RECENT CMS RESULTS WITH FOCUS ON NEW PHYSICS SEARCHES

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FPCapri2018 **Workshop**

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Outline

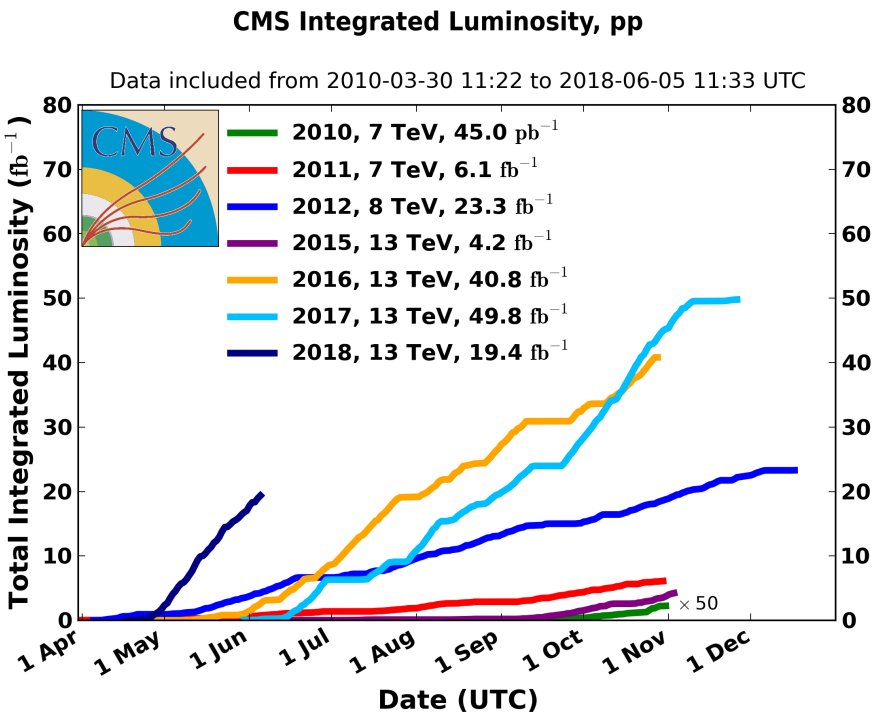
- LHC Performance
- Observation of the ttH production
- First 2017 data results
- Resonant searches
- Non-resonant searches
- Searches for dark matter

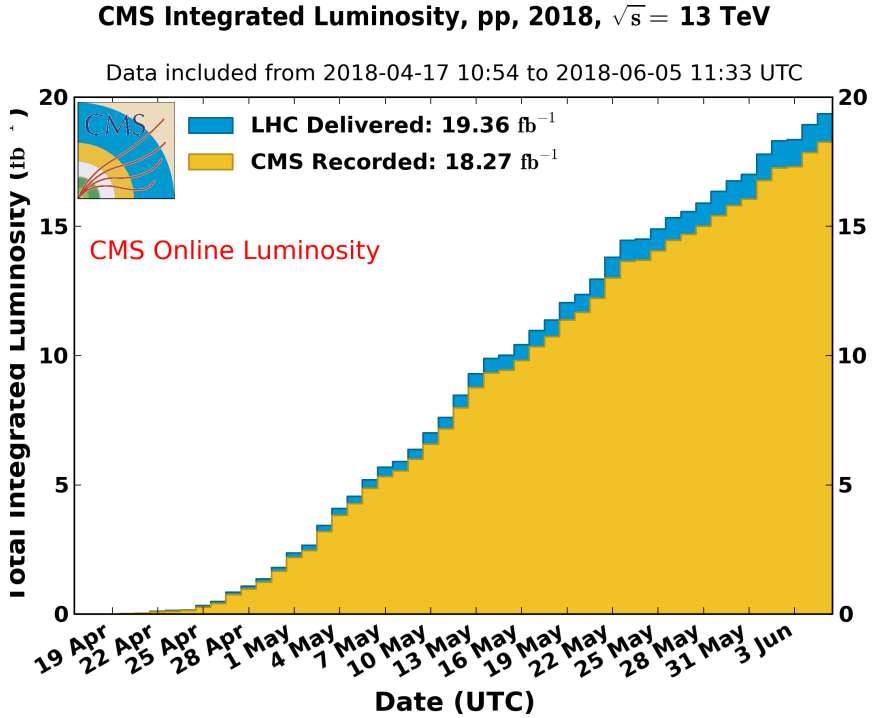
- Disclaimer: I'll mainly focus on the most recent results - either preliminary or just submitted - generally 6 month or more recent
- For the full searches landscape in CMS, see:
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG/index.html

The LHC Performance

2018 Data Taking

- About 20/fb has been already delivered by the LHC in 2018, exceeding the integrated luminosity projections
- 50% stable beam fraction so far, expect further increase
- Thank you, the LHC, for a good start of what should be another spectacular year!

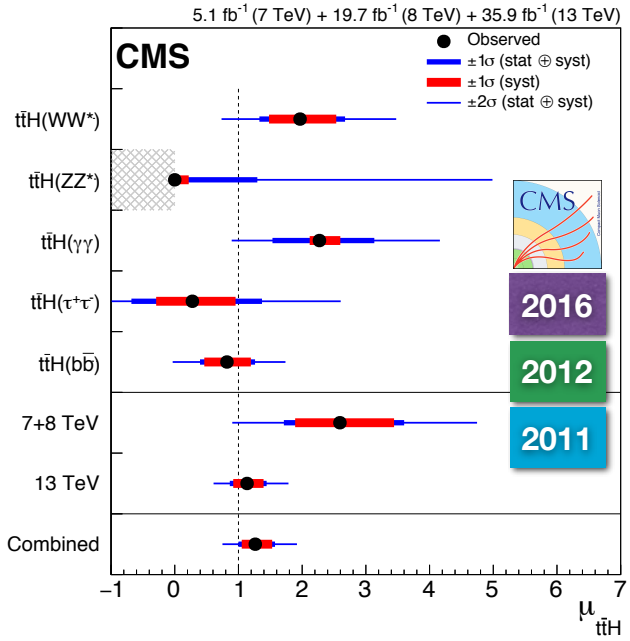




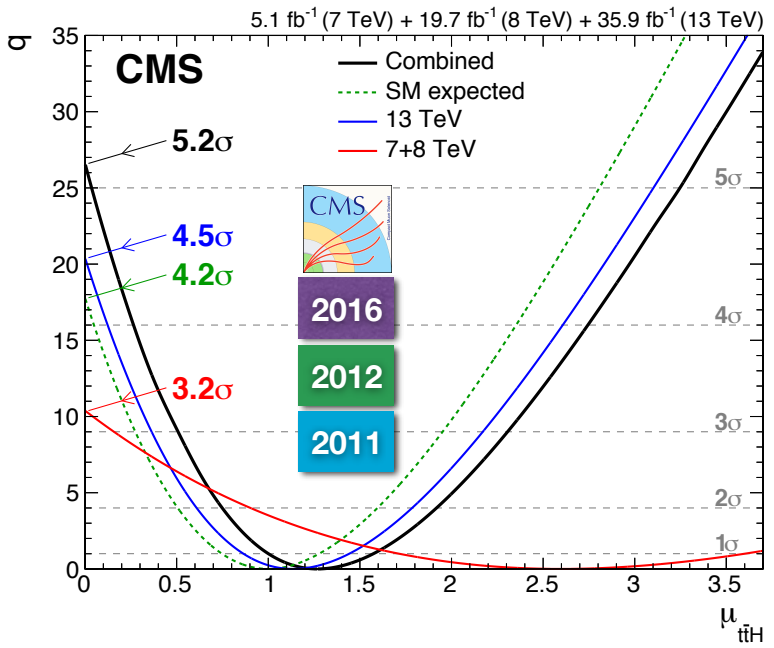

TOUR DE FORCE
THE TRUMPETS OF ROY ELDRIDGE • DIZZY GILLESPIE AND HARRY EDISO
Top Yukawa
Coupling

Observation of ttH

- Recently, CMS reported first observation of ttH production
  - Tour de force analysis, combining multiple channels (bb, ττ, γγ, multileptons), as well as 7, 8, and 13 TeV data
  - 5.2σ observed (4.2σ expected) significance, benefiting from an excess seen in Run 1 data
  - $\mu = 1.26^{+0.31}_{-0.26}$, in agreement with the SM

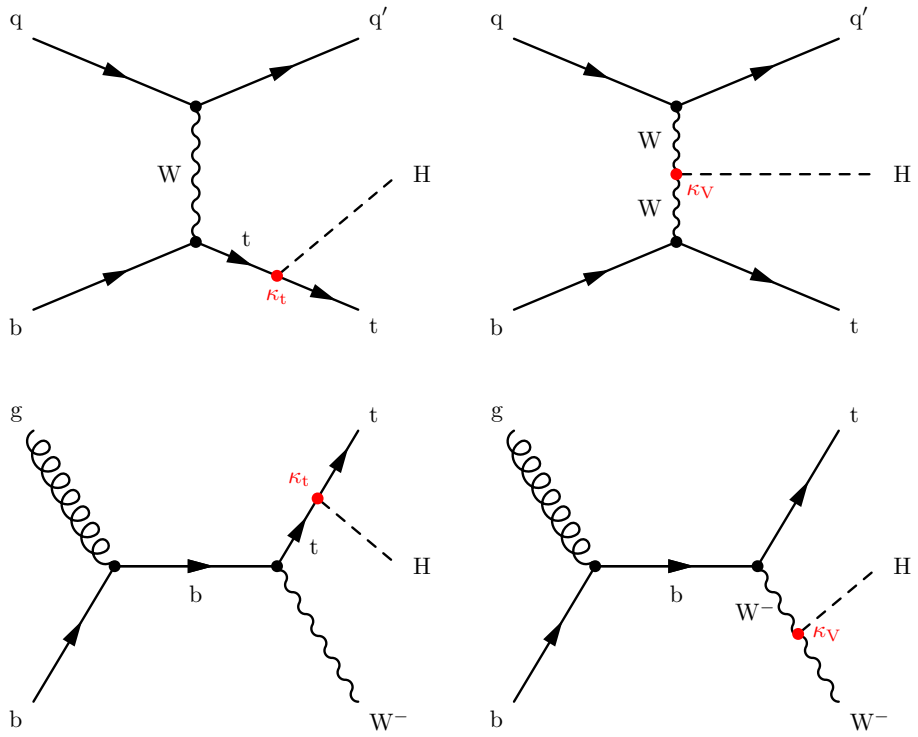


CMS arXiv:1804.02610

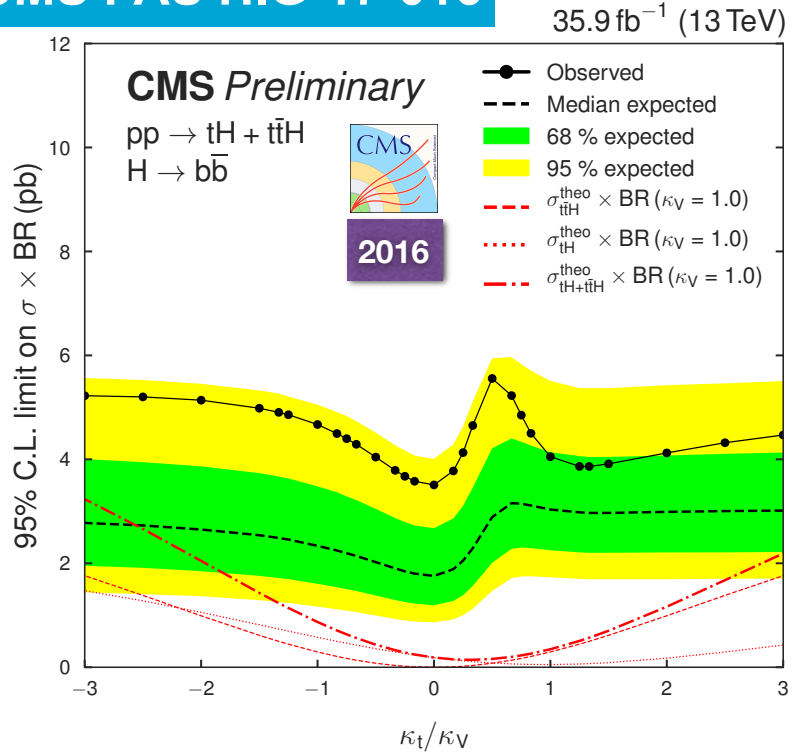


New tH(bb) Search

- Very sensitive to negative relative sign of the ttH vs. VVH coupling, which increases the cross section dramatically due to spoiled negative interference seen for the SM case w/ positive relative sign
- Complementary to the global fits, which only sensitive to loop effects
- Still more data are required to test concrete models



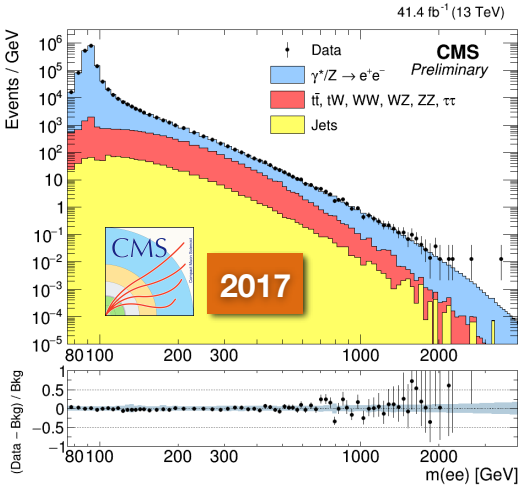
CMS PAS HIG-17-016



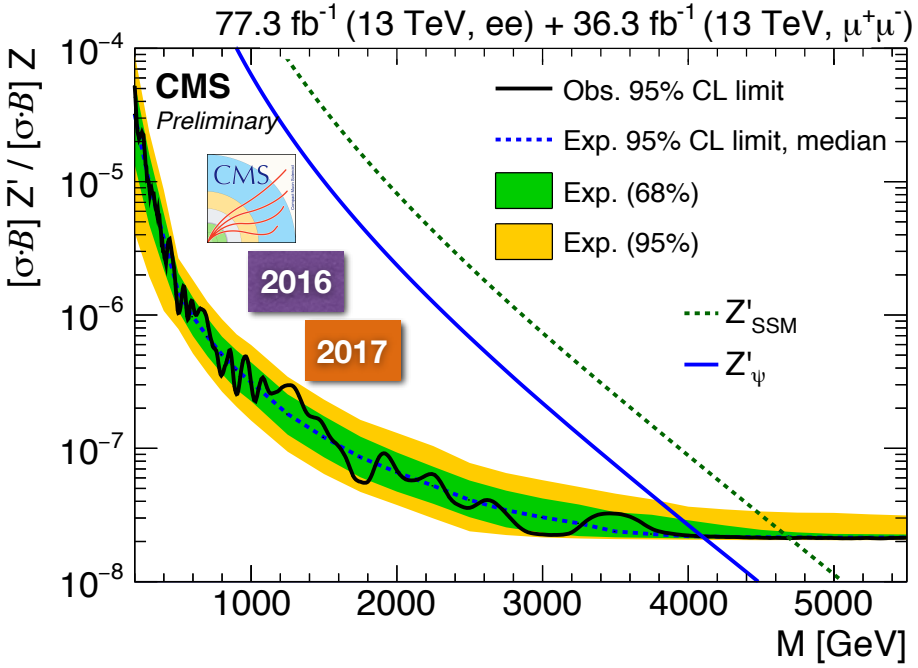
First 2017 Data Results

Z'(ll) Search

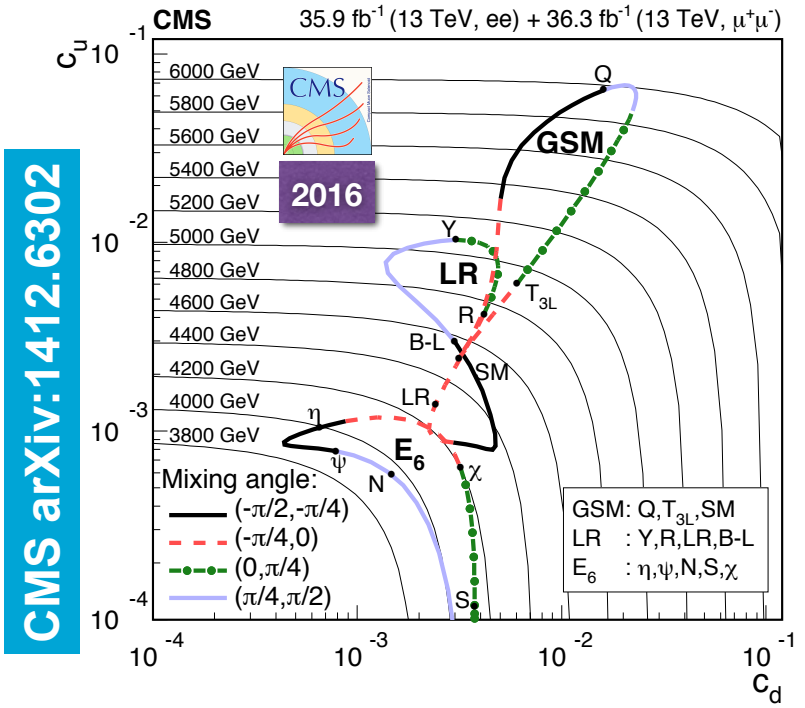
- CMS analysis based on 2016+2017 (ee) data
  - Use standard techniques well-tested in earlier reincarnations of the analyses
  - Limits on sequential Z' reached ~4.5 TeV
- Limits as a function of c_u/c_d couplings are done on 2016 data
- The results can also be interpreted as limits on quark-lepton compositeness



CMS PAS EXO-18-006

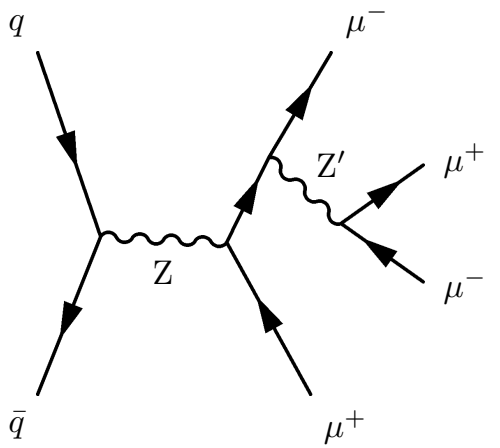


CMS arXiv:1412.6302



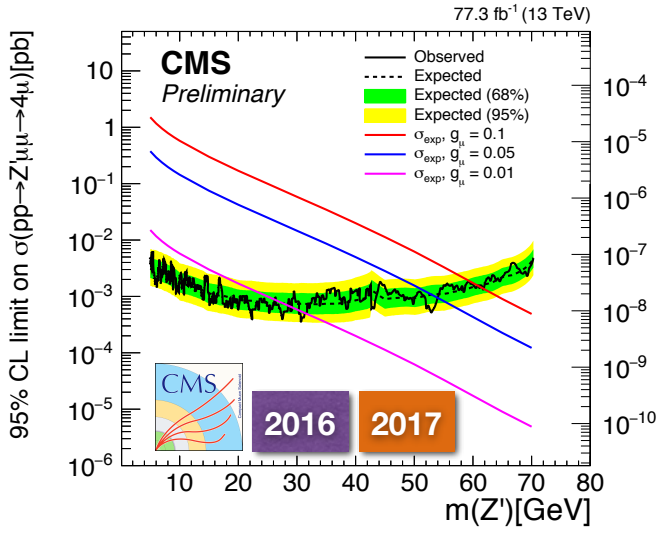
Search for Z' in Z → 4μ decay

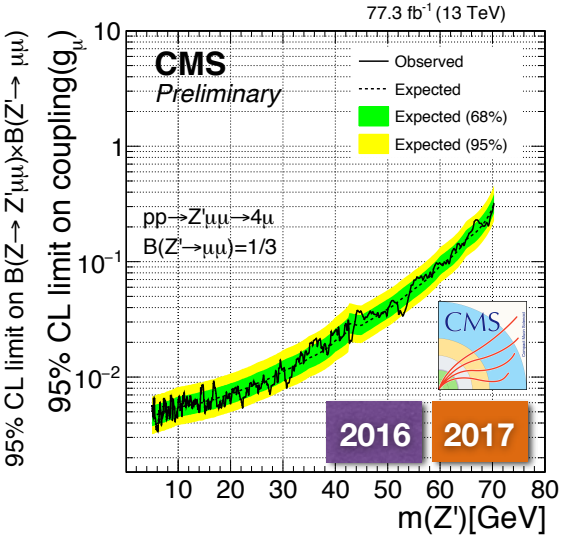
- Search for Z' with preferential coupling to second-generation particles, suggested as possible explanation of b → sμμ flavor anomalies
- Based on the H(ZZ) → 4μ analysis, using 2016+2017 data
- Closed significant fraction of the allowed parameter space in the L_μ - L_τ models

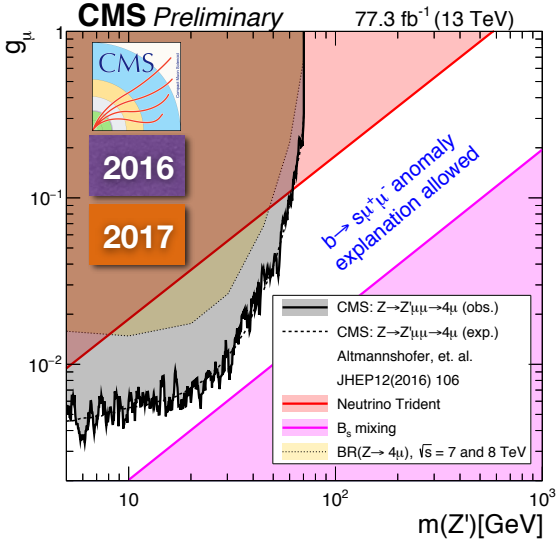


Altmannshofer et al. arXiv:1609.04026

CMS PAS EXO-18-008

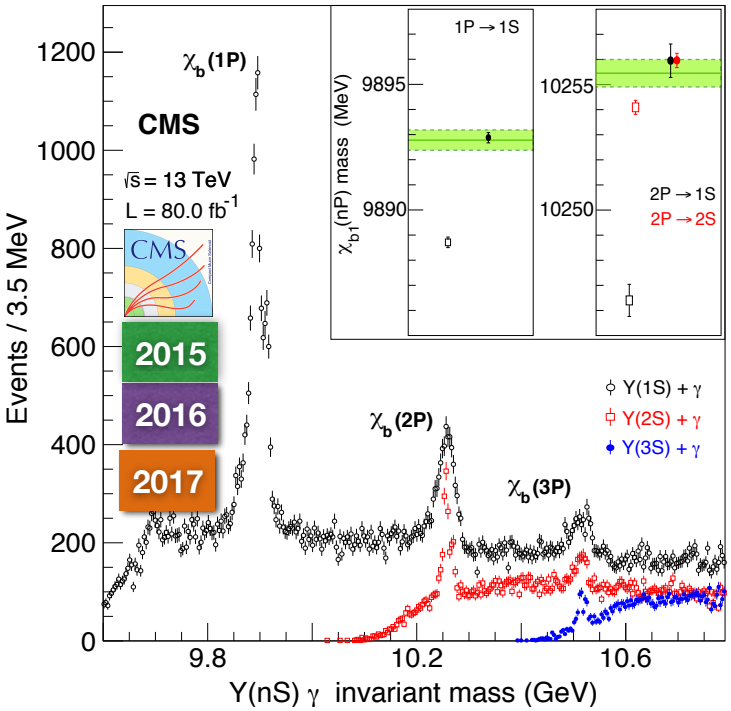




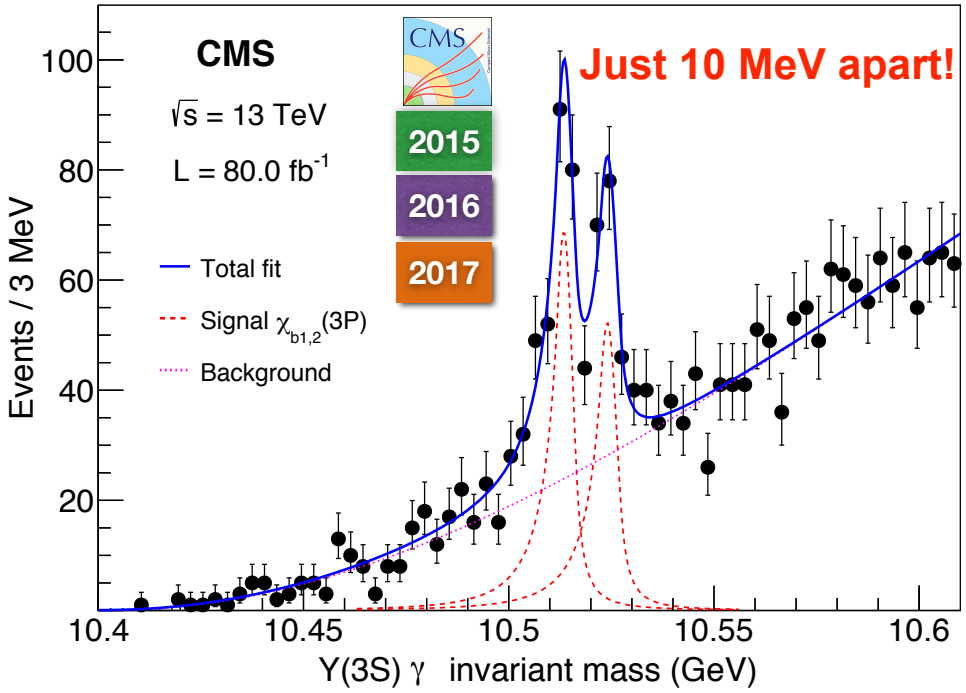


Observation of $\chi_{bJ}(3P)$

- First observation of excited, 3P χ_{bJ} states, J = 1, 2 via $\Upsilon(3S)\gamma$ decays using 2015-2017 data
- Detect low-p_T photons using conversions into e^+e^- pairs
- Achieved an unprecedented 5 MeV resolution in mass, and measured mass difference to be: $\Delta M = 10.60 \pm 0.64 \pm 0.17$ MeV



CMS arXiv:1805.11192

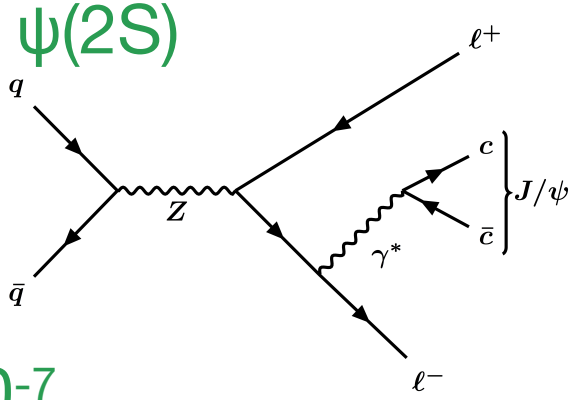



Resonant
Searches

Another Rare Z Decay

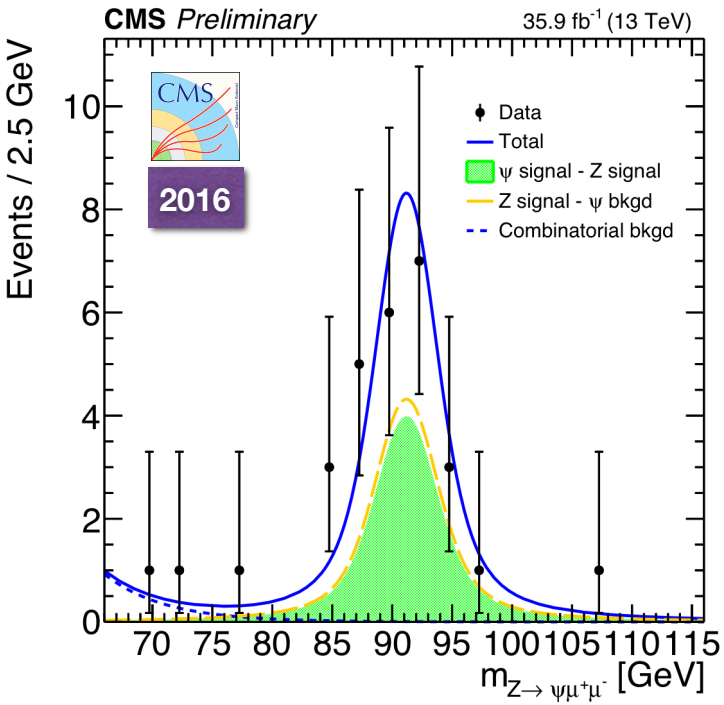
- Observation of the Z → ψl+l-, ψ = J/ψ + ψ(2S) decay in the 4μ + 2μ2e modes

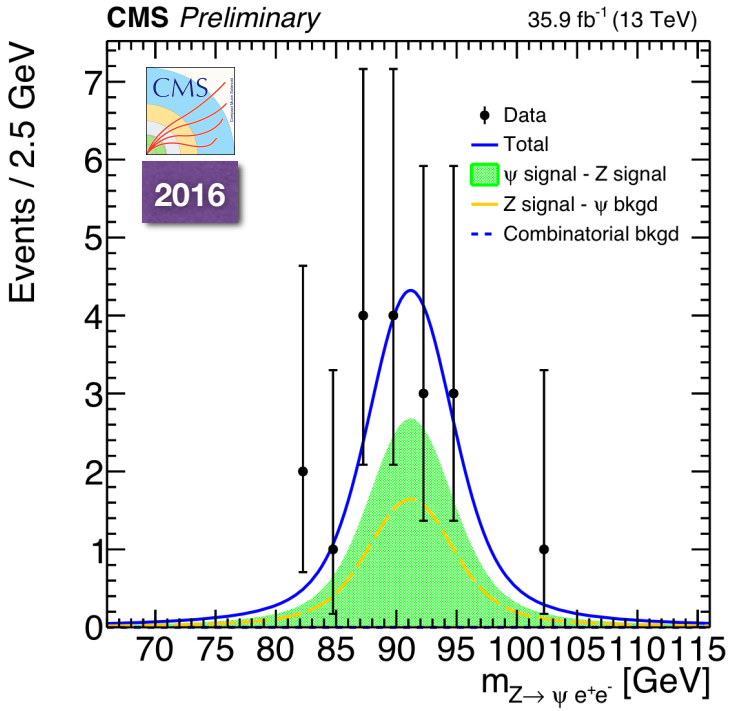
$$\frac{\mathcal{B}(Z \to J/\psi\, \ell^+\ell^-)}{\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-)} = 0.70 \pm 0.18\,(\text{stat}) \pm 0.05\,(\text{syst})$$



- B(Z → ψl+l-) ≈ 8 x 10-7, consistent w/ theoretical predictions of (6.7-7.7) x 10-7

CMS PAS BPH-16-001

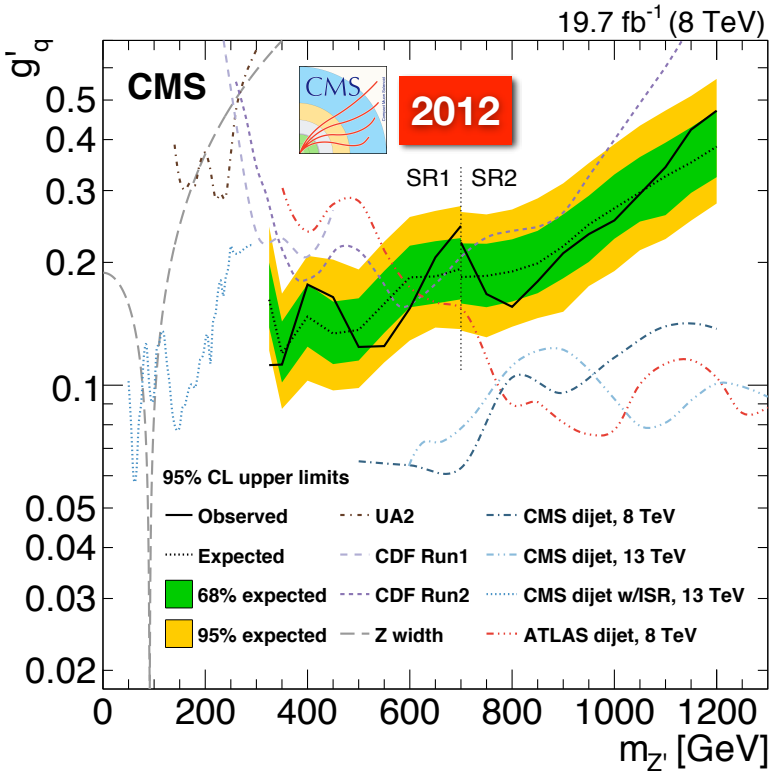


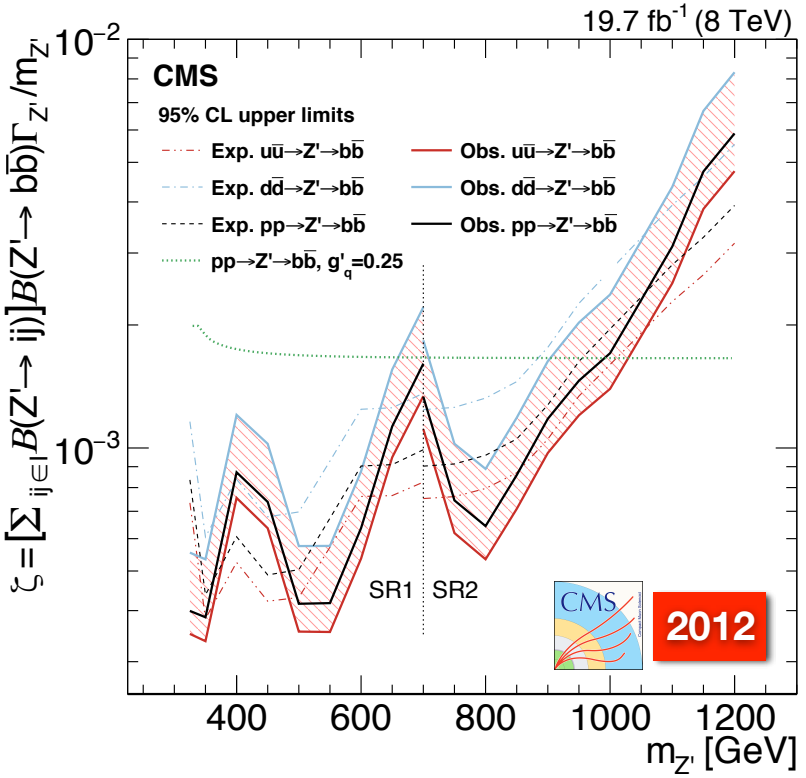


Low-Mass bb Dijet Search

- Likely the last search analysis based on 2012 data
- Uses dedicated b-tagged trigger, allowing for the first time to probe bb masses below the tt threshold
- Also, for the first time provide interpretation in the "zeta" simplified model framework [Chivukula et al., arXIv:1607.05525]

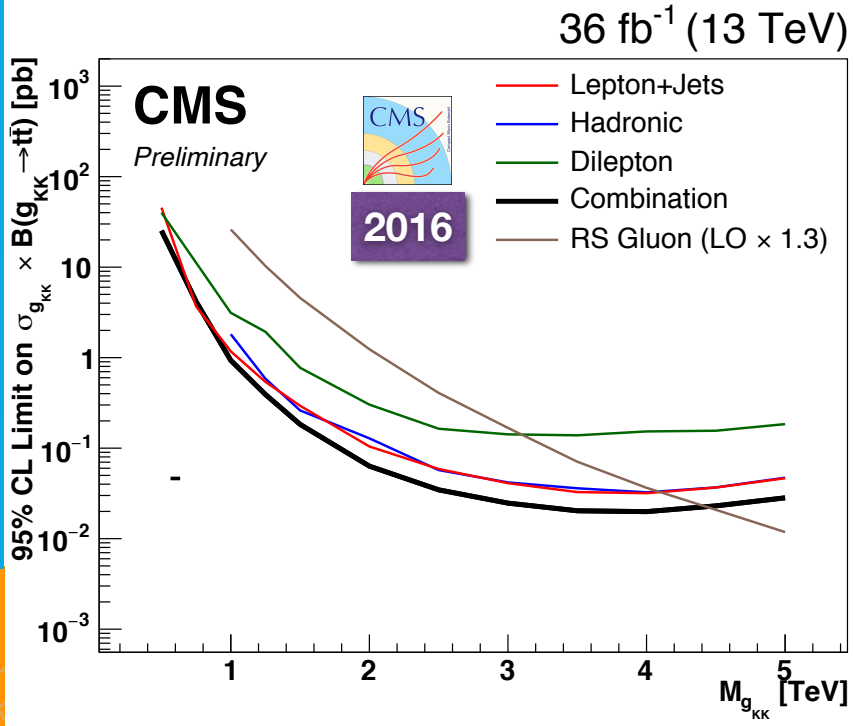
CMS arXiv:1802.06149



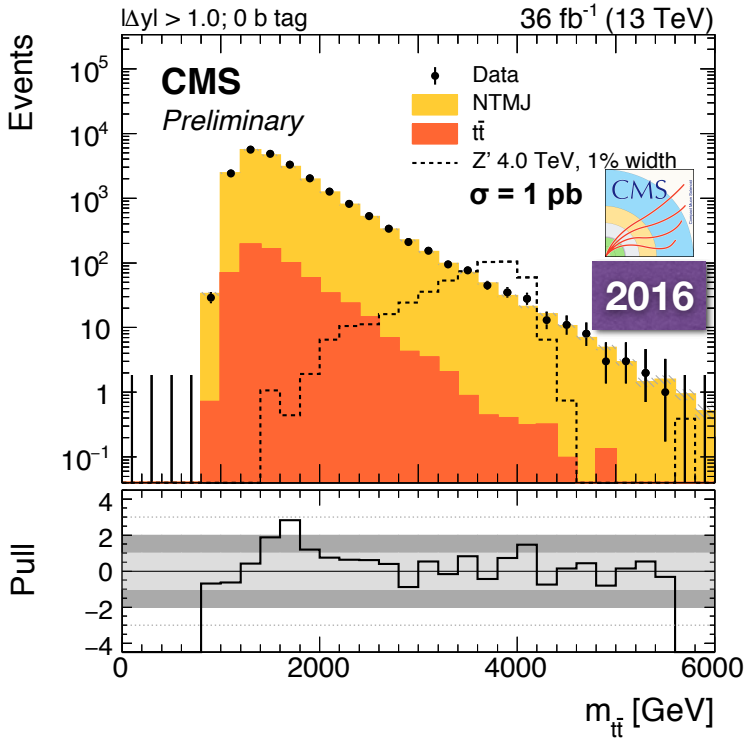


Searches for $t\bar{t}$ Resonances

- CMS search for $t\bar{t}$ resonances with 2016 data in the dilepton, semileptonic and all-hadronic final states, using both resolved decays and jet substructure
  - Limits on G_{KK} at 4.55 TeV are set @ 95% CL
  - Also, limits on Z' with $\Gamma/M = 0.1$ at 5.0 TeV are set, as well as limits as a function of the Z' width



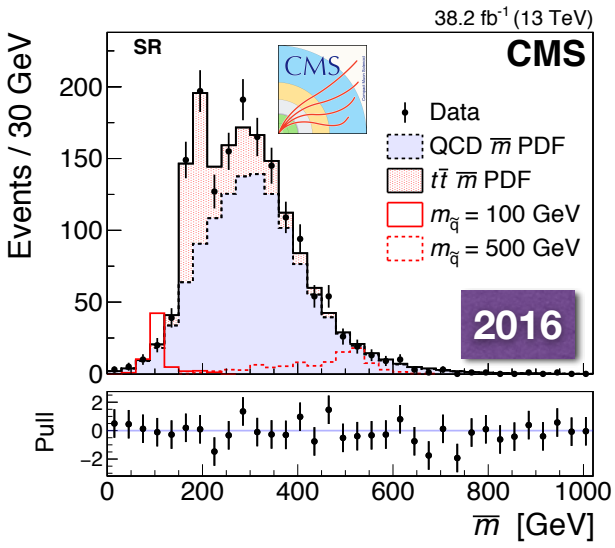
CMS PAS B2G-17-017

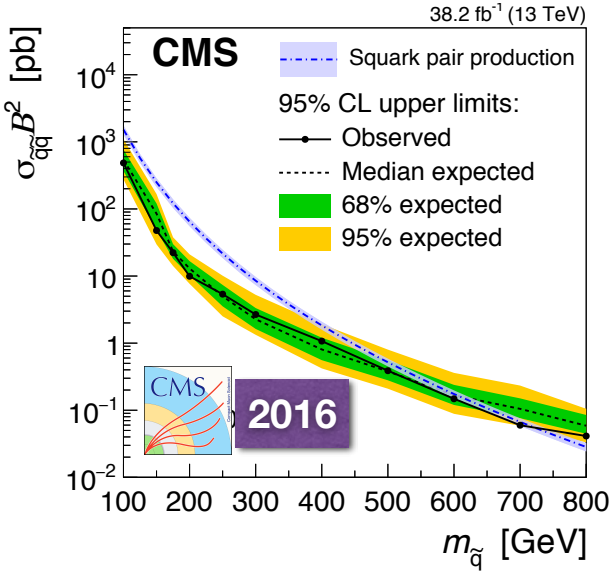


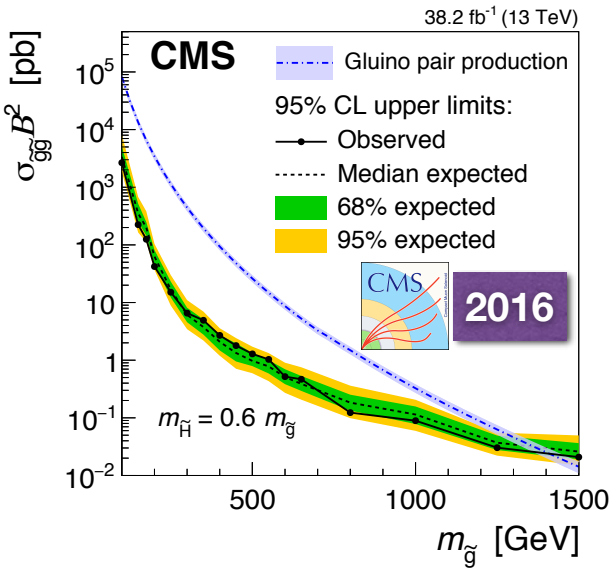
RPV SUSY w/ Multiple Jets

- Search for pair-produced squarks decaying to 4 quarks or gluinos decaying to 5 quarks via RPV UDD coupling, using very large radius jets (D=1.2) with substructure and N-subjettiness as a discriminating variable against backgrounds
- Estimate QCD background via event mixing technique
- Sensitive to squark/gluino masses as low as 100 GeV; complementary to resolved-jet searches that typically start at masses ~0.5 TeV

CMS arXiv:1806.01058



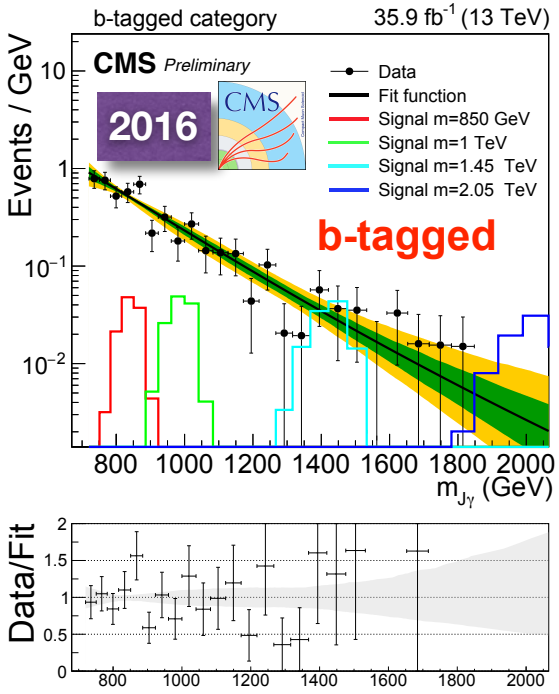


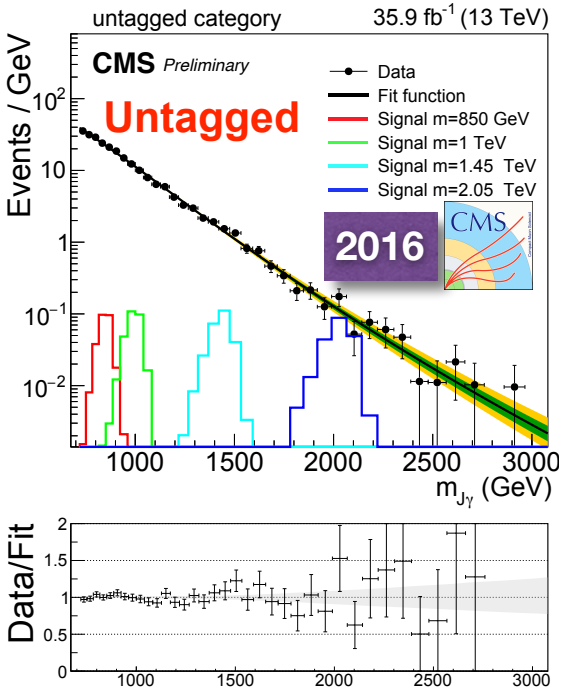


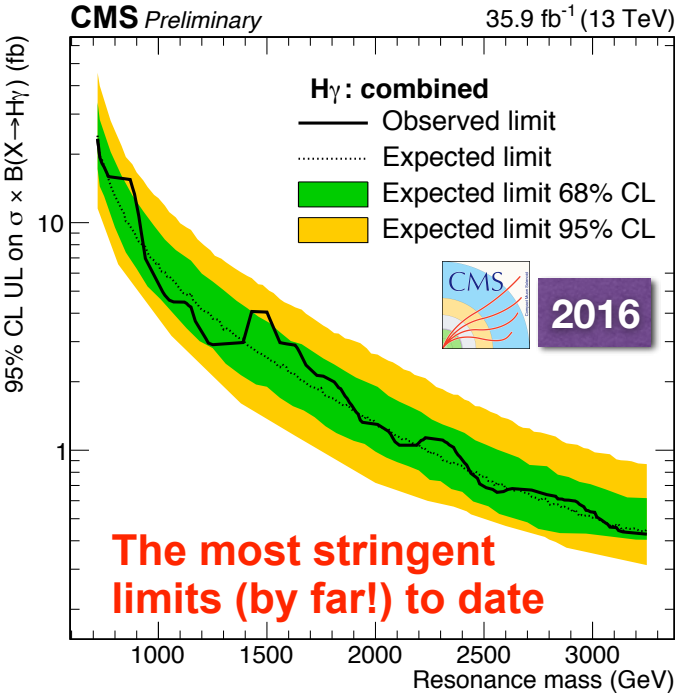
Hγ Search

- ATLAS/CMS has a number of Vg searches, with V = g, W, Z
- Natural extension: Hg, using H(bb) decay and boosted topology
- Classify events according to the double-b-tag discriminant
  - b-tagged topology most sensitive at relatively low masses
  - At large masses, untagged topology is more sensitive, as backgrounds are low

CMS PAS EXO-17-019



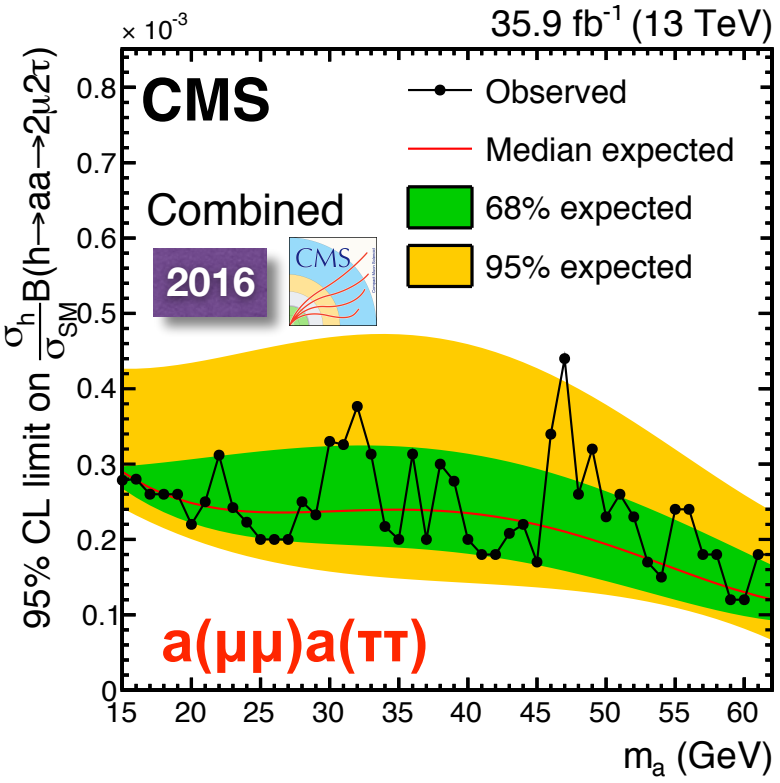




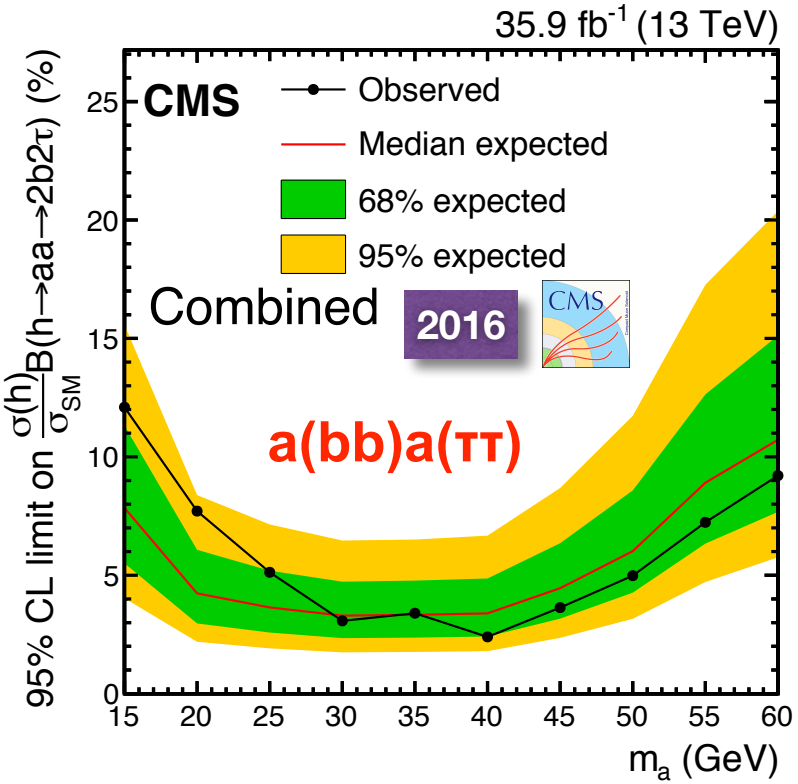
H → aa Searches

- Two recent results: H →a(μμ)a(ττ) and a(bb)a(ττ)
  - ττ is looked for in the τ_he, $\tau_h\mu$, eμ channels, and also $\tau_h\tau_h$ for the first case

CMS arXiv:1805.04865



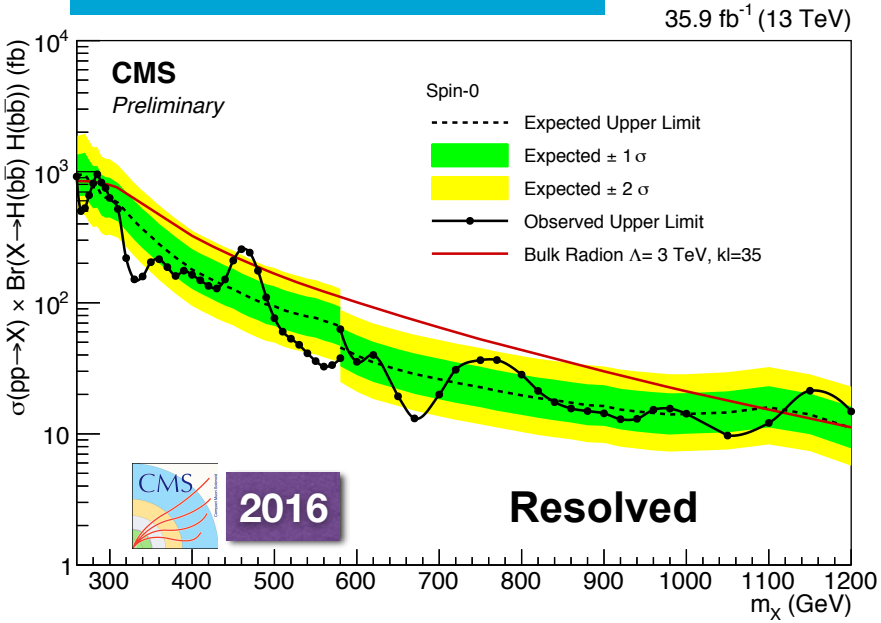
CMS arXiv:1805.10191



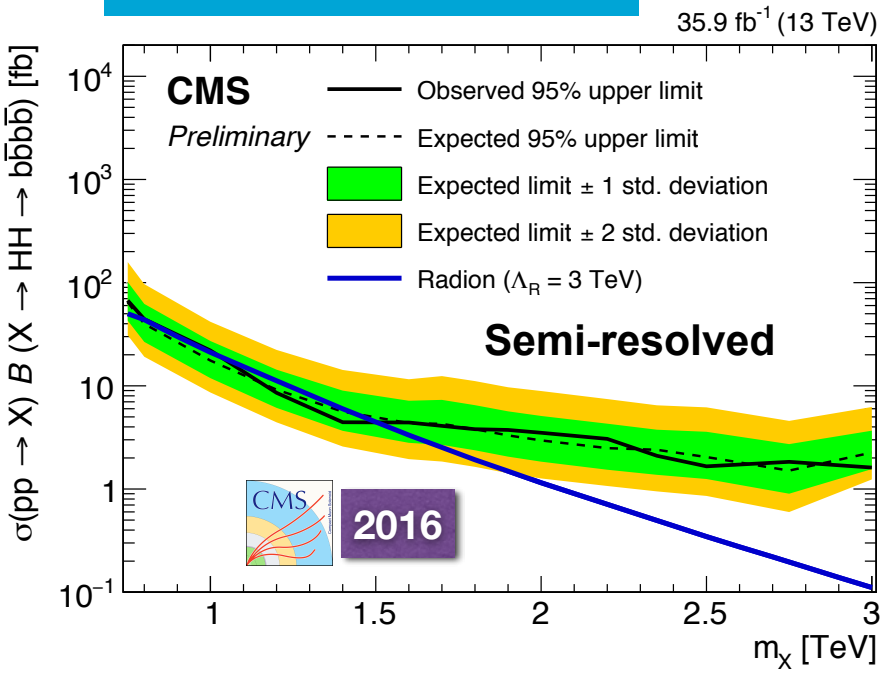
HH Resonance Searches

- Two new CMS HH resonance searches: in the fully-resolved and semi-resolved bbbb channel:
  - Probe both spin-0 radion and spin-2 bulk graviton models

CMS PAS HIG-17-009



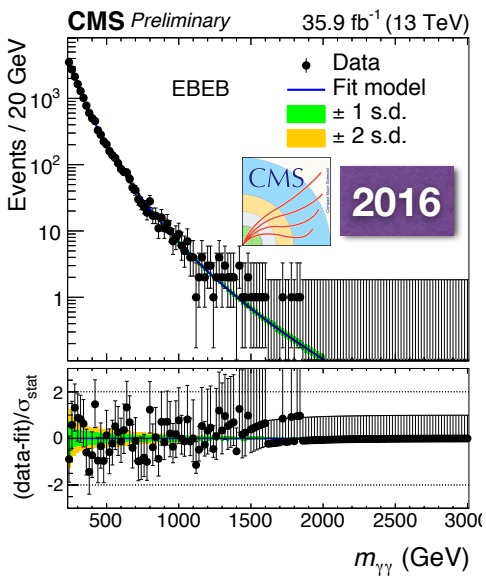
CMS PAS B2G-17-019

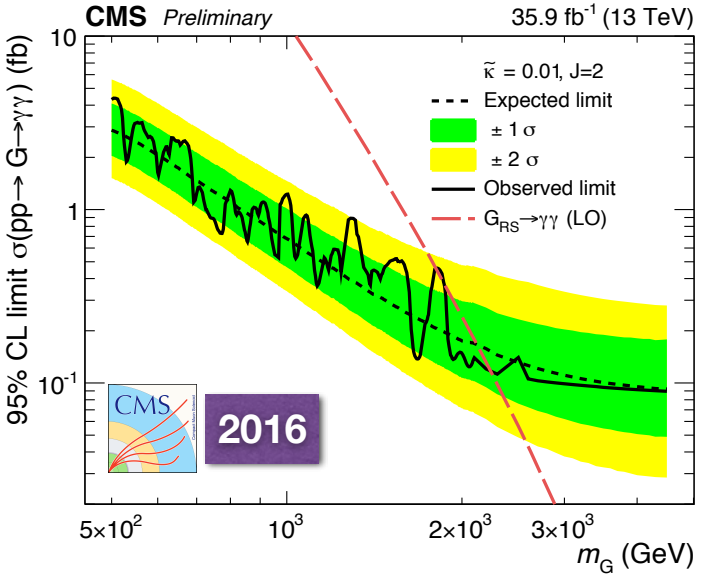


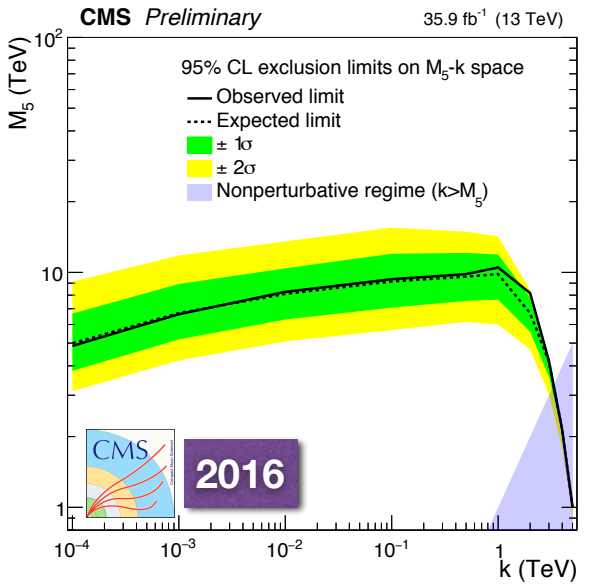
Search for Diphoton Resonances

- Search for narrow resonances and non-resonant phenomena in the diphoton mass spectrum
- Limits on spin-0 and spin-2 resonances; RS gravitons w/ $k/M_{Pl} = 0.1$ are excluded below 2.25 TeV
- Also set non-resonant limits: ADD $M_S > 5.6$-9.7 TeV and first limits on the parameters k, M_5 of a continuum clockwork model [Giudice et al., arXiv:1711.08437]

CMS PAS EXO-17-017





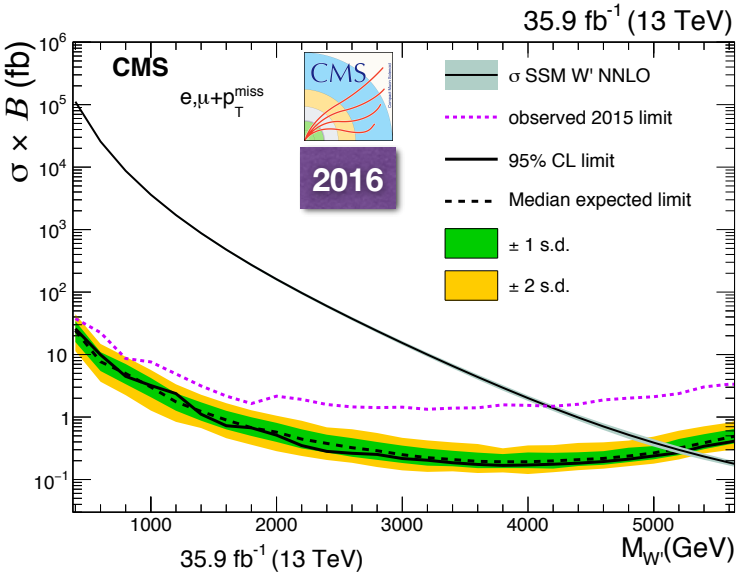


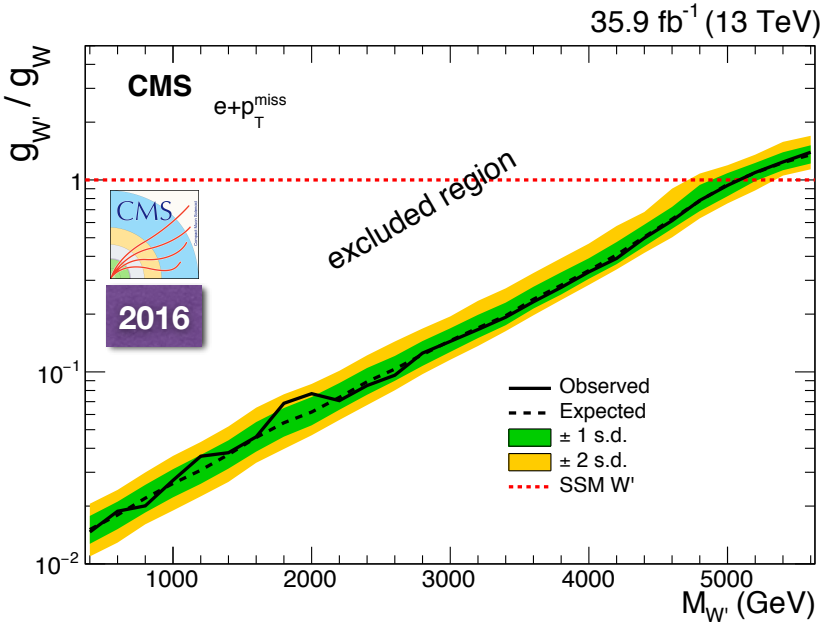

Non-Resonant
Searches

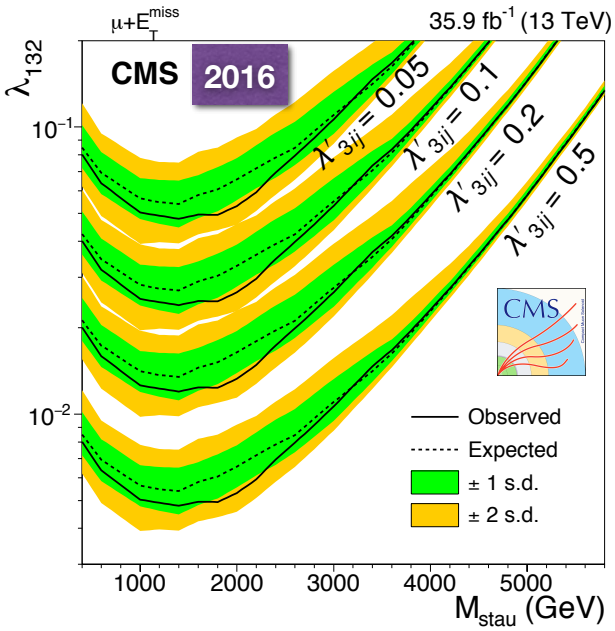
W'(lν) Search

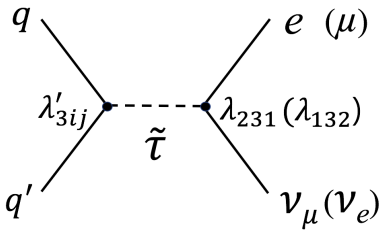
- Analyses based on 2016 CMS data
  - Use standard techniques well-tested in earlier reincarnations of the analyses
  - Limits on sequential W' reach ~5 TeV; also limits on UED, RPV SUSY

CMS arXiv:1803.11133





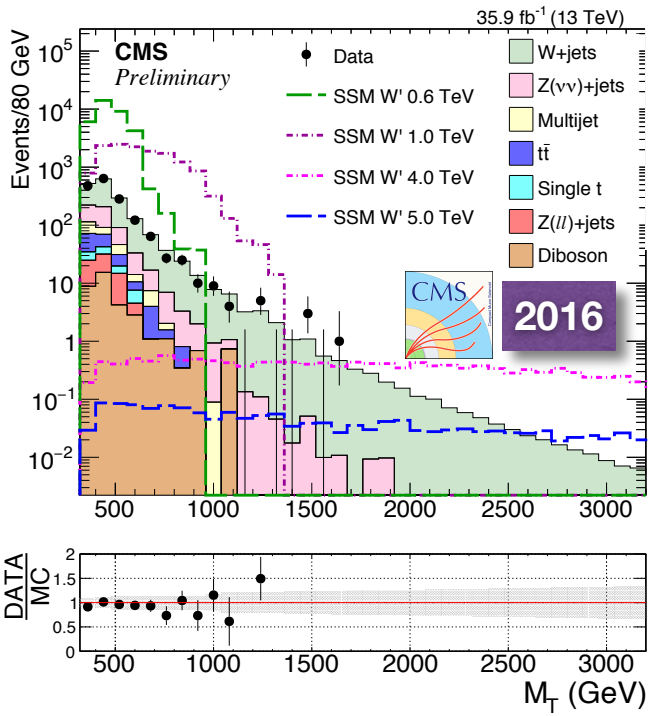


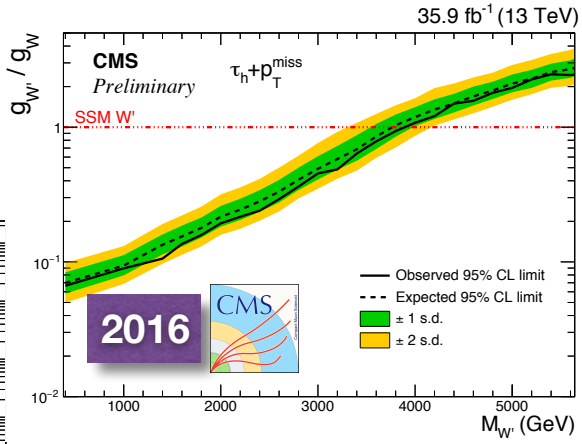


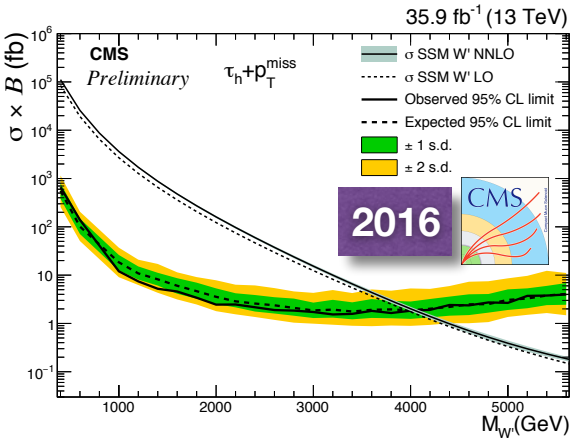
W'(τν) Search

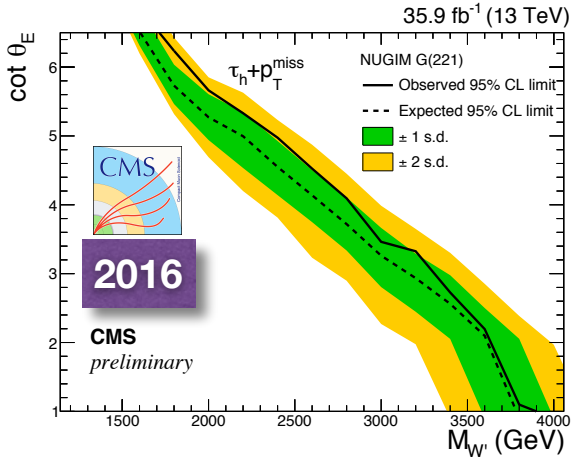
- Similar search in a challenging $\tau_h\nu$ channel
  - Sensitive to W' preferentially coupled to third-generation particles
- Set limits on SM-like W' and on W' in NUGIM G(221) model

CMS PAS EXO-17-008



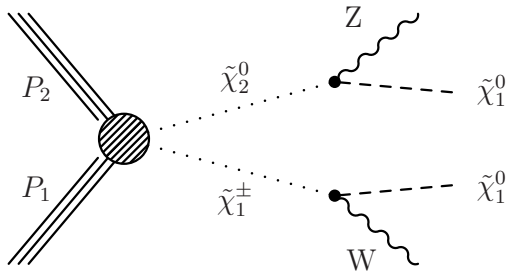


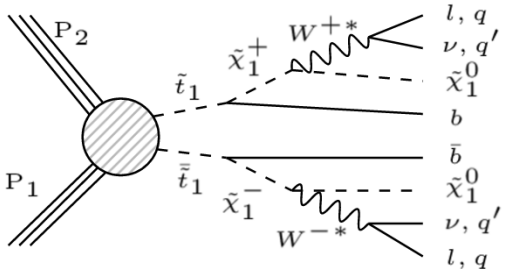


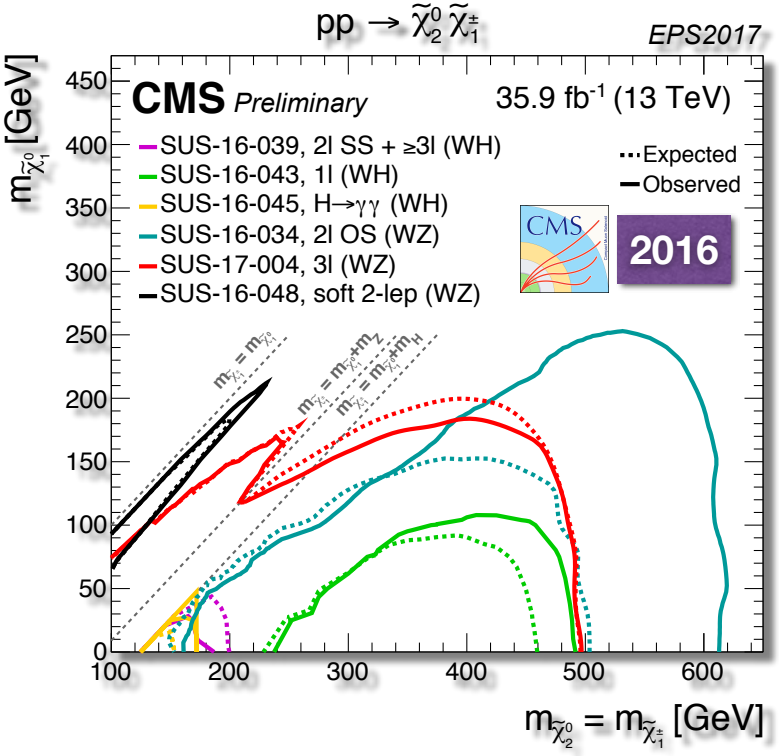


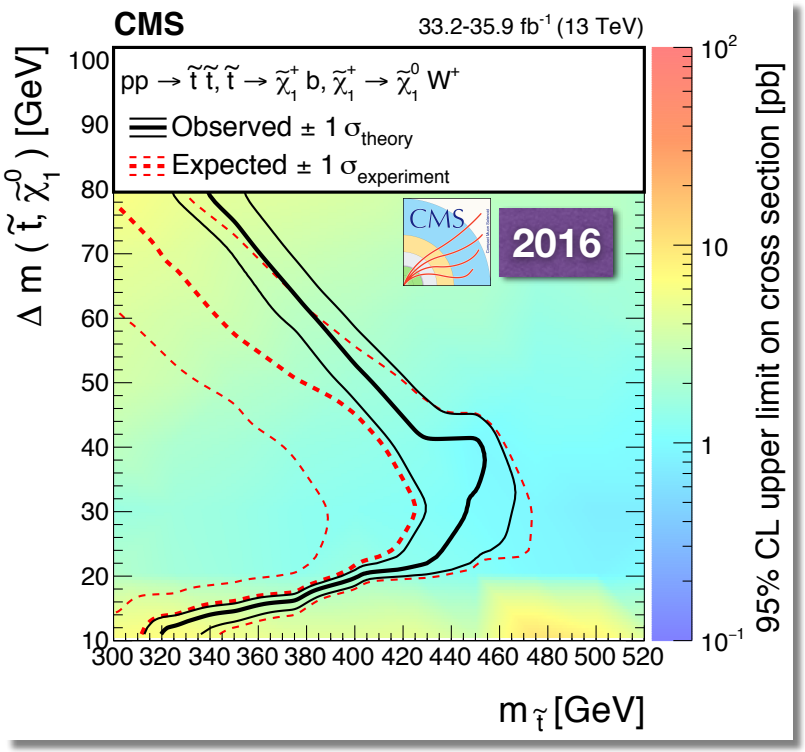
Soft OS Dilepton SUSY Search

- Could also require 2 OS dileptons ($5 < p_T < 30$ GeV) via dedicated trigger
- Sensitive to EW SUSY and direct stop production in small mass splitting scenarios





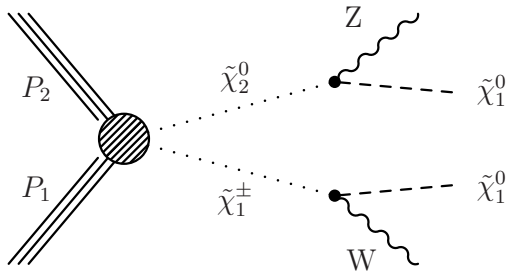


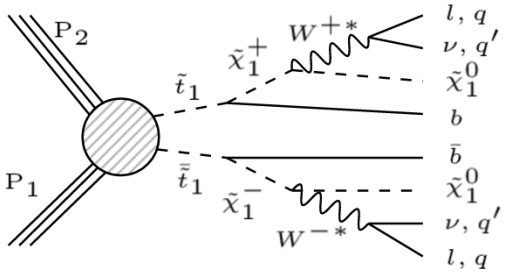


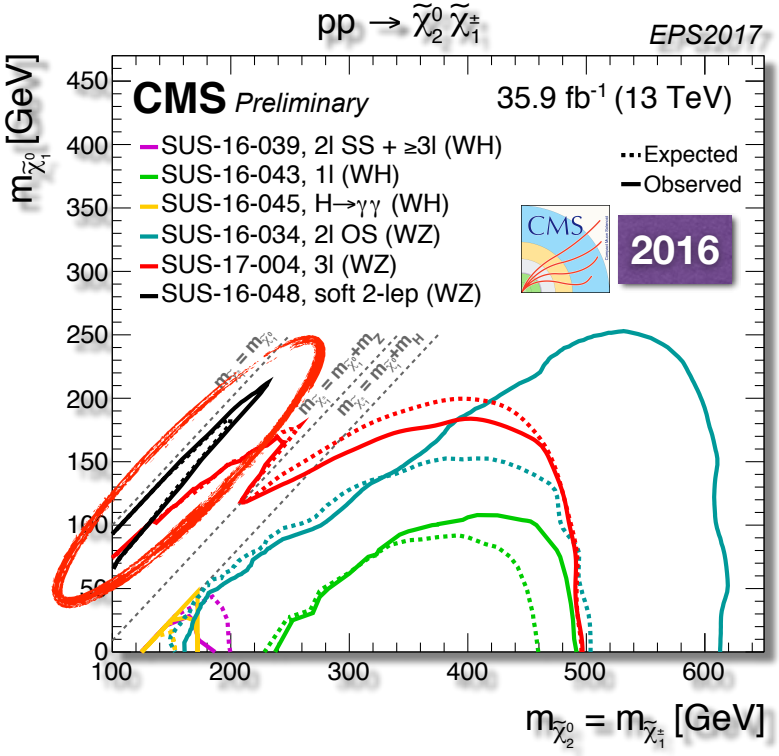
CMS arXiv1801.01846

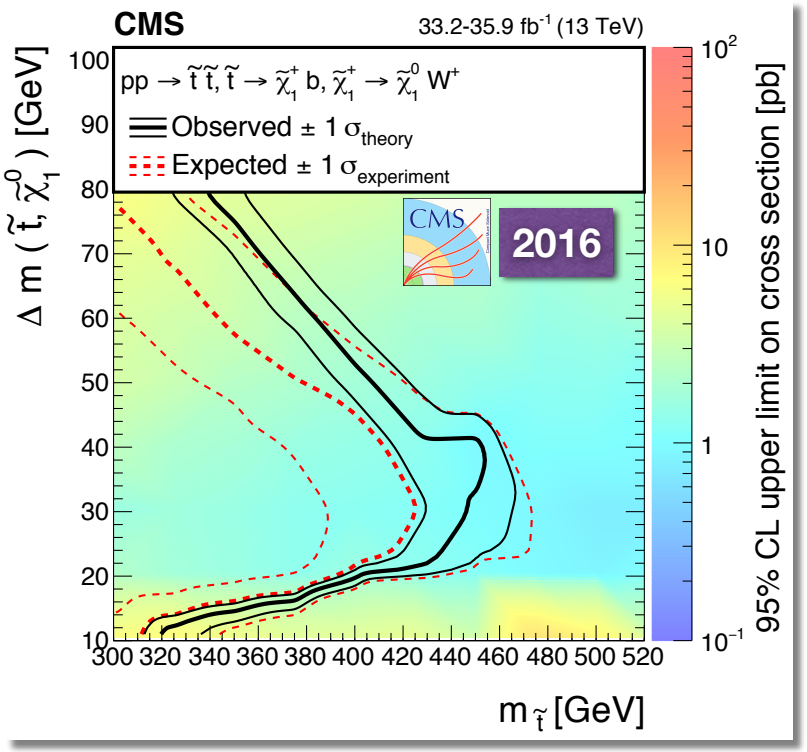
Soft OS Dilepton SUSY Search

- Could also require 2 OS dileptons ($5 < p_T < 30$ GeV) via dedicated trigger
- Sensitive to EW SUSY and direct stop production in small mass splitting scenarios







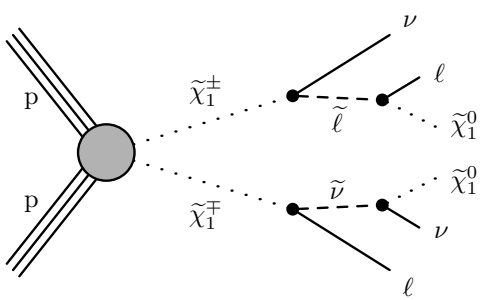


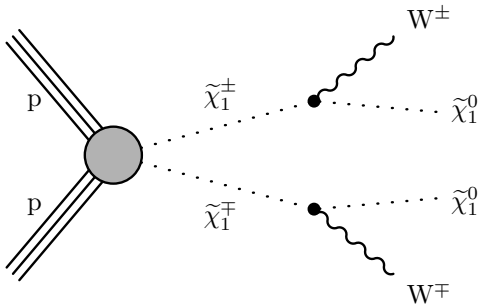
CMS arXiv1801.01846

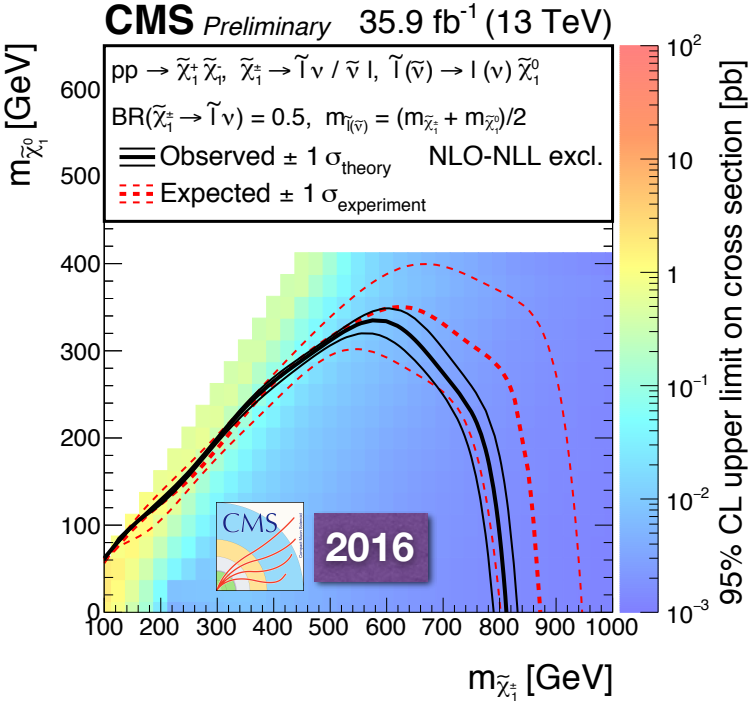
EW Production: Dileptons

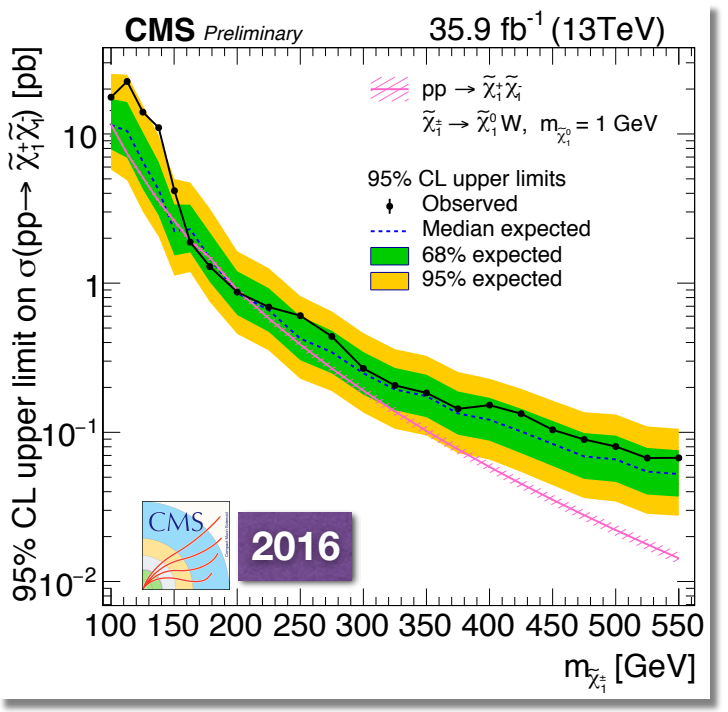
- Similar search in the dilepton channel, using M_{T2} to suppress dominant tt and WW background

CMS Collaboration
SUS-17-010









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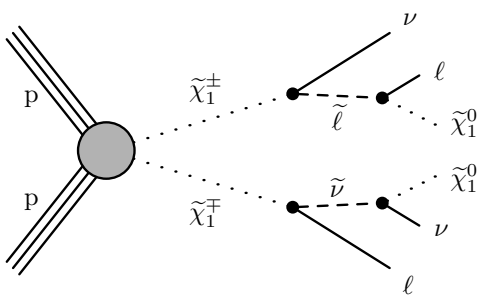
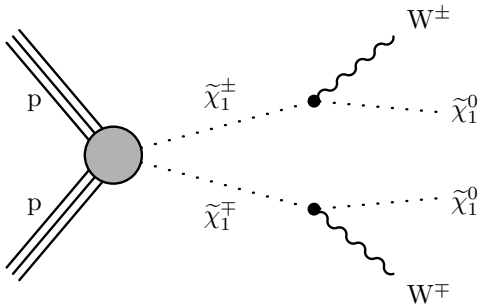
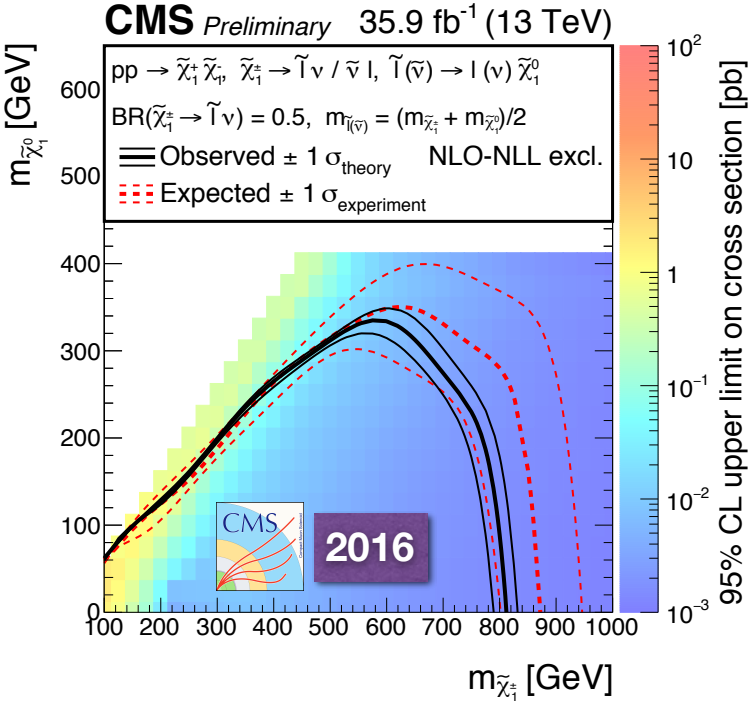
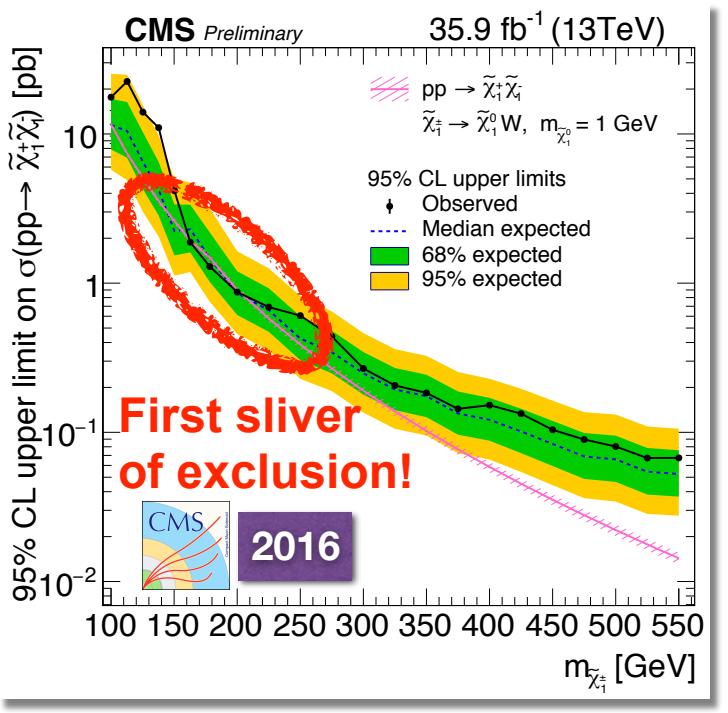
CMS Collaboration
SUS-17-010



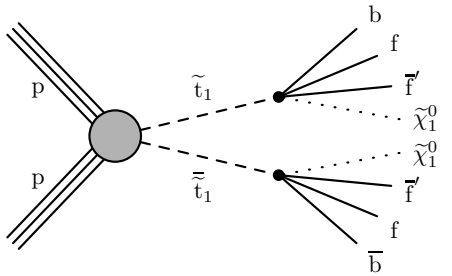


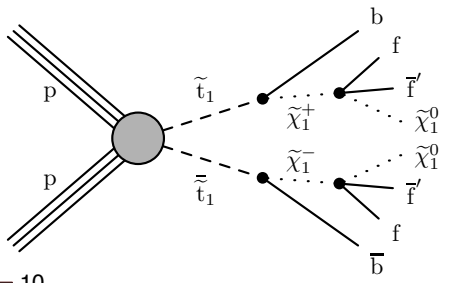


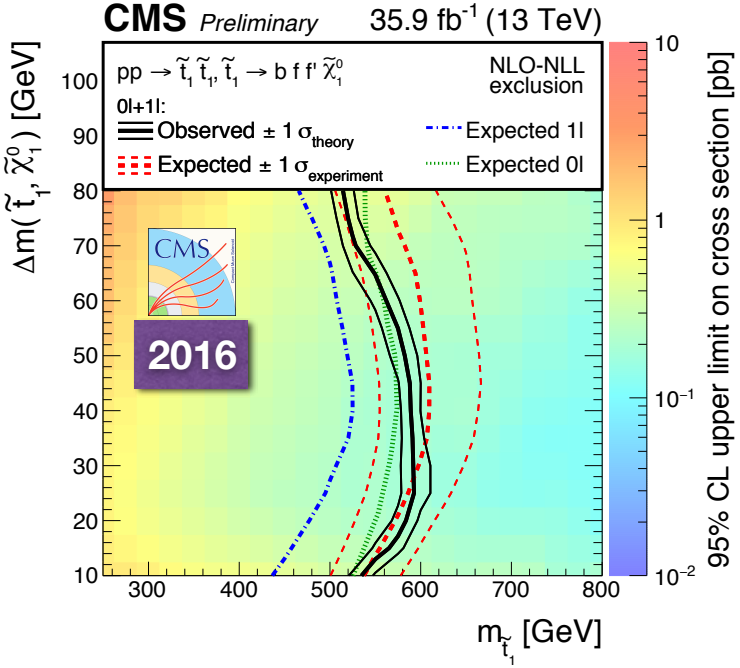


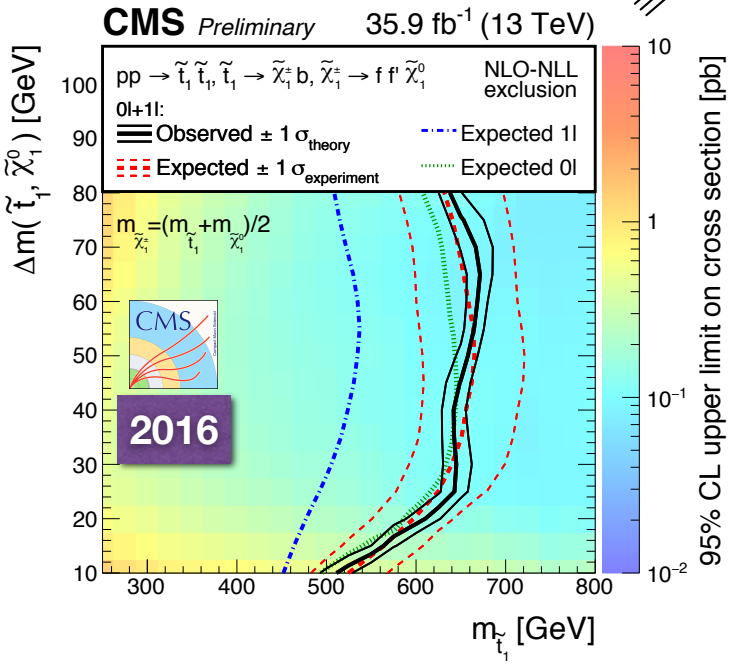
Search for 4-body Stop Decays

- For small mass splittings between stop and neutralino, expect 4-body decays via virtual chargino and W boson
- Require at least one soft lepton ($30 > p_T > 3.5$-5 GeV) and a hard ISR jet to aid the efficiency and triggering
- Background is dominated by diboson and W+jets production and determined using control regions in data
- Also sensitive to chargino-mediated stop decays
- Limits are further improved by combining with the all-hadronic search arXiv:1707.03316







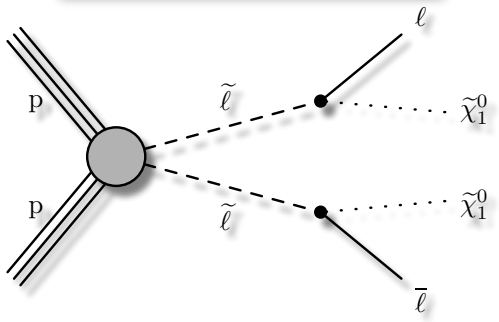


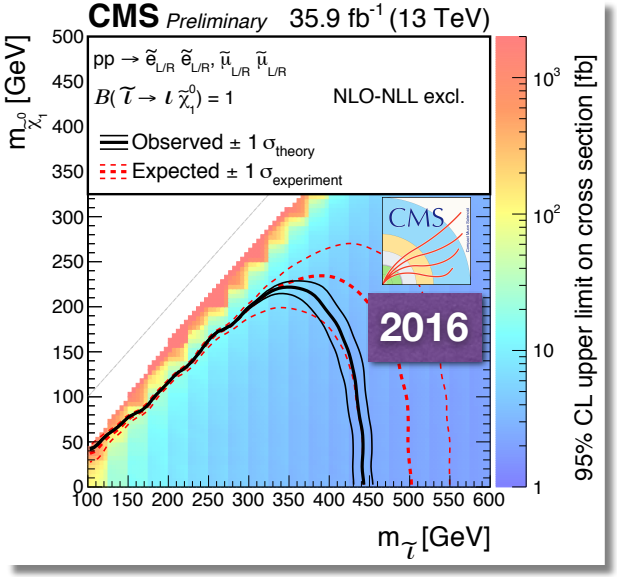
CMS Collaboration SUS-17-005

Slepton Searches

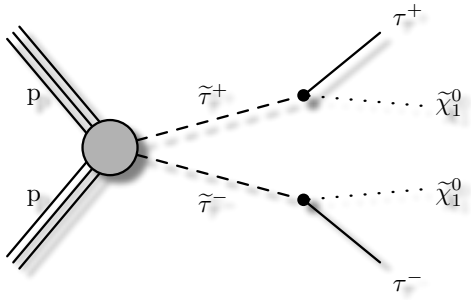
- Dilepton searches w/ M_{T2} variable with light or τ leptons probing direct slepton production and stau-mediated electroweakino decays

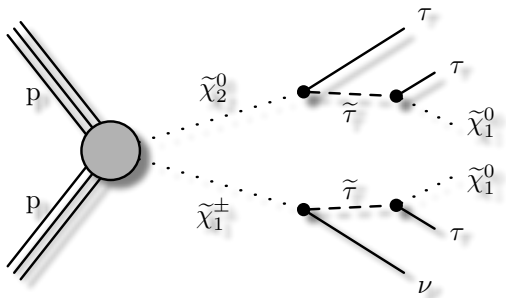
CMS Collaboration SUS-17-009

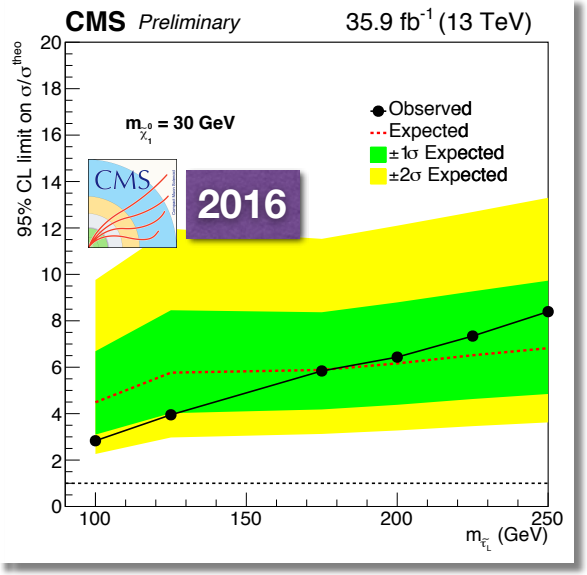


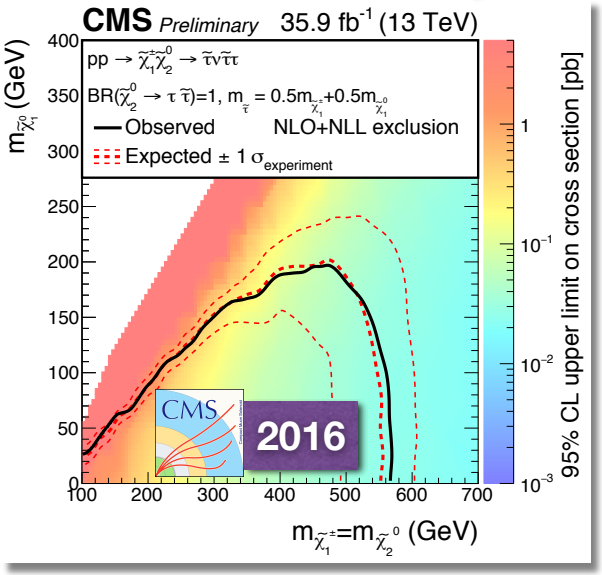


CMS Collaboration SUS-17-002





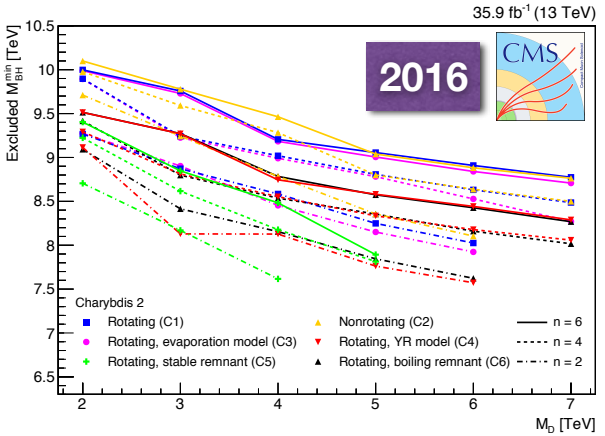


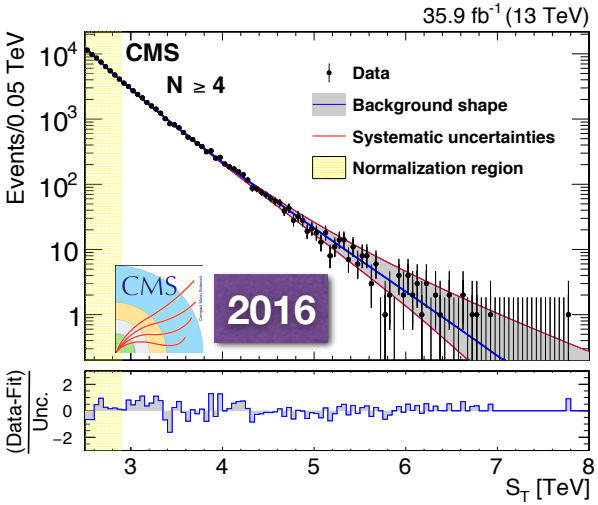


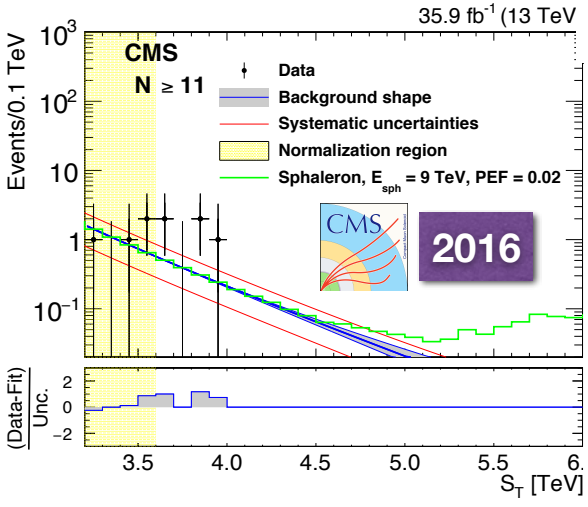
Search for Black Holes

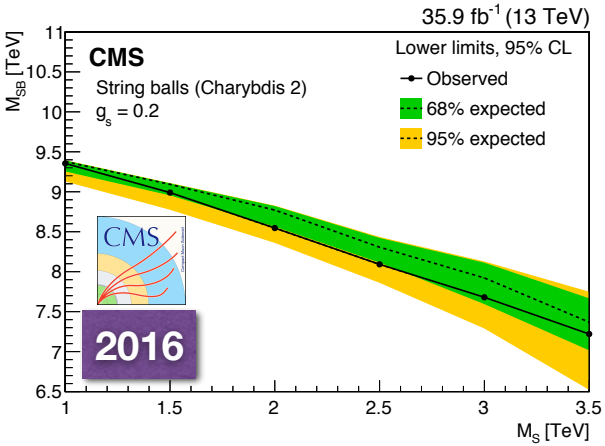
- Traditionally used to probe semiclassical black holes, also provide strong limits on high-multiplicity signatures often expected to come from RPV SUSY decays, axigluons, and other strong dynamics objects, quantum gravity
- Based on the S_T invariance: $ST = \Sigma p_T^j$ nearly independent of the multiplicity N
- Predict background from N = 3 distribution; go up to N > 11!
- Set both model-independent limits and limits in specific black hole or string ball models
- Limits are as high as 10 TeV on the BH mass

CMS arXiv:1805.06013









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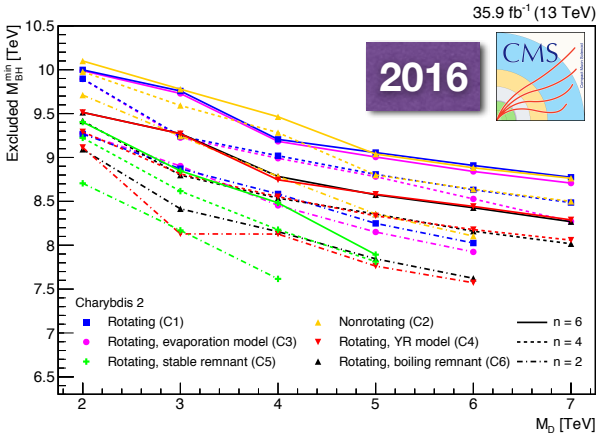
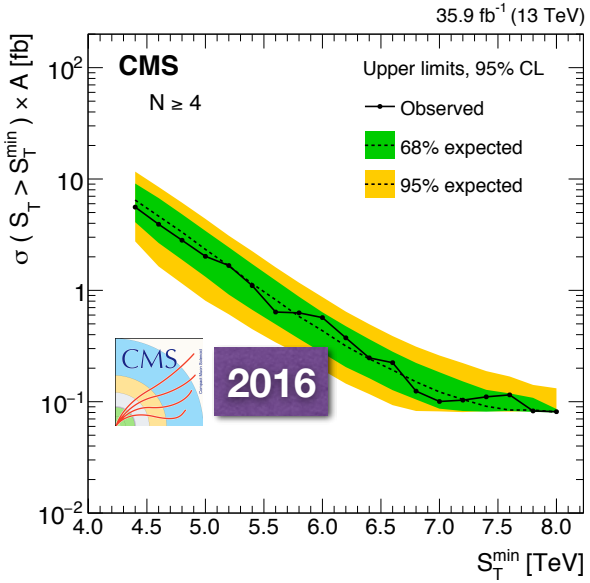
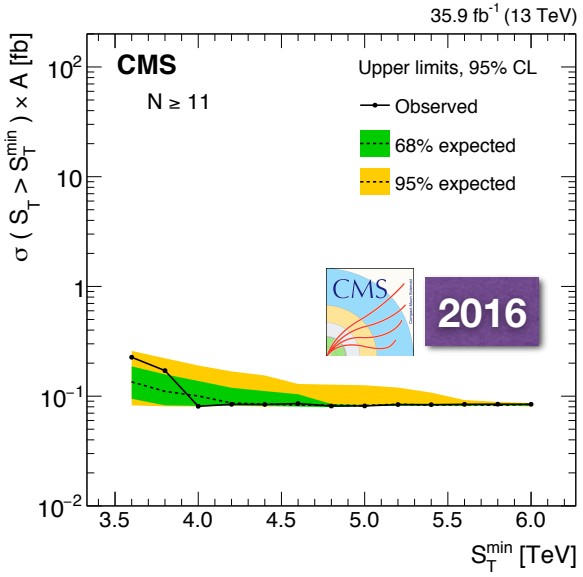
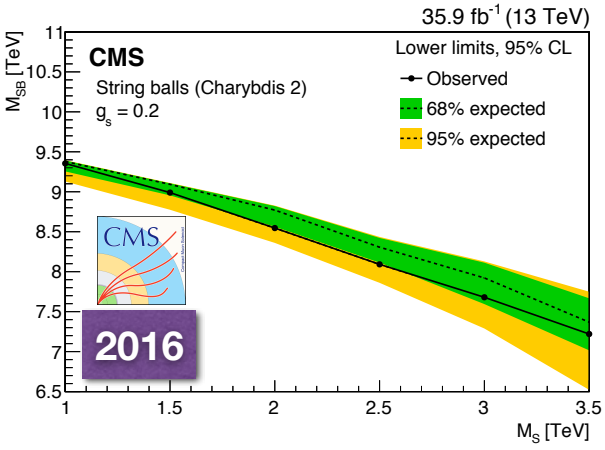






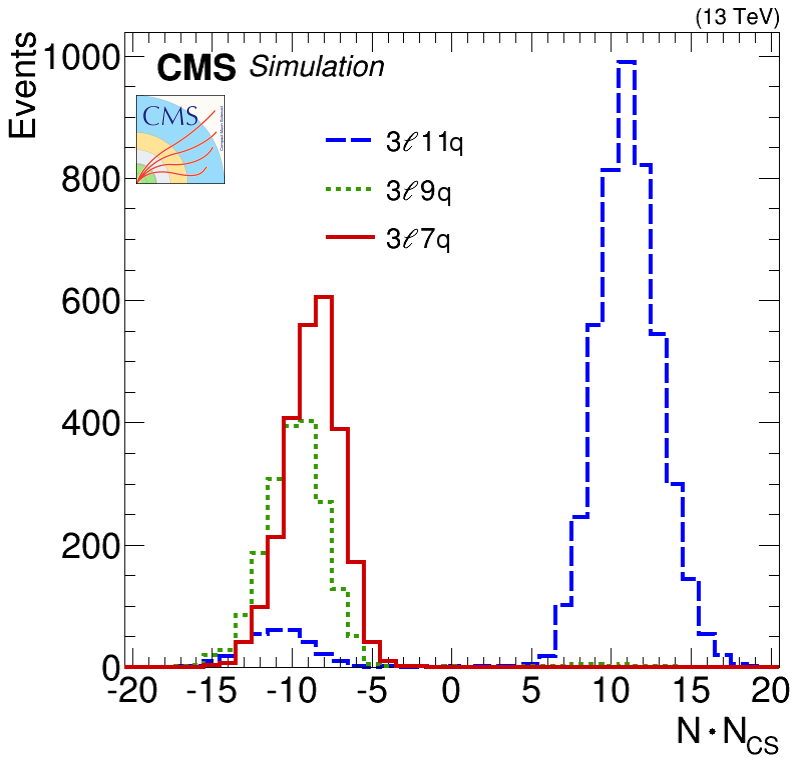


First Search for EW Sphalerons

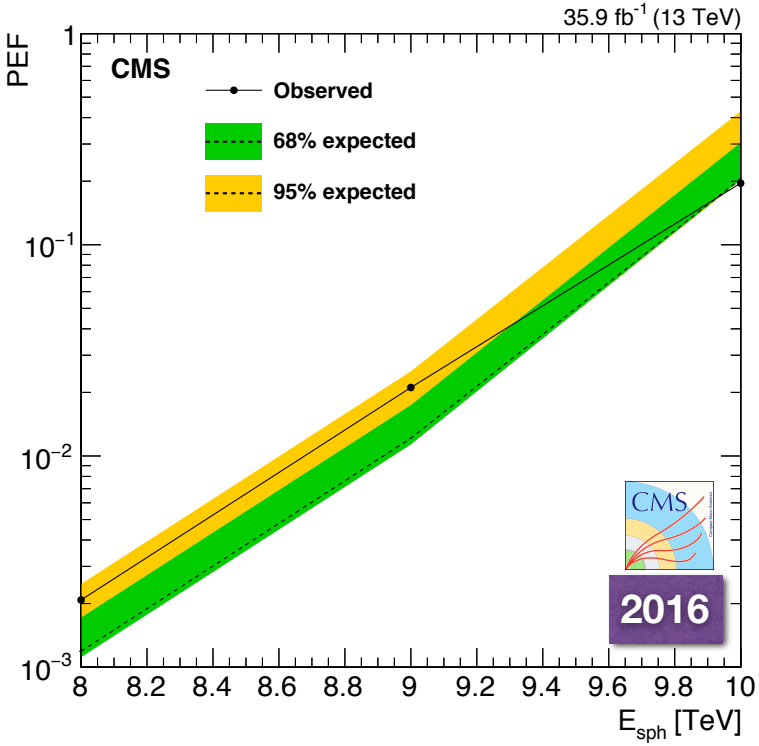
- Can reinterpret this result as a limit on EW sphalerons
- Sphalerons were proposed by `t Hooft as a non-perturbative solution of EW Lagrangian, which results in B+L non-conservation, while conserving B-L
- The discovery of the Higgs boson allowed to calculate the sphaleron transition, which, at LO is at E_{thr} = 9 TeV
- Recent work of Tye/Wong [arXiv:1505.3690] boldly suggested that due to periodicity of the potential there is no exponential suppression for the sphaleron transition just below the threshold, and no suppression at all above the threshold, i.e. observable at the LHC
- Sphaleron transition at leading order results in 12 fermions in the final state (3 x 3 quarks, and 3 leptons, one per generation)
  - Some of the f.s. quarks can "cancel" w/ the initial state, reducing the f.s. multiplicity
  - Typical example: $\mathrm{u} + \bar{\mathrm{u}} \rightarrow \mathrm{e}^{+}\mu^{+}\tau^{+}\ \bar{\mathrm{t}}\bar{\mathrm{t}}\bar{\mathrm{b}}\bar{\mathrm{c}}\bar{\mathrm{c}}\bar{\mathrm{s}}\bar{\mathrm{d}} + X$
- Ellis/Sakurai [arXiv:1601.03654] reinterpreted 2015 ATLAS BH search [arXiv: 1512.02586] and set first [phenomenological] limits on EW sphaleron production
- Here we present the first dedicated experimental search for EW sphalerons

Limits on EW Sphalerons

- Used BaryoGen generator [arXiv:1805.02786] developed in the course of the analysis
- Limits are set on the pre-exponential factor (PEF), which is the fraction of collisions with the c.o.m. energy above E_{thr}, which undergoes a sphaleron transition
- The limit is PEF < 0.021 @95% CL for E_{thr} = 9 TeV



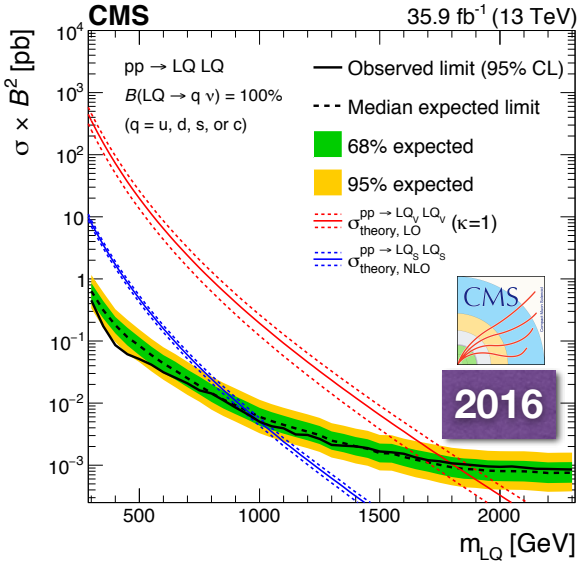
CMS arXiv:1805.06013

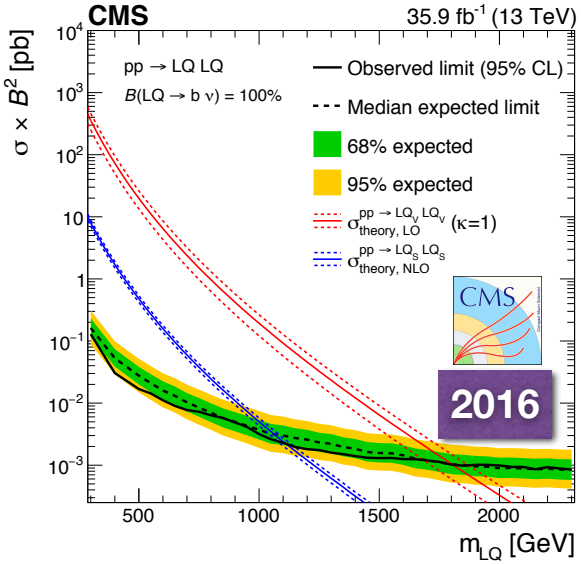


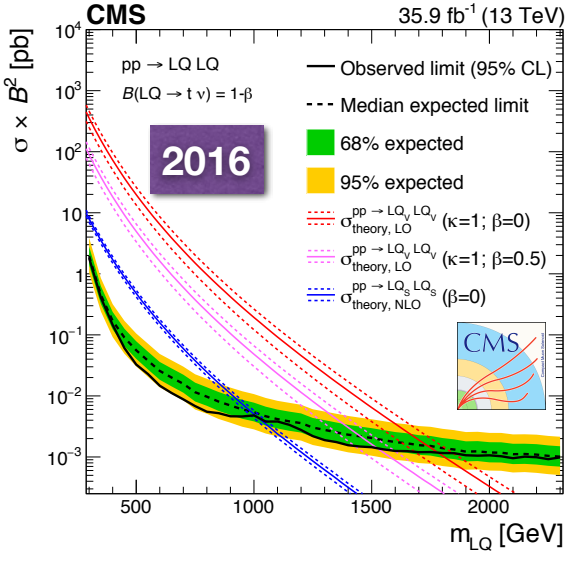
LQ3 Search & Flavor Anomalies

- Reinterpretation of the SUSY all-hadronic search with the M_{T2} variable [arXiv:1705.04650]
- Consider scalar and vector LQs decaying to νq, resulting in ννqq, ννbb, or ννtt topologies
  - Proposed for explanation of flavor anomalies
- Most stringent constraints to date for B(LQ → νq) ~ 50%

CMS arXiv:1805.10228

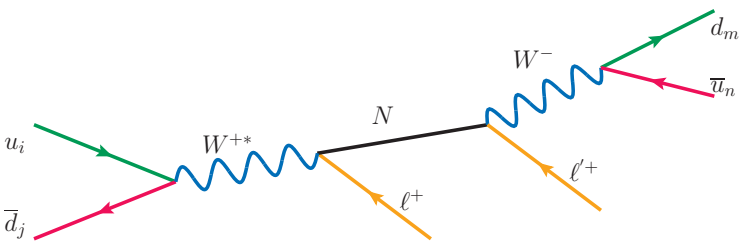


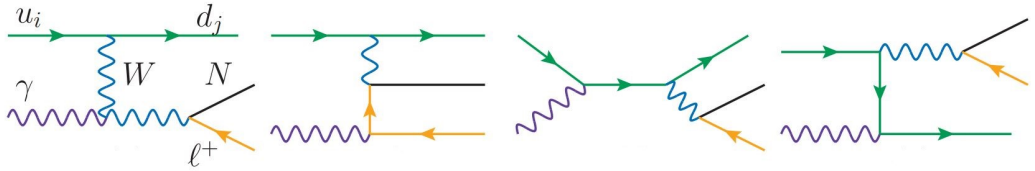




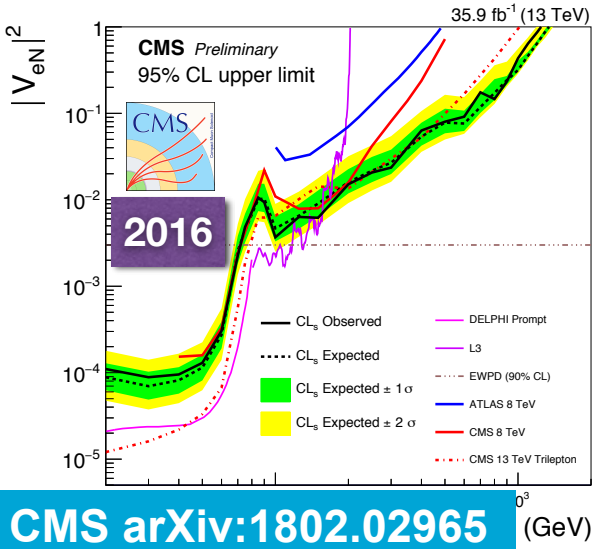
Majorana Neutrino Searches

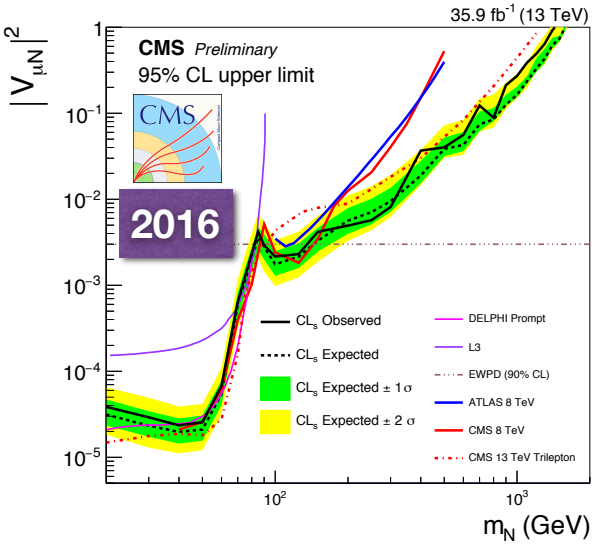
- Two new analyses: searches in trilepton and same-sign dilepton channels
- Includes qq production, and, for the first time photon-induced t-channel production in the dilepton channel, which takes over at high masses
- Most stringent limits on boxing parameters above m_N of 430 GeV and the first limits above 1200 GeV

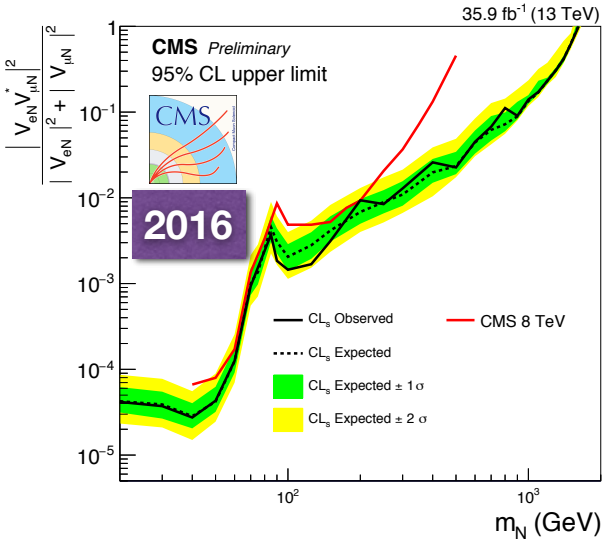




CMS PAS EXO-17-028



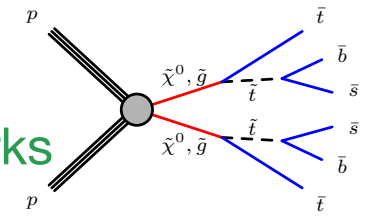


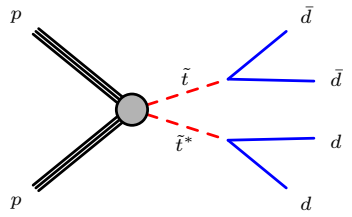


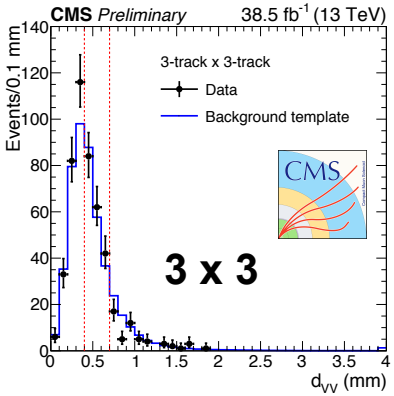
CMS arXiv:1802.02965

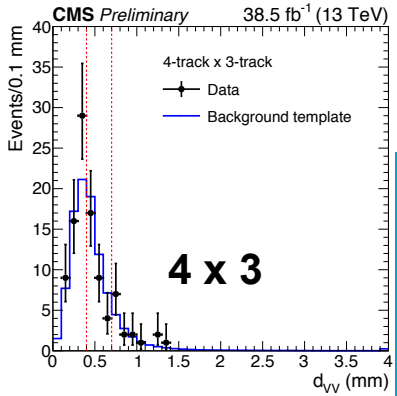
Displaced Multitrack Vertices

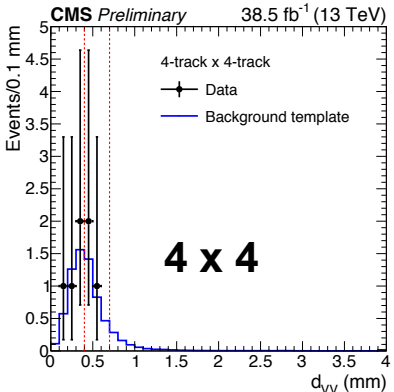
- Displaced jets are predicted in a number of BSM theories
- Dedicated search based on two multitrack displaced vertices
- Background prediction from events with a single displaced vertex
- Interpretation via RPV gluinos/t squarks

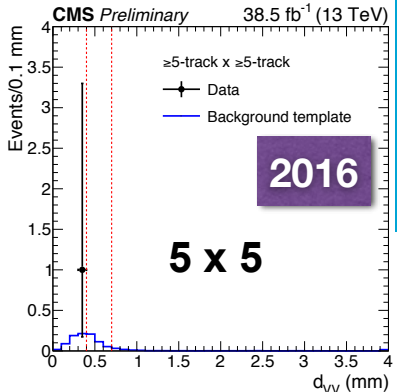




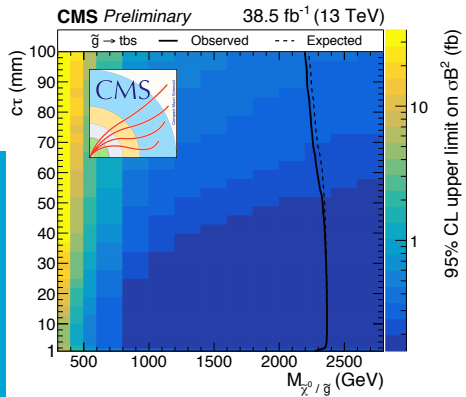


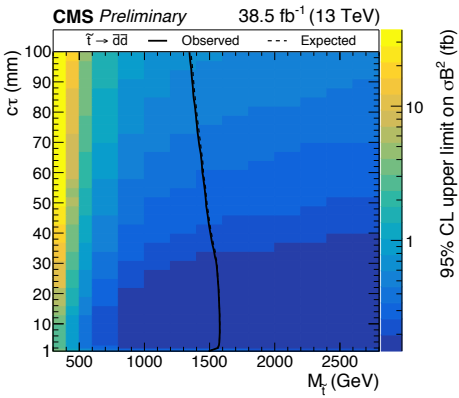


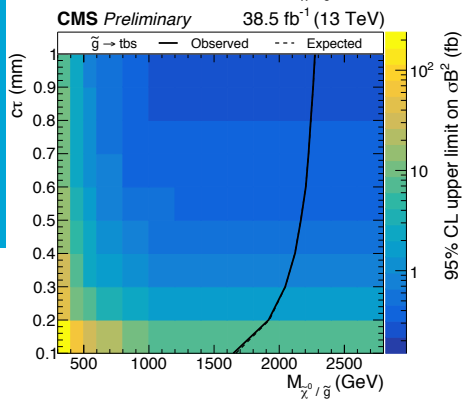


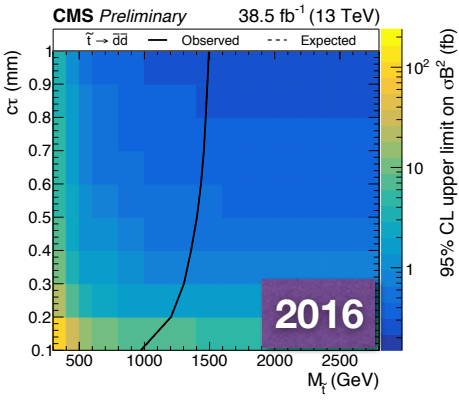


CMS PAS EXO-17-018





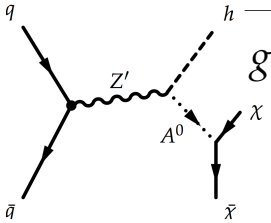





Dark Matter
Searches

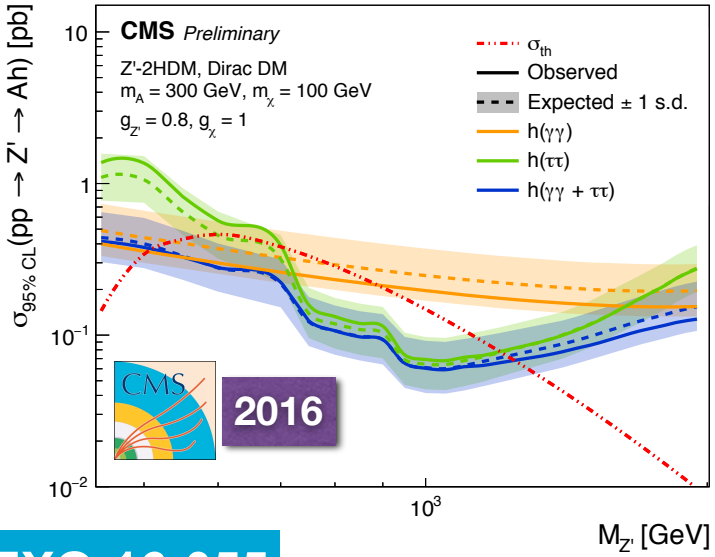
Mono-Higgs Production

- Mono-Higgs analysis in the context of 2HDM and vector mediator
- New combination of the H(γγ) and H(ττ) decay modes
- H(γγ) channel helps at very low and very high mediator masses, while H(ττ) is more sensitive at intermediate masses



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

Dijets: $g_{Z'} < 0.8$



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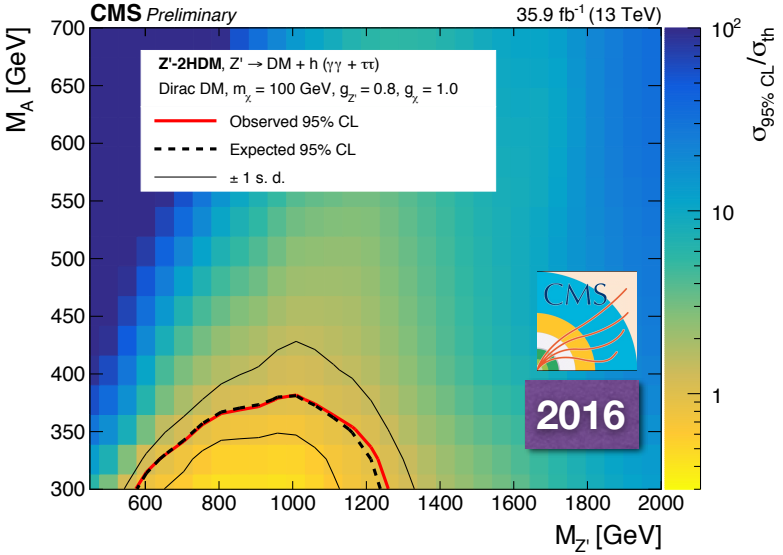
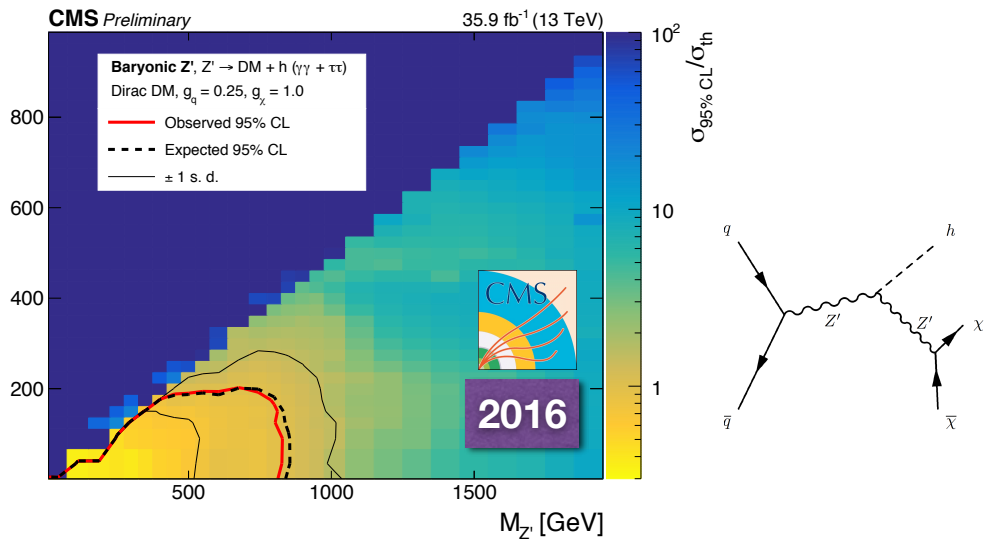
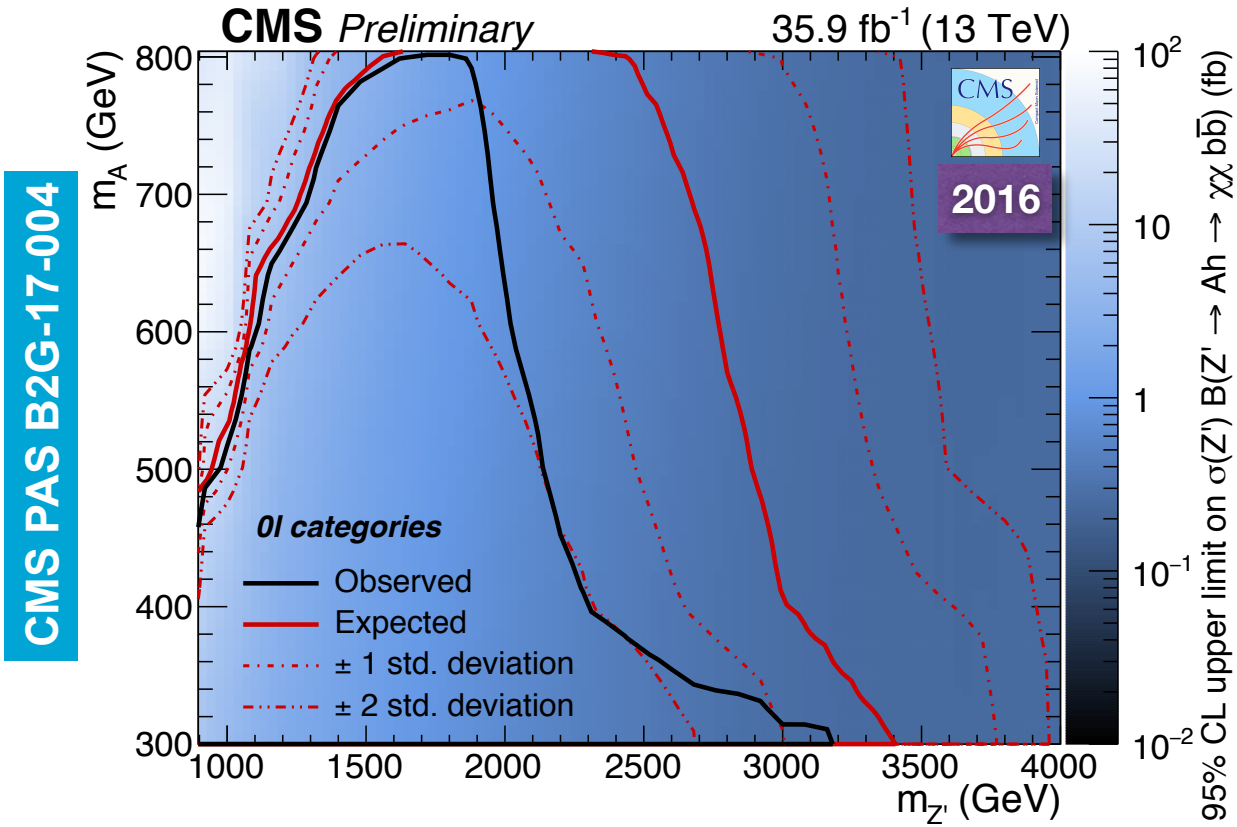




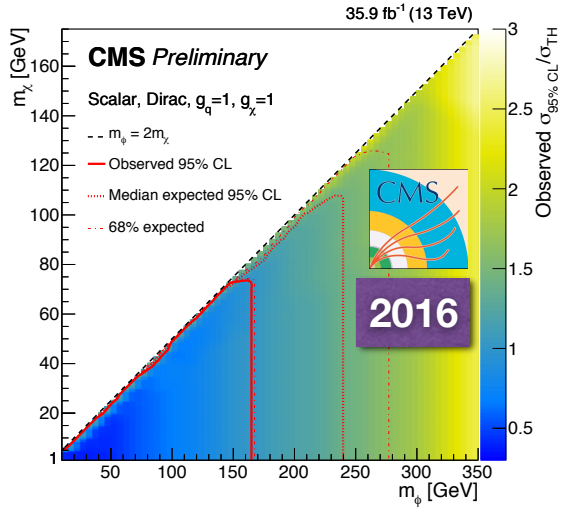
H(bb)+MET

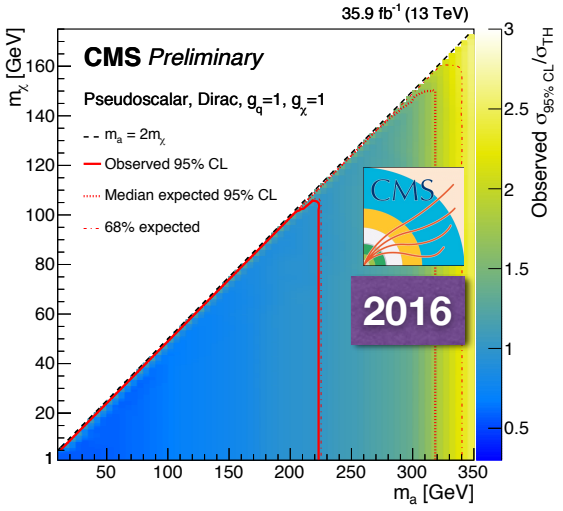
- New analysis - a reinterpretation of Z(vv)H(bb) analysis
- So far, only Z'-2HDM interpretation
- By far most restrictive limits on the model to date, even despite a slight excess observed



tt+DM Combination

- Combination of dilepton, single-lepton, and all-hadronic channels
- p_T^{miss} is the sensitive variable in all cases
- Strong pseudoscalar mediator limits





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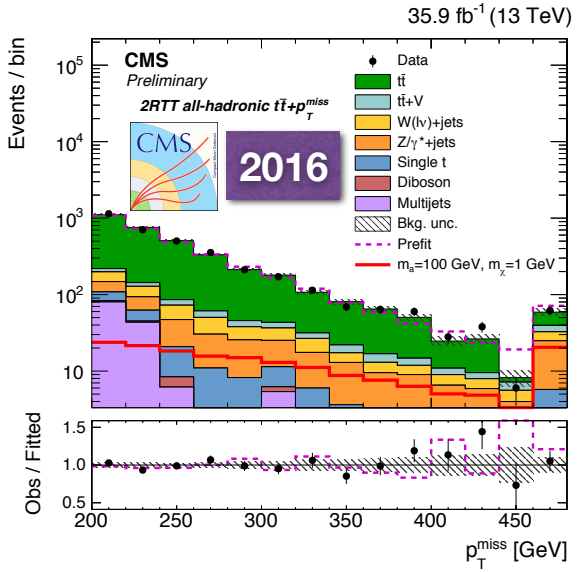
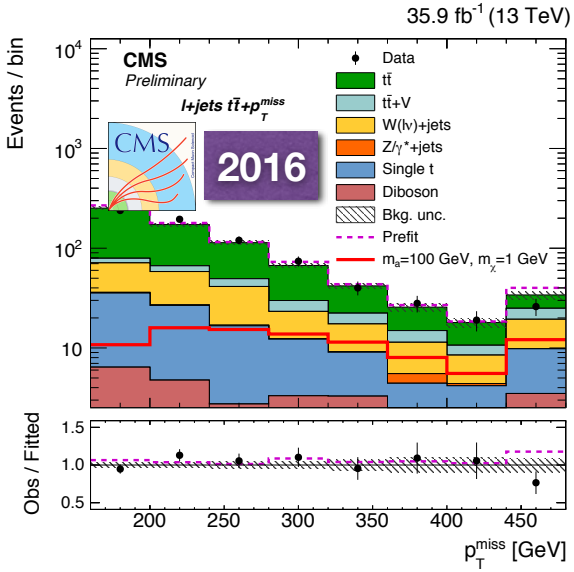
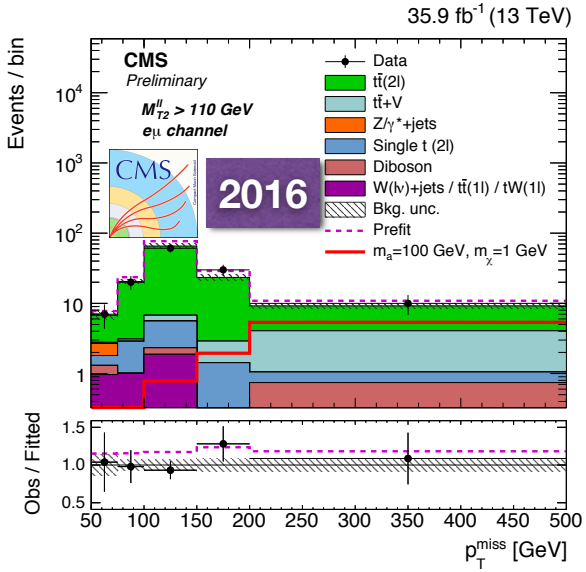




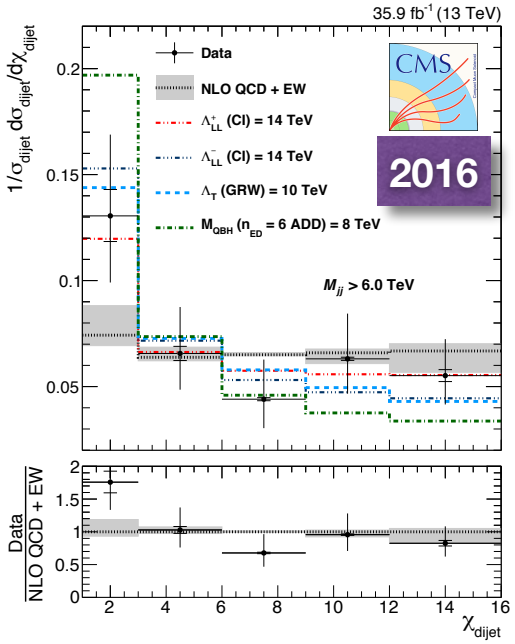


Angular Dijet Analysis

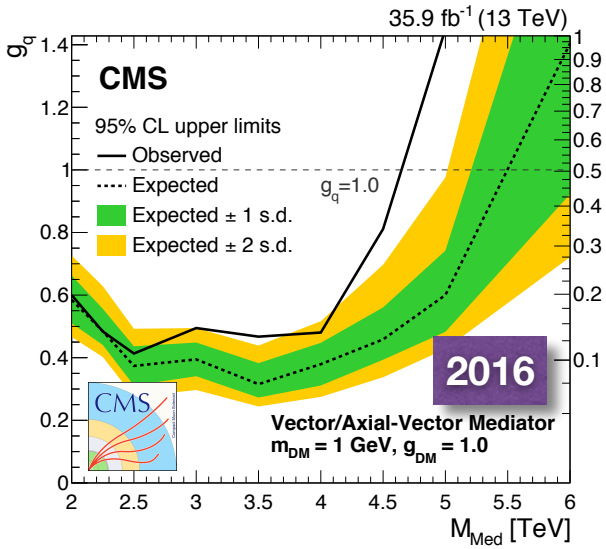
- Using the χ variable:

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

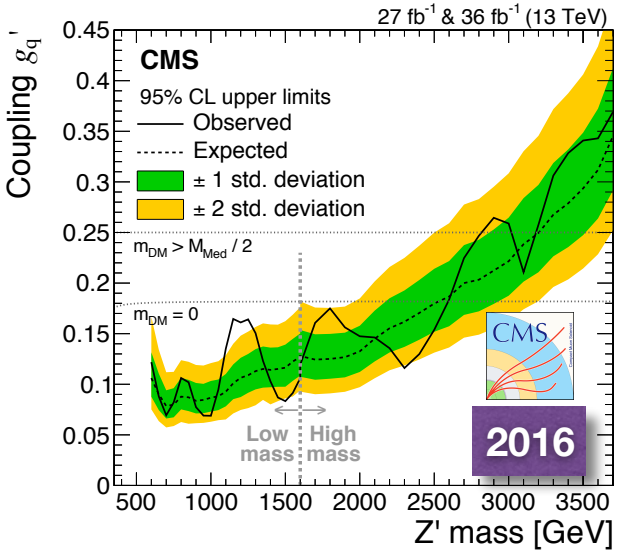
- ADD: M_{Pl} > 8.5-12 TeV; Compositeness: Λ > 9.2-22.4 TeV; Quantum black holes: M_{QBH} > 5.9-8.2 TeV
- Limits on DM mediator complementary with those from diet resonance searches (sensitive to large couplings)!



CMS arXiv:1803.08030



CMS arXiv:1806.00843



Future Run 2 Searches

- Parton luminosity arguments shaped the searches program in 2015-2018:
  - 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???