STUDIES OF (PSEUDO) SCALARS IN

Greg Landsberg

Scalars 2019, Warsaw, Poland, 11.09.2019

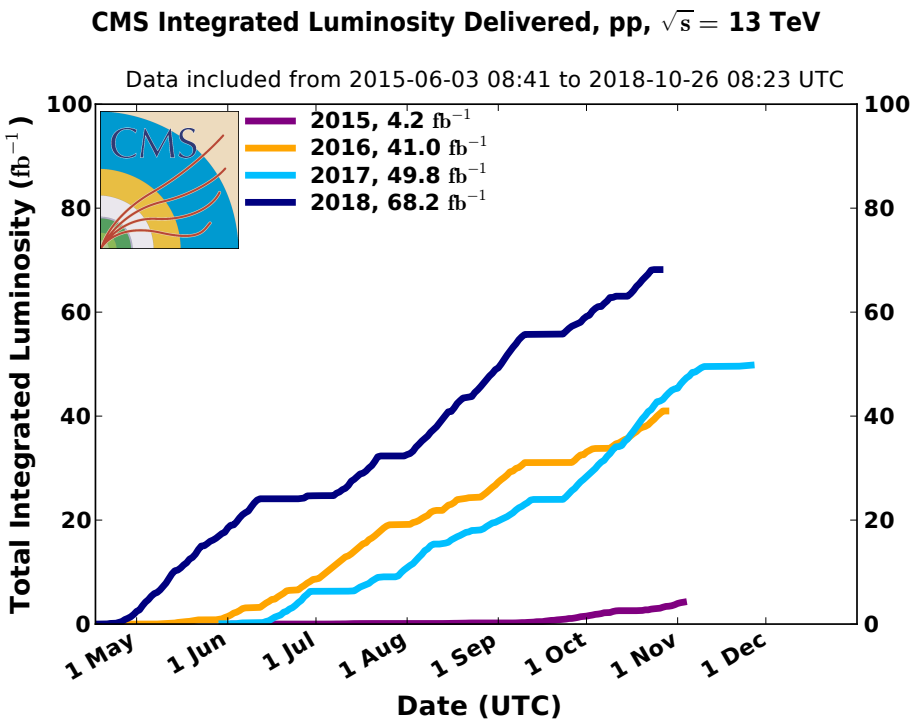
Outline

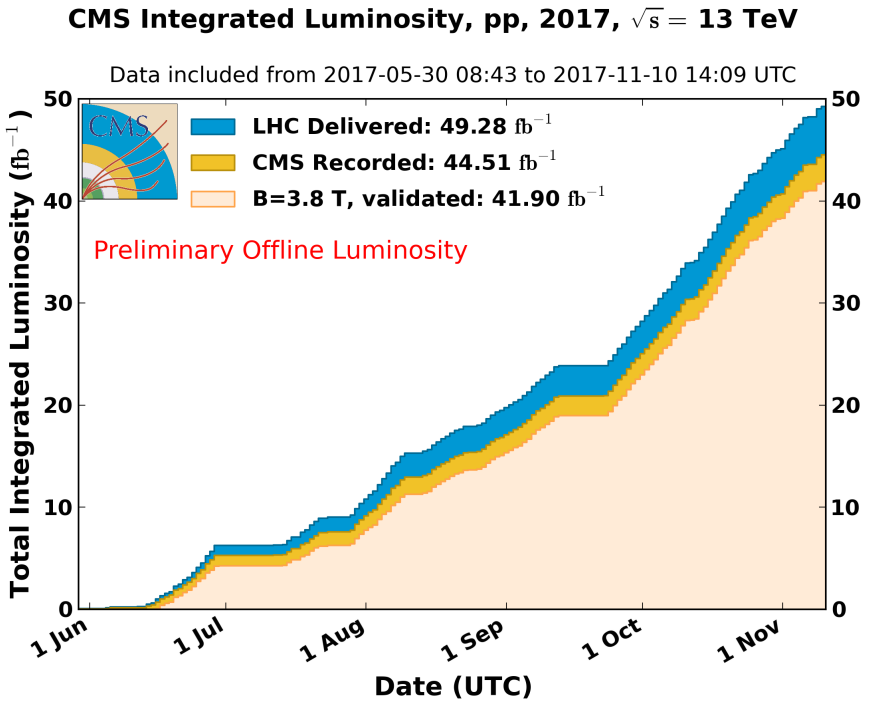
- Happy 7th birthday, Higgs!
- Dazzling precision
- Higgs and third generation
- Beyond the SM Higgs
- Higgs pair production
- Toward second generation
- Conclusions

- N.B. All PAS/paper labels are clickable!

LHC Run 2: Big Success

- 160 fb^{-1} has been delivered by the LHC in Run 2 (2015–2018), at a c.o.m. of 13 TeV, exceeding the original integrated luminosity projections
- Over 140 fb^{-1} of physics-quality data recorded by ATLAS/CMS
- Thank you, LHC, for a spectacular Run 2!





Higgs Turns Seven!

- 2012 - I am born!
- 2013 - First steps
- 2014 - Who am I?
- 2015 - Why am I alone?
- 2016 - Not afraid of dark!
- 2017 - Trip to the tau-land
- 2018 - Meet 3rd generation
- 2019 - This talk:

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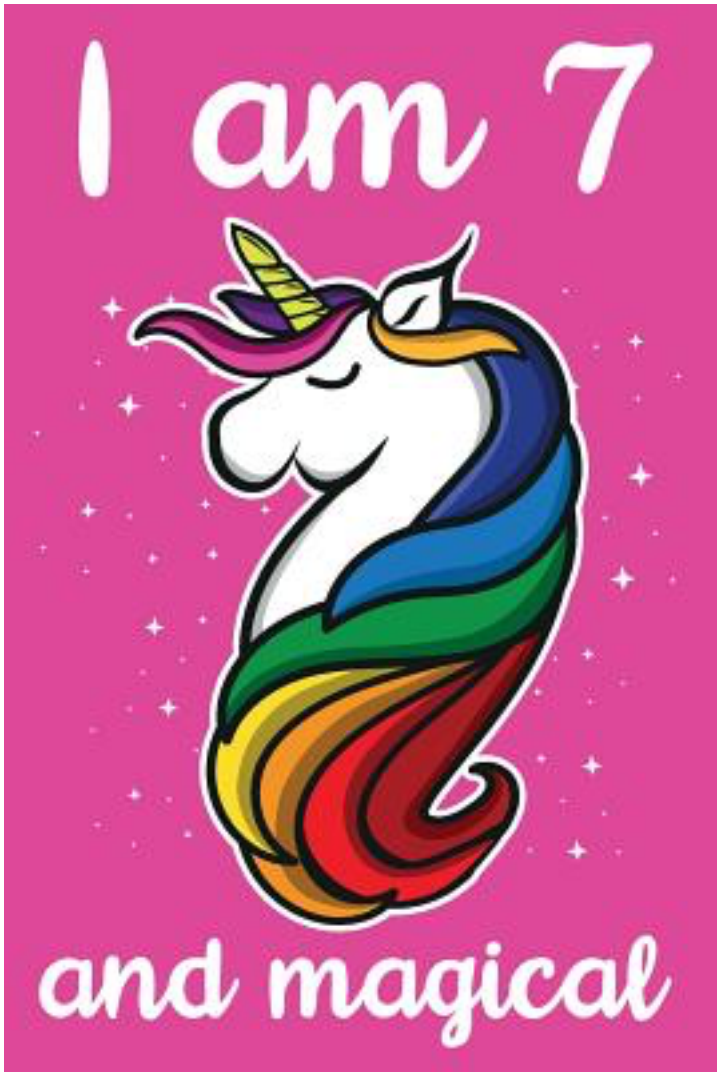
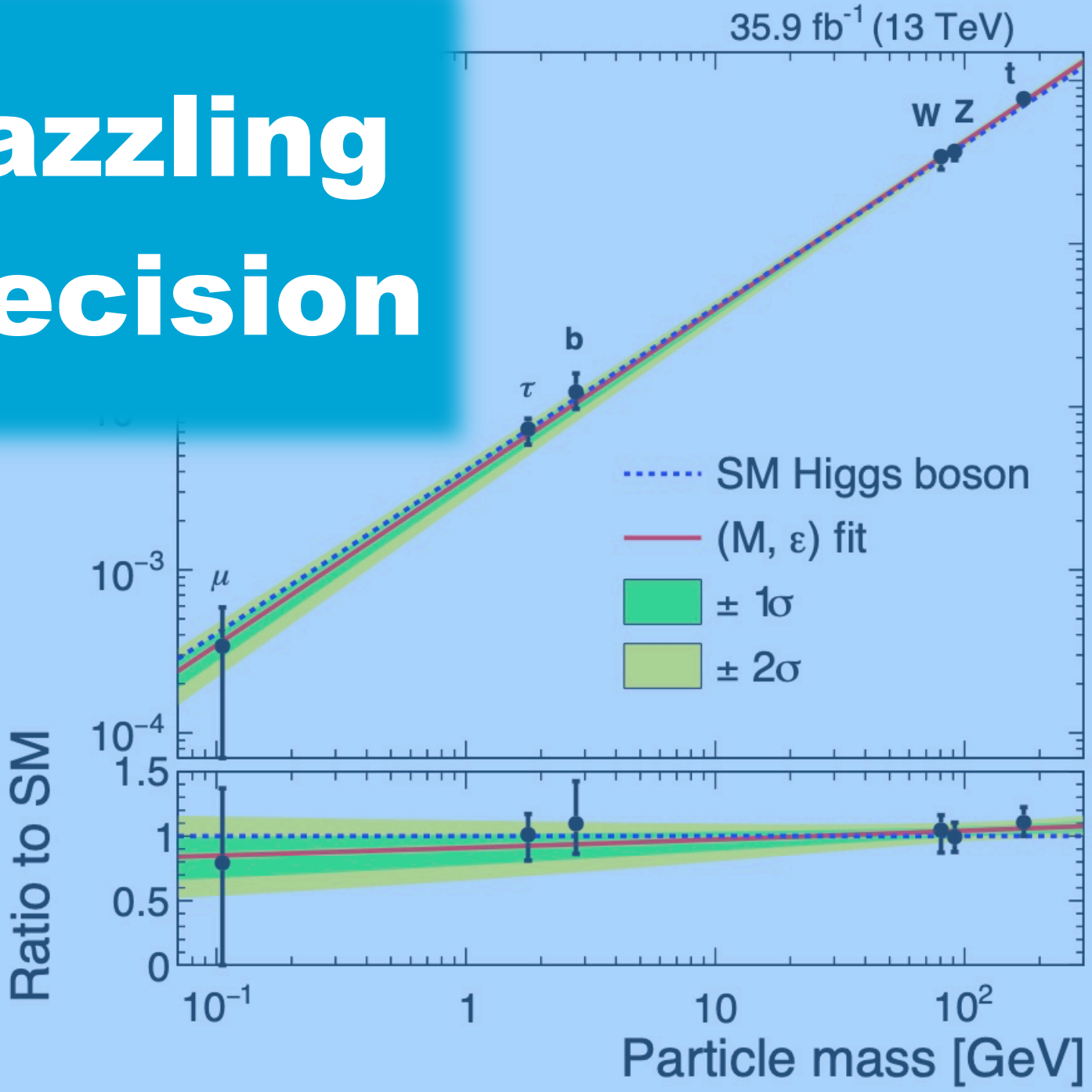
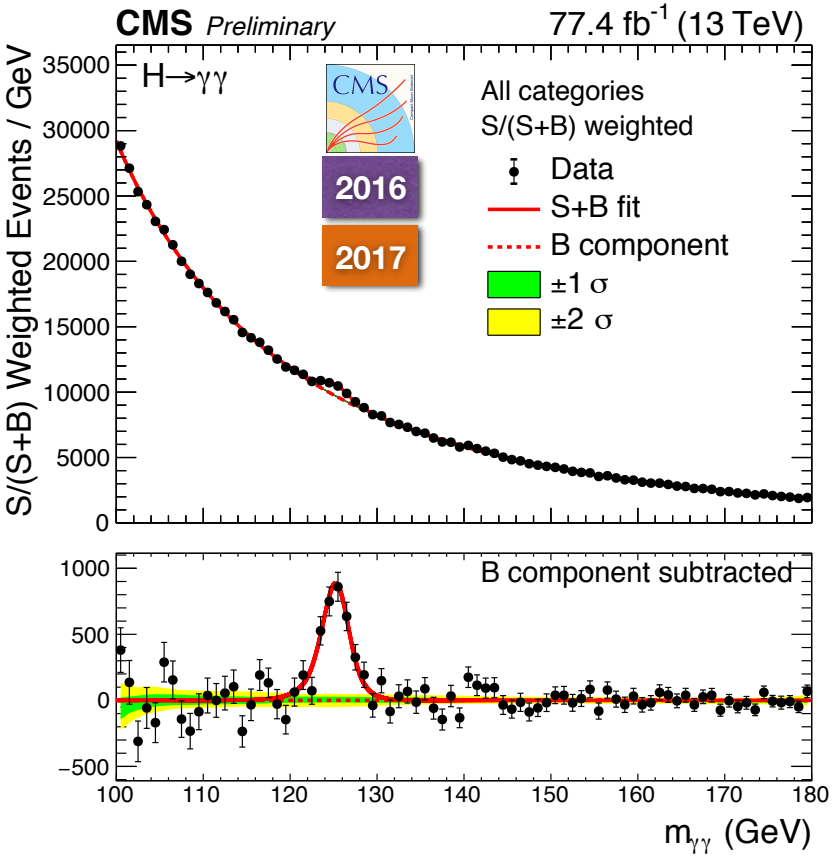


Dazzling Precision

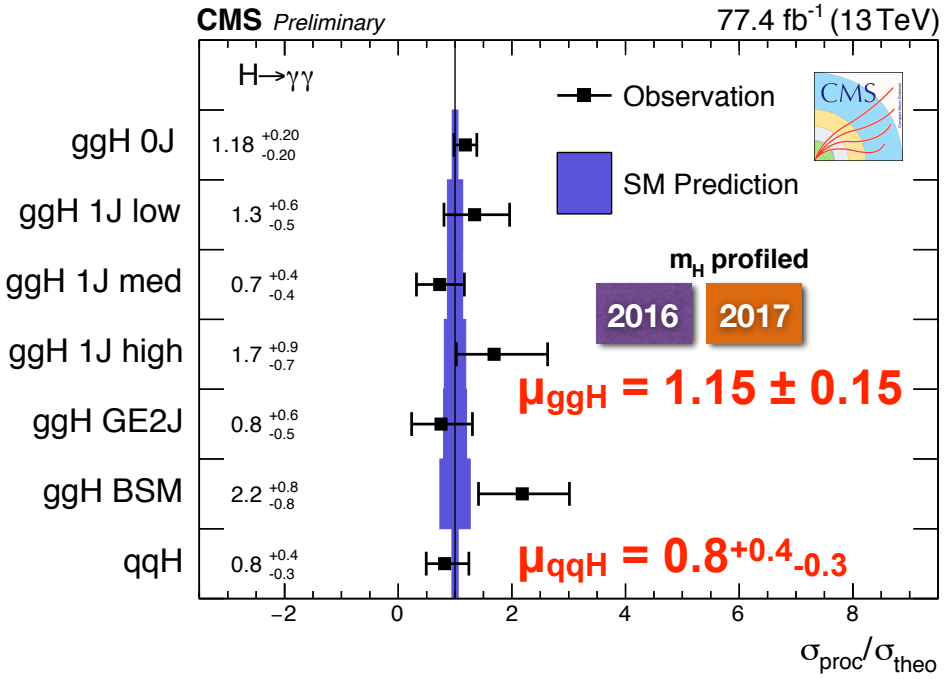


New MeaH(γγ)urement

- **Measurement of H(γγ) in ggF and VBF production**
  - ★ **Based on 2016+2017 data (77.4 fb^{-1})**
  - ★ **Interpretation in the STXS framework (YR4)**



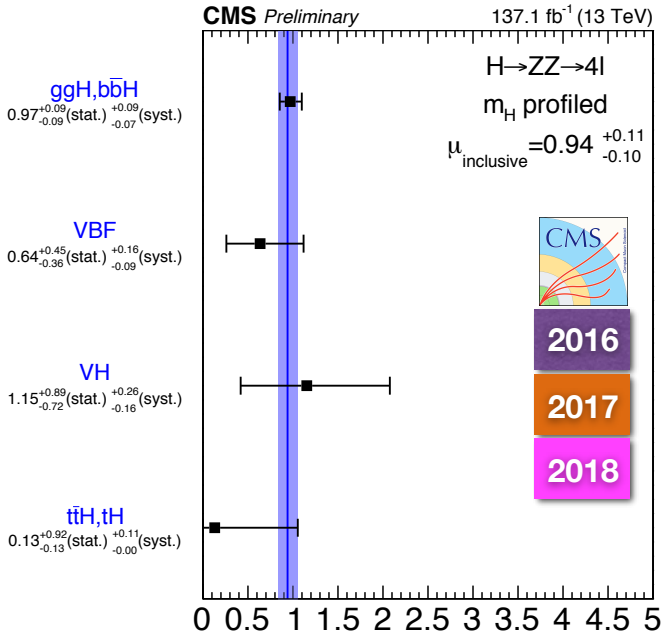
CMS PAS HIG-18-029

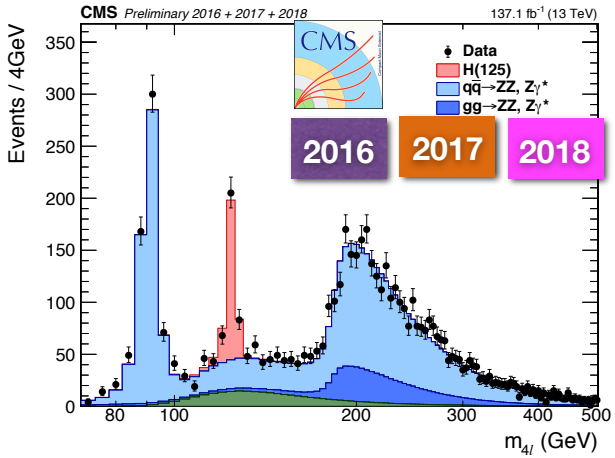


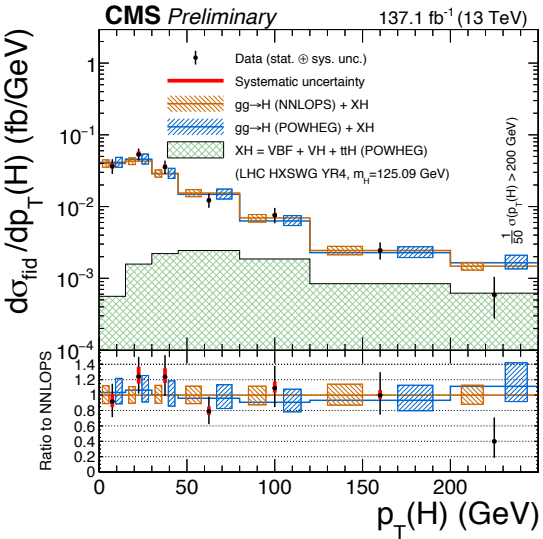
Run 2 MeaH(ZZ)urement

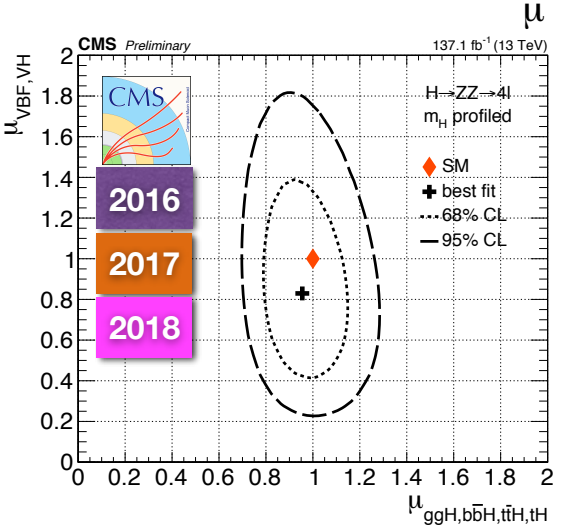
- The cleanest channel; has been updated to include full Run 2 data (137 fb^{-1})
  - ★ CMS standard MELA analysis
- Provide differential cross section measurements

CMS PAS HIG-19-001



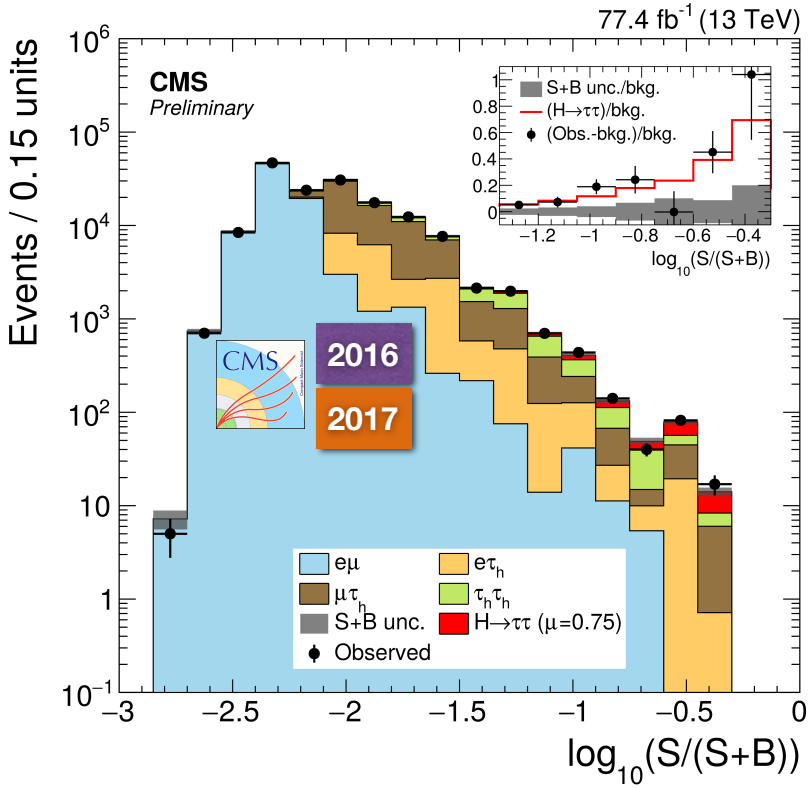




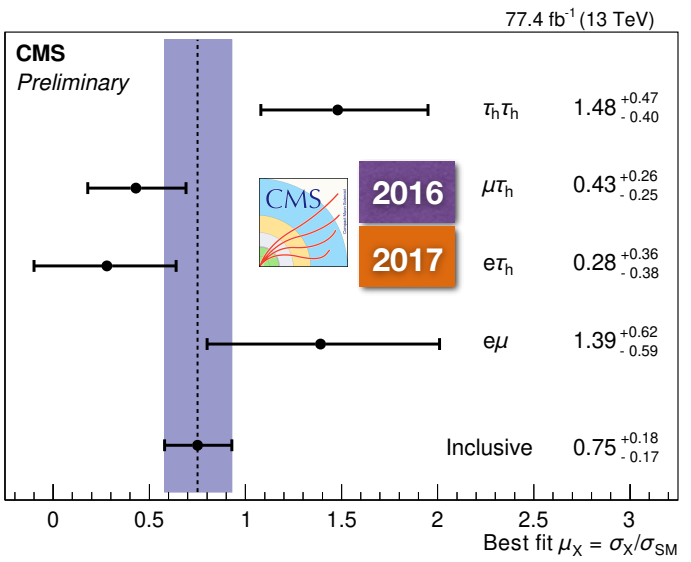


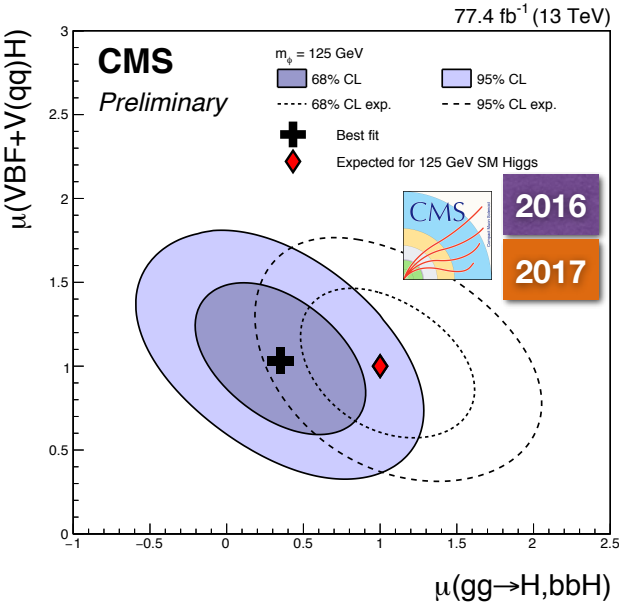
New MeasuremenH(ττ)

- **New measurement of H(ττ) production and decays in the eμ, eτh, μτh, and τhτh final states**
  - ★ **Simulation using τ embedding to estimate the Z(ττ) background**



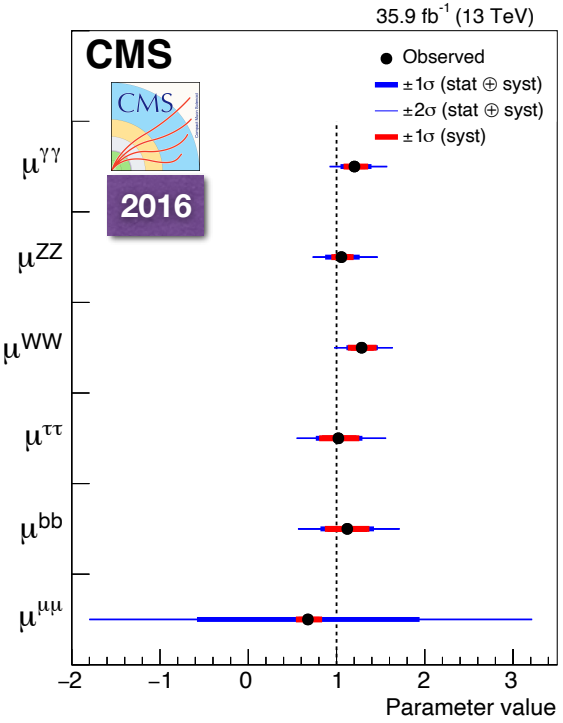
CMS PAS HIG-18-032

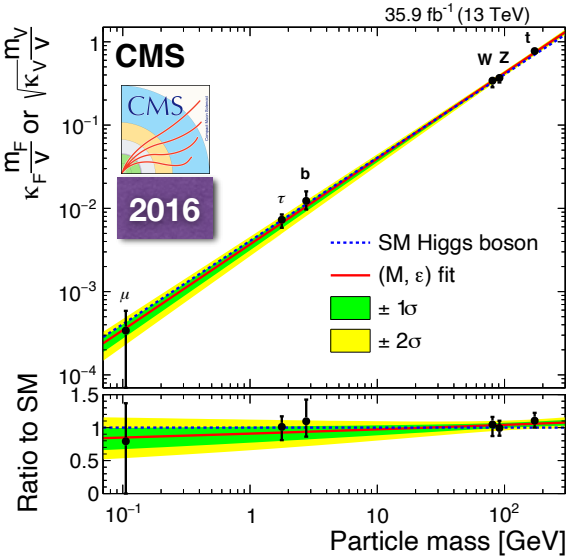


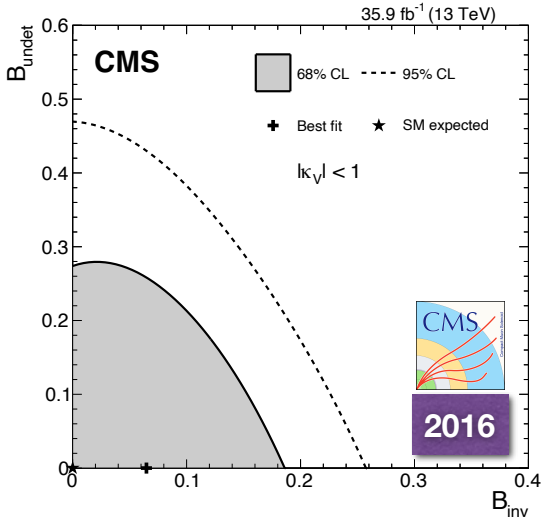


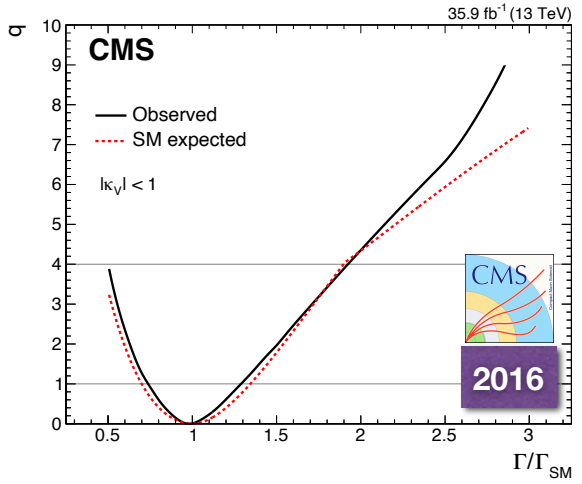
13 TeV Combination

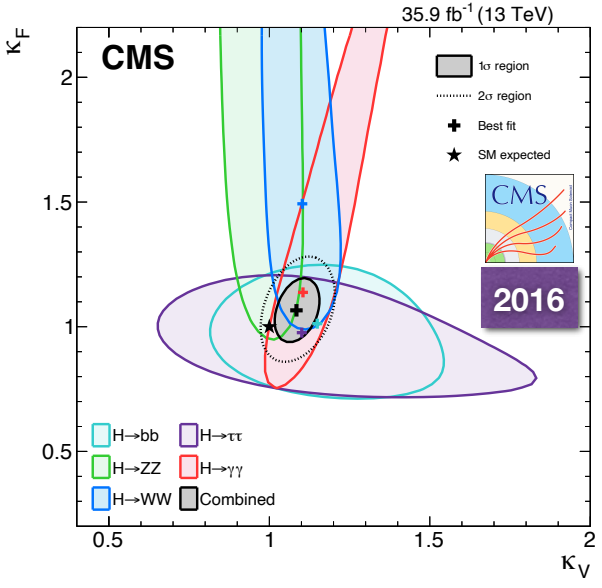
- **First 13 TeV combination based on 2016 data**









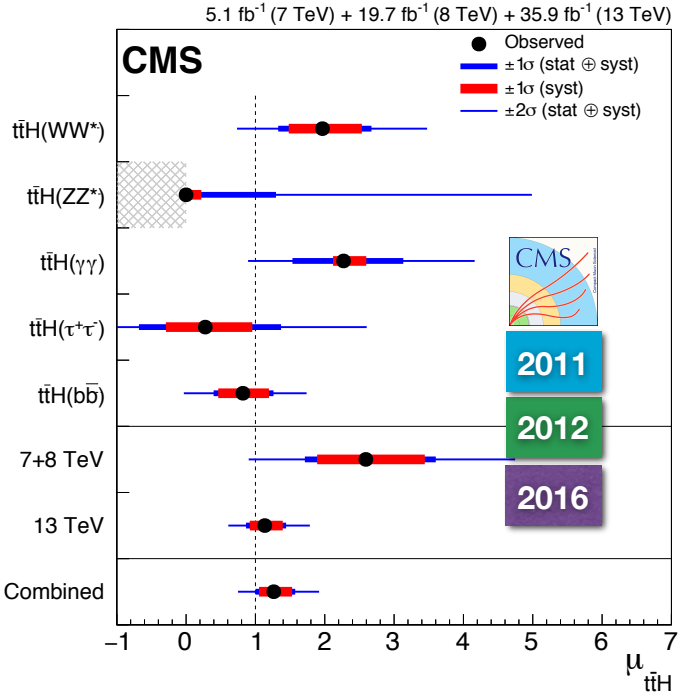


CMS arXiv:1809.10733

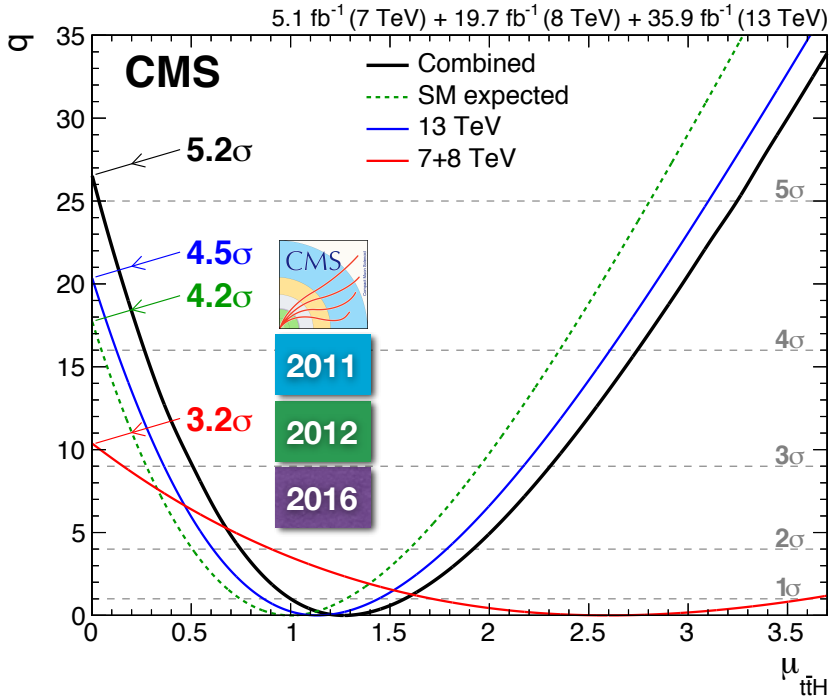
Third Generation

Observation of ProducttHion

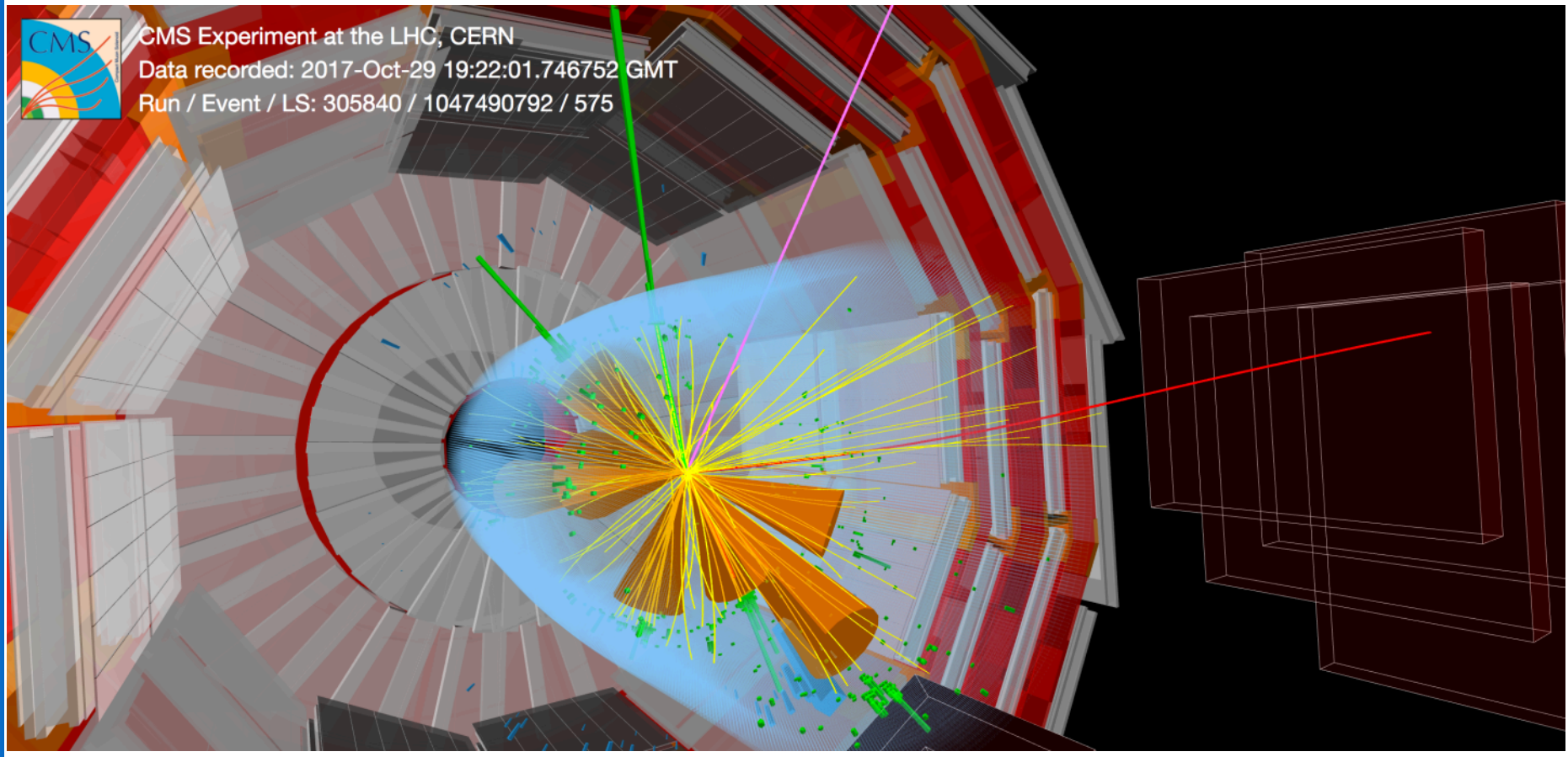
- **Last April, CMS reported first observation of ttH production**
  - ★ **Tour de force analysis, combining multiple channels (bb, ττ, γγ, multileptons), as well as 7, 8, and 13 TeV data**
  - ★ **5.2σ (4.2σ) observed (expected) significance, benefiting from an excess seen in Run 1 data**
  - ★ **$\mu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



CMS arXiv:1804.02610



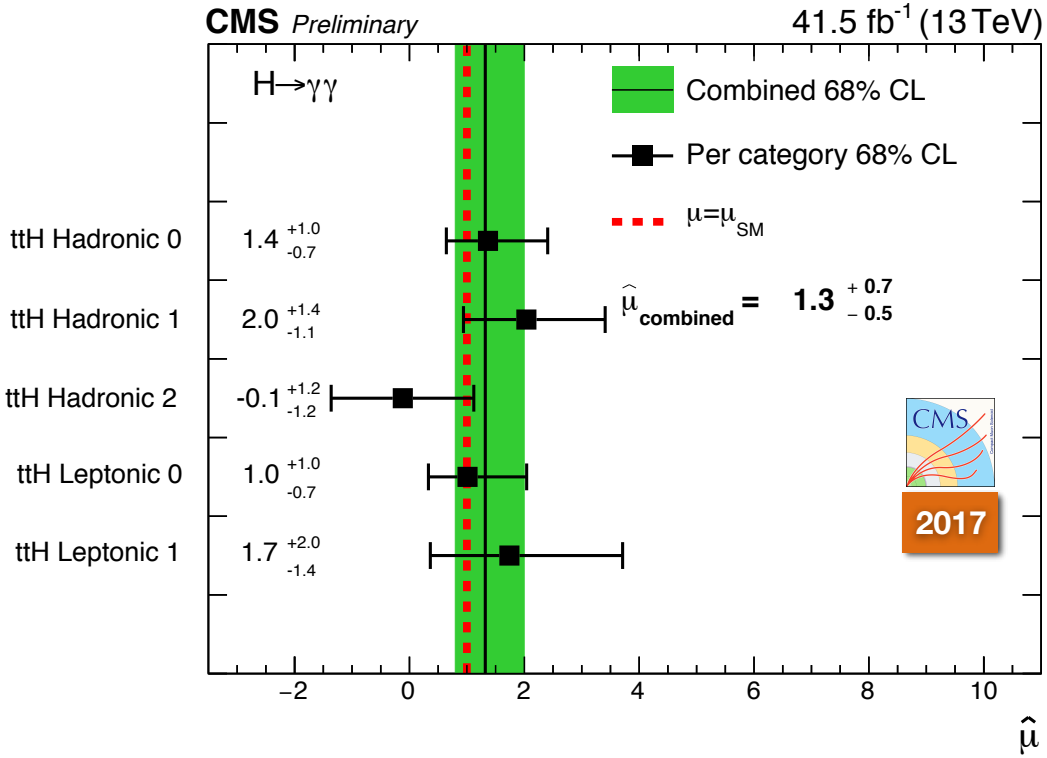
EventH Display

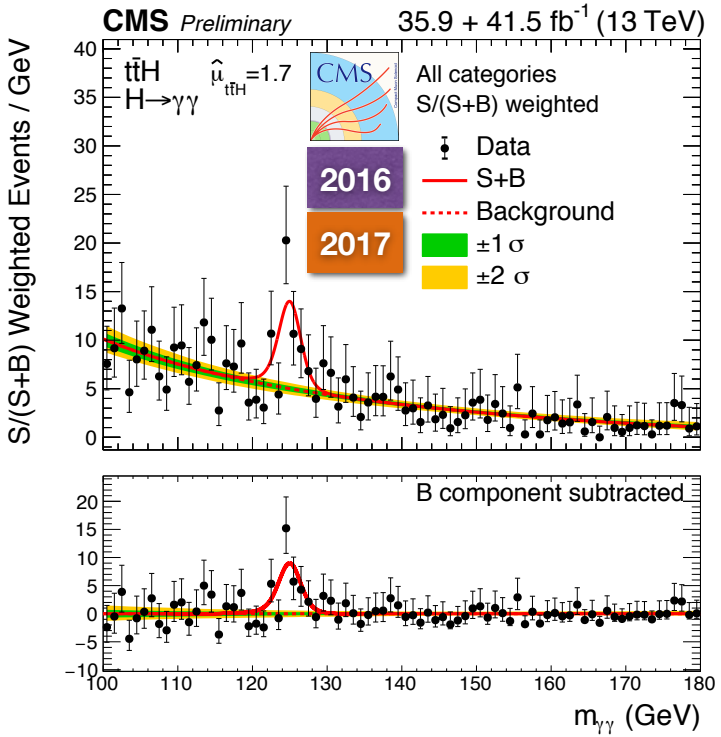


Half-a-Year LattHer...

- Analyzed the ttH(γγ) channel with 2017 data and combined with the 2016 measurement in the same channel
  - ★ 3.1 (2.2)σ observed (expected) significance (2017)
  - ★ 4.1 (2.7)σ observed (expected) significance (2016+2017)
  - ★ $\mu = 1.3^{+0.7}_{-0.5}$ (2017) or $1.7^{+0.6}_{-0.5}$ (2016+2017)

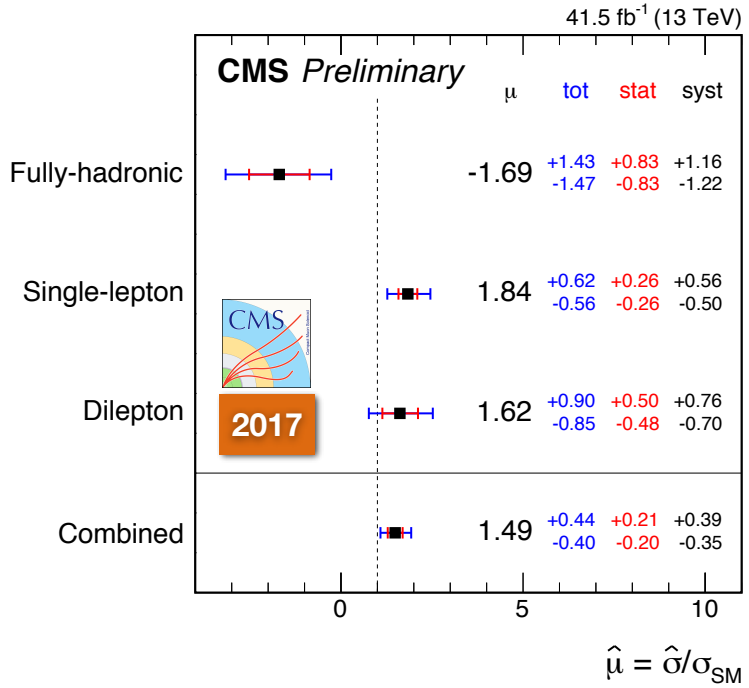
CMS PAS HIG-18-018

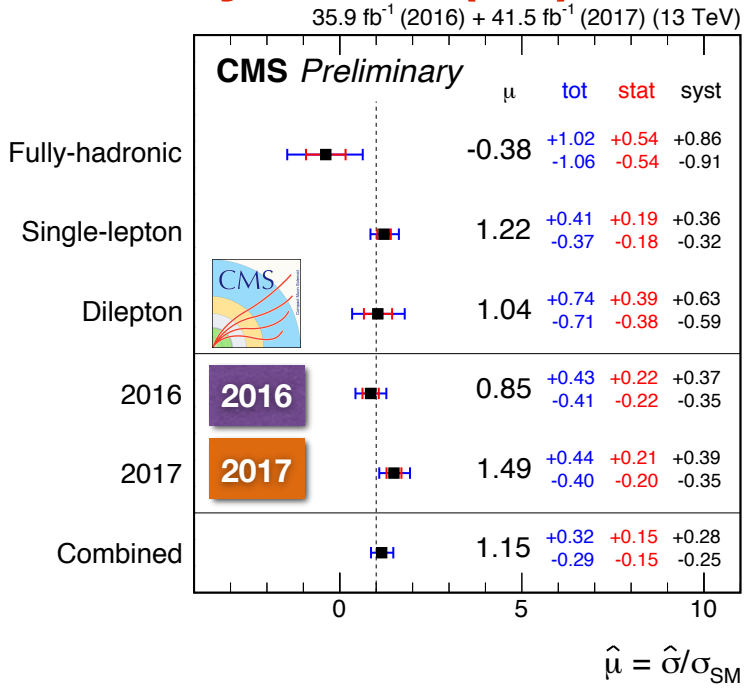




YettH Another Half-a-Year

- Analyzed 2017 data (41.5 fb^{-1}) in ttH(bb) mode, with all three decay modes of the top quark pair
  - ★ Similar analysis strategy (based on BDTs) to the observation paper
- Observed (expected) significance: 3.7 (2.6)σ
  - ★ Combined w/ the earlier 2016 analysis: 3.9 (3.5)σ

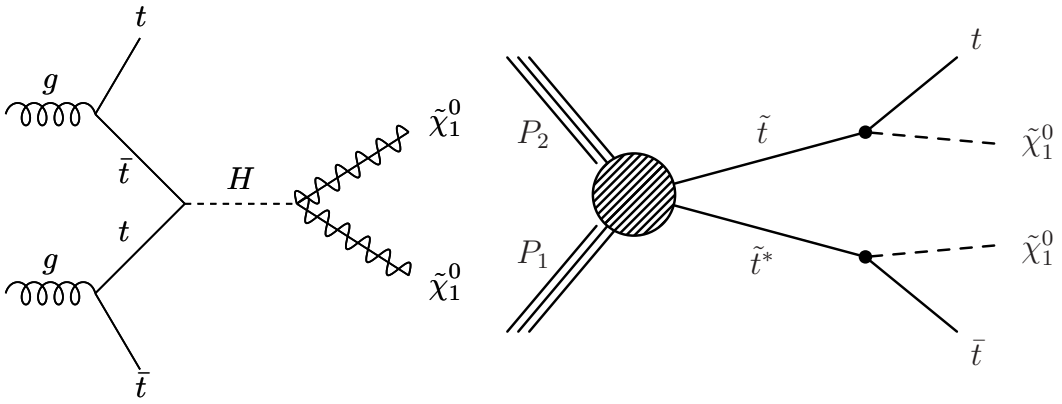


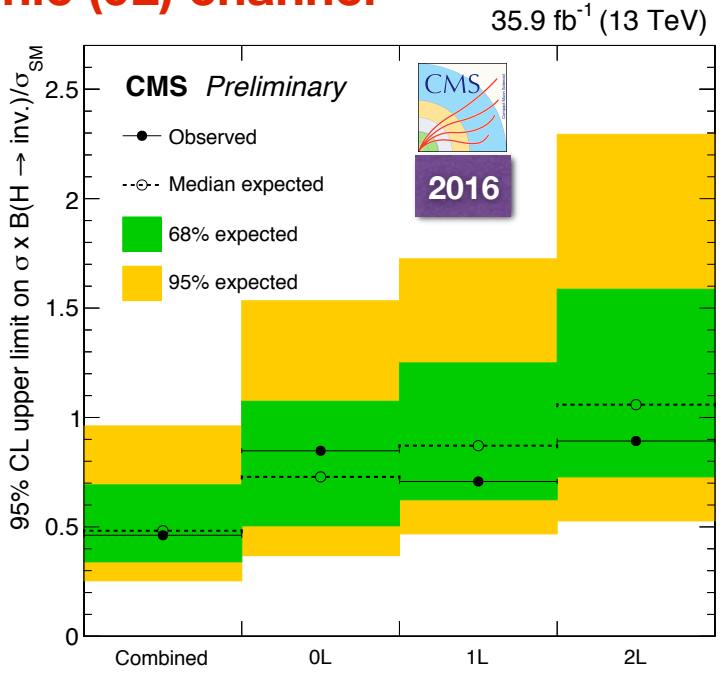


CMS PAS HIG-18-030

New Search ttHool

- Just a year after the first observation, use the ttH production mechanism as a tool for searches
- First limits on the H(inv.) decay in this channel
  - ★ Similar topology to top squark pair production (from one (pseudo)scalar to another!)
  - ★ Reinterpret SUSY searches in 0L, 1L, and 2L channels
  - ★ Sensitivity is dominated by the all-hadronic (0L) channel
- Result:
  - ★ B(H→inv.) < 0.46 (0.48 exp.) @ 95% CL

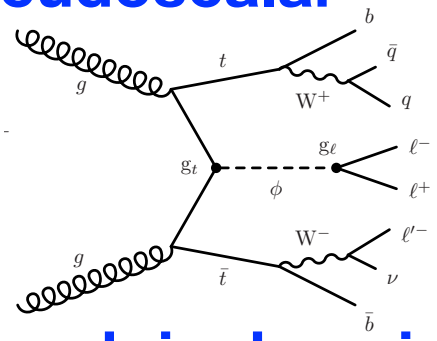




CMS PAS HIG-18-008

Multilepttϕn Search

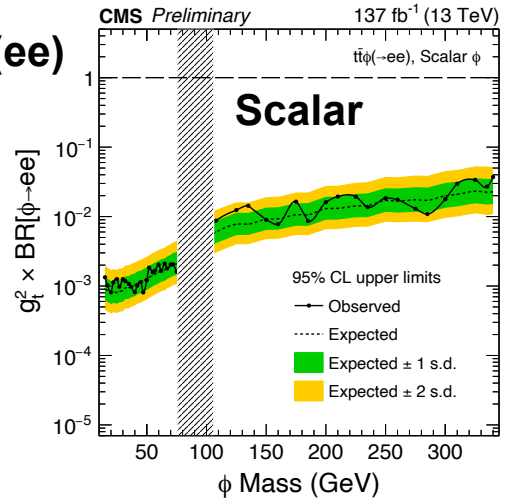
- New interpretation of a multilepton search with full Run 2 data: ttϕ production, where ϕ is a generic scalar or pseudoscalar

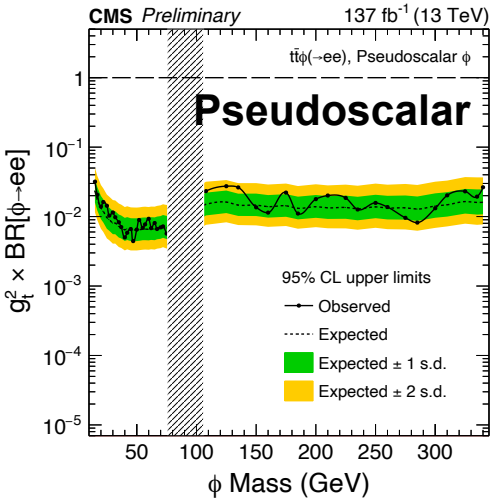


2016
2017
2018

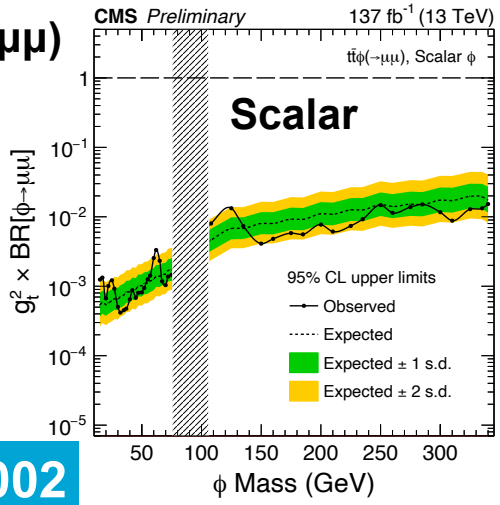
- Search is done in a number of 3L and 4L (L = e, μ) categories; on-Z, off-Z; w/and w/o b tags
- Use mass of the OSSF pair as the search variable

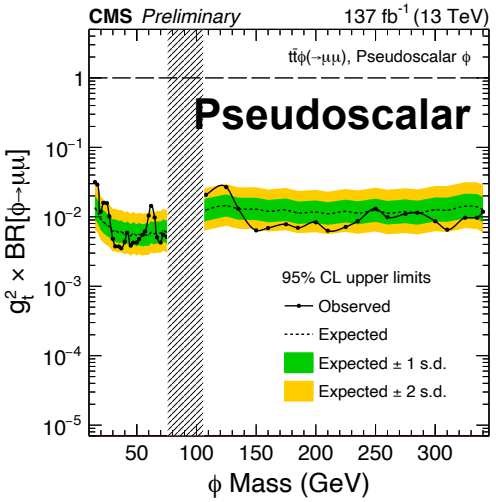
ϕ(ee)





ϕ(μμ)





CMS PAS EXO-19-002

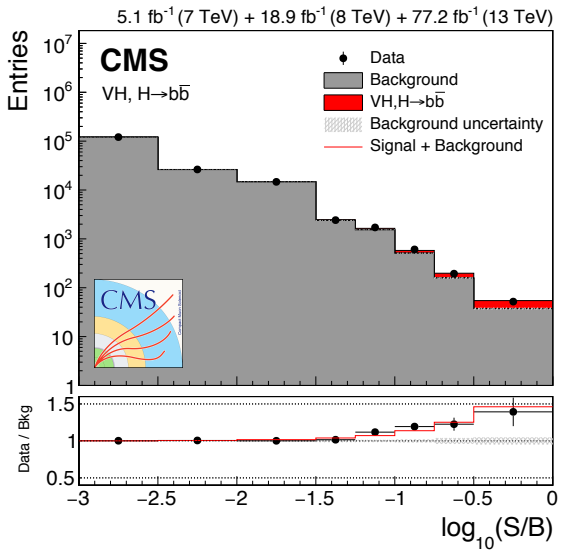
Observation of tH(bb)e Decay

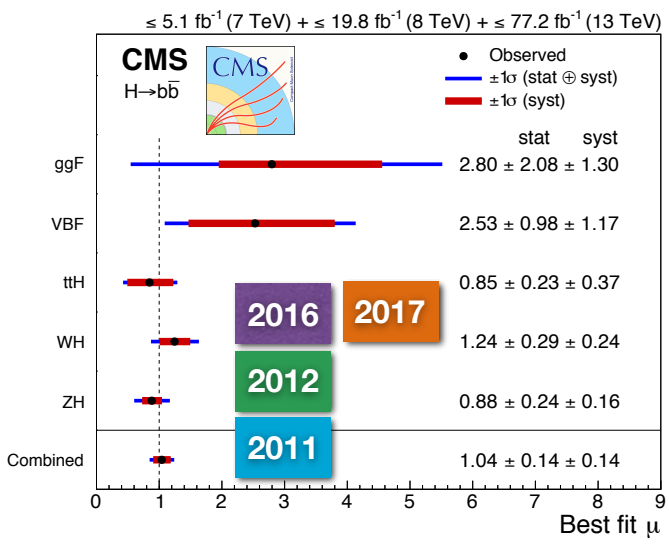
- Ironically, the dominant decay mode of the Higgs boson was the hardest one to observe!
  - ★ Took ATLAS and CMS over 6 years to publish first observation of the H(bb) decay
- Despite the large branching fraction, the dominant production mode (ggF) is swamped by overwhelming QCD background
- Until recently the only viable channels were VH
  - ★ But: there is a hope for observing H(bb) in ggF and even ttH(bb), as evident from the earlier slides

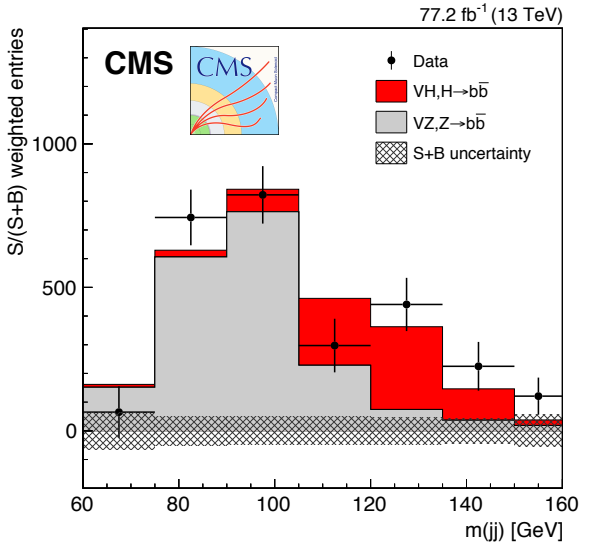
Observation of H(bb)

- Another tour-de-force analysis, using multiple event categories and MVA techniques, as well as advanced b tagging algorithms
  - ★ Includes 2011, 2012, 2016, and 2017 data sets
  - ★ The signal is evident in the b-tagged dijet mass distribution, weighted by the S/(S+B) ratio
- Observed (expected) significance: 5.6σ (5.5σ)
- $\mu = 1.04 \pm 0.20$

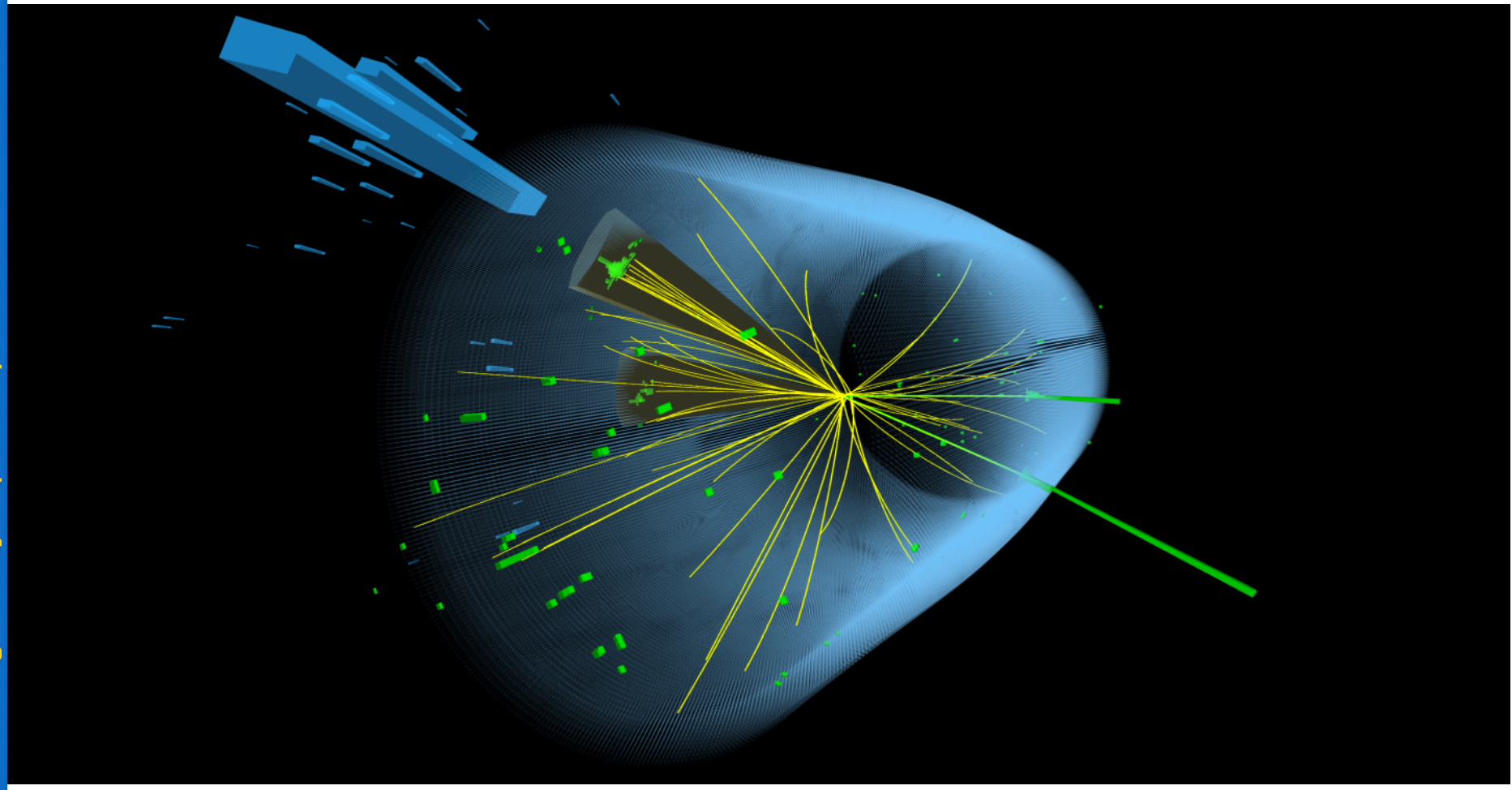
CMS arXiv:1808.08242





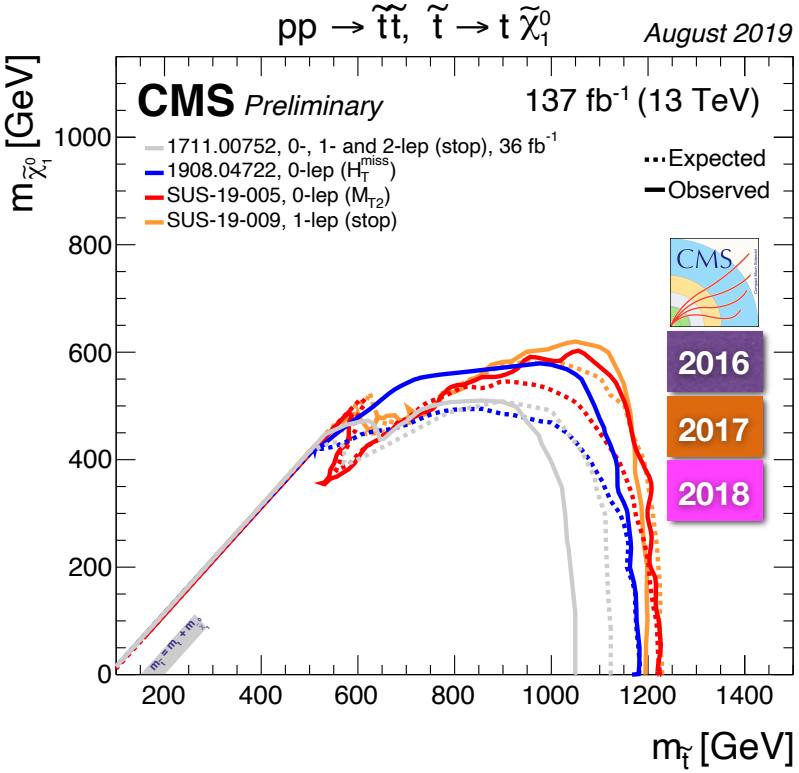


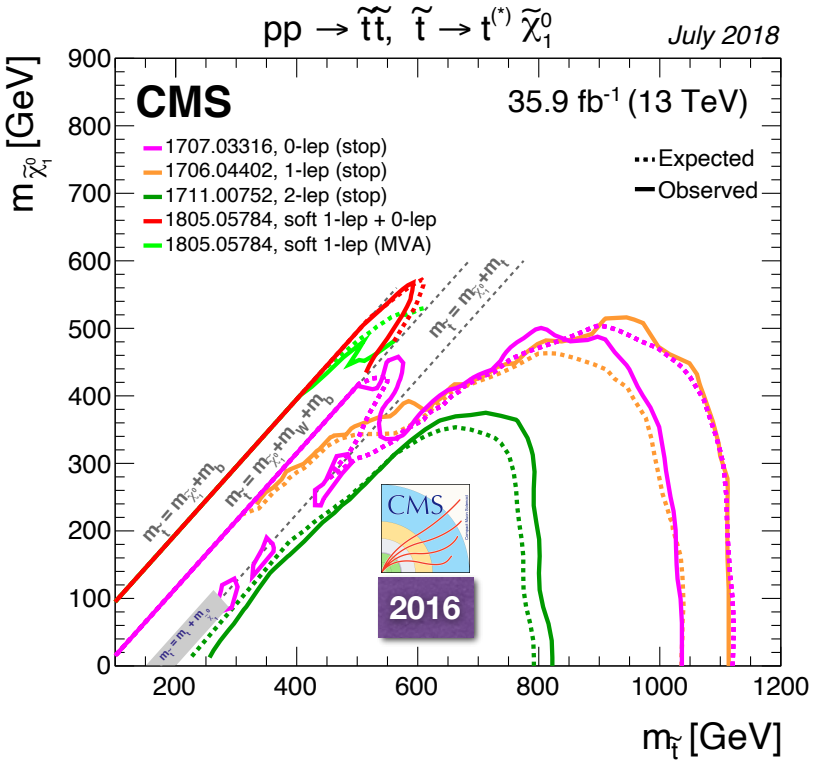
EvZ(ee)H(bb)nt Display



Pulling all the Stops

- SUSY models are rich in scalar and pseudoscalar particles
- Top squark (stop) is a spin-0 particle that must be relatively light in natural SUSY scenarios
  - ★ N.B. Stop is *NOT* a scalar particle; as a complex spin-0 field, it's a mixture of scalar and pseudoscalar states (no wonder we haven't found the "scalar top" at the LHC!)
- Pulling all the stops in a multitude of channels and scenarios





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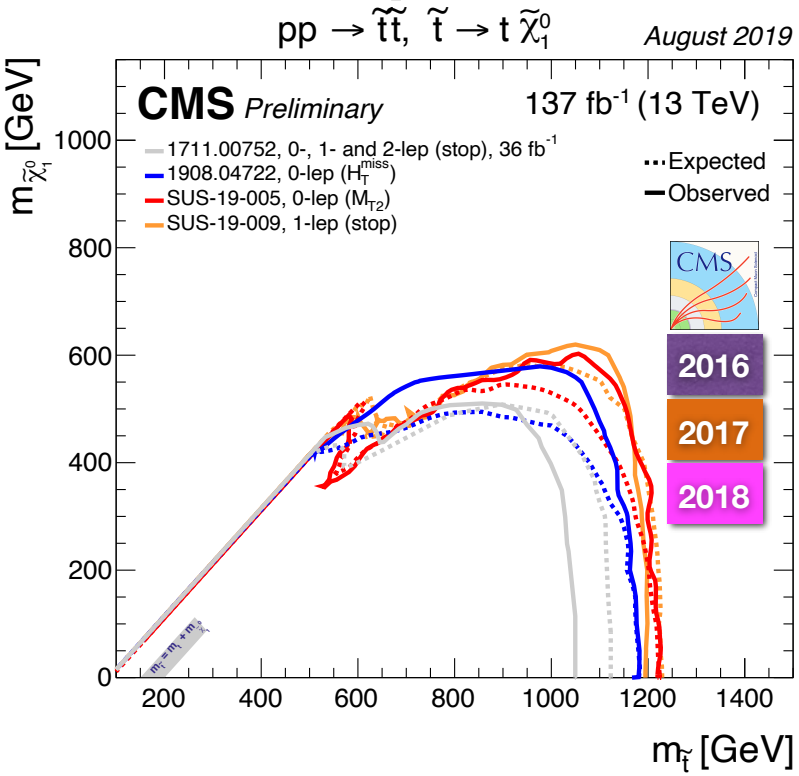
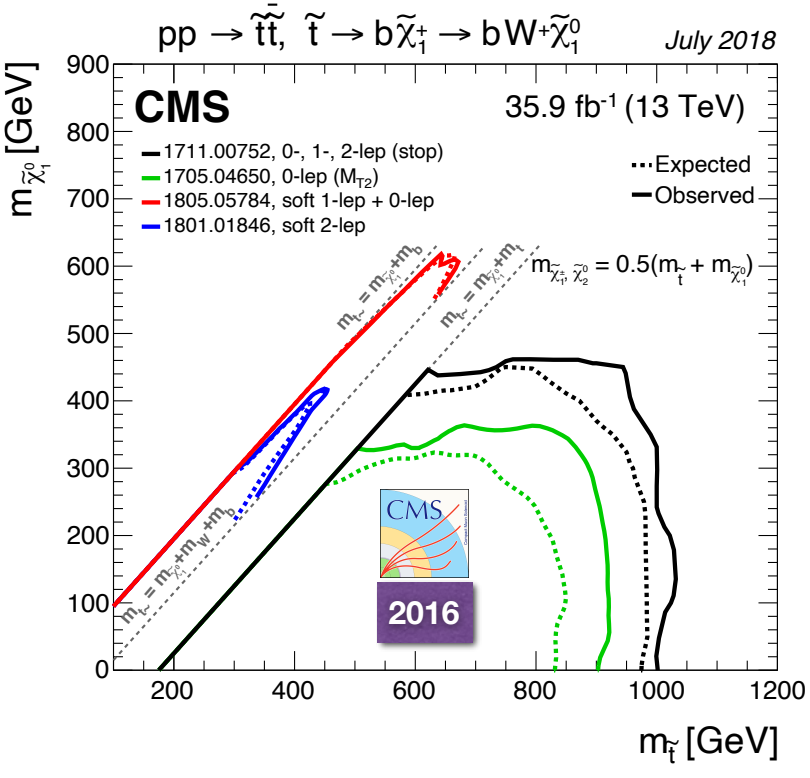
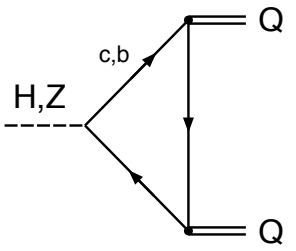


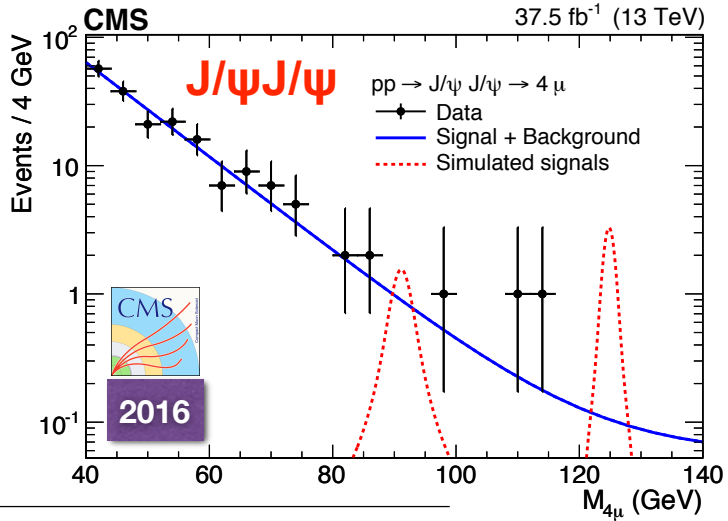


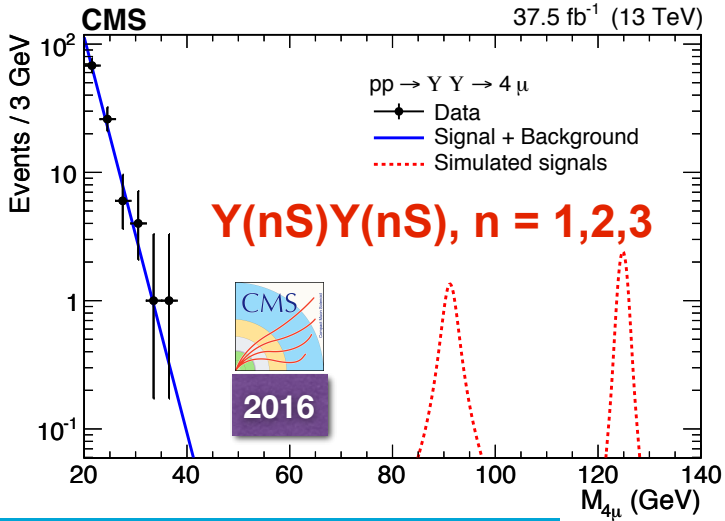
Exotic Decays

Search for Rare Decays

- A search for H(J/ψJ/ψ) and H(Y(nS)Y(nS)) (n=1-3) decays and the analogous Z boson decays using the 4μ channel
- Very rare in the SM (B ~ 10^{-5}-10^{-12}); huge range of predictions
  - ★ Can be substantially enhanced by BSM physics
  - ★ A single event can be a sign of new physics, especially in the YY channel







Unpolarized:

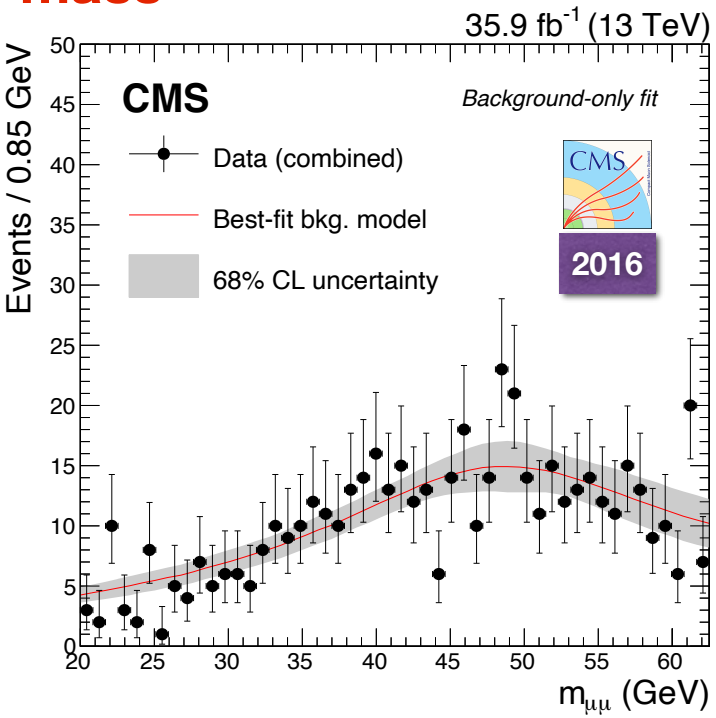
Process	Observed	Expected
$\mathcal{B}(H \to J/\psi J/\psi)$	1.8×10^{-3}	$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(H \to \Upsilon\Upsilon)$	1.4×10^{-3}	$(1.4 \pm 0.1) \times 10^{-3}$
$\mathcal{B}(Z \to J/\psi J/\psi)$	2.2×10^{-6}	$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$
$\mathcal{B}(Z \to \Upsilon\Upsilon)$	1.5×10^{-6}	$(1.5 \pm 0.1) \times 10^{-6}$

CMS arXiv:1905.10408

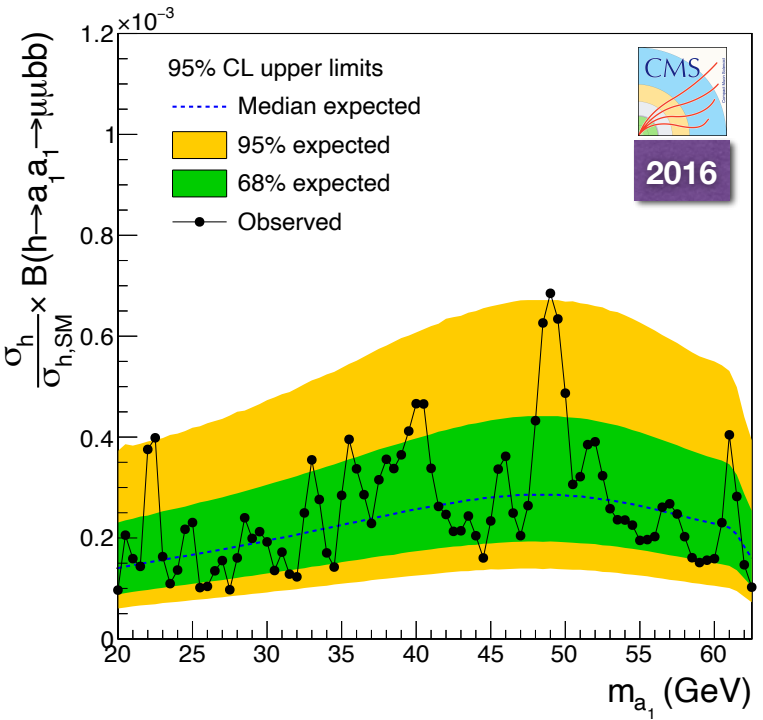
-20-30% to +10% change in limits for extreme polarization scenarios

Search(aa)

- One could look for light pseudoscalars (ALPs) in decays of the Higgs boson
- Latest search from CMS h→aa→2μ2b based on 2016 data
  - ★ Signal region is an ellipse in the $m_{\mu\mu}$ vs. m_{bb} plane
  - ★ Look for peaks in the projection on the high-resolution dimuon mass

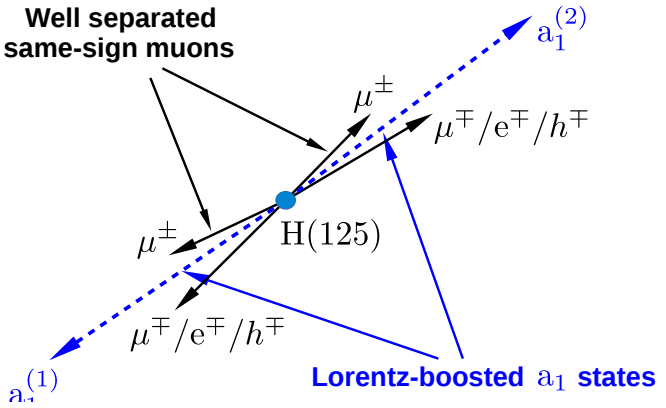


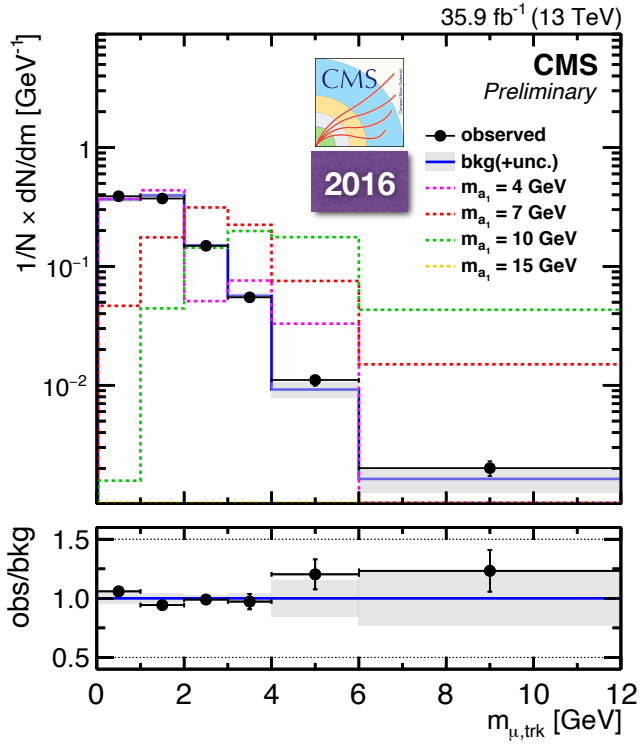
CMS arXiv:1812.06359



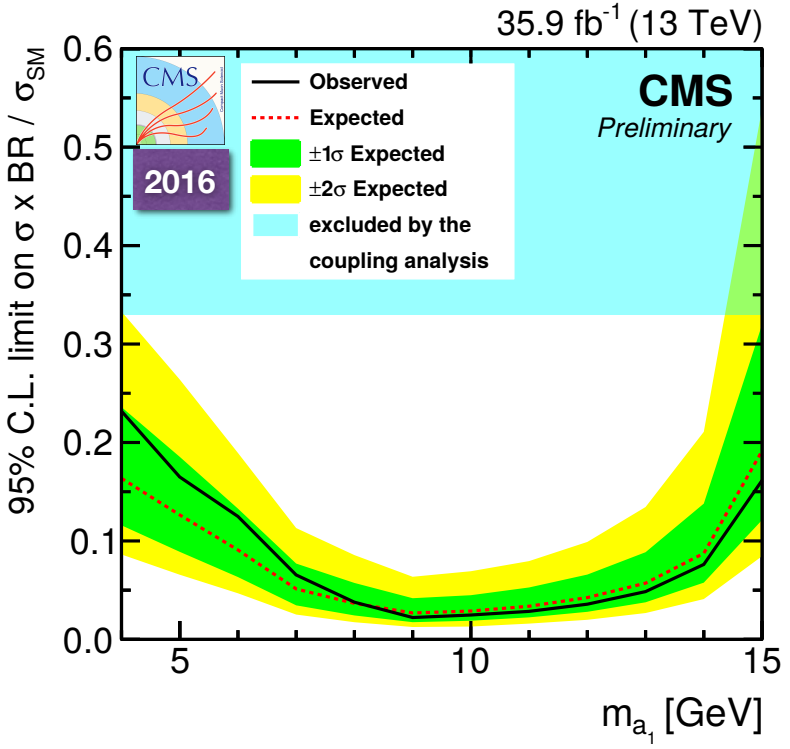
Another Search(aa)

- For even lighter a, one can use 4μ or 4τ final state, both accessible via 2SS μ + 2 nearby tracks
- Look for peaks in the mass of the muon and the nearby track





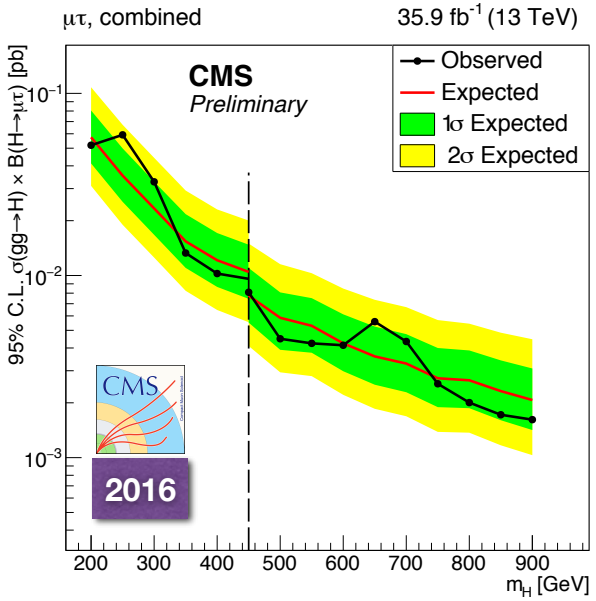
CMS PAS HIG-18-006



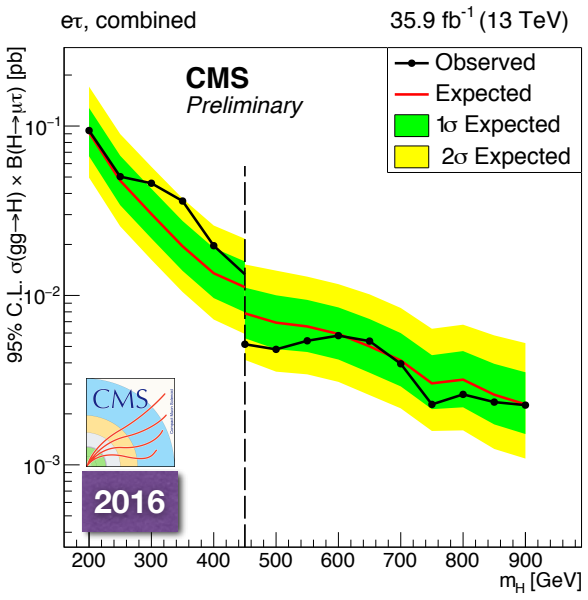
LFV in H⁰eavy Boson Decays

- Exciting CMS hint in H(τμ) circa Run 1, not confirmed w/ Run 2 data
- New search for H(τμ) and H(τe) decays w/ 2016 data in the 200-900 GeV mass range
  - ★ Four channels $e\tau_h$, $e\tau_\mu$, $\mu\tau_h$, $\mu\tau_e$; low- and high-mass regions
  - ★ Cutoff-based analysis, w/ M_{col} as the discriminating variable:

$$M_{\mathrm{col}} = M_{\mathrm{vis}}/\sqrt{x_{\mathrm{vis}}}, \quad x_{\mathrm{vis}} = \frac{p_{\mathrm{T}}^{\tau_{\mathrm{vis}}}}{p_{\mathrm{T}}^{\tau_{\mathrm{vis}}} + p_{\mathrm{T}}^{\nu_{\mathrm{est}}}}$$

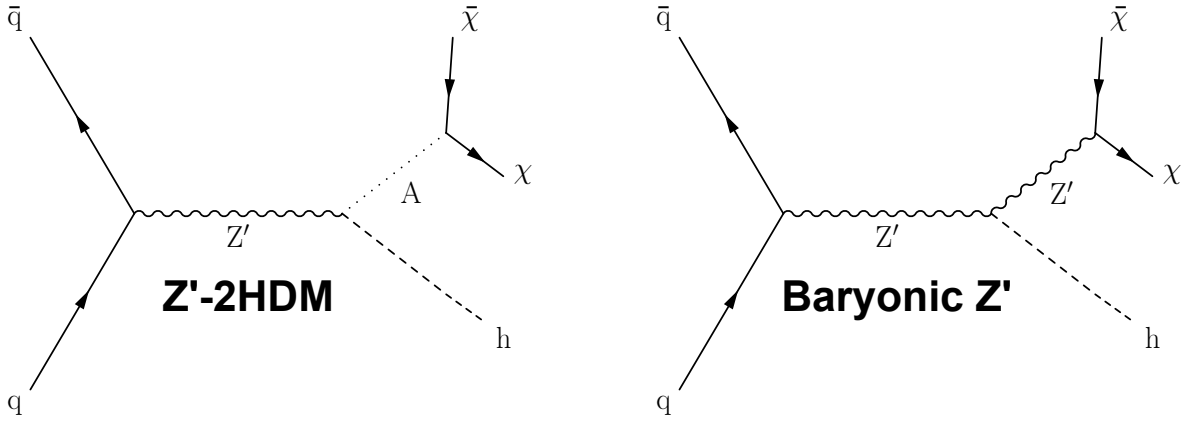


CMS PAS HIG-18-018



Higgs and Dark Matter

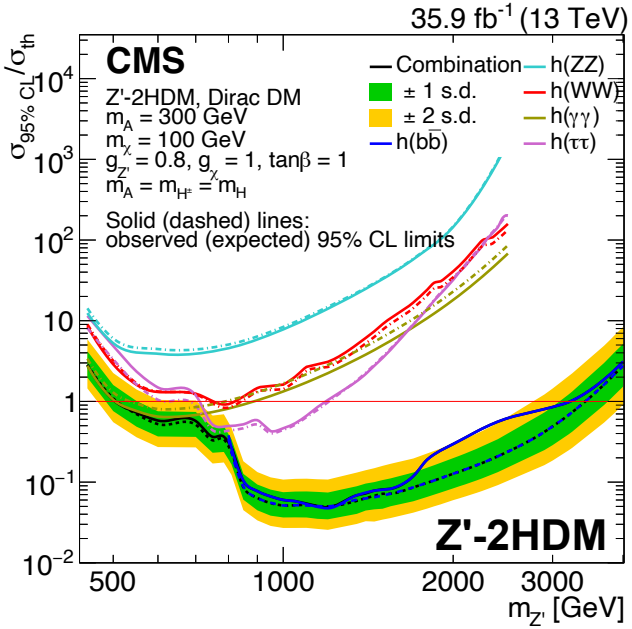
- Higgs boson could be a portal to DM
  - ★ Look for mono-Higgs production
  - ★ A number of scenarios proposed; focus here on two specific models: Z'-2HDM and baryonic Z'

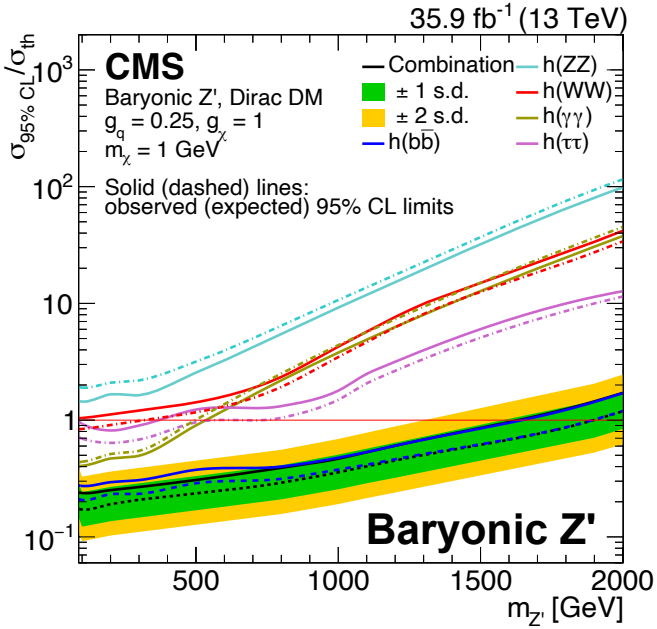


- New CMS combination of all five major Higgs bosons decay channels: WW, ZZ, bb, ττ, and γγ; the first two have never been explored before

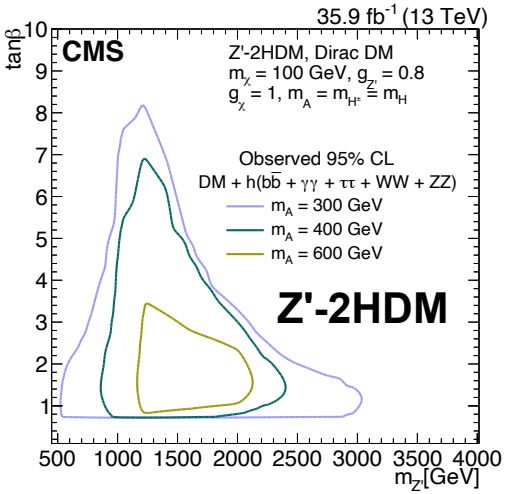
Higgs and DM: Results

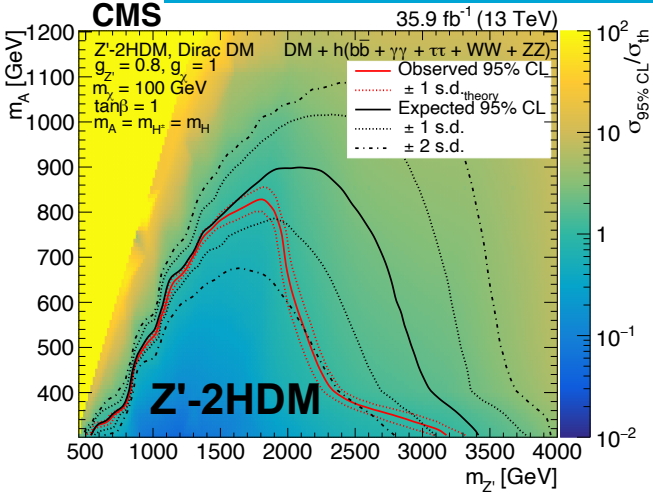
2016

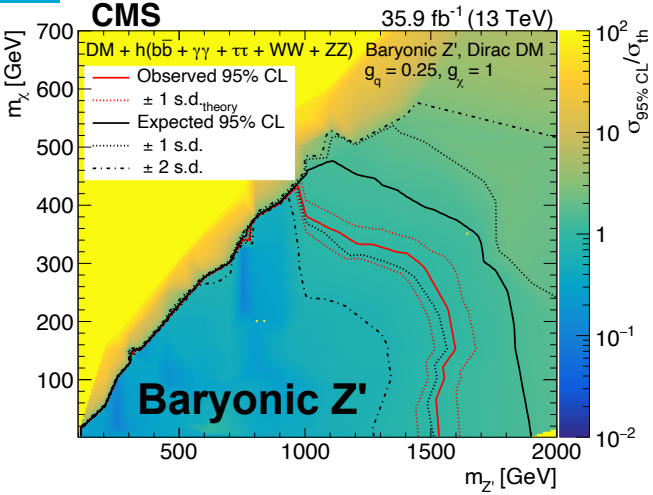




CMS arXiv:1908.01713



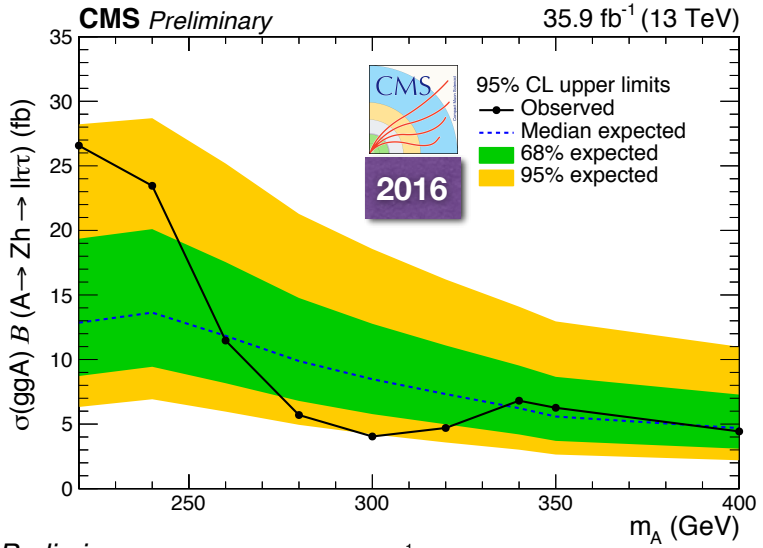


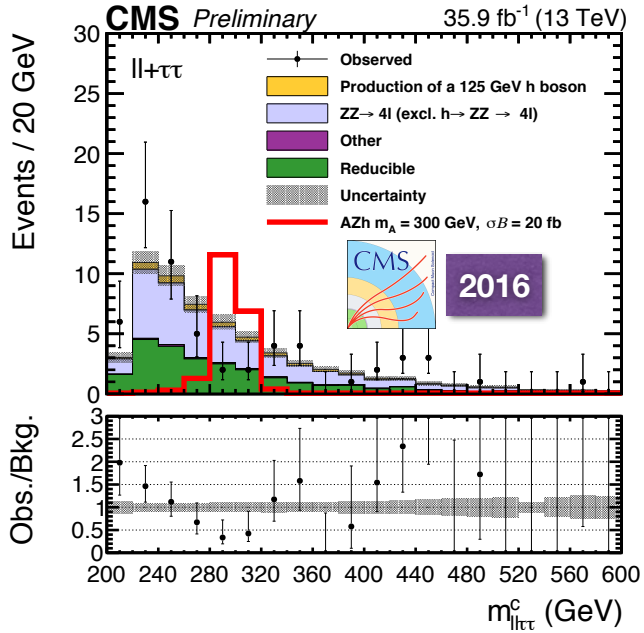



Beyond SM
Higgs Boson
THE BEYOND
STANDARD

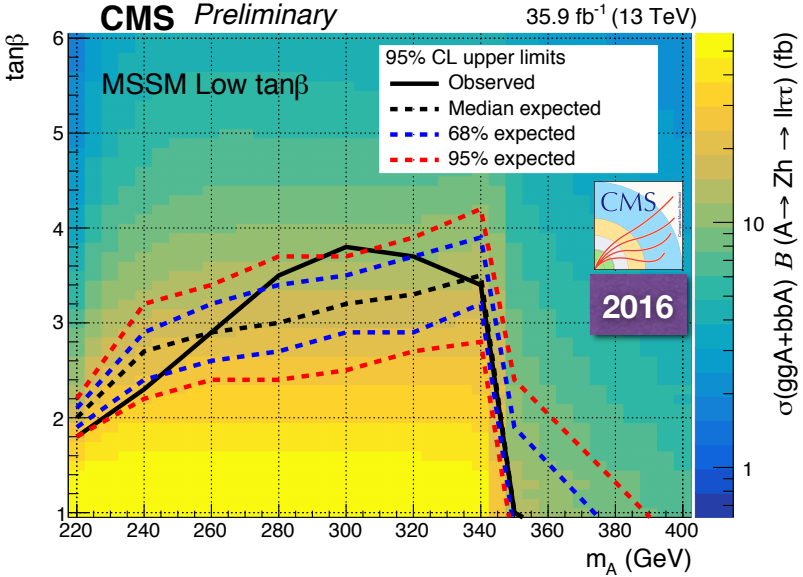
H/Avy Bosons

- Searches for CP-even (H) and CP-odd (A) heavy bosons, ubiquitous in 2HDM
- Many signatures and channels
- Production: ggF and bbA/H
- New CMS search for narrow A → Z(μμ)h(ττ), sensitive to low tanβ





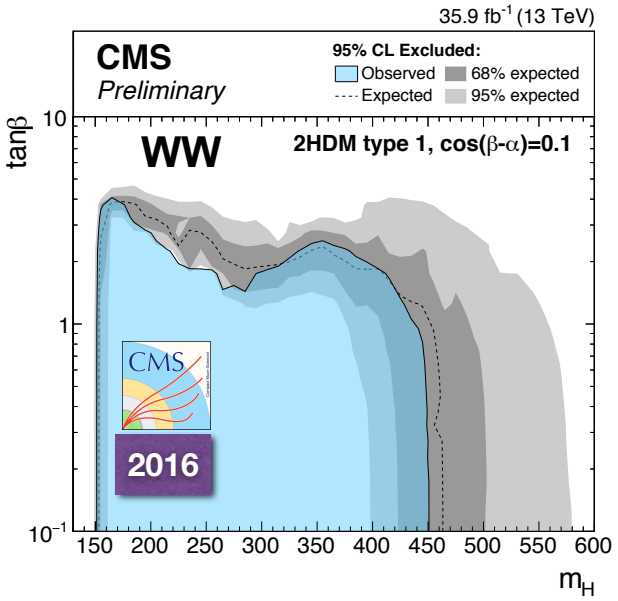
CMS PAS HIG-18-023

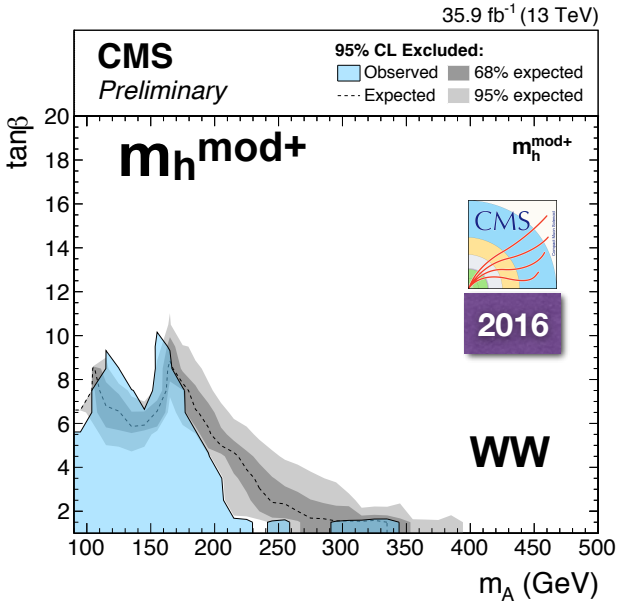


More Heavy SearcH/As

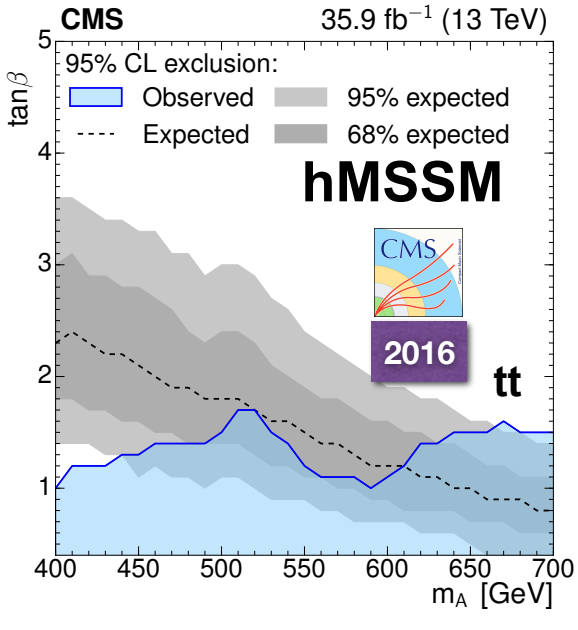
- Other promising channels for high-mass Higgs boson searches are WW, ZZ, and tt
- New CMS 2016 data searches in the WW and tt (2L and 1L decay modes) channels, with full interference taken into account

CMS PAS HIG-17-033



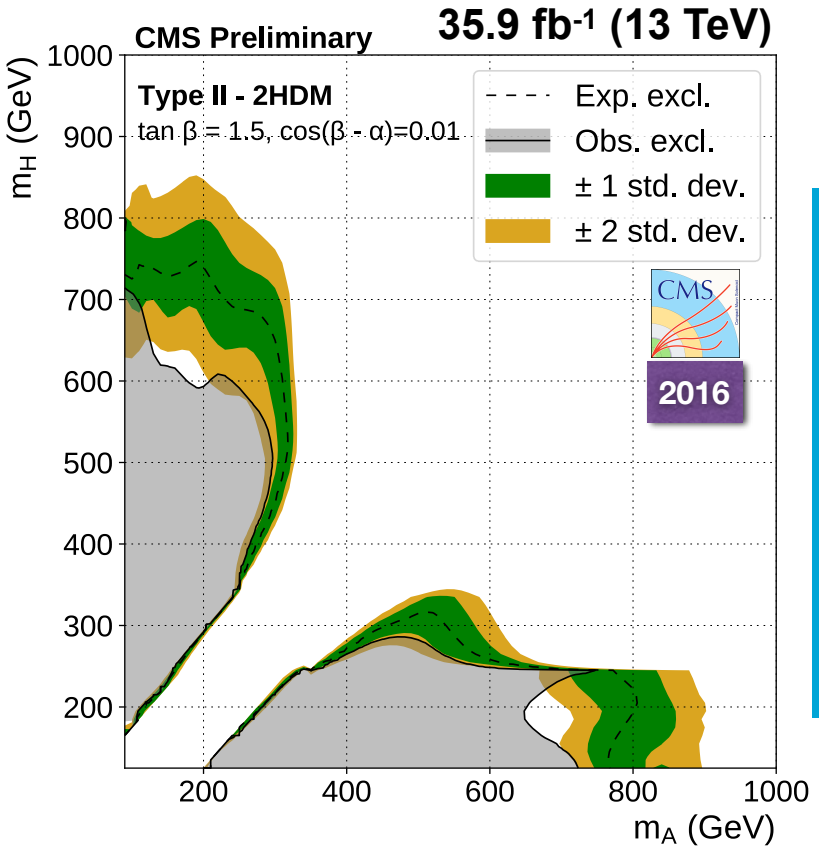


CMS arXiv:1908.01115

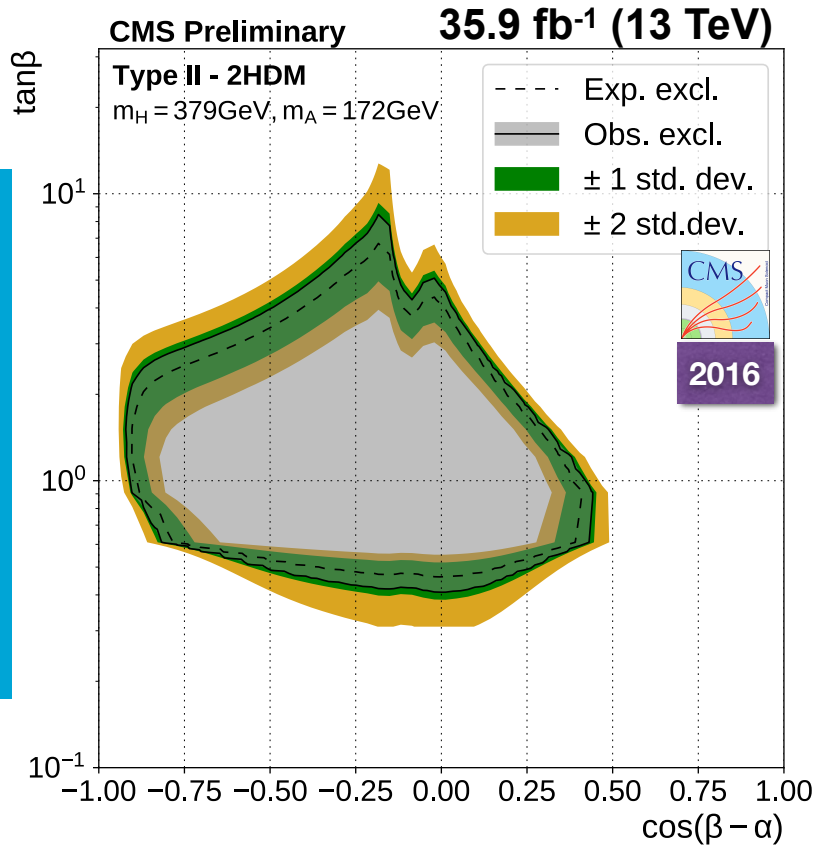


More Heavy SearcH/As

- Finally, could look for H → ZA (or vice versa, A → HZ), e.g., in the ℓℓbb final state
- Fit to S+B templates in the M(bb) vs. M(ℓℓbb) plane

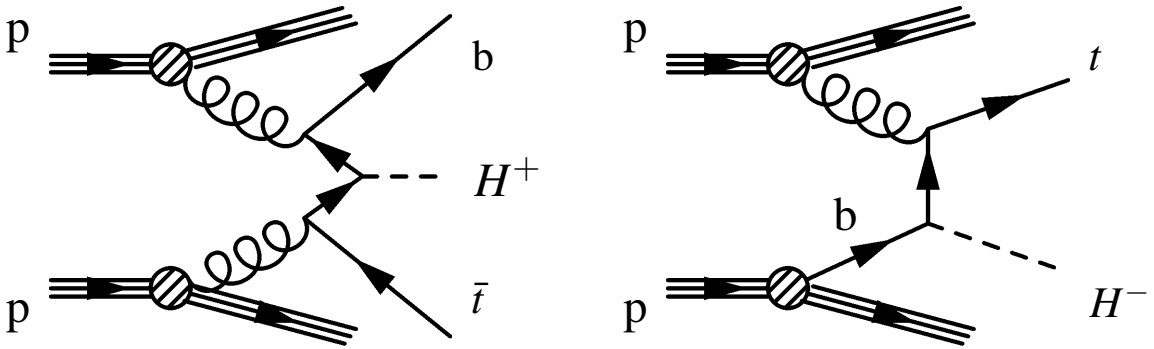


CMS PAS HIG-18-012



$H^{\pm}$iggs Bosons

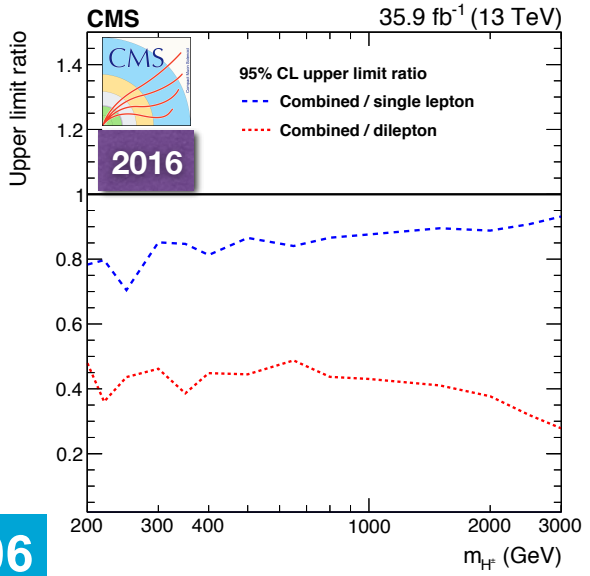
- Come in variety of 2HDMs, including MSSM
- Two regimes: heavy (above the top quark mass) and light
- For a heavy Higgs boson, could explore associated tH^- production with H^- decaying to a top antiquark and bottom quark (+c.c.)
- Depending on the decay channels of the two top quarks, could explore dilepton, single-lepton, and all-hadronic decay channels

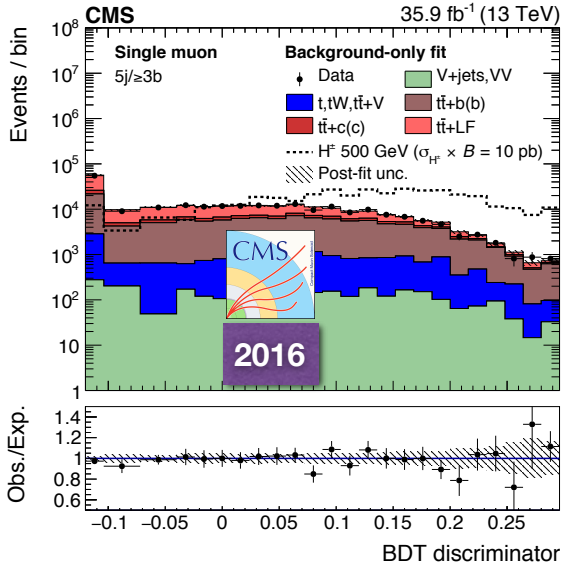


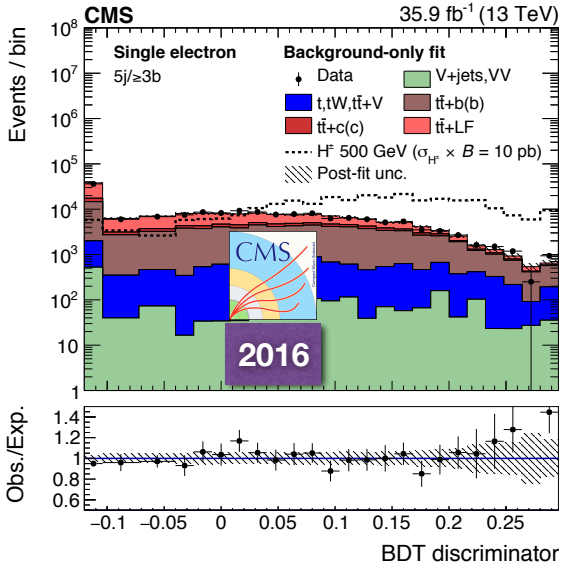
2L and 1L Search

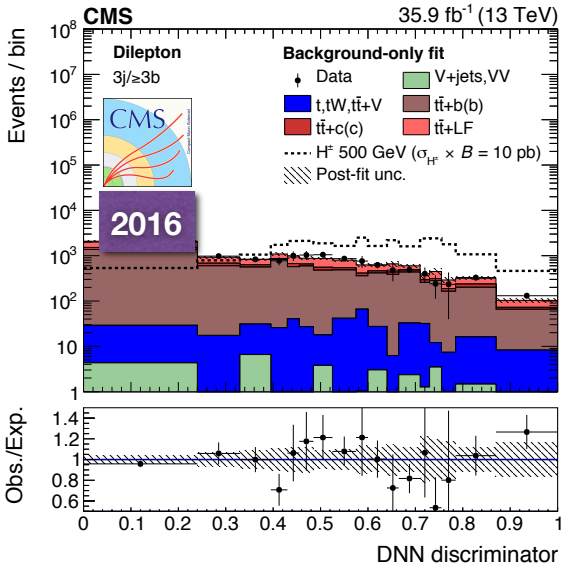
- New CMS analysis in the 2L and 1L (dominant) channels
- Multiple event categories, classified by the number of jets and b-tagged jets; the sensitivity is optimized by the use of BDTs (1L) or DNN (2L)

CMS arXiv:1908.09206





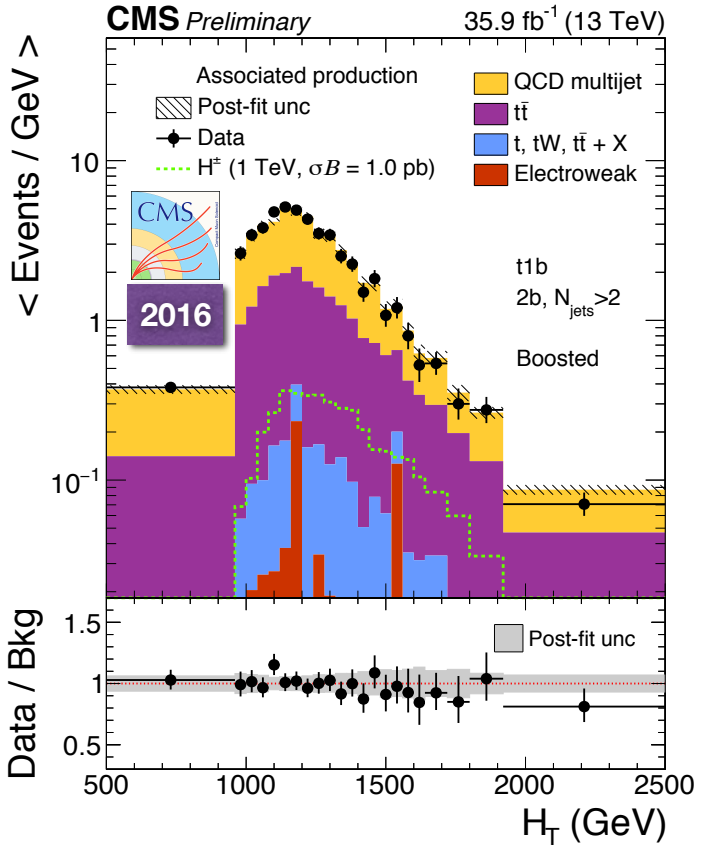


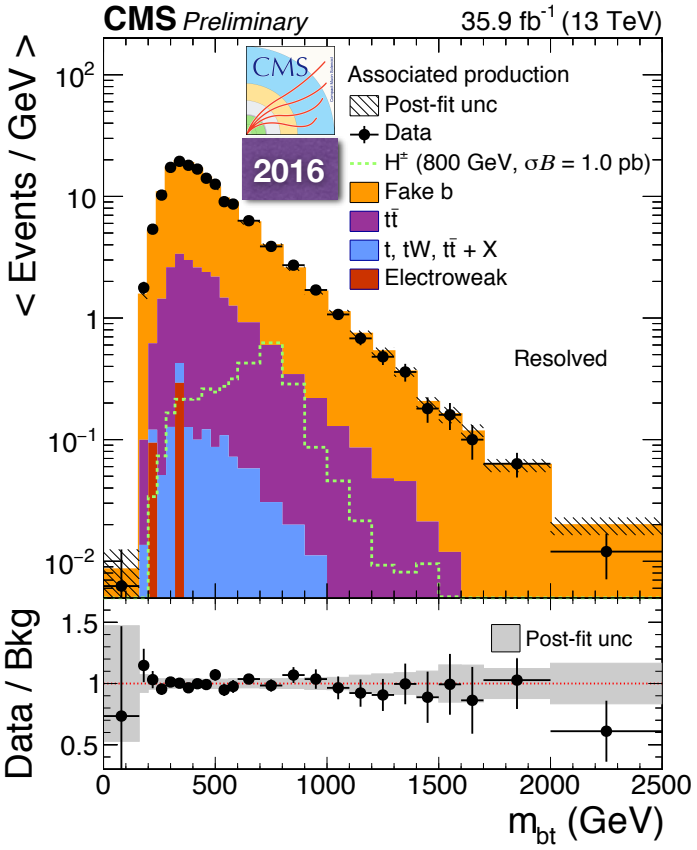


0L Search

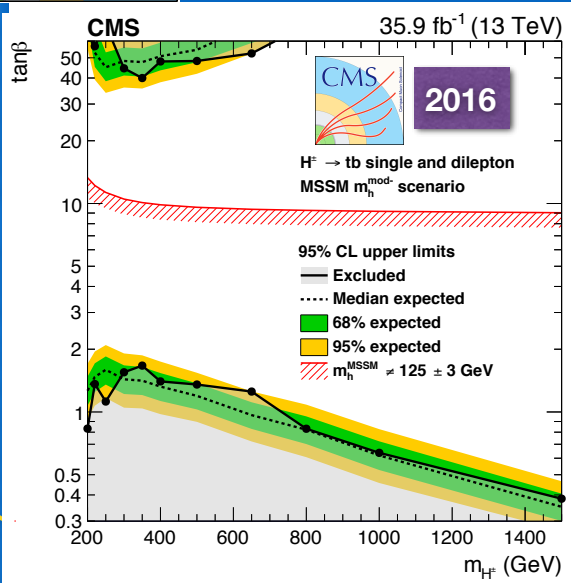
- In the all-hadronic channel, use both merged- and resolved-jet categories w/ full event reconstruction and BDT optimization
- H_T is used in the merged-jet analysis and m_{bt} in the resolved-jet one

CMS PAS HIG-18-015





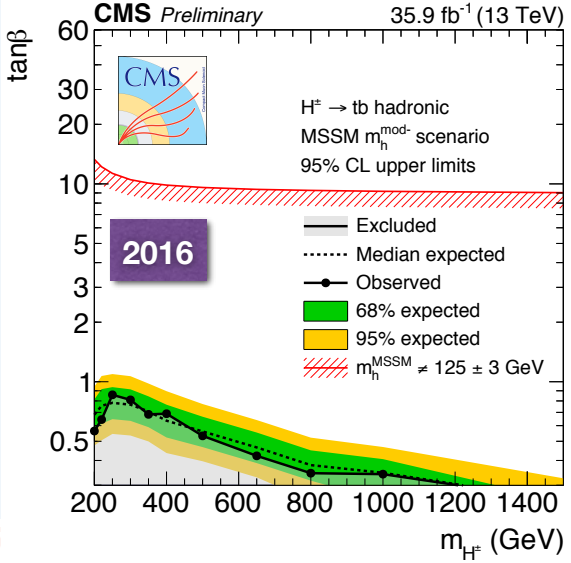
H±iggs Limits

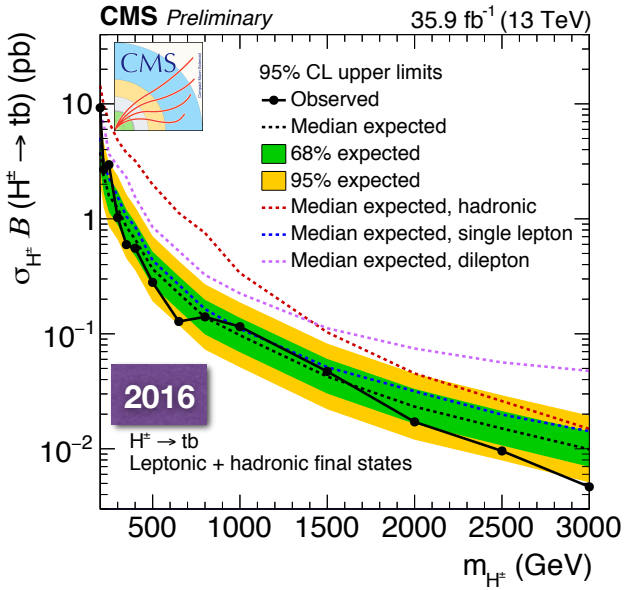


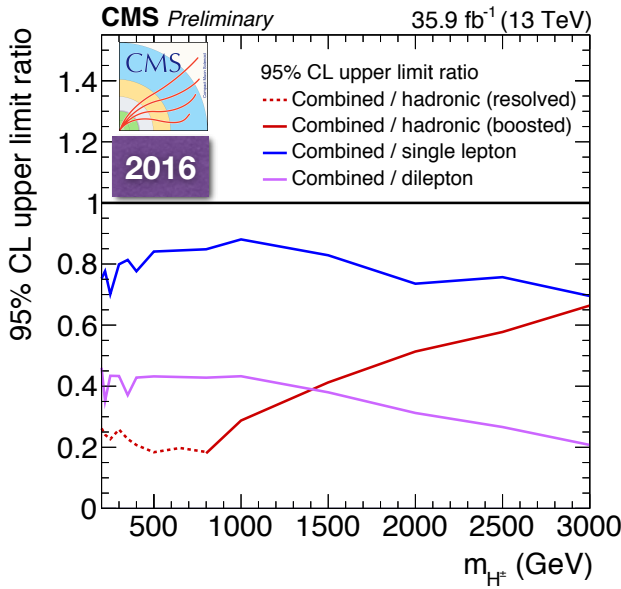
CMS arXiv:1908.09206

- Cross section limits set in a combination of 2L and 1L, as well as in 0L analysis, and then combined, with the sensitivity still dominated by the 1L channel
- MSSM interpretations for leptonic and hadronic analyses are also provided

CMS PAS HIG-18-015

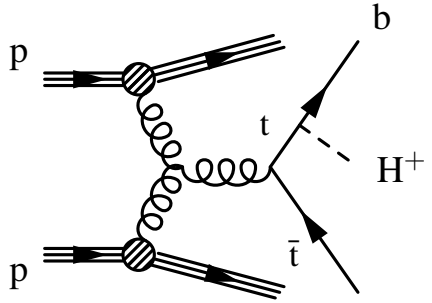




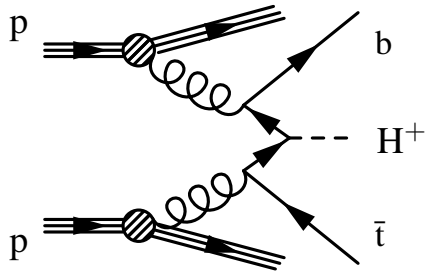


SearcH±(τν)

- New search for H → τν in the broad mass range (80 GeV to 3 TeV)

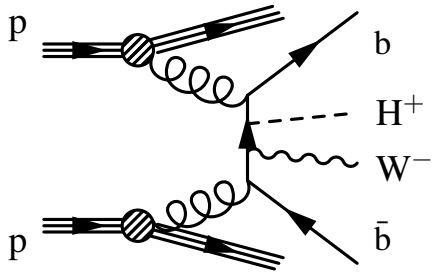


Light H±



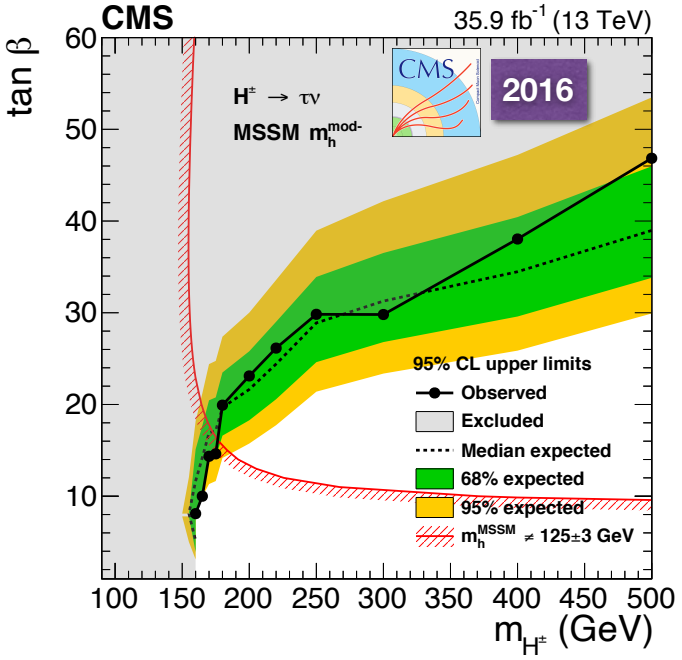
Heavy H±

Intermediate mases



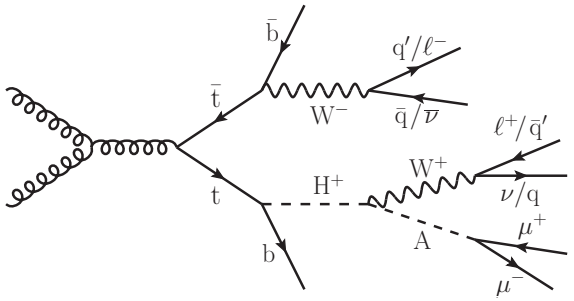
- Uses three final states: τ_h + jets, ℓ + τ_h, ℓ + no τ_h
- Uses transverse mass M_T based on the τ candidate and ME_T as discriminating variables

CMS arXiv:1903.04560

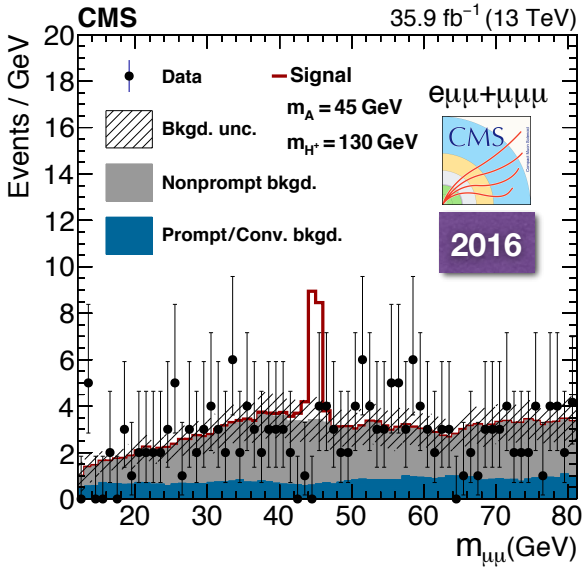


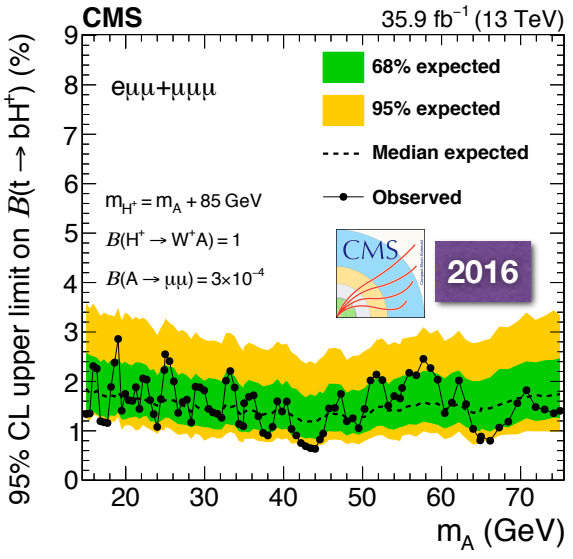
Light H±iggs Boson

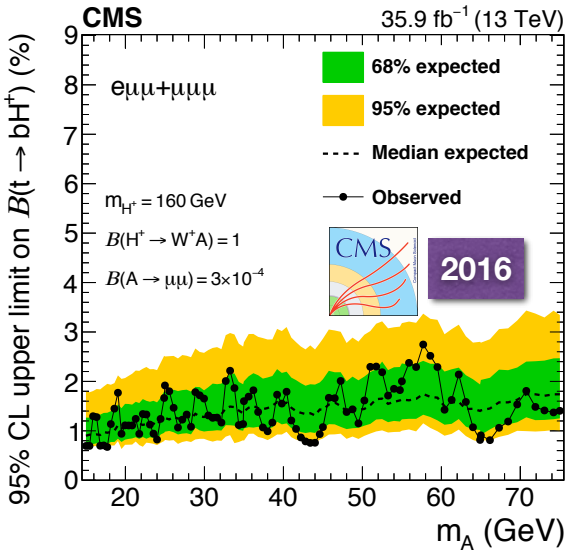
- A light charged Higgs boson can be produced in top quark decays
  - ★ H → τν is one possible channel
  - ★ Could also look for a decay involving another Higgs boson, e.g. H± → W±A via the trilepton signature, looking for narrow resonances in the dimuon mass spectrum - first search of a kind!

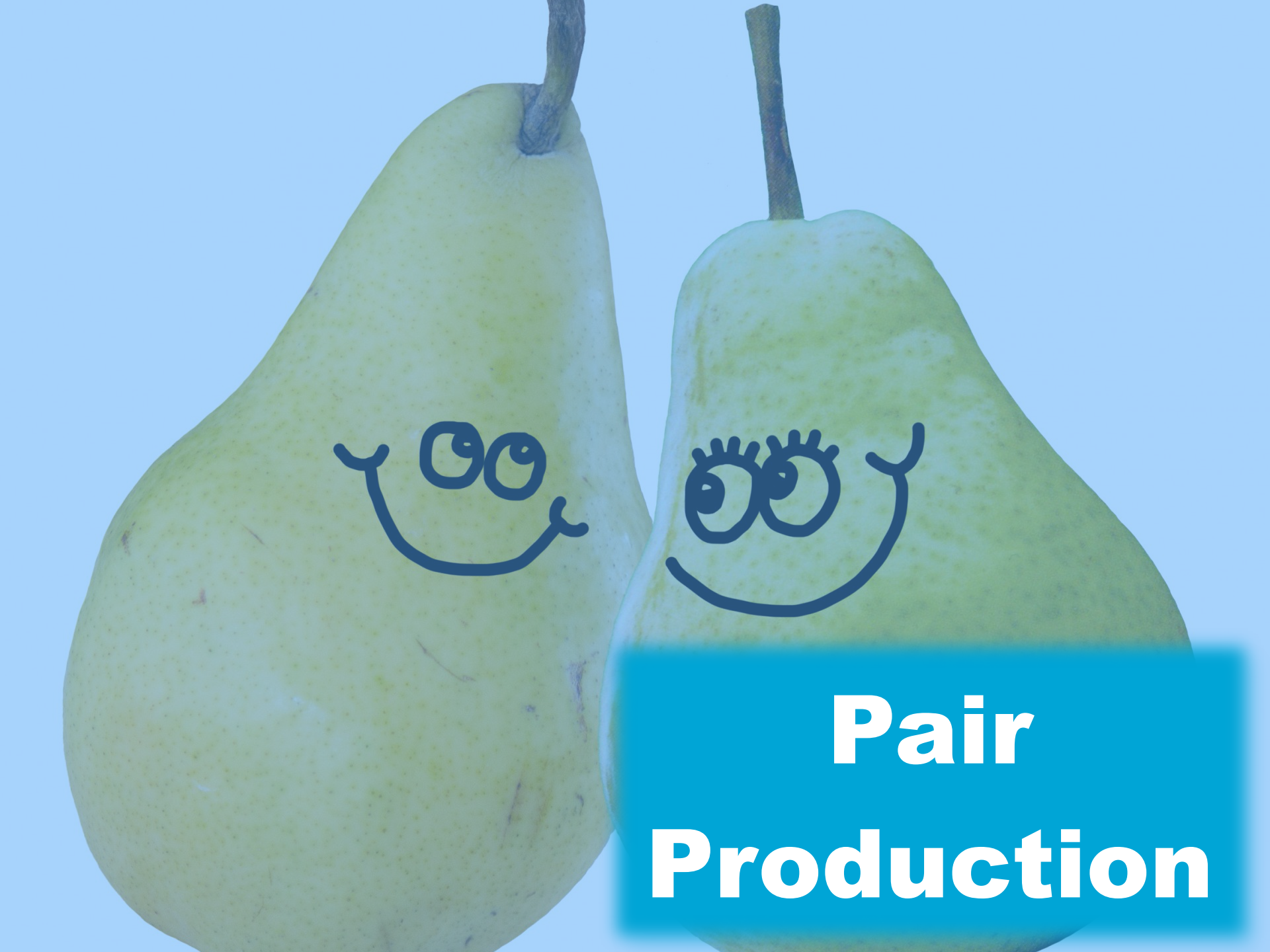


CMS arXiv:1905.07453



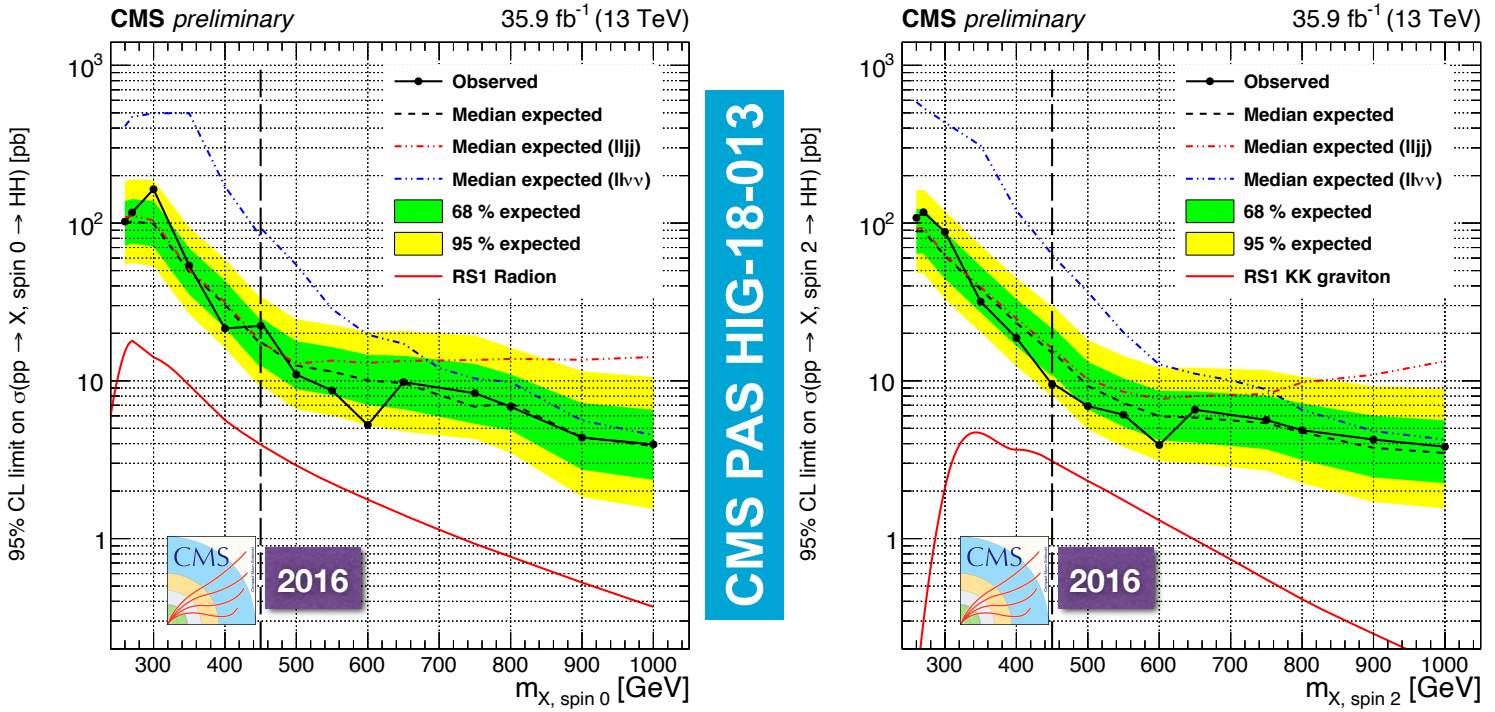





Pair
Production

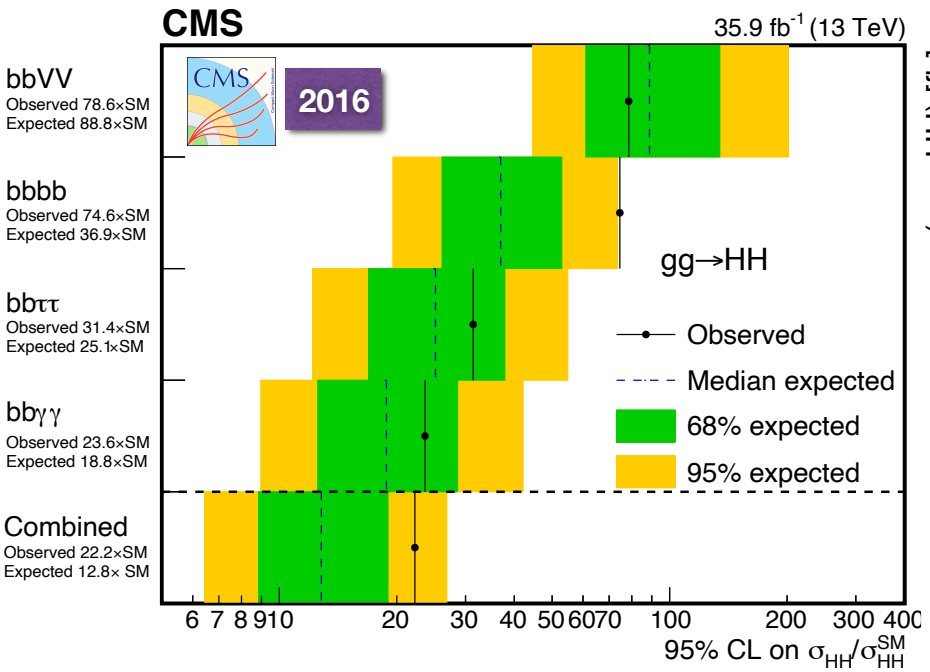
Pair ProducHHion

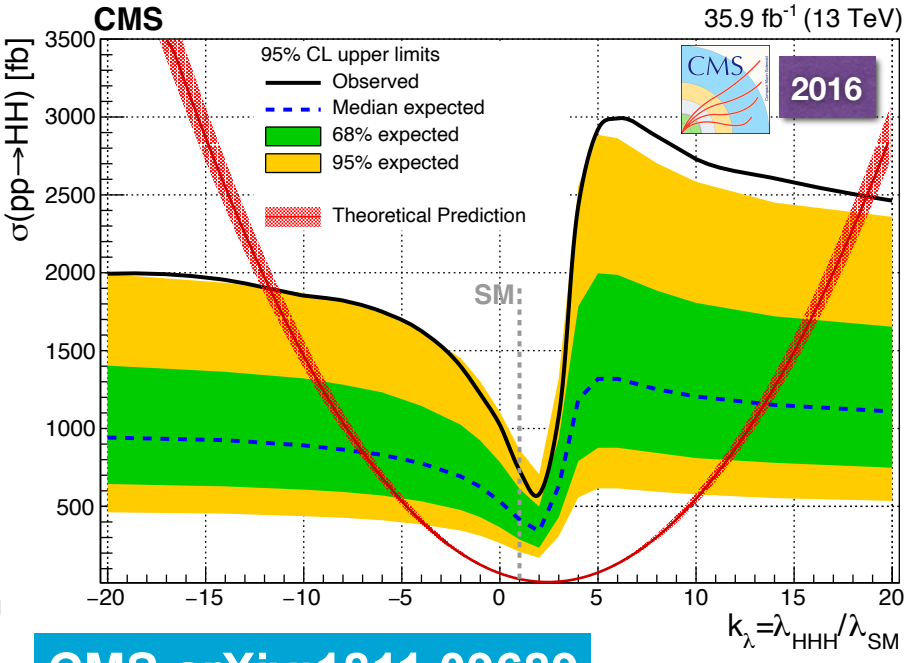
- Explore both resonant and non-resonant production
  - ★ The latter eventually would result in the measurement of λ
  - ★ Multiple decay channels are being considered
- Latest CMS results on resonant searches in the bbZZ channel, with ZZ -> ℓℓjj or ℓℓνν in RS G or radion model



CombinaHHion

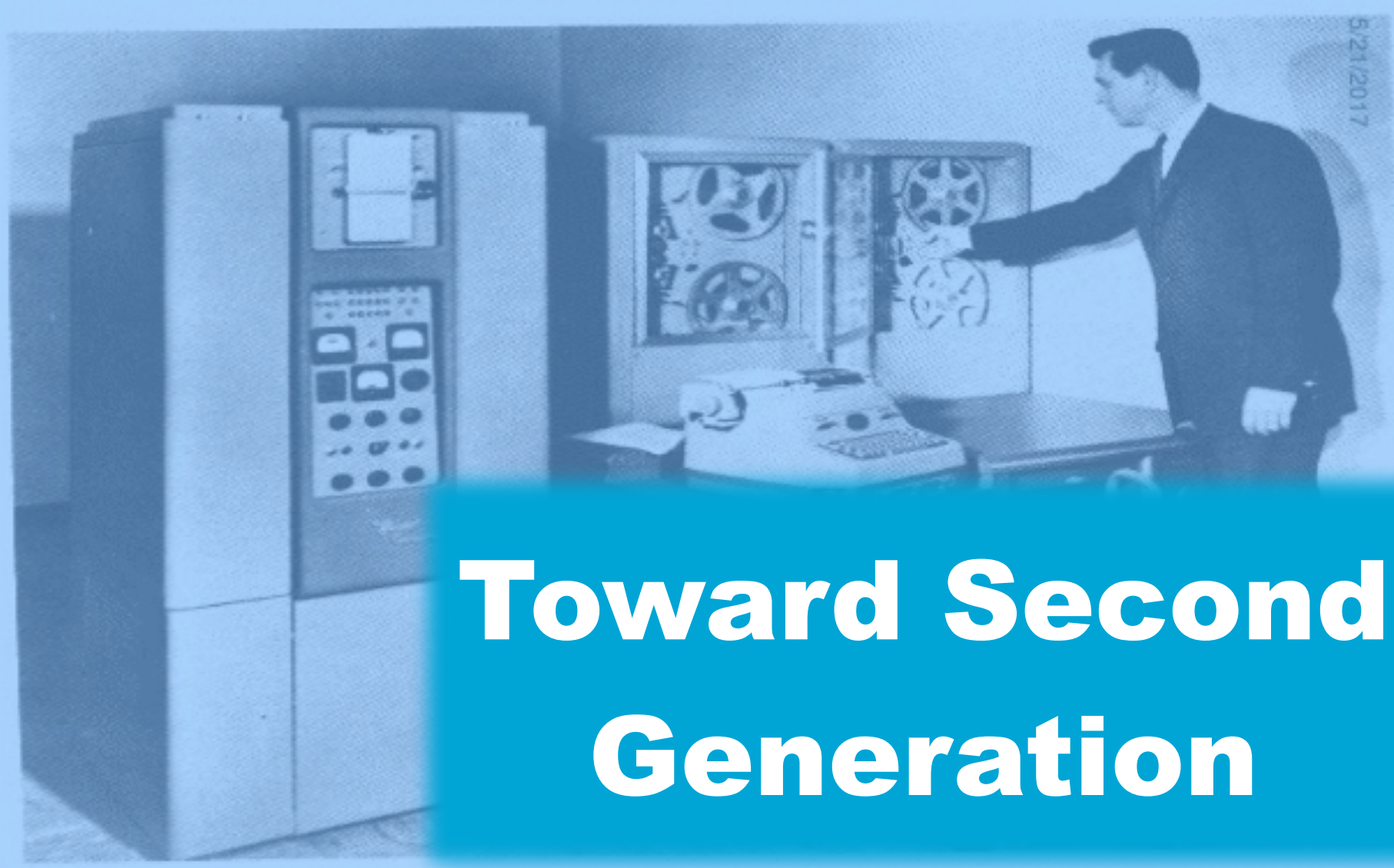
- **Best limits on non-resonant HH production come from the combination of a number of 2016 data analyses: bbWW/ZZ, bbbb, bbττ, and bbγγ**
  - ★ **The observed (expected) limit:**
    $-11.8 < k_\lambda < 18.8$ ($-7.1 < k_\lambda < 13.6$) @ 95% CL





CMS arXiv:1811.09689

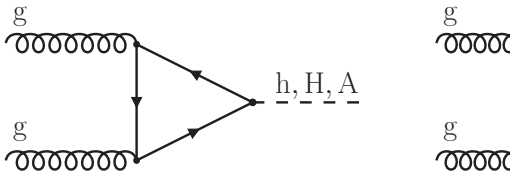
COMPUTER - SECOND GENERATION

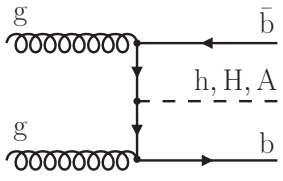


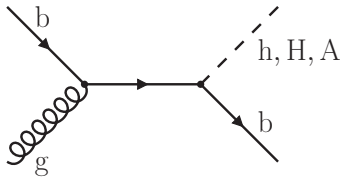
Toward Second Generation

MSSM H(μμ)

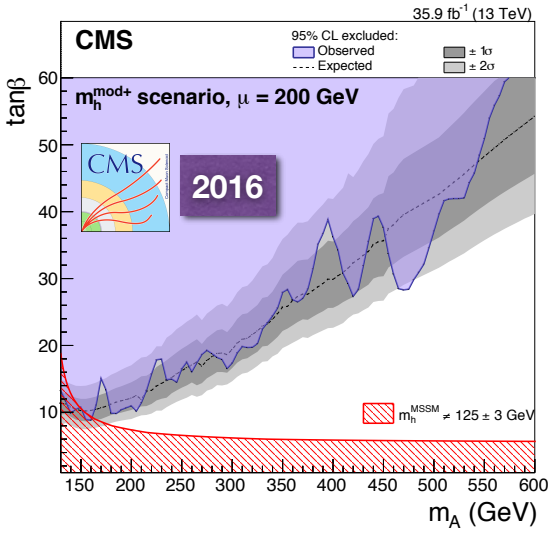
- Search for MSSM Higgs boson decays to μμ
- Considered both ggF and b(b)H/A associated production
  - ★ Analysis categories w/ and w/o b tags to maximize the sensitivity
- Limits set in specific MSSM scenarios, as well as for generic (pseudo)scalars w/ narrow and finite (Γ/M = 10%) widths

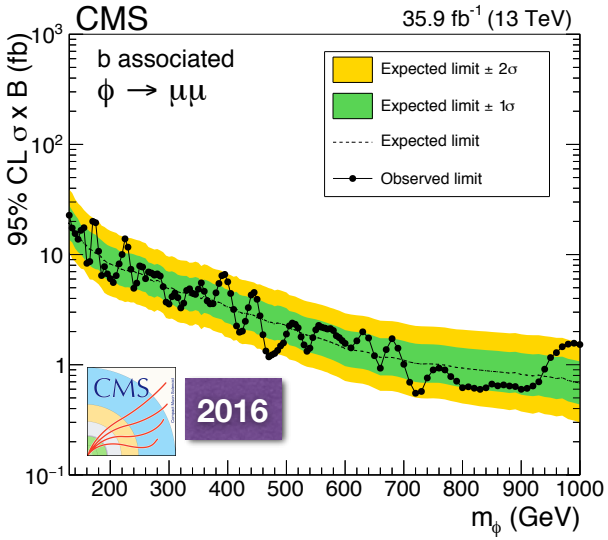


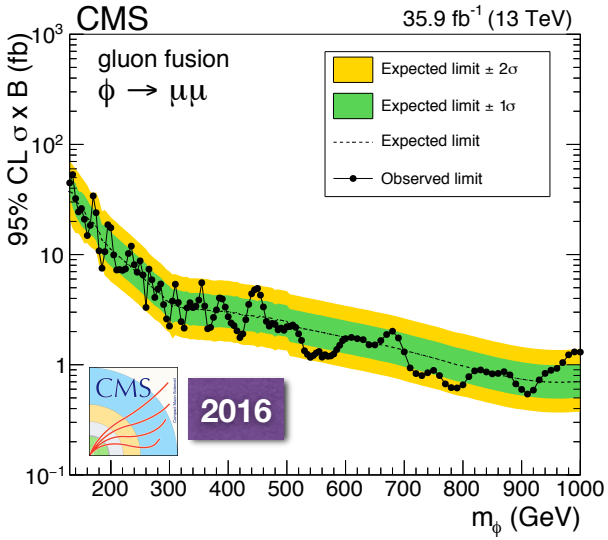




CMS arXiv:1907.03152

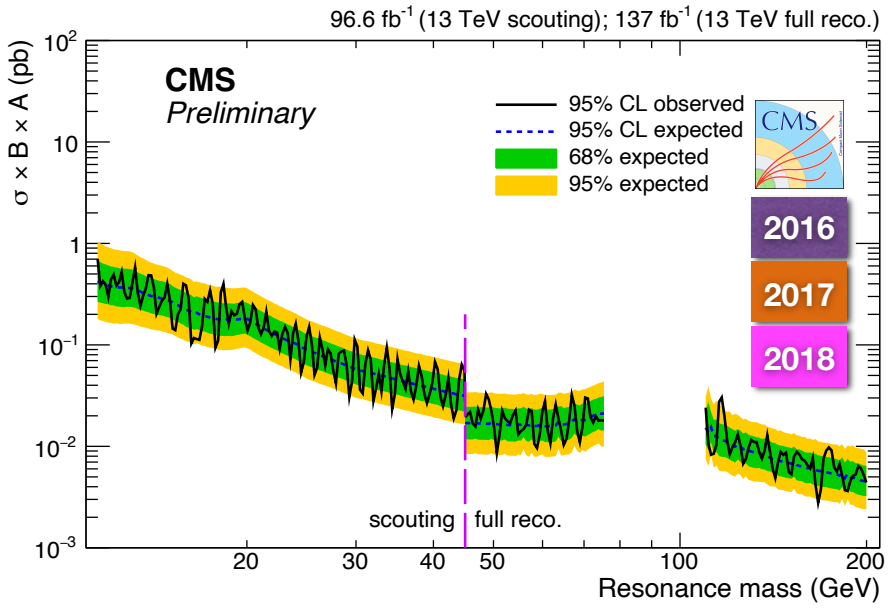




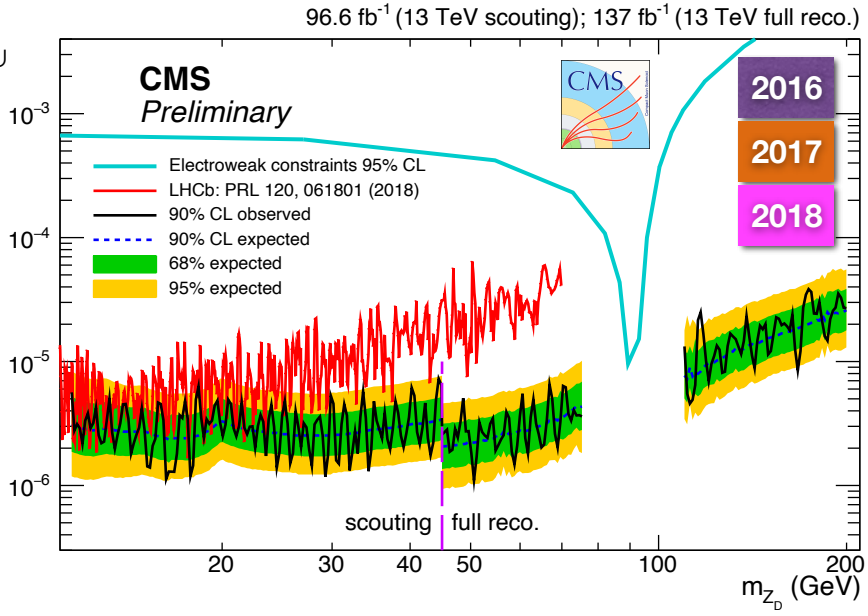


Low-Mass Sea(μμ)rch

- New CMS full Run 2 analyses based on the data scouting technique: write very limited trigger-level information about the event, thus drastically reducing the size and increasing the rate to tape
  - ★ Allows to use low-threshold triggers, e.g., dimuon ones
- Combined with the standard full event reconstruction at higher thresholds
- Interpretation is done in the dark photon (Z'_D) models, but equally applies to resonant ALP production; much improves on the LHCb limits



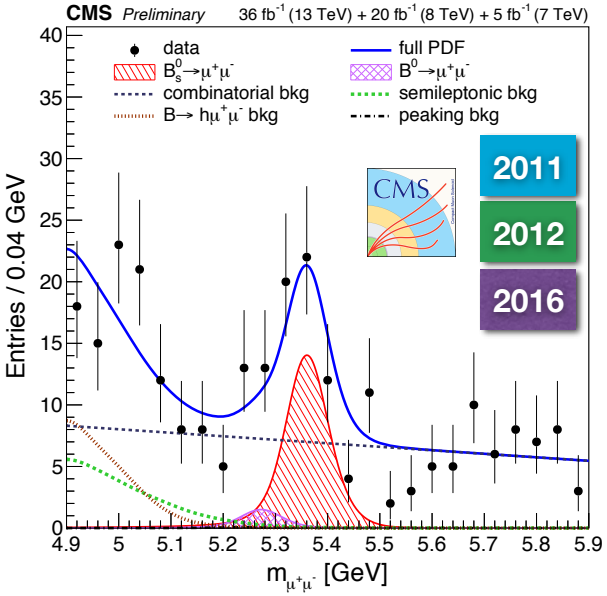
CMS PAS EXO-19-018

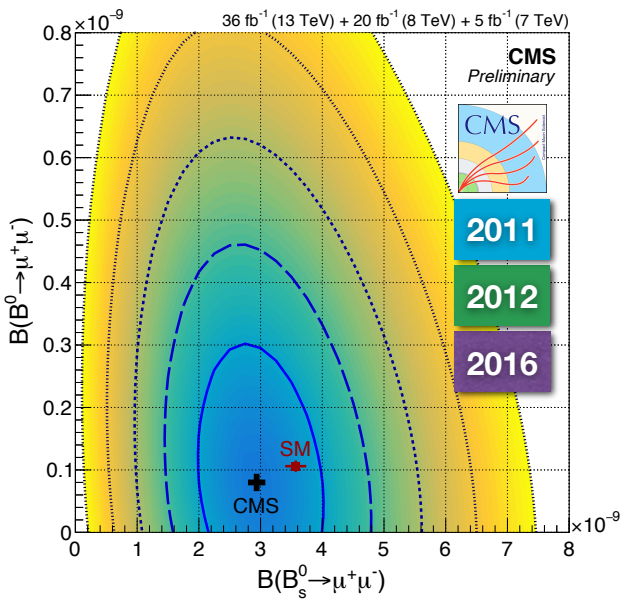


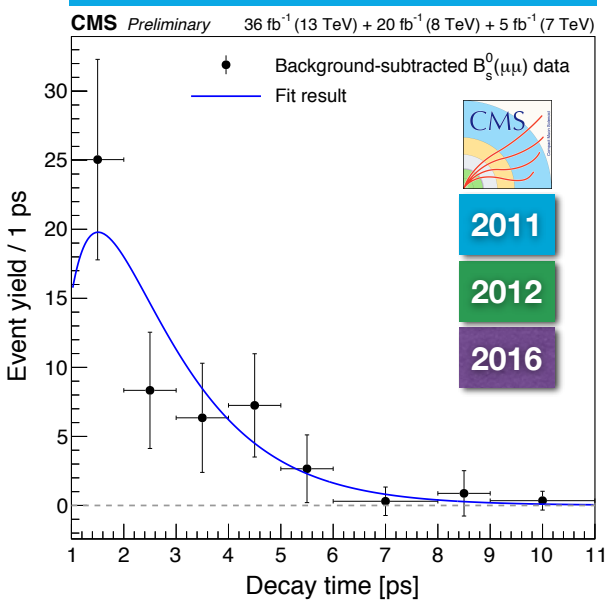
Pseudoscalar: $B_s(\mu\mu)$

- A new CMS measurement, based on Run 1 + 2016 Run 2 data has just been made public:
  - ★ $B(B_s \rightarrow \mu\mu) = [2.9^{+0.7}_{-0.6}\ (exp.) +0.2\ (frag.)] \times 10^{-9}$
    - ✤ Observed (expected) significance 5.6 (6.5) s.d.
  - ★ $B(B \rightarrow \mu\mu) < 3.6\ (3.1) \times 10^{-10}$ @ 95 (90)% CL
- Theory prediction: $(3.66 \pm 0.14) \times 10^{-9}$ (including mixing and latest form-factors)
- Naive 1D average: $2.92\ ^{+0.42}_{-0.38}$, i.e.,1.67σ below the SM prediction; 2D: ~2σ
- Effective lifetime measurement: $\tau = 1.70^{+0.61}_{-0.44}$ ps (expect: 1.615 ± 0.004 ps for the heavy state; light state: 1.415 ps)

CMS PAS BPH-16-004

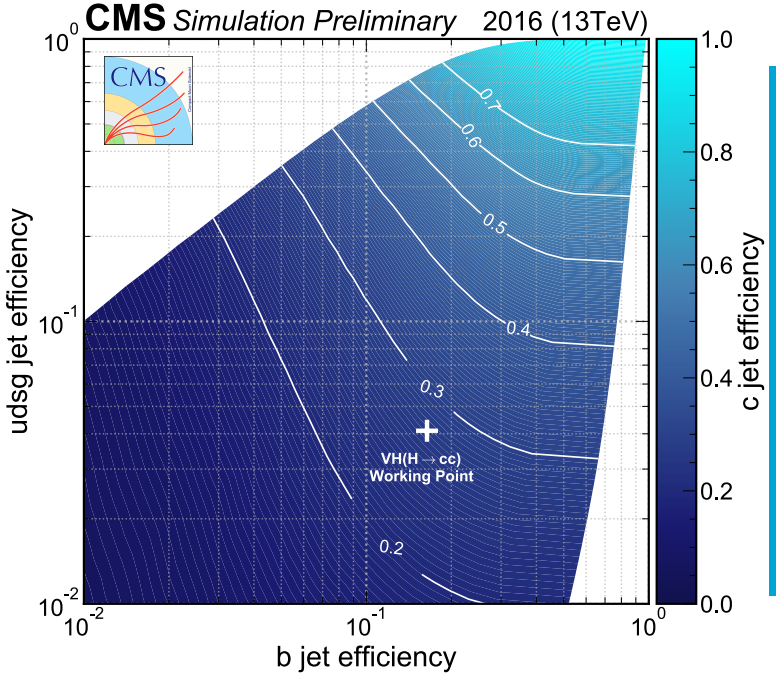






SearcH(cc)

- New, tour-de-force CMS analysis in this very challenging channel, using associated VH(cc) production, based on 2016 data
- Combines the resolved and merged h(cc) topologies, in three V boson decay channels: zero-lepton (Z(νν)), single-lepton (W(ℓν)), and dilepton (Z(ℓℓ))
- Based on a state-of-the-art DeepCSV flavor tagger with multiclassifier (b/c/LF) output
- Uses VZ(cc) as a control channel
  - ★ $\mu[VZ(cc)] = 0.55^{+0.86}_{-0.84}$
  - ★ 0.7 (1.3)σ observed (expected) significance



CMS PAS HIG-18-031

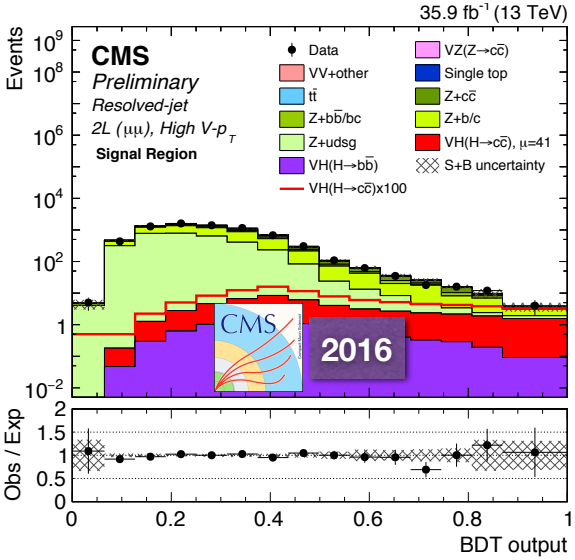
SearcH(cc) Results

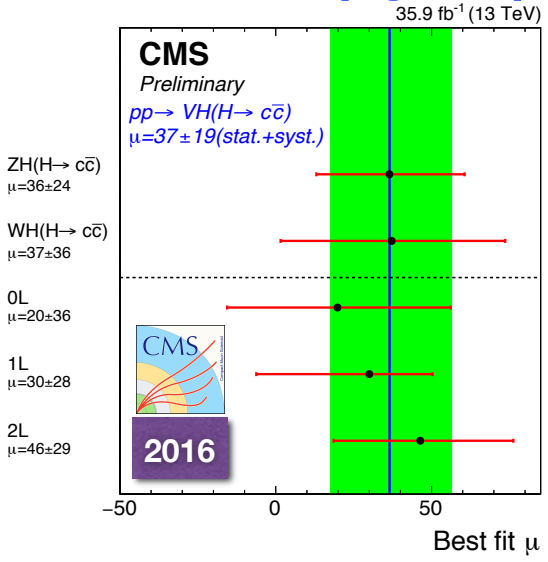
- BDT-based, highly optimized analysis
- Sensitivity is dominated by the 2L, resolved channel
  - ★ Slight (~2σ) excess observed in one of the 2L resolved analysis categories

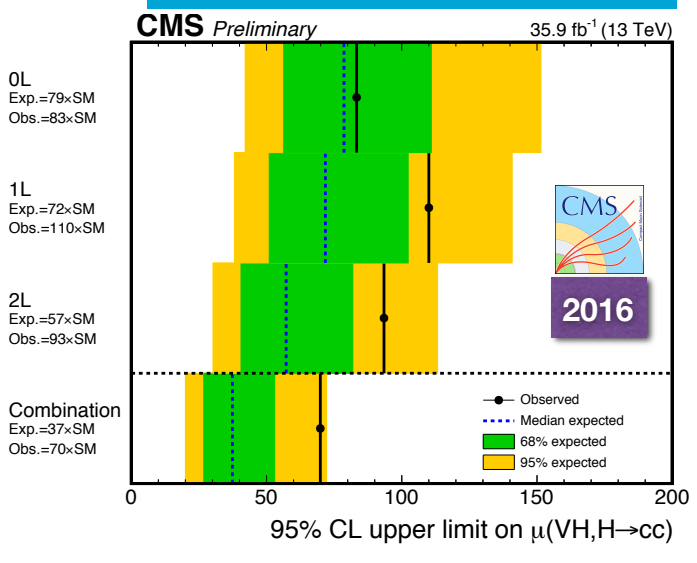
Limit on μ	Resolved-jet (inclusive)				Merged-jet (inclusive)			
	0L	1L	2L	All channels	0L	1L	2L	All channels
expected UL	84	79	59	38	81	88	90	49
observed UL	66	120	116	75	74	120	76	71

- Overall result: $\mu[VH(cc)] = 36^{+20}_{-19}$; $\mu < 70$ (37^{+16}_{-11}) @ 95% CL - most stringent limit to date (by far)

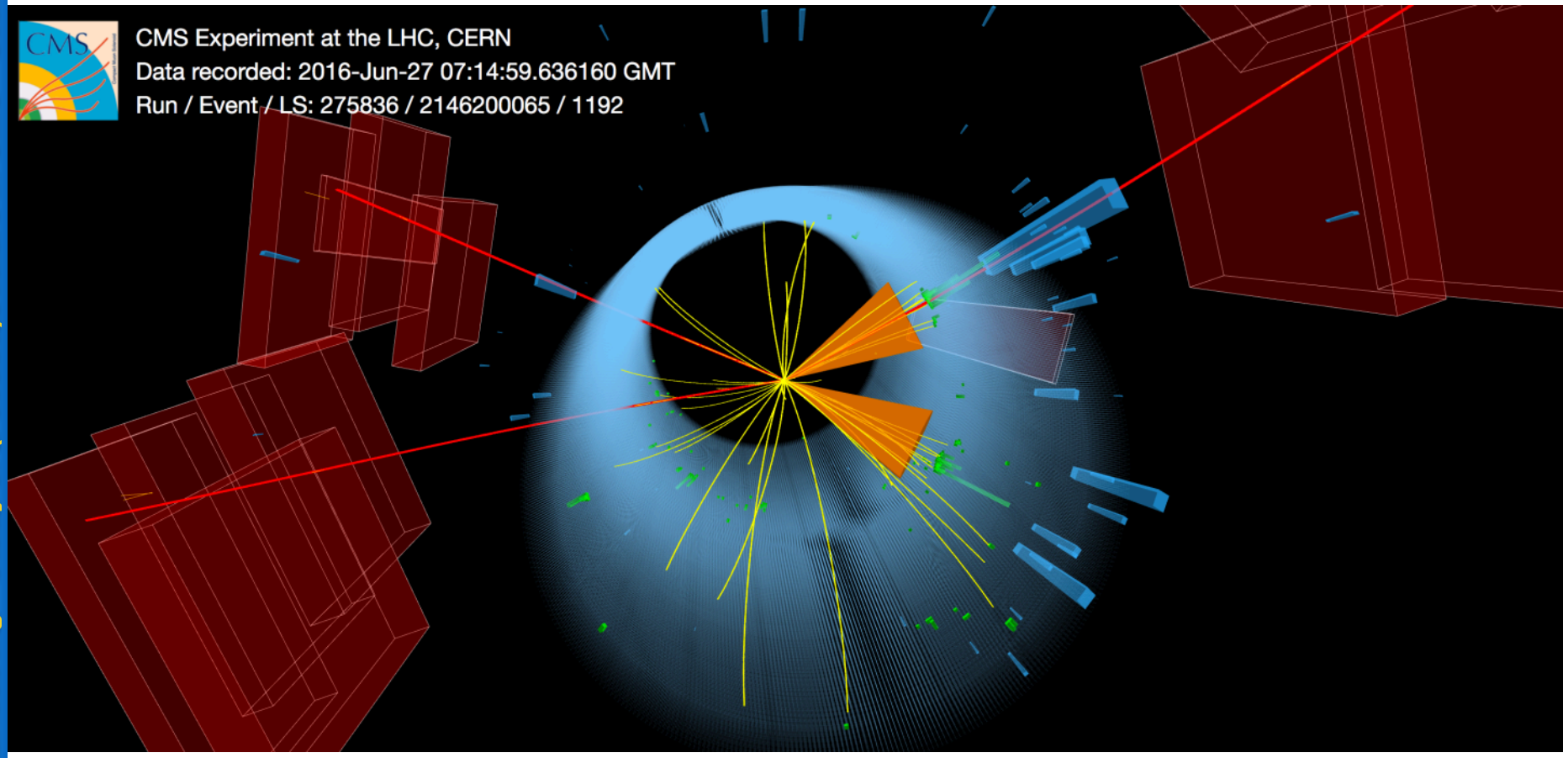
CMS PAS HIG-18-031







ZH(cc)andidate Event



Conclusions

- Higgs boson had a fun childhood and now goes to the primary school
  - ★ Will learn more about the properties, exotic decay channels, and possible deviations from the standard model predictions
- CMS has been a watchful parent for all these childhood years and will follow the school years with large Run 2 and beyond data samples
- With the third-generation couplings well established, our sights are shifting on the second generation and exotic decays, as well as on the precision differential measurements
- Stay tuned!