Rare and Exotic decays of H(125)

Yuri Gershtein

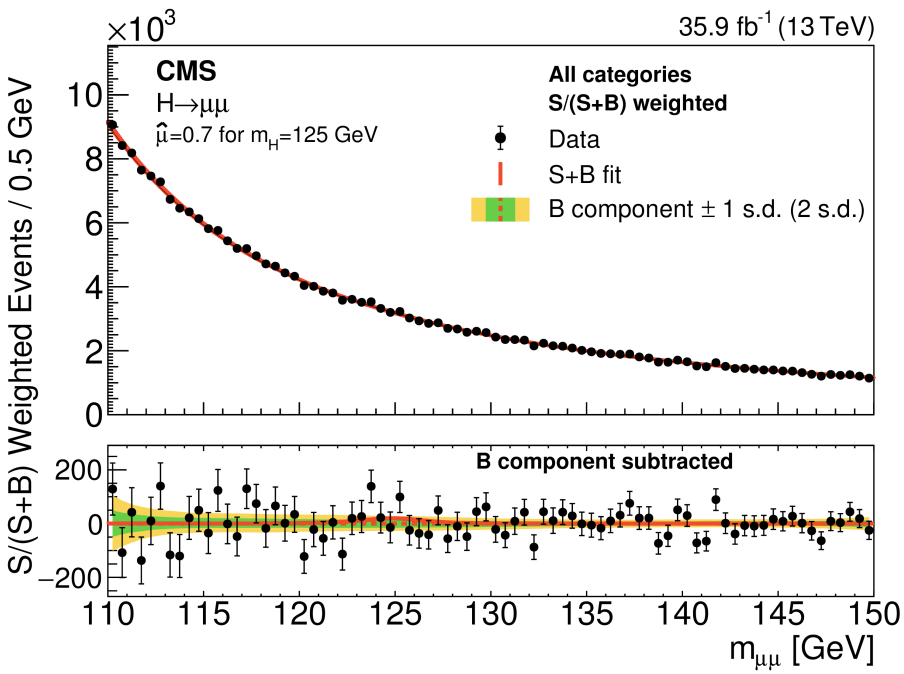
Outline

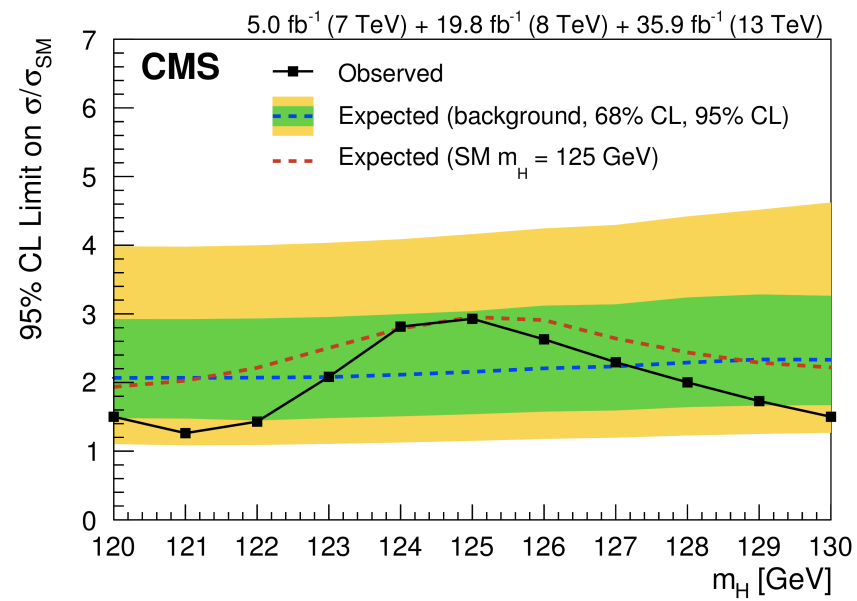
- Do the masses of the second and first generation fermions come from Yukawa couplings to the Higgs
  - $H \to \mu\mu$
  - $H \to cc$: Exclusive decays are used to reduce background (also see CMS VH(cc) talk for the first result using charm jet tagging)
- Can we detect new, otherwise unobservable new particles, through their interaction with the Higgs
  - $H \to$ invisible
  - $H \to \gamma\gamma_D$
  - $H \to 4$ fermions
- Outlook for Run 3 and HL-LHC
  - New triggers and detectors

H→μμ

CMS-HIG-17-019

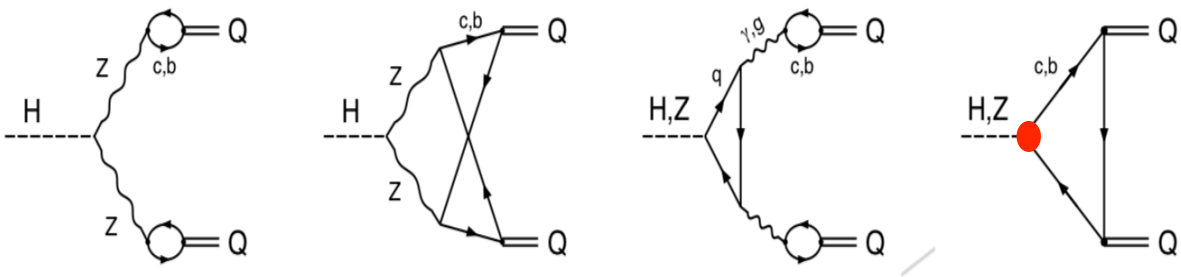
- Small signal on top of Drell-Yan background
- Events are classified according to kinematics (BDT) and expected resolution ($\max(|\eta(\mu_1)|, |\eta(\mu_2)|)$)
- 14 categories with algorithmically determined boundaries
  - most sensitive one is enriched with VBF production
  - Statistics dominates uncertainty; maximum systematics from category migration arising from jet energy scale and resolution



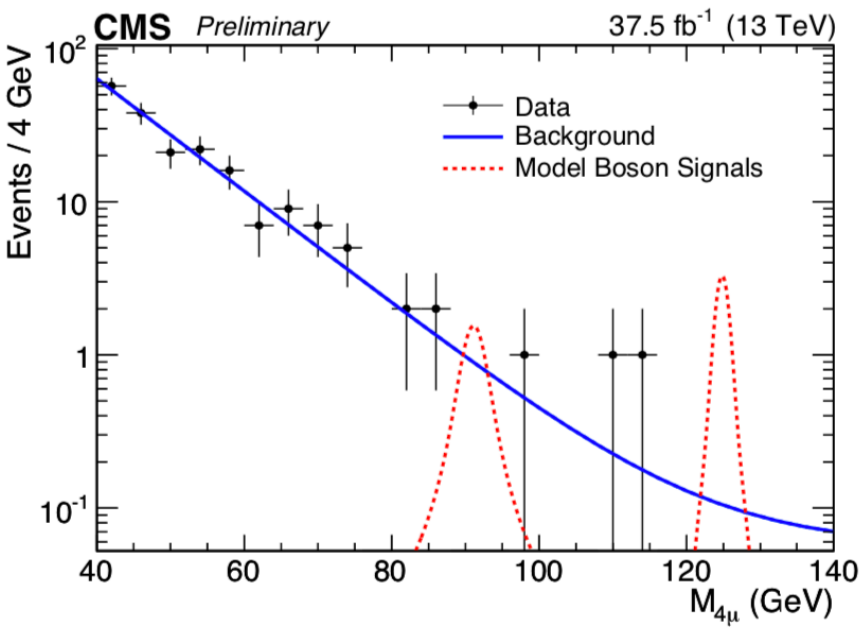


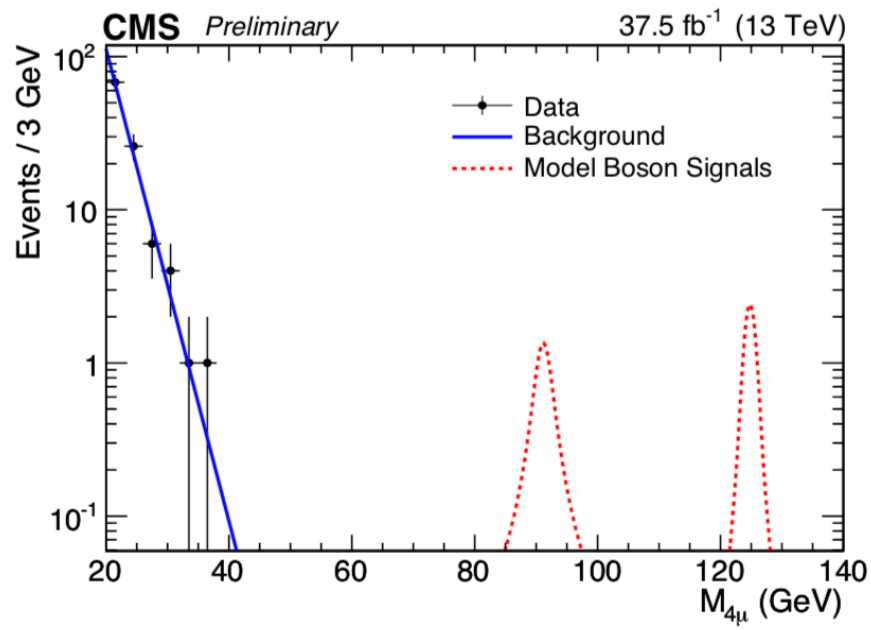
H→J/ψ J/ψ

CMS-HIG-18-025



- Clean 4μ final state
- For Higgs decays, contributions from Yukawa couplings mix with other SM



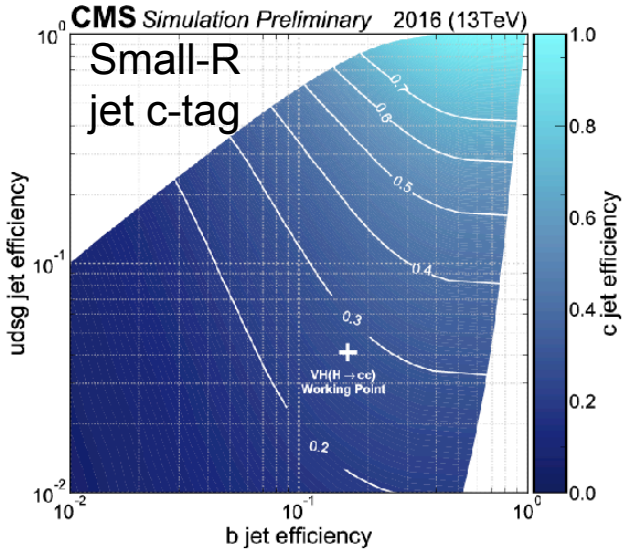


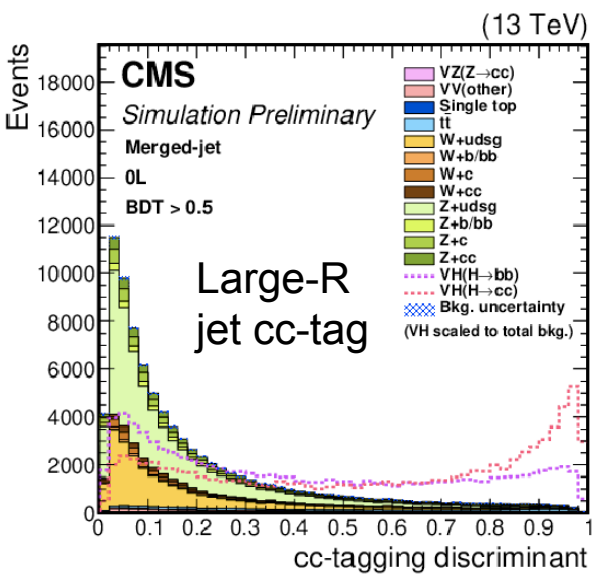
- The analysis is also sensitive to H→YY and Z decays
- Background is dominated by heavy flavor production, reduced by requiring the four muons to originate from the same vertex with a vertex probability of more then 5% (1% for YY), leaving mostly prompt di-J/ψ production

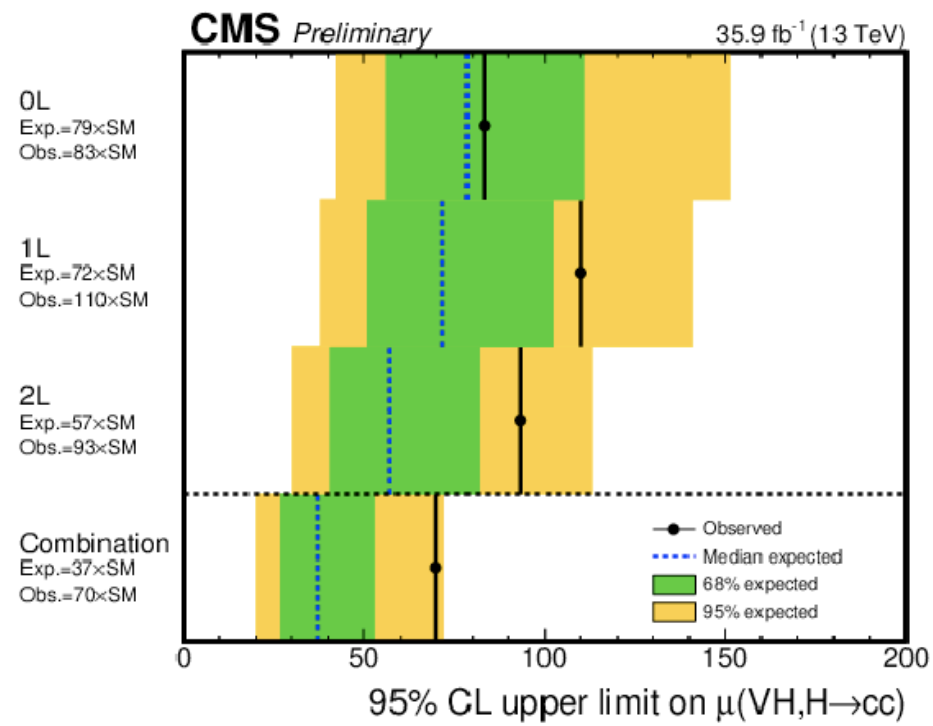
VH→cc with c-flavor tag

CMS-HIG-18-031

- First CMS search of its kind! See Loukas'es talk on Wednesday







- ~2σ excess
- μ < 70 (μ < 37 expected)

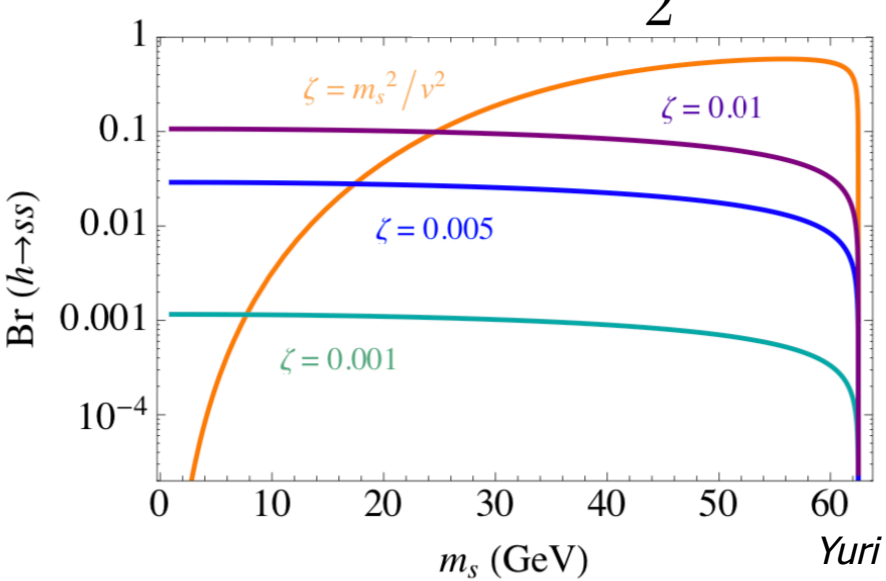
Rare Decay Summary

	observed	expected	SM value	ref
$H \to \mu\mu$	$5.7 \cdot 10^{-4}$	$4.1 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	CMS-HIG-17-019
$H \to ee$	0.0019	0.0024	$5 \cdot 10^{-9}$	CMS-HIG-13-007
$H \to \gamma\, J/\psi$	$7.6 \cdot 10^{-4}$	$5.2^{+2.4}_{-1.6} \cdot 10^{-4}$	$3 \cdot 10^{-6}$	CMS-SMP-17-012
$H \to J/\psi J/\psi$	$1.8 \cdot 10^{-3}$	$1.8^{+0.2}_{-0.1} \cdot 10^{-3}$	$1.5 \cdot 10^{-10}$	CMS-HIG-18-025
$H \to cc$ inclusive	2.1	$1.1^{+0.5}_{-0.3}$	0.03	CMS-HIG-18-031
$H \to \Upsilon\Upsilon$	$1.4 \cdot 10^{-3}$	$1.4 \pm 0.1 \cdot 10^{-3}$	$2 \cdot 10^{-9}$	CMS-HIG-18-025
$Z \to \gamma\, J/\psi$	$1.4 \cdot 10^{-6}$	$1.6^{+0.7}_{-0.5} \cdot 10^{-6}$	$9 \cdot 10^{-8}$	CMS-SMP-17-012
$Z \to J/\psi J/\psi$	$2.2 \cdot 10^{-6}$	$2.8^{+1.2}_{-0.7} \cdot 10^{-6}$		CMS-HIG-18-025
$Z \to \Upsilon\Upsilon$	$1.5 \cdot 10^{-6}$	$1.8 \pm 0.1 \cdot 10^{-6}$		CMS-HIG-18-025

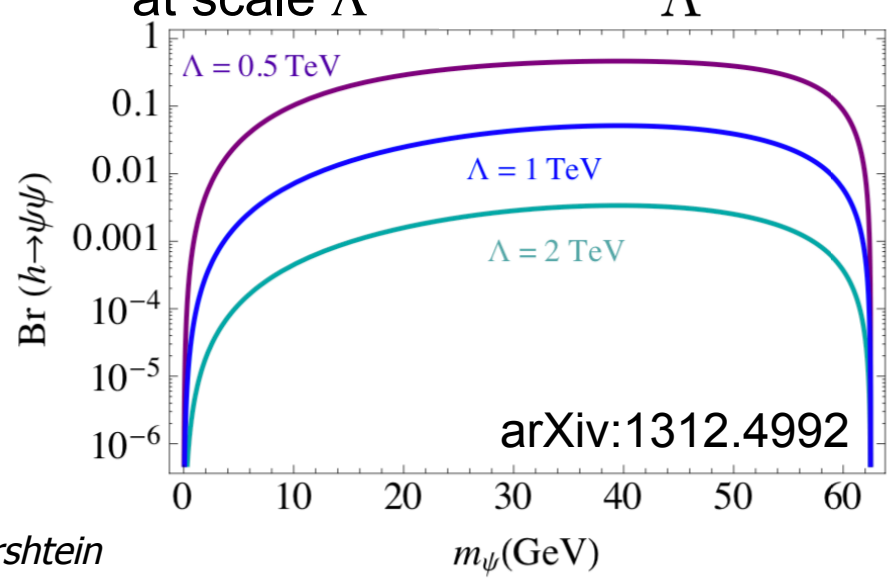
Exotic Higgs Decays

- Exotic Higgs decays do not have to be rare! $\Gamma_{SM} \sim 4$ MeV
  - Br(H→BSM)<34% @95% CL
- Plethora of BSM possibilities in the literature
  - Reflection of the experimental reality that DM exists but likely does not carry SM charges – yet we live in the same vacuum
  - Two out of three possible "portals" to hidden sectors involve the Higgs
  - Exotic Higgs decays are generically sensitive to large mass scales
- Target for BSM branching fractions: as low as possible!

scalar singlet $\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$



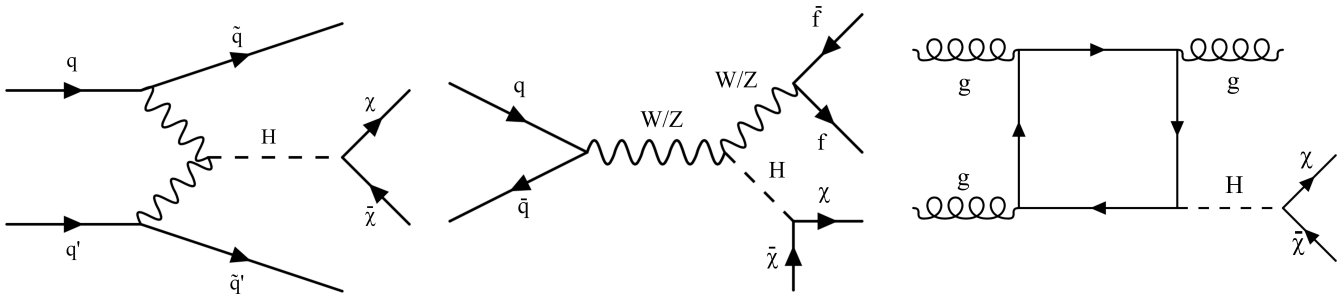
fermion coupled at scale Λ $\Delta\mathcal{L} = \frac{\mu}{\Lambda^2} |H|^2 \bar{\psi}\psi$



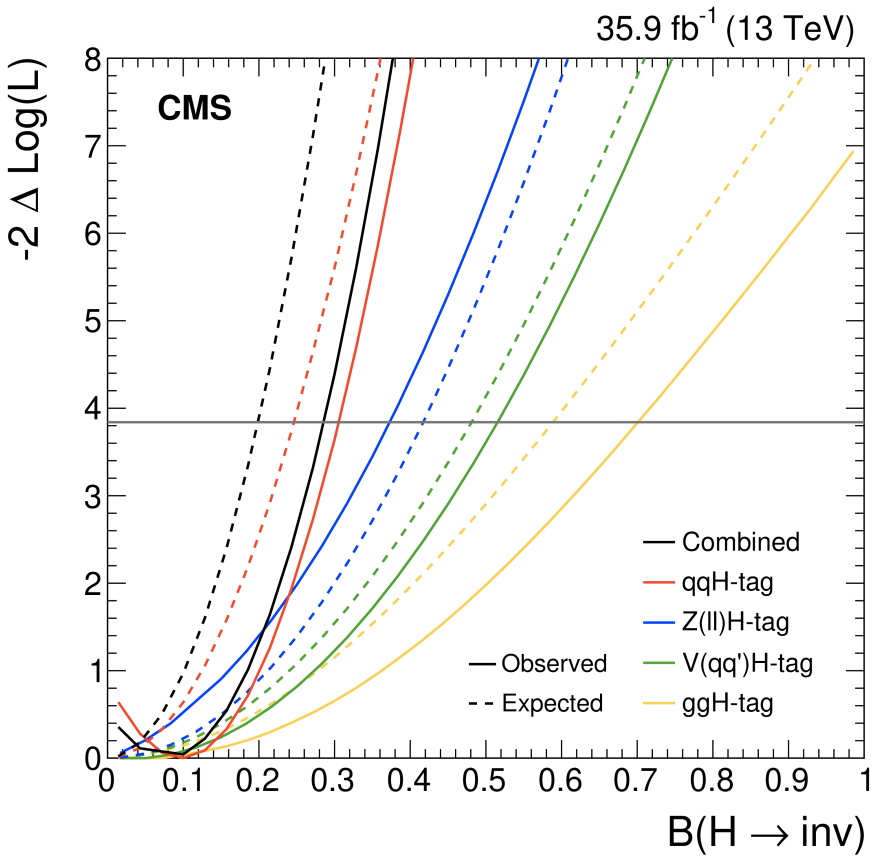
arXiv:1312.4992

H→invisible

CMS-HIG-17-023



- dedicated VBF analysis
- Z(ll)+H: EXO-16-052
- V(qq)+H: EXO-16-48
- ggH: EXO-16-048



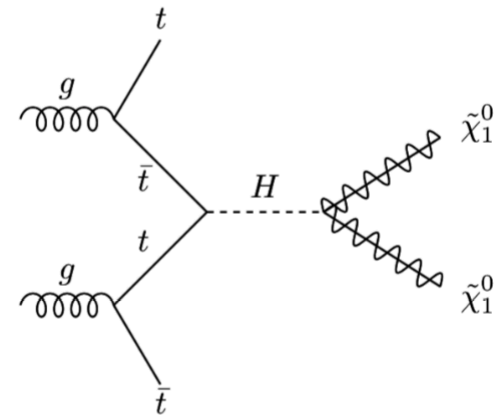
	observed	expected
VBF	0.33	0.25
Z(ll)H	0.40	0.42
V(qq')H	0.50	0.48
ggH	0.66	0.59

- VBF is the most sensitive
- Combining with 7 & 8 TeV

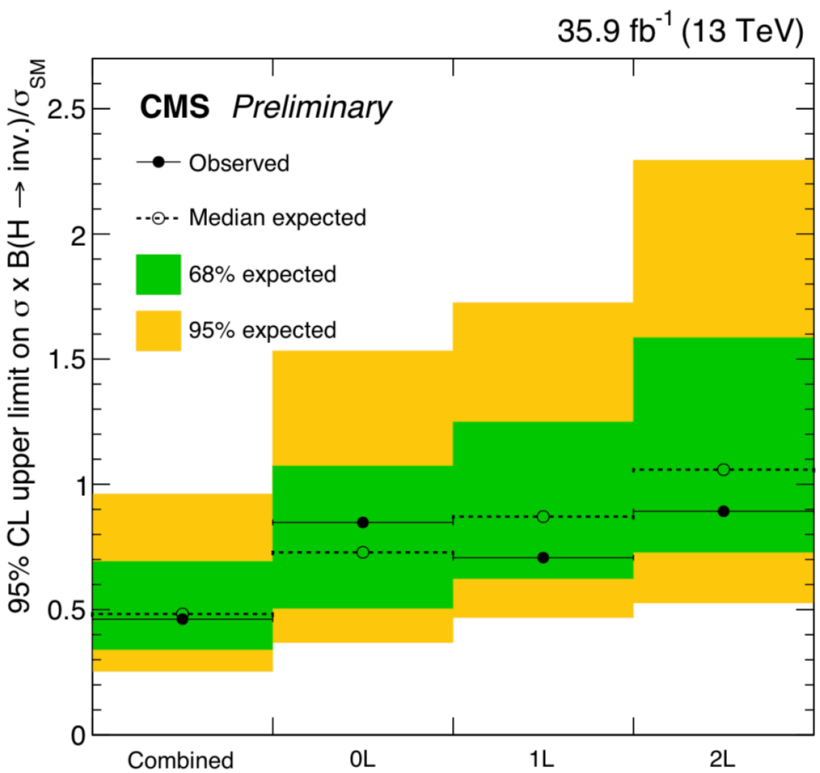
$$\mathrm{Br}(\mathrm{H} \rightarrow \mathrm{inv}) < 0.19\ (0.15)\ \ @95\%\ \mathrm{CL}$$

New: H→invisible in ttH

CMS-HIG-18-008



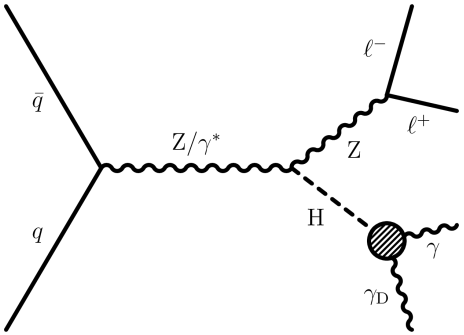
- Recast of SUSY stop searches in tt+MET
  - SUS-16-049: all-jets, 51 search regions
  - SUS-16-051: one lepton, 27 search regions (M_{lb})
  - SUS-17-001: OS leptons, 26 search regions (M_{T2})



- ~1.5 times better sensitivity then ggH, despite almost 100 times smaller cross section
  - ggH produces Higgs with low transverse momentum
  - Have to require large ISR jets in order to trigger and suppress QCD background offline
  - even more challenging for other (semi)visible hadronic Higgs decays

$H \rightarrow \gamma\gamma_D$

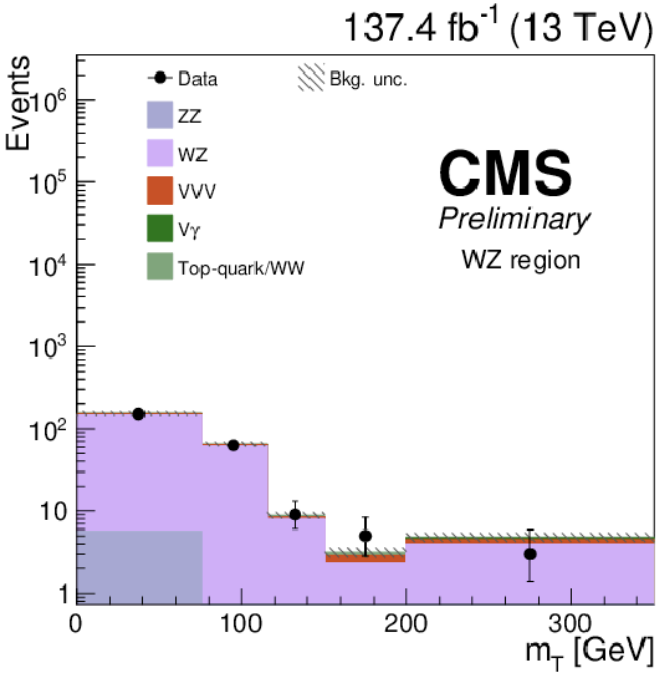
CMS-EXO-19-007



- Consider Z(→ll)H – use lepton trigger, small background
- OSSF leptons, 25/20 GeV, within 15 GeV from Z mass
- Photon above 25 GeV
- Use m_T(photon, MET) as sensitive variable
- Zγ/jet with fake MET can be suppressed to negligible level

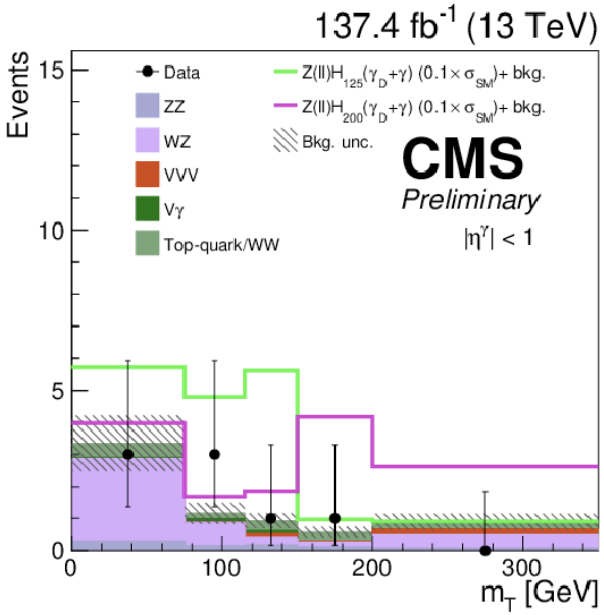
γ_D here is stable and massless

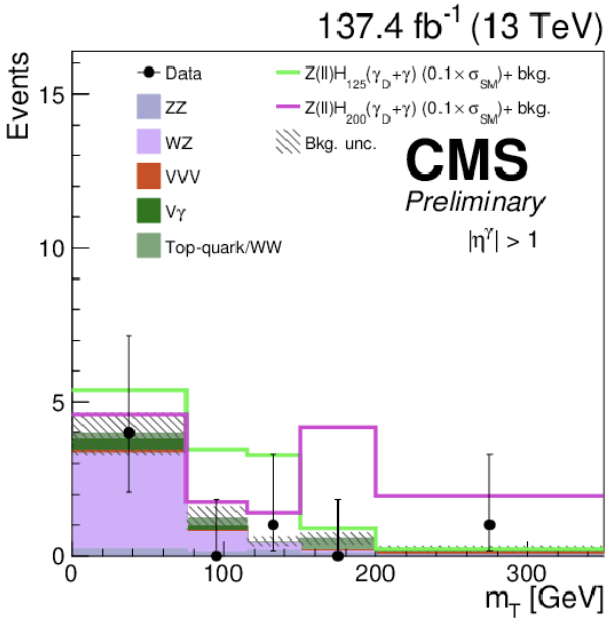
$\Delta\phi_{\vec{\ell\ell},\vec{p}_T^{miss}+\vec{E}_T^{\gamma}}$	>2.5 radians
$\lvert p_T^{\vec{p}_T^{miss}+\vec{E}_T^{\gamma}} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell}$	<0.4
$\Delta\phi_{jet,p_T^{miss}}$	>0.5
$p_T^{\ell\ell}$	> 60 GeV
$m_{\ell\ell\gamma}$	> 100 GeV
p_T^{miss}	> 110 GeV

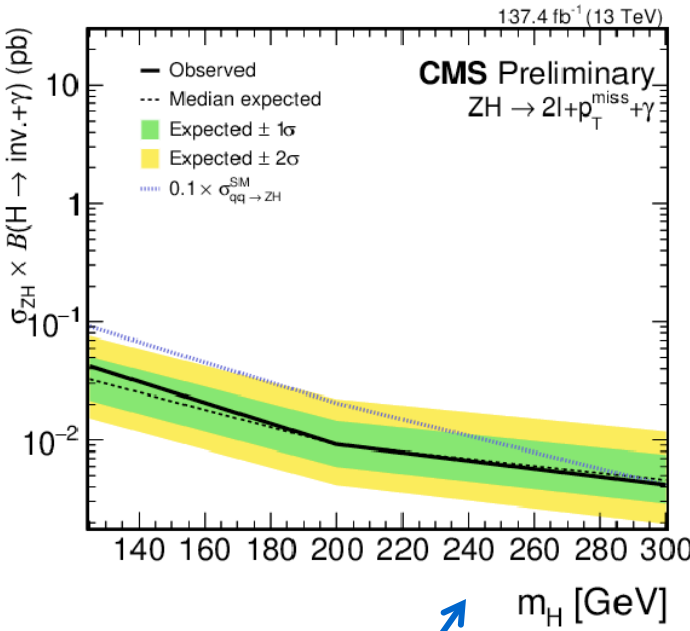


- Suppress top with b-veto
- Main background after that WZ→2l+e, with electron misidentified as a photon
- Separate $|\eta_\gamma|<1$ and $|\eta_\gamma|>1$ (tracker geometry)
- Fix the normalization from 3l control region

$H \to \gamma\gamma_D$







- Br($H\to\gamma\gamma_D$) < 4.6 (3.6) % (SM Br($H\to\gamma Z(\to\nu\nu)$)= $3\cdot10^{-4}$
- Also sensitive to other BSM decays

$$H \to \tilde{G}\,\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\,\gamma$$

$$H \to \tilde{\chi}_2^0\,\tilde{\chi}_1^0 \to \gamma\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

$$H \to NN \to (\gamma\nu)(\nu\bar{\nu}\nu)$$

- Also sensitive to heavier Higgs states

H→ 4 fermions

- Multiple scenarios give such final states
  - $H \to aa'$, ss', V_1V_2, $aV_1 \to (xx)(yy)$
    - *x* and *y* are quarks or leptons
    - Pseudo-scalars or scalars can also decay into photon or gluon pairs
    - (qq)(qq)
    - (ll)(qq)
    - (ll)(ll)
  - $H \to \chi_2\chi_1 \to a\chi_1\chi_1$ or $V\chi_1\chi_1$
    - (qq)+MET
    - (ll) + MET
  - These new particles may or may not decay preferentially to heavier particles (b's and τ's)
    - Also, the lifetime can be from prompt to displaced
- New CMS searches since HH2018:
  - $\mu\mu bb$ CMS-HIG-18-011
  - $\tau\tau\tau\tau$ CMS-HIG-18-006

Masses could be such that the leptons / quarks are soft and / or close together in ΔR

Generically, main difficulty is triggering and QCD background rejection, favoring use of the decays involving leptons and/or associated production

Notable exception are long-lived decays, where the main difficulty is the trigger

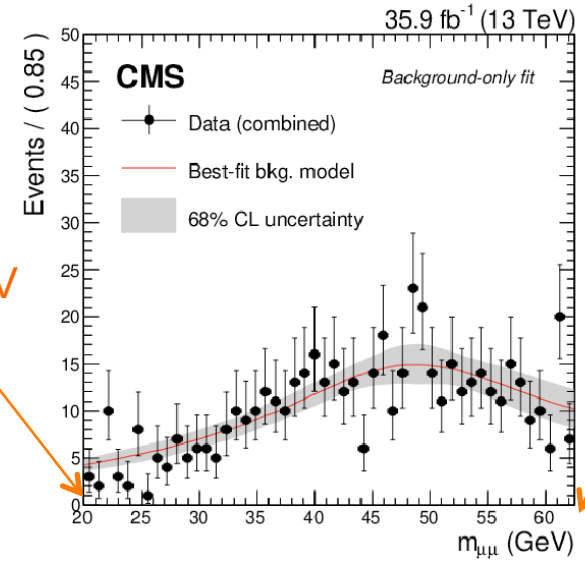
H→μμbb

- di-muon trigger
- assume one new resonance and cut on

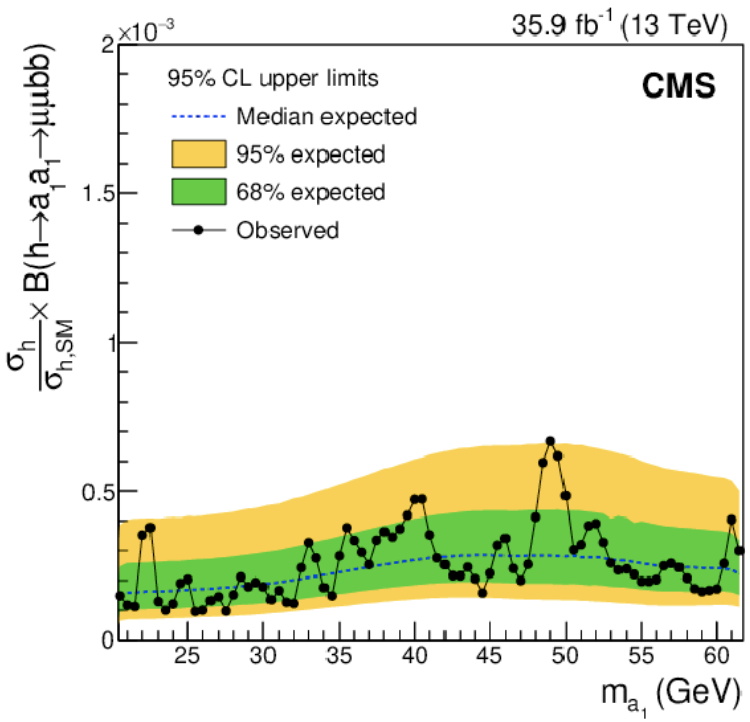
$$\chi^2 = \left(\frac{m_{bb} - m_{\mu\mu}}{\sigma_{bb}}\right)^2 + \left(\frac{m_{bb\mu\mu} - 125}{\sigma_{bb\mu\mu}}\right)^2 < 5$$

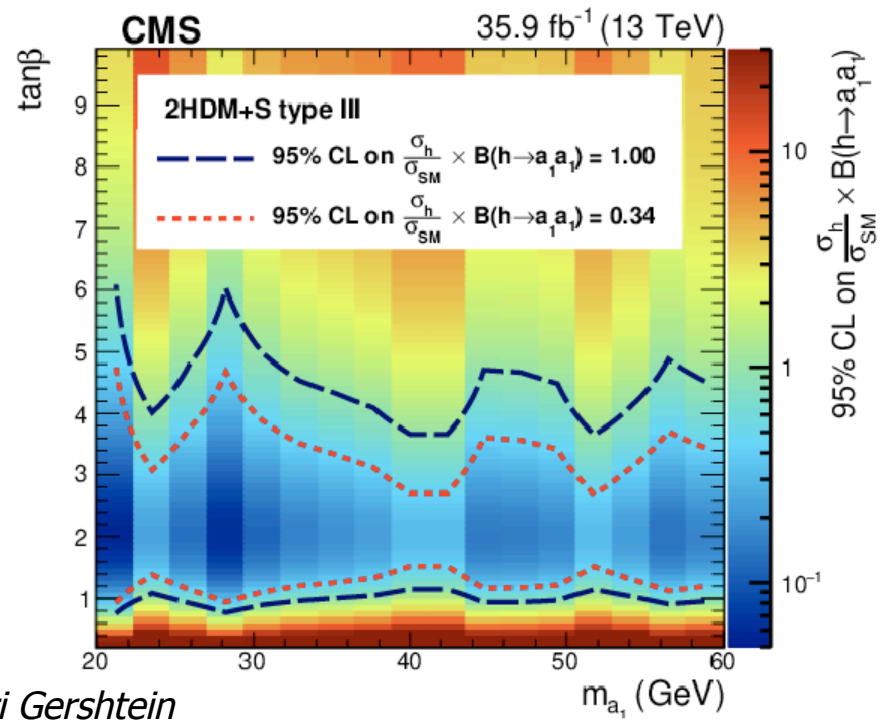
- Sensitive variable: dimuon mass
- Categories in b-tag tightness
- Limits Br(H→μμbb) ~ (1÷7)10^{-4}
  - Model is needed to get to Br(H→aa)

below 20 GeV b's merge' need substructure techniques



~$m_H/2$

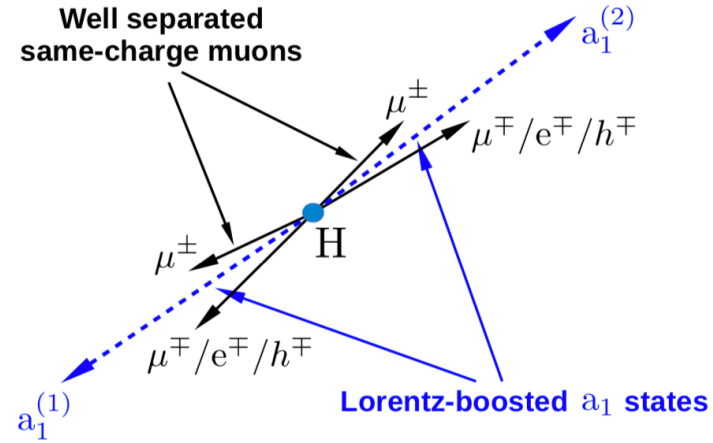


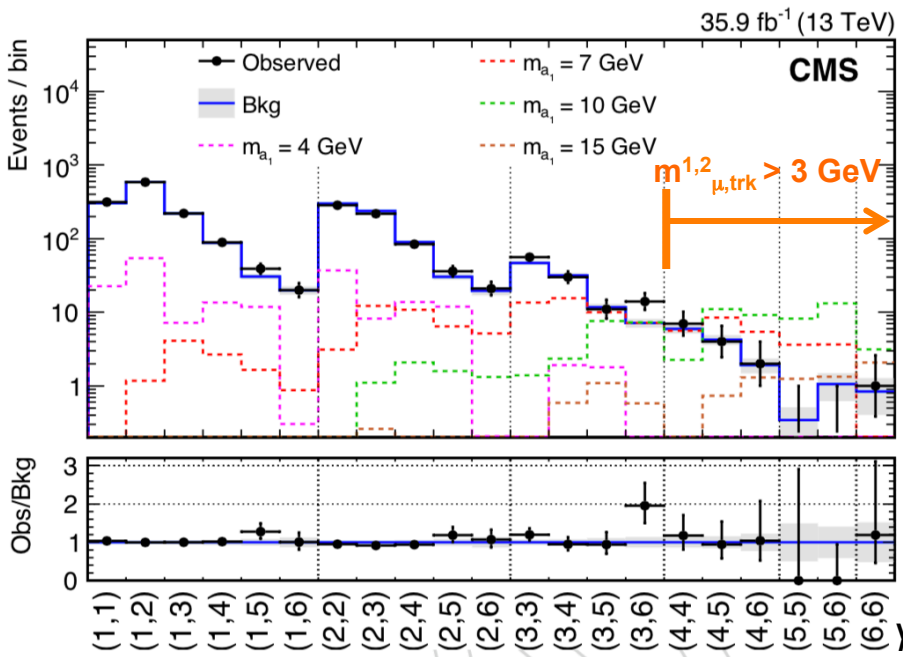


$H \to \tau\tau\tau\tau \to \mu^{\pm\pm}$ +2 tracks

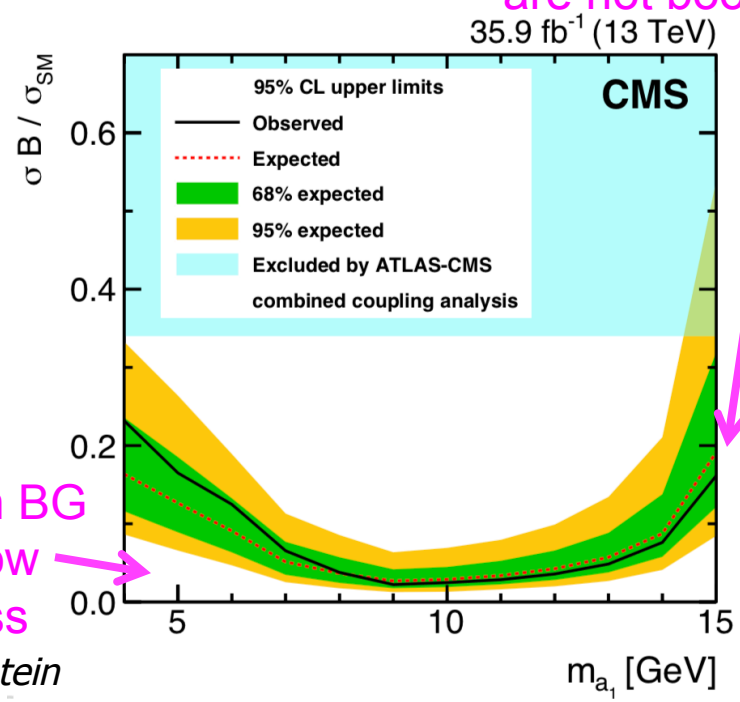
CMS-HIG-18-006

- Same sign muons (18/10 GeV), dR > 2
- Each has to have an opposite charge track within dR=0.5, and no other tracks above 1 GeV
- Events are classified based on the two observed μ-trk masses
  - 0-1, 1-2, 2-3, 3-4, 4-6, >6 GeV
- Contribution from $H \to \mu\mu\tau\tau$ is considered
  - But good $\mu\mu$ mass resolution is not exploited to keep analysis simple and general
- Important to extend for a_1 masses 12-60 GeV





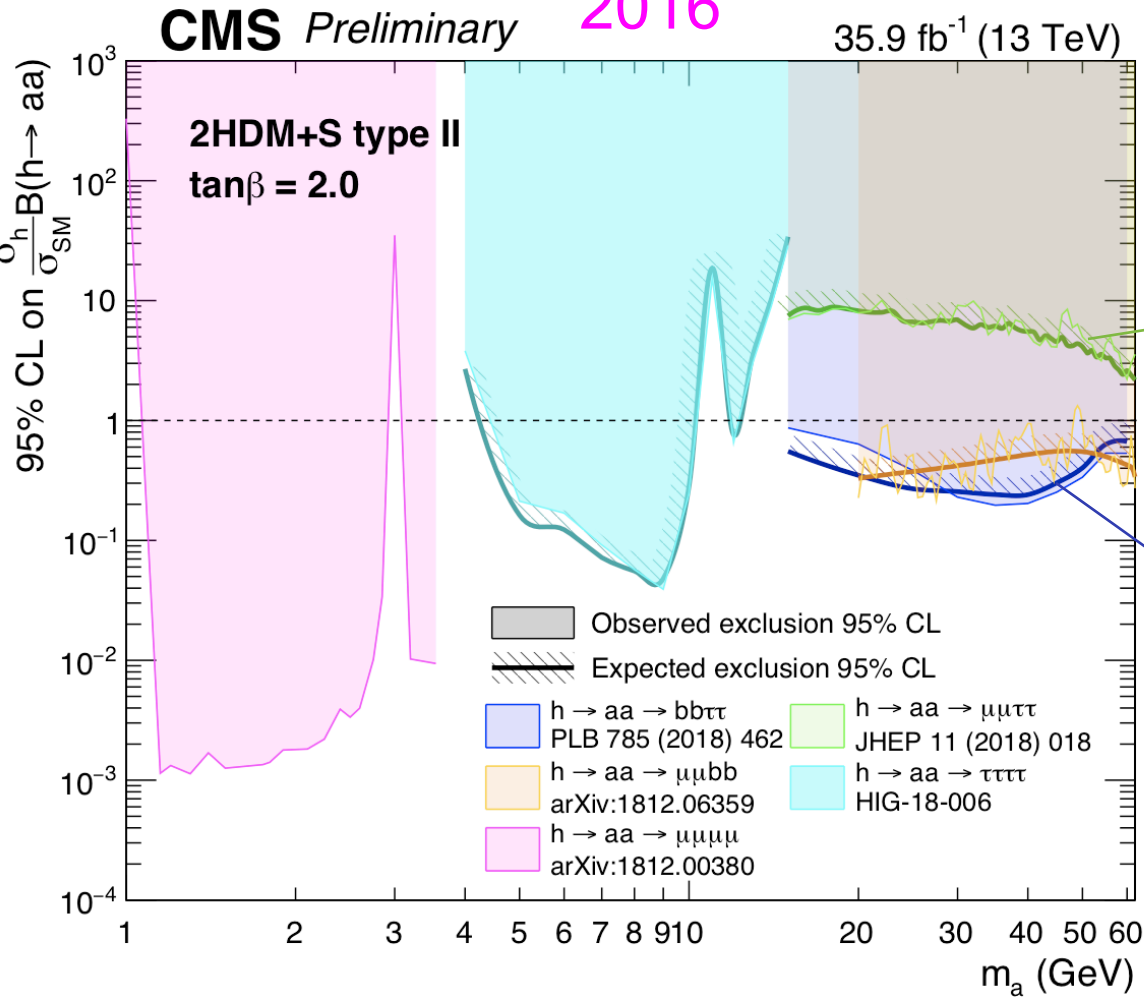
decay products of a_1 are not boosted



high BG at low mass

H→aa for a benchmark model

2016



2035

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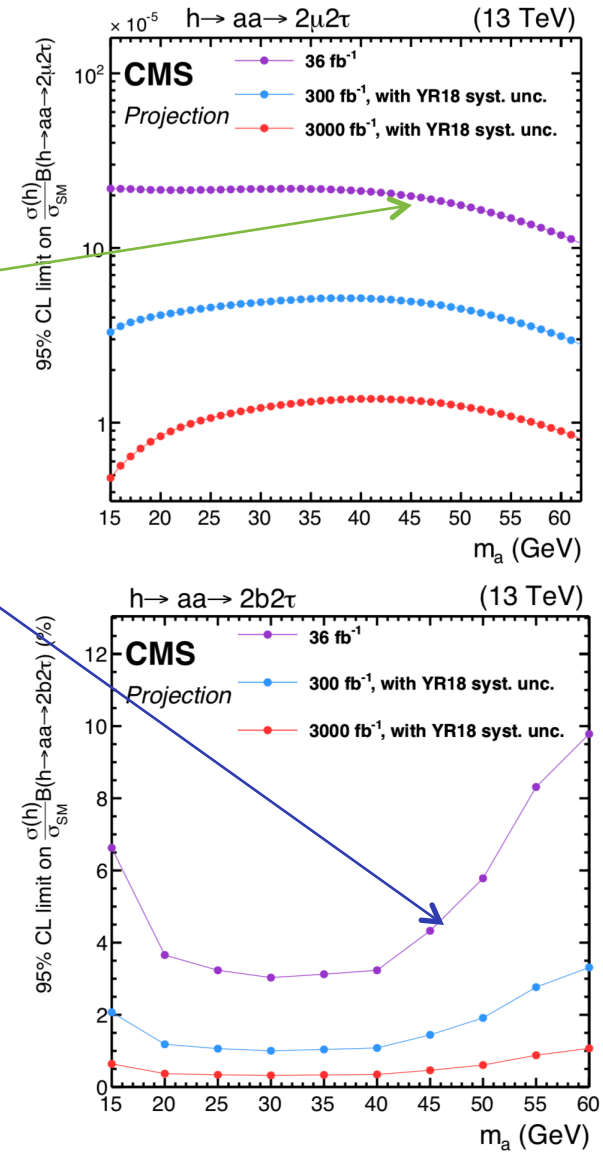

Developing new triggers and experimental techniques is imperative

Run 3 and HL-LHC

- Beginning in Run 3: standalone muon trigger on displaced muons

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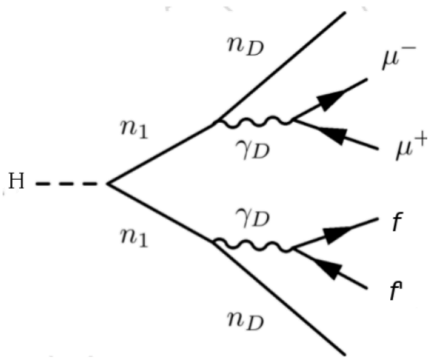
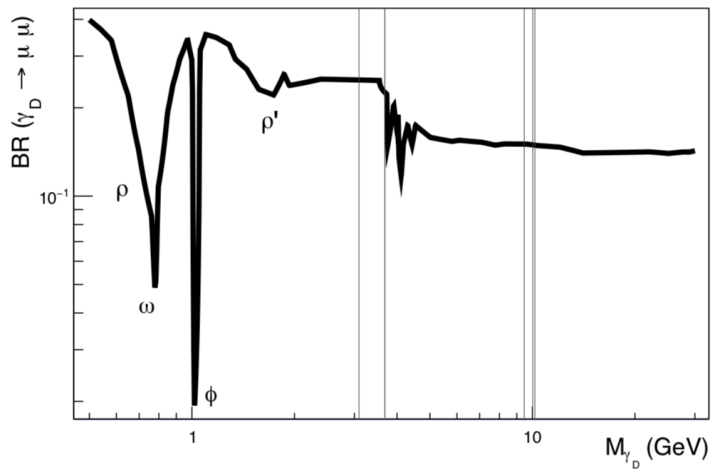
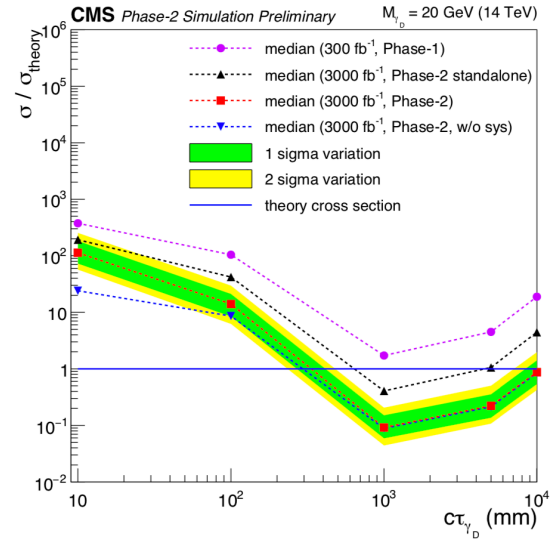
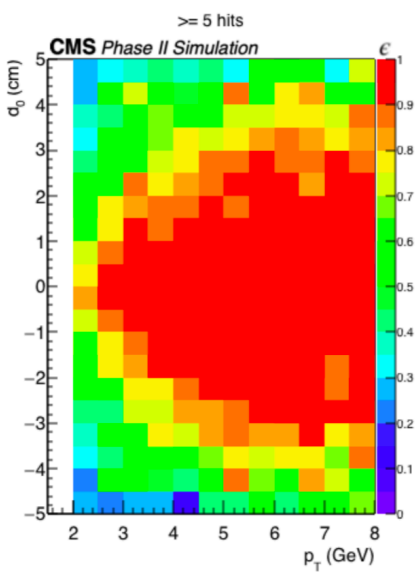


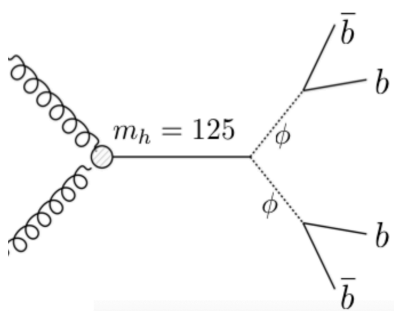


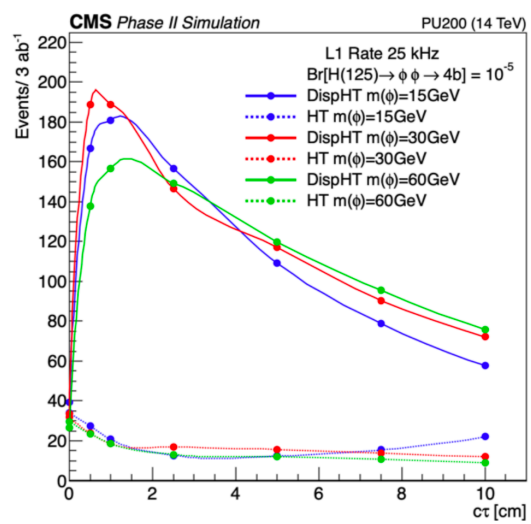


- HL-LHC: 30-40 ps timing for tracks and photons, track trigger efficient up to ~few cm

FTR-18-018







10^{-6} reach in Higgs branching fraction is plausible

Summary

- Legacy Run 2 analyses are progressing
  - $H \to \mu\mu$ is within striking distance – stay tuned!
- Higgs decays may be our only window on the Dark Sector
  - A lot of work is done, but we really only beginning to scratch the surface
    - Semi-visible final states, long-lived particles, etc.
- New triggers and experimental ideas are required to take full advantage of the large number of Higgs bosons LHC is producing
  - should be one of the main goals for HL-LHC and the upgrades