EXOTIC SEARCHES @ ATLAS AND CMS

Greg Landsberg

2017 ALPS Conference

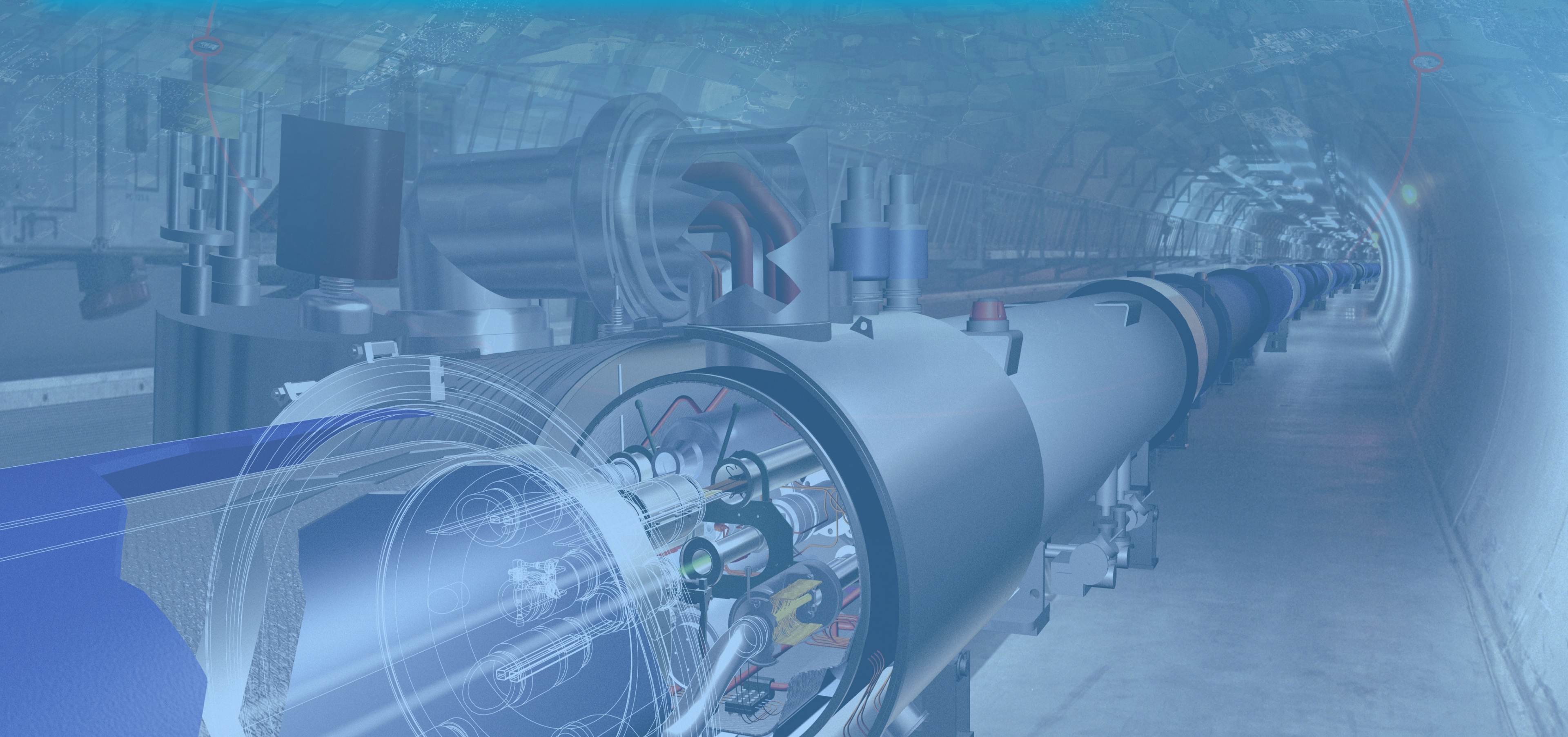
Obergurgl, Austria - April 19, 2017

Outline

- LHC Performance
- Run 2 searches
  - Low-hanging fruit (blue slopes)
  - Not-so-low-hanging fruit (red slopes)
  - High-hanging fruit (black slopes)
  - Out-of-reach fruit (experts only)
- Conclusions: hanging in there...

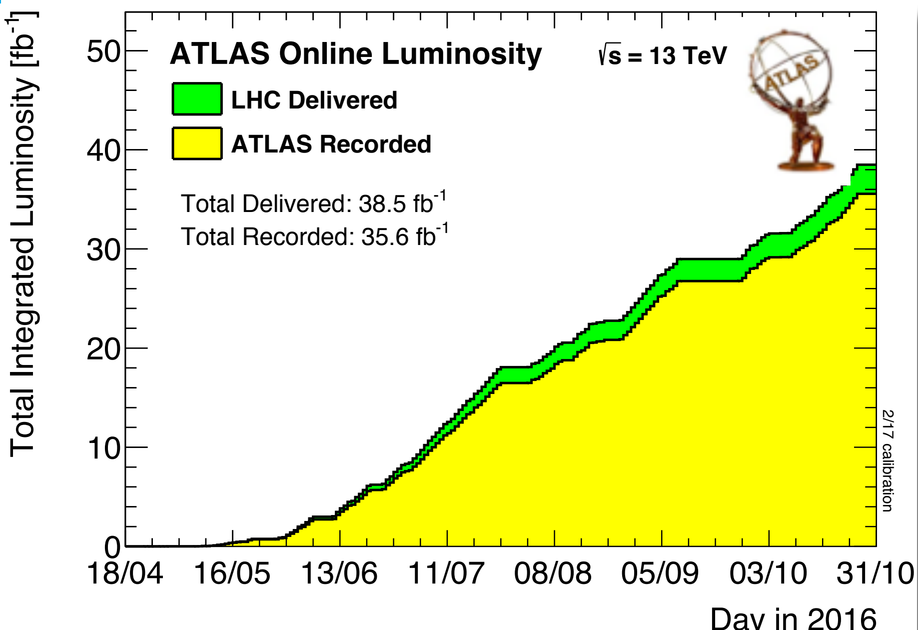
- Disclaimer: I'll mainly focus on the most recent results - either preliminary or recently submitted
- For the full exotica searches landscape in ATLAS and CMS, see:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html

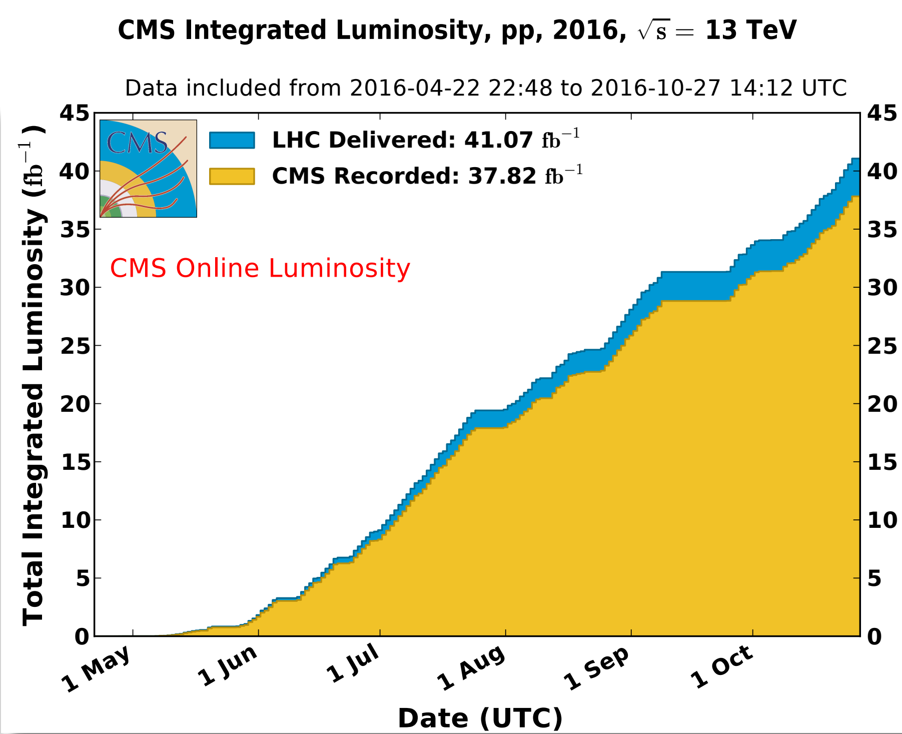
The LHC Performance



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!





Excellent Detector Performance

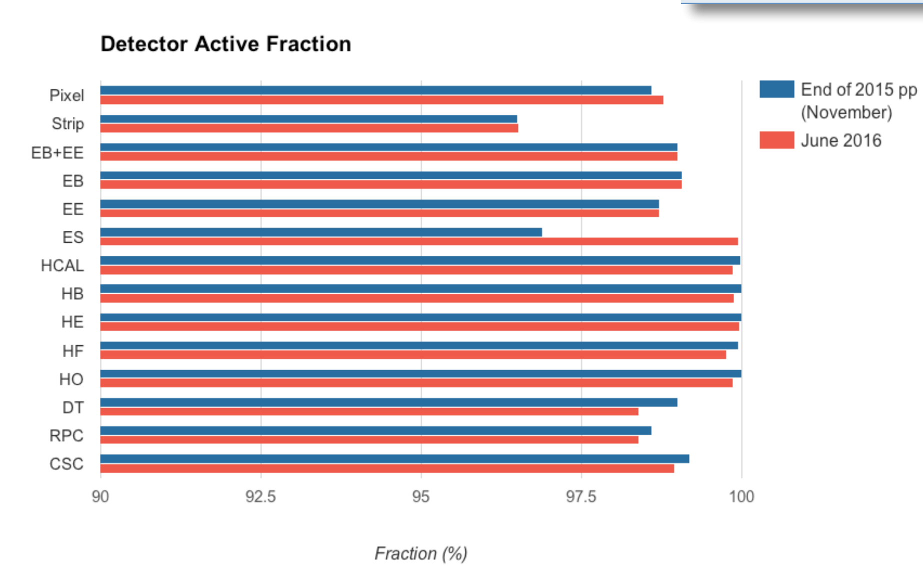
- The ATLAS and CMS detector have been working spectacularly with virtually no degradation in performance over the 3 years of Run 1 and 2 years of Run 2
  - In some cases, temporary losses in performance were recovered

ATLAS pp 25ns run: April-October 2016

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets		Trigger
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid	L1
98.9	99.9	99.7	99.3	98.9	99.8	99.8	99.9	99.9	99.1	97.2	98.3

Good for physics: 93-95% (33.3-33.9 fb^{-1})

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between April-October 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. The toroid magnet was off for some runs, leading to a loss of 0.7 fb^{-1}. Analyses that don't require the toroid magnet can use that data.



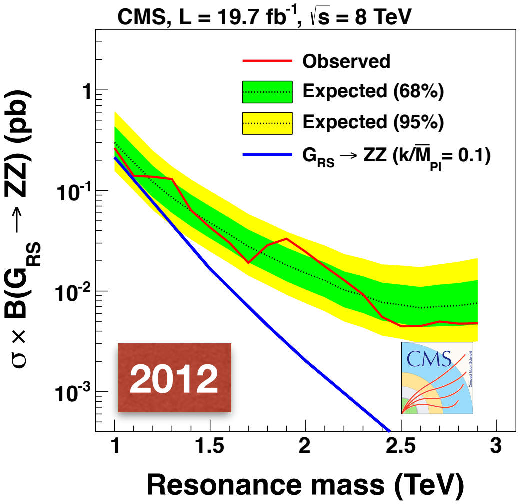
CMS Status in June 2016 (%)

Run 1 Excesses

Run 1 Excesses

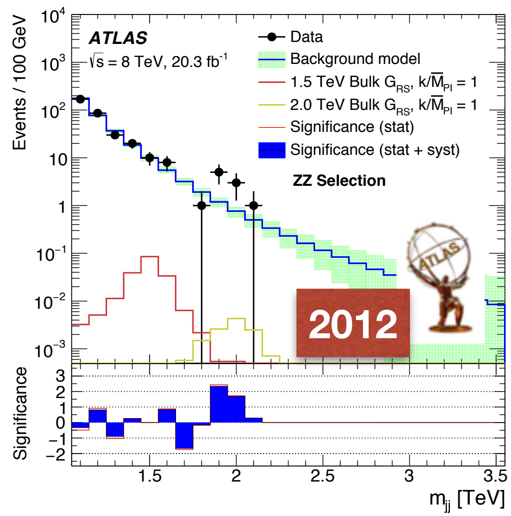
- Very few statistically interesting excesses remained after Run 1
  - A slight excess in the H(τμ) search (CMS saw about 2.4σ excess, while ATLAS was consistent with both zero and CMS)
  - A ~2.5σ excess in CMS 1st generation LQ search in both eejj and eνjj channels seen for the 650 GeV LQ mass hypothesis
  - 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

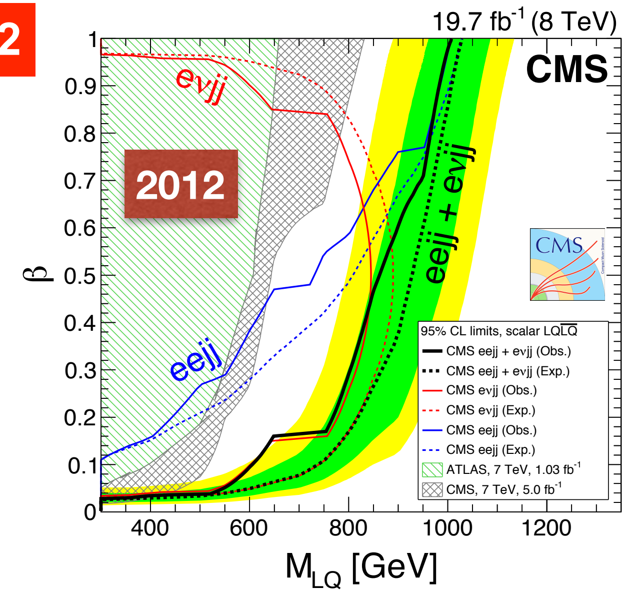
Old Hints for New Physics?



CMS arXiv:1405.1994

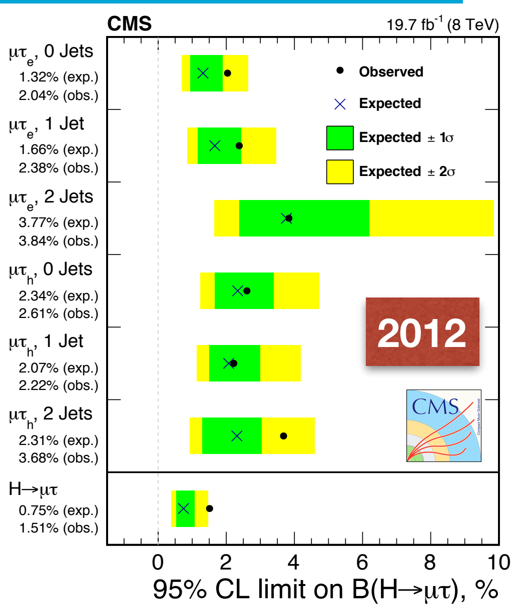
ATLAS arXiv:1506.00962

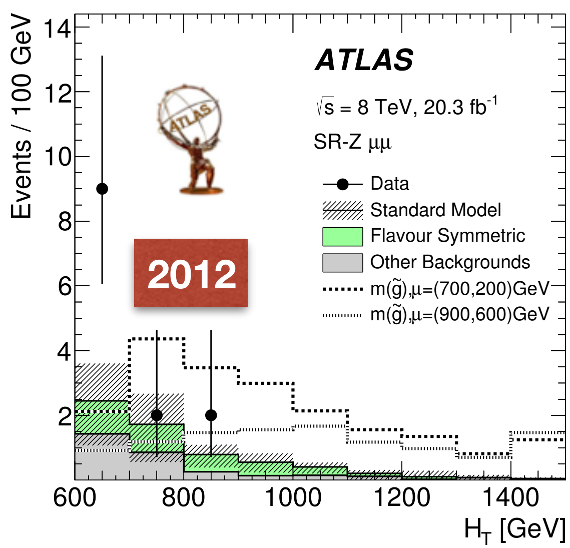




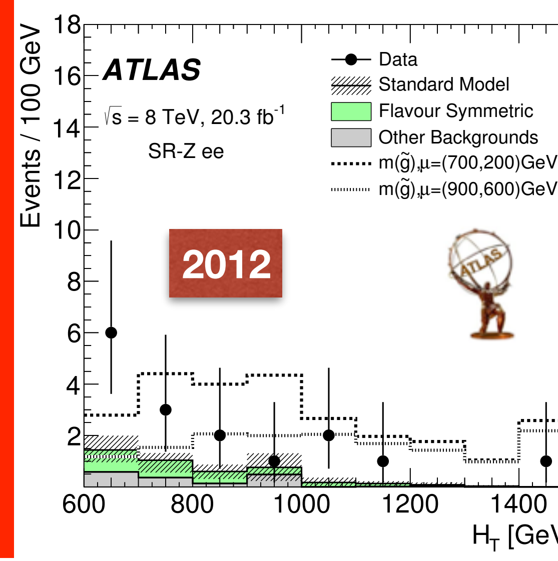
CMS arXiv:1509.03744

CMS arXiv:1502.07400





ATLAS arXiv:1503.03290

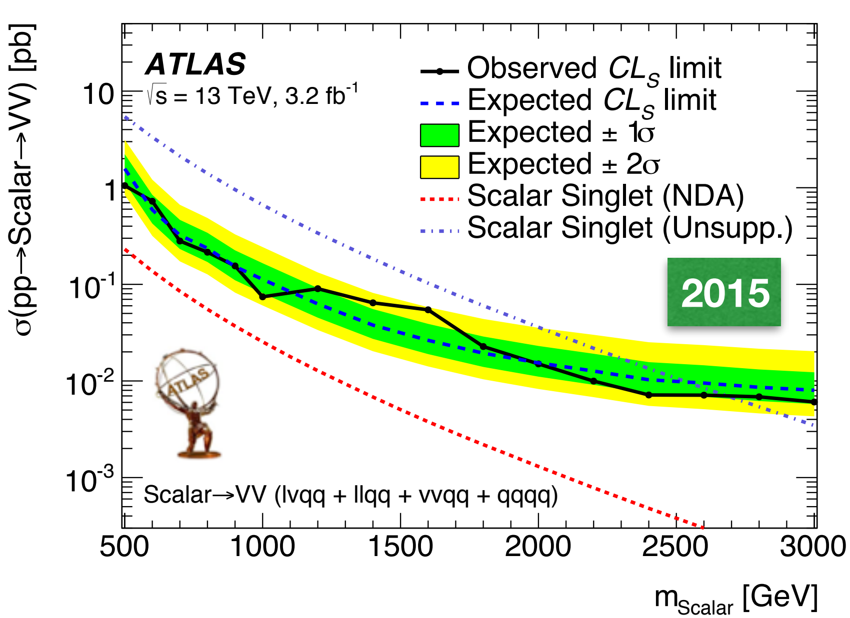


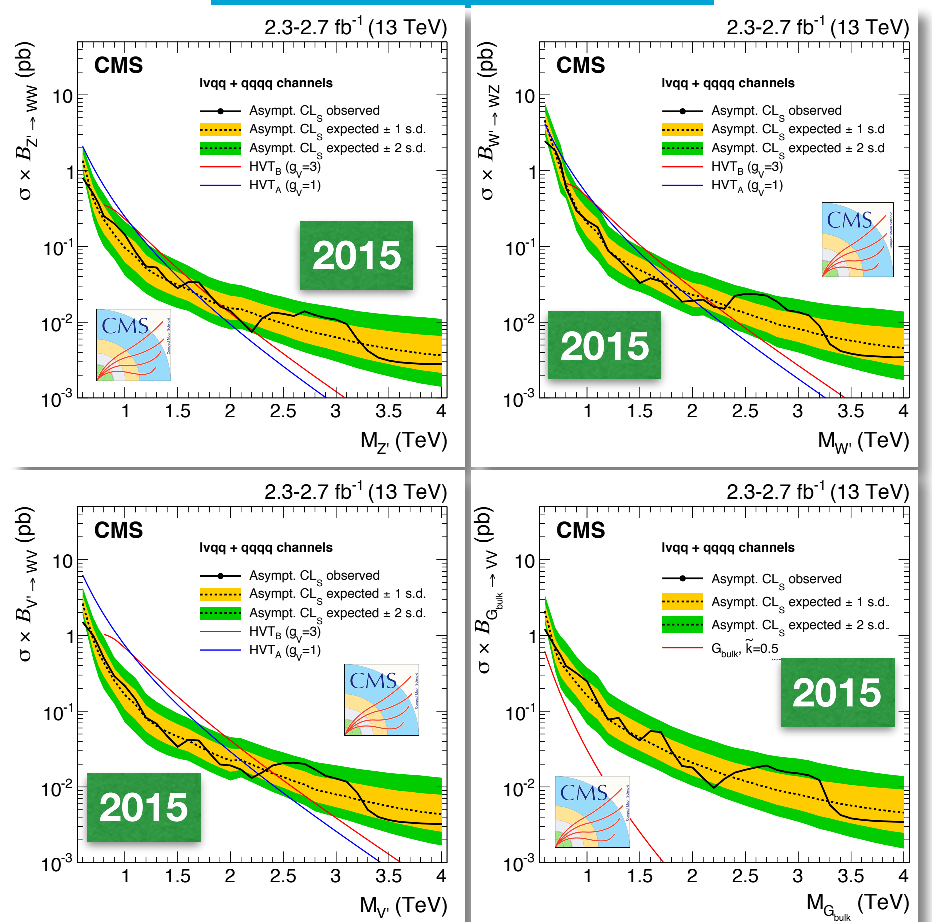
VV Excess Gone?

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

CMS arXiv:1612.09159

ATLAS arXiv:1606.04833



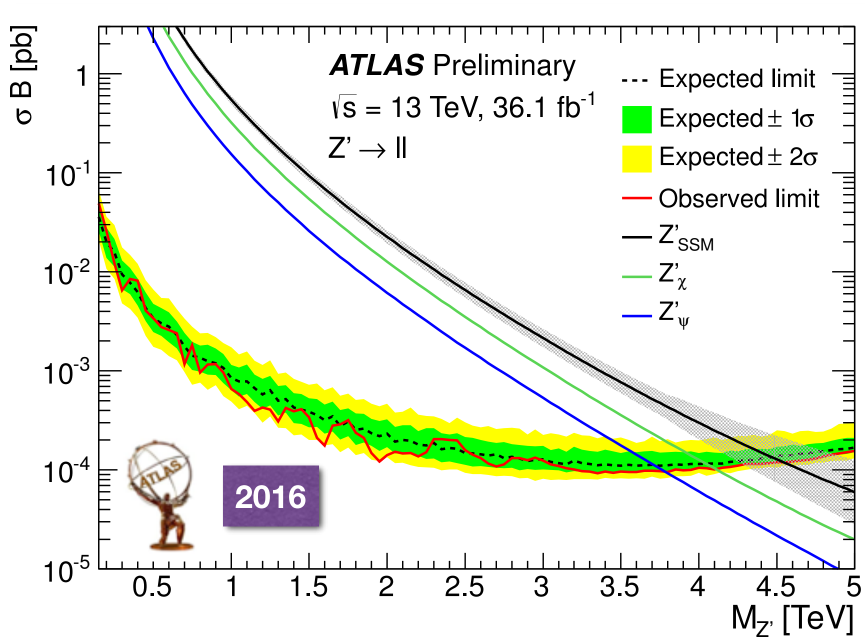


Low-Hanging Fruit

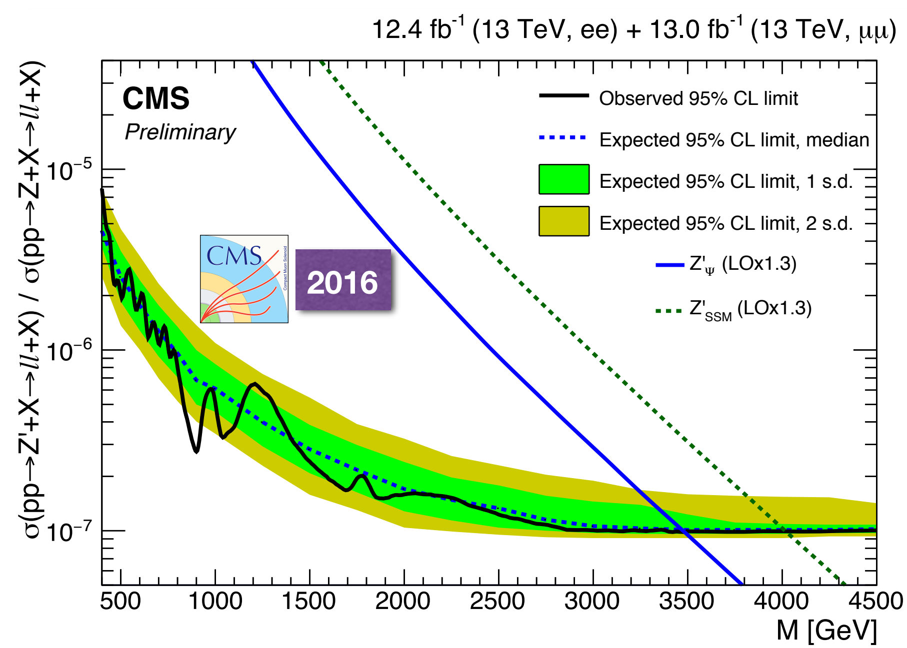
Z' Searches

- Analyses based on full (ATLAS) and partial (CMS) 2016 data
  - Use standard techniques well-tested in earlier reincarnations of the analyses
  - Limits on sequential Z' reached ~4-4.5 TeV

ATLAS CONF-2017-027



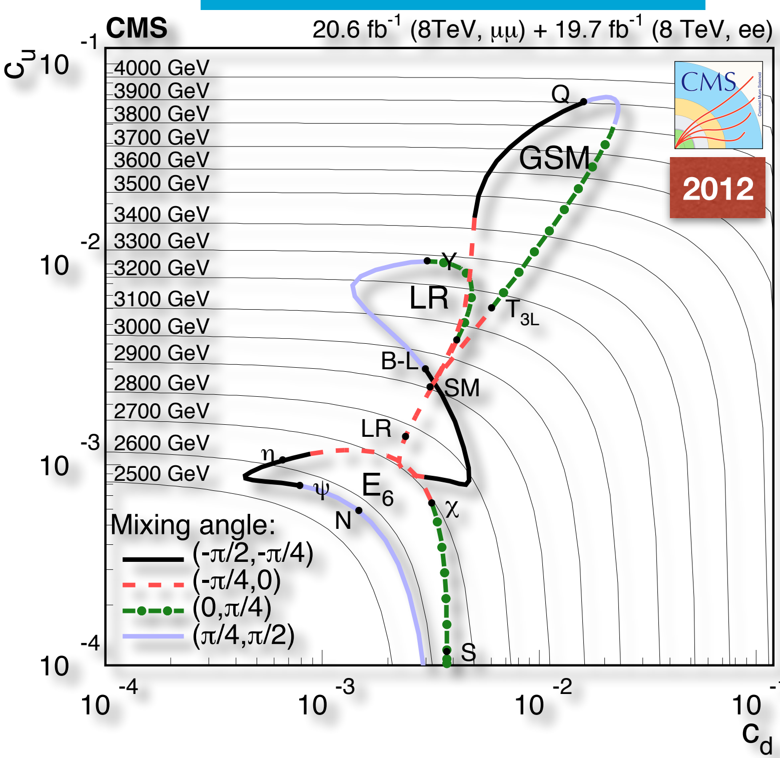
CMS PAS EXO-16-031



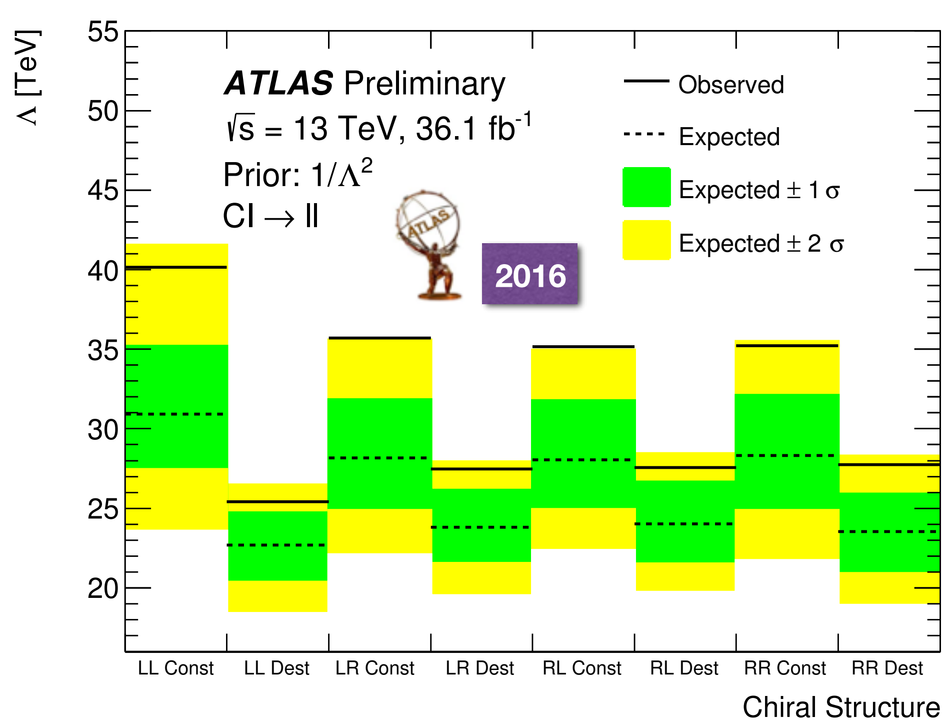
More Interpretations

- 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 and reach 25-40 TeV, which is a factor of two improvement compared to Run 1 limits

CMS arXiv:1412.6302



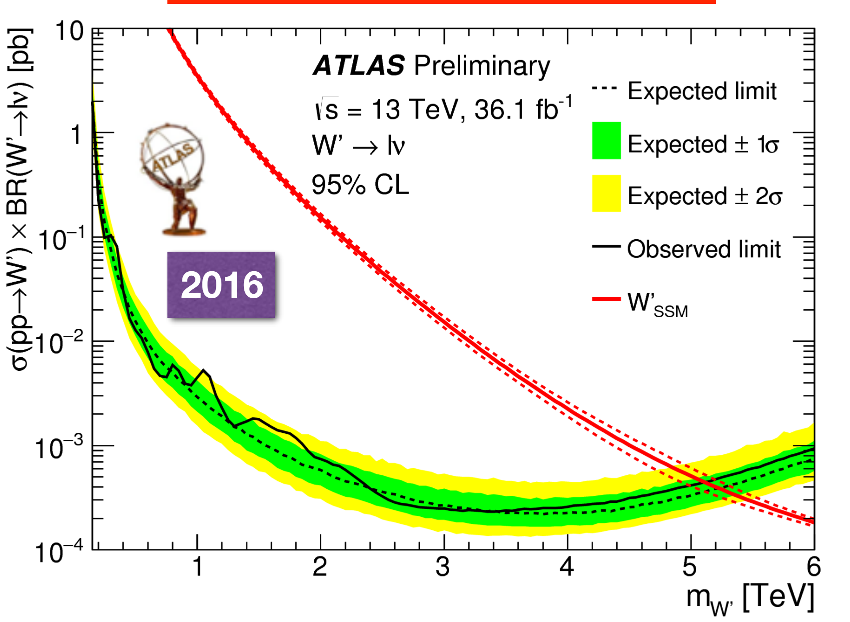
ATLAS CONF-2017-027



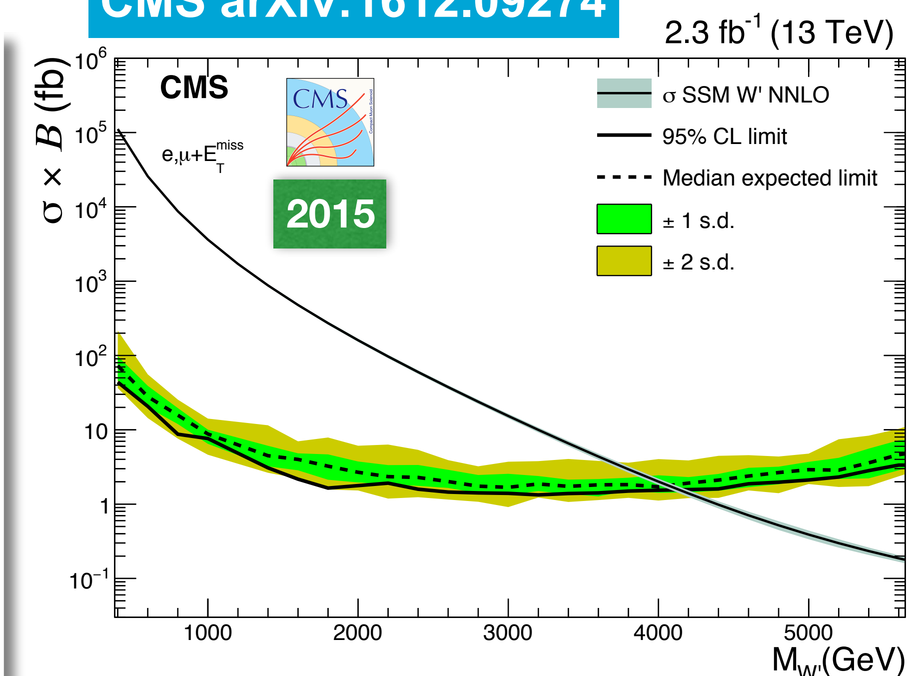
W' Searches

- Analyses based on 2016 (ATLAS) and 2015 (CMS) data
  - Use standard techniques well-tested in earlier reincarnations of the analyses
  - Limits on sequential W' reach ~4-5 TeV

ATLAS CONF-2017-016

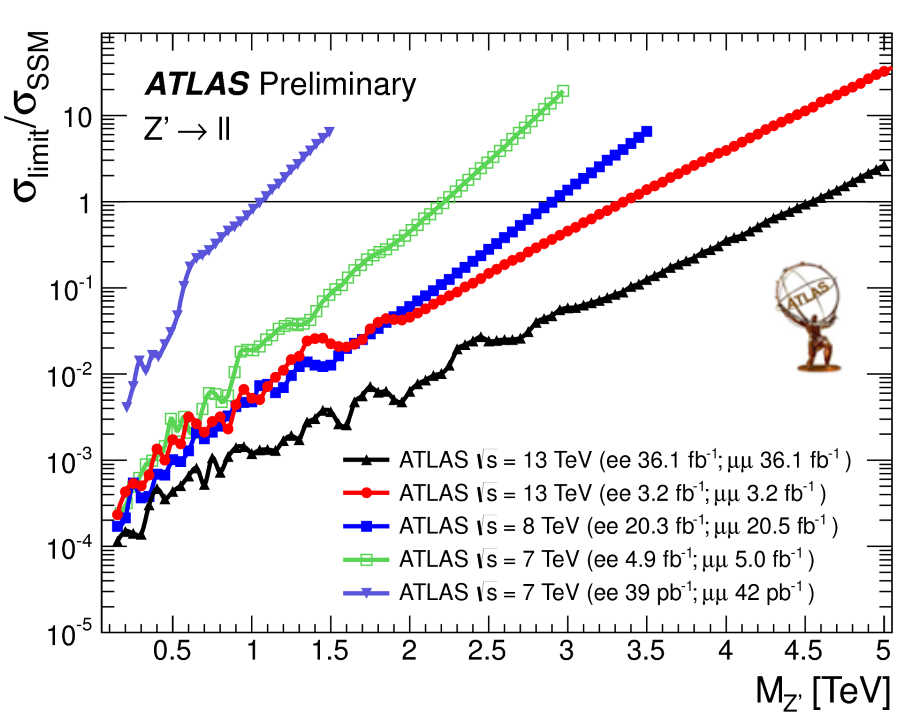


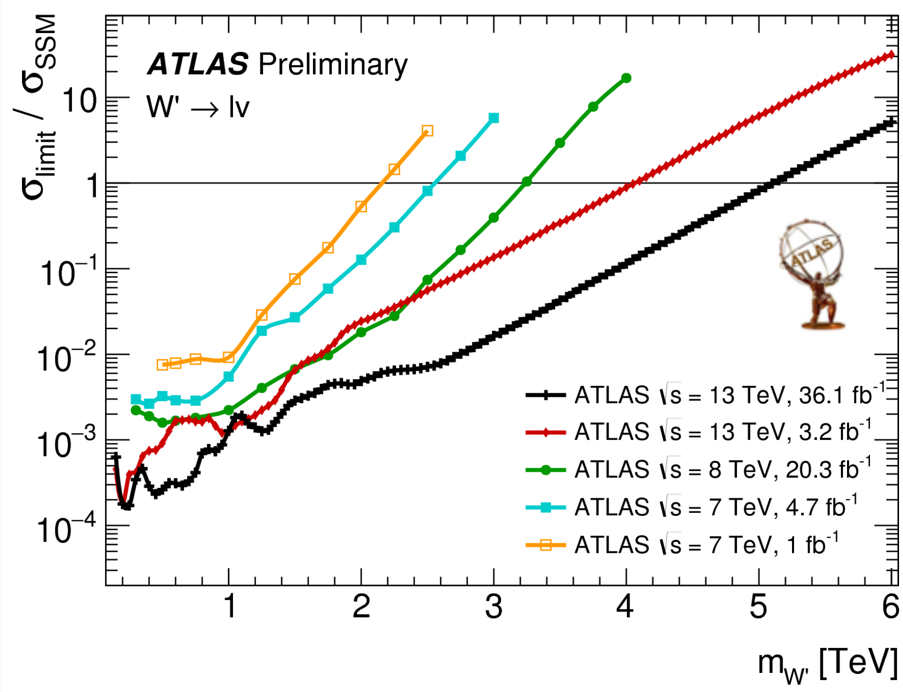
CMS arXiv:1612.09274



Luminosity Scaling

- ✦ Factor of 10 in luminosity brings about 1 TeV in sensitivity
  - ◉ Still another ~TeV in reach before HL-LHC!





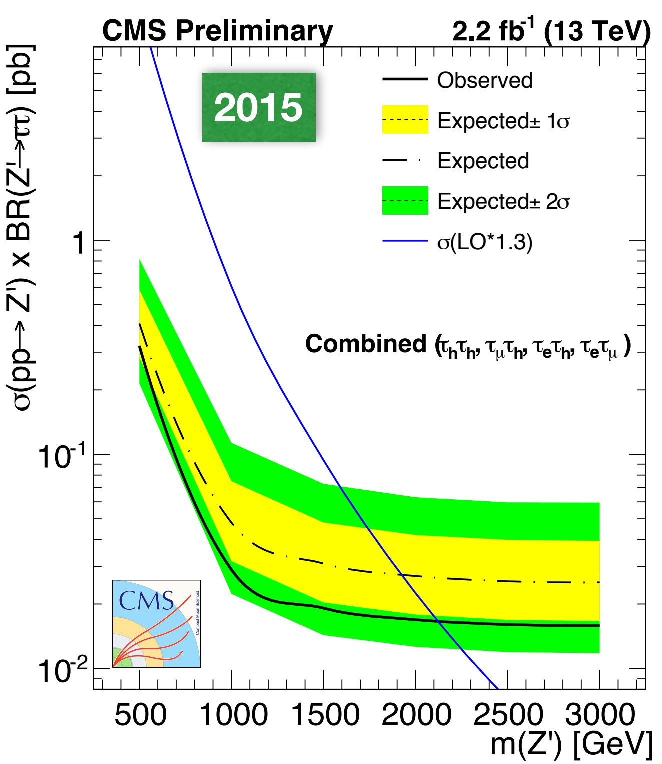
ATLAS CONF-2017-027

ATLAS CONF-2017-016

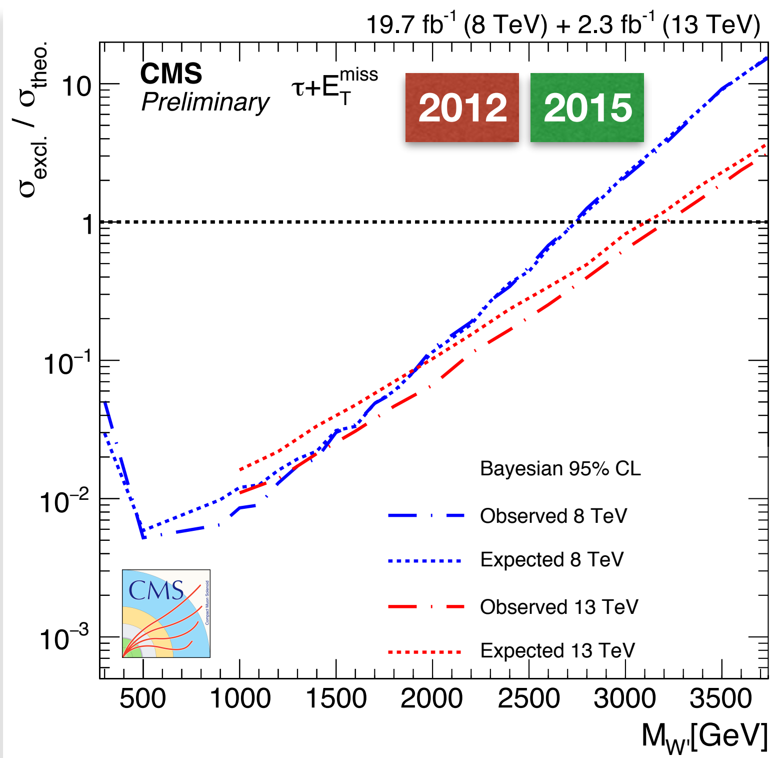
Z'/W' in τ channels

- 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



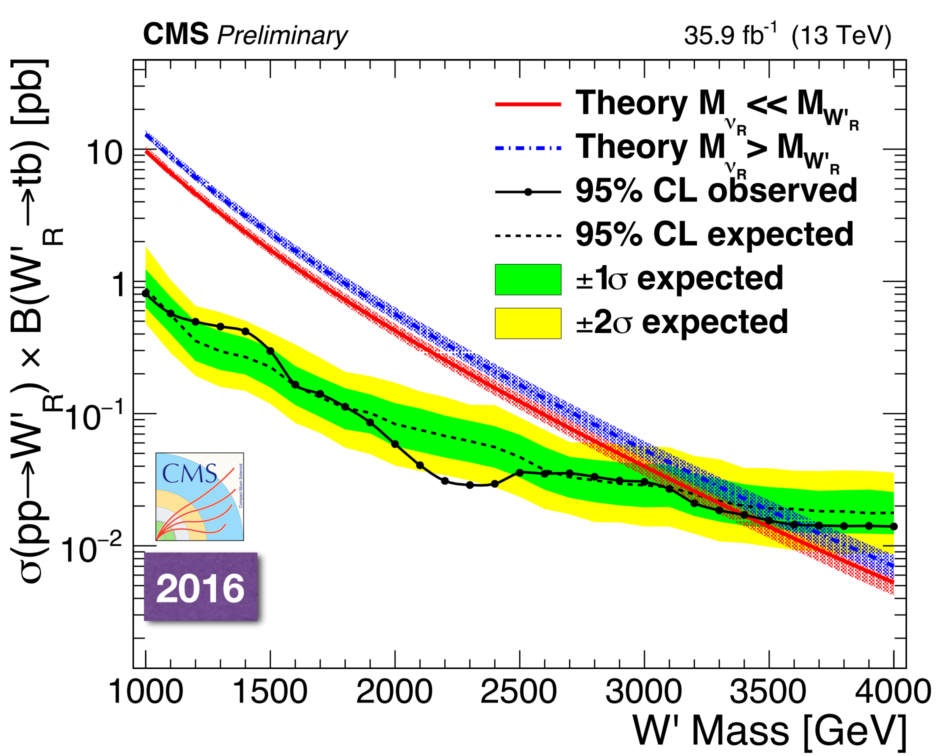
CMS PAS EXO-16-006

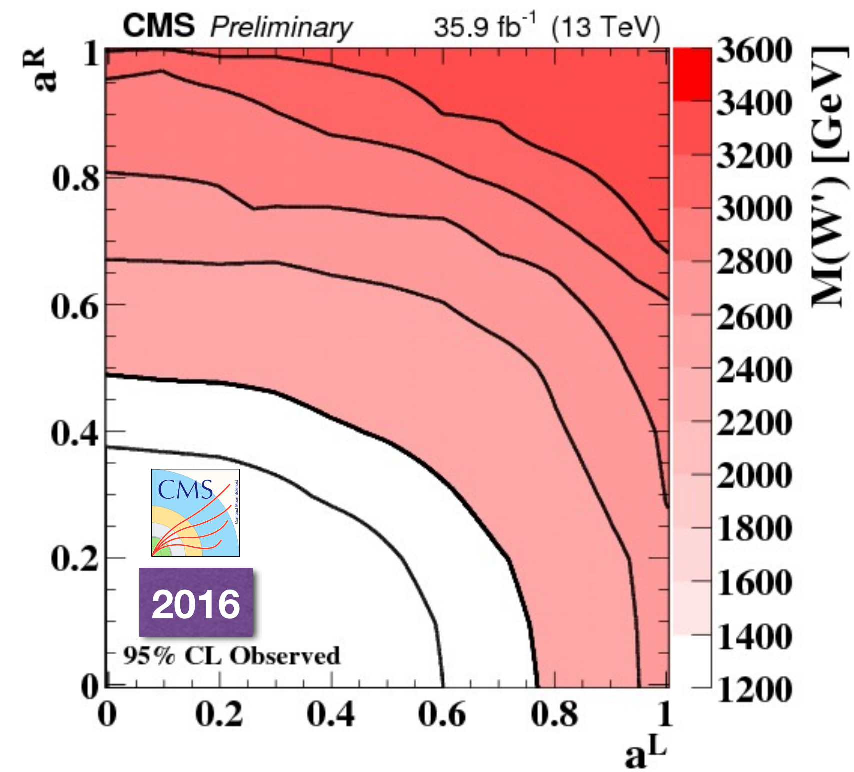


W'_R(tb) Search

- 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

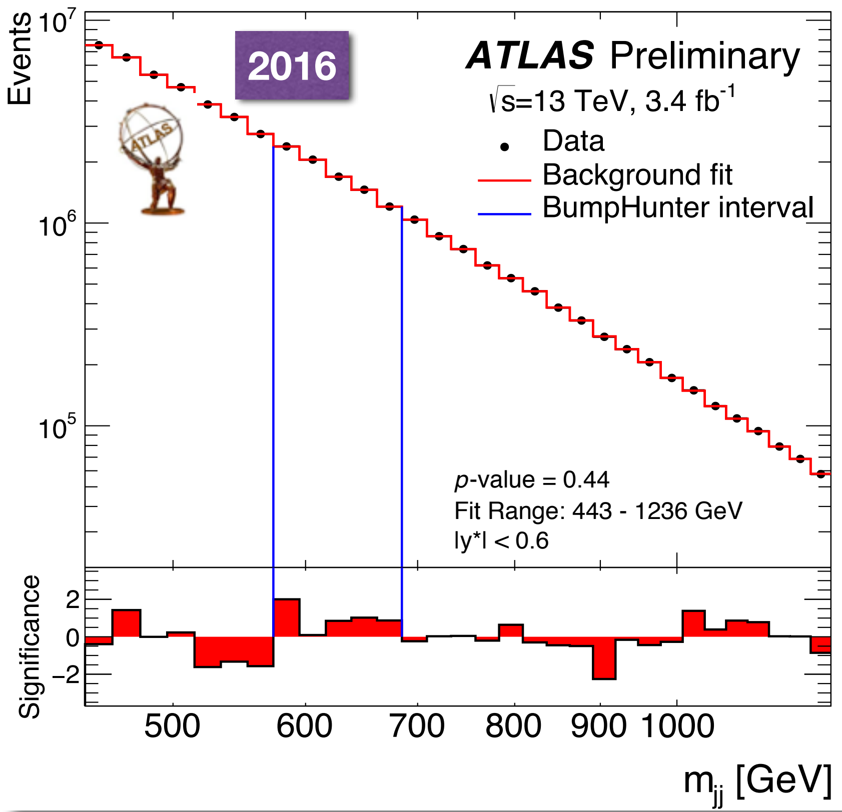




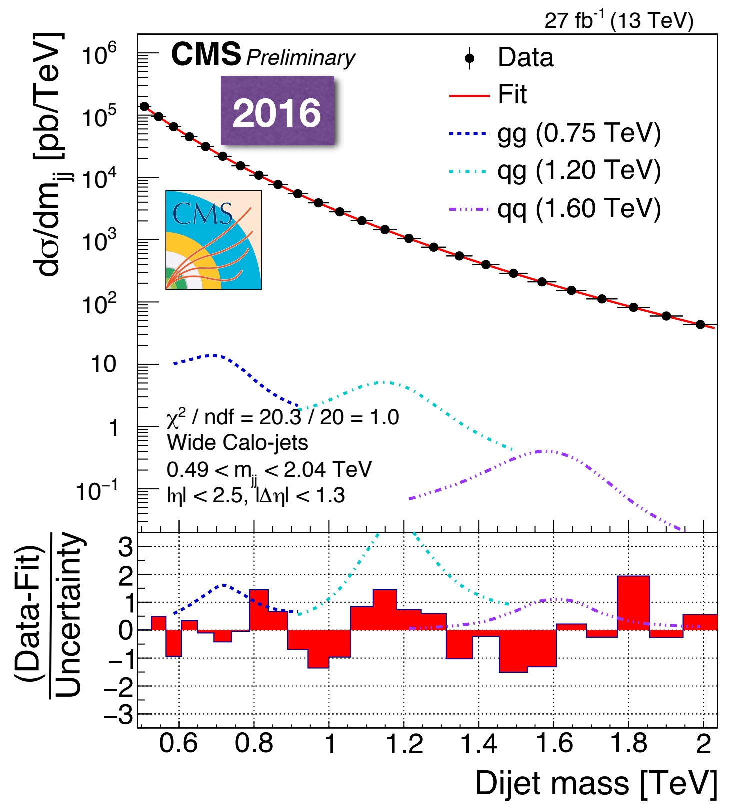
Dijet Resonance Searches

- 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

ATLAS CONF-2016-030



CMS PAS EXO-16-056



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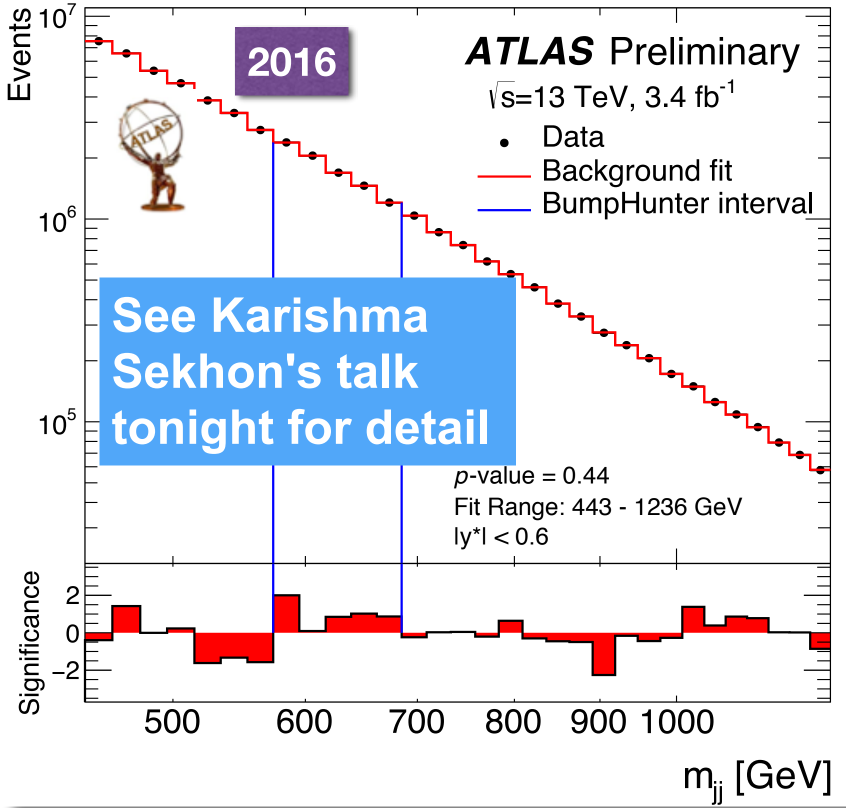
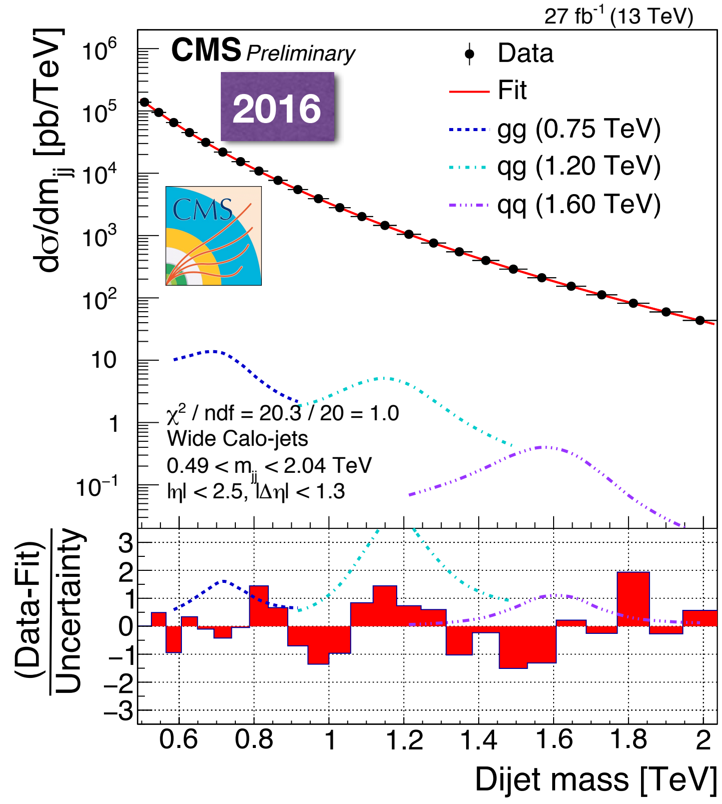
ATLAS CONF-2016-030



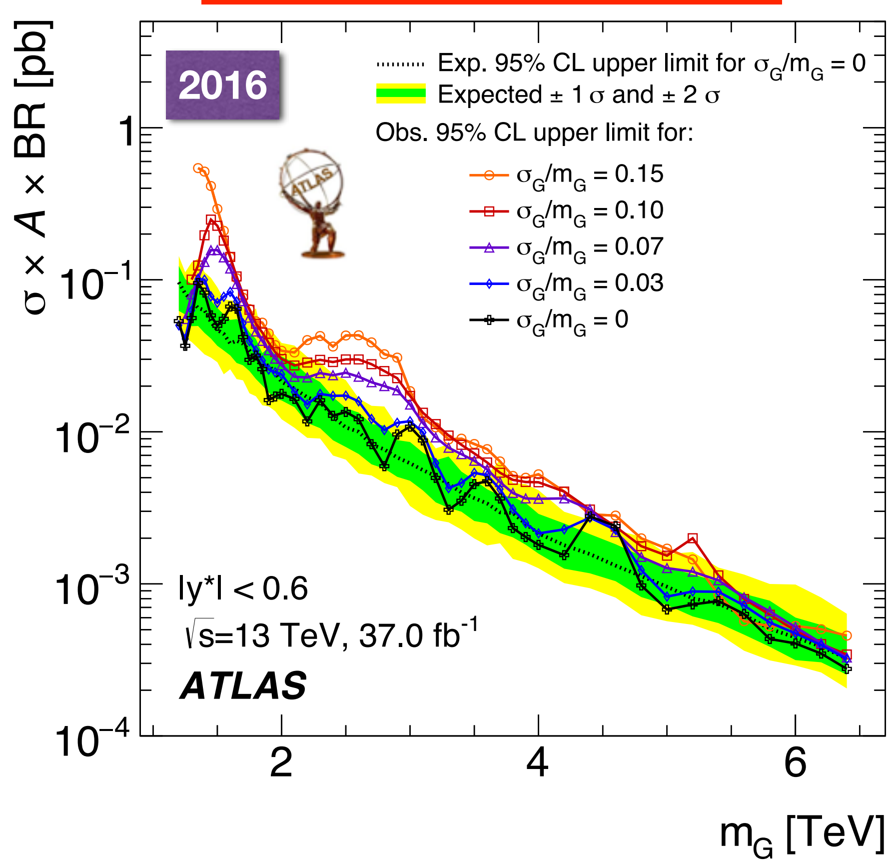
CMS PAS EXO-16-056



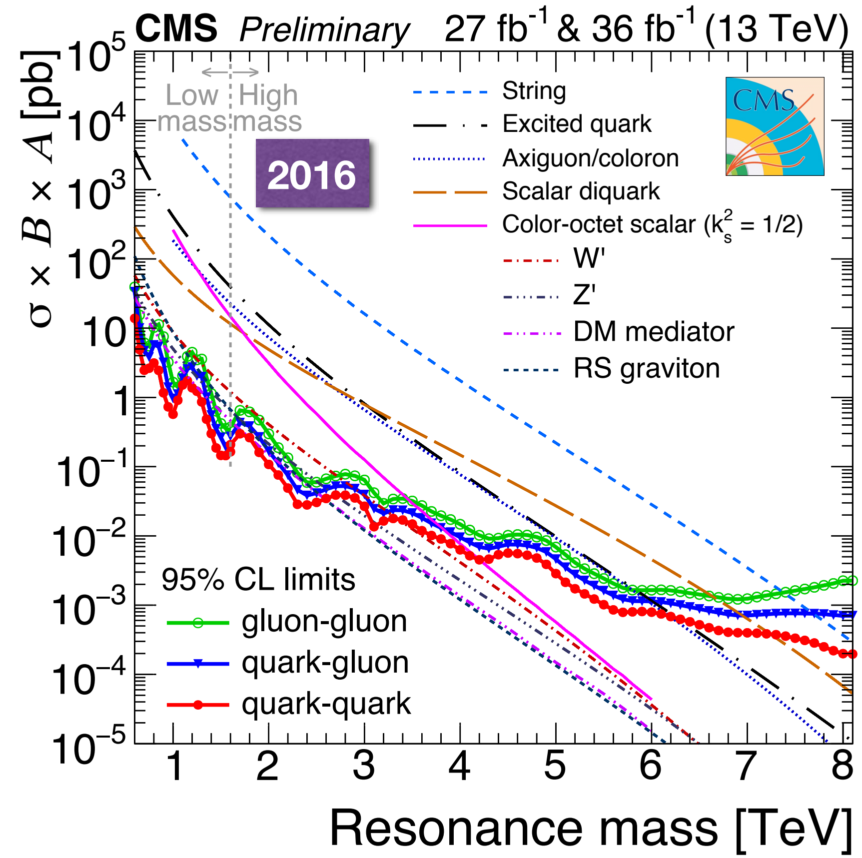
Generic Resonance Limit

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

ATLAS arXiv:1703.09127



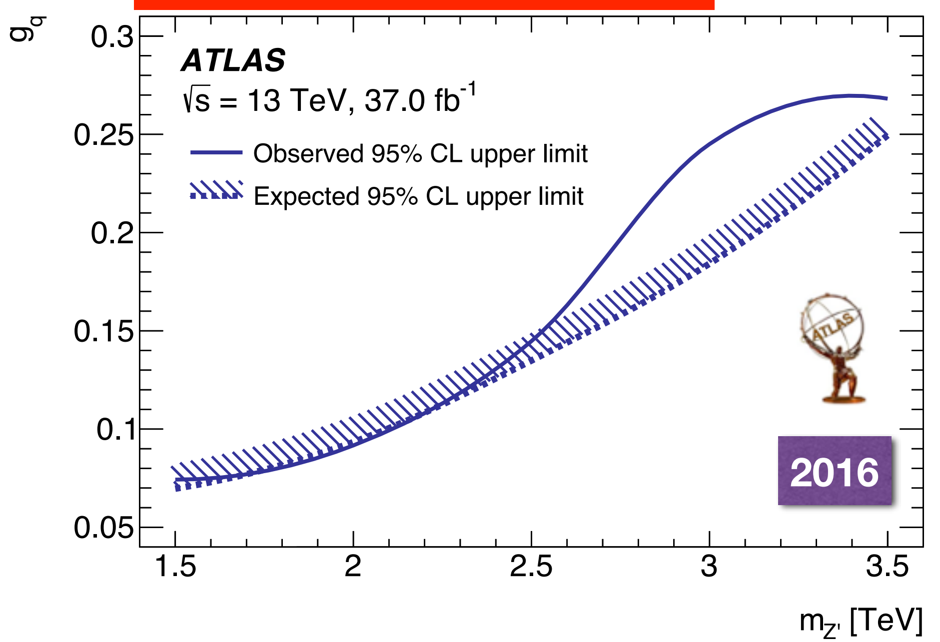
CMS PAS EXO-16-056



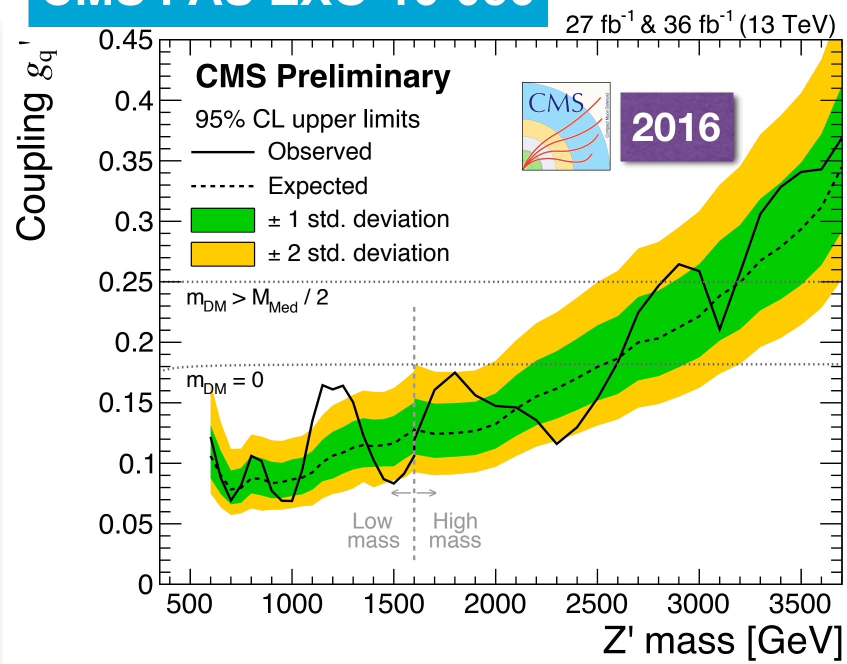
Dijets: Convenient Language

- 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 $g_q = g_B/6$

ATLAS arXiv:1703.09127



CMS PAS EXO-16-056

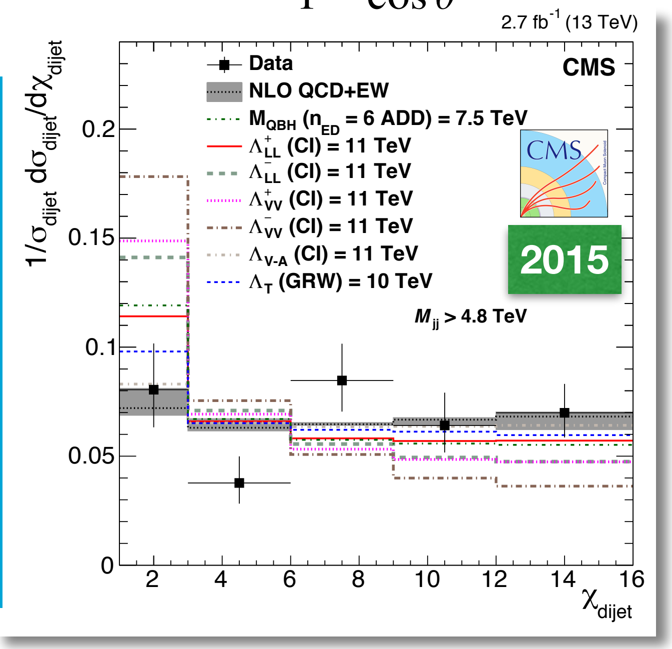


Angular Dijet Analysis

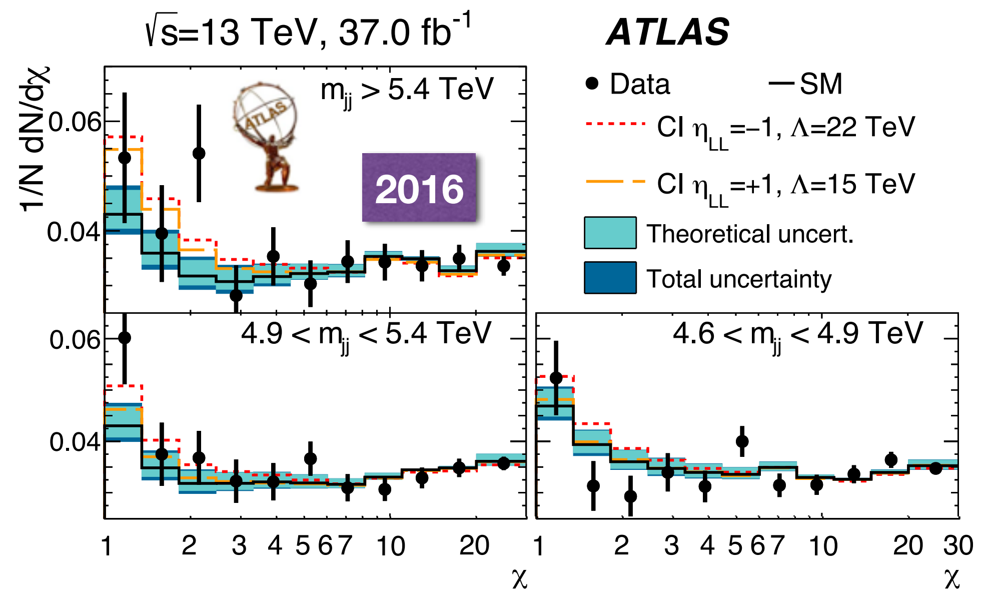
- Using the χ variable:

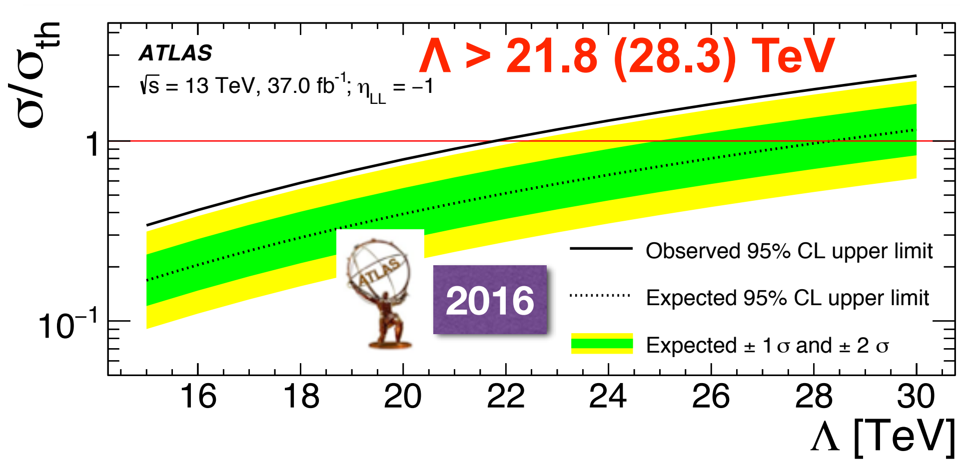
$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

CMS arXiv:1703.09986



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



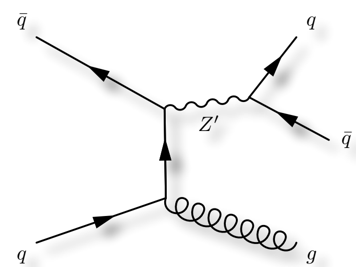


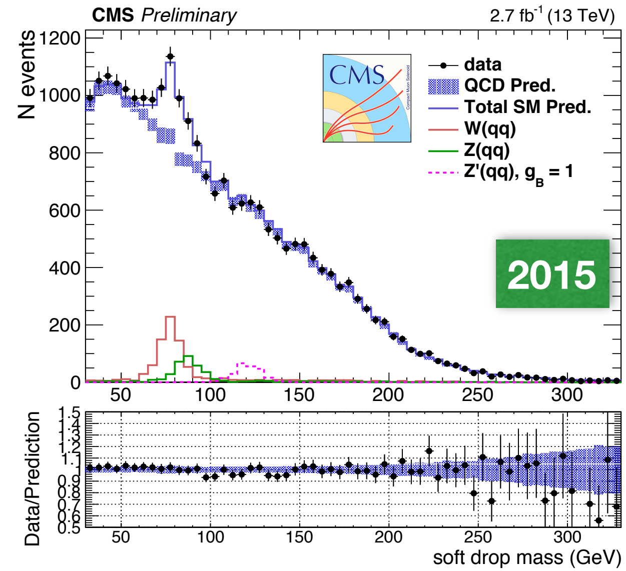
ATLAS arXiv:1703.09127

Not-So-Low Hanging Fruit

Trijets/jjγ as a Dijet Proxy

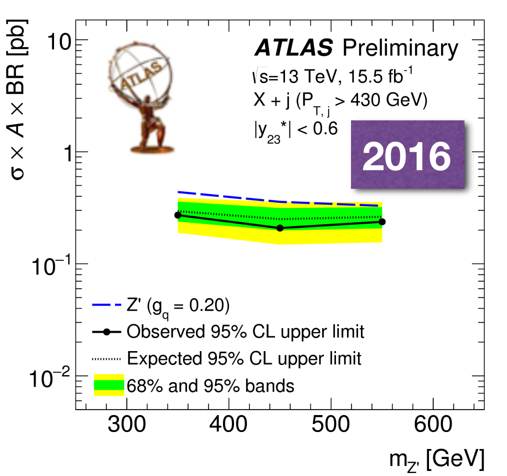
- Another way to look for low-mass dijets is to use photon or jet ISR to aid triggering and utilize jet substructure techniques to reconstruct boosted Z'
- Allows to lower the dijet mass reach to ~100 GeV, as demonstrated with the W/Z peak observation in CMS

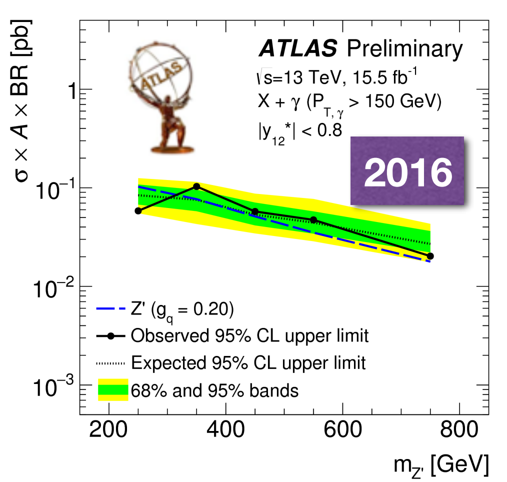


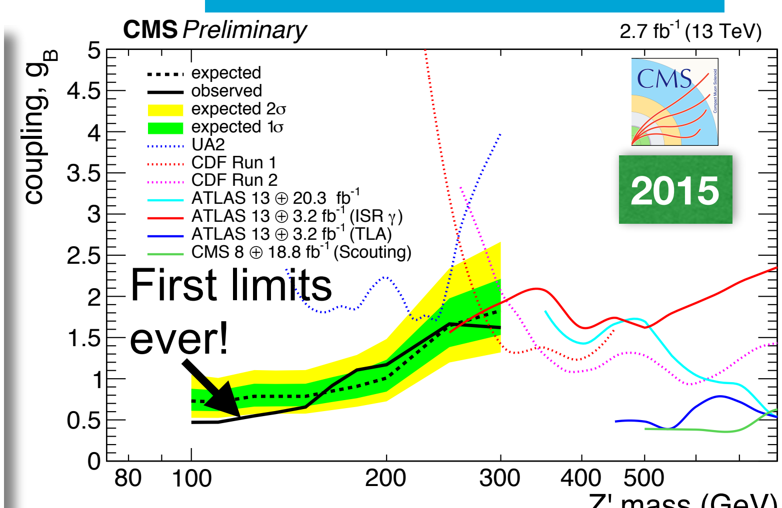


CMS PAS EXO-16-030

ATLAS CONF-2016-070

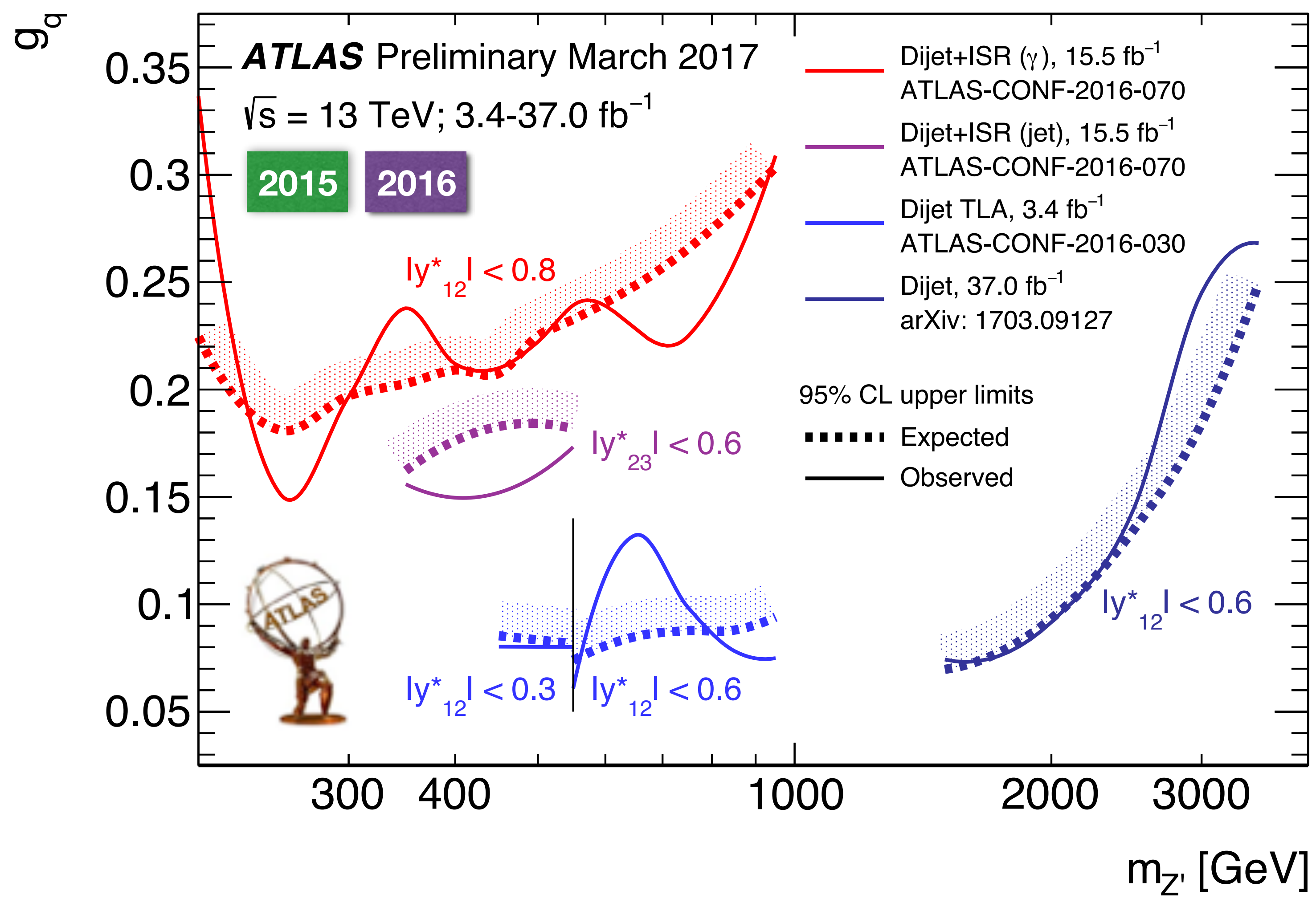






ATLAS Coupling Limits

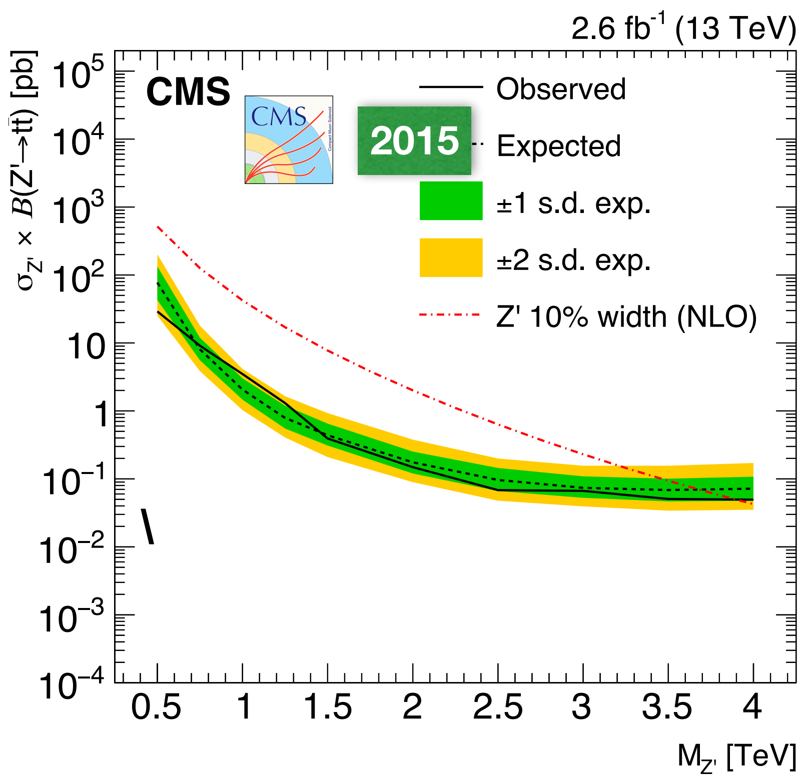
- Limits on the coupling q_g from various searches:



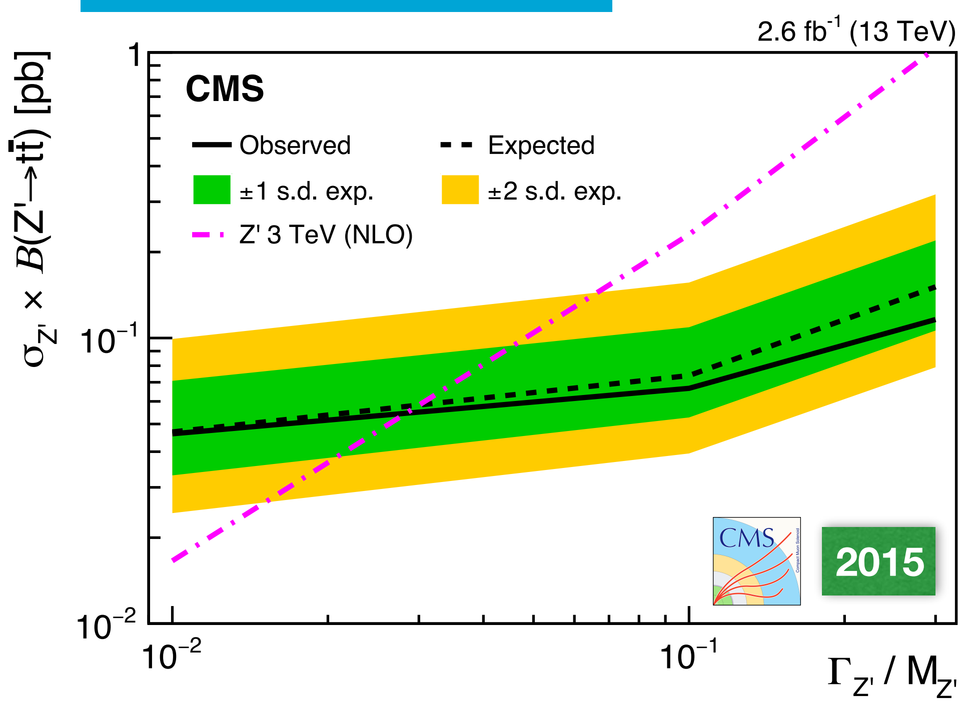
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_DarkMatter_Summary

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

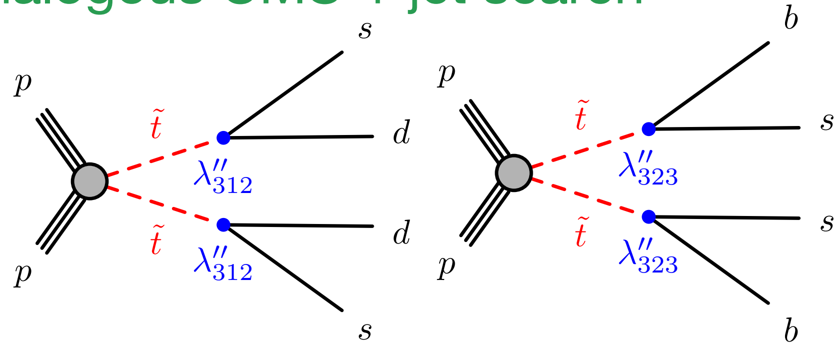


CMS arXiv:1704.03366

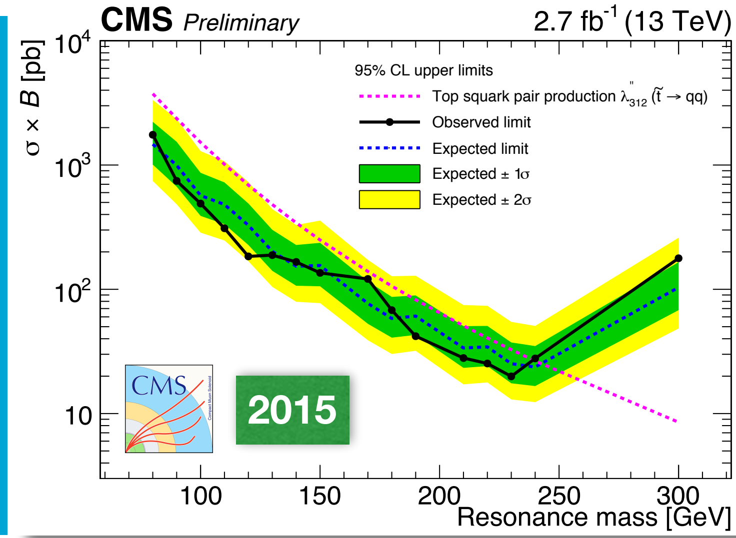


Pair-Produced Dijet Resonances

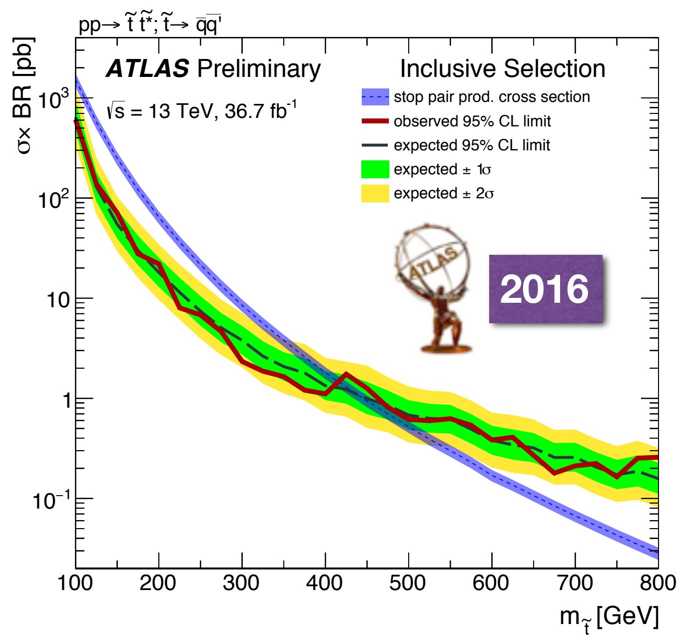
- ATLAS search for RPV top squark pair production with 4 jets and jjbb, and an analogous CMS 4-jet search

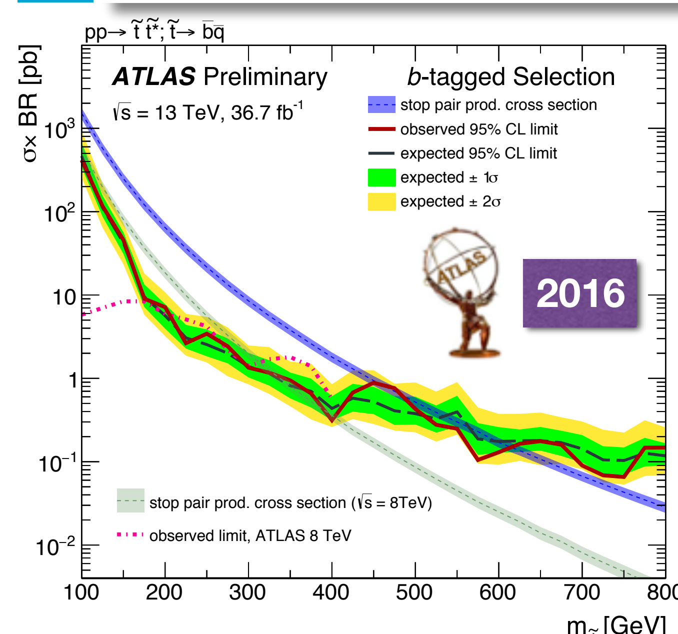


CMS PAS EXO-16-029



ATLAS CONF-2017-025

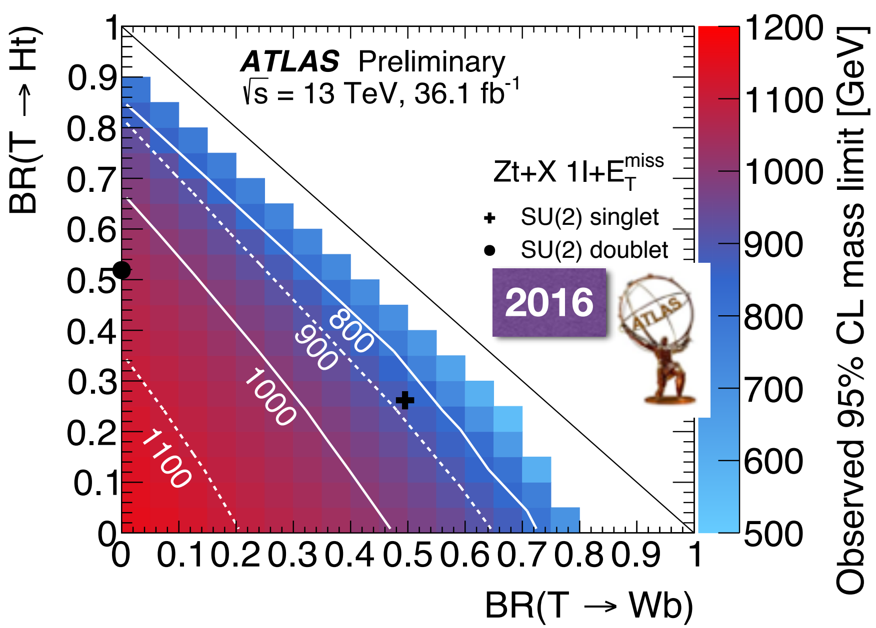




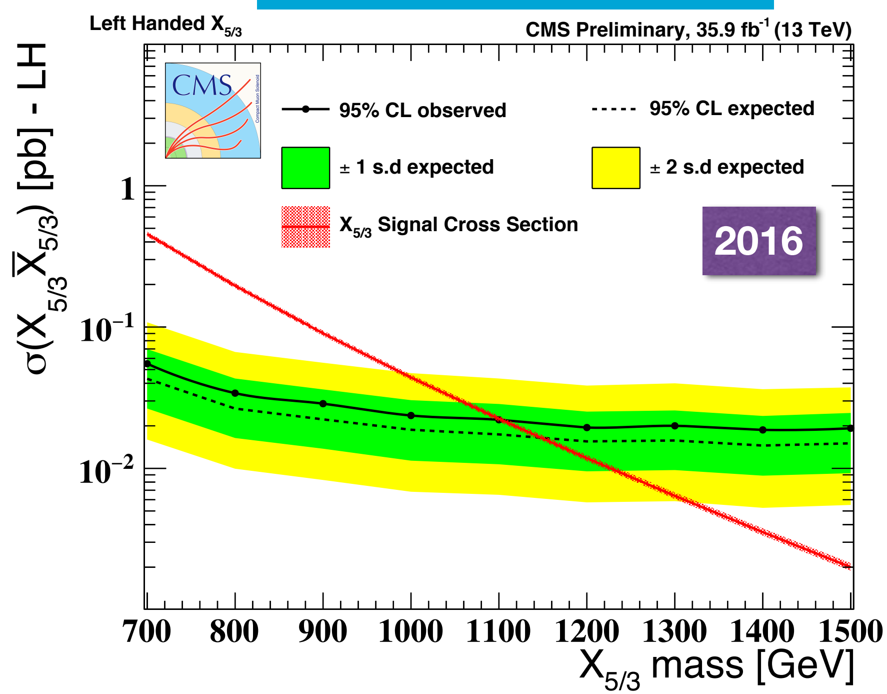
Pair-Produced VLQ Searches

- Classical T pair production searches:
  - T2/3 pair production, with T → bW, tZ, tH (semileptonic final states with multiple b tags); also tt+heavy flavors
  - T5/3 pair production, with T → tW (SS dileptons)
- Limits exceed similar ones set in Run 1 by ~250 GeV

ATLAS CONF-2017-015



CMS PAS B2G-16-019



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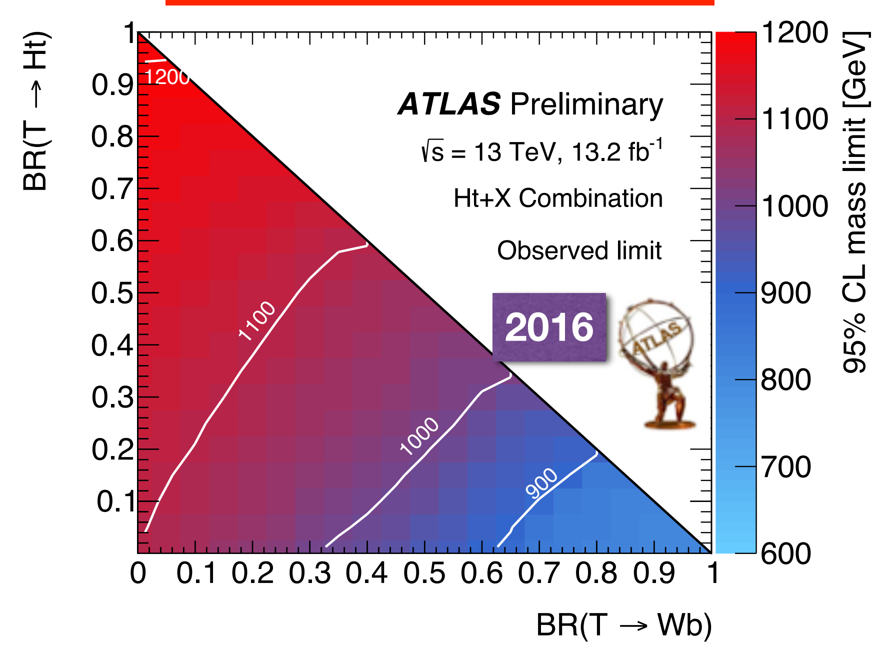
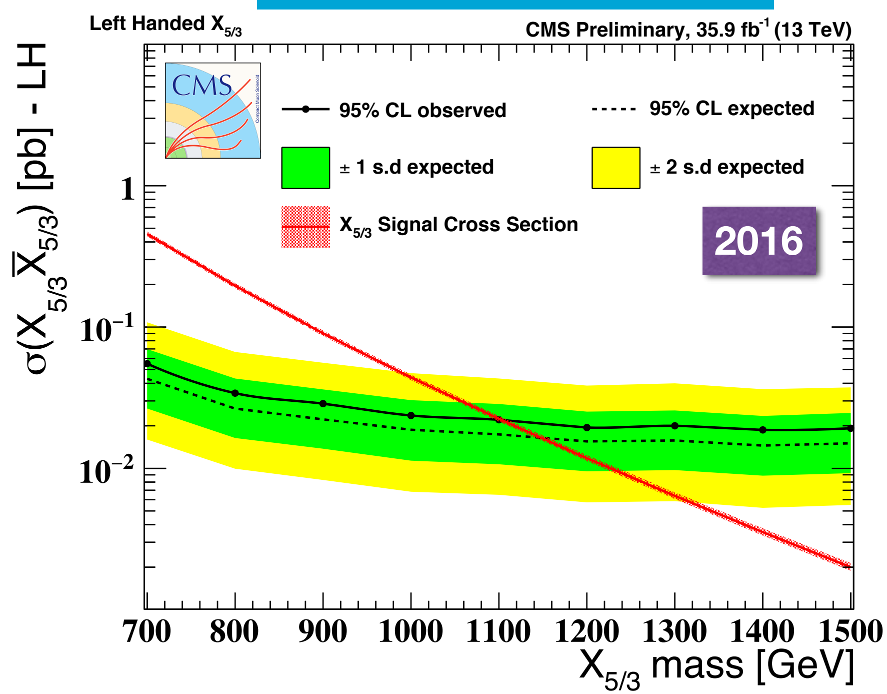
ATLAS CONF-2016-104



CMS PAS B2G-16-019



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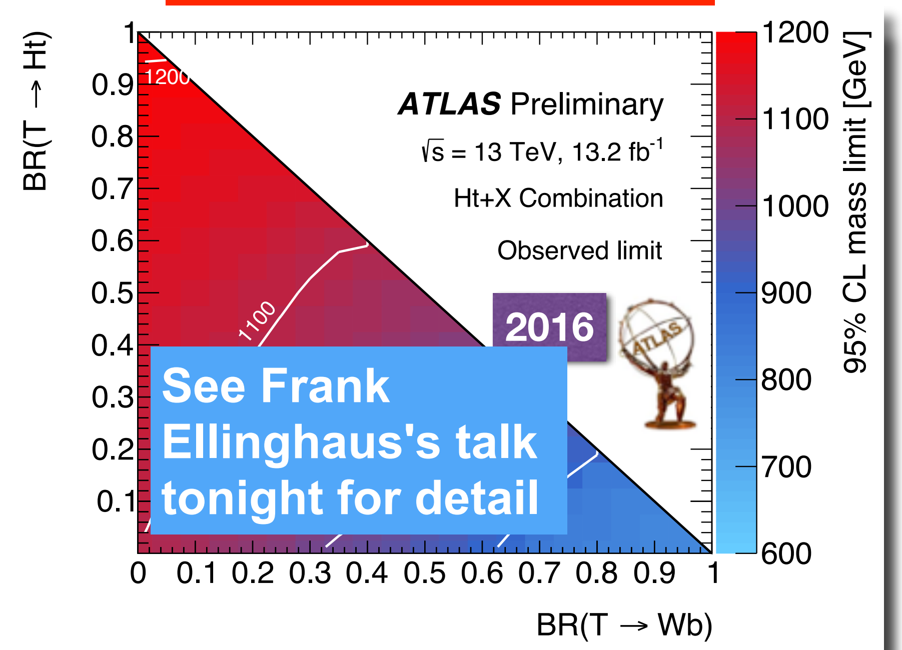
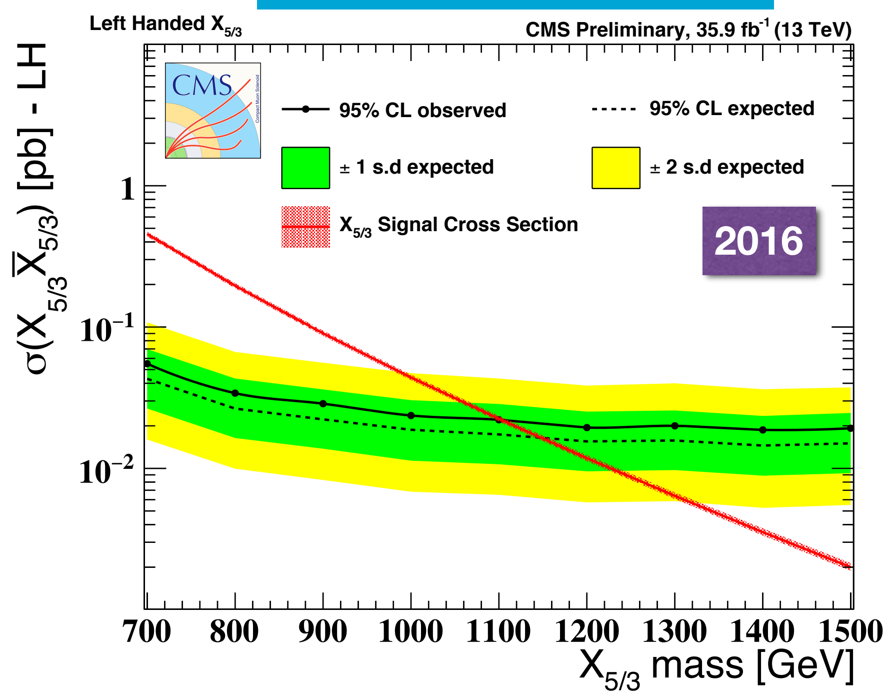
ATLAS CONF-2016-104

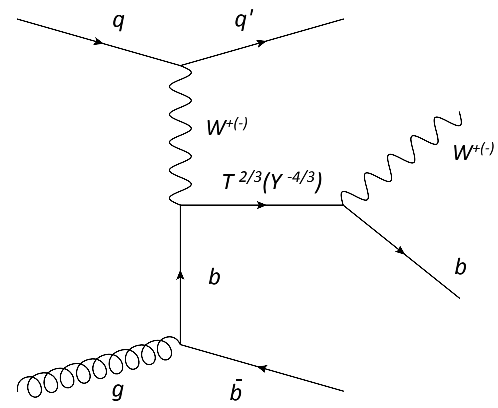


CMS PAS B2G-16-019

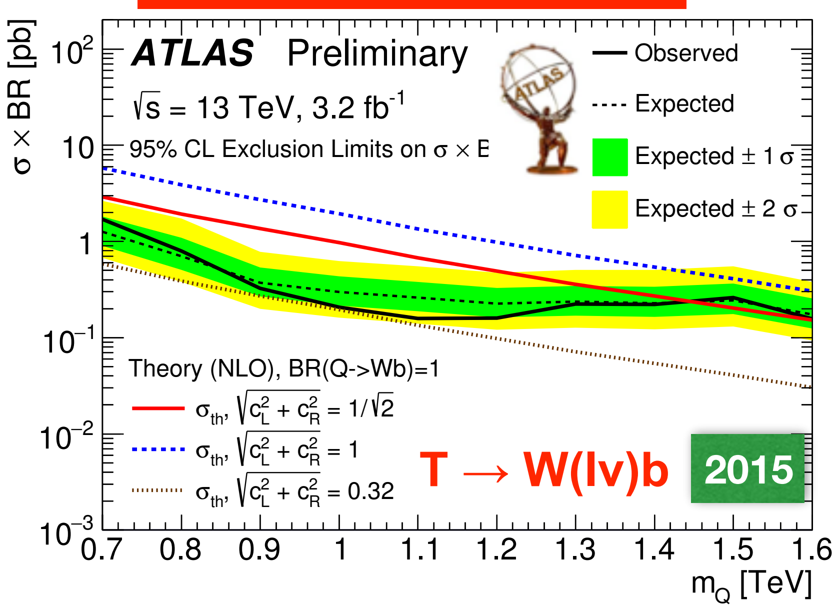


Single VLQ Production

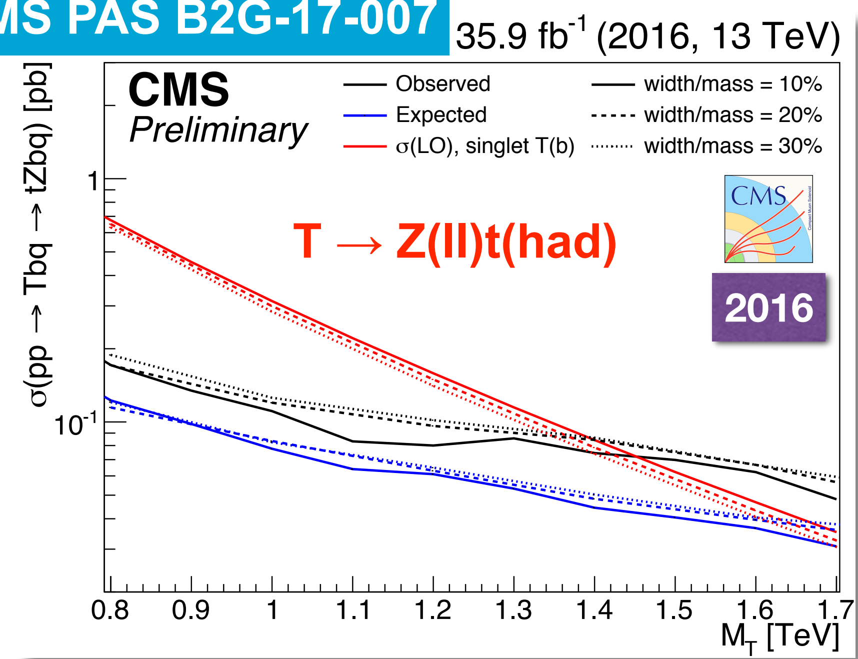
- Several VLQ searches with new data, including singly, EW produced VLQs in Wb, Zt, Zb channels
  - Limits are set on the VLQ mass for a fixed VLQ-W-b or VLQ-Z-t coupling/width or on the coupling as a function of the VLQ mass



ATLAS CONF-2016-072

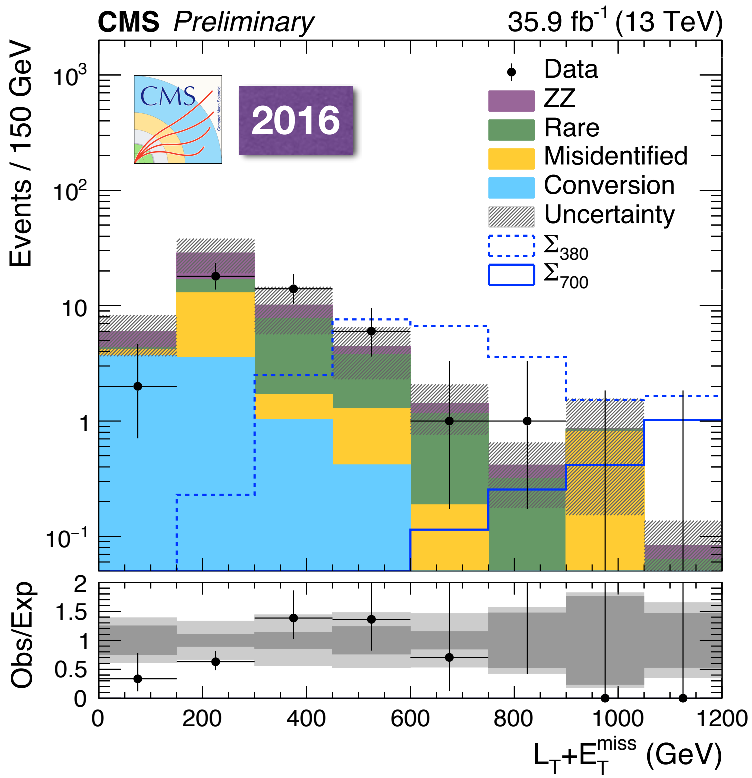


CMS PAS B2G-17-007

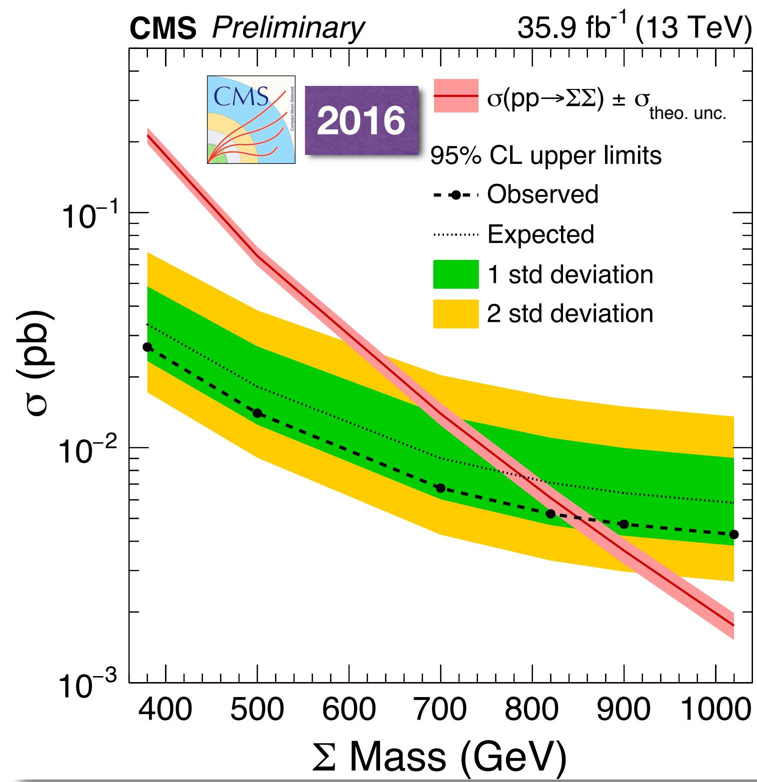


Type III Seesaw Search

- 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



High-Hanging Fruit

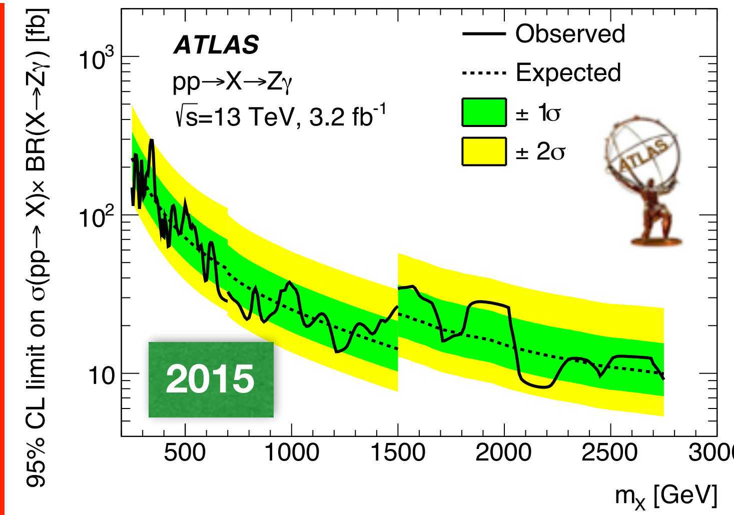
Diboson Searches

- 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

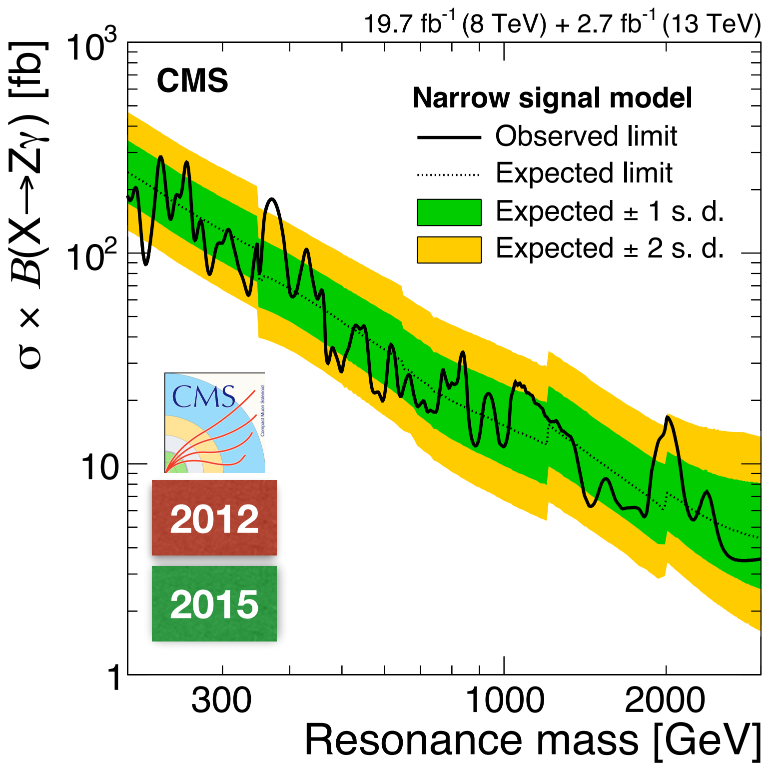
Zγ Searches

- 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)
  - A bit of an excess seen around 2 TeV in 2015 data; not confirmed w/ partial 2016 data

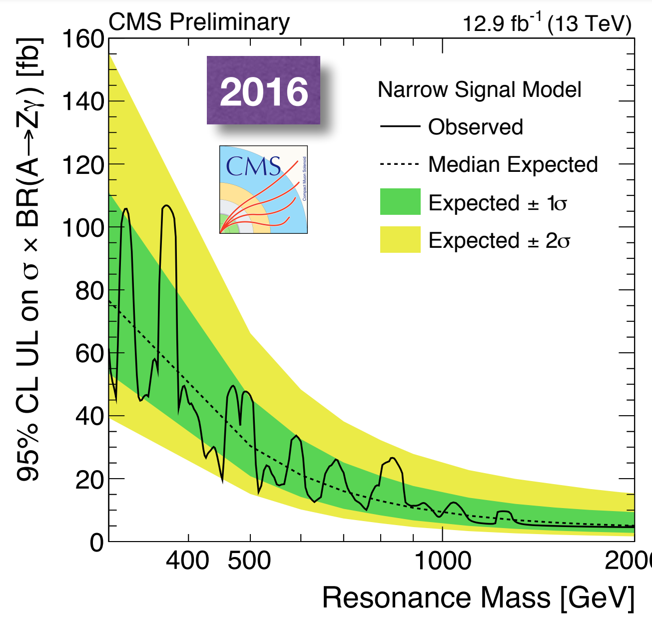
ATLAS arXiv:1607.06363



CMS arXiv:1612.09516



CMS PAS EXO-16-034



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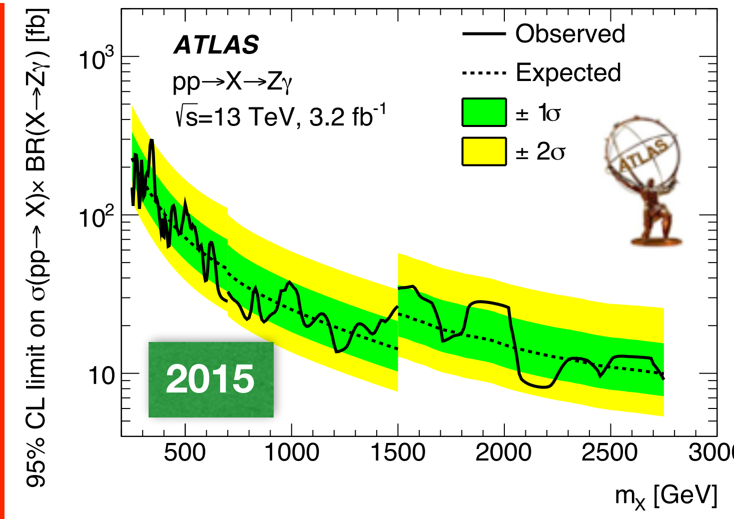
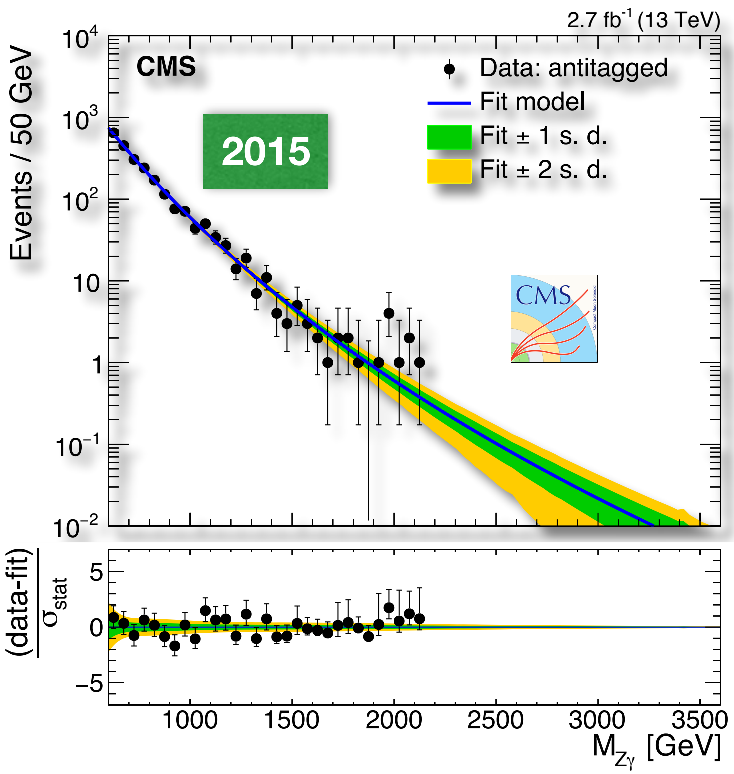
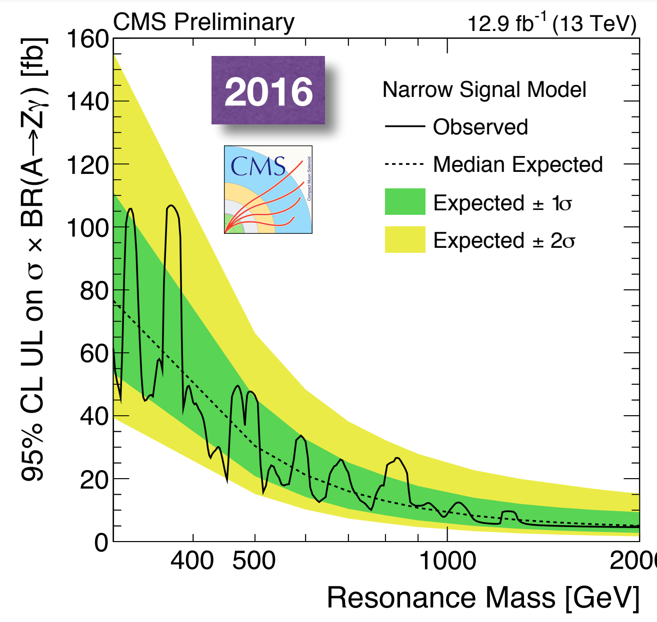
ATLAS arXiv:1607.06363



CMS arXiv:1612.09516



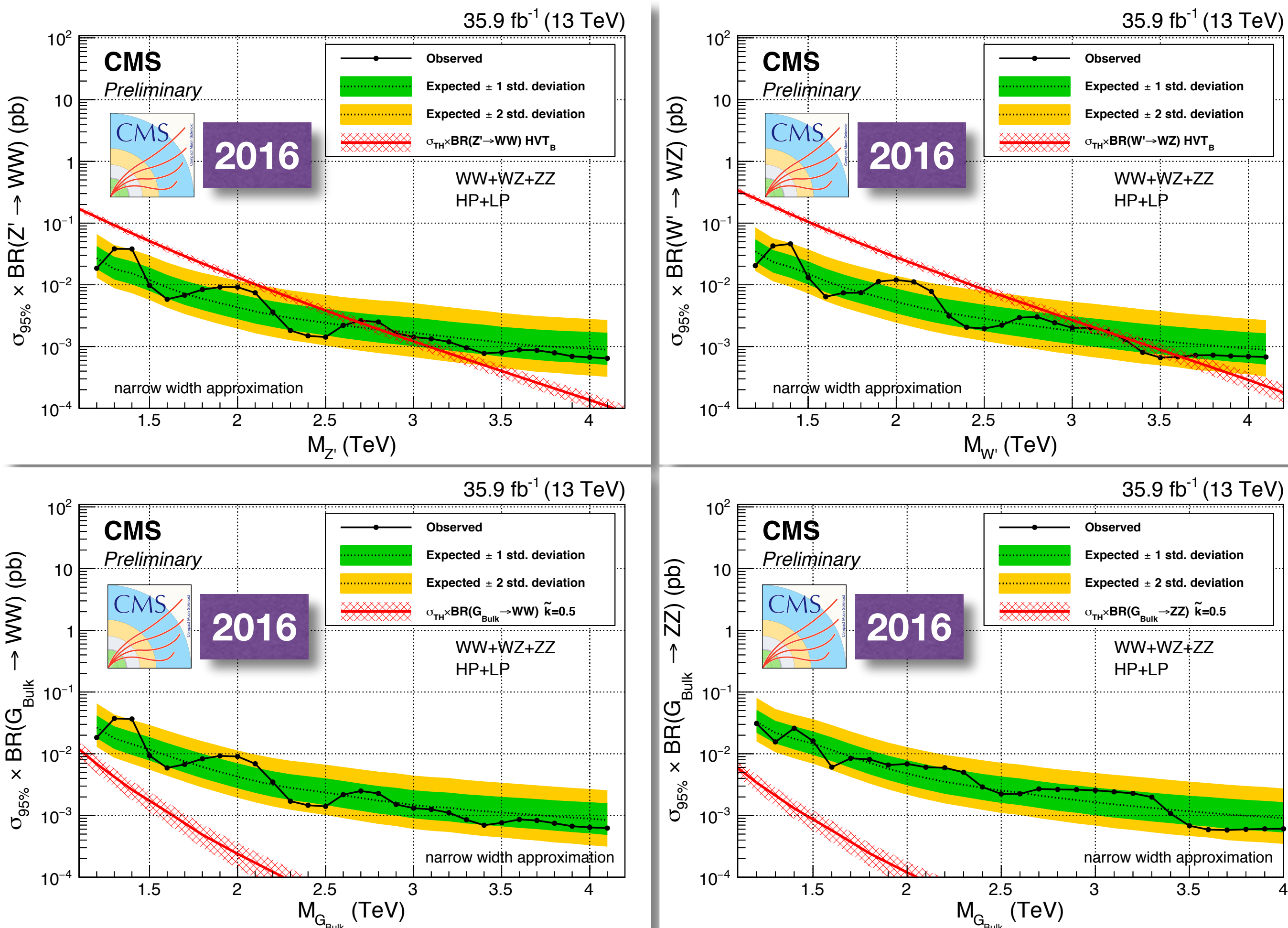
CMS PAS EXO-16-034



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



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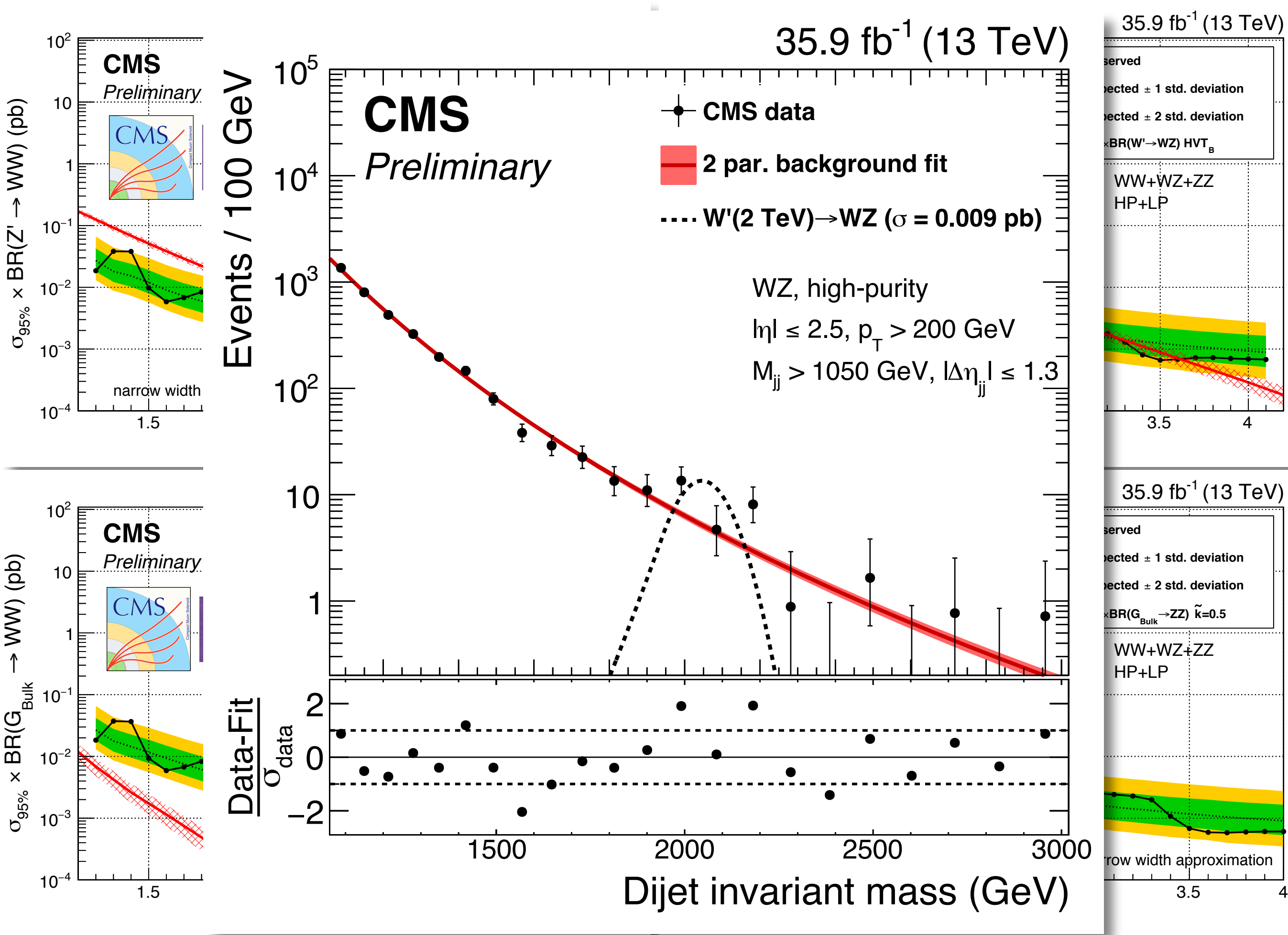
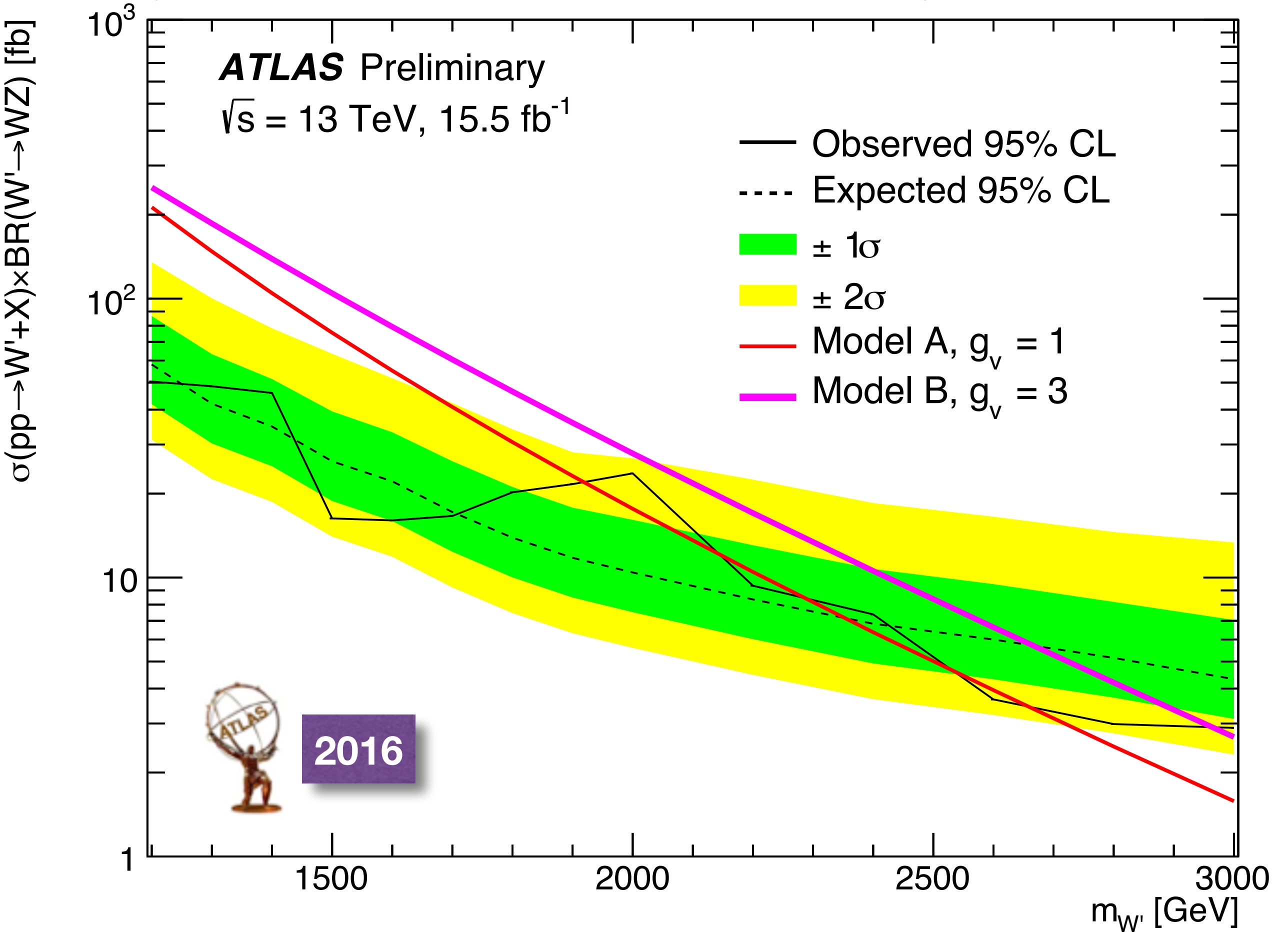


VV All-Hadronic (cont'd)

- 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

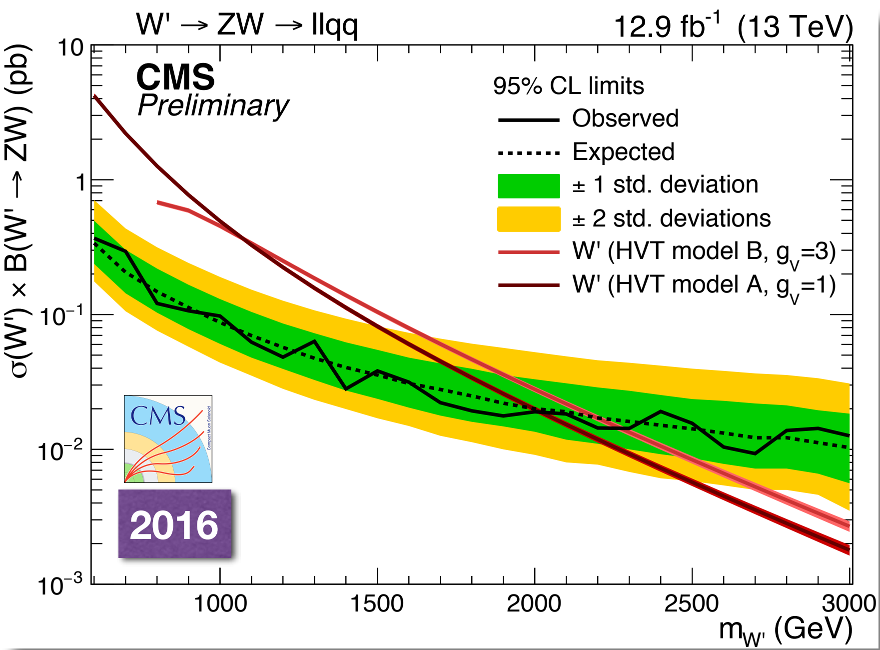
ATLAS CONF-2016-055



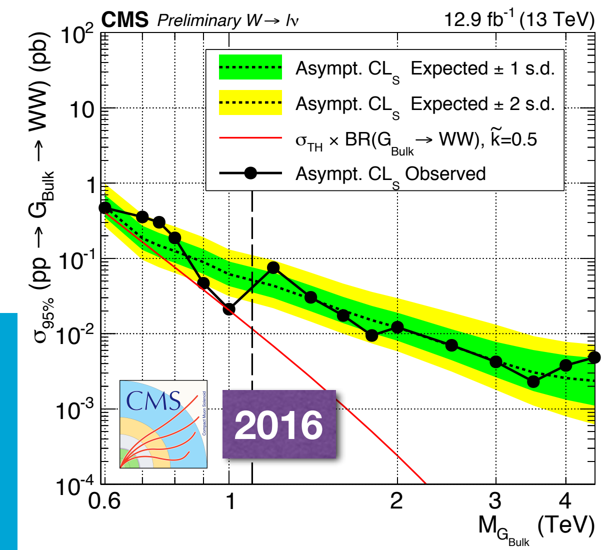
VV Semileptonic Searches

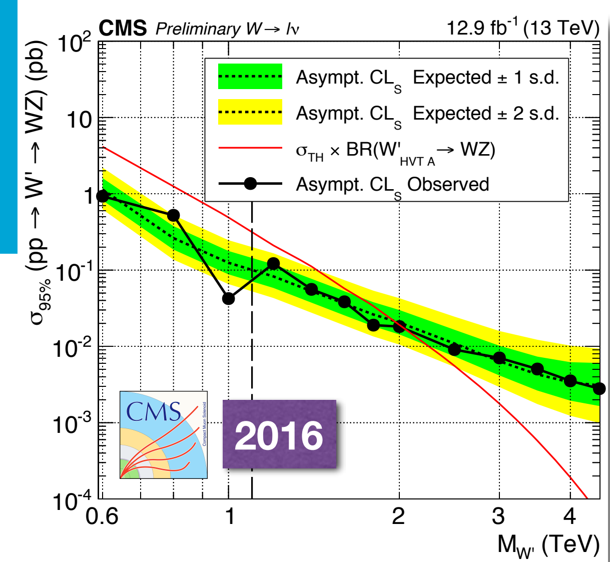
- Most recent CMS WW/WZ search in the lvjj channel (jj form a jet w/ substructure) and WZ in the lljj channel
  - No evidence for statistically significant excess in the 0.6-4.5 TeV range
  - See absolutely no excess at 2 TeV with 1/3 of the full 2016 data set

CMS PAS B2G-16-022



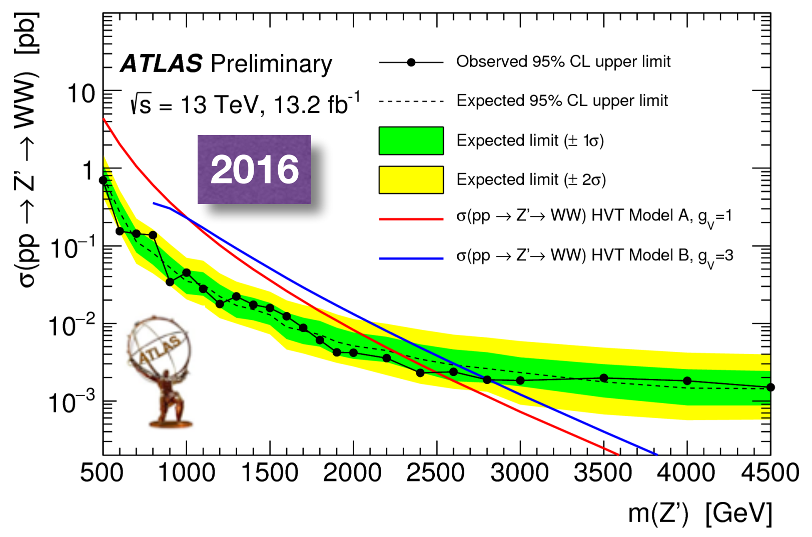
CMS PAS B2G-16-020

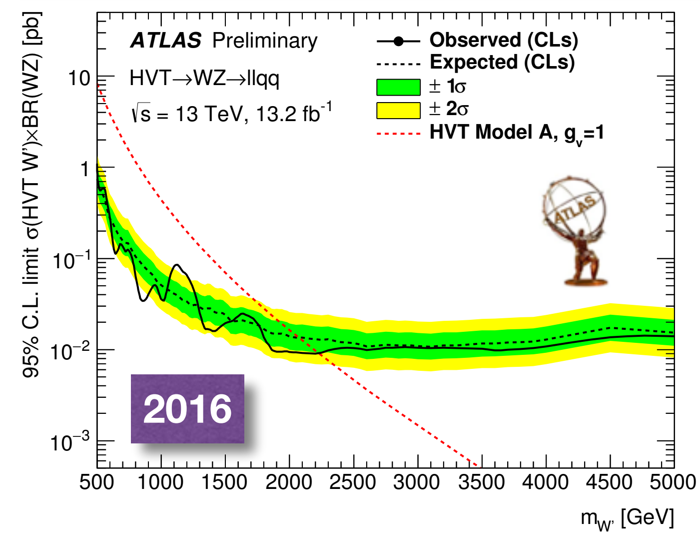




VV Semileptonic (cont'd)

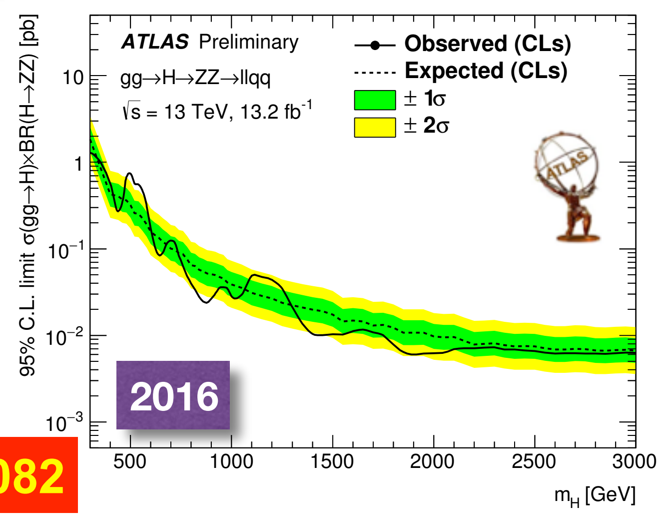
✦ ... and neither does ATLAS - the puzzle still stands...





ATLAS CONF-2016-062

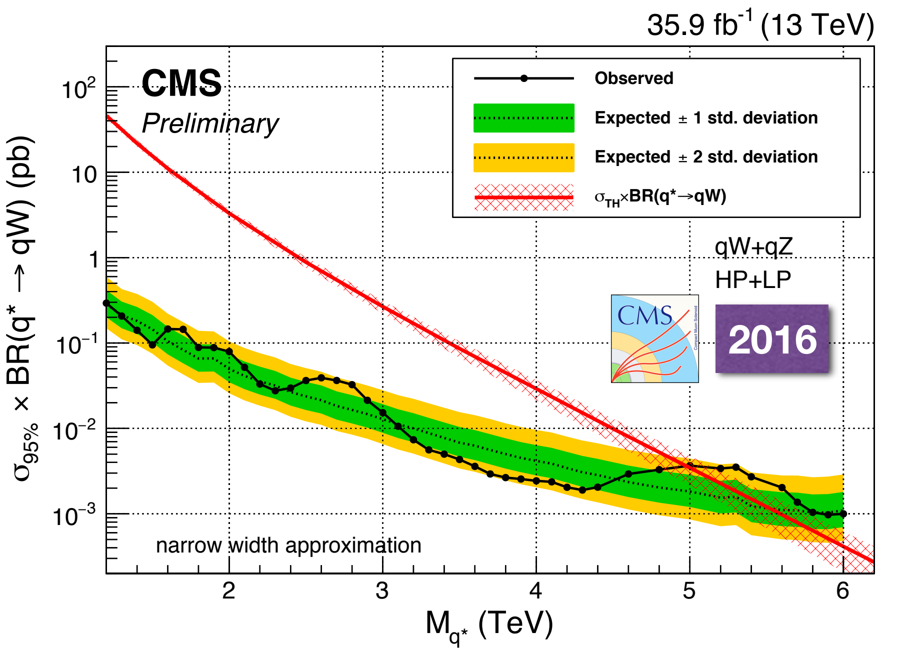
ATLAS CONF-2016-082

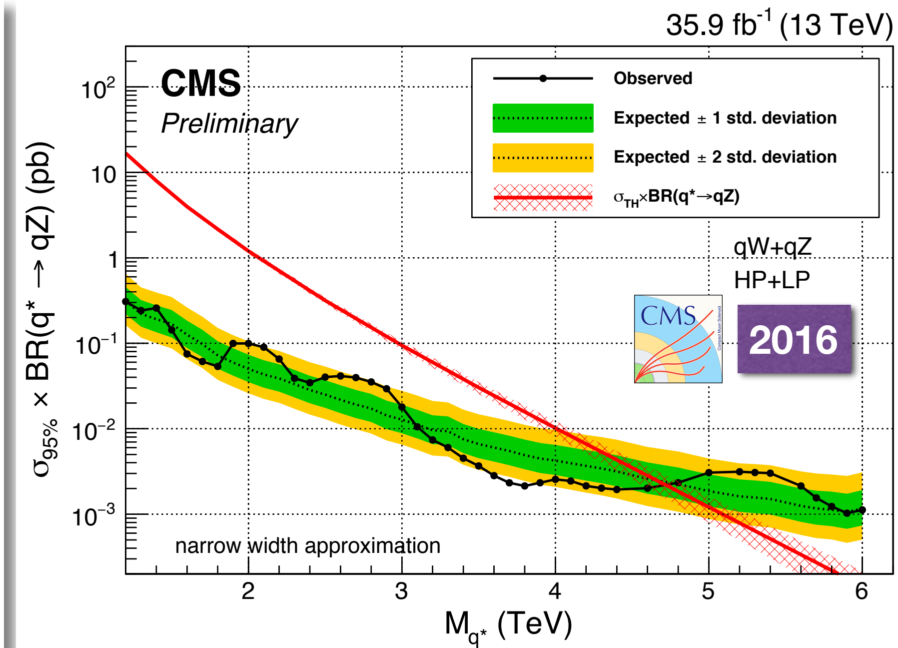


ATLAS CONF-2016-082

Search for Vq Resonances

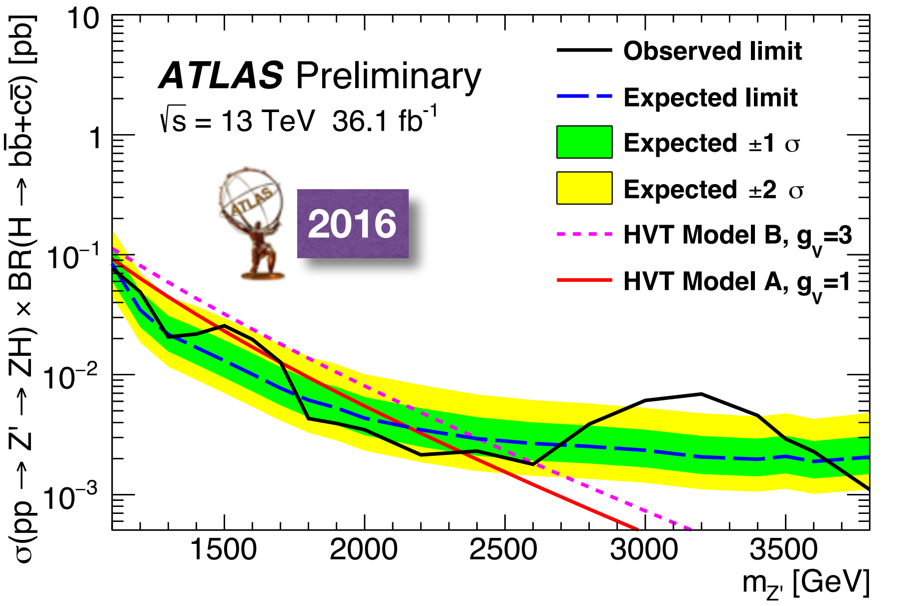
- Could also interpret the all-hadronic search as a search for Vq resonances (q*), with limits reaching 5 TeV

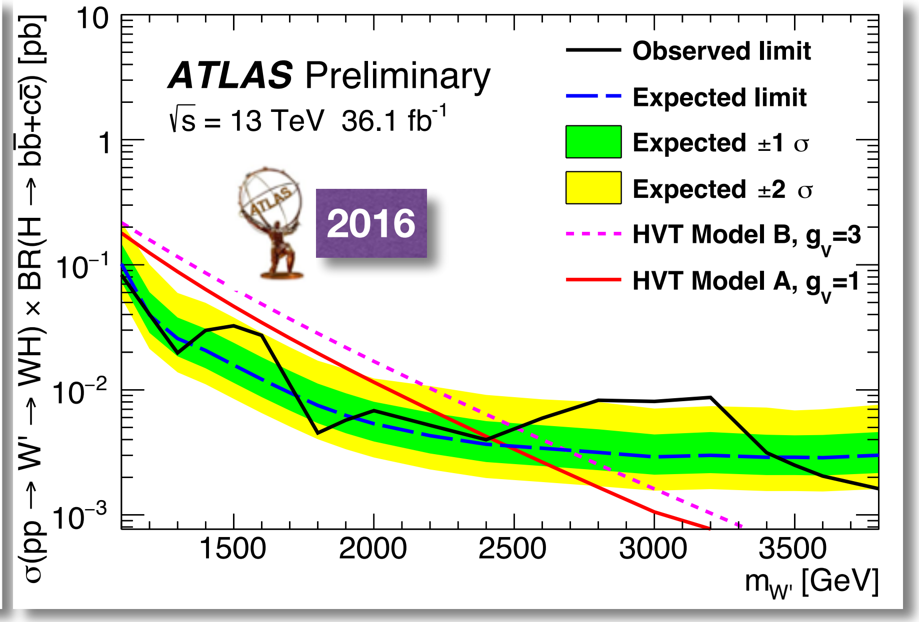




CMS PAS B2G-17-001

- One could instead require a b-tagged jet with substructure on one side and look for VH resonances
  - ATLAS sees a ~3.3σ (2.2σ global) bump at ~3 TeV

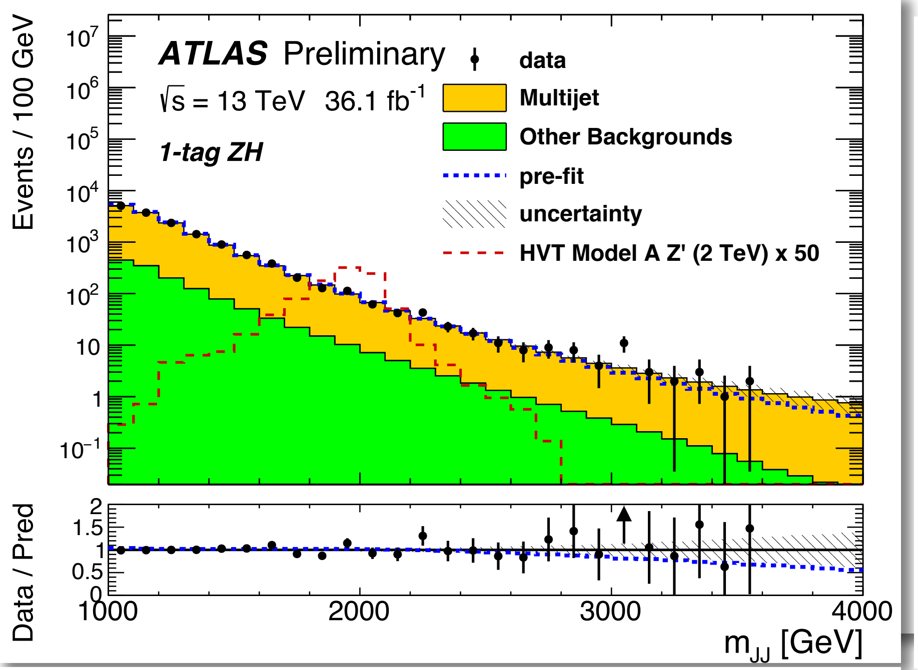


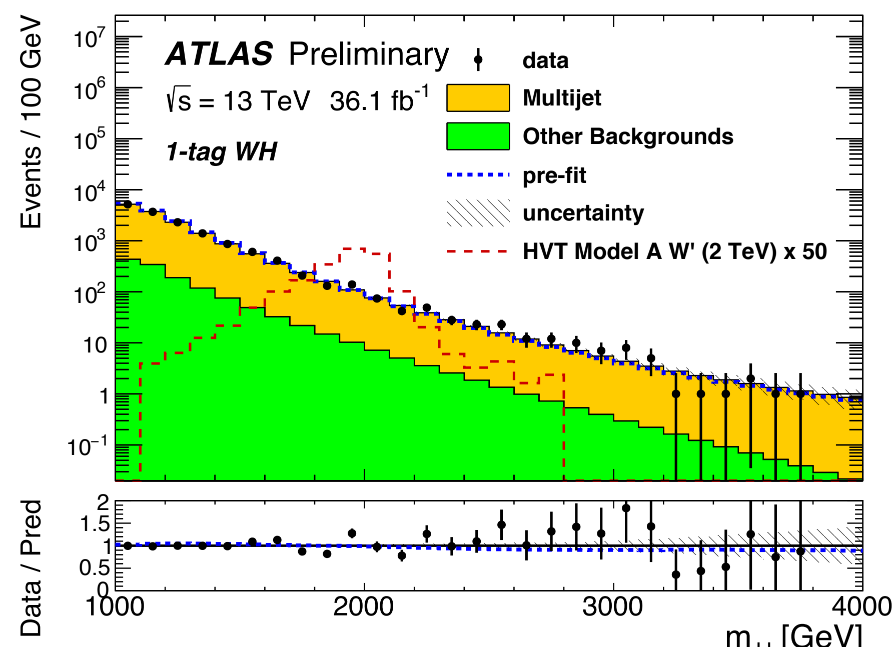


ATLAS CONF-2017-018

Searches for VH Resonances

- One could instead require a b-tagged jet with substructure on one side and look for VH resonances
  - ATLAS sees a ~3.3σ (2.2σ global) bump at ~3 TeV

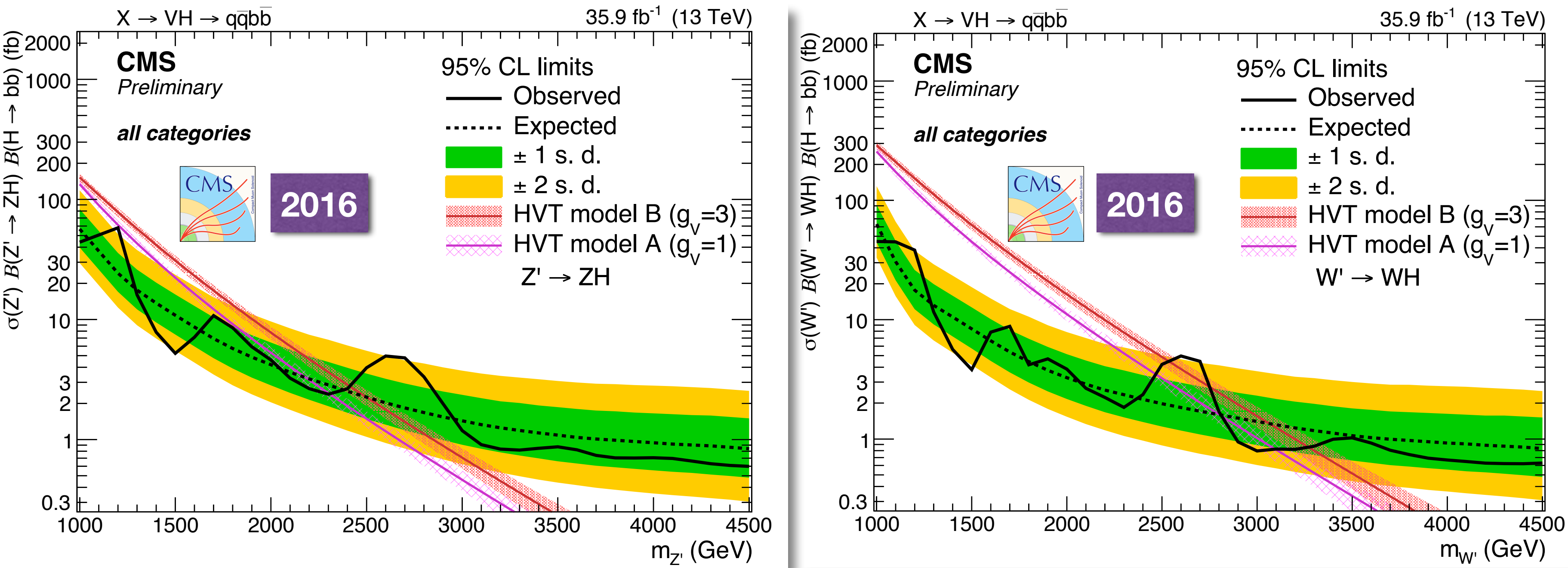




ATLAS CONF-2017-018

Searches for VH (cont'd)

- ...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

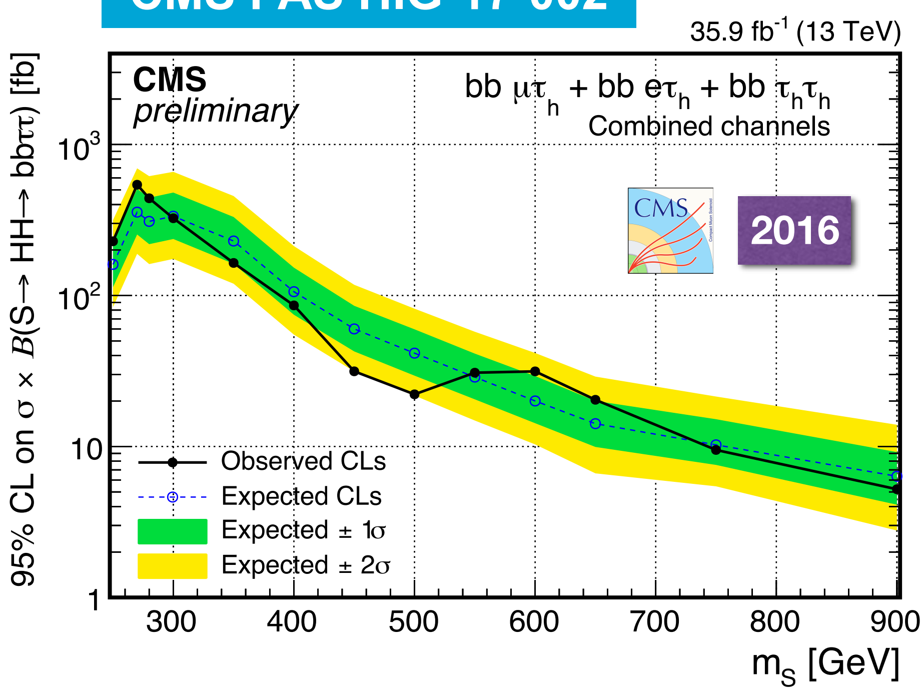


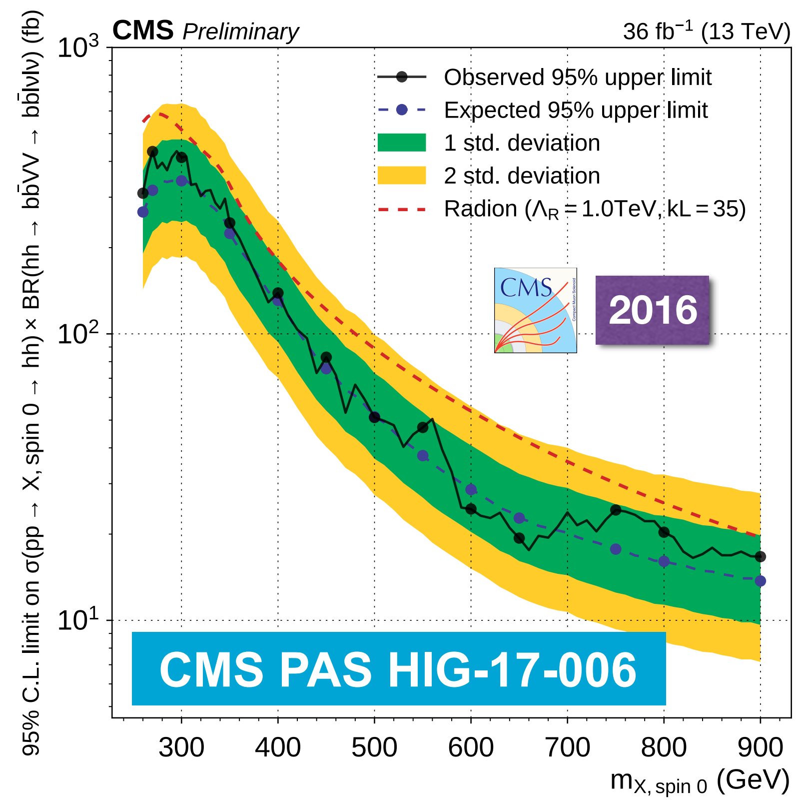
CMS PAS B2G-17-002

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 Ml 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



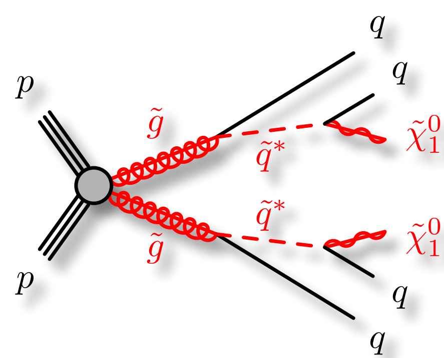


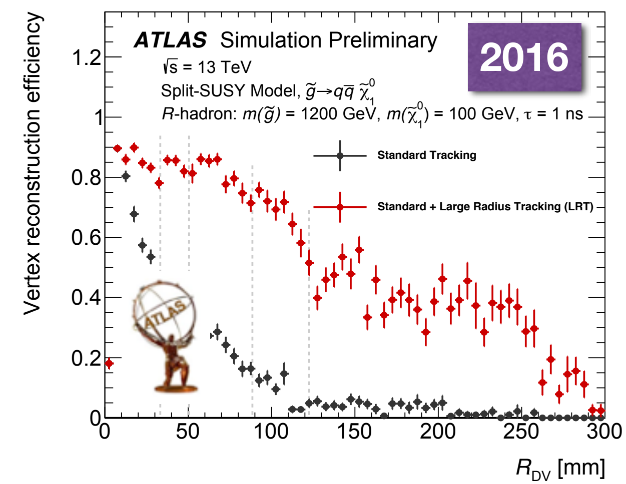
CMS PAS HIG-17-006

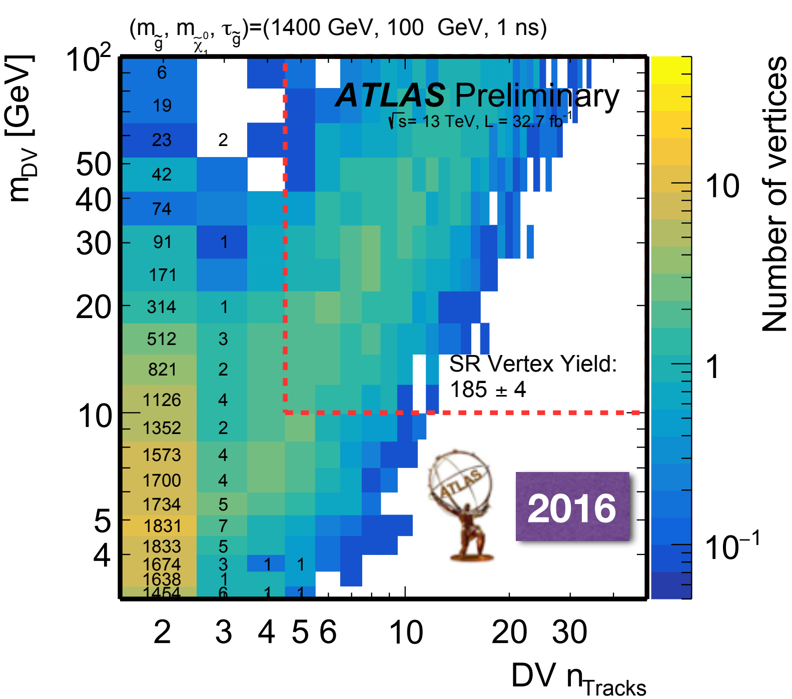

Out-of-Reach
Fruit?

Displaced Vertices Search

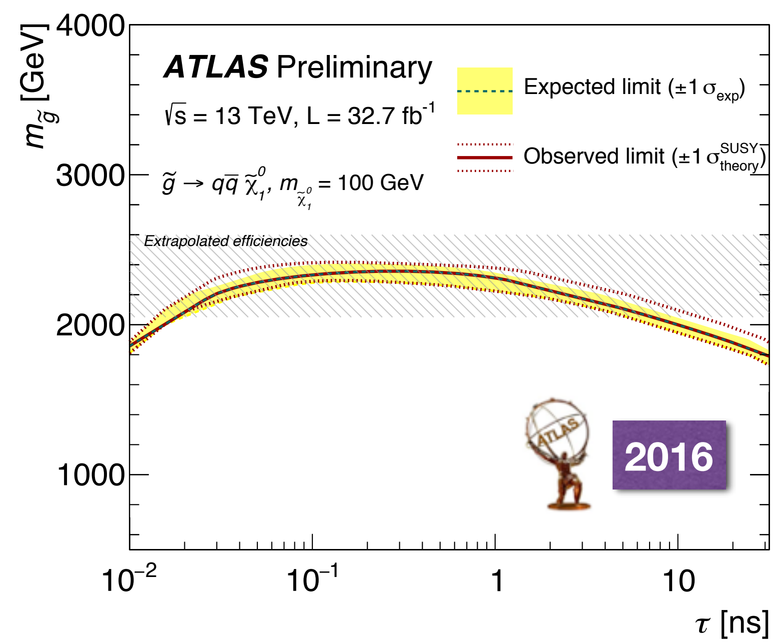
- ATLAS search for long-lived gluinos via displaced tracks
- Benefits from the new IBL pixel layer
- Limits on gluino mass reach ~2.5 TeV





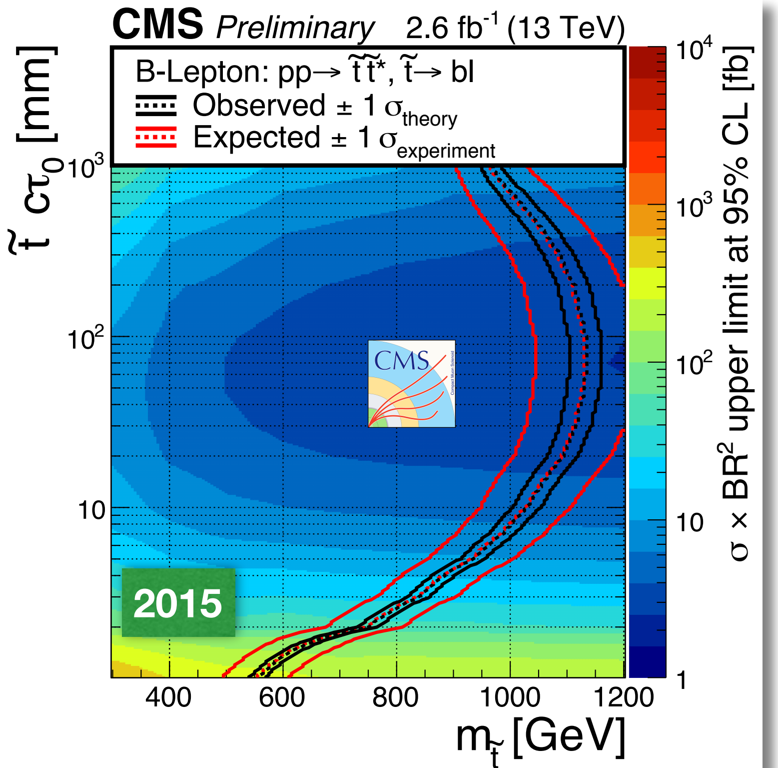


ATLAS CONF-2017-026

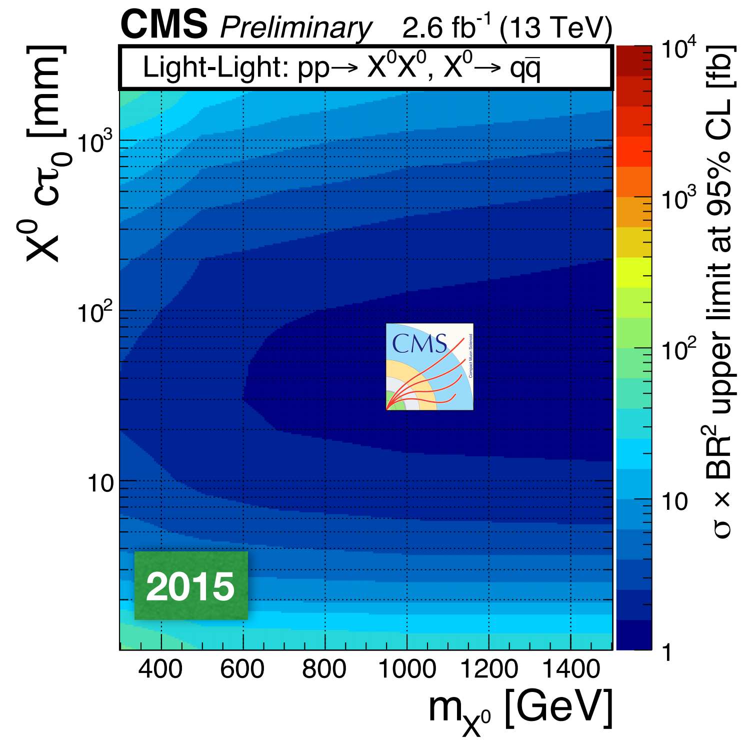


Search for Displaced Jets

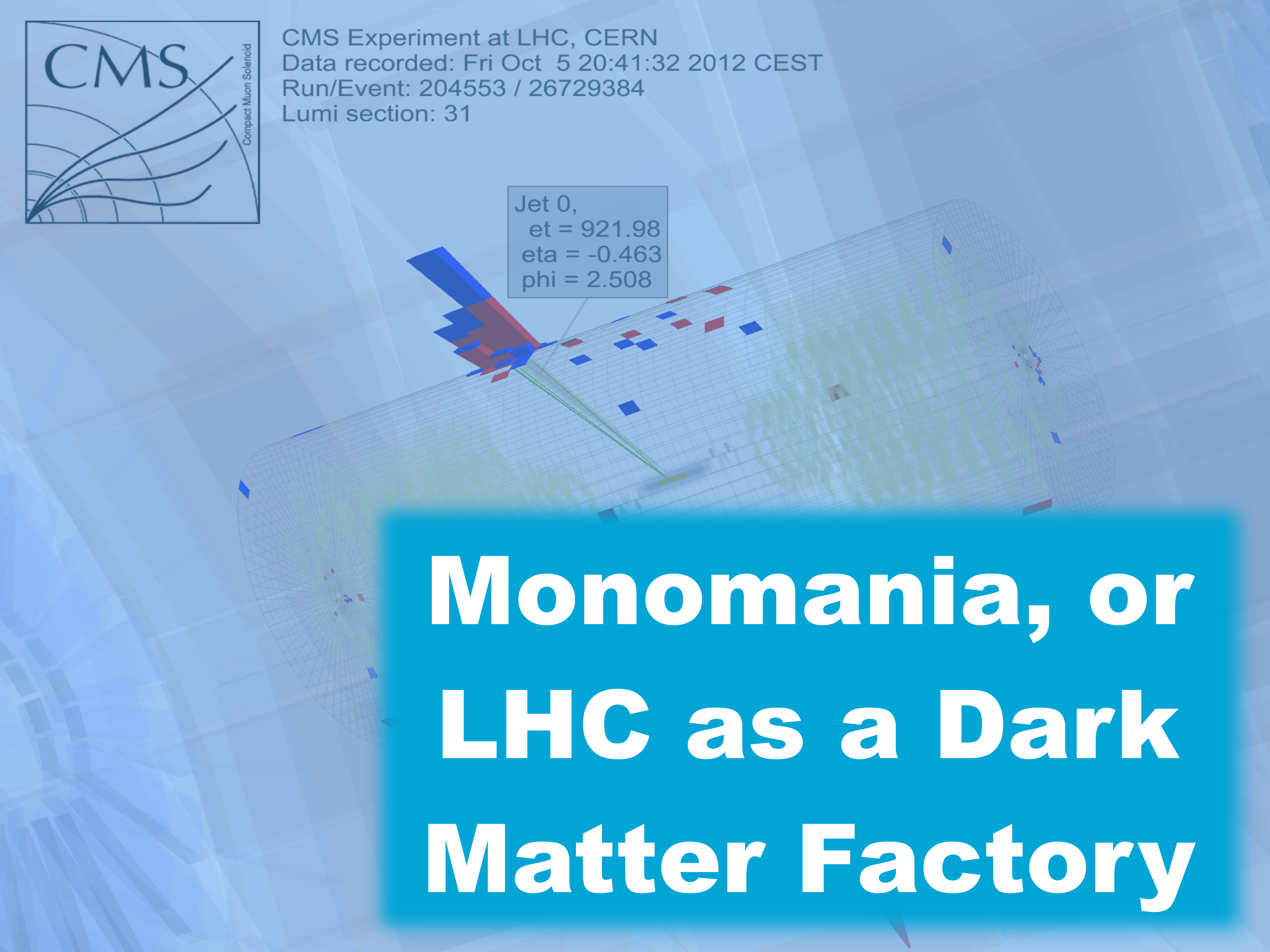
- CMS search based on dedicated triggers requiring at least two jets with low number of prompt tracks
- Special MVA displaced jet tagging based on the angular and displacement information for the tracks
- Signal benchmarks - pair production of top squarks with RPV decays into b quarks and leptons and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



CMS PAS EXO-16-003

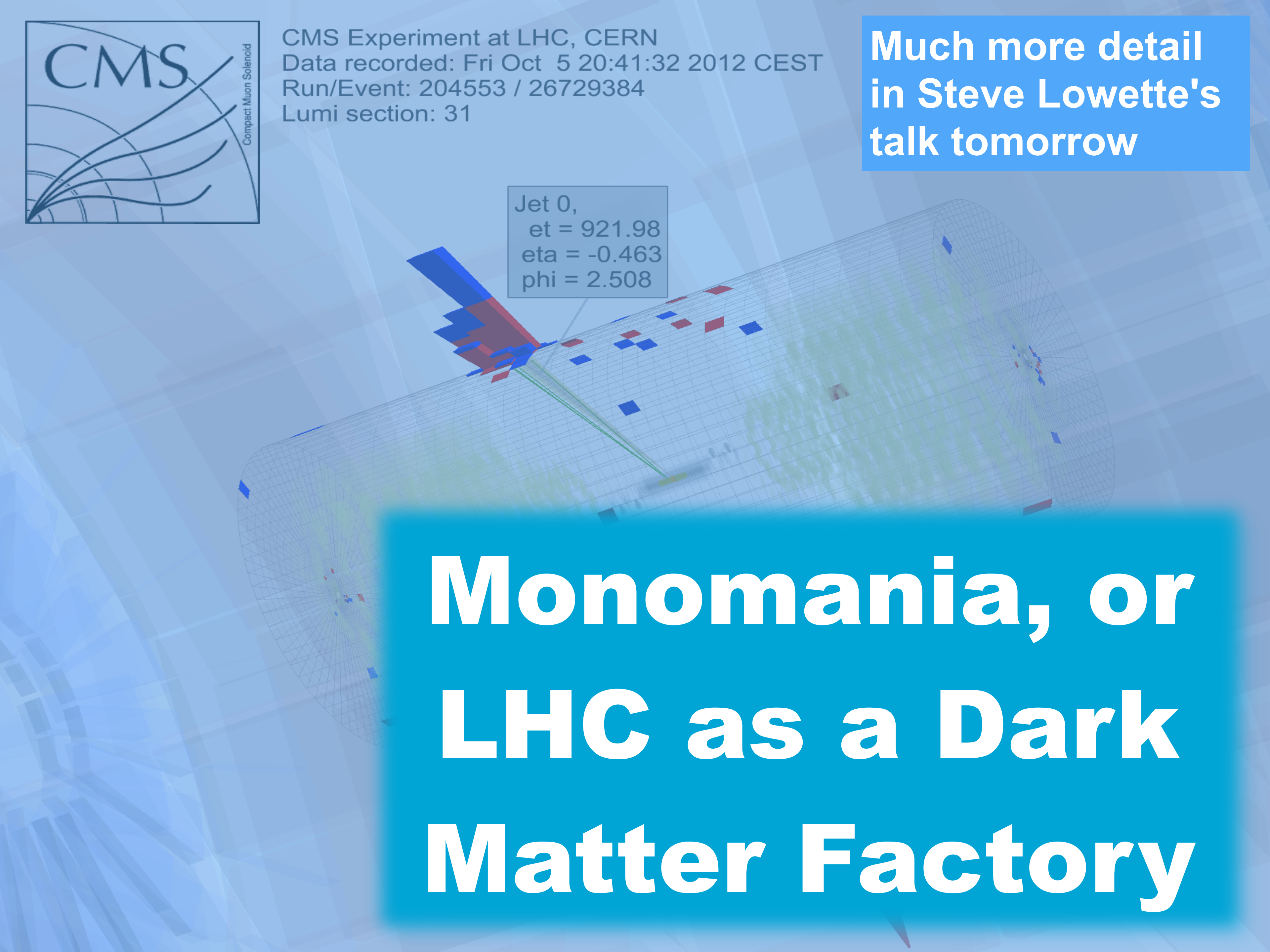


Monomania, or LHC as a Dark Matter Factory



Monomania, or LHC as a Dark Matter Factory

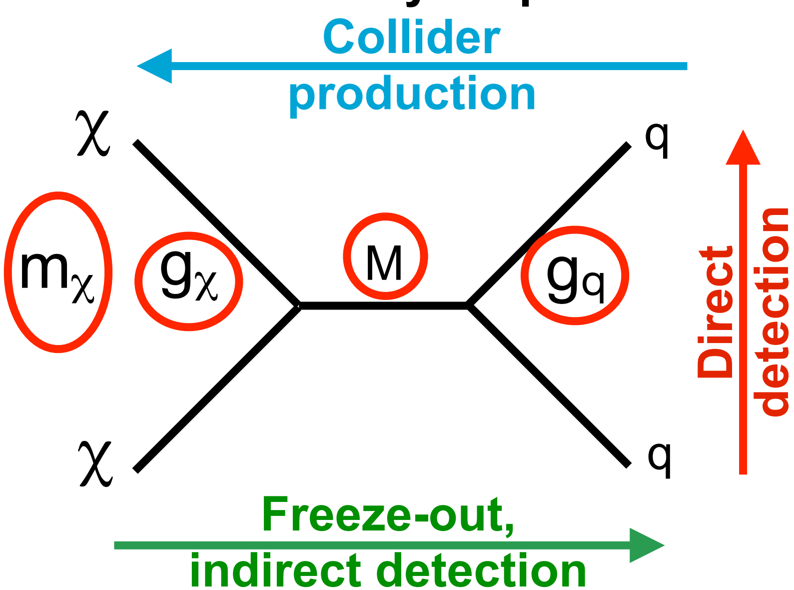
Much more detail in Steve Lowette's talk tomorrow



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

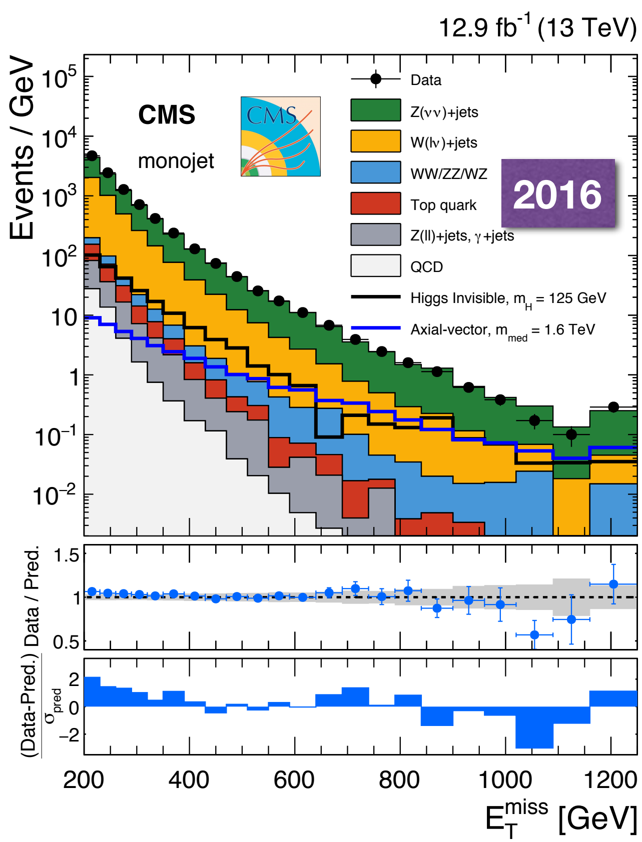
Fundamentally 4D problem!

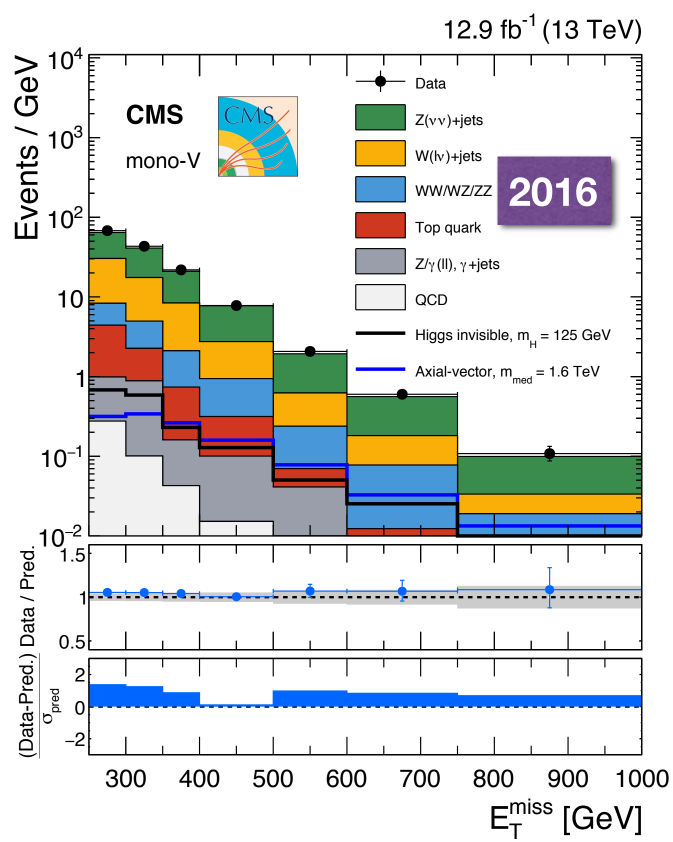


CMS Monojet Analysis

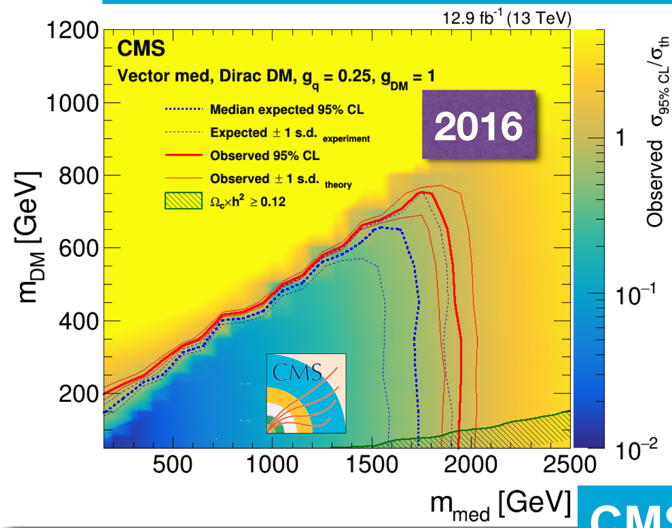
- The latest Run 2 analysis is built on the Run 1 techniques
  - Increased number of control regions (added e+jets, ee+jets)
  - Dropped the resolved mono-V channel, as it doesn't help the sensitivity at high mediator masses

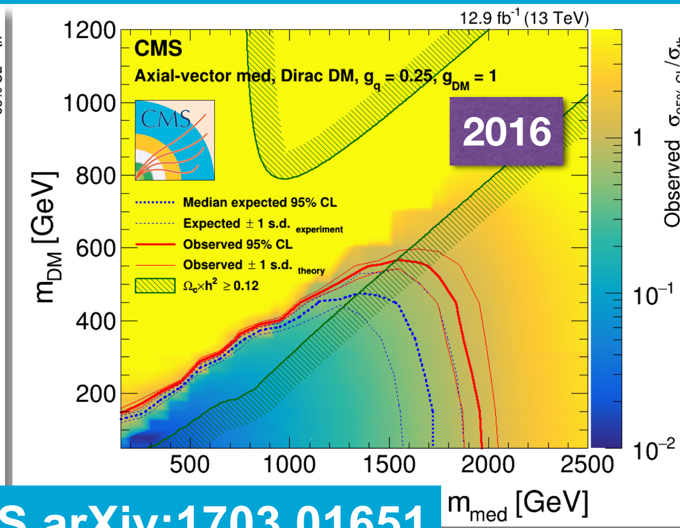
CMS arXiv:1703.01651



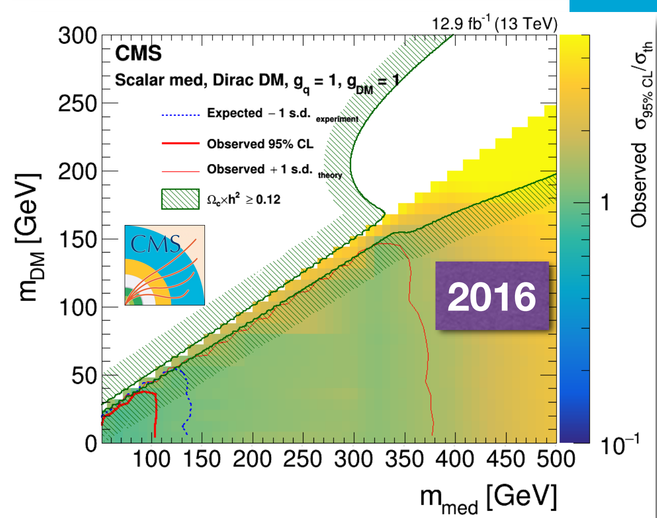


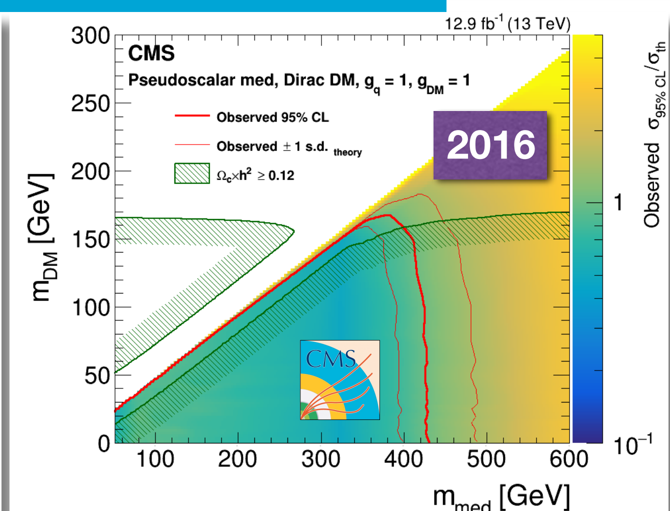
DM Interpretation



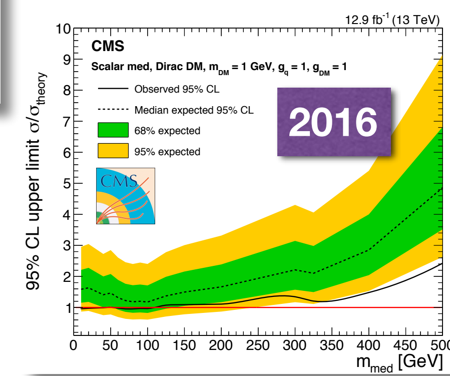


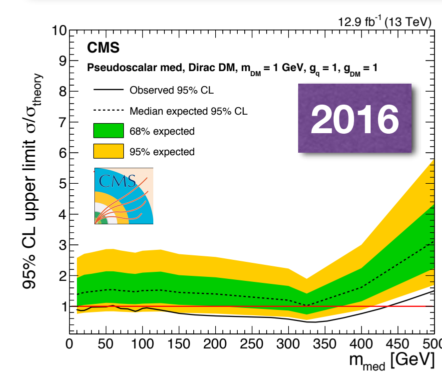
CMS arXiv:1703.01651





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

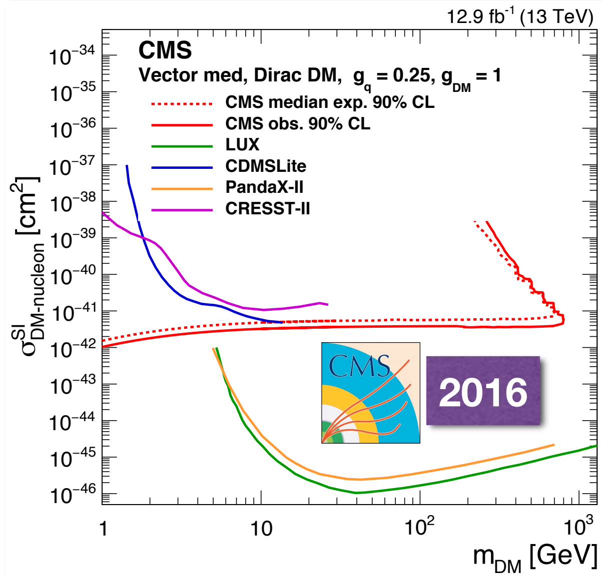


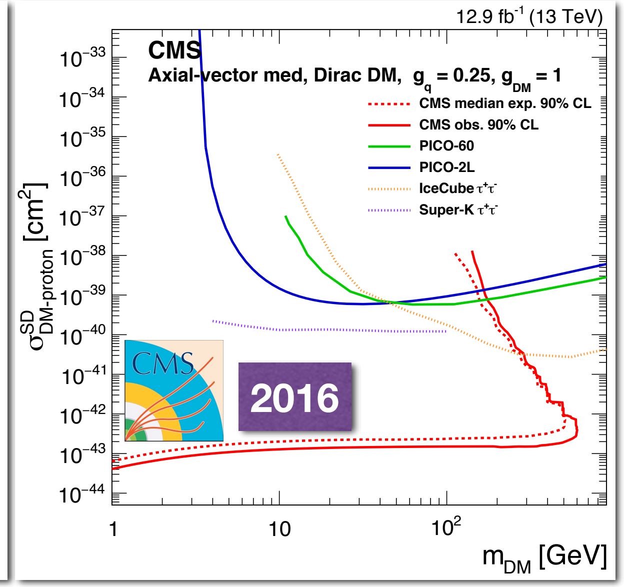


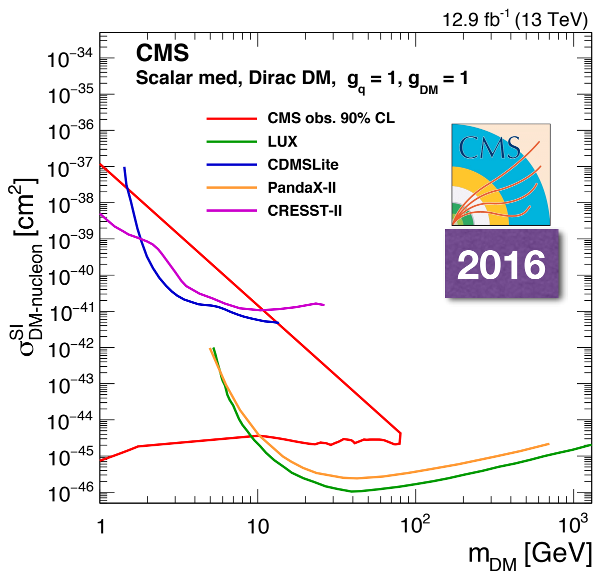
(Pseudo)scalar limits are a result of ~1σ stat. fluctuation

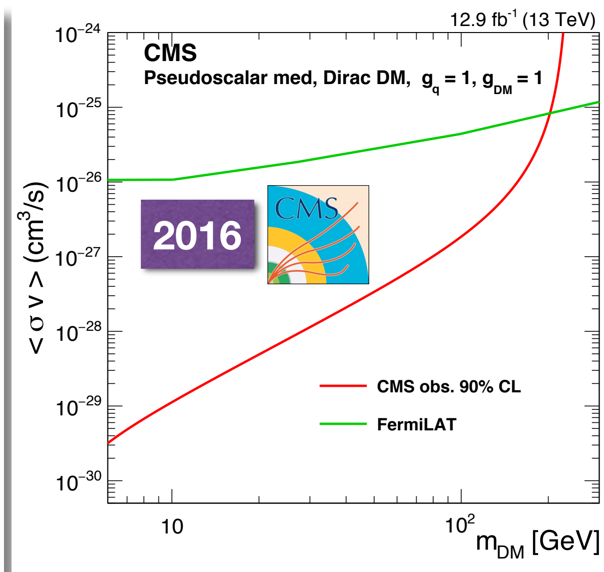
Comparison w/ I/DD

CMS arXiv:1703.01651





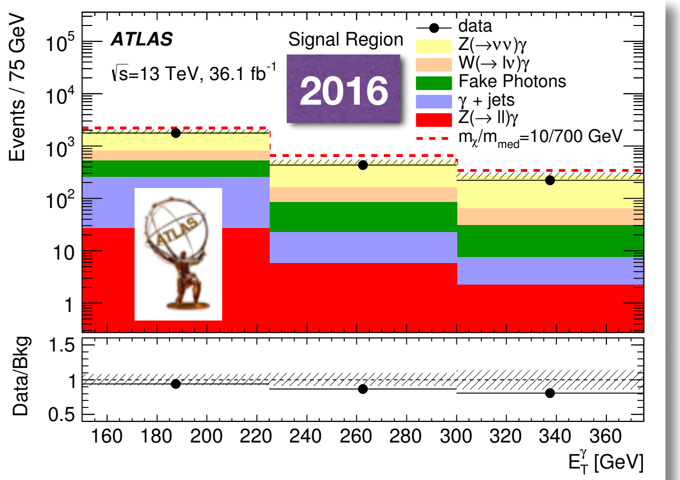


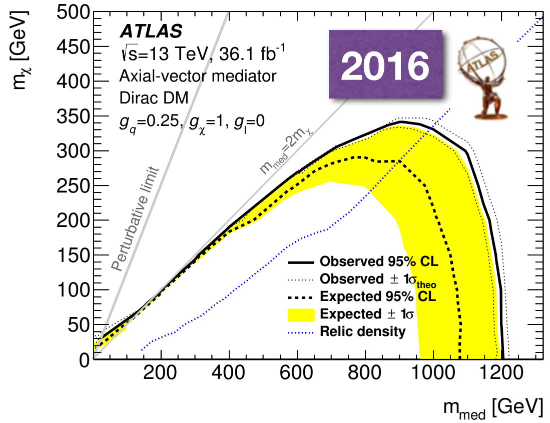


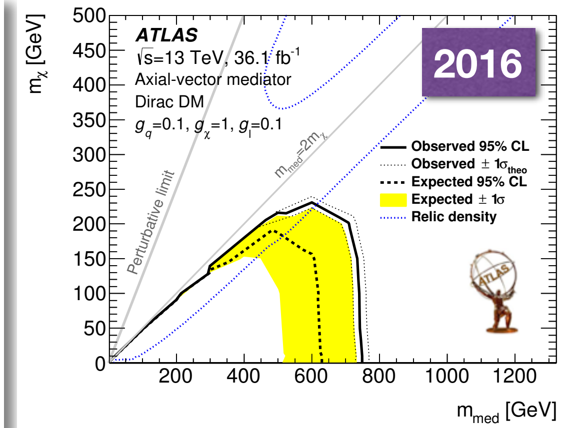
ATLAS Monophoton Analysis

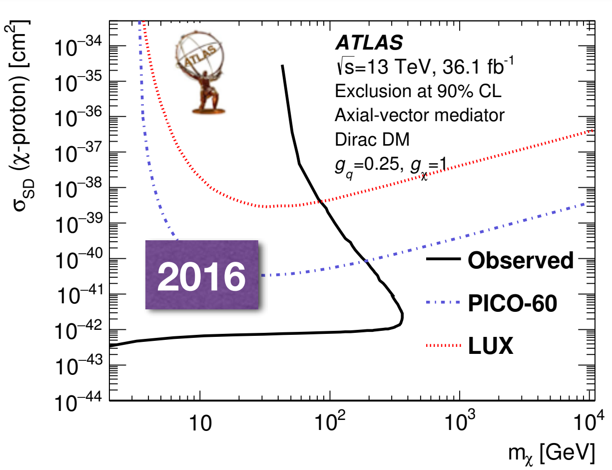
- ✦ New ATLAS search with full 2016 data set
  - ◉ First LHC analysis to probe the case with non-zero leptonic couplings

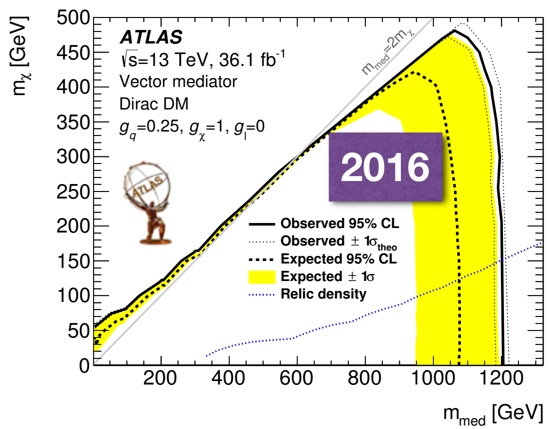
ATLAS arXiv:1704.03848

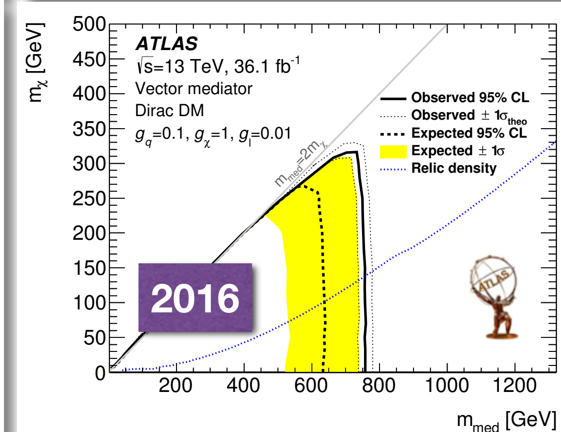












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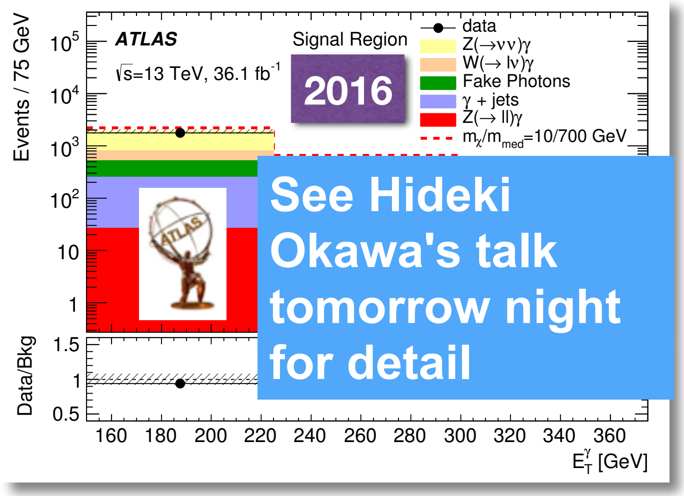
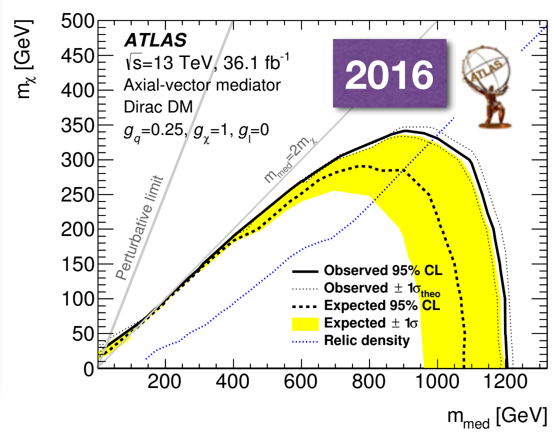
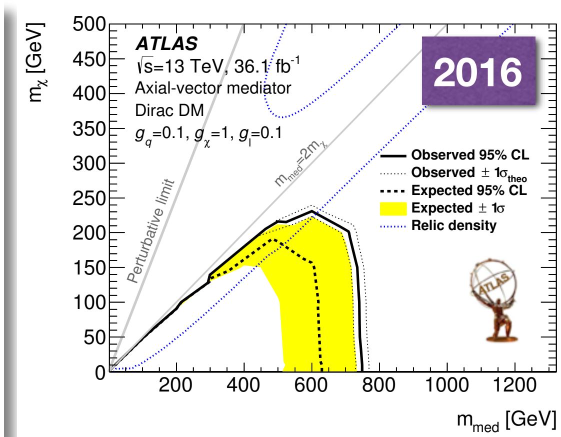
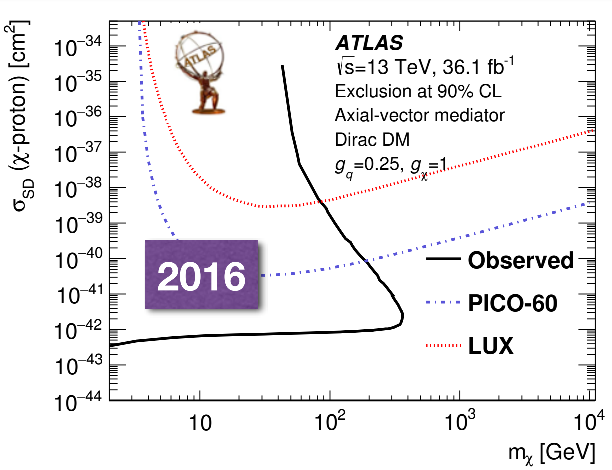
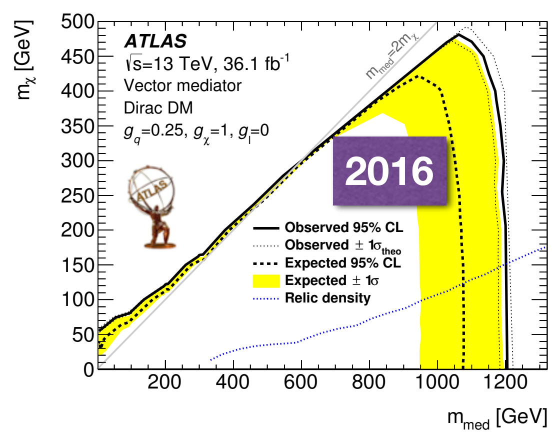


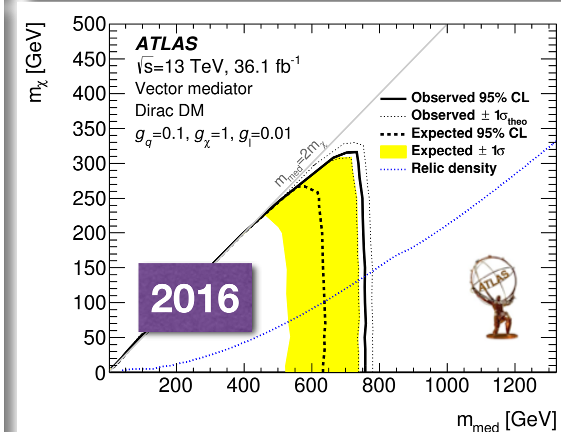
See Hideki Okawa's talk tomorrow night for detail





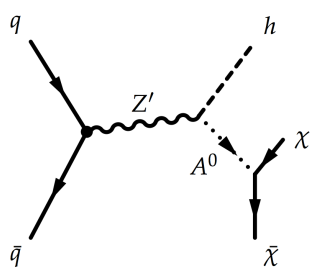






Mono-Higgs Production

- Mono-Higgs analysis in the context of 2HDM and vector mediator
- Explore H(bb) (resolved and boosted) and H(γγ) decay modes

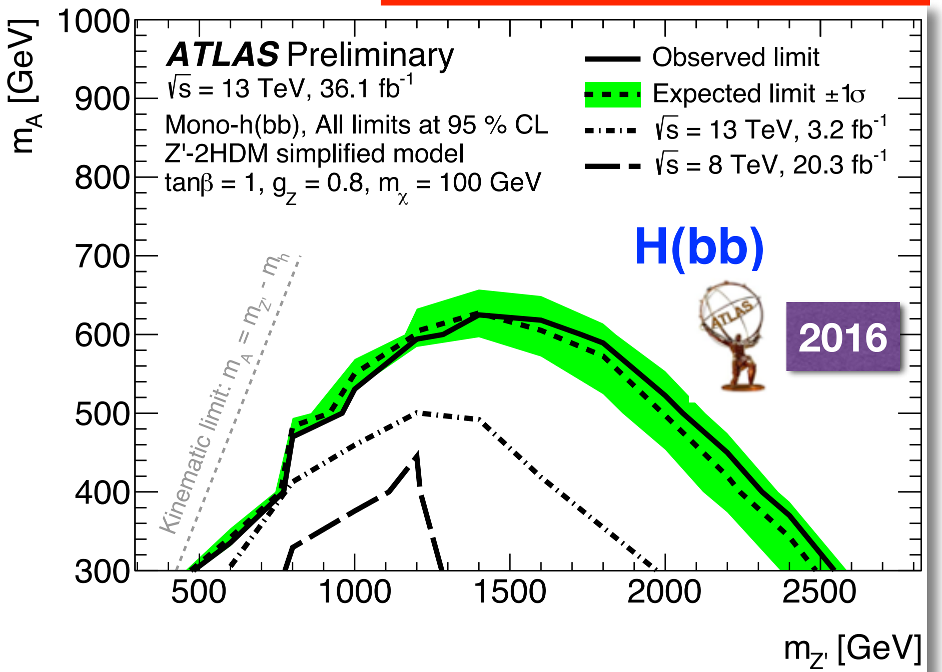


Precision EW:

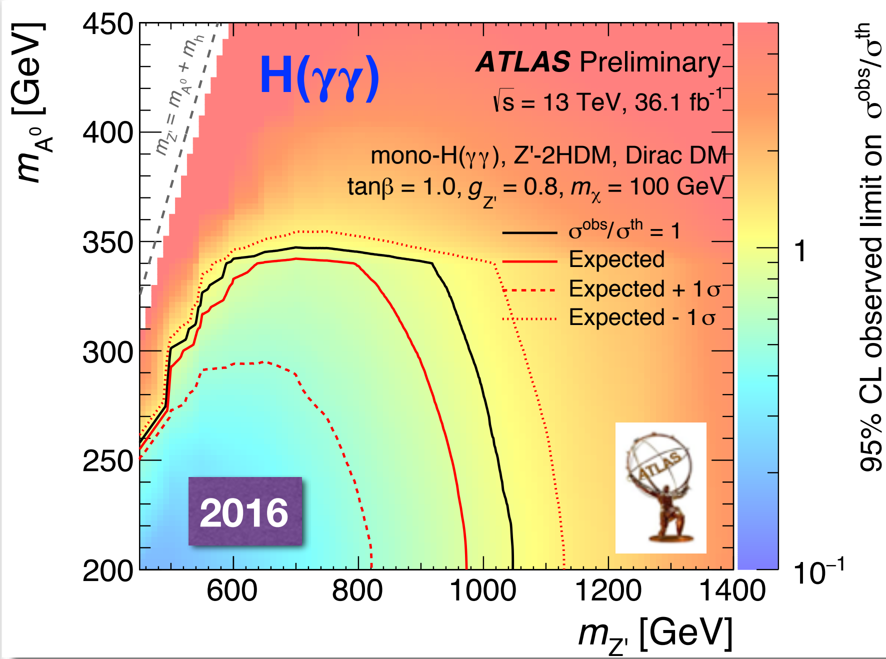
$$g_{Z'} \leq 0.03 \times \frac{g_W}{\cos\theta_W \times \sin^2\beta} \times \frac{\sqrt{m_{Z'}^2 - m_Z^2}}{m_Z}$$

Dijets: $g_{Z'} < 0.8$

ATLAS CONF-2017-028



ATLAS CONF-2017-024



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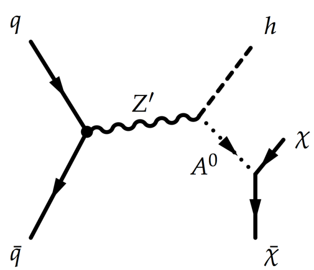

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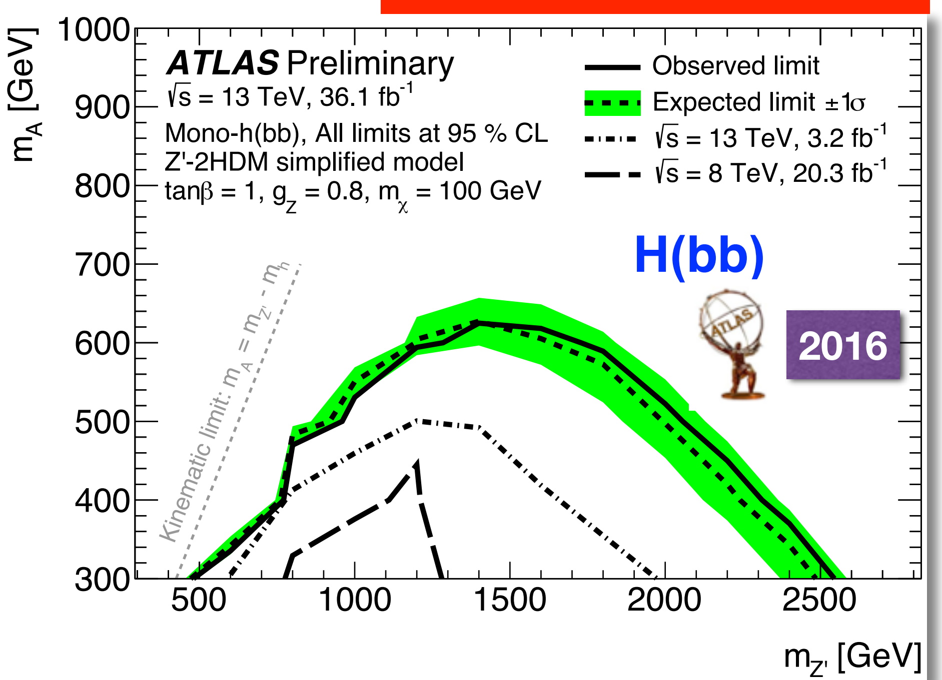
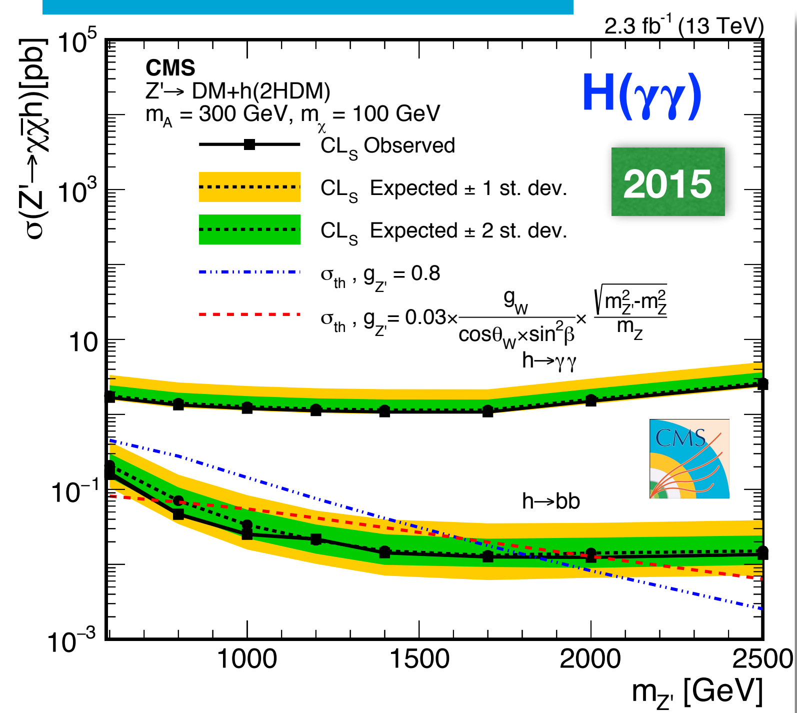
ATLAS CONF-2017-028



CMS arXiv:1703.05236



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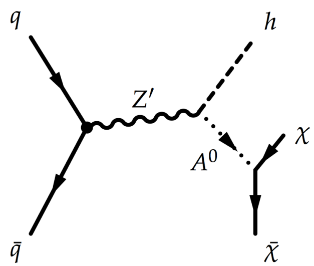

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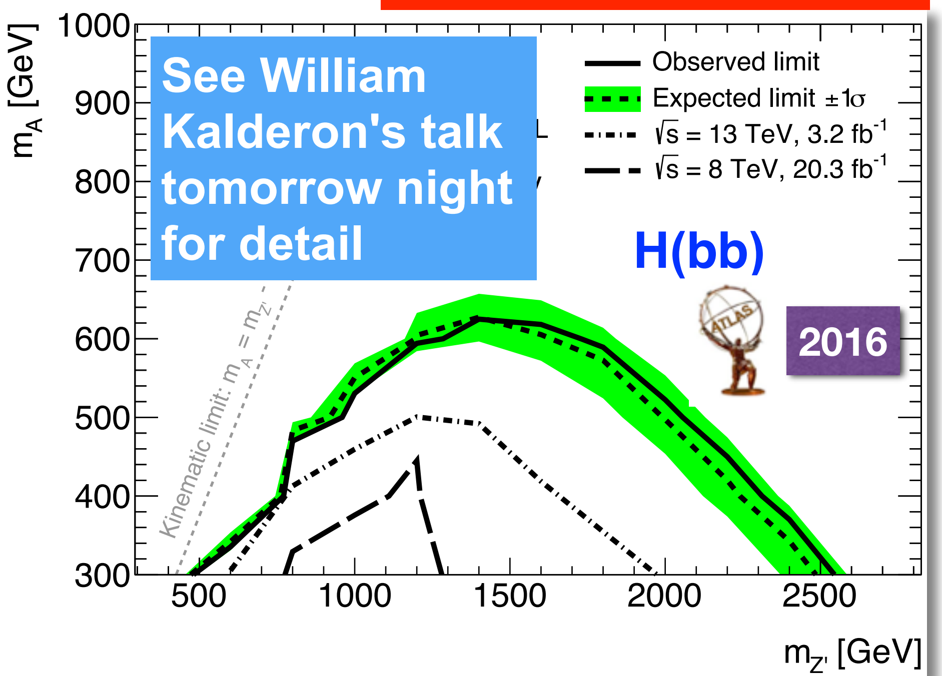
ATLAS CONF-2017-028



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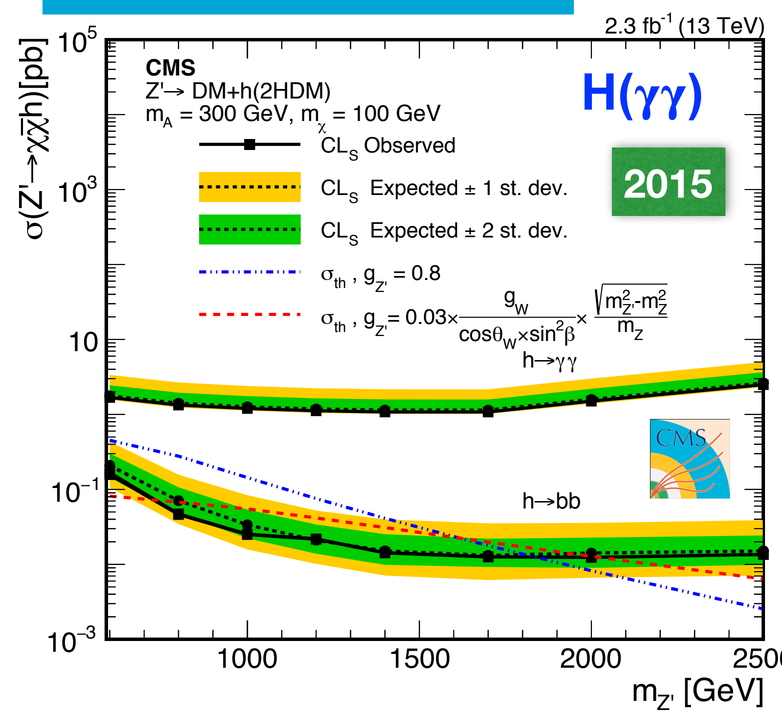
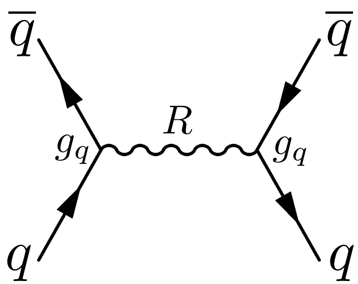


Search for the Mediator

BROWN

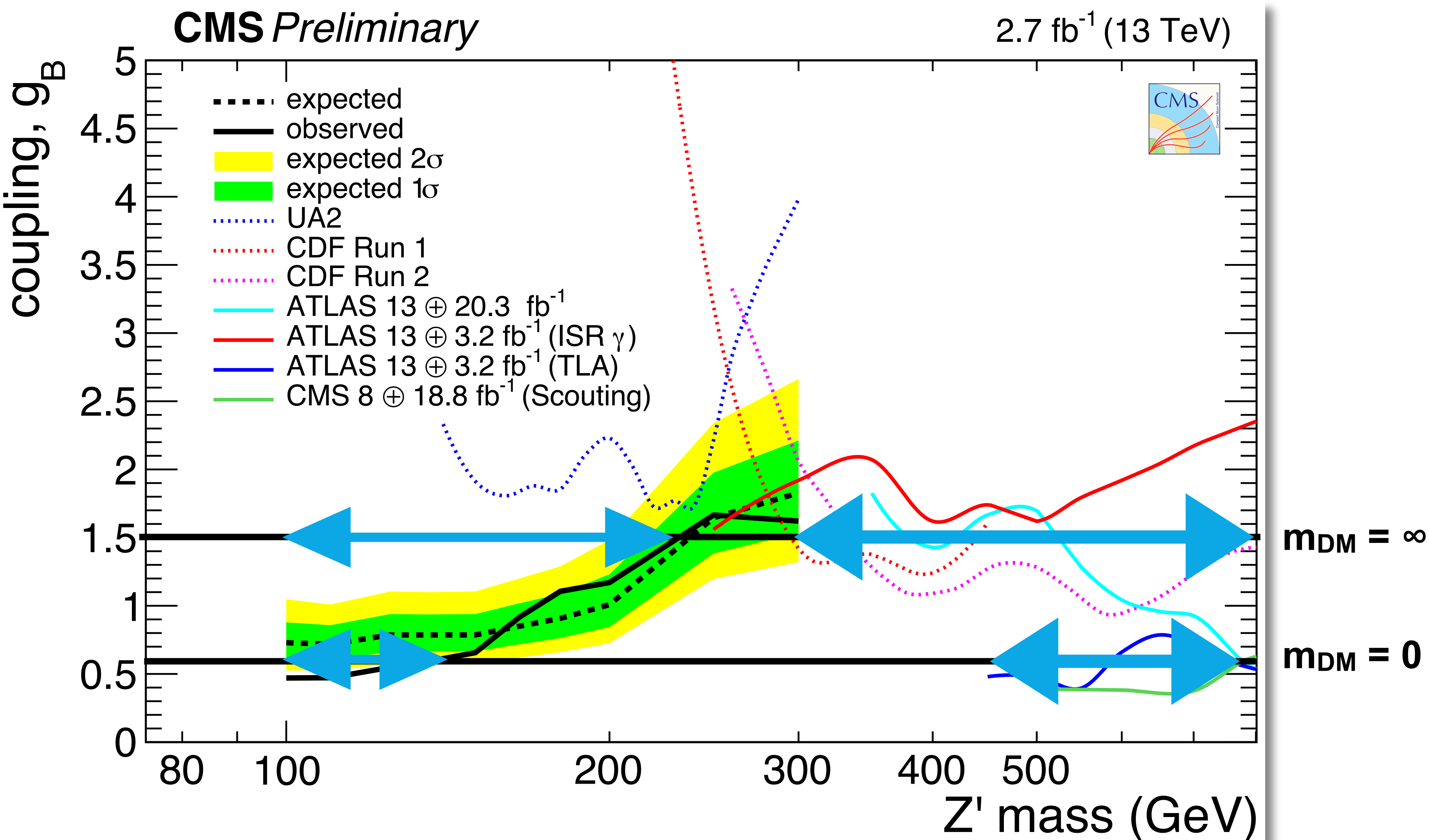
- One doesn't need to produce DM at the LHC to look for a mediator (mass M)



  - 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: $g_B^2 = \dfrac{9/4}{1 + \frac{16}{3N_f}\left\{1 - 4\left(\frac{m}{M}\right)^2\right\}^{\frac{3}{2}}}$

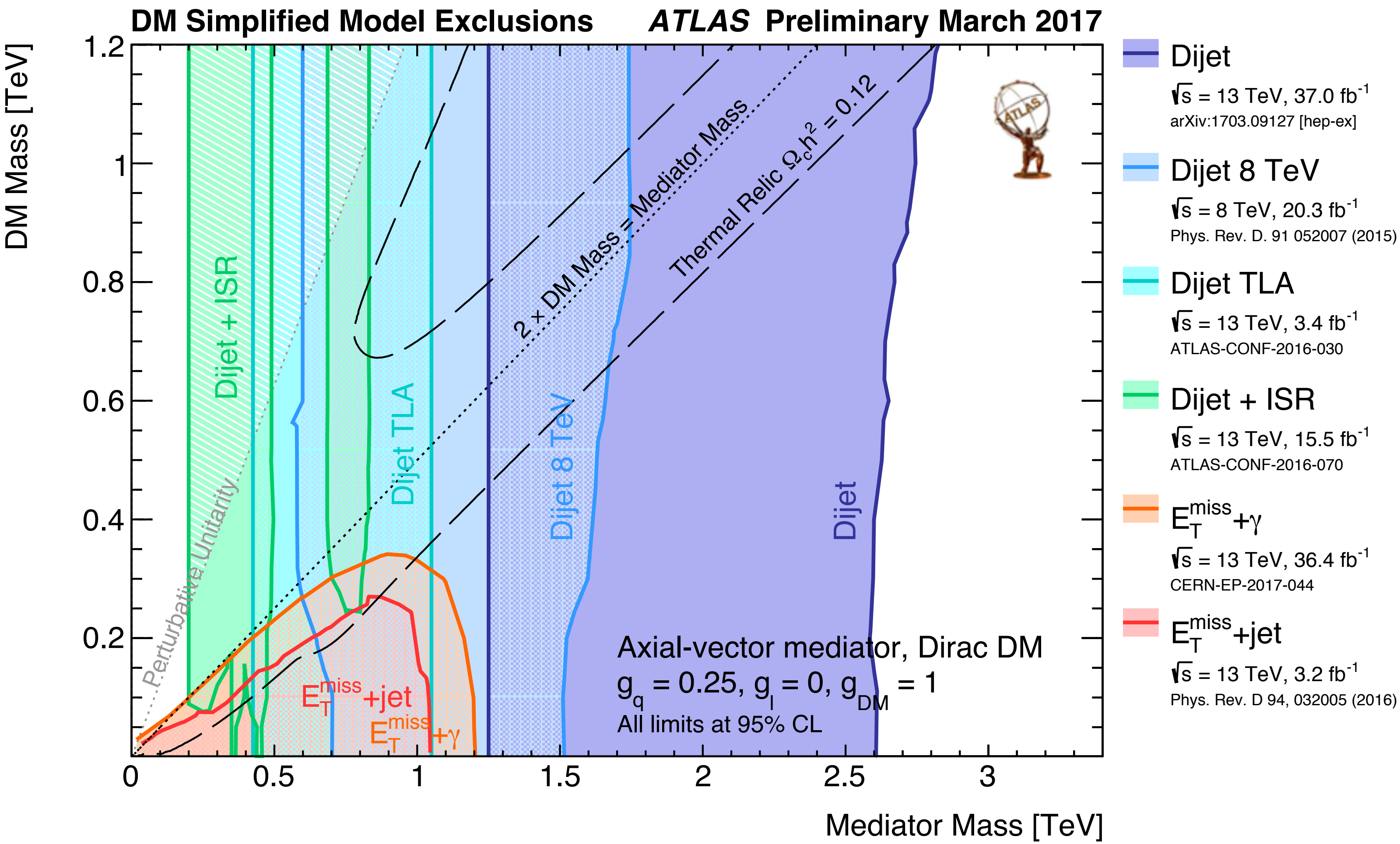
Using the g_B Plot

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



ATLAS Dijet Limits

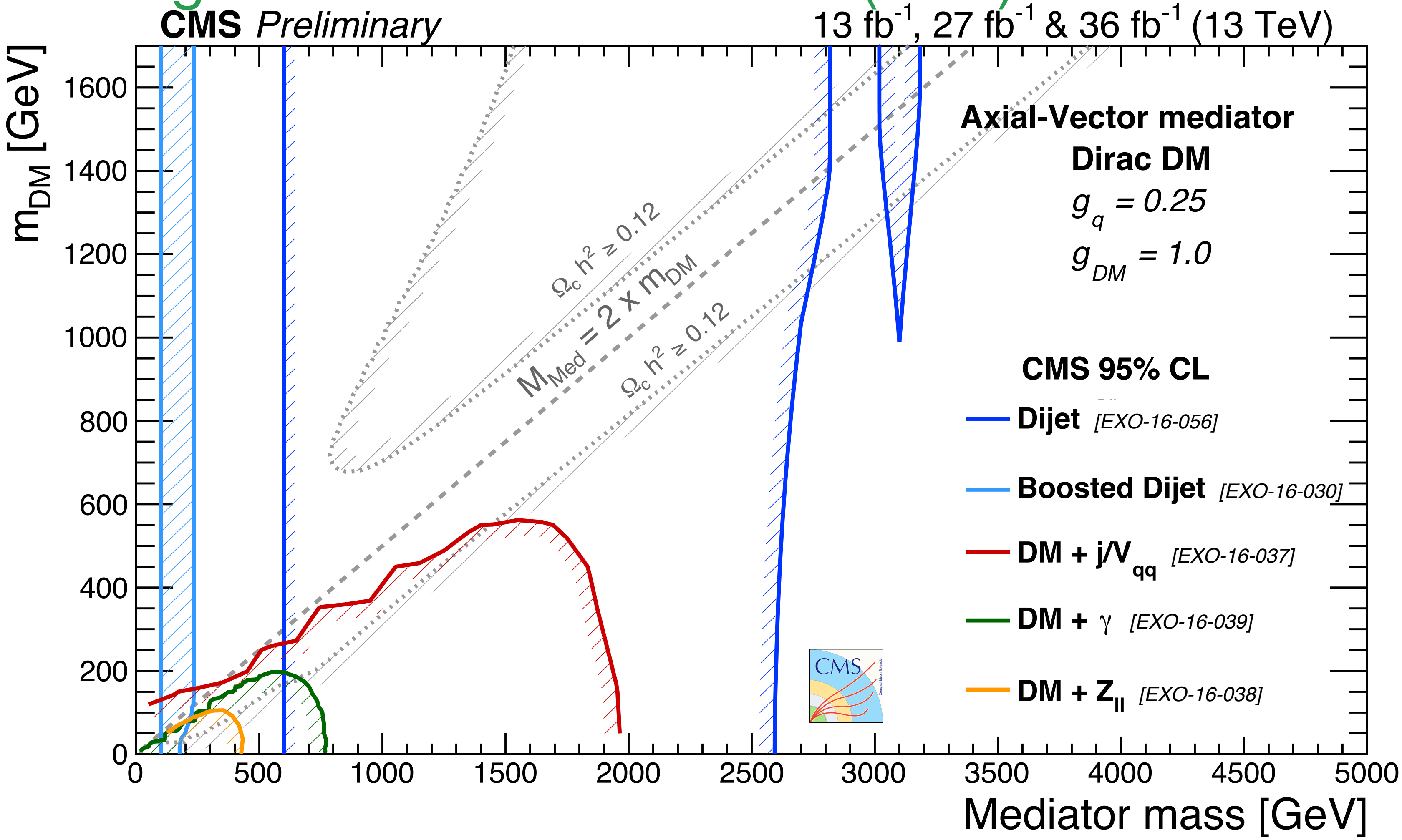
- Dijet limits on axial-vector mediator, compared with mono-X searches



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_DarkMatter_Summary

CMS Dijet Limits

✦ Analogous limits from CMS for (axial) vector mediators



http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-056/index.html

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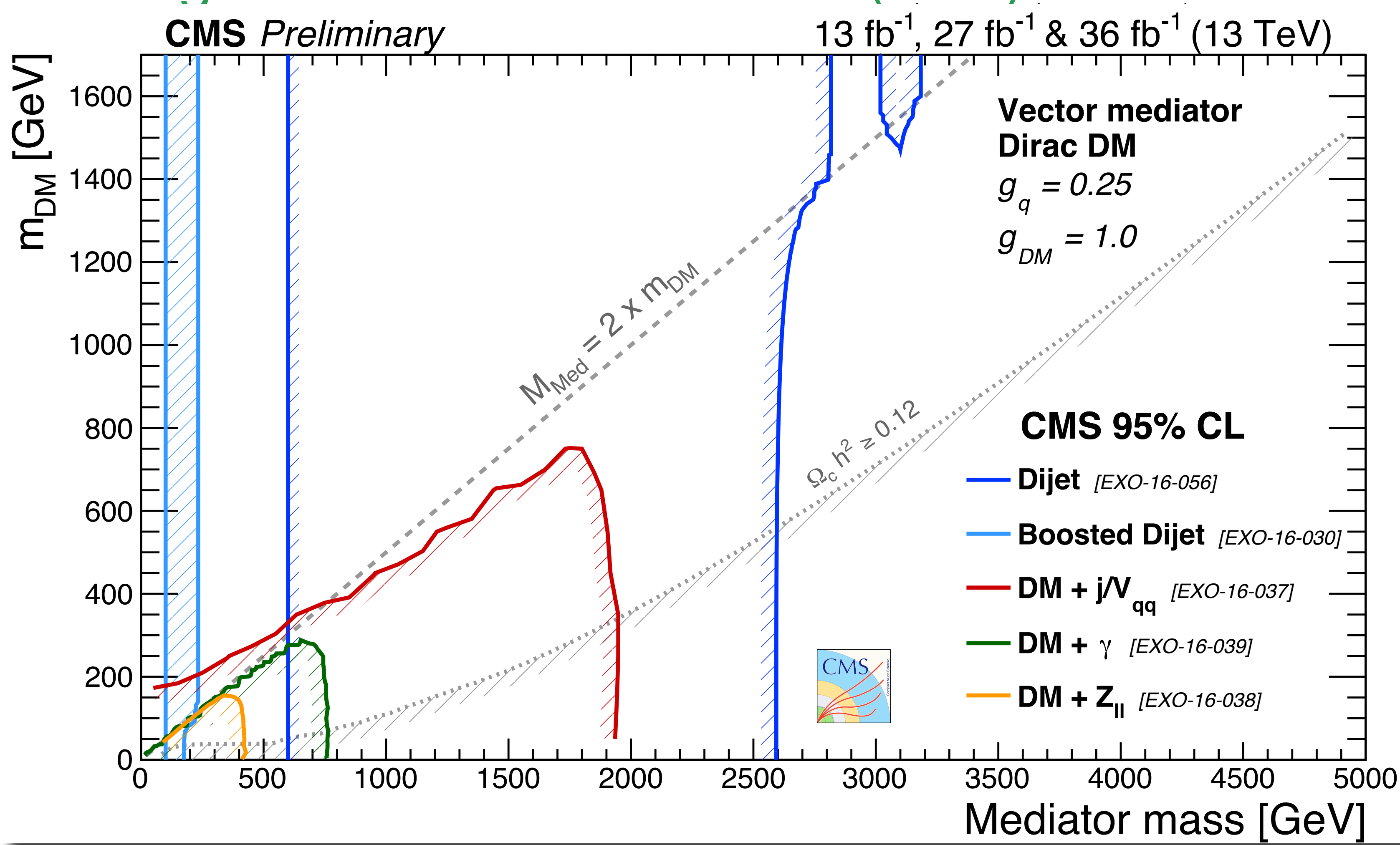
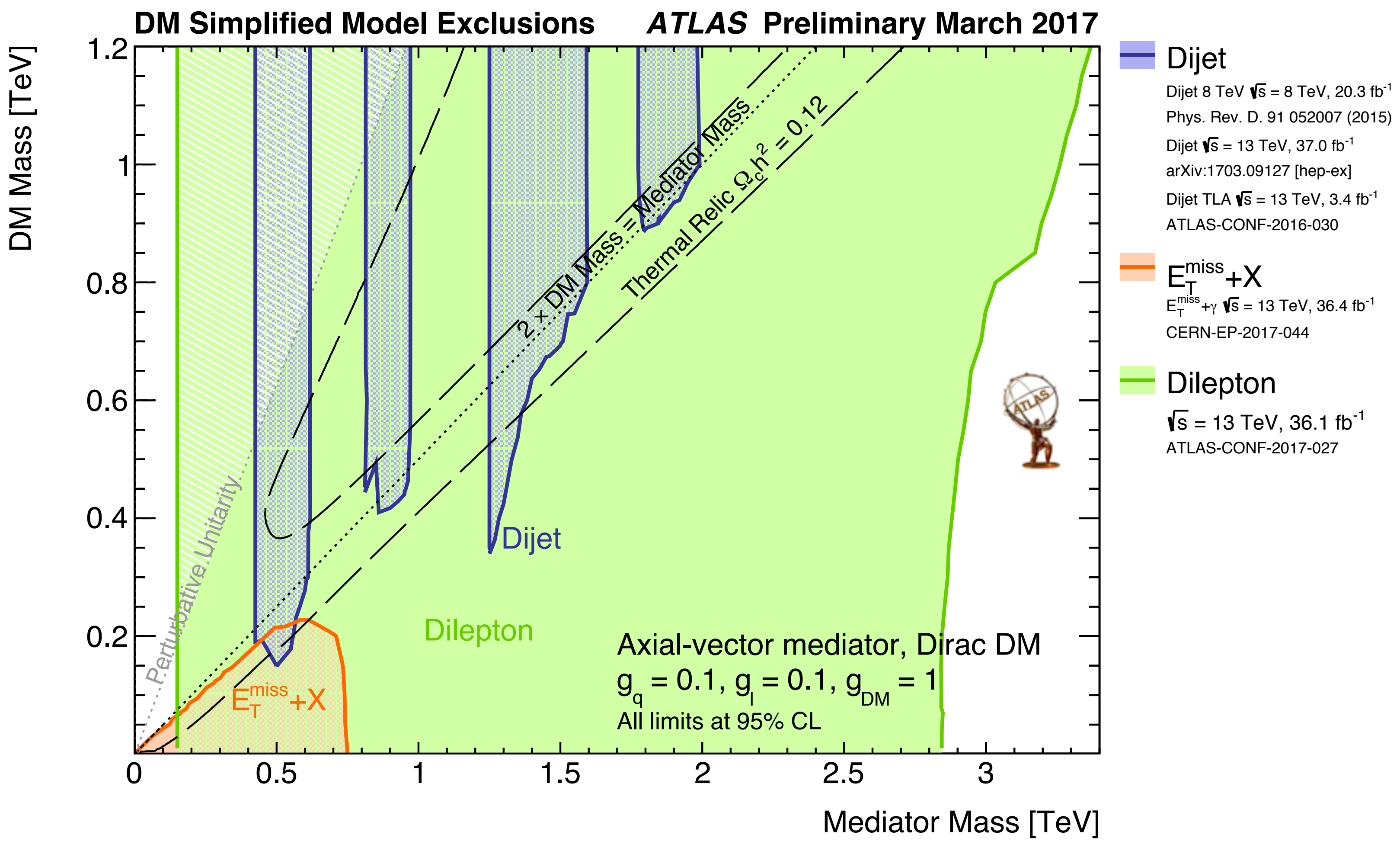


http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-056/index.html

Dijet & Dilepton Limits

- Dijet & dilepton limits on axial-vector mediator, compared with mono-X searches



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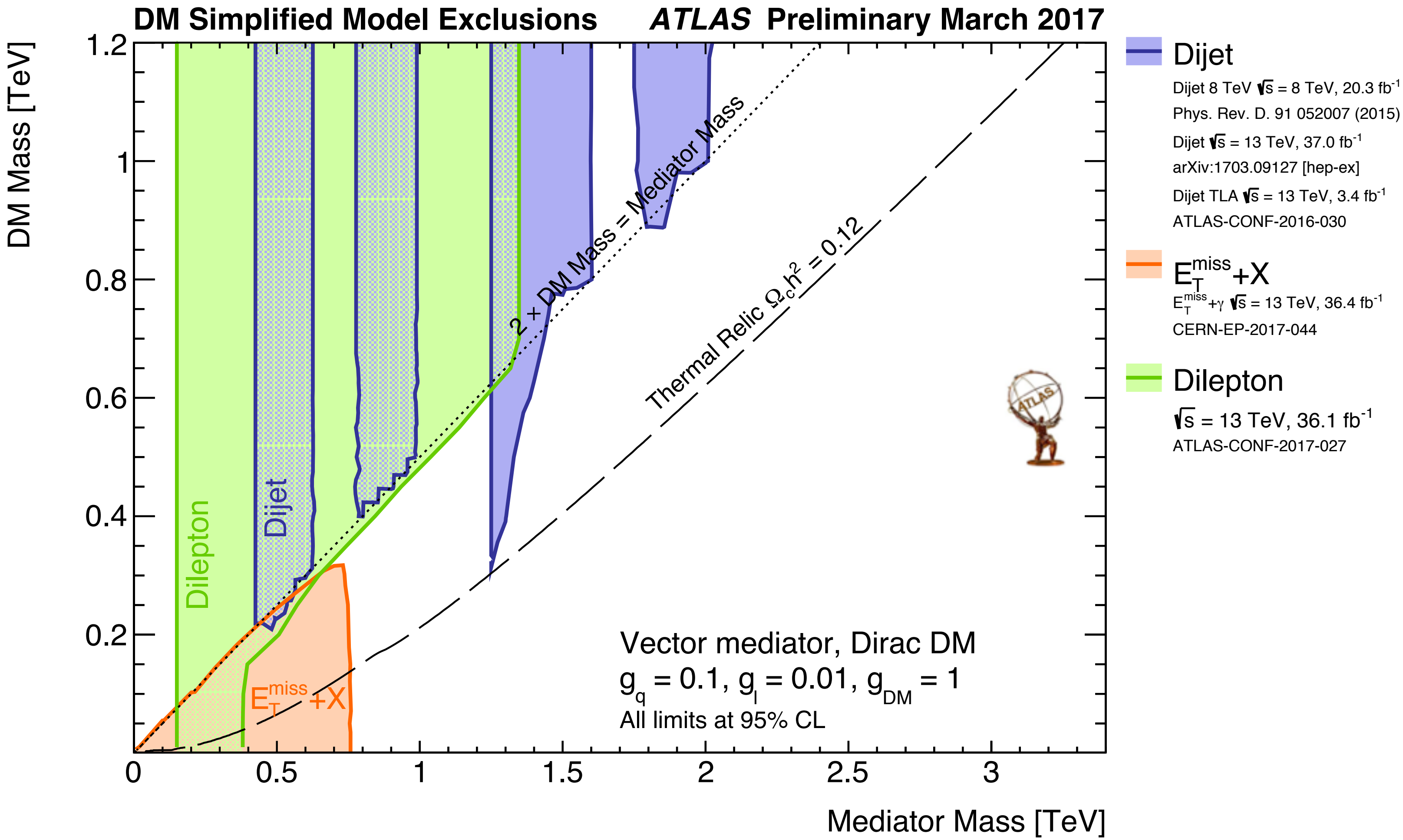
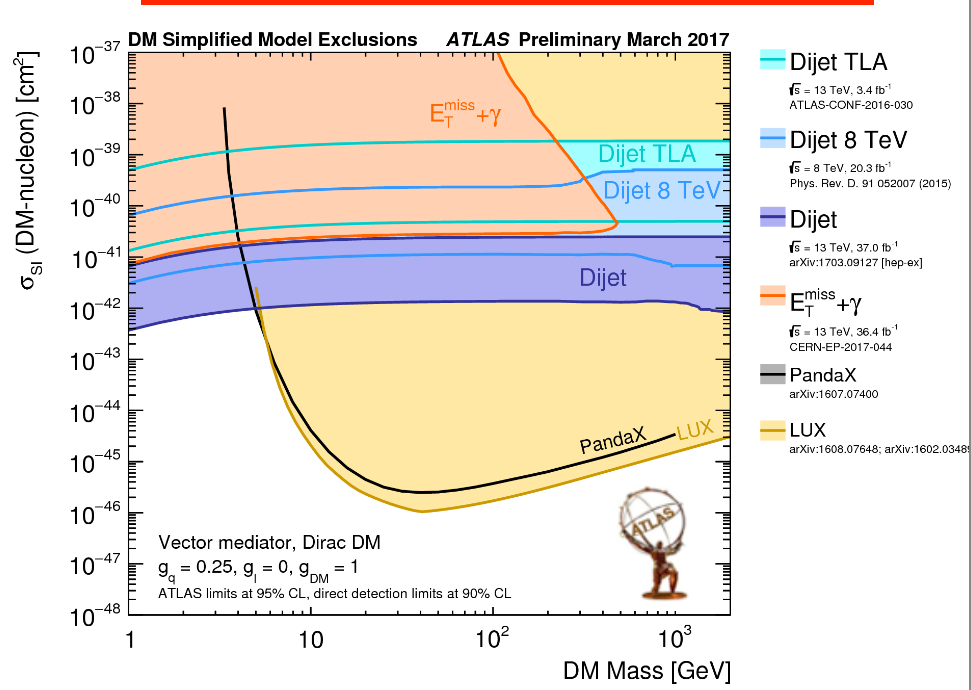


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_DarkMatter_Summary

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://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_DarkMatter_Summary



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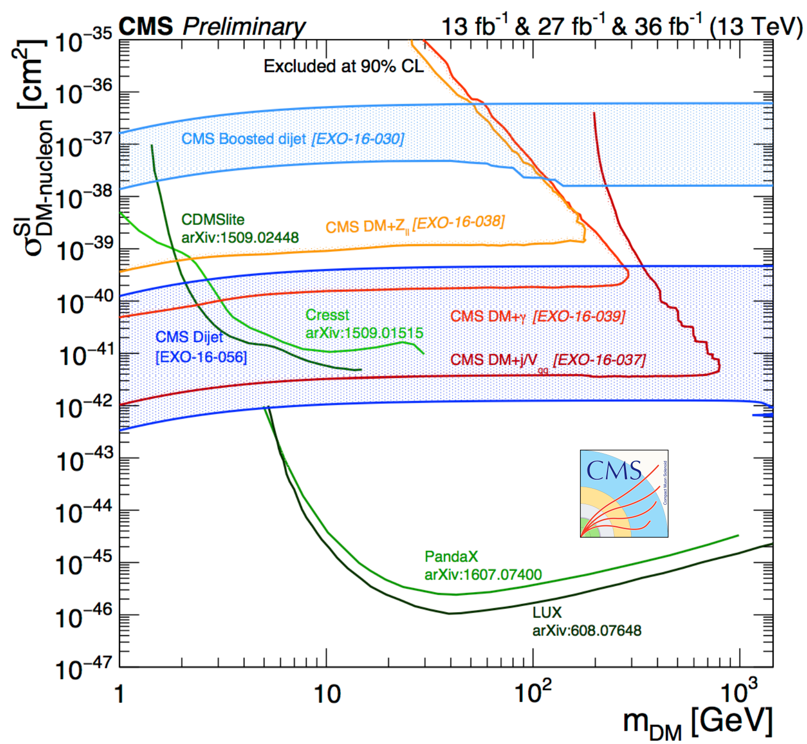
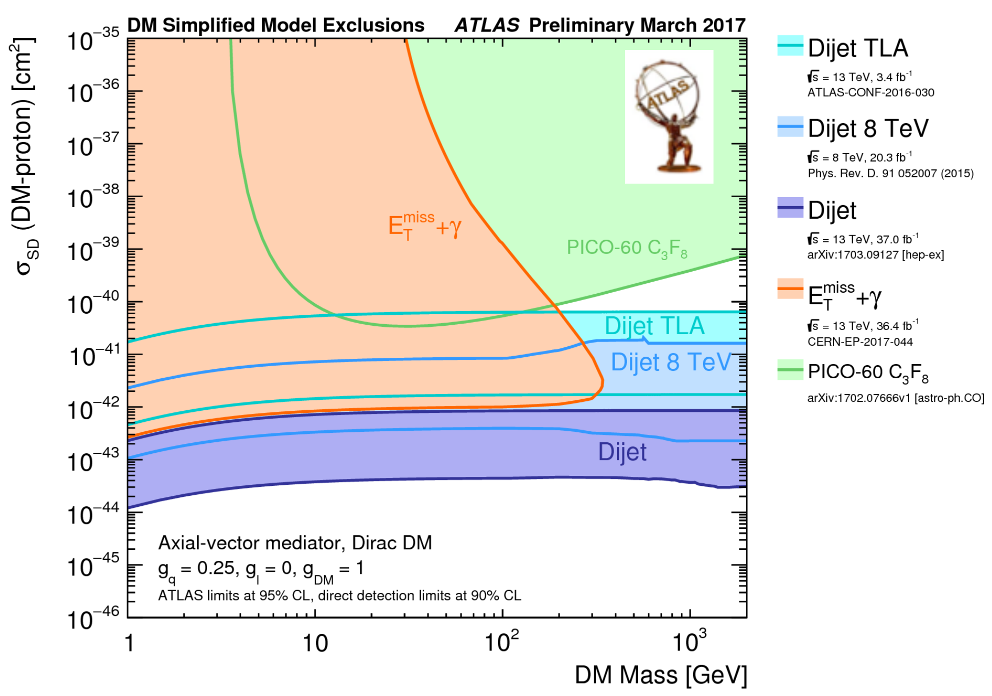


Comparison w/ Direct Detection

- 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://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html#ATLAS_DarkMatter_Summary



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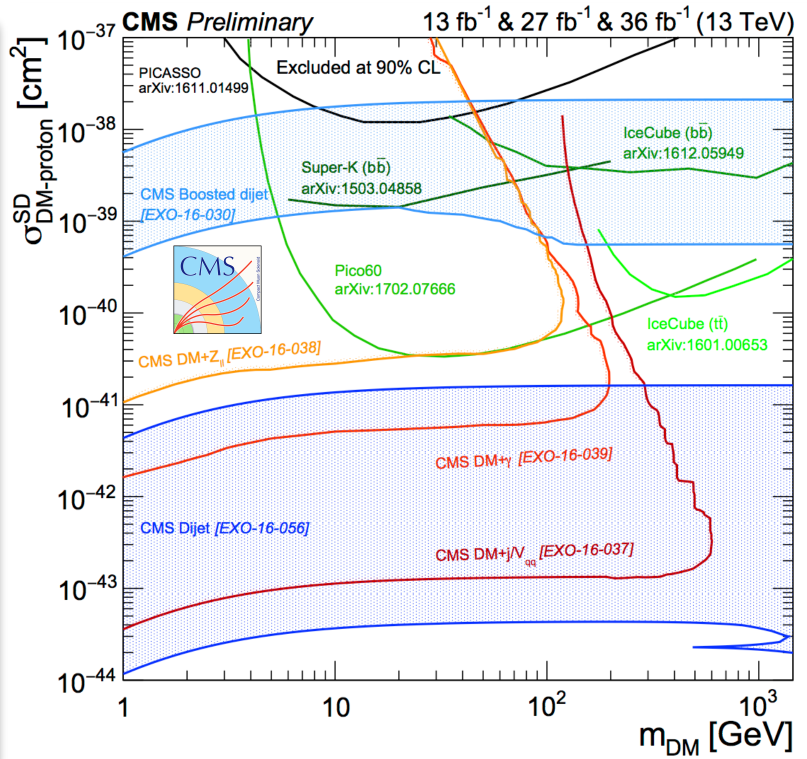

Future Run 2 Searches

- Parton luminosity arguments shaped the searches program in 2015 and early 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 in 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???