New Physics from CMS: Hints from Run 1 and Prospects for Run 2

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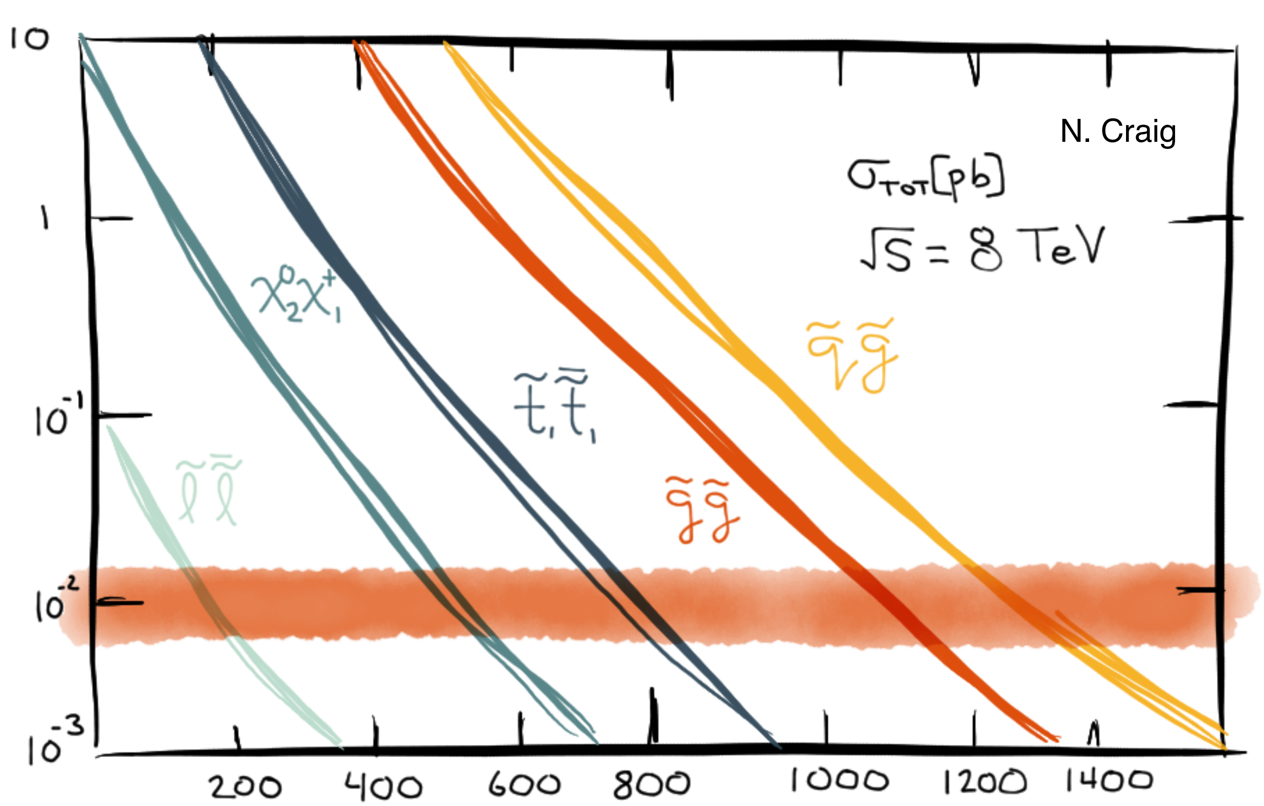
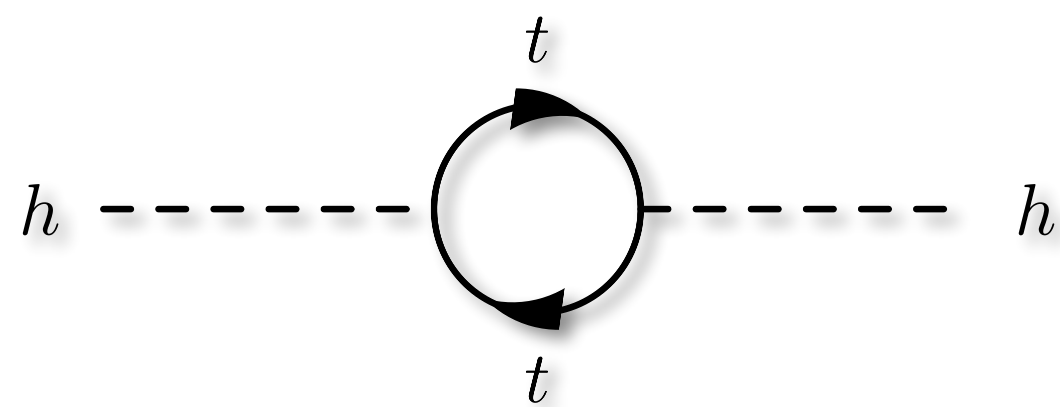
NATURALNESS

- In order to solve the hierarchy problem, strongly produced states (of some sort) in the 100–1000 GeV range are (almost) an inevitability
  - SUSY, (large/RS/universal/etc.) extra dimensions, composite Higgs, etc. all give you such states



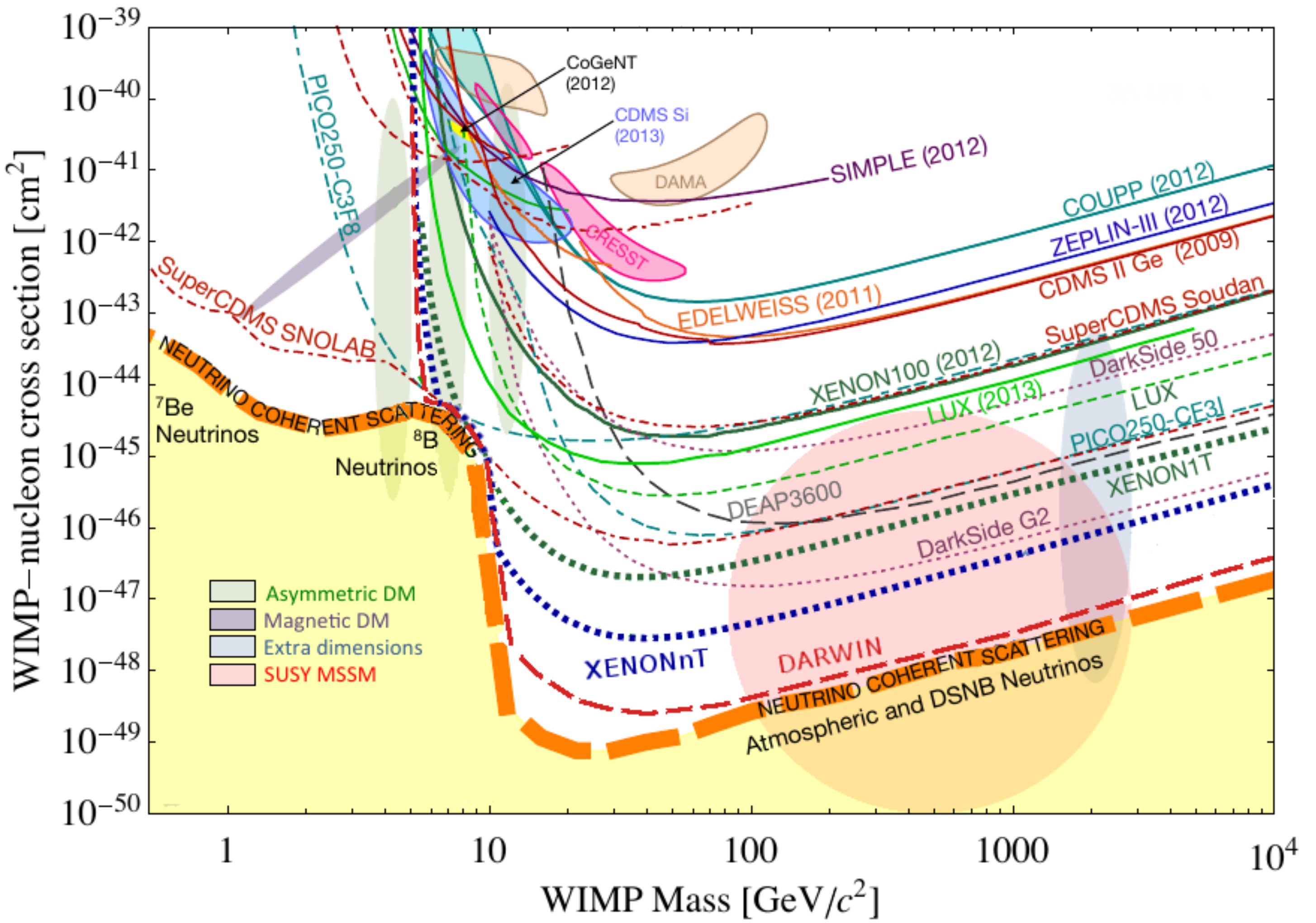


Stop pair production provides the scale that we need to explore: ~10 fb

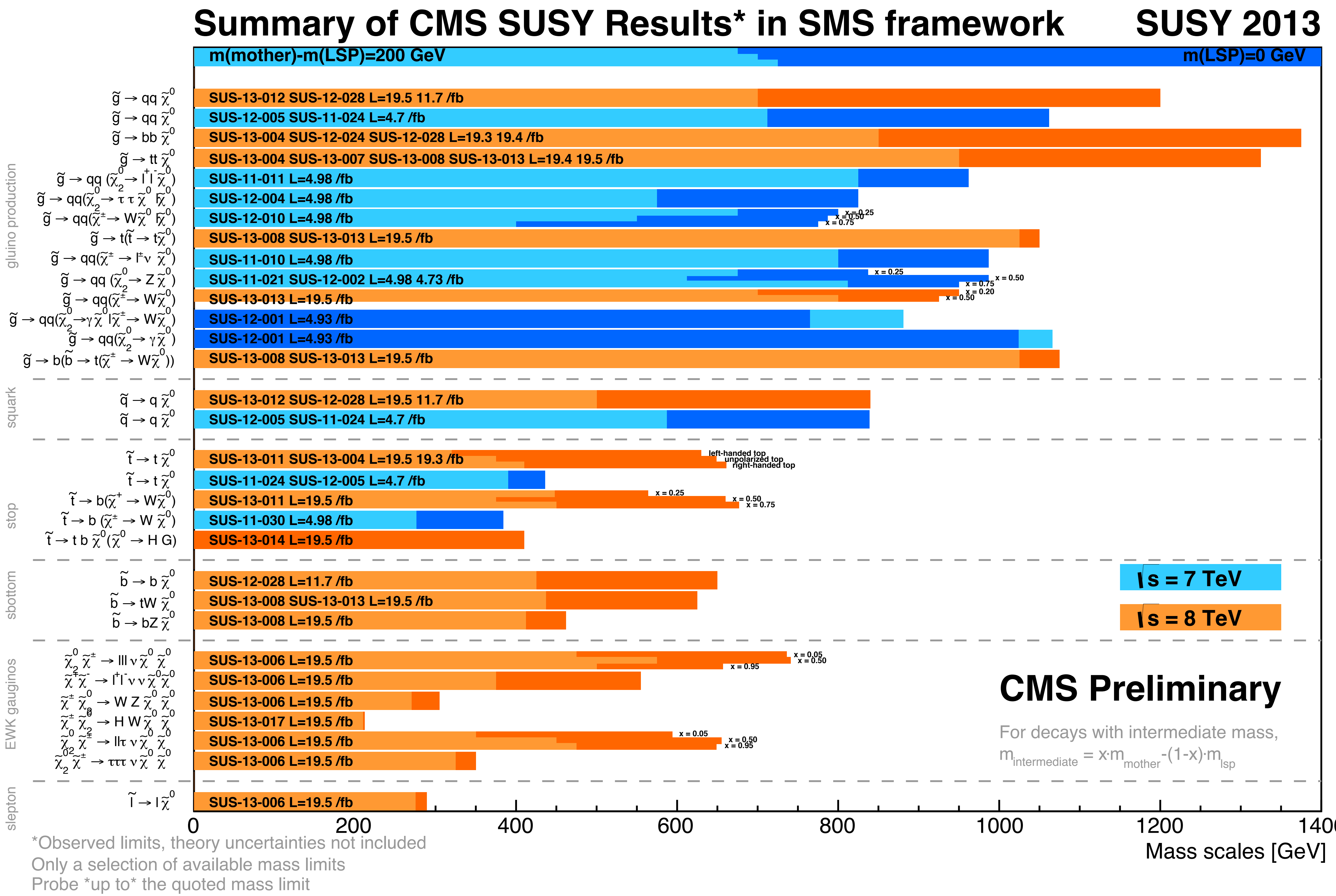
If you don't like SUSY, just mentally replace your favorite strongly produced state every time I say "squark"

DARK MATTER

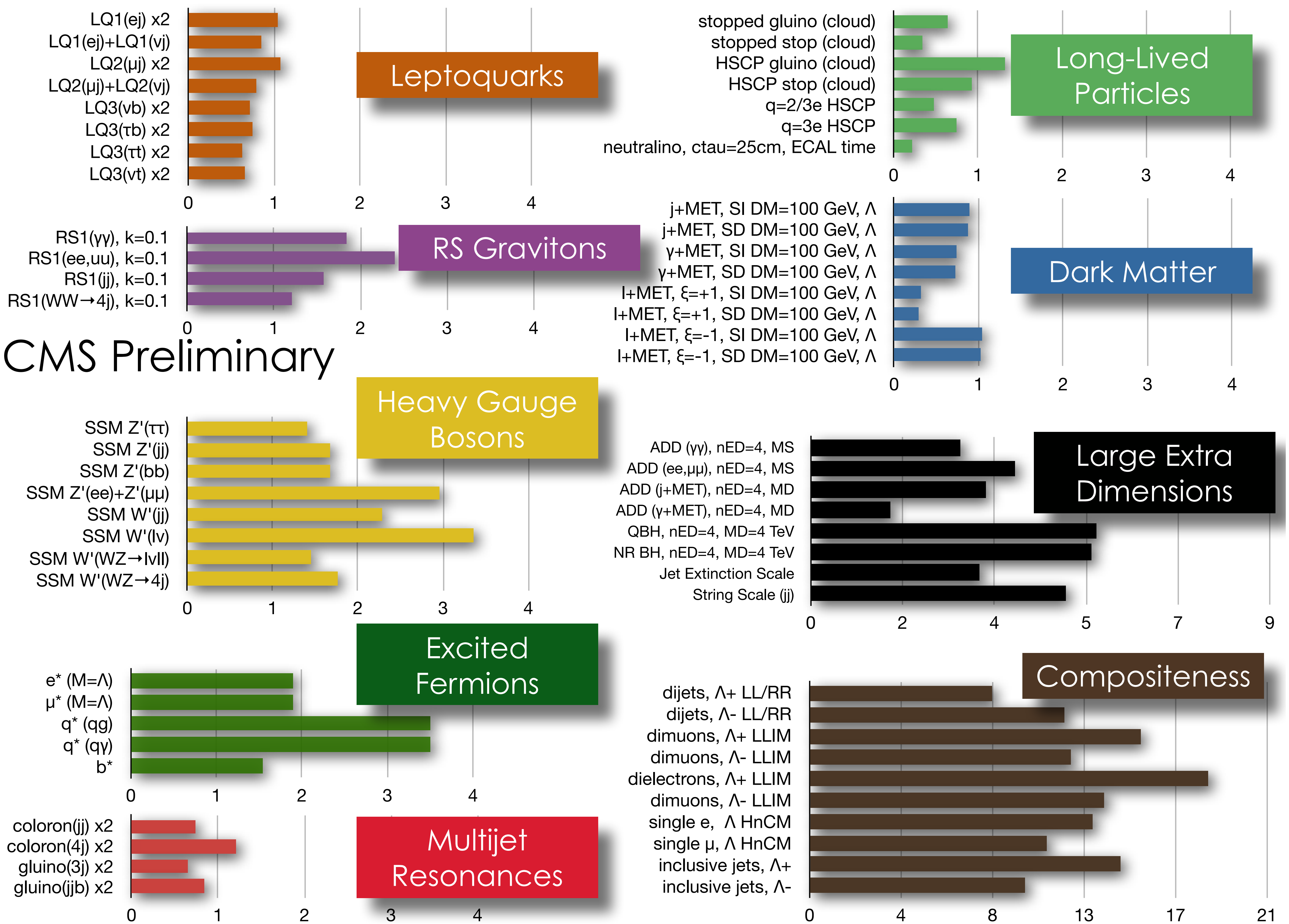
- Strong reasons to prefer a particle interpretation to galactic dark matter observations
  - WIMP interpretation suggests new particles at the EWK scale



SUSY RESULTS

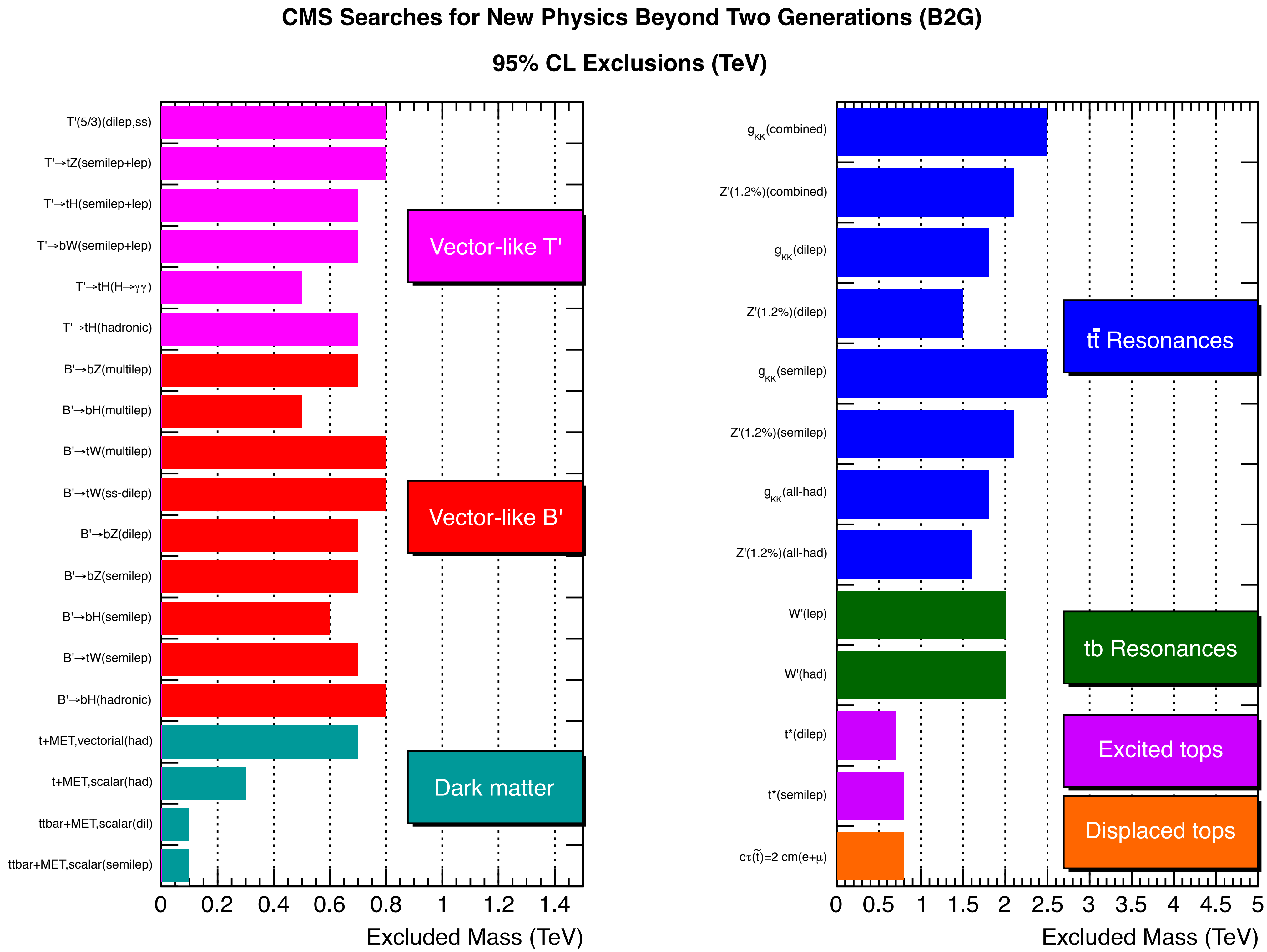


EXOTICA RESULTS



CMS Exotica Physics Group Summary – ICHEP, 2014

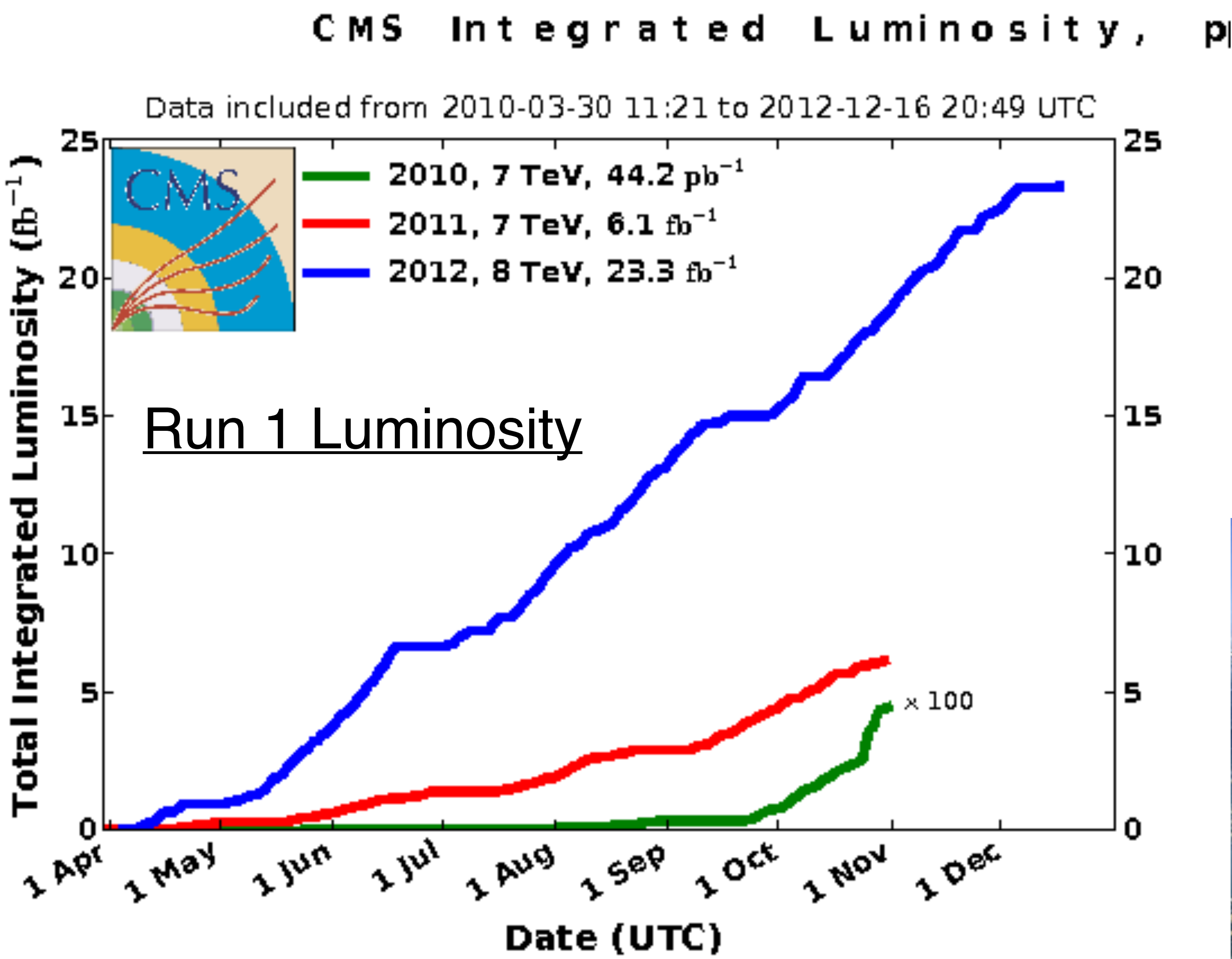
SEARCHES FOR BEYOND 2 GENERATIONS



WHY HAVE WE NOT SEEN NEW PHYSICS?

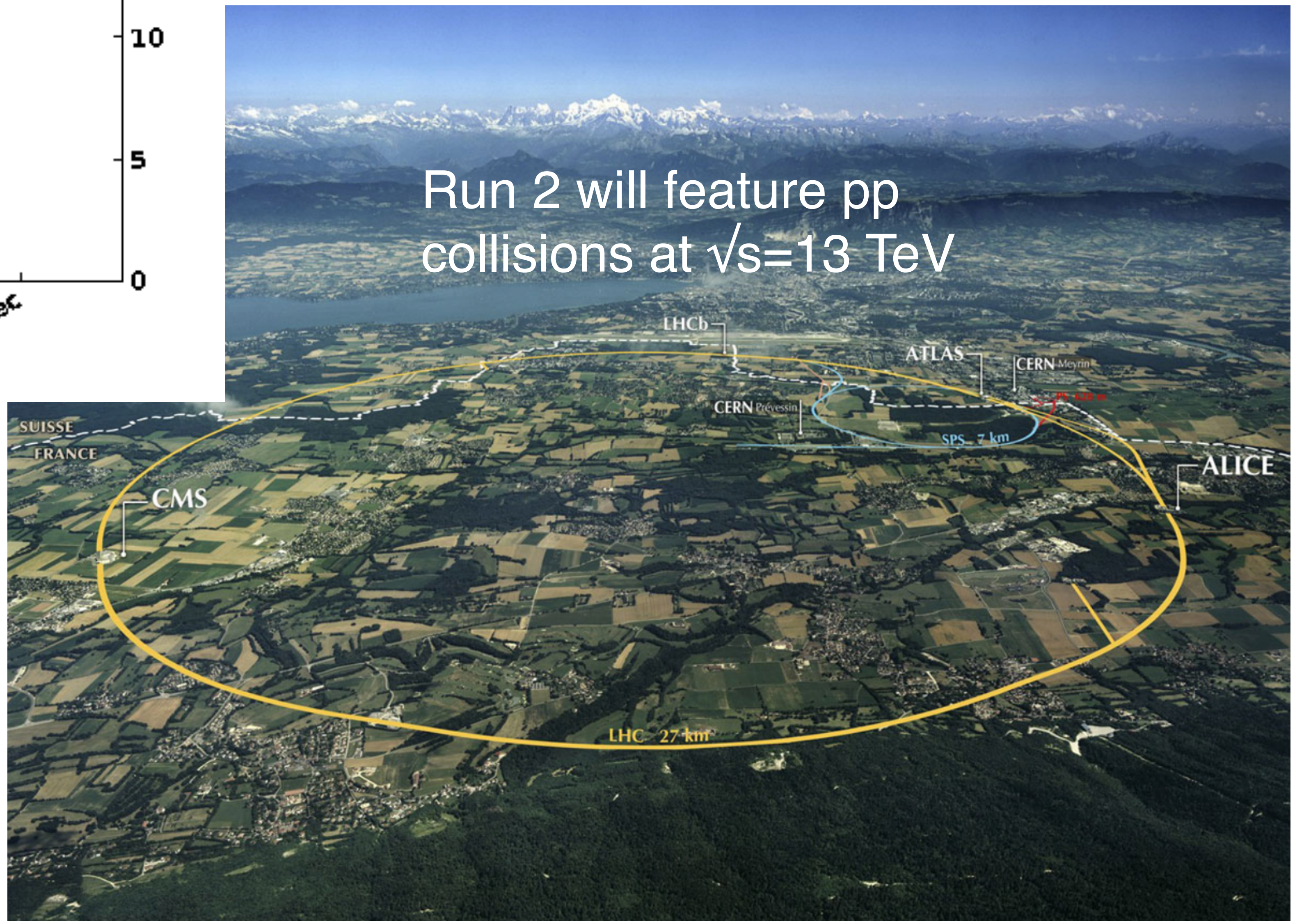
- Some possibilities are:
  - There is **no** new physics (at least accessible at the LHC)
  - There **is** new physics accessible at the LHC, we are just…
    - not yet sensitive because of energy
    - not yet sensitive because of luminosity
    - not asking the right questions
- This talk will focus in particular on these last two possibilities

PROTON COLLISIONS AT THE LHC



Run 1 Luminosity

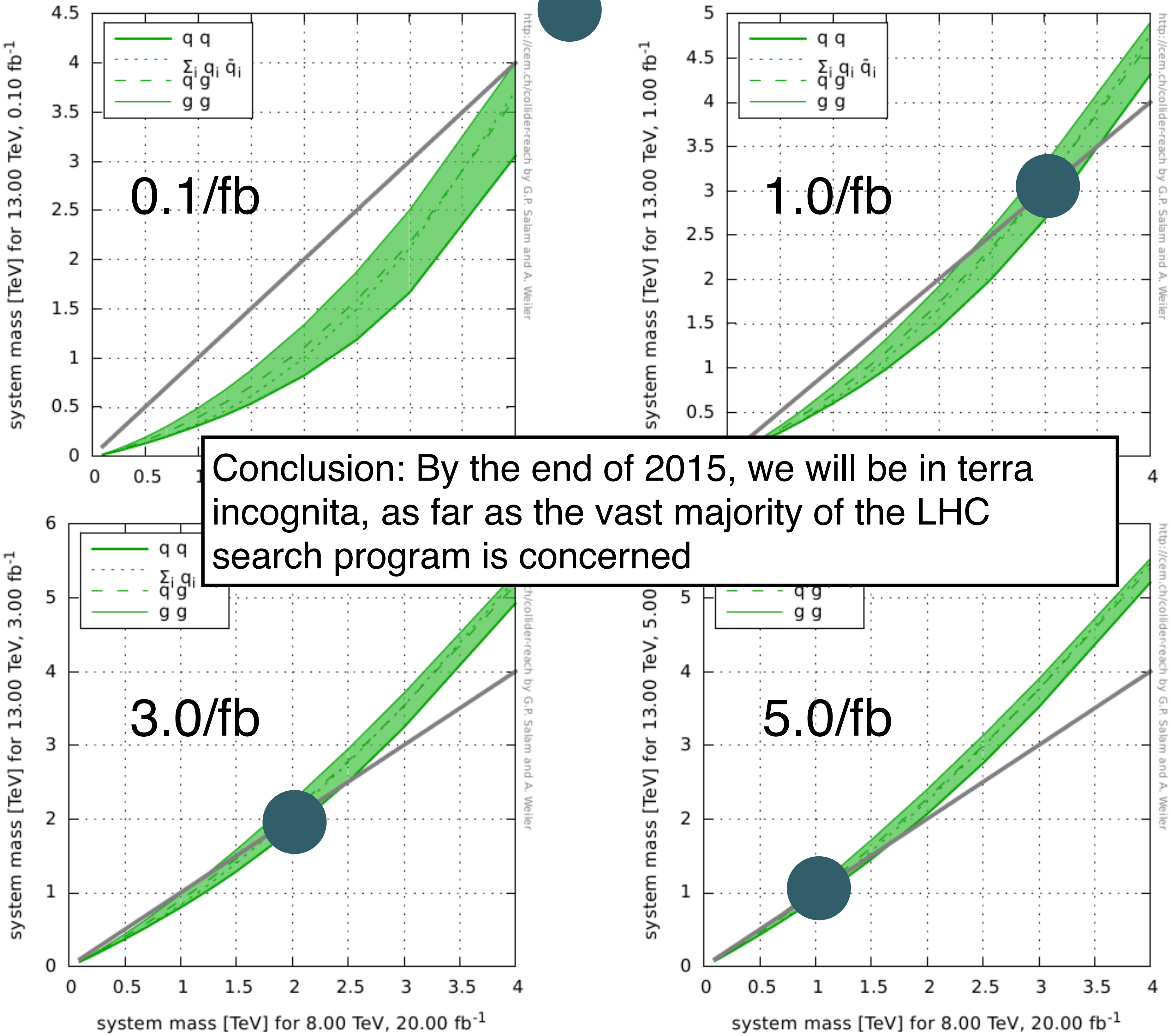
Run 2 Instantaneous Luminosity Goal
1.3 x 10^{34} cm^{-2} s^{-1} and operation with 25 ns bunch spacing, giving an estimated pile-up of 40 events per bunch crossing



Run 2 will feature pp collisions at √s=13 TeV

Run2 Integrated Luminosity Goal
2015 : 10 fb^{-1} (1 fb^{-1} @ 50ns in June)
Run2: ~100-120 fb^{-1} (better estimation by end of 2015)

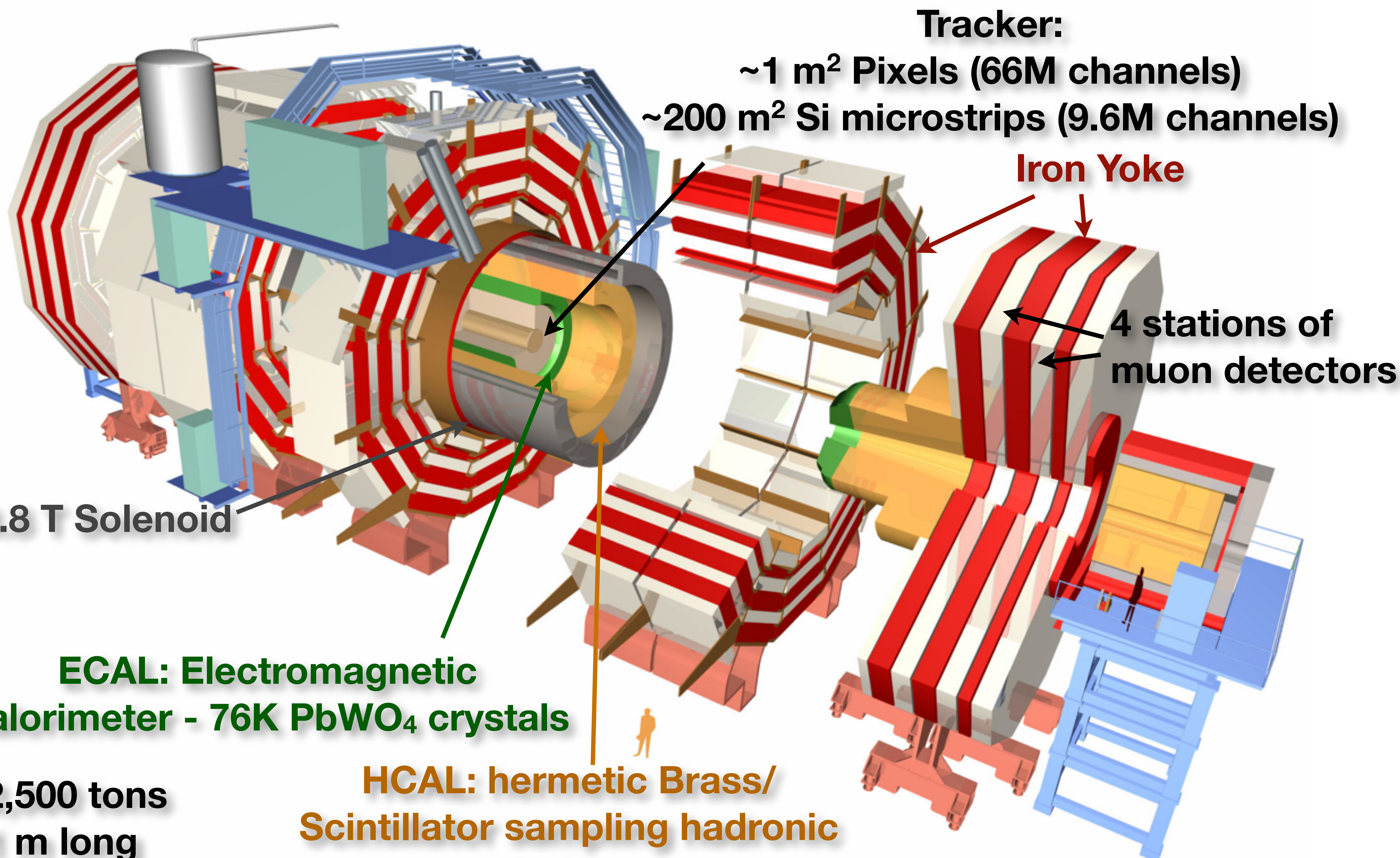
2015 LHC Reach



Conclusion: By the end of 2015, we will be in terra incognita, as far as the vast majority of the LHC search program is concerned

- With 1/fb we have added sensitivity to ~3 TeV objects
  - (~1.5 TeV for pair production)
- With 5/fb we have added sensitivity to ~1 TeV objects
  - (~0.5 TeV pair production)

The Compact Muon Solenoid



12,500 tons
21 m long
15 m diameter

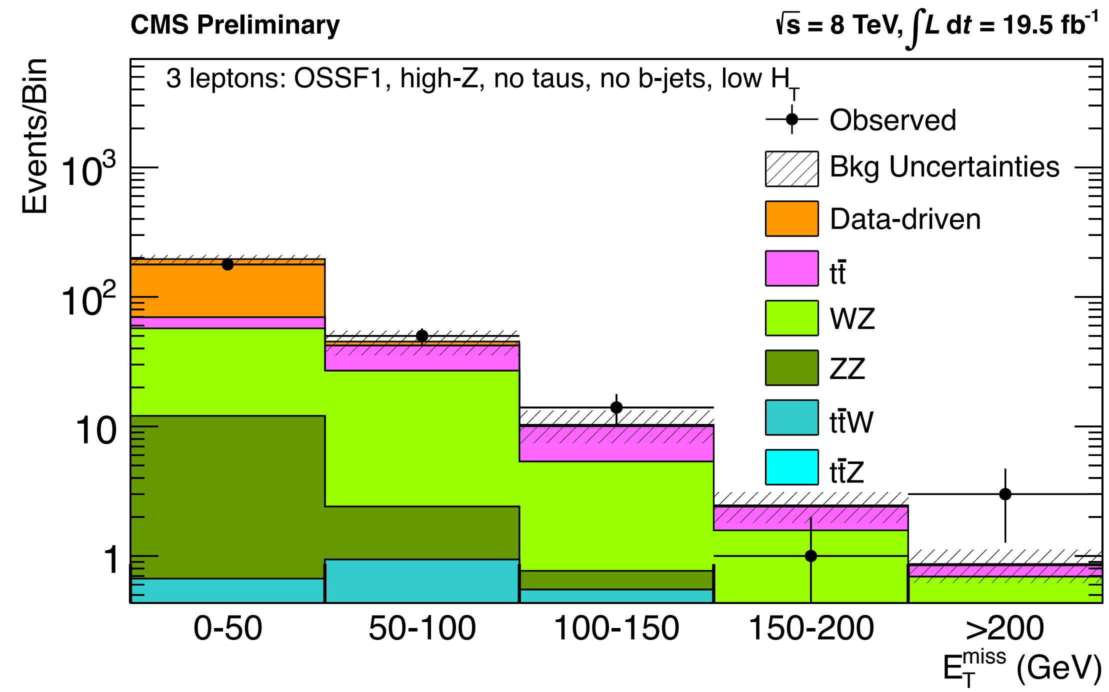
Hints of New Physics(?) from Run I

Caveat Emptor

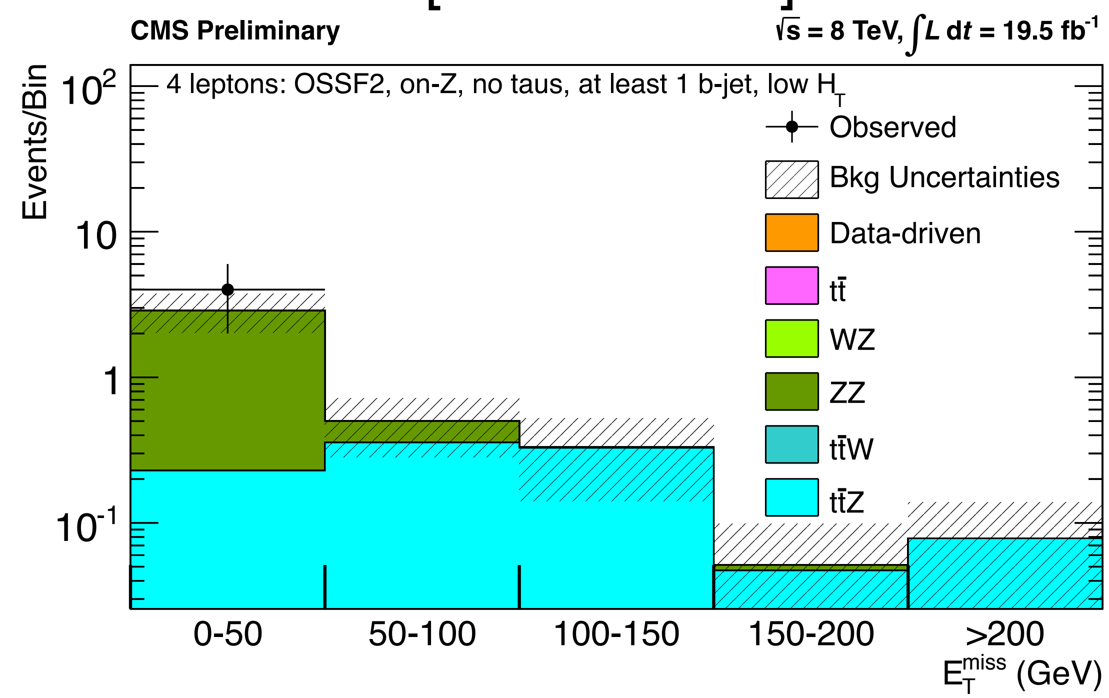
- Before getting too excited, it's important to remember that the "global" look-elsewhere effect is significant
  - I counted 88 distinct published and preliminary results from the Exotica, SUSY, and B2G groups on the **8 TeV 2012 dataset alone**
    - Some of these analyses are very particular and look at a very specific corner of phase space
    - Some of these analyses are extremely broad, and by themselves cover hundreds of distinct final states
  - We should certainly **expect** some 3-sigma fluctuations
    - nevertheless, there is no reason a priori why these might not be hints of new physics
    - even if one takes a skeptical stance, this gives us an opportunity to test how robust our discovery strategy is

MULTILEPTON SEARCHES

- Search for anomalous multilepton production establishes paradigm of “high resolution” searches at CMS
  - Emphasized **binning** rather than cutting on events with **≥3 isolated leptons (e or mu)**
    - ME_T and H_T
    - number of leptons
      - pT thresholds are 20,10, & 10 GeV
    - number of taus
    - number of b tags
    - # of opposite-sign same flavor (OSSF) lepton pairs
    - on/off shell Z

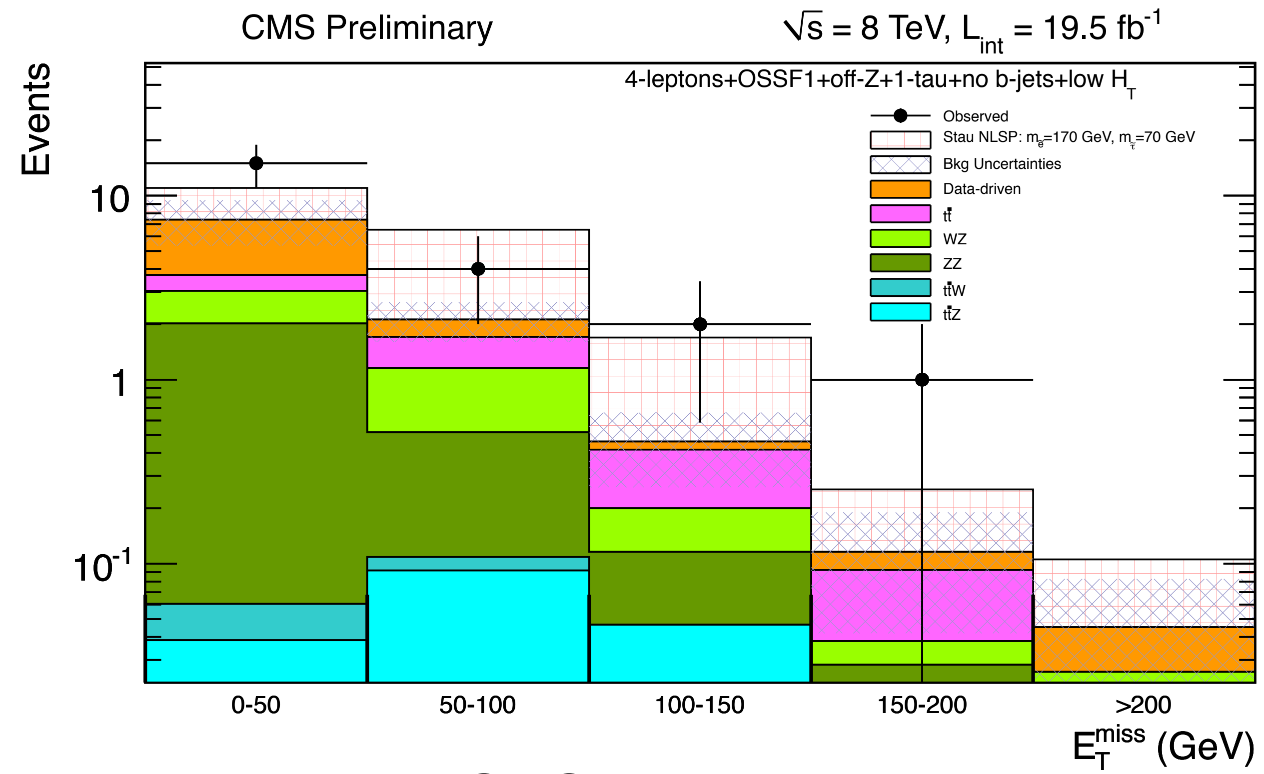


[SUS-13-002]



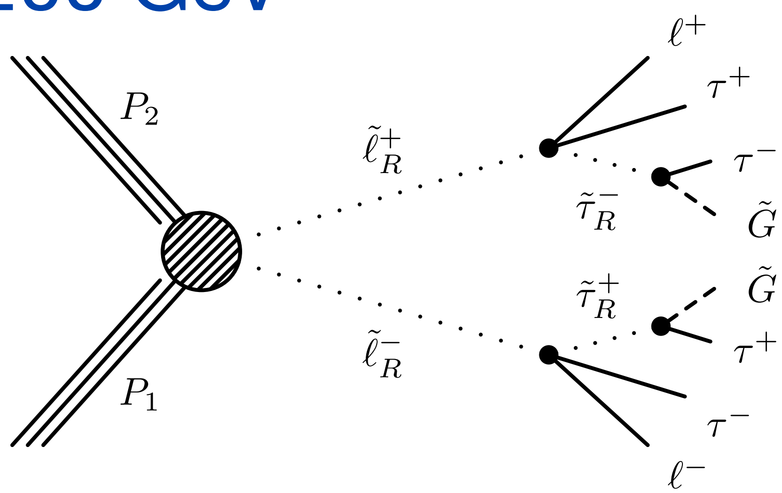
Stau (N)NLSP?

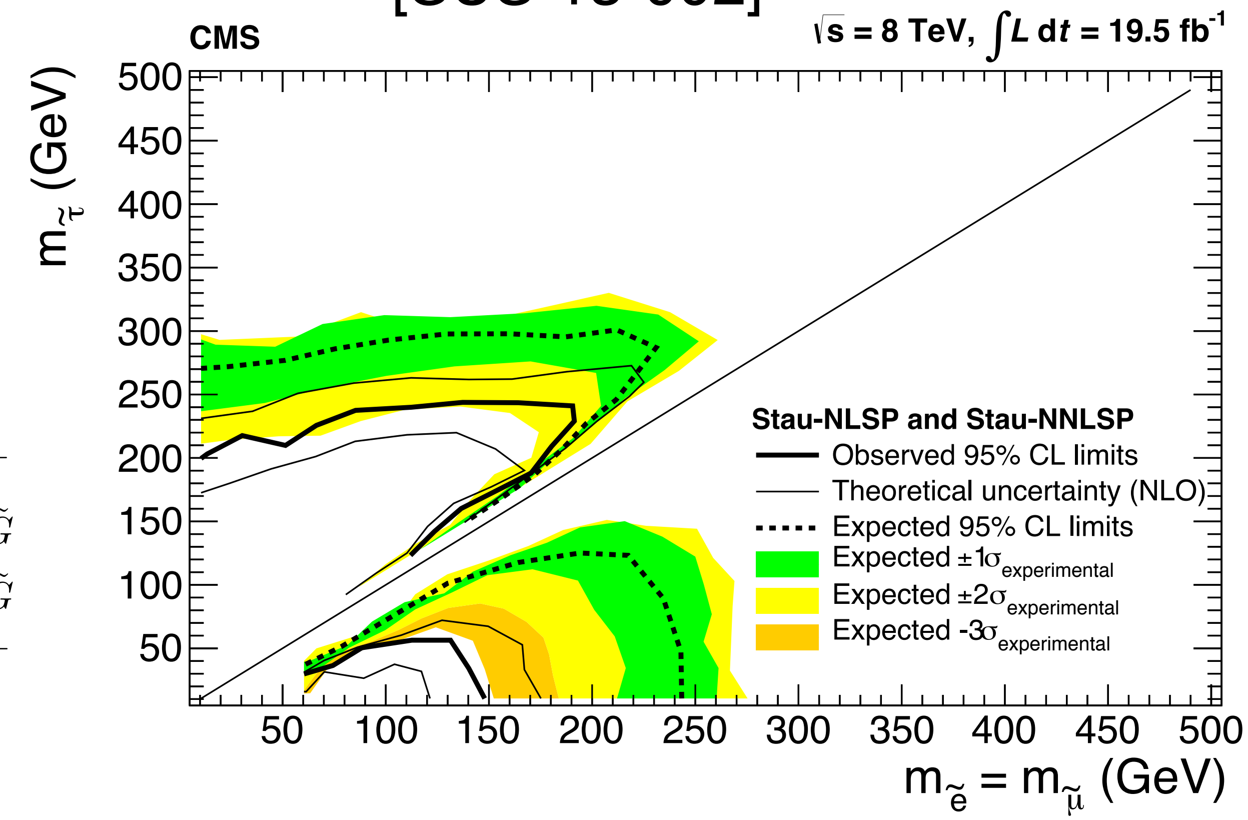
- Broad excess in 4 lepton events with…
  - 1 tau
  - off-shell Z(ee or uu)
  - no b jets
  - H_T<200 GeV



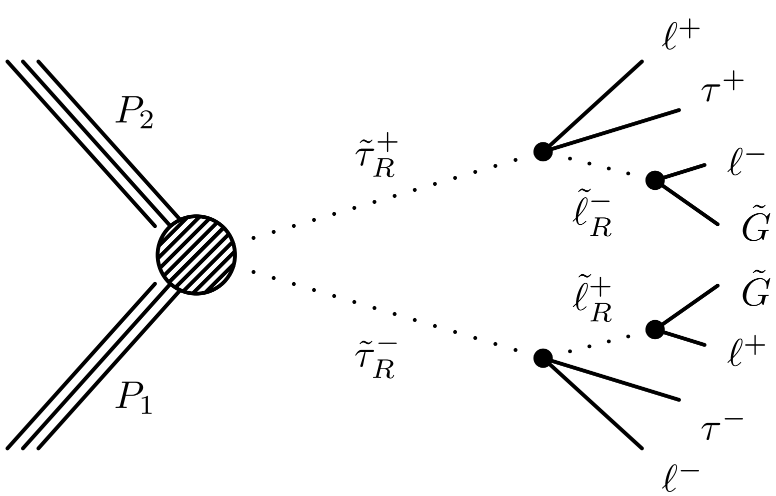
[SUS-13-002]

“stau NLSP”





“stau NNLSP”



THE EDGE

- Dilepton+jets+MET channel
  - Njets ≥ 2 and MET > 150 GeV

    OR
  - Njets ≥ 3 and MET > 100 GeV
    - Excess observed below 70 GeV in dilepton mass spectrum

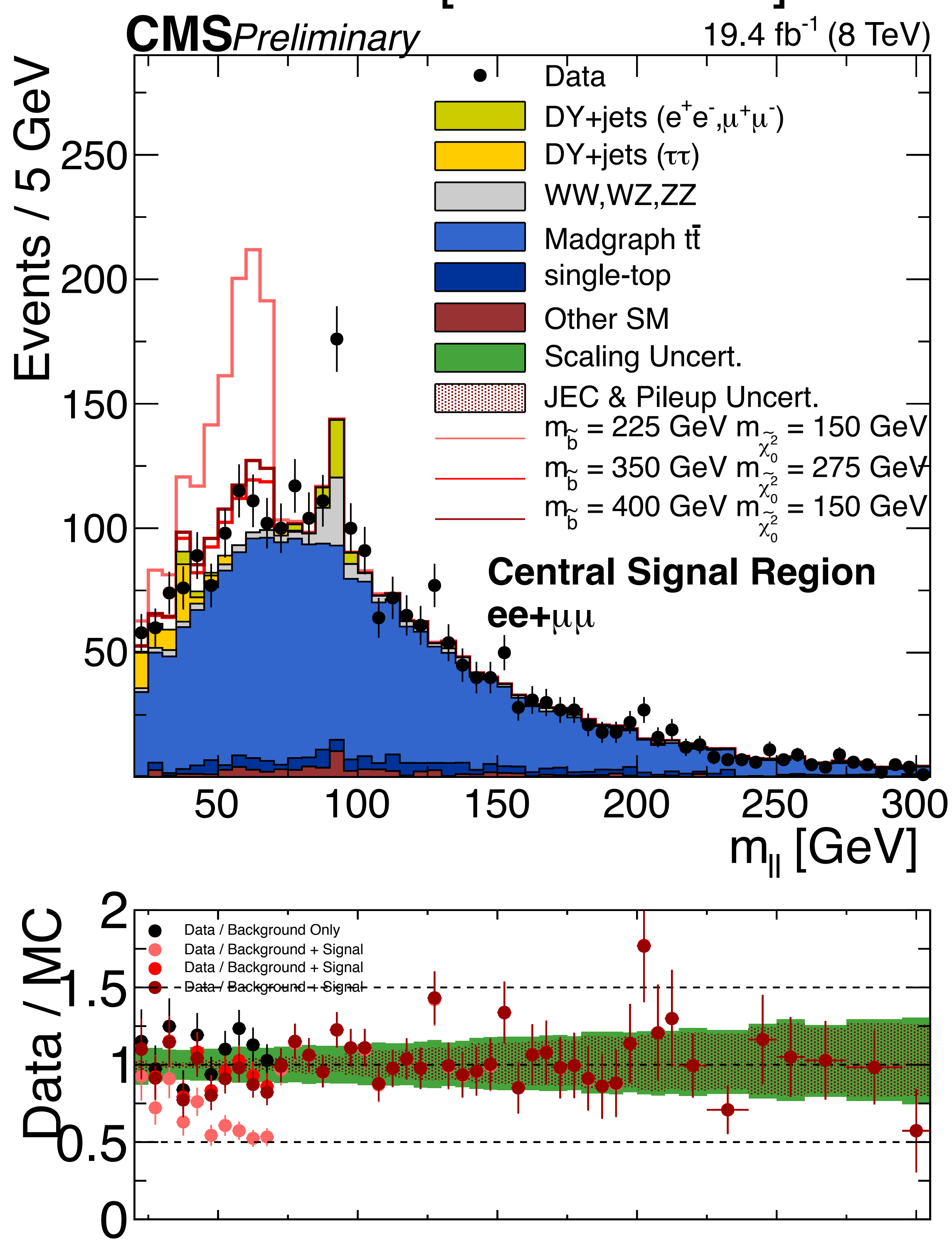
$$\tilde{b}\tilde{b}^{\star} \rightarrow \tilde{\chi}_2^0 b \tilde{\chi}_2^0 b$$

$$\tilde{\chi}_2^0 \rightarrow \ell\tilde{\ell} \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$$

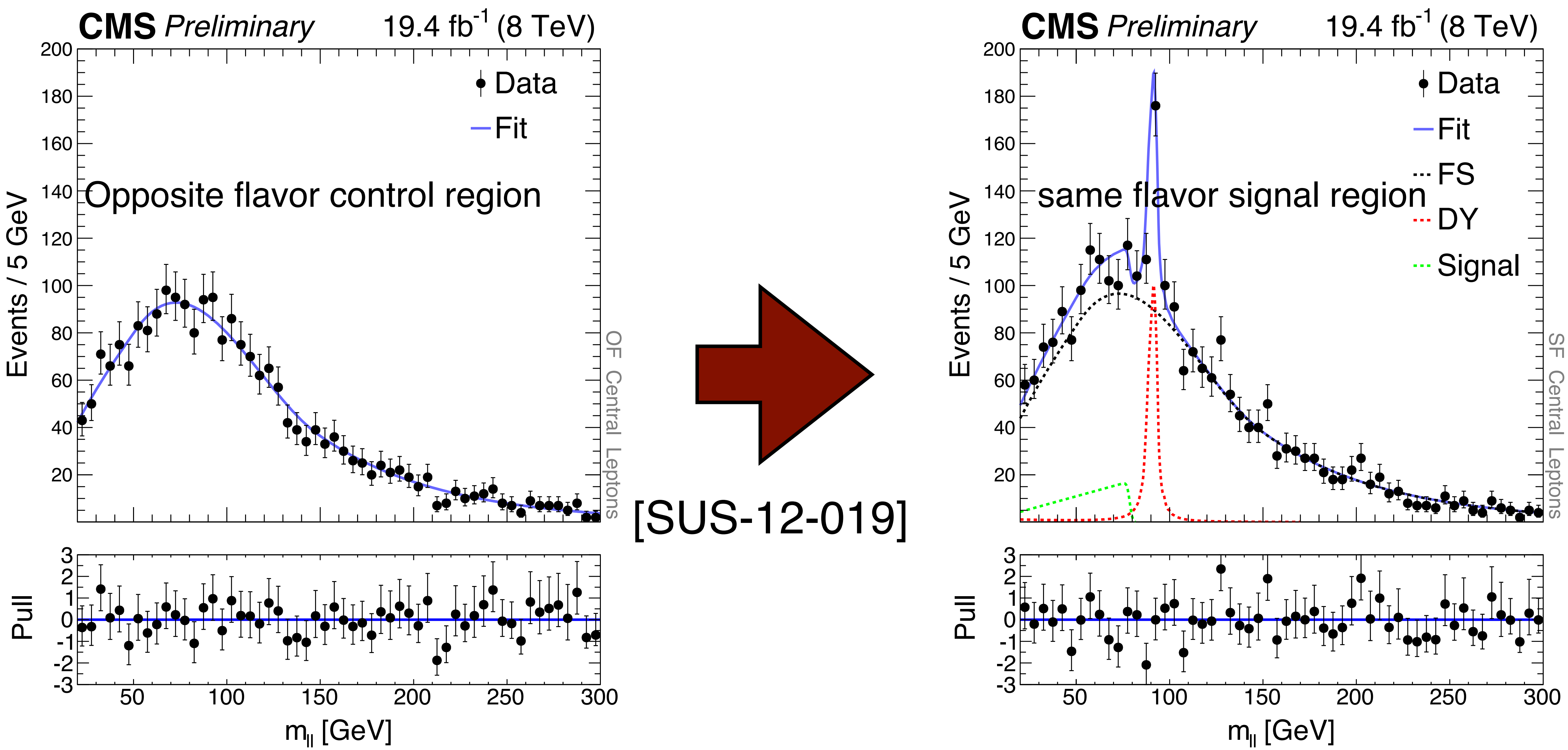
$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^{\star} \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$$

  - Both modes → kinematic edge at $m(\chi^0{}_2)-m(\chi^0{}_1)$

[SUS-12-019]



THE EDGE EXCESS



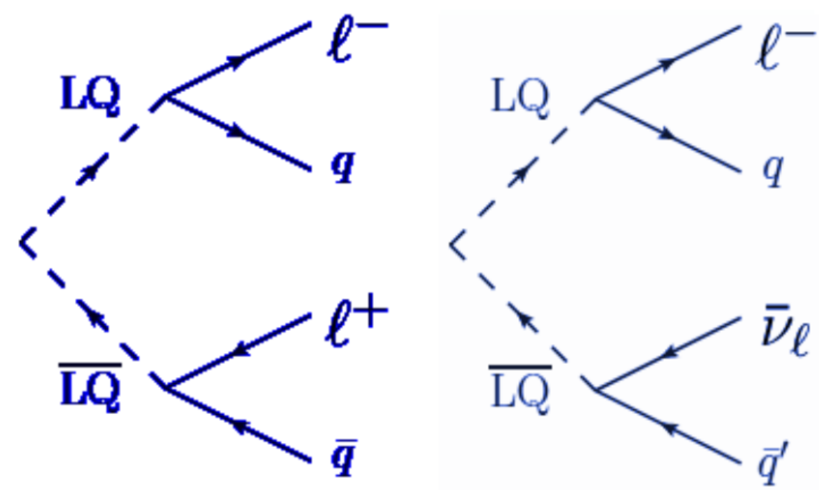
- 2.4 σ local (fit), 2.6 σ global (counting experiment)

- *ATLAS recently performed the same search and does not see the same excess [arXiv:1503.03290]* 😕

1ST GENERATION LEPTOQUARKS

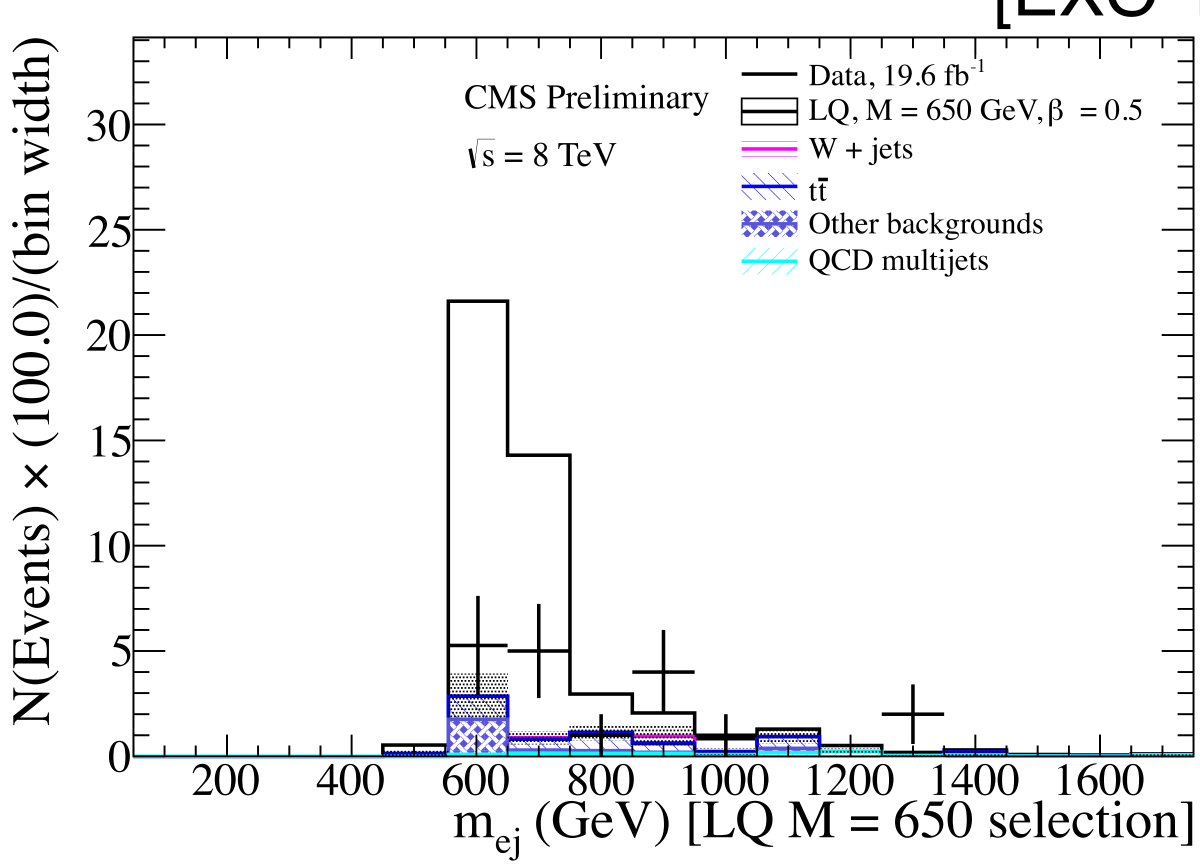
- Search for 1st generation LQs in eejj and eνjj final states
  - optimize cuts for individual LQ mass hypotheses on M(l,ν), M(ll), S_T, MET to suppress backgrounds
    - saw broad excess in both channels for a 650 GeV LQ mass hypothesis

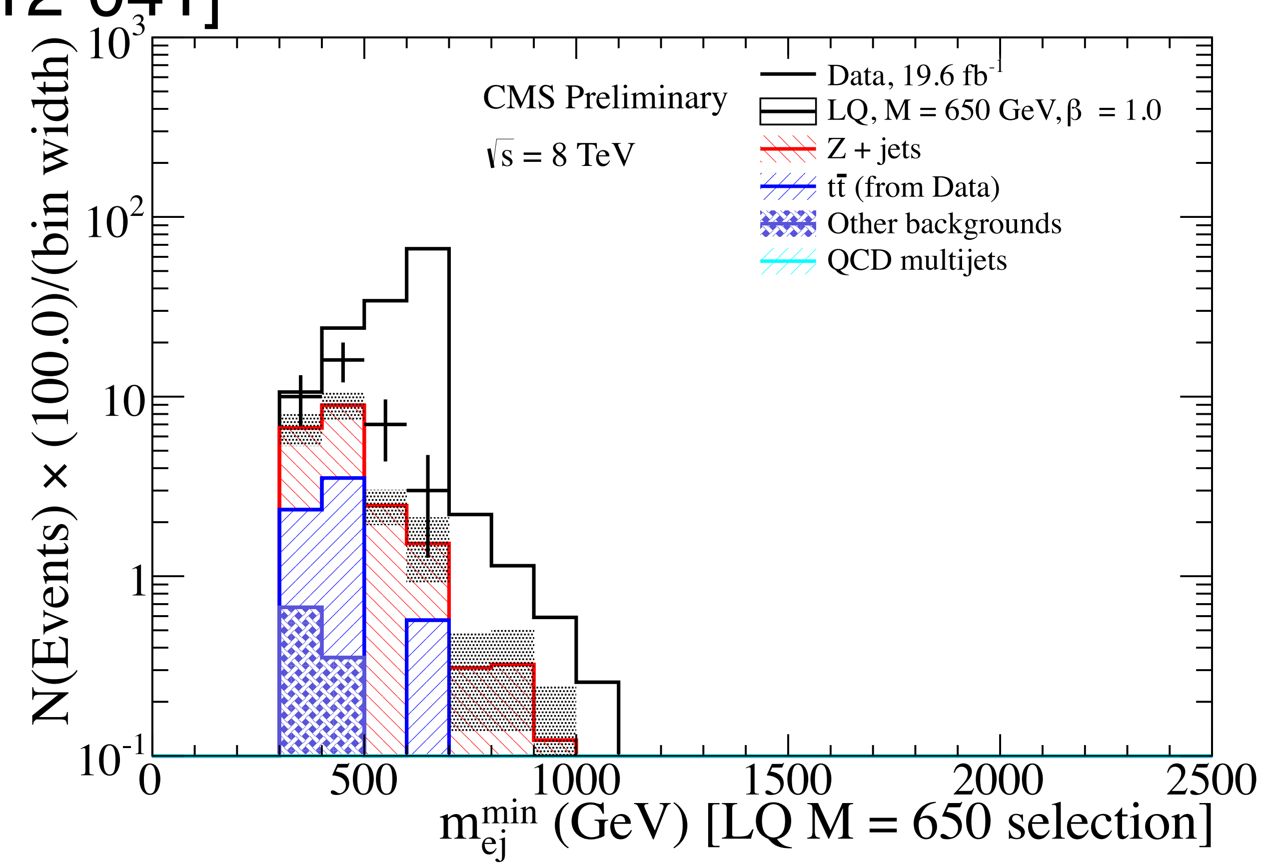
β = branching fraction to the lq final state



LQ1, LQ2
$\ell = e, \mu$

[EXO-12-041]

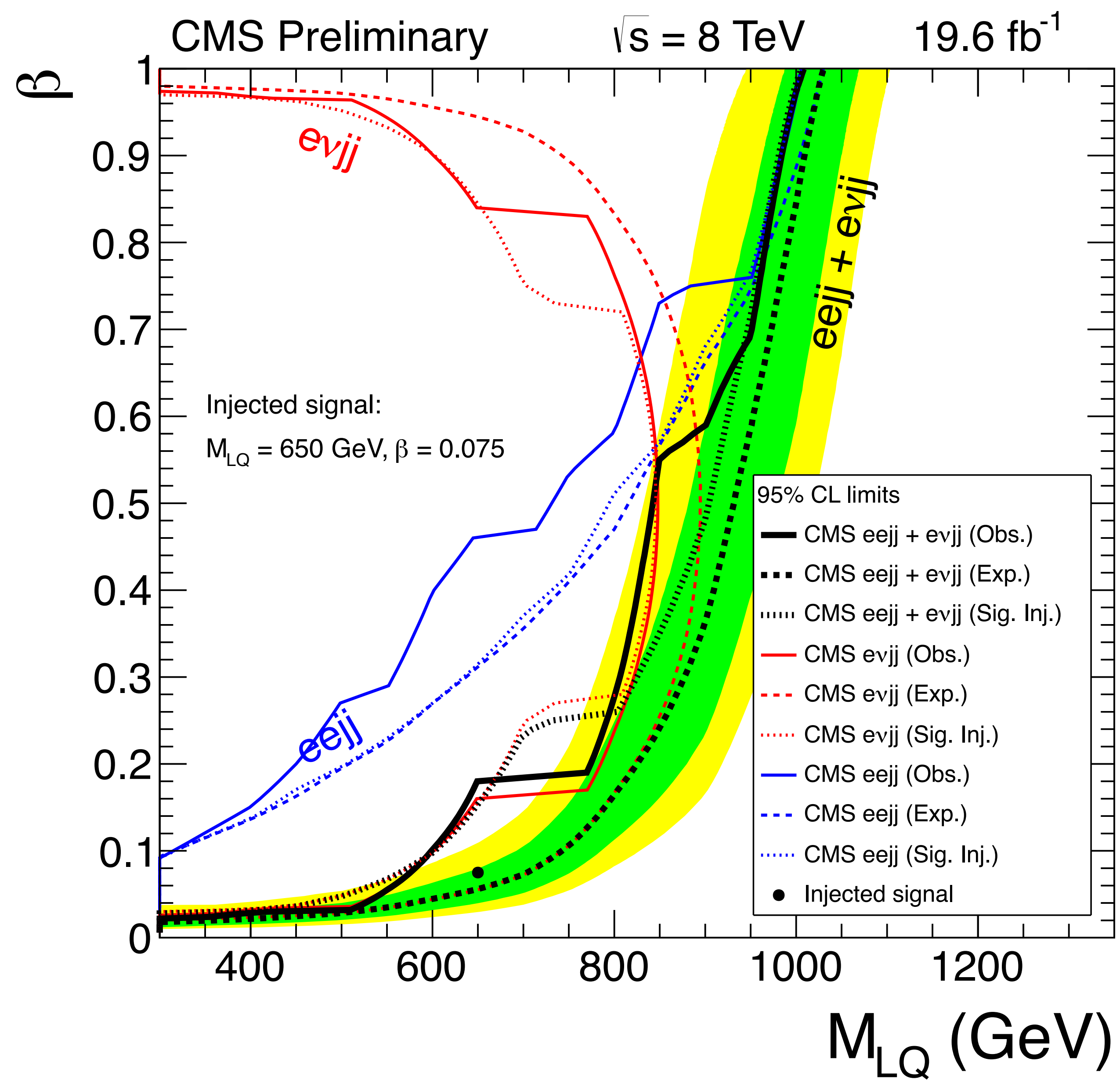




1ST GENERATION LEPTOQUARKS

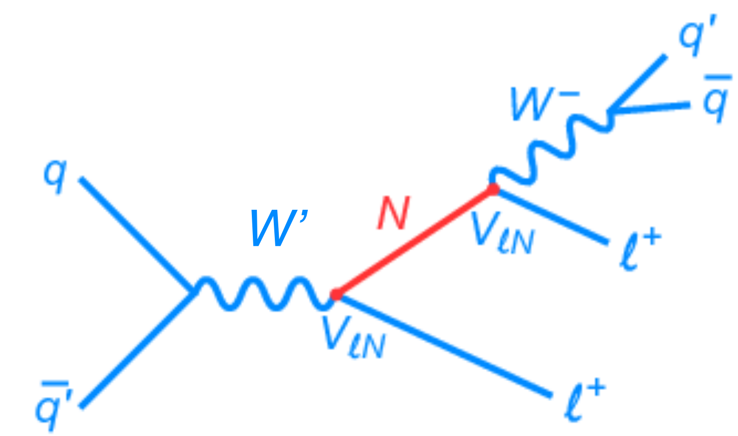
- Very difficult to reconcile with a LQ hypothesis
  - kinematics are too broad (no peak structure)
- Other possibilities?
  - several propsals, e.g.: arXiv:1410.5947, arXiv:1408.5439, arXiv:1408.1082, arXiv:1407.4466

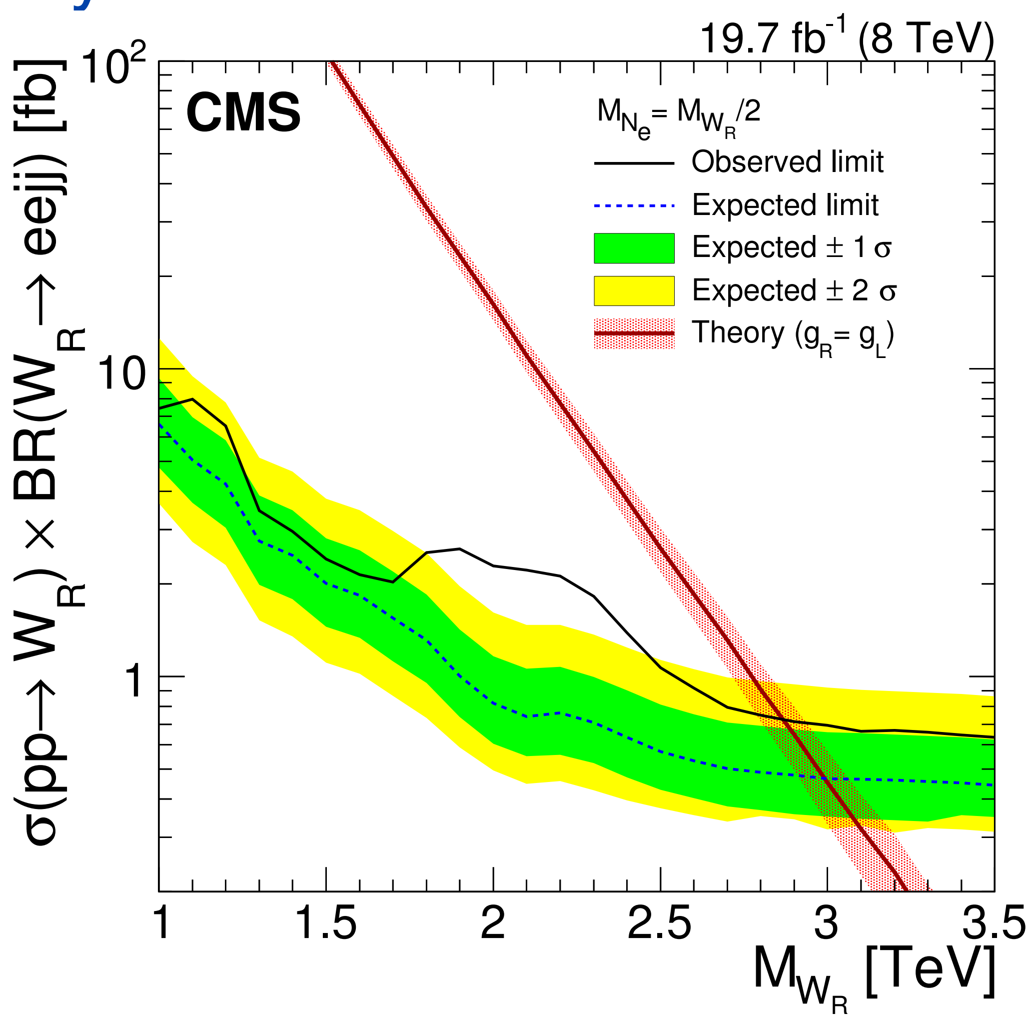
[EXO-12-041]

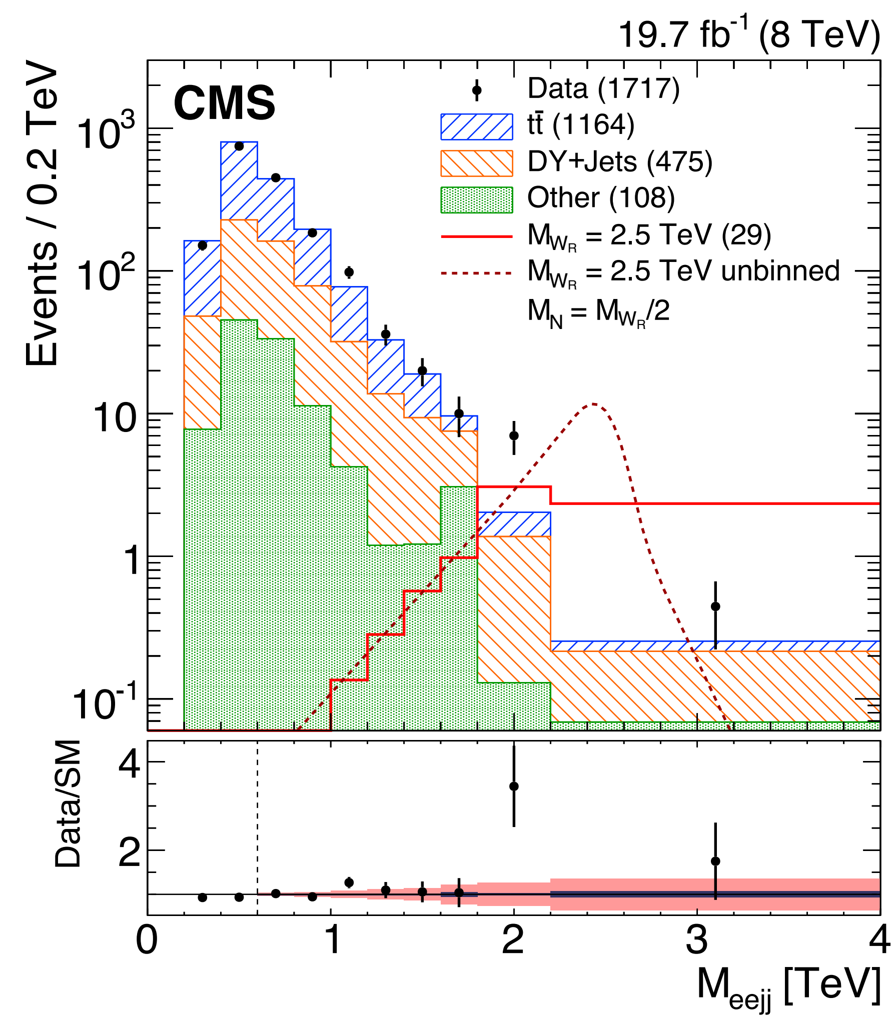


W’ and Heavy Neutrino

- Interestingly, a search motivated by W’ decays through heavy neutrinos also exhibited an excess in the same (eejj) final state
  - Search looks for a bump in the eejj invariant mass
  - there is little overlap in events between this and the LQ analysis







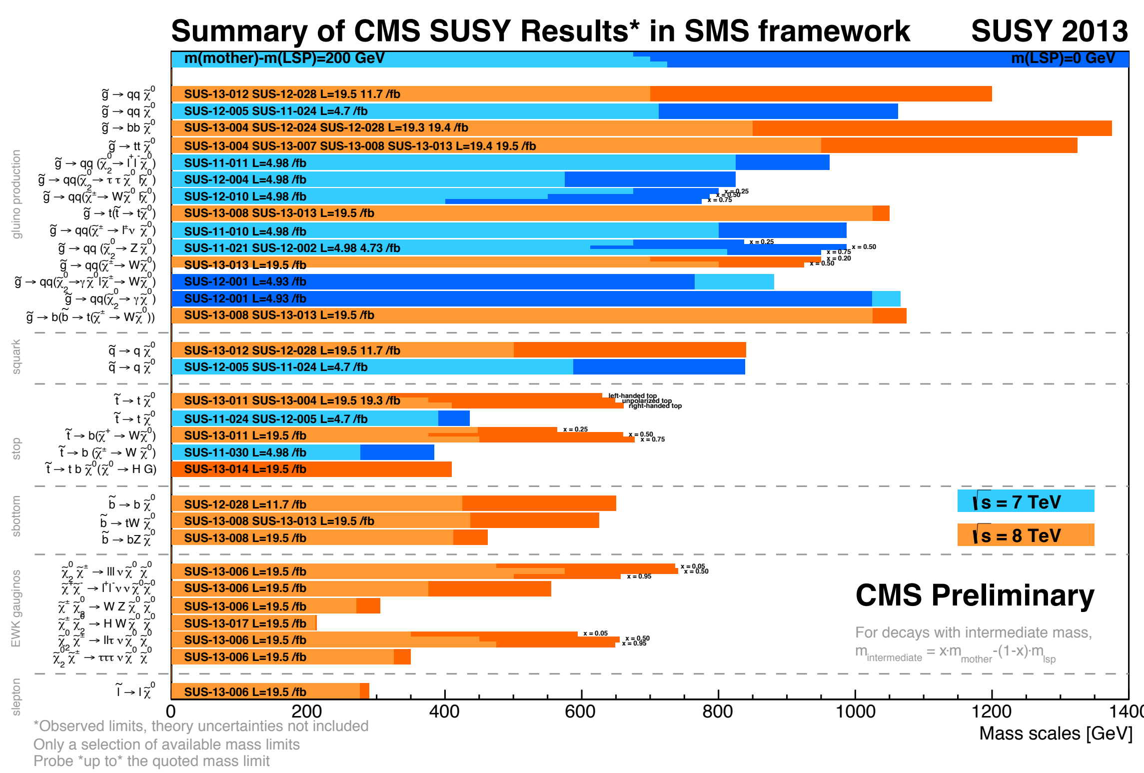
Hiding New Physics from View

SEARCHES WITH MET

- Part of the folklore of SUSY is that it can solve both the Hierarchy problem and dark matter problem in one fell swoop
  - It seems natural then to look for final states with lots of missing E_T, presumably from the lightest superparticle which is stable and a dark matter candidate
    - This is a nice, elegant picture, but it may also be wrong

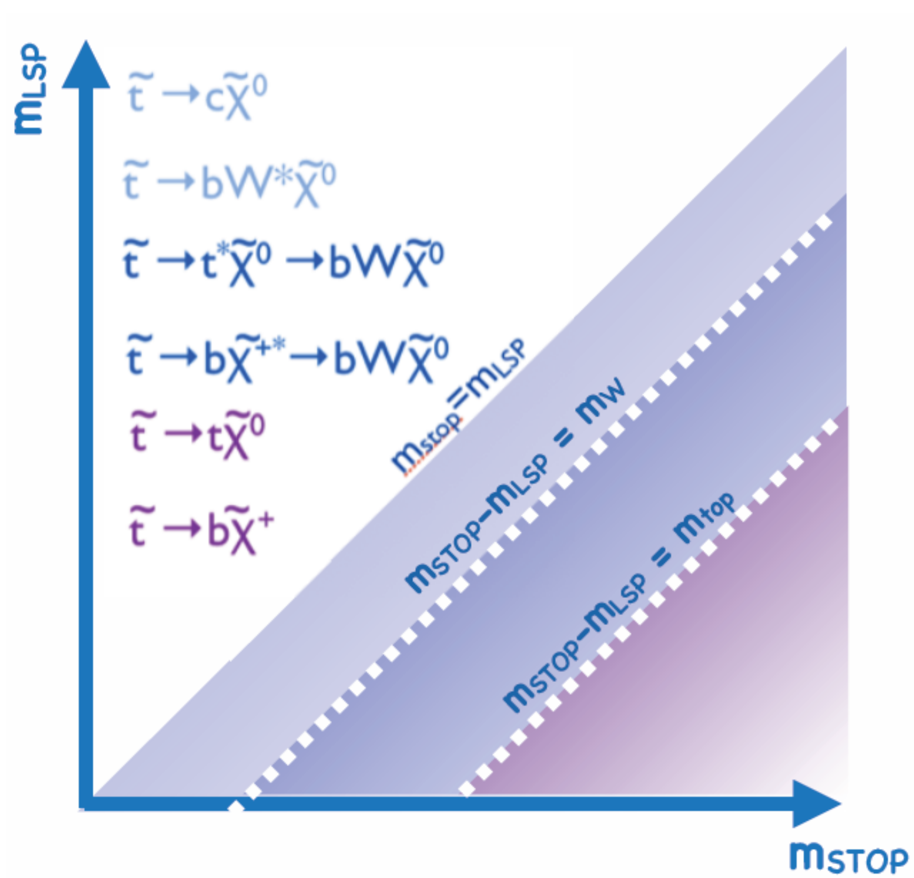
Even within the SUSY paradigm, there are many ways to suppress the missing E_T in the final state:

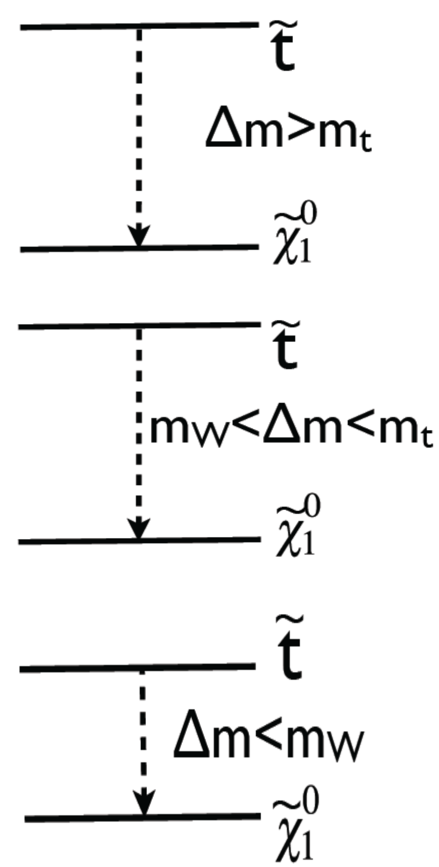
- compressed SUSY
- stealth SUSY
- R parity violating SUSY
- long-lived SUSY

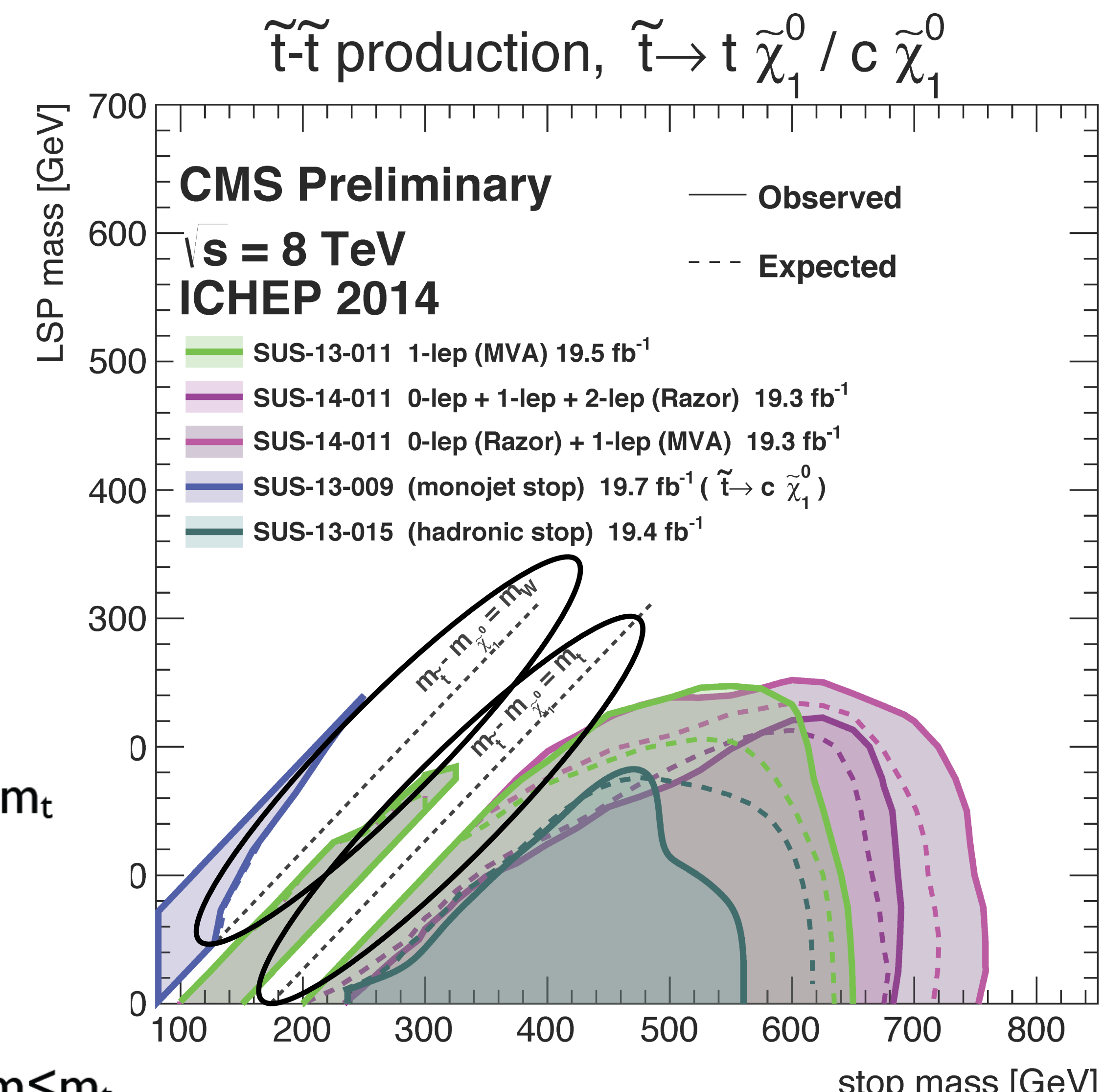


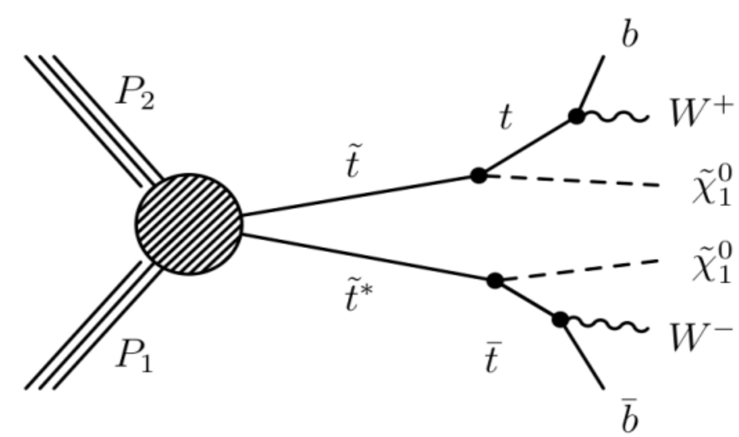
Compressed Spectra

- If the lightest super particle is close in mass to colored particles, the missing E_T and hadronic activity are substantially reduced, leading to a reduction in sensitivity
  - in principle, the missing energy signature can be recovered with a substantial enough boost from initial state radiation



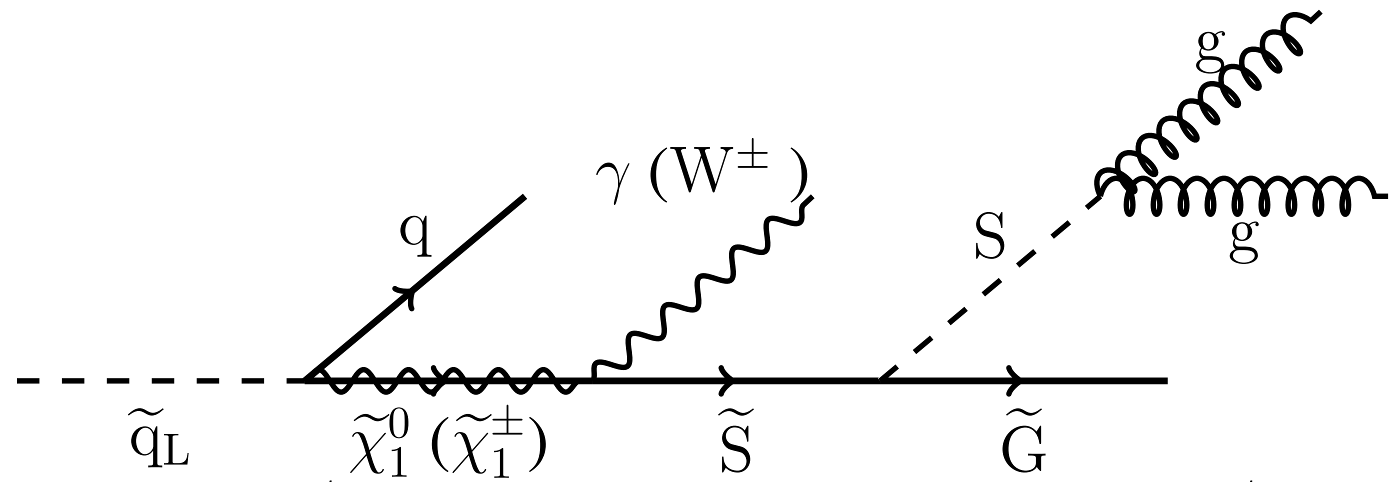


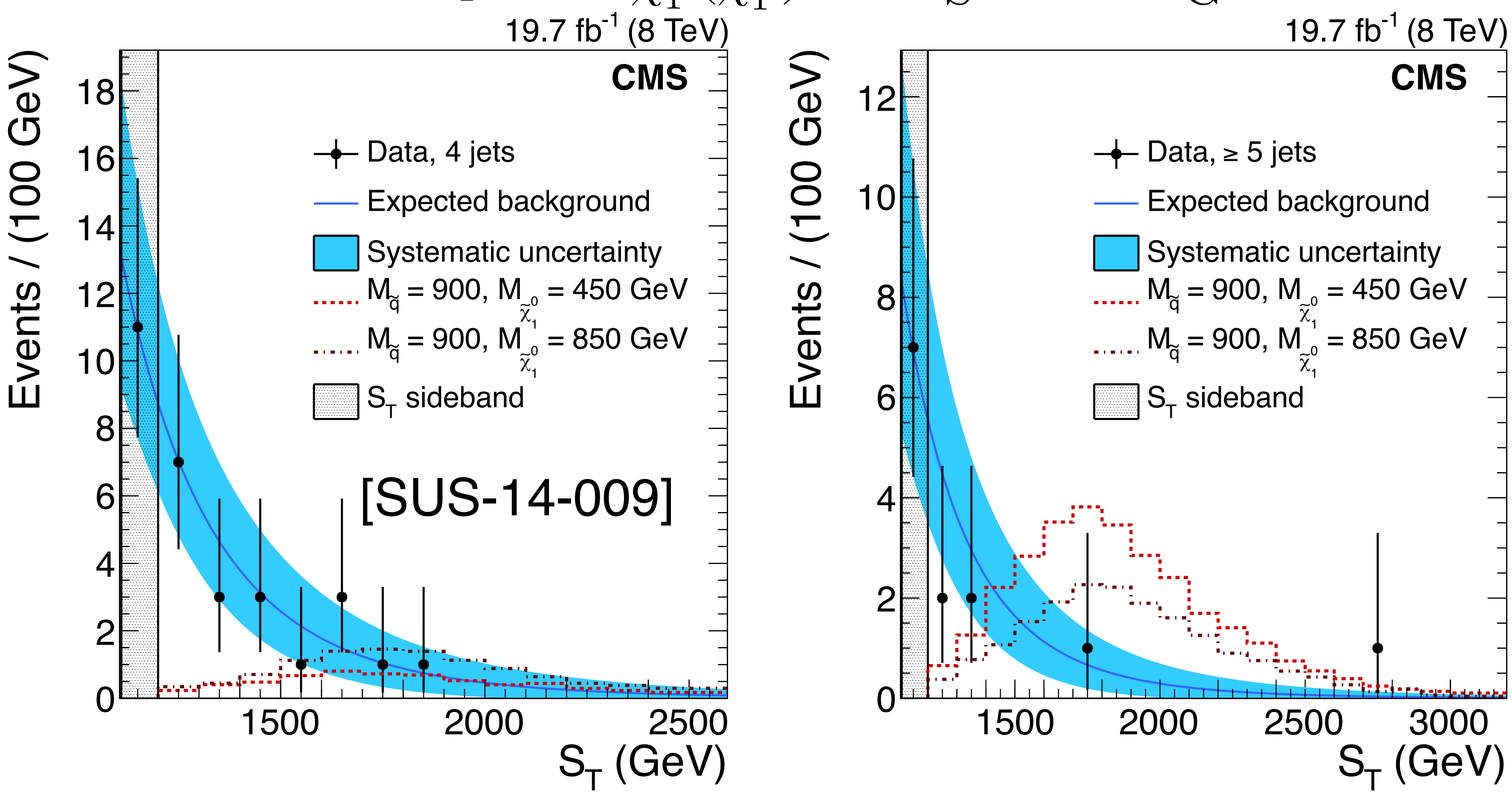




STEALTH SUSY

- Systematic reduction of MET due to the presence of a naturally degenerate singlet-singlino pair

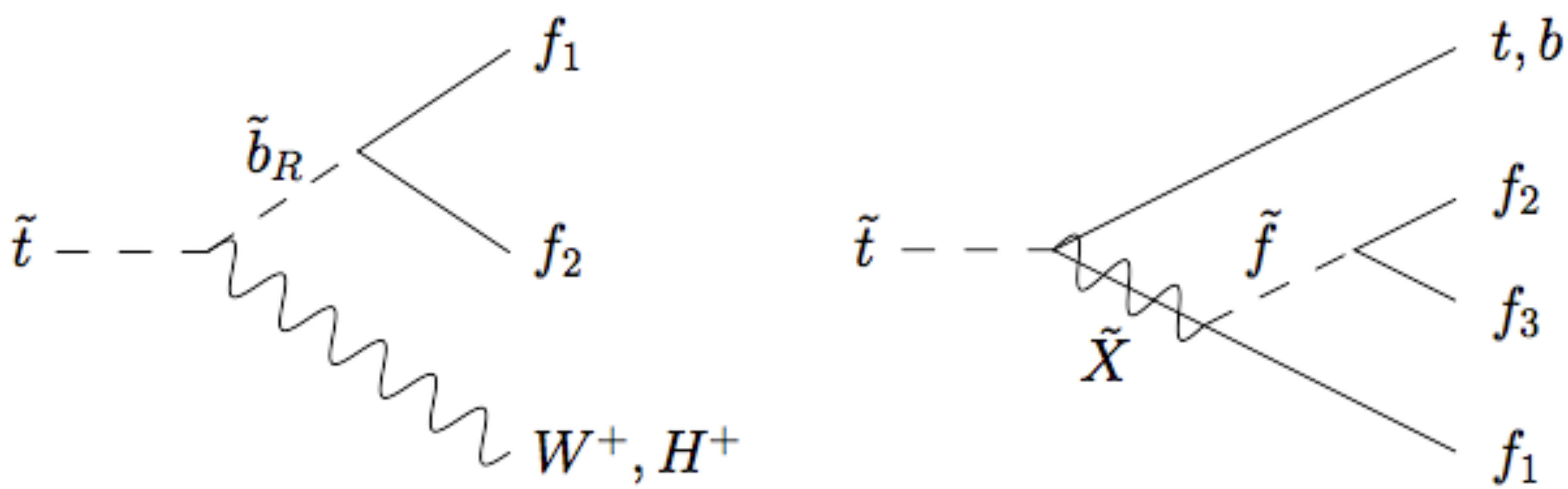




Characteristic signature is 1-2 photons (or 1-2 leptons) plus many jets **but with little missing E_T**

RPV SUSY

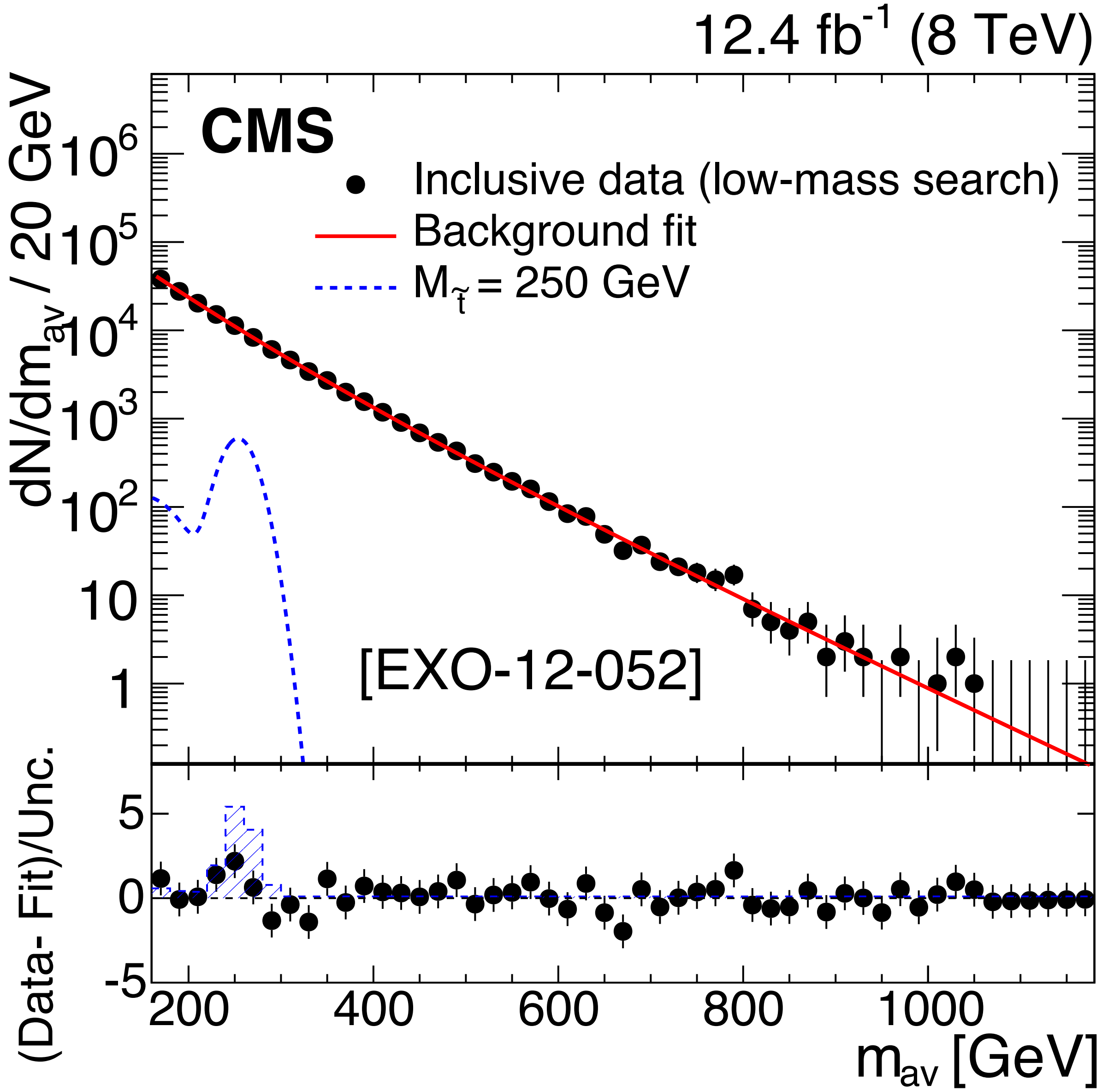
- Tackling Dark Matter and the hierarchy problem simultaneously may not be the right approach
  - allowing the lightest super particle to decay allows for an incredibly diverse set of **potentially unexplored** final states
    - as long as R-parity violating (RPV) couplings are small, this does not run afoul of proton decay constraints, neutron EDM, and the like
  - Kats, Evans, JHEP 04 (2013) 028 identifies final states dominated by many jets and/or taus **to be largely uncovered**, even after considering the vast majority of the CMS/ATLAS physics program



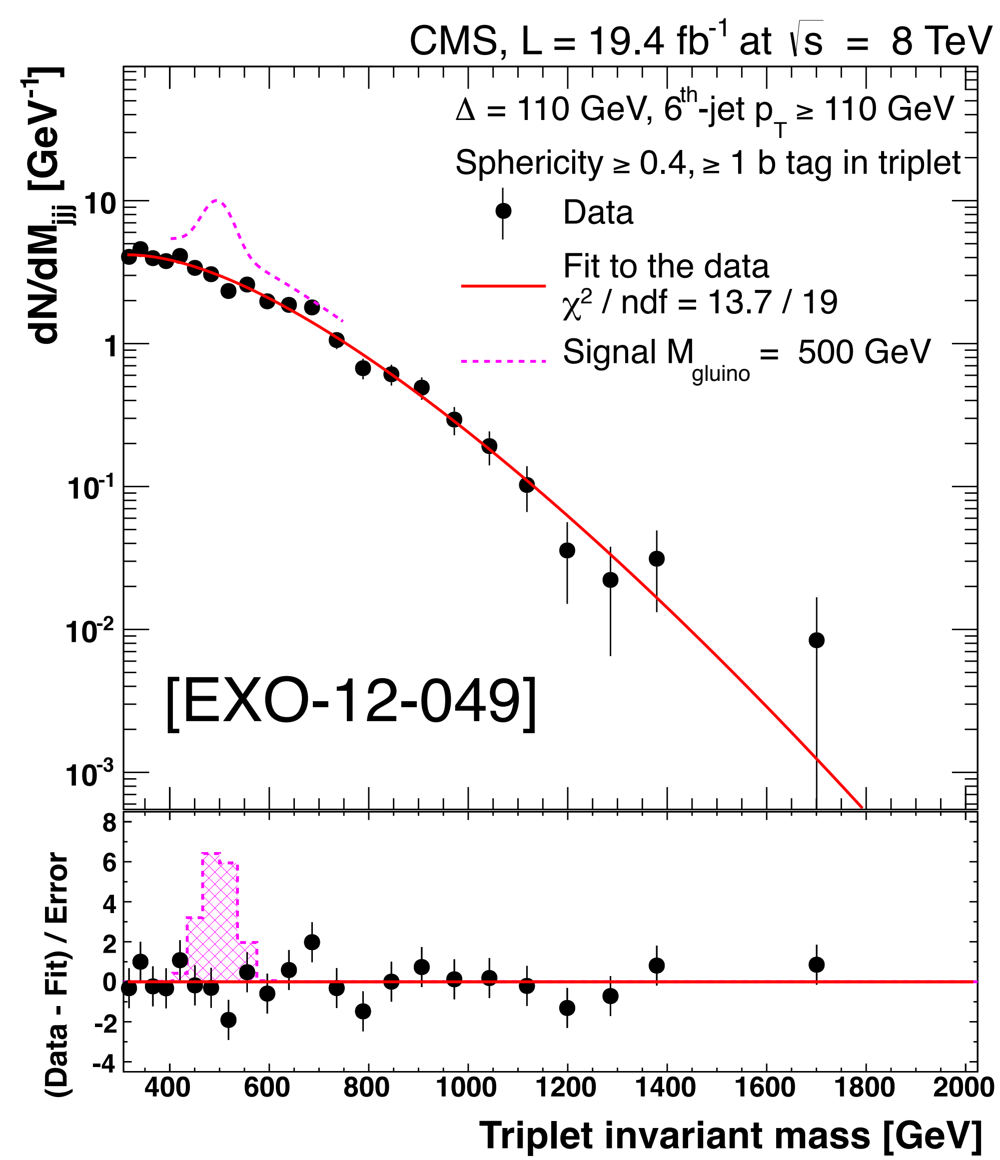
ALL HADRONIC RPV SUSY

- The **simplest** case of hadronic RPV: pair production of stops or gluinos decaying to 2 or 3 jets

stop→jj

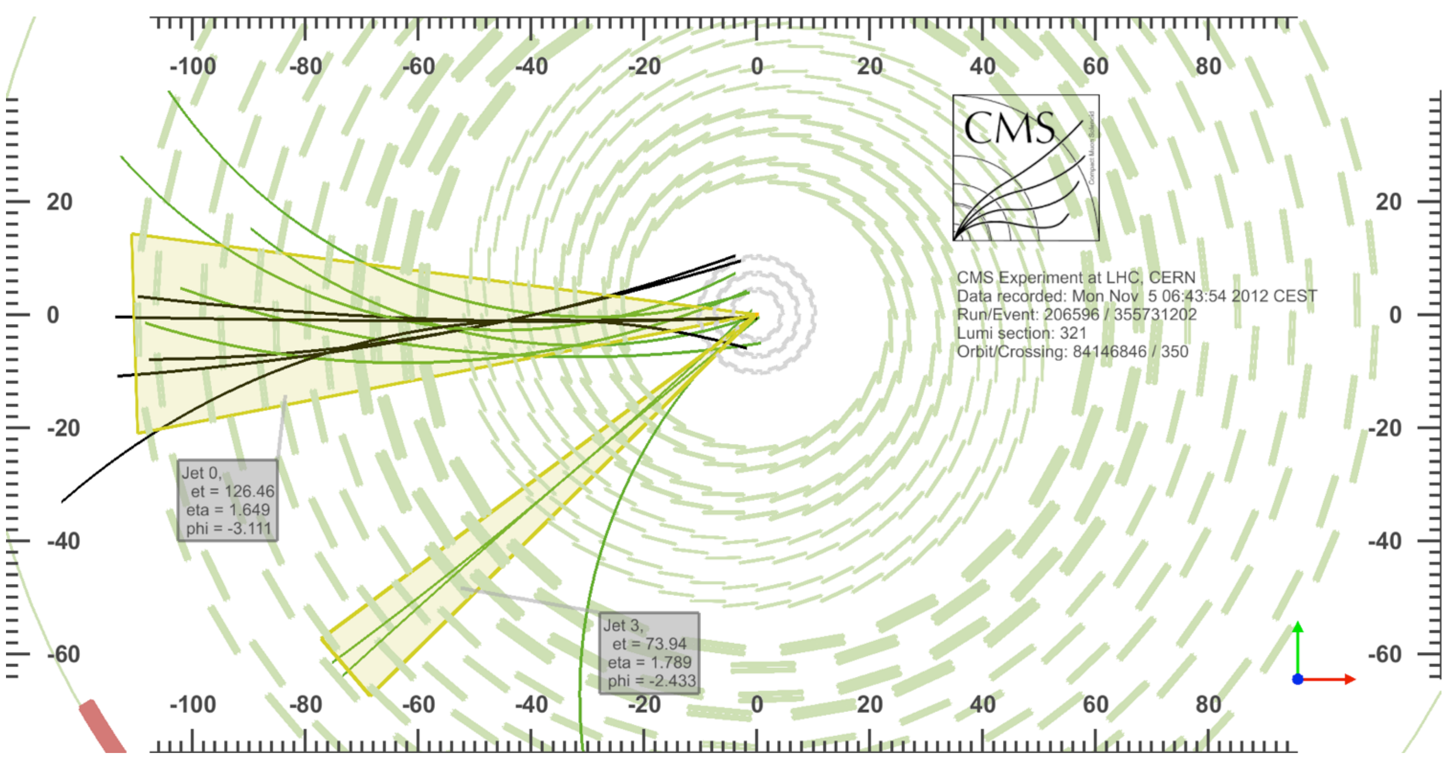


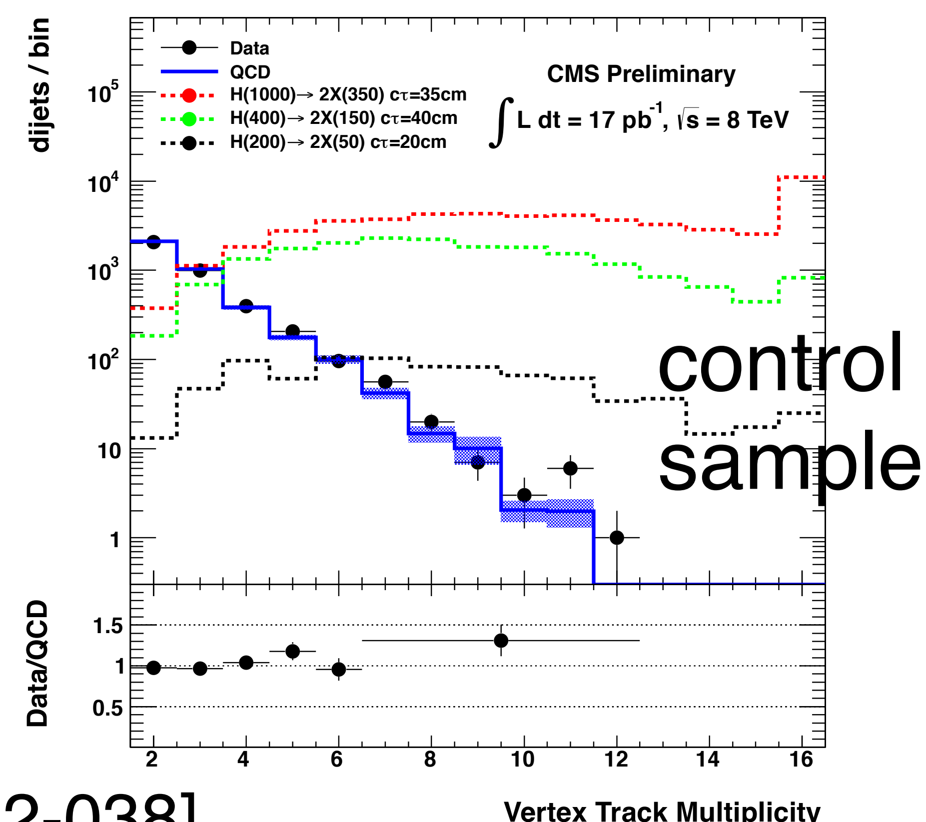
gluino→jjj



DISPLACED DIJETS

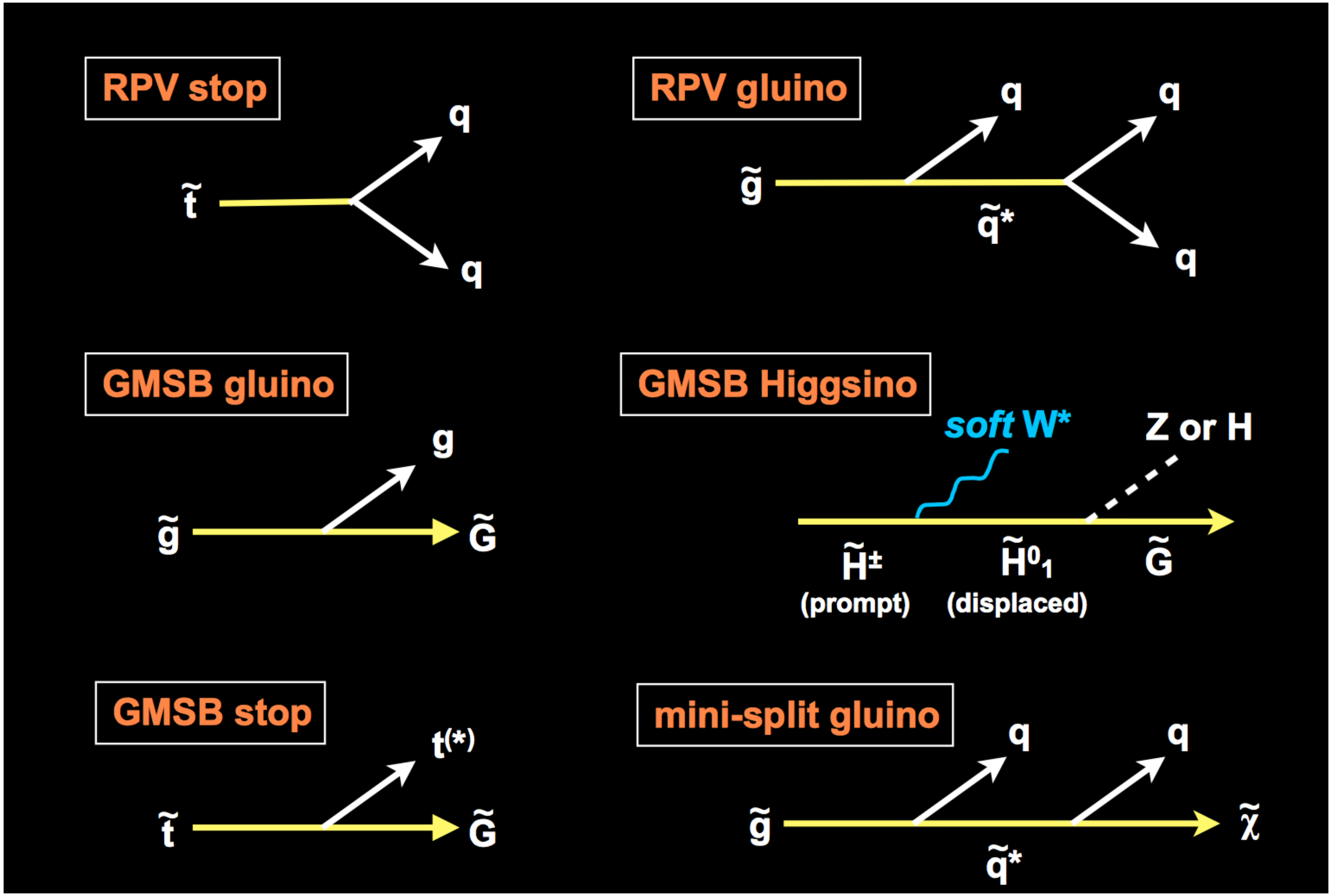
- Massive long-lived particles can decay to jets
  - Split SUSY, RPV SUSY, Gauge Mediated SUSY, Hidden Valley models, etc.
- Search for events with **dijets from a common, displaced vertex**
  - Trigger on events with H_T>300 GeV and **≥2 jets with small fraction of prompt tracks**
    - Offline: form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



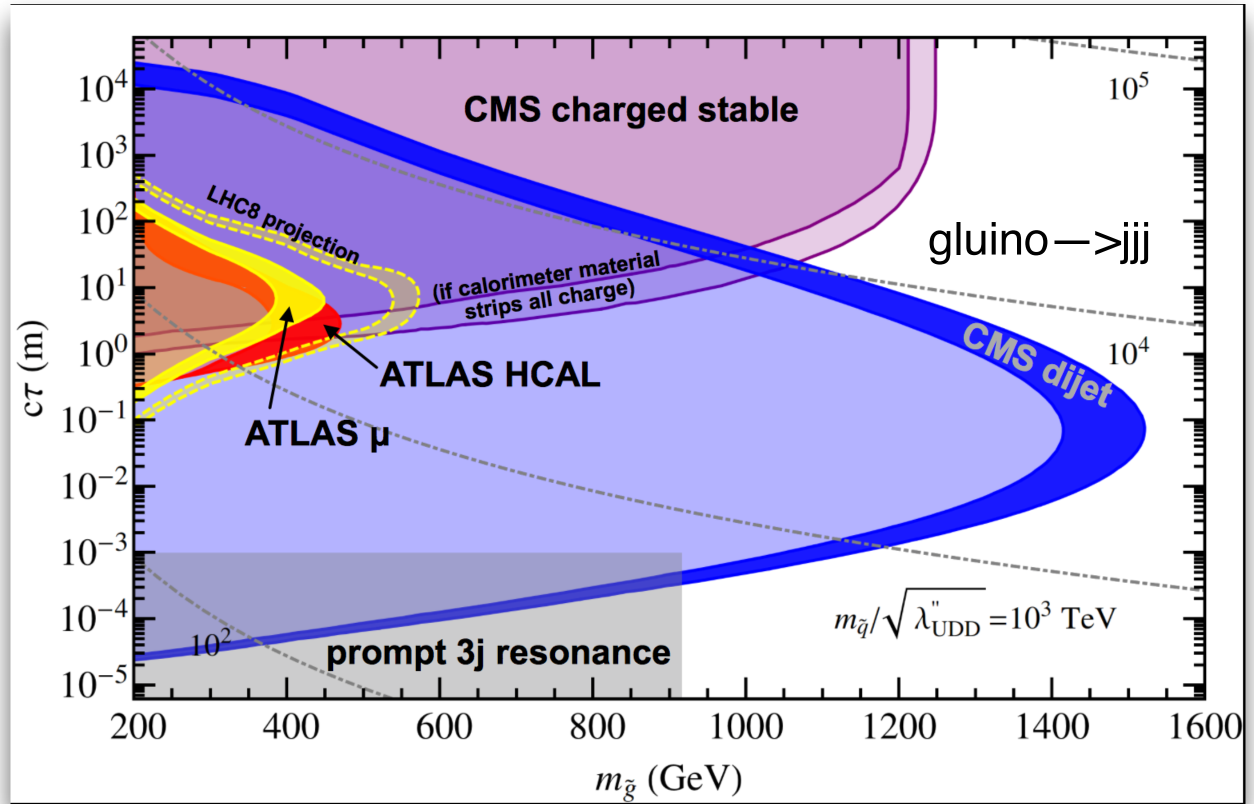


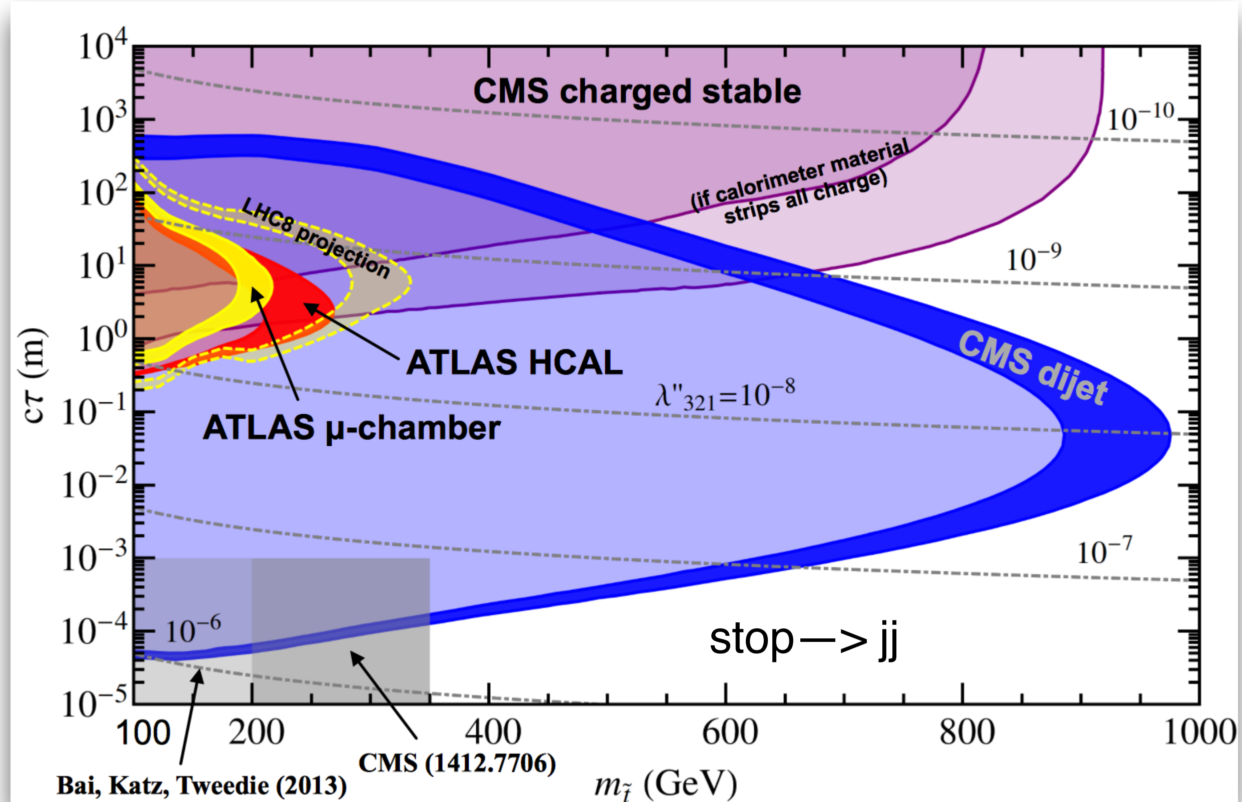
[EXO-12-038]

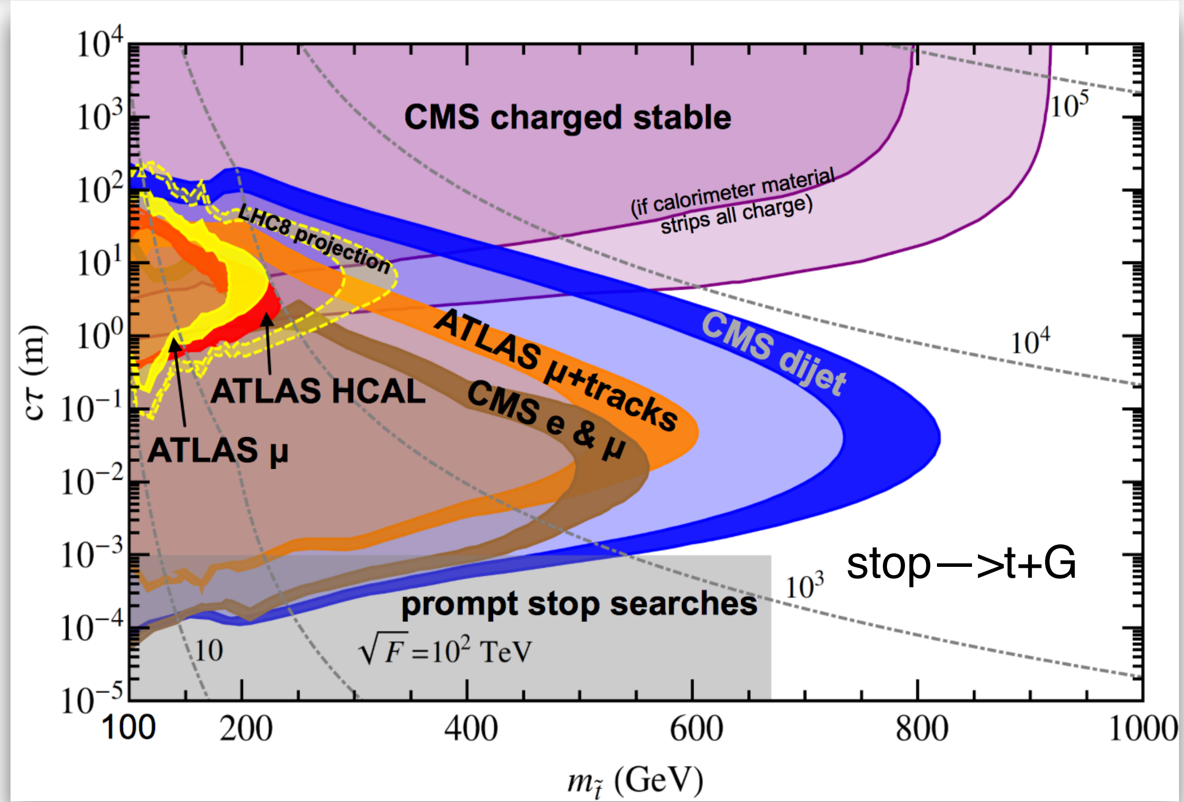
Displaced Dijet Models

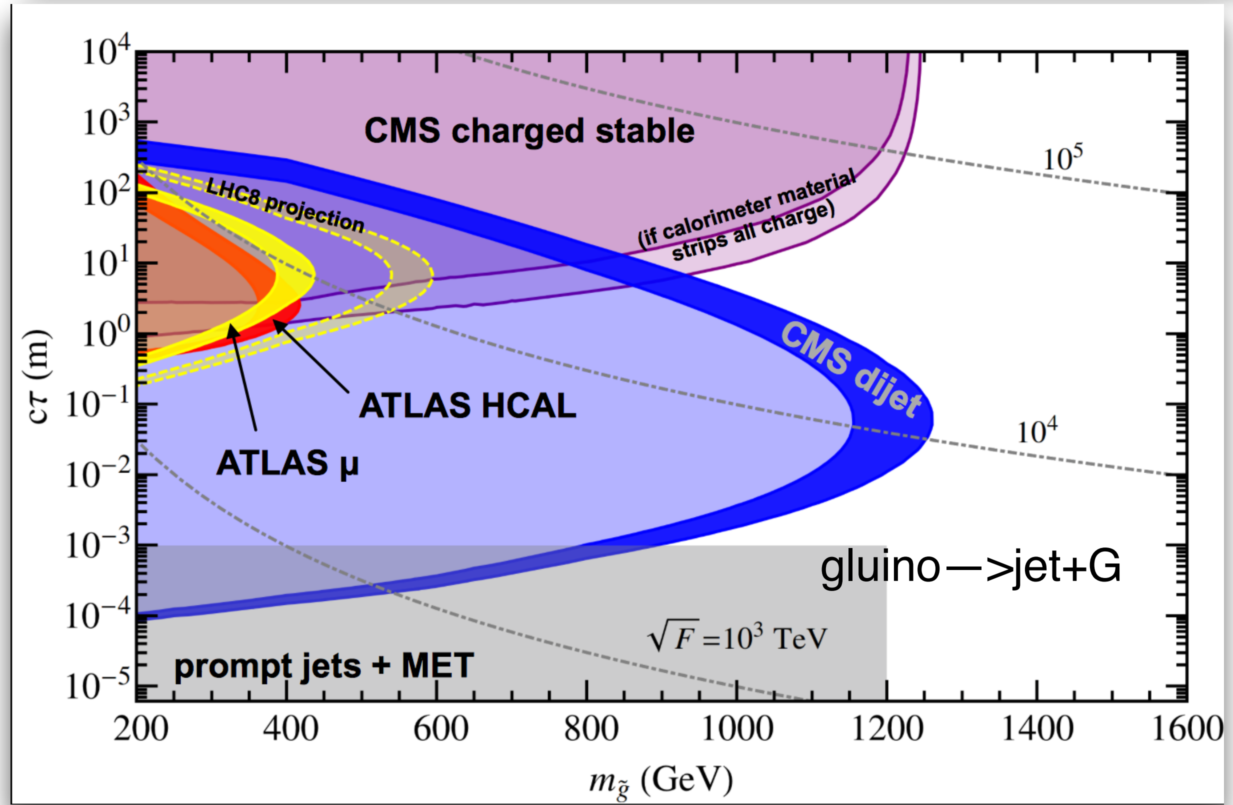


Displaced Dijet Sensitivity



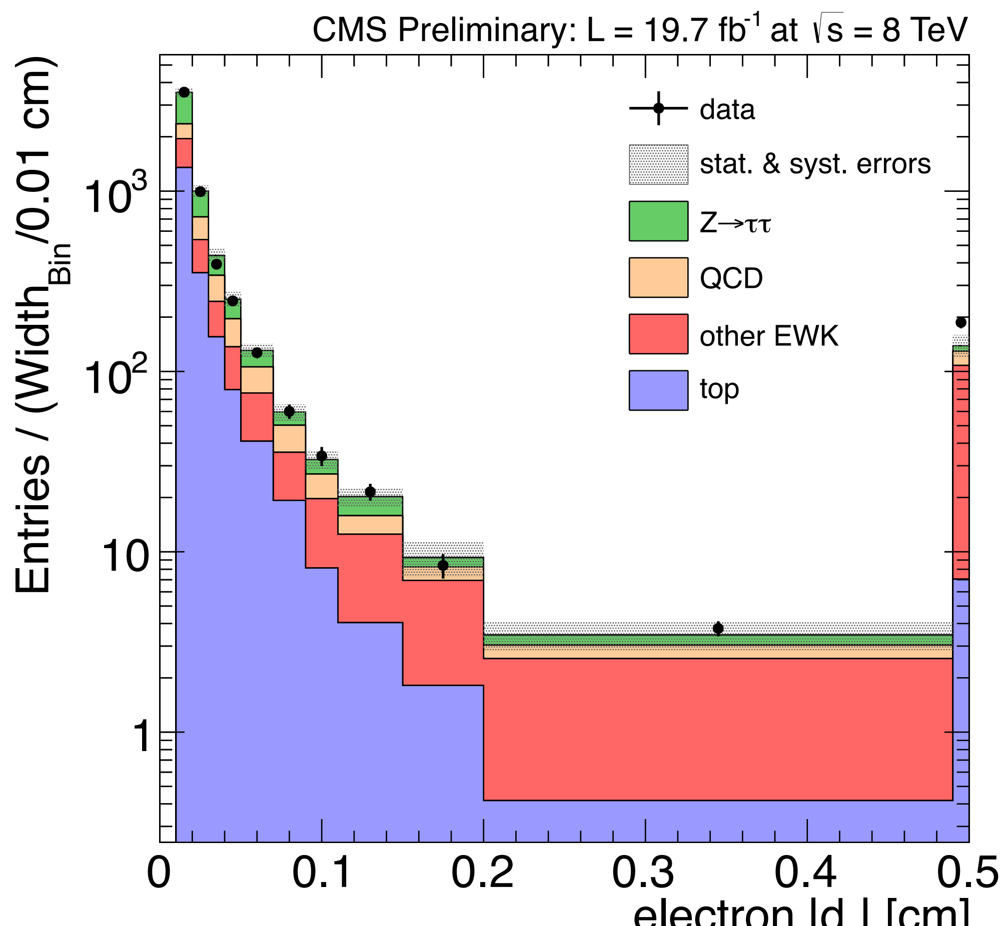




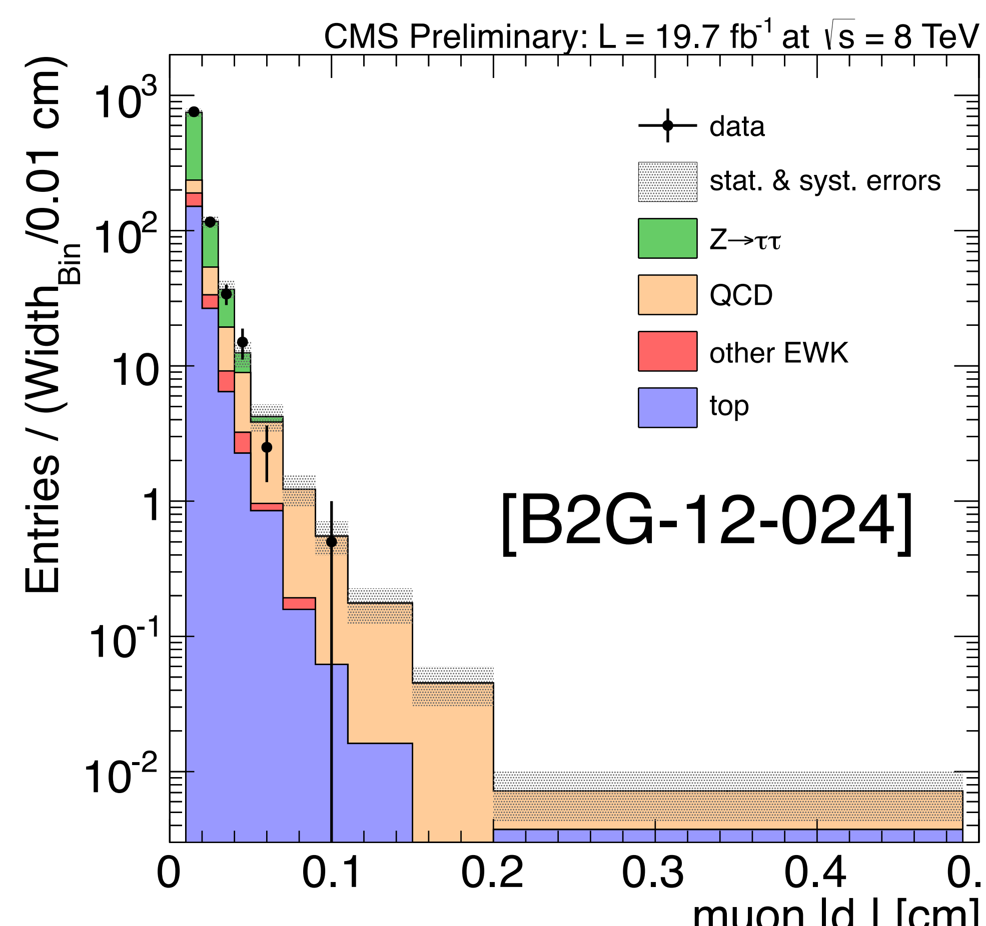


(Slightly) Displaced Leptons

- 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

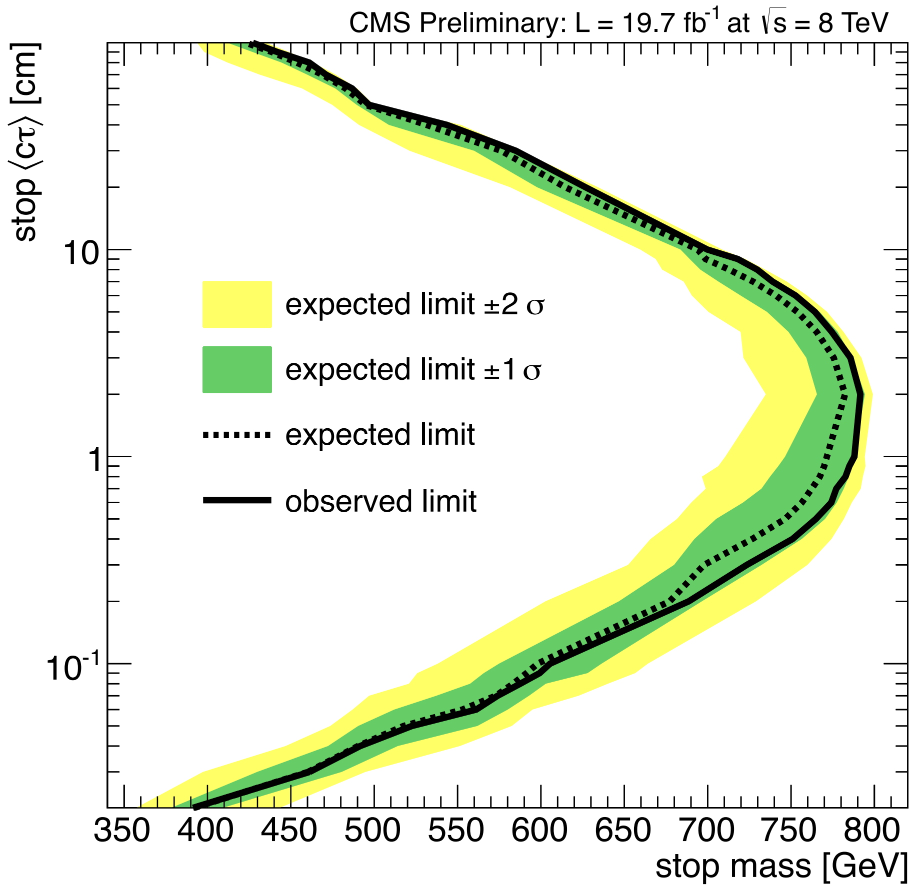


non-prompt u and prompt e

DISPLACED LEPTON LIMITS

- 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

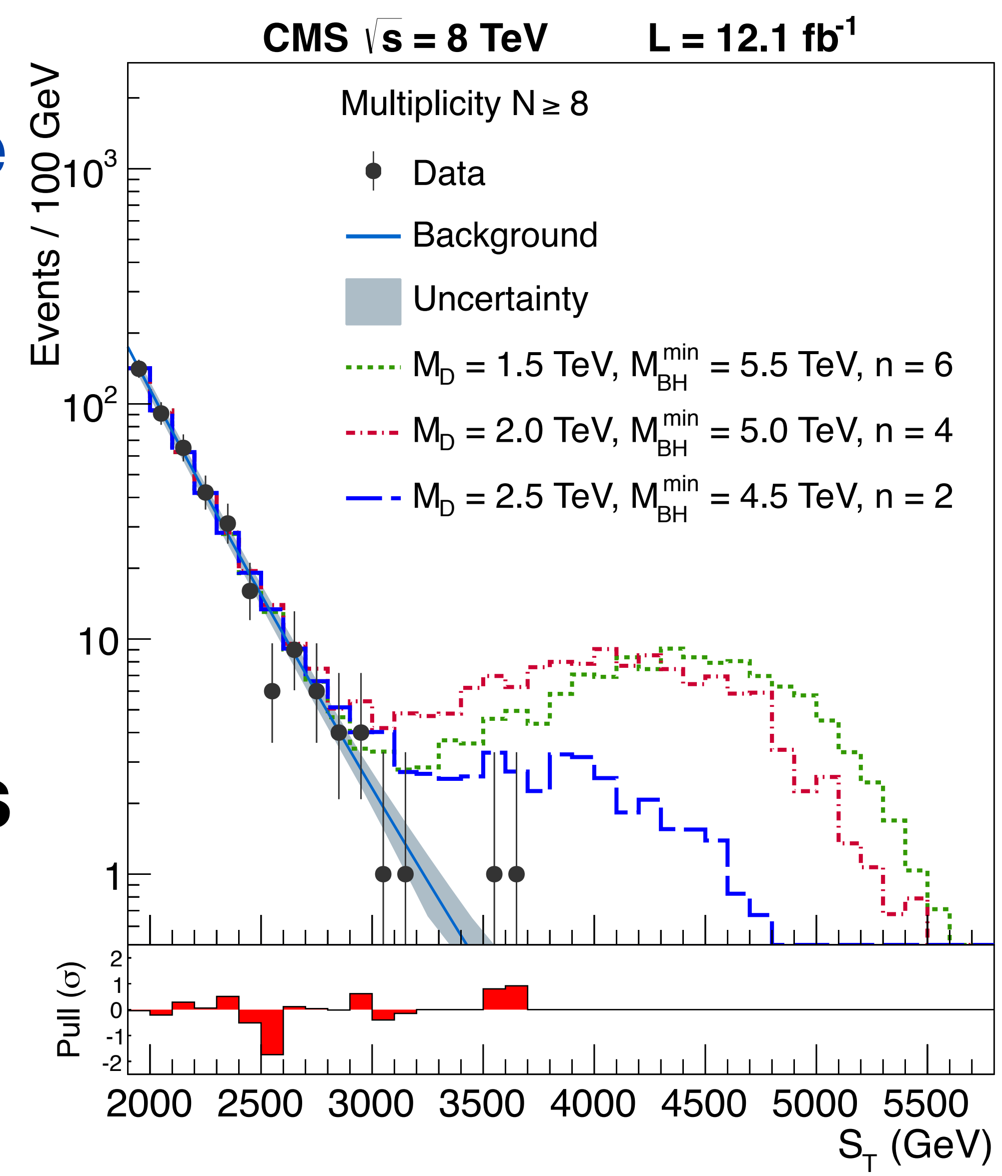


Event Source	0.02 cm $< \lvert d_0 \rvert < 0.05$ cm	0.05 cm $< \lvert d_0 \rvert < 0.1$ cm	$\lvert d_0 \rvert > 0.1$ cm
other EWK	$0.65 \pm 0.13 \pm 0.08$	$(0.89 \pm 0.53 \pm 0.11) \times 10^{-2}$	$<(89 \pm 53 \pm 11) \times 10^{-4}$
top	$0.767 \pm 0.038 \pm 0.061$	$(1.25 \pm 0.26 \pm 0.10) \times 10^{-2}$	$(2.4 \pm 1.3 \pm 0.2) \times 10^{-4}$
$Z \rightarrow \tau\tau$	$3.93 \pm 0.42 \pm 0.32$	$(0.73 \pm 0.73 \pm 0.06) \times 10^{-2}$	$<(73 \pm 73 \pm 6) \times 10^{-4}$
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
$pp \rightarrow \tilde{t}_1 \tilde{t}_1^*$			
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	$4.73 \pm 0.30 \pm 0.17$	$5.57 \pm 0.32 \pm 0.20$	$26.27 \pm 0.70 \pm 0.93$

What are we missing?

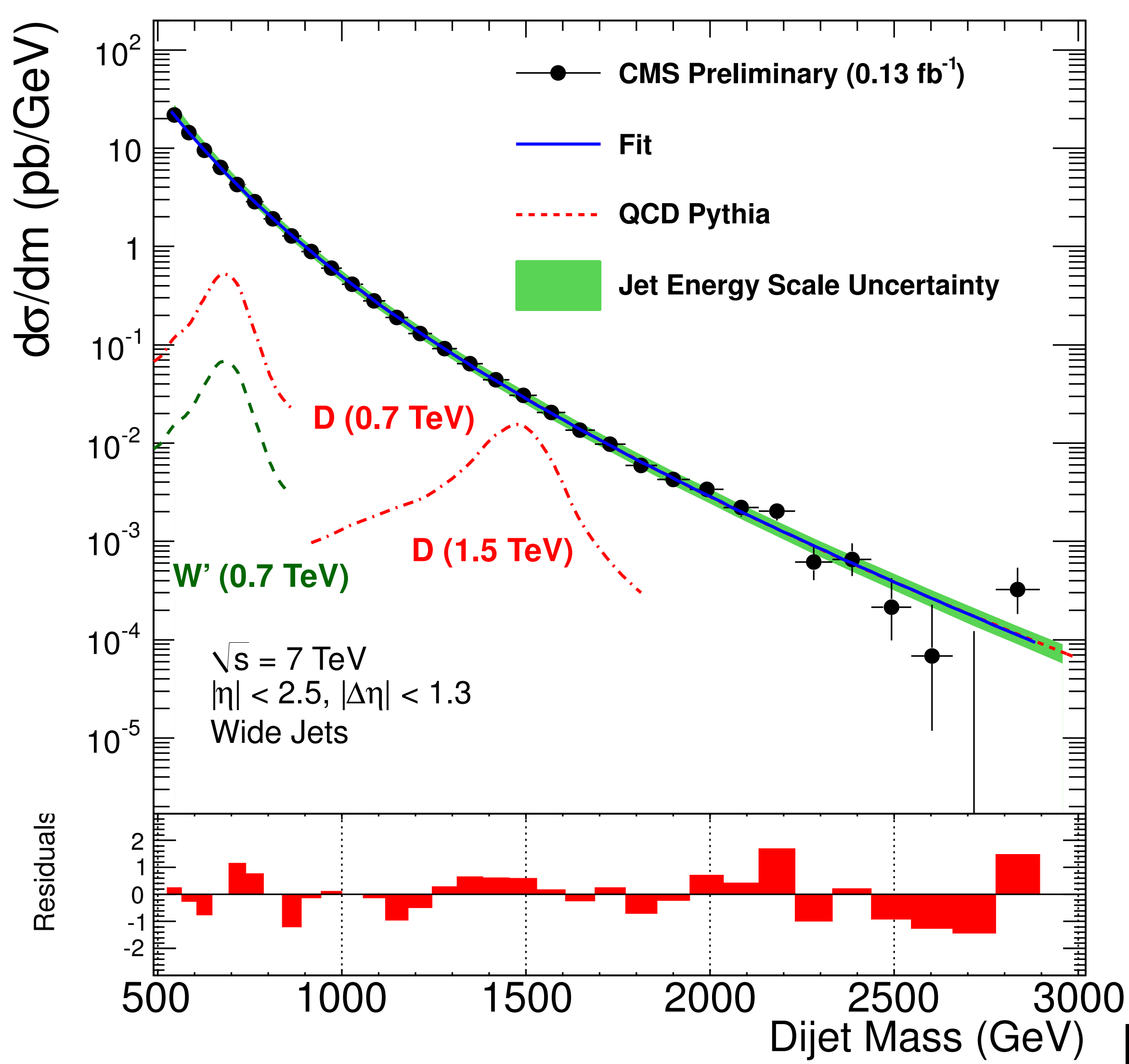
MULTIJETS

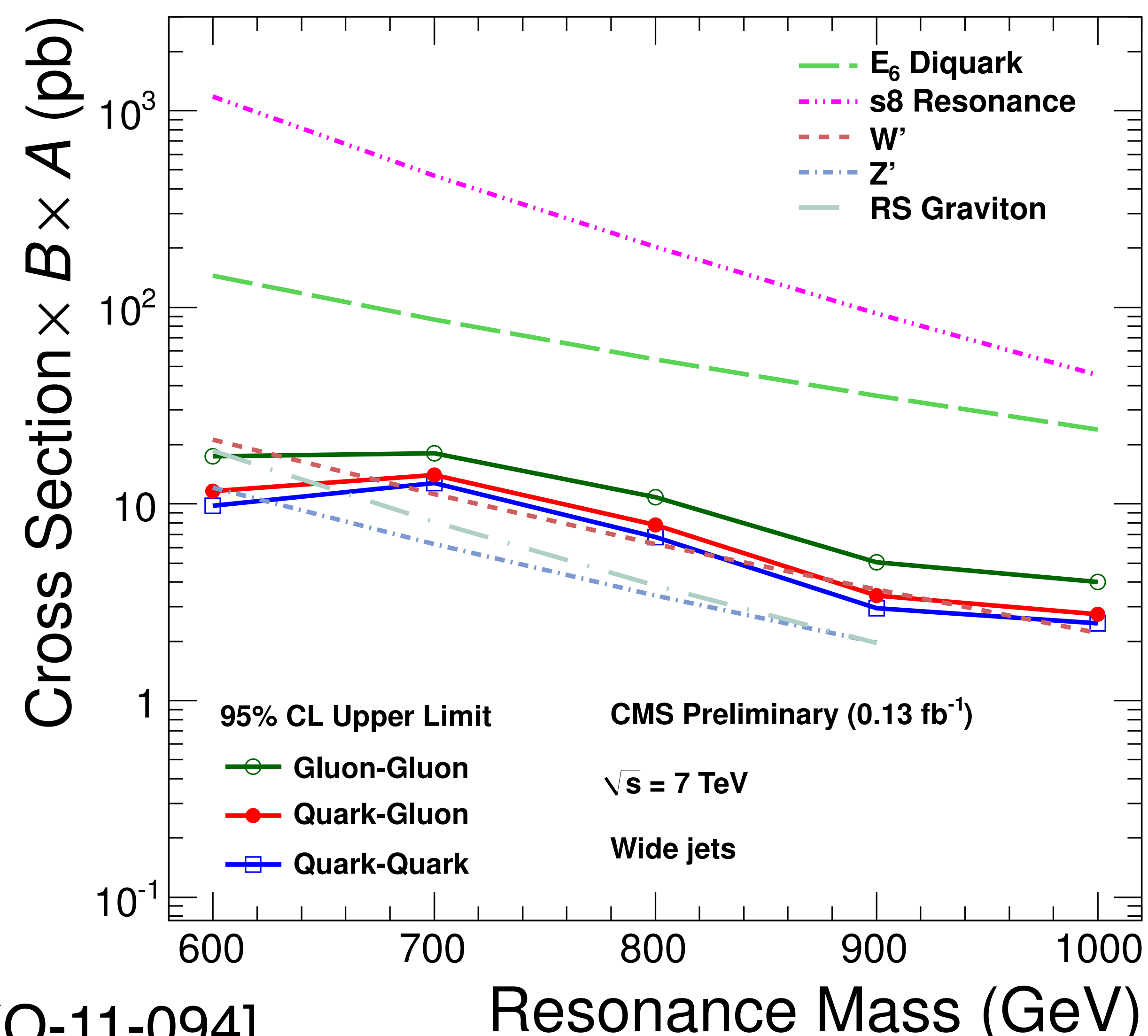
- Search for high multiplicity jet final states (with no missing E_T) is very challenging
  - One approach (motivated by classical black holes) is to look at the tails of the S_T distribution (scalar sum p_T of objects)
  - data-driven approach seems to work well here, but limited to tails
    - what about below 2 TeV?
- Targeting **electroweak mass scales** will be significant challenge
  - estimating the background
    - need higher order Monte Carlos
  - trigger thresholds



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]

CONCLUSIONS

- 2015 will be an exciting opportunity to discover new physics, however it shows up
  - Still, it is important to keep an open mind about where new physics could be
  - In the grail legends, the land falls to ruin because Perceval fails to ask the Question
    - Hopefully, this time, we ask the right Questions: the quest for new physics is at stake!