(PSEUDO)SCALAR PHYSICS @

Greg Landsberg

Scalars 2017 Conference

Warsaw, November 30, 2017

In Memoriam Maria Krawczyk

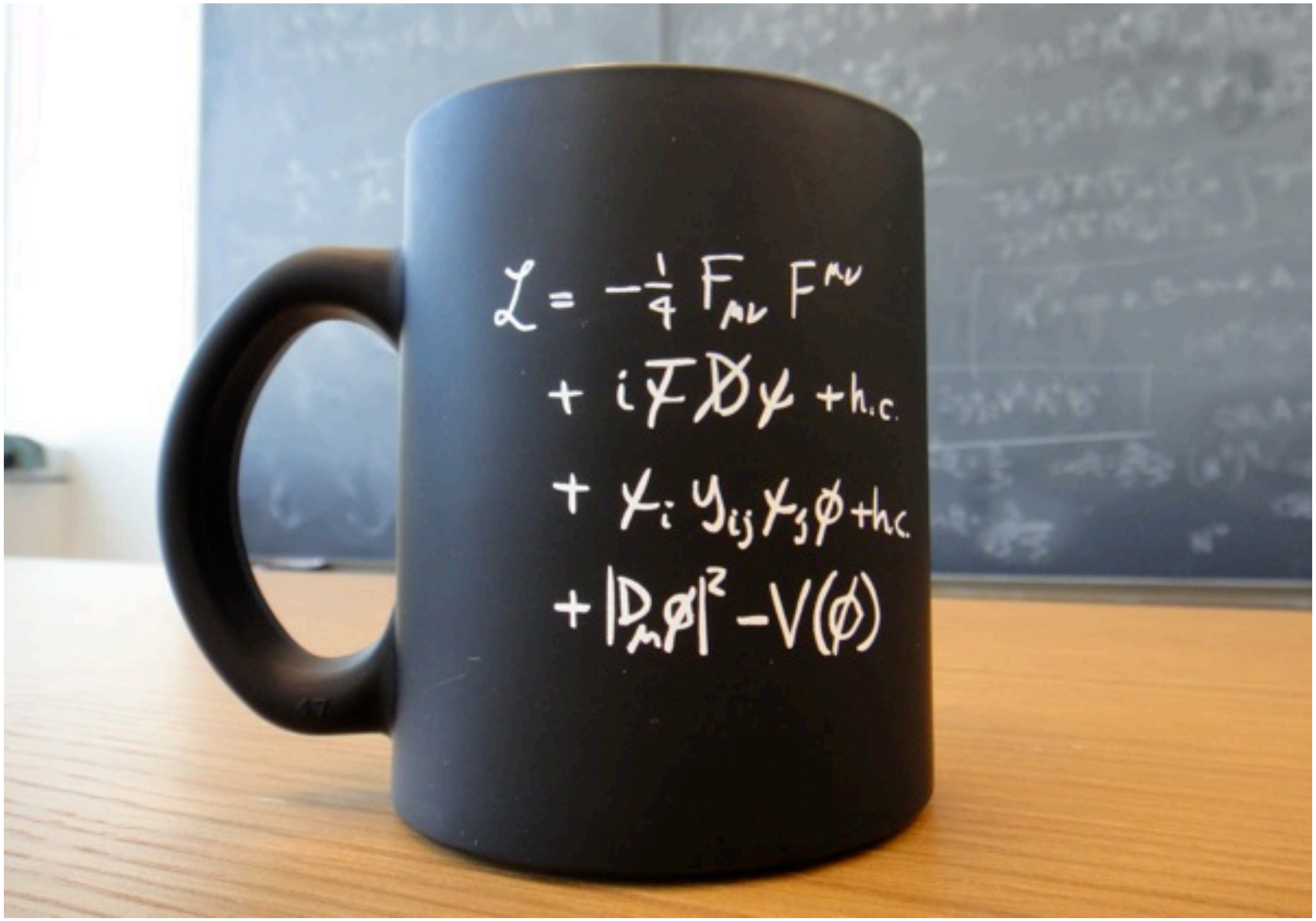
Outline

- (Pseudo)Scalar Physics at CMS
  - Higgs boson gauge sector interactions
    - Mass and width of the Higgs boson
  - Higgs boson Yukawa sector interactions
  - Limits on Higgs boson self-coupling
  - Exotic decays of the Higgs boson
- (Pseudo)scalars and Dark Matter
- Toward the future
- Conclusions

Disclaimer: focus only on the most recent results, most of them with full 2016 data set.
For a complete list, please refer to:
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

SM Higgs Lagrangian

- I organized this talk by the terms of the Higgs Lagrangian



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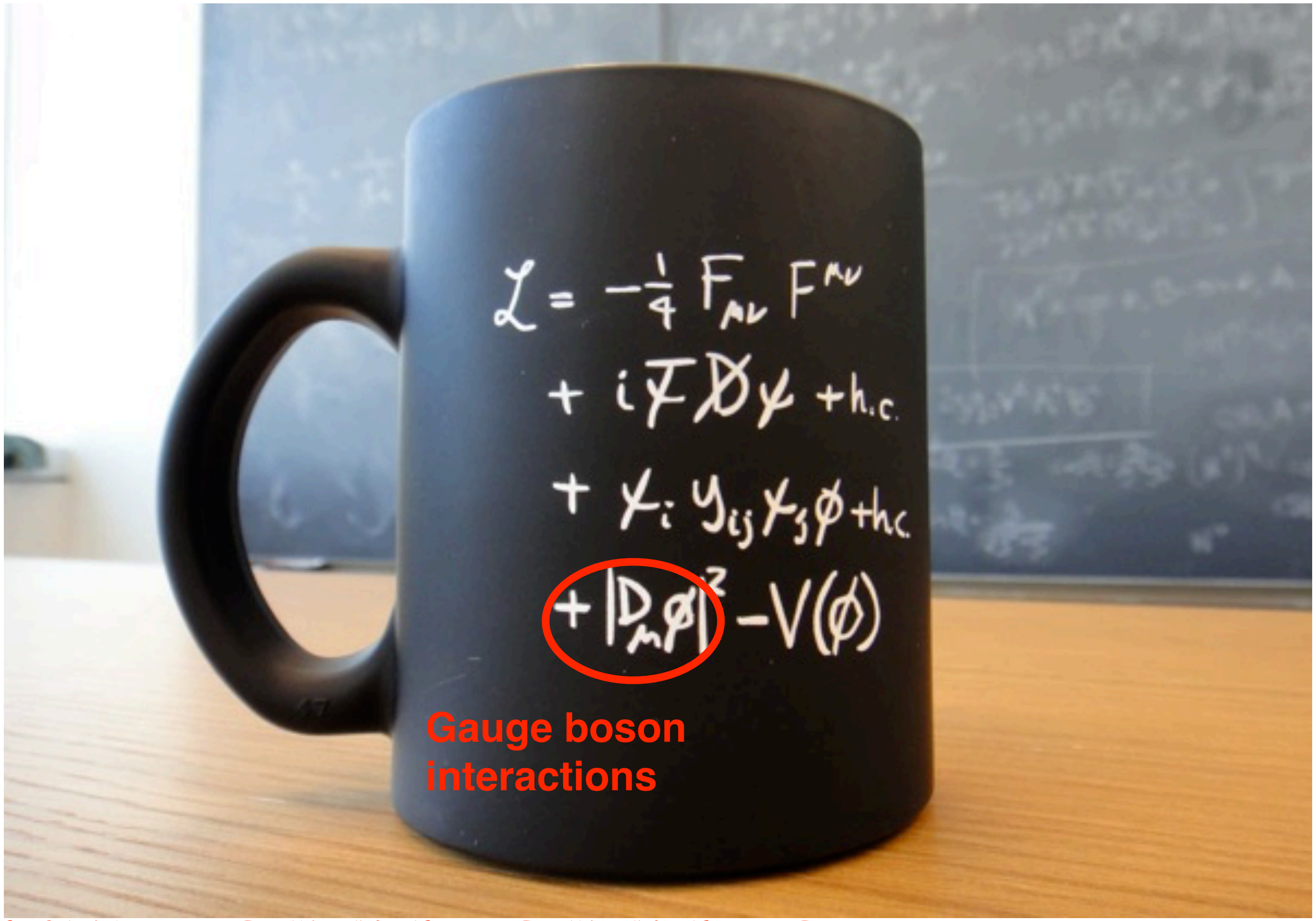

$$(D_\mu\phi)^\dagger D^\mu\phi \xrightarrow{\theta^i=0} \frac{1}{2}\partial_\mu H\partial^\mu H + (v+H)^2\left\{\frac{g^2}{4}W_\mu^\dagger W^\mu + \frac{g^2}{8\cos^2\theta_W}Z_\mu Z^\mu\right\}$$

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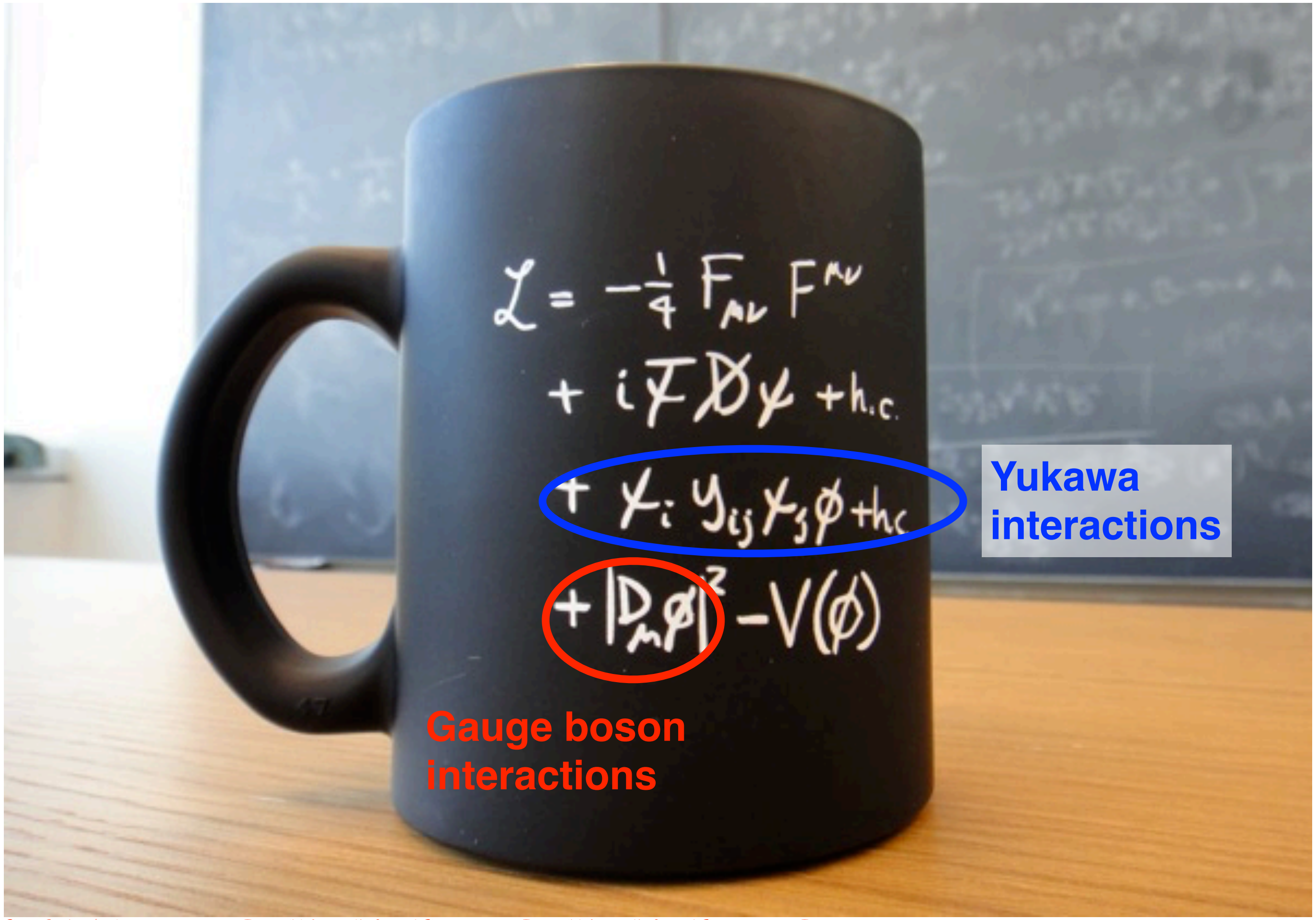

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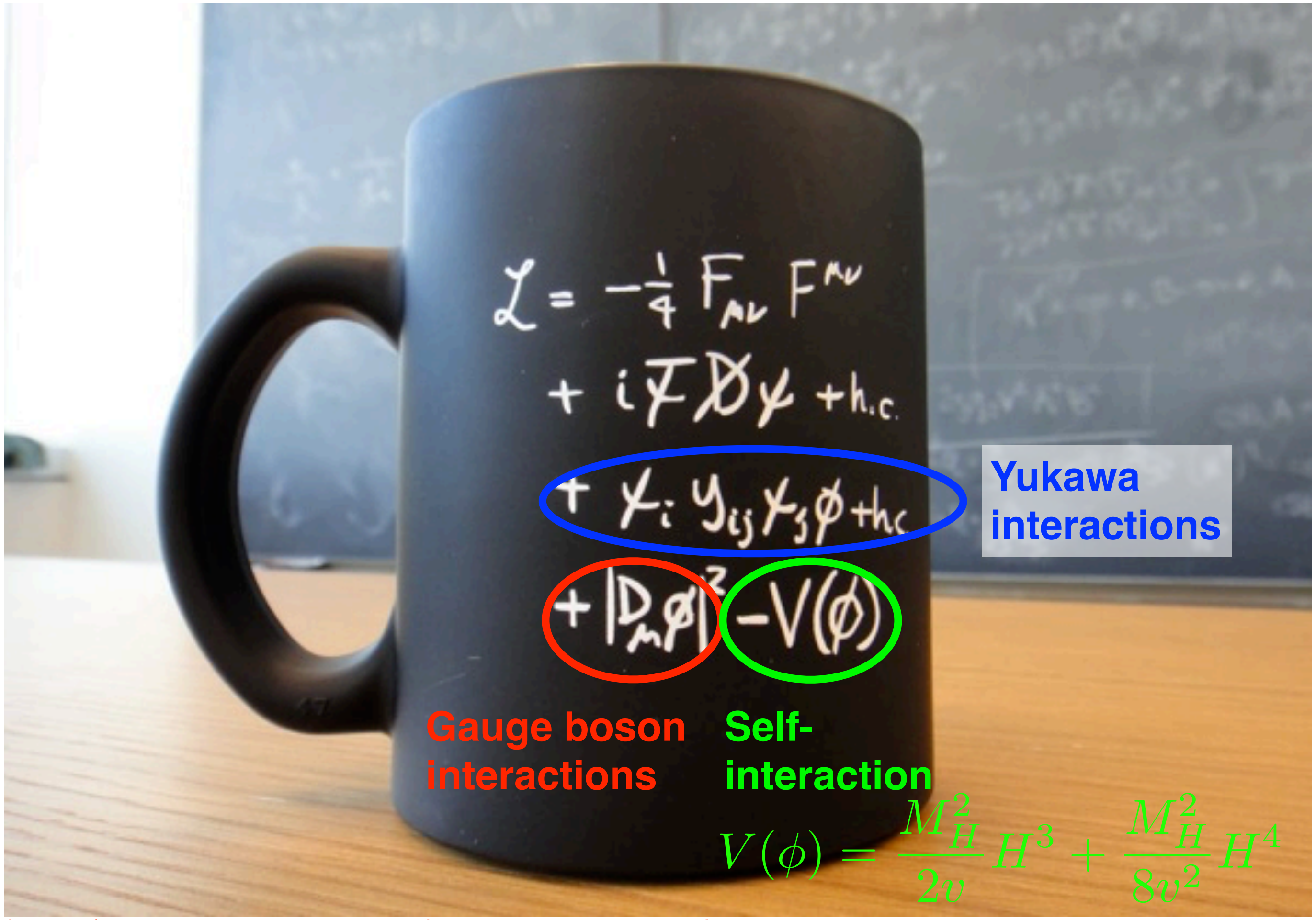

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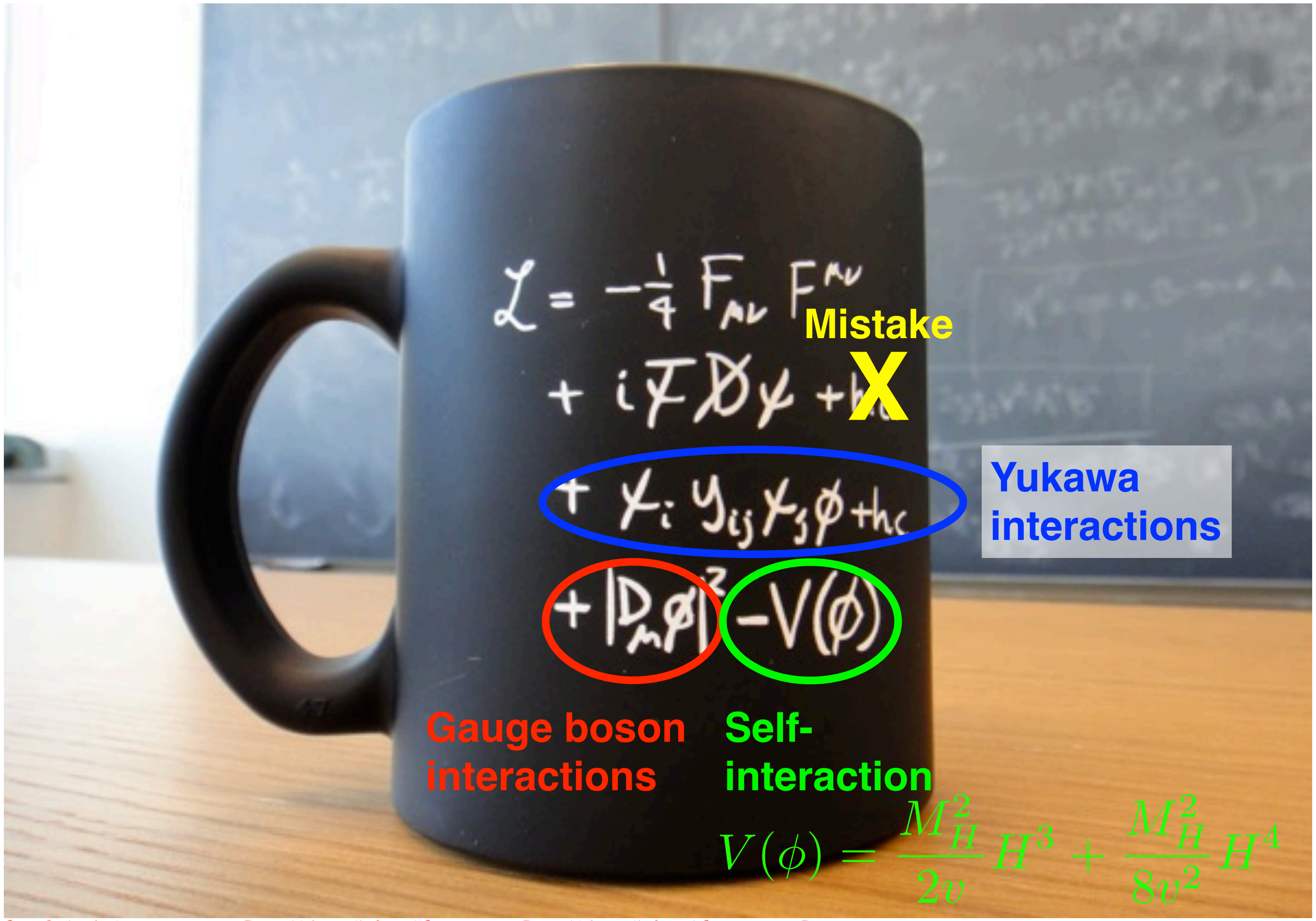

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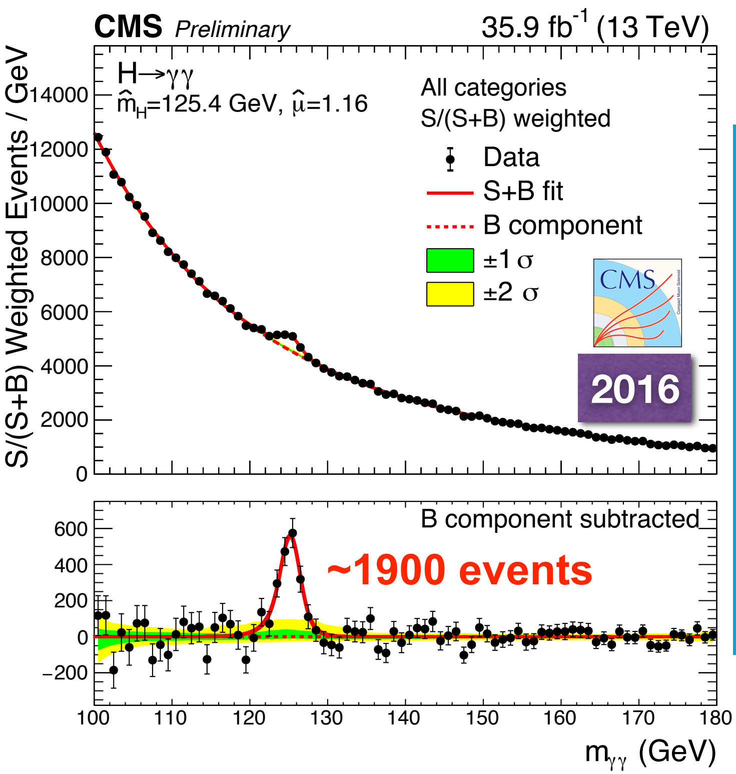
Higgs & Gauge Sector

Seeing Higgs w/ Light

- Analysis strategy similar to the one that led to the H(125) discovery in 2012:
  - ggH, VH, ttH, and VBF categories
  - Use of MVA for particle ID and analysis optimization



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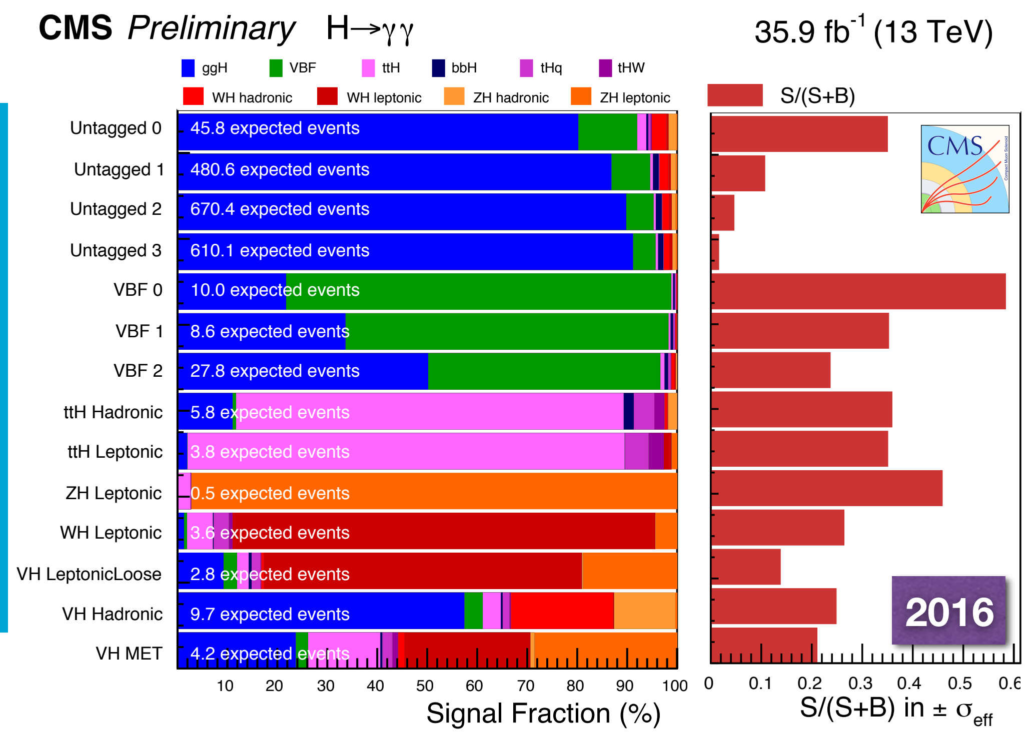
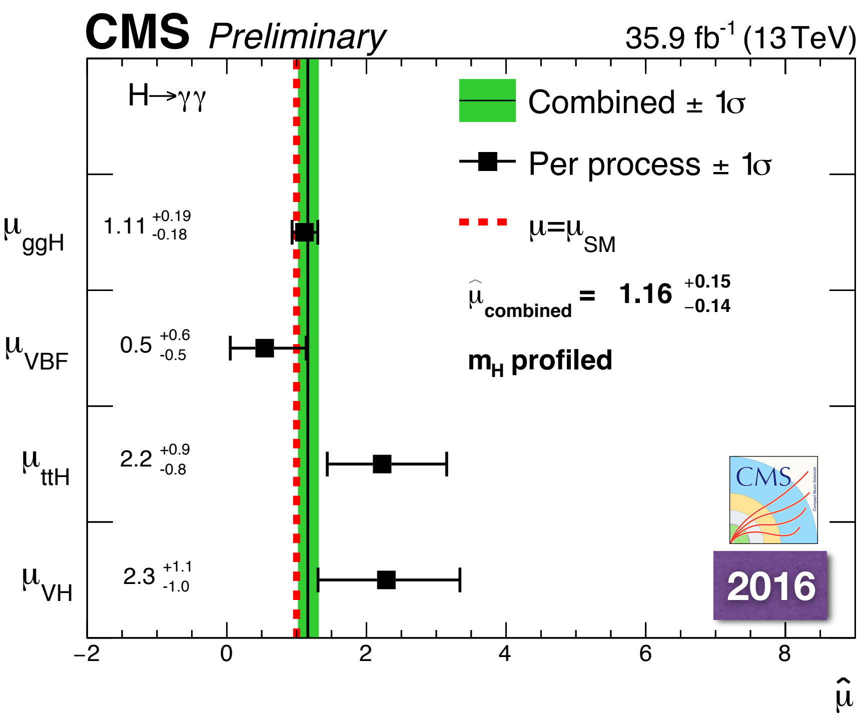
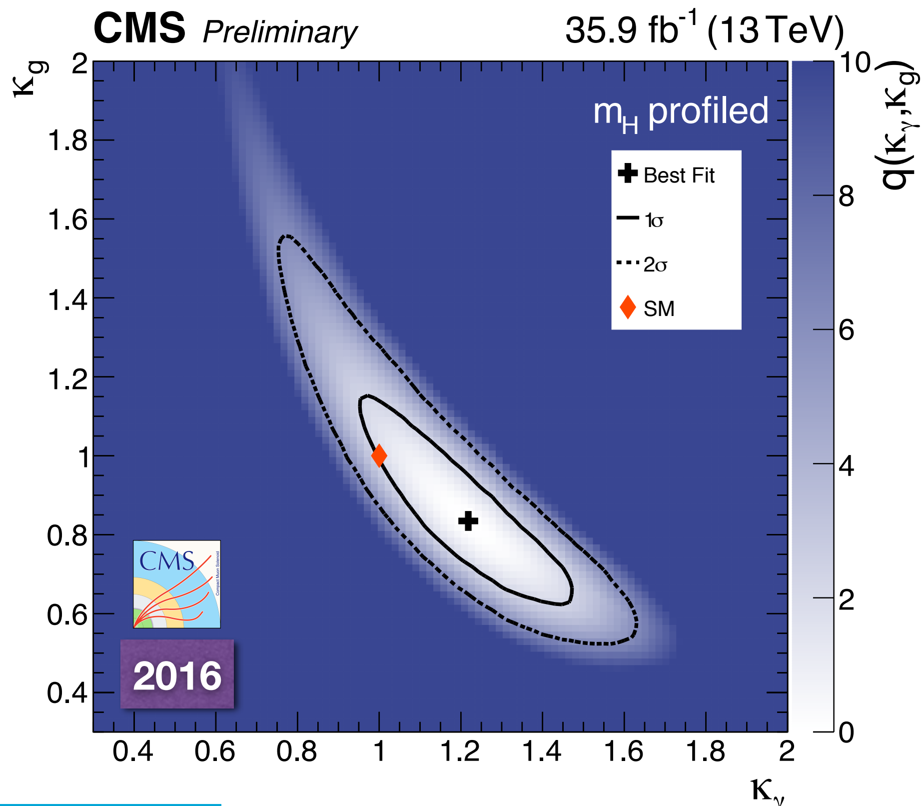


H(γγ), cont'd

- Measurements of signal strength and coupling modifiers are consistent with the SM within 1σ
  - $\mu = 1.16^{+0.15}_{-0.14}$

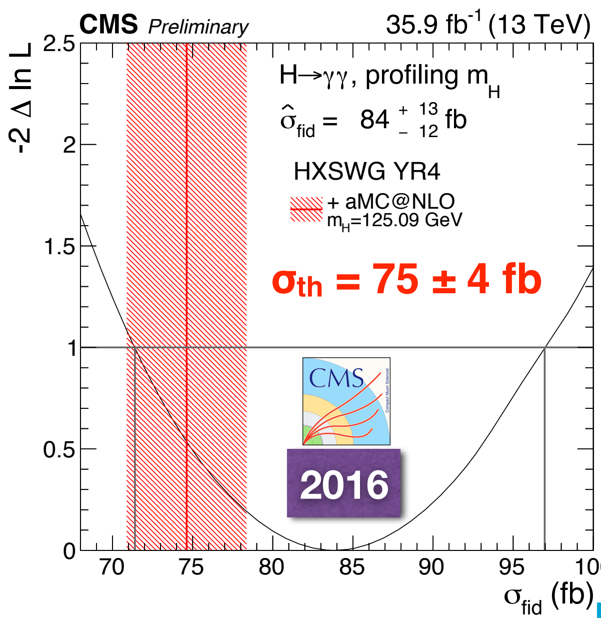


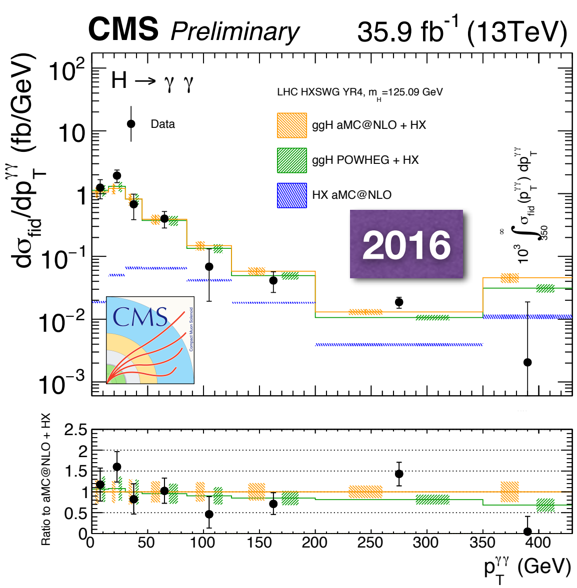


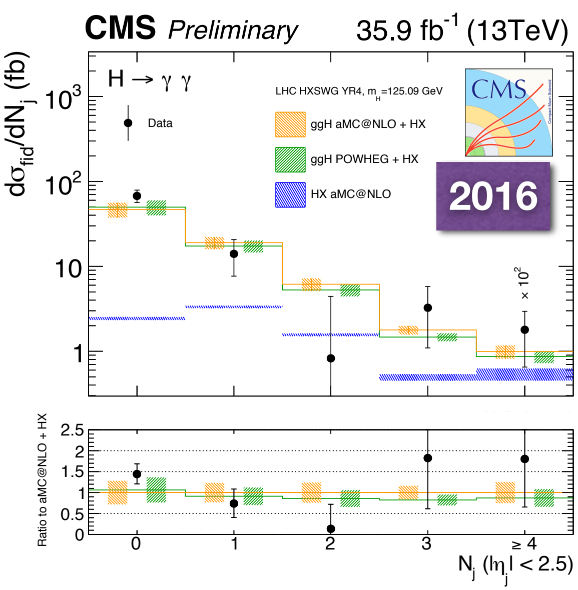
CMS PAS HIG-16-040

$H(\gamma\gamma)$ Differential $d\sigma/da$

- Large number of events observed (S ~ 1900, S/B ~ 1/4) allows for fiducial total and differential cross section measurements
  - Categories changed to classify events by the mass resolution
  - Fiducial phase space: $p_T/m_{\gamma\gamma}$ < 1/3 (1/4) for the leading (subleading) photon; $|\eta_\gamma|$ < 2.5; $Iso|_{dR = 0.3}$ < 10 GeV
- Data agree well with the NLO predictions on the fiducial and differential cross sections



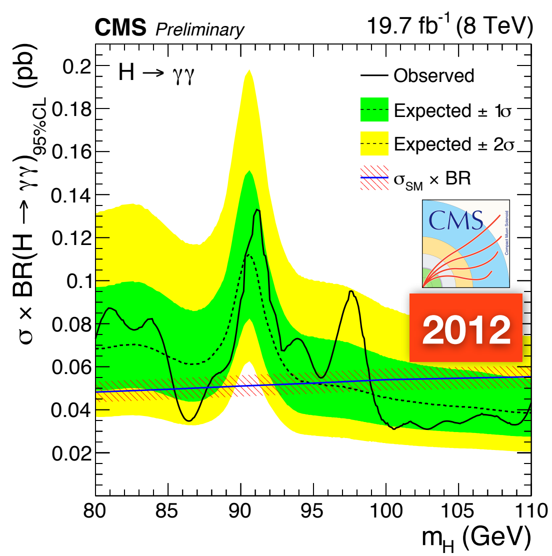


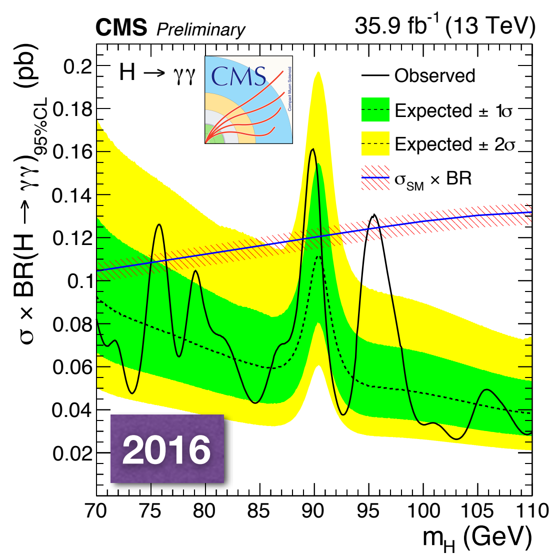


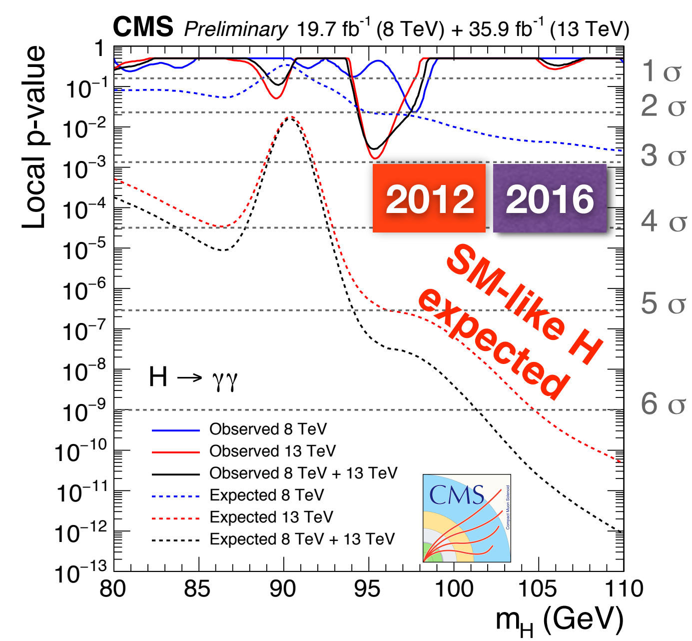
CMS PAS HIG-17-015

Search for Low-Mass H(γγ)

- First LHC search for additional Higgs bosons at low mass (70-110 GeV) in the diphoton channel
  - Follows closely the strategy of the H(γγ) measurement
  - Based on the combination of the 8 and 13 TeV data
- Slight excess observed around 96 GeV, with an overall local (global) significance of about 2.8σ (1.3σ)



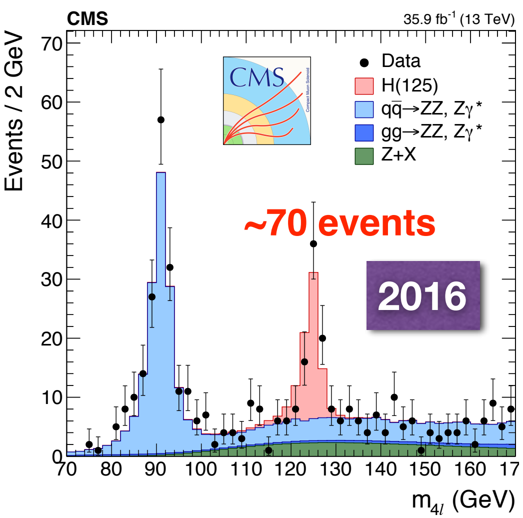


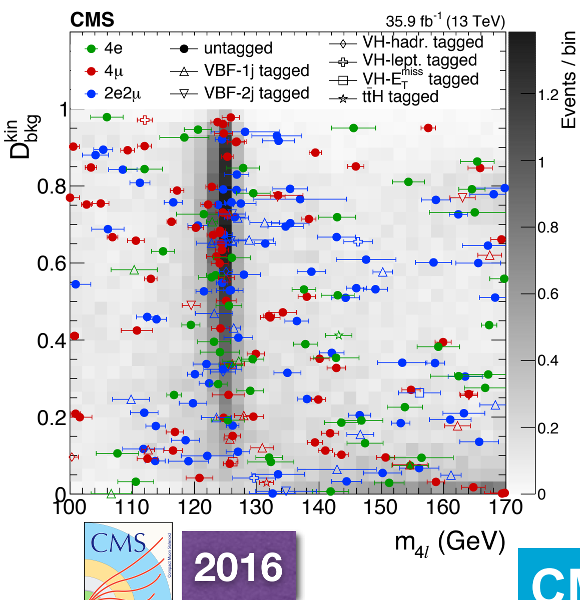


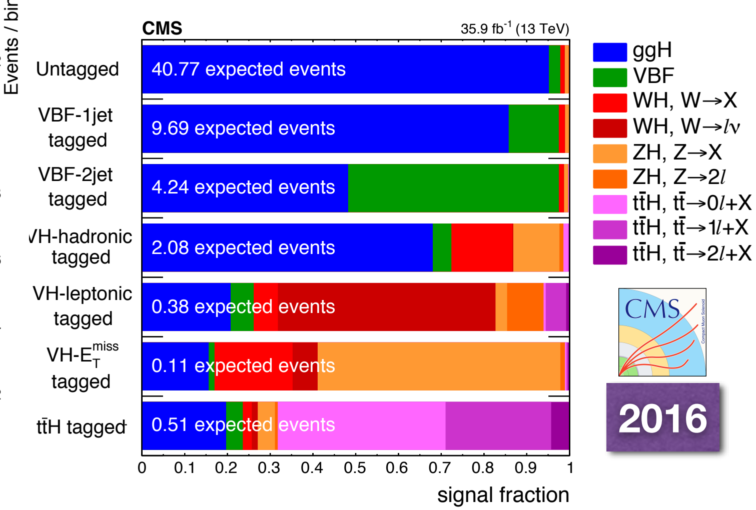
CMS PAS HIG-17-013

H(ZZ) Channel

- H(ZZ) measurement in the 4-lepton channel also follows closely the discovery strategy
  - Based on the MELA kinematic discriminant and event categorization according to the production mechanism
  - About 70 events observed, with large S/B ratio
  - Used to measure the signal strength, cross section, mass, and set limits on the width and anomalous couplings







CMS arXiv:1706.09936

H(ZZ) Signal Strength

- Signal strength is consistent with the SM prediction within 1 s.d.
  - Combined $\mu = 1.05^{+0.19}_{-0.17}$
  - All observed best signal strength fits, except for the ggH channel, somewhat curiously are at zero
- Fiducial cross section was measured in a simplified kinematic parameter space and is consistent with the SM predictions.

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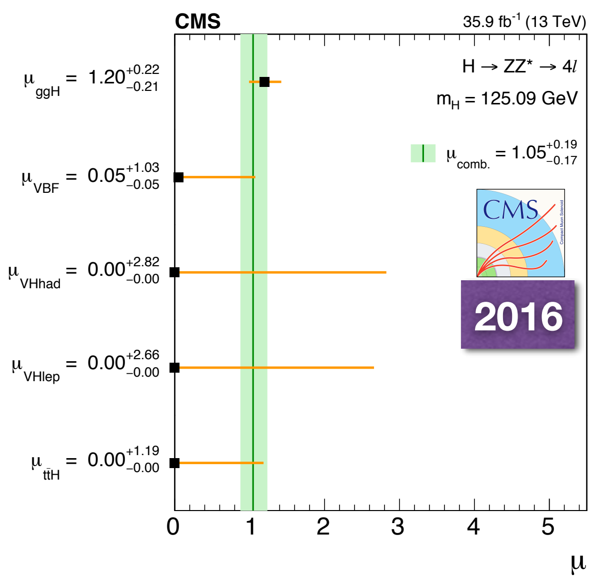

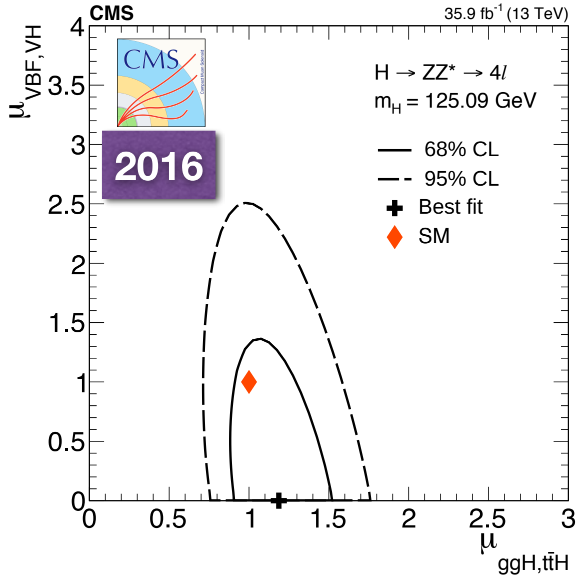

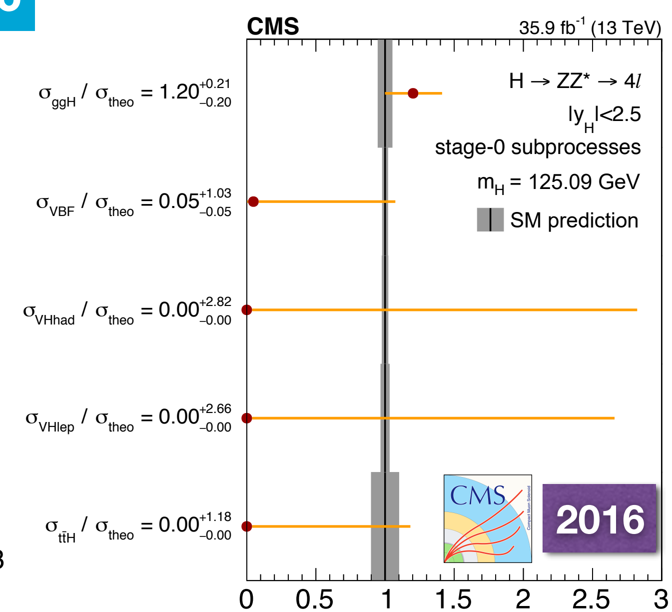

Differential Cross Sections

✦ Clean mass peak allows to measure fiducial and differential cross sections

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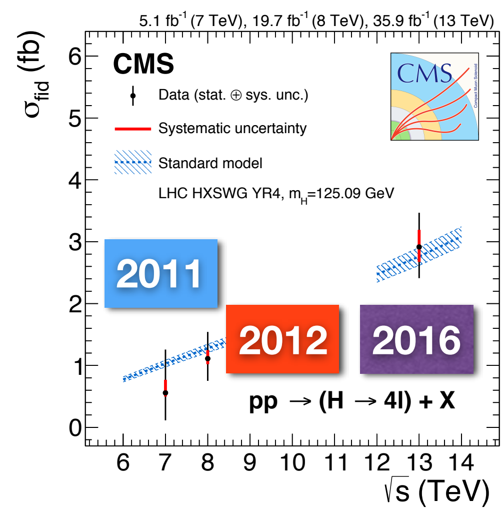

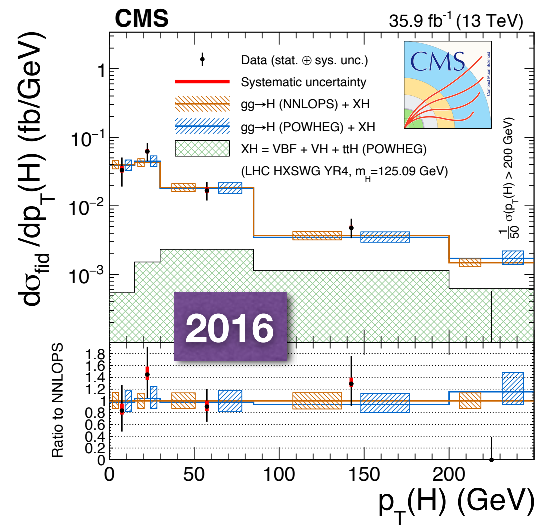

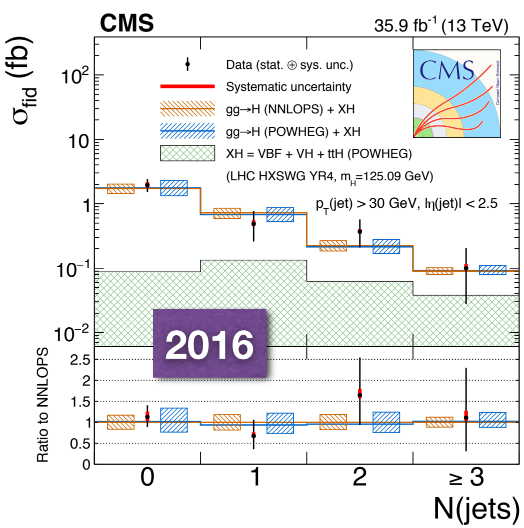

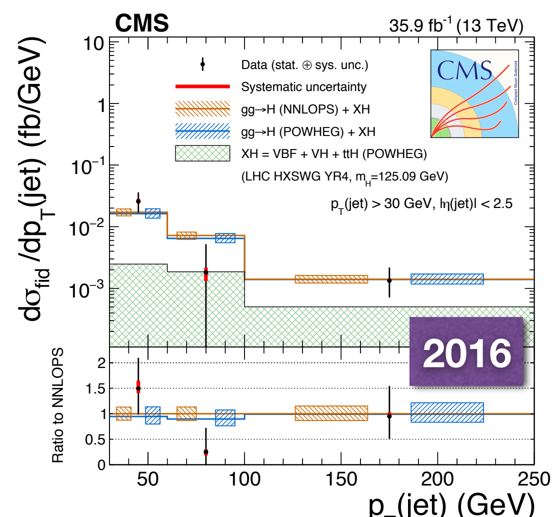

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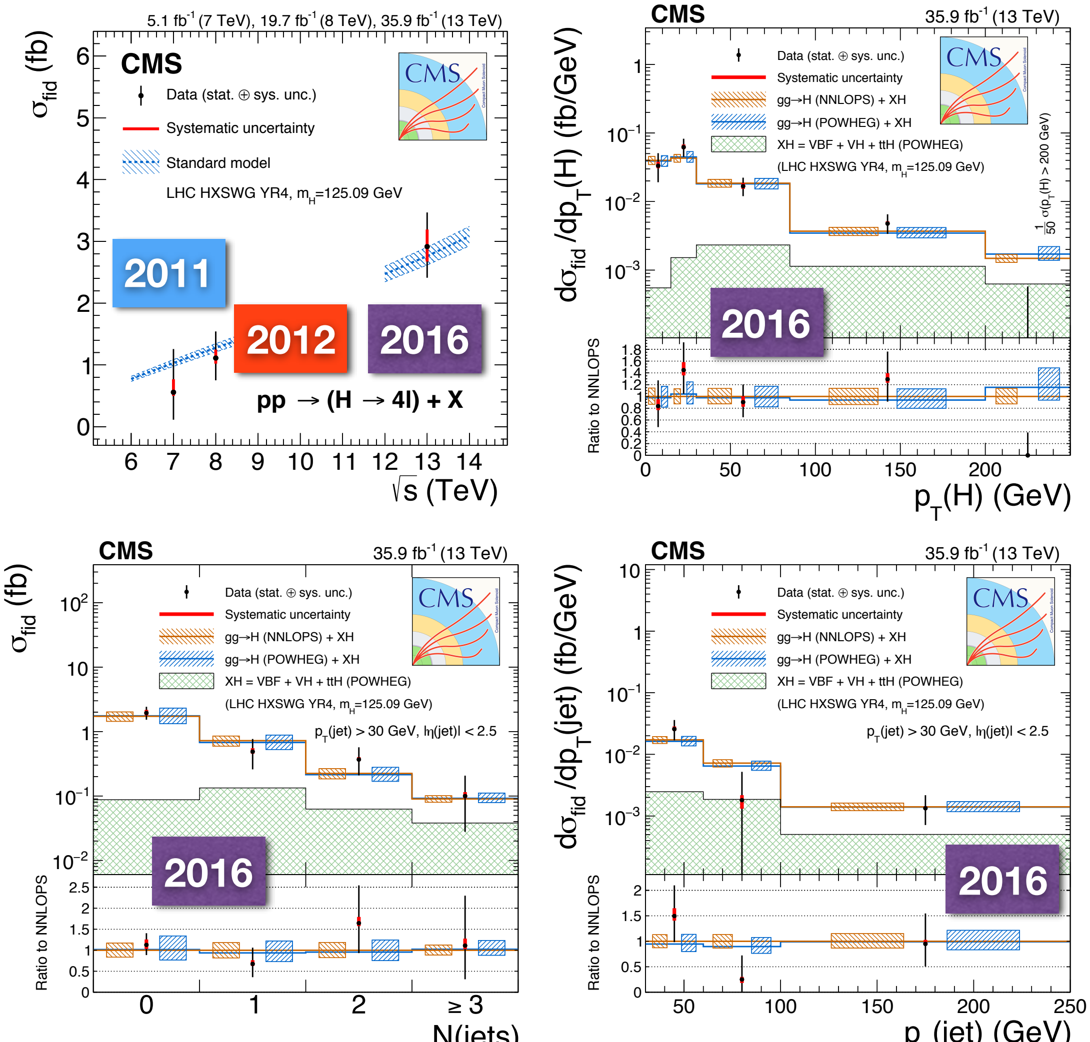
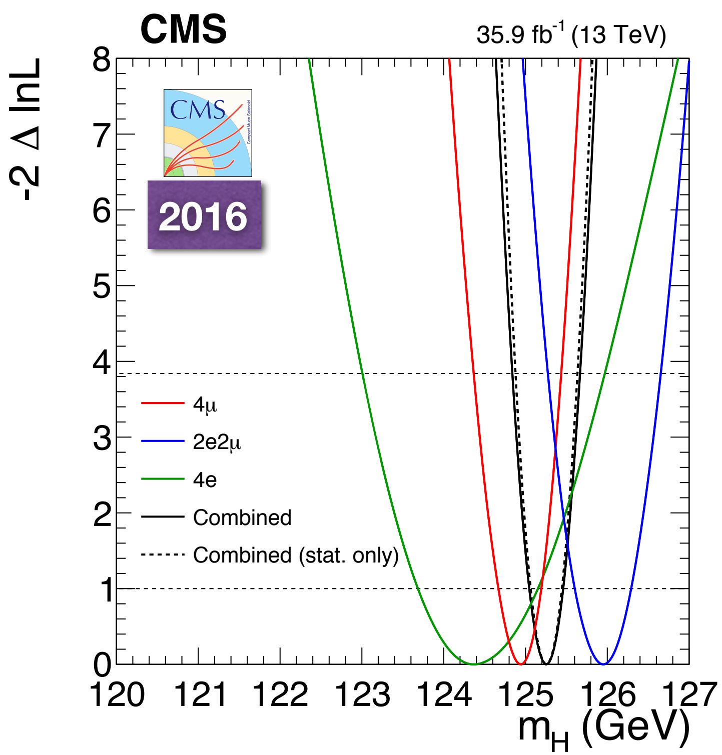


Good agreement with the SM predictions

Mass and Width Measurements

- ✦ Single, most precise Higgs boson mass measurement to date: $m_H = 125.36 \pm 0.21$ GeV
  - N.B. also an indirect measurement of the self-coupling in the V(ϕ)
- ✦ Direct limit on the Higgs boson width of 1.1 GeV (1.6 GeV expected) at 95% CL (again, most stringent to date)



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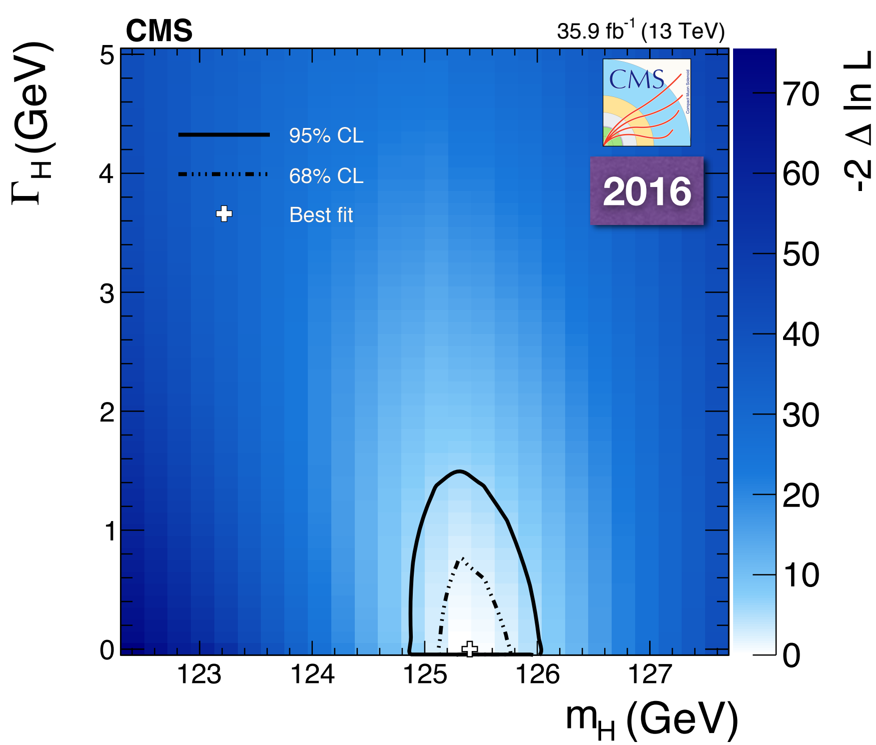

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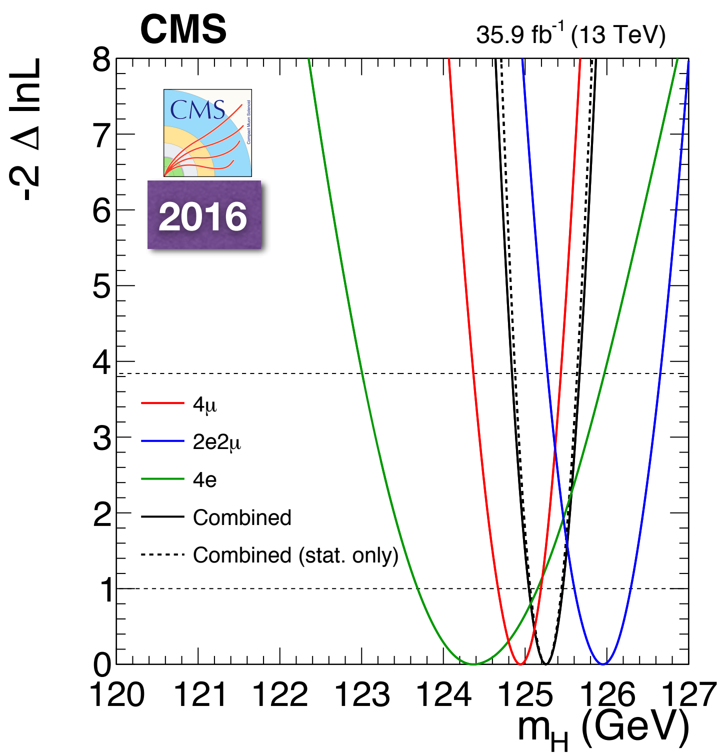

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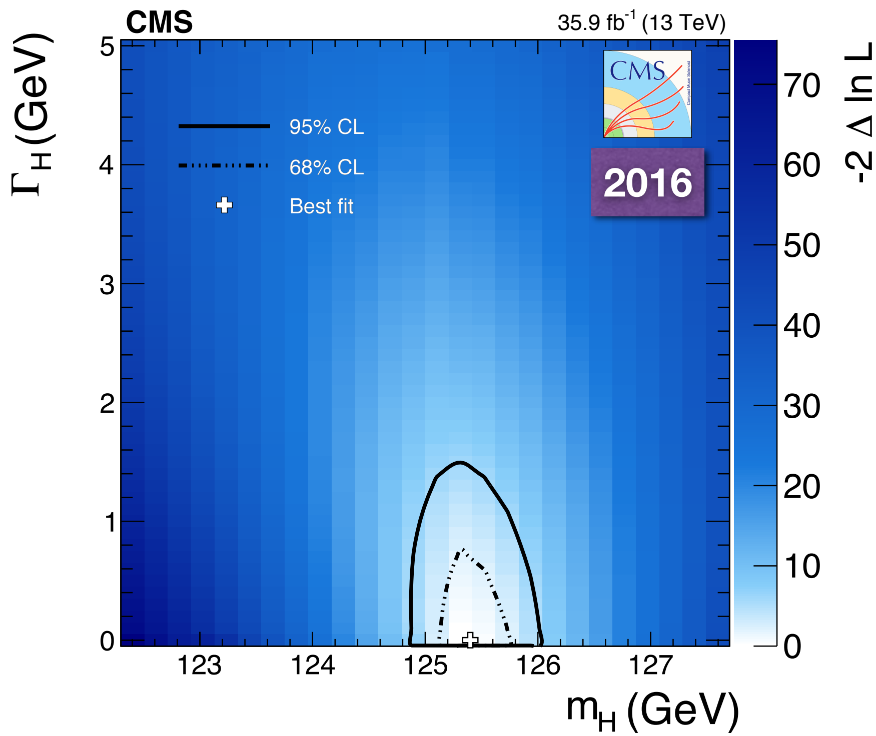

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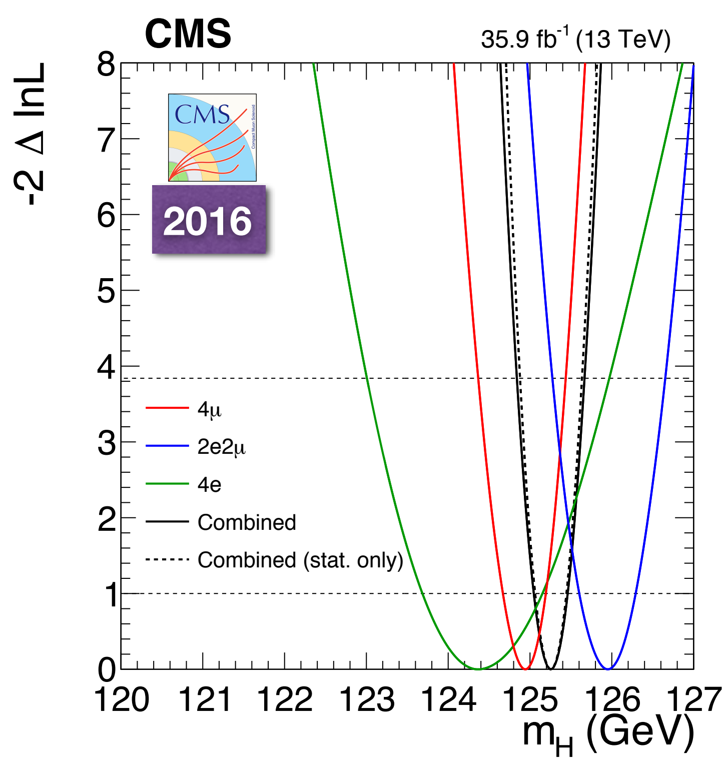

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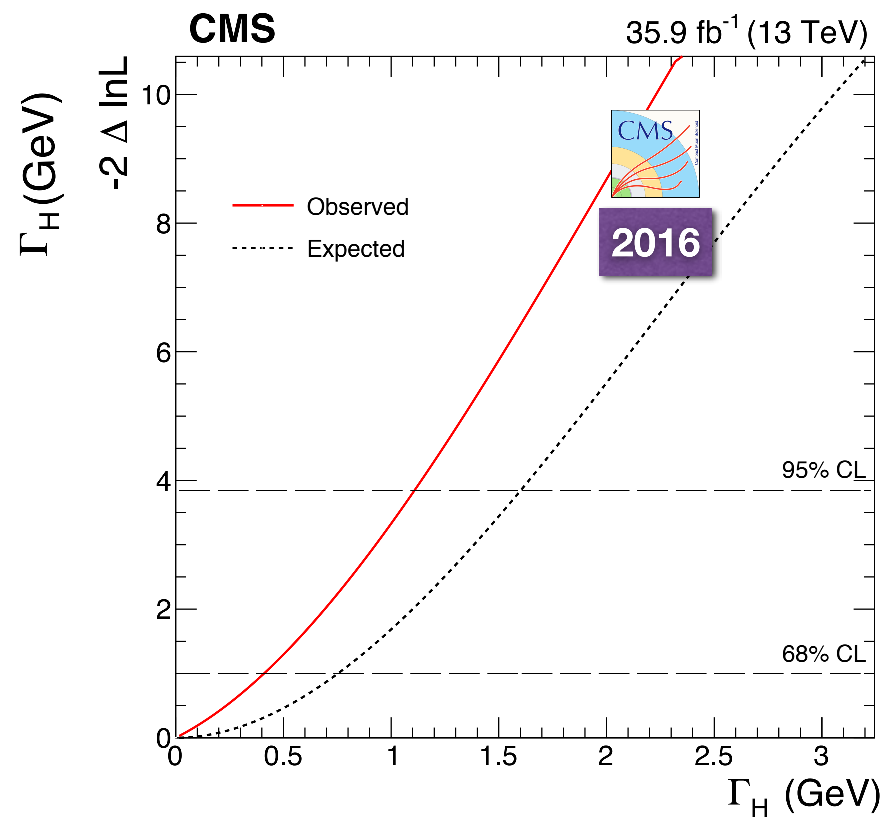

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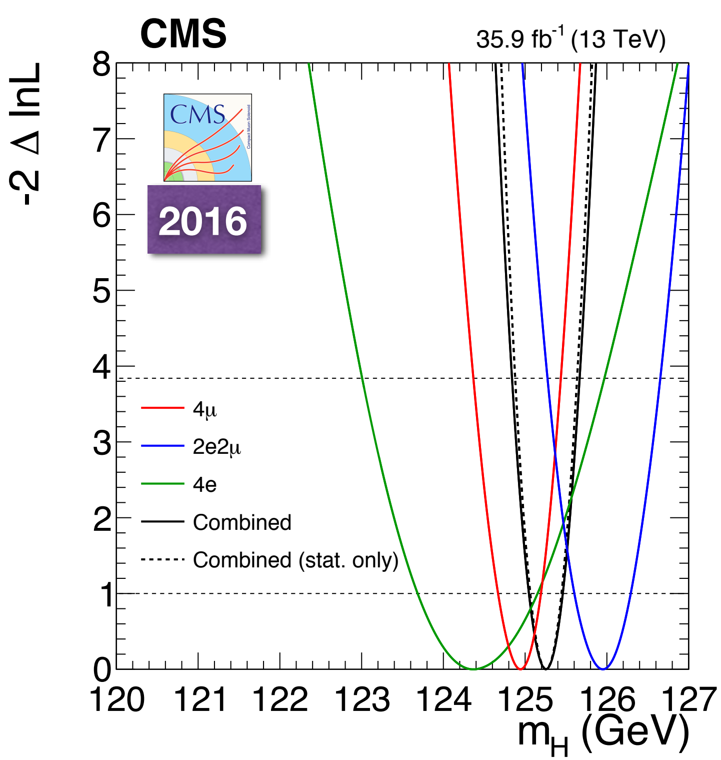

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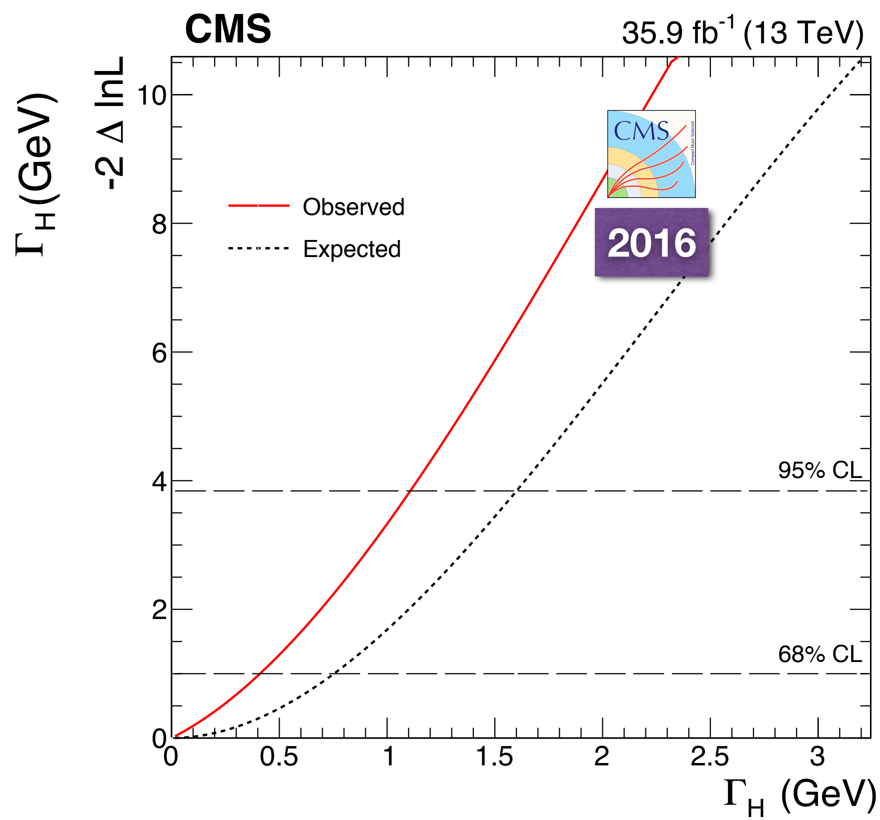

Anomalous HVV Couplings

- Combined with Run 1 data, can set limits on anomalous HVV couplings:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- Custodial symmetry dictates for tree-level terms: $a_1^{ZZ} = a_1^{WW}$
  - We additionally assume: $a_{2,3}^{ZZ} = a_{2,3}^{WW}$; $\kappa_{1,2}^{ZZ} = \kappa_{1,2}^{WW}$
- Gauge invariance and Bose-Einstein symmetry require:

$$\kappa_1^{ZZ} = \kappa_2^{ZZ} = -\exp(i\phi_{\Lambda 1}^{ZZ}),\ \kappa_{1,2}^{\gamma\gamma} = \kappa_{1,2}^{gg} = \kappa_1^{Z\gamma} = 0,\ \kappa_2^{Z\gamma} = -\exp(i\phi_{\Lambda 1}^{Z\gamma})$$

- That leaves us w/ 4 anomalous couplings: $a_2, a_3, \kappa_2/\Lambda_1^2$, and $\kappa_2^{Z\gamma}/\left(\Lambda_1^{Z\gamma}\right)^2$
- Express everything in terms of fractional cross sections:

$$f_{ai} = |a_i|^2\sigma_i \Big/ \sum |a_j|^2\sigma_j, \text{ and } \phi_{ai} = \arg\left(a_i/a_1\right)$$

where a_i refers to all four couplings
- Define several MELA-like kinematic discriminants, separately for ggH, VBF, and VH production and perform a likelihood fit

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CP violation (0^{-+})

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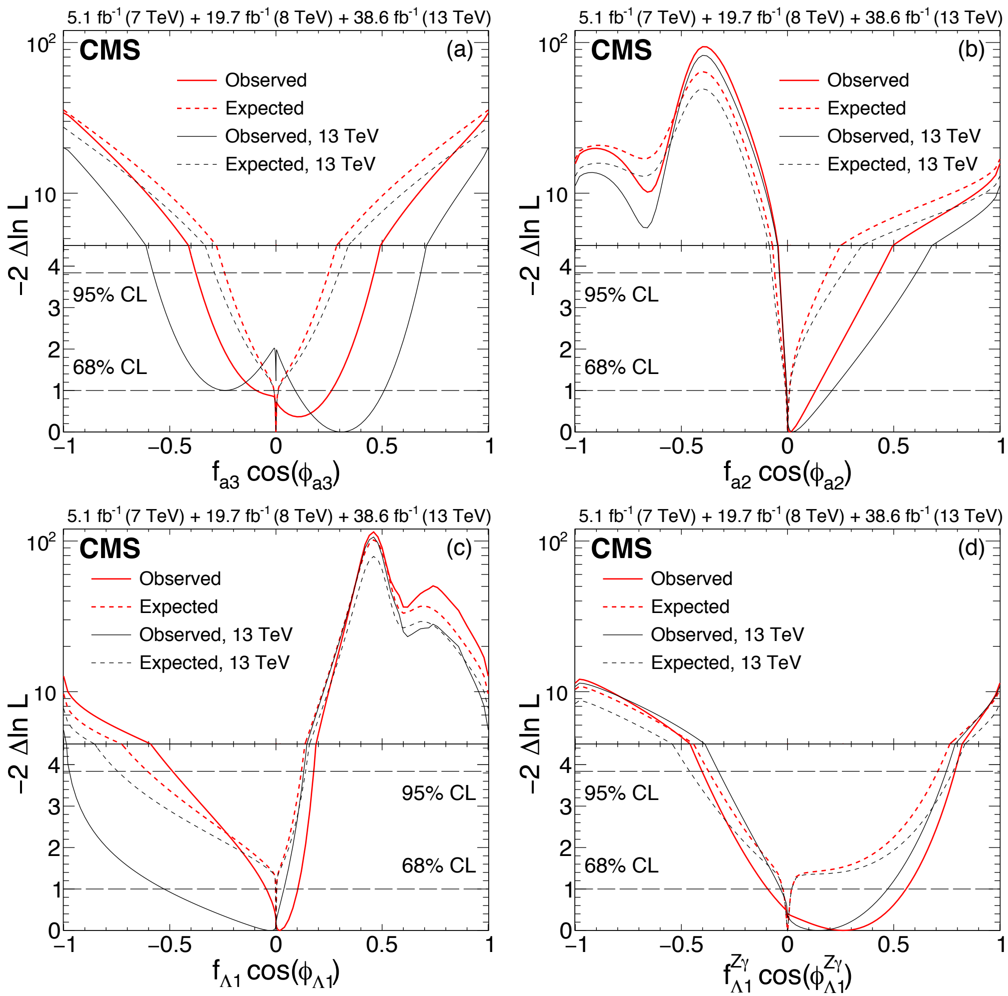
Anomalous Coupling Limits

- The results are as follows (a slight improvement seen in combination with Run 1 data)

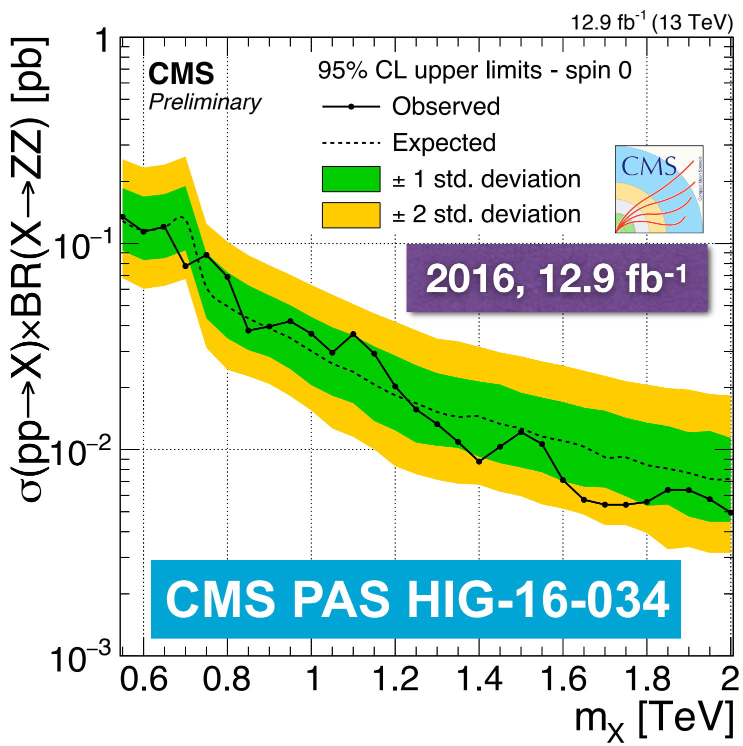
CMS arXiv:1707.00541



2011
2012
2016

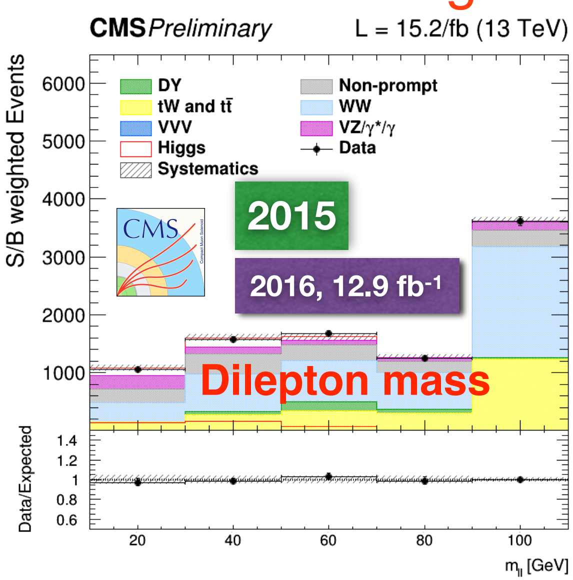
Heavy H(ZZ) Search

- The ZZ channel has high sensitivity to additional high-mass Higgs bosons
  - To maximize the sensitivity, the search is conducted in the Z(ll)Z(jj) channel, with two jets merged in a single large-radius jet
  - Categorization based on ggH and VBF production, as well as b-tagged jets from Z(bb)
  - Use of BDT improves the sensitivity by ~20%
  - Analysis is based on a partial 2016 data set (12.9 fb^{-1})
- Limits set on the production cross section time branching fraction to ZZ of narrow scalar (and tensor) resonances, significantly extending Run 1 limits

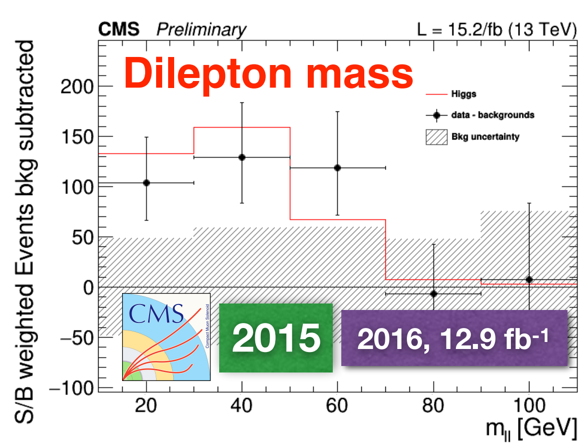


H(WW) Channel

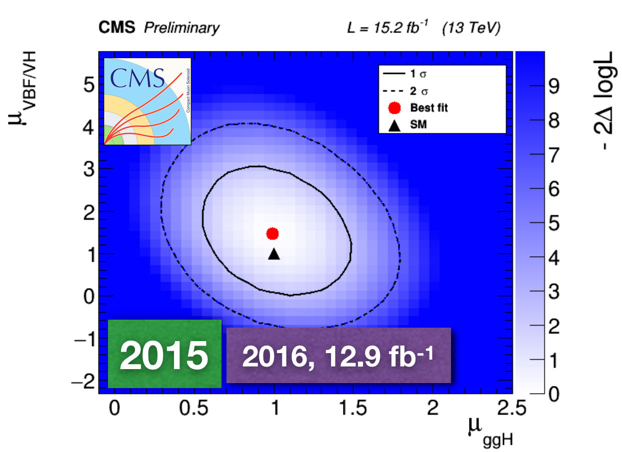
- The analysis is based on 2015 (2.3 fb^{-1}) and partial 2016 (12.9 fb^{-1}) data at 13 TeV
  - Only uses the eμ channel, which offers by far the best sensitivity
  - Several event categories: ggH (0, 1, and ≥2 jets), VBF and VH (≥2 jets), and WH (trilepton)
  - Signal is extracted via fitting a 2D distribution of dilepton mass and Higgs transverse mass: $m_{\mathrm{T}}^{\mathrm{H}} = \sqrt{2 p_{\mathrm{T}}^{\ell\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi(\ell\ell, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}))}$
  - Combined signal strength: $\mu = 1.05^{+0.27}_{-0.25}$, with 4.3σ significance



CMS PAS HIG-16-021



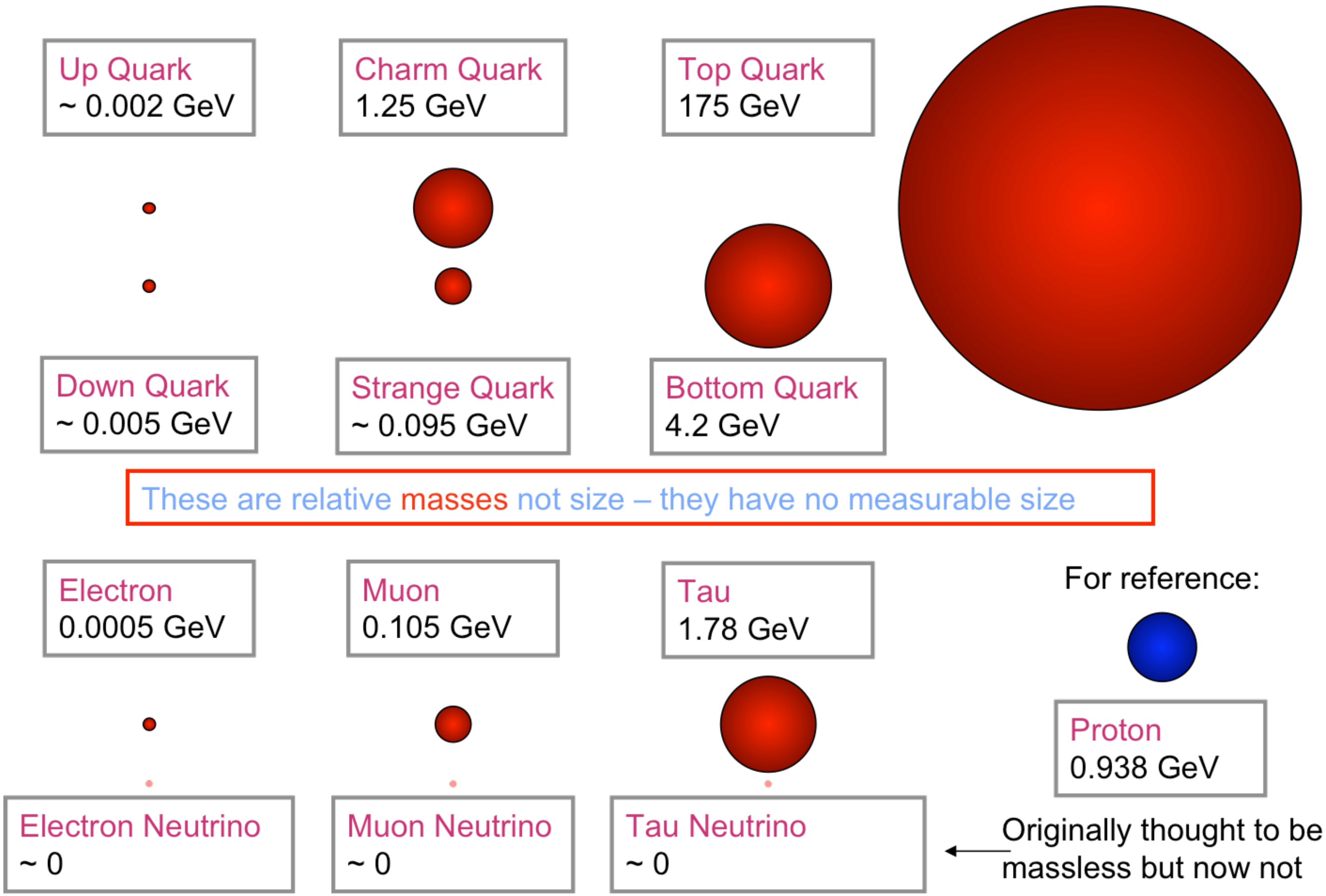
μ in ggH vs. VBF



Higgs Yukawa Couplings

Probing Yukawa Couplings

✦ Going after four Yukawa couplings: y_t, y_b, y_τ, and y_μ



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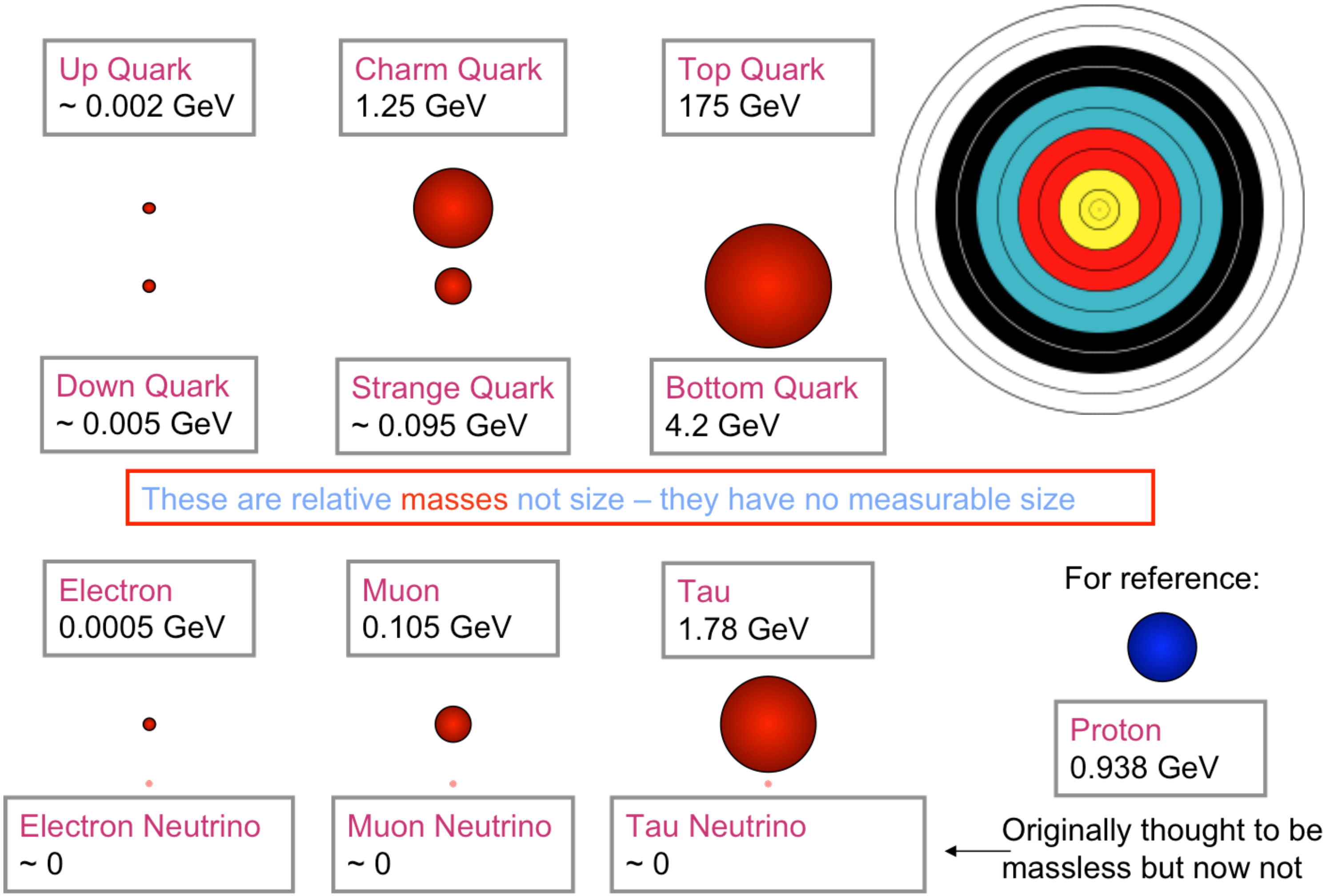

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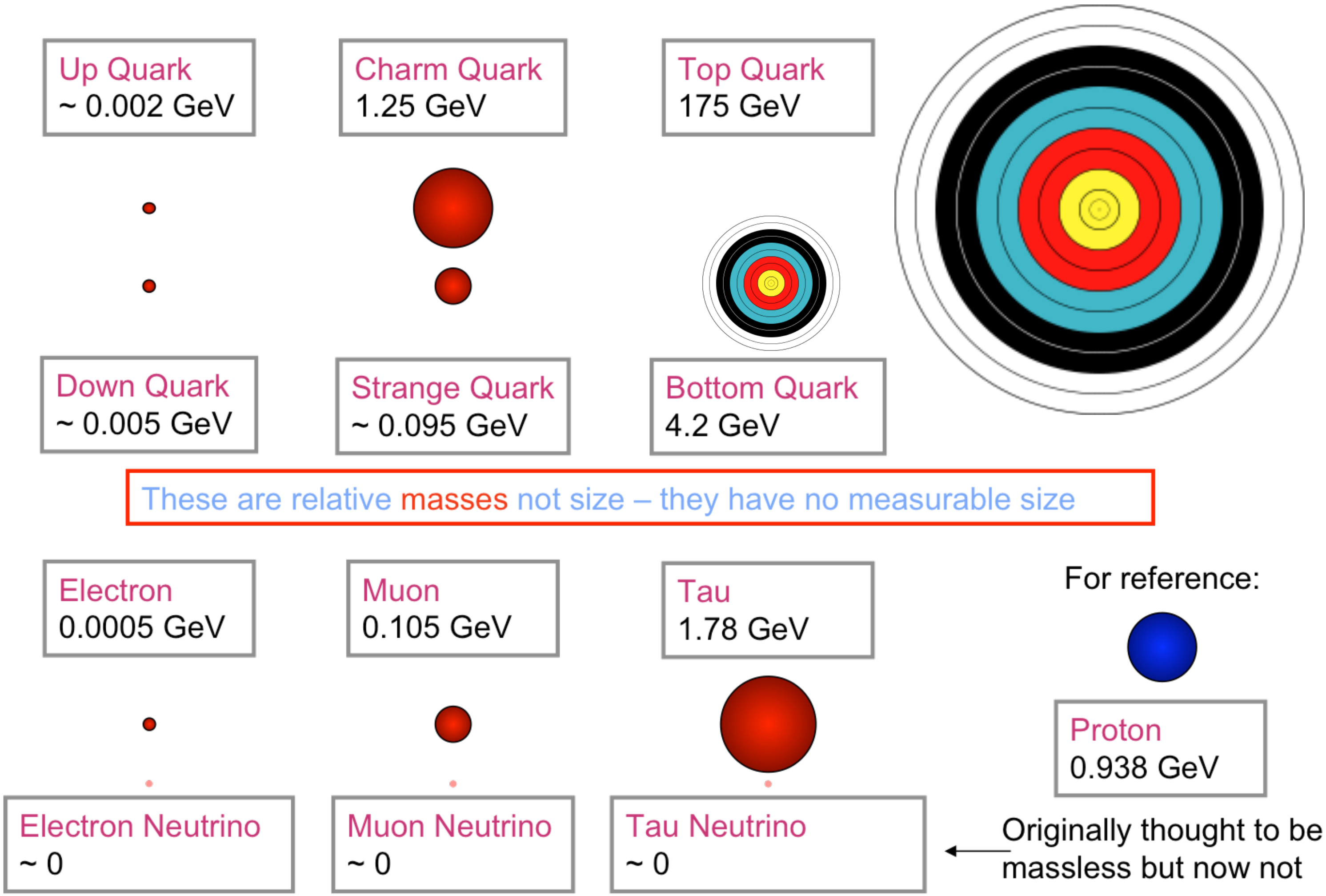

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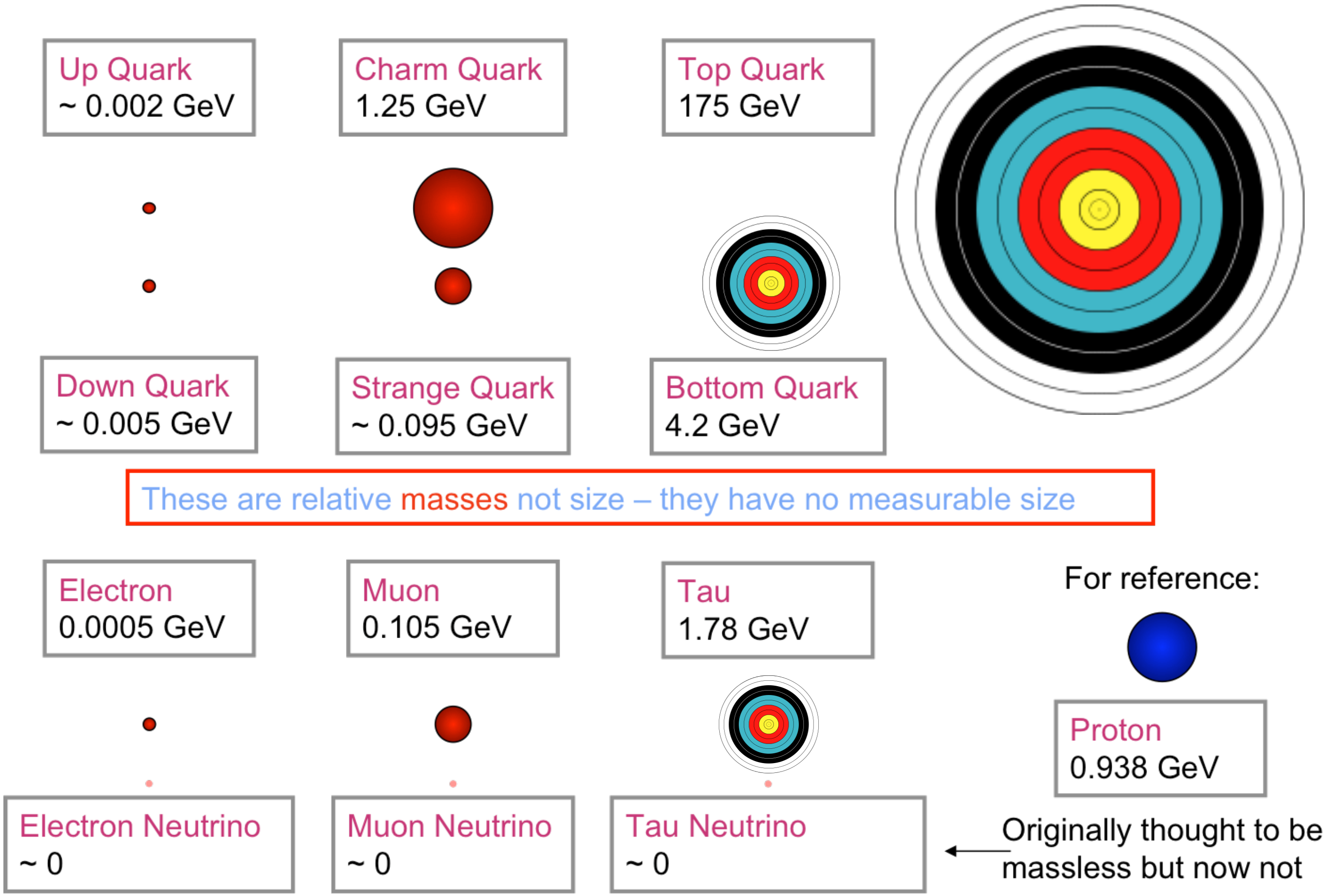

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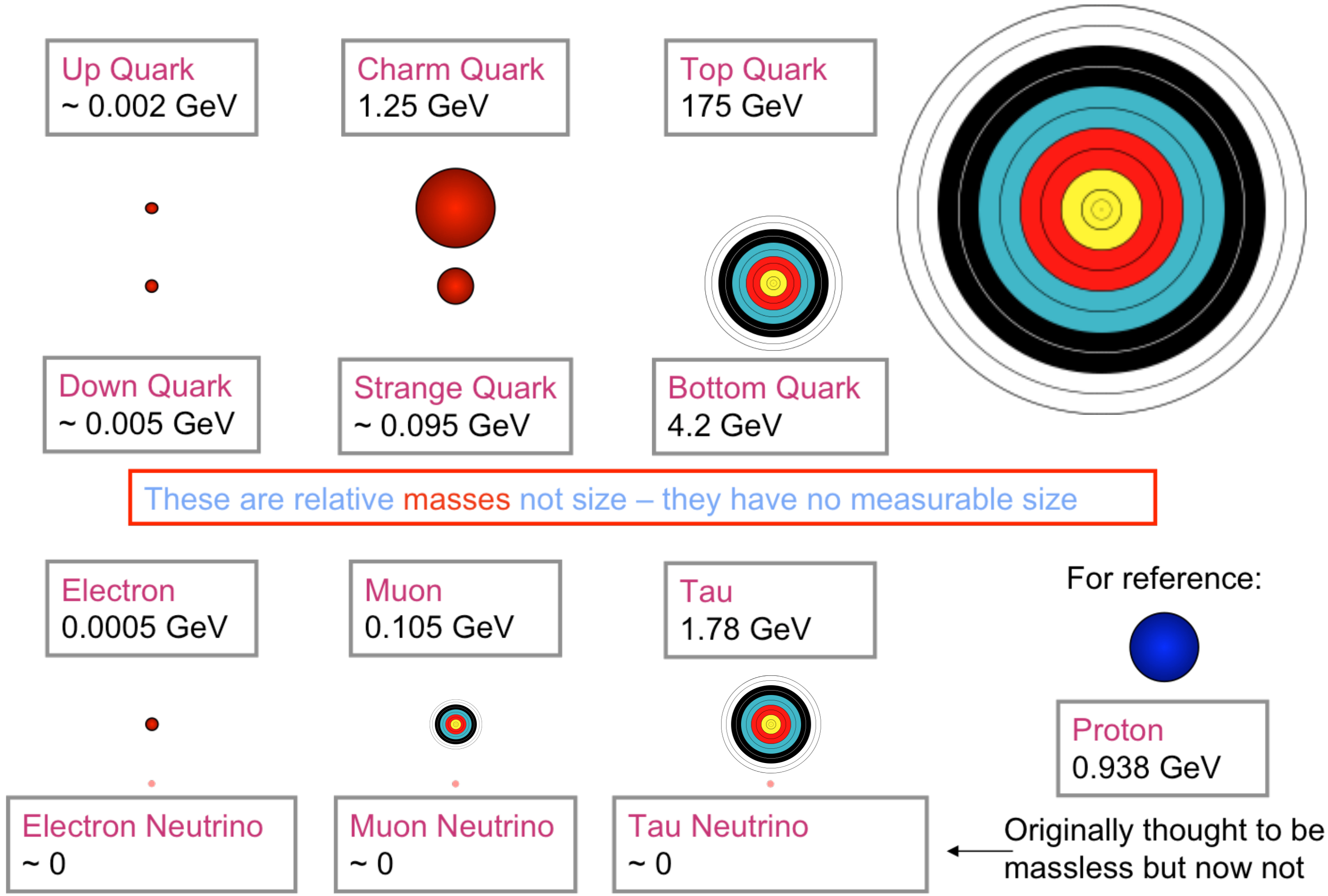
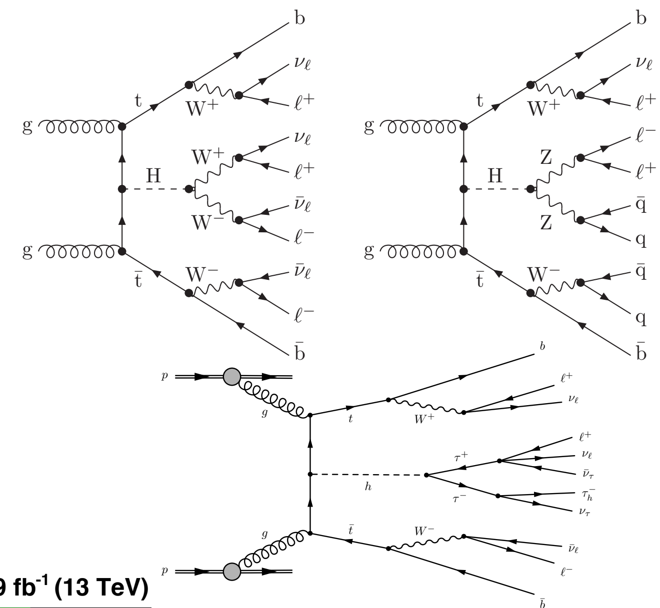
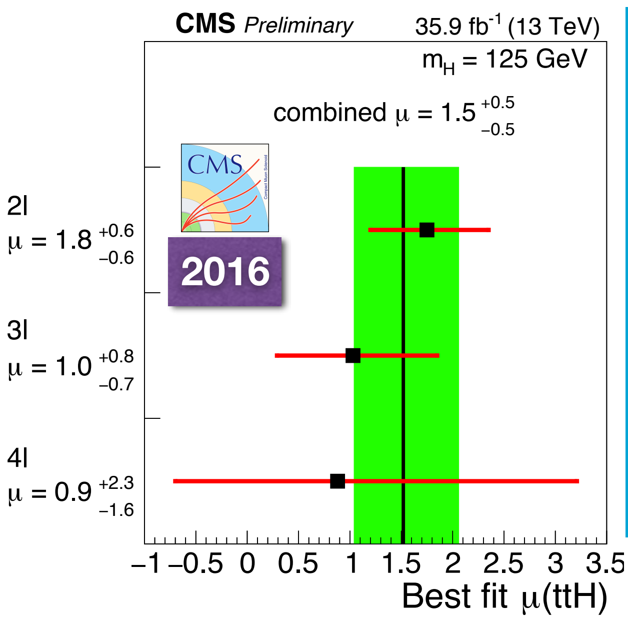


Evidence for ttH Production

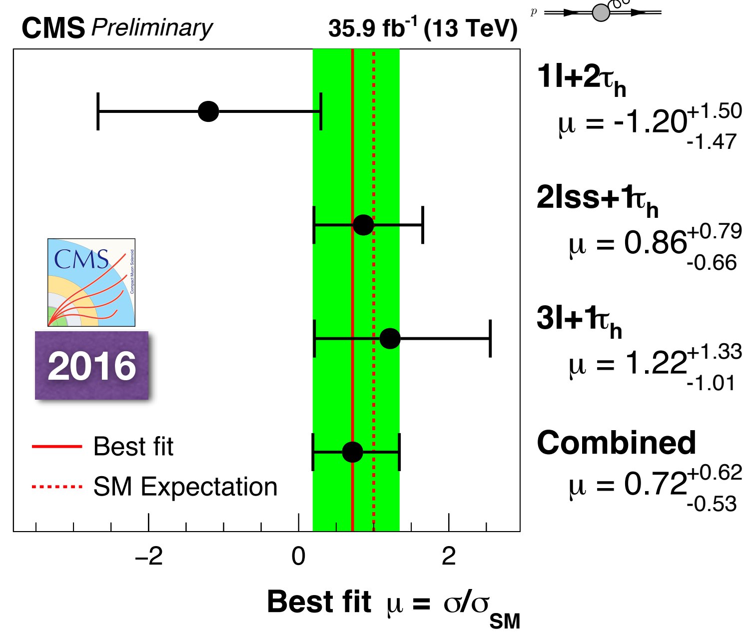
- Search conducted in multilepton and τ lepton channels; the former dominates the sensitivity
- Split by (τ) lepton multiplicity; use of BDT to extract signal
- Multilepton: μ = 1.5 +-/- 0.5 (3.3/2.5σ) observed/ expected significance
- τ lepton: $\mu = 0.72^{+0.62}_{-0.53}$ (1.4/1.8σ)
- Finalizing the combination; expect ~3σ significance



CMS PAS HIG-17-004



CMS PAS HIG-17-003

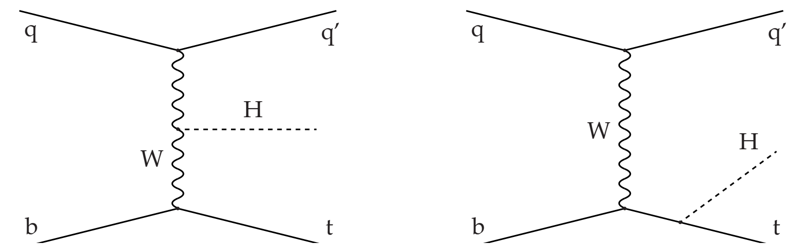


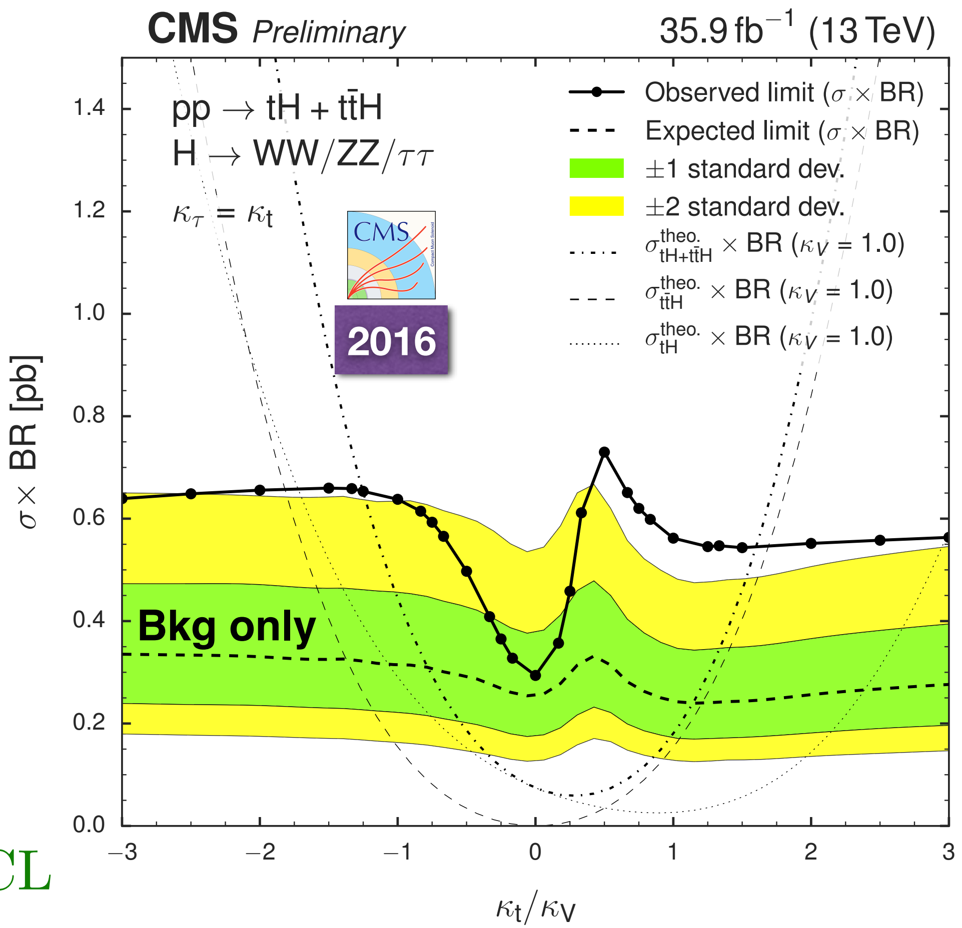
Search for tH Production

- Associated production w/ single top quark is suppressed in the SM due to negative interference between the two diagrams
  - Would be significantly enhanced if couplings to fermion and bosons have opposite sign (or if the ratio is modified compared to the SM)
- Use likesign eμ and μμ, and trilepton events, w/ BDT-based analysis

$$-1.25 < \kappa_t/\kappa_V < 1.60 \text{ @ } 95\% \text{ CL}$$

CMS PAS HIG-17-005





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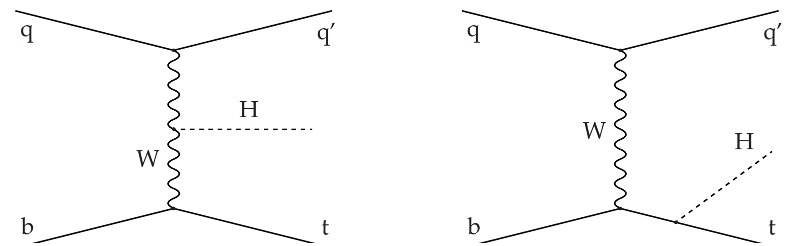
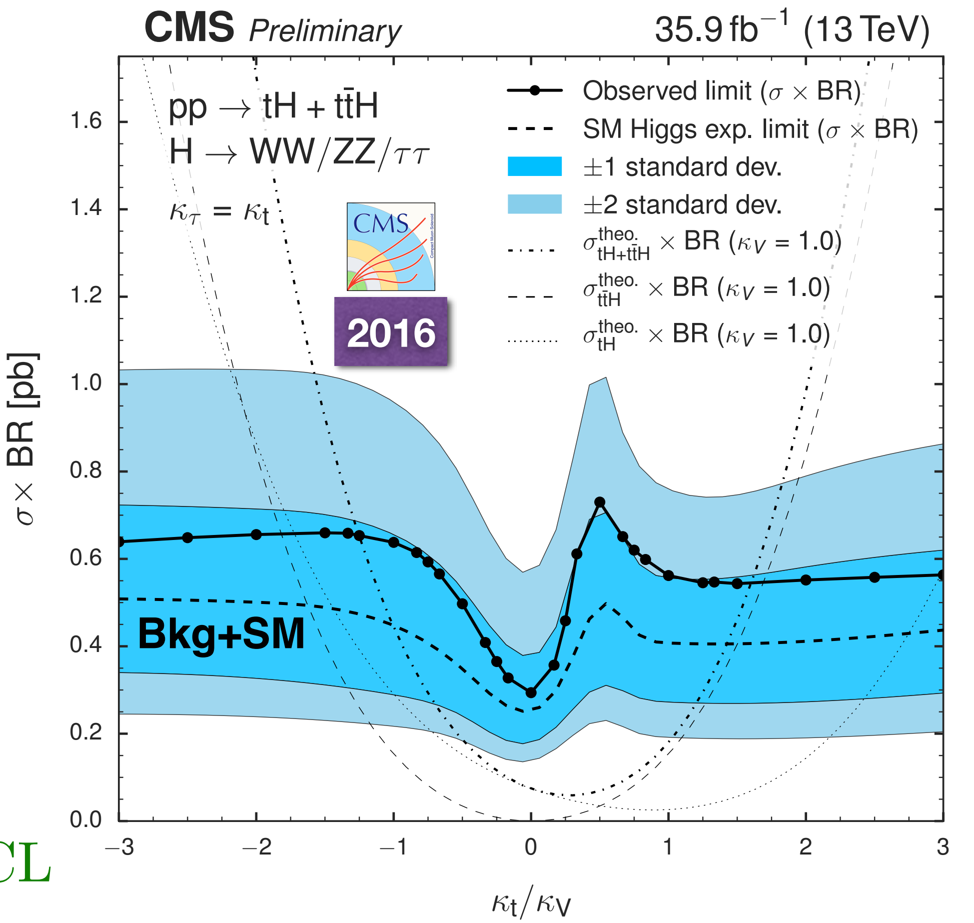
CMS PAS HIG-17-005

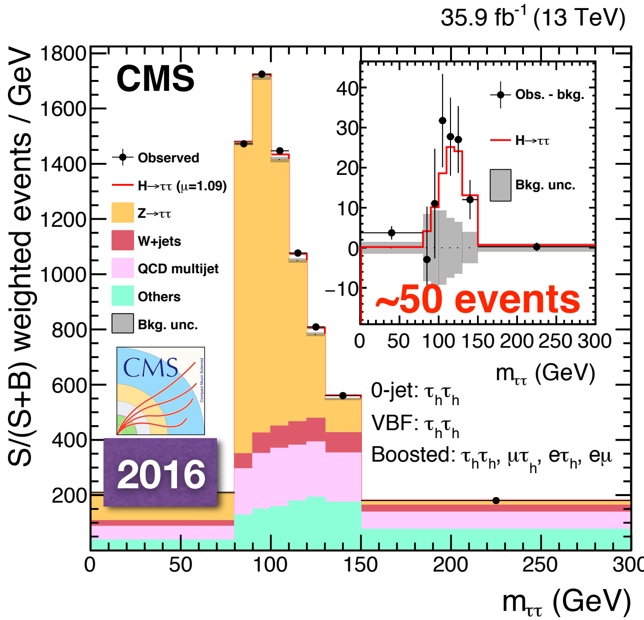


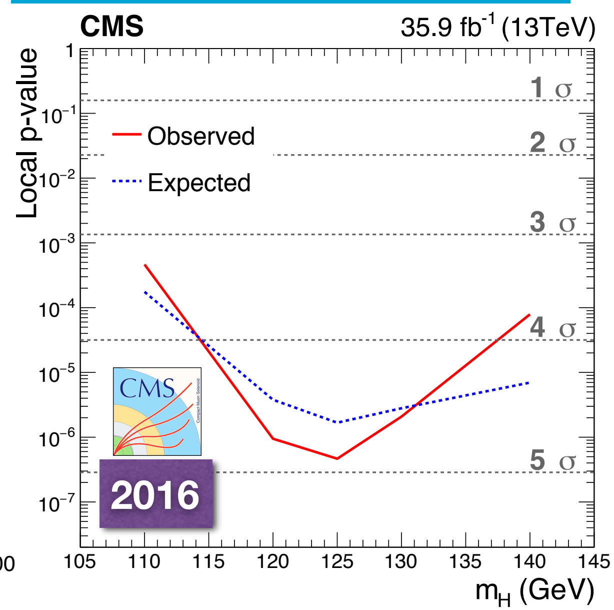


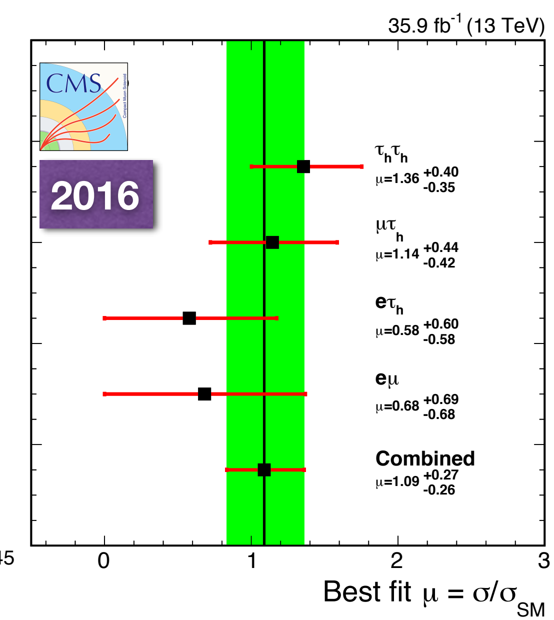
Observation of H(ττ)

- Measurement in four most important channels: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$
  - 0-jet, VBF-like, and boosted categories
  - Use of the SVFIT technique for most precise $m_{\tau\tau}$ reconstruction
- Observed signal strength $\mu = 1.09^{+0.27}_{-0.26}$, 4.9σ significance
- Combination with Run 1: $\mu = 0.98 \pm 0.18$, 5.9σ significance

CMS arXiv:1708.00373

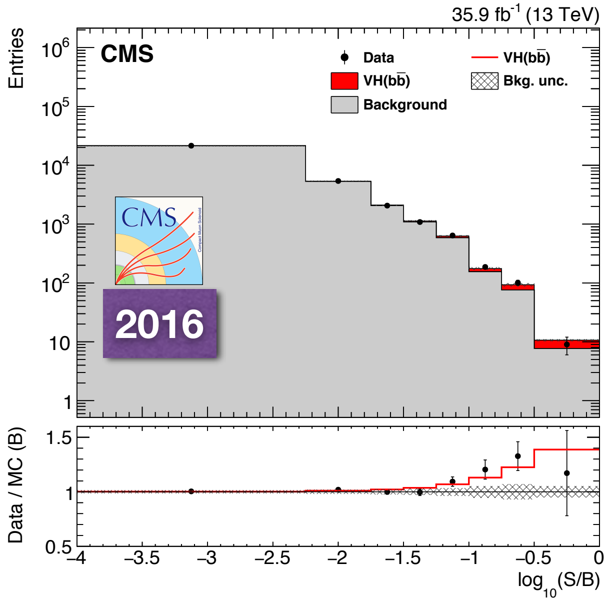


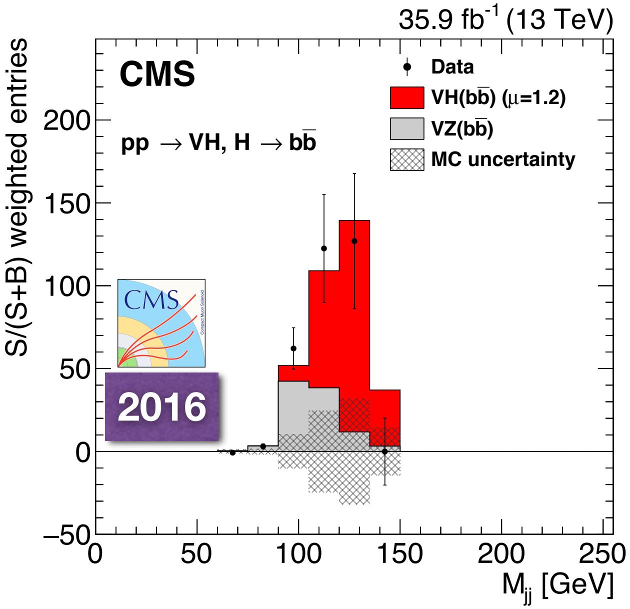


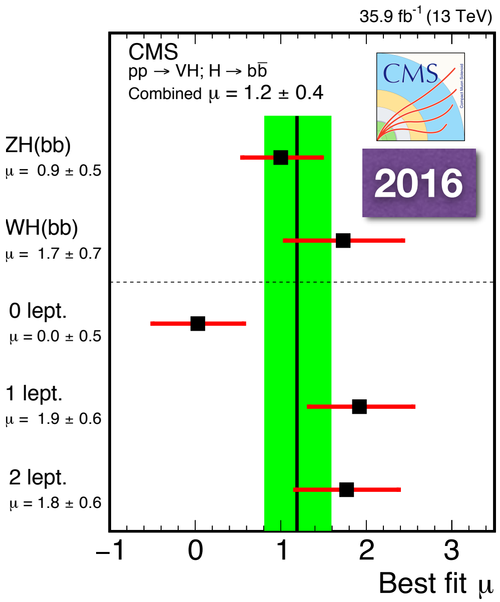


Evidence for H(bb)

- Similar strategy as used for Run 1 "legacy" paper:
  - Target associate VH production, with high $p_T(H)$
  - 0-, 1-, and 2-lepton categories, use of b-jet energy scale regression, and analysis BDT
  - Z(bb) validation; seen at 5σ significance
- Observed signal strength $\mu = 1.19^{+0.40}_{-0.38}$; 3.3σ (2.8σ) observed (expected) significance
- Combined with Run 1 result, obtain: $\mu = 1.06^{+0.31}_{-0.29}$; at 3.8σ (3.8σ)



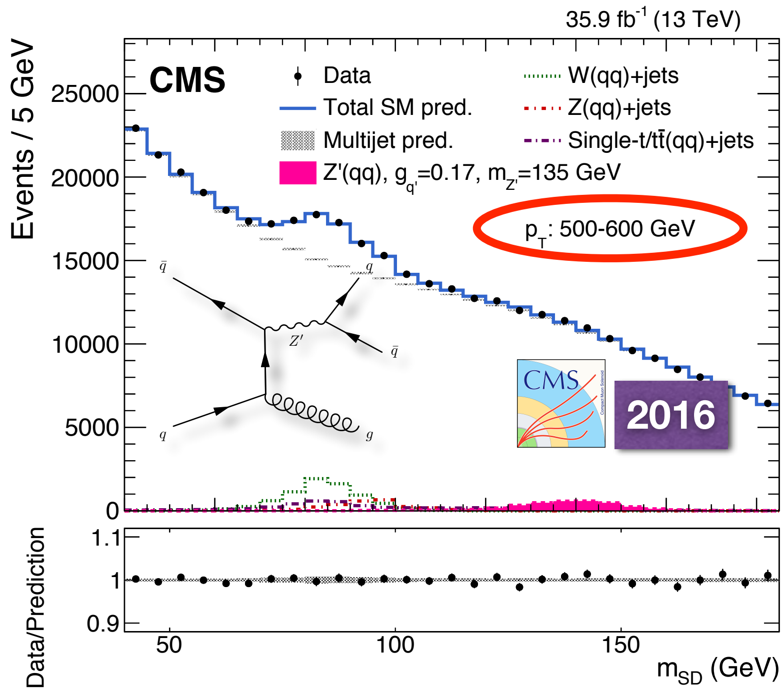




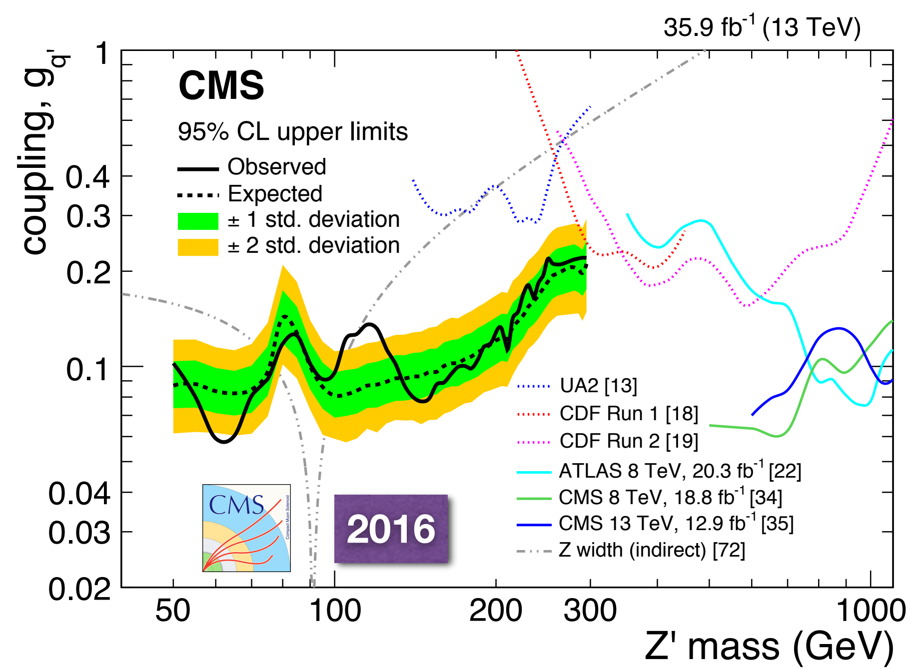
CMS arXiv:1709.07497

Trijets as Dijet Proxies

- Standard approach fails for ggH(bb) production, due to overwhelming backgrounds
  - Thought to be impossible, until recent advances in jet substructure techniques
- ISR to rescue: look at low-mass dijets recoiling against an ISR jet to aid triggering and utilize jet substructure techniques to reconstruct boosted dijet mass
- Allows to lower the dijet mass reach to ~50 GeV, as demonstrated with the W/Z peak observation in CMS in a low-mass dijet search, validating the technique

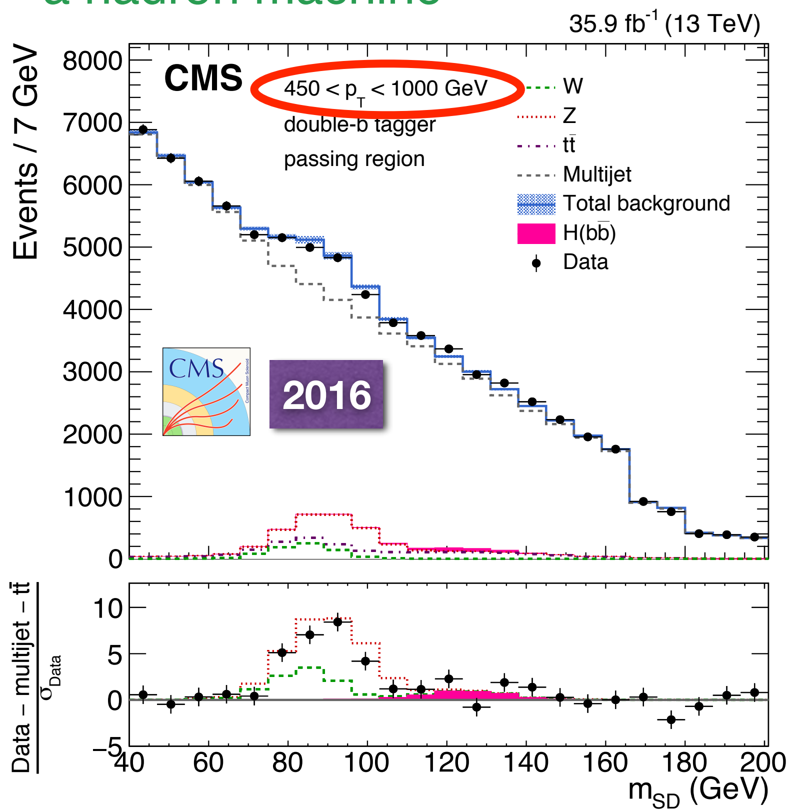


CMS arXiv:1710.00159

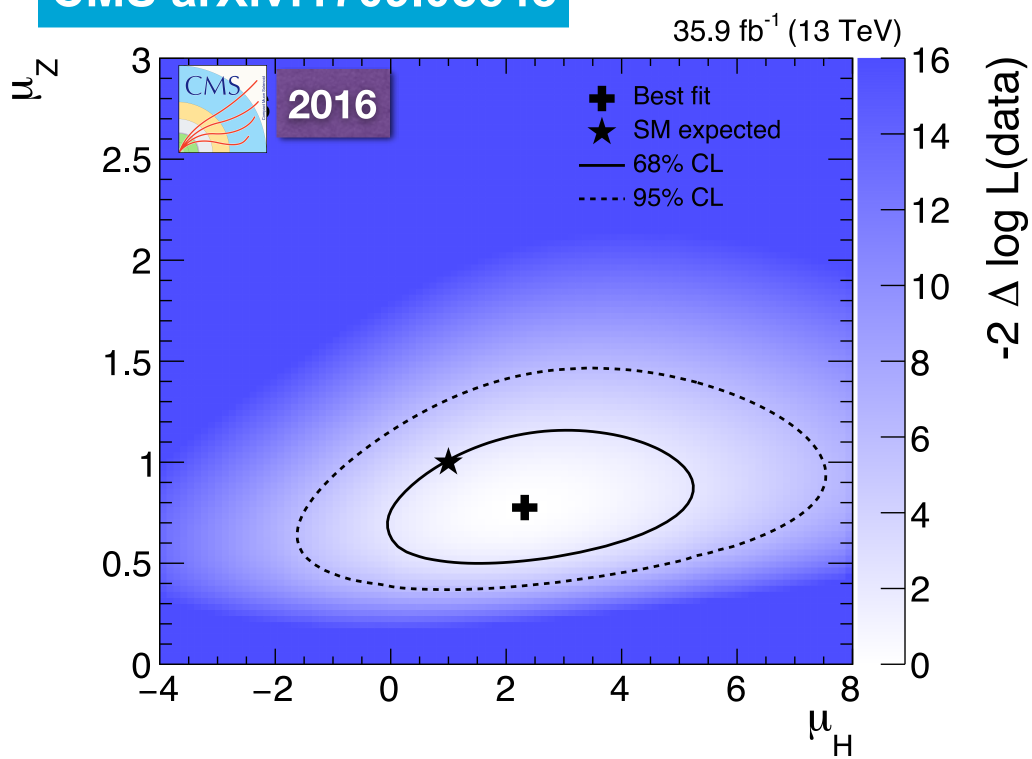


H(bb) in Boosted Channel

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



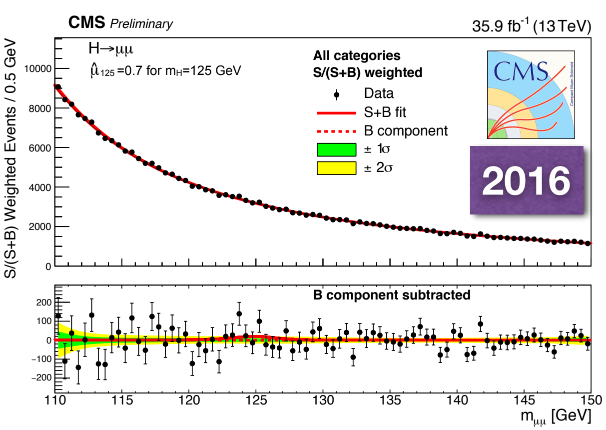
CMS arXiv:1709.05543

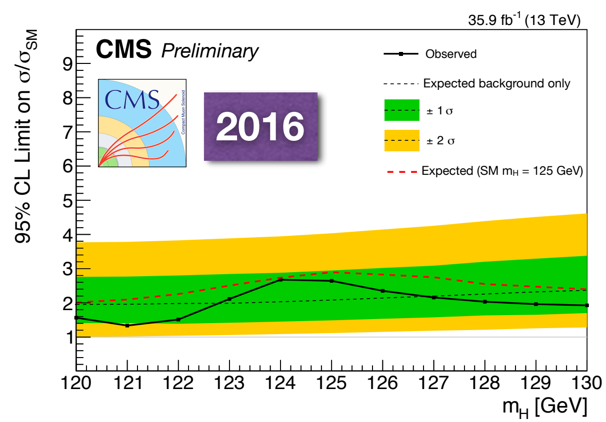


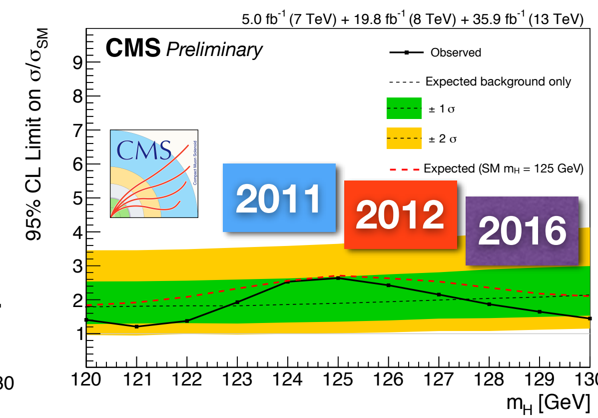
Search for H(μμ) Decay

- H(μμ) offers most promising way to look for Higgs boson couplings to the lighter two generations of fermions
  - Capitalize on excellent CMS muon momentum resolution translating in 2% mass resolution
  - Use BDT with variables targeting ggH, ttH, and VBF production
- Observed (expected) 95% CL limit of $\mu < 2.64$ (2.08); observed (expected) significance 0.74σ (0.98σ)
- Can combine with the Run 1 analysis, which yields 95% CL limit of $\mu < 2.64$ (1.89) or $\mu = 0.9^{+1.0}_{-0.9}$ and significance 0.98σ (1.09σ)
  - This is the best limit on the H(μμ) decay to date: $B(H \rightarrow \mu\mu) < 5.7 \times 10^{-4}$

CMS PAS HIG-17-019







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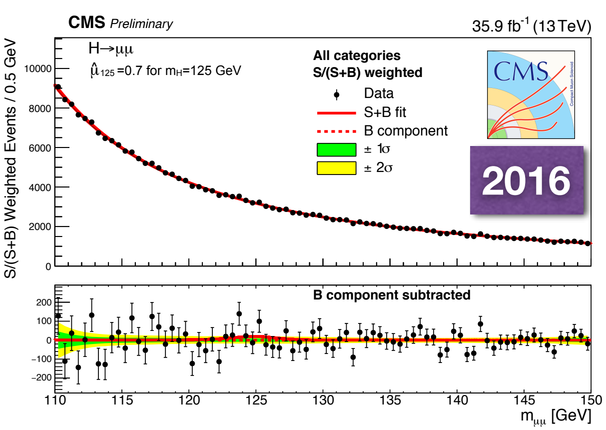

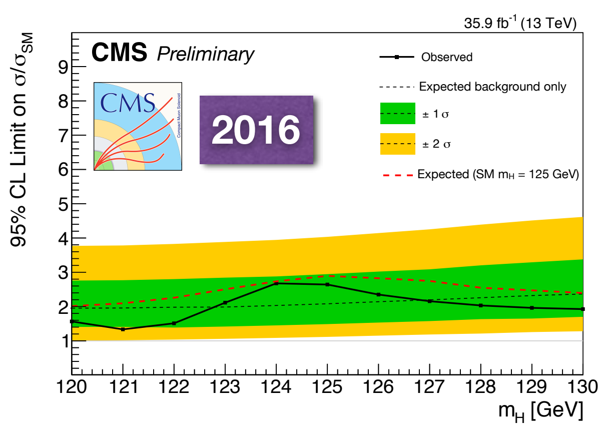

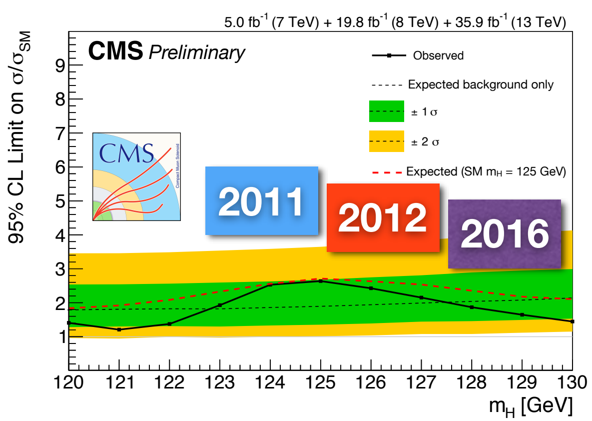

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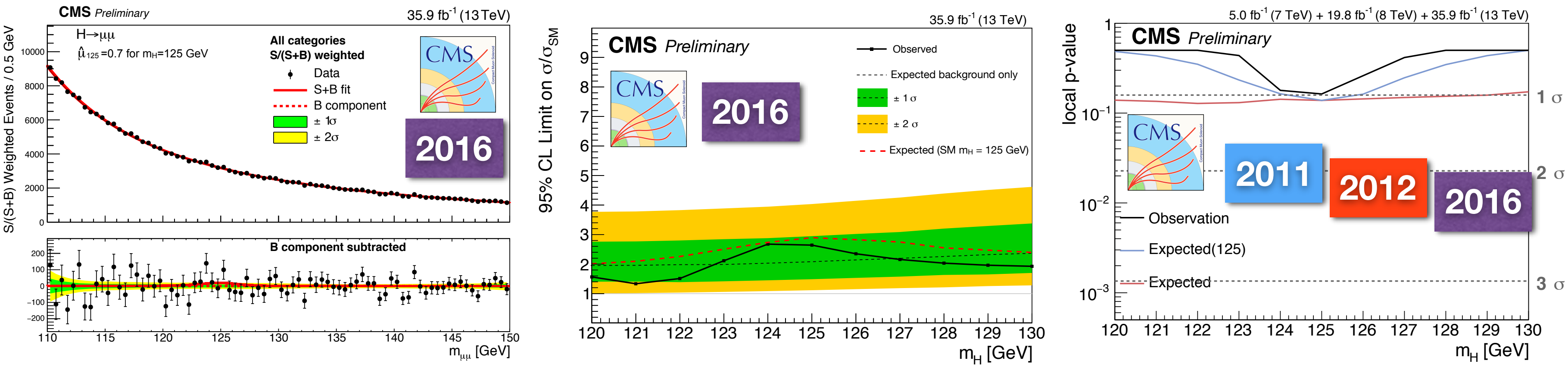

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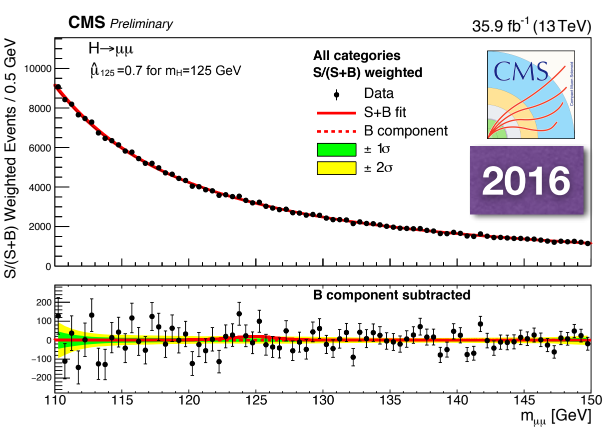
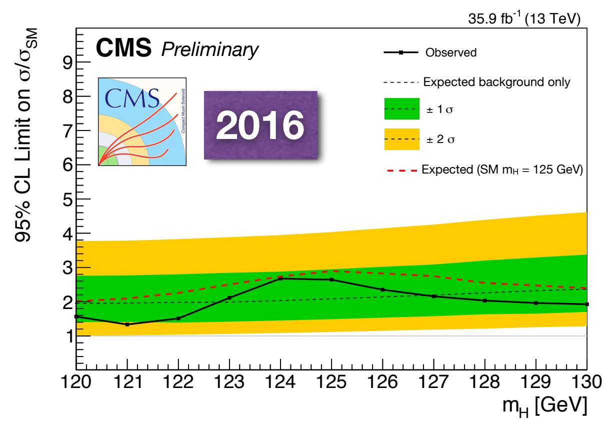
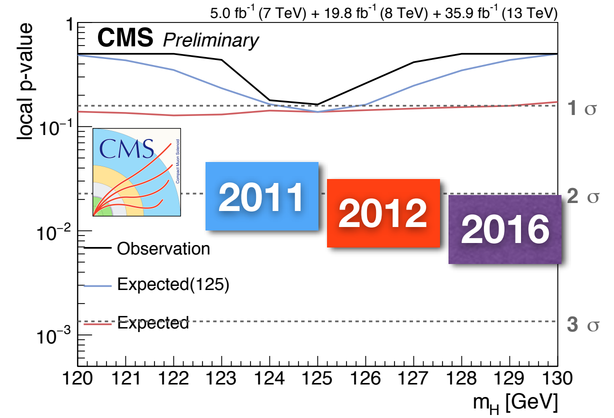




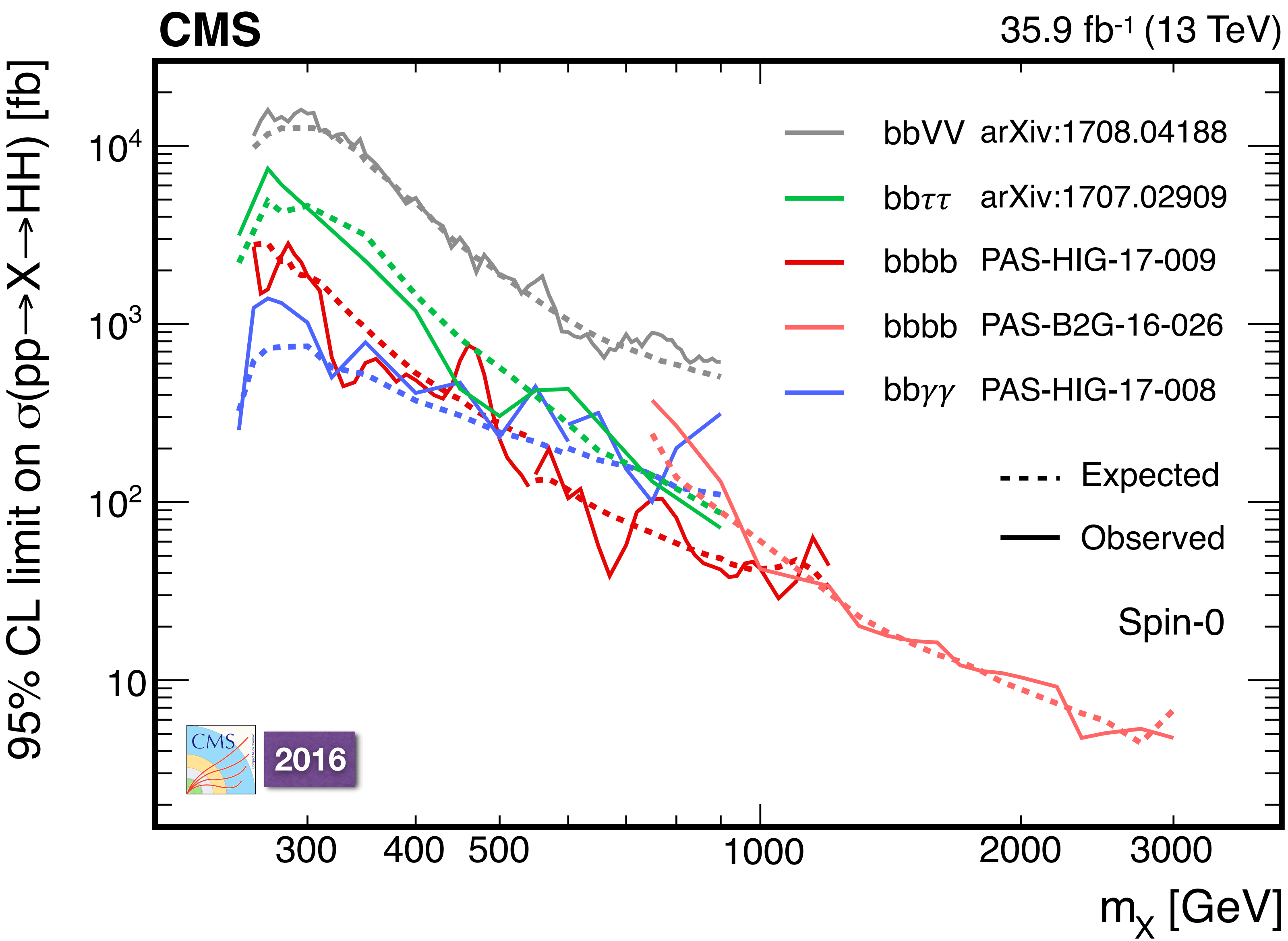


Higgs Self-Coupling

Higgs Pair Production

- The only way to directly measure the self-coupling term in the Lagrangian
- Rates are extremely small - need full HL-LHC data set to be able to see SM diHiggs production
  - Nevertheless, it can be enhanced in a variety of BSM models
- Look for both resonant and non-resonant HH production in various channels: HH(4b, bbWW, bb$\gamma\gamma$, bb$\tau\tau$,...)
  - Most sensitive channels are bb$\gamma\gamma$ (low masses) and 4b (high masses); the former also gives best sensitivity to SM HH production
  - Will highlight only these analyses

Grand Picture: X → HH



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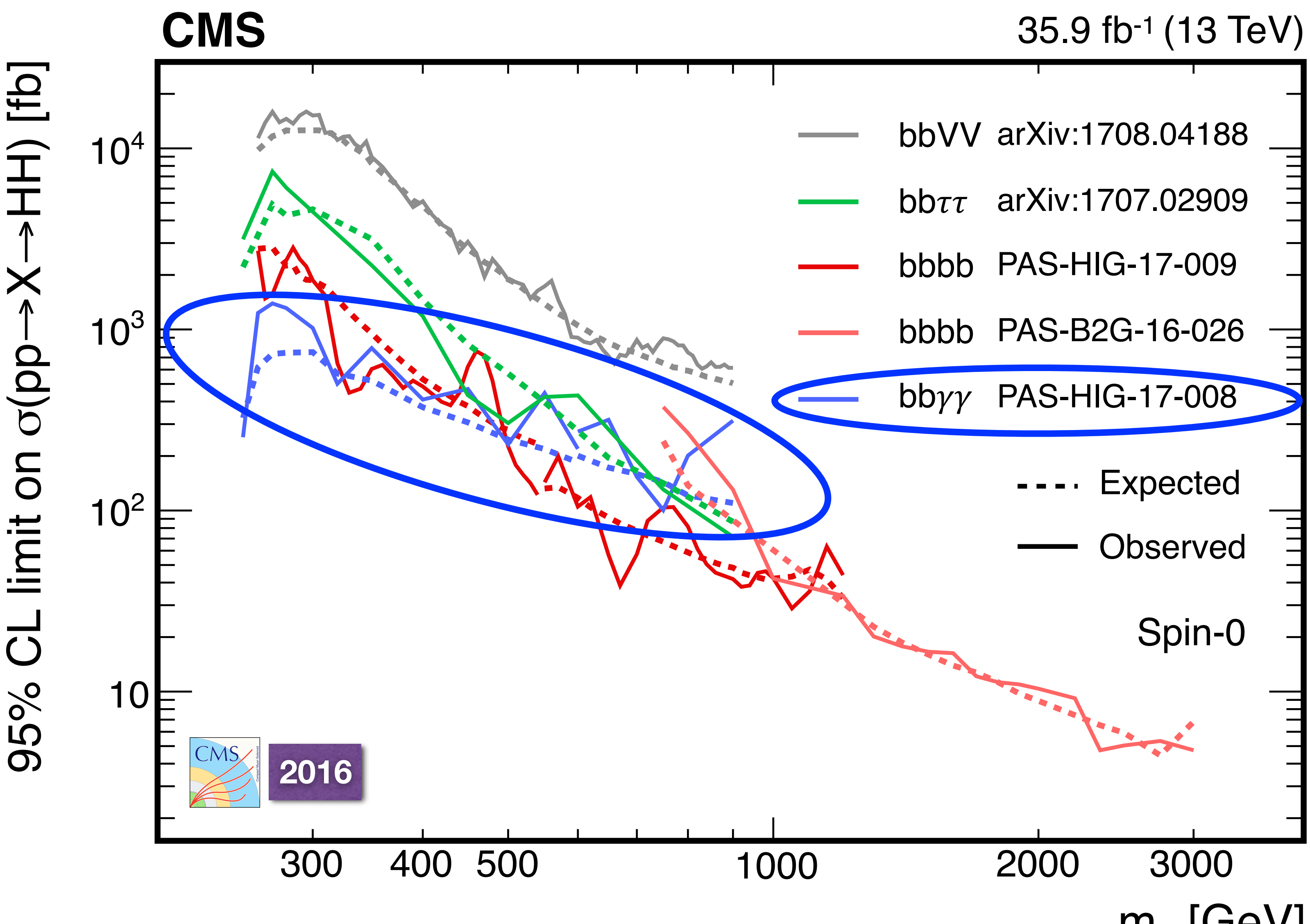

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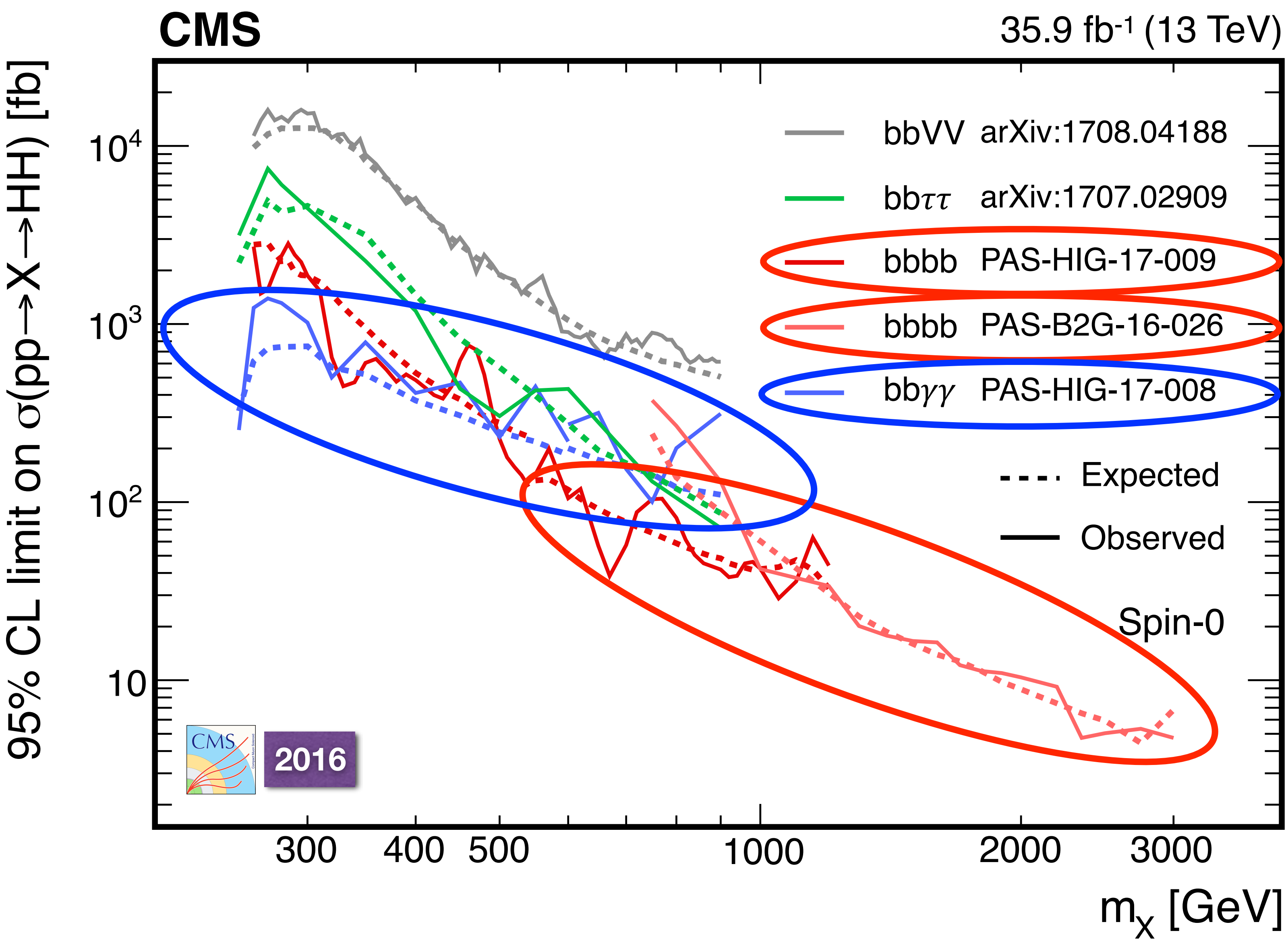
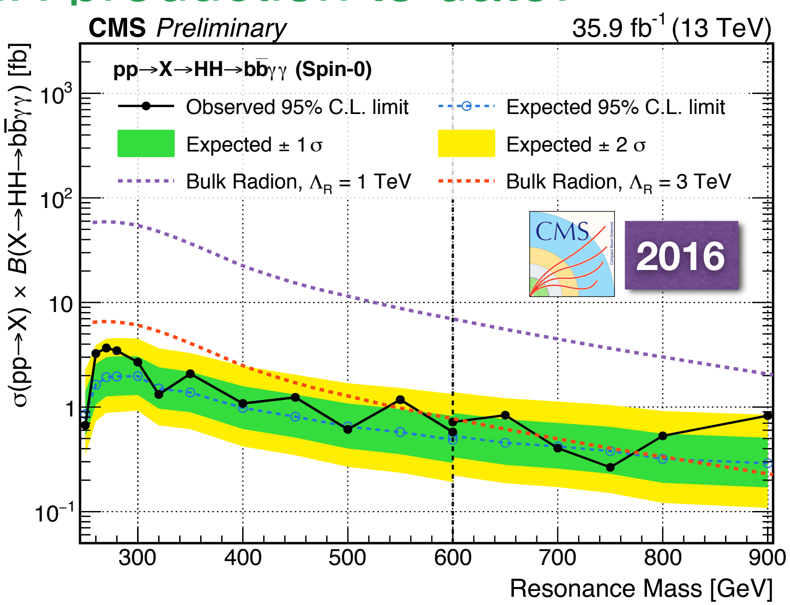
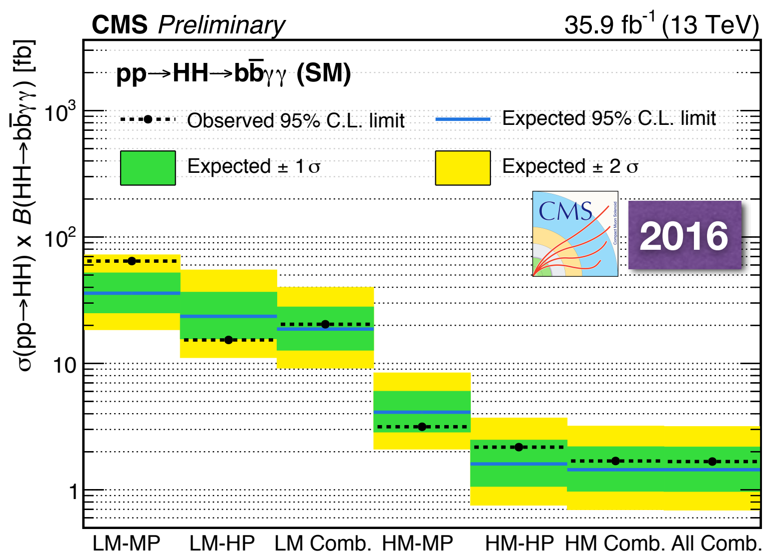


H(bb)H(γγ) Search

- Low backgrounds; sensitive to both resonant and non-resonant production
  - Use BDT unbiased in M(bb) and M(γγ) to reduce backgrounds
  - Eight optimizations: low- and high-mass; medium- and high-purity; and resonance and non-resonance analysis
- Results: $\mu_{HH} < 19.2$ (16.5) observed (expected) @95% CL [$\sigma^{95}(pp \to HH \to bb\gamma\gamma) < 1.67$ (1.44) fb] - the most stringent limit on HH production to date!



CMS PAS HIG-17-008



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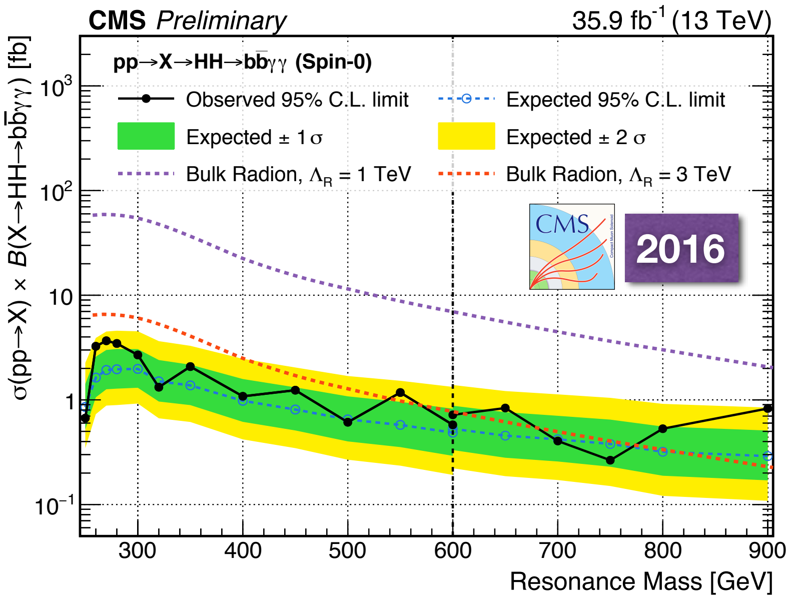
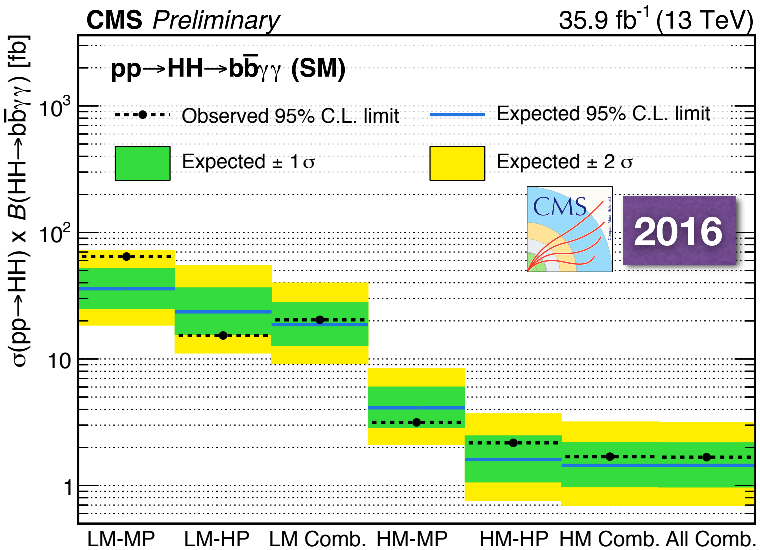


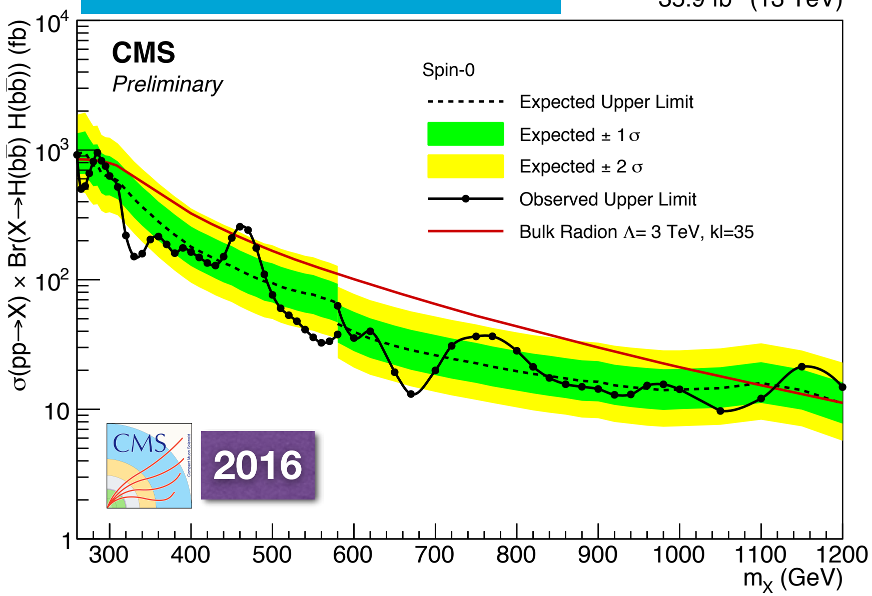
CMS PAS HIG-17-008



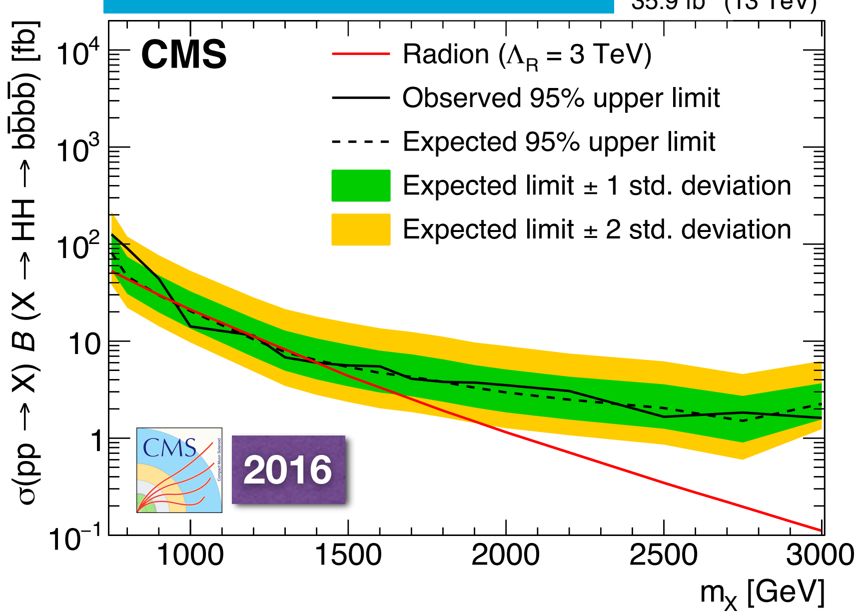
H(bb)H(bb) Searches

- Two resonant searches w/ somewhat different strategies
  - HIG-17-009: low- (250-550 GeV) and medium-mass (550-1200 GeV) regimes; resolved b jets in both cases
    - Select event in the $M_{bb}M_{bb}$ plane; use BDT to reduce backgrounds
  - arXiv:1710.04960: high-mass regime (1250-3000 GeV); each H(bb) reconstructed as a single large-radius jet, with both jets double-b-tagged
    - Two categories, depending on the b-tag quality: TT and TL

CMS PAS HIG-17-009



CMS arXiv:1710.04960



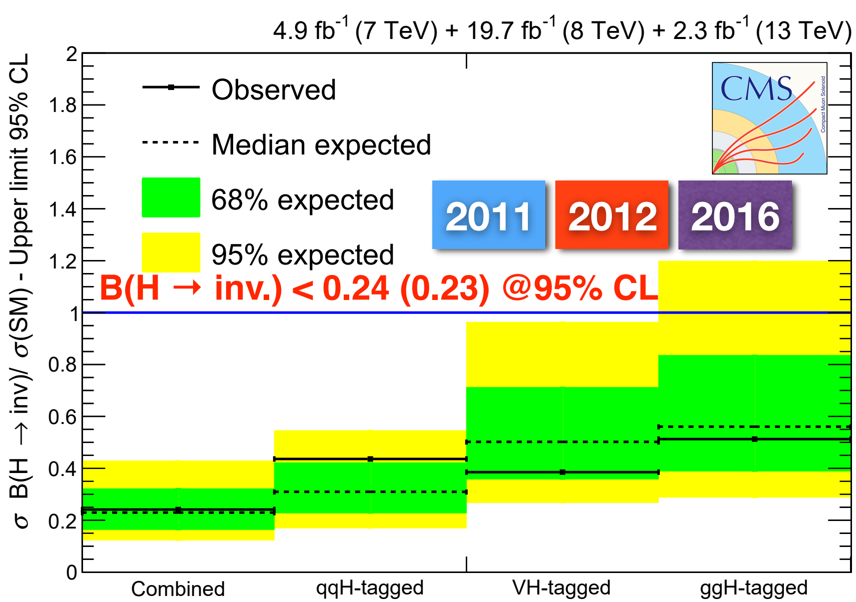
Exotic Higgs

Exotic Higgs Decays

- Vibrant search program for exotic Higgs boson decays as well as searches for light (pseudo)scalars either in the Higgs boson decays or directly
- Will highlight just a few recent results:
  - H(inv.) combination
  - Search for $H \rightarrow \mu\tau, e\tau$
  - Search for $H \rightarrow aa \rightarrow 4\mu, 4\tau, 2\mu 2\tau, 2\mu 2b$
- Also recent, but not covered in this talk:
  - $pp \rightarrow bba(\mu\mu)$ [arXiv:1707.07283]
  - Search for doubly-charged $H^{\pm\pm}$ in 4l [PAS HIG-16-036]
  - Search light bosons decaying to $\mu\mu$ [PAS HIG-16-035]

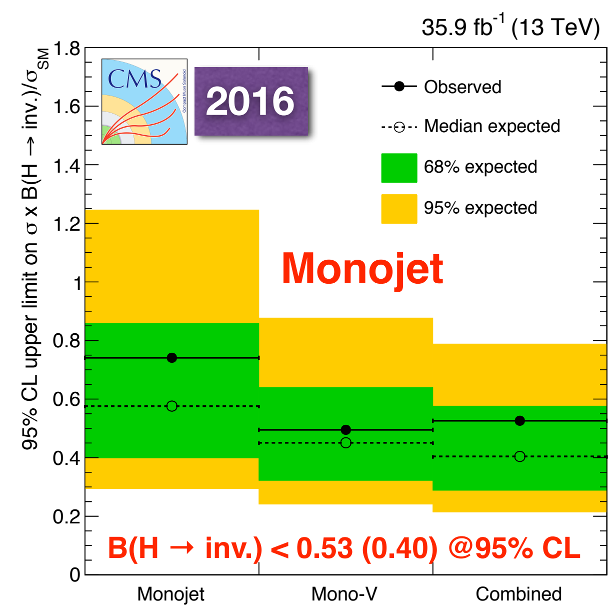
Search for H(inv.) Decays

- Direct searches have been historically conducted in the Z(ll,bb)H(inv.), ggH+ISR (monojet) and VBF production
- Grand combination using 7, 8, and 2015 13 TeV data: B(H → inv.) < 0.24 (0.23) @95% CL - tightest limit to date
- Since then, new limits from monojet and Z(ll)+MET analyses with 2016 data: B(H → inv.) < 0.53 (0.40) @95% CL [arXiv:1711.xxxxx] and B(H → inv.) < 0.45 (0.44) @95% CL [arXiv:1711.00431]
  - They haven't been included in the combination and will further improve it



CMS arXiv:1610.09218

CMS arXiv:1711.0xxxx



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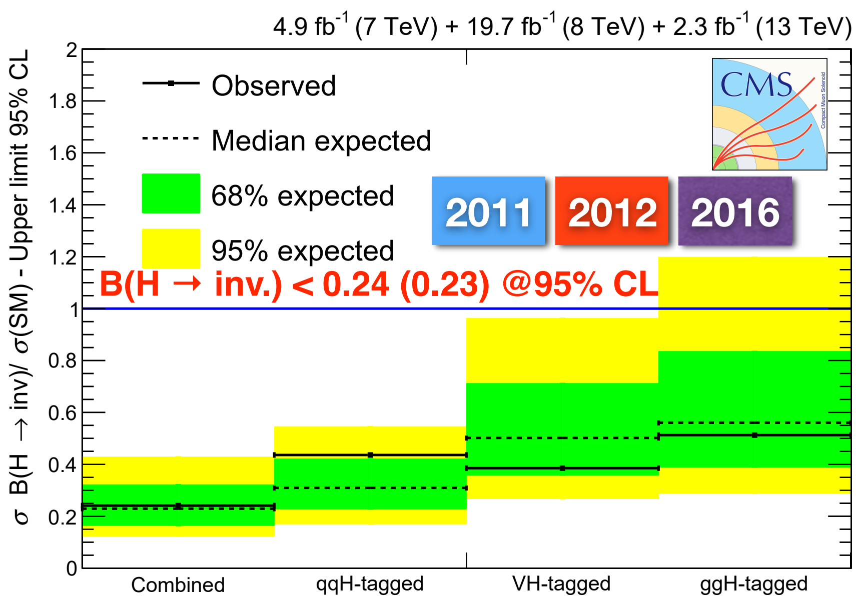

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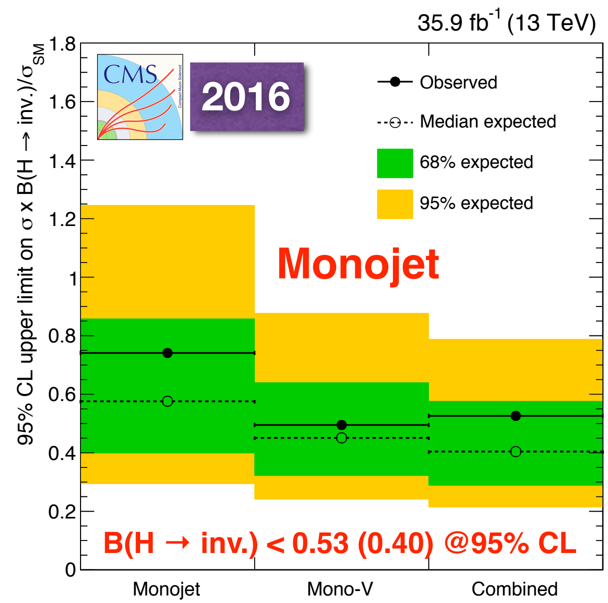


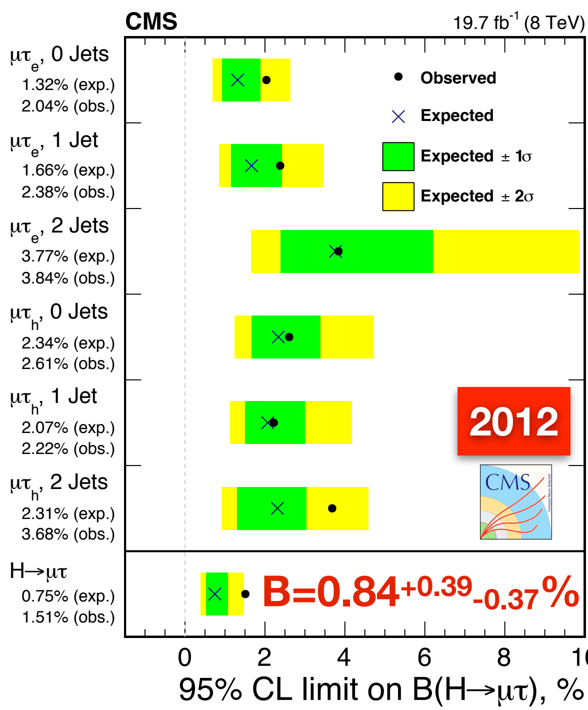
What about H(μτ)?

✦ New result from CMS based on full 2016 data:

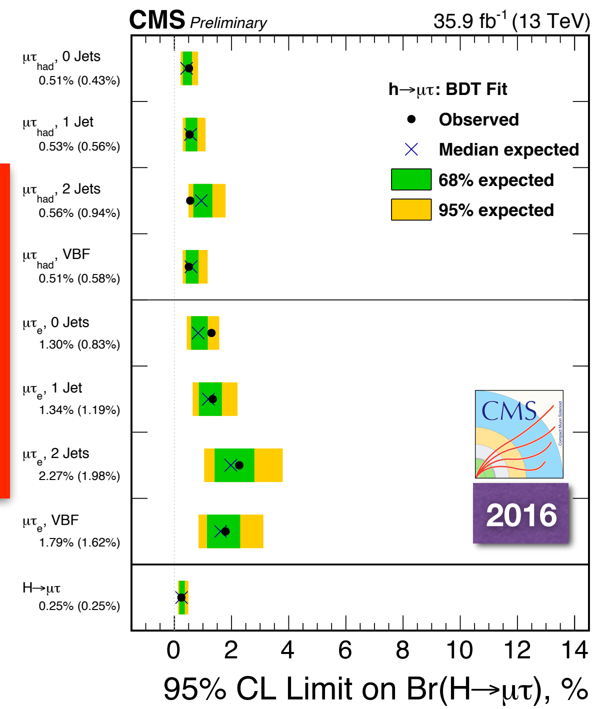
◉ Definitively excludes the 2.4σ Run 1 excess (alas...)

CMS PAS HIG-17-001

CMS arXiv:1502.07400



ATLAS arXiv:1604.07730: $B = 0.53 \pm 0.51\%$
Naïve combination w/ 2012 CMS result: $B = 0.73 \pm 0.30$ (still 2.4σ away from zero)



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

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CMS PAS HIG-17-001

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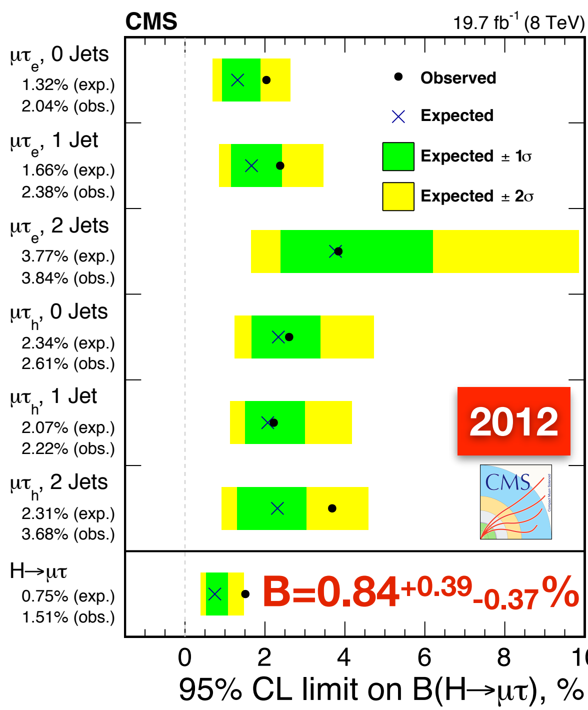

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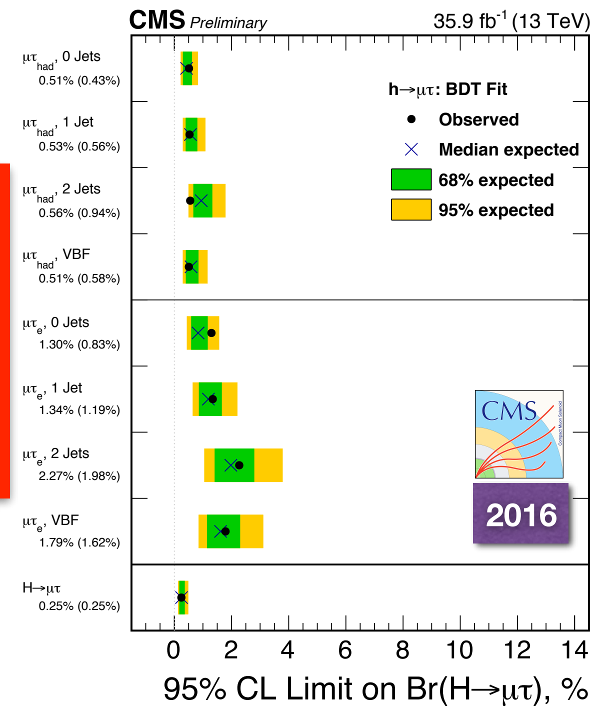
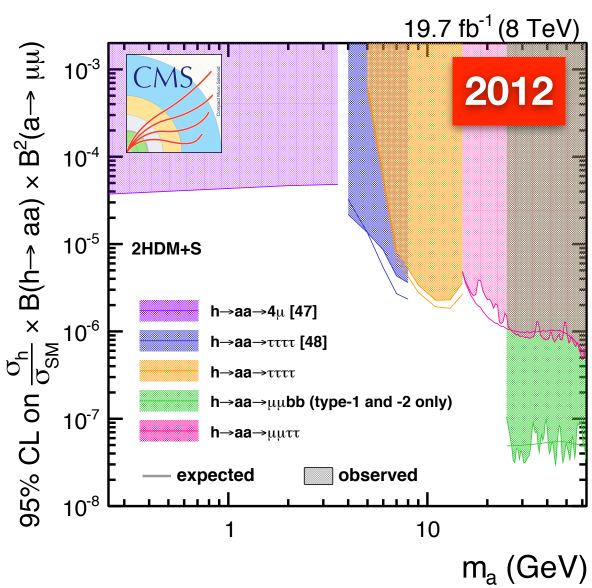


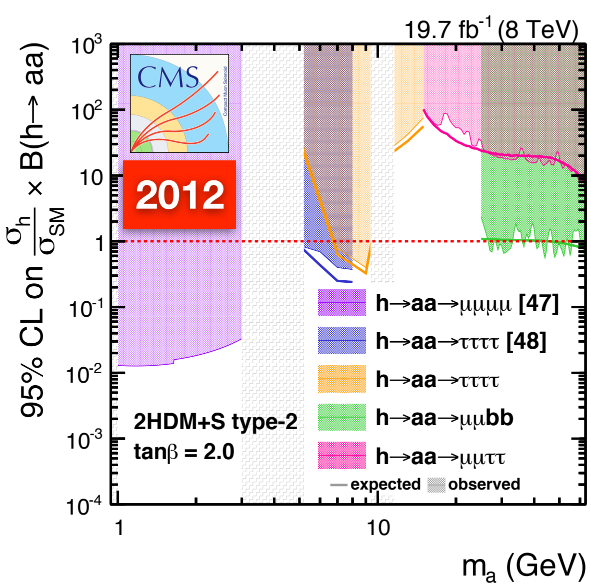
	Observed(Expected) limits (%)		Best fit branching fraction (%)	
	M_{col}-fit	BDT-fit	M_{col}-fit	BDT-fit
$H \to \mu\tau$	<0.51 (0.49) %	<0.25 (0.25)%	$0.02 \pm 0.20\%$	0.00 ± 0.12 %
$H \to e\tau$	<0.72 (0.56) %	<0.61 (0.37) %	0.23 ± 0.24 %	0.30 ± 0.18 %

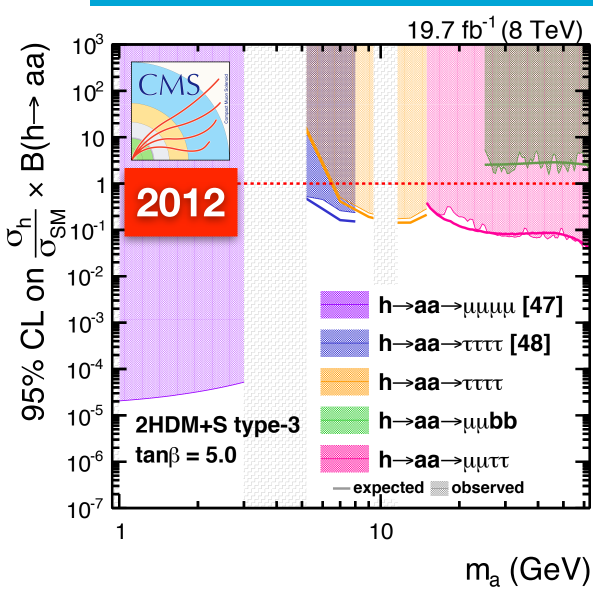
Search for Light Pseudoscalar

- One recent 8 TeV result to highlight is a search for light pseudoscalars in Higgs boson decays: H → aa →2f2f'
  - Consider 4τ, 2μ2τ, and 2μ2b final states
  - Also combines with earlier searches in 4μ [arXiv:1506.00424] and 4τ [1510.06534] final states
  - Interpreted as limits on product of branching fractions or in several benchmark 2HDM scenarios

CMS arXiv:1701.02032



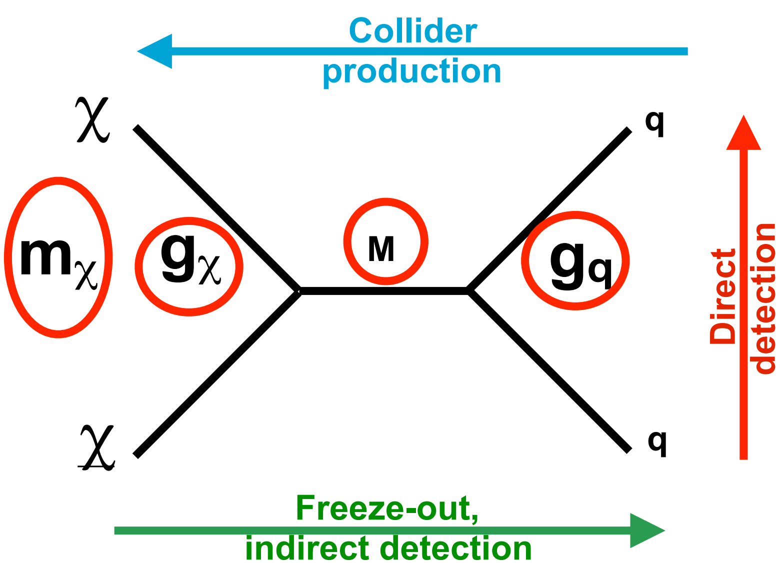


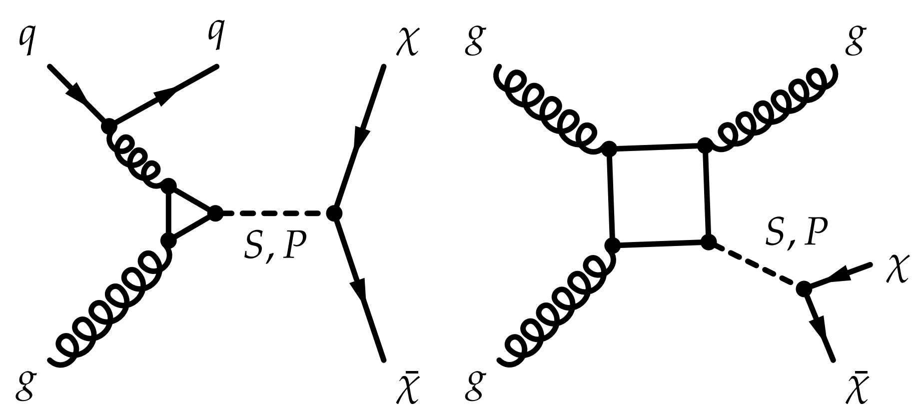


Dark Matter (Pseudo)Scalars

Dark Matter at Colliders

- 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 topological permutations of the same Feynman diagram:
  - But: how to trigger on a pair of DM particles at colliders?
  - ISR (g, γ, W/Z, H, …) to rescue!
- Sensitivity to (pseudoscalar) mediators via ggF or qg production
  - Typically assume Yukawa couplings between the mediators and quarks

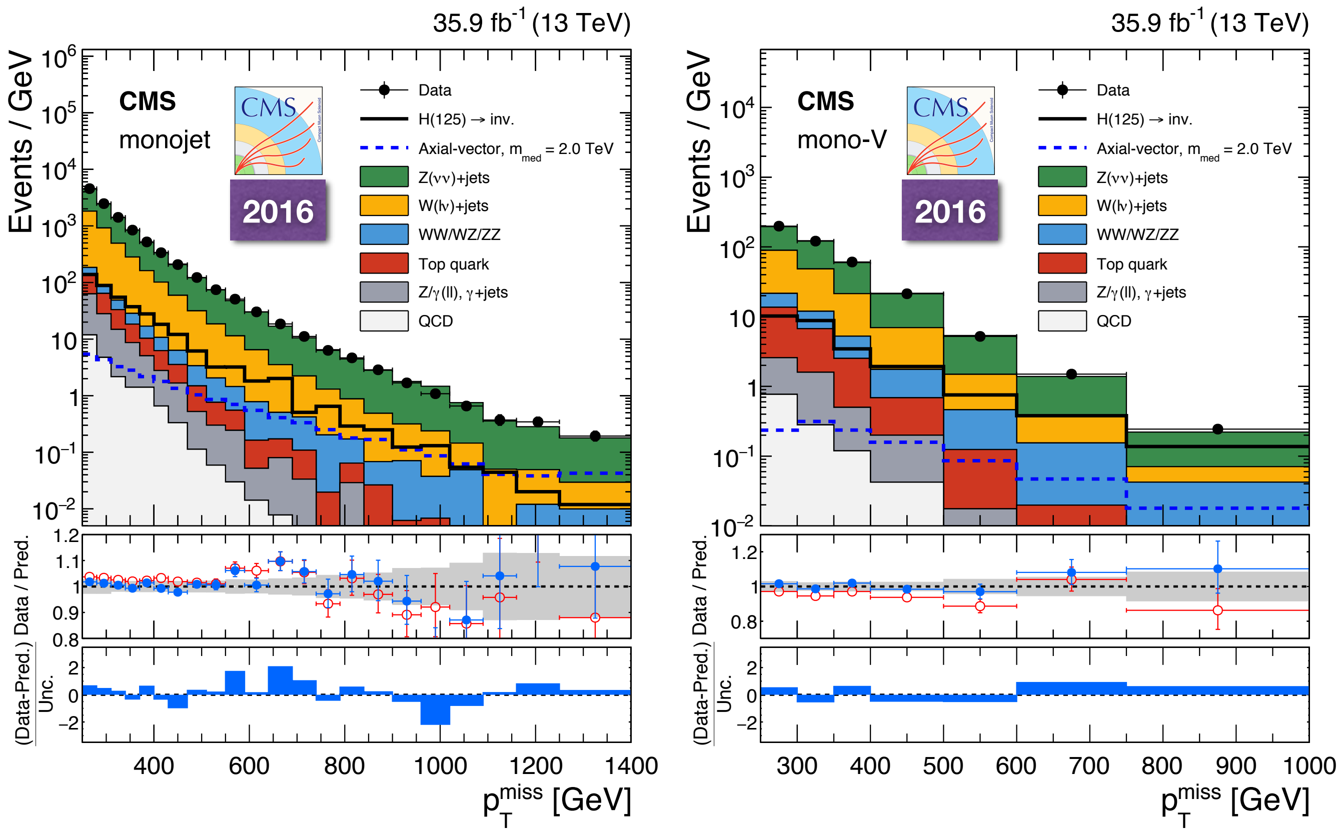




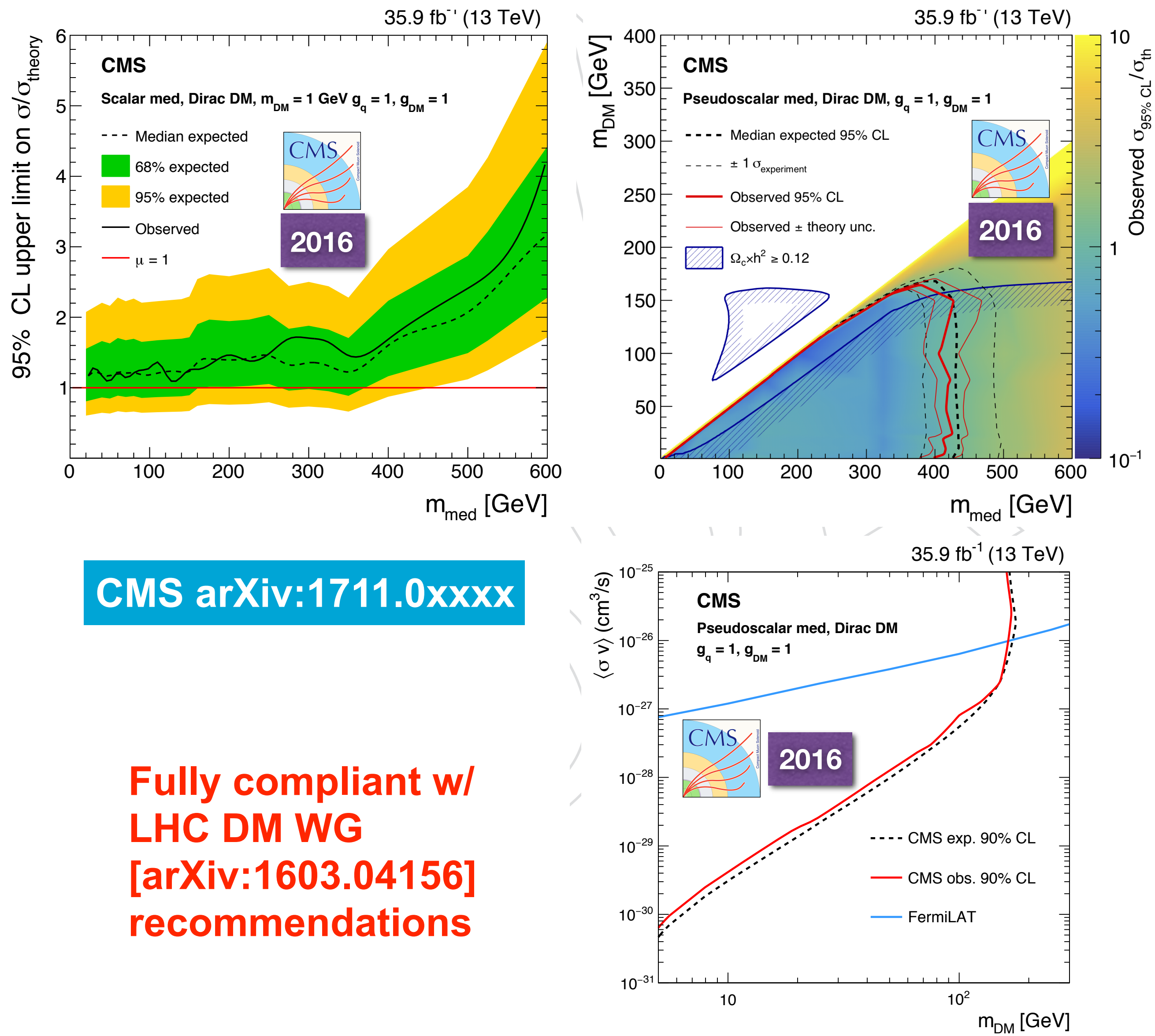
CMS Monojet Analysis

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

CMS arXiv:1711.0xxxx



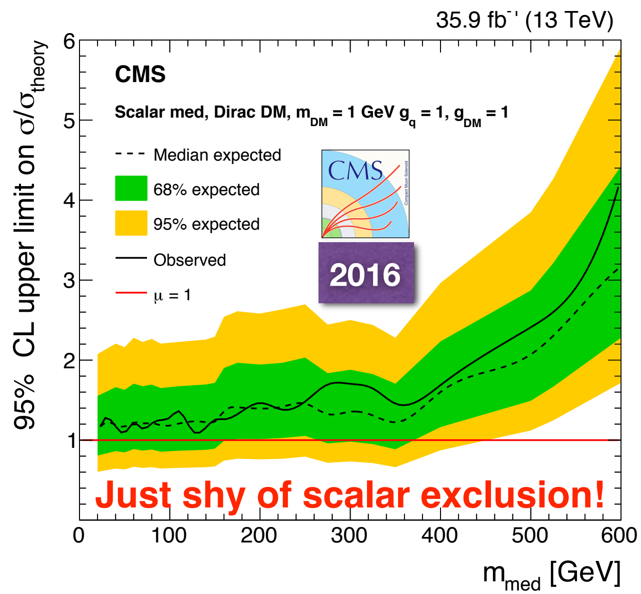
(Pseudo)Scalar Mediators

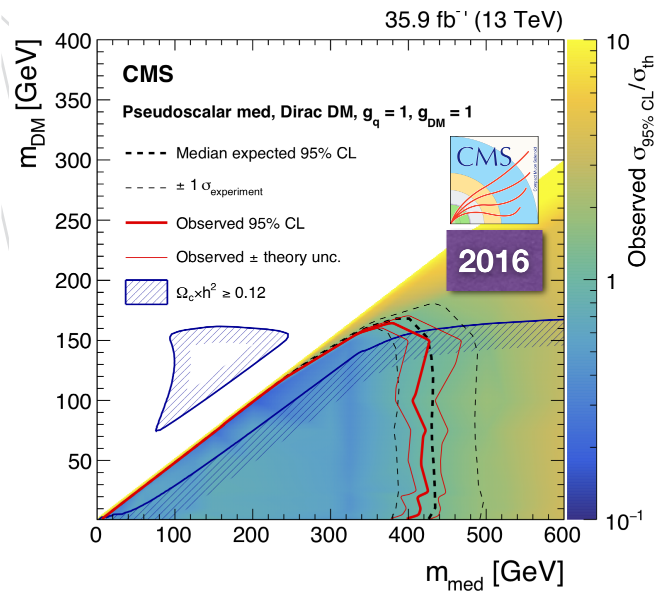


CMS arXiv:1711.0xxxx

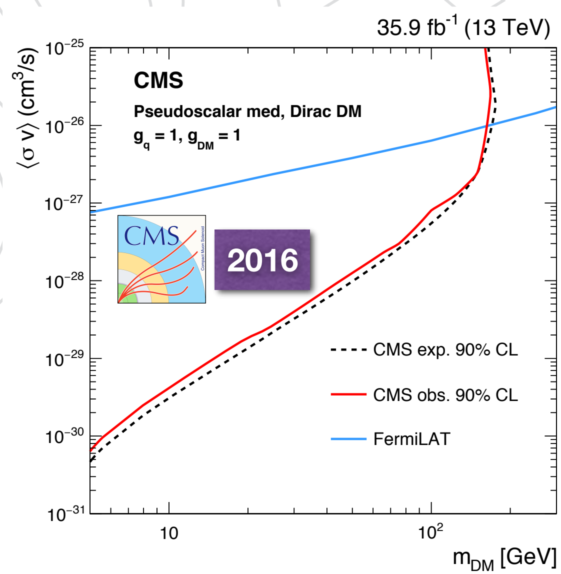
Fully compliant w/ LHC DM WG [arXiv:1603.04156] recommendations

(Pseudo)Scalar Mediators





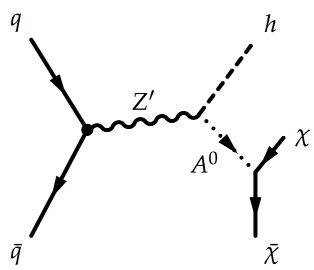
CMS arXiv:1711.0xxxx



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

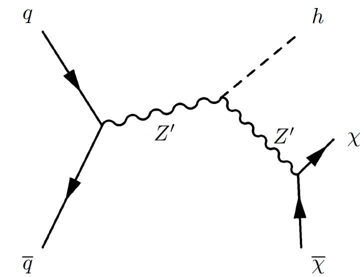
Mono-Higgs Production

- ✦ Another example is a mono-Higgs analysis in the context of 2HDM and vector mediator models: Higgs boson is a tag
- ✦ Explore the H(γγ) decay mode

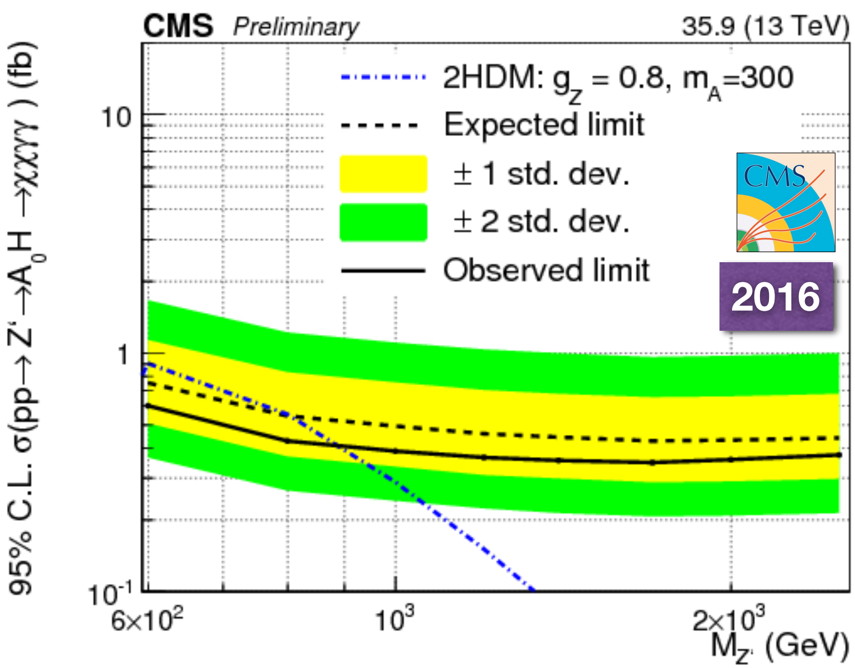


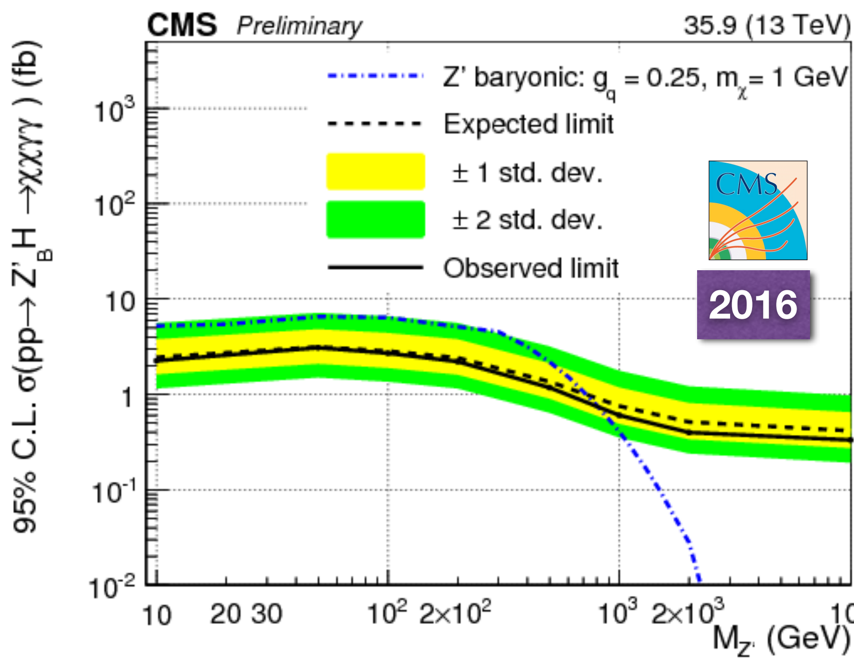
$$g_{Z'} \leq 0.03 \times \frac{g_W}{\cos\theta_W \times \sin^2\beta} \times \frac{\sqrt{m_{Z'}^2 - m_Z^2}}{m_Z}$$

Dijets: $g_{Z'} < 0.8$



CMS PAS EXO-16-054

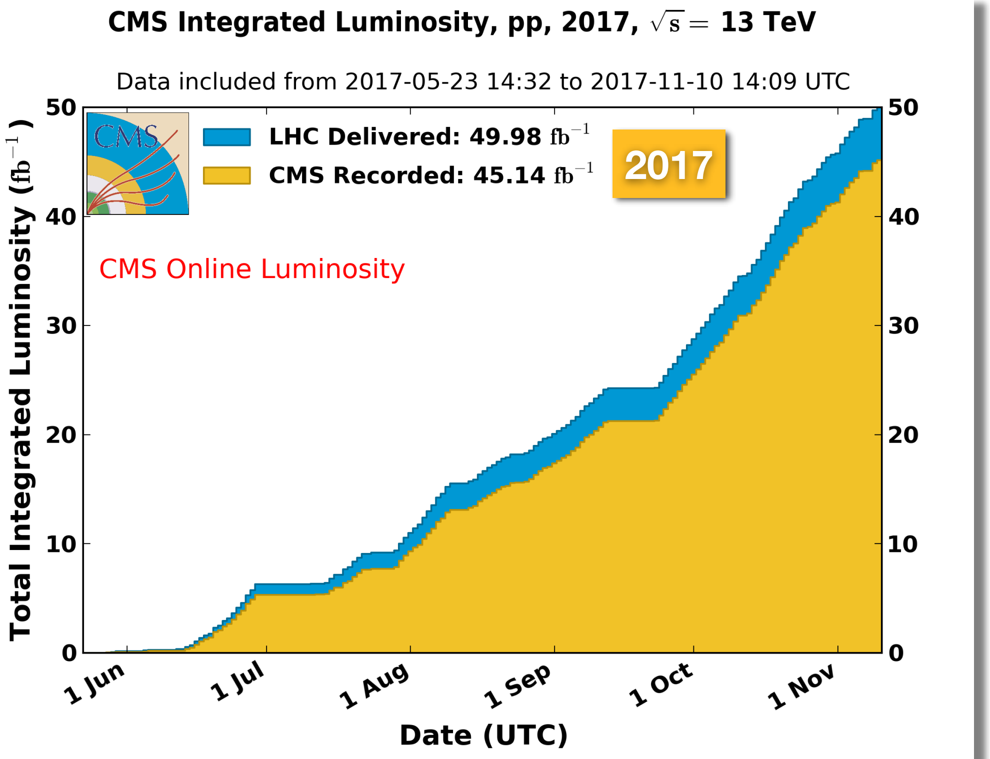




Toward the Future

Toward the Future

- Another spectacular year at the LHC:
  - 50 fb^{-1} delivered; 45 fb^{-1} recorded by CMS
    - Upgraded pixel detector w/ 4 layers and higher resolution
    - Expect first results ready for Winter 2018 conferences
- Looking forward to >100 fb^{-1} usable data @ 13 TeV by the end of 2018, which will significantly extend (pseudo)scalar sector program at CMS



Conclusions

- CMS is pursuing vibrant (pseudo)scalar program of measurement and searches
- Focus is on precision measurement of Higgs boson properties, searches for exotic decays of the Higgs boson, and extended Higgs sectors
- Deep connection with dark matter searches (first limits on pseudoscalar mediators) and SUSY searches with Higgs bosons (not covered in this talk)
- 13 TeV data allowed to improve on Run 1 legacy results, including:
  - Observation of H($\tau\tau$) and strong evidence for H(bb) decays
  - Best measurement of the Higgs boson mass to date and most restrictive direct limit on its width
  - Best limits on invisible decays of the Higgs boson
  - Best limit on the H($\mu\mu$) decay
- Looking forward to completing Run 2 program with 3-4x more data!

Thank You!