RECENT RESULTS FROM SEARCHES FOR NEW PHYSICS @

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CERN-CKC Workshop

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Outline

- LHC Performance
- Run 2 searches
  - Low-hanging fruit
  - Not-so-low-hanging fruit
  - High-hanging fruit
  - Out-of-reach fruit
  - Conclusions: hanging in there...

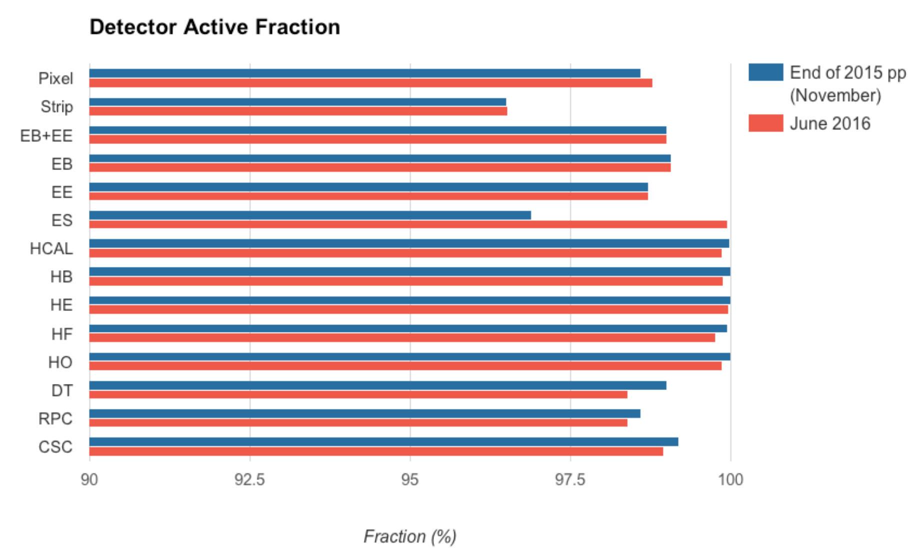
- Disclaimer: I'll mainly focus on the most recent results - either preliminary or recently submitted
- For the full searches landscape in CMS, see:
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html

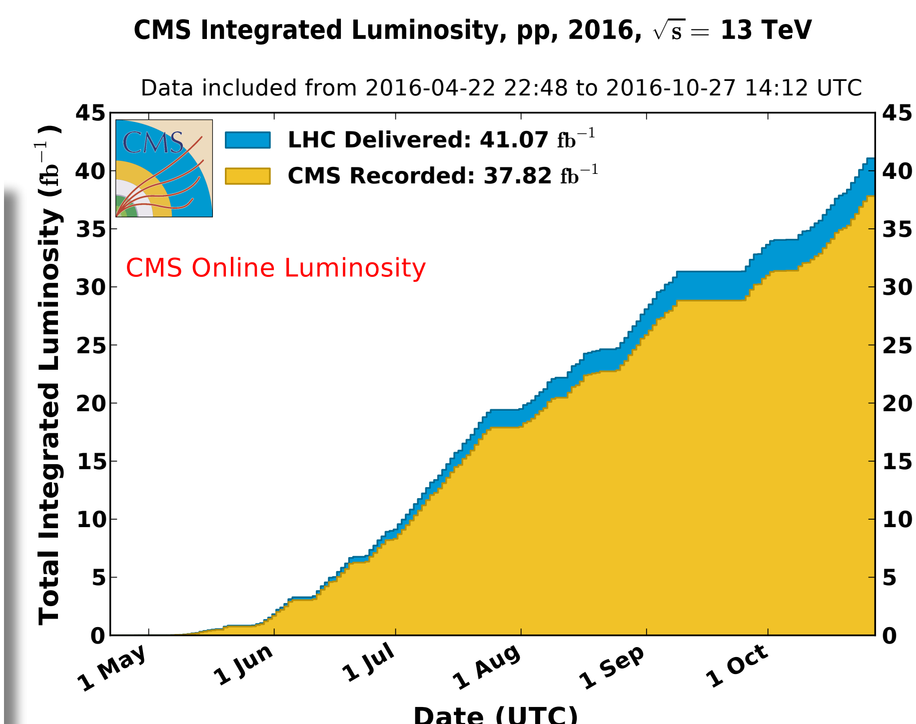
The LHC Performance

2016 Data Taking

- ✦ About 40/fb has been delivered by the LHC in 2016, exceeding the integrated luminosity accumulated in all years before 2016 and expectations
- ✦ Thank you, the LHC, for a spectacular year!

CMS Status in June 2016 (%)





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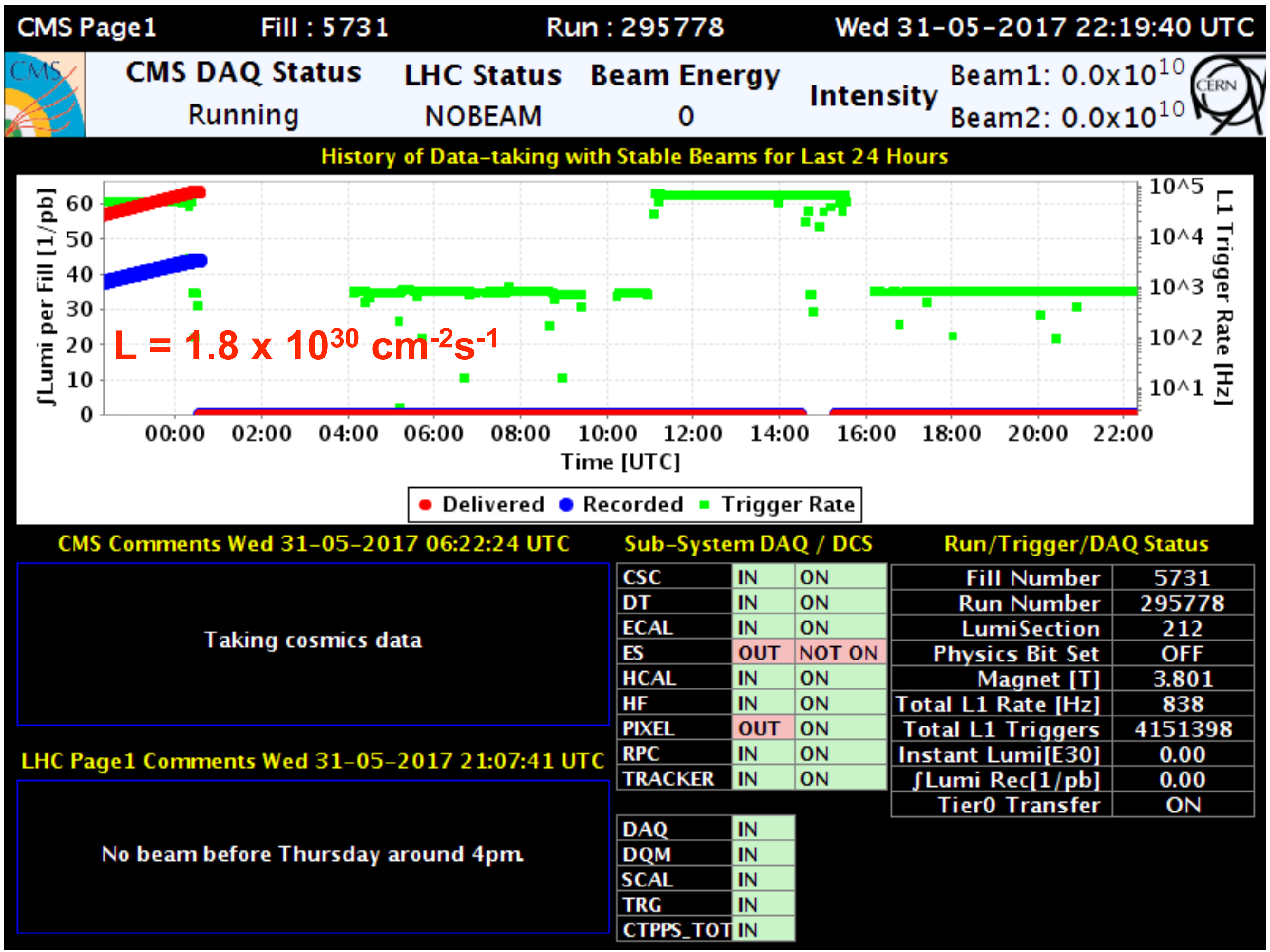
The Giant is Awaking

- Already delivering first luminosity; will go with 600 x 600 bunch collisions later today or Friday

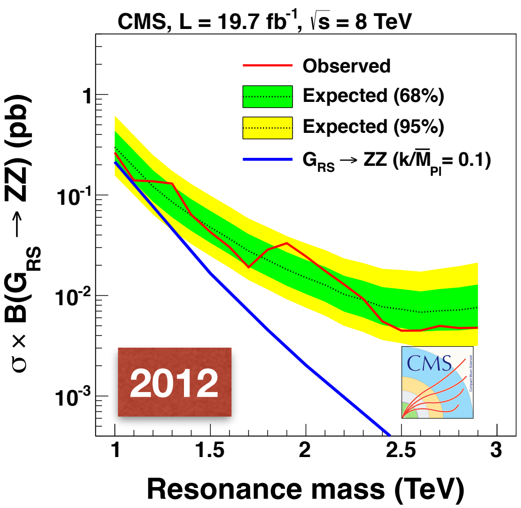



Run 1
Excesses

Run 1 Excesses

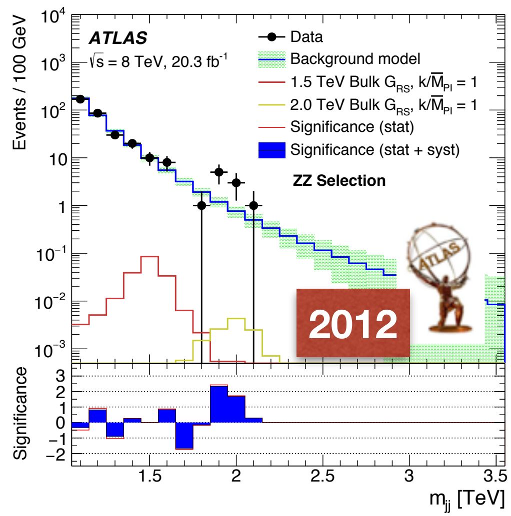
- Very few statistically interesting excesses remained after Run 1
  - A slight excess in the H(μτ) search (CMS saw about 2.4σ excess, while ATLAS was consistent with both zero and CMS)
  - A ~2.5σ excess in CMS 1st generation LQ search in both eejj and eνjj channels seen for the 650 GeV LQ mass hypothesis
  - A ~3σ ATLAS on-Z excess in the OS dilepton search (SUSY "edge" search)
  - A 2-3σ excess in the VV mass spectrum at ~2 TeV in both ATLAS and CMS
- Most of those were not confirmed with 2015 13 TeV data, including the diboson one
- Large data sets collected in 2016 would allow to ultimately test those

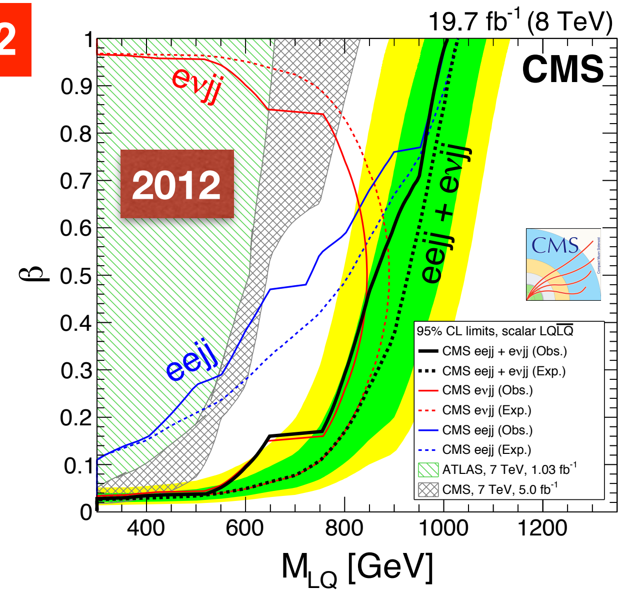
Old Hints for New Physics?



CMS arXiv:1405.1994

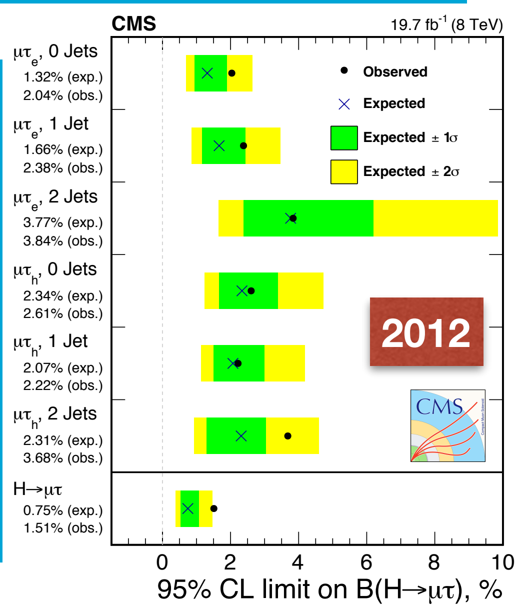
ATLAS arXiv:1506.00962

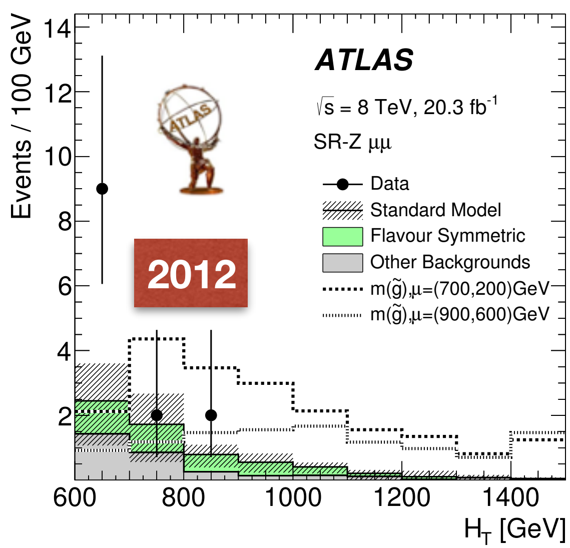




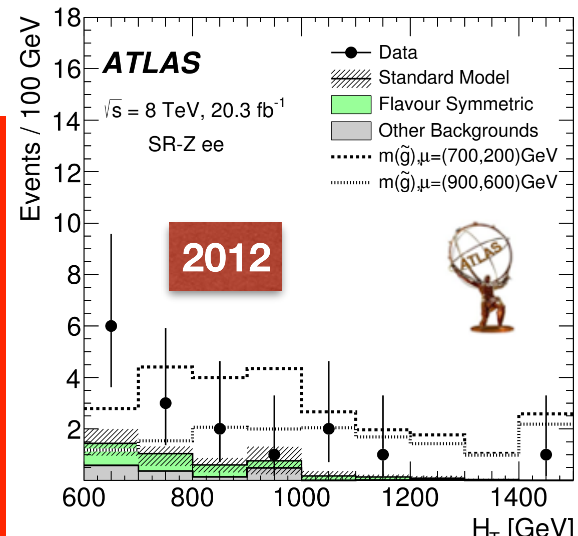
CMS arXiv:1509.03744

CMS arXiv:1502.07400





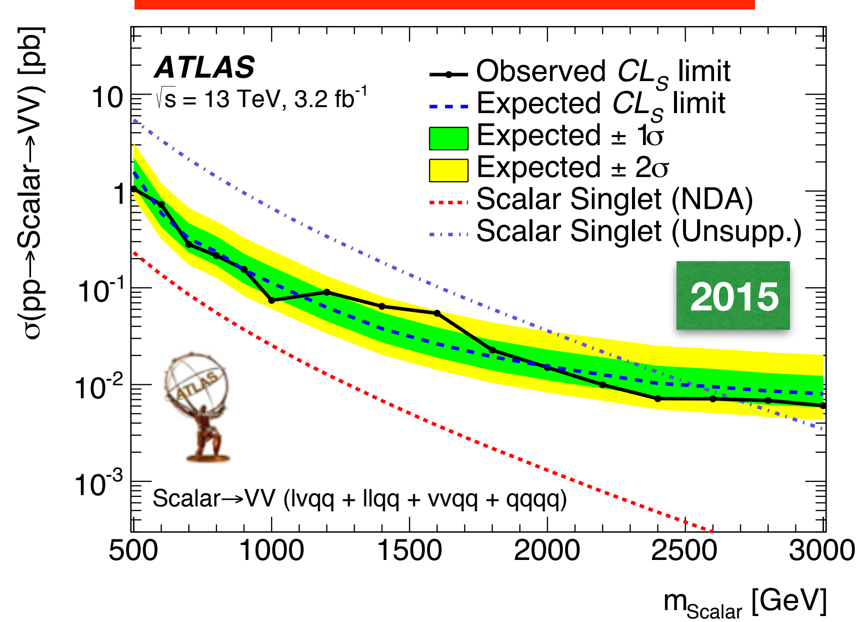
ATLAS arXiv:1503.03290



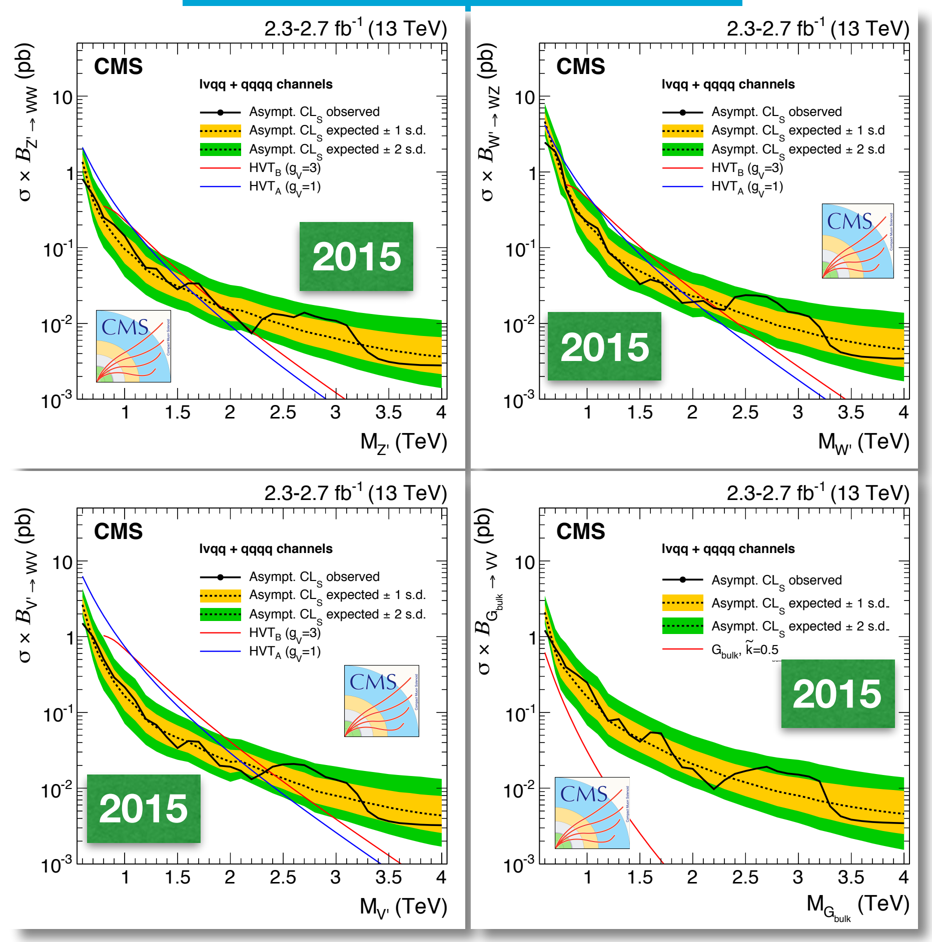
VV Excess Gone?

- ✦ Analysis of the first 13 TeV data did not confirm the VV excess, neither in ATLAS, nor in CMS

ATLAS arXiv:1606.04833



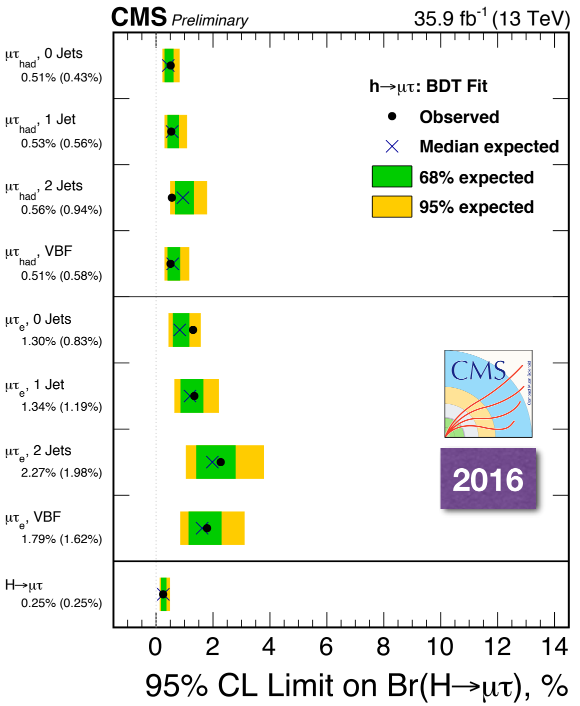
CMS arXiv:1612.09159



What about H(μτ)?

- Brand new result from CMS based on full 2016 data
  - Definitively excludes the Run 1 excess (alas...)

CMS PAS HIG-17-001



Expected limits (%)	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	< 0.83	< 1.19	< 1.98	< 1.62	< 0.59
$\mu\tau_h$	< 0.43	< 0.56	< 0.94	< 0.58	< 0.29
$\mu\tau$	< 0.25				

Observed limits (%)	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	< 1.30	< 1.34	< 2.27	< 1.79	< 0.86
$\mu\tau_h$	< 0.51	< 0.53	< 0.56	< 0.51	< 0.27
$\mu\tau$	< 0.25				

Best fit branching fractions (%)	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	0.61 ± 0.36	0.22 ± 0.46	0.39 ± 0.83	0.10 ± 1.37	0.35 ± 0.26
$\mu\tau_h$	0.12 ± 0.20	-0.05 ± 0.25	-0.72 ± 0.43	-0.22 ± 0.31	-0.04 ± 0.14
$\mu\tau$	0.00 ± 0.12				

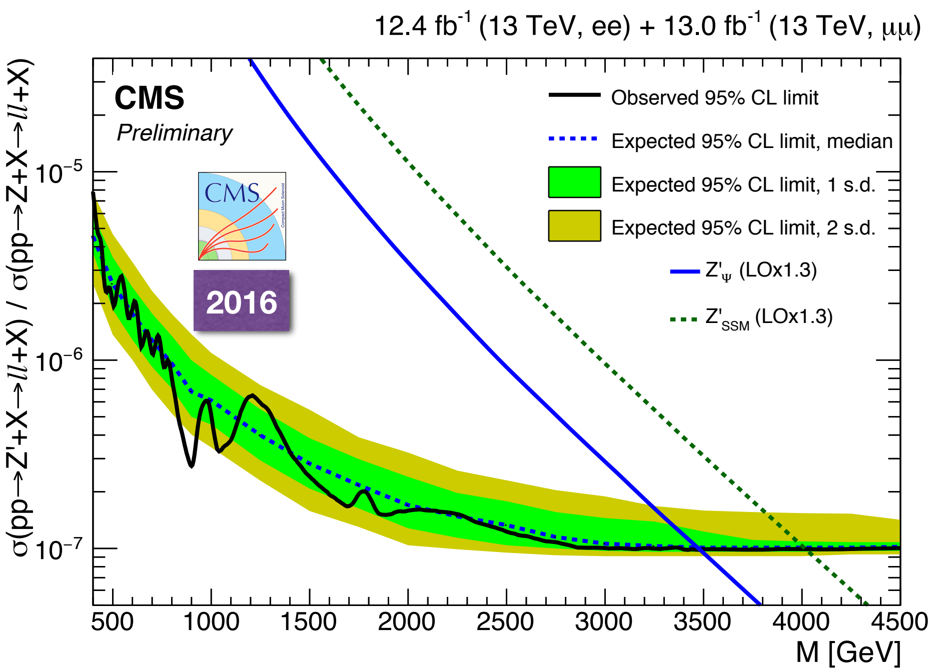
	Observed(Expected) limits (%)		Best fit branching fraction (%)	
	M_{col}-fit	BDT-fit	M_{col}-fit	BDT-fit
$H \to \mu\tau$	<0.51 (0.49) %	<0.25 (0.25)%	0.02 ± 0.20%	0.00 ± 0.12 %
$H \to e\tau$	<0.72 (0.56) %	<0.61 (0.37) %	0.23 ± 0.24 %	0.30 ± 0.18 %


Low-Hanging
Fruit

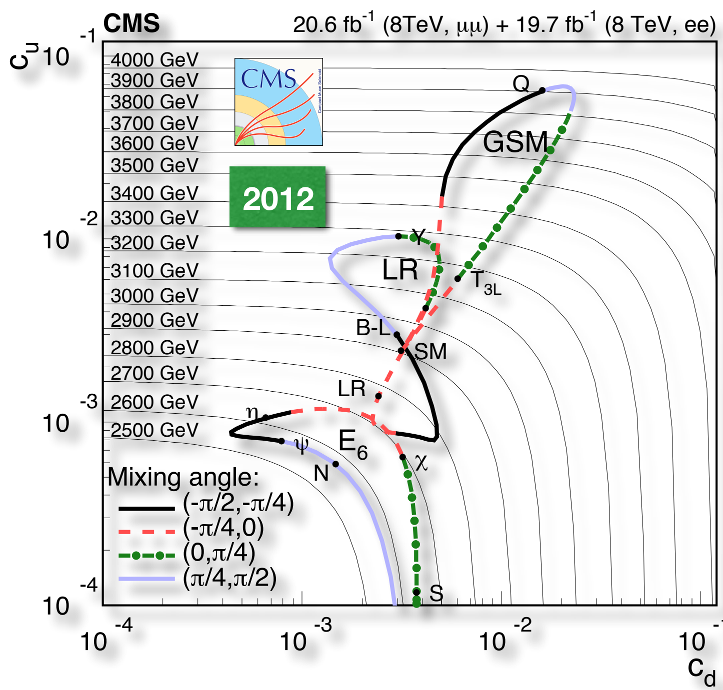
Z'(ll) Search

- CMS analysis based on partial 2016 data
  - Use standard techniques well-tested in earlier reincarnations of the analyses
  - Limits on sequential Z' reached ~4 TeV
- Limits as a function of c_u/c_d couplings last done in Run 1, but time is ripe to do this in Run 2!
- The results can also be interpreted as limits on quark-lepton compositeness

CMS PAS EXO-16-031



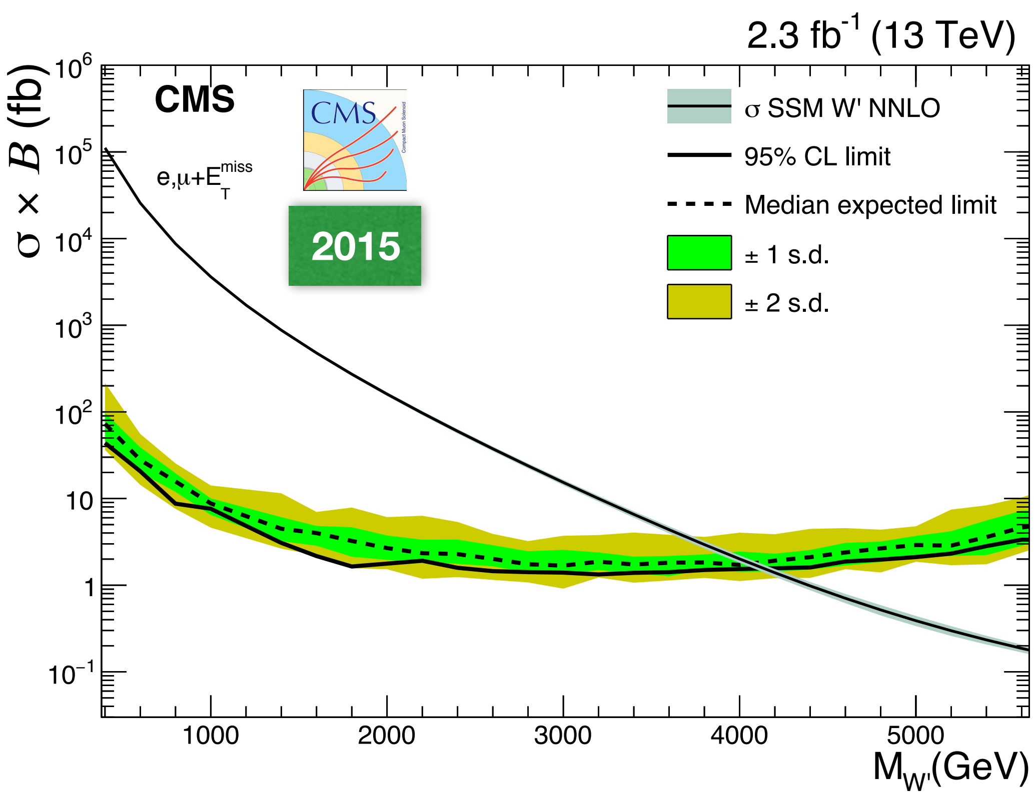
CMS arXiv:1412.6302



W'(lν) Search

- Analyses based on 2015 CMS data
  - Use standard techniques well-tested in earlier reincarnations of the analyses
  - Limits on sequential W' reach ~4 TeV

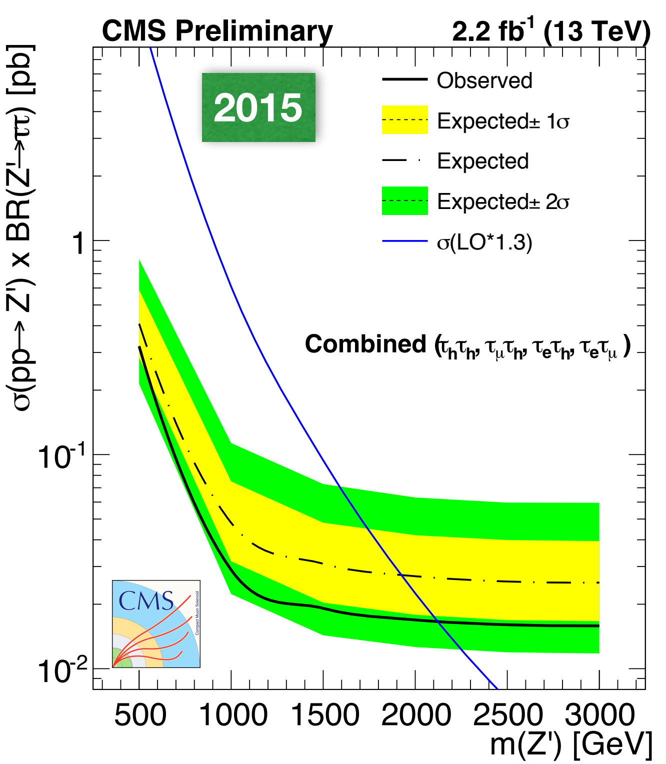
CMS arXiv:1612.09274



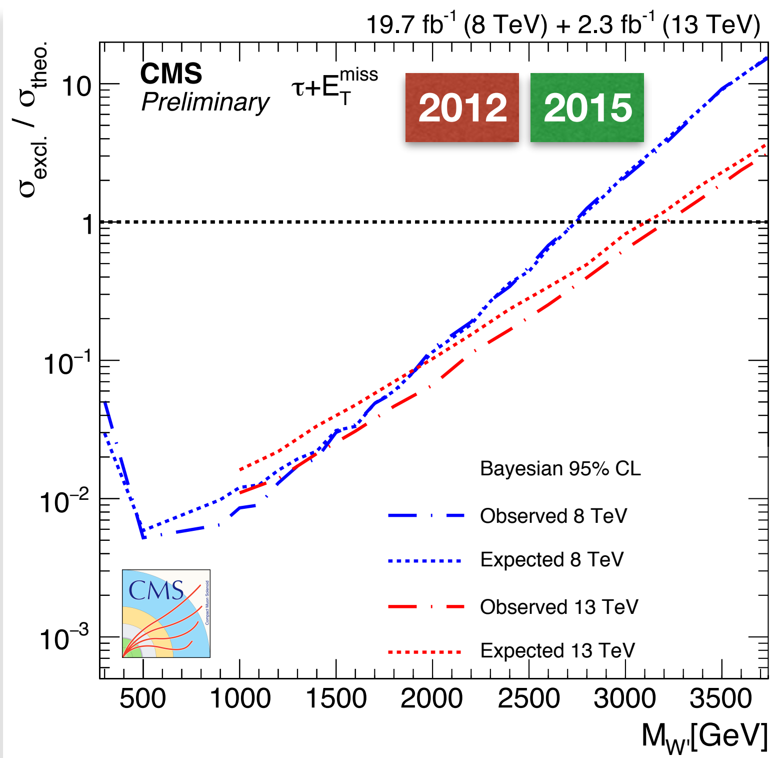
Z'/W' in τ channels

- Could also do the same search in τ channels, in case of preferential coupling to third generation
  - Still using SSM as a convenient benchmark, set limits around 2 TeV on Z' and 3 TeV on W', exceeding Run 1 limits

CMS PAS EXO-16-008



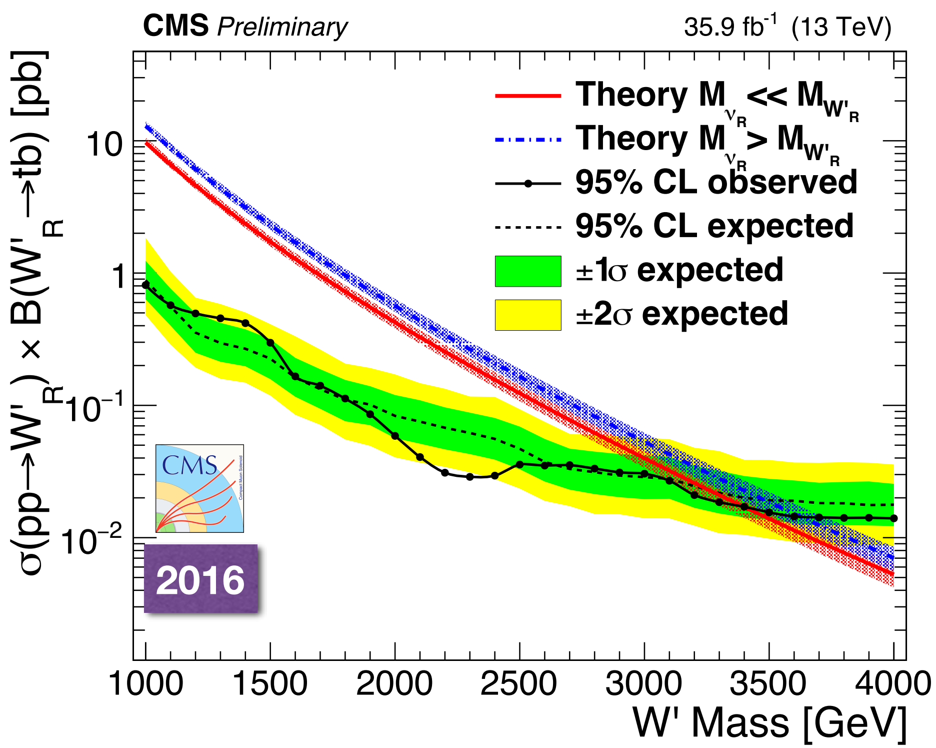
CMS PAS EXO-16-006

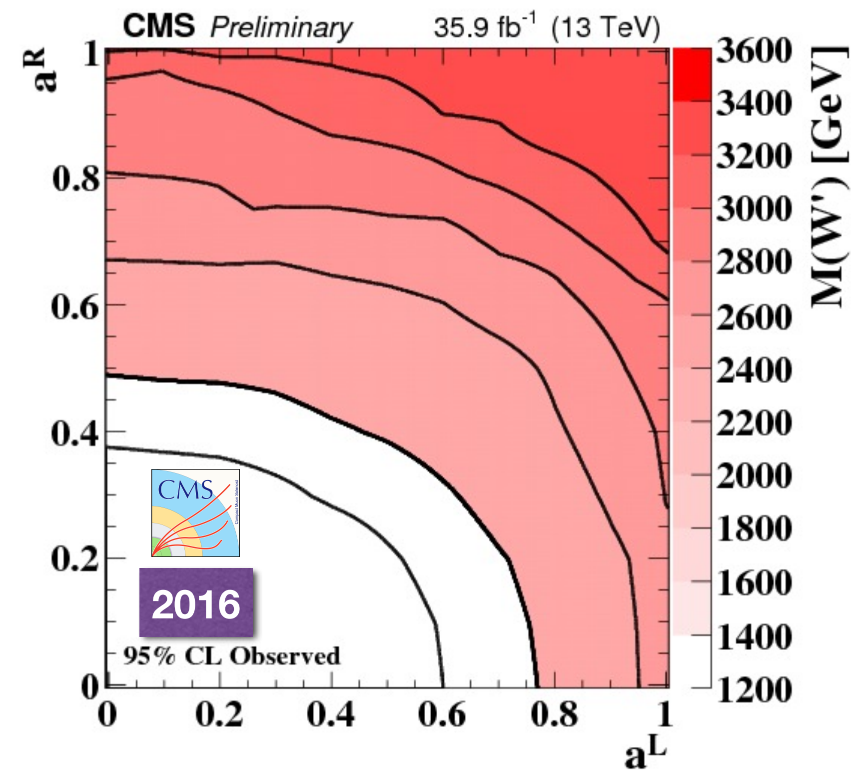


W'_R(tb) Search

- Can also search for W' in the semileptonic decay channel of the top quark decay
  - Limits on W'_R are set up to 3.6 TeV, depending on the right-handed neutrino mass

CMS PAS B2G-17-010

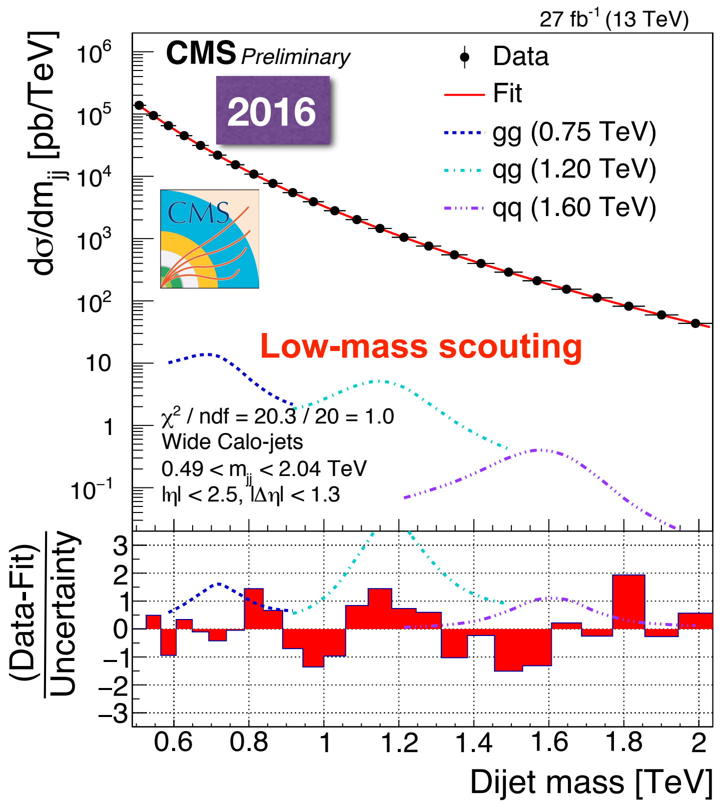


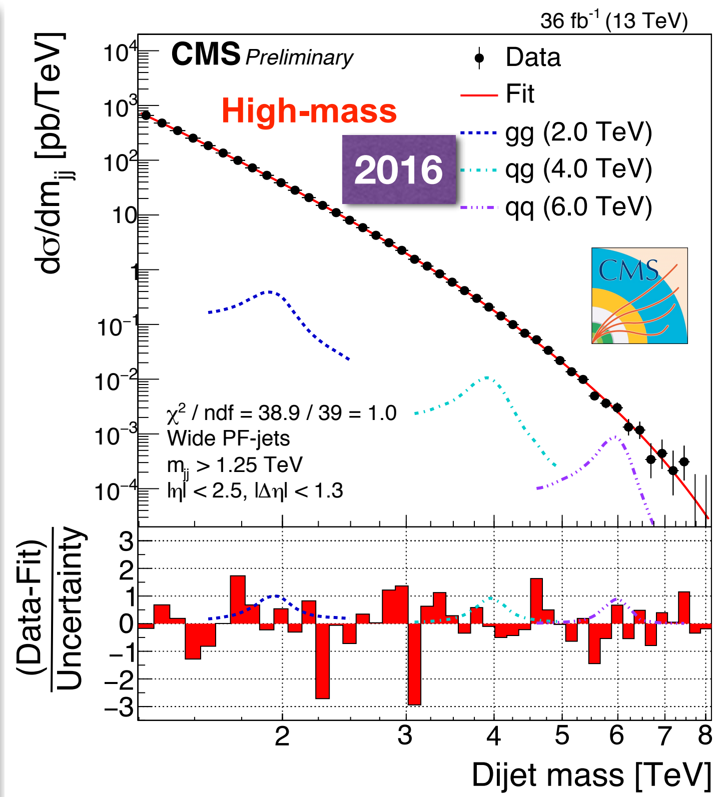


Dijet Resonance Searches

- Standard search to do at any new energy
  - Recent additions to the dijet search portfolio:
    - Scouting (trigger-level) analysis based on low-threshold triggers writing only very limited information about the event

CMS PAS EXO-16-056

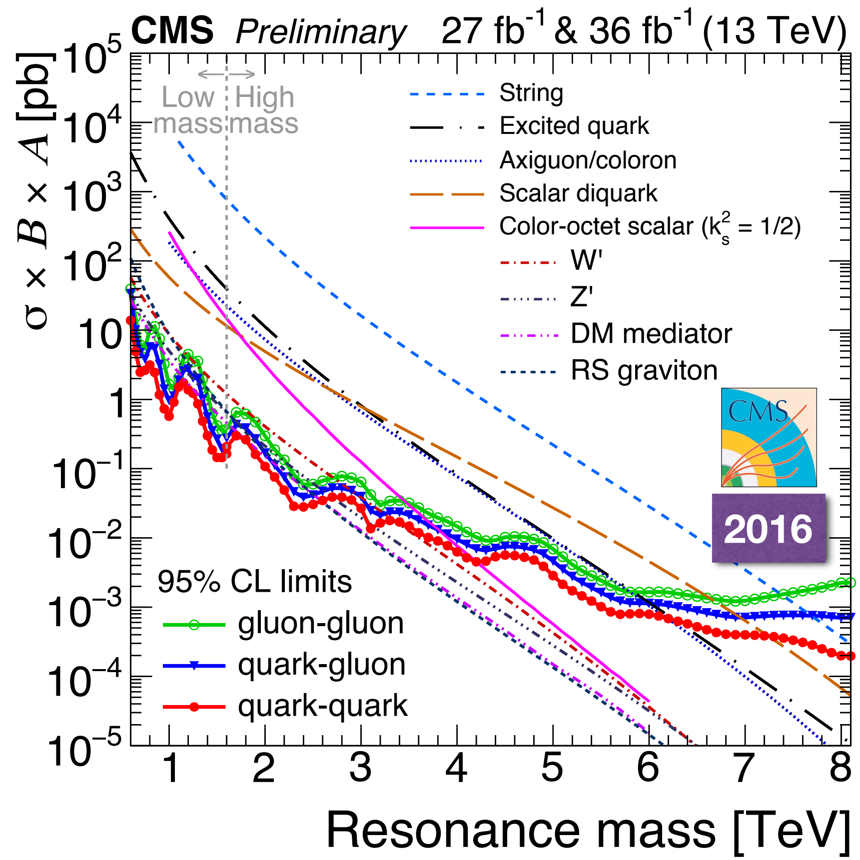




Generic Resonance Limit

- N.B. Gaussian resonance shape (ATLAS) gives artificially stronger limits compared to BW resonances due to large lower tail from PDFs

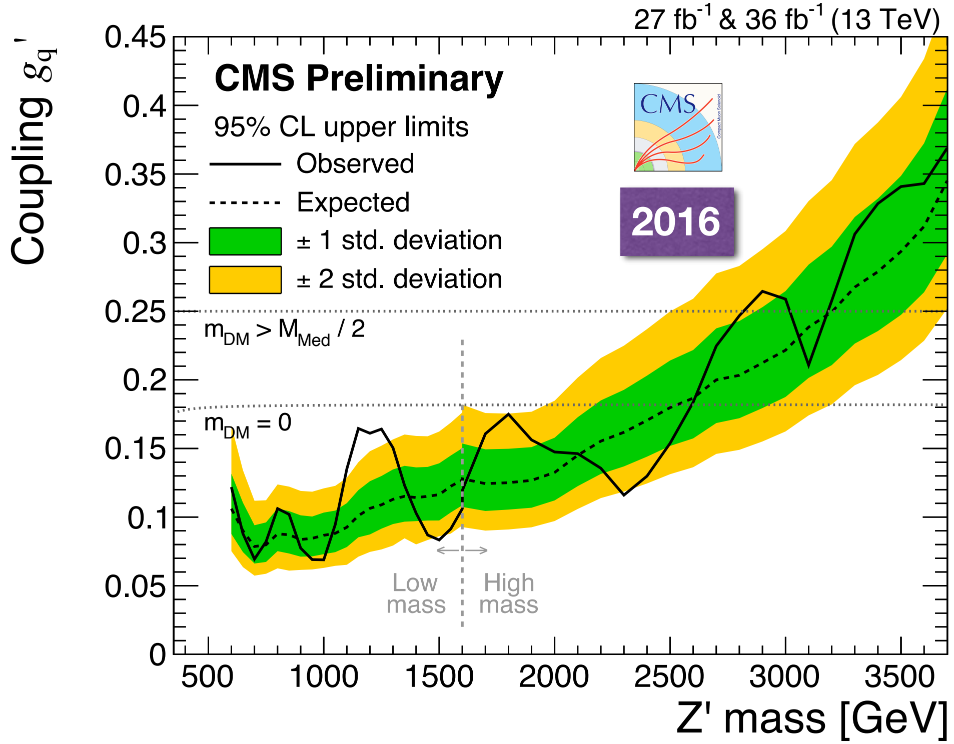
CMS PAS EXO-16-056



Dijets: Convenient Language

- For many applications, it's convenient to express limits in terms of a Z'_B like object with a coupling g_B to a baryon number [Dobrescu, Yu, arXiv:1306.2629] given by $\frac{g_B}{6} Z'_{B\mu} \bar{q} \gamma^\mu q$, $\alpha_B = g_B^2/4\pi$
- The decay width: $\Gamma(Z'_B \to jj) = \frac{5\alpha_B}{36} M_{Z'_B} \left(1 + \frac{\alpha_s}{\pi}\right)$
- Parameterize everything as a function of $g_q = g_B/6$

CMS PAS EXO-16-056



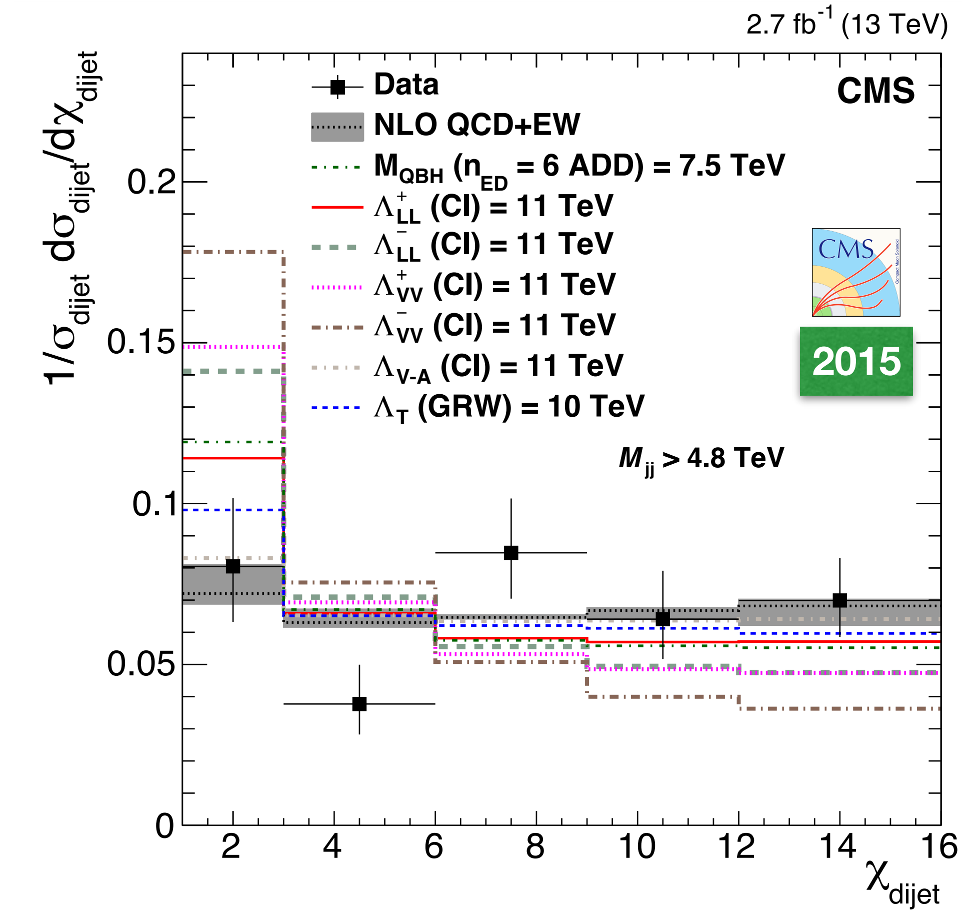
Angular Dijet Analysis

- Using the χ variable:

$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

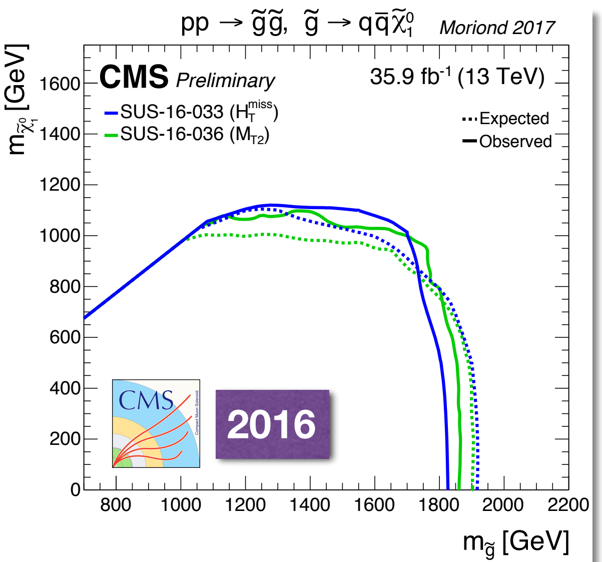
- ADD:
  M_{Pl} > 7.9-11.2 TeV
- Compositeness:
  Λ > 11.5-14.4 TeV
- Quantum black holes:
  M_{QBH} > 5.3-7.8 TeV

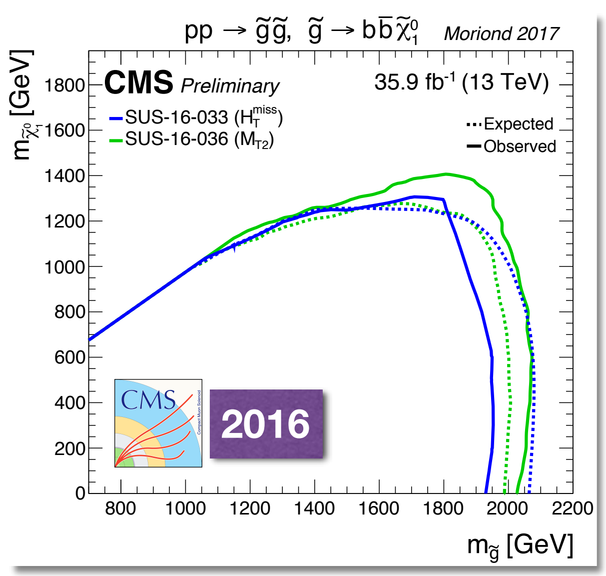
CMS arXiv:1703.09986

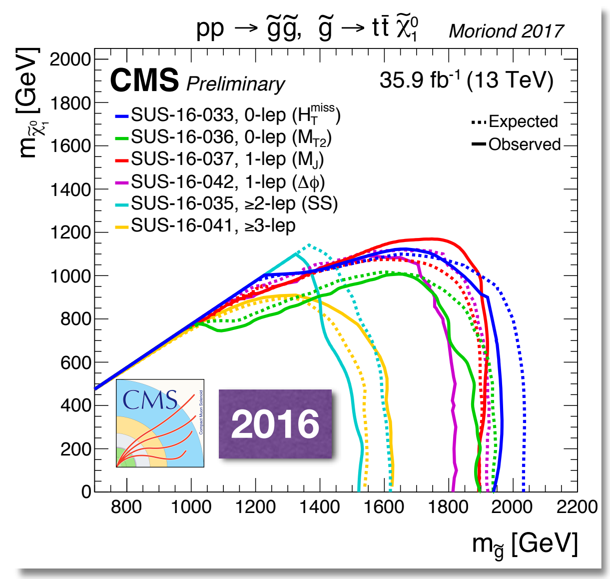


Gluino-Mediated SUSY

- ✦ Variety of searches in 0, 1, 2, >3 lepton final states, using different gluino decay modes, techniques, and "designer" variables
- ✦ Gluinos below about 2 TeV are excluded nearly up to kinematic limit



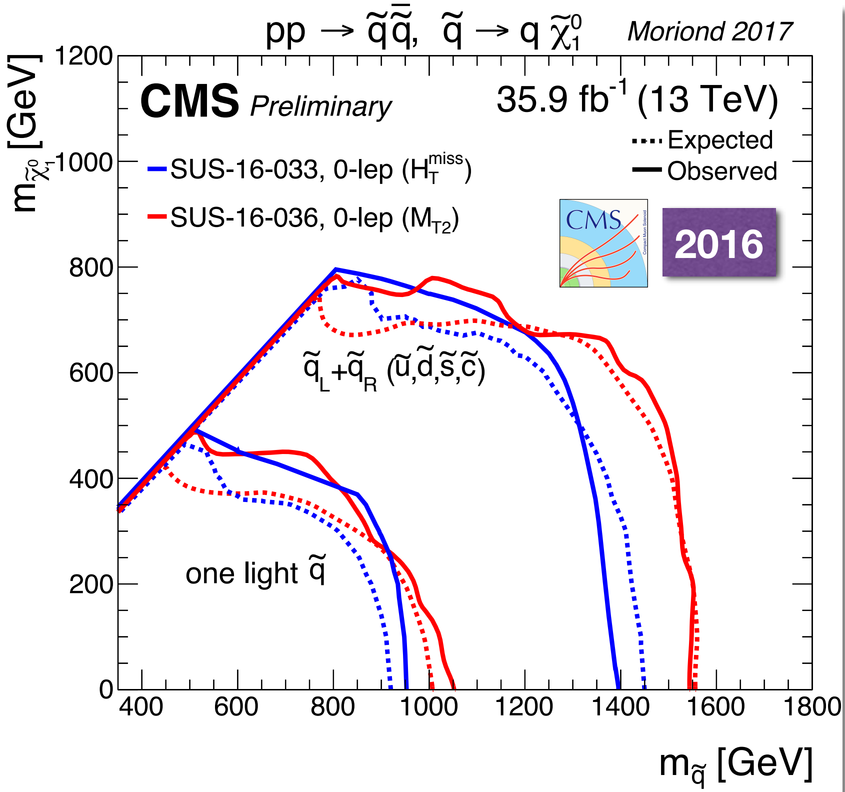


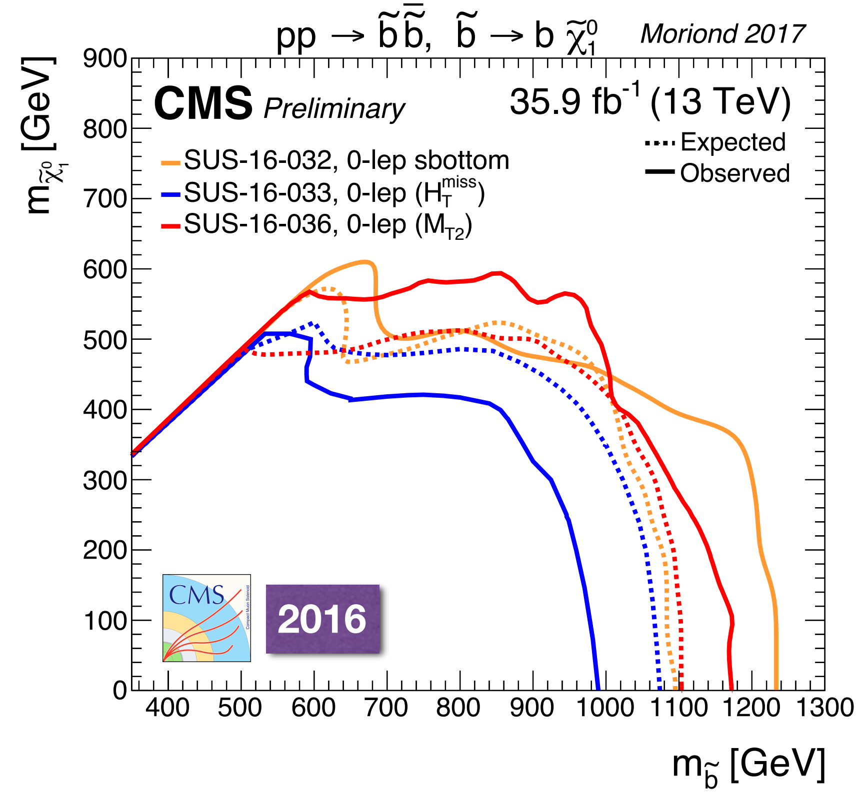


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Summer_Conferences_2017_36_fb_1

Squark Production

- All-hadronic analyses can also be used to set limits on light-generation squarks
  - Here limits reach 1.5 TeV, but only in the case of four degenerate squarks
  - If online light squark is allowed, the limits are still below 1 TeV





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Summer_Conferences_2017_36_fb_1

Not-So-Low Hanging Fruit

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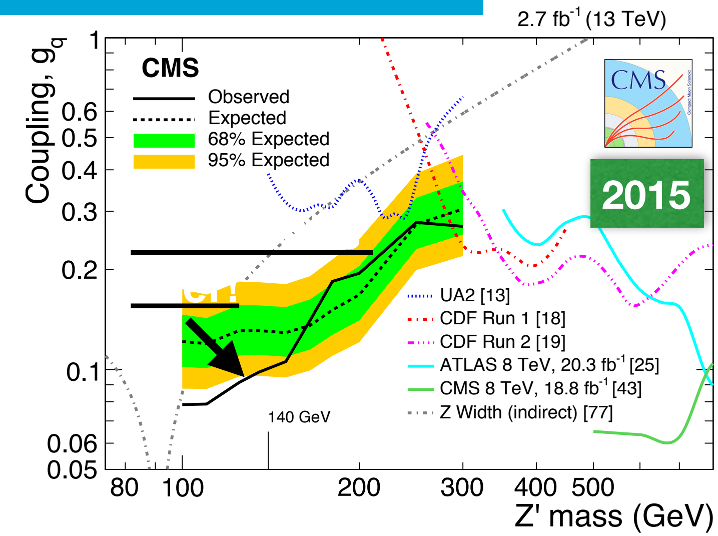
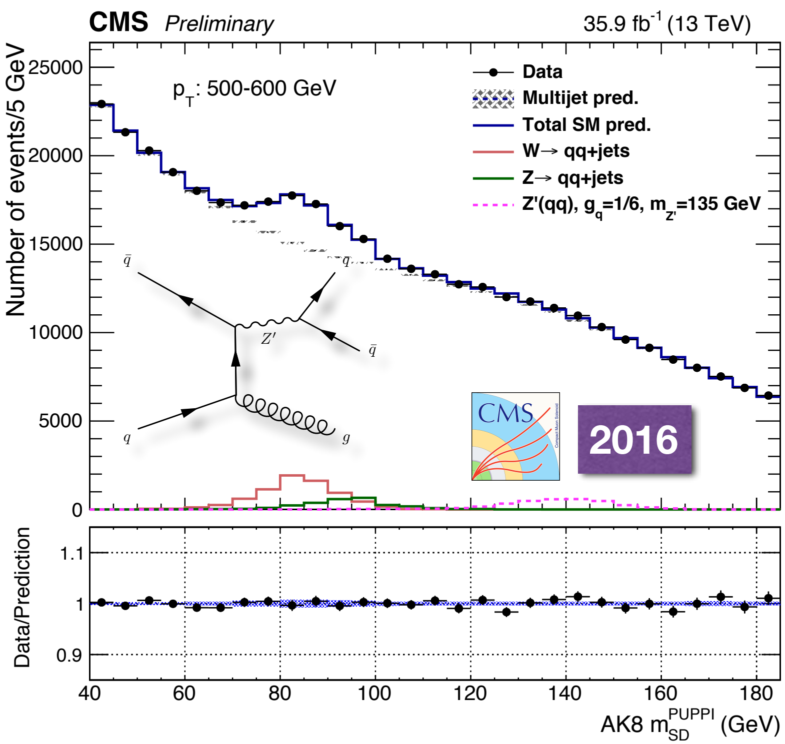
Trijets/jjγ as a Dijet Proxy

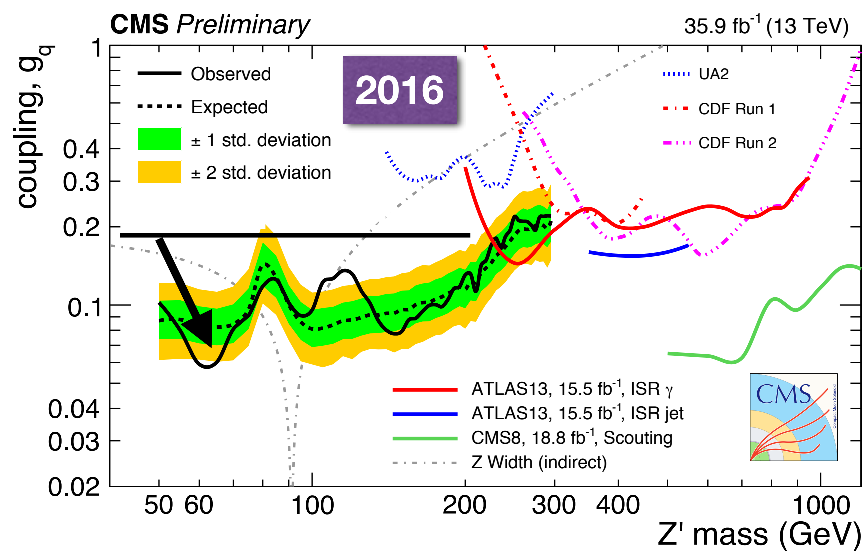
- ✦ Another way to look for low-mass dijets is to use photon or jet ISR to aid triggering and utilize jet substructure techniques to reconstruct boosted Z'
- ✦ Allows to lower the dijet mass reach to ~100 GeV, as demonstrated with the W/Z peak observation in CMS

CMS arXIv:1705.10532



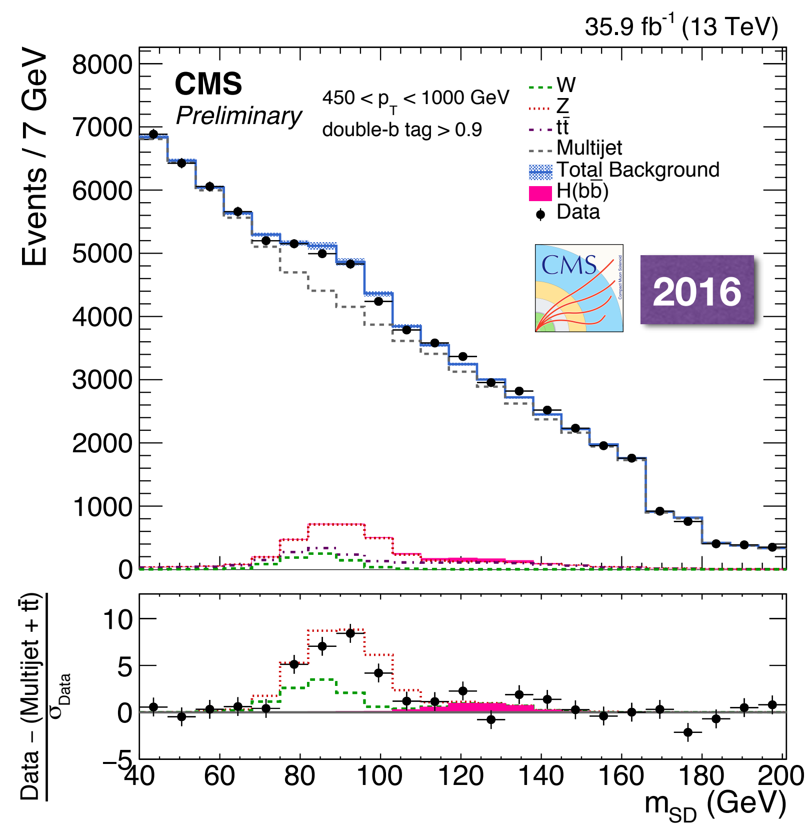


CMS PAS EXO-17-001

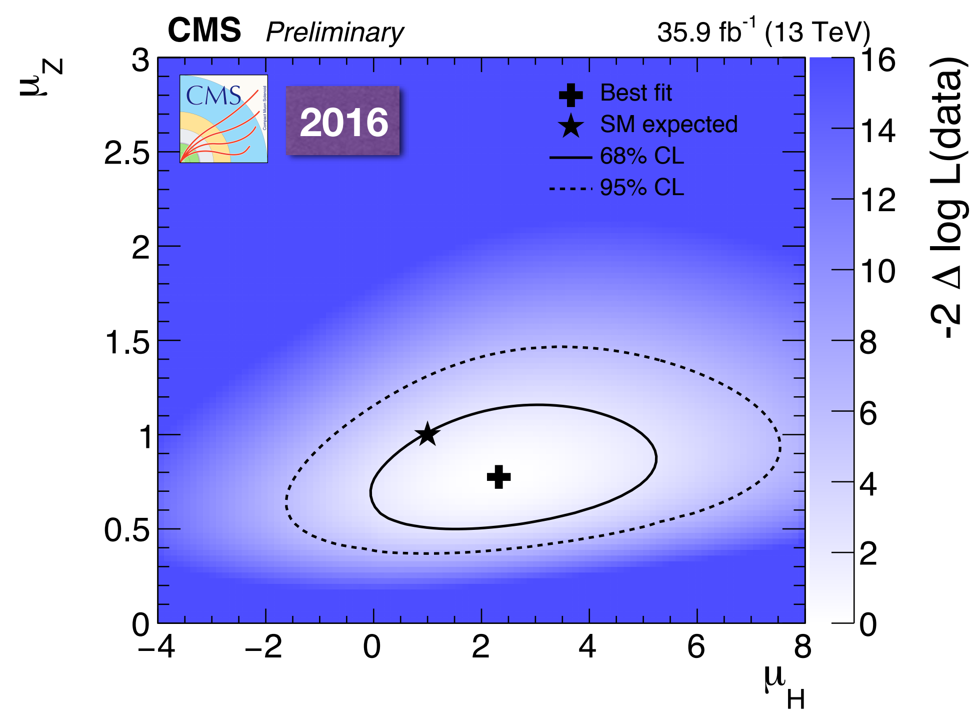


H(bb) in Boosted Channel

- Could use the same approach to look for H(bb) decays in b-tagged large-cone jet
- Currently limited by the trigger; work on specialized triggers is ongoing
- First results are very promising: achieved ~1σ sensitivity w/ 2016 data
- Ultimately would like to probe the H(gg) decay, which can't be seen otherwise

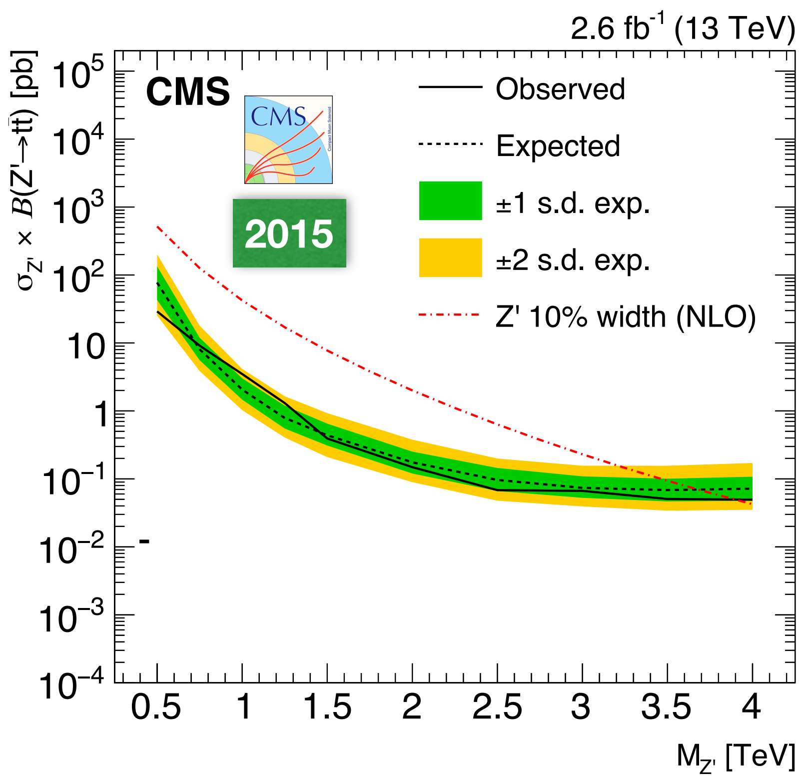


CMS PAS HIG-17-010

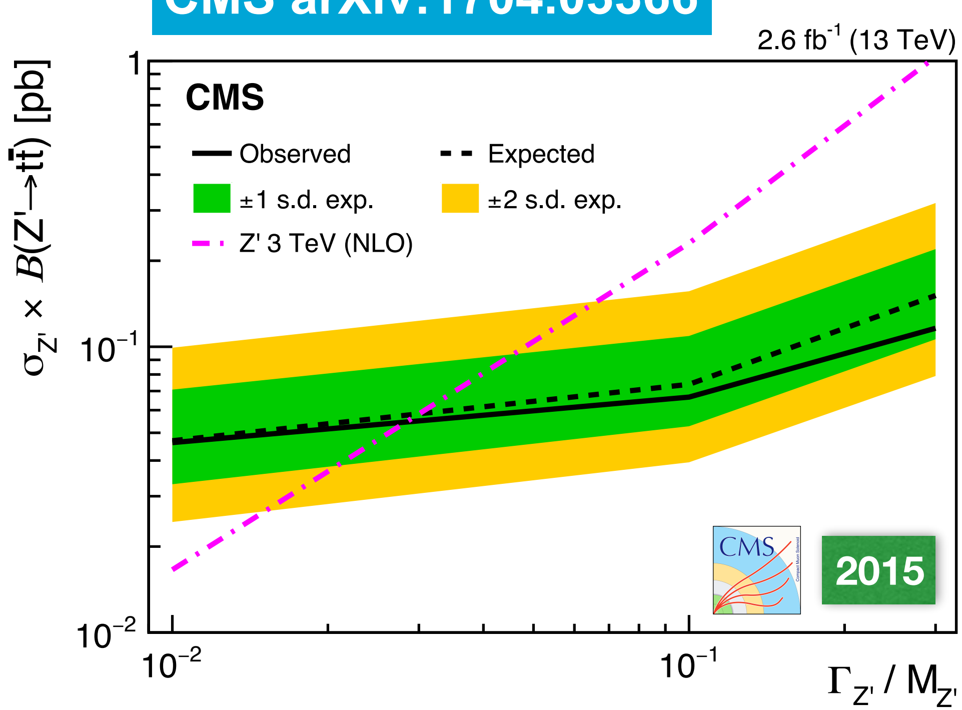


Searches for $t\bar{t}$ Resonances

- CMS search for $t\bar{t}$ resonances with 2015 data in the semileptonic and all-hadronic final states, using jet substructure
  - Limits on Z' with Γ/M = 0.1 at 3.9 TeV are set, as well as limits as a function of the width
  - Also limits on g_{KK} at 3.3 TeV are set @ 95% CL

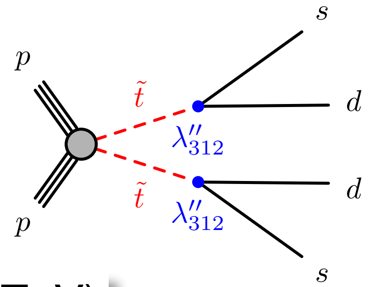


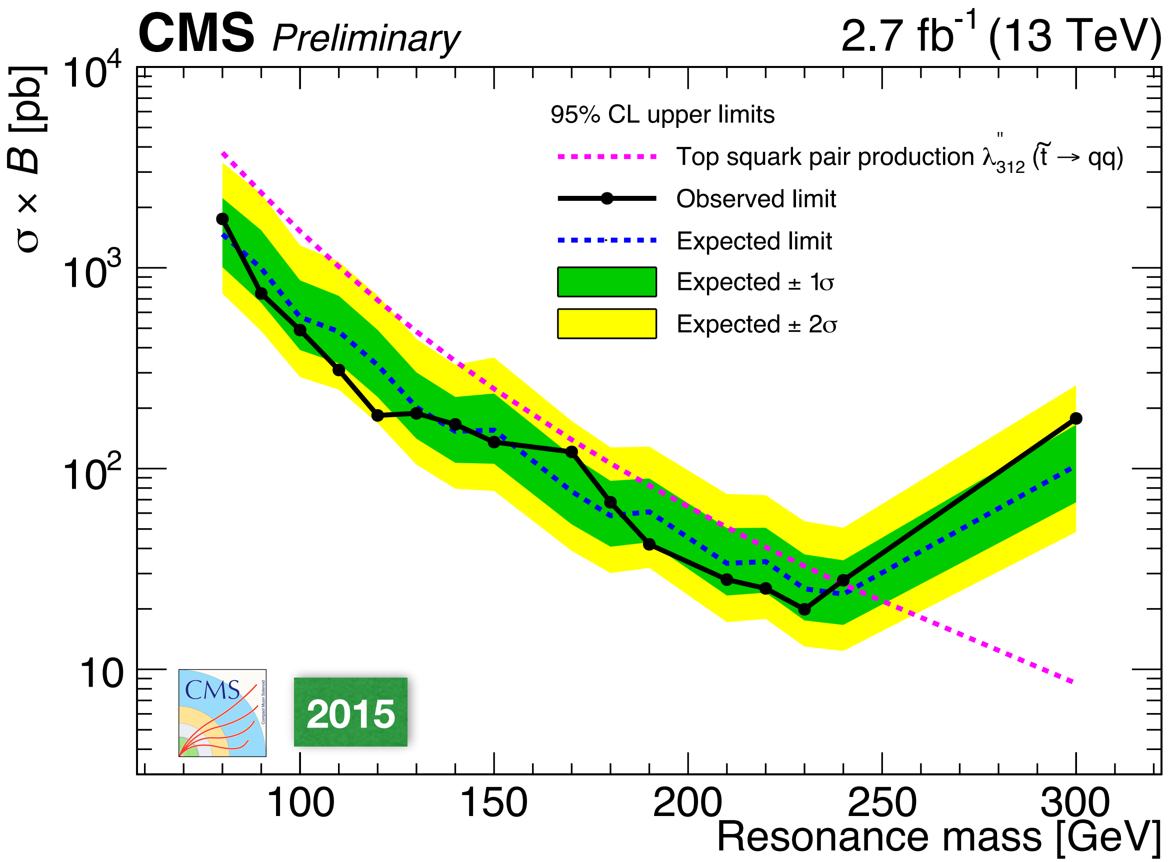
CMS arXiv:1704.03366



Pair-Produced Dijet Resonances

- A search for RPV top squark pair production with 4 jets and jjbb



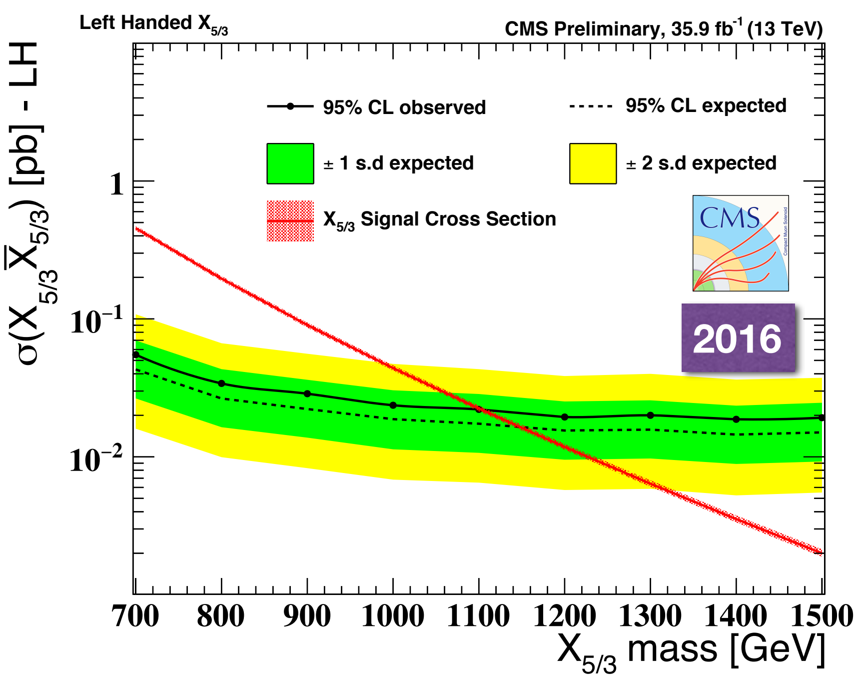


CMS PAS EXO-16-029

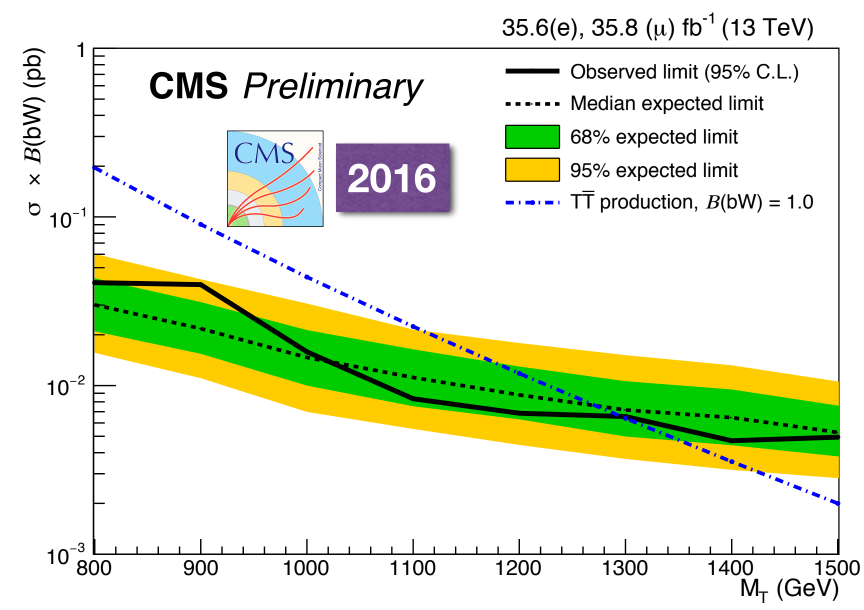
Pair-Produced VLQ Searches

- Classical T/Y pair production searches:
  - T5/3 pair production, with T → tW (SS dileptons and semileptonic)
  - T2/3 and Y4/3 production in the bWbW semileptonic channel
- Limits exceed similar ones set in Run 1 by ~500 GeV

CMS PAS B2G-16-019



CMS PAS B2G-17-003



Pair-Produced VLQ Searches

- Classical T/Y pair production searches:
  - T5/3 pair production, with T → tW (SS dileptons and semileptonic)
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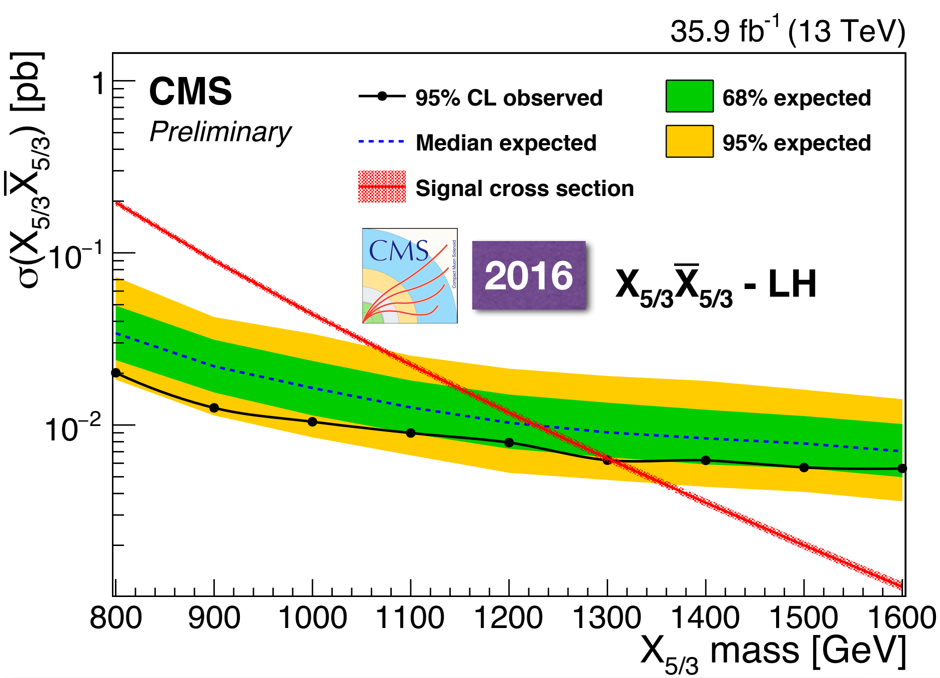
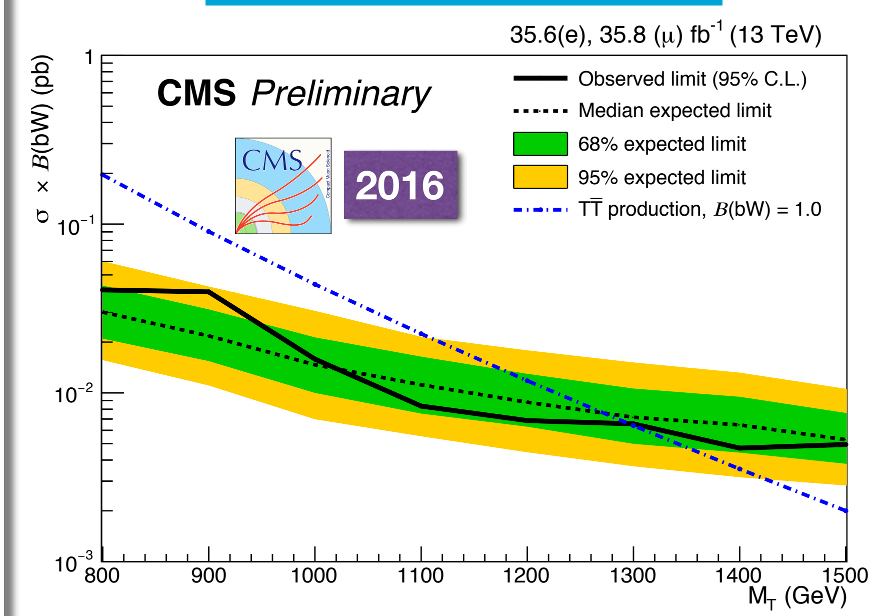
- Limits exceed similar ones set in Run 1 by ~500 GeV

CMS PAS B2G-17-008

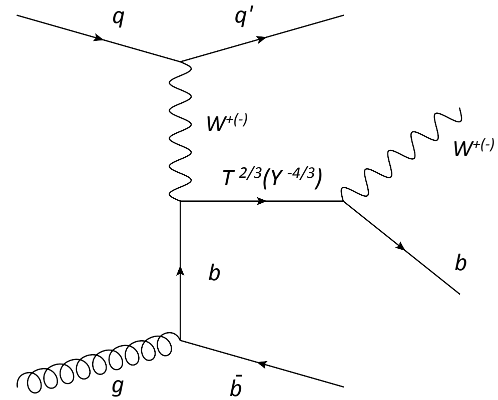


CMS PAS B2G-17-003

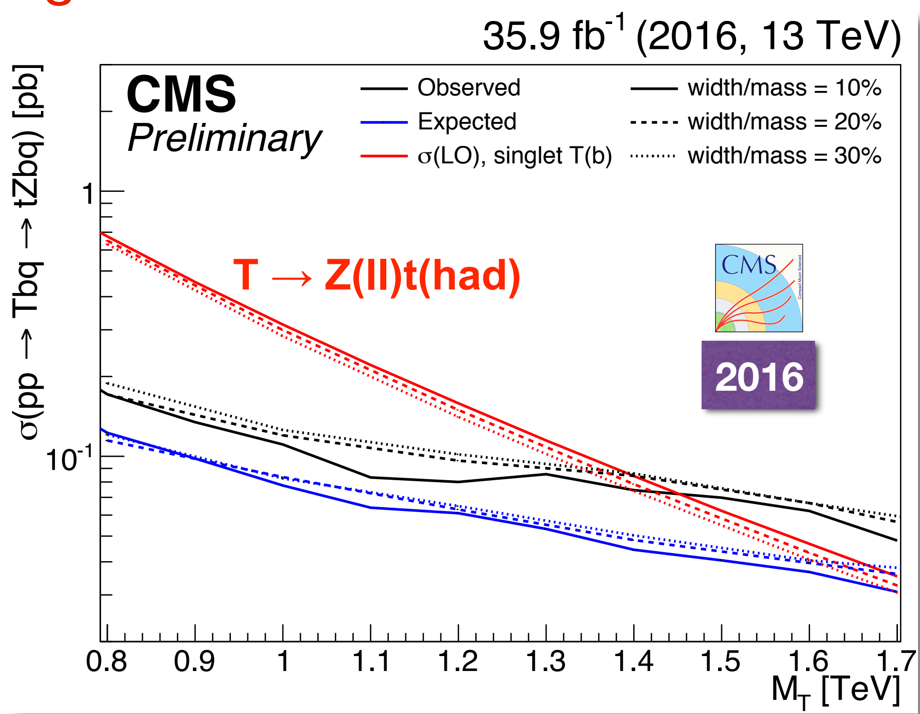


Single VLQ Production

- ✦ Several VLQ searches with new data, including singly, EW produced VLQs in Wb, Zt, Zb channels
  - ◉ Limits are set on the VLQ mass for a fixed VLQ-W-b or VLQ-Z-t coupling/width or on the coupling as a function of the VLQ mass

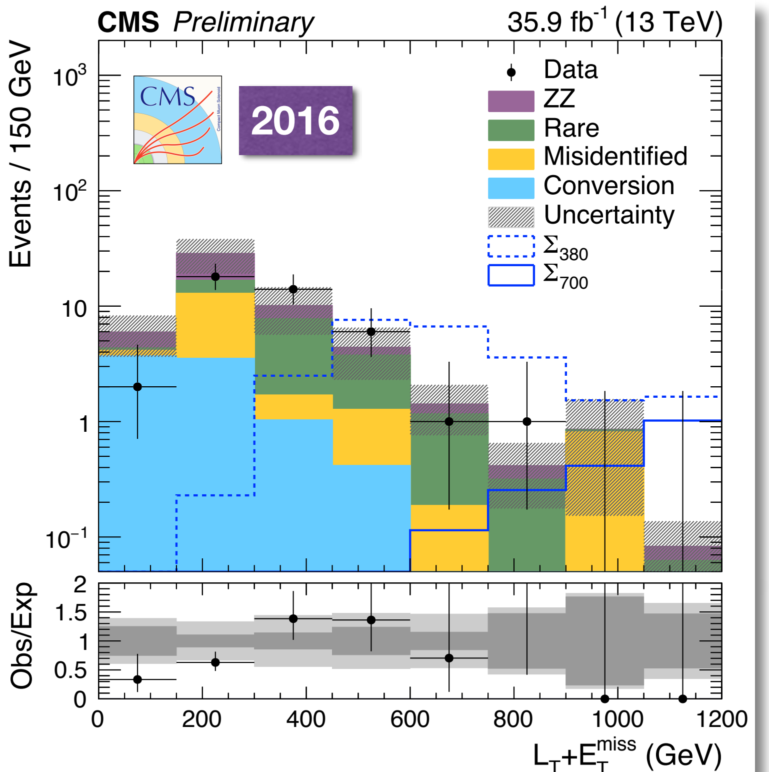


CMS PAS B2G-17-007

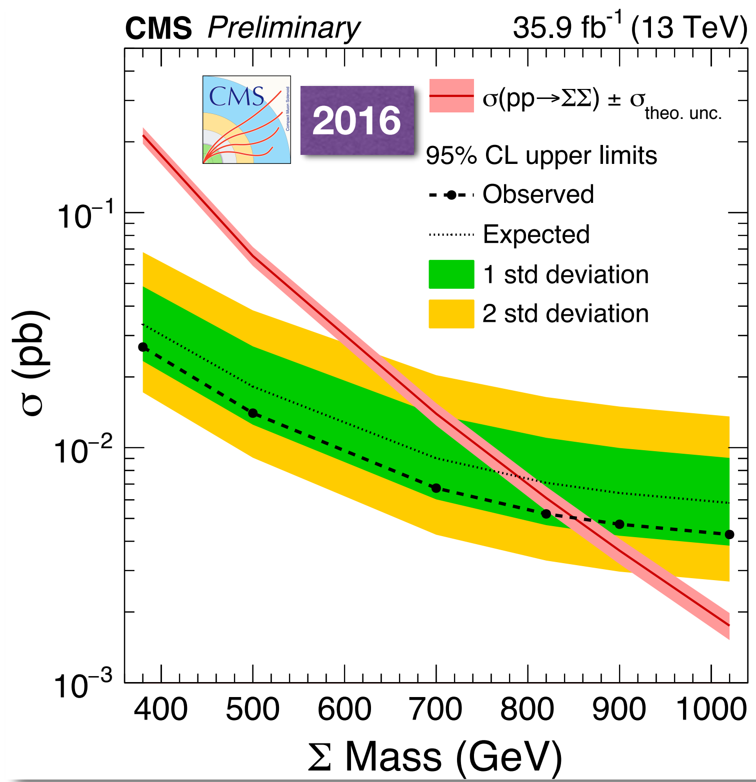


Type III Seesaw Search

- Search for heavy fermions $\Sigma^{\pm}$ and Σ^{0} in Type III seesaw models
  - Drell-Yan pair production
  - Decay: $\Sigma^{\pm} \to W^{\pm}\nu$, $Zl^{\pm}$, $Hl^{\pm}$; $\Sigma^{0} \to W^{\pm}l^{\mp}$, $Z\nu$, $H\nu$
- Consider all 27 final states via multilepton search (3 or more e, μ)



CMS PAS EXO-17-006

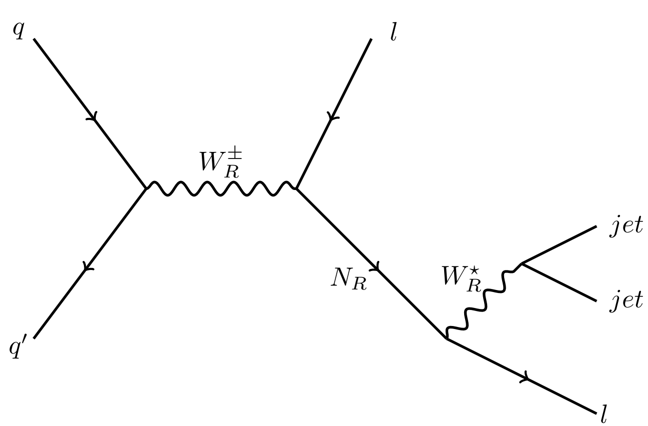


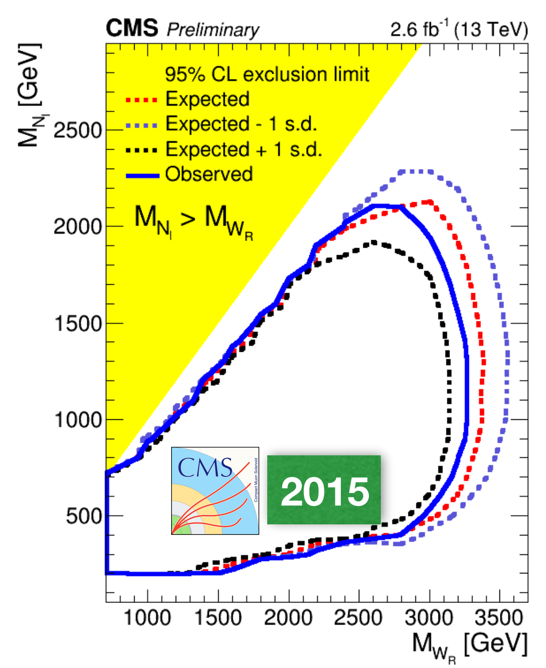
Majorana Neutrino Search

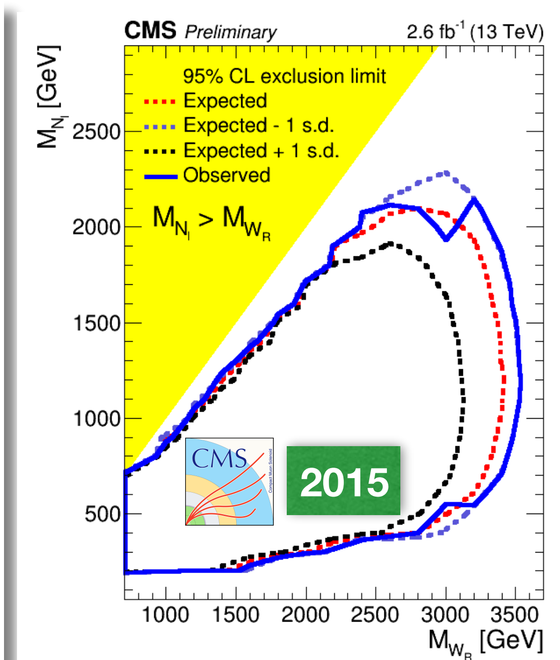
- ✦ Classical search in dilepton + dijet channel; a slight excess was seen in Run 1, but not confirmed w/ 13 TeV data
  - ◉ Stringent limits on heavy electron and muon neutrinos are set

CMS PAS EXO-16-045

$$W_R \to \ell_1 \mathrm{N}_\ell \to \ell_1 \ell_2 W_R^* \to \ell_1 \ell_2 q \bar{q}'.$$

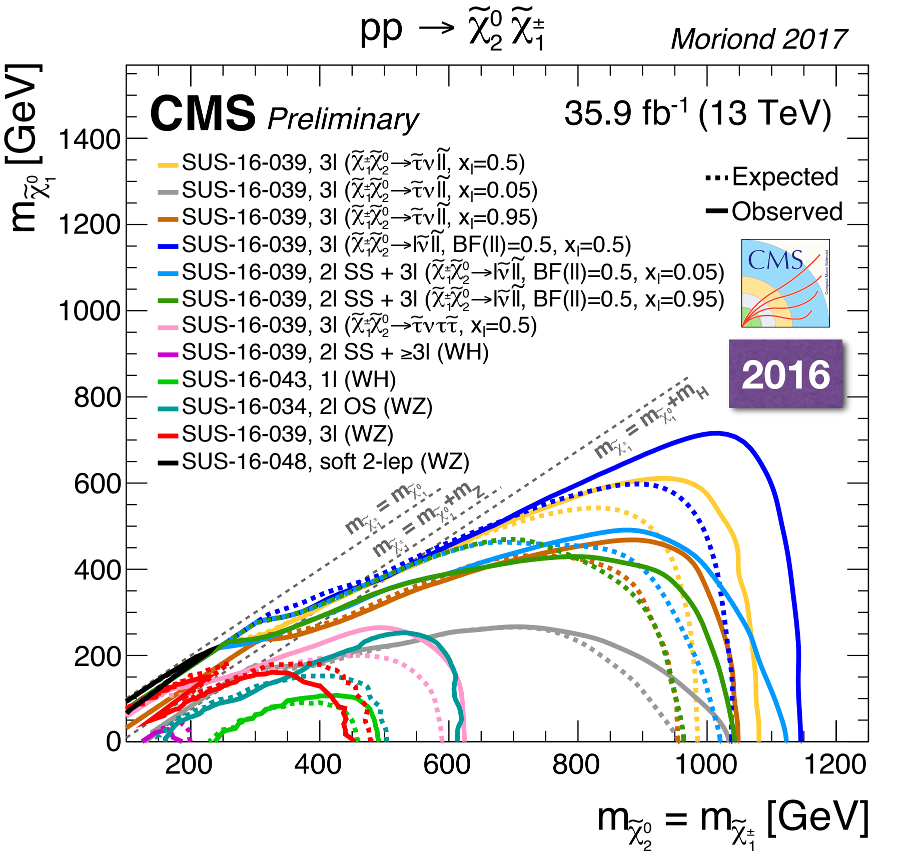


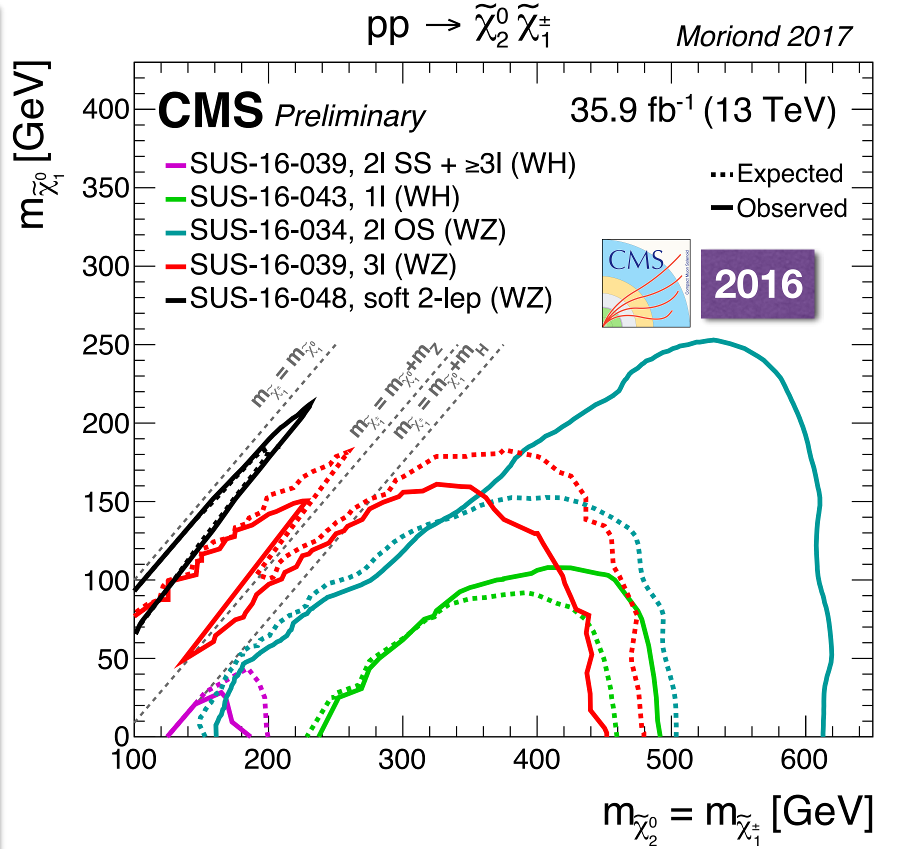




SUSY: Electroweak Production

✦ Variety of channels and signatures, including the decays via WZ/WH

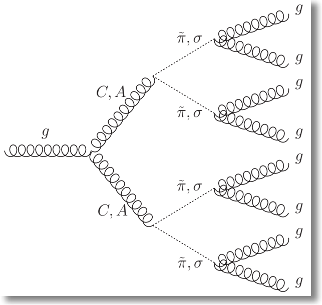


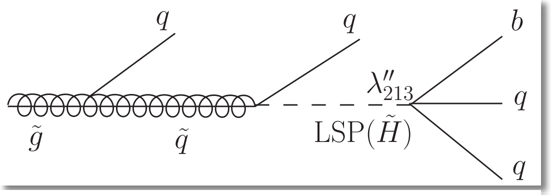


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Summer_Conferences_2017_36_fb_1

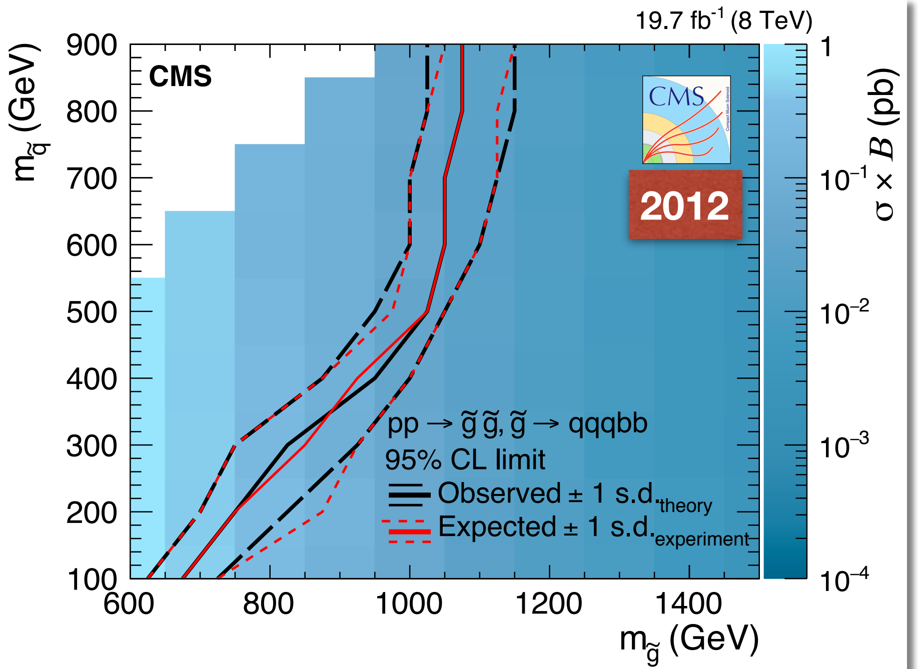
Multijet Searches

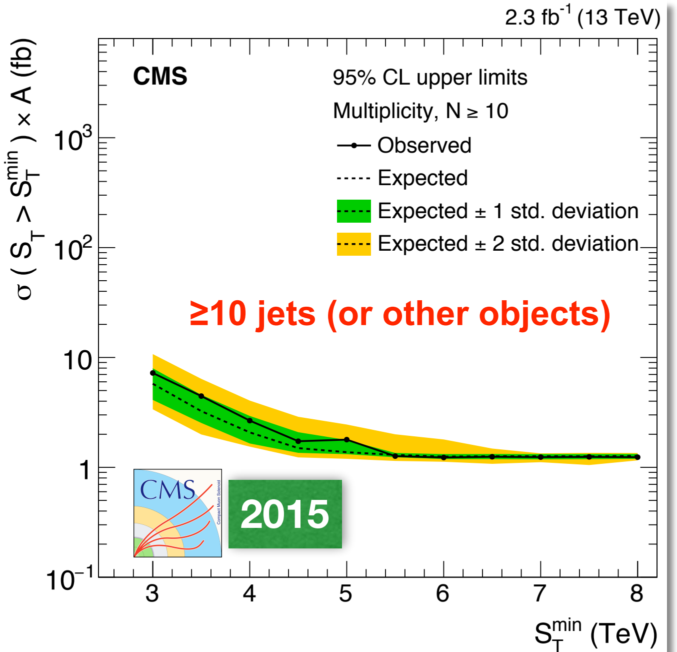
- Traditionally used to probe semiclassical black holes, also provide strong limits on high-multiplicity signatures often expected to come from RPV SUSY decays, axigluons and other strong dynamics objects, quantum gravity
- Often some of the jets come from b quarks





CMS arXiv:1608.01224





CMS arXiv:1705.01403

High-Hanging Fruit

Diboson Searches

- Many new physics models predict diboson resonances
- If an excess is seen in one channel (e.g. $\gamma\gamma$), it has to be present in coupled channels (ZZ, Zγ, possibly WW), and the relative strengths would allow to understand the SU(2) structure of the underlying theory
- Thus searches in VV, Vγ, VH, HH channels are an important part of the LHC physics program, and is also valuable for SM physics, VBS, and TGC studies
- The HH studies are going to ultimately lead to the constraints of the Higgs boson self-coupling

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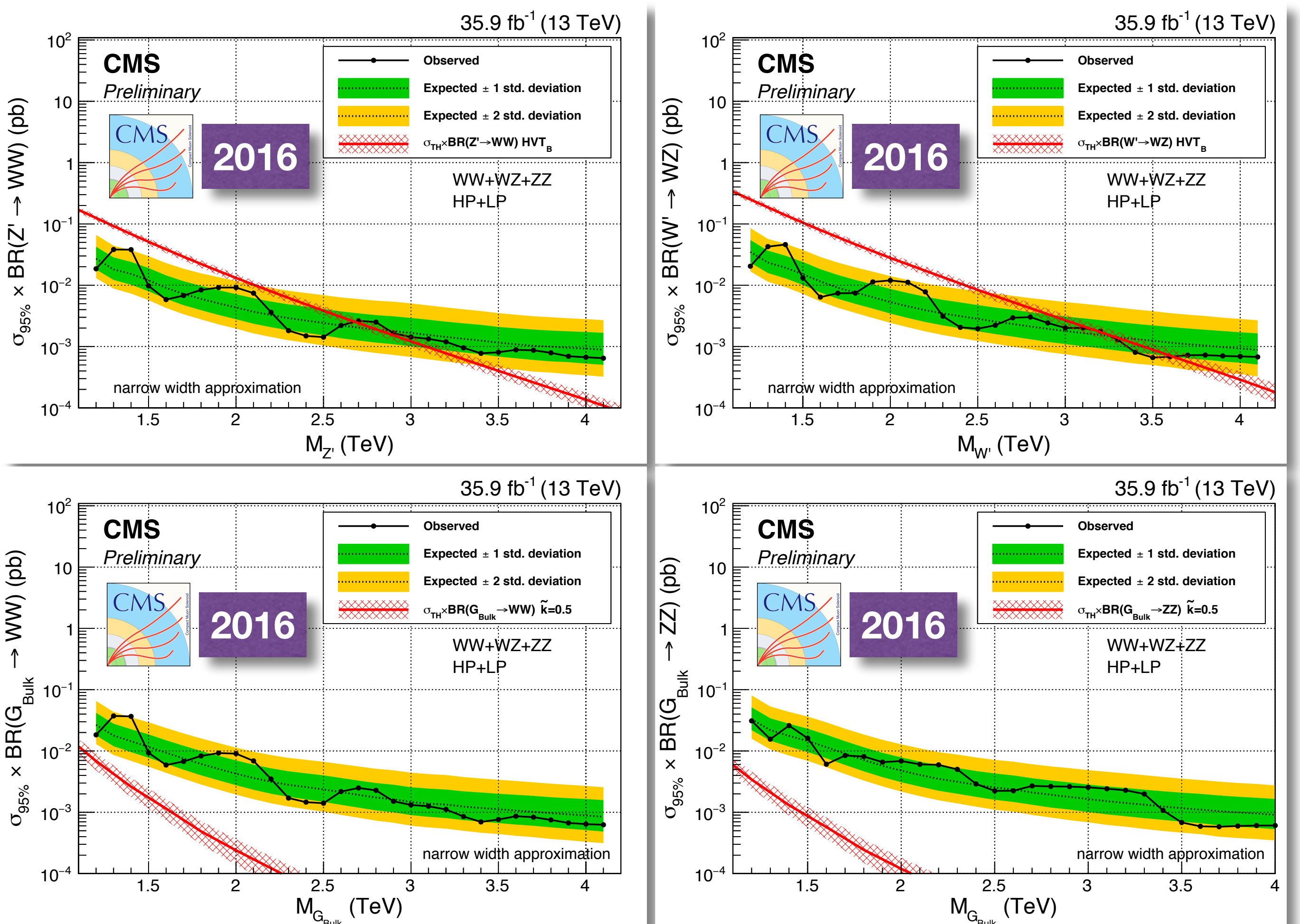
VV All-Hadronic Searches

- Searches for WW, WZ, and ZZ resonances
  - The 2 TeV bump is back, after disappearing for a year

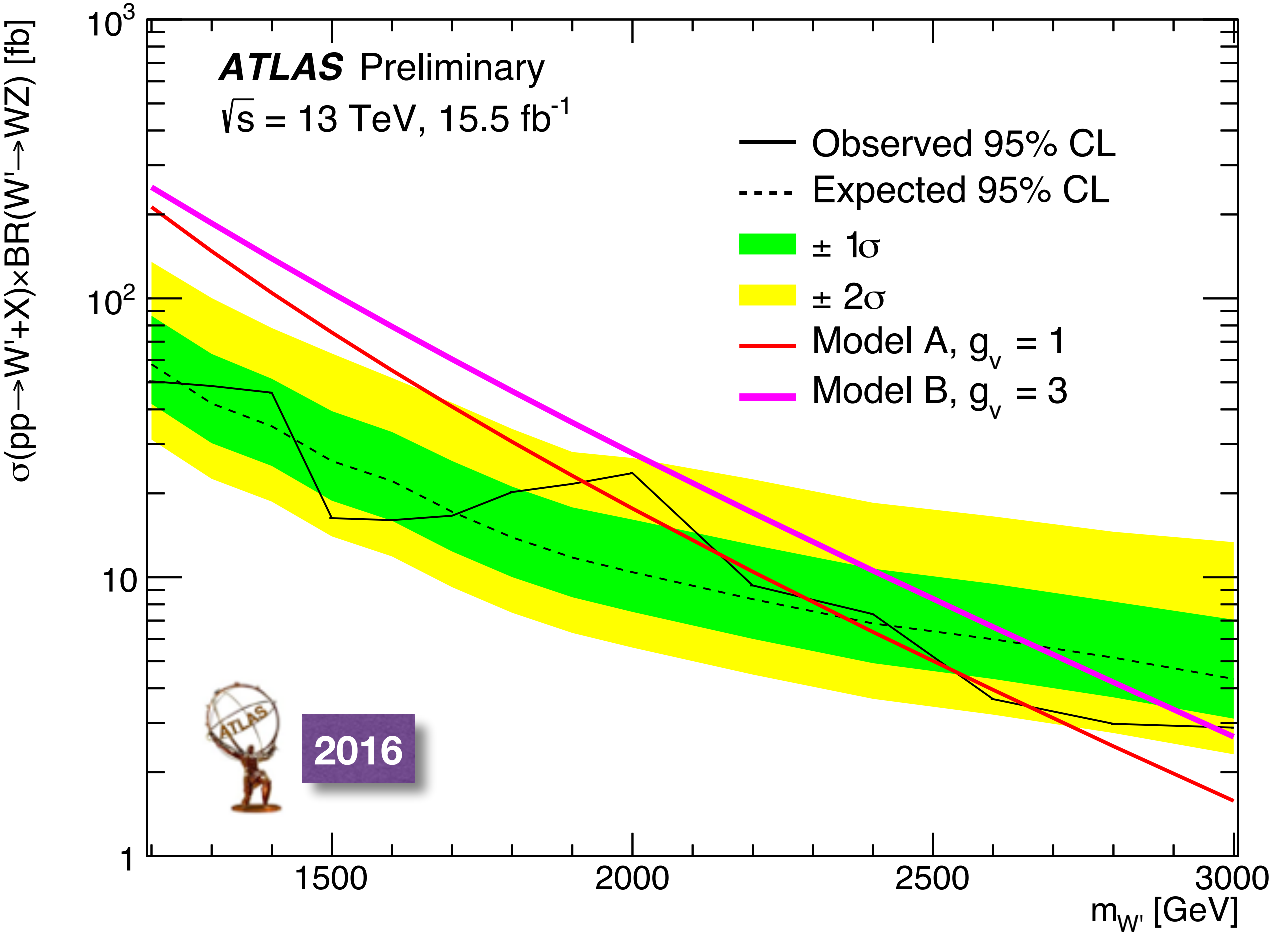
CMS PAS B2G-17-001



VV All-Hadronic (cont'd)

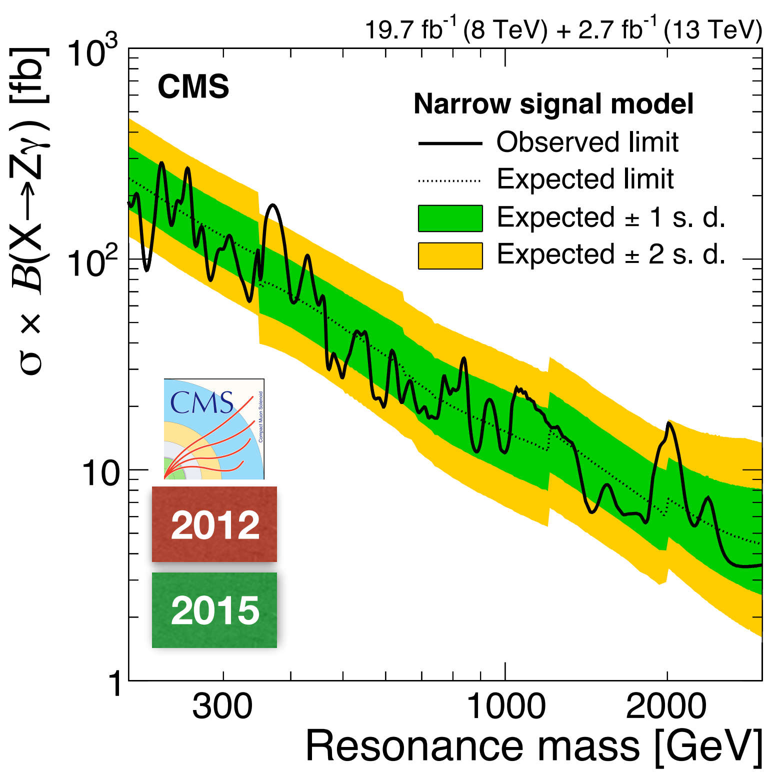
- And there is a slight excess in the all-hadronic channel at 2 TeV in ATLAS as well
  - Curiously, both collaborations see it only in the all-hadronic channel

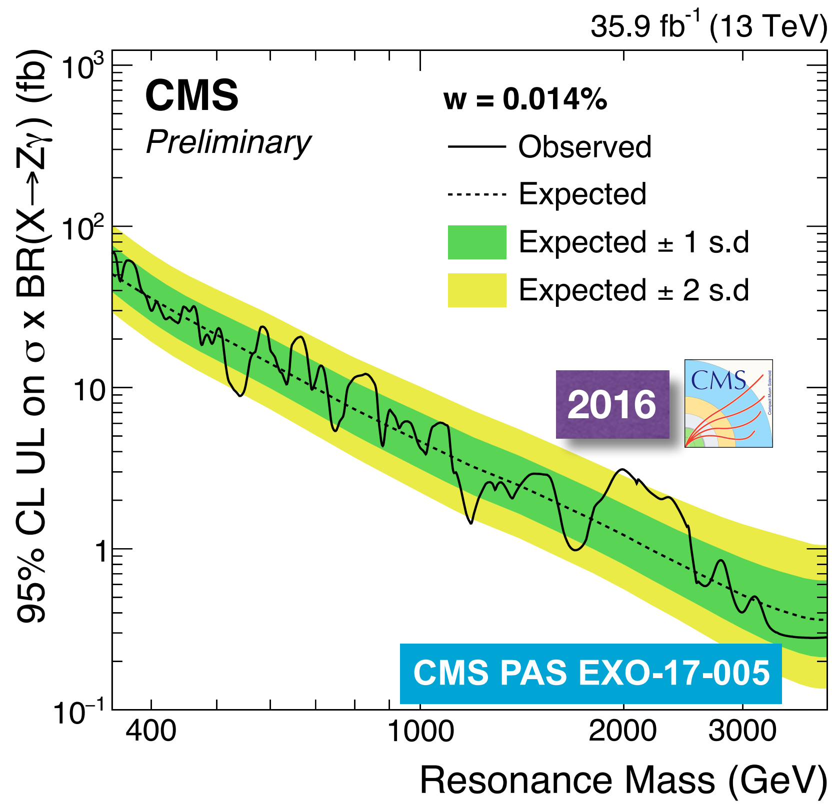
ATLAS CONF-2016-055



Zγ Searches

- Two types of searches pursued:
  - Leptonic search Z(ll)γ - best at low mass
  - Boosted hadronic search Z("j")γ, w/ categorization according to the "j" b tag (CMS) - best at high masses (> 1.5 TeV)
  - An excess seen around 2 TeV (!) in both 2015 and 2016 data





CMS arXiv:1612.09516

Zγ Searches

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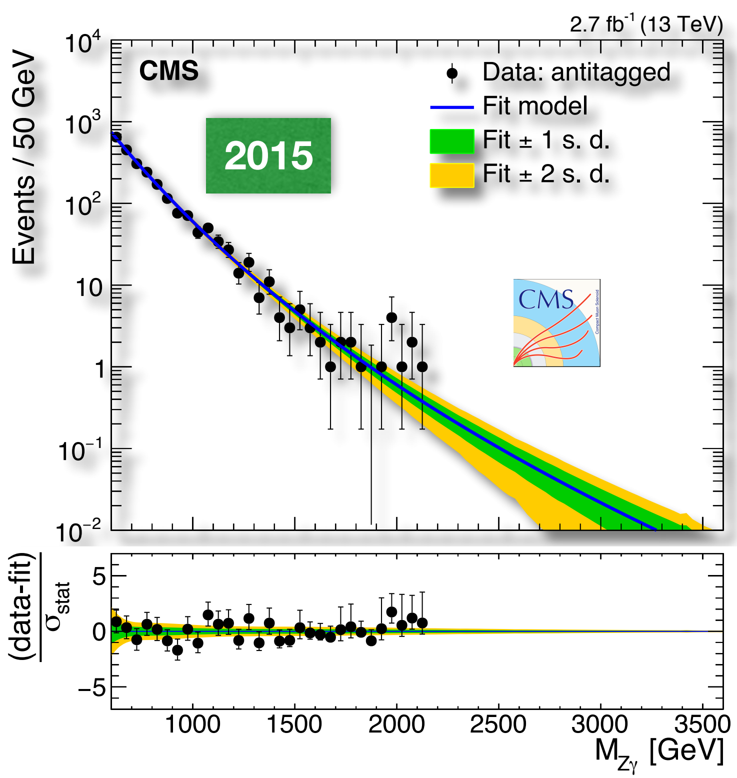
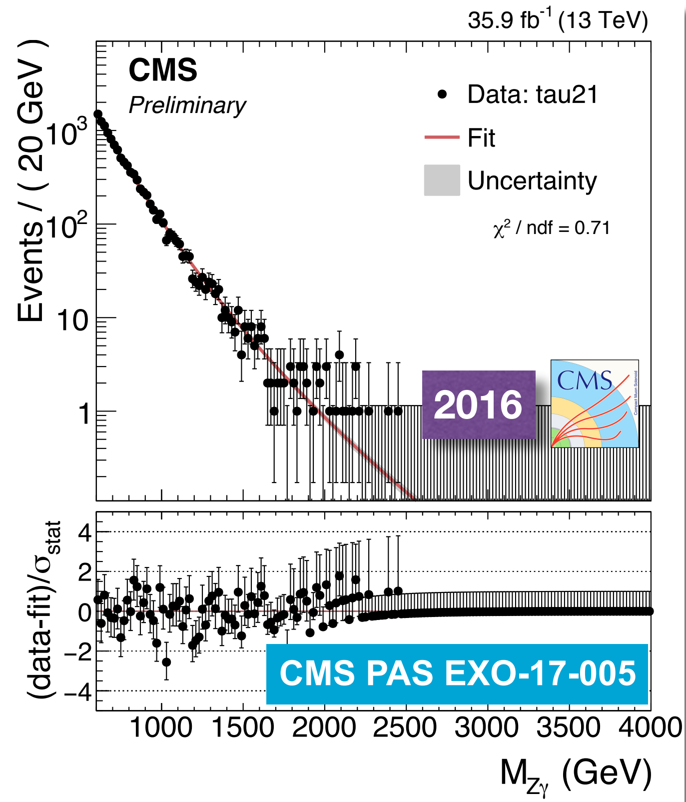
CMS arXiv:1612.09516

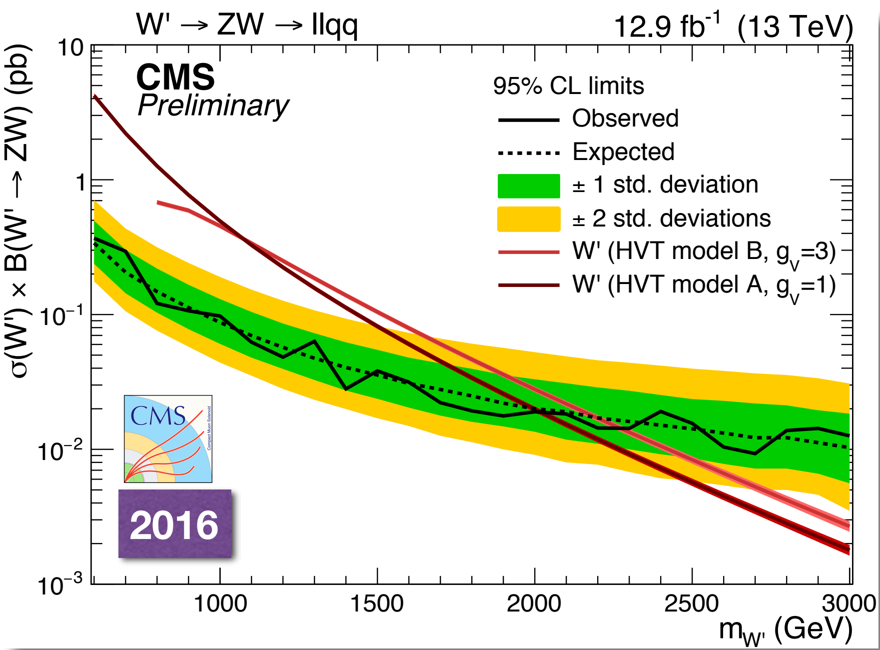




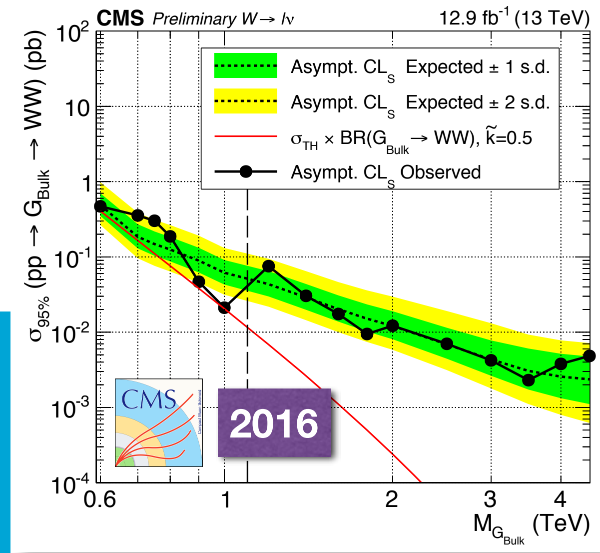
VV Semileptonic Searches

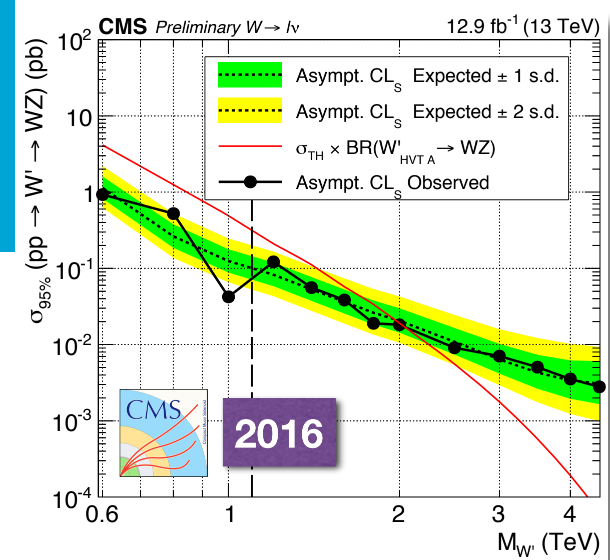
- Most recent CMS WW/WZ search in the lvjj channel (jj form a jet w/ substructure) and WZ in the lljj channel
  - No evidence for statistically significant excess in the 0.6-4.5 TeV range
  - See absolutely no excess at 2 TeV with 1/3 of the full 2016 data set

CMS PAS B2G-16-022



CMS PAS B2G-16-020

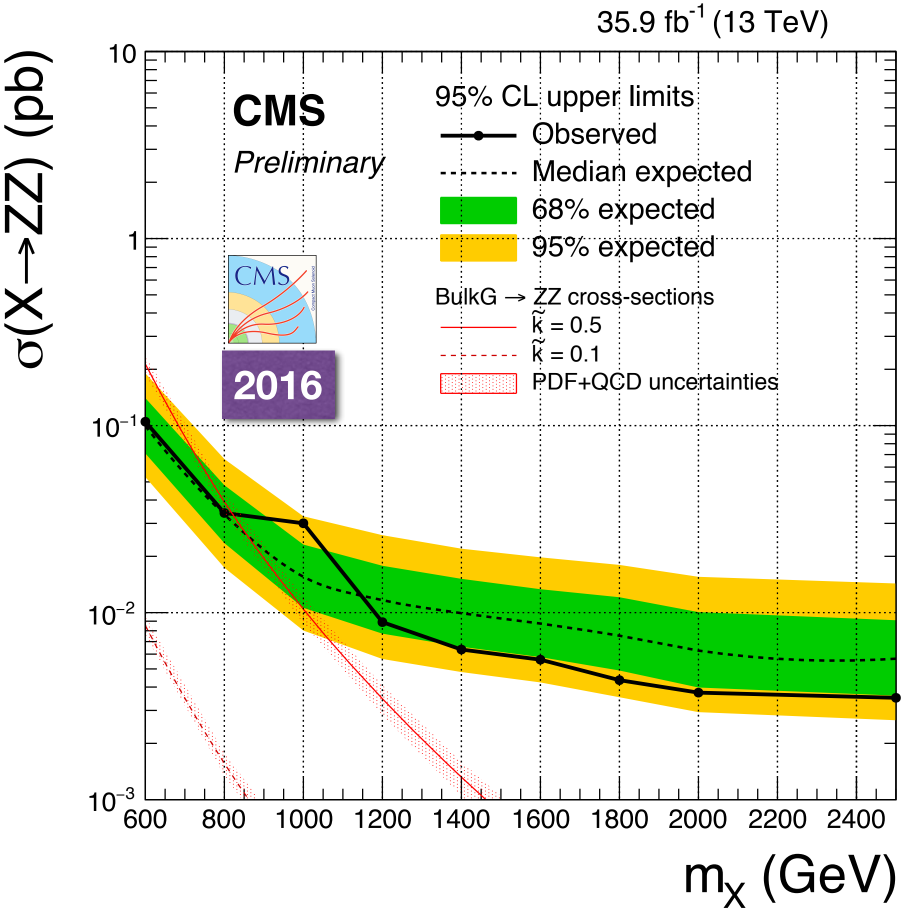




ZZ Leptonic Search

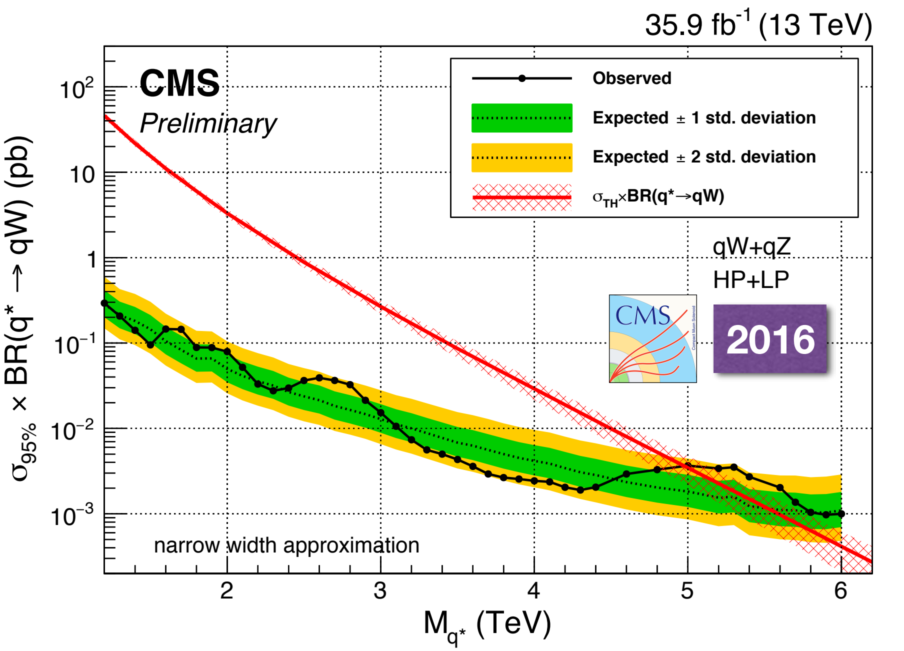
- ✦ Search for ZZ resonances in the 2l2v channel also doesn't show anything exciting at 2 TeV (or other masses)

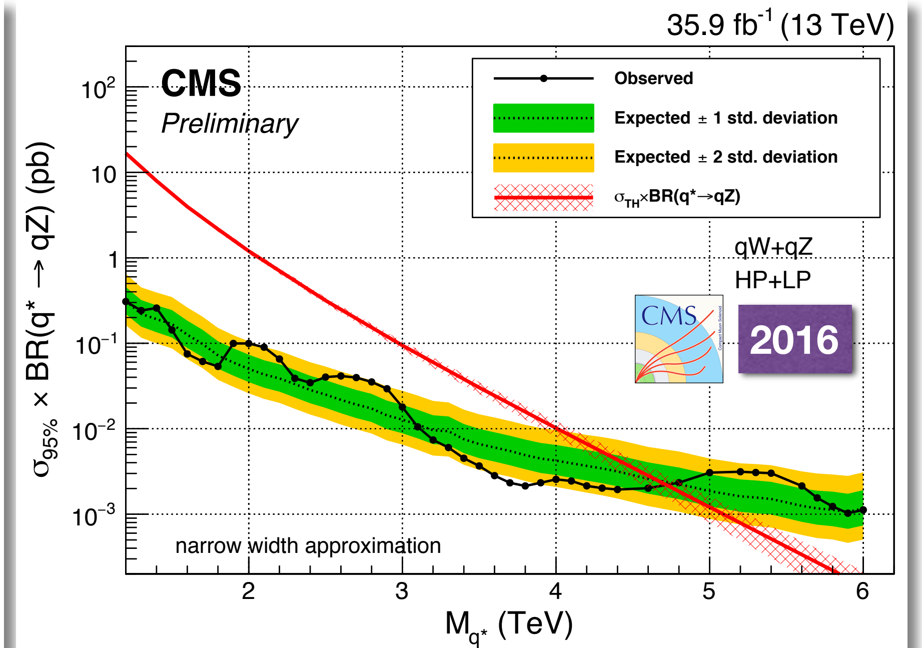
CMS PAS B2G-16-023



Search for Vq Resonances

- Could also interpret the all-hadronic search as a search for Vq resonances (q*), with limits reaching 5 TeV

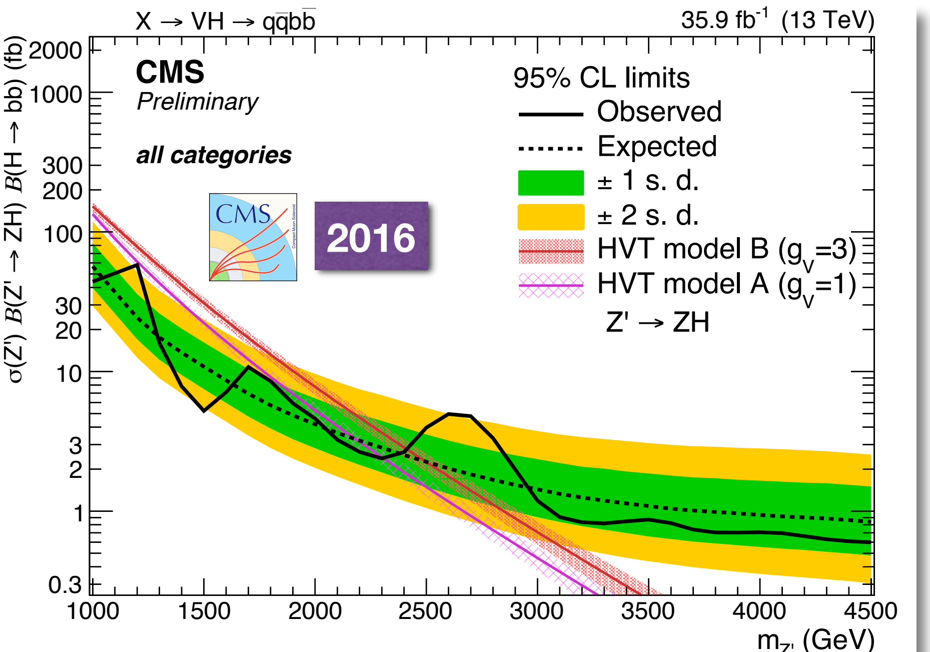


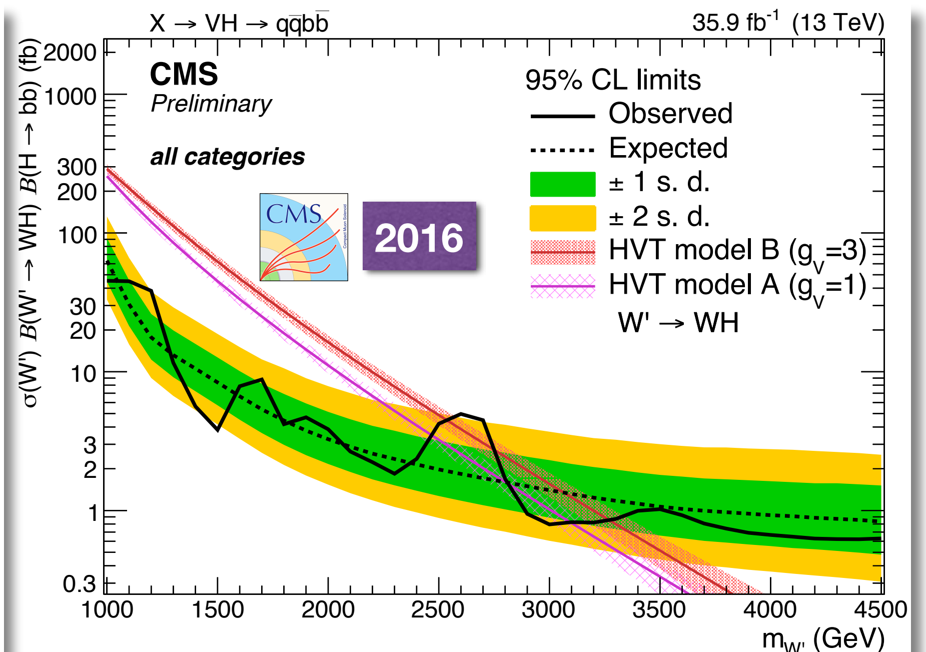


CMS PAS B2G-17-001

Searches for VH resonances

- ATLAS's 3σ bump at 3 TeV is not confirmed by CMS (and neither is the 2.6 TeV CMS bump by ATLAS)
  - Doesn't look like any new physics is hiding in this channel



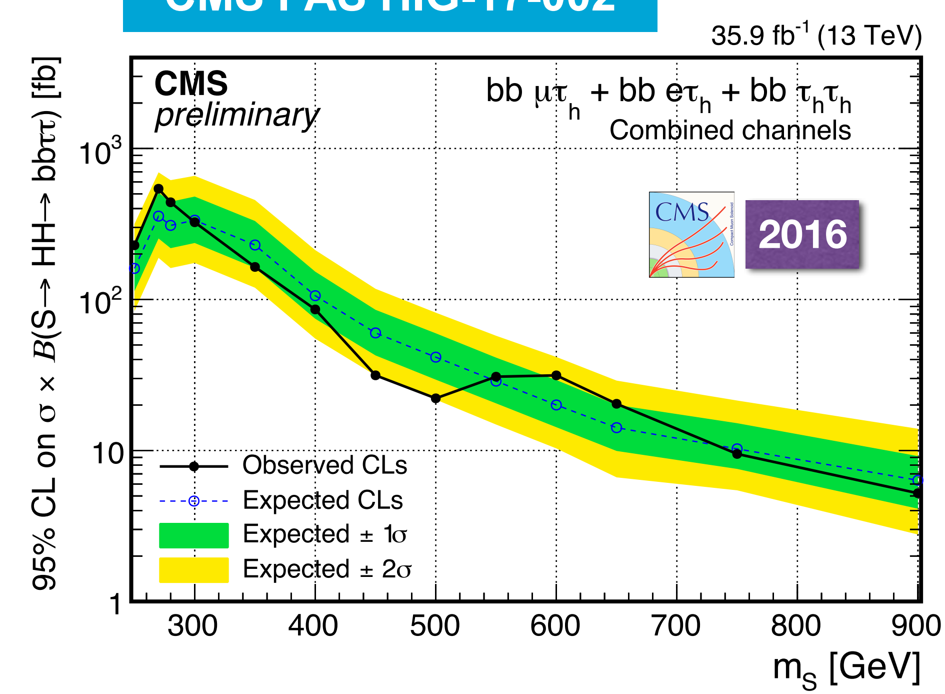


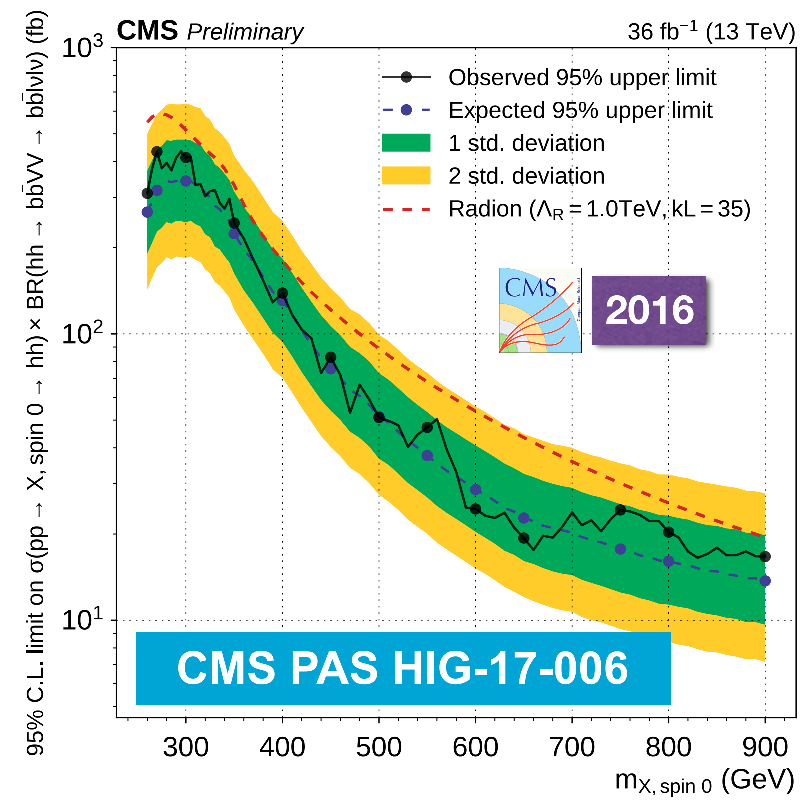
CMS PAS B2G-17-002

HH Resonance Searches

- Two new, low-mass CMS HH resonance searches: in the bb$\tau\tau$ and bbWW channels:
  - bb$\tau\tau$ search is performed in 3 channels: $\tau_e\tau_h$, $\tau_e\tau_\mu$, $\tau_h\tau_h$; in boosted and resolved categories and sets MI limits on a narrow spin-0 resonance
  - bbWW search is done in the bblvlv channel and interpreted in the narrow spin-0 and spin-2 resonance models

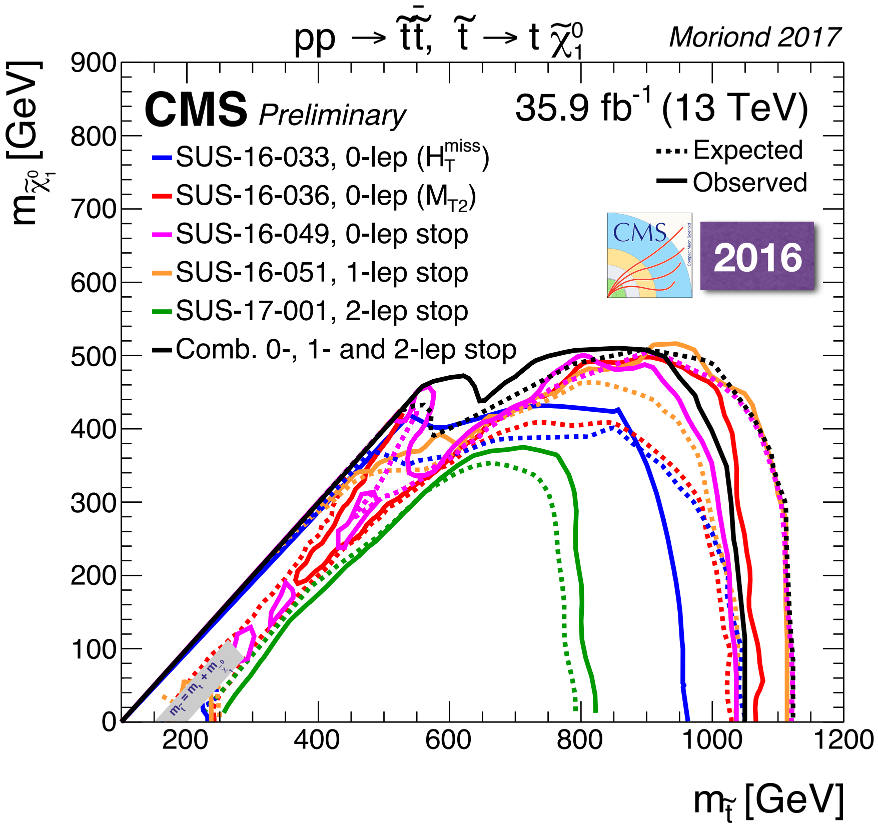
CMS PAS HIG-17-002

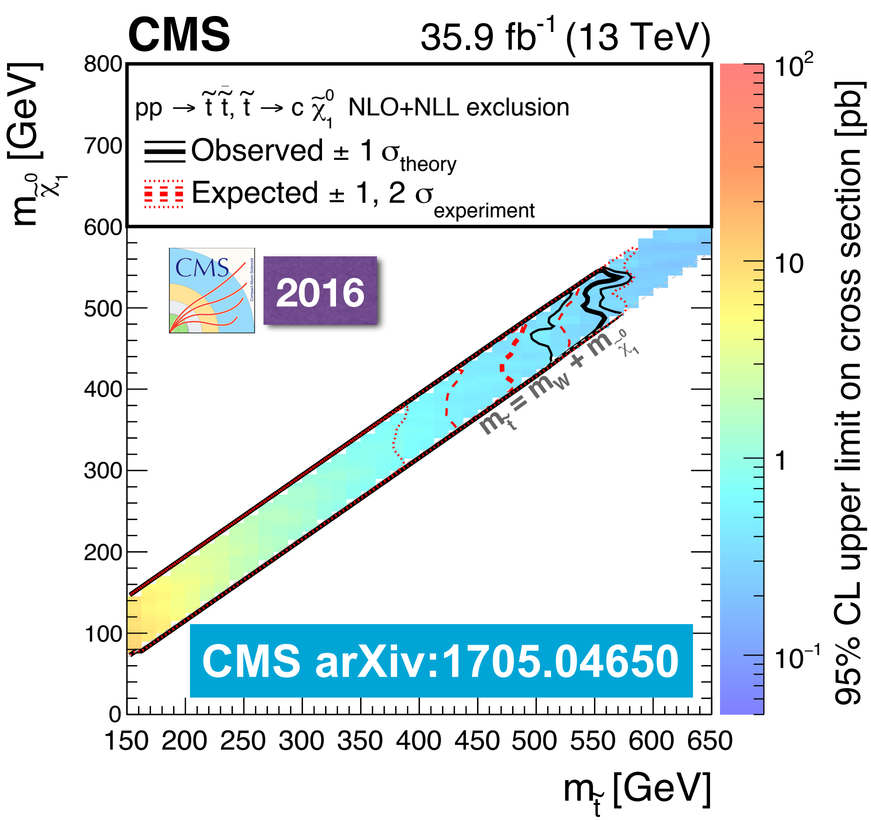




Top Squark Searches

- Direct top squark searches are fairly optimized for this particular SUSY signature and also explore 3- and 4-body decays, as well as FCNC ones

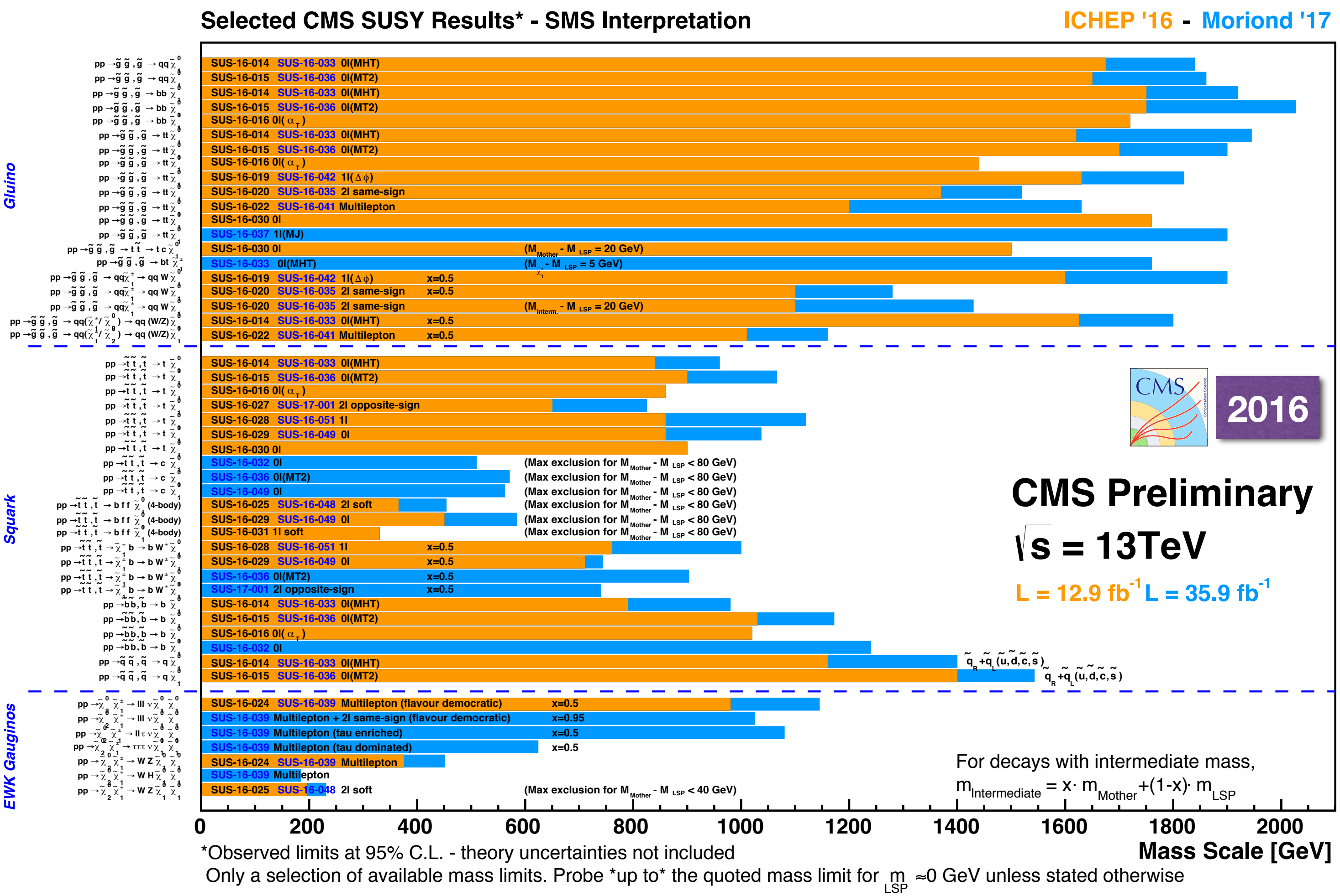




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Summer_Conferences_2017_36_fb_1

Supersymmetry or Supercemetry?

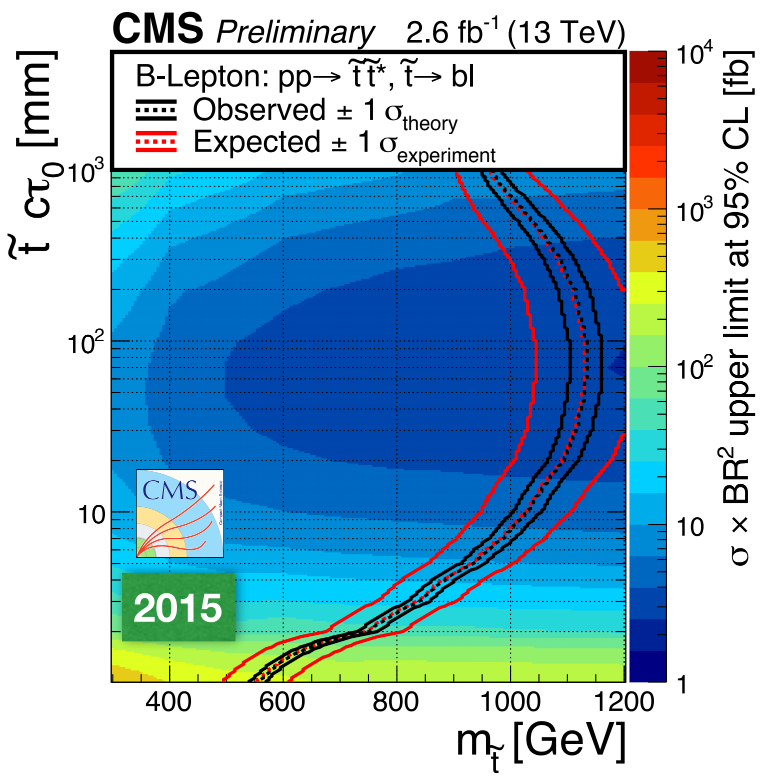
- 2016 data set put significant dent into natural SUSY landscape, particularly in EW gauging sector



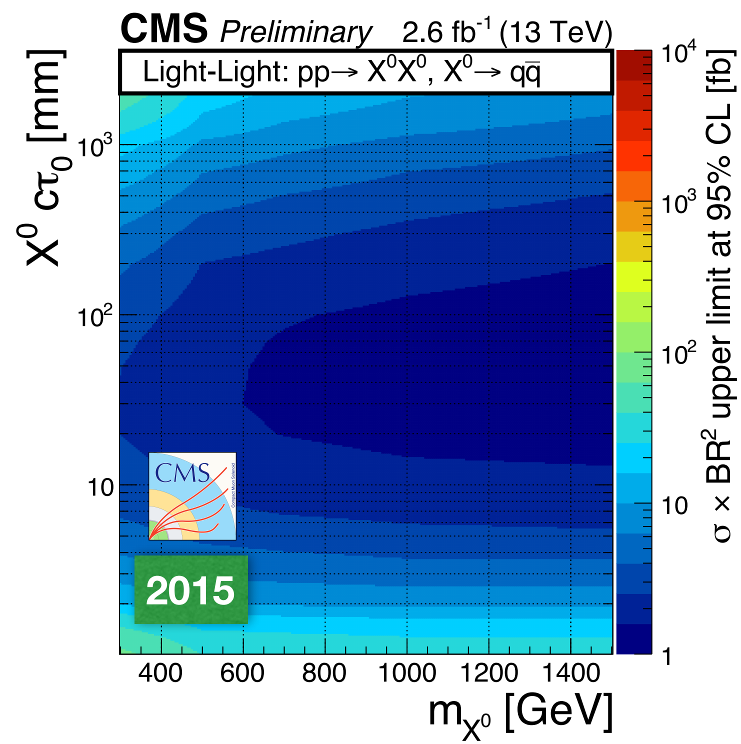

Out-of-Reach
Fruit?

Search for Displaced Jets

- CMS search based on dedicated triggers requiring at least two jets with low number of prompt tracks
- Special MVA displaced jet tagging based on the angular and displacement information for the tracks
- Signal benchmarks - pair production of top squarks with RPV decays into b quarks and leptons and pair-produced resonances decaying to dijets

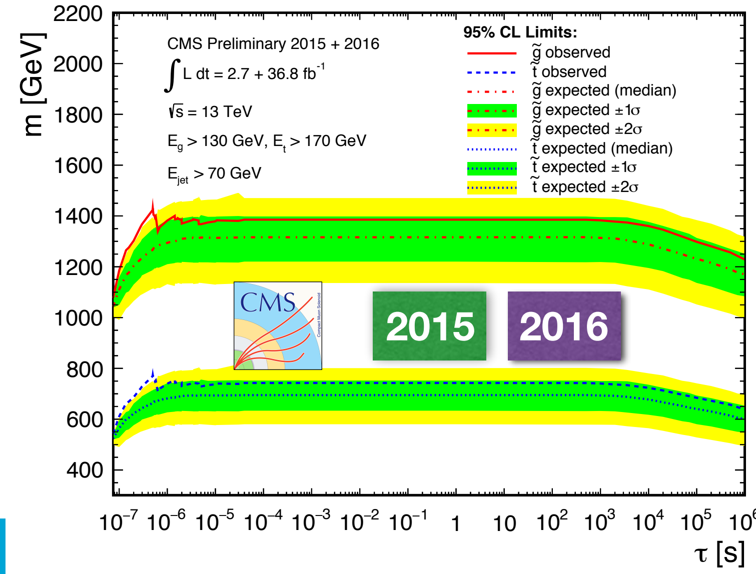


CMS PAS EXO-16-003

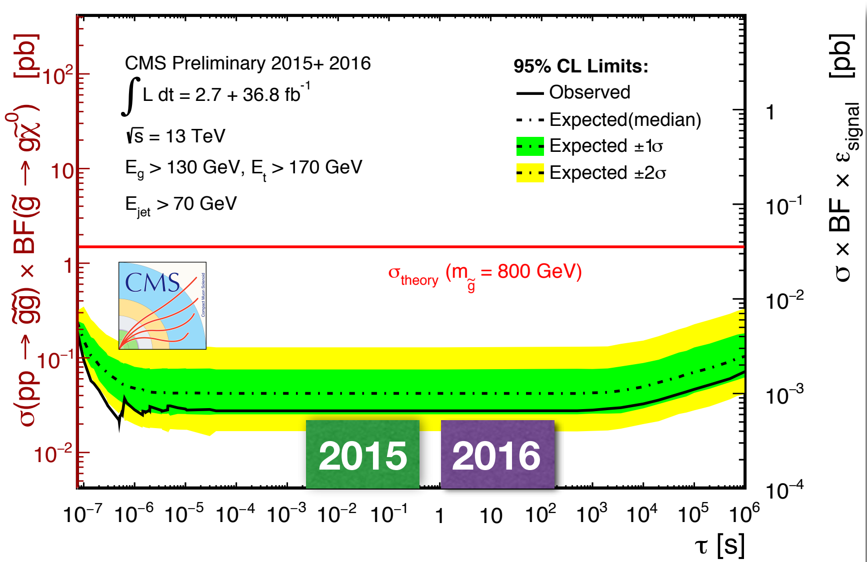


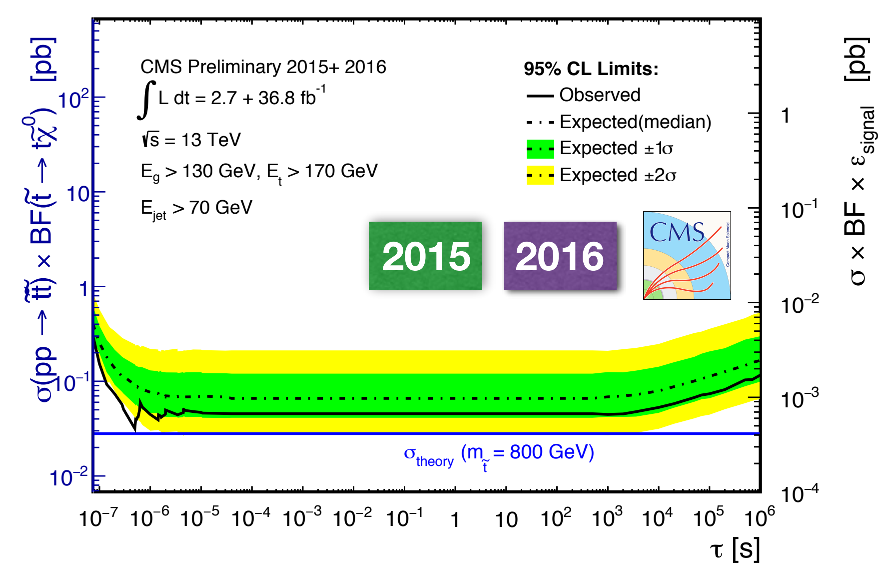
Search for Stopped Particles

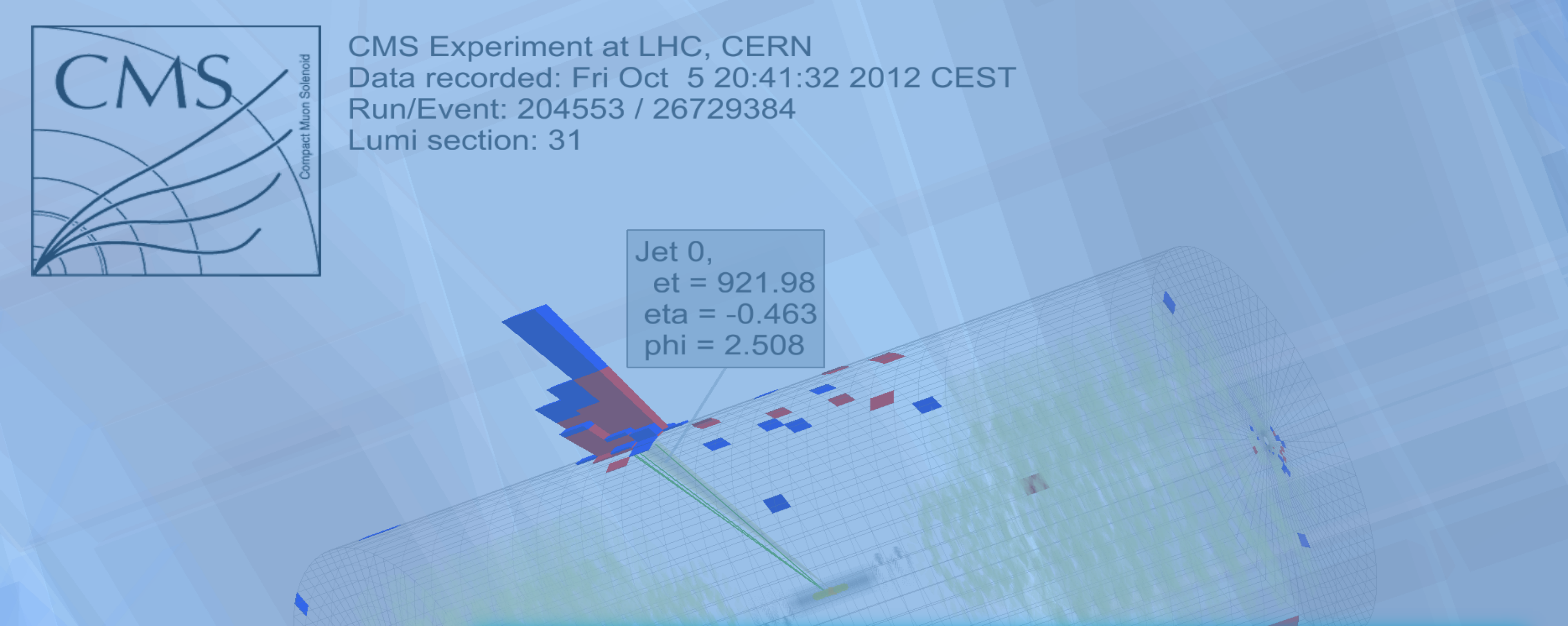
- Search for long-lived gluinos and top squarks stopped in the detector and decaying out of sync with beam crossings in the CMS calorimeters
- Sensitive to 13 orders of magnitude in lifetime



CMS PAS EXO-16-004





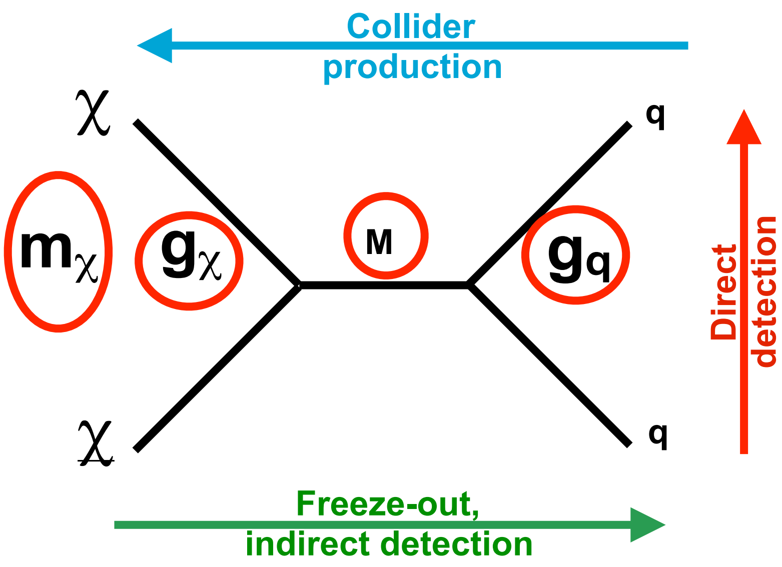


Monomania, or LHC as a Dark Matter Factory

Dark Matter Interactions

- There are three main approaches to detect dark matter (DM):
  - DM-nucleon scattering (direct detection, or DD)
  - Indirect detection (annihilation)
  - Pair production at colliders
- All three processes are nothing but topological permutations of one and the same Feynman diagram:
  - But: how to trigger on a pair of DM particles at colliders?
  - ISR (g, γ, W/Z, H, …) to rescue!
- Early DM searches: EFT based
  - Since then understood the fundamental limitations of EFT and moved to simplified models
- Moving away from EFT allows for a more fair LHC vs. DD experiment comparison and emphasizes the complementarity of the two approaches
  - arXiv:1507.00966
  - arXiv:1603.04156
  - arXiv:1703.05703

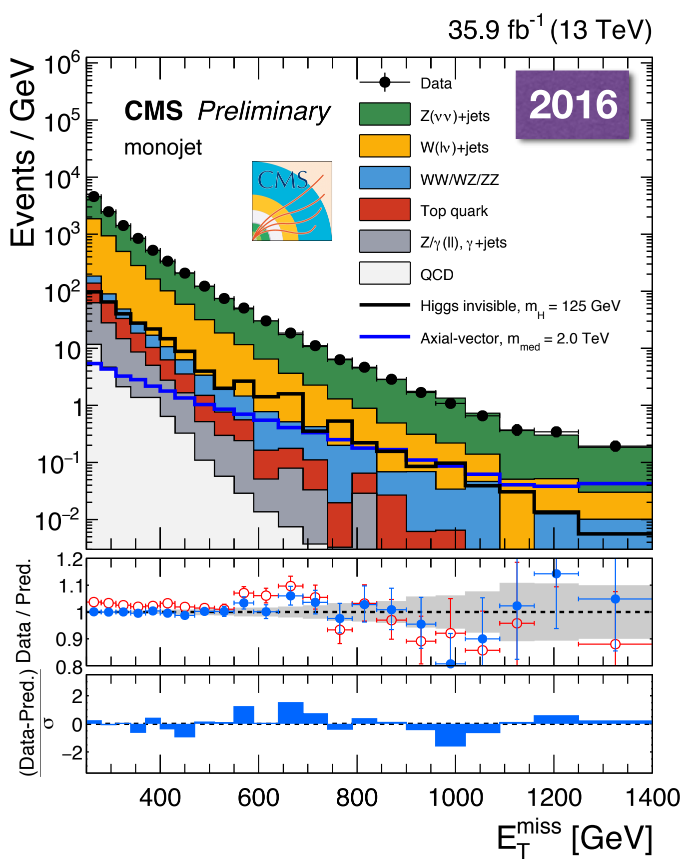
Fundamentally 4D problem!

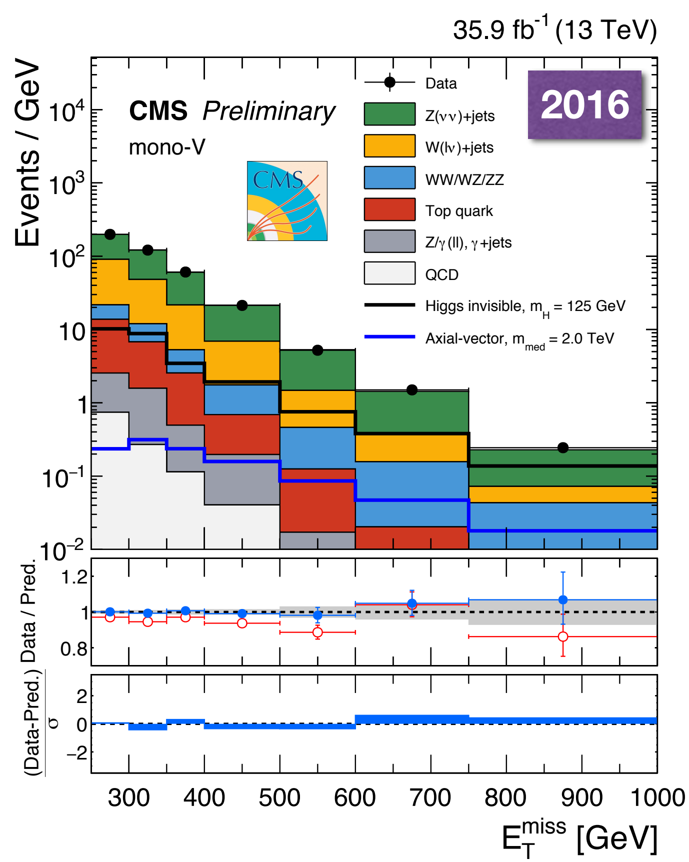


CMS Monojet Analysis

- The latest Run 2 analysis is built on the Run 1 techniques
  - Increased number of control regions (added e+jets, ee+jets)
  - Theoretically consistent treatment of EW/QCD corrections to SM V+jets processes, after Lindert et al., arXiv:1705.04464

CMS PAS EXO-16-048





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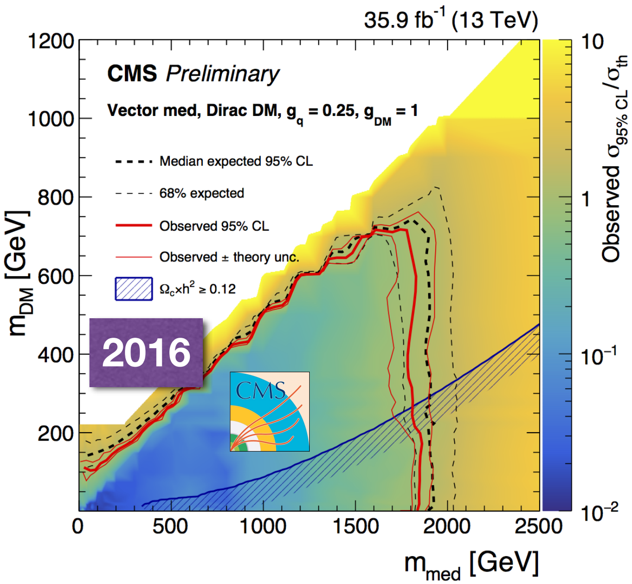
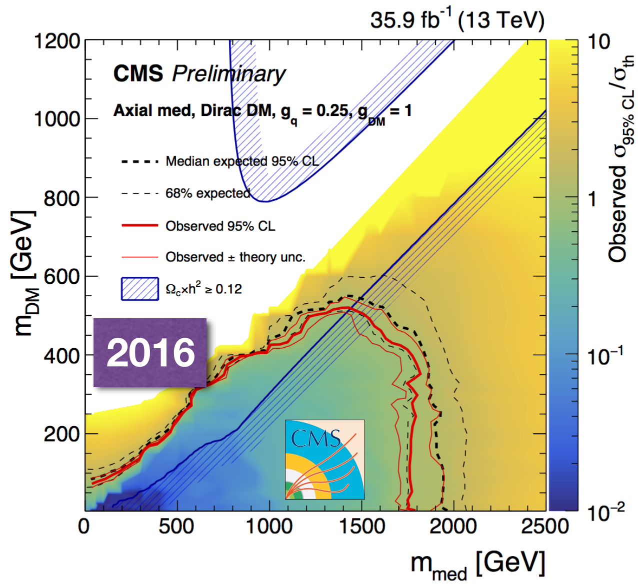
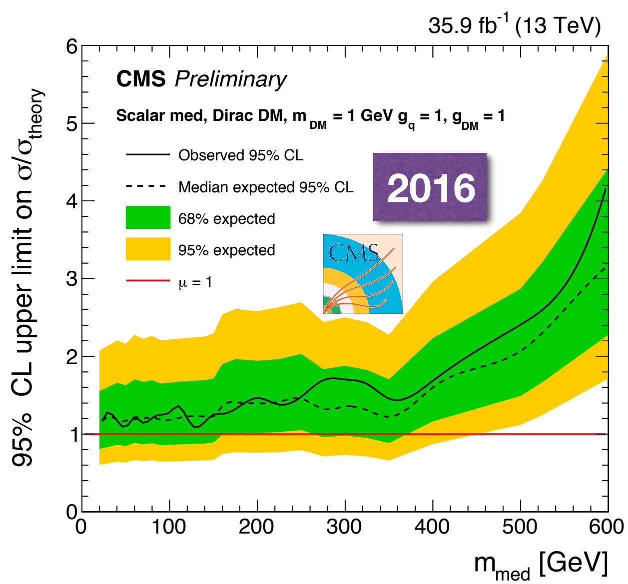
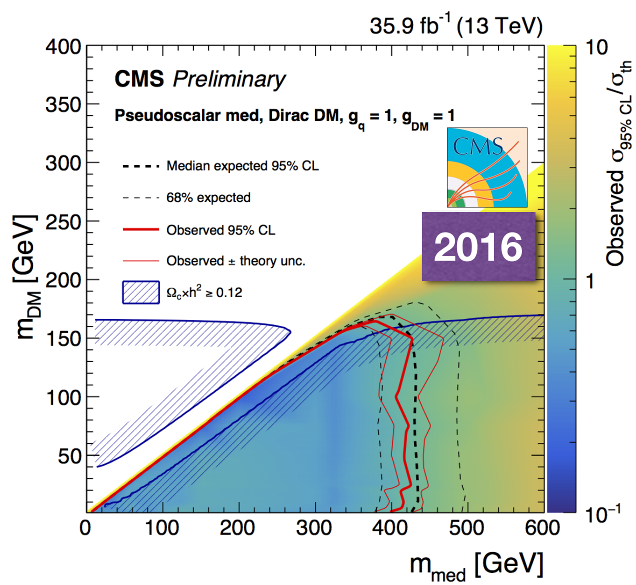
DM Interpretation

CMS PAS EXO-16-048





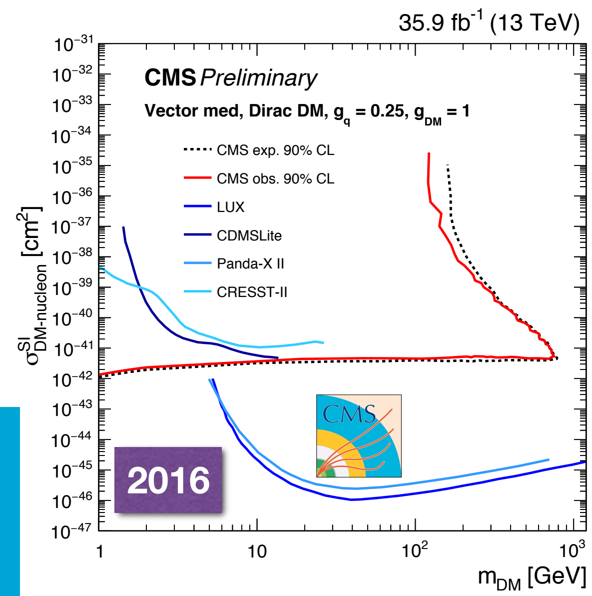


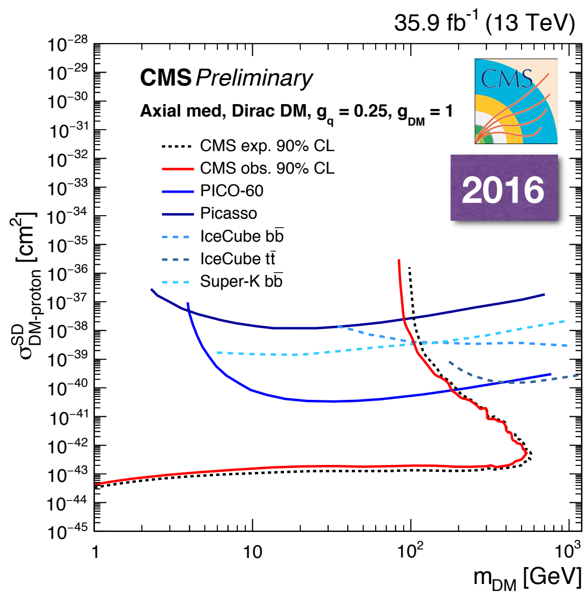


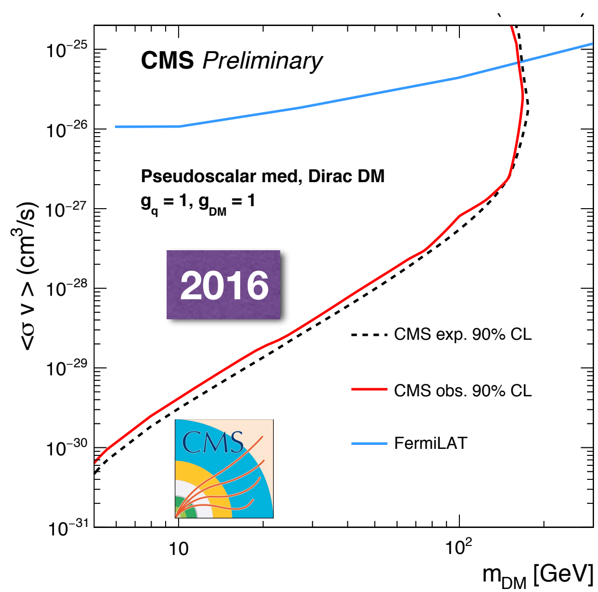
Fully compliant w/ LHC DM WG [arXiv:1603.04156] recommendations

Comparison w/ I/DD

CMS PAS EXO-16-048

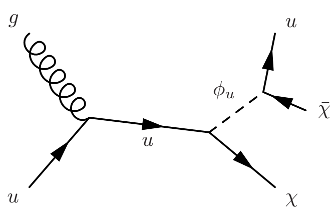


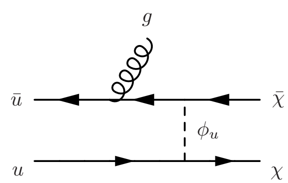


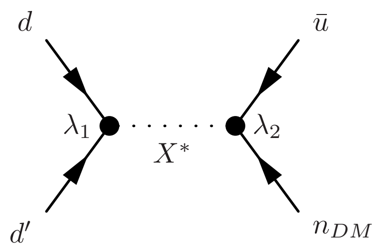


Other Interpretations

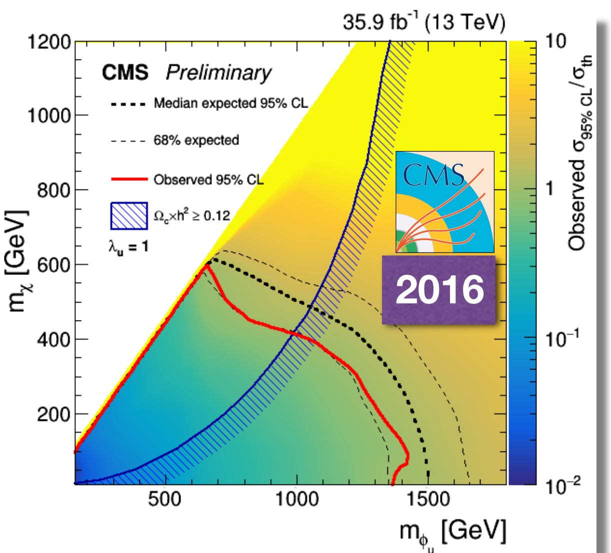
- Also sets first limits on Dirac fermion [Bai/Berger, arXiv: 1308.0612] and non-thermal [Dutta/Gao/Kamon, arXiv: 1401.1825] DM models and new limits on models with large extra dimensions

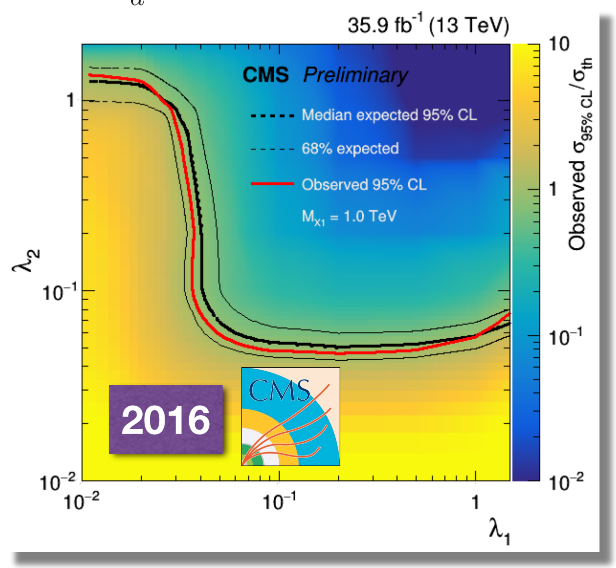


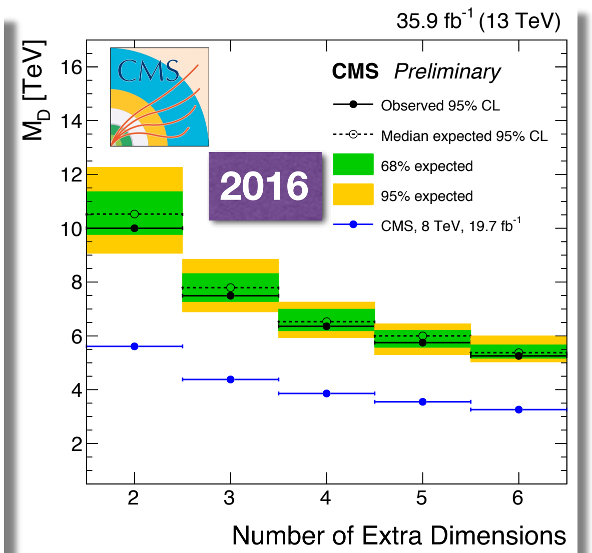




CMS PAS EXO-16-048







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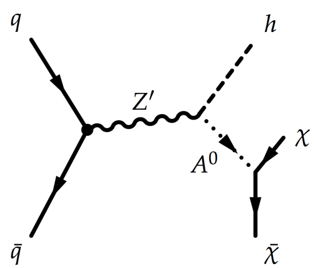
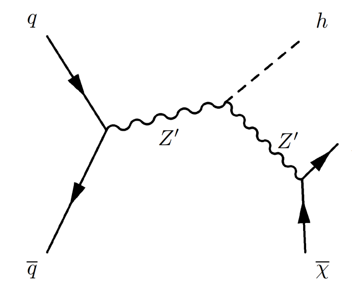
Mono-Higgs Production

- Mono-Higgs analysis in the context of 2HDM and vector mediator
- Explore the H(γγ) decay mode

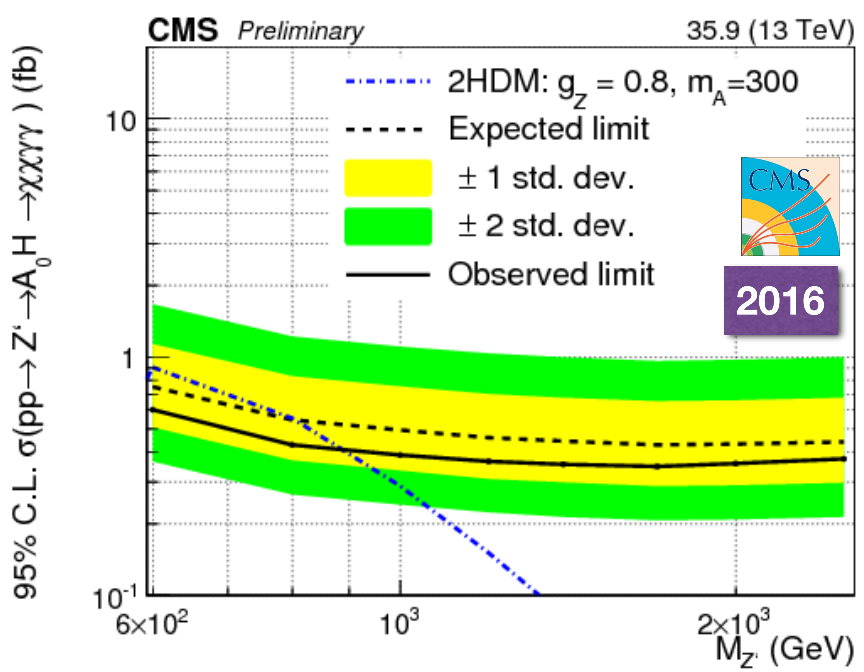


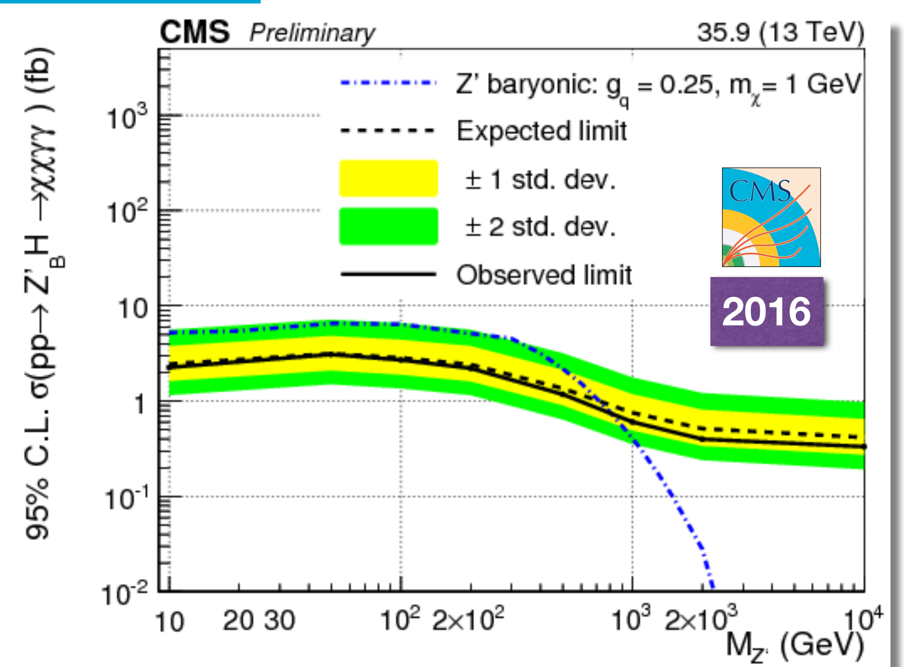
$$g_{Z'} \leq 0.03 \times \frac{g_W}{\cos\theta_W \times \sin^2\beta} \times \frac{\sqrt{m_{Z'}^2 - m_Z^2}}{m_Z}$$

Dijets: $g_{Z'} < 0.8$



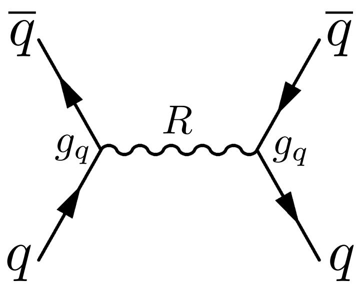
CMS PAS EXO-16-054





Search for the Mediator

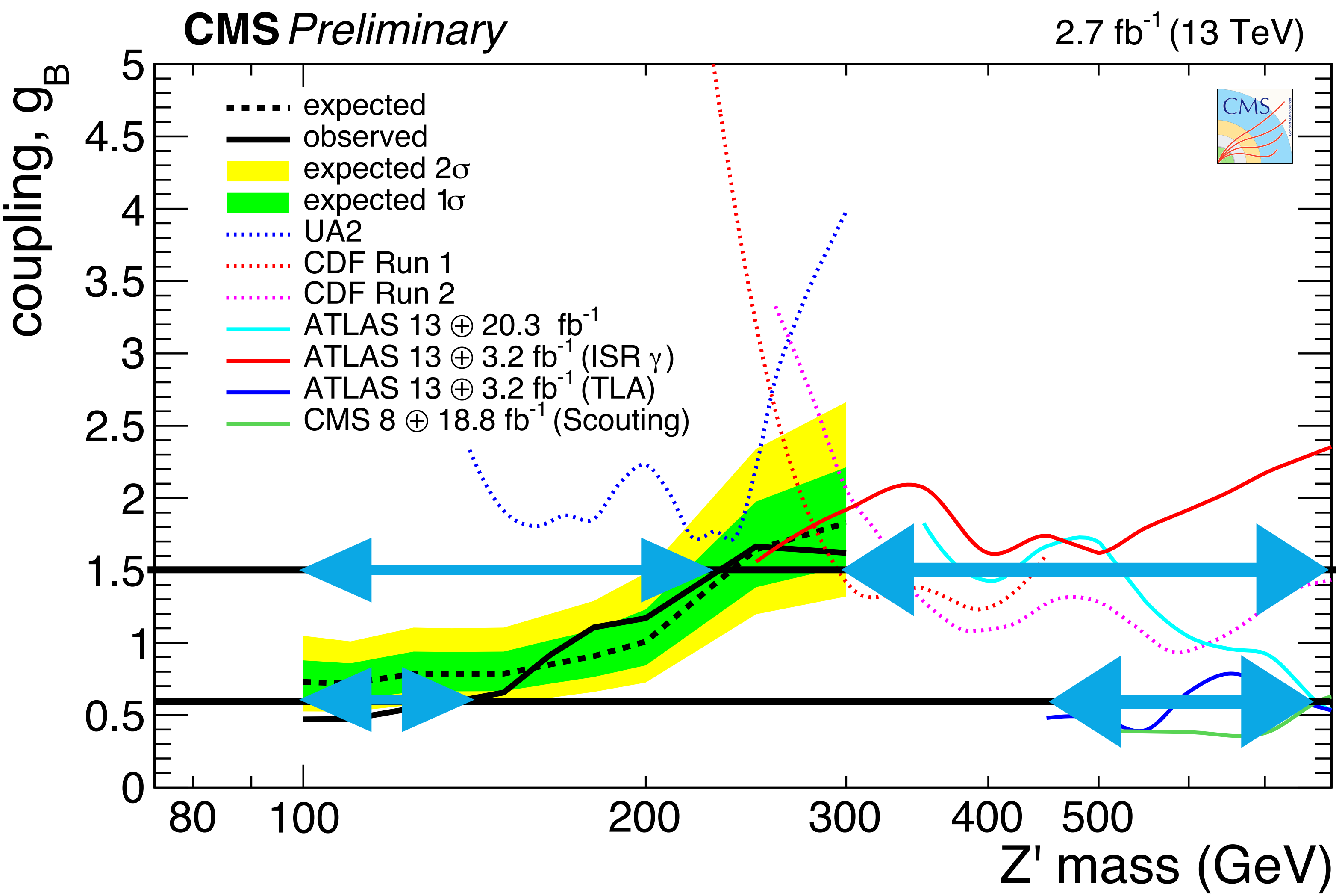
- One doesn't need to produce DM at the LHC to look for a mediator (mass M)



  - Since it's coupled to the initial state, one could look for dijet decays of the mediator by "recycling" the dijet resonance searches
  - Also possible to recycle dilepton searches if the mediator couples to leptons in addition to quarks
  - g_B/g_q framework provides a convenient language for translation, which should take into account the additional decay width from the mediator decay to DM particles (mass m), not present in the Z'_B framework
  - For $g_q = 0.25$ one gets: $g_B^2 = \dfrac{9/4}{1 + \frac{16}{3N_f}\left\{1 - 4\left(\frac{m}{M}\right)^2\right\}^{\frac{3}{2}}}$

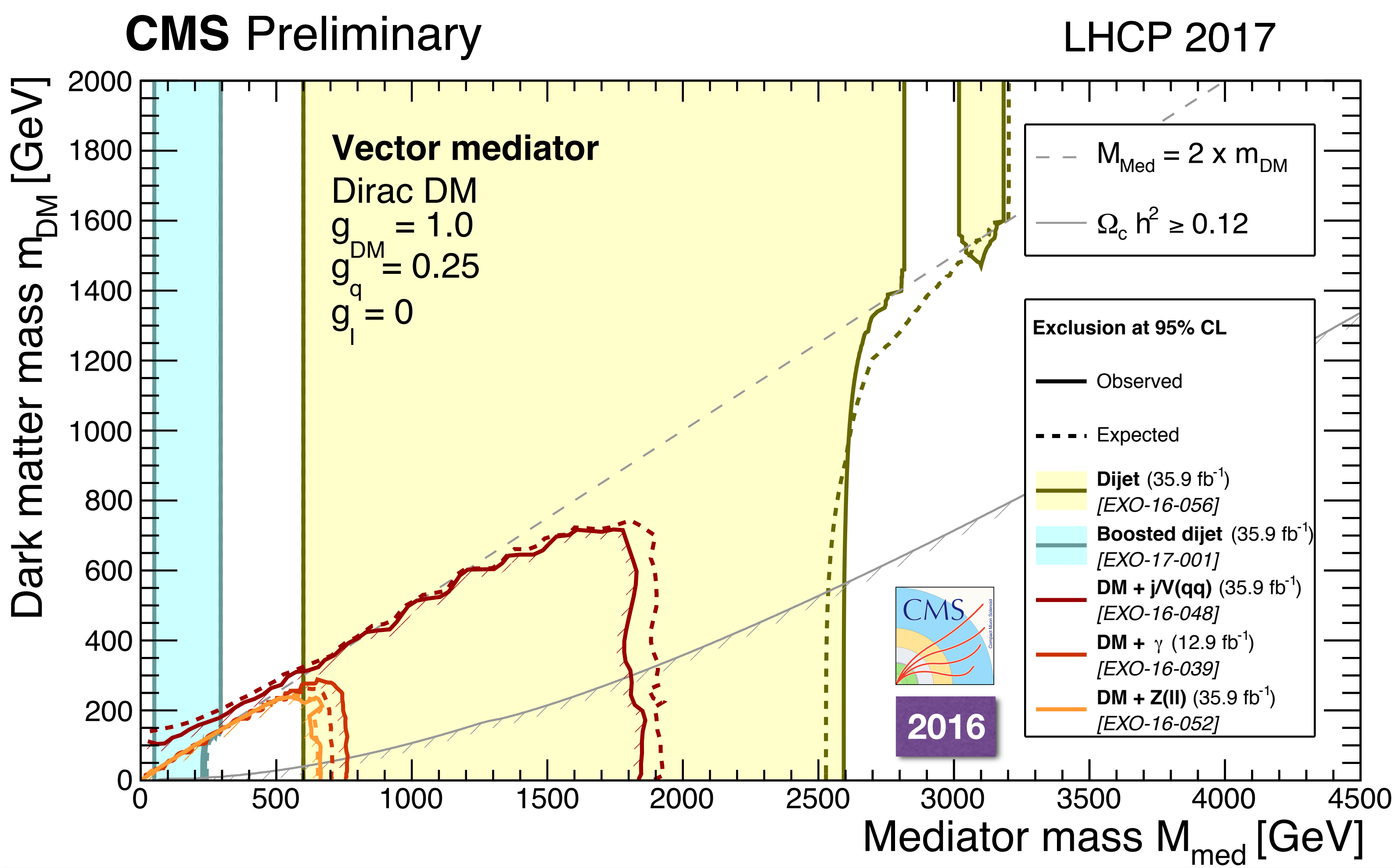
Using the g_B Plot

- ✦ Reading axial M_{med} limits from the g_B plot:



CMS Dijet Limits

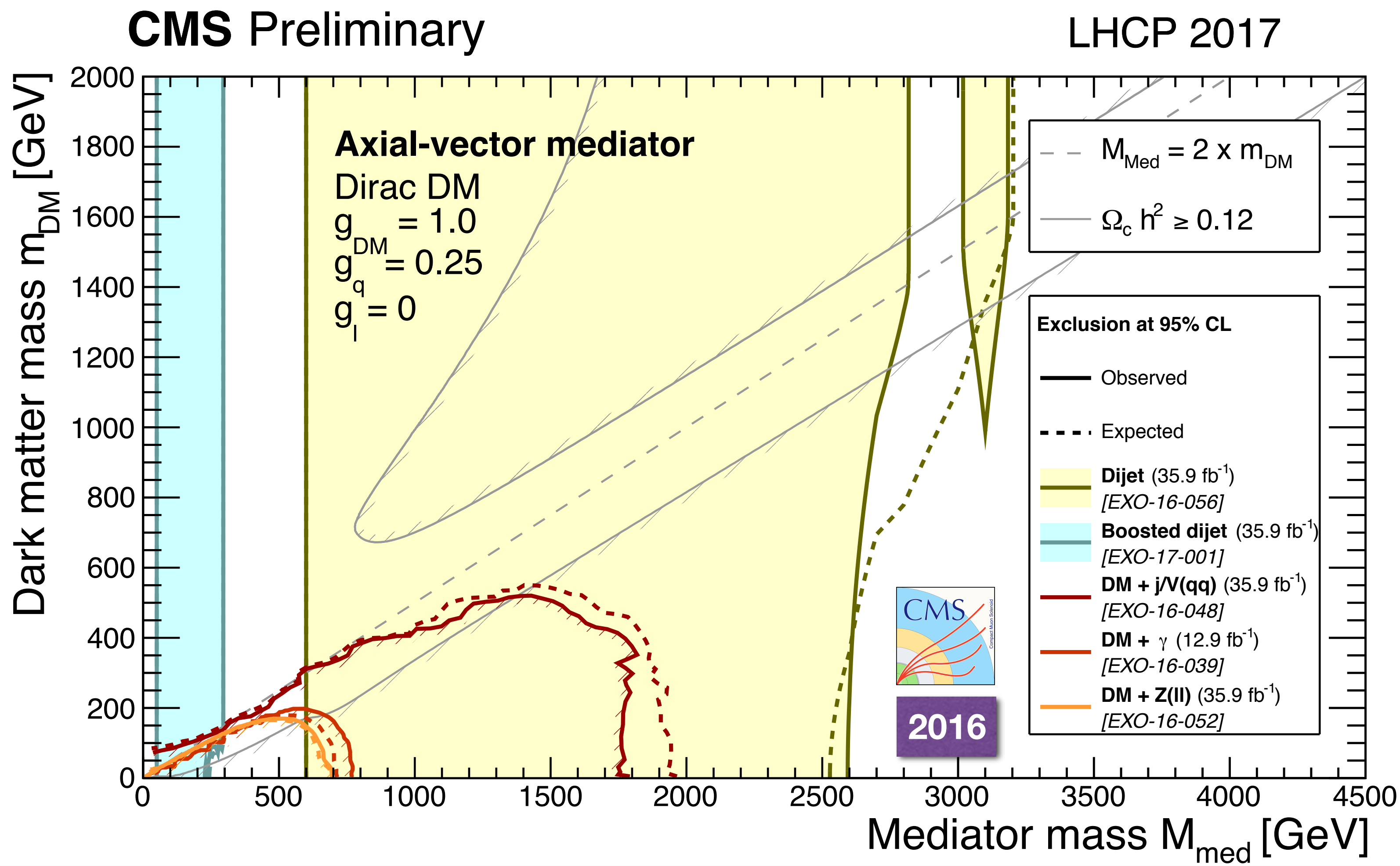
✦ Analogous limits from CMS for (axial) vector mediators



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM_summary_plots_LHCP_2017.pdf

CMS Dijet Limits

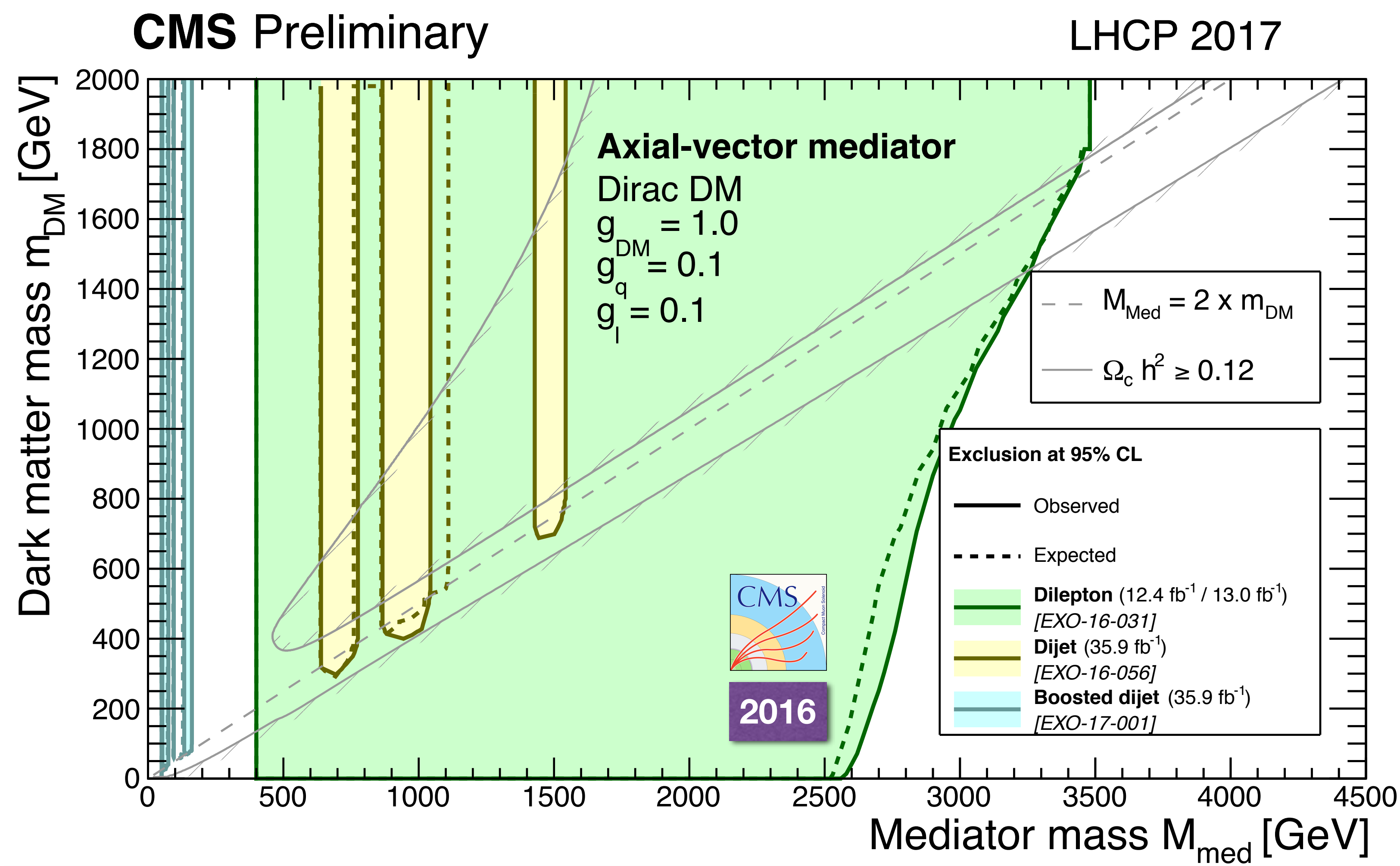
✦ Analogous limits from CMS for (axial) vector mediators



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM_summary_plots_LHCP_2017.pdf

Dijet & Dilepton Limits

- Dijet & dilepton limits on axial-vector & vector mediators



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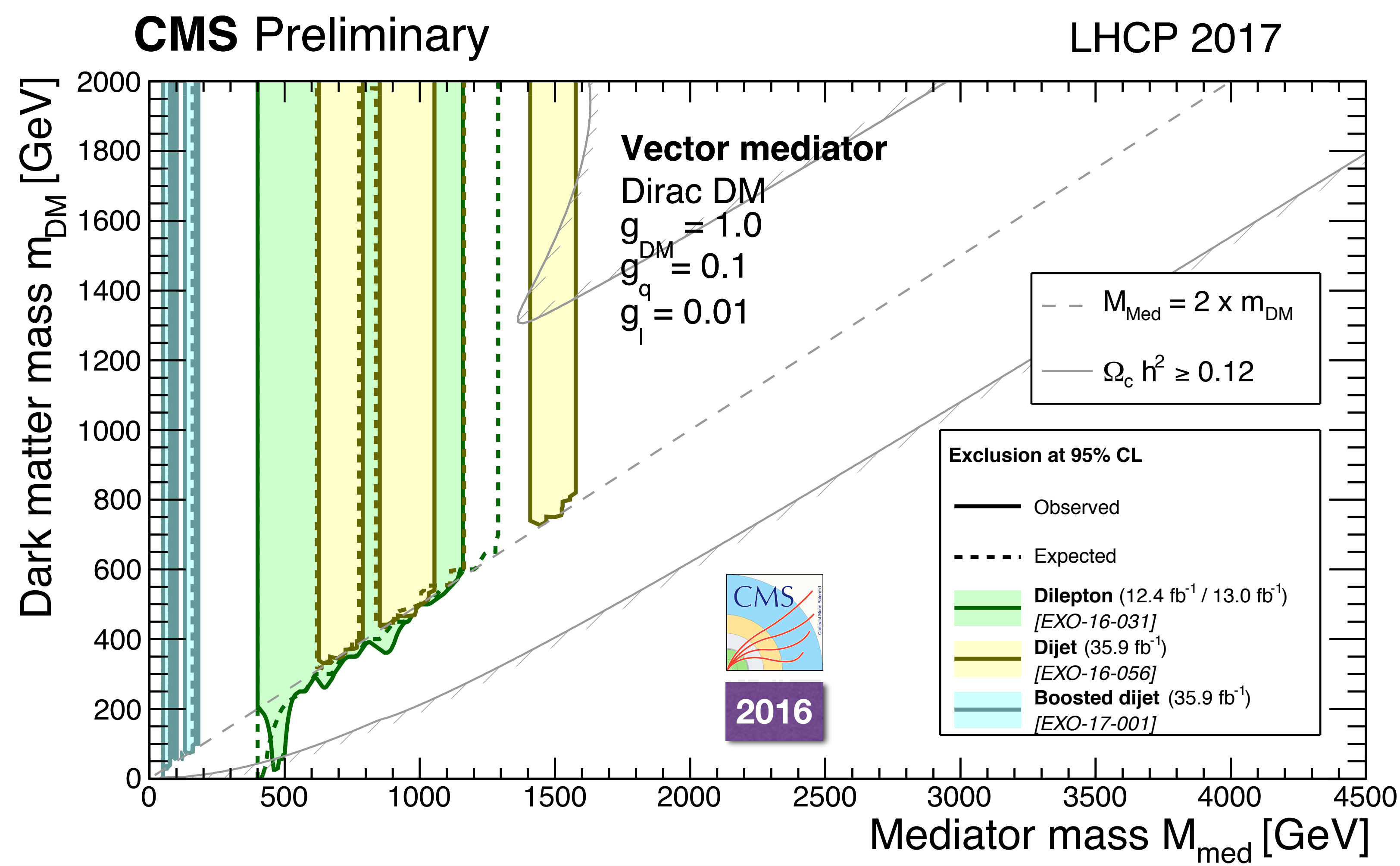
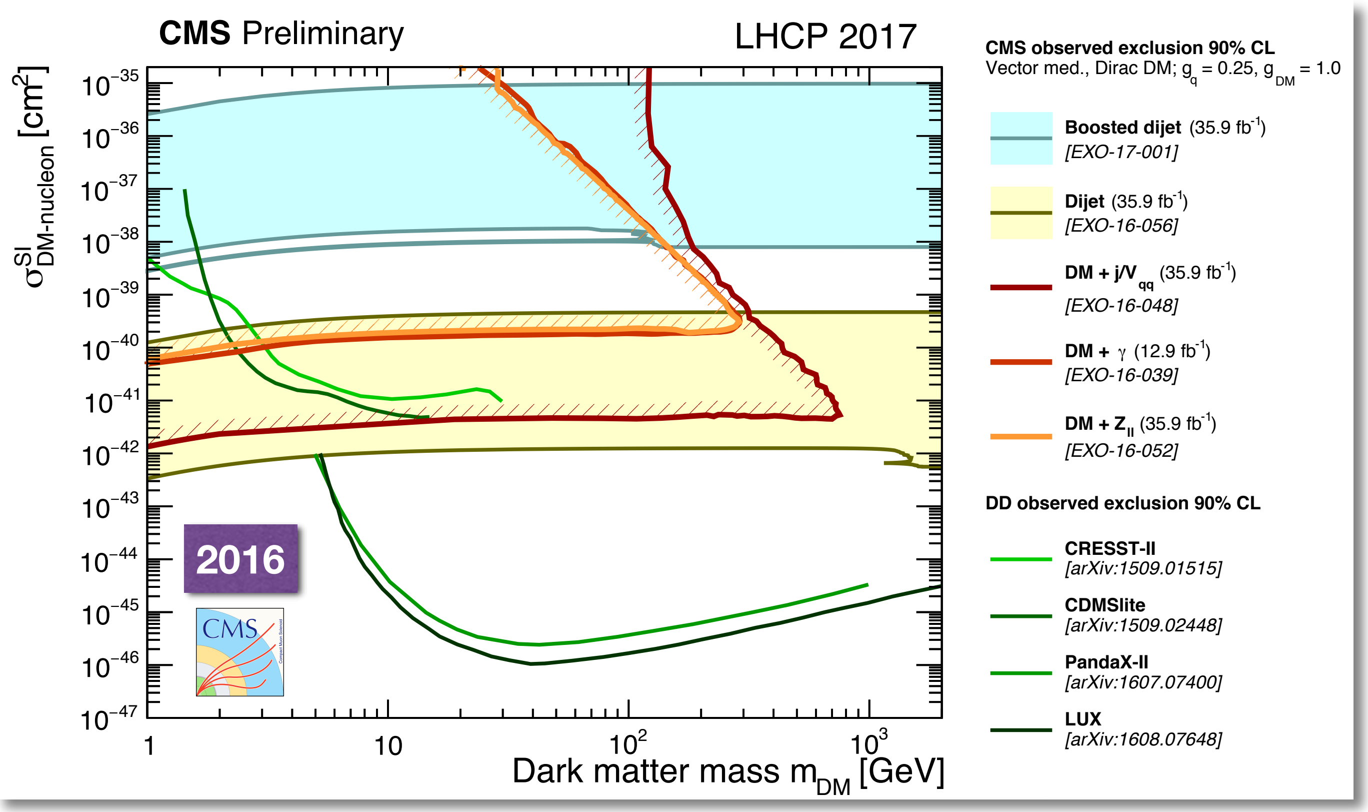


https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM_summary_plots_LHCP_2017.pdf

Comparison w/ Direct Detection

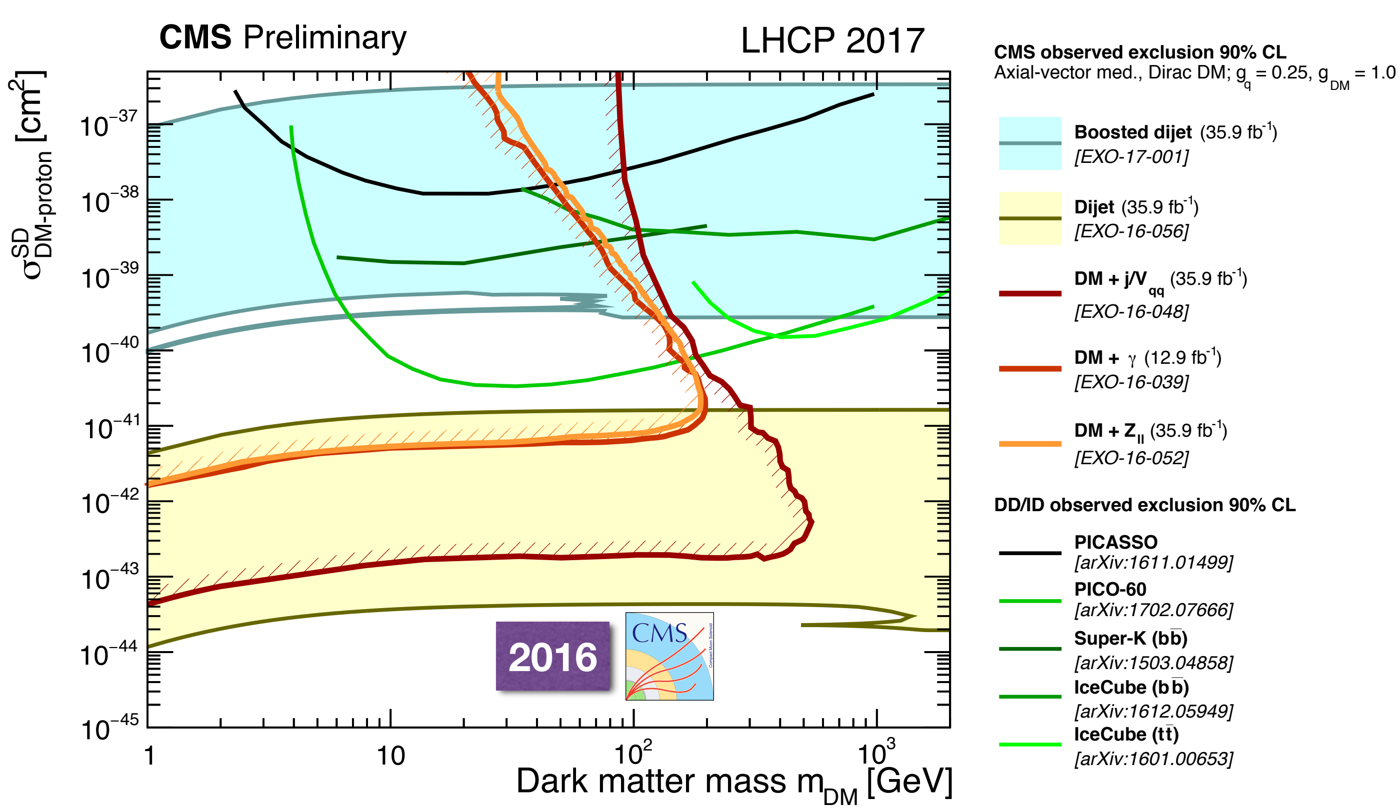
- Vector mediators
  - DD experiments get a resonant enhancement on a nucleus due to spin-independent scattering cross section
  - Colliders only win at low DM masses



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM_summary_plots_LHCP_2017.pdf

Comparison w/ Direct Detection

- ✦ Axial vector mediators
  - No resonant enhancement due to spin-dependent cross section
  - Colliders typically win over the DD experiments up to a few hundred GeV DM masses



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/DM_summary_plots_LHCP_2017.pdf

Future Run 2 Searches

- Parton luminosity arguments shaped the searches program in 2015 and 2016:
  - Look for high-mass singly or pair-produced objects:
    - Gluinos, squarks (SUSY)
    - Z', W', dijet, tt, and diboson resonances, vector-like quarks, leptoquarks, black holes (Exotica)
- The situation has finally changed after 2016, since the data doubling time from now on for the first time would exceed 1 year, approaching a "lifetime" of a graduate student
- Expect more sophisticated searches in complicated final states that haven't been explored before, using advanced analysis techniques, ISR and VBF probes, etc.
- The LHC searches are moving away from the lampposts (both theoretical and experimental) and enter really unprobed territory

Conclusions

New Physics - WHERE ARE YOU???