Exotic Physics at the LHC

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RUTGERS
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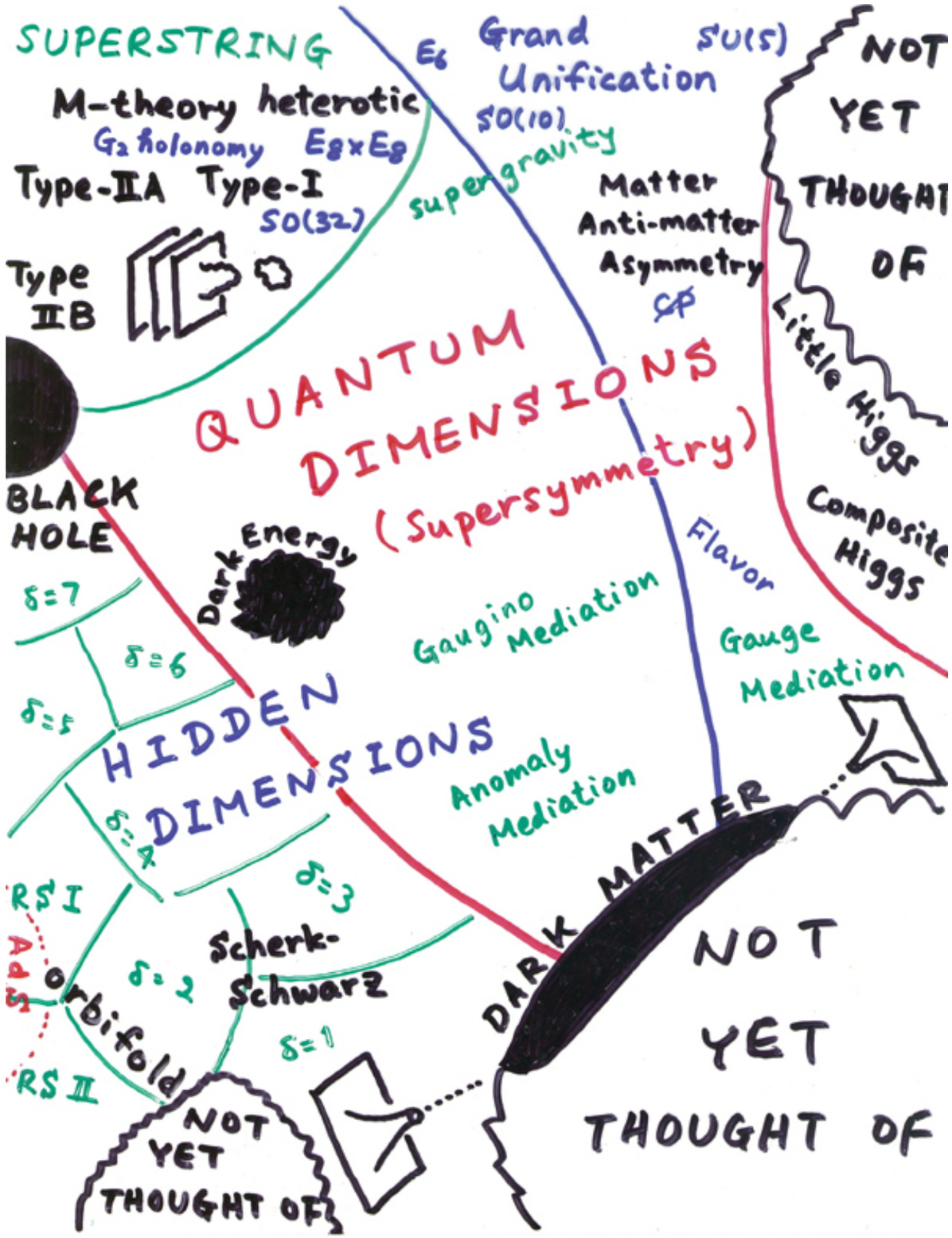
OF NEW JERSEY

MODELS, MODELS EVERYWHERE

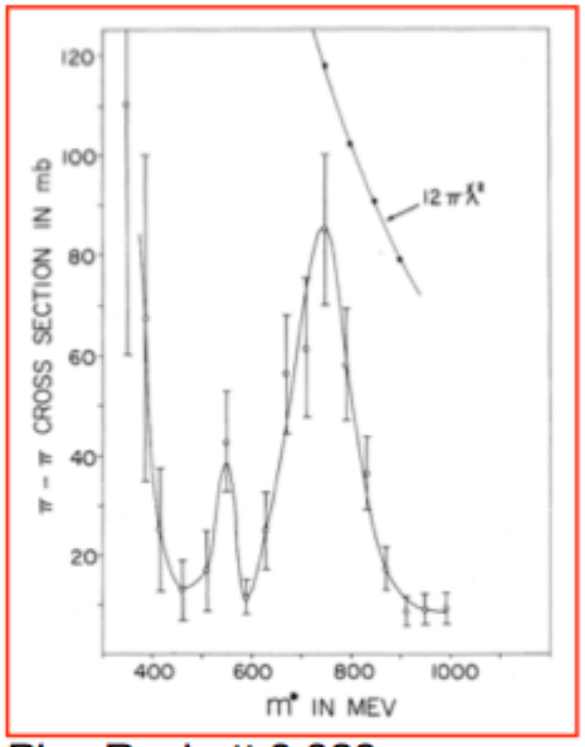
- The LHC's search program is vast
  - Try to focus on some of the more recent, interesting results
    - bump hunts
    - pair production
    - dark matter
    - long-lived particles
- What are we missing?



Bump Hunts at the LHC

Motivating Bump Hunts

1961: ρ(770)→ππ



PhysRevLett.6.628

1961: K*(892)→Kπ

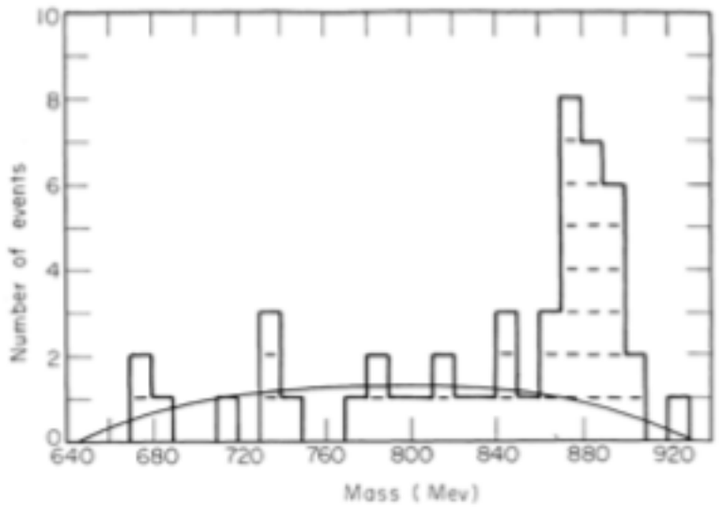
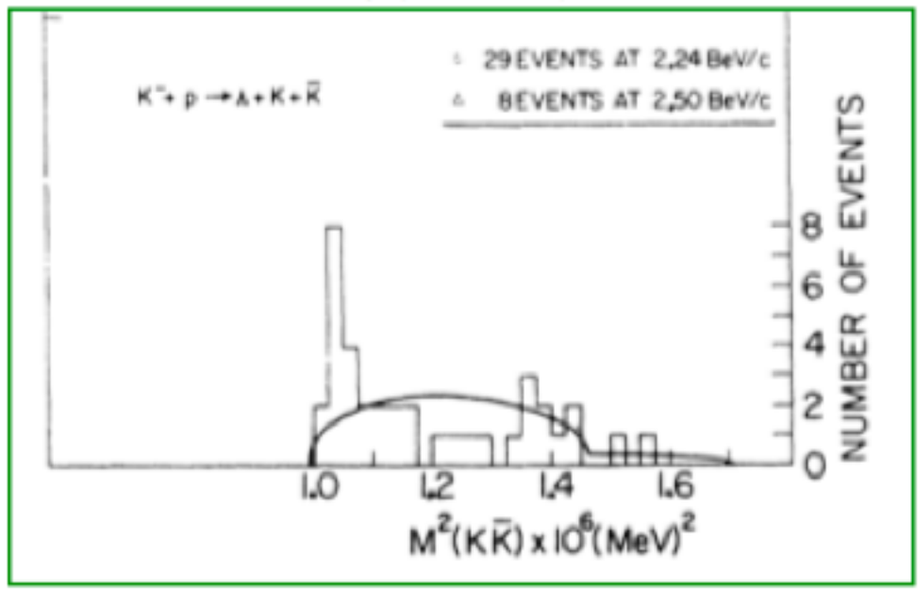


FIG. 2. Mass spectrum of the $\bar{K}^0$-π^- system. The solid line represents the phase-space curve normalized to background events.

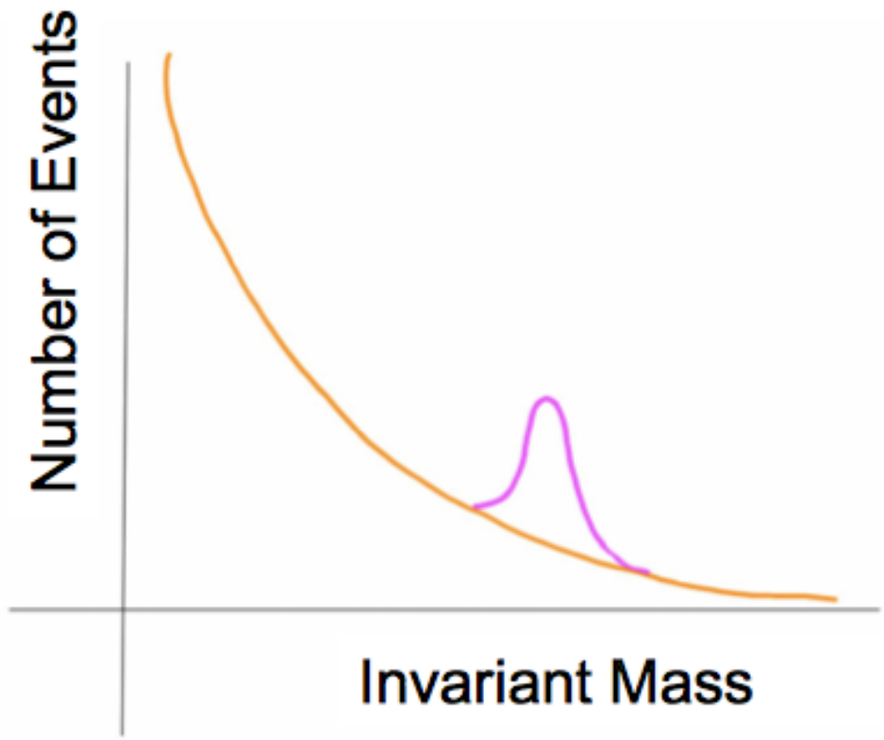
PhysRevLett.6.300

1961: φ(1020)→KK

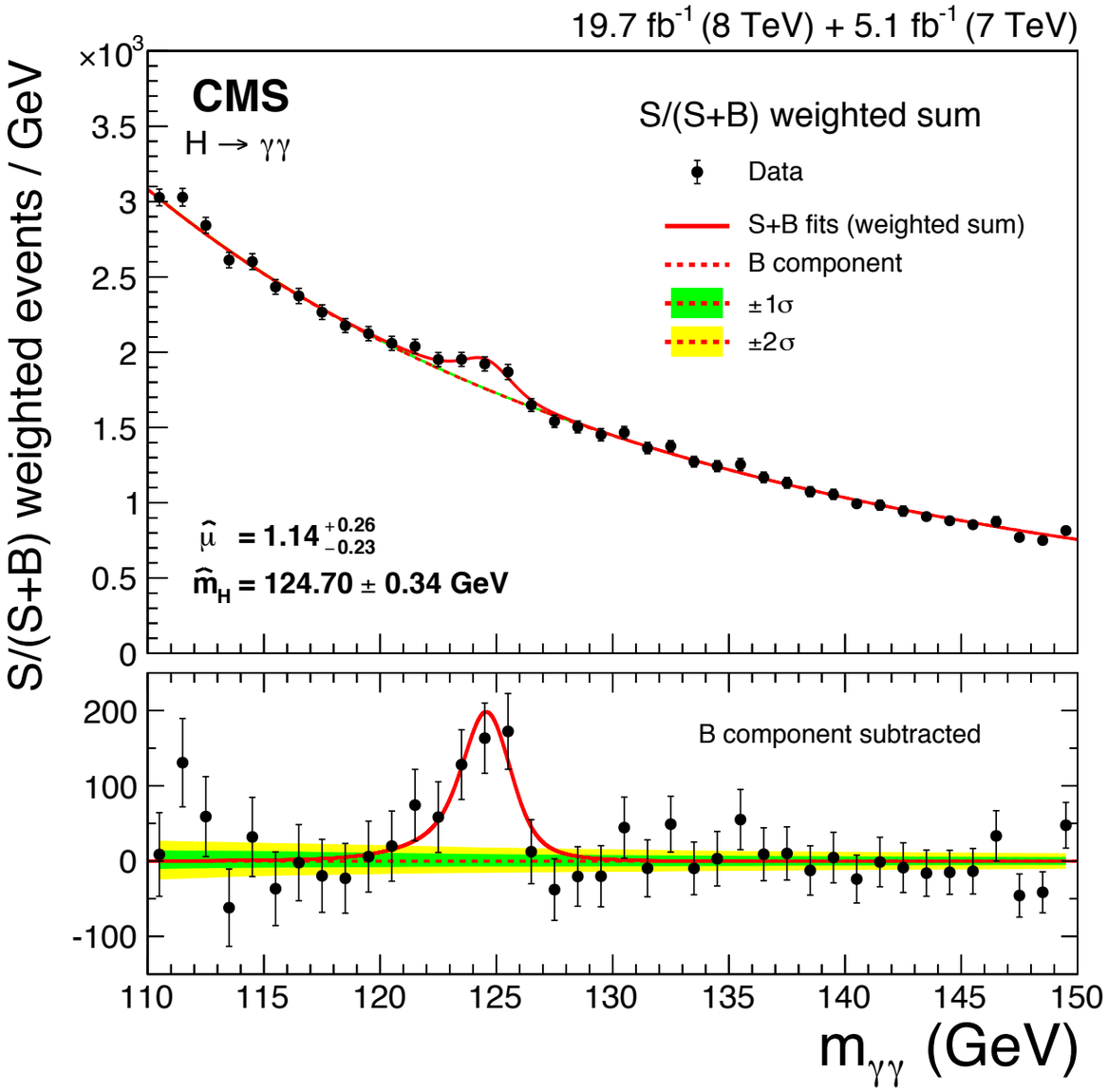


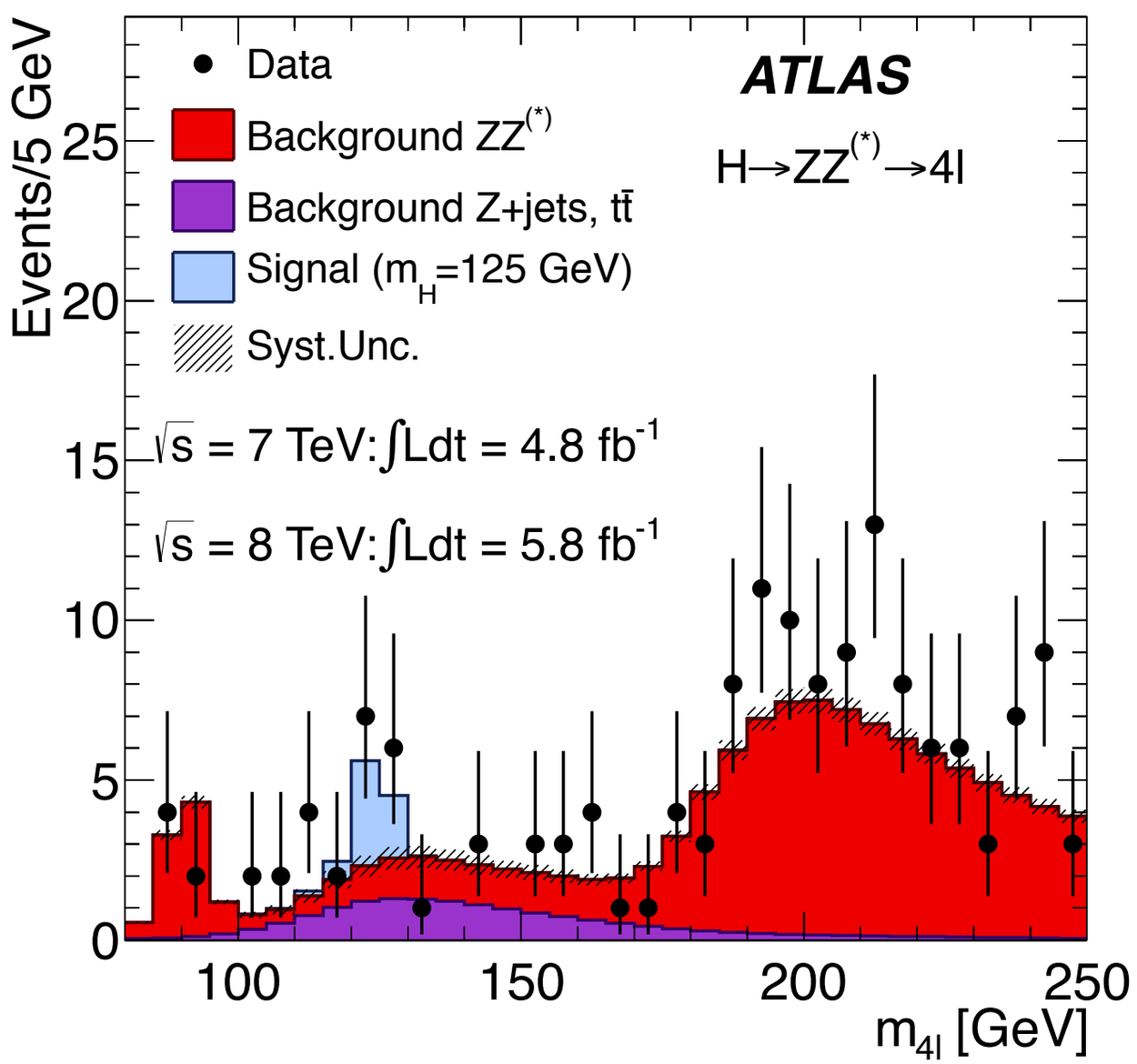
PhysRevLett.9.180

and many more after…



A RECENT EXAMPLE



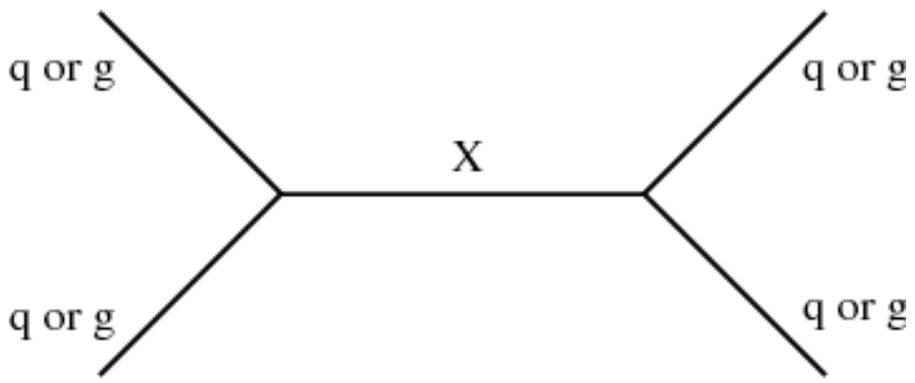


- The discovery of the Higgs boson was performed through a "bump hunt"

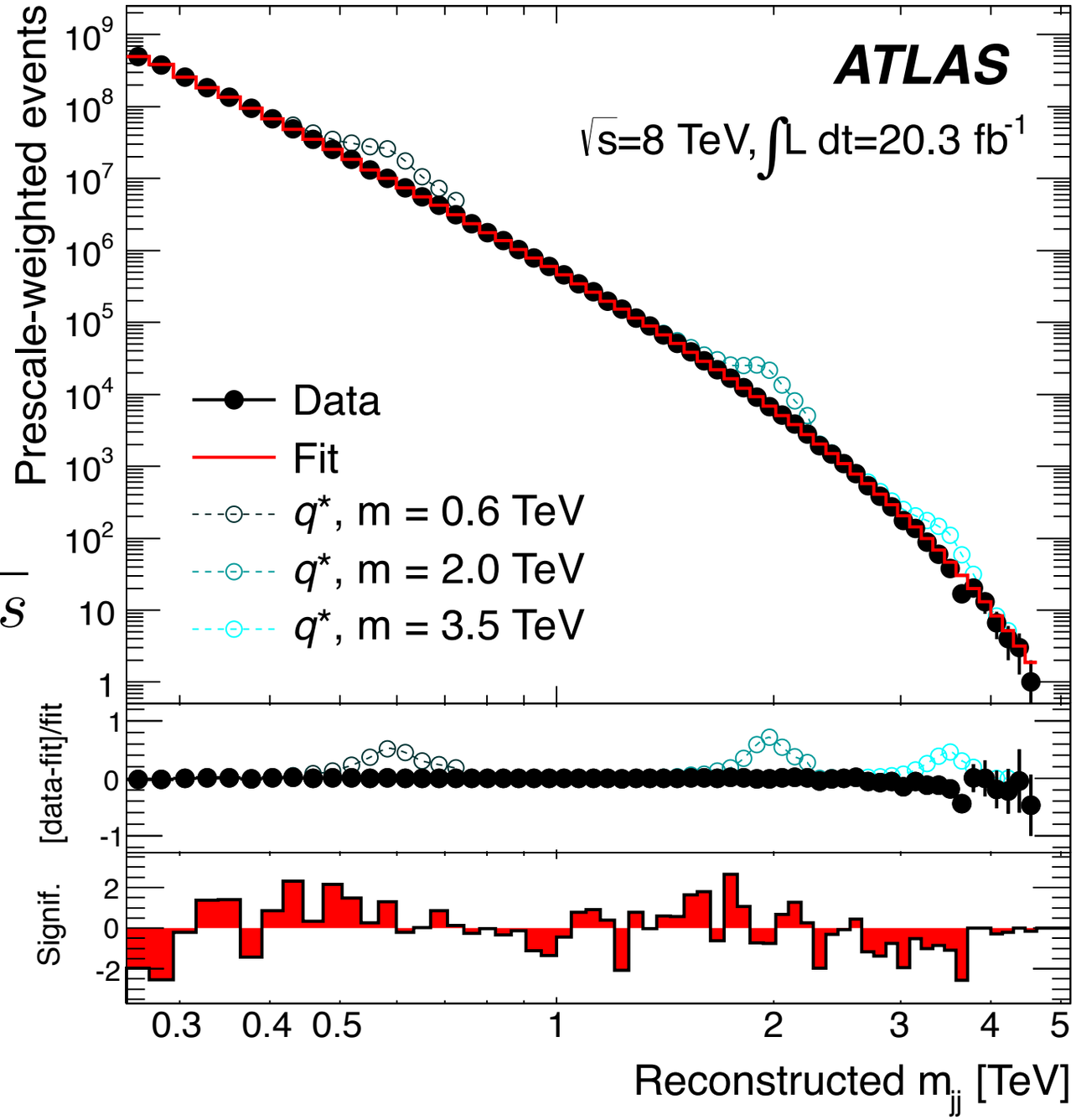
DIJET RESONANCES

- The dijet invariant mass distribution is not especially well modeled by simulation
  - Fit for the background **directly with the data**
    - important that the background function is smooth and falling

$$f(x) = \frac{p_0(1-x)^{p_1}}{x^{p_2+p_3 \log x}}; \qquad x \equiv M_{\mathrm{jj}}/\sqrt{s}$$

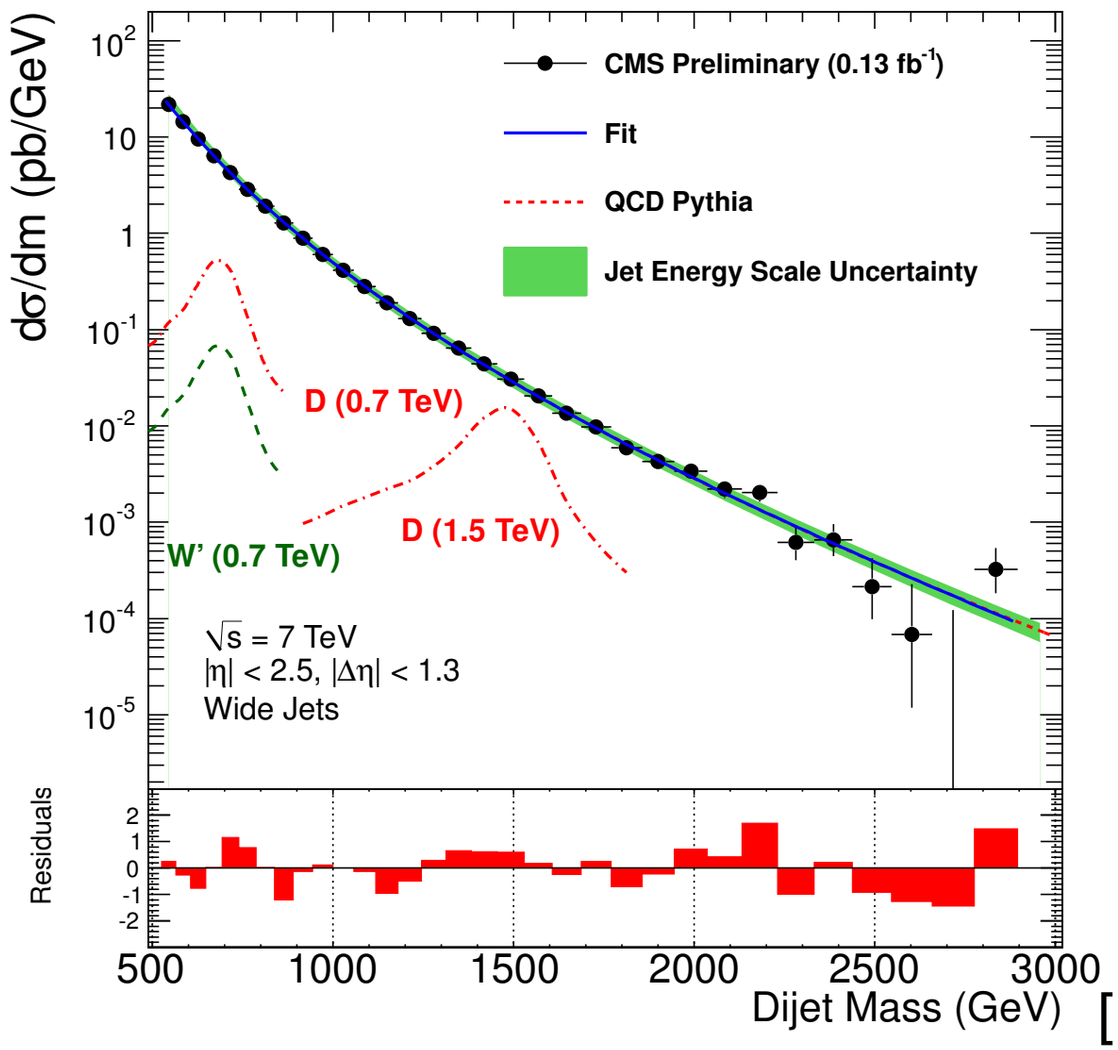


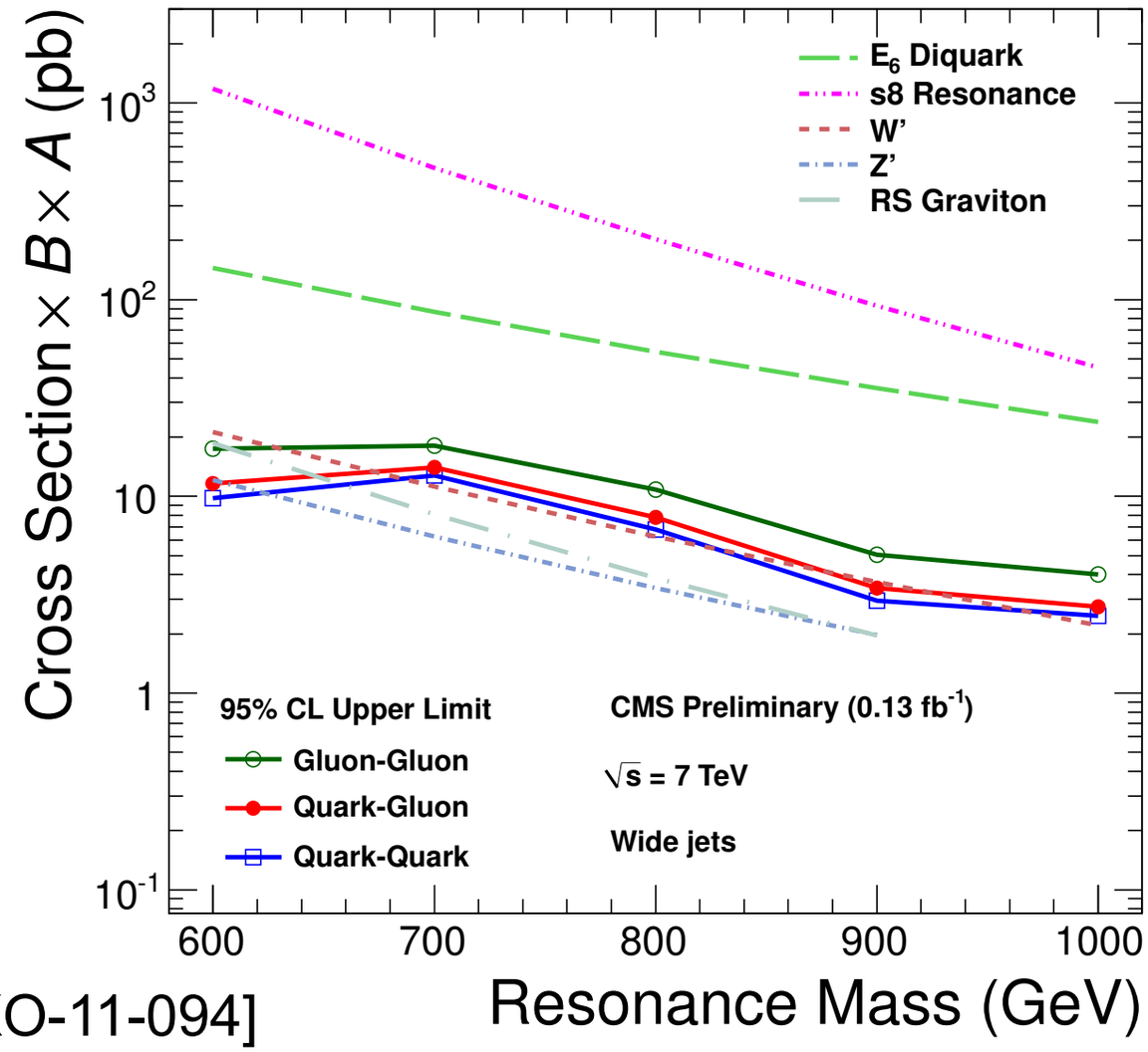
[arxiv:1407.1376]



Data Scouting

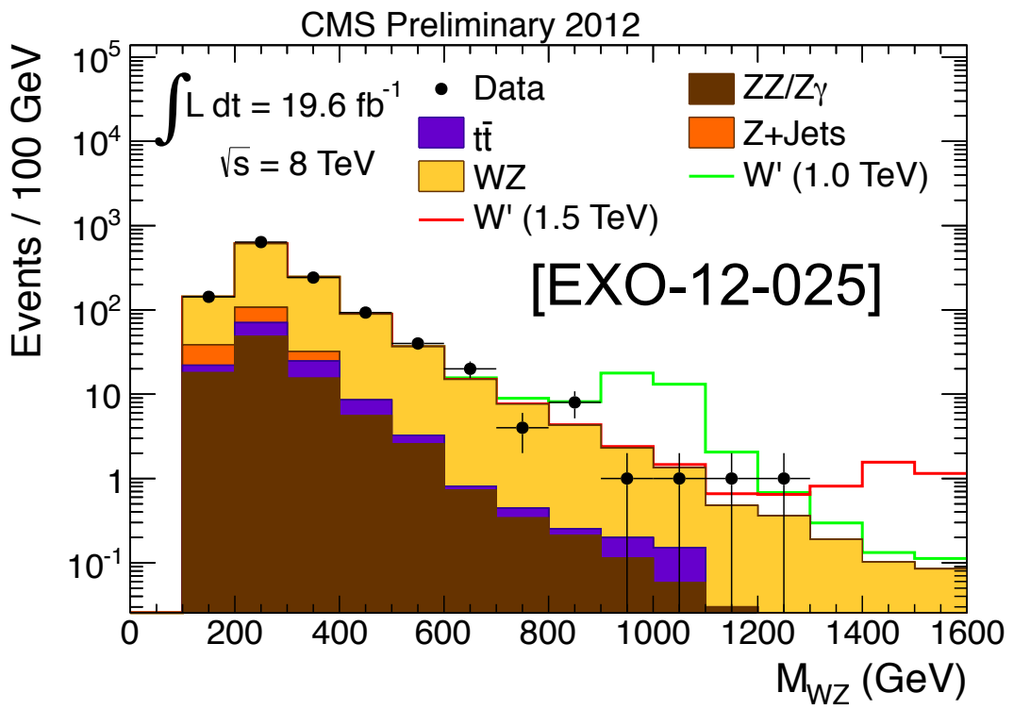
- Novel trigger, DAQ, and analysis strategy to search below 1 TeV
  - Low jet-trigger thresholds means high event rate (~KHz)
  - Store reduced data format (i.e. jets reconstructed at trigger level)

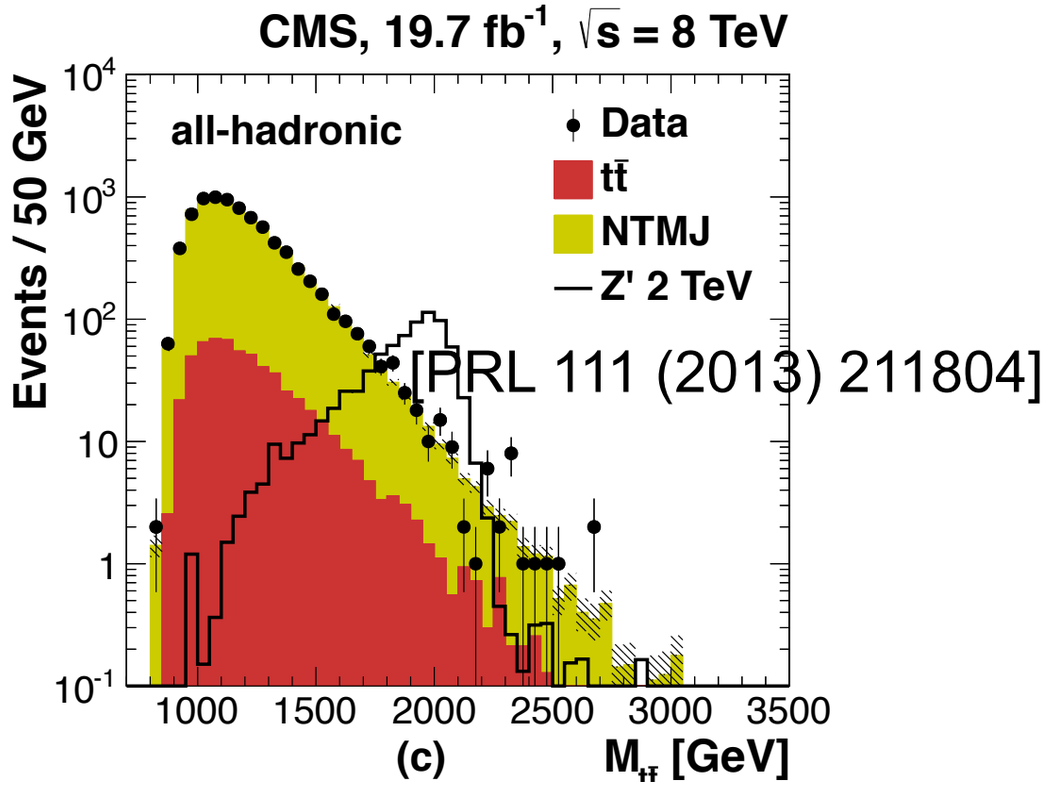




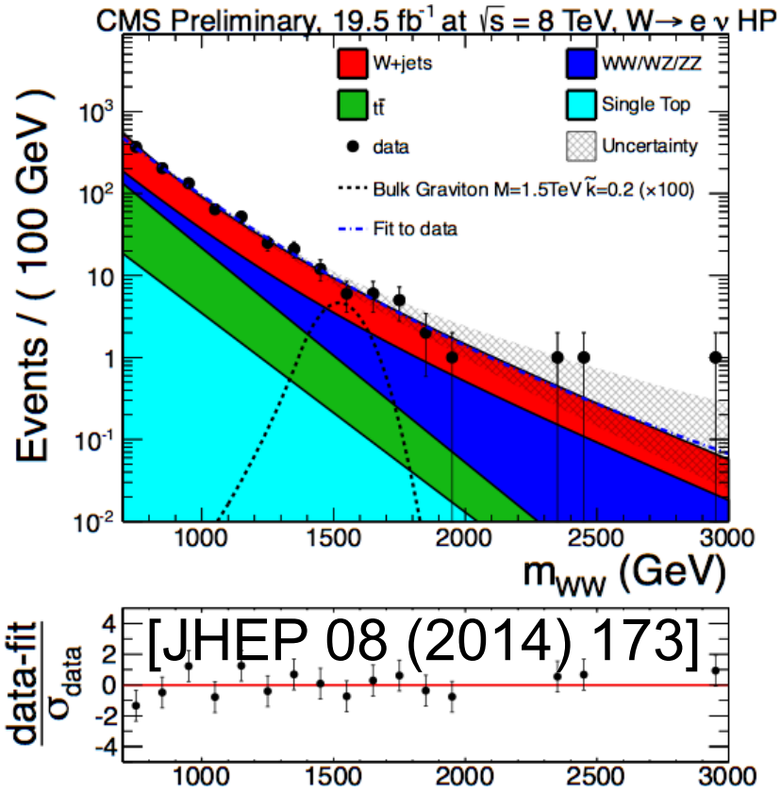
[EXO-11-094]

RESONANCES AND RESONANCES

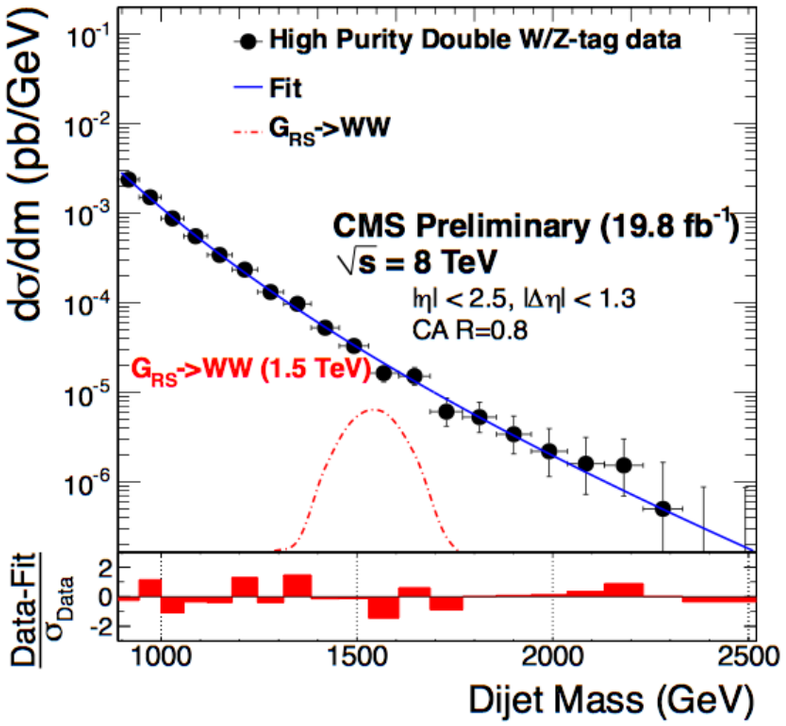




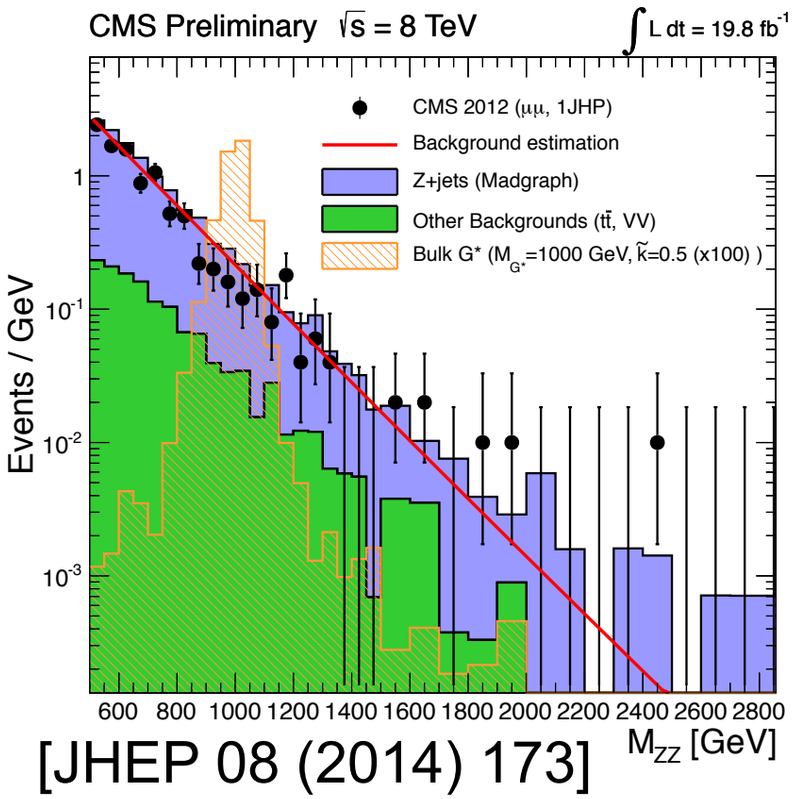
[PRL 111 (2013) 211804]



[JHEP 08 (2014) 173]



[JHEP 08 (2014) 174]

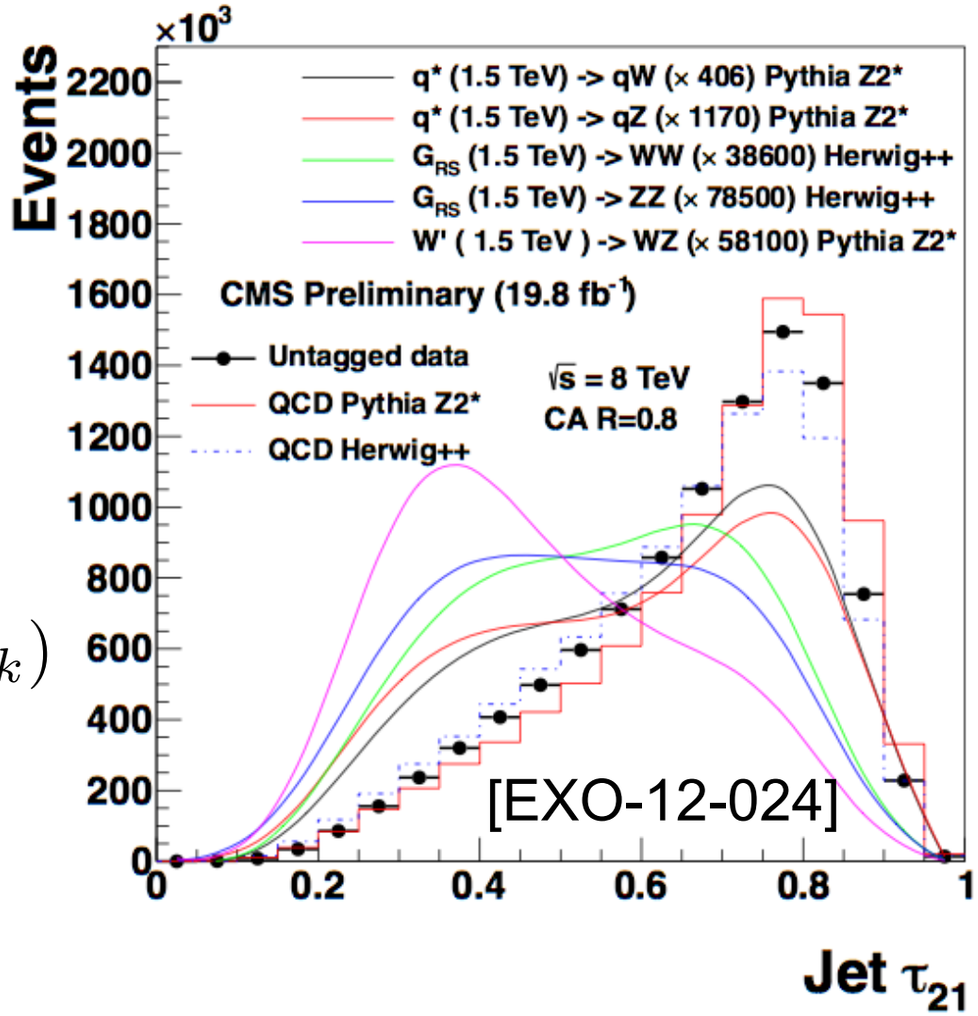


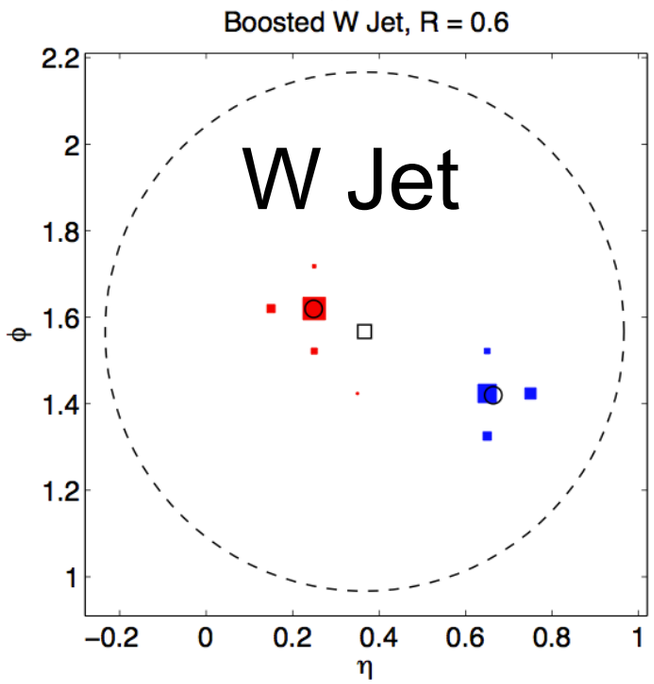
[JHEP 08 (2014) 173]

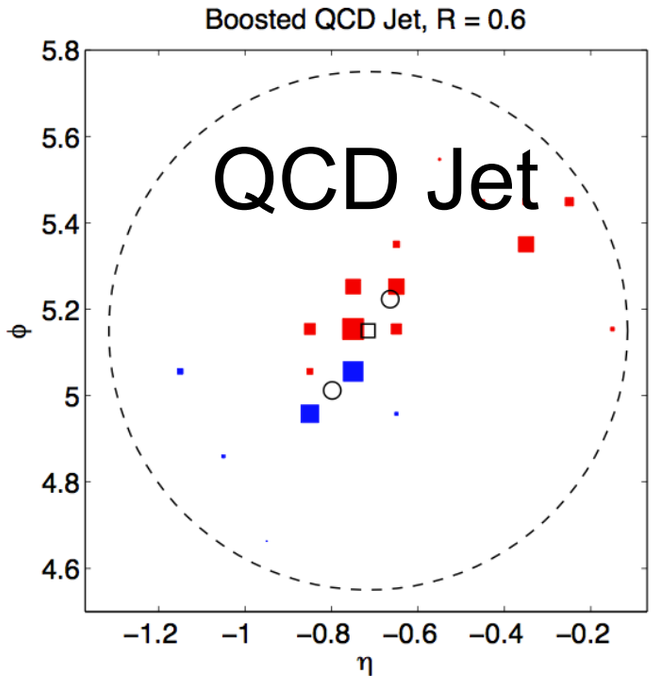
N SUBJETTINESS

- Several different techniques to identify merged jets are on the market...
  - N-subjettiness, τ_N, uses $\tau_{21}=\tau_2/\tau_1$ as a discriminant to separate QCD jets from merged W/Z jets

$$\tau_N = \frac{1}{d_0} \sum_k p_{\mathrm{T},k} \min\left(\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right)$$





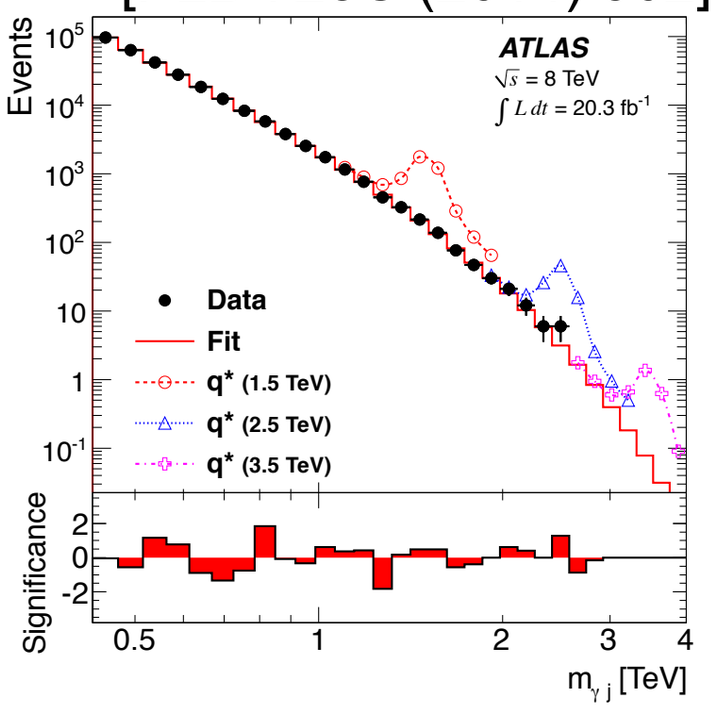


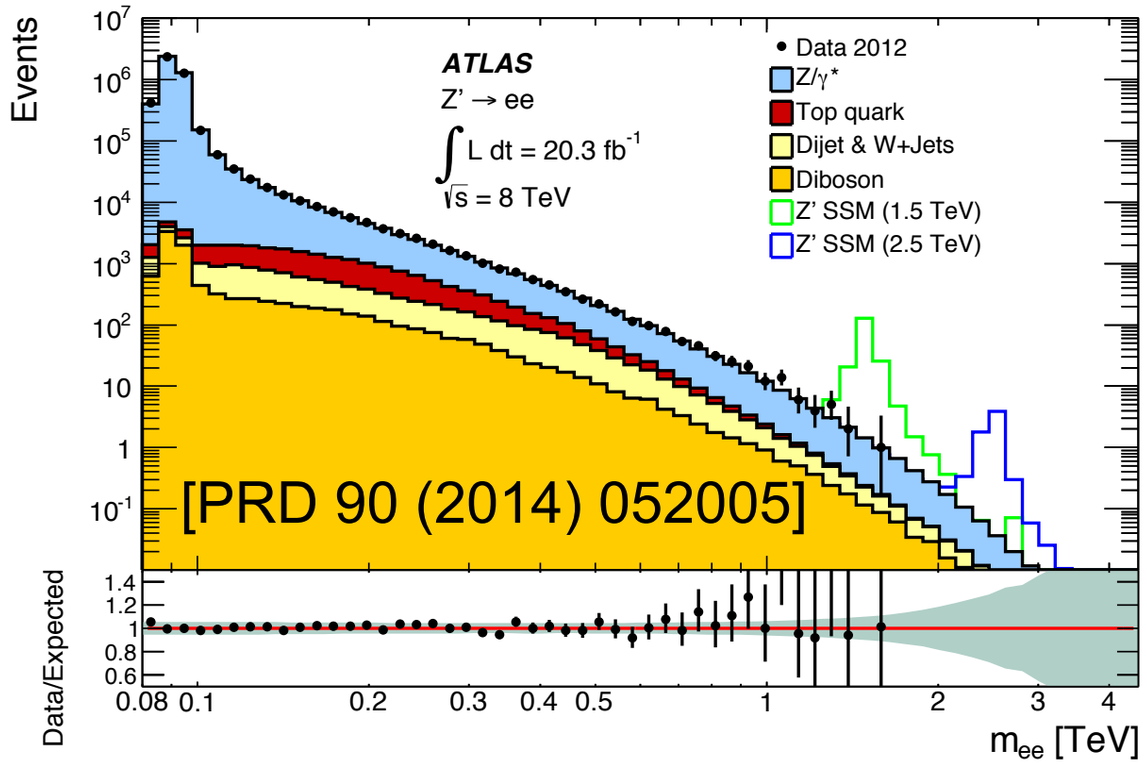
[Thaler, Tilburg, arXiv:1011.2268]

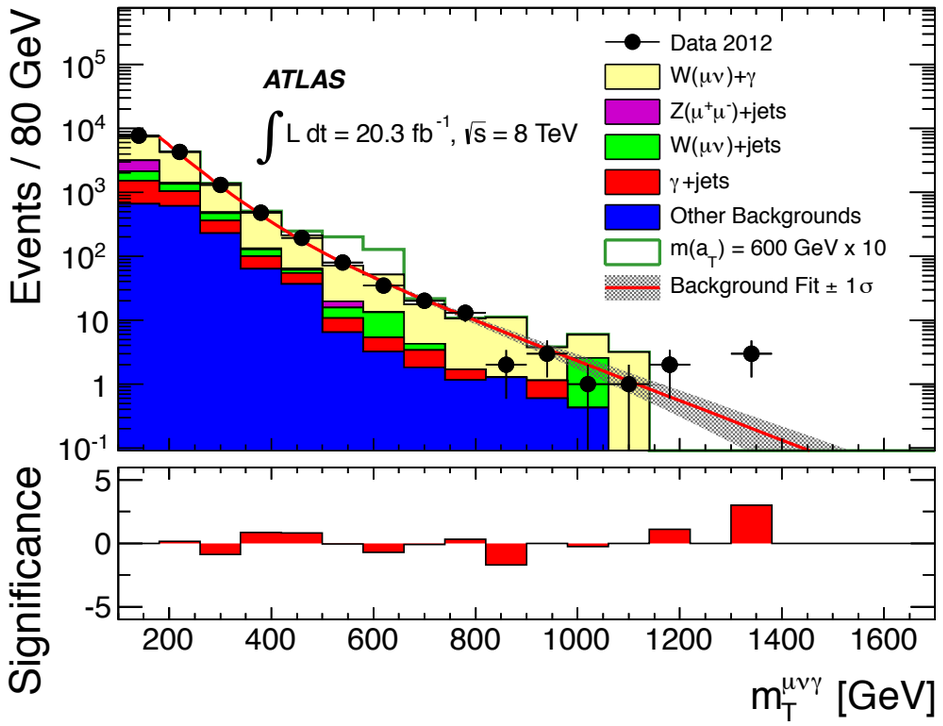
- combine with **pruned jet mass** to select hadronic W's and Z's

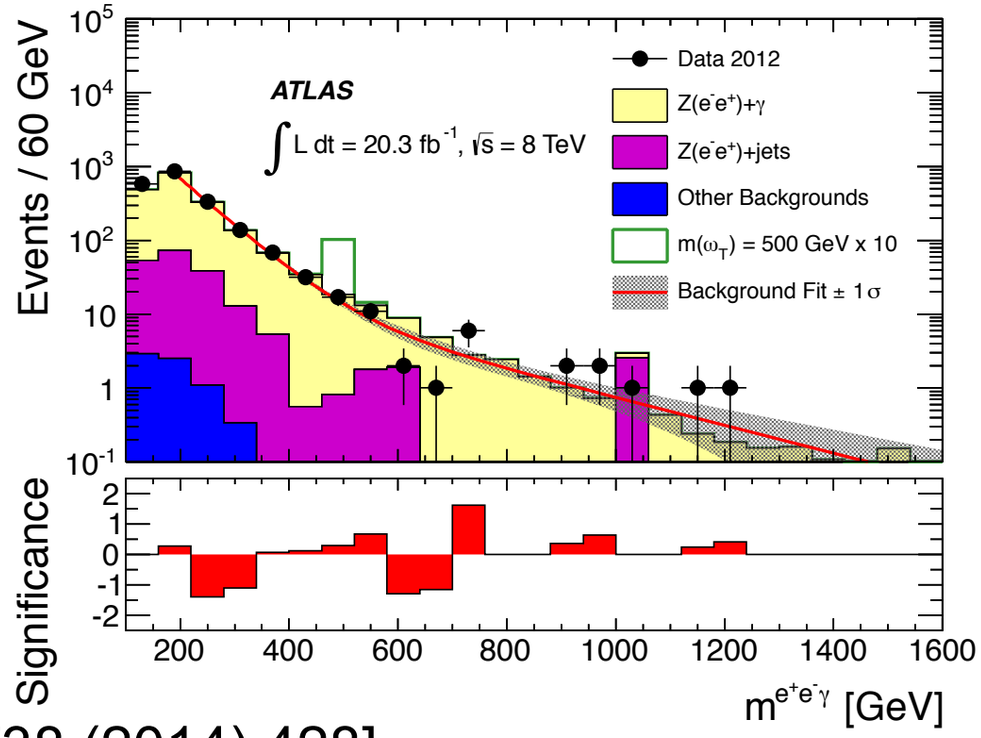
RESONANCES AND RESONANCES

[PLB 728C (2014) 562]







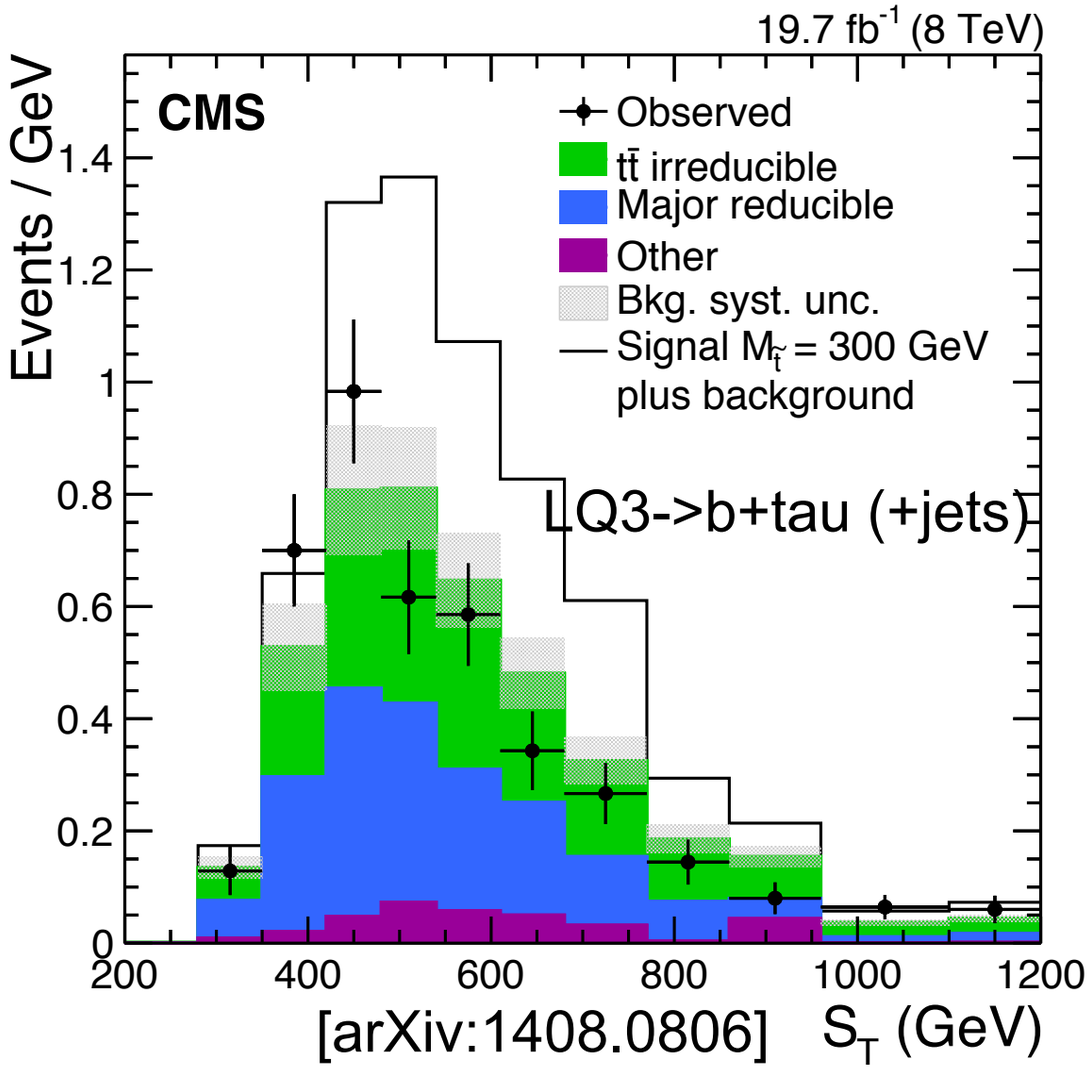


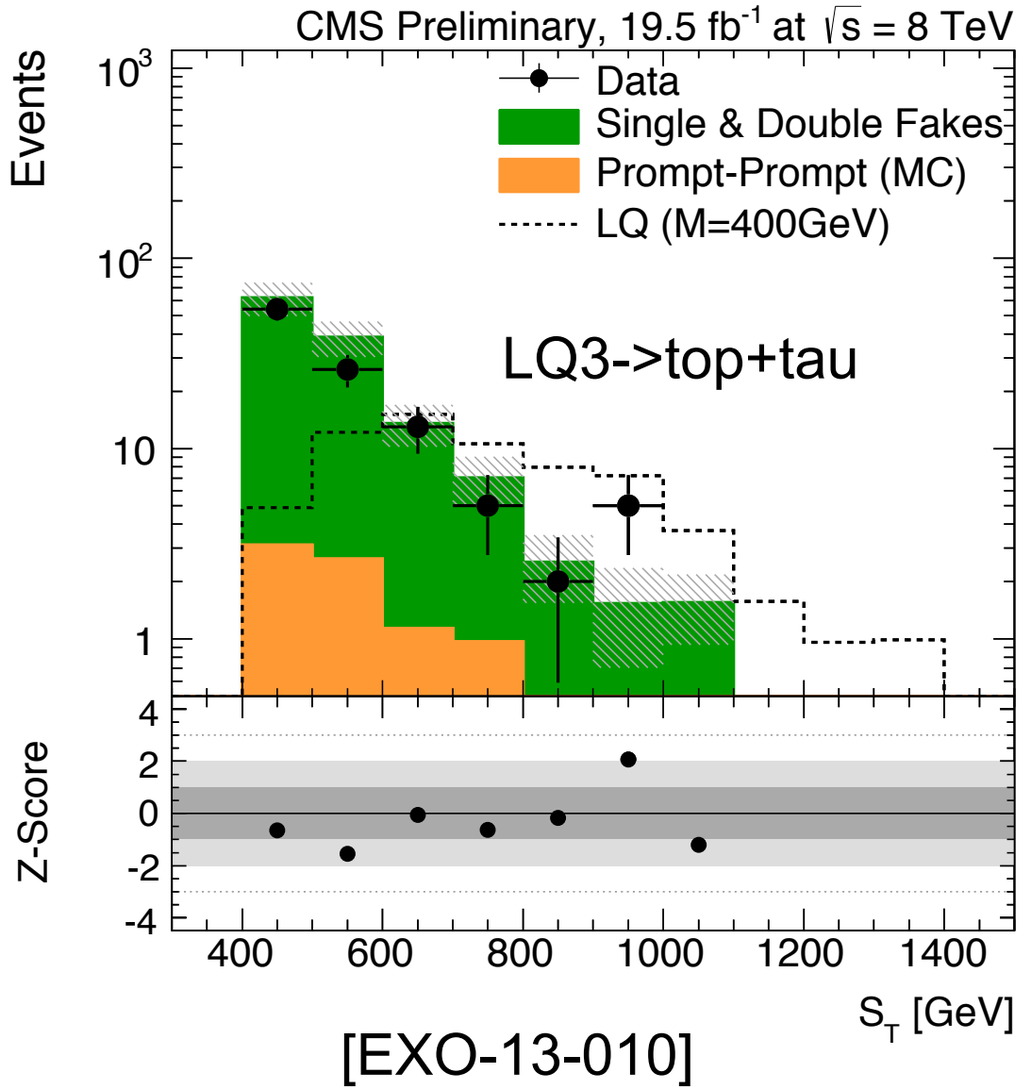
[PLB 738 (2014) 428]

Pair Produced Resonances

3rd Generation ~~Leptoquarks~~ Stops

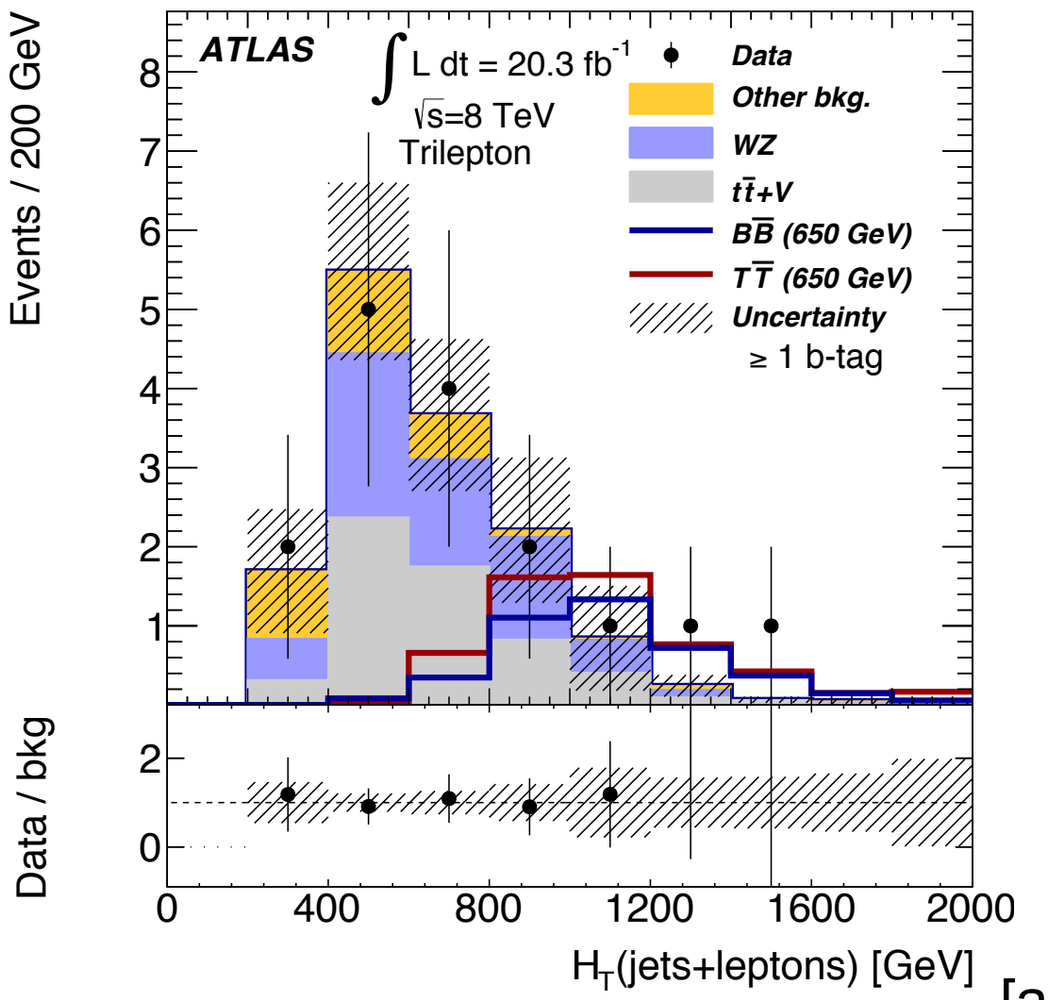
- Broad program to search for leptoquark pair production
  - (Of course, a leptoquark is also an LQD RPV stop, so this is also search for "natural" SUSY)
    - in general, greater emphasis on final states with taus is needed

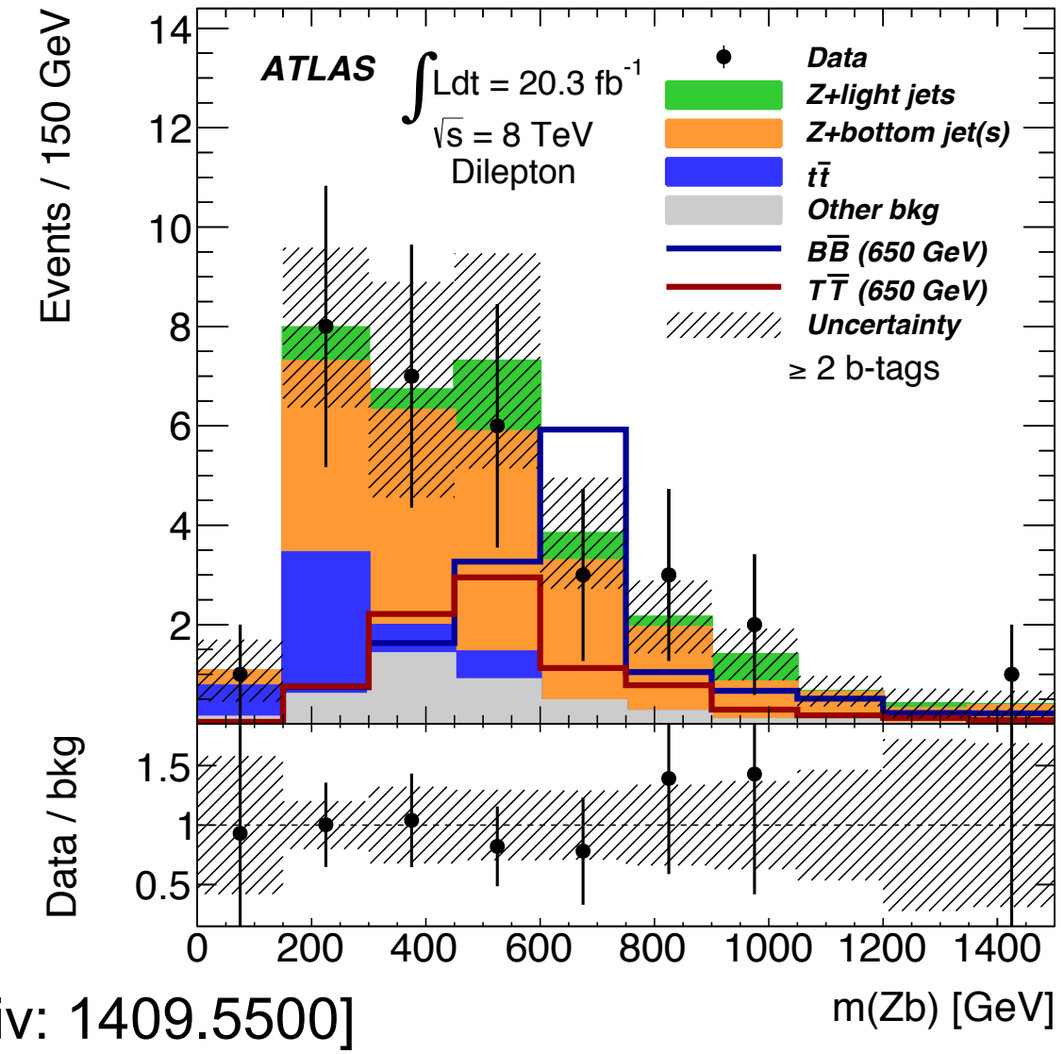




VECTOR-LIKE QUARKS DECAYING TO Z+Q

- Look for Z+0 or 1 extra leptons
  - backgrounds primarily estimated through MC simulation
  - vary number of leptons, b-tags, forward jets, etc.

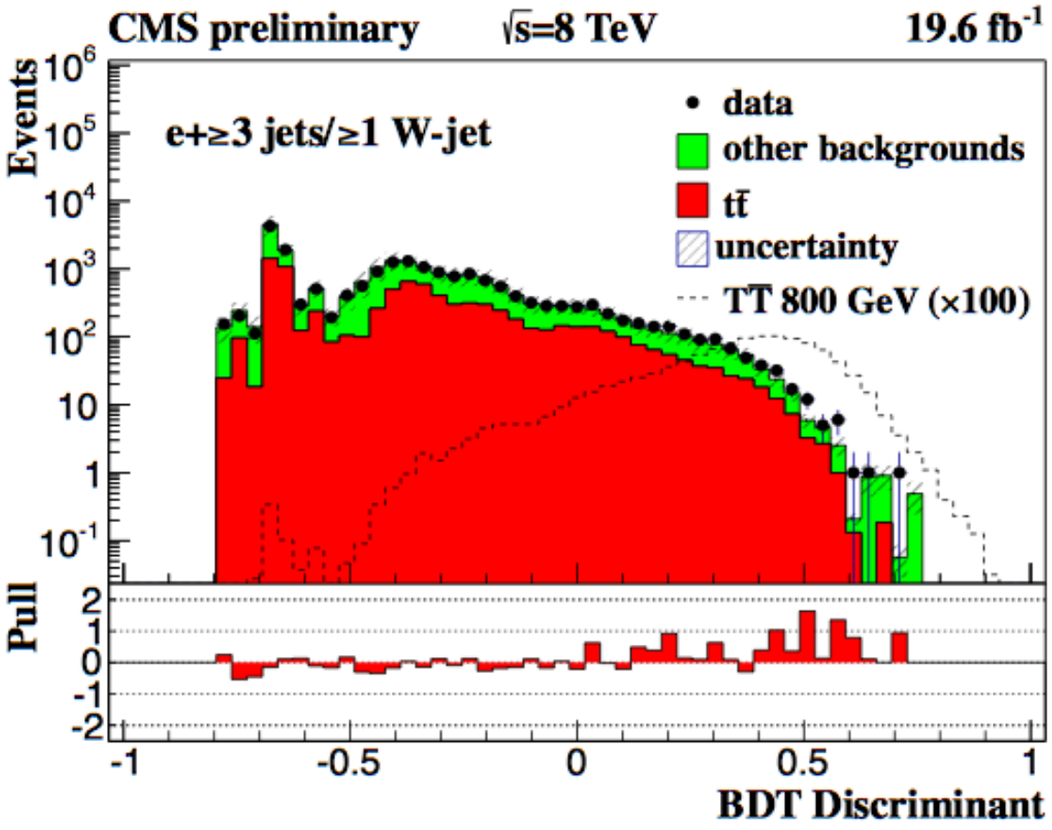


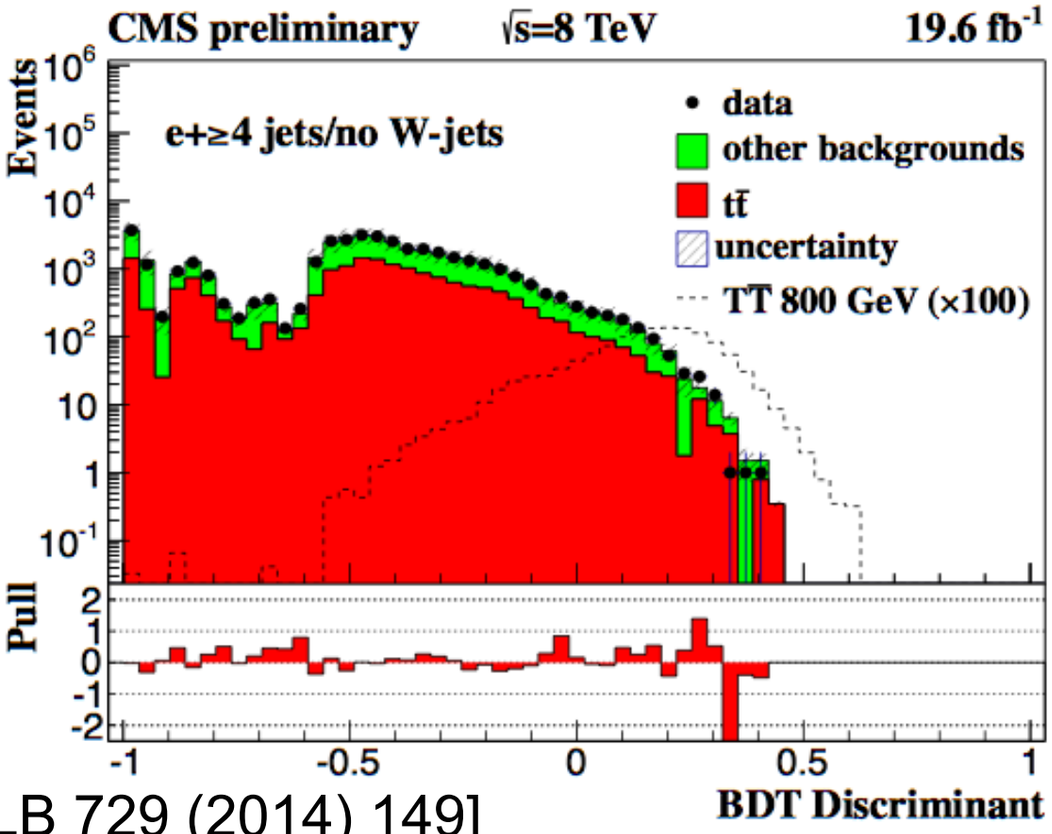


[arXiv: 1409.5500]

VECTOR-LIKE T'→TZ/TH/BW

- Combine information from single lepton, SS dilepton, OS dilepton, and trilepton searches
  - Use BDT trained on # jets, # b-jets, H_T, MET, lepton p_T, 3rd/4th jet p_T
  - Separate BDTs for events **w/ and w/out W-tagged jets**
  - Also consider other categories of events based on the number of leptons, lepton sign, and Z vetos



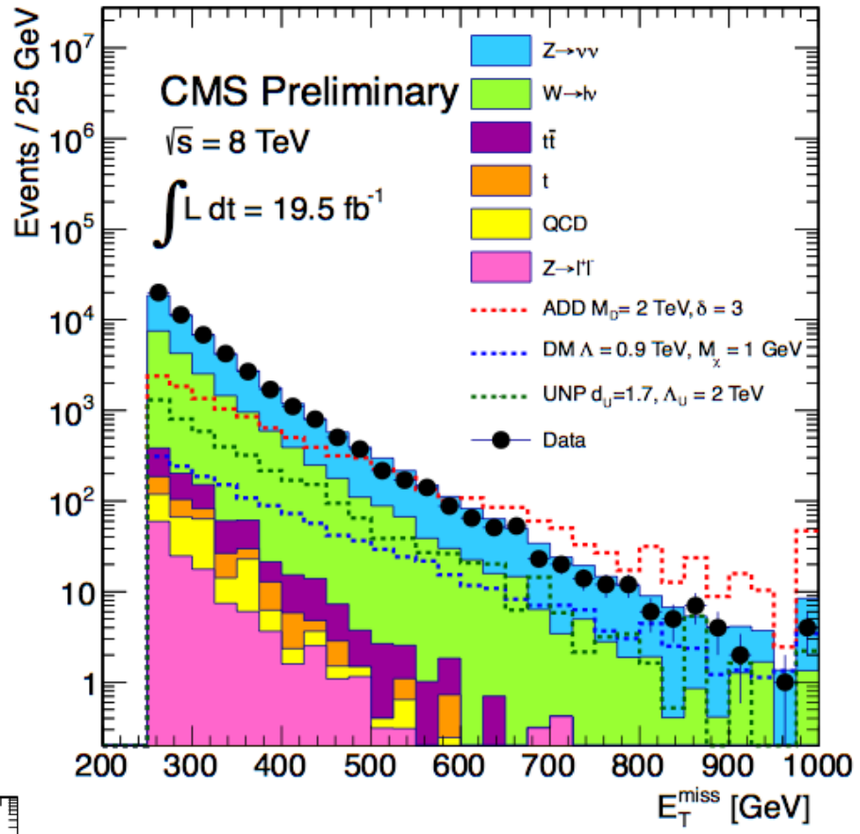


[PLB 729 (2014) 149]

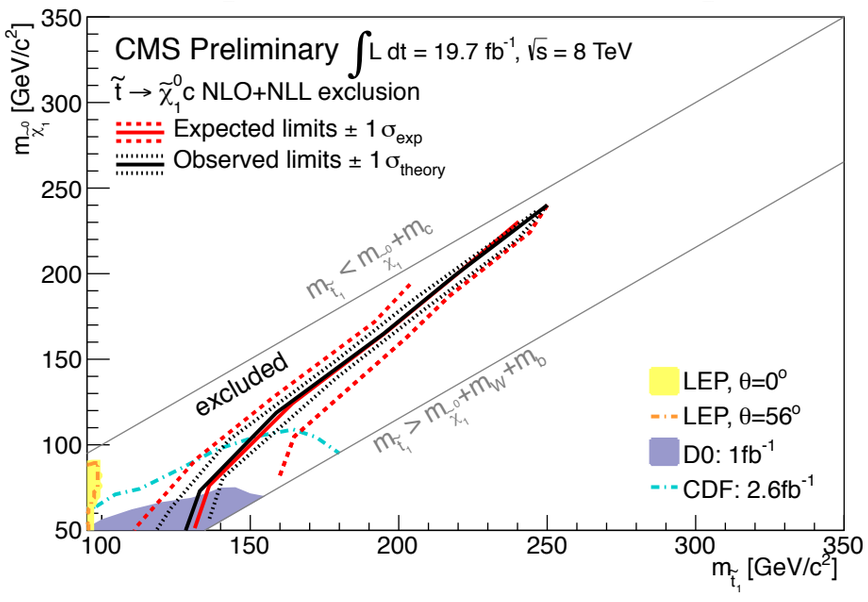
Dark Matter

MONOJETS

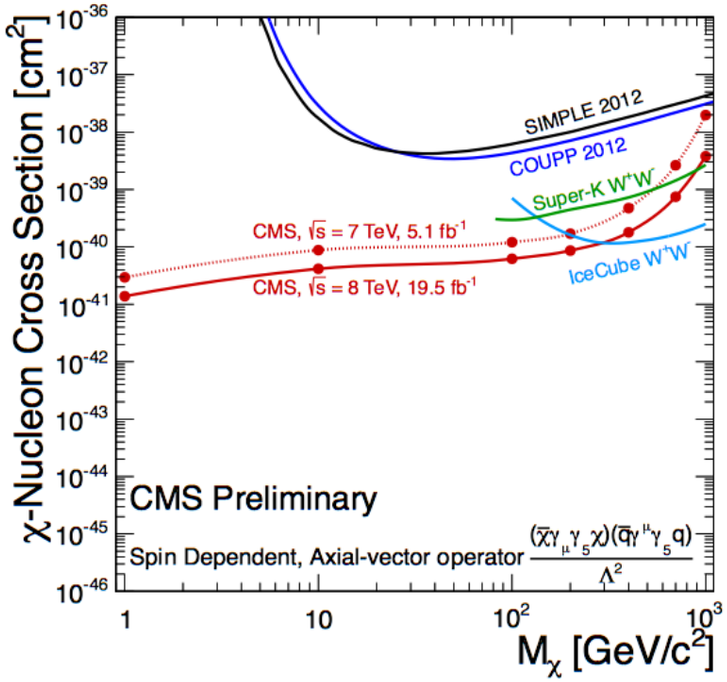
- Search for **1-2 jets** recoiling against MET
  - Leading jet has p_T>110 GeV and $|\eta|$<2.4
    - allow second jet with p_T>30 GeV
  - **MET threshold determined by trigger**
- Re-optimized cuts to look for stop→c+LSP
  - no charm tagging; just require harder 2nd jet

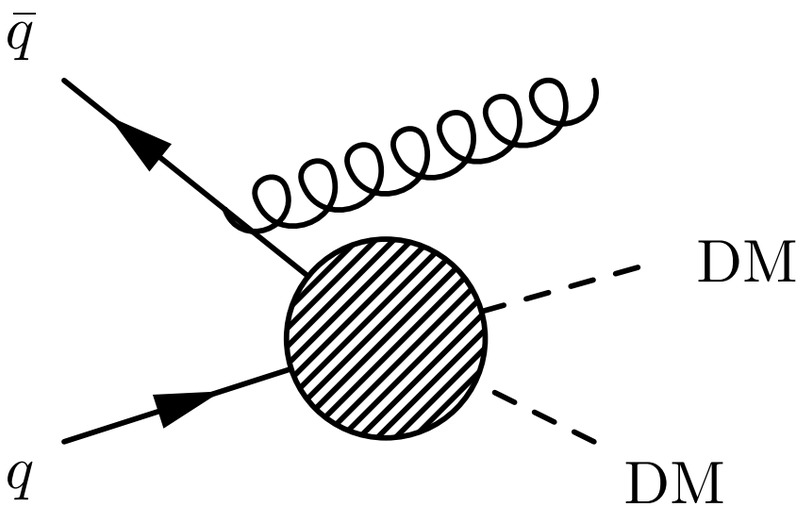


[CMS-SUS-13-009]



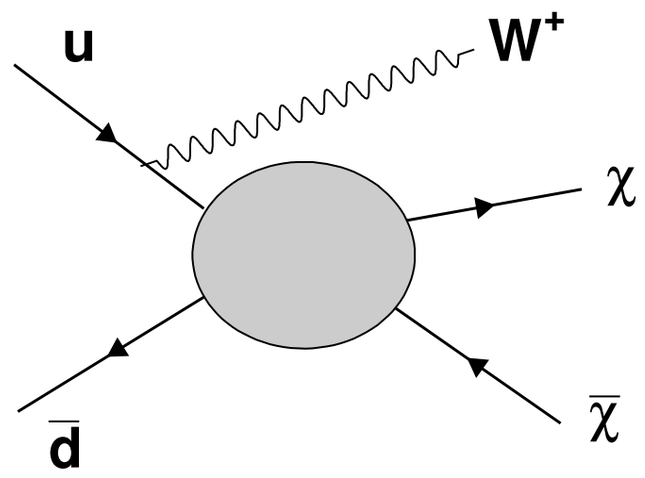
[arXiv:1408.3583]

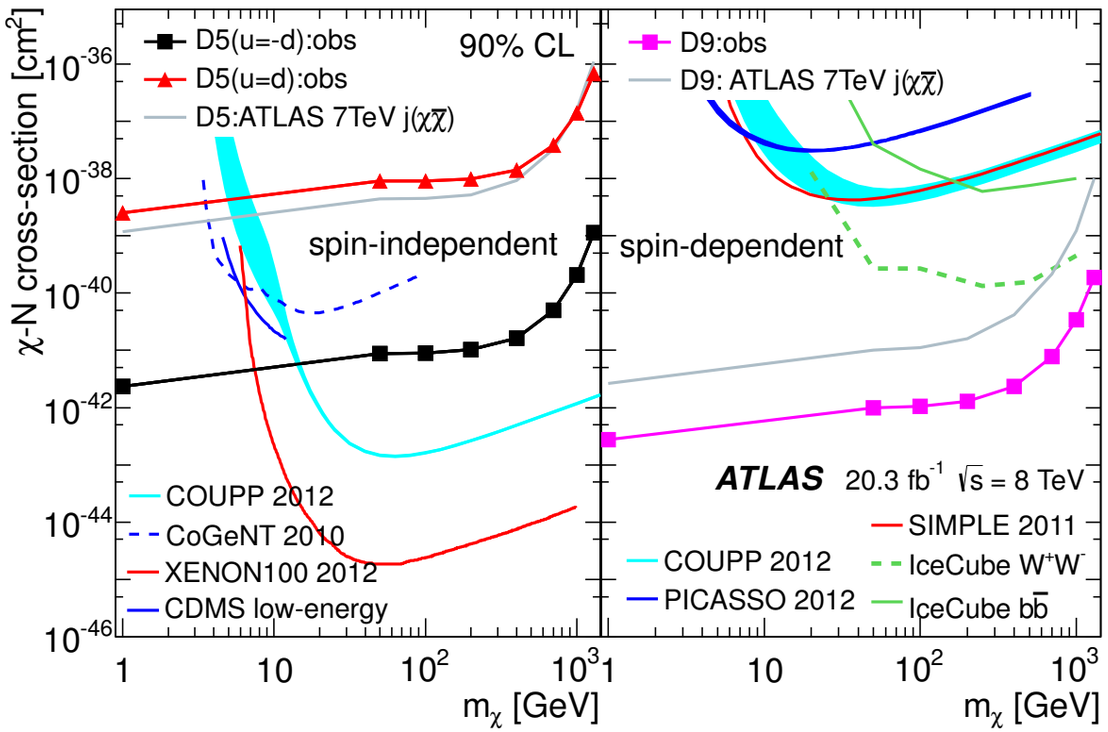


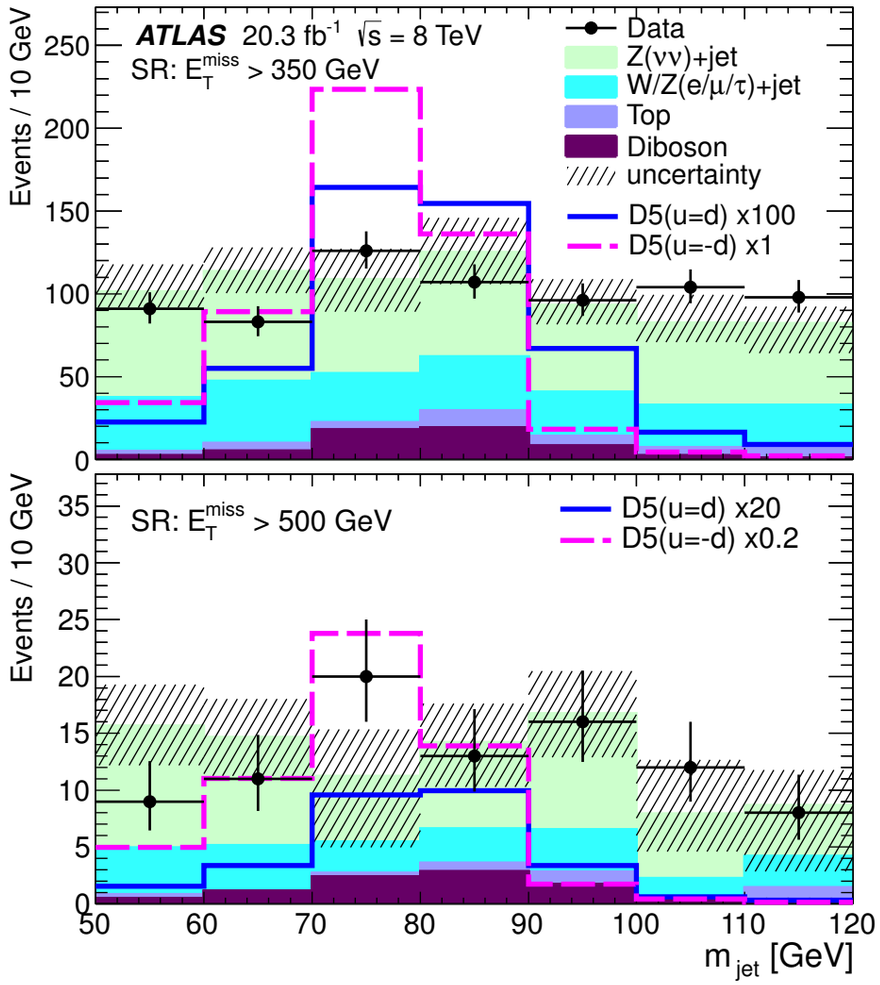


MONO-W(HADRONIC)

- Fat CA 1.2 jet with mass-drop filtering to “tag” hadronic W
  - use leptonic W/Z to control dominant Z(vv)+jet backgrounds
    - note that interference of W with u/d can lead to large enhancements in the production xs



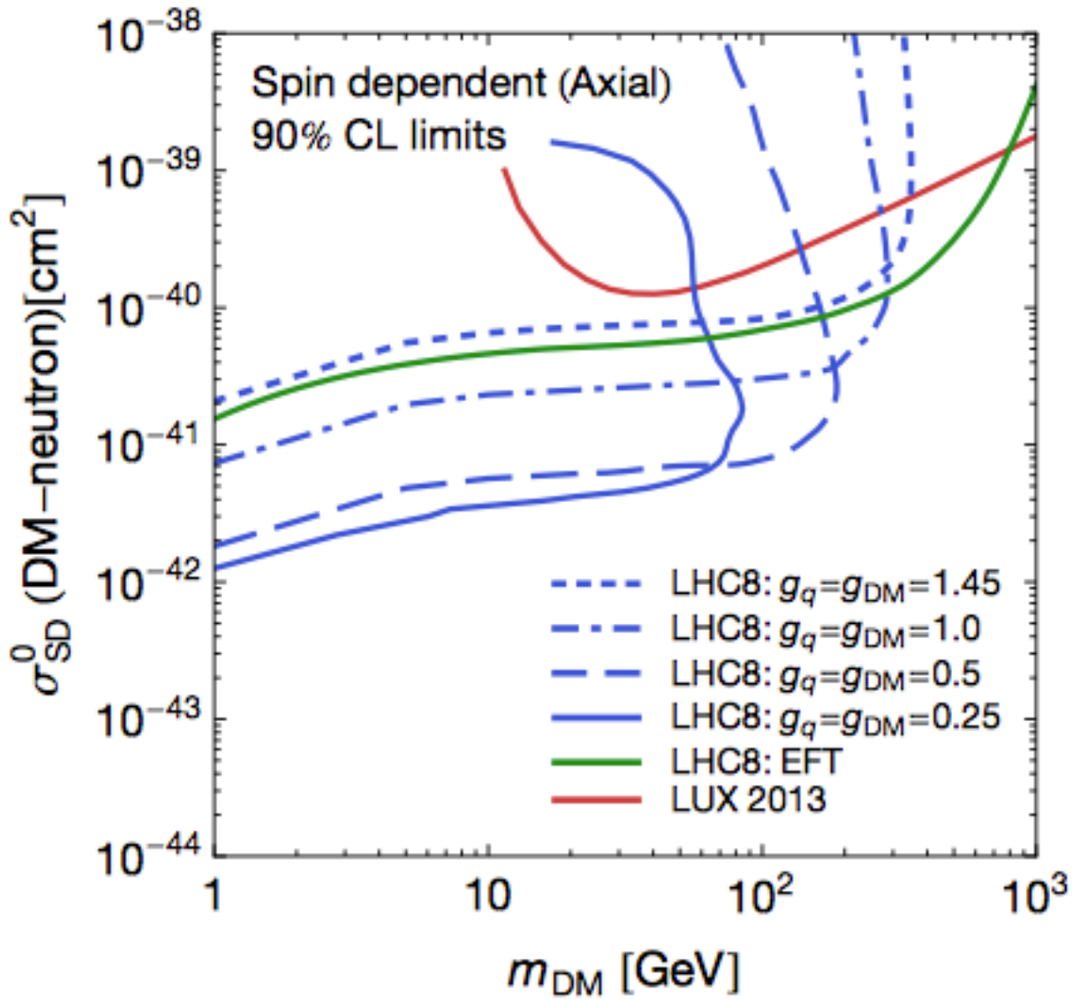


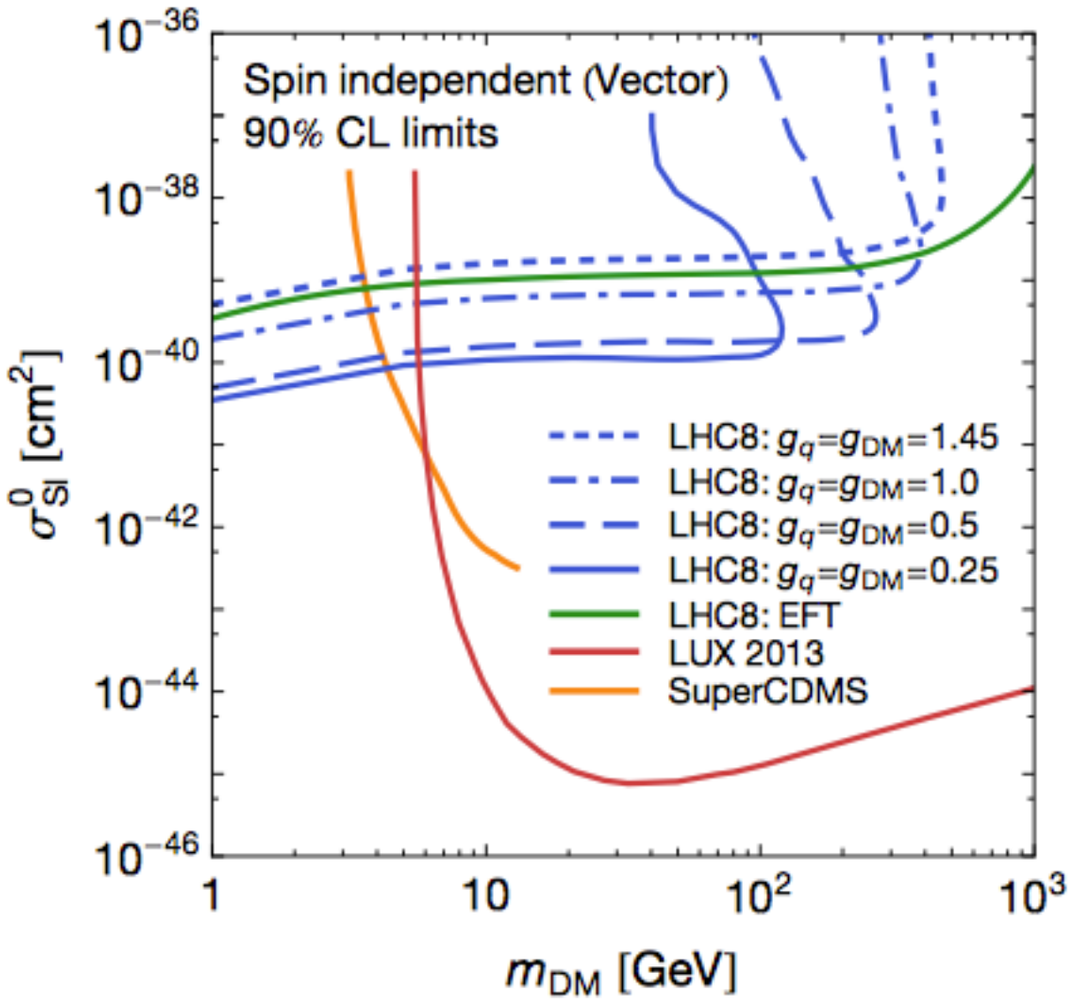


BEYOND EFTS

- Integrating in an s-channel mediator (a la Z prime) gives qualitatively different bounds than the EFT approach
  - sometimes more conservative, sometimes more aggressive

[arXiv:1409.4075]





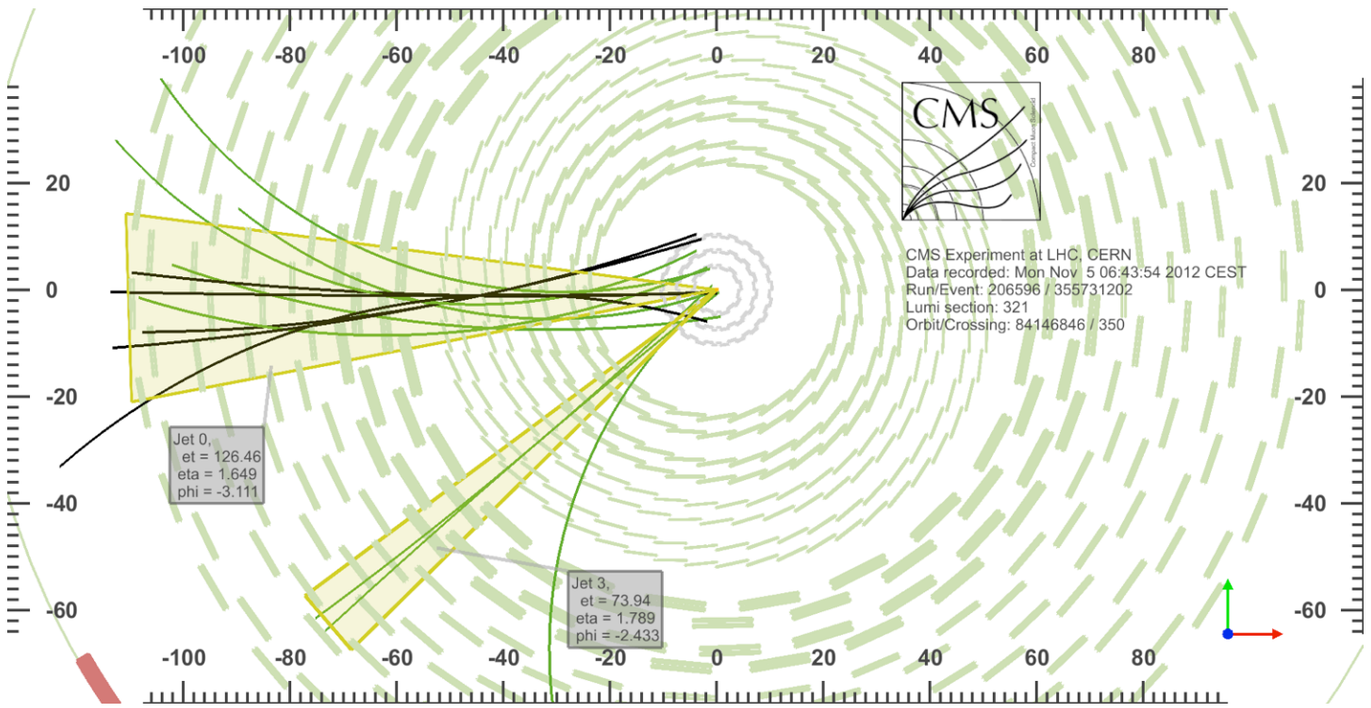
Beyond Dark Matter

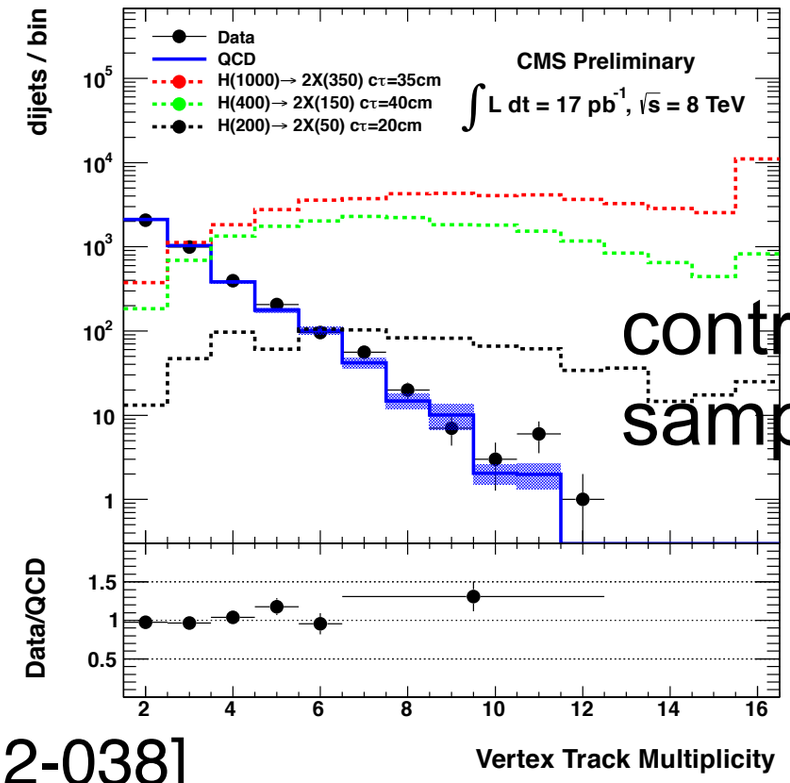
- Monojet searches are really a strategy for new physics searches where we can't trigger on the underlying physics
  - Fundamentally an ISR jet trigger + invisible/unknown/poorly understood/badly reconstructed new physics
  - An entire physics program awaits where we have only scratched the surface
    - Monojet where the jet is b/W/Z/H/non-SM tagged
    - Monojet + soft lepton(s)
    - Monojet + highly ionizing track(s)
    - Monojet + disappearing track(s)
    - Monojet + displaced track(s)/jet(s)/lepton(s)
    - …
- Don't forget that the EWK-scale is only ~200 GeV
  - i.e. why it's important to keep the trigger thresholds as low as possible

Long-Lived Searches

Displaced Dijets

- Massive long-lived particles can decay to jets
  - Split SUSY, RPV SUSY, Gauge Mediated SUSY, Hidden Valley models, etc.
- Search for events with **dijets from a common, displaced vertex**
  - Trigger on events with H_T>300 GeV and **≥2 jets with small fraction of prompt tracks**
    - Offline: form multivariate discriminant based on vertex track multiplicity, fraction of tracks with positive d0, # of missing hits, and variables from a **dedicated track clustering algorithm**





control sample

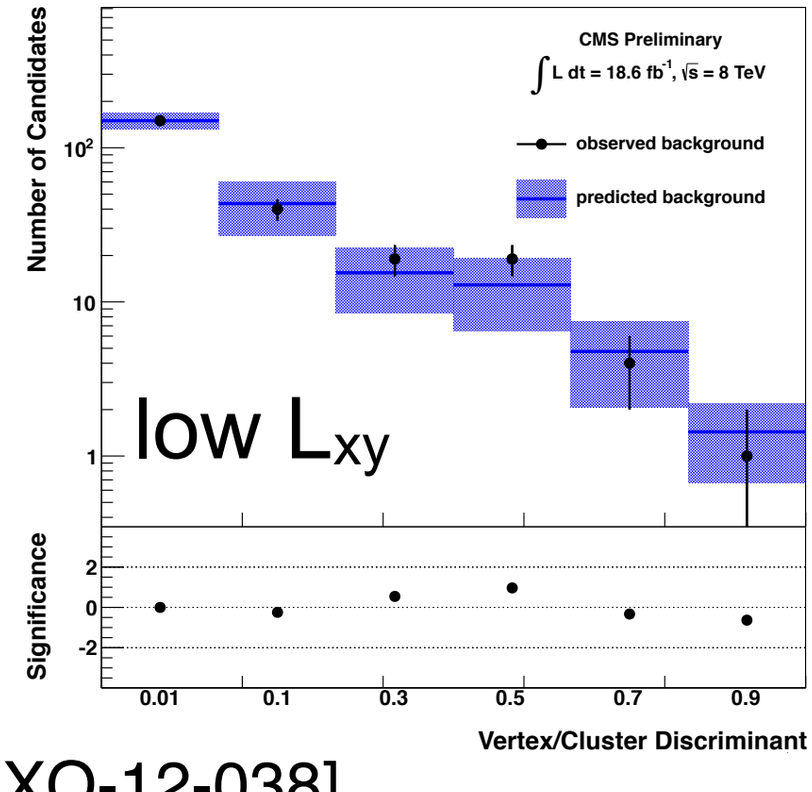
[EXO-12-038]

DISPLACED DIJETS

- Search strategy: Identify two (overlapping) search regions targeting signals with low and high L_{xy}

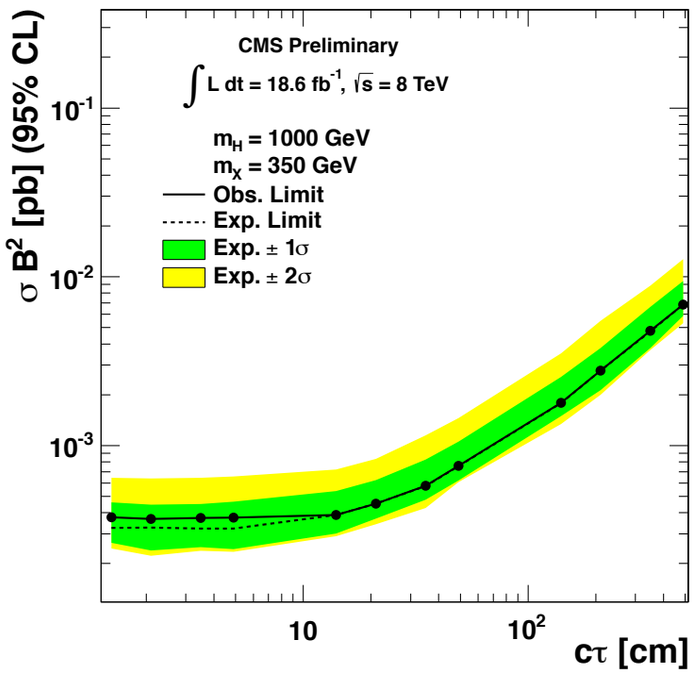
$\mathbf{L_{xy}}$	$< \mathbf{20\ cm (low)}$	$> \mathbf{20\ cm (high)}$
prompt tracks	≤ 1	≤ 1
prompt energy fraction	< 0.15	< 0.09
vertex/cluster disc.	> 0.9	> 0.8
expected background	$1.60 \pm 0.26(stat.) \pm 0.51(syst.)$	$1.14 \pm 0.15(stat.) \pm 0.52(syst.)$
observed	**2**	**1**

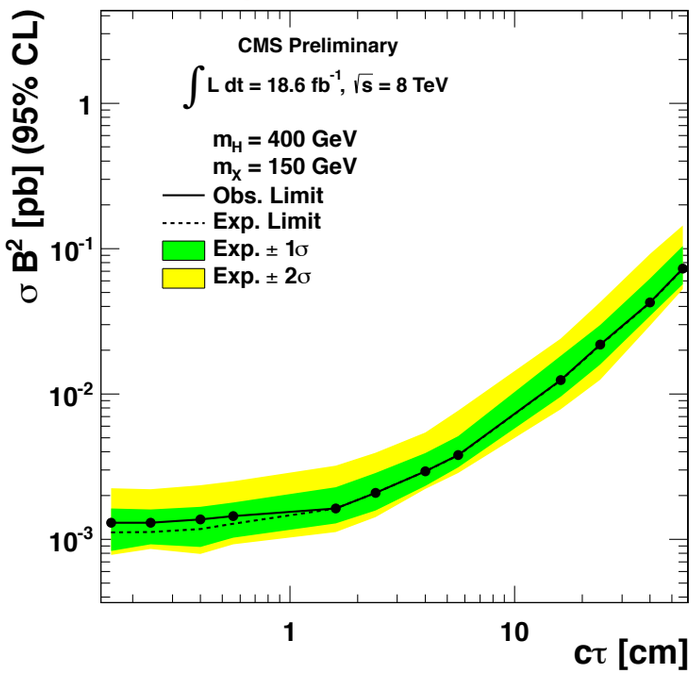
Table 1: Predicted background and the number of observed candidates for optimised selections.



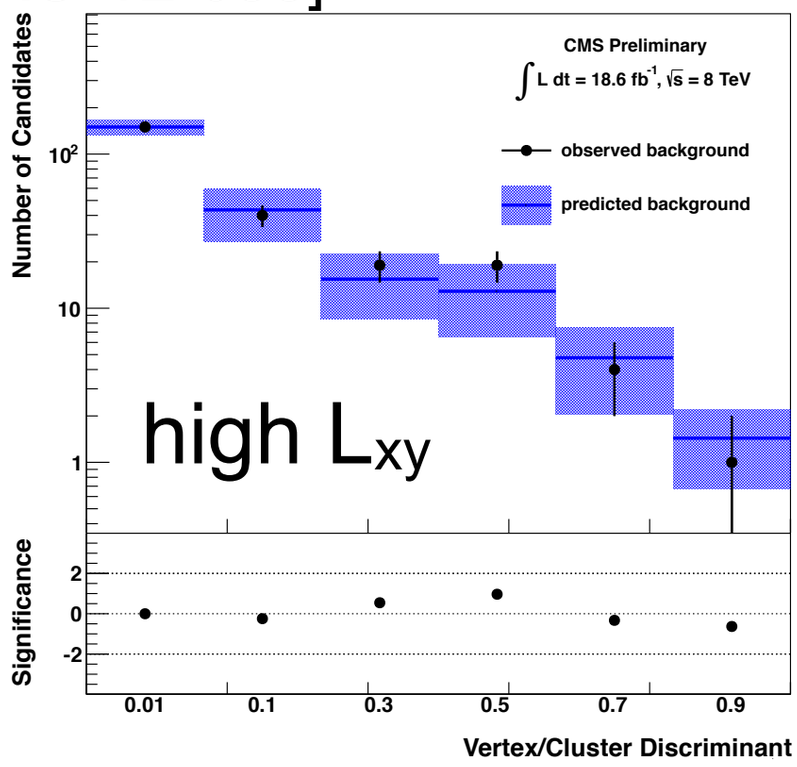
[EXO-12-038]

- Use data-driven techniques (generalized ABCD method) to estimate backgrounds





Set limits on H→XX→(jj)(jj)



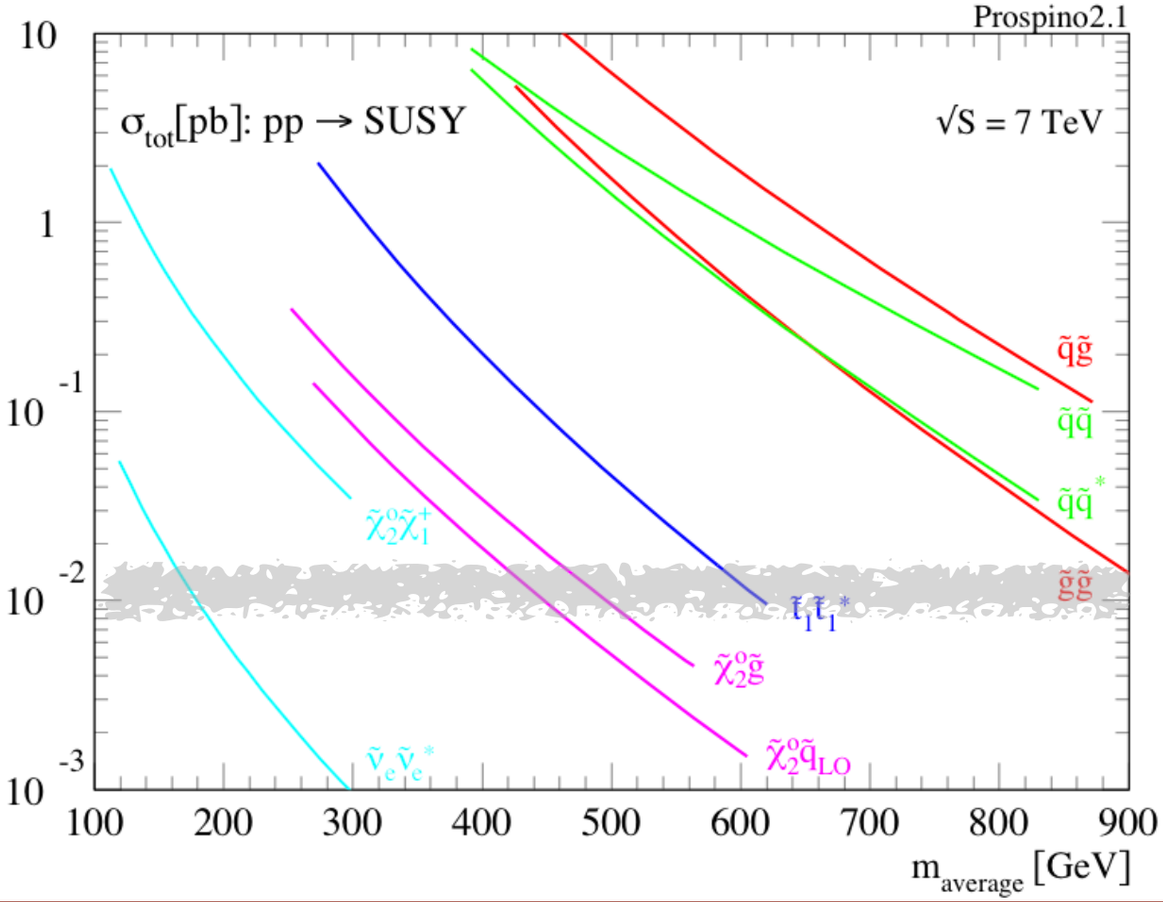
What's Missing from Displaced Dijets?

- The analysis requires two displaced jets from the same vertex
  - Note that some models have two displaced jets from the same vertex, but because of the boost, the jets merge
- Trigger requires HT>300 GeV
  - Can't go after H(125) because of this
  - Should look in other channels: inclusive VBF, lepton+X, etc.
- Insensitive to lifetimes $\lesssim$1 mm and $\gtrsim$1 m

What we haven’t search for

GAPS IN COVERAGE

- Despite significant progress over the past few years, there are still many gaps
  - Of course, defining a "gap" is arbitrary: can always make things heavier or more weakly coupled
    - For concreteness, consider **pair production** of **colored states** with masses at the **EWK scale**. Are there any decay topologies that we missed?



Stop pair production provides the scale that we need to explore: ~10 fb

RPV SUSY AS MOTIVATION

- paper by Evans and Kats (JHEP 04 (2013) 028) examined virtually every search performed by CMS and ATLAS and evaluated the sensitivity to stops decaying via UDD, LQD, and LLE operators
  - upshot: little sensitivity to final states dominated by multijets (and no MET) and taus
    - (assuming m_{stop} ~100-500 GeV)

Abstract

We examine the sensitivity of recent LHC searches to signatures of supersymmetry with R-parity violation (RPV). Motivated by naturalness of the Higgs potential, which would favor light third-generation squarks, and the stringent LHC bounds on spectra in which the gluino or first and second generation squarks are light, we focus on scenarios dominated by the pair production of light stops. We consider the various possible direct and cascade decays of the stop that involve the trilinear RPV operators. We find that in many cases, the existing searches exclude stops in the natural mass range and beyond. However, typically there is little or no sensitivity to cases dominated by UDD operators or LQD operators involving taus. We propose several ideas for searches which could address the existing gaps in experimental coverage of these signals.

Super Light Gluinos

- Bound on colored particles from alphaS running: >~ 50 GeV
  - Kaplan, Schwartz PRL 101 (2008) 022002
- Bounds from Tevatron on all-hadronic decays of gluons begin around 100 GeV
  - no bounds between 50-100 GeV!

Other Gaps

- Bounds on decays with lots of MET are strongly constrained
  - However, easy to replace MET with jets (RPV, stealth, etc.) where bounds are much weaker
- Strong constraints on events with >=3 isolated leptons
  - constraints considerably weaker if leptons are systematically non-isolated
- Many models of long-lived/hard to reconstruct particles not explored
  - triggering is a big issue: need think of mono-jet, mono-photon, mono-lepton, VBF, etc, as **model-dependent backup triggers** for really exotic physics
- Resonances decaying into non-SM particles
- And many more…

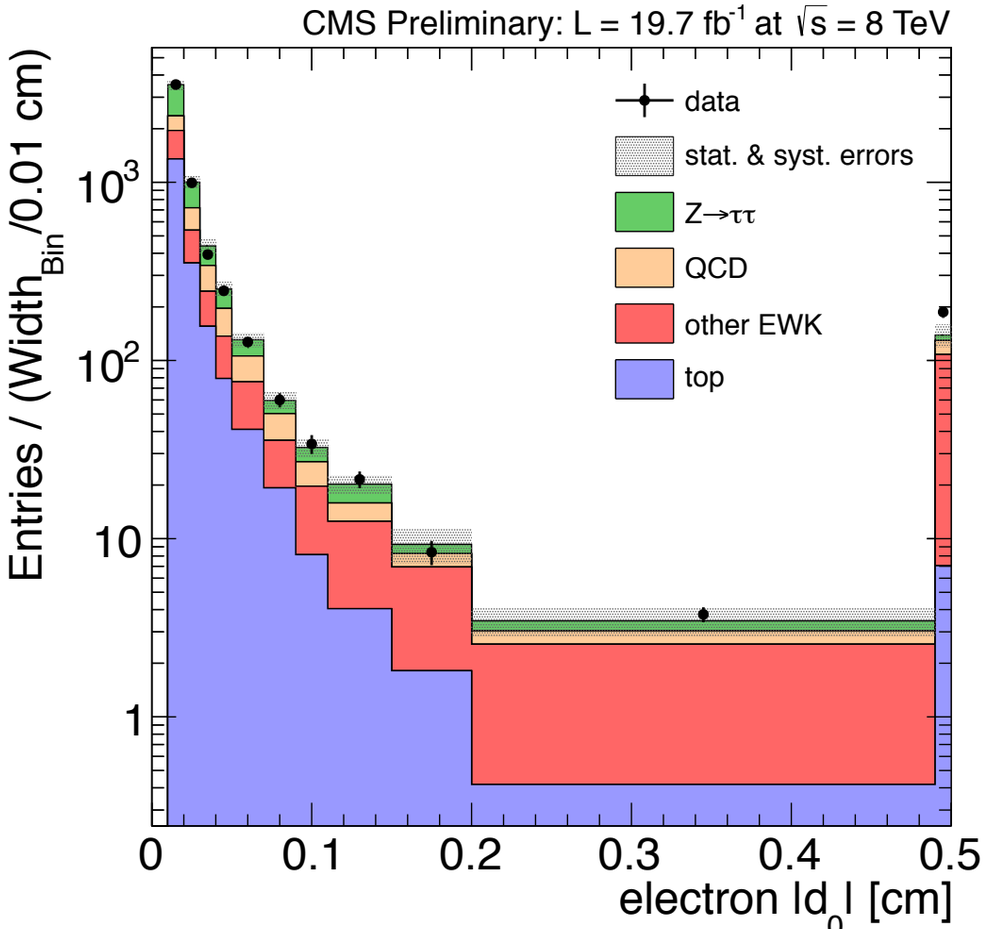
Conclusions

- Searches for new physics is covering a very large space
  - Still, gaps remain, even as we are trying to close them
    - s-channel resonances are pretty strongly constrained
      - nevertheless, resonances produced in association with other particles is largely unexplored territory
  - Electro-weak scale physics will only get more difficult as we increase the sqrt(s)
    - Should be thinking now about trigger strategies, etc. (this is especially bad for **multijet and tau final states**)
  - monojet, monophoton, VBF, inclusive lepton are **model dependent** ways of triggering on physics that we may not have anticipated yet
    - a large fraction of the LHC long-lived program could be re-implemented on these triggers and increase their (model dependent) sensitivity tremendously
- Lots of room for new ideas and techniques
  - And of course, there is no substituting for sqrt(s)!

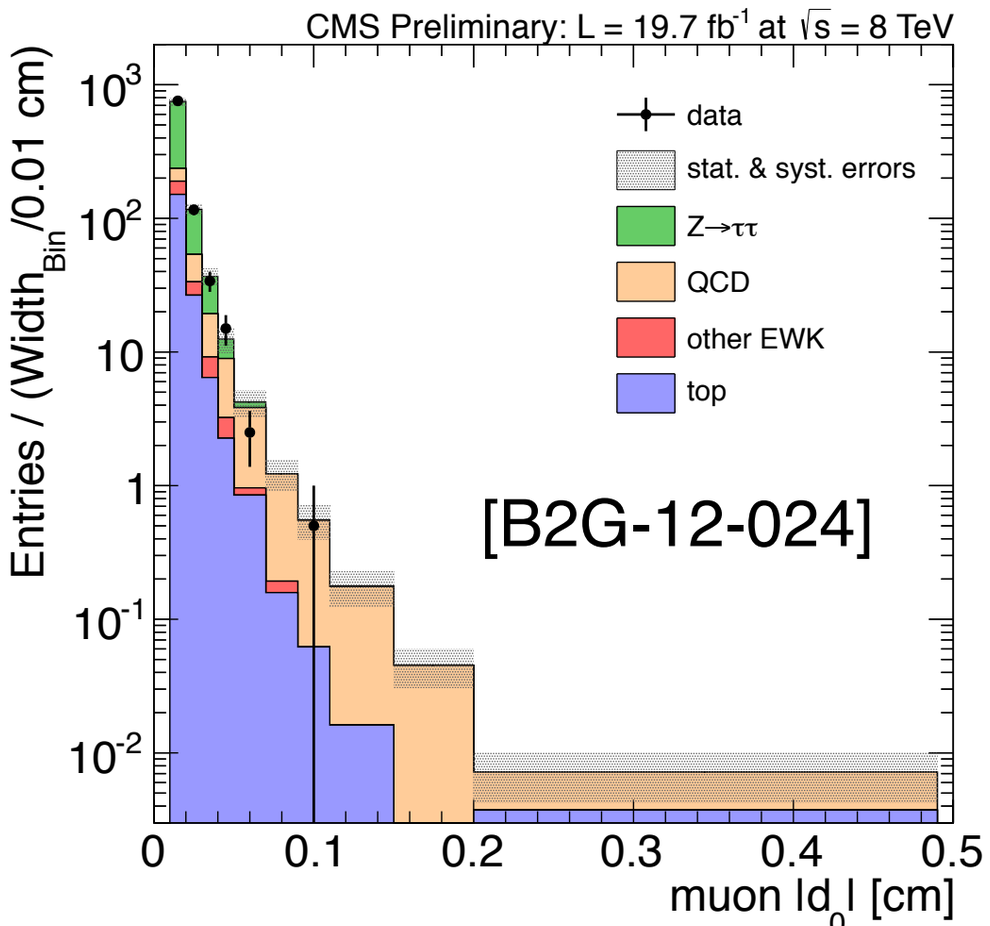
Backup

SEARCH FOR DISPLACED LEPTONS

- Look for two isolated, opposite-sign, opposite-flavor leptons
  - require 2D impact parameters **between 0.05 cm and 2.0 cm**
    - Does **not require** that the two leptons originate from a common vertex
  - Dominant backgrounds: $Z \rightarrow \tau\tau$ and QCD
    - Check (below) that leptons with moderate displacements are still well-reconstructed



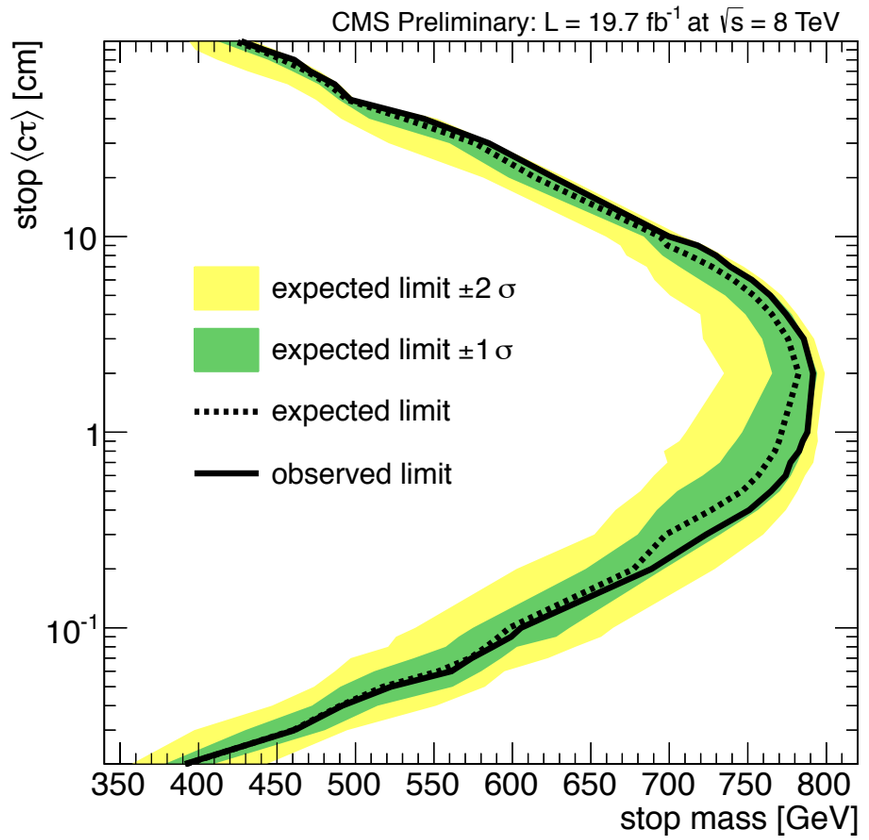
non-prompt e and prompt u



non-prompt u and prompt e

SEARCH FOR DISPLACED LEPTONS

- QCD background estimated with "ABCD" method
  - Opposite Sign v. Same Sign and Isolated v. Non-Isolated
- Three non-overlapping signal regions based on the minimum lepton d0
  - interpreted in terms of RPV stops



Event Source	0.02 cm < $\lvert d_0 \rvert$ < 0.05 cm	0.05 cm < $\lvert d_0 \rvert$ < 0.1 cm	$\lvert d_0 \rvert$ > 0.1 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
$pp \to \tilde{t}_1 \tilde{t}_1^*$			
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	$4.73 \pm 0.30 \pm 0.17$	$5.57 \pm 0.32 \pm 0.20$	$26.27 \pm 0.70 \pm 0.93$