Searches for extended Higgs sectors with the CMS experiment

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On behalf of the CMS Collaboration

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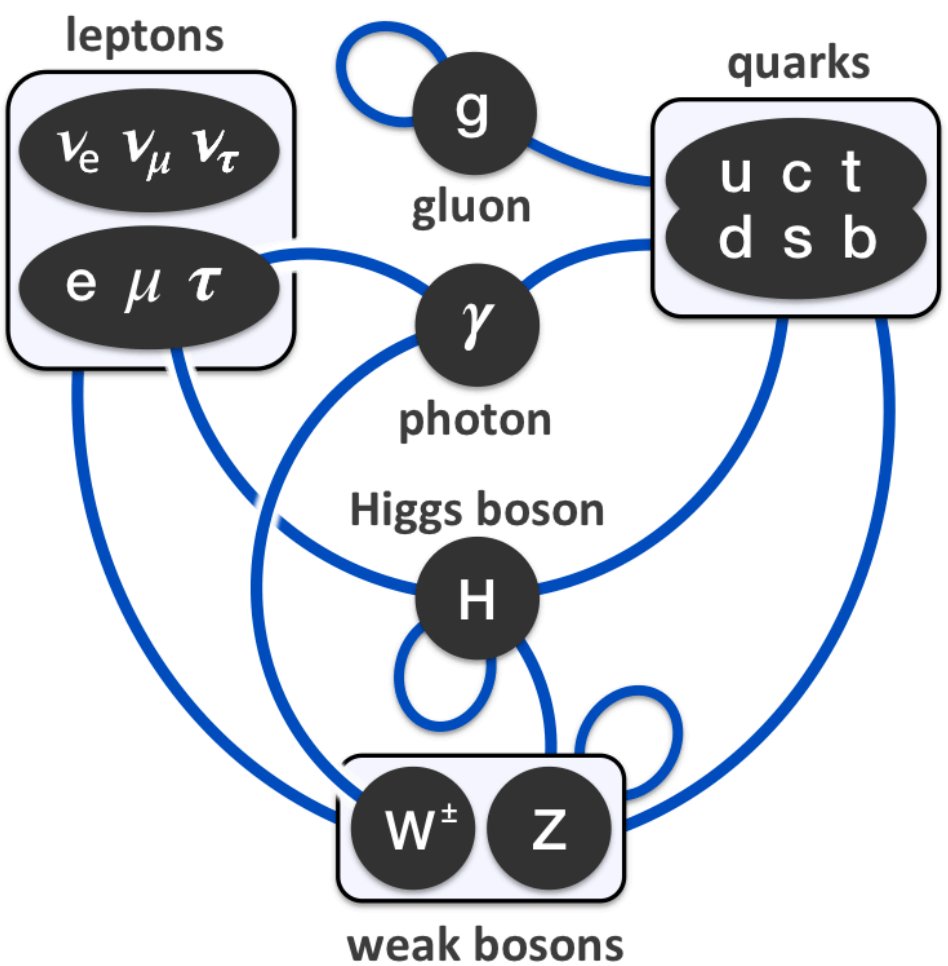
Looking for BSM physics

- Standard Model (SM): our current theory of matter and interaction



- Unfortunately, it cannot provide a complete description of the Universe:
  - → Higgs Mass is unprotected against quantum corrections in the SM: $m_h^2 \sim m_{h0}^2 - \alpha\lambda_f^2\Lambda^2$
  - → Baryogenesis:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$

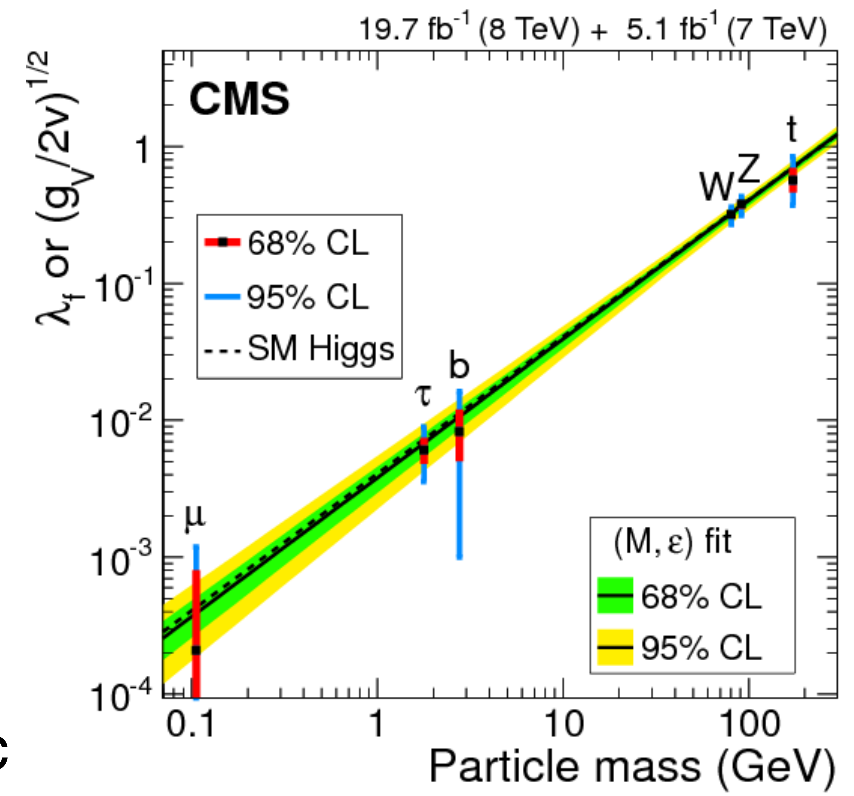
  - → Neutrino physics
  - → Dark Matter

- No hints of physics beyond the Standard Model:
  - → Still room for BSM decay of Higgs boson or additional Higgs (2HDM, 2HDM+S models)
  - → Or: are we looking in the right place?
    - → Null results may point us towards the true nature of the Universe (Hidden sectors with only tiny interactions with the SM)

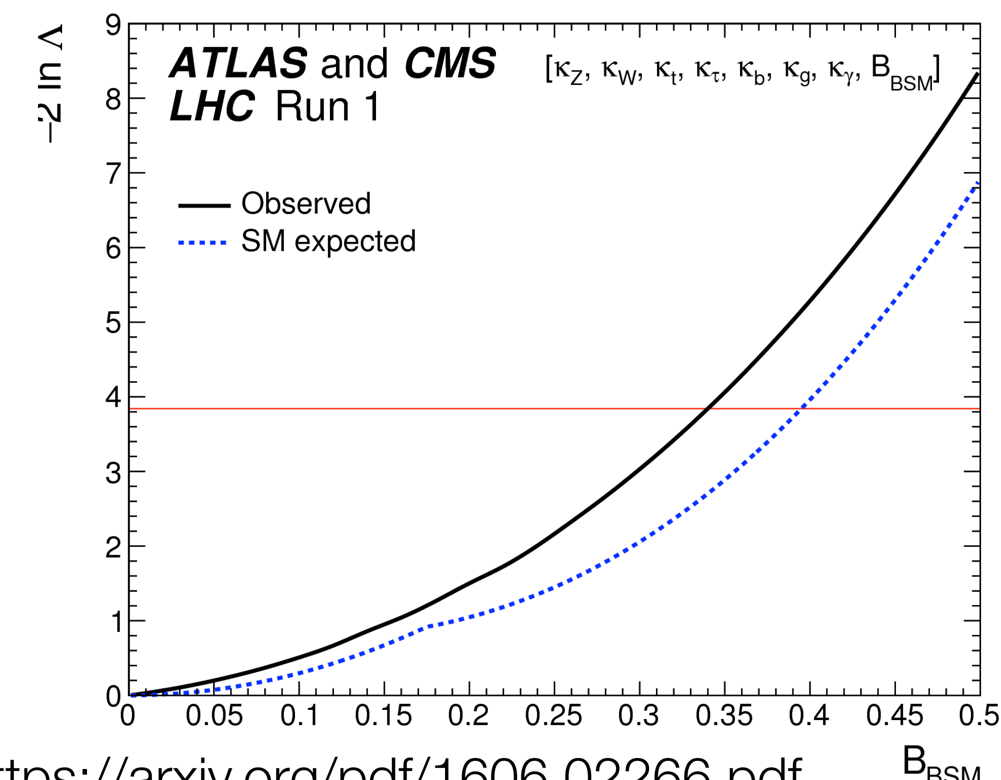
What do we know about SM Higgs?

- Higgs-like particle has been observed:
  - → $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$
  - → $\Gamma_H < 26$ MeV (for $f_{\Lambda Q}=0$ at the 95% CL.)
  - → $J^{PC} = 0^{++}$

(https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG)



- No SUSY has been discovered so far, but:
  - → Still good to focus in naturalness
  - → General interest on sparticles with influence on quadratic term in Higgs potential
  - → See if newly found resonance is part of an extended Higgs sector is of primary importance!



- Still room for BSM decay of Higgs boson:
  - → BR (h→BSM) < 34% at 95% CL

https://arxiv.org/pdf/1606.02266.pdf

Extending the Higgs sector

- Several ways to test BSB phenomena in the Higgs sectors

Search for **deviation** on the Higgs **properties** expected from the SM

Spin
Couplings
CP

Search on **BSM phenomena**

Additional H-like scalars

Neutral/charged Higgs
They could decay to SM or h (e.g. H->hh)

BSM Higgs decay and couplings

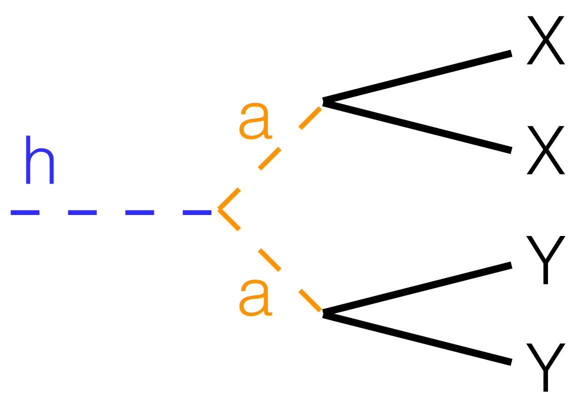
New light resonances
Flavor violating couplings
Invisible decays
Long-lived particles

This talk is NOT an extensive review of all CMS searches, but will focus on few examples

Extending the Higgs sector

- BSM Higgs decays and couplings. Examples:

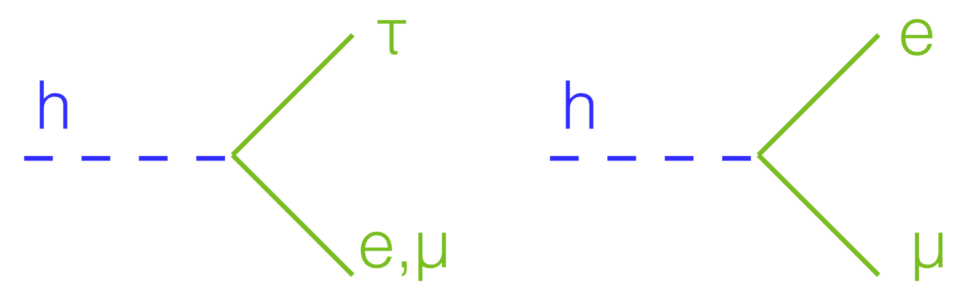
Higgs Decays to new particles



X and Y are SM particles

Flavor violating couplings

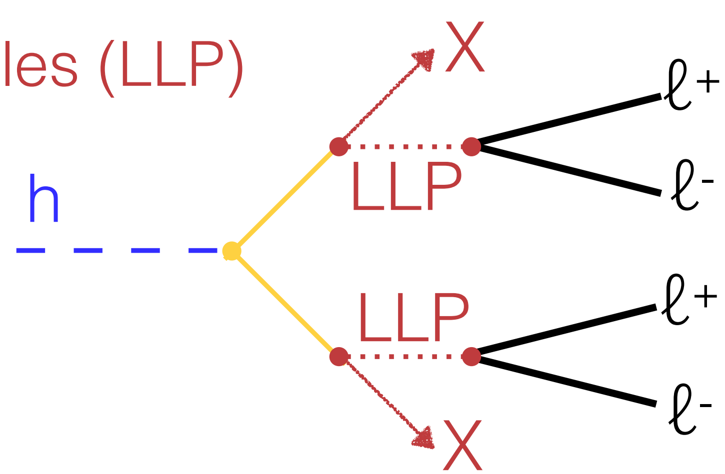
lepton decays



FV in quark sector also considered

Long lived particles (LLP)

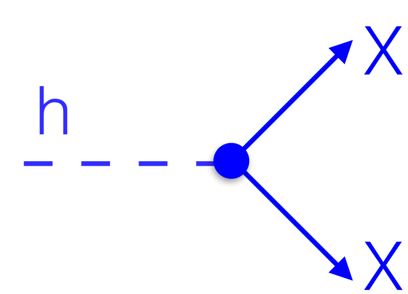
Many possible signatures that are sensitive to a broad range of lifetimes



2x2ℓ lepton jets

Nx2ℓ (4x2ℓ…) also possible

Invisible Decays

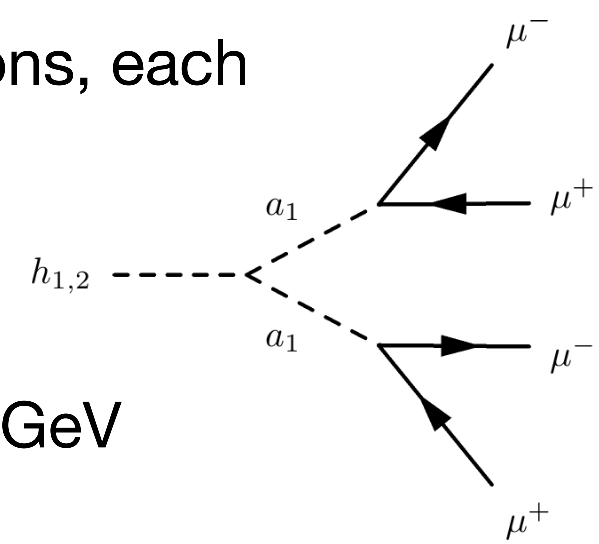


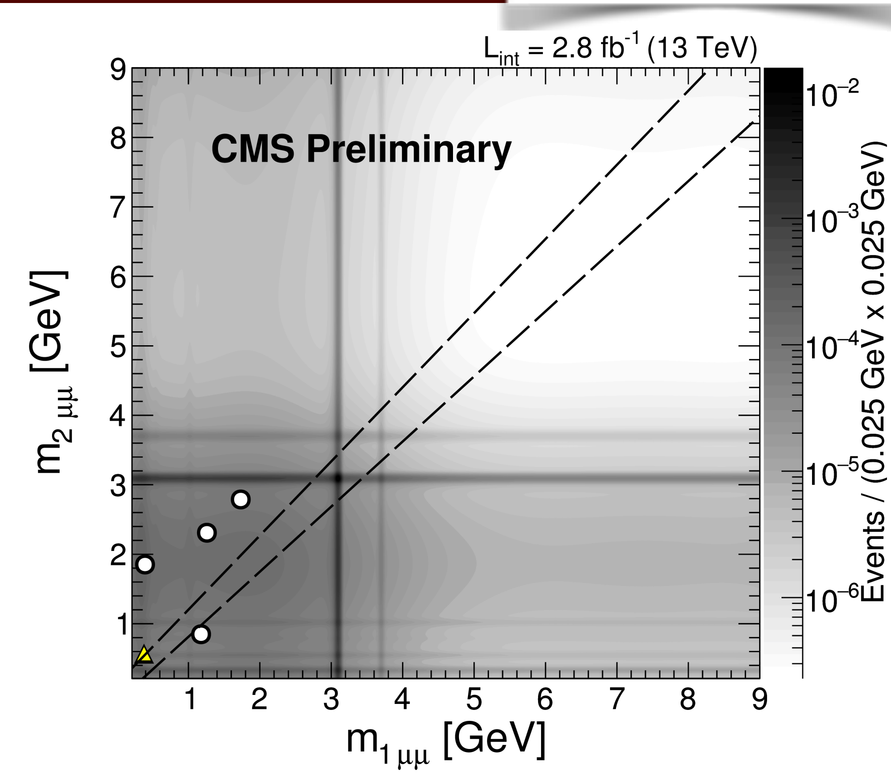
X gives E_T^{miss} signature

Verena M. Outschoorn, Search for non-standard Higgs states with 13 TeV data, Rencontres de Moriond

H→aa→μμμμ (NMSSM)

- Signal:
  → Pair production of new light bosons, each decaying into a pair of muons

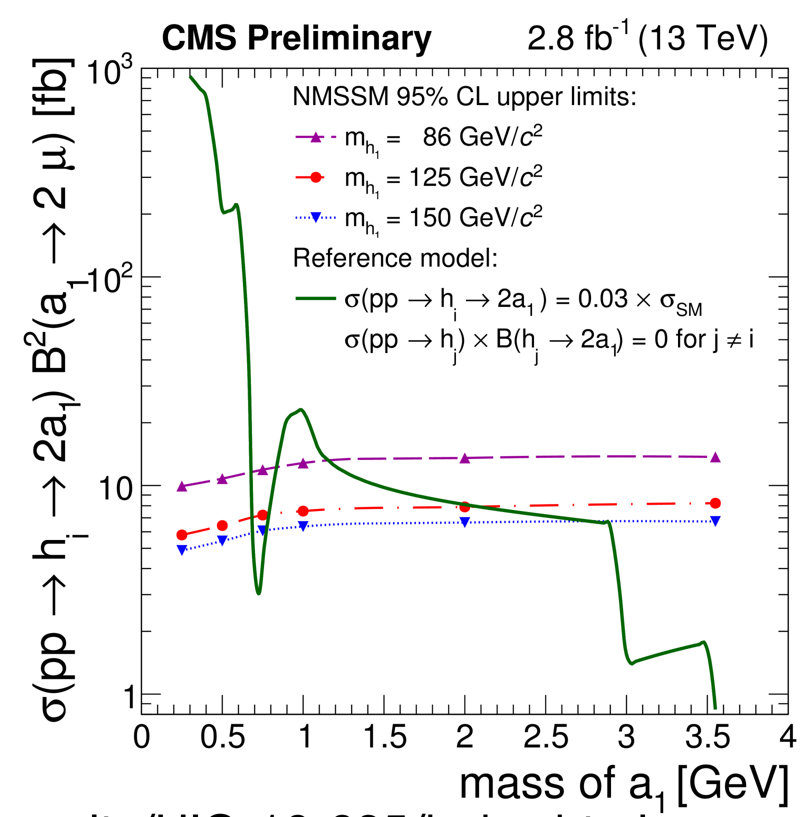




- Selection:
  → P_{T1}>17 GeV; $|\eta_1|$ <0.9; $P_{T2,3,4}$ > 8 GeV
  → $|z_{1\mu\mu} - z_{2\mu\mu}|$ < 1 mm

- Main background:
  → $b\bar{b}$, double J/Ψ (SPS and DPS)

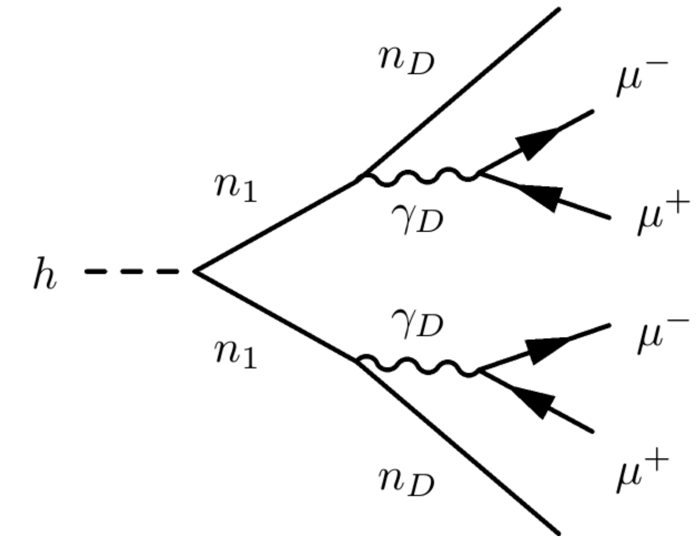
- Excess searched on the diagonal:
  $|m_{1\mu\mu} - m_{2\mu\mu}| < 0.13$ GeV $+ 0.065(m_{1\mu\mu} + m_{2\mu\mu})/2$
  → Model independent search, benchmark model is NMSSM
  → Assume SM-like production σ for $h_{1,2}$ to simplify interpretation



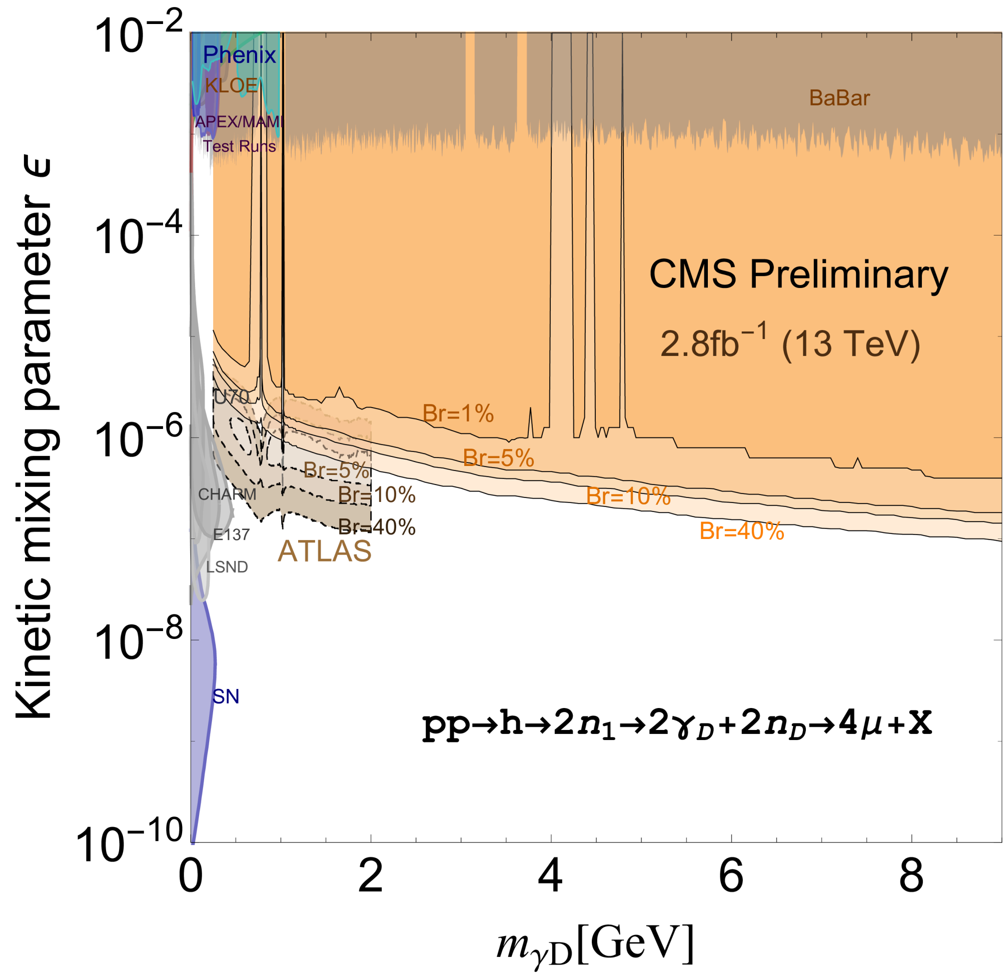
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-035/index.html

H→aa→μμμμ (dark SUSY)

- Additional Benchmark: Dark SUSY
  $h \rightarrow n_1 n_1 \rightarrow n_D n_D \gamma_D \gamma_D + X$
  → Dark photons could have an appreciable life-time before decay
  → Dark photons are generated with m(γ) in the range 0.25–2.0 GeV and a decay length in the range of 0–20 mm



- 95% CL limit on H boson production σ·B.R.
  → The limit set in the $[m(\gamma_D),\varepsilon]$ plane.
  → Implies model dependence when comparing to low energy results
  → Nice complementarity with ATLAS analysis searching for decays far from the interaction point



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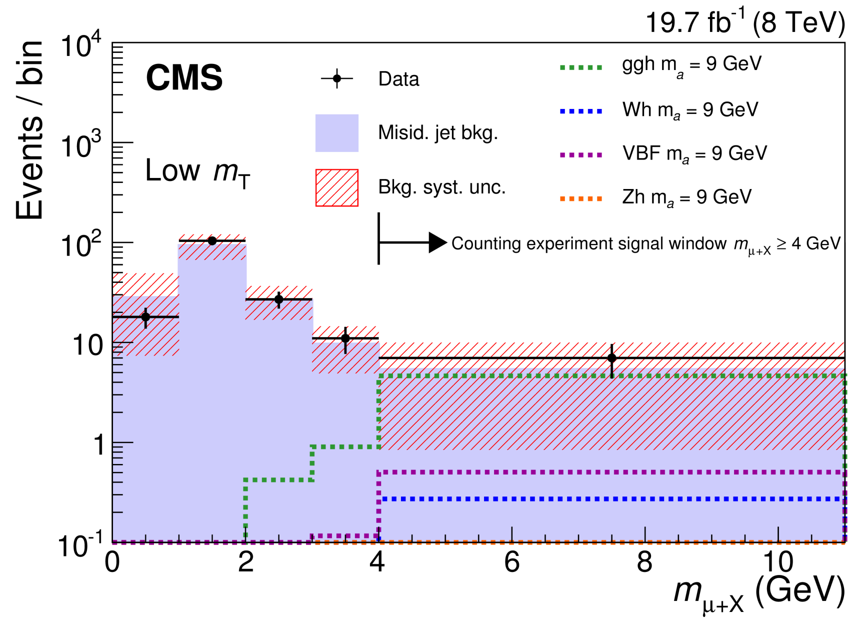
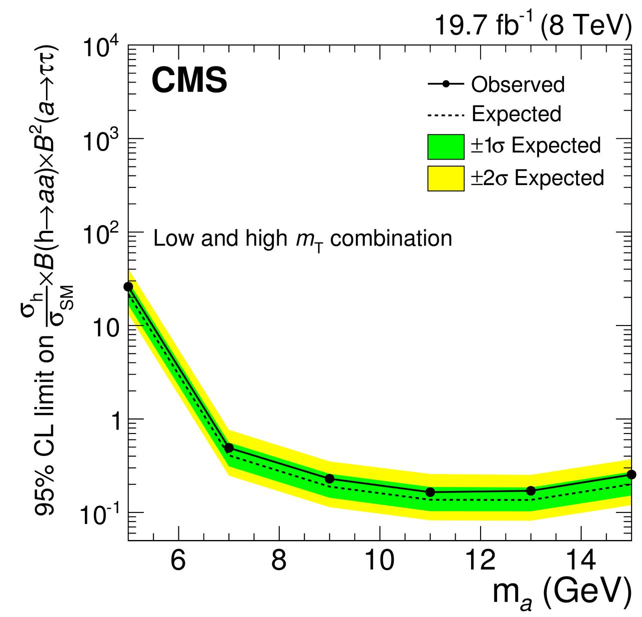
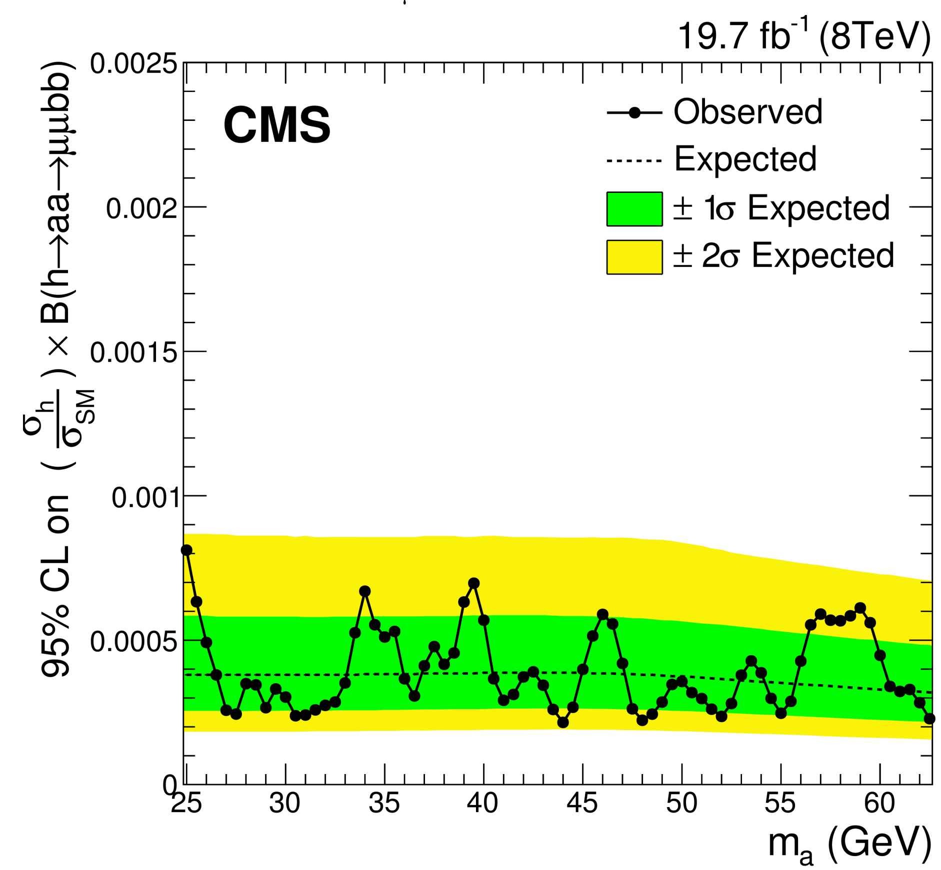
H→aa→ττττ/μμbb/μμττ

- H→aa→ττττ (from ggH/Zh/Wh/VBF)
  - → m(a) є[5-15]GeV due to Br(a→ττ)
    - → Special boosted ττ technique (one τ have to decay into a μ)
  - → 2 search regions: low/high m_T to separate production modes (m_T between high-p_T μ and E_t^{miss})
  - → Dedicated $\tau_\mu \tau_x$ reconstruction





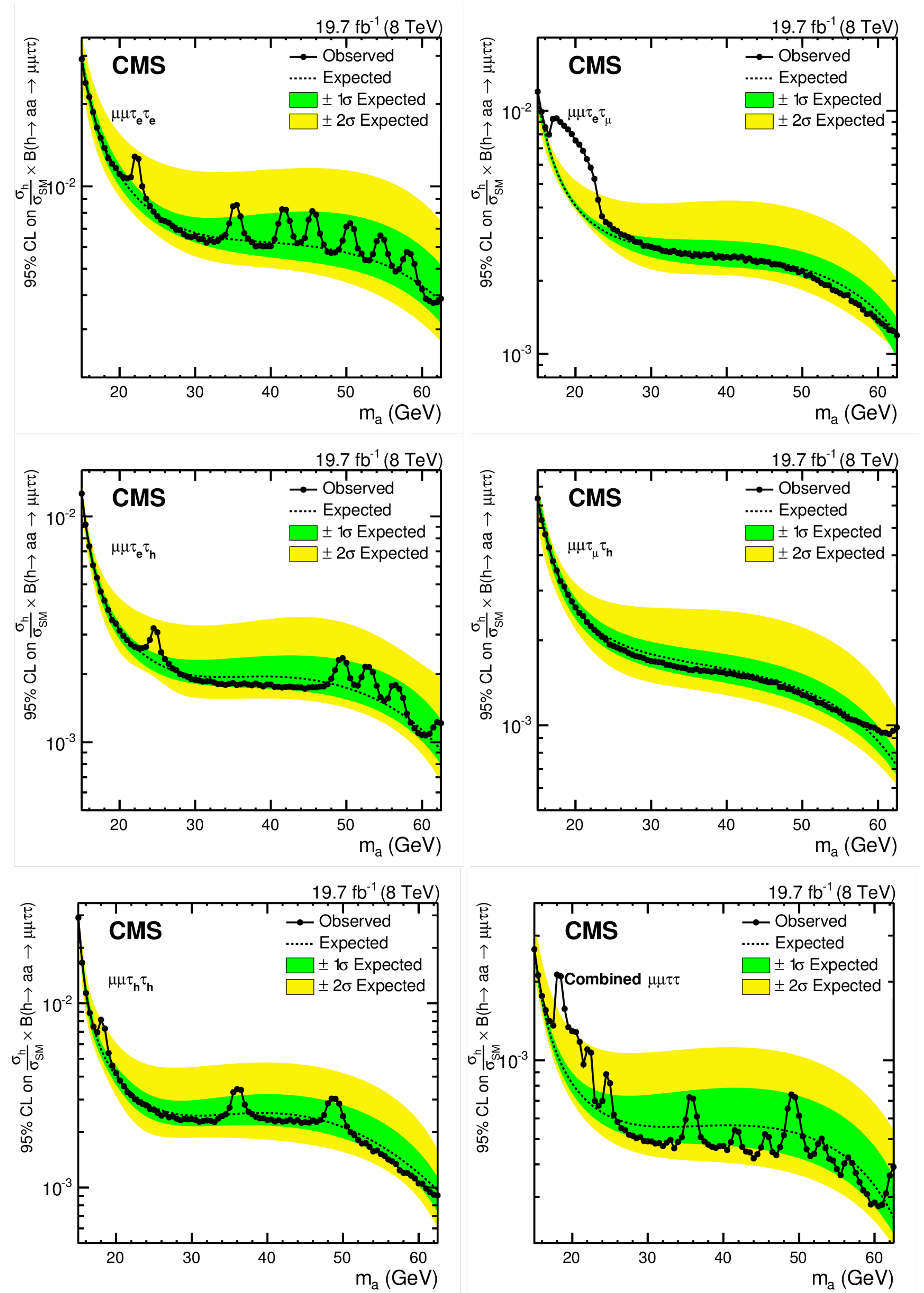
- H→aa→μμbb (from ggH)
  - → 2 muons with p_T > 24 and 9 GeV (isolated and opposite charge)
  - → 2 jets with p_T >15 GeV (b-tag: 65% eff. + 99% puruty)
  - → |m(μμbb)-125| < 25 GeV
  - → Signal shape is a weighted sum of Voigt profile and Crystal Ball



https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-015/index.html

H→aa→ττττ/μμbb/μμττ

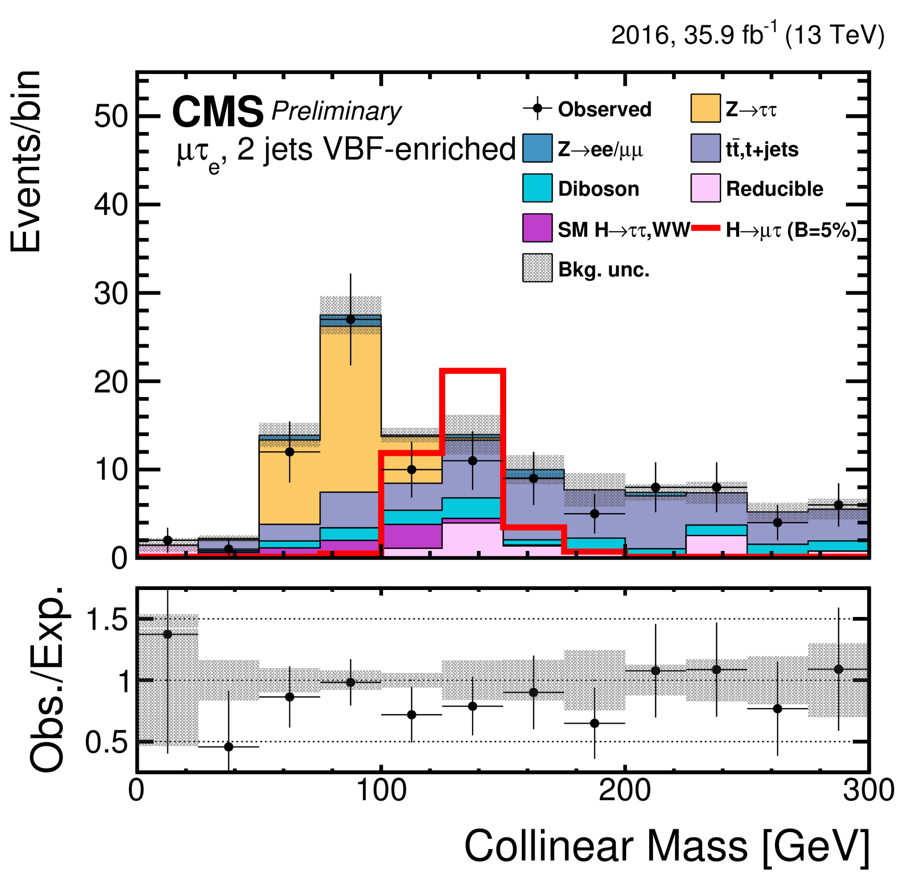
- H→aa→μμττ
  - → Five final states depending on τ decay: $\mu\mu\tau_e\tau_e$, $\mu\mu\tau_e\tau_\mu$, $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_h\tau_h$ (no $\mu\mu\tau_\mu\tau_\mu$ due to ambiguity)
  - → m(μμ) use to extract limits
  - → μμ selection:
    - → $p_T(\mu)>5$ and $|\eta|<2.4$ in $\mu\mu\tau_e\tau_\mu/\mu\mu\tau_\mu\tau_h$
    - → $p_T(\mu)>18$-9 GeV in other channels
  - → In 3-muon final state the highest in p_T is paired with the opposite one in sign (90% of the time is correct)
  - → Electron: $p_T(e)>7$ GeV, $|\eta|<2.5$
  - → Hadrons: $p_T(h)>15$ GeV, $|\eta|<2.3$
  - → If jet is b-tagged event is rejected
  - → 4 objects need to be separated
  - → $|m(\mu\mu\tau\tau)-125|<25$
  - → $|m(\mu\mu)-m(\tau\tau)|/m(\mu\mu)<0.8$

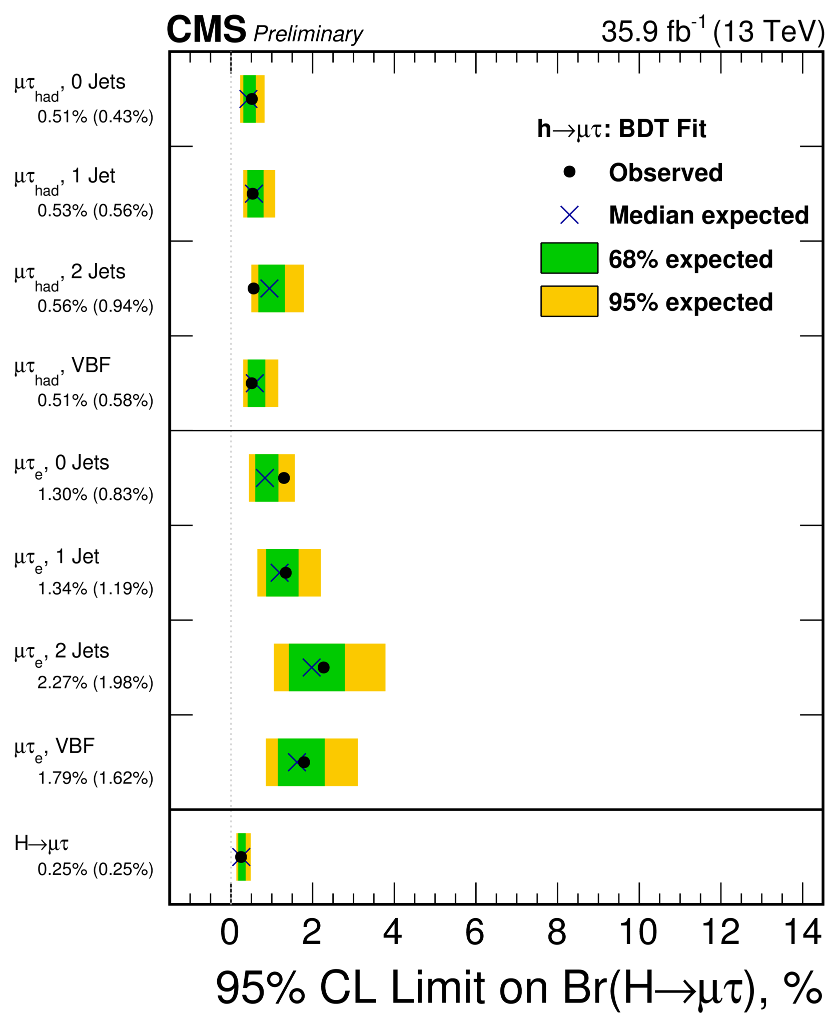


https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-16-015/index.html

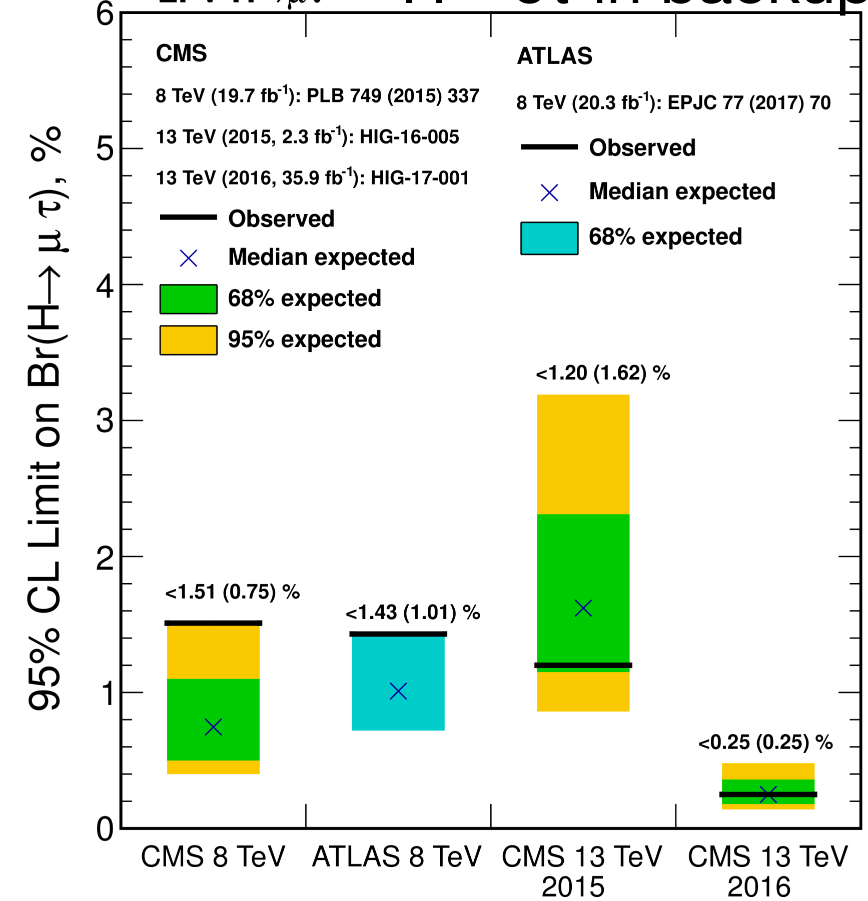
Lepton Flavor Violation

- 4 decay channels: $H \to \mu\tau_e$ / $\mu\tau_h$ / $e\tau_\mu$ / $e\tau_h$
- 4 jets categories: (0/1/2/VFB)
- Use of collinear mass (M_{coll})
  - → Estimates m(H) mass assuming ν collinear to other decays product
- Limits provided by fitting BDT discriminator (cross-check by also fitting M_{coll} shape)
- $Z \to \tau\tau$ main background (also W+jets, QCD)





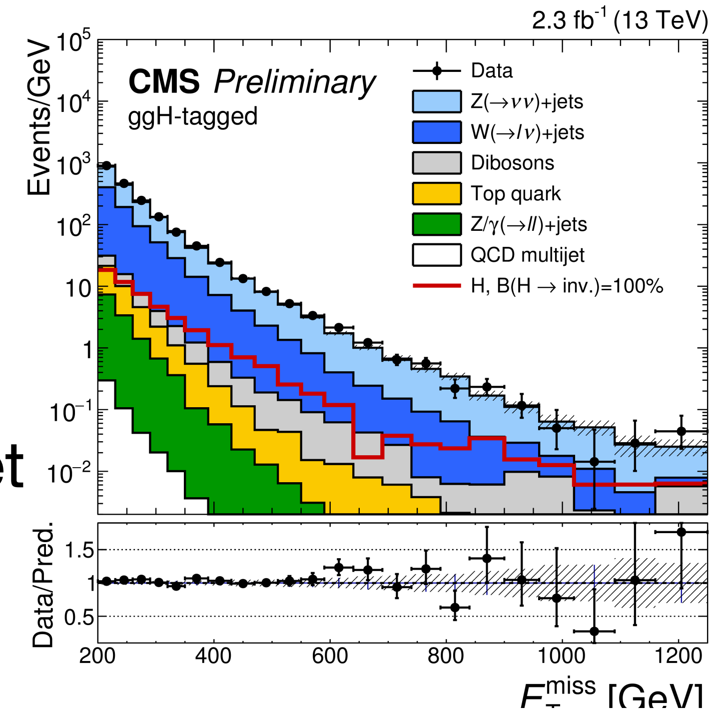
H→eτ in backup

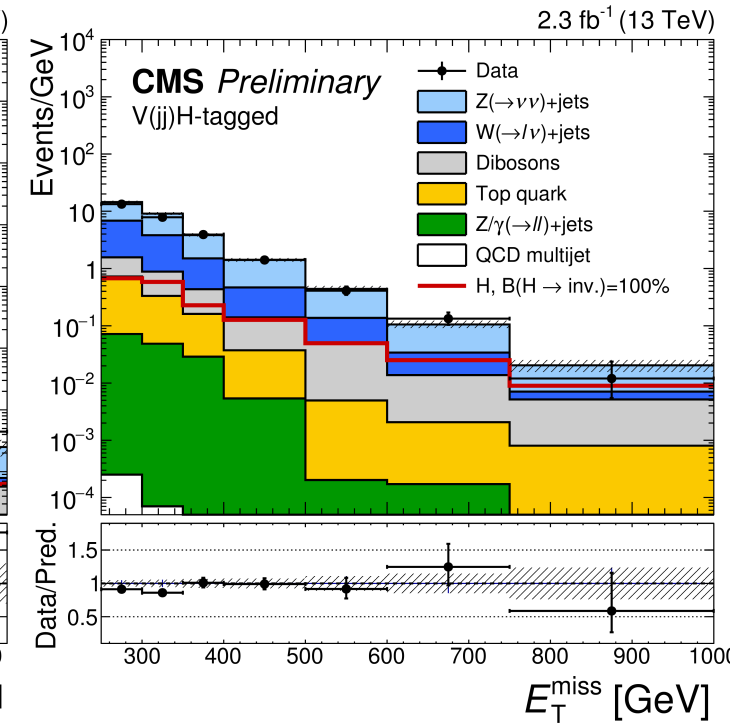


https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-17-001/index.html

Invisible Higgs

- Targeting production modes
- Results also interpreted in the context of Higgs-portal dark matter models
- Jets/lept recoiling against large E_t^{miss}
- Several exclusive regions
  - → VBF, VH (Z→ll, Z→bb V→jj), monoJet

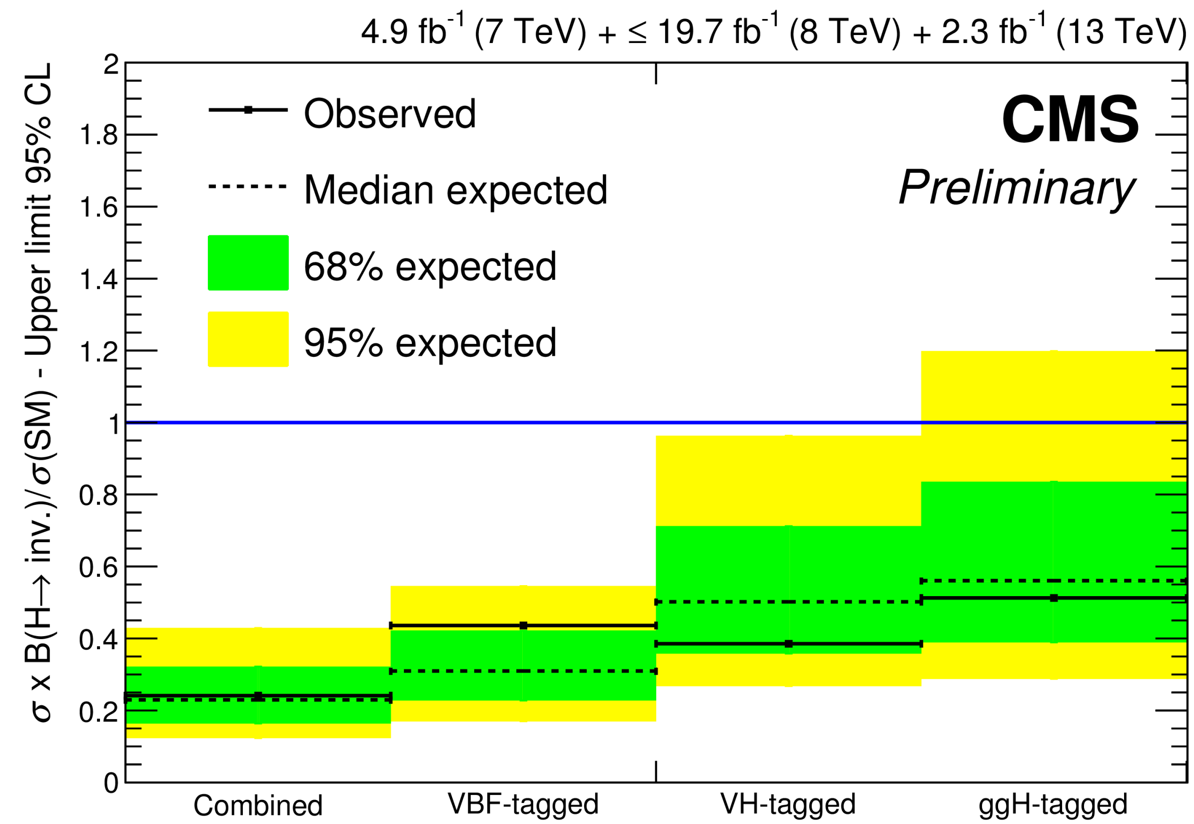




- VFB:
  - → |Δη(jj)>3.6|, m(jj)>1200 GeV
  - → E_t^{miss}>90 (200) GeV at 8 (13) TeV
  - → 8 TeV analysis has E_t^{miss} significance cut

- VH (dilepton):
  - → ZZ, WZ are main backgrounds
  - → Observable is m_T of dilepton and E_t^{miss}

- VH (dijet) and monoJet:
  - → 2 categories depending on jet properties
  - → Z(vv)+jets, W(lv)+jets main backgrounds

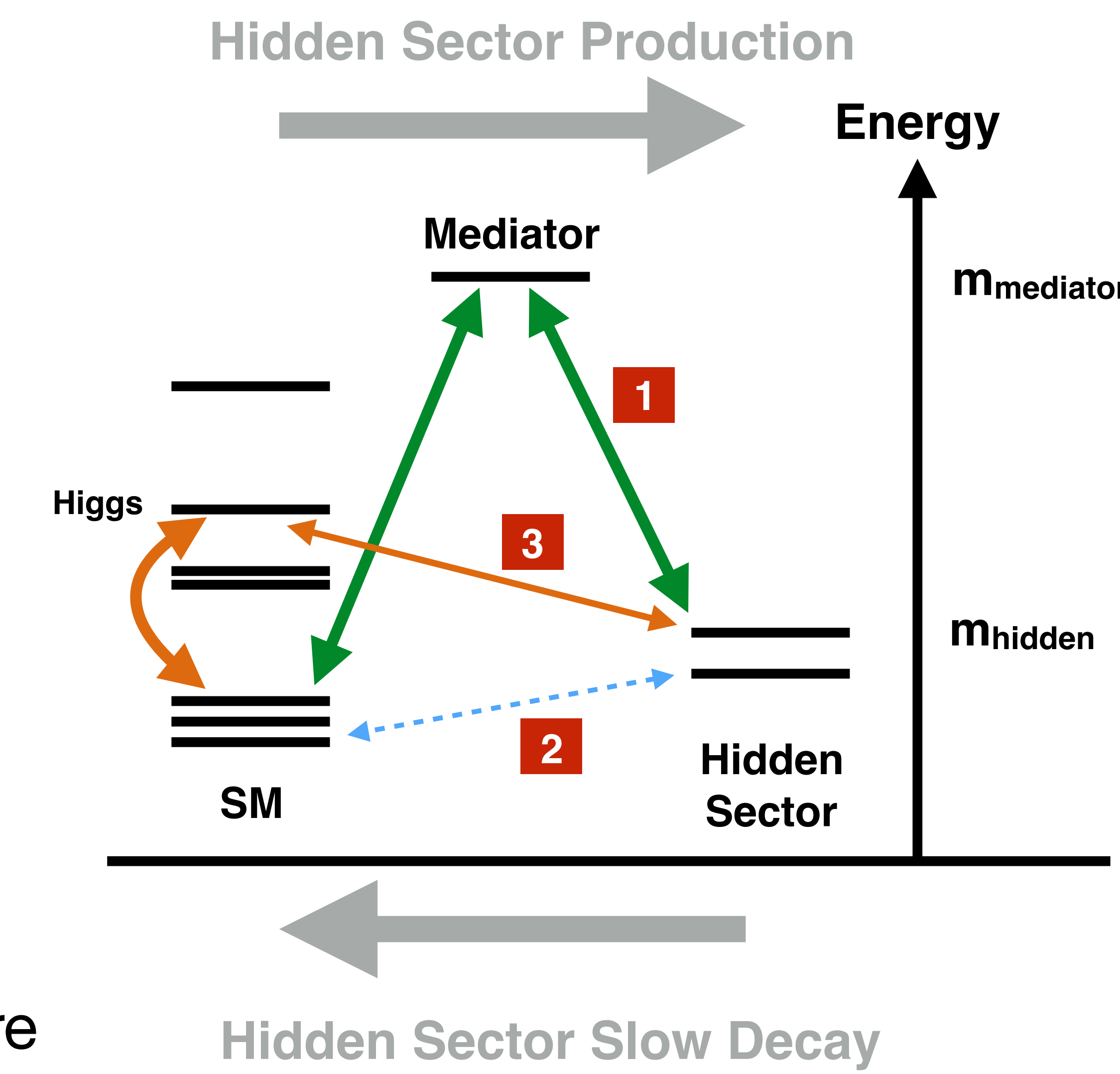


https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-016/index.html

What about hidden sectors?

❖ Quest for new physics is not one-dimensional!
  → New physics not necessarily at higher energies
  → New physics could lie at m_{hidden} < TeV
    (hidden by small coupling to SM)

❖ Possible for a hidden sector to contain just 1 species of particles with no non-gravitational interactions but…
  → BSM is motivated if the hidden sectors play a part in solving SM shortcoming
  → Hidden sectors can be connected to the SM via small effective couplings (portals)



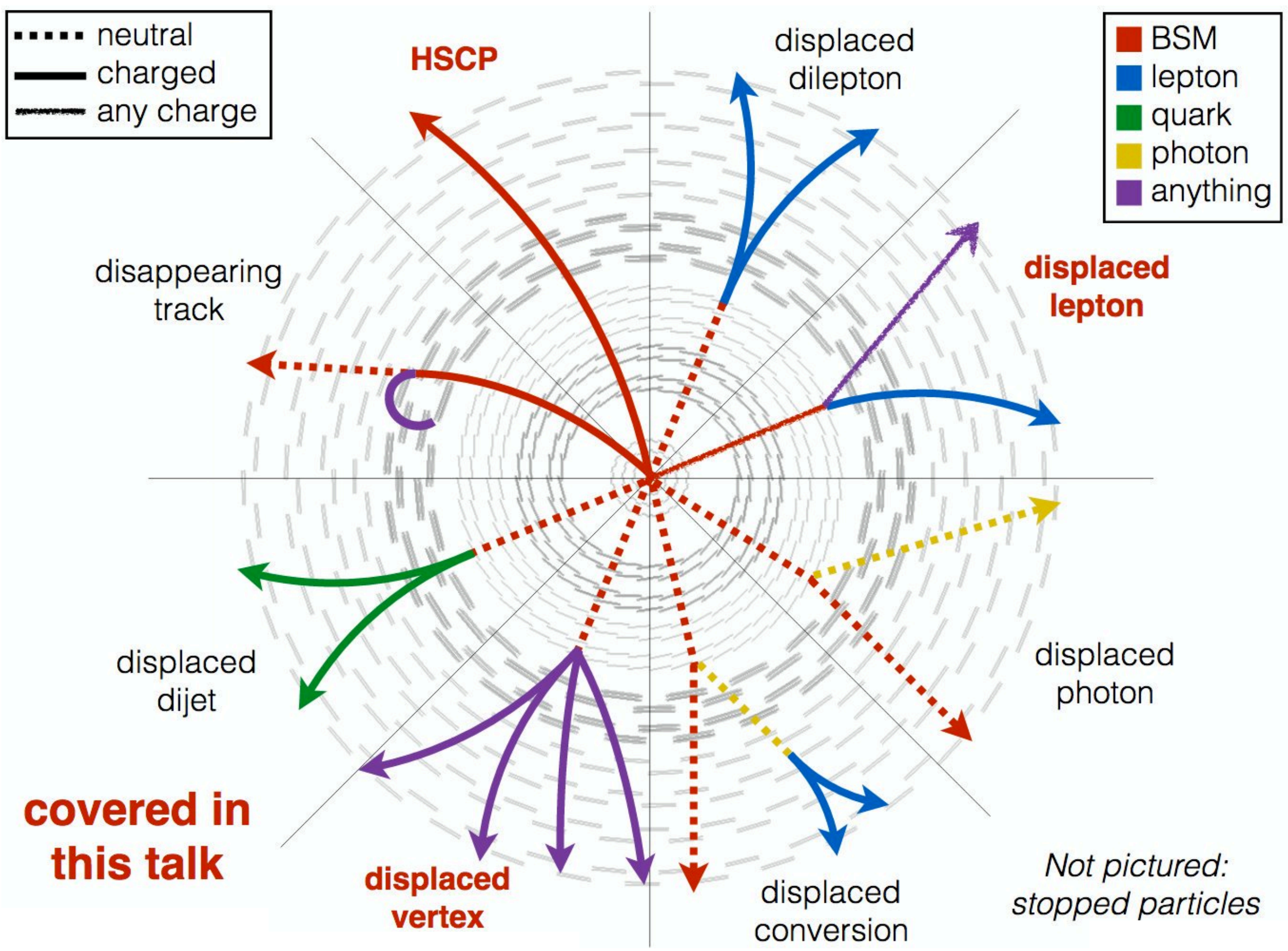
❖ Rich phenomenology depending on Mediator nature (Heavy mediator, photon-dark photon oscillation, etc…)

❖ Portal is a tiny keyhole: decay can take a long time (Long-Lived Particles, LLP)

Flashes of Hidden Worlds at Colliders, D. Curtin and R. Sundrum, Submitted to Physics Today, arXiv:1702.02524

Long Lived Particle at Colliders

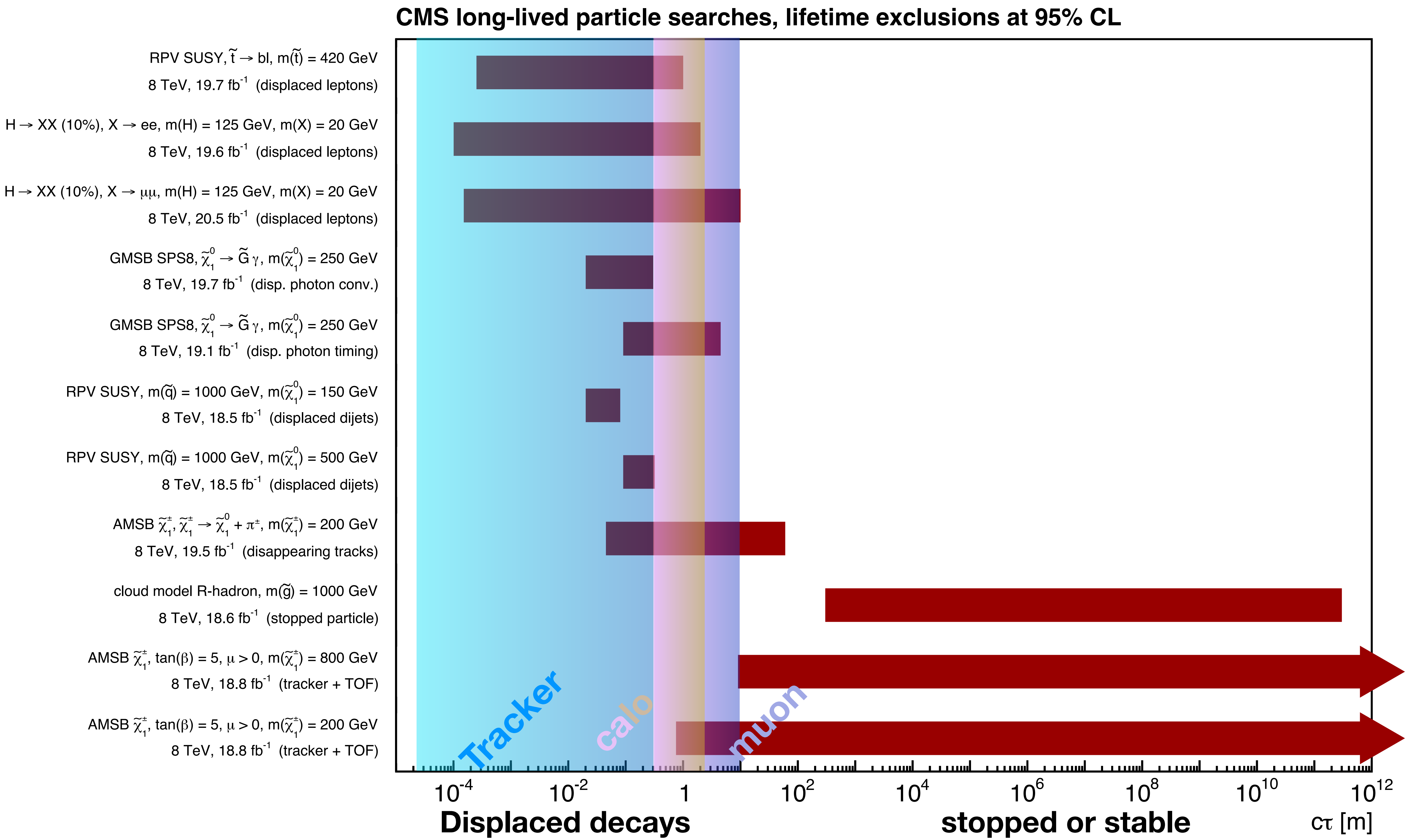
- LHC allows to probe Hidden Sectors with $m_{mediator}$ or m_{hidden} at/above the EWK scale
- High-Luminosity (HL) LHC upgrade will increase the number of collisions by factor 10 (~1.5×10^8 Higgs bosons)
- LLP production typically occurs at low rates: each individual displaced decay is so spectacular that backgrounds are orders of magnitude lower



- LLP in thermal equilibrium with the SM plasma in early Universe
- As the universe cooled, first elements were formed (Big Bang Nucleosynthesis, BBN) took place
- With few exceptions, LLPs decaying during/after BBN would disrupt the process
  → LLP parameter space is finite!

Karsten Jedamzik. Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles. Phys. Rev., D74:103509, 2006.

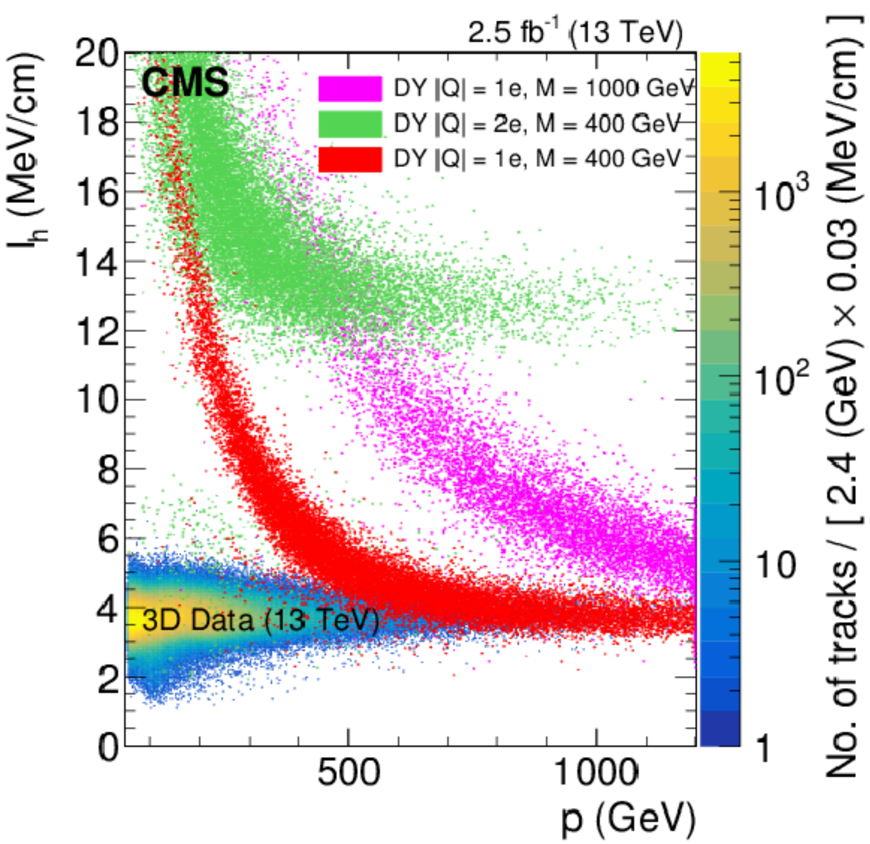
Long Lived Particle at CMS

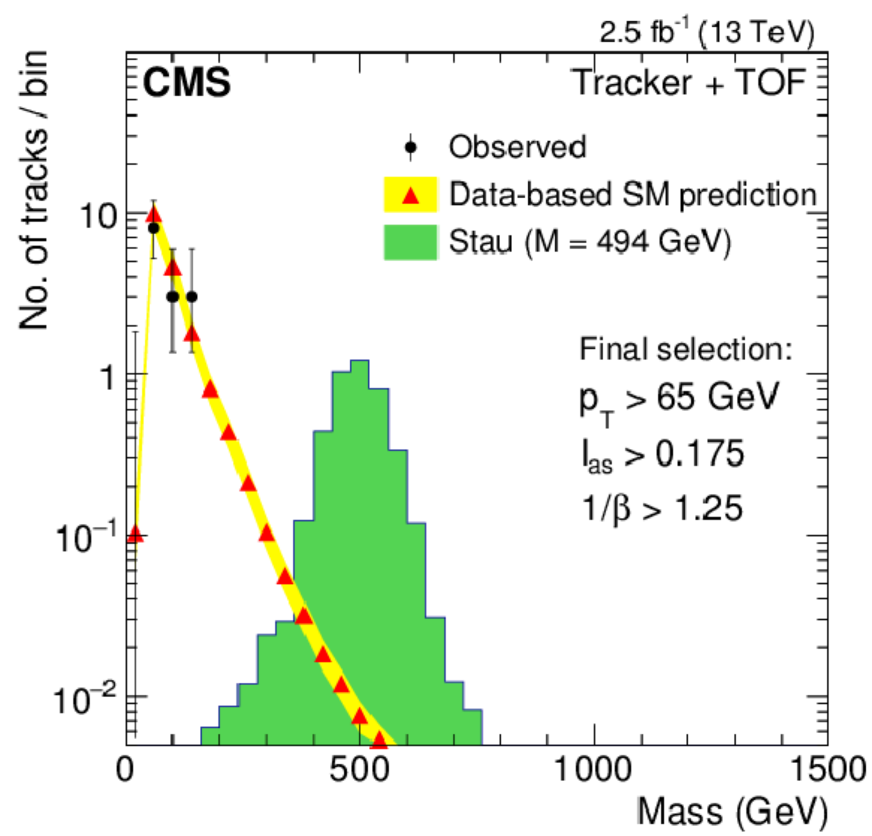


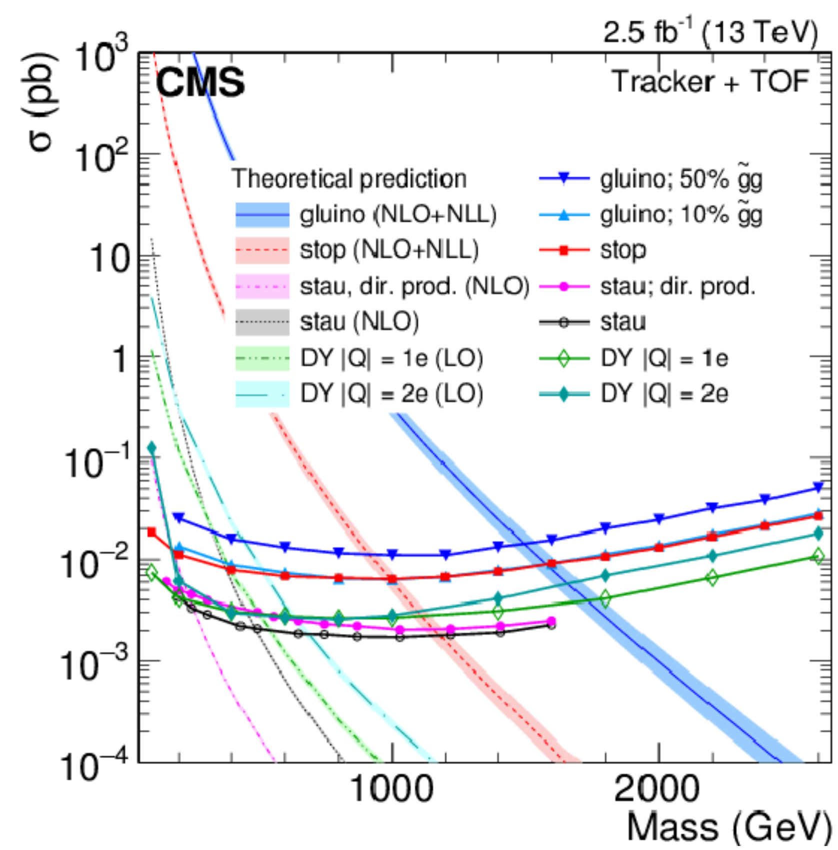
Decays to dark sector particles at CMS: long-lived signatures Ted Kolberg (Florida State University) Dark Interactions 2016, BNL

Charged Long Lived Particles

- HSCP might have high momentum, speed smaller than *c*, and/or Q not equal to the elementary charge ±e
- Possible to distinguish |Q|≥1e particles with $\beta < 0.9$ from light SM particles using E loss
- Two ways to reconstruct HSCP:
  - → Requiring tracks only in the silicon detectors (tracker-only)
  - → Requiring tracks in both the silicon detectors and muon system (tracker+TOF)
- Muon trigger more efficient than E_t^{miss} trigger
- Very well reconstructed track (muon) on the tracker-only (tracker-TOF) analysis



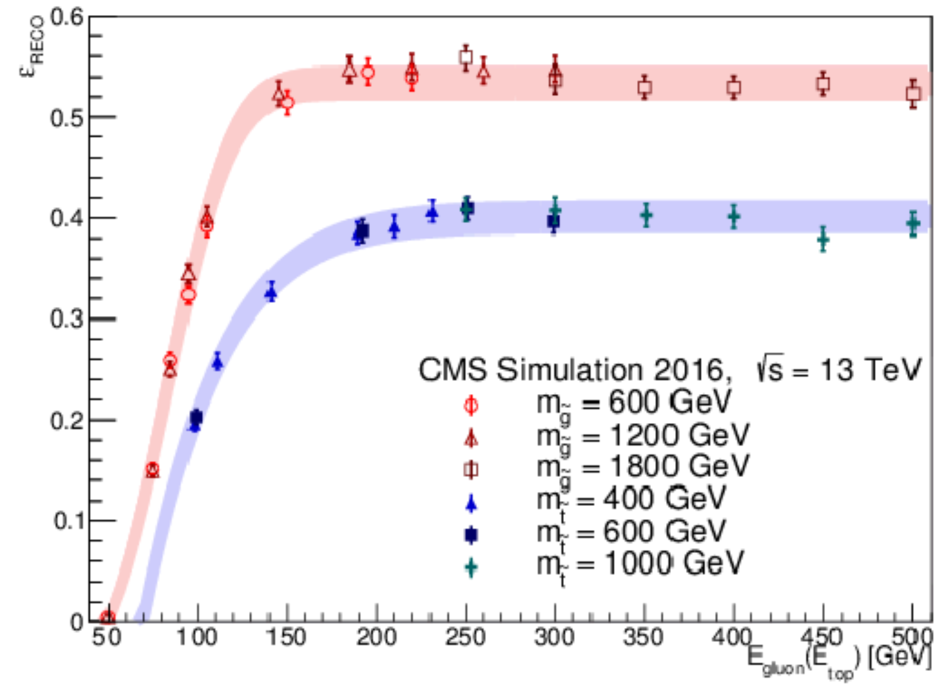




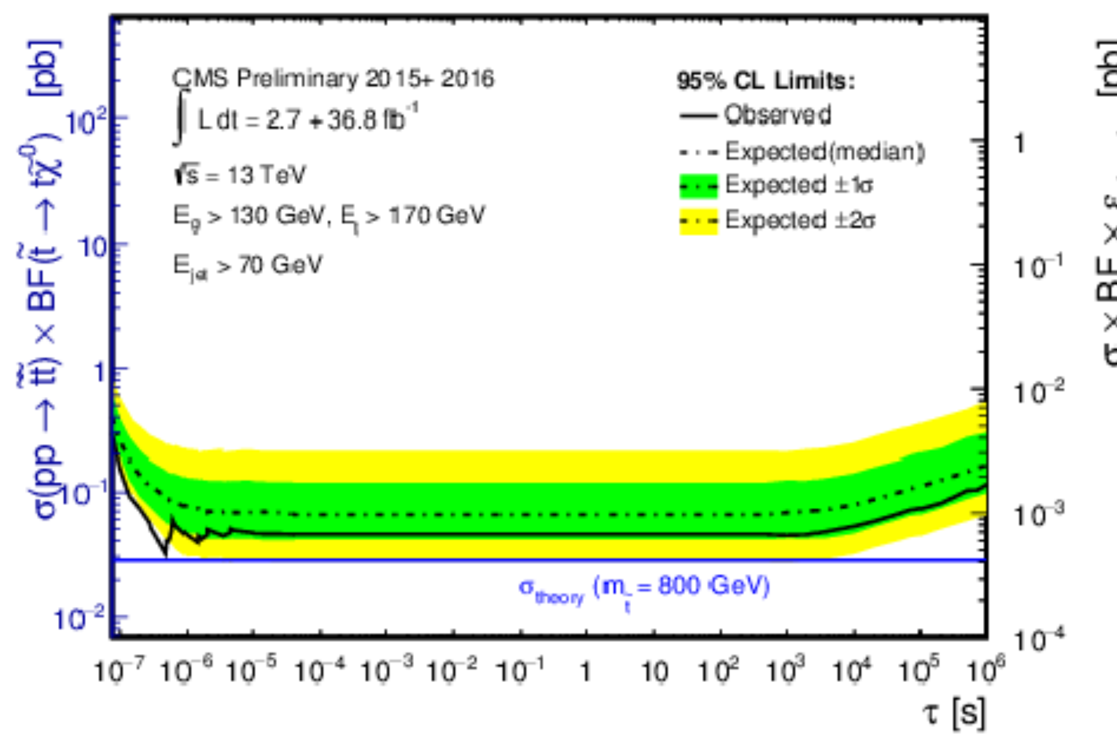
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-15-010/index.html

Stopped Long Lived Particles

- LLP (gluinos, stops..) could be pair produced and hadronize into R-hadrons that interact with detector material (nuclear interactions & ioniz.)
  - → Below a critical velocity, kinetic energy go to zero and (some later time) decays
- If LLP decays to at least one SM particle:
  - → High-energy jet not coincident with collisions
  - → Only rare background processes



- Dedicated trigger used to select out-of-time events
  - → At least two BXs away from bunches passing the detector
  - → Trigger requires at least one jet with E>50 GeV
  - → Calorimeter-based jet with E>70 GeV
- Main background: halo muons
  - → Can emit photons striking calorimeters
  - → Reduced by rejecting events with at least two DT segments in the outermost barrel station



http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-004/index.html

Conclusions

- Program of dedicated searches for non-standard decays of the Higgs boson ongoing
  - → Room for BSM Higgs boson decays
  - → Signatures motivated by broad range of phenomenology
- No stone should be left unturned
  - → Quest for new physics is not uni-dimensional!
  - → Absence of new physics could point us toward the new nature of the Universe
- CMS has an expanding program:
  - → Boosted topologies, Low-mass searches, Long-lived particles…
- Long Lived Particles searches start from trigger design
  - → Triggering on LLPs involves either dedicated triggers or generic triggers
  - → Trends from Run1 to Run2 have mostly been to either raise thresholds in order to cope with pileup or design a more signal-specific trigger

Backup

Extending the Higgs sector

- Higgs sector could result extended in many ways.

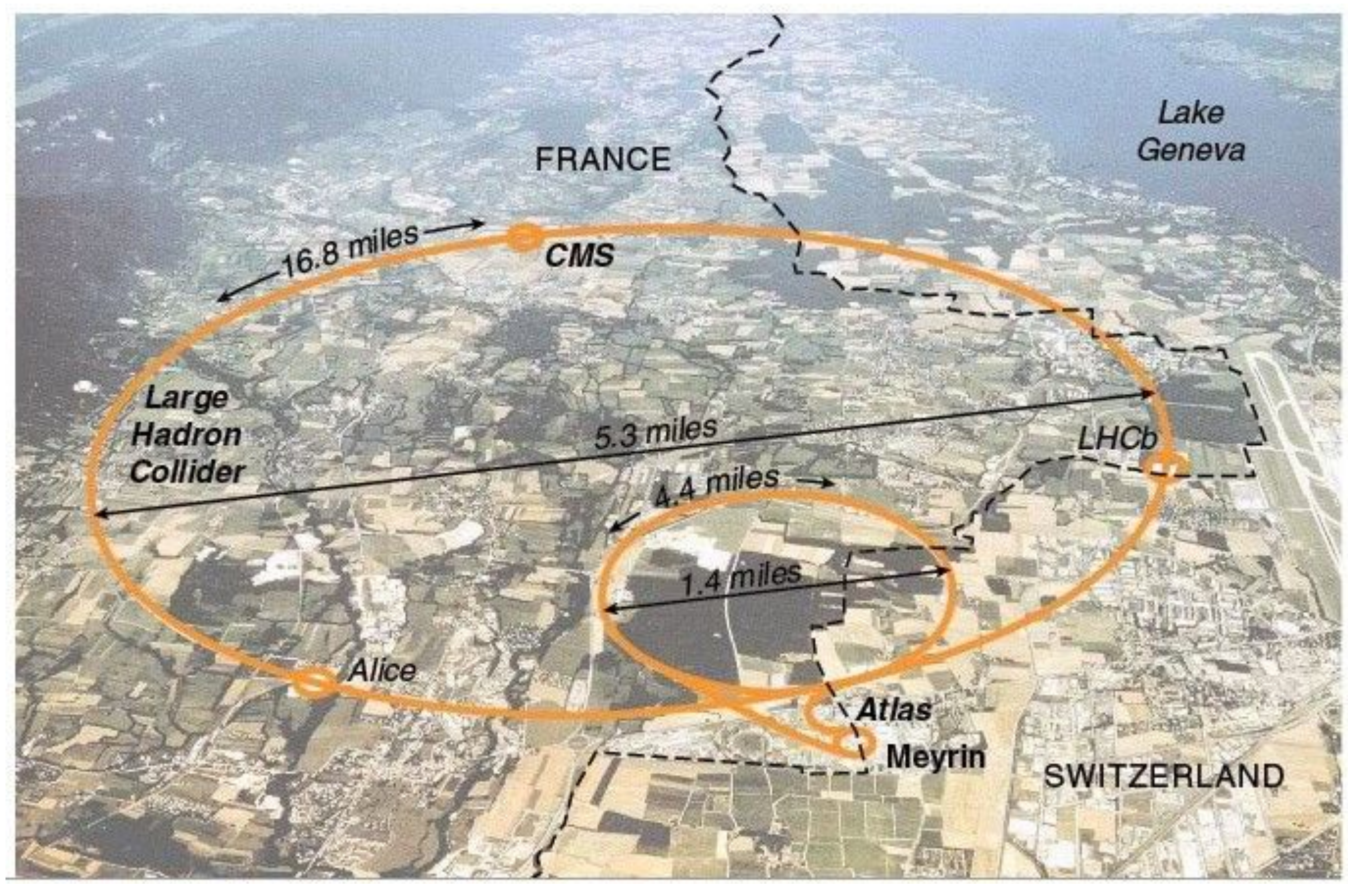
Model	Description	Higgs bosons
SM (one doublet of complex scalar fields)	3 d.o.f. give mass to $W^{\pm}$ and Z, Yukawa couplings generate fermion mass	h
SM + real singlet	Used in the context of EWK baryogenesis, DM…	h, H
2HDM (contains a second doublet)	Prerequisite for SUSY, natural in GUT, DM originating from 2HDM	h, H, A, $H^{\pm}$
2HDM + complex singlet (e.g. NMSSM)	Solve the mu-problem in MSSM (where H(125) is unnaturally heavy)	h_1, h_2, h_3, a_1, a_2, $H^{\pm}$
SM + triplet	Natural explanation for small neutrino masses	h, H, A, $H^{\pm}$, $H^{\pm\pm}$

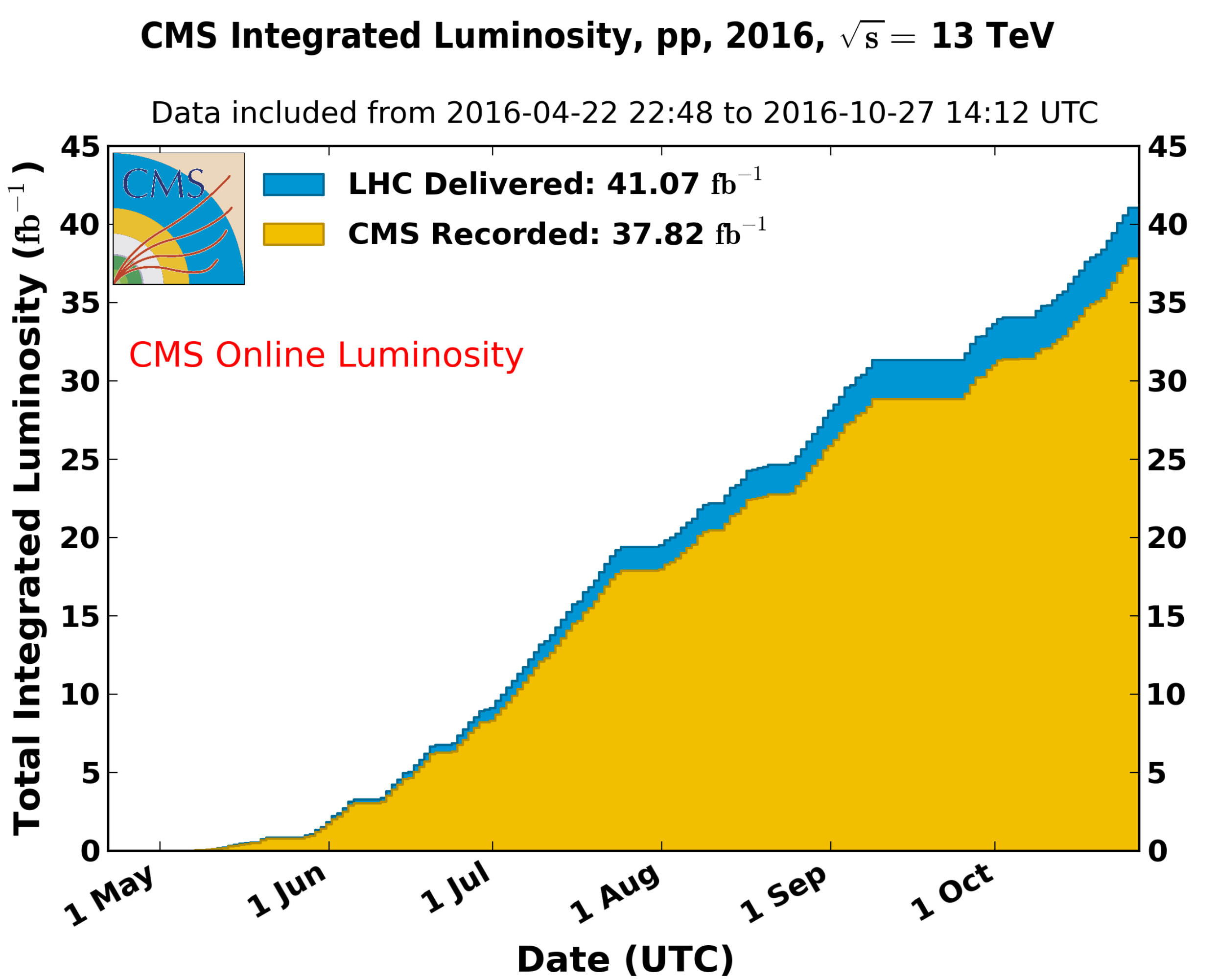
The Large Hadron Collider

- Run 2 is officially started!
  → About 3 fb^{-1} collected in 2015
  → 37.8 fb^{-1} by the end of 2016

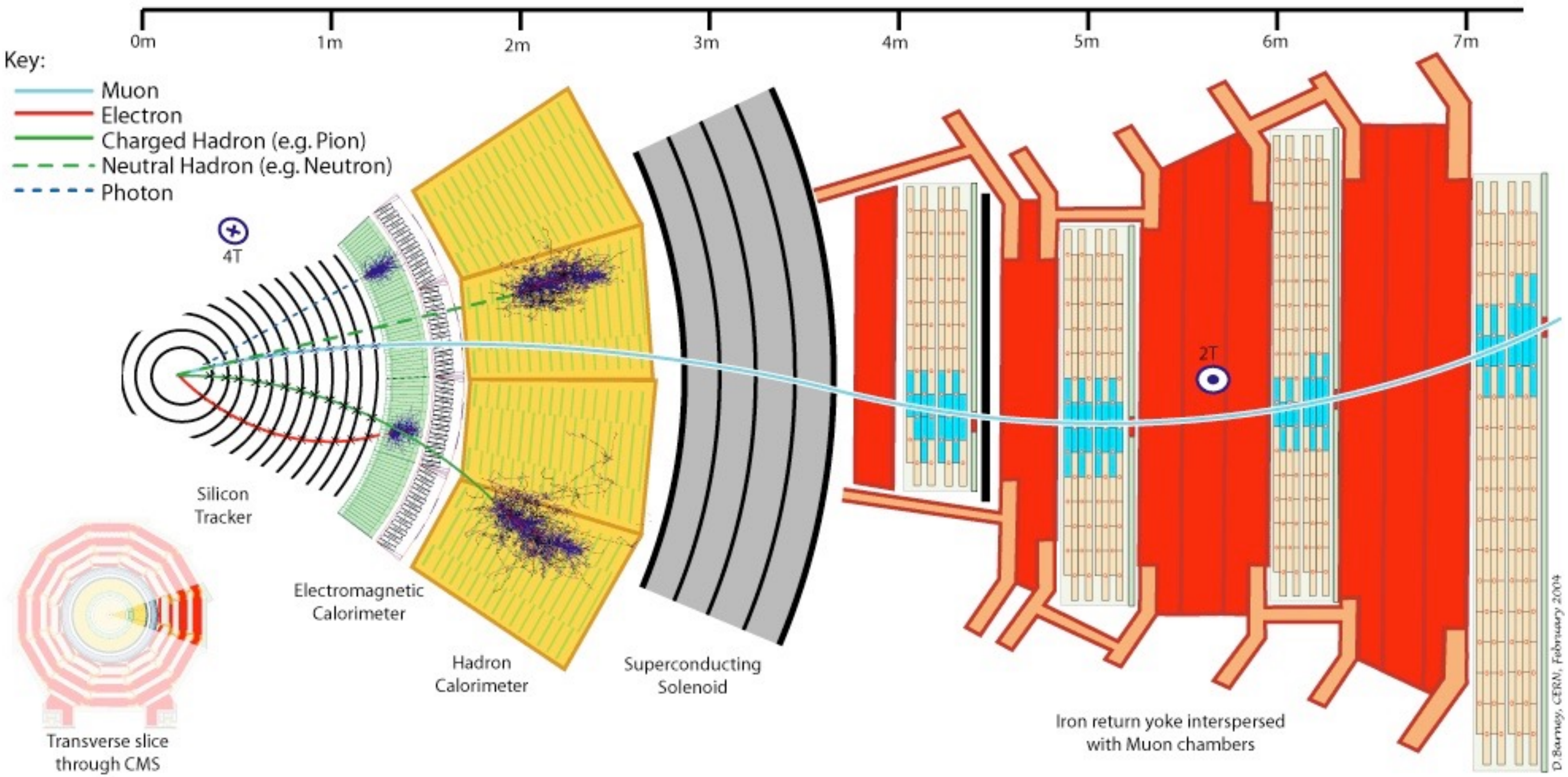
- Comparison with 8 TeV:

• 160% larger collision energy → $\sqrt{s}$=13 TeV
• 200% larger number of bunches → 2800 bunches
• 200% larger pileup → 40 interactions/crossing
• 33% smaller β* → 40 cm
• 170-220% larger peak Lumi. → (13-17)x10^{33} $cm^{-2}s^{-1}$





The Compact Muon Solenoid



Heavy Higgs searches in Run 1

- Several analysis considered:
  - → H → WW/ZZ (145<m<1000 GeV), 55 event categories in WW(2l2v), WW(2l2q), ZZ(4l), ZZ(2l2v), ZZ(2l2q).
  - → A/H/h → ττ (90<m<1000 GeV), sensitive variable is $m_{\tau\tau}$. ($\tau_\mu\tau_\mu$, $\tau_e\tau_\mu$, $\tau_\mu\tau_h$, $\tau_e\tau_h$ and $\tau_h\tau_h$) and → μμ (115<m<300 GeV). Most sensitive CMS search to all three neutral Higgs bosons in the MSSM.
  - → $H^\pm$ → τν-tb (τν dominates sensitivity). Divided in low and high mass region.
  - → A/H → bb (100<m<900 GeV). Prod. in assoc. with b-jets. Discriminant variable: invariant mass of the 2 leading b-jets.
  - → A → ZH (140<m<1000 GeV). Z goes into leptons, H into b-quarks or τ. In the llbb final state discriminating variables are m(bb) and m(llbb) (2-dimensional shape analysis). The decay A → ZH is 2HDM specific. In MSSM it is kinematically not allowed (A and H are degenerate in mass, with $m_H \geq m_A$)

- Two ways to obtain limits:
  - → Templates for the full signal prediction for each value in the exclusion plane of the considered scenario (m_A-tanβ for MSSM; m_H-tanβ for 2HDM).
  - → 95% CL limits on σ·Br of a single, narrow-width resonance (except for H → WW ZZ analysis). Limits translated into the exclusion plane.

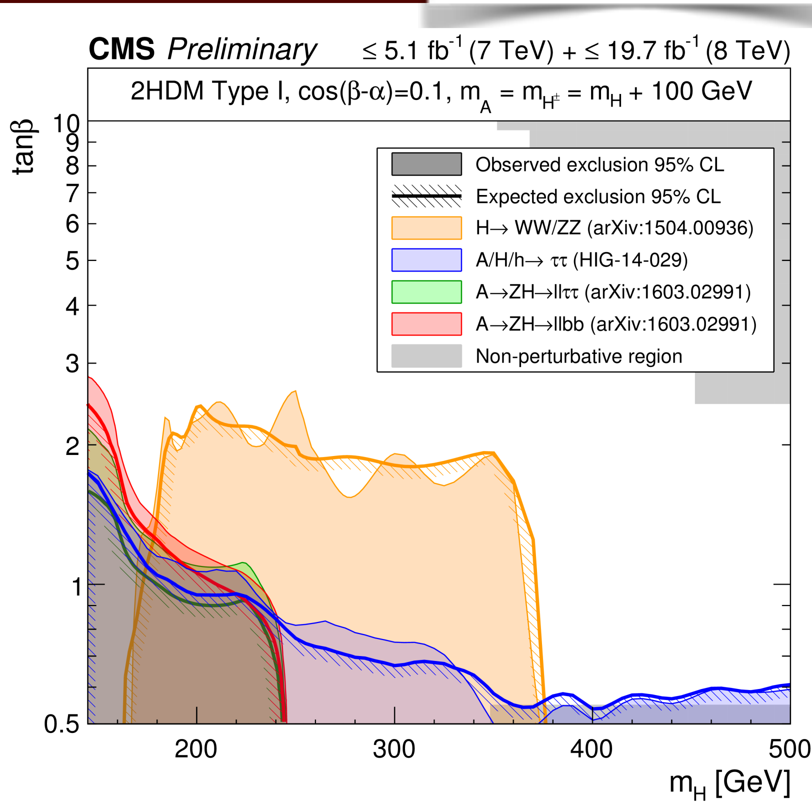
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-007/

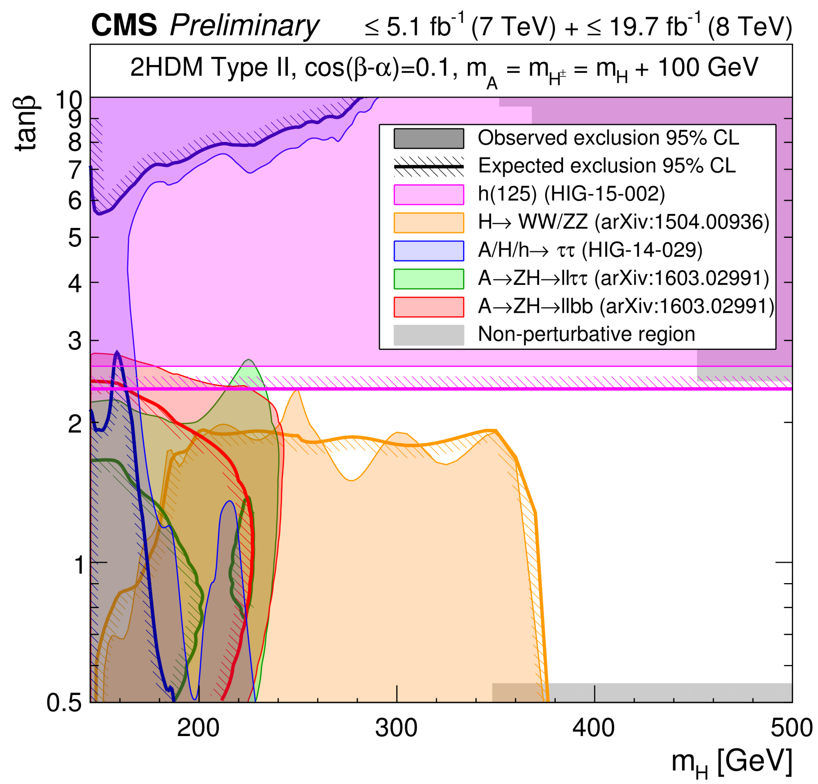
- By definition the whole parameter space that is displayed is mostly compatible with the constraints imposed by the couplings of the Higgs.
  - → Observed exclusion: transparently filled areas
  - → Expected exclusion: slightly darker shade| (with hatching)
  - → The gray shaded areas: non-perturbative or unstable.

- Lower boundary in m_H marks the kinematically allowed region for WW/ZZ. Upper boundary coincides with the opening of the decay into top-quarks.

- A→ZH analysis sharp edge at $m_H \sim 240$ GeV coincides with opening of the decay of the A into top-quarks. Final state llbb shows the larger expected exclusion range.

- A/H/h → ττ: for type-I the dominant contribution to the exclusion originates from the production via gluon fusion.





https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-007/

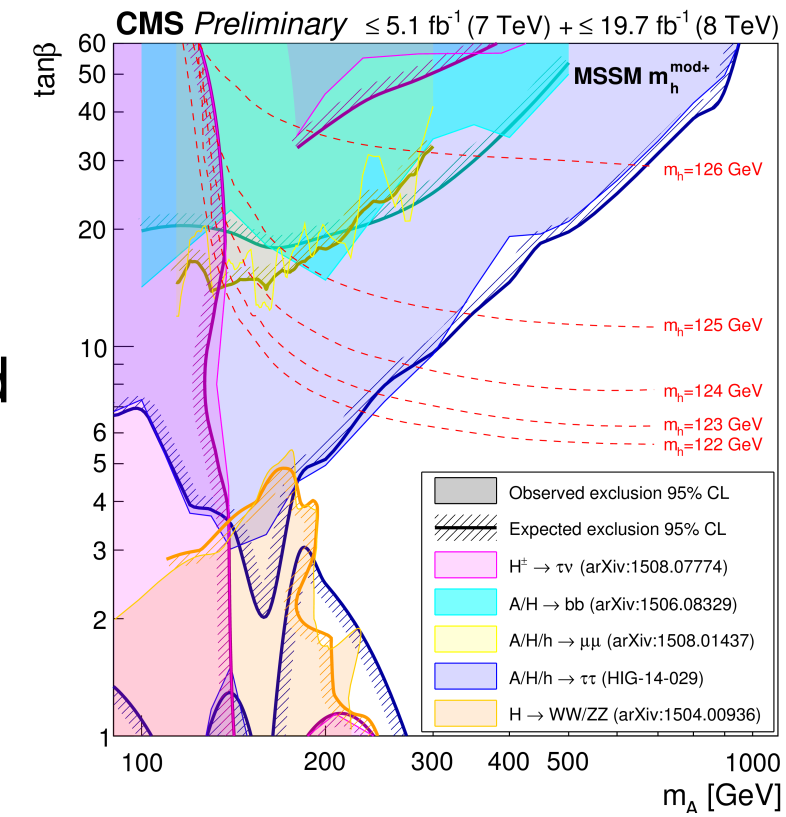
Heavy Higgs searches in Run 1

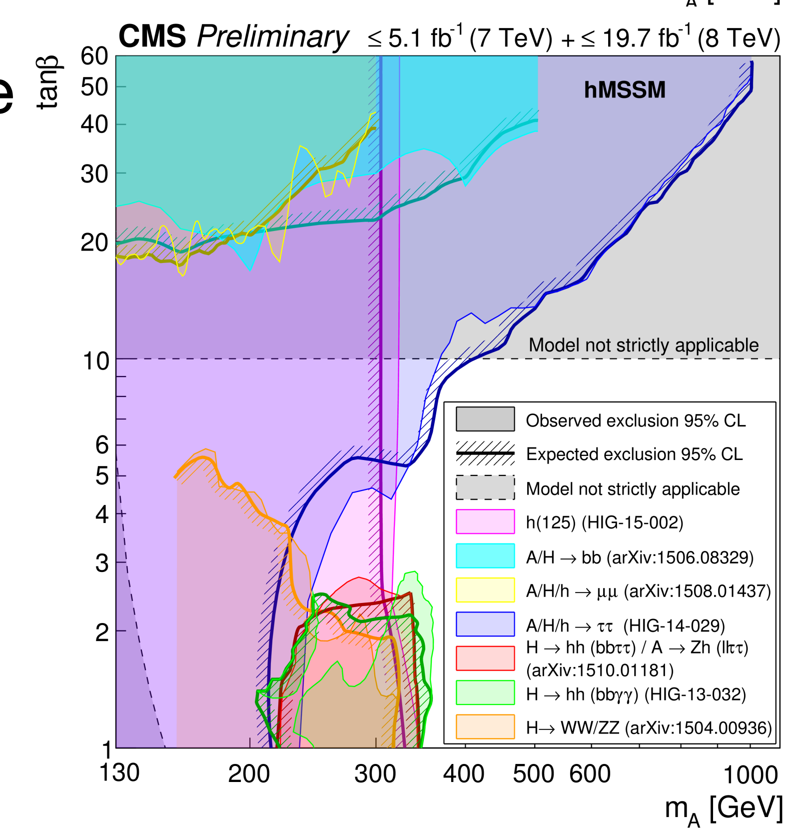
- Exclusion up to tan β ≈ 60 for masses up to m_A=1 TeV. For larger values of tanβ predictions in turn unstable.

- Most sensitive search: A/H/h → ττ (unable to separate S and B due to the presence of Z → ττ events with $m_Z \approx m_A$). The strongest exclusion sensitivity for high values of m_A and tanβ.

- Supported by the A/H → bb and A/H/h → μμ searches. Note: coupling of the Higgs bosons being proportional to the mass of the final state particle + difficulty to distinguish the signal from the large background from QCD multi-jet (in the case of b-quarks).

- H → WW/ZZ search leads to an exclusion for low values of m_A and tan β, where the H-coupling to vector bosons allows for a significant branching fraction in the $m^{mod+}{}_h$.

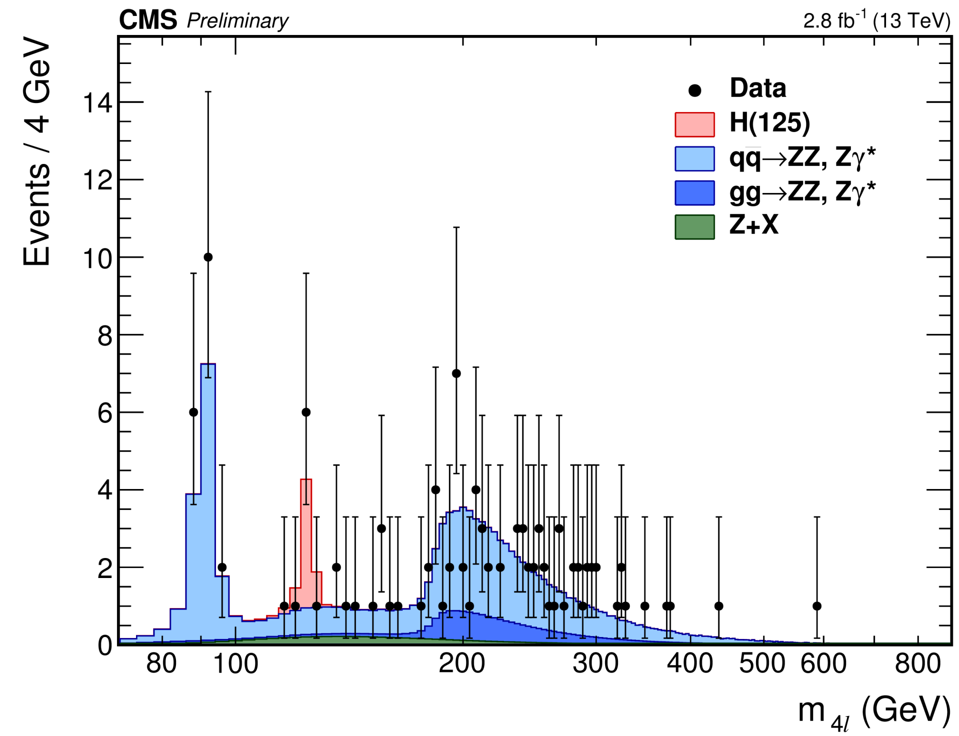




https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-007/

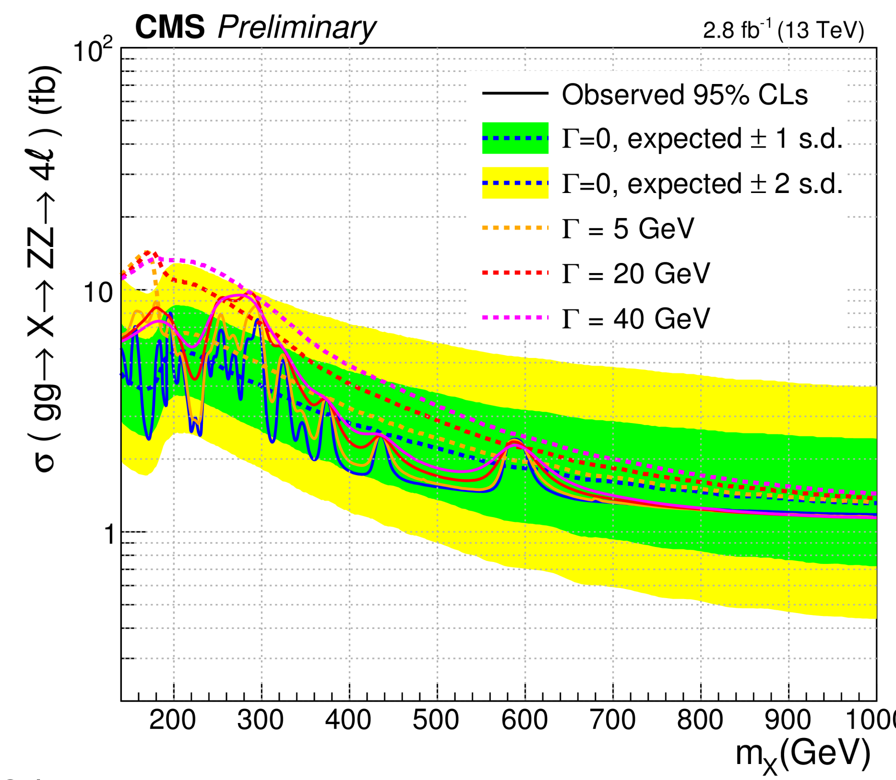
H→ZZ→4l @13 TeV

- Signal:
  - → H → ZZ → 4l (l = e,μ): analysis measures both SM-H and limits on additional resonances.
  - → Significance for SM-H: 2.5σ



- Backgrounds:
  - → ZZ (irreducible): estimated by simulation
  - → Z+jets, tt, Zγ + jets, WW+jets, WZ + jets (reducible): estimated by two independent control regions

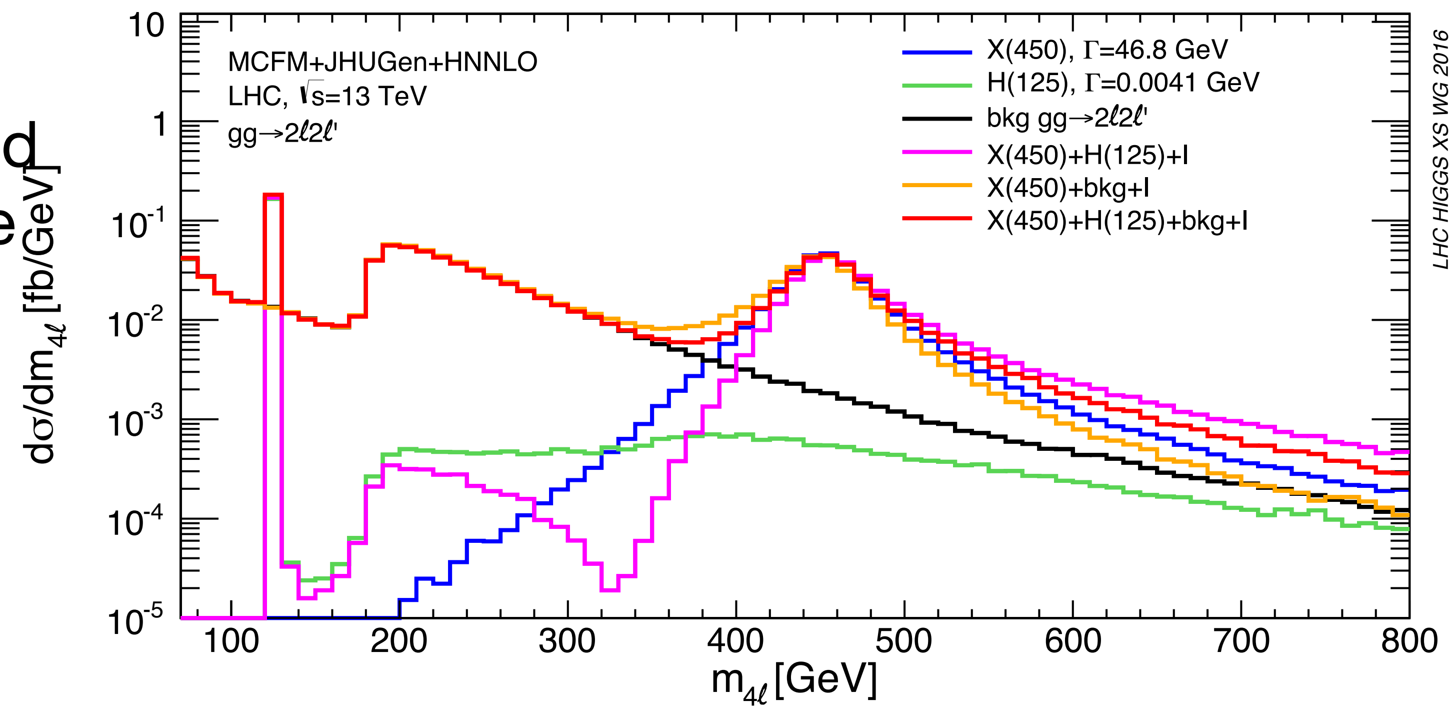
- Search for add. narrow resonance, width less than 1% of m_H (dominated by the resolution)
  - → Acceptance and efficiency modeled using gluon fusion production for masses 120 - 850 GeV



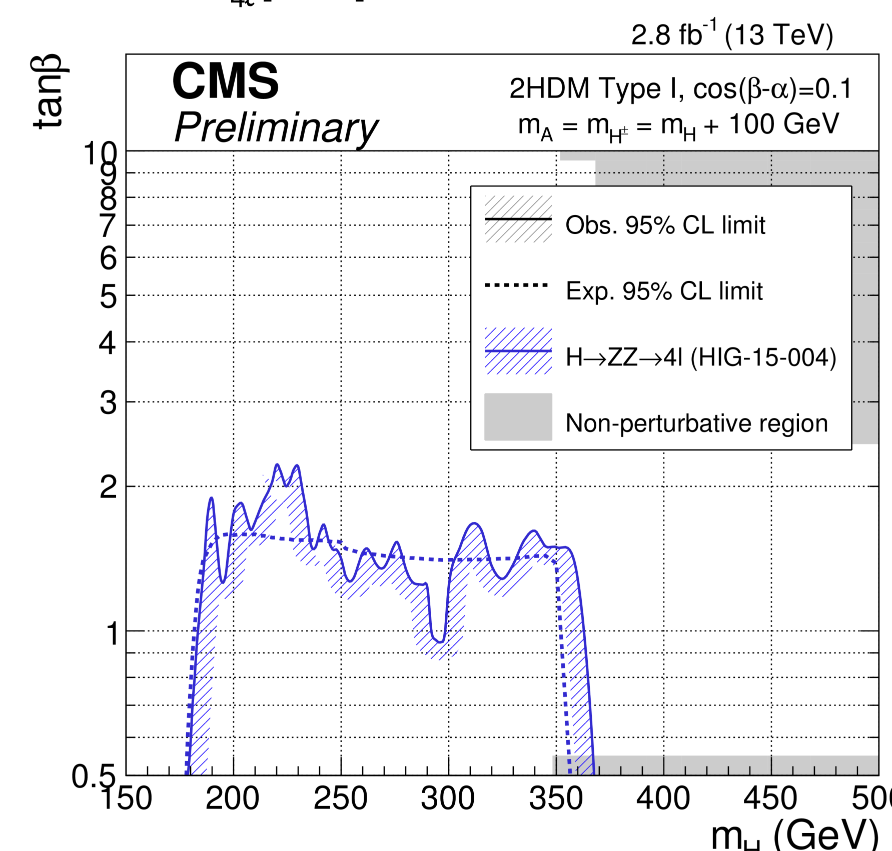
- Few systematic uncertainties treated as shape (EWK correction). Fit to derive a 95% on σ × BR

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-15-004

- Search for any resonance is of high priority. Recent hints of an excess around $m_{\gamma\gamma} \sim$ 750 GeV make this task even more urgent.



- Production mechanism at high mass is predominantly gluon fusion with substantial contribution from VBF (here only gluon fusion).



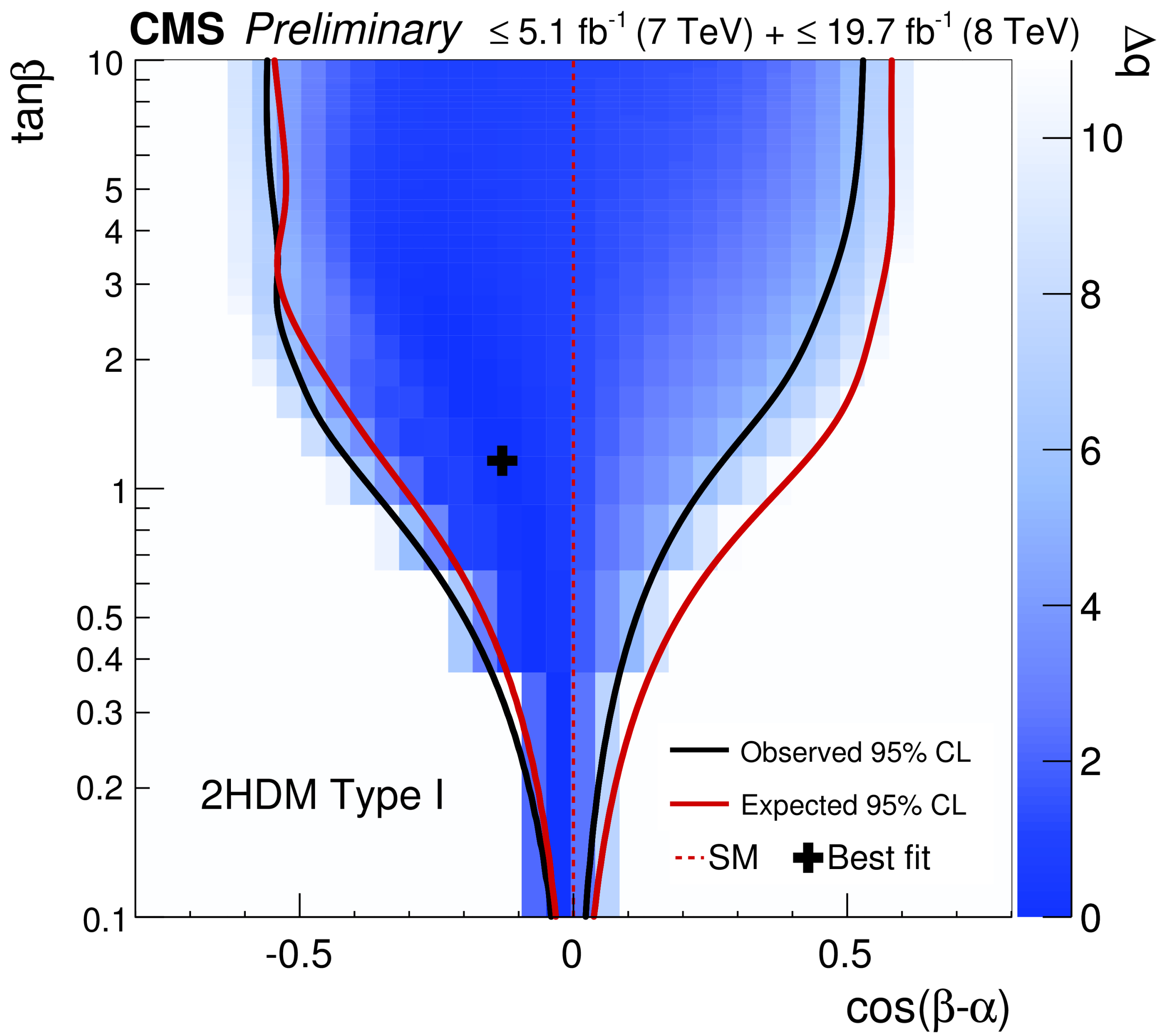
- Treated as one process in gg-fusion:
  → P(m_{4l}, m_X, Γ_X, σ_X) for the gg → bkg + H(125)* + X(mX) → 4l allows inclusion of interference, including off-shell tail of H(125)
  → m_H, Γ_H, m_X, Γ_X are also included as general parameters of the model
  → Limits at the 95% CL on σ·Br for several values of Γ_X

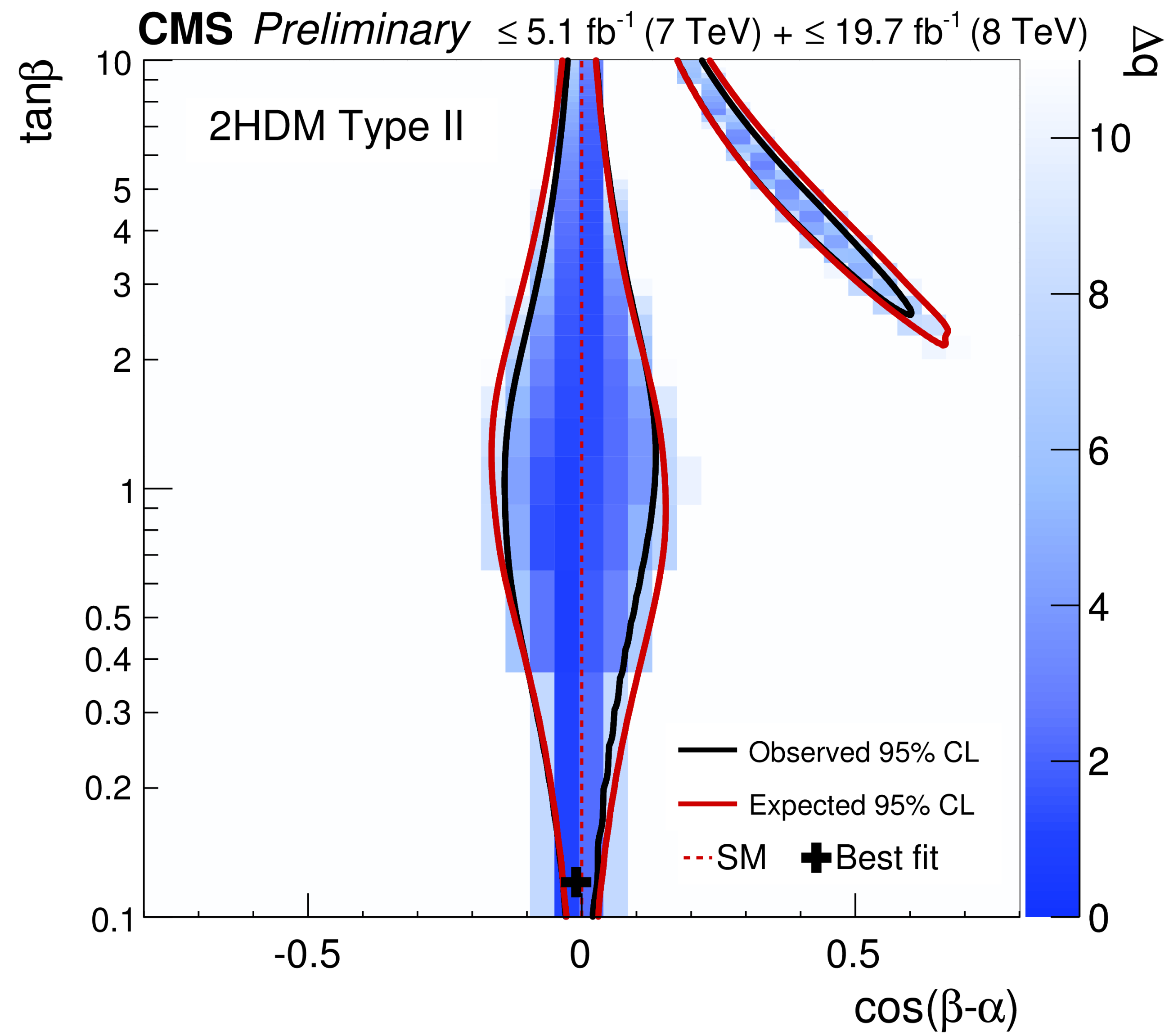
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-15-004

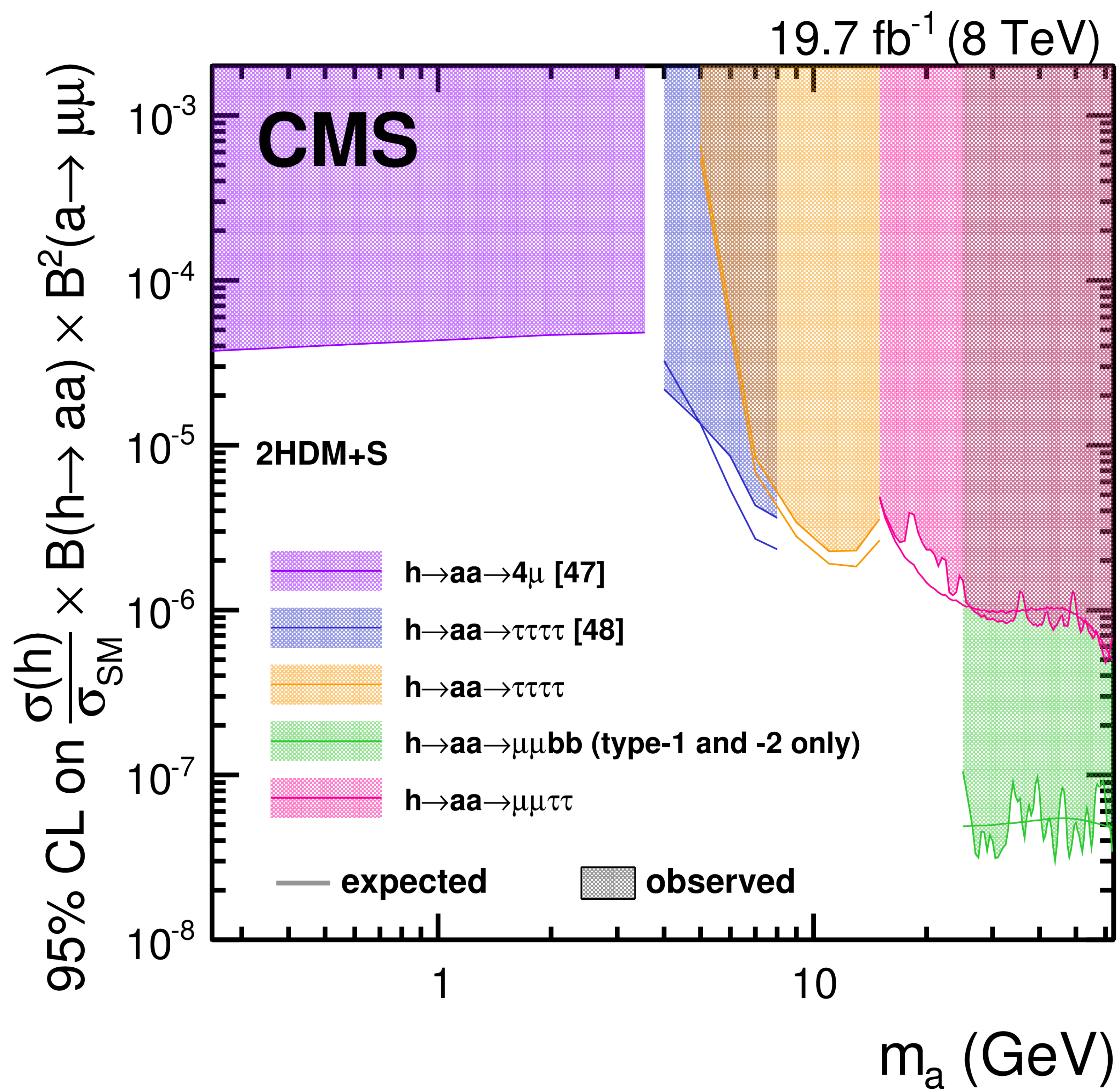
Constrain from h(125) observation

- 2HDM is constrained from H(125) properties:
  Preventing FCNC leave only two free parameters in the Higgs sector
  → tanβ: ration of vev's associated with the doublets
  → α: mixing between the fields associated with the doublets

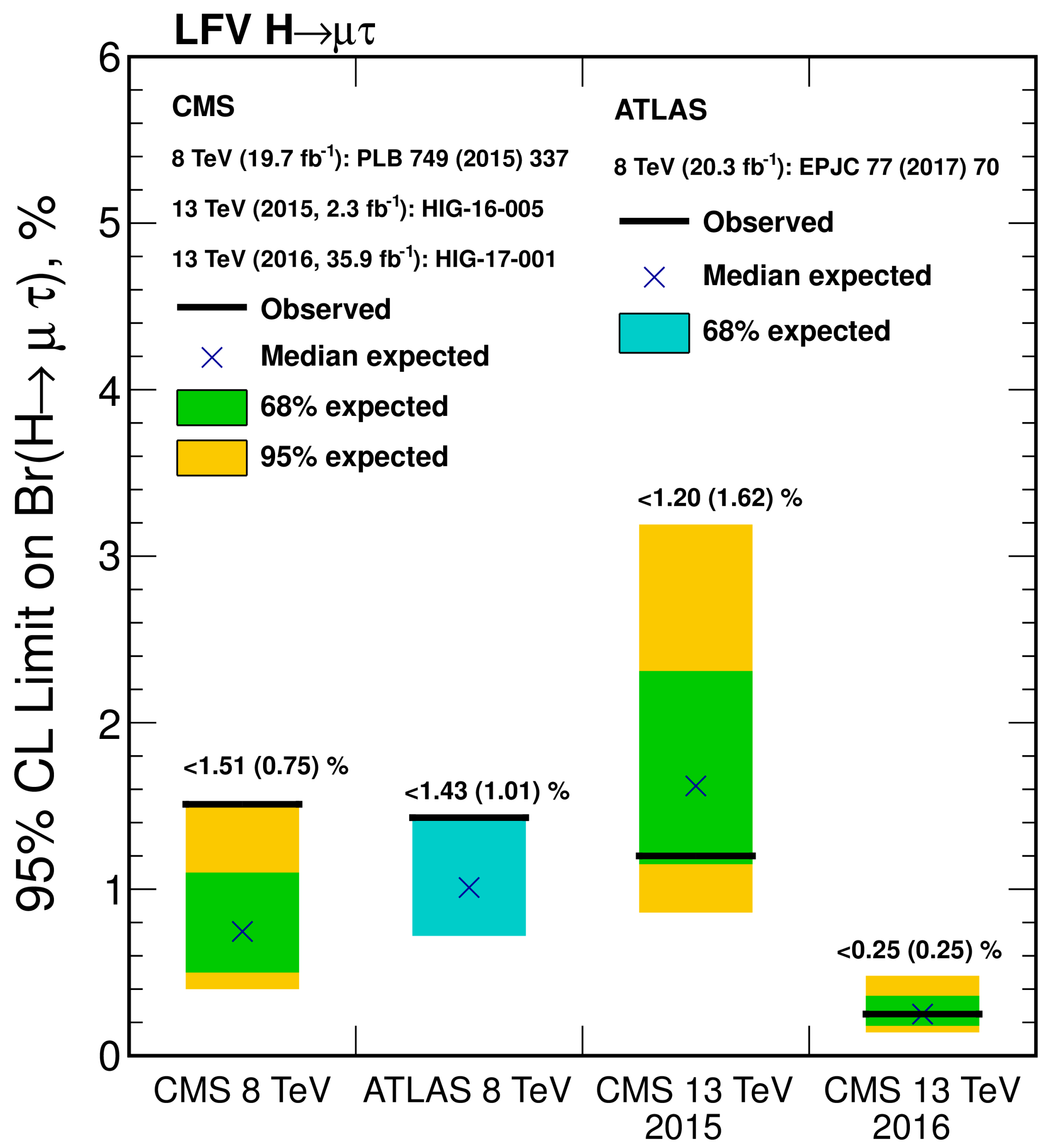
$$q(\lambda_{du}, \lambda_{Vu}, \kappa_{uu}) = -2\ln\left(\frac{\mathcal{L}(\text{data}|\lambda_{du}, \lambda_{Vu}, \kappa_{uu})}{\mathcal{L}(\text{data}|\hat{\lambda}_{du}, \hat{\lambda}_{Vu}, \hat{\kappa}_{uu})}\right)$$

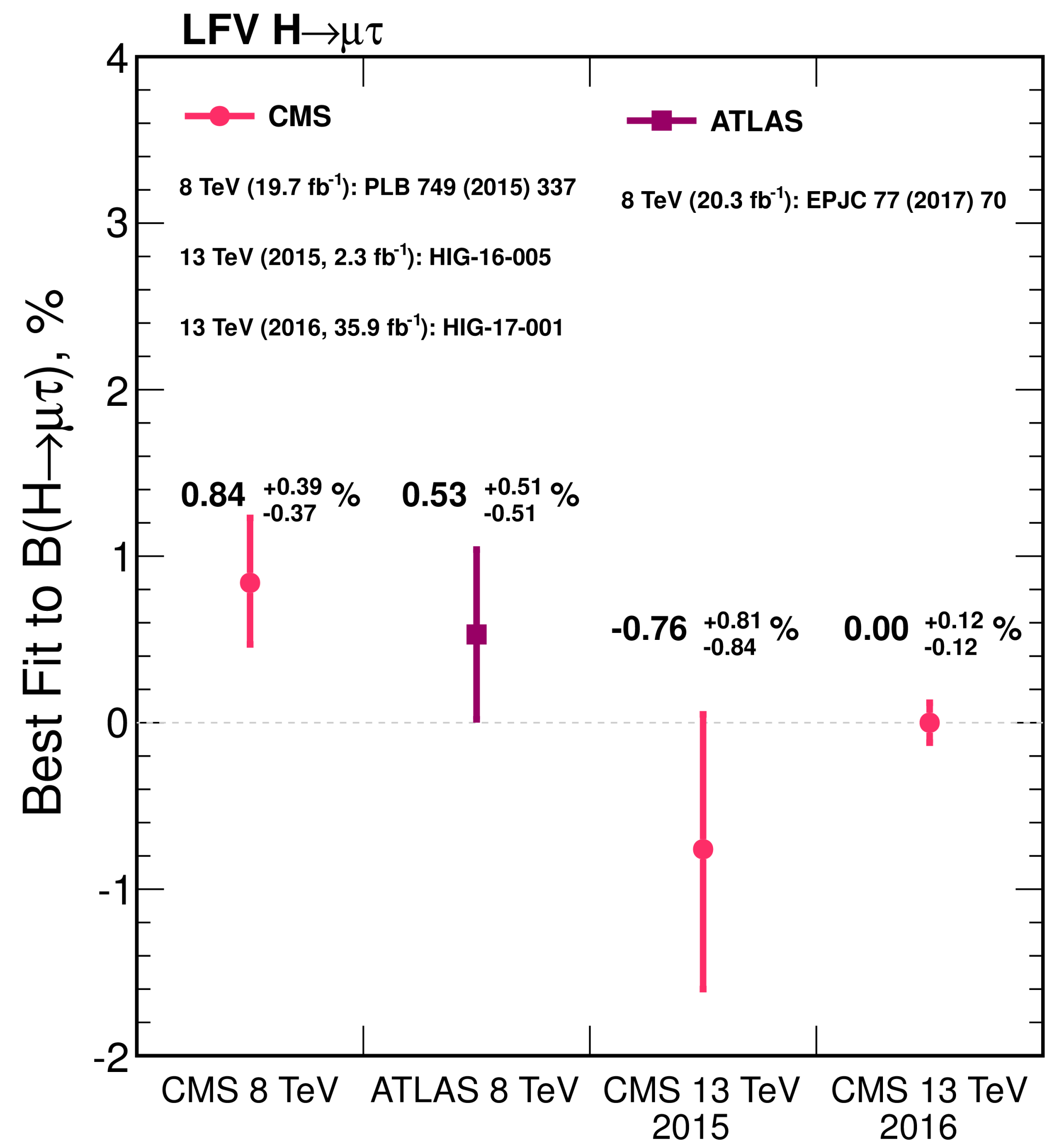


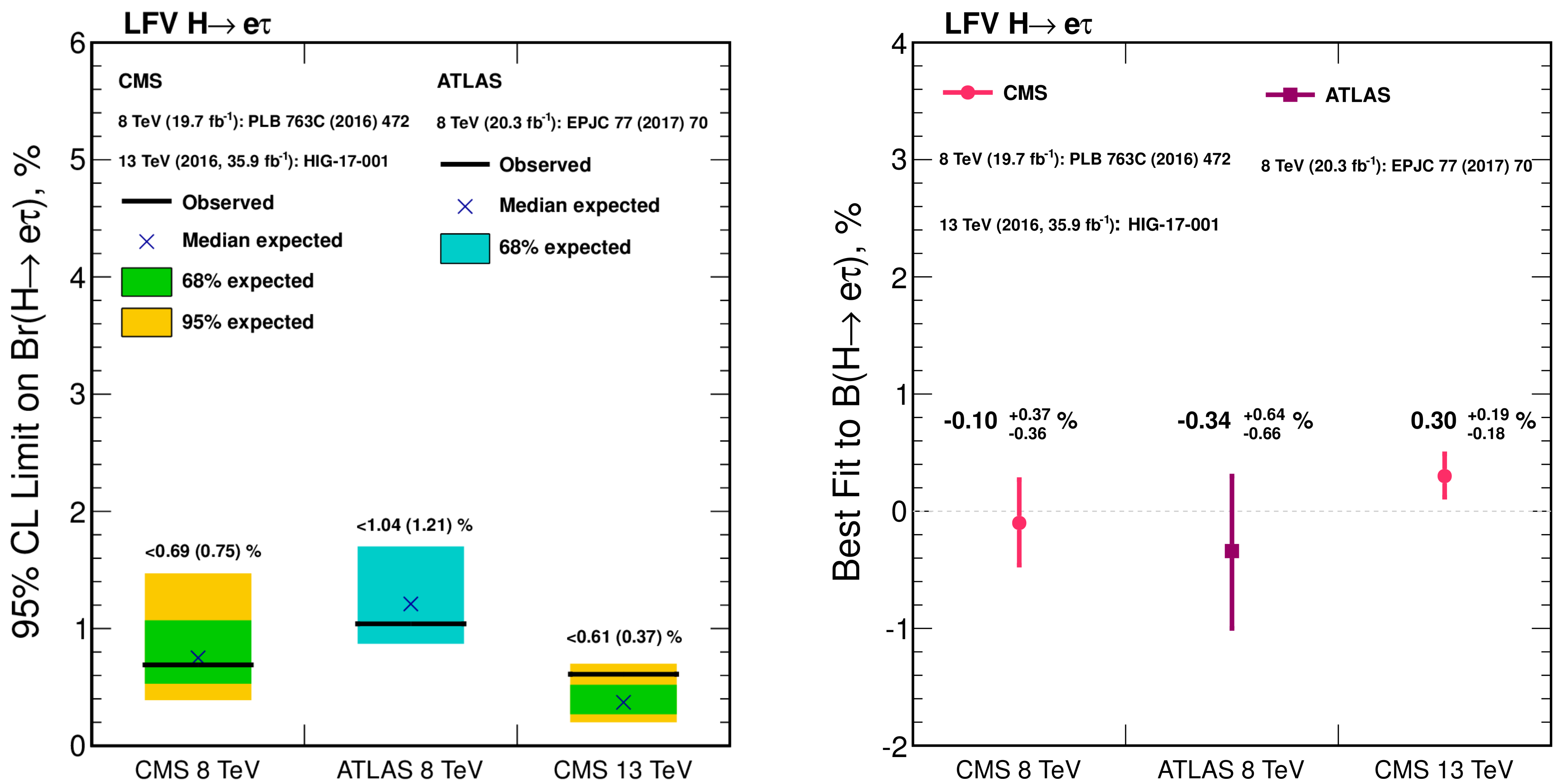




19.7 fb^{-1} (8 TeV)
CMS
2HDM+S
h→aa→4μ [47]
h→aa→ττττ [48]
h→aa→ττττ
h→aa→μμbb (type-1 and -2 only)
h→aa→μμττ
expected
observed
95% CL on $\frac{\sigma(h)}{\sigma_{SM}} \times B(h \to aa) \times B^2(a \to \mu\mu)$
m_a (GeV)


LFV H→μτ
95% CL Limit on Br(H→ μ τ), %
CMS
8 TeV (19.7 fb-1): PLB 749 (2015) 337
13 TeV (2015, 2.3 fb-1): HIG-16-005
13 TeV (2016, 35.9 fb-1): HIG-17-001
Observed
Median expected
68% expected
95% expected
ATLAS
8 TeV (20.3 fb-1): EPJC 77 (2017) 70
Observed
Median expected
68% expected
<1.51 (0.75) %
<1.43 (1.01) %
<1.20 (1.62) %
<0.25 (0.25) %
CMS 8 TeV
ATLAS 8 TeV
CMS 13 TeV 2015
CMS 13 TeV 2016


LFV H→μτ
Best Fit to B(H→μτ), %
CMS
ATLAS
8 TeV (19.7 fb-1): PLB 749 (2015) 337
13 TeV (2015, 2.3 fb-1): HIG-16-005
13 TeV (2016, 35.9 fb-1): HIG-17-001
8 TeV (20.3 fb-1): EPJC 77 (2017) 70
0.84 +0.39 -0.37 %
0.53 +0.51 -0.51 %
-0.76 +0.81 -0.84 %
0.00 +0.12 -0.12 %
CMS 8 TeV
ATLAS 8 TeV
CMS 13 TeV 2015
CMS 13 TeV 2016



LFV H→ eτ
95% CL Limit on Br(H→ eτ), %
CMS
8 TeV (19.7 fb-1): PLB 763C (2016) 472
13 TeV (2016, 35.9 fb-1): HIG-17-001
Observed
Median expected
68% expected
95% expected
ATLAS
8 TeV (20.3 fb-1): EPJC 77 (2017) 70
Observed
Median expected
68% expected
<0.69 (0.75) %
<1.04 (1.21) %
<0.61 (0.37) %
CMS 8 TeV
ATLAS 8 TeV
CMS 13 TeV
LFV H→ eτ
Best Fit to B(H→ eτ), %
CMS
ATLAS
8 TeV (19.7 fb-1): PLB 763C (2016) 472
8 TeV (20.3 fb-1): EPJC 77 (2017) 70
13 TeV (2016, 35.9 fb-1): HIG-17-001
-0.10 +0.37 -0.36 %
-0.34 +0.64 -0.66 %
0.30 +0.19 -0.18 %
CMS 8 TeV
ATLAS 8 TeV
CMS 13 TeV