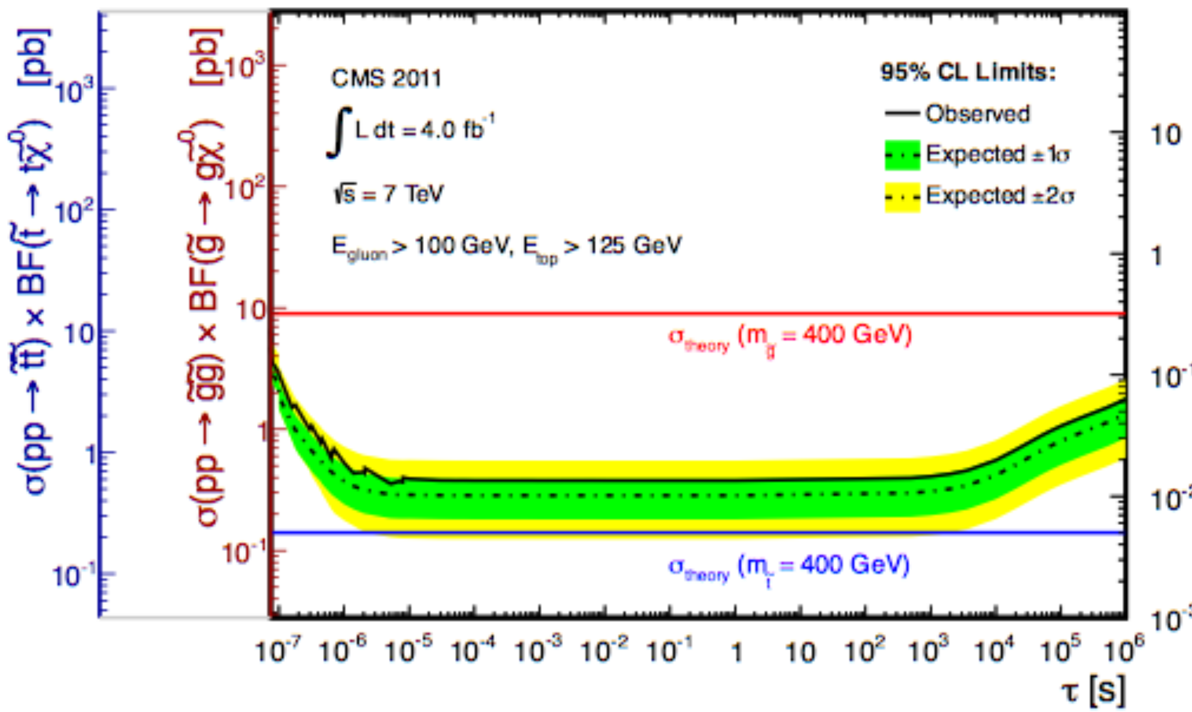




Some comments on these analyses

- So far has only been done as a counting experiment
  - *Distributions of energy depositions in calorimeters would provide addition discrimination*
- Not yet been any attempt to really reconstruct the decays
  - *Use inappropriate in-time, IP referenced, default construction for expediency since "good" enough*
  - *Dedicated reconstruction only likely in case of significant excess*
- Nevertheless, analyses still take time (more as rings have become more full with bunches)
  - *Very limited manpower/expertise*

Cross section exclusions



JHEP 1208 (2012) 026

What can we expect from such searches in Run 2 (and beyond)?

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- **Intra-fill** data is collected on dedicated calorimeter triggers that have a a low-ish threshold, but are gated by the absence of a coincidence between two electrostatic pickups on either side of the beam (BPTX)
    - *This will continue to be the case in Run 2, but*
    - *Bunch spacing will be 25 ns*
        - **Not much time per orbit left for triggers to be live**
- Limited **inter-fill** data was collected in Run 1 (even during the HI run), but has not been easily analyzable (or clear it was worth it)

BPTX

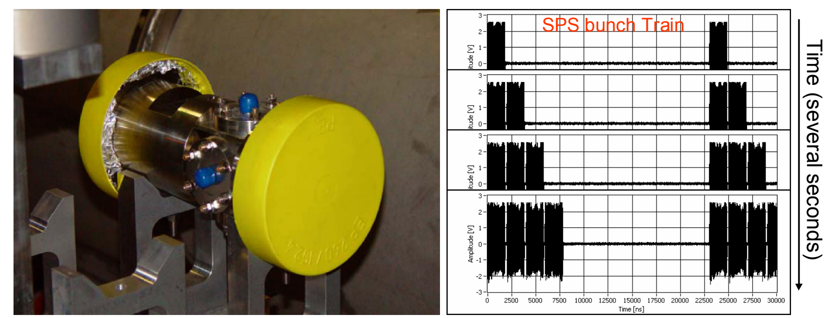
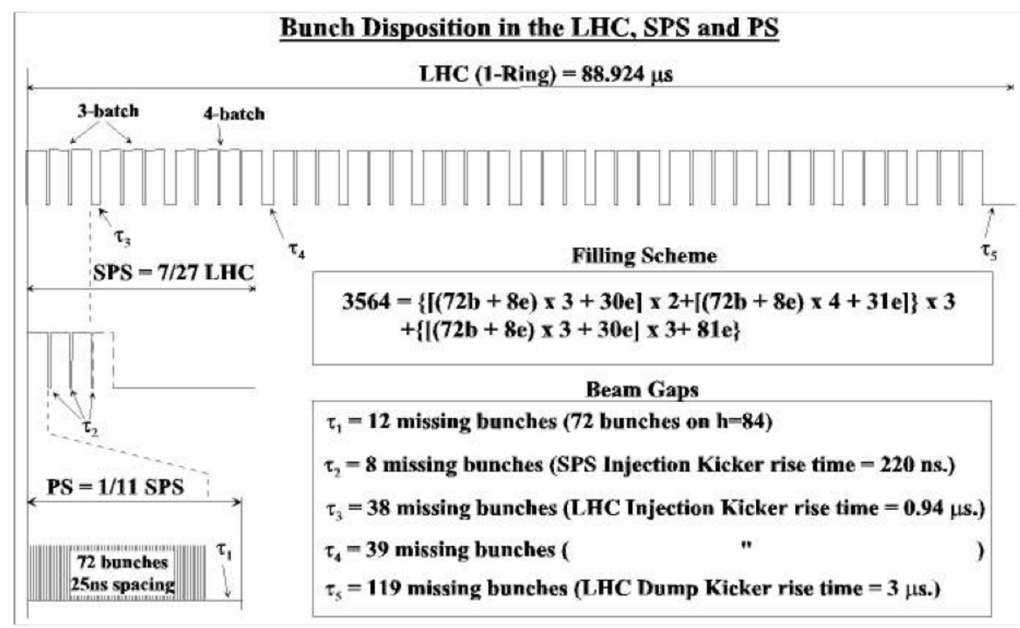
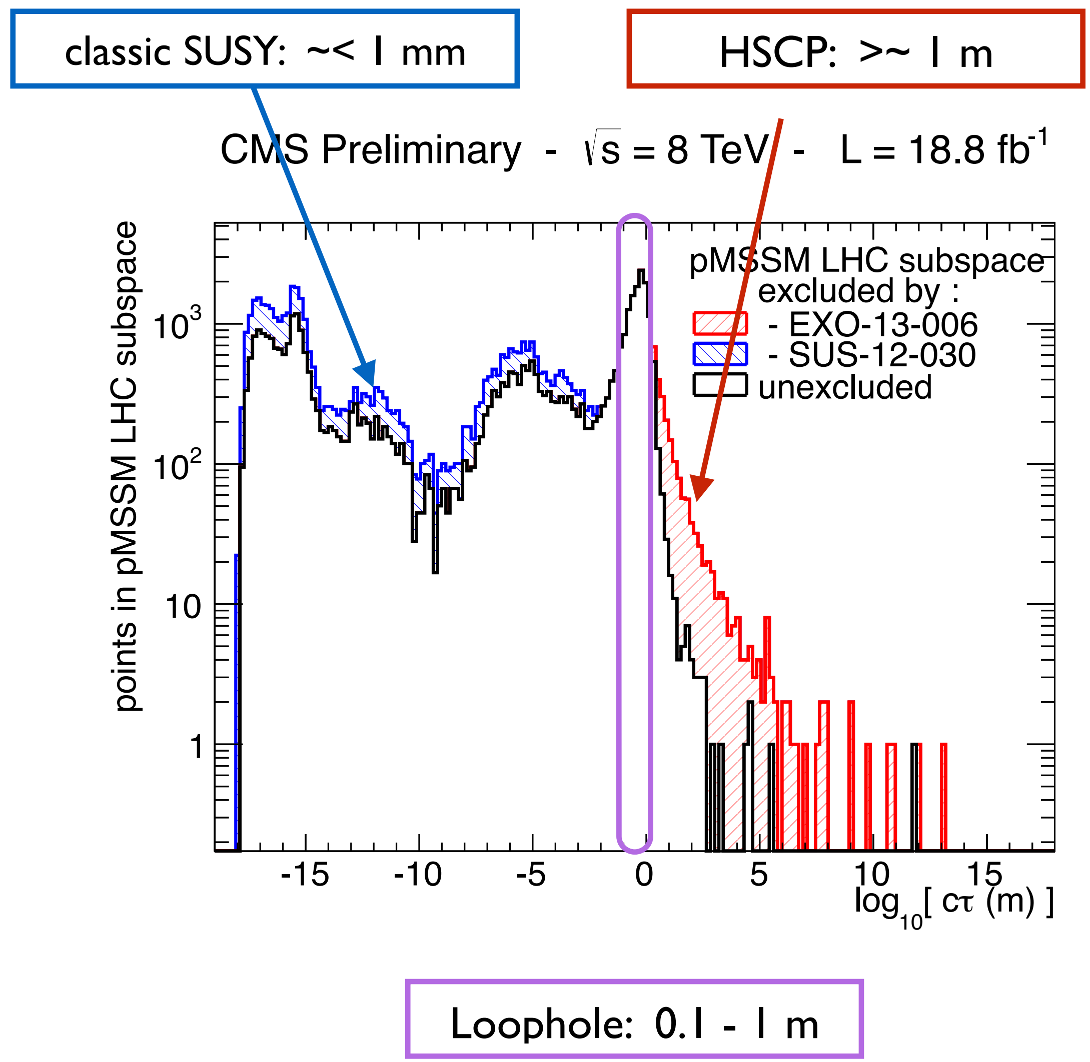


Fig 9. (Left) One set of BPTX electrodes situated on the LHC, ±175m from the CMS I.P. The proton beams passing through the center induce a charge into the electrodes giving highly accurate beam timing and position information. (Right) An example of the readout capability of the BPTX. Here, the signal timing and amplitude measurements are used to reconstruct the filling scheme of the SPS test beam.



Back to the pMSSM scans

- The plots at right show the exclusion of model points (of the same previously defined pMSSM LHC sub-space) as a function of ctau
  - *By the prompt CMS searches in blue*
  - *By the stable particle dE/dx +TOF CMS search in red*
    - **Notice there is an uncovered region at short-ish ctau**
    - **Note this region is a peak, i.e. highest density of pMSSM points**



A lot of NP could populate this region

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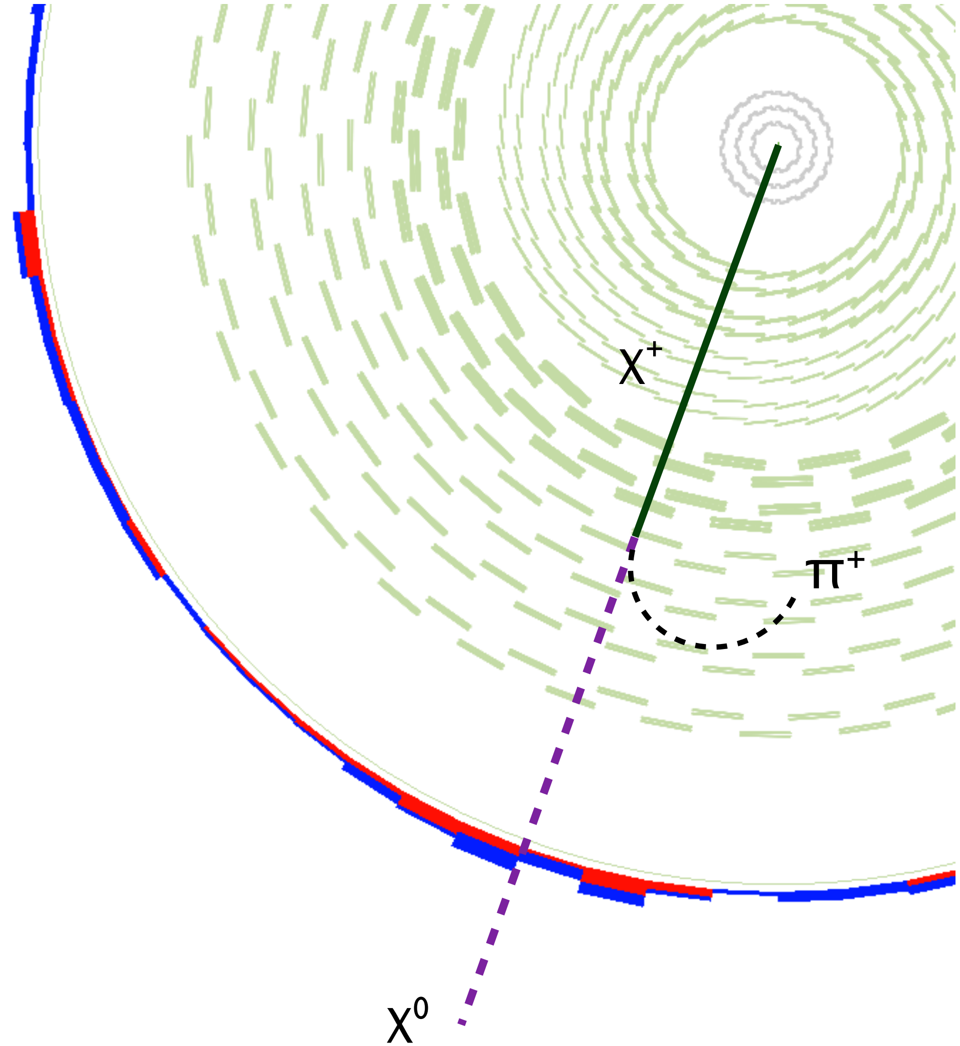
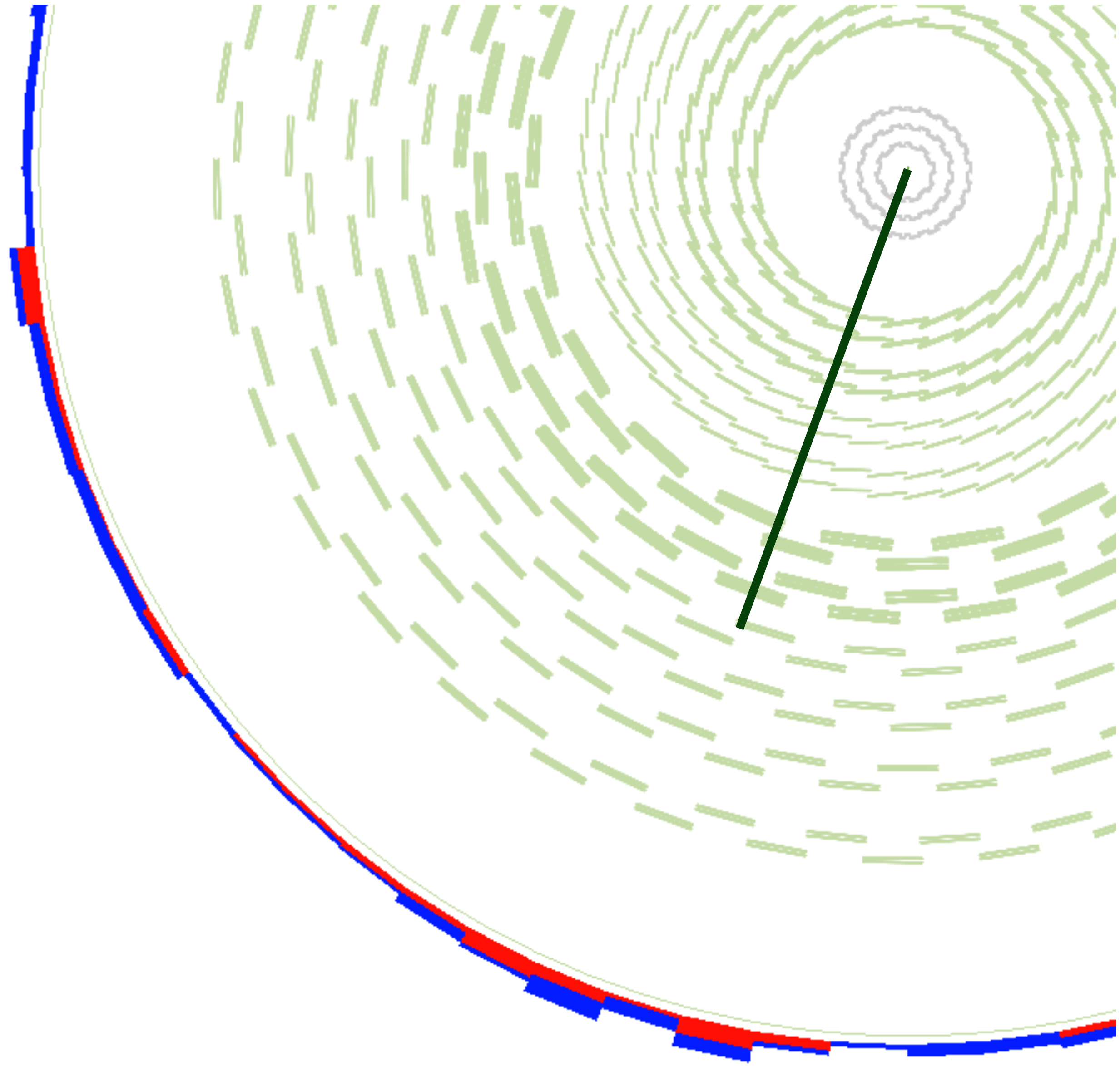
- Signatures include:
  - *Long-lived particles decaying to two or more charged objects (e.g. Hidden valley models)*
    - **displaced vertices**
      - *leptons*
      - *lepton "jets"*
      - *jets*
  - *Charged particle decaying to one charged object with different momentum*
    - **Kinked tracks**
  - *Charged particle decaying to neutral object (e.g. AMSB)*
    - **Disappearing tracks**



What do these have in common? They are all experimentally difficult and the analyses take a long-time …

Let me illustrate this with “Disappearing Tracks”

- What we see in our detector (without dedicated additional reconstruction to attempt to recover the pion,) is a track that stops midway through the detector
    - *A track with missing outer hits*
    - *Also little E in calorimeter region associated with the track*



A bunch of tricky backgrounds

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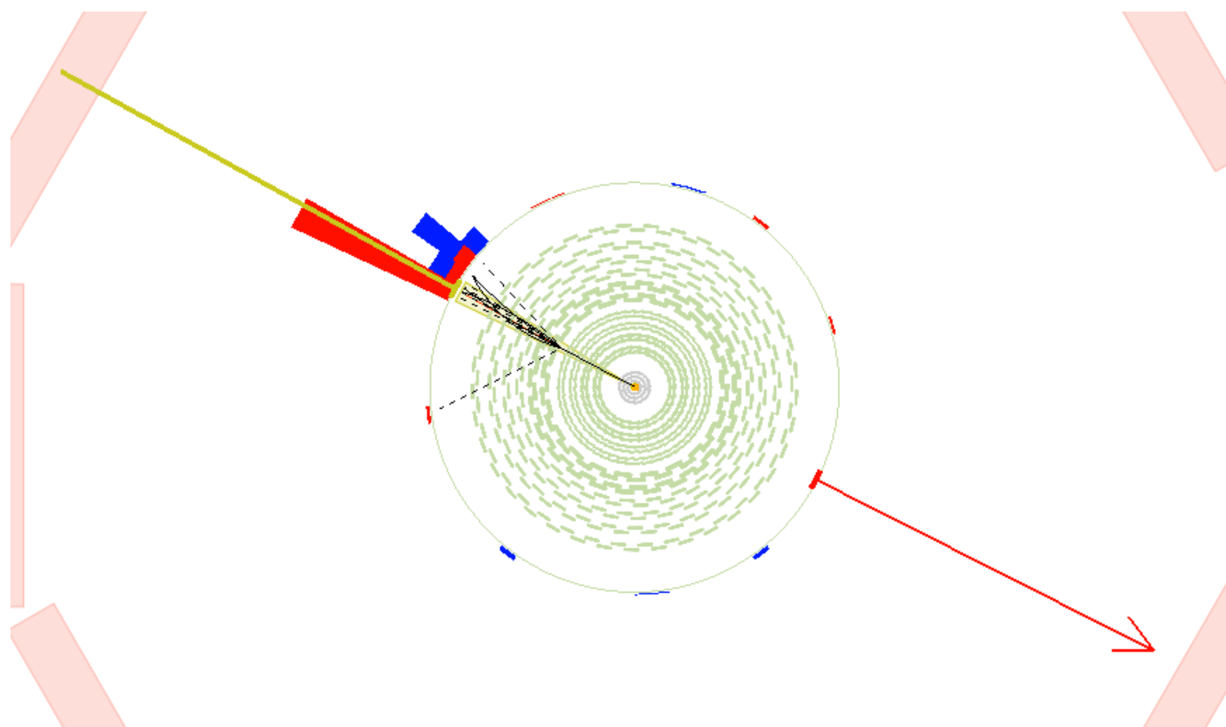
- Must understand all the ways this can happen (experiment specific)
    - *Isolated charged pions (from W to tau ν) that become neutral after nuclear interactions with material*
    - *Leptons (from W to lν) which are not reconstructed for some reason*
    - *"Fake tracks", i.e. false trajectories formed from random hits not a real particle*

charged hadron

π from $\tau \to \pi\nu$

where the pion undergoes a nuclear interaction (denoted by the black tracks)



Some examples of how this can happen

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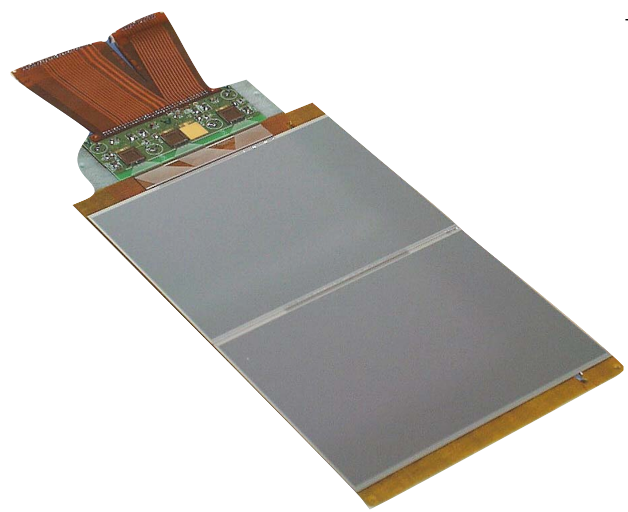
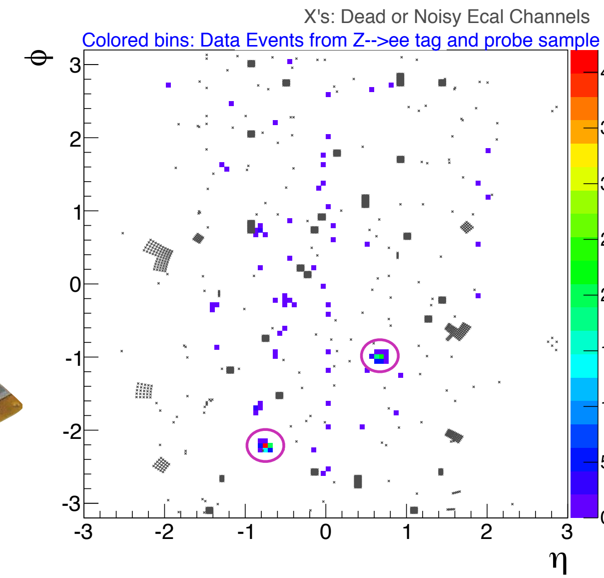
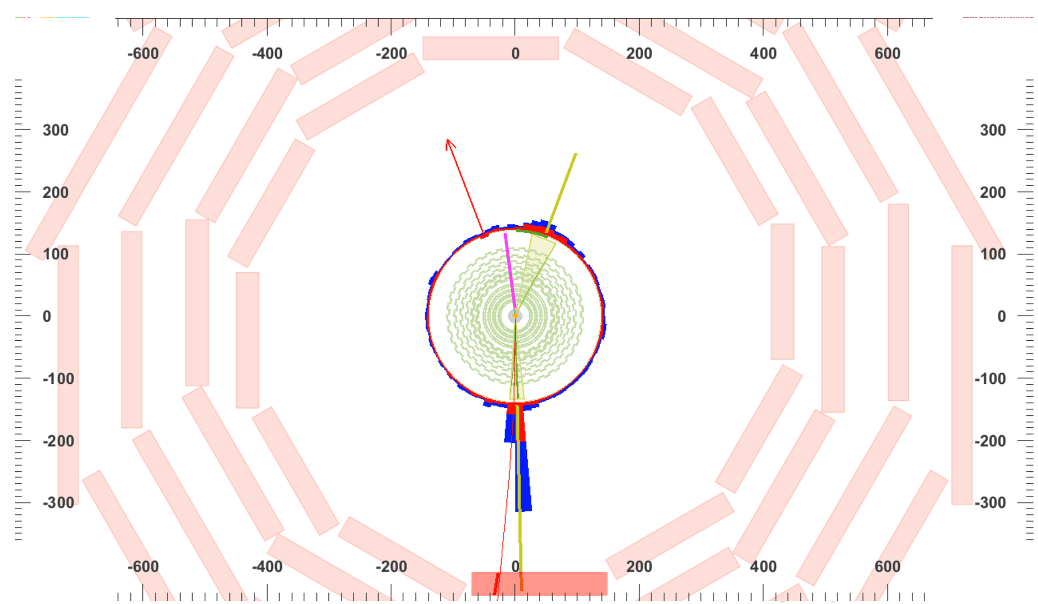
- Tracks from muons can disappear if they go through a glue joint in a silicon sensor and subsequently hit a hole in the muon system
    - *Muons can also decay in flight*
- Tracks from electrons can also disappear for the same reason if they impinge on a dead/noisy tower in the ECAL
    - *Electrons with significant brem can also lead to missing outer hits*
- Sometimes algorithmic failures lead to the selection of a trajectory with missing outer hits over the true trajectory (which does not have any such missing hits)
- Tracks with missing outer hits are prone to momentum mis-measurement (shorter lever arm), which can lead to reconstruction failures (E won't be consistent with p)







Understanding these things take time

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- Consequently, like stopped particles, these analyses are not the quickest to complete
  - *While ATLAS has published their results (see right), CMS still in progress*
- Also, like stopped particles, limited manpower & expertise
- While I have focussed on disappearing tracks, these statements generally apply to the other moderately long-lived signatures

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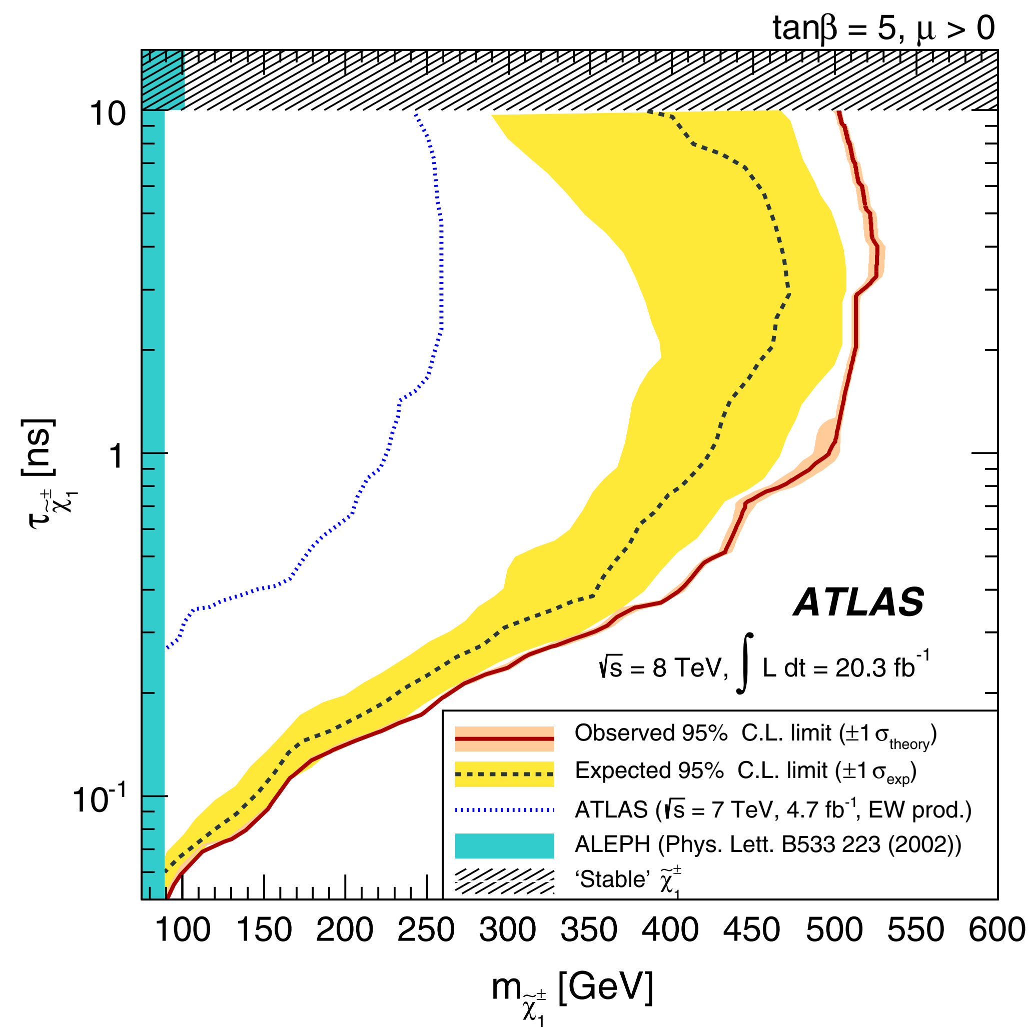
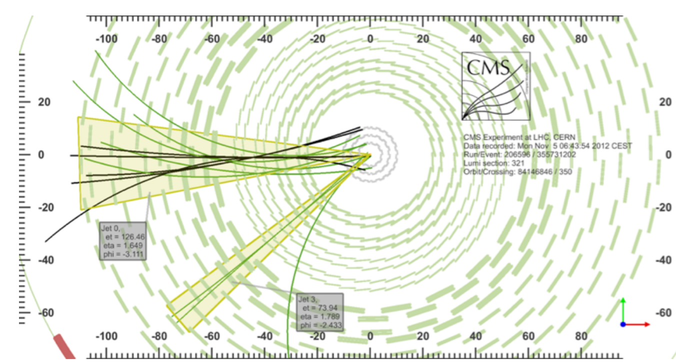


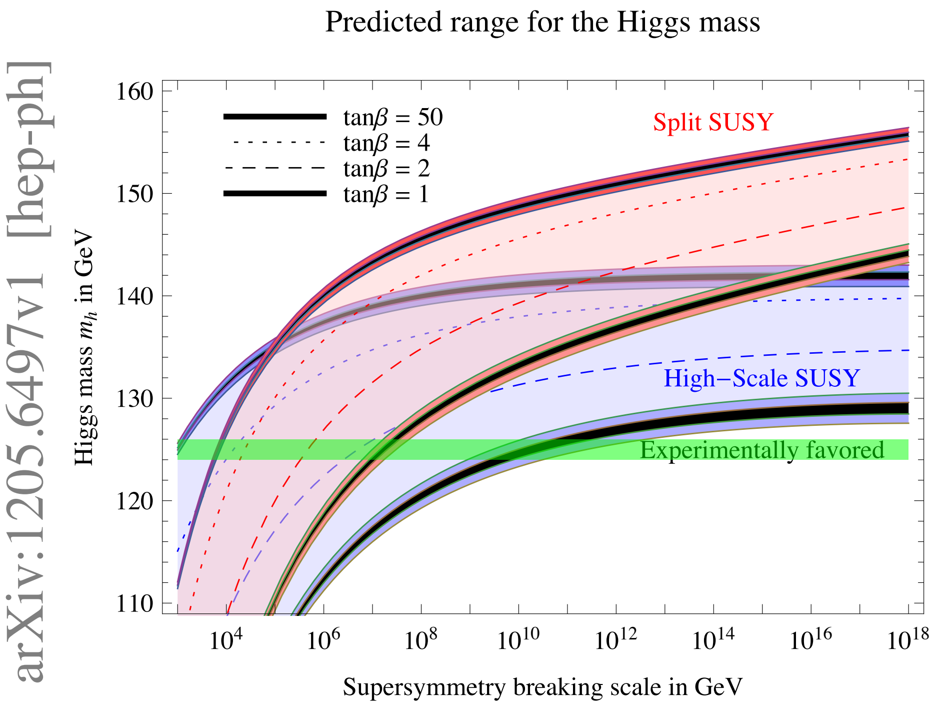
What can we expect from such searches in Run 2 (and beyond)?

- Main (non-human) limitation is triggers:
- For disappearing tracks,
  - *Like DM, invisible final state so must trigger on radiation*
  - *Eventually, will be able to trigger on the disappearing track directly*
    - **Both experiments adding tracking triggers for HL-LHC**
- For displaced leptons:
  - *Pile-up complicates tracking*
    - **Significantly displaced tracks may not be reconstructed (at least not by default)**
    - **Vertexing efficiency consequently degraded**
- For displaced jets:
  - *Similar issues to displaced leptons*



What I am really worried about …

- Despite everything I've said about these difficult searches (that we have to do, to close all the loopholes in the search for NP), I am not really that worried about them*
    - *The signatures are very distinctive*
    - *We will find people to do the analyses*
    - *They may take time, but they will get done*
- What I am really concerned with right now is
    - *100 μm < cτ < 1 cm*
        - **Largely unexplored, at least by direct searches … some sensitivity with inclusive searches, but how much? (see Andy's talk)**
        - **In some cases, very similar to SM bkgs (e.g. gluinos hiding as b's)**



- E.g. Mini-split scenarios
    - Favored because of M_H (not to mention null results of long-lived searches discussed earlier)

*Likewise the "easy" prompt searches will also get done, so I am not worried about them either

Searching for less-obviously long-lived particles

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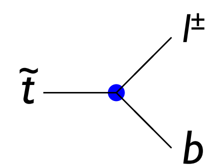
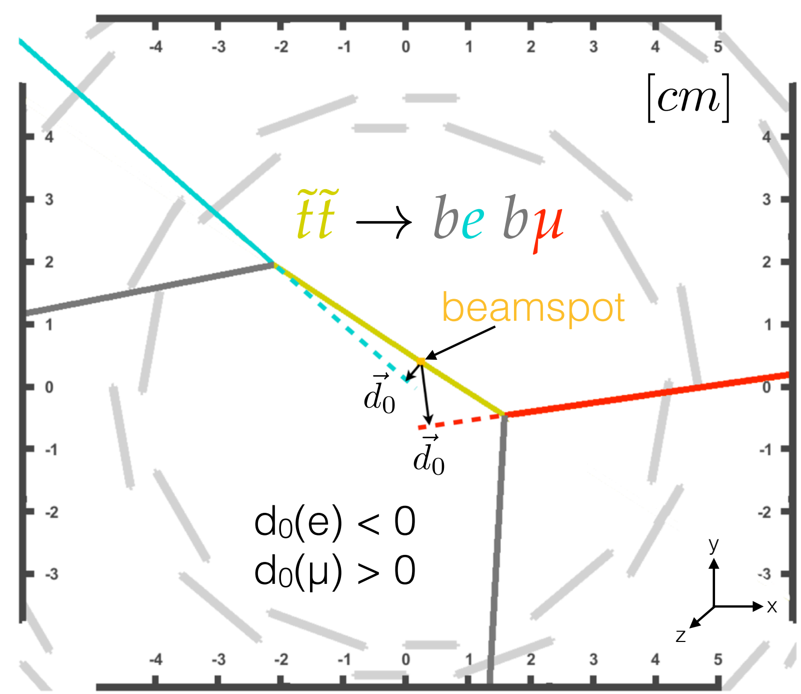
- Wanted to conduct as model independent search for such modestly long-lived pls
    - *Make no requirement on number of jets*
    - *Make no requirement on MET*
    - *Only use displacement to separate S/B*
        - **Do not require displaced objects to form displaced vertex**
            - *but don't exclude either*
    - *While hadronic signals are part of the eventual plan, start with search for signals that produce displaced leptons*
        - **First step, require two isolated displaced (opposite flavor) leptons**
        - **Leave non-isolated leptons (since these really look like b-jets) for later**

- "Displaced Supersymmetry" (P. Graham et al) as representative model
    - *Small RPV couplings generate long-lived LSP*



$\tilde{t}\tilde{t}^{*} \rightarrow bbl^{+}l^{-}$ $BR(e,\mu,\tau) = 1/3$



Results of this search

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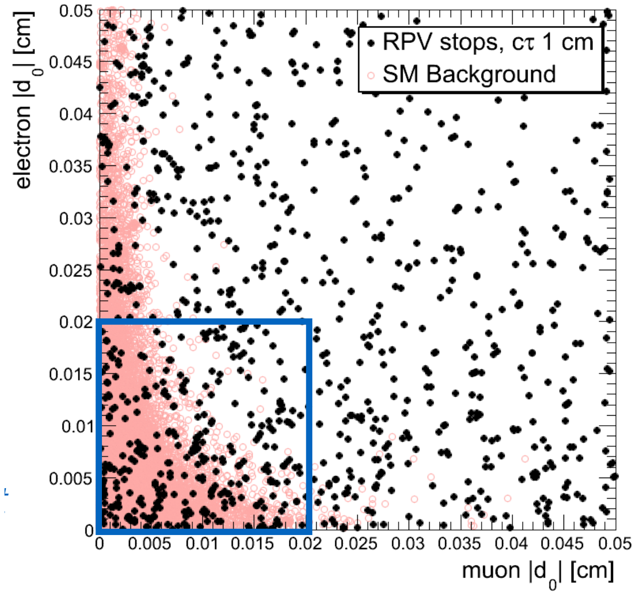
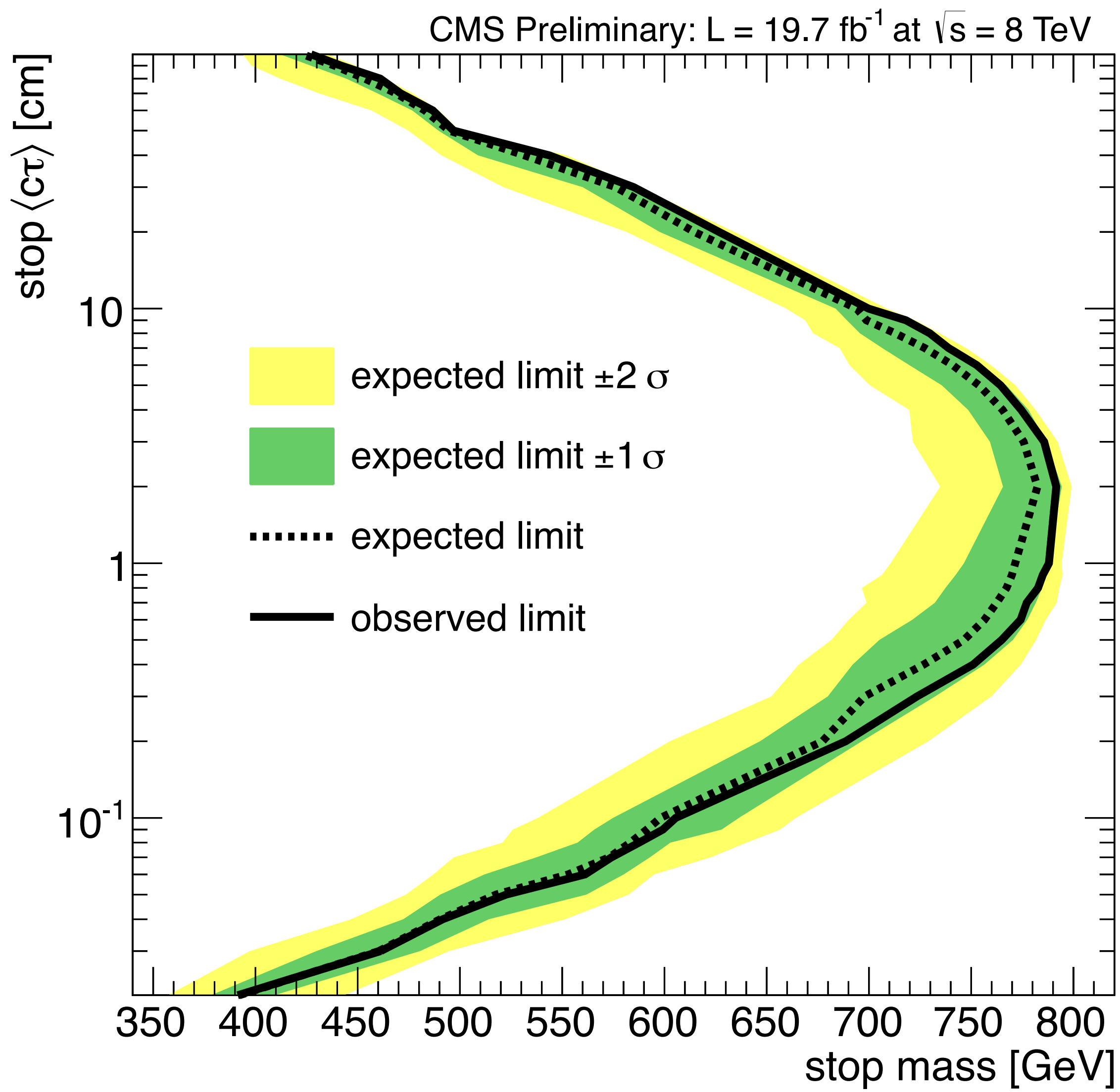
- Displacement alone is a good discriminator from background
    - *Adding same-flavor requirement largely removes any residual SM contributions*
- Backgrounds mainly from Z to tau tau and QCD (heavy-flavor)
- Search done in three bins of displacement
    - *Unfortunately, no evidence of BSM particles in any of these bins*



Event Source	$0.02\ \text{cm} < \lvert d_0\rvert < 0.05\ \text{cm}$	$0.05\ \text{cm} < \lvert d_0\rvert < 0.1\ \text{cm}$	$\lvert d_0\rvert > 0.1\ \text{cm}$
other EWK	$0.65 \pm 0.13 \pm 0.08$	$(0.89 \pm 0.53 \pm 0.11) \times 10^{-2}$	$<(89 \pm 53 \pm 11) \times 10^{-4}$
top	$0.767 \pm 0.038 \pm 0.061$	$(1.25 \pm 0.26 \pm 0.10) \times 10^{-2}$	$(2.4 \pm 1.3 \pm 0.2) \times 10^{-4}$
$Z \to \tau\tau$	$3.93 \pm 0.42 \pm 0.32$	$(0.73 \pm 0.73 \pm 0.06) \times 10^{-2}$	$<(73 \pm 73 \pm 6) \times 10^{-4}$
QCD	$12.7 \pm 0.2 \pm 3.8$	$(98 \pm 6 \pm 30) \times 10^{-2}$	$(340 \pm 110 \pm 100) \times 10^{-4}$
Total expected background	$18.0 \pm 0.5 \pm 3.8$	$1.01 \pm 0.06 \pm 0.30$	$0.051 \pm 0.015 \pm 0.010$
Observation	19	0	0
$pp \to \widetilde{t}_1 \widetilde{t}_1^*$			
$M = 500$ GeV, $\langle c\tau \rangle = 1$ mm	$30.1 \pm 0.7 \pm 1.1$	$6.54 \pm 0.34 \pm 0.24$	$1.34 \pm 0.15 \pm 0.05$
$M = 500$ GeV, $\langle c\tau \rangle = 1$ cm	$35.3 \pm 0.8 \pm 1.3$	$30.3 \pm 0.7 \pm 1.1$	$51.3 \pm 1.0 \pm 1.9$
$M = 500$ GeV, $\langle c\tau \rangle = 10$ cm	$4.73 \pm 0.30 \pm 0.17$	$5.57 \pm 0.32 \pm 0.20$	$26.27 \pm 0.70 \pm 0.93$

Limits supersymmetry search

- Set limits on "displaced supersymmetry" as a representative model
- Since analysis was designed to be pretty inclusive, results should impact more scenarios than this
  - *Will provide efficiency parameterizations so that results can be used more generally*
  - *Suggestions welcome on how to do this …*



What can we expect from such searches in Run 2 (and beyond)?

The Ohio State University

- As mentioned before, this was a first step, for Run 2 more inclusive (but more difficult) searches are planned
  - *Triggers should not be a problem (at least for leptonic final states)*
  - *Pile-up also not a problem*
- Variations on displaced leptonic final states:
  - *Remove the same-flavor requirement*
  - *Remove the isolation requirement to get at semi-leptonic final states*
  - *Go down to ≥1 displaced lepton?*
  - *Utilize other information (e.g. dE/dx)?*
- Extend to hadronic final states?
  - *Overlap with "displaced jets" searches, but these tend to focus on larger cτ and generally require a significantly displaced vertex*

So are we ready for LHC Run 2?

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- Here's my goals for the run again:
  - *Find the "natural" solution to the hierarchy problem*
    - **Direct evidence by observing BSM states**
    - **And/or increasingly precise measurements of Higgs properties**
  - *Conduct searches in a way that if do not find any such solution can draw (some) conclusions about correctness of naturalness arguments*
    - **No loop holes!**

- Bulk of the direct search program will be looking for stops/gluinos higher mass, trying hard to access as compressed spectra as possible.
- Some trigger challenges, but basically will be ok - see Maurizio's talk? (Electroweakinos may need time beyond Run 2)
- Likewise, Higgs program is established and is ok
- My focus (in general and in this talk) has been on the second goal — identifying any holes in these programs and plugging them if we can
- Prior to Run 1 this kind of exercise led implementation of the searches that I have discussed (and during the run to things like expanded RPV efforts)
- Now is time to assess coverage for for Run 2, esp. since addressing any issues will likely have long lead-time, as I've tried to illustrate

Summary

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- I've tried to show you the thought process I've gone through to ask myself if we are ready for LHC Run 2
  - *1st question: Are the basics covered?*
    - **Yes, and many people working hard at it**
  - *2nd question: Where are the main gaps in this coverage (and how do you identify them)?*
    - **Compressed spectra SUSY**
    - **Moderate lifetime long-lived SUSY (or other BSM)**
  - *3rd question: Can we address these in the next run?*
    - **I think so, but some work is required**
    - **Any suggestions about how to implement these searches are welcome**
  - *4th question: Is there anything I might be missing?*
    - **That's where you come in …**

} Shows up in pMSSM scans, what else can we do?

Points for Discussion

- What do you think — are we ready to find NP at LHC in Run 2?
  - *Are there any potential BSM signals that are not covered by the mainstream LHC program (or any of the variants I have discussed)?*
    - **Is there anything we can do now (along the lines i've suggested or something new, even crazy ideas) that would add another arrow to our experimental quiver?**
    - **Ideas for triggers, measurements, searches, etc. that open up new areas of investigation**
  - *Do we have adequate tools to assess this coverage?*
    - **Can we be confident that we have left no stone unturned?**
    - **Is there anything we can do now to be more thorough/less biased?**

- (If we exhaust discussion about Naturalness program — we could discuss dedicated DM searches at LHC, i.e. "mono-mania" which I didn't cover in the talk)
    - **I am much less confident we know what we are doing here, and**
    - **This could be the discovery we get first …**

My bet for Run 2 …

The Ohio State University

2011 Copenhagen Conference

Wager on Supersymmetry

Yes & No	Yes	No	Abstain
Marius Gaudesius	MAKEENKO	G. 't Hooft *)	Neuberger
	Stelle	Z. Komargodski	Kiermaier
	SHIH	A. JENKINS	Jakob Gath
	D. O'Connell	P.H. Damgaard	
	Emil Bjerrum-Bohr	Alexander Karlberg	
	Kim SPLITTORFF	Savvas Nesseris	
	Nima Arkani-Hamed	SIMON BADGER	
	[illegible] ★	KOSTYA ZAREMBO	

★ with ≥ 1 particle with $c\tau \sim 1$ cm