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

John Paul Chou
Rutgers University

Friday, January 16th, 2015

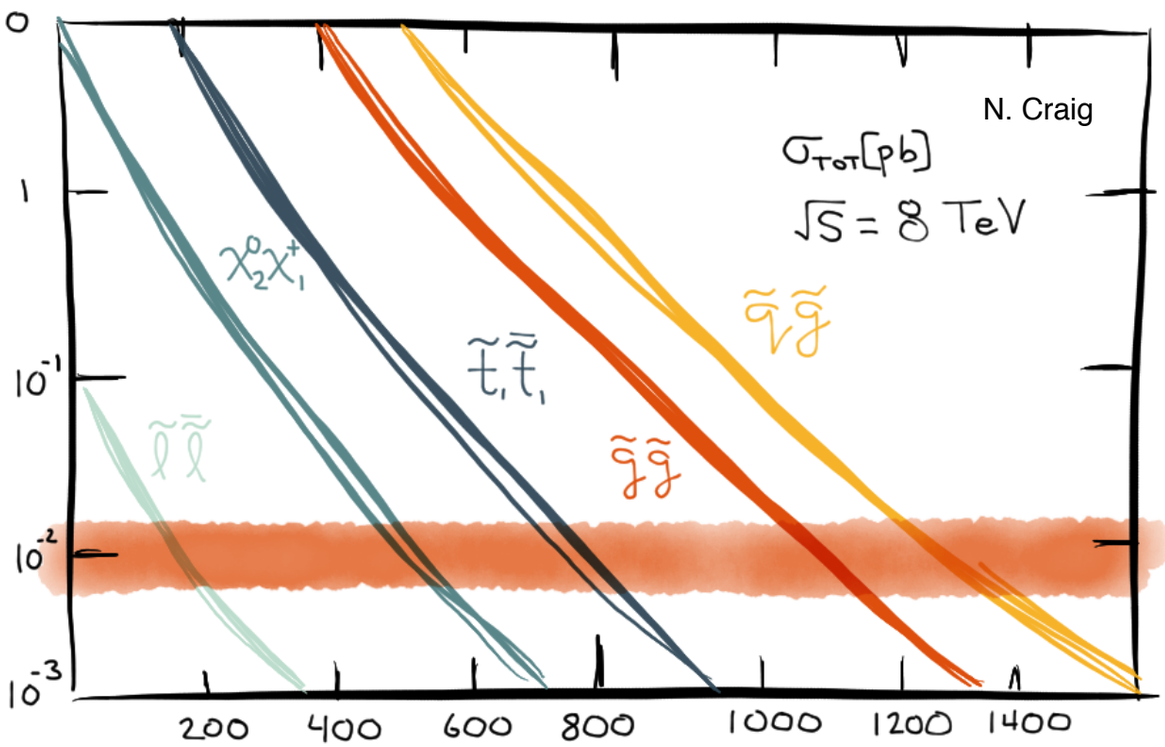
RUTGERS
THE STATE UNIVERSITY
OF NEW JERSEY

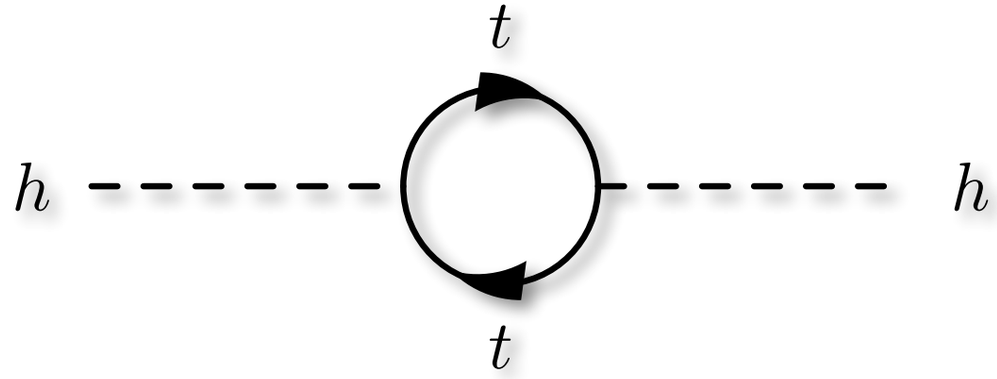
LPC CMS Data Analysis School 2015

- Congratulations to the winners of the CMS DAS 2015 analysis presentations

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



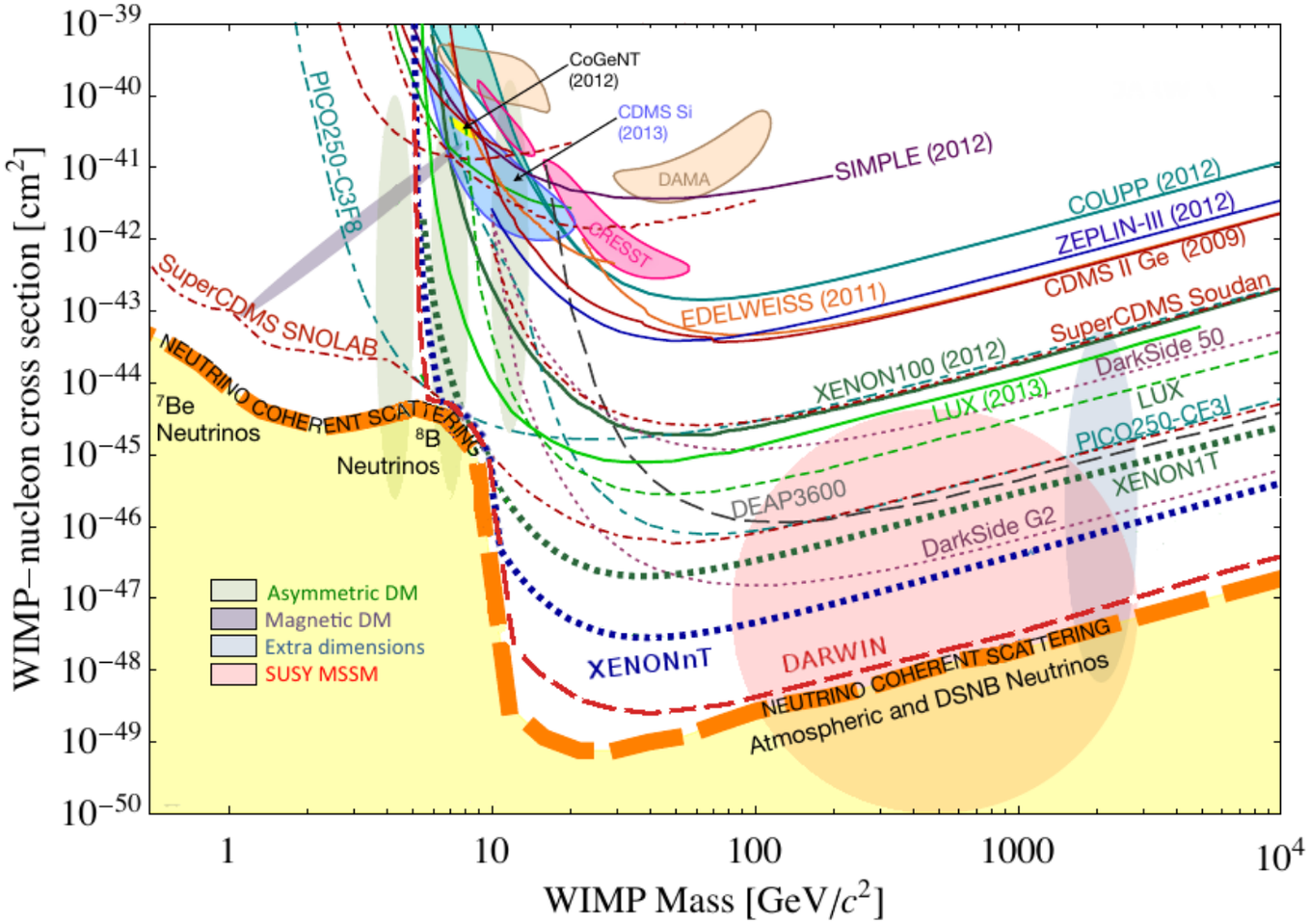


Stop pair production provides the scale that we need to explore: ~10 fb

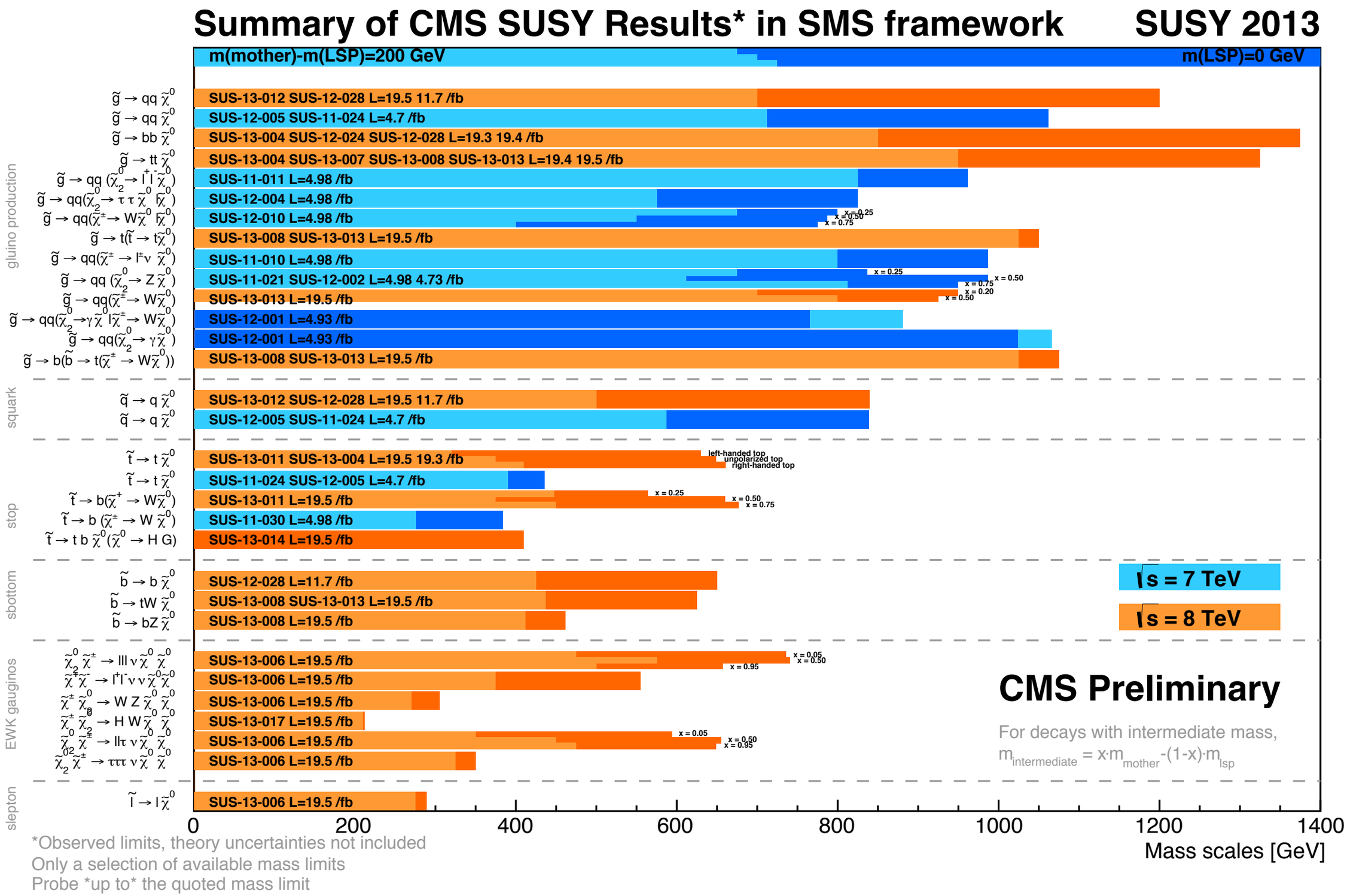
If you don't like SUSY, just mentally replace your favorite strongly produced state every time I say "squark"

Dark Matter

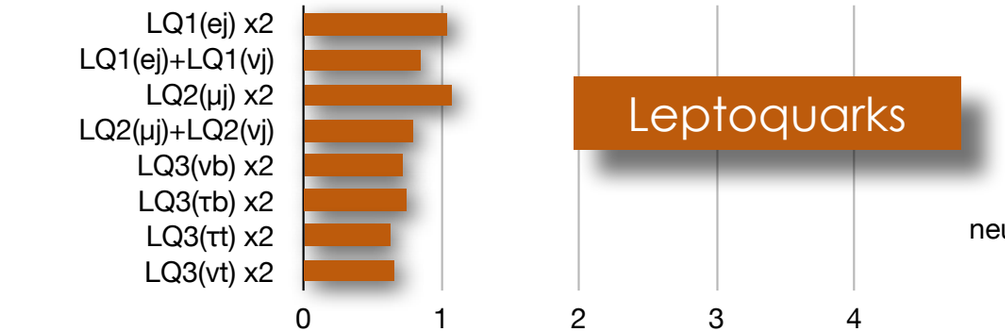
- Strong reasons to prefer a particle interpretation to galactic dark matter observations
  - WIMP interpretation suggests new particles at the EWK scale

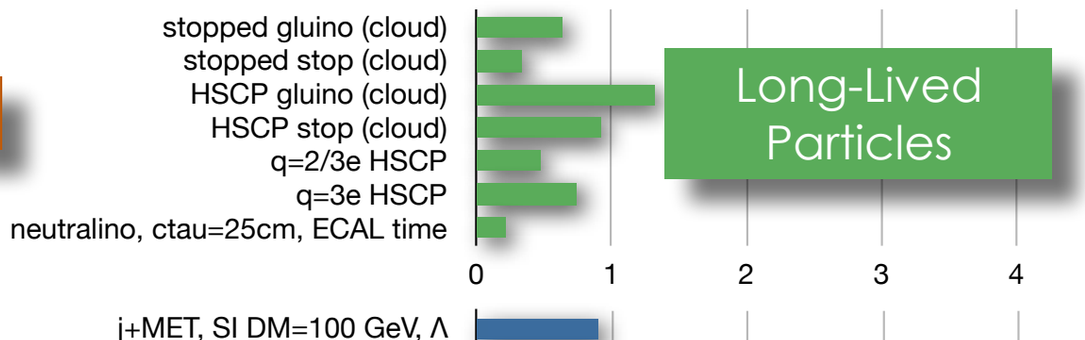


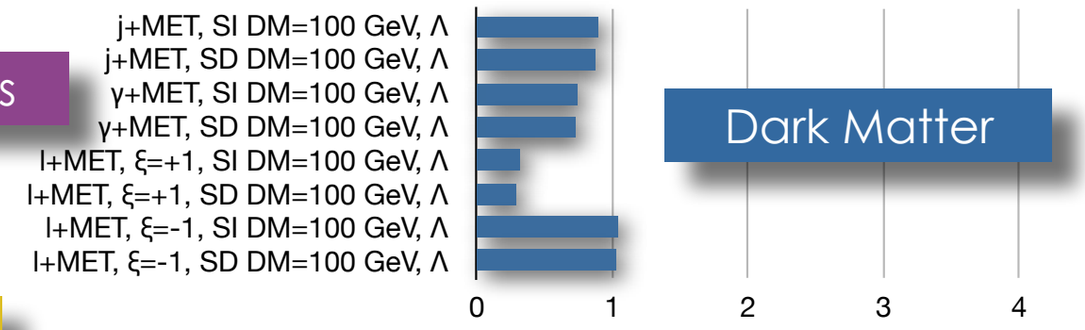
SUSY RESULTS



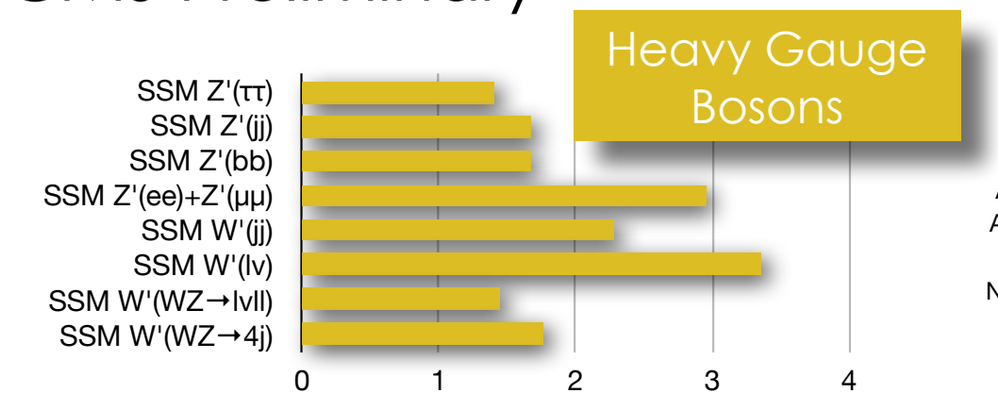
EXOTICA RESULTS

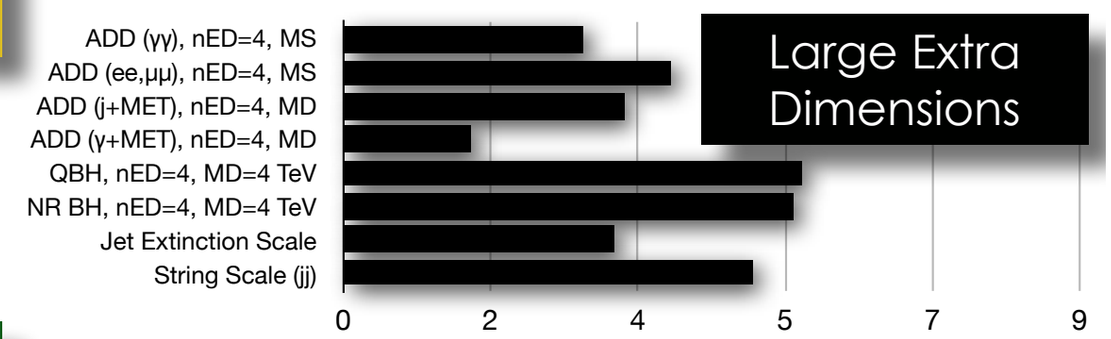


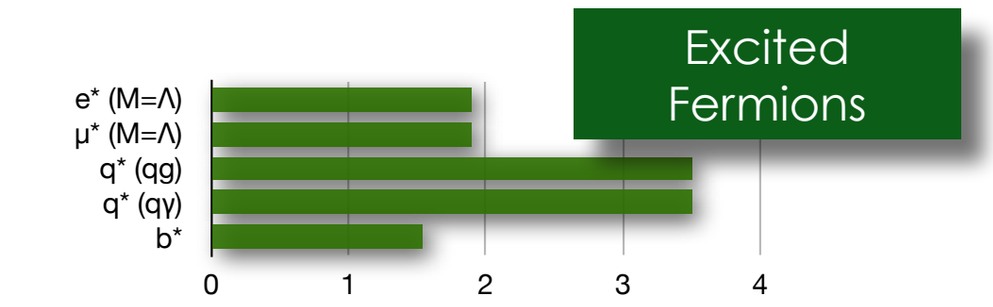


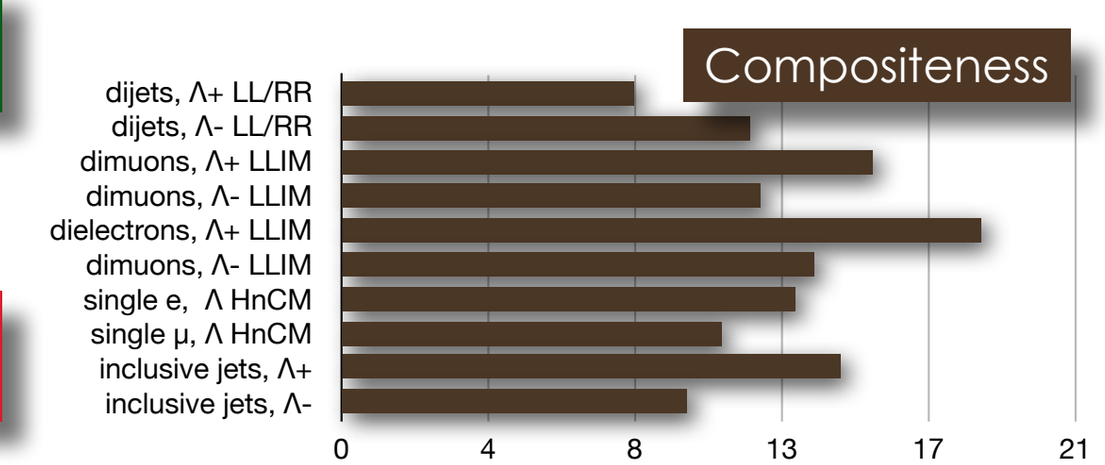


CMS Preliminary



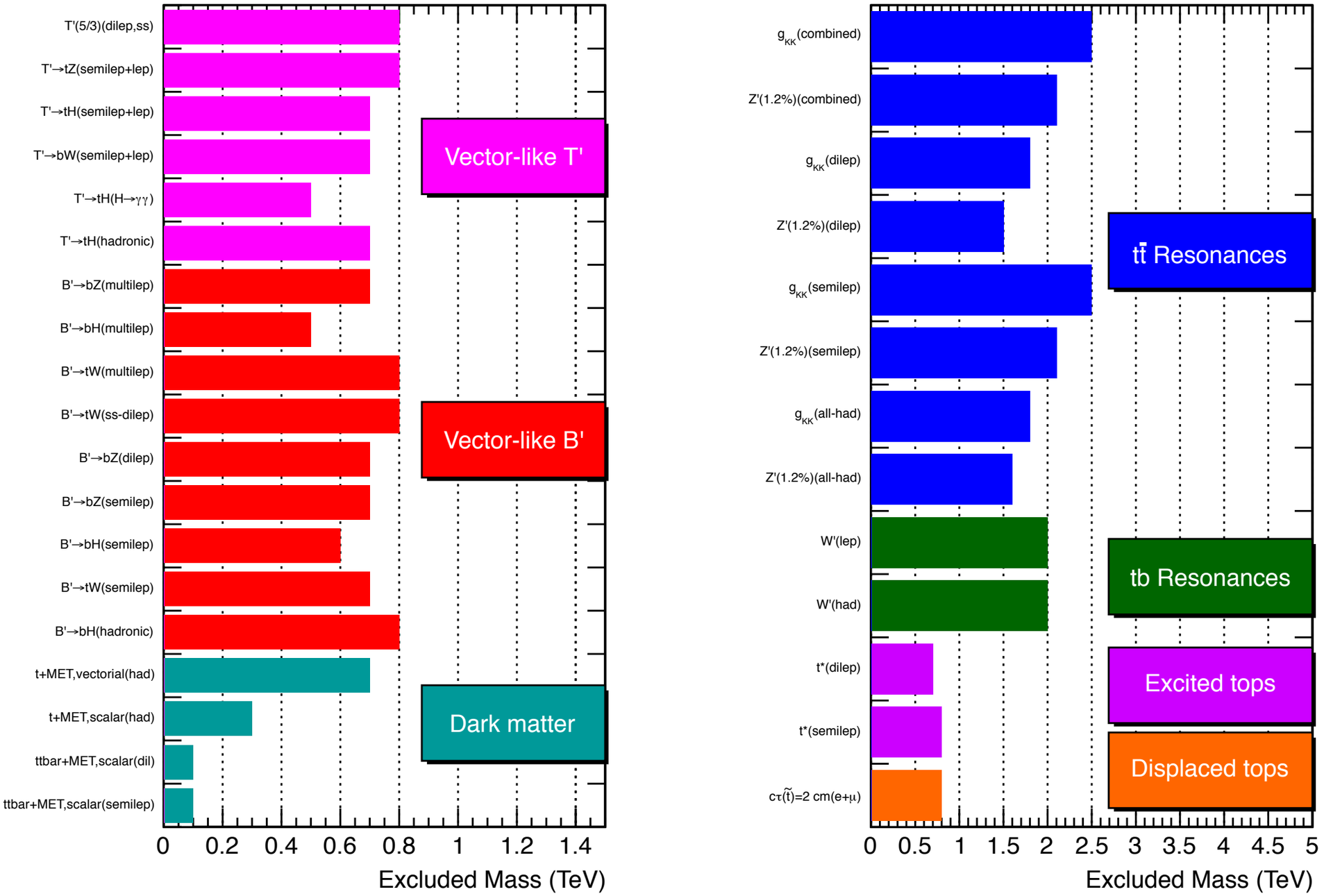






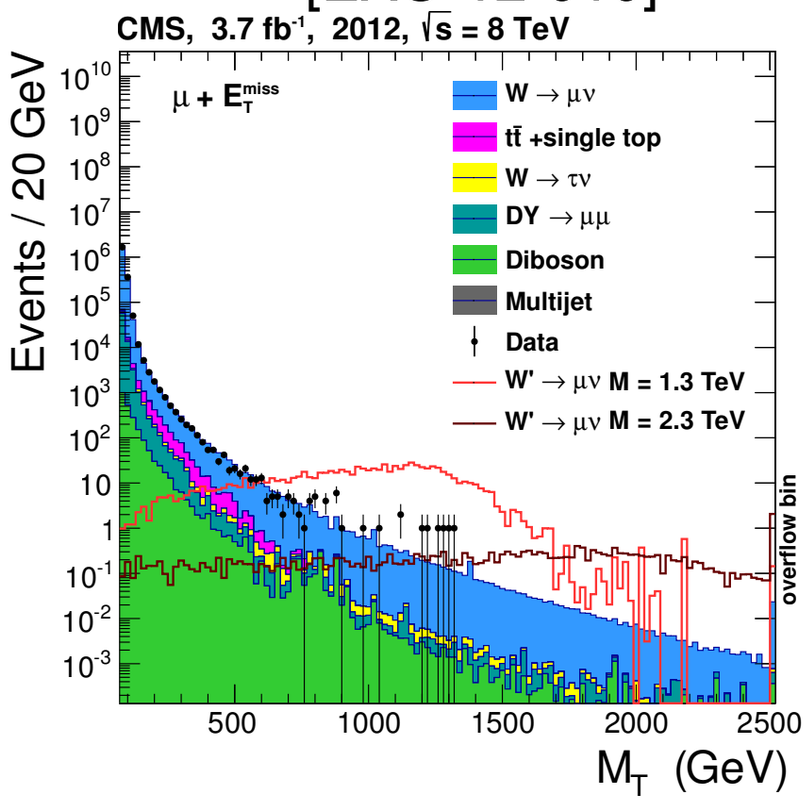
CMS Exotica Physics Group Summary – ICHEP, 2014

SEARCHES FOR BEYOND 2 GENERATIONS

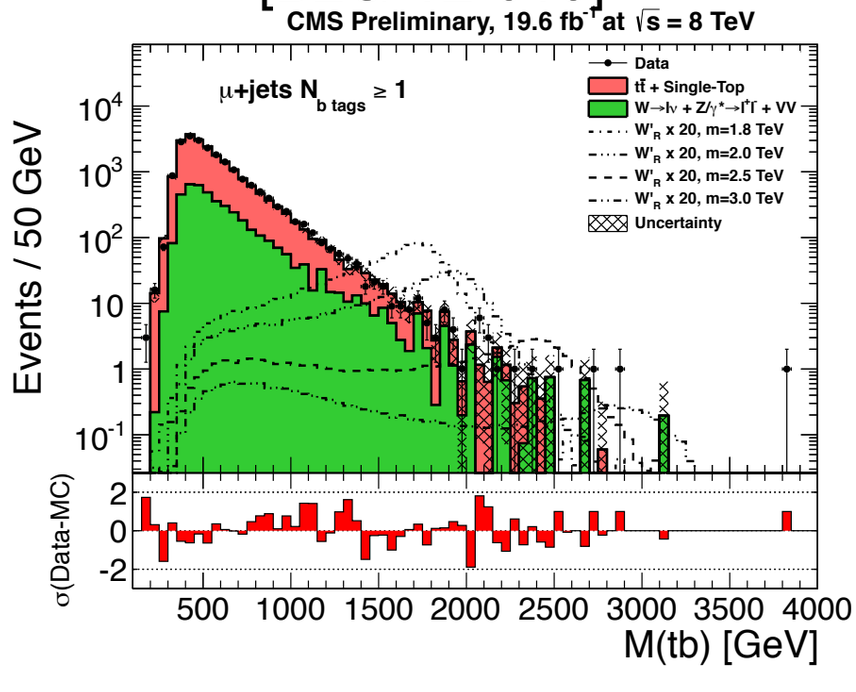


RESONANCES

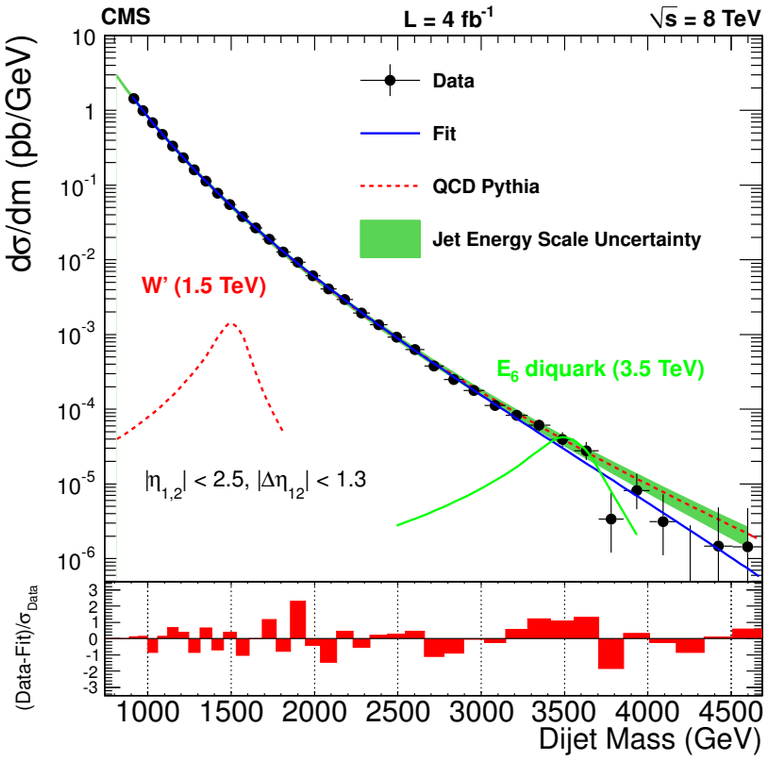
[EXO-12-010]



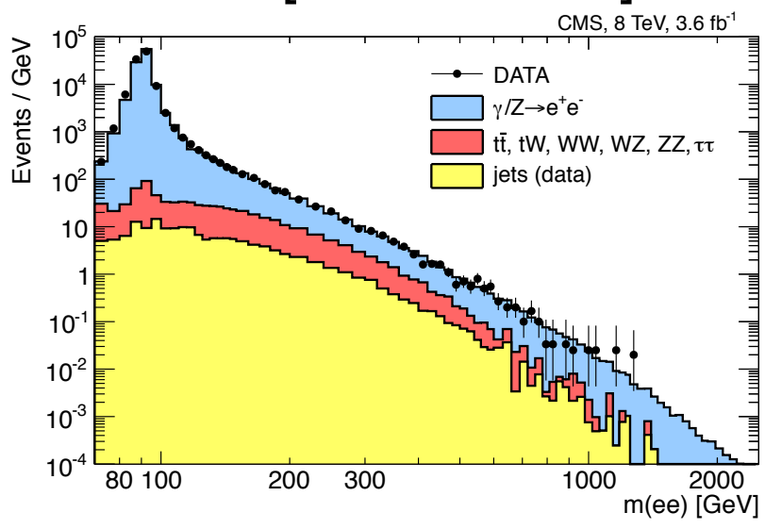
[B2G-12-010]



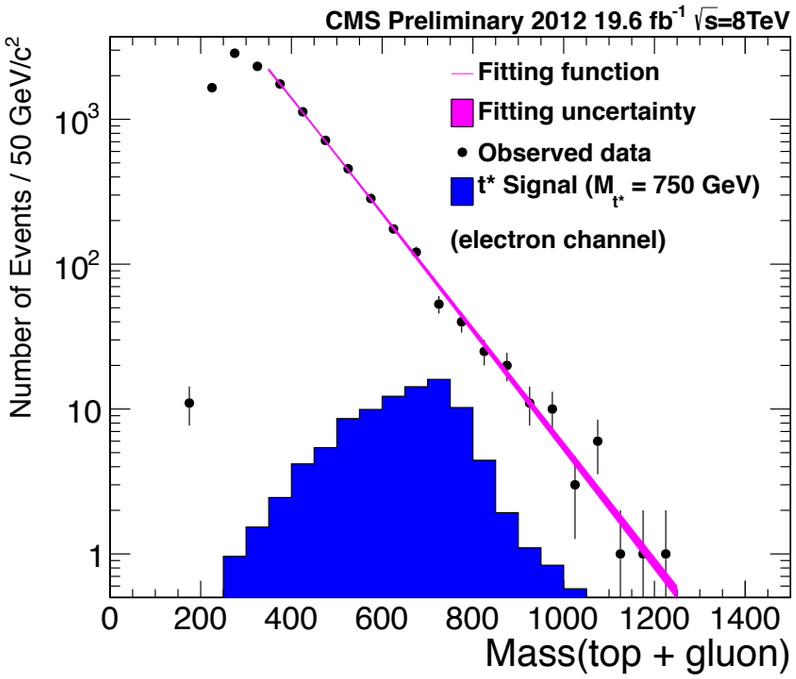
[EXO-12-016]



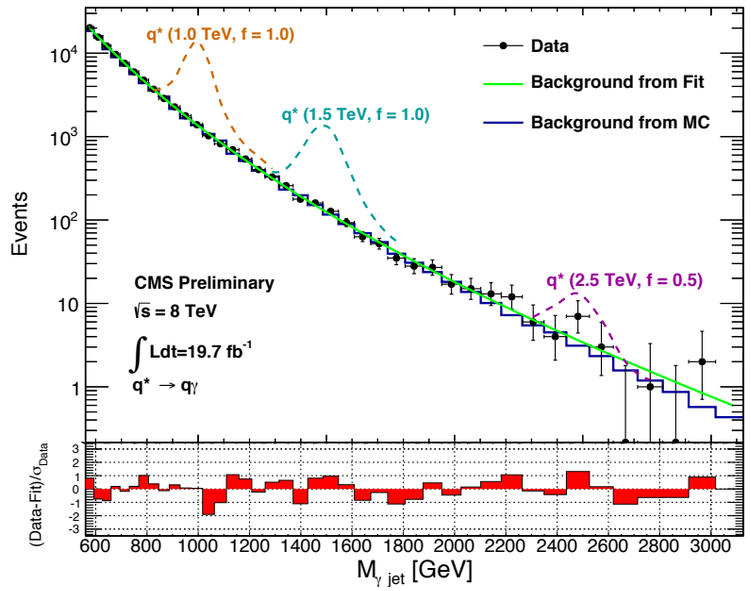
[EXO-12-015]



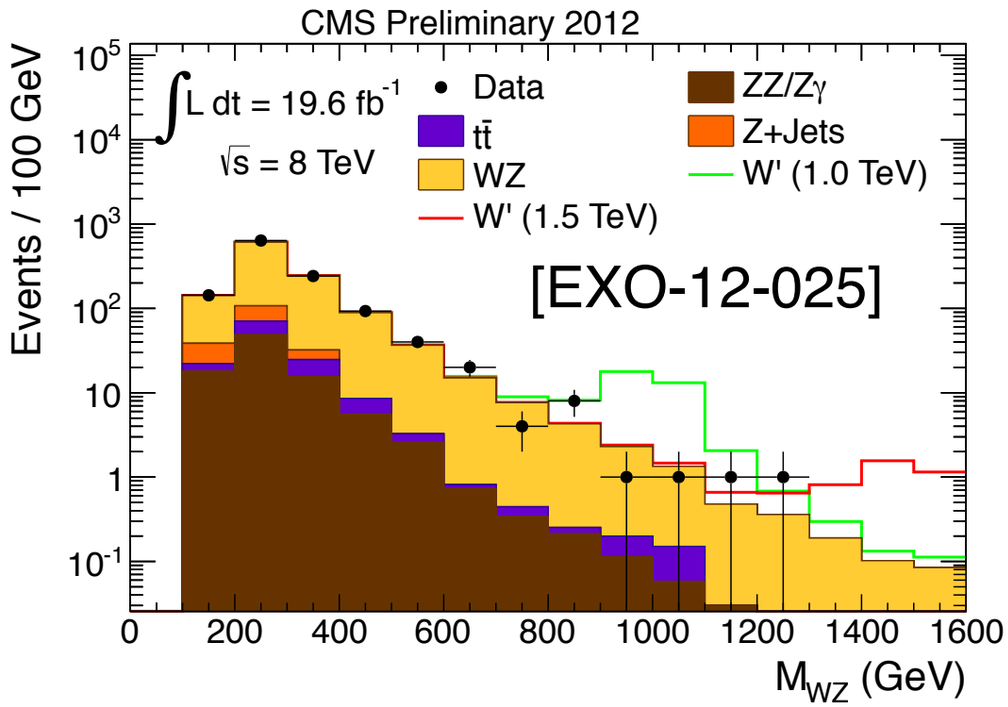
[B2G-12-014]

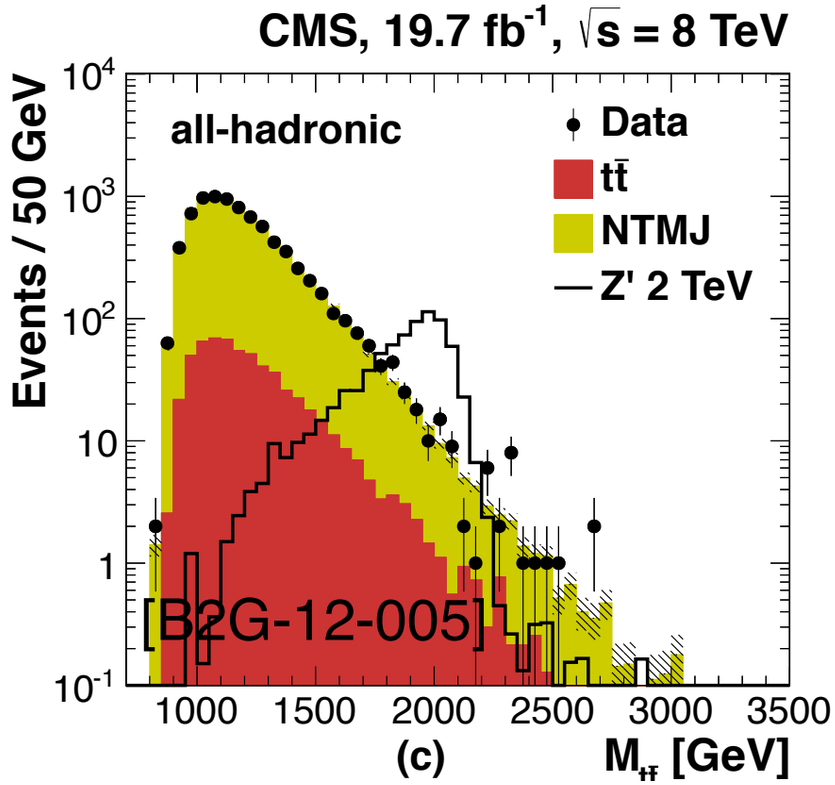


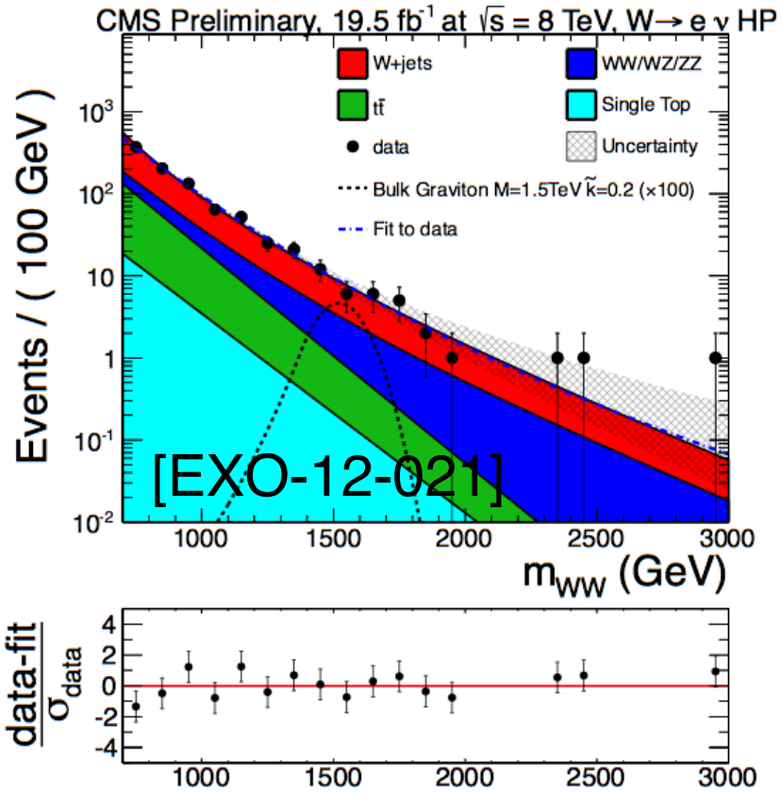
[EXO-13-003]

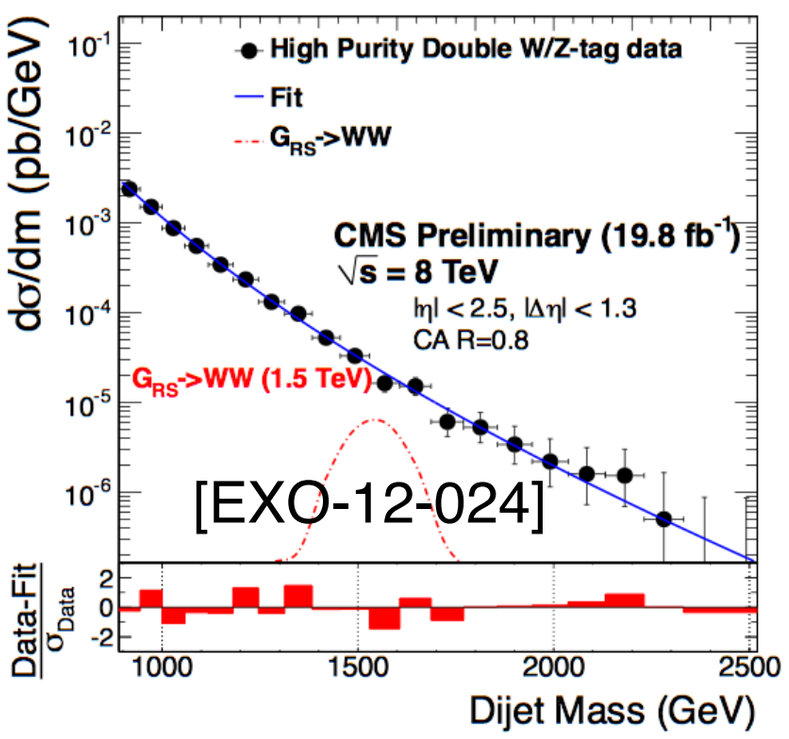


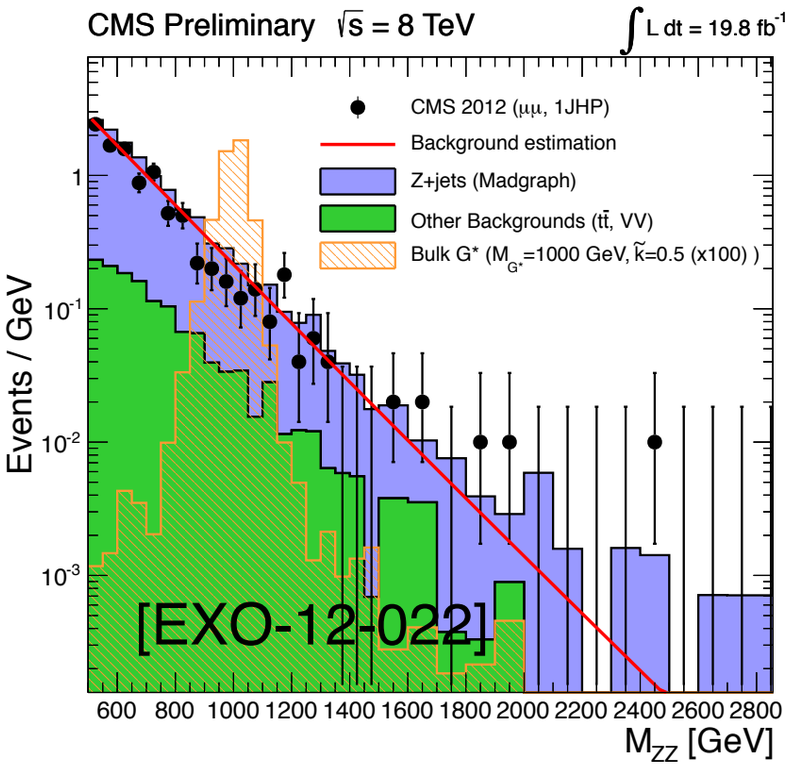
…AND MORE RESONANCES!





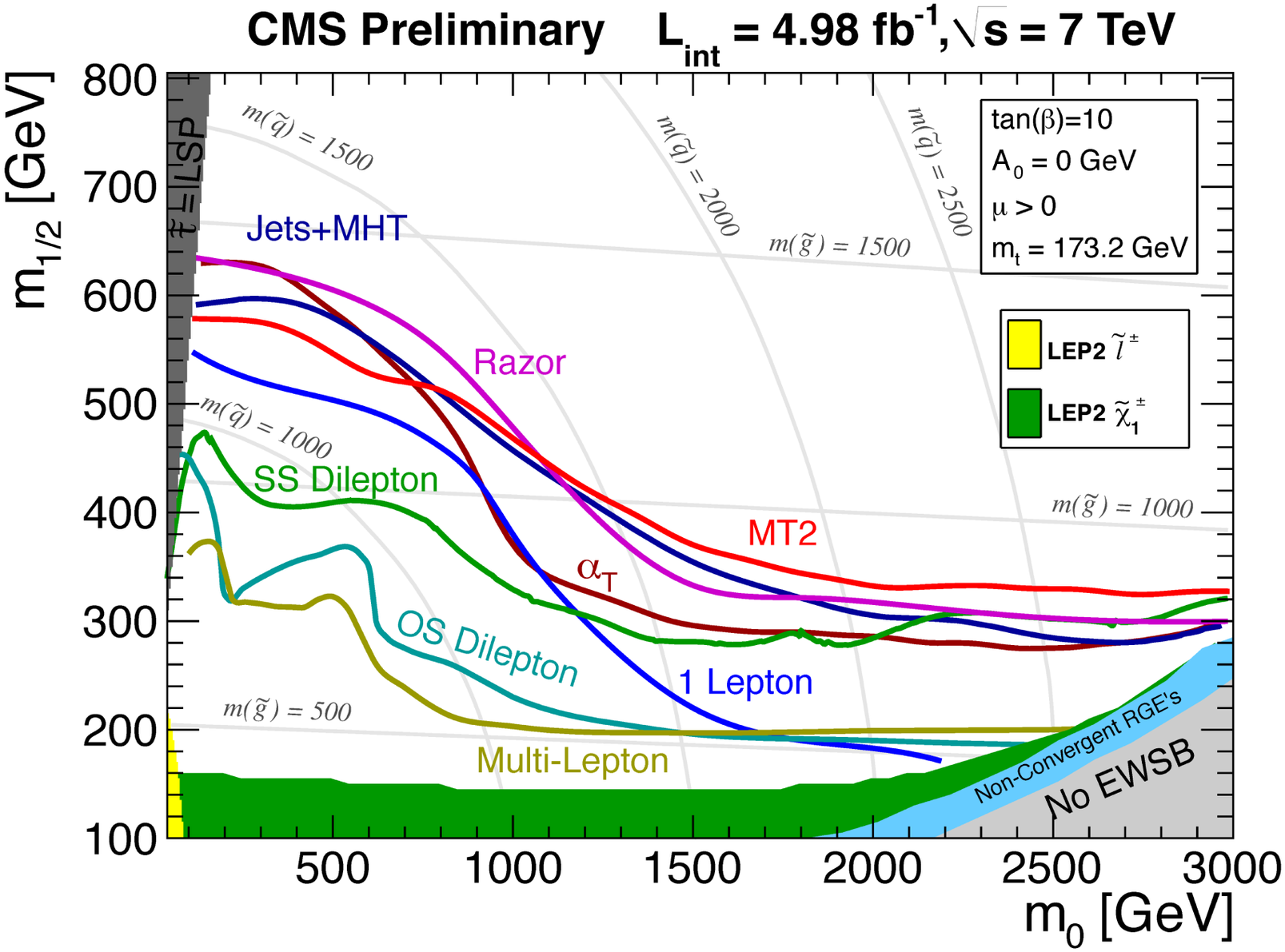






CONSTRAINED MSSM HIT HARD

- X+jets+Missing E_T program has made a significant dent in the MSUGRA plane

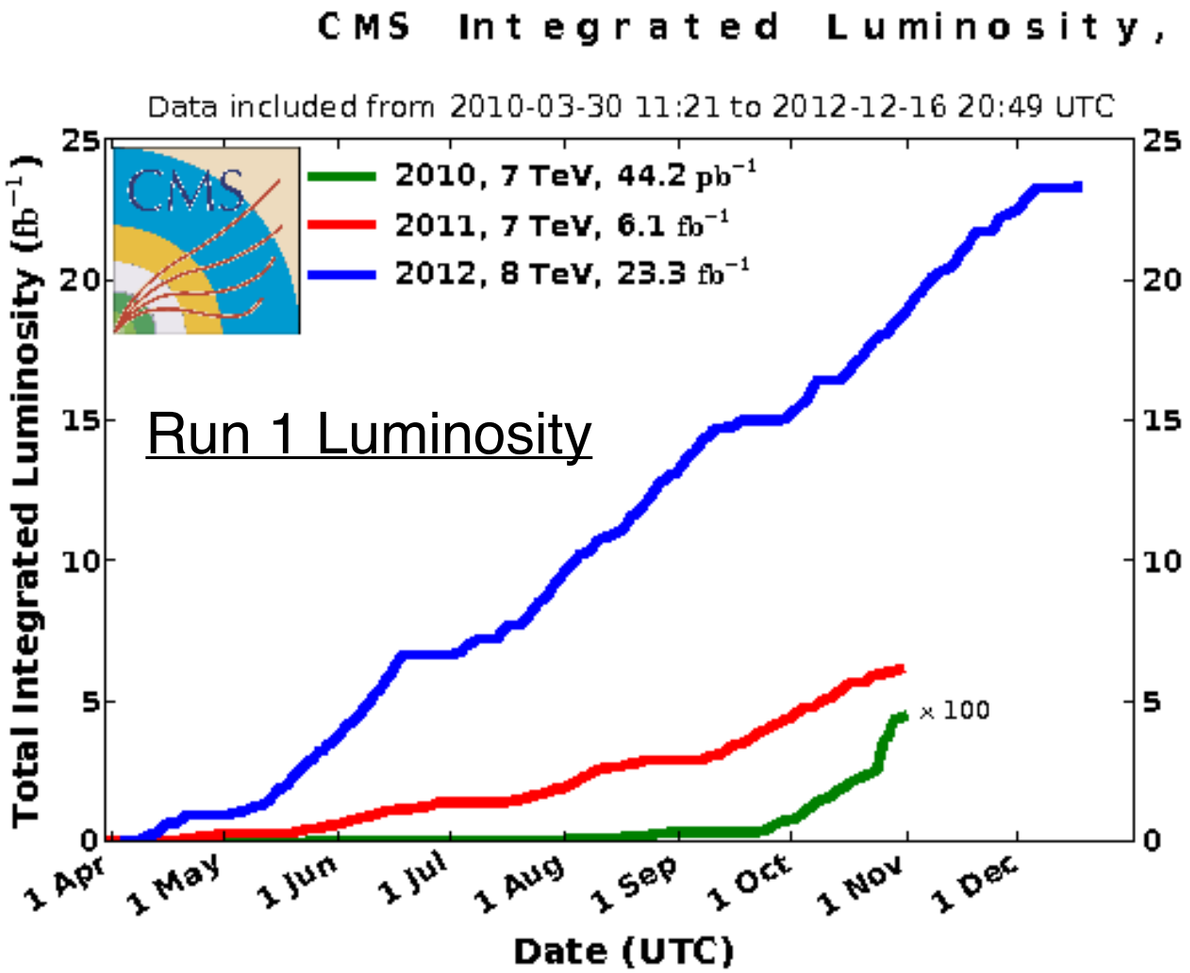


WHY HAVE WE NOT SEEN NEW PHYSICS?

- 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

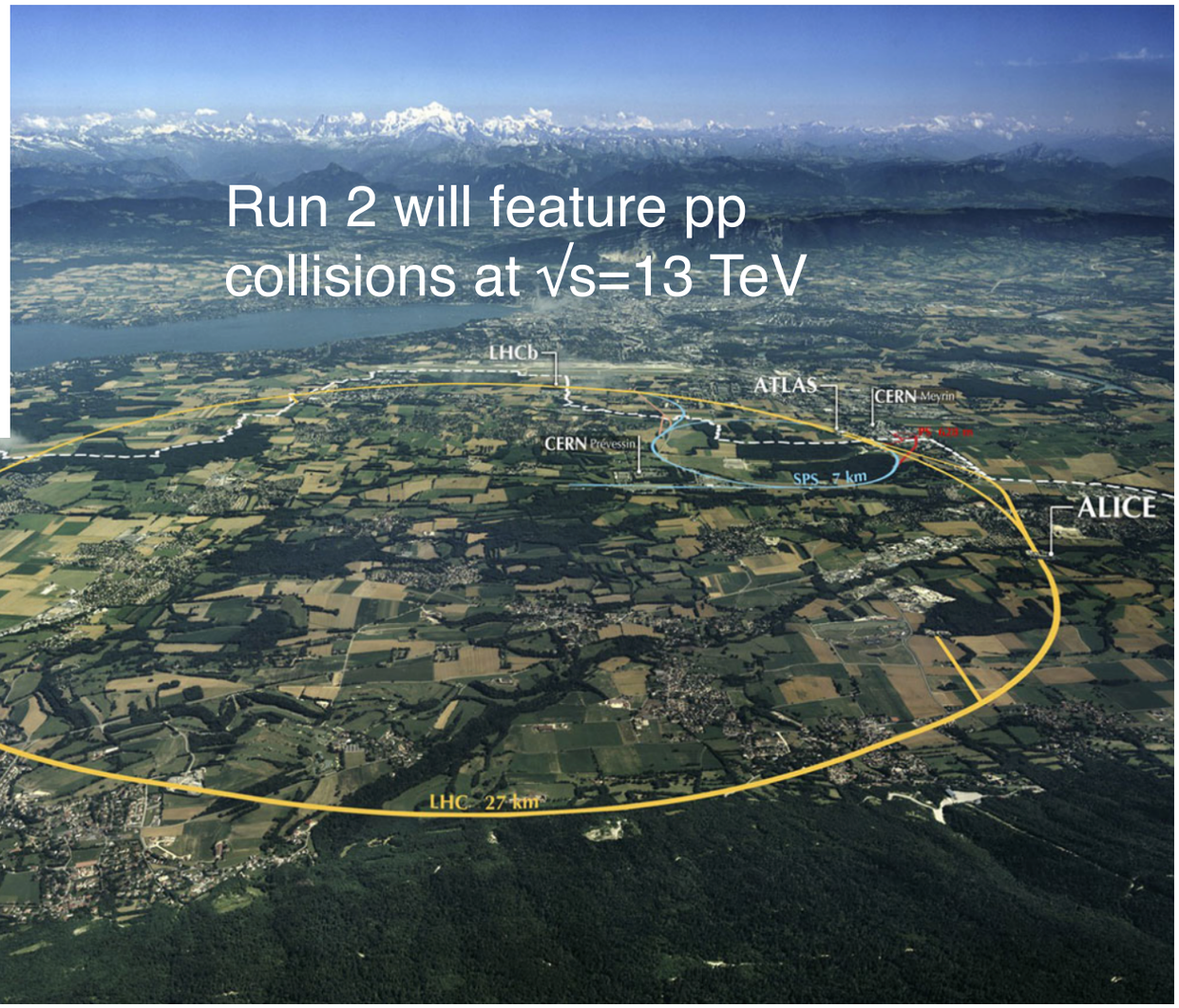
- This talk will focus in particular on these last two possibilities

PROTON COLLISIONS AT THE LHC



Run 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

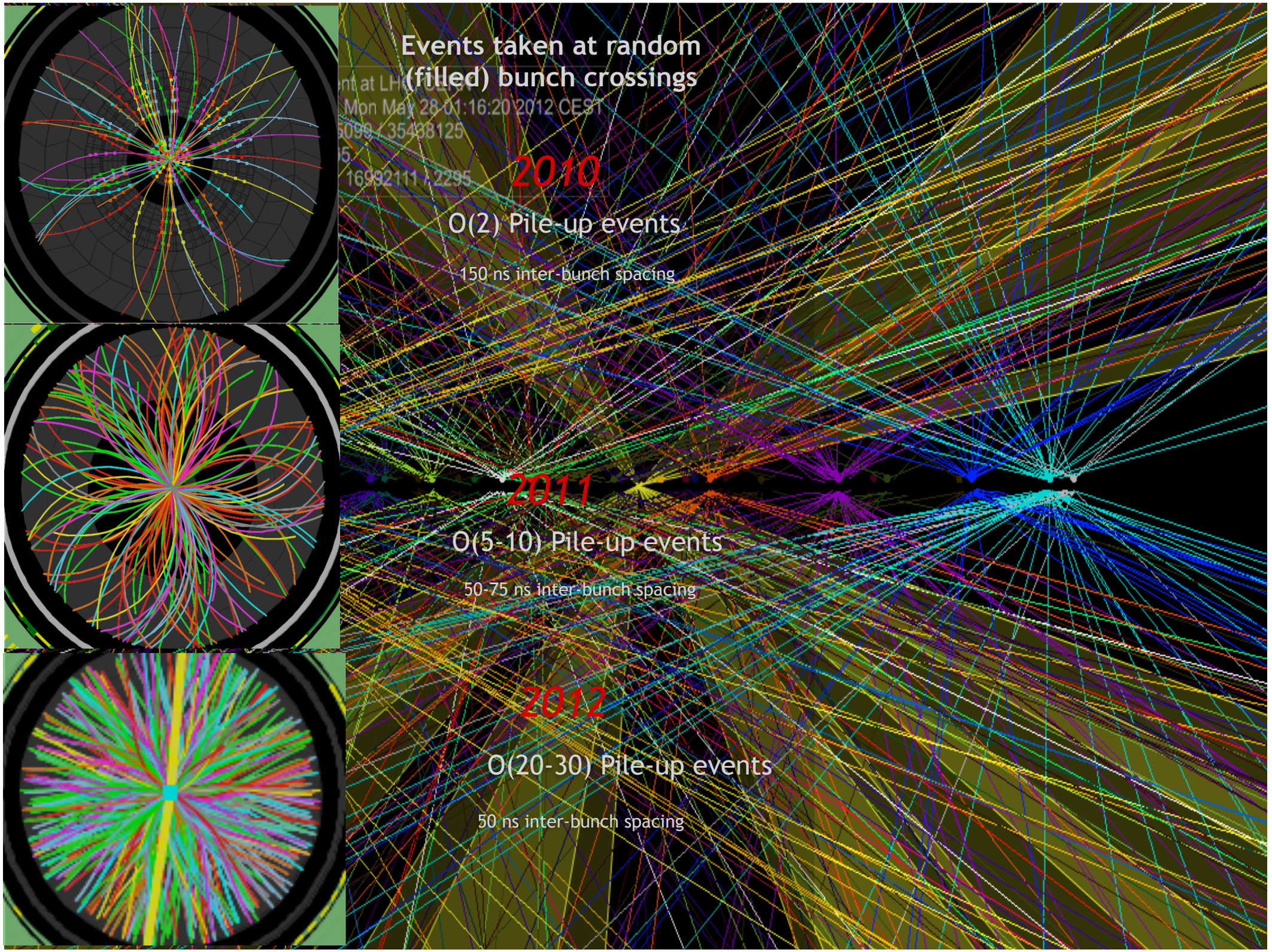


Run2 Integrated Luminosity Goal

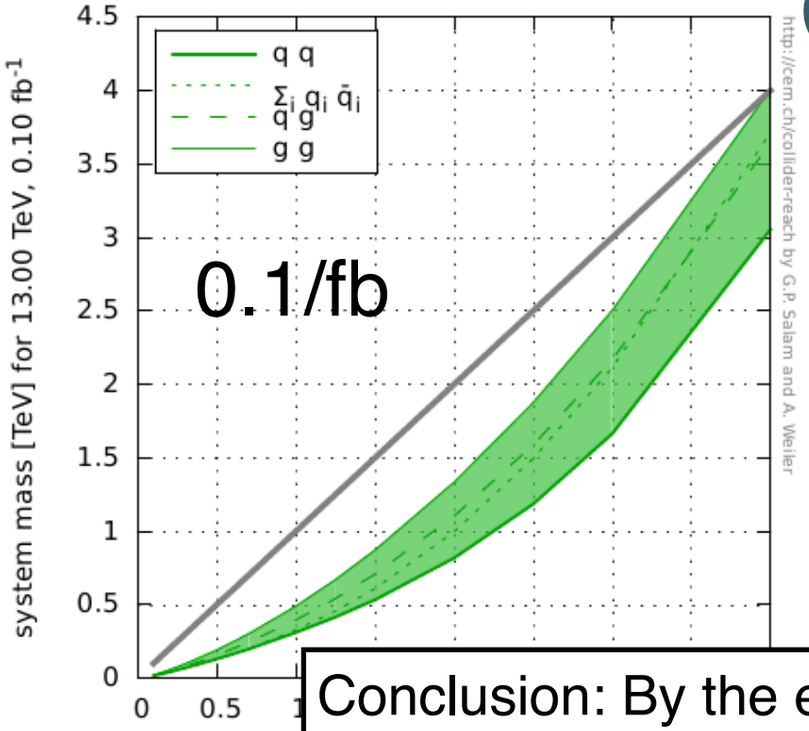
2015 : 10 fb^{-1} (1 fb^{-1} @ 50ns in June)

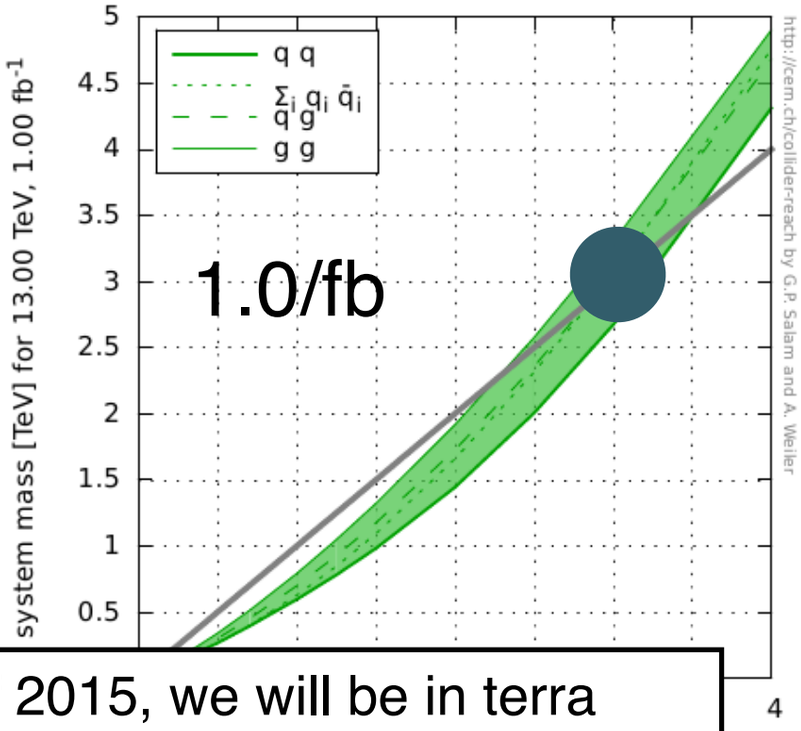
Run2: ~100-120 fb^{-1} (better estimation by end of 2015)

THE PILEUP CHALLENGE

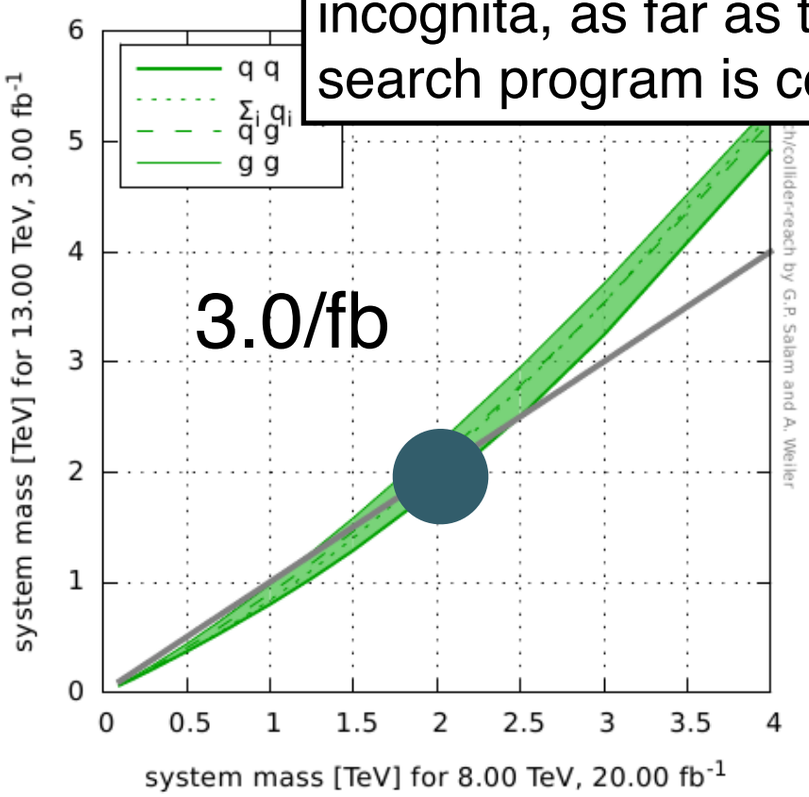


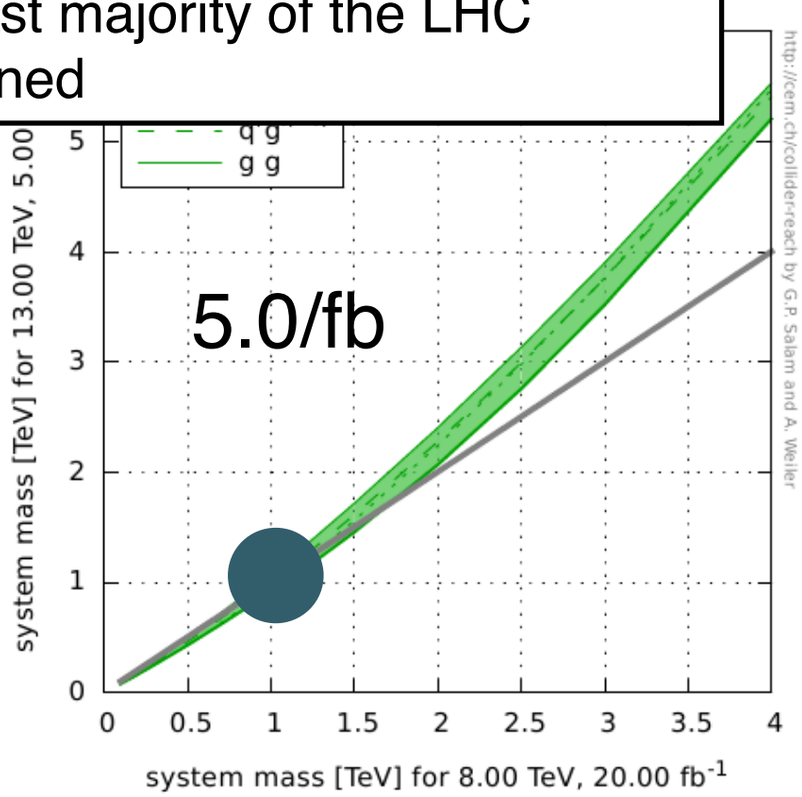
2015 LHC Reach





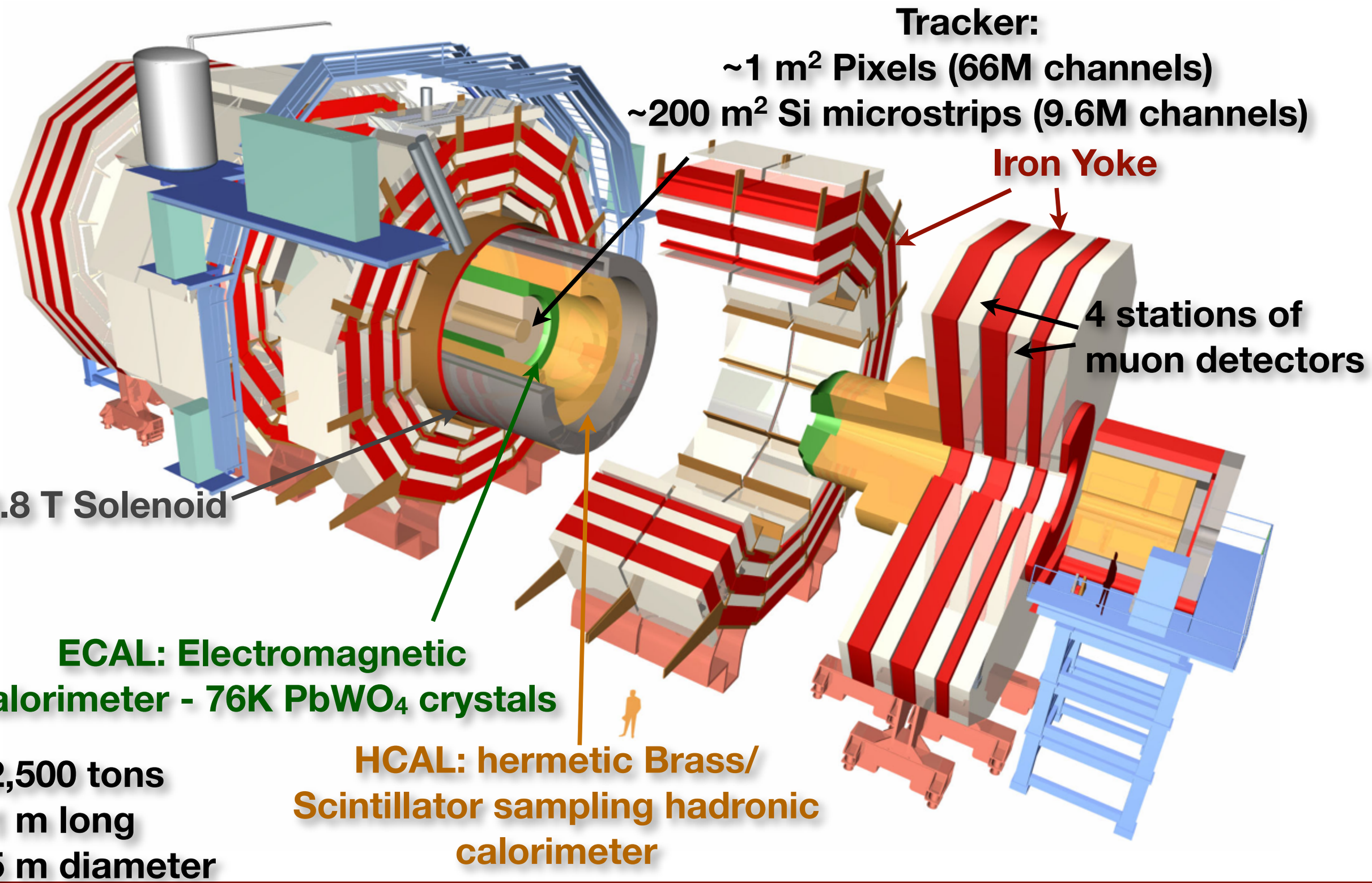
Conclusion: By the end of 2015, we will be in terra incognita, as far as the vast majority of the LHC search program is concerned



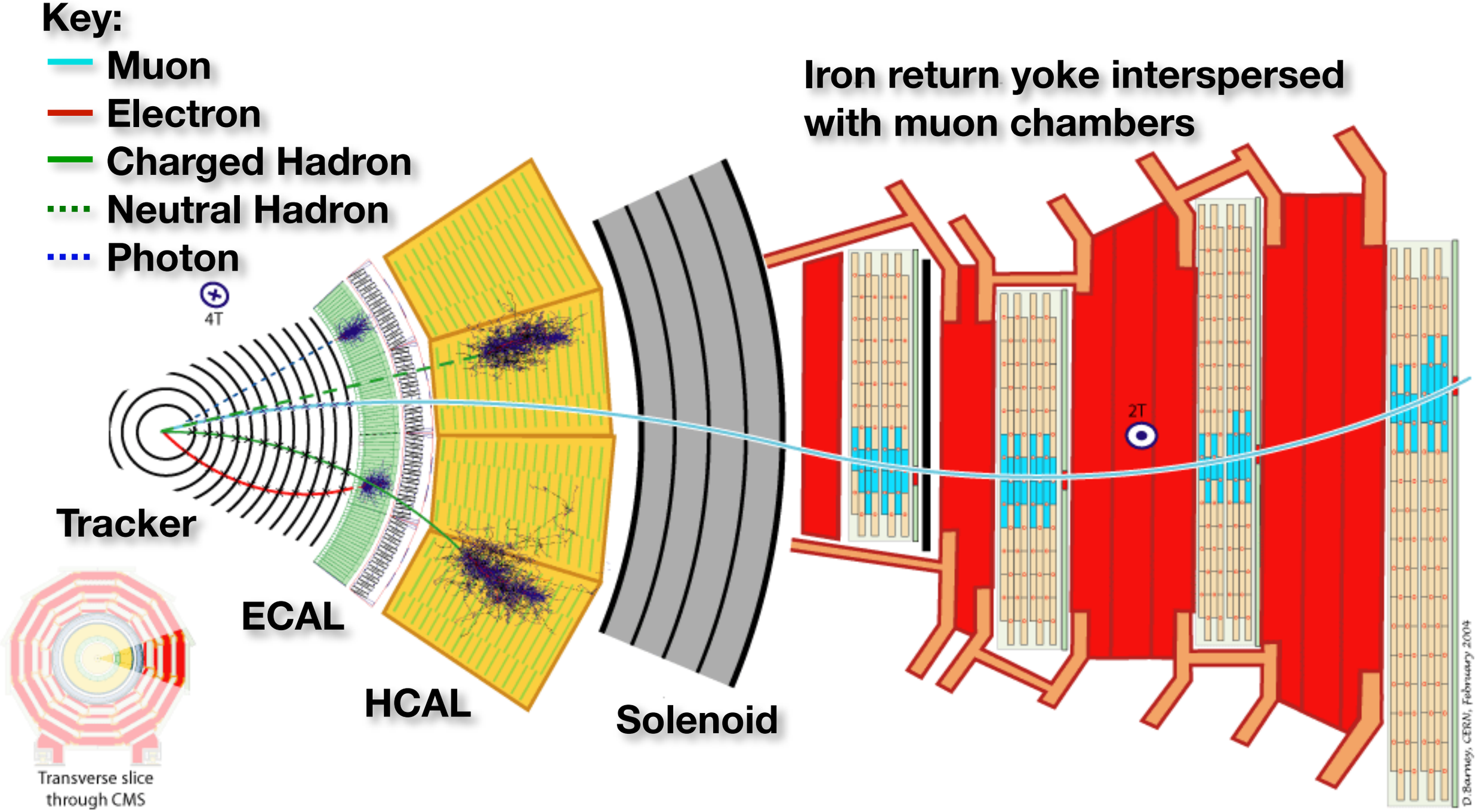


- With 1/fb we have added sensitivity to ~3 TeV objects
  - (~1.5 TeV for pair production)
- With 5/fb we have added sensitivity to ~1 TeV objects
  - (~0.5 TeV pair production)

The Compact Muon Solenoid



Particle Detection at CMS



Hints of New Physics(?) from Run I

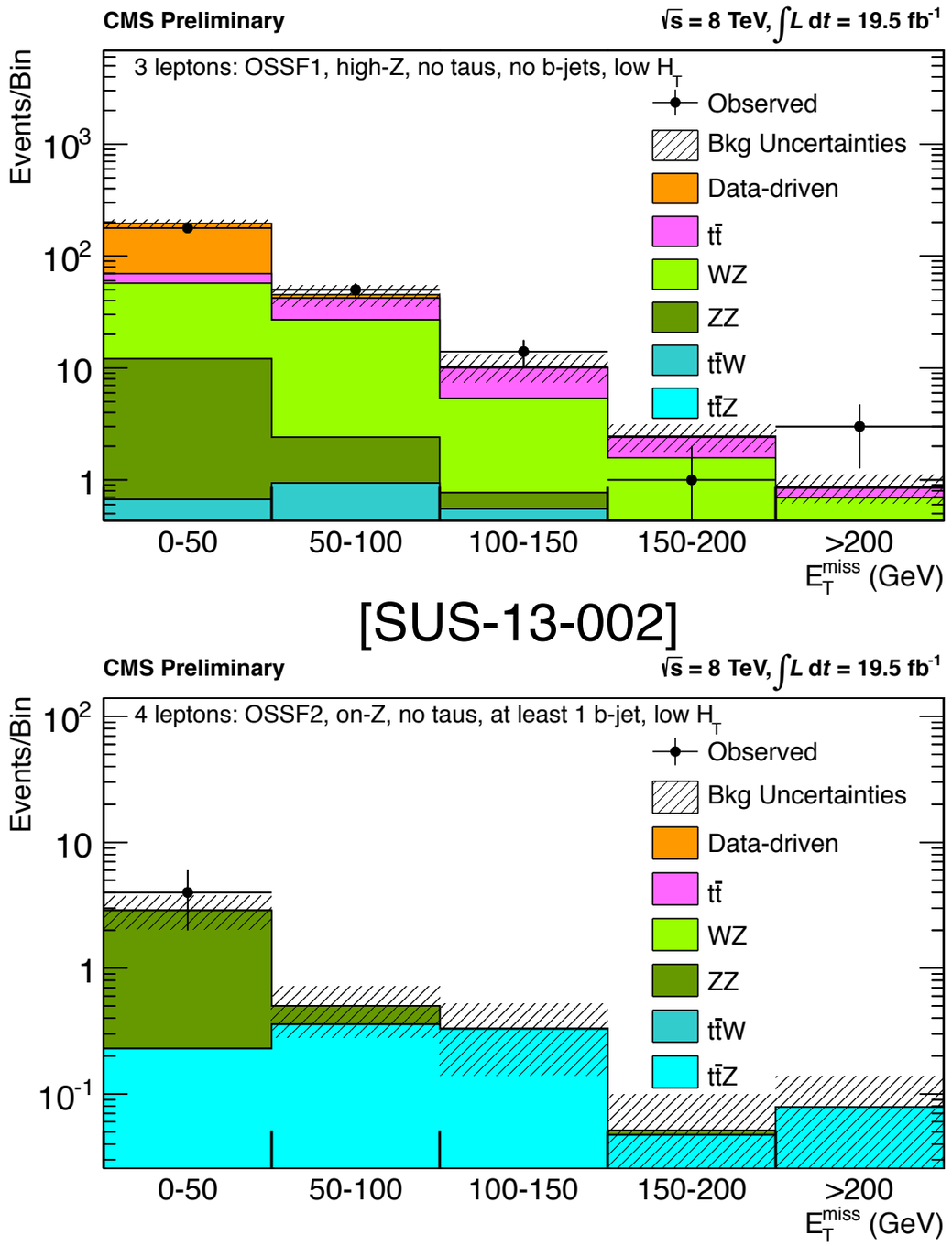
CAVEAT EMPTOR

- 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

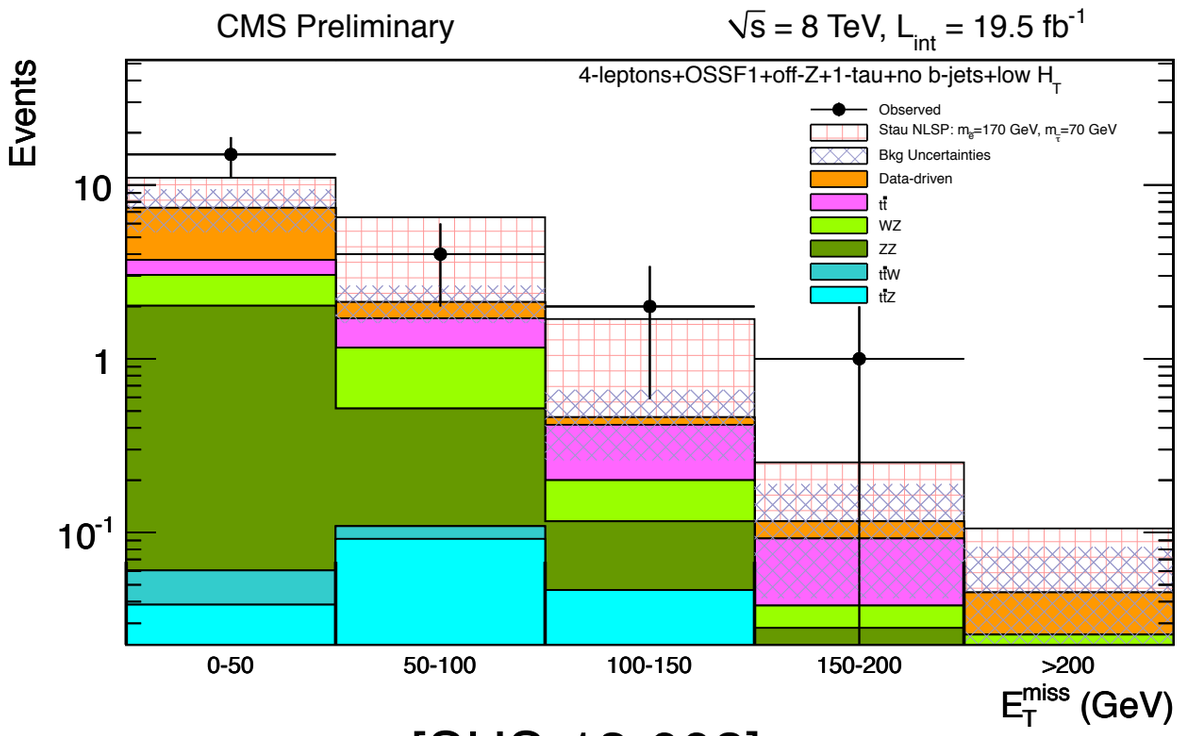
MULTILEPTON SEARCHES

- 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

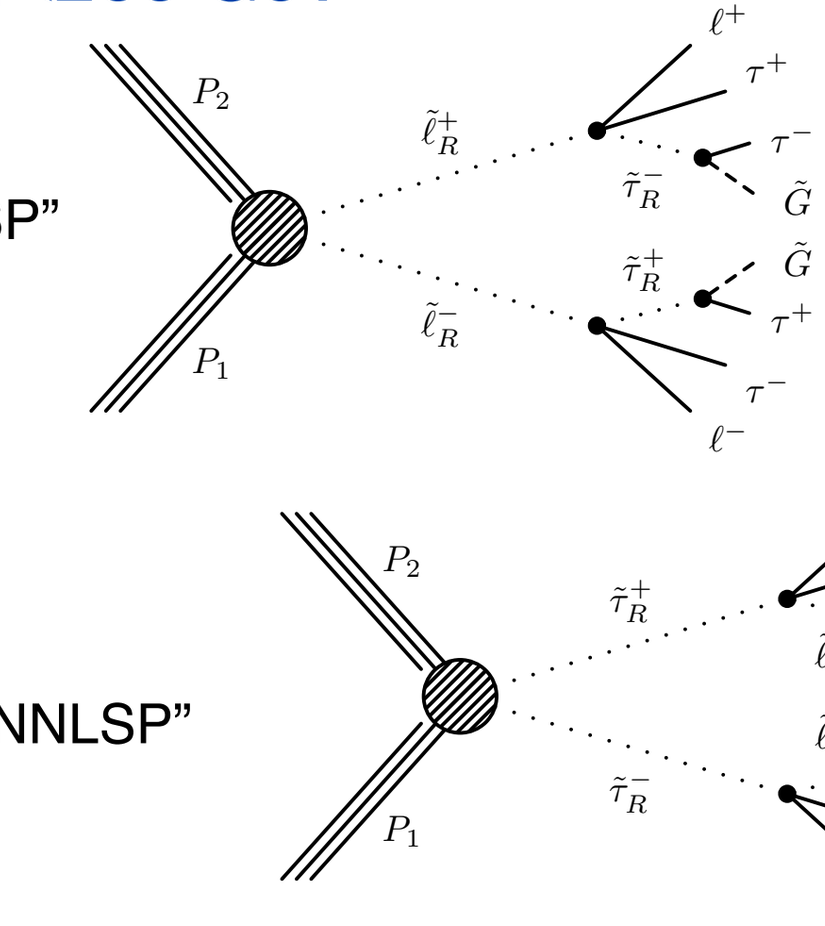


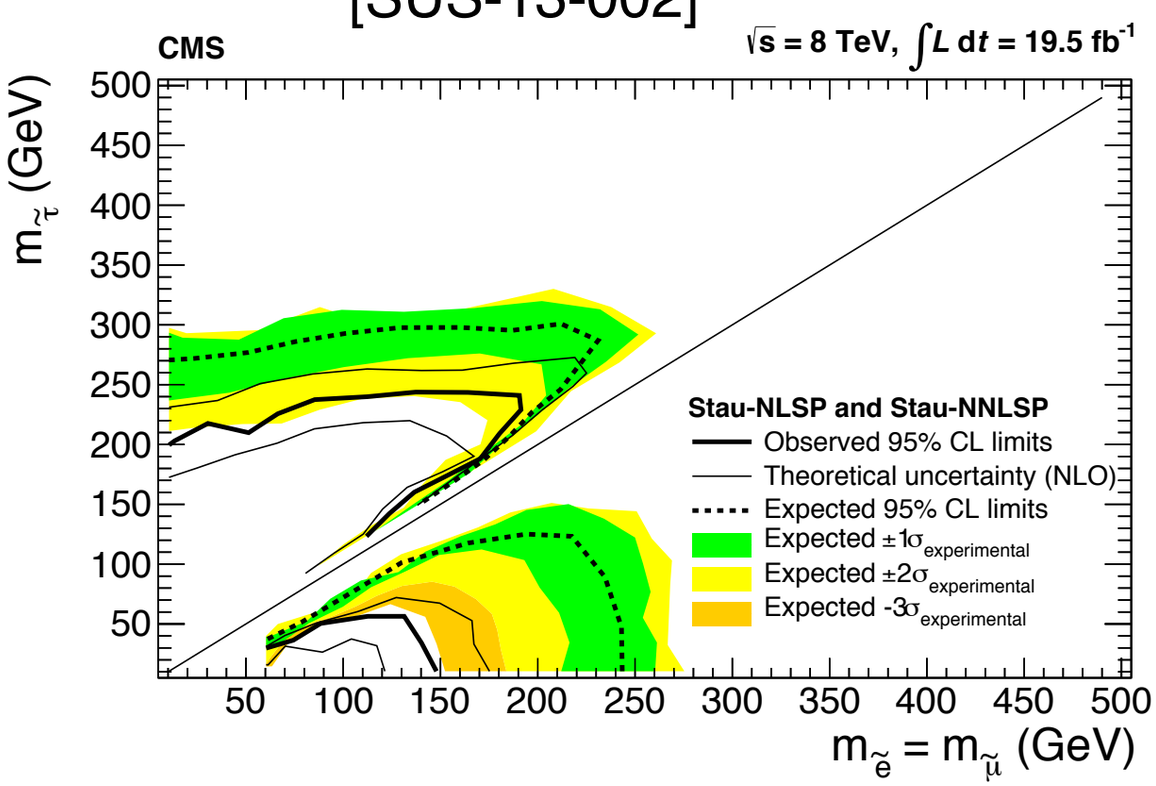
STAU (N)NLSP?

- 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]





The Edge

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

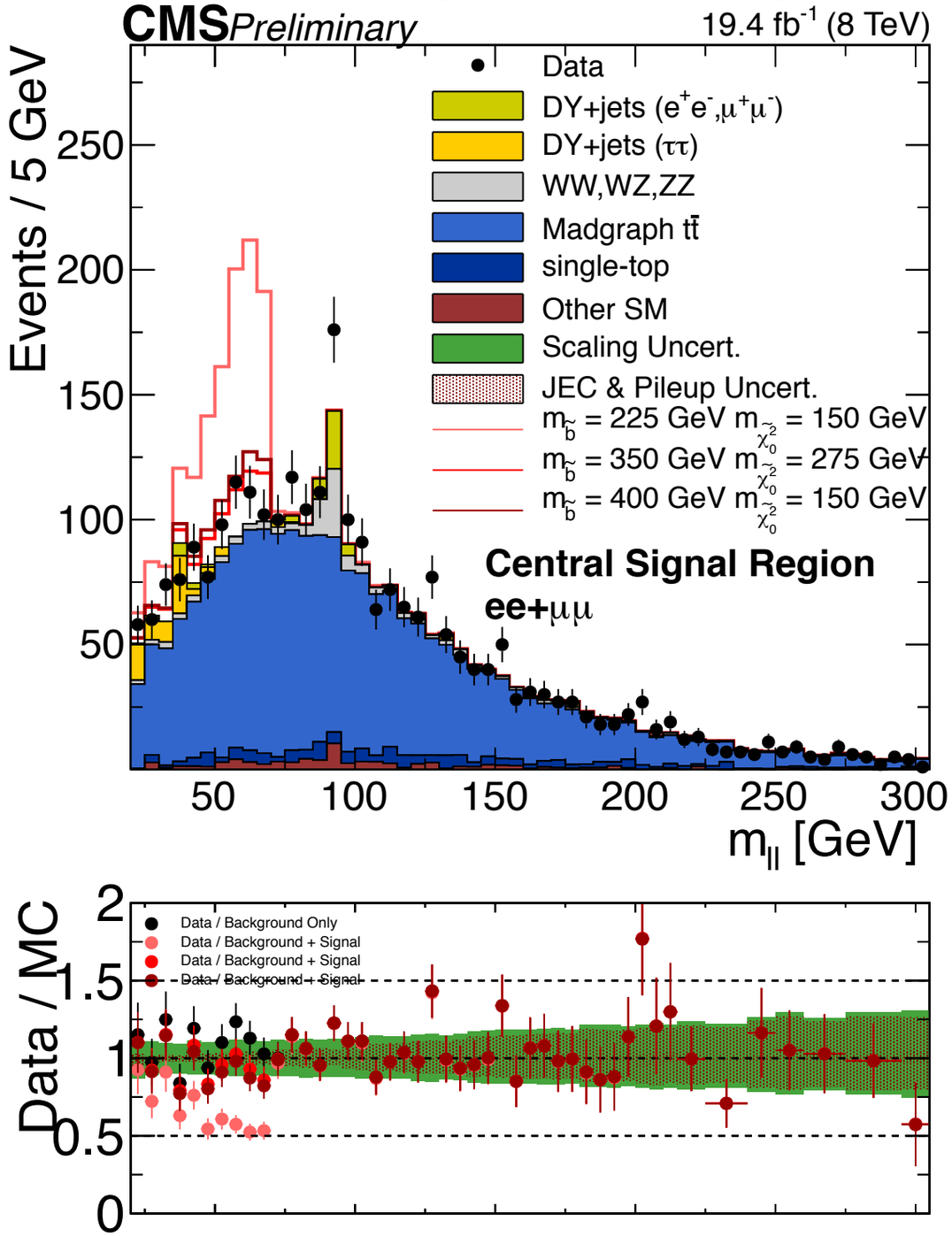
    OR
  - Njets ≥ 3 and MET > 100 GeV

    - Excess observed below 70 GeV in dilepton mass spectrum

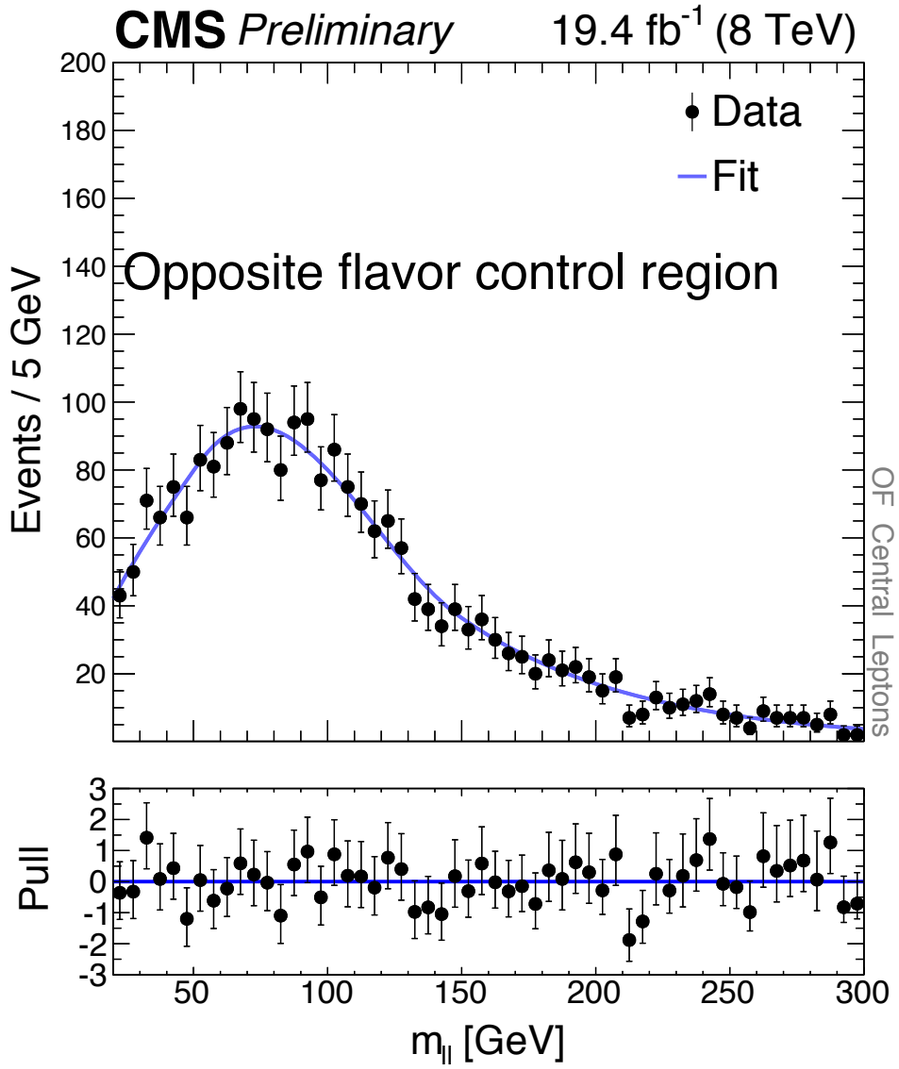
$$\tilde{b}\tilde{b}^{\star} \to \tilde{\chi}_2^0 b \tilde{\chi}_2^0 b$$
$$\tilde{\chi}_2^0 \to \ell\tilde{\ell} \to \tilde{\chi}_1^0 \ell^+\ell^-$$
$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^{\star} \to \tilde{\chi}_1^0 \ell^+\ell^-$$

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

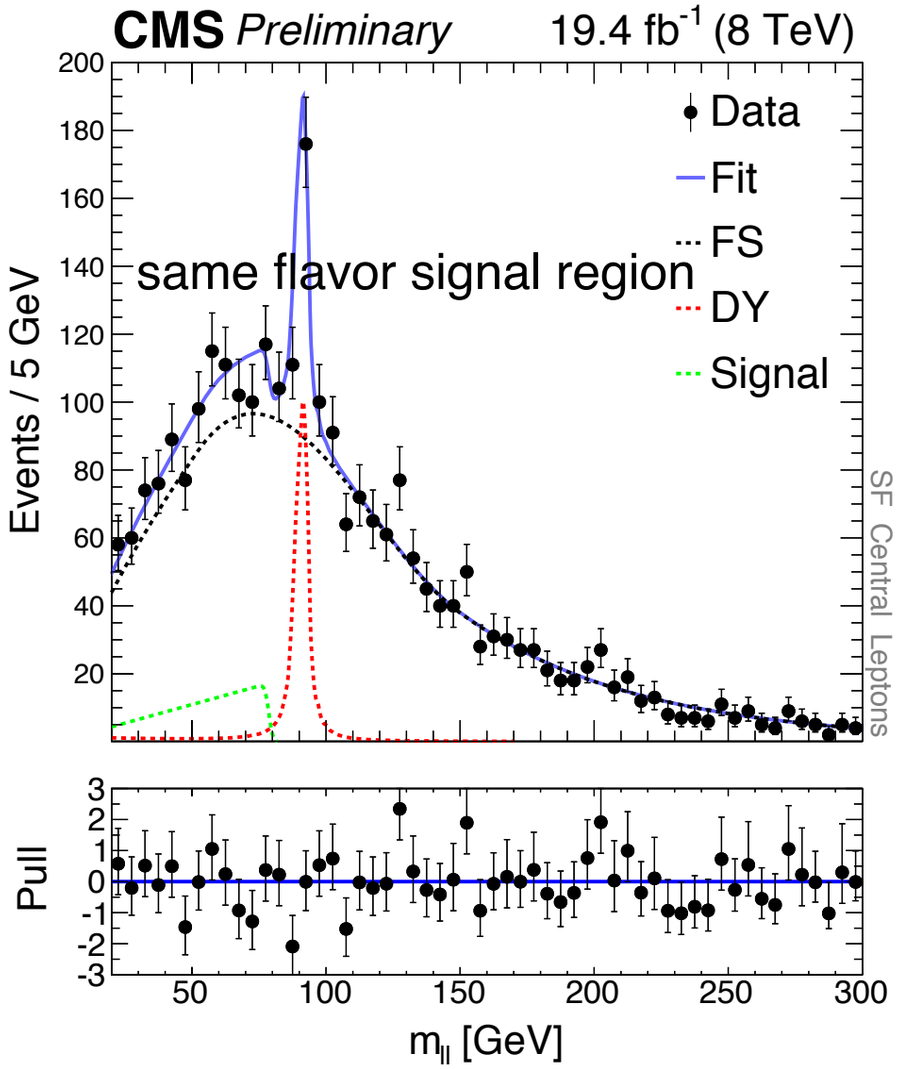
[SUS-12-019]



The Edge Excess



[SUS-12-019]

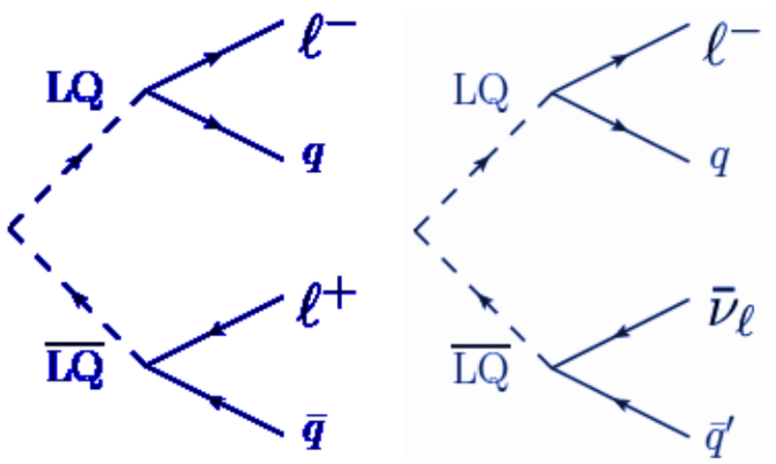


- 2.4 σ local (fit), 2.6 σ global (counting experiment)
  - Is this compatible with null results from other sbottom searches?
    - Tension with other LHC null results could be relaxed with other possible models. c.f. arXiv:1409.3532 or arXiv:1410.4998

1ST GENERATION LEPTOQUARKS

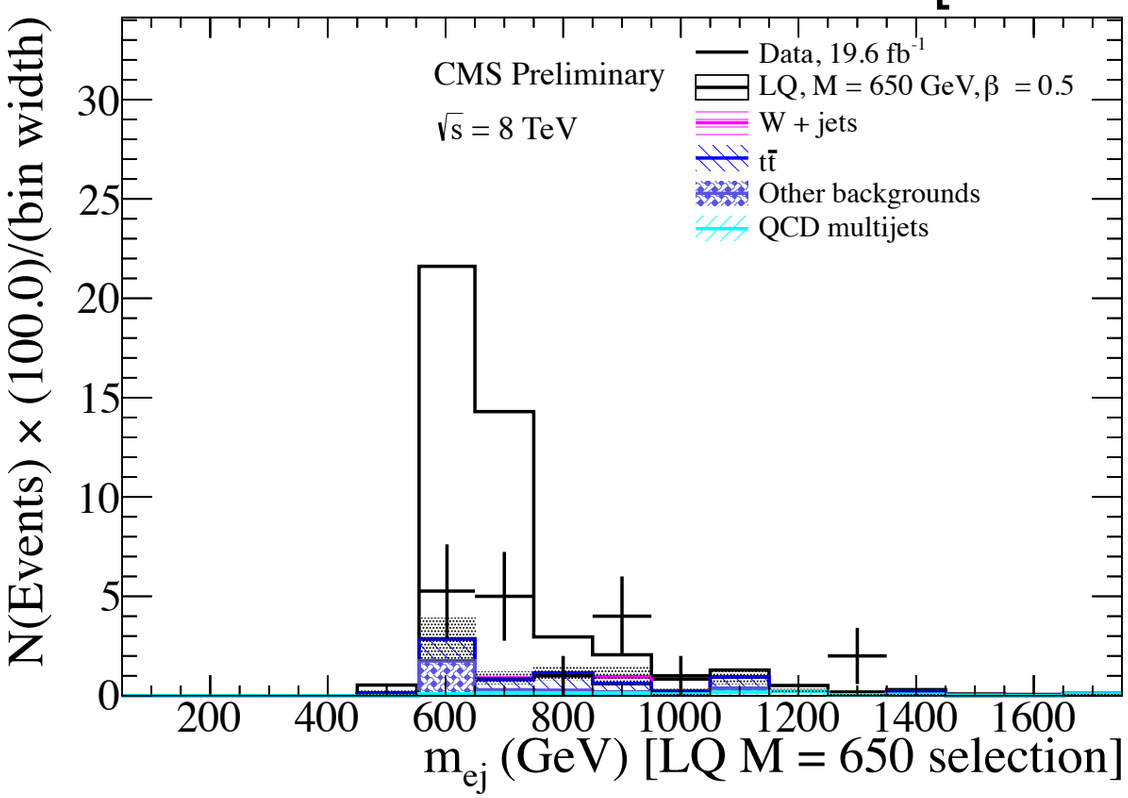
- Search for 1st generation LQs in eejj and evjj final states
  - optimize cuts for individual LQ mass hypotheses on M(l,ν), M(ll), S_T, MET to suppress backgrounds
    - saw broad excess in both channels for a 650 GeV LQ mass hypothesis

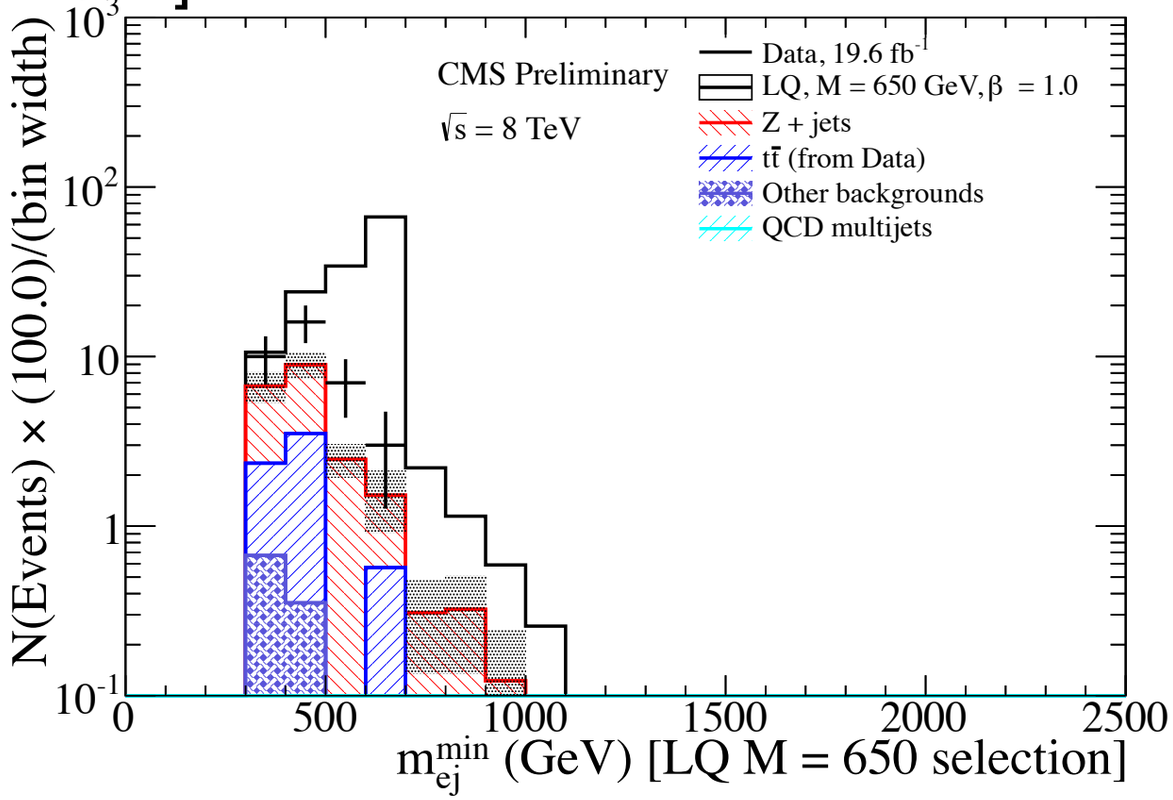
β = branching fraction to the lq final state



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

[EXO-12-041]

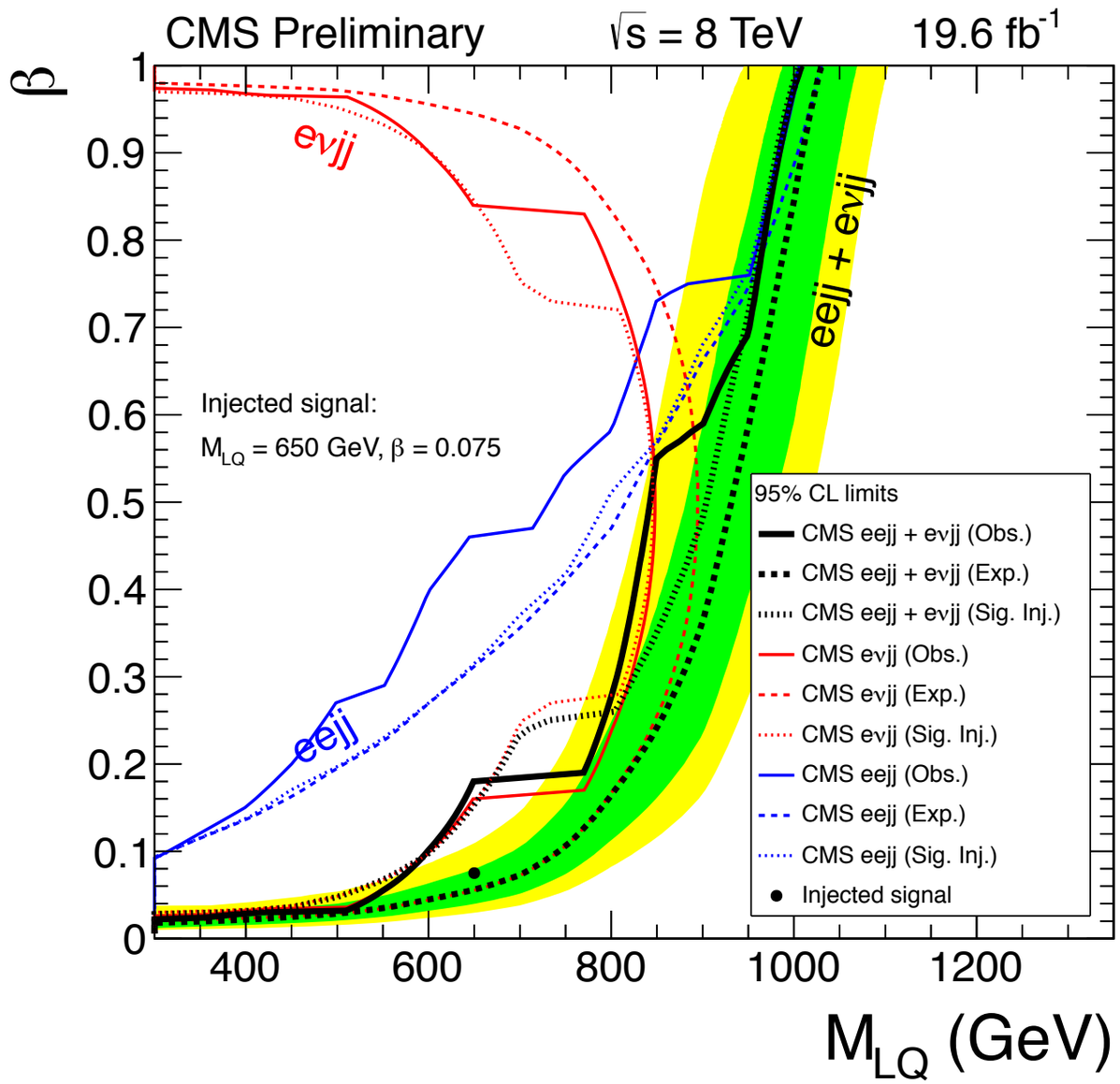




1ST GENERATION LEPTOQUARKS

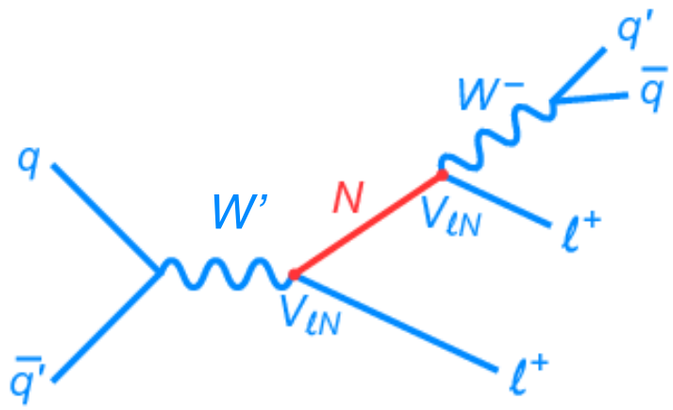
- Very difficult to reconcile with a LQ hypothesis
  - kinematics are too broad (no peak structure)
- Other possibilities?
  - several propsals, e.g.: arXiv: 1410.5947, arXiv:1408.5439, arXiv:1408.1082, arXiv: 1407.4466

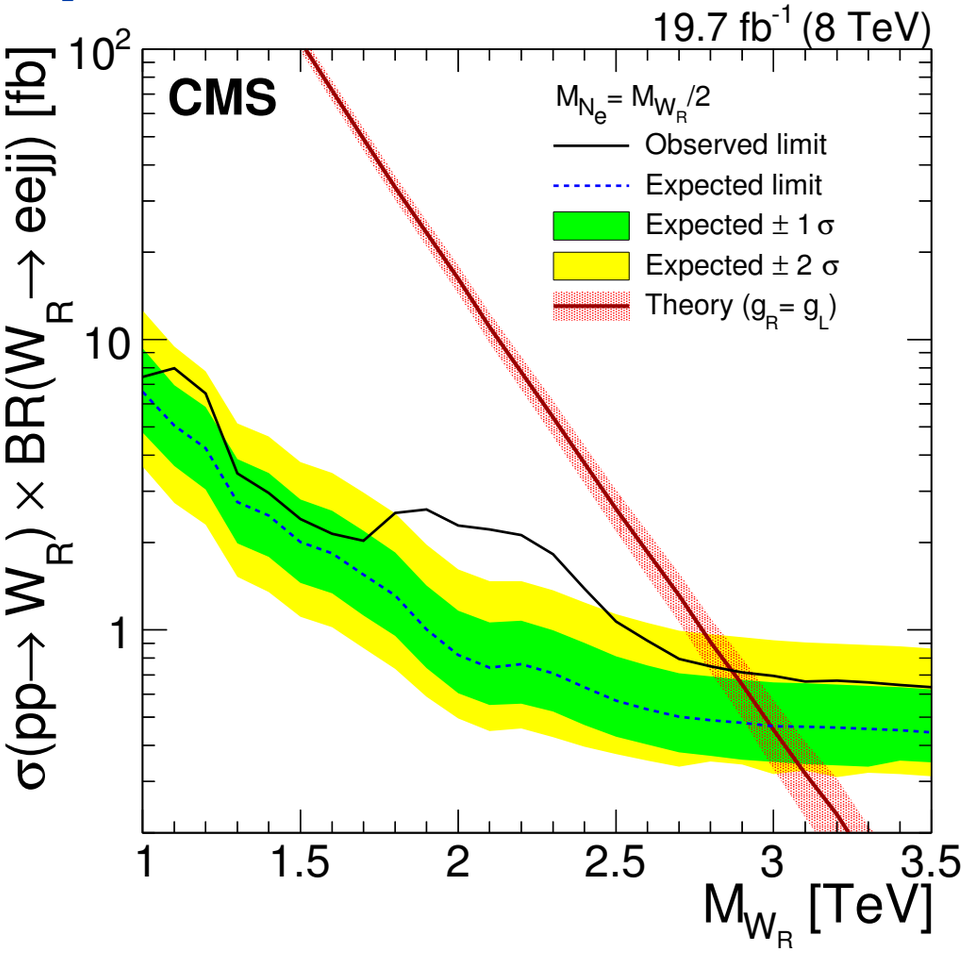
[EXO-12-041]

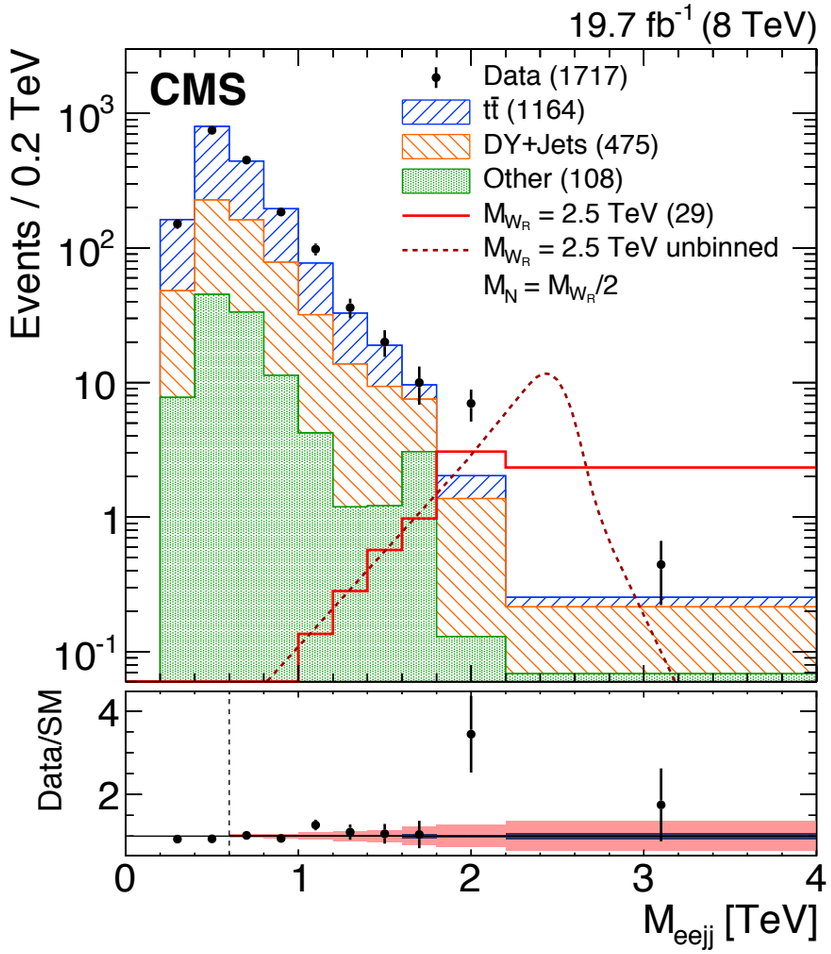


W' AND HEAVY NEUTRINO

- 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

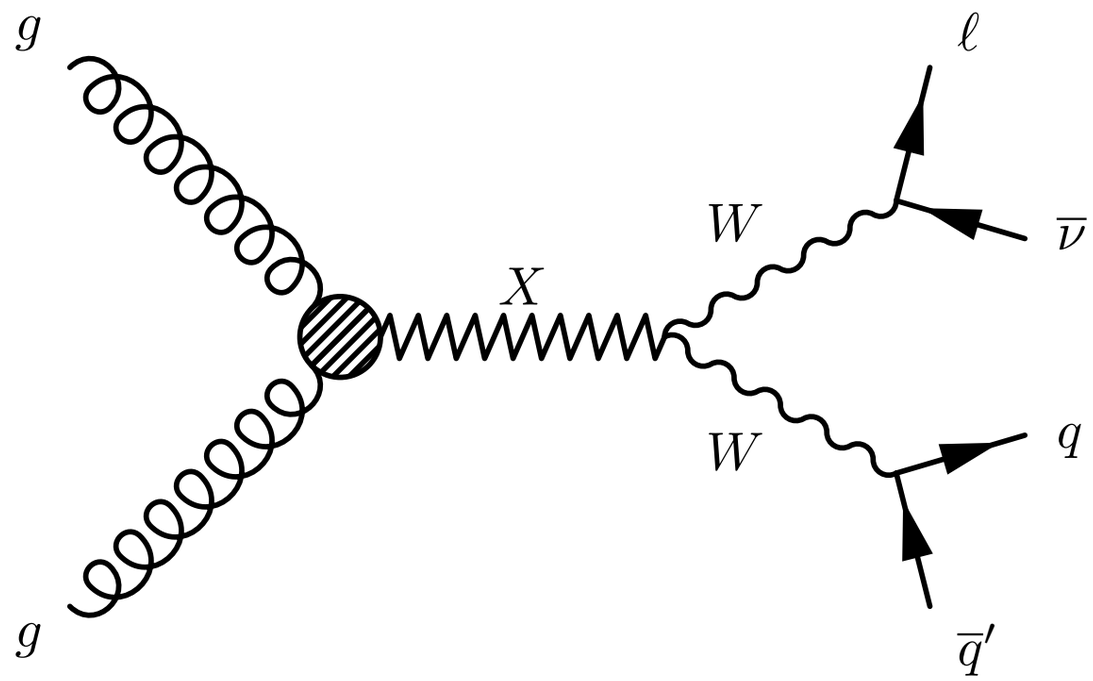






DIBOSON RESONANCES

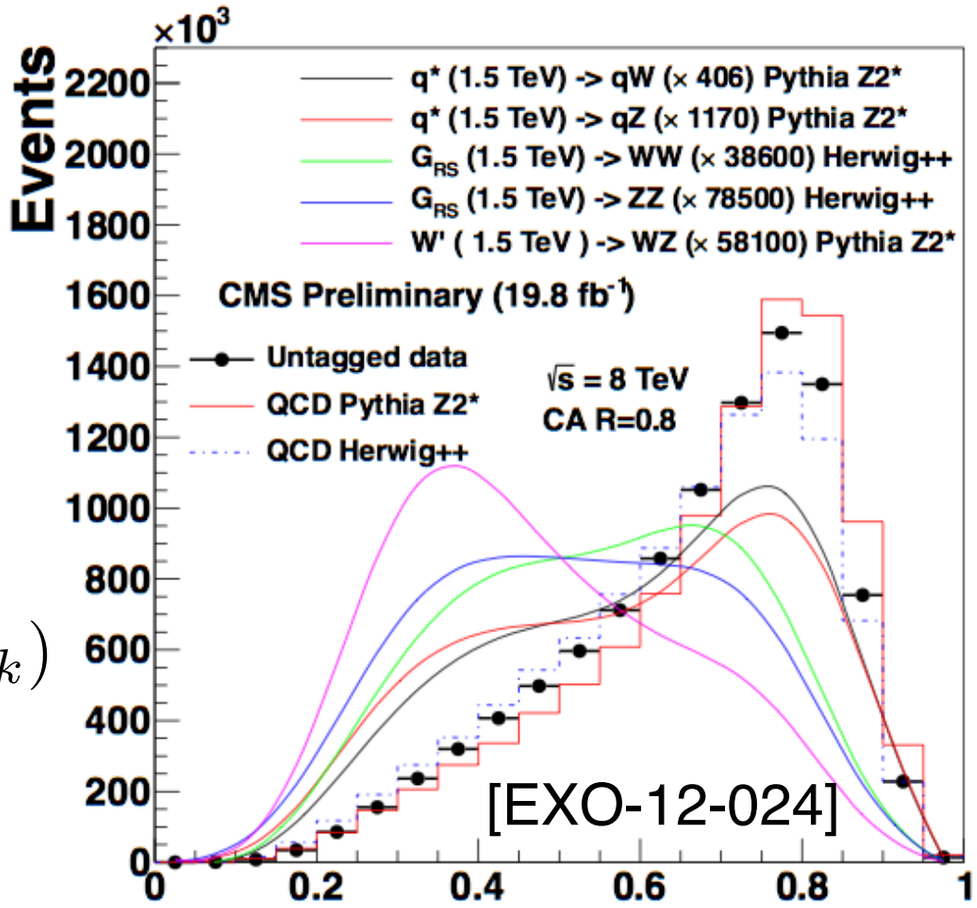
- Growing effort to explore high-mass disboson resonances in a large variety of final states
  - WW, WZ, ZZ, WH, ZH, HH
  - W, Z, and H all have significant branching fractions to jets
    - When X is massive (typically ~700-900 GeV), the jets begin to merge into the same cone
    - Need to use advance techniques to identify (and even b-tag!) merged jets

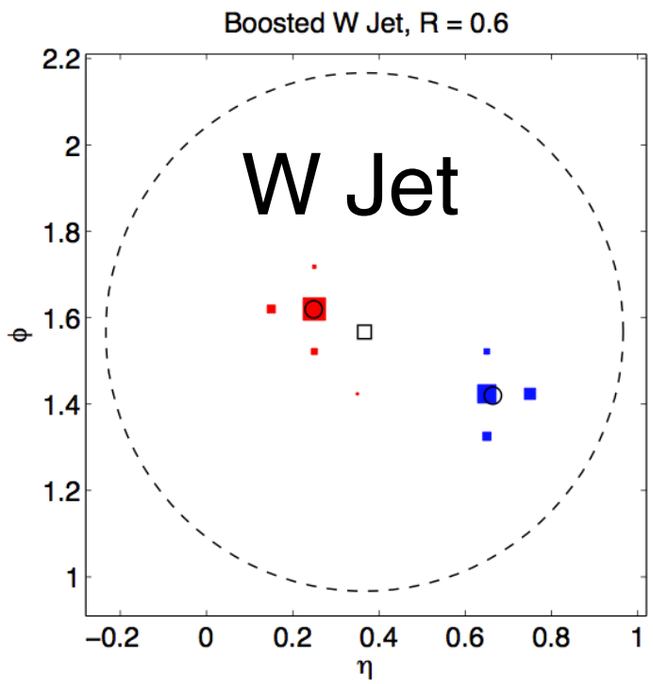


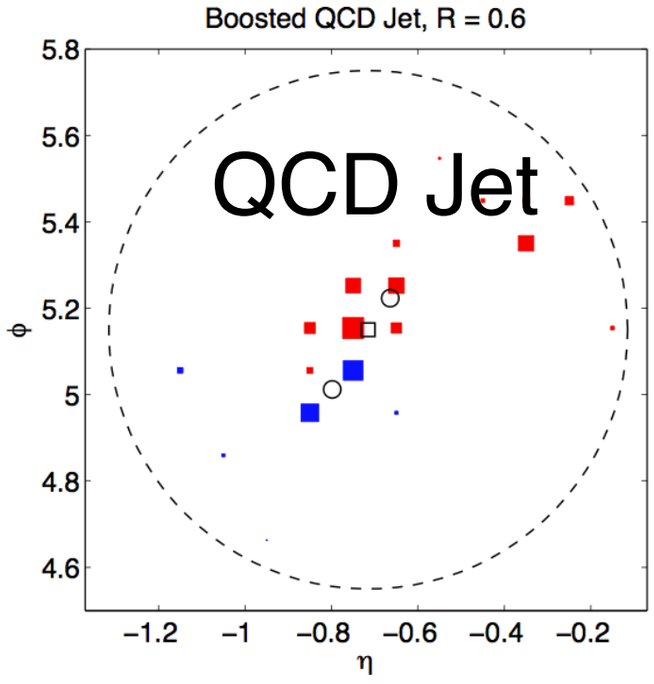
N-SUBJETINESS

- 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

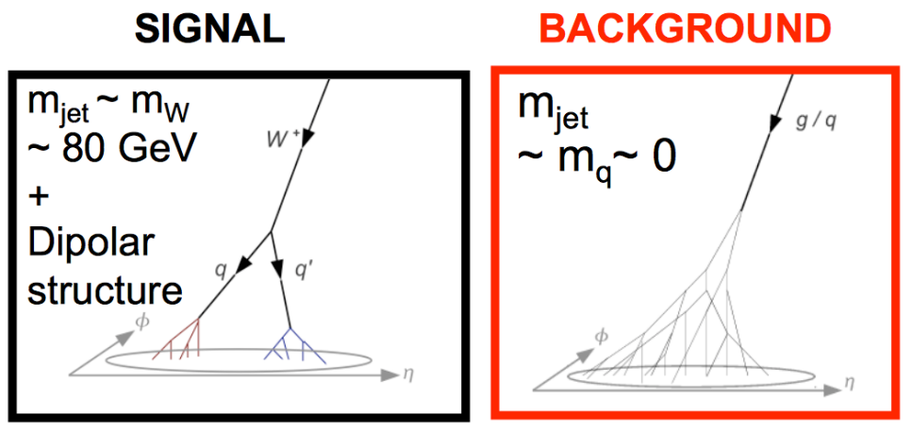
$$\tau_N = \frac{1}{d_0}\sum_k p_{\mathrm{T},k}\,\min\left(\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right)$$



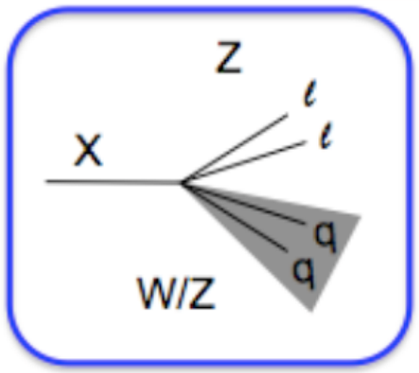


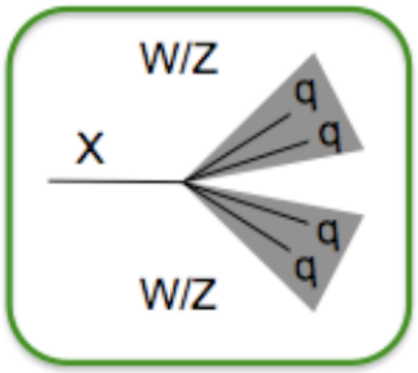


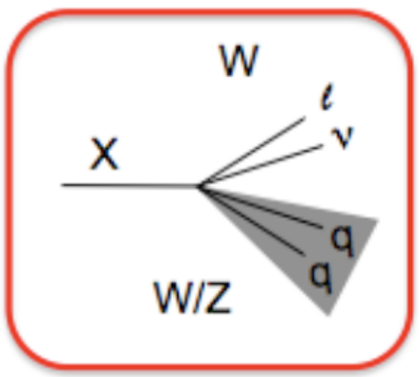
[Thaler, Tilburg, arXiv:1011.2268]



WW/WZ/ZZ Resonances

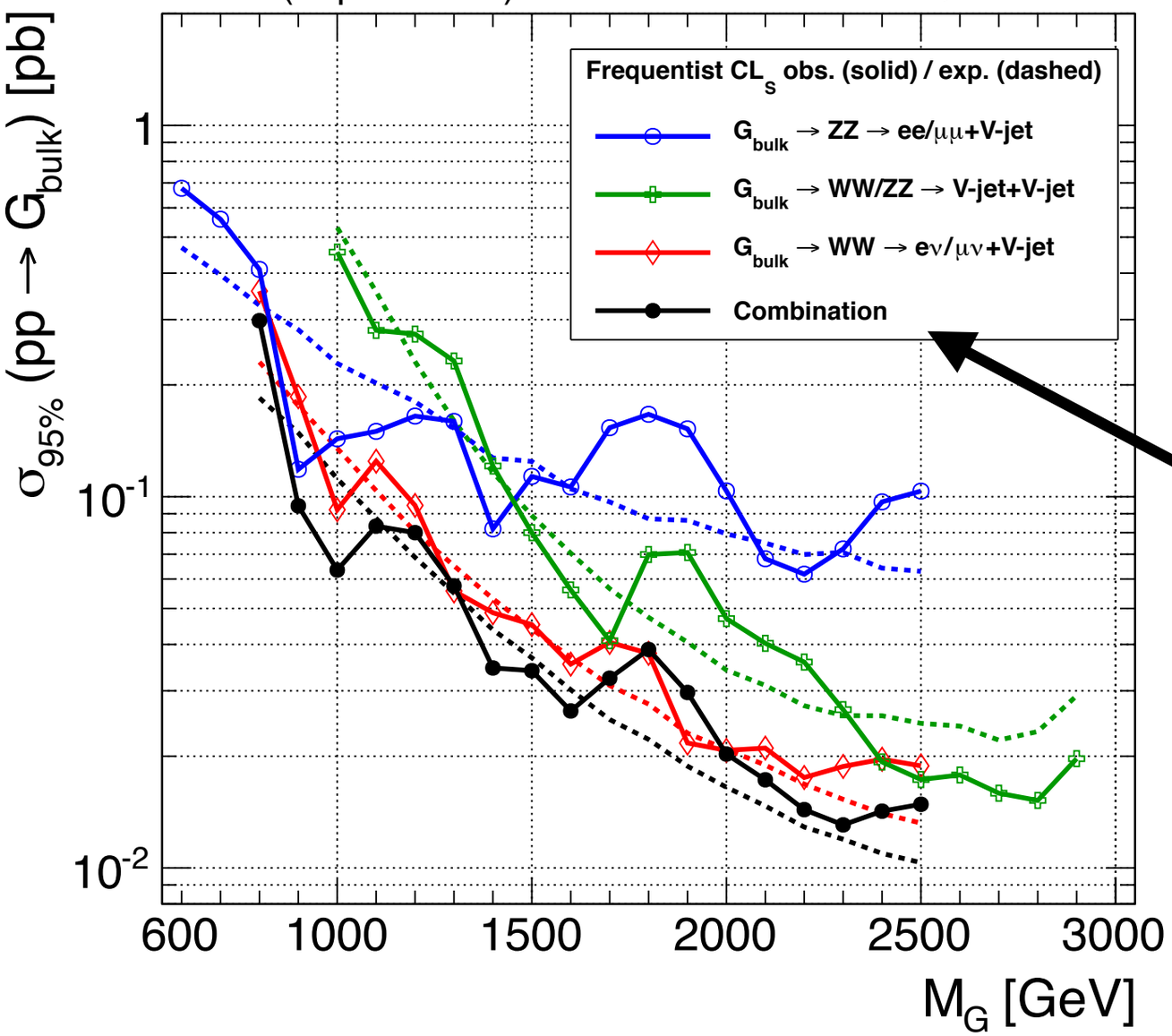




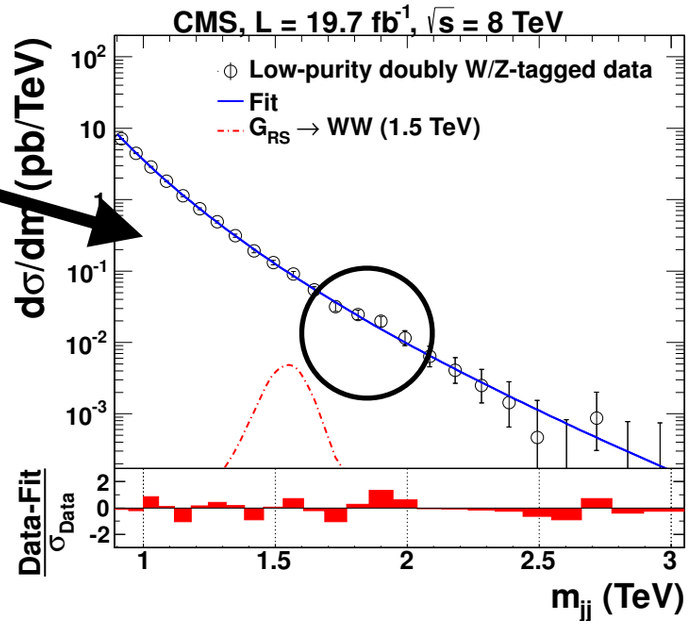


Excess in all-hadronic sample diluted after re-analysis of the dataset

[EXO-13-009]



[EXO-12-024]



Combination assumes BRs and efficiencies of narrow bulk graviton model

Largest excess at M~1.8 TeV (~1.5σ)

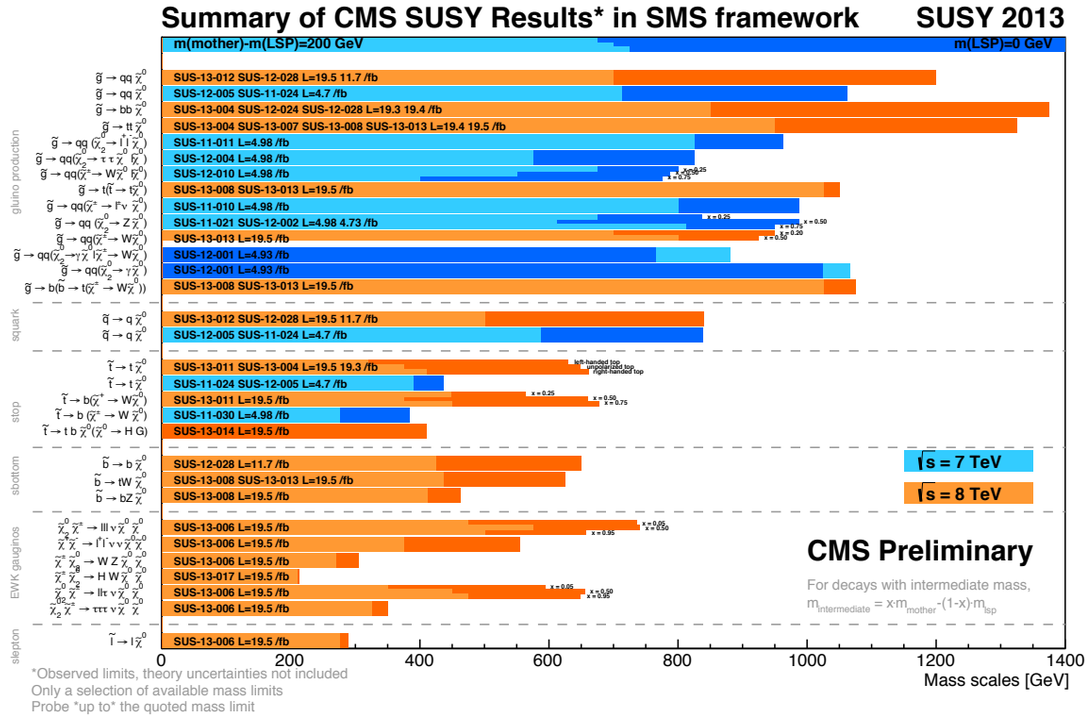
Hiding New Physics from View

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

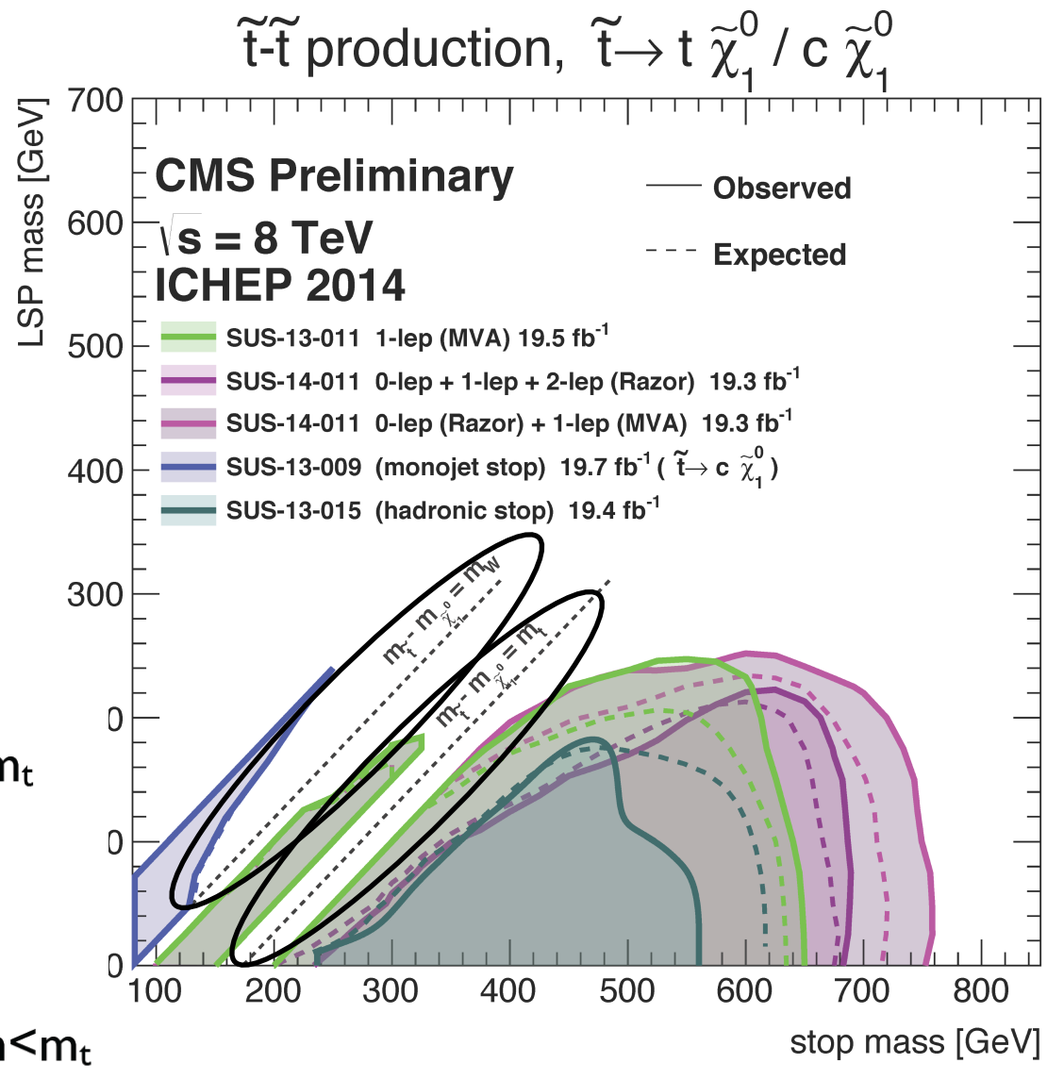
Even within the SUSY paradigm, there are many ways to suppress the missing E_T in the final state:

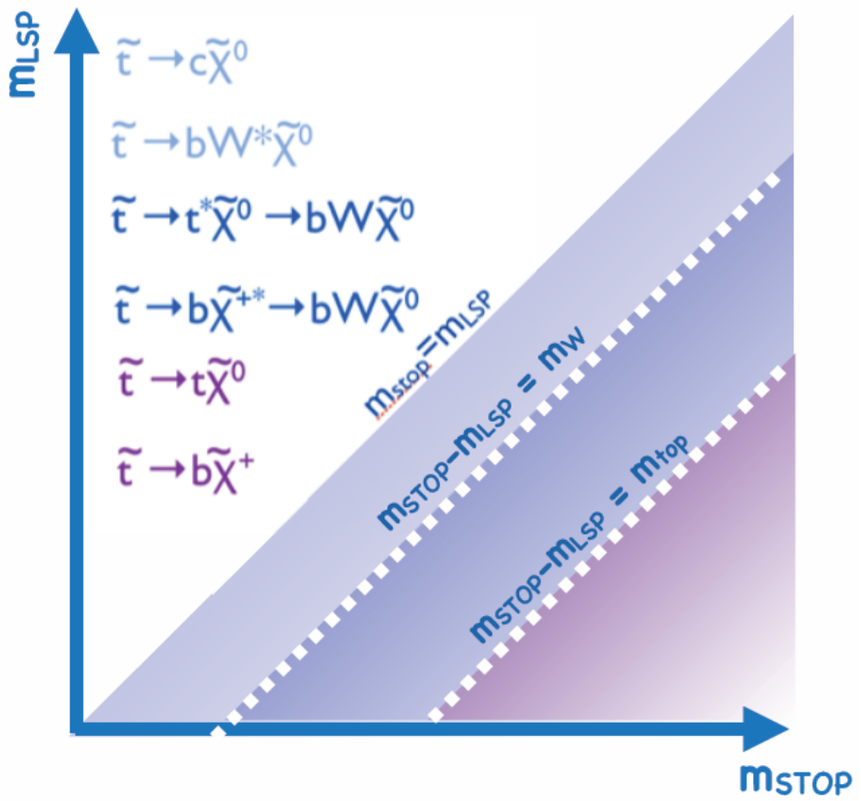
- compressed SUSY
- stealth SUSY
- R parity violating SUSY
- long-lived SUSY

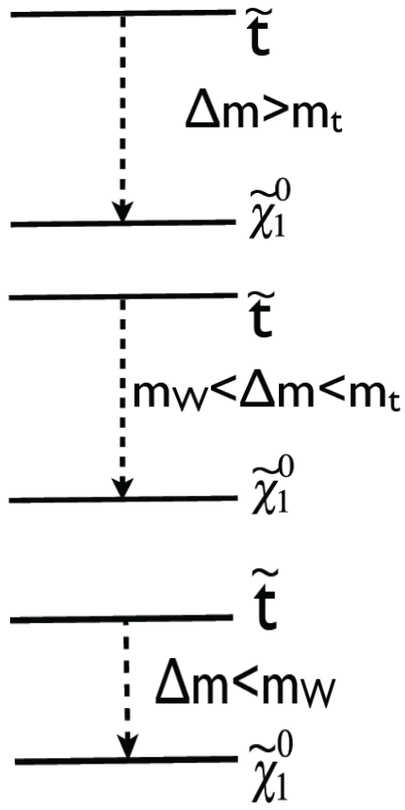


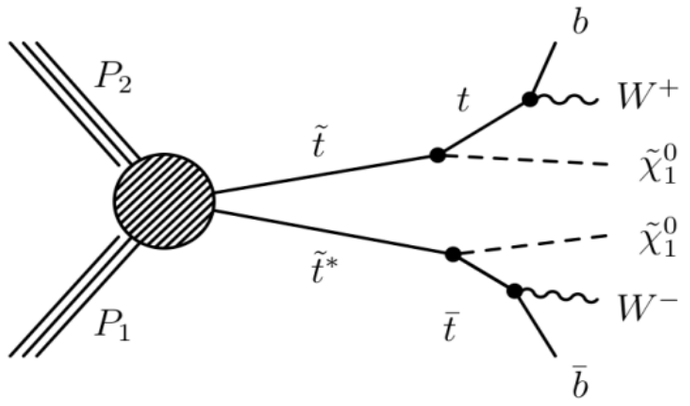
COMPRESSED SPECTRA

- 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



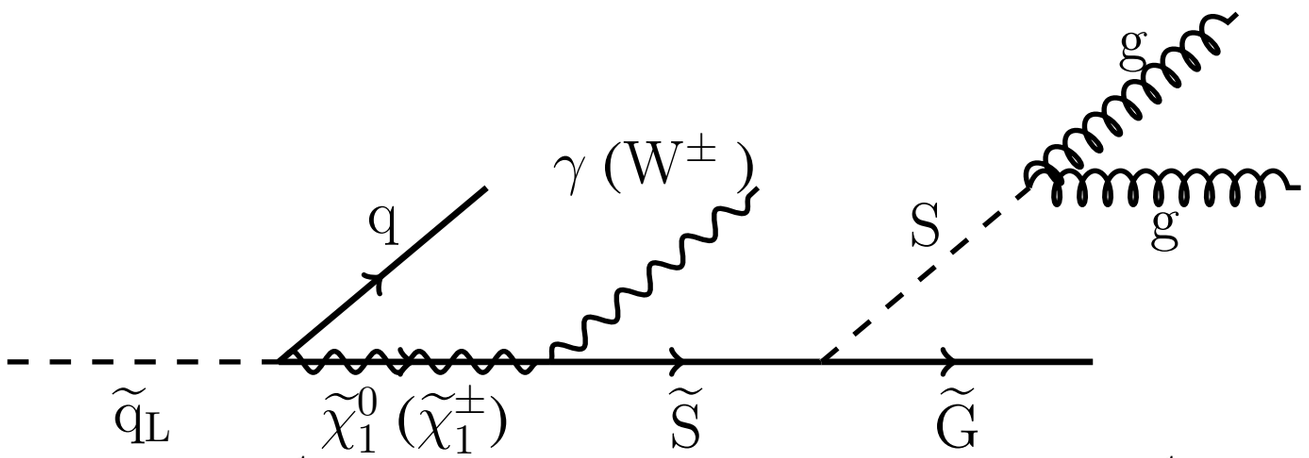


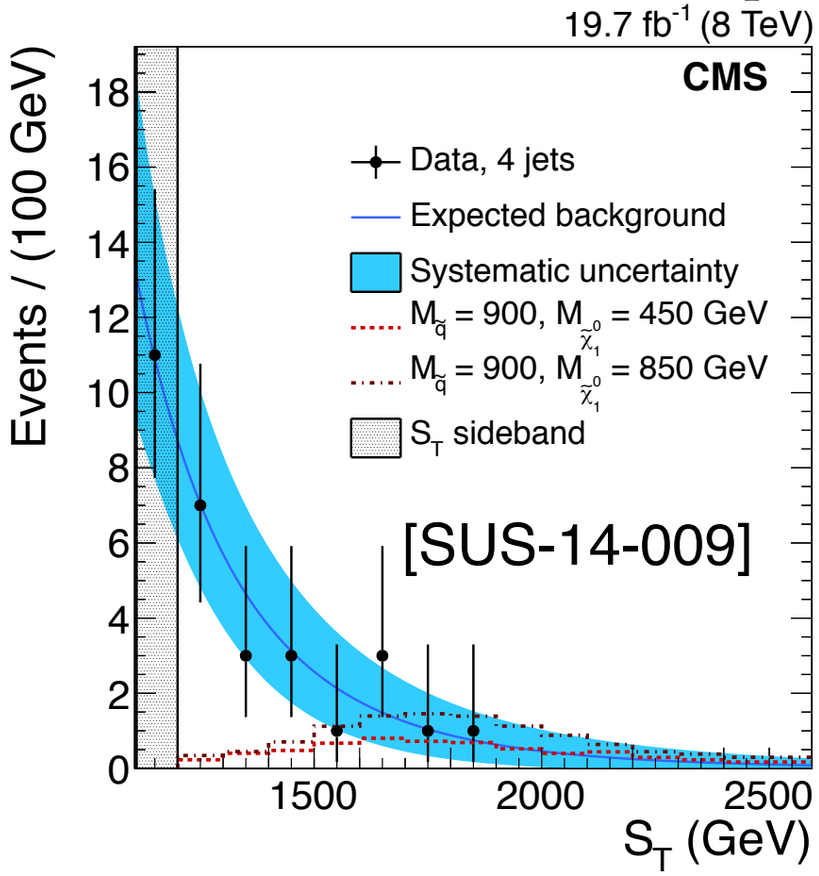


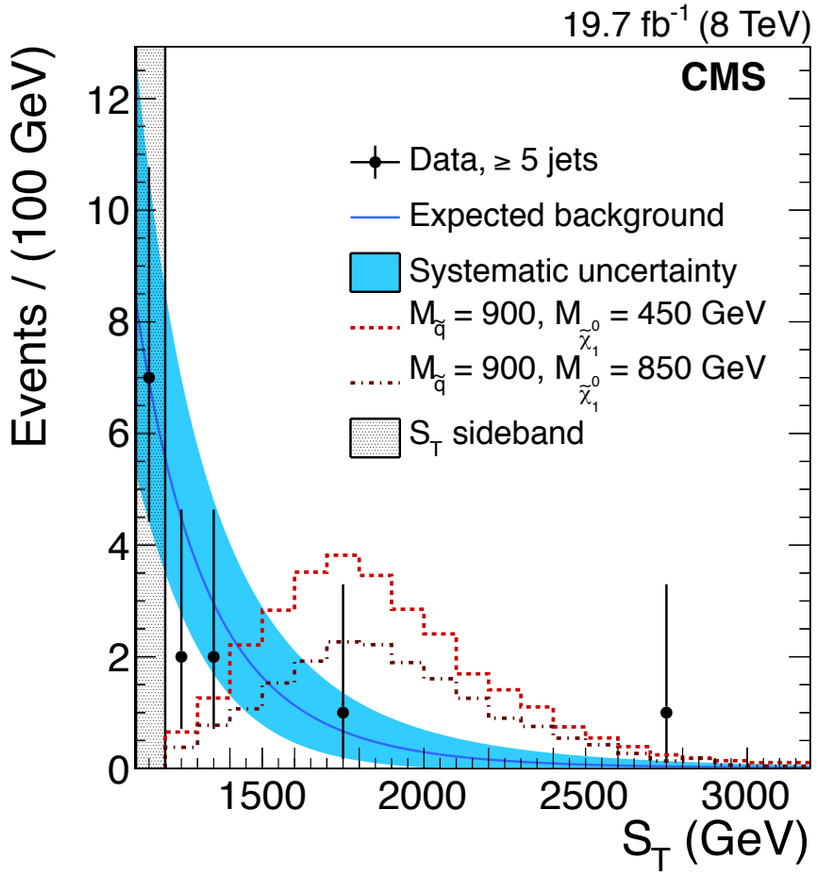


STEALTH SUSY

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



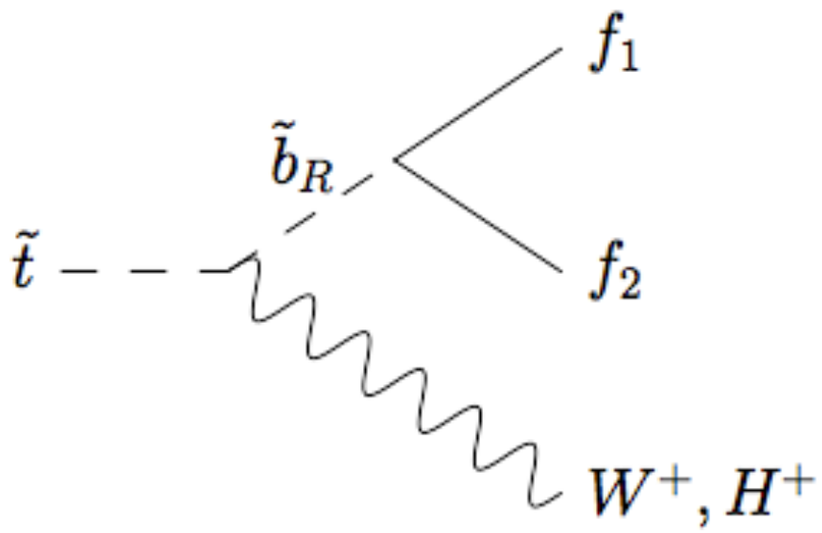


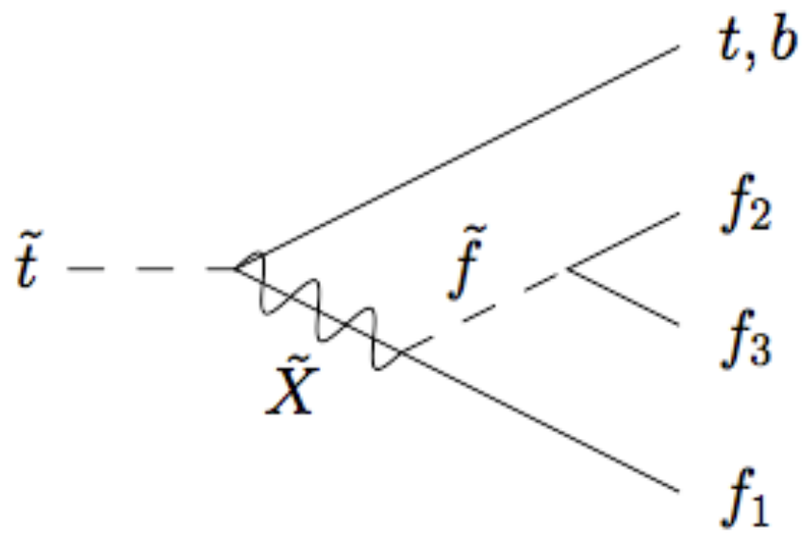


Characteristic signature is 1-2 photons (or 1-2 leptons) plus many jets **but with little missing E_T**

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

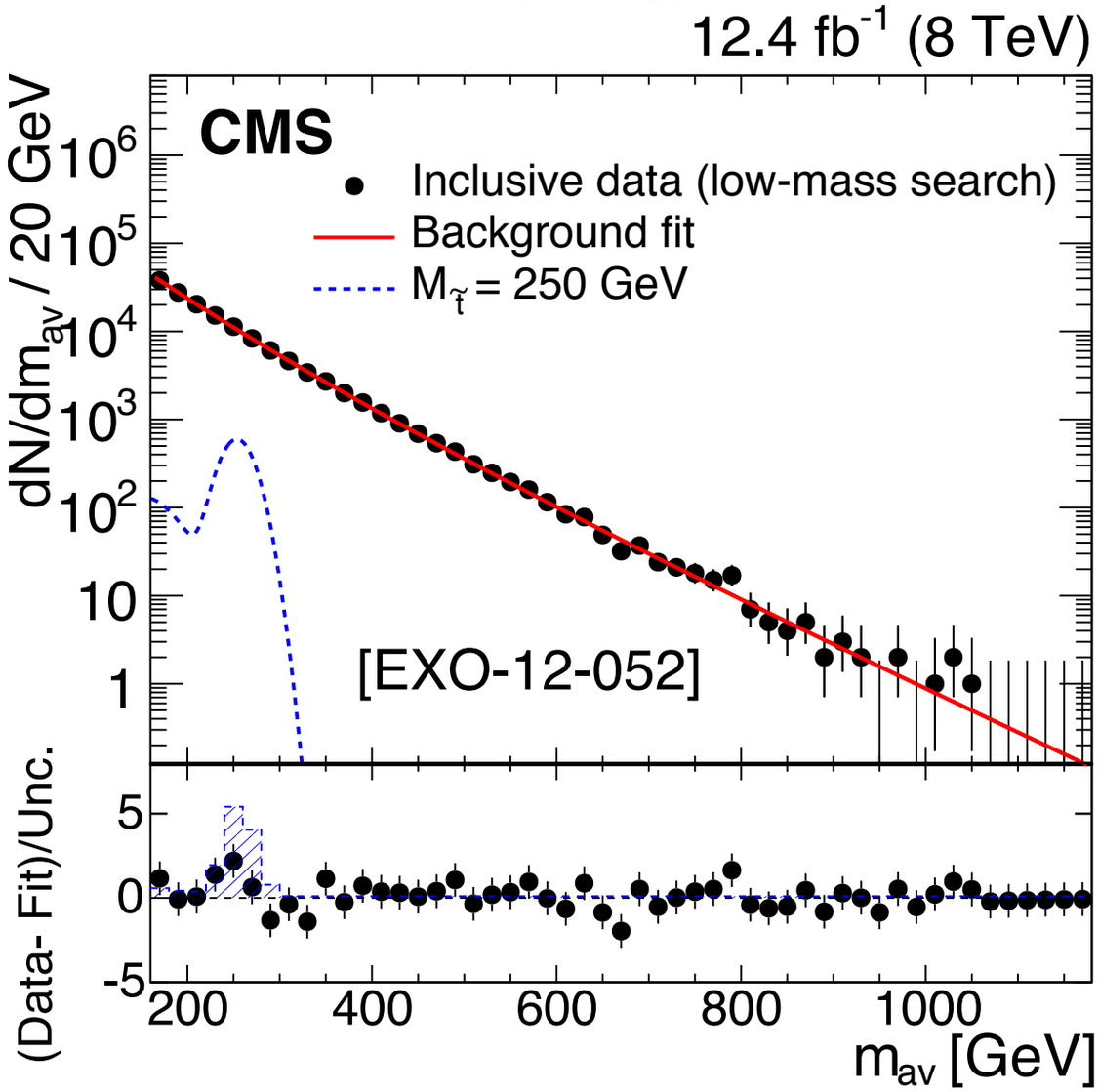




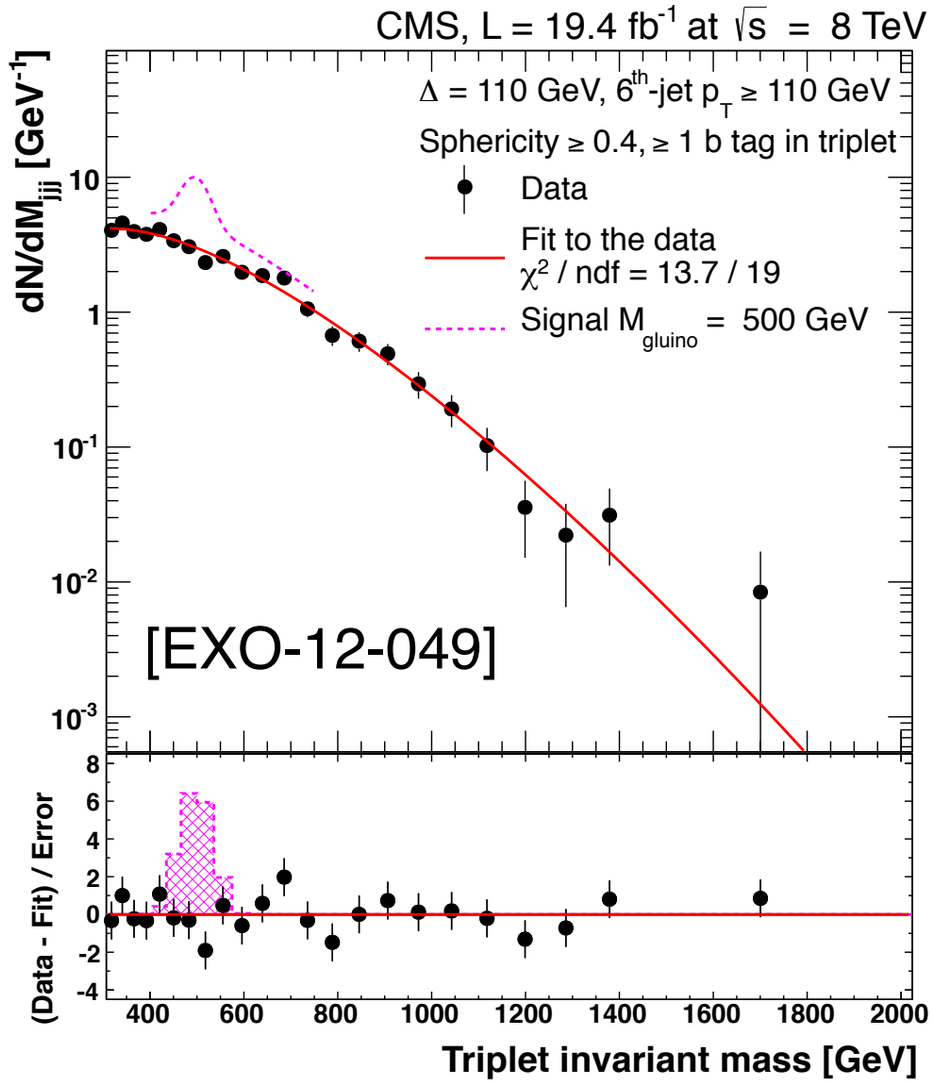
ALL HADRONIC RPV SUSY

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

stop→jj

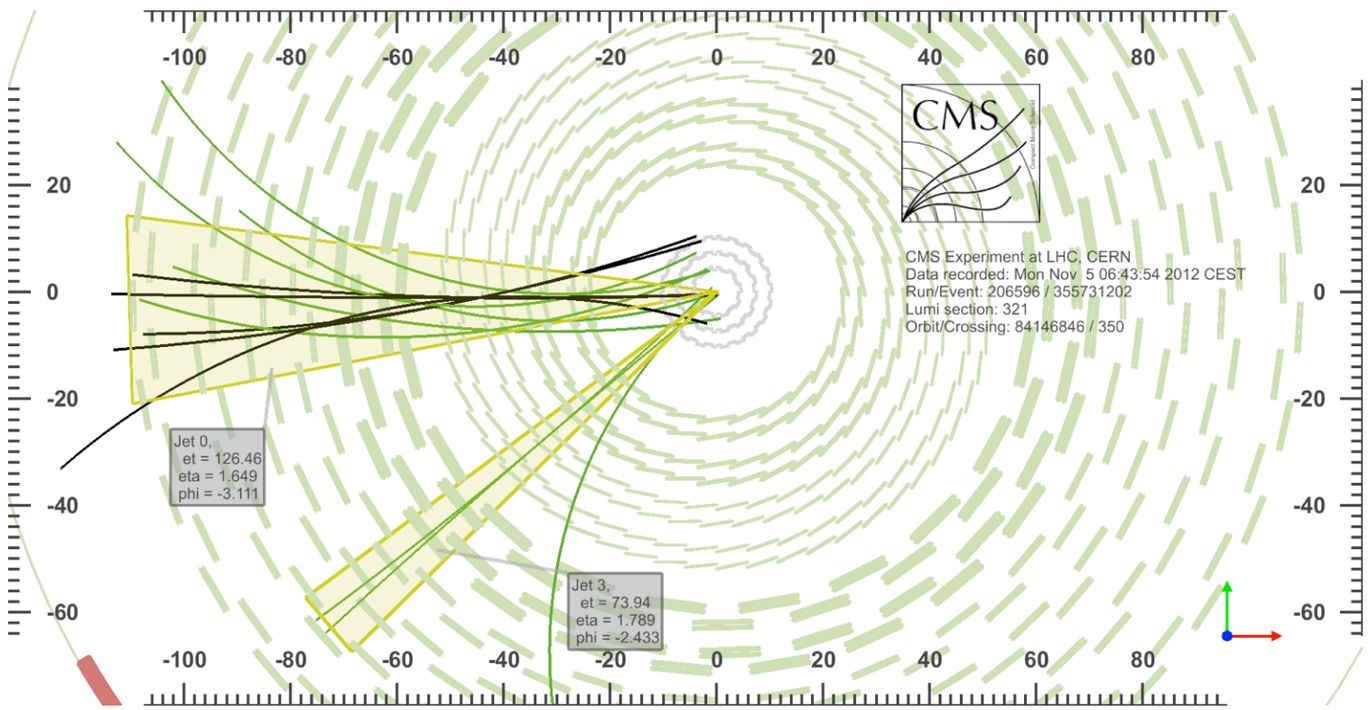


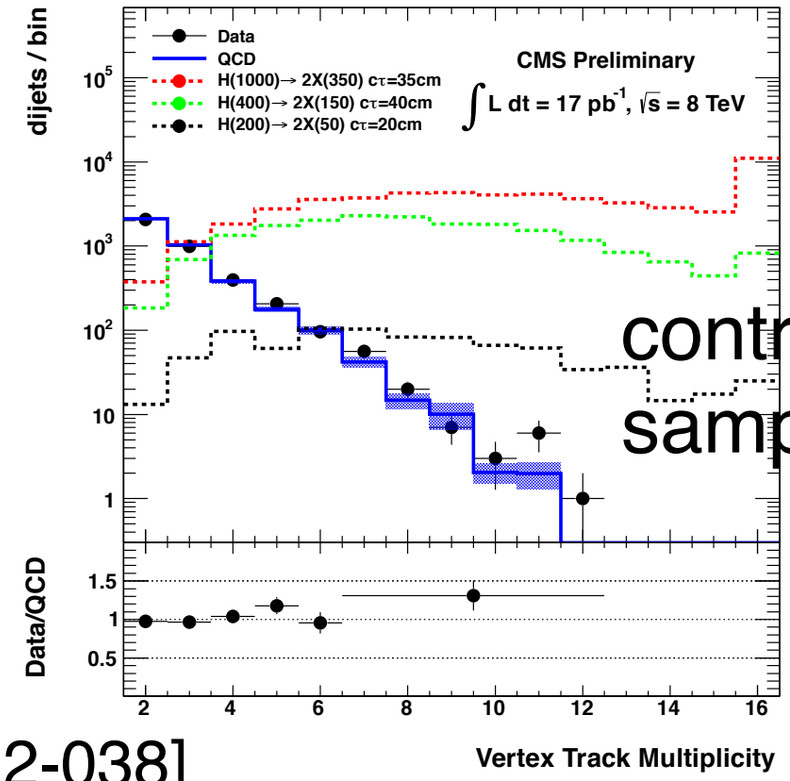
gluino→jjj



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**





control sample

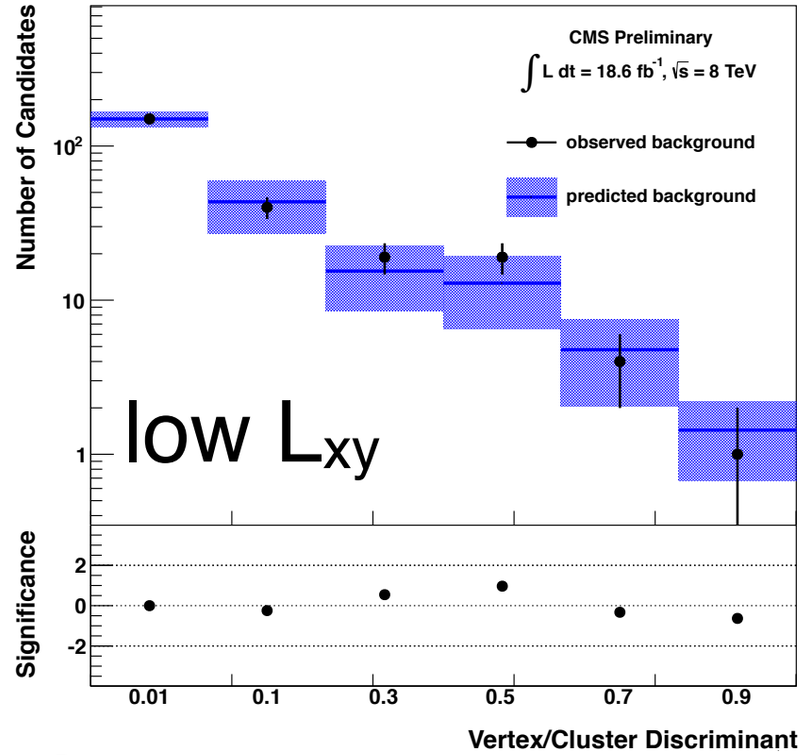
[EXO-12-038]

DISPLACED DIJETS

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

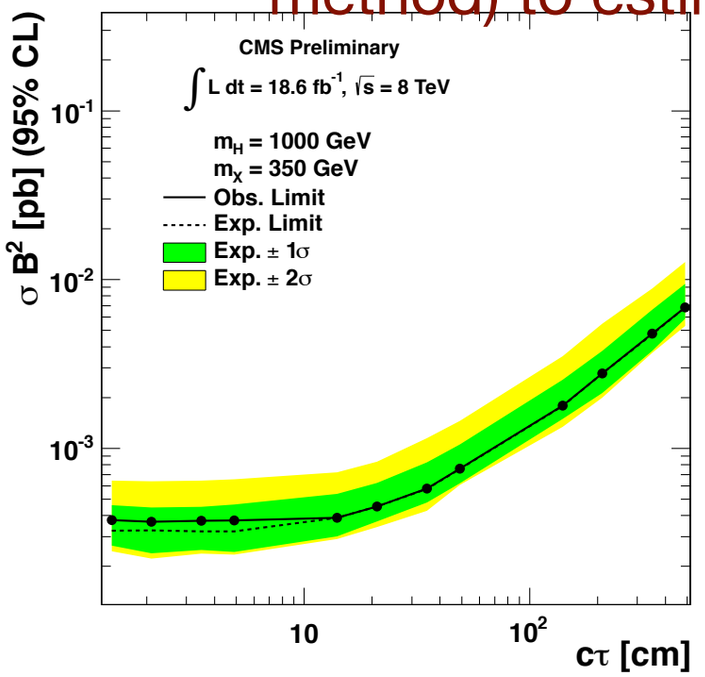
$\mathbf{L_{xy}}$	$< \mathbf{20\ cm (low)}$	$> \mathbf{20\ cm (high)}$
prompt tracks	≤ 1	≤ 1
prompt energy fraction	< 0.15	< 0.09
vertex/cluster disc.	> 0.9	> 0.8
expected background	$1.60 \pm 0.26(stat.) \pm 0.51(syst.)$	$1.14 \pm 0.15(stat.) \pm 0.52(syst.)$
observed	**2**	**1**

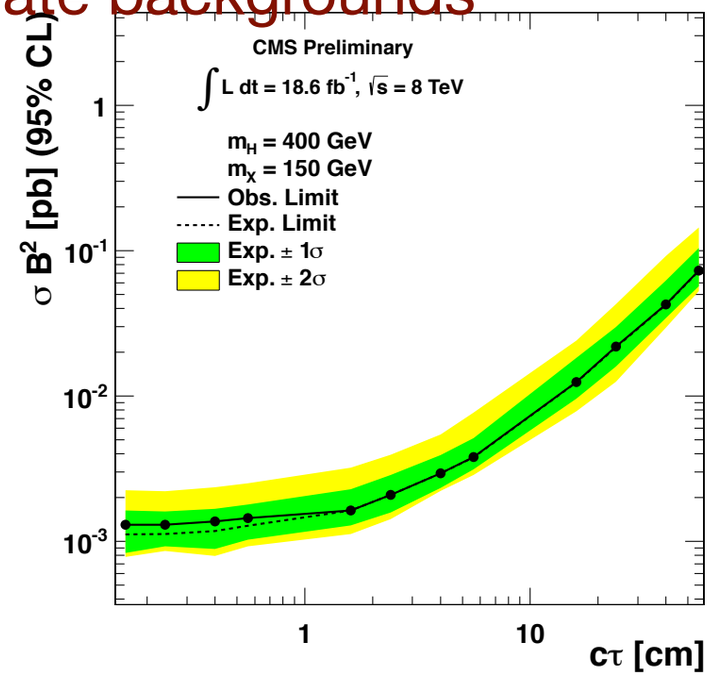
Table 1: Predicted background and the number of observed candidates for optimised selections.

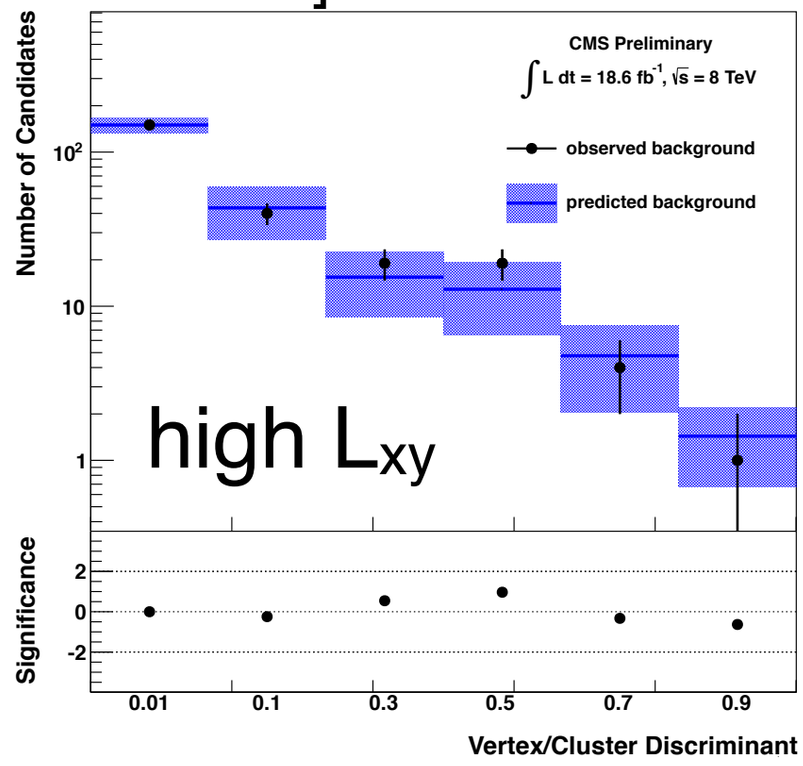


[EXO-12-038]

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







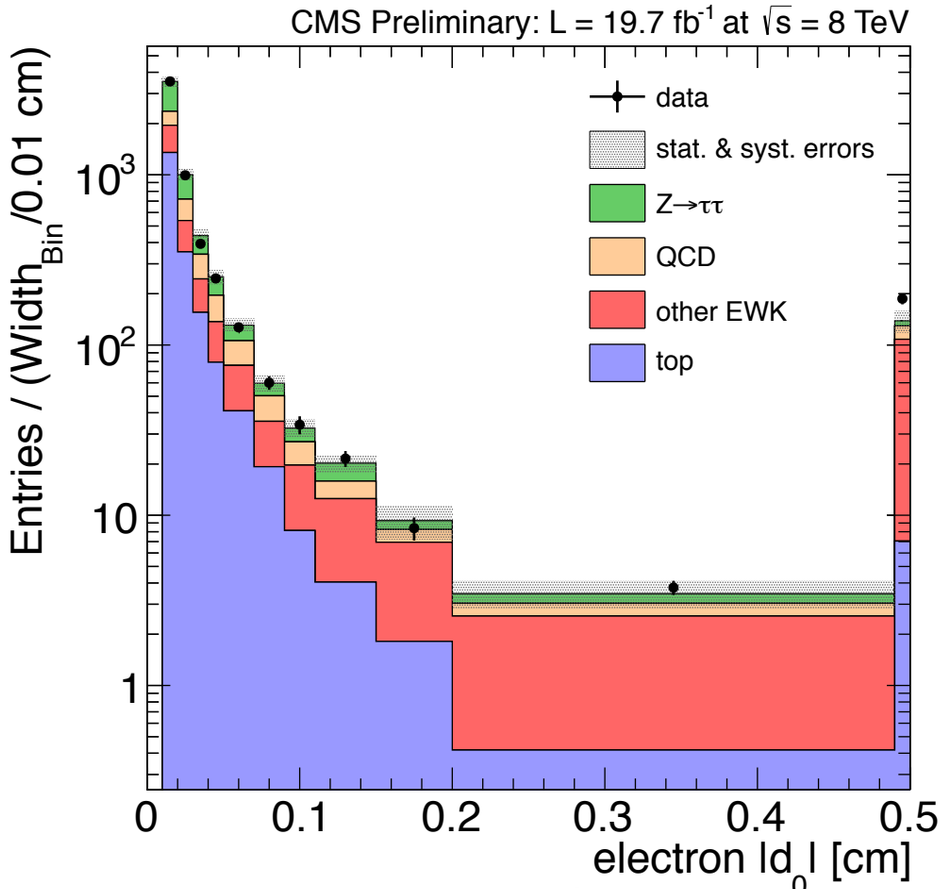
Set limits on $H \rightarrow XX \rightarrow (jj)(jj)$

What's Missing from displaced dijets?

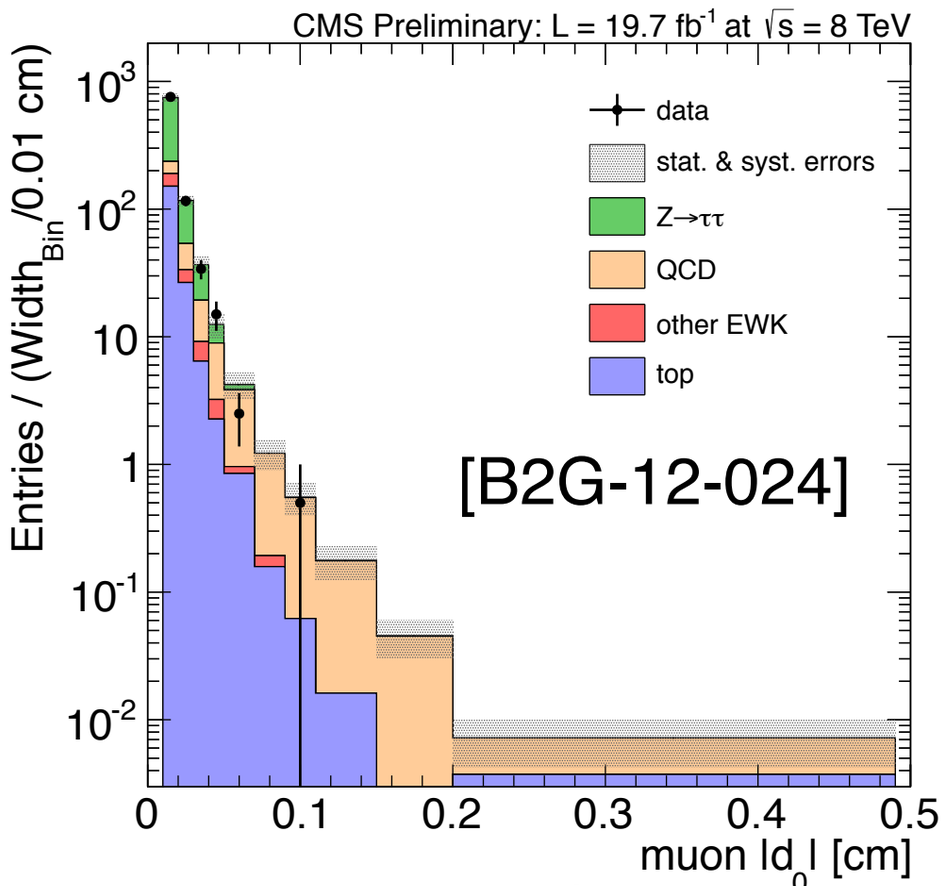
- The analysis requires **two** displaced jets from the same vertex
  - Note that some models have two displaced jets from the same vertex, but because of the boost, the jets merge
- Trigger requires **H_T>300 GeV**
  - Can't go after H(125) because of this
  - Should look in other channels: inclusive VBF, lepton+X, etc.
- Analysis has prompt energy fraction requirement
  - If the long-lived particle has electric charge, then sensitivity could be suppressed
- Less sensitive to lifetimes $\lesssim$1 mm and $\gtrsim$1 m

(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



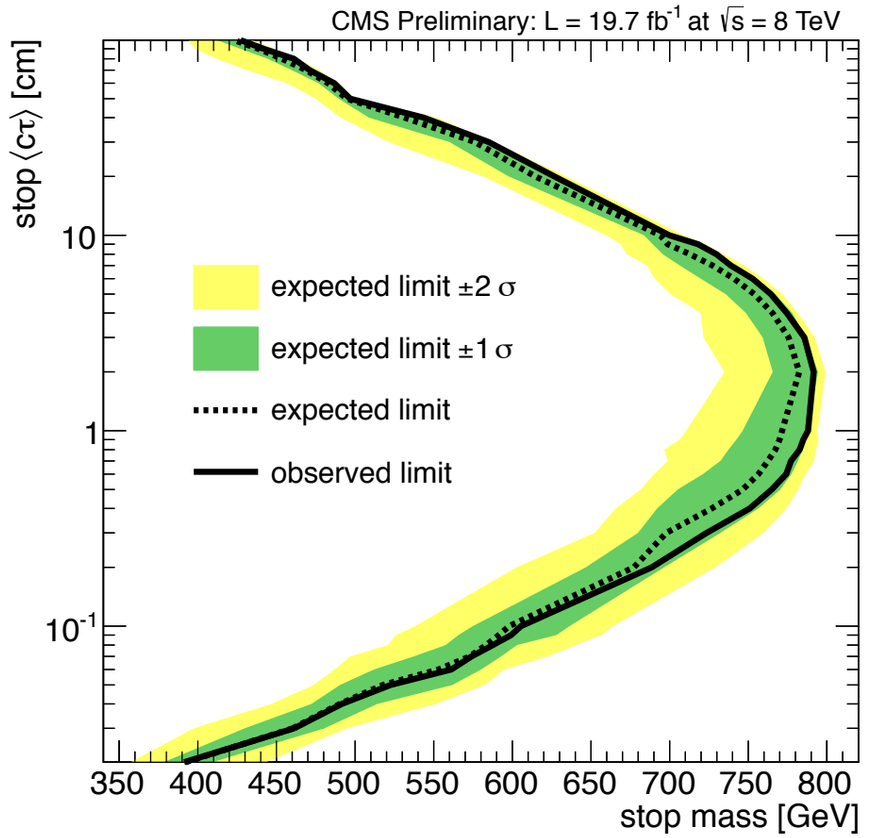
non-prompt e and prompt μ



non-prompt μ 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

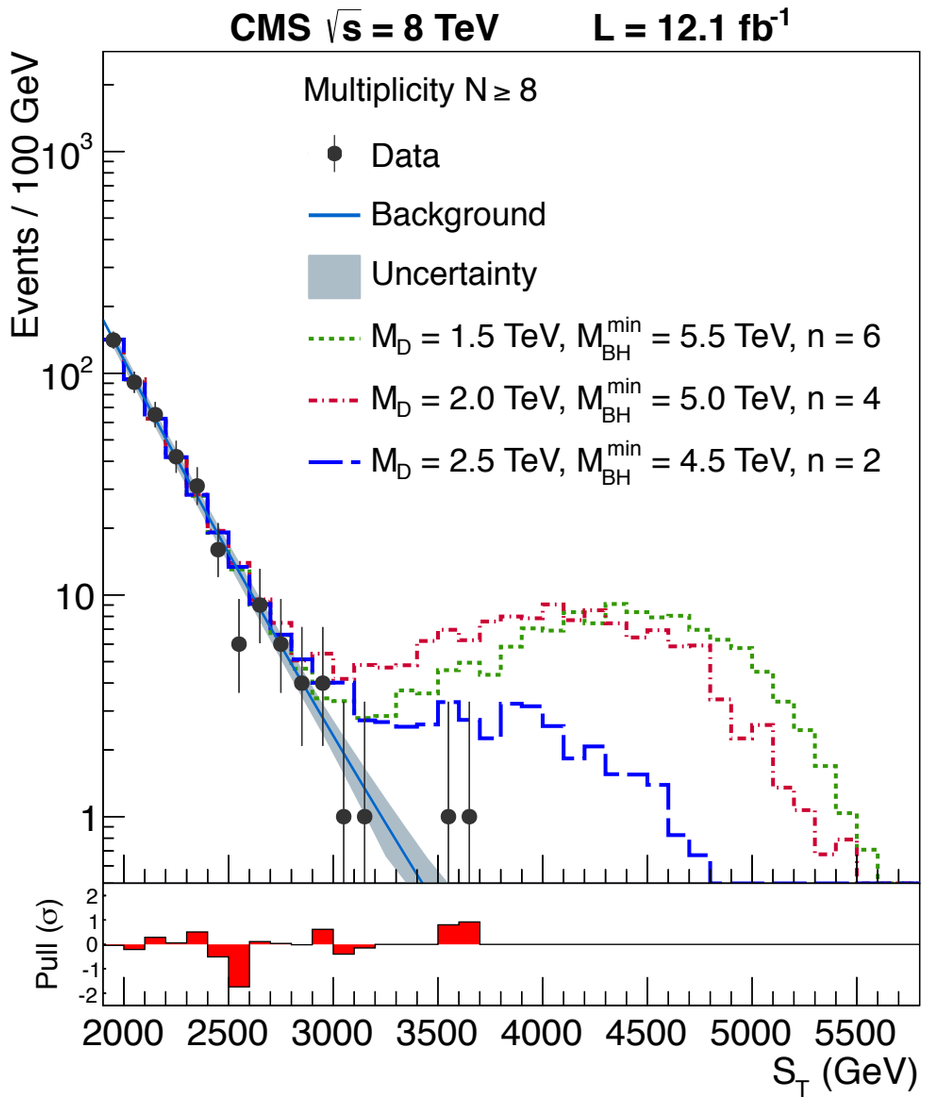


Event Source	$0.02\text{ cm} < \lvert d_0\rvert < 0.05\text{ cm}$	$0.05\text{ cm} < \lvert d_0\rvert < 0.1\text{ cm}$	$\lvert d_0\rvert > 0.1\text{ cm}$
other EWK	$0.65 \pm 0.13 \pm 0.08$	$(0.89 \pm 0.53 \pm 0.11) \times 10^{-2}$	$<(89 \pm 53 \pm 11) \times 10^{-4}$
top	$0.767 \pm 0.038 \pm 0.061$	$(1.25 \pm 0.26 \pm 0.10) \times 10^{-2}$	$(2.4 \pm 1.3 \pm 0.2) \times 10^{-4}$
$Z \to \tau\tau$	$3.93 \pm 0.42 \pm 0.32$	$(0.73 \pm 0.73 \pm 0.06) \times 10^{-2}$	$<(73 \pm 73 \pm 6) \times 10^{-4}$
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
$pp \to \tilde{t}_1 \tilde{t}_1^*$			
$M = 500$ 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?

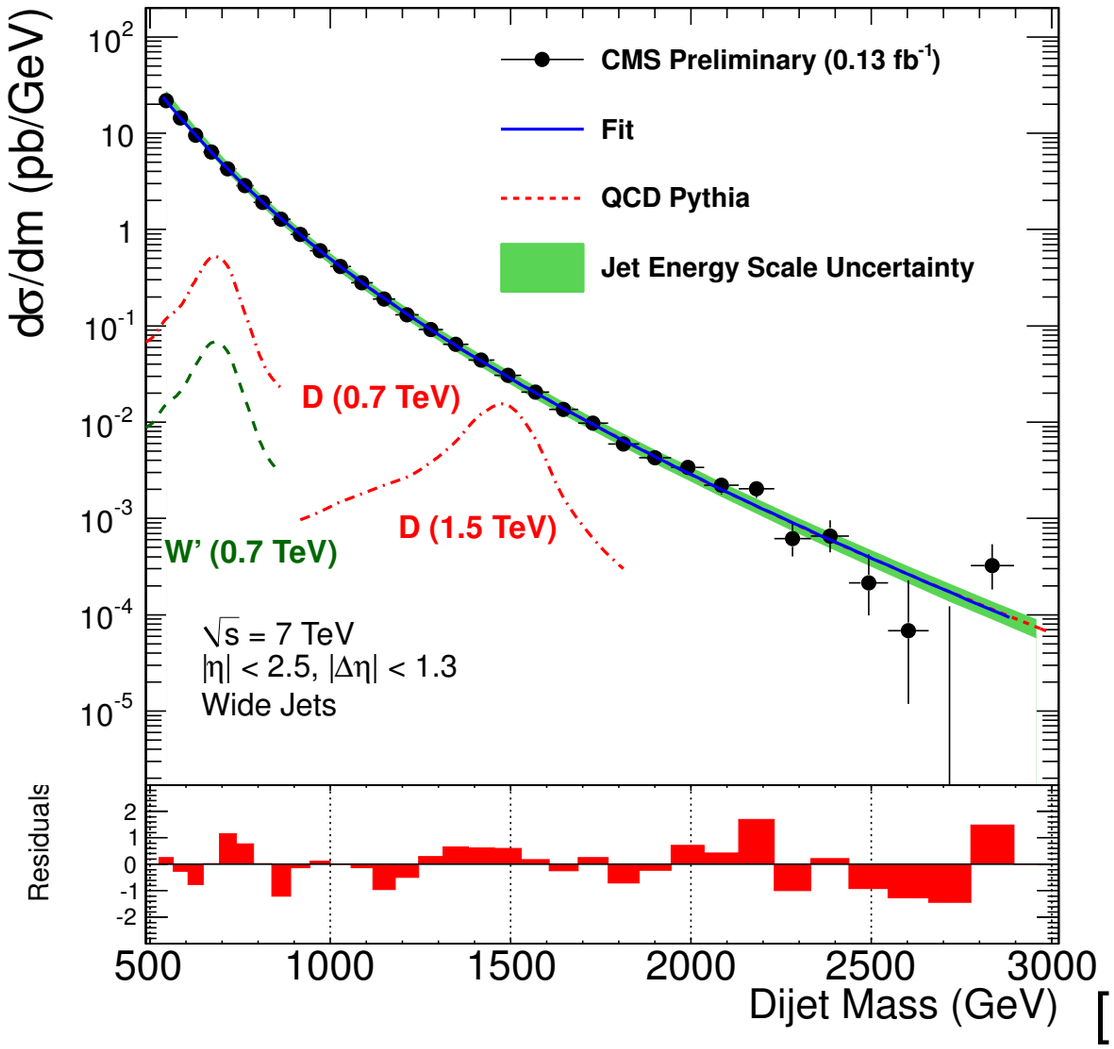
MULTIJETS

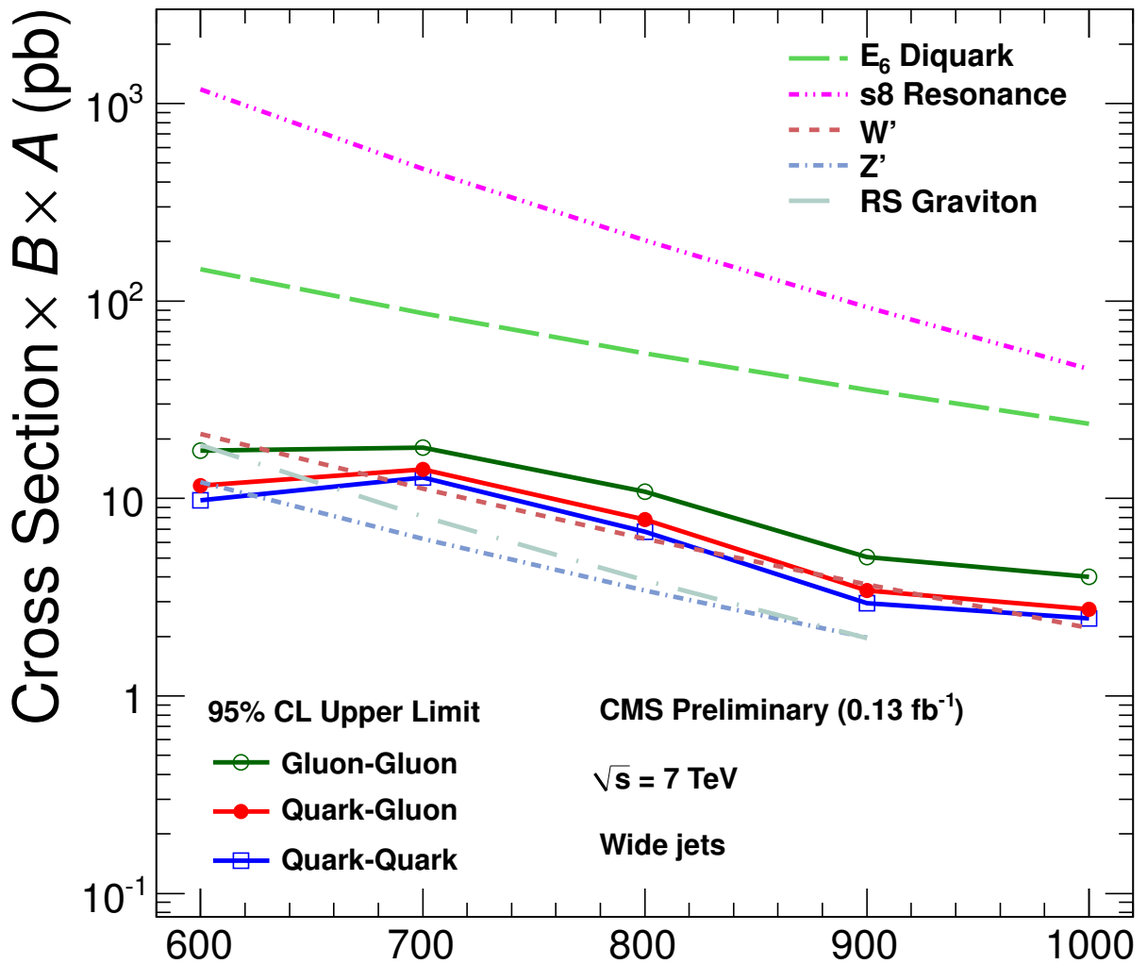
- Search for high multiplicity jet final states (with no missing E_T) is very challenging
  - One approach (motivated by classical black holes) is to look at the tails of the S_T distribution (scalar sum p_T of objects)
  - data-driven approach seems to work well here, but limited to tails
    - what 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]

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
    - need to investigate these ideas more thoroughly
- 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

- 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!